IGFAE
Instituto Galego de Física de Altas Enerxías

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Electrons for the LHC - LHeC/FCC-eh and Perle Workshop
LAL, Orsay, June 27th-29th 2018

LHeC

FCC hh ee he

Summary: Small x and Physics with eA

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Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"

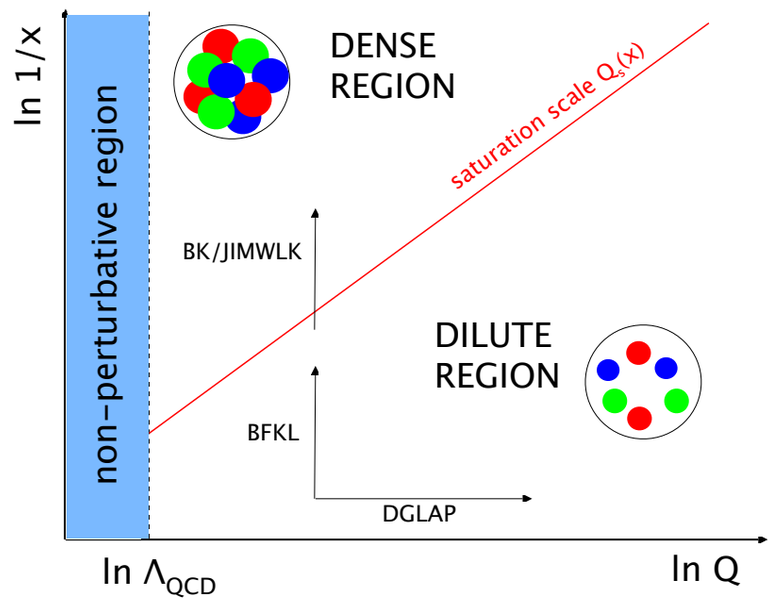
EXCELENCIA MARÍA DE MAEZTU

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

XUNTA DE GALICIA

The problem:

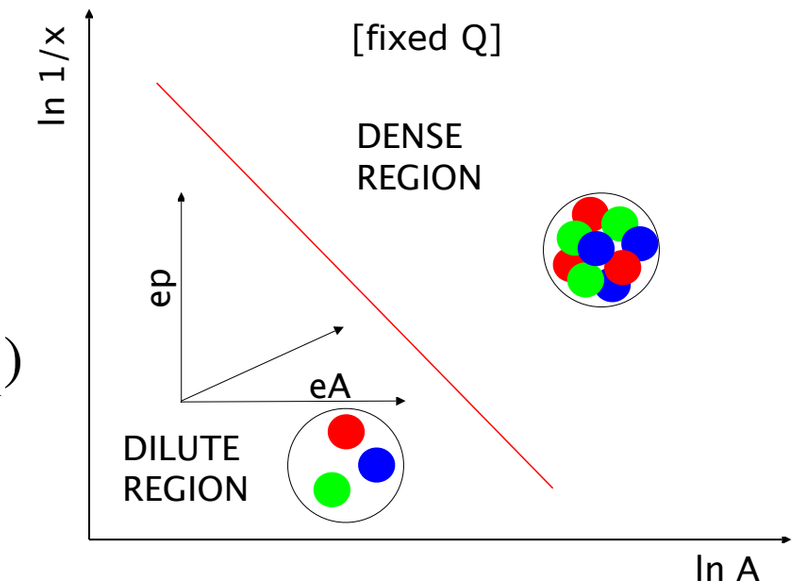
- Behaviour of QCD at high energies/A ≡ high partonic densities.



$$\frac{xG_A(x, Q^2_{s,A})}{\pi R_A^2 Q^2_{s,A}} \sim 1$$

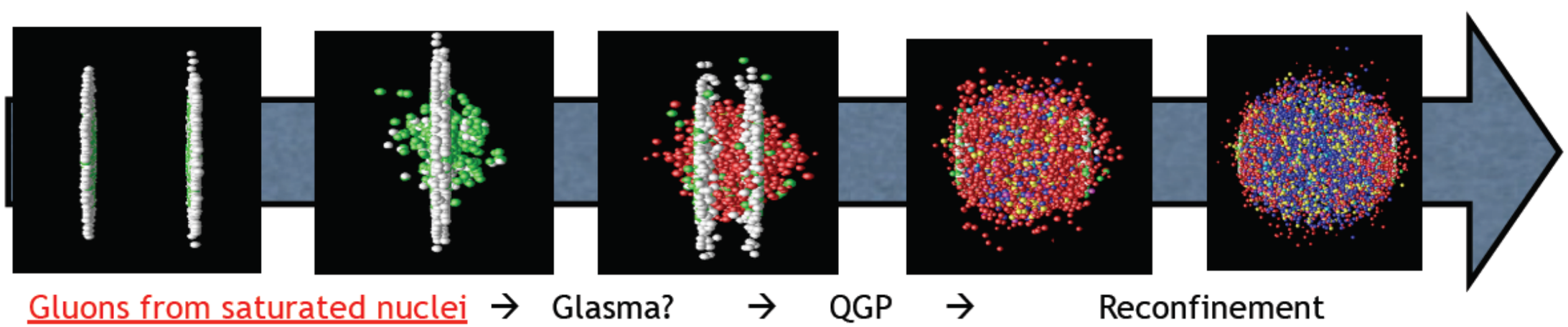
$$\Longrightarrow Q^2_{s,A} \propto A^{1/3} x G_p(x, Q^2_{s,A})$$

$$\propto A^{1/3} \frac{1}{x^{1/3}}$$

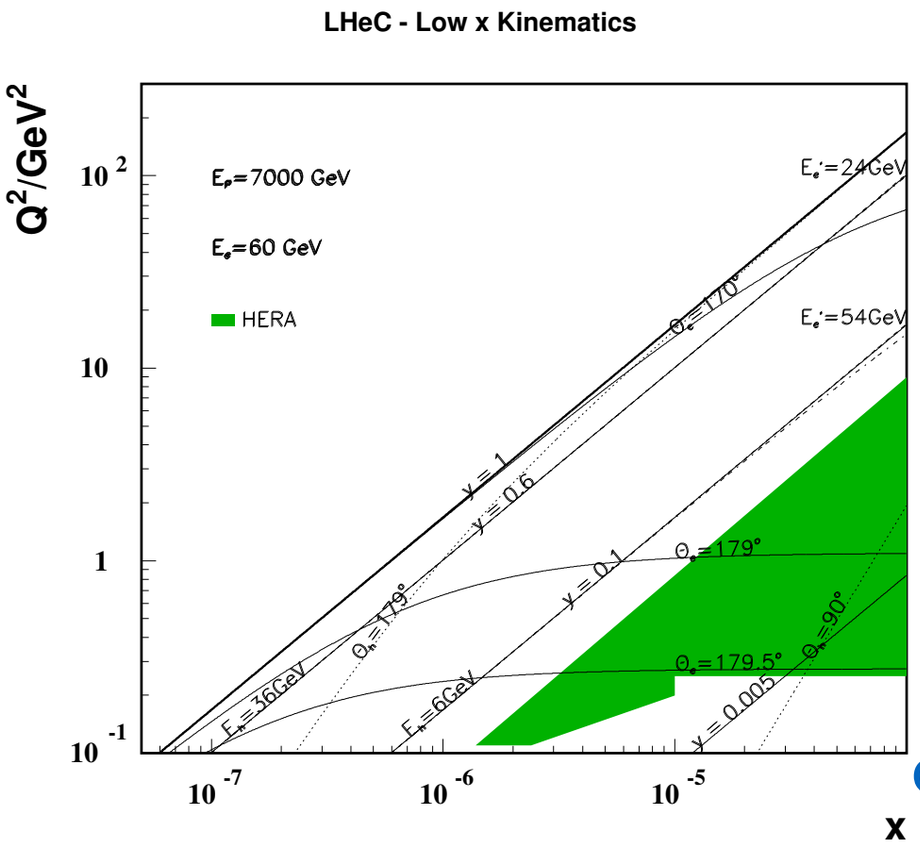


with implications on pp/pA/AA collisions and the small systems problem (thermalisation?; emergence of macroscopic properties?)

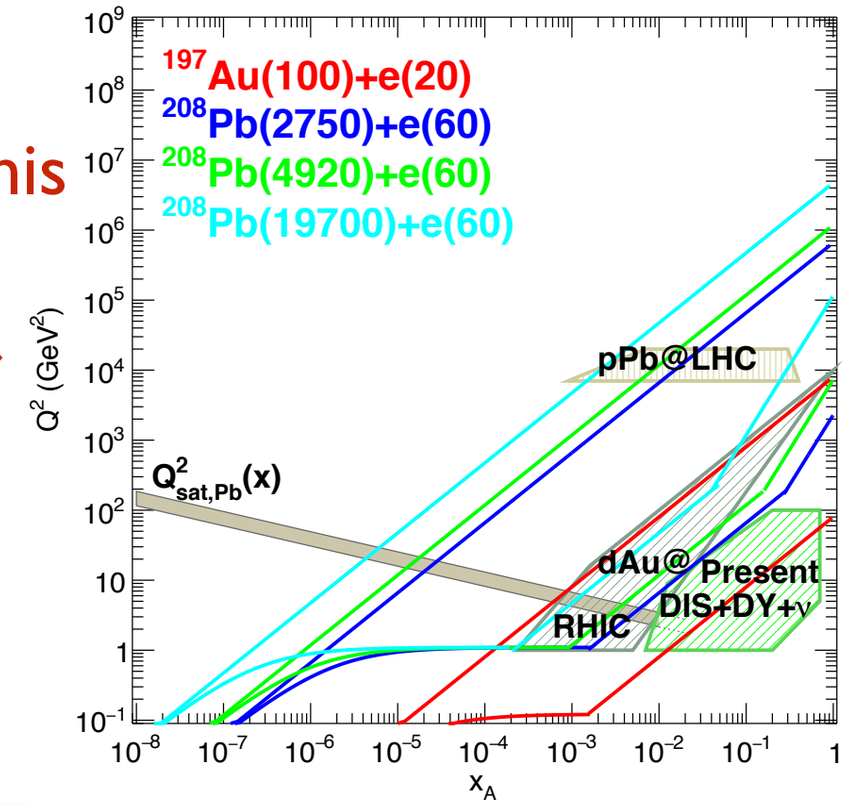
[B. Cole]



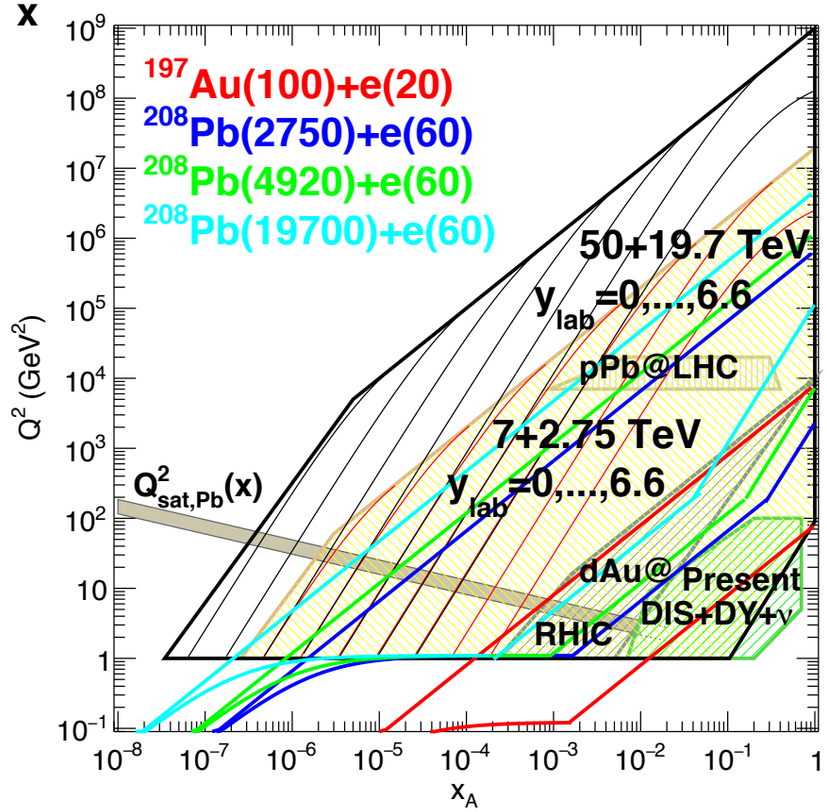
Our task:



What can we do with this



while keeping an eye on this?



Talks:

➜ *The Electron Ion Collider*, Bernd Surrow, Wednesday morning.
➜ *Impact of resummation on Higgs and other observables*, Simone Marzani, Wednesday afternoon.
➜ *Resummation*, Amanda Cooper-Sarkar, Wednesday afternoon.
➜ *Color fluctuations and photon-nucleus scattering*, Mark Strikman, Wednesday afternoon.
➜ *Exclusive vector meson production with eSTARLIGHT*, Spencer Klein, Wednesday afternoon.
➜ *Diffraction*, Anna Stasto, Thursday morning.
➜ *Elastic vector meson production*, Heikki Mantysaari, Thursday morning.
➜ *Open questions in QCD at high parton density (e+p, e+A, p+A)*, Cyrille Marquet, Thursday morning.
➜ *How could heavy ion physics at the energy frontier profit from LHeC measurements (EXP point of view)*, Astrid Morreale, Thursday morning.
➜ *How could heavy ion physics at the energy frontier profit from LHeC measurements (TH point of view)*, Elena G. Ferreiro, Thursday morning.
➜ *Novel High-Energy Electron-Proton Collider Physics at the LHeC*, Stanley Brodsky, Thursday afternoon.

Thank you very much to all of them!!!

EIC:

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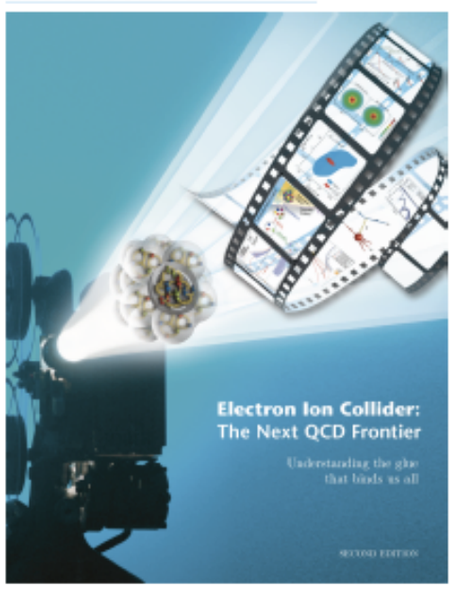
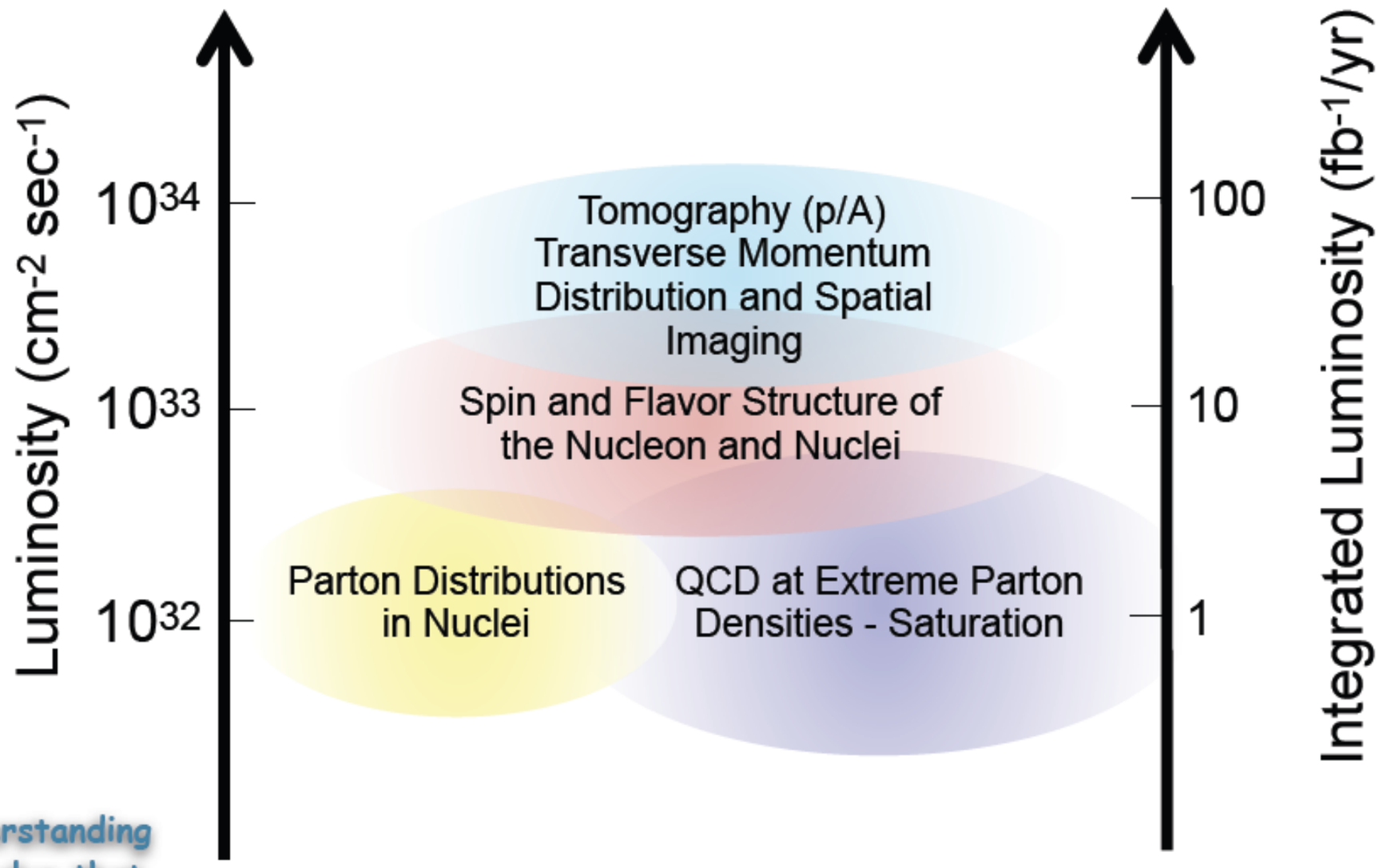
The EIC Physics Pillars

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper:

arXiv:1212.1701



Understanding the glue that binds as all!



