2015 LHeC Workshop
Chavannes-de-Bogis, June 26 2015

Heavy Ion Physics in e-A and p/A-A

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for the LHeC Study group, http://cern.ch/lhec

Using slides from Nestor Armesto's previous talks

Plan of this talk

1. Introduction.

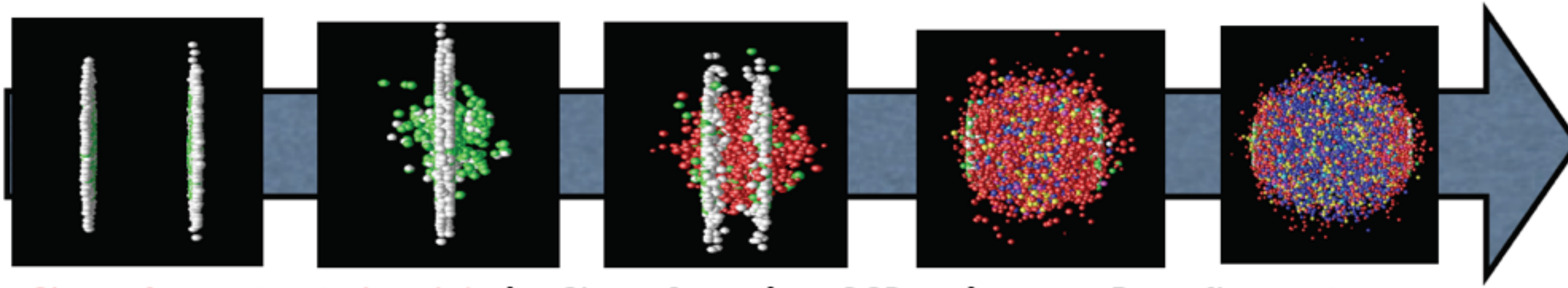
2. eA at the LHeC and comparison to the LHC.

3. Physics case in eA:
   - Inclusive measurements and nuclear PDFs.
   - Diffraction.
   - Final states: dynamics of QCD radiation and hadronization.

4. Summary and outlook.

CDR, arXiv:1206.2913, J. Phys. G 39 (2012) 075001;
arXiv:1211.4831; arXiv:1211.5102.
See talk by Max on FHeC this afternoon

Relevance for the HI program:



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

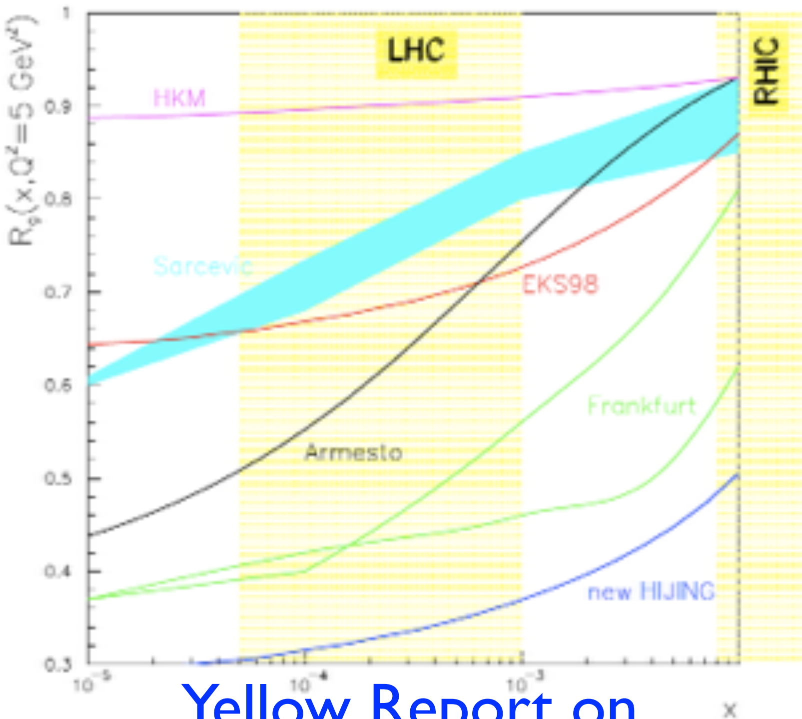
- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

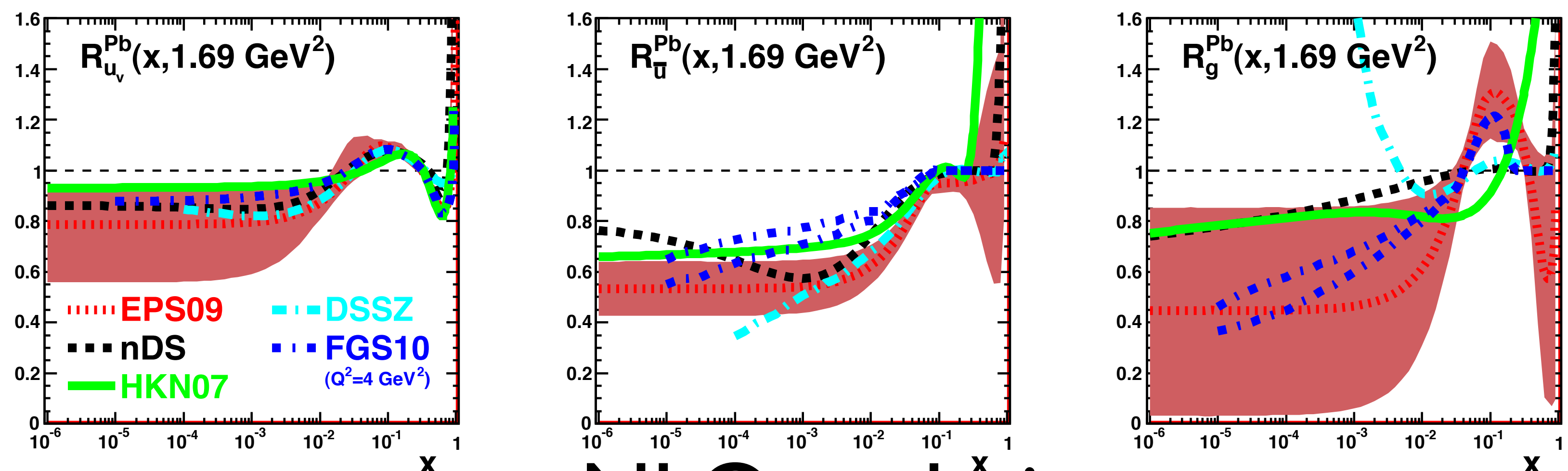
nPDFs: $R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$



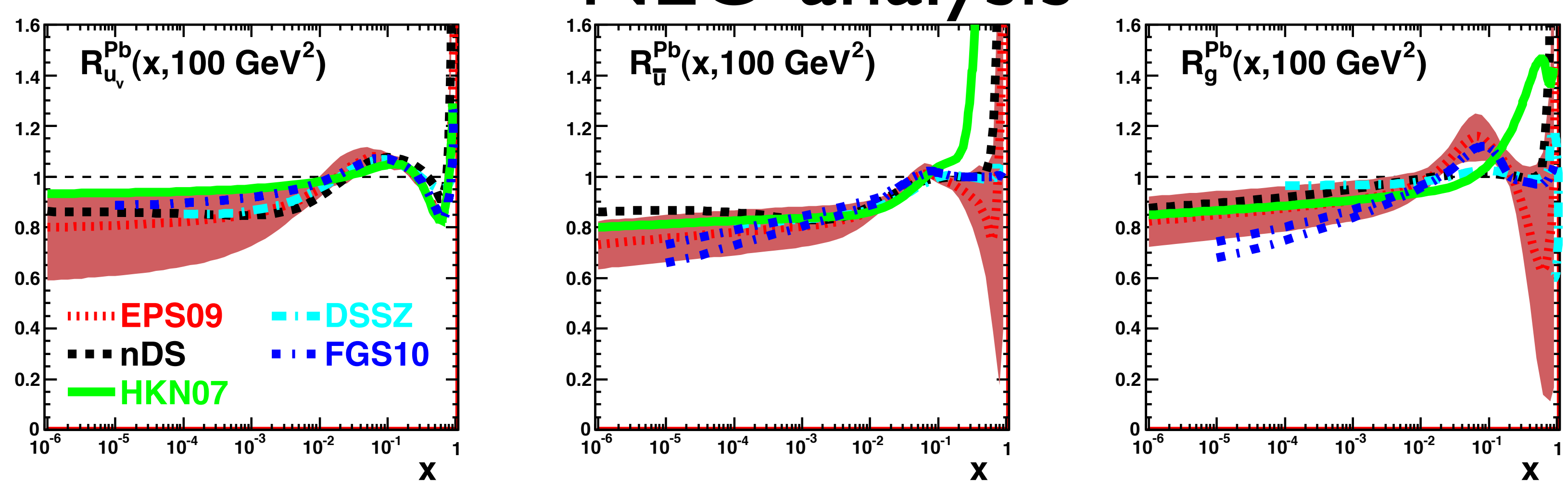
Yellow Report on Hard Probes, 2004

- Lack of data ⇒ models give vastly different results for the nuclear glue at small scales and x: problem for benchmarking in HIC.

- Available DGLAP analysis at NLO show large uncertainties at small scales and x.



NLO analysis



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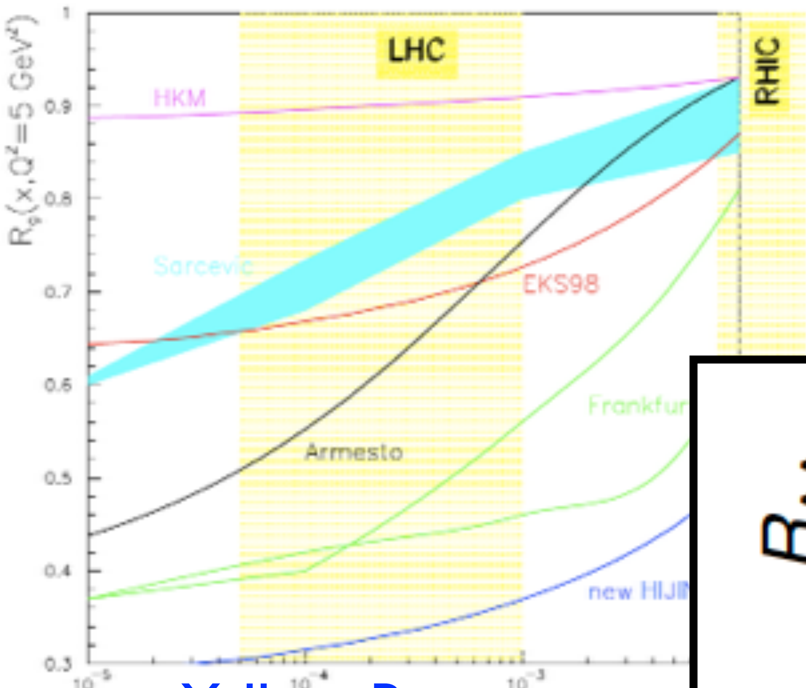

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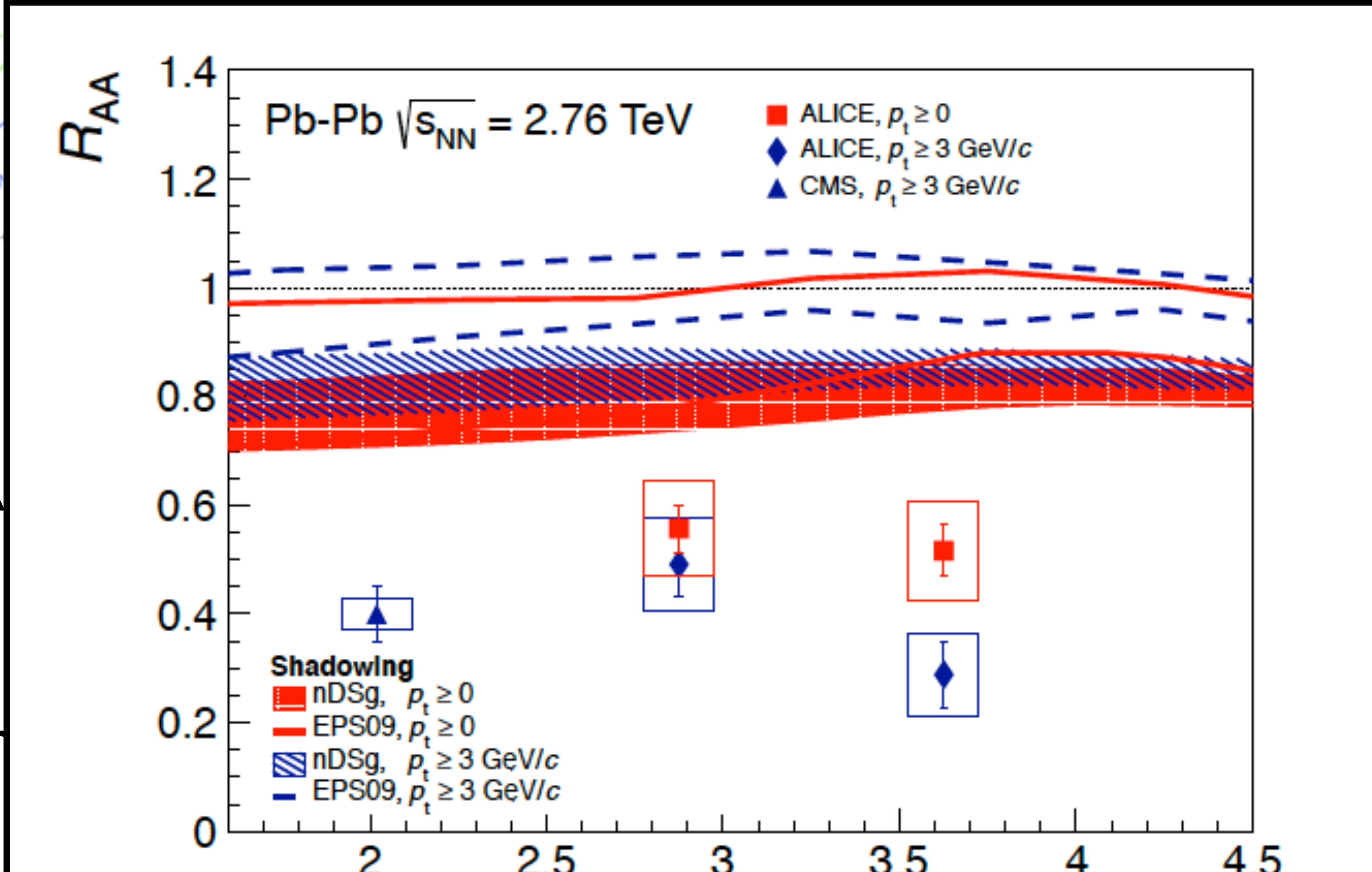
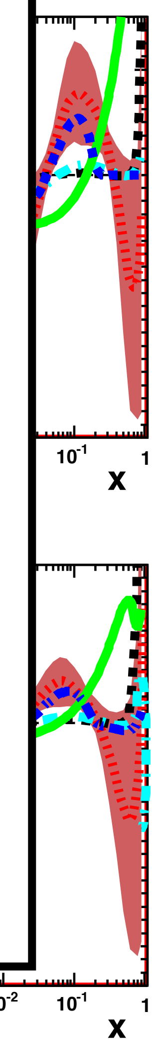


Inclusive J/ψ, 1202.1383



Cold Nuclear Matter Effects in Hadroproduction

In heavy-ion collisions, one has to fold in cold matter effects, typically studied in pA or dA interactions from fixed-target energies to colliders

Hard probes, where production is calculable in QCD, are best to study differences between initial and final state effects

Important cold nuclear matter effects in hadroproduction include:

- Initial-state nuclear effects on the parton densities (nPDFs)
- Initial- (or final-) state energy loss
- Final-state absorption on nucleons
- Final-state break up by comovers (hadrons or partons)
- Intrinsic $Q\overline{Q}$ pairs

In this talk, I will concentrate on nuclear parton densities, not including any other effect

R. Vogt

Nuclear PDFs at NLO

Gluon shadowing ratios compared at the J/ψ and Υ production scales

EPS09 NLO (black) and EKS98 LO (magenta) very similar for $x > 0.002$, significant antishadowing, nDS NLO (blue) and nDSg NLO (red) have almost no antishadowing, nDSg and EKS98 have stronger shadowing than central EPS09 at low x

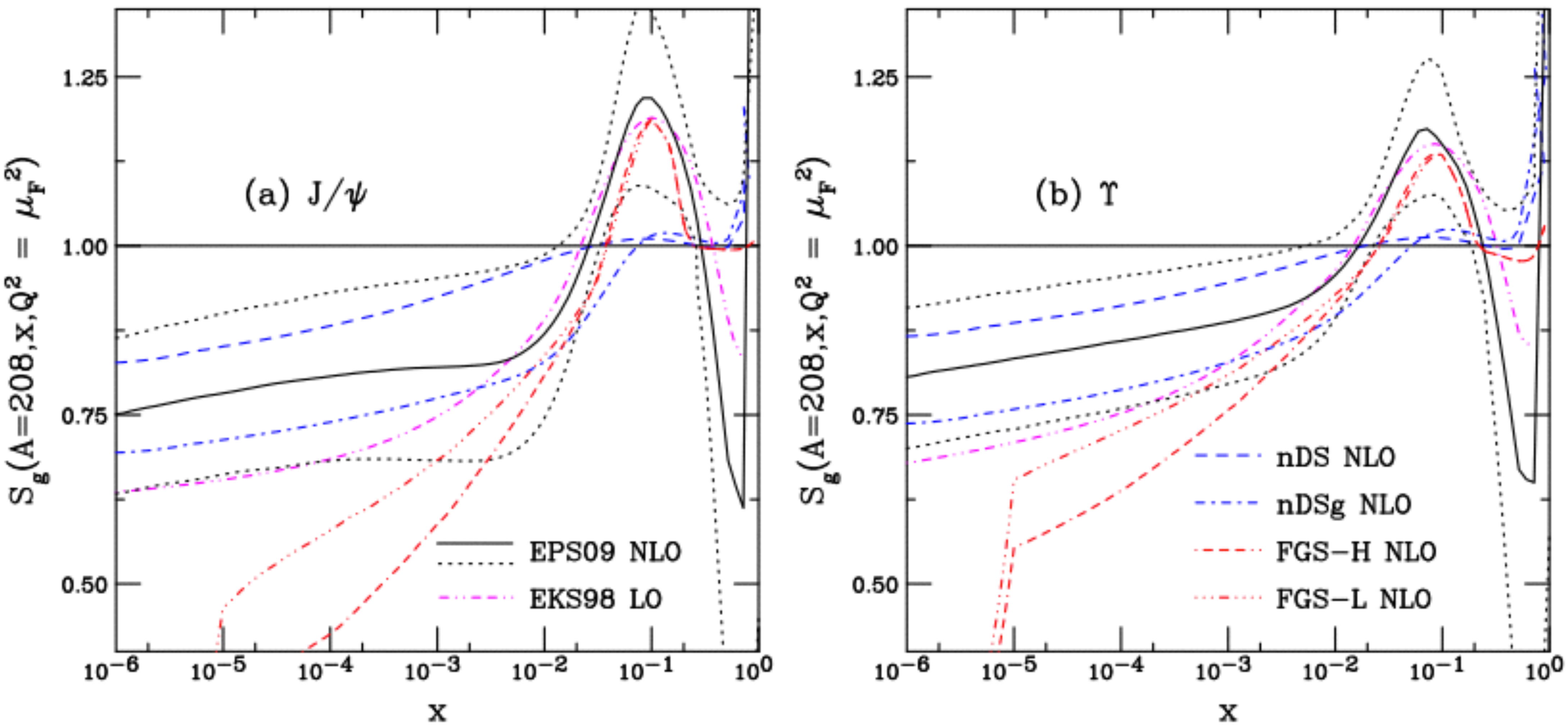
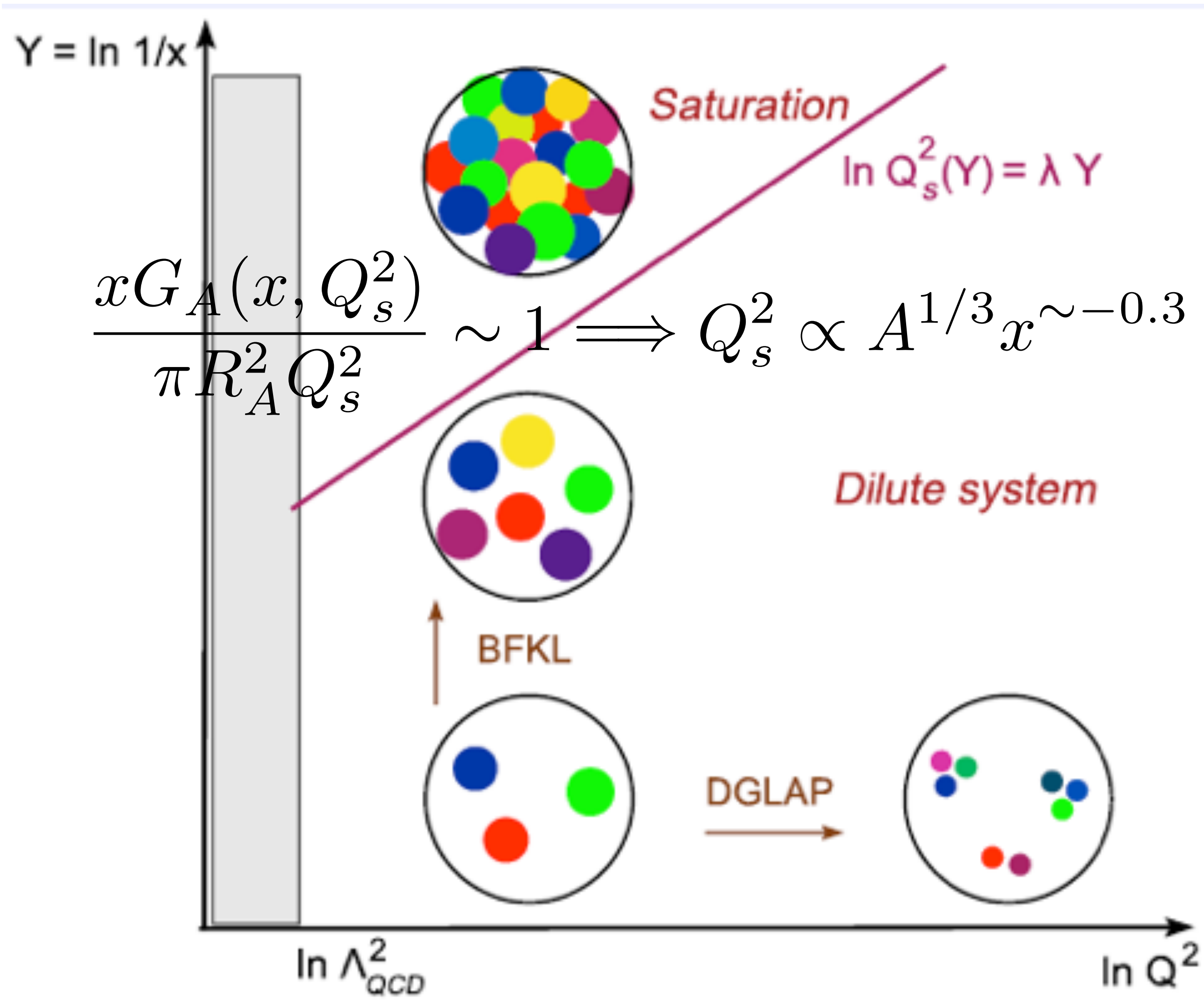


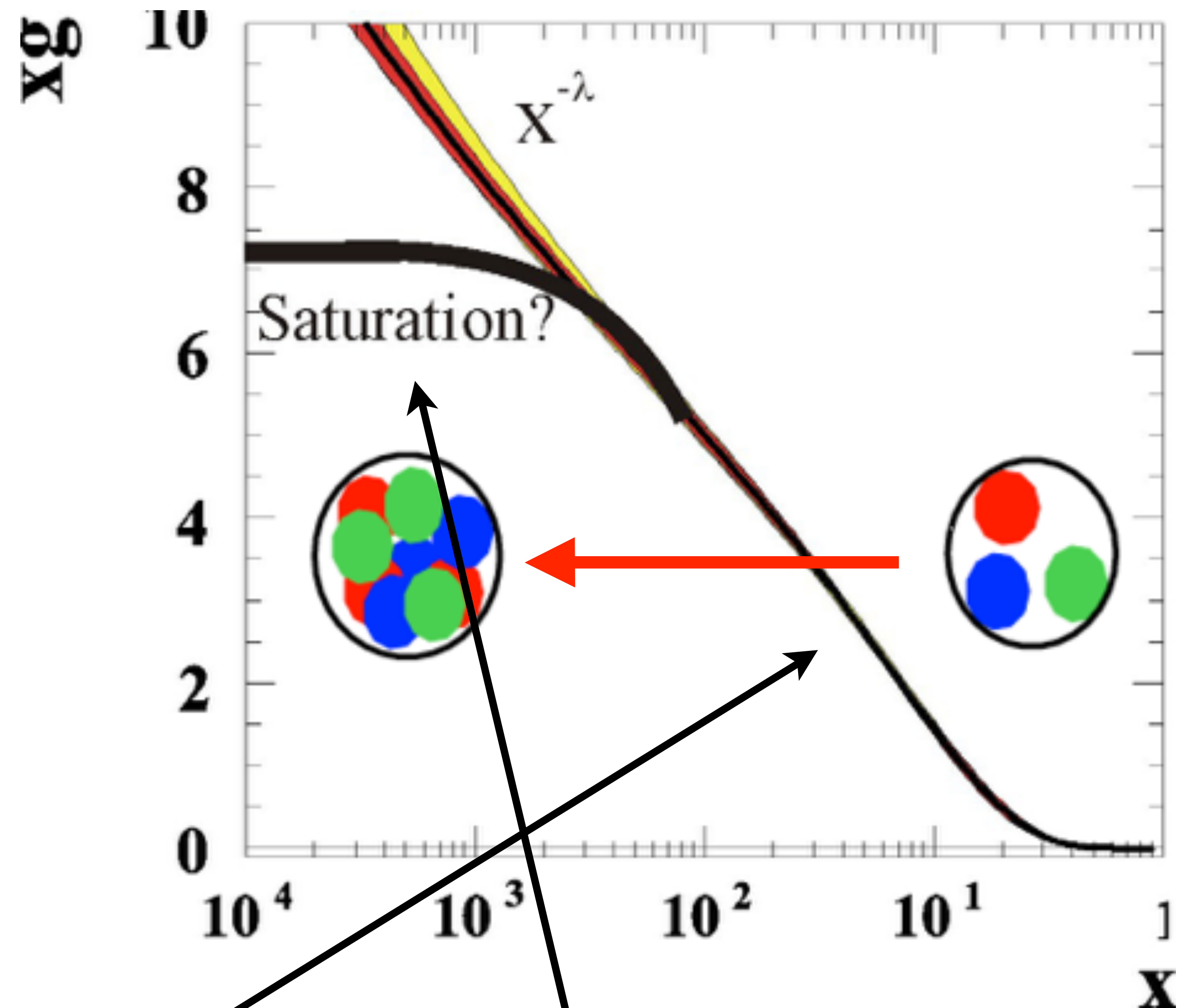
Figure 7: Gluon shadowing ratios calculated for Pb nuclei ($A = 208$) calculated at the central value of the fitted factorization scales for J/psi (left) and Υ (right). EPS09 NLO is shown by the black solid curve while the uncertainty band is outlined by the black dotted curves. The NLO nDS and nDSg parameterizations are given in the blue dashed and red dot dashed curves. The LO EKS98 parameterization is in magenta (dot-dot-dot-dash-dashed).

