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LHC Working Group on Forward Physics and Diffraction
CERN, March 21st 2017

Small-x Physics in ep, eA and pA at the FCC

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

Contents:

I. Introduction: why and where.

2. Determining the small-x PDFs.

3. Searching for physics beyond DGLAP.

4. Summary.

References:
➜ ***ep/eA***: LHeC CDR, arXiv:1206.2913, J. Phys. G 39 (2012) 075001;
arXiv:1211.4831; arXiv:1211.5102;
2015 LHeC Workshop http://indico.cern.ch/event/356714/.
➜ ***pA***: arXiv:1605.01389.
See the talks by Liliana Apolinário, Stefano Camarda, Emma Slade and Frank Zimmermann at the FCC Physics Week.

Disclaimer: not a full overview; FCC-eh work in progress.

Contents:

1. Introduction: why and where.

System	$\sqrt{s_{NN}}$ [TeV]	$\mathcal{L}_{int}$/run [nb^{-1}]
pPb	63	8000
PbPb	39	33

2. Determining the small-x PDFs.

3. Searching for physics beyond DGLAP.

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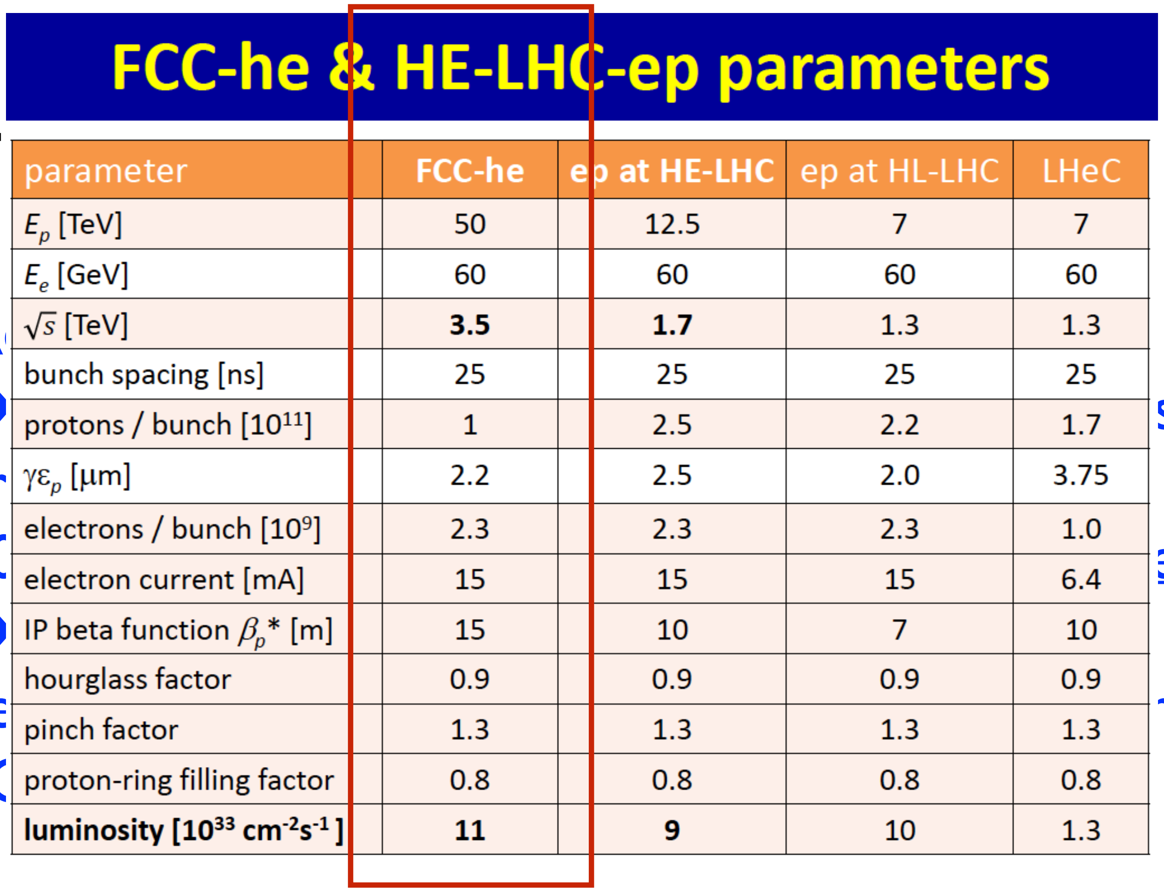
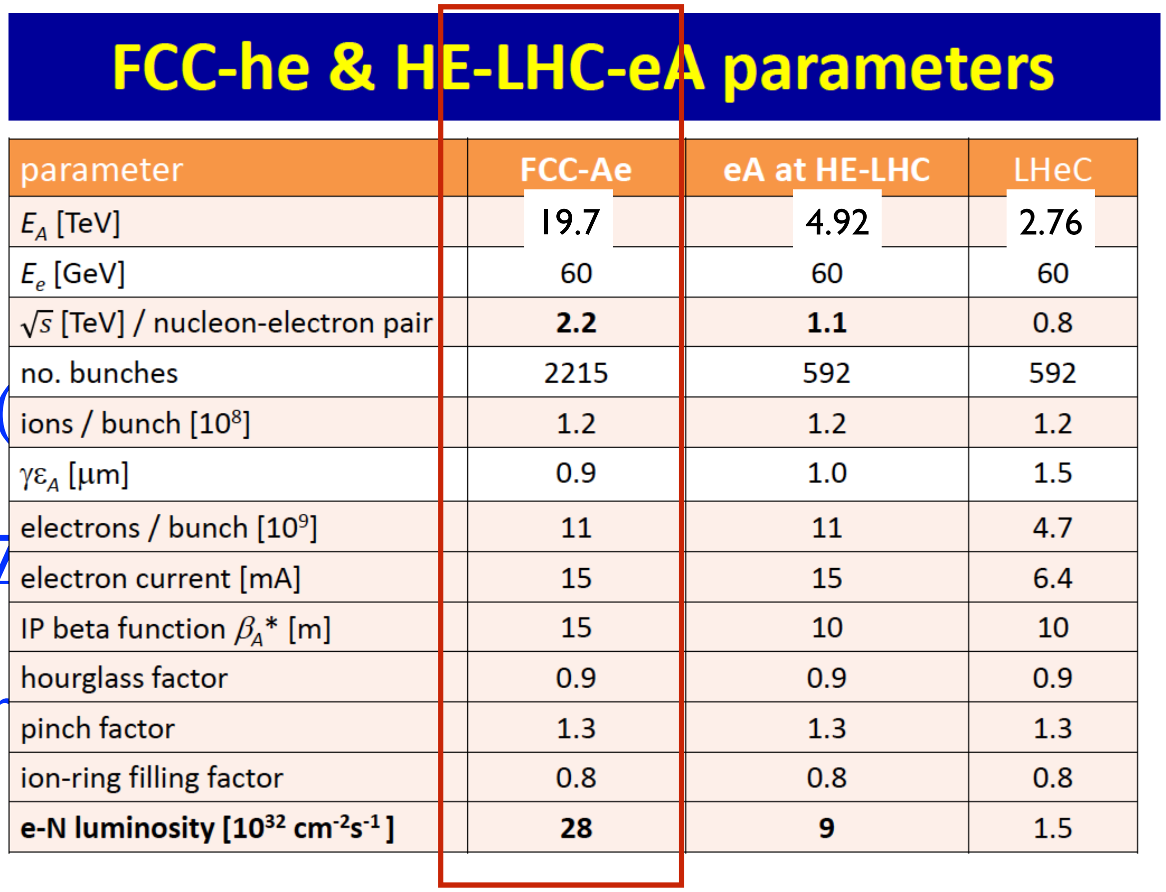


FCC-he & HE-LHC-ep parameters

parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	**3.5**	**1.7**	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\varepsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p^* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} cm^{-2}s^{-1}]	**11**	**9**	10	1.3



FCC-he & HE-LHC-eA parameters

parameter	FCC-Ae	eA at HE-LHC	LHeC
E_A [TeV]	19.7	4.92	2.76
E_e [GeV]	60	60	60
$\sqrt{s}$ [TeV] / nucleon-electron pair	**2.2**	**1.1**	0.8
no. bunches	2215	592	592
ions / bunch [10^8]	1.2	1.2	1.2
$\gamma\varepsilon_A$ [μm]	0.9	1.0	1.5
electrons / bunch [10^9]	11	11	4.7
electron current [mA]	15	15	6.4
IP beta function β_A^* [m]	15	10	10
hourglass factor	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3
ion-ring filling factor	0.8	0.8	0.8
e-N luminosity [10^{32} cm^{-2}s^{-1}]	**28**	**9**	1.5

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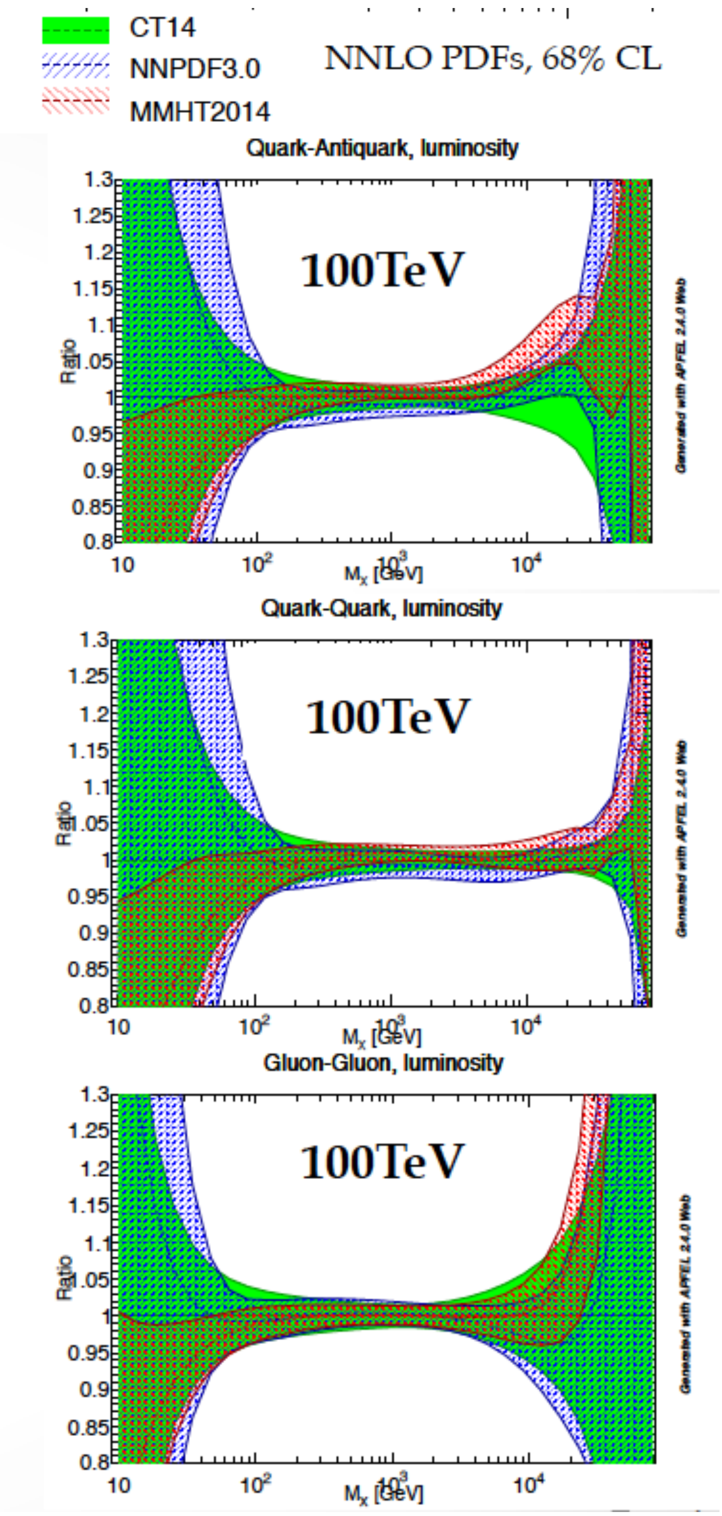
Why (I):

- Assuming collinear factorisation holds, small -x PDFs poorly known for particle production (even for heavy objects at the FCC).

Parton luminosities



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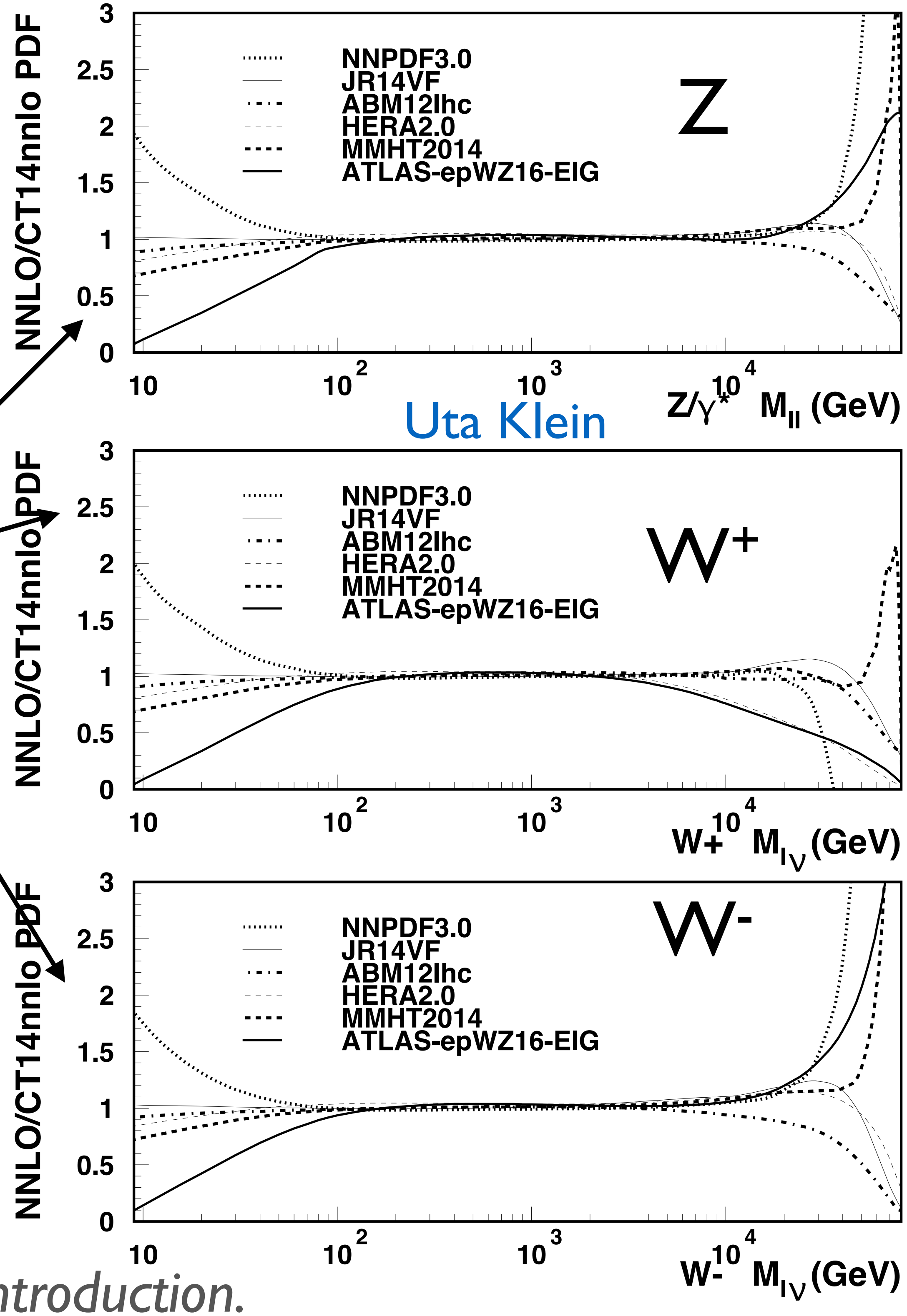

Uta Klein

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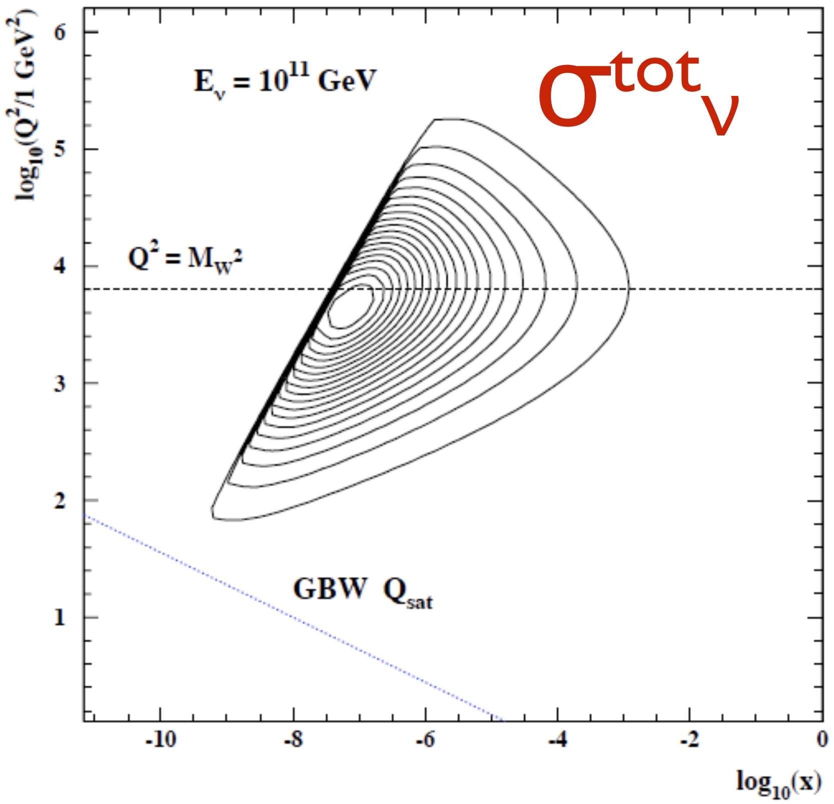
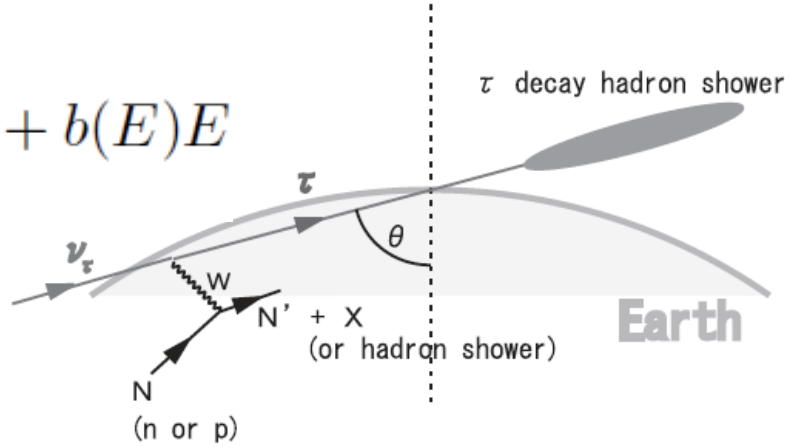
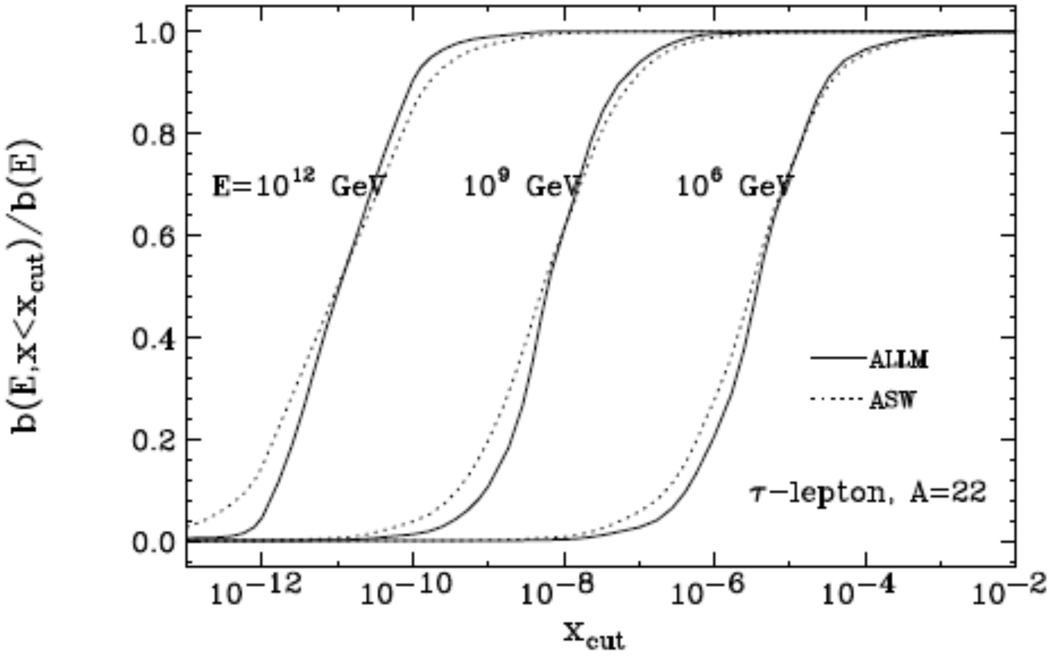


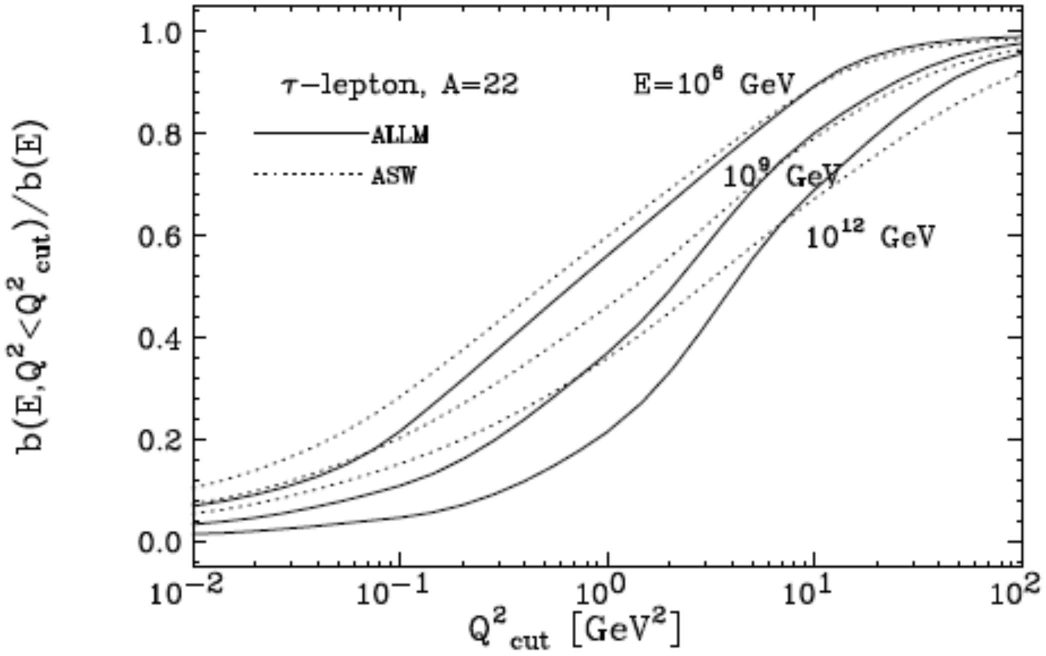
$\sigma^{tot}{}_\nu$

- ν-n/A cross section (τ energy loss) dominated by DIS structure functions / (n)PDFs at small x and large (small) Q^2.

