GLUON SATURATION SEARCH AT $x<10^{-4}$

Not including CEP and UPC processes

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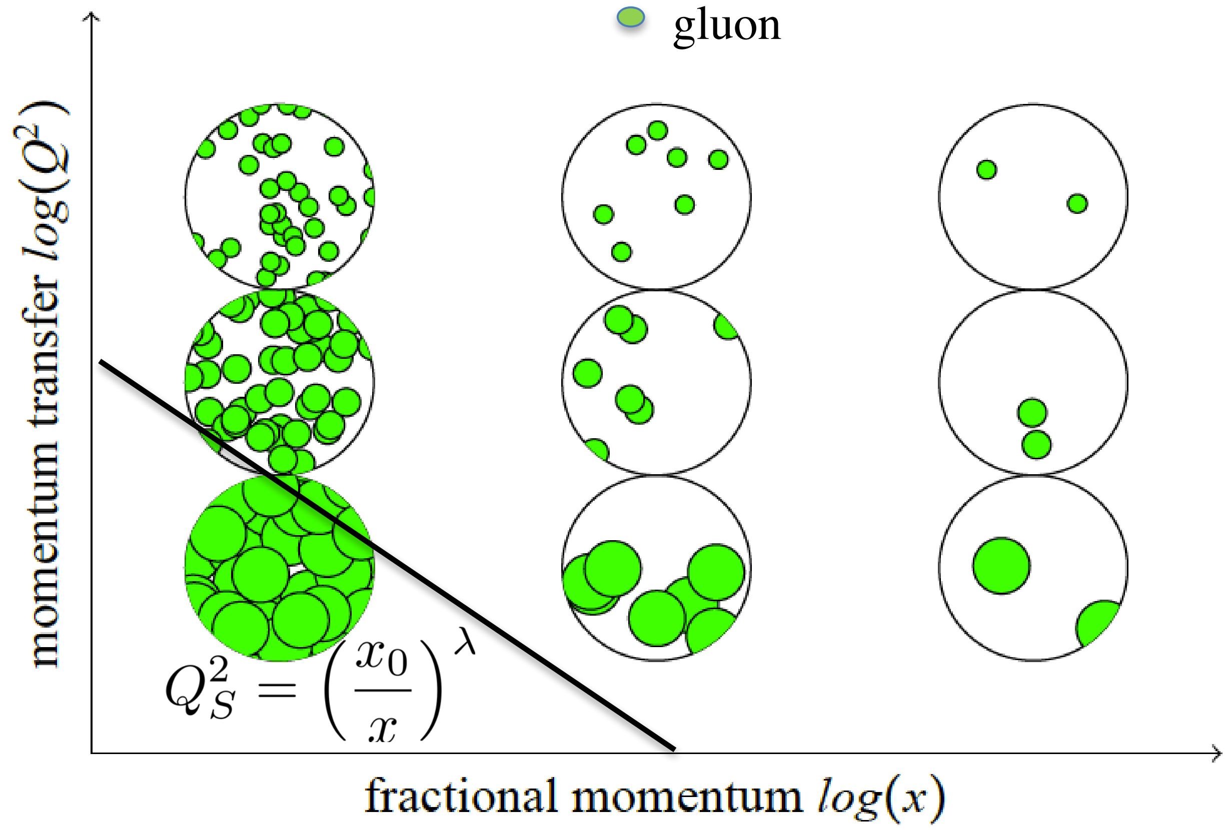
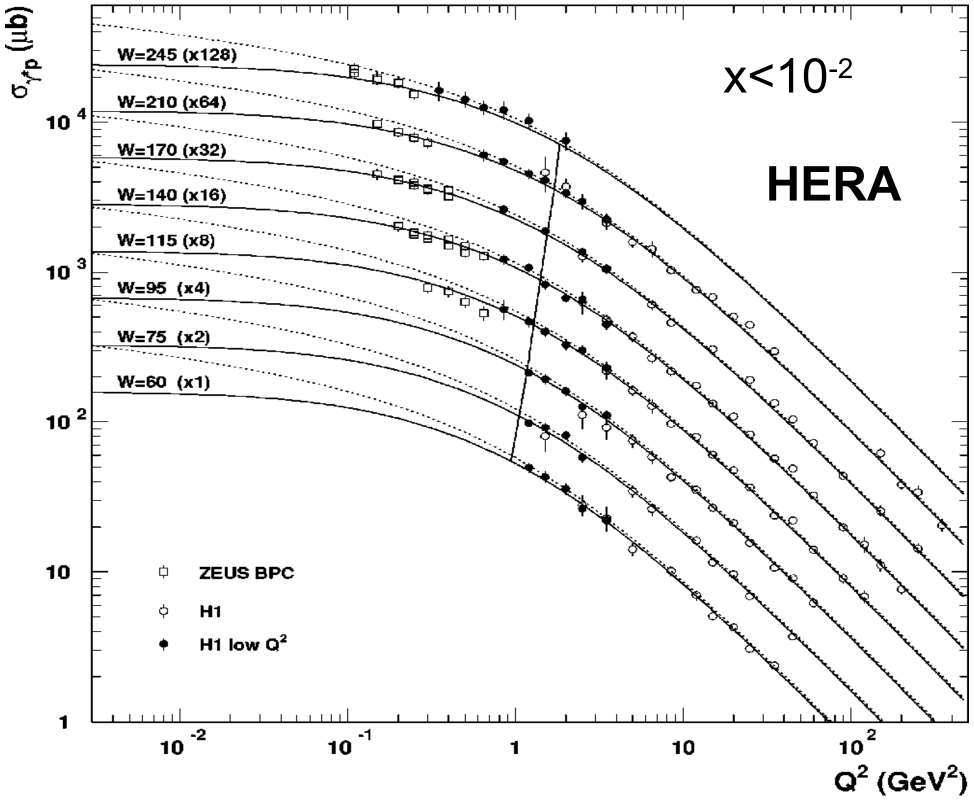
Supported by DOE/OS Early Career Program

SURGE Collaboration Meeting and Workshop
Brookhaven National Lab   June 28-30, 2023

Where Gluon Saturation is Expected ?



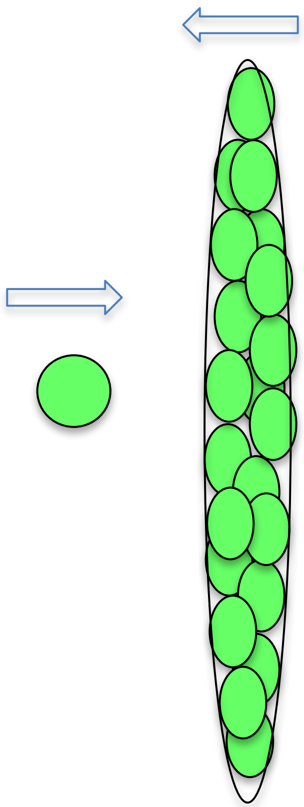
K. Golec-Biernat and M. Wüsthoff
*PR*D59, 014017(1998)



	σ_0 (mb)	λ	x_0	χ^2/(no.exp.po.)
No charm	23.03	0.288	3.04×10^{-4}	441/372=1.18
With charm	29.12	0.277	0.41×10^{-4}	558/372=1.50

x_0 and λ determined from DIS data fits.

Gluon Saturation in p+A Collisions



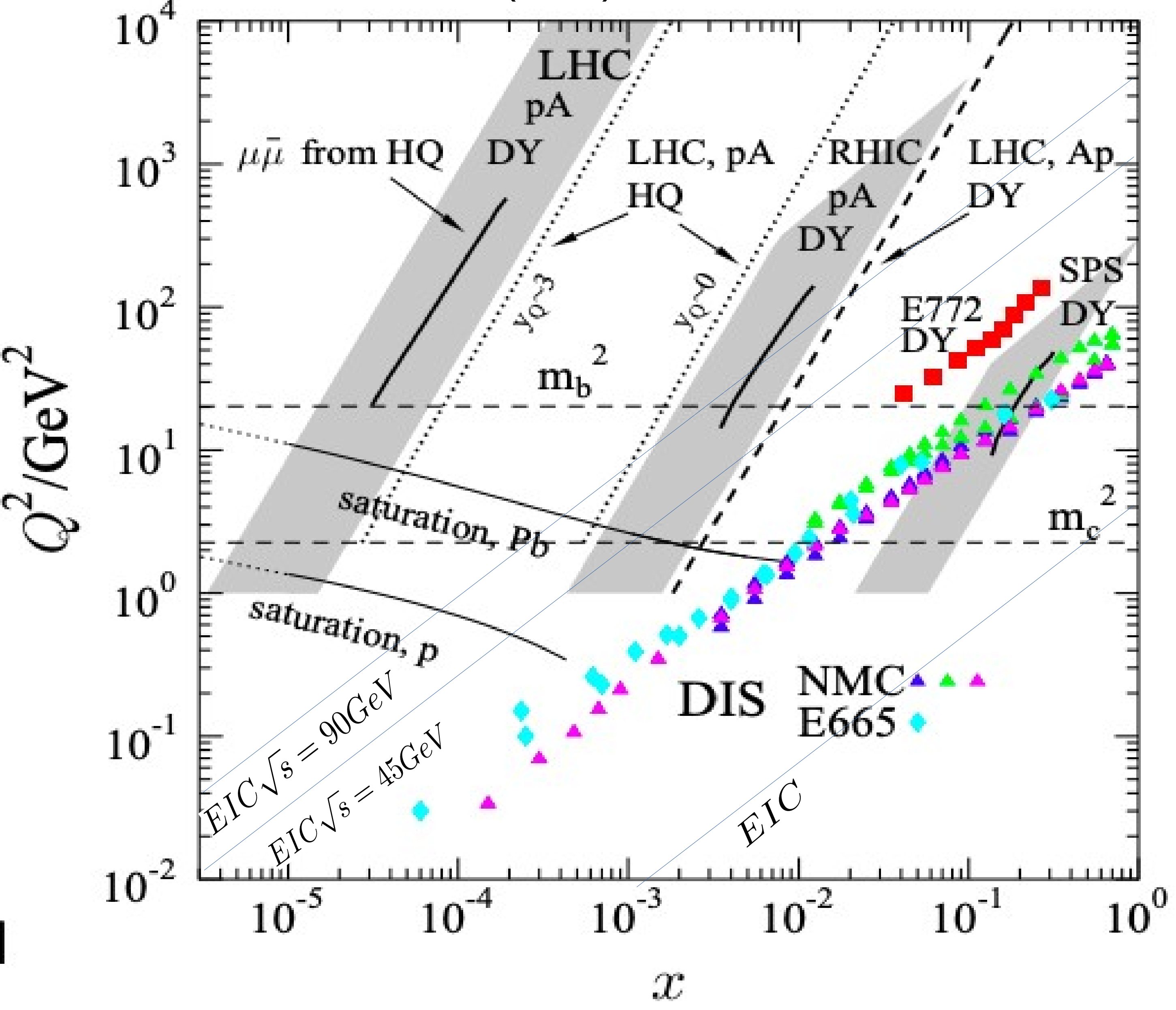
Gluon density is enhanced by the Lorentz contraction of the nucleus at the probe rest frame.

$$Q^2_{S,A} \propto A^{1/3} Q^2_{S,p}$$

Saturation scale would be seen at a x and Q2 smaller than in pp collisions.

H. Kowalski, T. Lappi, and R. Venugopalan *PRL*100, 022303 (2008)

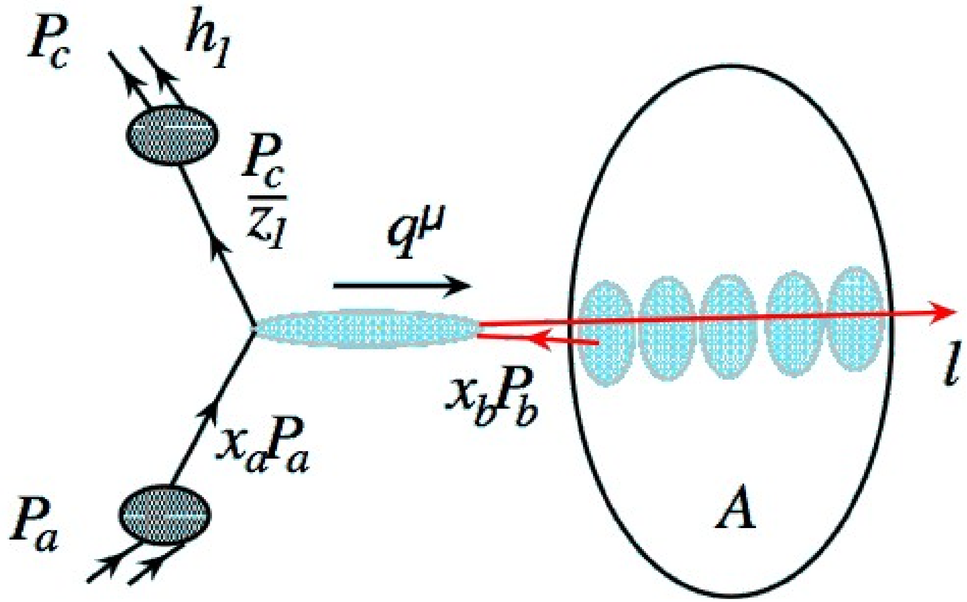
Armesto (2006) arXiv:0604108



Forward rapidity detectors at LHC using pPb data are at the right spot to observe gluon saturation using perturbative processes.

Competing Nuclear Effects

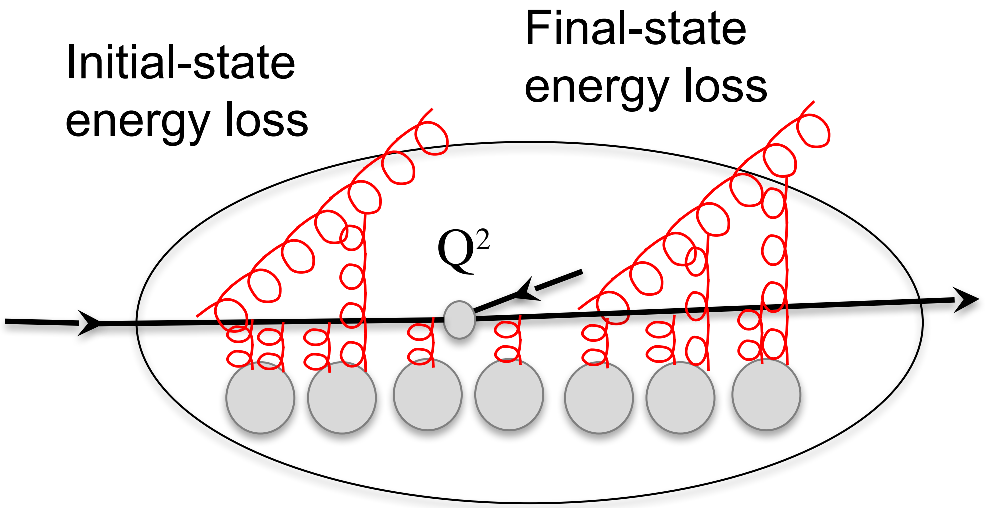
Coherent Multiple interactions



The probe is larger than the contracted nucleon in the nucleus.

Causes a yield/nucleon reduction at small-x (shadowing).

Energy Loss



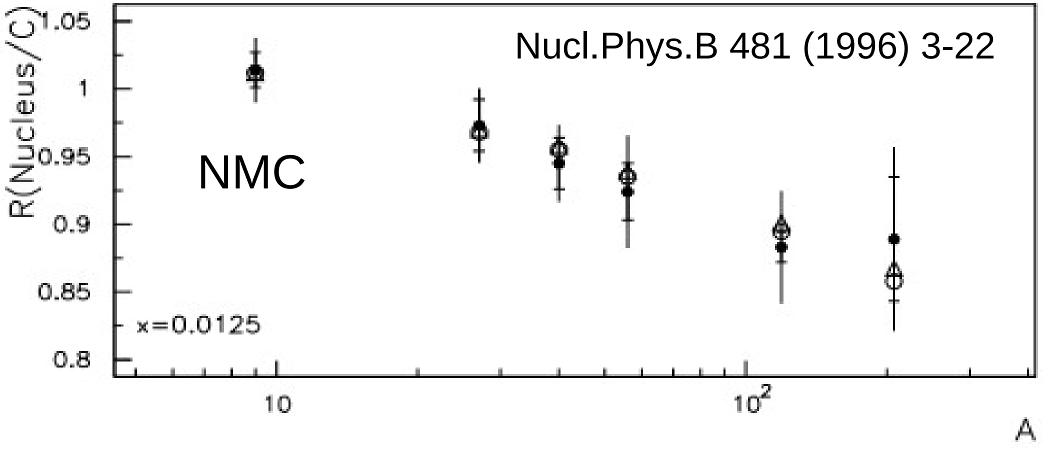
The probe loses energy before the hard scattering.

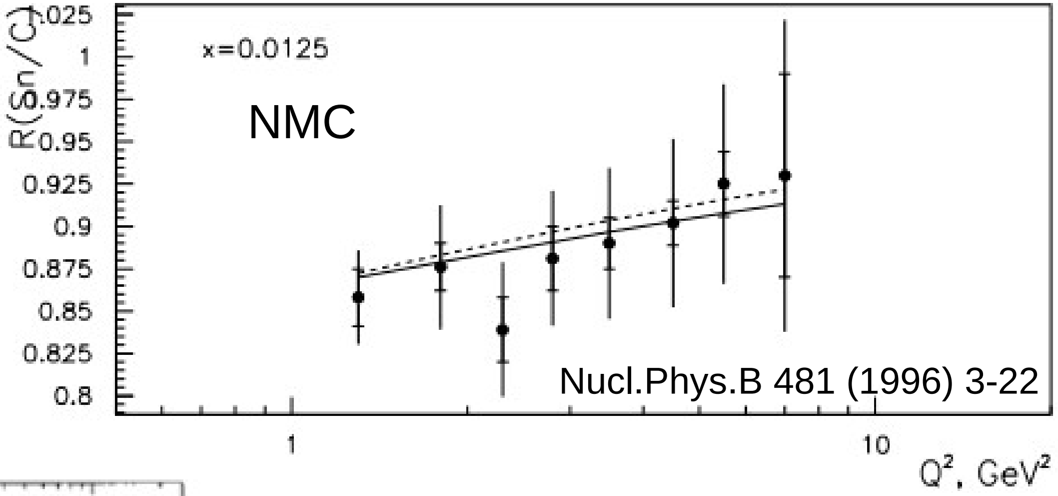
The scattering products lose energy in the medium.

