EICでの物理（実験）

TAKU GUNJI

CENTER FOR NUCLEAR STUDY

THE UNIVERSITY OF TOKYO

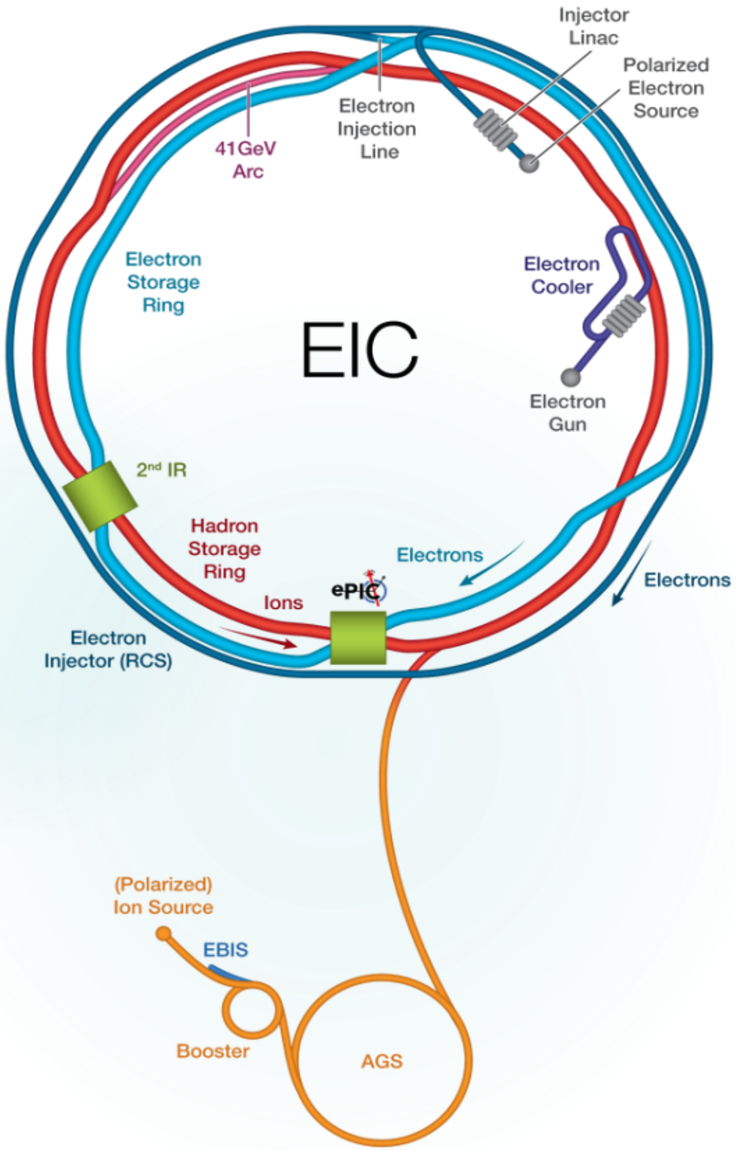
東京大学 大学院
理学系研究科・理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

Outline

- What is EIC and Why EIC is so important (my personal view)?
- High-Energy QCD Physics
- DIS and Parton distribution
- Physics topics at the EIC
  - 3D parton structure
  - spin, mass, pressure
  - gluon saturation, hadronization
- Experiment
- Summary

What is EIC and why EIC is so important (my personal view)?

Electron-Ion Collider



EIC = a machine that will unlock the secrets of the strongest force in Nature

- **the major US project in the field of nuclear physics**
- **the world's first collider for polarized electron and polarized proton (and light ions) and electron-nucleus collisions**

- EIC hosted at Brookhaven National Laboratory
- 80% polarized electrons from 5-18 GeV
- 70% polarized protons from 40-275 GeV
- Ions from 40-110 GeV/u
- Polarized light ions 40 -184 GeV (He^3)
- 100-1000 x HERA luminosities:10^{33}-10^{34} $cm^{-2}s^{-1}$
- CMS energies: $\sqrt{s}$ = 29–140 GeV
- foreseen to start operation in early 2030's

Electron-Ion Collider

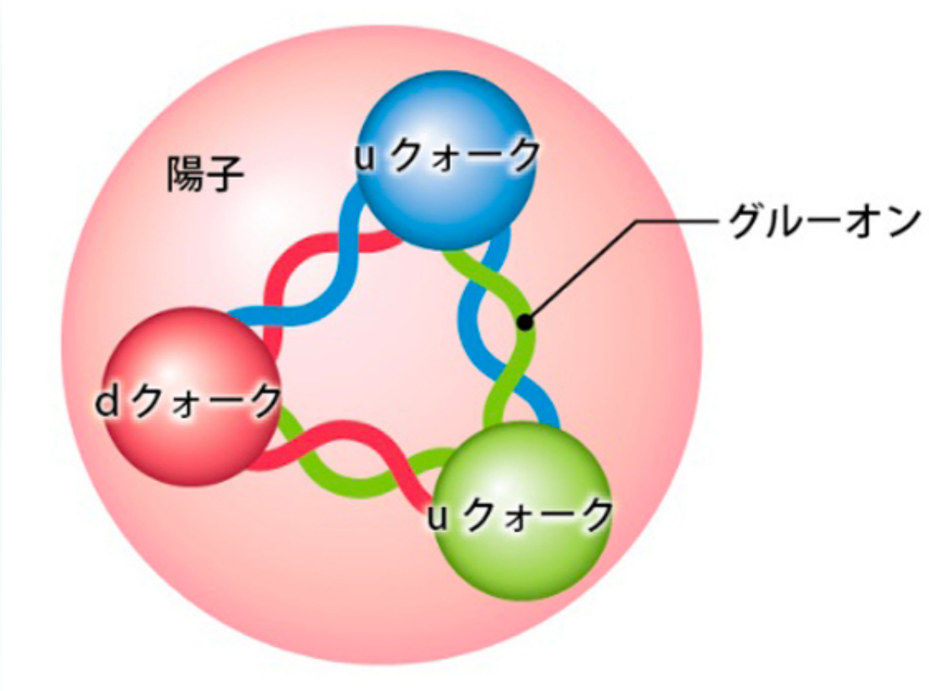
Internal structure of nucleon and nucleus

教科書的には

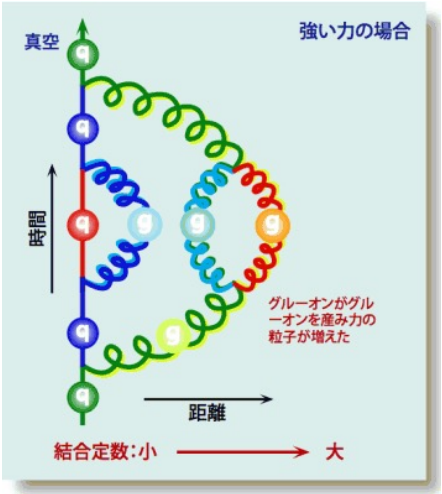
実際は

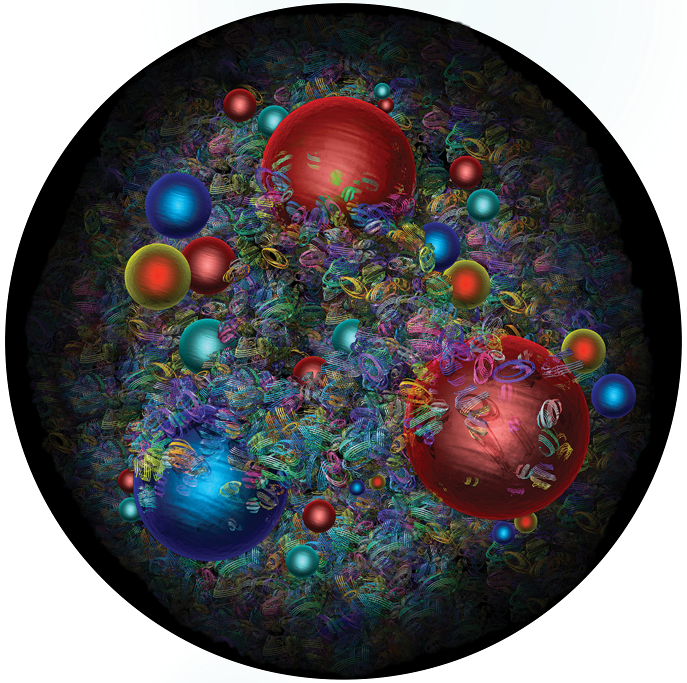
3 valence quarks

Dense quark & anti-quark pairs and gluons



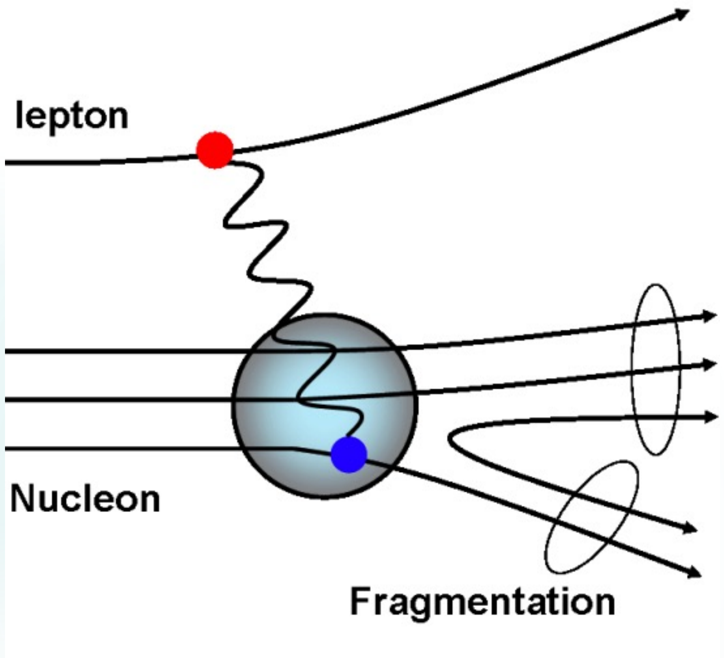
quantum fluctuation

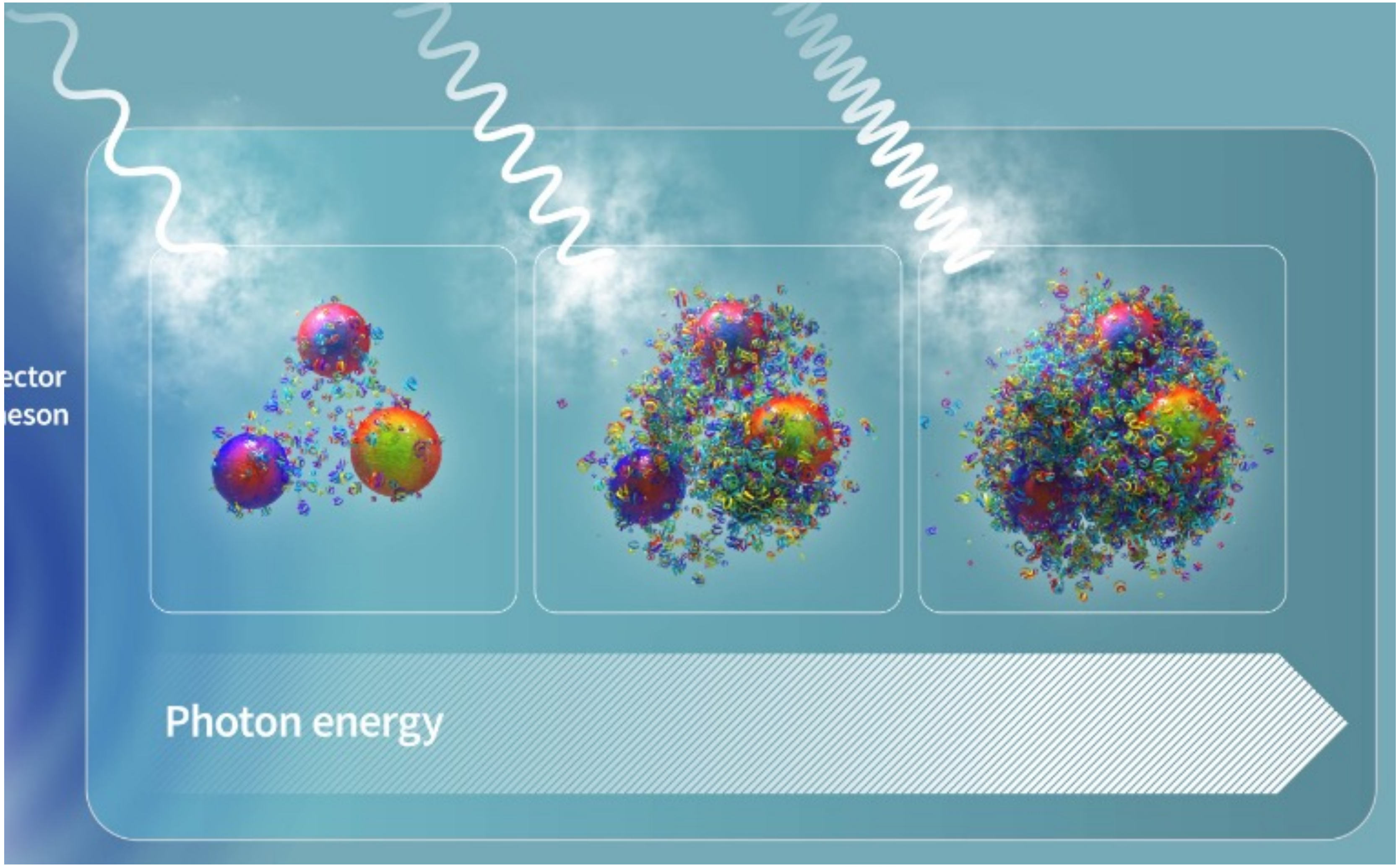




https://cerncourier.com/a/the-proton-laid-bare/

Electron-Ion Collider

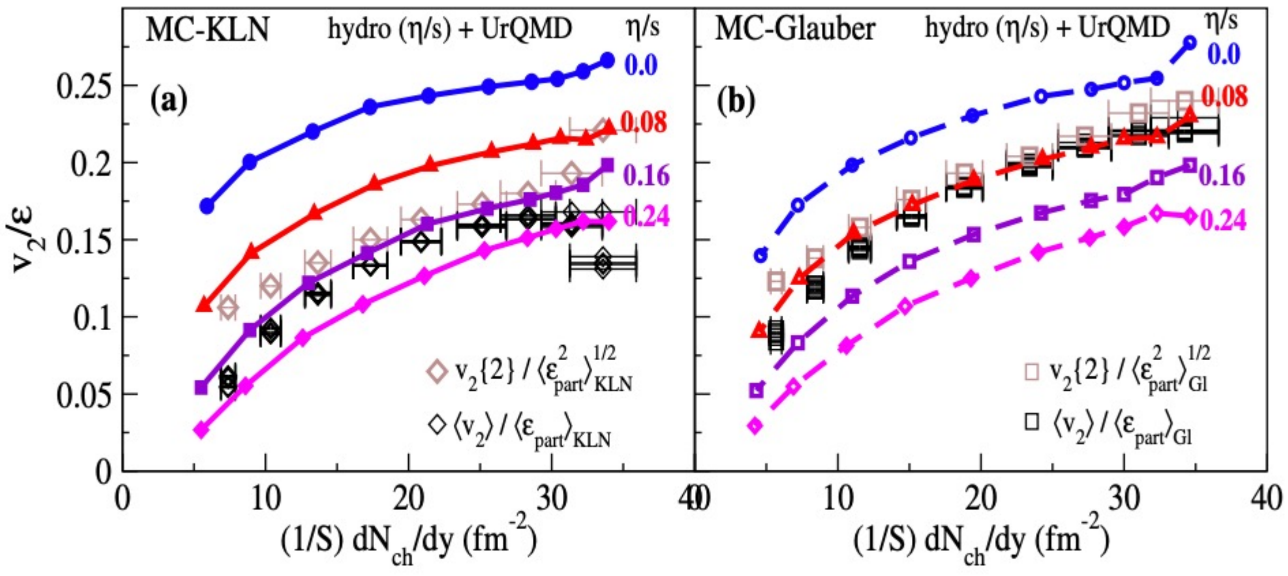


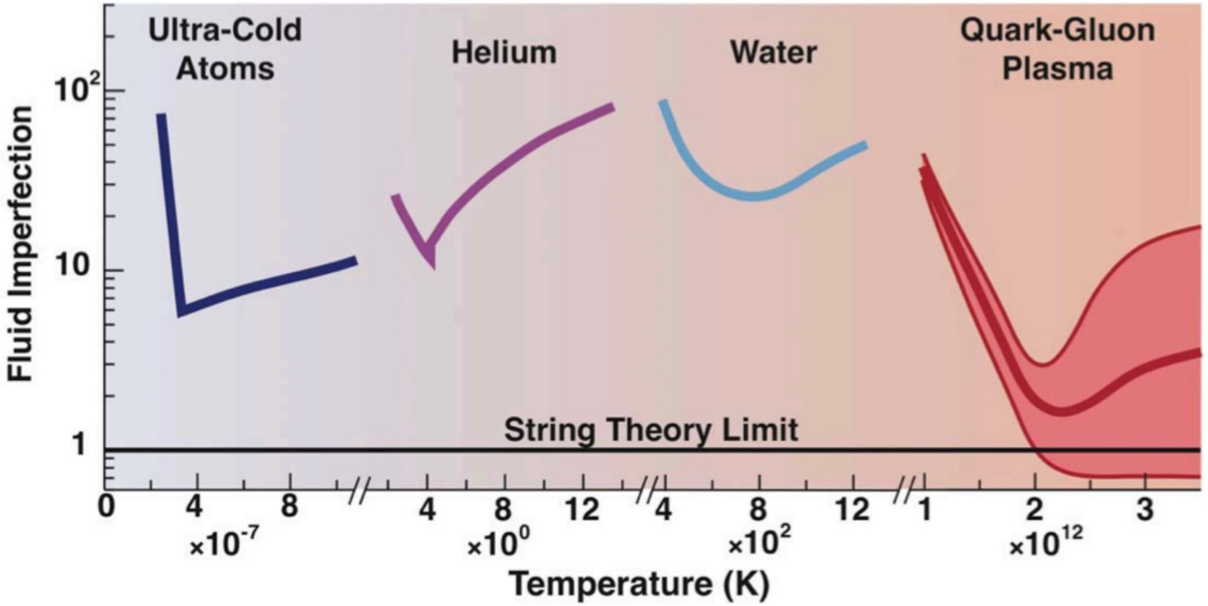


https://alice-collaboration.web.cern.ch/2023_ALICE_UPC

Why EIC is so important?

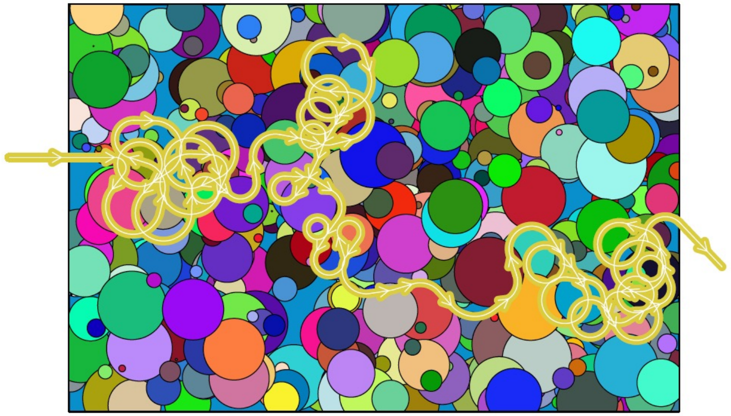
- To understand QGP properties more precisely
  - Initial conditions and early dynamics

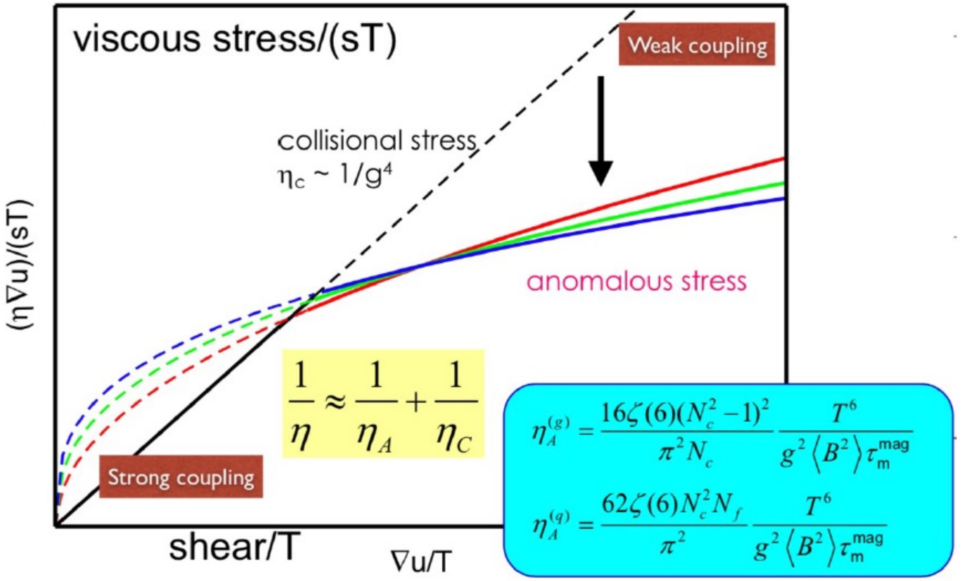




Why EIC is so important?

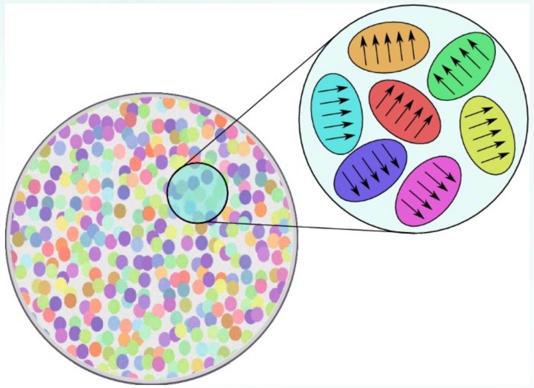
- **Characterization of gluonic matter**
  - **unique matter composed of Gauge bosons**
  - **Anomalous viscosity in glasma?**
    - **Soft color fields generate anomalous transport coefficients**
  - **Synergies with spin-glass?**

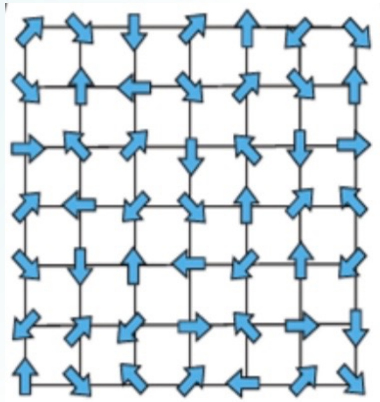




$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

M. Asakawa, S.A. Bass & B. Mueller: Phys. Rev. Lett. 96: 252301 (2006)



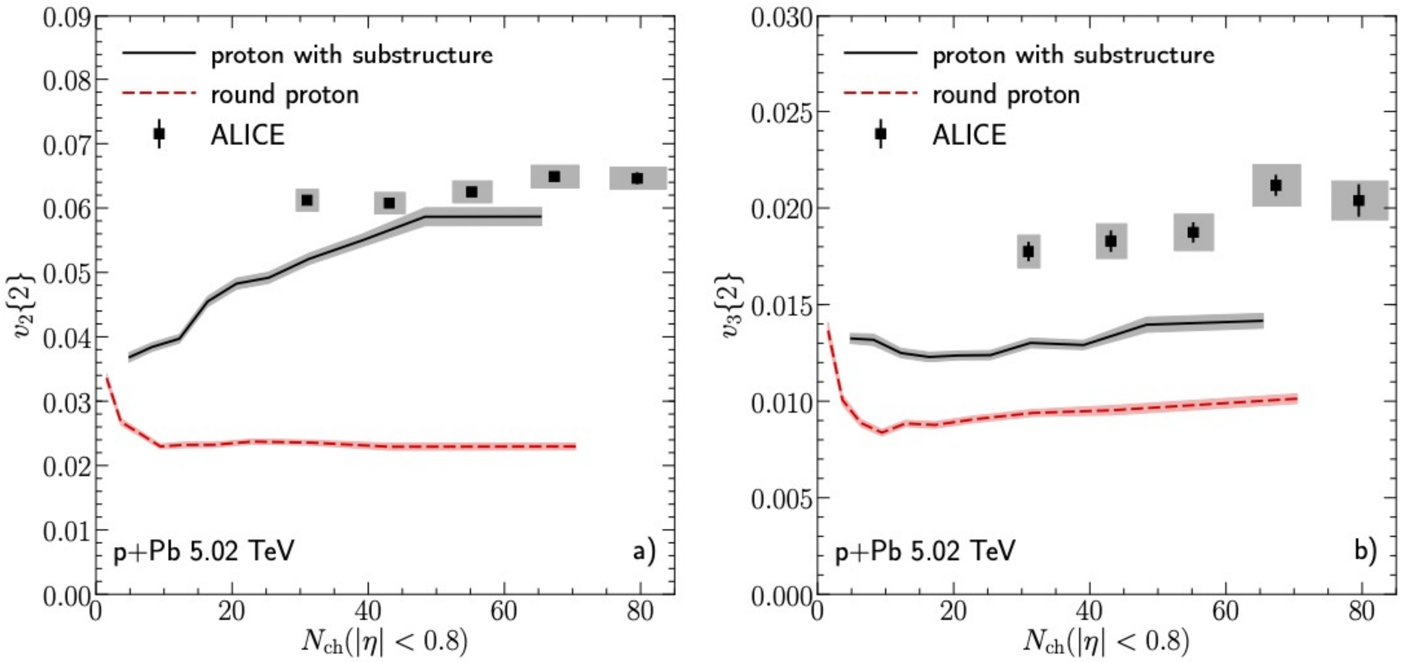


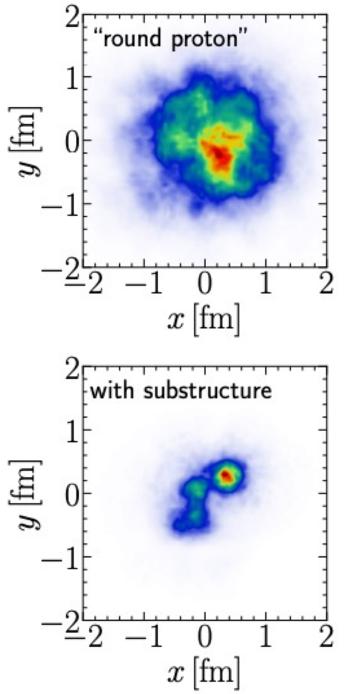
temperature evolution: $\eta_A < \eta_C$ $\eta_A < \eta_C$ $\eta_A > \eta_C$ η_{HG}

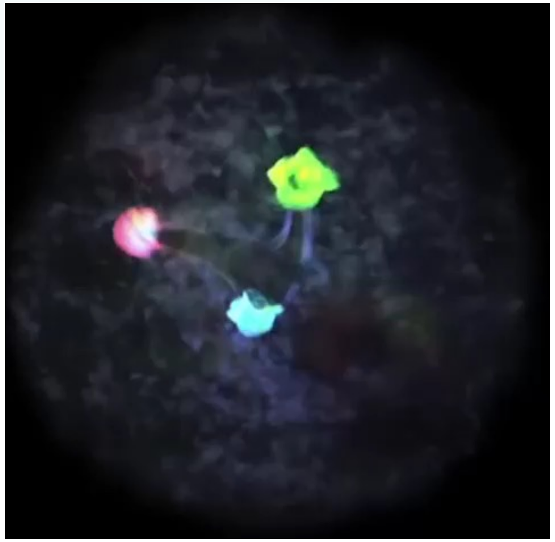
Why EIC is so important?

- **Origin of collectivity in small systems -> quantum fluctuations ("eccentric" proton)**

arXiv:2102.11189





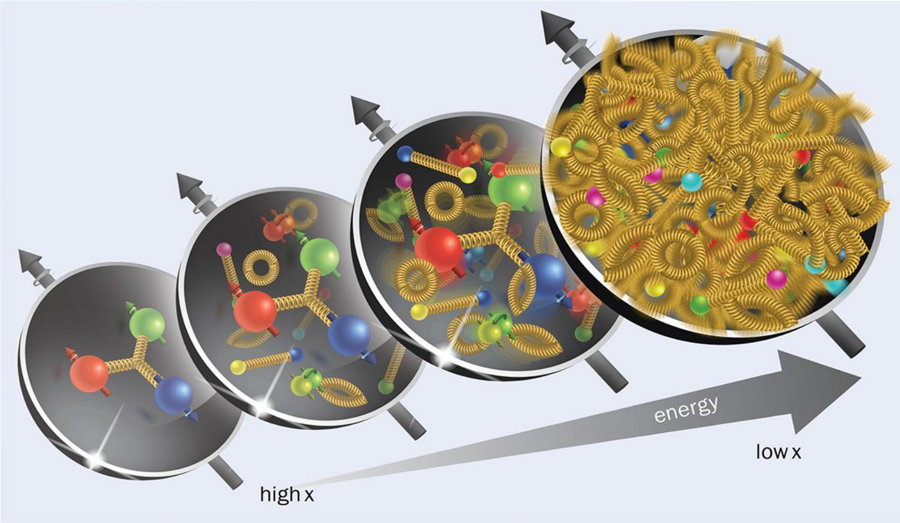


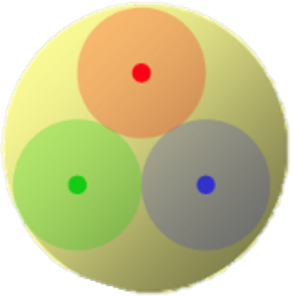
Quantum fluctuations in protons at very short time scale

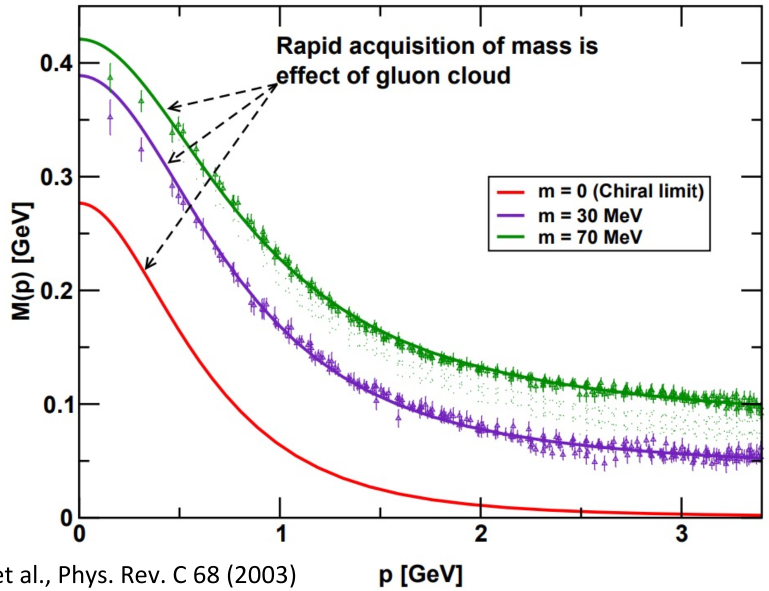
Dynamical structure of protons (fluctuations in parton distribution functions)

Why EIC is so important?

- Why proton and nucleus has so high toughness?
  - What mechanisms keep mass and spin constant?
  - Mechanisms of emergence of effective degree of freedom (localization)? -> Connection to condensed matter physics
    - Strongly correlated electrons, Heavy-fermions, superconductors, Mott-insulator



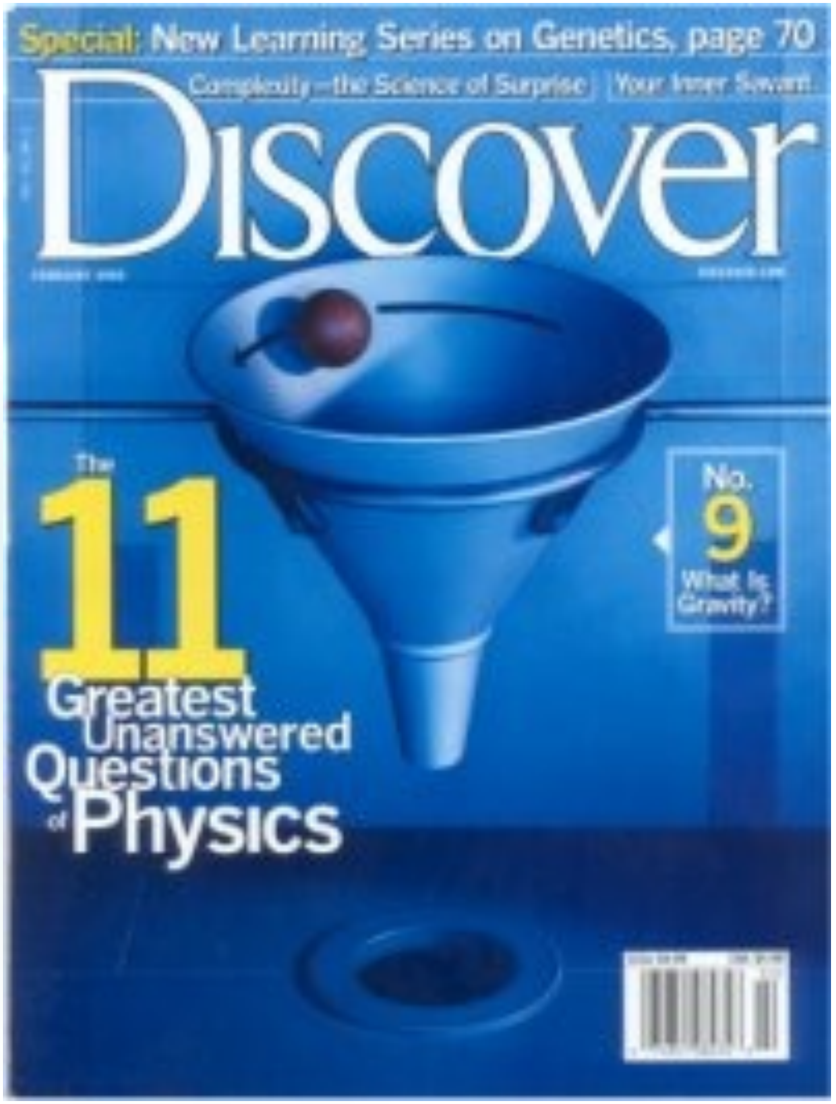




[Bhagwat et al., Phys. Rev. C 68 (2003)

High-Energy QCD Physics

11 Science Questions in 21 century

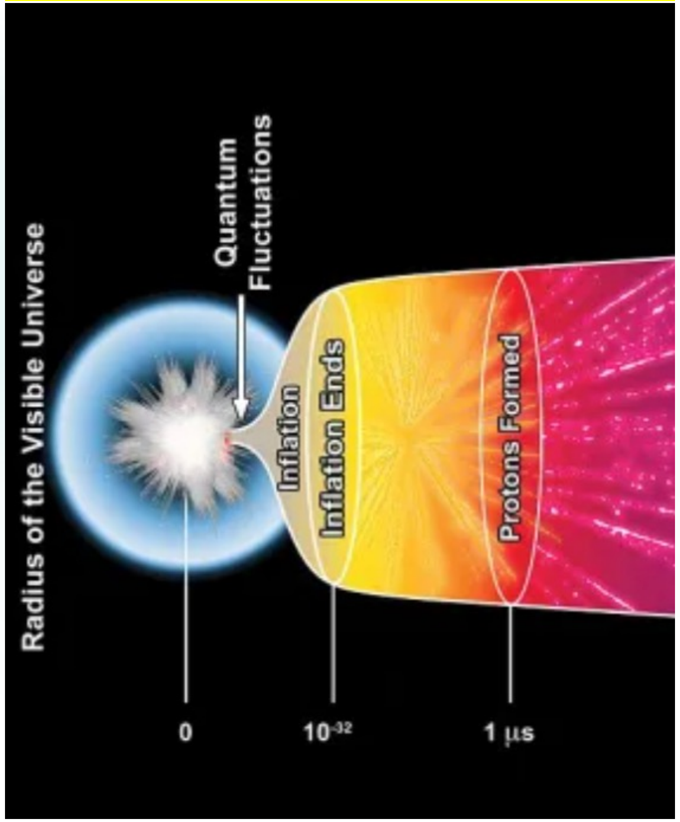


1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from Iron to Uranium made?
4. Do neutrinos have a mass?
5. Where do ultra-high energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultra-high temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the Universe begin?

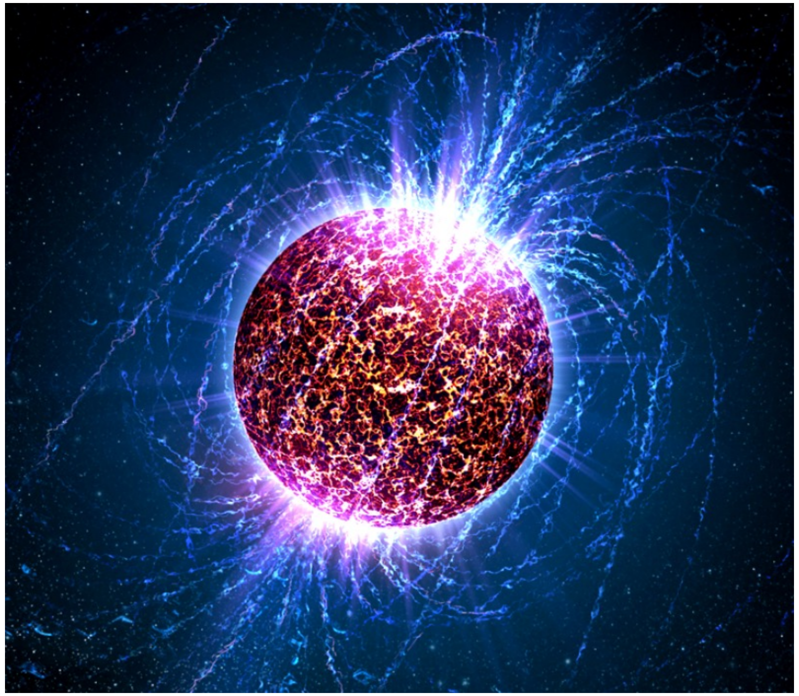
11 Science Questions in 21 century

7. Are there new states of matter at ultra-high temperatures and densities?

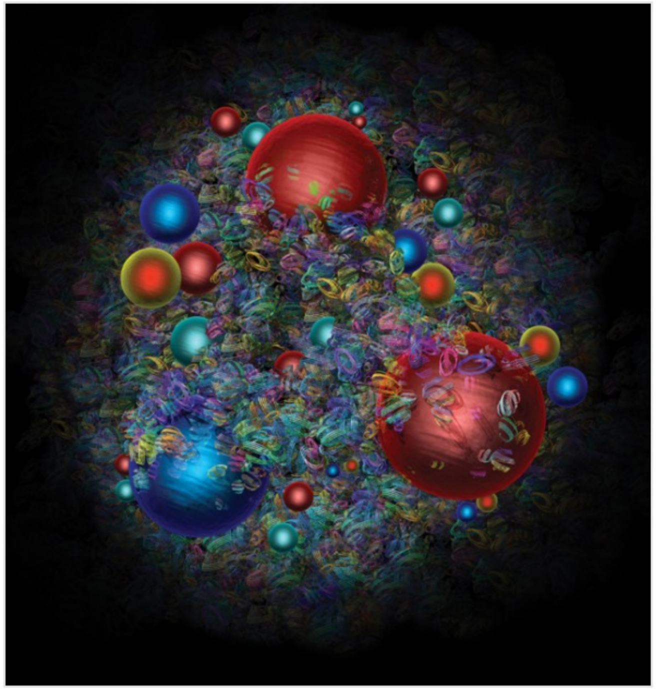
Very early universe (T > 100 MeV, t < 10 μsec)



Neutron stars ($\rho > 10^{15}$ g/cm^3)



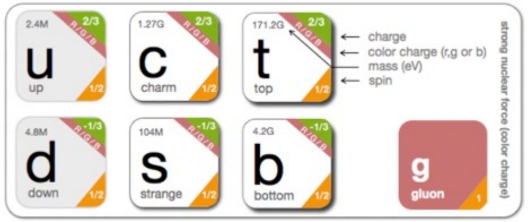
Dense partonic structure inside high energy proton/nuclei

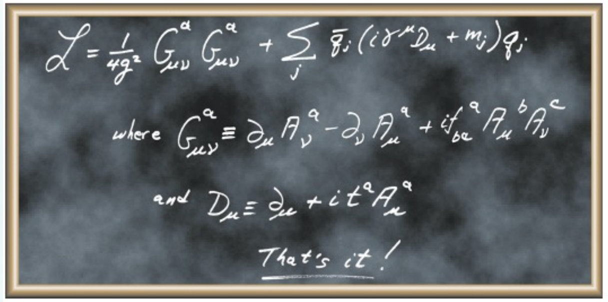


未来の学術構想2022

国際高エネルギー量子科学フロンティア：海外施設で展開するQCD研究

学術振興の「ビジョン」





Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

Frank Wilczek

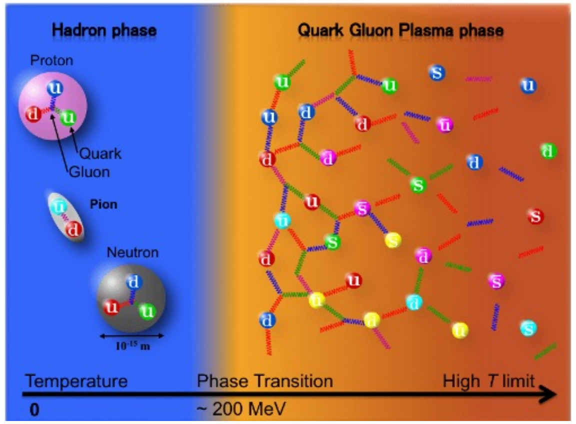
http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf

- 様々な状況で現れるQCDの複雑性・創発性・多様性を統一的に理解
  - 高温・高密度クォーク・グルーオン物質や核物質の相構造と物性
  - 高エネルギー核子内部の高密度クォーク・グルーオン状態
  - クォーク・グルーオン凝縮に伴うQCD真空構造とその相転移

- 素粒子物理学・物性物理学をつなぐ普遍的な自然法則を探求
- 次世代のQCD物理学を創生（例、素粒子物性物理学）

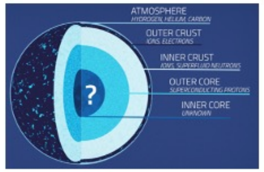
高温QCD

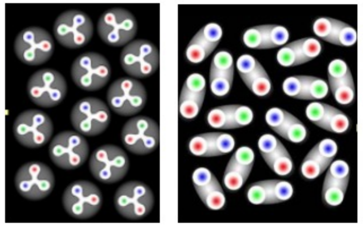
初期宇宙の物質創生
クォークグルーオンプラズマの物性
QCD相転移



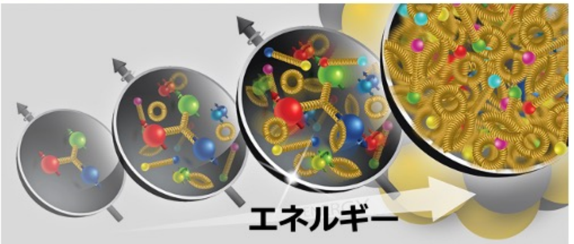
高密度・ストレンジネスQCD

中性子星内部構造
ストレンジネス核物質～カラー超伝導相
QCD相転移





高エネルギーQCD



核子内パートン構造
グルーオン飽和
質量の起源
摂動的QCD真空

未来の学術構想2022

国際高エネルギー量子科学フロンティア：海外施設で展開するQCD研究

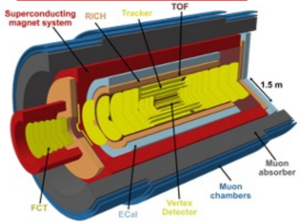
計画：海外施設で展開する国際共同実験

CERN-LHC加速器(2007-)

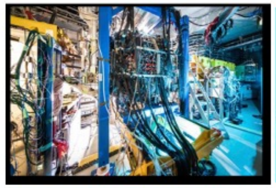
ALICE実験

~2000人、40カ国、173機関

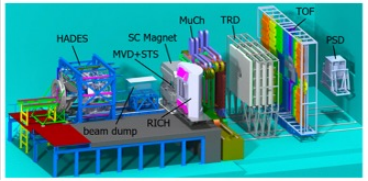
ALICE3実験



GSI-FAIR(建設中, 2027-)



WASA-FRS HypHI実験



CBM実験

~400人、11カ国、47機関

国際高エネルギー量子科学フロンティア

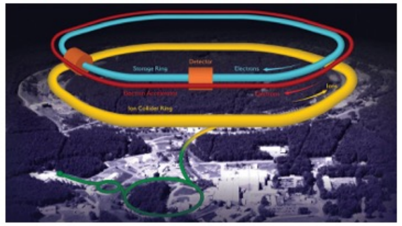
- 高温QCD
- 高エネルギーQCD
- 計算QCD
- QCD理論
- 高密度・ストレンジネスQCD

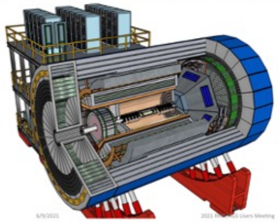
海外施設で長期的に国際共同研究を主導

QCD理論と計算QCDとの協同

BNL-EIC(CD1、2032-)

アメリカ原子核物理の最優先計画





EPIC実験

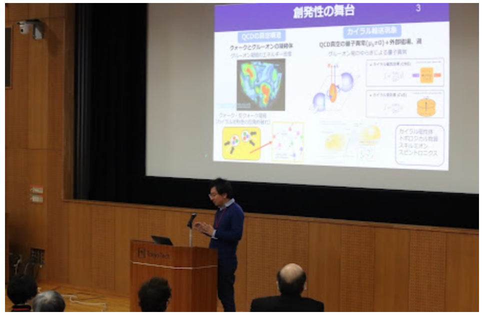
EIC-Users Group:
米、欧、アジアから
の参加者~1300名

核談70周年記念シンポジウム

https://indico.rcnp.osaka-u.ac.jp/event/2286/

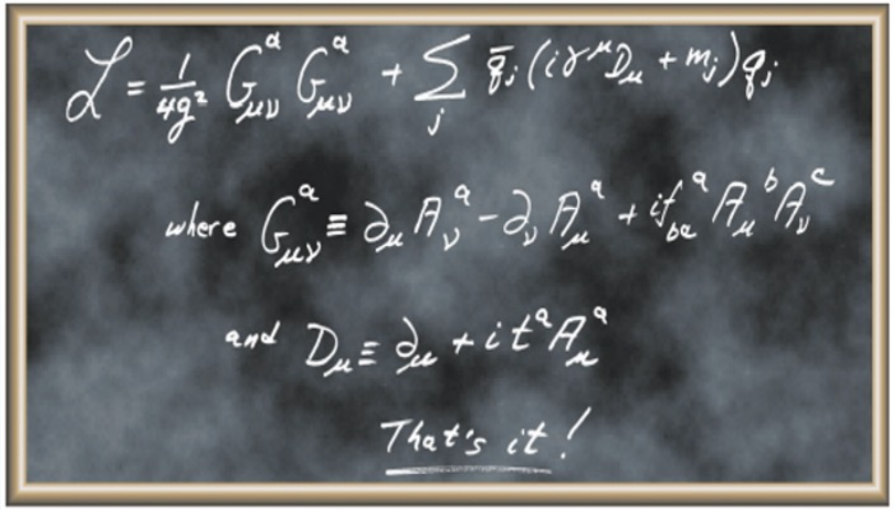
11:00	ニイタカヤマノボレ・ナンブヤマノボレ	延與 秀人	10:55 - 11:20
	高エネルギークォーク核物理の将来：さらなる高みへ	郡司 卓	11:20 - 11:45
	KEK-PSで始めた高エネルギー核物理	田中 万博	11:45 - 12:10
12:00	ストレンジネス核物理の展開	今井 憲一	12:10 - 12:35
	J-PARCでのハドロン・ハイパー核物理の進展と展望	三輪 浩司	12:35 - 13:00

*私見に基づく



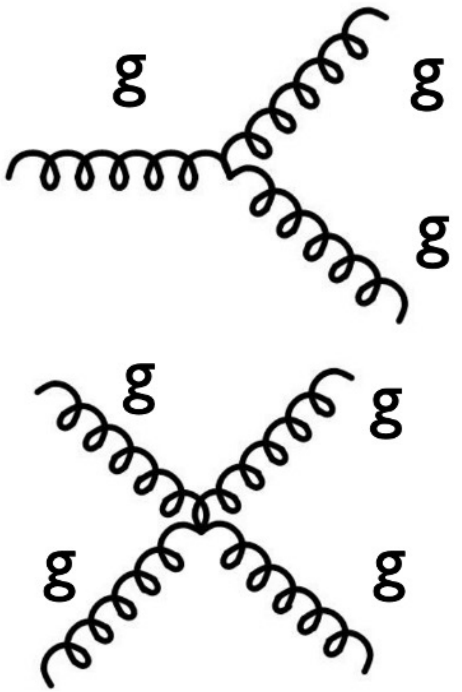
高エネルギーQCD研究の目標

クォークとグルーオン多体系の創発性を通じて、（非摂動領域の）QCDを究める

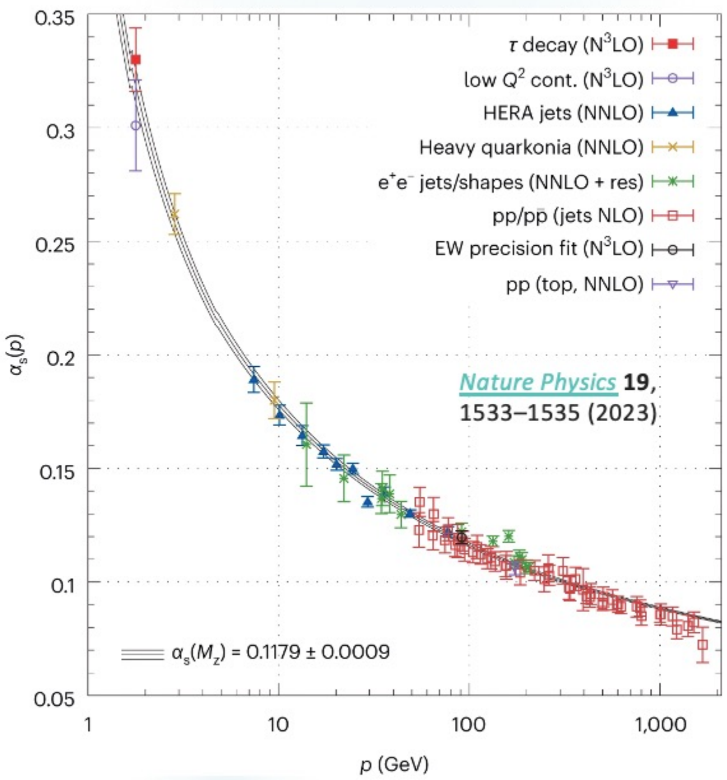


http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf

グルーオンの自己相互作用



漸近的自由性

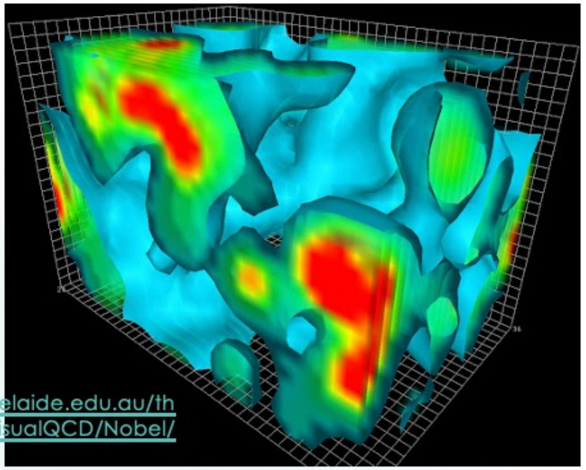


創発性の舞台

QCDの真空構造

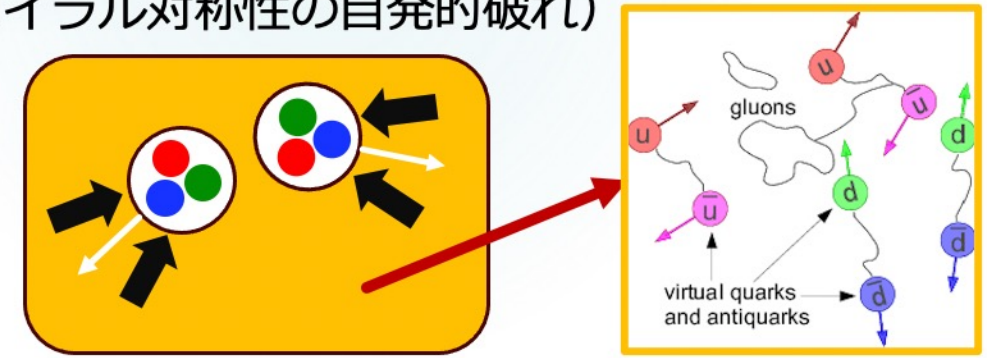
クォークとグルーオンの凝縮体

グルーオン凝縮のエネルギー密度



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

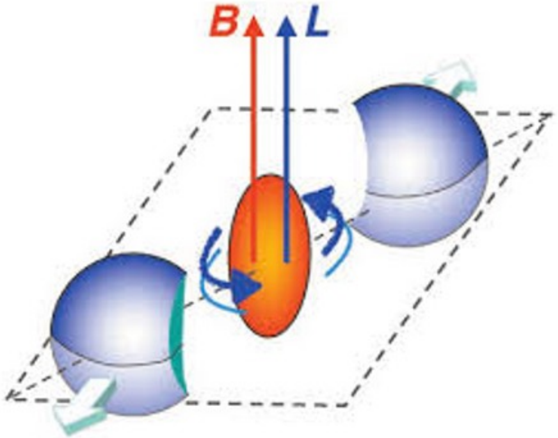
クォーク・反クォーク凝縮
（カイラル対称性の自発的破れ）



カイラル輸送現象

QCD真空の量子異常($\mu_5 \neq 0$)＋外部磁場、渦

グルーオン場のゆらぎによる量子異常

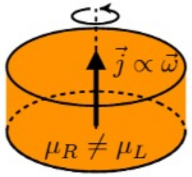


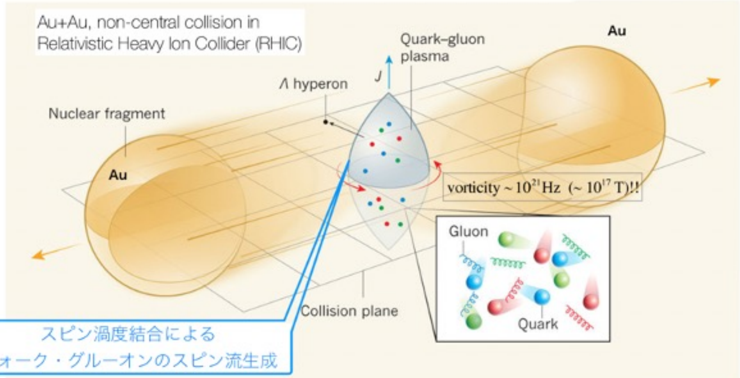
◆ カイラル磁気効果 (CME)　[Fukushima et al.2008, Vilenkin 1980]

$$\vec{j} = \frac{e\mu_5}{2\pi^2}\vec{B}$$

◆ カイラル渦効果 (CVE)　[Erdmenger et al. 2008, Son-Surowka 2009]

$$\vec{j} = \frac{\mu\mu_5}{2\pi^2}\vec{\omega}$$



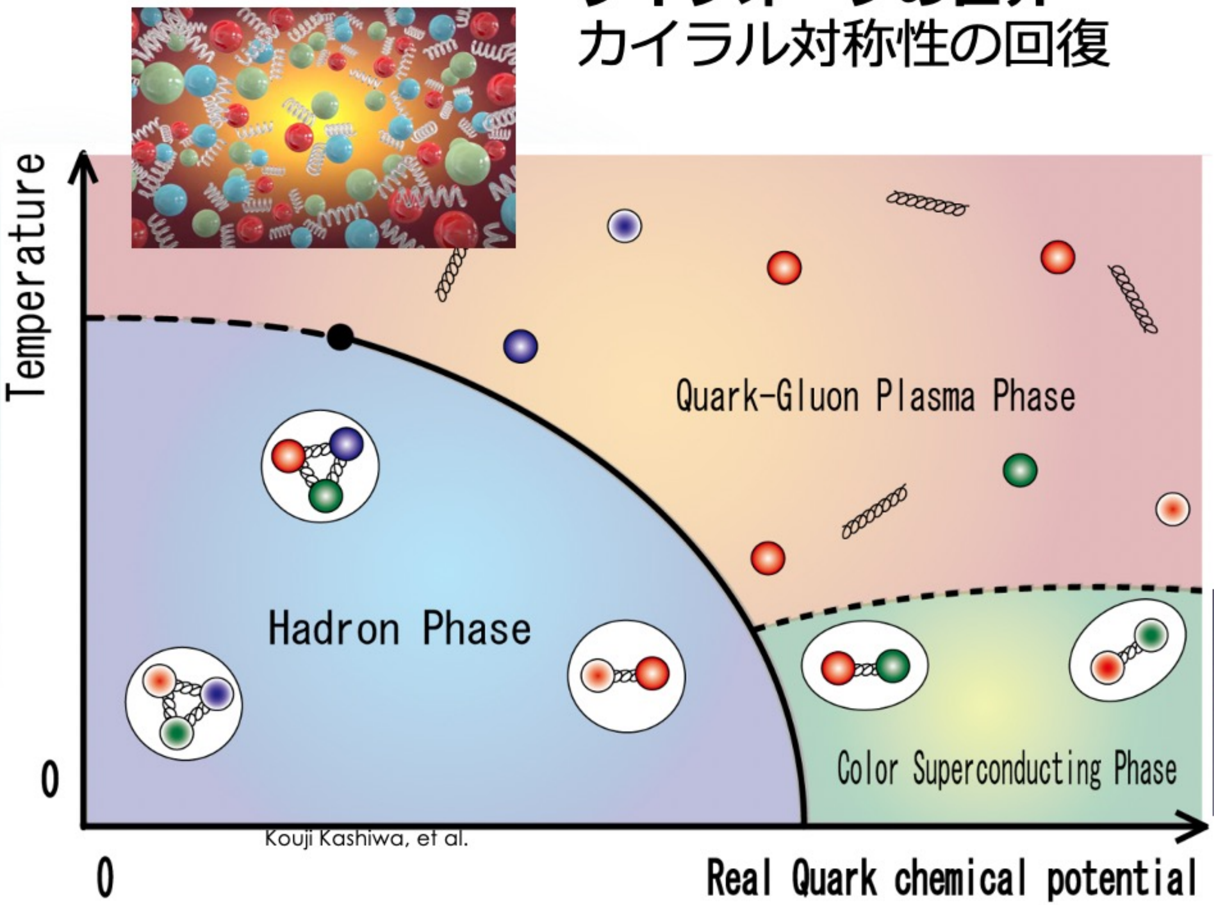


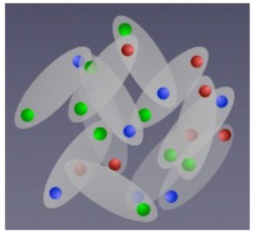
カイラル磁性体
トポロジカル物質
スキルミオン
スピントロニクス
…

創発性の舞台

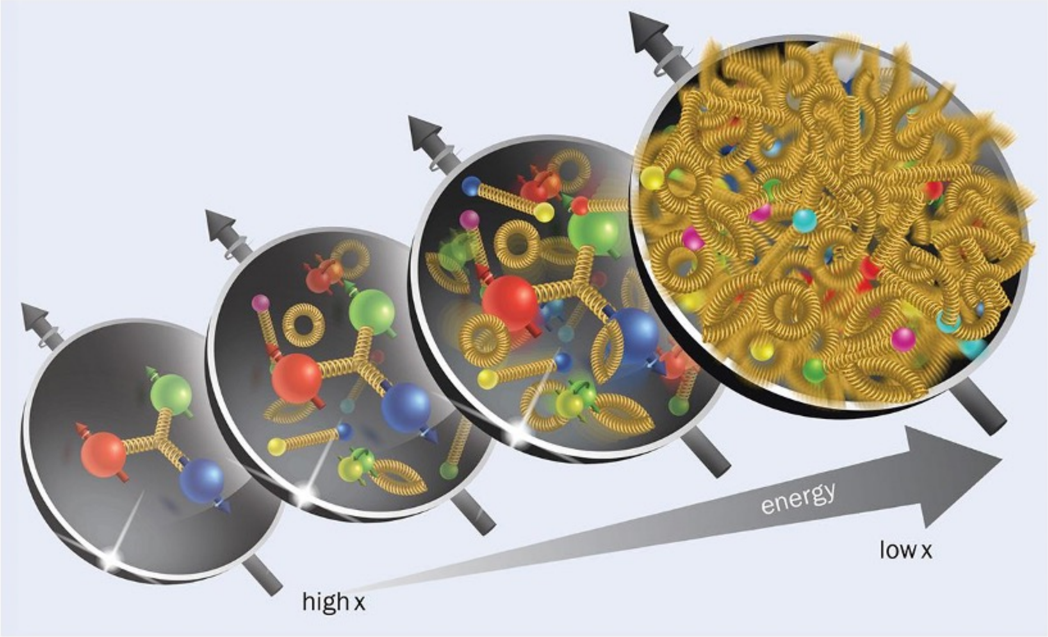
QCD物質の相構造

クォーク・反クォークの世界
ダイクォークの世界
カイラル対称性の回復





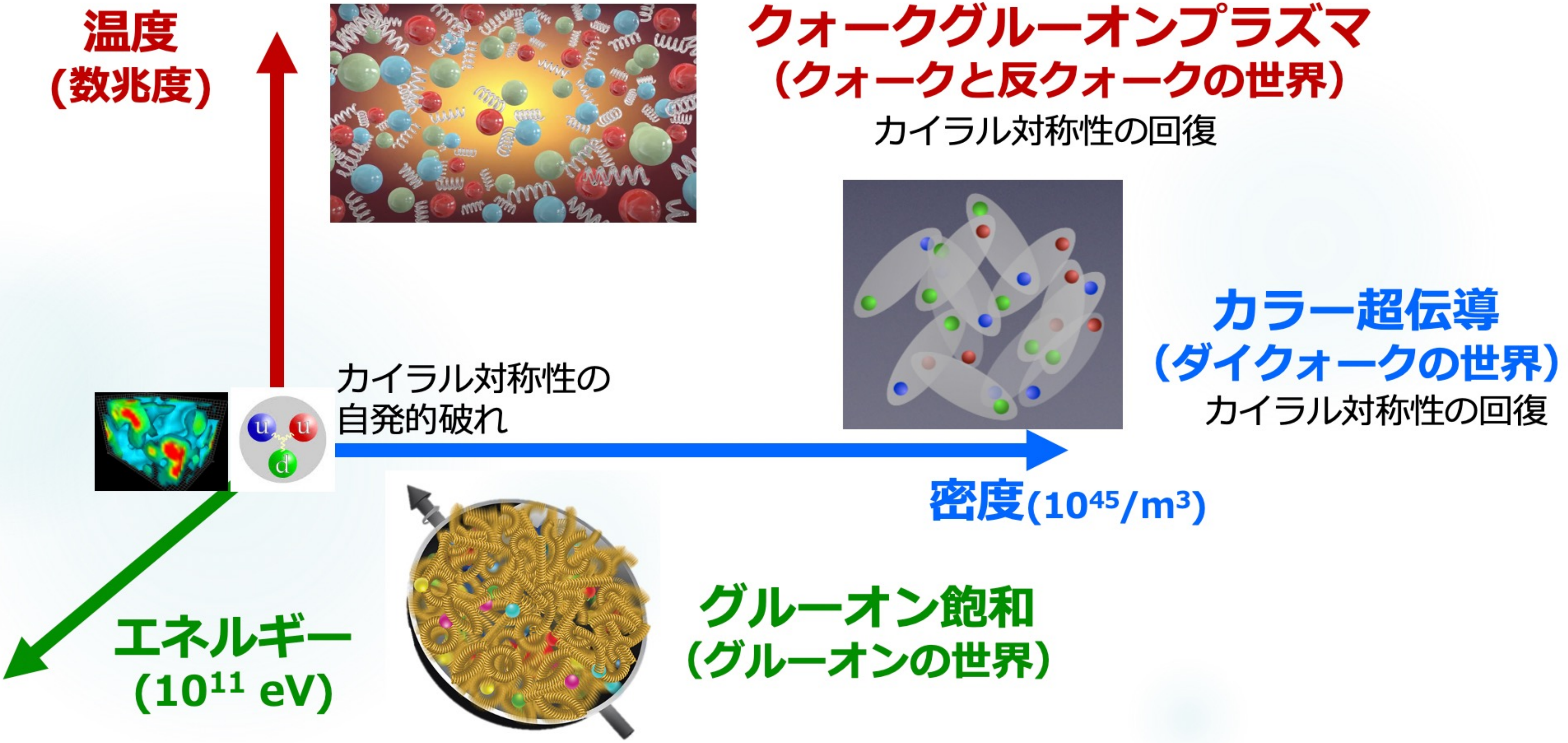
核子と原子核の内部構造・核スピン



高密度グルーオンの世界

真空の揺らぎ
クォークとグルーオン相互作用の平衡状態
核子の質量・スピンの起源・閉じ込め

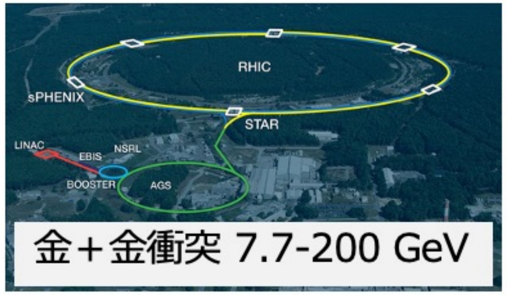
創発性の舞台



温度
(数兆度)
クォークグルーオンプラズマ
(クォークと反クォークの世界)
カイラル対称性の回復
u
u
d
カイラル対称性の
自発的破れ
カラー超伝導
(ダイクォークの世界)
カイラル対称性の回復
密度(10^{45}/m^3)
グルーオン飽和
(グルーオンの世界)
エネルギー
(10^{11} eV)

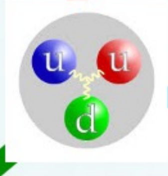
創発性を探る実験の舞台

温度
(数兆度)

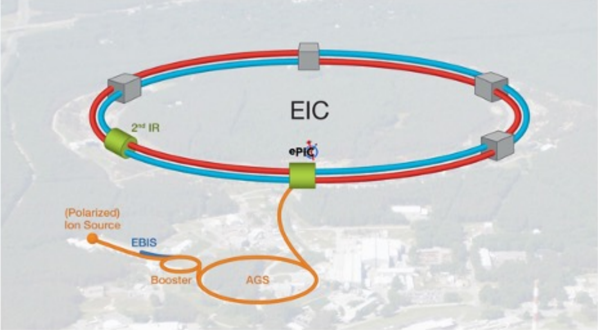


RHIC(米)
LHC(欧州)
稼働中

FAIR（独）
J-PARC-HI（日）
2028-



密度(10^{45}/m^3)



電子＋陽子、電子＋金: 29-140 GeV

エネルギー
(10^{11} eV)

EIC（米）
2030-

アメリカ原子核業界の最優先計画。RHICの次の大型計画（世界で唯一建設が決まっている加速器）

EIC workshop

https://indico3.cns.s.u-tokyo.ac.jp/event/315/

研究会「EICで展開する新たな原子核・素粒子物理」

28–30 May 2024
University of Tokyo
Asia/Tokyo timezone

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- Registration
- Participant List

連絡先

eic_workshop_2024@c…

2020年に行われたKEK研究会「素粒子・原子核コライダー物理の交点」を受けて、今回は、米国の次期大型計画EIC（Electron-Ion Collier）に焦点を置き、EICが今後の素粒子物理学と原子核物理学にどのような新しい展開をもたらすかを議論したいと思います。

EICはアメリカ原子核物理の最優先計画であり、ブルックヘブン国立研究所に建設される世界初の偏極電子＋偏極陽子及び原子核衝突型加速器です。EIC計画は現在アメリカエネルギー省から計画実行段階への権限を与えられ、次の施設建設段階へ、そして2032年頃の建設完了に向けて、順調に進んでいます。