$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E$$







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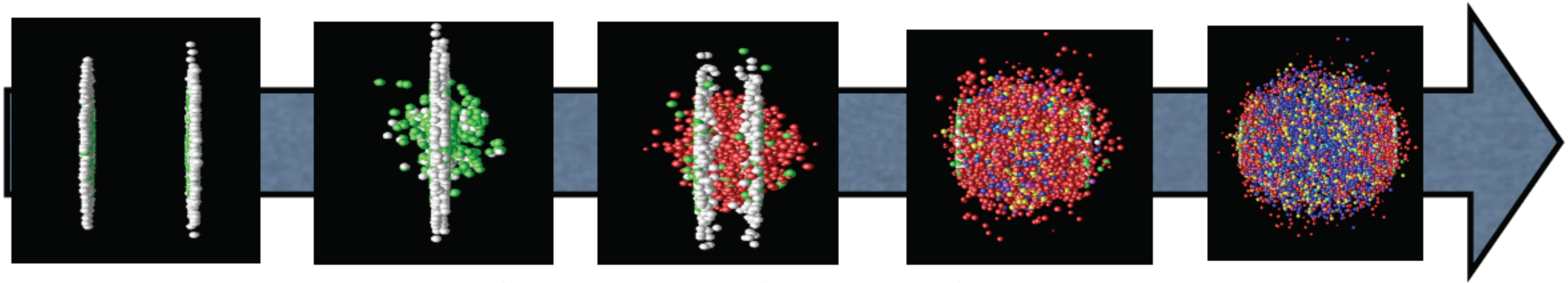


Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

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

- Particle production at the very beginning: which factorisation?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation.

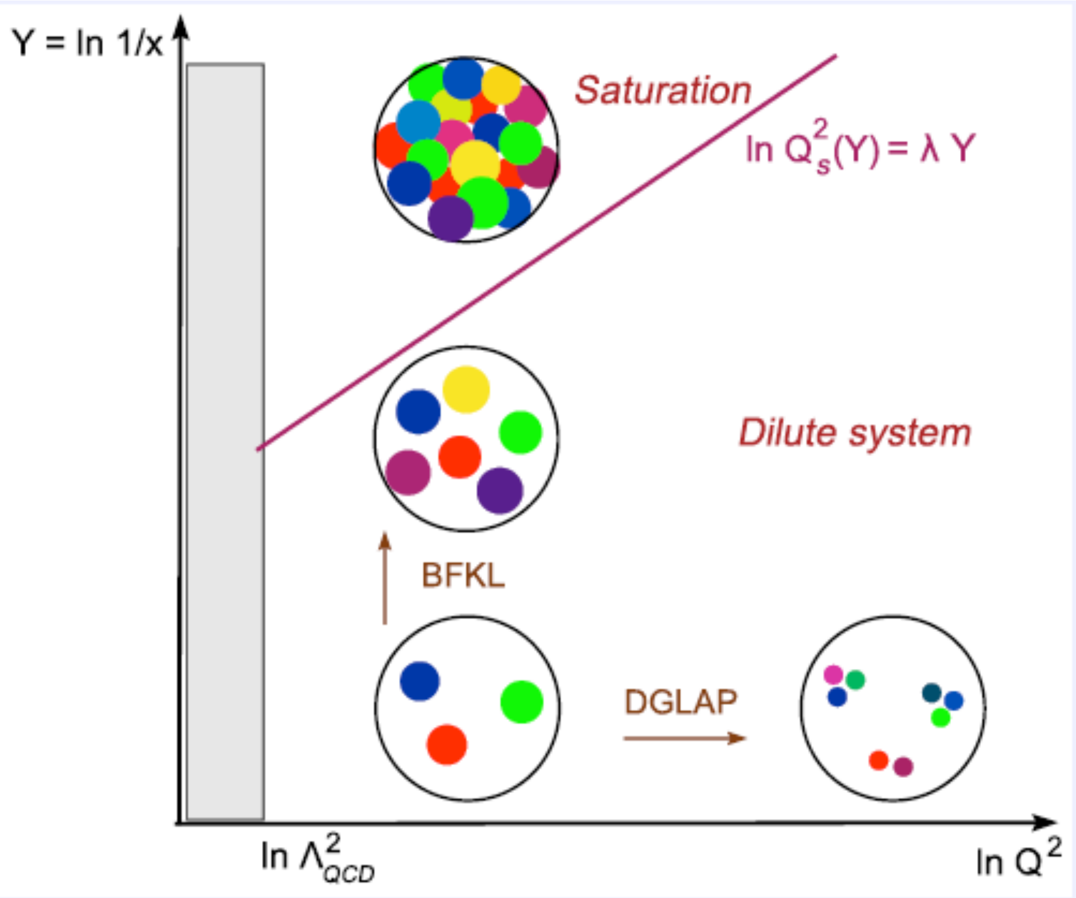
Why (II):

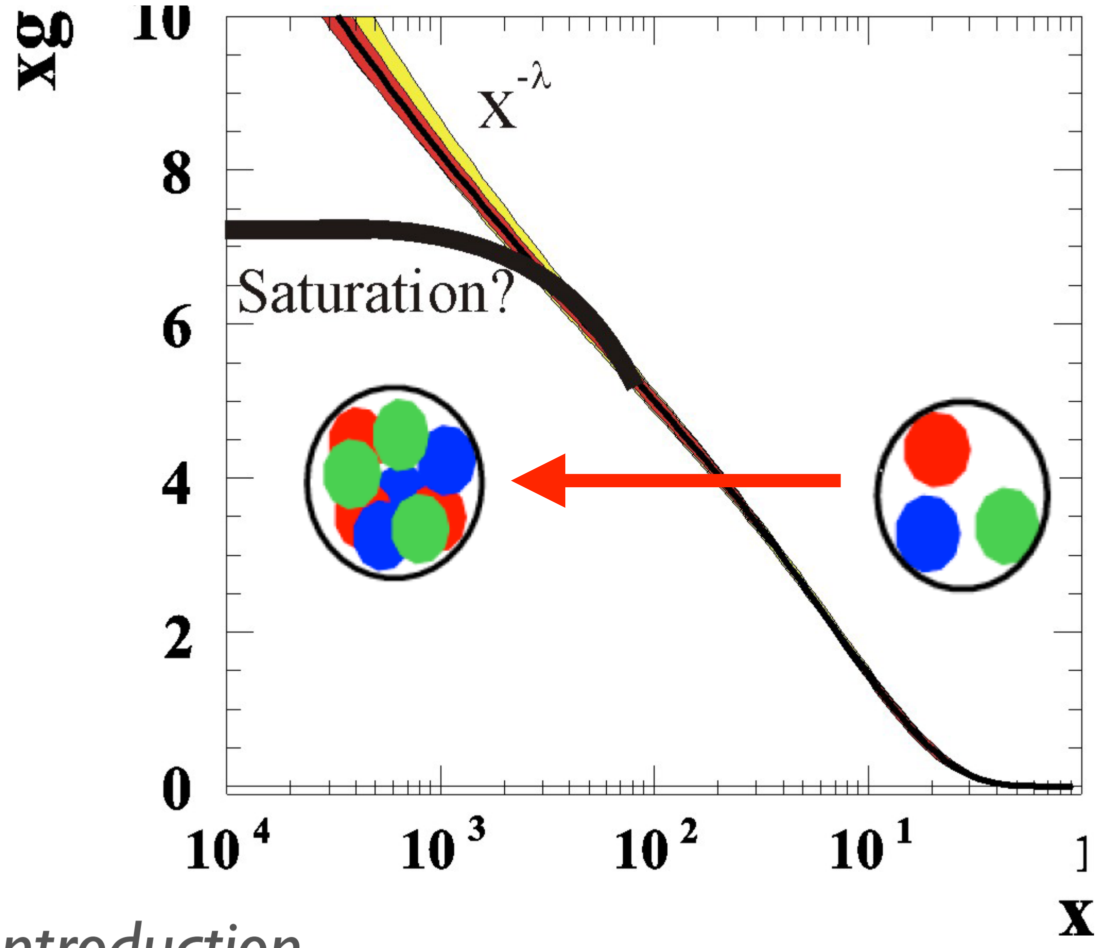
- Standard fixed-order perturbation theory (DGLAP, linear evolution) must eventually fail:

➜ Large logs e.g. $\alpha_s \ln(1/x) \sim 1$: resummation (BFKL,CCFM,ABF,CCSS).

➜ High density ⇒ linear evolution must not hold: saturation, either perturbative (CGC) or non-perturbative.

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





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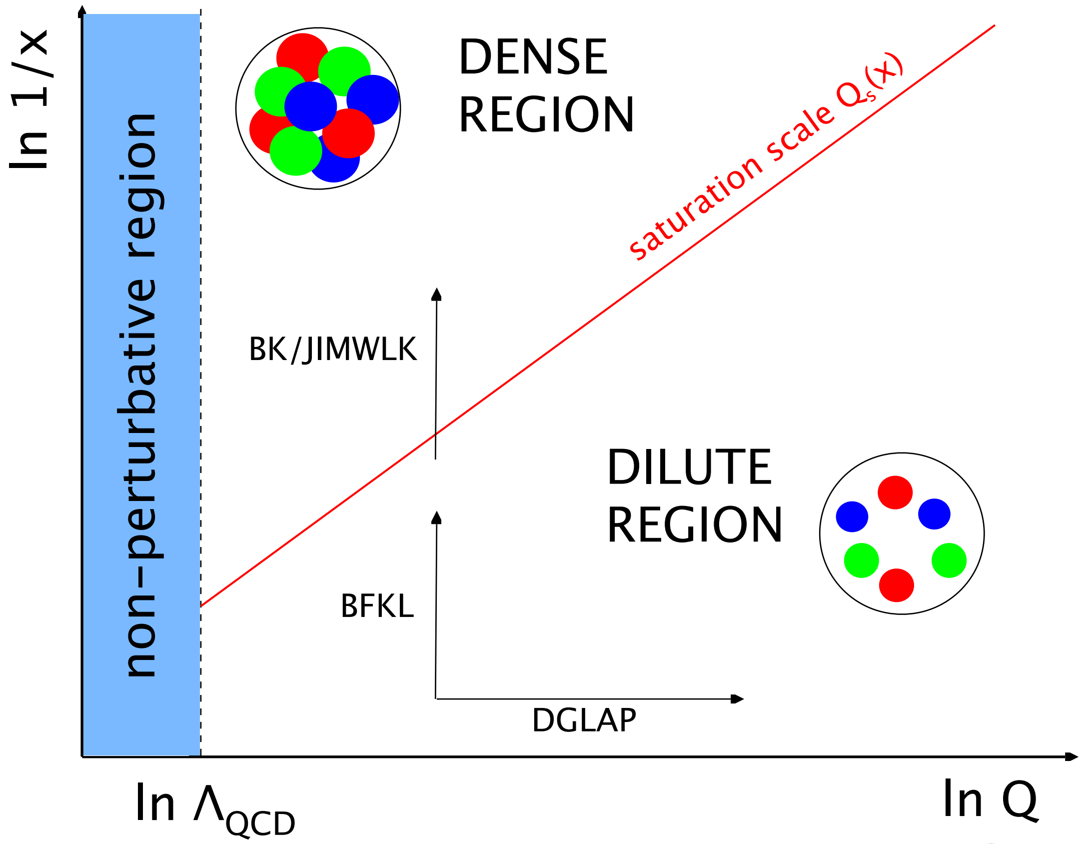
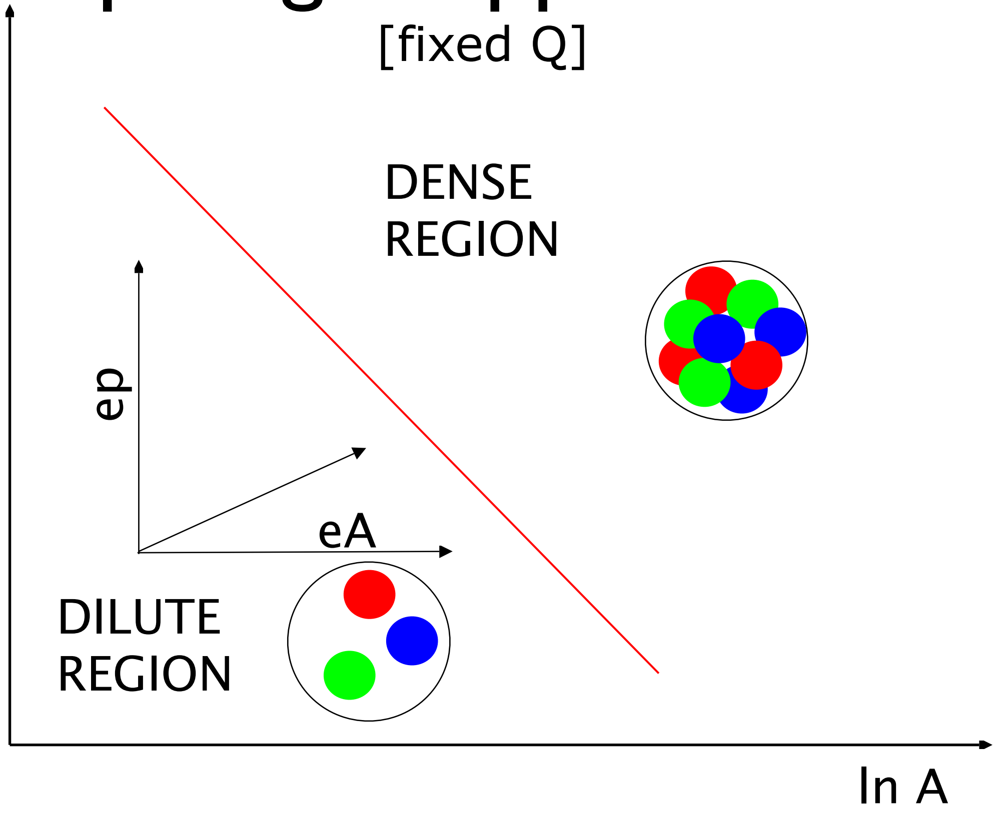
- Non-linear effects driven by density⇒2-pronged approach: ↓x/↑A.





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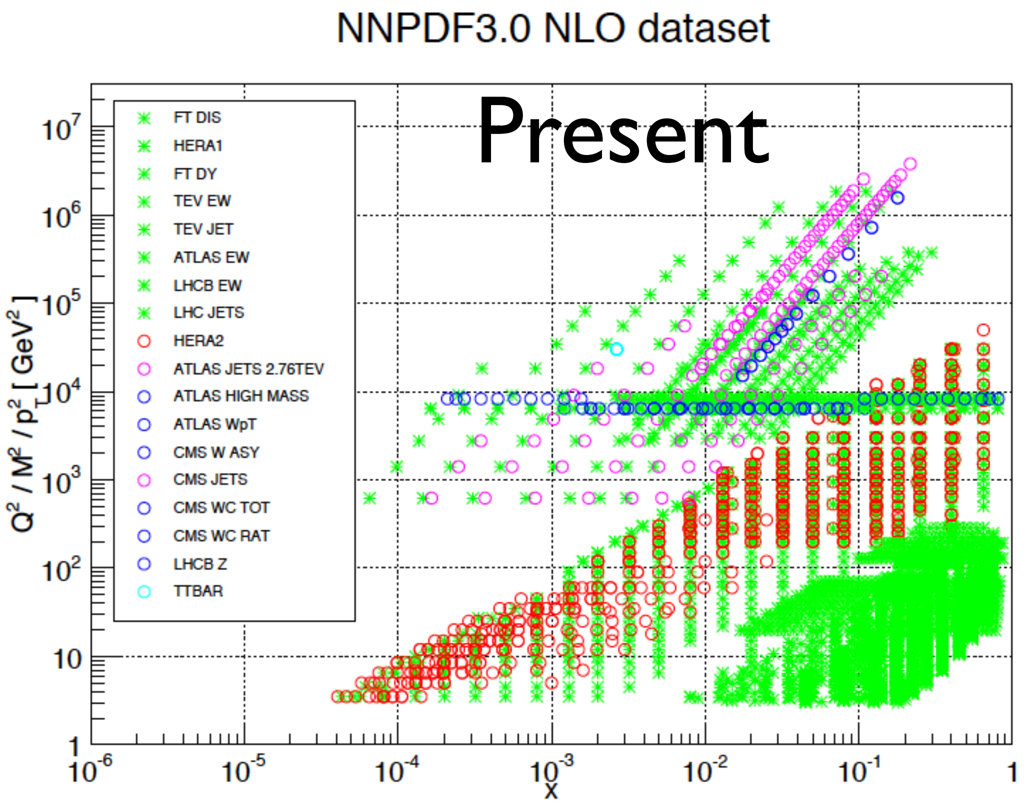