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Bernd Surrow

EIC:

The EIC Physics Pillars

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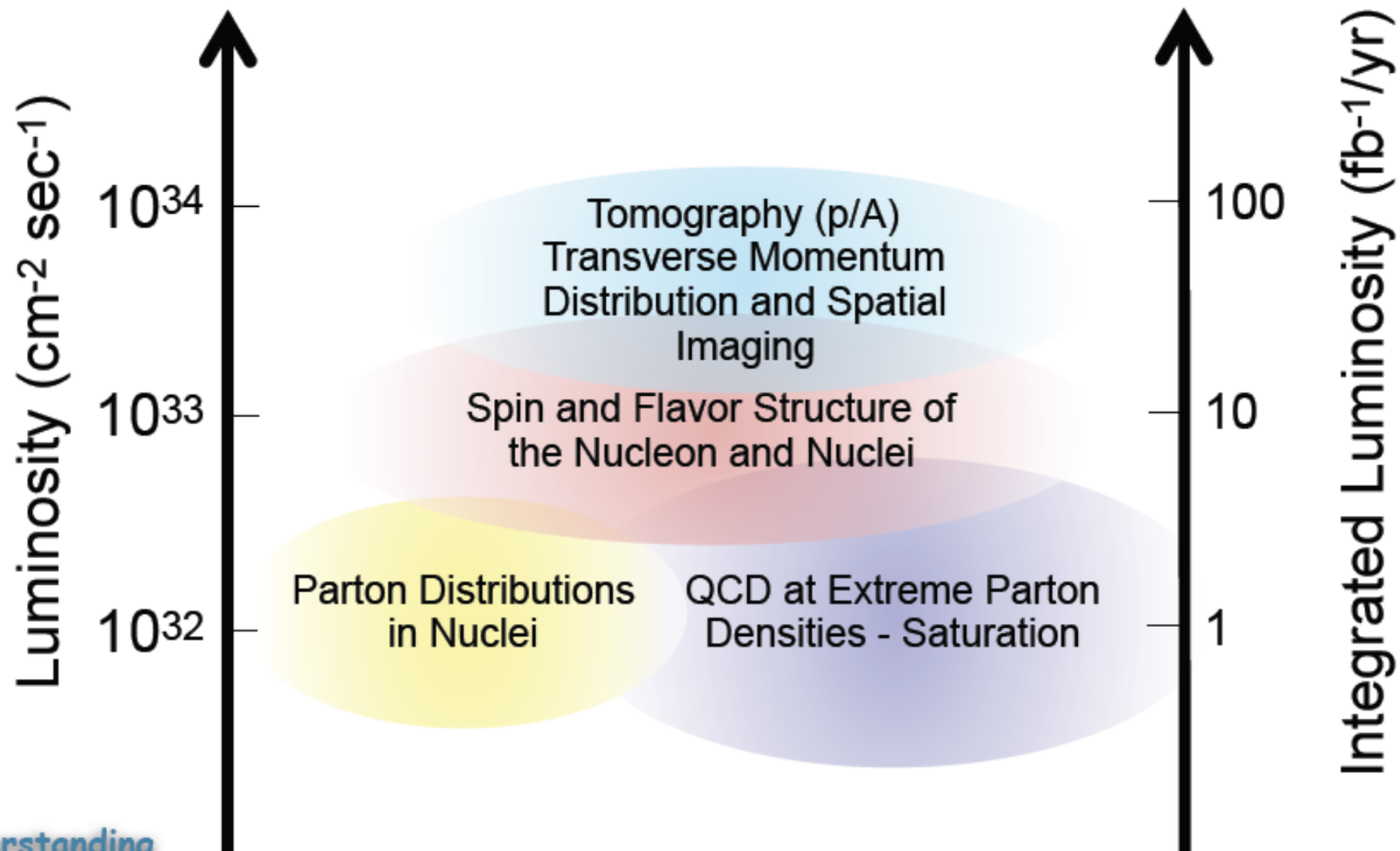

Understanding

- EIC ↔ LHeC: complementarity in the kinematic region, detector aspects, and physics opportunities.

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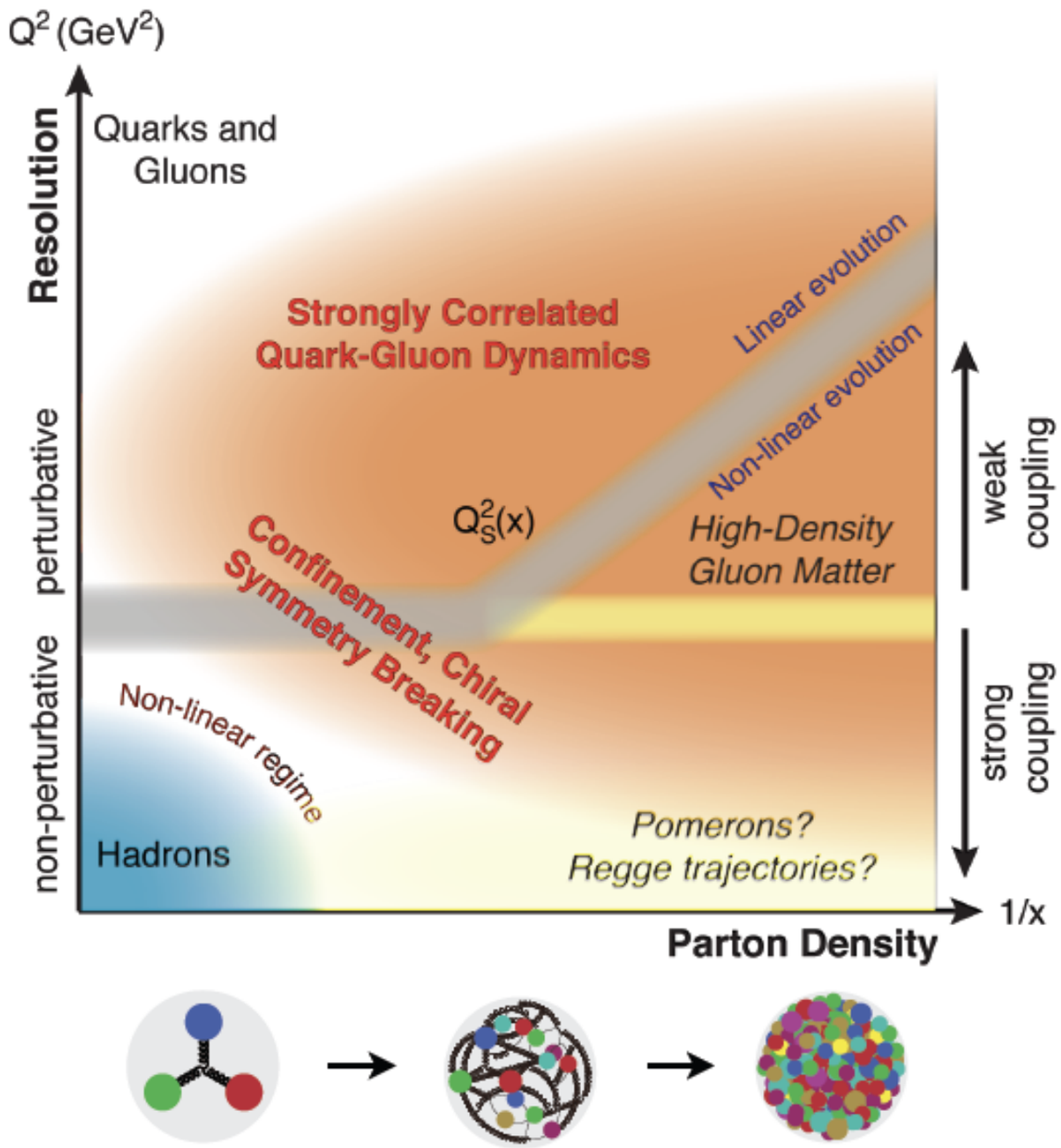
EIC:

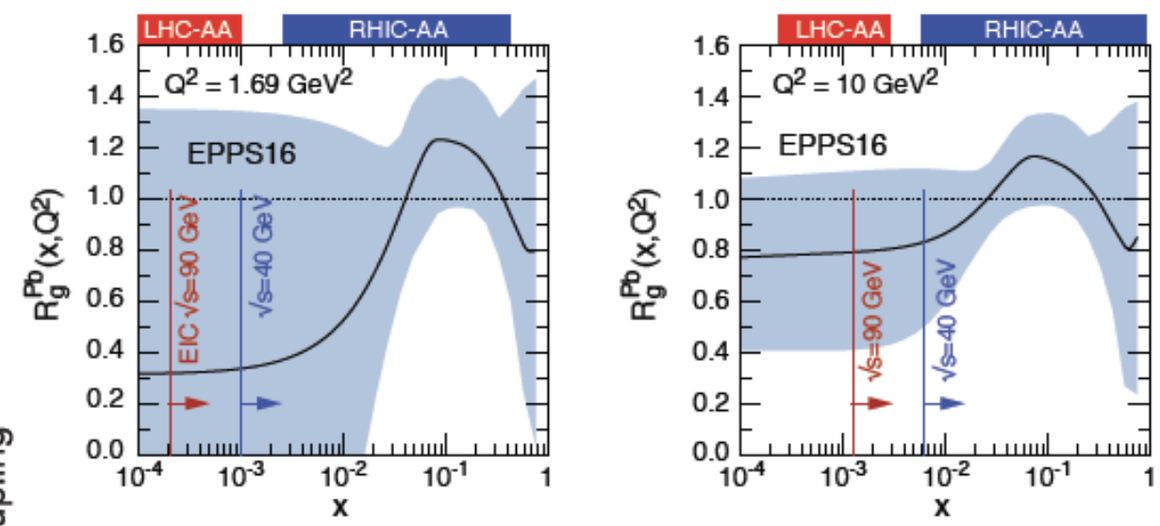
5

The EIC Physics Pillars

- QCD dynamics / Parton distributions in nuclei

arXiv:1708.01527





- Study modifications of gluons in nuclear environment complementing LHC-AA and RHIC-AA programs.

- Explore QCD landscape in various aspects over a wide range in x and Q^2 - Heavy nuclei at high energy critical to explore high-density gluon matter!

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Bernd Surrow

EIC:

The EIC Physics Pillars

- Transverse Momentum Distribution and Spatial Imaging

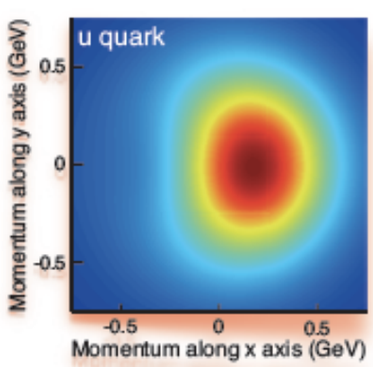
$f(x, k_T)$ 1+2D

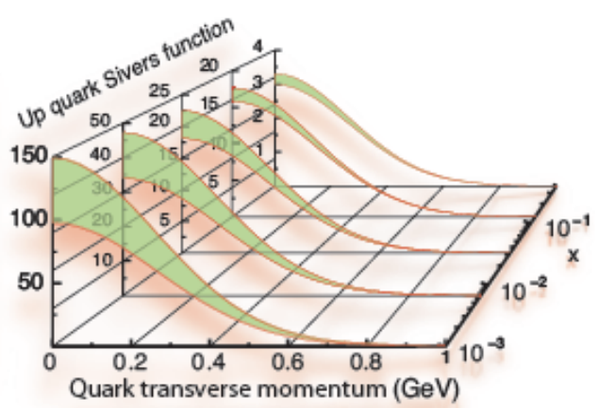
$\int d^2 b_T$ $W(x, b_T, k_T)$ $\int d^2 k_T$

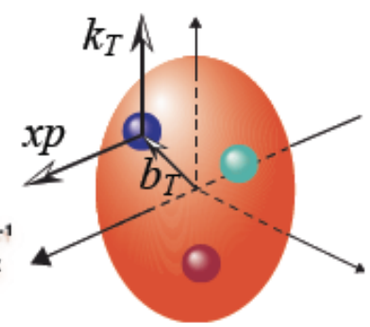
$f(x, b_T)$ 1+2D

Transverse Momentum Distribution (TMD) ← Wigner Distribution → Impact Parameter Distribution

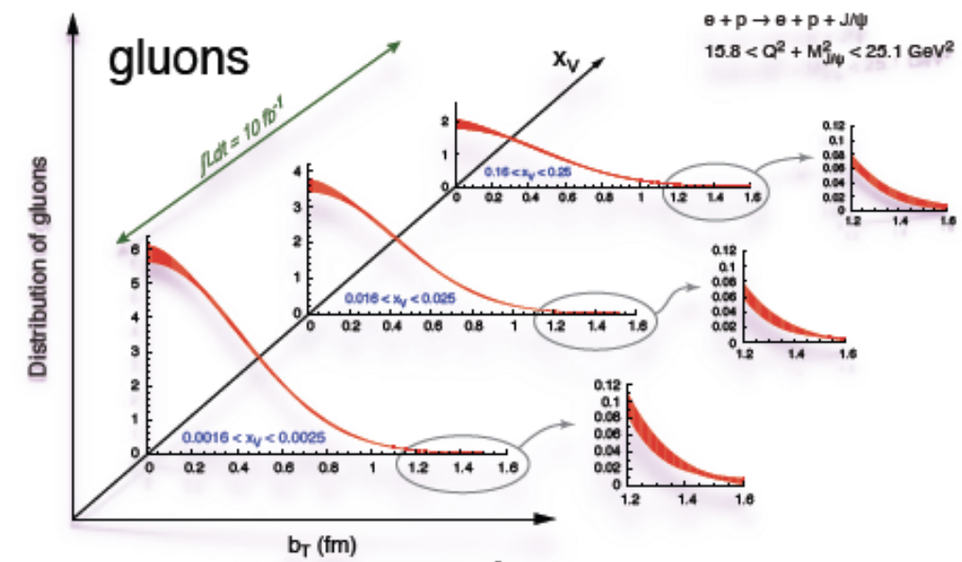
quarks







gluons



- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering
- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

Fourier transf.
$b_T \longleftrightarrow \Delta$: $t = -\Delta^2$

$H(x, 0, t)$

$\xi = 0$

$H(x, \xi, t)$

Generalized Parton Distribution (GPD)

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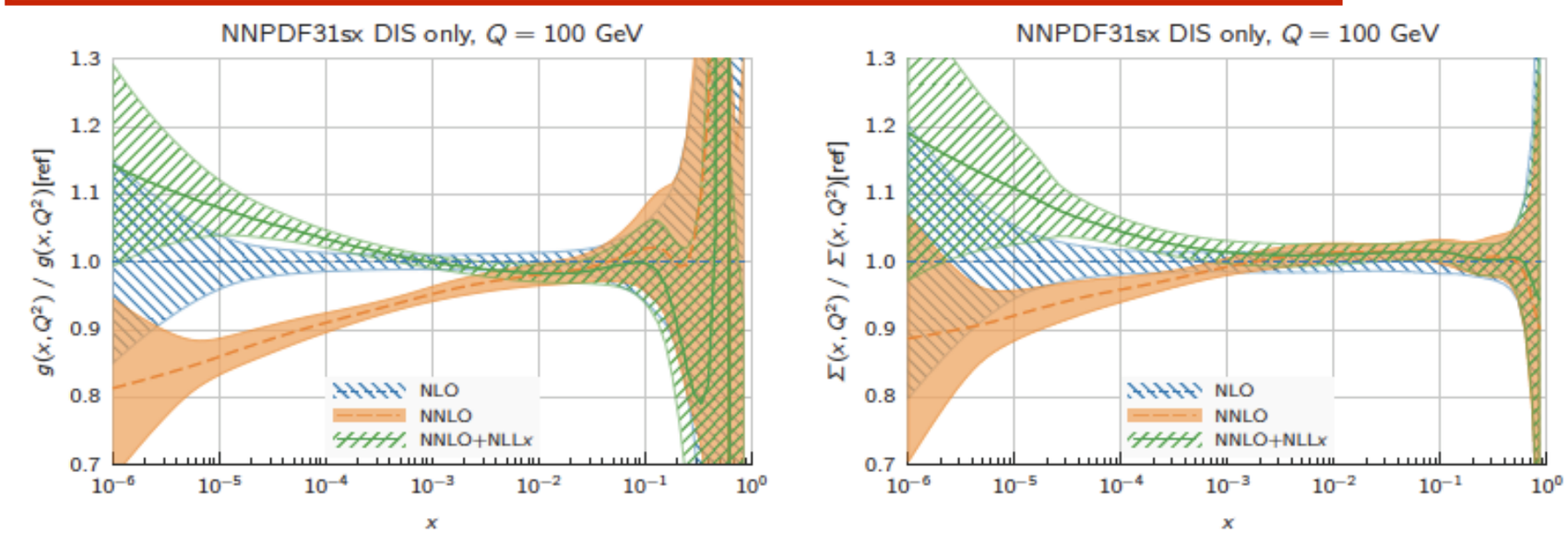
Bernd Surrow

Small-x resummation:

SIMONE MARZANI - LHeC / FCCeH 13

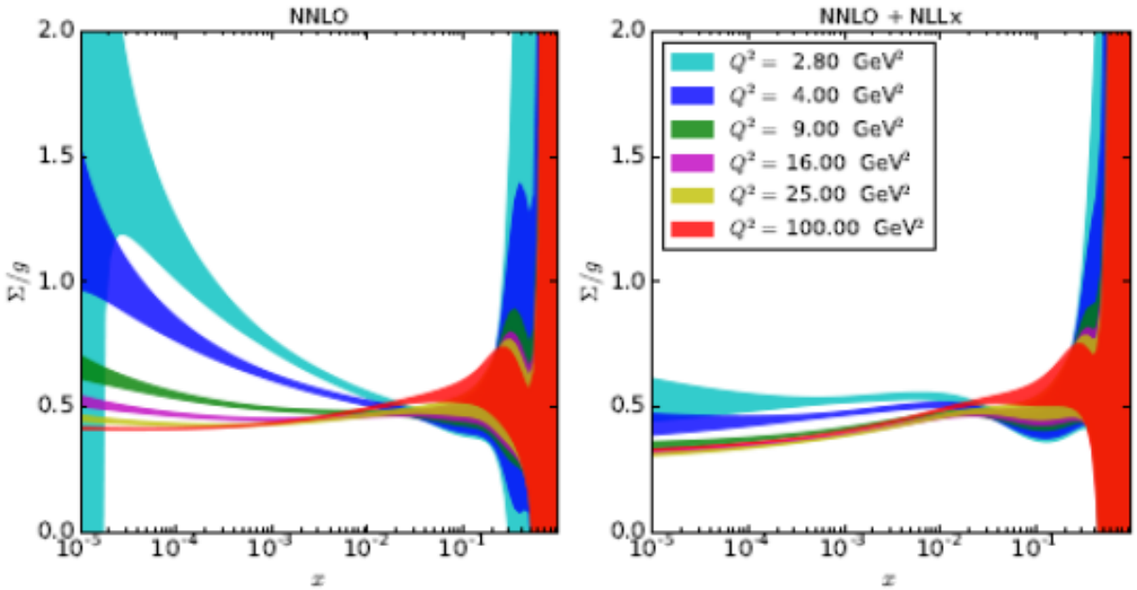
PERTURBATIVE STABILITY

- NNLO and NNLO+NLLx differ quite dramatically
- one could question the reliability of the resummed procedure
- what gives us confidence we're not talking rubbish?
- resummation cures perturbative instability of NNLO



Resummation at HERA:

Further study of the shapes of the gluon and the sea



In fixed order fits at NNLO the gluon dips below the sea at low-x as Q^2 is reduced.
This is a general feature of NNLO fits- not just of HERAPDF.