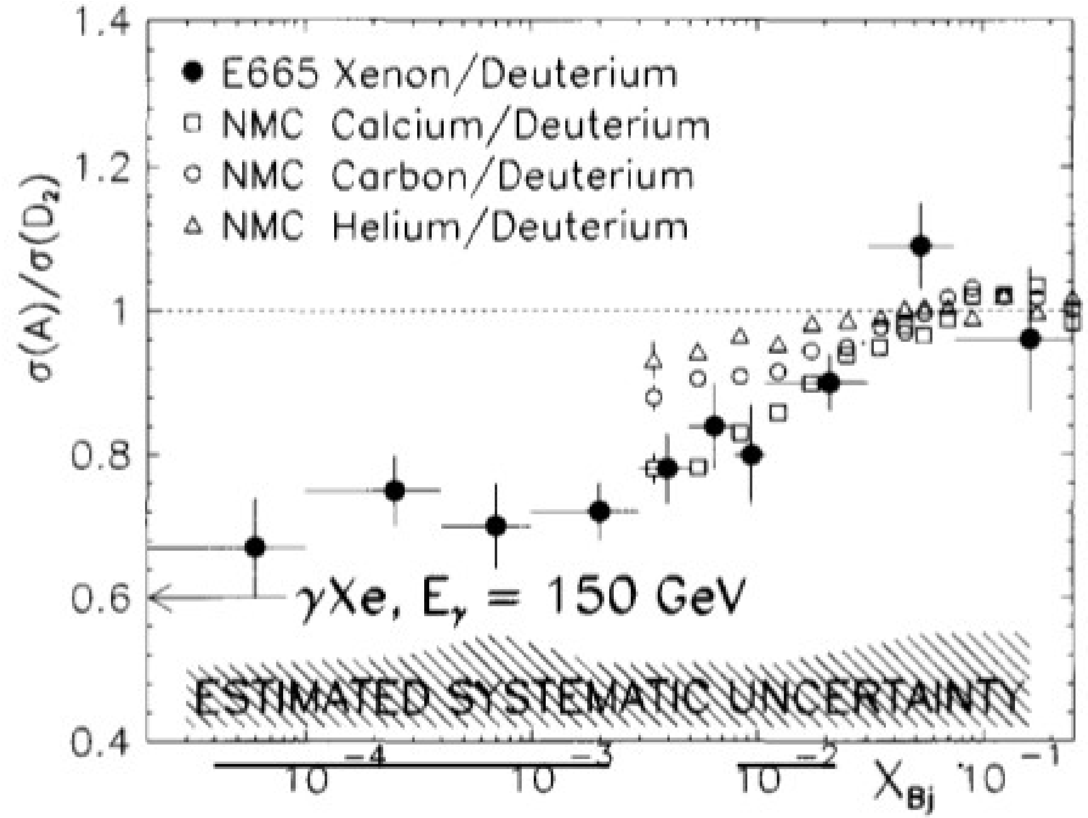
Causes yield/nucleon reduction.

Review of initial state effects can be found in Nucl.Phys.A 972, 18, 2018

Early Measurements







E665: Phys.Rev Lett 42, 553 (1979)

NMC: Nucl.Phys.B 441, 3-11 (1995)

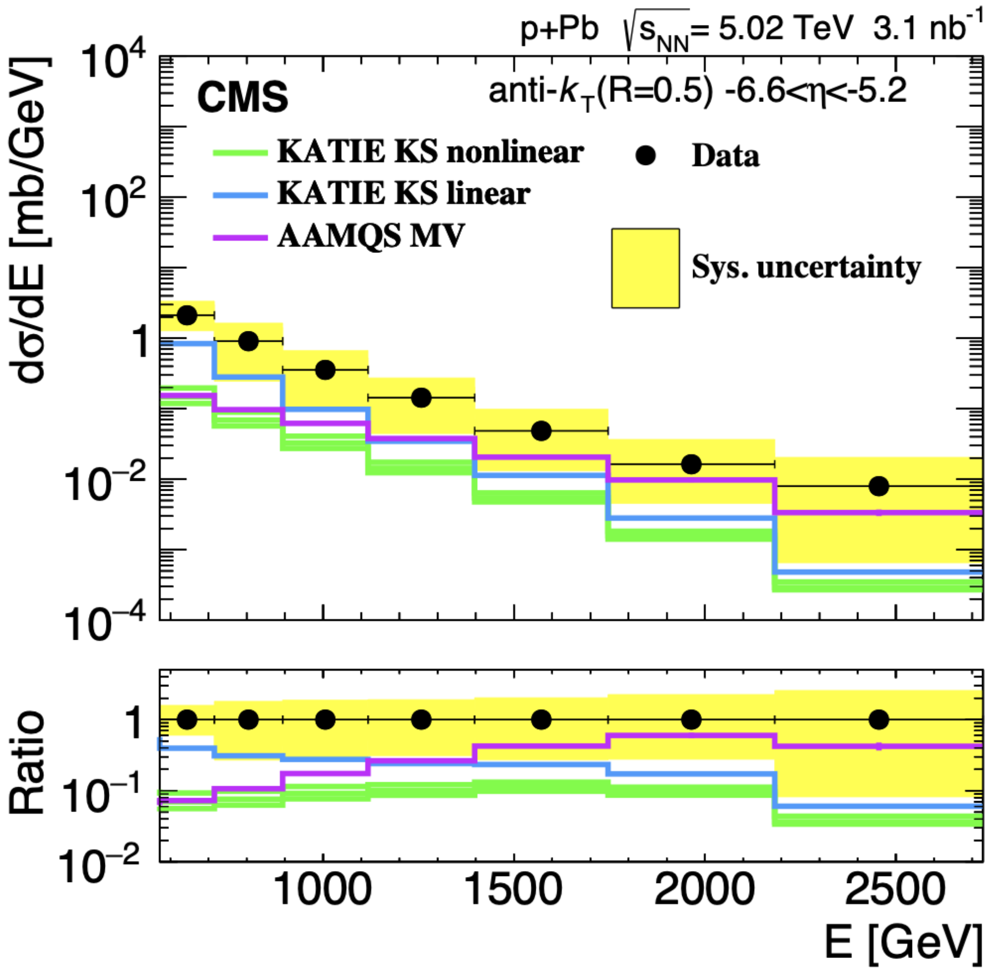
E665 (FNAL): hadron photoproduction

NMC (SPS): muon DIS

Jet probes in pPb

Forward jets in CMS

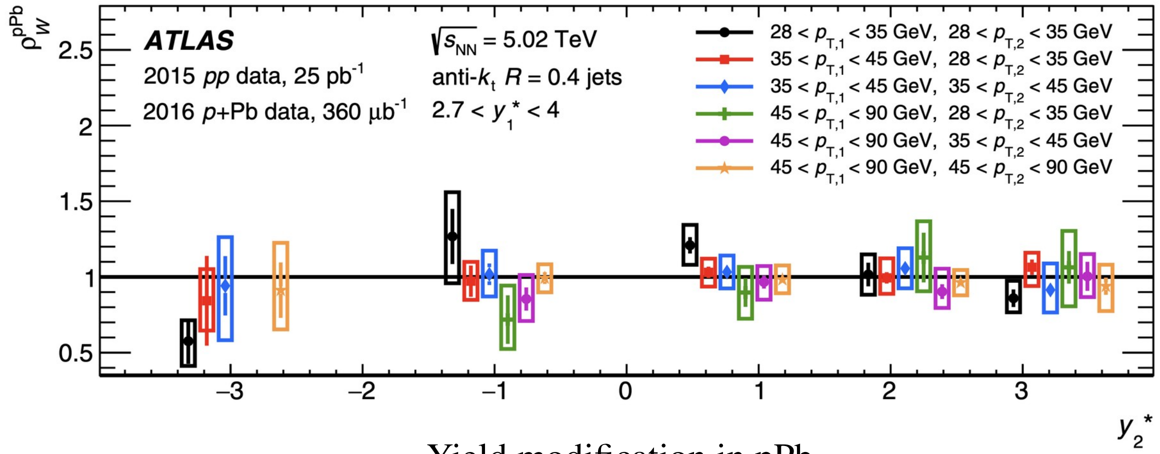
JHEP 05 (2019) 043



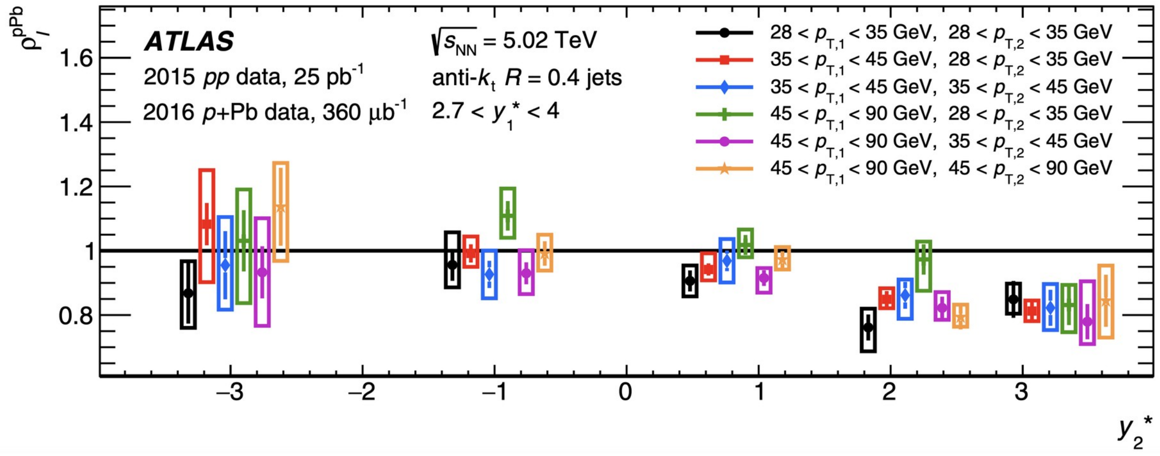
Dijets in ATLAS

PRC **100**, 034903 (2019)

Azimuthal angular correlation modification in pPb



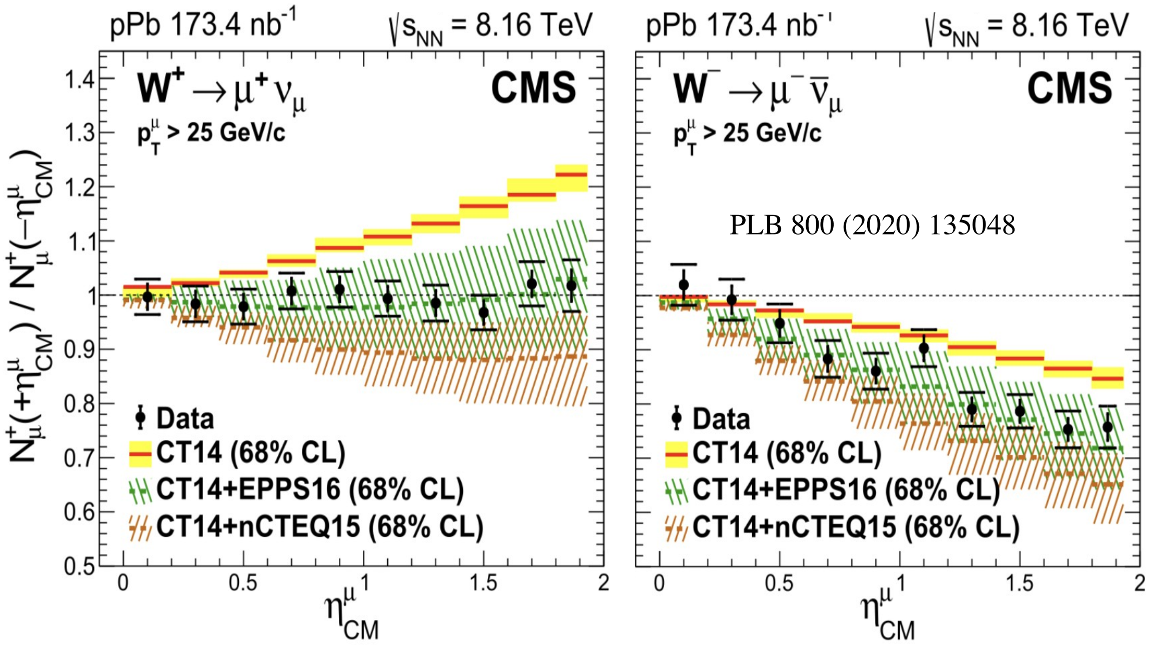
Yield modification in pPb



Modest nuclear modification at small-x and large Q^2

Electroweak Probes in pPb

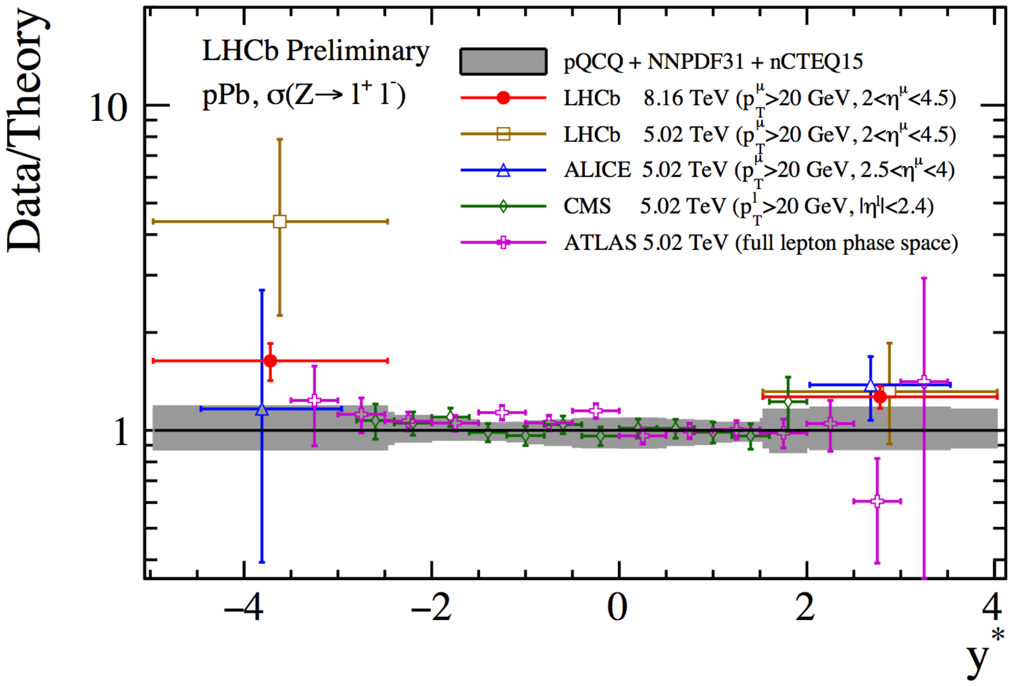
Los Alamos NATIONAL LABORATORY



W bosons accounts for iso-spin effects

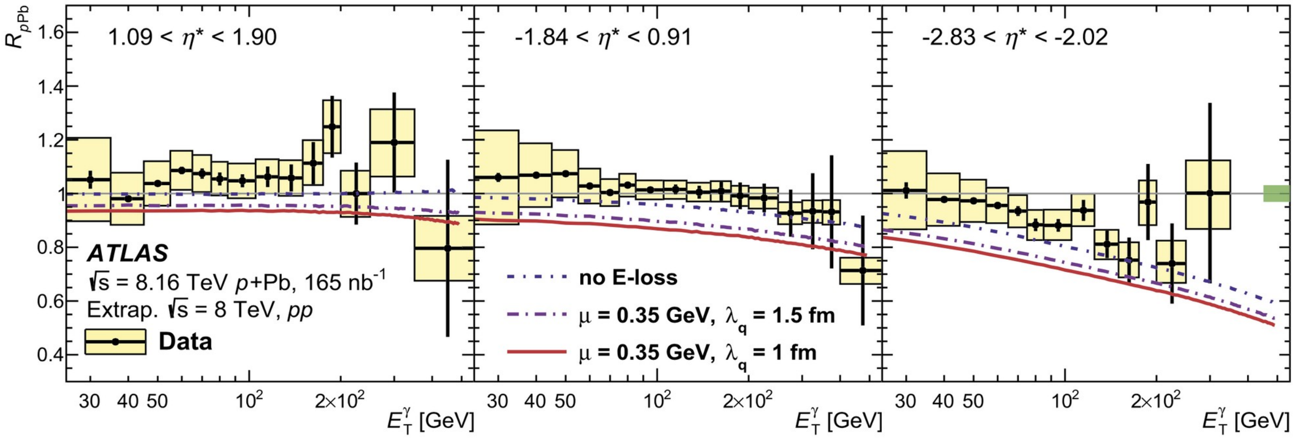
Z bosons

【LHCb-CONF-2019-003】



High-pT prompt photon in ATLAS

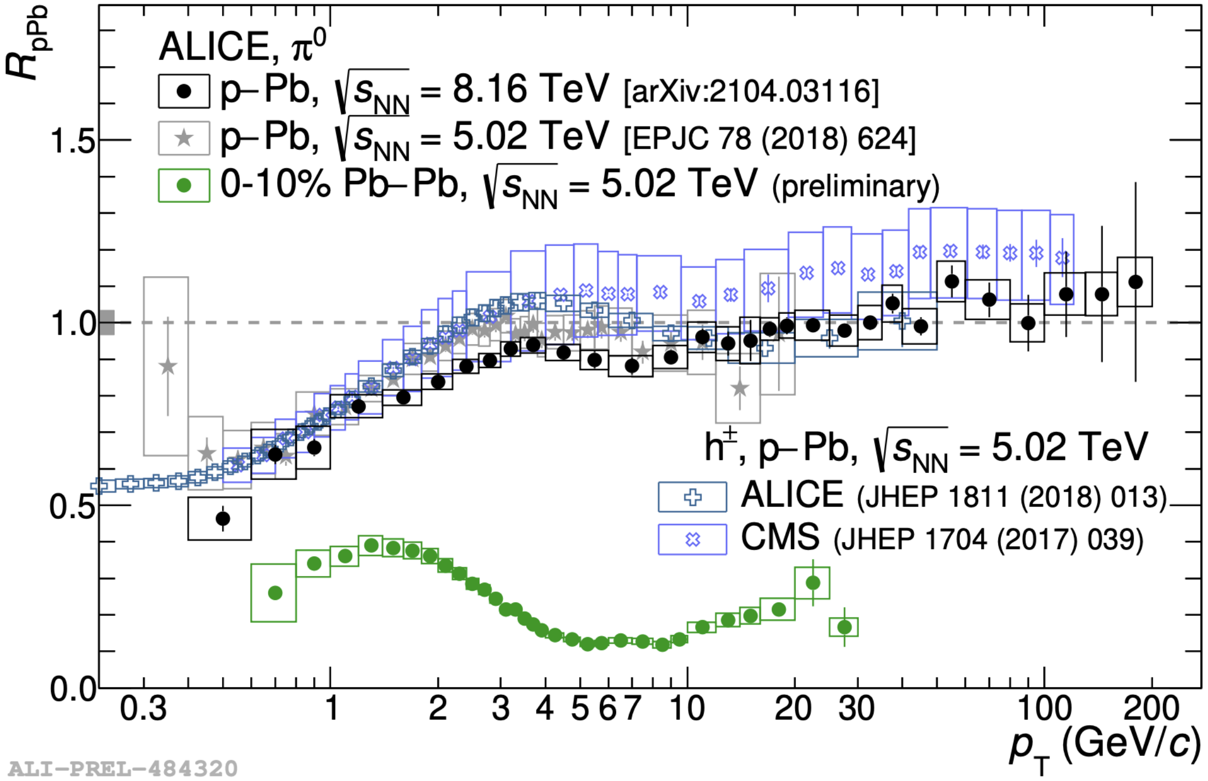
PLB 796, 230 (2019)