EICは今後10年程度で実現する新たなコライダーとしては唯一のものとなる可能性もあり、原子核物理分野と素粒子物理分野が協力して推進することを目指したいと思います。

3日間の研究会を予定しています。初日の午後は、EICの物理に関する簡単なスクールを実施します。2-3日目に議論を行います。素粒子物理、高エネルギーQCD物理、ハドロン物理、原子核物理の観点から、EICでの展望を議論します。また、EICにおける加速器技術、先端的な半導体測定器技術やデータ収集や処理技術に関する議論も行い、分野を超えた共同研究の可能性を議論したいと思います。

基調講演：The Electron-Ion Collider: the ultimate electron microscope	Prof. Gordon Baym	Koshiba-hall, University of Tokyo	09:45 - 10:35	
coffee break		Koshiba-hall, University of Tokyo	10:35 - 10:55	
RHICスピン物理の発展	Yuji Goto	Koshiba-hall, University of Tokyo	10:55 - 11:20	Spin
ePIC Experiment Overview	Yano Satoshi	Koshiba-hall, University of Tokyo	11:20 - 11:45	technologies
Lunch		Koshiba-hall, University of Tokyo	11:45 - 13:15	
Studies of exotic-hadron candidates in high-energy reactions		Koshiba-hall, University of Tokyo		Hadron structure
Study of internal structure of baryons using hadron beam		Koshiba-hall, University of Tokyo		
Searching for Lepton Flavor Violation at EIC	Kaori Fuyuto	Koshiba-hall, University of Tokyo	14:05 - 14:35	BSM
Workshop photo // coffee break		Koshiba-hall, University of Tokyo	14:35 - 14:55	
Recent trend of timing silicon detectors and development plan for future colliders	Koji Nakamura	Koshiba-hall, University of Tokyo	14:55 - 15:20	technologies
MAPS (TBD)	Katsuro Nakamura	Koshiba-hall, University of Tokyo	15:20 - 15:45	
Streaming readout DAQ development and standardization by SPADI Alliance	Prof. Shinsuke OTA	Koshiba-hall, University of Tokyo	15:45 - 16:10	
coffee break		Koshiba-hall, University of Tokyo	16:10 - 16:30	
基調講演： Status of Collinear PDFs and the impact of the EIC da	Enrico Tassi	Koshiba-hall, University of Tokyo	16:30 - 17:20	PDF
Measurement of Hadron Mass in nuclei	Megumi Naruki	Koshiba-hall, University of Tokyo	17:20 - 17:45	mass
ハドロンの重力形状因子と質量分解	Kazuhiro Tanaka	Koshiba-hall, University of Tokyo	17:45 - 18:10	

The color entanglement in TMD-factorization	…of. Christine Aidala	Koshiba-hall, University of Tokyo	09:00 - 09:25	entanglement
EIC Physics from Lattice QCD: The Nucleon Mass and Spin Decomposition (zoom)	Raza Sufian	Koshiba-hall, University of Tokyo	09:25 - 09:50	Lattice, QC
格子QCDの量子計算に向けて	Arata Yamamoto	Koshiba-hall, University of Tokyo	09:50 - 10:15	
coffee break		Koshiba-hall, University of Tokyo	10:15 - 10:35	
Introduction to TMD and higher twist frameworks and their expected role in EIC	…hinsuke Yoshida	Koshiba-hall, University of Tokyo	10:35 - 11:00	TMD
Fragmentation functions for nucleon structure measurements	Ralf Seidl	Koshiba-hall, University of Tokyo	11:00 - 11:25	
Initial and final state effects on QGP in relativistic heavy-ion collision	Shingo Sakai	Koshiba-hall, University of Tokyo	11:25 - 11:50	QGP
Lunch		Koshiba-hall, University of Tokyo	11:50 - 13:00	
cluster and SRC を含む原子核物理の最近のトピック（TBD）		Koshiba-hall, University of Tokyo		Nuclear cluster
hadron spectroscopy from Belle to EIC		Koshiba-hall, University of Tokyo		Hadron structure
Hadron structure studies with antiproton beam at J-PAR		Koshiba-hall, University of Tokyo		
coffee break		Koshiba-hall, University of Tokyo	- 14:50	
kaon-nucleus bound systems	Sakuma	Koshiba-hall, University of Tokyo	- 15:15	Hadron cluster
cSeaQuest実験・COMPASS実験で何が分かったのか？〜陽子のフレーバー&スピン構造〜	Yoshiyuki Miyachi	Koshiba-hall, University of Tokyo	15:15 - 15:40	
Measurements of Generalized Parton Distribution functions using lepton and hadron beam	Natsuki Tomida	Koshiba-hall, University of Tokyo	15:40 - 16:05	Spin, GPD
coffee break		Koshiba-hall, University of Tokyo	16:05 - 16:25	
議論		Koshiba-hall, University of Tokyo	16:25 - 17:05	
Closing	Yuji Goto	Koshiba-hall, University of Tokyo	17:05 - 17:15	

JPS symposium

16日 B132会場　16pB132　13:30〜16:45

実験核物理領域，素粒子論領域，素粒子実験領域，理論核物理領域
電子-イオン衝突型加速器EICが展開する新たな原子核・素粒子物理

1　**（一般シンポジウム講演）EICとePIC実験の現状**
東大CNS
郡司卓

2　**（一般シンポジウム講演）EICへの理論からの期待とグルーオン飽和の物理**
東大理
福嶋健二

3　**（一般シンポジウム講演）EICで明らかにするハドロン物理と質量起源**
広島大先進理工
八野哲

4　**（一般シンポジウム講演）原子核の多次元量子イメージとハドロンの発現機構**
成蹊大理工
渡邉和宏

休憩　（15:15〜15:30）

5　**（一般シンポジウム講演）低エネルギー原子核物理**
理研
久保田悠樹

6　**（一般シンポジウム講演）素粒子物理の観点**
信大理
川出健太郎

7　**（一般シンポジウム講演）ePIC実験の技術と波及**
奈良女子大理
蜂谷崇

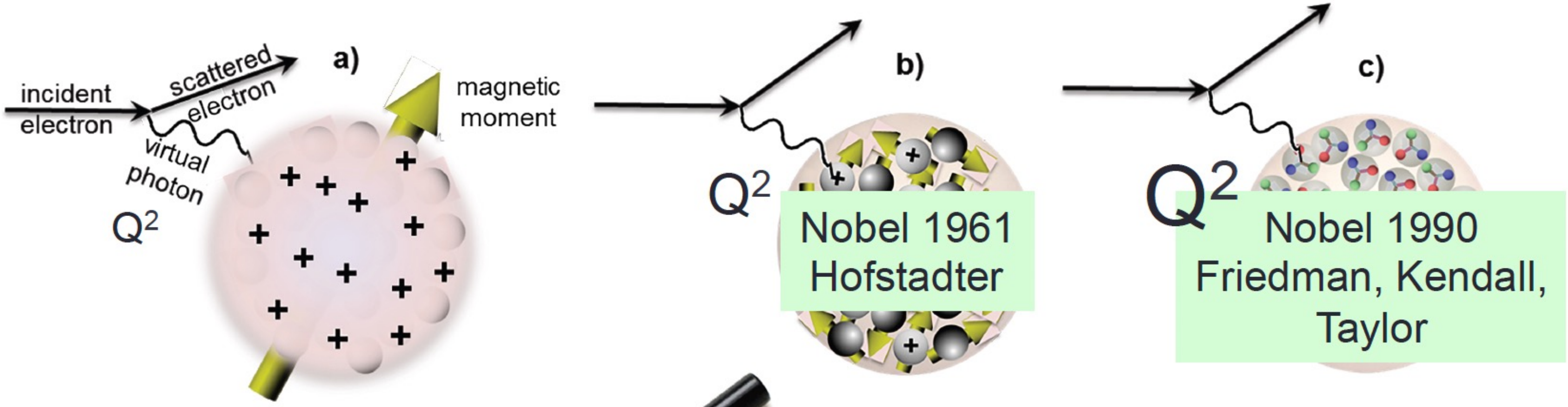
DIS and Parton distribution

Deep inelastic scattering

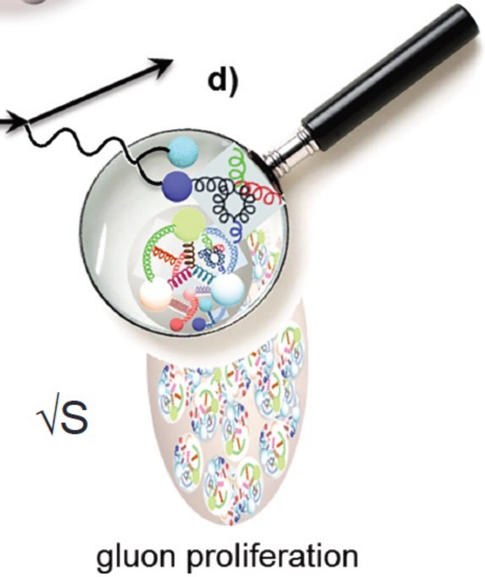
原子核の電荷分布の発見 (Lyman-Hanson-Scott)
電子と原子核の弾性散乱実験 (1951)
ベータトロン@イリノイ (15.7MeV)

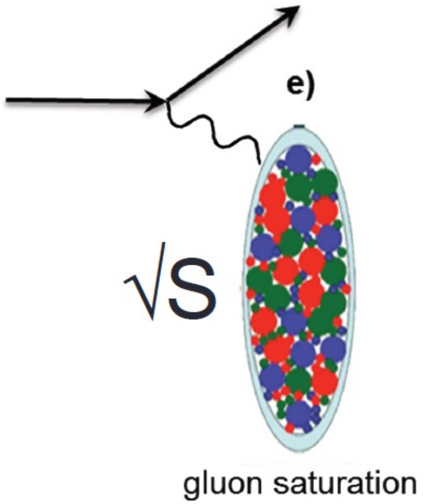
核子構造の発見 (Hofstadter) → Nobel Prize (1961)
電子と核子の弾性散乱実験(1956)
リニアック@スタンフォード (187 MeV)

クォークの発見 (Kendall-Friedman-Taylor)
電子と核子の非弾性散乱実験(1967-1973)
リニアック@SLAC (-20 GeV)



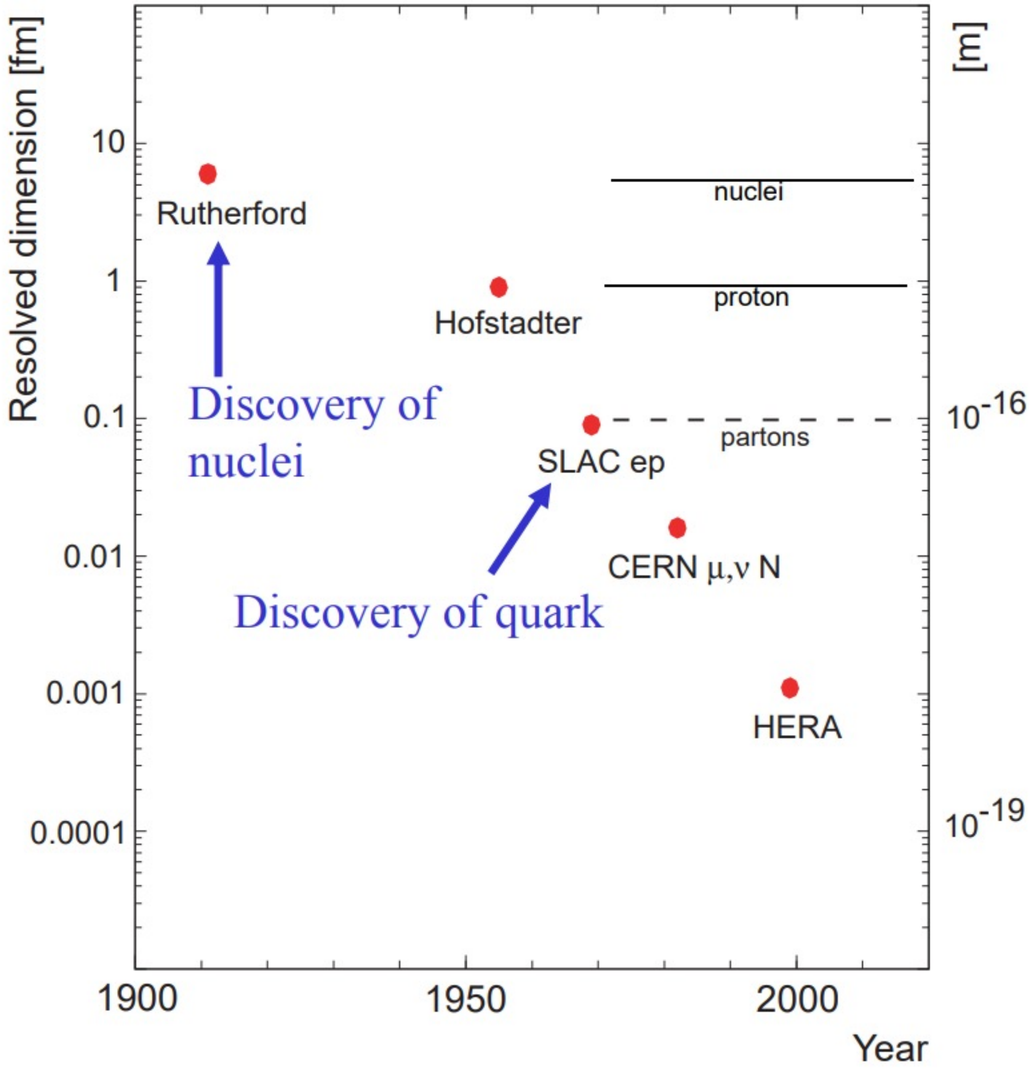
核子の1次元構造
電子/陽電子 と陽子の非弾性衝突実験(1991-2007)
HERA(シンクロトロン)@DESY (重心系 320 GeV)





QGPとEICで
ノーベル賞をめざしましょう
（QGPがノーベル賞にならないのは何故か？）

Resolution power



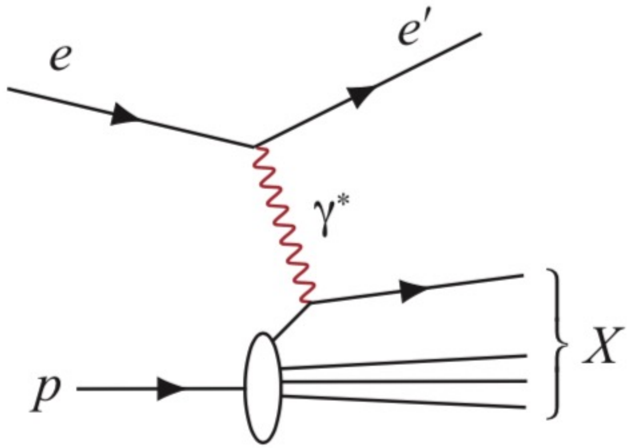
$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{Q^2}}$$

HERA:
(27.5 GeV e vs 920GeV p)

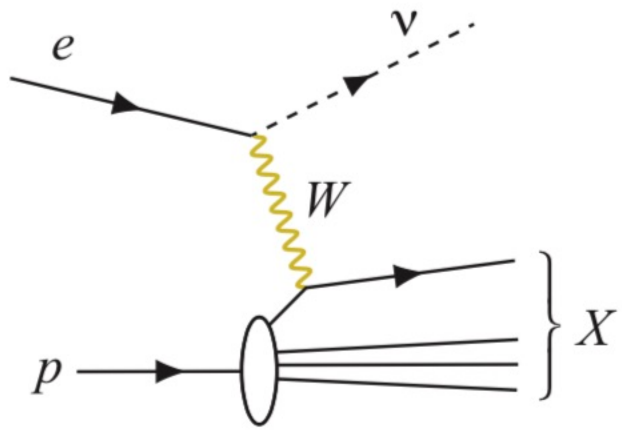
$Q^2_{max} = s = 4E_eE_p \sim 10000\text{GeV}^2$

Reactions to be measured in DIS

Neutral-current Inclusive DIS: $e + p/\mathrm{A} \longrightarrow e' + X$; for this process, it is essential to detect the scattered electron, e', with high precision. All other final state particles (X) are ignored. The scattered electron is critical for all processes to determine the event kinematics.

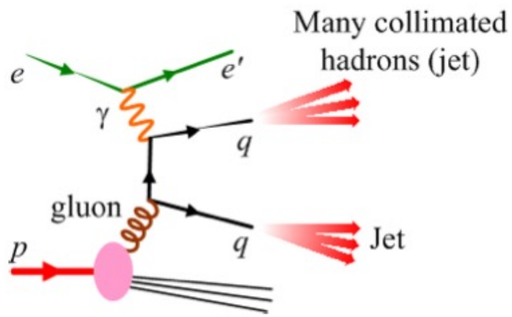


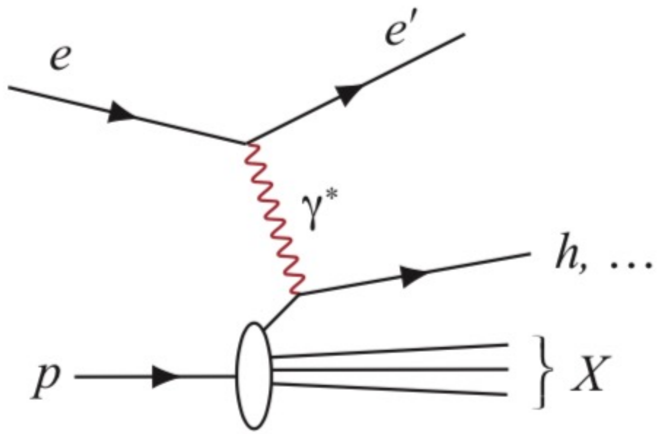
Charged-current Inclusive DIS: $e + p/\mathrm{A} \longrightarrow \nu + X$; at high enough momentum transfer Q^2, the electron-quark interaction is mediated by the exchange of a $W^{\pm}$ gauge boson instead of the virtual photon. In this case the event kinematic cannot be reconstructed from the scattered electron, but needs to be reconstructed from the final state particles.



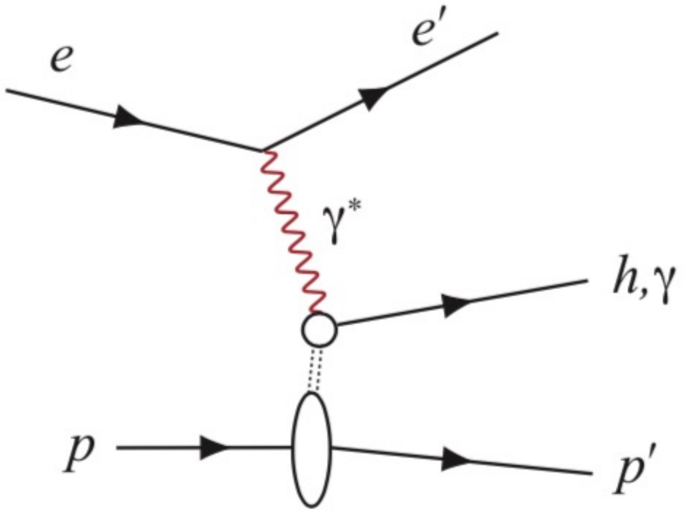
Reactions to be measured in DIS

Semi-inclusive DIS: $e + p/\mathrm{A} \longrightarrow e' + h^{\pm,0} + X$, which requires measurement of *at least one* identified hadron in coincidence with the scattered electron.

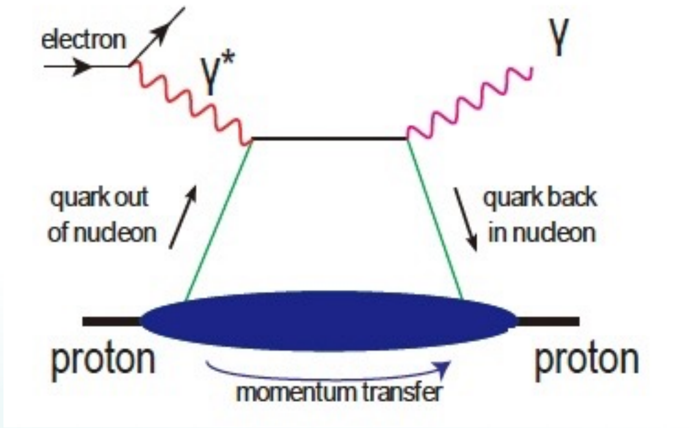


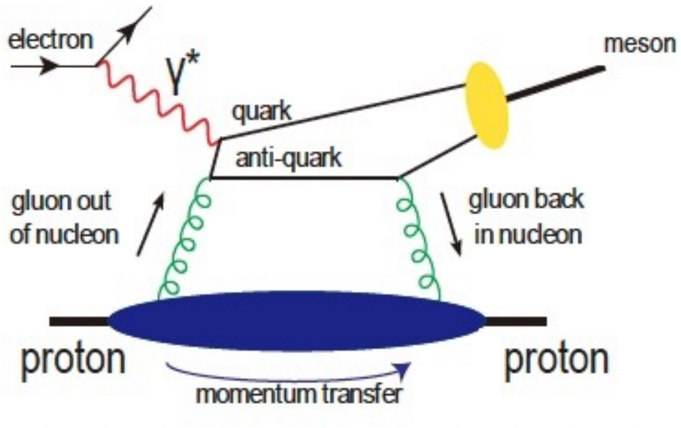


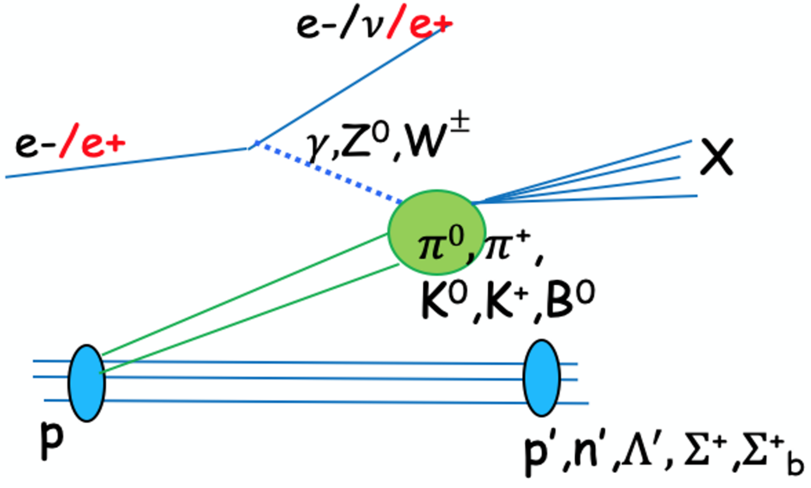
Exclusive DIS: $e + p/\mathrm{A} \longrightarrow e' + p'/A' + \gamma/h^{\pm,0}/VM$, which require the measurement of *all* particles in the event with high precision.

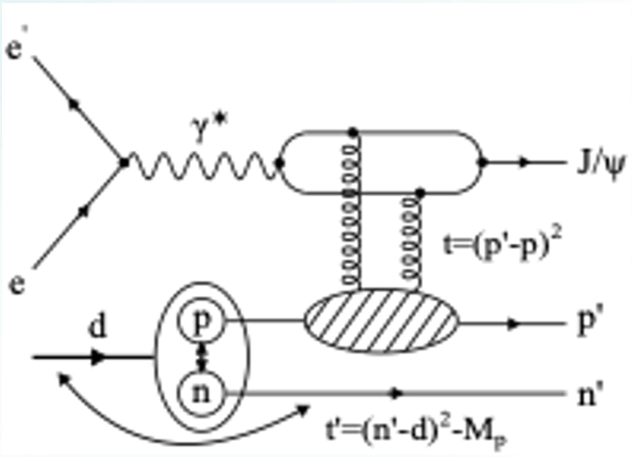


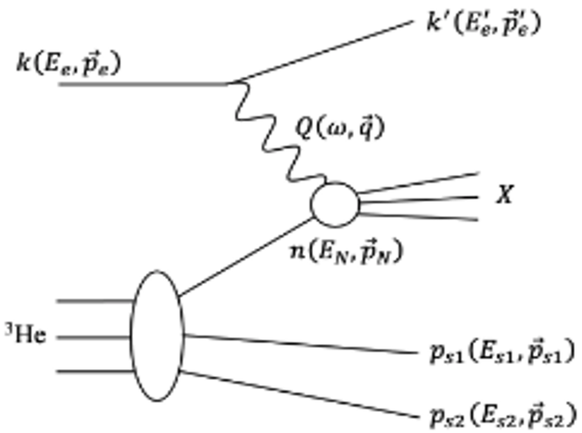
Reactions to be measured in DIS

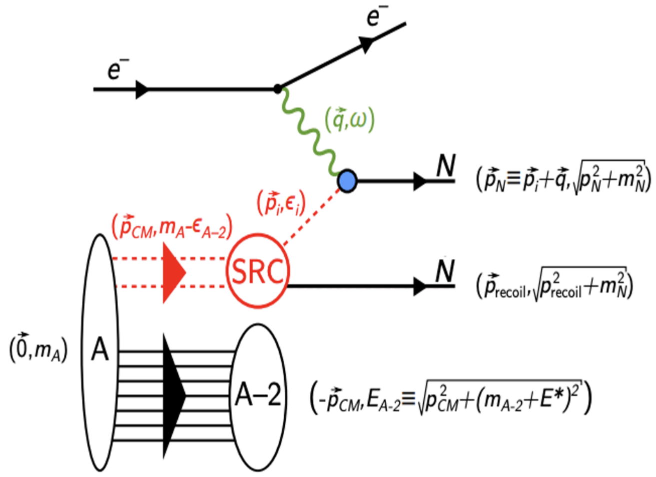




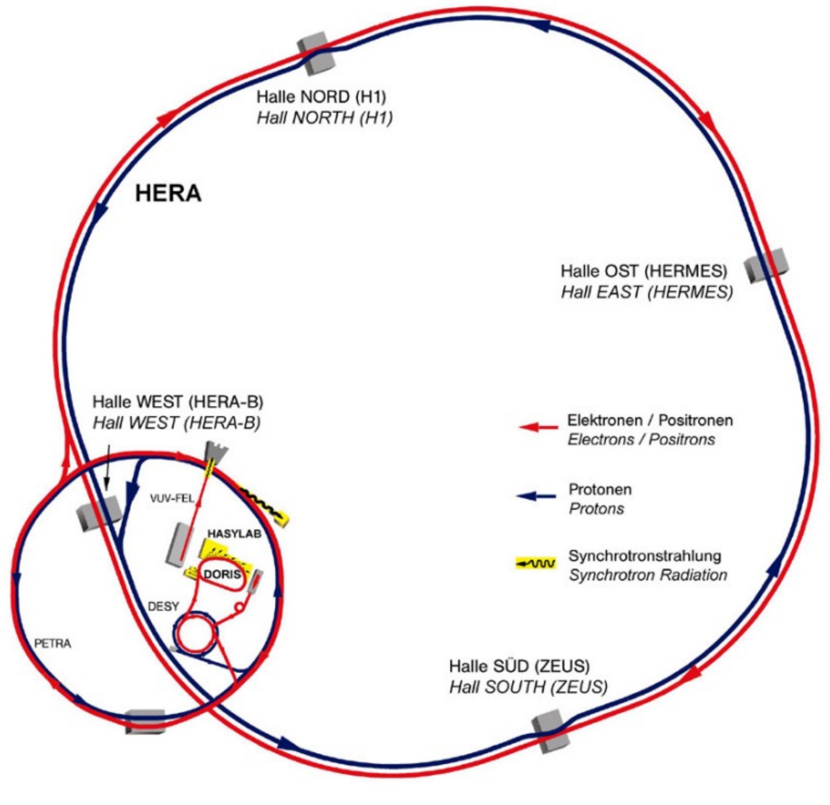








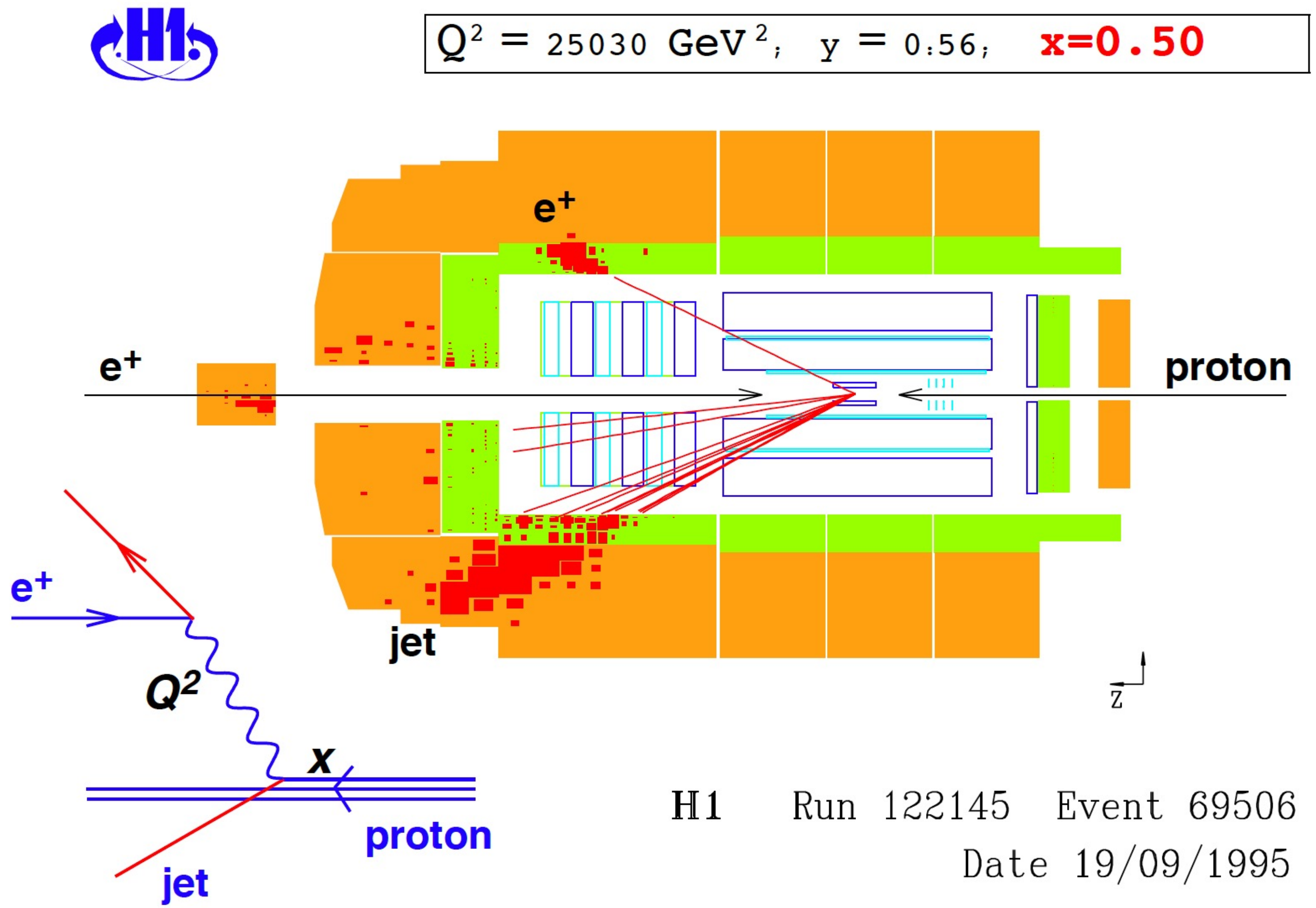
HERA @ DESY



- At Hamburg in Germany
- 6.3 km circumstance

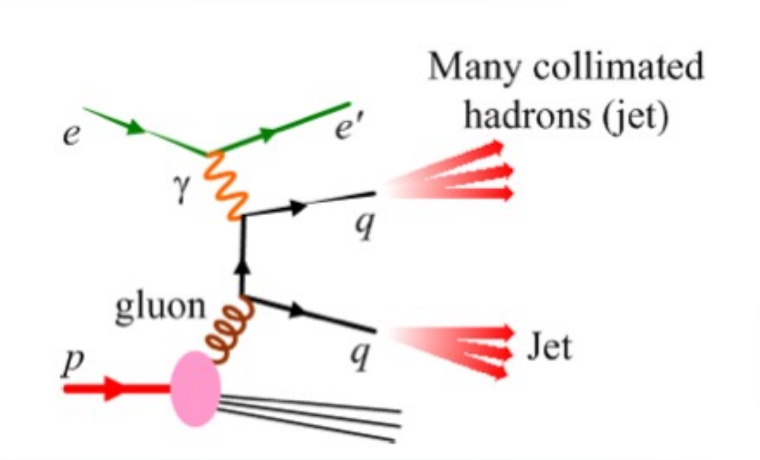
- proton beam = 920 GeV
- electron beam = 27.5 GeV
- $\sqrt{s}$ = 318 GeV

HERA @ DESY

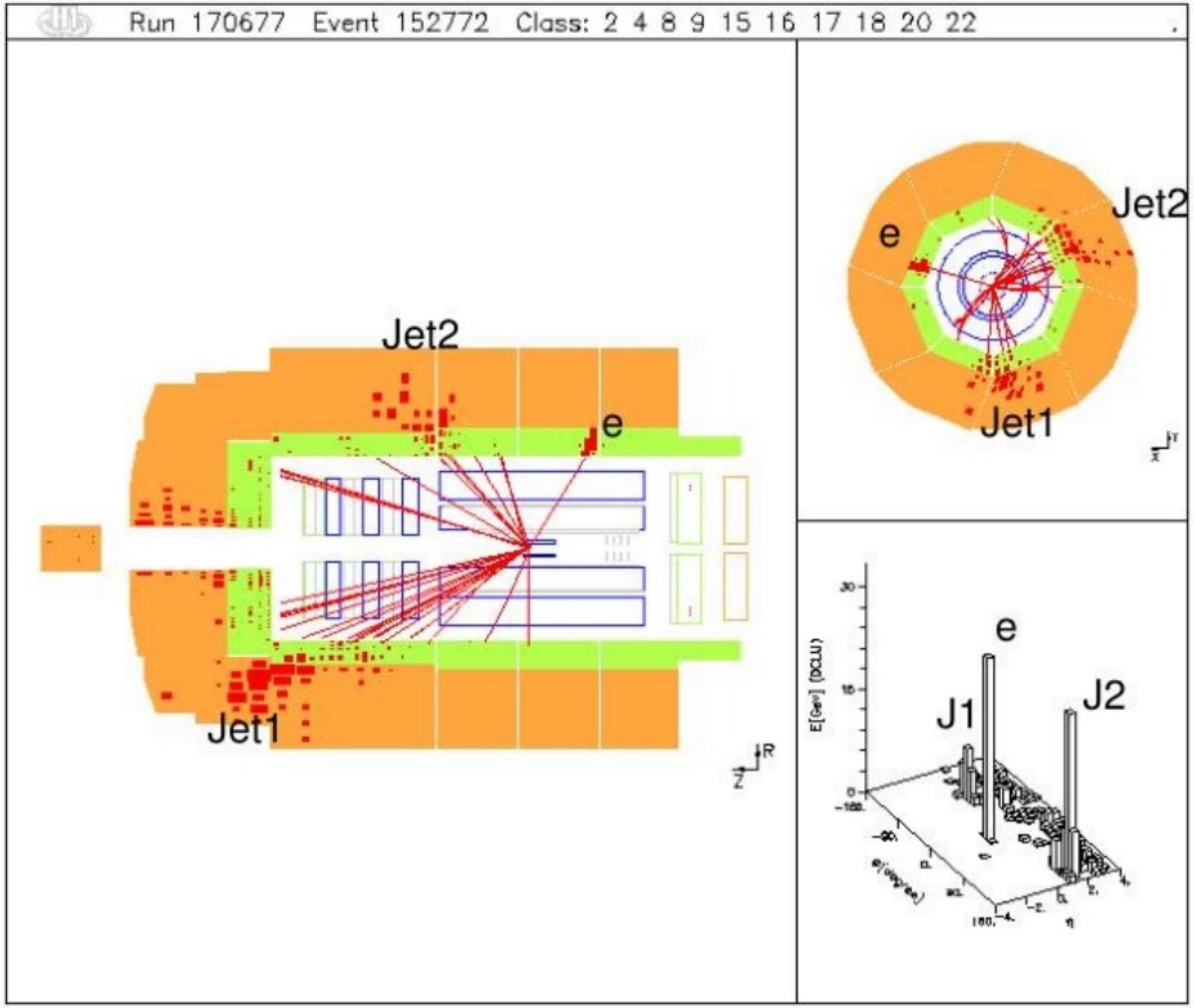


H1
Q^2 = 25030 GeV^2, y = 0.56; x=0.50
e+
e+
proton
jet
z
e+
Q^2
x
proton
jet
H1 Run 122145 Event 69506
Date 19/09/1995

HERA @ DESY

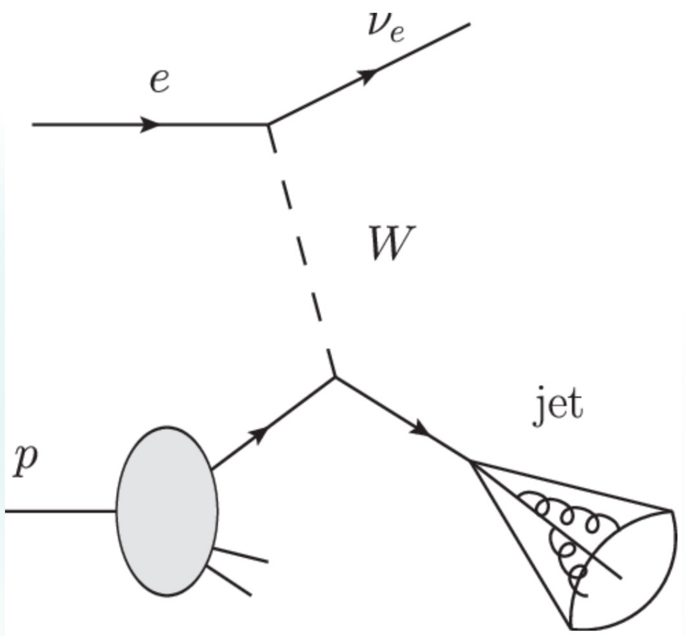


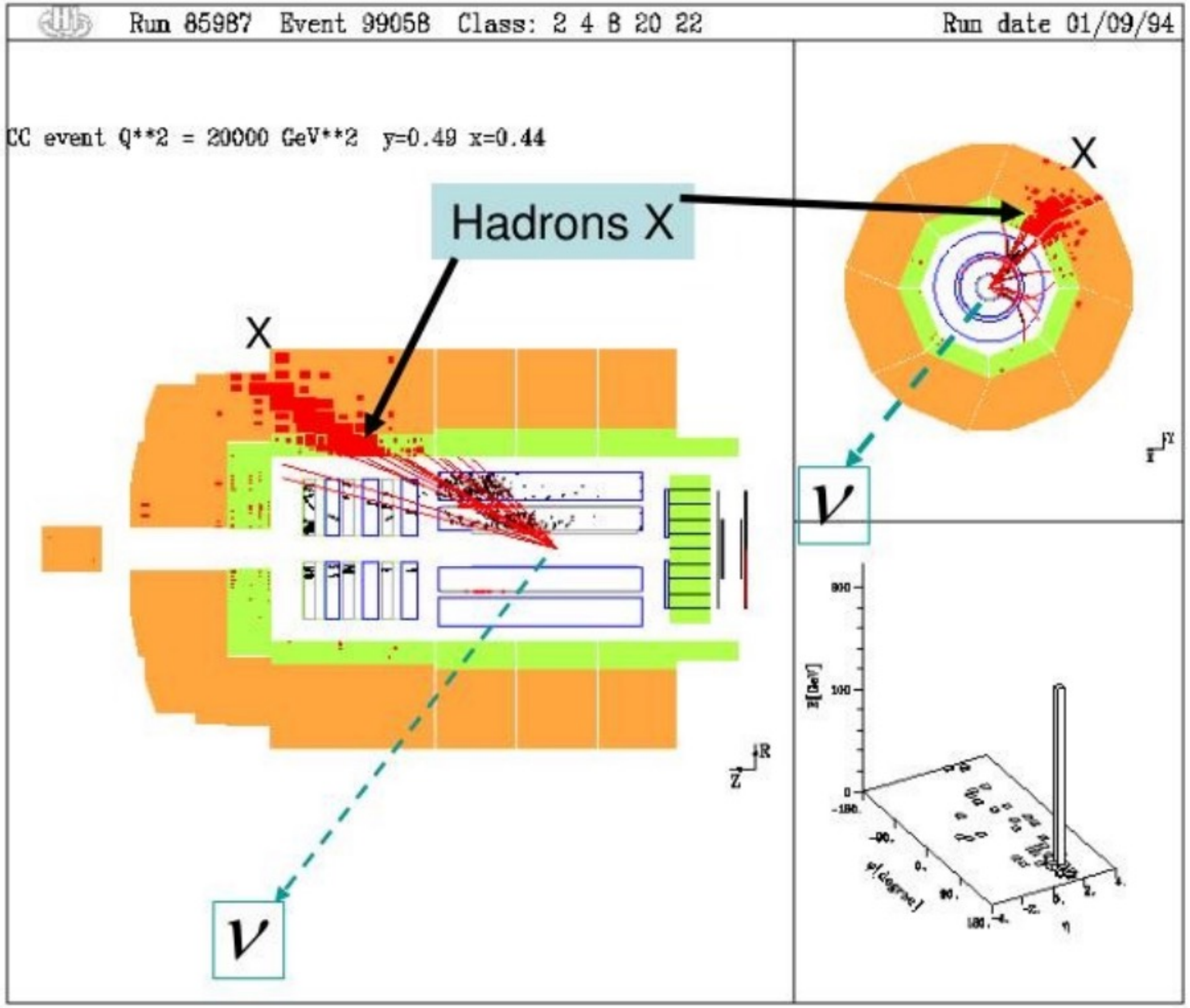
Many collimated hadrons (jet)
e
e′
γ
q
gluon
q
p
Jet



Run 170677 Event 152772 Class: 2 4 8 9 15 16 17 18 20 22
Jet2
e
Jet1
Jet2
e
Jet1
e
J1
J2

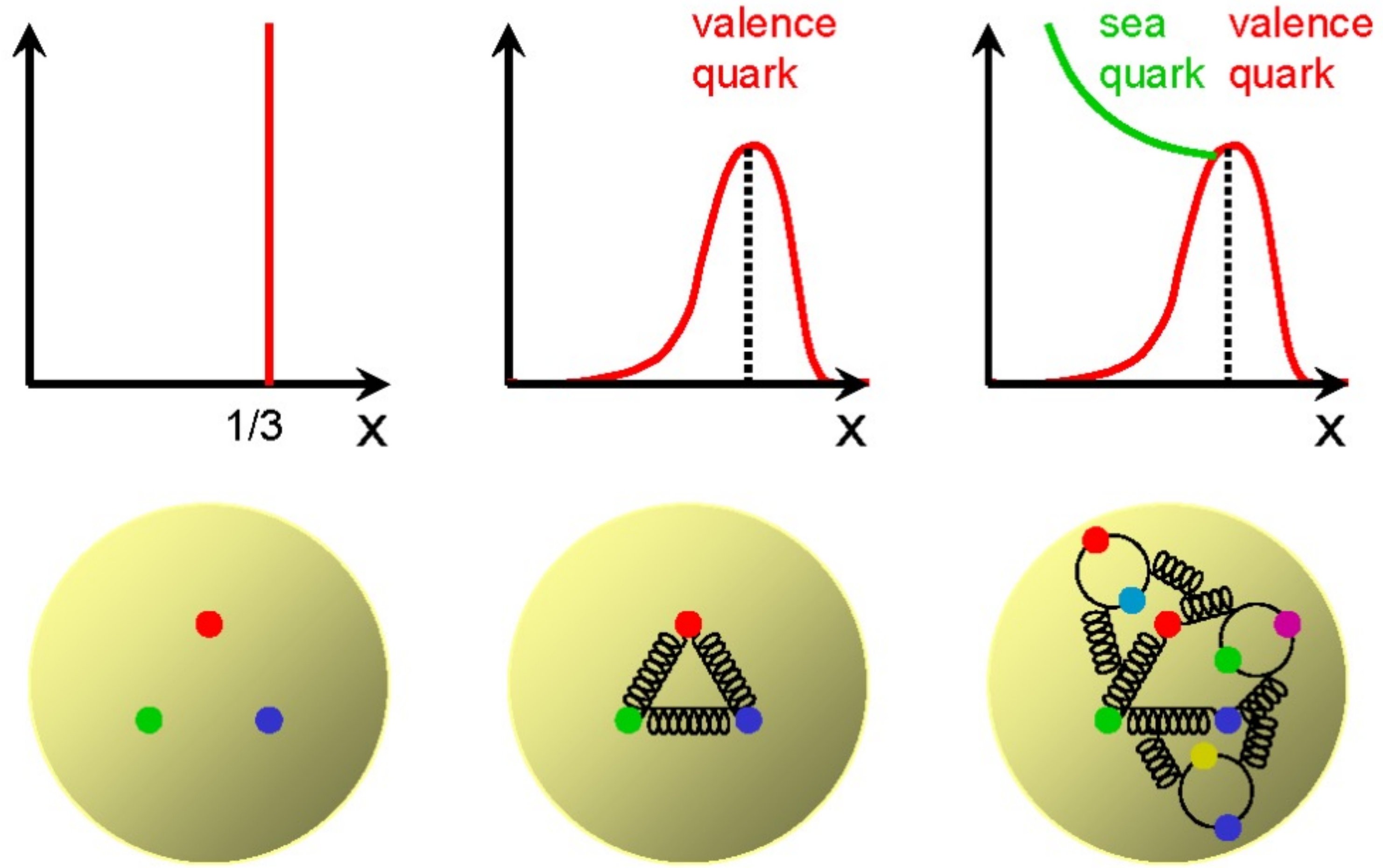
HERA @ DESY


e
ν_e
W
p
jet

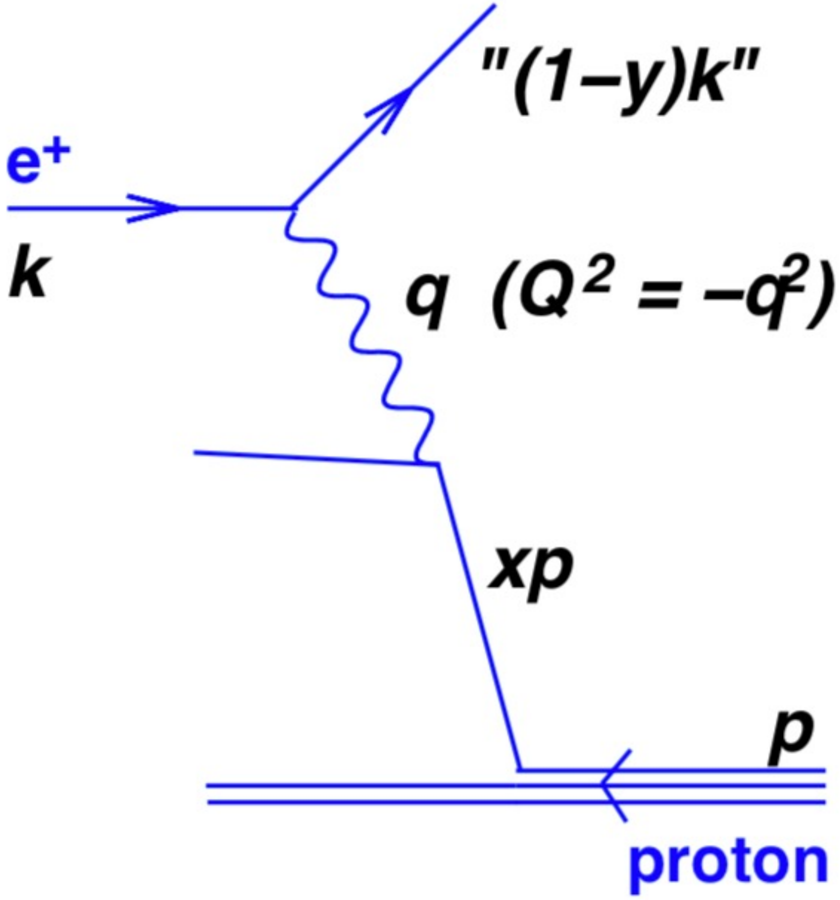

Run 85987 Event 99058 Class: 2 4 8 20 22
Run date 01/09/94
CC event Q**2 = 20000 GeV**2 y=0.49 x=0.44
Hadrons X
X
X
ν
ν

Parton Distribution Function

The probability of a parton of type i having a fraction x of the proton energy



Kinematics of DIS



Kinematic relations:

$$x = \frac{Q^2}{2p.q}; \quad y = \frac{p.q}{p.k}; \quad Q^2 = xys$$

$\sqrt{s}$ = c.o.m. energy

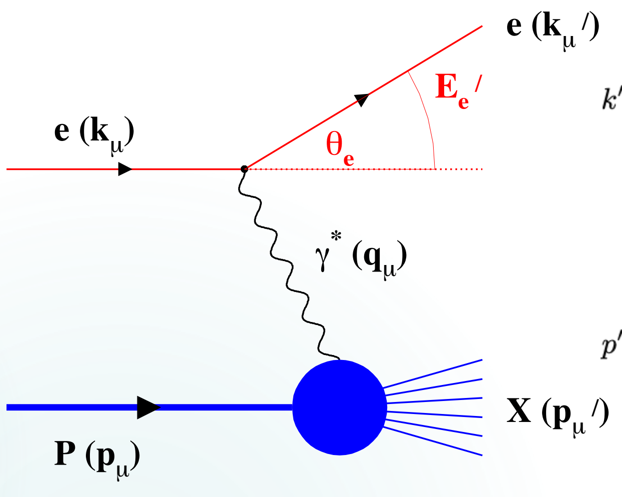
- Q^2 = photon virtuality $\leftrightarrow$ *transverse resolution* at which it probes proton structure
- x = *longitudinal momentum fraction* of struck parton in proton
- y = momentum fraction lost by electron (in proton rest frame)

y=0: small scattering angle limit
y=1: backscattering i.e. total momentum transfer to the hadronic system

Deep inelastic scattering (again)

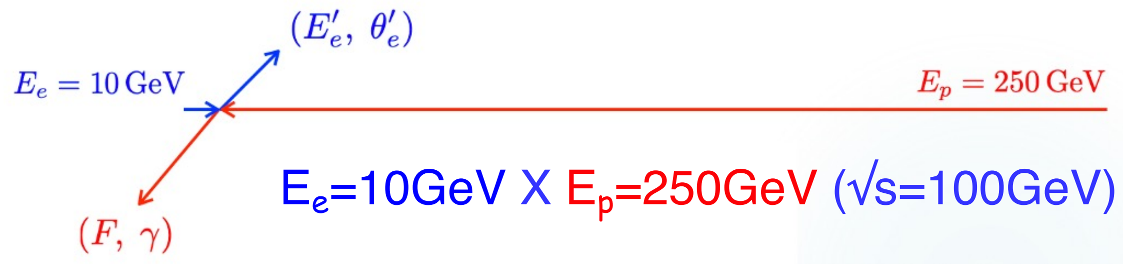
$$k = \begin{pmatrix} E_e \\ 0 \\ 0 \\ -E_e \end{pmatrix}$$

$$p = \begin{pmatrix} E_P \\ 0 \\ 0 \\ E_P \end{pmatrix}$$

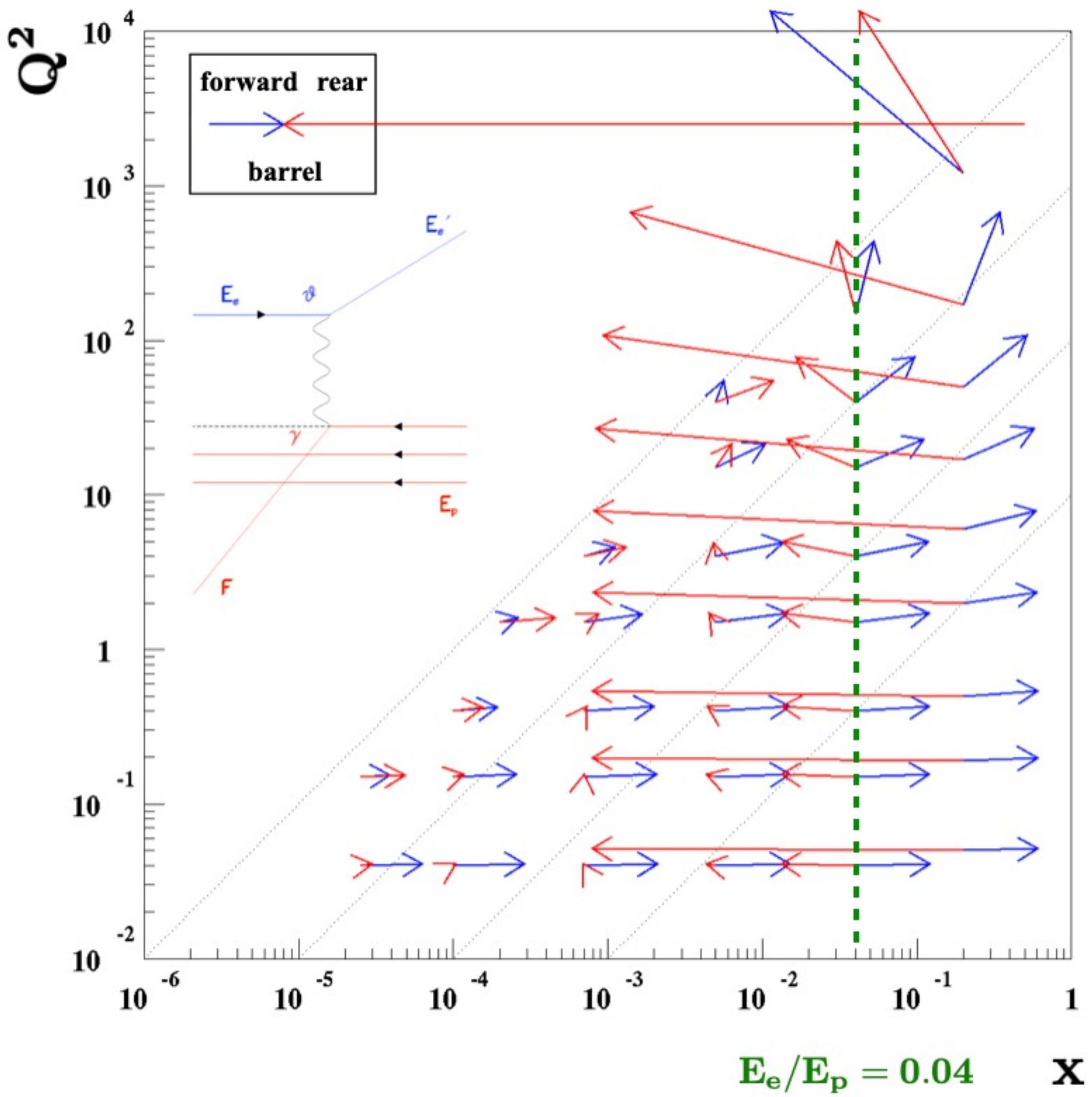


$$k' = \begin{pmatrix} E'_e \\ E'_e \sin\theta'_e \cos\phi'_e \\ E'_e \sin\theta'_e \sin\phi'_e \\ E'_e \cos\theta'_e \end{pmatrix}$$

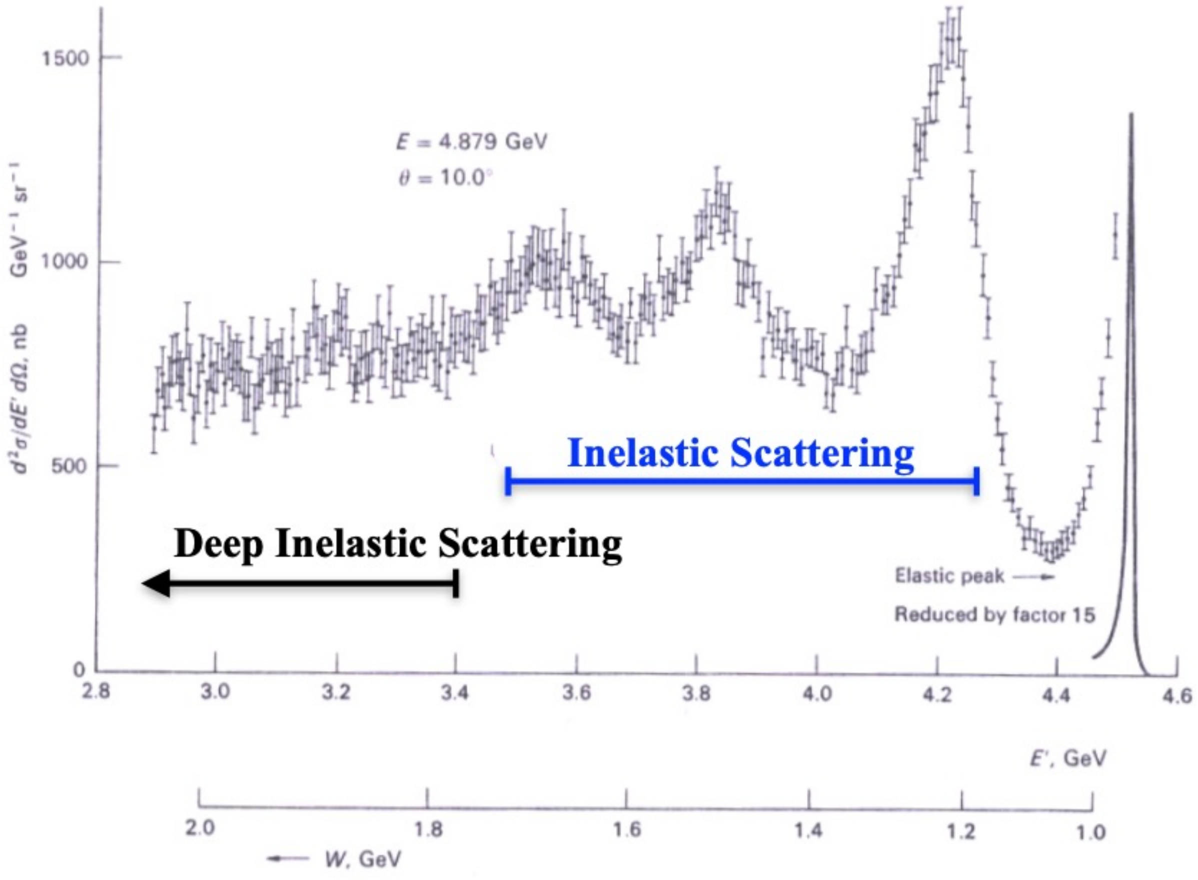
$$p' = \begin{pmatrix} \sum_h E_h \\ \sum_h p_{X,h} \\ \sum_h p_{Y,h} \\ \sum_h p_{Z,h} \end{pmatrix}$$



E_e=10GeV X E_p=250GeV ($\sqrt{s}$=100GeV)



e+p→e+X



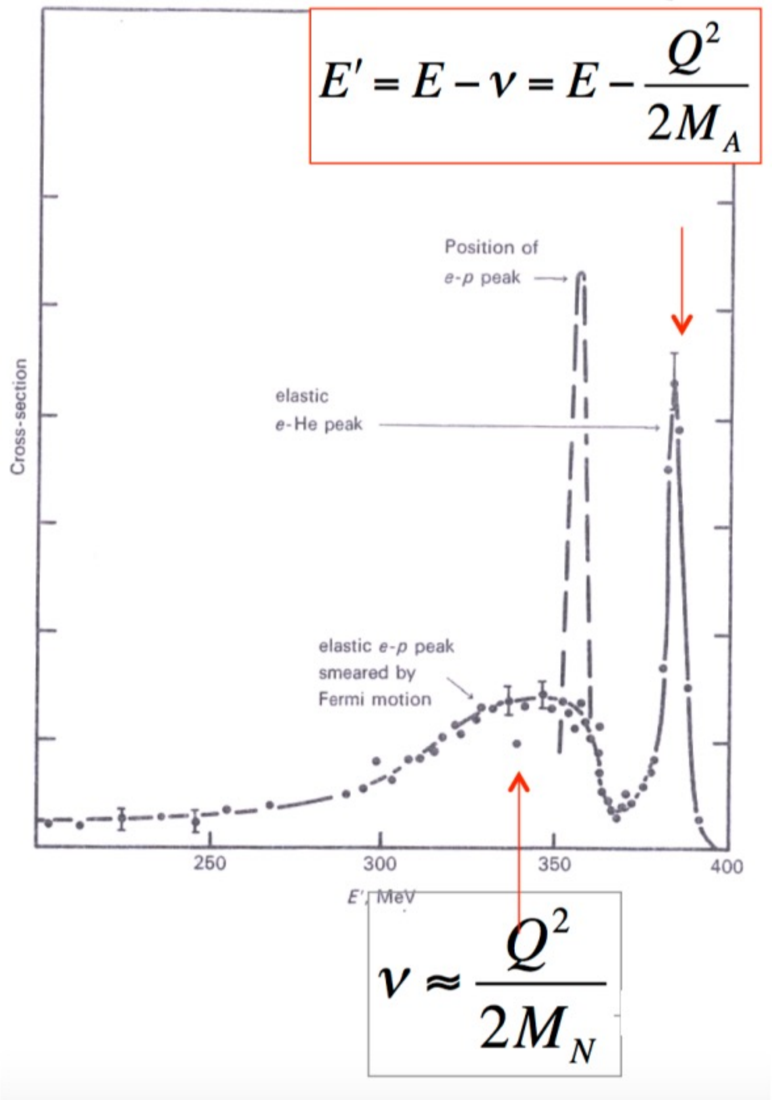
- Elastic peak at x=1 ($Q^2=2M\nu$)
- Inelastic scattering at larger q^2 : the peaks correspond to “excited states” of the proton, e.g. $\Delta^+(1232)$, …
- Deep Inelastic Scattering: proton breaks up resulting in many particles final state (large W)

$W^2=(P+q)^2$: invariant mass of the hadronic final state

Scattering of 4.879 GeV electron from proton at rest

- Detector at 10 deg. w.r.t the beam, and measure the energy of the scattered electron
- Kinematics fully determined from the electron energy and the angle

e+A->e+X



- Elastic peak at high value of E’ (low value of Q2)

- The broader peak at larger q^2 corresponds to quasi-elastic scattering on single nucleons
  - If nucleons were free, we would have a single narrow peak at $\nu \approx Q^2/(2M_N)$
  - Nucleons are in a potential wall of radius R ~ 1 fm, so they have a Fermi momentum p_F ~ 1/R ~ 200 MeV which broaden the elastic peak:
    - $\Delta\nu/\nu = \pm p_F/M_N \sim 10\%$

Structure function

Write DIS X-section to zeroth order in α_s ('quark parton model'):

$$\frac{d^2\sigma^{em}}{dxdQ^2} \simeq \frac{4\pi\alpha^2}{xQ^4}\left(\frac{1+(1-y)^2}{2}F_2^{em} + \mathcal{O}(\alpha_s)\right)$$

$\propto F_2^{em}$ [structure function]

$$F_2(x) = \sum_i e_i^2 x f_i(x)$$

e-p scattering

$$\frac{1}{x}F_2^{ep} = \left(\frac{2}{3}\right)^2(u^p+\bar{u}^p) + \left(\frac{1}{3}\right)^2(d^p+\bar{d}^p) + \left(\frac{1}{3}\right)^2(s^p+\bar{s}^p)$$

e-n scattering (from e-d scattering)

$$\frac{1}{x}F_2^{en} = \left(\frac{2}{3}\right)^2(u^n+\bar{u}^n) + \left(\frac{1}{3}\right)^2(d^n+\bar{d}^n) + \left(\frac{1}{3}\right)^2(s^n+\bar{s}^n),$$

Structure function

e-p scattering

$$\frac{1}{x}F_2^{ep} = \left(\frac{2}{3}\right)^2 (u^p + \bar{u}^p) + \left(\frac{1}{3}\right)^2 (d^p + \bar{d}^p) + \left(\frac{1}{3}\right)^2 (s^p + \bar{s}^p)$$

e-n scattering (from e-d scattering)

$$\frac{1}{x}F_2^{en} = \left(\frac{2}{3}\right)^2 (u^n + \bar{u}^n) + \left(\frac{1}{3}\right)^2 (d^n + \bar{d}^n) + \left(\frac{1}{3}\right)^2 (s^n + \bar{s}^n),$$

exchanging an up quark for a down turns basically a proton into a neutron (iso-spin symmetry)

$$u := u_v + u_s = u^p = d^n$$
$$d := d_v + d_s = d^p = u^n.$$

the three lightest quark flavors (u,d,s) occur with equal probability in the sea:

$$S := u_s = \bar{u}_s = d_s = \bar{d}_s = s_s = \bar{s}_s.$$

$$\frac{1}{x}F_2^{ep} = \frac{1}{9}(4u_v + d_v) + \frac{4}{3}S$$
$$\frac{1}{x}F_2^{en} = \frac{1}{9}(4d_v + u_v) + \frac{4}{3}S.$$

Structure function

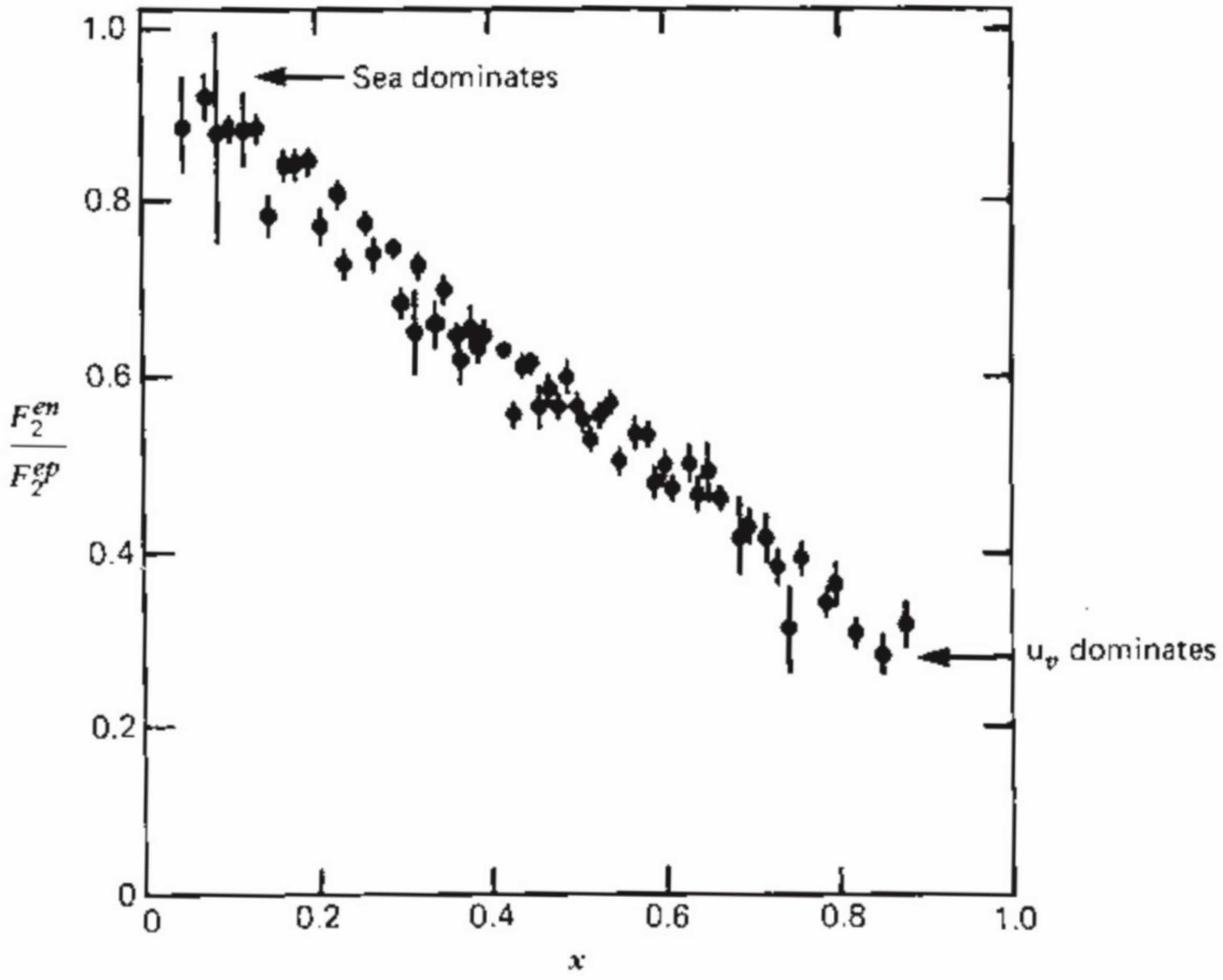
$$\frac{1}{x}F_2^{ep} = \frac{1}{9}(4u_v + d_v) + \frac{4}{3}S$$
$$\frac{1}{x}F_2^{en} = \frac{1}{9}(4d_v + u_v) + \frac{4}{3}S.$$