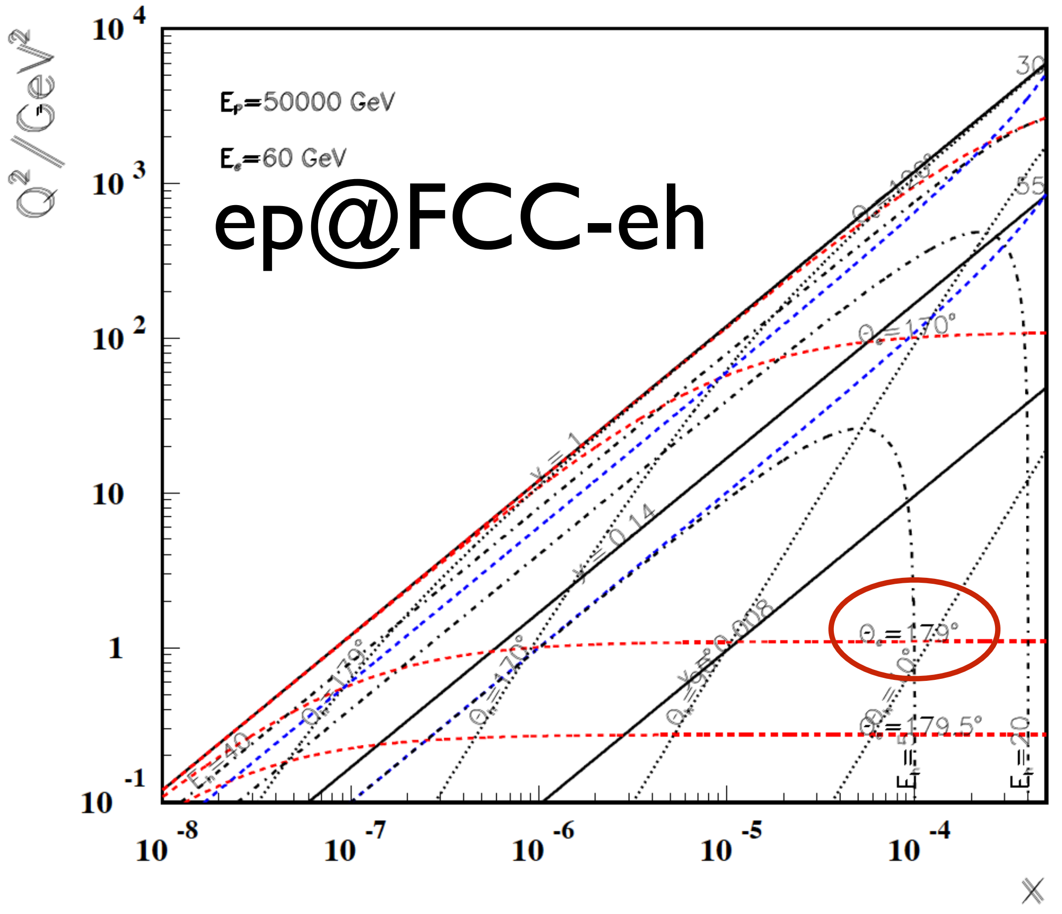

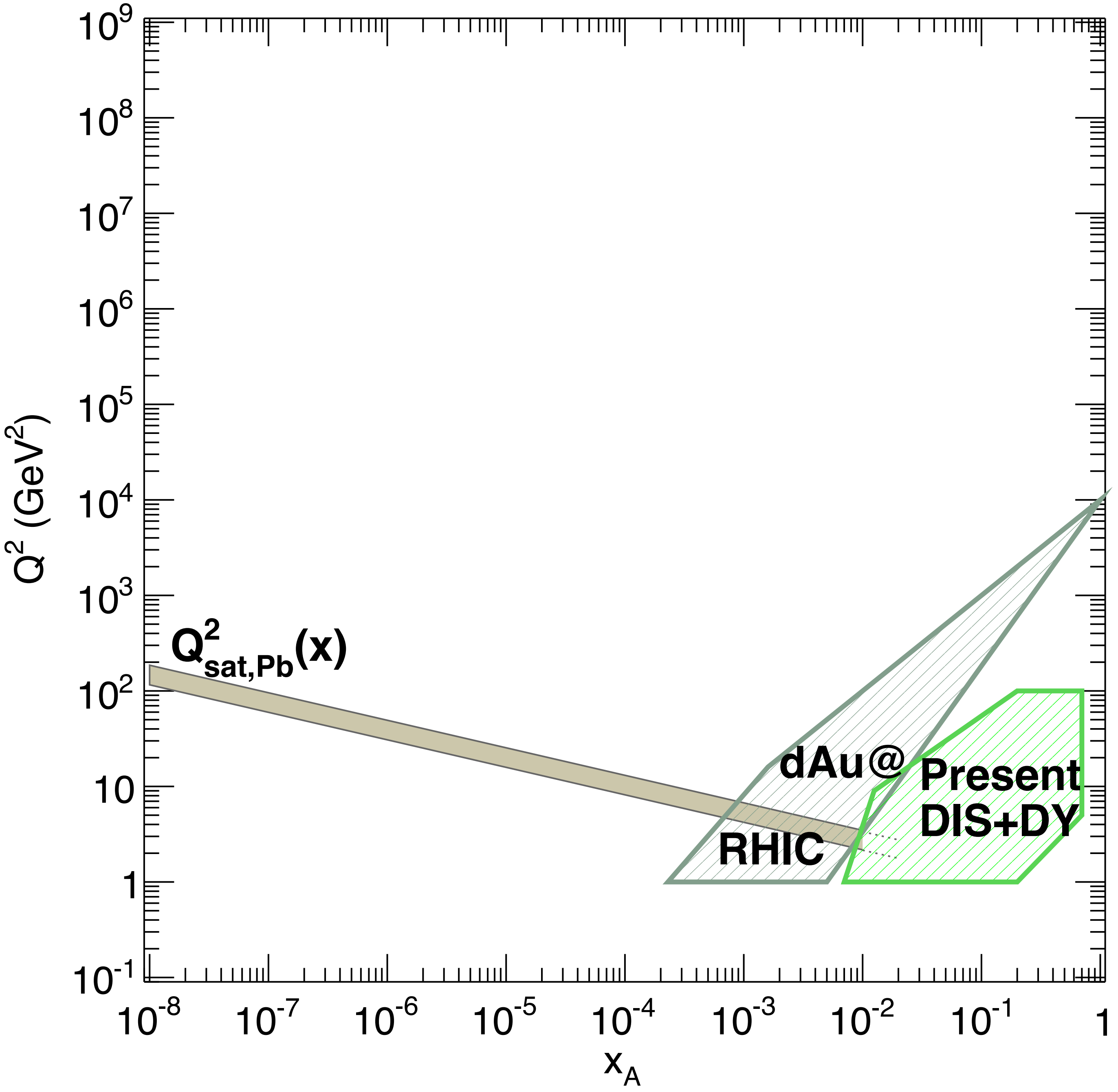

- Small-x demands ~1 degree acceptance [$Q^2_{min}(x\to 1)\propto E_e^2$].

- High-x and Q^2 linked to small x via evolution (HERA final analysis).

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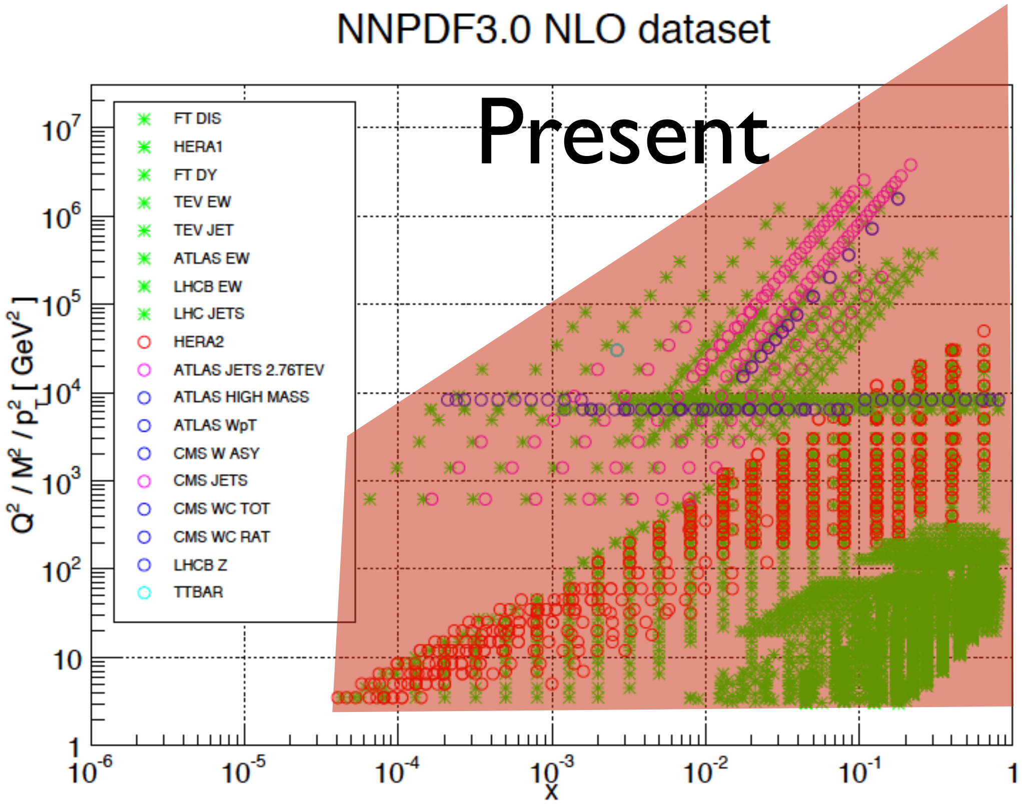

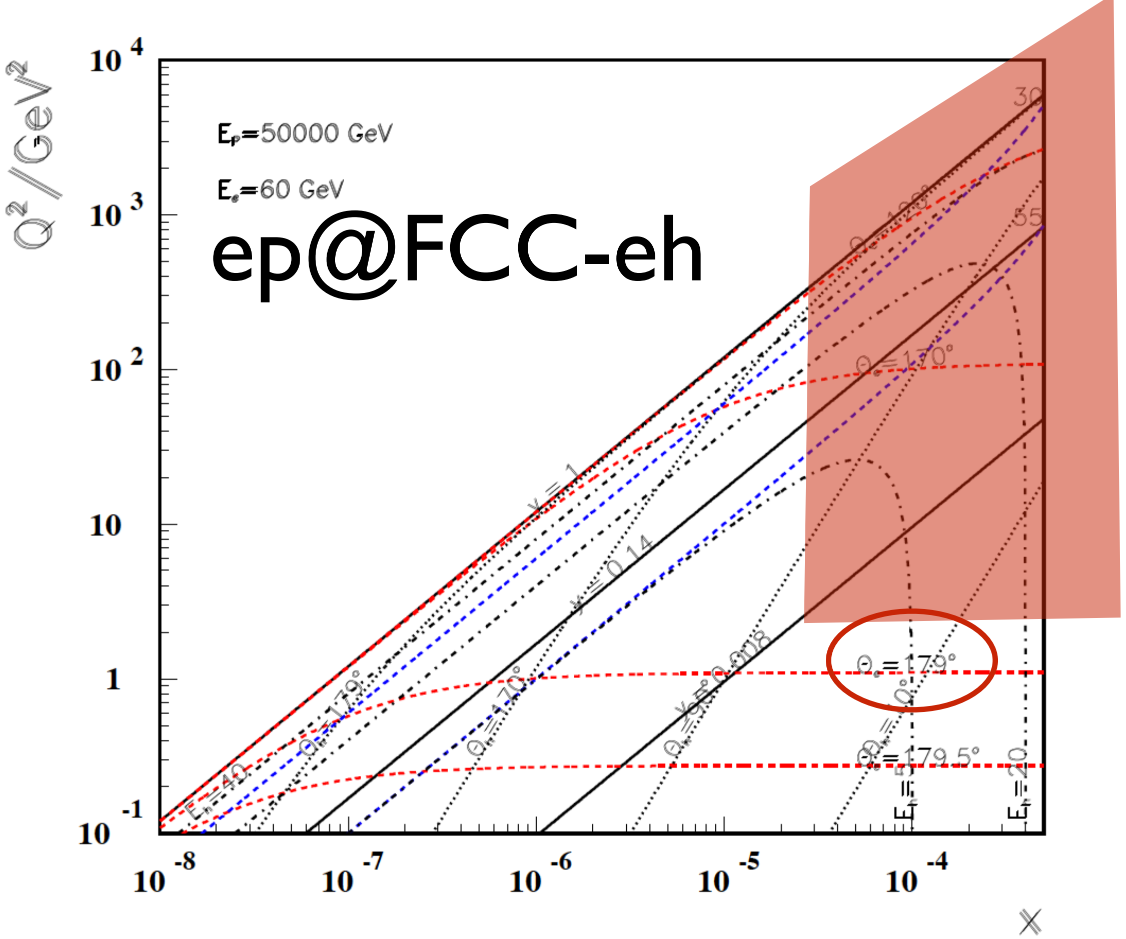

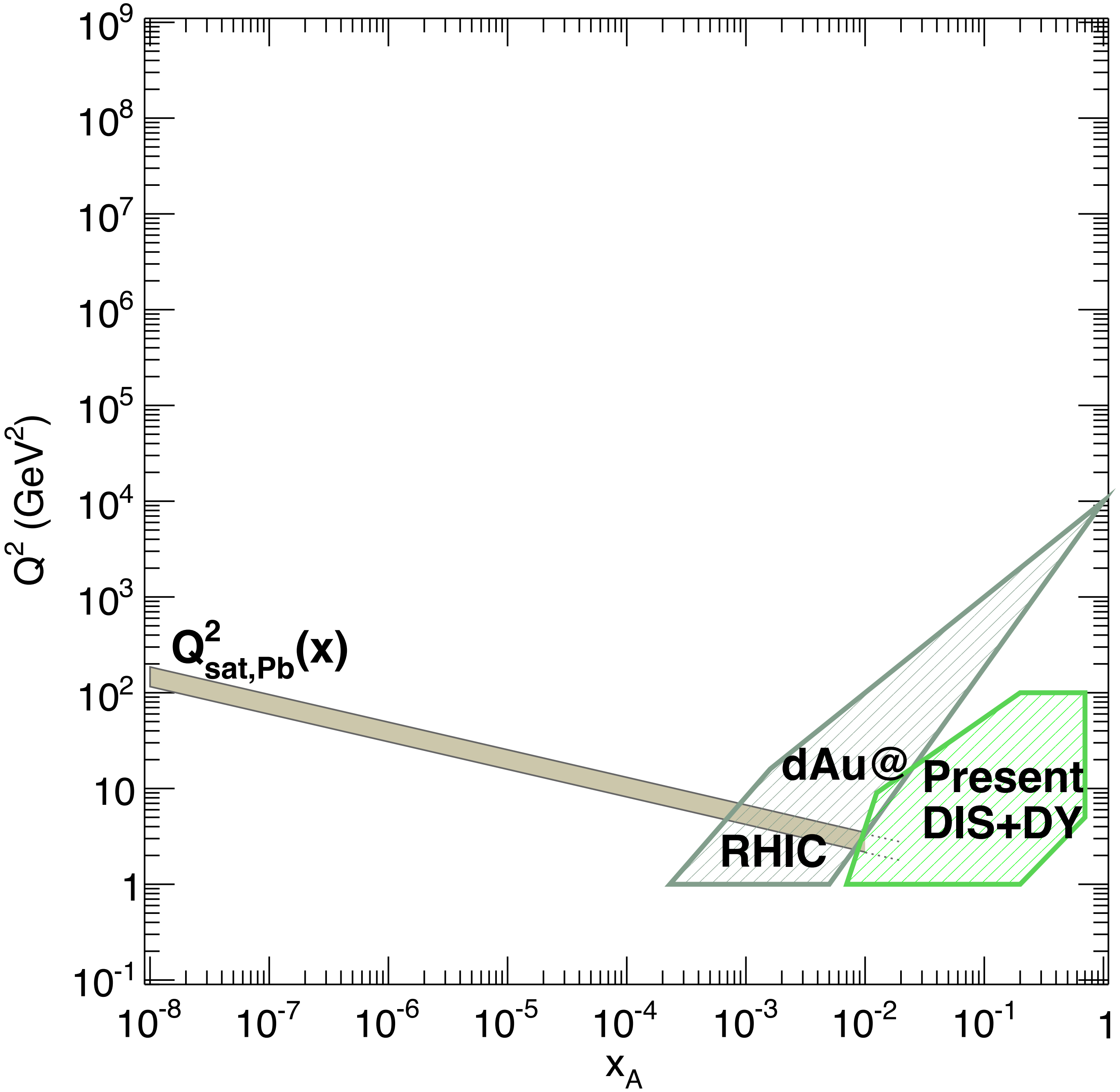

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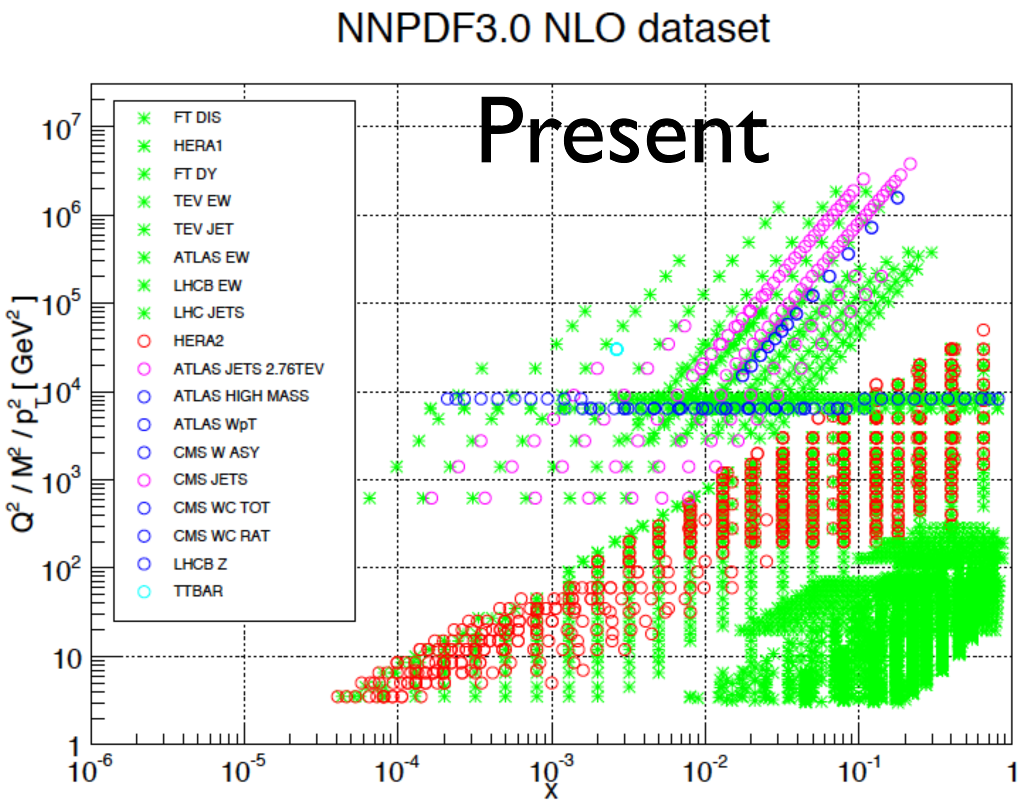

