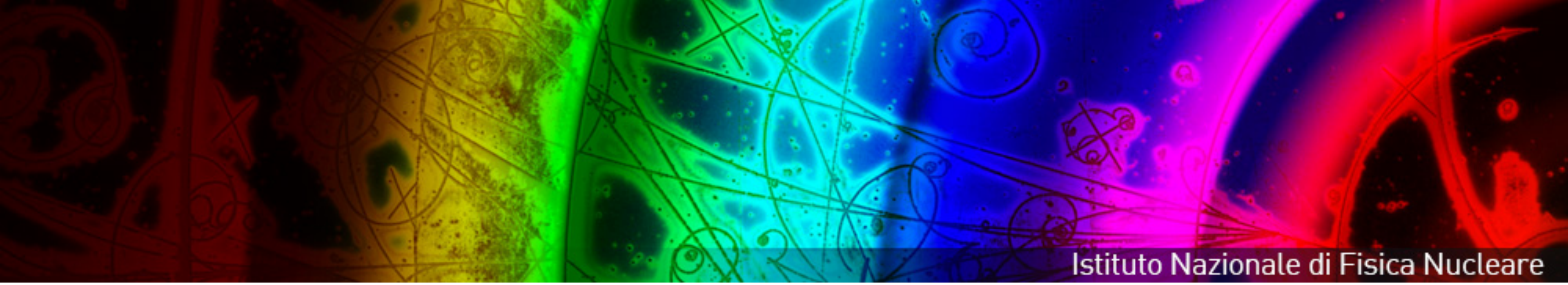


Nuclear Physics at the Electron-Ion Colliders

Pasquale Di Nezza

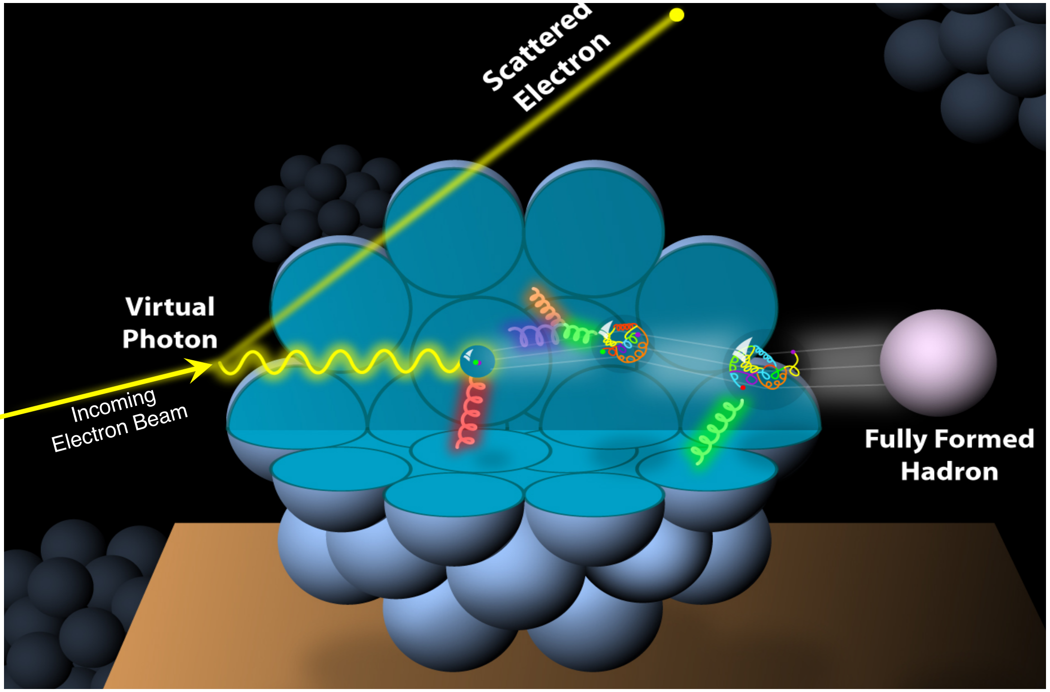
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Torino, 10/10/17

An eA collider: why use nuclei?

DIS offers a clean experimental environment:

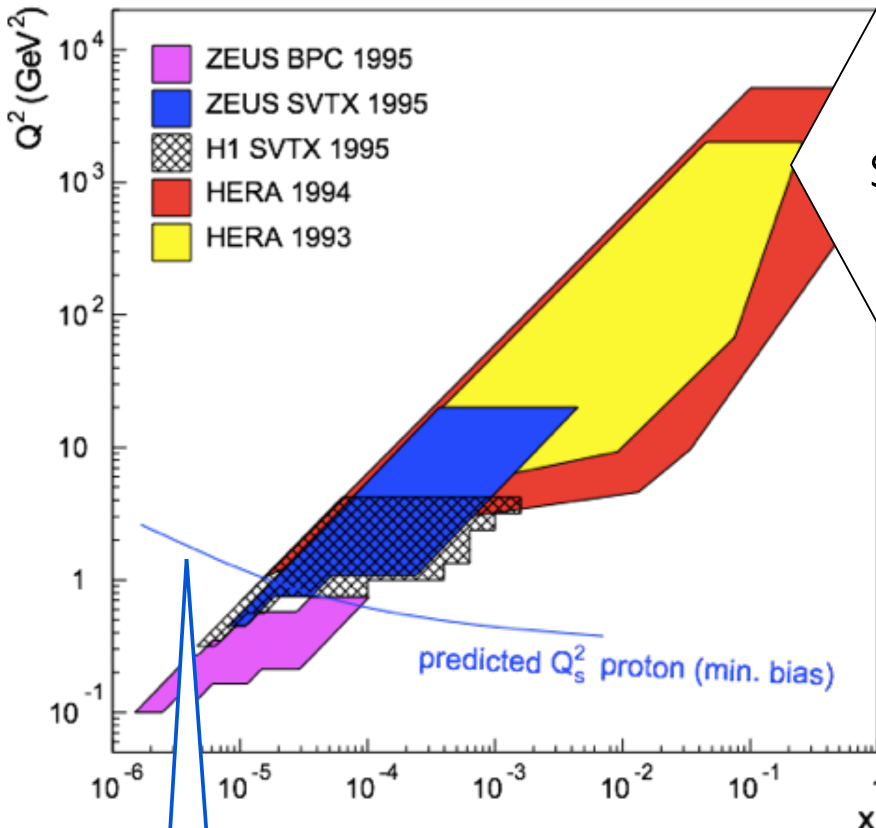
- Lower multiplicity, no pileups, fully constrained kinematics
- More controlled theoretical setup: most of the existing computations are in dilute-dilute and dilute-dense regime



Several open issues can be addressed and, may be, fixed at *high density with A*

- non-linear QCD dynamics (gluon recombination, multiple scattering, …)
- saturation: partonic densities from power-like to logarithmic
- imaging
- nuclear PDFs
- breakdown of collinear factorization: dynamical generation of transverse momentum scale
- Essential input for heavy-ion programmes (initial conditions, hadronization, …)

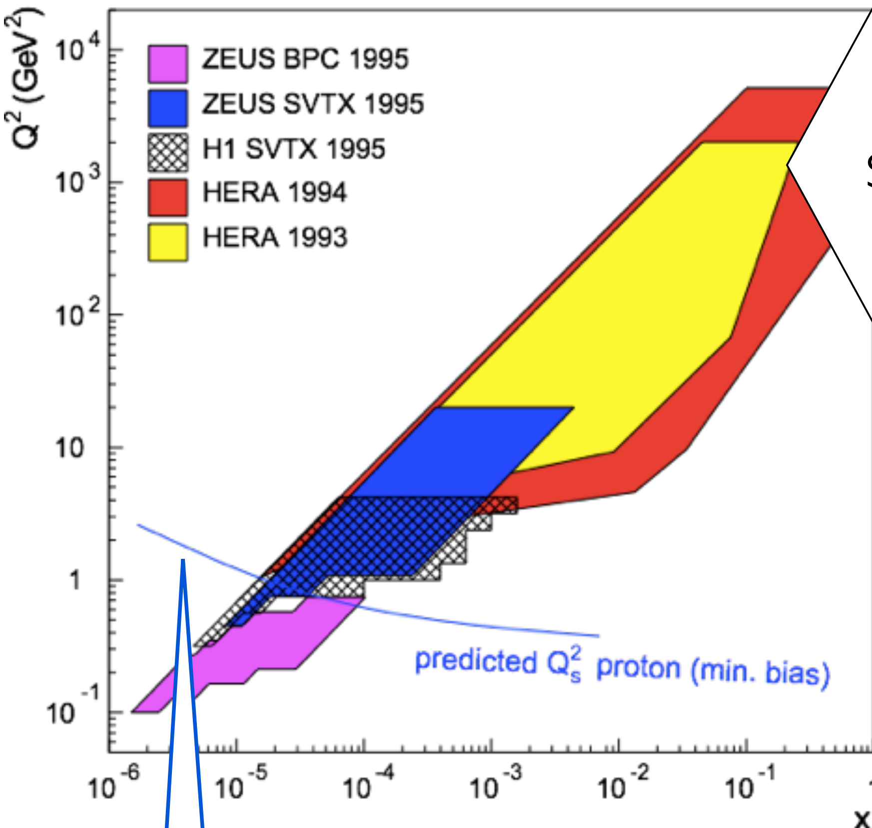
An eA collider: why use nuclei?



Reaching predicted saturation scale in e-p needs **very low x** → **1-2 TeV machine**

Need even lower x than HERA accessed

An eA collider: why use nuclei?



Need even lower x than HERA accessed

Reaching predicted saturation scale in e-p needs **very low x** → **1-2 TeV machine**

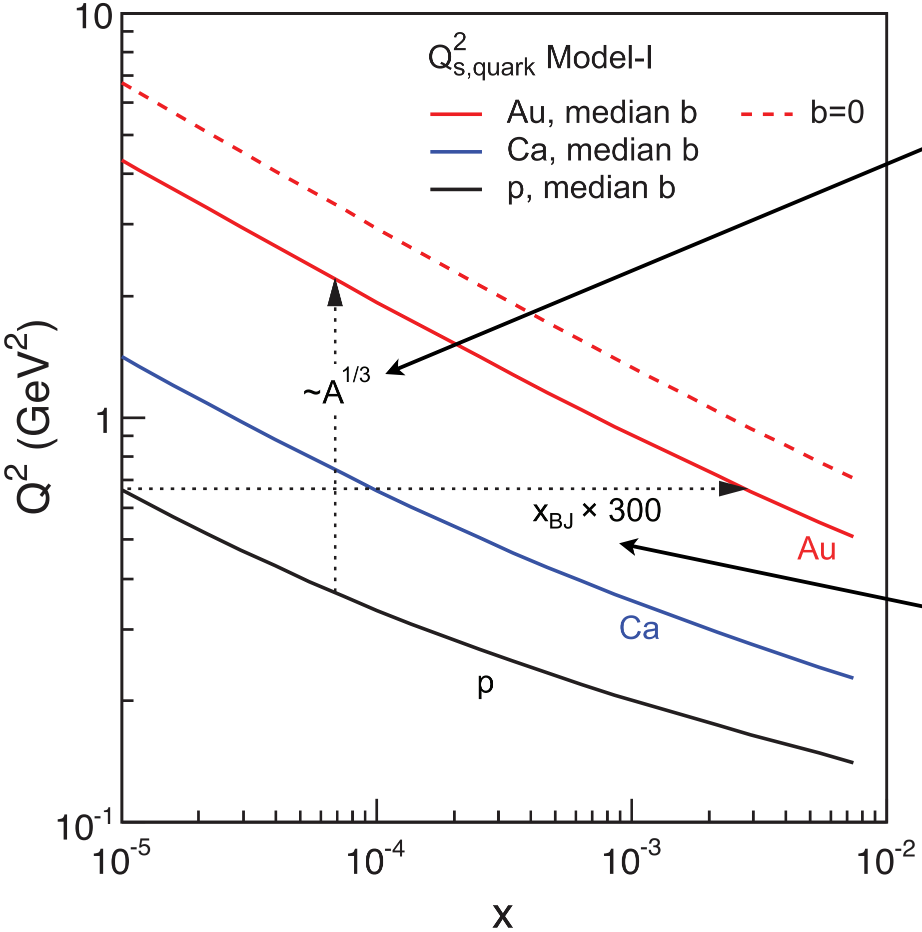
Amplification of non-linear effects at small-x

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

Note this is a "Pocket Formula", there's more to it

Density effects and not different physical mechanisms

An eA collider: why use nuclei?