At small momentum fractions (x ≈ 0) the structure function is dominated by low- momentum $q\bar{q}$-pairs constituting the “sea”.

$$\frac{F_2^{en}}{F_2^{ep}} \to 1,$$

for x ≈ 1 the valence quarks dominate

$$\frac{F_2^{en}}{F_2^{ep}} \to \frac{1}{4}.$$



Gluons

Summing the measured momenta of the partons give the proton momentum.

$$\int_0^1 dx\ x(u + \bar{u} + d + \bar{d} + s + \bar{s}) = 1 - \varepsilon_g;$$

$$\int_0^1 dx F_2^{ep} = \frac{4}{9}\varepsilon_u + \frac{1}{9}\varepsilon_d = 0.18,$$

$$\int_0^1 dx F_2^{en} = \frac{1}{9}\varepsilon_u + \frac{4}{9}\varepsilon_d = 0.12.$$

$$\varepsilon_u = 0.36$$

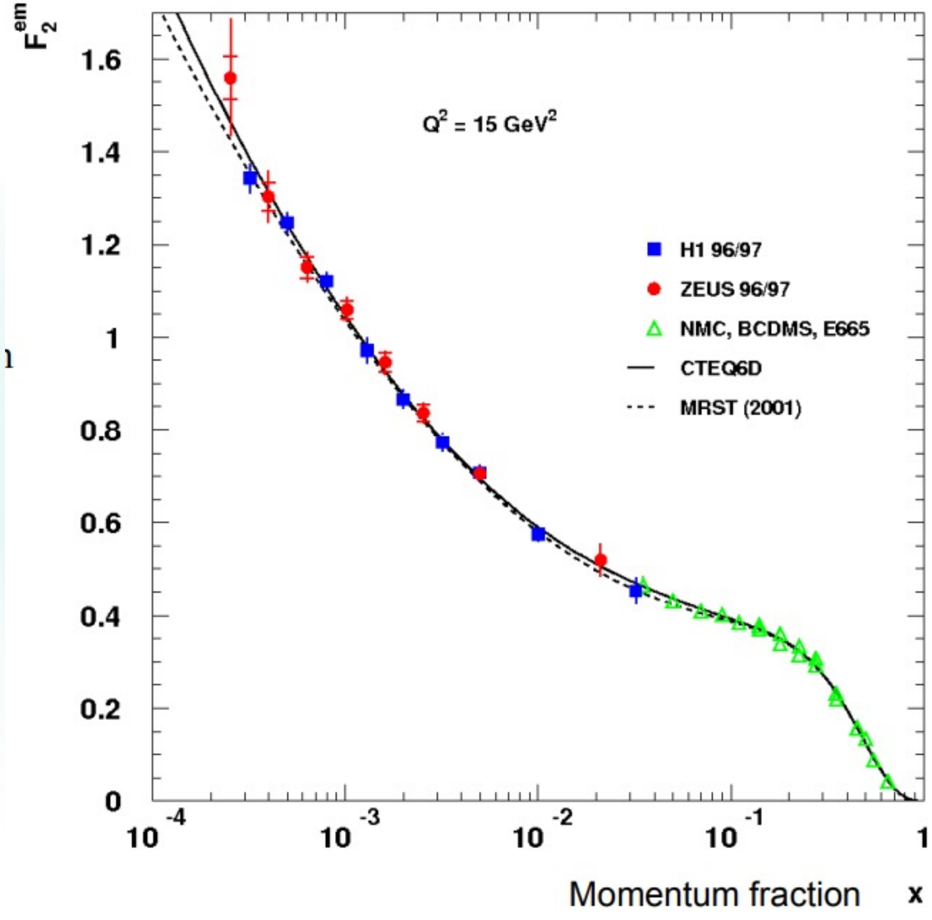
$$\varepsilon_d = 0.18,$$

$$\varepsilon_g = 1 - \varepsilon_u - \varepsilon_d = 0.46.$$

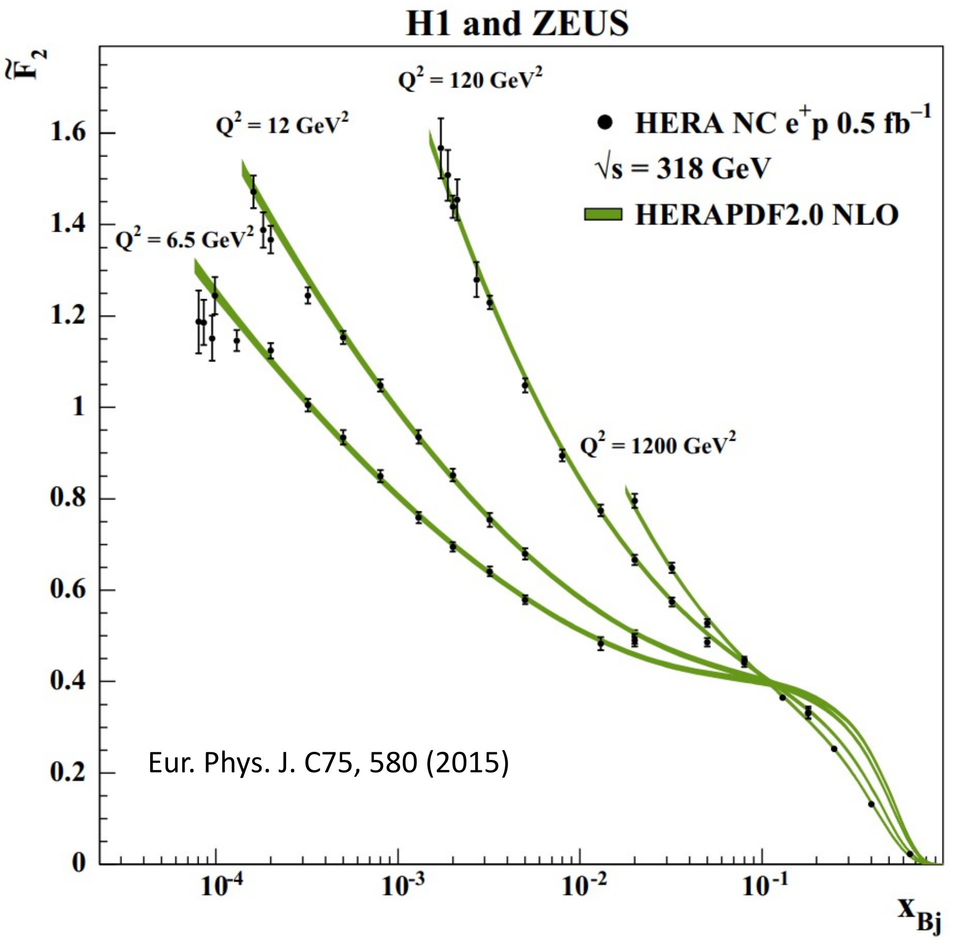
Almost half of the proton momentum is carried by gluons

Structure functions at HERA

Contribution of sea quarks
Contribution increases as smaller-x



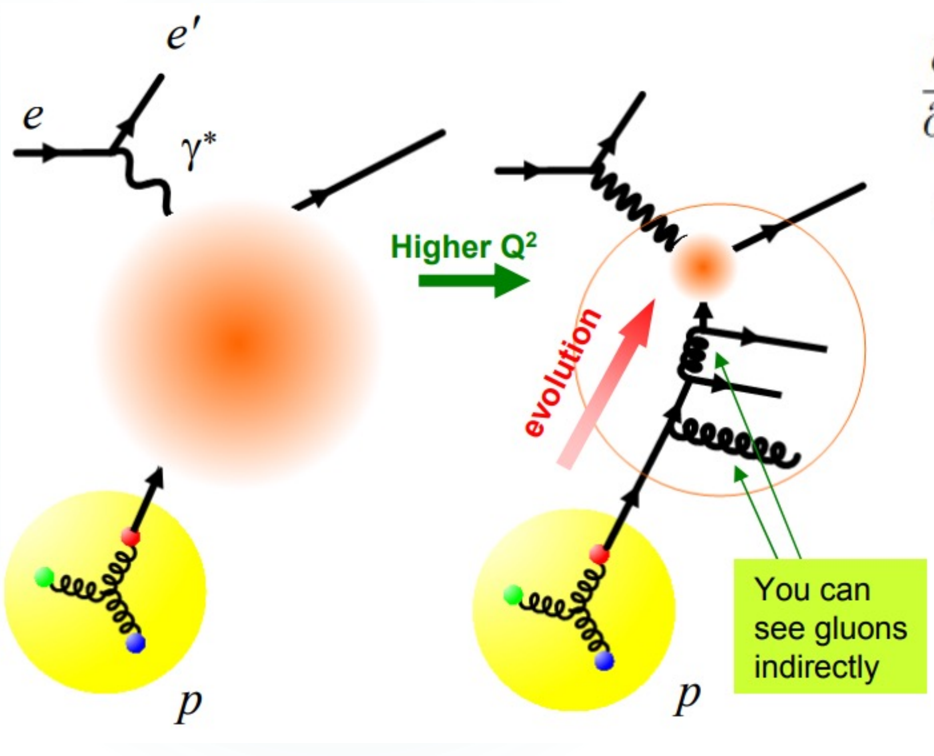
Sea quarks dynamically created at high Q^2



Dynamical picture of evolution

Increased spatial resolution Q^2 → Shorter interaction time τ_i ($\tau_i = 1/Q^2$)

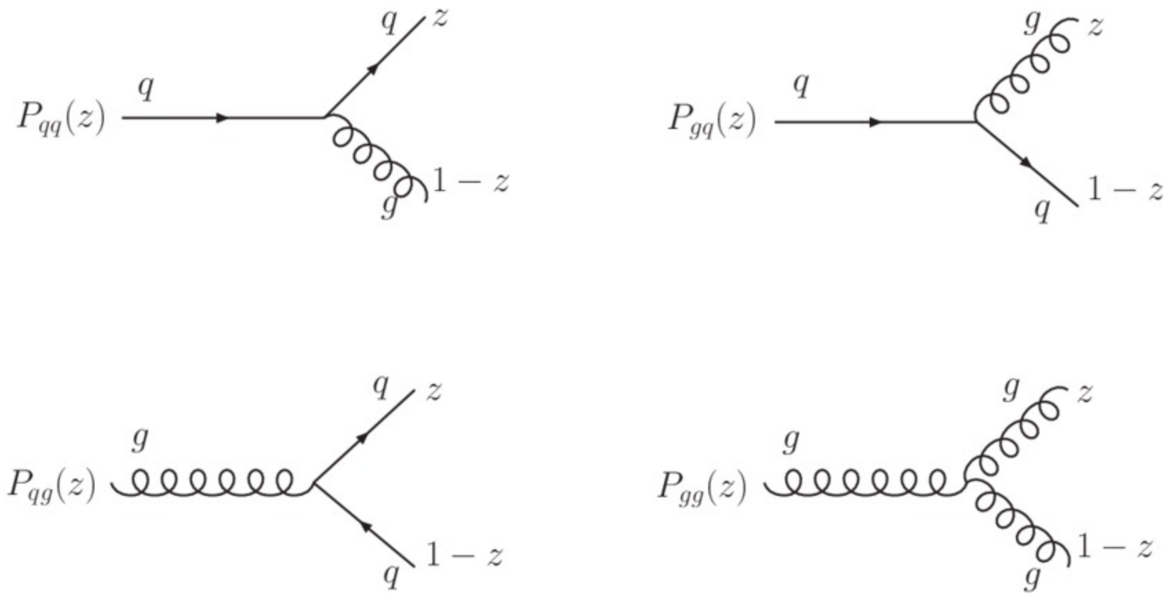
- **Quantum fluctuations :** Gluon splits into a pair of quark and anti-quark, and in turn recombines back to gluon later.
- With EM interaction (e-p scattering via γ), gluon cannot be seen directly (gluons cannot directly interact with γ) , but is indirectly seen as **"increase of quarks with smaller x as Q^2 gets higher"**



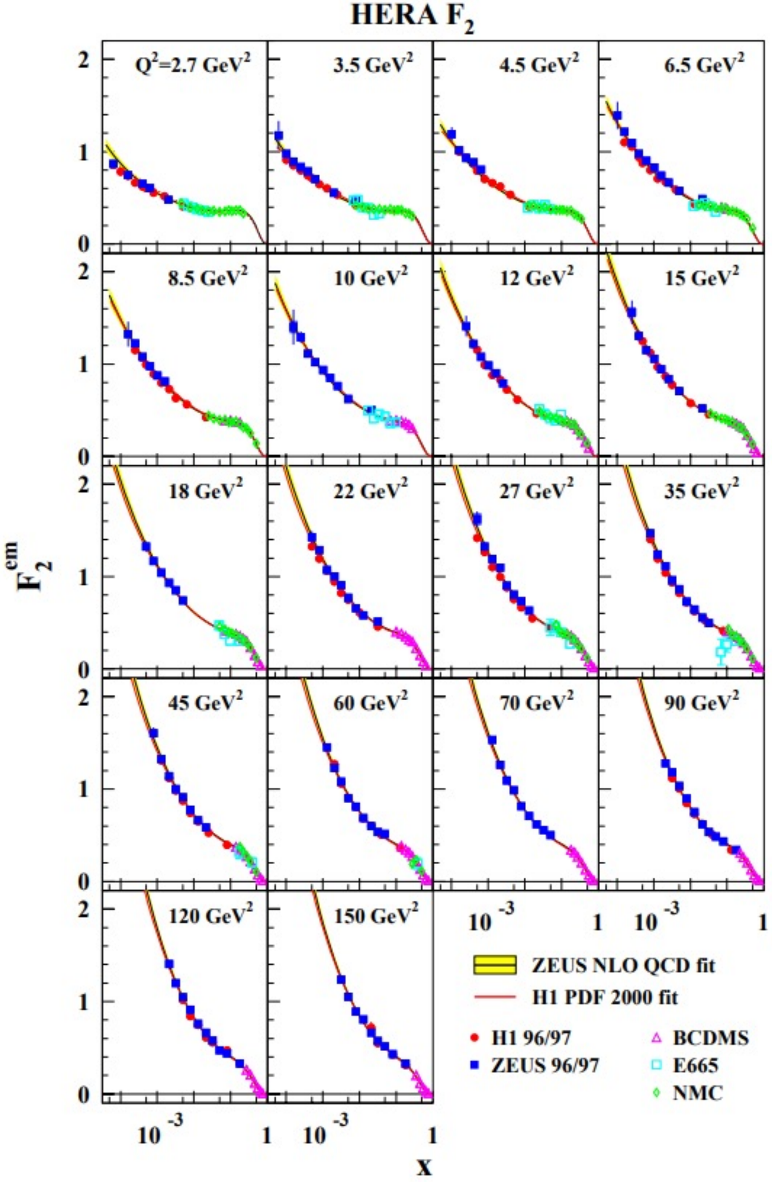
Dokshitzer-GribovLipatov-Altarelli-Parisi (DGLAP) evolution equation

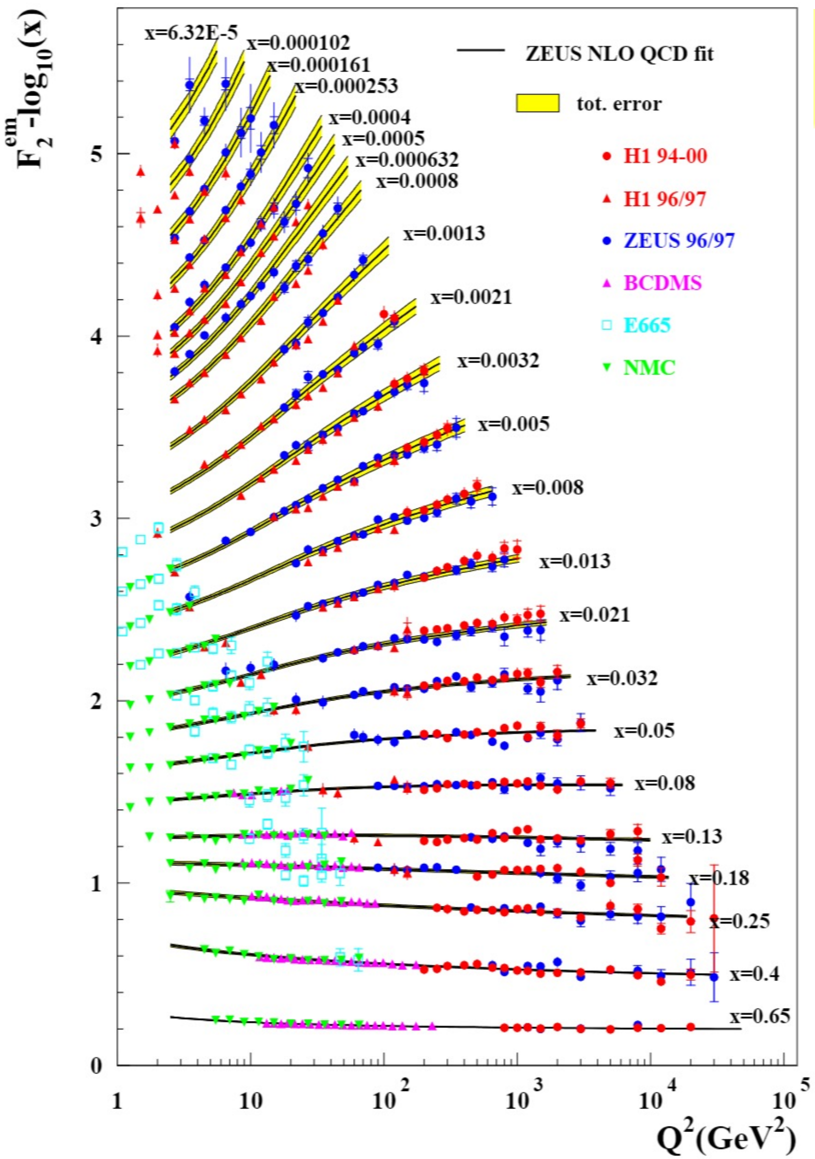
$$\frac{\partial}{\partial t}\begin{pmatrix} q_i(x,t)\\ g(x,t)\end{pmatrix} = a_s(t)\sum_{j=1}^{2n_f}\int_x^1 \frac{dz}{z}\left[\begin{pmatrix} P_{q_iq_j}\left(\frac{x}{z},a_s(t)\right) & P_{q_ig}\left(\frac{x}{z},a_s(t)\right)\\ P_{gq_j}\left(\frac{x}{z},a_s(t)\right) & P_{gg}\left(\frac{x}{z},a_s(t)\right)\end{pmatrix}\begin{pmatrix} q_j(z,t)\\ g(z,t)\end{pmatrix}\right],$$

$$t = \ln Q^2,$$

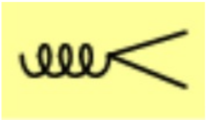


Structure functions at HERA

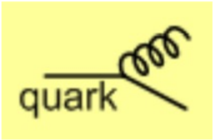




Small-x



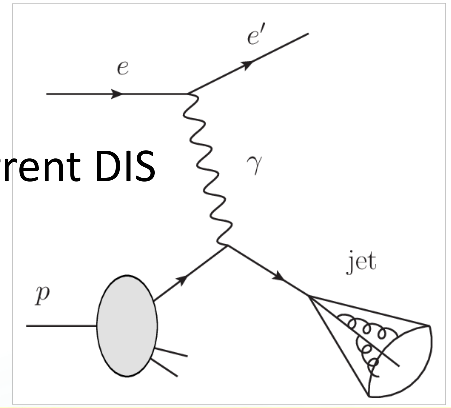
DGLAP evolution describes well



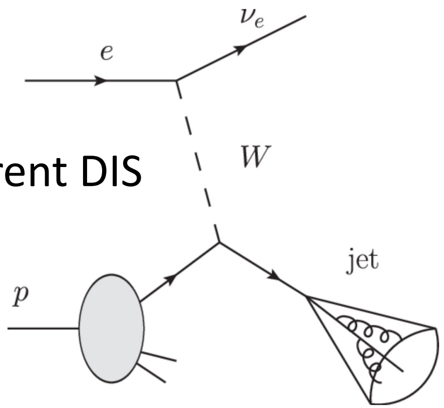
Large-x

Structure functions at HERA

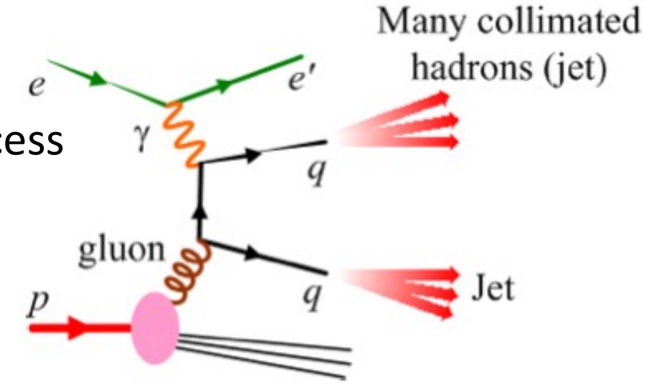
Neutral current DIS



Charged current DIS



Di-jet process



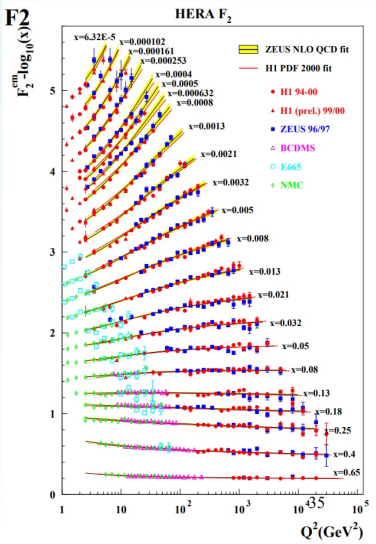
$\gamma, Z^0 \rightarrow F_2 \propto \sum x(q + \bar{q})$ Sea + valence quark

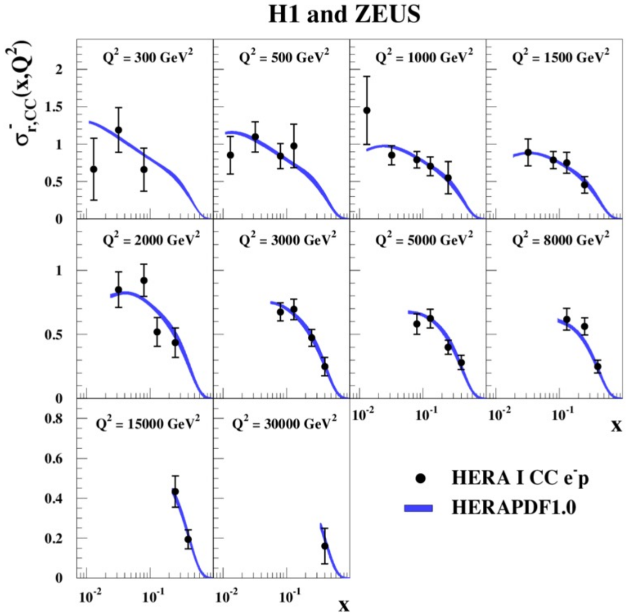
$$\frac{\partial F_2}{\partial \ln Q^2} \propto xg$$ gluon

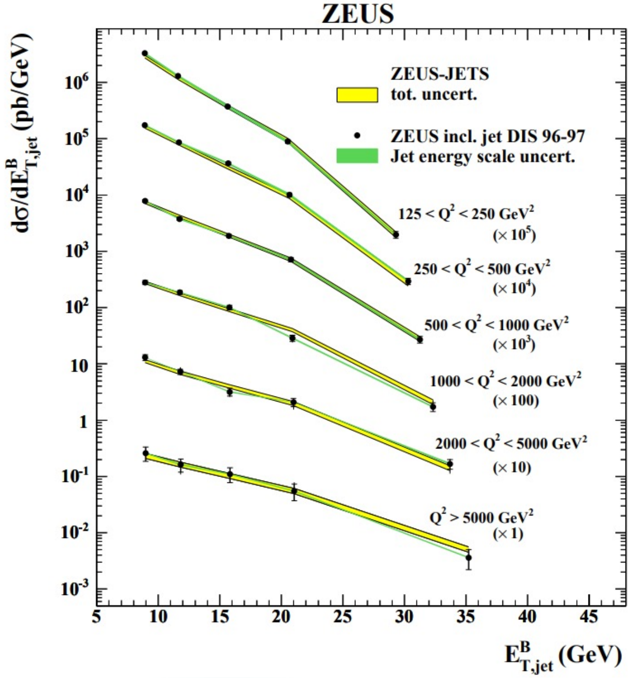
Charge selective interaction

e^- : u quark e^+: d quark

Directly sensitive to gluon density







PDF Parameterization for global fit

PDF Parameterization

u-valence (xu_v)	$A_{uv}\, x^{b_{uv}}\, (1-x)^{c_{uv}}\, (1+d_{uv}x)$
d-valence (xd_v)	$A_{dv}\, x^{b_{dv}}\, (1-x)^{c_{dv}}\, (1+d_{dv}x)$
Sea (xS)	$A_S\, x^{b_S}\, (1-x)^{c_S}$
gluon (xg)	$A_g\, x^{b_g}\, (1-x)^{c_g}\, (1+d_g x)$
dbar-ubar ($x\Delta$)	$0.27\, x^{0.5}\, (1-x)^{c_\Delta}$

$$F_2(x) = \sum_i e_i^2 x f_i(x)$$

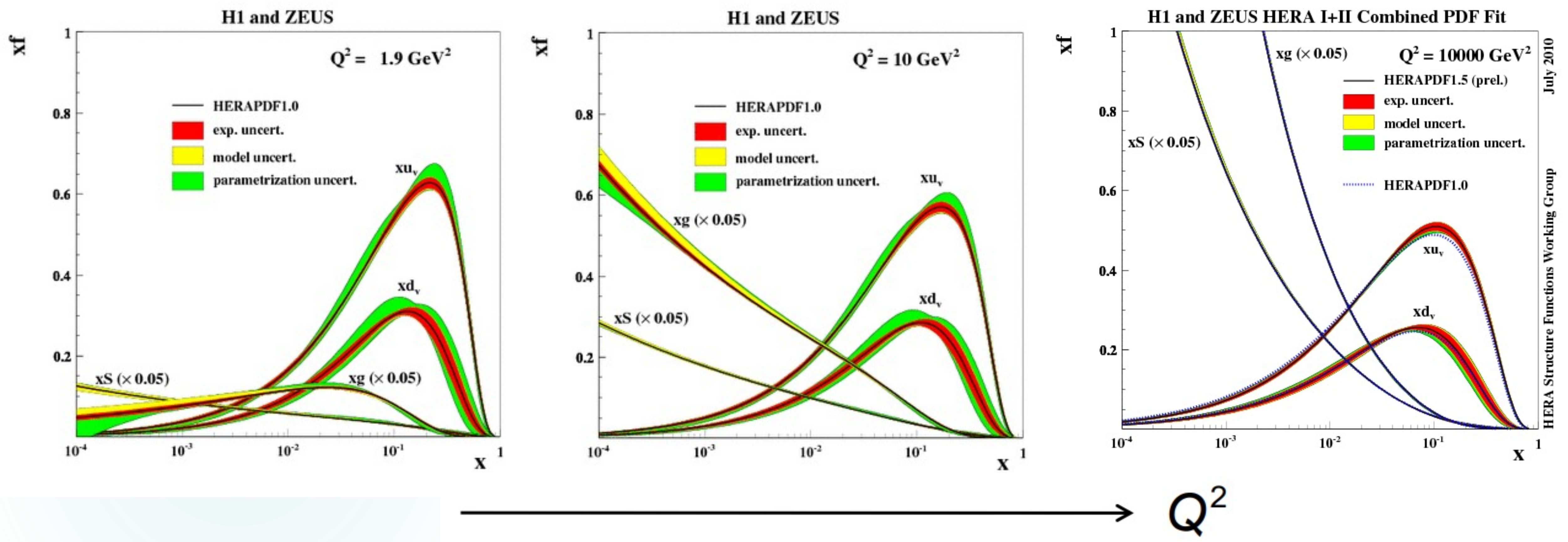
Constraints

- Momentum and number sum rule
- Equal behaviour of u_v and d_v at low x
- Δ : consistent with Gottfried sum rule and Drell Yan

11 free parameters

Parton distribution function

JHEP 1001:109(2010)



The most dramatic of these experimental consequences, that the protons viewed at ever higher resolution would appear more and more as field energy (soft gluons) , was only clearly verified at HERA ... F. Wilczek [Nobel Prize 2004]

Polarized PDF

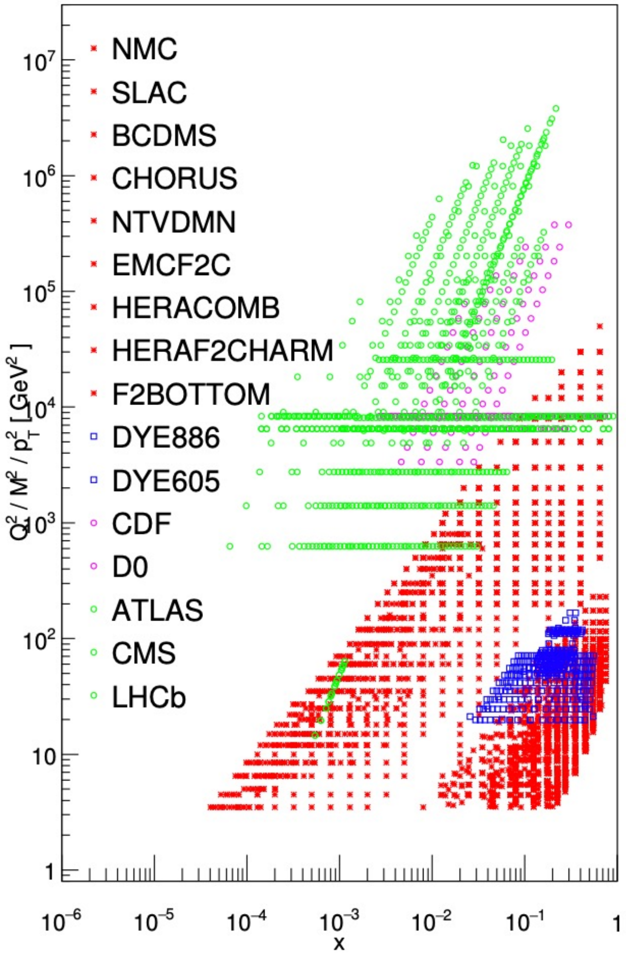
Unpolarized PDF

$$f(x) \equiv f^{\uparrow}(x) + f^{\downarrow}(x)$$

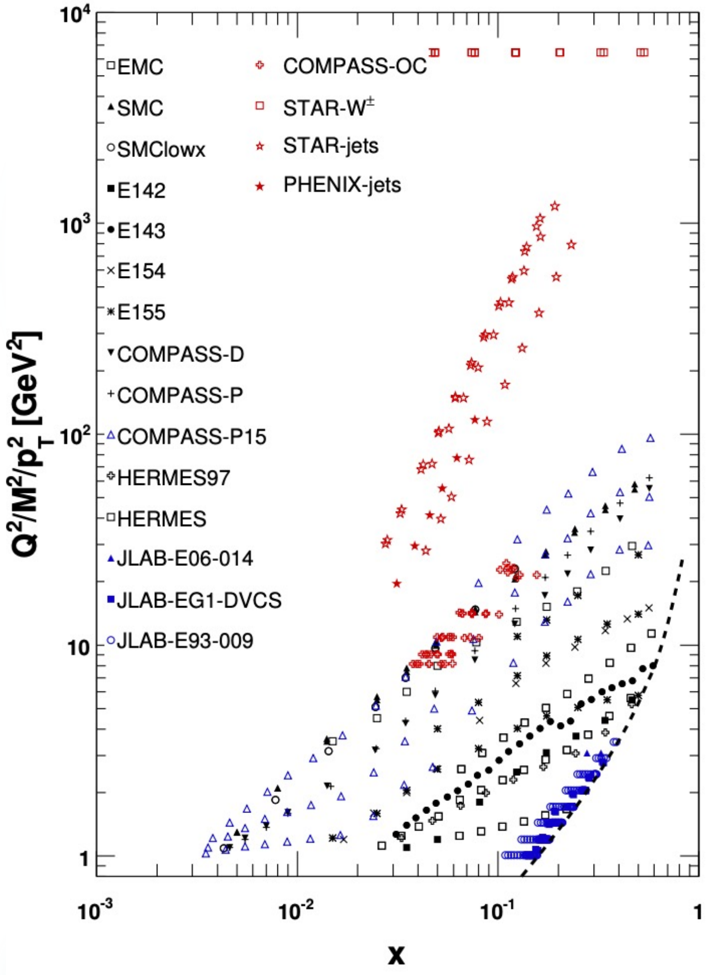
Polarized PDF

$$\Delta f(x) \equiv f^{\uparrow}(x) - f^{\downarrow}(x)$$

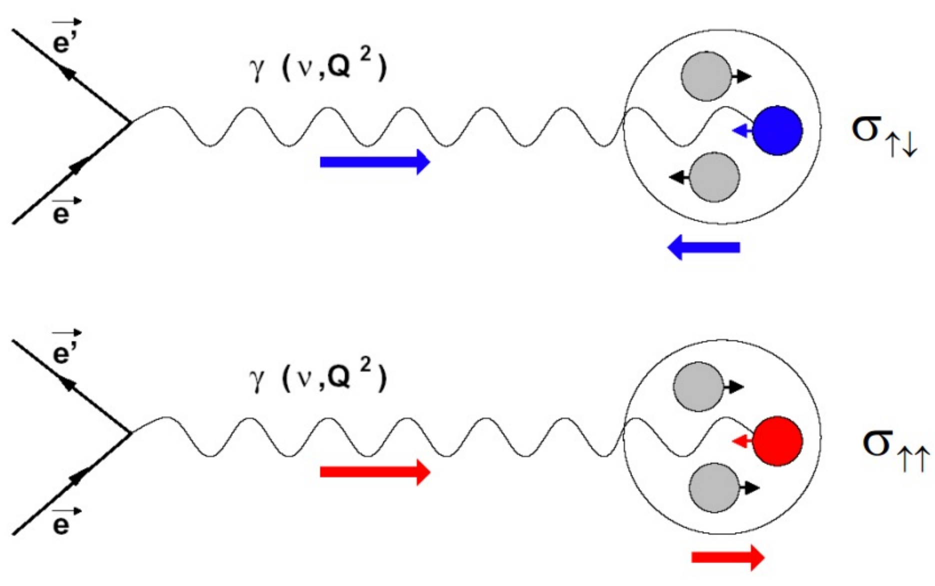
Unpolarized PDF



Polarized PDF



Asymmetry (DIS)

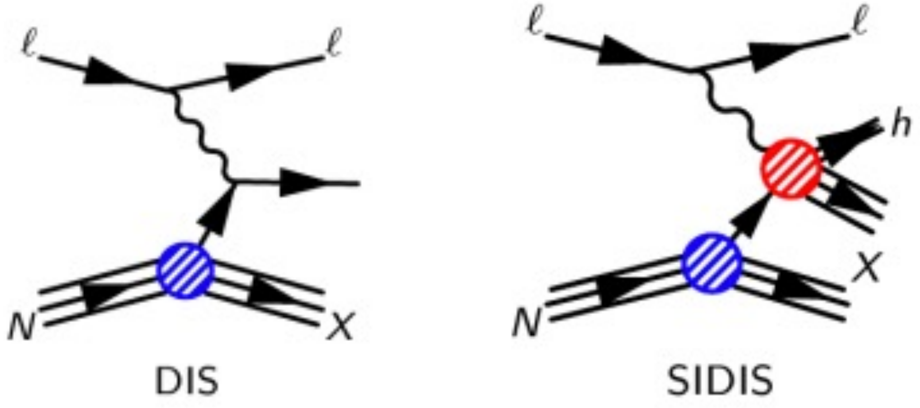


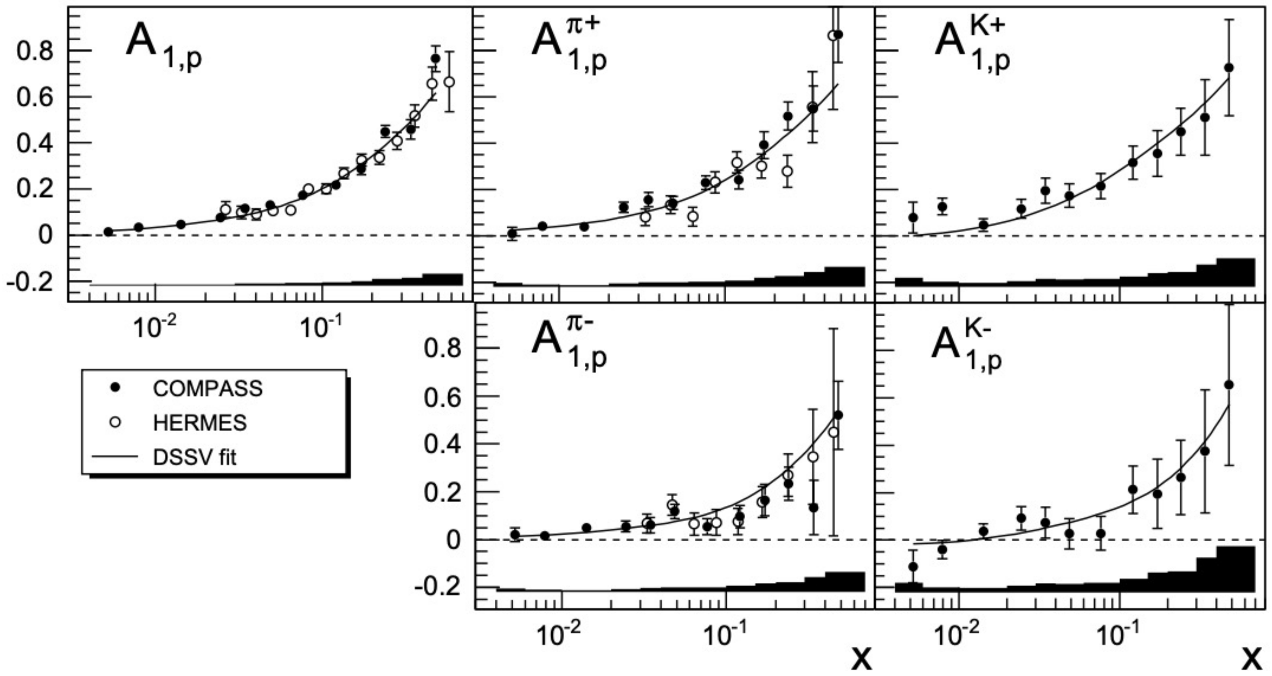
Inclusive DIS

$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \, \Delta q(x,Q^2)}{\sum_q e_q^2 \, q(x,Q^2)}$$

Semi-Inclusive DIS

$$A_1^h(x,z,Q^2) = \frac{\sigma_{\uparrow\downarrow}^h - \sigma_{\uparrow\uparrow}^h}{\sigma_{\uparrow\downarrow}^h + \sigma_{\uparrow\uparrow}^h} \approx \frac{\sum_q e_q^2 \, \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 \, q(x,Q^2) D_q^h(z,Q^2)}$$



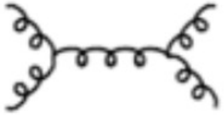


Asymmetry (pp)

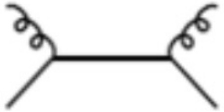
RHIC polarized p+p collisions

dijets

$\vec{g}\vec{g} \rightarrow gg$

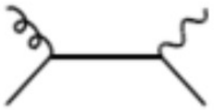


$\vec{q}\vec{g} \rightarrow qg$



promptp photon

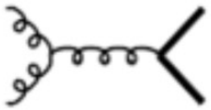
$\vec{q}\vec{g} \rightarrow \gamma q$

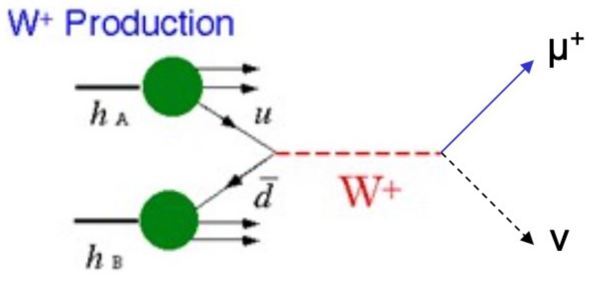


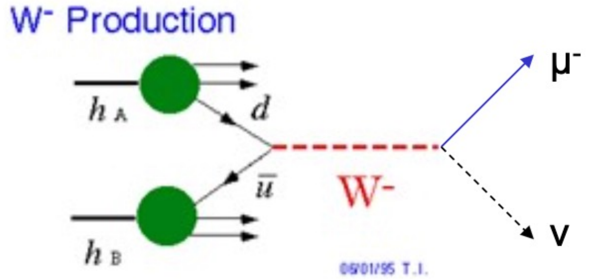
charm/bottom

$\vec{g}\vec{g} \rightarrow c\bar{c}$

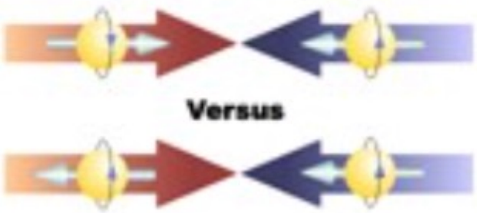
$\vec{g}\vec{g} \rightarrow b\bar{b}$



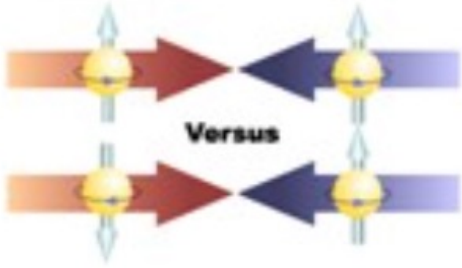




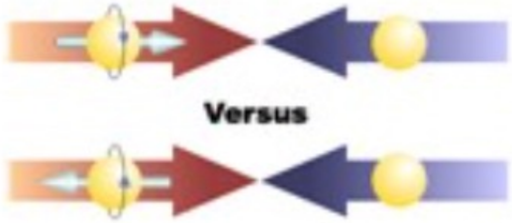
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



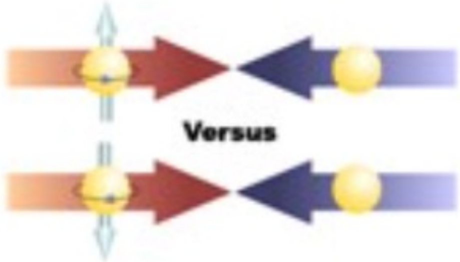
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



$$A_{L} = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$

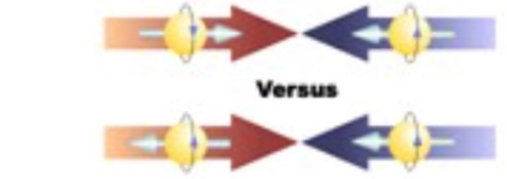


$$A_{T} = \frac{\sigma(\uparrow)-\sigma(\downarrow)}{\sigma(\uparrow)+\sigma(\downarrow)}$$

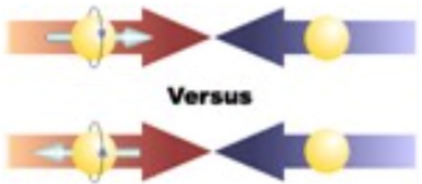


Asymmetry measured at RHIC

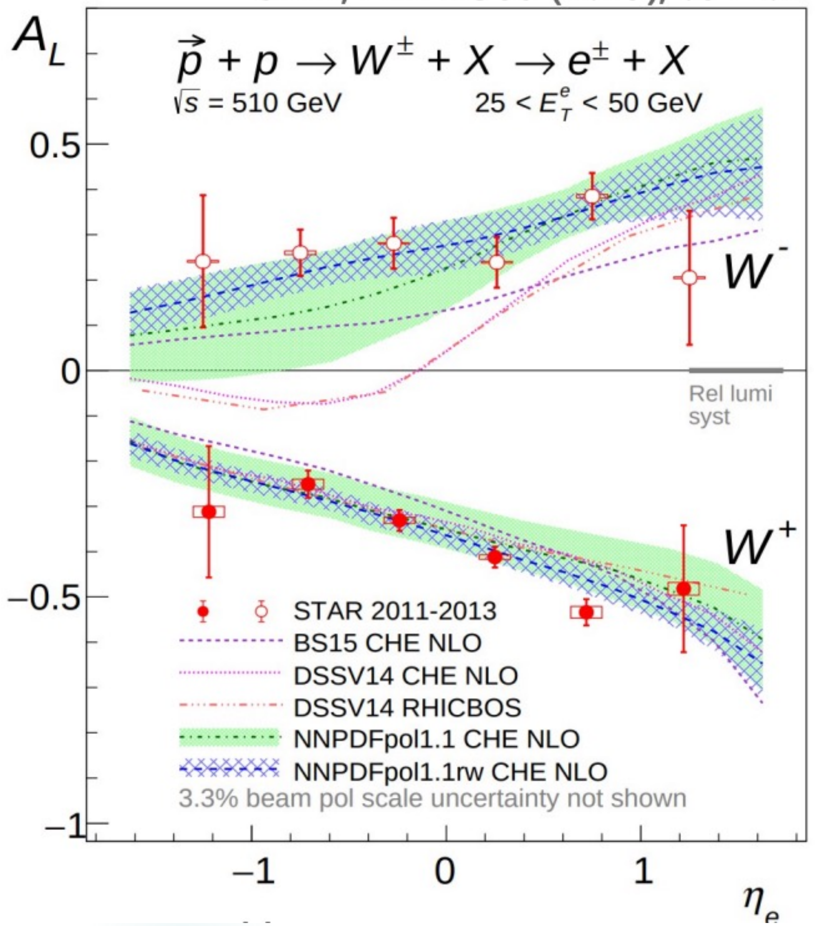
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



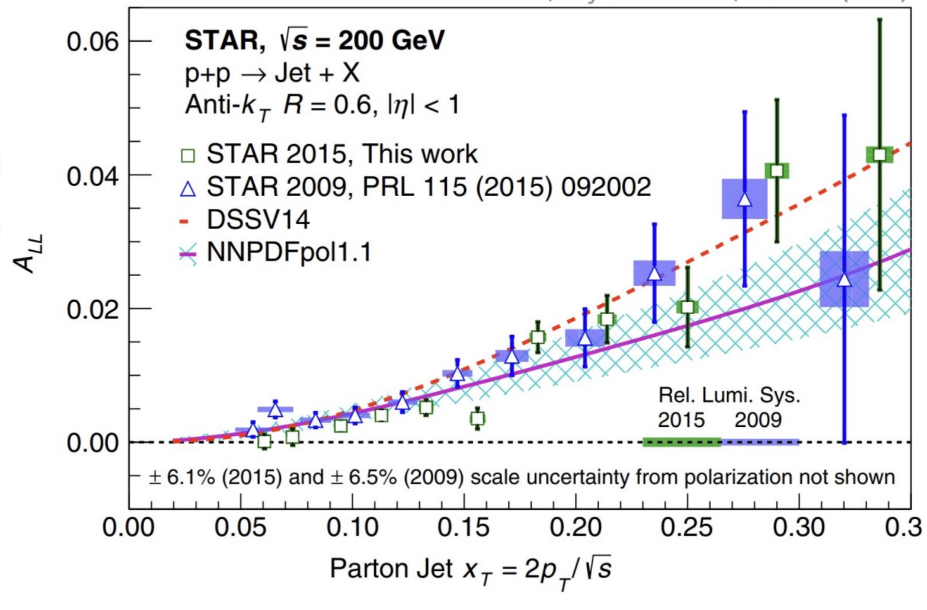
$$A_{L} = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$

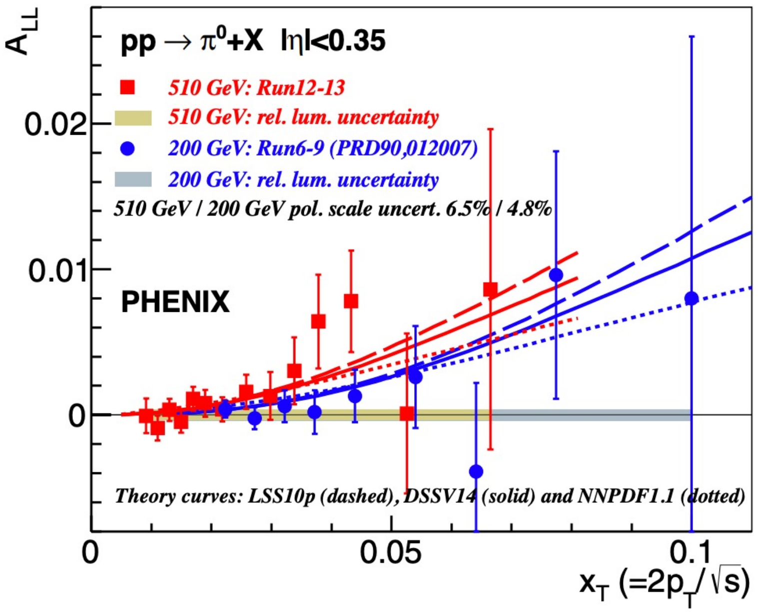


STAR, PRD RC 99 (2019), 051102



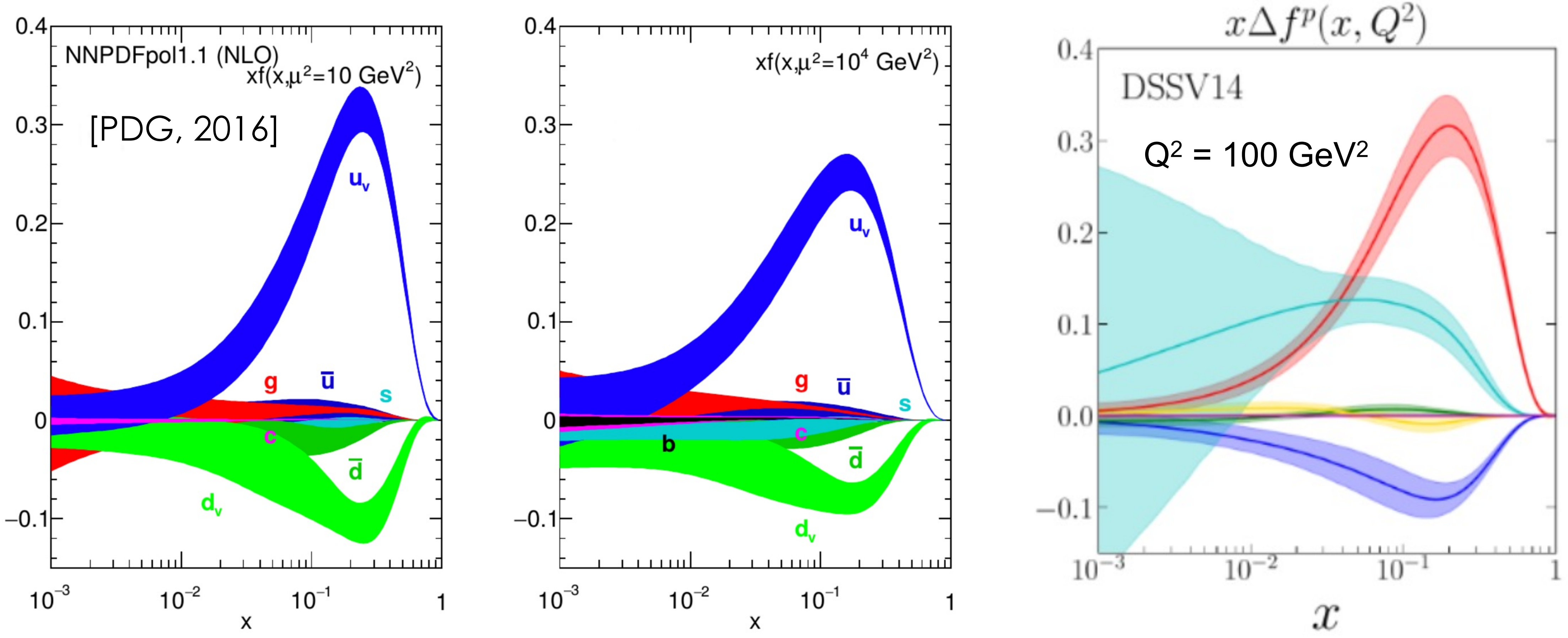
STAR, Phys. Rev. D 103, L091103 (2021)





Global Fit for Polarized PDF

arXiv:1711.07916

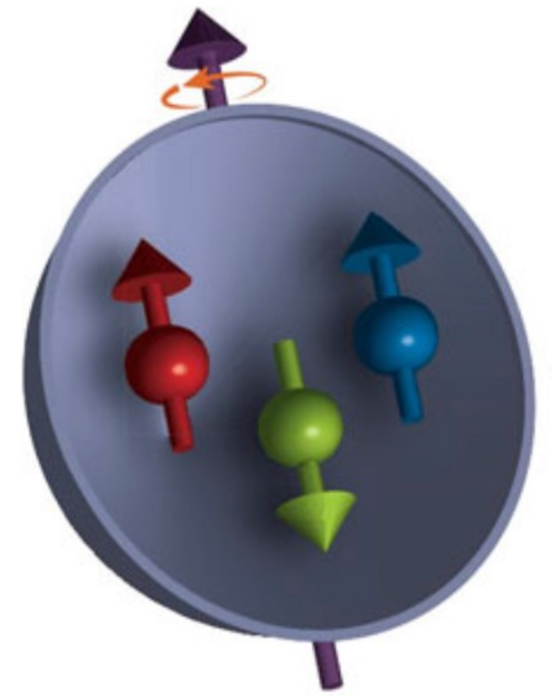


The most recent analyses of polarized PDFs are DSSV14[29] and NNPDFpol1.1[18]. Motivated by the interest in assessing the impact of RHIC proton–proton data, they upgrade the corresponding previous analyses, DSSV08[[19], [222]] and NNPDFpol1.0[227], with data respectively on double-spin asymmetries for inclusive jet production[228] and π^0 production[229] (DSSV14[9]), and on double-spin asymmetries for high-p_T inclusive jet production[[228], [230], [231]] and single-spin asymmetries for $W^\pm$ production[232] (NNPDFpol1.1). The new data have been included in NNPDFpol1.1 by means of Bayesian reweighting[233], and in DSSV14 by means of a full refit.

Overall, both the DSSV14 and NNPDFpol1.1 PDF determinations are state-of-the-art in the inclusion of the available experimental information. The data sets in the two analyses differ between each other only in fixed-target SIDIS and RHIC π^0 production measurements, included in DSSV14, but not in NNPDFpol1.1. The information brought in by these data is complementary to that provided by RHIC $W^\pm$ production and inclusive jet production data respectively, although fraught with larger theoretical uncertainties related to fragmentation.

Nucleon spin

- **Constitute Quark model : spin is 100% from constituent quarks**



$$|p\uparrow> = \sqrt{\frac{1}{2}}\left(p_S\chi(M_S) + p_A\chi(M_A)\right)$$

$$P(M_S) = \frac{1}{\sqrt{6}}[(ud+du)u - 2uud]$$

$$P(M_A) = \frac{1}{\sqrt{2}}(ud-du)u$$

$$\chi(M_S) = \frac{1}{\sqrt{6}}(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)$$

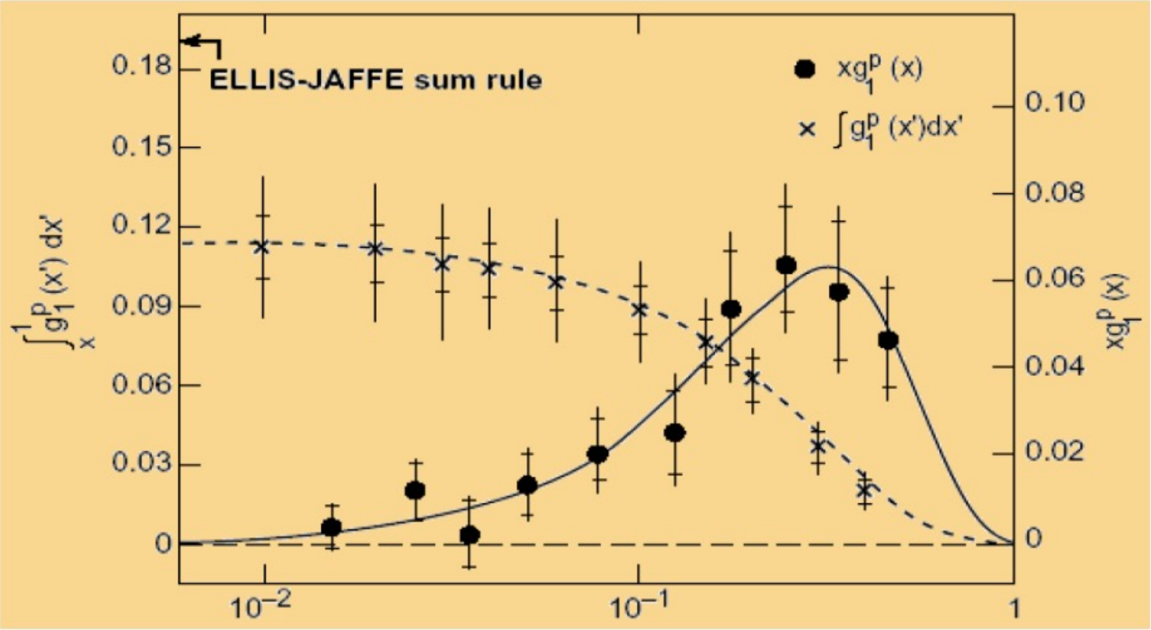
$$\chi(M_A) = \frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s$$

Nucleon spin

- **Discovered by EMC experiment at CERN (polarized muon + polarized proton) Confirmed by SMC, SLAC, HERMES: Quark contribution is ~25% ("Spin Crisis")**



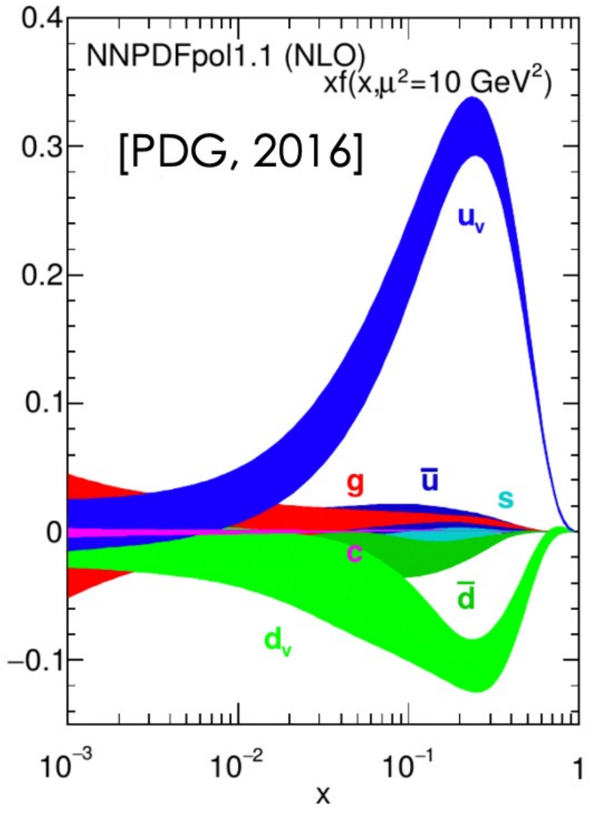
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\,[\Delta q(x) + \Delta\bar{q}(x)]$$

$$\int_0^1 g_1^p(x)dx = 0.126 \pm 0.018$$

$$\Delta\Sigma = \sum_q [\Delta q + \Delta\bar{q}] = 0.12 \pm 0.17$$

Nucleon spin

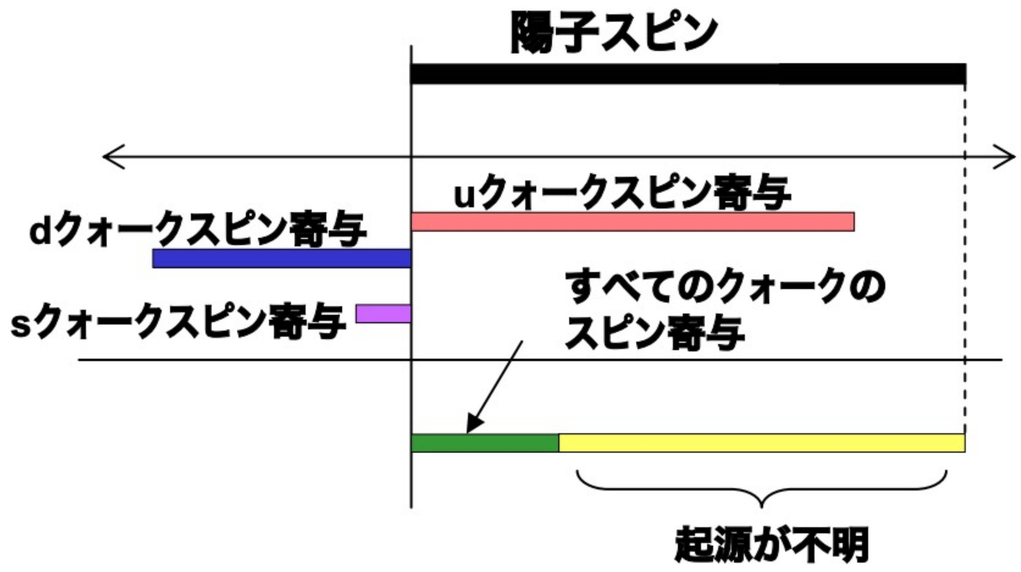
- **Discovered by EMC experiment at CERN (polarized muon + polarized proton) Confirmed by SMC, SLAC, HERMES: Quark contribution is ~25% ("Spin Crisis")**



$$\Delta u = 0.82 \pm 0.02$$

$$\Delta d = -0.43 \pm 0.02$$

$$\Delta s = -0.10 \pm 0.02$$



Nucleon spin

- **Current picture of spin composition**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Gluon spin

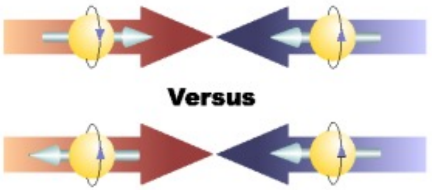
↓

RHIC spin program (polarized proton)

Angular momentum of all quarks and gluons

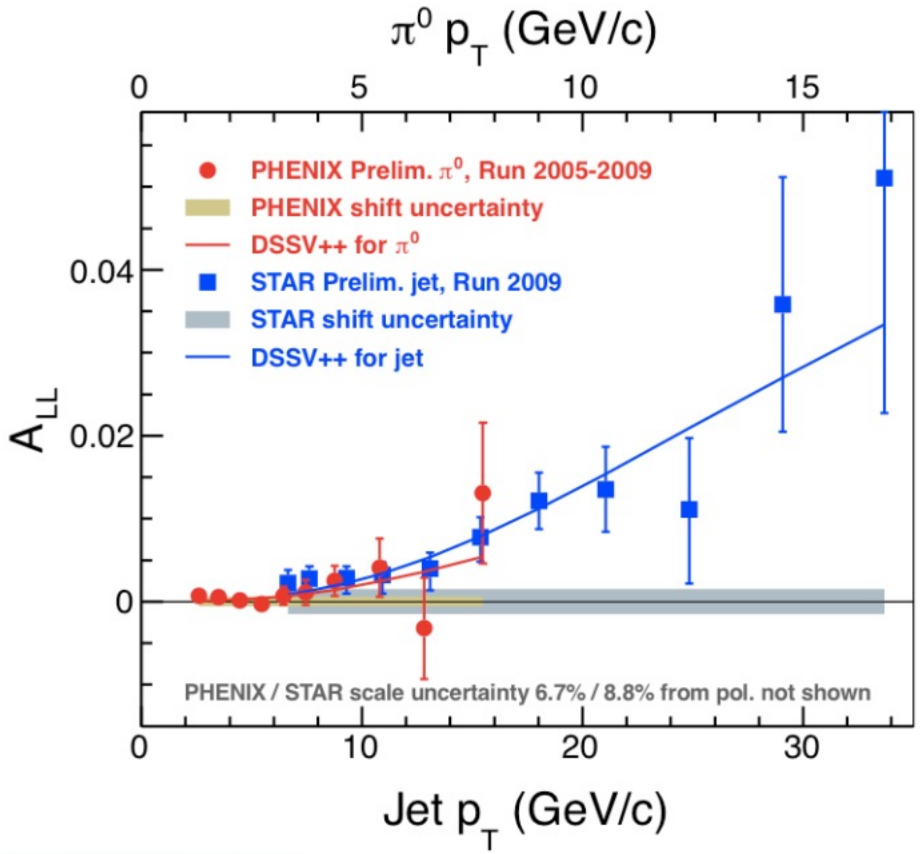
Measurement at RHIC

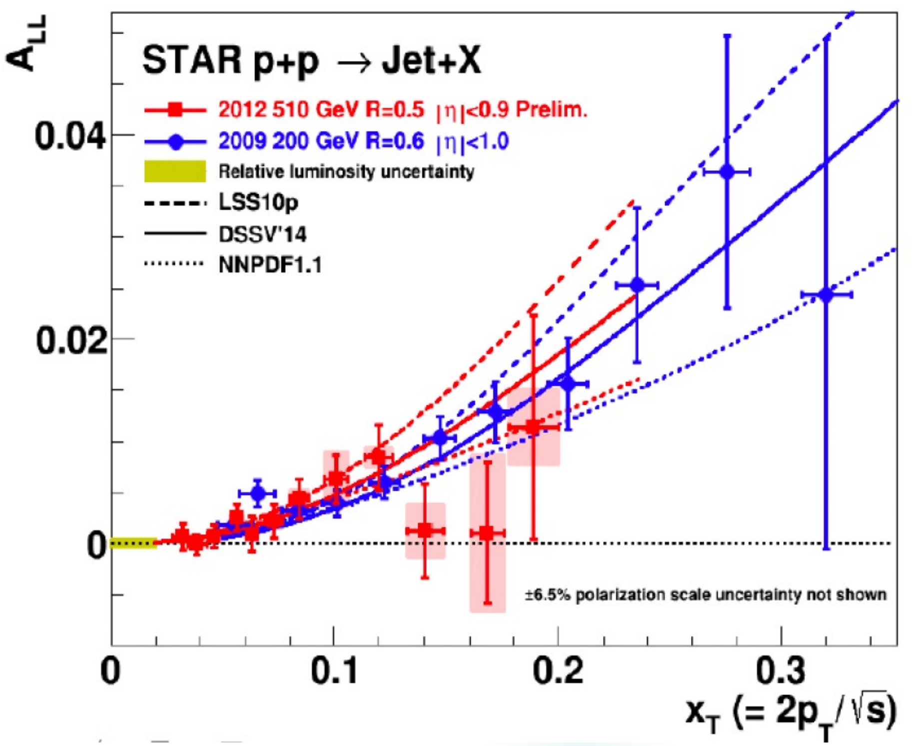
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



- **Longitudinal spin asymmetry : A_{LL}**

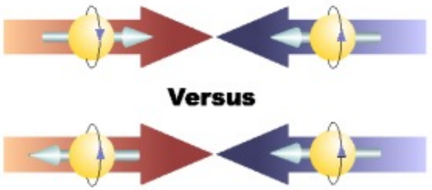
observation of non-zero A_{LL} associated with non-zero ΔG (~0.3)