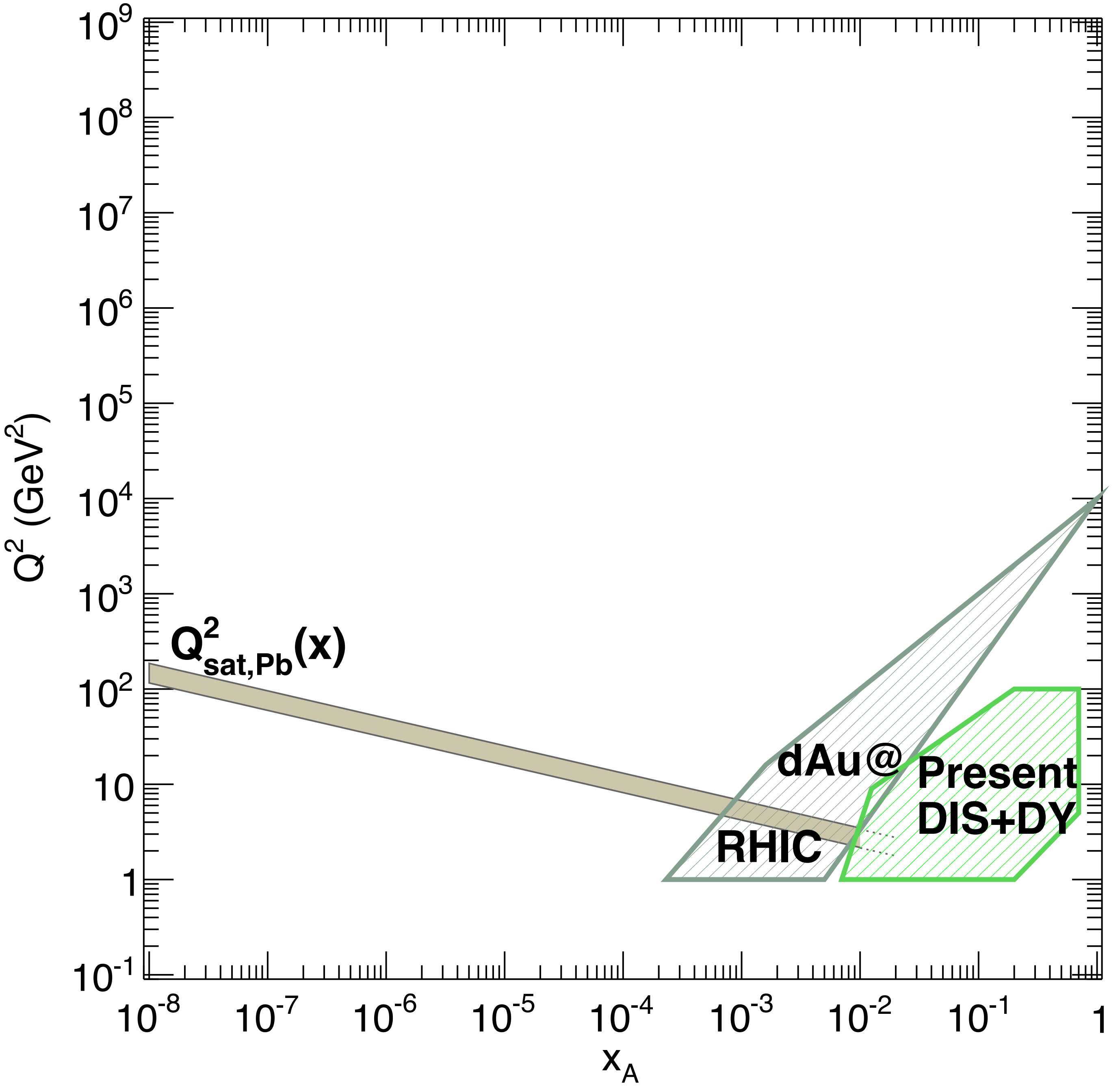

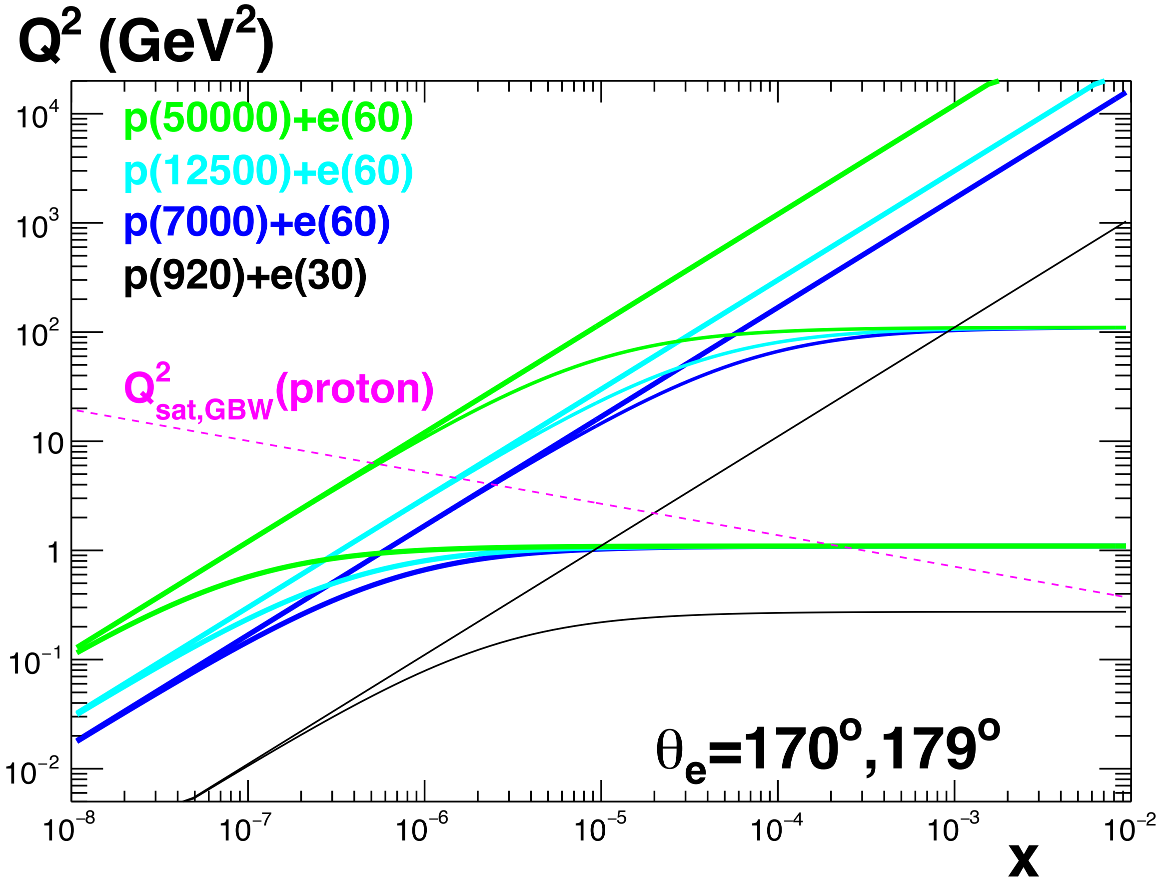

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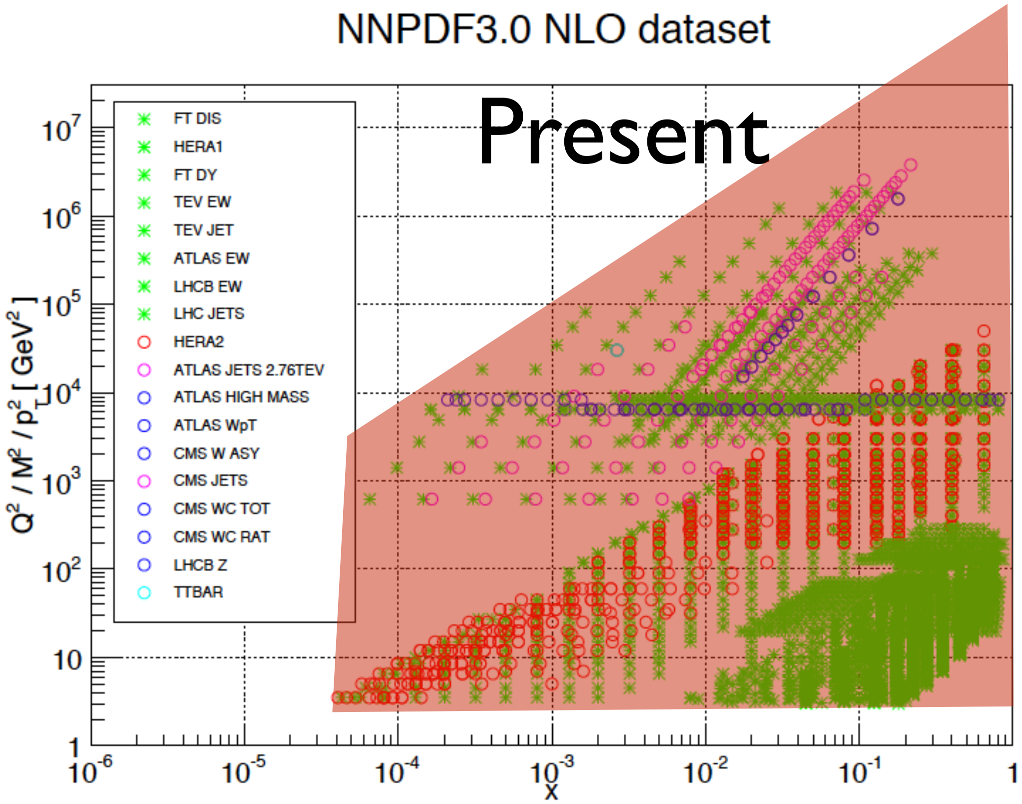

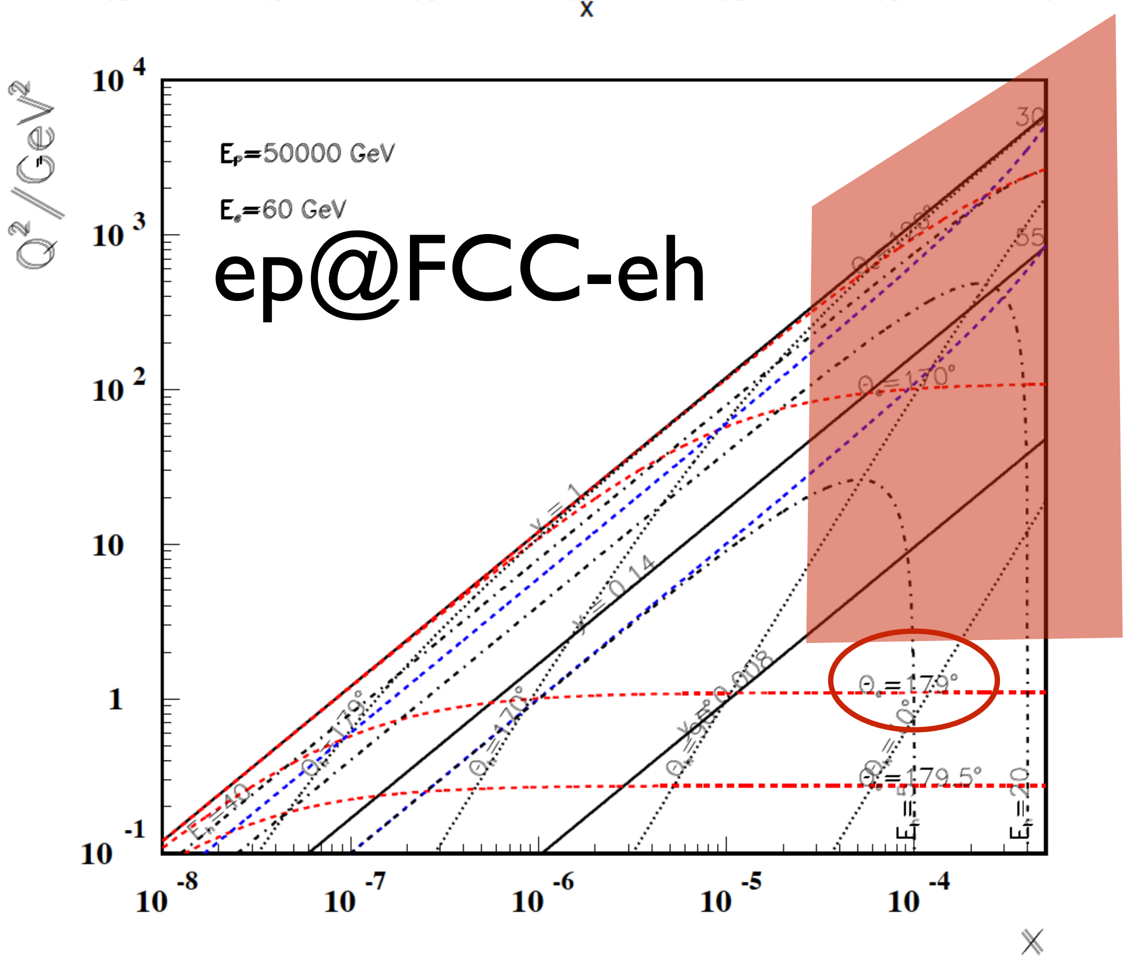

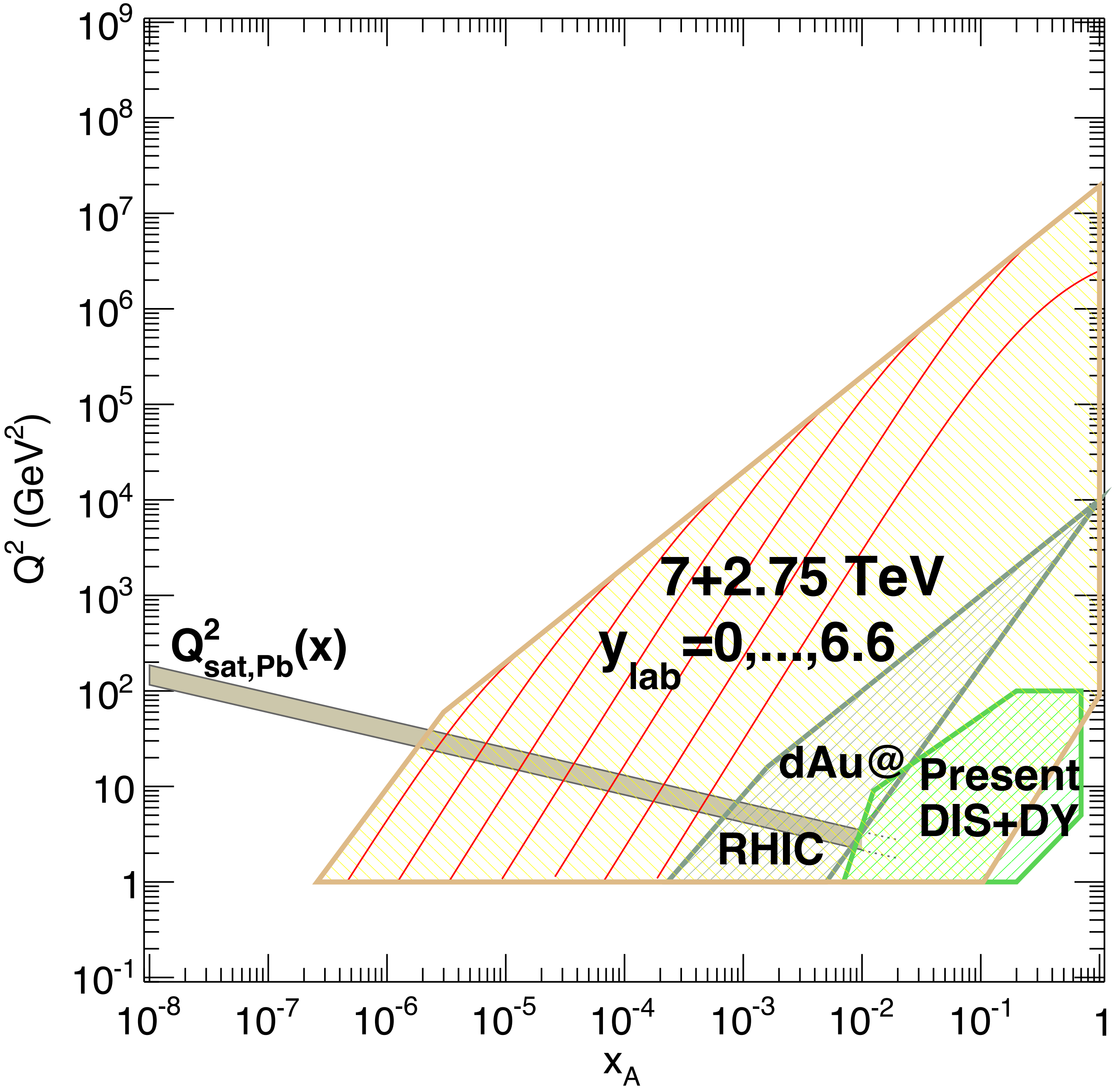

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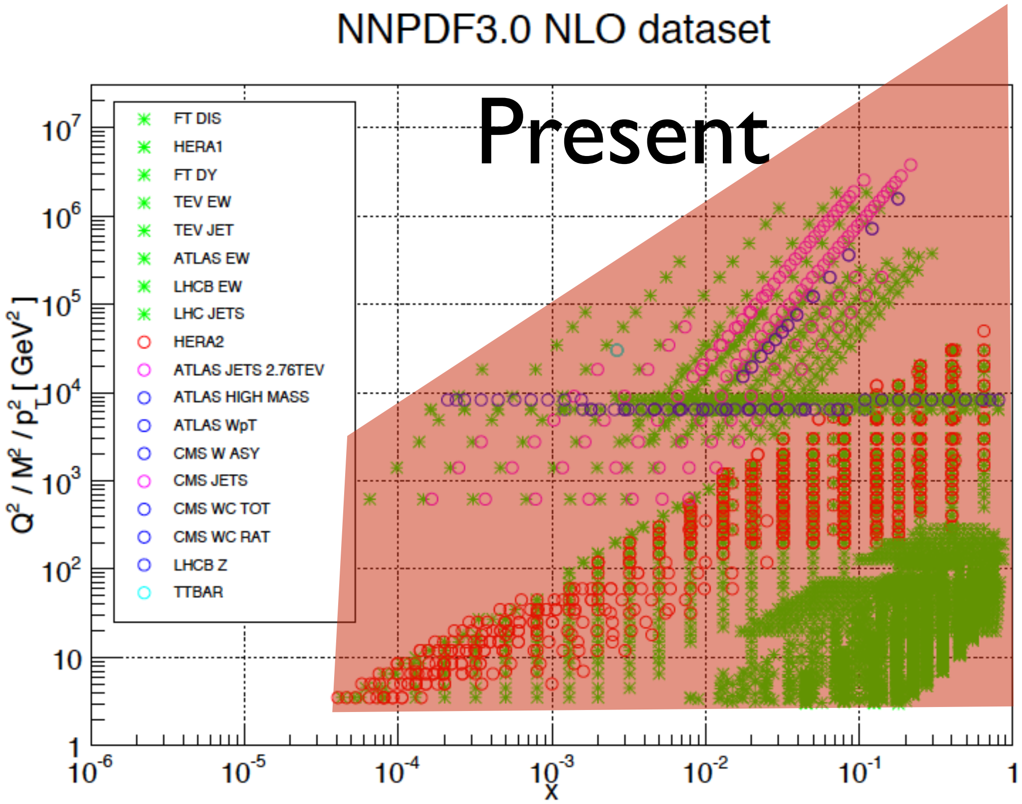

