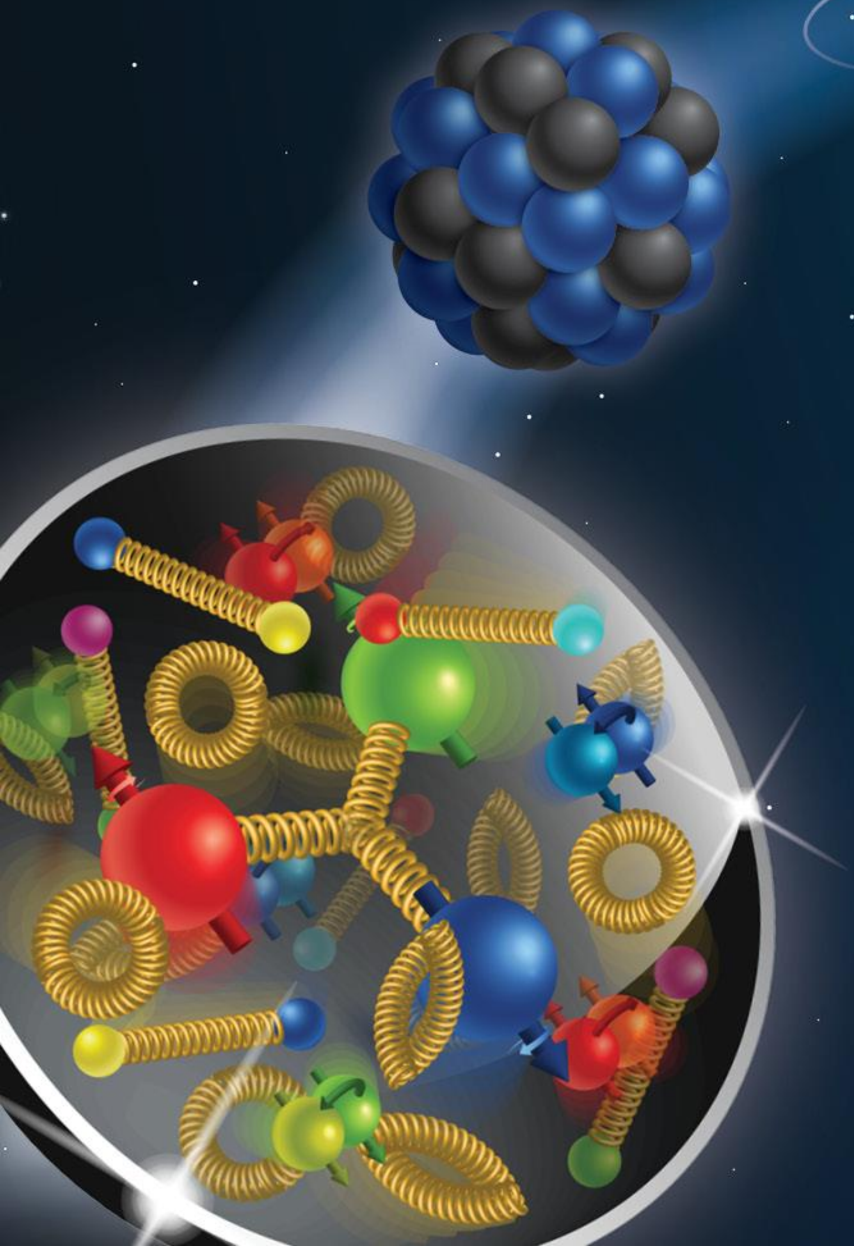


# How EIC Physics can impact LHC

E.C. Aschenauer
BNL

Papers on EIC Science:
https://wiki.bnl.gov/eic/index.php/Presentations#Publications

## Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

# Facts about the EIC

## What is the EIC:

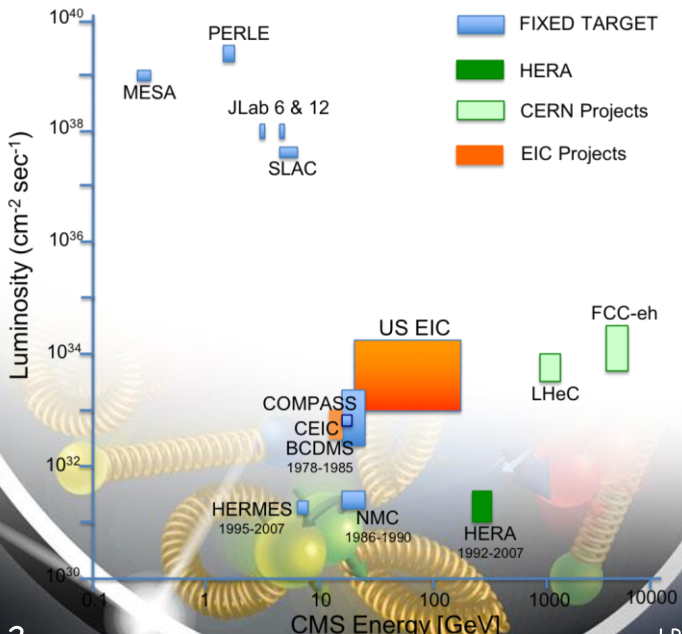
A high luminosity ($10^{33}$ – $10^{34}$ $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 20 – 140 GeV

## What is new/different:

Hera: factor 100 to 1000 higher luminosity
both electrons and protons / light nuclei polarized
nuclear beams: d to U

Two Proposals:

BNL: add an electron Beam to RHIC    JLab: add a hadron facility to Cebaf

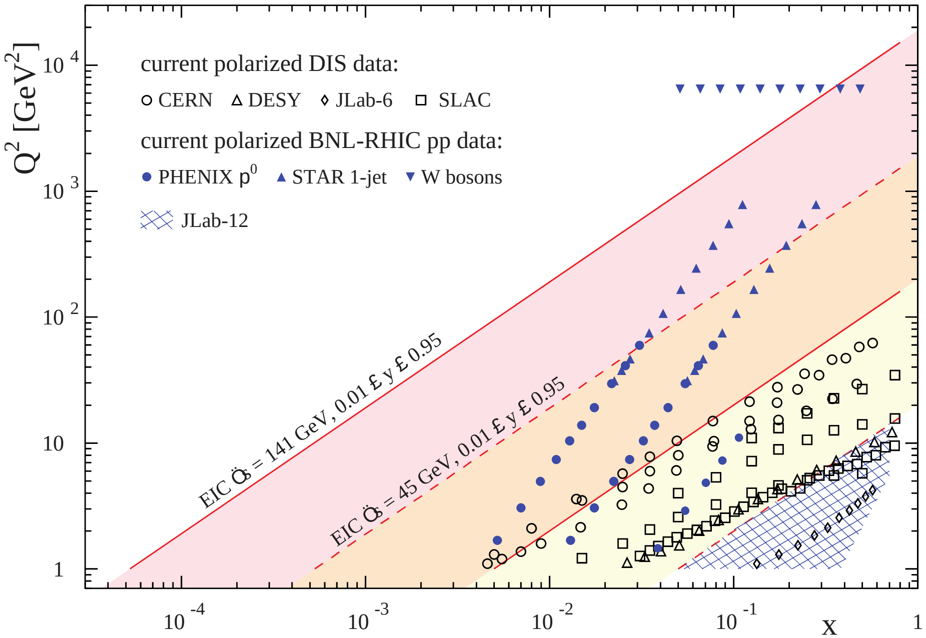



**US-EIC:**
polarization, ion species together with its luminosity and $\sqrt{s}$ coverage makes it a completely unique machine worldwide.

**Documents on EIC:**
Physics: arXiv: 1212.1701 and arXiv:1708.01527
Summary on JLEIC & eRHIC accelerator designs:
http://icfa-bd.kek.jp/Newsletter74.pdf

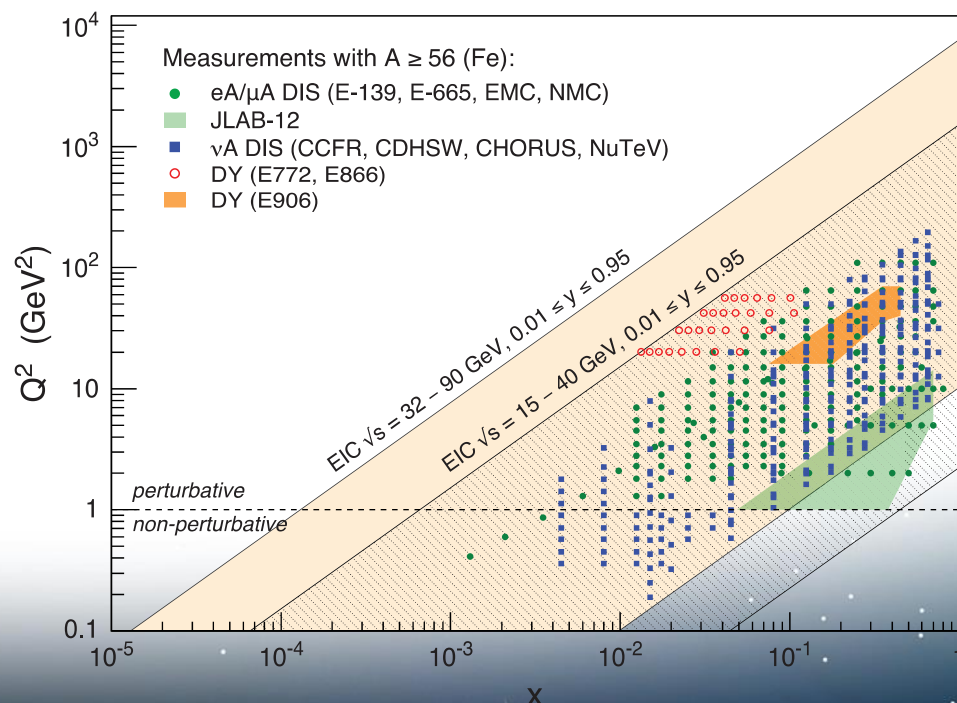
# EIC's kinematic reach in x and $Q^2$

## ep:




EIC extends kinematic coverage for data with polarised beams and nuclei by 2 decades in x at a fixed $Q^2$ and by 2 decades in $Q^2$ at a fixed x

## eA:




## EIC:

A high luminosity ($10^{33}$ – $10^{34}$ $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 20 – 140 GeV

# The inner life of hadrons
# Parton distribution functions

# The Path to Imaging Quarks and Gluons

4+1-D

Wigner function

$\mathbf{W(x, k_T, b_T)}$

QCD genetic map of nucleons

$\int d^2b_T$ $\int d^2k_T$

2+1-D

$\mathbf{f(x, k_T)}$

transv. mom. dep. PDF

semi-inclusive DIS

not related by Fourier transf.

$\mathbf{f(x, b_T)}$

impact par. dep. PDF

$\mathbf{b \leftrightarrow t}$

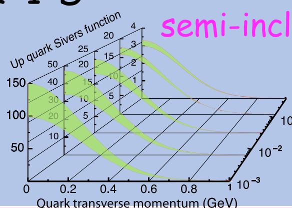
$\mathbf{H(x, 0, t)}$

$\xi \to 0$

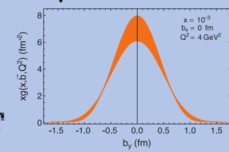
$\mathbf{H(x, \xi, t)}$

generalized PDF

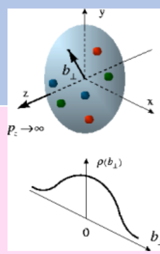
exclusive processes

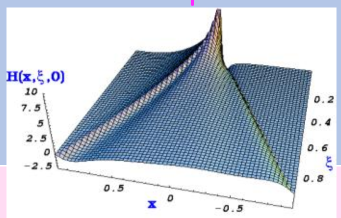



$\int d^2k_T$ $\int d^2b_T$

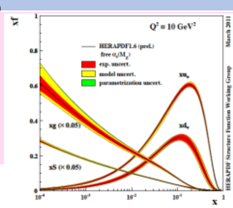



$\int dx$






1-D



$\mathbf{f(x)}$

parton densities

$\mathbf{F(t)}$

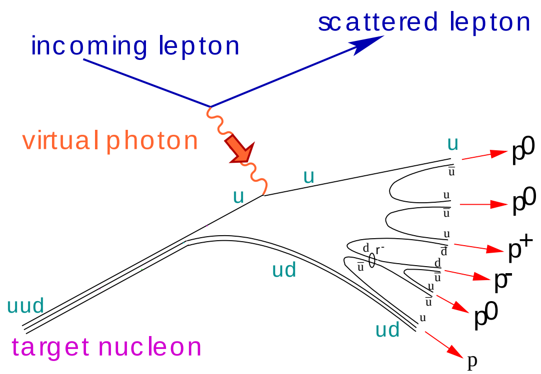
form factor

There are many reasons why one wants to have a 3d picture of nucleons and nuclei collective effects is one of them.

Obtaining a full information is an other one

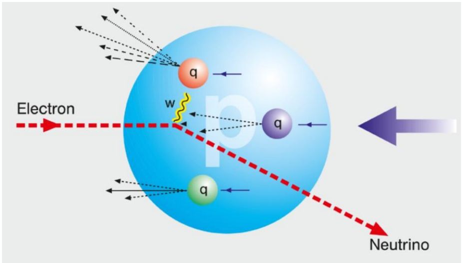
# HOW TO ACCESS PARTONS IN DIS

## DIS / SIDIS:



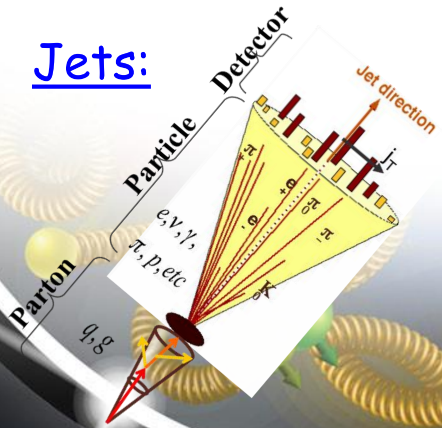

Detect scattered lepton → limited flavor separation
→ Detector: excellent e/h separation, $p_T$ and Θ resolution
Detect identified hadrons in coincidence to scattered lepton
→ needs fragmentation functions to correlate hadron type with parton flavor
→ Detector: PID over a wide range of η

## Charge Current:




W-exchange: direct access to the quark flavor
no FF – complementary to SIDIS
→ Detector: large rapidity coverage and large √s

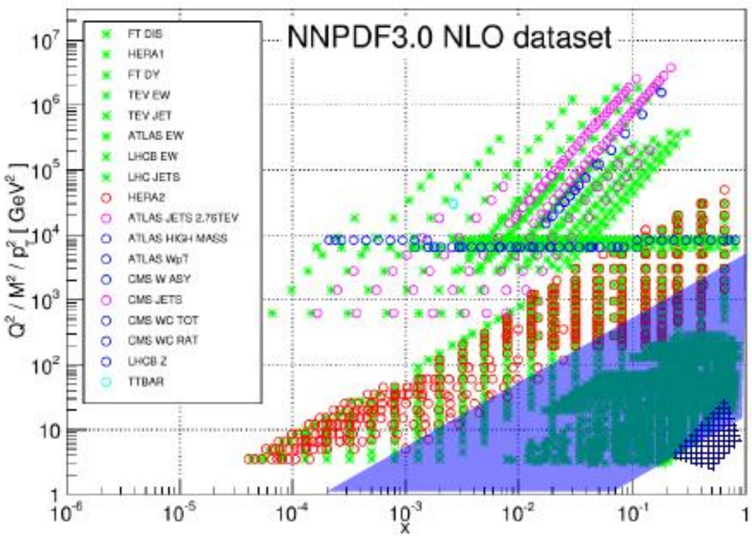
## Jets:



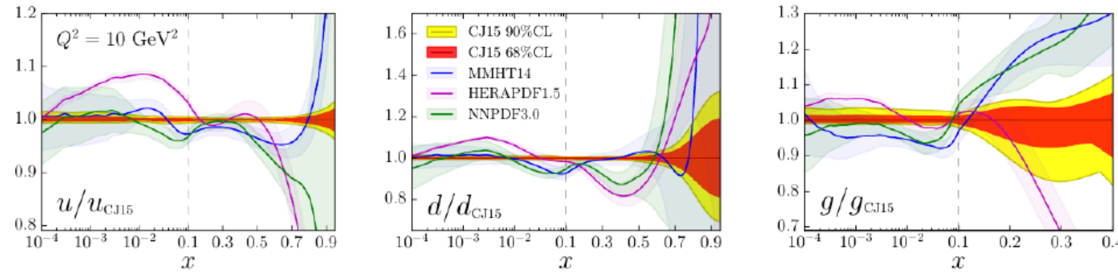

tag sea-quarks through the sub-processes and jet substructure
→ Detector: large rapidity coverage and PID

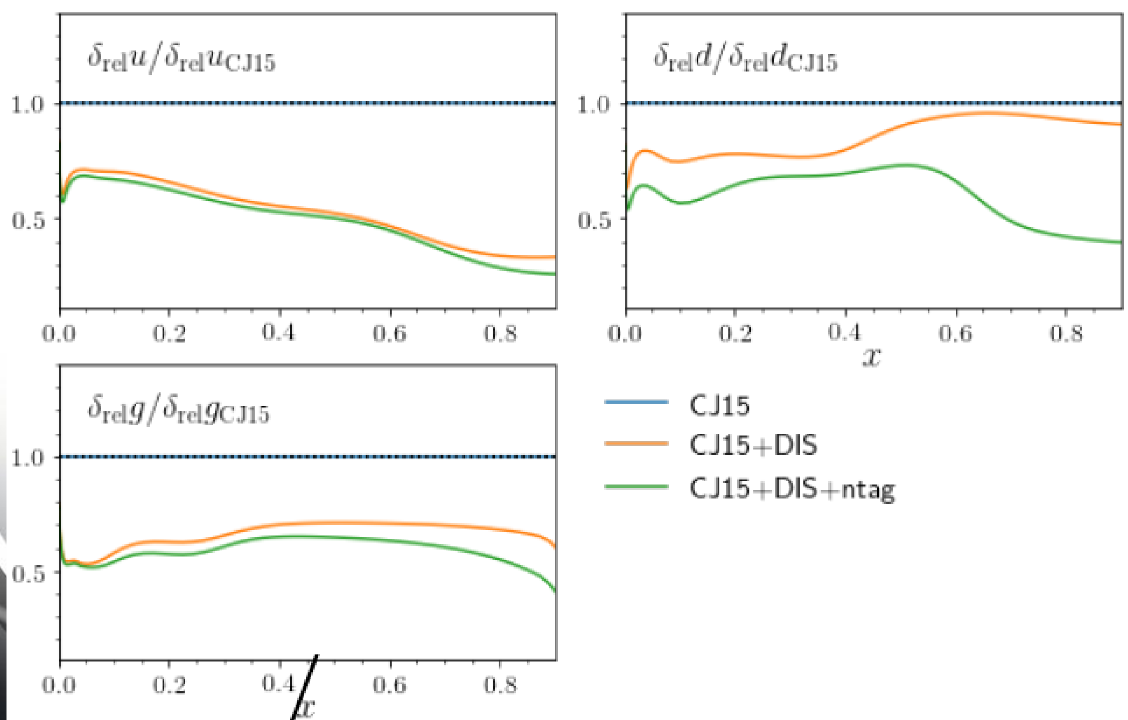
A. Accardi et al.

# Proton PDFs at high x




## Baseline: CJ-15




## Relative error improvement:

- pseudo-data for 0.01 < x < 0.9
- NC Cross sections on proton target
- $F_2^n$ from deuterium with tagged proton spectator
- 10x100 $GeV^2$ at 100 $fb^{-1}$,
- energy scan $\sqrt{s}$=57, 49, 28 GeV at 10 $fb^{-1}$

→ more studies in progress

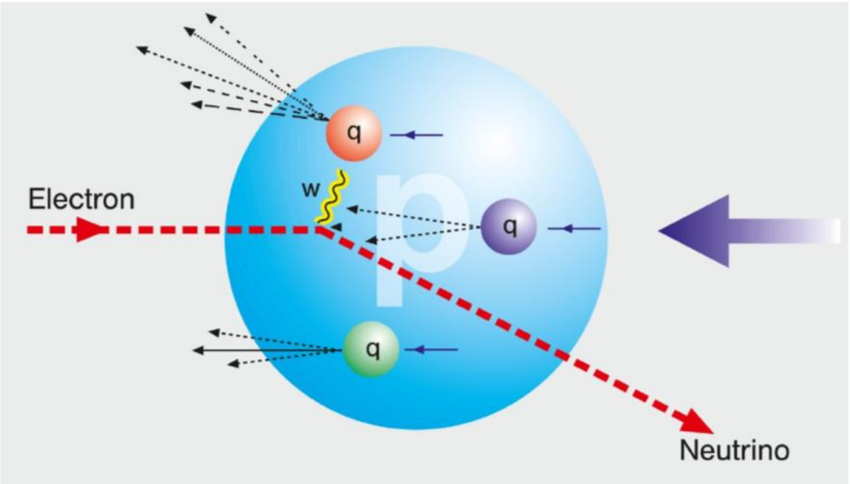
# Observables: Charge Current in ep and eA

W-exchange:
direct access to the quark flavor

Ws are maximally parity violating
→ Ws couple only to one parton helicity

$$W^- + p \rightarrow u\bar{d}$$

$$W^- + n \rightarrow d\bar{u}$$

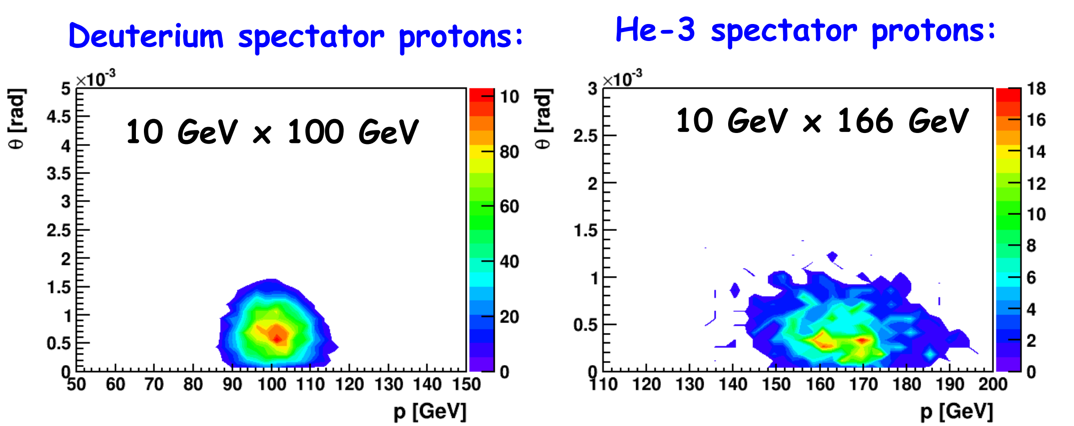



Complementary to SIDIS:

- high $Q^2$-scale: > 100 $GeV^2$
- best way to measure at very high x
- extremely clean theoretically
- No Fragmentation function

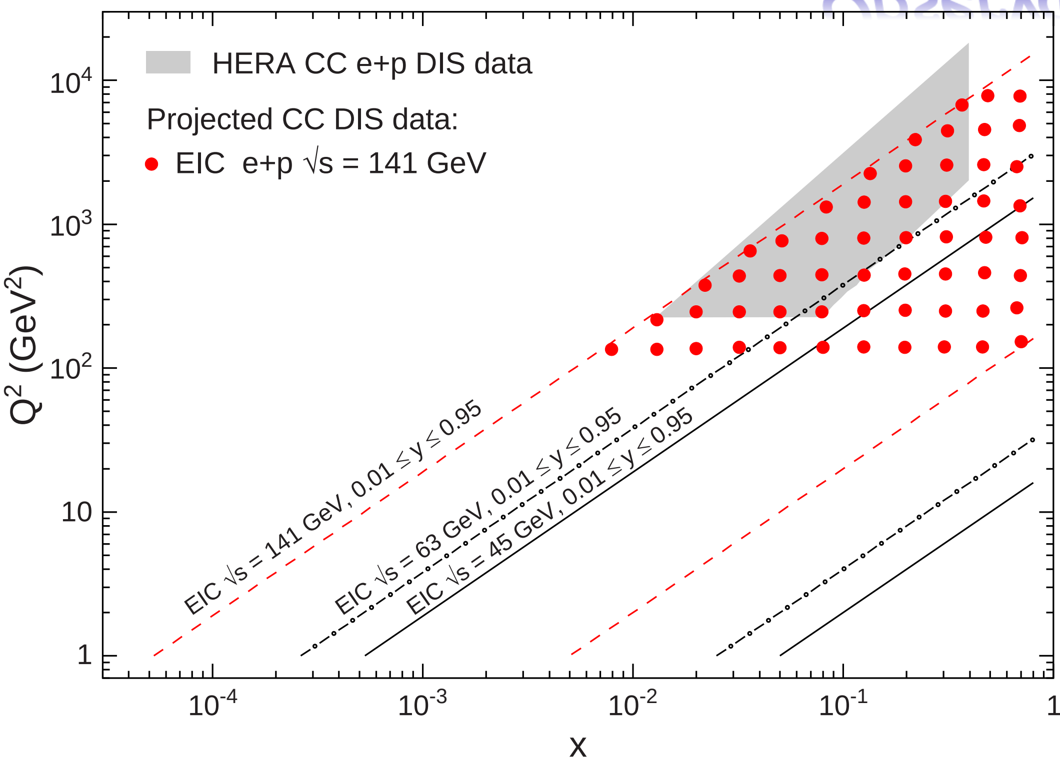
→ stringent test on theory approach for SIDIS
UNIVERSALITY of PDFs

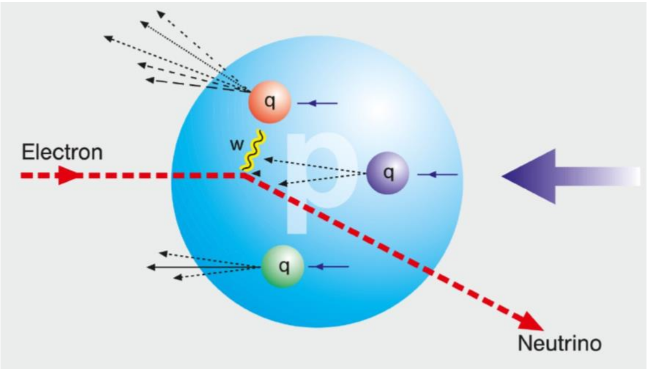
effective neutron target:
(un)polarized Deuterium or /and He-3
through tagging the spectator proton(s)

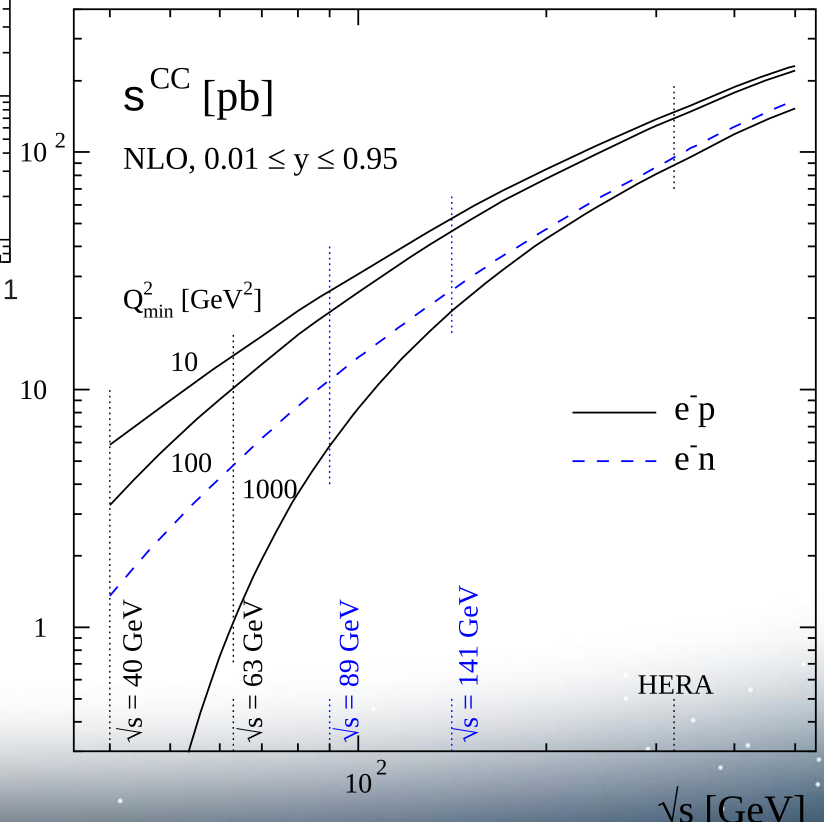



EIC:
first time charge current physics in polarized ep and eA collisions

# Observables: Charge Current in ep



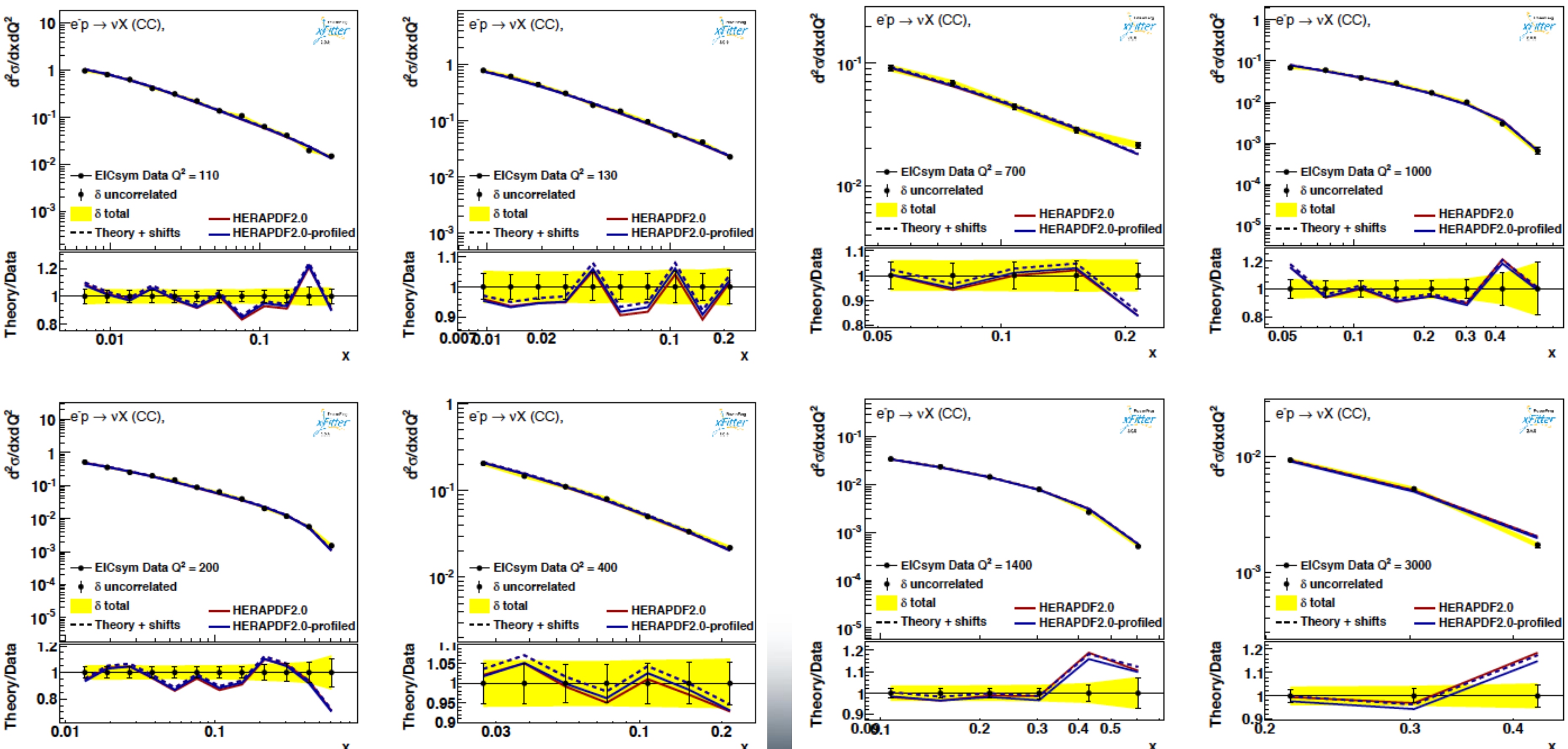

EIC has a large kinematic coverage for charge current events ( ○ )