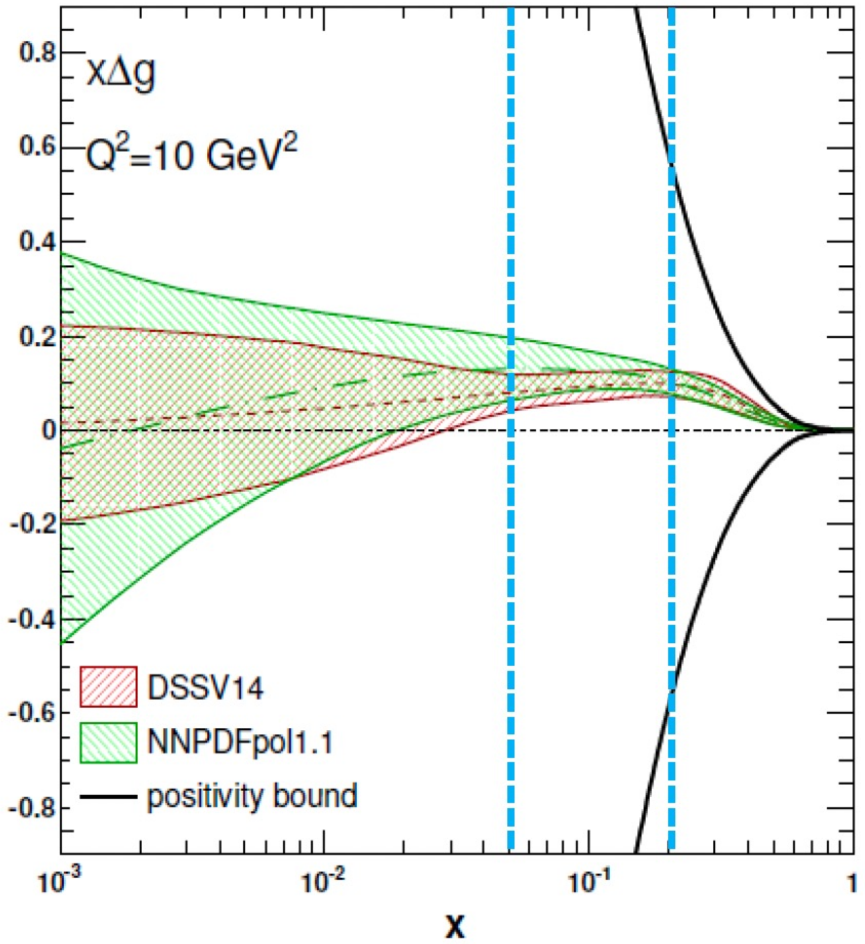
Gluon contribution to spin

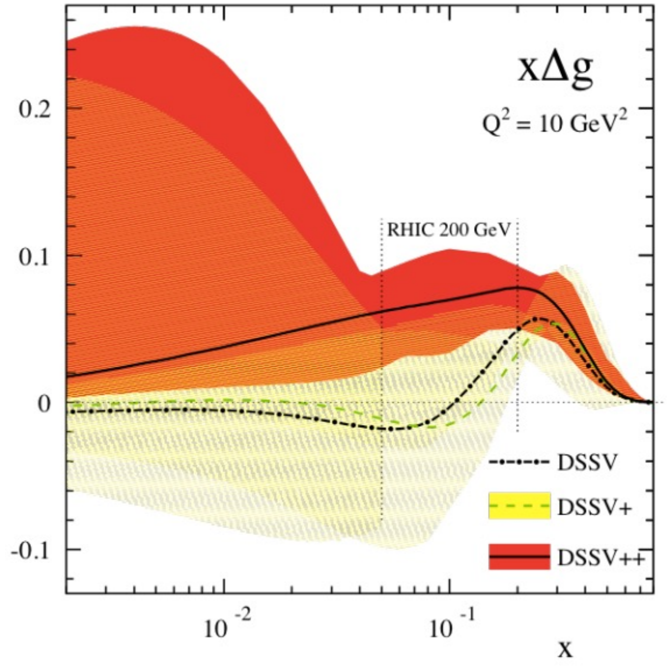
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$

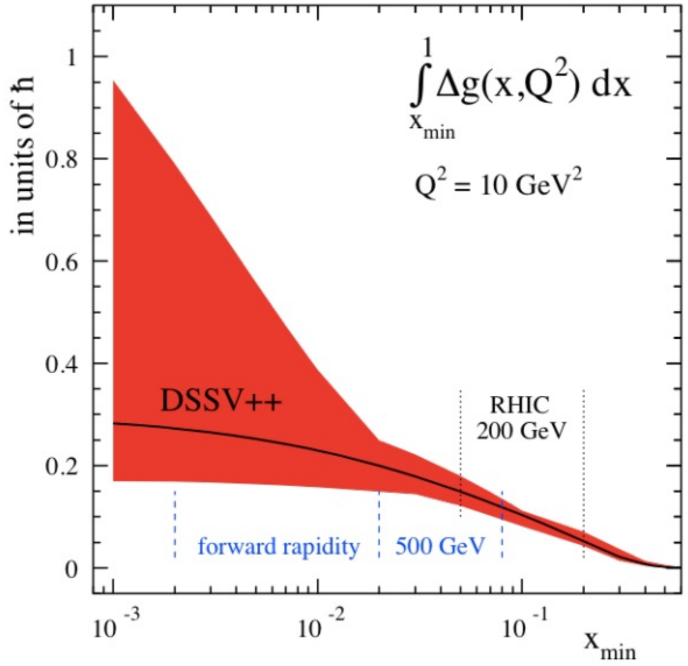


- **Longitudinal spin asymmetry : A_{LL}**

arXiv:1503.03518



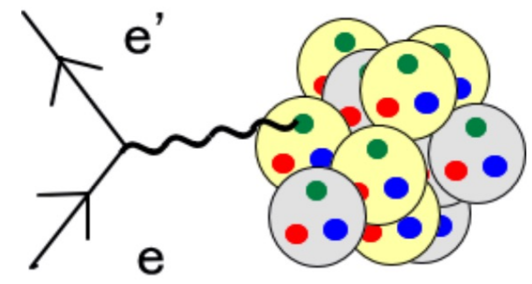




$Q^2 = 10$ GeV^2	$\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$
NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$

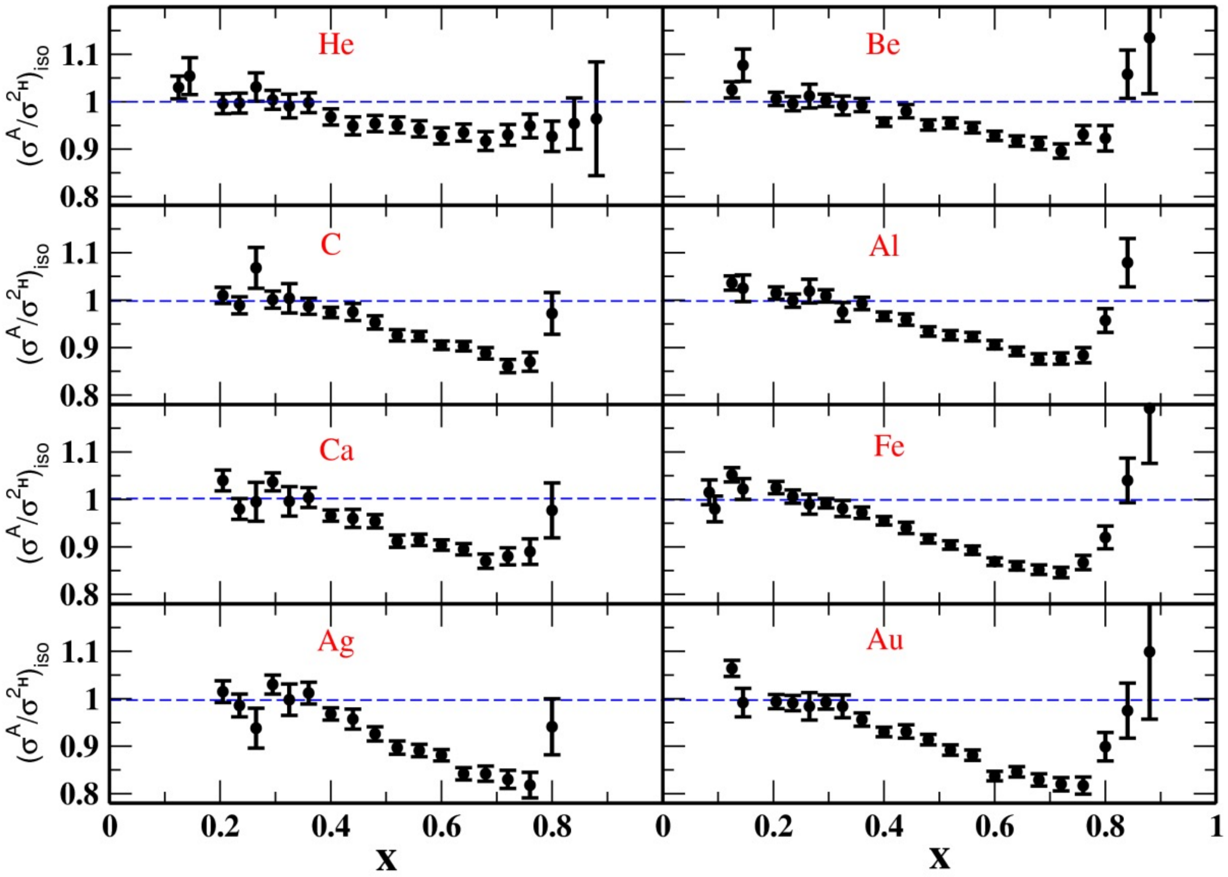
PDF in nuclei (x>0.3)

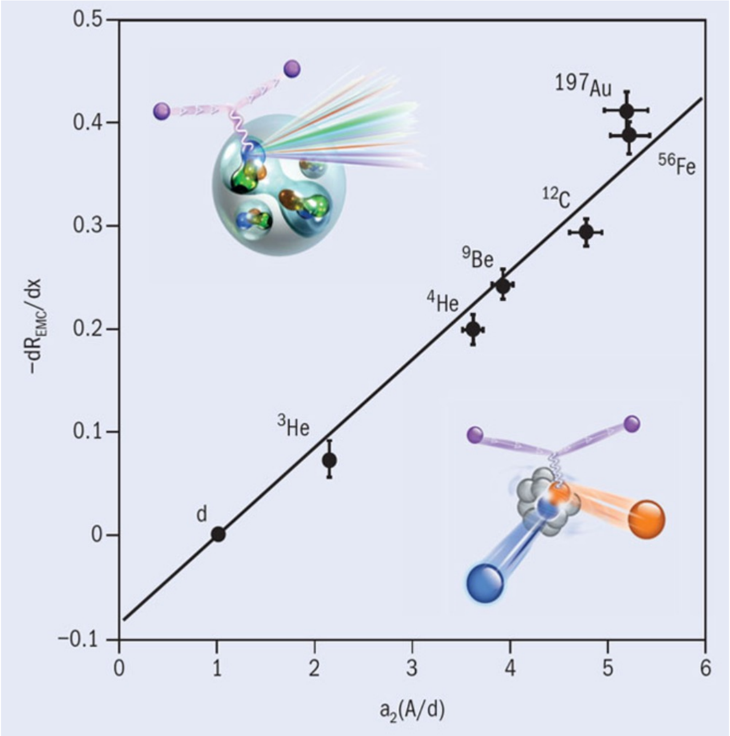
- **Proton bound in the nucleus is different from a free proton?**



Naïve expectation was nuclear effects in DIS would be small since DIS energy is much larger than binding energy.

Phys. Rev. D 49, 4348 (1994)





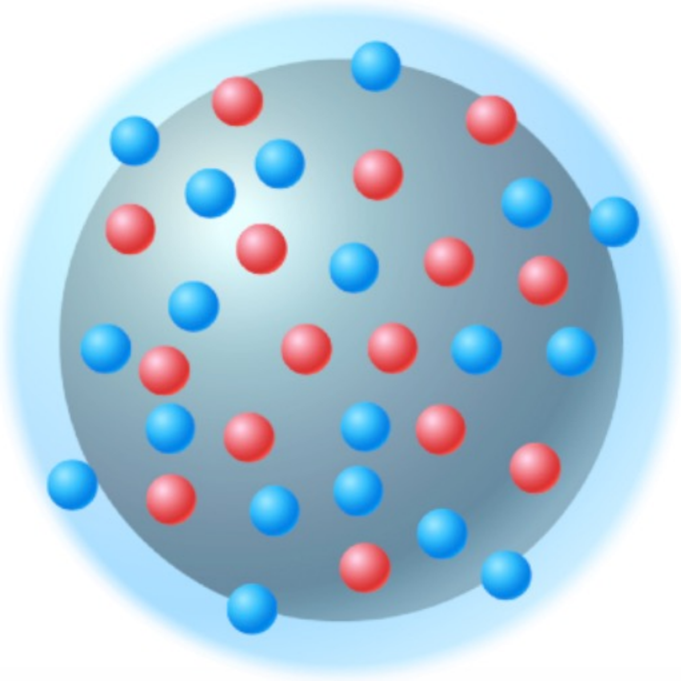
DIS off a bound nucleon ≠ DIS off a free nucleon (EMC effect)

Clusters in nuclei

- **Modern view of atomic nucleus**

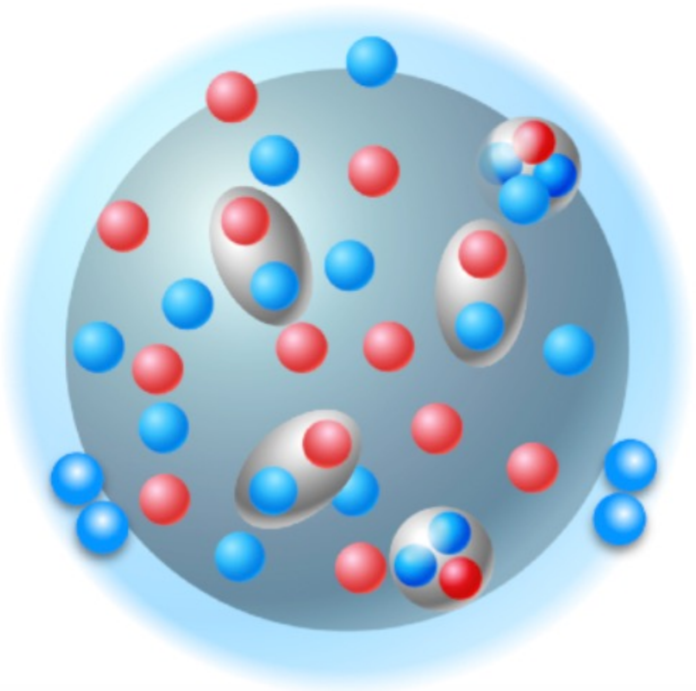
Conventional picture

Uniform nuclei formed by independent neutrons and protons



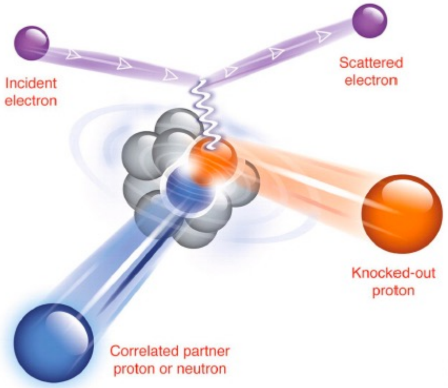
Modern picture

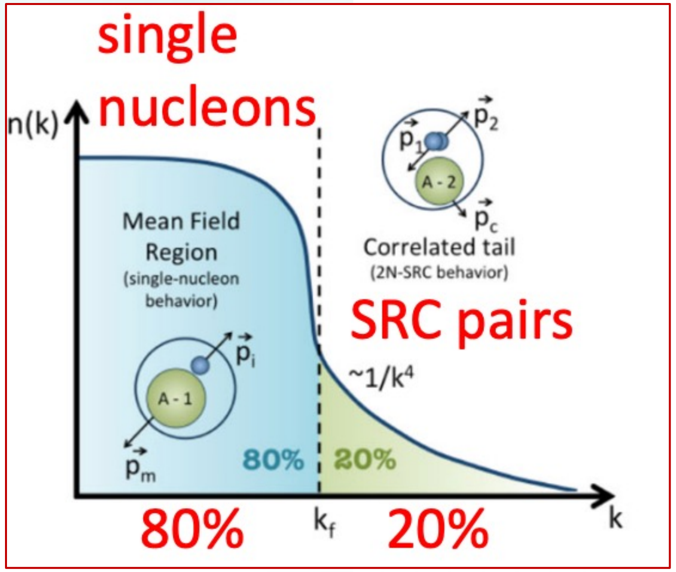
Various clusters (***d***, ***t***, **^{3}He**, ***α***, **…**) develop in all nuclei

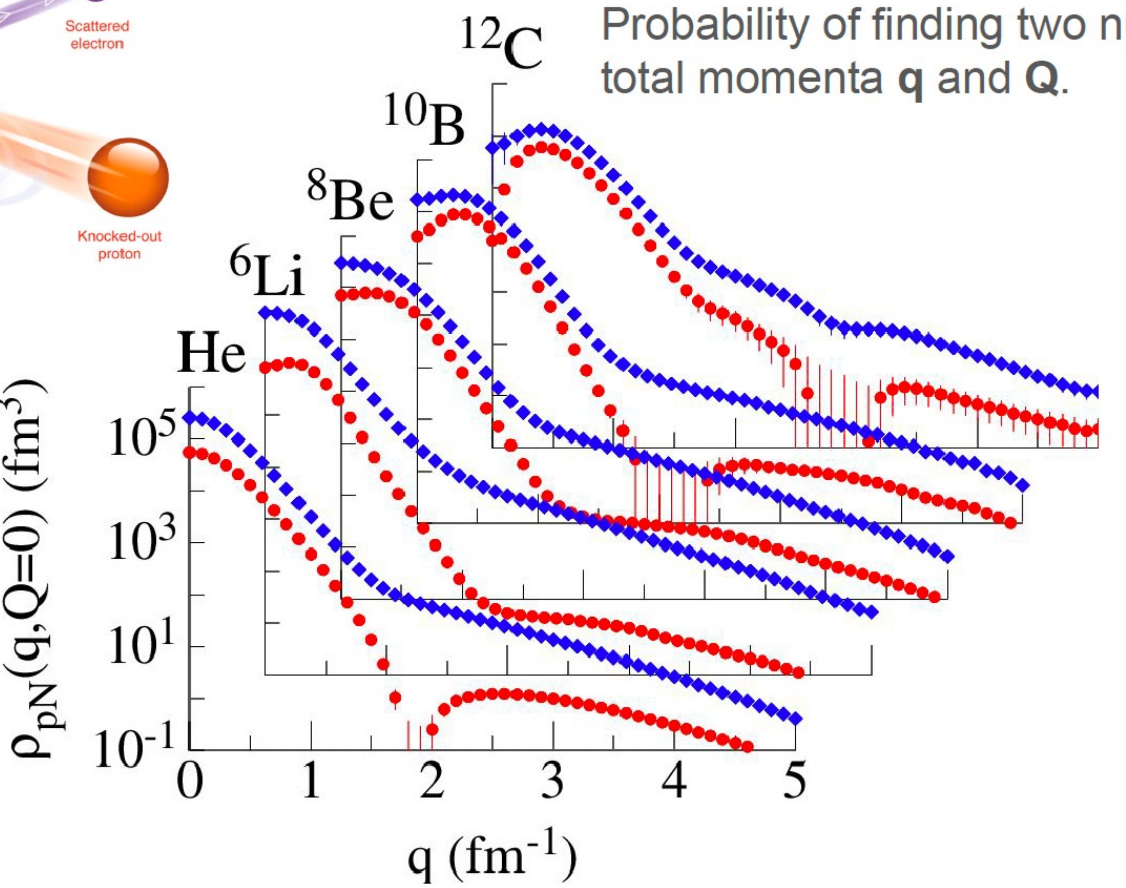


Clusters in nuclei

Two-nucleon correlations & momentum distributions







pp-pairs; np-pairs

Probability of finding two nucleons with relative and total momenta **q** and **Q**.

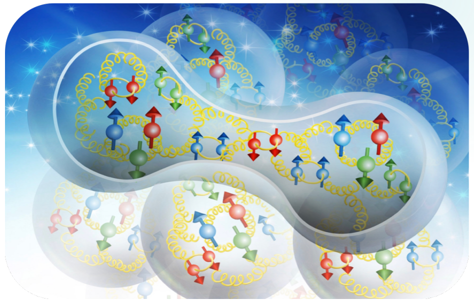
Tensor correlations lead to large differences in the np versus pp distributions.

These differences are observed in A(e, e′np) and A(e, e′pp) reactions.

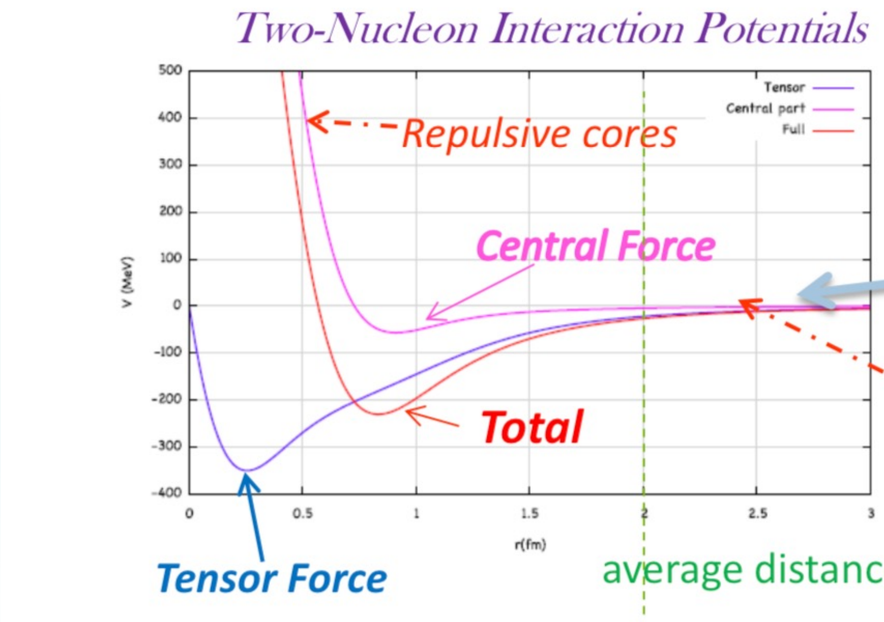
Schiavilla Carlson Wiringa Pieper
PRL98(2007) & PRC89(2014)

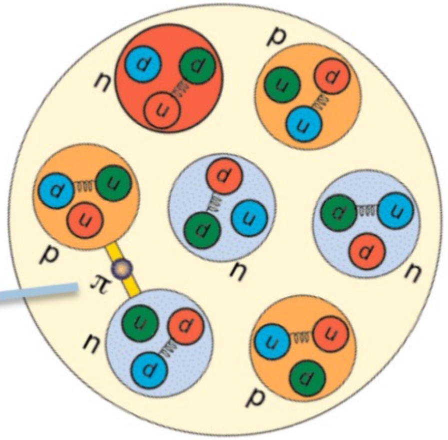
Short range correlation

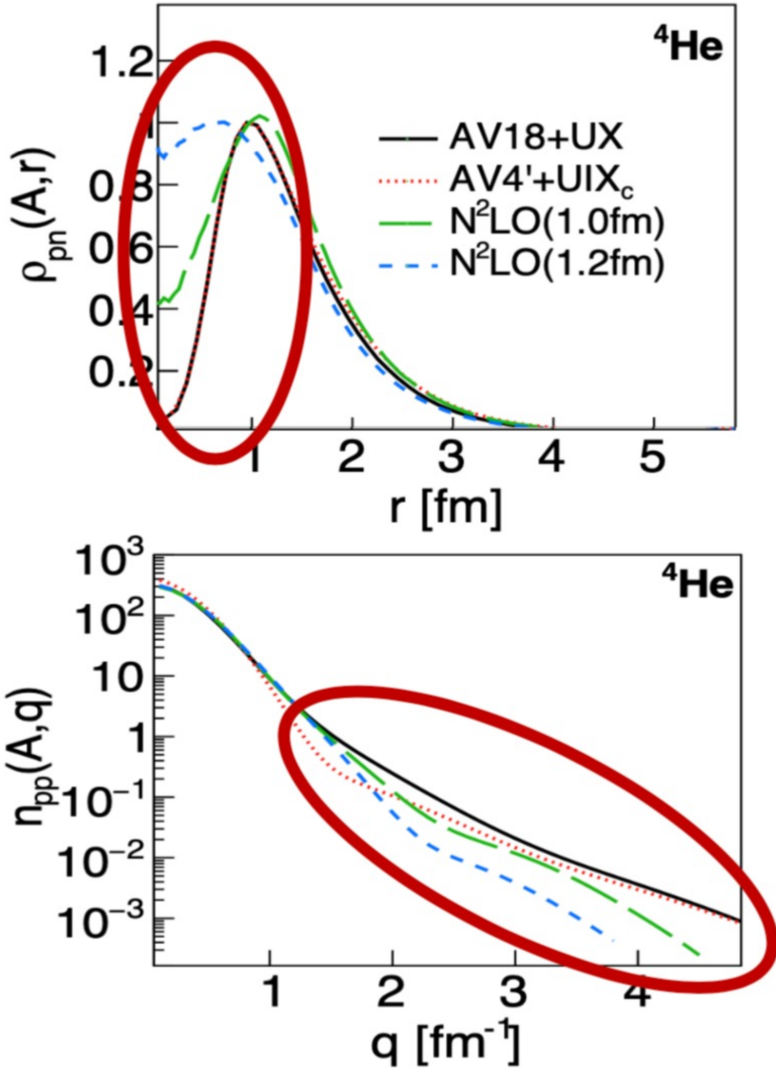
NN Short-range correlation



Realistic Nucleon-Nucleon Interactions:







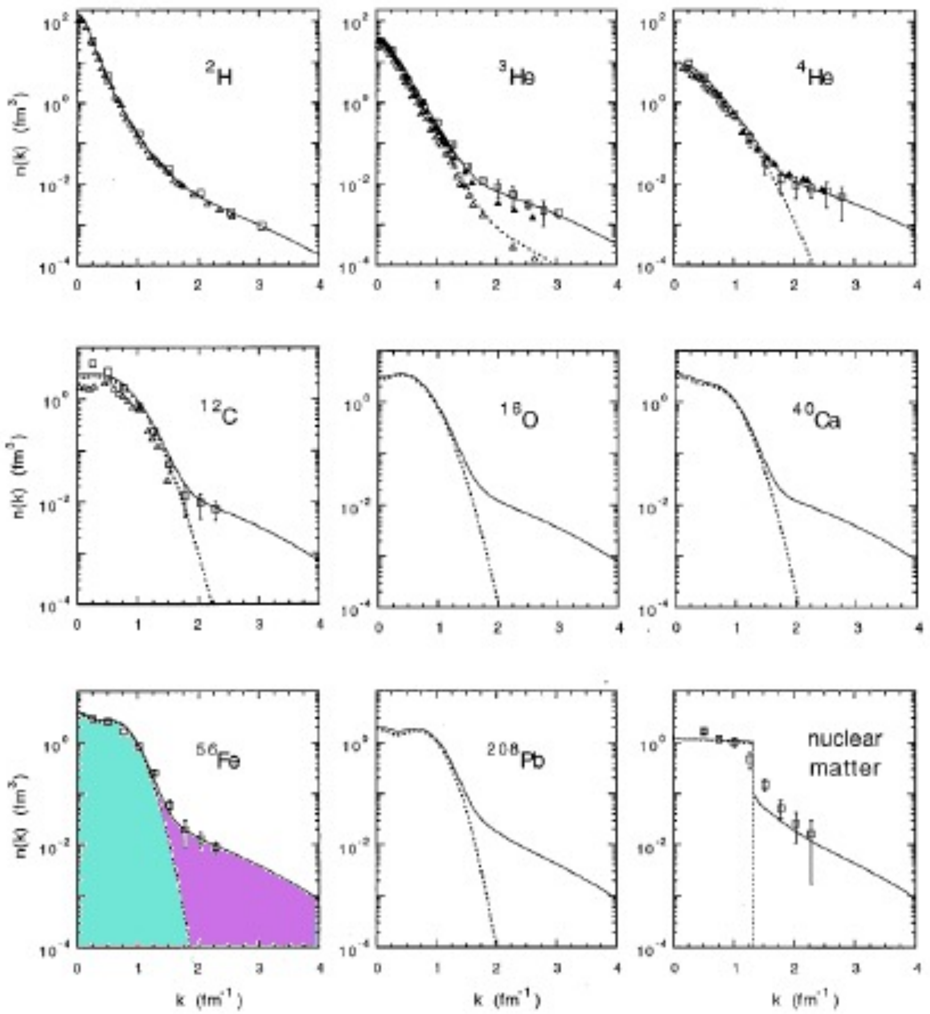
Large model dependence at short-distance / high-momentum

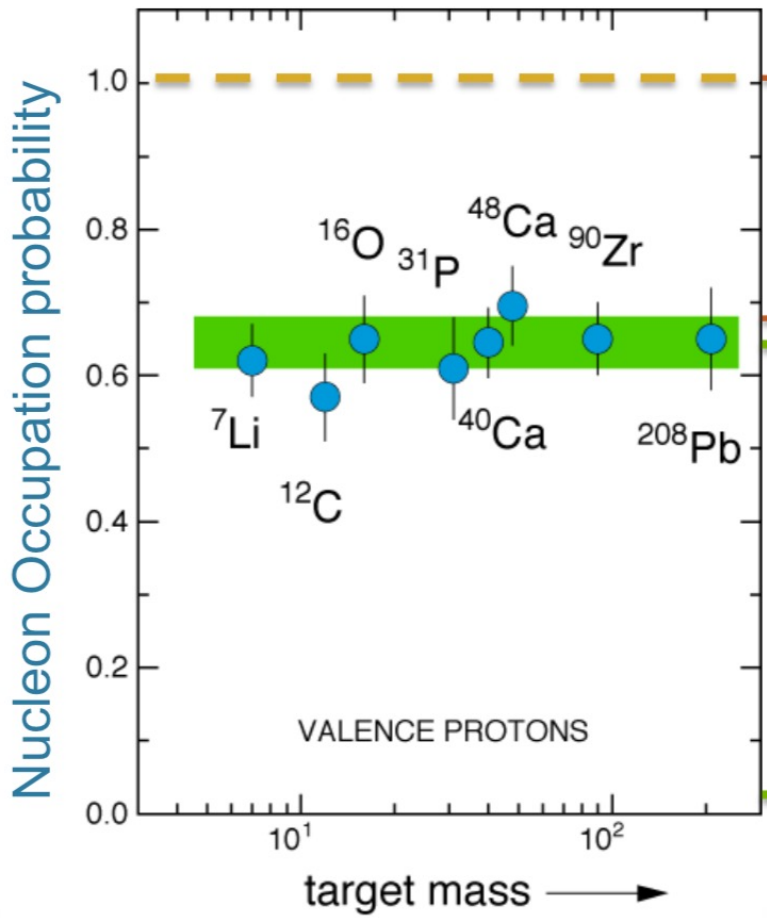
Short range correlation

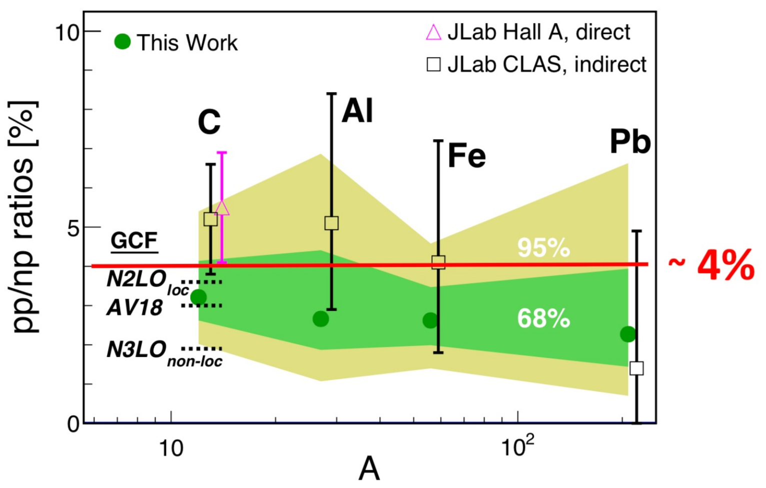
NN Short-range correlation

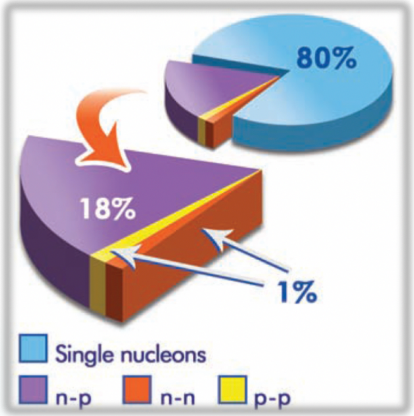
L. Lapiks, Nuclear Physics A 553, 297 (1993)

65% for naïve shell model calculations. Fraction reaches 80% in more modern calculations





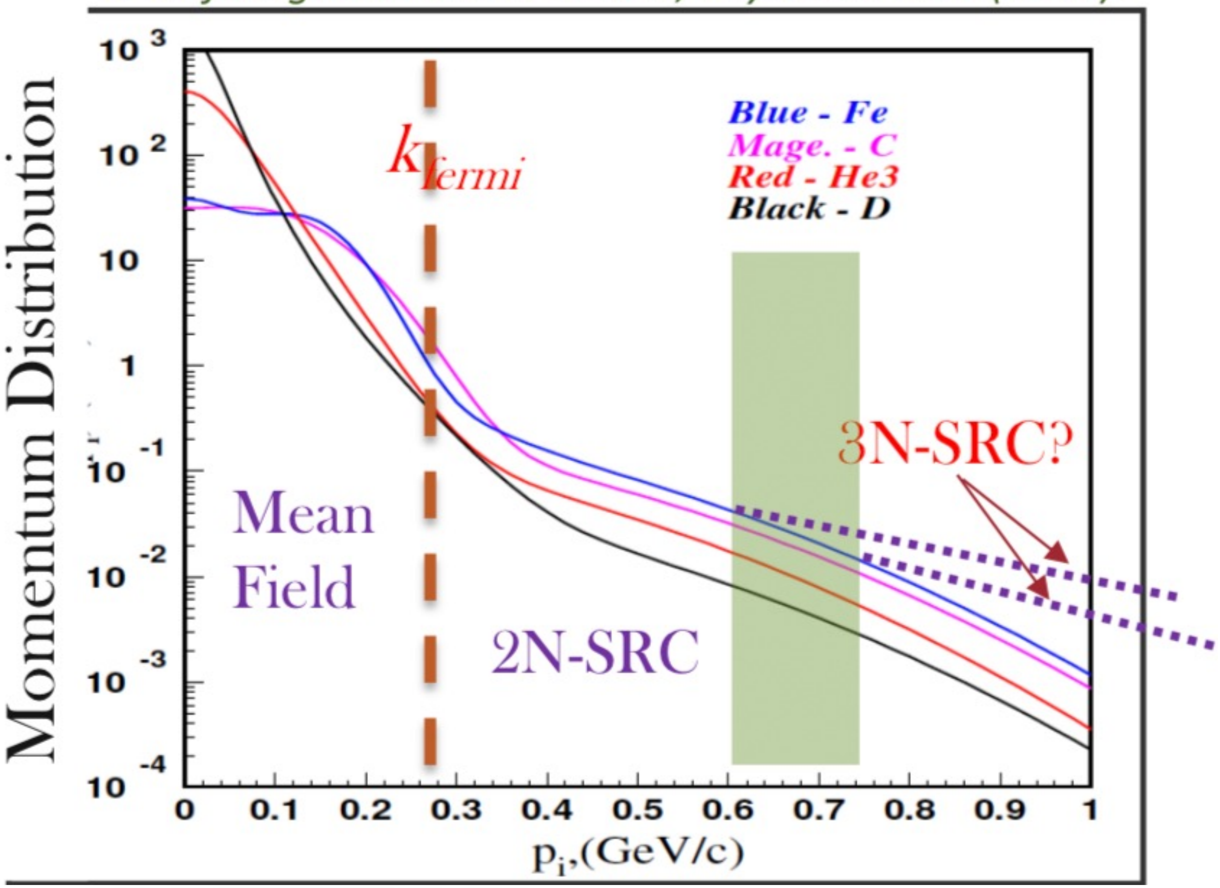




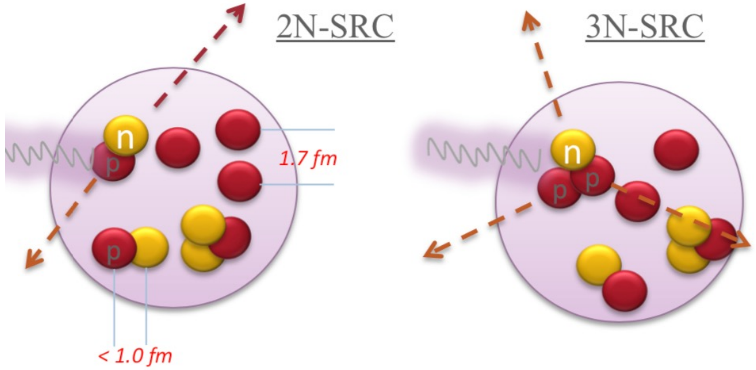
Short range correlation

NN Short-range correlation:
From 2-nucleons (2N-SRC) to 3-nucleons/4-nucleons(alpha?)-SRC

C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996).



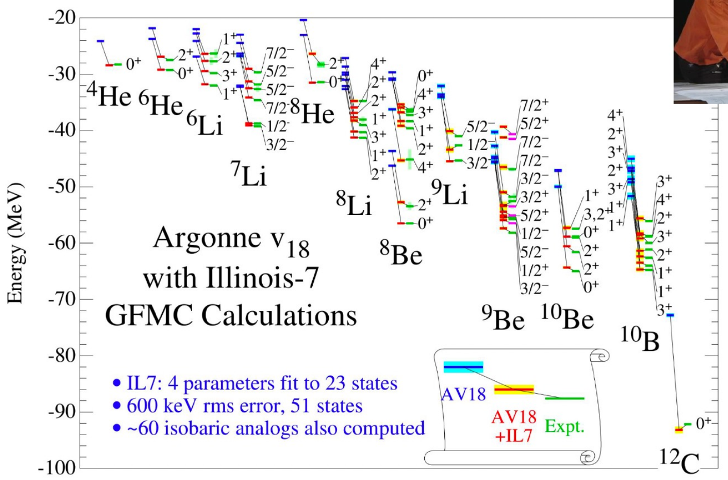
Zhihong Ye, iHIC2018

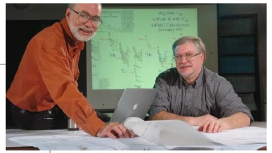


- 重い原子核における2N-SRC, 3N-SRC, 4N-SRC

→ deutron, 3H/3He, alpha cluster?
→ 高密度原子核物質へ(EMC effects, 中性子星EOS)

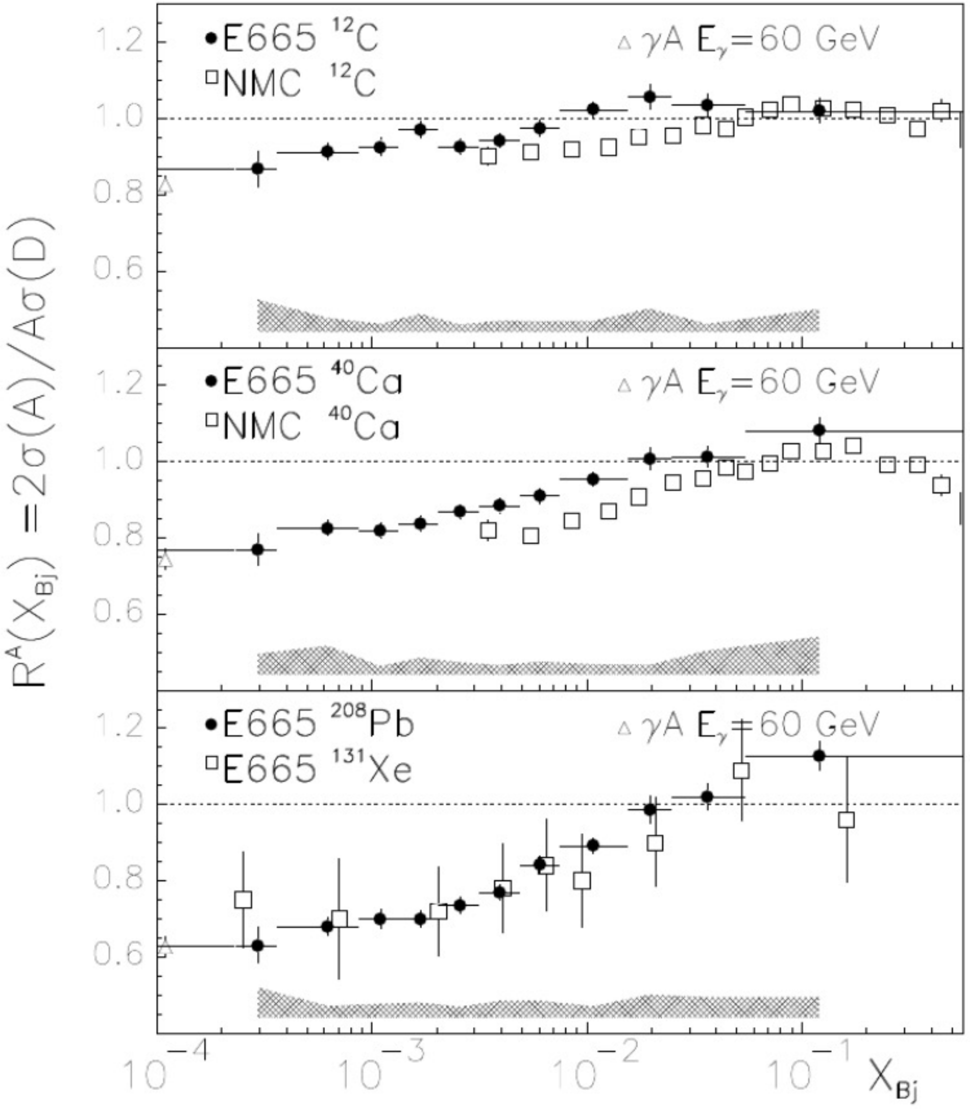
Spectra of light nuclei with AV18+IL7



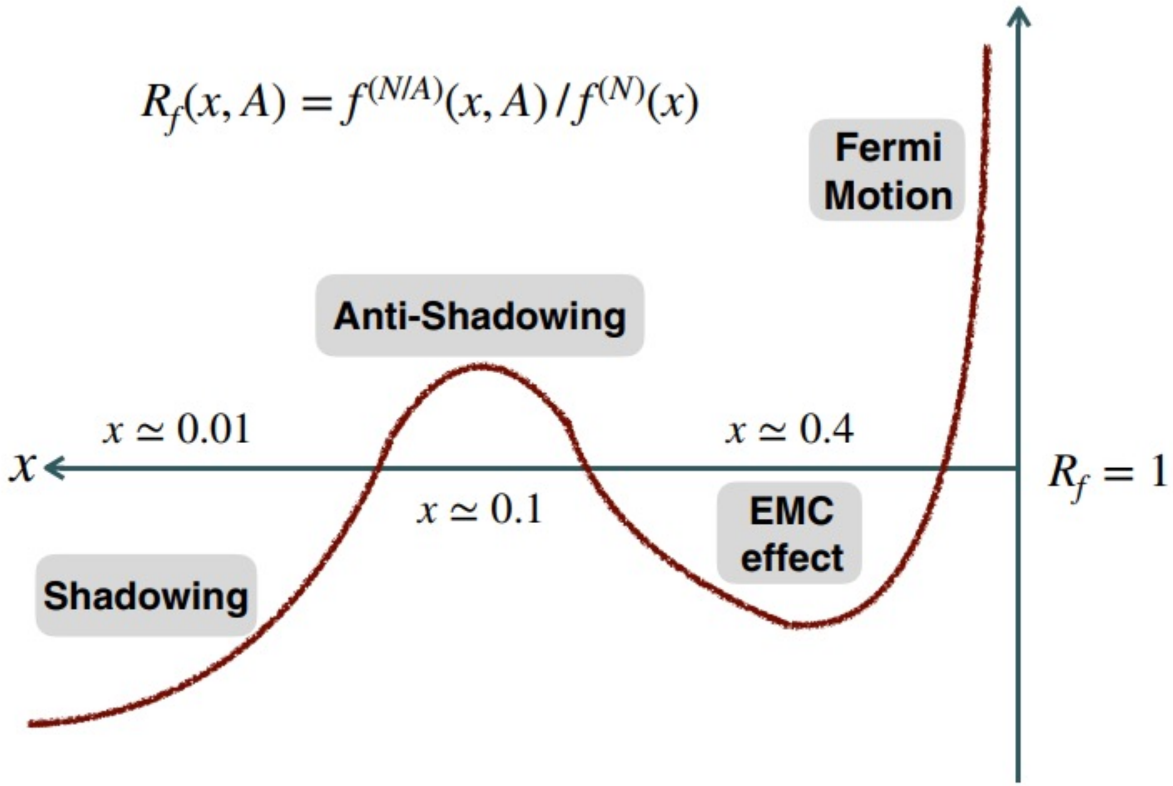


PDF in nuclei (x<0.3)

Phys. Rev. Lett. 68 (1992) 3266

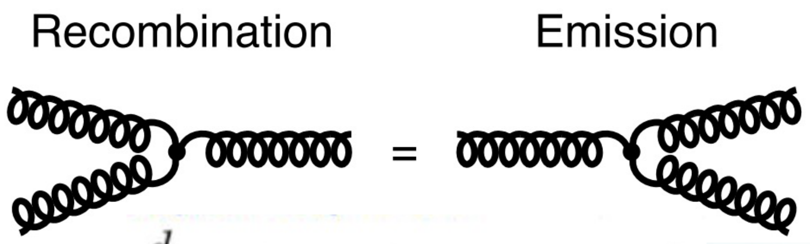


- **Reduction of PDF in small-x (x<0.3) called "shadowing".**



Gluon Saturation

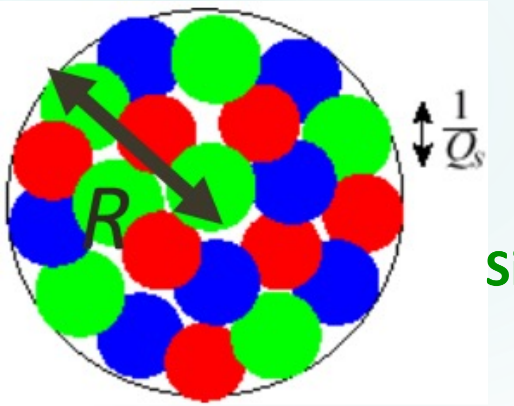
- **We know that at small-x, gluons are dominated in proton and nuclei.**
- **When the density of gluons becomes high, they start to interact with each other and gluons are saturated.**



$$\frac{d}{dt}N(t) = \kappa\left[N(t) - N(t)^2\right]$$

- **Saturation scale = $Q_s(x, A)$: Typical transverse momentum carried by gluons**

Gluons fill the transverse area of hadron (πR^2)

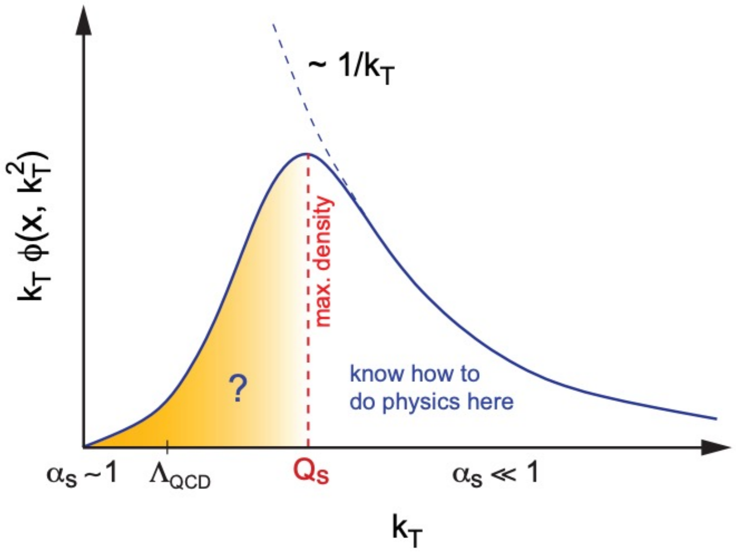


$$\frac{\alpha_s}{Q^2} \cdot xG(x, Q^2) = \pi R^2$$

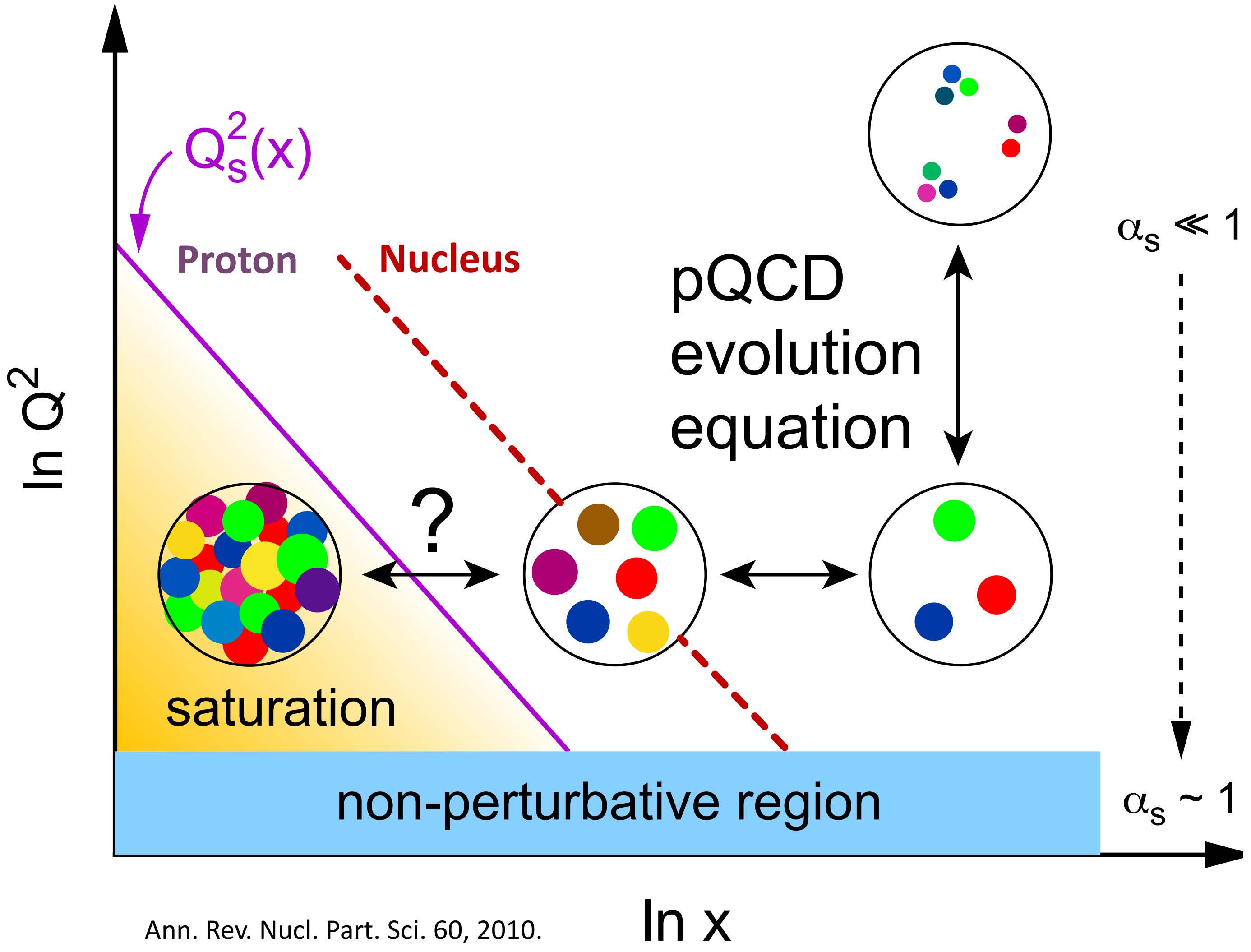
Size of gluons

Number of gluons

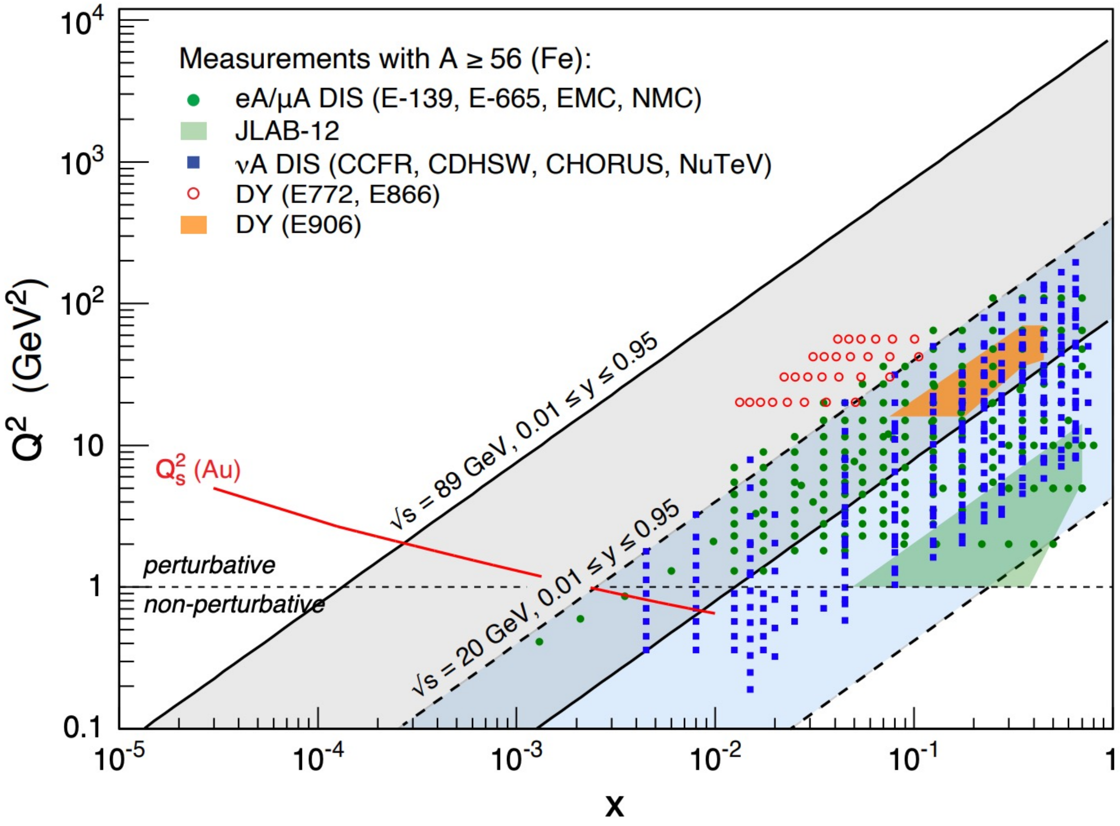
$$Q_s\,(x, A) = A^{1/3} x^{-\lambda}$$



Phase diagram of proton and nucleus



Ann. Rev. Nucl. Part. Sci. 60, 2010.



Phase diagram of proton and nucleus

DIS in e–A collisions:
The Electron-Ion-Collider

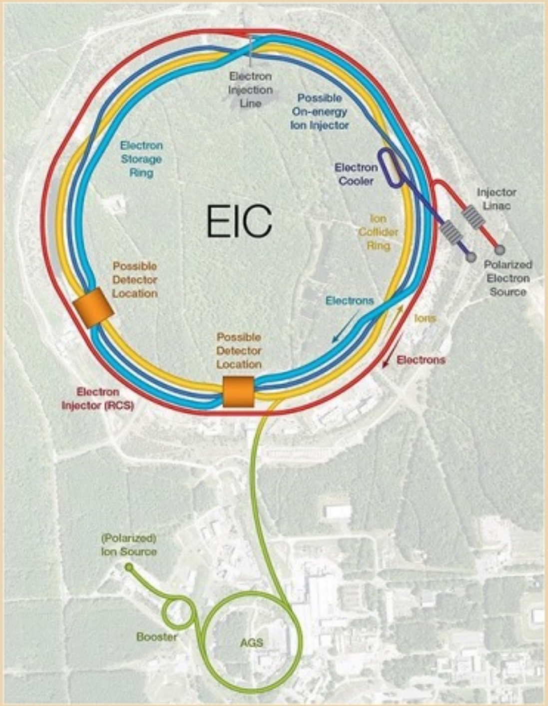
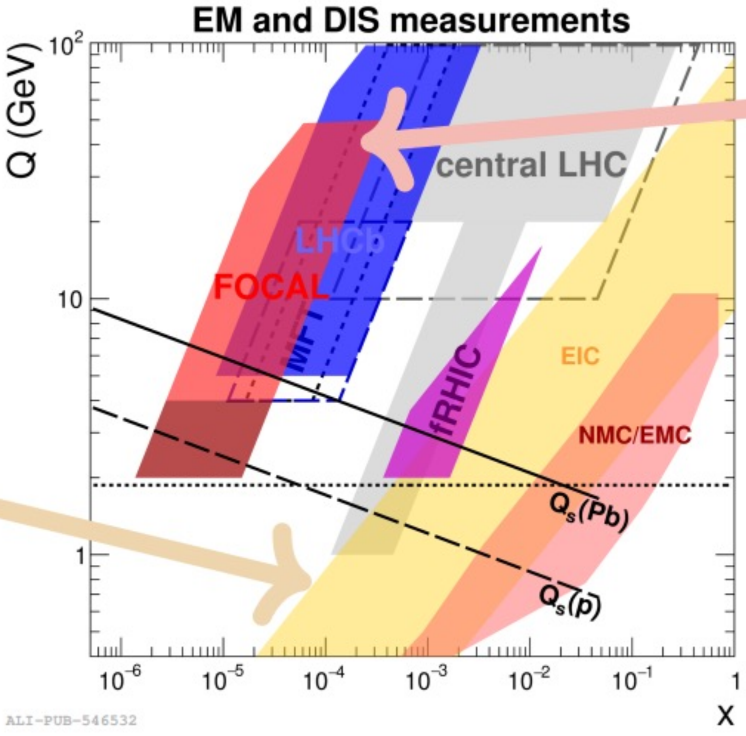
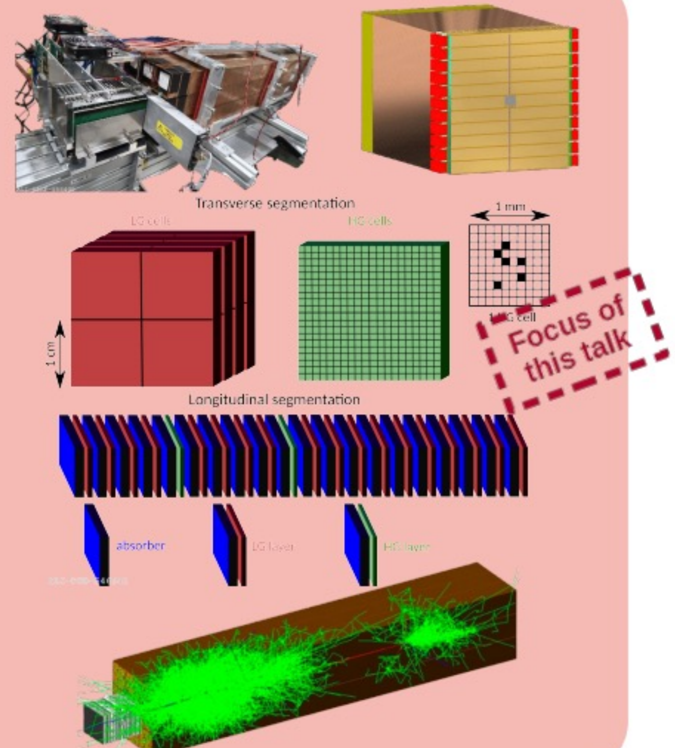


Image credit: DOE



$\Rightarrow$ Large x and Q coverage

Forward p+A collisions:
The ALICE FoCal



CERN-LHCC-2024-004

Main Physics at the EIC

Science Goal of EIC

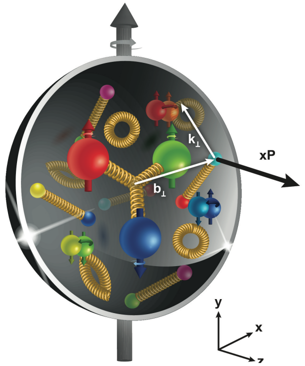
SPIN is one of the fundamental properties of matter.
All elementary particles, but the Higgs carry spin.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum.

Does the mass of visible matter emerge from quark-gluon interactions?

Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called "QCD trace anomaly

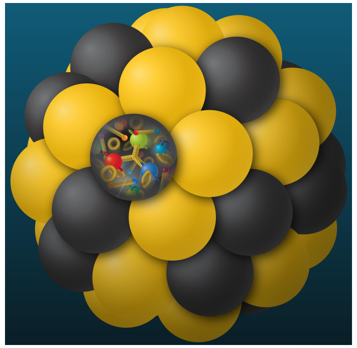


How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

How do the nucleon properties emerge from them and their interactions?

How can we understand their dynamical origin in QCD?

What is the relation to Confinement?

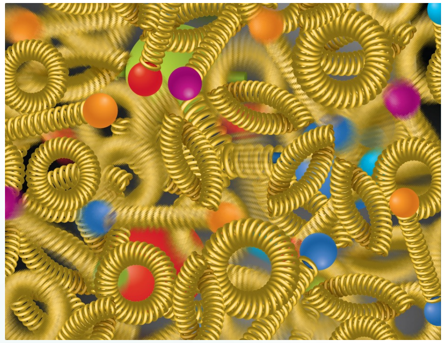


Is the structure of a free and bound nucleon the same?