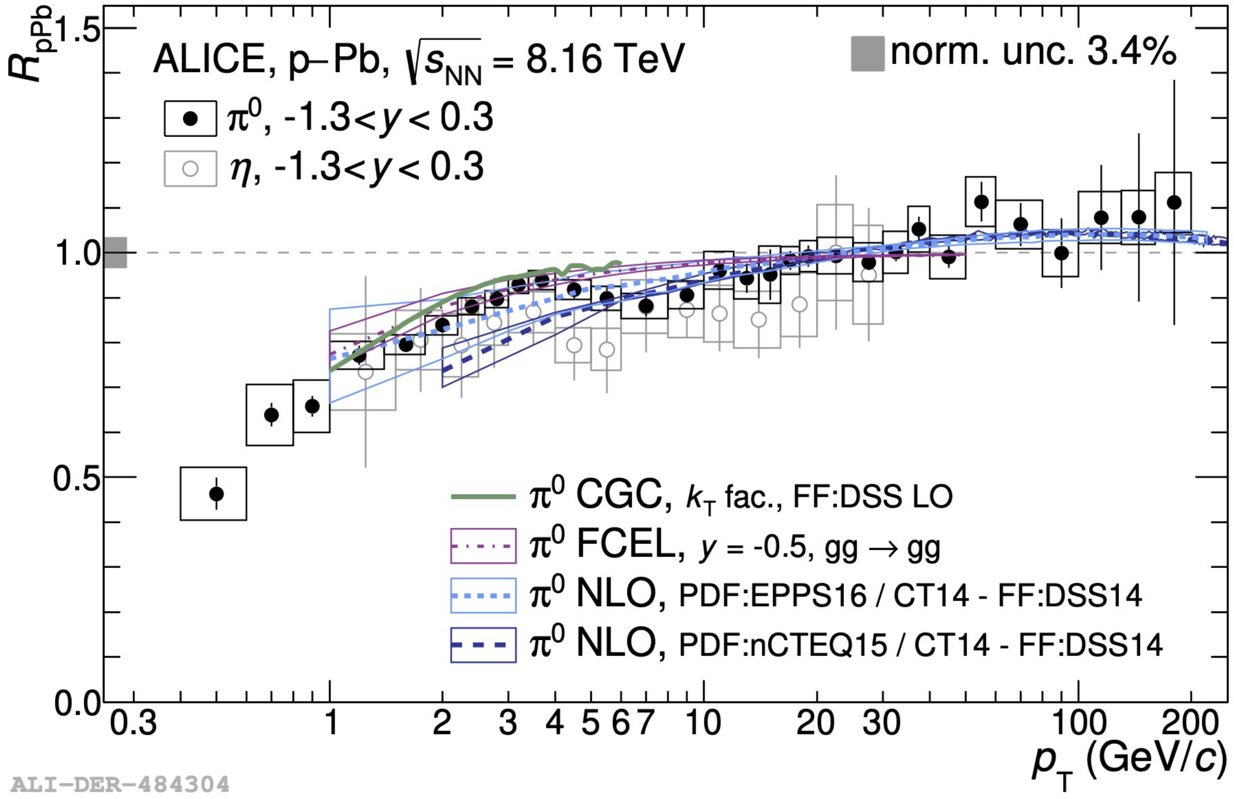


Covering high Q^2

Mostly modest or no CNM effects.

Mid-rapidity charged particles and neutrals in pPb





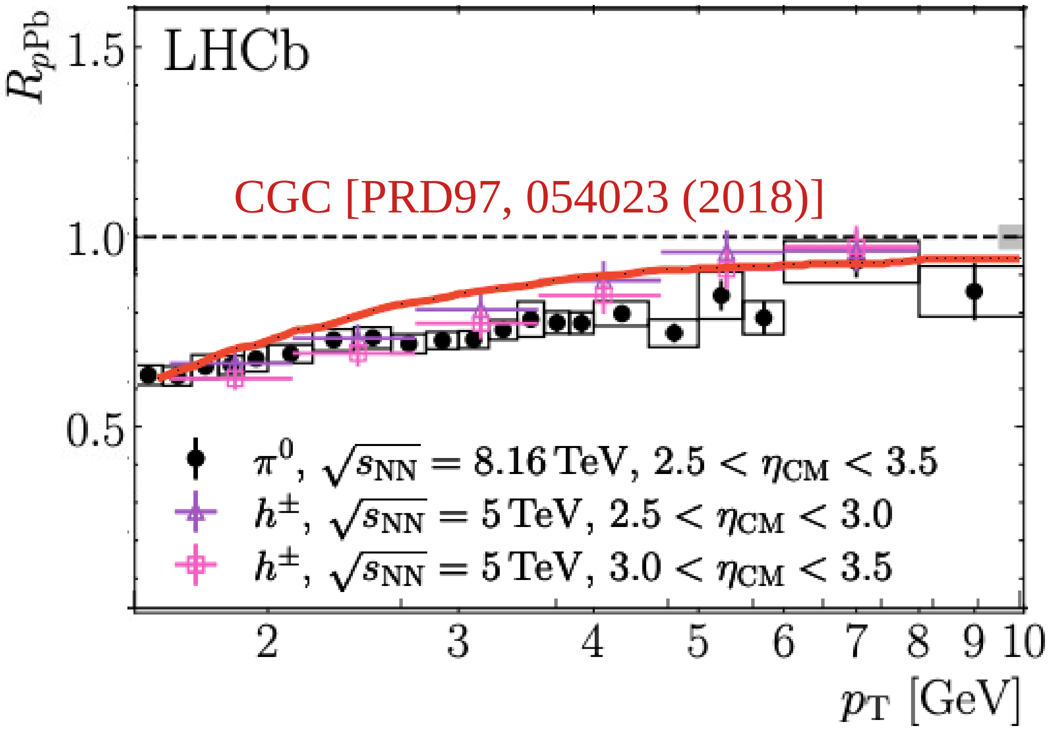
arXiv:2104:03116

Systematic observation of suppression at p_T<2 GeV/c.

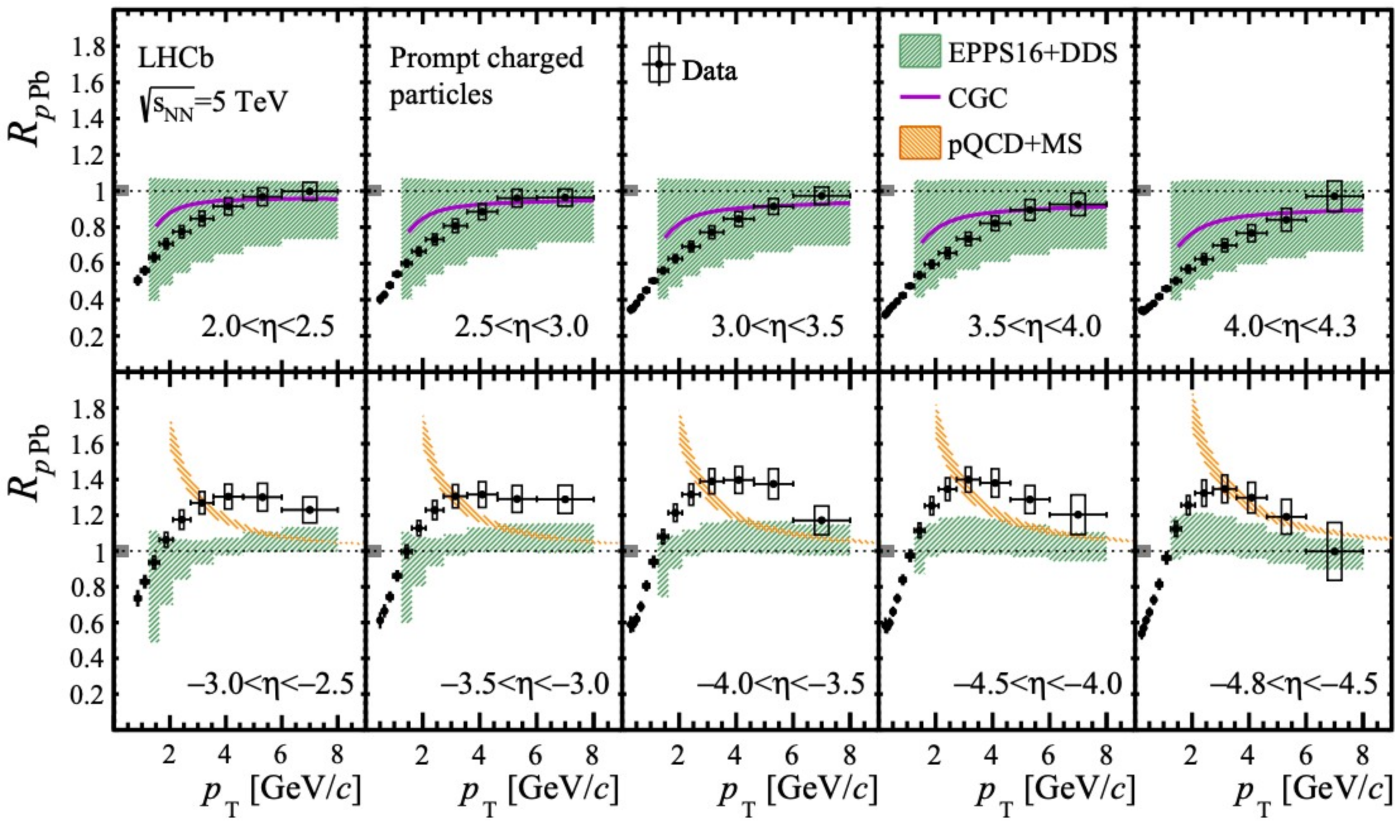
Contrast with Cronin effect observed in PbPb collisions.

Forward charged particles and neutrals in pPb

arXiv:2204.10608



PRL 128 (2022), 142004



Pion average fragmentation fraction z~0.2.

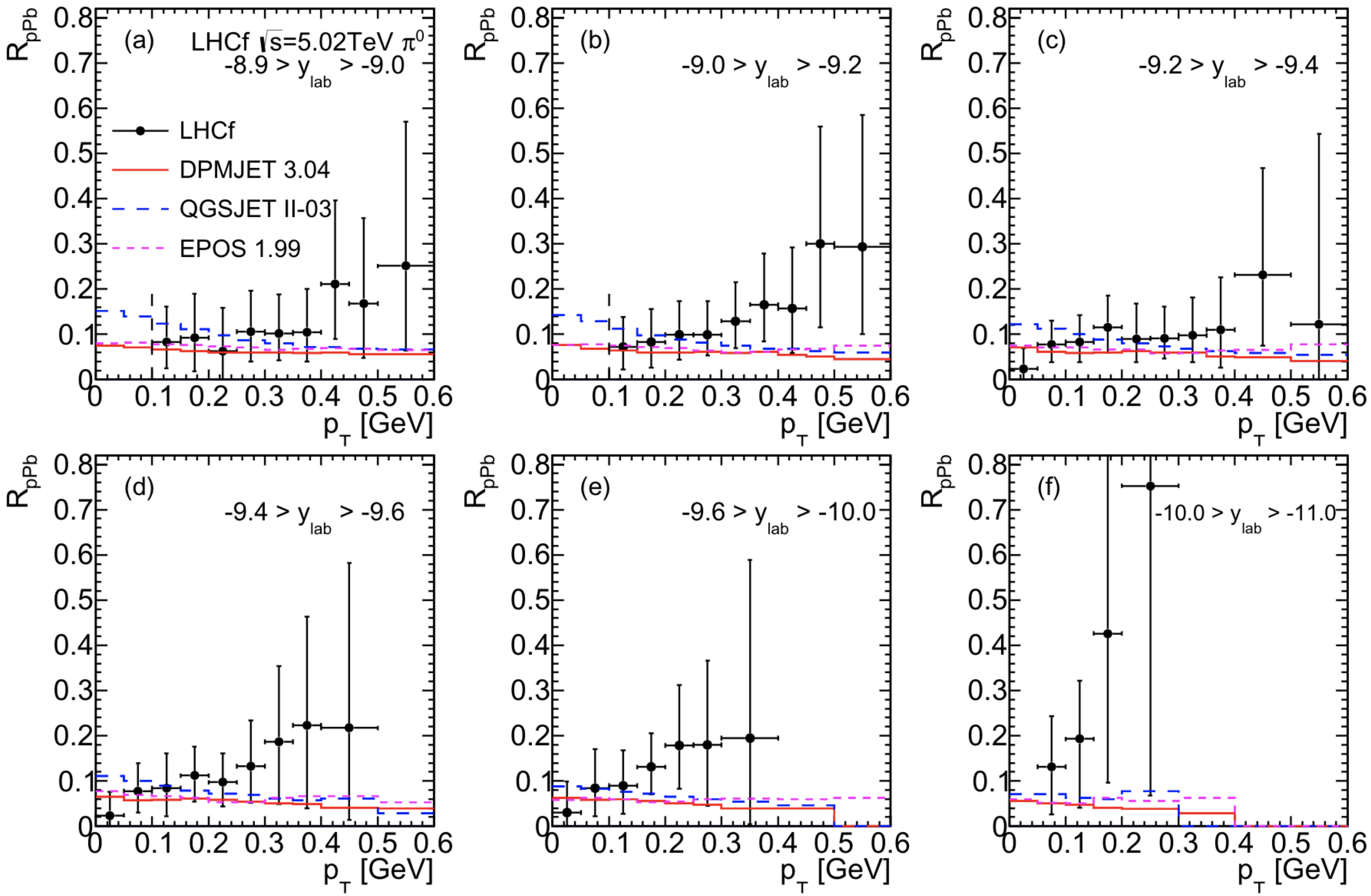
An 1 GeV/c pion may come from a Q^2>20 GeV jet.

The smallest x measured by LHCf

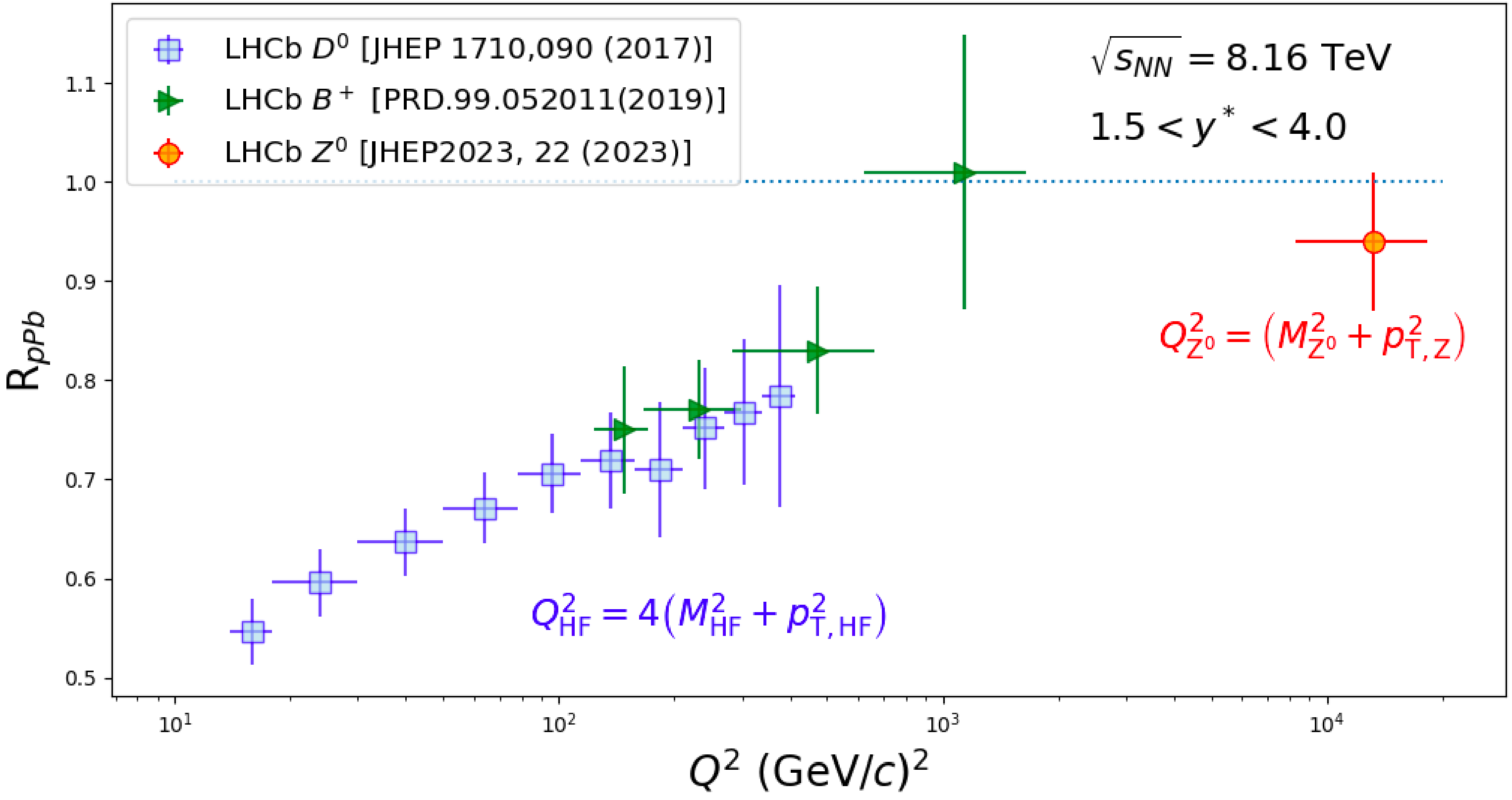
Phys. Rev. C 89 (2014) 065209.