# CC@EIC: Impact on PDFs

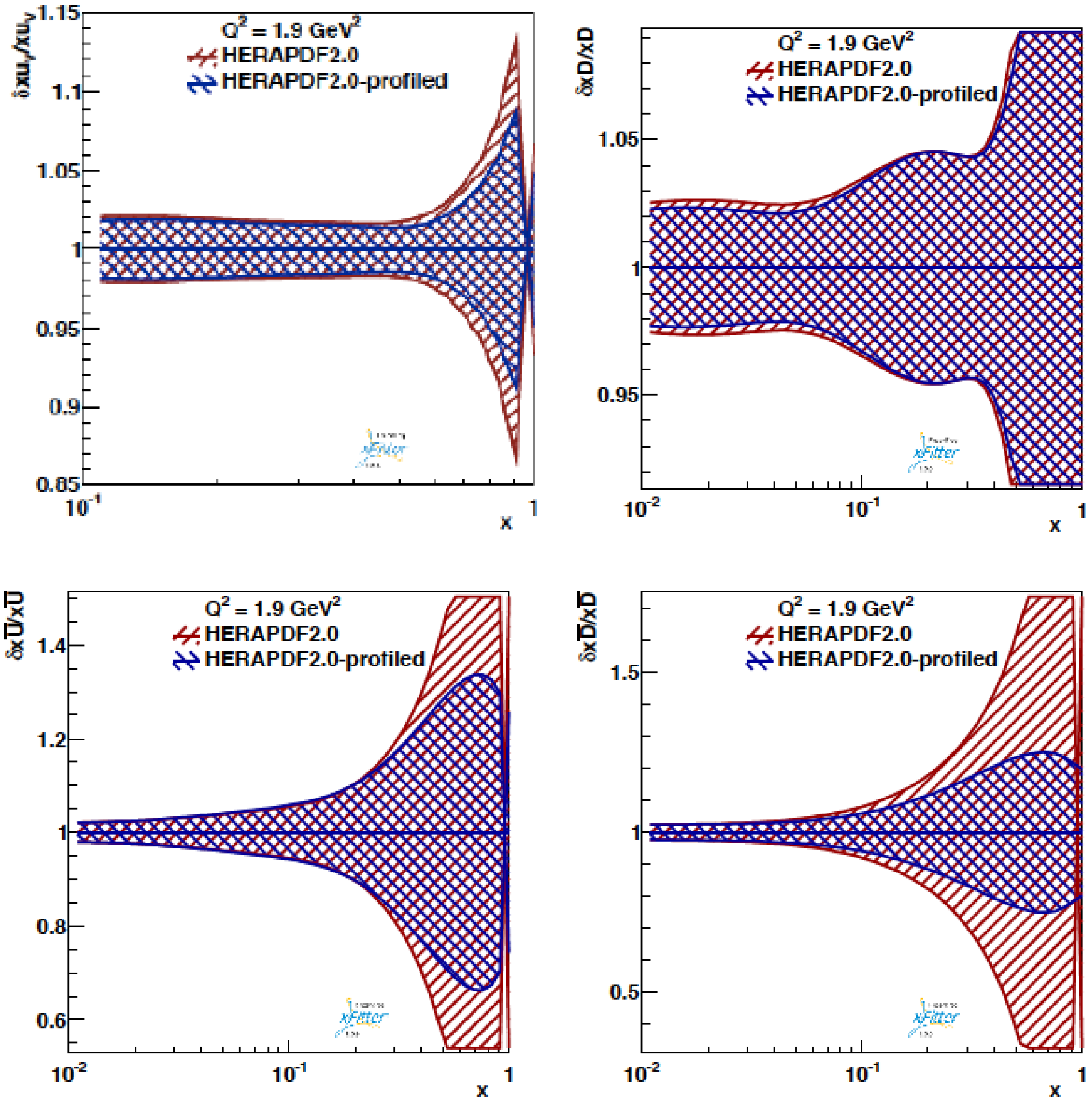
Generated 10 $fb^{-1}$ worth of ep CC events with DJANGOH for 20 GeV x 250 GeV

xFitter is used to get the impact on PDFs

good agreement between pseudo-data and prediction



# Impact of CC@EIC to PDFs

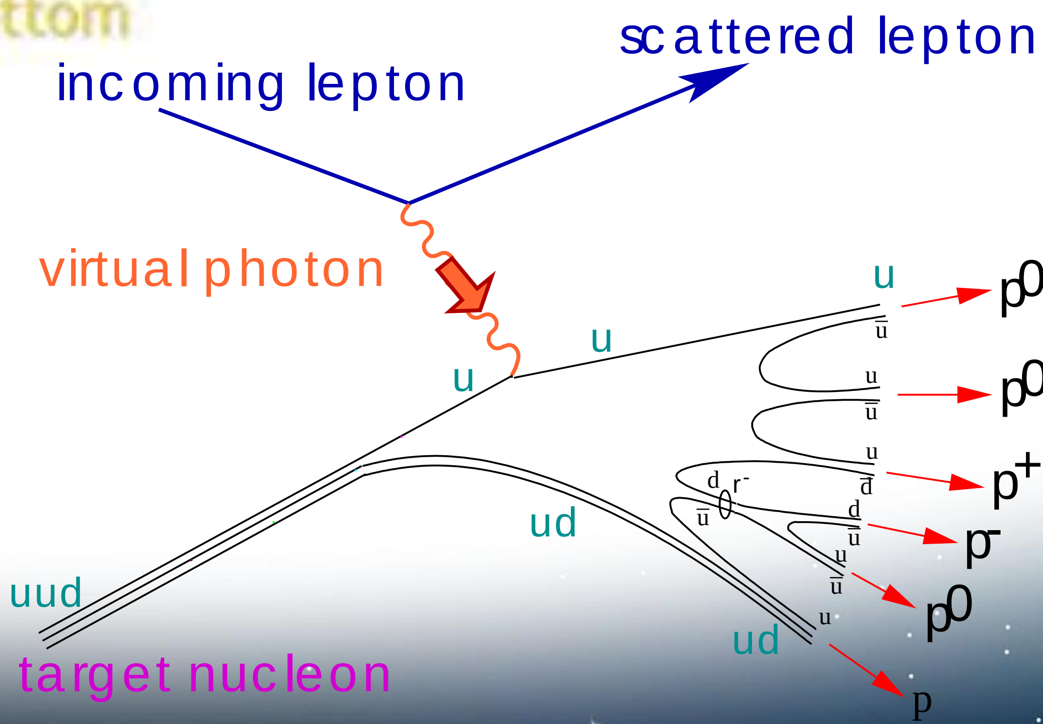



$$xU = xu + xc$$
$$xD = xd + xs$$
$$x\bar{U} = x\bar{u} + x\bar{c}$$
$$x\bar{D} = x\bar{d} + x\bar{s}$$
$$xu_v = xU - x\bar{U}$$
$$xd_v = xD - x\bar{D}$$

Very strong impact on $x\bar{D}$
significant impact on $xu_v$
Need to still understand in detail why there is impact on $x\bar{U}$

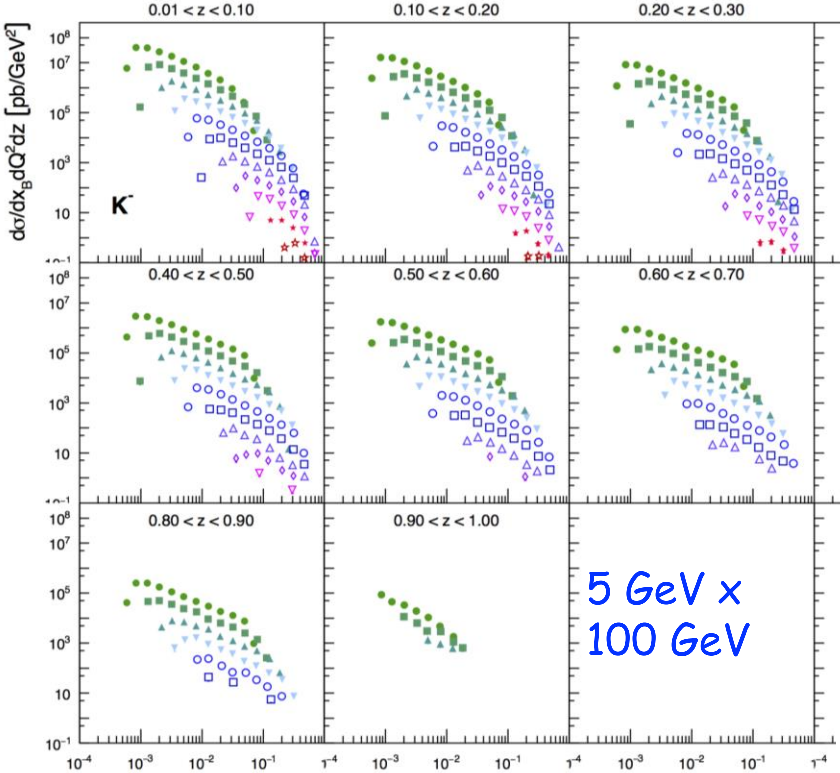
→ very promising first results

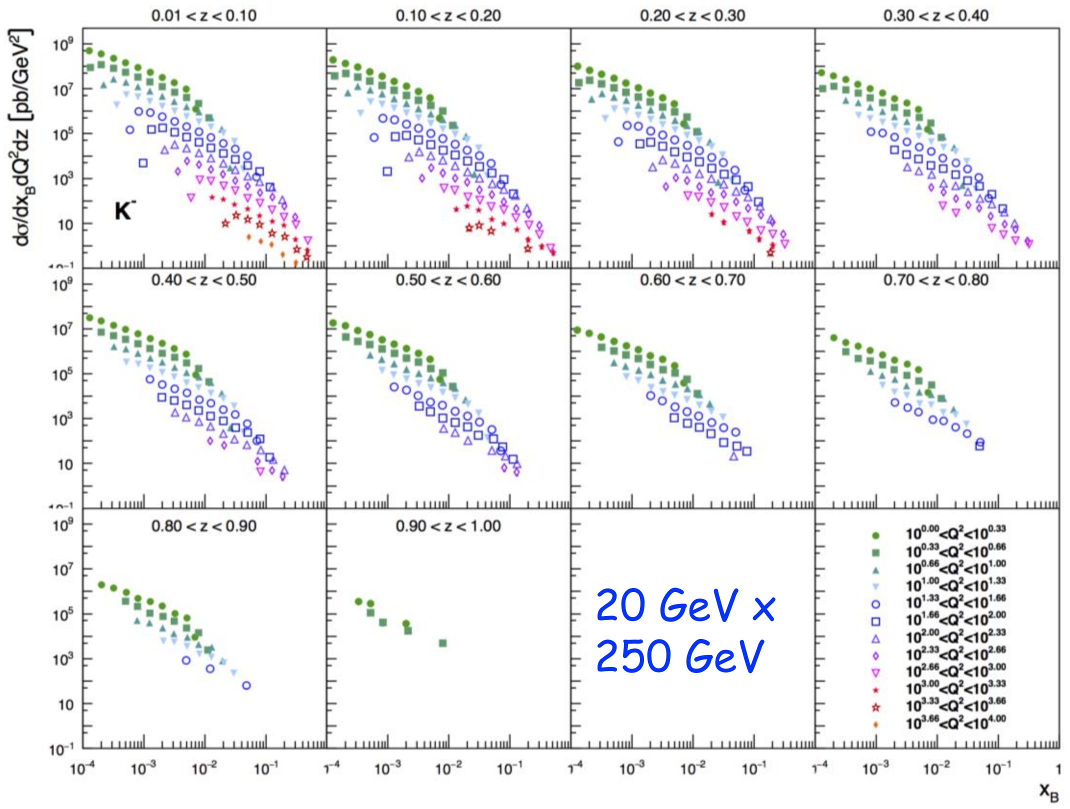
# Access the Flavor Structure: SIDIS

# What can SIDIS@EIC Teach us

very precise 3d cross section covering a wide kinematics in z,x,$Q^2$



# PDFs: flavor separation from SIDIS@EIC

Use reweighting method to define EIC SIDIS data impact on collinear unpolarized PDFs and Fragmentation functions

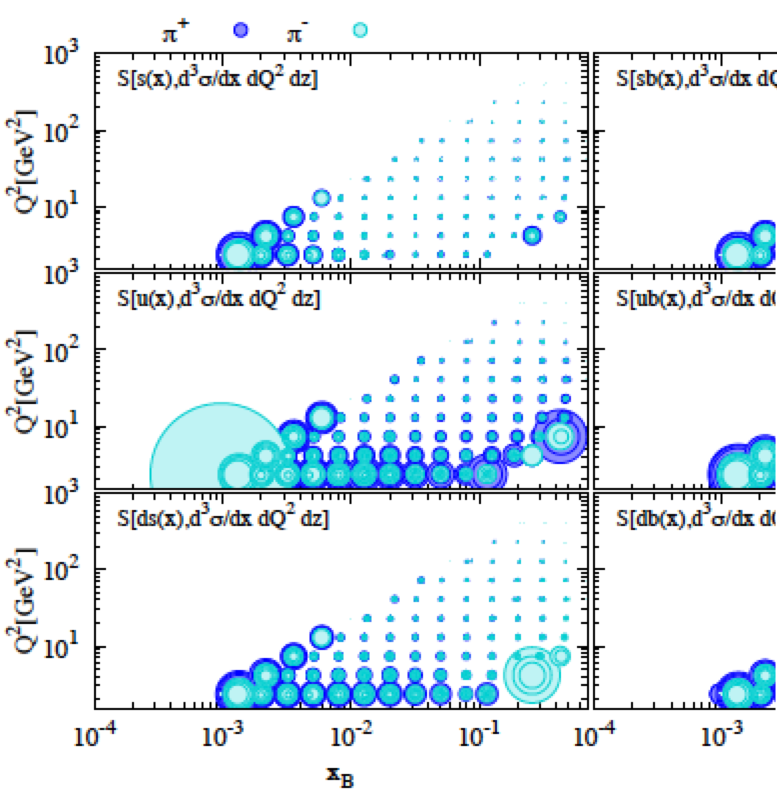
Correlation factor of observable $\mathcal{O}$ to a flavor i

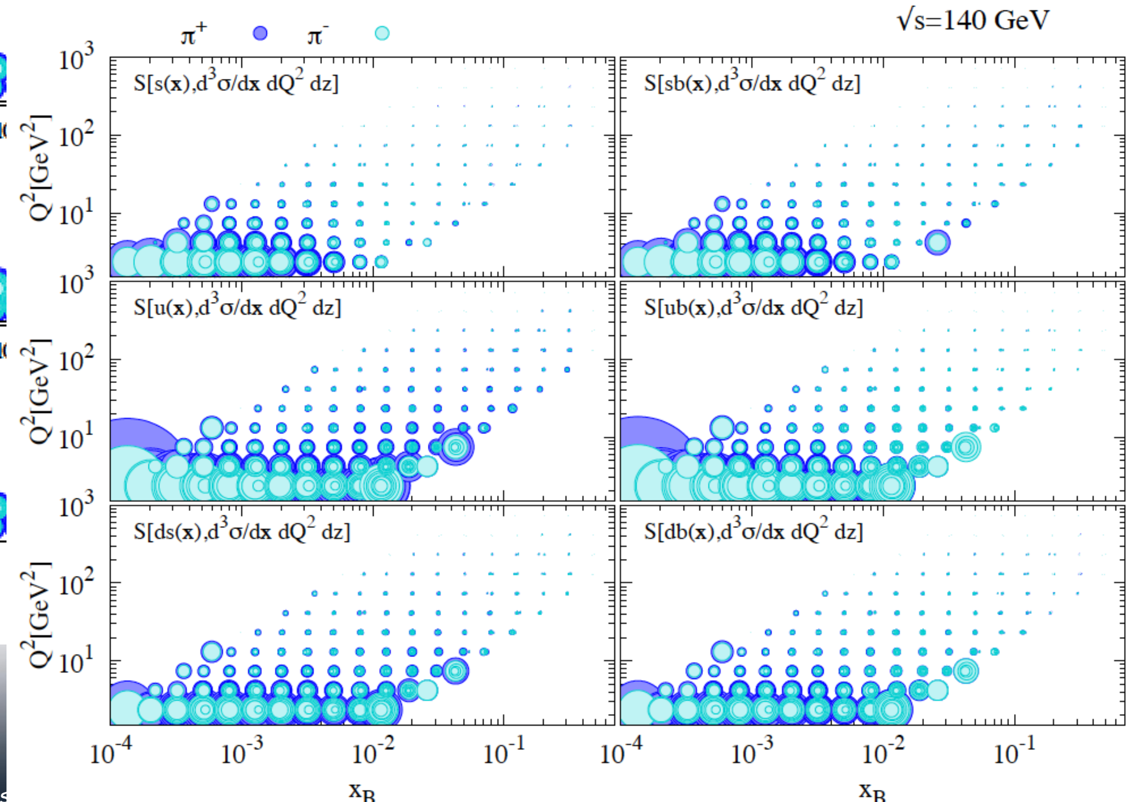
$$\rho\,[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\Delta\mathcal{O}\Delta f_i}\,, \quad \xrightarrow{\text{account for uncertainties}} \quad S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\xi\,\Delta\mathcal{O}\Delta f_i}\,,$$

$$\xi \equiv \frac{\delta\mathcal{O}}{\Delta\mathcal{O}}$$

$\delta\mathcal{O}$ : exp. uncertainty Observable

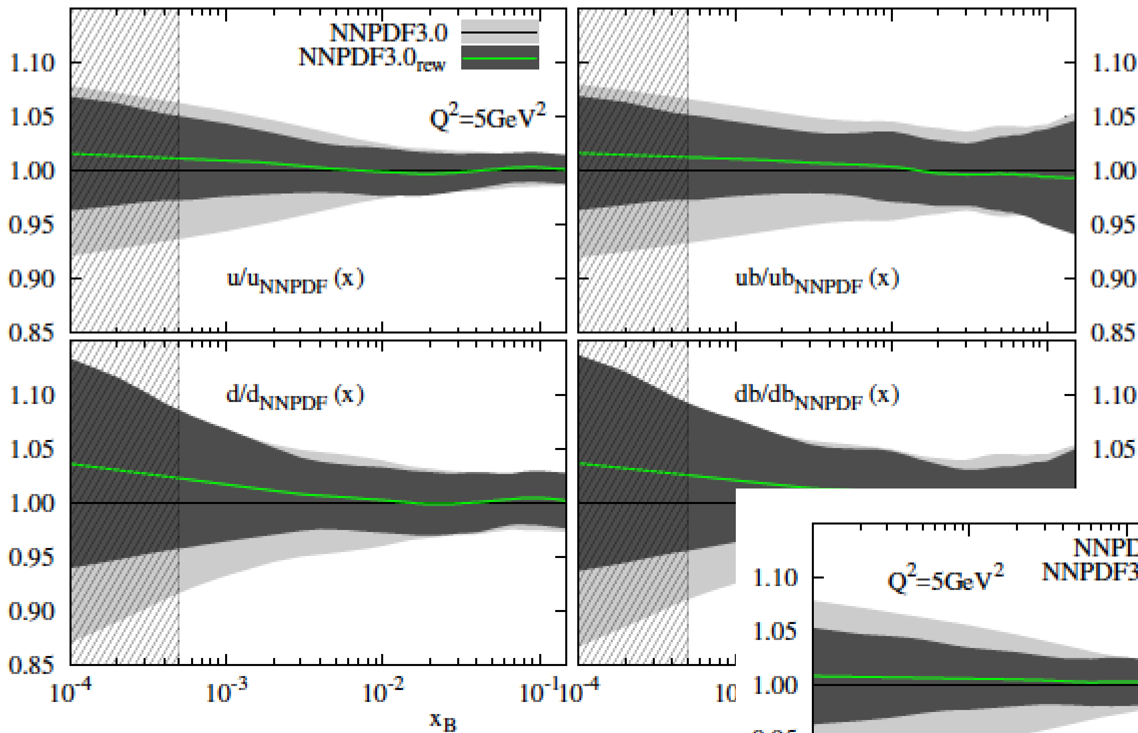
$\Delta$ PDF in Observable



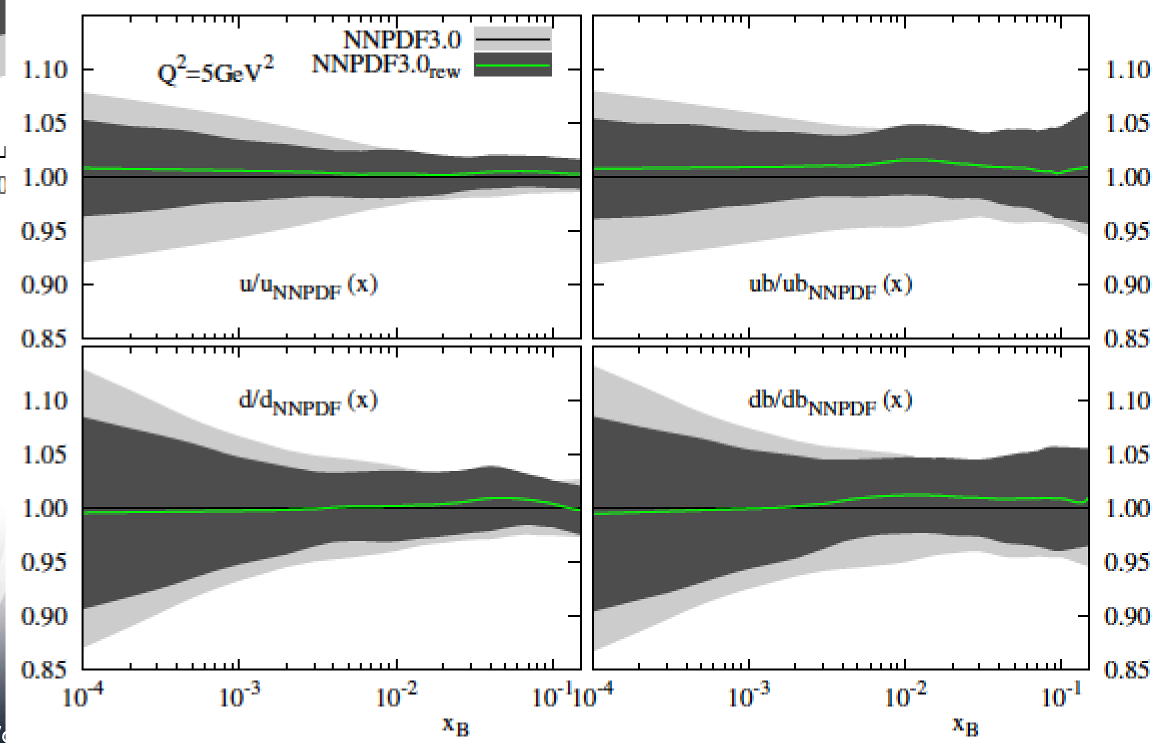



# PDF Constrain from SIDIS@EIC

√s=45 GeV



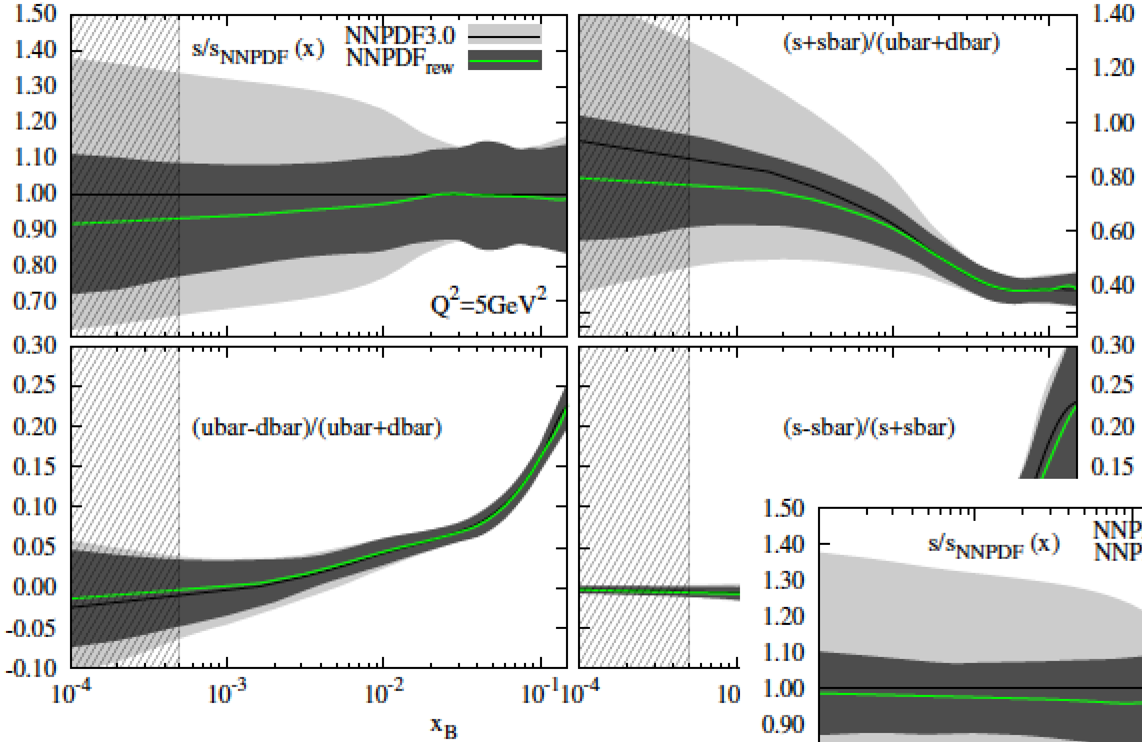

√s=145 GeV



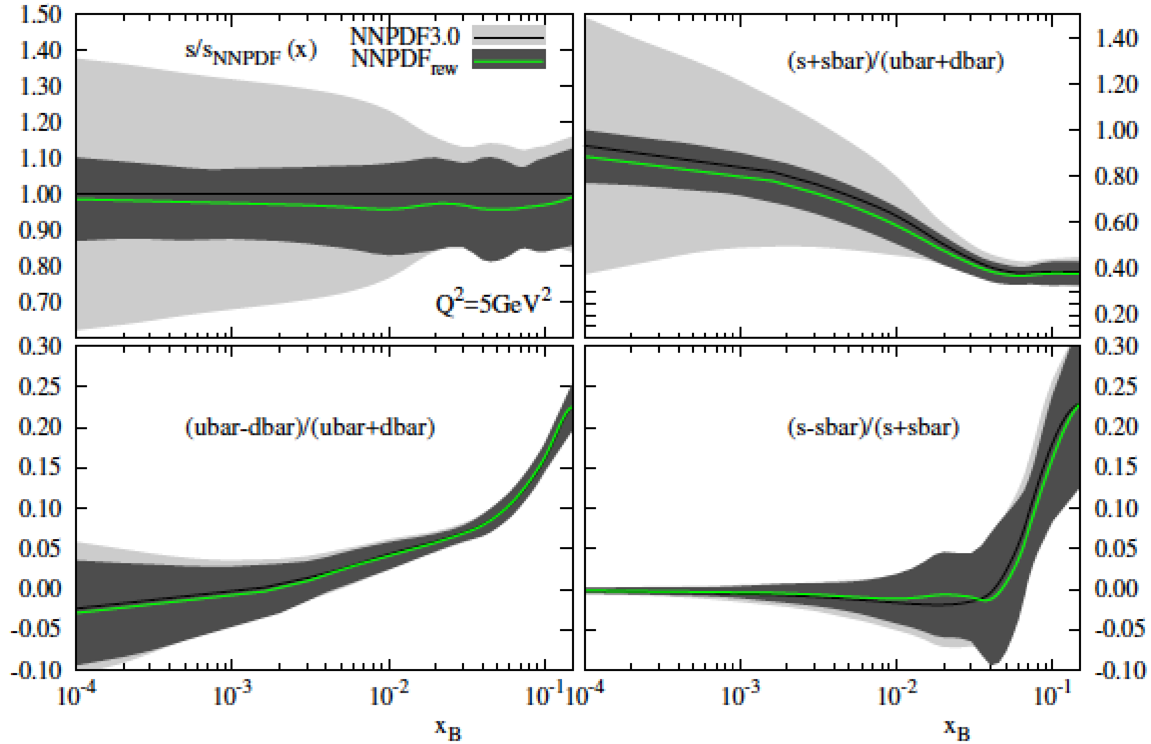

Impressive constrain of light quarks for $x < 0.1$
need to investigate $x > 0.1$ more
→ impact grows with √s