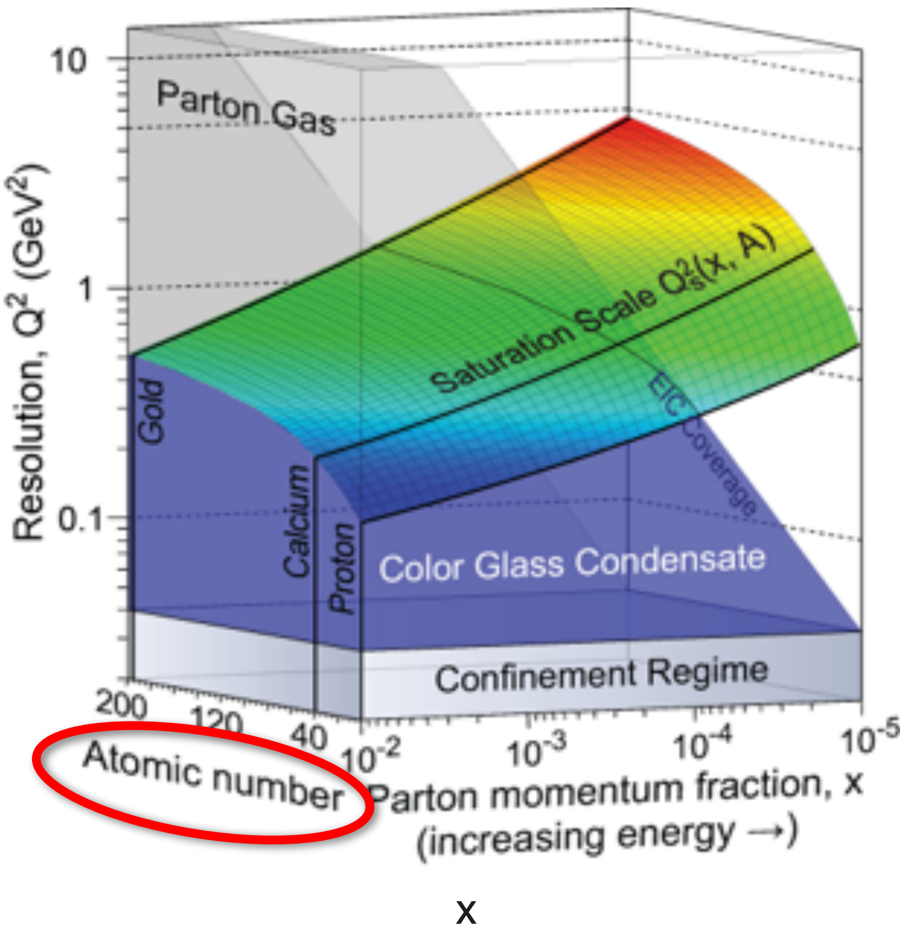
- Nuclear **amplification** of saturation scale

$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$$

- "Effective x" is much smaller in nuclei

→ Access saturation with ~100 **G**eV eA machine

An eA collider: why use nuclei?



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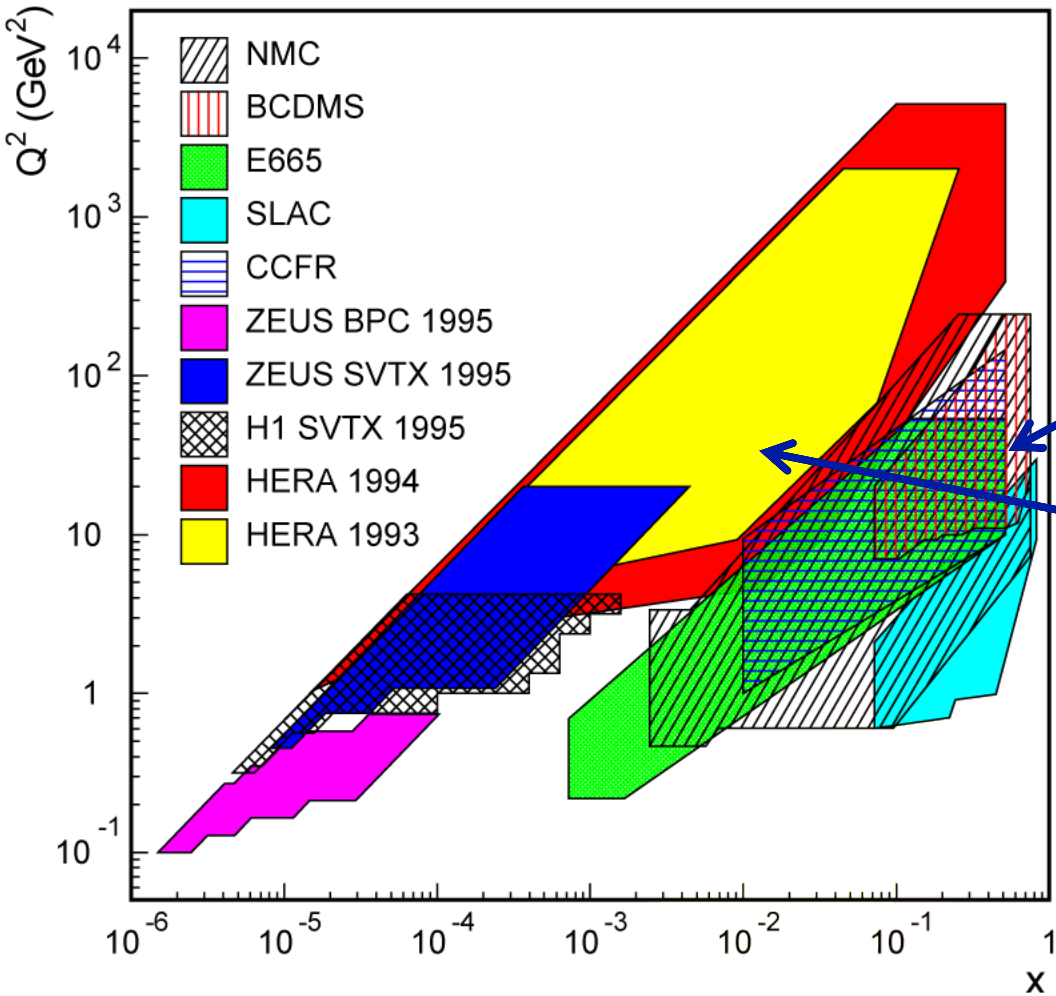
eA landscape

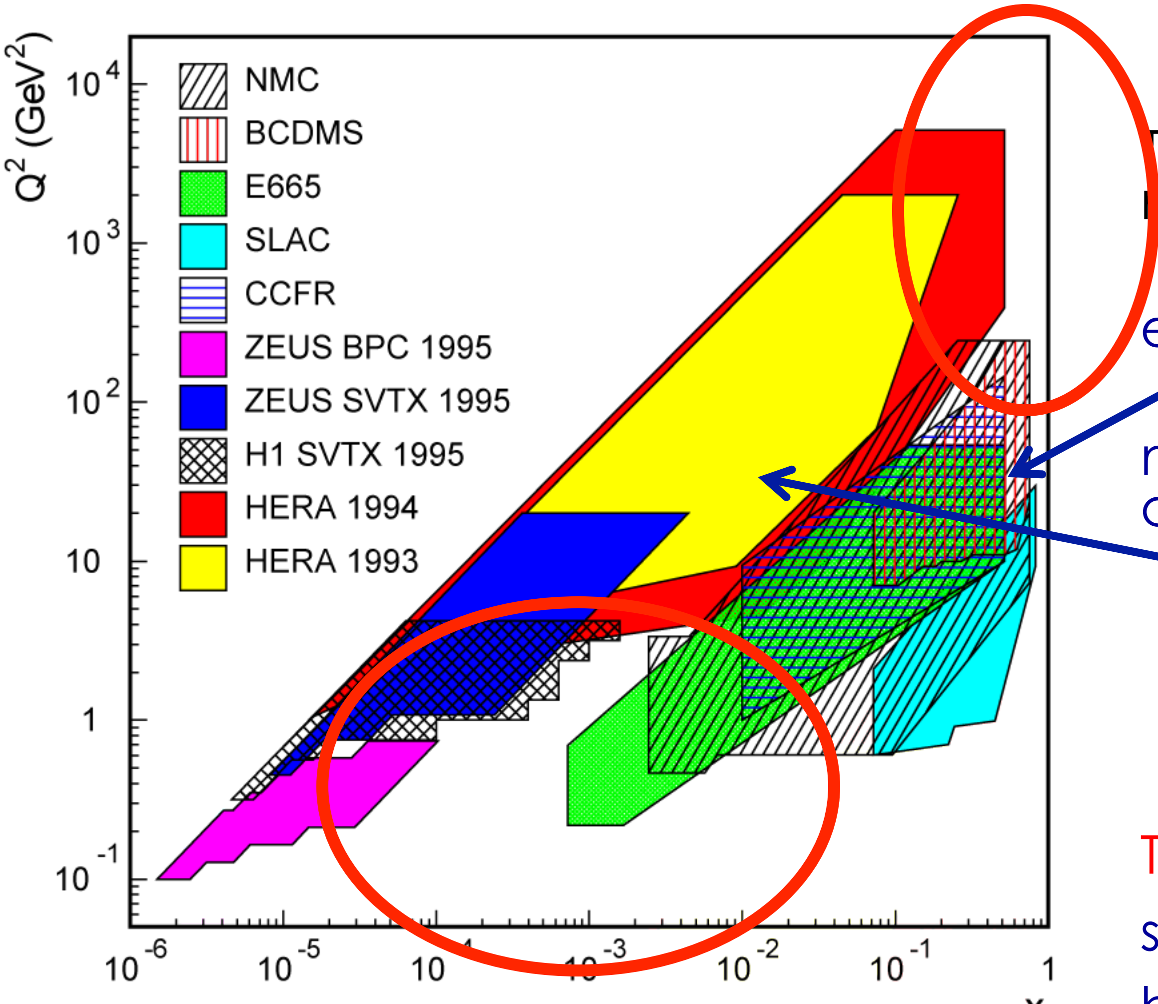


The x, Q^2 plane looks well mapped out, however …

except for ℓ+A (νA)

many of those have small A and very low statistics

eA landscape



The x, Q^2 plane looks well mapped out, however …

except for ℓ+A (νA)

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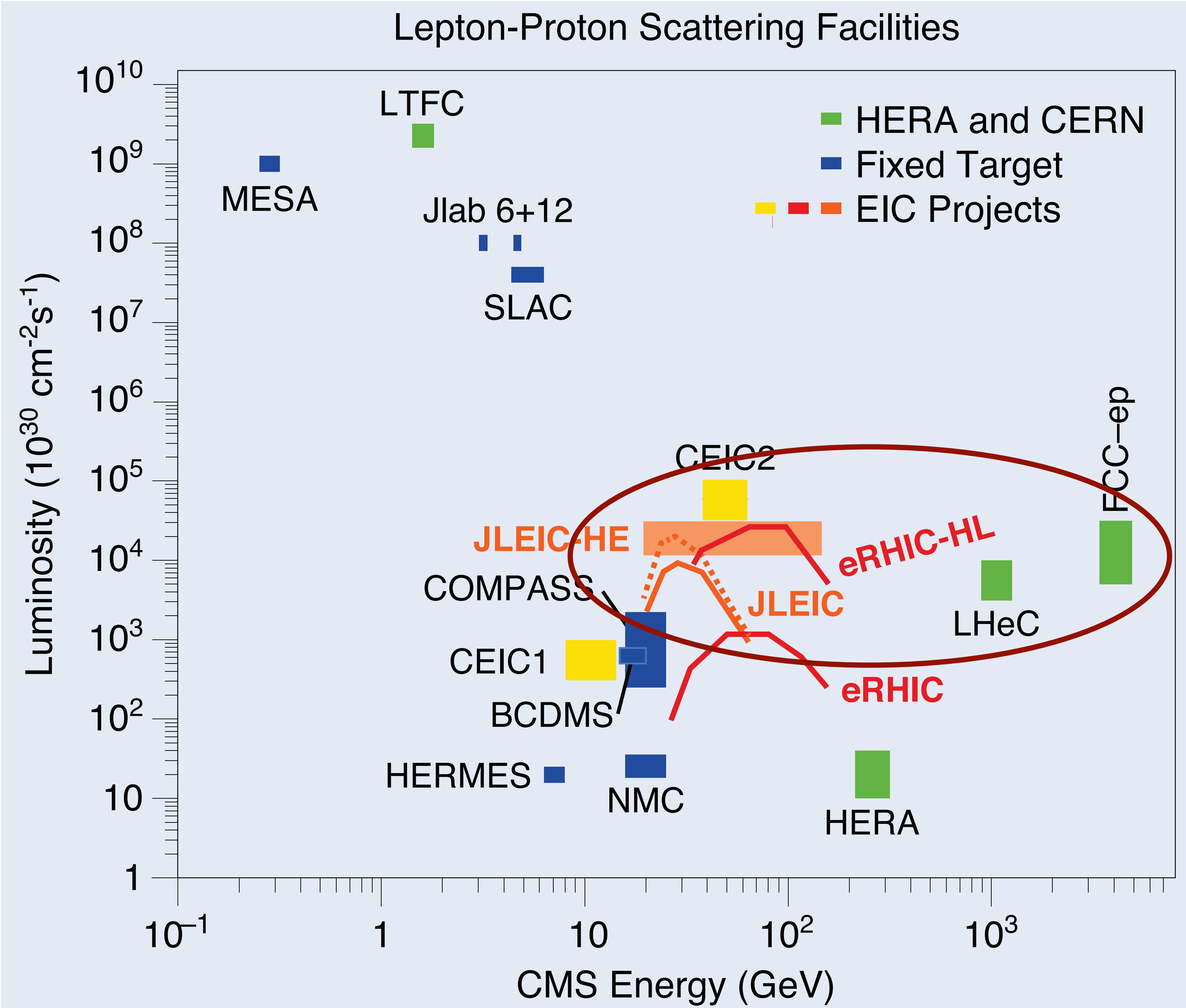
Terra incognita:

small-x, $Q \approx Q_s$

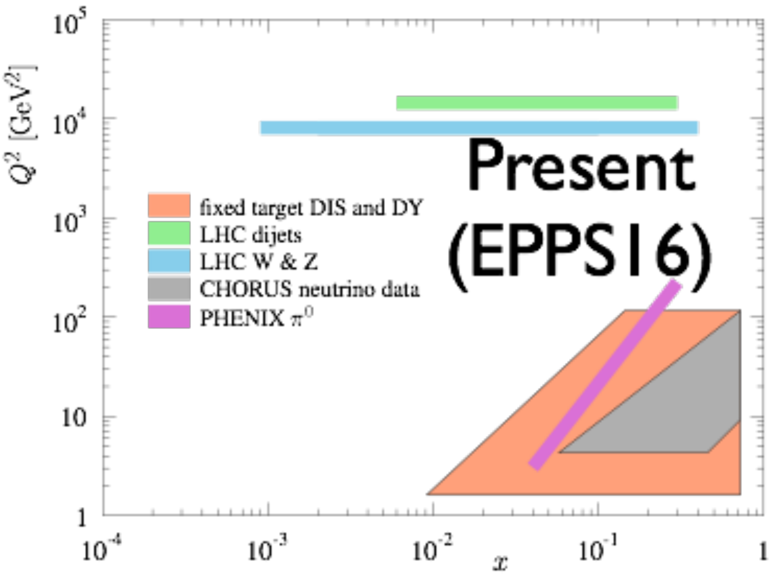
high-x, large Q^2



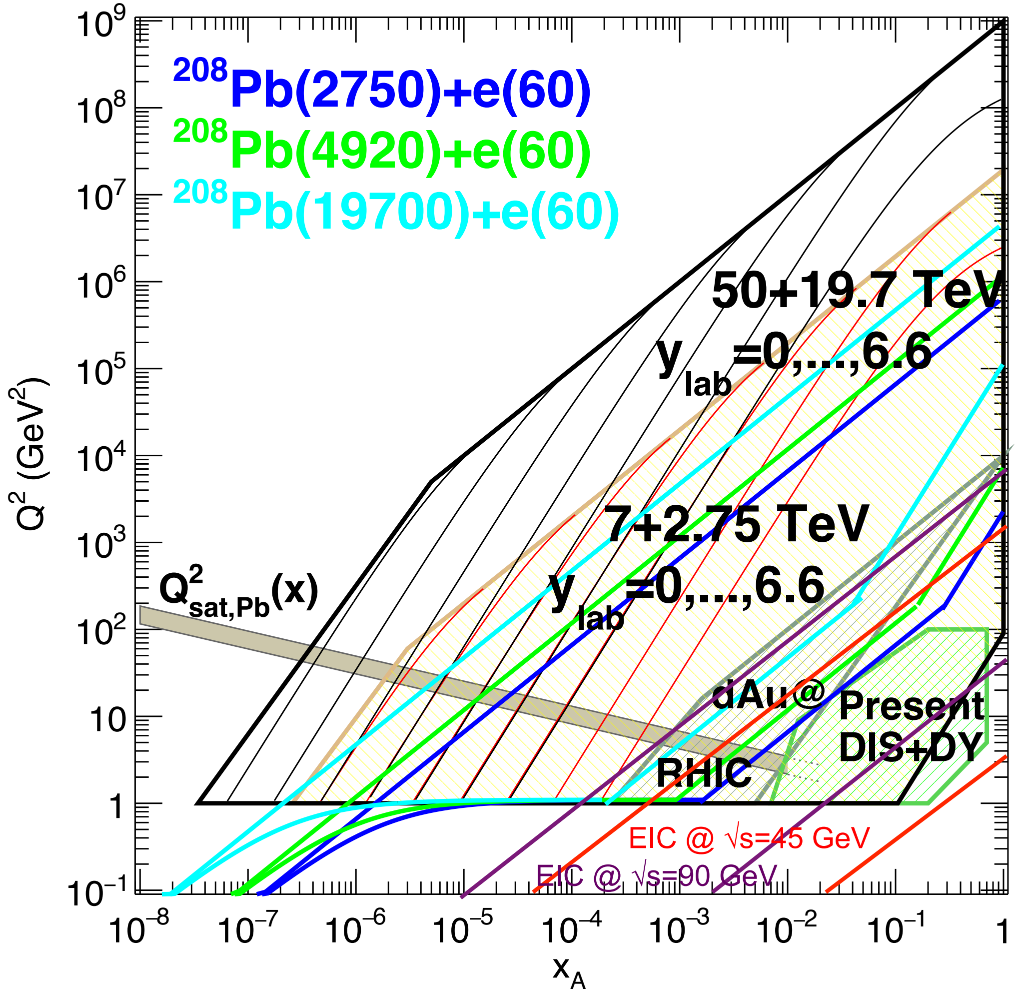
Lepton-Proton Scattering Facilities
HERA and CERN
Fixed Target
EIC Projects
LTFC
MESA
Jlab 6+12
SLAC
CEIC2
JLEIC-HE
eRHIC-HL
FCC–ep
COMPASS
JLEIC
LHeC
CEIC1
BCDMS
eRHIC
HERMES
NMC
HERA
Luminosity (10^{30} cm^{-2}s^{-1})
CMS Energy (GeV)

nPDF: Kinematical space

nPDFs



EIC
LHeC
FCC-eh



Extend reach far beyond the existing data

nPDFs in heavy-ion data

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

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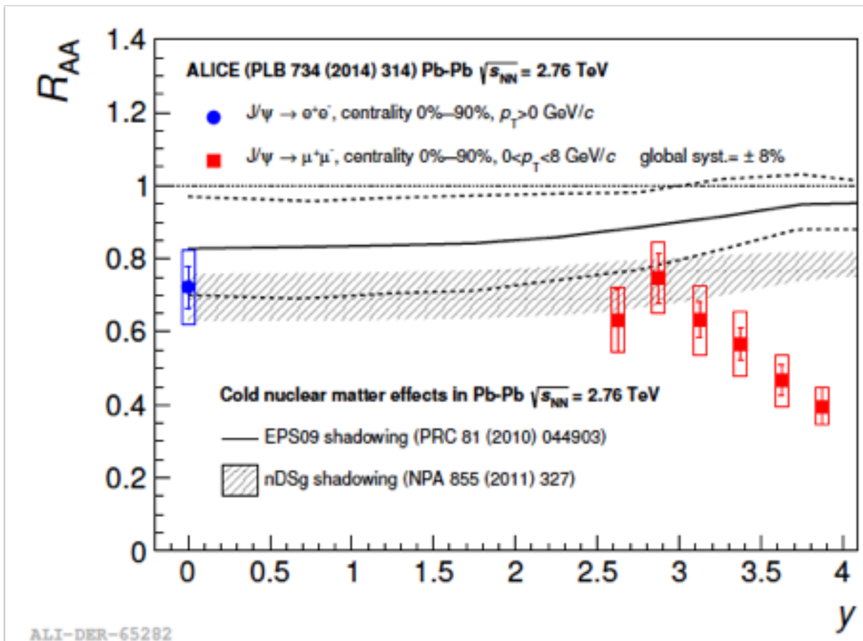
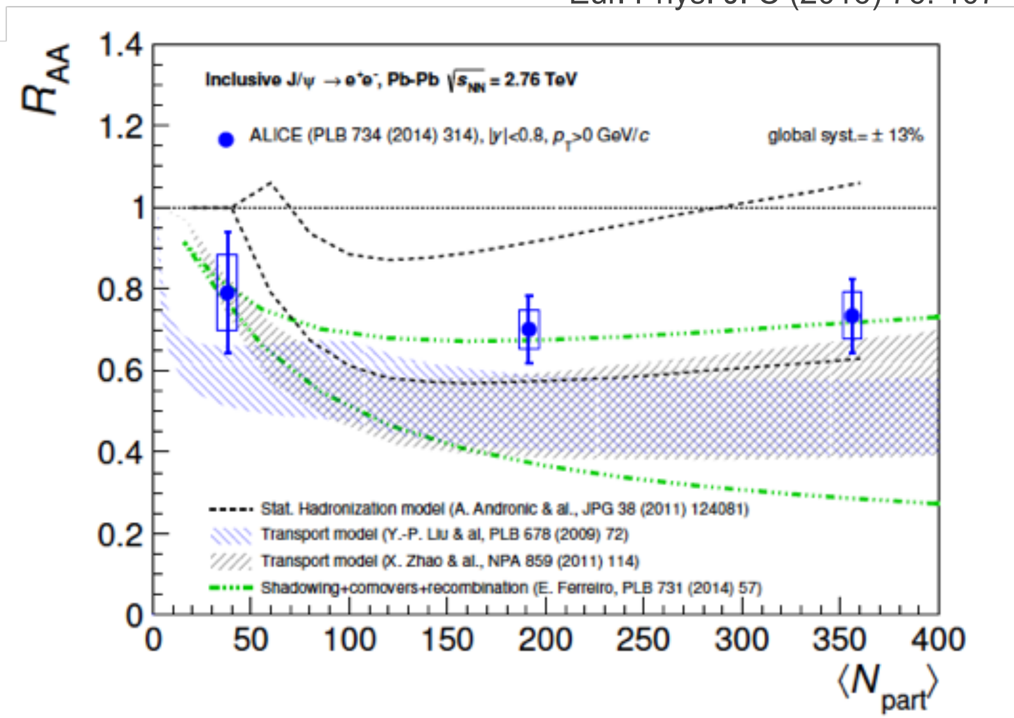




- Large lack of data
- Large uncertainties for the nuclear PDFs → major limitation for extraction of QGP parameters