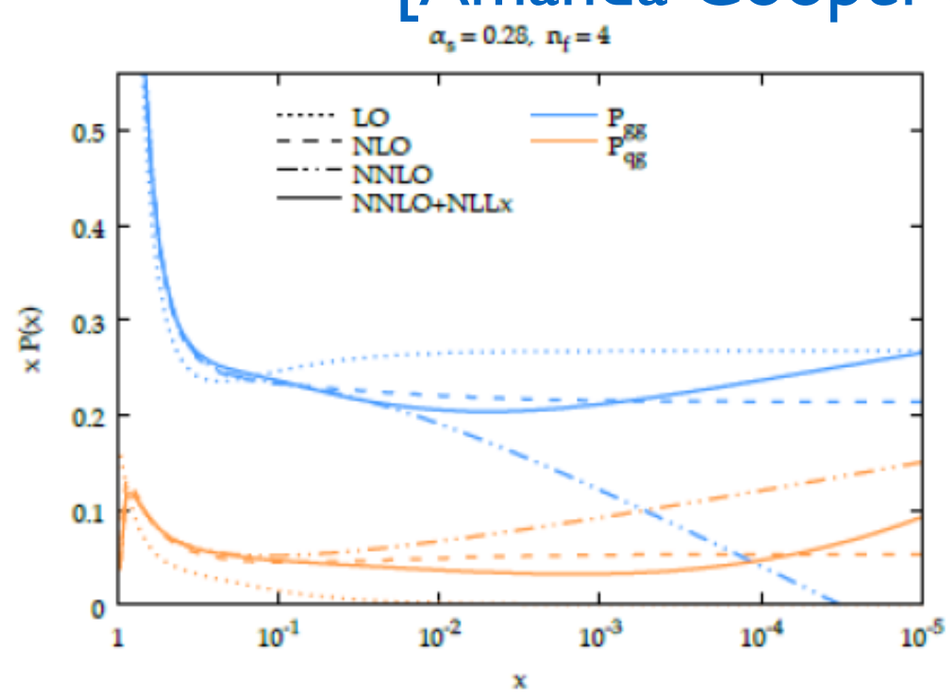
These plots show the ratio of total sea Σ to gluon vs x for various Q2 for NNLO and NNLO+NLLx fits.
The ratio is much more stable with Low x resummation

[Amanda Cooper-Sarkar]

This arises from the behaviour of the P_{qg} and P_{gg} splitting functions.
At NNLO $xP_{qg}(x) > xP_{gg}(x)$ for $x \lesssim 10^{-3}$,

Whereas for NNLO+NLLx

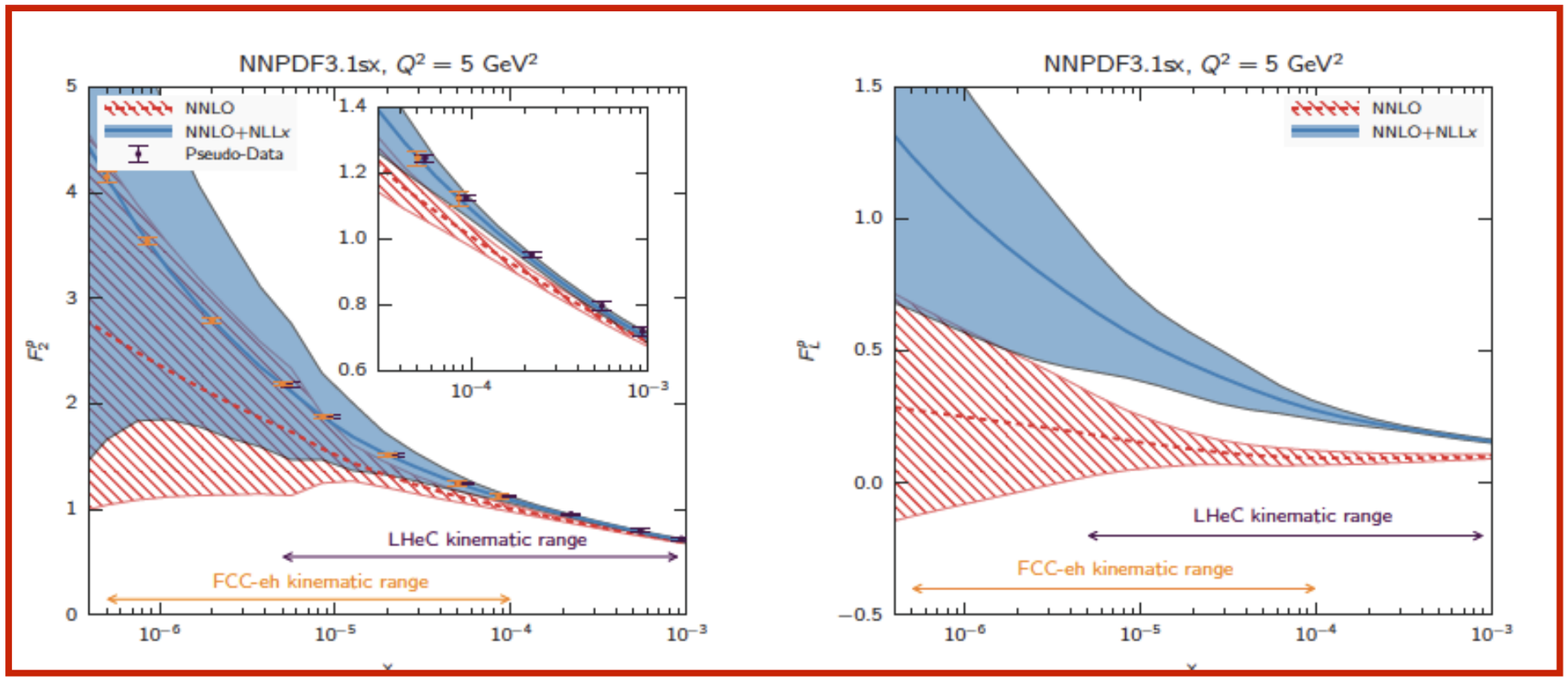
$$xP_{qg}(x) < xP_{gg}(x)$$



Small-x resummation:

SIMONE MARZANI - LHeC / FCCeH 17

BFKL: THE GHOST OF CHRISTMAS YET-TO-COME



- small-x physics will be crucial at future circular colliders
- *e* (60 GeV) - *p* (7 TeV or 50 TeV) collisions
- to gauge the impact: fits including (resummed) pseudo-data

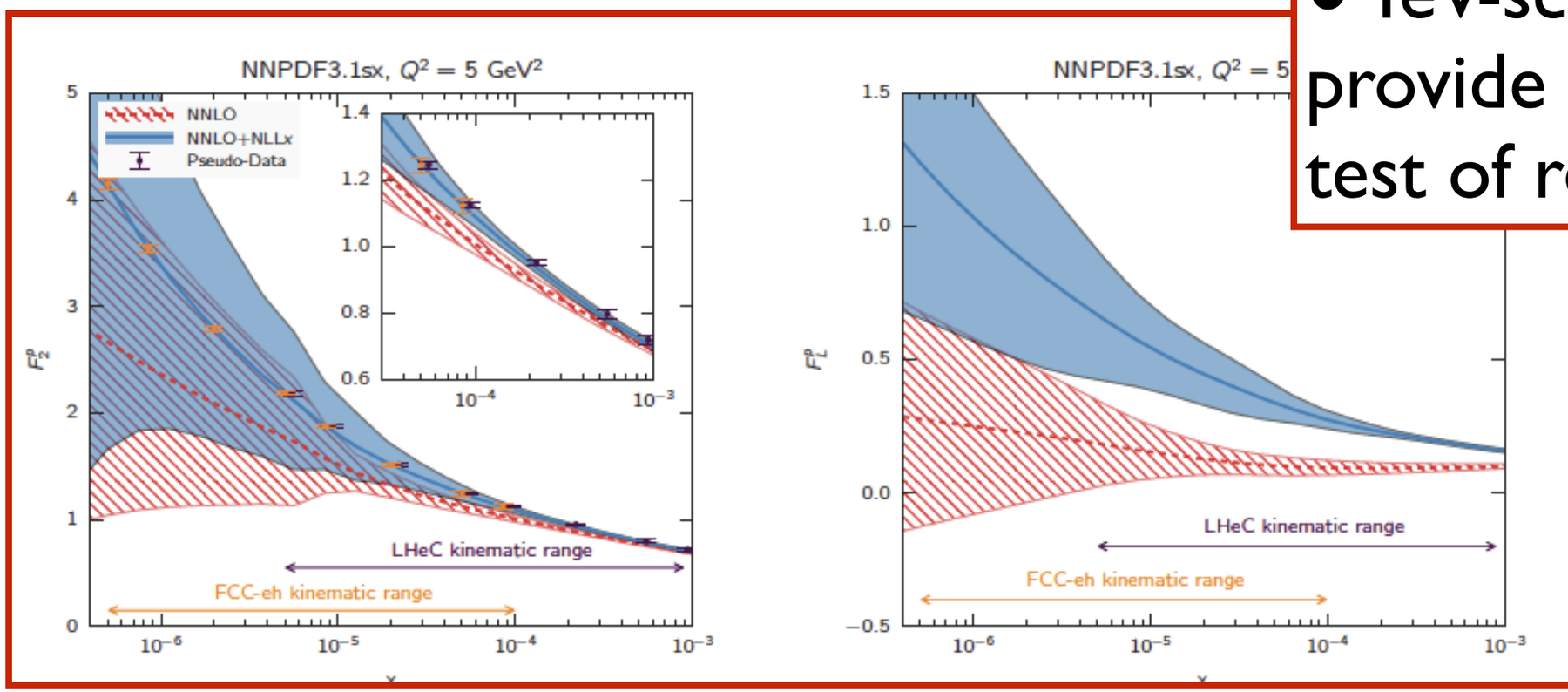
	N_{dat}	χ^2/N_{dat} NNLO	χ^2/N_{dat} NNLO+NLLx	$\Delta\chi^2$
HERA I+II incl. NC	922	1.22	1.07	-138
LHeC incl. NC	148	1.71	1.22	-73
FCC-eh incl. NC	98	2.72	1.34	-135
Total	**1168**	**1.407**	**1.110**	**-346**

N. Armesto, 29.06.2018 - Summary: Small x and eA.

Small-x resummation:

SIMONE MARZANI - LHeC / FCCeH 17

BFKL: THE GHOST OF CHRISTMAS YET-TO-COME



- TeV-scale ep to provide a decisive test of resummation.

- small-x physics will be crucial at future circular colliders
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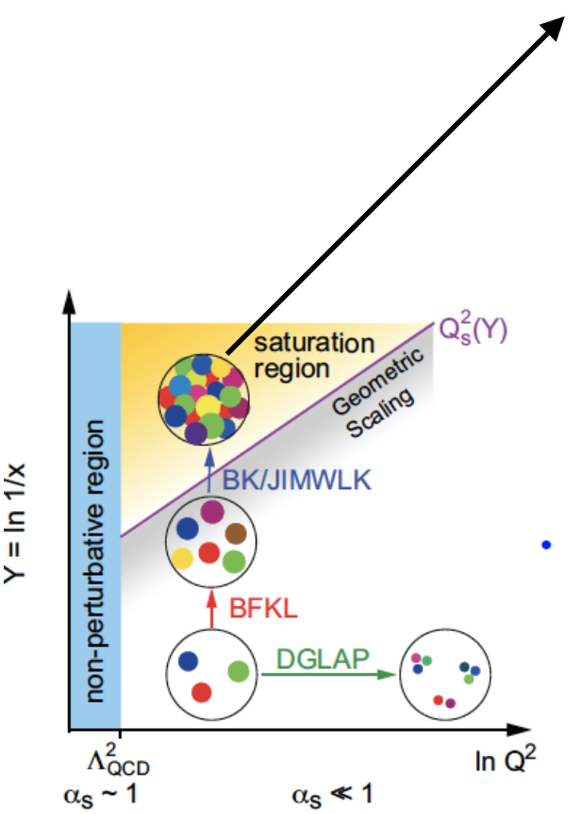
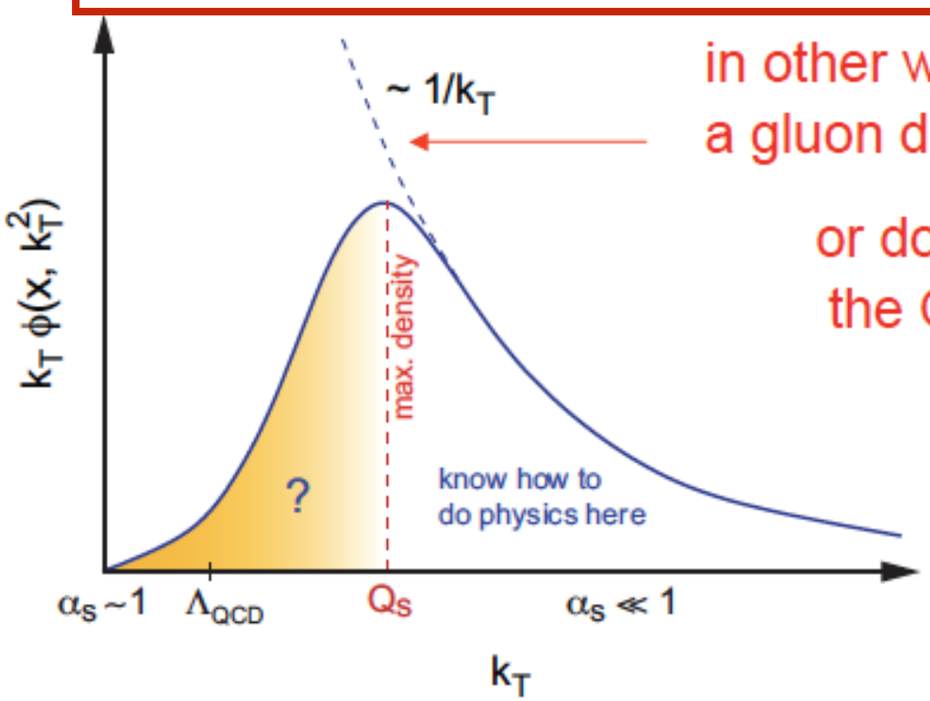
Small x:

[Cyrille Marquet]

A big open question

- is this relevant at today's colliders ?





in other words: can we get away with using such a gluon distribution (with ad hoc cutoff if necessary) ?

or do we need to properly take into account the QCD dynamics at $k_T \sim Q_S$ and below ?

the CGC phenomenology is successful for every collider process that involves small-x partons and $k_T \sim Q_S$, i.e. for a broad range for high-energy observables:

multiplicities in p+p, d+Au, Au+Au and Pb+Pb; forward spectra and correlations in p+p and d+Au; total, diffractive and exclusive cross sections in e+p and e+A, …

- main limitation:

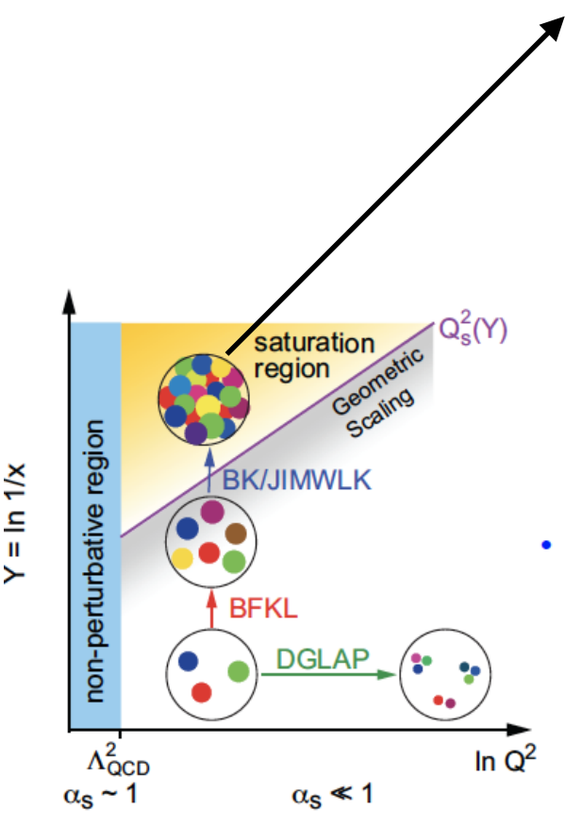
  - the applicability of the theory can be questioned when values of Q_S start to drop below 1 GeV (e.g. p+p and peripheral d+Au at RHIC)

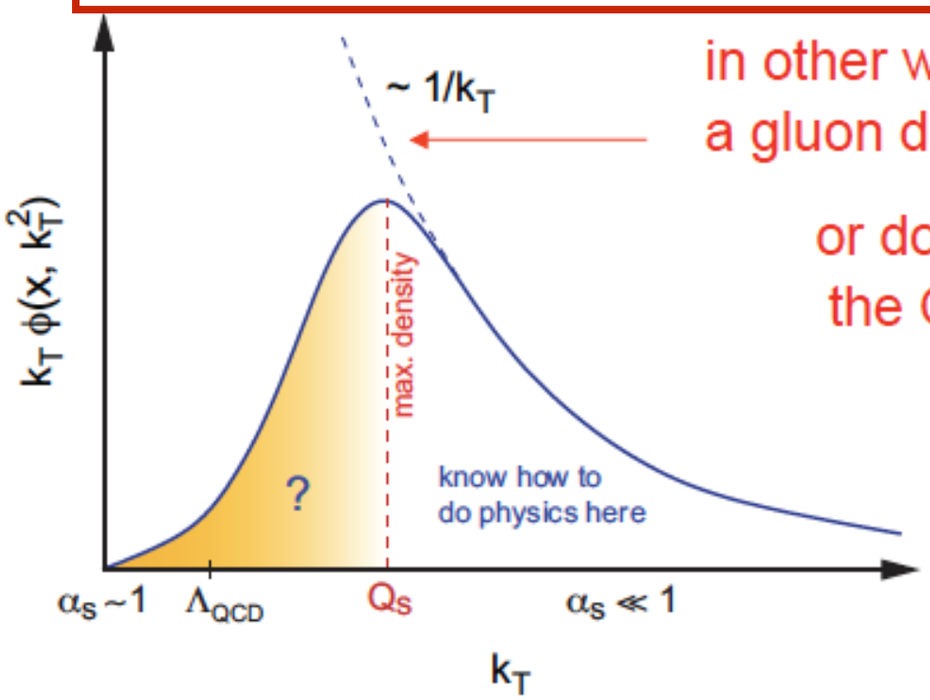
Small x:

[Cyrille Marquet]

A big open question

- is this relevant at today's colliders ?





in other words: car
a gluon distribution
or do we need
the QCD dyna
the CG
for eve
small-x
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?