Detector in the p direction.
Very forward rapidity.

$$Q^2 < 1 GeV^2$$
$$5 \cdot 10^{-10} < x < 1.7 \cdot 10^{-8}$$



Hard Probes R_{pA} scaling in pPb



Forward suppression scales with the momentum transferred in the process.

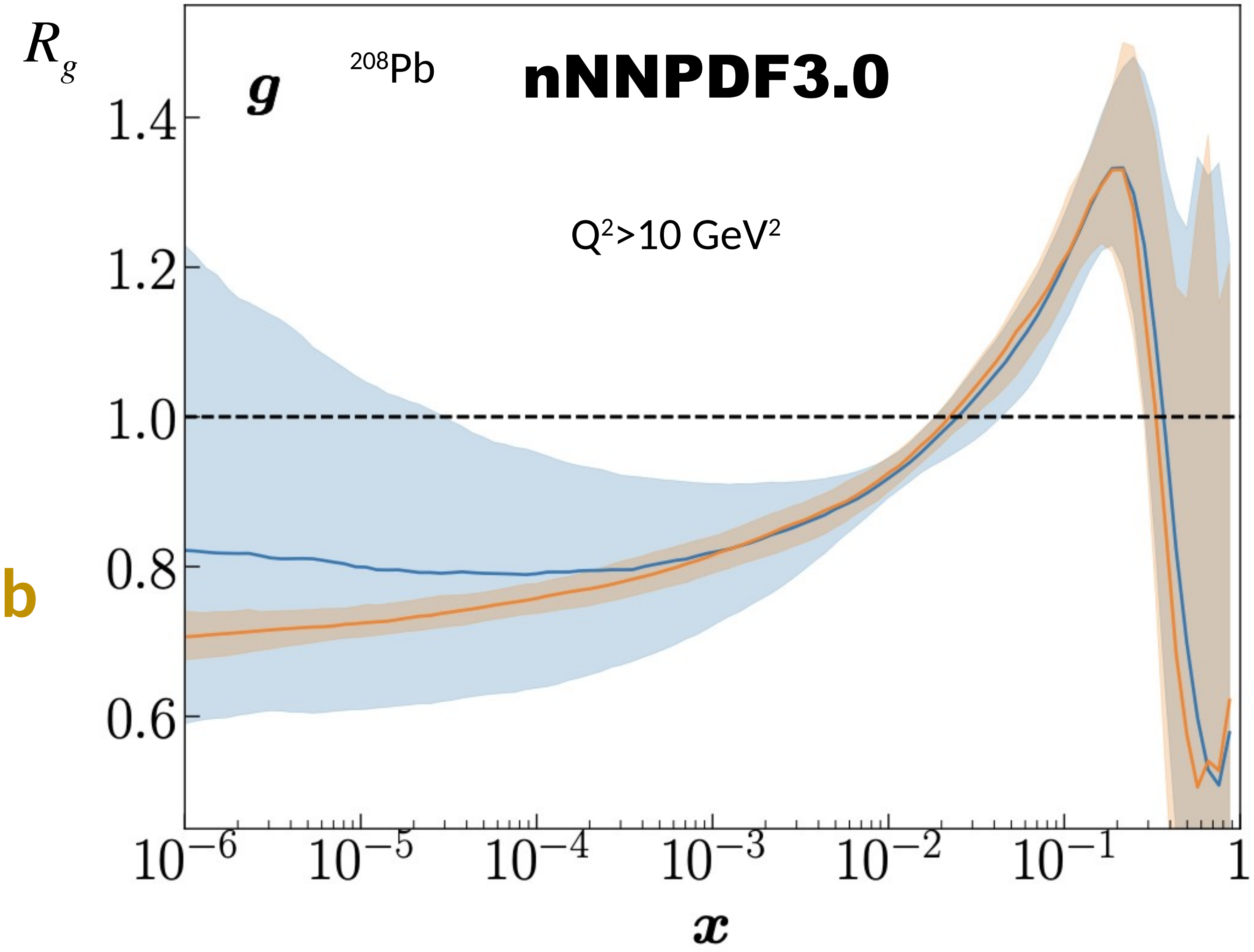
Keep in mind that the x range coverage changes with Q^2.

Isospin effect may prevent R_{pA}=1 at high Q^2.

Not at the expected gluon saturation region Q^2< 10 GeV^2

Impact of the LHCb D^0 measurements in pPb and Pbp

arXiv:2201.12363

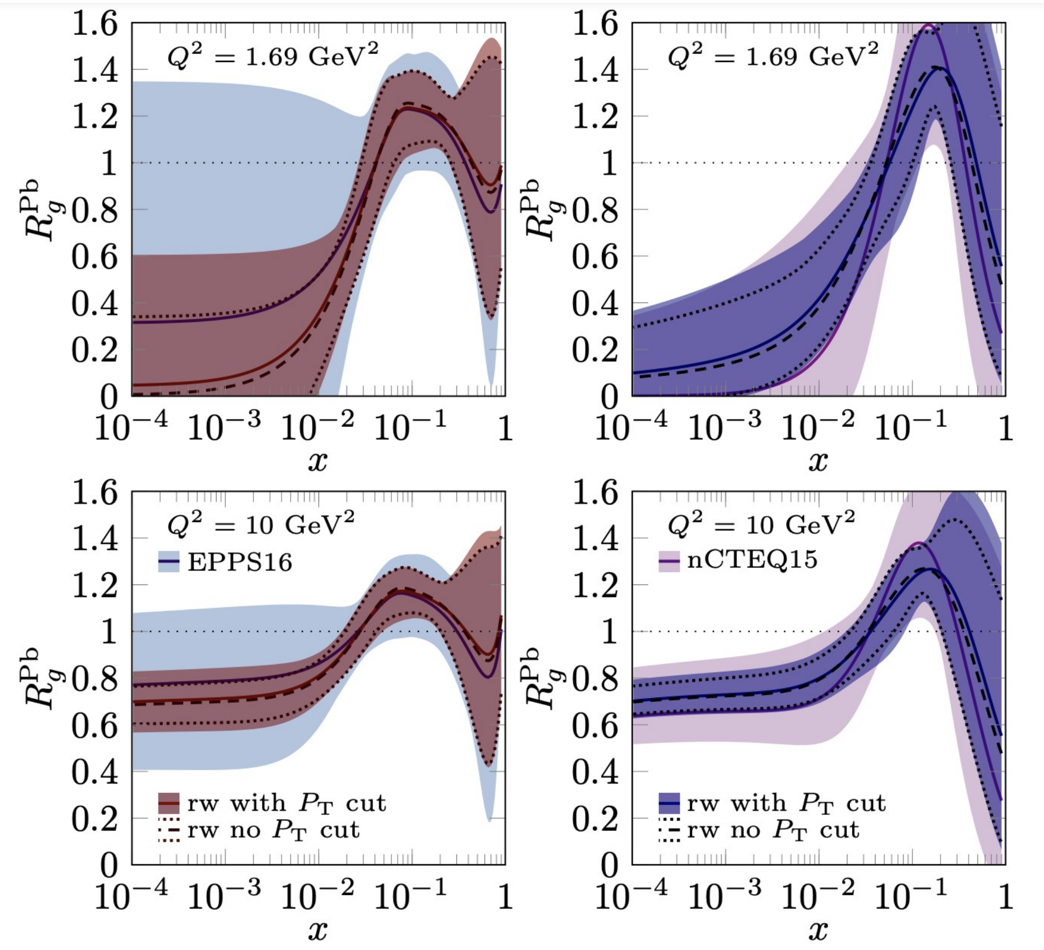


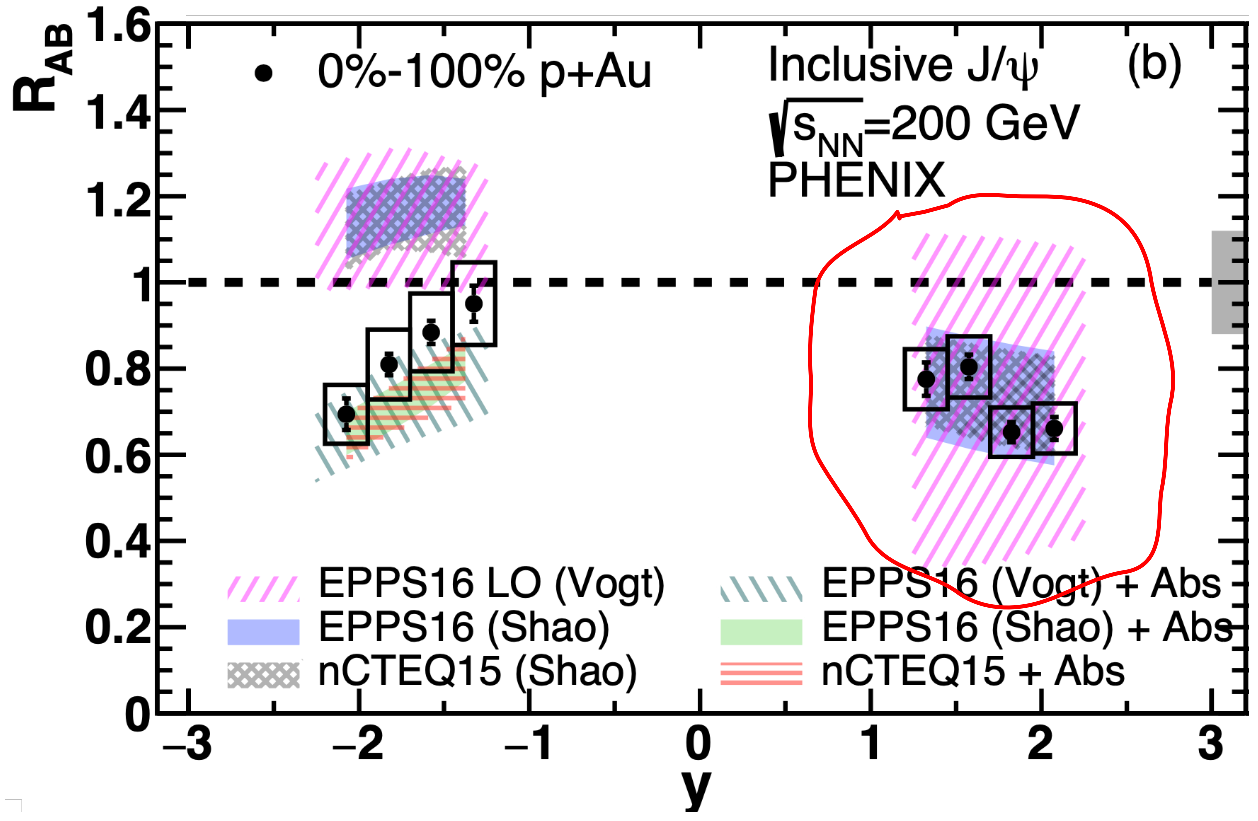
adding LHCb D^0 in pPb

Large uncertainties at small-x are gone for Q^2>10 GeV^2 !!!

nPDF Universality

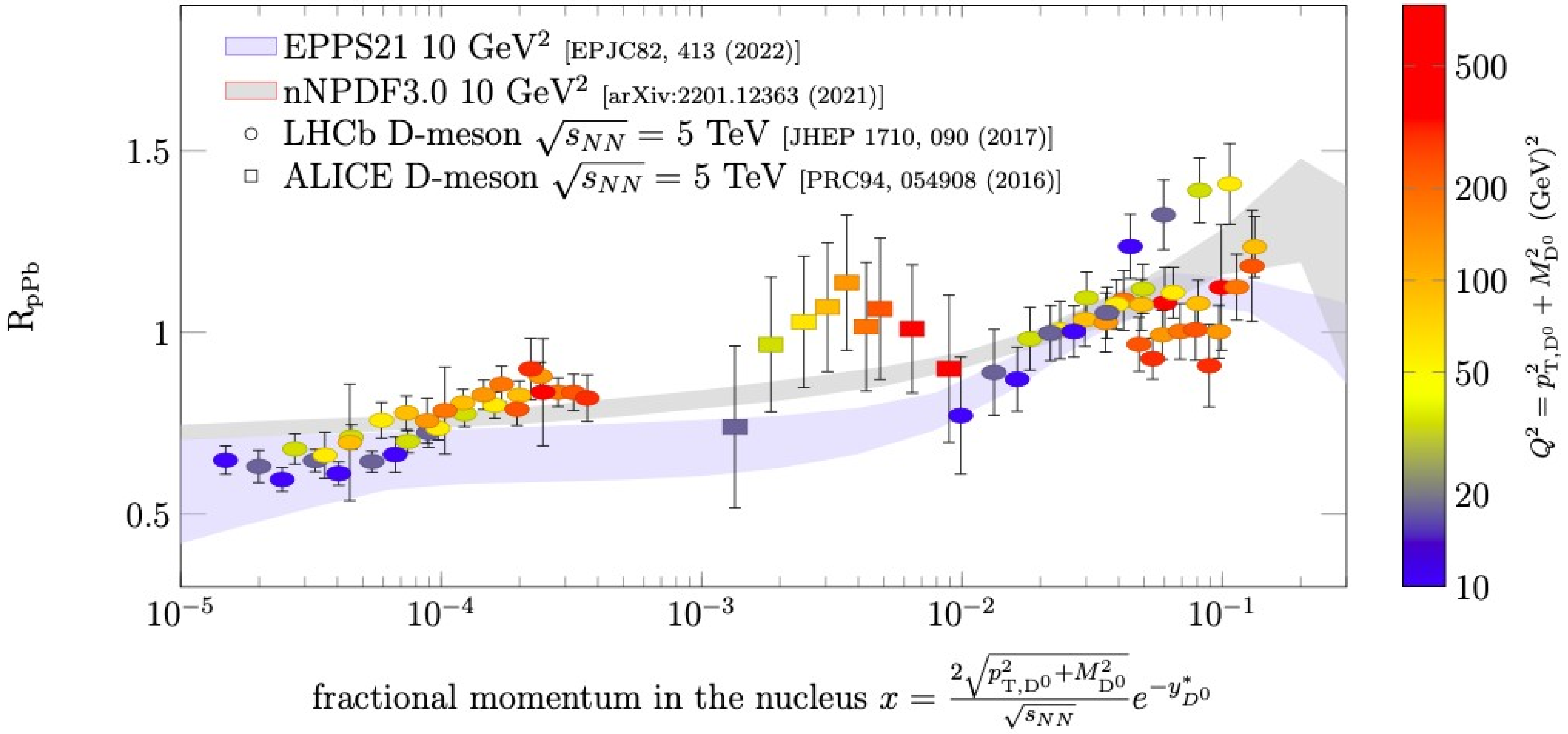
JHEP 05, 037 (2020)

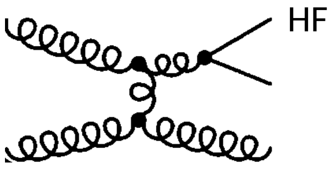




- nPDF constrained by LHC data (EPPS16-Shao) describes RHIC J/psi data at forward rapidity.

D-meson nuclear modification in pPb and Pbp collisions



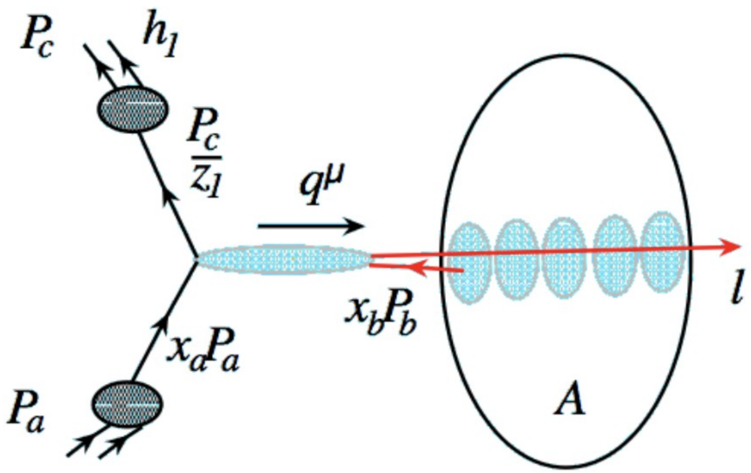


CAVEAT : x is an approximation given that most of heavy flavor are produce from gluon splitting in LHC

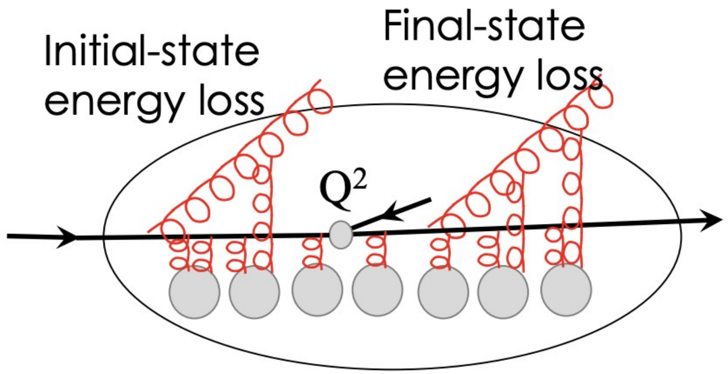
EPPS21 based on DGLAP evolution, may not be valid in a non-lineal gluon saturated regime

HOW TO ISOLATED SATURATION EFFECTS ?

