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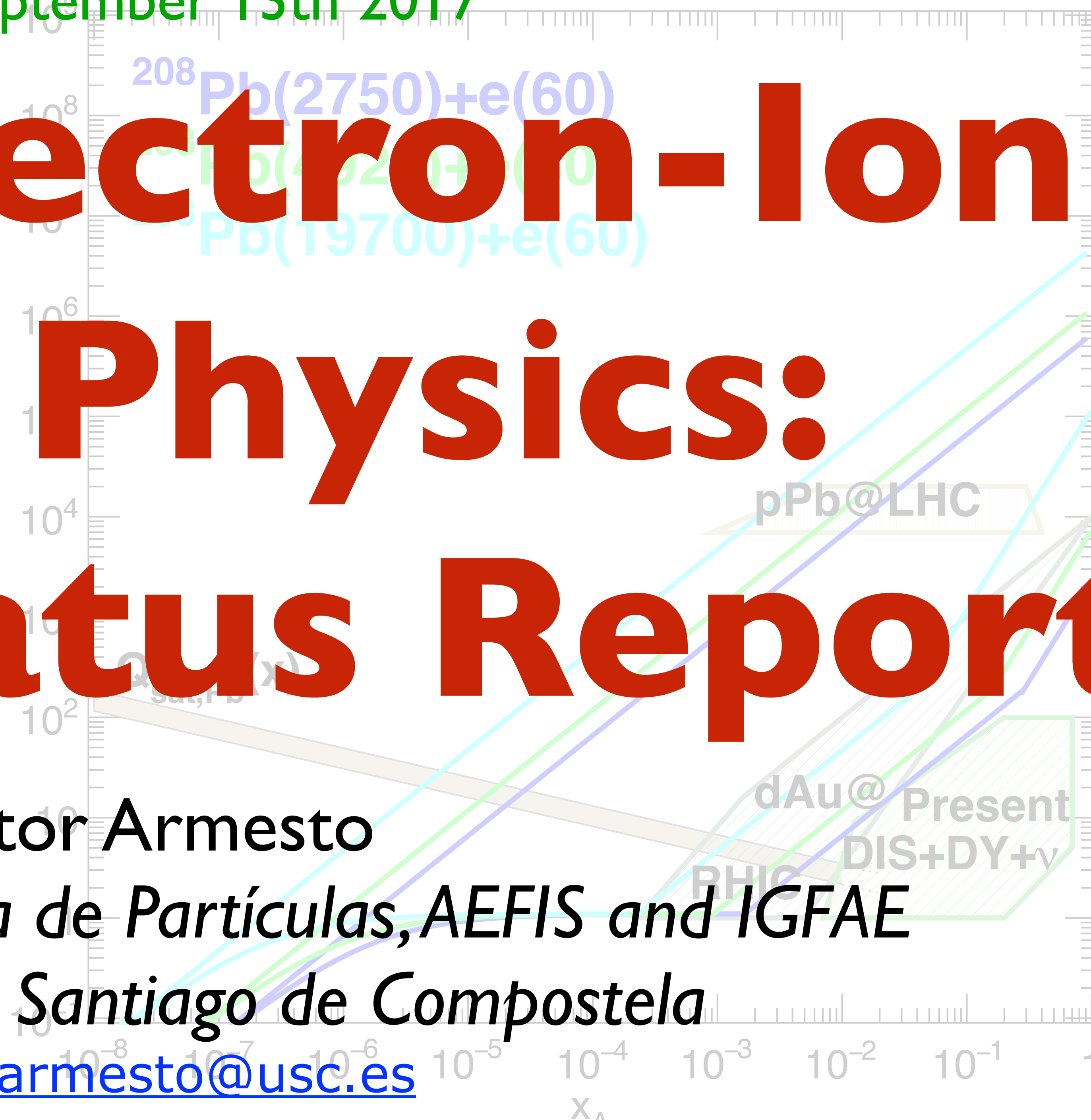
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Workshop on the LHeC and the FCC-eh
CERN, September 13th 2017

FCC hh ee he

LHeC

Electron-Ion Physics: Status Report



Néstor Armesto

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

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Comisión Europea

EXCELENCIA MARÍA DE MAEZTU

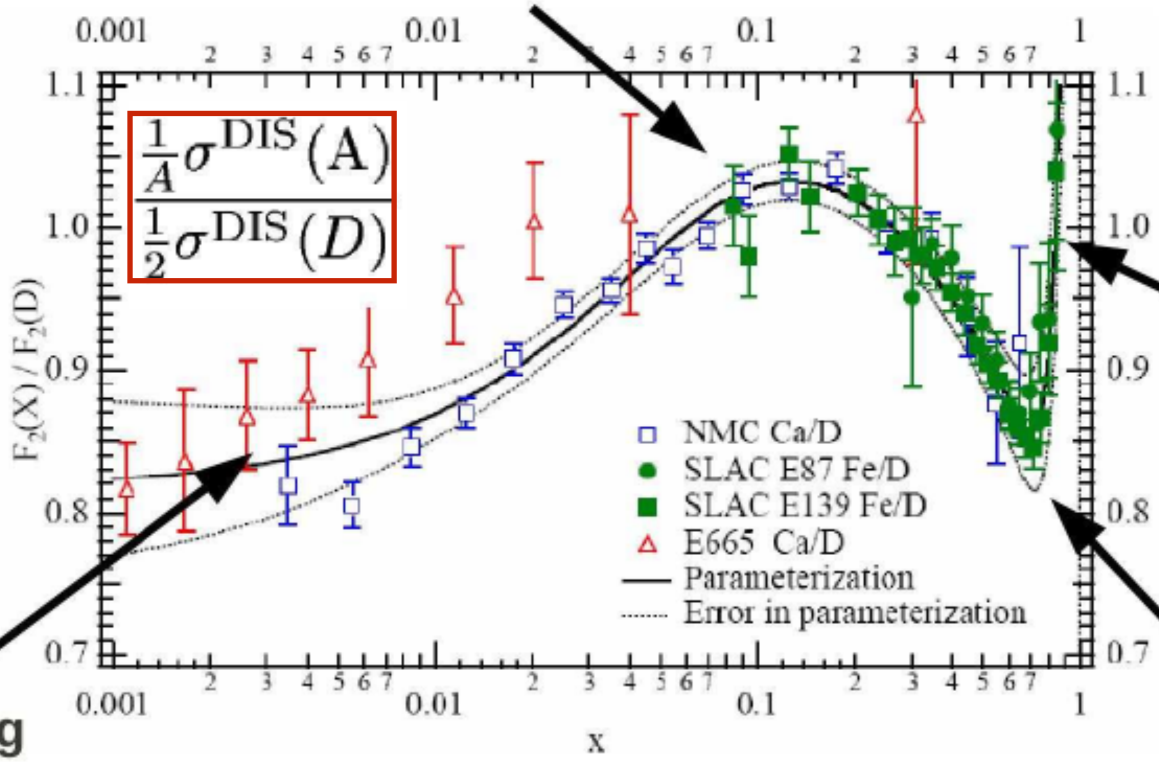
GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

XUNTA DE GALICIA

Contents:

See the talks by Vadim Guzey, Paul Newman, Fred Olness, Anna Stasto, Konrad Tywoniuk and Pia Zurita; also my talk on Monday.

Motivation: nPDFs



- Bound nucleon ≠ free nucleon: search for process independent nPDFs that realise this condition, assuming collinear factorisation.

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\overline{q},g} f_i^A(\mu^2)\otimes\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)$$

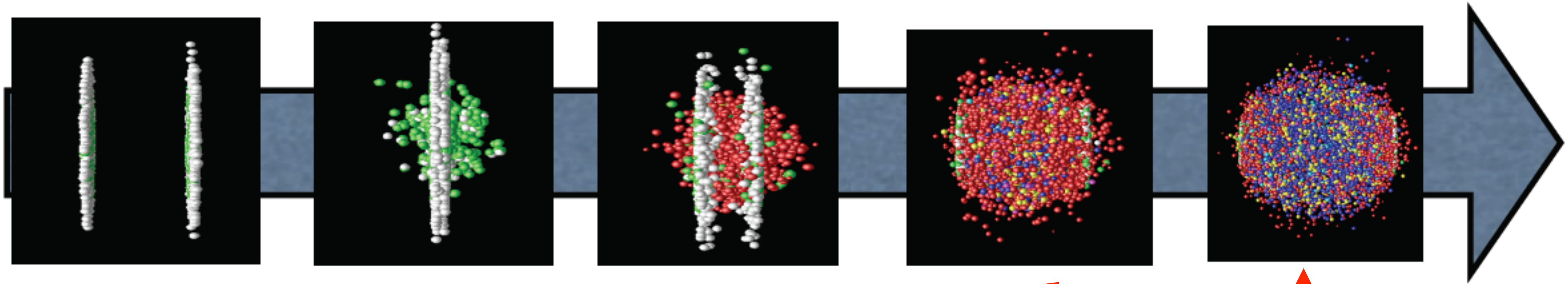
Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

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

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

Relevance for HIC:



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.

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1. Introduction.

2. Kinematics and luminosity.

3. Physics opportunities:
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   ➜ Diffraction.
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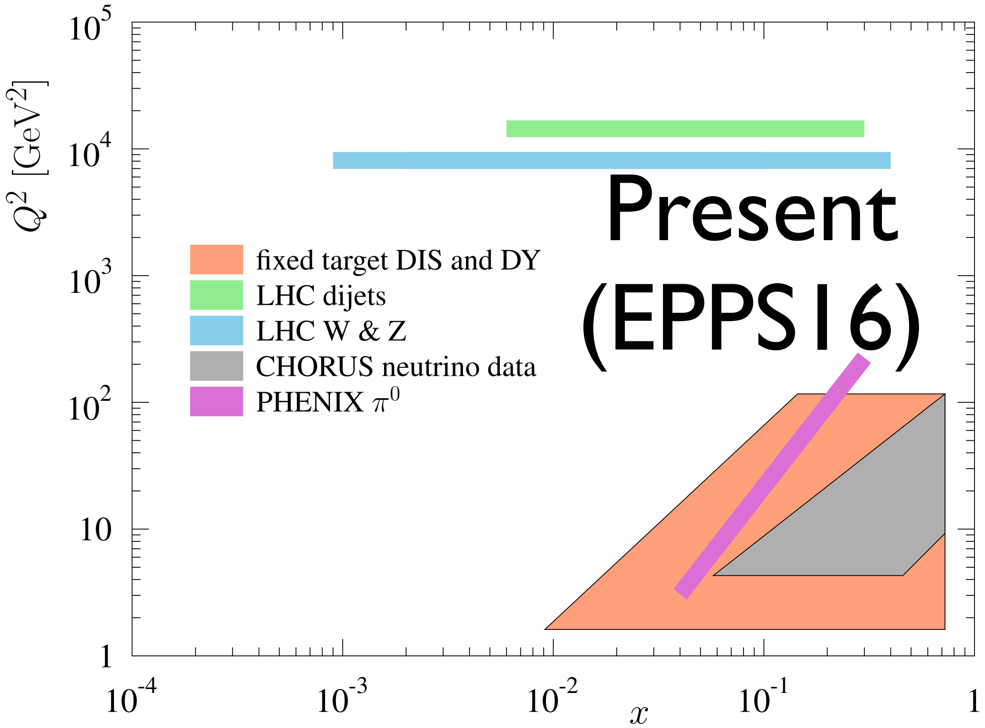
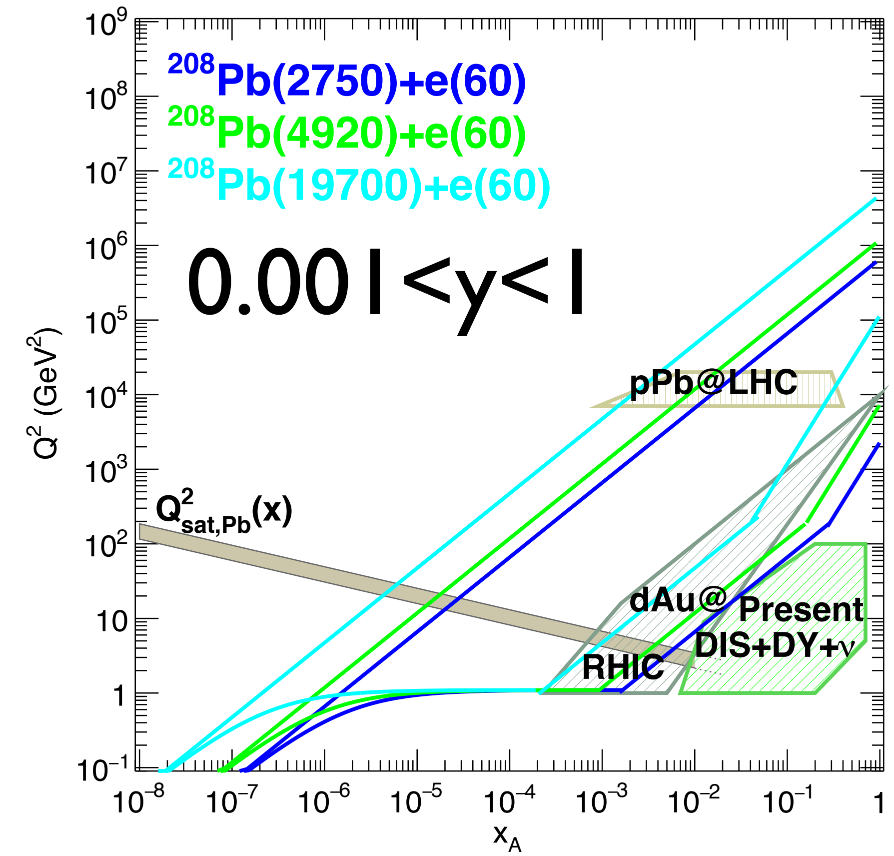
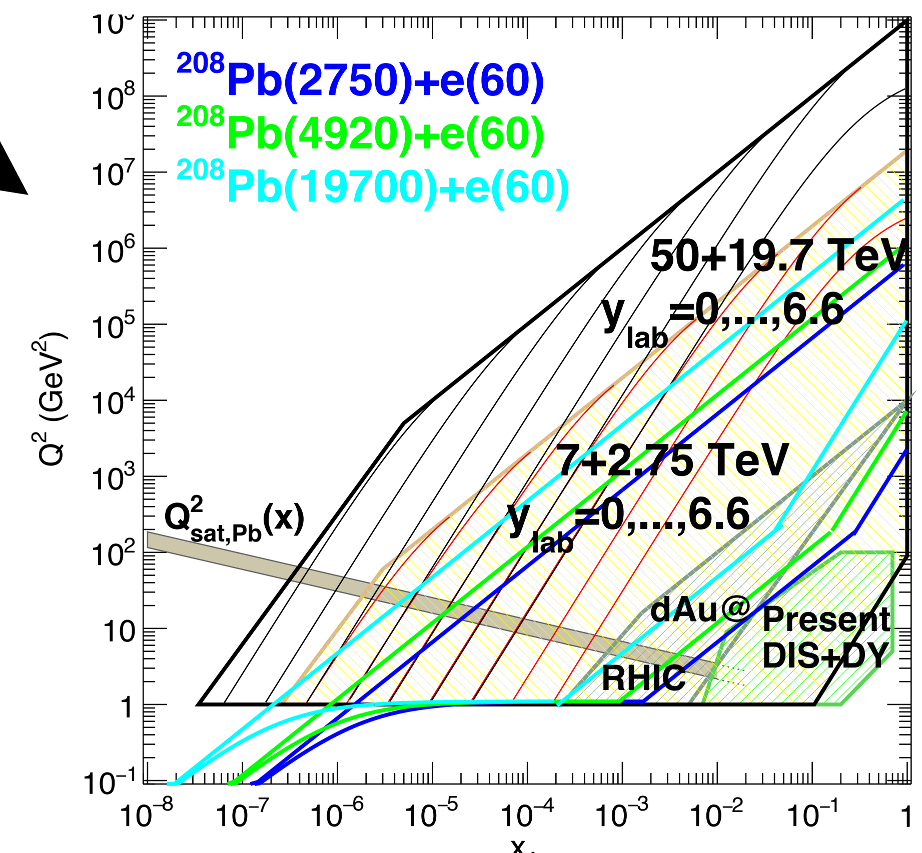
Kinematics:

- Kinematical reach:







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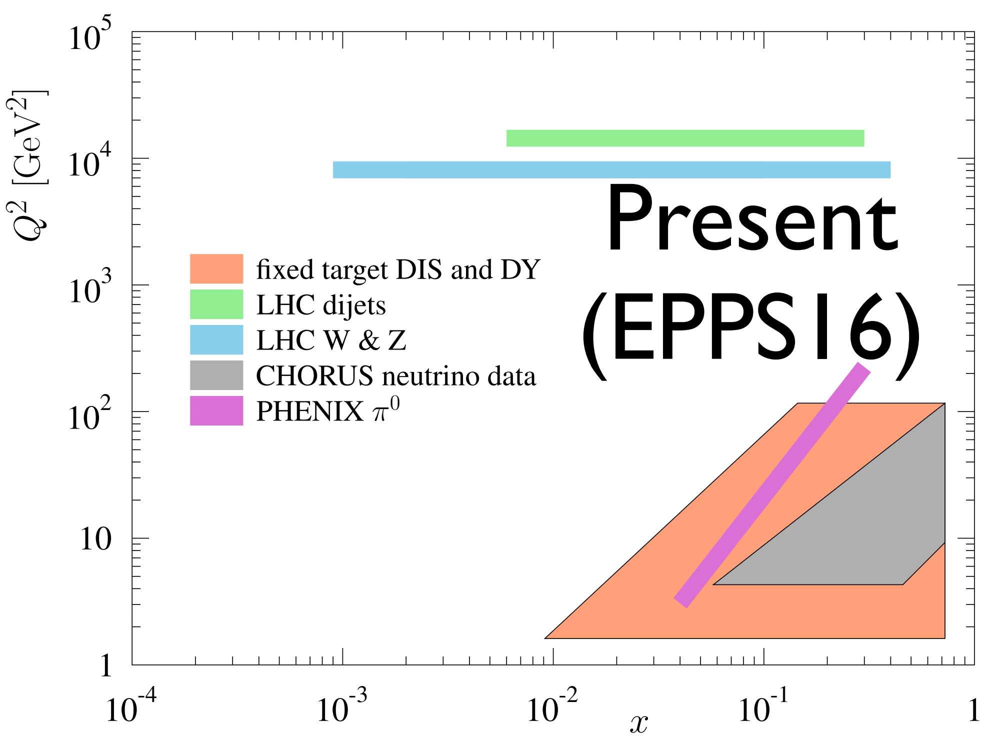

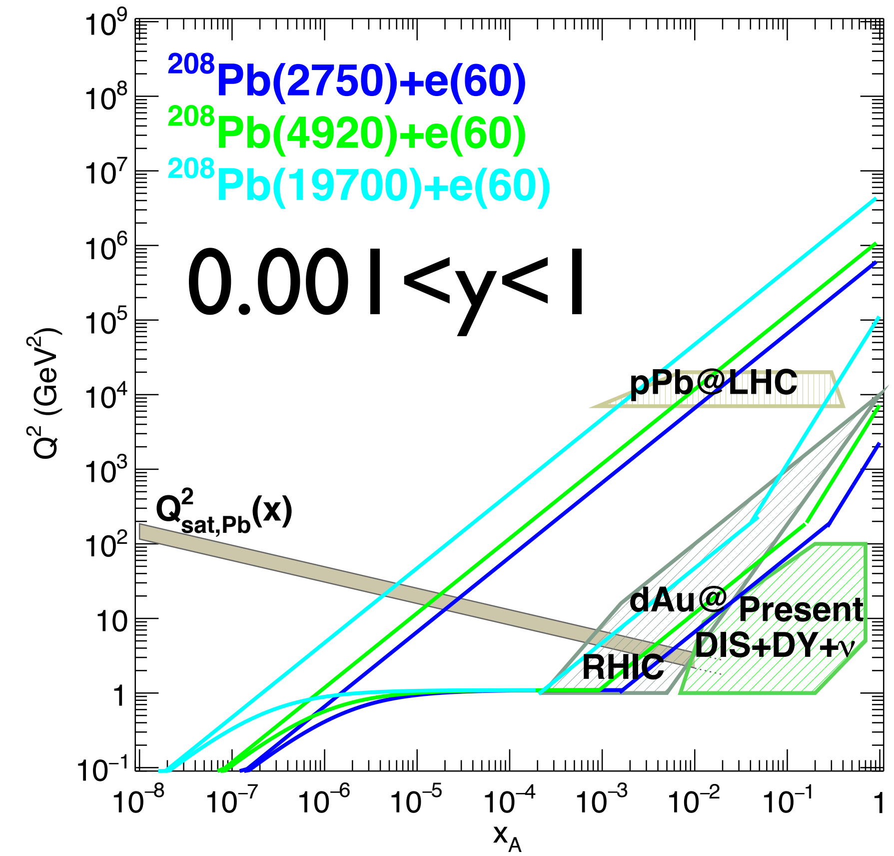

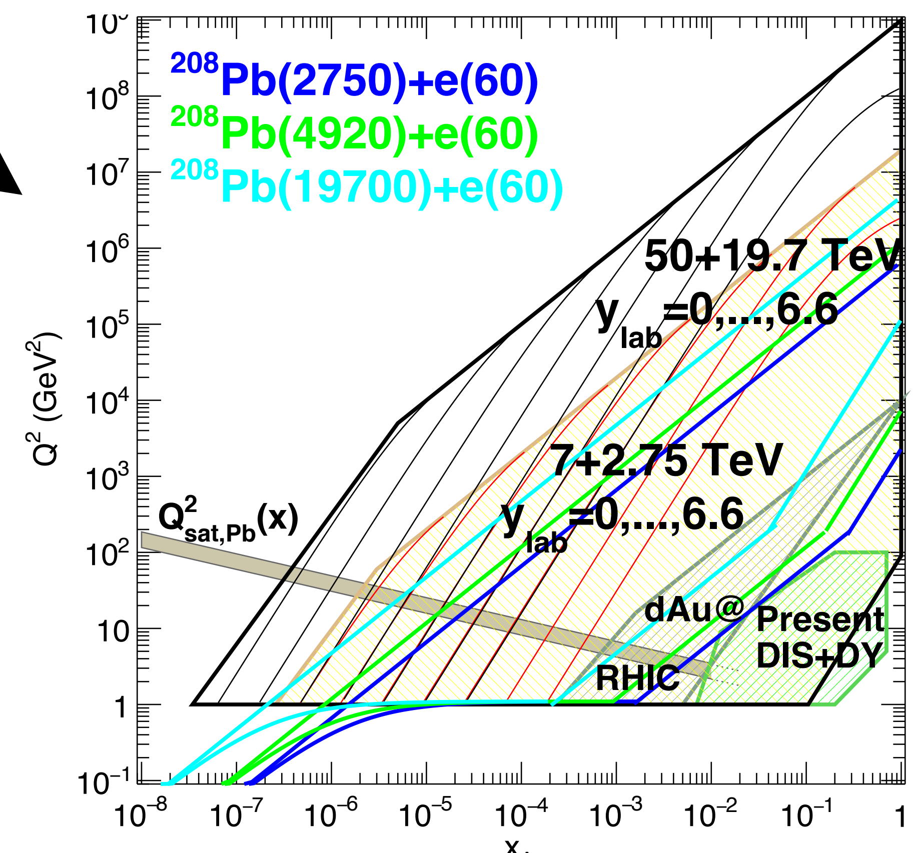

- DIS offers:

➜ A clean experimental environment: lower multiplicity, no pileup, fully constrained kinematics;

➜ A more controlled theoretical setup: most first-principles calculations in a dilute-dilute/dense regime.