R. Vogt

Small x and saturation:



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$



- QCD radiation of partons when x decreases leads to a large number of partons (gluons), provided each parton evolves independently (linearly, Δ[xg] ∝ xg).
- This independent evolution breaks at high densities (small x or high mass number A): non-linear effects (gg→g, Δ[xg] ∝ xg - k(xg)^2).

Status of small-x physics:

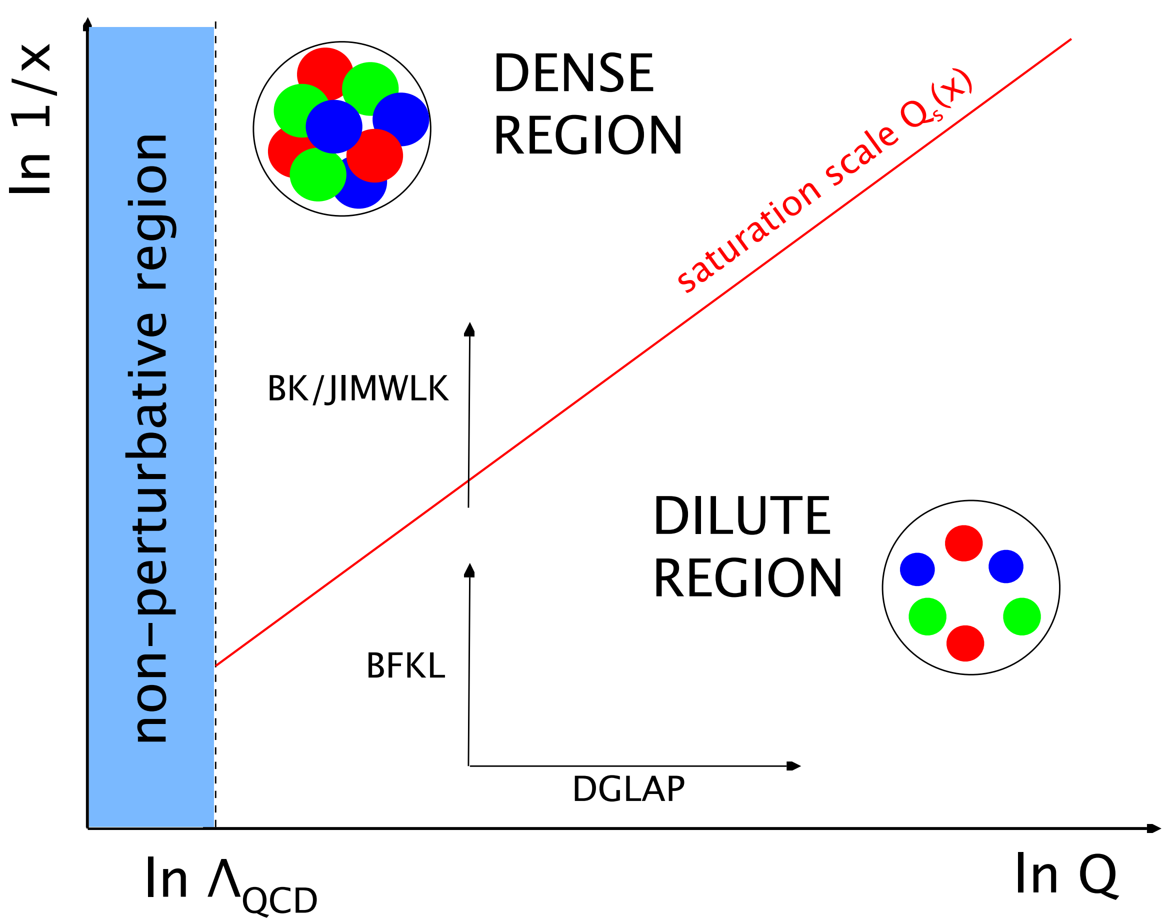
- Three pQCD-based alternatives to describe small-x ep and eA data (differences at moderate $Q^2(>\Lambda^2_{QCD})$ and small x):

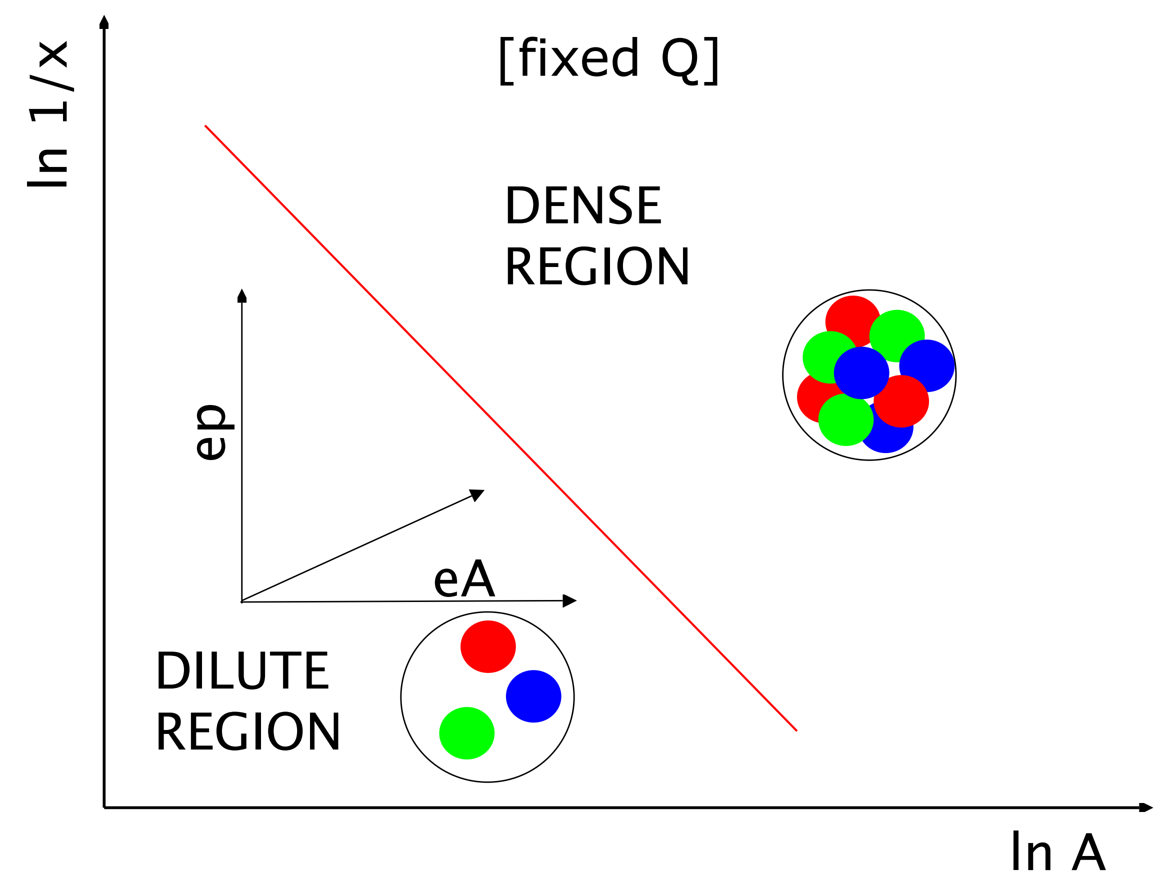
→ DGLAP evolution (fixed order perturbation theory).

→ Resummation schemes: BFKL, CCFM, ABF, CCSS.

→ Saturation (CGC, dipole models).

- **Non-linear effects** (unitarity constraints) are density effects: where? ⇒ **two-pronged approach at the LHeC**: ↓ x / ↑ A.





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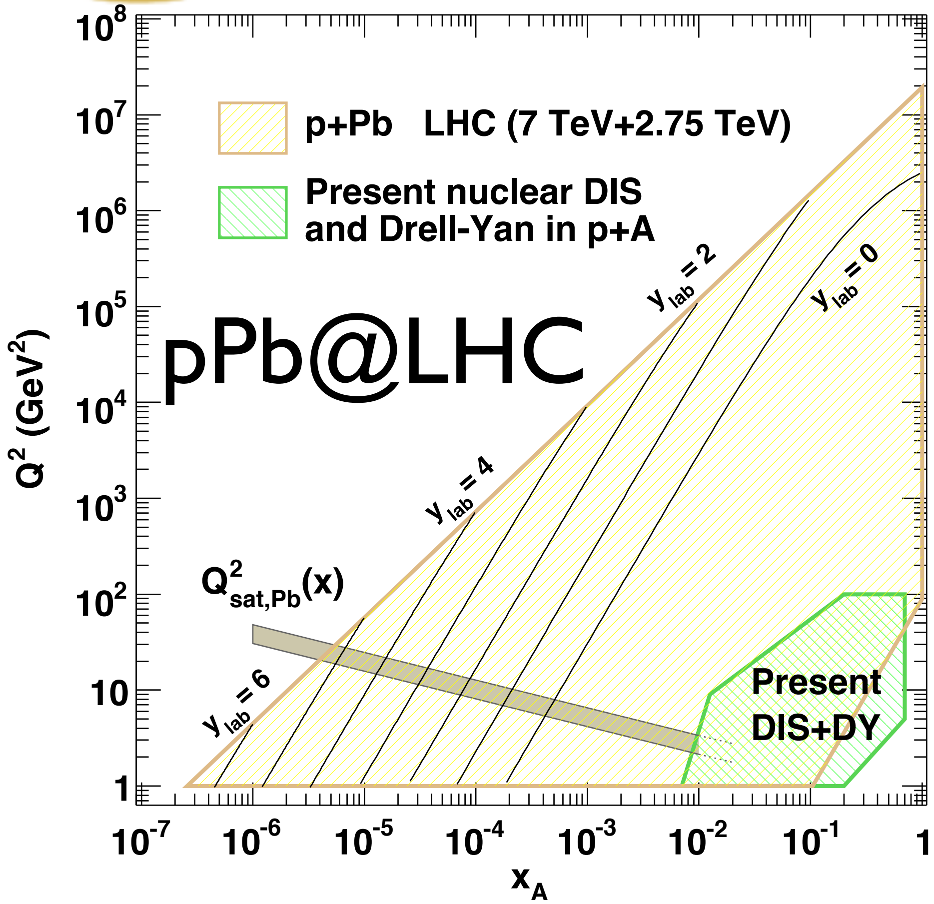
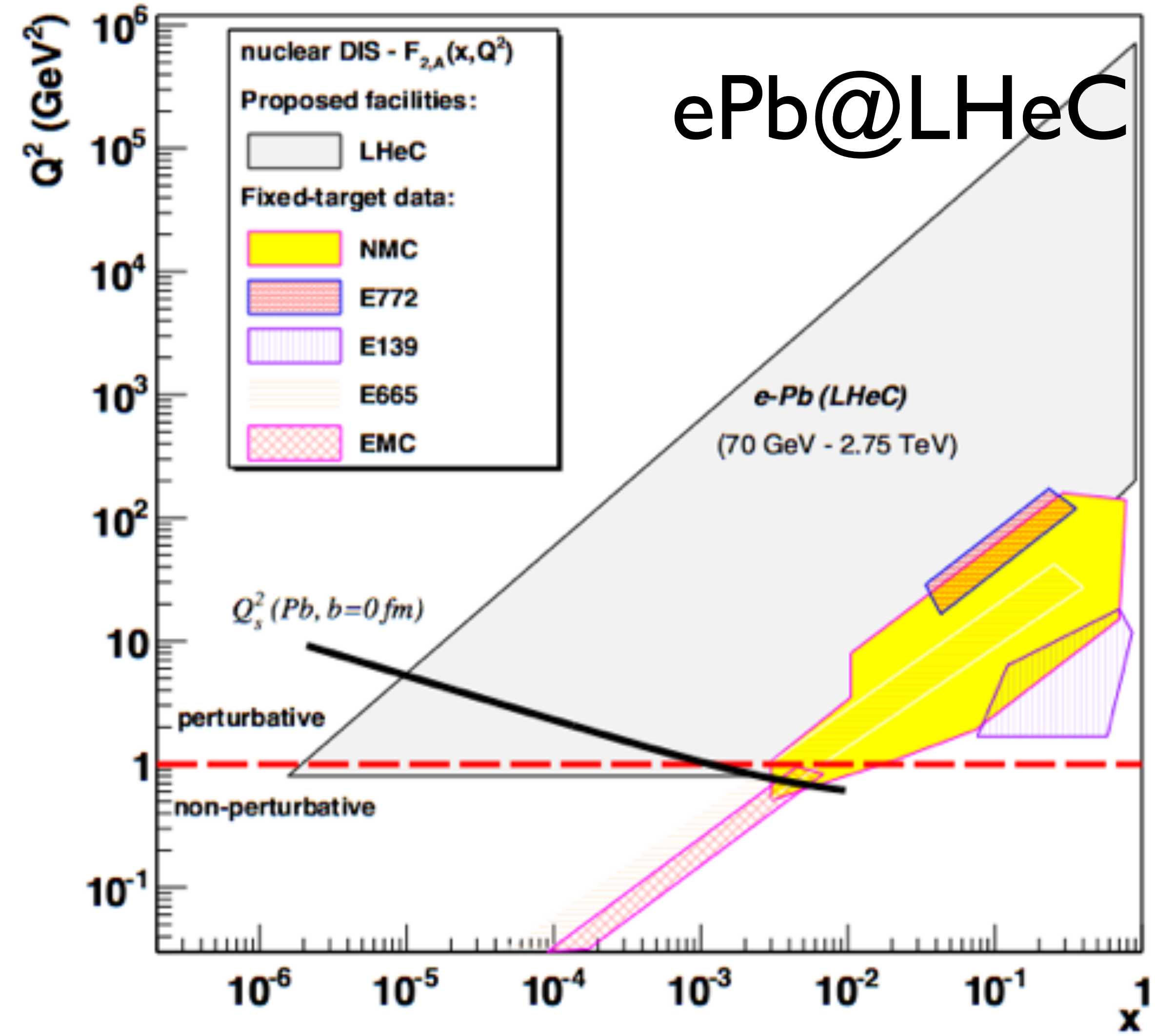
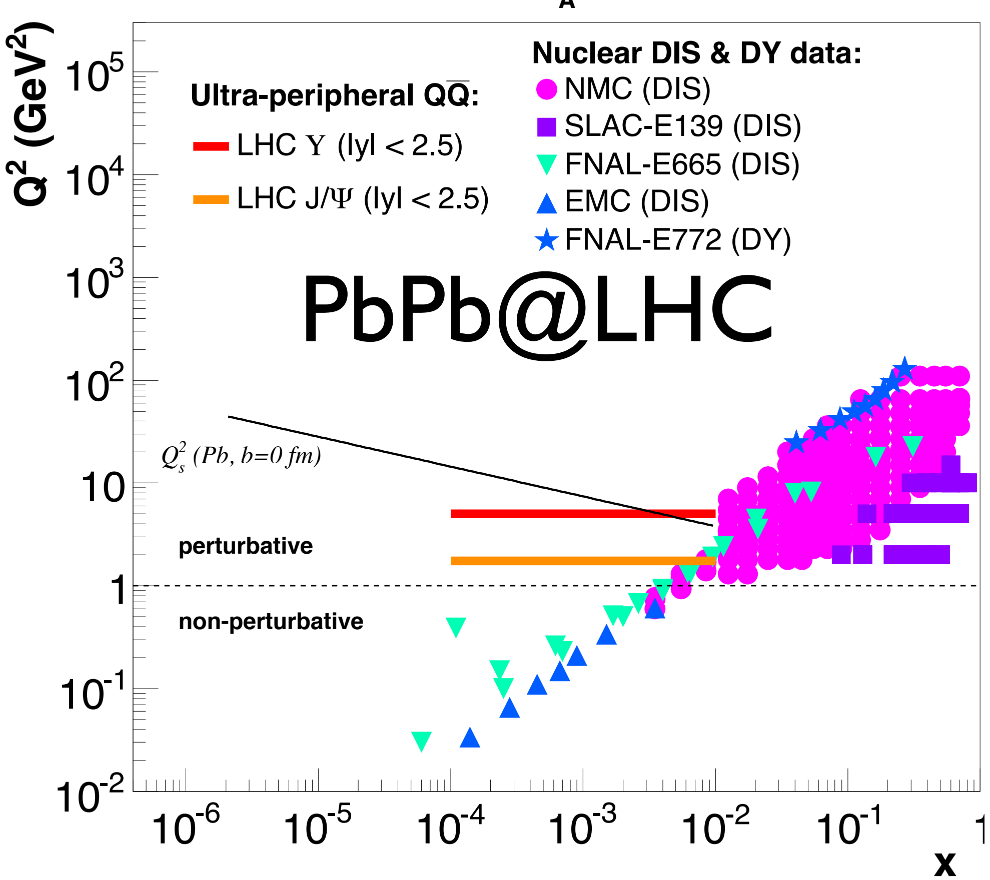
LHC vs. LHeC:



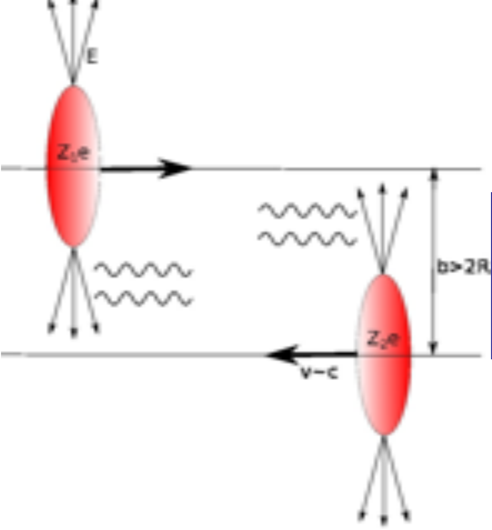




- The LHeC will explore a region overlapping with the LHC:

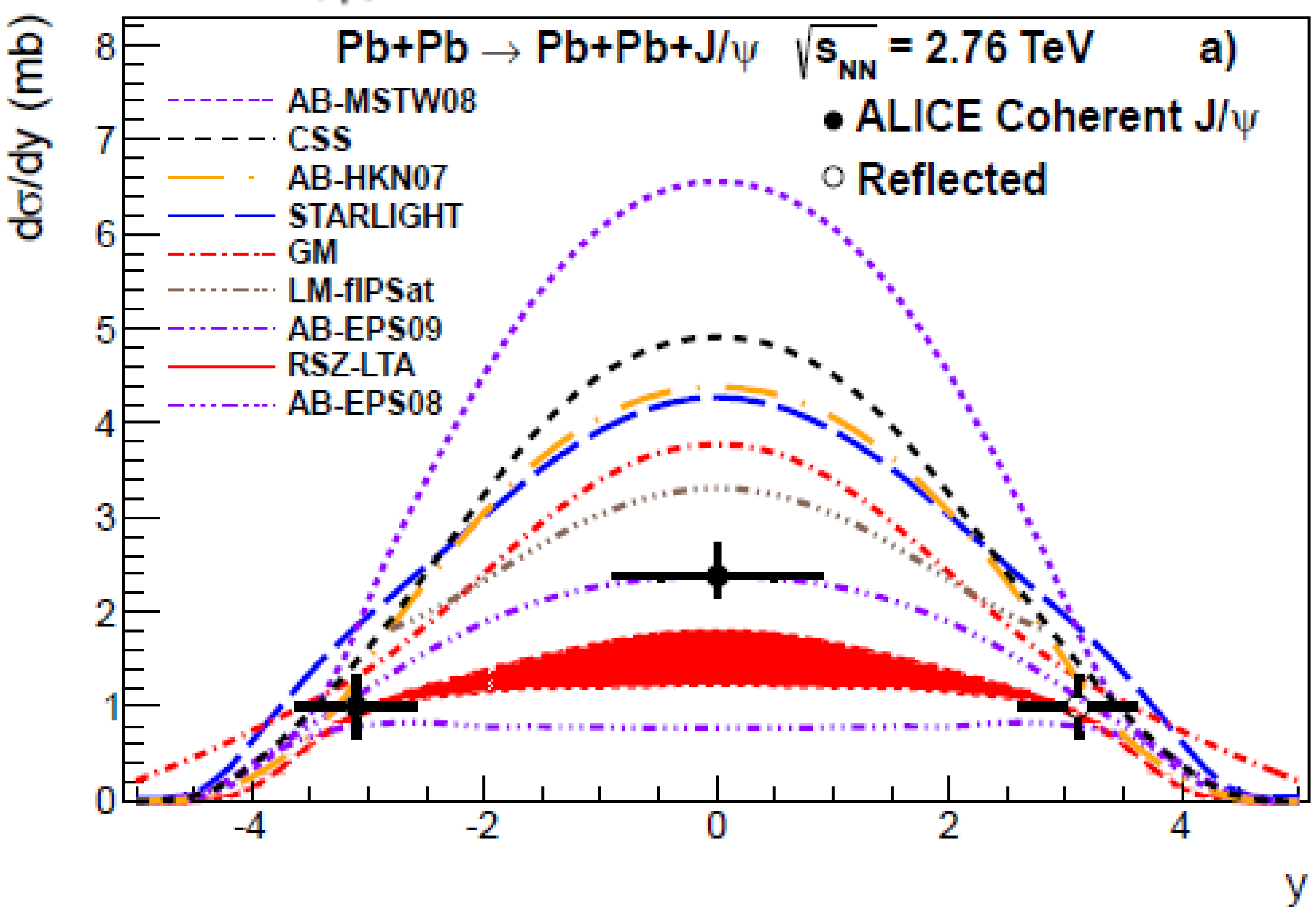
➜ in a cleaner experimental setup;

➜ on firmer theoretical grounds.