# PDF Constrain from SIDIS@EIC

√s=45 GeV



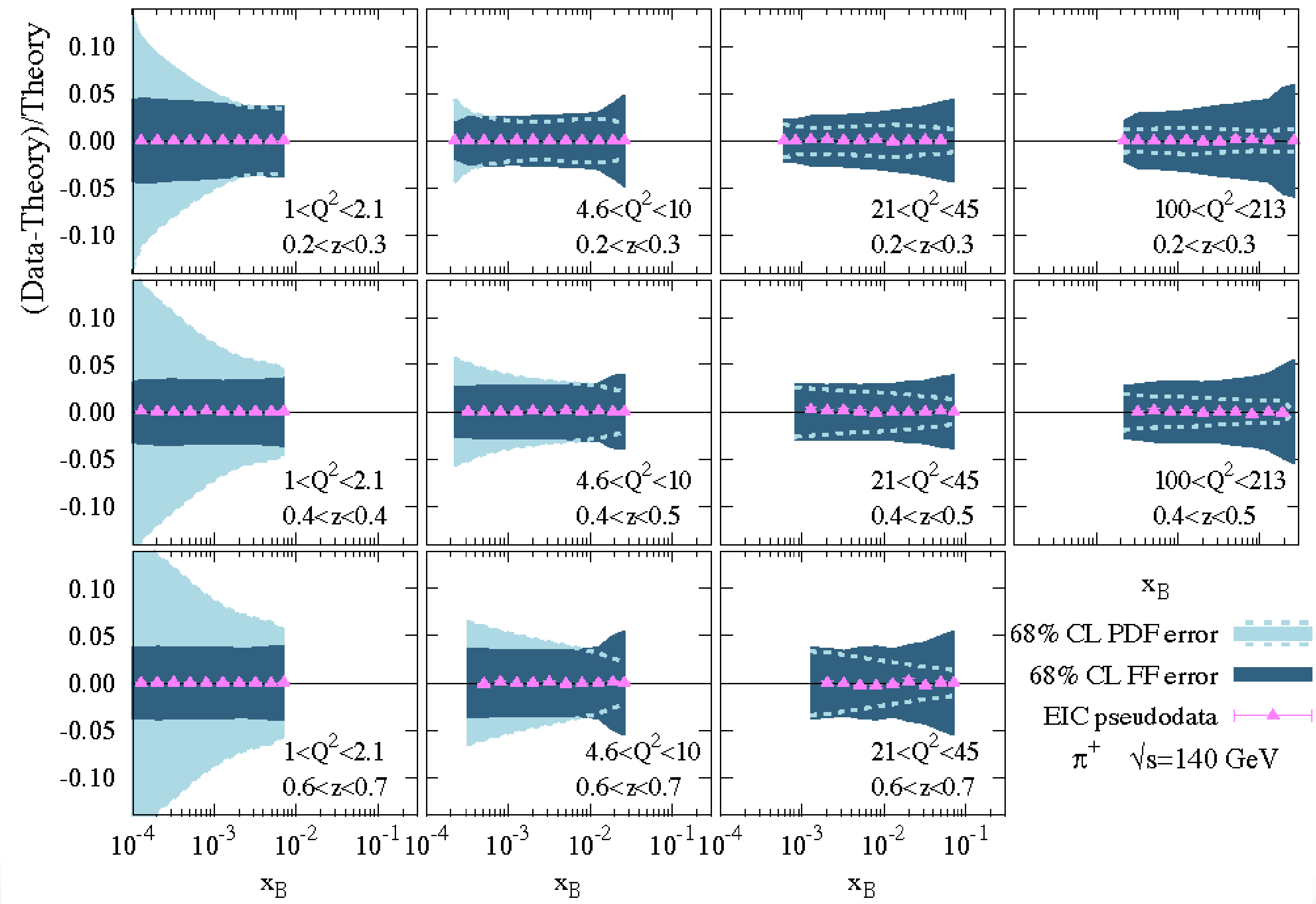

√s=145 GeV




If you want to know
s-PDF ask the EIC
→ impact grows with √s


LPC W

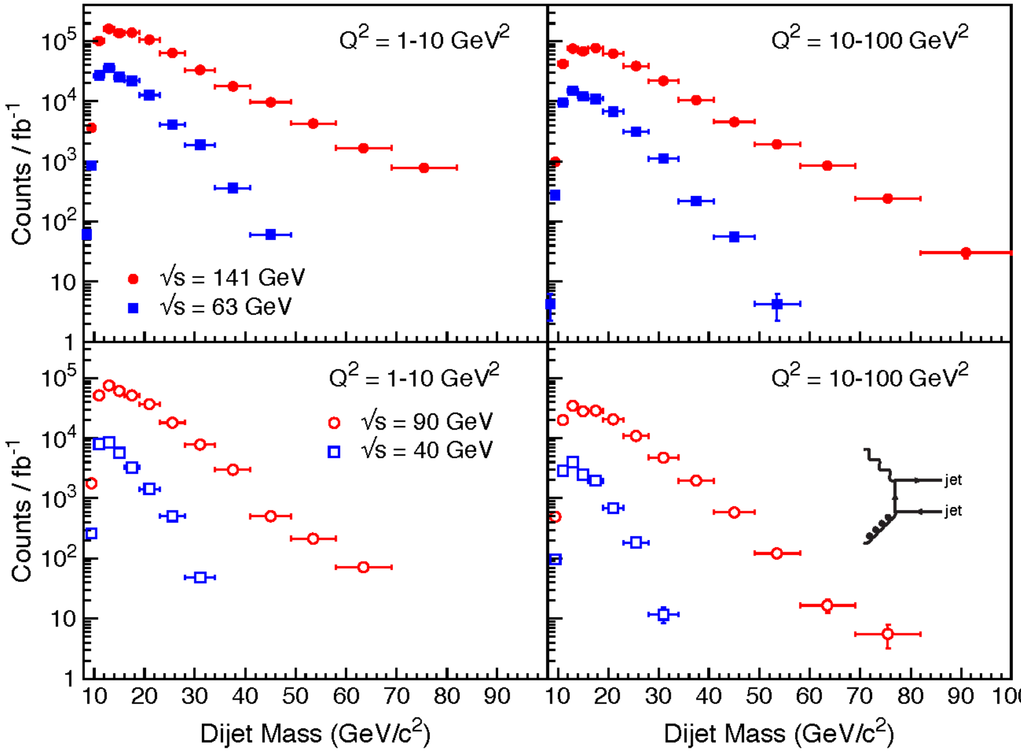
# Lesson learnt



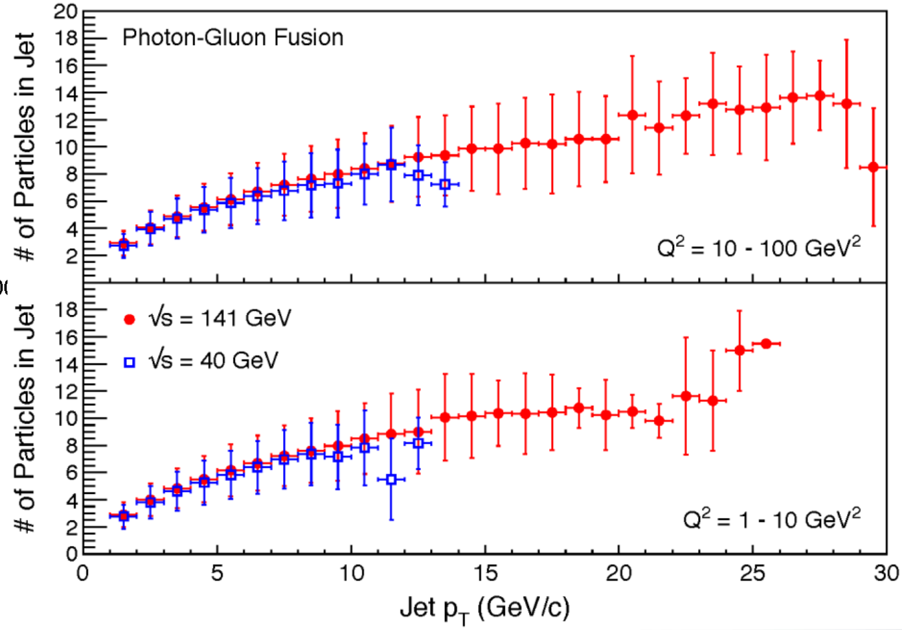

If one wants to obtain the best PDF and FF constrain it will be critical **to perform a combined fit**

# Jets at EIC

# Observables: Di-Jets

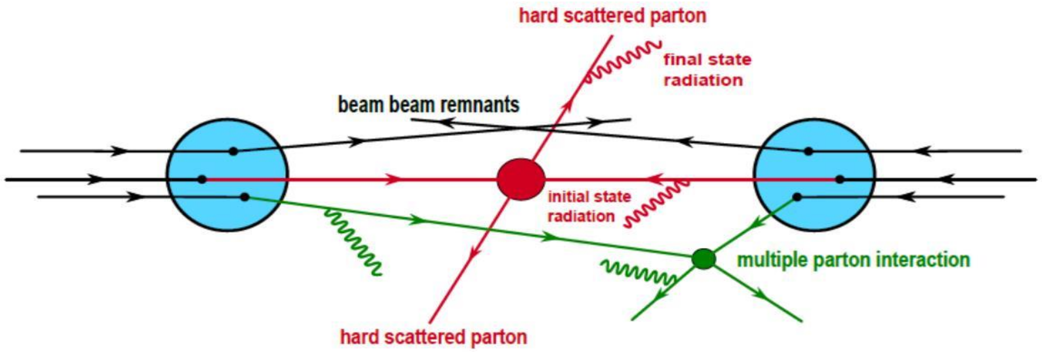


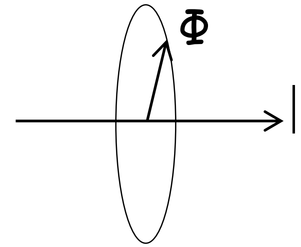

Experimental Aspects of Jet Physics at a Future EIC arXiv:1911.00657



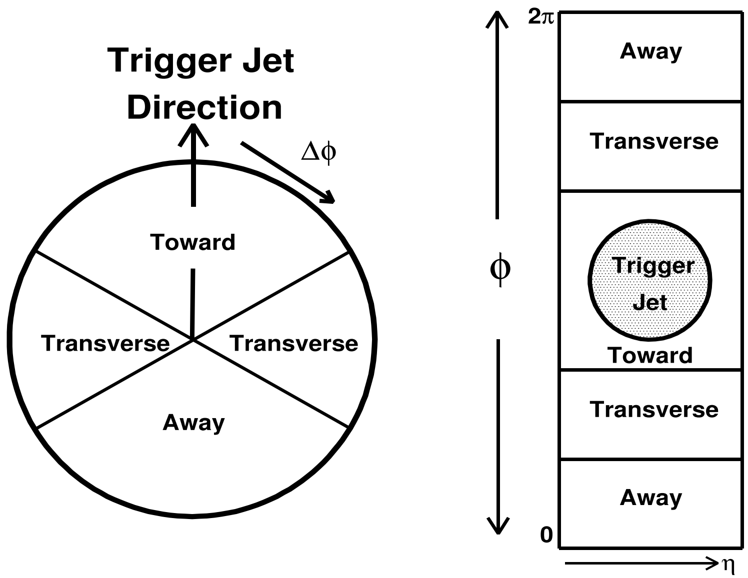

Only with highest EIC center-of-mass energies one can reach high di-jet masses cannot be compensated with higher luminosity at lower √s

# Underlying Event




Underlying event: everything except the particles fragmented from the hard scatted partons

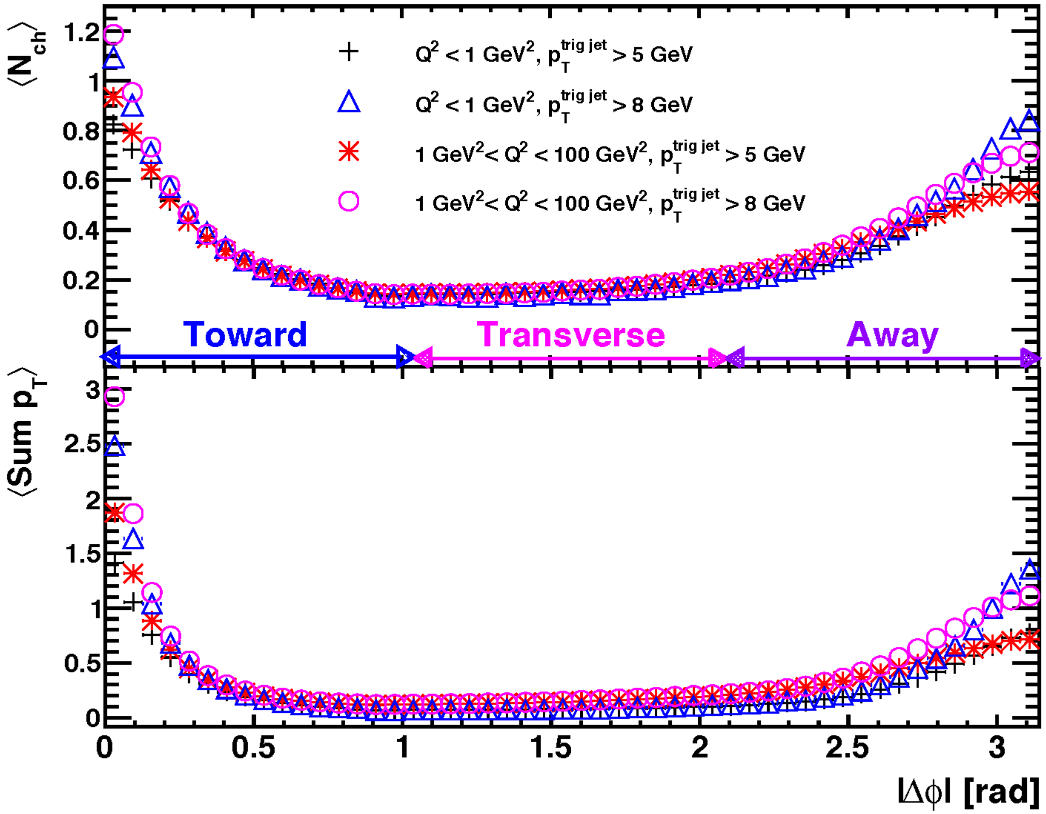


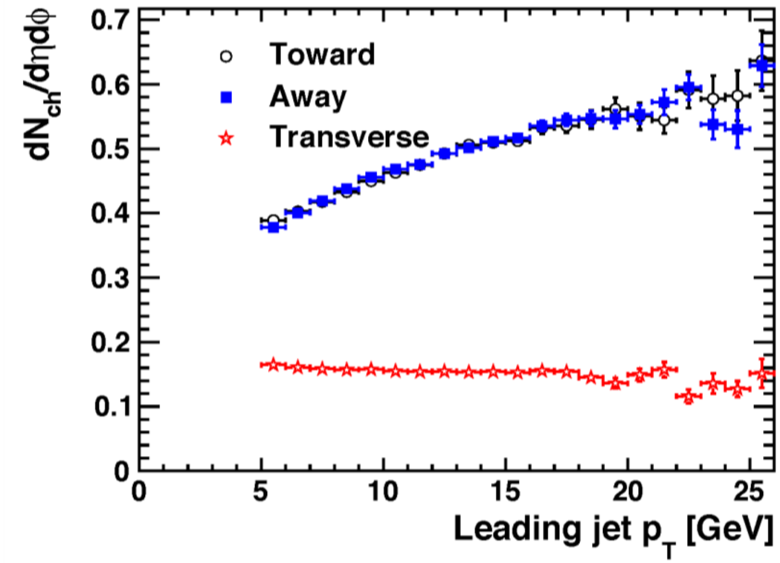

- Toward: $|\Delta\Phi| < 60$ degree,
- Transverse: $60 < |\Delta\Phi| < 120$,
- Away: $|\Delta\Phi| > 120$

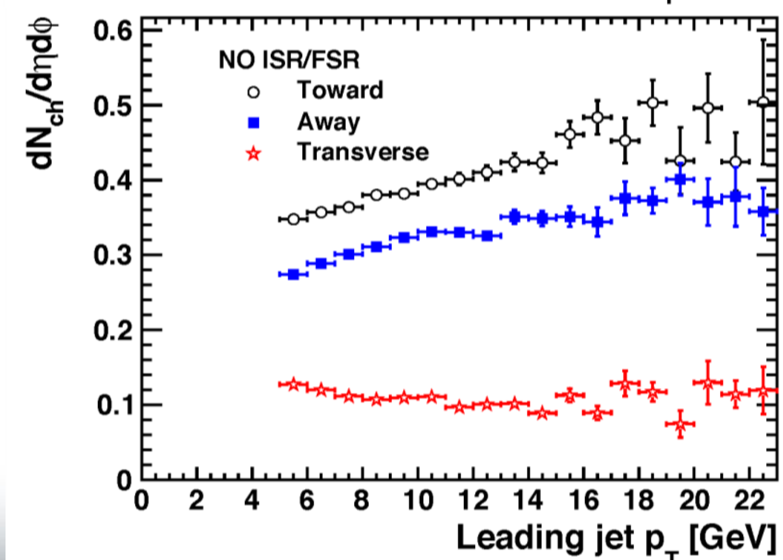
- Trigger Jet is Jet with highest $p_T$, $\Delta\Phi = \Phi_{part} - \Phi_{Jet1}$

- *Measurements*
- charged multiplicity density, sum $p_t$ density
- Density difference in 3 regions

# Underlying Event

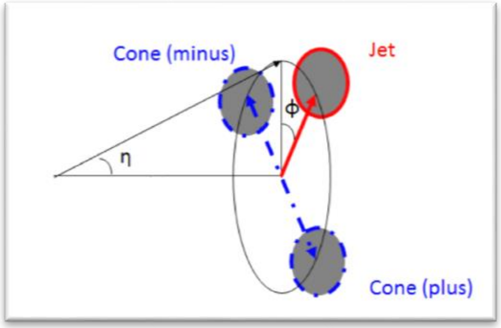


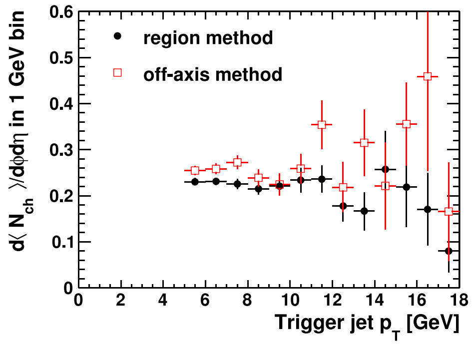



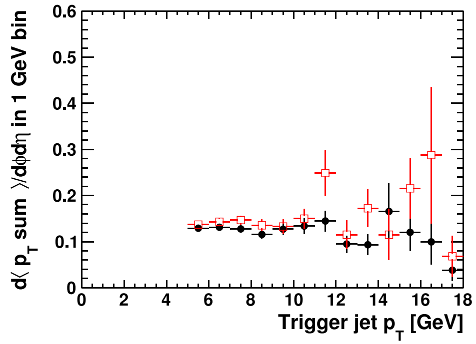

- The underlying event is very small, which makes jet physics at an EIC extremely clean
- No big effect from ISR and FSR on underlying event

# Underlying Event: Comparison to pp

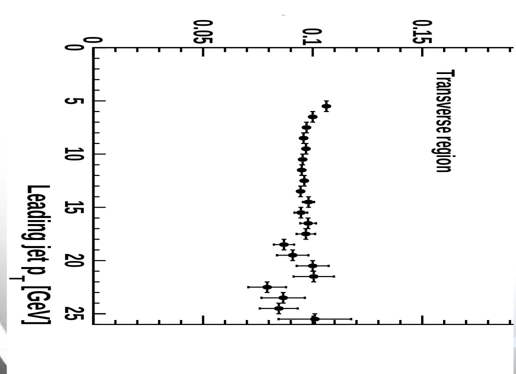


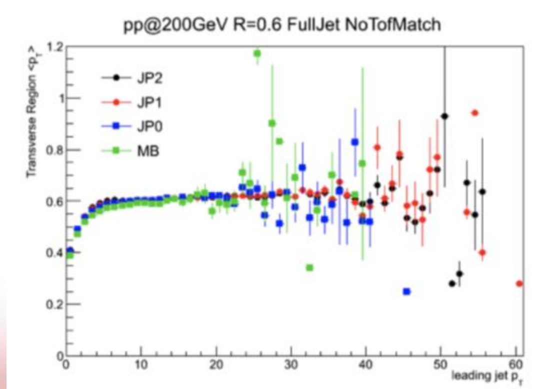

- ✓ In each event, we analyze jets with high momentum, jet by jet.
- ✓ For each jet, we define two cones (r = 0.4).
- ✓ Each cone is centered at the same as the jet but $\pm\pi/2$ away in $\Phi$ from the jet $\Phi$.
- ✓ Take the particles from the two cones as underlying event.



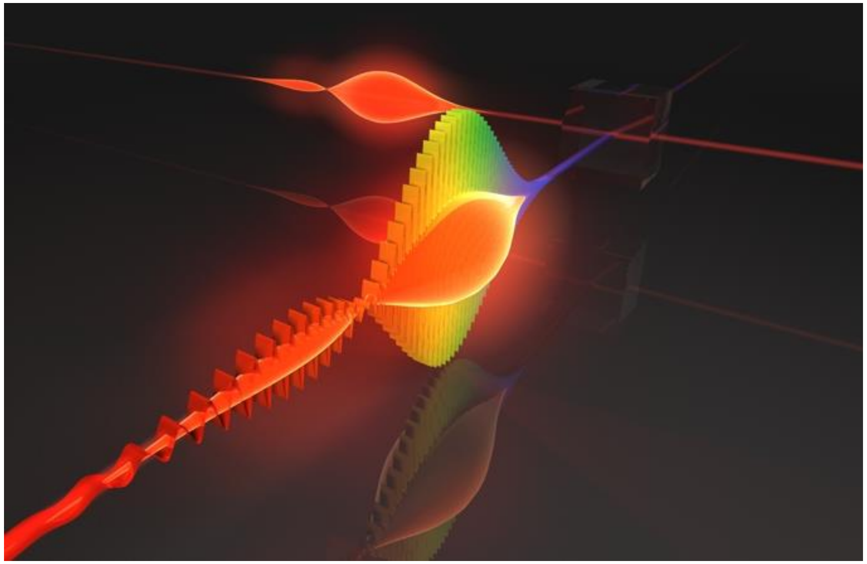

Results from the two different methods are consistent.




$1\ GeV^2 < Q^2 < 10\ GeV^2$, transverse region, $p_T$ corrections at EIC, much smaller than STAR

EIC rapidity cut (-4,4) instead of using (-1,1) as for STAR



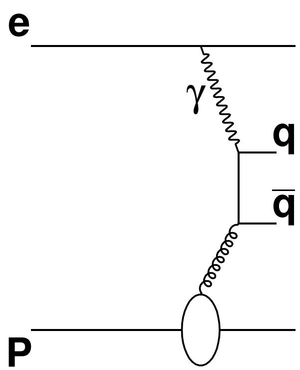
# Example for Jet Physics at an EIC:

# Unpolarized and polarized parton structure of photons

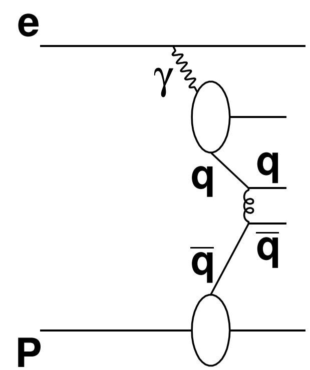
Details: X. Chu, ECA arXiv:1705.08831

# Photon Parton Structure

In high energy ep collision, two types of processes lead to the production of di-jets:



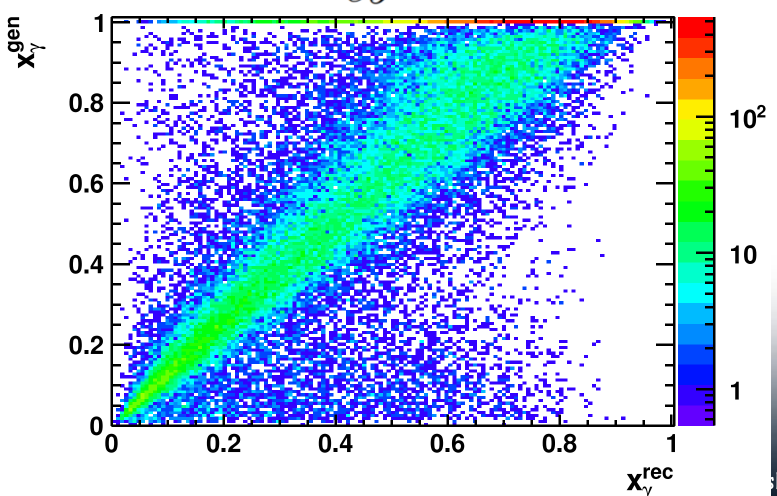

direct: point-like photon

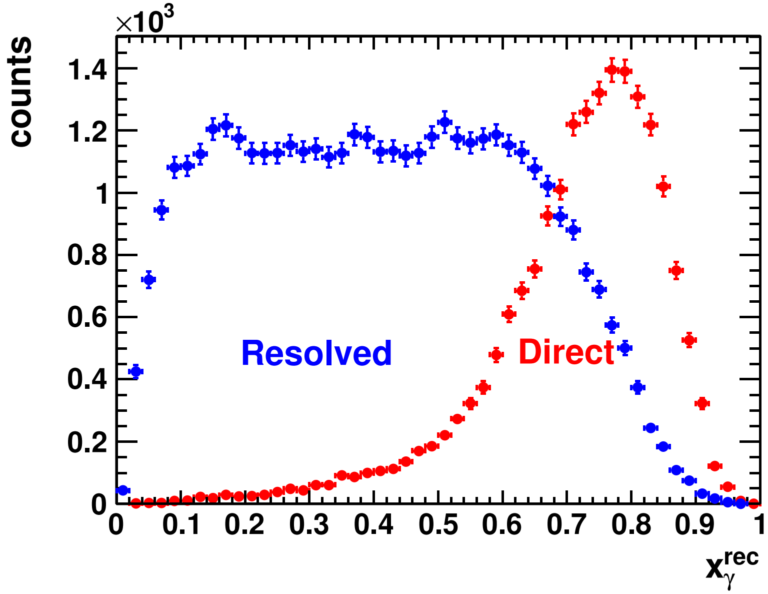



resolved: hadronic photon

- **Di-jets@EIC ideal probe to constrain (un)polarised Photon-PDFs**
  - **Direct/resolved contributions can be separated** reconstructing $x_\gamma$

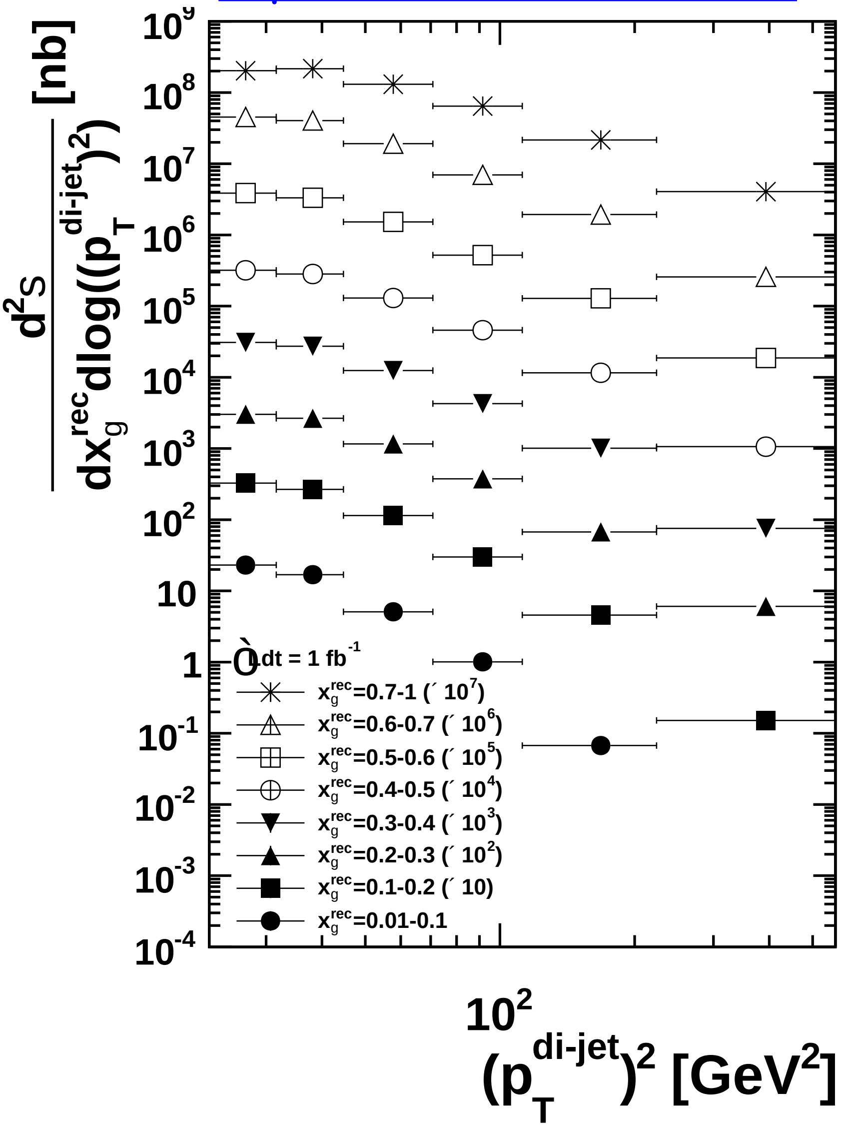
$$x_\gamma^{rec} = \frac{1}{2E_e y}(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2})$$



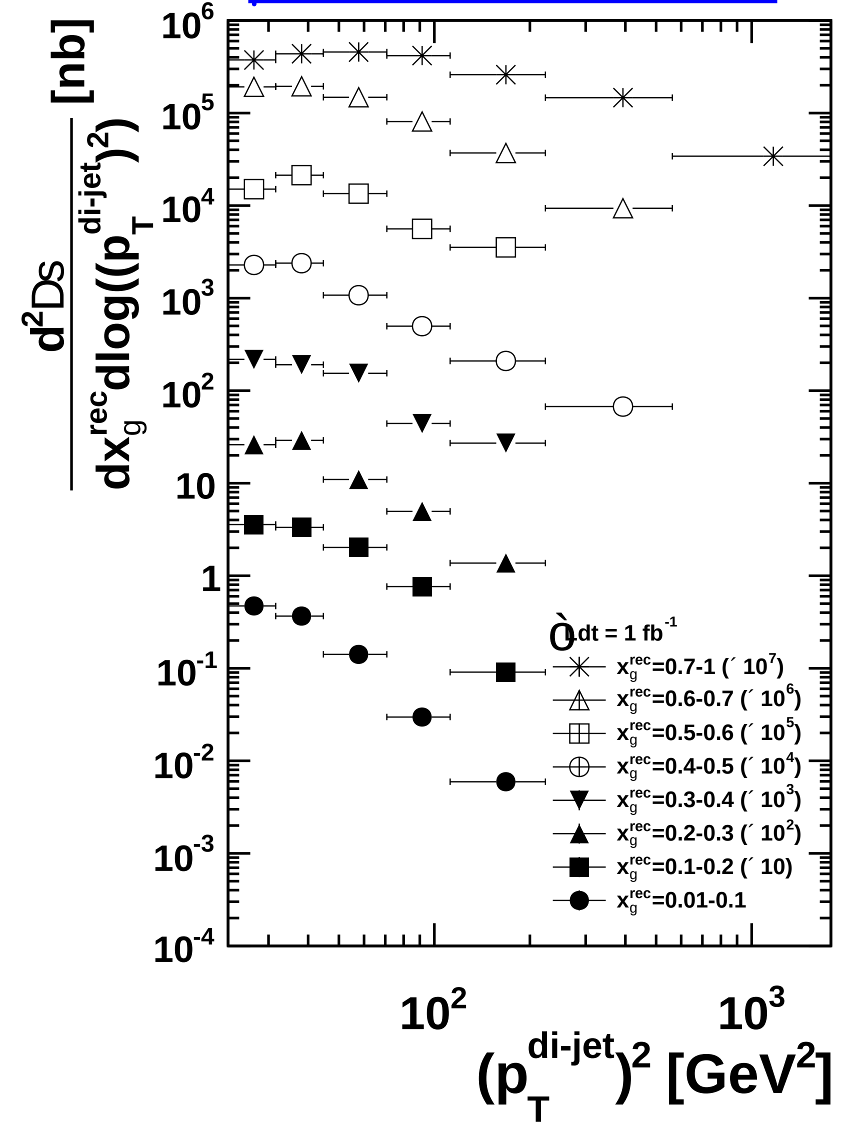
# Photon Parton Structure

unpolarized cross section:



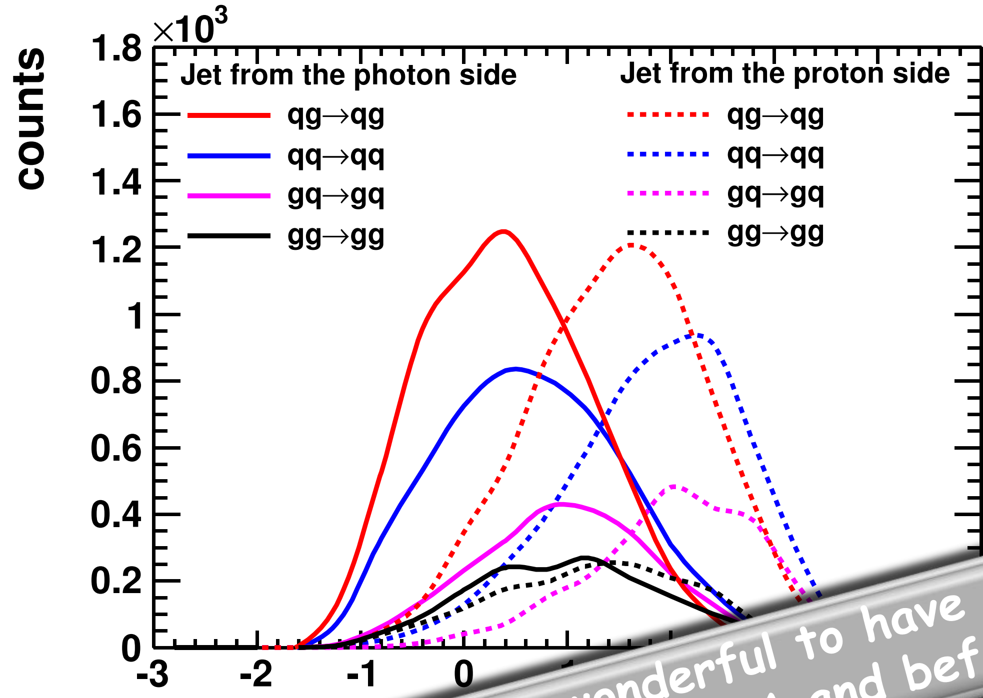

Input: proton-CTEQ-5 & $\gamma$: SAS

polarized cross section:




Input: proton-DSSV &
$\gamma$: PLB 337 373 (1994)

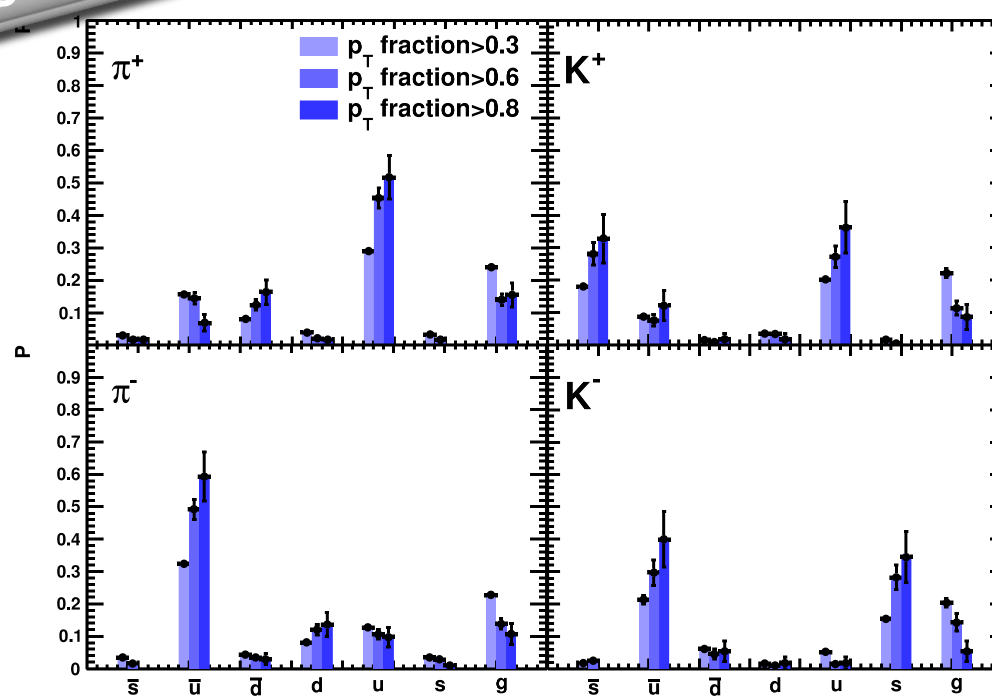
# Photon Parton Structure

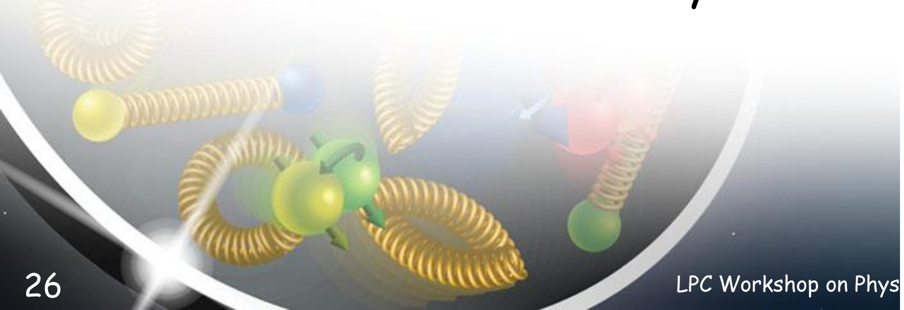



Jets from photon and proton side are well separated in $\eta$ for quark initiated processes

It would be wonderful to have unpolarised photon PDFs with all data (LEP & HERA and before) fitted with uncertainties

identified hadron tagging in jet enhances flavor sensitivity

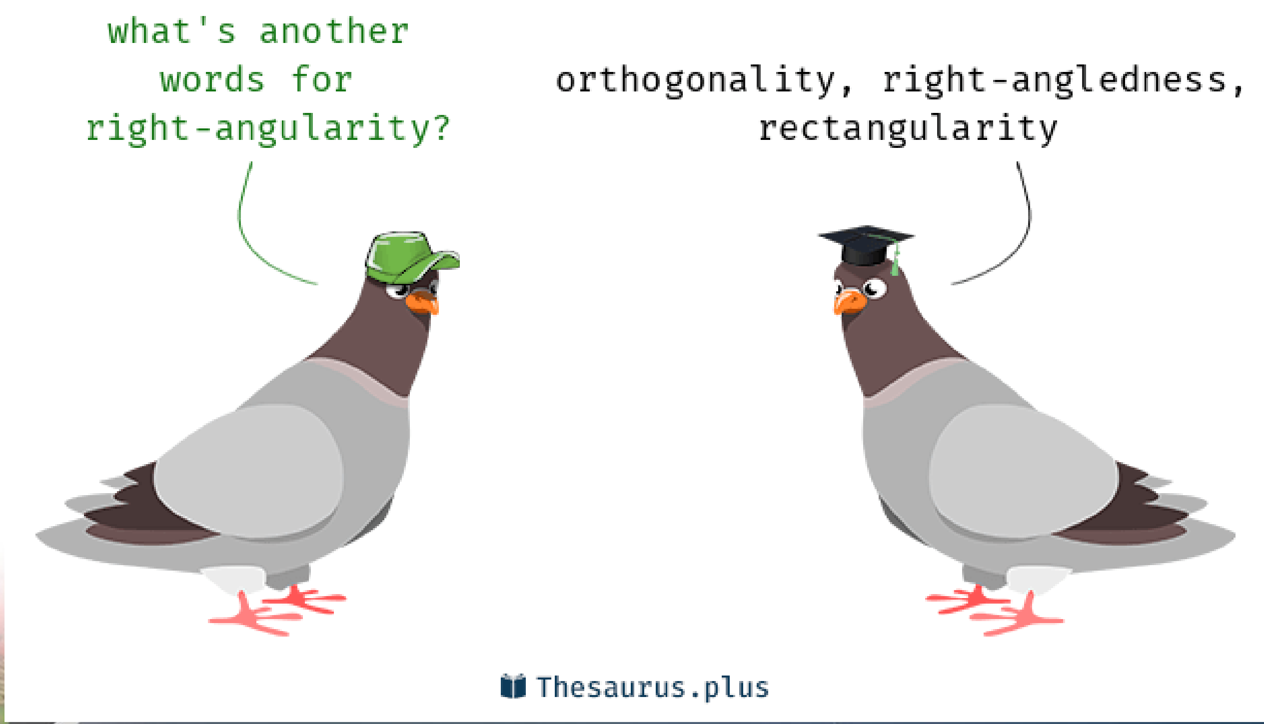


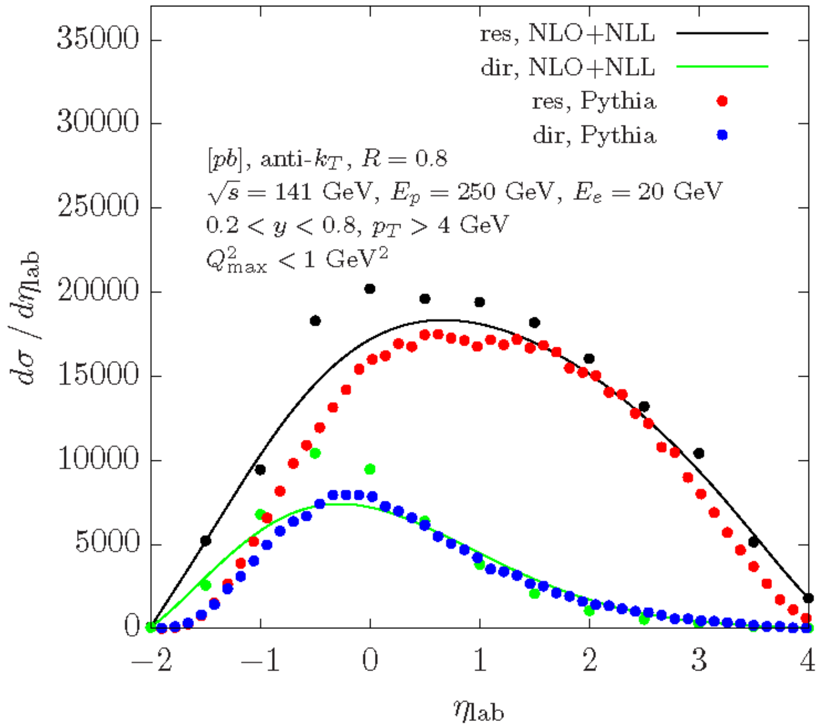
# Jet Angularity

$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

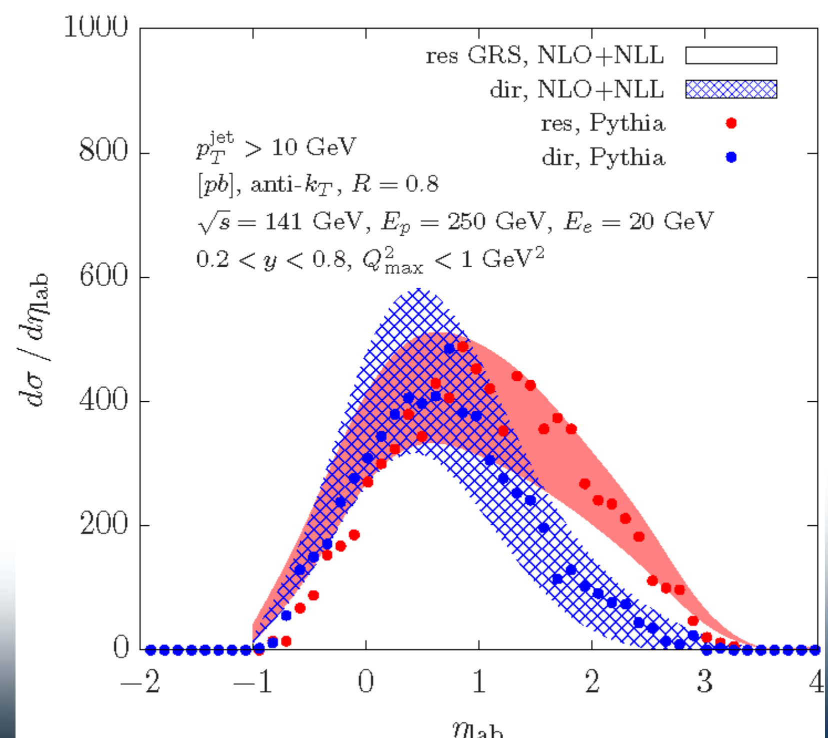
arXiv:1910.11460



# Photoproduction Cross Section

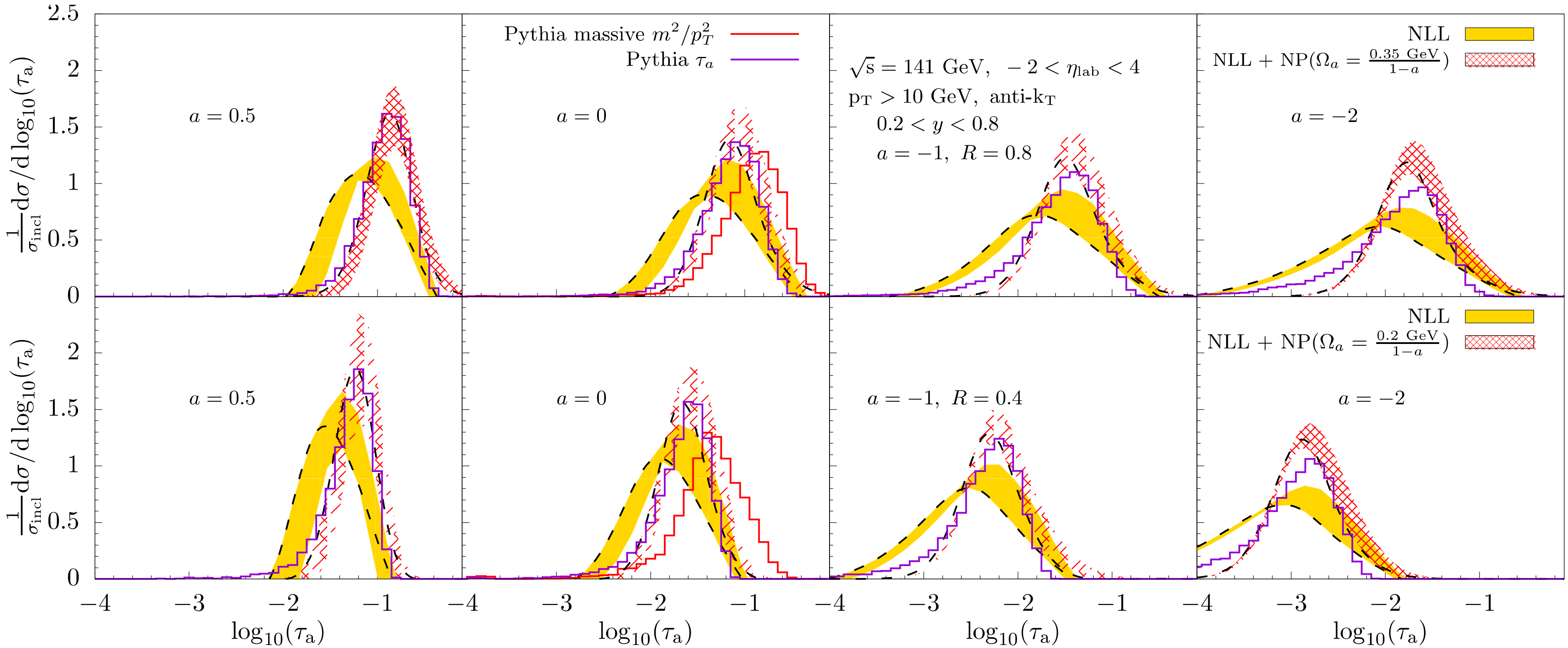



- Carry out angularity studies in photoproduction region ($10^{-5} < Q^2 < 1$)
- Resolved and direct cross sections from PYTHIA in good agreement with theoretical expectations (F. Ringer, K. Lee)



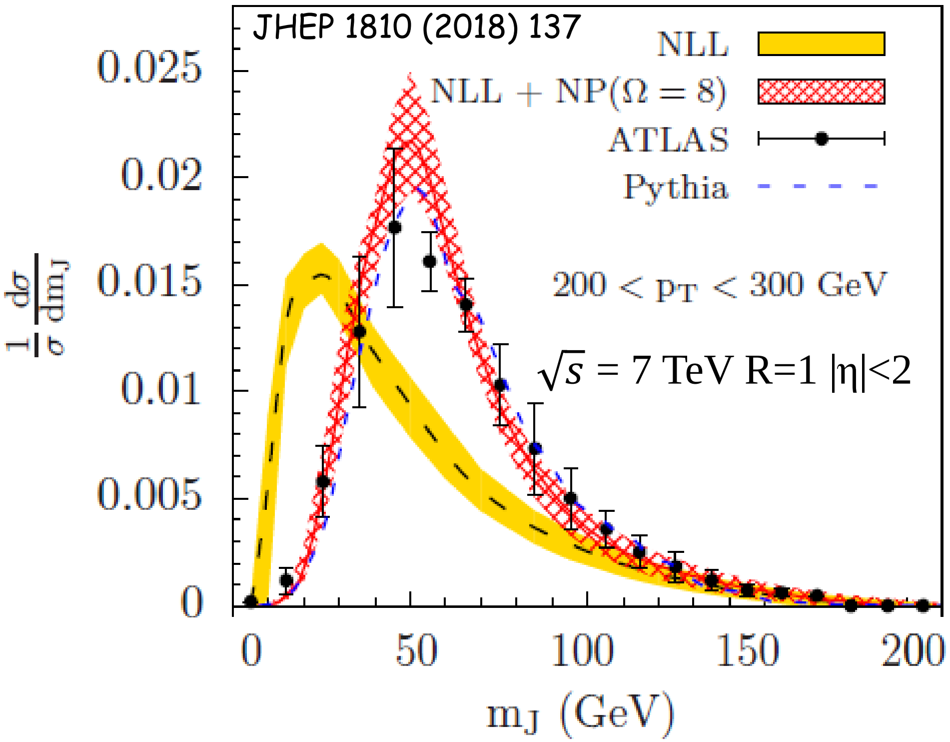

- Jet Radius = 0.8
- 0.2 < inelasticity < 0.8
- Lab Frame
- Cross sections shown for jet $p_T > 4$ and jet $p_T > 10$ GeV

# Angularity: Theory Vs PYTHIA




Good agreement with PYTHIA if non-perturbative effects, if the purely perturbative result obtained within QCD factorization are convolved with a shape function

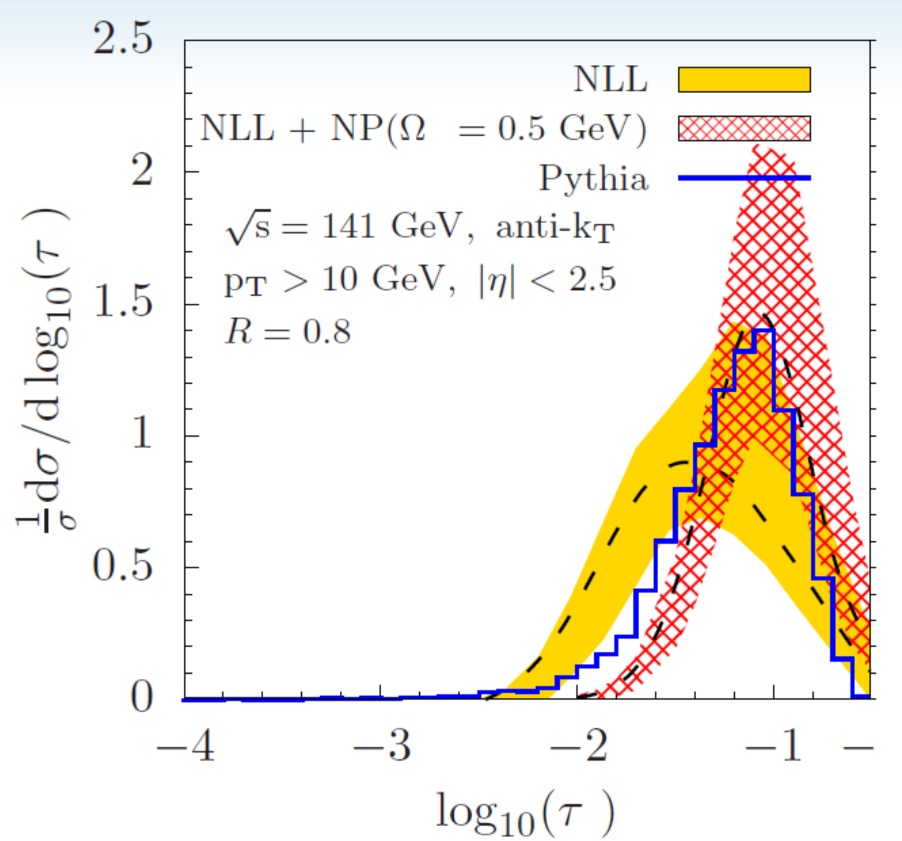
# Non-Perturbative Effects




- Non-perturbative effects (MPI and pileup) are large at the LHC but the correction shifts the perturbative results to match the data
- At the EIC, the perturbative results already agree quite well and only a small correction factor is needed to make the agreement better

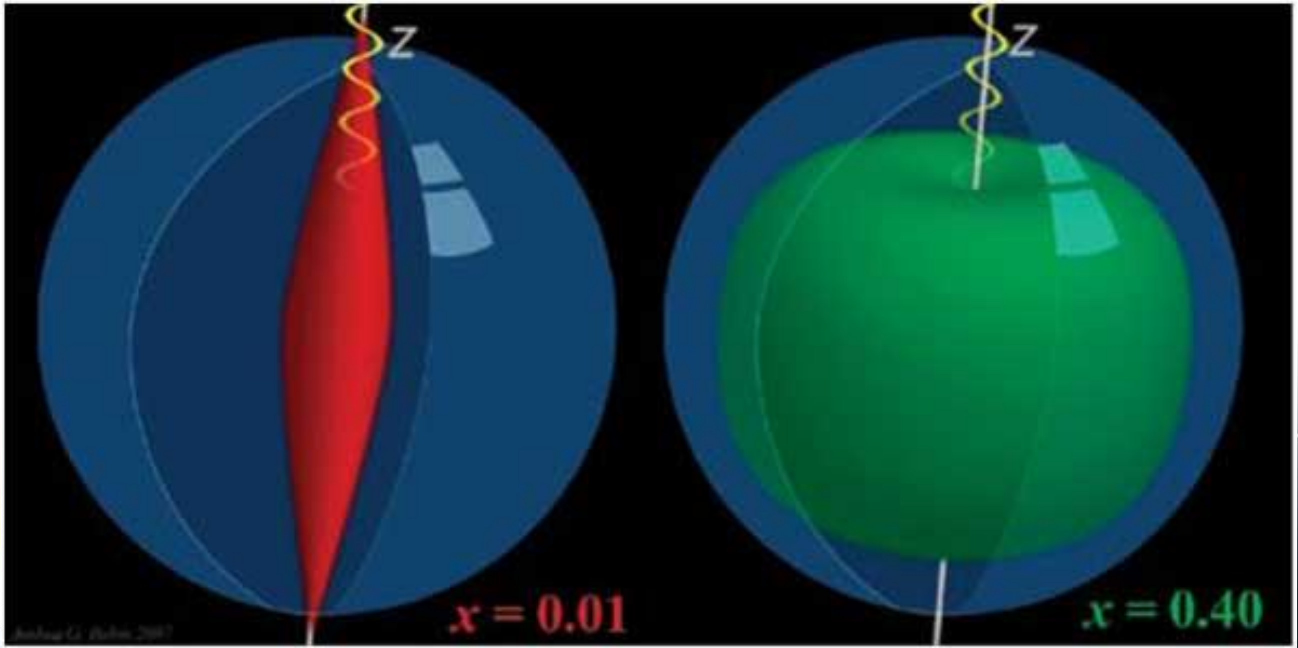
- Non-perturbative effects are modeled using a single parameter shape function which is convoluted with the perturbative cross section

$$F_\kappa(k) = \frac{4k}{\Omega_\kappa^2} exp\left(-\frac{2k}{\Omega_\kappa}\right)$$