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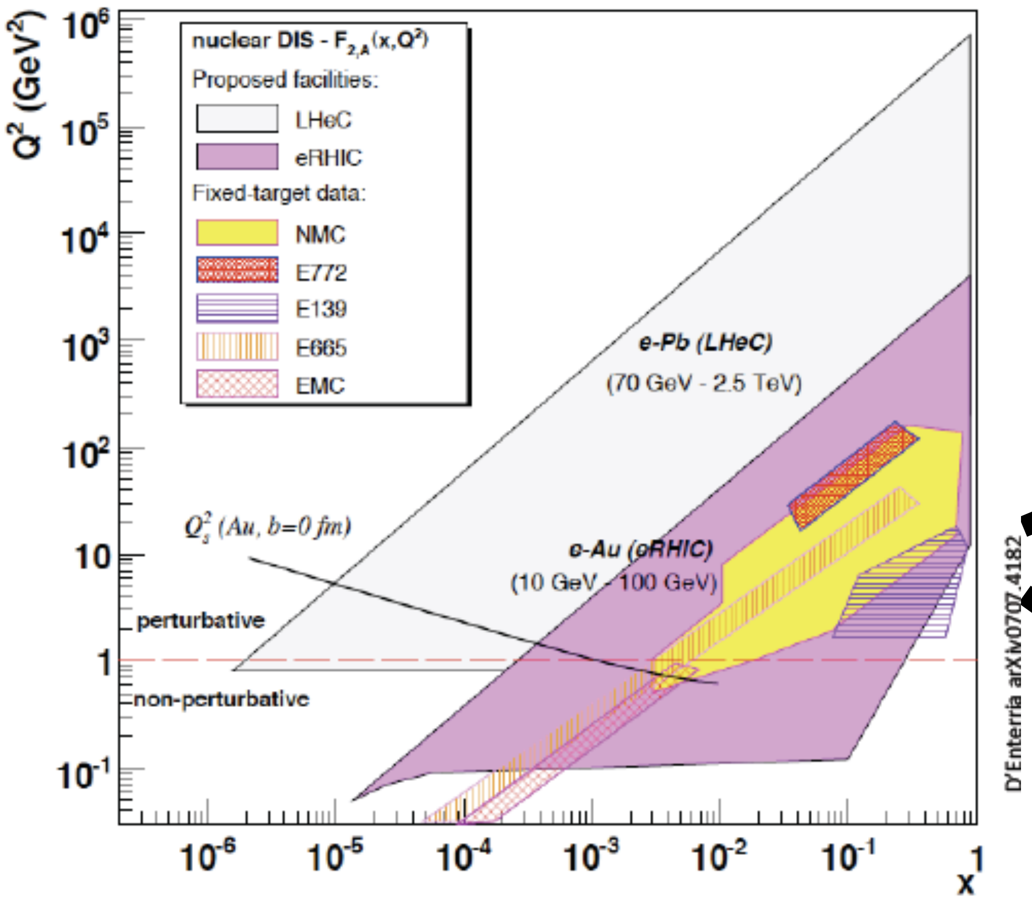

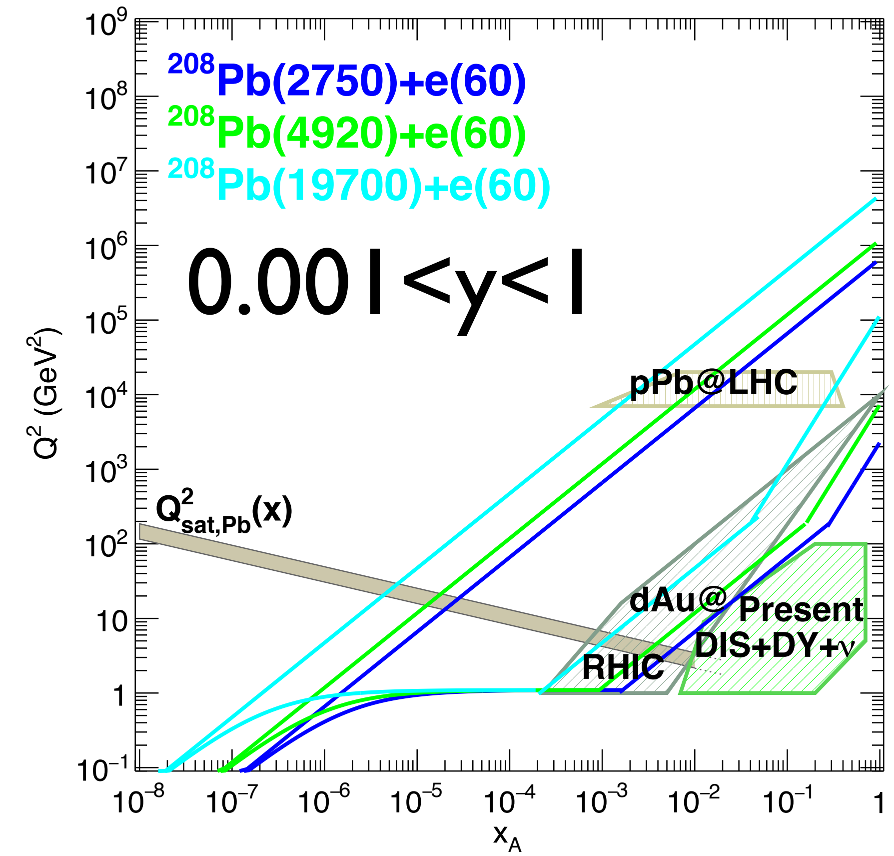

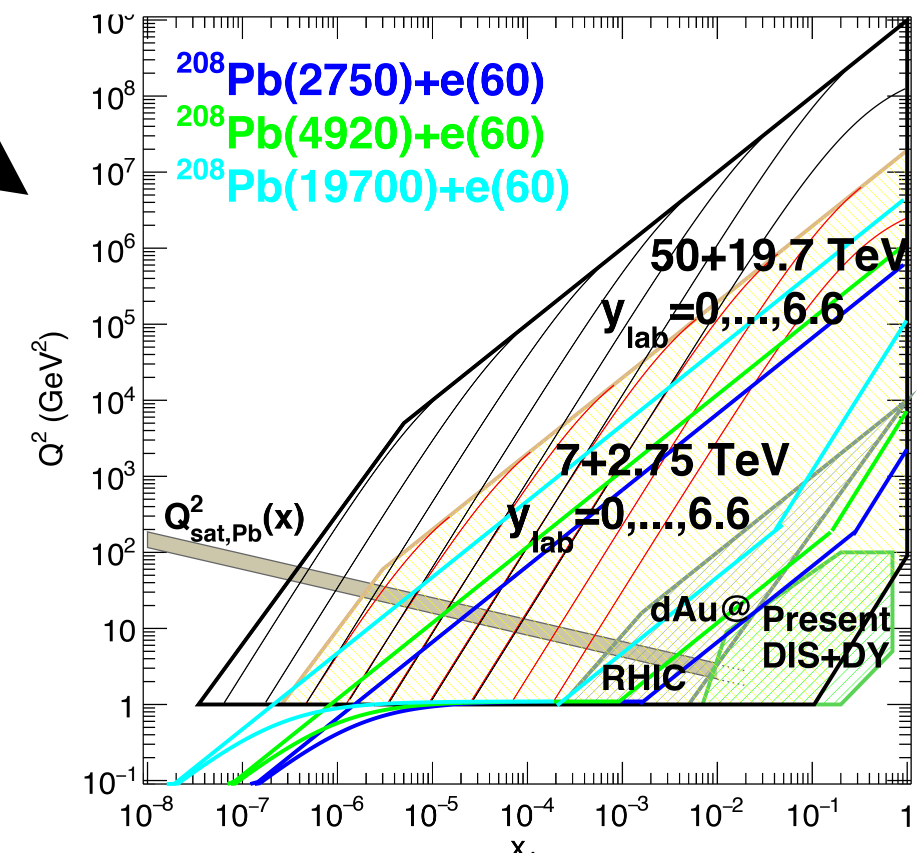

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Luminosity:

- Nominal case: 60 GeV electron beam against the hadron beams.
- CDR values ($N_{Pb}=7\times10^7$/bunch) ⇒ ~0.1 fb^{-1}/month.

$$L_{eN} = \begin{cases} 9\times10^{31}\ \mathrm{cm^{-2}s^{-1}} & \text{(Nominal Pb)} \\ 1.6\times10^{32}\ \mathrm{cm^{-2}s^{-1}} & \text{(Ultimate Pb)} \end{cases}$$

eD: $L_{eN} \gtrsim 3\times10^{31}\ \mathrm{cm^{-2}s^{-1}}$

(Pb numbers ~ 3 times higher with updated Pb parameters).

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NOW

Bruning et al.

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54
Integrated lumi. in 10 y. (fb^{-1}) ~~	6	15	45

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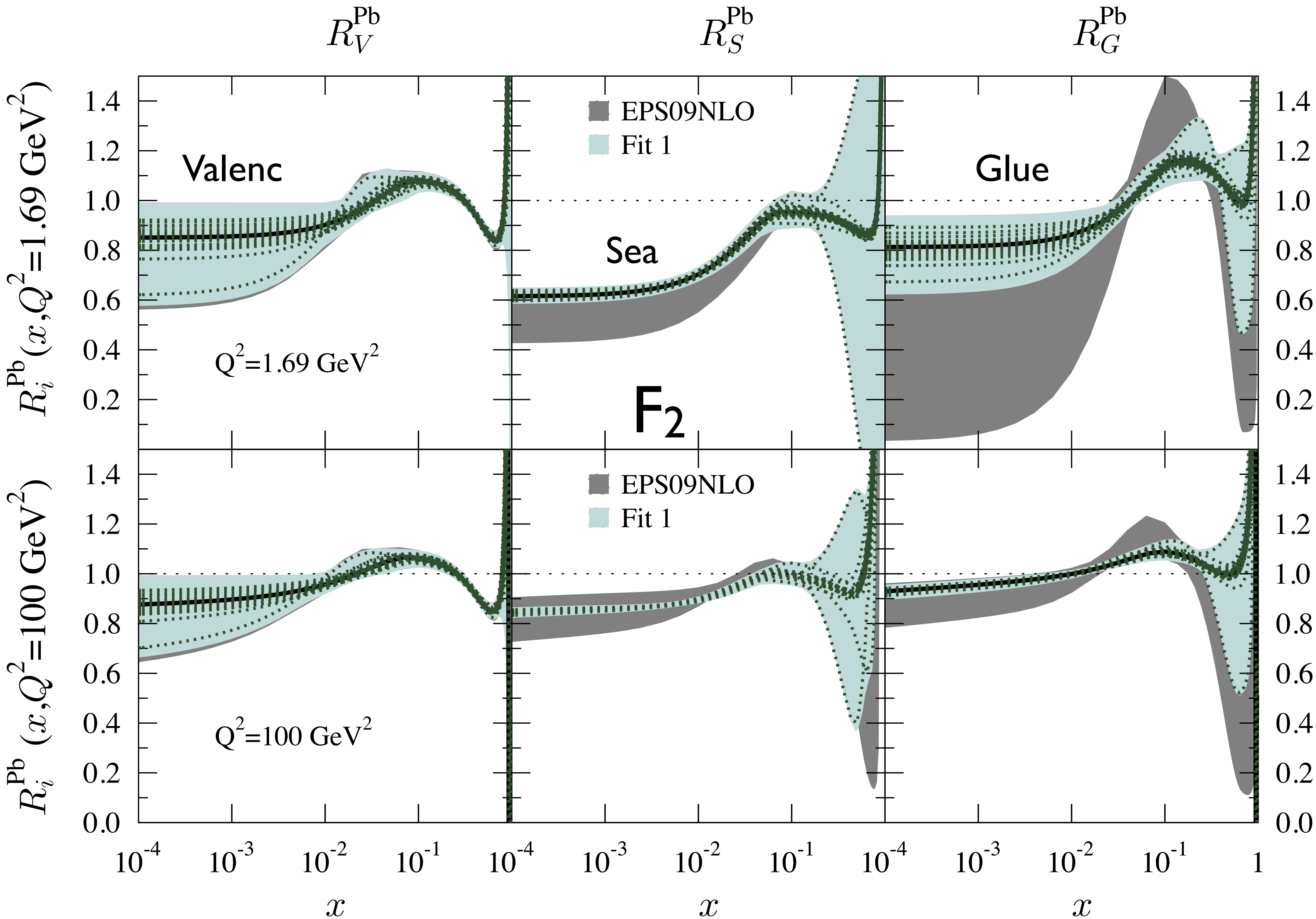

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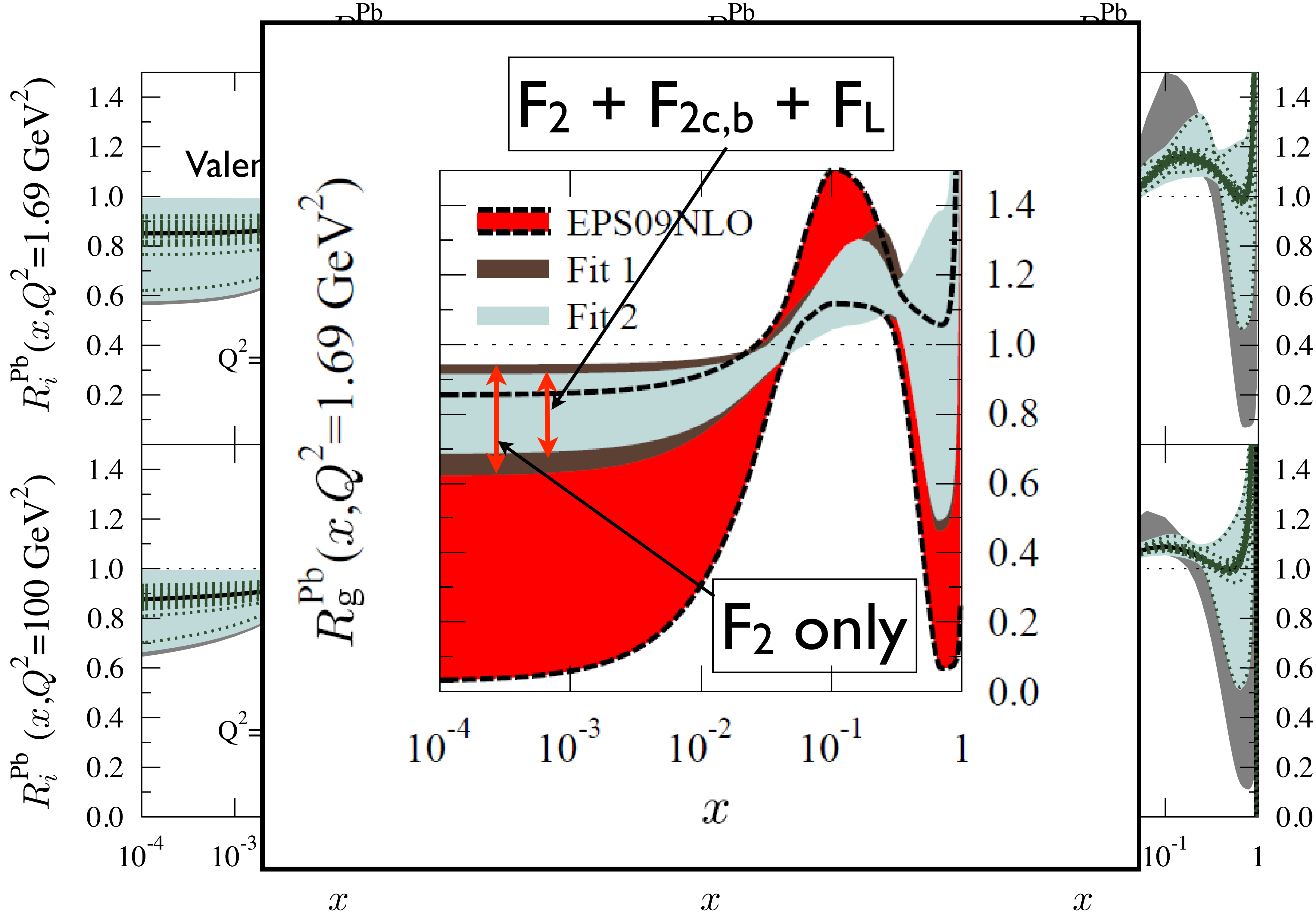

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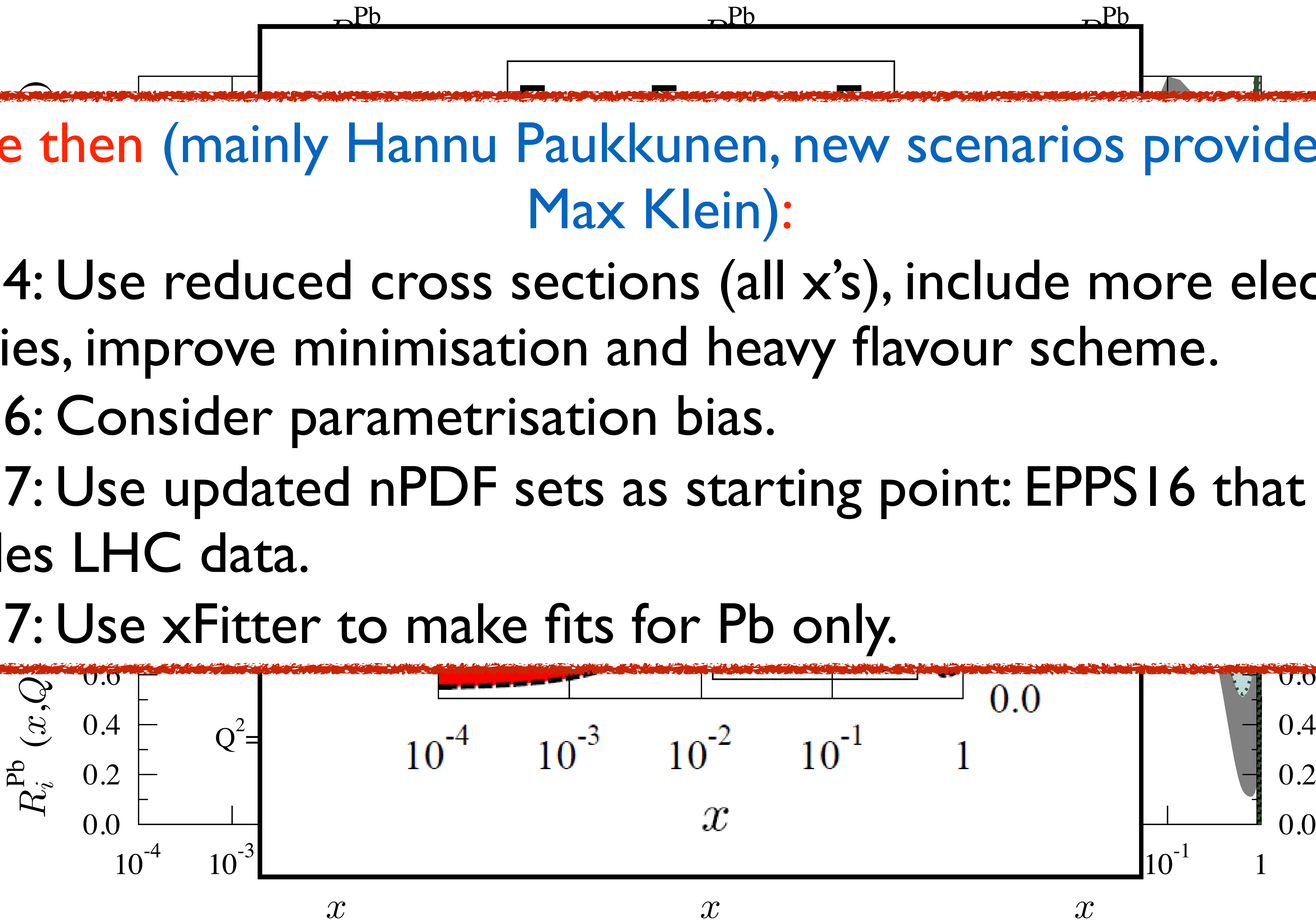


Since then (mainly Hannu Paukkunen, new scenarios provided by Max Klein):

- 2014: Use reduced cross sections (all x's), include more electron energies, improve minimisation and heavy flavour scheme.
- 2016: Consider parametrisation bias.
- 2017: Use updated nPDF sets as starting point: EPPS16 that includes LHC data.
- 2017: Use xFitter to make fits for Pb only.