How do quarks and gluons, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



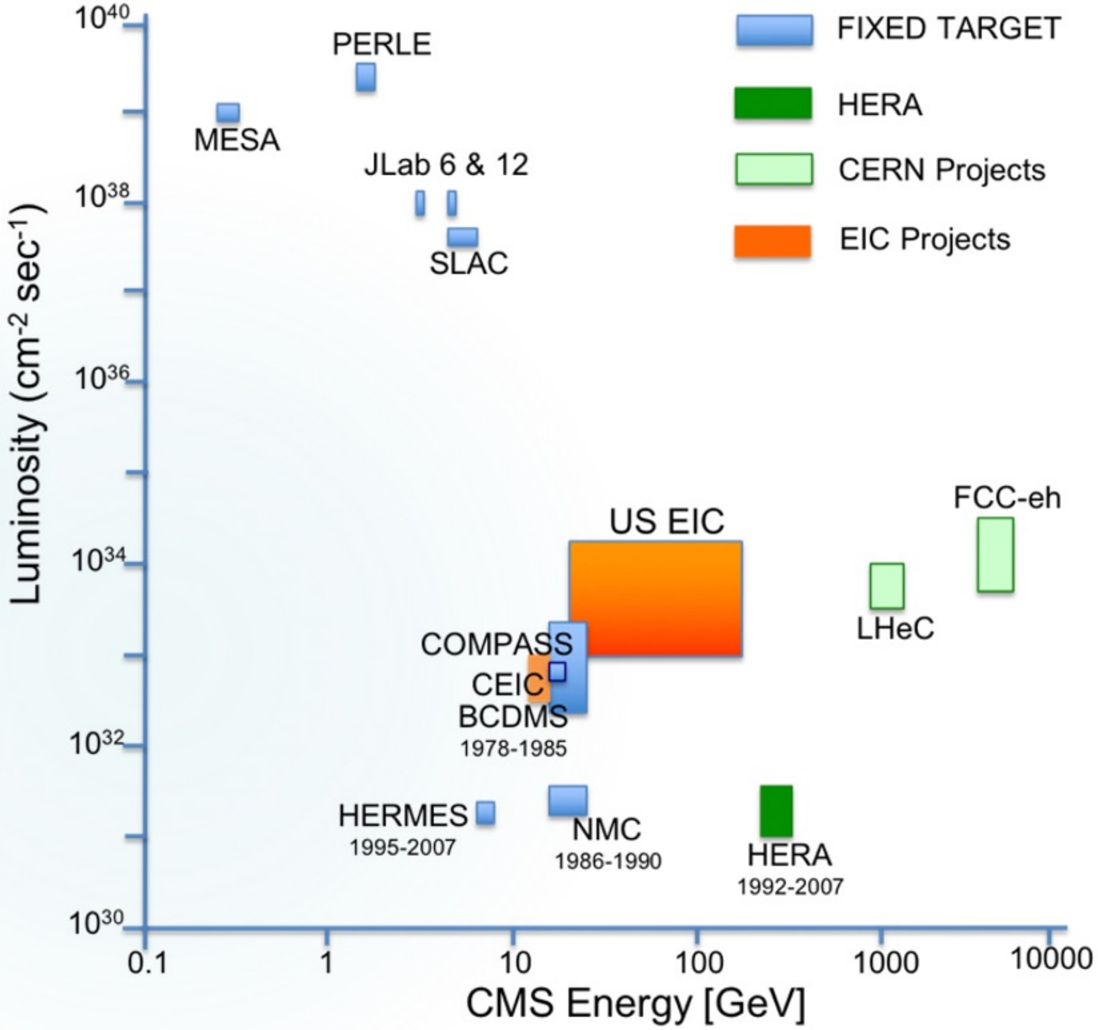
How many gluons can fit in a proton?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

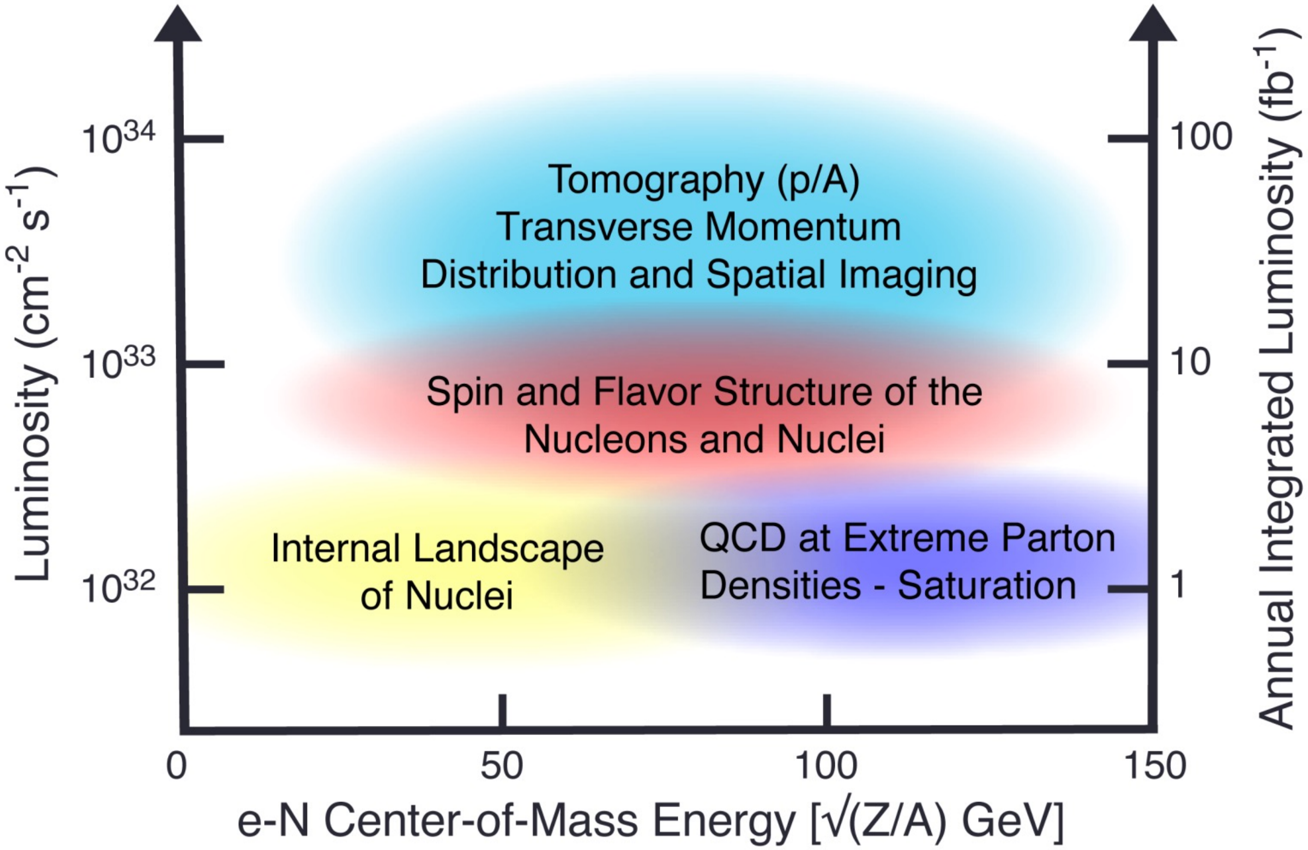
What happens to the gluon density in nuclei? Does it saturate at high energy?

gluon splitting ?= gluon recombination

Luminosity

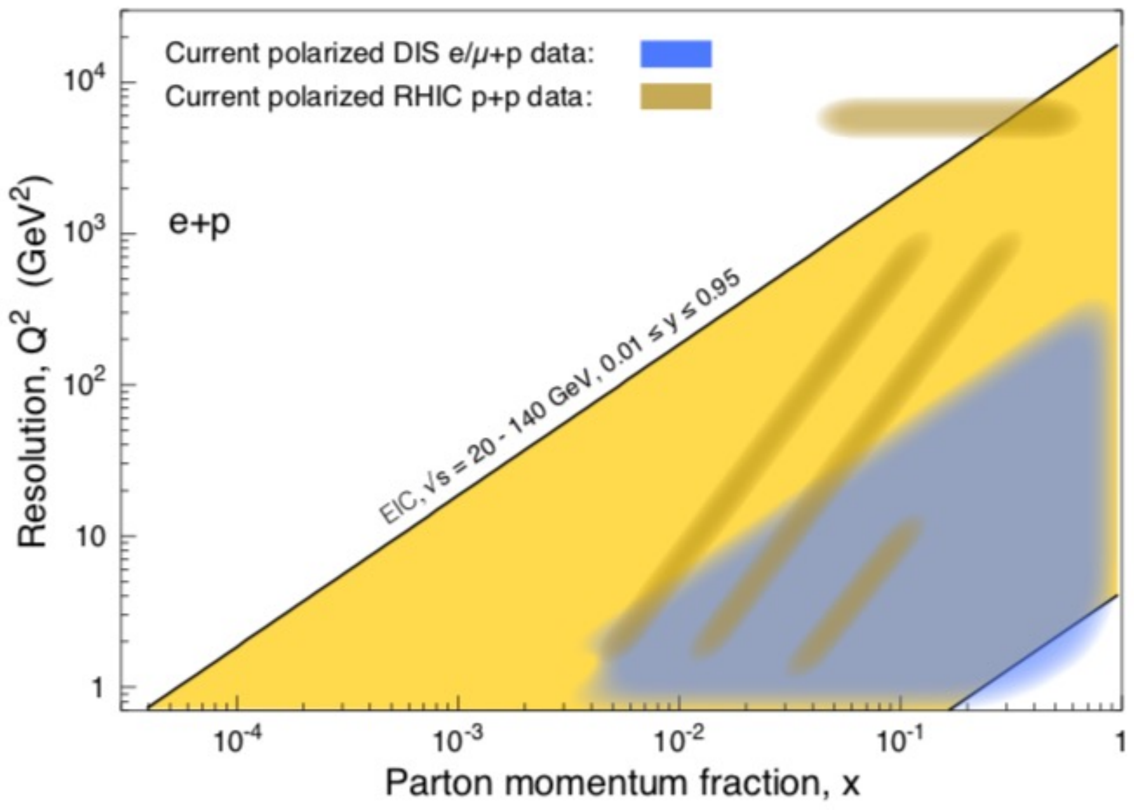


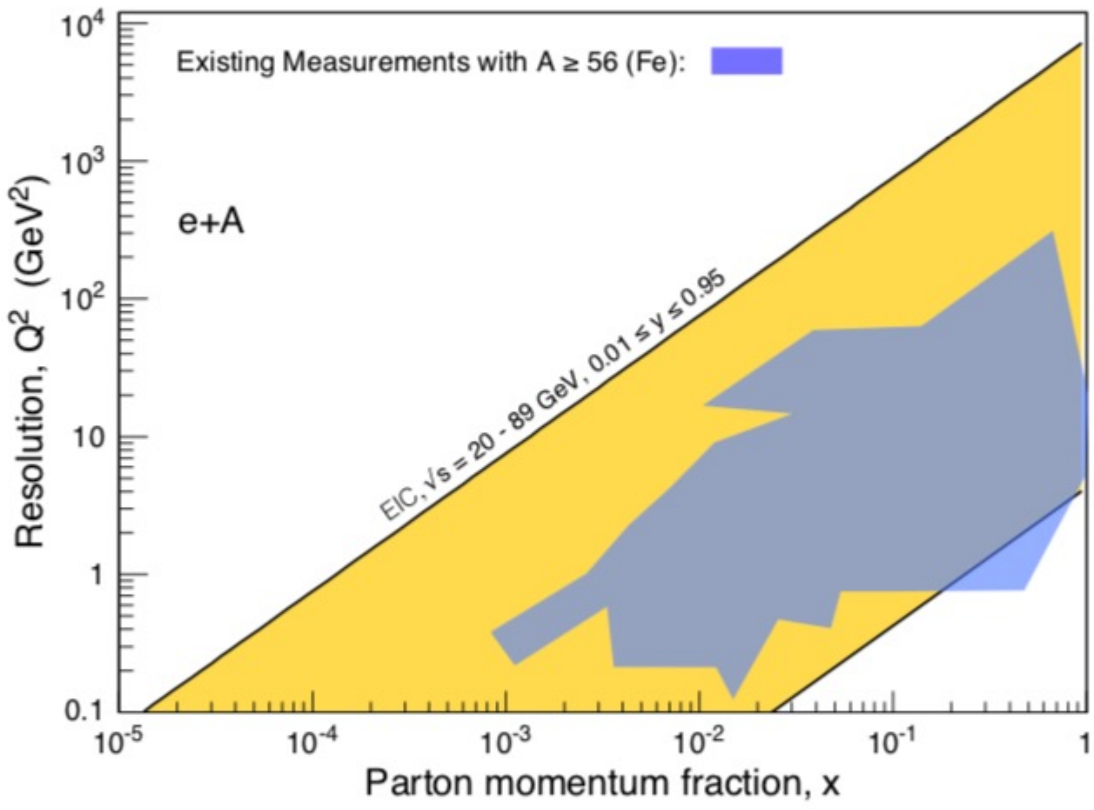
FIXED TARGET
HERA
CERN Projects
EIC Projects
PERLE
MESA
JLab 6 & 12
SLAC
US EIC
FCC-eh
LHeC
COMPASS
CEIC
BCDMS
1978-1985
HERMES
1995-2007
NMC
1986-1990
HERA
1992-2007
Luminosity (cm^{-2} sec^{-1})
10^{40}
10^{38}
10^{36}
10^{34}
10^{32}
10^{30}
0.1
1
10
100
1000
10000
CMS Energy [GeV]



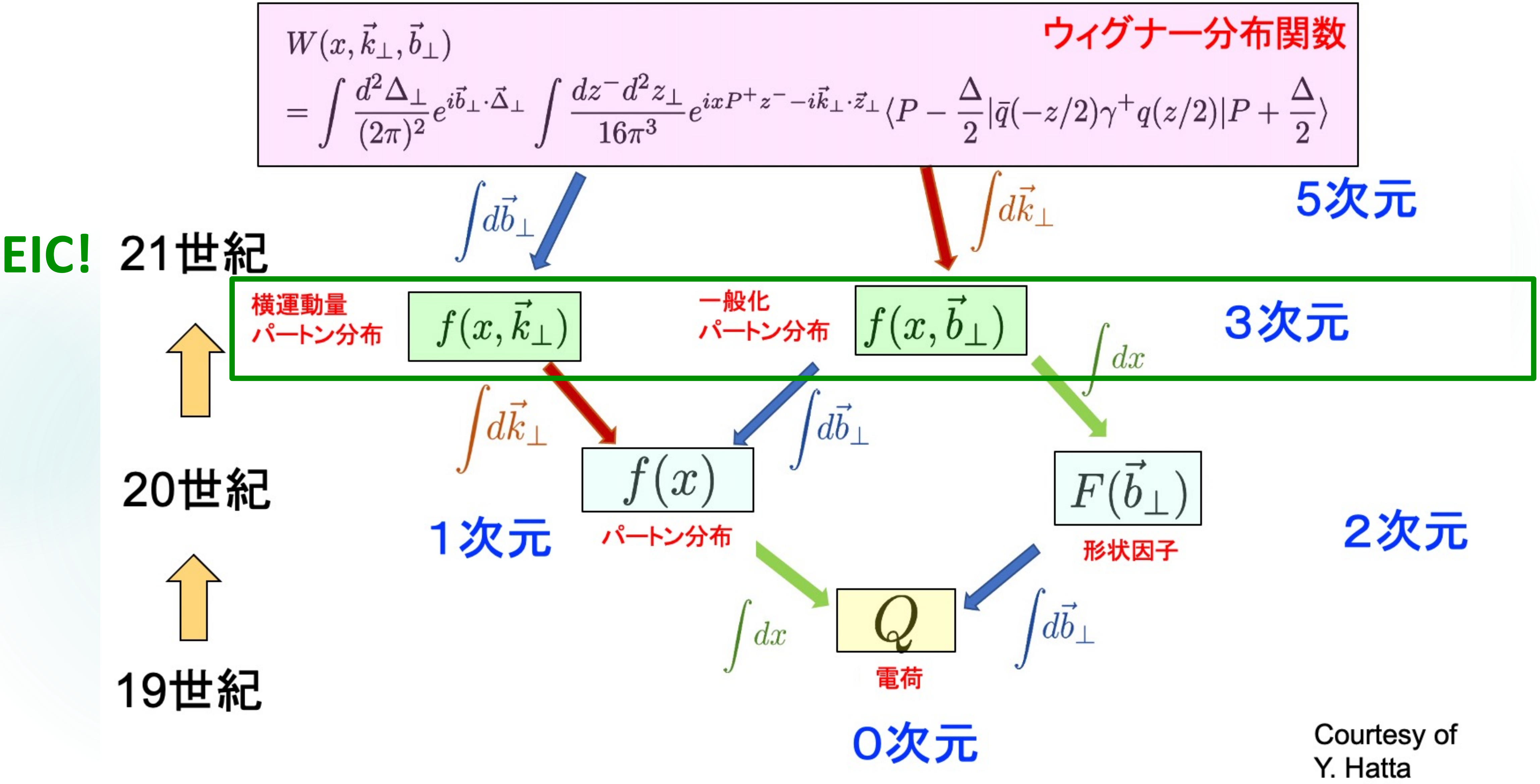
Tomography (p/A)
Transverse Momentum
Distribution and Spatial Imaging
Spin and Flavor Structure of the
Nucleons and Nuclei
Internal Landscape
of Nuclei
QCD at Extreme Parton
Densities - Saturation
Luminosity (cm^{-2} s^{-1})
10^{34}
10^{33}
10^{32}
Annual Integrated Luminosity (fb^{-1})
100
10
1
0
50
100
150
e-N Center-of-Mass Energy [√(Z/A) GeV]

(x, Q^2) coverage



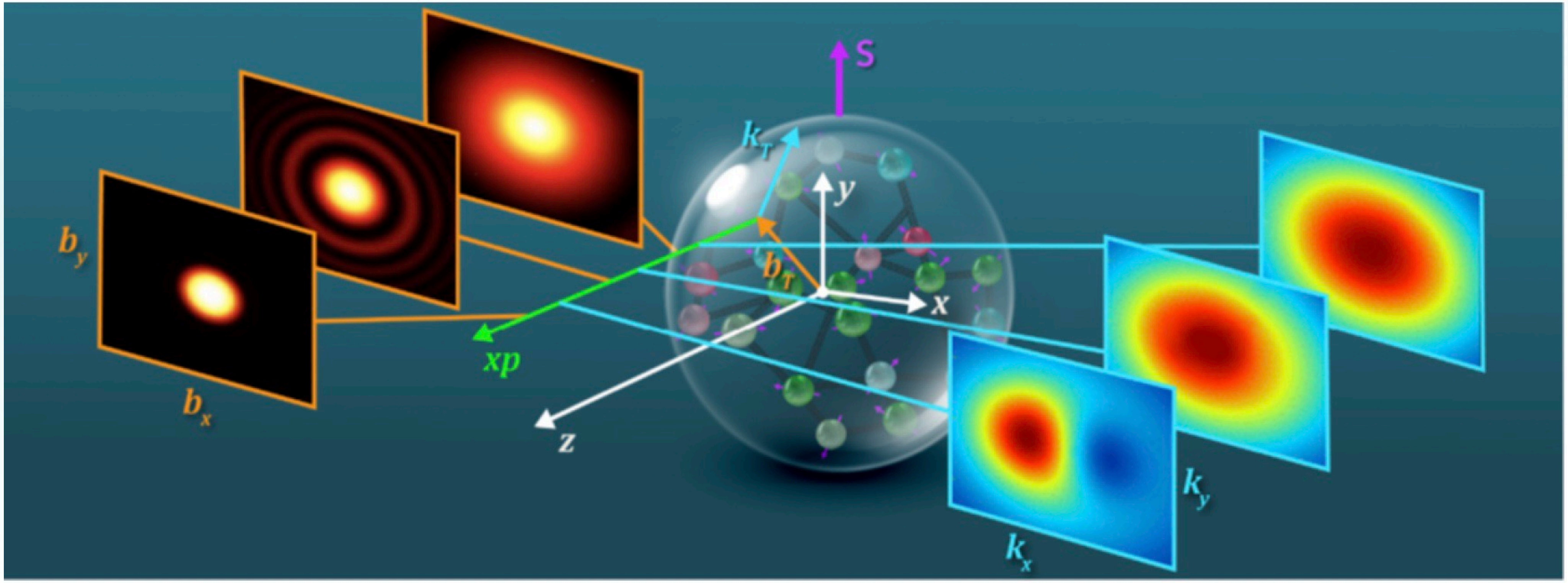


Further understanding of PDF by EIC



3D parton distribution

- **Generalized Parton Distributions (GPDs)**
  - Transverse position & longitudinal momentum fraction of partons
- **Transverse Momentum Dependent Parton Distributions (TMDs)**
  - Transverse momentum & longitudinal momentum fraction of partons



TMD Handbook (>400 pages!)

https://arxiv.org/pdf/2304.03302


arXiv:2304.03302v1 [hep-ph] 6 Apr 2023

Preprints: JLAB-THY-23-3780, LA-UR-21-20798, MIT-CTP/5386

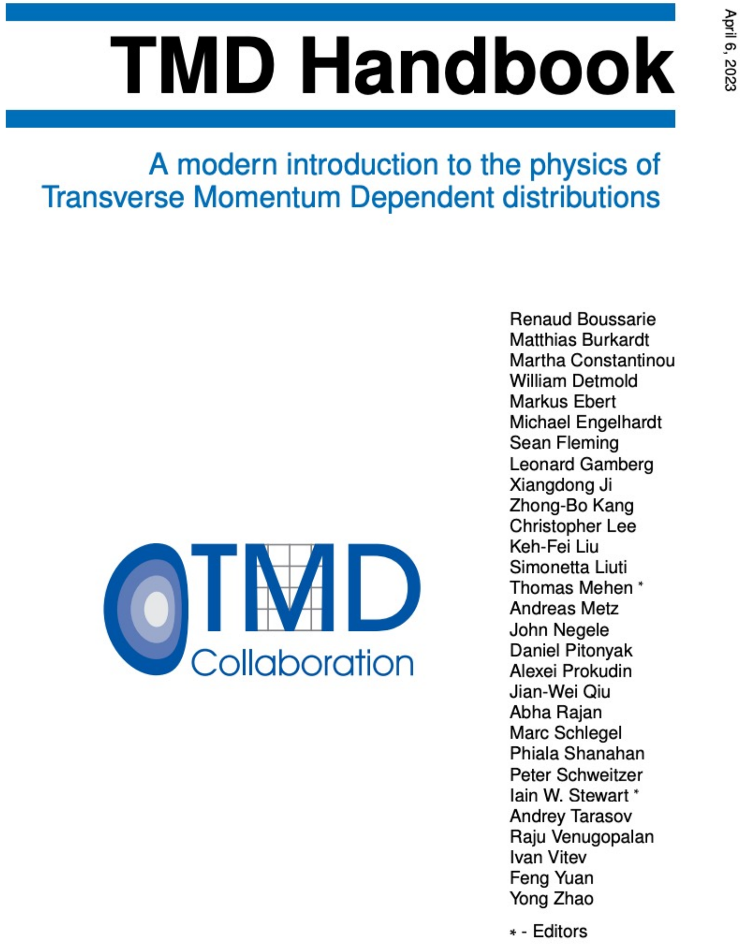
TMD Handbook

Renaud Boussarie[1], Matthias Burkardt[2], Martha Constantinou[3], William Detmold[4], Markus Ebert[4,5], Michael Engelhardt[2], Sean Fleming[6], Leonard Gamberg[7], Xiangdong Ji[8], Zhong-Bo Kang[9], Christopher Lee[10], Keh-Fei Liu[11], Simonetta Liuti[12], Thomas Mehen[13], Andreas Metz[3], John Negele[4], Daniel Pitonyak[14], Alexei Prokudin[7,16], Jian-Wei Qiu[16,17], Abha Rajan[12,18], Marc Schlegel[2,19], Phiala Shanahan[4], Peter Schweitzer[20], Iain W. Stewart[4], Andrey Tarasov[21,22], Raju Venugopalan[18], Ivan Vitev[10], Feng Yuan[23], Yong Zhao[24,4,18]

[1]CPHT, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91128 Palaiseau, France
[2]Department of Physics, New Mexico State University, Las Cruces, NM 88003
[3]Department of Physics, Temple University, Philadelphia, PA 19122 - 1801, USA
[4]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139
[5]Max Planck Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany
[6]Department of Physics, University of Arizona, Tucson, AZ 85721
[7]Division of Science, Penn State University Berks, Reading, PA 19610
[8]Maryland Center for Fundamental Physics, University of Maryland, College Park, 20742, USA
[9]Department of Physics and Astronomy, University of California, Los Angeles, CA 90095
[10]Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545
[11]Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506
[12]Department of Physics, University of Virginia, Charlottesville, VA 22904
[13]Department of Physics, Duke University, Durham, NC 27708
[14]Department of Physics, Lebanon Valley College, Annville, Pennsylvania 17003
[15]Department of Physics, Old Dominion University, Norfolk, VA 23529
[16]Theory Center, Jefferson Lab, Newport News, Virginia 23606
[17]Department of Physics, William & Mary, Williamsburg, Virginia 23187
[18]Physics Department, Brookhaven National Laboratory, Upton, NY 11973
[19]Institute for Theoretical Physics, Tübingen University, 72076 Tübingen, Germany
[20]Department of Physics, University of Connecticut, Storrs, CT 06269
[21]Department of Physics, North Carolina State University, Raleigh, NC 27607
[22]Joint BNL-SBU Center for Frontiers in Nuclear Science at Stony Brook University, Stony Brook, NY 11794
[23]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[24]Physics Division, Argonne National Laboratory, Lemont, IL 60439

Abstract

This handbook provides a comprehensive review of transverse-momentum-dependent parton distribution functions and fragmentation functions, commonly referred to as transverse momentum distributions (TMDs). TMDs describe the distribution of partons inside the proton and other hadrons with respect to both their longitudinal and transverse momenta. They provide unique insight into the internal momentum and spin structure of hadrons, and are a key ingredient in the description of many collider physics cross sections. Understanding TMDs requires a combination of theoretical techniques from quantum field theory, nonperturbative calculations using lattice QCD, and phenomenological analysis of experimental data. The handbook covers a wide range of topics, from theoretical foundations to experimental analyses, as well as recent developments and future directions. It is intended to provide an essential reference for researchers and graduate students interested in understanding the structure of hadrons and the dynamics of partons in high energy collisions.


April 6, 2023

TMD Handbook

A modern introduction to the physics of Transverse Momentum Dependent distributions

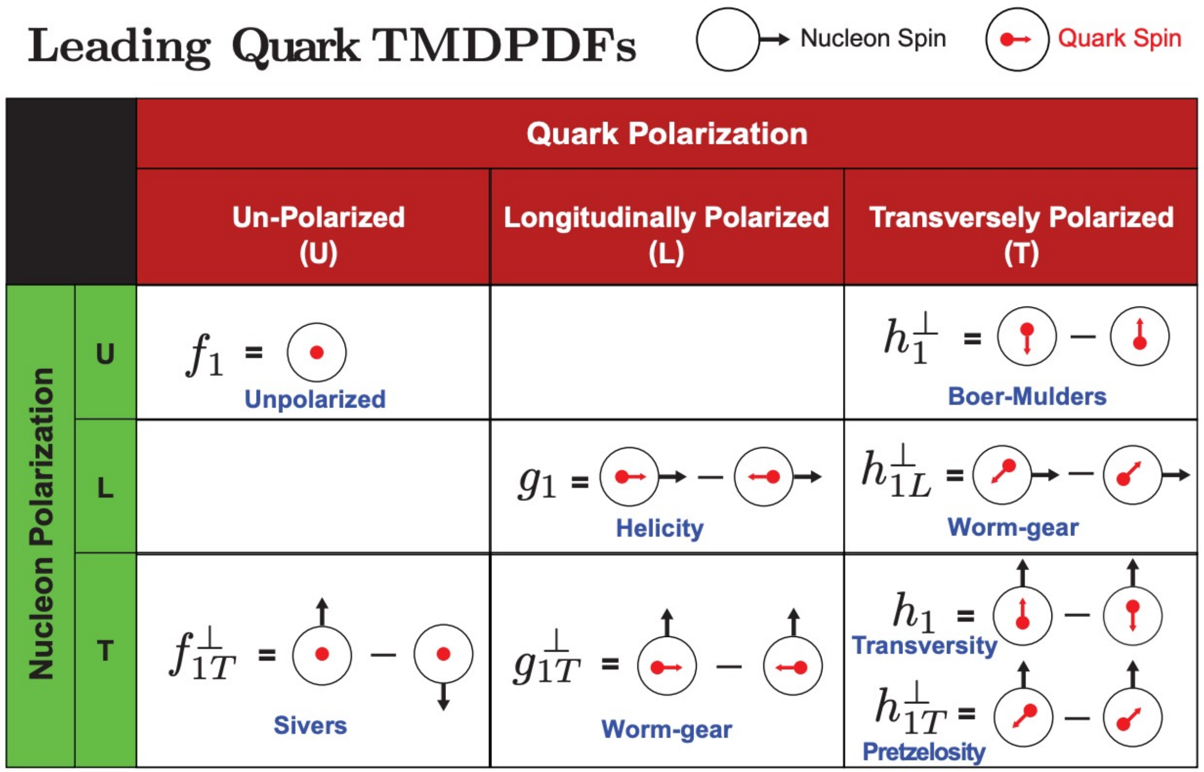
TMD Collaboration

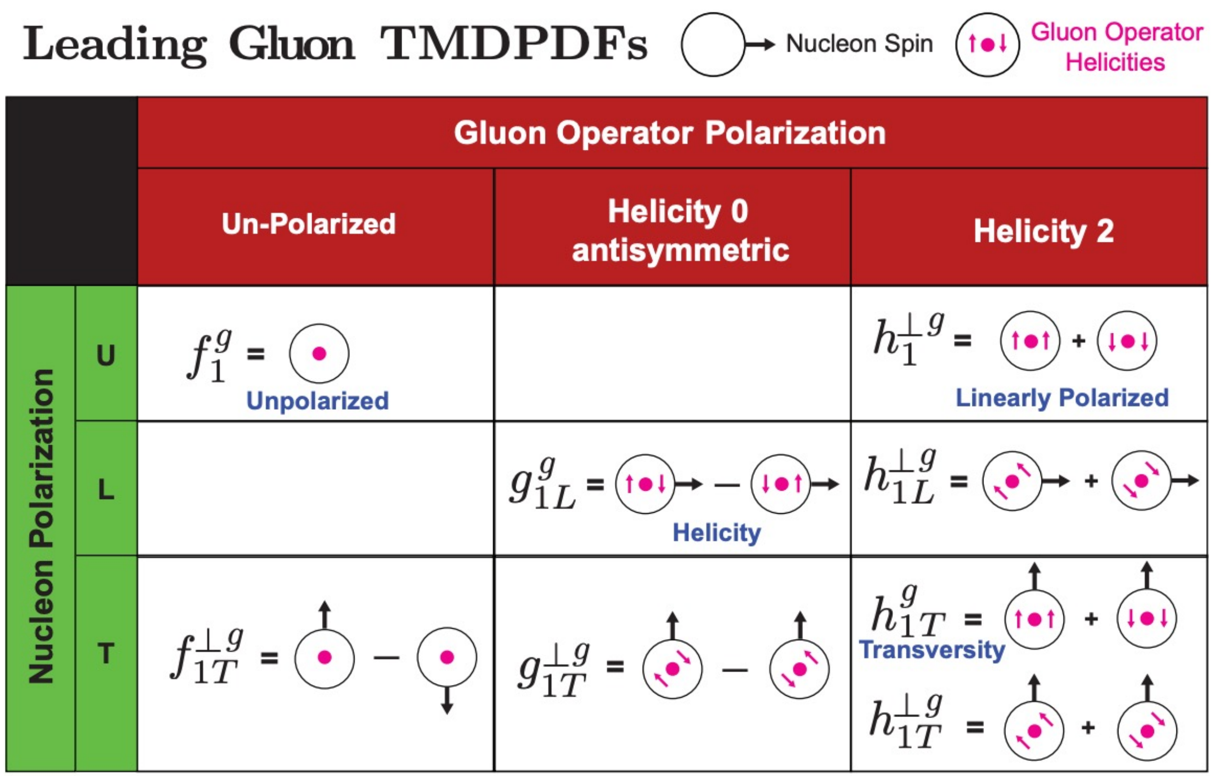
Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

* - Editors

（全く読めていません）
勉強不足ですみません

A lot of TMDs …


Leading Quark TMDPDFs
Nucleon Spin
Quark Spin
Quark Polarization
Un-Polarized (U)
Longitudinally Polarized (L)
Transversely Polarized (T)
Nucleon Polarization
U
L
T
f_1 =
Unpolarized
$h_1^\perp$ =
Boer-Mulders
g_1 =
Helicity
$h_{1L}^\perp$ =
Worm-gear
$f_{1T}^\perp$ =
Sivers
$g_{1T}^\perp$ =
Worm-gear
h_1 =
Transversity
$h_{1T}^\perp$ =
Pretzelosity

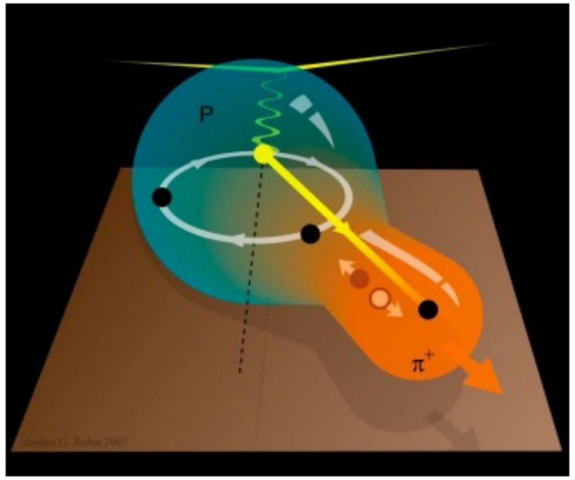

Leading Gluon TMDPDFs
Nucleon Spin
Gluon Operator Helicities
Gluon Operator Polarization
Un-Polarized
Helicity 0 antisymmetric
Helicity 2
Nucleon Polarization
U
L
T
f_1^g =
Unpolarized
$h_1^{\perp g}$ =
Linearly Polarized
g_{1L}^g =
Helicity
$h_{1L}^{\perp g}$ =
$f_{1T}^{\perp g}$ =
$g_{1T}^{\perp g}$ =
h_{1T}^g =
Transversity
$h_{1T}^{\perp g}$ =

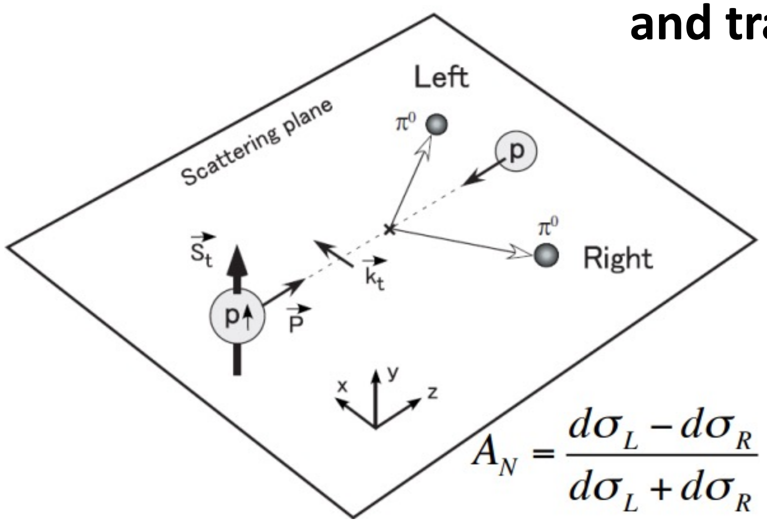
Sivers effect and TSA

- **RHIC: Transverse Spin Asymmetry (A_N)**

Sivers effect

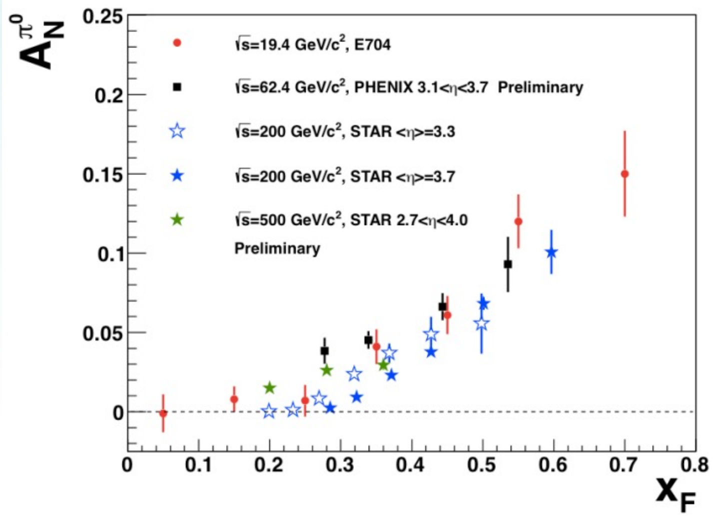
Correlation between nucleon transverse spin and transverse momentum of partons

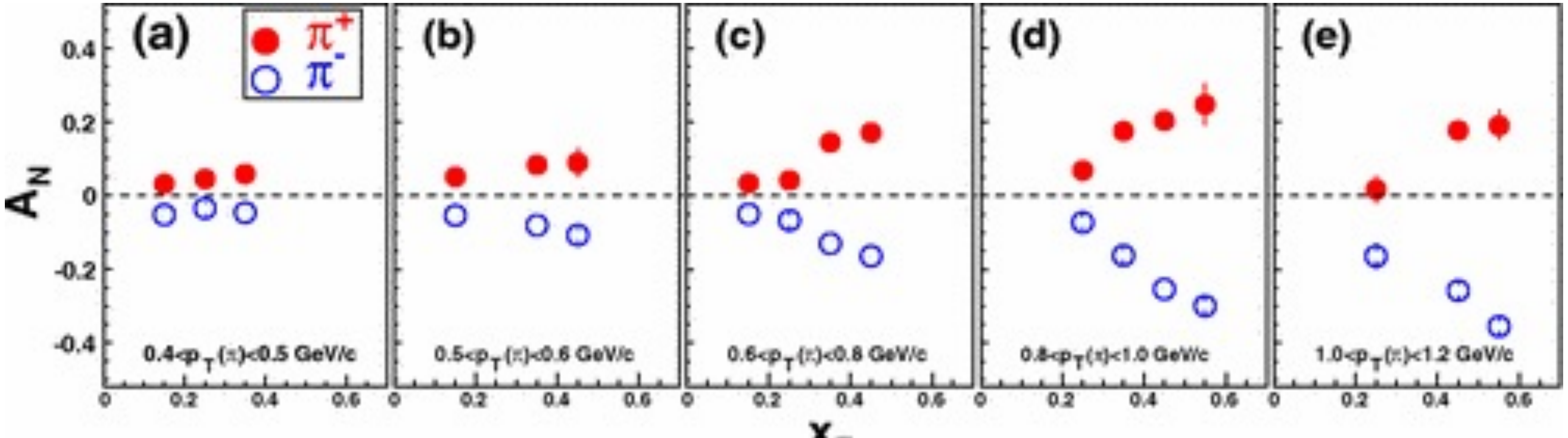




$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

Non-zero A_N and charge dependent
-> opposite spin-k_T properties of valence u and d quarks





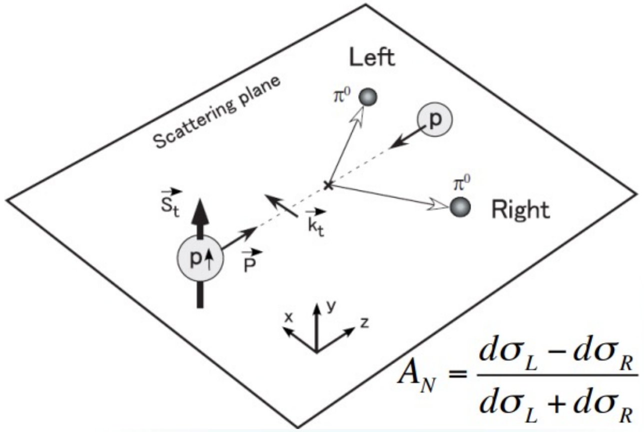
Phys. Rev. Lett. **101**, 042001

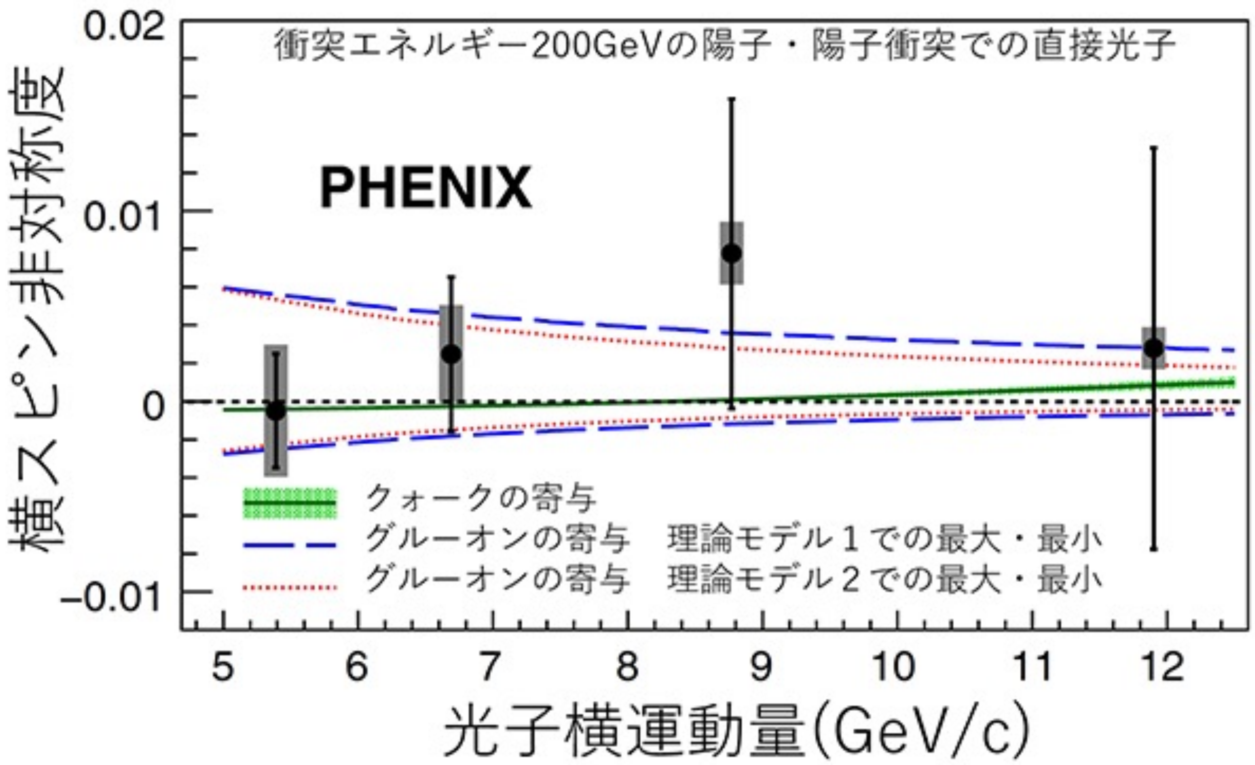
Sivers effect and TSA

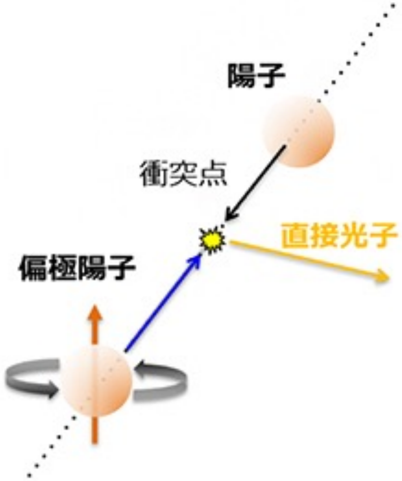
- **RHIC: Transverse Spin Asymmetry (A_N)**

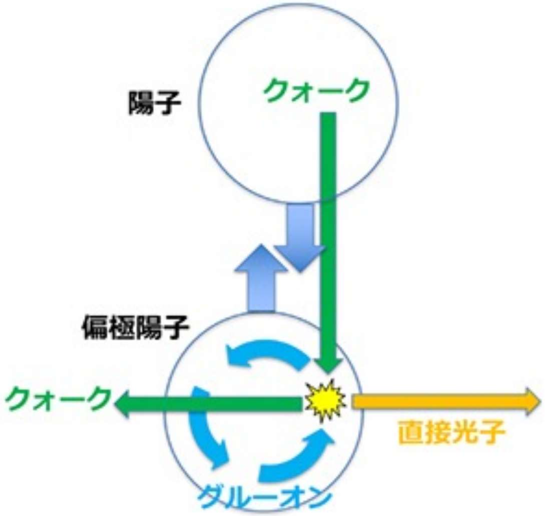
https://www.riken.jp/press/2021/20211015_1/index.html

Direct photon A_N sensitive to gluon angular momentum







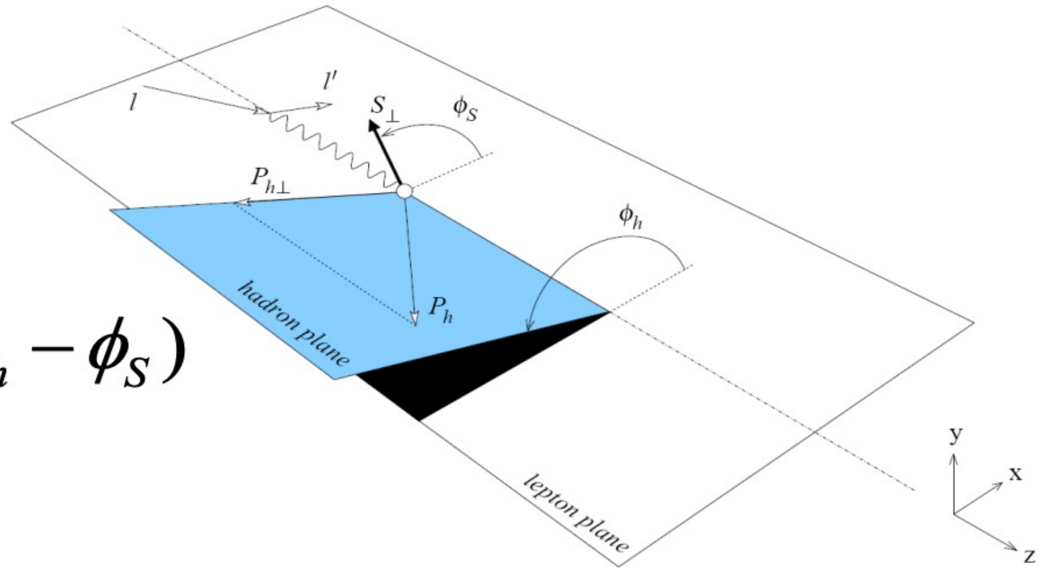


TMD at EIC through SI-DIS

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$



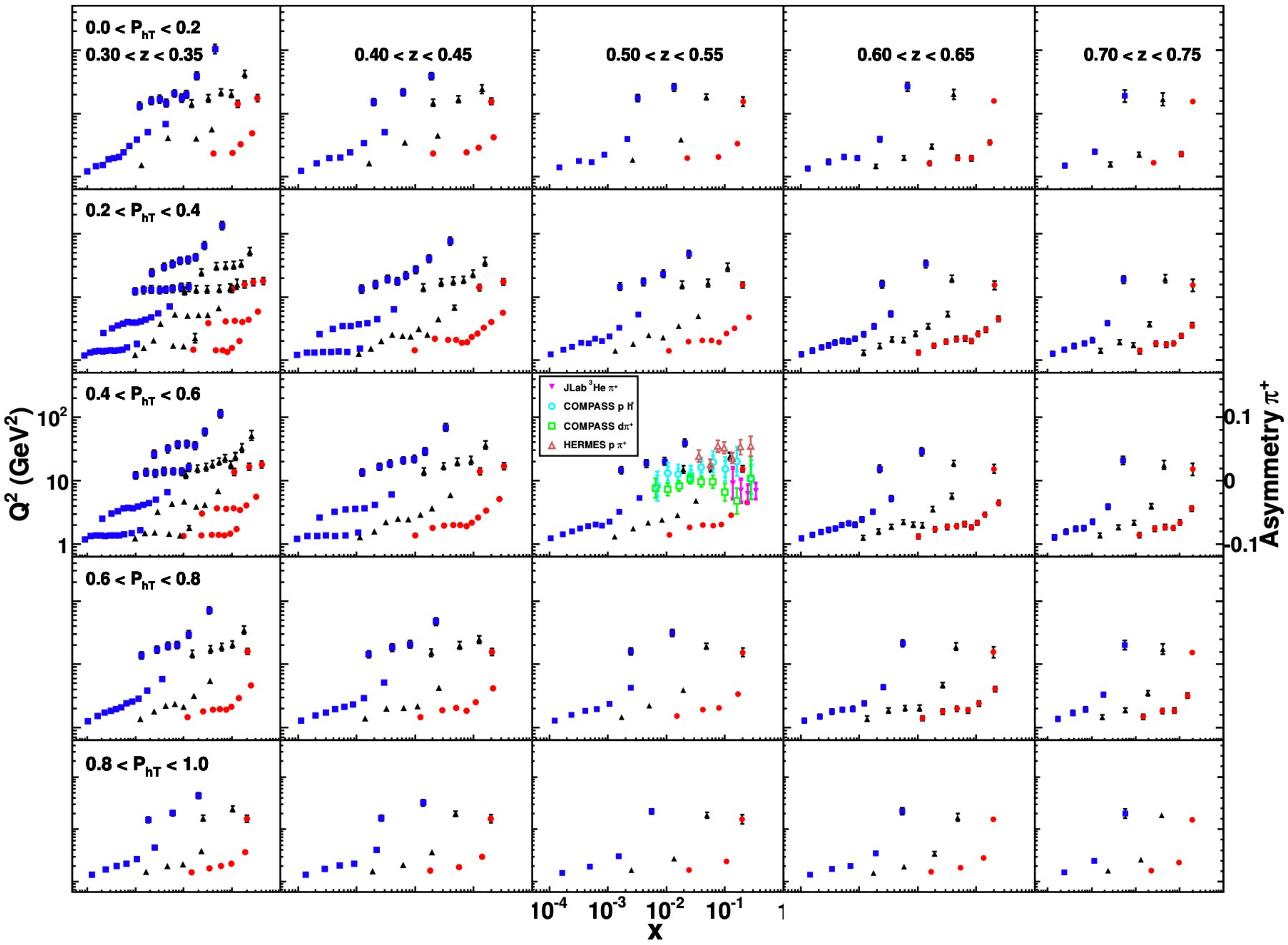
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

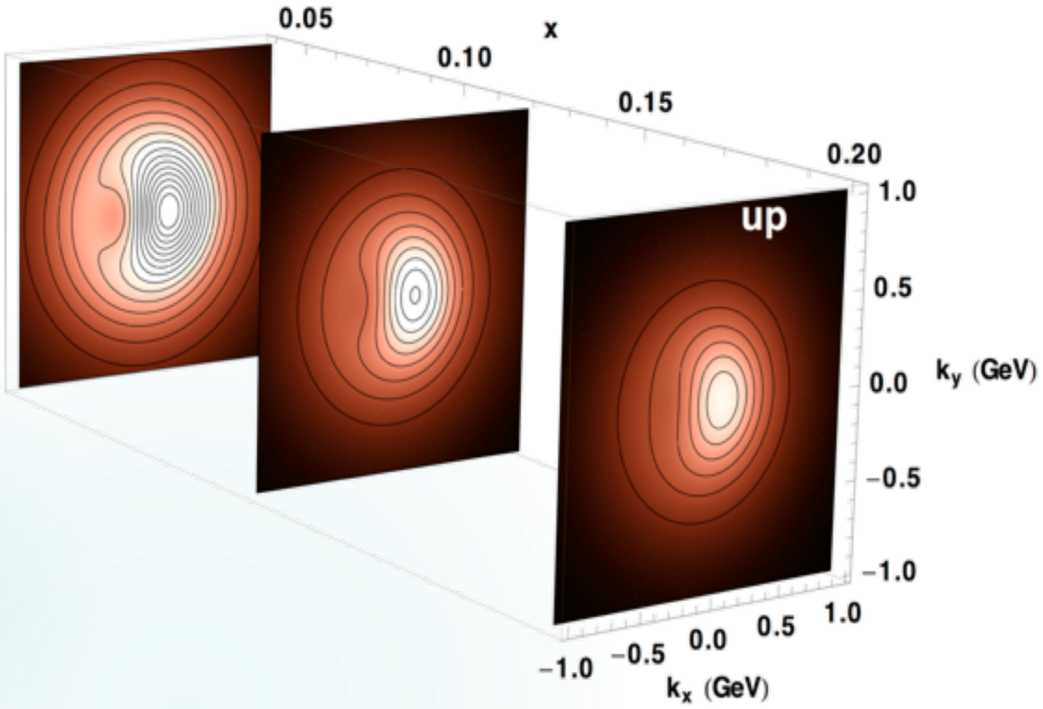
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

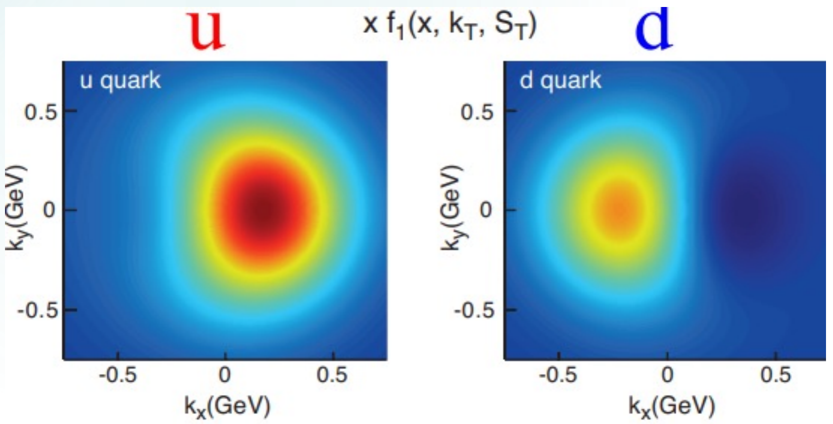
TMD at EIC through SI-DIS

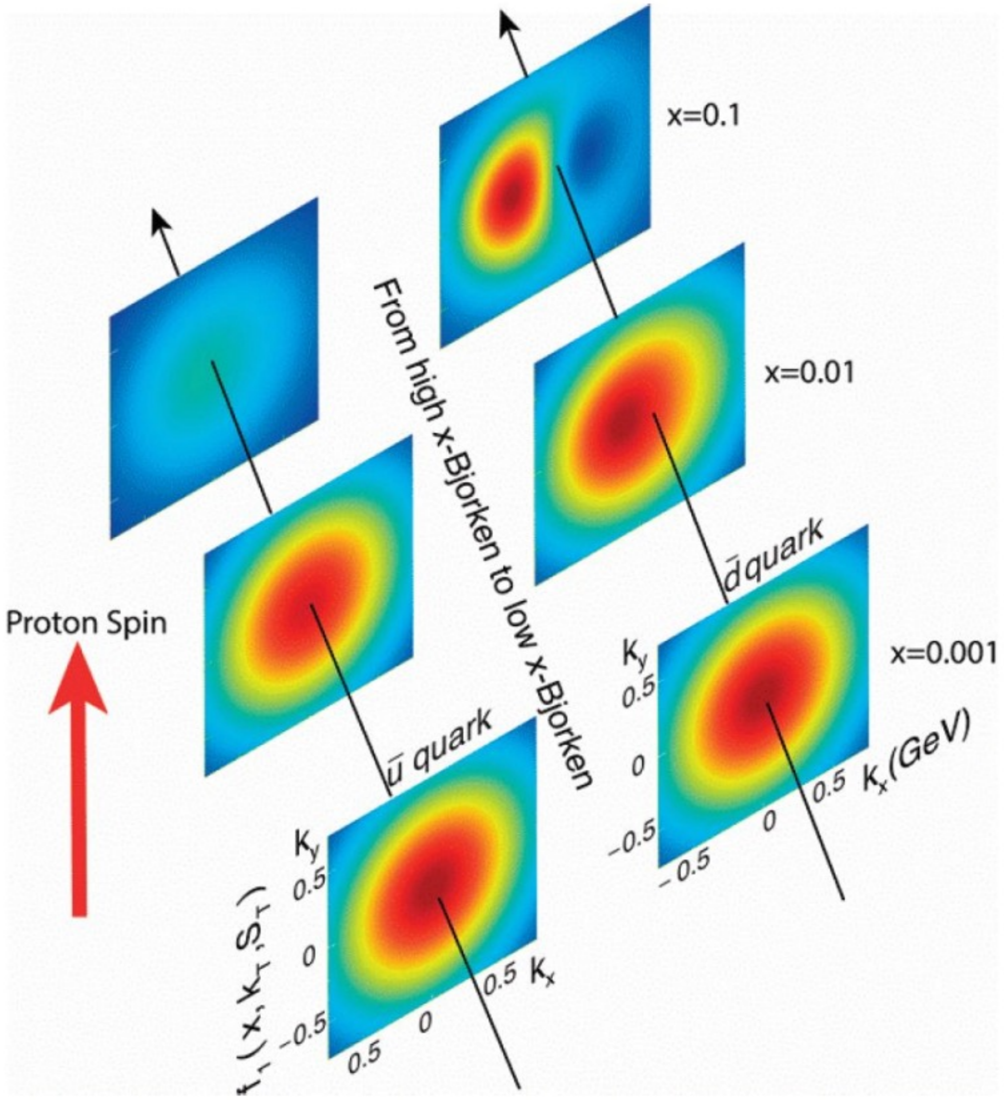
√s = 140 GeV
√s = 45 GeV
√s = 15 GeV



Momentum imaging







Generalized Parton Distributions

About 200 pages…

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Generalized parton distributions

M. Diehl

Deutsches Elektronen-Synchroton DESY, 22603 Hamburg, Germany

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editor: W. Weise

Abstract

We give an overview of the theory for generalized parton distributions. Topics covered are their general properties and physical interpretation, the possibility to explore the three-dimensional structure of hadrons at parton level, their potential to unravel the spin structure of the nucleon, their role in small-x physics, and efforts to model their dynamics. We review our understanding of the reactions where generalized parton distributions occur, to leading power accuracy and beyond, and present strategies for phenomenological analysis. We emphasize the close connection between generalized parton distributions and generalized distribution amplitudes, whose properties and physics we also present. We finally discuss the use of these quantities for describing soft contributions to exclusive processes at large energy and momentum transfer.

PACS: 13.60.−r; 13.88.+e; 14.20.Dh

Keywords: Nucleon structure; Parton distributions; Hard exclusive processes

Contents

E-mail address: markus.diehl@desy.de (M. Diehl).

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Physics Reports 418 (2005) 1–387

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Unraveling hadron structure with generalized parton distributions

A.V. Belitsky[a,*], A.V. Radyushkin[b,c,1]

[a] *Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504, USA*
[b] *Physics Department, Old Dominion University, Norfolk, VA 23529, USA*
[c] *Theory Group, Jefferson Laboratory, Newport News, VA 23606, USA*

Accepted 8 June 2005

editor: W. Weise

Dedicated to Anatoly V. Efremov on occasion of his 70th anniversary

Abstract

The generalized parton distributions, introduced nearly a decade ago, have emerged as a universal tool to describe hadrons in terms of quark and gluonic degrees of freedom. They combine the features of form factors, parton densities and distribution amplitudes—the functions used for a long time in studies of hadronic structure. Generalized parton distributions are analogous to the phase-space Wigner quasi-probability function of nonrelativistic quantum mechanics which encodes full information on a quantum-mechanical system. We give an extensive review of main achievements in the development of this formalism. We discuss physical interpretation and basic properties of generalized parton distributions, their modeling and QCD evolution in the leading and next-to-leading orders. We describe how these functions enter a wide class of exclusive reactions, such as electro- and photo-production of photons, lepton pairs, or mesons. The theory of these processes requires and implies full control over diverse corrections and thus we outline the progress in handling higher-order and higher-twist effects. We catalogue corresponding results and present diverse techniques for their derivations. Subsequently, we address observables that are sensitive to different characteristics of the nucleon structure in terms of generalized parton distributions. The ultimate goal of the GPD approach is to provide a three-dimensional spatial picture of the nucleon, direct measurement of the quark orbital angular momentum, and various inter- and multi-parton correlations.

PACS: 13.60.−r; 13.88.+e; 14.20.Dh

* Corresponding author. Tel.: +1 480 965 2218; fax: +1 480 965 7954.
E-mail address: andrei.belitsky@asu.edu (A.V. Belitsky).
[1] Also at Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia.

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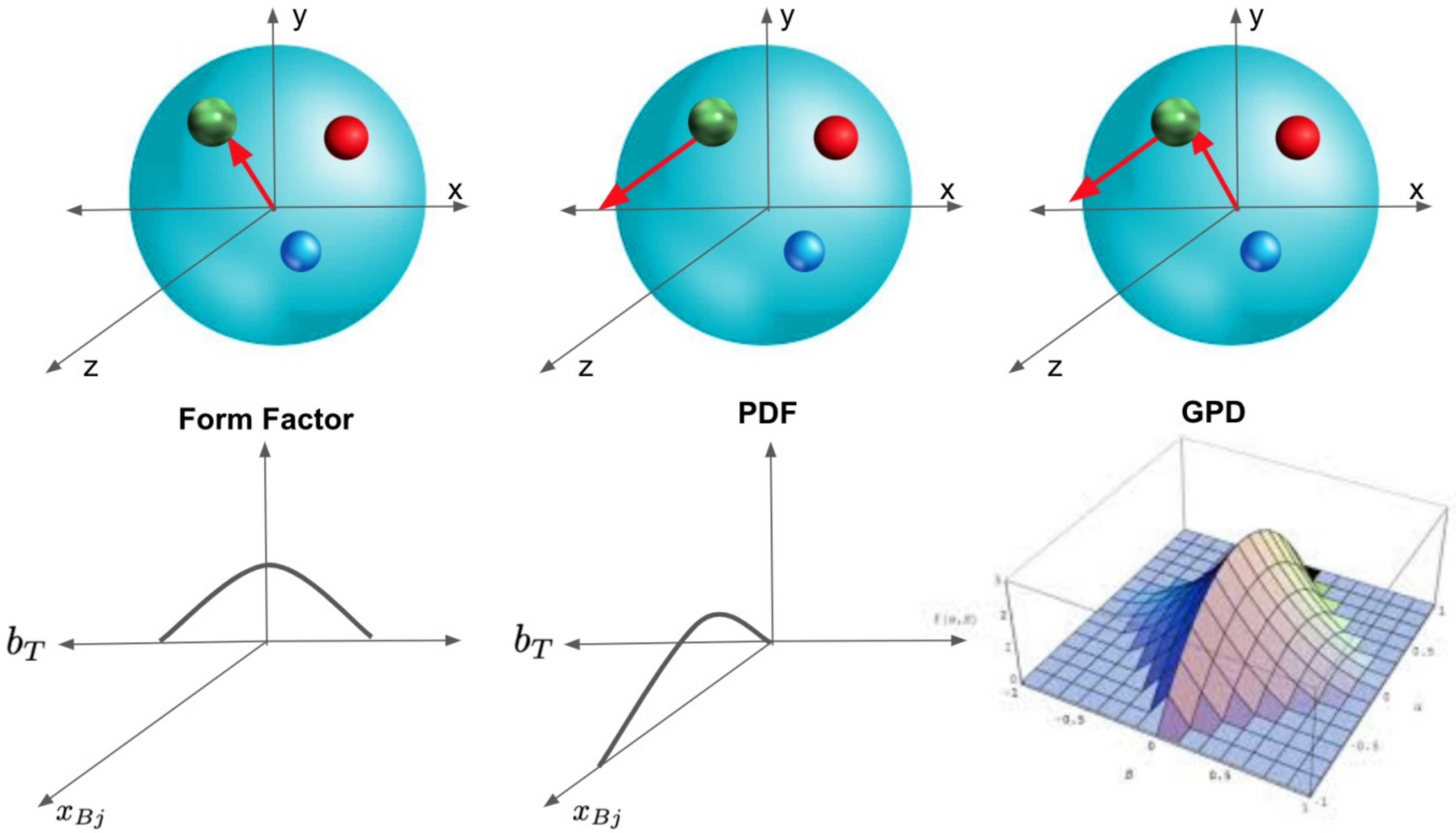
Generalized Parton Distributions

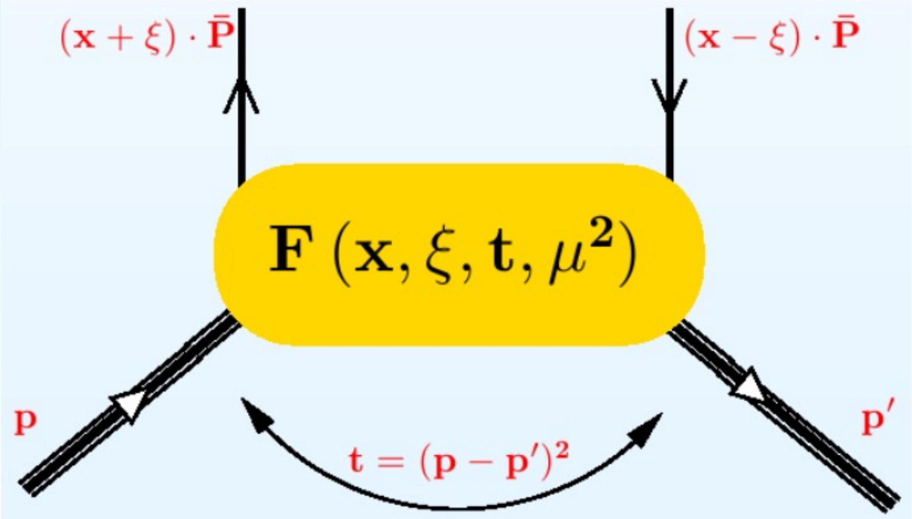


Generalized Parton Distributions

The nucleon (spin-1/2) has four quark and gluon GPDs. Like usual PDFs, GPDs are non-perturbative functions defined via the off-forward matrix elements of well-defined parton operators:

異なる運動量を持つ初期状態と終状態の核子間のクォーク演算子の行列要素

$$
\begin{aligned}
F^q &= \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0} \\
&= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]
\end{aligned}
$$



$\Delta = p' - p$

$t = (p' - p)^2$

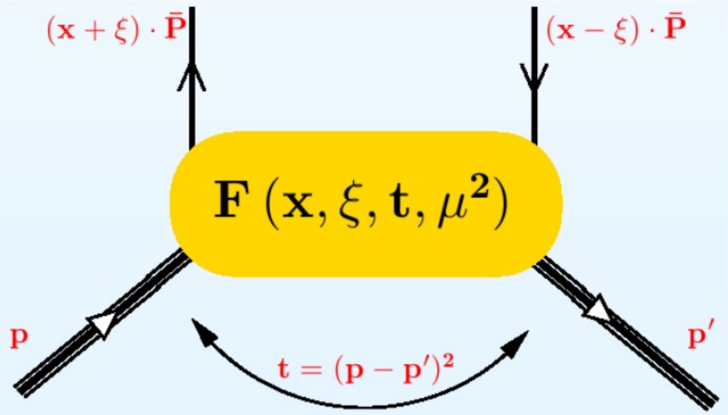
$\bar{P}^+ = (p' + p)/2$

$x \pm \xi$ -- long. mom. fractions

μ^2 -- factorization scale

$\xi = x_B/(2 - x_B)$ -- fixed

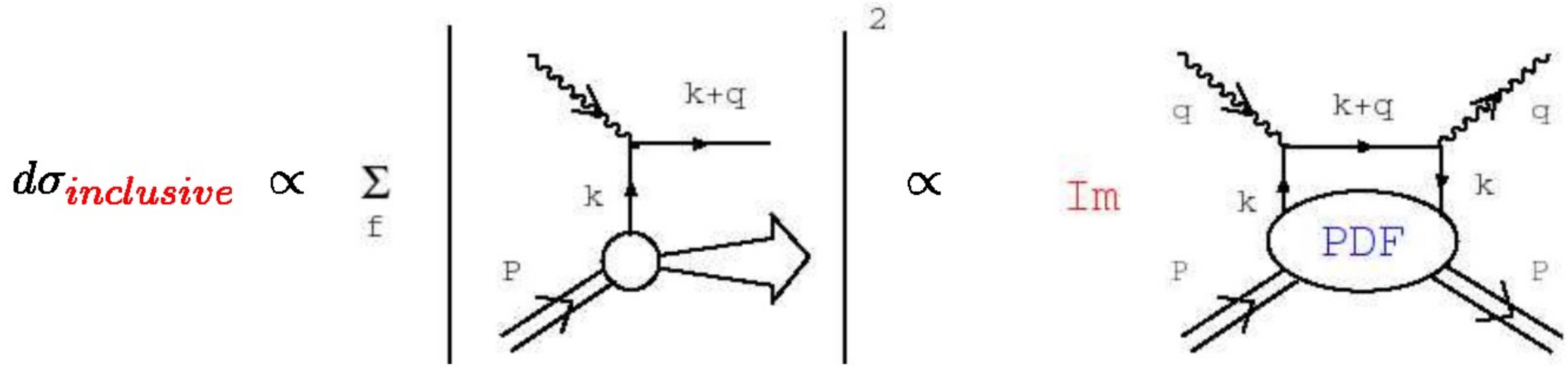
Basic Properties of GPD



Forward Limit

ξ→0, t→0 : 1D parton distribution (PDFs)

$H^q(x,0,0) = q(x)$ Unpolarized $\tilde{H}^q(x,0,0) = \Delta q(x)$ Polarized

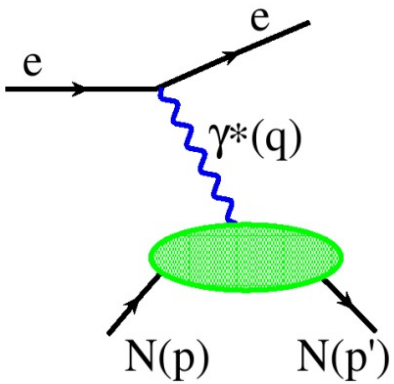


Basic Properties of GPD

Connection to elastic Form Factors
(charge radius and magnetic radius)

$$\int_0^1 dx\, H^q(x,\xi,t,\mu^2) = F_1^q(t)$$

$$\int_0^1 dx\, E^q(x,\xi,t,\mu^2) = F_2^q(t)$$



$$\langle N(p')|J^\mu(0)|N(p)\rangle = \bar{u}(p')\left[F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N}\right]u(p)$$

Dirac form factor   Pauli form factor

$F_1^p(0) = 1$ $F_2^p(0) = \kappa^p = 1.79$

$F_1^n(0) = 0$ $F_2^n(0) = \kappa^n = -1.91$

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_N^2}F_2(q^2)$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$

Connection to spin, mass, pressure

$$\frac{1}{2}\int_0^1 dx\, x\, \left[H^q(x,\xi,t=0,\mu^2) + E^q(x,\xi,t=0,\mu^2)\right] = J^q(\mu^2)$$

$$\frac{1}{2}\int_0^1 dx\, x\, \left[H^g(x,\xi,t=0,\mu^2) + E^g(x,\xi,t=0,\mu^2)\right] = J^g(\mu^2)$$

$$\sum_q J^q + J^g = \frac{1}{2}$$

$J^q = S^q + L^q$

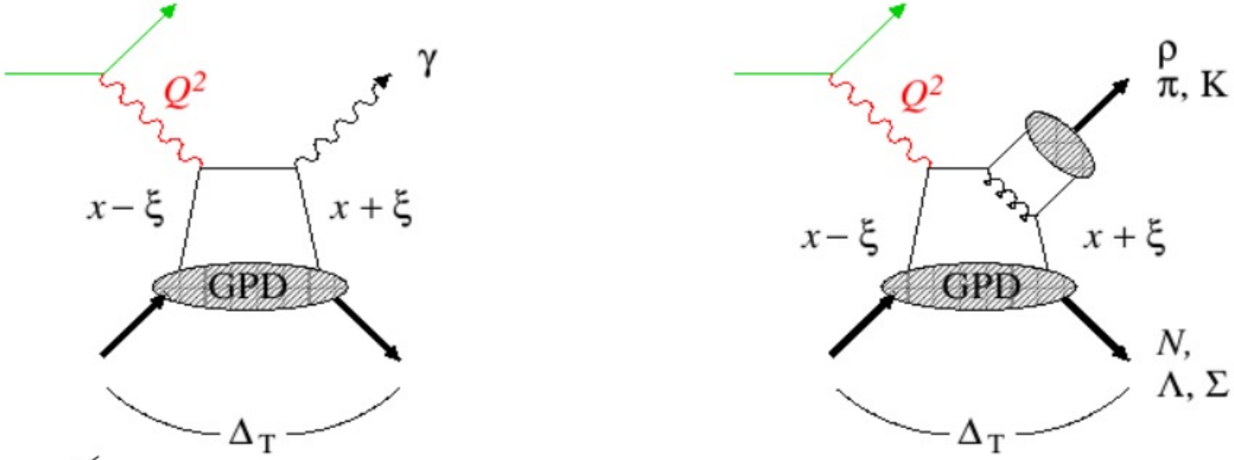
$J^g = \Delta G + L^g$

$$\int_{-1}^{1} dx\, x\, H(x,\xi,t) = M_2^Q(t) + \frac{4}{5}d^Q(t)\xi^2$$

Mass   Pressure

Measurement of GPD

- **Deeply Virtual Compton Scattering and Deeply Virtual Merson Production**



Deeply virtual Compton scattering

(e) Deeply virtual meson production

$$\mathcal{A}_{\mathrm{DVCS}}(\xi, t, Q^2) \propto \sum_q e_q^2 \int_0^1 dx \, \frac{2x}{x^2 - \xi^2} H^q(x, \xi, t, Q^2) + \text{other GPDs}$$

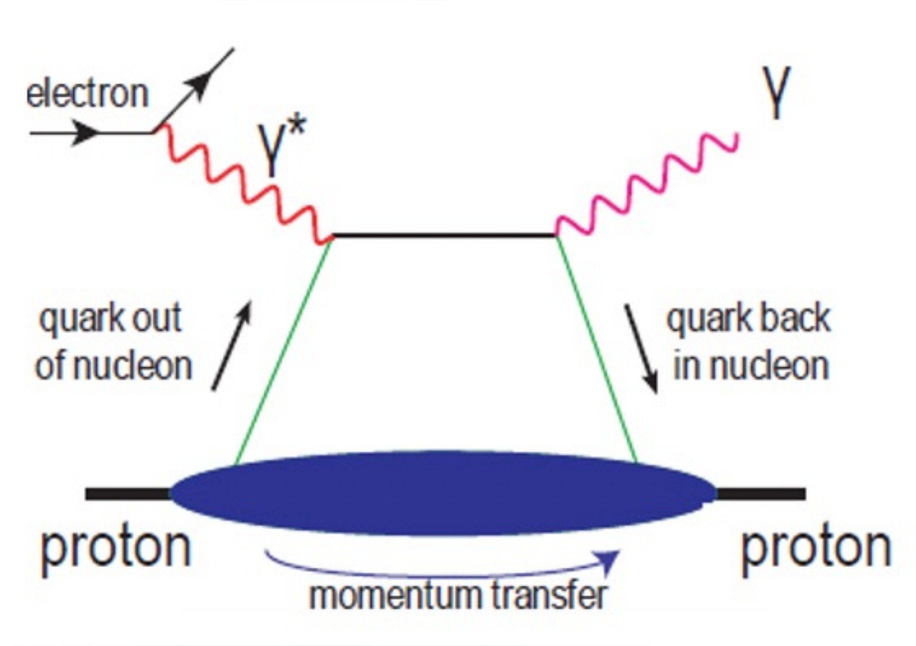
Perturbative

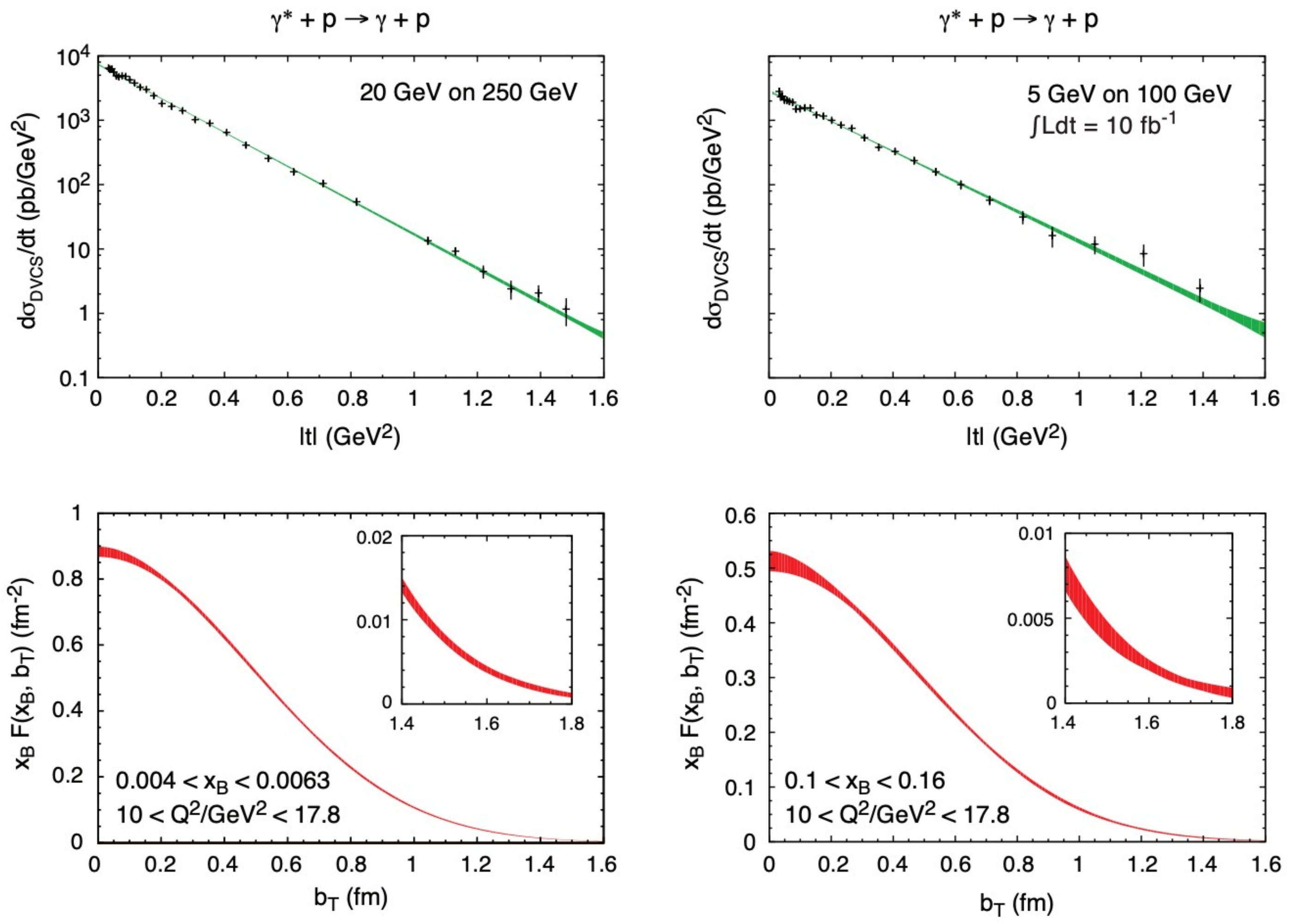
GPDs

3D tomography of nucleons (GPD)

- **Deeply Virtual Compton Scattering**

Fourier transform of momentum transferred=(p-p') → Spatial distribution



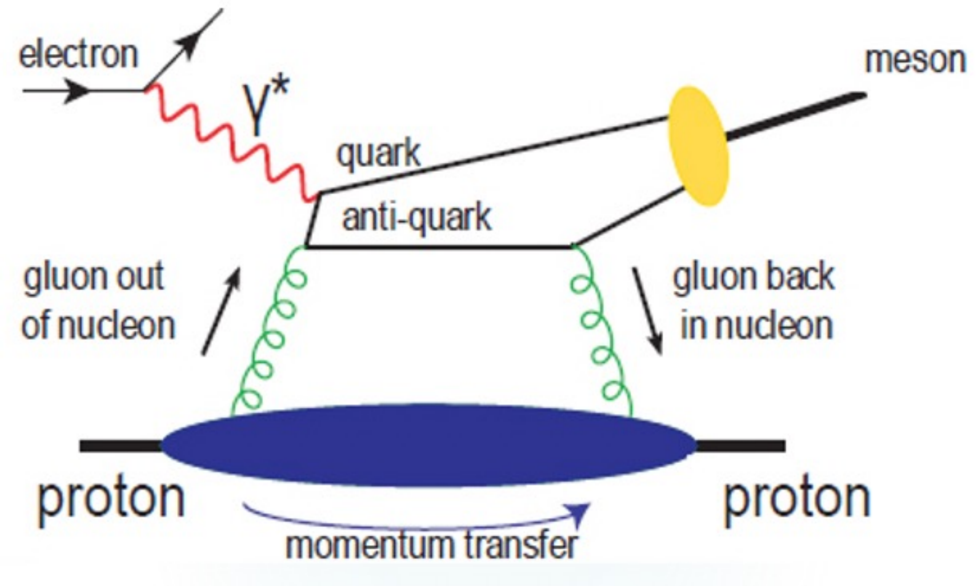


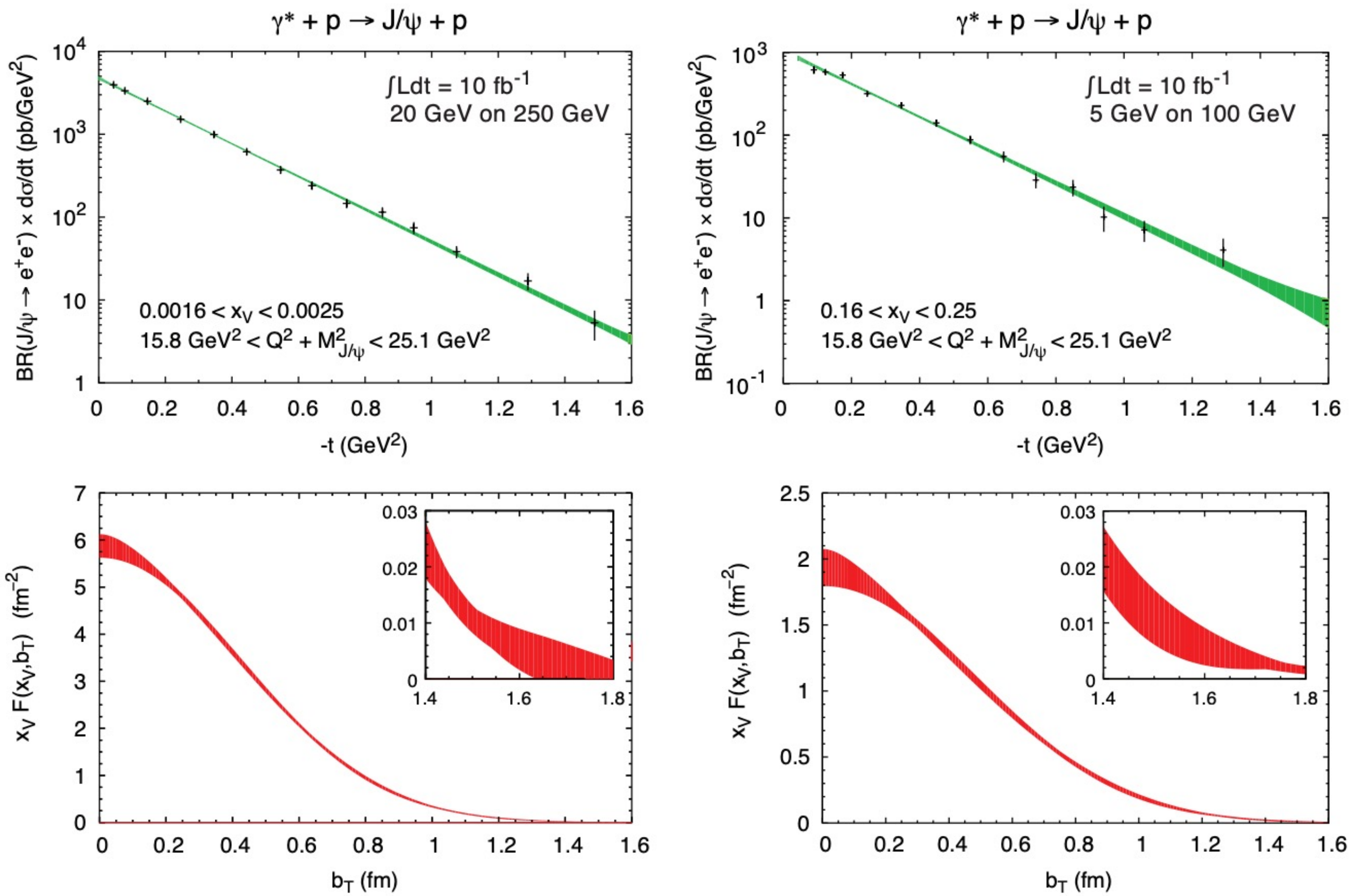
Proton radius of quarks (x)!