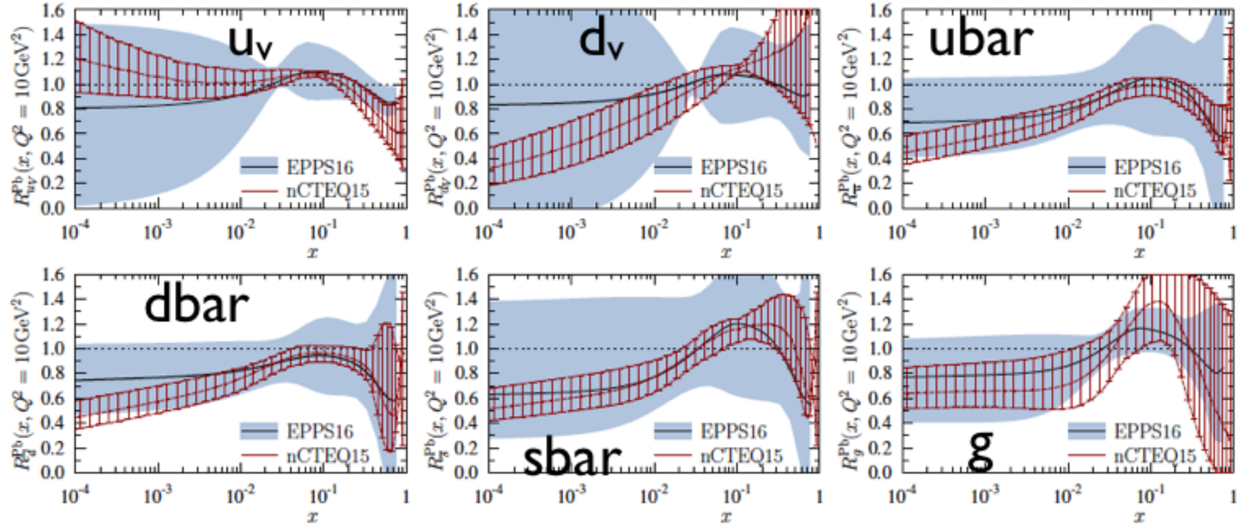
nPDFs at present

$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)$$

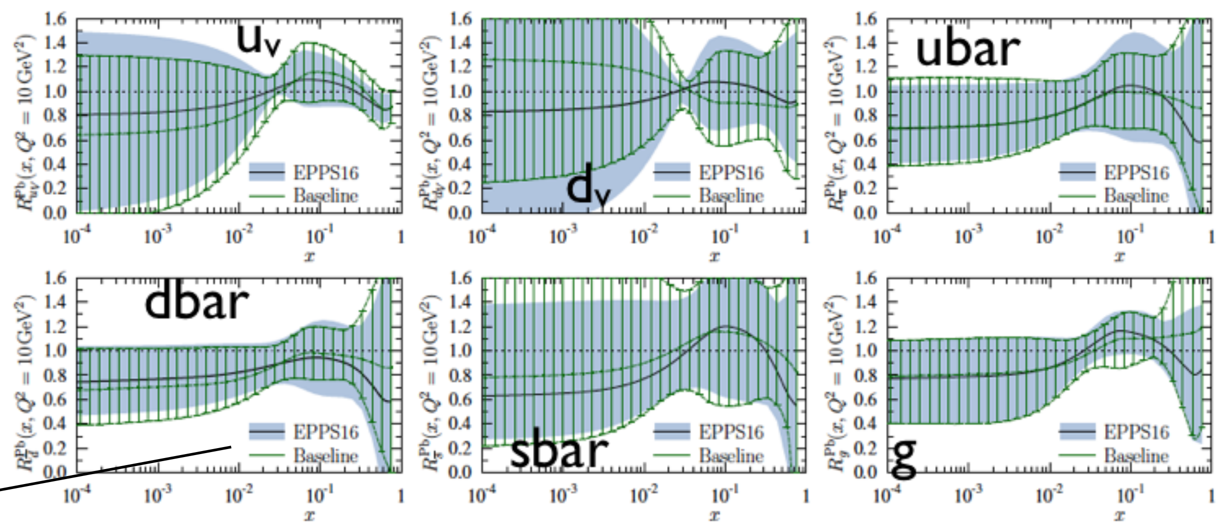
1612.05741

nCTEQ15 no neutrino data included, different functional form than EPPS16

The uncertainties are artificially smaller

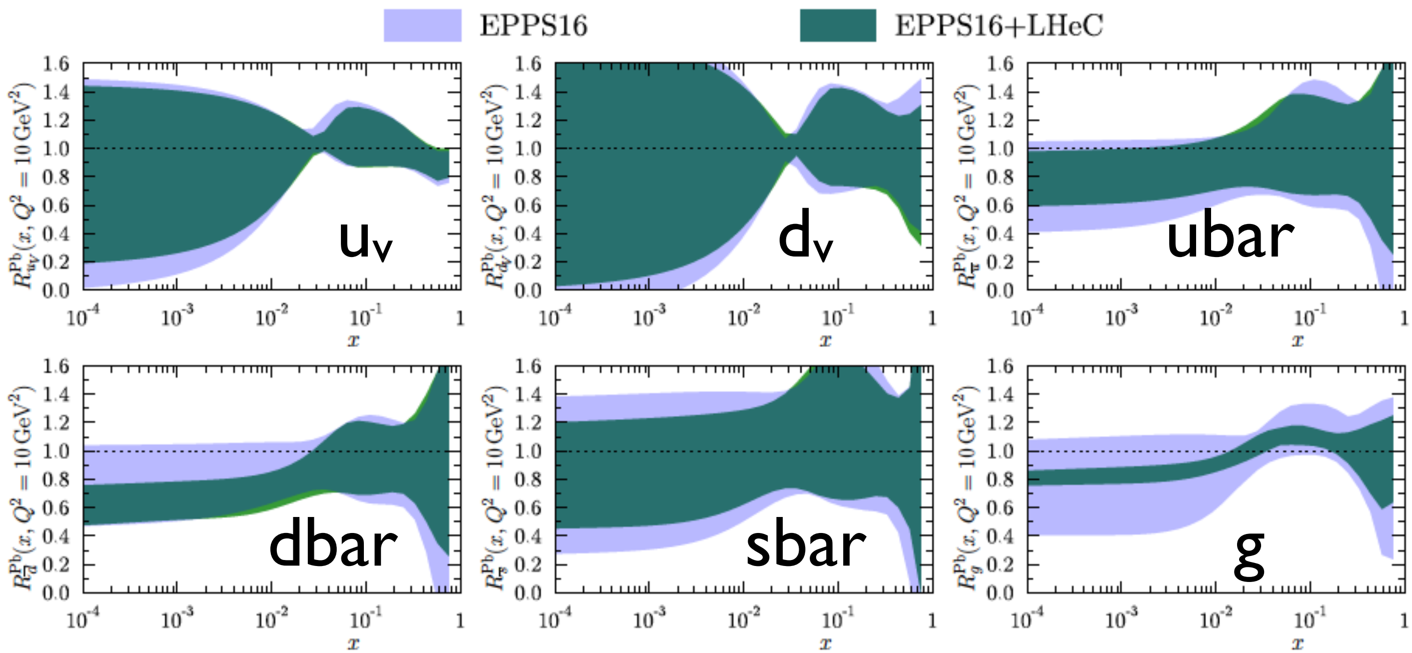


Presently available LHC data don't seem to have a large effect

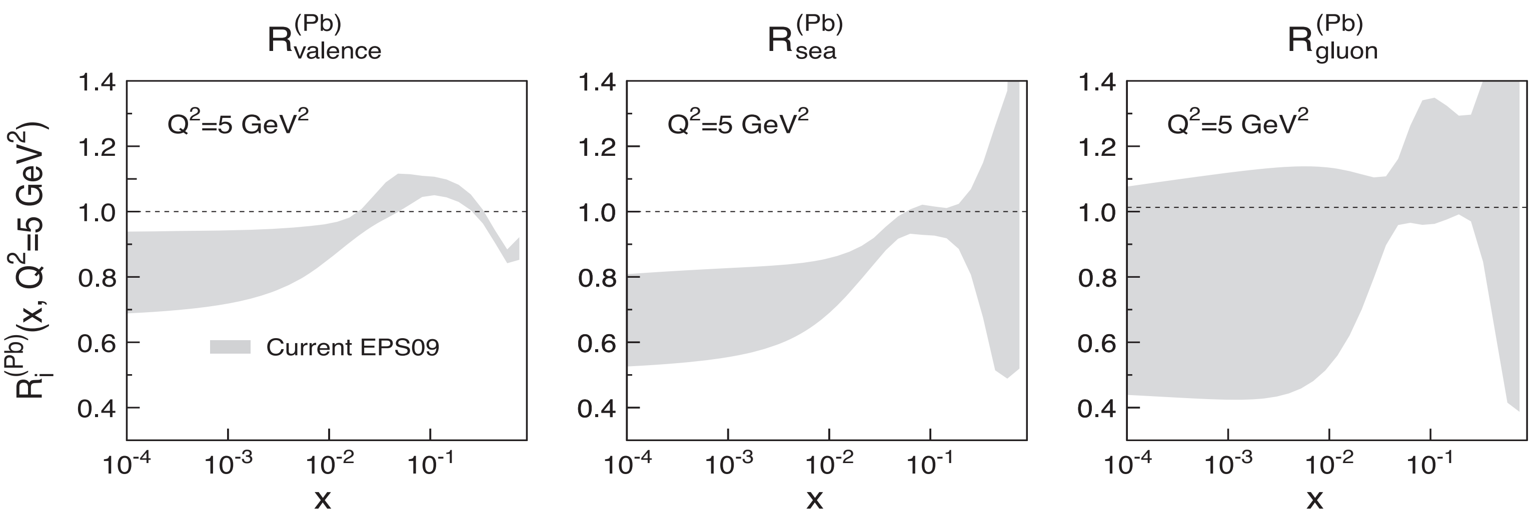


Baseline includes EPS09 (fixed targets DIS, DY, RHIC)
EPPS16: baseline + Chorus data + LHC (dijet, W, Z) pPb

nPDFs in eA colliders



LHeC

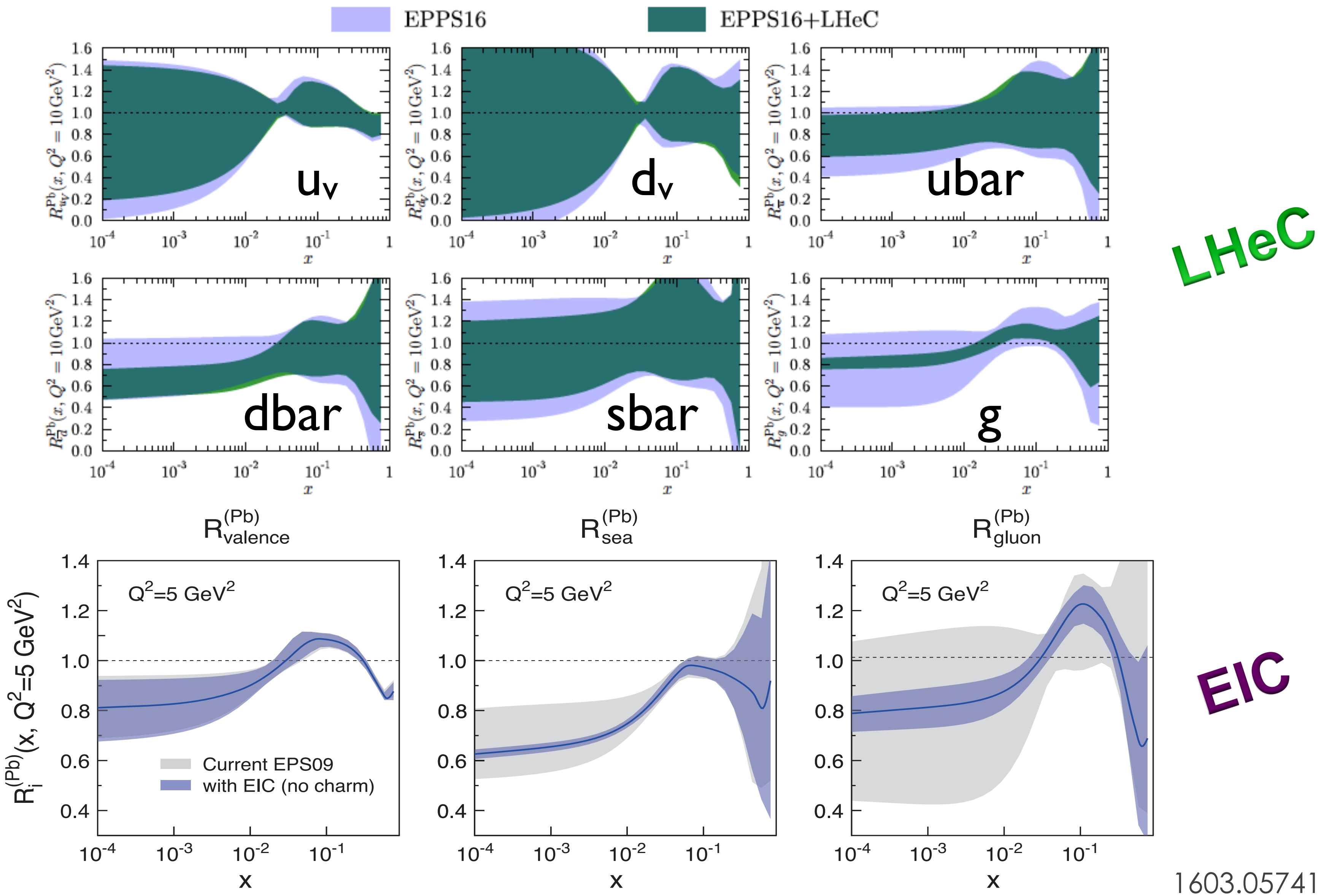


EIC

1603.05741

Large reduction of uncertainties, impossible to achieve at RHIC or LHC

nPDFs in eA colliders



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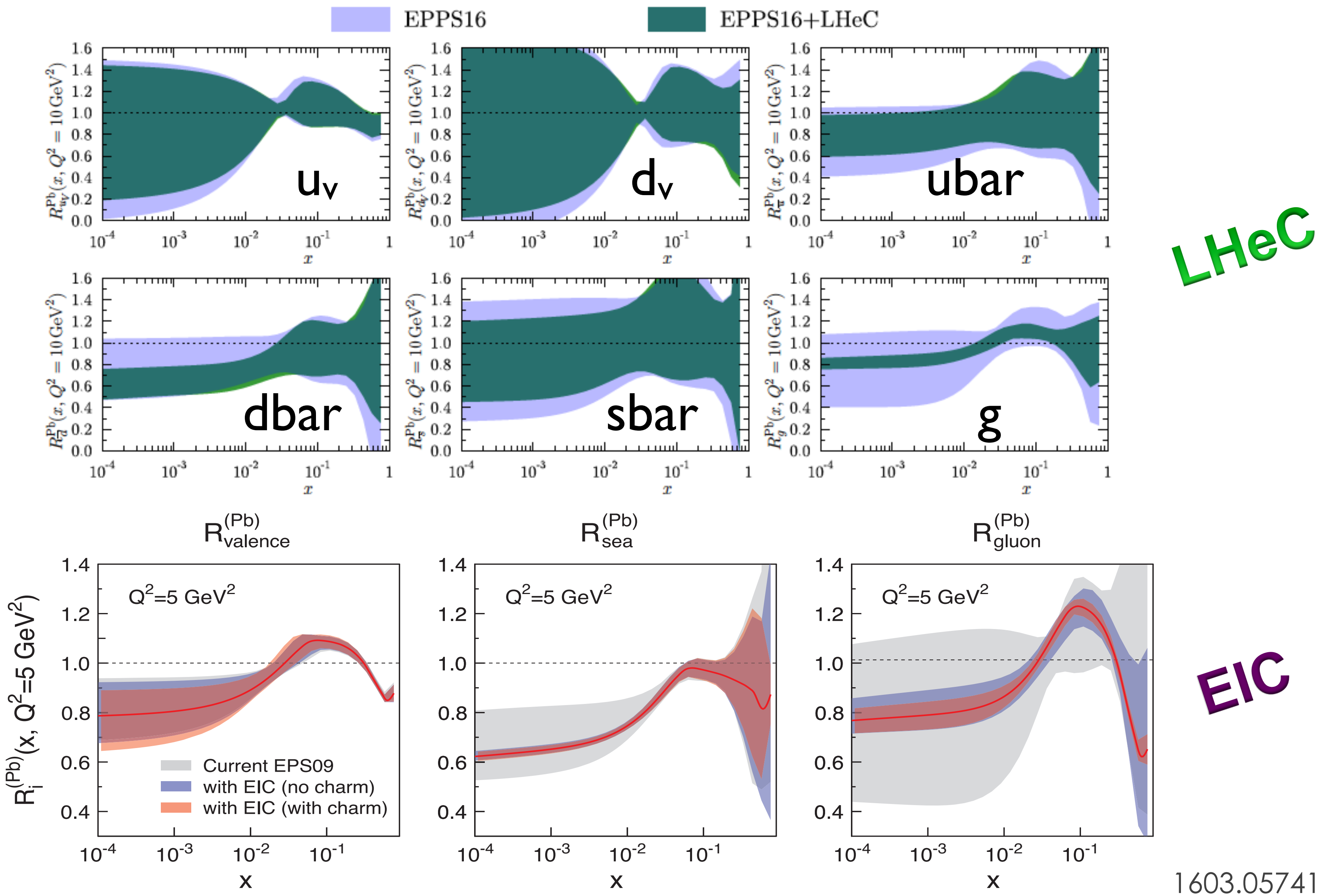
nPDFs in eA colliders