The LHeC pseudodata

- Assume $\mathcal{L}_{\rm ep} = 10\,{\rm fb}$, $\mathcal{L}_{\rm ePb} = 1\,{\rm fb}$ (per nucleon)
- The assumed energy configs: $\sqrt{s_{\rm p}} = 7\,{\rm TeV}$, $\sqrt{s_{\rm Pb}} = 2.75\,{\rm TeV}$ (per nucleon) on $E_e = 60\,{\rm GeV}$ electrons.
- The pseudodata are here obtained from ratios of reduced cross sections σ^i and relative point-to-point ($\delta^i_{\rm uncor.}$) and normalization ($\delta^i_{\rm uncor.}$) uncertainties as

$$R_i = R_i(EPS09) \times \left[1 + \delta^i_{\rm uncor.} r^i + \delta_{\rm norm.} r^{\rm norm.}\right]$$

where

$$R_i(EPS09) = \frac{\sigma^i_{\rm ePb}(CTEQ6.6 + EPS09)}{\sigma^i_{\rm ep}(CTEQ6.6)},$$

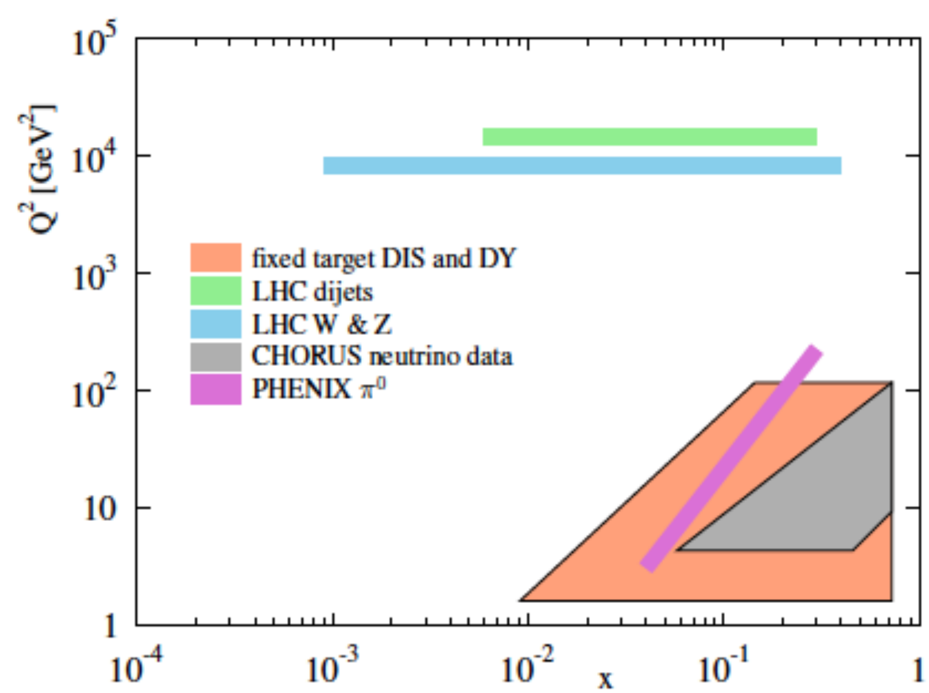
and r^i and $r^{\rm norm.}$ are Gaussian random numbers.

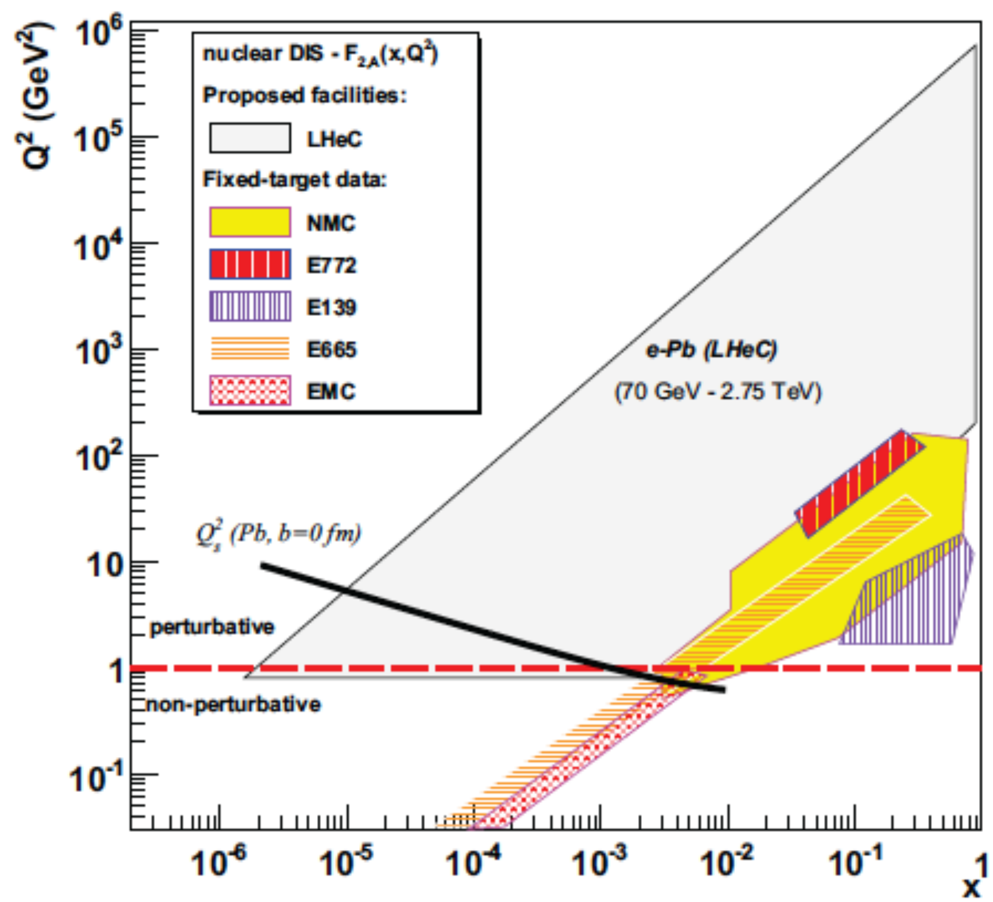
- In EPS09 $R_{u_{\rm V}} \approx R_{d_{\rm V}}$, $R_{\overline{u}} \approx R_{\overline{d}} \approx R_{\overline{s}}$ (free in EPPS16, but would not expect large deviations from this)

DIS17 (I):

The analysis framework

- The fit framework same as in the EPPS16 analysis [EPJ C77, 163]
- Include the same data as in EPPS16 plus LHeC (NC and CC) pseudo data.
- Hessian uncertainty analysis with $\Delta\chi^2 = 52$ (as in EPPS16)

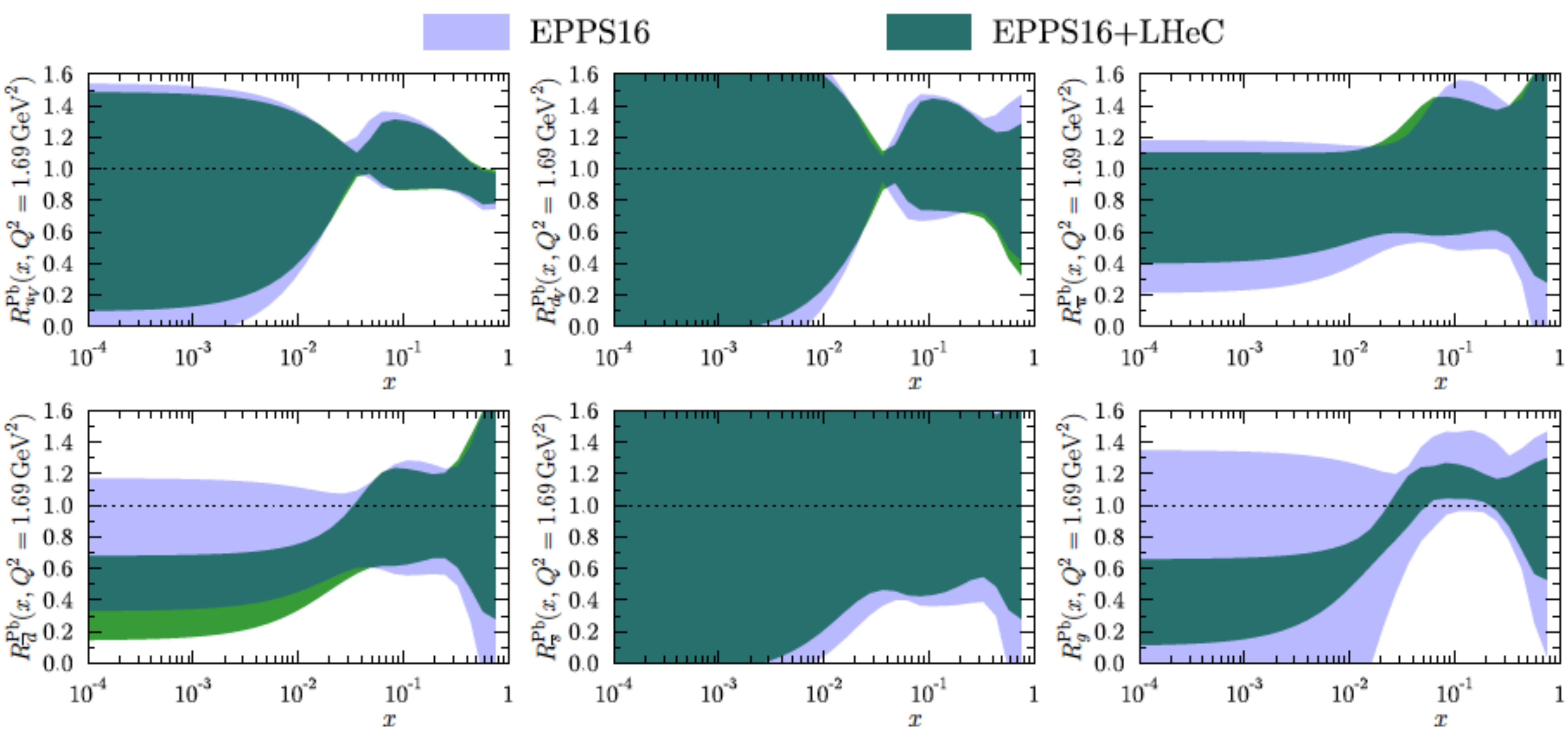




DIS17 (I):

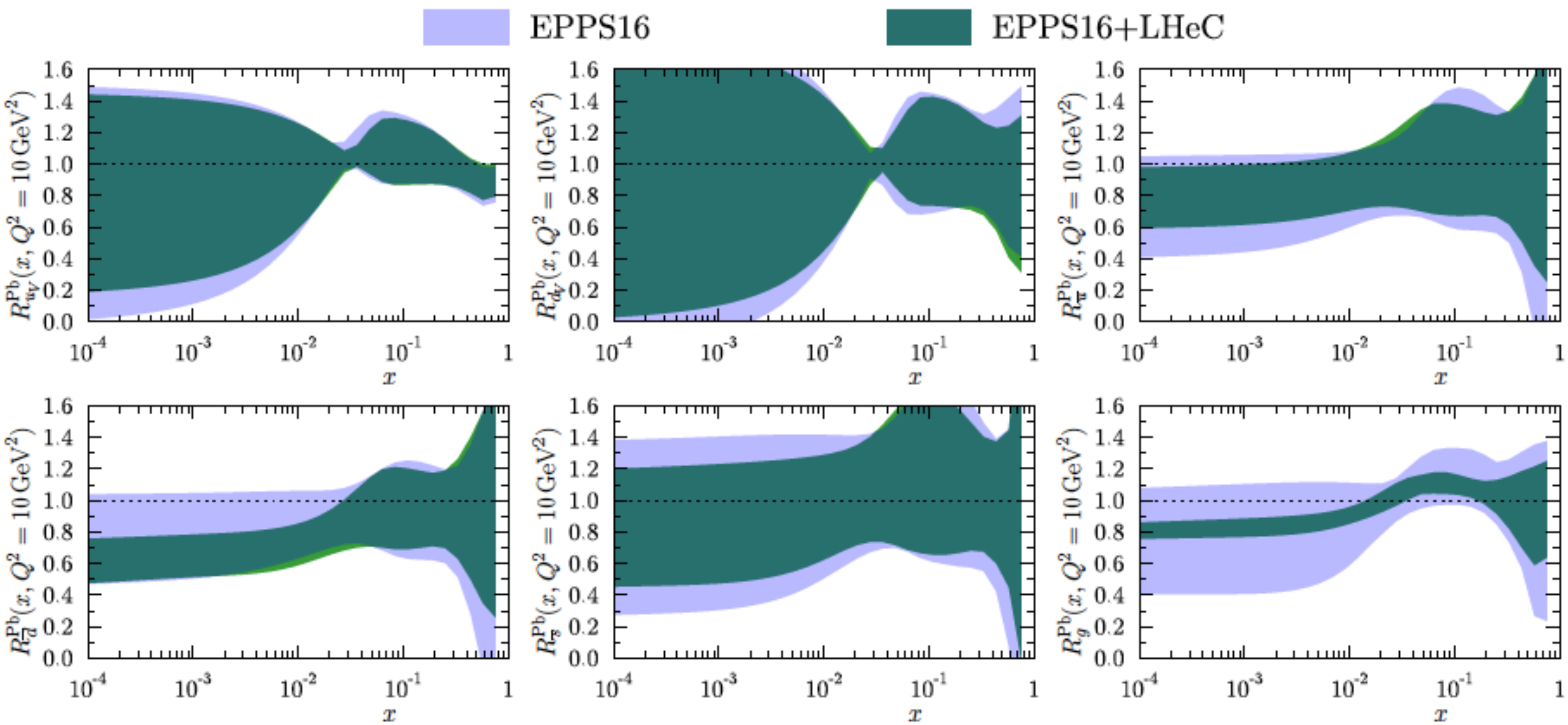
The effect of LHeC pseudodata

- The improvement after adding the LHeC data ($Q^2 = 1.69\,\mathrm{GeV}^2$)



The effect of LHeC pseudodata

- The improvement after adding the LHeC data ($Q^2 = 10\,\mathrm{GeV}^2$)

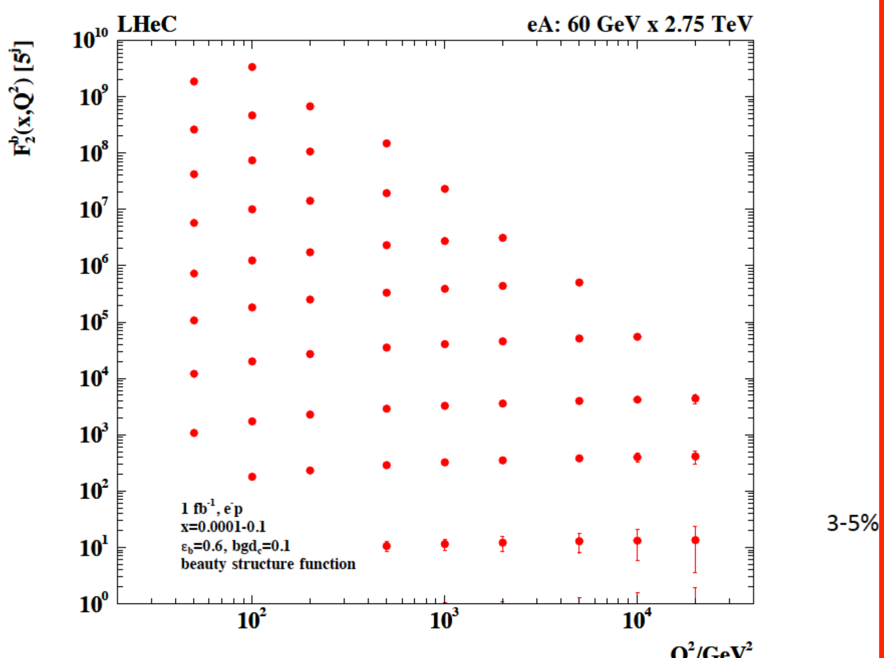


DIS17 (I):

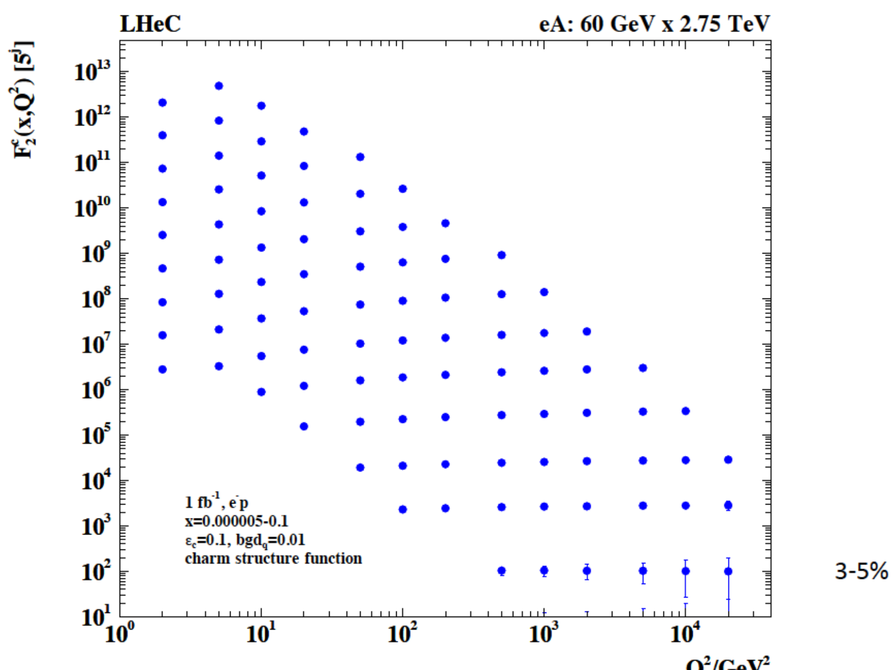
The effect of LHeC pseudodata

Heavy flavour not yet in.

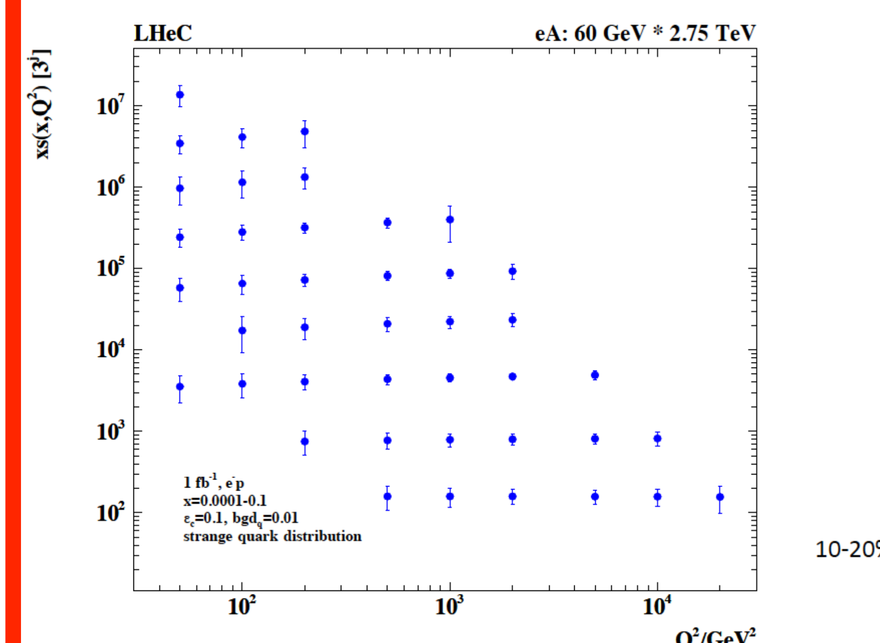
Heavy Flavour – Beauty in ePb - from NC

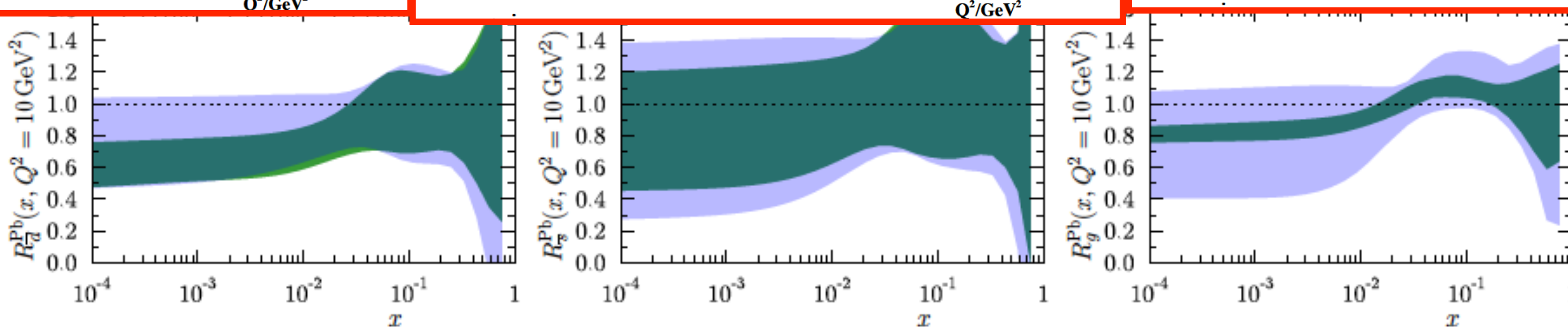


Heavy Flavour – Charm in eA - from NC



Heavy Flavour – Strange in ePb - from CC





DIS17 (II):

The effect of LHeC pseudodata

- Why it's so hard to pin down the flavor dependence?
- Take the valence up-quark distribution u_V^A as an example:

$$u_V^A = \frac{Z}{A} R_{u_V} u_V^{\rm proton} + \frac{A-Z}{A} R_{d_V} d_V^{\rm proton}$$

- Write this in terms of average modification R_V and the difference δR_V

$$R_V \equiv \frac{R_{u_V} u_V^{\rm proton} + R_{d_V} d_V^{\rm proton}}{u_V^{\rm proton} + d_V^{\rm proton}}, \qquad \delta R_V \equiv R_{u_V} - R_{d_V}$$

$$u_V^A = R_V \left(\frac{Z}{A} u_V^{\rm proton} + \frac{A-Z}{A} d_V^{\rm proton} \right) + \delta R_V \left(\frac{2Z}{A} - 1 \right) \frac{u_V^{\rm proton}}{1 + u_V^{\rm proton}/d_V^{\rm proton}}$$

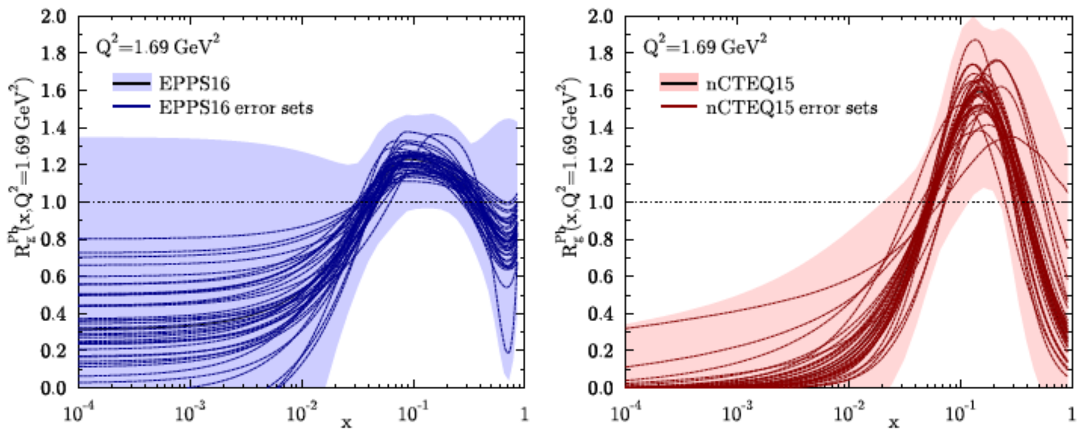
Leading term   "Correction term"

- The effects of flavour separation (i.e. δR_V here) are suppressed in cross sections — but also so in most of the nPDF applications.