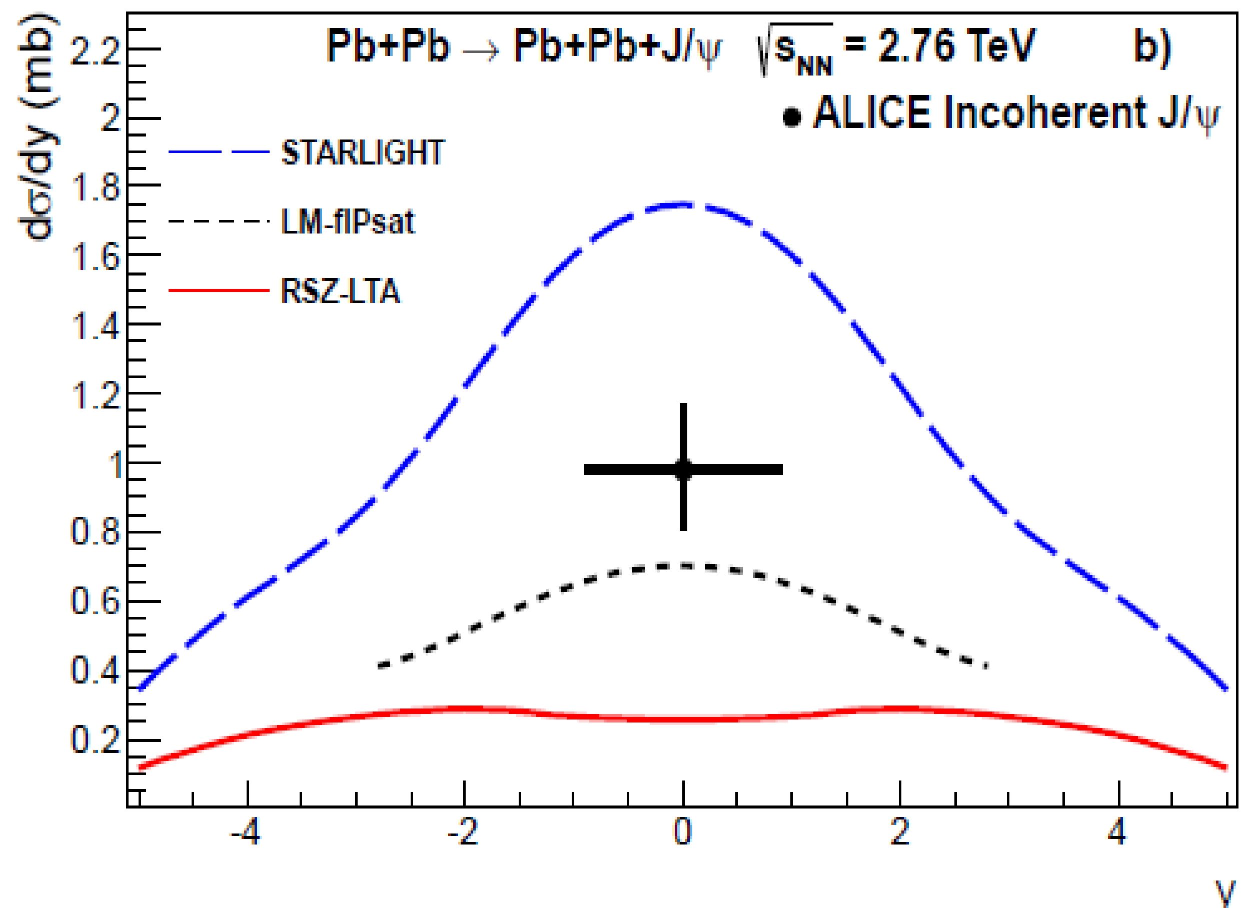


Data *and* theoretical predictions

Coherent J/ψ



Incoherent J/ψ



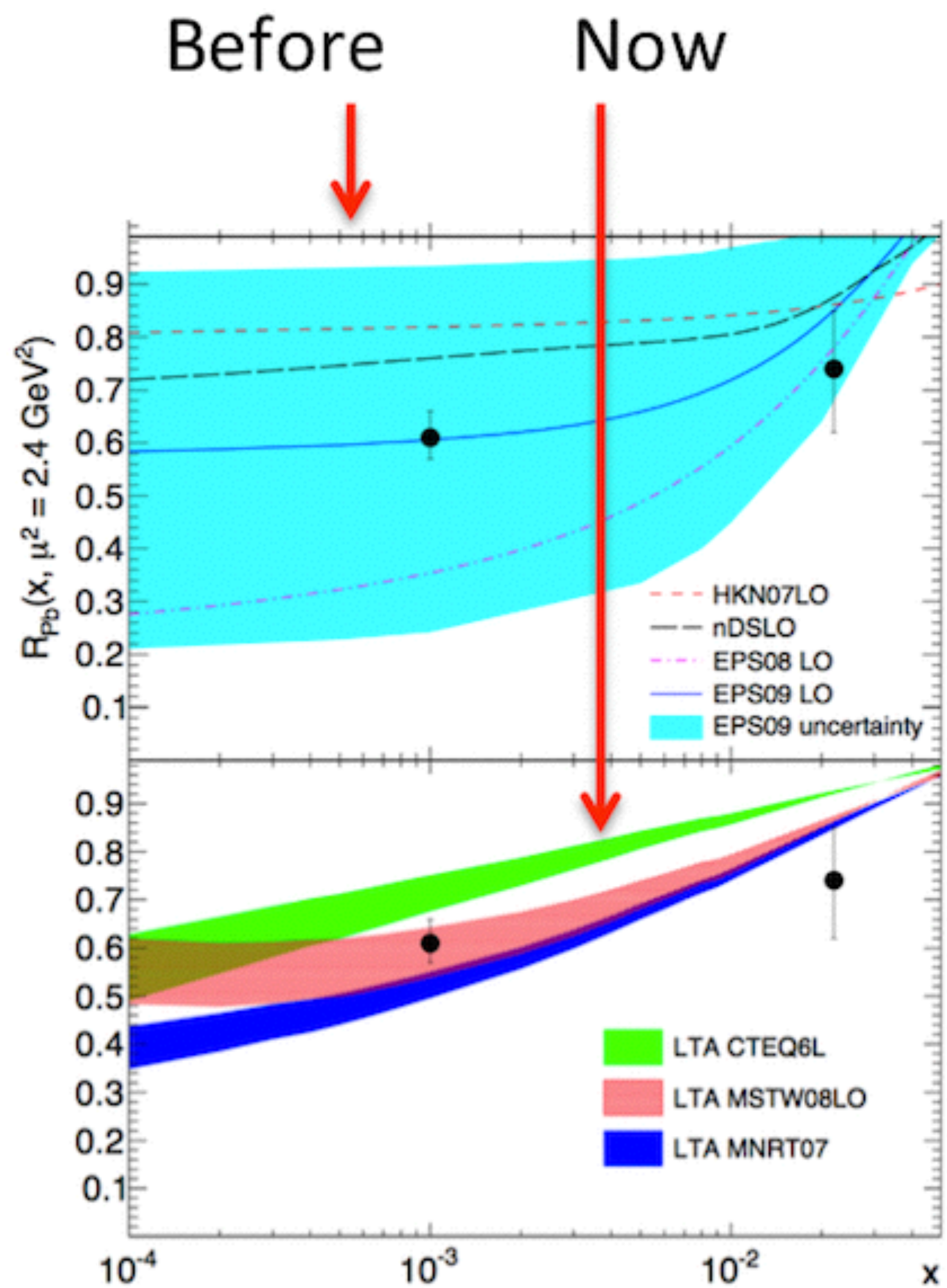
Best agreement with EPS09 shadowing

At mid-rapidity, Bjorken-x $\sim 10^{-3}$

Phys.Lett. B718 (2013) 1273-1283
arXiv:1305.1467 [nucl-ex]

Coherent J/ψ photoproduction

First attempt to use UPC data for constraining the nPDF



PLB 726 (2013) 290

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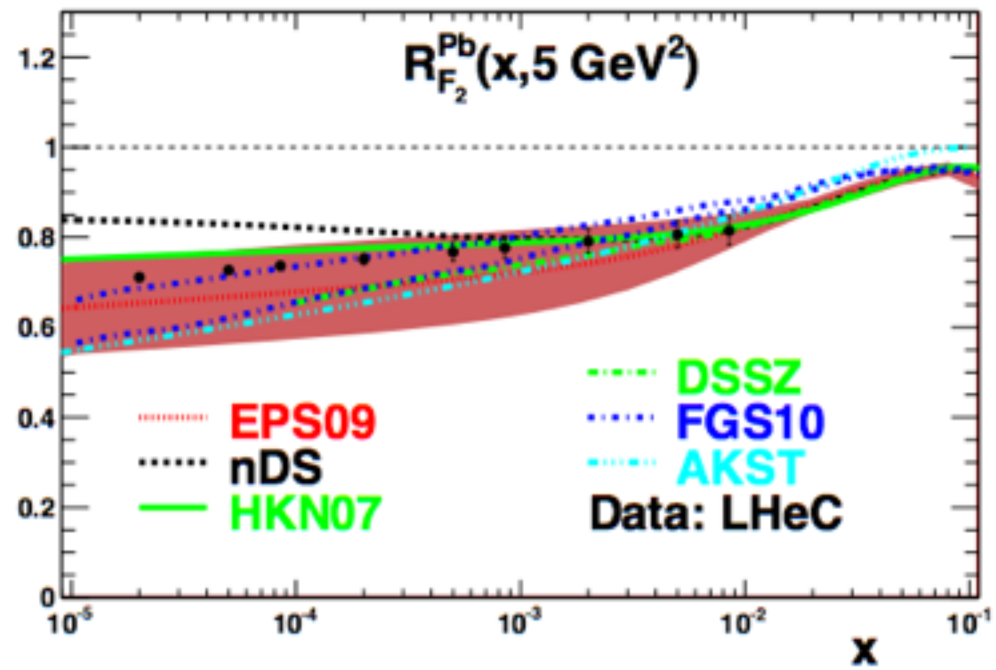
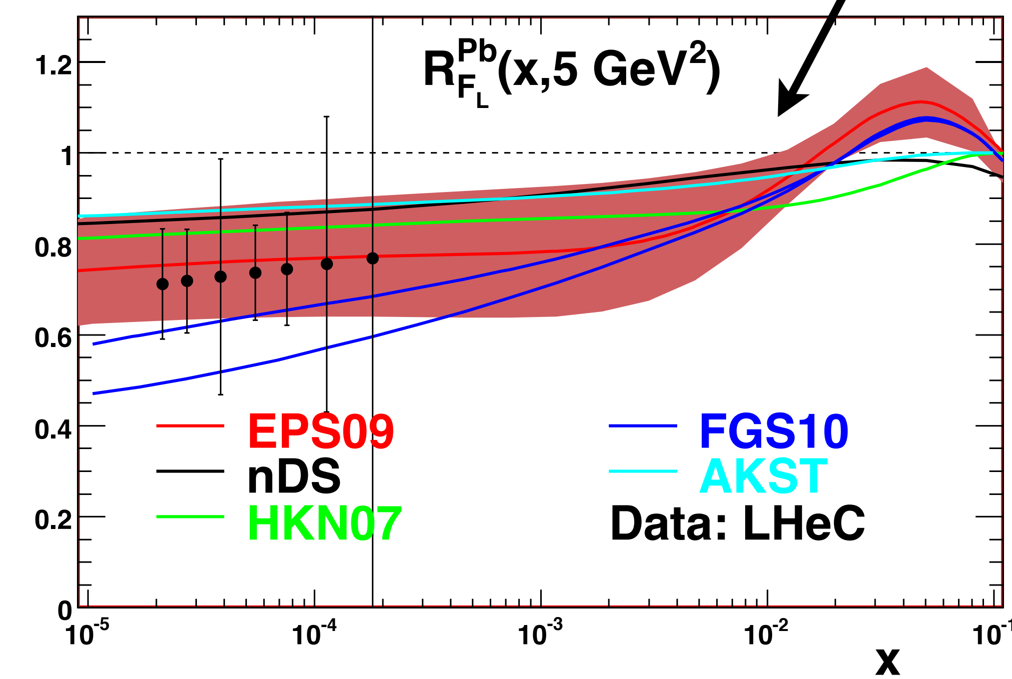
eA inclusive: comparison

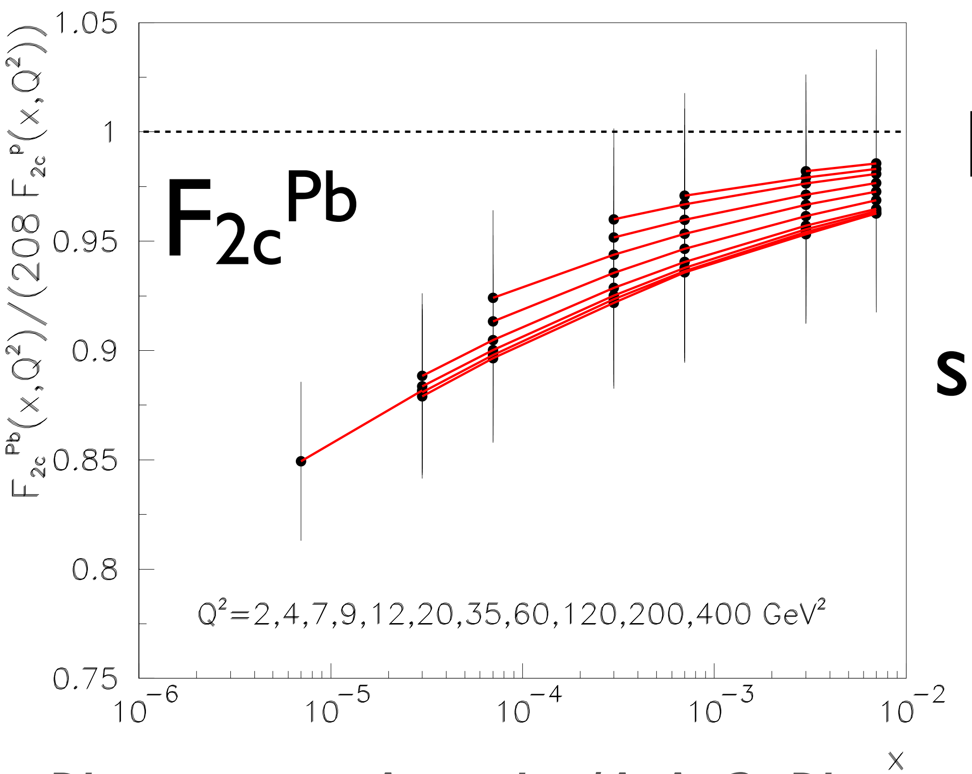
- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x

(Glauberized 3-5 flavor GBW model, NA '02).

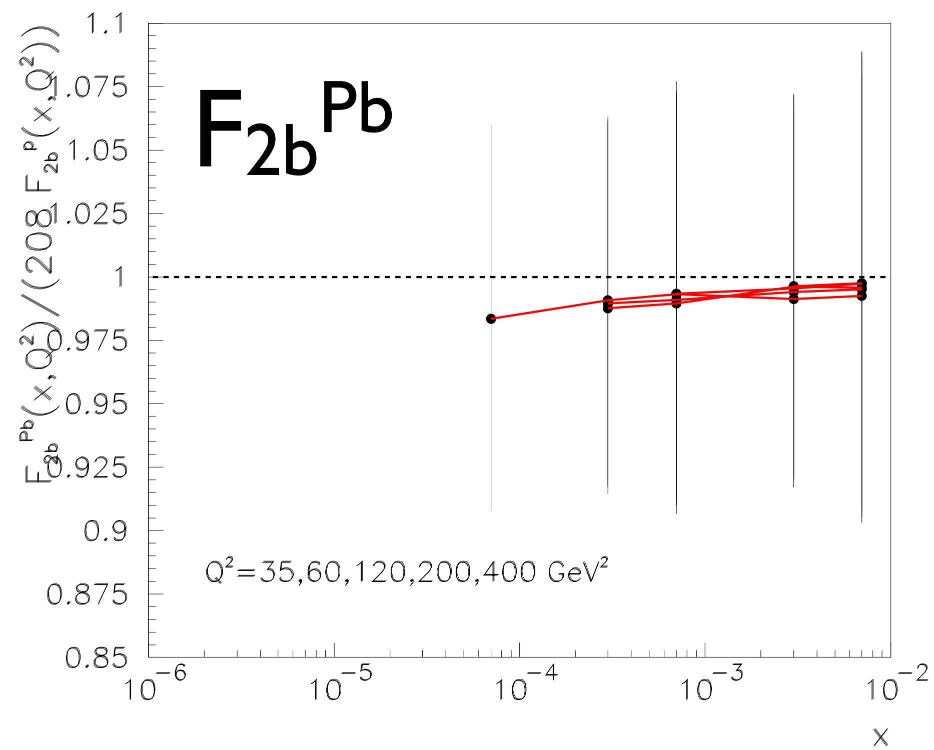
Not optimized!





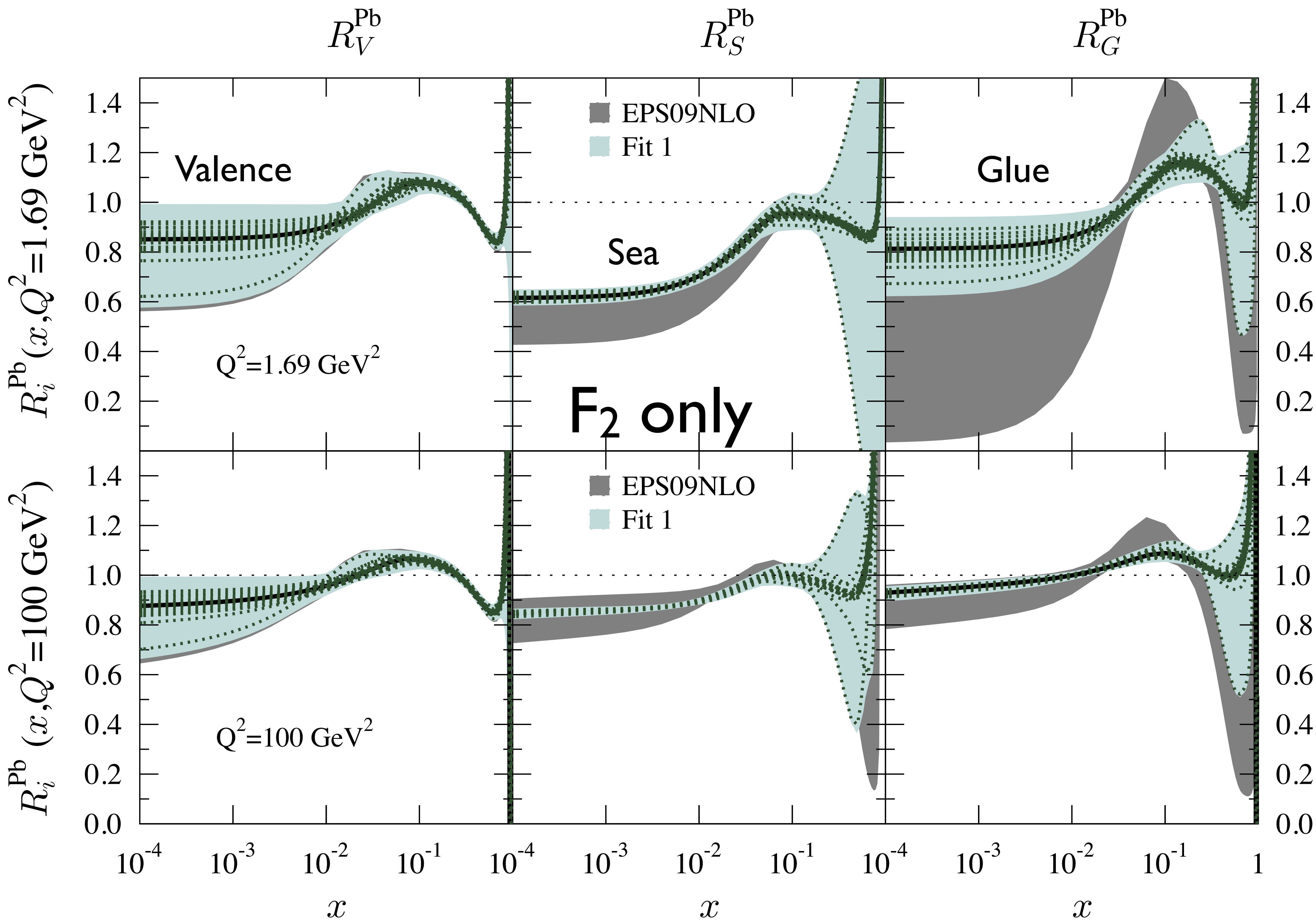


Note the scale!!!



Nuclear PDFs at small x:

- F_2 data substantially reduce the uncertainties in DGLAP analysis; inclusion of charm, beauty; and F_L also give constraints.



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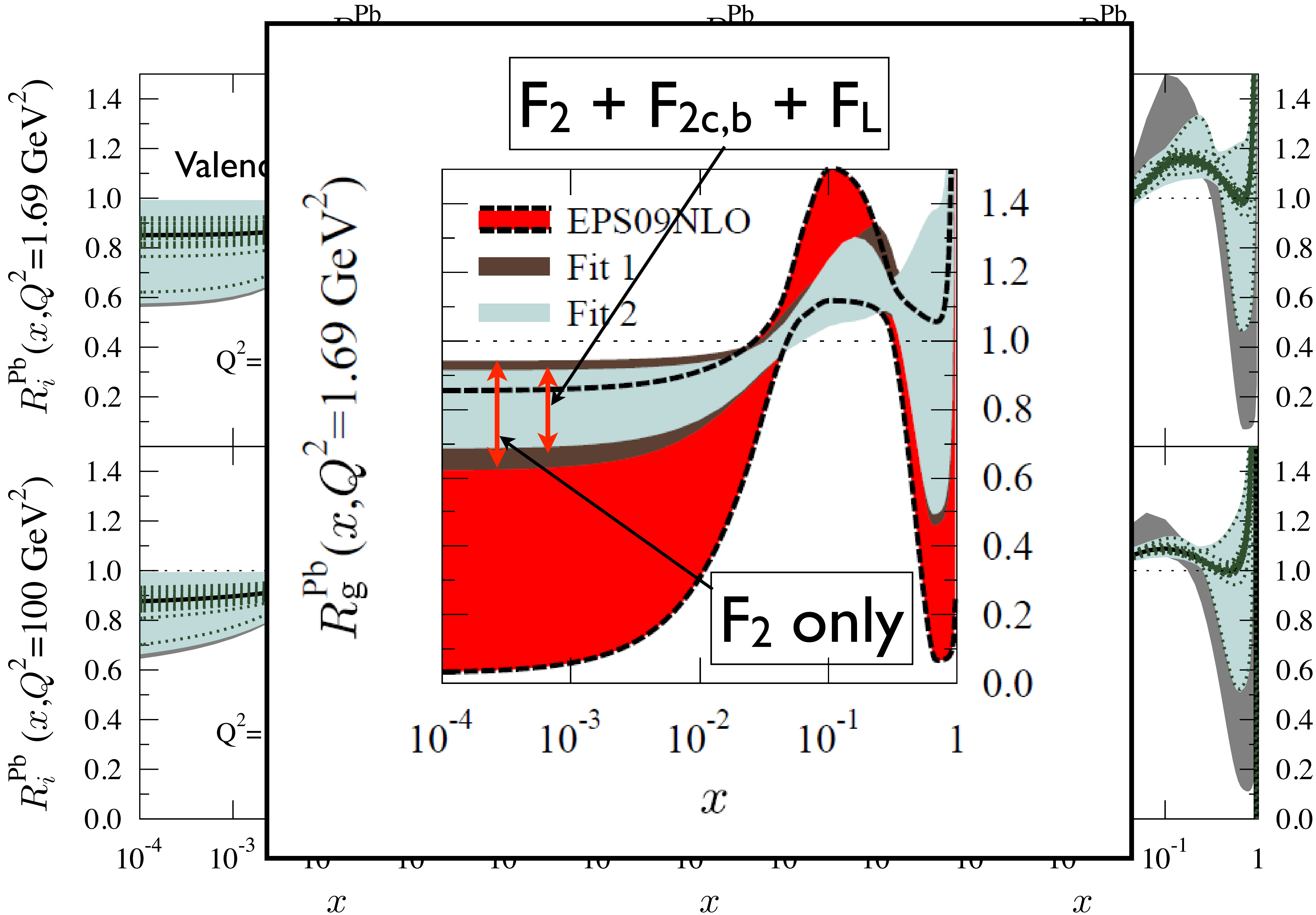
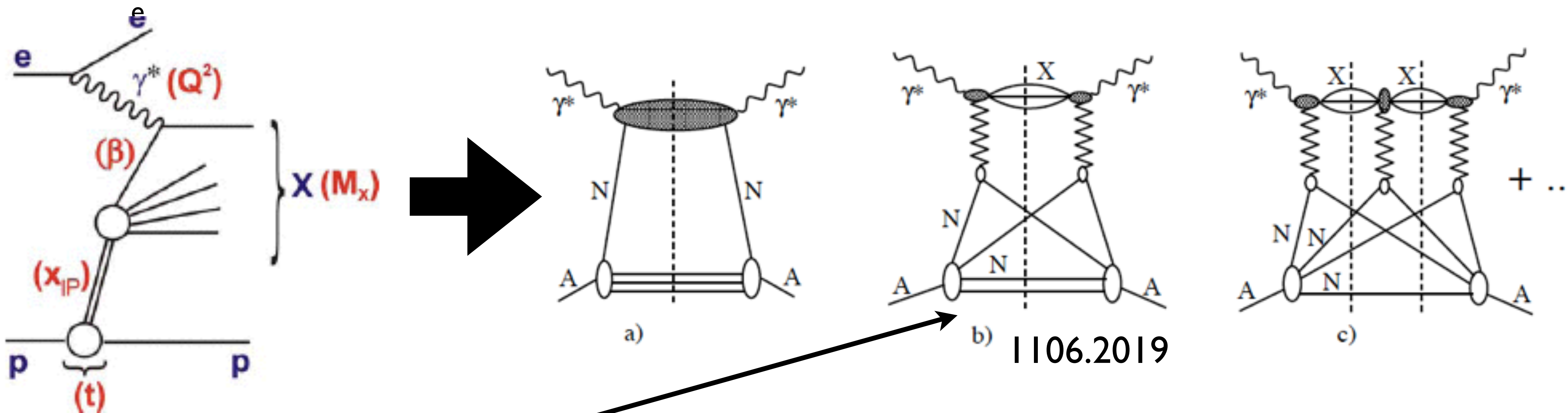
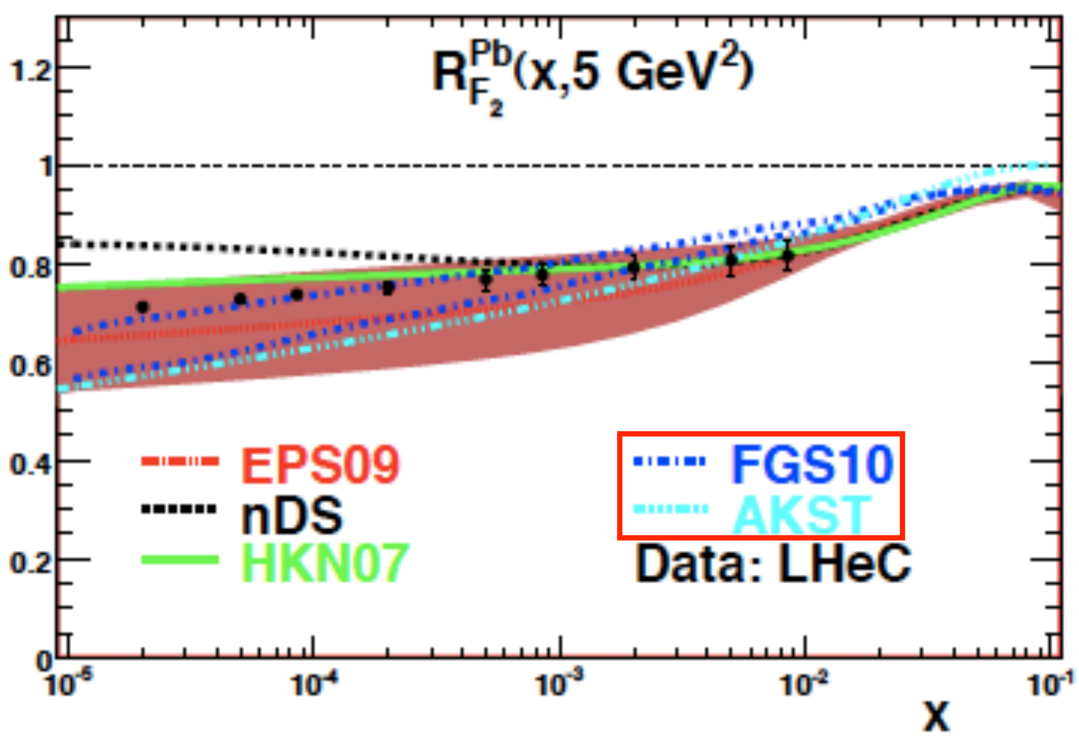
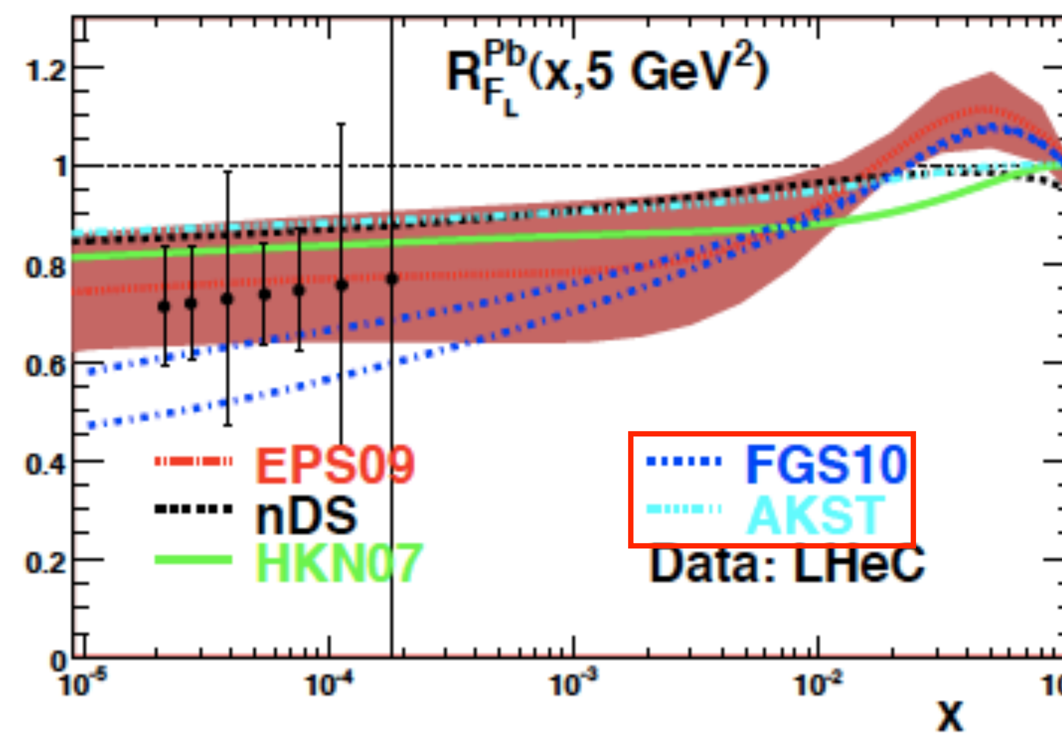