# Generalized Parton Distributions (GPDs)

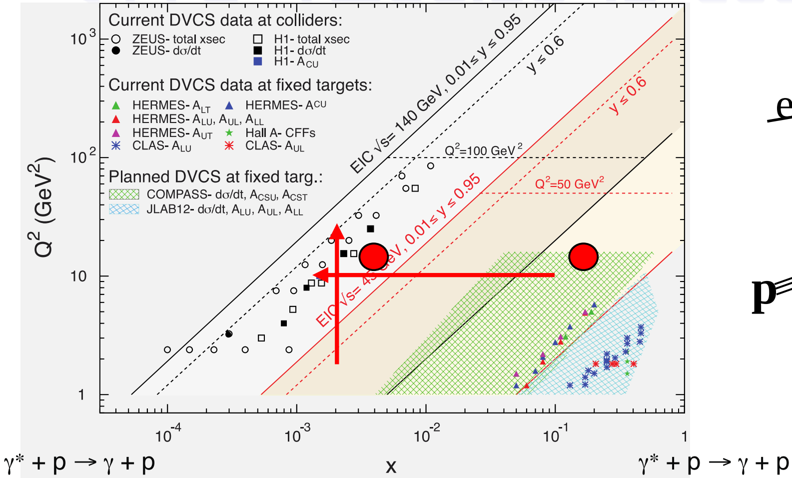

or

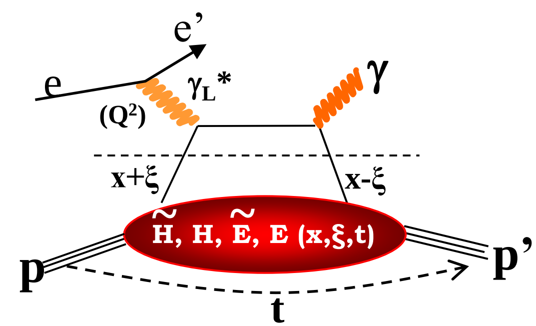


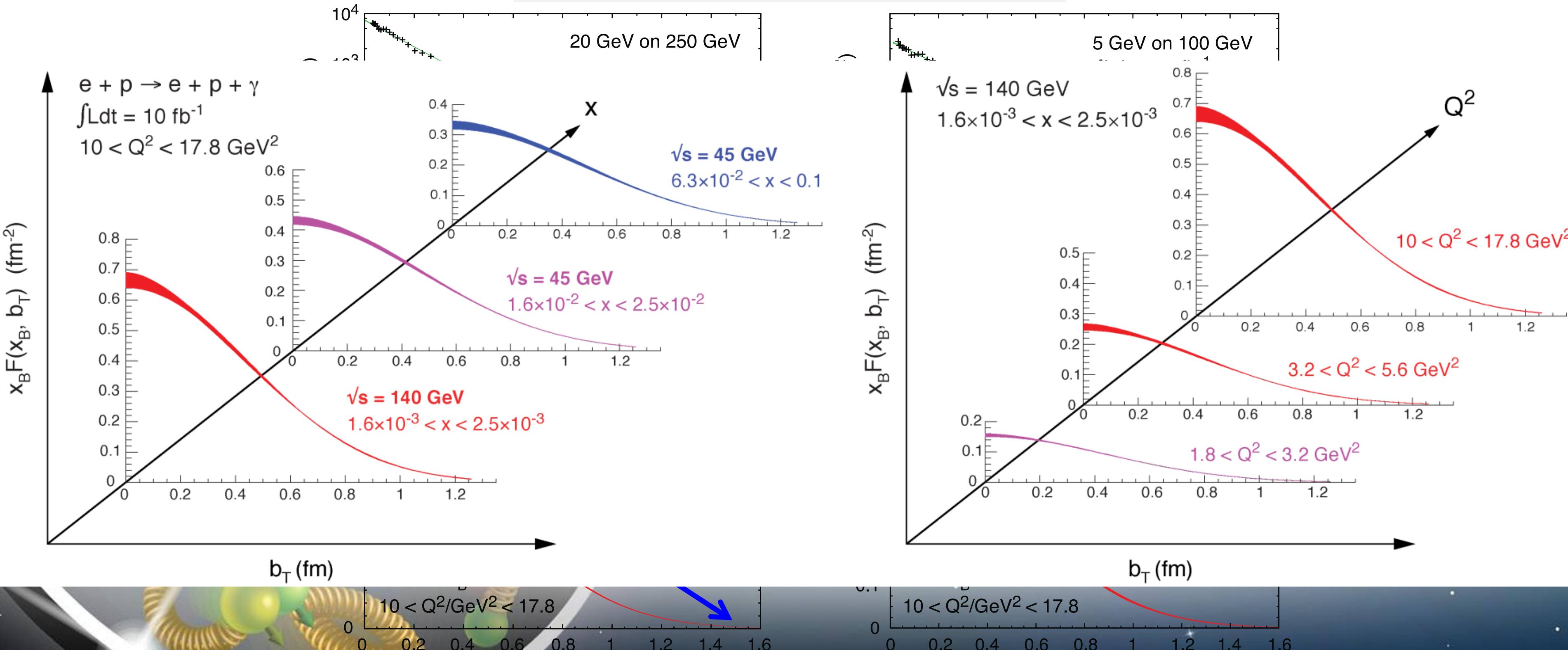
# 2+1d-Imaging in coordinate space

High precision imaging at EIC at low and high x

Golden channel: DVCS



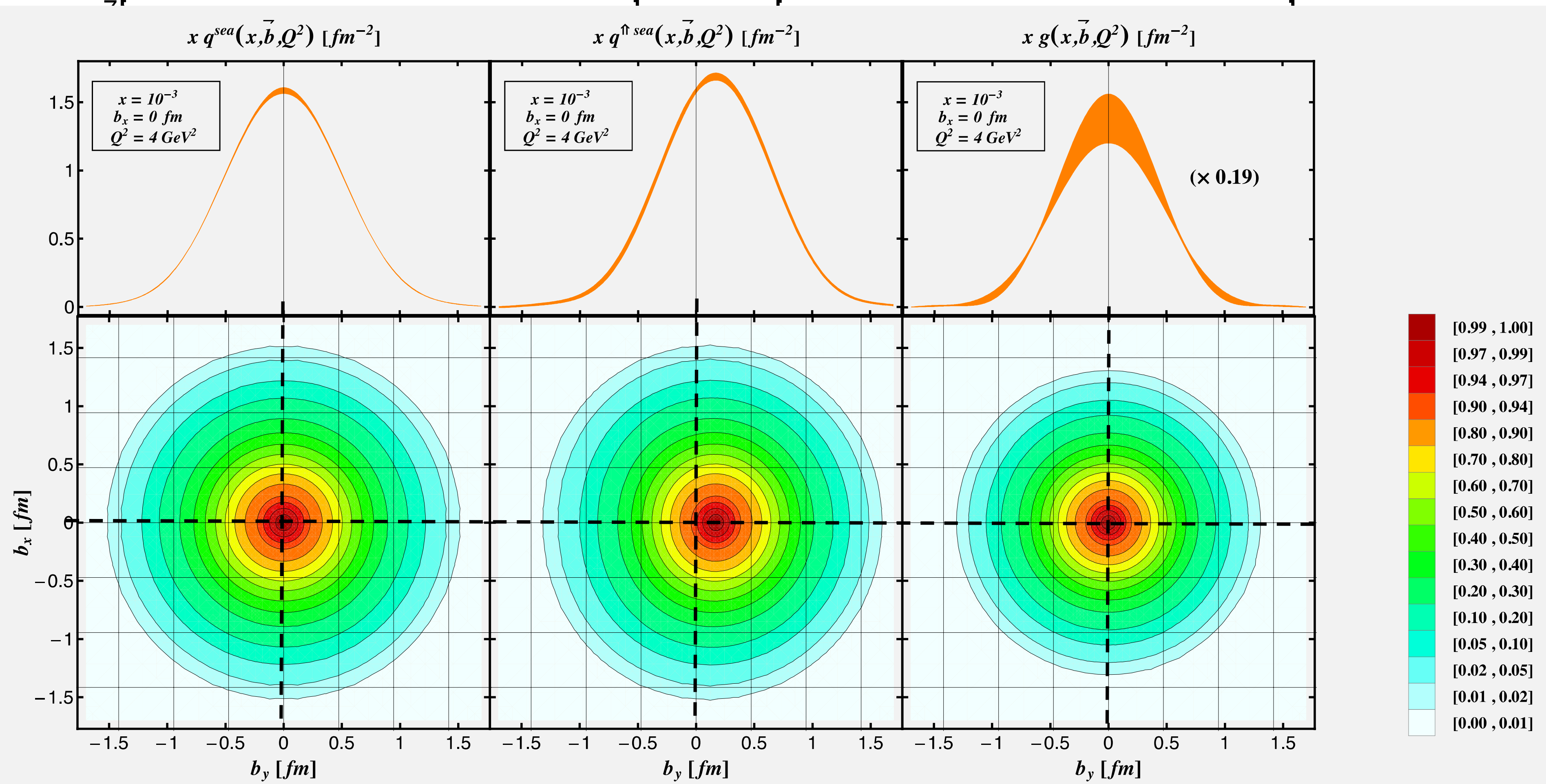



# What will we learn about 2d+1 structure of the proton

GPD H and E as function of t, x and $Q^2$

GPD H and E 1d+1

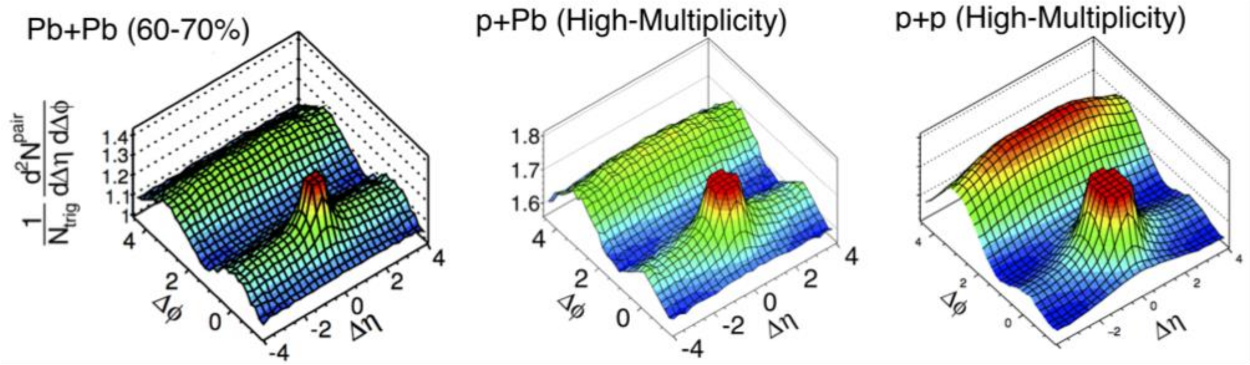
arXiv:1304.0077




GPD H and E 2d+1 structure for sea-quarks and gluons

# Proton structure important for QGP in small systems

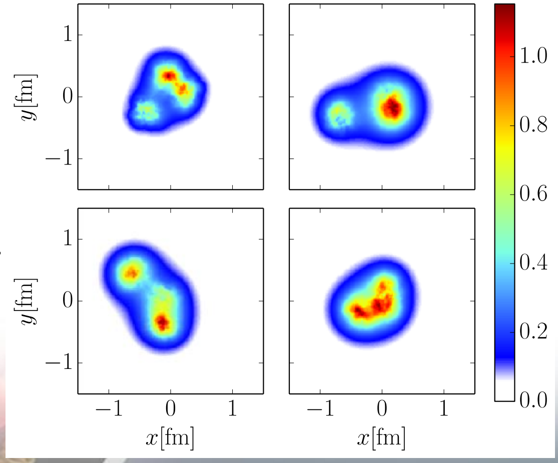
Collective phenomena seen in pA collisions, i.e. ATLAS & CMS




H. Mäntysaari & B. Schenke
arXiv:1607.01711

In a hydro-picture (used in AA) fluctuations in the proton are crucial to understand the seen pA@LHC behaviors

Examples of proton density profiles at $x \sim 10^{-3}$



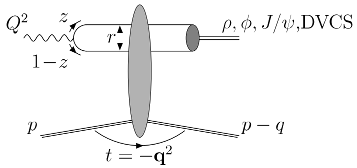

Study coherent and incoherent J/Ψ prod.

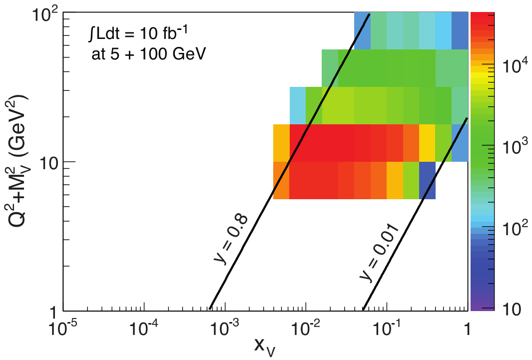
EIC can map out the spatial quark and gluon structure of the proton in x and $Q^2$

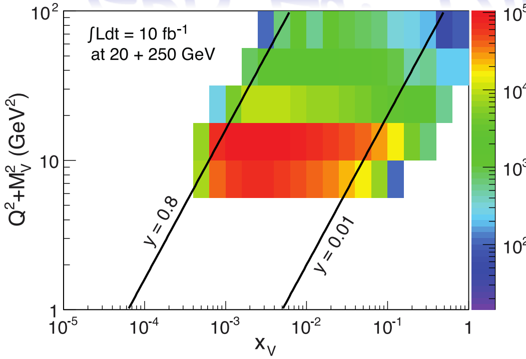
# GPD $H^g$: J/ψ

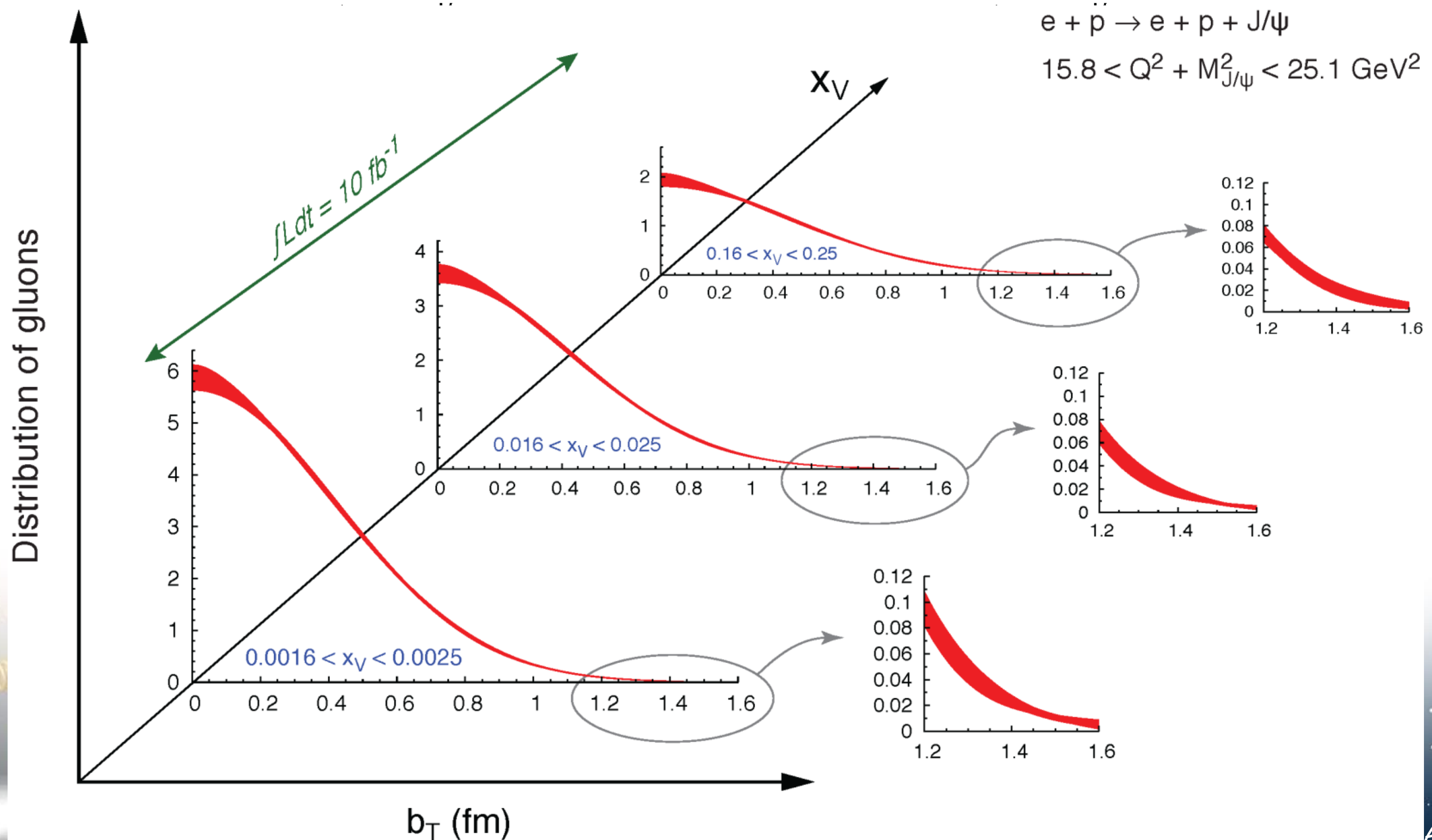
To improve imaging on gluons add J/ψ observables

- cross section
  - $A_{UT}$
    - .....

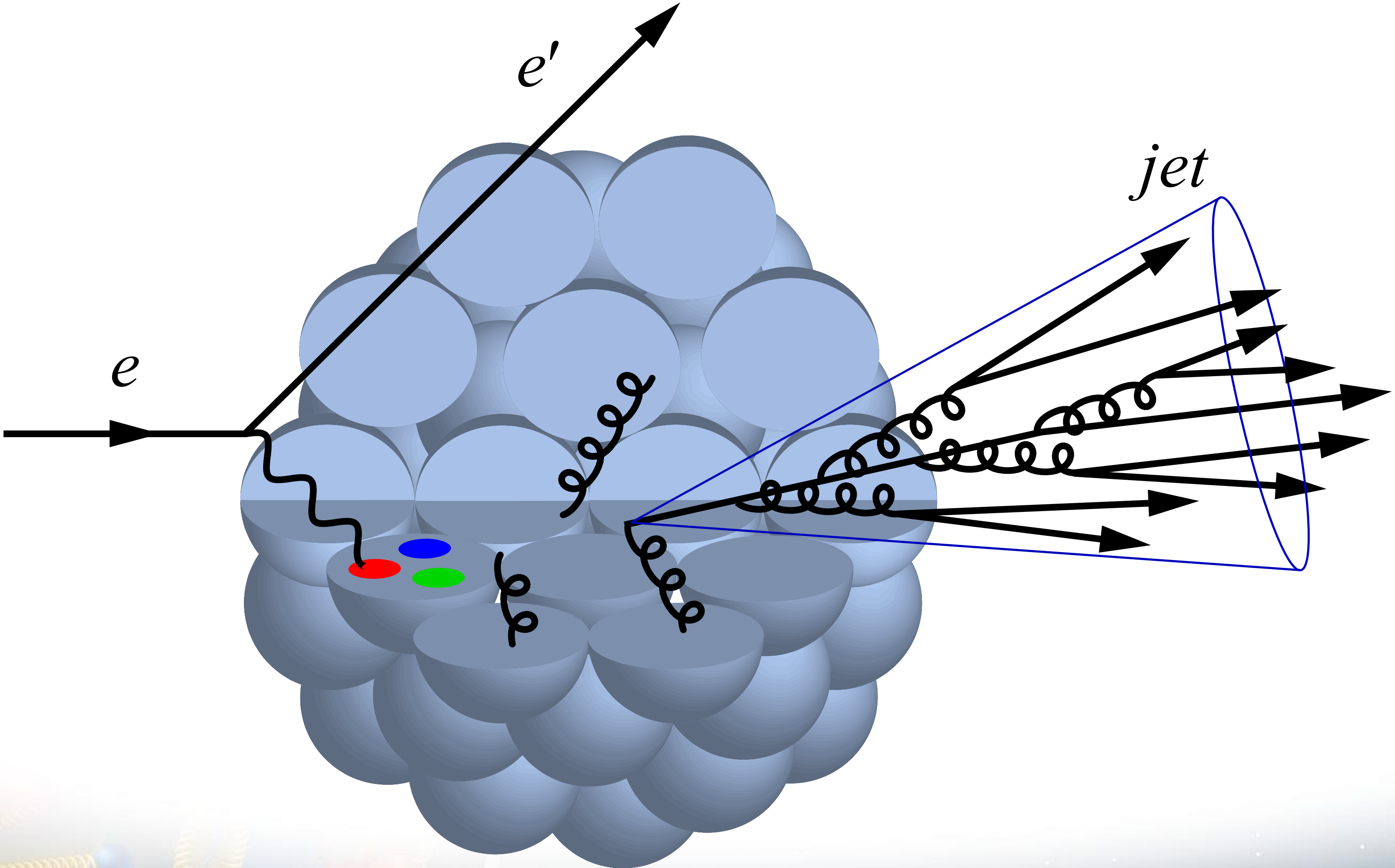


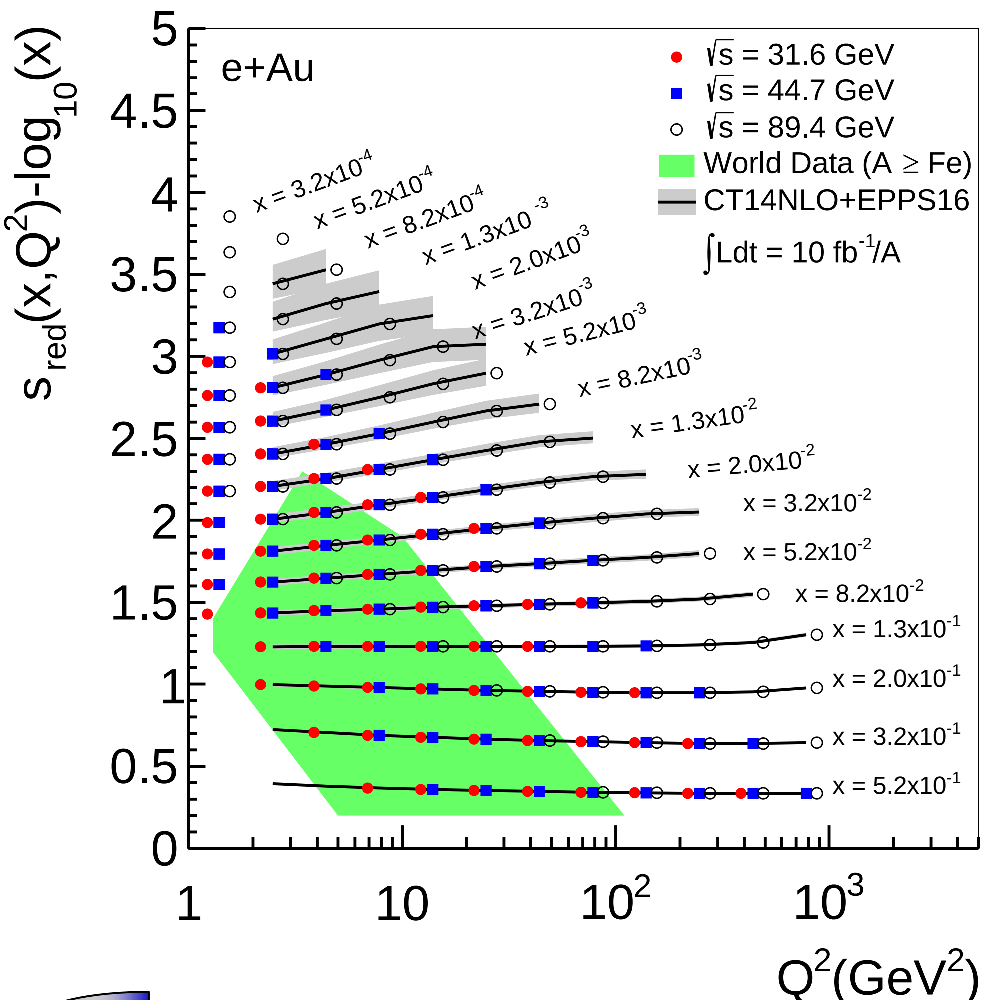



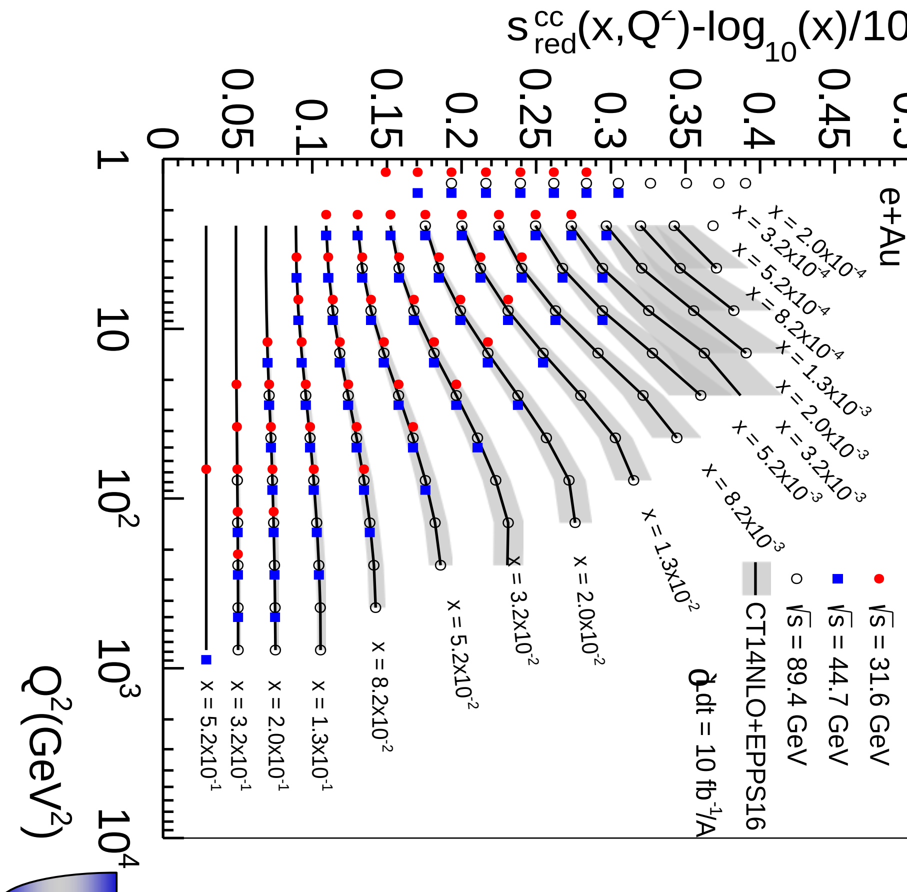
# What about Nuclei?



# Inclusive Cross-Sections in eA

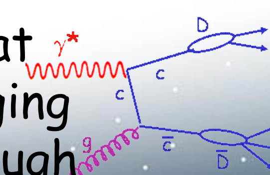
arXiv:1708.05654



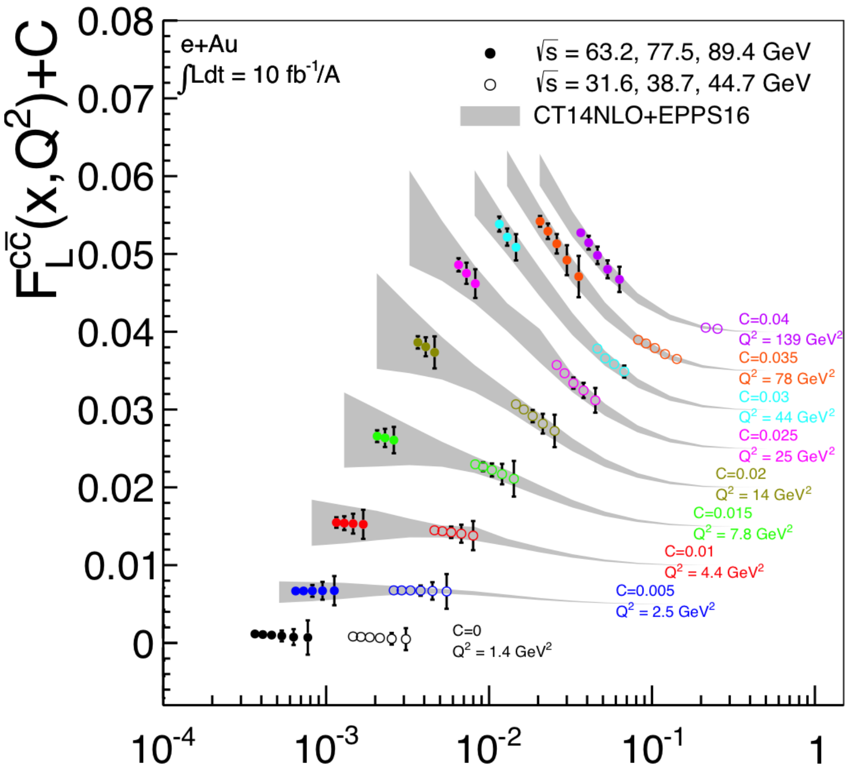

Gluon distribution ~ $d\sigma(x,Q^2)/d\ln Q^2$

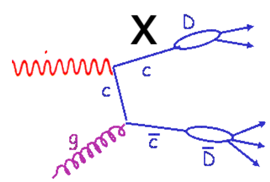
Direct Access to gluons at medium to high x by tagging photon-gluon fusion through charm events

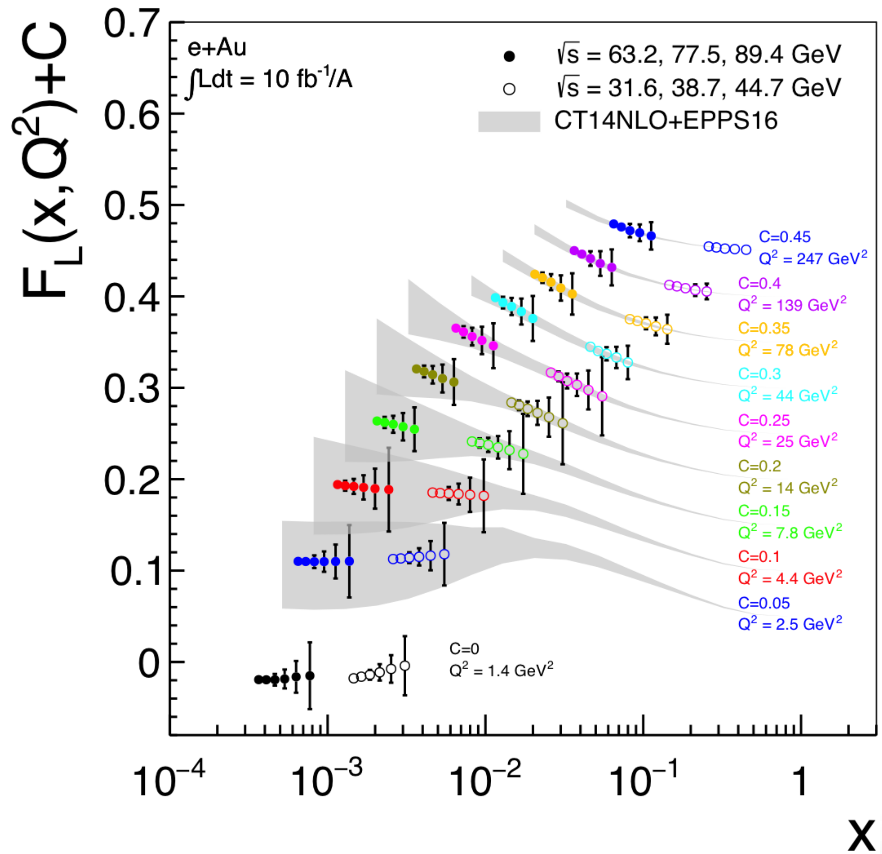


# Direct Access to Gluons in eA

For Details: arXiv:1708.05654



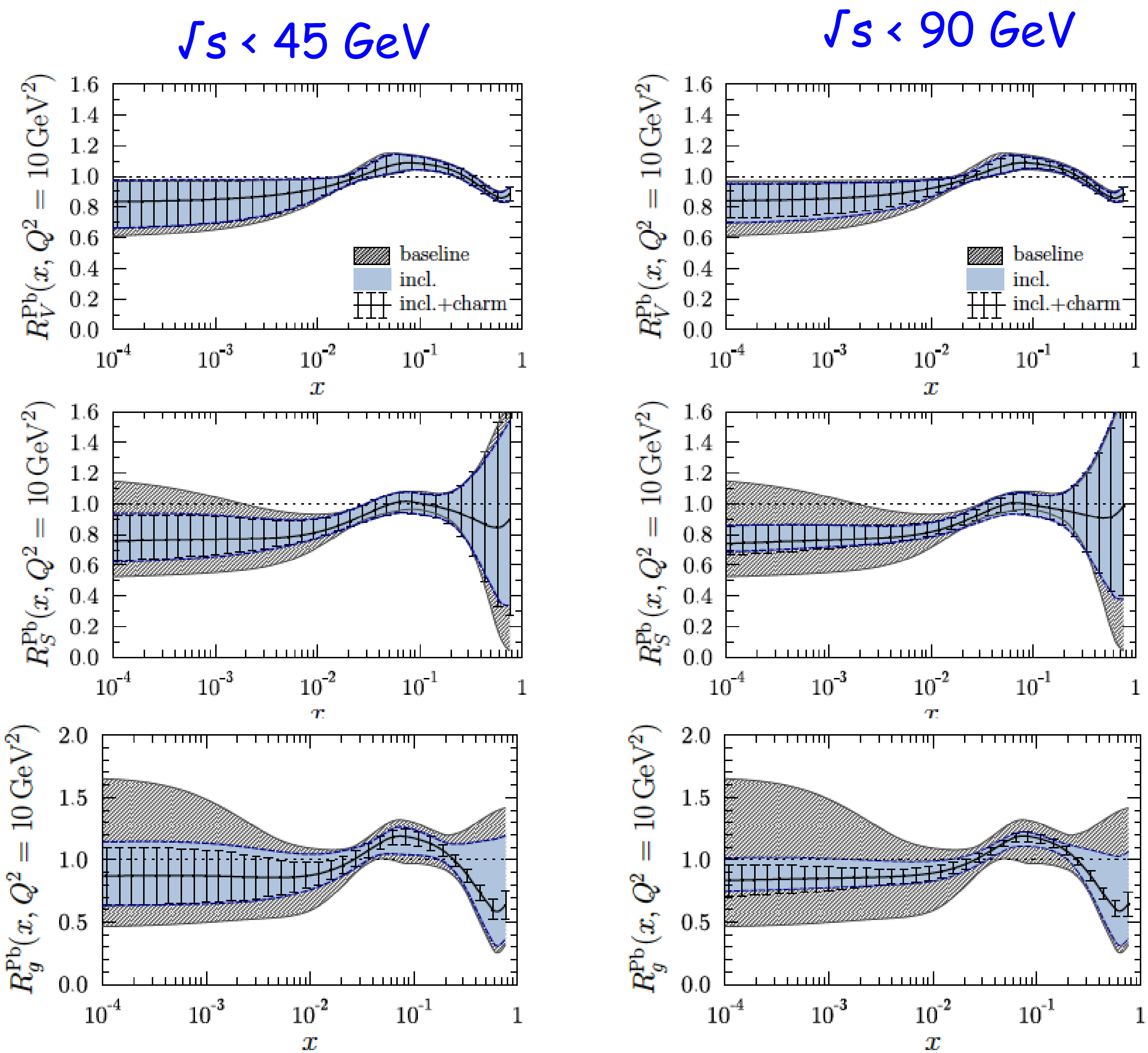




Direct Access to gluons at medium to high x by tagging photon-gluon fusion through charm events

high precision $F_L^{charm}$ will offer an opportunity to benchmark different GM-VFNS schemes with an unprecedented precision.