DIS17 (II):

$$R^{\mathrm{EPS09}}(x) = \begin{cases} a_0 + a_1 (x - x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

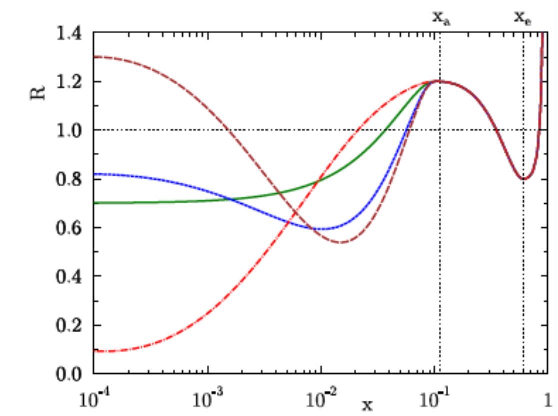
$$R^{\mathrm{nCTEQ15}}(x) = \left[c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}\right] / f^p(x)$$



$$R(x \le x_a) = a_0 + a_1(x-x_a)^2 + \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right) + \dots\right]$$

or

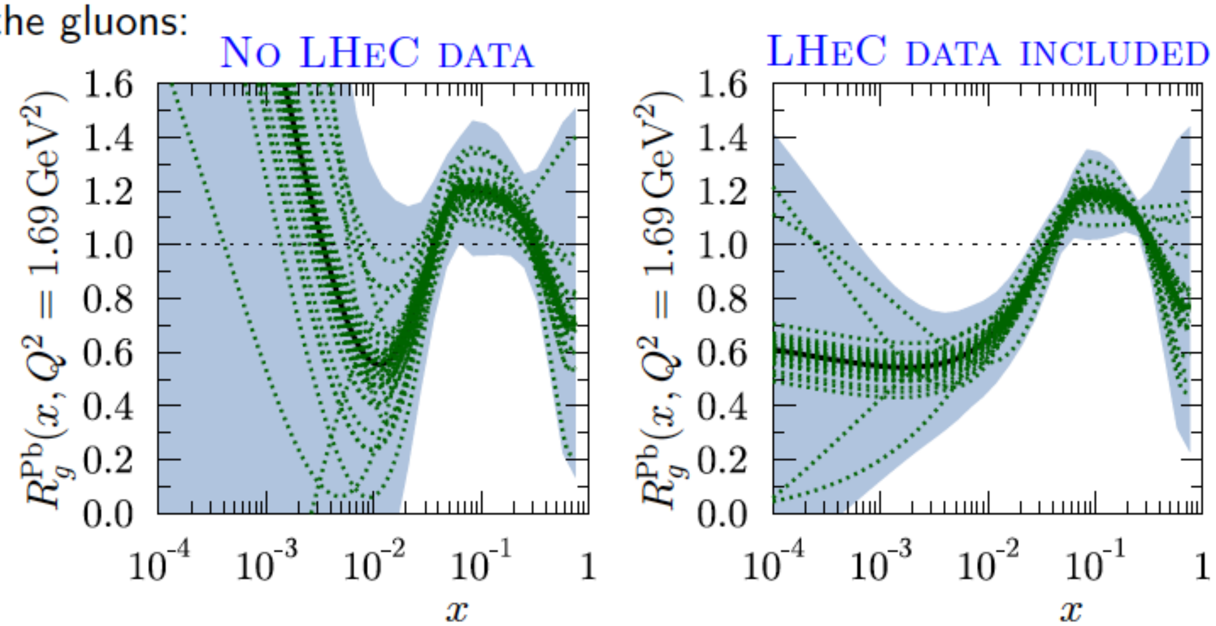
$$R(x \le x_a) = a_0 + (x-x_a)^2\left[a_1 + a_2 x^{\alpha} + a_3 x^{2\alpha} + a_4 x^{3\alpha} + \dots\right], \ \alpha \ll 1$$



- Would need Monte-Carlo methods to more reliably map the uncertainties

  ⟹ Further work needed

- Despite all the shortcomings, a typical result using a more flexible form for the gluons:



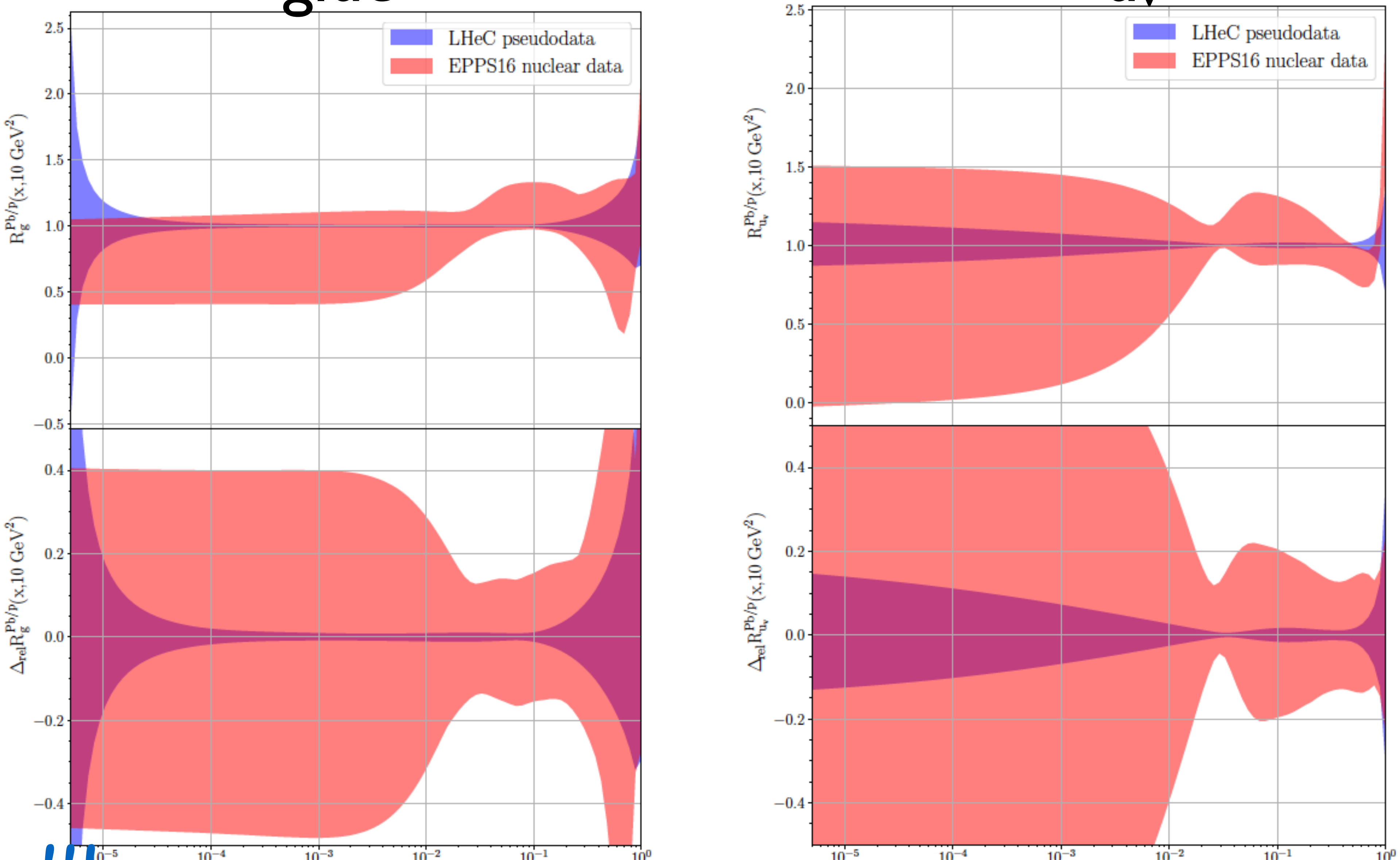
Pb PDFs with xFitter:

- Proof of principle: Pb-only PDFs with the same pseudodata as before, using xFitter: HERAPDF2.0 parametrisation, NNLO, RTOPT mass scheme, to estimate the 'ultimate' precision (P. Agostini, NA):

glue $\qquad$ u_v

Ratios

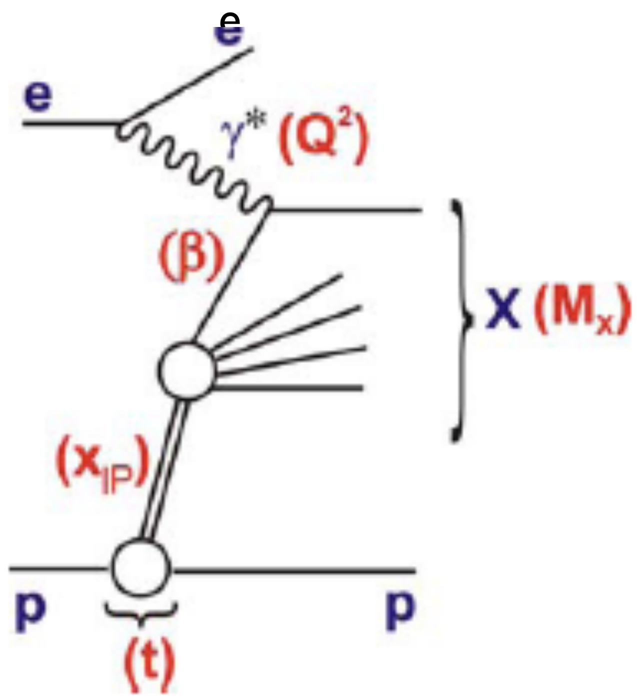
Uncertainty on ratios

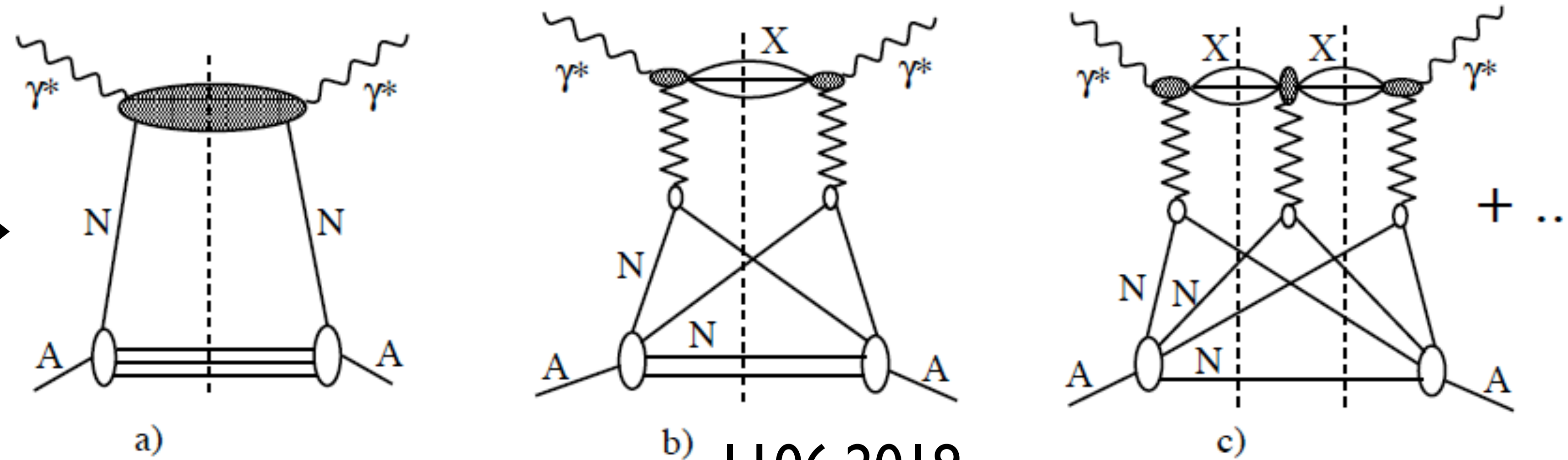


x $\qquad$ x

Thanks Voica!!!

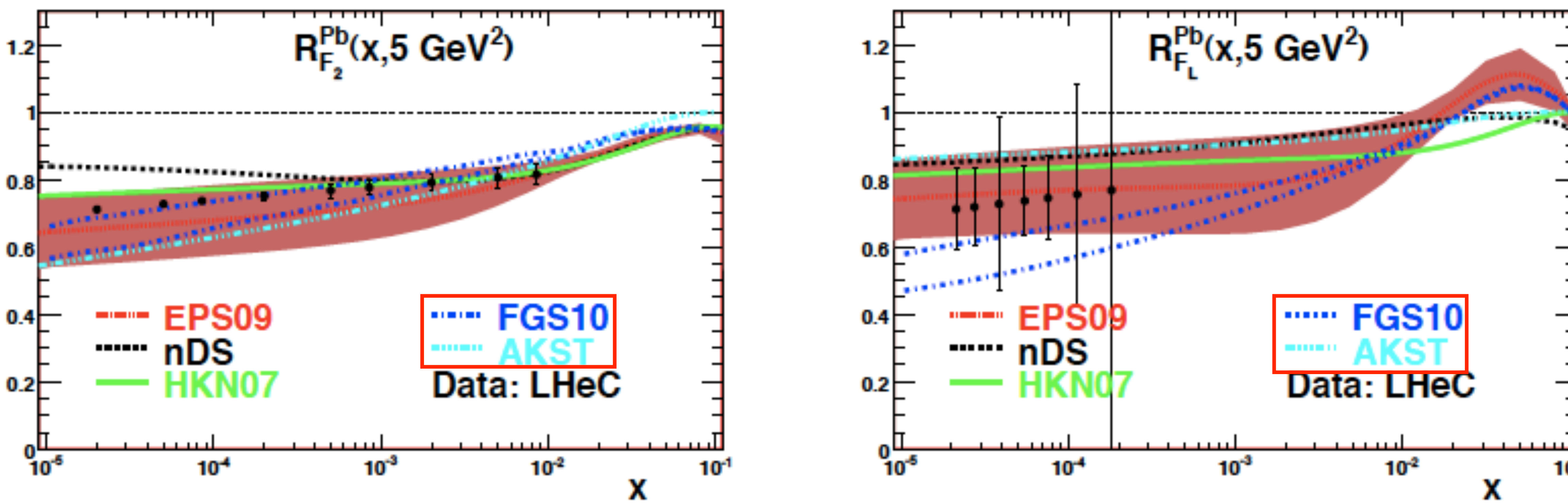
Diffraction & shadowing:





1106.2019

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



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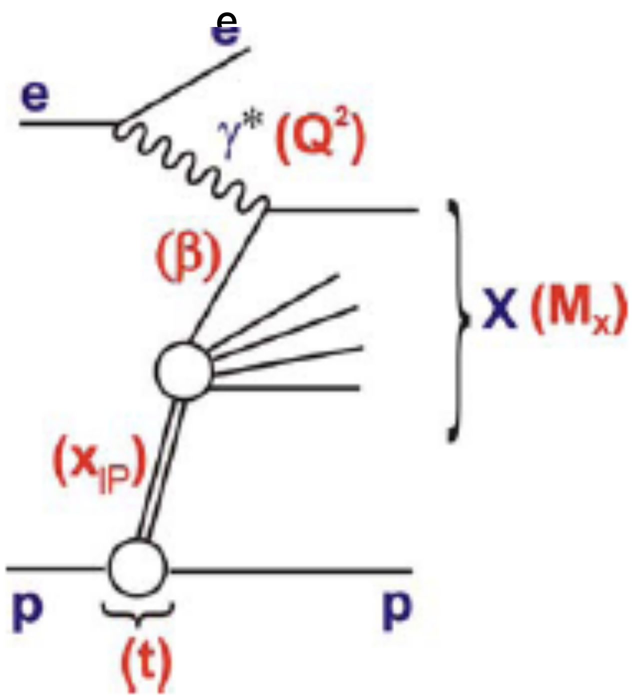