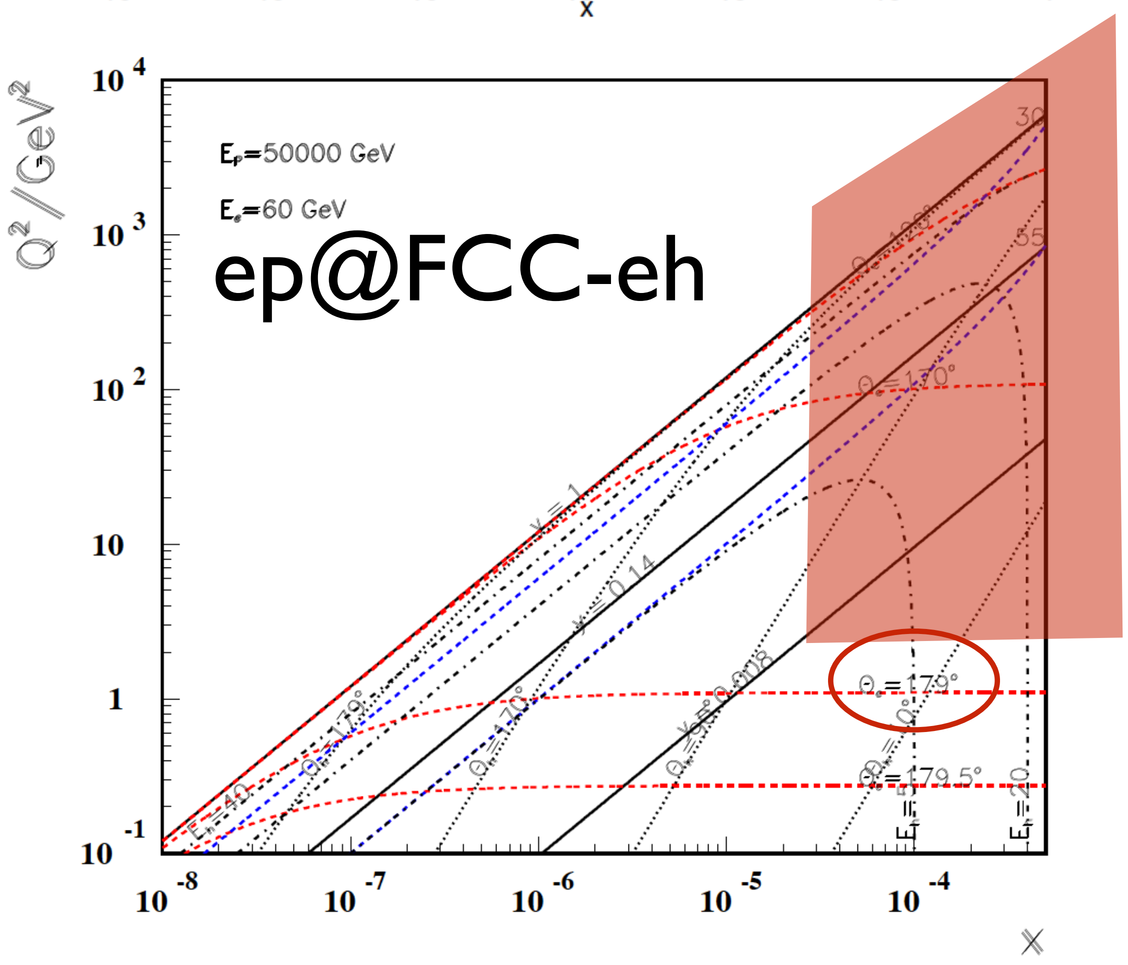

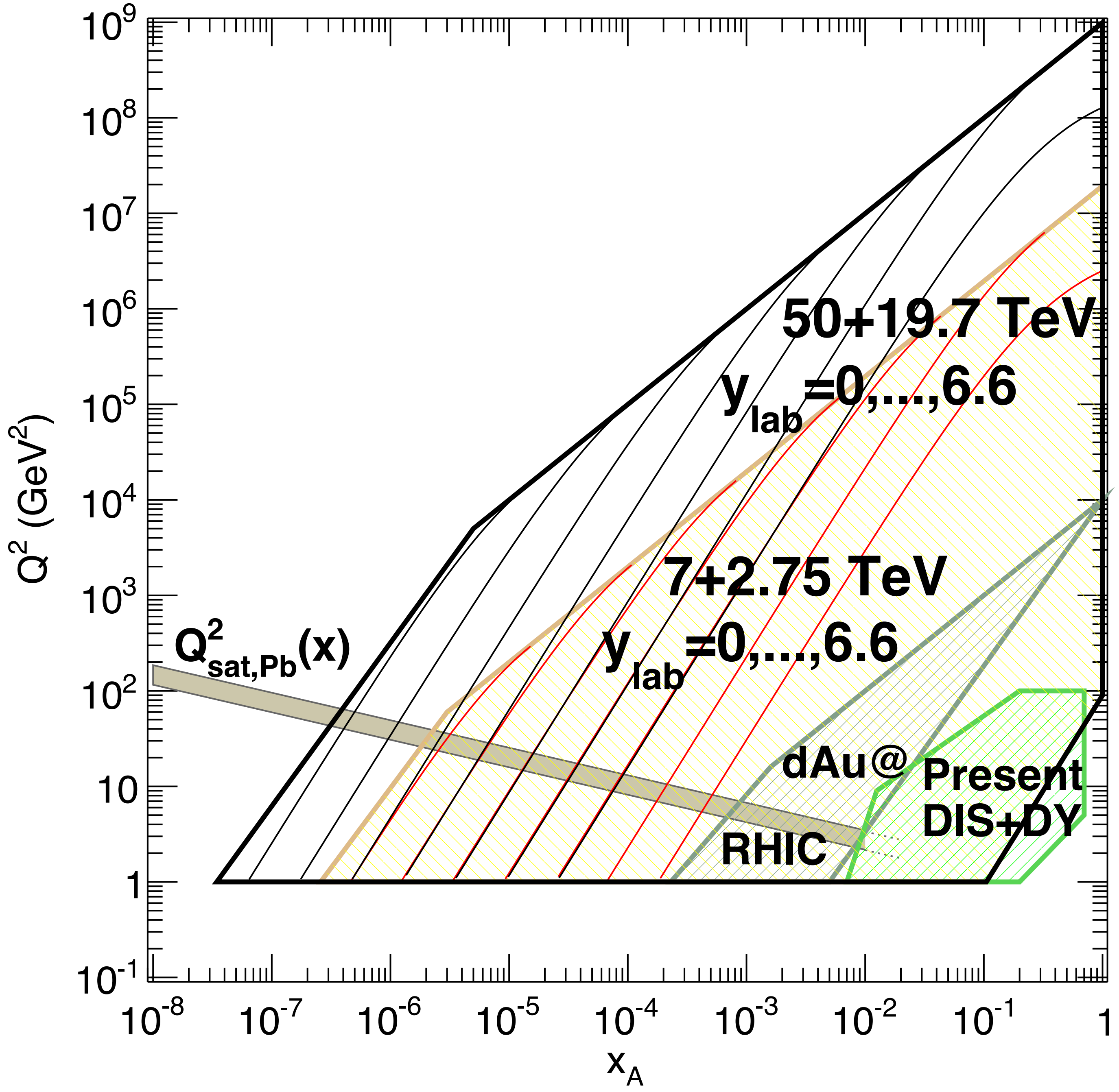

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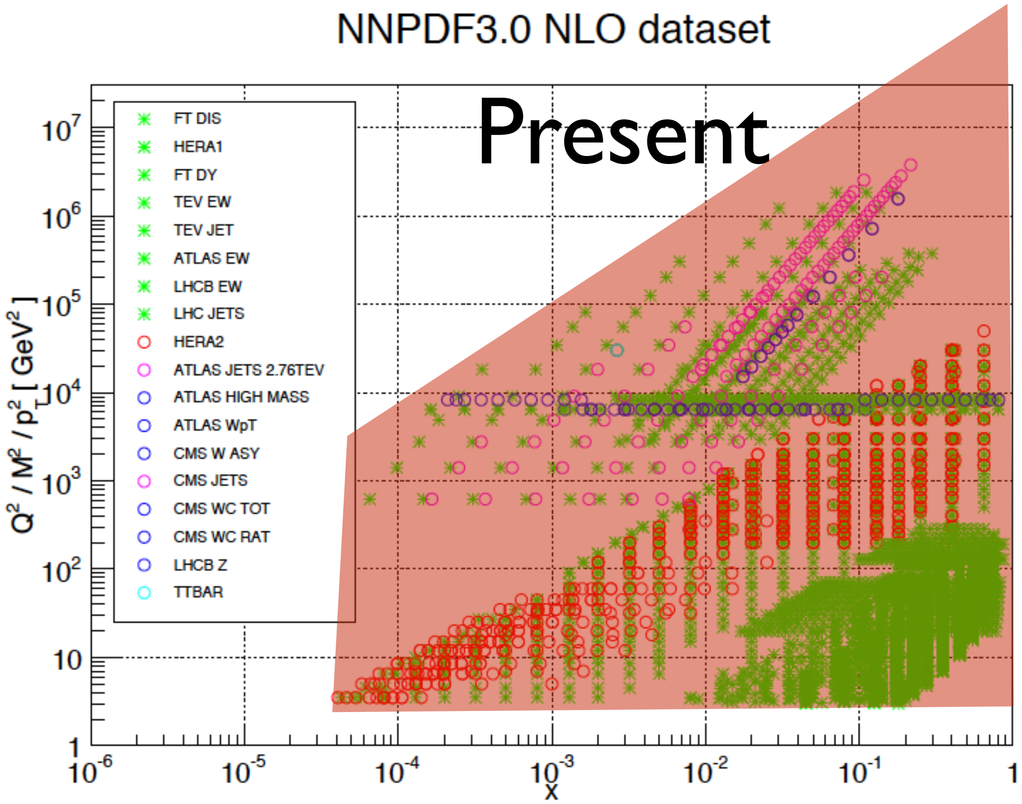

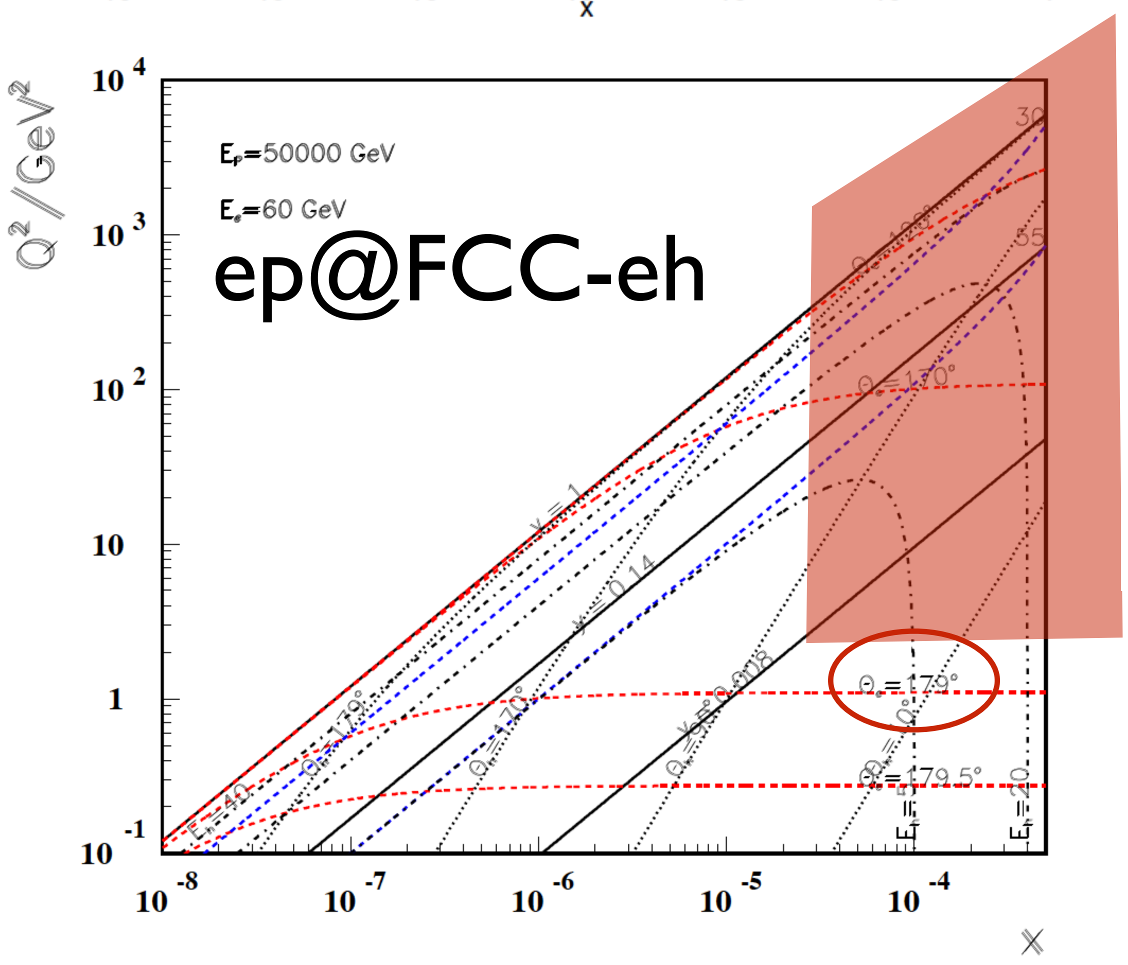

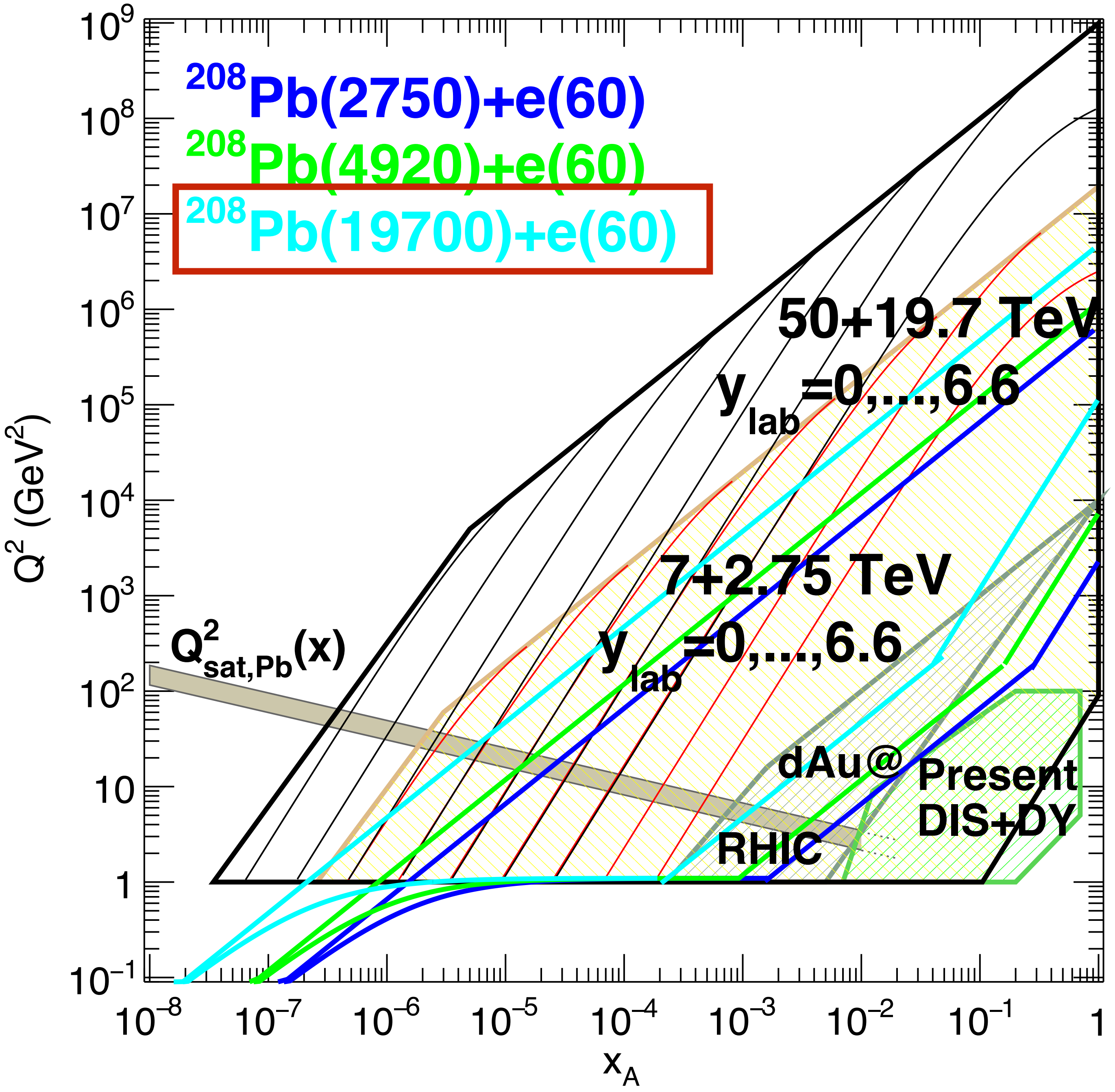

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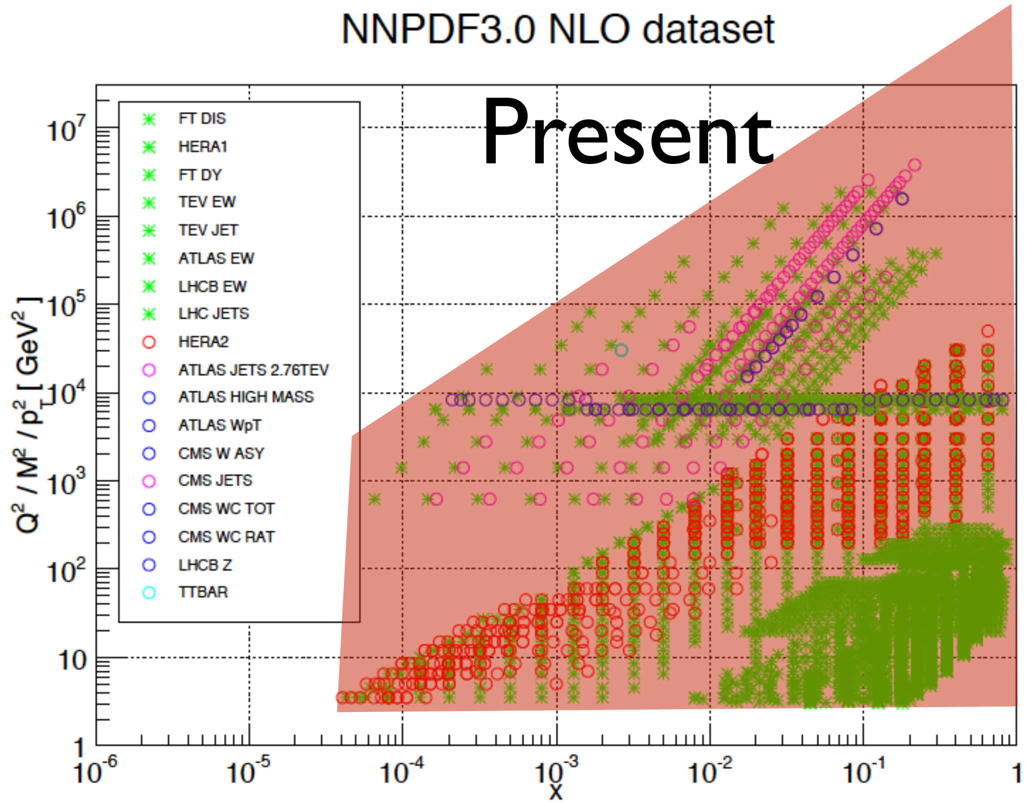