Diffraction in ep and shadowing:

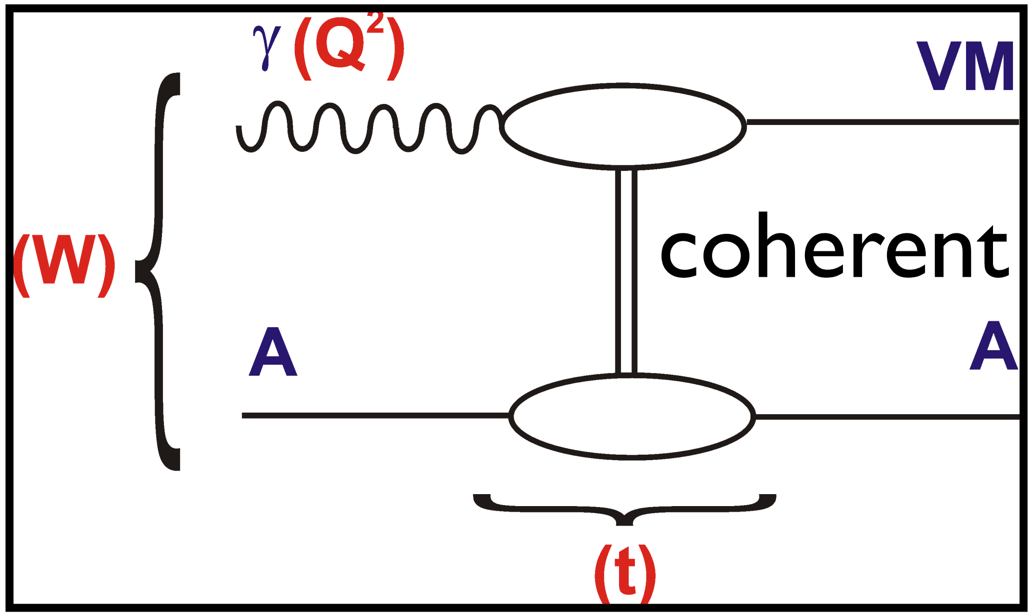


- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the 'benchmark' for new effects.



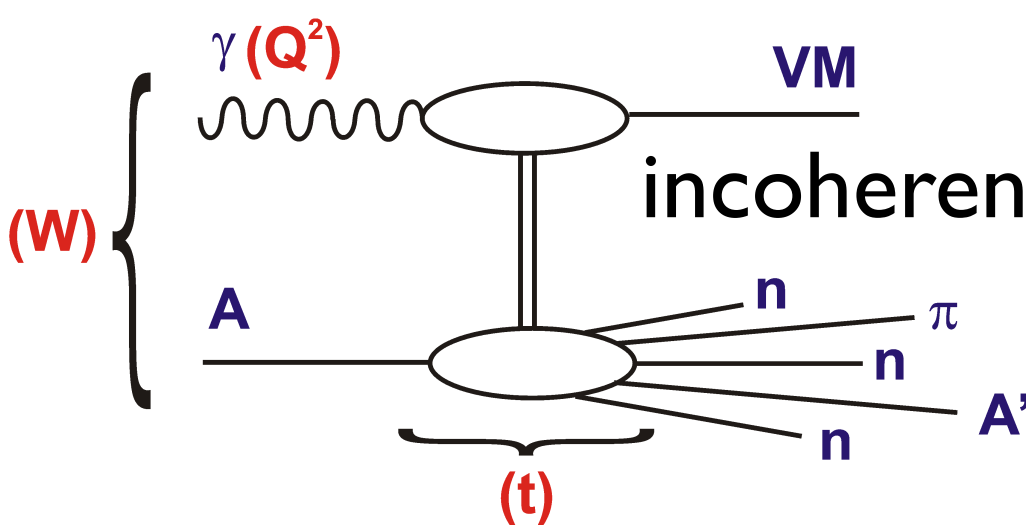


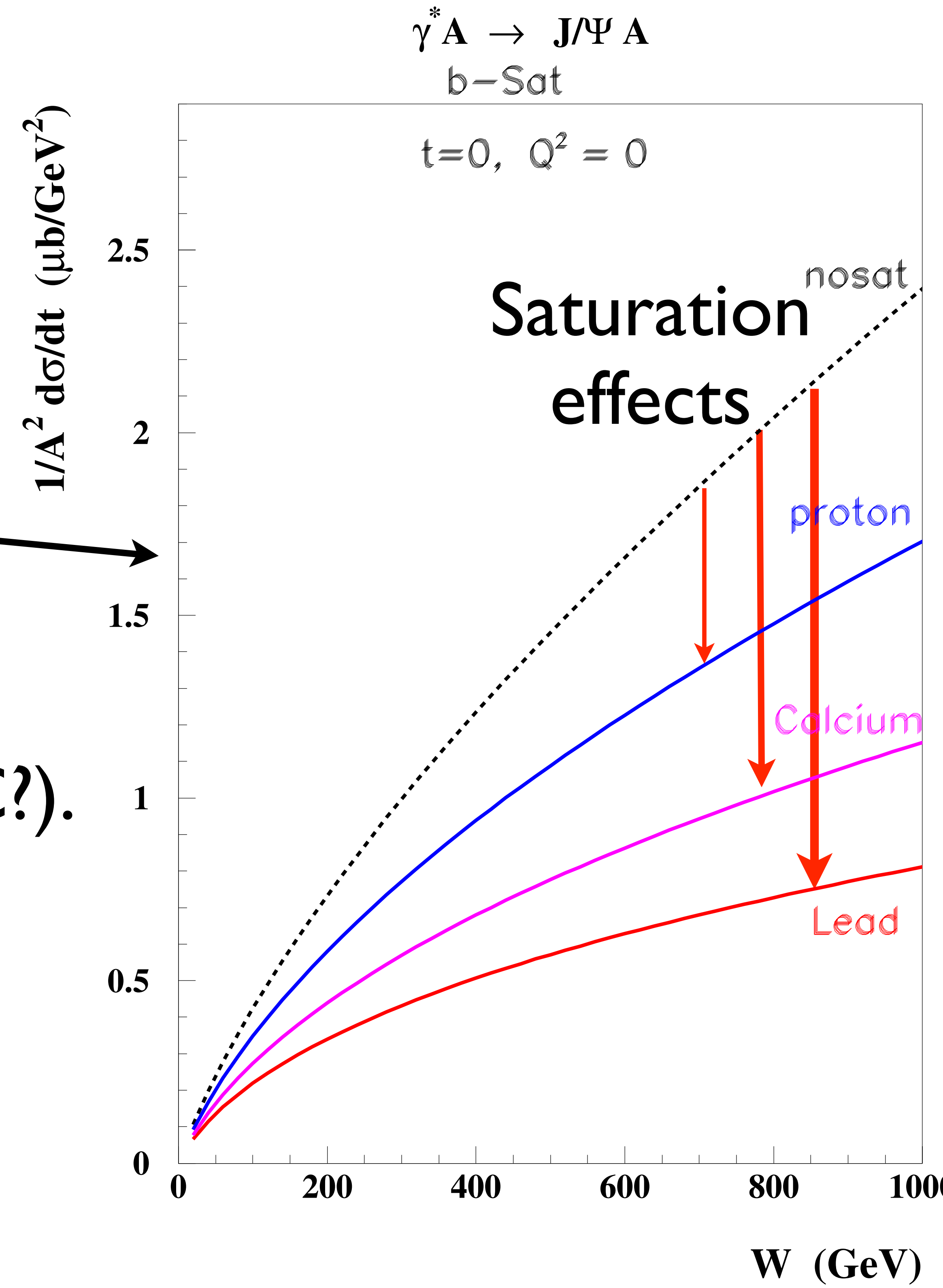
Elastic VM production in eA:



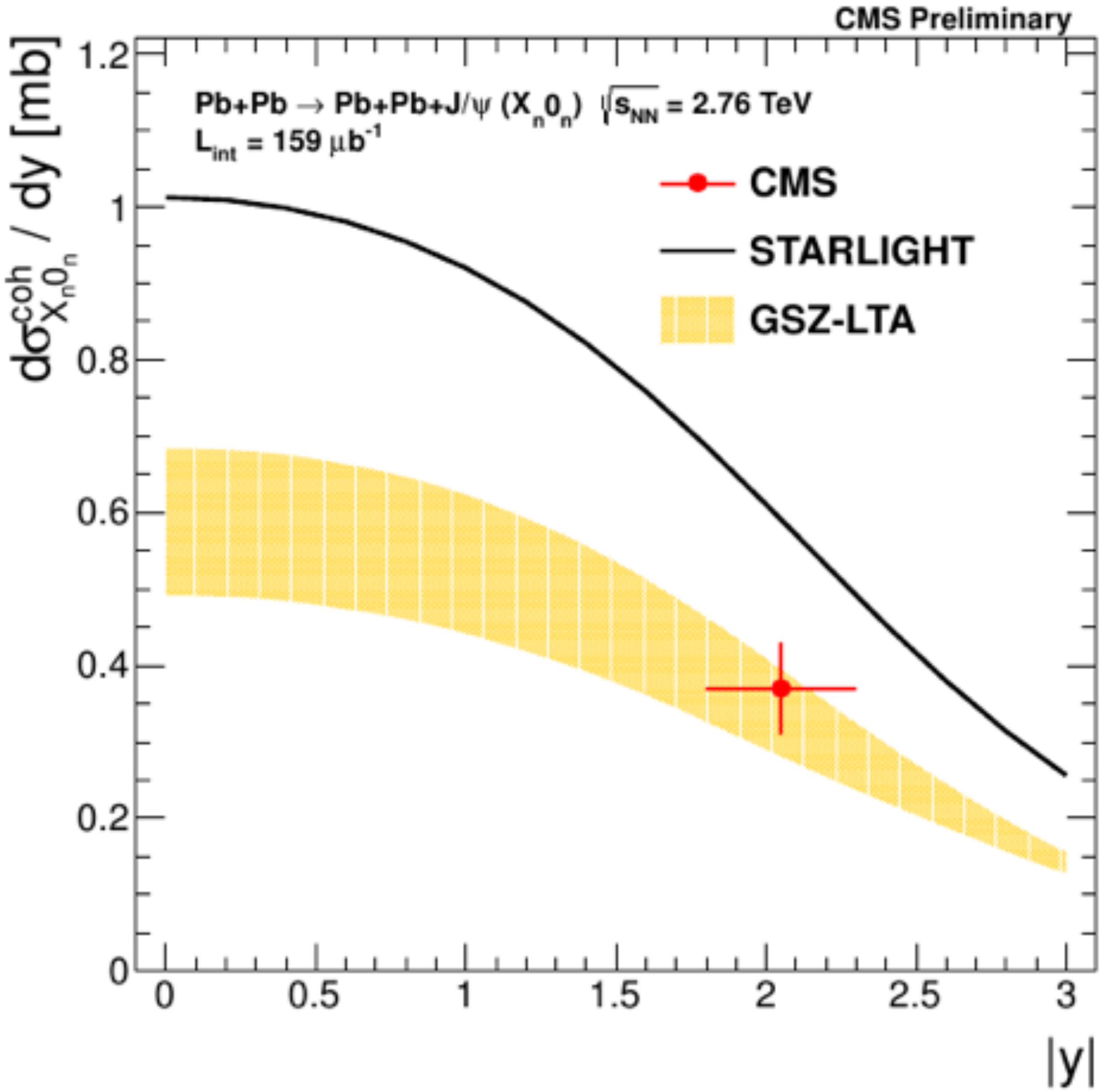
- For the coherent case, predictions available.

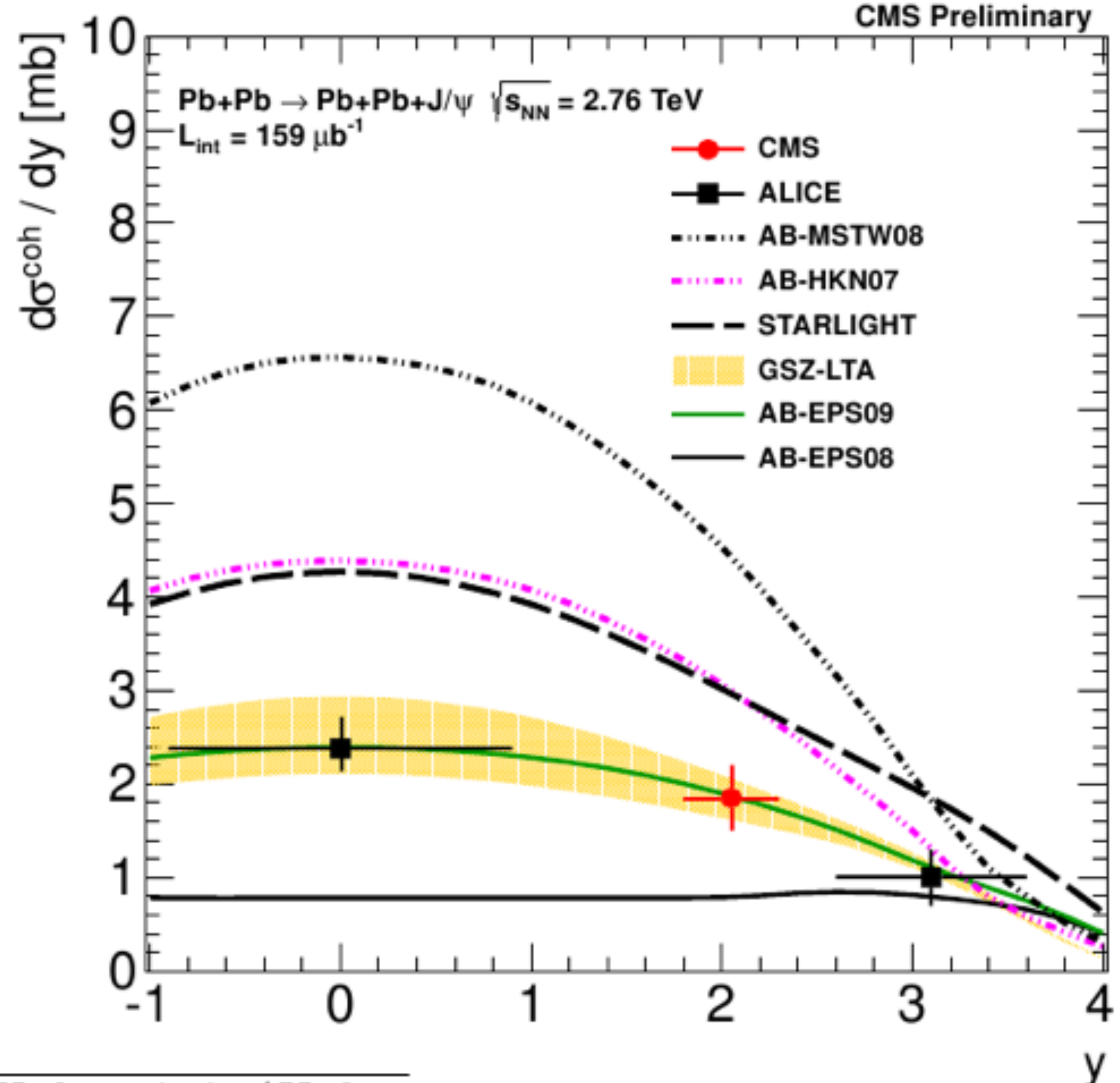
- Challenging experimental problem (neutron tagging in ZDC?).





Coherent J/ψ photoproduction

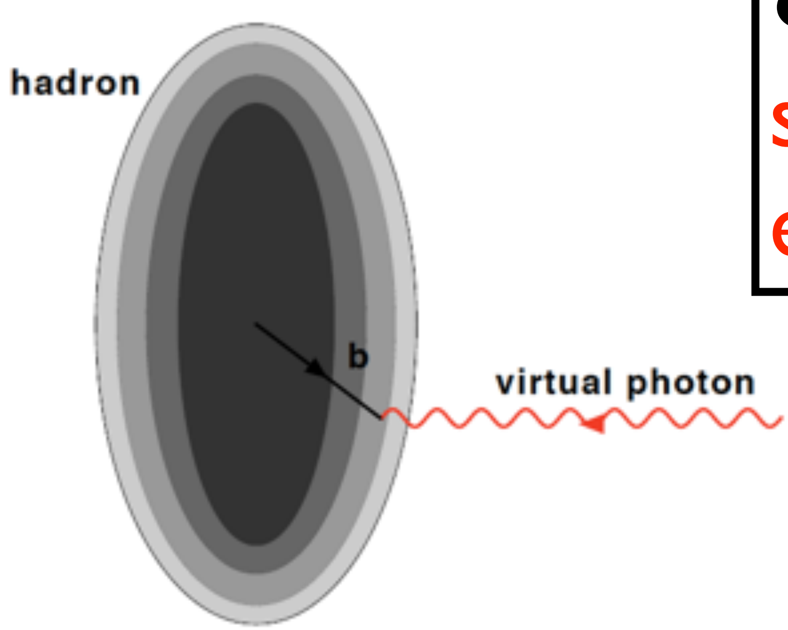




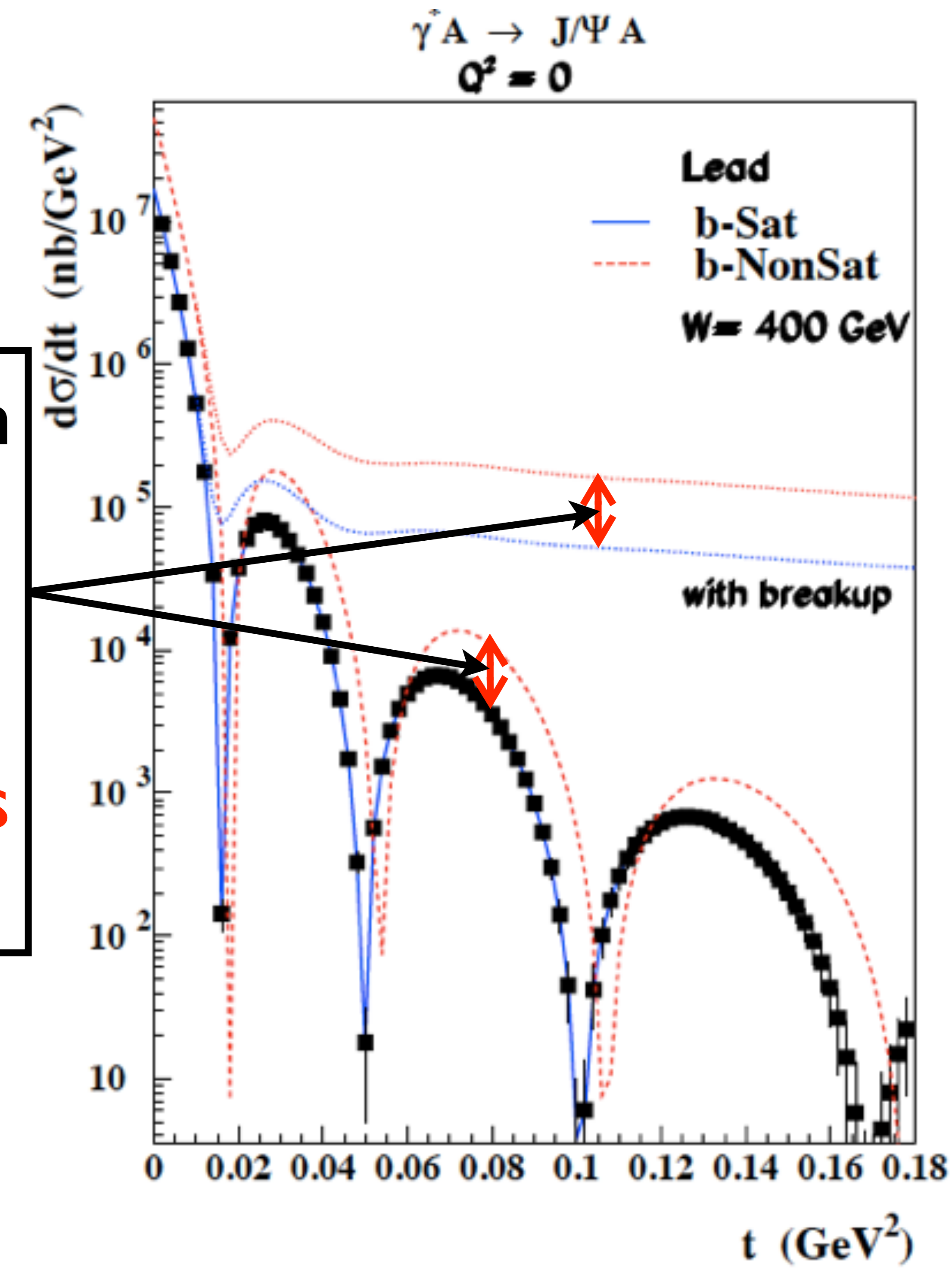
J/ψ with $p_T < 0.15$ GeV/c	X_nX_n/X_n0_n	$1_n0_n/X_n0_n$	$1_n1_n/X_n0_n$
Data	0.36±0.04	0.26±0.03	0.03±0.01
STARLIGHT	0.37	N/A	0.02
GSZ	0.32	0.30	0.02