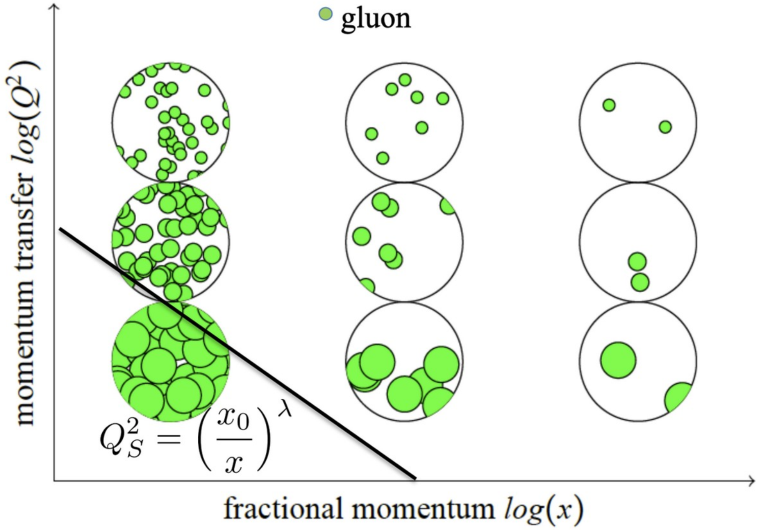
Multiple interactions



Energy Loss



Gluon Saturation



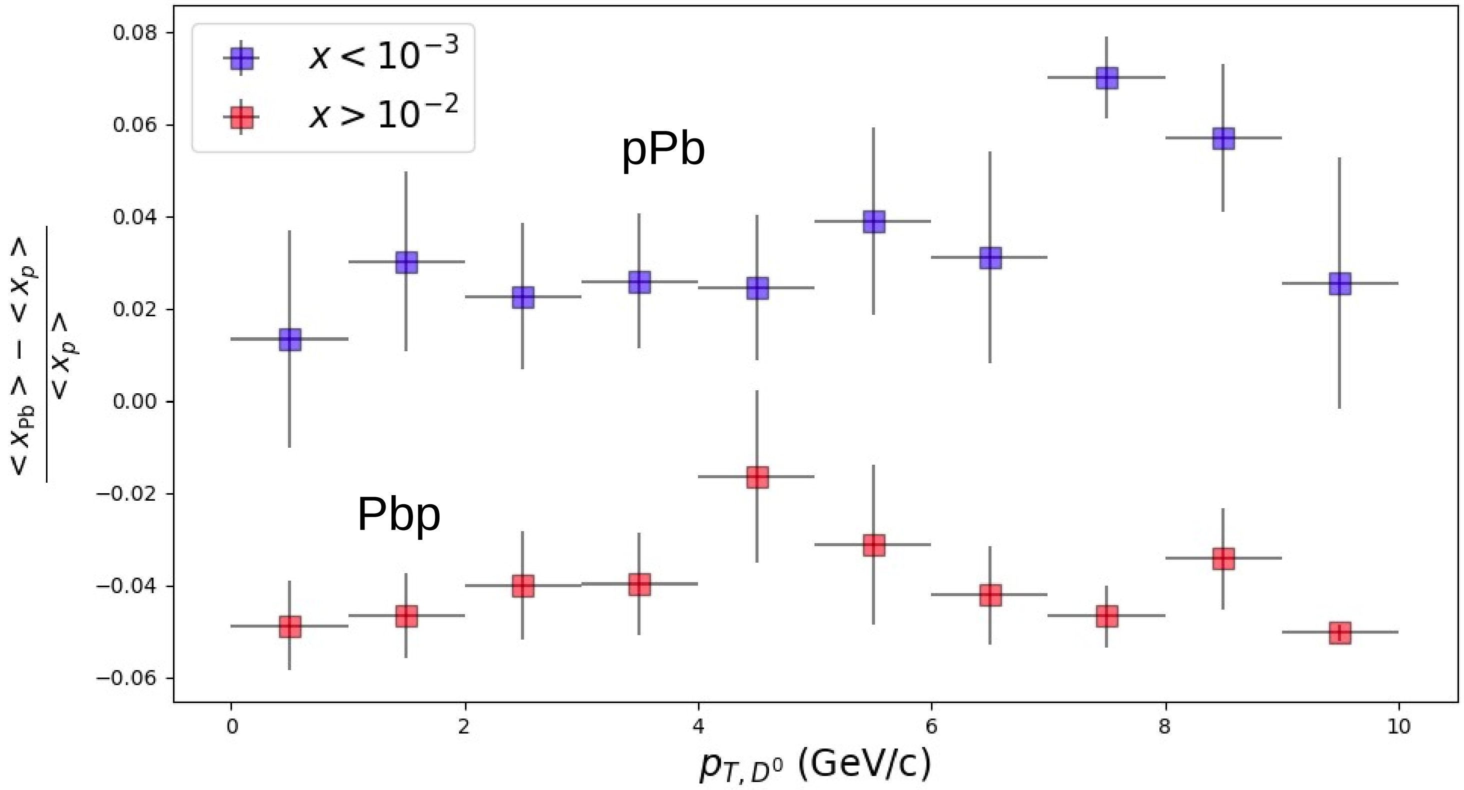
Suppression in nucleus caused by a shift in the gluon x

Suppression caused by the saturation of gluon density towards small-x in the nucleus

Important to measure in *x* for unambiguous interpretation of the gluon suppression.

x shift in D^0 yields

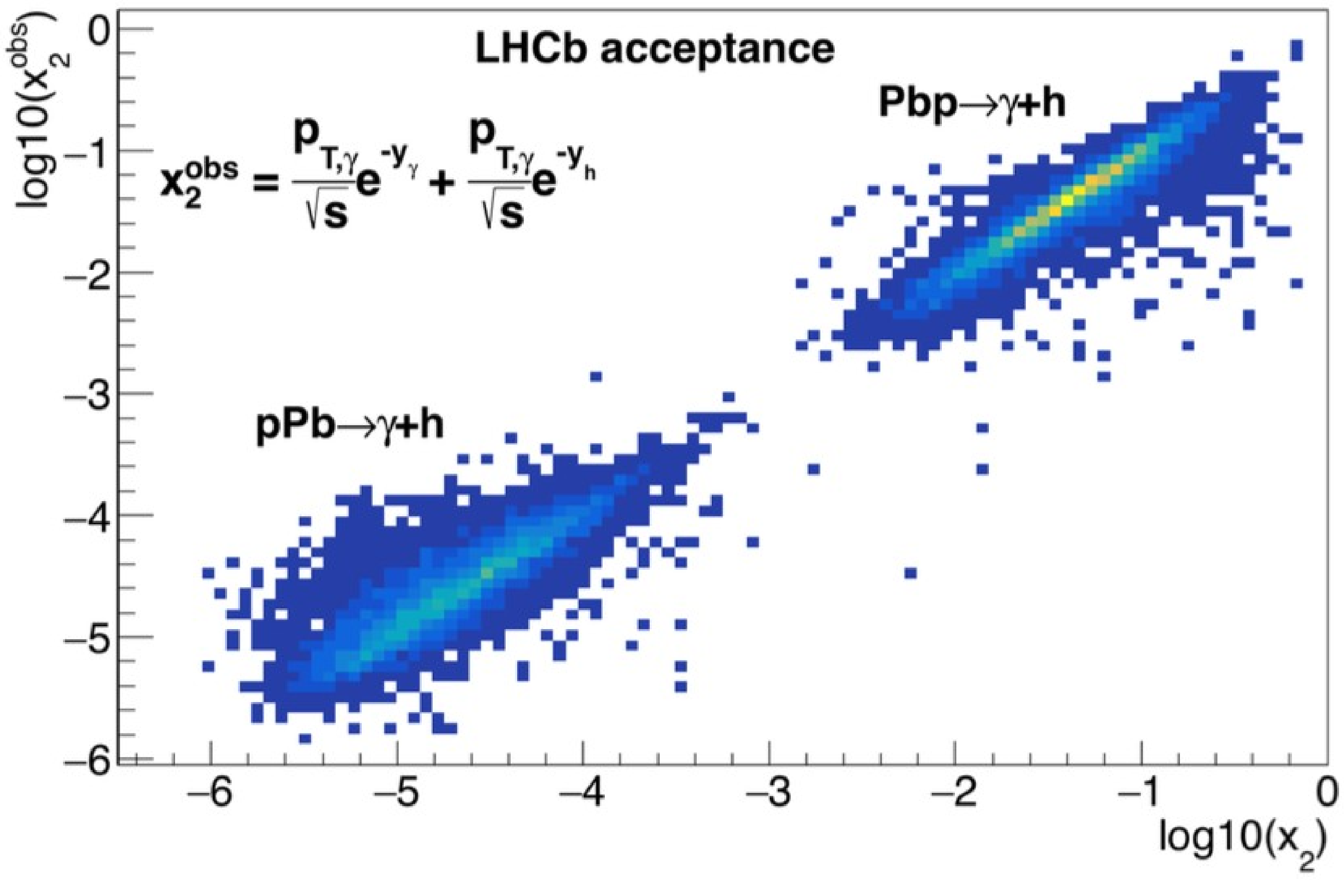
From D^0 yields measured by LHCb

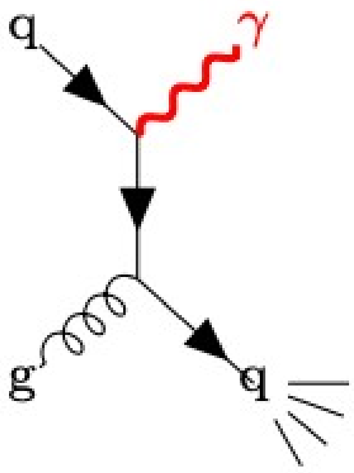


Another way to study sources of gluon suppression at small-x.

FUTURE PERSPECTIVES

Photon probes in pPb





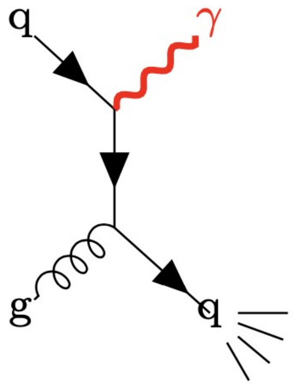
$$Q^2 \sim 2p_{T,\gamma}^2$$

Precise measurement of x in nucleus

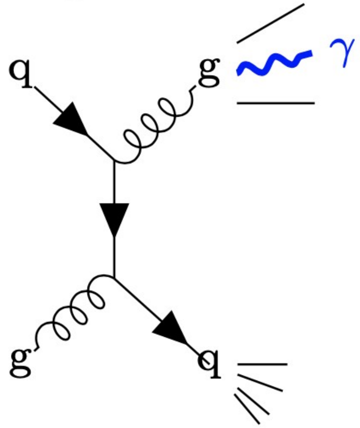
Can measure $Q^2 < 10\ GeV^2$ where shadowing and gluon saturation is favored.

Photon probes in pPb

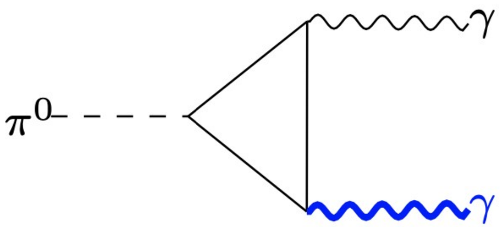
Compton or direct



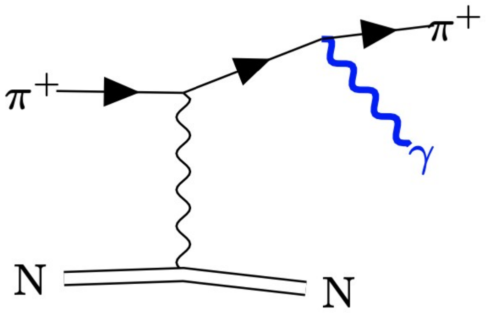
Fragmentation



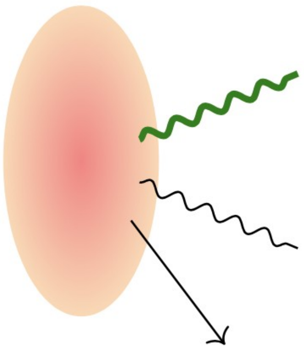
Neutral decays



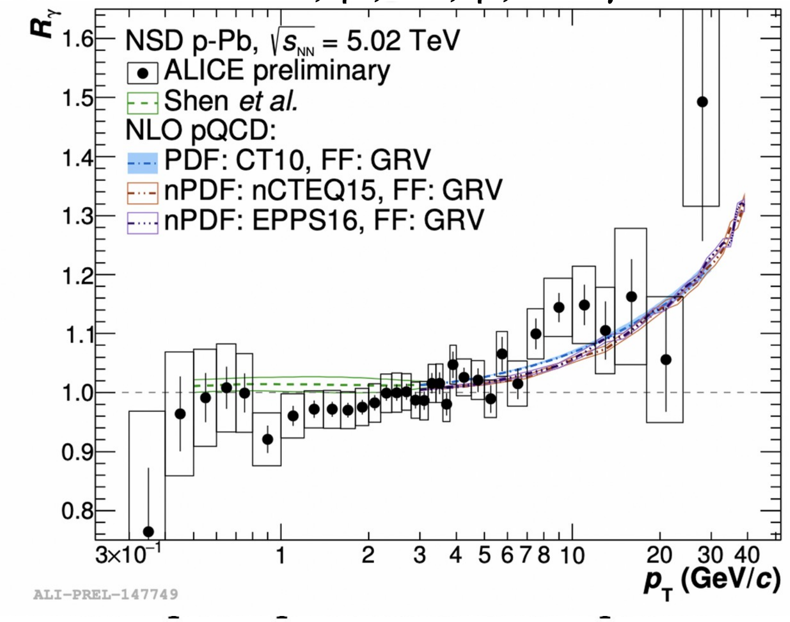
Bremsstrahlung



Thermal

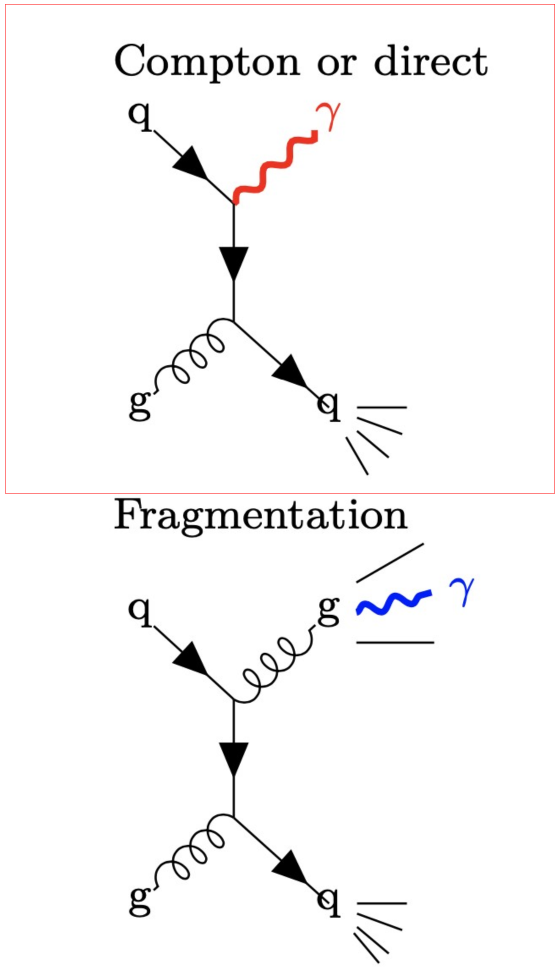


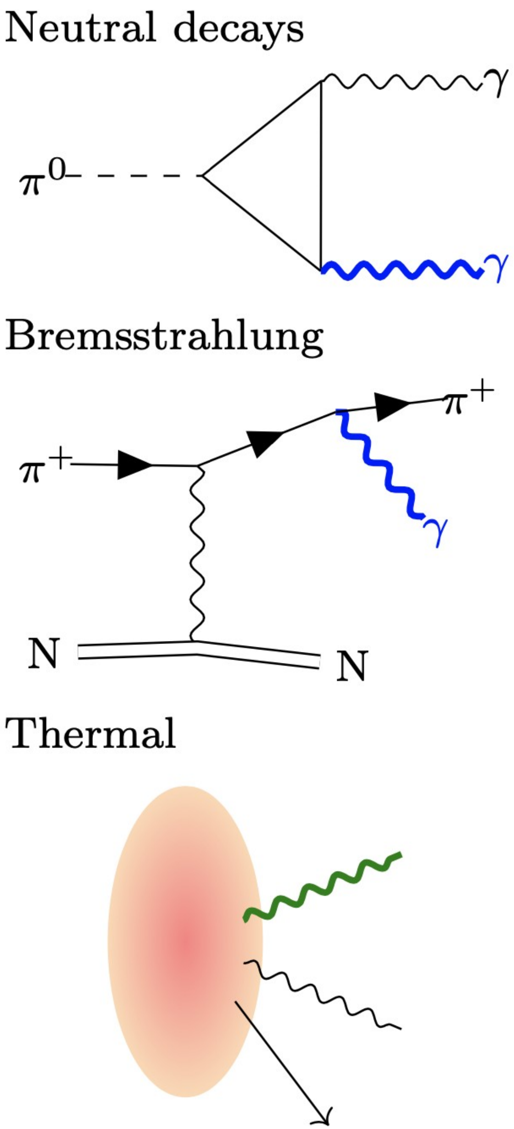
$$R_\gamma = \frac{inclusive\,\gamma}{\pi^0, \eta^0, K^\pm, \eta', \omega \rightarrow \gamma}$$