# EIC: Impact on the Knowledge of 1D Nuclear PDFs

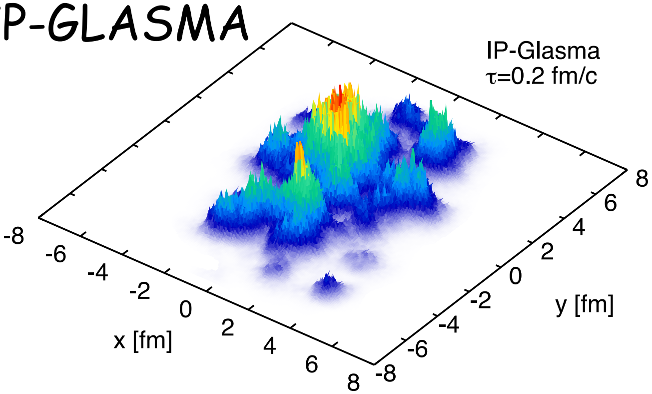



**Ratio of PDF of Pb over Proton**

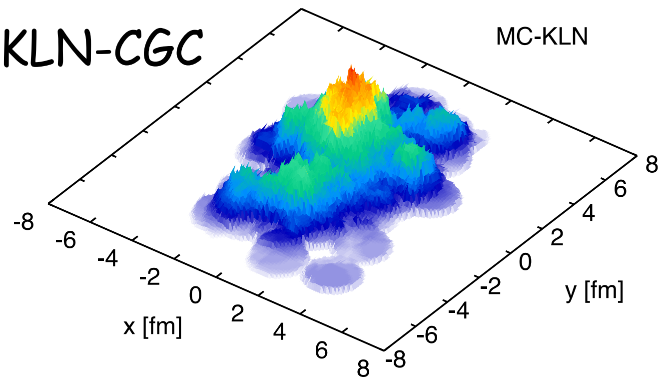
- Without EIC, large uncertainties
  → With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x?
  → relevant to very high-energy cosmic ray studies
  → critical input to AA
- submitted to PRD arXiv:1708.05654

# The influence of the initial state in AA

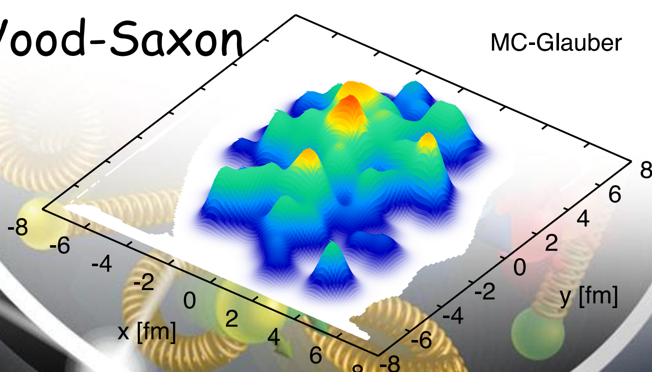
IP-GLASMA




KLN-CGC

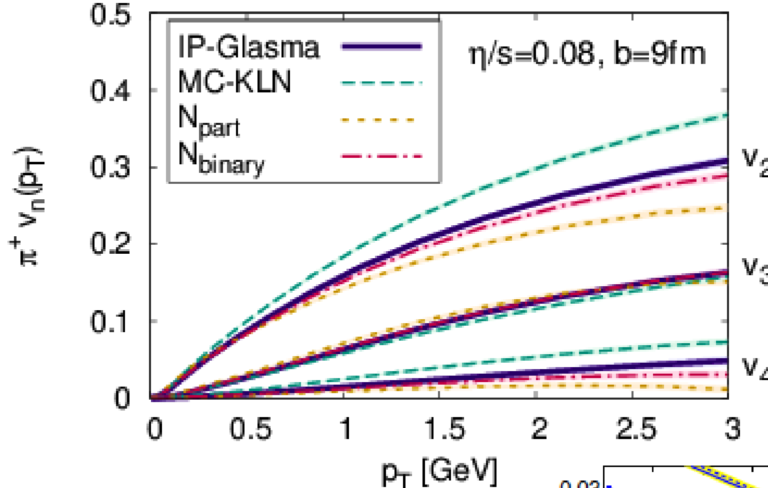



Glauber
Wood-Saxon

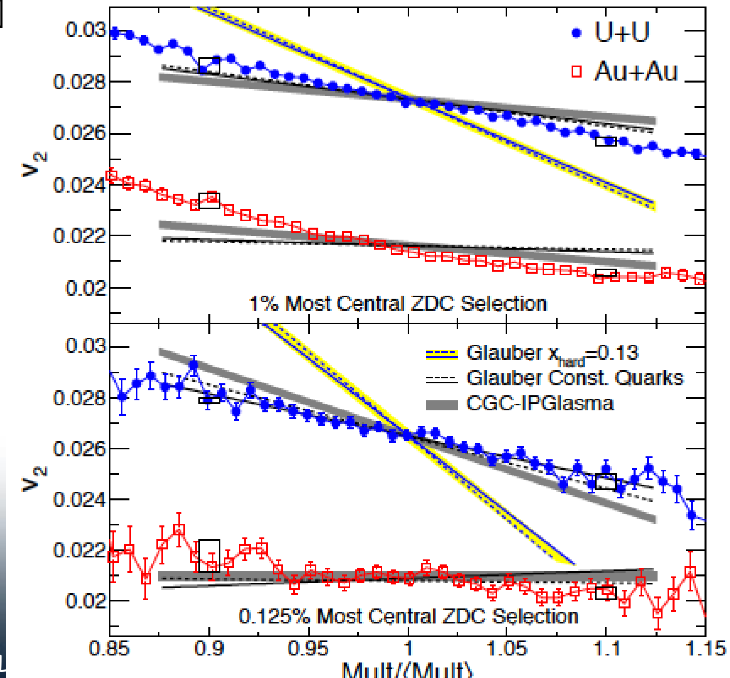



AdS/CFT predicts for a perfect fluid:
$\eta/s = 1/(4\pi) \sim 0.08$

Schenke, Tribedy, Venugopalan arXiv:1202.6646

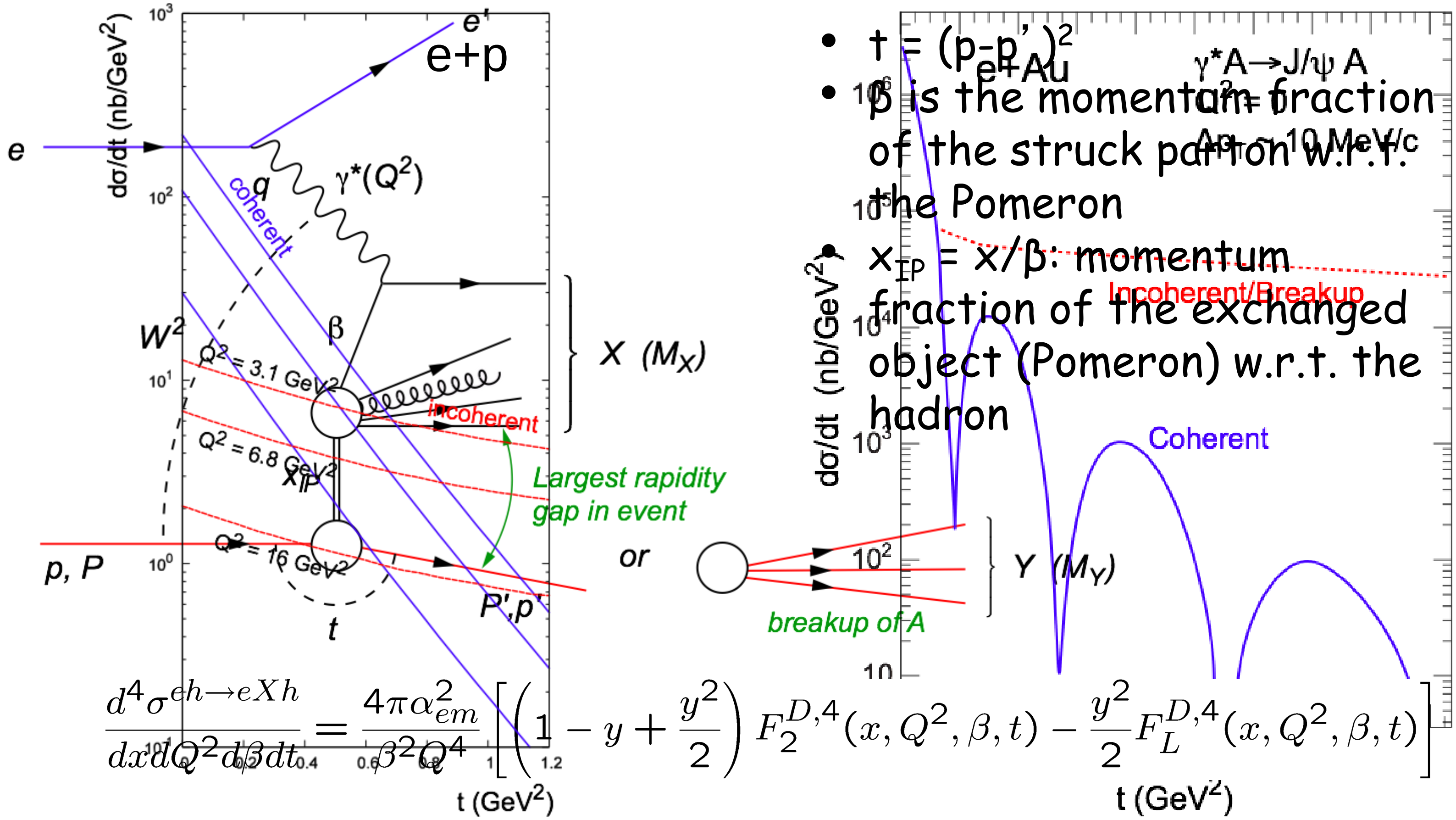



Different initial states = different fluctuation scales



# Diffraction in DIS at Small x

- $t = (p - p')^2$
- $\beta$ is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron




$$\frac{d^4\sigma^{eh\to eXh}}{dx\,dQ^2\,d\beta\,dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2^{D,4}(x,Q^2,\beta,t) - \frac{y^2}{2} F_L^{D,4}(x,Q^2,\beta,t)\right]$$

Diffraction in e+p:

- coherent ⇔ p intact
- incoherent ⇔ breakup of p
- HERA: 15% of all events are hard diffractive

Diffraction in e+A:

- coherent diffraction (nuclei intact)
- breakup into nucleons (nucleons intact)
- incoherent diffraction
- Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

# eRHIC: Spatial Gluon Distribution from dσ/dt

1950-60: Measurement of charge (proton) distribution in nuclei

Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ, φ, ρ

Ongoing: Measurement of neutron distribution in nuclei

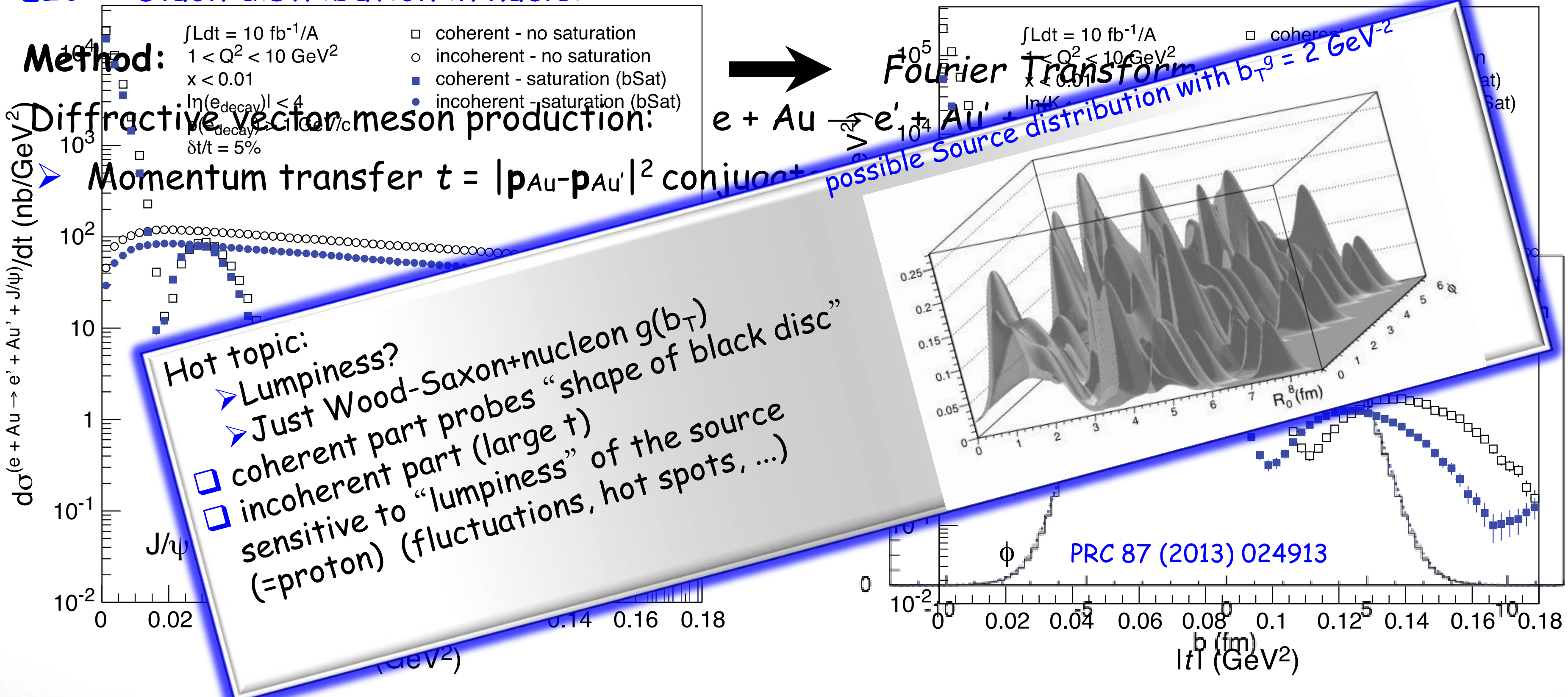
EIC ⇒ Gluon distribution in nuclei

**Method:**

Diffractive vector meson production: e + Au → e′ + Au′ + ...

➢ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$ conjugate ...

Fourier Transform




➢ Converges to input F(b) rapidly: |t| < 0.1 almost enough

➢ Recover accurately any input distribution used in model used to generate pseudo-data (here Wood-Saxon)

dσ/dt: diffractive pattern known from wave optics

• φ sensitive to saturation effects, smaller J/ψ shows no effect

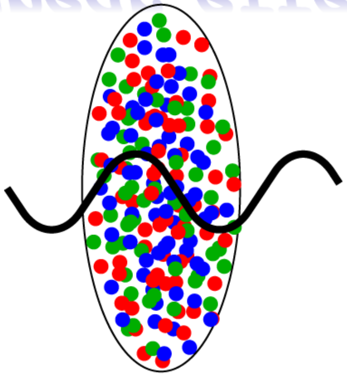
• J/ψ perfectly suited to extract source distribution

➢ Systematic measurement requires ∫Ldt ≈ 1 fb$^{-1}$/A

# Studying non-linear effects

Scattering of electrons off nuclei:

- Probes interact over distances $L \sim (2m_N x)^{-1}$
- For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon
- Probe interacts *coherently* with all nucleons

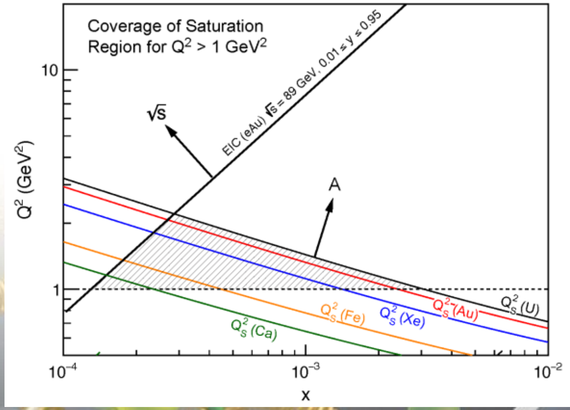



$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

Nuclear "Oomph" Factor
Pocket Formula:

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of $Q_S$ with $A$ ⇒ non-linear QCD regime can be reached at significantly lower energy in A than in proton




Tagging centrality in eA collision will be important

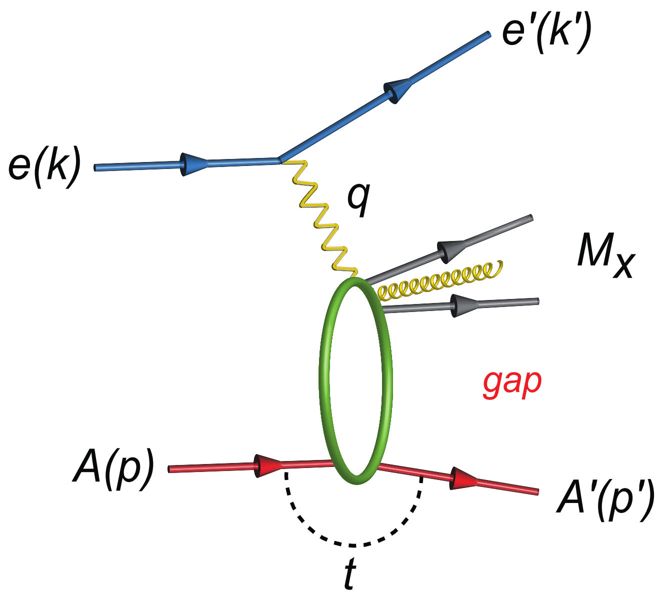
→ stringent cut on centrality ~ 1%

→ effective energy boost by ~3

→ effective increase of A

→ utilized in p/dA and AA all the time

# Diffraction:

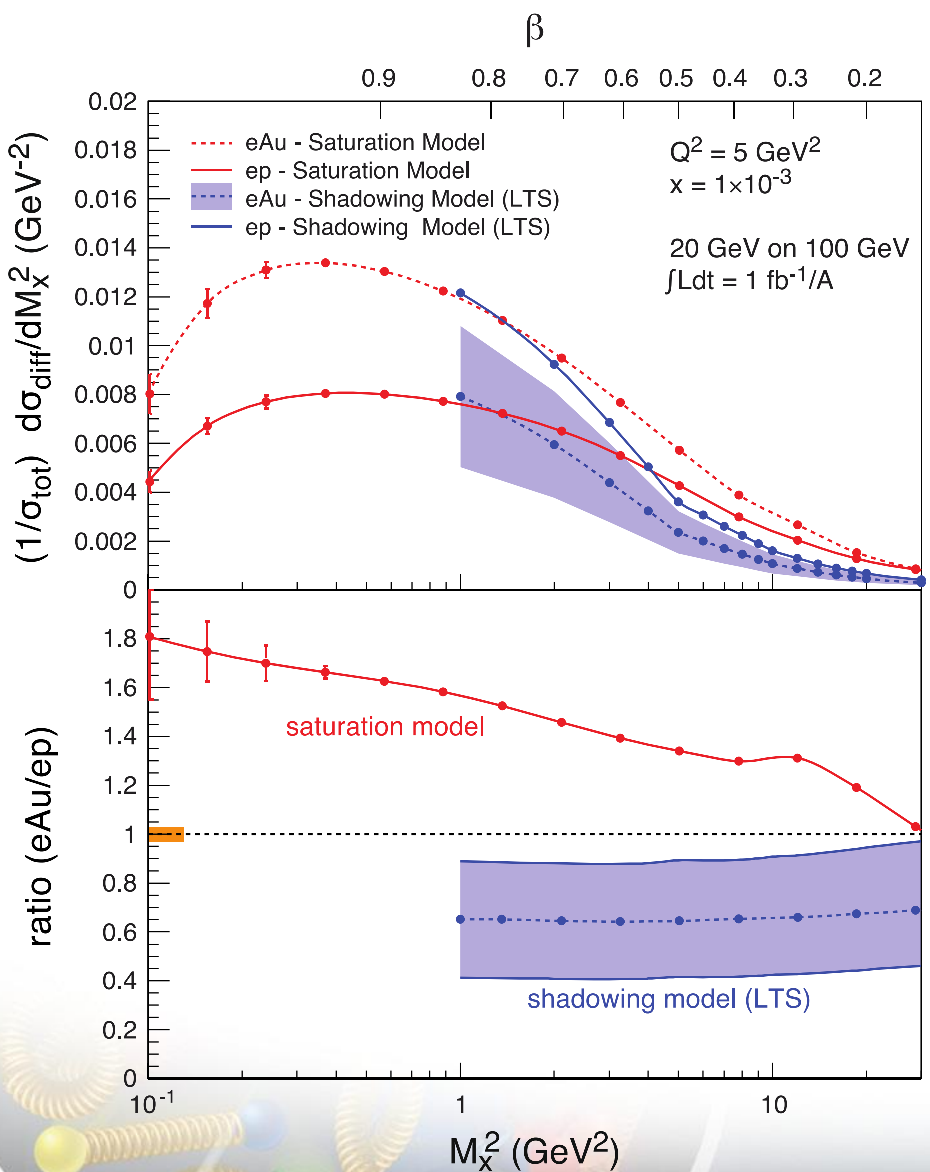



Diffractive events are indicative of a color neutral exchange between the virtual photon and the proton or nucleus over several units in rapidity.

$M_X^2$: Squared mass is the diffractive final state

$x_{IP}$: Momentum fraction of the "Pomeron" with respect to the hadron. The rapidity gap between produced particles and the proton or nucleus is $Y \sim \ln(1/x_{IP})$

# Inclusive Diffraction



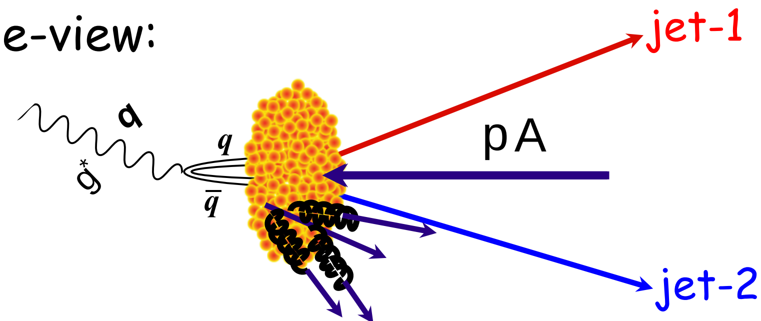

- HERA observed: ~14% of all events are diffractive
- Saturation models (CGC) predict up to σdiff/σtot ~ 25% in eA
- Ratio enhanced for small MX and suppressed for large MX
- Standard QCD predicts no MX dependence and a moderate suppression due to shadowing.

It would be nice to have equally rigorous extraction of diffractive PDF as the "std. PDFs"
→ both for proton and nuclei

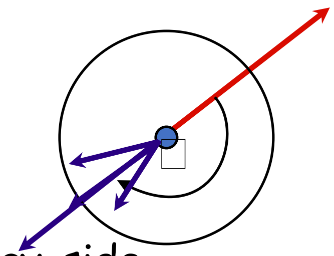
# Key Observables for Saturation

## Di-Hadron Correlations:

side-view:



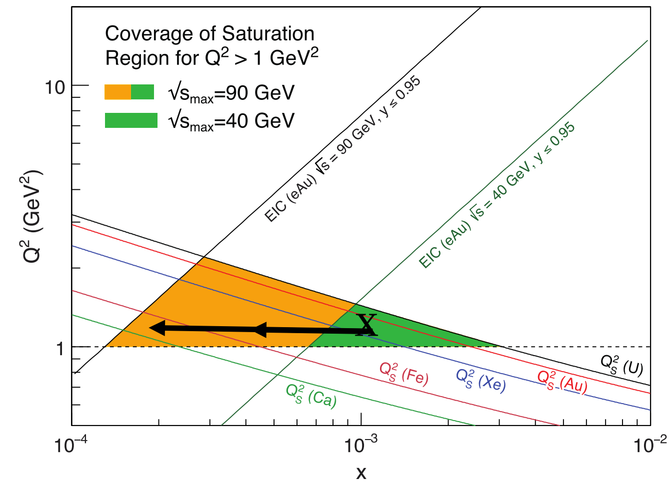

beam-view:

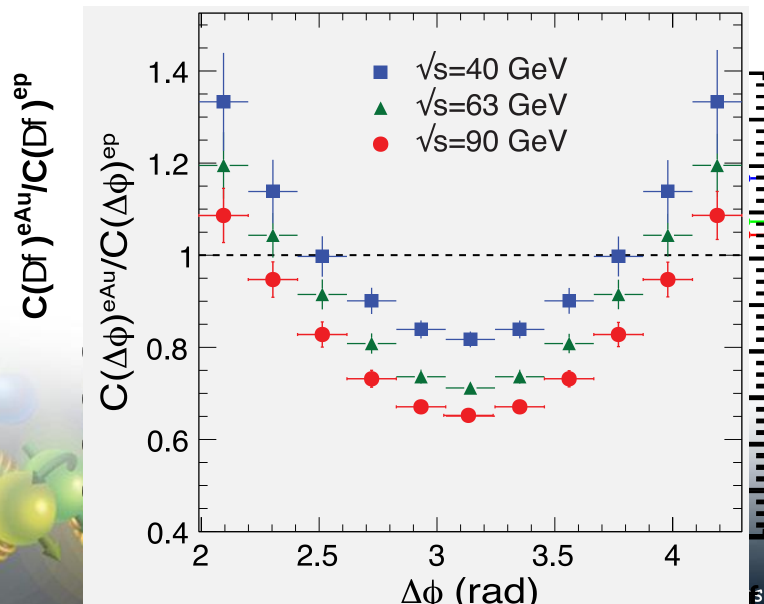


High gluon density (eA):
2 → many process
⇒ expect broadening of away-side

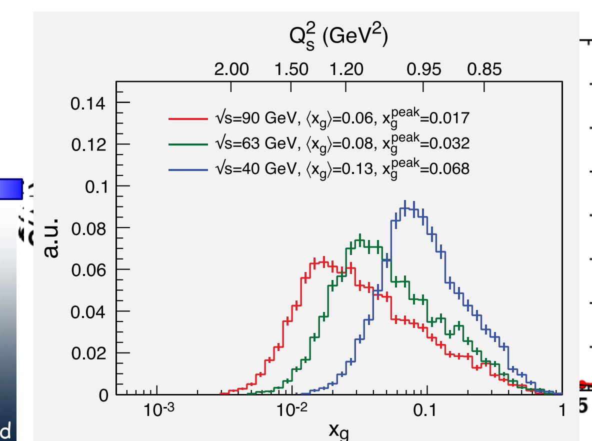
Low gluon density (ep):
pQCD predicts 2→2 process
⇒ back-to-back di-jet

EIC allows to study the evolution of $Q_s$ with x

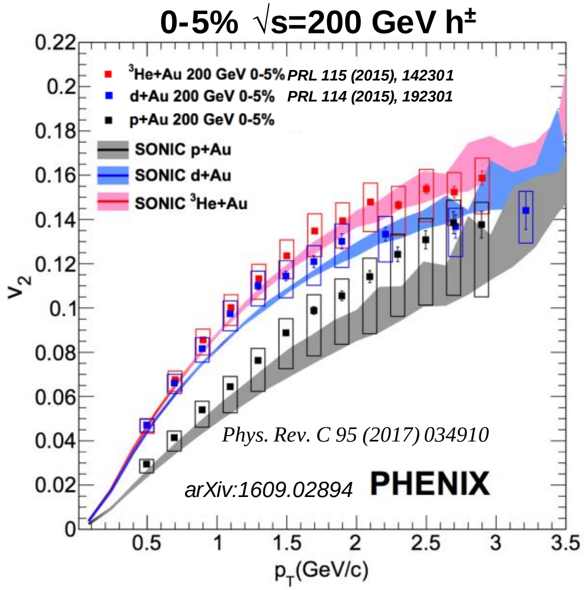


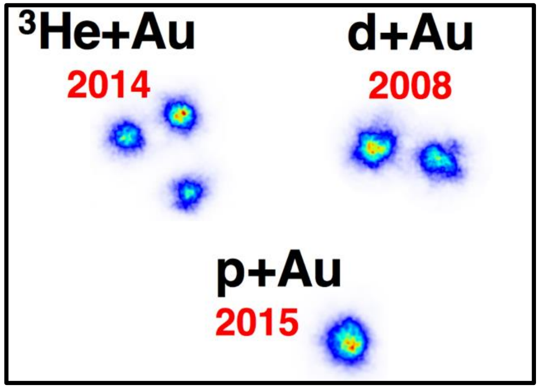

Ratio



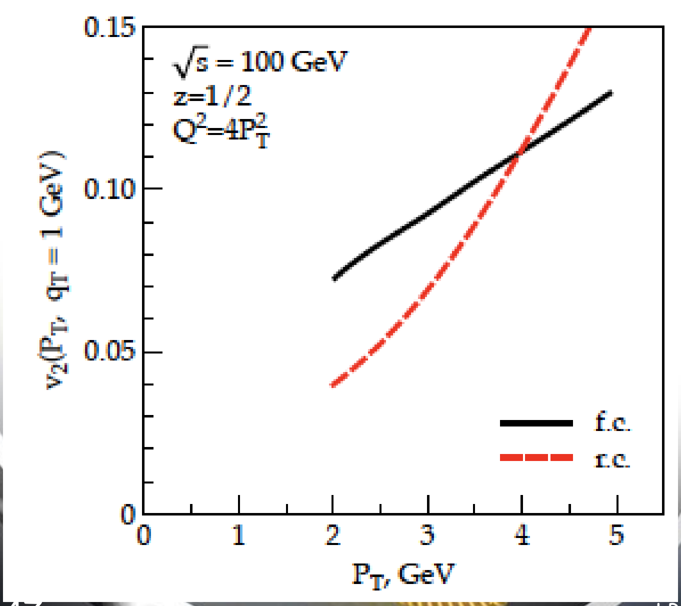
# TMDs and "QGP" in small systems




Collective flow signatures seen even in the smallest systems and at RHIC energies




TMD formalism in DIS predicts a distribution for linearly polarized gluons in an unpolarized target. This is reflected in cos(2φ) asymmetries in dijet production



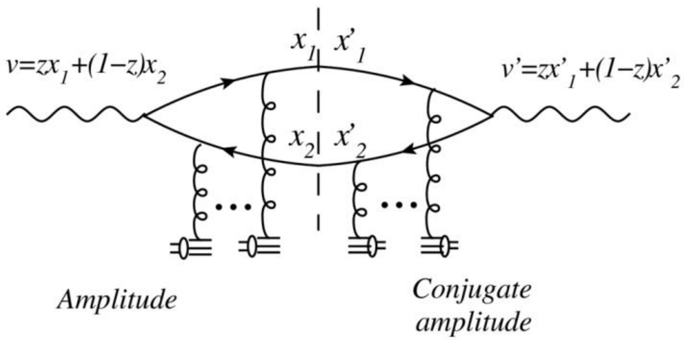

Study azimuthal anisotropy as a function of the rapidity dis-balance of the jets

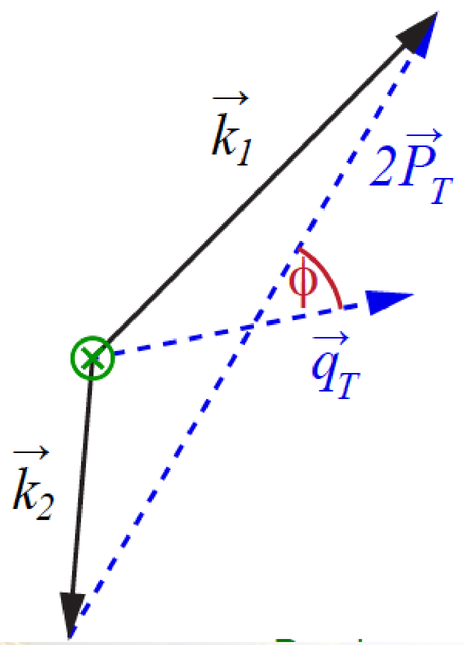
→ Process sensitive to unpolarized and linearly polarized gluon distribution

$$xG^{ij}_{ww} = \frac{1}{2}\delta^{ij}xG^{(1)} - \frac{1}{2}\left(\delta^{ij} - \frac{2k^i k^j}{k^2}\right)xh_\perp^{(1)}$$


A. Metz and J. Zhou, Phys. Rev. D84 , 051503 (2011), arXiv:1105.1991.
D. Boer, P. J. Mulders, and C. Pisano, Phys. Rev. D80 , 094017 (2009), arXiv:0909.4652
D. Boer, S. J. Brodsky, P. J. Mulders, and C. Pisano, Phys. Rev. Lett. 106 , 132001 (2011), arXiv:1011.4225.
F. Dominguez, J.-W. Qiu, B.-W. Xiao, and F. Yuan, Phys. Rev. D85 , 045003 (2012), arXiv:1109.6293.
A. Dumitru, L. McLerran, and V. Skokov, Phys. Lett. B743 , 134 (2015), arXiv:1410.4844.
A. Dumitru and V. Skokov, Phys. Rev. D91 , 074006 (2015), arXiv:1411.6630.
A. Dumitru, T. Lappi, and V. Skokov, Phys. Rev. Lett. 115 , 252301 (2015), arXiv:1508.04438.
A. Dumitru and V. Skokov, Phys. Rev. D94 , 014030 (2016), arXiv:1605.02739.