Transverse scan: elastic VM

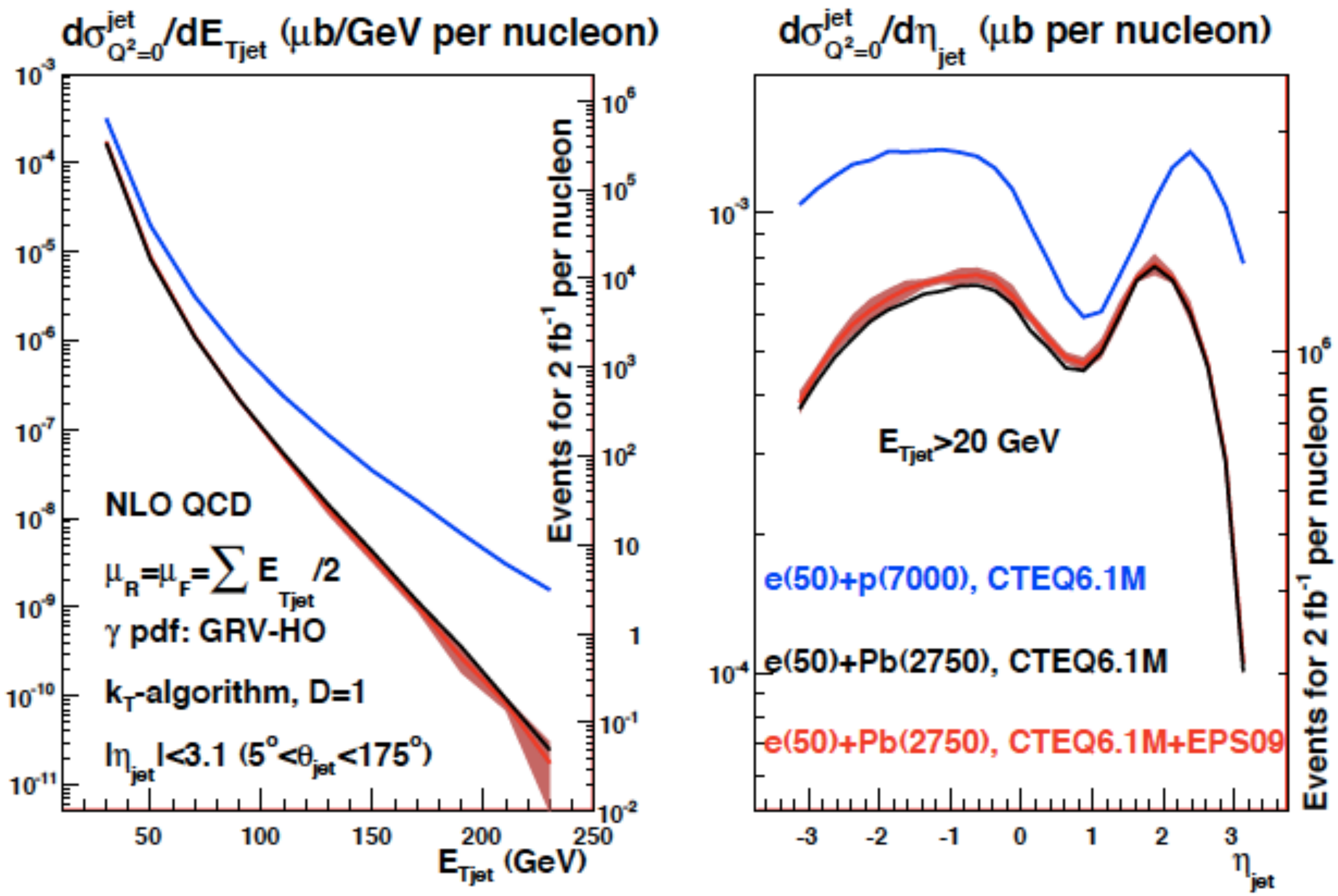
- t-differential measurements give a gluon tranverse mapping of the hadron/nucleus.



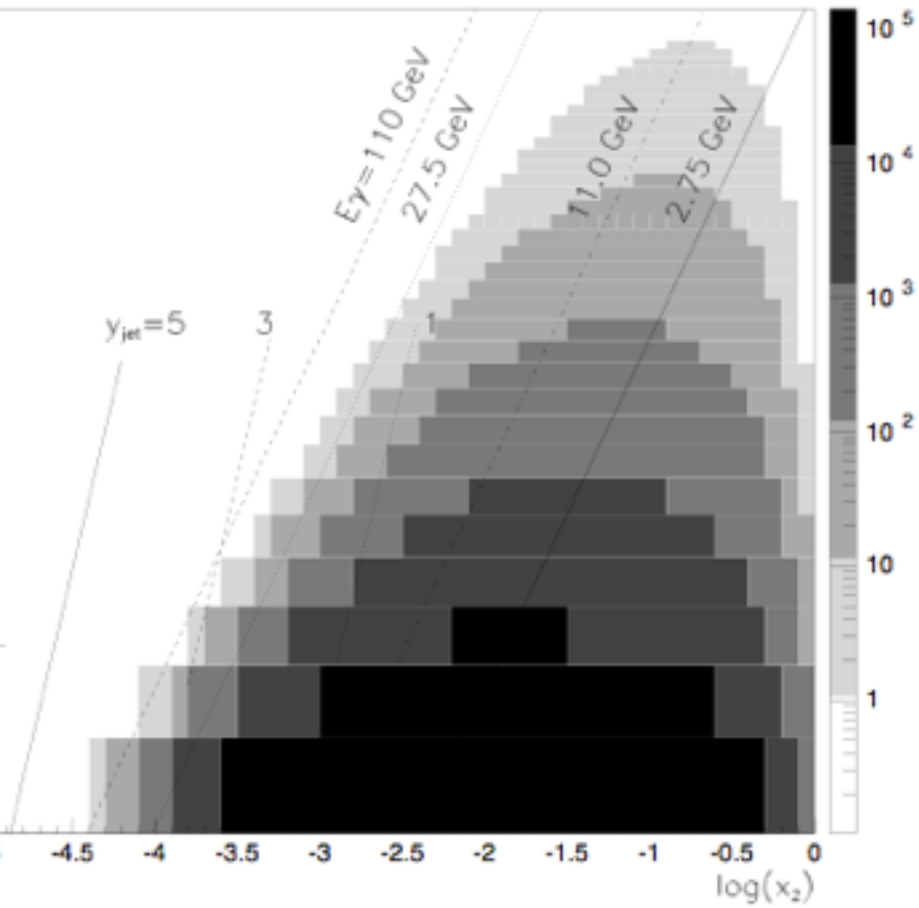
- Large extent in t with good precision.
- Sizable saturation effects expected.



Jets:



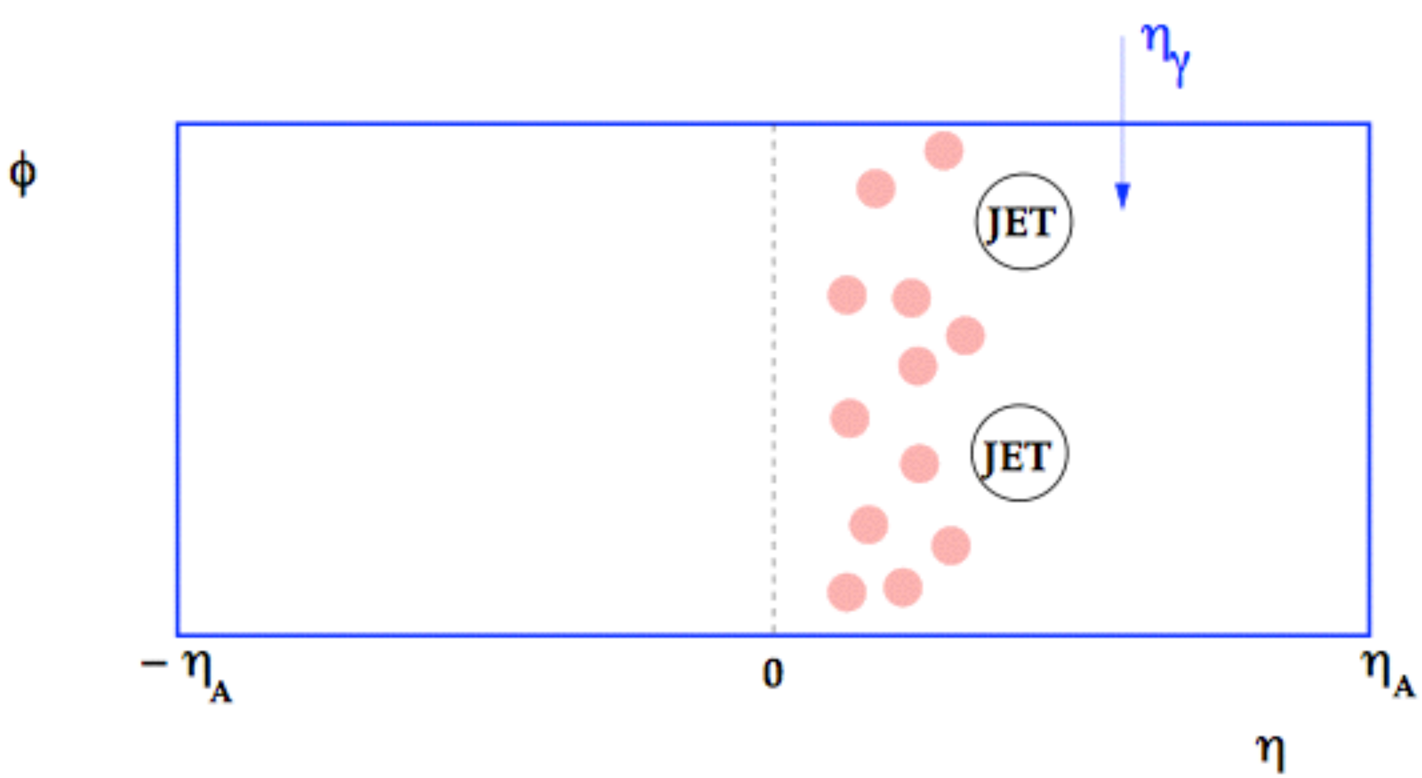
- Jets: large E_T even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.



Vogt, S.White, MS, 2005

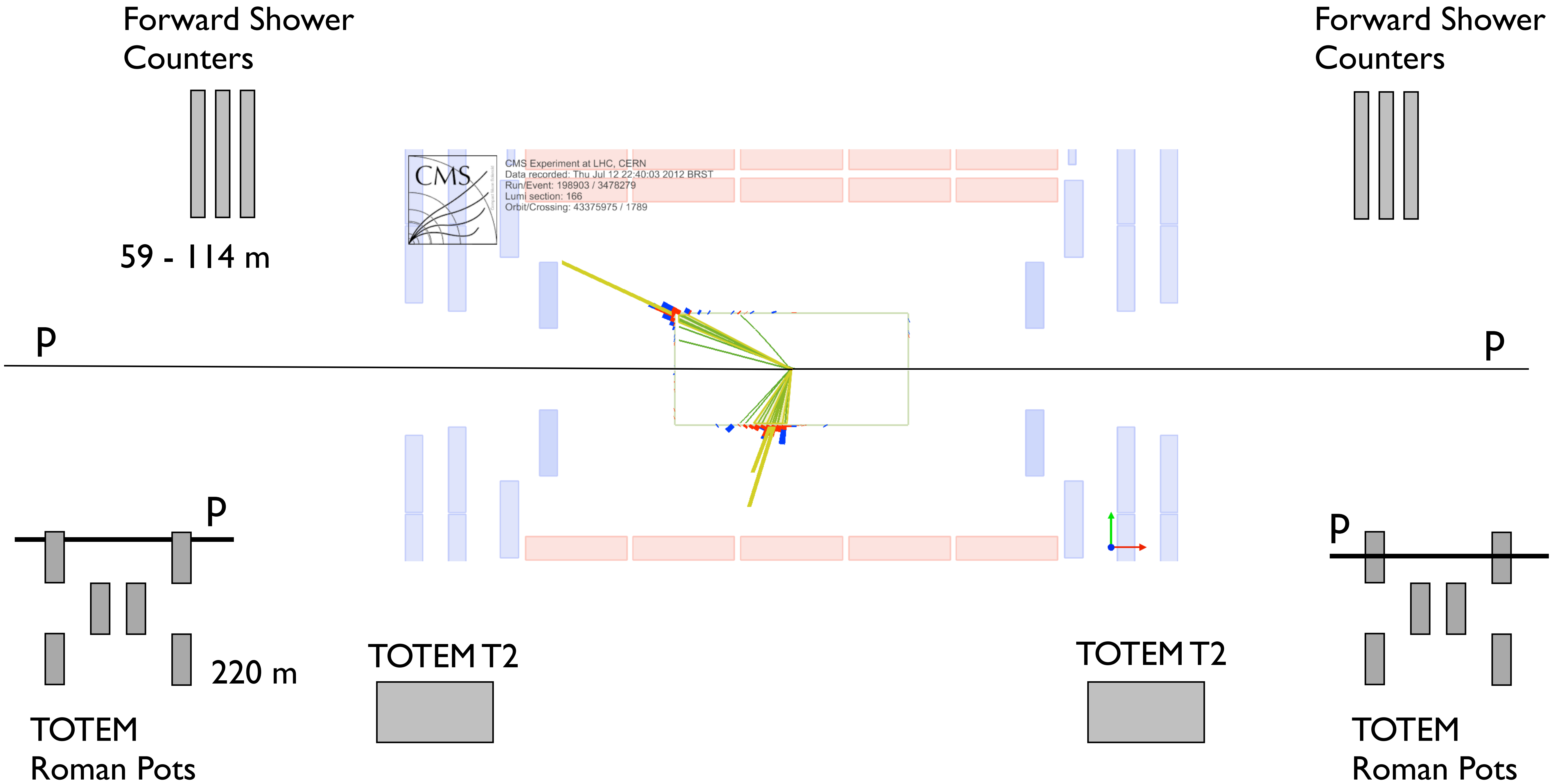
Expected rate of dijet photoproduction for a 1 month LHC Pb+Pb run at 0.4×10^{27} $cm^{-2}s^{-1}$. Rates are counts per bin of ±0.25 x_2 and 2 GeV/c in p_T. Large rates for b-meson jets as well.

Many more important handles to study dynamics, for example associated multiplicity at different rapidities,...



UPC induced direct photon hard diffraction: AA––> AA + 2jets +X

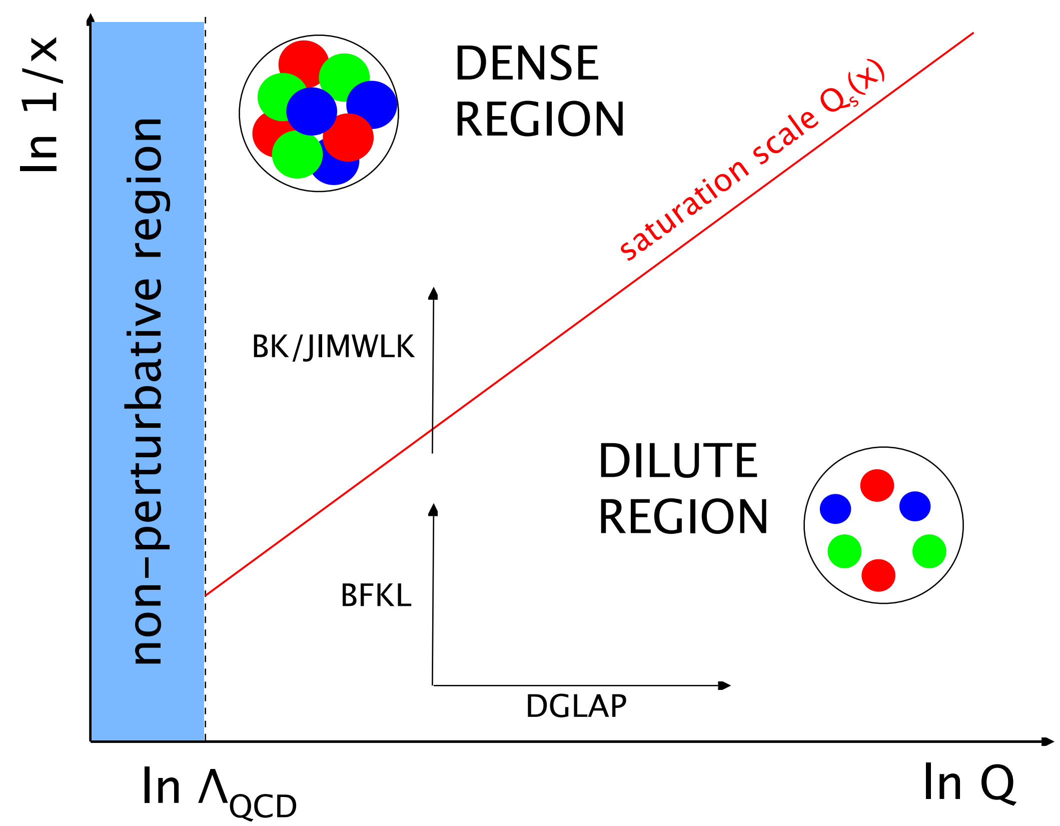
Dijet: CMS+TOTEM

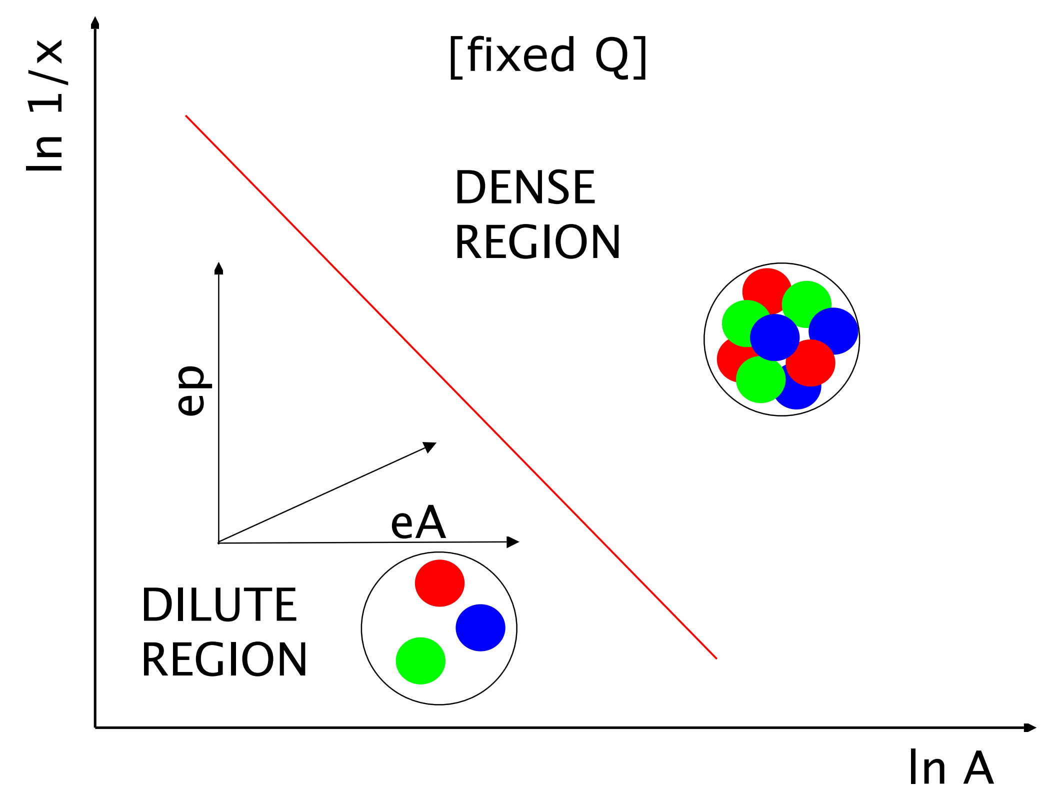


CMS: |η| < 5 **T2: 5.3 < |η| < 6.5** **FSC: 6 < |η| < 8** **TOTEM RP** **very large rapidity coverage !**

Summary:

- ***At an LHeC@CERN***:
  - ➜ High-precision tests of collinear factorization(s) and determination of PDFs.
  - ➜ Unprecedented access to small x in p and A.
  - ➜ Novel sensitivity to physics beyond standard pQCD.
  - ➜ Stringent tests of QCD radiation and hadronization.
  - ➜ Transverse scan of the hadron/nucleus at small x.
  - ➜ ... with implications on our understanding of QGP.
- **The LHeC will answer the question of saturation/ non-linear dynamics.**





Outlook:

• With CERN and NuPECC mandate to further motivate the physics case and produce a TDR around 2015, several items have to be done/improved:

➜ Refine DGLAP fits with flavour decomposition (include neutrino data, relax assumptions) and optimized F_L scenarios, and LHC data.
➜ Monte Carlo generators!!!
➜ Studies on diffraction: separation of coherent from incoherent, ndPDFs, dijets,...
➜ Large x, EW bosons.
➜ Nuclear GPDs: nuclear DVCS etc.
➜ eD.
➜ Jet reconstruction, angular decorrelation,...
➜ ...

Thanks for your attention!

→ Synergies with EIC in some of these items exist.

Backup:

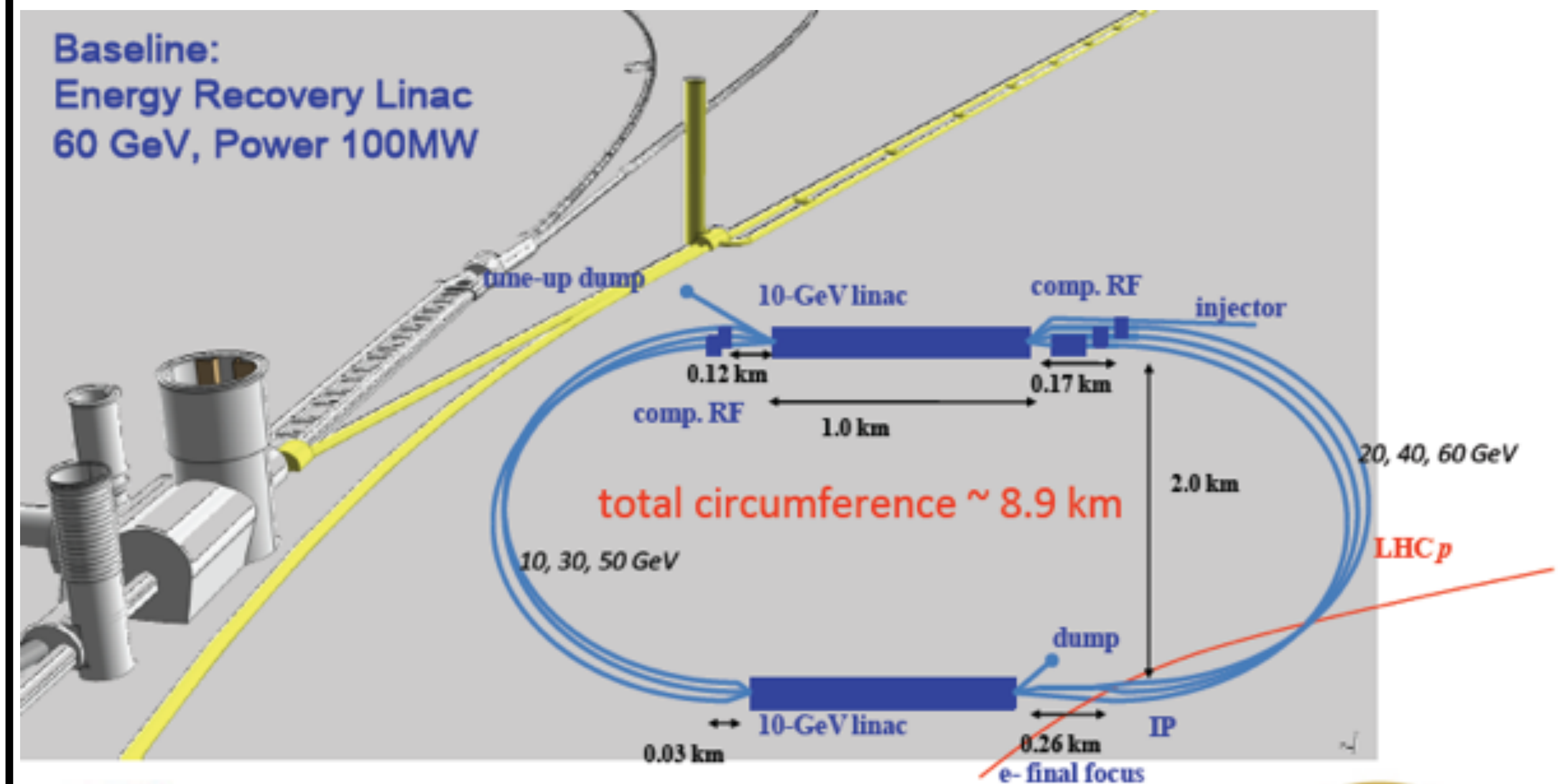
LHeC

Accelerator:

electron beam	LR ERL	LR
e- energy at IP[GeV]	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	10	0.44
polarization [%]	90	90
bunch population [10^9]	2.0	1.6
e- bunch length [mm]	0.3	0.3
bunch interval [ns]	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.12	0.14
full crossing angle [mrad]	0	0
geometric reduction H_{hg}	0.91	0.94
repetition rate [Hz]	N/A	10
beam pulse length [ms]	N/A	5
ER efficiency	94%	N/A
average current [mA]	6.6	5.4
tot. wall plug power[MW]	100	100

CDR numbers for luminosity, to be considered now as lower bounds.