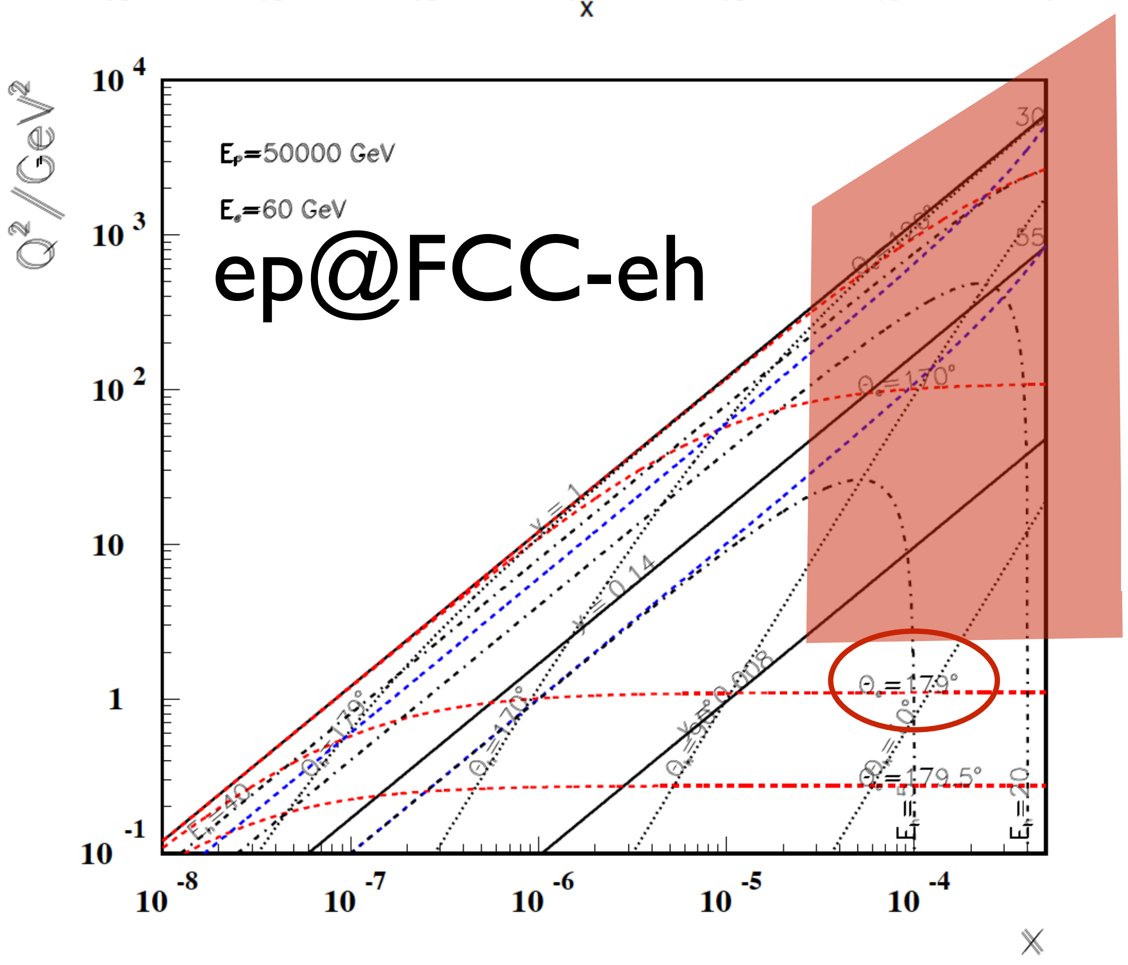

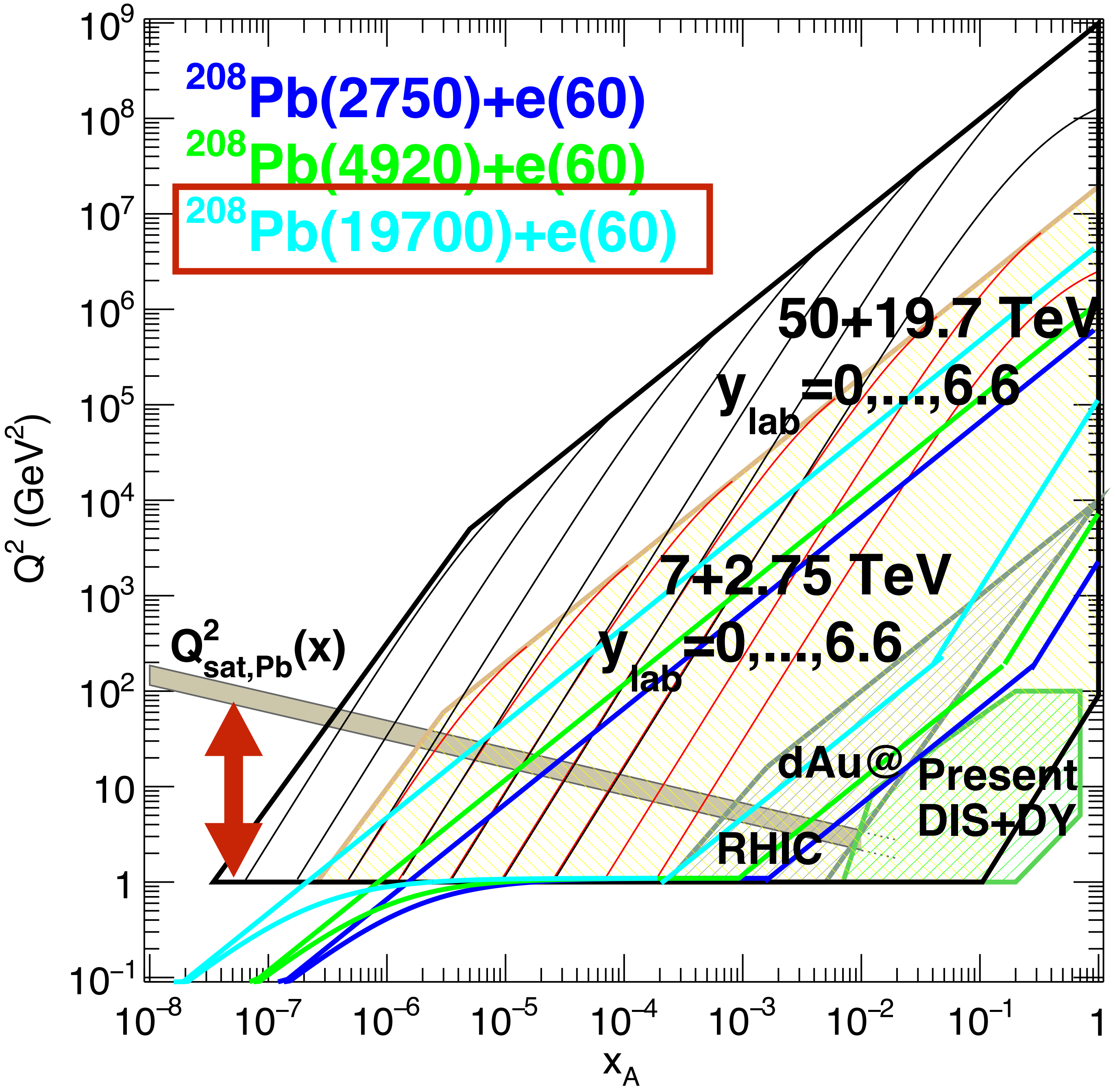

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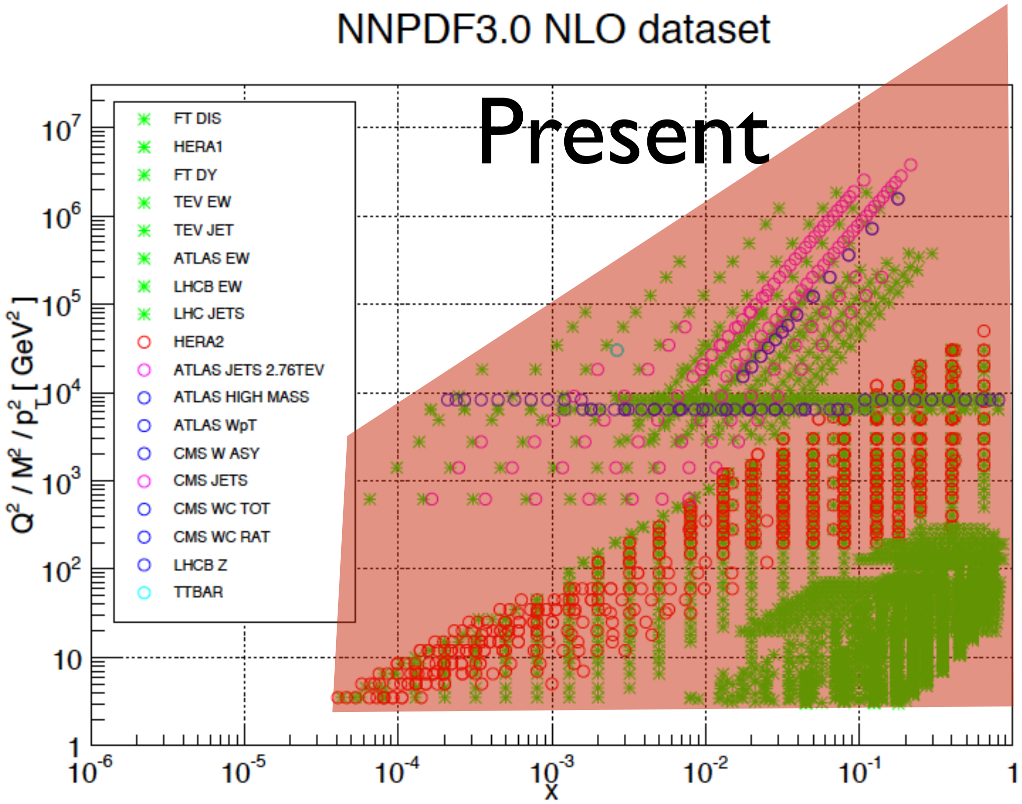

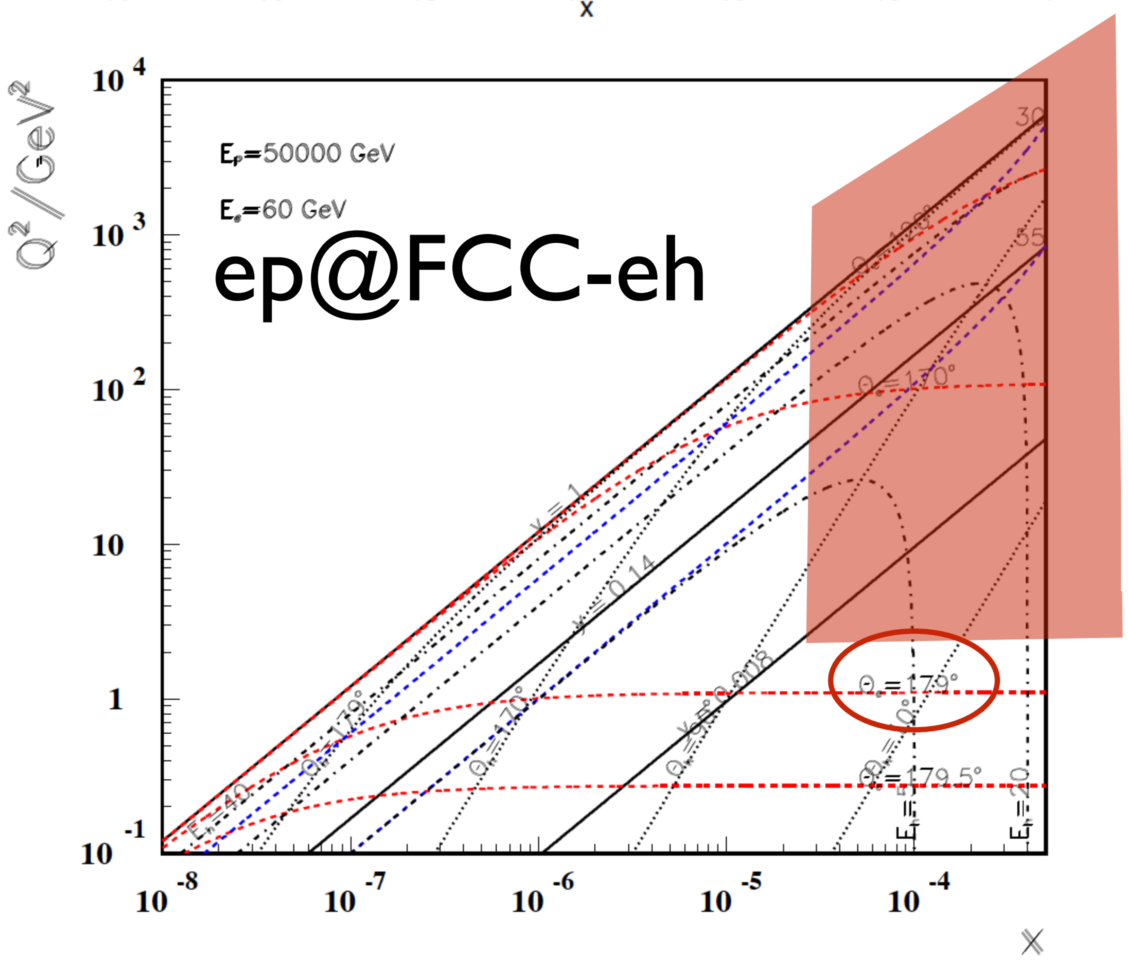

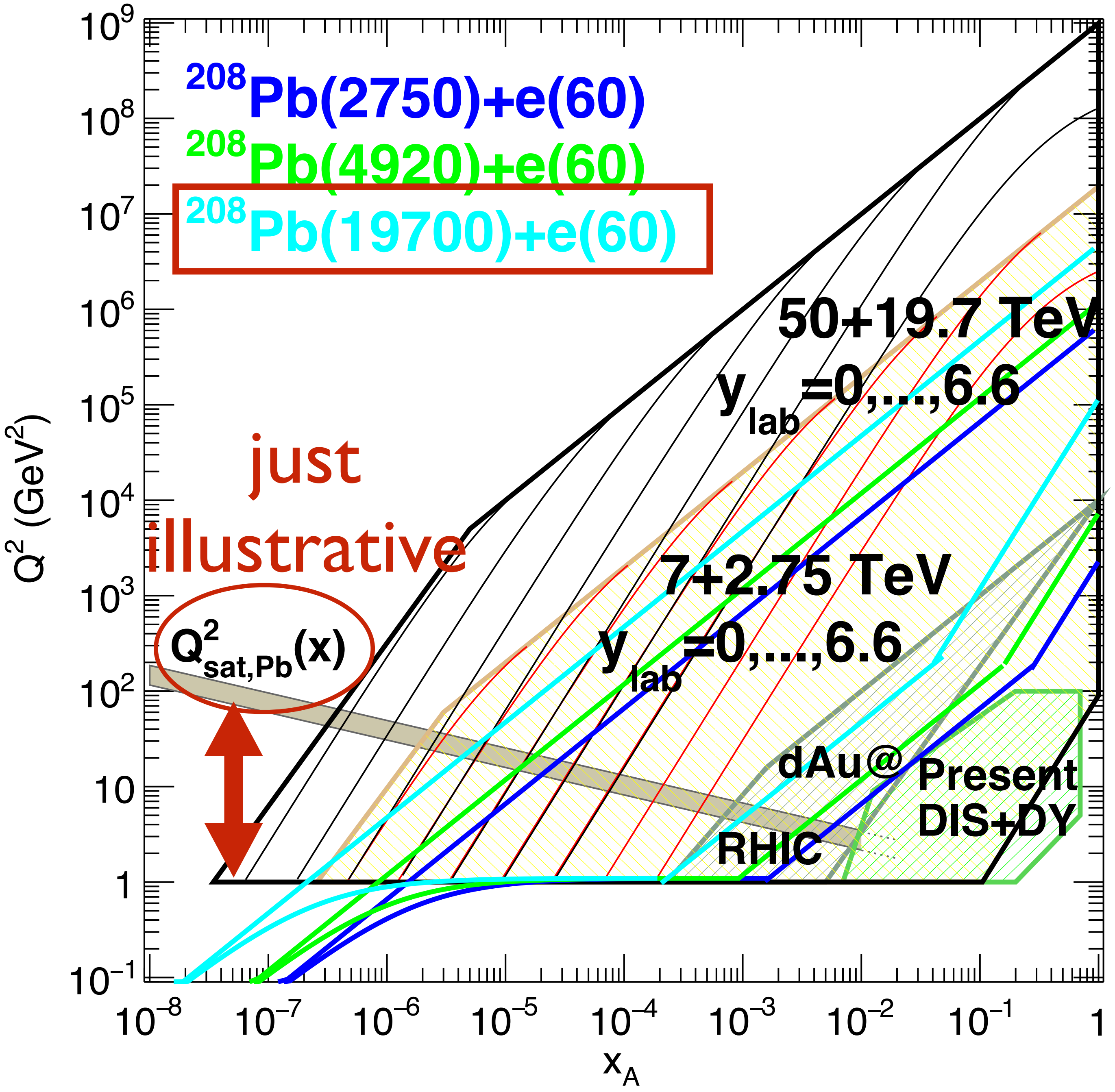

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Contents:

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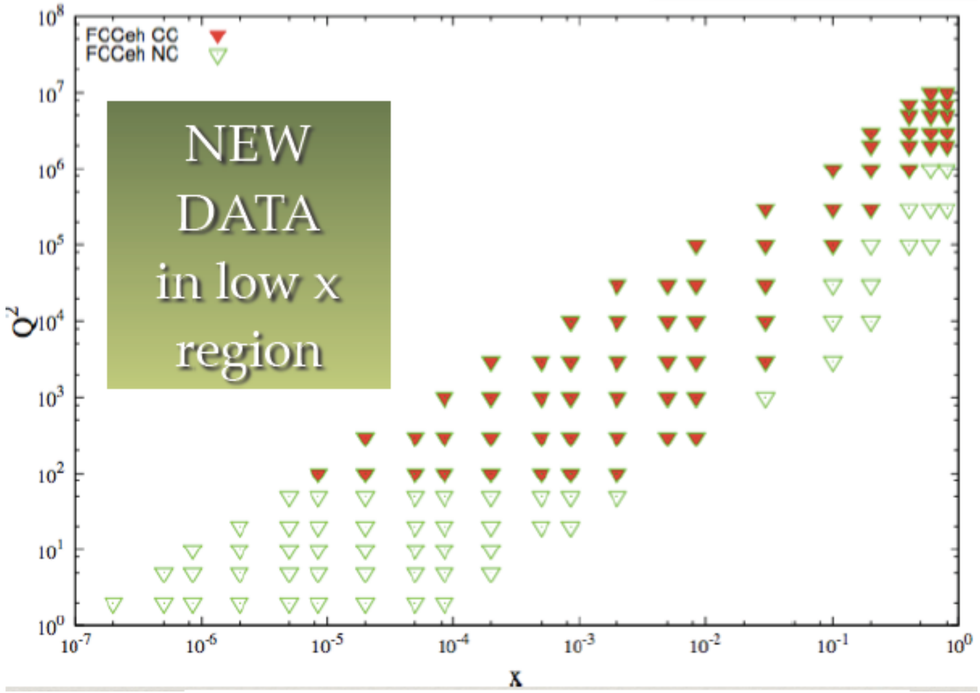
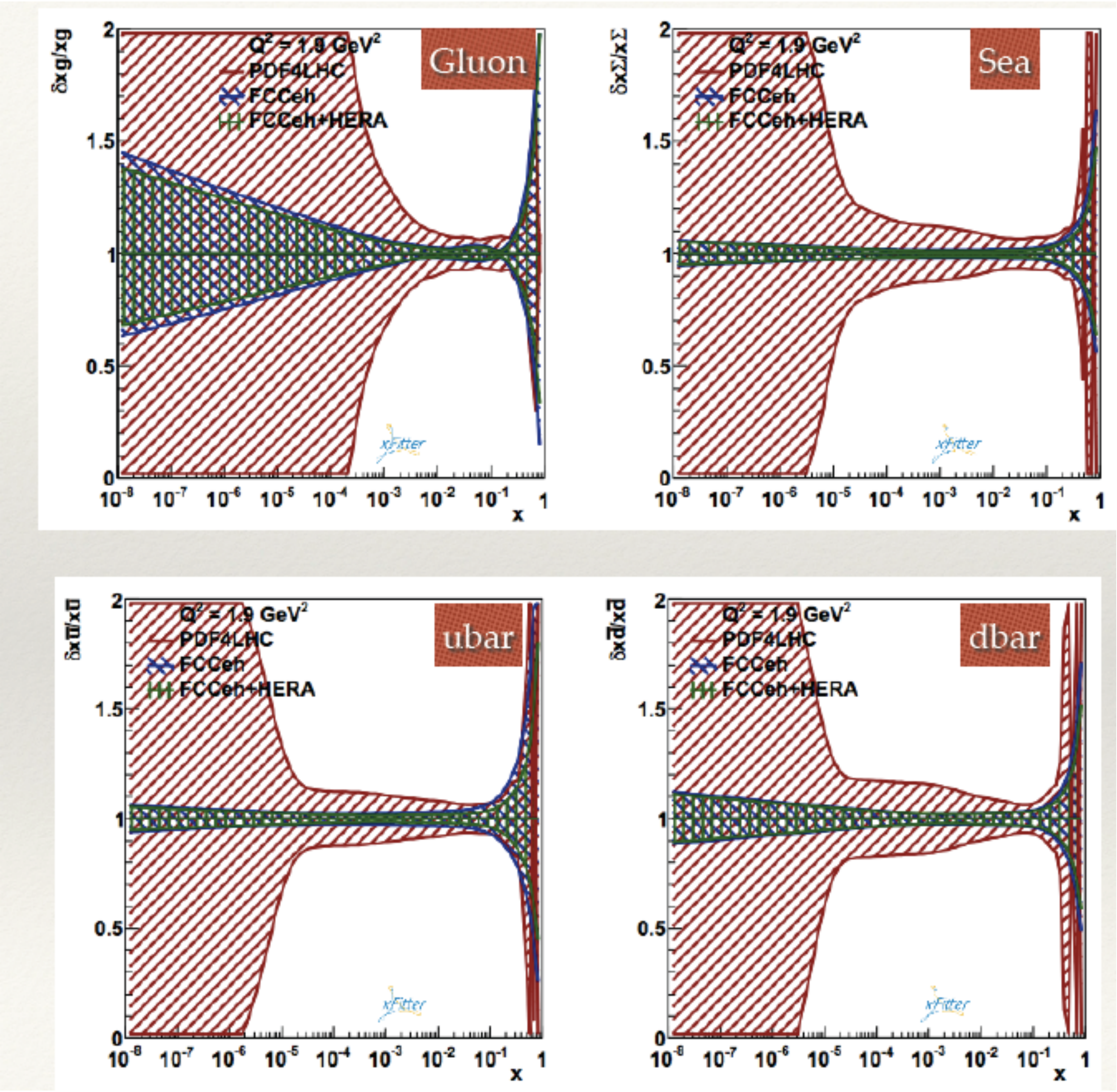
   - ➜ eA.
   - ➜ pA.
   - ➜ Diffractive PDFs.

3. Searching for physics beyond DGLAP.

4. Summary.

ep:



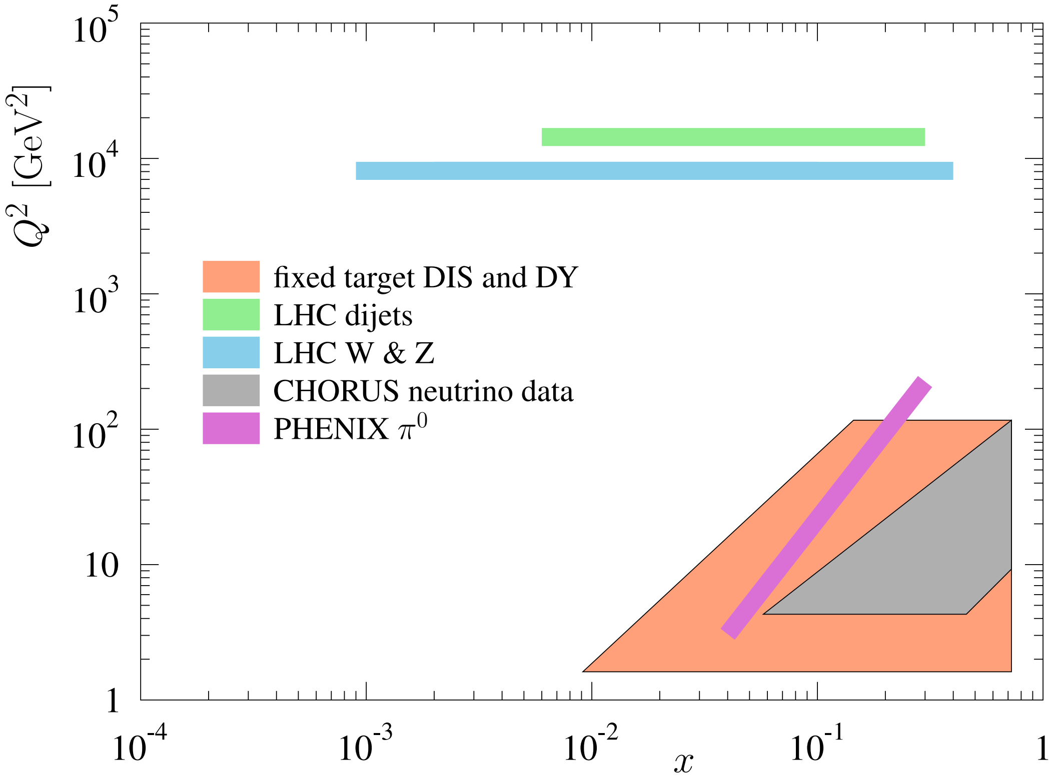


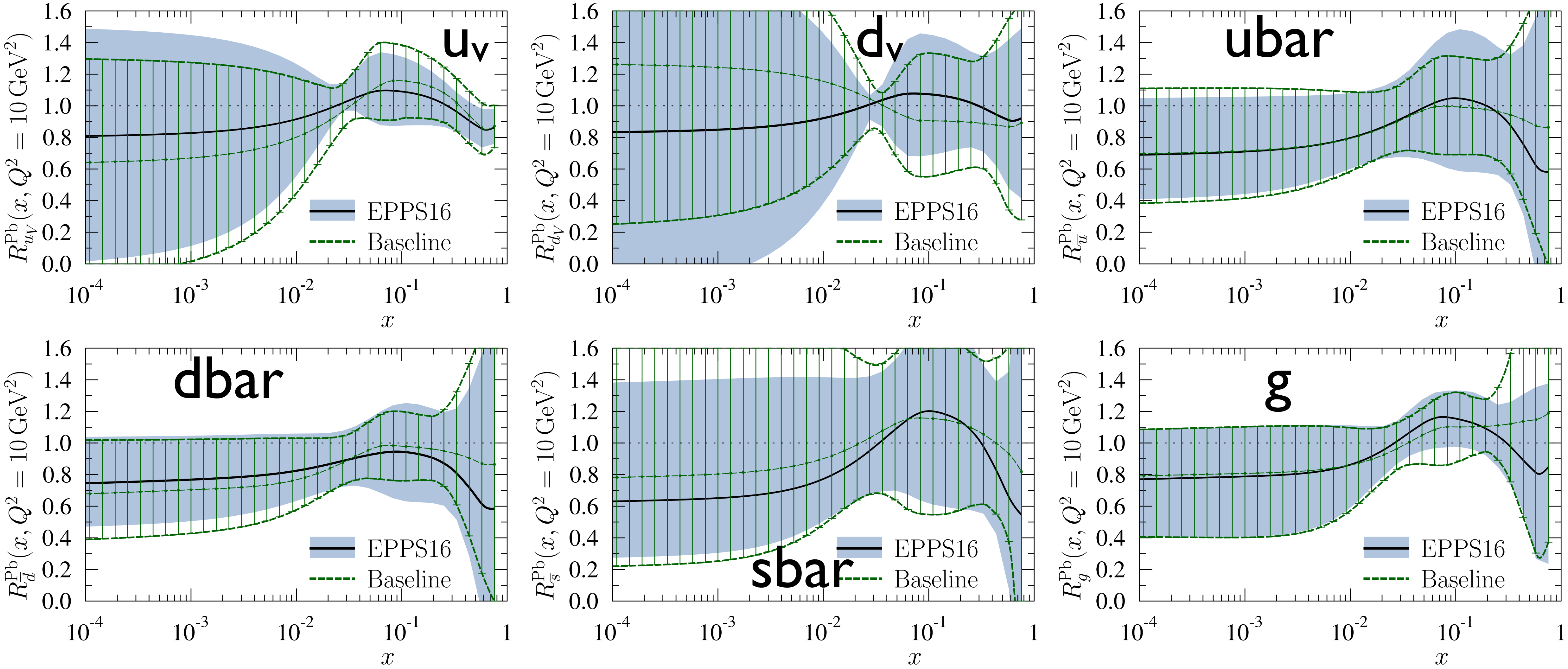
- Large improvements at small x (xFitter analysis).

eA (I):

- New setup EPPS16 [1612.05741] including baseline (fixed target DIS, DY, RHIC) plus neutrino and LHC (dijet, W, Z) pPb data. More flexible parametrisation, GM-VFNS, $R_u \neq R_d$.