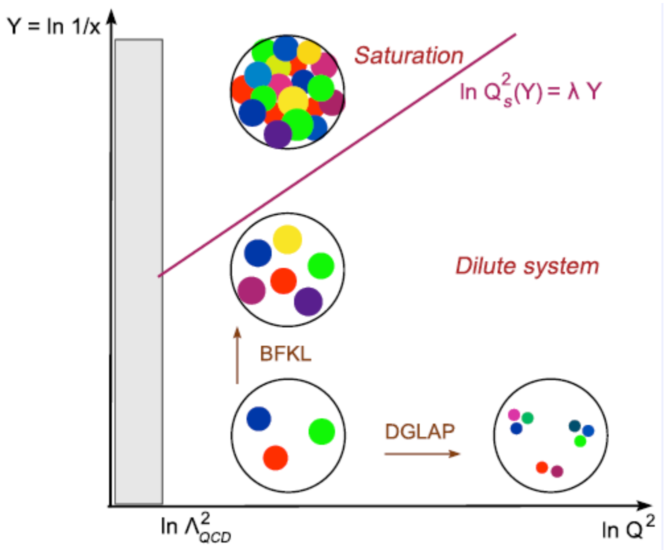
1603.05741

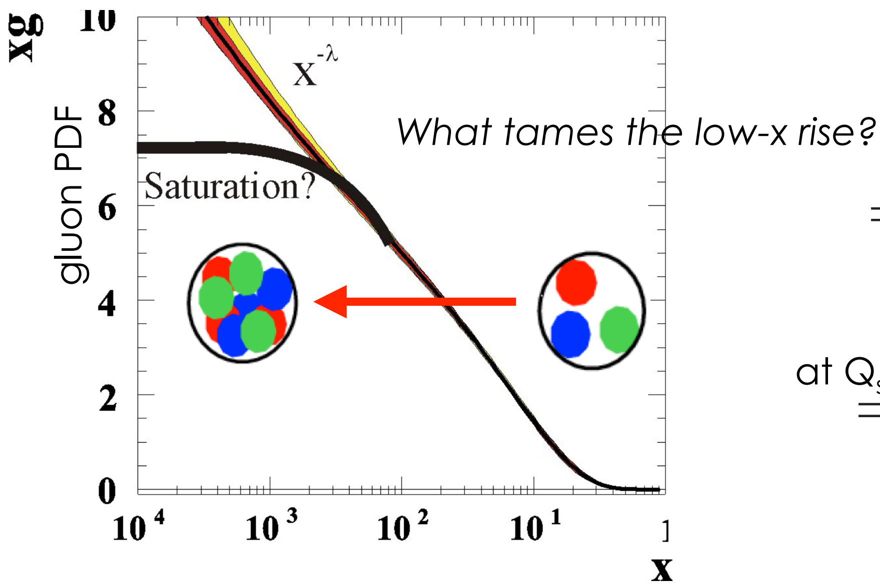
Large reduction of uncertainties, impossible to achieve at RHIC or LHC

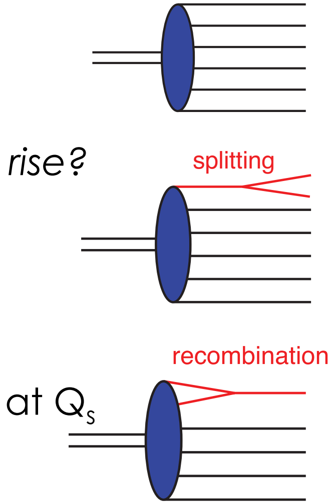
Small-x and non-linear dynamics

1702.00839

Determining the dynamics at small x has been a major subject at HERA, RHIC and the LHC both in pp, pA and AA







Several approaches have been developed to address small-x/high-density dynamics

DGLAP/BFKL (linear evolution):
predicts Q^2 but not A-dependence and x-dependence
Saturation models (non-linear evolution: BK/JIMWLK):
predict A-dependence and x-dependence but not Q^2
→ Need: large Q^2 lever-arm for fixed x, A-scan

Small-x and non-linear dynamics

1702.00839

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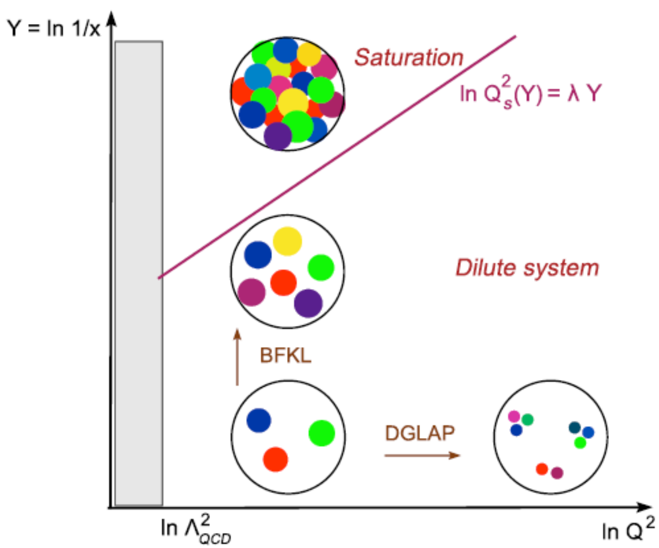
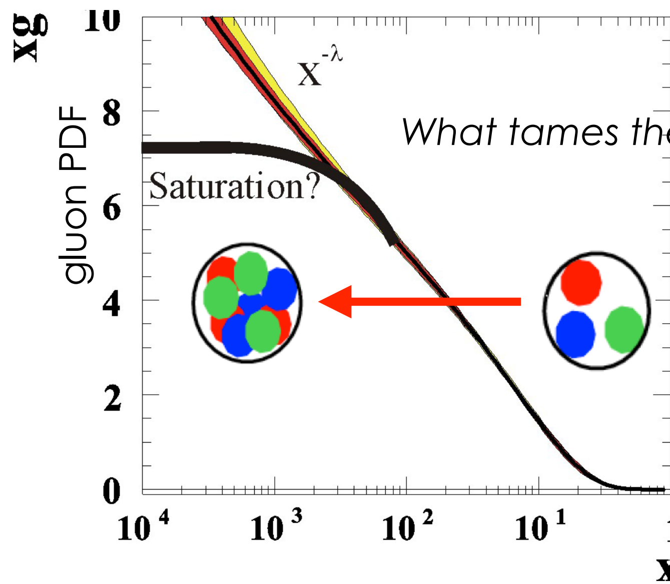
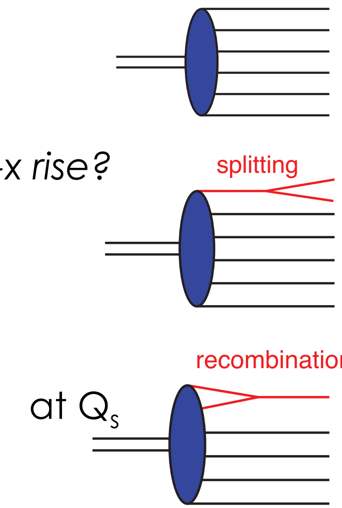




What tames the low-x rise?

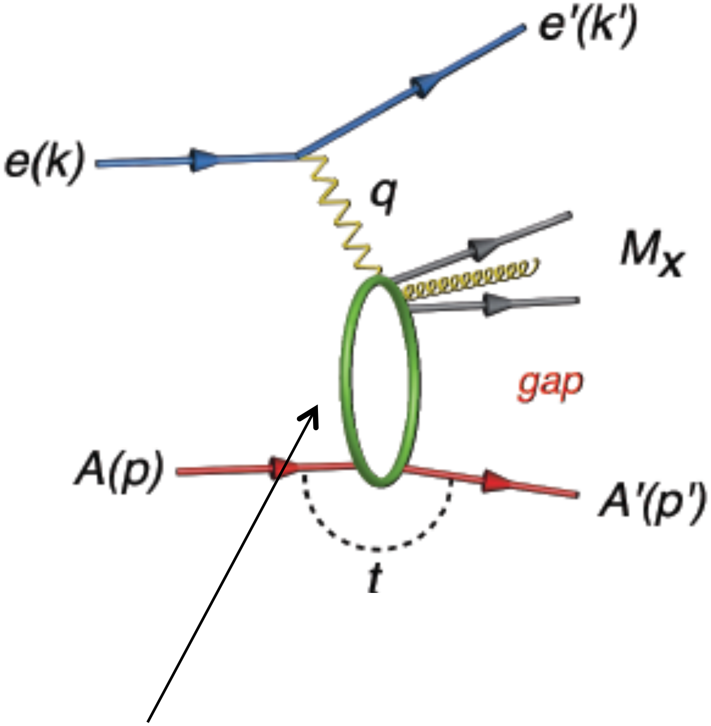


First observation of gluon recombination effects <u>in nuclei</u>:
→leading to a collective gluonic system!

First observation of g-g recombination <u>in different nuclei</u>:
→ Is this an universal property?
→ Is the Color Glass Condensate the correct effective theory?
→ Do we need a new evolution equation at low-x and moderate Q^2?

Key measurement - Diffraction

Smoking gun for the breakdown of the collinear factorization



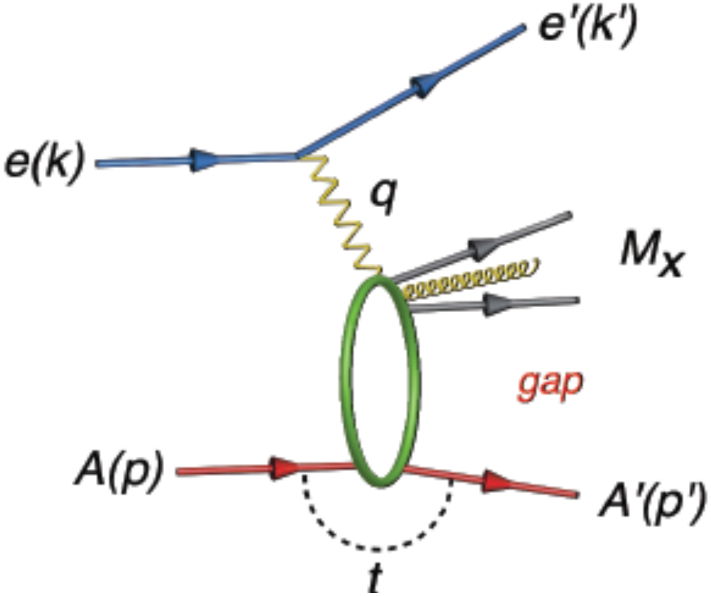
Diffractive physics plays a major role in eA.
Surprisingly at HERA ~15% of DIS events were diffractive.
It is expected 25-40% in eA !