$\sqrt{s}\simeq 0.8$ TeV/nucleon

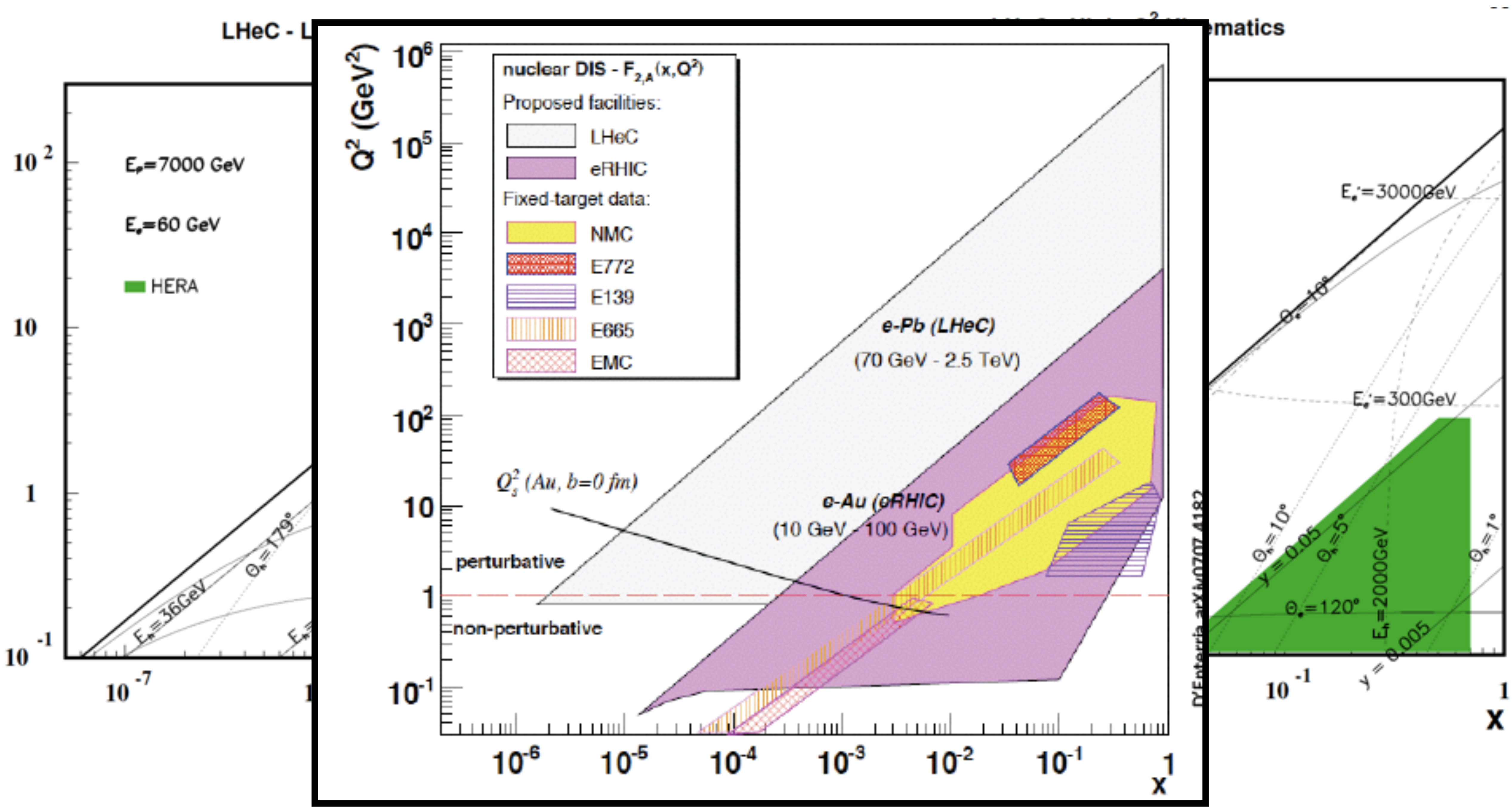


Luminosity per nucleon

$$L_{eN} = \begin{cases} 9\times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Nominal Pb)} \\ 1.6\times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Ultimate Pb)} \end{cases}$$

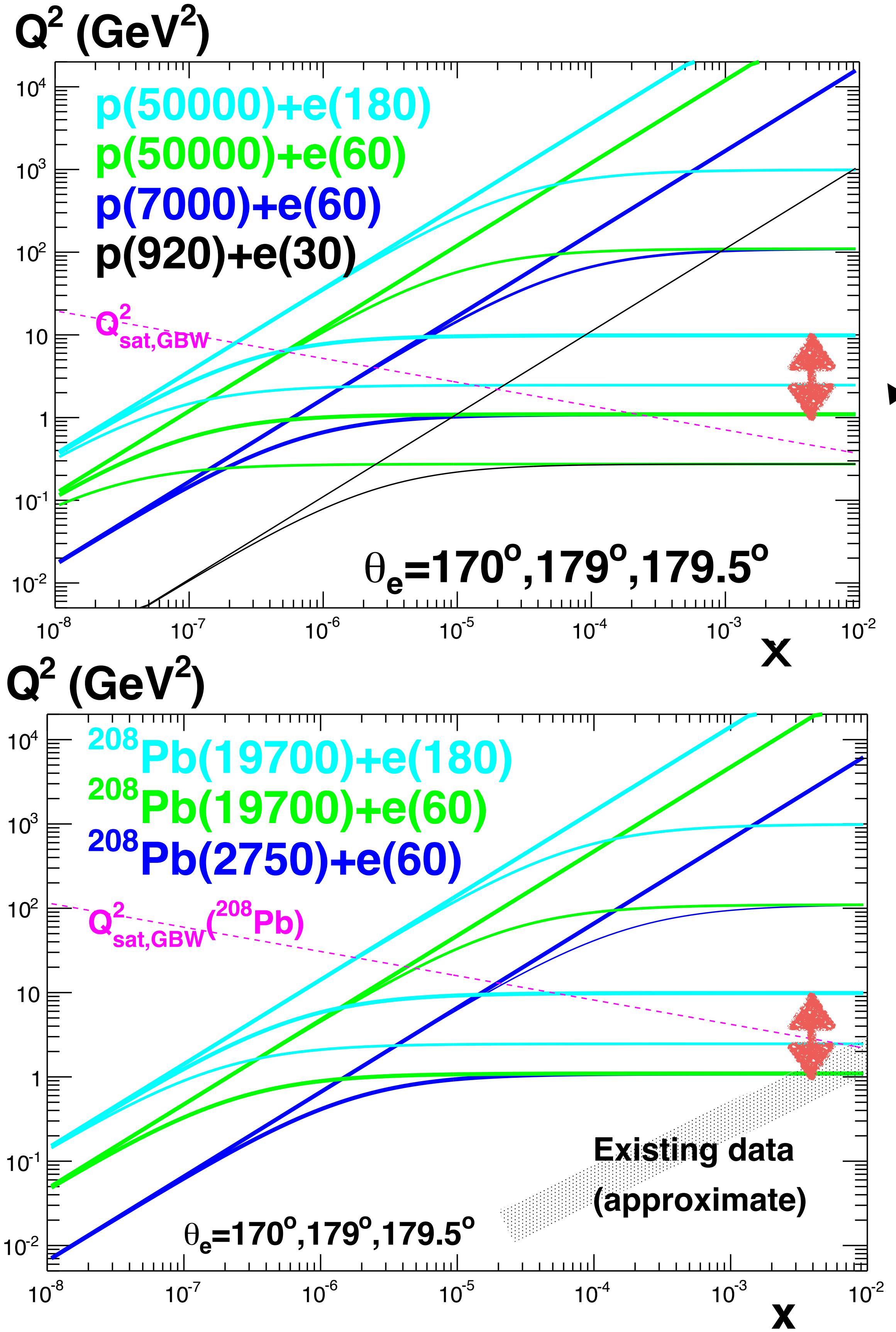
eD: $L_{eN}=AL_{eA}>\sim 3\times 10^{31}$ $cm^{-2}s^{-1}$

Kinematics:



- Small-x demands 1 degree acceptance.
- Higher luminosity would benefit high-x and Q^2 studies.

Kinematics for FHeC:



- Obvious extension of the kinematics.

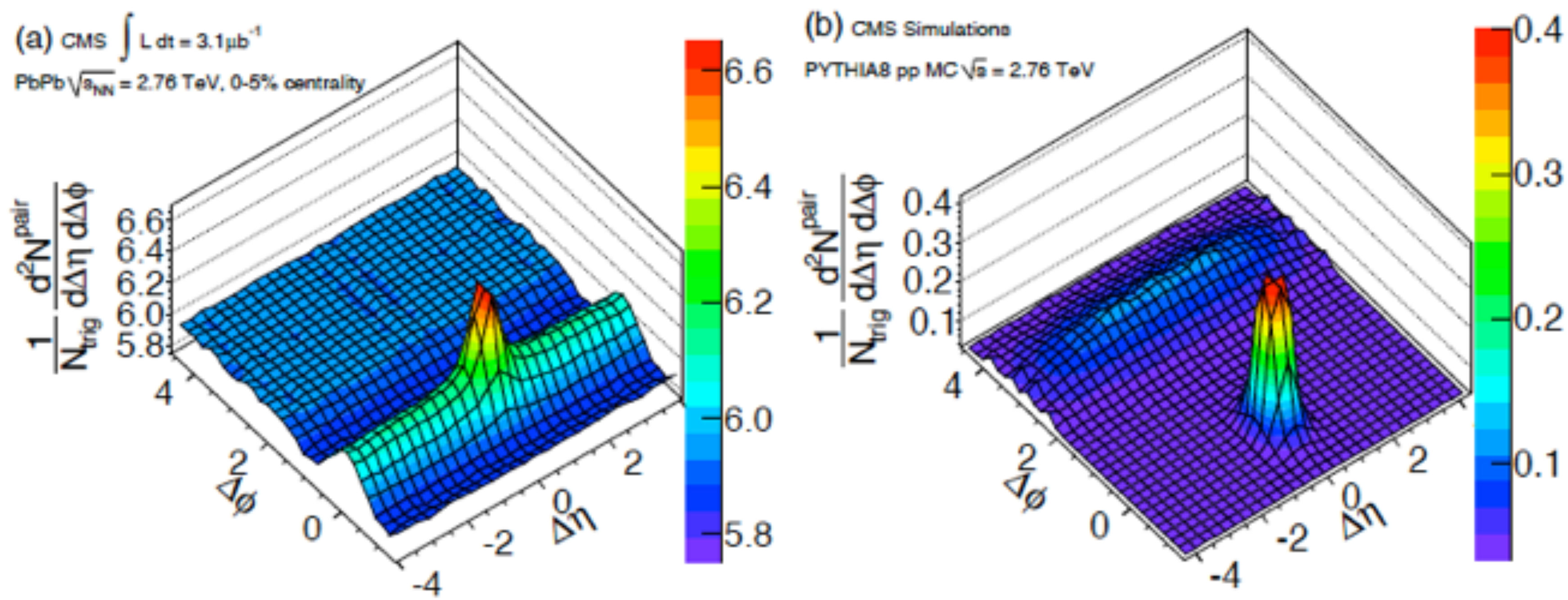
- Larger electron energy drastically compromises small-x unless we can enlarge substantially the acceptance for e.

LHC studies: PbPb

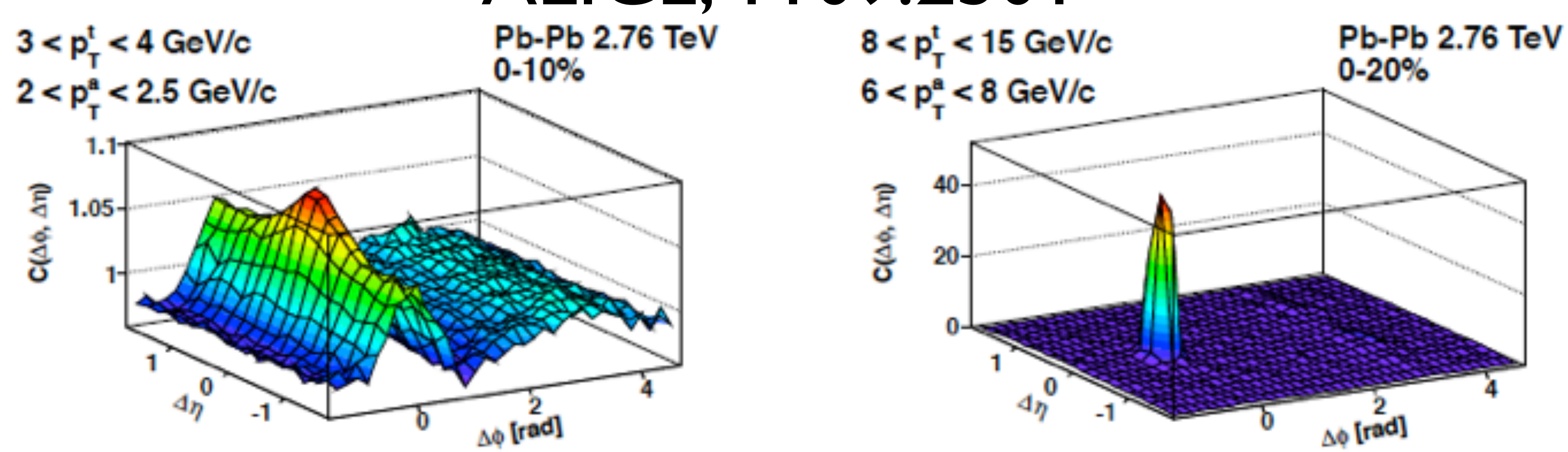
→ Benchmarking: EW bosons or VM production in UPCs, both sensitive to nPDFs.

→ Search for 'non-standard' physics like saturation: multiplicities, the ridge,…

CMS, 1105.2438

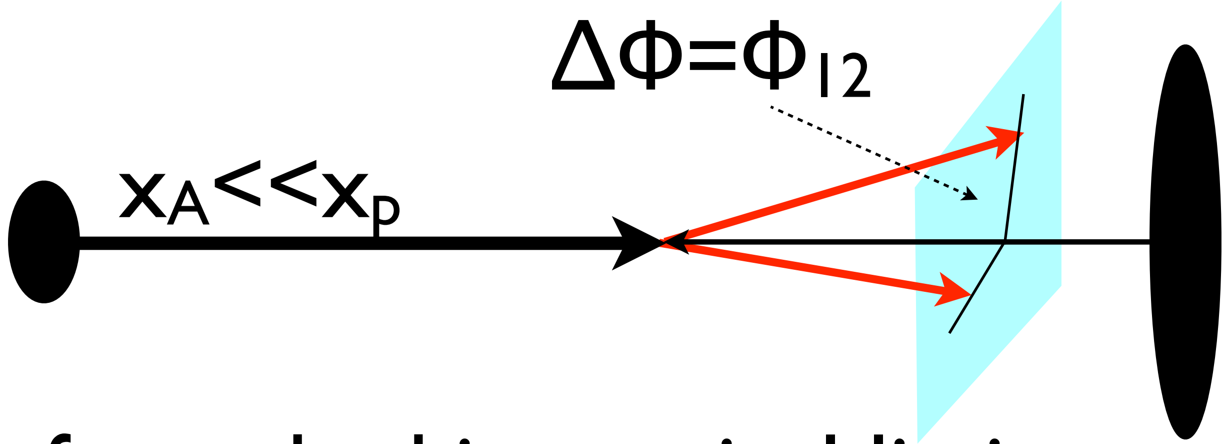


ALICE, 1109.2501

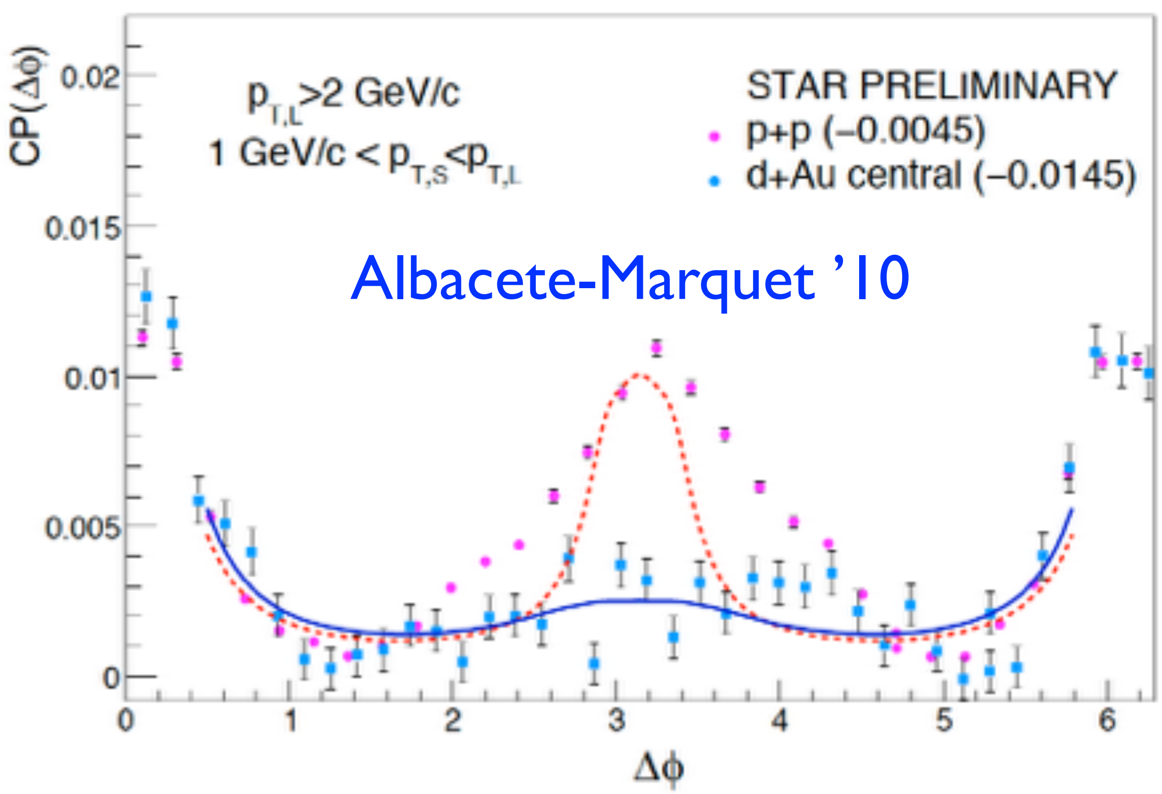


Dihadron azimuthal decorrelation:

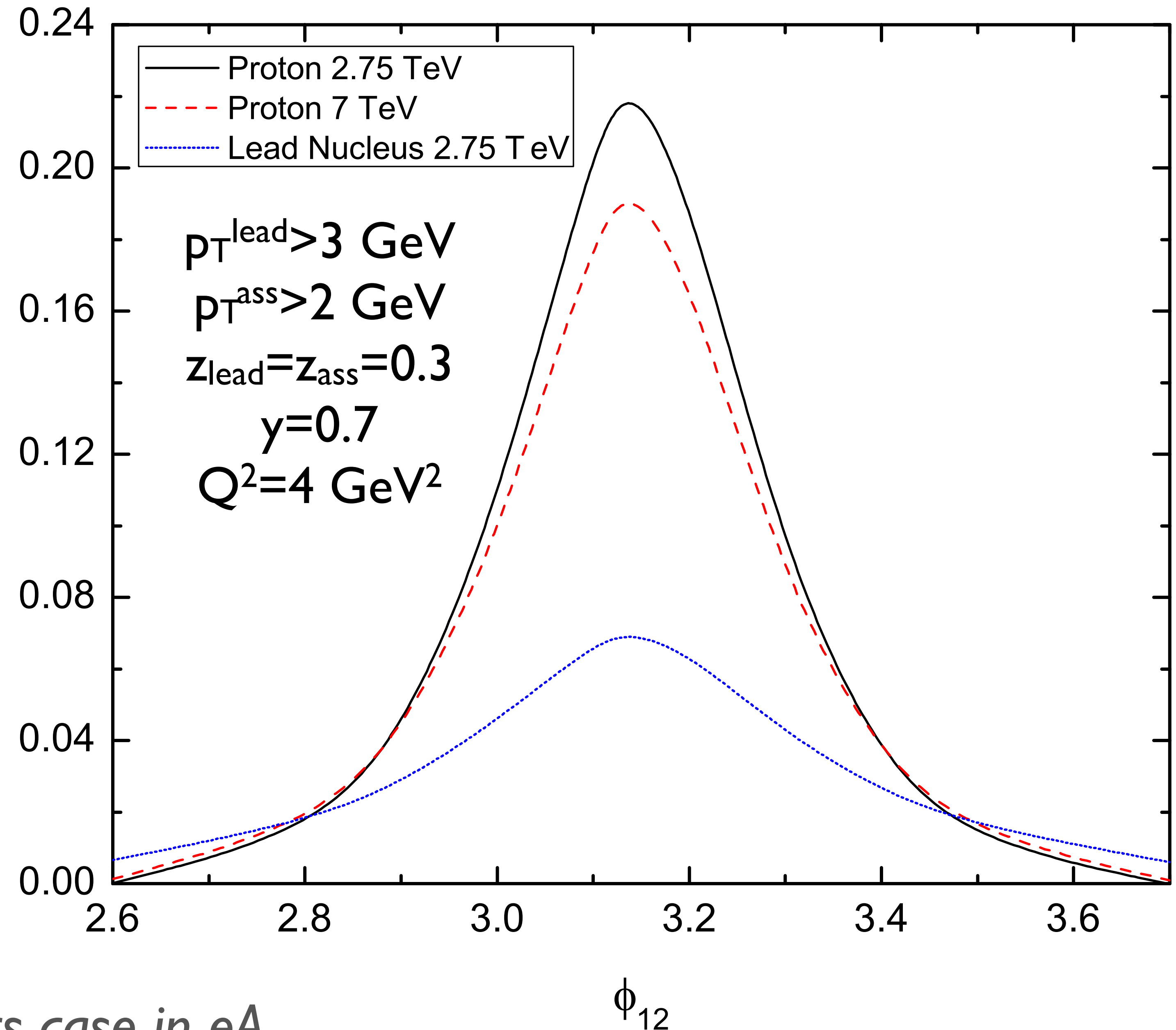
- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.



- At the LHeC it could be studied far from the kinematical limits.