3D tomography of nucleons (GPD)

- **Deeply Virtual Compton Scattering**

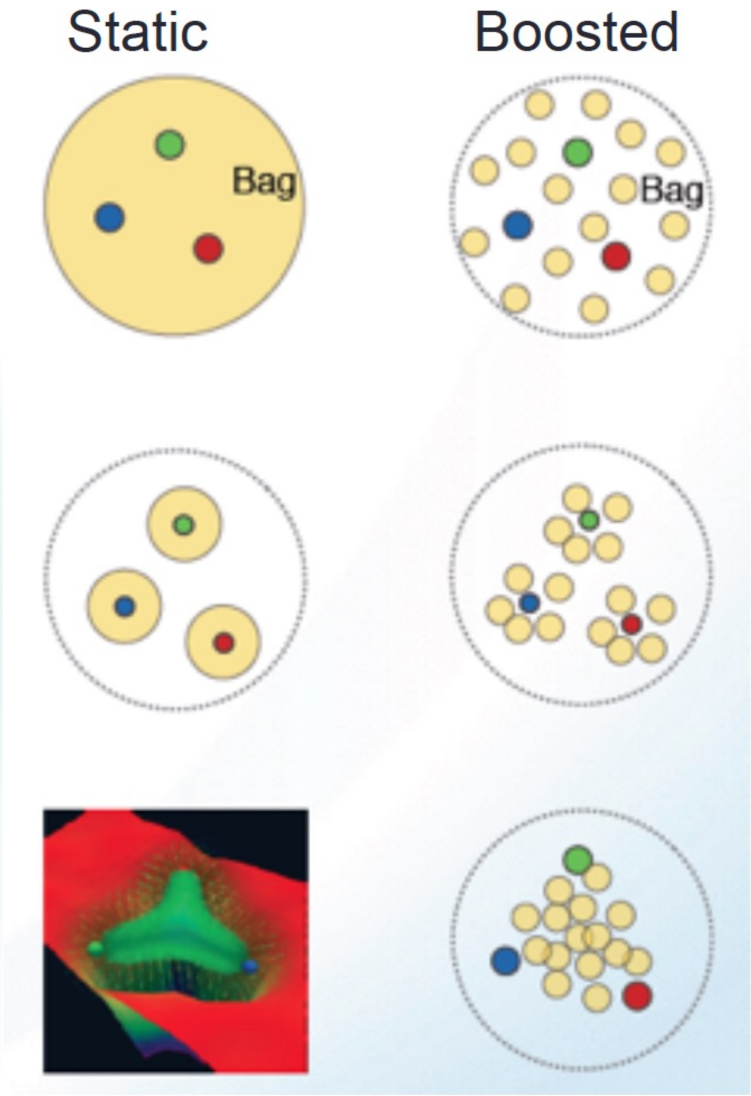
Fourier transform of momentum transferred=(p-p') → Spatial distribution





Proton radius of gluons (x)!

3D tomography of nucleons (GPD)



Bag Model:

- Gluon field distribution is wider than the fast moving quarks.
- Gluon radius > Charge Radius

Constituent Quark Model:

- Gluons and sea quarks hide inside massive quarks.
- Gluon radius ~ Charge Radius

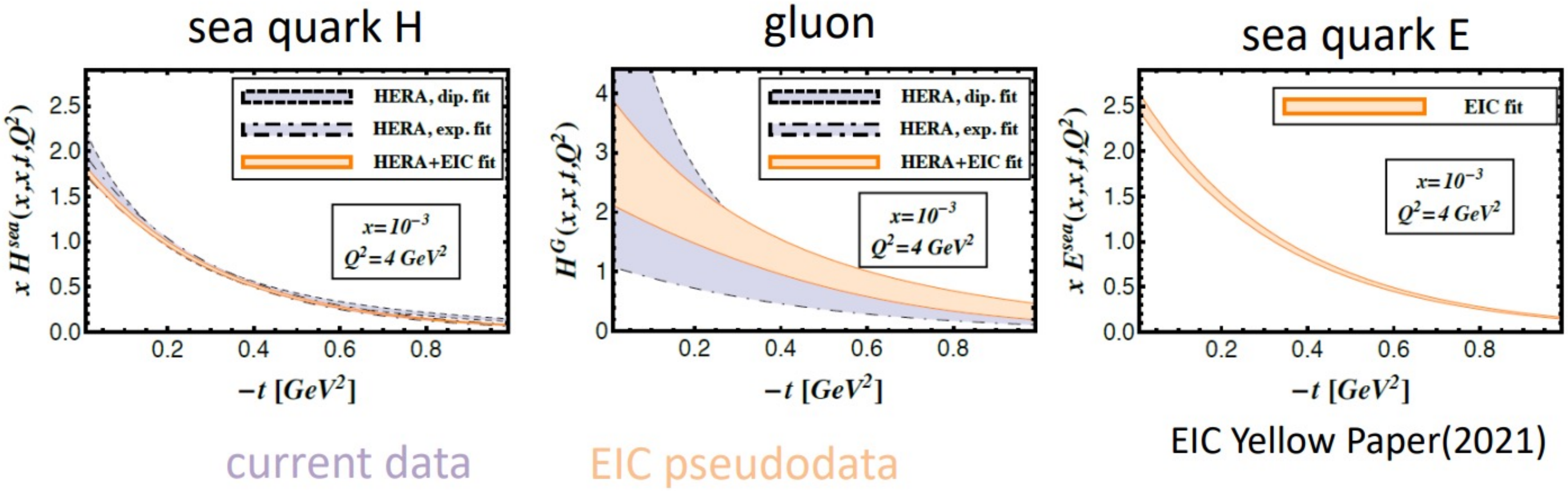
Lattice Gauge theory (with slow moving quarks),

- gluons more concentrated inside the quarks:
- Gluon radius < Charge Radius

Need transverse images of the quarks and gluons in protons

GPD at EIC

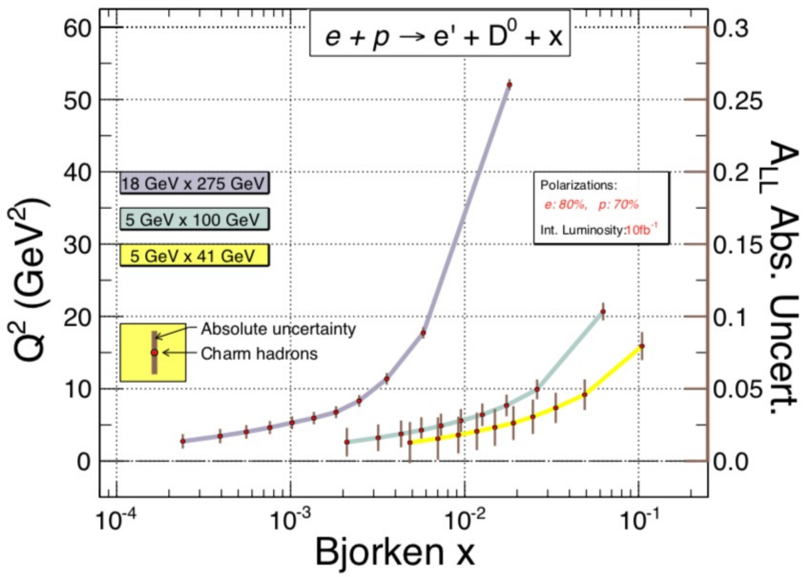
- DVCS in wider phase space ⇒ valence and sea quarks
- DVMP of heavy meson (J/ψ,Υ), light vector and pseudoscalar meson ⇒ gluon @ low x, flavor separation

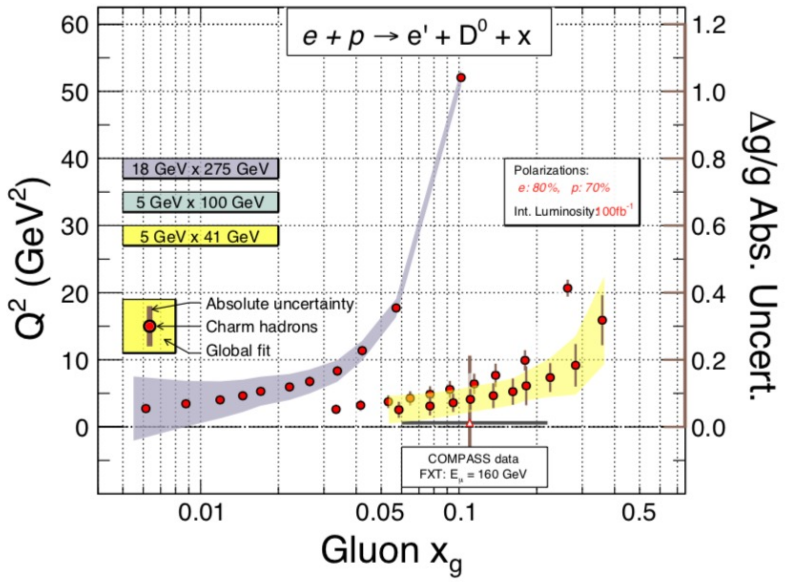


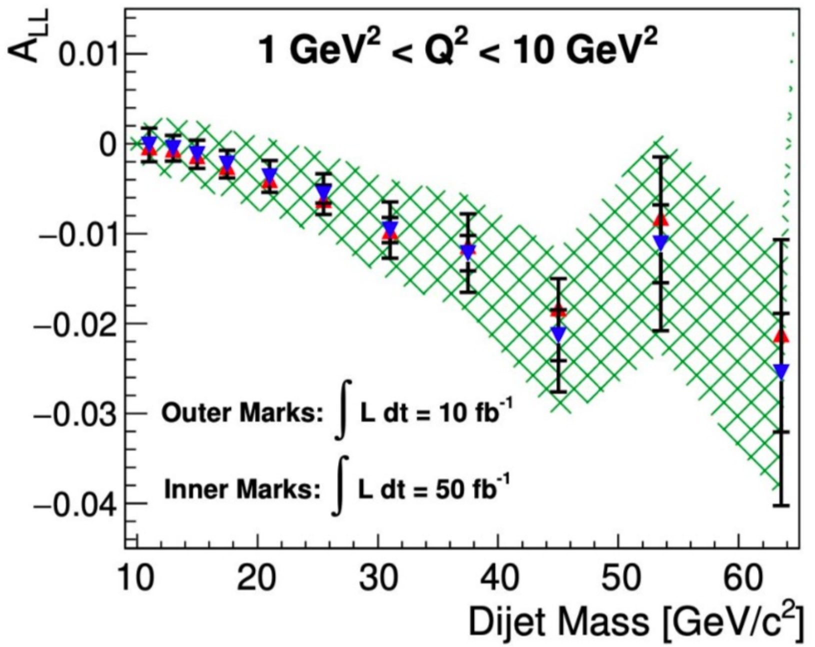
EIC Yellow Paper(2021)

Spin: A_{LL} and Polarized PDF at EIC

- Polarized PDF from A_{LL} measurements at the EIC
  - SIDIS, charm
  - dijets

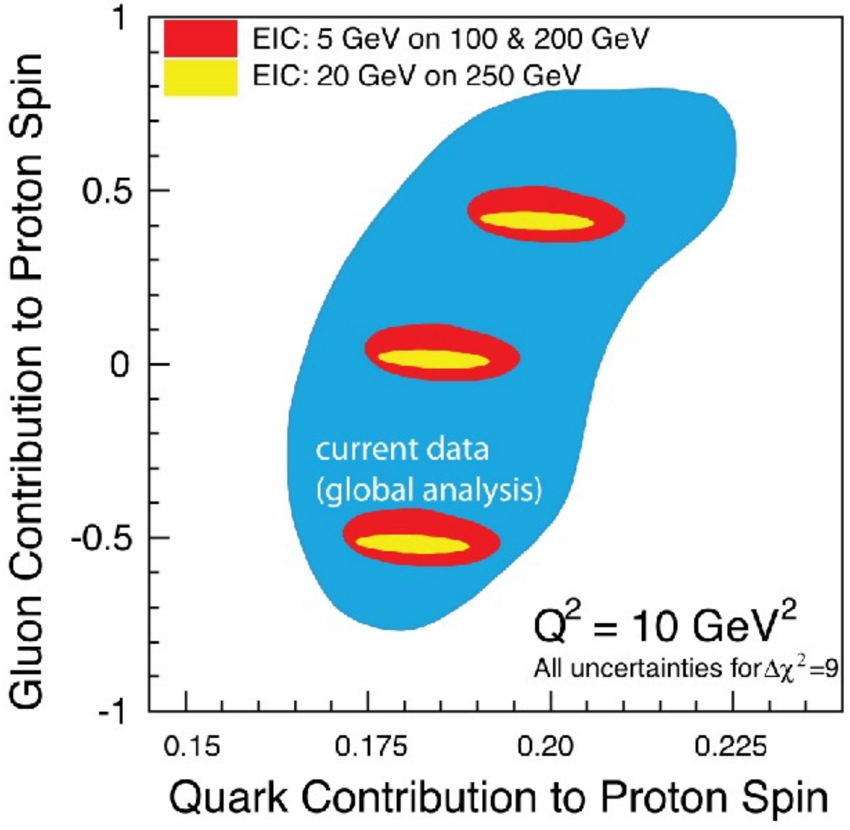


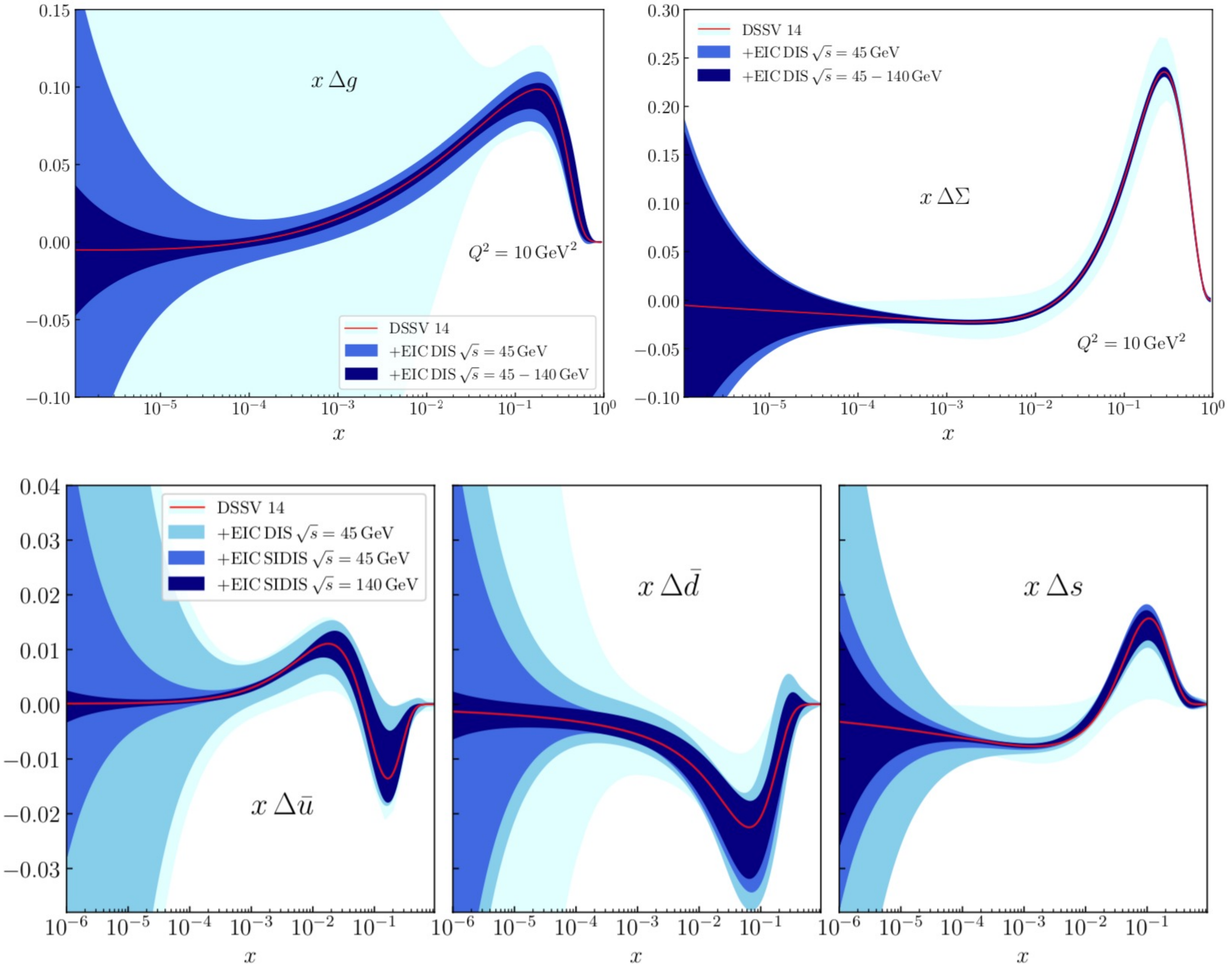




Spin: A_{LL} and Polarized PDF at EIC

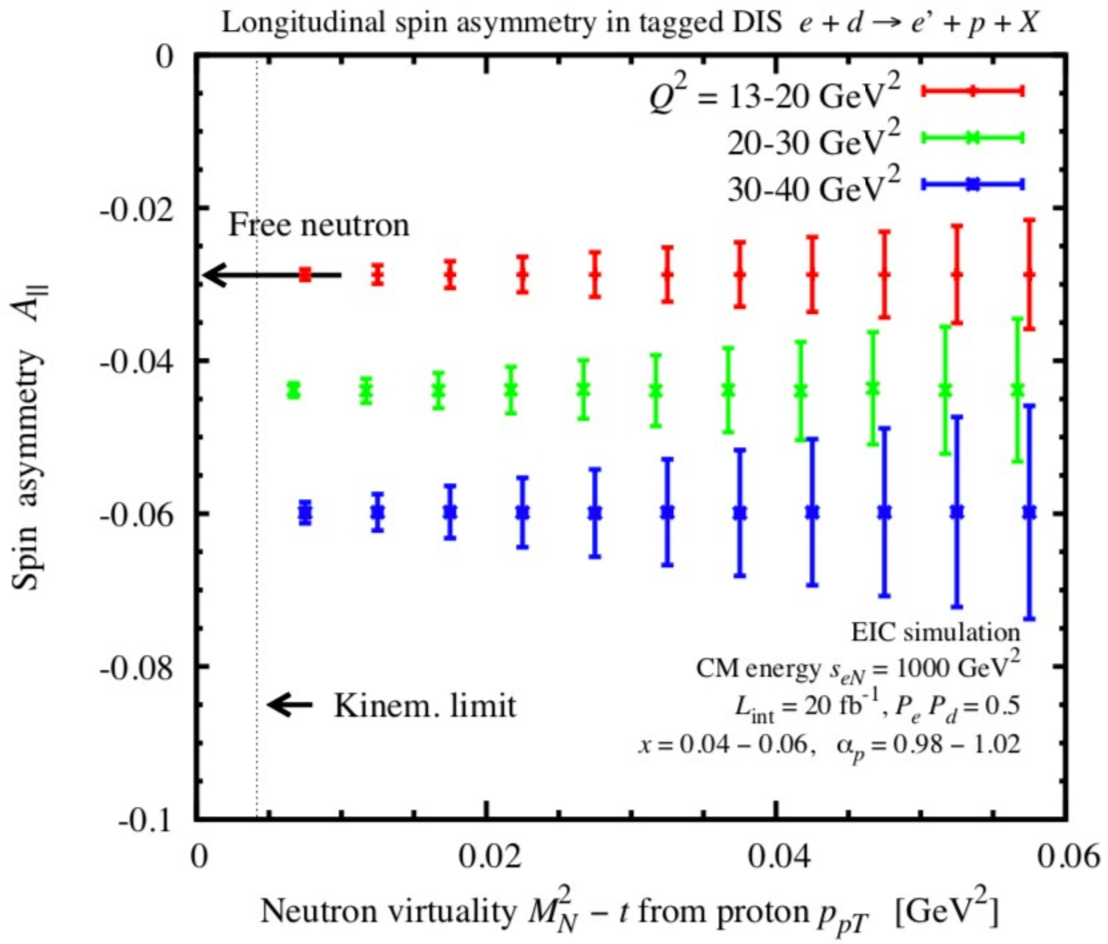
- **Polarized PDF from A_{LL} measurements at the EIC**

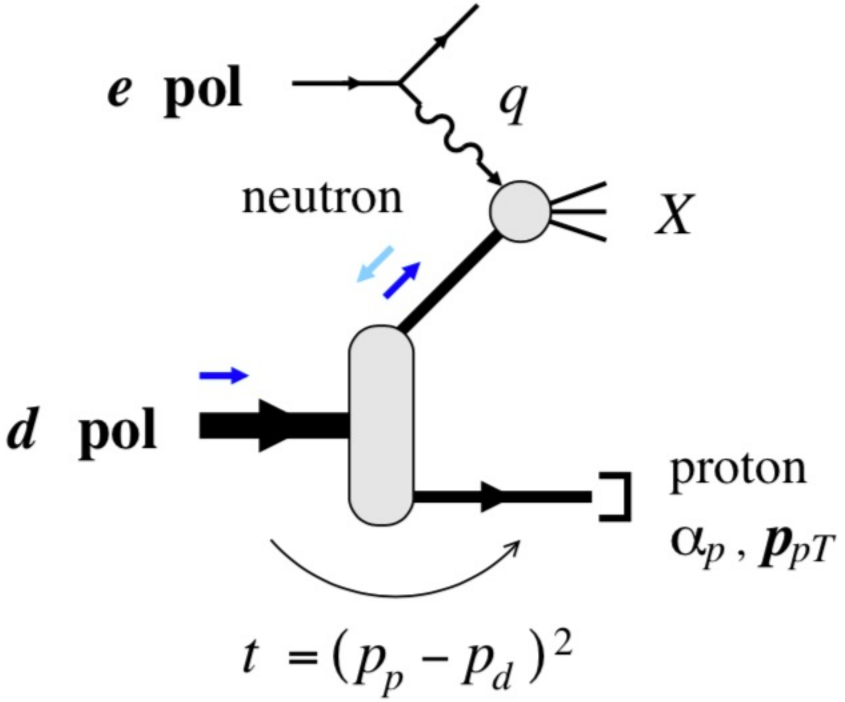




Spin: A_{LL} and Polarized PDF at EIC

- **New: neutron spin structure from e+d and e+^{3}He**

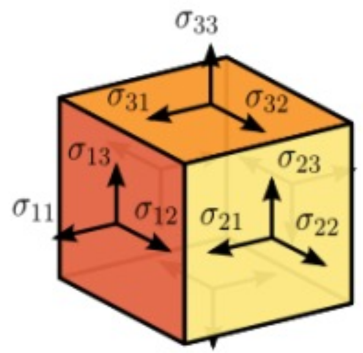


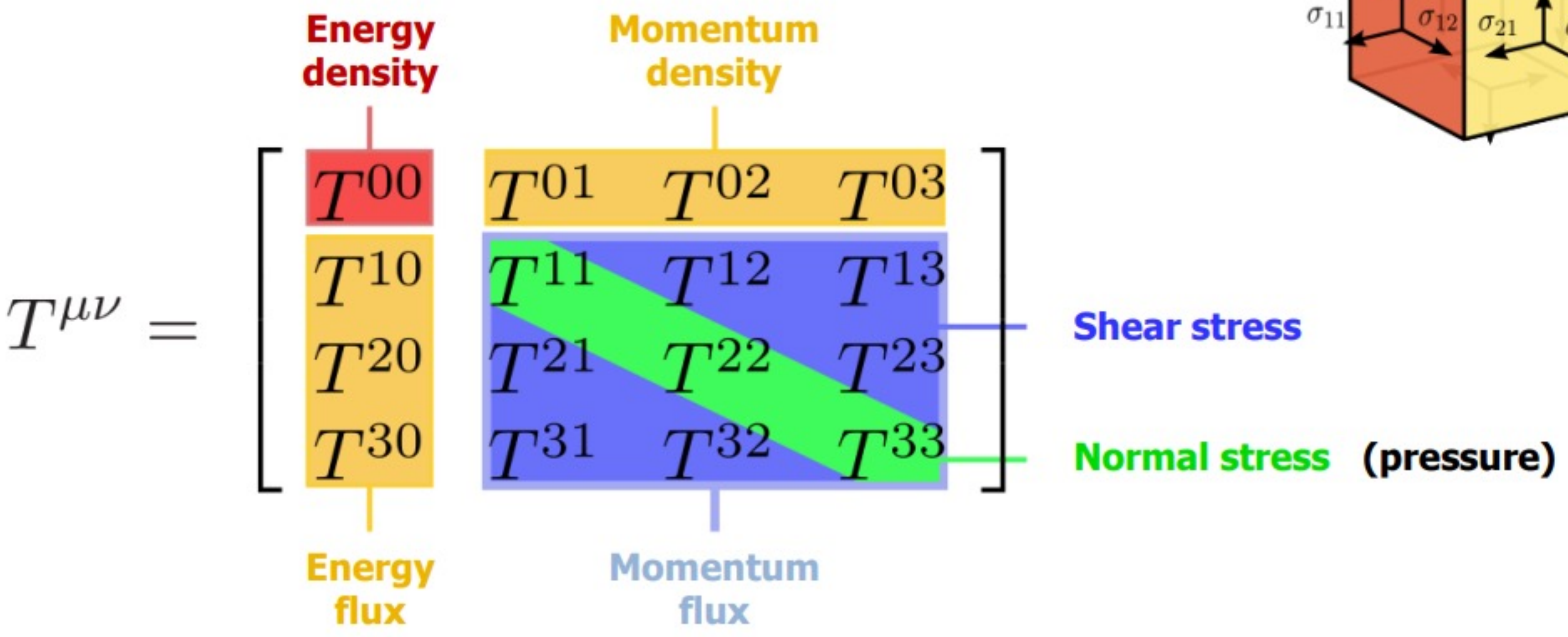


Energy Momentum Tensor

EMT is a key fundamental object.

Mass, spin, and pressure are all encoded in the ETM.





ETM and GPD (GFF)

Gravitational form factors (GFFs) encode information in the ETM

$$\langle p' \,|\, T_i^{\mu\nu} \,|\, p\rangle = \bar{u}(p')\left[A_i(t)\,\frac{P^\mu P^\nu}{M} + D_i(t)\,\frac{\Delta^\mu\Delta^\nu - \Delta^2 g^{\mu\nu}}{4\,M} + J_i(t)\,\frac{P^{\{\mu}i\sigma^{\nu\}\alpha}\Delta_\alpha}{2\,M} + \bar{c}_i(t)\,M\,g^{\mu\nu}\right]u(p)$$

- $A_q(0) + A_g(0) = 1, \quad J(t) = \frac{1}{2}\,[A(t) + B(t)], \quad B_q(0) + B_g(0) = 0,$ and $\bar{c}_q(t) + \bar{c}_g(t) = 0$
- Related to mass and angular momentum distributions, and pressure and shear forces

GFFs are related to GPDs (i = quark, gluons)

$$\int_{-1}^{1} \mathrm{d}x\,[x\,H_i(x,\xi,t), x\,E_i(x,\xi,t)] = [A_i(t) + \xi^2 D_i(t),\; B_i(t) - \xi^2 D_i(t)]$$

Forward limit:

$$\langle p \,|\, T_i^{\mu\nu} \,|\, p\rangle = 2\,[A_i(0)\;p^\mu p^\nu + \bar{c}_i(0)\,M^2\,g^{\mu\nu}]\,, \quad \langle p \,|\, T_{i\,\mu}^{\mu} \,|\, p\rangle = 2\,M^2\,[A_i(0) + 4\,\bar{c}_i(0)]\,, \quad \langle p \,|\, T_\mu^\mu \,|\, p\rangle = 2\,M^2$$

- Any hadron mass decomposition should depend on at most two quantities

ETM from QCD

QCD's Energy-Momentum Tensor (EMT)

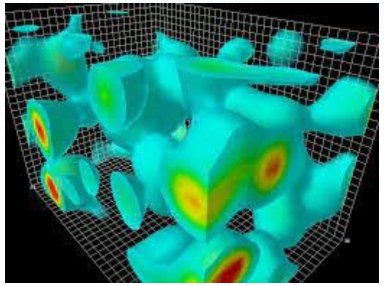
$$T^{\mu\nu} = \frac{1}{2}\overline{\psi}\, iD^{(\mu}\gamma^{\nu)}\,\psi + \frac{1}{4}g^{\mu\nu}\,F^2 - F^{\mu\alpha}F^{\nu}_{\alpha}, \qquad T^{\mu\nu} = T^{\nu\mu}, \qquad \partial_\mu T^{\mu\nu} = 0,$$

In the chiral limit (m → 0) classical EMT is traceless

QCD is scale invariant if EMT is traceless — scale-invariant theories can only have massless states

QCD has a trace anomaly, which breaks scale invariance and is therefore responsible for hadron masses

$$T^{\mu}_{\mu} = m_q\,\overline{\psi}_q\psi_q + \gamma_m\, m_q\,\overline{\psi}_q\psi_q + \frac{\tilde{\beta}(g)}{2g}F^2$$



This trance anomaly gives trace decomposition (ex, Ji's mass decomposition)

$$M = \left.\frac{\langle p|\int d^3x\, T^{00}(0,\mathbf{x})|\,p\rangle}{\langle p|p\rangle}\right|_{\text{at rest}} = \underbrace{M_q + M_g}_{\text{quark \& gluon energies}} + \underbrace{M_m}_{\text{quark mass}} + \underbrace{M_a}_{\text{trace anomaly}}$$

$$M_q = \tfrac{3}{4}(a-b)\,M, \quad M_g = \tfrac{3}{4}(1-a)\,M, \quad M_m = b\,M, \quad M_a = \tfrac{1}{4}(1-b)\,M,$$

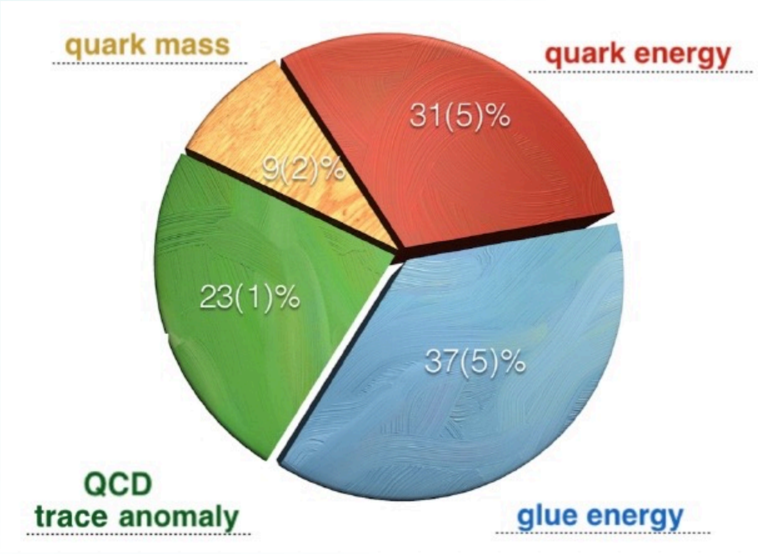
Proton mass decomposition

- **Mass Decomposition**

$$M = \left.\frac{\langle p | \int d^3x\, T^{00}(0,x) | p \rangle}{\langle p | p \rangle}\right|_{\text{at rest}} = \underbrace{M_q + M_g}_{\text{quark \& gluon energies}} + \underbrace{M_m}_{\text{quark mass}} + \underbrace{M_a}_{\text{trace anomaly}}$$

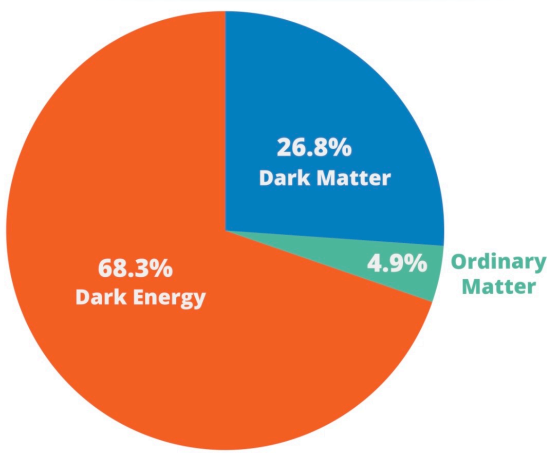
[X.D. Ji, Phys. Rev. Lett. 74, 1071 (1995); X. D. Ji, Phys. Rev. D 52, 271 (1995)]

陽子のエネルギー分解



クォーク ⇔ バリオン
グルーオン　⇔ ダークマター
真空のひずみ ⇔ ダークエネルギー

宇宙のエネルギー分解



初田氏

Proton mass decomposition

????

$$\langle p|T_i^{\mu\nu}|p\rangle = 2\left[A_i(0)\, p^\mu p^\nu + \bar{c}_i(0)\, M^2 g^{\mu\nu}\right], \quad \langle p|T_{i\mu}^{\mu}|p\rangle = 2M^2\left[A_i(0) + 4\,\bar{c}_i(0)\right], \quad \langle p|T_{\mu}^{\mu}|p\rangle = 2M^2$$

- Any hadron mass decomposition should depend on at most two quantities

$$M = \left.\frac{\langle p|\int d^3x\, T^{00}(0,\boldsymbol{x})|p\rangle}{\langle p|p\rangle}\right|_{\text{at rest}} = \underbrace{M_q + M_g}_{\text{quark \& gluon energies}} + \underbrace{M_m}_{\text{quark mass}} + \underbrace{M_a}_{\text{trace anomaly}}$$

K. Tanaka@EIC workshop,本郷

https://indico3.cns.s.u-tokyo.ac.jp/event/315/contributions/2724/attachments/945/1627/utokyo24_05_29_tanaka.pdf

$$M = \underset{0.4}{M_q} + \underset{0.6}{M_g}$$

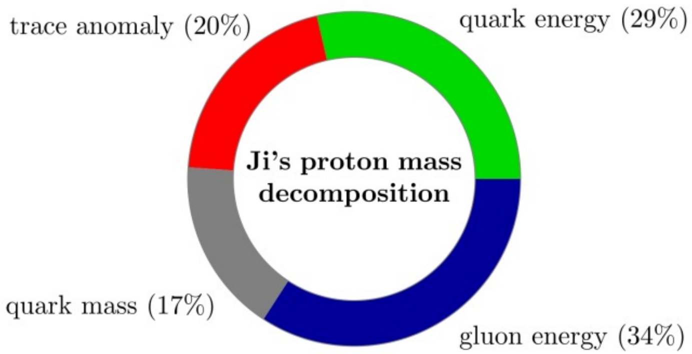
$$M_{q,g} = \left(\underset{0.6,\ 0.4}{A_{q,g}(0)} + \underset{-0.2,\ 0.2}{\bar{C}_{q,g}(0)}\right) M$$

$$M = \left(\underset{0.3}{M_q - M_m}\right) + \underset{0.1}{M_m} + \underset{0.6}{M_g}$$

$$\underset{0.1}{M_m} = \left\langle \int d^3x\, m\bar{\psi}\psi \right\rangle = \frac{\sigma_{\pi N} + \sigma_s}{M} M$$

$$M = \left(\underset{0.3}{M_q - M_m - \Delta M_q}\right) + \underset{0.1}{M_m} + \left(\underset{0.4}{M_g - \Delta M_g}\right) + \left(\underset{0.2}{\Delta M_q + \Delta M_g}\right)$$

$$\underset{0.2}{\Delta M_q + \Delta M_g} = \frac{1}{4}\left\langle \int d^3x \left(\frac{\beta(g)}{2g} F^2 + \gamma_m(g)\, m\bar{\psi}\psi\right)\right\rangle = \frac{1}{4}\left(M - M_m\right)$$



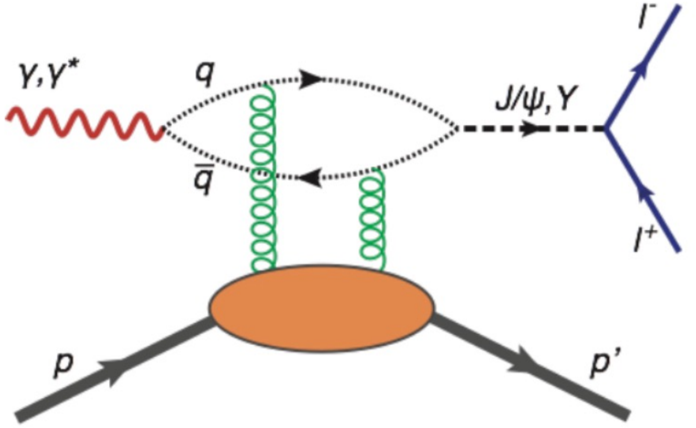
Proton mass decomposition

$$M = \frac{\langle p | \int d^3x \, T^{00}(0,x) | p \rangle}{\langle p | p \rangle}\Bigg|_{\text{at rest}} = \underbrace{\underbrace{M_q}_{} + \underbrace{M_g}_{}}_{\text{quark \& gluon energies}} + \underbrace{M_m}_{\text{quark mass}} + \underbrace{M_a}_{\text{trace anomaly}}$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M, \quad M_g = \frac{3}{4}(1-a)\, M,$$

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)}\, b\, M, \quad M_a = \frac{1}{4}(1-b)\, M$$

a = quark momentum fraction, b = QCD trace anomaly parameter

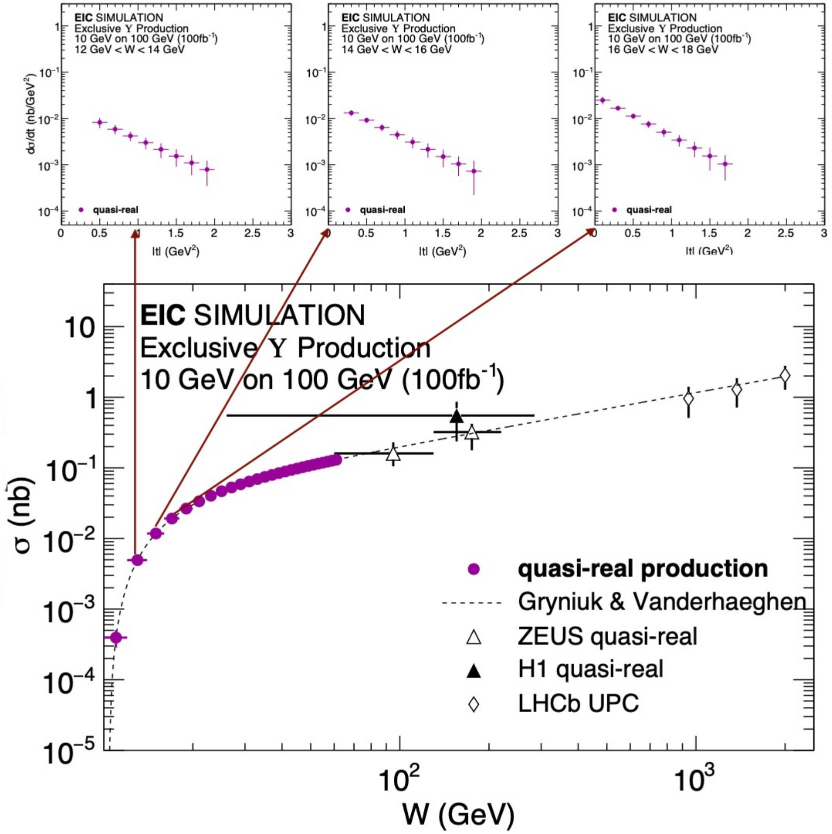


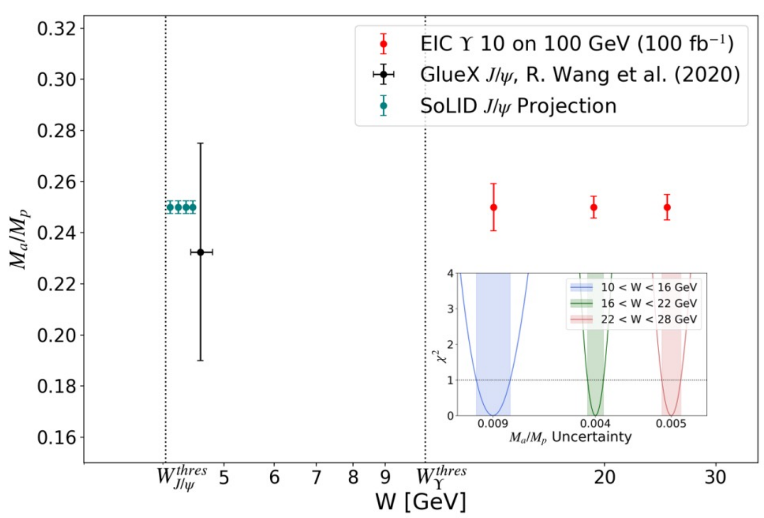
$$\frac{d\sigma_{J/\Psi N \to J/\Psi N}}{dt}\Bigg|_{t=0} = \frac{1}{64\pi} \frac{1}{m_{J/\Psi}^2(\lambda^2 - m_N^2)} |F_{J/\Psi N}|^2$$

$$F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N \middle| \sum_{i=u,d,s} m_i \bar{q}_i q_i \middle| N \right\rangle\right)$$

$$\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right)$$

$$\simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2(1-b).$$





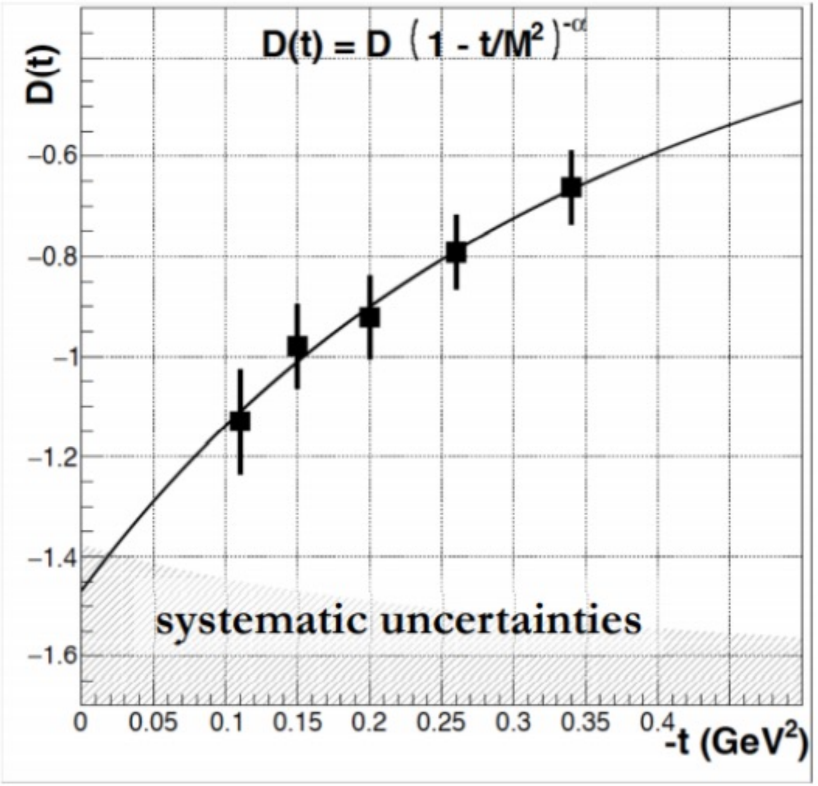
Pressure

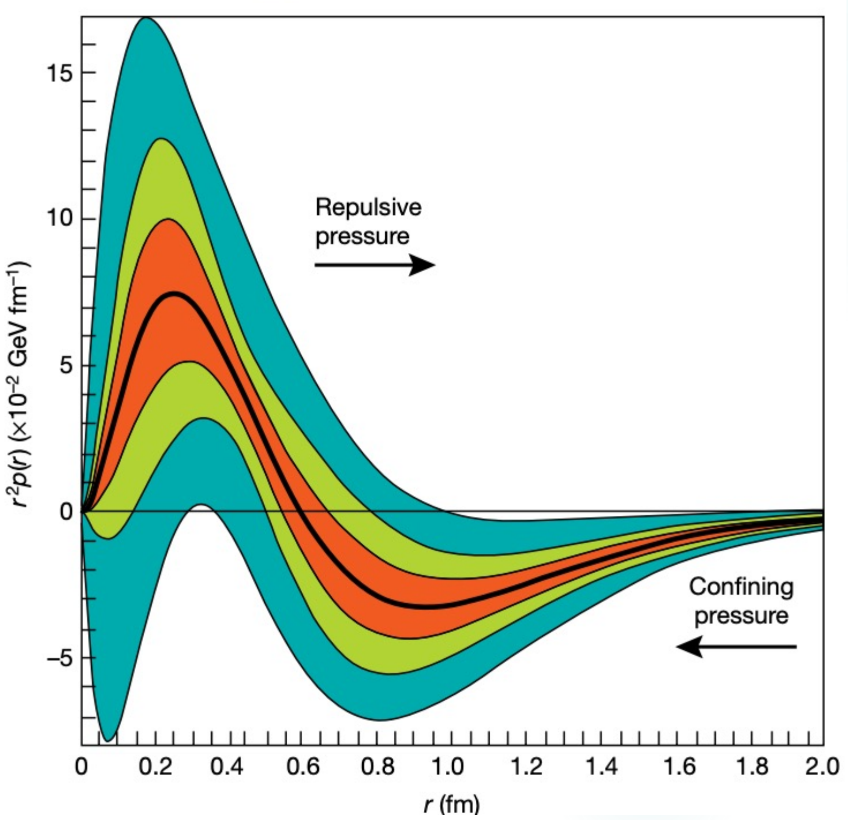
$$\langle p' \,|\, T_i^{\mu\nu} \,|\, p\rangle = \bar{u}(p')\left[A_i(t)\,\frac{P^\mu P^\nu}{M} + D_i(t)\,\frac{\Delta^\mu \Delta^\nu - \Delta^2 g^{\mu\nu}}{4\,M} + J_i(t)\,\frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_\alpha}{2\,M} + \bar{c}_i(t)\,M\,g^{\mu\nu}\right] u(p)$$

$$\int_{-1}^{1} \mathrm{d}x\,[x\,H_i(x,\xi,t), x\,E_i(x,\xi,t)] = [A_i(t) + \xi^2 D_i(t),\;\; B_i(t) - \xi^2 D_i(t)]$$

DVCS from JLab *Nature* **volume 557**, pages396–399 (2018)

$$p(r) = \int_0^\infty d\sqrt{-t}\sqrt{-t}J_0(r\sqrt{-t})d(t).$$





Pressure

Phys. Rev. Lett. **122**, 072003

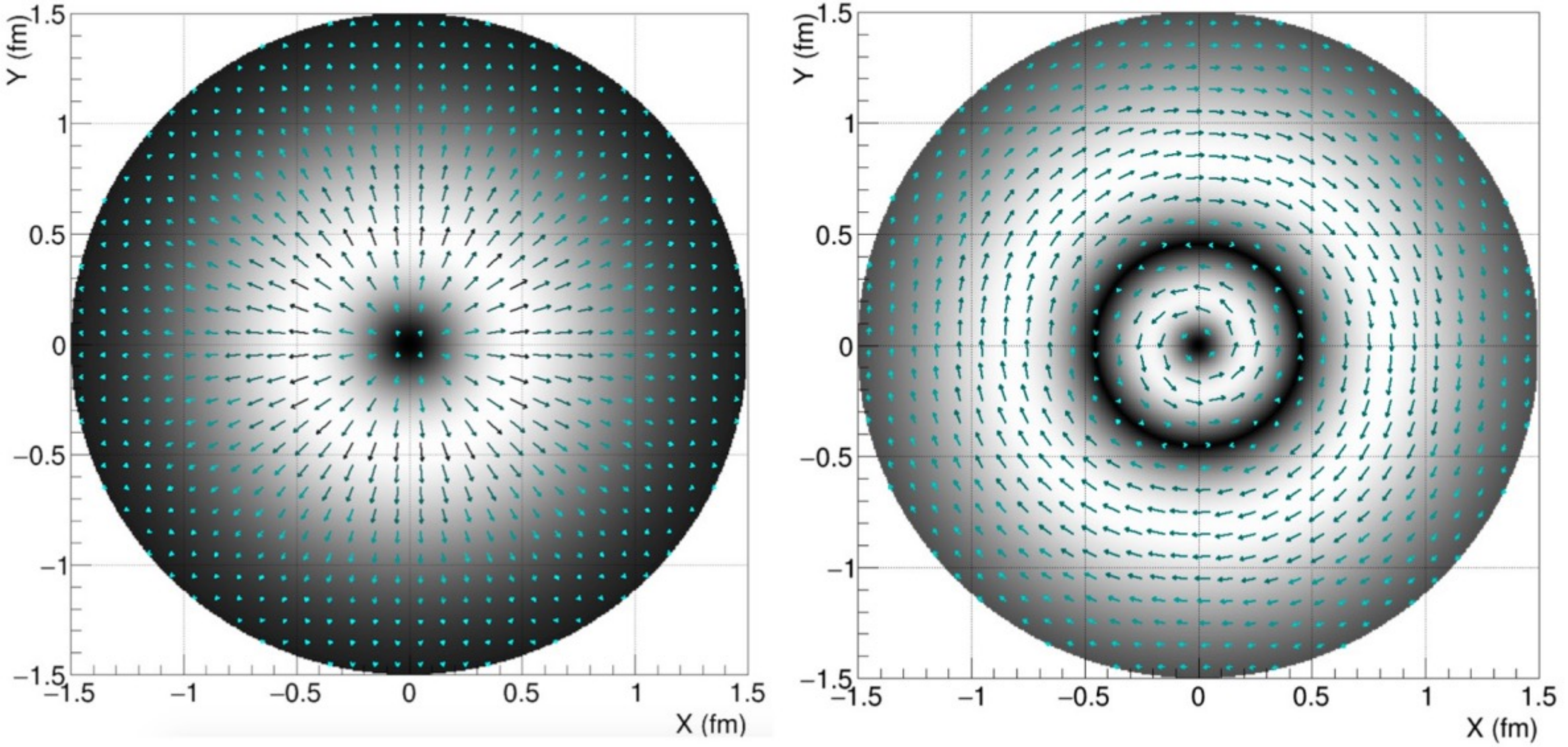
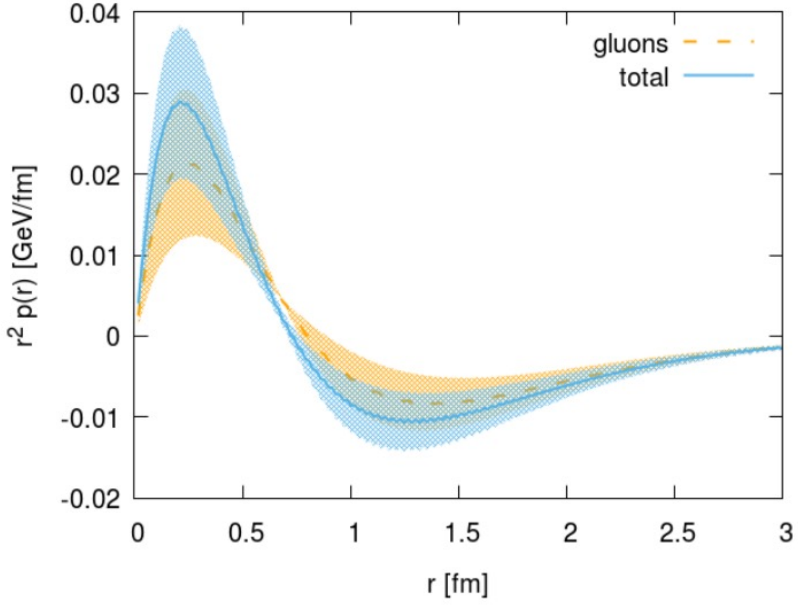
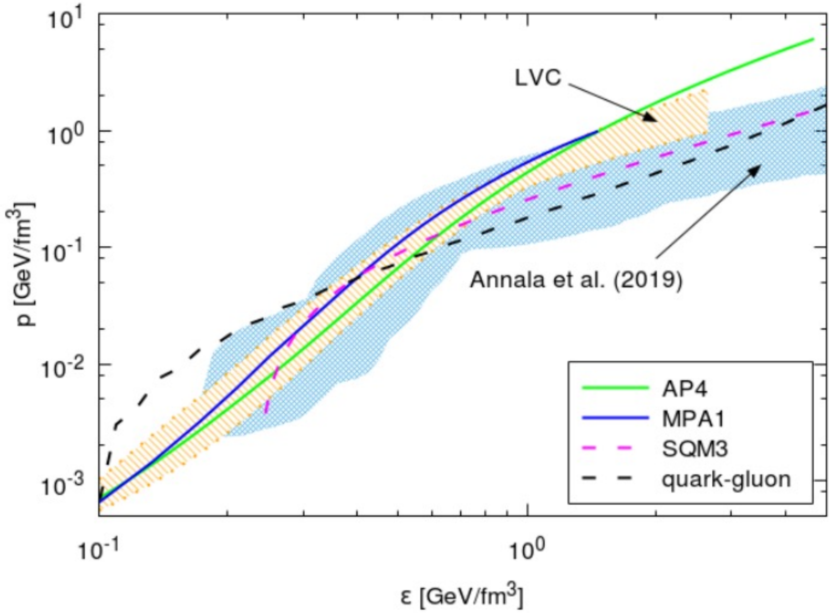


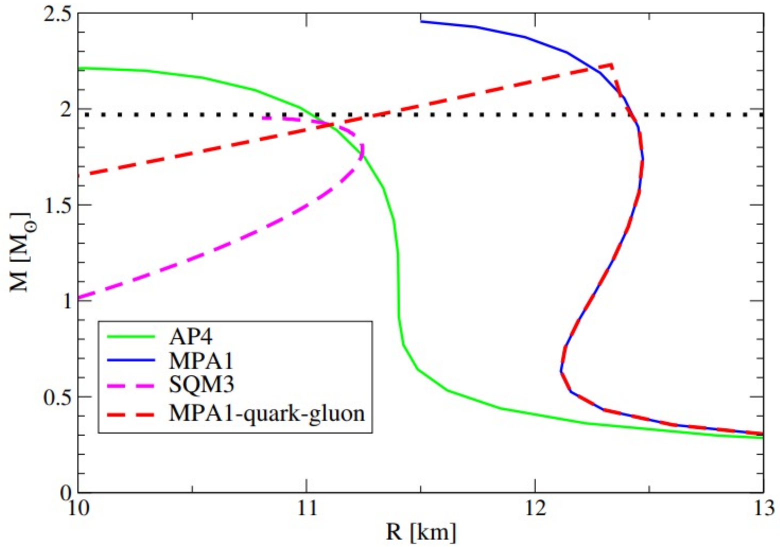
FIG. 14 2D display of the quark contribution to the distribution of forces in the proton as a function of the distance from the proton's center (Burkert et al., 2021b). The light gray shading and longer arrows indicate areas of stronger forces, the dark shading and shorter arrows indicate areas of weaker forces. Left panel: Normal forces as a function of distance from the center. The arrows change magnitude and point always radially outwards. Right panel: Tangential forces as a function of distance from the center. The forces change direction and magnitude as indicated by the direction and lengths of the arrows. They change sign near 0.4 fm from the proton center.