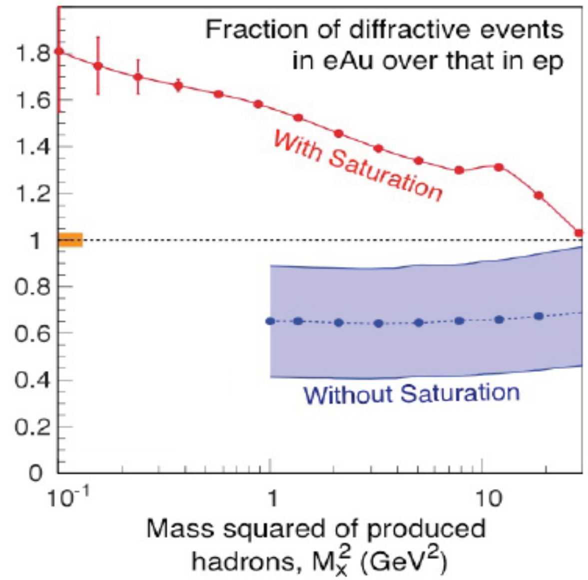
Clear signature. Absence of activity over wide rapidity.

Ideal to study gluons: $\sigma_{diff} \approx [g(x,Q^2)]^2$
At LO, color-neutral exchange, e.g. 2 gluons (Pomeron)

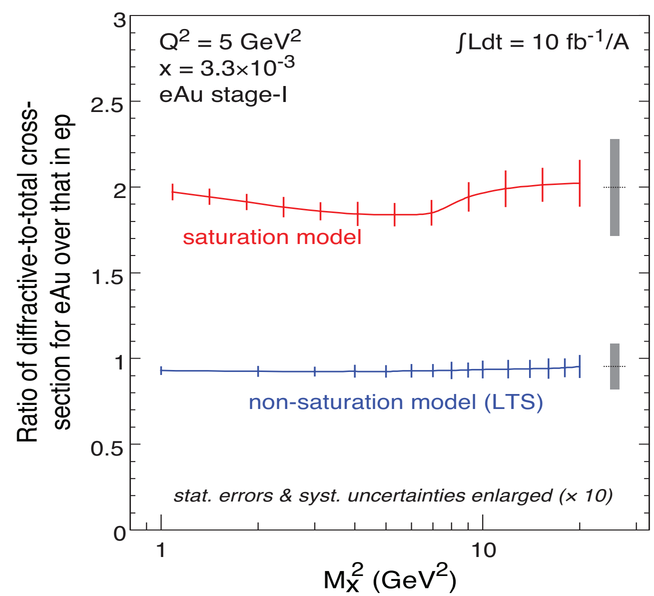
Key measurement - Diffraction

Smoking gun for the breakdown of the collinear factorization





LHeC

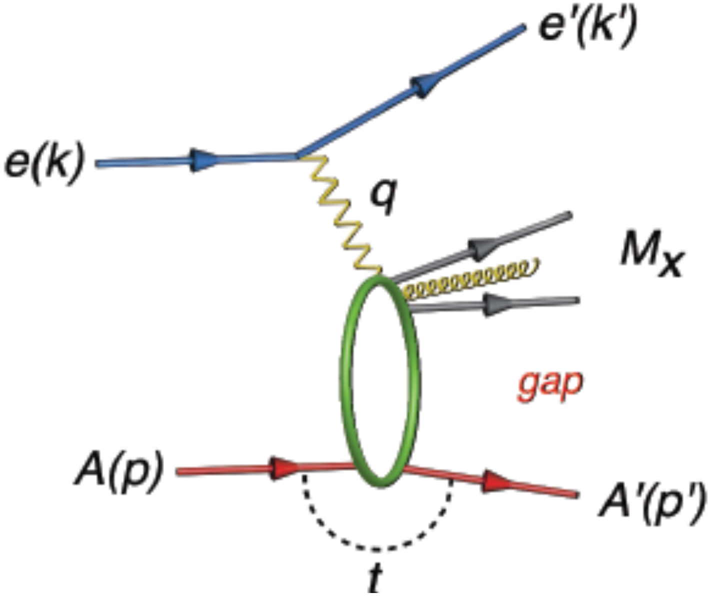


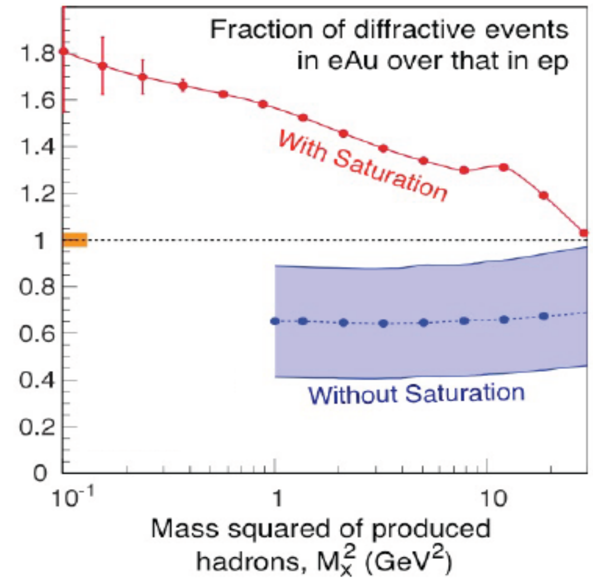
EIC

Strong distinguishing power

Key measurement - Diffraction

Smoking gun for the breakdown of the collinear factorization





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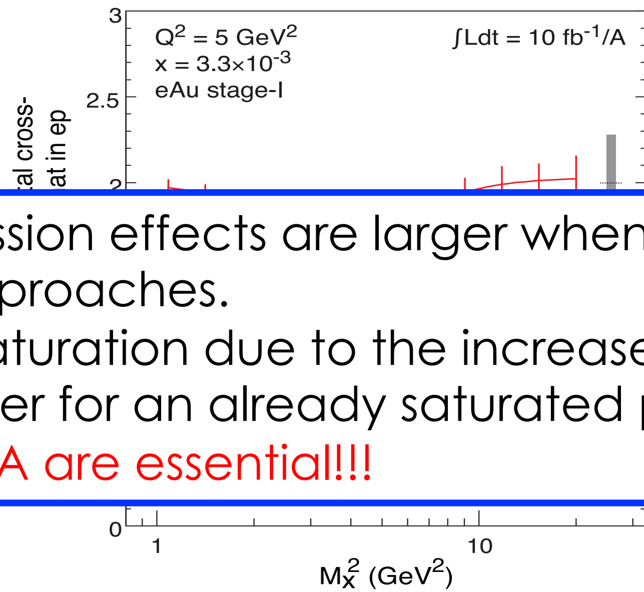
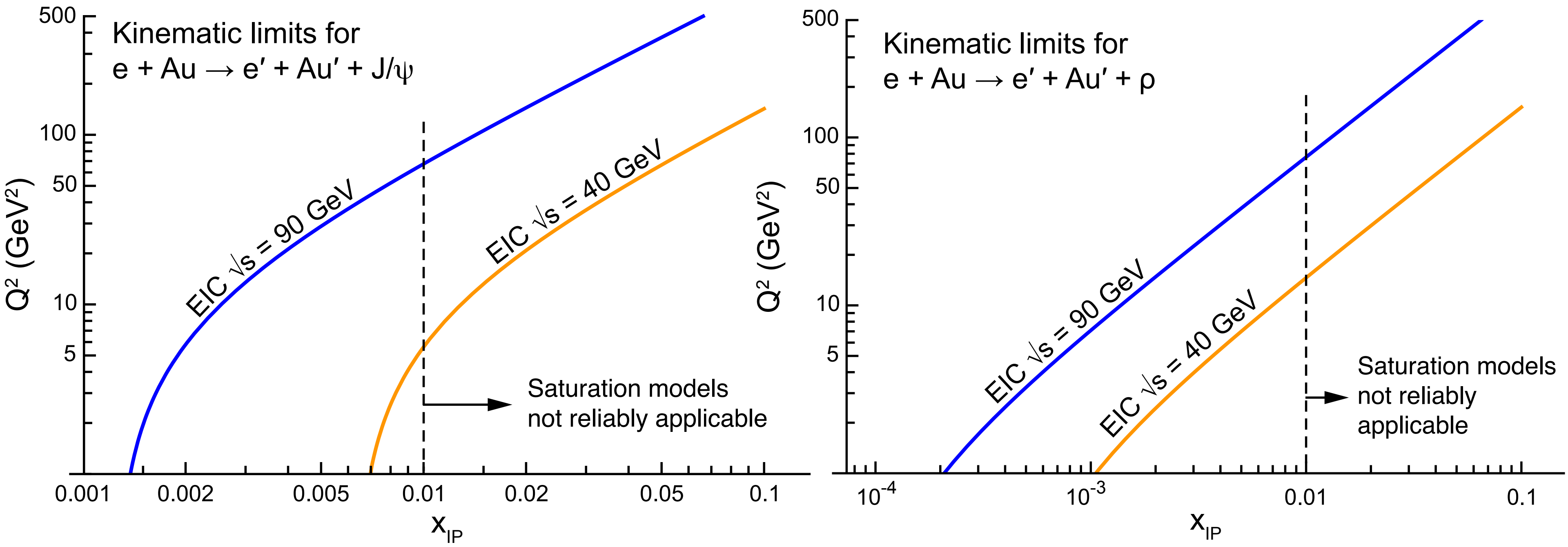


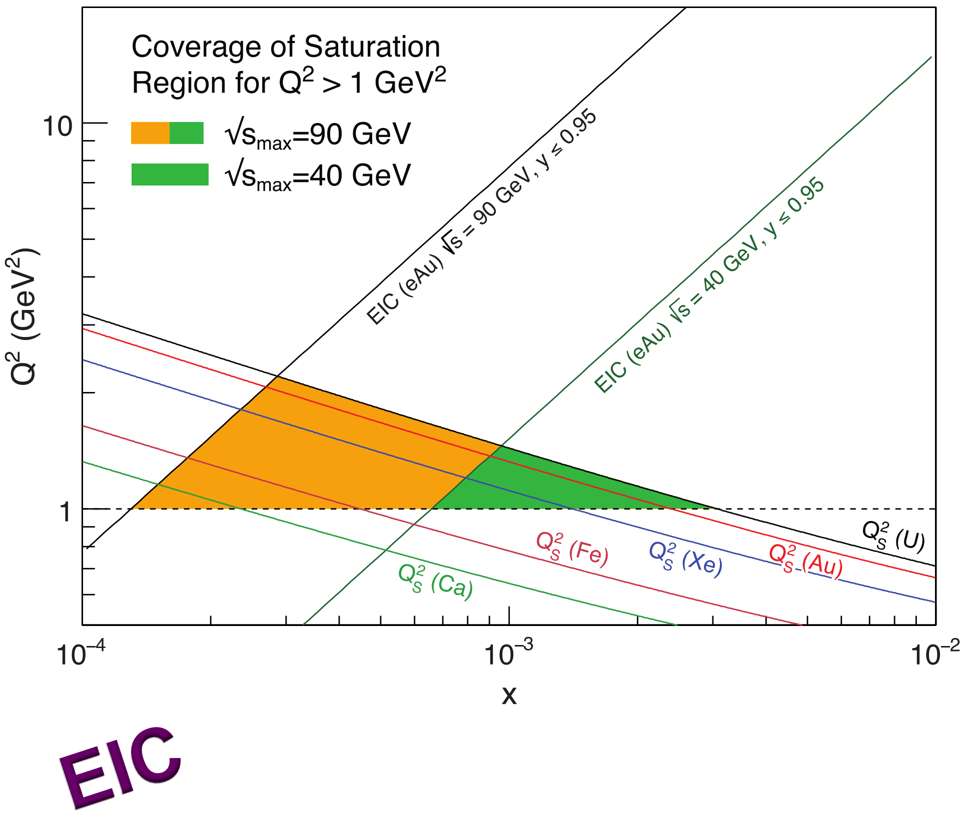
One would expect naively that suppression effects are larger when going from p to A in saturation than in collinear approaches.
This is not generically so because the saturation due to the increase of density when going from p to A could be smaller for an already saturated proton

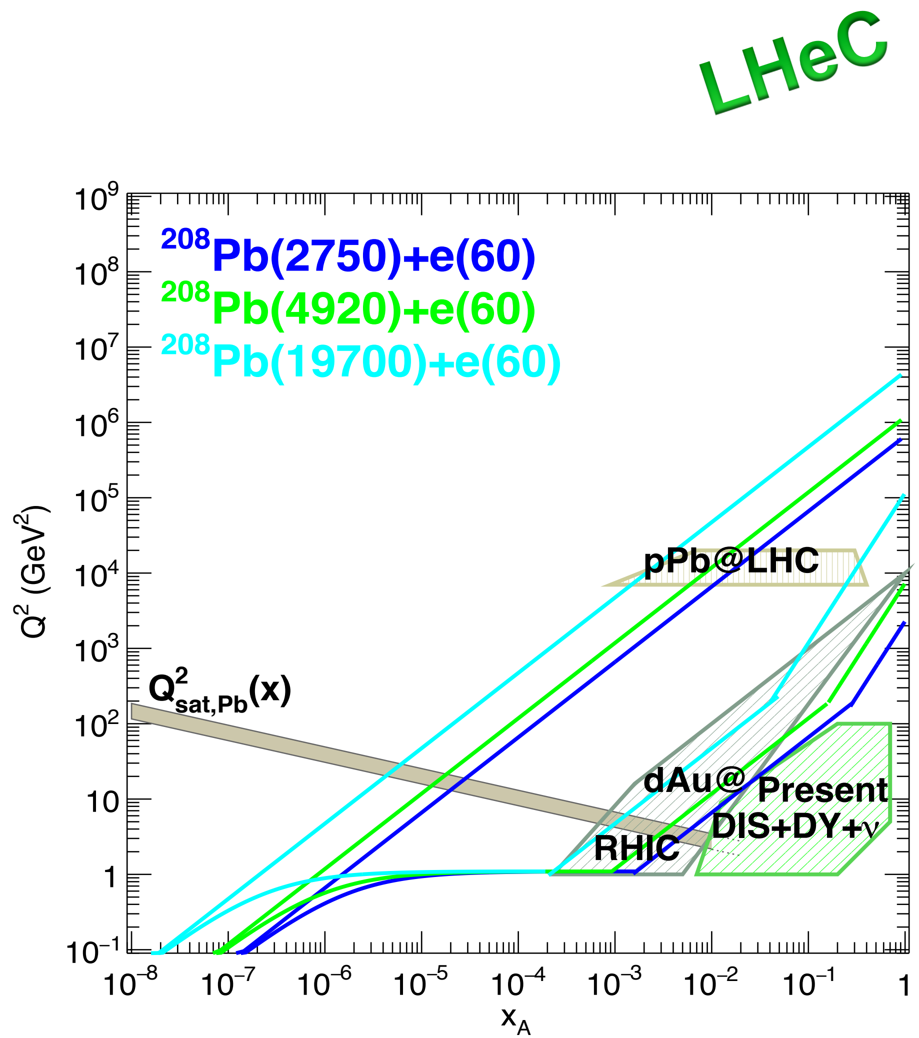
both ep and eA are essential!!!