$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$

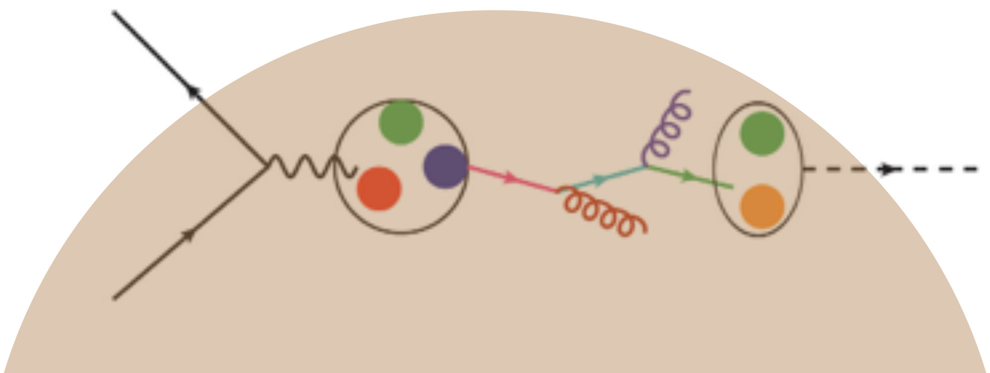


Radiation and hadronization:

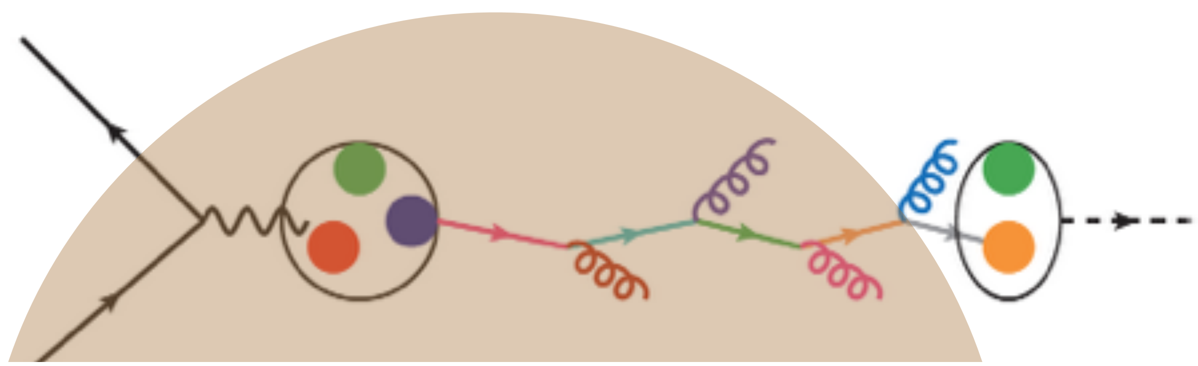
- LHeC: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

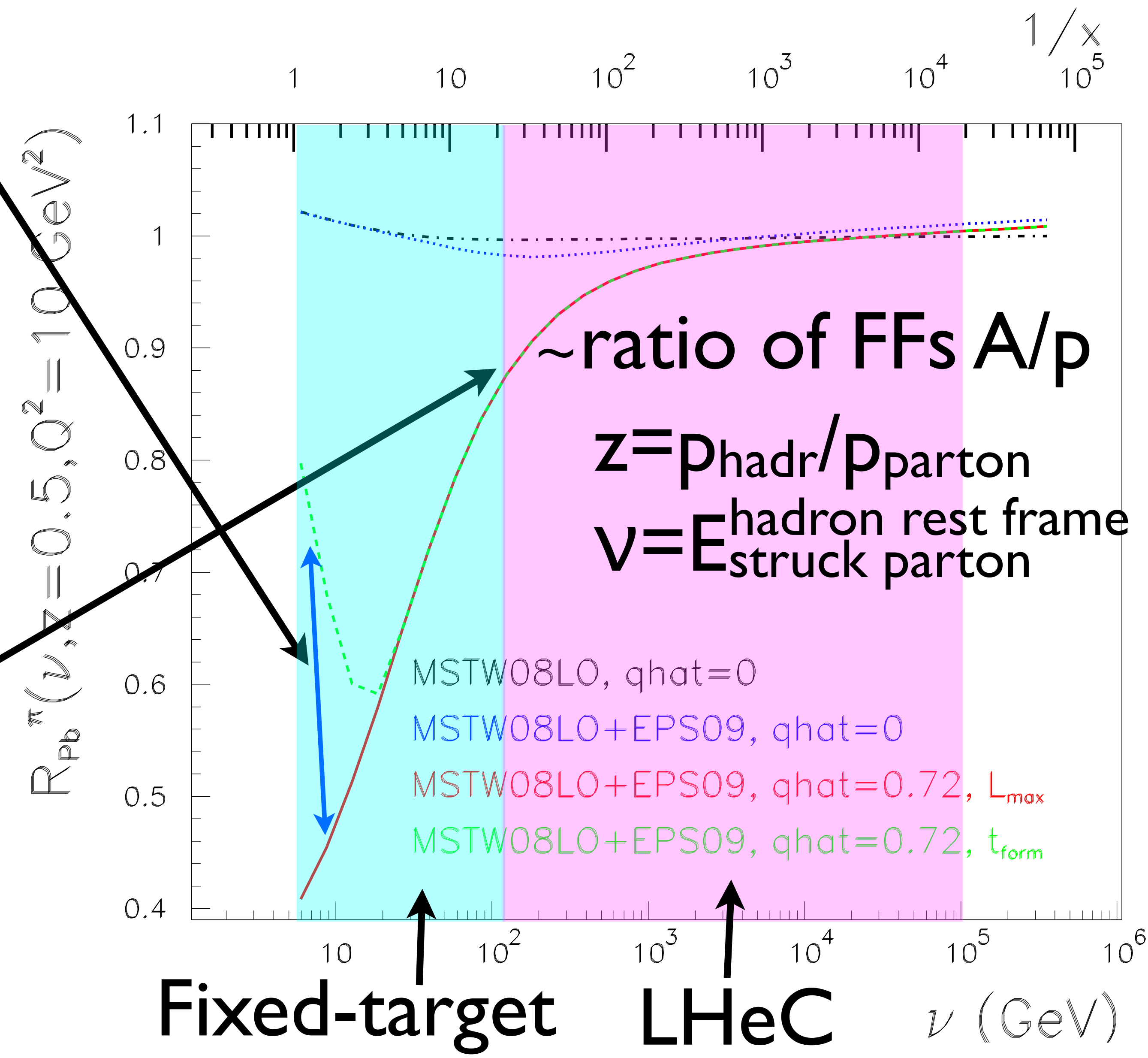
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Bigg/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$

- Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...



- High energy: partonic evolution altered in the nuclear medium.





LHC studies: PbPb

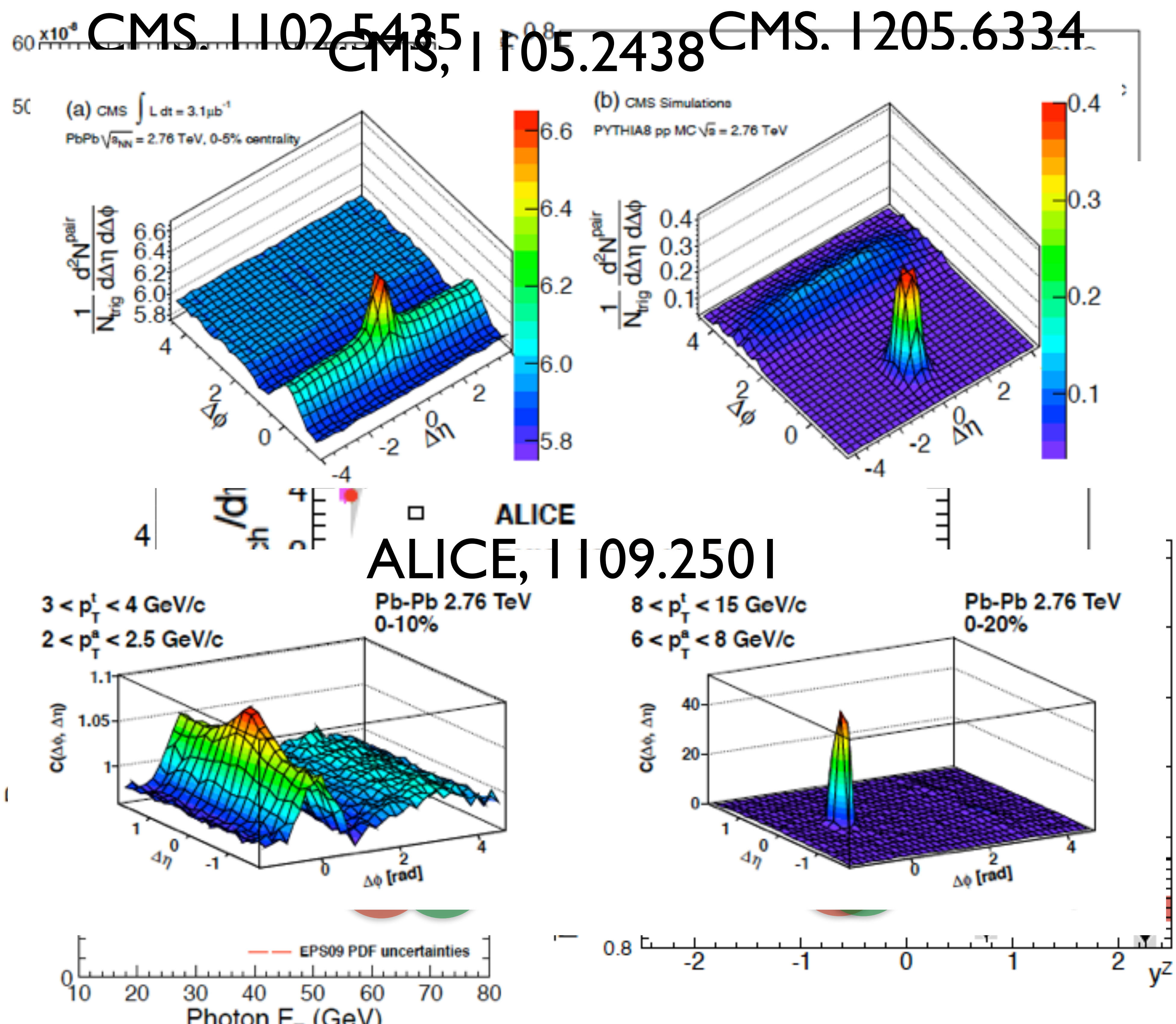
➜ EW bosons: nPDFs.
➜ VMs in UPCs: nPDFs.

Benchmarking

Searches

➜ Multiplicities: particle production.
➜ Ridge: particle production.

➜ ...



LHC studies: pPb

Searches

- ➜ Ridge.
- ➜ Flow.
- ➜ Charged particles.

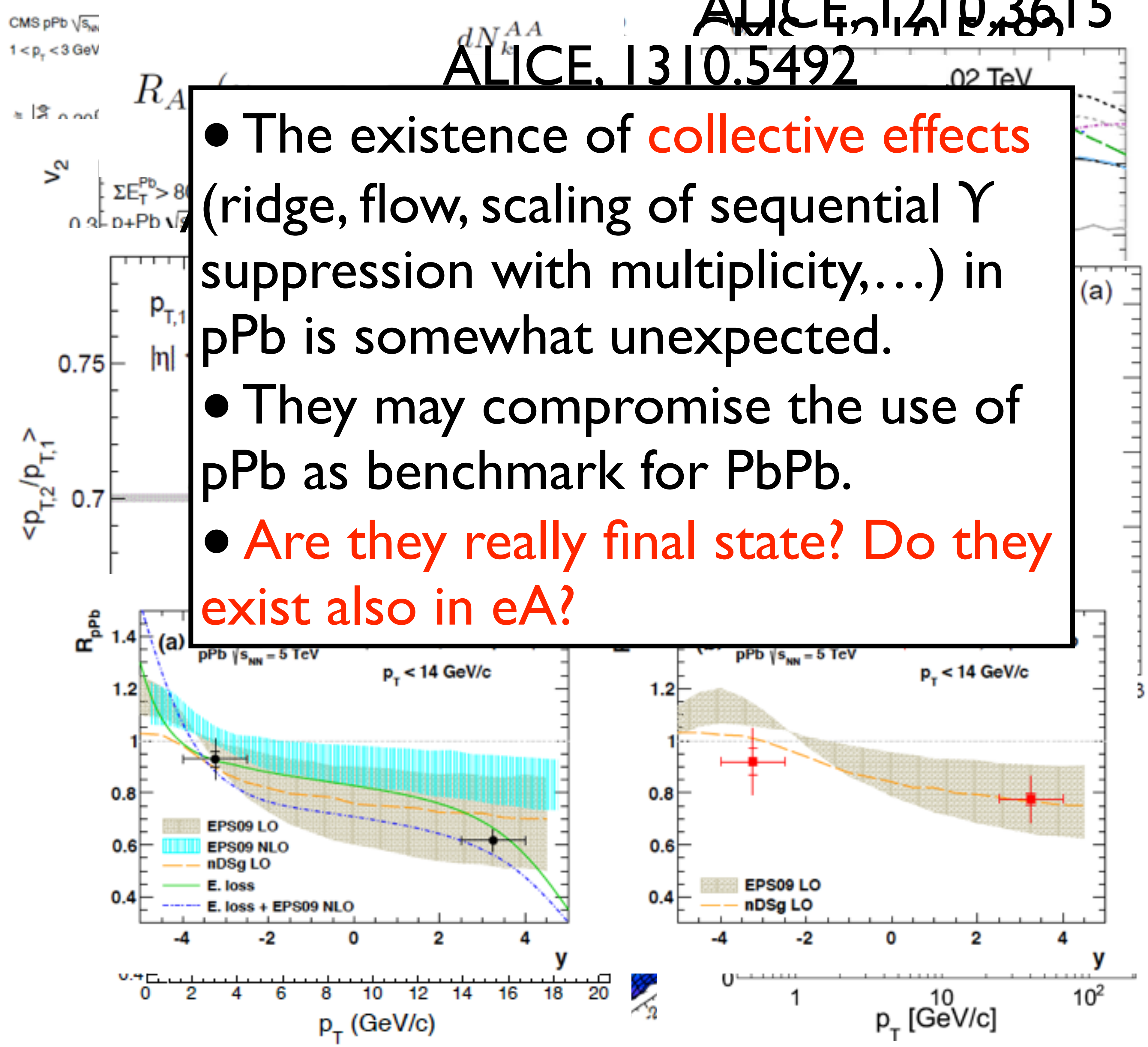
- ➜ Jets and interjet activity.
- ➜ VMs, HF.

Benchmarking

- ➜ Back-to-back correlations, central/forward?
- ➜ EW bosons, DY?
- ➜ UPCs?
- ➜ ...

ALICE, 1210.3615

ALICE, 1310.5492



- The existence of collective effects (ridge, flow, scaling of sequential Υ suppression with multiplicity,…) in pPb is somewhat unexpected.
- They may compromise the use of pPb as benchmark for PbPb.
- Are they really final state? Do they exist also in eA?

LHeC scenarios:

For F_2

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	10^{-3}	10^{-3}	0.4	10^{-3}	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp
I	50	3.5	Ca	$5 \cdot 10^{-3}$		?	$5 \cdot 10^{-3}$	?	?	eCa

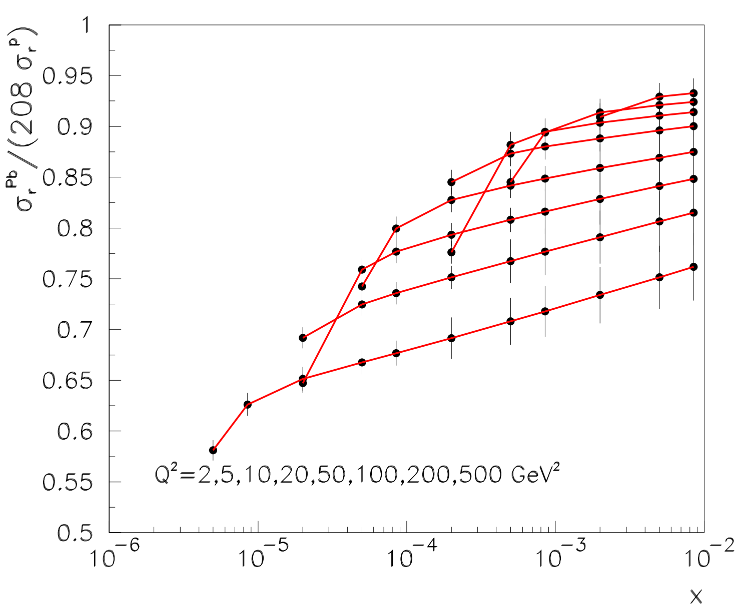
- For F_L: 10, 25, 50 + 2750 (7000); $Q^2 \leq sx$; Lumi=5,10,100 pb^{-1} respectively; charm and beauty: same efficiencies in ep and eA.

Note: F_L in eA

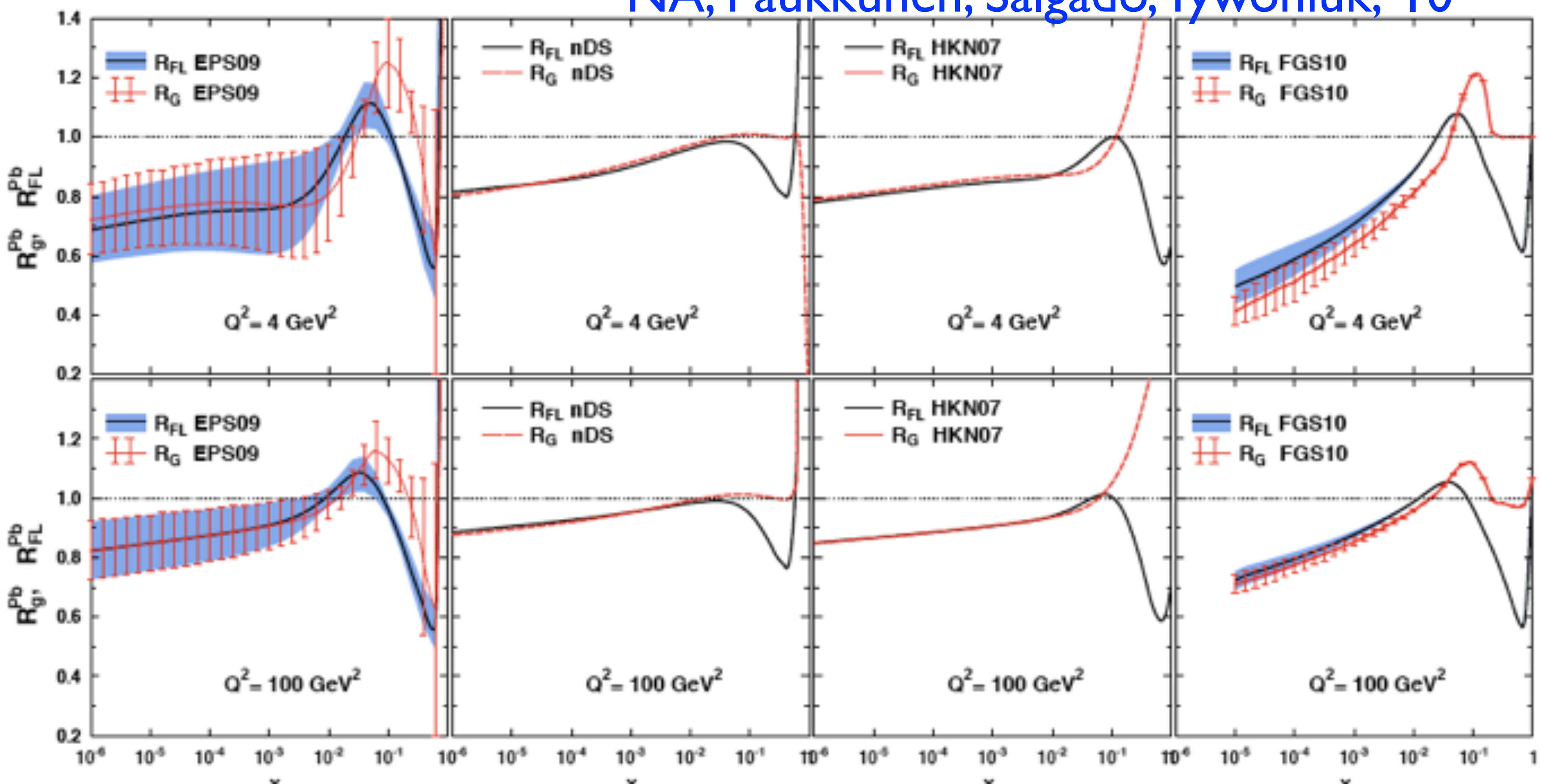
$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+} \frac{F_L}{F_2}\right], \qquad Y_+ = 1 + (1-y)^2$$

- F_L traces the nuclear effects on the glue (Cazarotto et al '08).
- Uncertainties in the extraction of F_2 due to the unknown nuclear effects on F_L of order 5 % (larger than expected stat.+syst.) ⇒

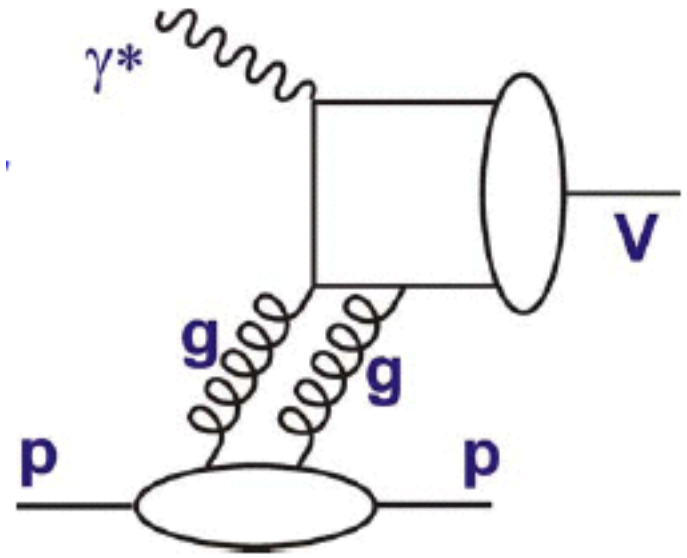
measure F_L or use the reduced cross section (but then ratios at two energies...).

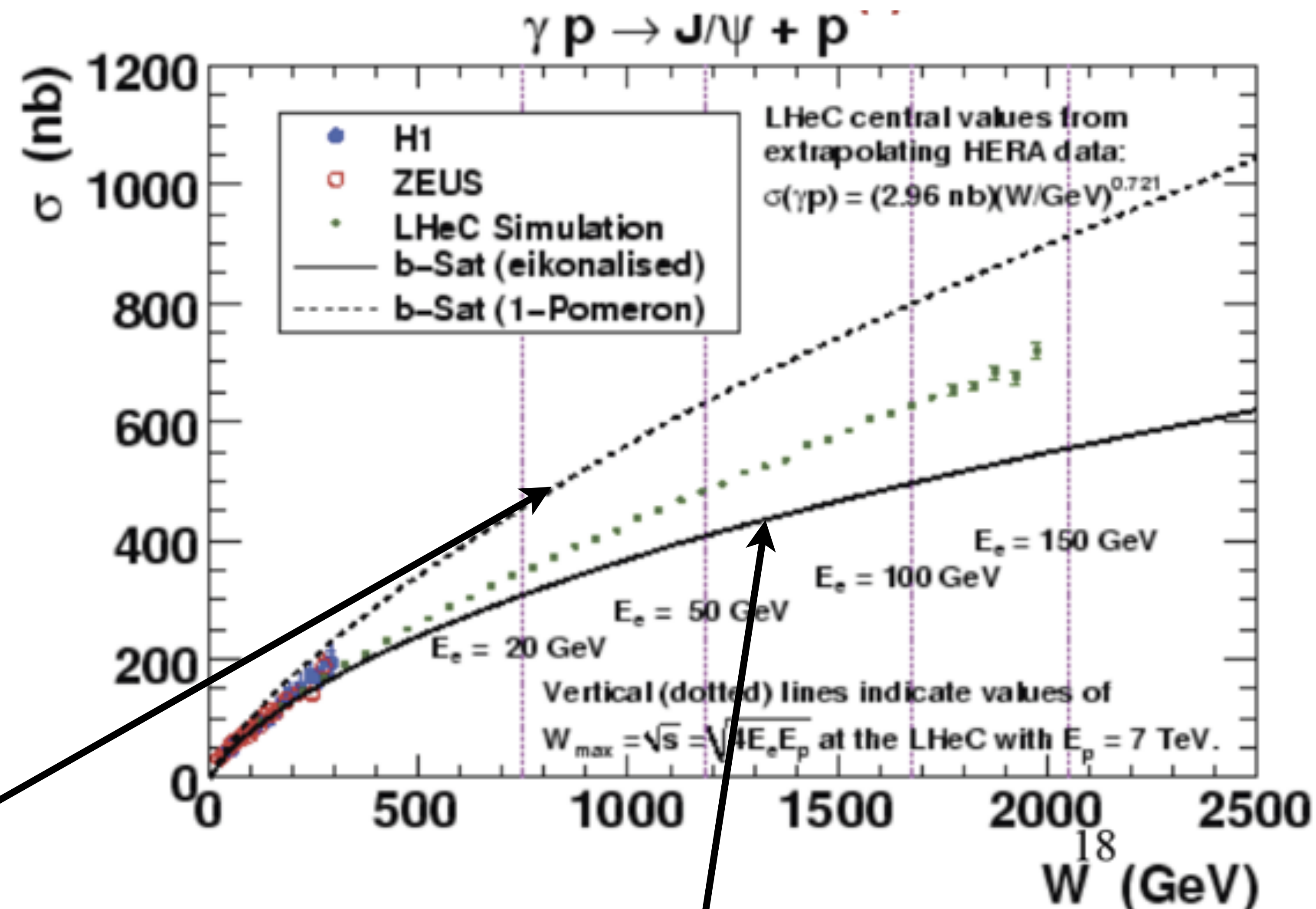


NA, Paukkunen, Salgado, Tywoniuk, '10

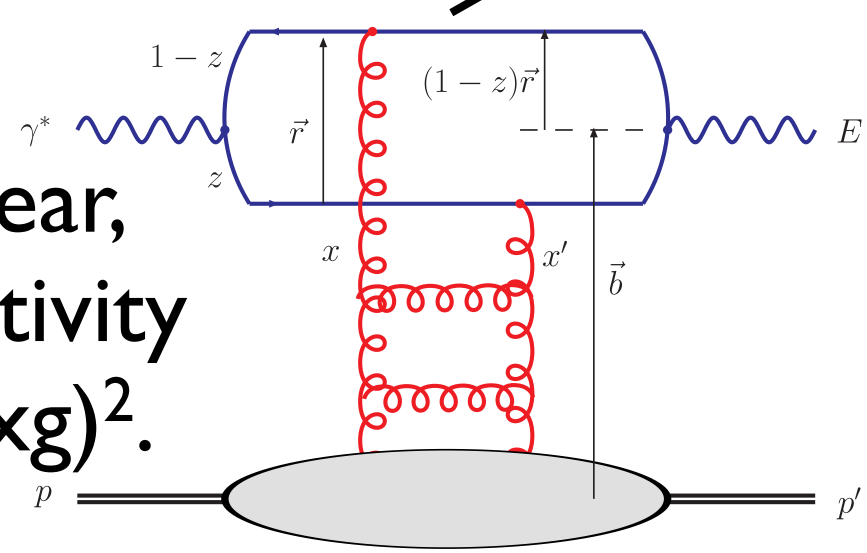


Elastic VM production in ep:

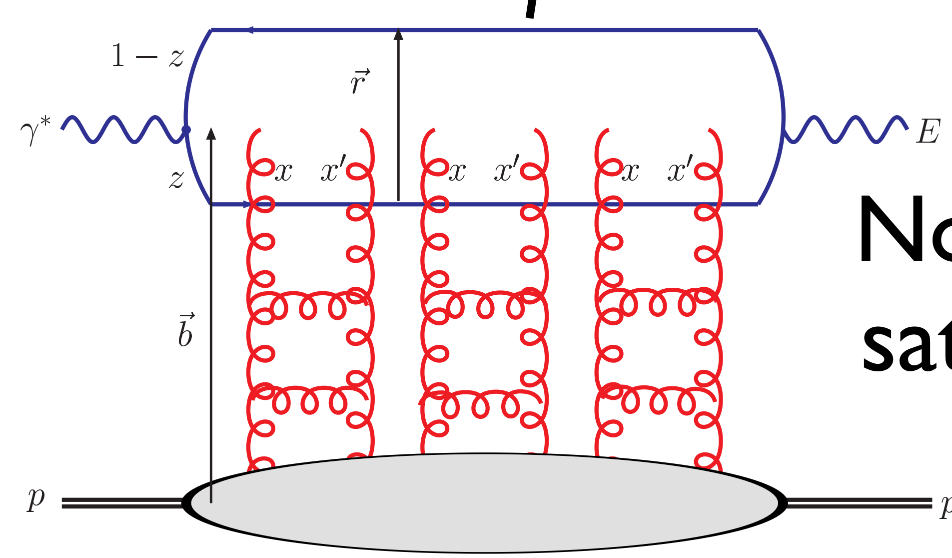




- Elastic J/ψ production appears as a candidate to signal saturation effects at work!!!