- TeV-scale ep and eA required to provide x and Q^2 lever arm and set the relevance of this phenomenon.

multiplicities in p+p, d+Au, Au+Au and Pb+Pb; forward spectra and correlations in p+p and d+Au; total, diffractive and exclusive cross sections in e+p and e+A, …

- main limitation:
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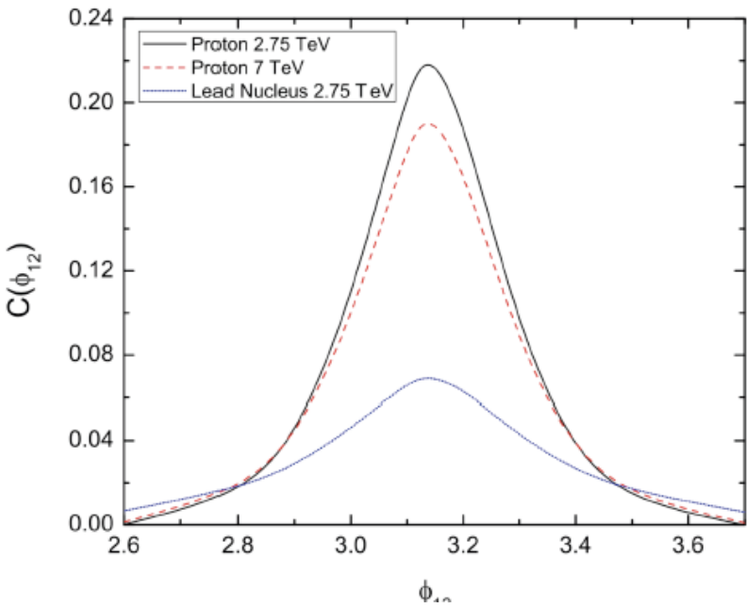
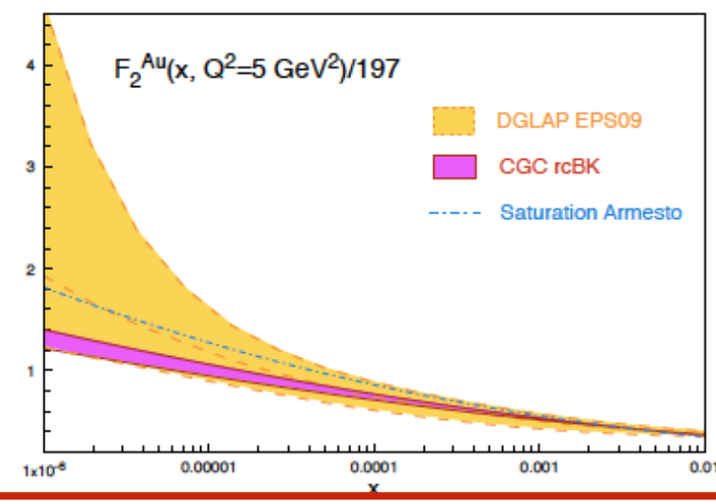
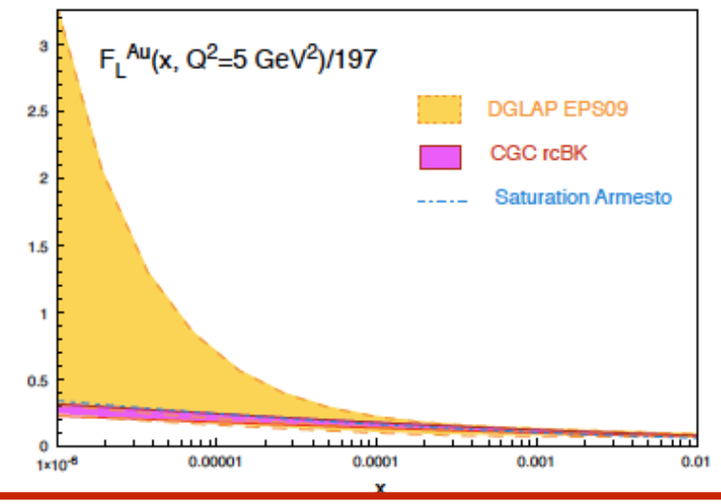
Small x:

[Cyrille Marquet]

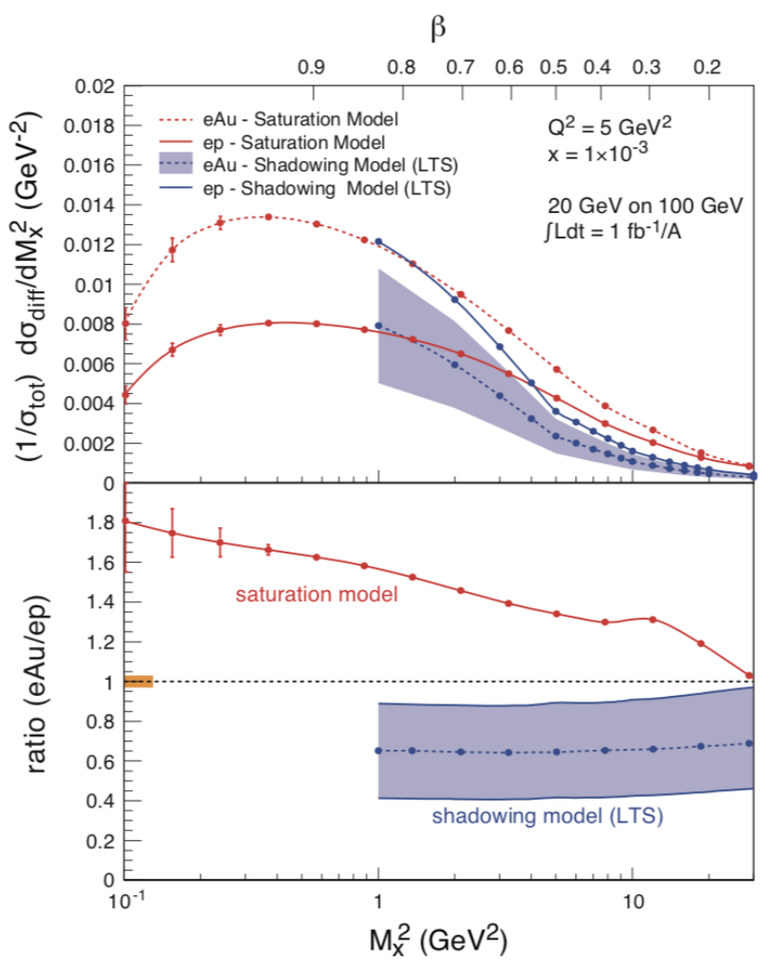






NLO DGLAP cannot simultaneously accommodate F_2 and F_L LHeC data if saturation sets in according to current models

(the same cannot be said for the lower energy EIC CM, R-Moldes and Zurita (2017))



- Several observables can provide evidence of the high-density non-linear regime of QCD: correlations, different quark and sea evolution, diffraction,…
- Resummation is required for a stable small-x evolution.

Small x:

Spin physics w/o polarized beams

considering only hadronic/nuclear states that are *unpolarized*

$$2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ixp_A^-\xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \left\langle A \middle| \mathrm{Tr}\left[F^{i-}\left(\xi^+, \boldsymbol{\xi}_t\right) F^{j-}(0)\right] \middle| A \right\rangle$$

$$= \frac{\delta_{ij}}{2}\mathcal{F}(x,k_t) + \left(\frac{k_i k_j}{k_t^2} - \frac{\delta_{ij}}{2}\right)\mathcal{H}(x,k_t)$$

unpolarized gluon TMD

linearly-polarized gluon TMD

[Cyrille Marquet] we can still be sensitive to gluon polarization

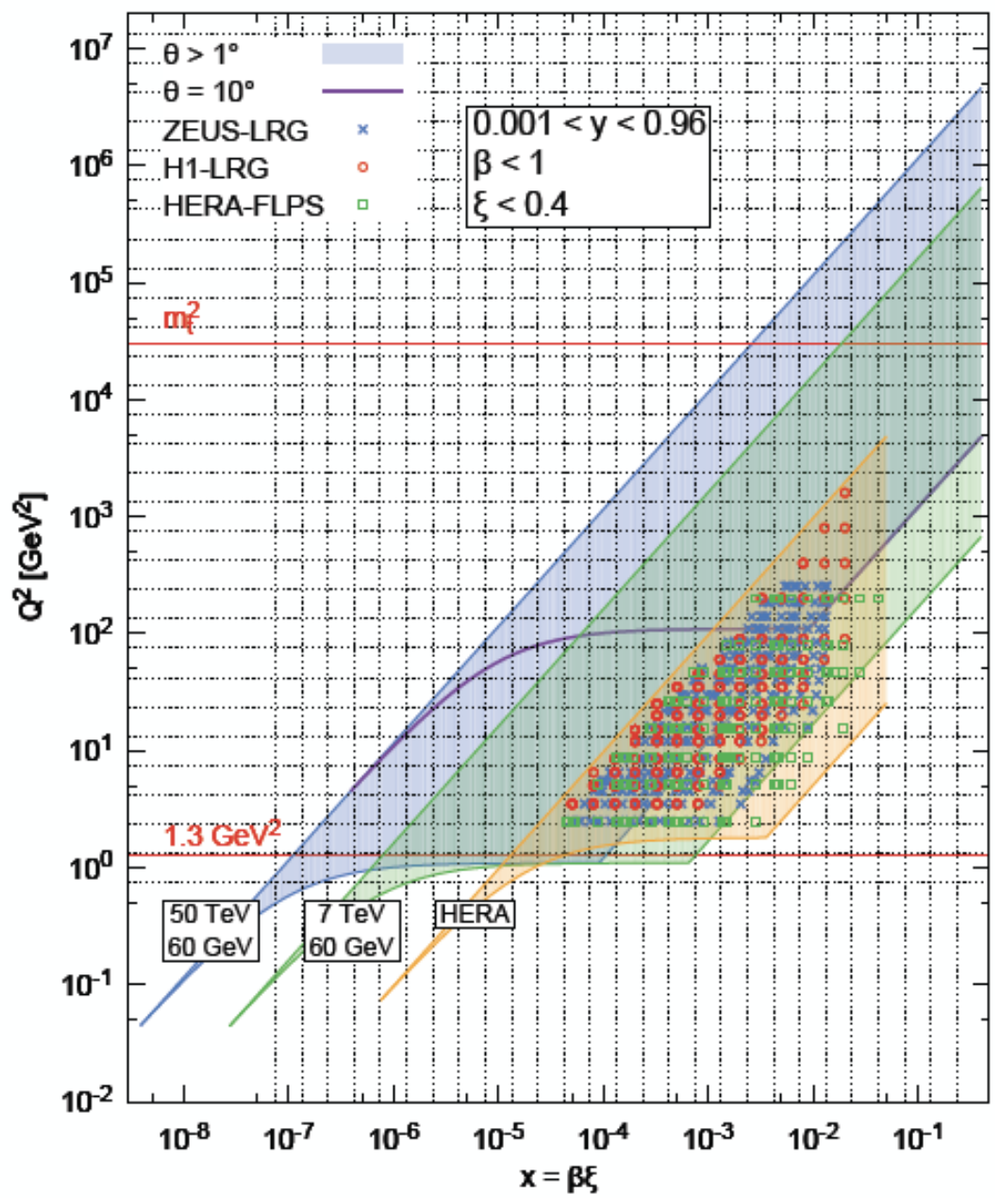
the Weizsäcker-Williams H function can be extracted at the LHeC in di-jet/di-hadron production with non-zero Q^2 and/or heavy quarks produced

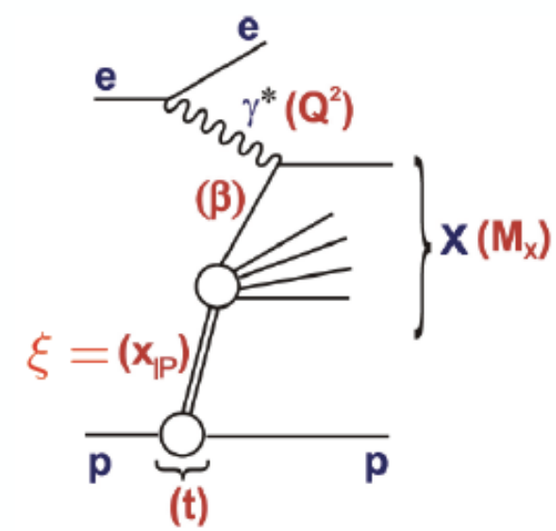
Metz and Zhou (2011)

- Spin physics without polarised beams, requires dedicated studies.

Inclusive diffraction:

Phase space: HERA to LHeC to FCC-eh





$E_e = 60\ GeV$

[Anna Stasto]

- $E_p = 7$ TeV vs. HERA
  - $x_{\min}$ down by factor ~20
  - $Q^2_{\max}$ up by factor ~100
- $E_p = 50$ TeV vs. 7 TeV
  - $x_{\min}$ down by factor ~10
  - $Q^2_{\max}$ up by factor ~10

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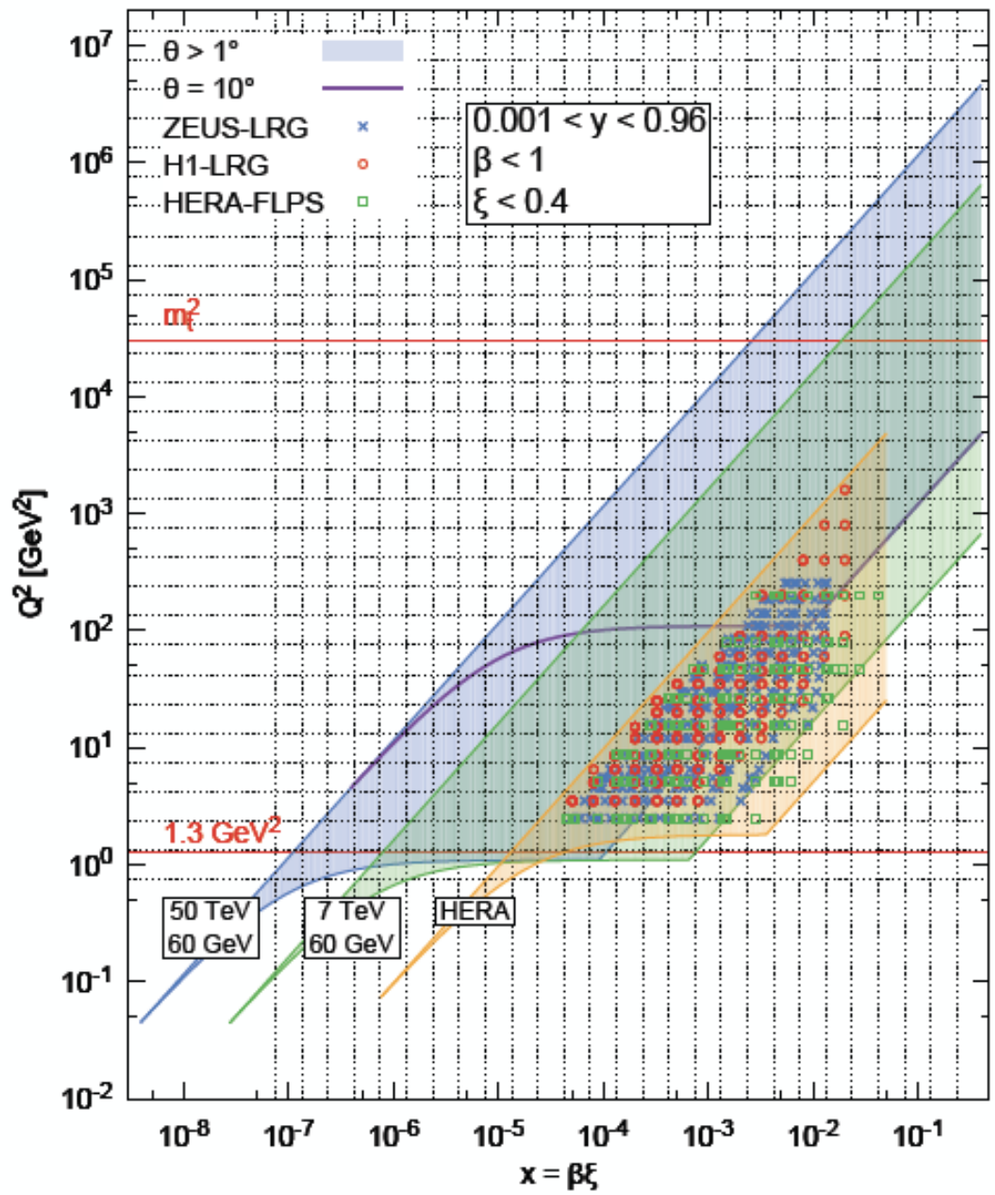
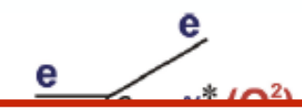
Inclusive diffraction:

Phase space: HERA to LHeC to FCC-eh





- Huge extension of the kinematic plane with respect to HERA, requires large acceptance (or smaller E_e).

$E_e = 60\ GeV$

[Anna Stasto]

- $E_p = 7$ TeV vs. HERA
  - $x_{\min}$ down by factor ~20
  - $Q^2_{\max}$ up by factor ~100
- $E_p = 50$ TeV vs. 7 TeV
  - $x_{\min}$ down by factor ~10
  - $Q^2_{\max}$ up by factor ~10

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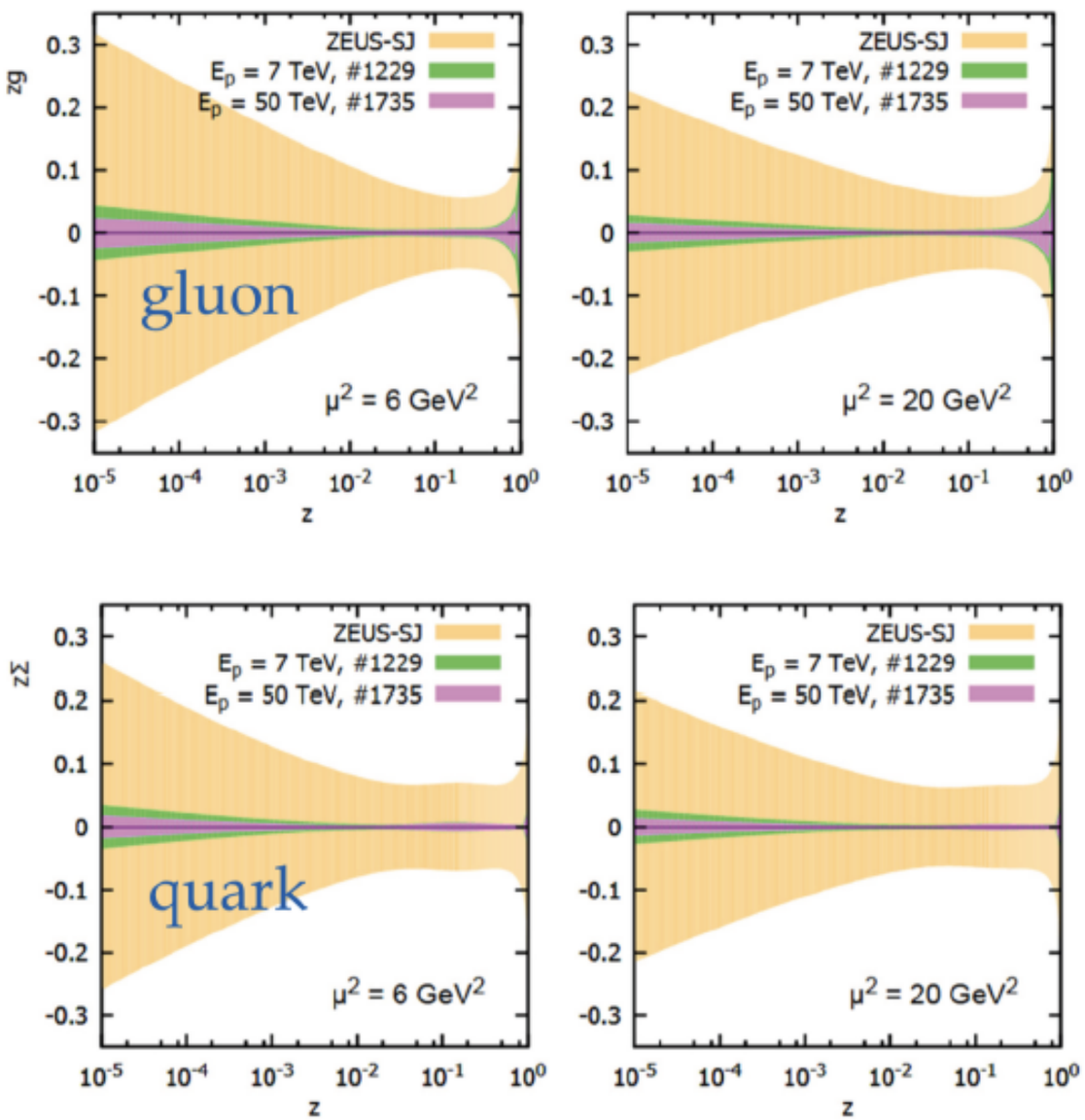
Inclusive diffraction:

[Anna Stasto] **DPDFs error bands**



$Q^2_{\min} \approx 5\ \mathrm{GeV}^2$

Accuracy increased by

- ✓ factor ~10 for LHeC
- ✓ factor ~20 for FCC-he

- Extraction robust under changes in $Q^2_{\min}$, inclusion of top, statistics,…
- Precise determination of DPDFs in a new kinematic domain.