EoS for neutron star

https://arxiv.org/pdf/1812.01479







$$\varepsilon_{q,g}(r) = \int \frac{d^2\boldsymbol{\Delta}_T}{(2\pi)^2} e^{i\boldsymbol{\Delta}_T\cdot\mathbf{b}} A_2^{q,g}(t),$$

$$p_{q,g}(r) = \int \frac{d^2\boldsymbol{\Delta}_T}{(2\pi)^2} e^{i\boldsymbol{\Delta}_T\cdot\mathbf{b}} \frac{t}{M^2} \underline{C_2^{q,g}(t)}.$$

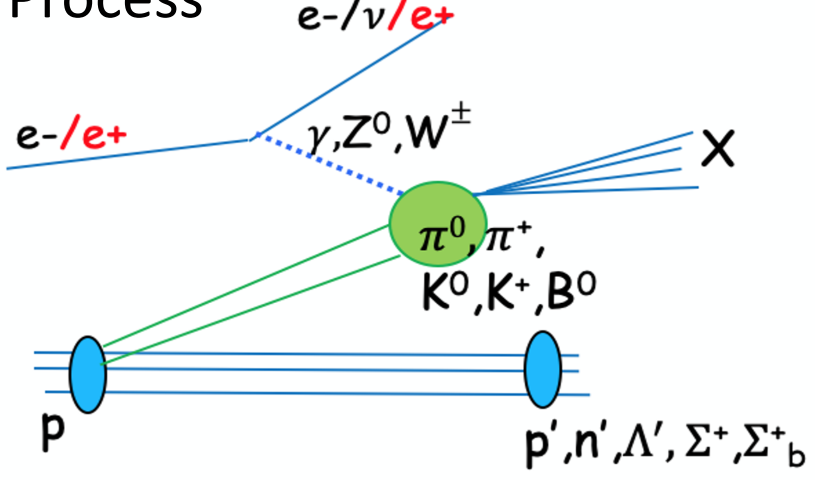
D(t)

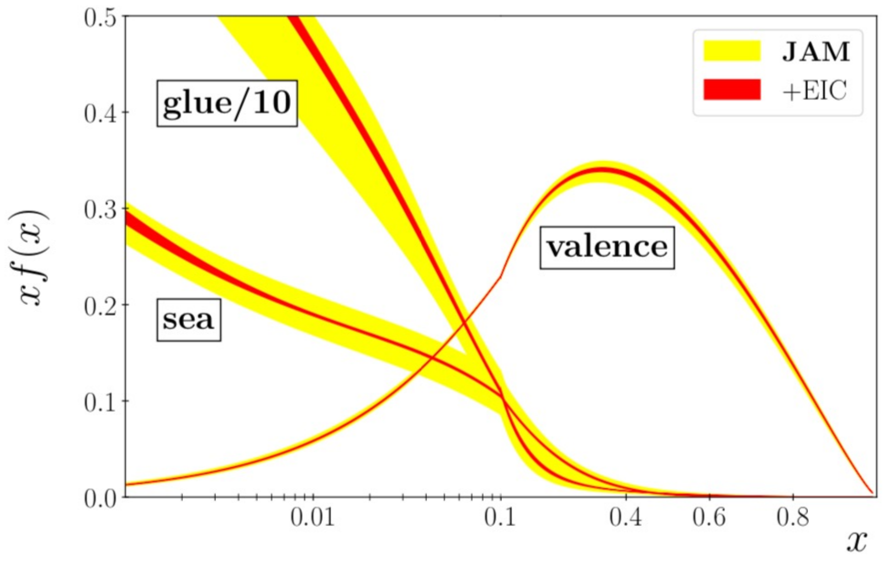
Our main result is that the EoS obtained from the EMT is dominated by the gluon contribution, the quark contribution being largely suppressed

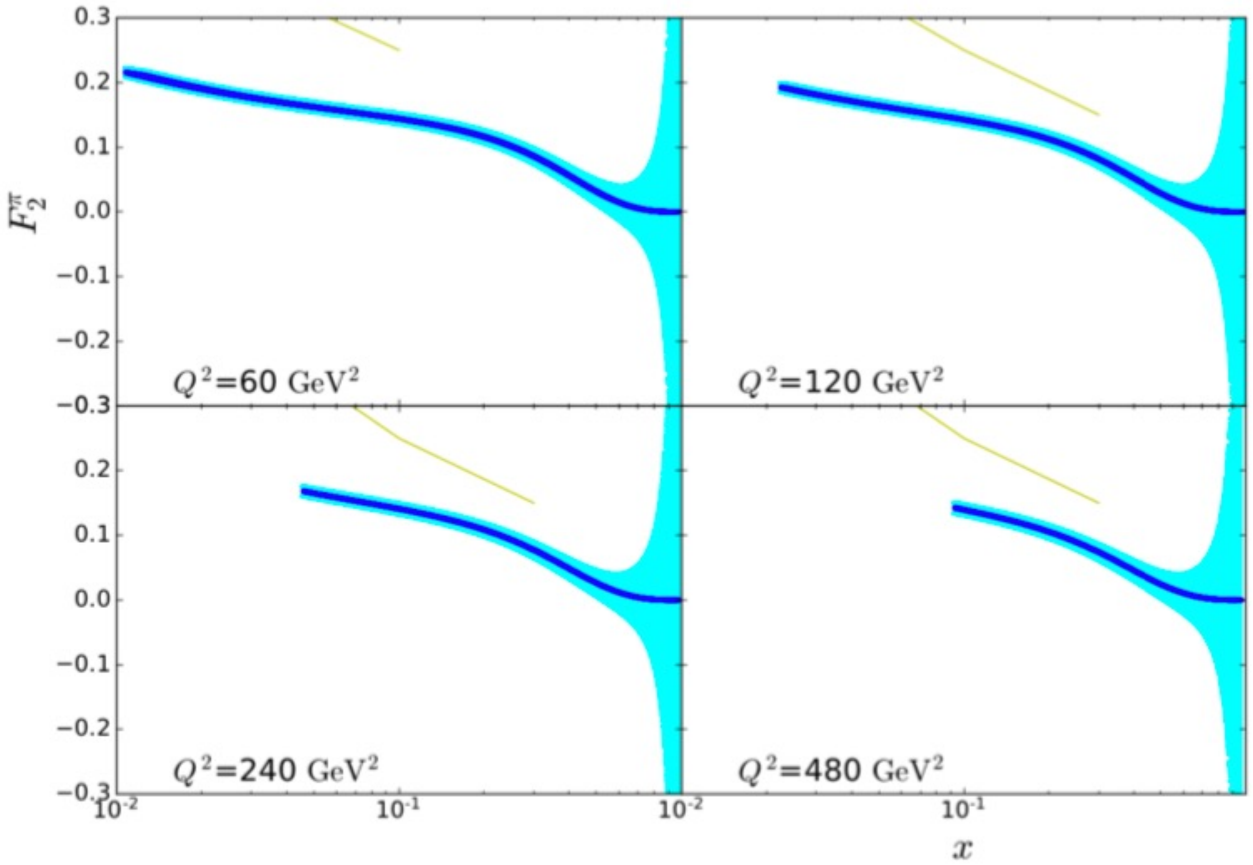
the EoS of dense matter in QCD can be obtained from first principles, using ab initio calculations for both quark and gluon degrees of freedom. Gluons, in particular, dominate the EoS, and provide a trend in the high density regime which is consistent with the constraint from LIGO

Pion and Kaon structure

Sullivan Process

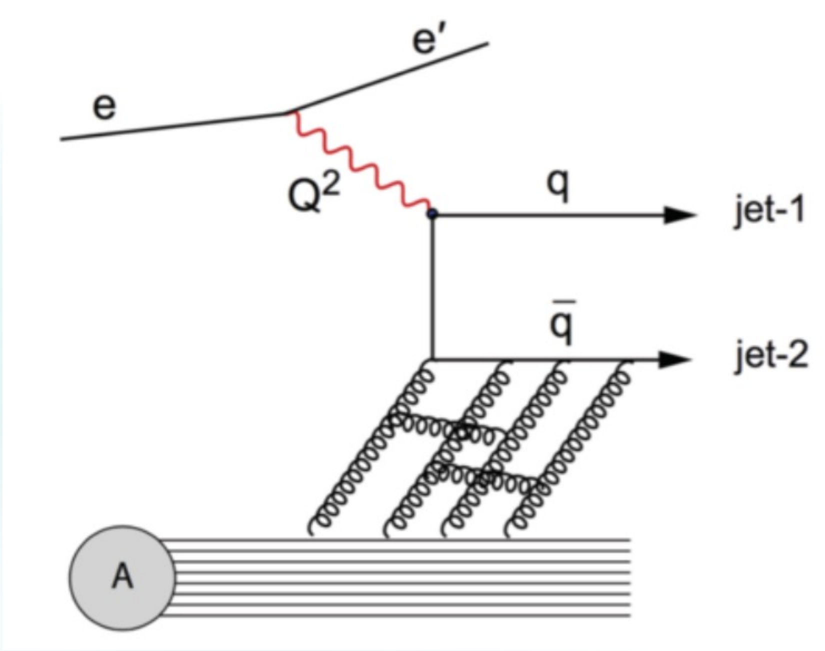


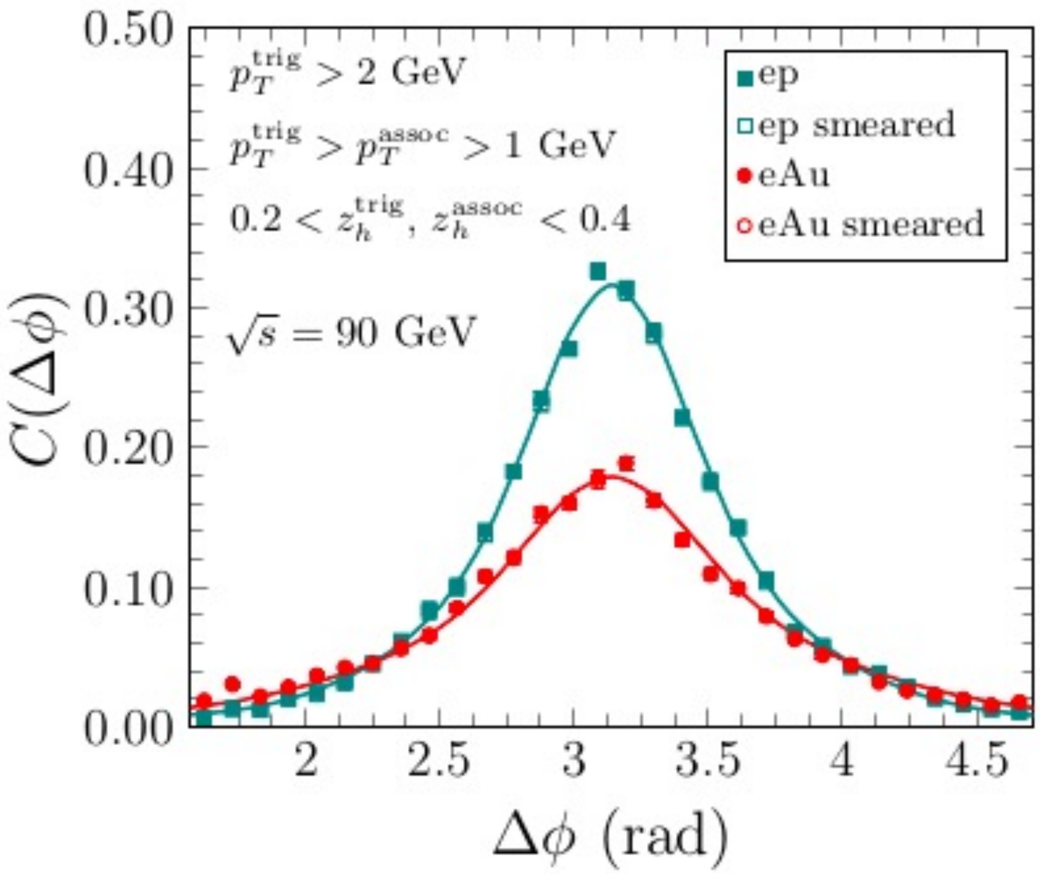




Gluon Saturation

Measure back-to-back hadron(jet) - hadron or hadron(jet) - photon correlations
Suppression of away peak as indication for saturation





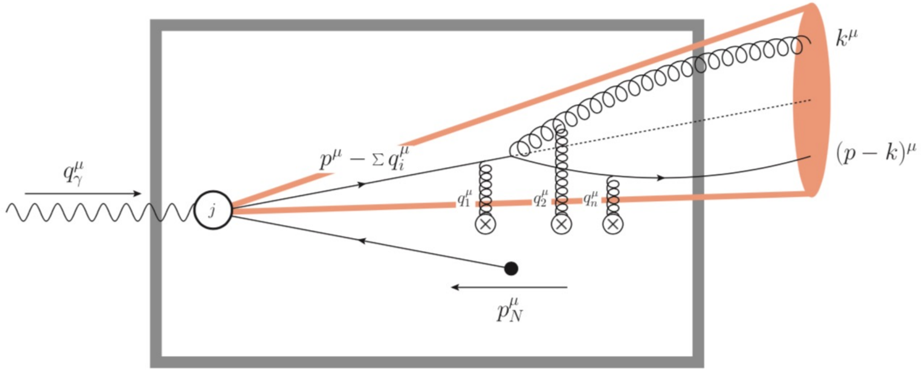
Other signatures: vector meson production in diffractive processes.

Energy loss in gluon matter

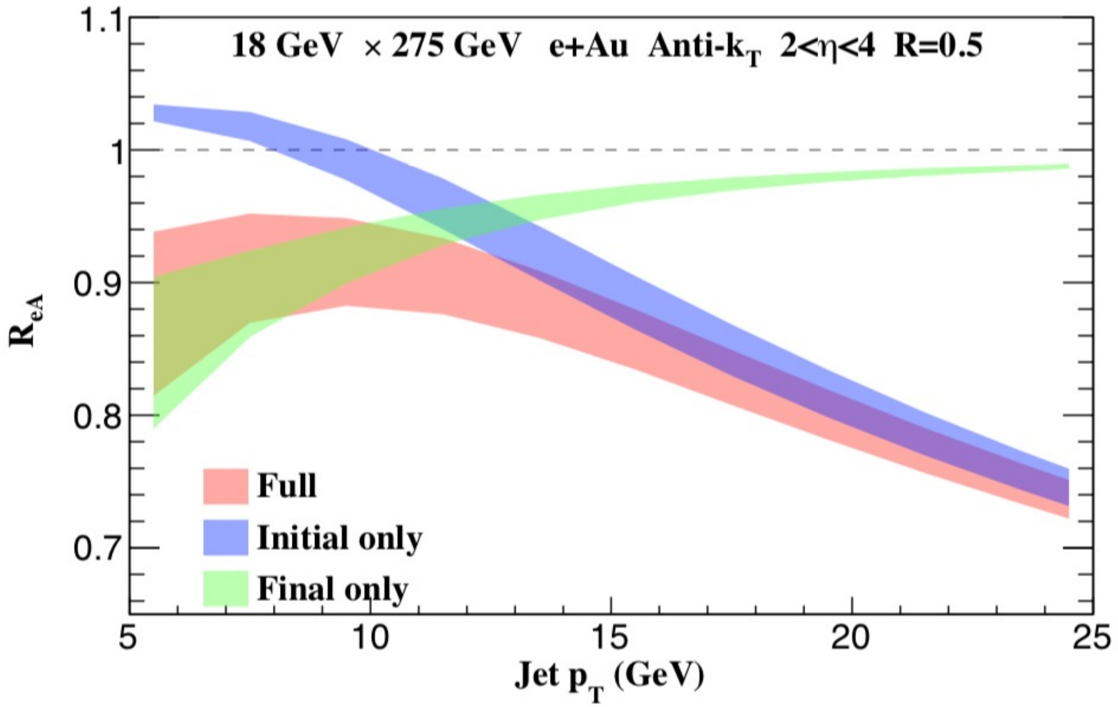
Particle propagation through matter and transport properties of nuclei

Parton showers and energy loss in cold nuclear matter

$\hat{q}$ ~ 0.02 – 0.14 GeV^2/fm



$$R_{eA}(R) = \frac{1}{A} \frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+p}} .$$



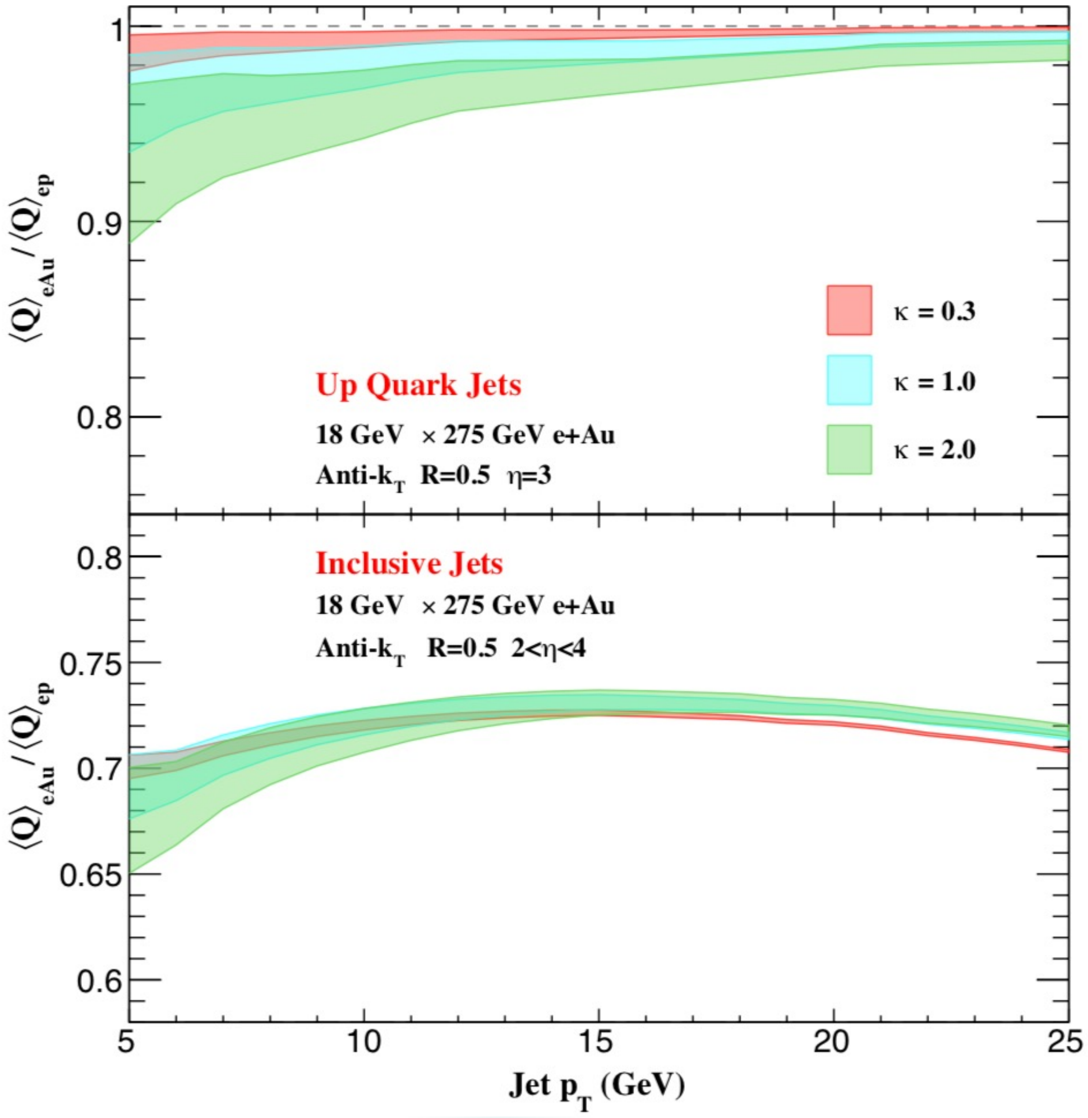
Energy loss in gluon matter

Particle propagation through matter and transport properties of nuclei

Parton showers and energy loss in cold nuclear matter

$\hat{q}$ ~ 0.02 – 0.14 GeV²/fm

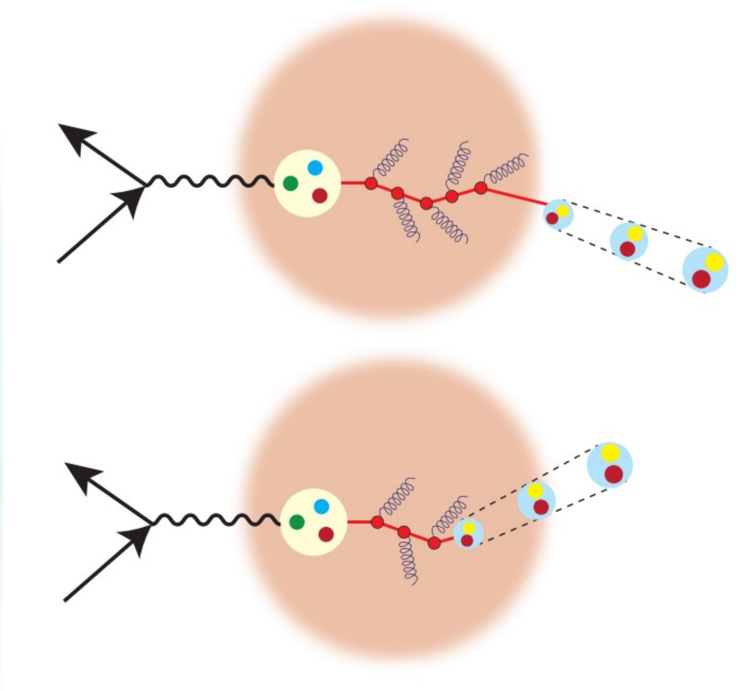
$$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^{\kappa}} \sum_{i\in\text{jet}} Q_i \left(p_T^i\right)^{\kappa}, \quad \kappa > 0$$



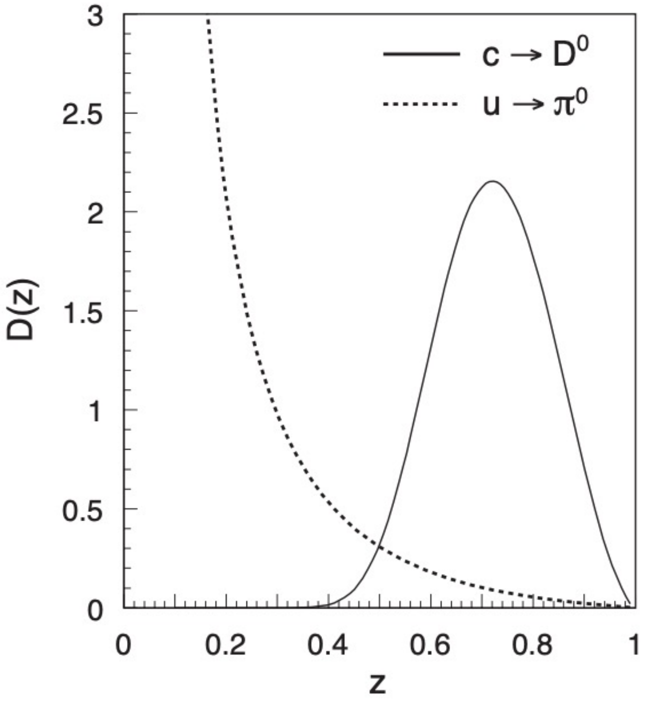
Hadronization

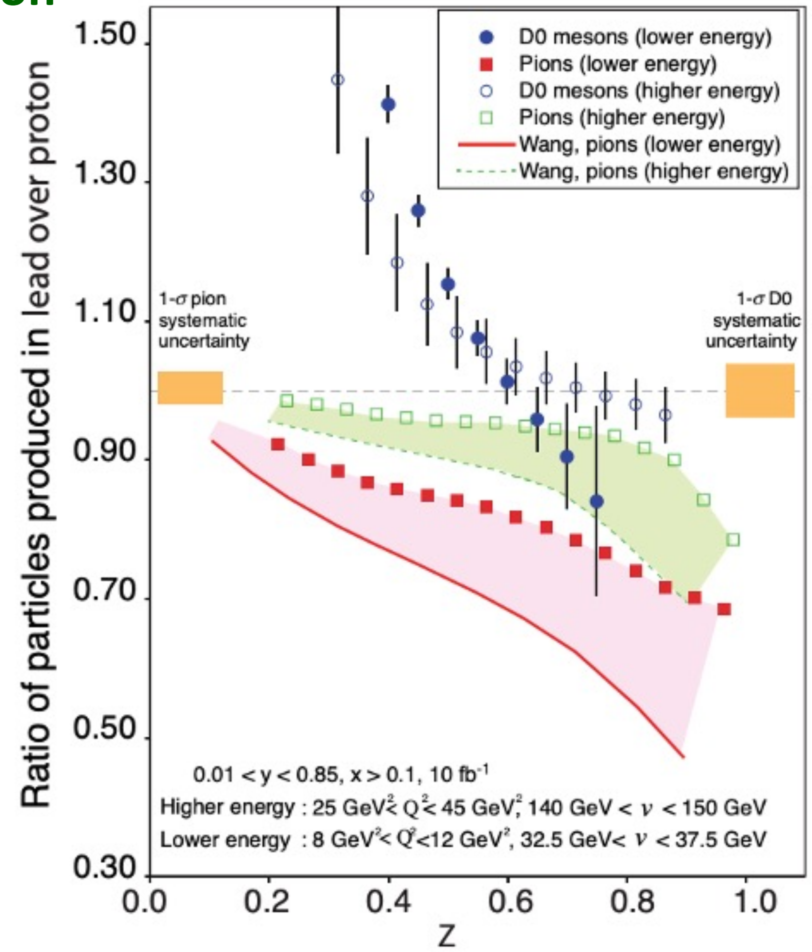
How Hadrons are Emerged from Quarks and Gluons?

Ions as femtometer sized detectors



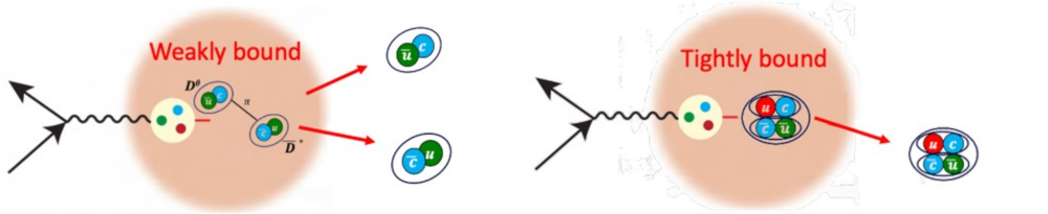
Mass dependence of hadronization





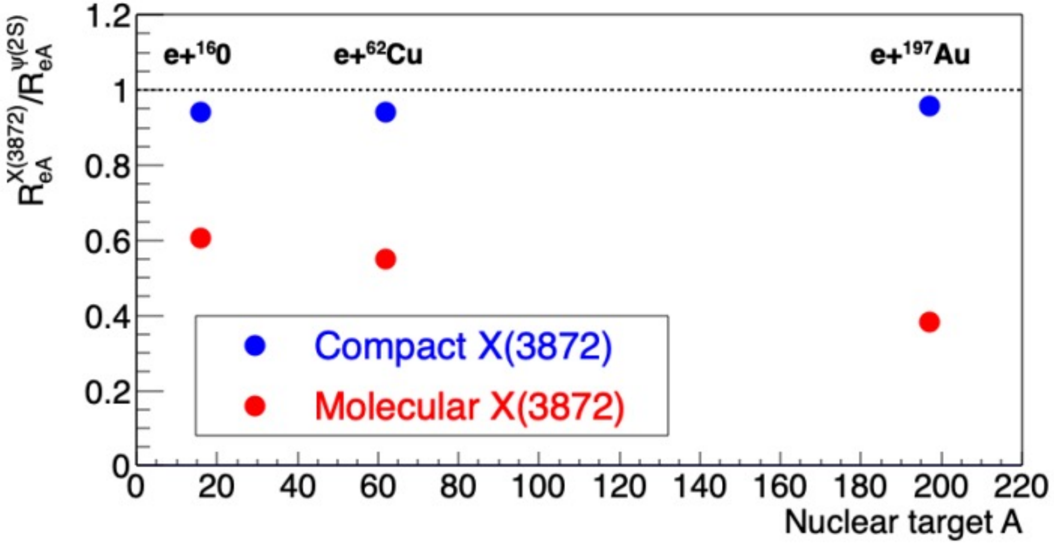
Well controlled hard-scattering kinematics and well known final state
Able to go from production inside medium (low-energy) to production outside of medium (high energy)
Topics of momentum broadening and color transparency can also be explored

Exotic hadrons



Weakly bound hadronic molecule has large radius, samples large volume of nucleus

Tightly bound compact tetraquark has small radius, could more easily escape nucleus unscathed



Use eA collisions – nucleus as a filter to differentiate between tightly bound (quark) and molecular states

TABLE II: Integrated cross sections (in units of pb) for $l + p \to$ HM+all, where HM = $X(3872)$, $Z_c(3900)^{0/+}$, $Z_c(4020)$, and seven P_c states. The listed quantum numbers for these

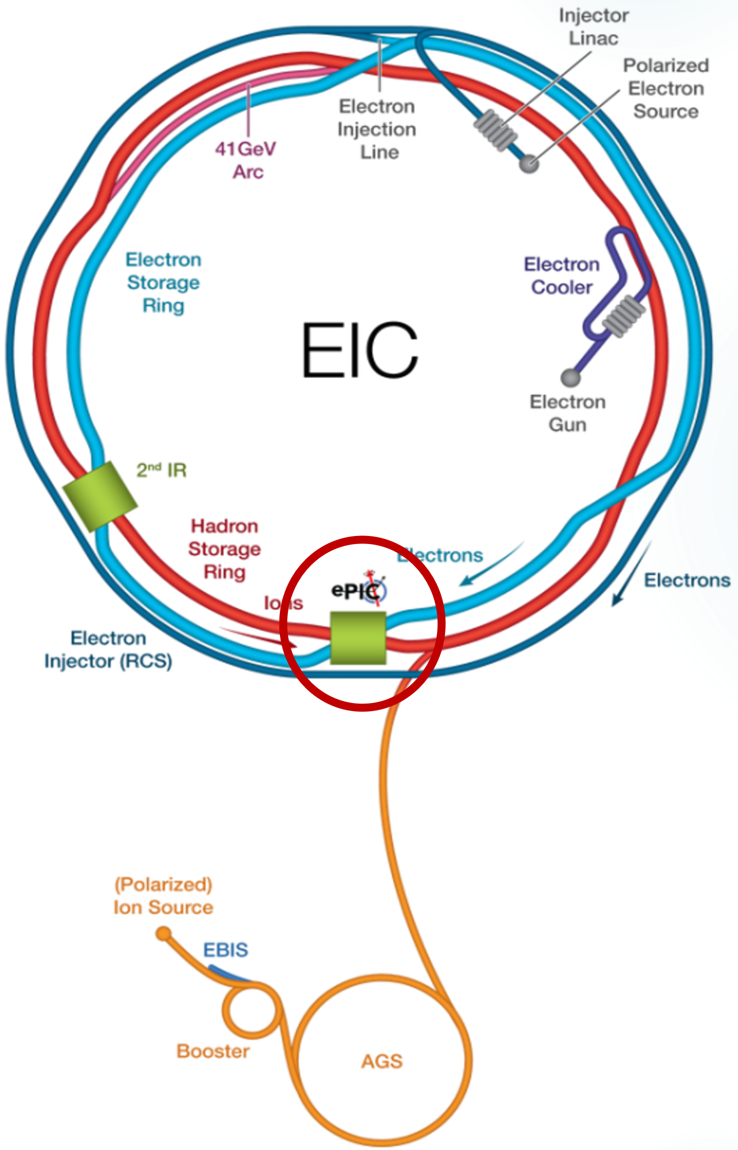
	Constituents	$J^{P(C)}$	COMPASS	EicC	US-EIC
$X(3872)$	$D\bar{D}^*$	1^{++}	19(78)	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	$0.3\times10^3(1.2\times10^3)$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	1^{+}	$0.2\times10^3(0.9\times10^3)$	$0.3\times10^3(1.0\times10^3)$	$2.7\times10^3(9.9\times10^3)$
$Z_c(4020)^0$	$D^*\bar{D}^*$	1^{+-}	$0.1\times10^3(0.5\times10^3)$	$0.2\times10^3(0.6\times10^3)$	$1.7\times10^3(6.3\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	1^{+}	8.3(29)	19(69)	253(901)
Z_{cs}^{*-}	$D^{*0}D_s^{*-}$	1^{+}	6.2(22)	14(51)	192(679)
$P_c(4312)$	$\Sigma_c\bar{D}$	$\frac{1}{2}^-$	0.8(4.1)	0.8(4.1)	15(73)
$P_c(4440)$	$\Sigma_c\bar{D}^*$	$\frac{3}{2}^-$	0.6(4.3)	0.7(4.7)	11(79)
$P_c(4457)$	$\Sigma_c\bar{D}^*$	$\frac{1}{2}^-$	0.5(2.0)	0.6(2.2)	9.9(36)
$P_c(4380)$	$\Sigma_c^*\bar{D}$	$\frac{3}{2}^-$	1.6(8.0)	1.6(8.4)	30(155)
$P_c(4524)$	$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}^-$	0.8(3.6)	0.8(3.9)	14(67)
$P_c(4518)$	$\Sigma_c^*\bar{D}^*$	$\frac{3}{2}^-$	1.2(6.6)	1.2(6.9)	22(123)
$P_c(4498)$	$\Sigma_c^*\bar{D}^*$	$\frac{5}{2}^-$	1.1(9.3)	1.2(9.8)	21(173)

+ Charm and bottom hypernuclei (arXiv:2211.15746) $^{A}Z(e,e'D^-)^{A}_{\Lambda_c^+}Z$

There will be around X(3872) 4 × 10^5 events produced per day at US-EIC.
The branching fractions B(X(3872) → J/ψππ) = (3.8 ± 1.2)%, B(J/ψ → l +l −) = 12% and assuming the detection efficiency to be 50%, then the reconstructed event numbers will be about 1000 per day for US-EIC.

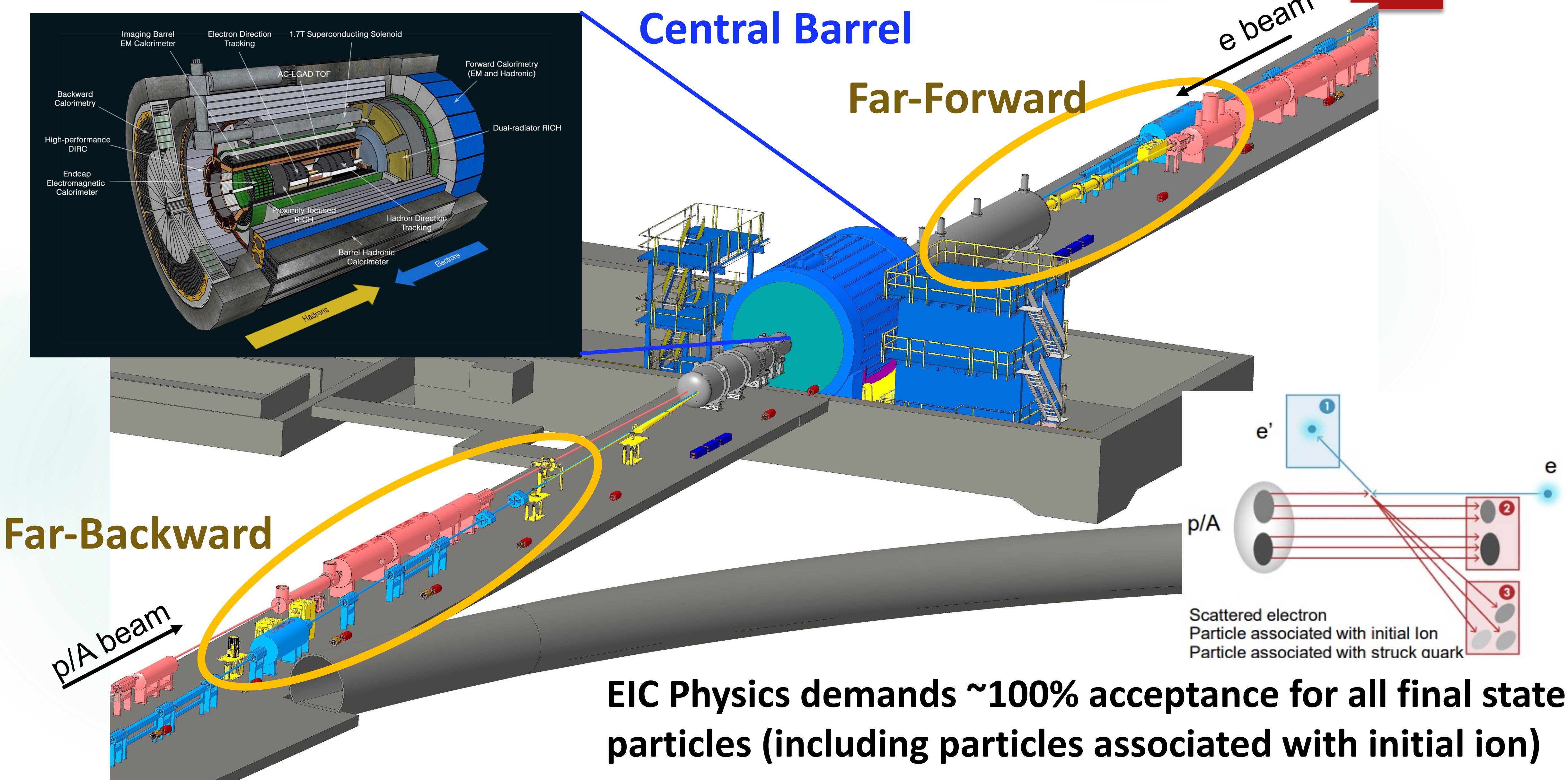
arXiv:2107.12247

Experiment



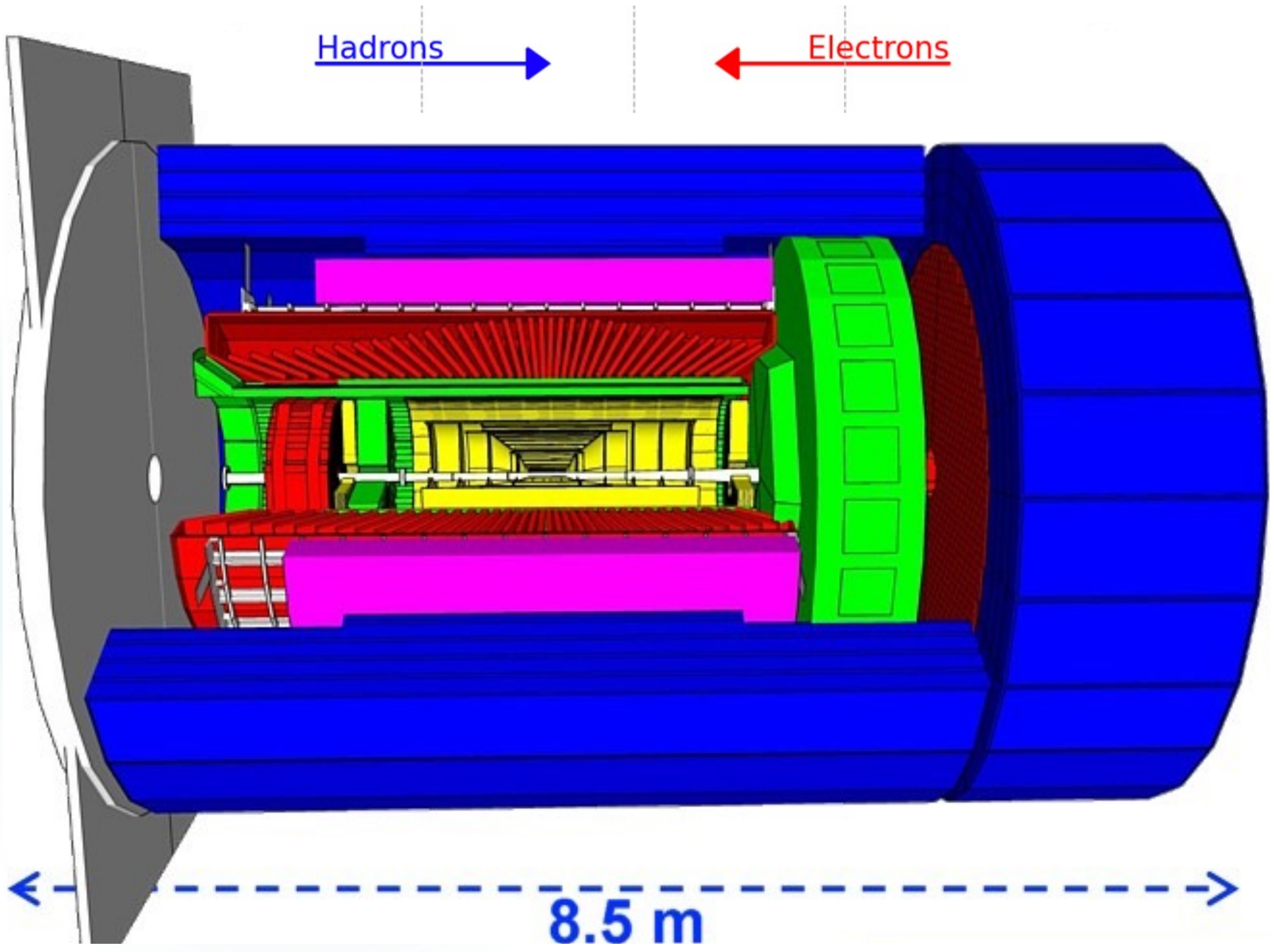
Injector Linac
Polarized Electron Source
Electron Injection Line
41GeV Arc
Electron Storage Ring
EIC
Electron Cooler
Electron Gun
2nd IR
Hadron Storage Ring
Electrons
Electrons
ePIC
Electron Injector (RCS)
(Polarized) Ion Source
EBIS
Booster
AGS

ePIC experiment



EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

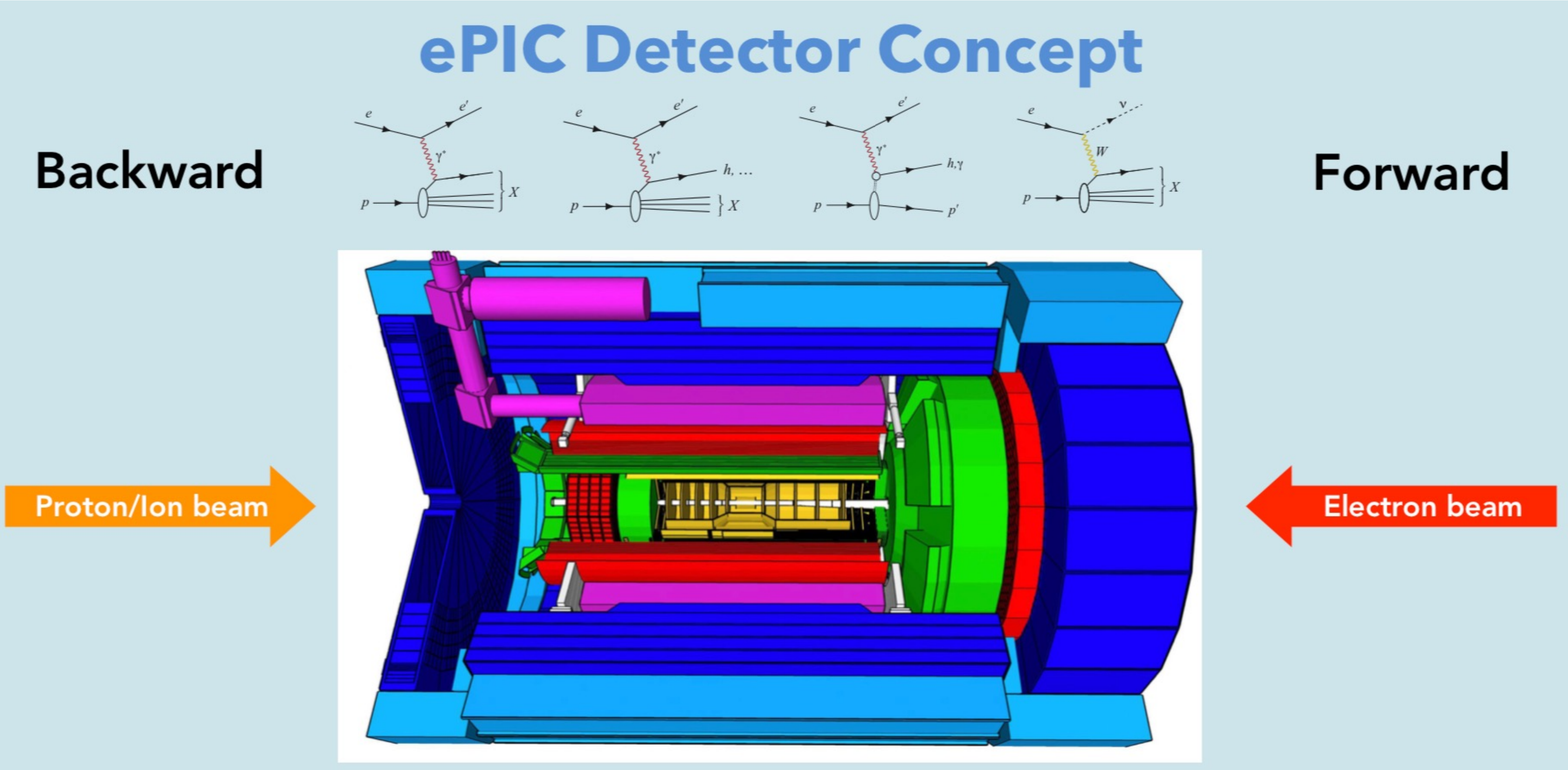
ePIC experiment



- hadronic calorimeters
- e/m calorimeters
- ToF, DIRC, RICH detectors
- MPG & MAPS trackers
- solenoid coils

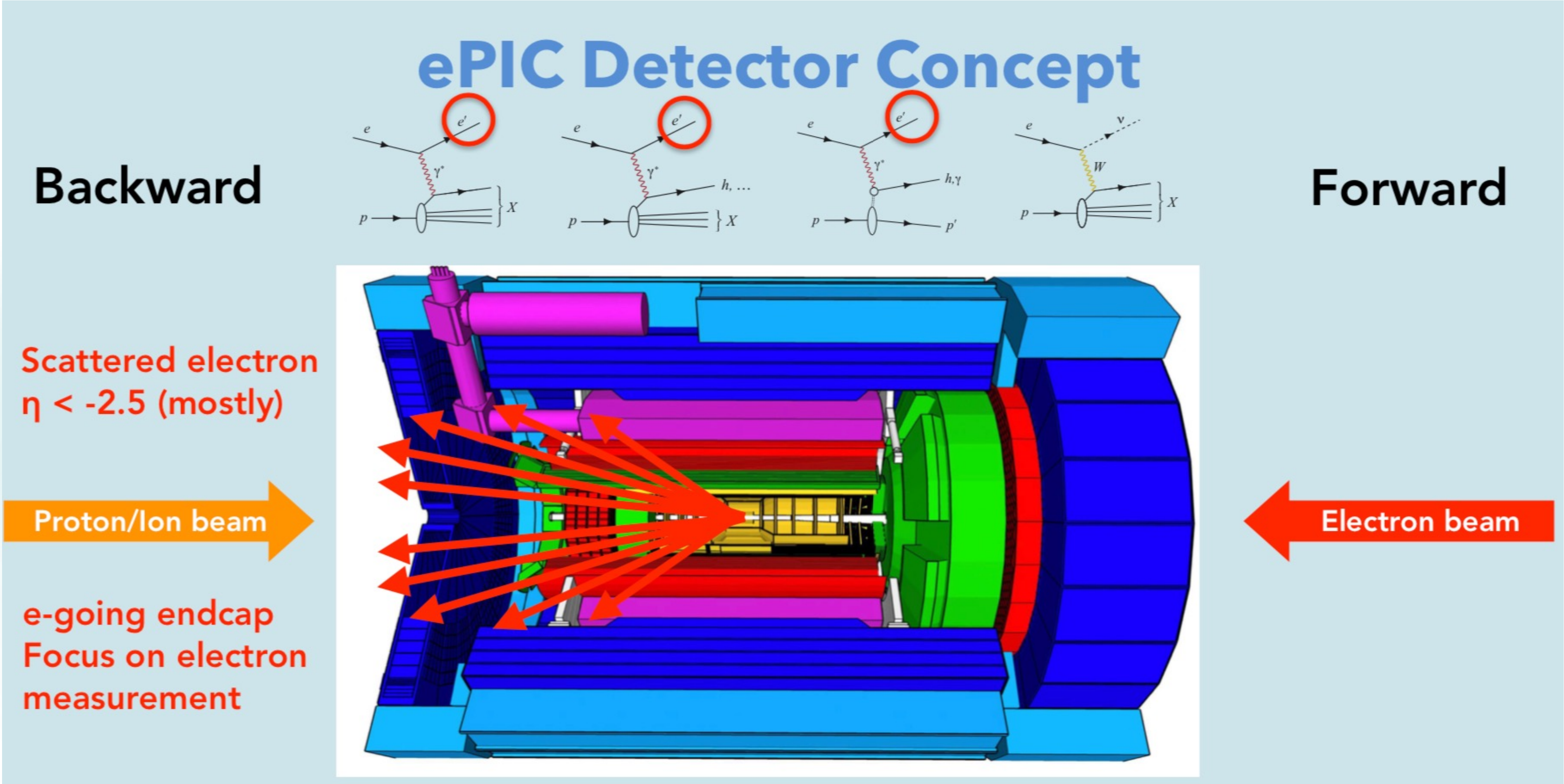
ePIC experiment

八野さんのスライドより(EIC研究会)



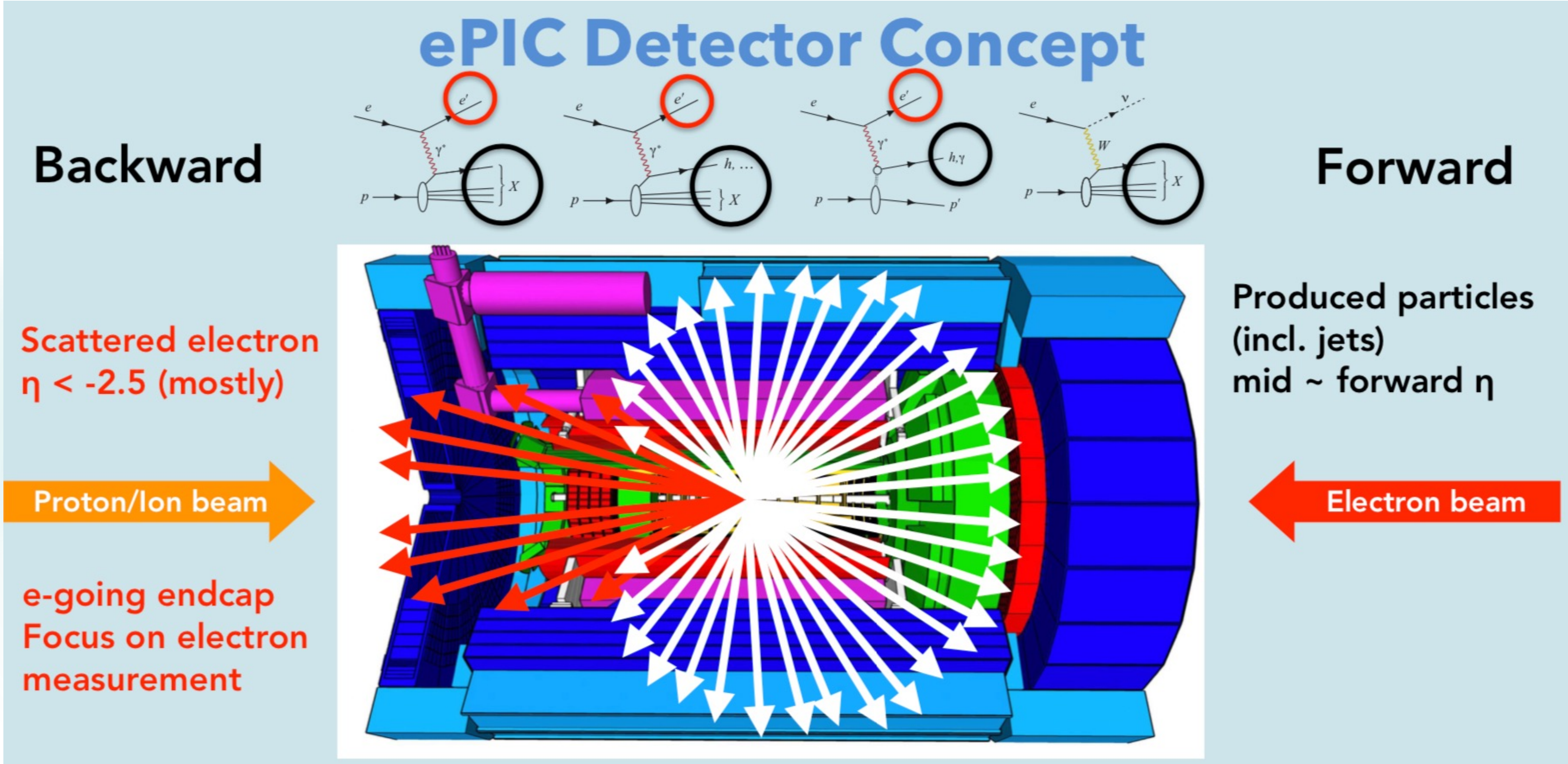
ePIC experiment

八野さんのスライドより(EIC研究会)



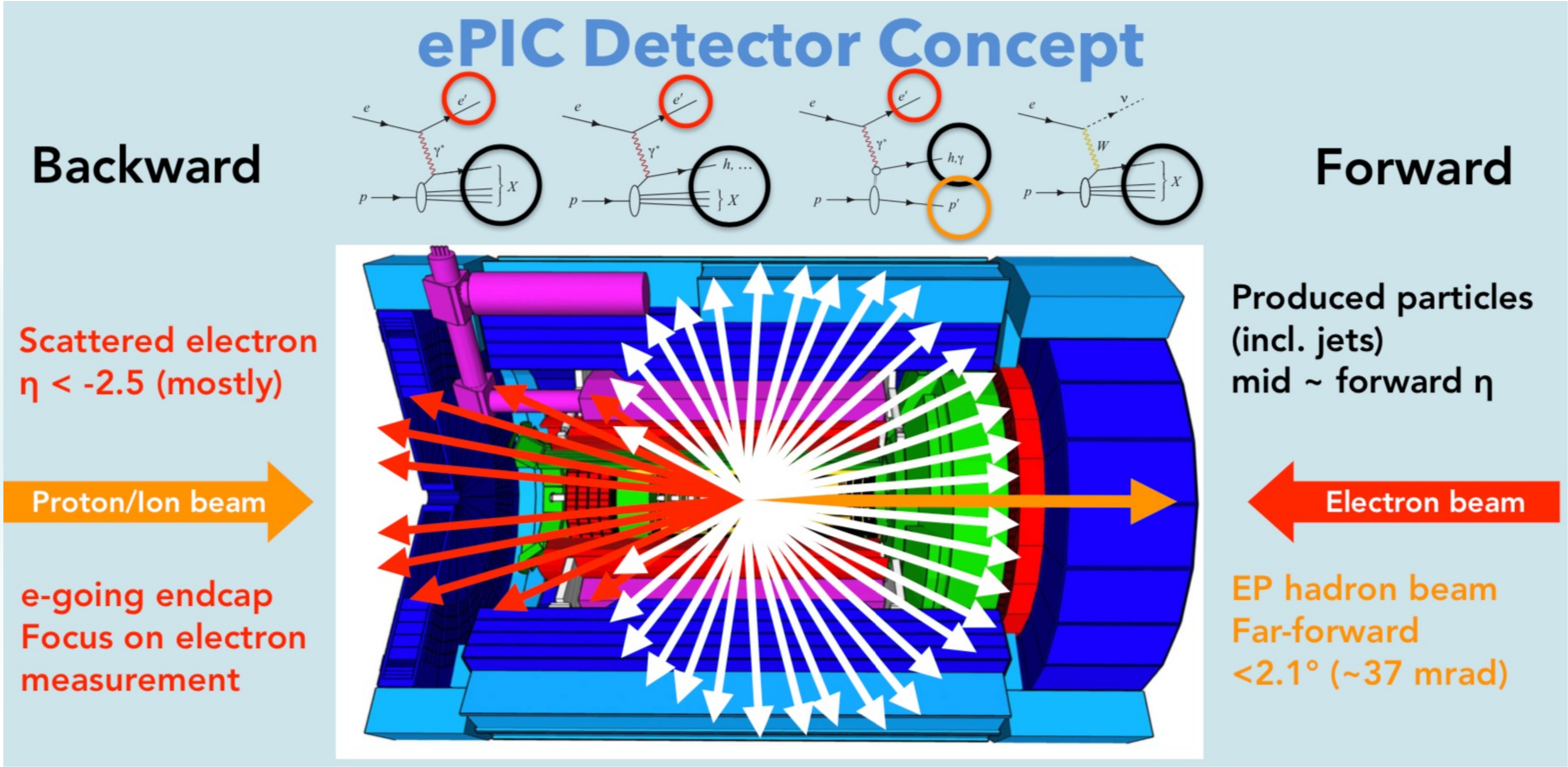
ePIC experiment

八野さんのスライドより(EIC研究会)



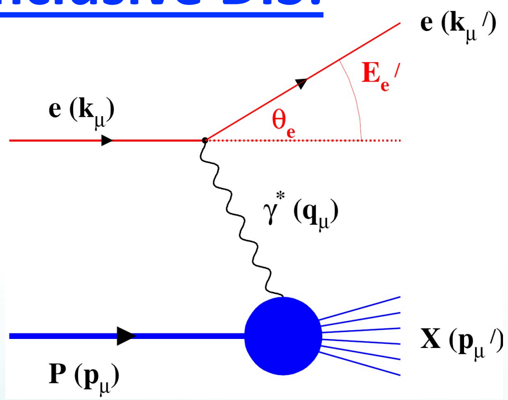
ePIC experiment

八野さんのスライドより(EIC研究会)

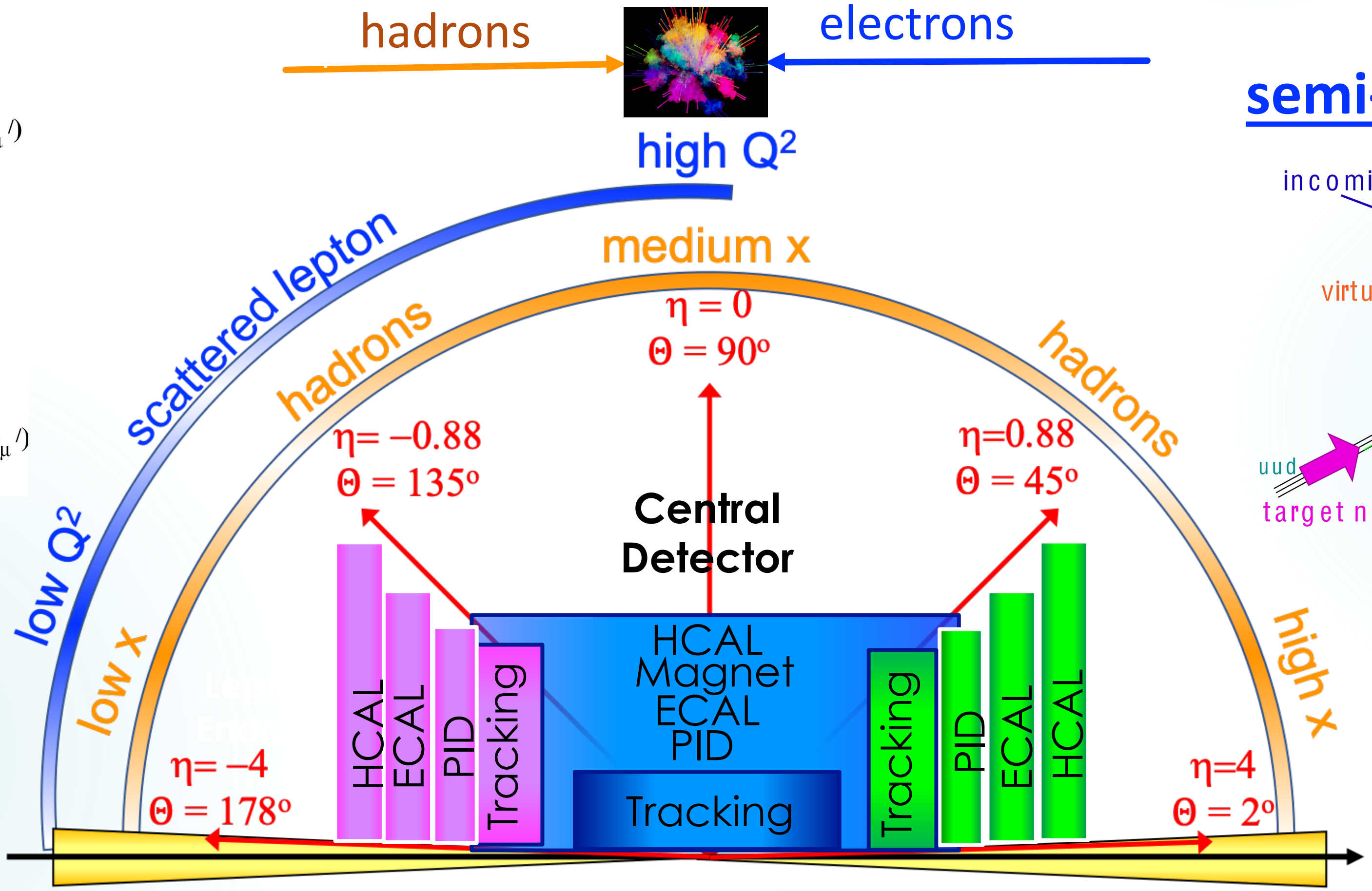


Coverage of ePIC

inclusive DIS:



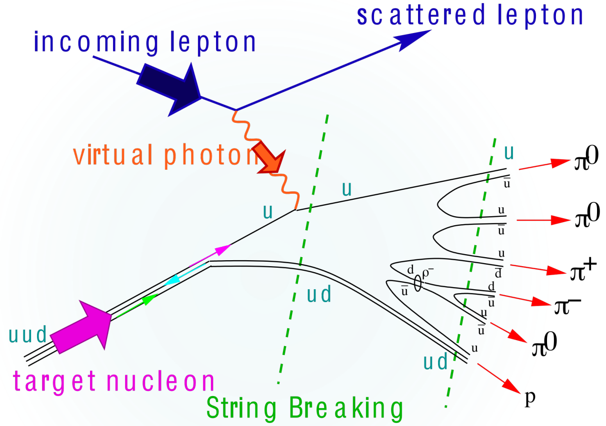
Detect only the scattered lepton in the detector



very low Q^2 scattered lepton
Bethe-Heitler photons for luminosity

Luminosity Detector
Low Q^2-Tagger

semi-inclusive DIS



Detect the scattered lepton in coincidence with identified hadrons/jets

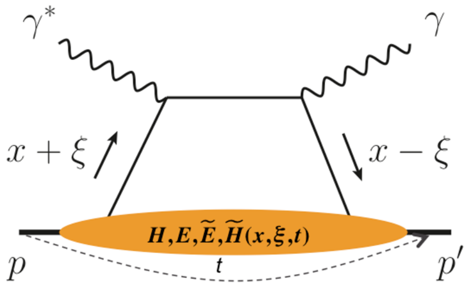
particles from nuclear breakup and from diffractive reactions

ZDC

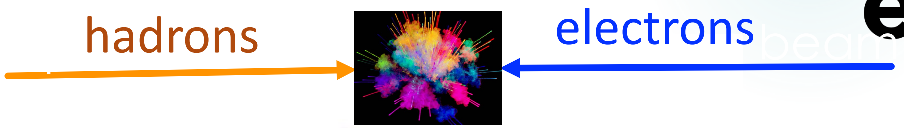
Forward Tracking

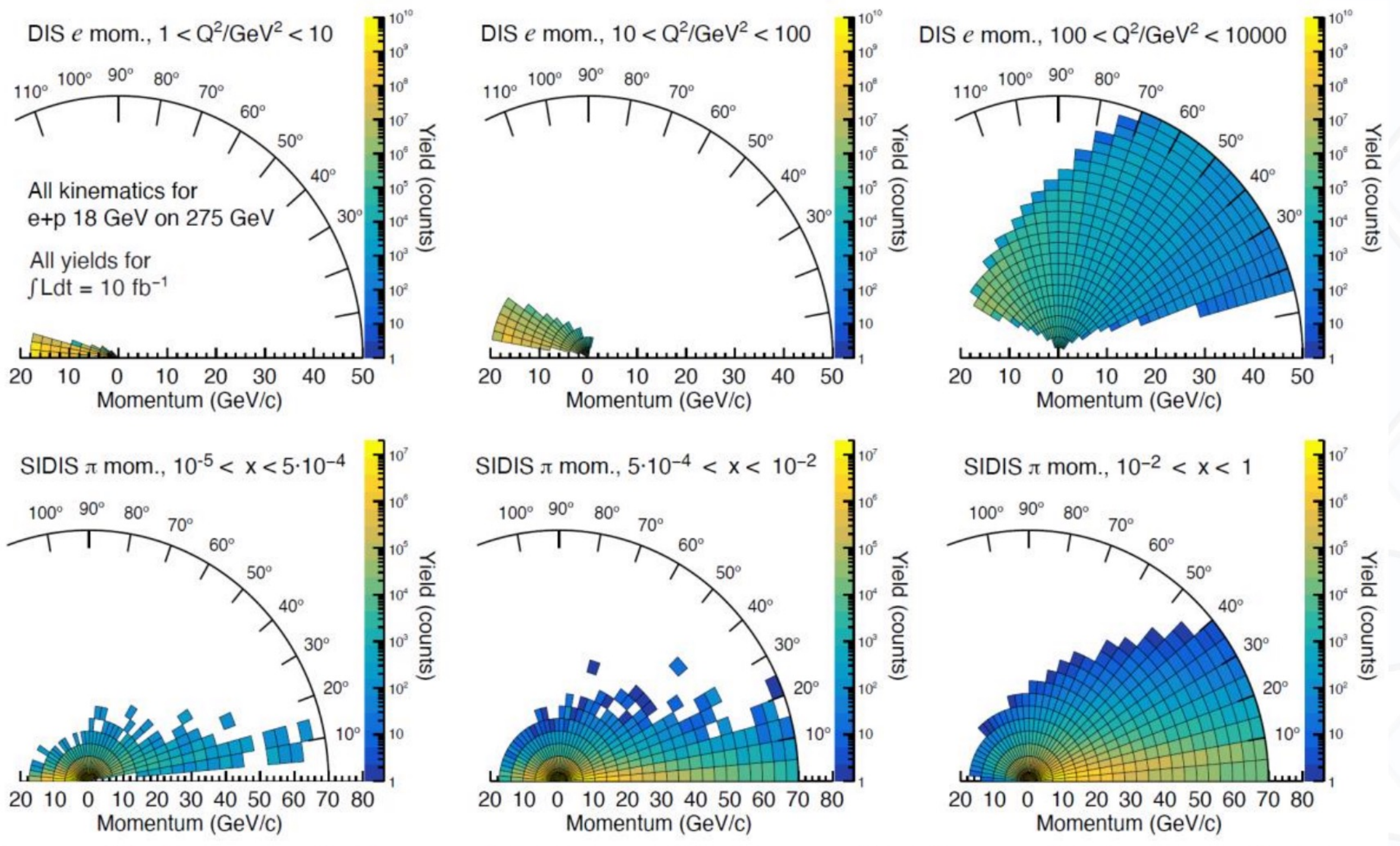
exclusive DIS

Detect scattered lepton, identify produced hadrons/jets and target remnants



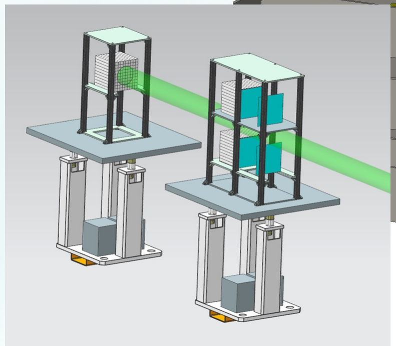
Coverage of ePIC





Far-Forward/Backward

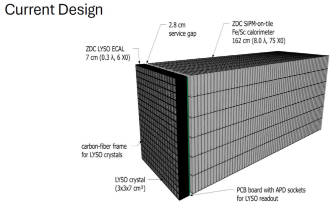
Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with
2 tracking layers of AC-LGAD
Calorimeter: Tungsten-powder + SciFi SPACAL

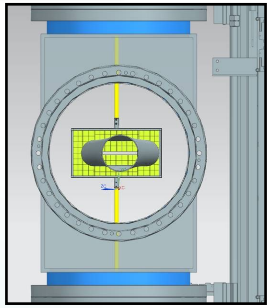


Luminosity System

Main Function:
detection of forward scattered neutrons and γ
Technology:
EMCAL: 2x2x20 cm^3 $PbWO_4$ or LYSO
HCAL: Steel-SiPM-on-Tile

Zero Degree Calorimeter

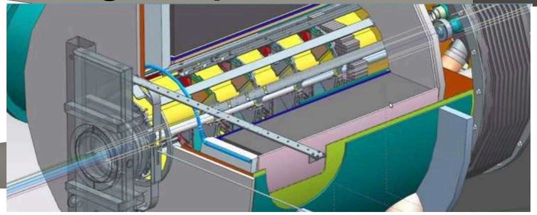




Roman Pots and Off-Momentum Detectors

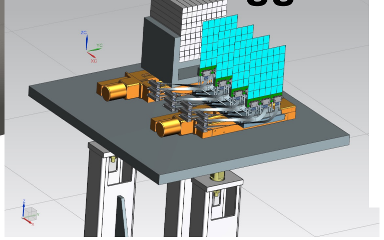
Main Function:
detection of forward scattered protons and nuclei
Technology:
2 stations with 2 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)

B0 Magnet Spectrometer



Main Function:
detection of forward scattered protons and and γ
Technology:
4 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)
Synergy with forward ToF
EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter

Low-Q2 Taggers

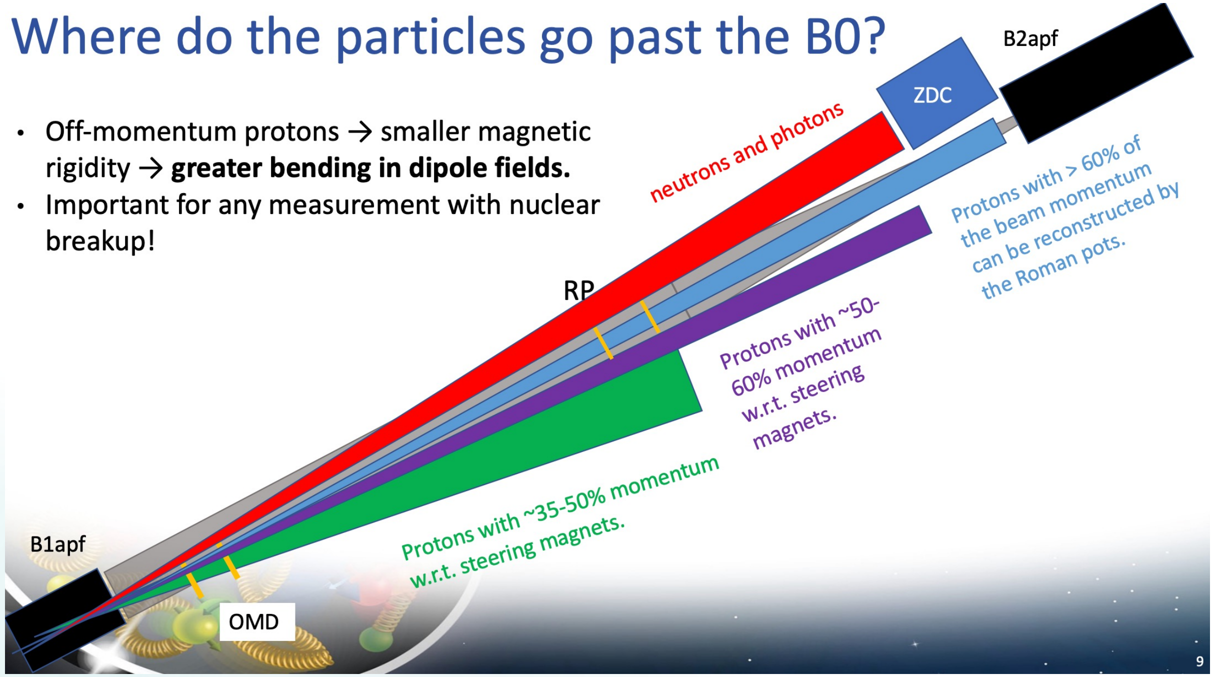


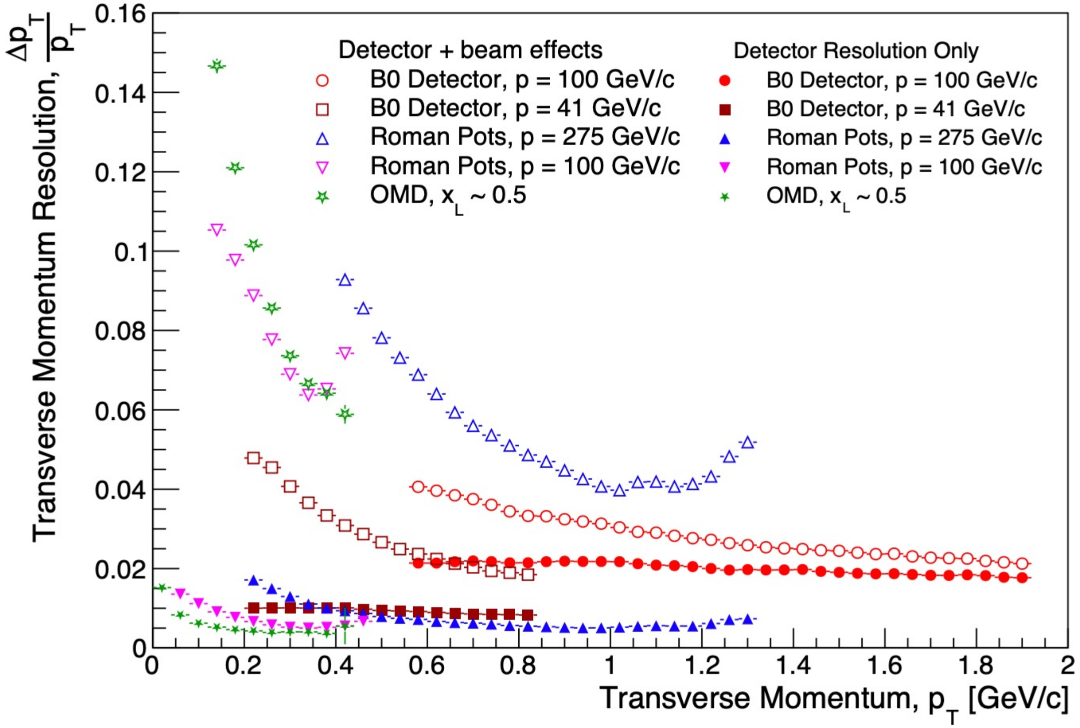
Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2)
Si / Timepix4
Calorimeter: Tungsten-powder + SciFi SPACAL

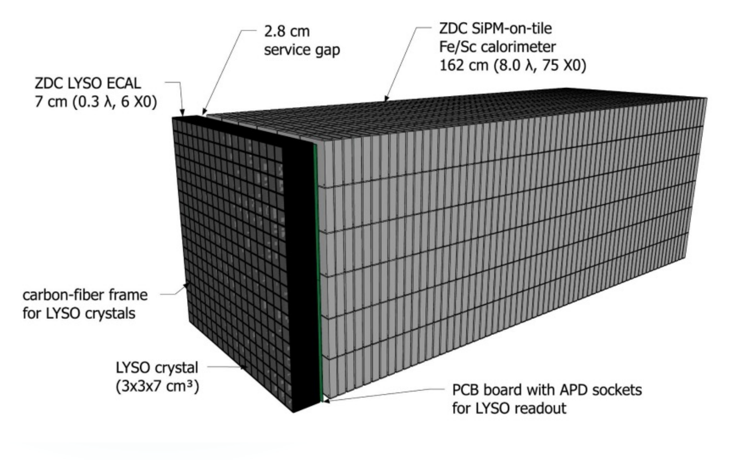
Far-Forward/Backward

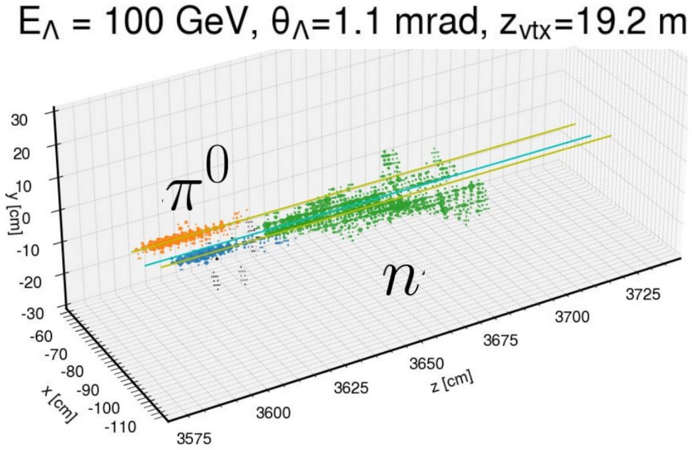
Where do the particles go past the B0?