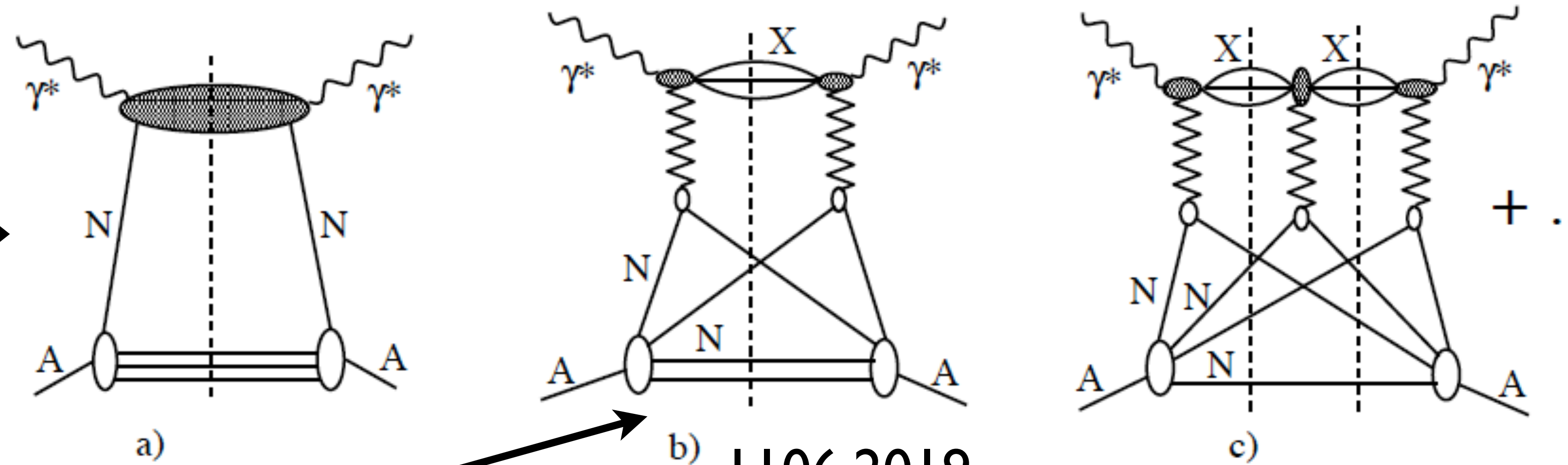

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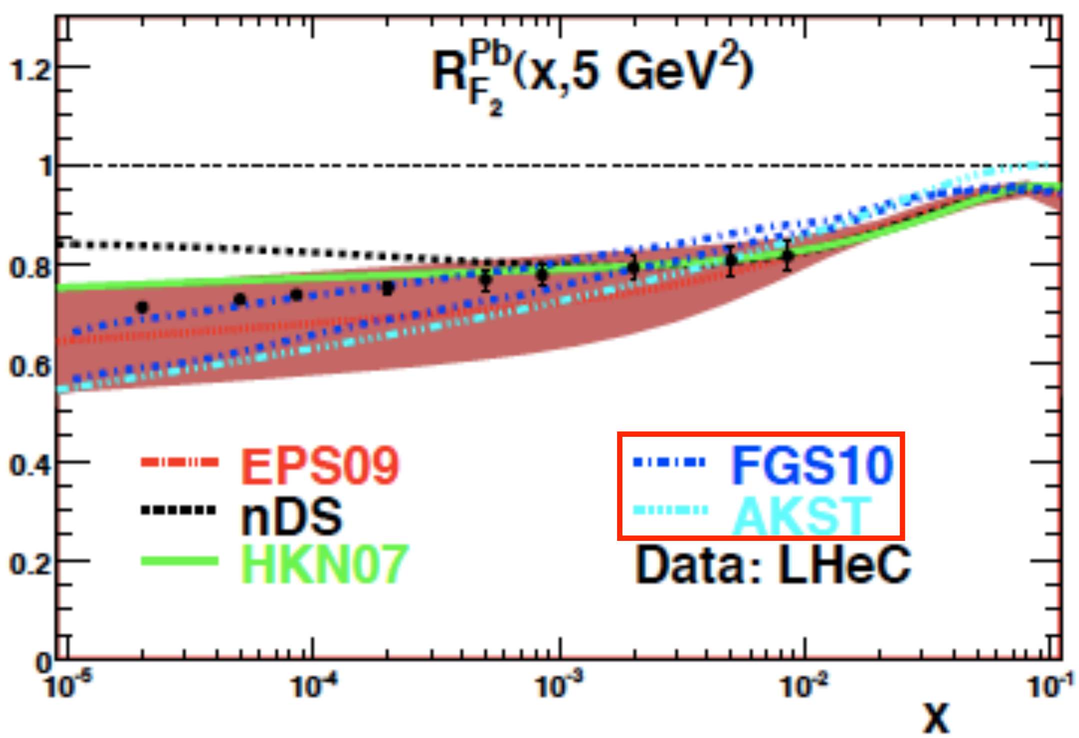
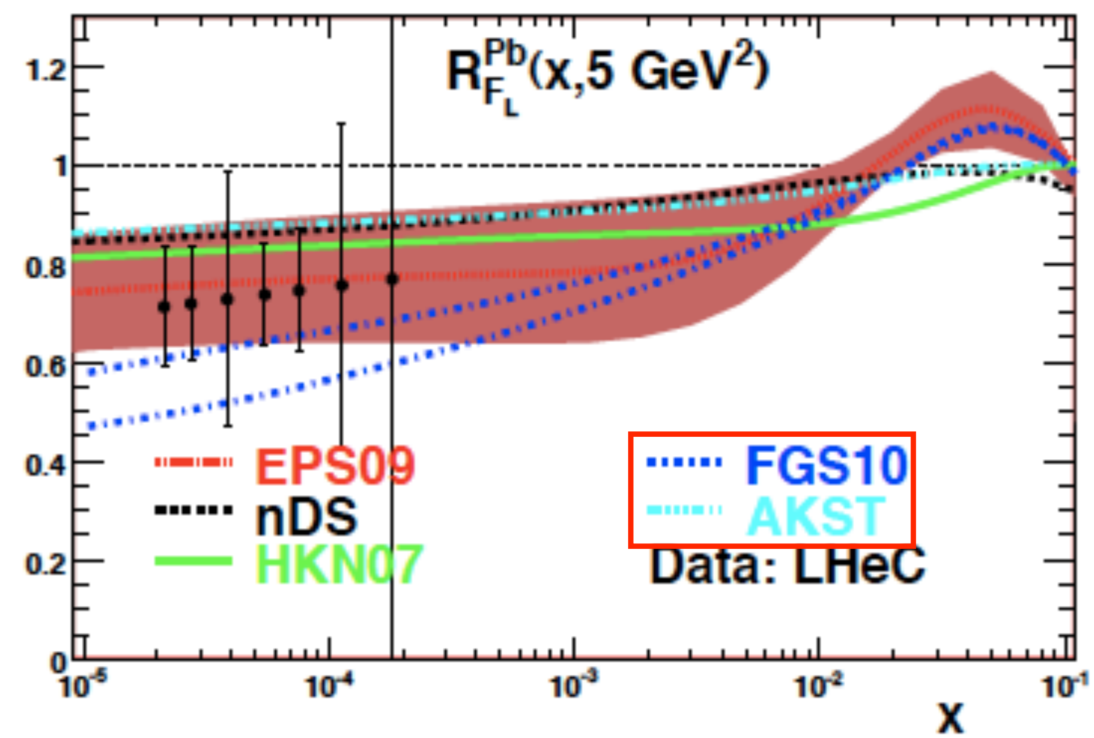
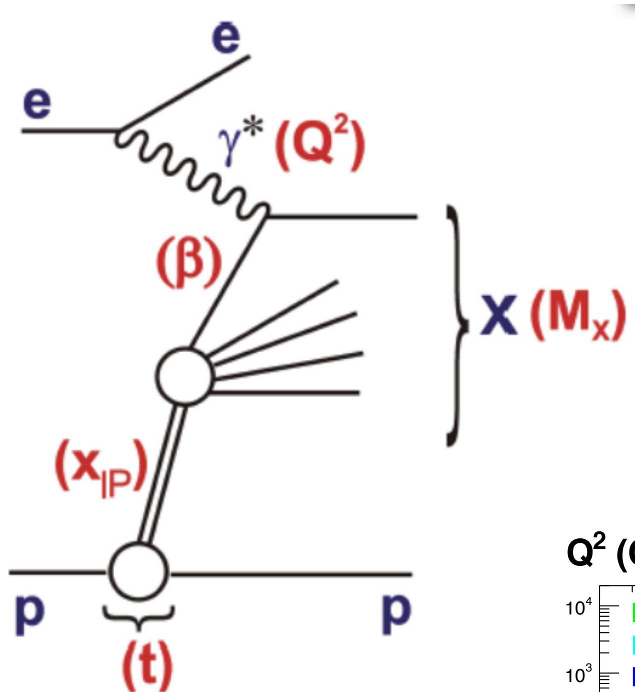
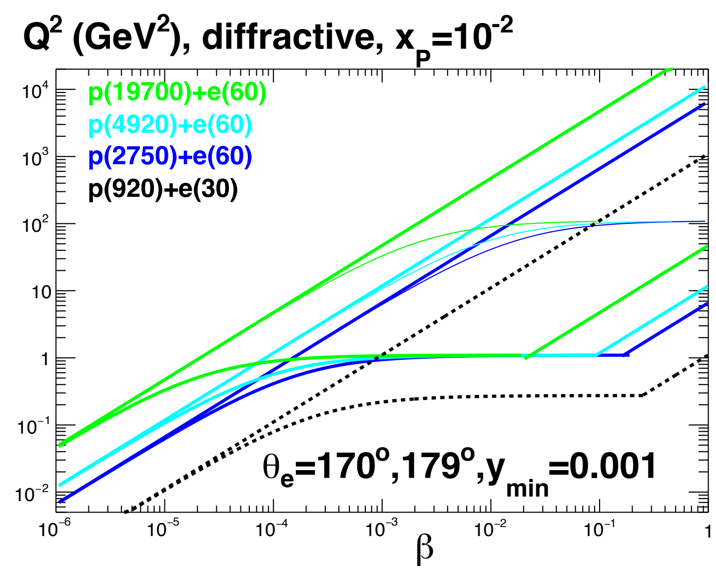


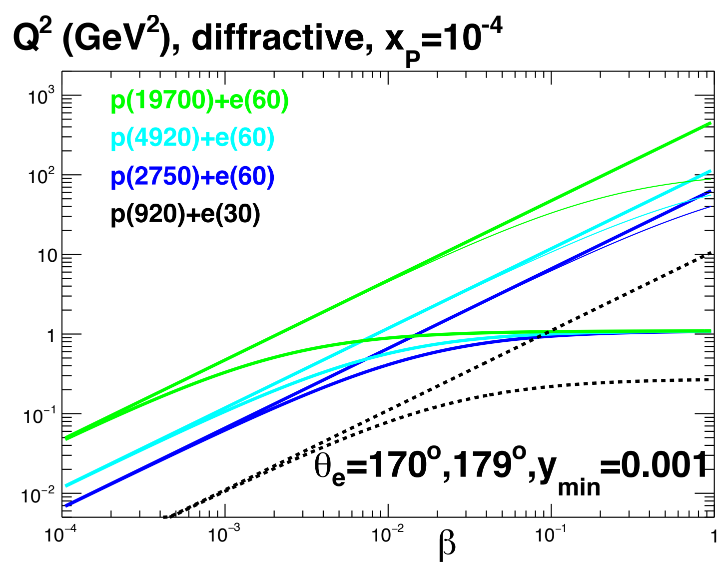


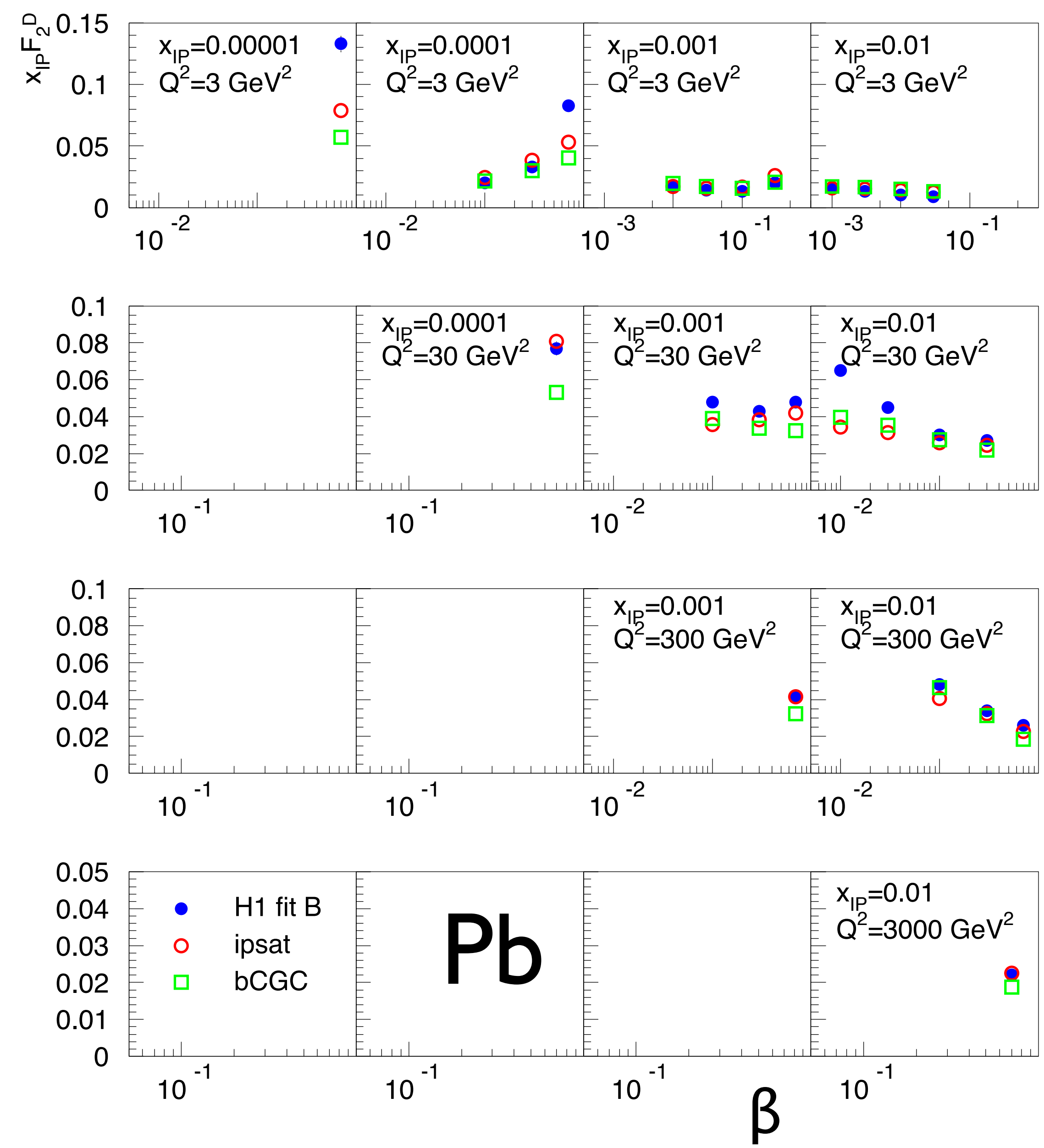
Diffractive DIS (CDR):



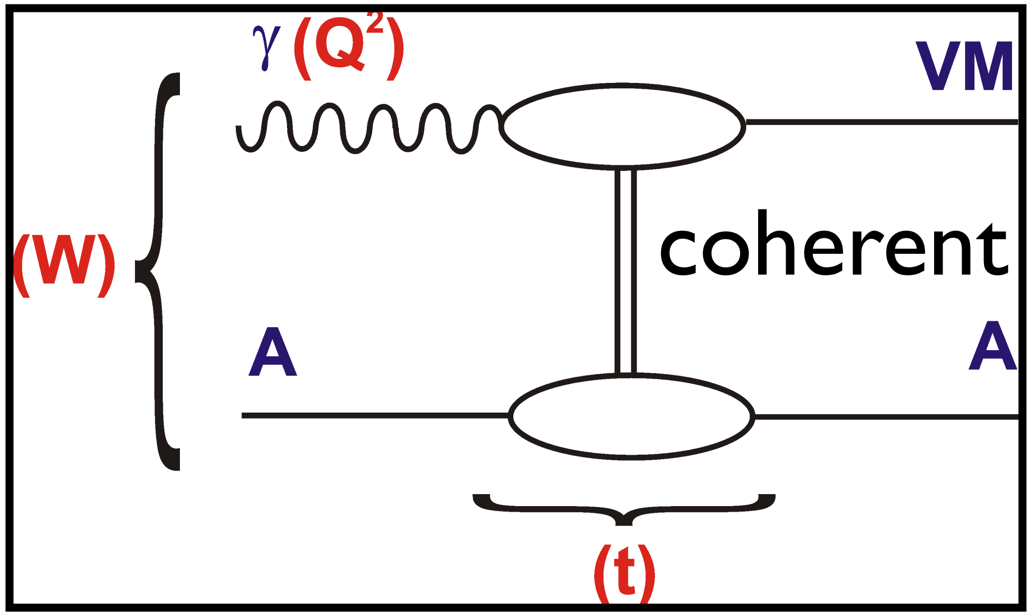
- Large increase in the M^2 (diffractive heavy states up to ~0.5 TeV), $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.
- First determination of nDPDFs.





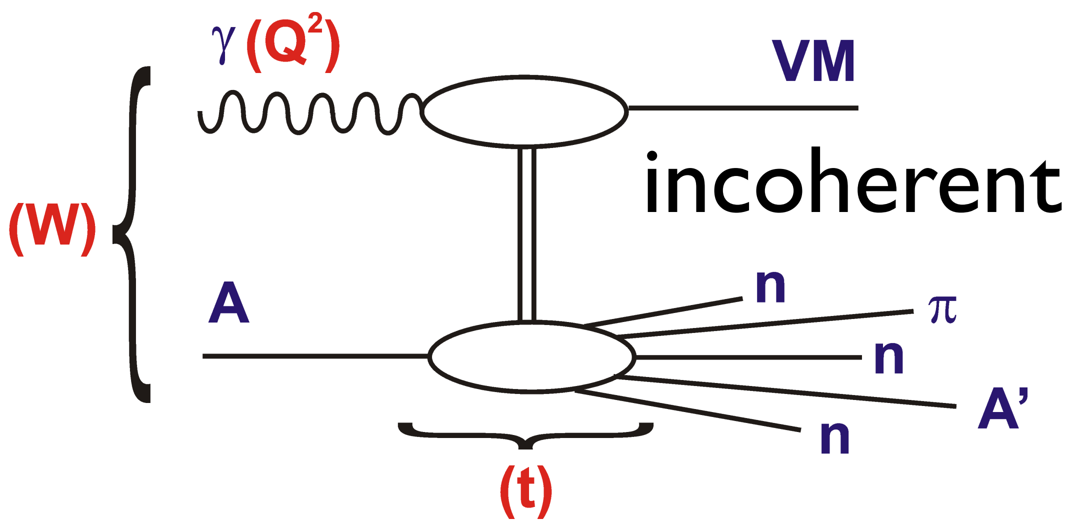


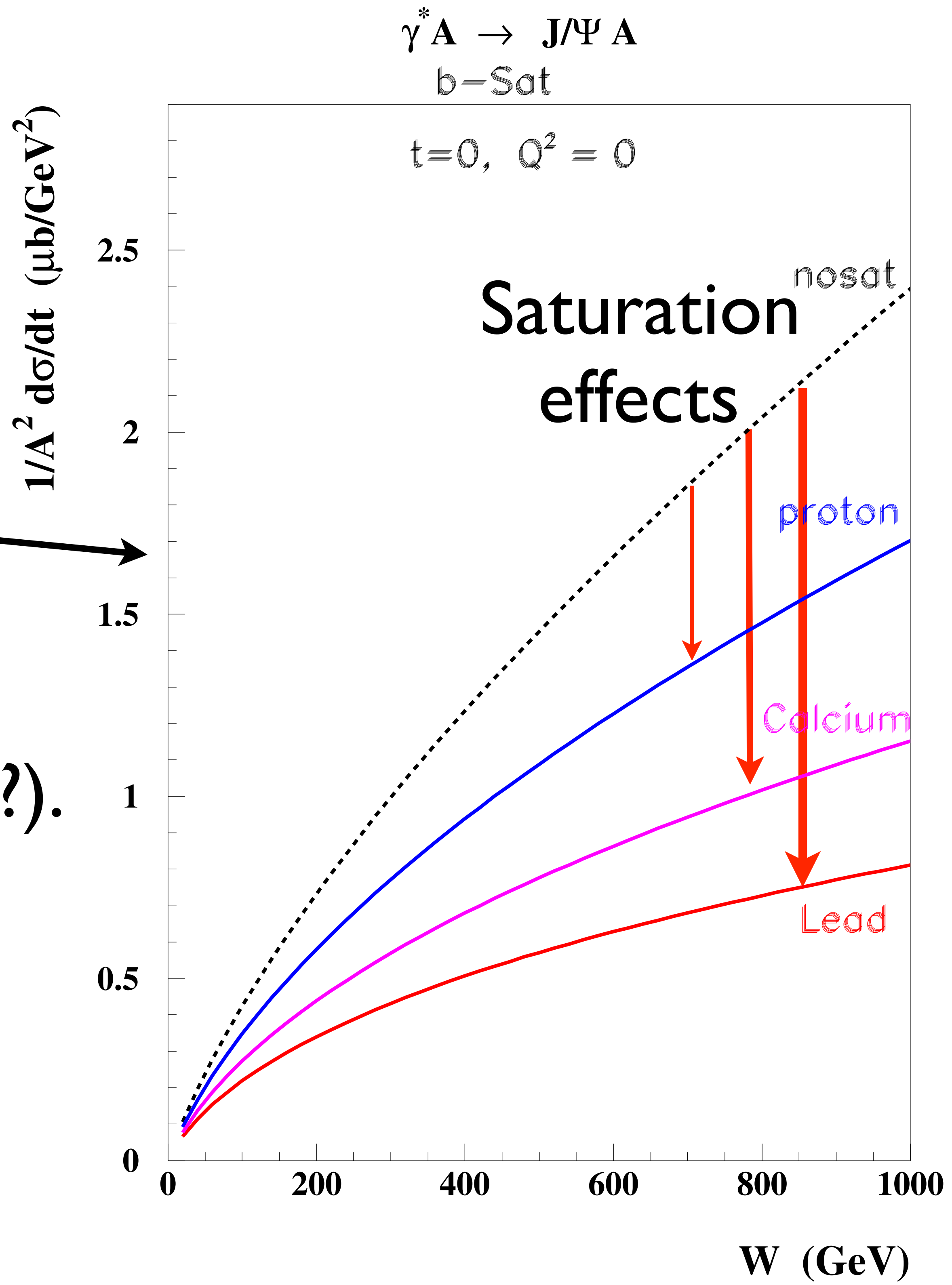
Elastic VM (CDR):



- For the coherent case, predictions available.

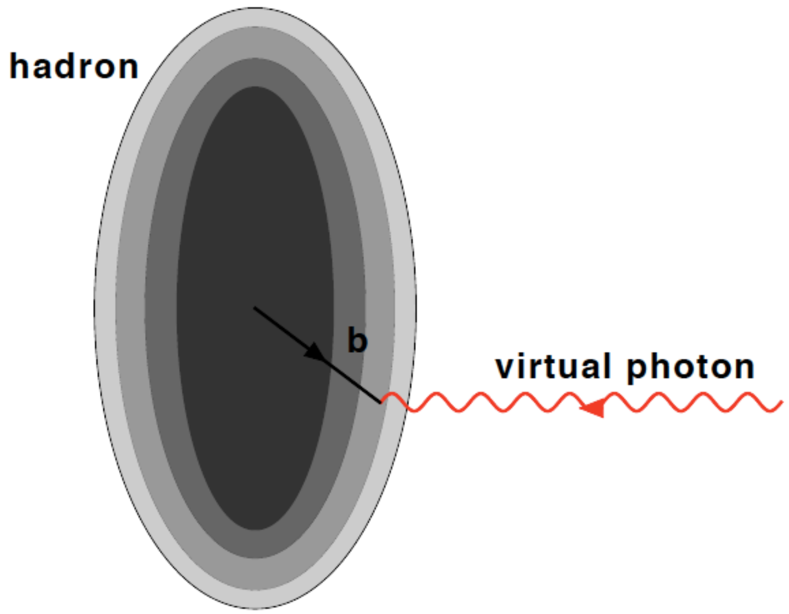
- Challenging experimental problem (neutron tagging in ZDC?).