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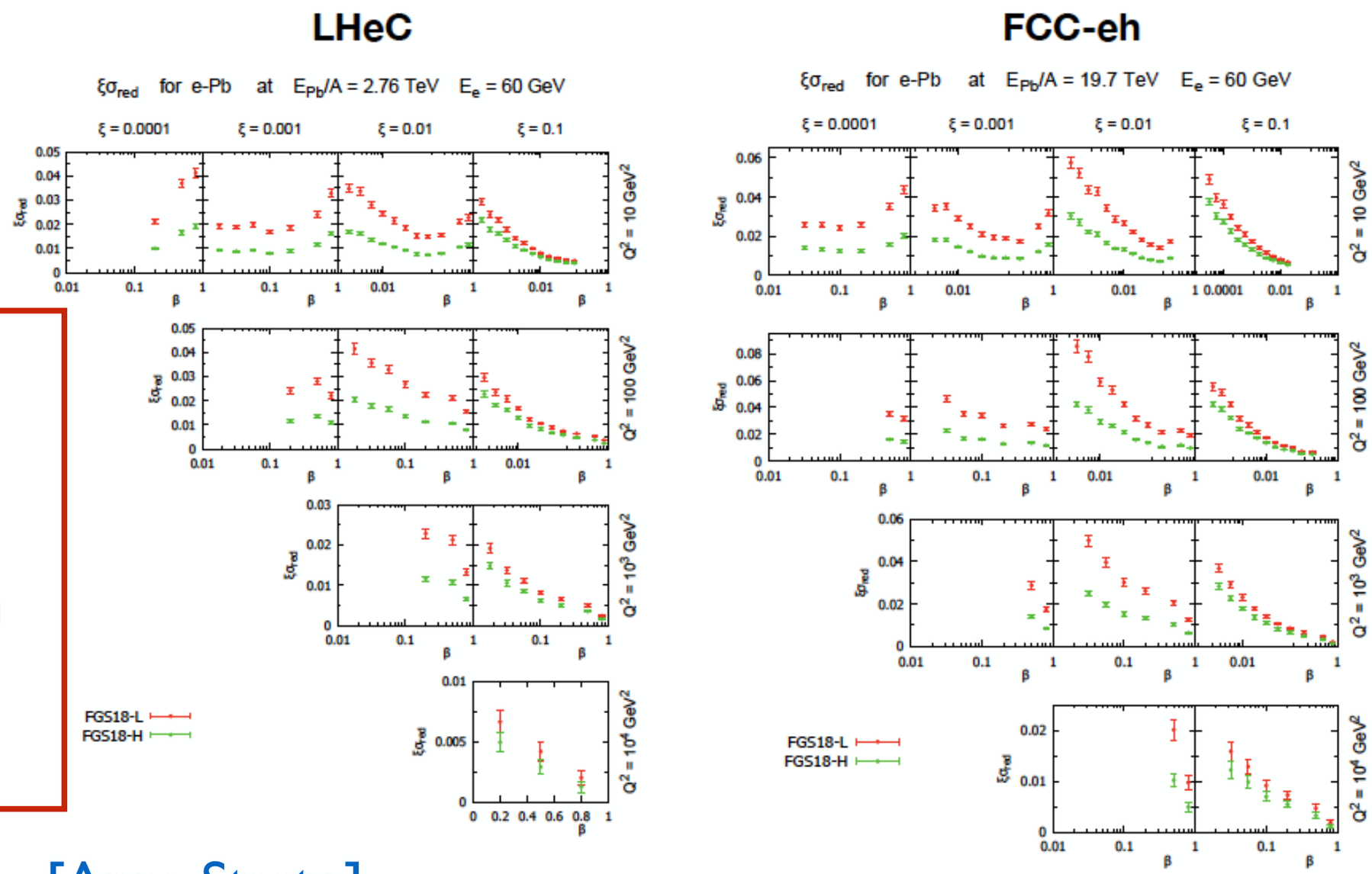
Inclusive diffraction:

Nuclear diffractive cross sections



- 1st analysis for diffraction in ePb, never measured before, extraction of nuclear DPDFs possible.

[Anna Stasto]

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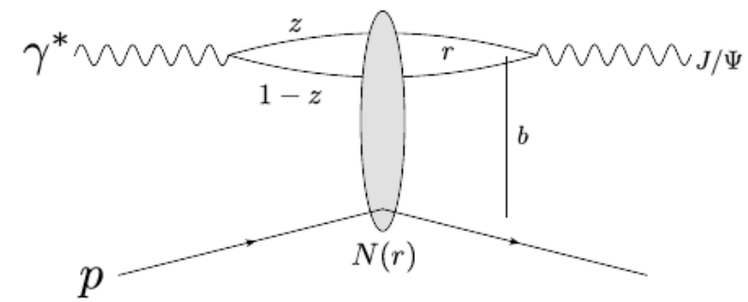
Elastic VMs:

Two components – two target averages



Coherent diffraction:
Target remains in the same quantum state
Probes average density

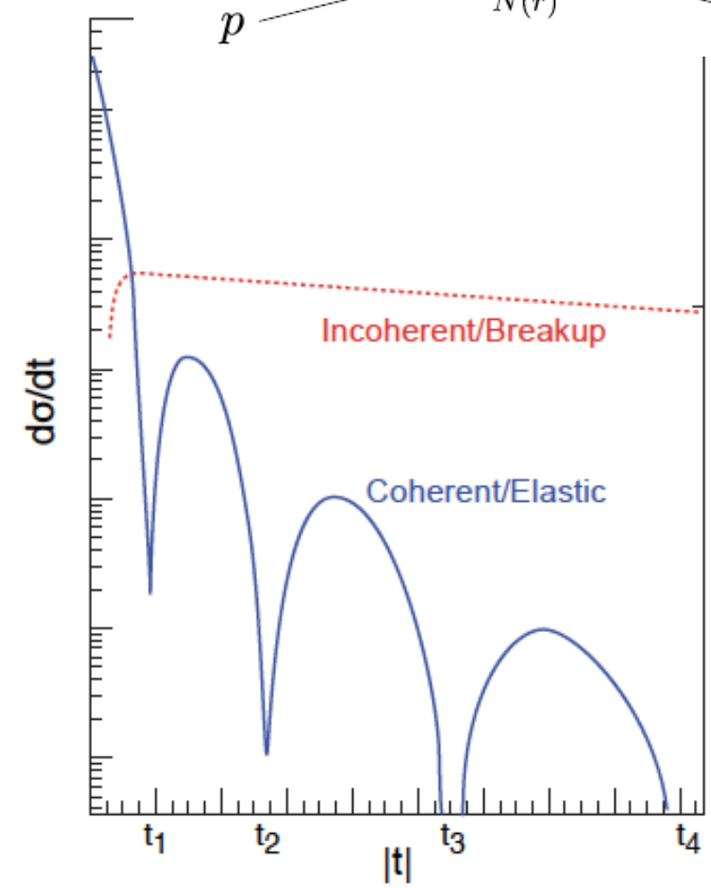
$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Incoherent/target dissociation:
Total diffractive – coherent cross section
Target breaks up

$$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} \sim \langle |\mathcal{A}^{\gamma^* p \to Vp}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Variance, measures the amount of fluctuations!

$\langle\,\rangle$: average over target configurations [N(r, **b**)]



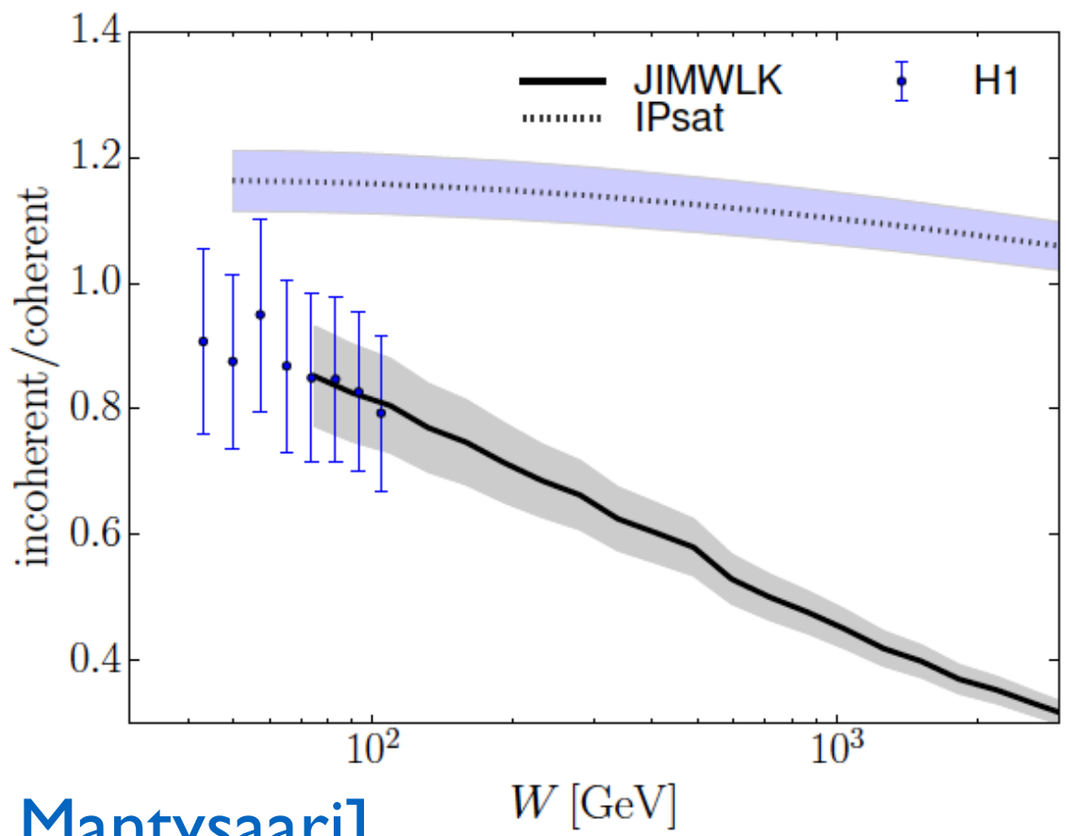
Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

[Heikki Mantysaari]

Elastic VMs:

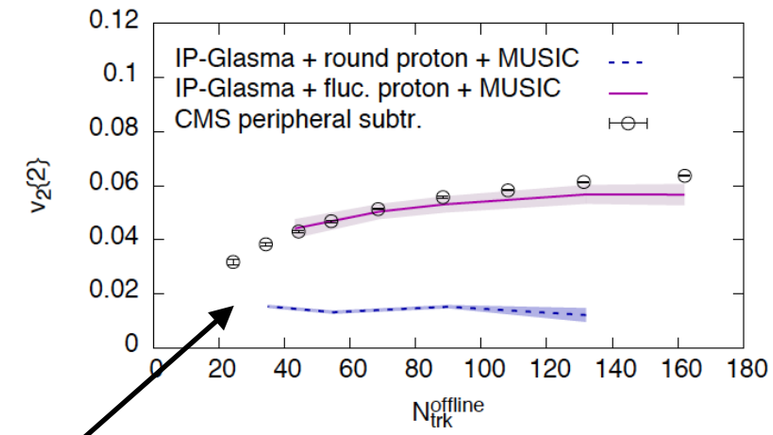
Energy evolution

Bjorken-x evolution by solving perturbative JIMWLK equation
Initial state geometry is lost in the evolution

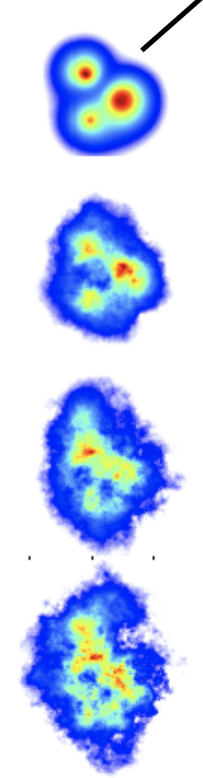


[Heikki Mantysaari]

Note: parameters fixed at $W = 75$GeV, the rest is prediction H.M, B. Schenke, arXiv:1806.06783



$W = 75$ GeV:



$W = 680$ GeV

- Incoherent vs. coherent diffraction gives information about hot spots in the proton.
- Most relevant for hadronic collisions.

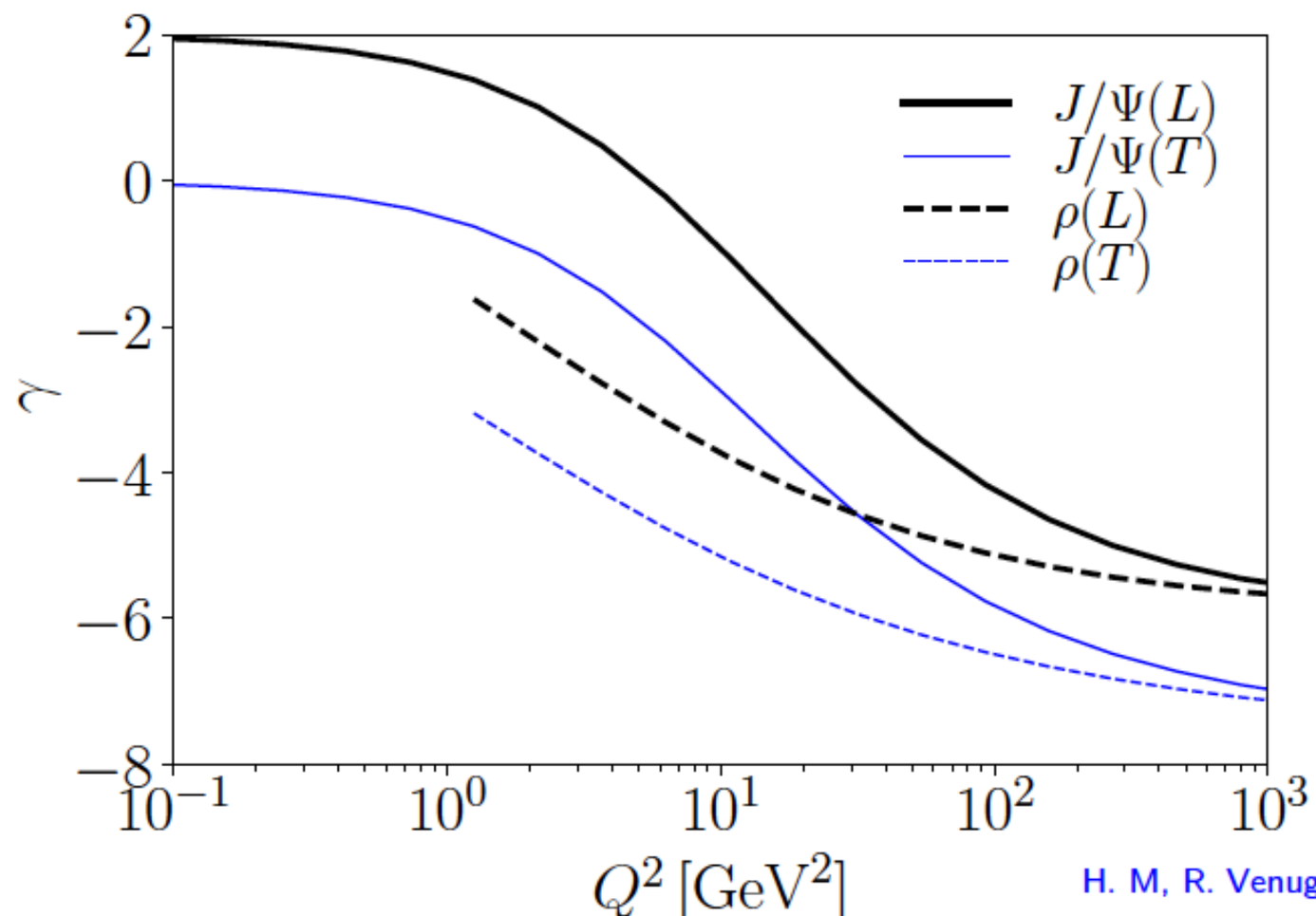
Elastic VMs:

Scaling exponents: dense ↔ dilute transition

- Lever arm in Q^2 at small x required to establish the relevance of non-linear phenomena.

$$\sigma^{\gamma+A\to J/\Psi+A} \sim Q^{\gamma}$$

$$\gamma^* + \mathrm{Au} \to V + \mathrm{Au},\, x_{\mathbb{P}} = 0.01$$



H. M, R. Venugopalan, 1712.02508

Large Q^2 lever arm needed to see the transition, and to probe the x dependence!

eSTARLIGHT:

[Spencer Klein]

eSTARlight http://estarlight.hepforge.net

- Monte Carlo for photoproduction and electroproduction of vector mesons at an EIC
  - Here, photoproduction is $Q^2 < 1$ GeV^2, while electroproduction is $Q^2 > 1$ GeV^2
- Physics model follows STARlight UPC event generator, but covers photons with arbitrary Q^2
- A fast, complete, reasonably accurate model of vector meson production, not a sophisticated theoretical calculation
  - For detector simulations….
  - Electron (or positron) -> γ^* -> vector meson -> final state
  - Vector meson polarization and decay angular distribution
  - Based on data where possible, phenomenology elsewhere
    - *Some extrapolations required
- Designed to be easily extensible

M. Lomnitz & S. Klein, arXiv:1803.06420, to appear in Phys. Rev. C 4

eSTARLIGHT:

[Spencer Klein]

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- A fast, complete, reasonably accurate model of vector meson production, not a sophisticated theoretical calculation
  - For detector simulations….
  - Electron (or positron) -> γ^* -> vector meson -> final state

- Tools under development, essential for:

➜ detector design (large acceptance);

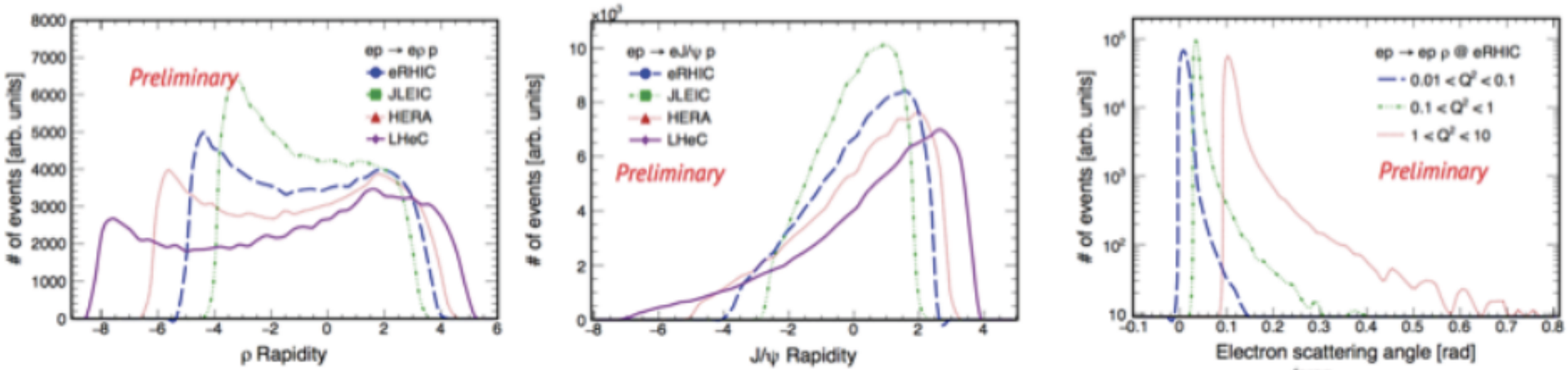
➜ proposing new observables (exotic spectroscopy, diffractive ttbar,…).