# Kinematics: Di-jets in $\gamma^*A$




Key observables: $P_T$ and $q_T$

- the difference in momenta (imbalance)

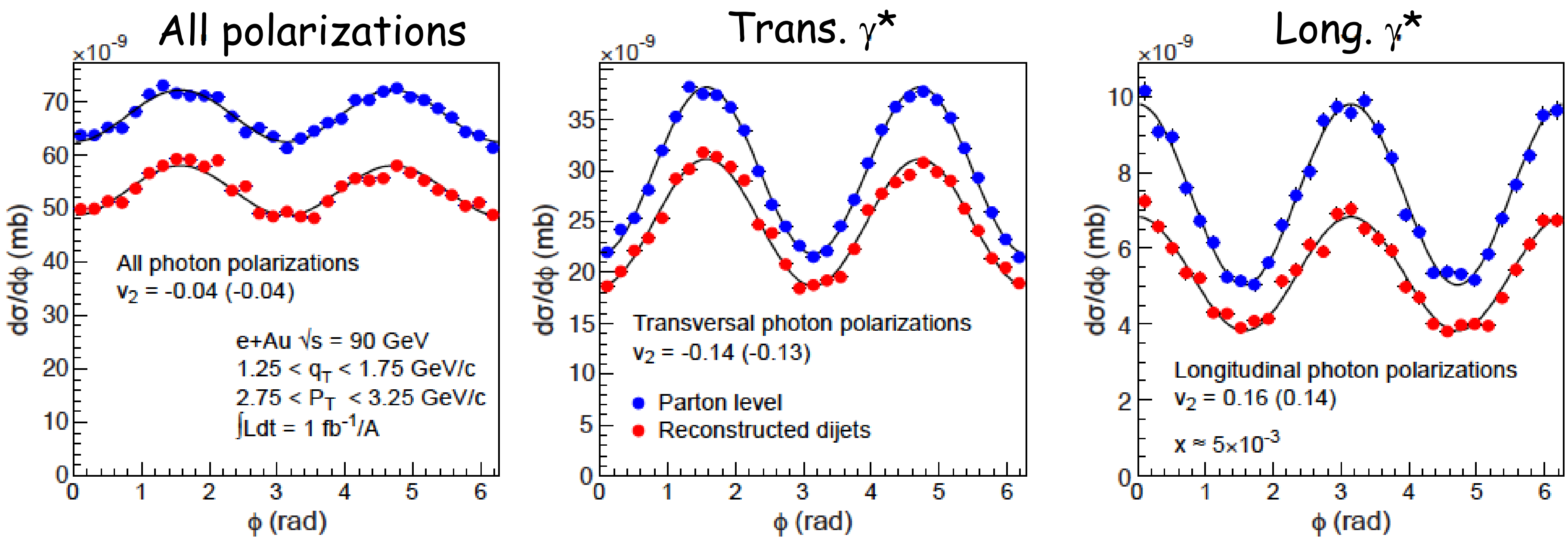
  $\overrightarrow{q_T} = \overrightarrow{k_1} + \overrightarrow{k_2}$
- the average transverse momentum of the jets

  $\overrightarrow{P_T} = (1\text{-}z)\overrightarrow{k_1} - z\overrightarrow{k_2}$
- $\Phi$ is angle between $P_T$ and $q_T$
- work in "correlation limit" $P_T \gg q_T$
- azimuthal asymmetry arising from the linearly polarized gluon distribution:

  $v_2 = \langle \cos 2\Phi \rangle$

# Elliptic Anisotropy in Di-Jet Production

Dipartons from McDijet event generator (V. Skokov) → showers via Pythia → experimental cuts → jet-finding with ee-kt (FastJet)




- Dijets recover the anisotropy (v2) quite well
- NOTE: phase shift between long. and trans. γ*

Ansatz for Gluon TMDs:

$$v_2^L = \frac{1}{2}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)} \quad , \quad v_2^T = -\frac{\epsilon_f^2 P_\perp^2}{\epsilon_f^4 + P_\perp^4}\frac{h_\perp^{(1)}(x,q_\perp)}{G^{(1)}(x,q_\perp)}$$

EIC will provide highest precision data to unravel the secrets of hadron structure
→ critical information for LHC science program

# Let’s get to work and built EIC

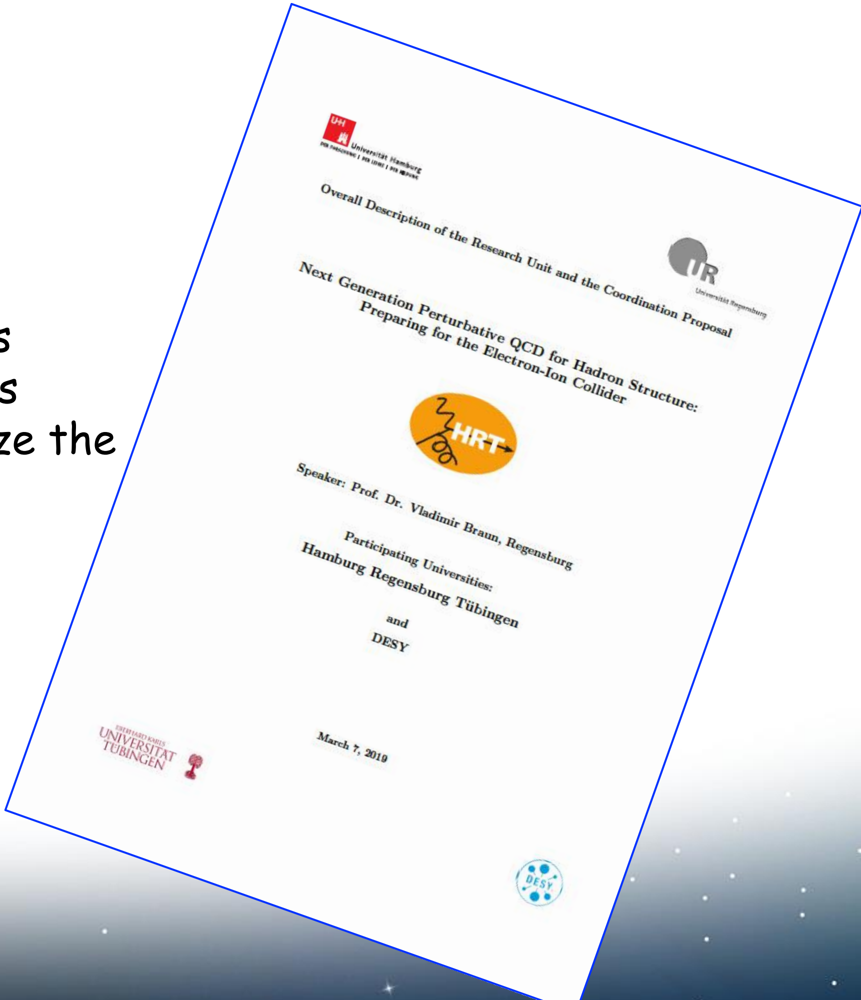
## Proposal to DFG:

"Next Generation Perturbative QCD for Hadron Structure: Preparing for the Electron-Ion Collider"

Fully approved, started October 2019

## Work packages:

- QCD evolution at one percent precision
- Parton distributions and fragmentation functions
- Multiparton interactions and higher-twist effects
- Theoretical and experimental interplay to optimize the EIC design
- Semi-inclusive reactions from low to high pT


Universität Hamburg

Overall Description of the Research Unit and the Coordination Proposal

Next Generation Perturbative QCD for Hadron Structure:
Preparing for the Electron-Ion Collider

HRT

Speaker: Prof. Dr. Vladimir Braun, Regensburg

Participating Universities:
Hamburg Regensburg Tübingen
and
DESY

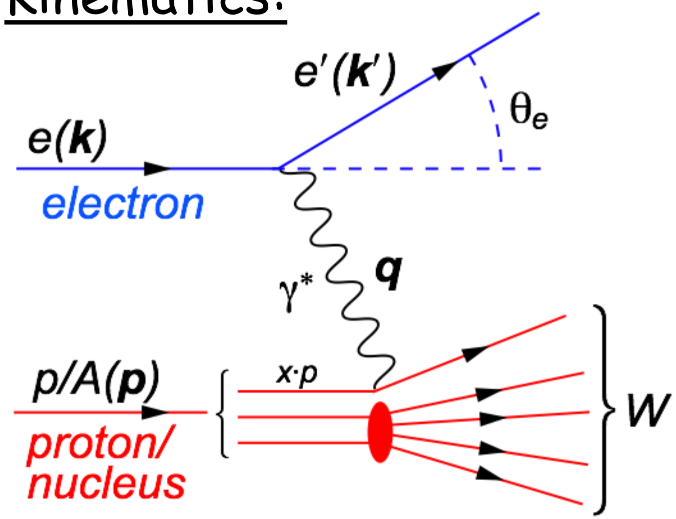
March 7, 2019

Universität Tübingen


BACK UP

# Deep Inelastic Scattering

Kinematics:




$$Q^2 = 2E_e E'_2(1-\cos\theta_{e'}) = -q^2$$

Measure of resolution power

$$y = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq}$$

Measure of momentum fraction of struck quark

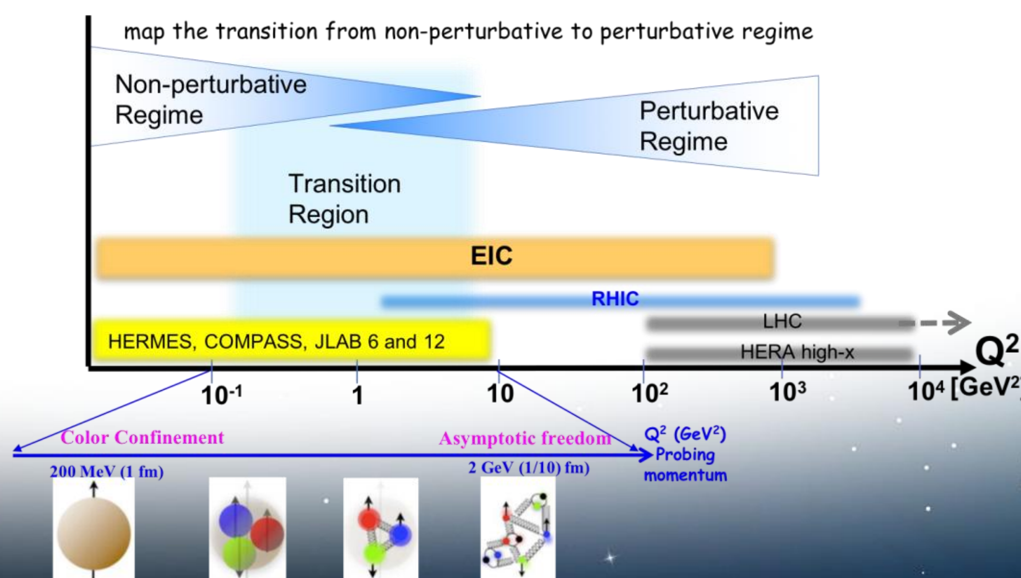
$$\sqrt{s} = 2\sqrt{E_e E_p}$$

center-of-mass energy of electron-hadron system

$$Q^2 = s \cdot x \cdot y$$

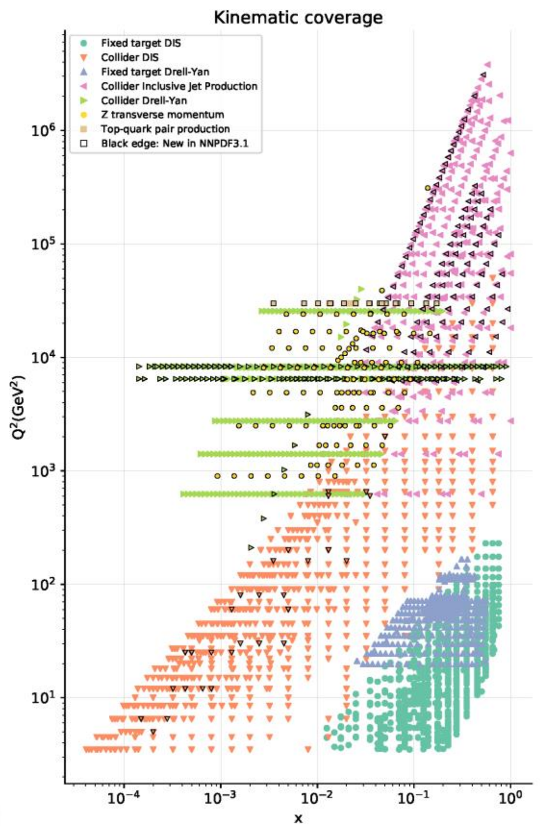
Deep Inelastic Scattering (DIS):

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent determination of parton kinematics of physics processes through scattered lepton

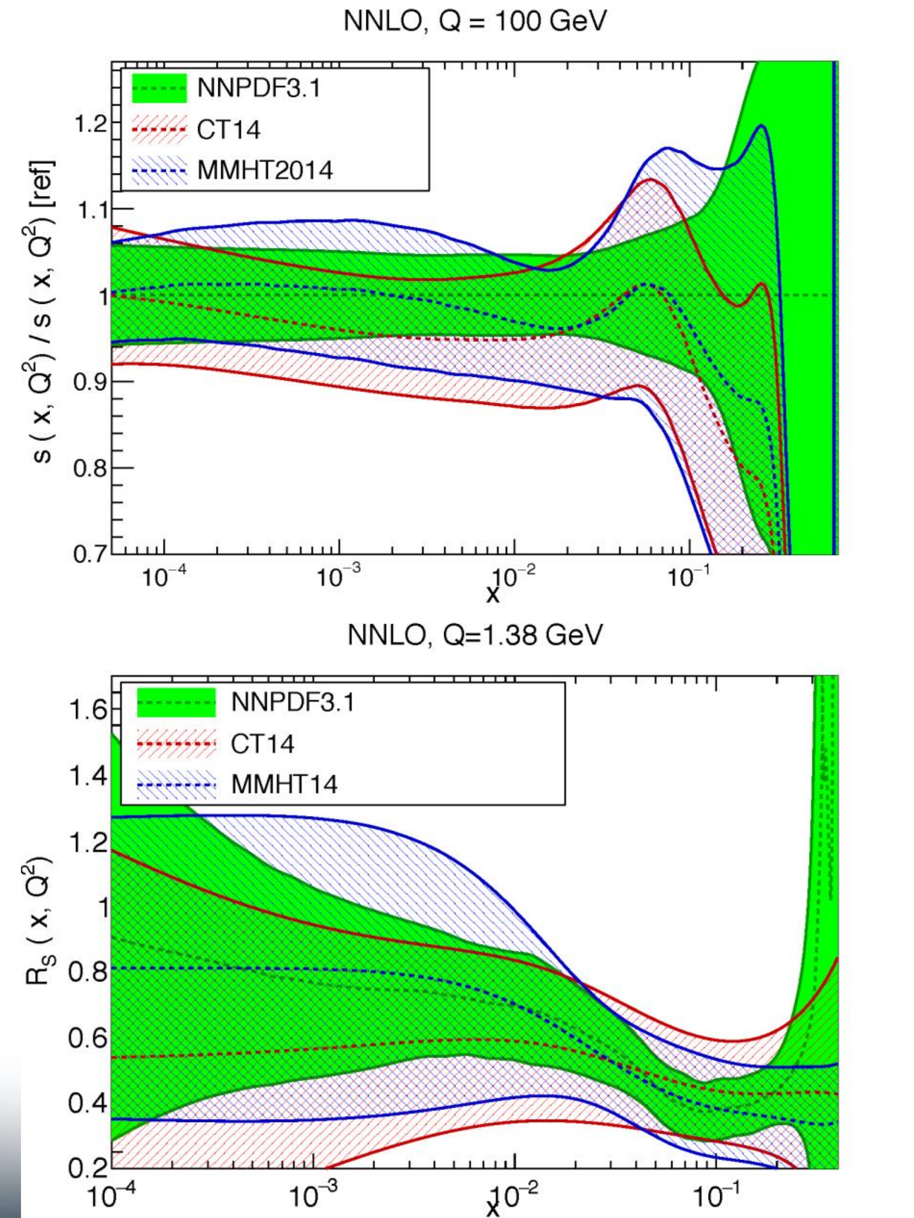


# s(x) and sbar(x) where do we stand?

NNPDF 3.1 arXiv:1706.00428




$$r_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{d}(x,Q^2)+\bar{u}(x,Q^2)}\,.$$



# Observables: Charge Current in ep and eA

Just some of the physics opportunities:

polarized ep/en:

- test models based on helicity retention $\Delta d/d \rightarrow 1$
  (Phys.Rev.Lett. 99 (2007) 082001)
- precision test models assuming charge symmetry violation
- precision test handiness of Ws
- tag charm in coincidence with CC event → $\Delta s$

unpolarized ep/en:

- impact on PDFs → high x quark PDFs
  - tag charm in coincidence ot CC event → s
- precision constrain on light quark weak neutral current couplings $a_u$, $v_u$, $a_d$ $v_d$

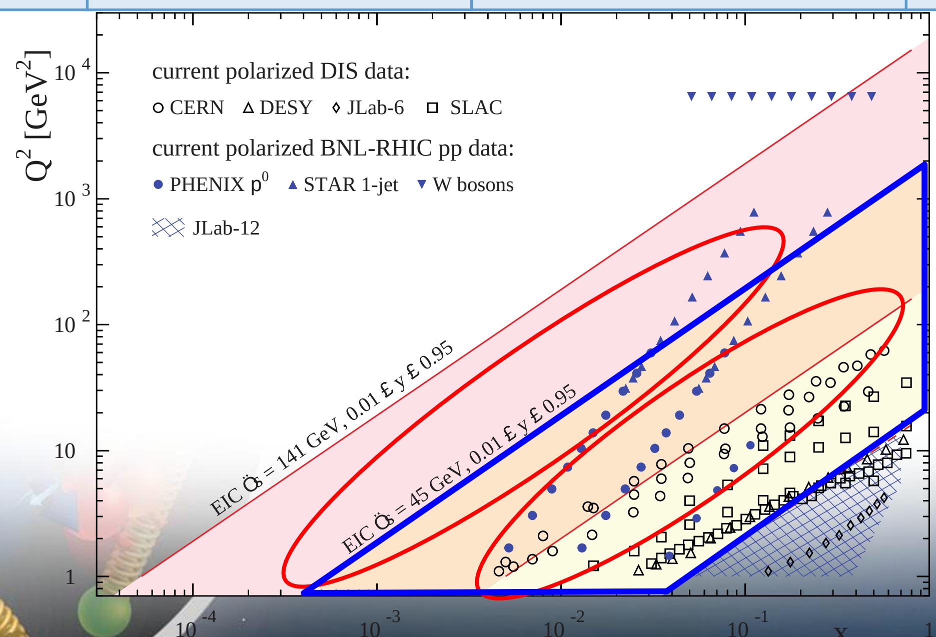
unpolarized eA:

- Test Models for the EMC-effect
  - charge symmetry violation
  - Isovector EMC effect
    (Cloet, Bentz, Thomas et. al., PRL 102 252301 )

# How to access Gluons in DIS

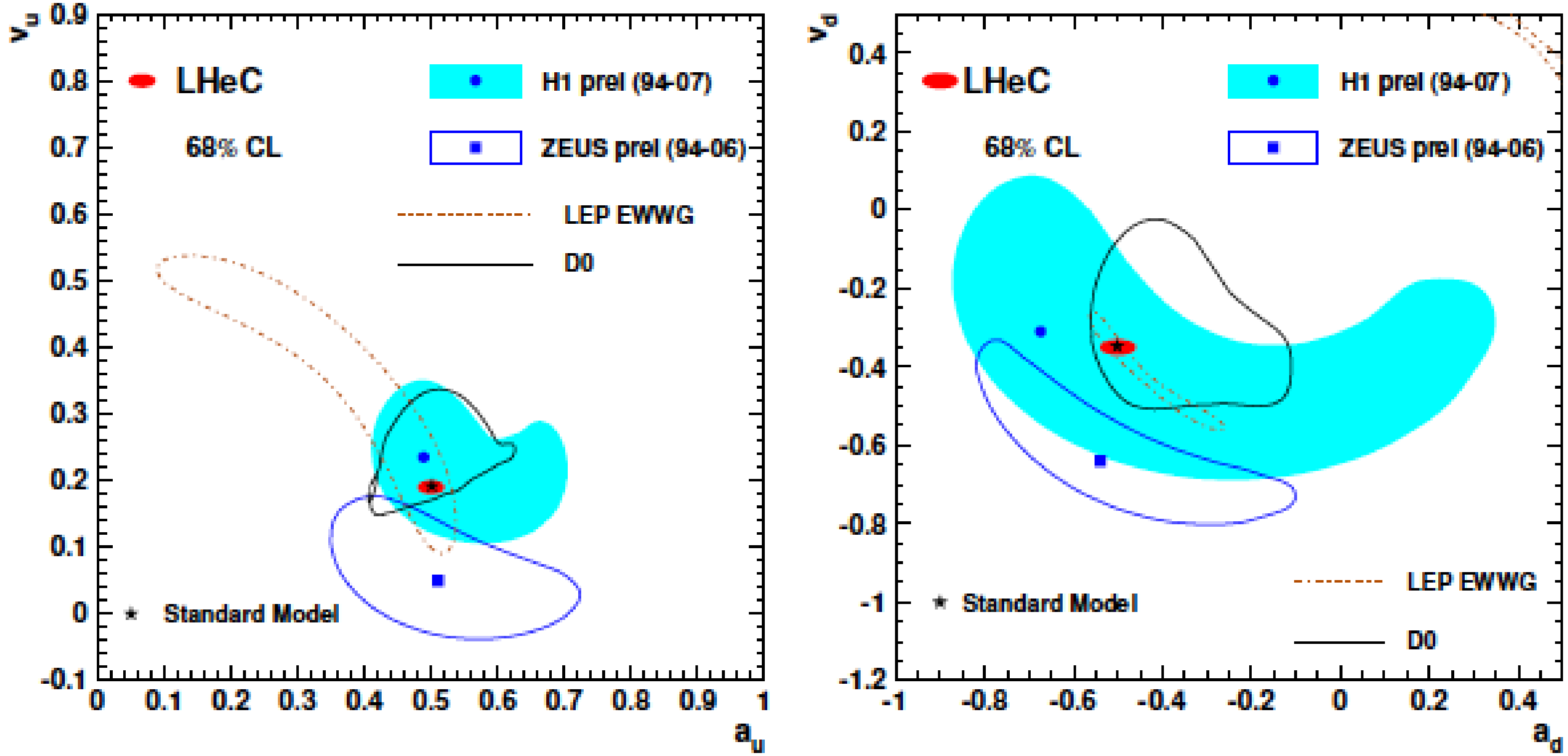
Several different complementary channels to access gluons

| | | Photon Gluon Fusion | |
|---|---|---|---|
| **Scaling Violation** | **$F_L$** | **Di-jets** | **Charm** |
| all $x$-$Q^2$<br>$x_g = x_{Bj}$ | only accessible if y is large<br>$x_g = x_{Bj}$ | wide coverage in $x_{Bj}$-$Q^2$<br>$x_g = x_{Bj}(1+M^2/Q^2) > x_{Bj}$ | same coverage in $x_{Bj}$-$Q^2$ as incl. $F_2$<br>$x_g \gtrsim x_{Bj}$ |
| only limited by detector acceptance | need several beam energies | need a wide acceptance detector | needs excellent m-vertex detector and particle ID |



# What can an EIC Do?

Should study what NC and CC cross sections at EIC can tell us on the vector and axial-vector weak neutral current couplings



# PDFs: flavor separation from SIDIS@EIC

Use reweighting method to define EIC SIDIS data impact on collinear unpolarized PDFs and Fragmentation functions

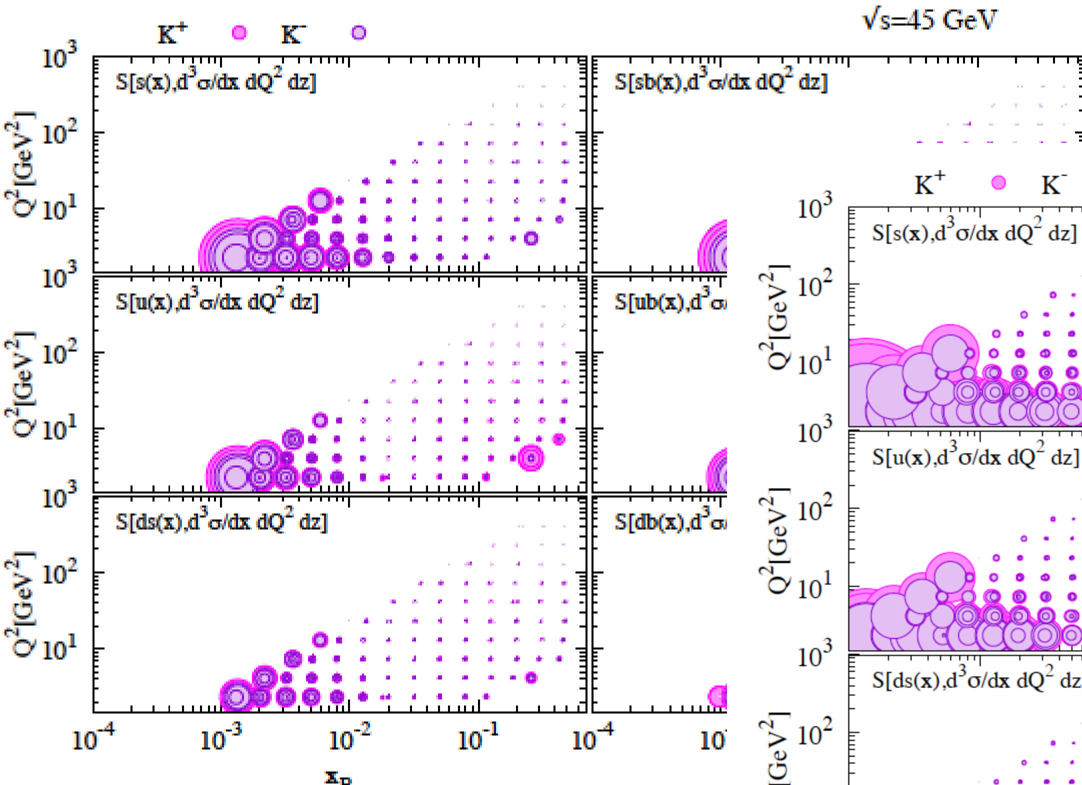
$\delta\mathcal{O}$ : exp. uncertainty Observable