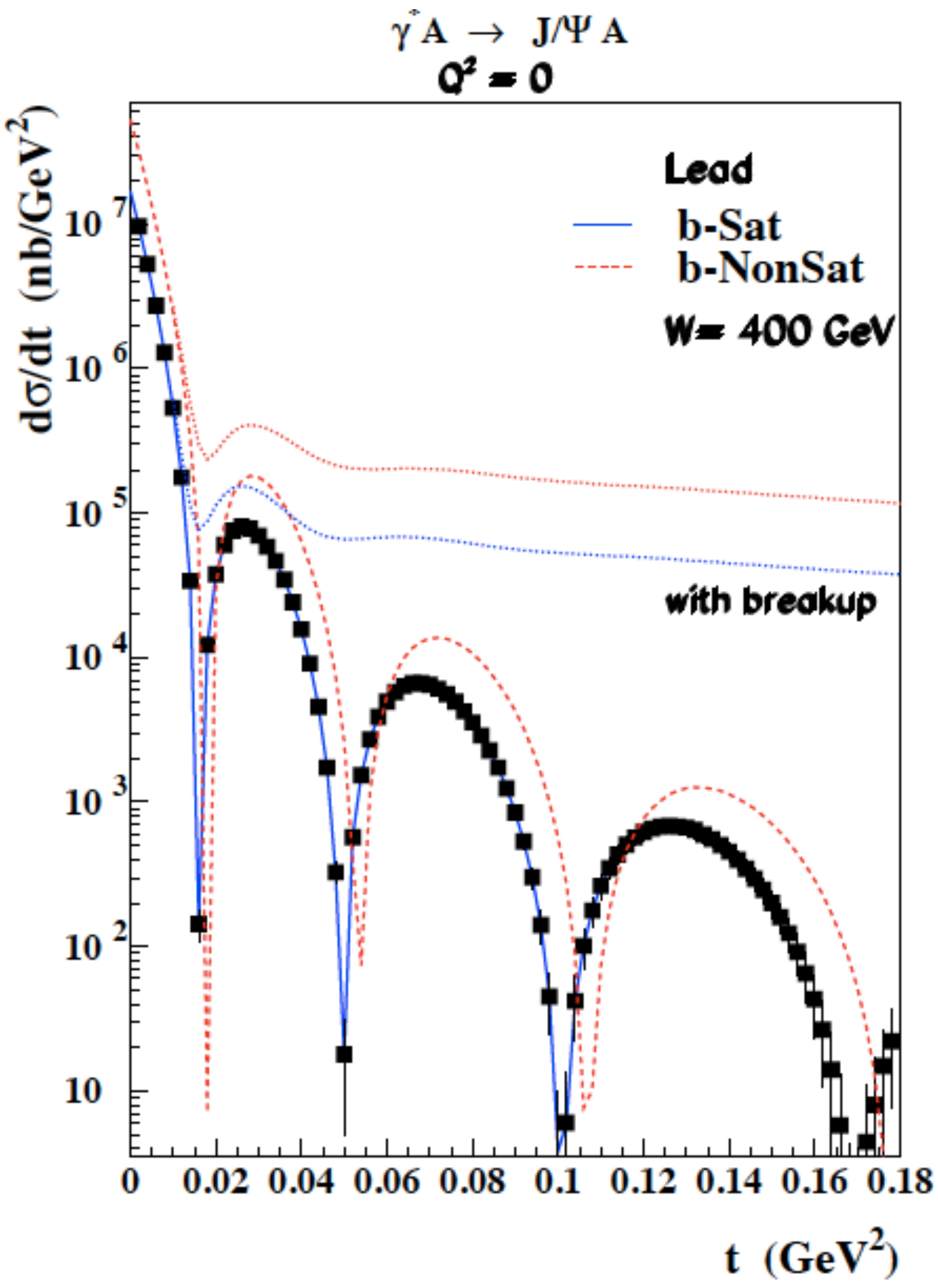




Transverse scan (CDR):

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





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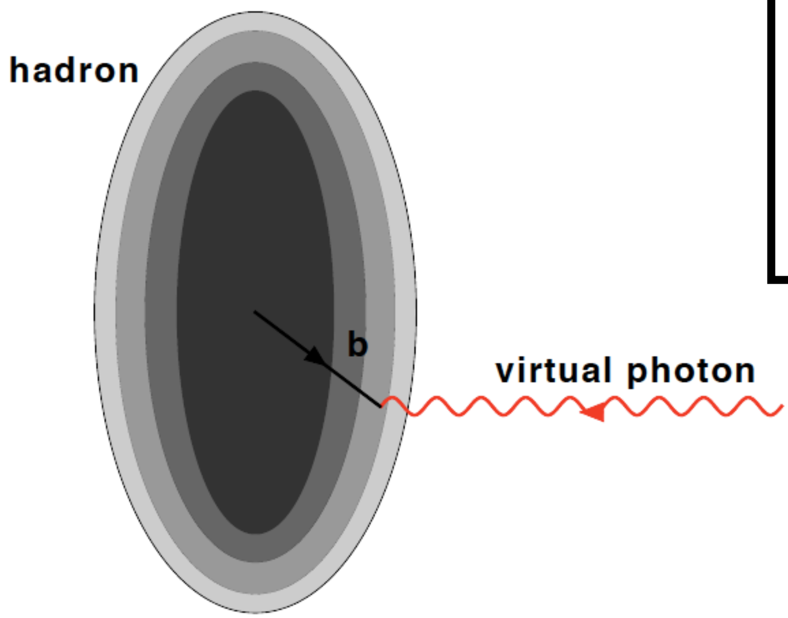
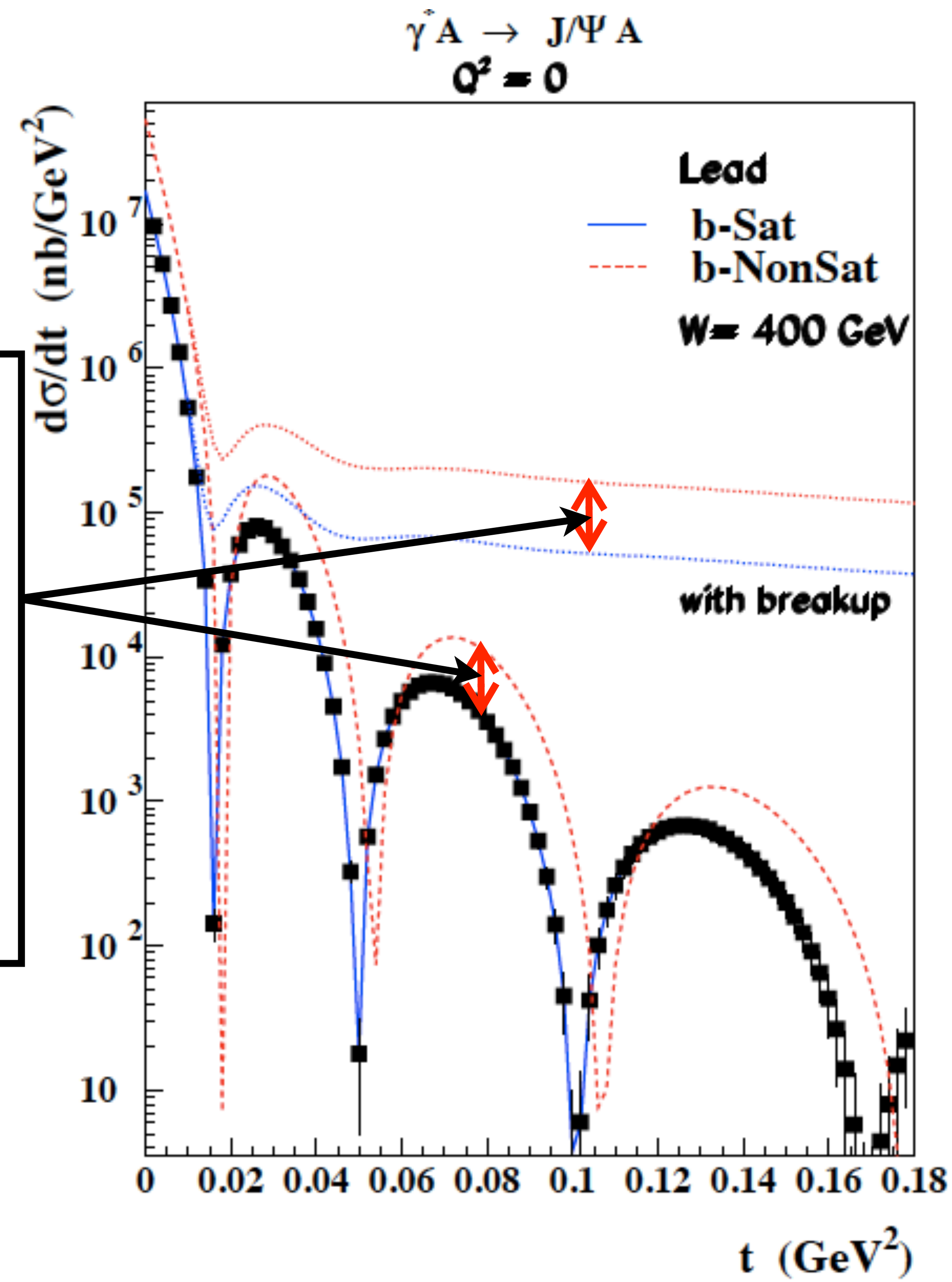


- Large extent in t with good precision.
- Sizable saturation effects expected.



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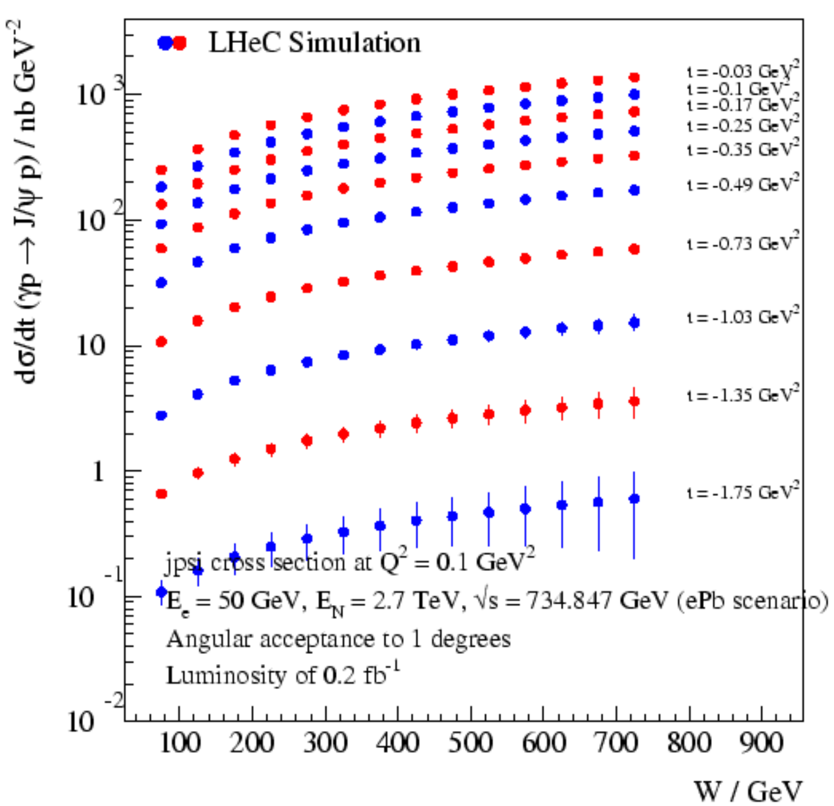

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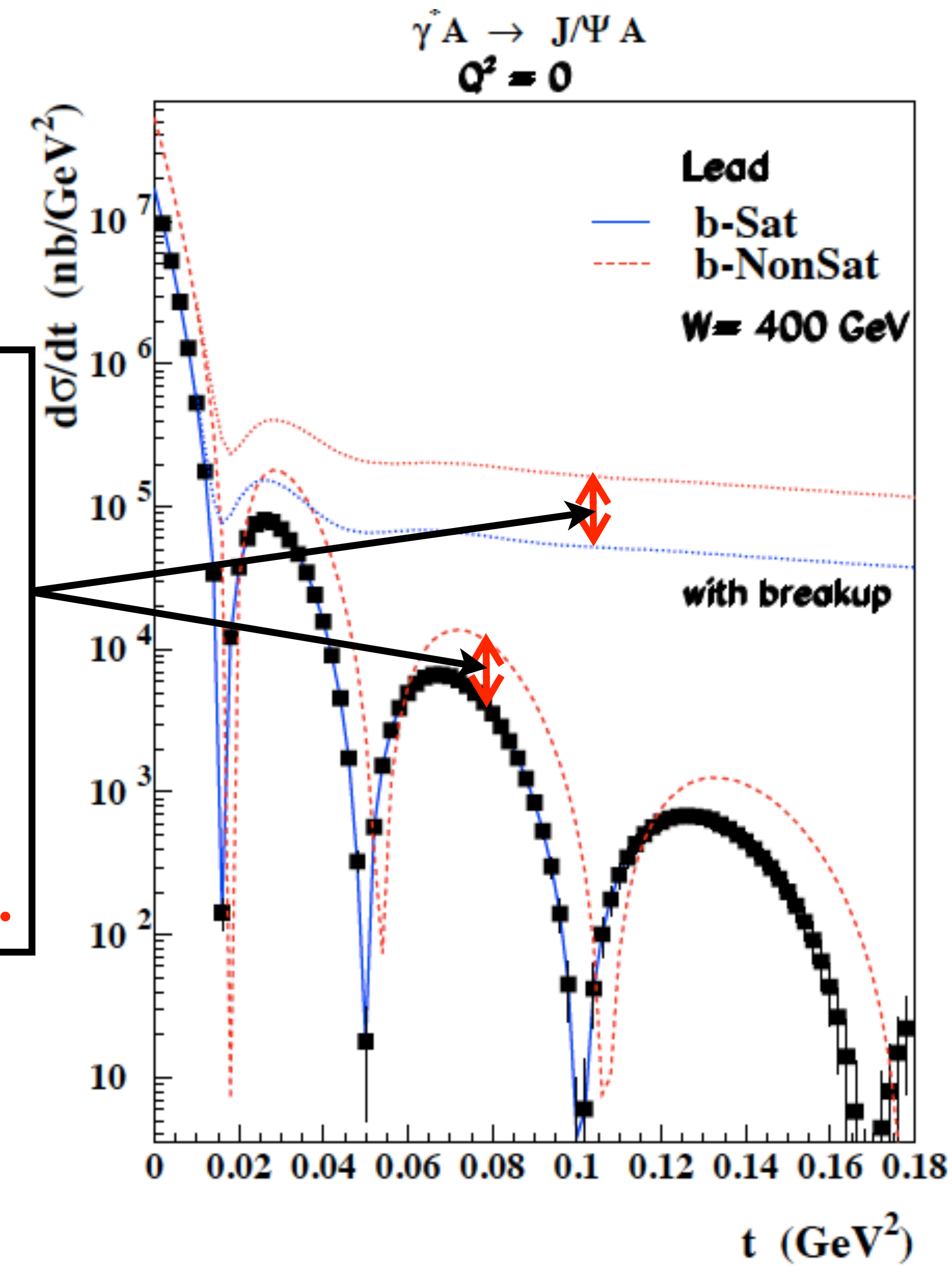

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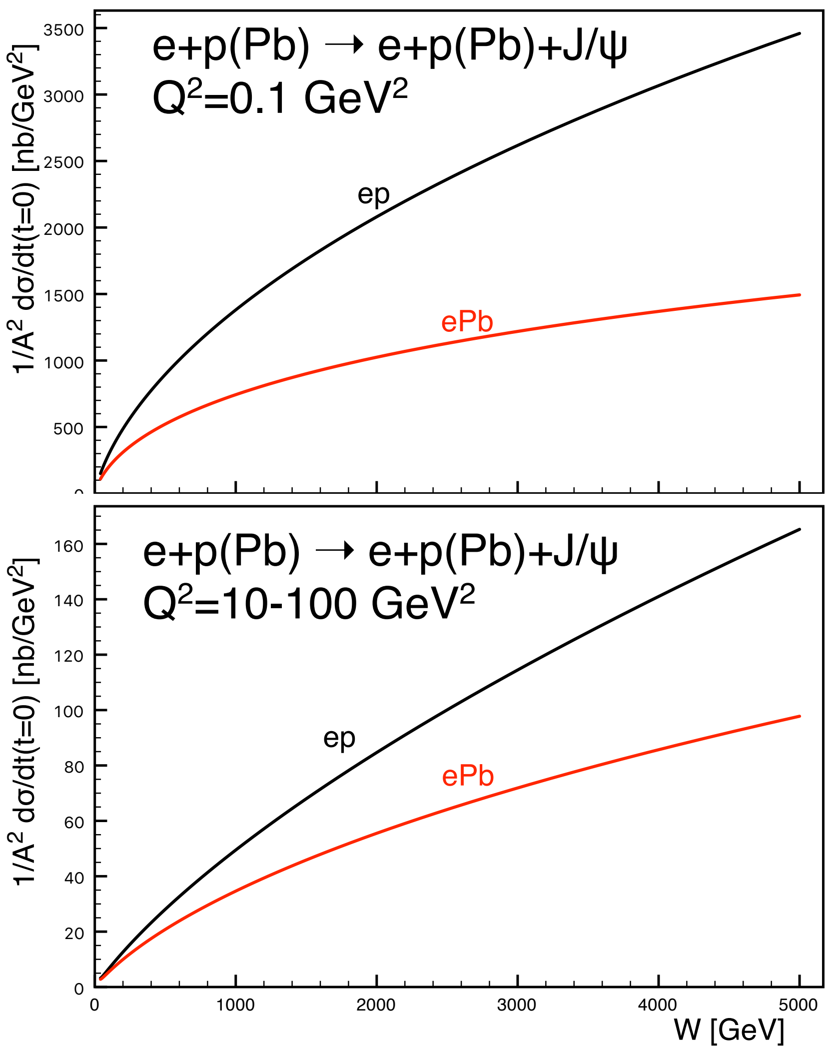