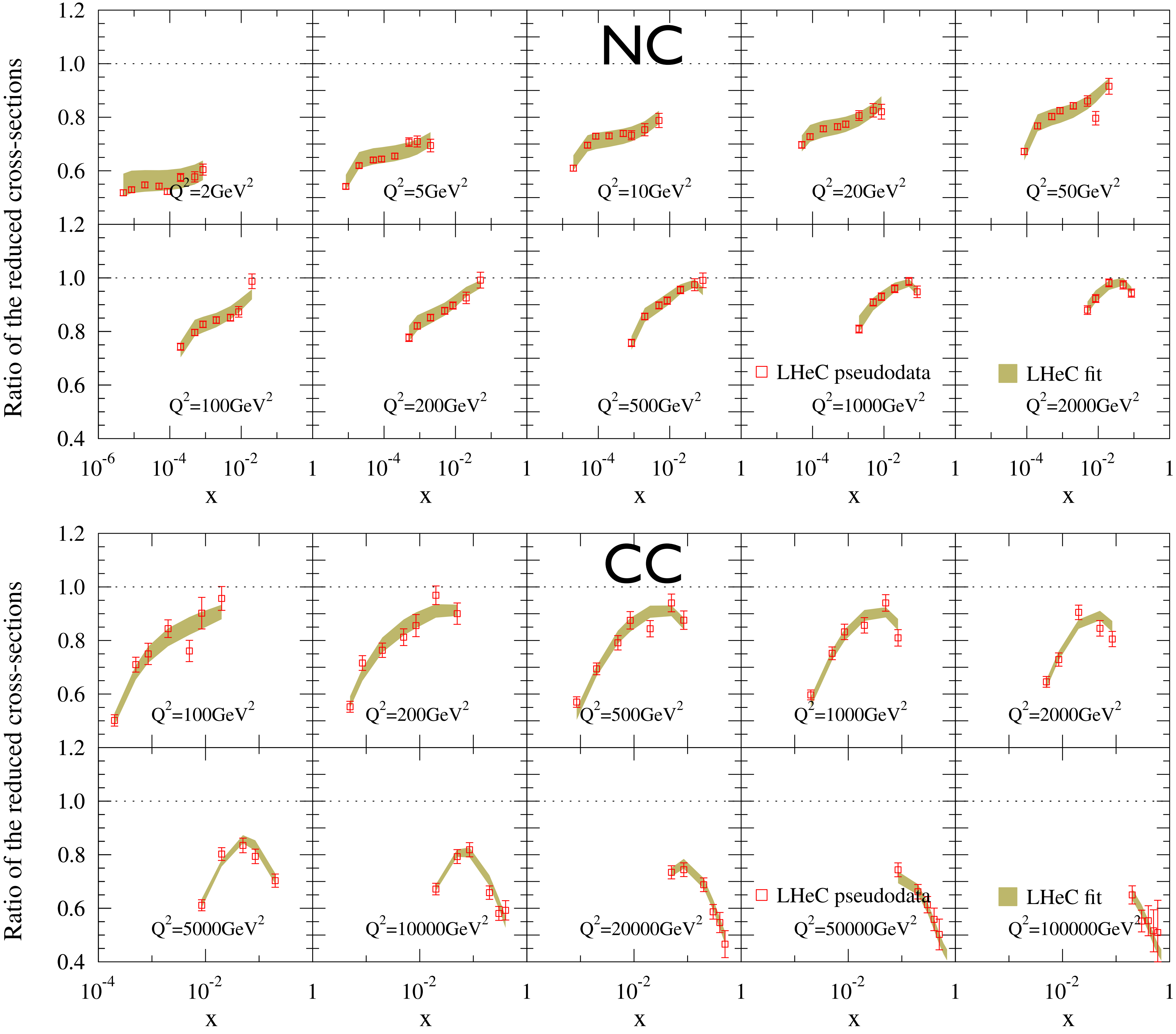
$$f_i^{\mathrm{p}/A}(x,Q^2) = \boxed{R_i^A(x,Q^2)}\, f_i^{\mathrm{p}}(x,Q^2)$$





eA (II):

- Including eA (60+2760) NC and CC pseudodata reduces the uncertainties (notably on g), but u,d decomposition difficult (factor 2Z/A-1). [Paukkunen]



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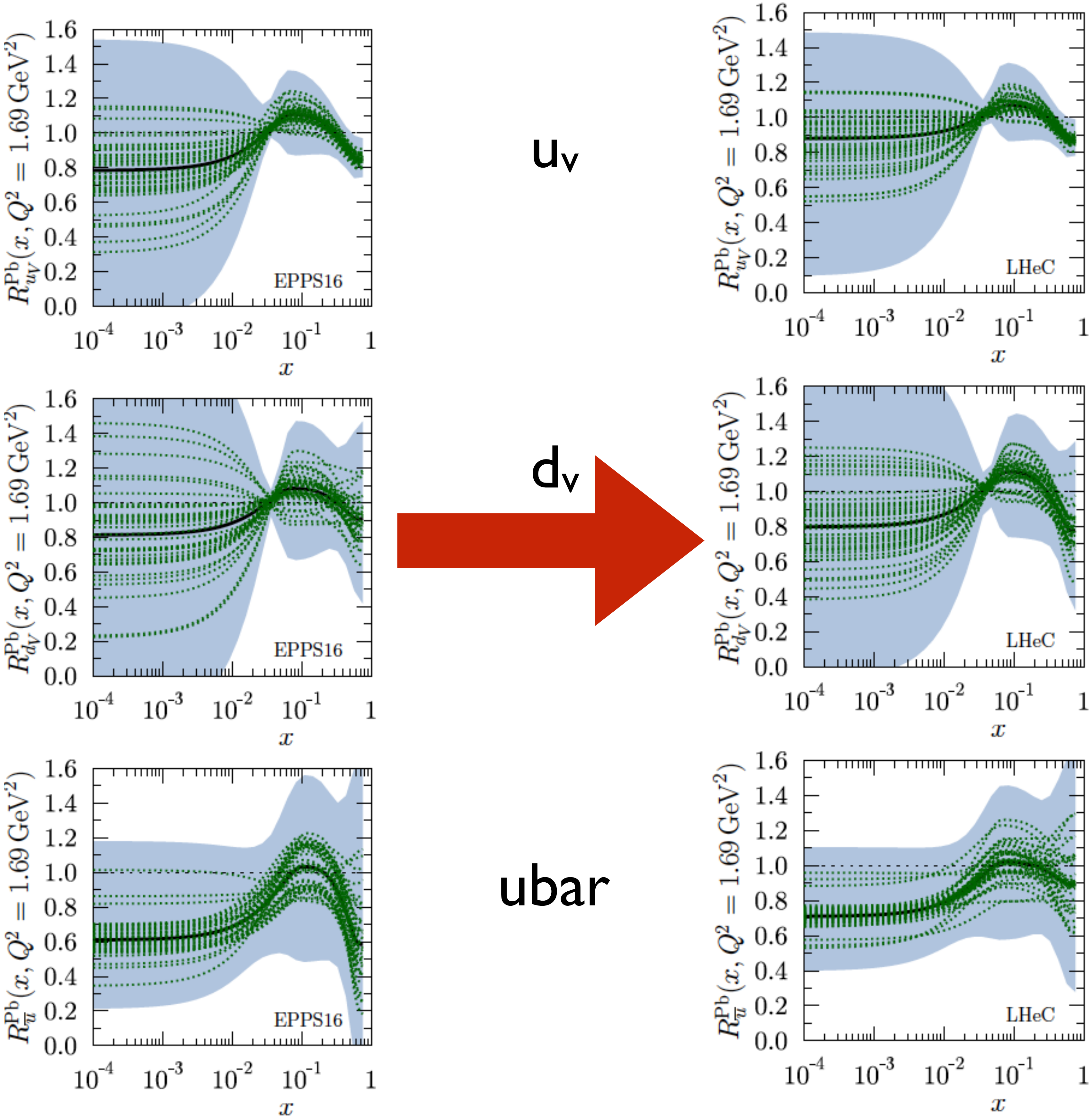

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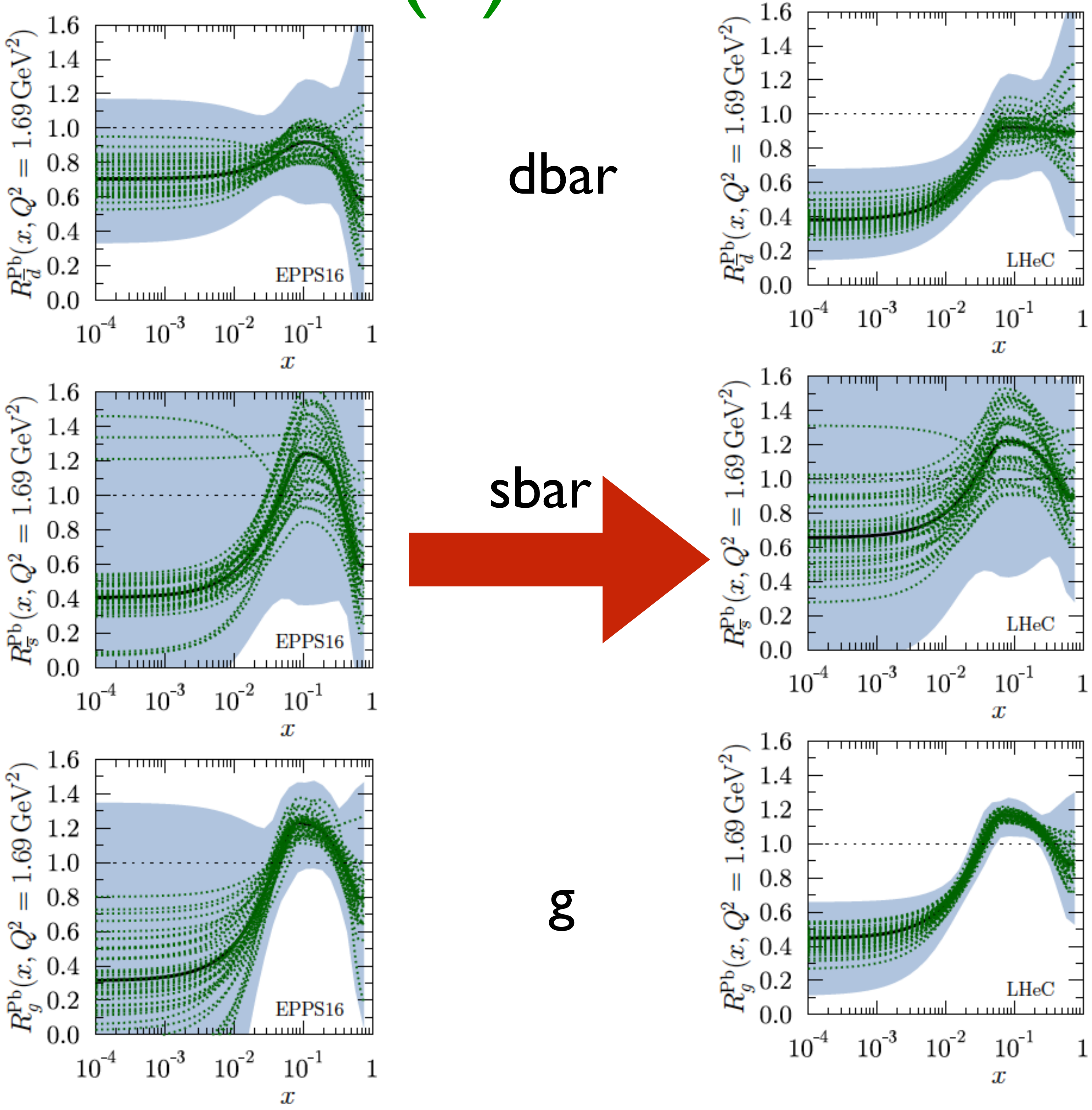
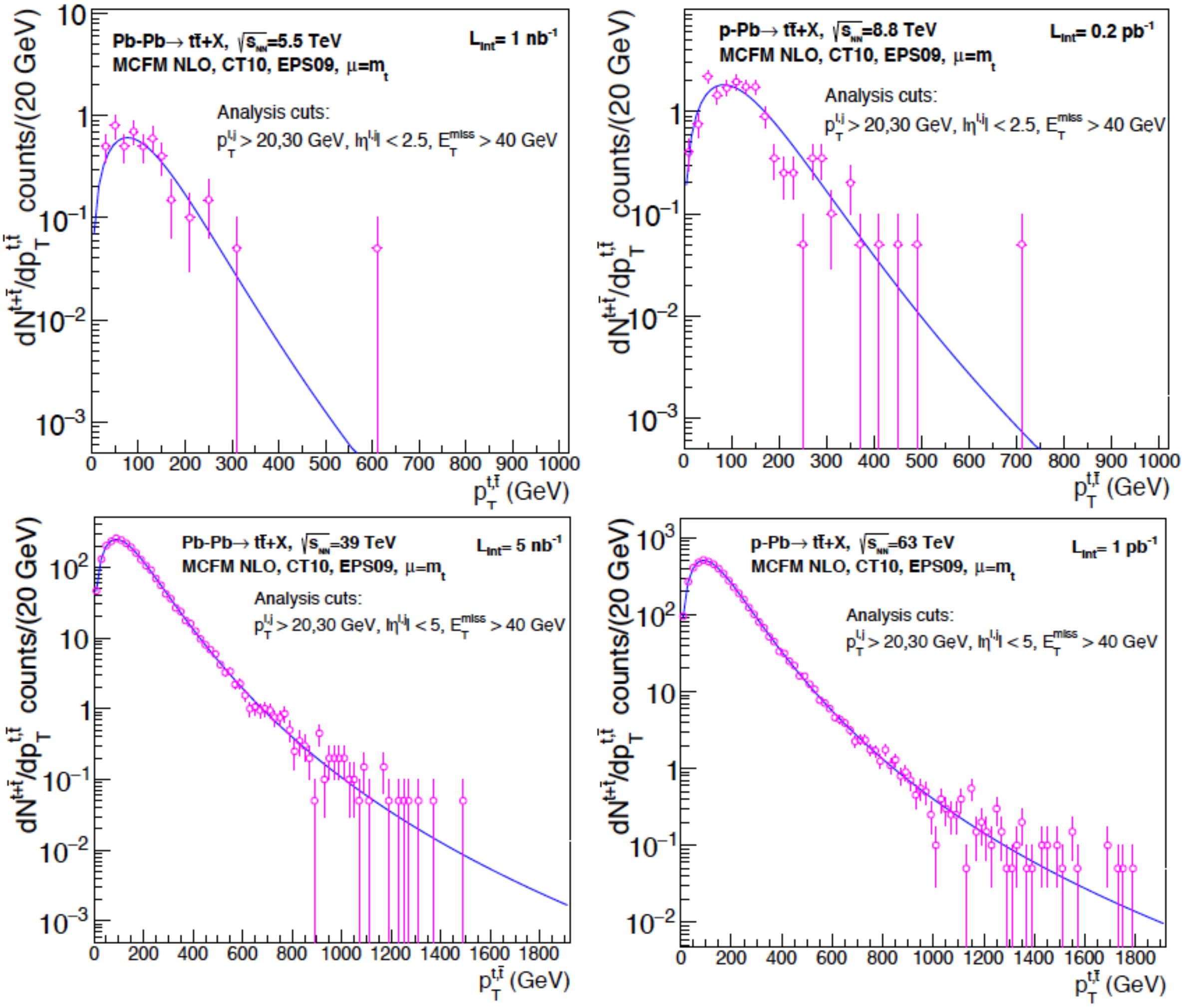


pA:

- Tops could be used to constrain the nuclear glue as done now in pp collisions at the LHC. d'Enterria, Krajczac, Paukkunen, 1501.05879, Hessian reweighting

Modest $\mathcal{L}_{\rm int}$, ATLAS-like cuts.

System	$\sqrt{s}$	$\mathcal{L}_{\rm int}$	Number of top+antitop quarks $t\bar{t} \to b\,\bar{b}\,\ell\ell\,\nu\nu$	Number of top+antitop quarks $tW \to b\,\ell\ell\,\nu\nu$
Pb-Pb	5.5 TeV	1 $\rm nb^{-1}$	90	3
p-Pb	8.8 TeV	0.2 $\rm pb^{-1}$	300	10
Pb-Pb	39. TeV	5 $\rm nb^{-1}$	47 000	1 300
p-Pb	63. TeV	1 $\rm pb^{-1}$	100 000	2 600



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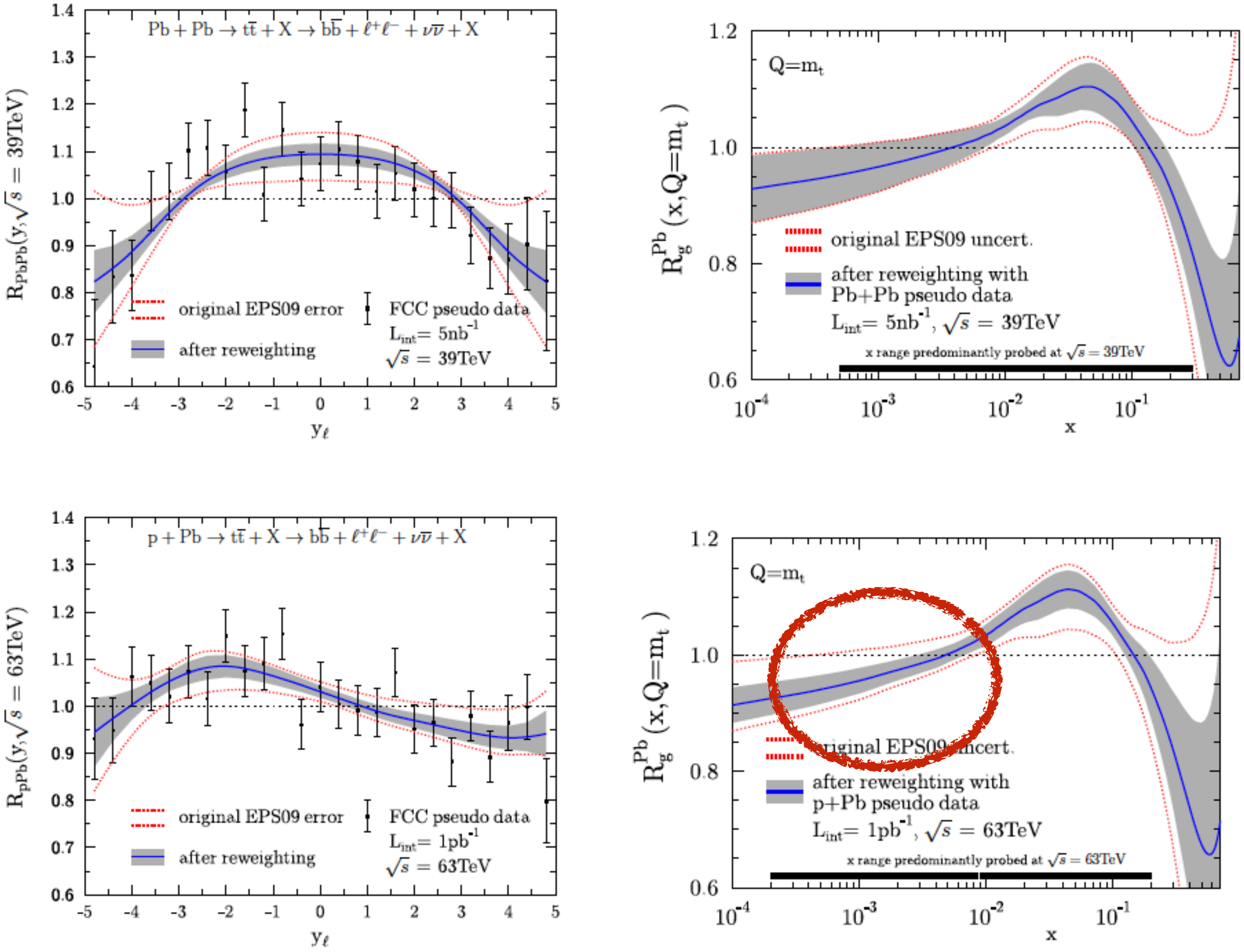