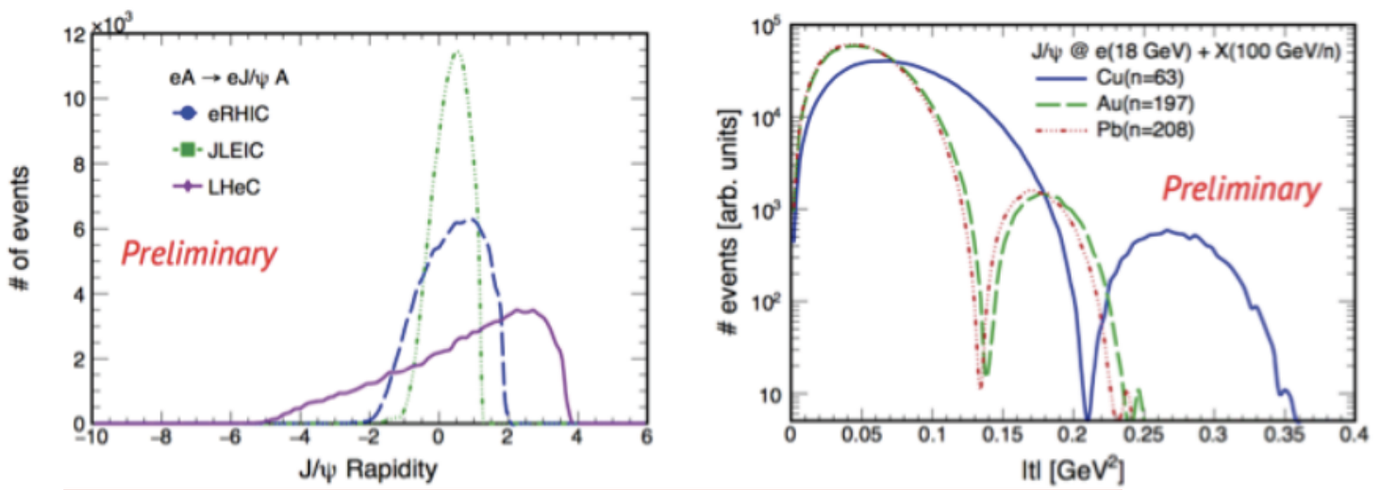
eSTARLIGHT:

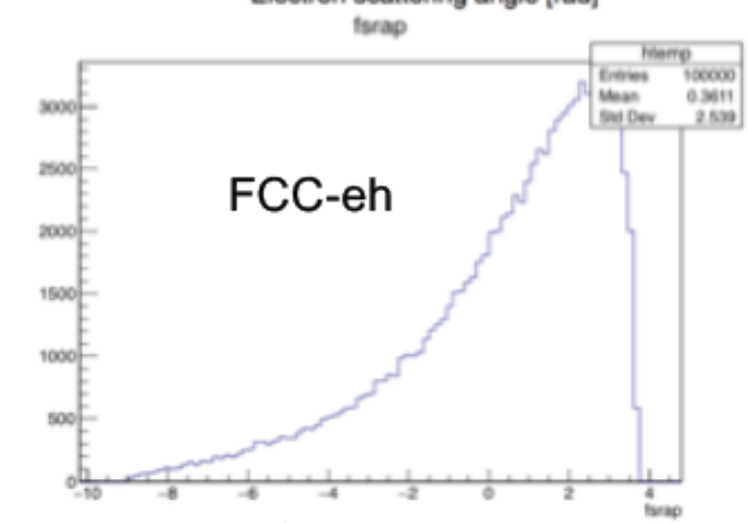
[Spencer Klein]

Rapidity and Angular distributions

- Vector meson production over a wide rapidity range
  - N. b. unscaled distributions here







J/ψ rapidity

Rapidity peak similar to LHeC;
Tail at larger -y

- Electrons scattering angle is small (no surprise)

Colour fluctuations:

We will refer fluctuations of the strength of interaction of nucleon, photon,.. as color fluctuations of interaction strength - studying them allows to go beyond single parton 3-D mapping of the nucleon

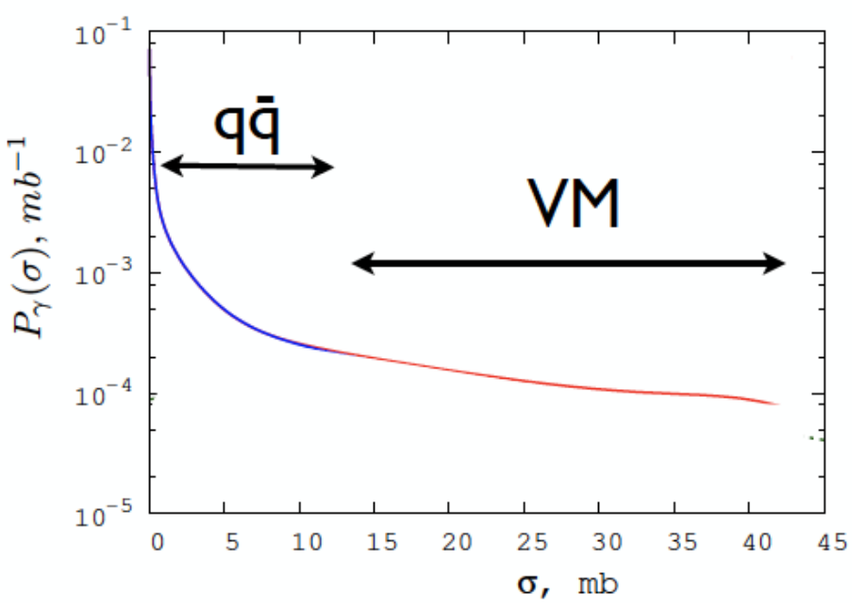
- Understanding correlations of partons inside particles essential for hadron averages in CGC, MPIs,…

Color fluctuations in photon - nucleus collisions

Photon is a multiscale state:

Probability, $P_\gamma(\sigma)$ for a photon to interact with nucleon with cross section σ, gets contribution from point - like configurations and soft configurations (VM like)

$P_\gamma(\sigma) \propto 1/\sigma$ for $\sigma \ll \sigma(\pi N)$ $\quad$ $P_\gamma(\sigma) \propto P_\pi(\sigma)$ for $\sigma > \sigma(\pi N)$



[Mark Strikman]

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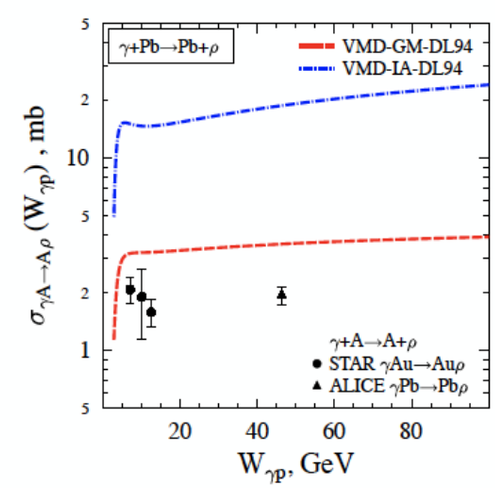
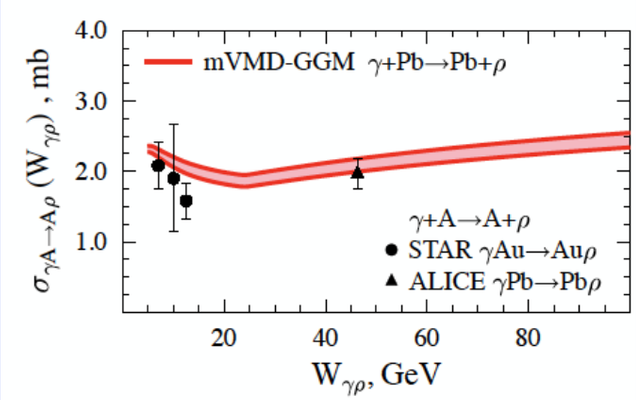
- Glauber model grossly overestimates the cross section (at LHC factor ~2)



- Gribov - Glauber model with cross section fluctuations



Colour fluctuations:

- Calculation of distribution over the number of wounded nucleons

(a) Color fluctuation model

$$\sigma_\nu = \int d\sigma P_\gamma(\sigma) \binom{A}{\nu} \times \int d\vec{b} \left[\frac{\sigma_{in}(\sigma)T(b)}{A}\right]^\nu \left[1 - \frac{\sigma_{in}(\sigma)T(b)}{A}\right]^{A-\nu}$$

$$p(\nu) = \frac{\sigma_\nu}{\sum_1^\infty \sigma_\nu}.$$

- eA to probe them, requires spectator tagging: forward instrumentation.

(b) Generalized Color fluctuation model (includes LT shadowing for small σ)

interaction of small dipoles is screened much stronger than in the eikonal model

evidence from J/psi production - next slide

$$P_\gamma(\sigma) \binom{A}{\nu} \times \frac{\sigma^{in}}{\sigma^{in}_{eff}} \int d\vec{b} \left[\frac{\sigma_{eff}T(b)}{A}\right]^\nu \left[1 - \frac{\sigma_{eff}T(b)}{A}\right]^{A-\nu}$$

σ_{eff}/σ calculated in the LT nuclear shadowing theory for small σ

[Mark Strikman]

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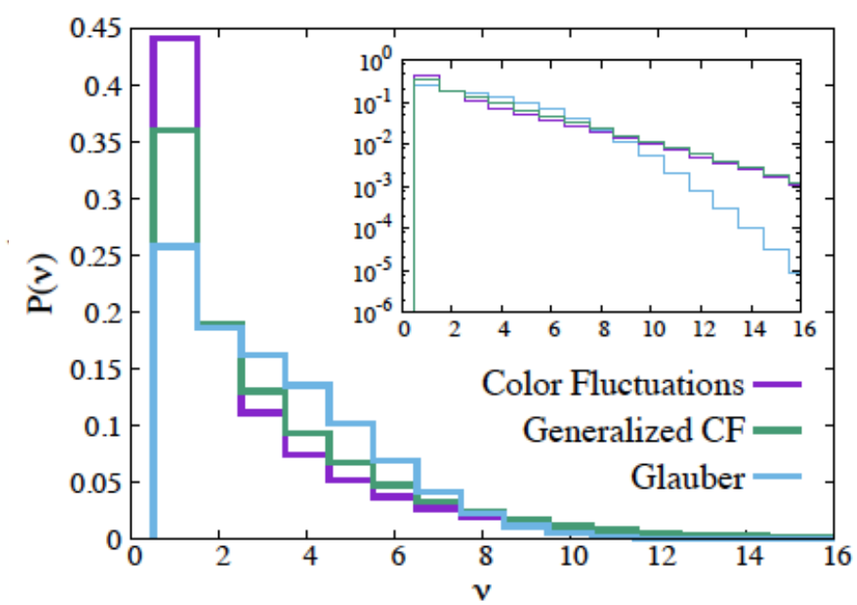


Phy

distribution over the number of wounded nucleons in γA scattering, W ~ 70 GeV

Colour fluctuations:

Tuning strength of interaction of configurations in photon using forward (along γ information) . Novel way to study dynamics of γ &γ interactions with nuclei*

- A full picture requires lever arm in x and Q^2 to select configurations leading to stronger or weaker interaction.

[Mark Strikman]

"2D strengthonometer" - EIC & LHeC - Q^2 dependence - decrease of role of "fat" configurations, multinucleon interactions due to LT nuclear shadowing

Comment: Forward γA & γp physics at the LHC mostly within acceptance of central ATLAS, CMS detectors

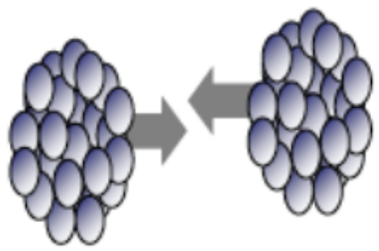
18

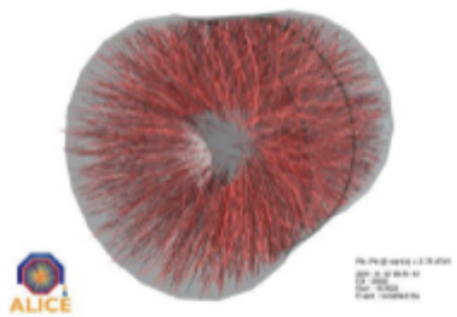
eA for heavy ions:

Old paradigm: the three systems (understanding before 2012)

[Astrid Morreale]

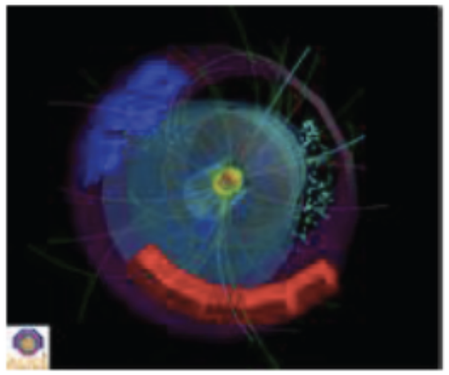
Pb-Pb





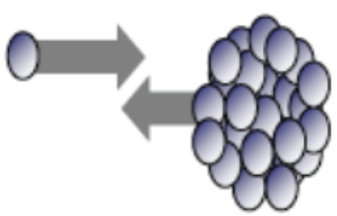
Hot QCD matter:
This is where we expect the QGP to be created in central collisions

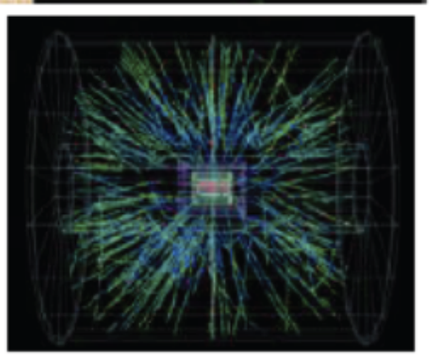
pp



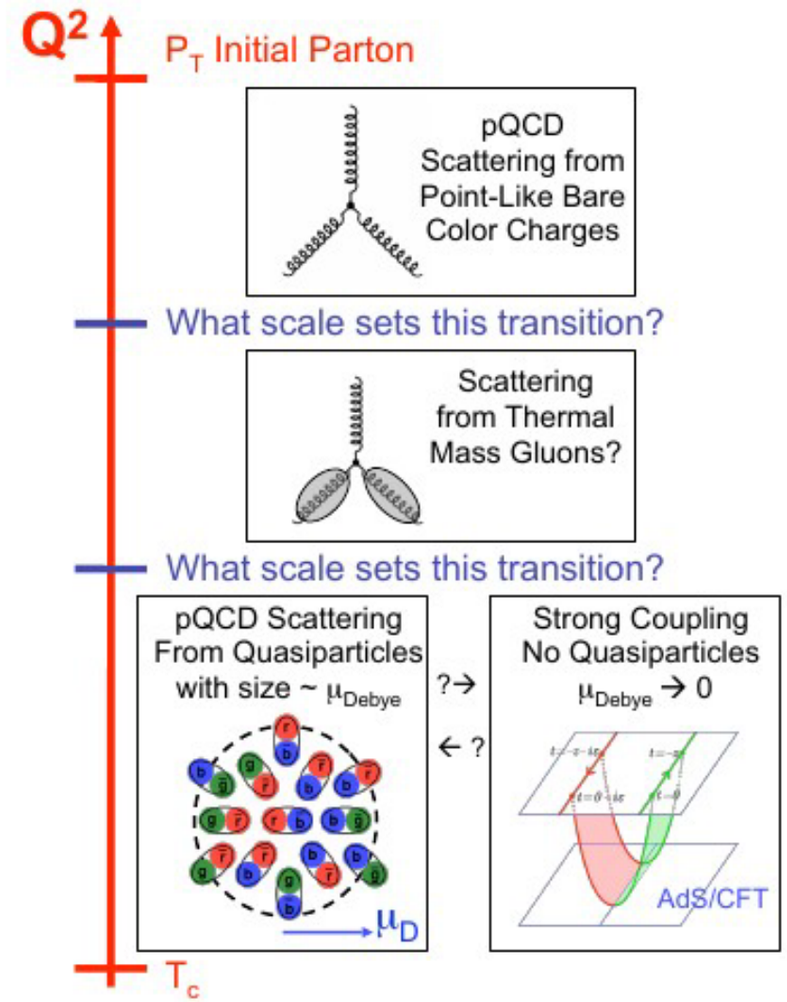
QCD baseline:
This is the baseline for "standard" QCD phenomena

p-Pb





Cold QCD matter:
This is to isolate nuclear effects in absence of QGP, e.g. nuclear pdfs



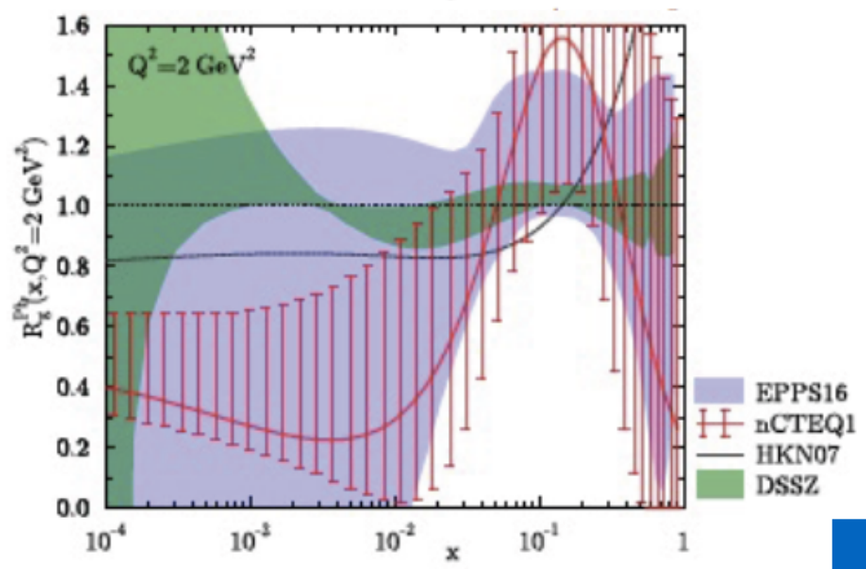
E. G. Ferreiro USC & LLR — How could HI physics at the energy frontier profit from LHeC — LAL Orsay 28/6/2018

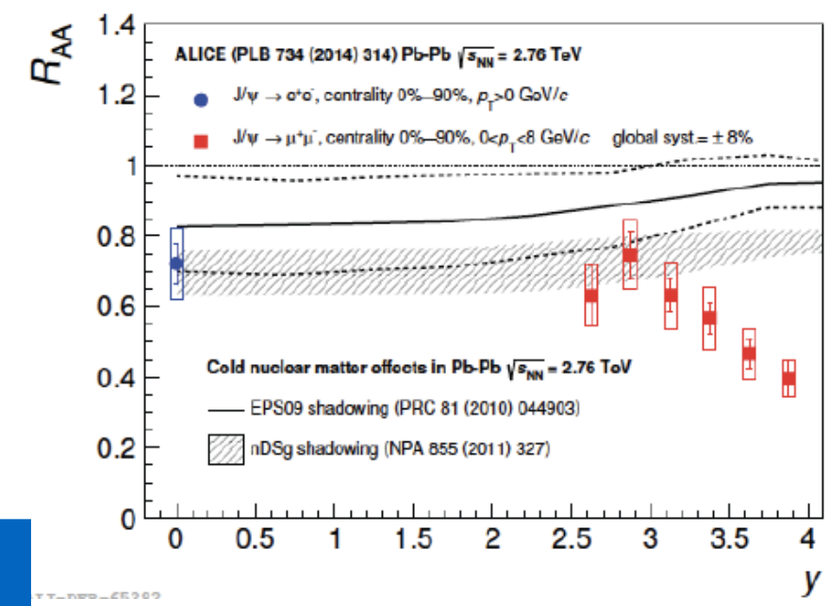
- eA to provide key information for a full understanding of the findings in AA whose interpretation is under revision: small systems.