Fraction of direct photons <5% for p_T<5 GeV/c

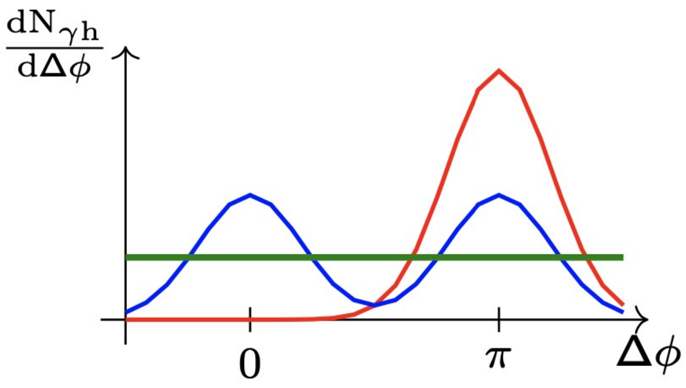
Photon probes in pPb





Can probe $Q^2<10$ GeV^2

Isolated photons (not belonging to jets)

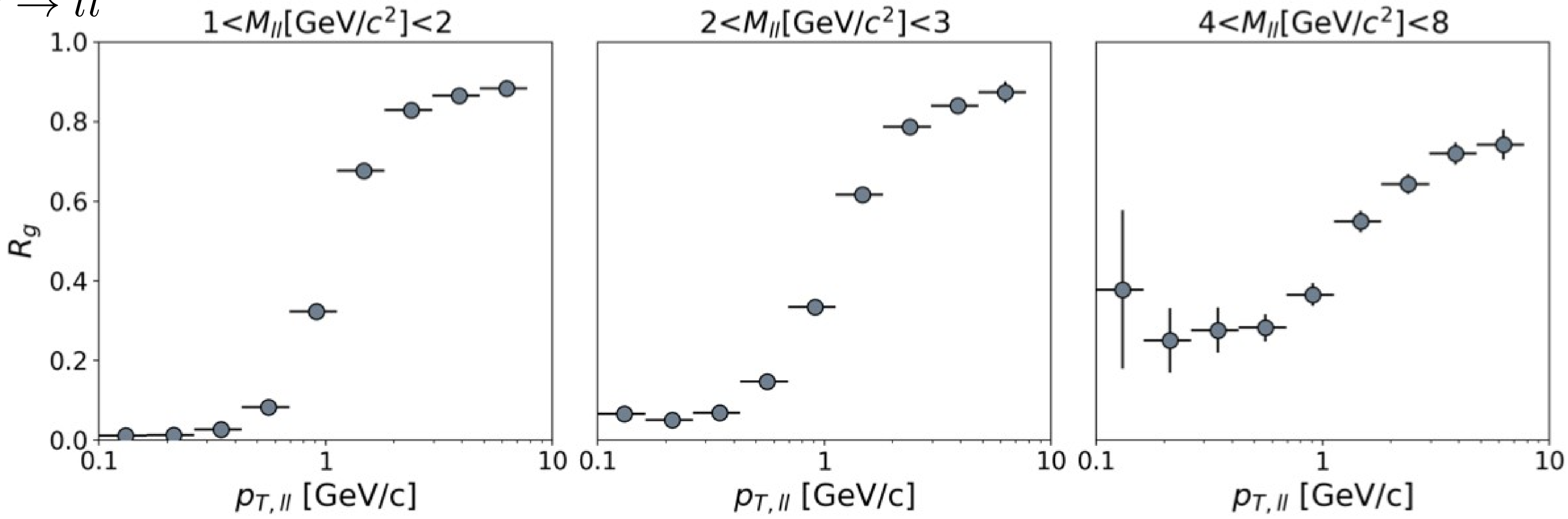


- $\Delta\phi$ line shape of direct photons from inverse Compton processes is unique

Fraction of direct photons <5% for p_T<5 GeV/c

Drell-Yan

$$R_g = \frac{qg \to ll + q}{q\bar{q} \to ll}$$



Plots obtained from PYTHIA and scaled to pQCD calculations [PRD65, 034006 (2002)]

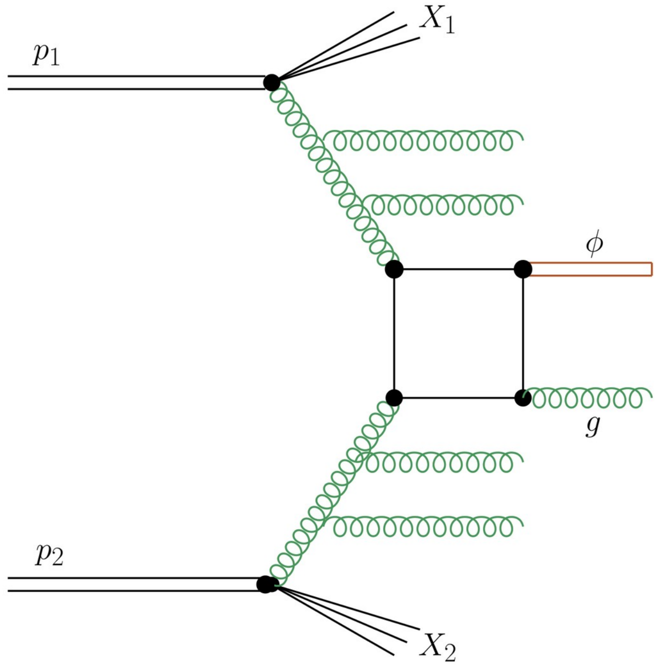
Small p_T probes sea quarks

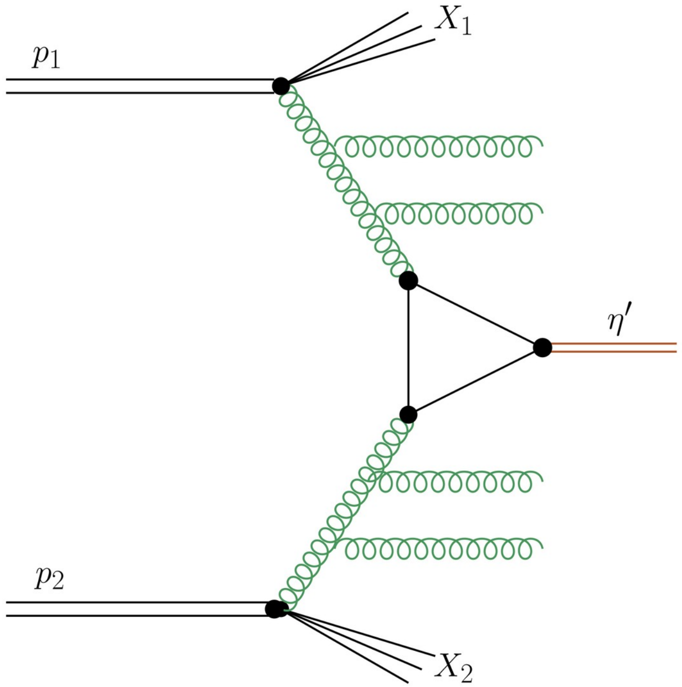
$p_T > m_{DY}$ probes gluons

Challenging given the large heavy flavor background

Light meson enhancement from gluon-gluon ?

A. Cisek, A Szczurek PRD 103, 114008 (2021)

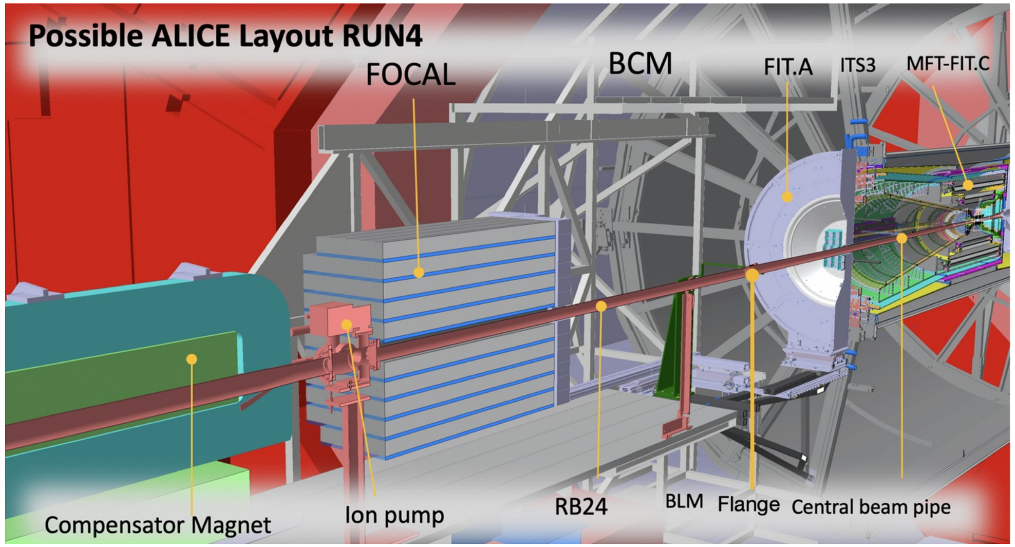




- The gluon fusion which causes saturation may also enhance some exclusive light meson production

Upgrades aiming gluon saturation search

FOCAL in ALICE

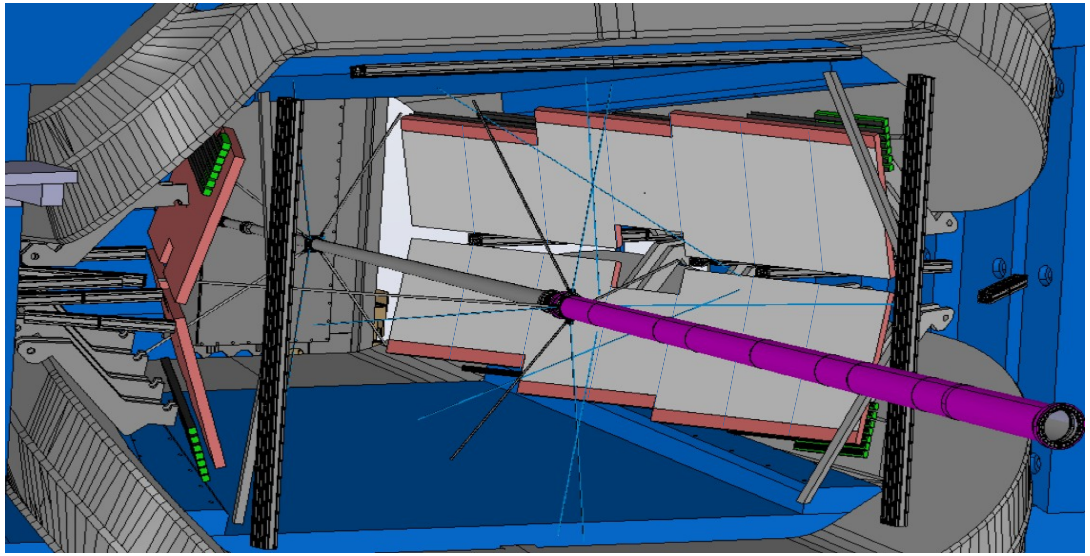


FOCAL (forward calorimeter) will put ALICE in the game of forward physics with photons and neutrals.

$3.4 < \text{eta} < 5.8 \quad p_T > 2$ GeV/c

Schedule 2028-

Magnet Station in LHCb



A scintillator-based tracker inside the dipole magnet to measure particles from very low Q^2 processes.

$1.8 < \text{eta} < 4 \quad p_T > 0.1$ GeV/c

Schedule 2028-

TAKE AWAY

- Nuclear modification factors have limited discrimination between gluon saturation and pQCD effects

- Most pA probes (maybe none so far) don't reach the saturation scale $Qs^2<10$ GeV^2 expected at the forward rapidity LHC

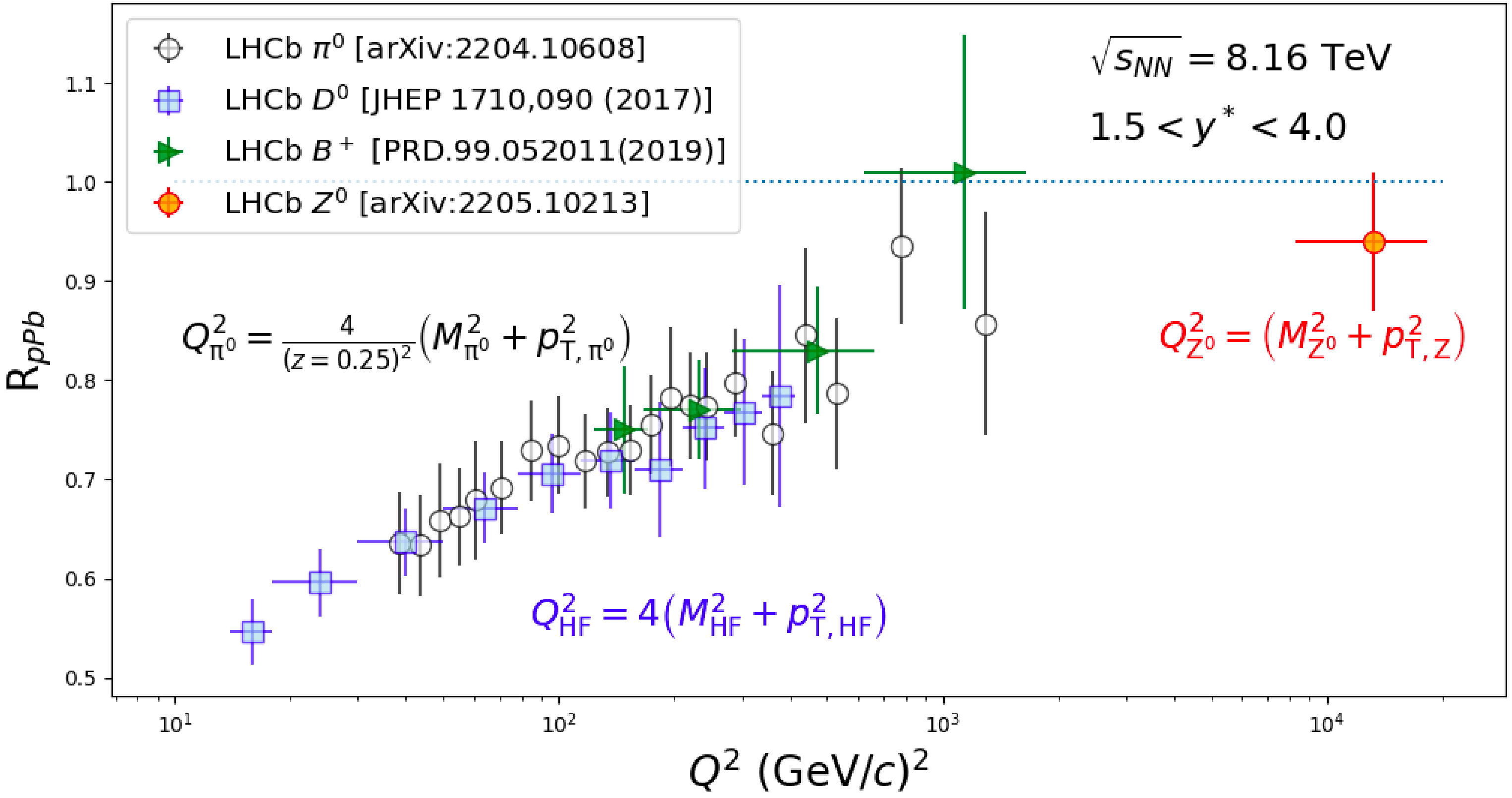
- Novel manners for gluon saturation search should be explored. My modest suggestions :
  - Q^2 vs. x scanning with the inverse Compton process
  - x shift measurements
  - Exclusive light meson production from gluon fusion
  - Low mass Drell-Yan

- New detectors are expected to come online in few years dedicated to small-x physics in nucleus.

- SURGE is a great opportunity to suggest new measurements, make predictions and discuss results

BACKUP SLIDES

Light and Hard Probes R_{pA} scaling in pPb



Forward suppression scales with the momentum transferred in the process.

Keep in mind that the x range coverage changes with Q^2.

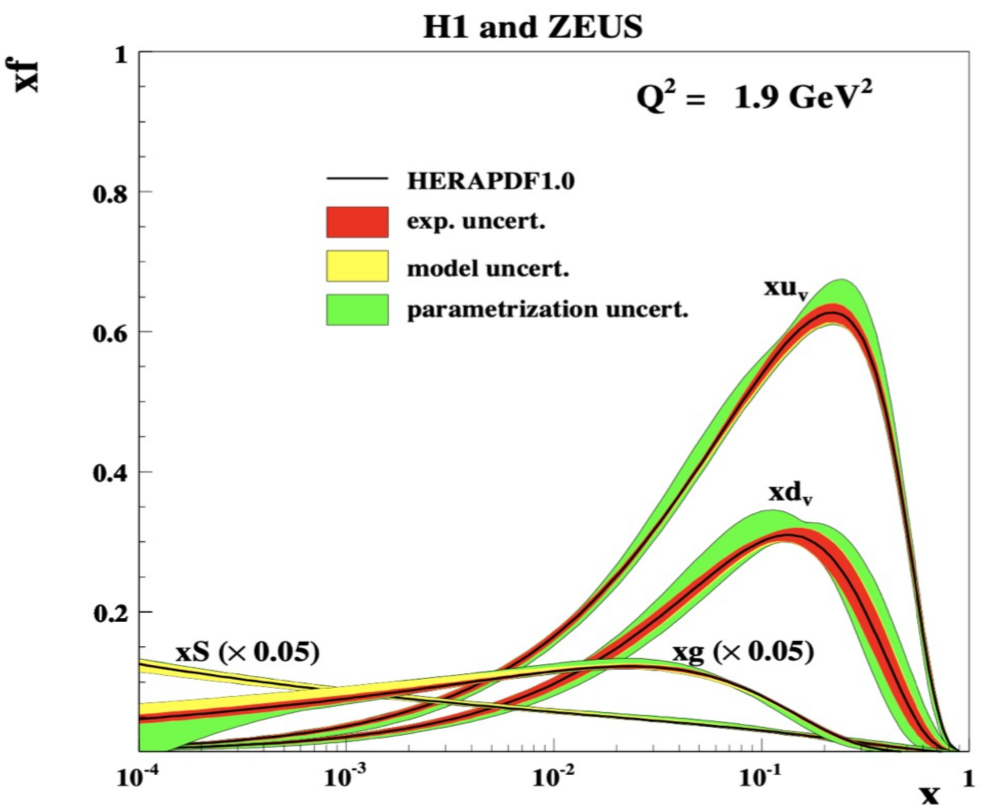
Isospin effect may prevent RpA=1 at high Q^2.