Coverage of saturation region



Coverage of saturation region





What do the diffractive cross sections tell us

Coherent: target remains intact
~ average density

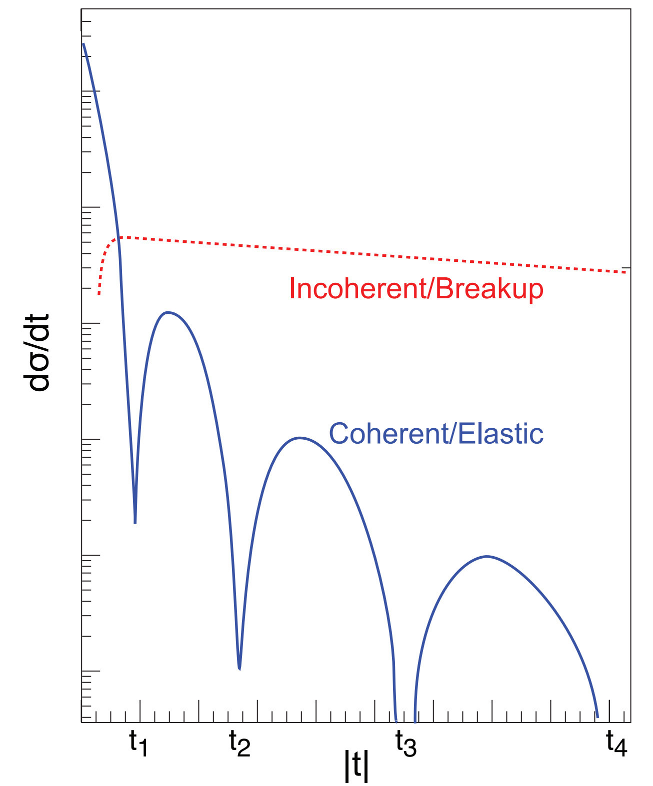
$$\frac{d\sigma_{coh}}{dt} = \frac{1}{16\pi} \left|\langle \mathcal{A} \rangle\right|^2$$

Incoherent: target dissociation ($f \neq i$)

$$\sigma_{incoh} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle$$

$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|A|i\rangle^\dagger \langle i|A|i\rangle$$

$$= \langle i|\,|\mathcal{A}|^2|i\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \langle|\mathcal{A}|^2\rangle - |\langle\mathcal{A}\rangle|^2$$

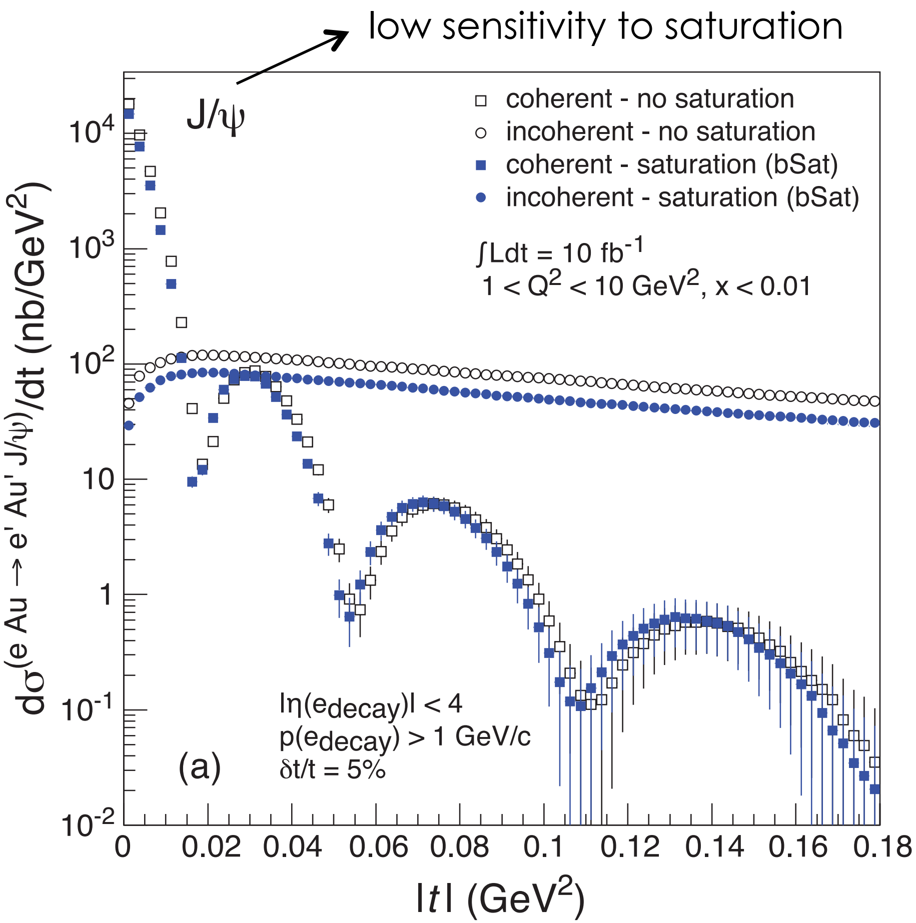


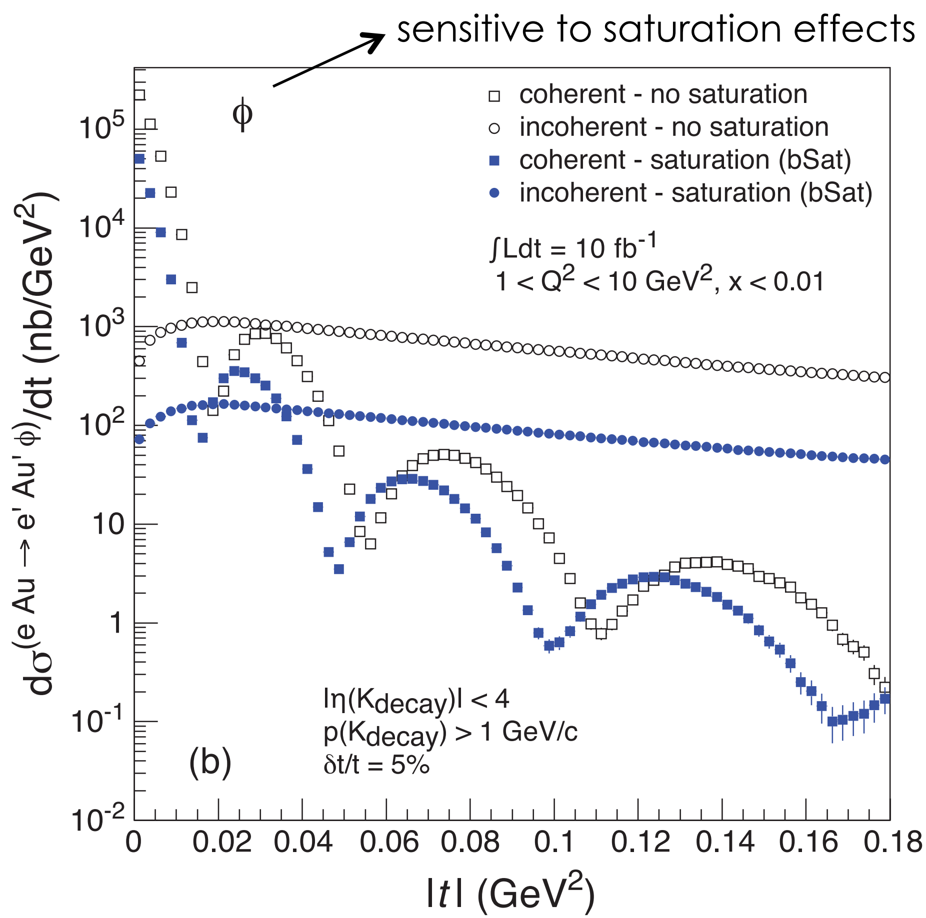
$\mathbf{t_i \sim 1/R^2}$

Variance of amplitude $\mathcal{A}$
⇒ measure of fluctuating source density

Does the low-x dynamics (Saturation) modify the transverse gluon distribution?

Vector Meson Production in eA



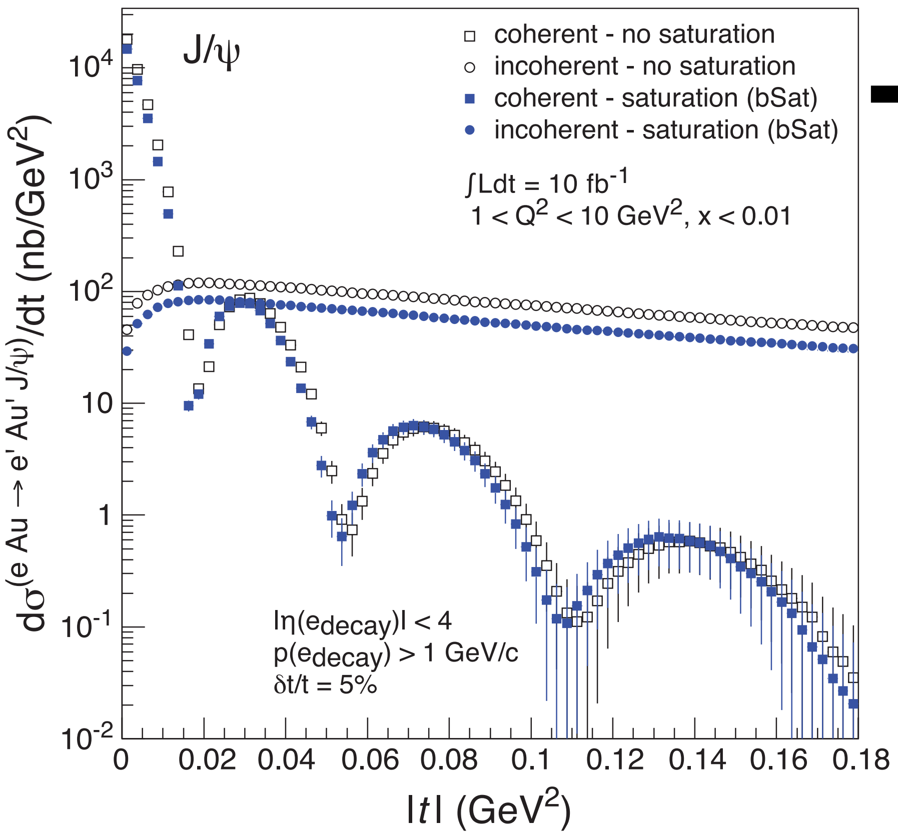


- Diffractive pattern for coherent (non-breakup) part
- Saturation effects seen especially in light meson production
- Need: t resolution, kinematical reach, luminosity for x binning