Nuclear PDFs:

$$f_i^A(x,Q^2) = R_i^A(x,Q^2) f_i(x,Q^2)$$

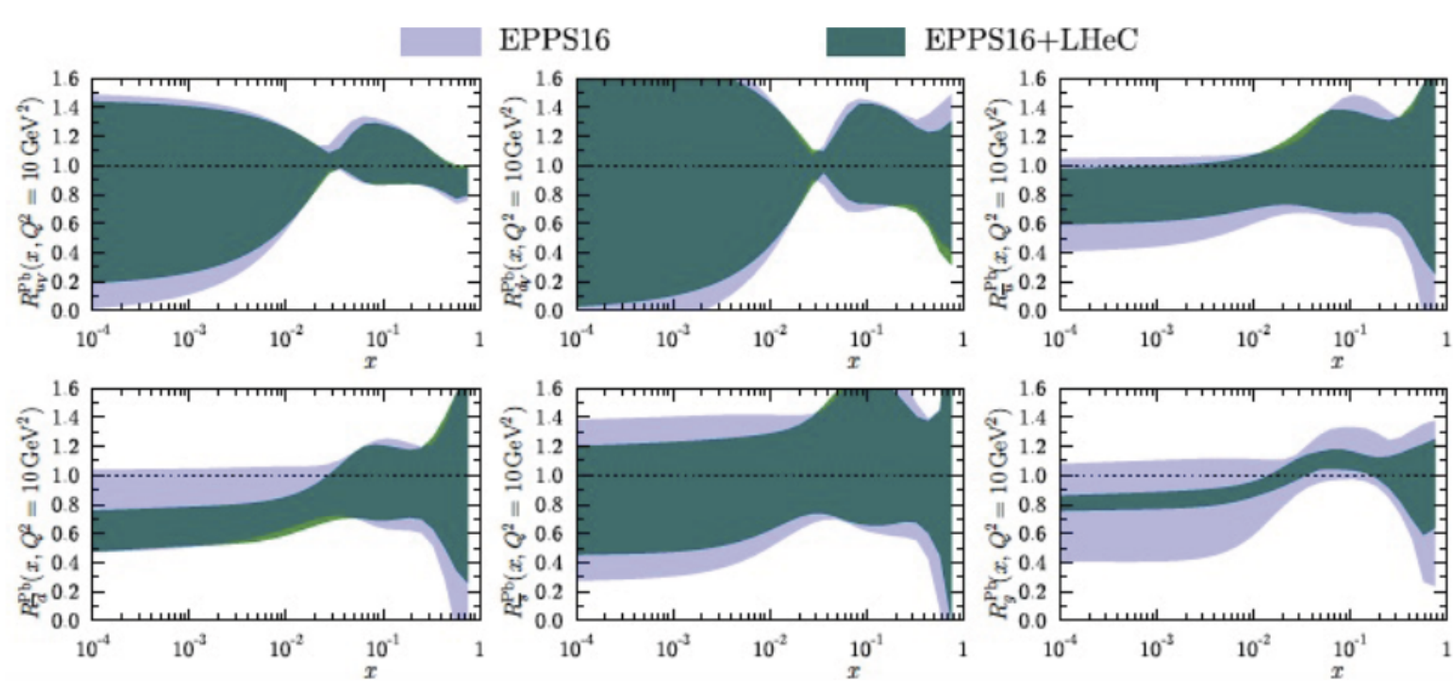
assuming collinear factorization





[Elena Ferreiro]

The improvement after adding the LHeC pseudodata at Q^2 = 10 GeV^2

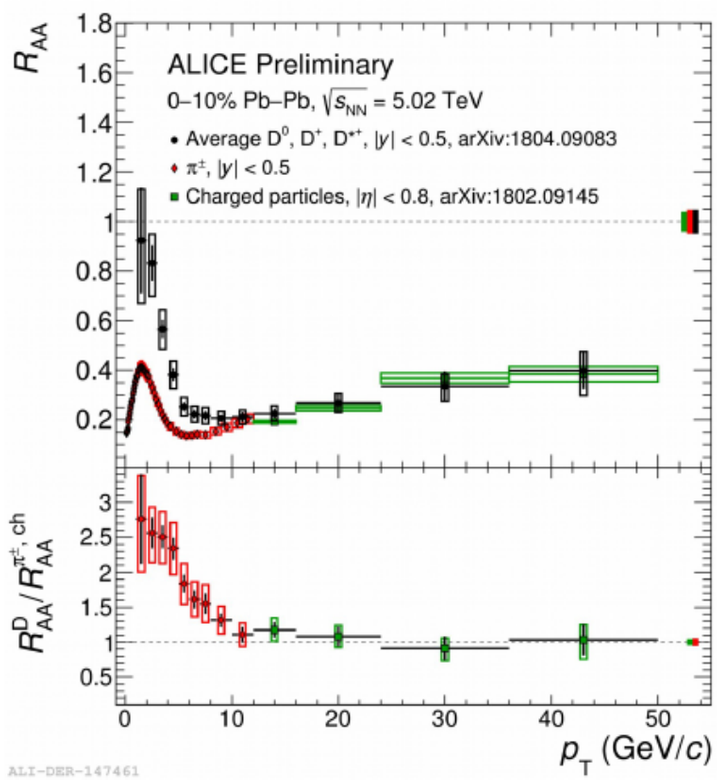


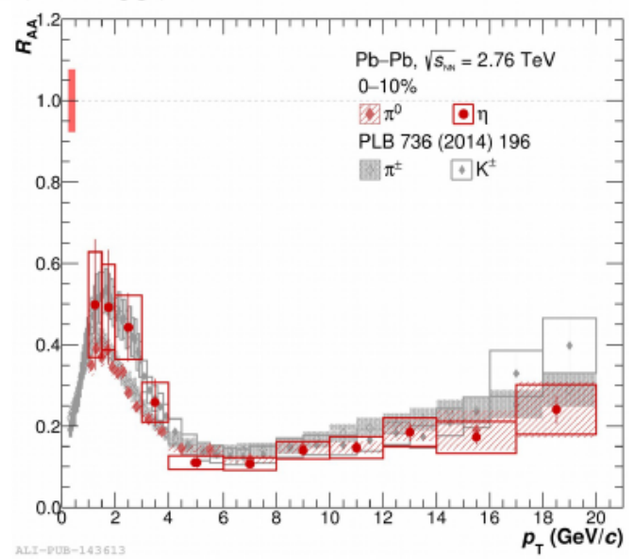
- eA for a reduction of the uncertainties in the initial state: nuclear WF, nuclear PDFs.

Jet quenching:

[Astrid Morreale]

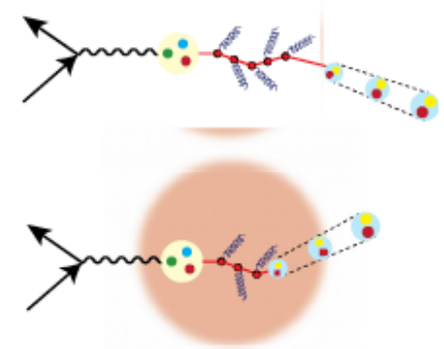
$$R_{AA} = \frac{AA}{\text{scaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$

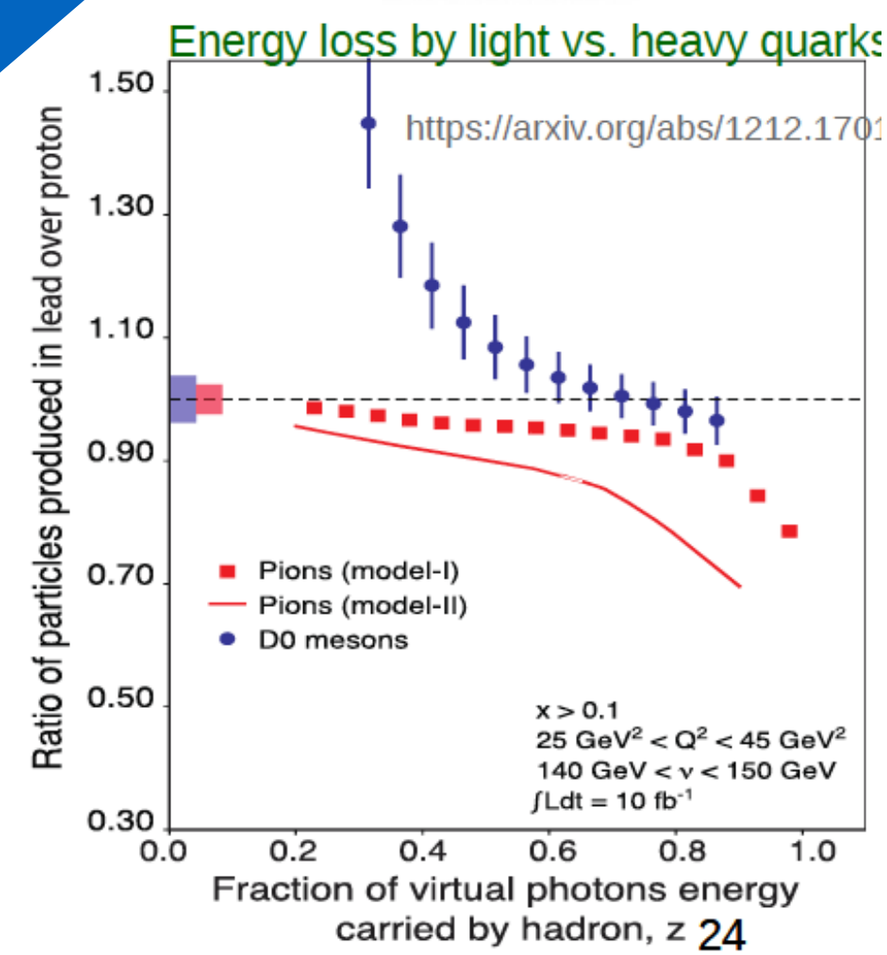




Pb-Pb suppression
- Similar to that of pions (at high enough p_T)

-ALICE-PUBLIC-2017-003
-https://arxiv.org/abs/1803.05490

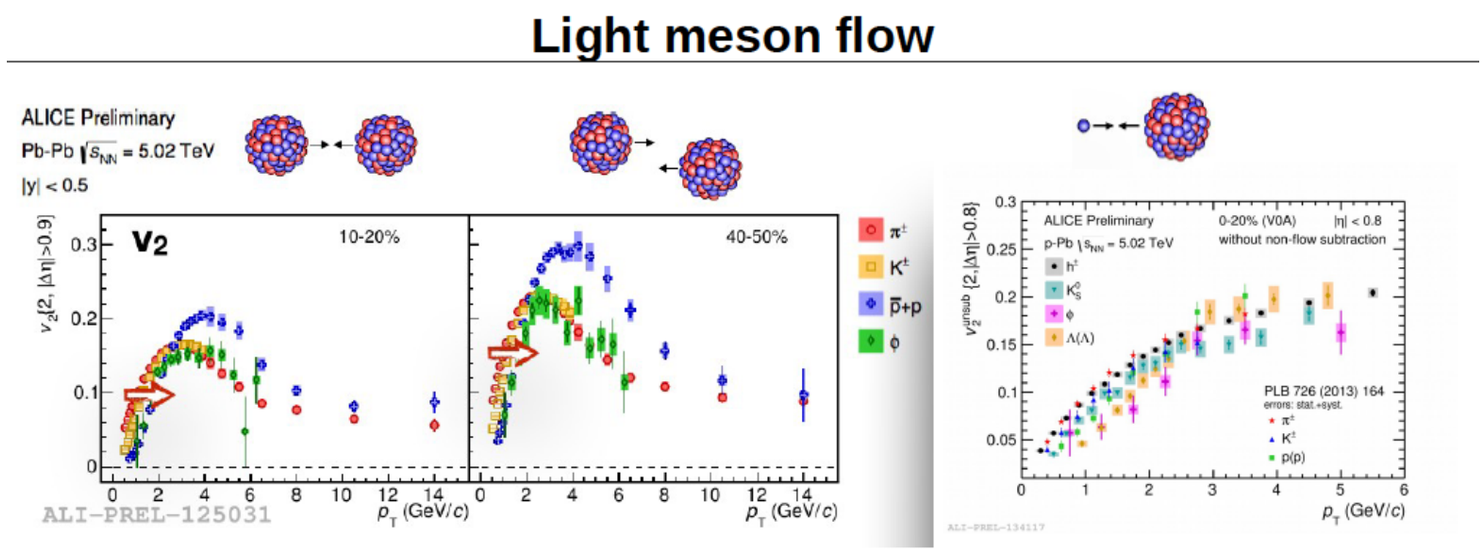


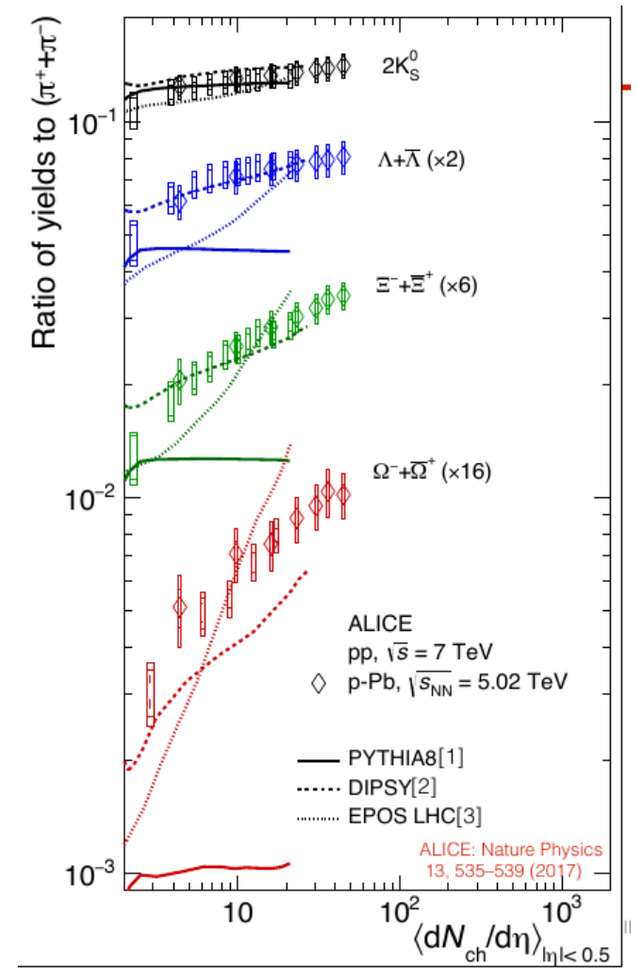


- eA for a reduction of the uncertainties in the final state: QCD branching and hadronisation in the nuclear medium.

Small systems:

[Astrid Morreale]





-Low p_T : Mass ordering expected in a collective expansion scenario.

-Low-p_T : v_2 sensitive to hydrodynamic expansion and initial conditions (geometry).

-**Similar results observed in a high multiplicity p-Pb environment.**

-Effect in these systems may be due to initial state (saturation?) or final state effects (expansion and/or thermal equilibrium ?)

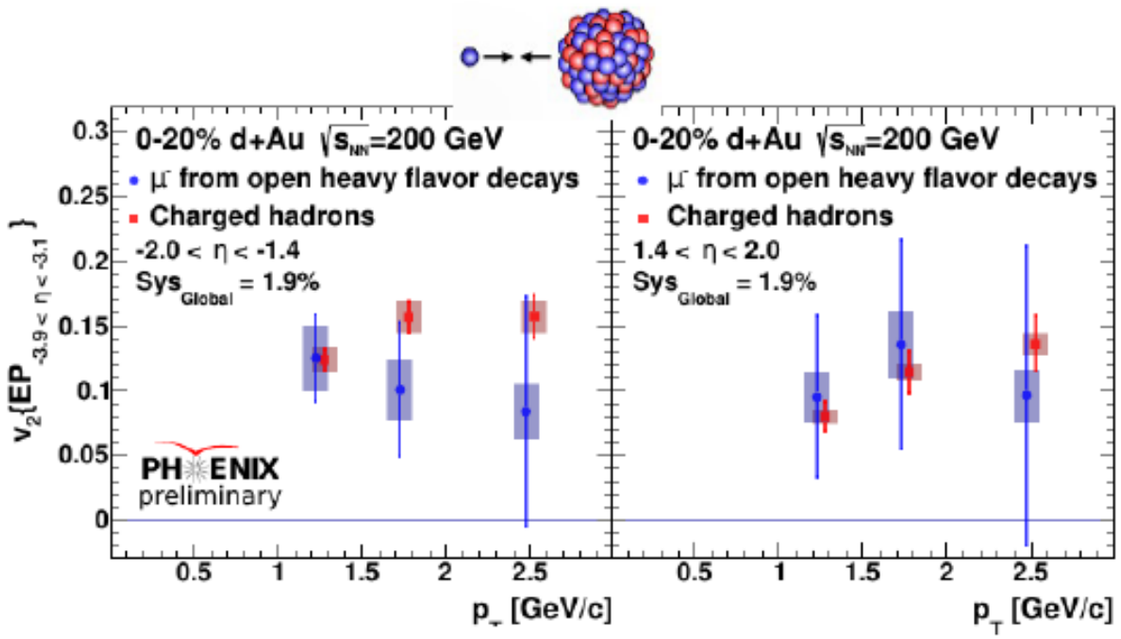
Astrid Morreale electrons for the LHC 2018 18

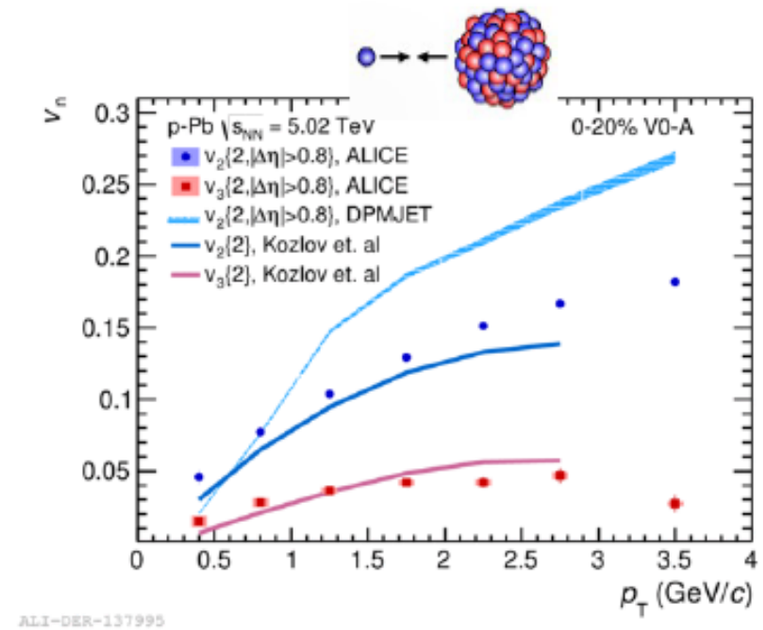
- Striking similarities and a smooth transition between pp, pPb and PbPb (QGP-like features in small systems) ⇒ new paradigm that all systems become equally interesting: QGP in small systems (final state interactions) or properties of the initial state? [emergence].