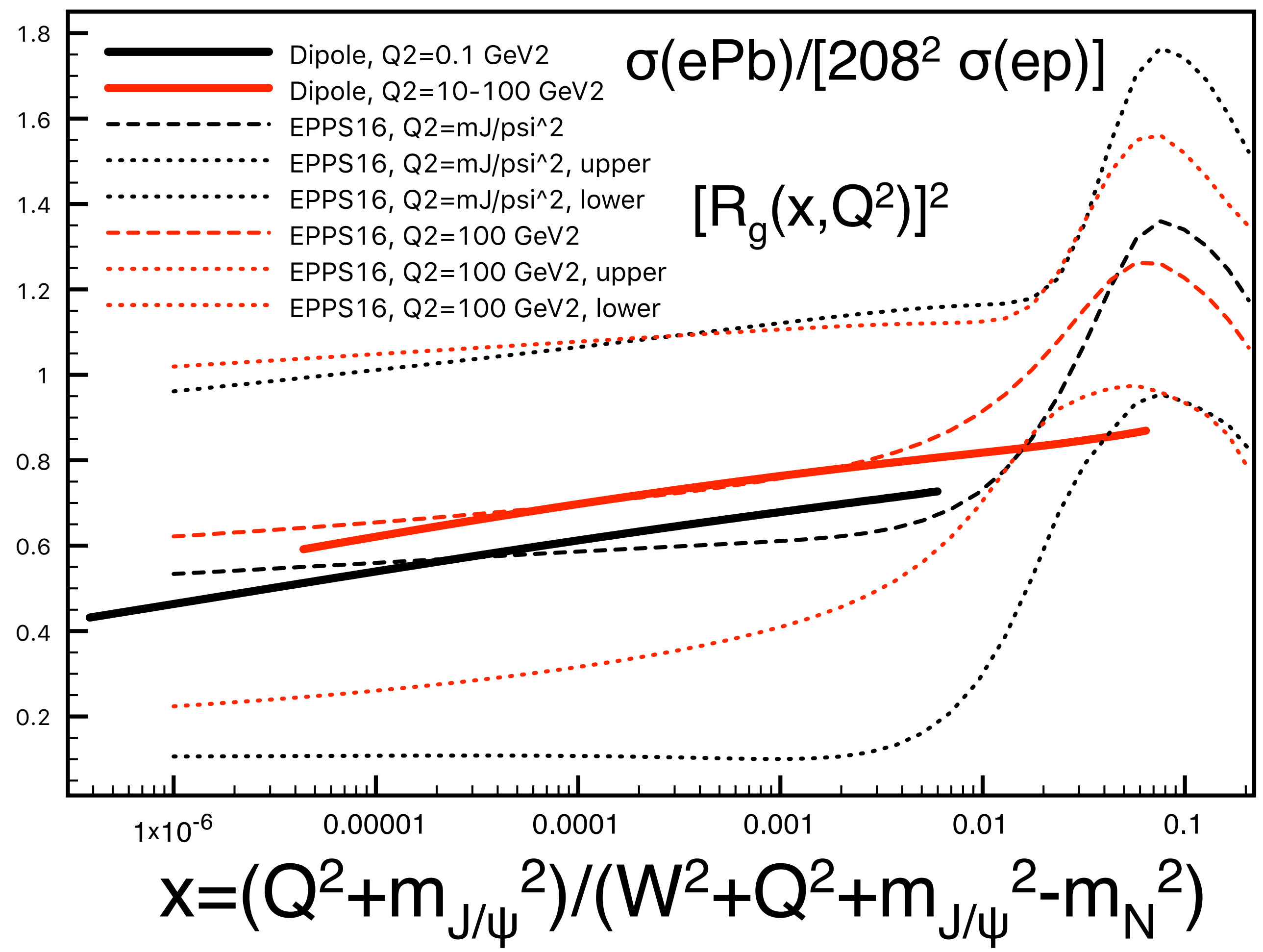

Mantysaari, Paukkunen

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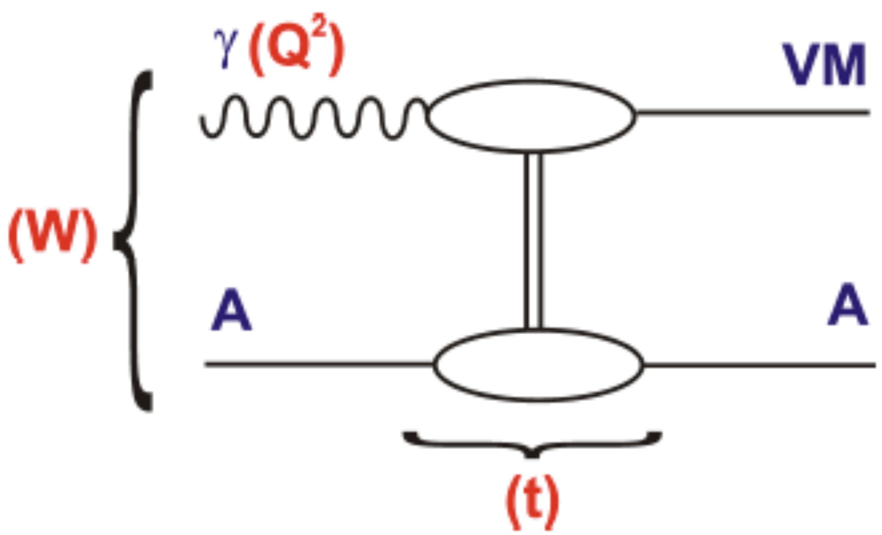
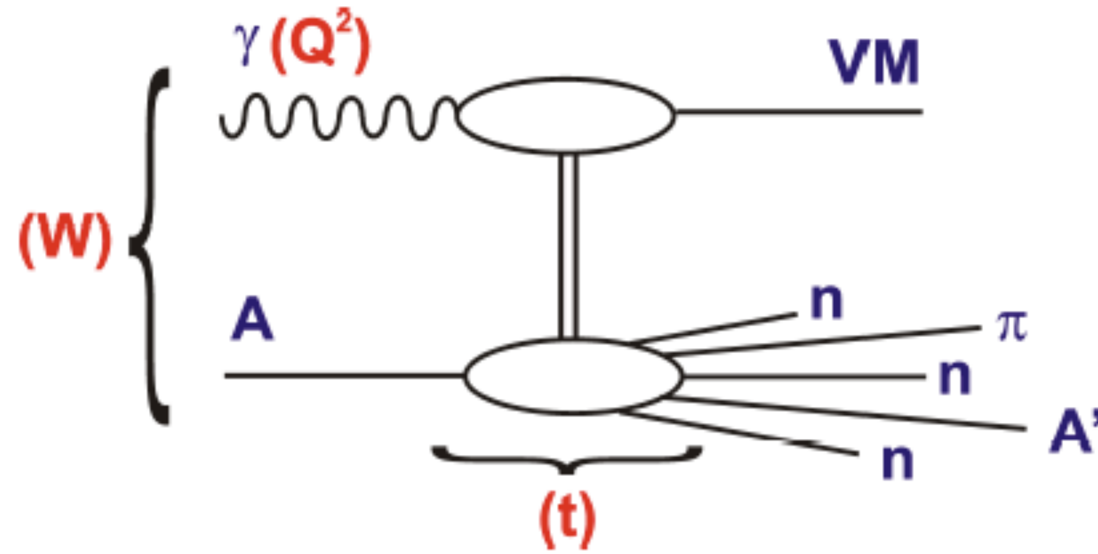
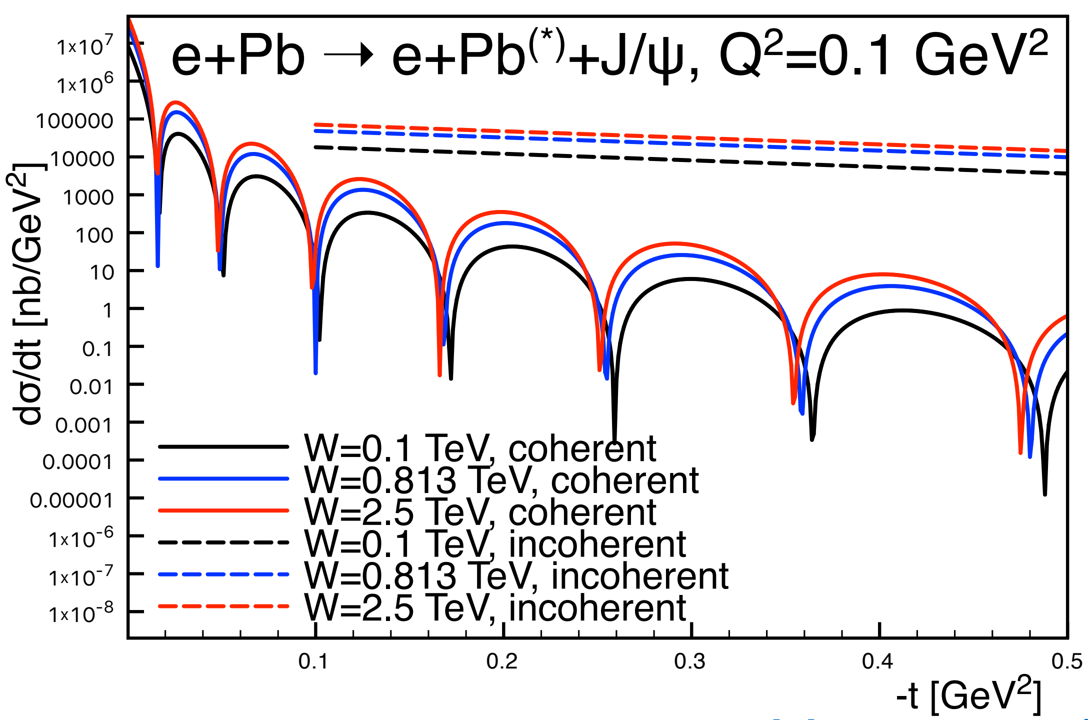
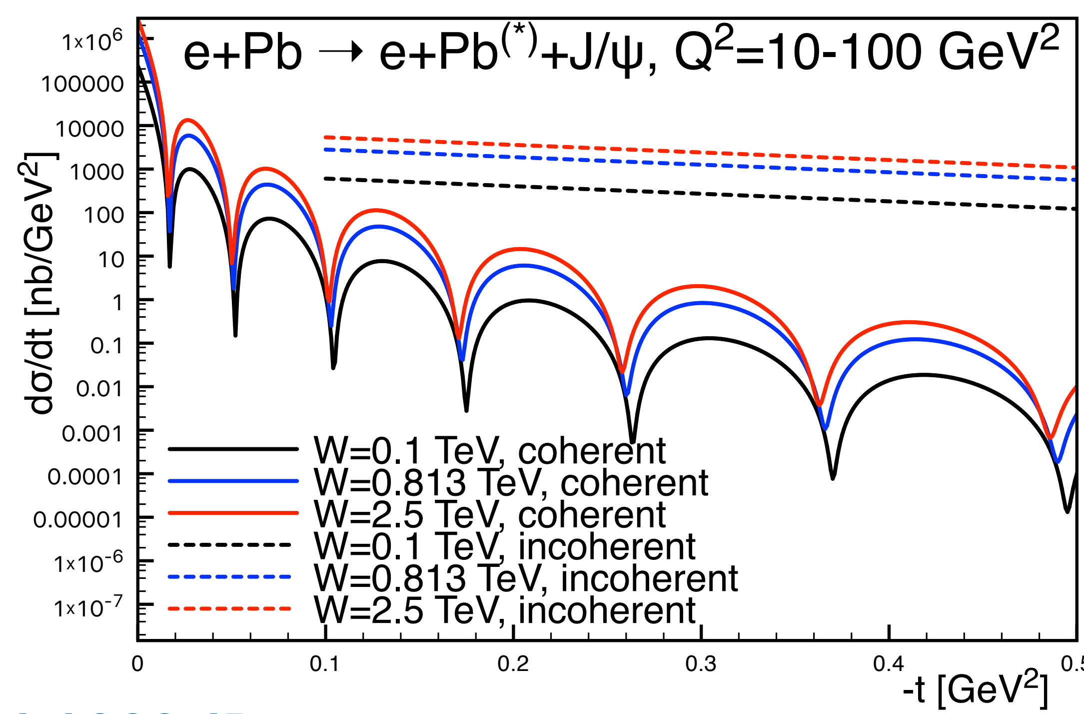




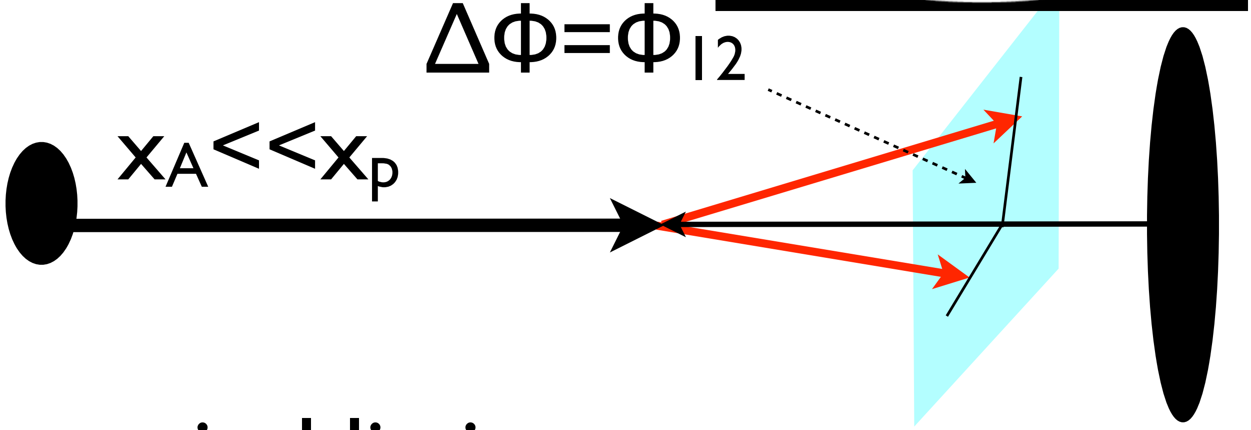


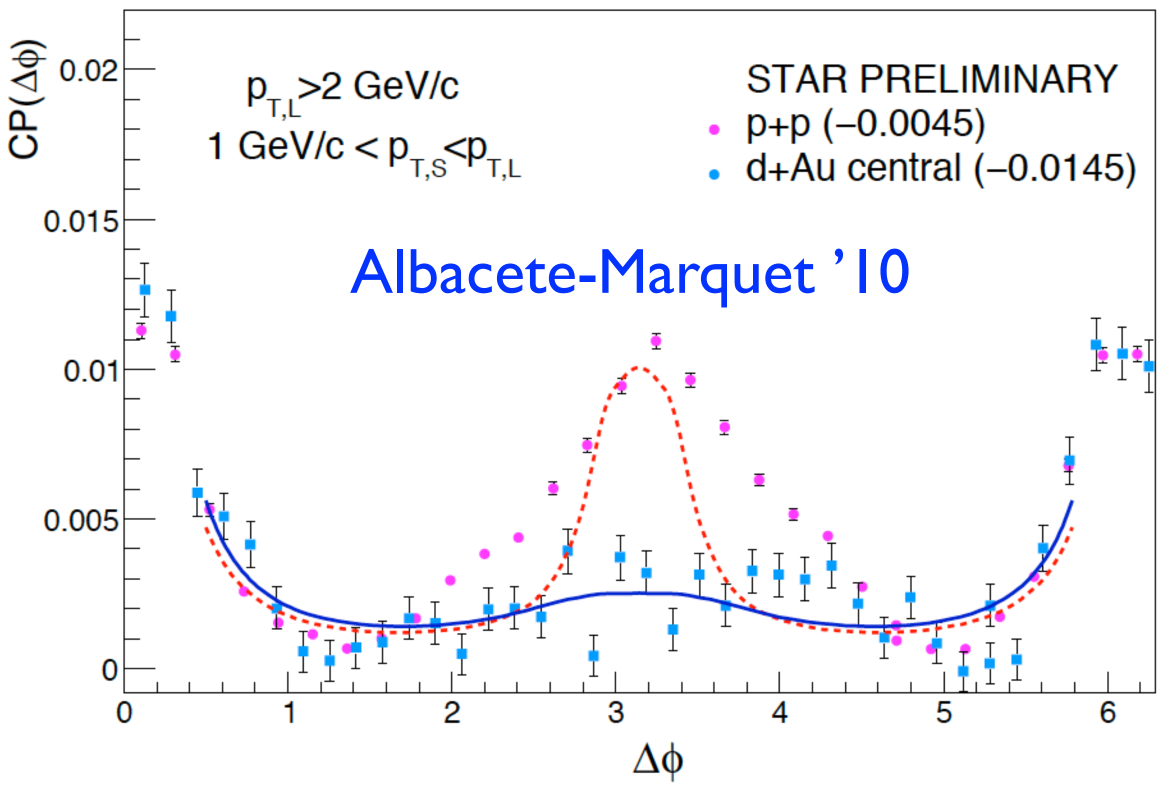


Mantysaari, 1011.1988, IPsat

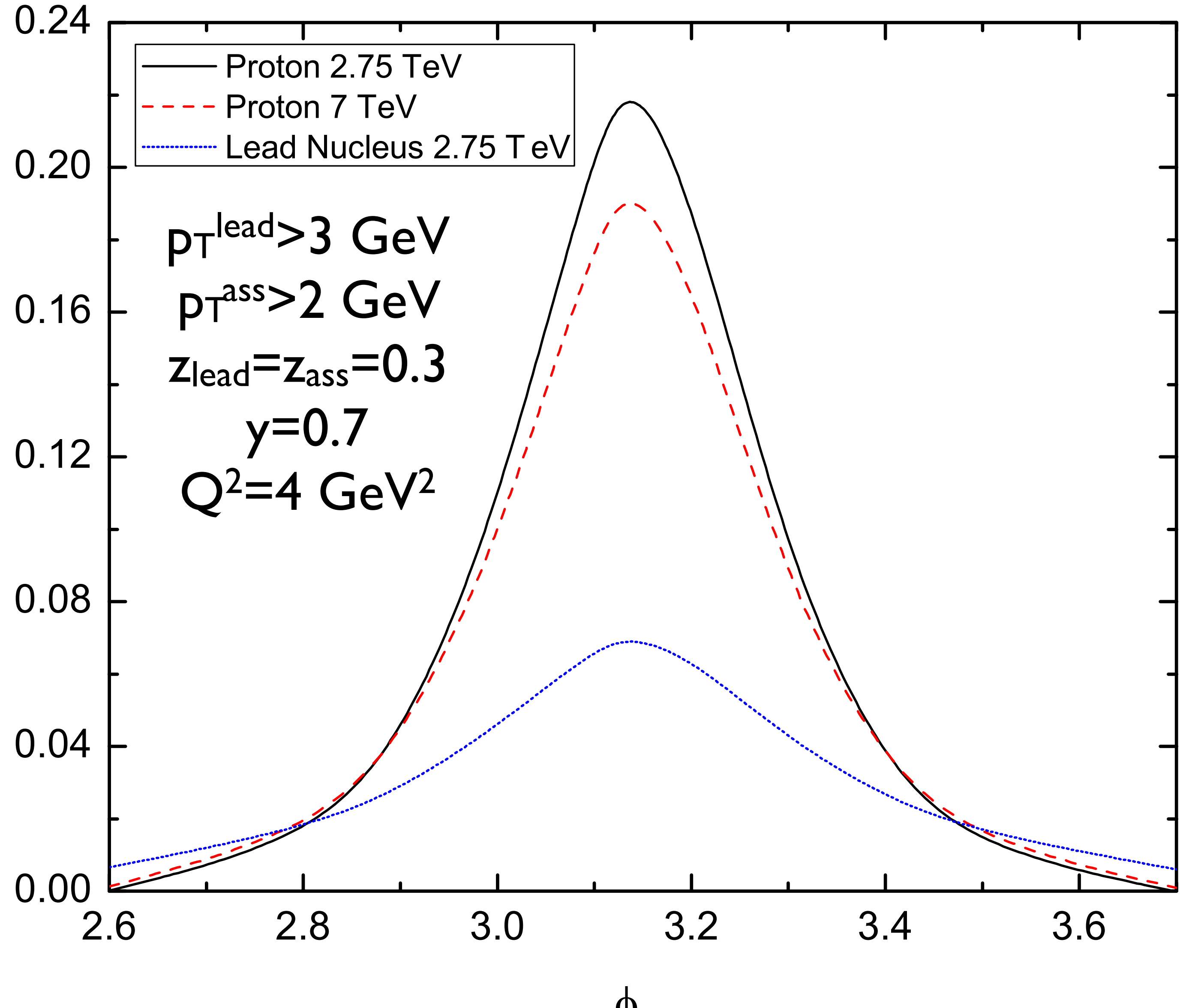
Azimuthal decorrelation (CDR):

- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- It could be studied far from the kinematical limits.

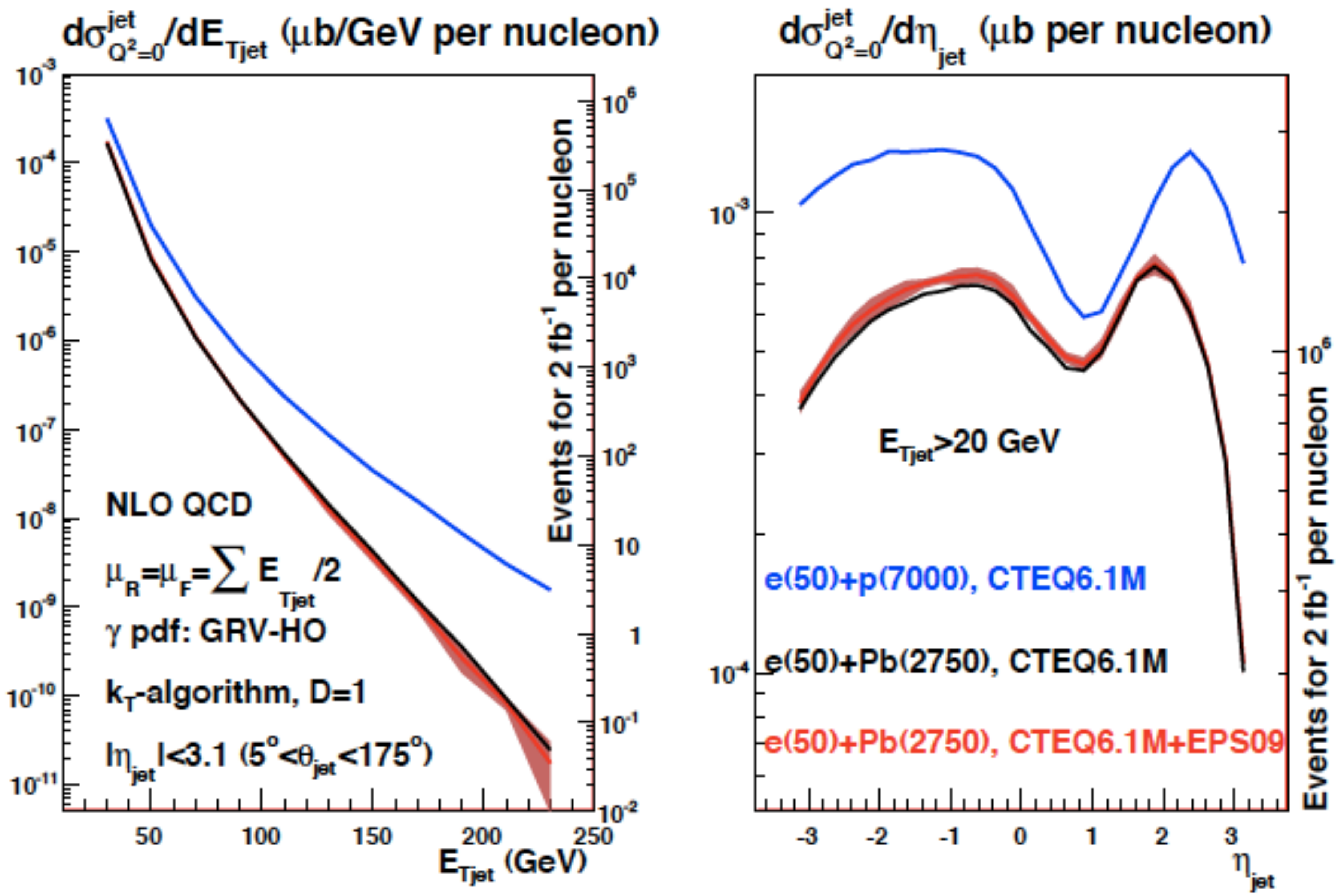




$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$



Jets (CDR):



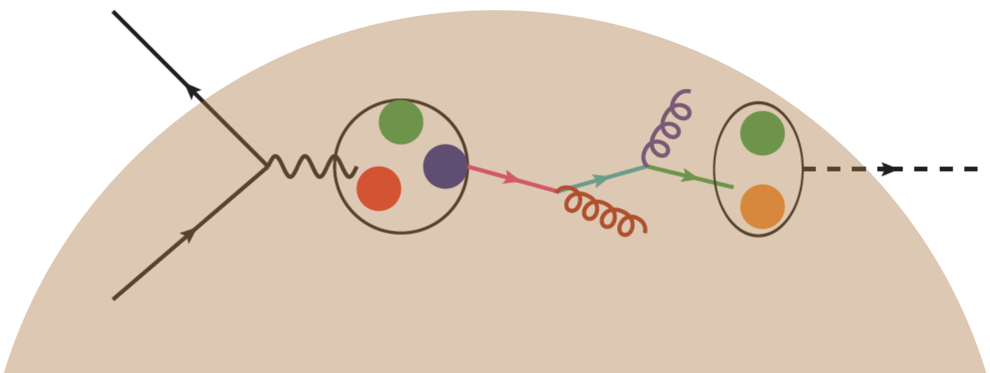
- Jets: large E_T even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.