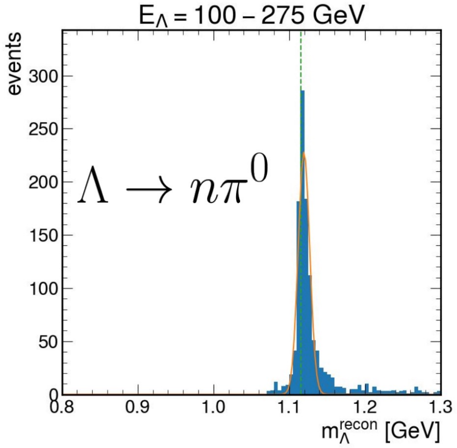
- Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields.**
- Important for any measurement with nuclear breakup!



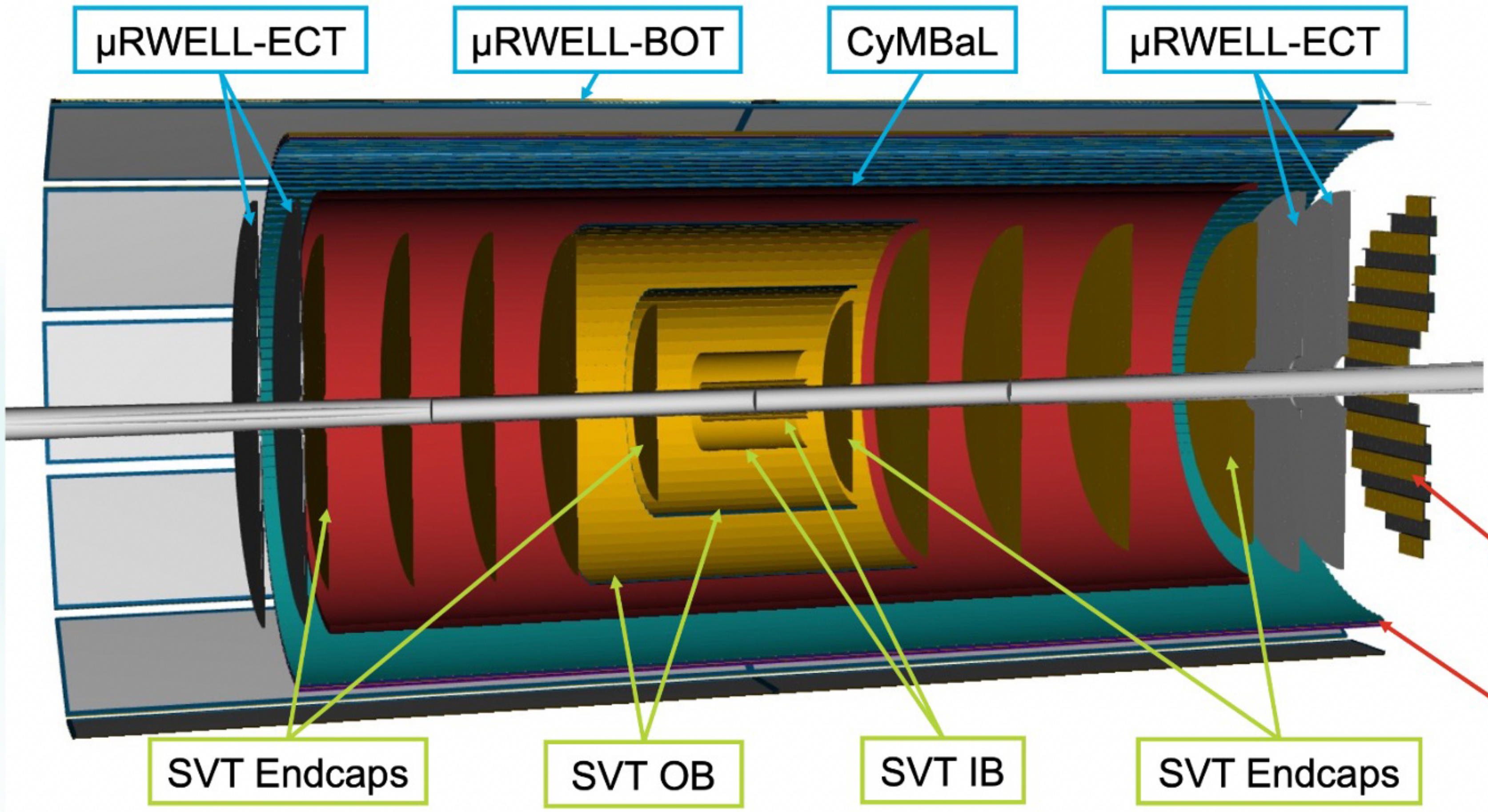






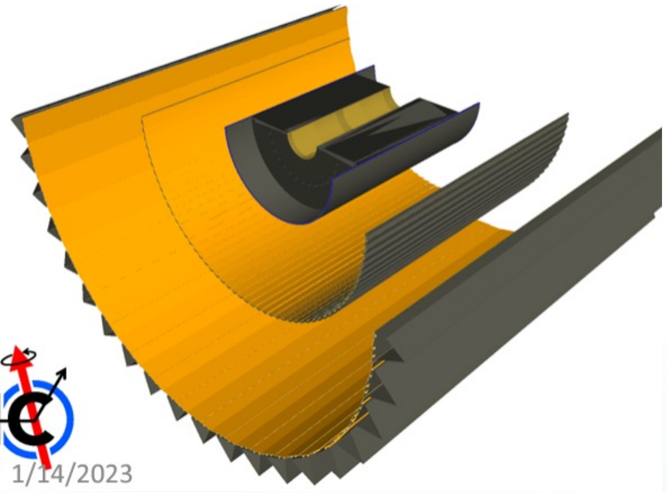


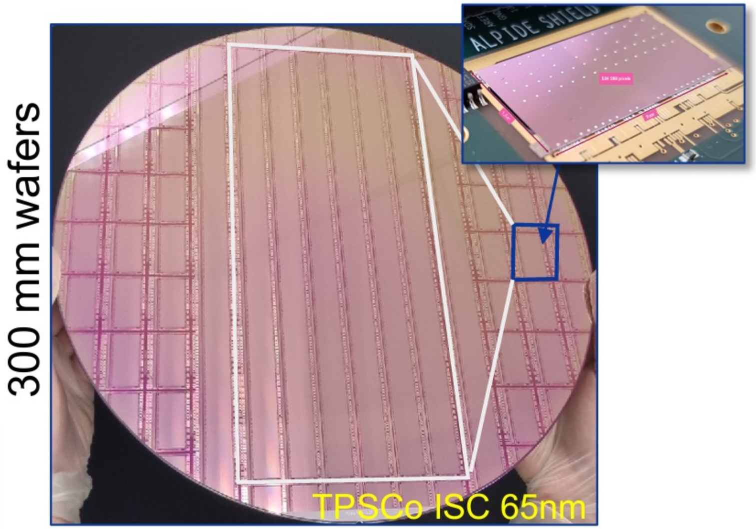
Tracking



- MPGD
  - BOT Length: 340 cm
  - BOT Radius: 72.5 cm
- Silicon
  - Outer Length: 84 cm
  - Outer Radius: 42 cm
- AC-LGAD
  - ToF: Part of PID

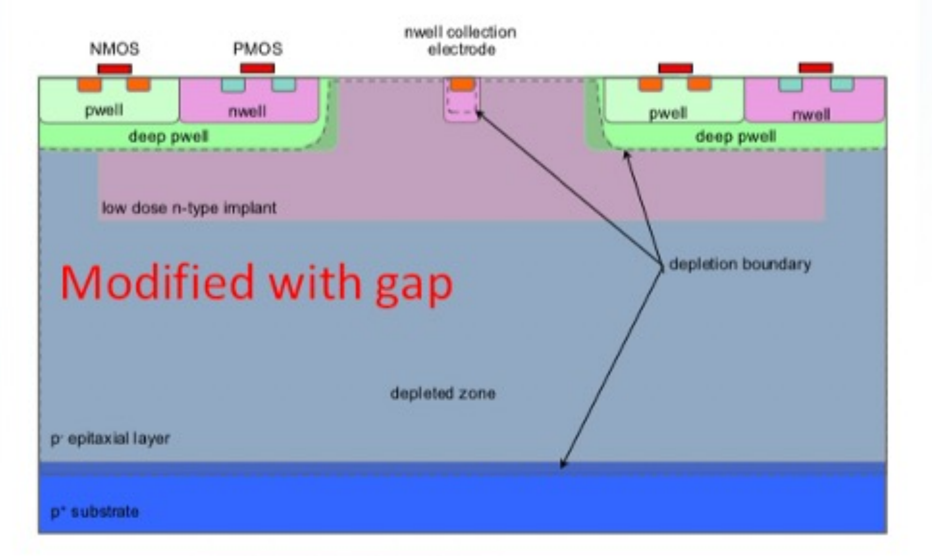
Tracking : MAPS

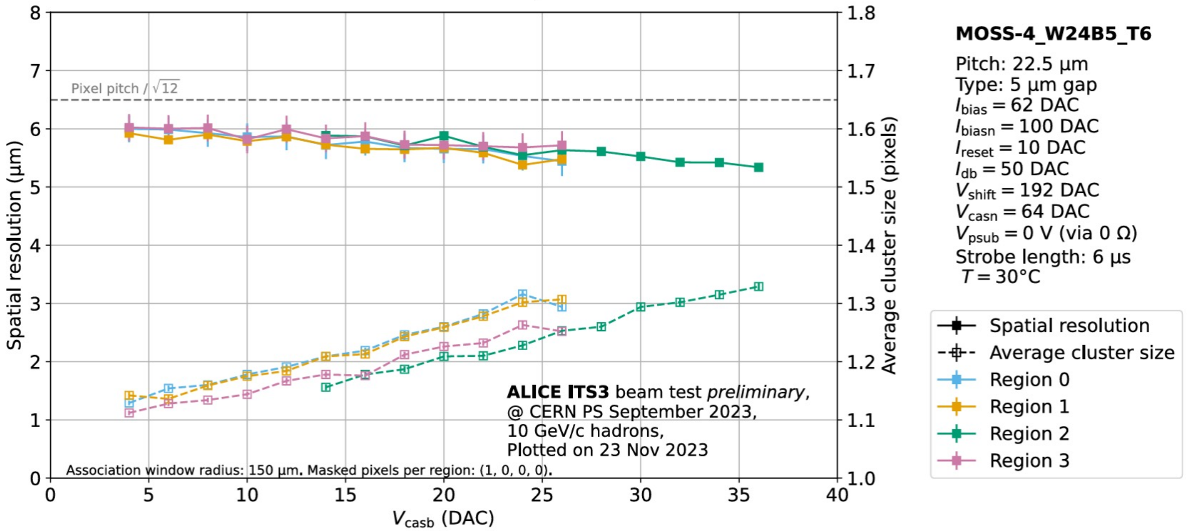




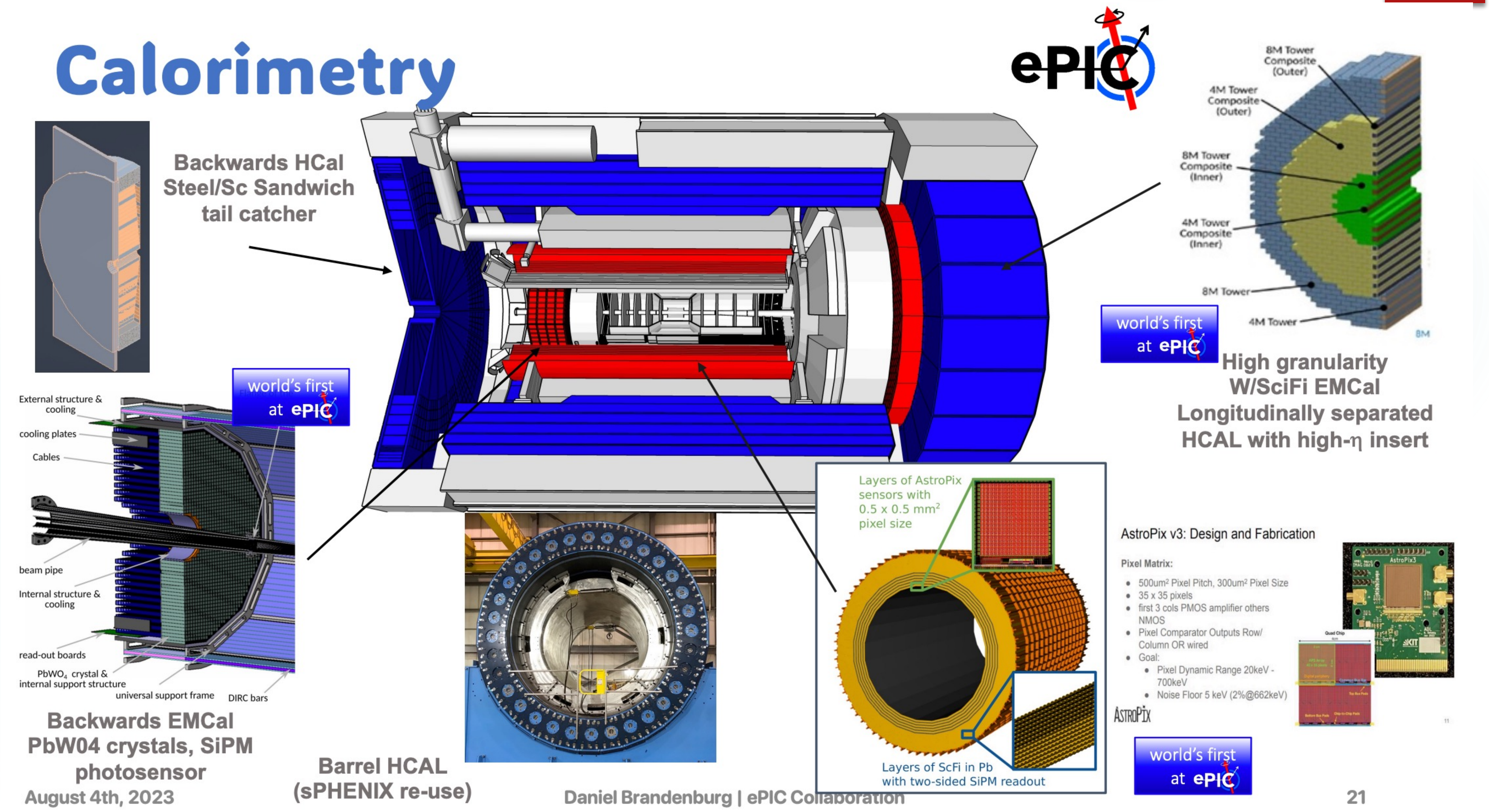
from reticle-size to wafer-size

thin (<50µm CMOS can be curled)



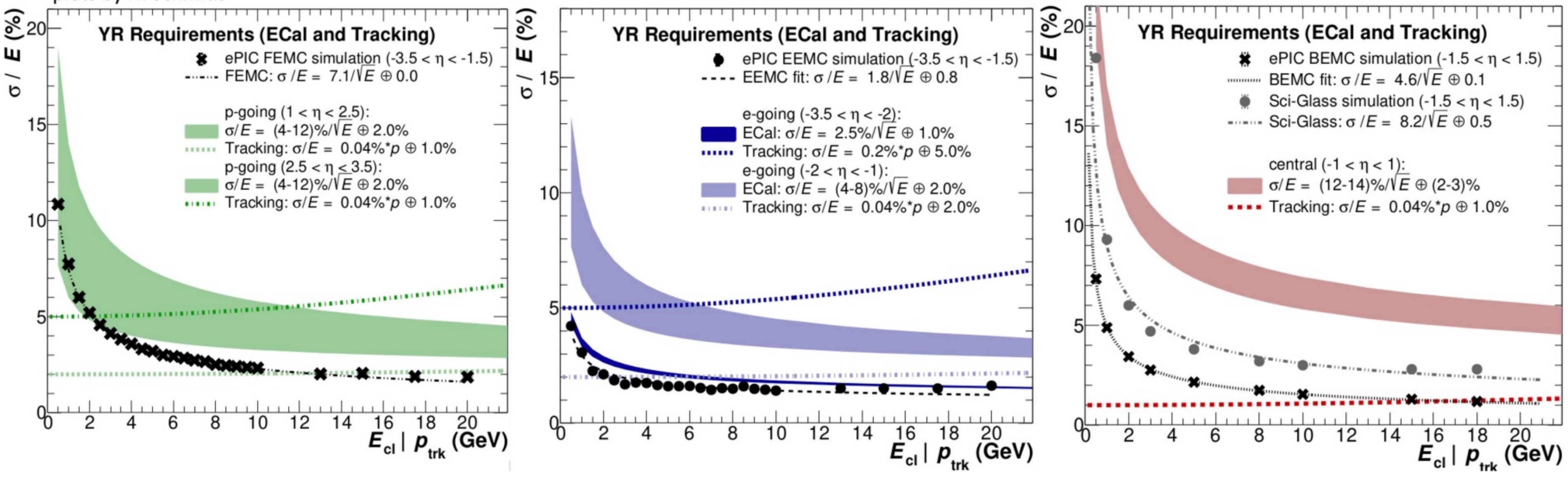


Calrimeter

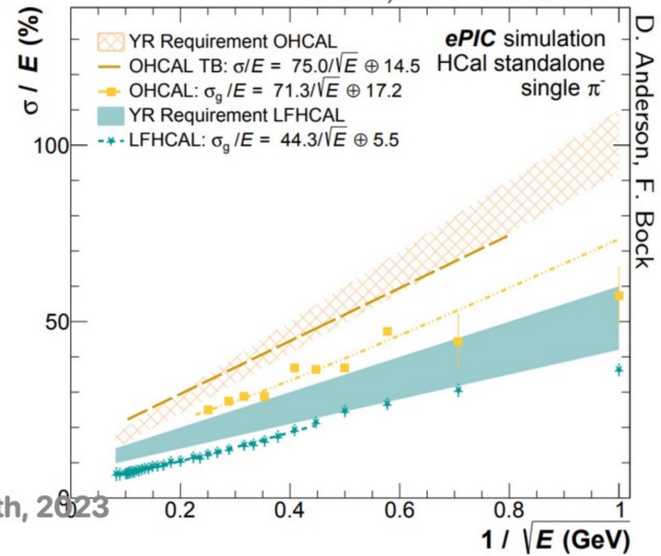

Calorimetry
ePIC
Backwards HCal
Steel/Sc Sandwich
tail catcher
External structure & cooling
cooling plates
Cables
beam pipe
Internal structure & cooling
read-out boards
PbWO4 crystal & internal support structure
universal support frame
DIRC bars
world's first at ePIC
Backwards EMCal
PbW04 crystals, SiPM
photosensor
Barrel HCAL
(sPHENIX re-use)
Layers of AstroPix sensors with 0.5 x 0.5 mm² pixel size
Layers of ScFi in Pb with two-sided SiPM readout
8M Tower Composite (Outer)
4M Tower Composite (Outer)
8M Tower Composite (Inner)
4M Tower Composite (Inner)
8M Tower
4M Tower
world's first at ePIC
High granularity
W/SciFi EMCal
Longitudinally separated
HCAL with high-η insert
AstroPix v3: Design and Fabrication
Pixel Matrix:
500um² Pixel Pitch, 300um² Pixel Size
35 x 35 pixels
first 3 cols PMOS amplifier others NMOS
Pixel Comparator Outputs Row/ Column OR wired
Goal:
Pixel Dynamic Range 20keV - 700keV
Noise Floor 5 keV (2%@662keV)
world's first at ePIC
August 4th, 2023
Daniel Brandenburg | ePIC Collaboration
21

Calrimeter

plots by N. Schmidt



F. Bock, Hard Probes 2023



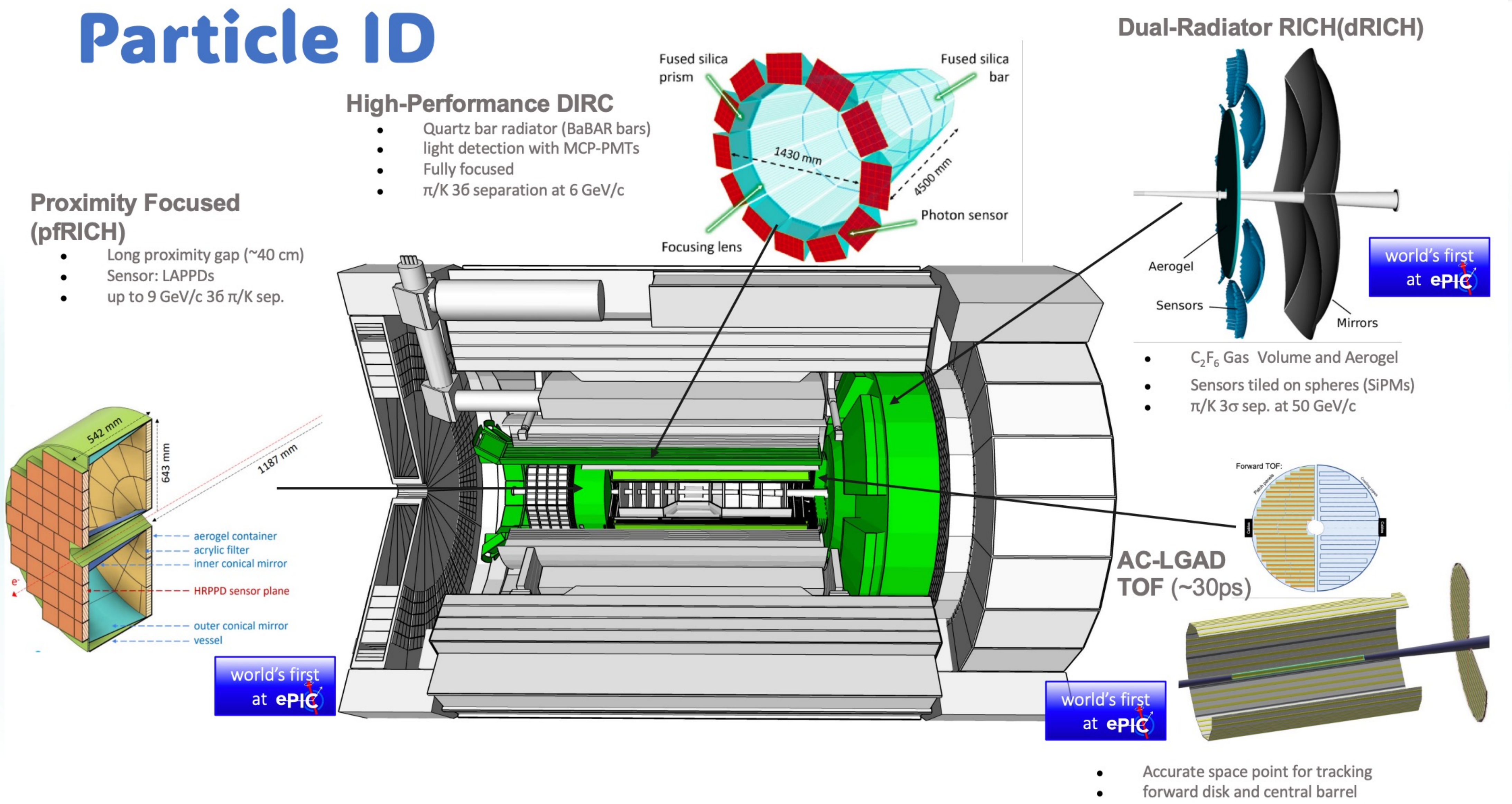
Performance on energy resolution and matching

- Technologies fulfill YR requirements on energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry and reconstruction algorithms

Ongoing work on Monte-Carlo validation

- Validation for high Z absorbers

Particle identification

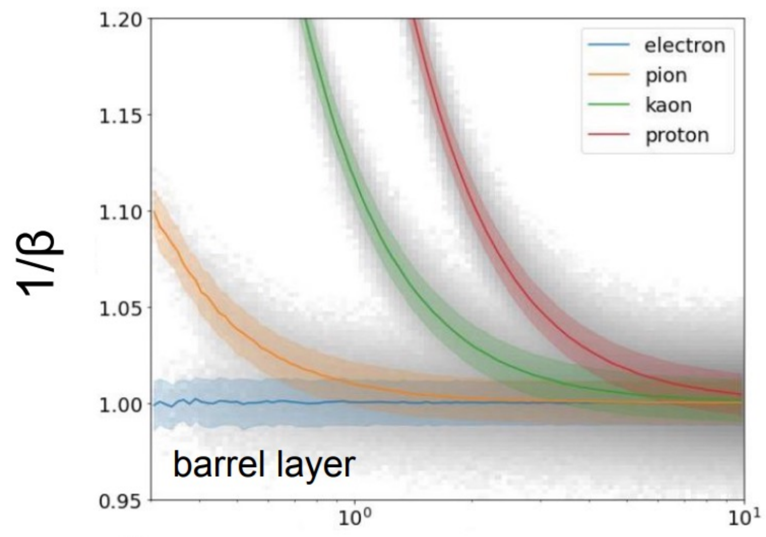


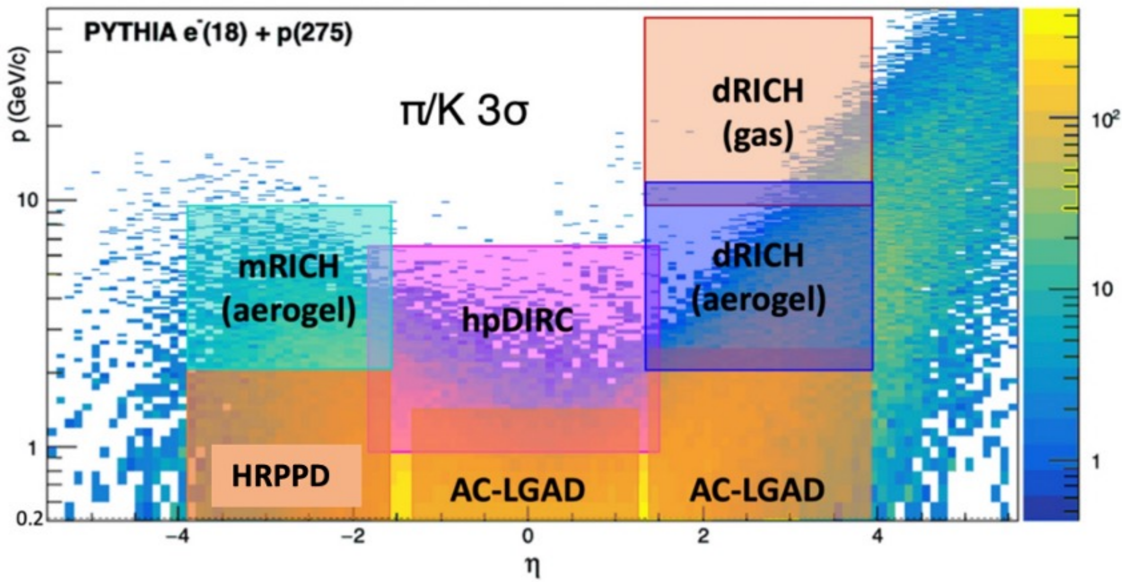
Particle identification

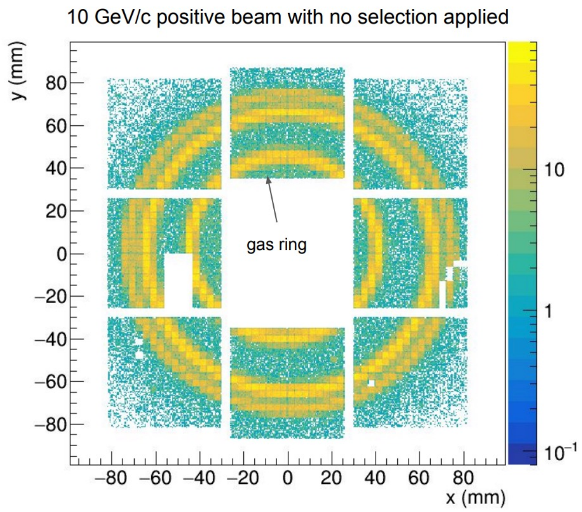
Particle IDentification needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly provided by calorimetry and tracking**
- Charged pions, kaons and protons from each other on track level ⟶ **Cherenkov detectors**
  - Cherenkov detectors, complemented by ToF

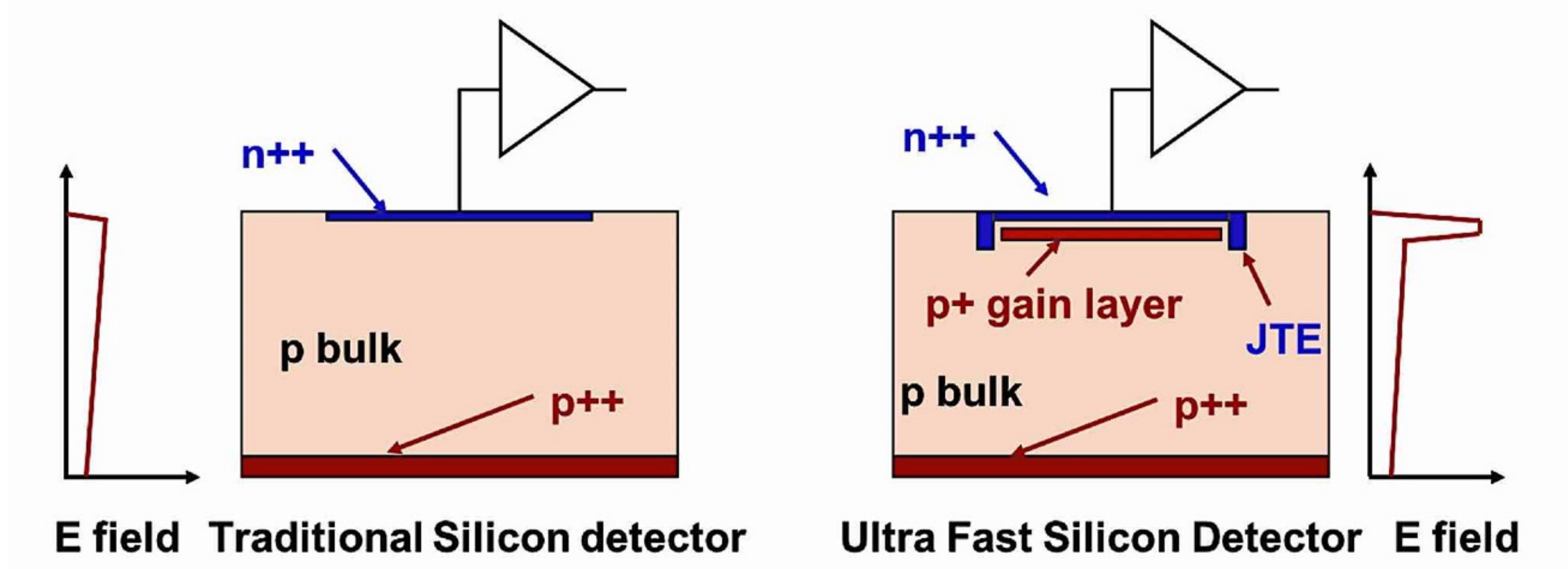
Rapidity	π/K/p and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c



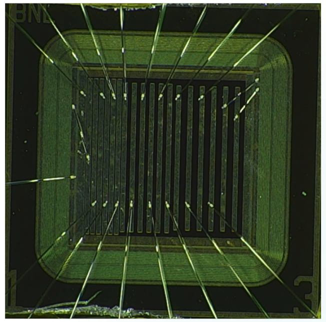




Particle identification : AC-LGAD

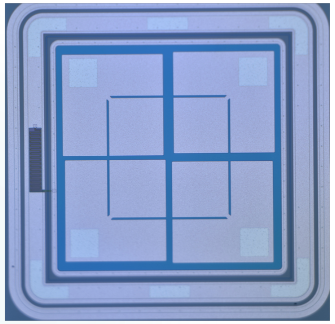


Strip type by BNL



3x3 mm²
Sensor size
100μm, 150 μm, 200 μm

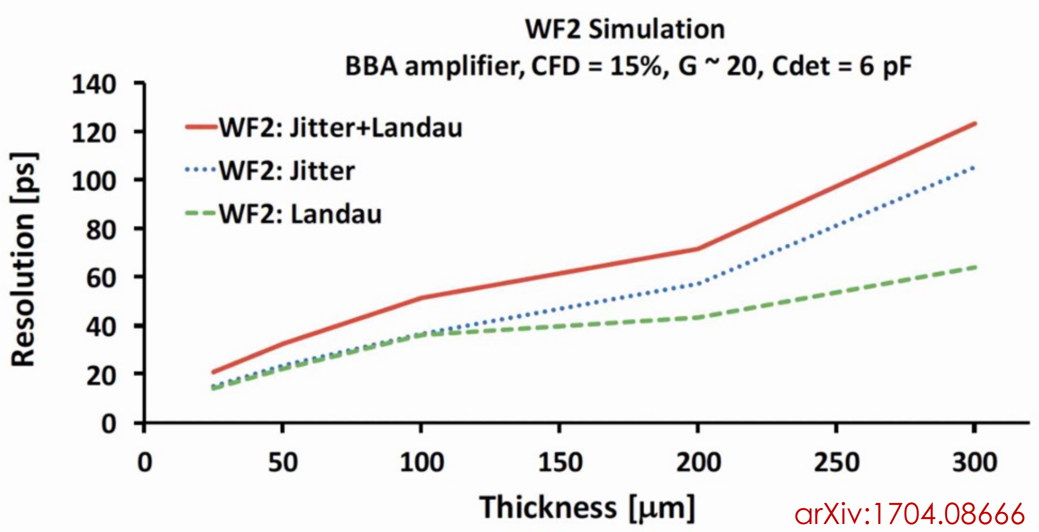
Pad type by HPK



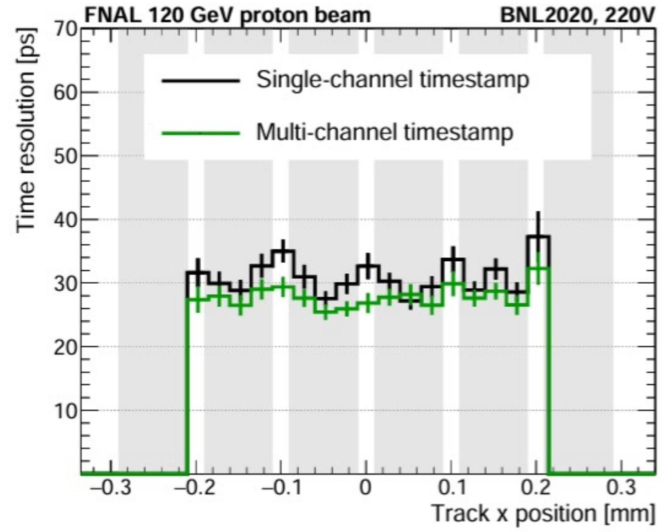
3x3 mm²
Sensor size

Ramo's theorem

$$\frac{di_G}{dt} \propto \frac{G}{d}$$

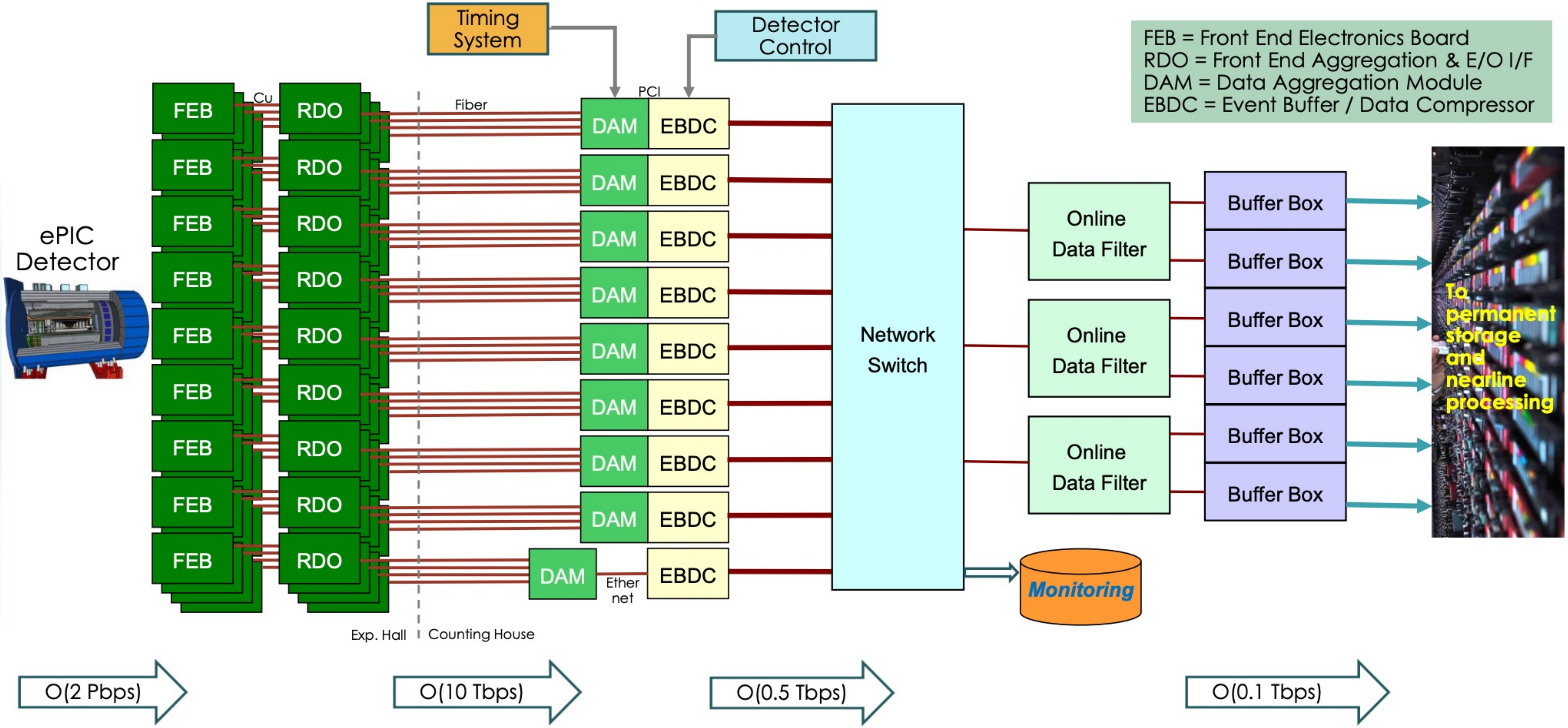


arXiv:1704.08666

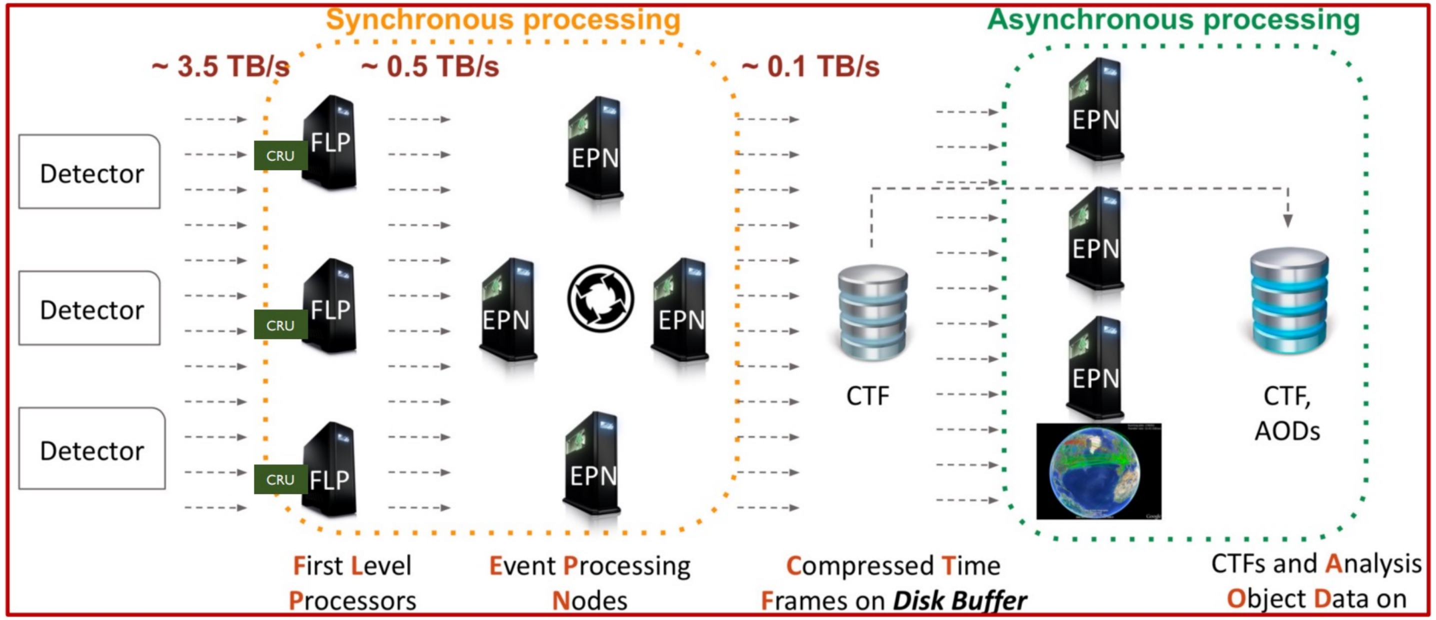


Streaming DAQ

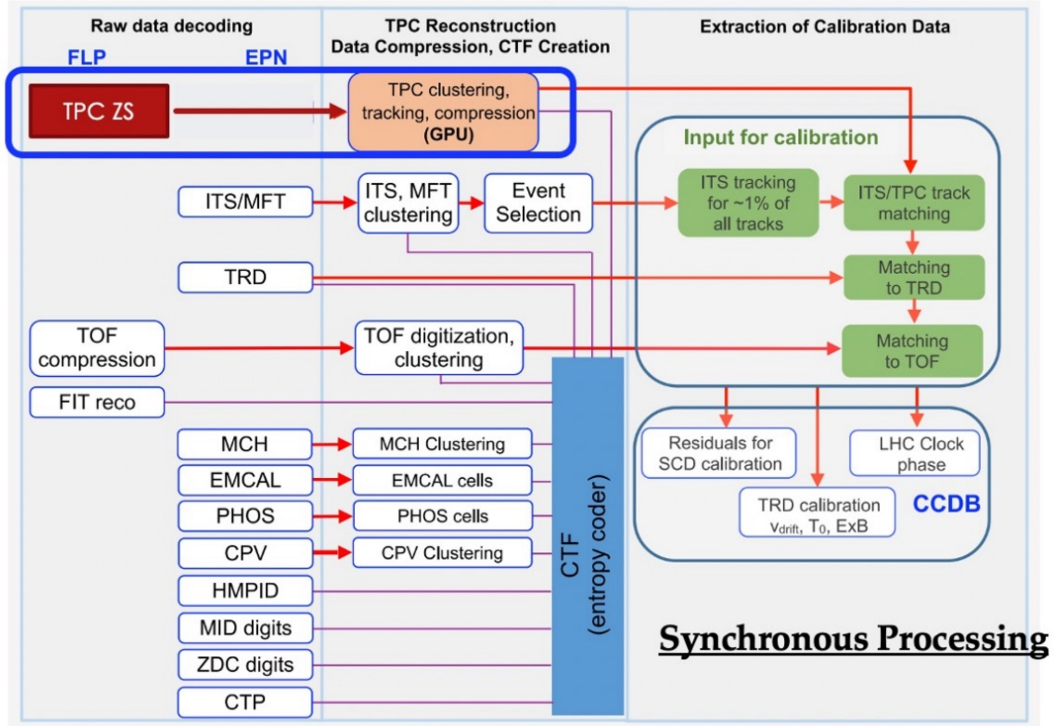
- No External trigger
- All collision data digitized but aggressively zero suppressed at FEB
- Low / zero deadtime
- Collision data flow is independent and unidirectional-> no global latency requirements
- Avoiding hardware trigger avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage ensuring that biases are controlled
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector

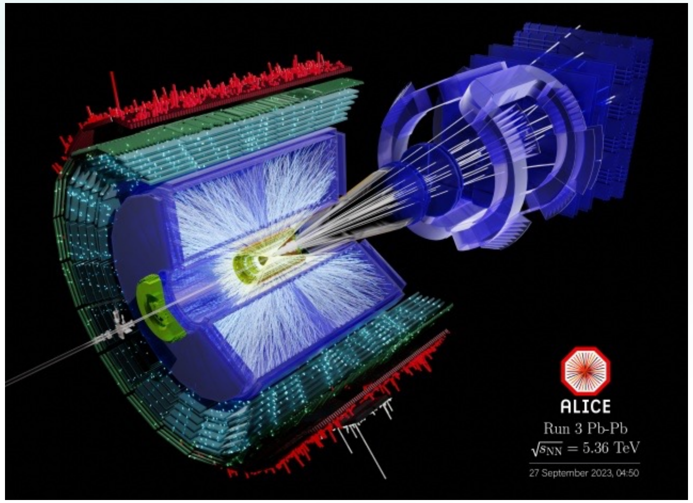


Streaming DAQ : ALICE case

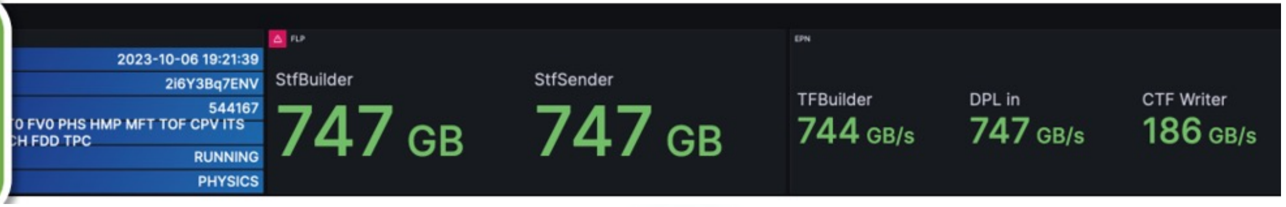


Synchronous processing of TFData in EPN (250 EPNs, 2000 GPUs)





15 detectors
Data Volume as predicted
Acquisition with 364 equivalent MI50 EPNs

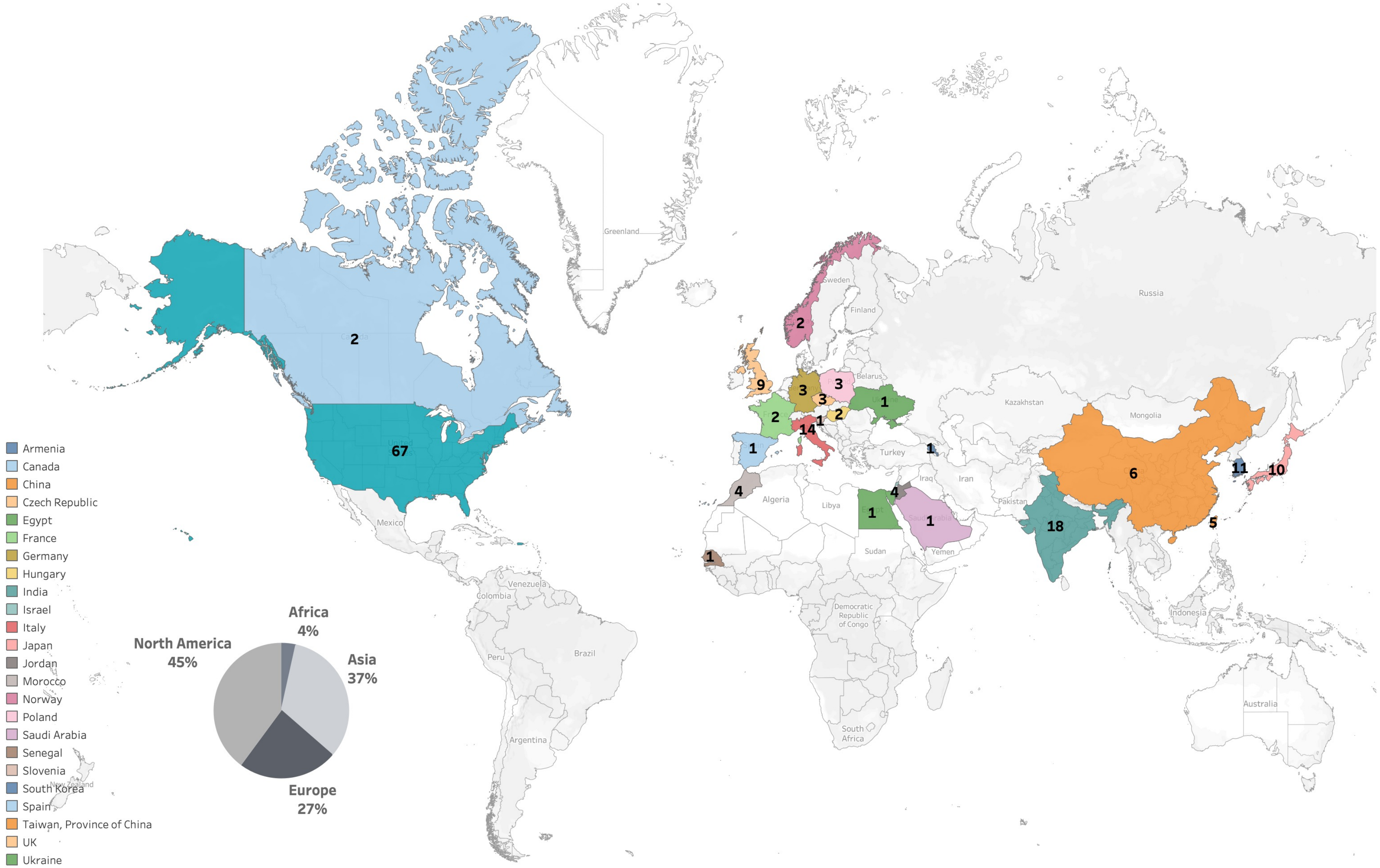


Japanese Institutes in ePIC

ePIC Institutions
173

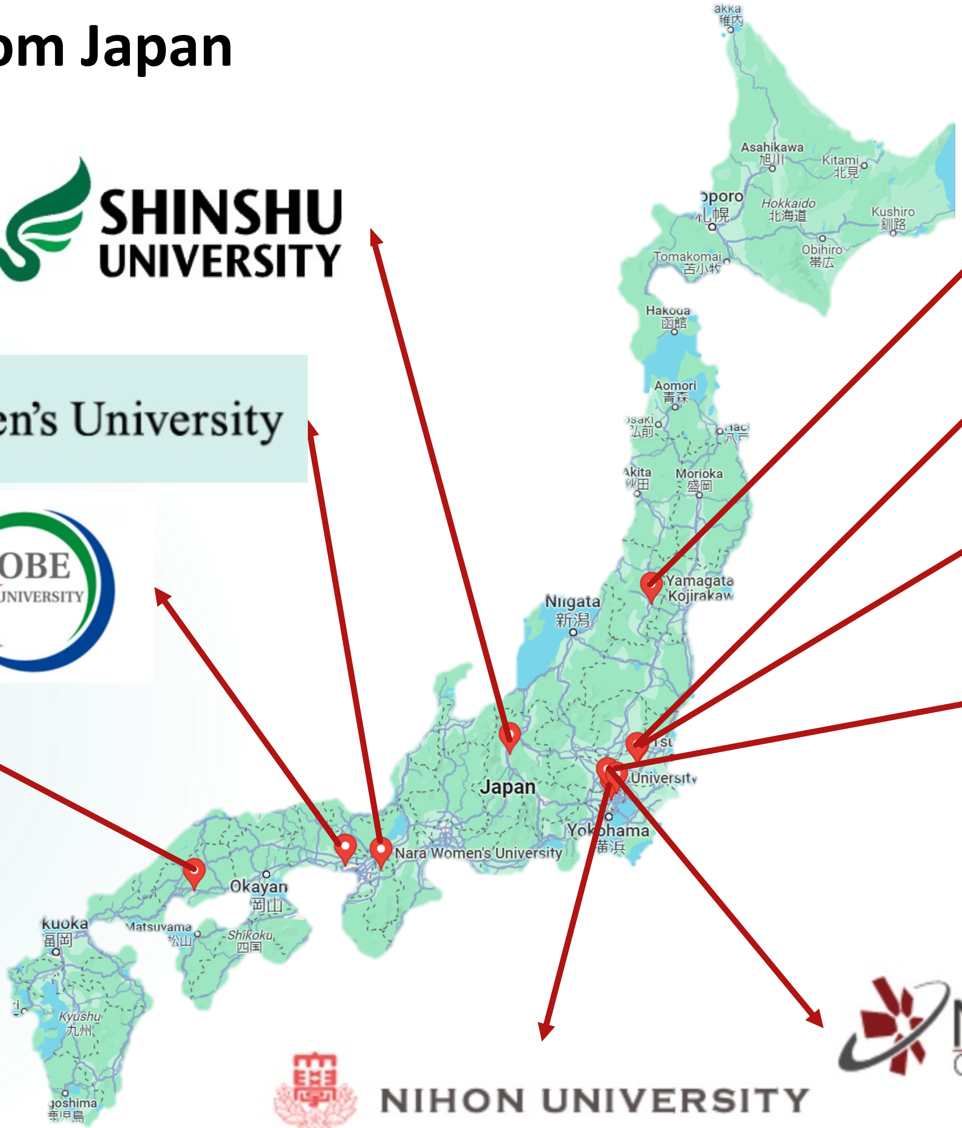
ePIC Countries
25

ePIC World Region
4



Japanese Institutes in ePIC

- **10 institutes from Japan**



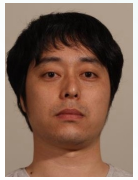
SHINSHU UNIVERSITY

Nara Women's University

KOBE UNIVERSITY

HIROSHIMA UNIVERSITY

SKCM² WPI HIROSHIMA UNIVERSITY wpi



S. Yano, TOF-DSC

NIHON UNIVERSITY

Yamagata University

University of Tsukuba

National University Corporation Tsukuba University of Technology

Center for Nuclear Study The University of Tokyo

T. Gunji, Executive Board member

Y. Goto , ZDC DSTC

RIKEN NISHINA CENTER RIKEN Nishina Center for Accelerator-Based Science RIKEN

Japanese Institutes in ePIC

- **Japanese team consists of the institutes with different research backgrounds**

Nucleon structure
(COMPASS/AMBER, RHIC, SeaQuest, SpinQuest)

山形大学 YAMAGATA UNIVERSITY

RIKEN NiSHiNA CENTER — RIKEN Nishina Center for Accelerator-Based Science

NIHON UNIVERSITY

High-Energy particle physics
(ZEUS@HERA, ATLAS@LHC)

SHINSHU UNIVERSITY

KOBE UNIVERSITY

Heavy-Ion Physics
((s)PHENIX@RHIC, ALICE@LHC)

Center for Nuclear Study — The University of Tokyo

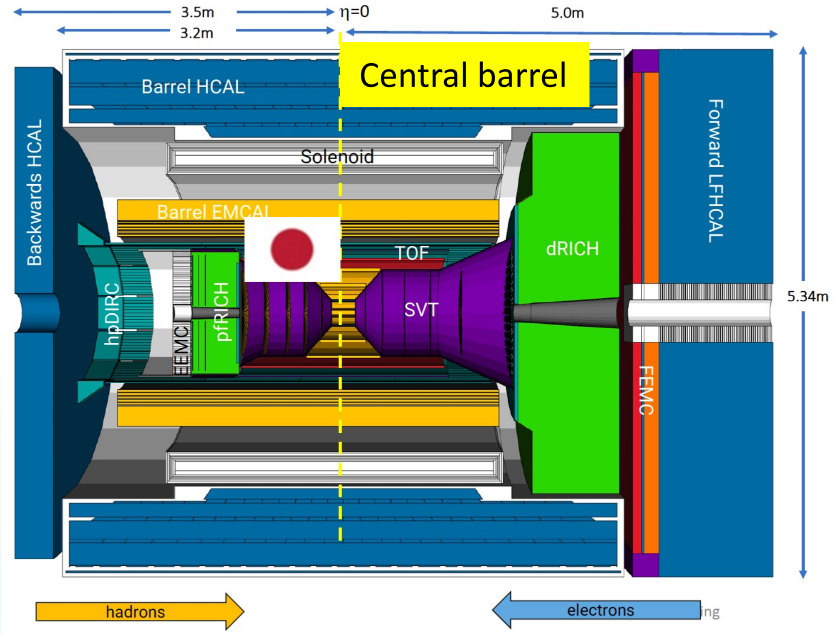
University of Tsukuba

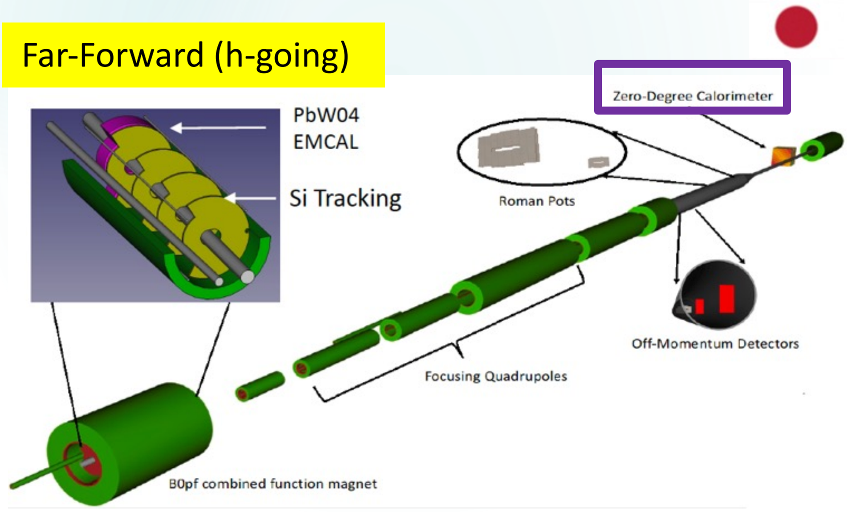
National University Corporation Tsukuba University of Technology

国立大学法人 奈良女子大学 Nara Women's University

HIROSHIMA UNIVERSITY

Japanese contributions

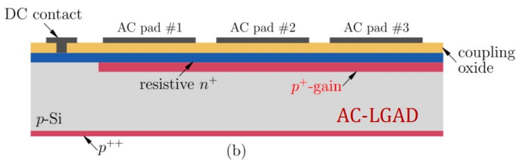


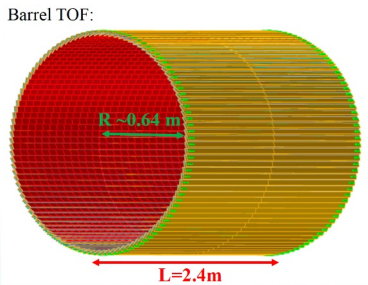


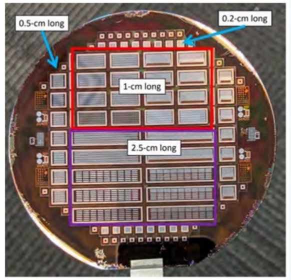
Japanese contributions

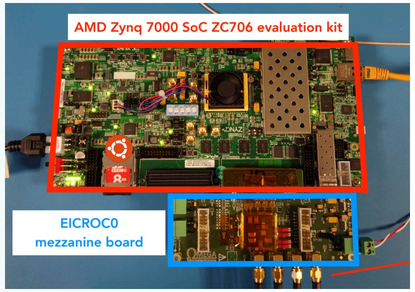
- **Barrel AC-LGAD TOF and ZDC R&D and construction**
- **Streaming DAQ and online data filter**

AC-LGAD R&D

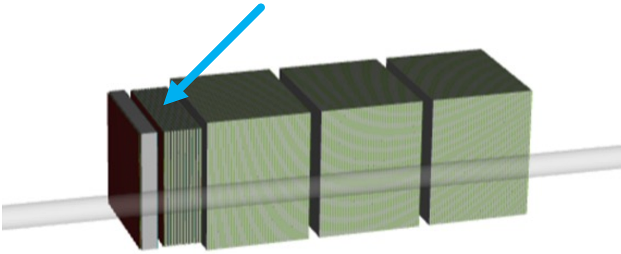


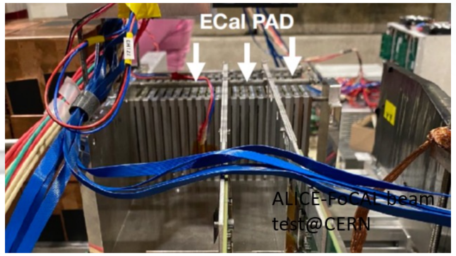




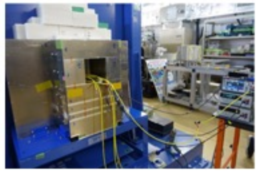


ZDC R&D (W+Si ALICE-FoCAL)

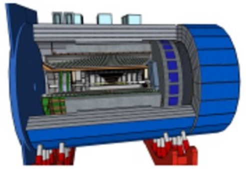


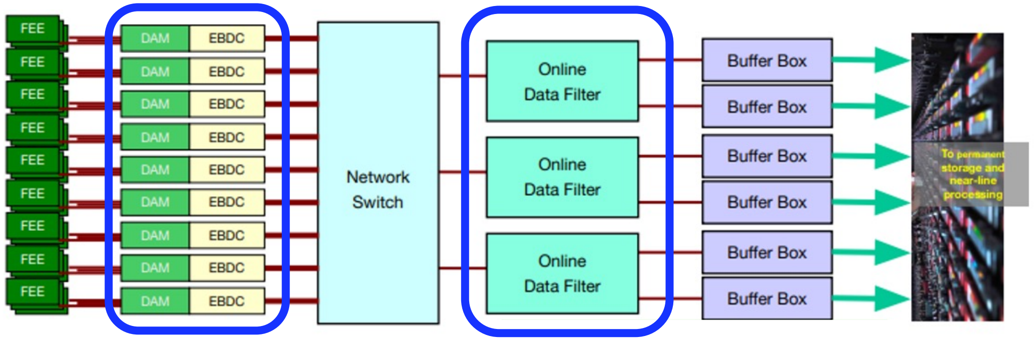


Neutron tests at RIKEN



Streaming DAQ online data filter by FPGA/GPU/CPU





In collaboration with SPADI-Alliance in Japan

Summary

- EICは多くの発見と他分野へ多くの波及をもたらす可能性がある
- しかしながら、TMDやGPDをはじめ、EICの物理は難しい…
- 定期的に勉強会を開いて、一緒に勉強しませんか？
- EICに興味のある人、eic-japan@ml.riken.jpに参加しませんか？
  - 郡司(gunji@cns.s.u-tokyo.ac.jp)と後藤(goto@bnl.gov)まで連絡をください
- EICを契機にして、クォーク・グルーオン～原子核～原子・分子～生命～宇宙を繋ぎ、クォーク物理・原子核物理・物性物理を融合する「マルチスケール基礎量子科学」を振興したい
  - 階層を超えた普遍性の探求、分野を超えた知見を取り入れる
  - どの階層に進んでも戦える力をつける。多様なキャリアパスの実現。