Spatial distribution from dσ/dt

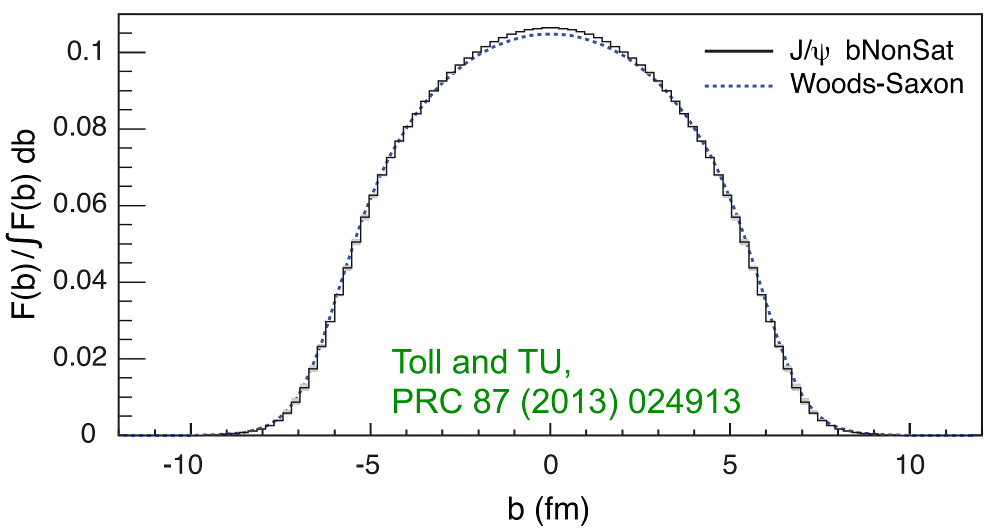
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi$

- Momentum transfer $t = |p_{Au}-p_{Au'}|^2$ conjugate to b_T



$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$t \approx \Delta^2$

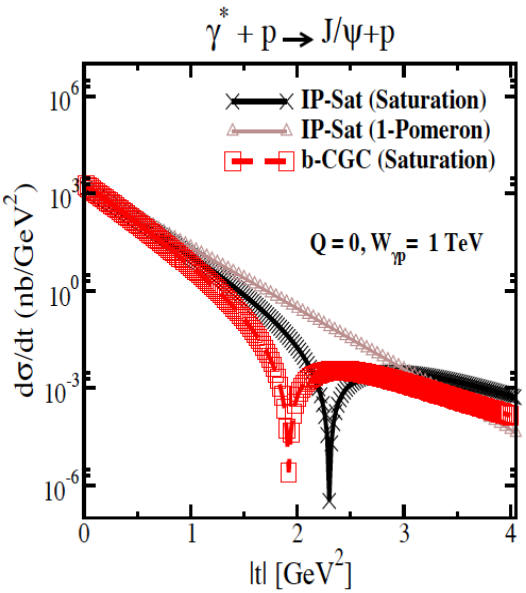


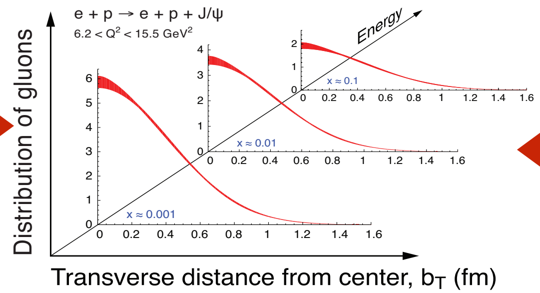
Can extract transverse profile of small-x gluons!

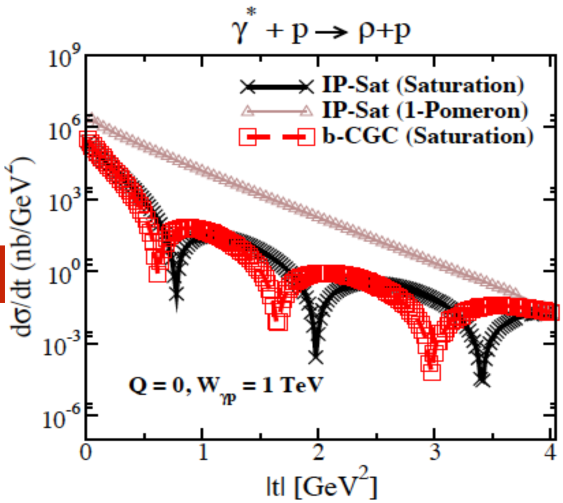
VM production

- Exclusive VM production ←→ DVCS provides a transverse scan of the partonic structure of the hadron

1402.4831







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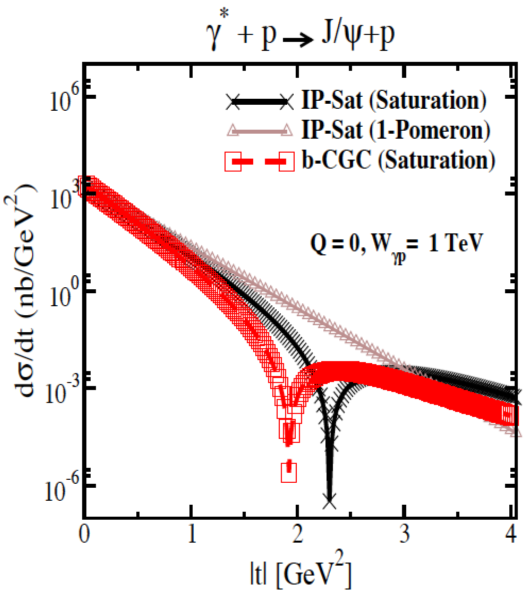
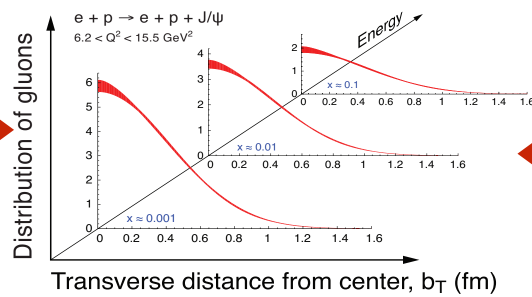
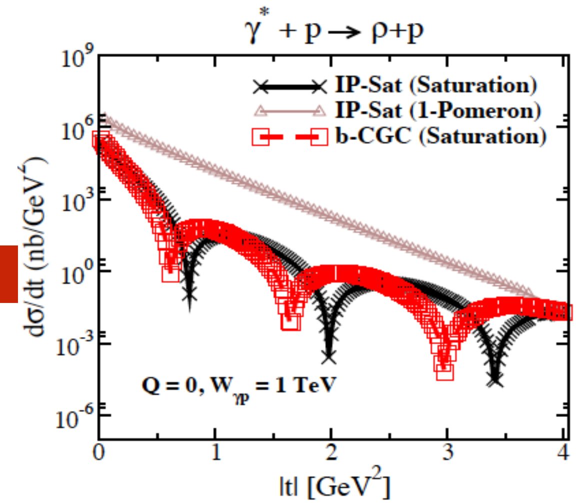
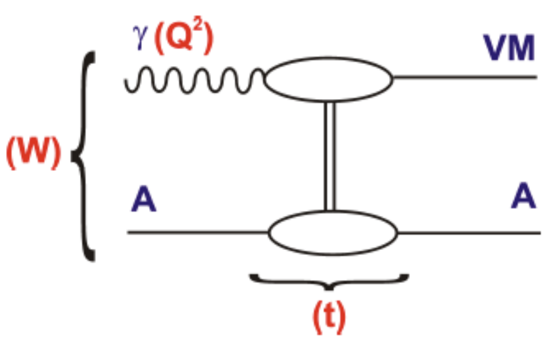
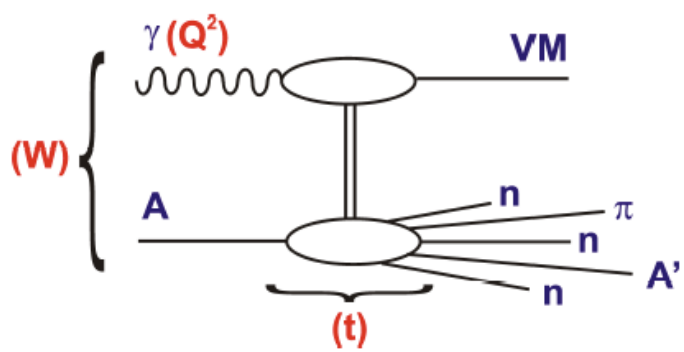






- Coherent vs incoherent diffraction can solve the issue that the gluonic density of the proton in the transverse plane is distributed around the constituent quarks (**hot spots**) relevant for fluctuations, azimuthal asym, definition of MPIs...



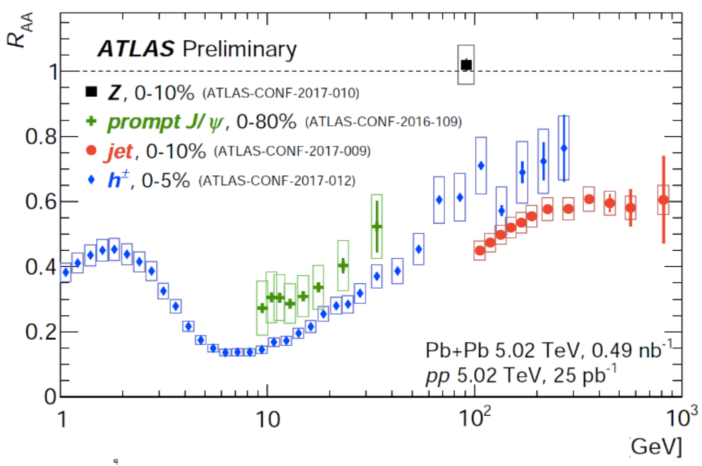


1608.07559
1011.1988
1703.09256

Hard probes

Extremely successful *self generated* probes for QGP and pQCD in AA collisions, but with a lot of issues to be understood, e.g.:

- The traditional picture of semihard large angle gluon radiation (interference with several scattering centres) could be replaced by the interplay between the medium resolving power and the jet scale (radiation off from total to individual color charge)
- Hadronisation is *assumed* to happen outside the medium, except for QQbar



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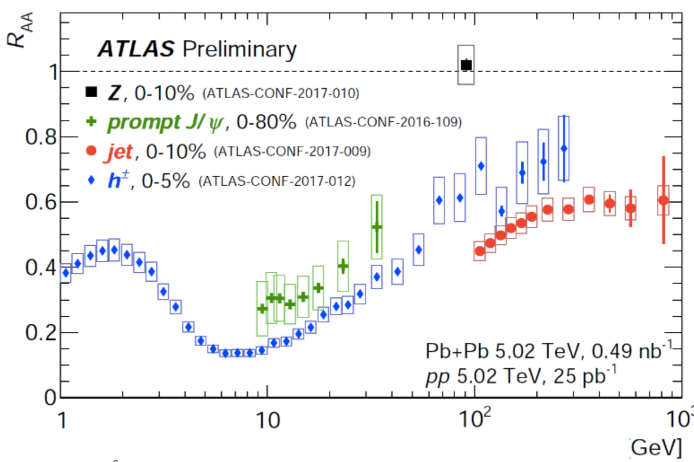
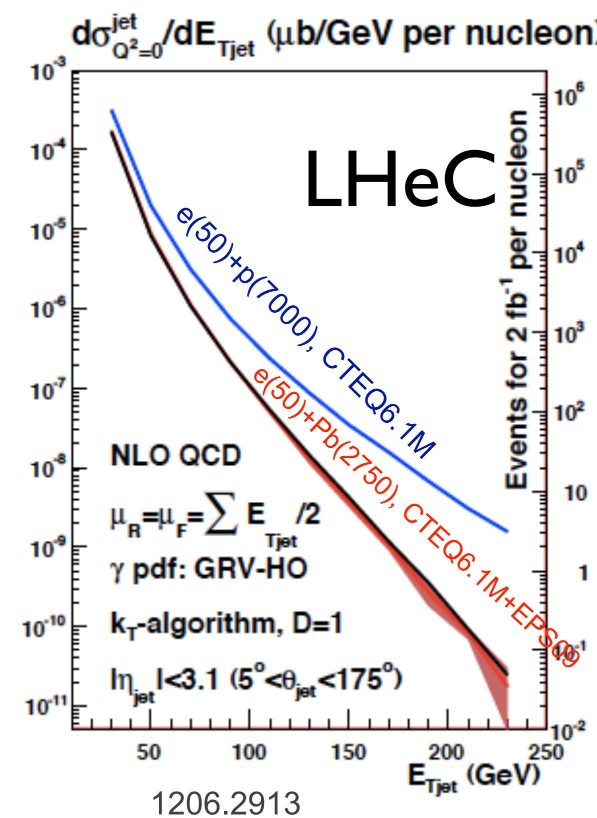


HP will be abundantly produced in eA colliders up to sizable E_T … at least for LHeC.

They can be used to test factorisation and for precision studies QCD radiation in the nuclear environment.



1206.2913

Conclusions

ep/eA colliders offer huge possibilities not yet fully exploited:

- To provide most interesting information about QCD on their own:
  - partonic structure
  - new regimes of QCD
  - transverse structure of hadrons and nuclei
  - particle production and correlations

- To clarify aspects of pp, pA and AA collisions at high energy:
  - initial conditions for macroscopic descriptions
  - nature of collectivity
  - uncertainties in the extraction of parameters of the QCD

Pasquale Di Nezza

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  - initial conditions for macroscopic descriptions
  - nature of collectivity
  - uncertainties in the extraction of parameters of the QCD

> For these and other reasons, ep and eA colliders would be highly desirable …but pay attention at the energy scale

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