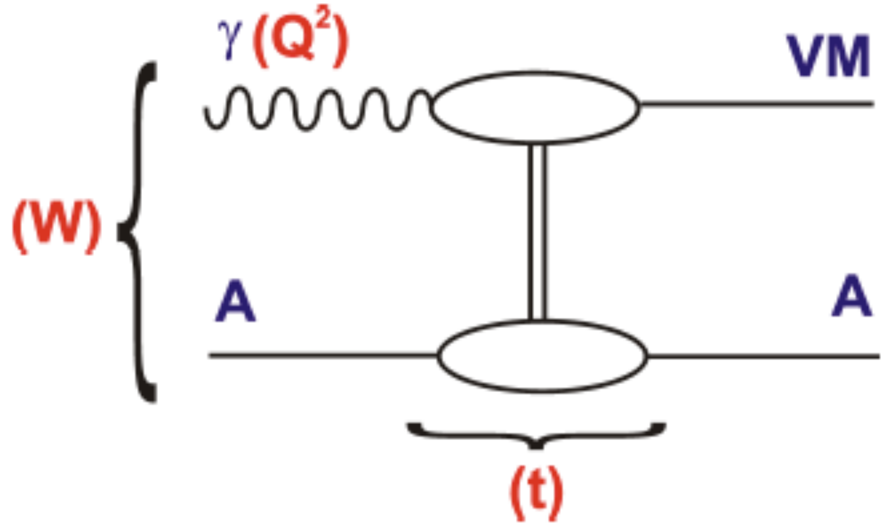


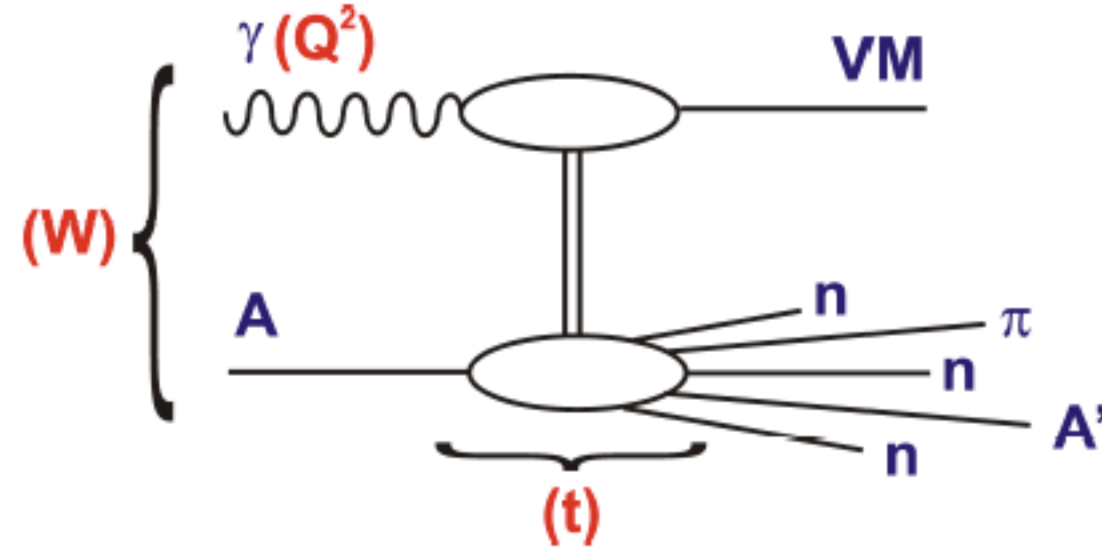
Linear, sensitivity to $(xg)^2$.



Non-linear, saturation.

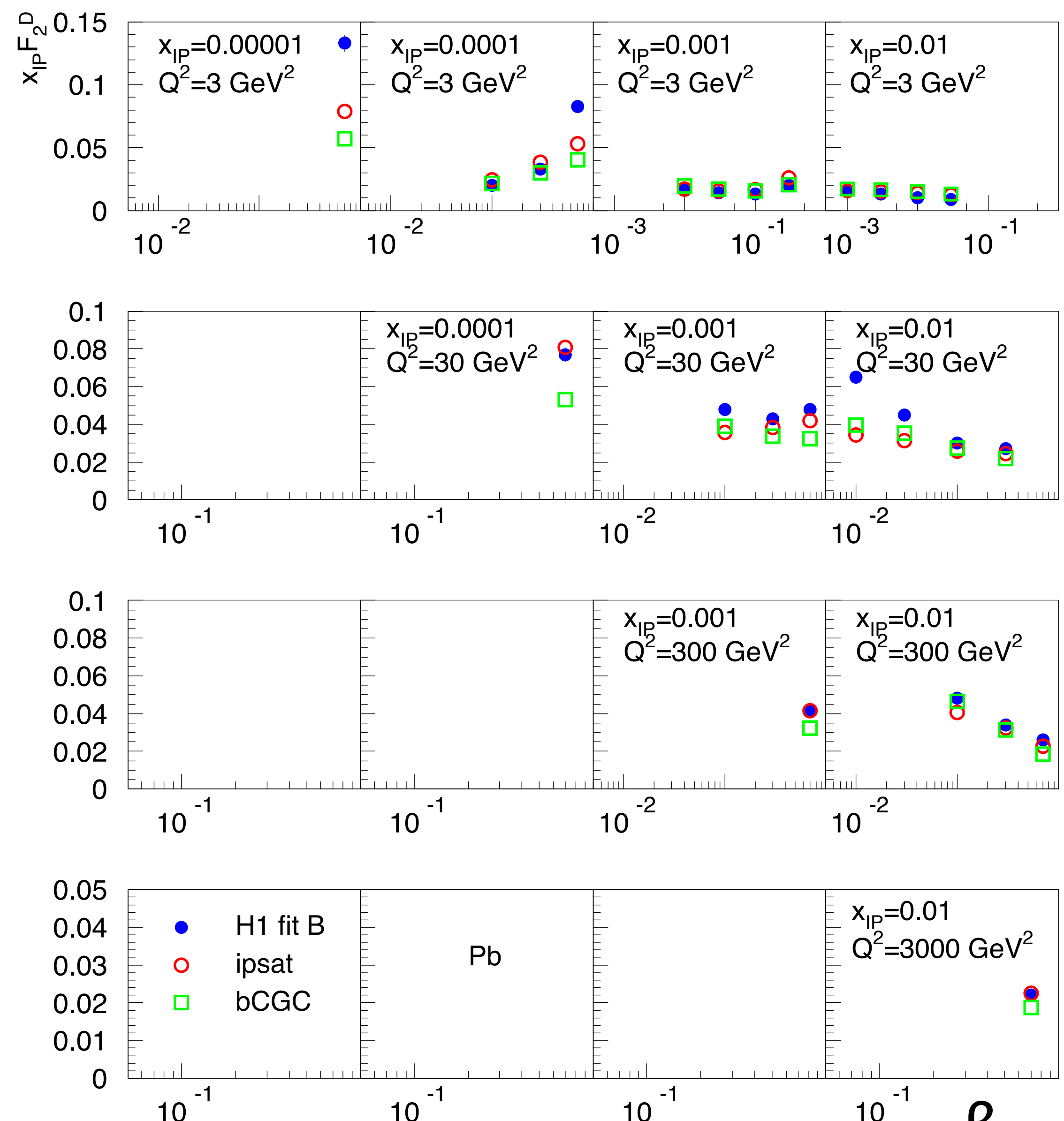
Diffractive DIS on nuclear targets:





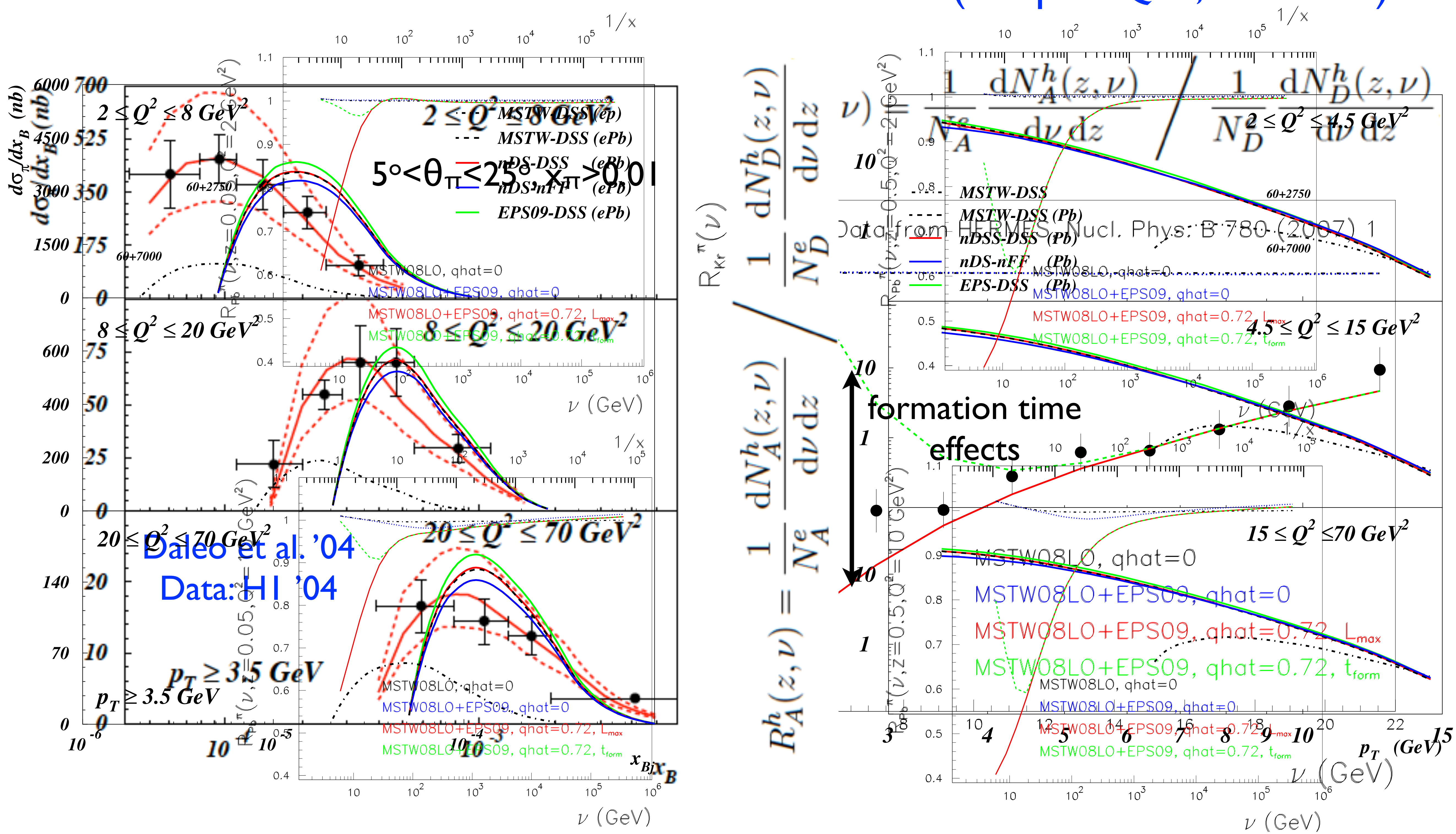
- Challenging experimental problem, requires Monte Carlo simulation with detailed understanding of the nuclear break-up.

- For the coherent case, predictions available.



Radiation and hadronization:

- Large (NLO) yields at small-x (H1 cuts, 3 times higher if relaxed).
- Nuclear effects in hadronization at small ν (LO plus QW, Arleo '03).

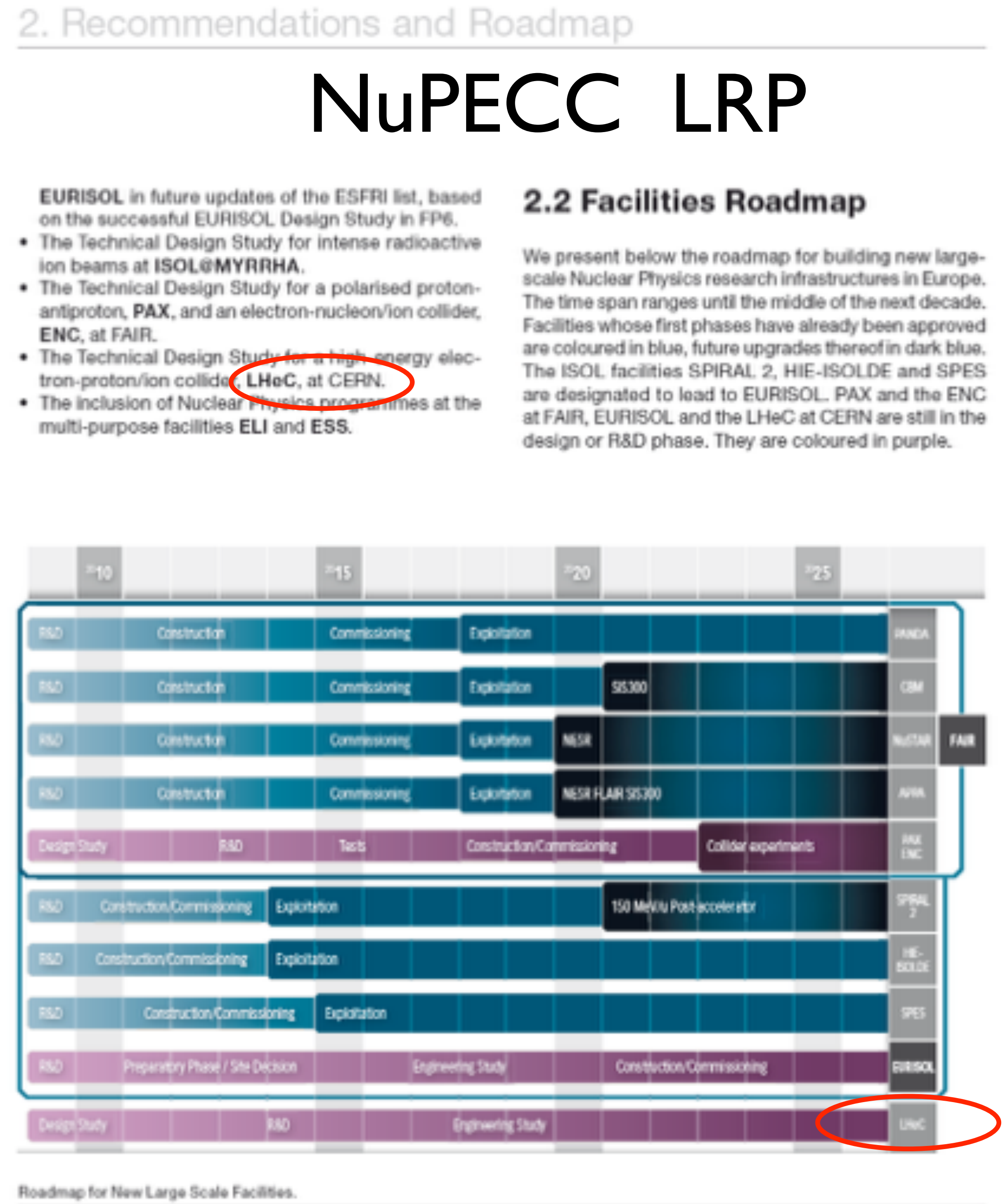


Outlook:

- With CERN and NuPECC mar physics case and produce a TDR be done/improved:

➜ Refine DGLAP fits with flavo data, relax assumptions) and opti
➜ Monte Carlo generators!!!
➜ Studies on diffraction: separat ndPDFs, dijets,...
➜ Large x, EW bosons.
➜ Nuclear GPDs: nuclear DVCS
➜ eD.
➜ Jet reconstruction, angular de
➜ ...

→ Cooperation with EIC in som


2. Recommendations and Roadmap

NuPECC LRP

EURISOL in future updates of the ESFRI list, based on the successful EURISOL Design Study in FP6.
- The Technical Design Study for intense radioactive ion beams at ISOL@MYRRHA.
- The Technical Design Study for a polarised proton-antiproton, PAX, and an electron-nucleon/ion collider, ENC, at FAIR.
- The Technical Design Study for a high-energy electron-proton/ion collider, LHeC, at CERN.
- The inclusion of Nuclear Physics programmes at the multi-purpose facilities ELI and ESS.

2.2 Facilities Roadmap

We present below the roadmap for building new large-scale Nuclear Physics research infrastructures in Europe. The time span ranges until the middle of the next decade. Facilities whose first phases have already been approved are coloured in blue, future upgrades thereof in dark blue. The ISOL facilities SPIRAL 2, HIE-ISOLDE and SPES are designated to lead to EURISOL. PAX and the ENC at FAIR, EURISOL and the LHeC at CERN are still in the design or R&D phase. They are coloured in purple.

Roadmap for New Large Scale Facilities.

20 | Perspectives of Nuclear Physics in Europe – NuPECC Long Range Plan 2010

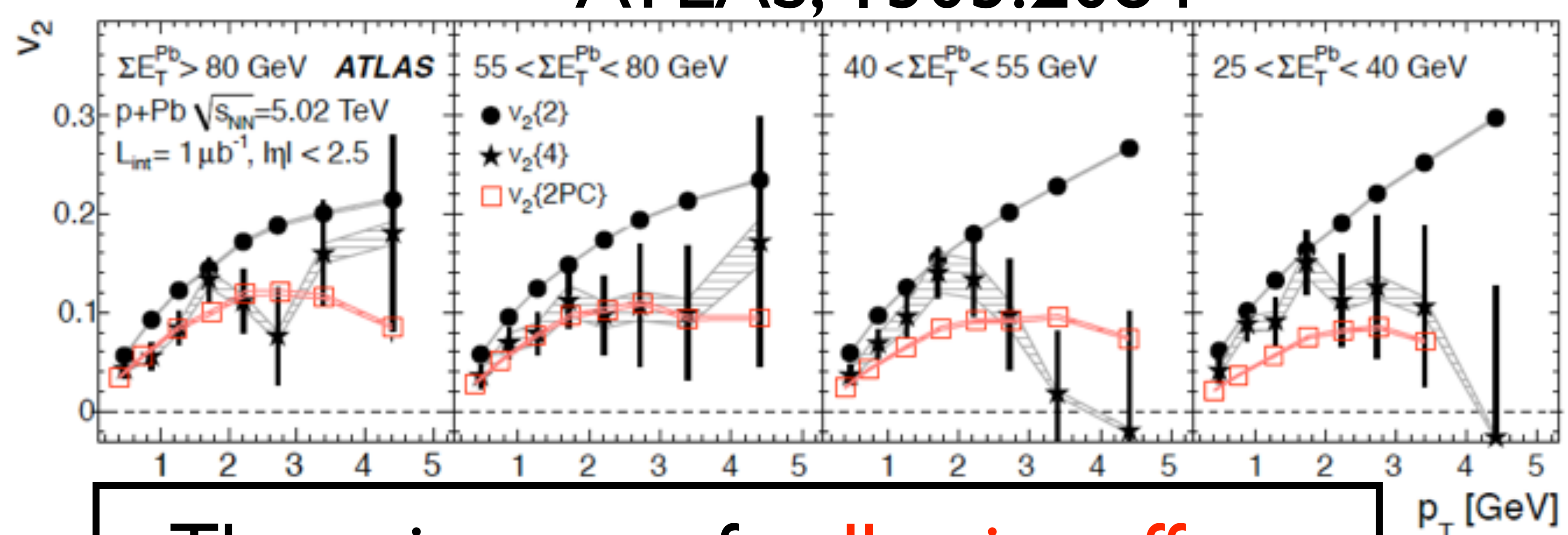
Thanks for your attention!

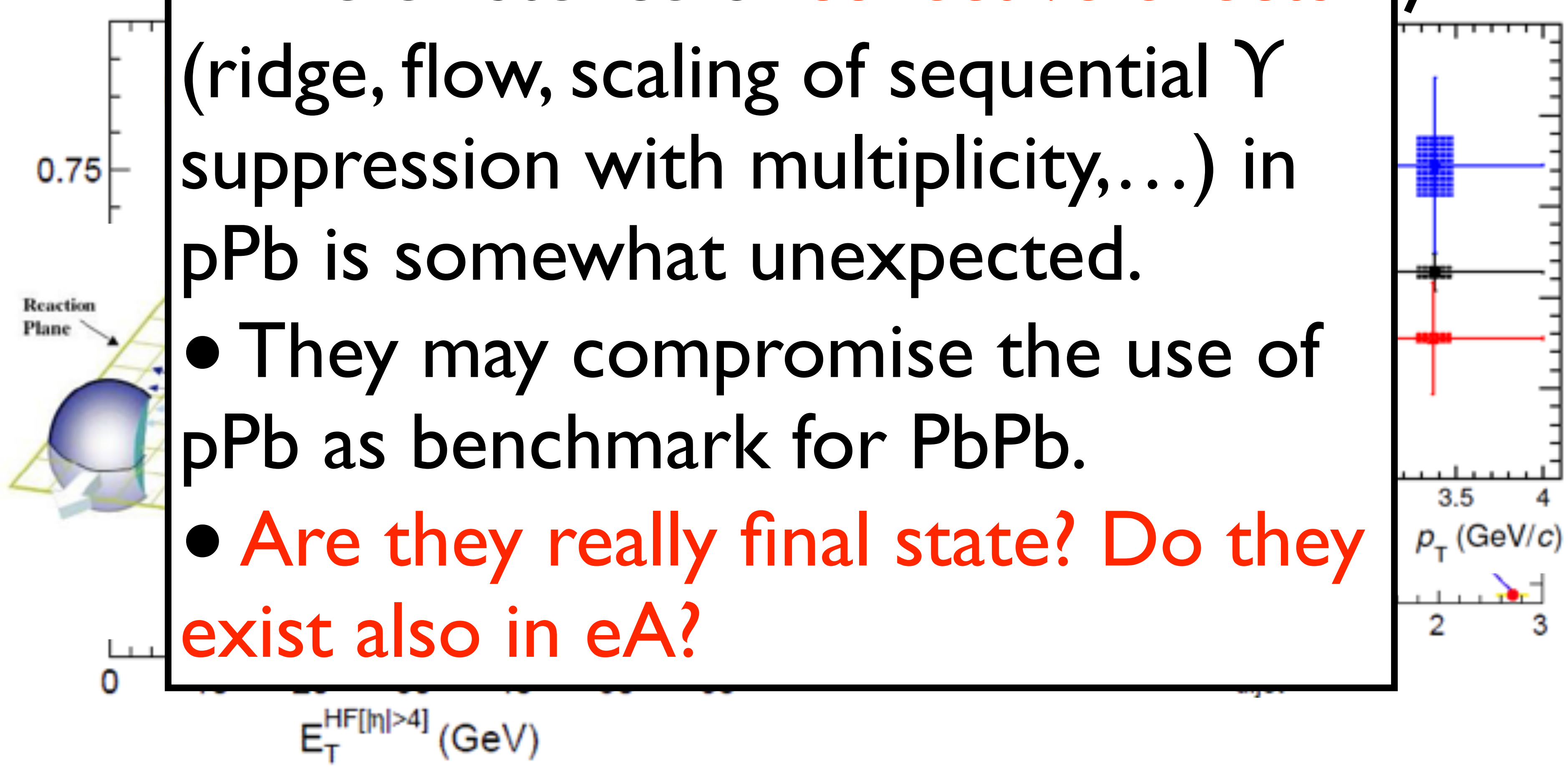
LHC studies: pPb

➜ Benchmarking: jets, quarkonia and heavy flavours.

➜ Search for 'non-standard' physics like saturation: multiplicities and p_T distributions, flow, ridge.

ATLAS, 1303.2084





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