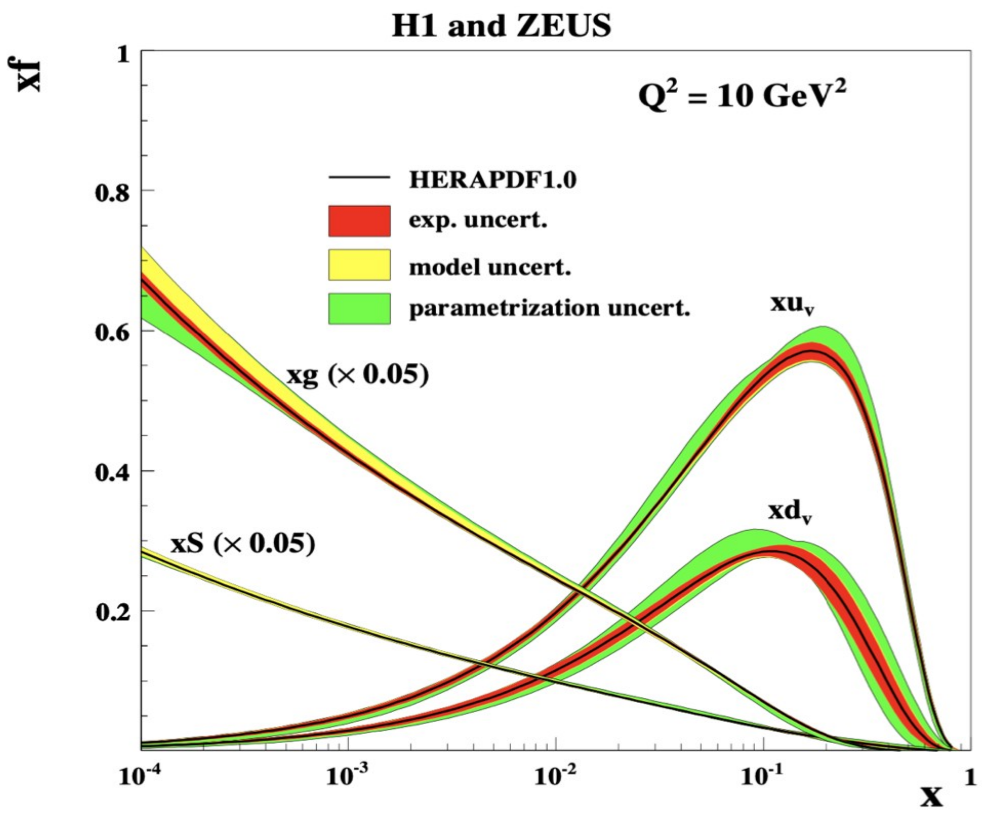
Fragmentation factor $z = \frac{E_{hadron}}{E_{parton}}$ needed for light hadrons.

Proton Distribution

DIS at HERA $E_e \simeq 27.5$ GeV $E_p = 920$ GeV $\sqrt{s} \simeq 320$ GeV

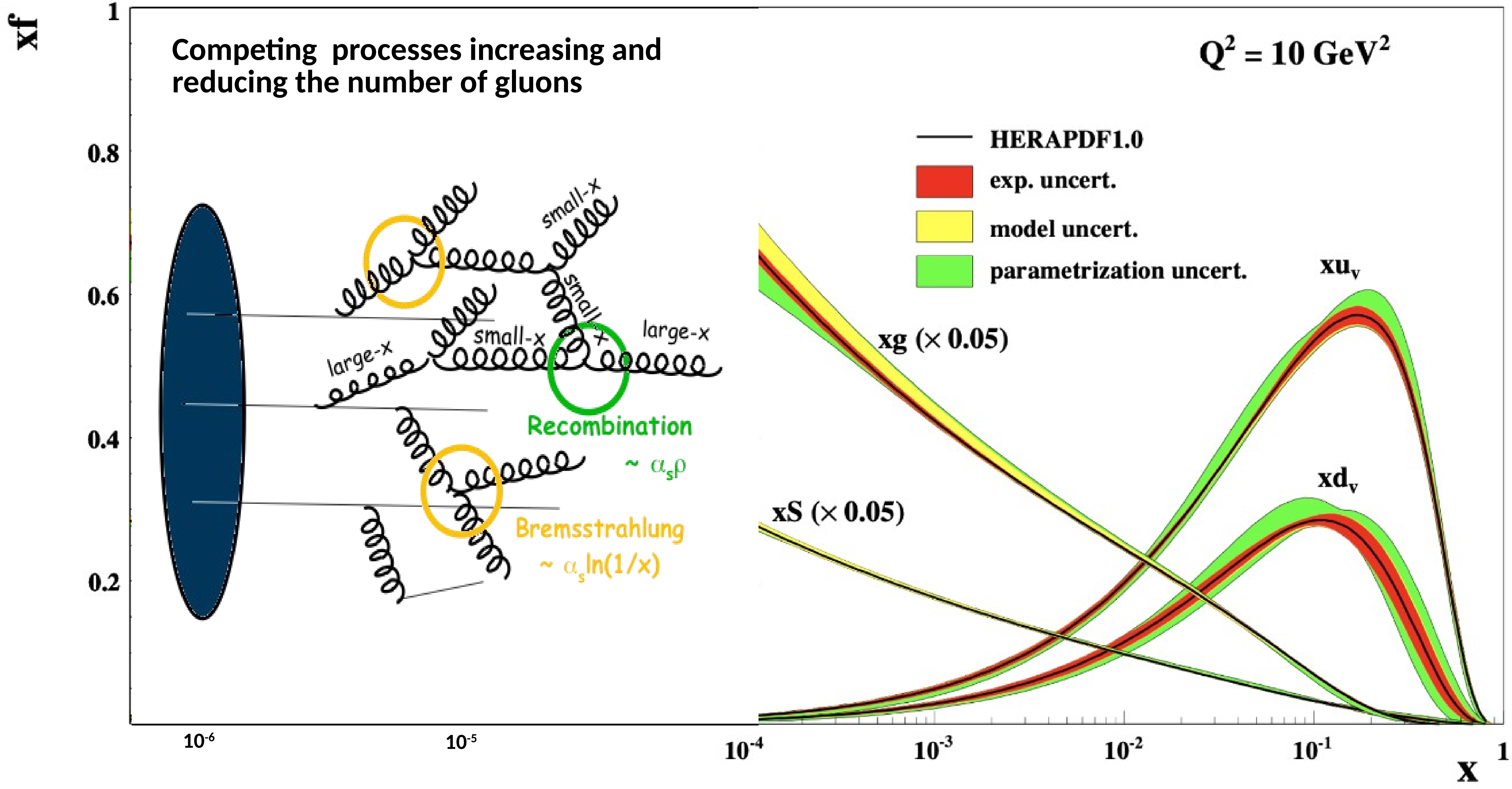
JHEP01(2010)109

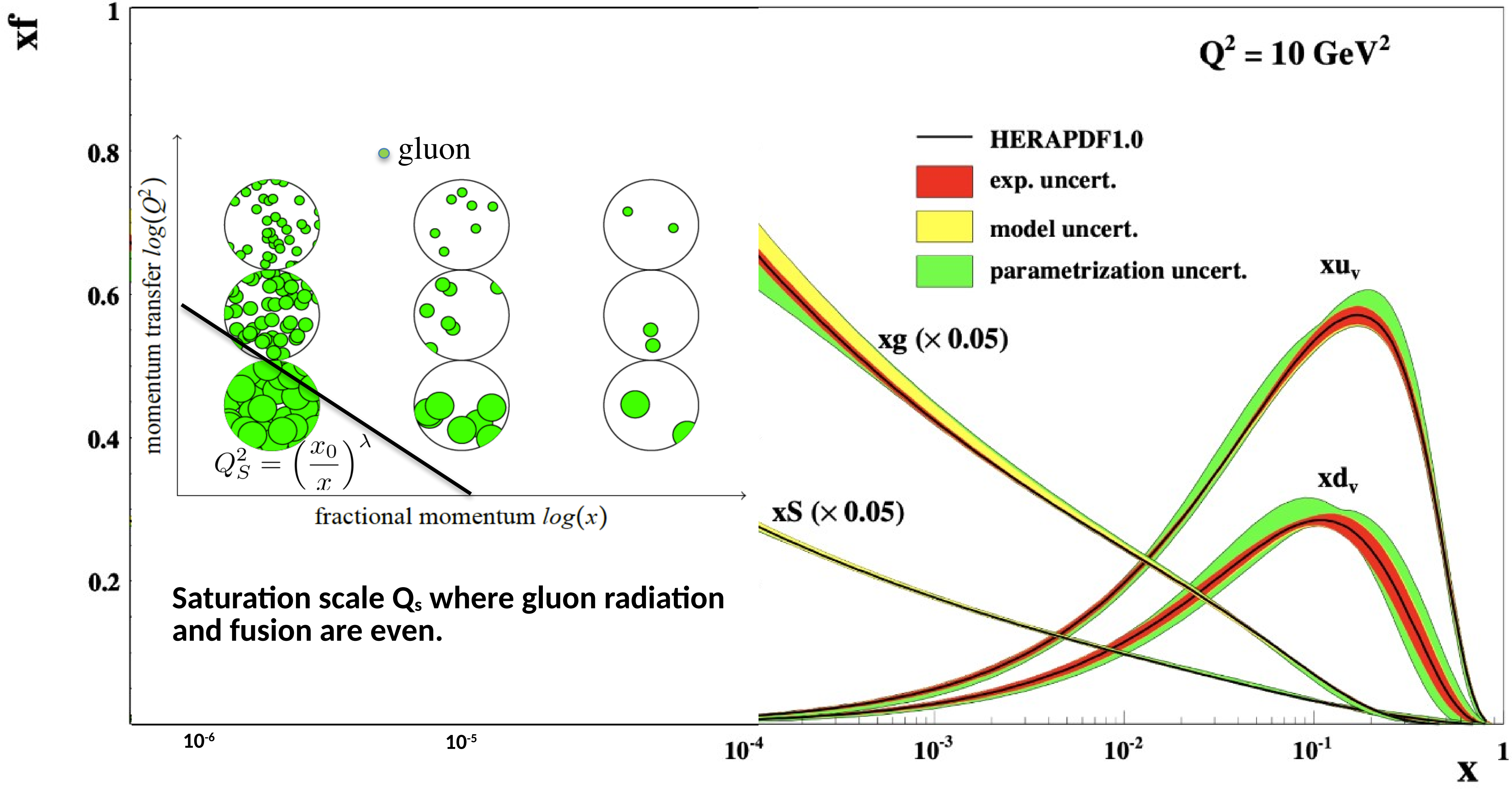




Sea quarks dominate small-x and very small Q^2
Gluon density grows toward small-x for larger Q^2

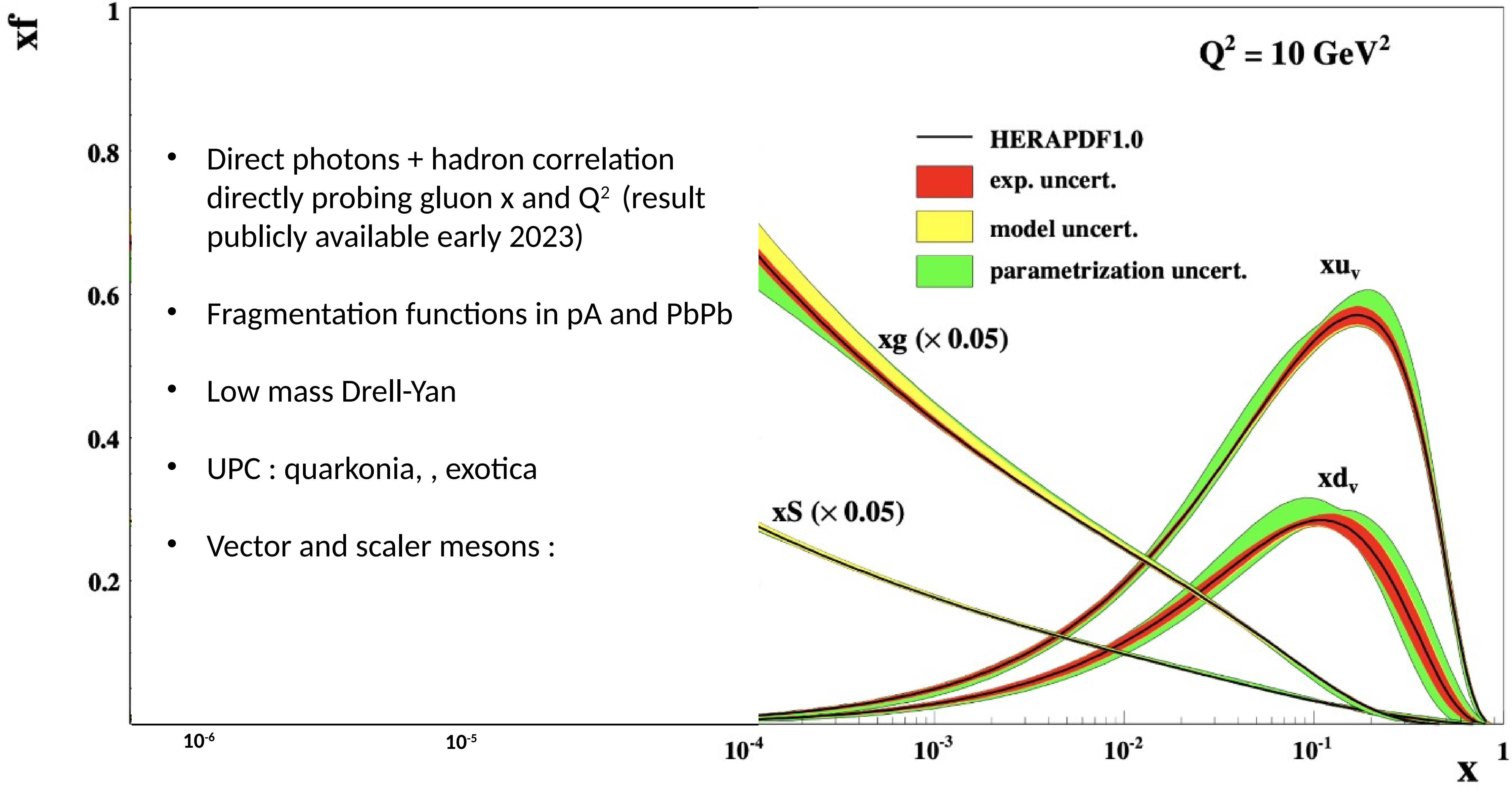
Competing processes increasing and reducing the number of gluons



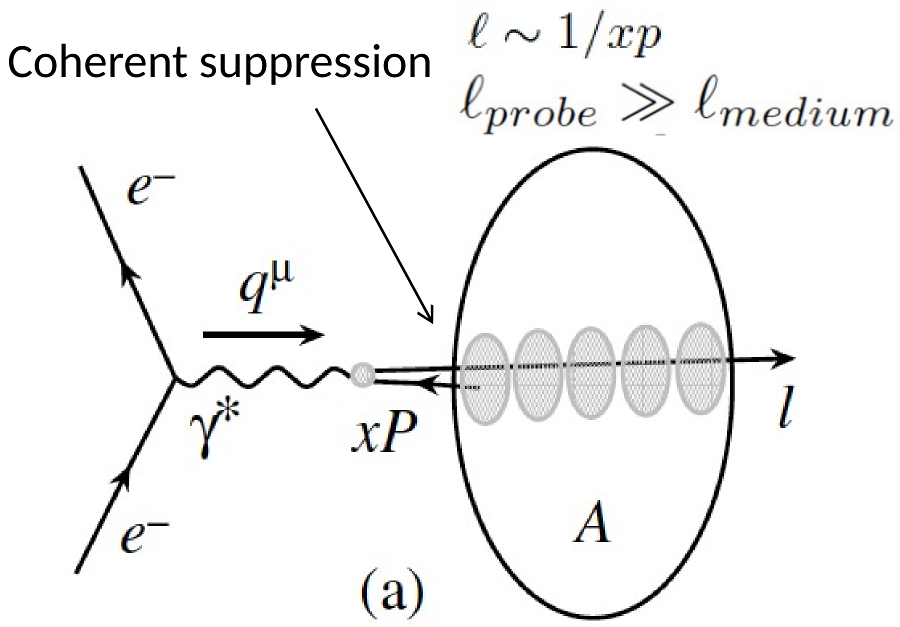


Saturation scale Q_s where gluon radiation and fusion are even.