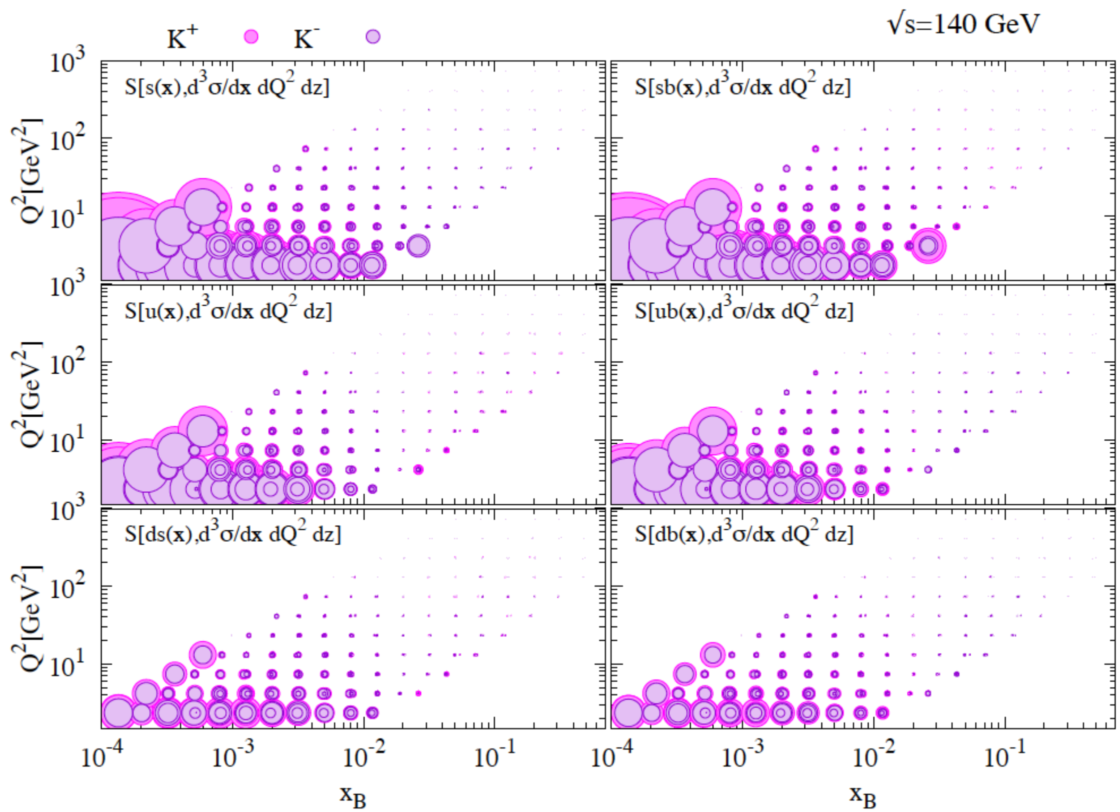
$\Delta$ PDF in Observable

Correlation factor of observable $\mathcal{O}$ to a flavor i

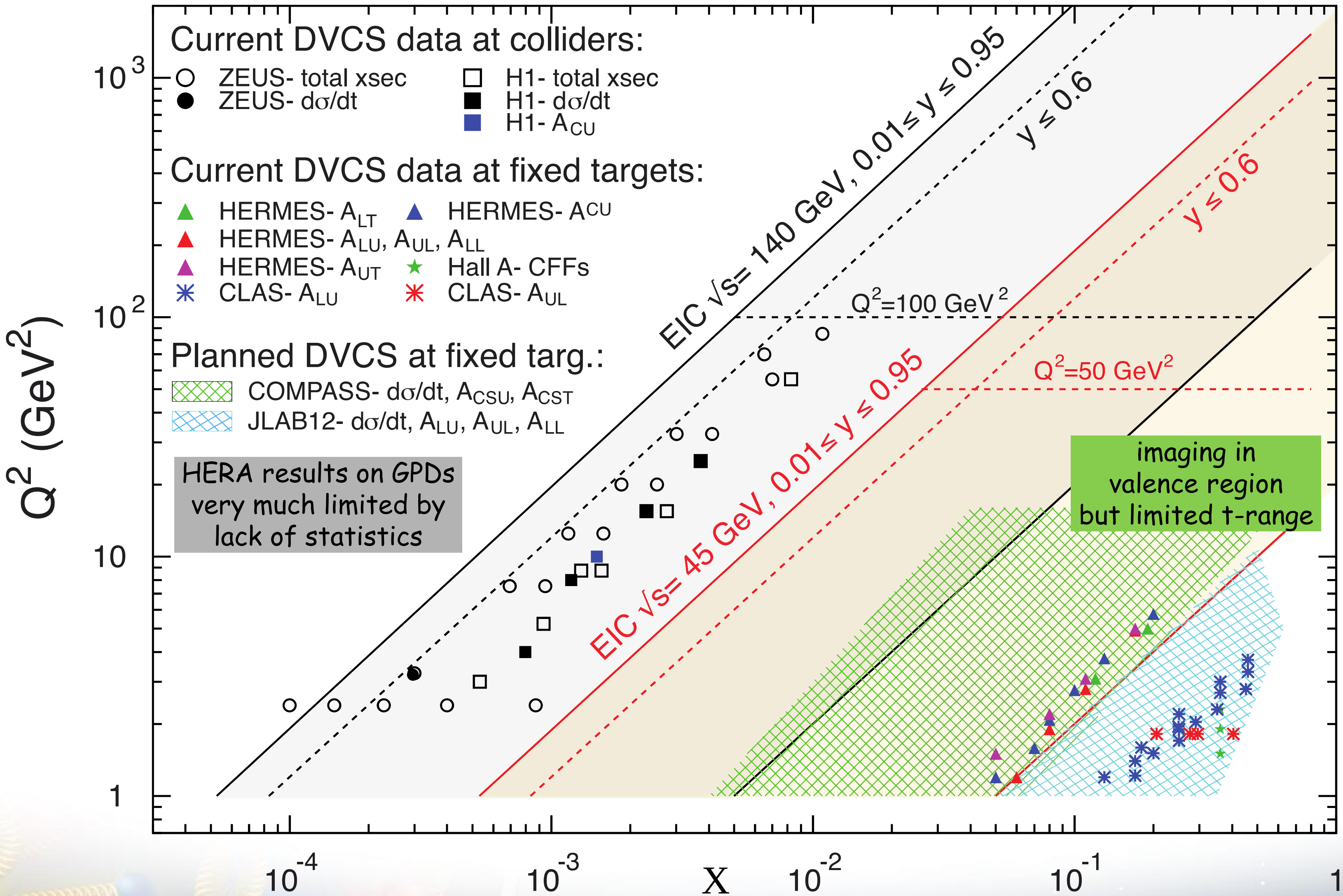
$$\rho\,[f_i,\mathcal{O}] = \frac{\langle \mathcal{O}\cdot f_i\rangle - \langle \mathcal{O}\rangle\langle f_i\rangle}{\Delta\mathcal{O}\Delta f_i}\,, \quad \xrightarrow{\text{account for uncertainties}} \quad S[f_i,\mathcal{O}] = \frac{\langle \mathcal{O}\cdot f_i\rangle - \langle \mathcal{O}\rangle\langle f_i\rangle}{\xi\,\Delta\mathcal{O}\Delta f_i}\,,$$

$$\xi \equiv \frac{\delta\mathcal{O}}{\Delta\mathcal{O}}$$



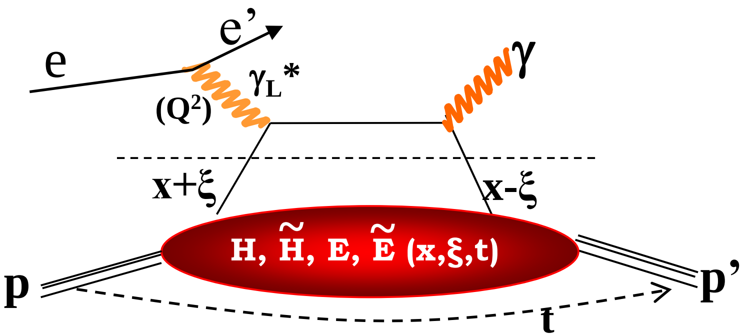
# The DVCS Phase Space




quantum numbers of final state → selects different GPD

DVCS: wide range of observables ($\sigma$, $A_{UT}$, $A_{LU}$, $A_{UL}$, $A_C$) to disentangle GPDs

# DVCS at eRHIC

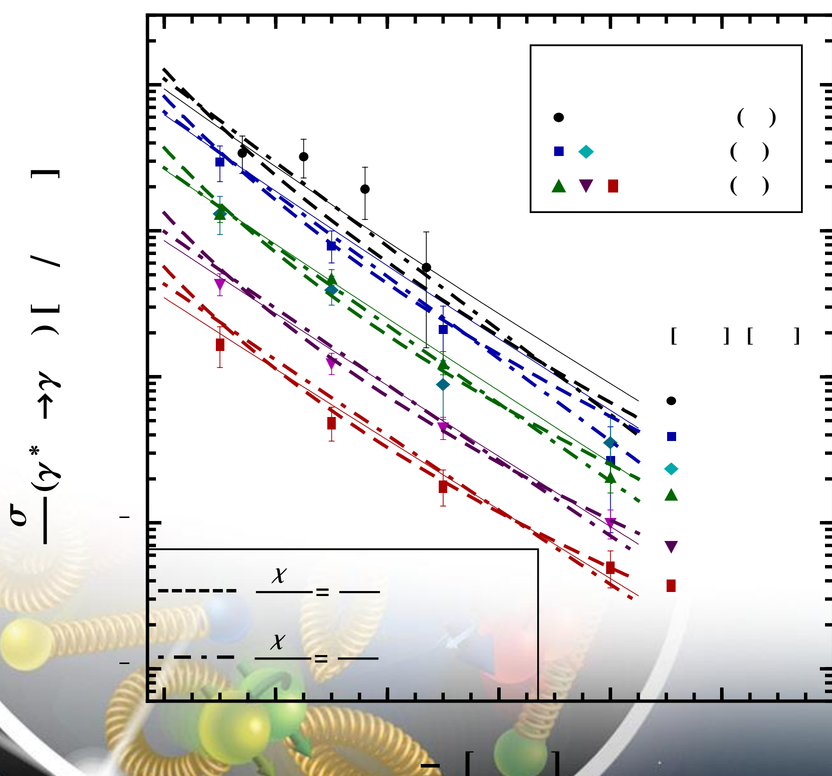


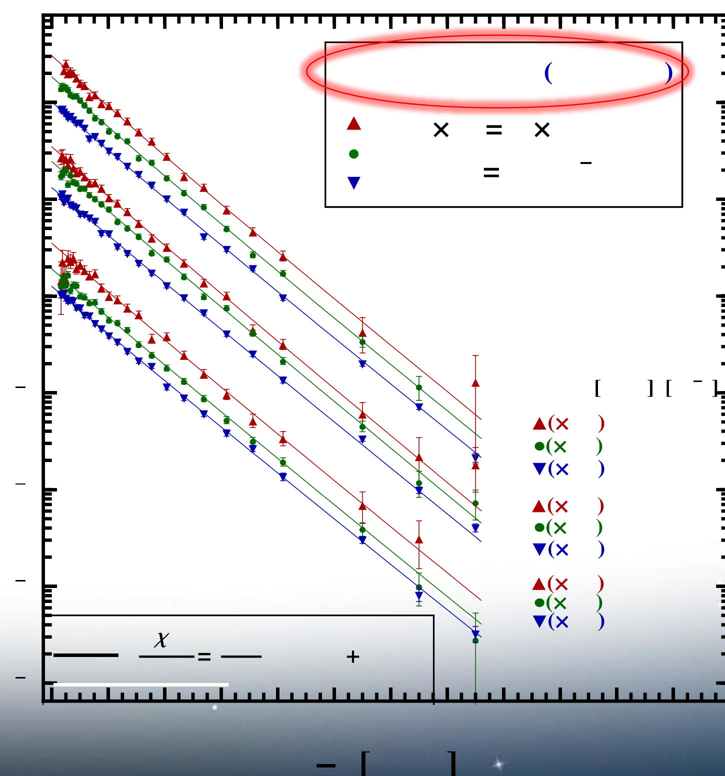

DVCS: Golden channel
theoretically clean
wide range of observables
($\sigma$, $A_{UT}$, $A_{LU}$, $A_{UL}$, $A_C$)
to disentangle different GPDs

## DVCS data at end of HERA


D. Mueller, K. Kumericki
S. Fazio, and ECA


arXiv:1304.0077



# DVCS Asymmetries

$$d\sigma \sim \left(\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH}\right) + |\tau_{BH}|^2 + |\tau_{DVCS}|^2$$

→ different charges: $e^+$ $e^-$:

$$\Delta\sigma_C \sim \cos\phi \cdot \mathrm{Re}\{ H + \xi\tilde{H} + \ldots \}$$ ➡ H

→ polarization observables:

$$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{H + \xi\tilde{H} + kE\}$$ ➡ H

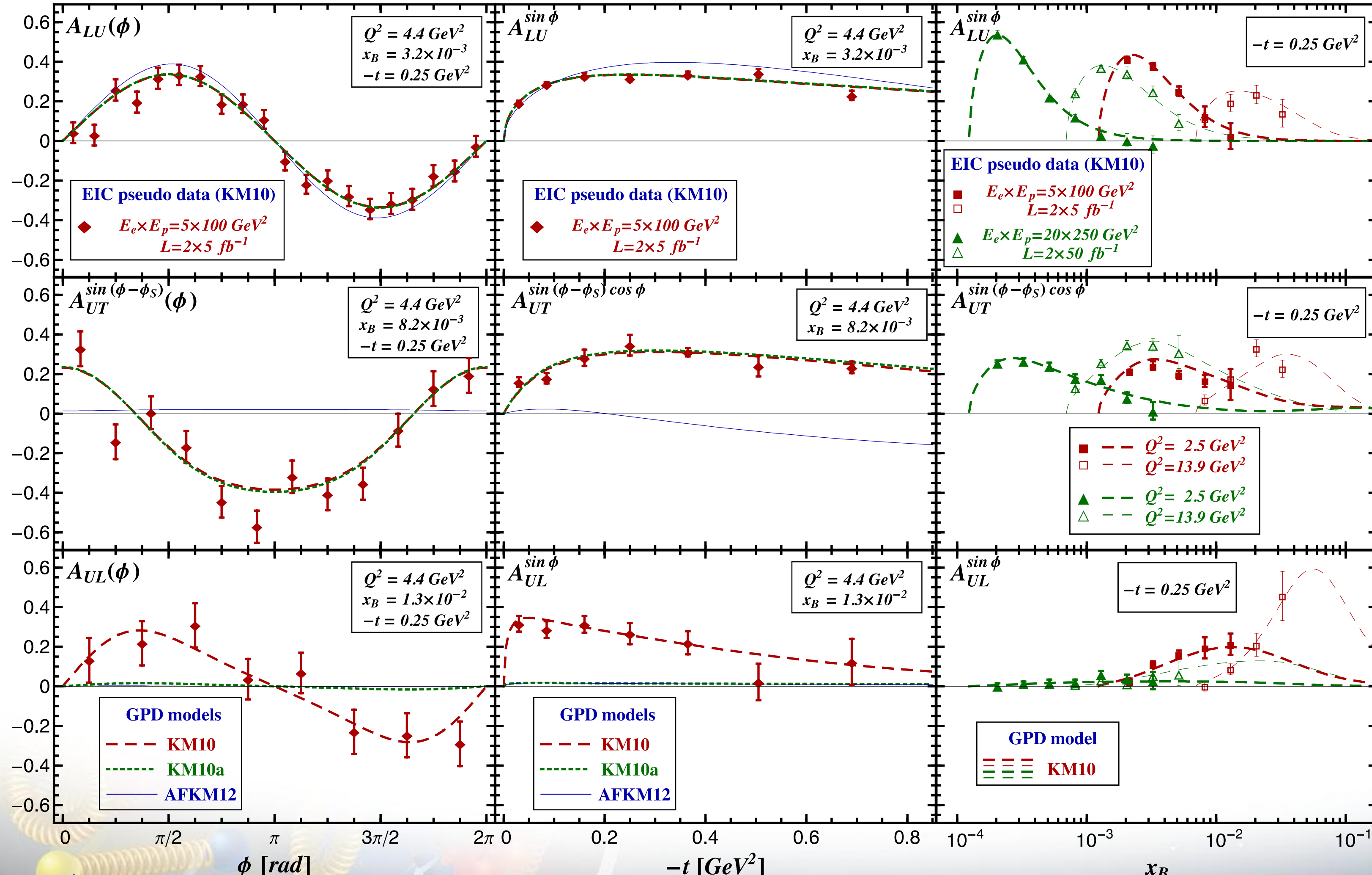
$$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{\tilde{H} + \xi H + \ldots\}$$ ➡ $\tilde{H}$

$$\Delta\sigma_{UT} \sim \sin\phi \cdot \mathrm{Im}\{k(H - E) + \ldots\}$$ ➡ H, E

$\xi = x_B/(2-x_B)$ $k = t/4M^2$ kinematically suppressed

# Disentangle different GPDs

Vary electron and proton beam spin directions:

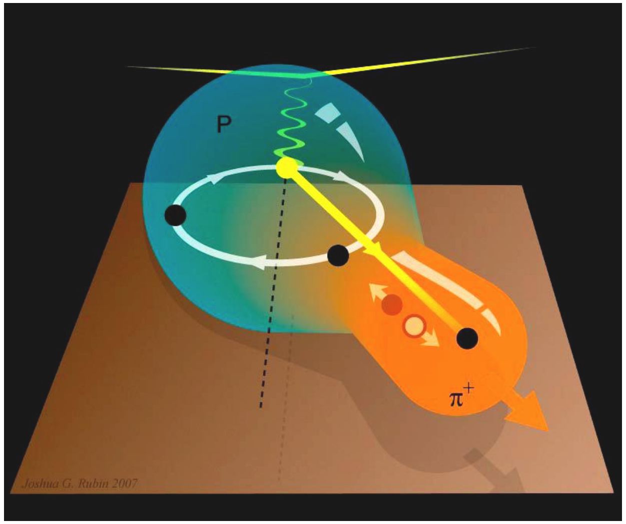



electron beam longitudinal polarised → $H$

proton beam transverse polarised → $H, E$

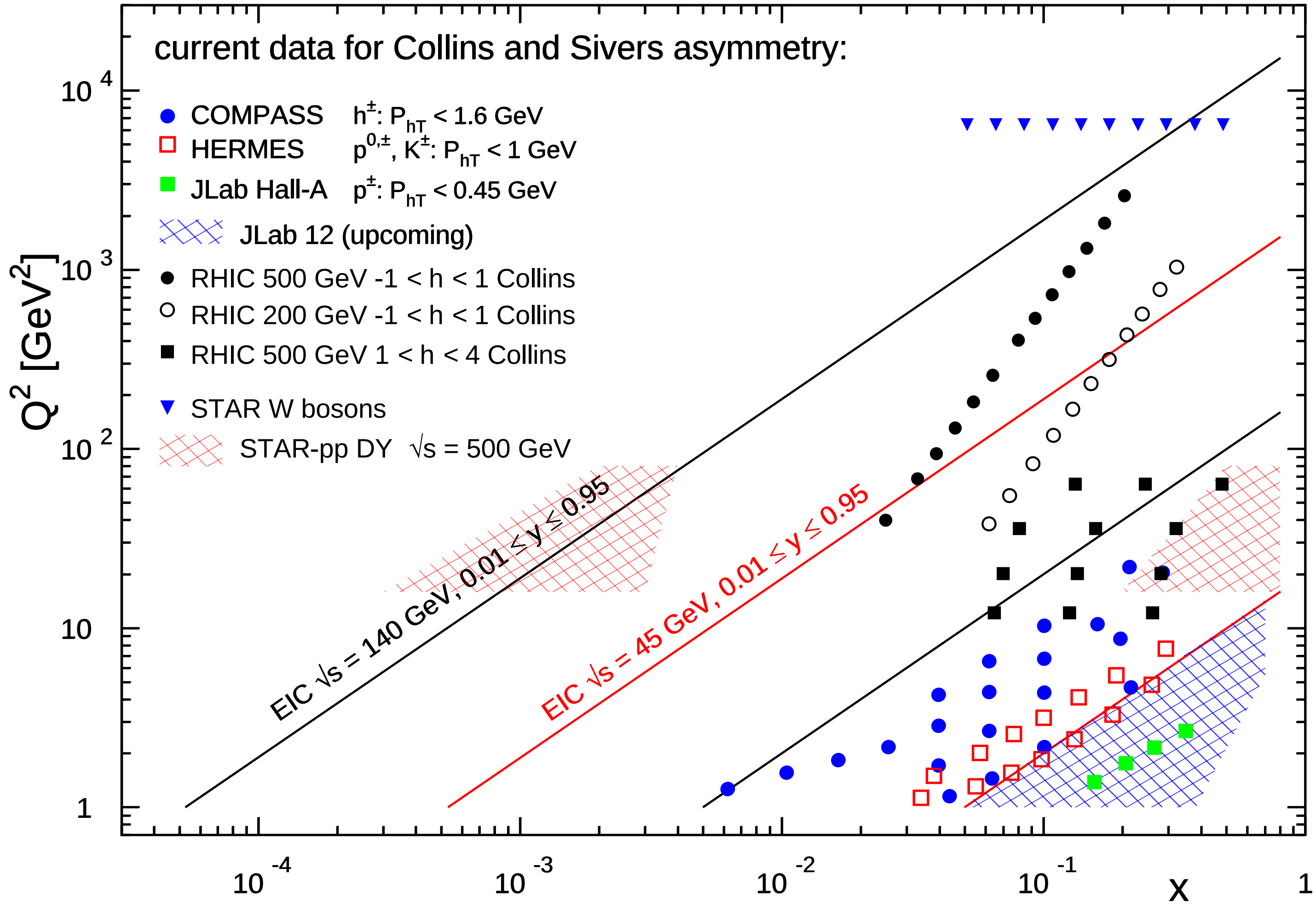
proton beam longitudinal polarised → $\tilde{H}$

$\Delta\sigma_{UT}$ → beam, target




# Transverse momentum dependent distributions (TMD)

# TMDs at STAR




Before STAR TMDs came only from fixed target data → high x @ low $Q^2$

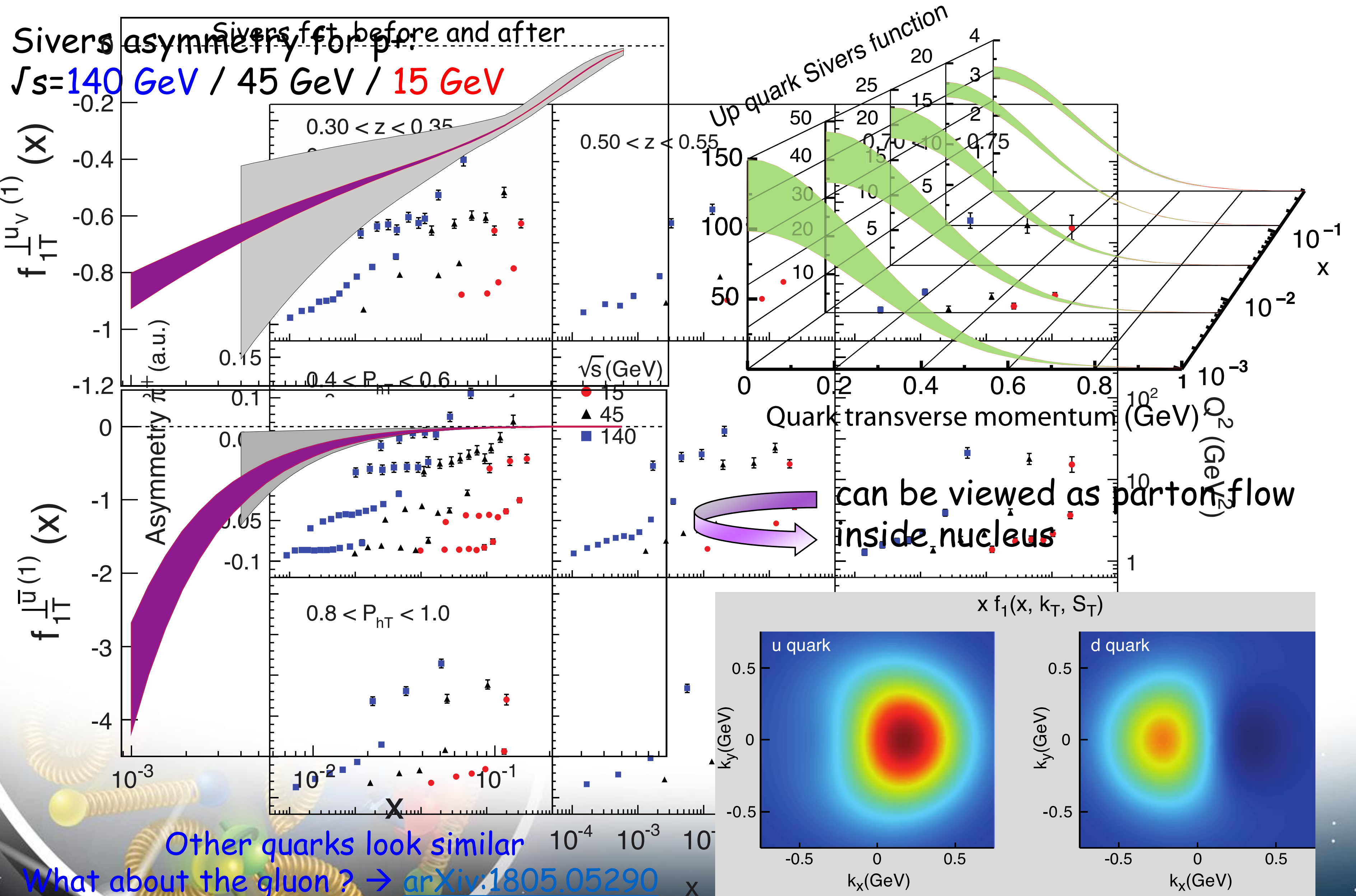
needed to establish concept at high $Q^2$ and wide range in x

polarised pp at RHIC

STAR unique kinematics: from high to low x at high $Q^2$

Sivers asymmetry for p+:

$\sqrt{s}$=140 GeV / 45 GeV / 15 GeV




can be viewed as parton flow inside nucleus

Other quarks look similar

What about the gluon ? → arXiv:1805.05290

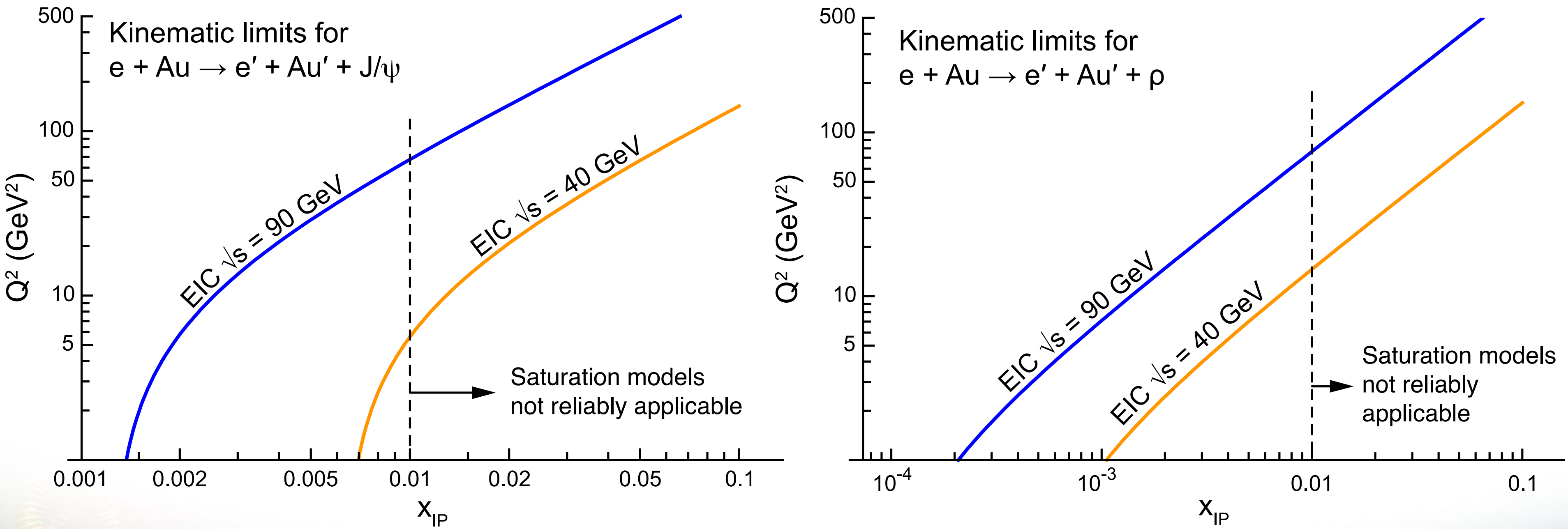
# 3d-Imaging of Nuclei

1950-60: Measurement of charge (proton) distribution in nuclei
Ongoing: Measurement of neutron distribution in nuclei
EIC ⇒ spatial gluon distribution in nuclei → Saturated or non-saturated ?

**Method:**

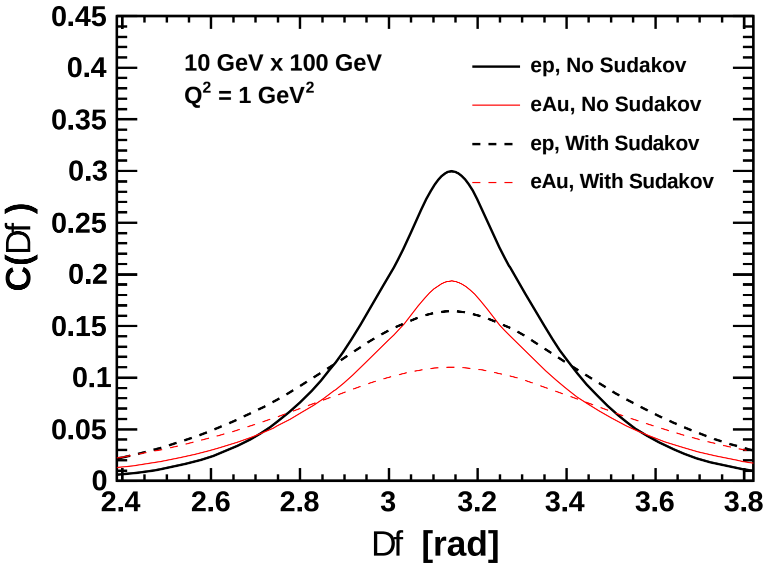
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \varphi, \rho$

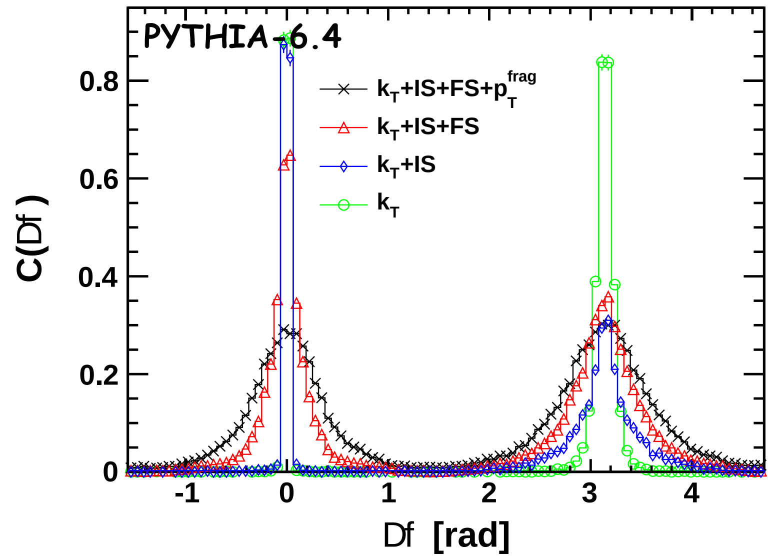
- Momentum transfer $t = |\mathbf{p}_{Au}-\mathbf{p}_{Au'}|^2$ conjugate to $b_T$



# Are other effects important?

## What is the impact of sudakov factors ← → parton showers?




Sudakov / parton showers have a critical impact
→ how well do we know them in nuclei?
→ can use forward correlation peak to calibrate them

For details on the study:
arXiv:1403.2413