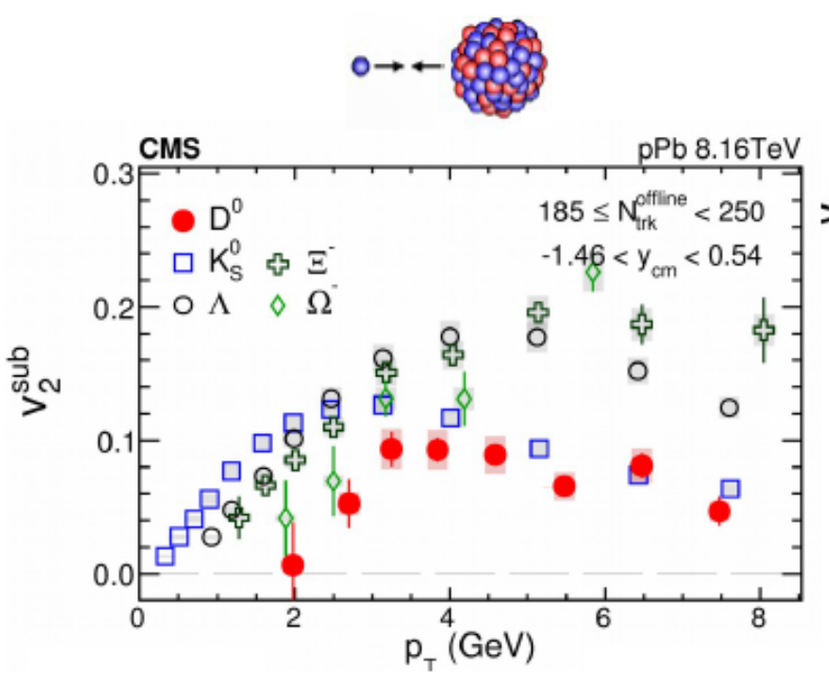
Small systems:

[Astrid Morreale]

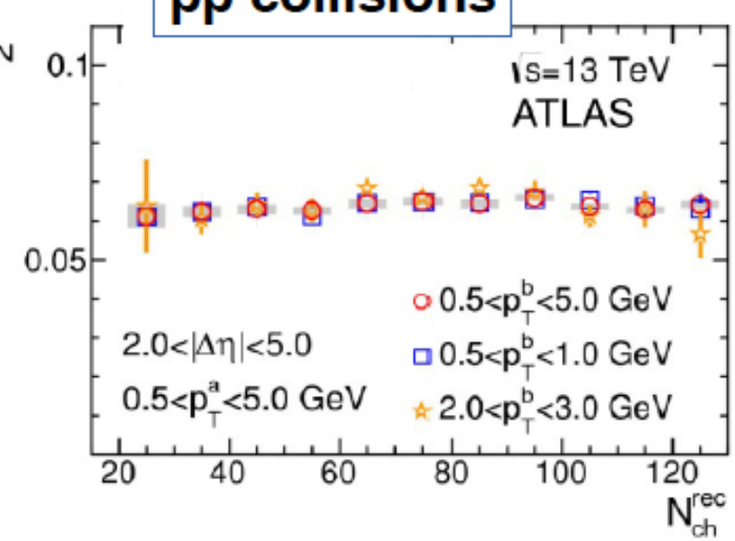
Flow in small systems?







pp collisions



$\sqrt{s_{pA}}$=200 GeV PHENIX
QM2018 Talk

$\sqrt{s_{pA}}$=5.02 TeV ALICE
JHEP 09 (2017) 032

$\sqrt{s_{pA}}$=8.16 TeV CMS:
arxiv:1804.09767

$\sqrt{s}$=13 TeV ATLAS:
PRL116, 172301 (2016)

These effects have not seen at LEP nor HERA

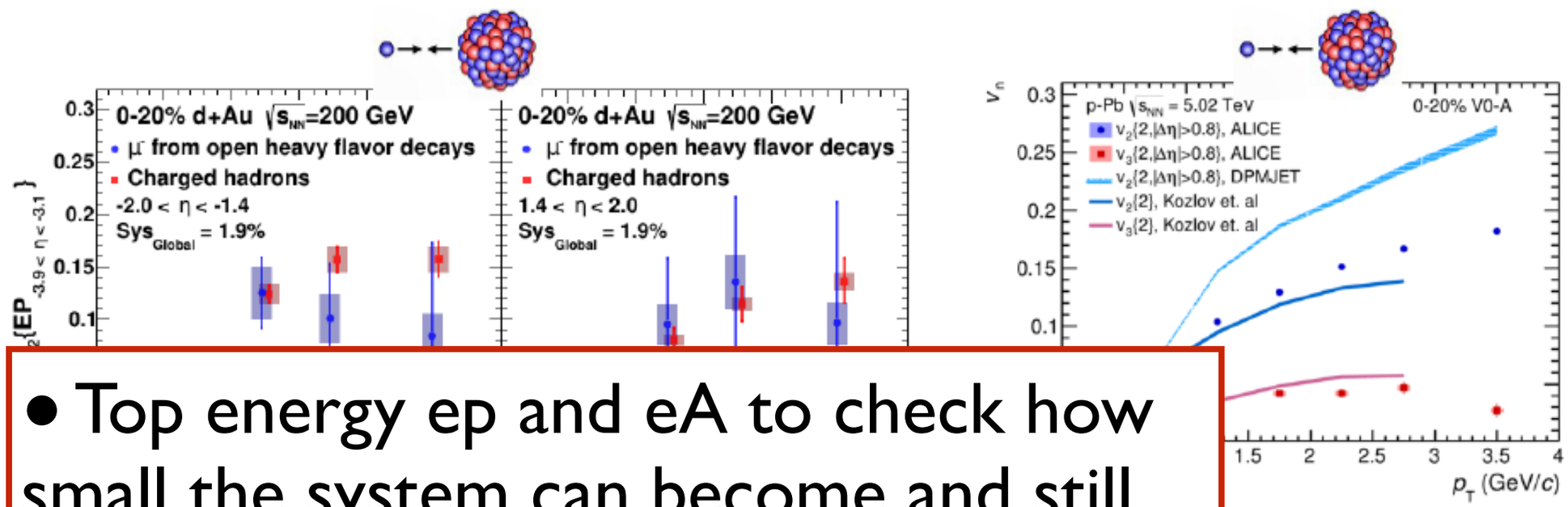
Astrid Morreale electrons for the LHC 2018

20

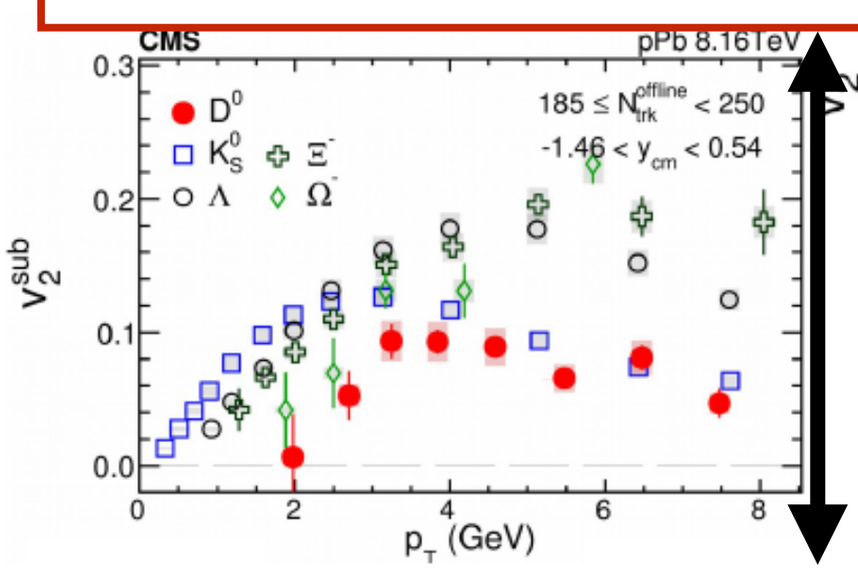
Small systems:

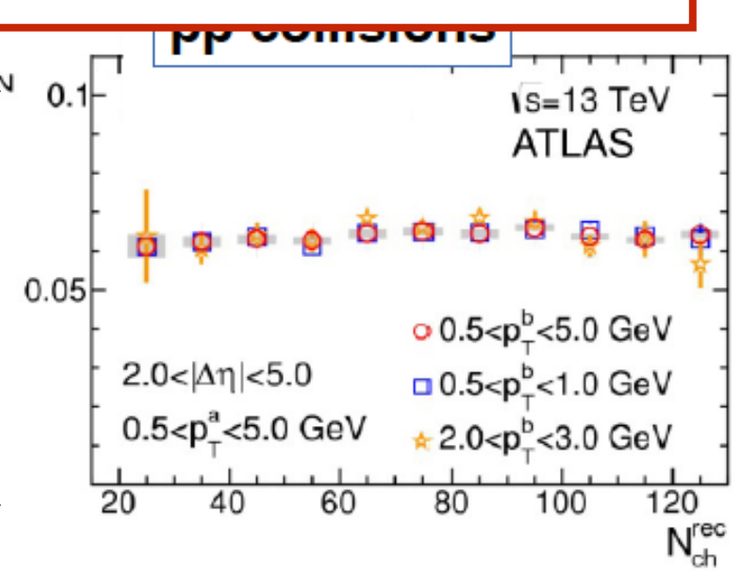
[Astrid Morreale]

Flow in small systems?



- Top energy ep and eA to check how small the system can become and still show collective features.





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√s=13 TeV ATLAS: PRL116, 172301 (2016)

These effects have not seen at LEP nor HERA

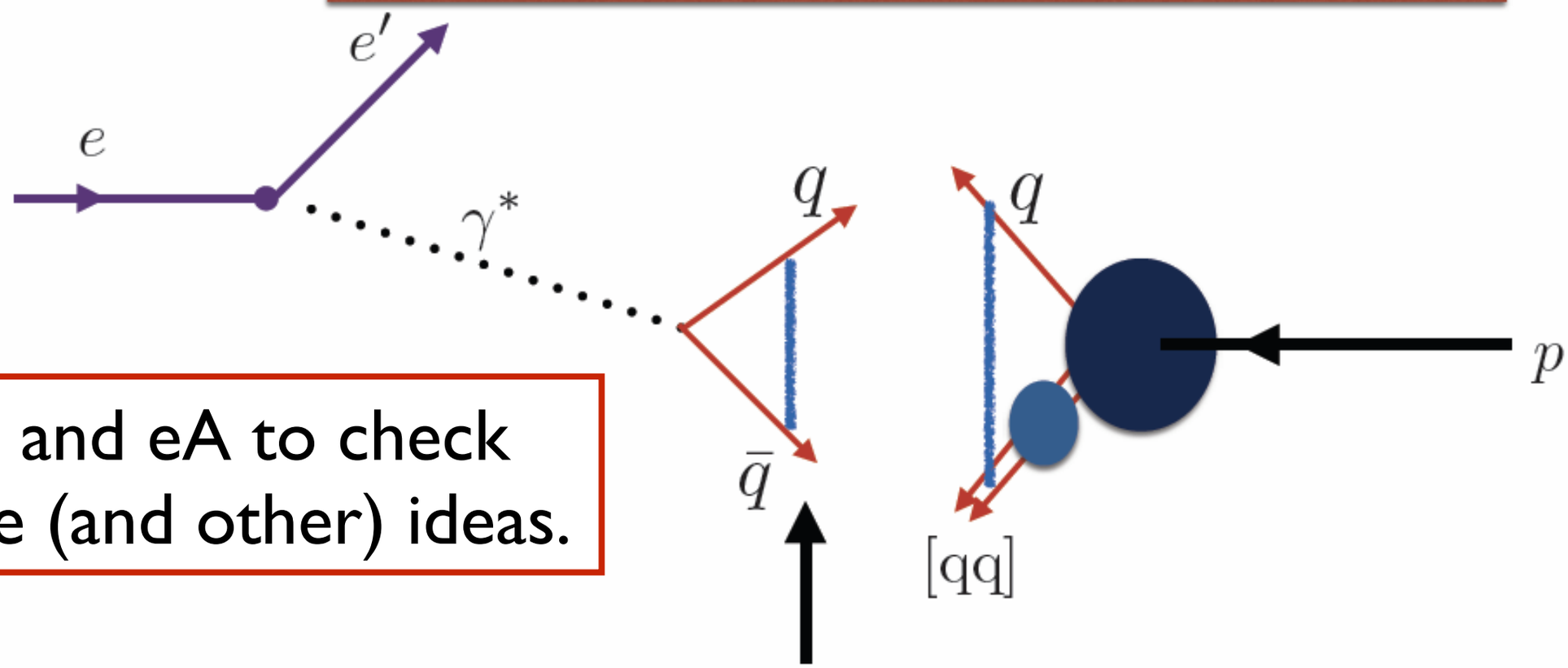
The ridge:

[Stanley Brodsky]

Collisions of Aligned Flux Tubes produce high multiplicity events: Ridges

Brown, Glazek, Goldhaber, sjb

Ridge Production at the LHeC



- ep and eA to check these (and other) ideas.

Flux tube aligned with the plane of the scattered electron

Ridges of produced hadrons will correlate with scattering plane of proton!

eA for heavy ions:

New paradigm: small systems

Totally unexpected:

the discovery of correlations –ridge, flow- in small systems pA & pp

- Smooth continuation of heavy ion phenomena to small systems and low density
- Small systems as pA and pp show QGP-like features

Two serious contenders remain today:

- initial state: quantum correlations as calculated by CGC
- final state: interactions leading to collective flow described with hydrodynamics => equilibration?

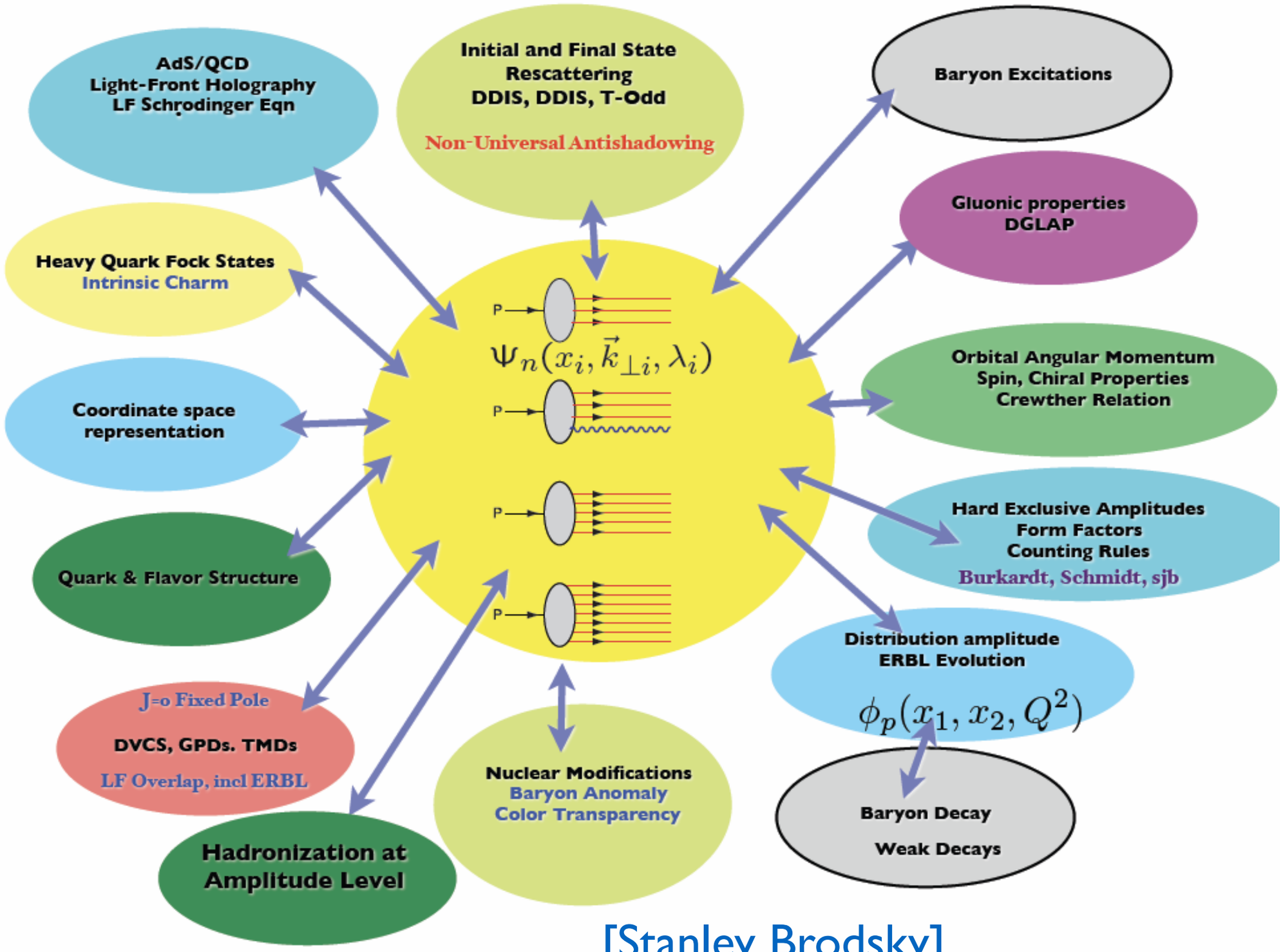
The old paradigm that

- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as comparison data appears no longer sensible

We should examine a new paradigm, where the physics underlying soft collective signals can be the same in all high energy reactions, from e^+e^- to central AA

It becomes fundamental to have access to ep & eA collisions

QCD on the light front:

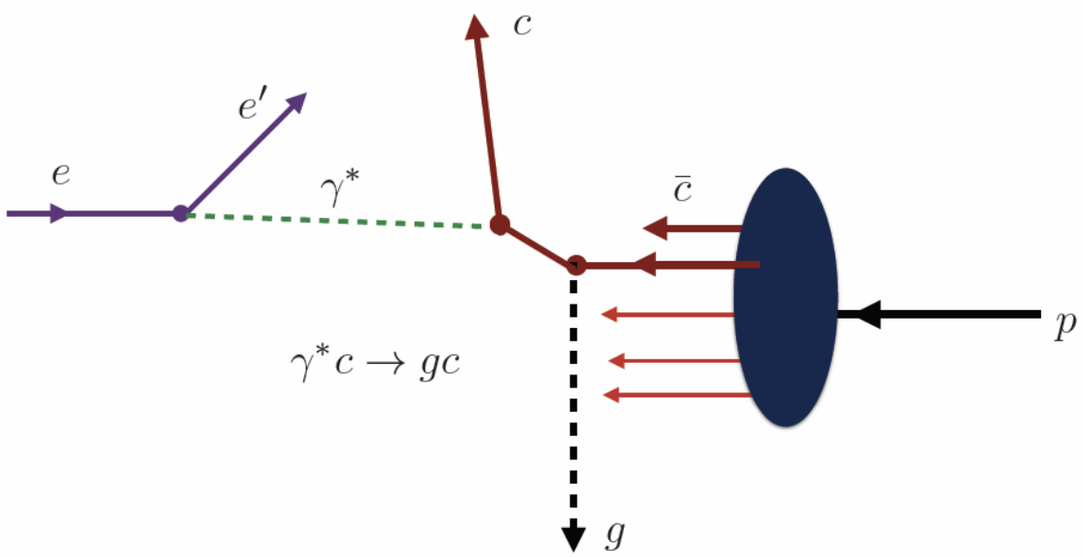


[Stanley Brodsky]

- Many aspects of the hadron wave function to be probed in ep/eA.

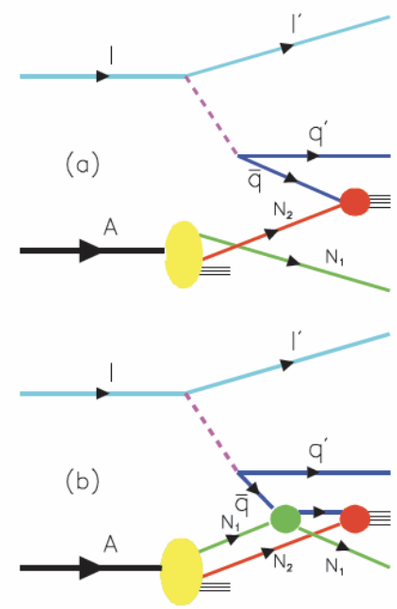
QCD on the light front:

$$ep \to e'cgX, ep \to e'bgX,$$



LHeC: Measure c(x,Q), b(x,Q) at large x

- Intrinsic charm.



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.

Regge

If the scattering on nucleon N_1 is via ~~pomeron~~ exchange, the one-step and two-step amplitudes are ~~opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.~~

constructive in phase
thus increasing the flux reaching N_2

Reggeon DDIS produces nuclear flavor-dependent anti-shadowing

Anti-shadowing

- Flavour dependent antishadowing.

[Stanley Brodsky]

To end:

- Beautiful discussions and results presented here.
- The physics case is clear, interplay with detector design (acceptance, forward instrumentation) essential for its success.
- Irrespective of what exactly we find, the LHeC will change our field, and the knowledge that we gain is essential for the physics programmes in hadronic colliders.

THANK YOU [Simone Marzani]

TO THE SPEAKERS AND TO YOU ALL!

if we have seen further it is only by standing on the shoulders of giants