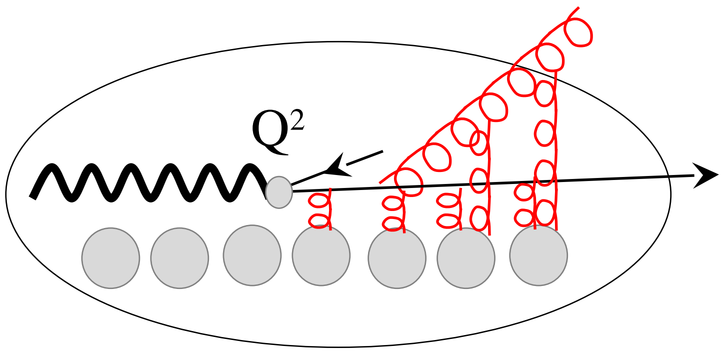
- Direct photons + hadron correlation directly probing gluon x and Q^2 (result publicly available early 2023)
- Fragmentation functions in pA and PbPb
- Low mass Drell-Yan
- UPC : quarkonia, , exotica
- Vector and scaler mesons :



DIS

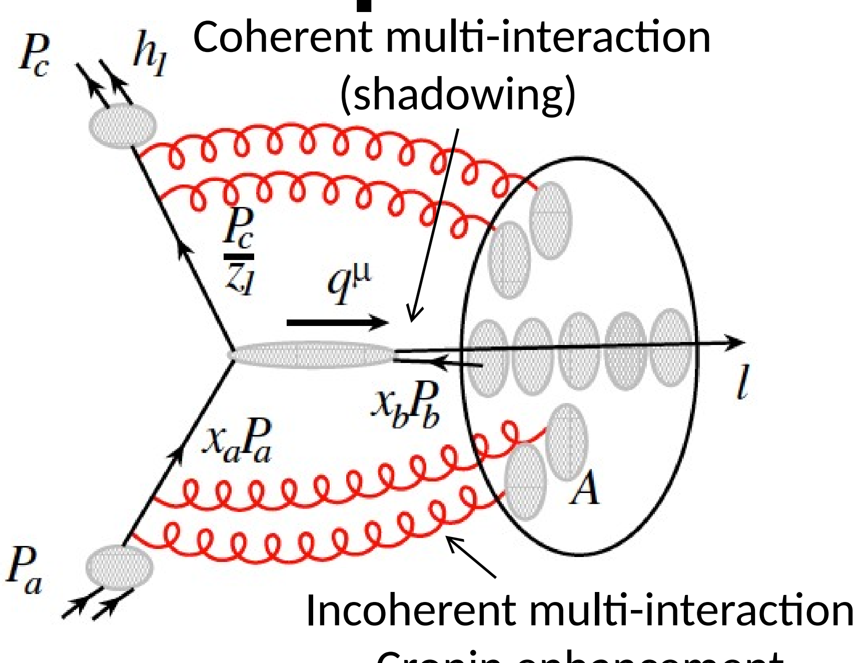


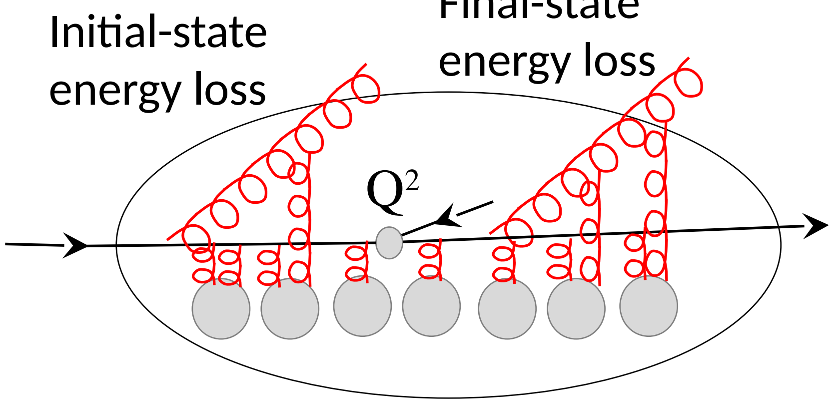
For x<0.01, l_{probe} > nuclear thickness



Final-state energy loss

p+A

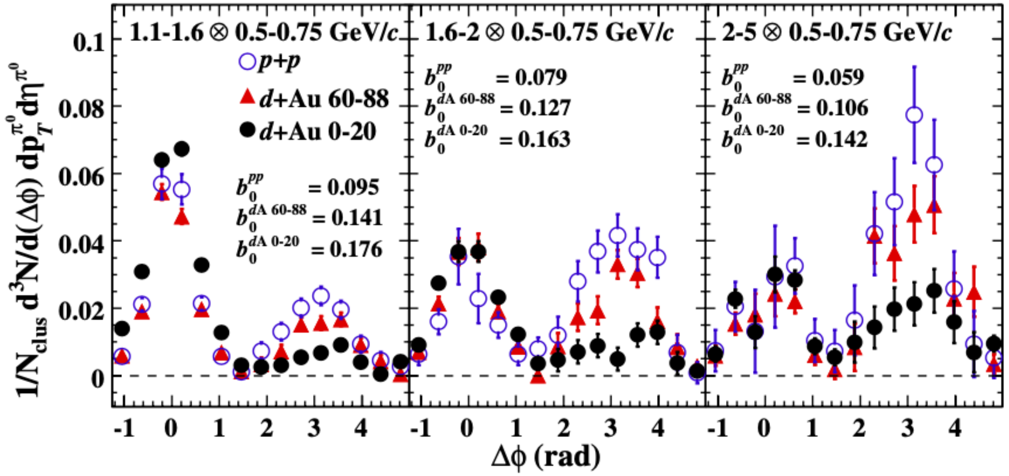


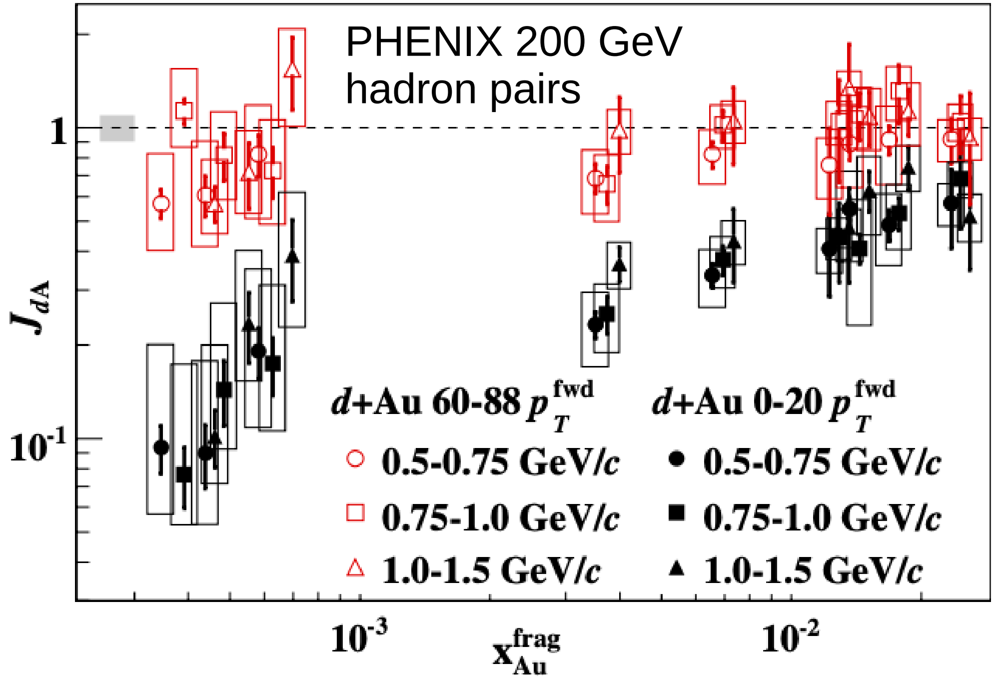


Precision and large kinematic coverage is key to understand competing effects.

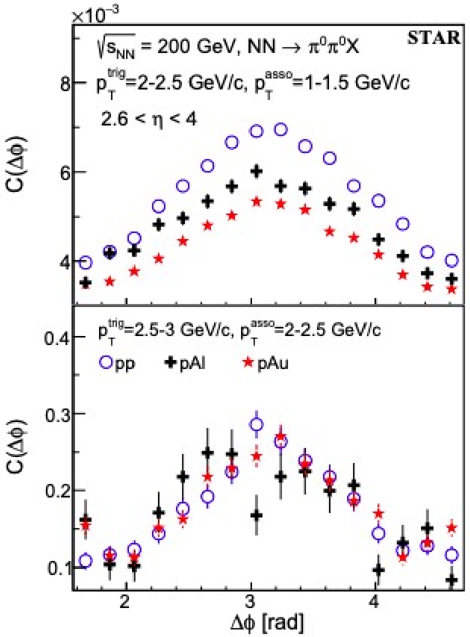
Small-x at RHIC

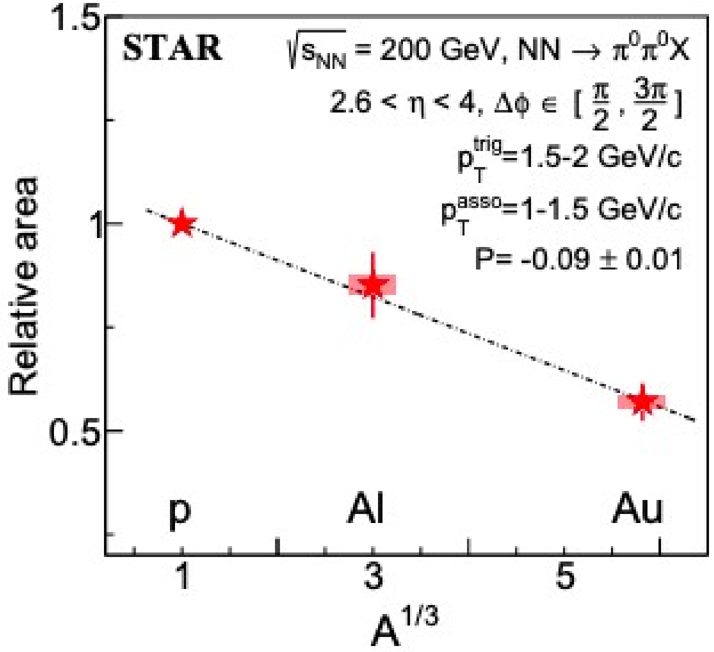
PRL 107, 172301 (2011)





arXiv:2111.10396

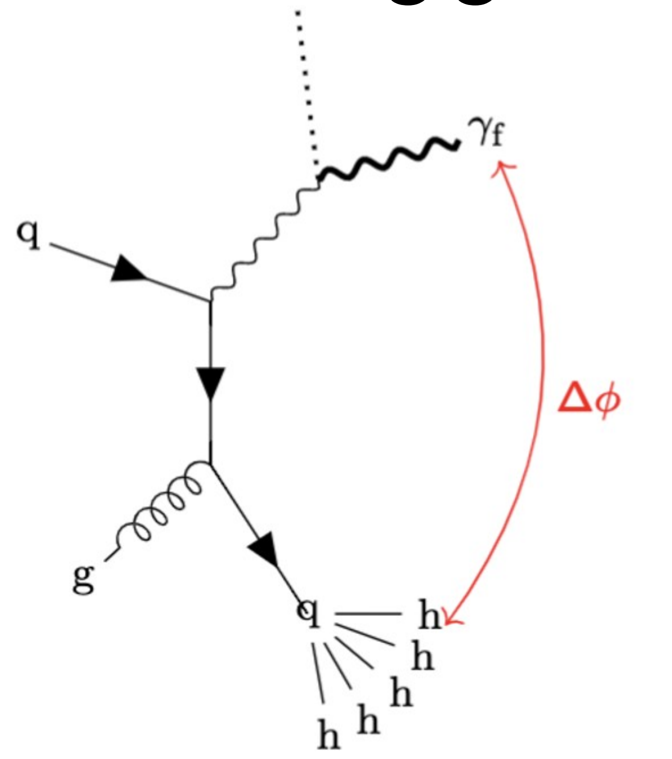




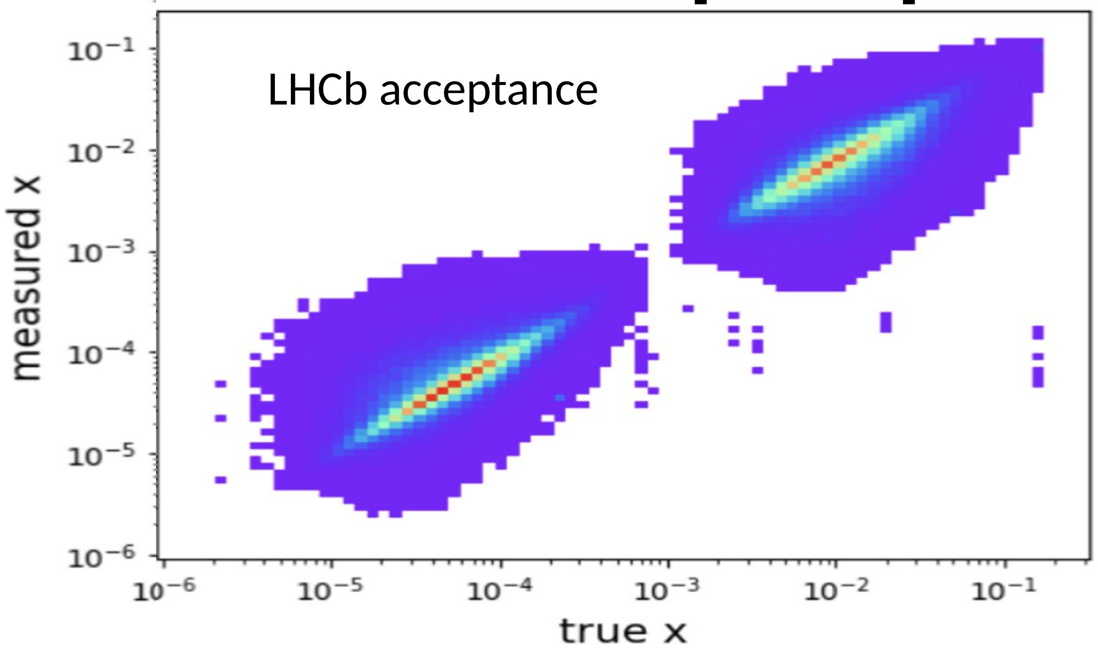
Away-side peak broadening predicted by color-glass condensate not seen.

Suppression can be reproduced by shadowing+energy loss Phys.Rev. D85 (2012) 054024.

Accessing gluon-x with inverse Compton process



$$\begin{aligned}
p_{T,\gamma} &= p_{T,q} \\
x_{p_z>0} &= \frac{p_{T,\gamma}}{\sqrt{s_{NN}}}\left(e^{y_\gamma}+e^{y_q}\right) \\
x_{p_z<0} &= \frac{p_{T,\gamma}}{\sqrt{s_{NN}}}\left(e^{-y_\gamma}+e^{-y_q}\right) \\
Q^2 &= p_{T,\gamma}^2\left(1+e^{y_q-y_\gamma}\right) \sim 2p_{T,\gamma}^2
\end{aligned}$$



Being a 2->2 process, inverse Compton process provides a precise measurement of the gluon-x.

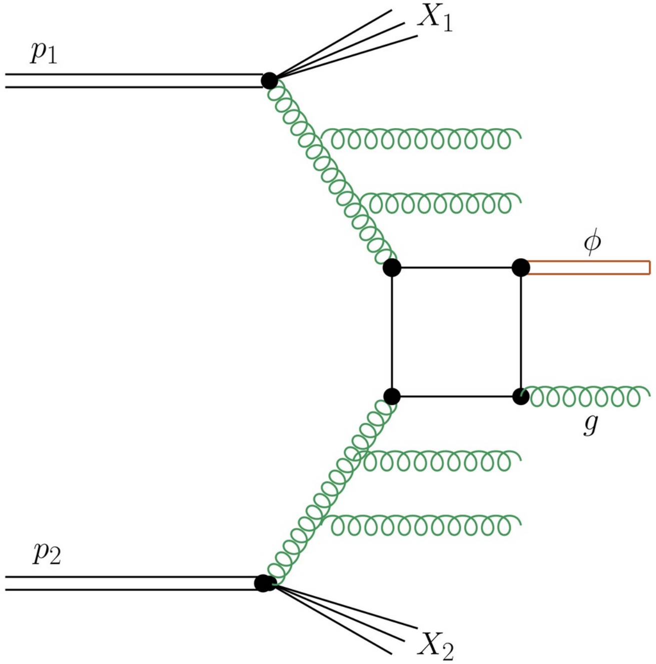
- Search of the saturation scale
- Check of any x shift from shadowing or energy loss

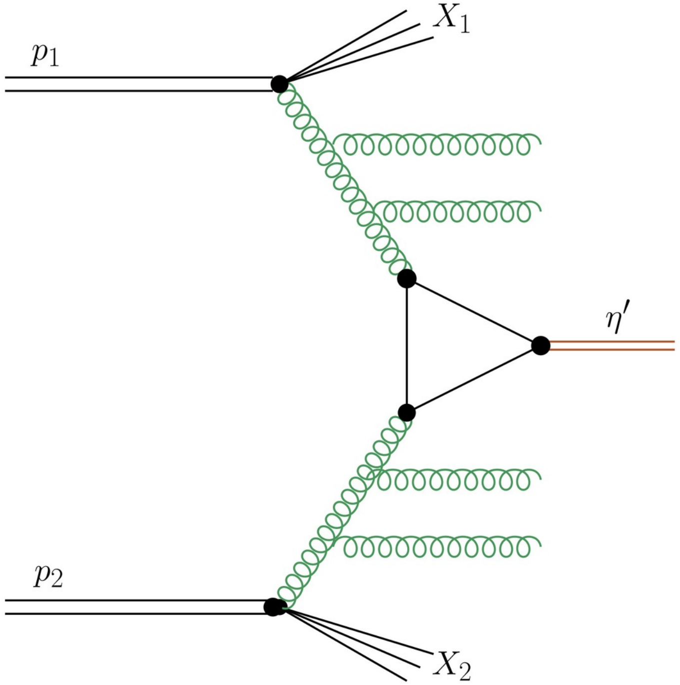
Result under internal LHCb review. Expect a public release early 2023.

- GeV/c,
- MeV/c,

Light meson enhancement from gluon-gluon ?

A. Cisek, A Szczurek PRD 103, 114008 (2021)





- The gluon fusion which causes saturation may also enhance some exclusive light meson production
  - +h correlation
  - isolated

Idea not explored by theorists yet ….
Other hadrons ? What about glueballs ?