Radiation & hadronization (CDR):

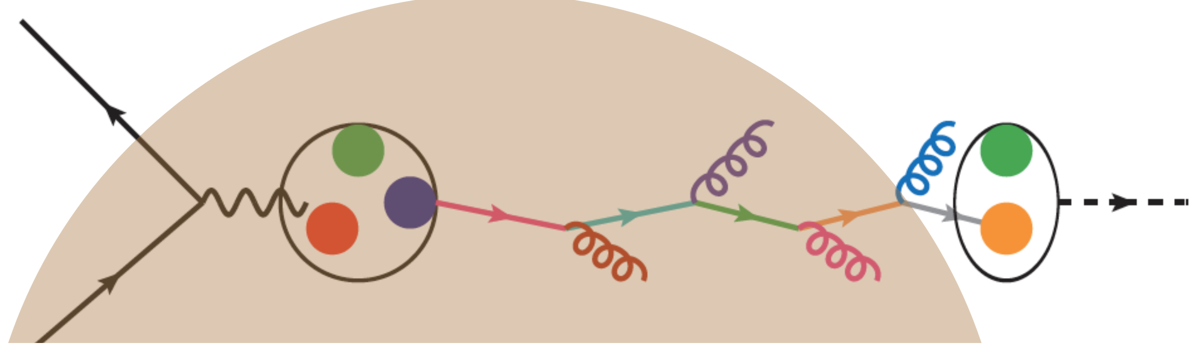
- Dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

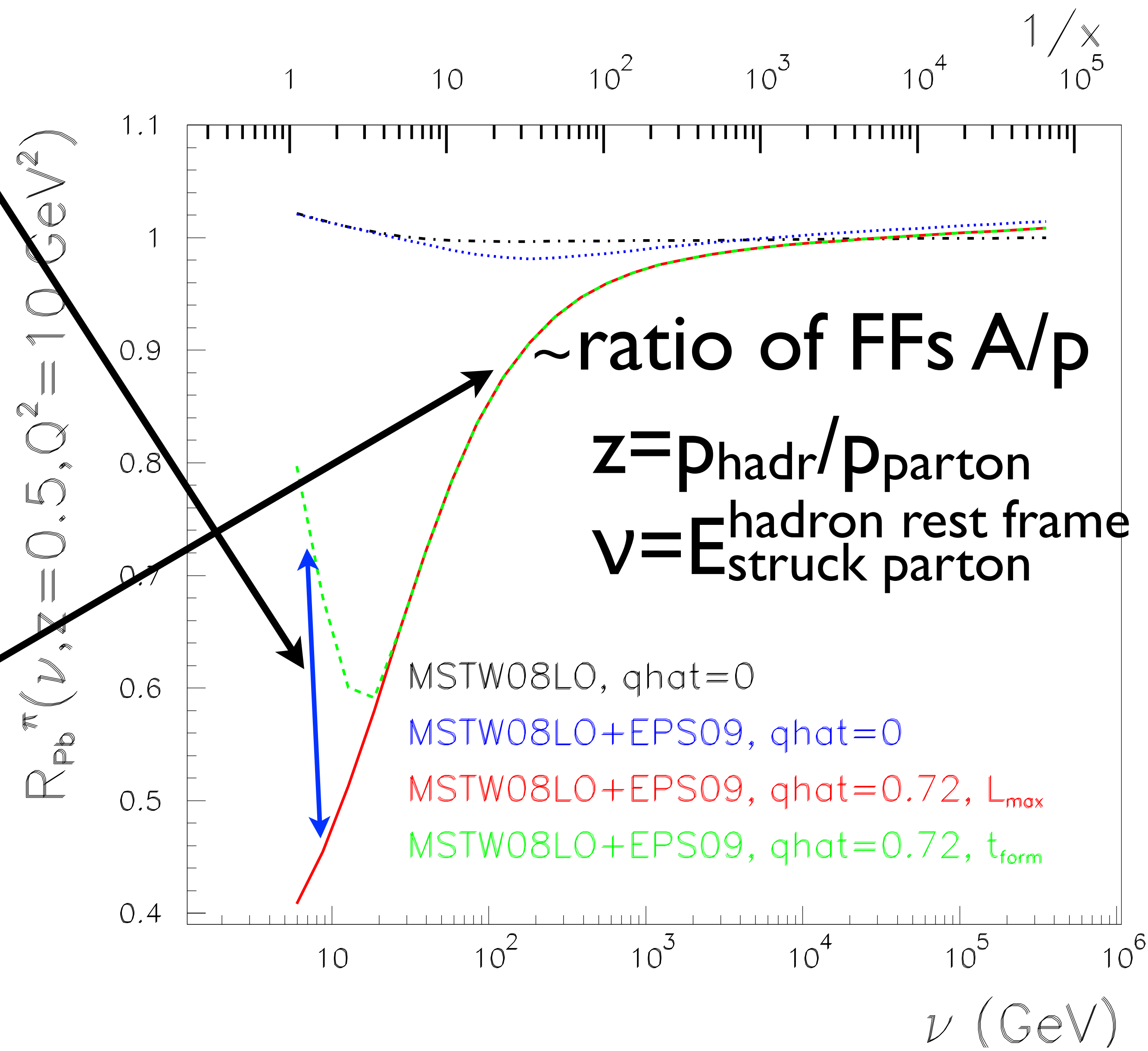
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Big/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$

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



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





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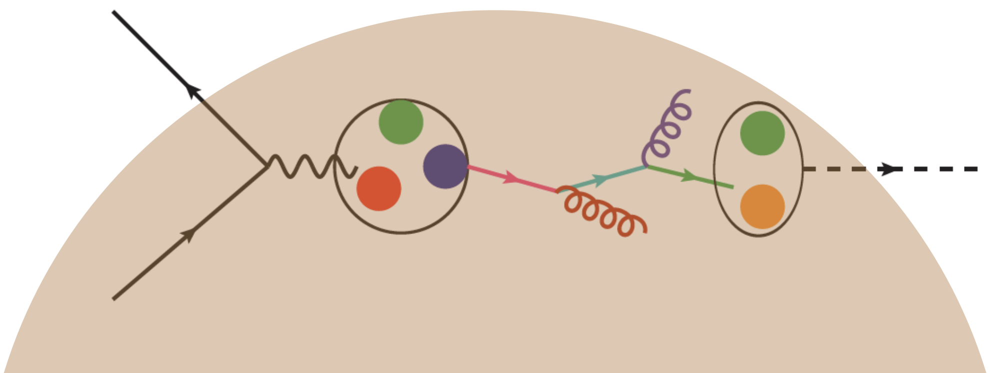

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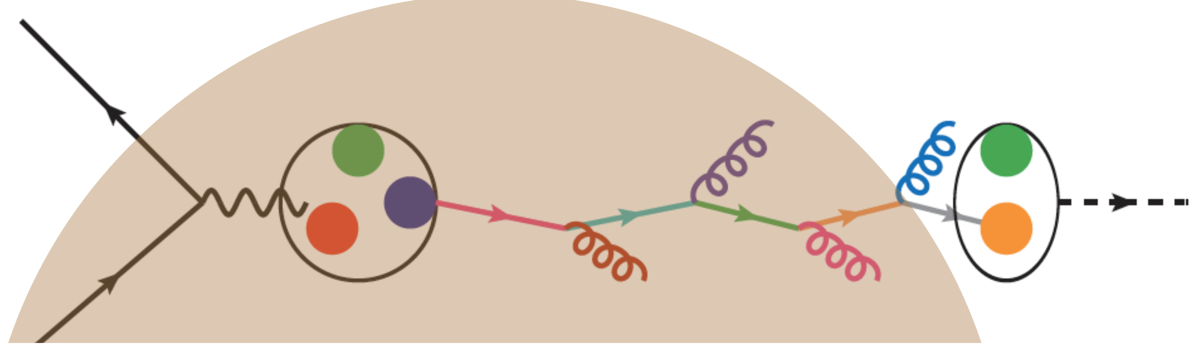
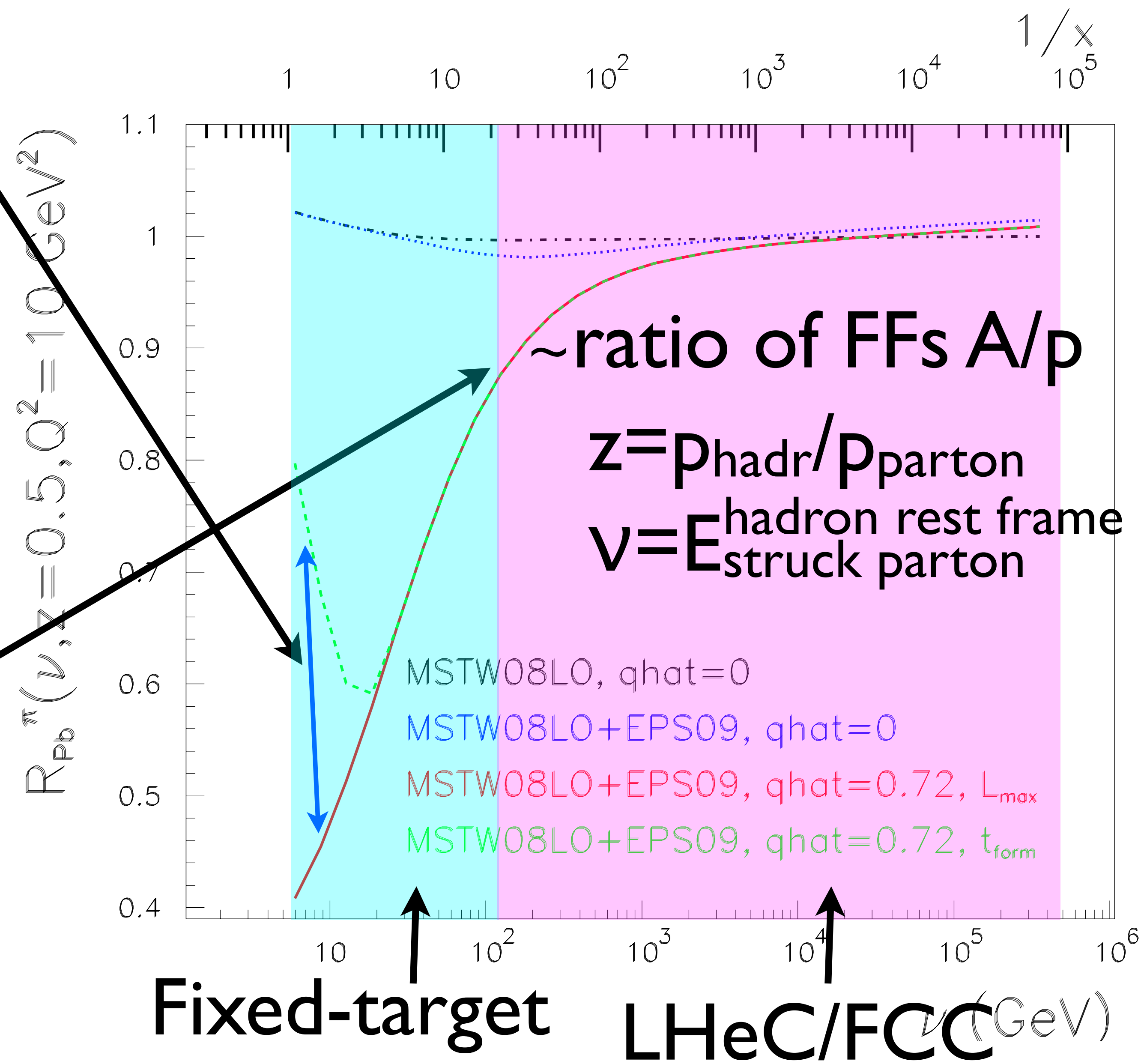




Summary:

- Several items have to be done/ improved for the CDR update (2018):

➜ DGLAP fits, extend to FCC-eh.

➜ Nuclear GPDs: nuclear DVCS, etc.

➜ Studies on diffraction: separation of coherent from incoherent, nDPDFs, dijets,…

➜ Monte Carlo generators.

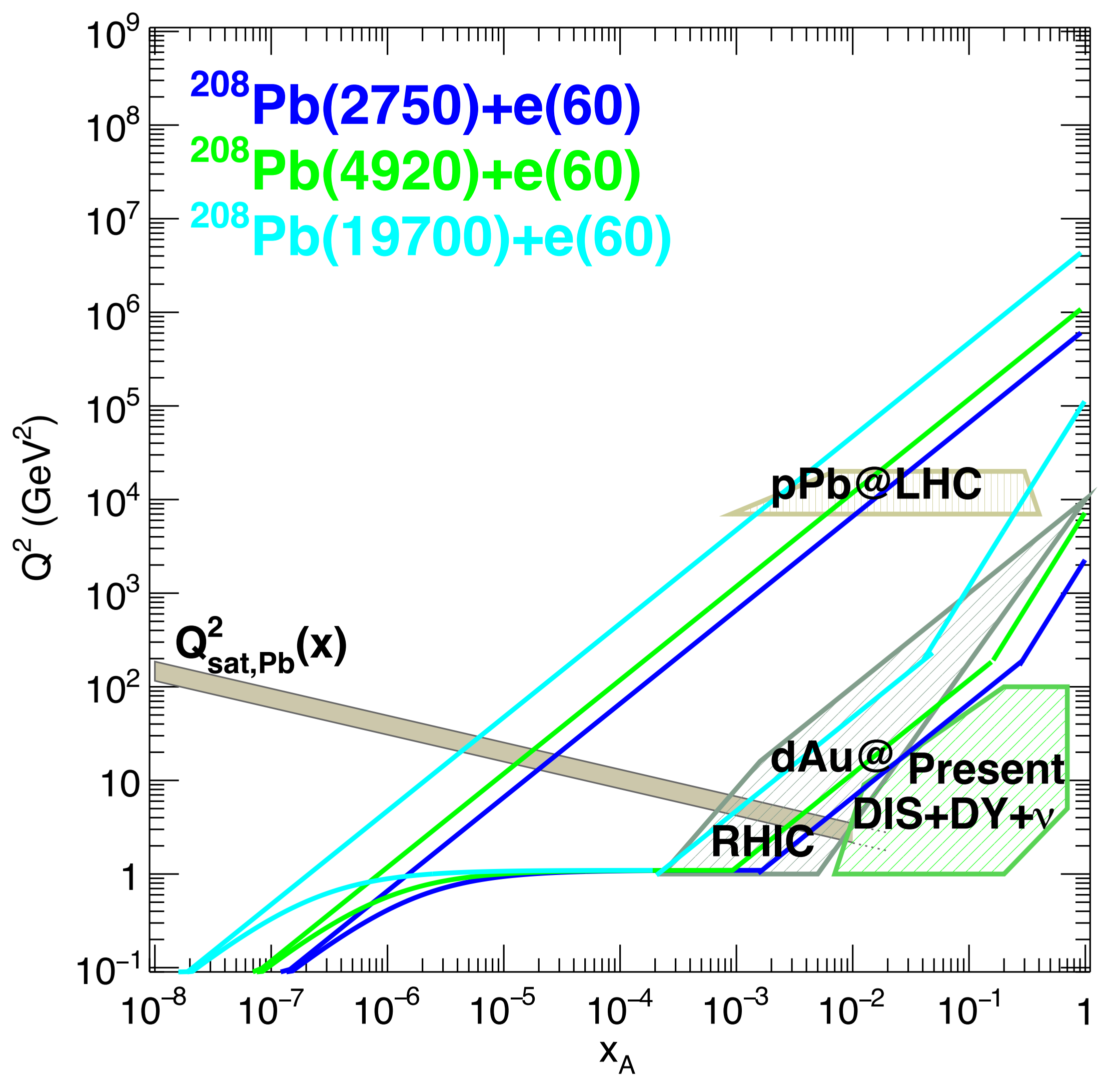
➜ Large x, EW bosons, Higgs.

➜ eD.

➜ Jet reconstruction, angular decorrelation,...

➜ ...

☛ *Manpower is the bottleneck (EIC?): everybody is welcome!!!!!*



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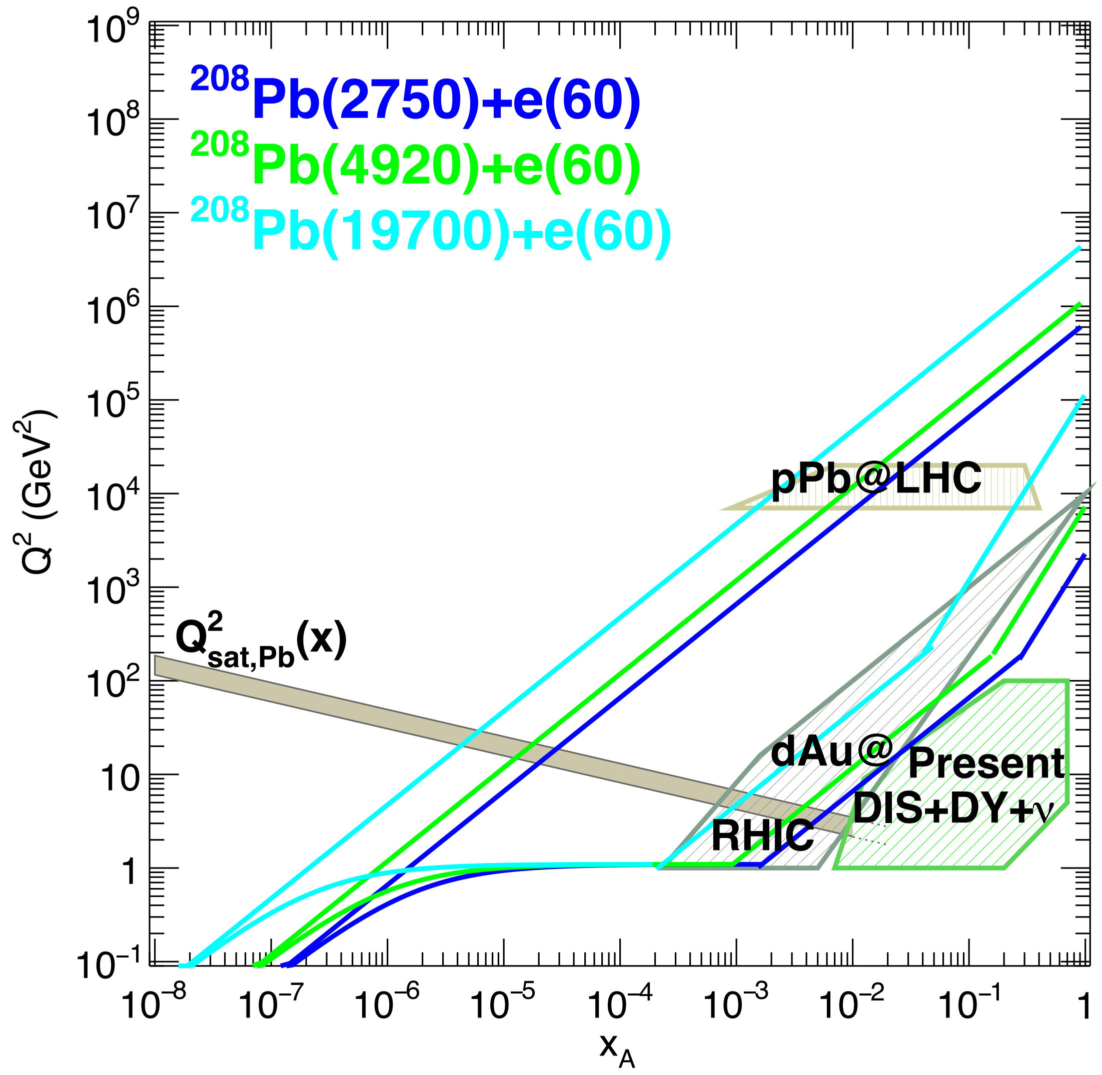

Many thanks for your attention!!!

Backup:

nPDFs at present:

SET		**HKN07** PRC76 (2007) 065207	**EPS09** JHEP 0904 (2009) 065	**DSSZ** PRD85 (2012) 074028	**nCTEQ15** PRD93 (2016) 085037	**KA15** PRD93 (2016) 014036	**EPPS16** EPJC C77 (2017)163
	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘	✔
	νDIS	✘	✘	✔	✘	✘	✔
	pPb	✘	✘	✘	✘	✘	✔
# data		1241	929	1579	740	1479	1811
order		NLO	NLO	NLO	NLO	NNLO	NLO
proton PDF		MRST98	CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO
mass scheme		ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS
comments		$\Delta\chi^2$=13.7, ratios, no EMC for gluons	$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, flavour sep., ratios, LHC pPb data

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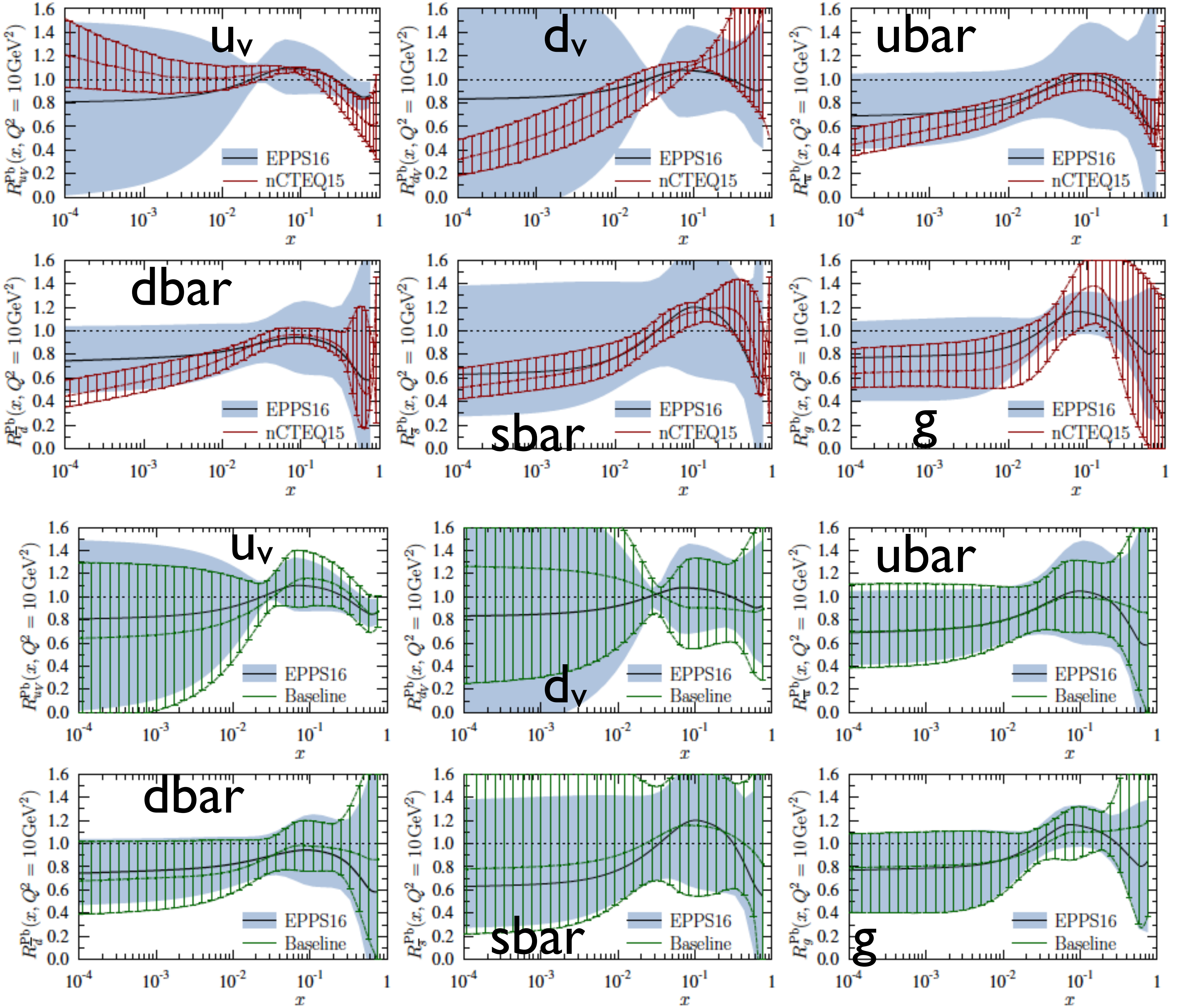
nPDFs at present:

- nCTEQ15 vs. EPPS16: beware of the parametrisation bias.

- Presently available LHC data seem not to have a large effect.



High-energy QCD:

- Different alternatives (evolutions, factorisations) to describe small-x data from ep to AA collisions:
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  - ➜ Non-perturbative approaches: Regge theory, holographic models,…
- All approaches eventually have to comply with unitarity constraints ⇒ non-linear effects that are density effects, **ep & eA needed**.