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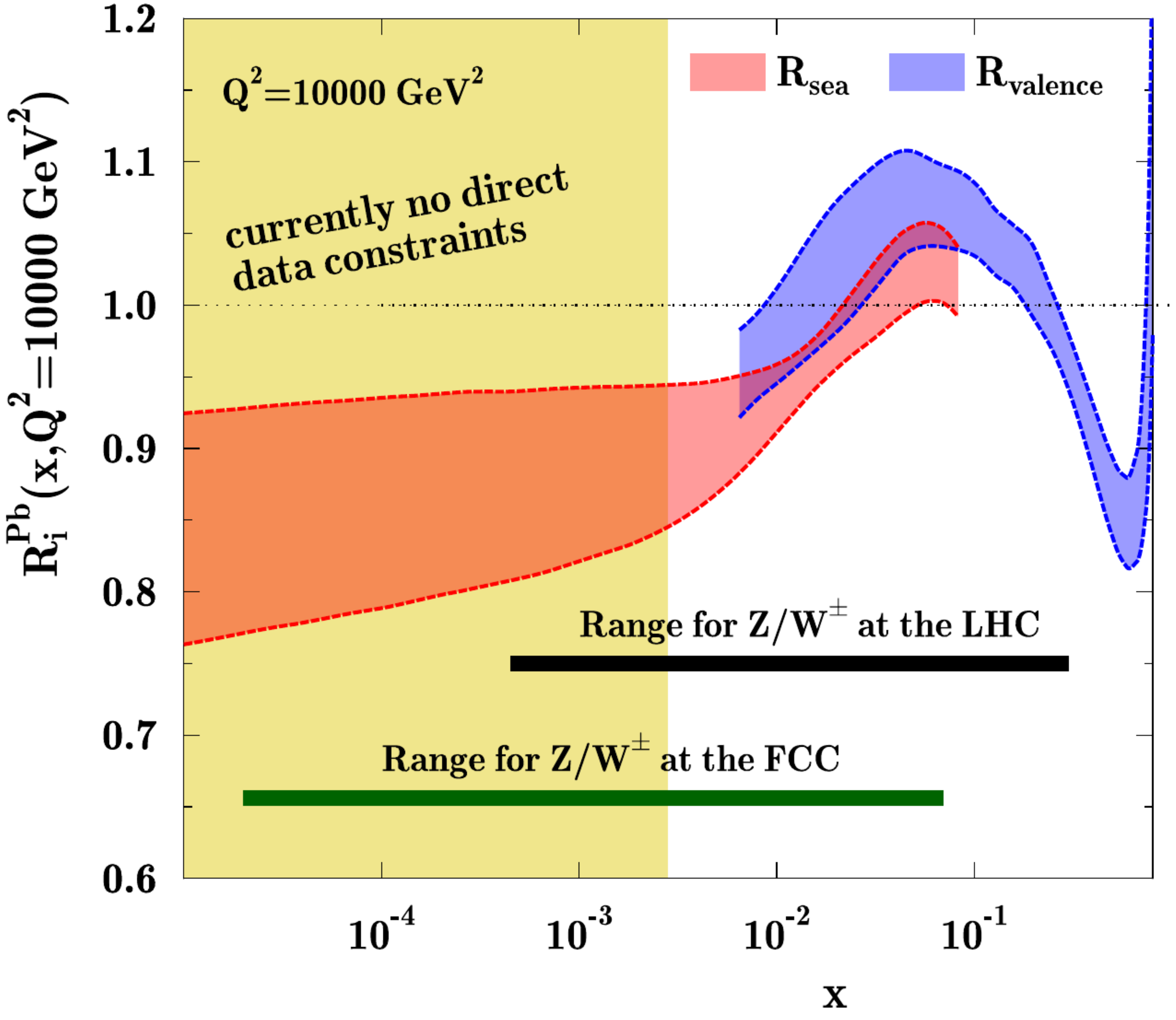
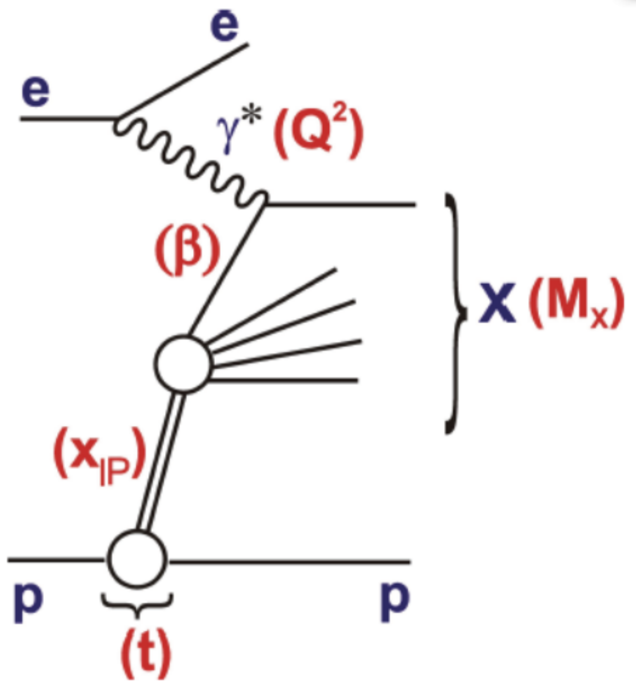
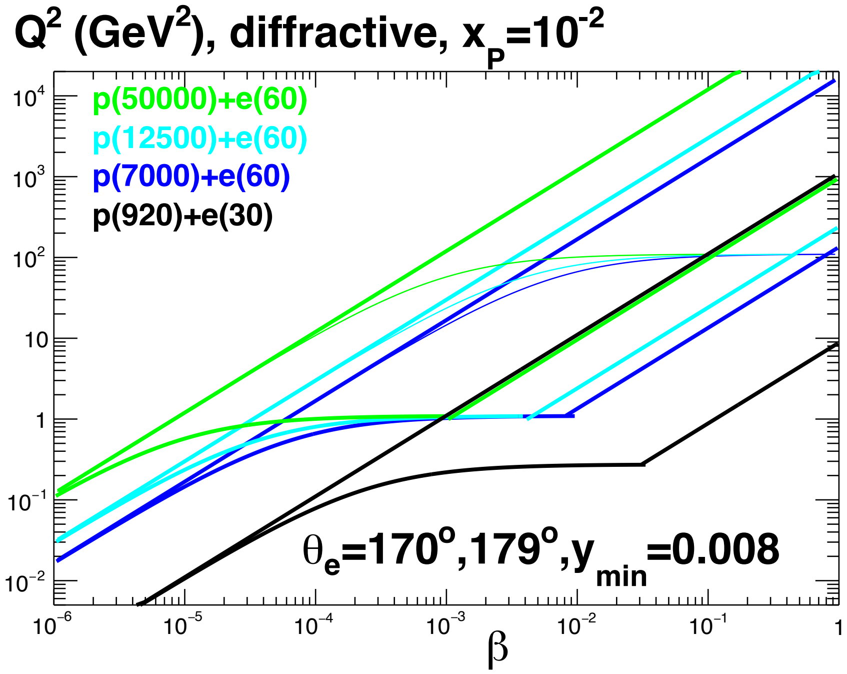
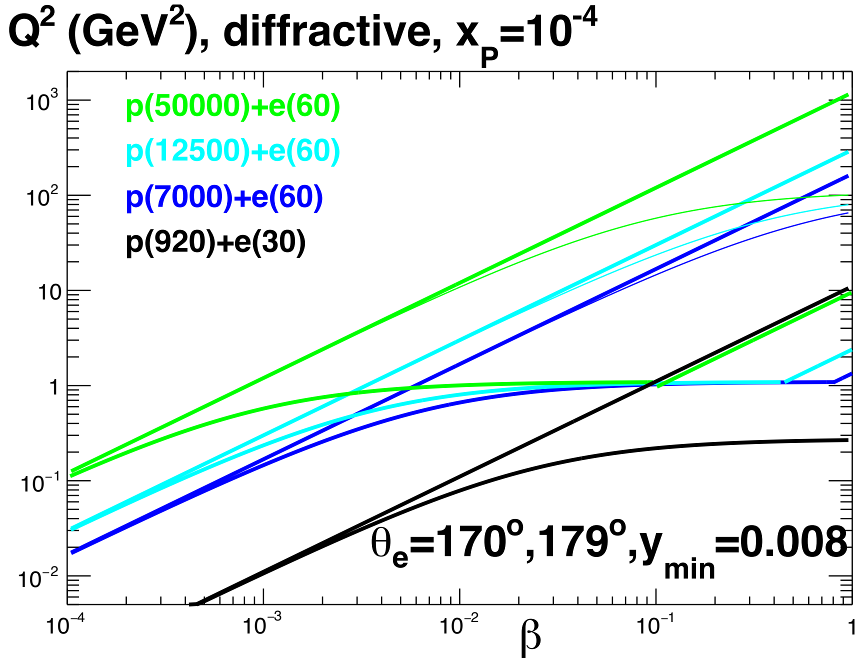


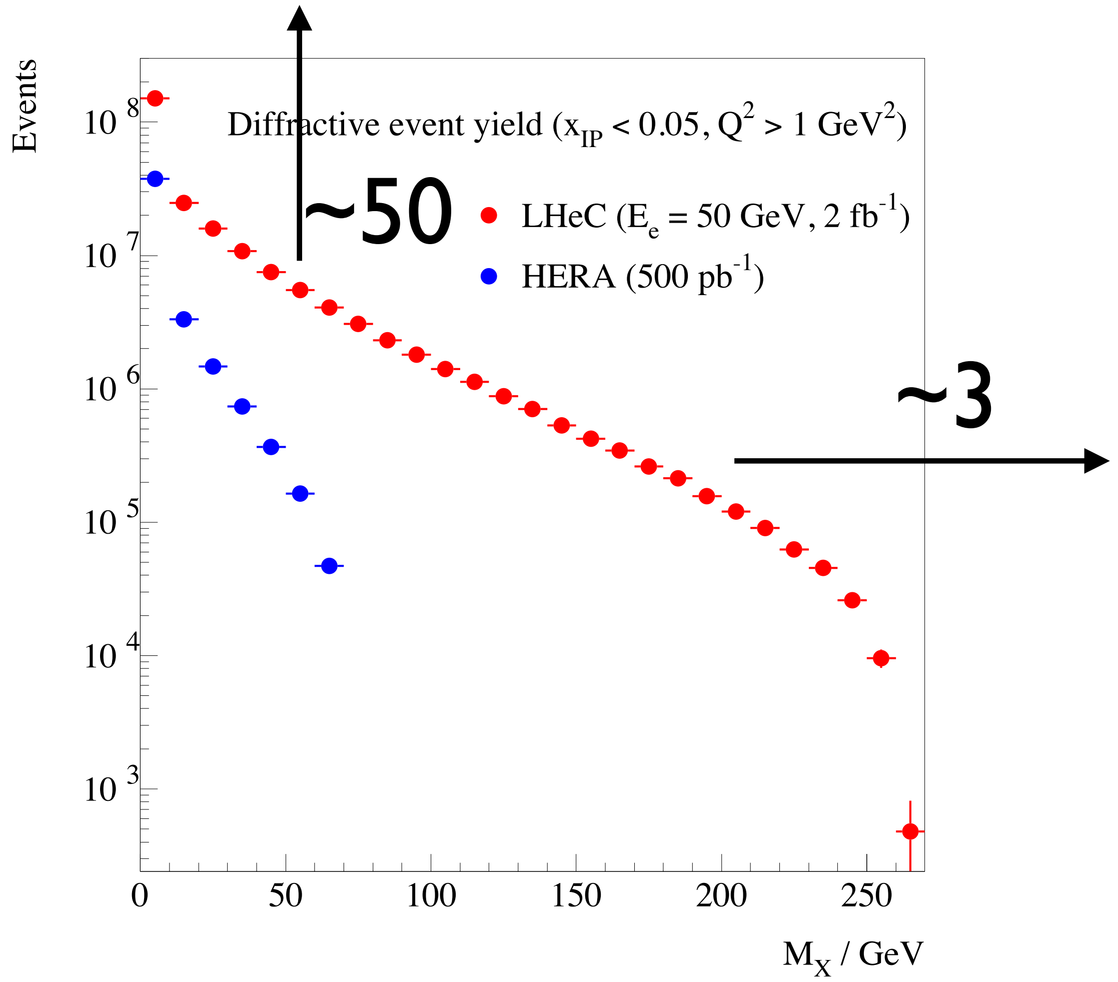
Diffraction in ep:



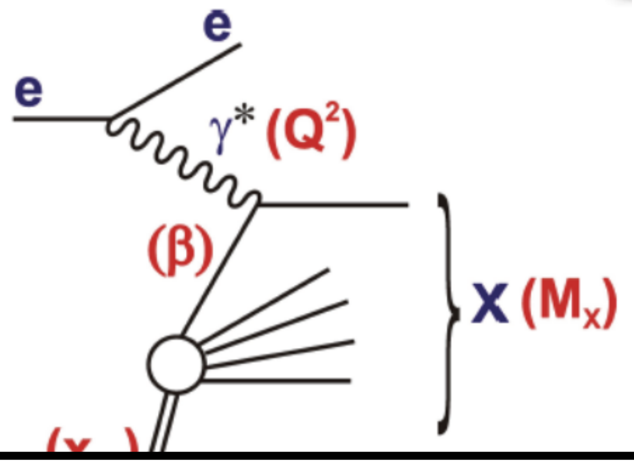


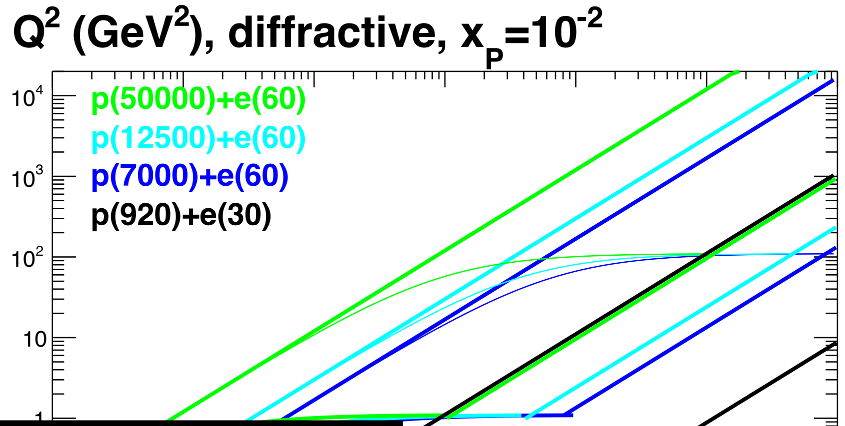


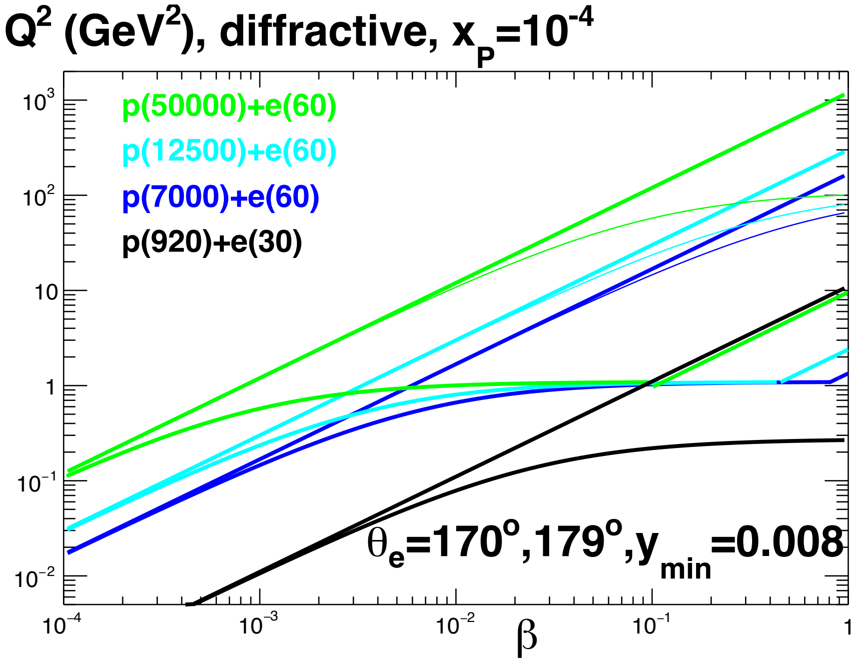
- Large increase in the M^2 (diffractive heavy states up to ~0.5 TeV), $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.
- Possible to combine rapidity gap and p tagging.
- Precise determination of DPDFs.

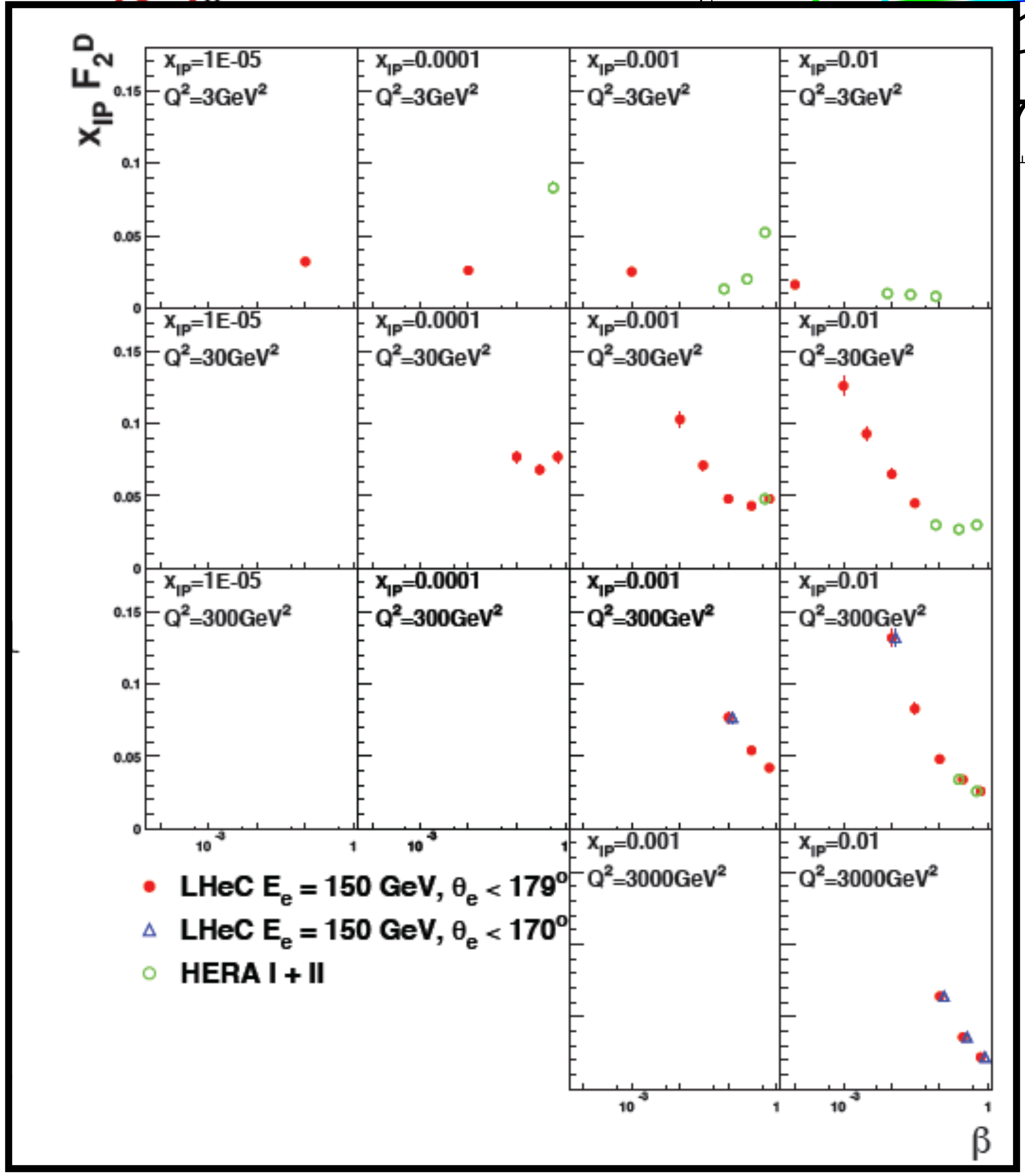


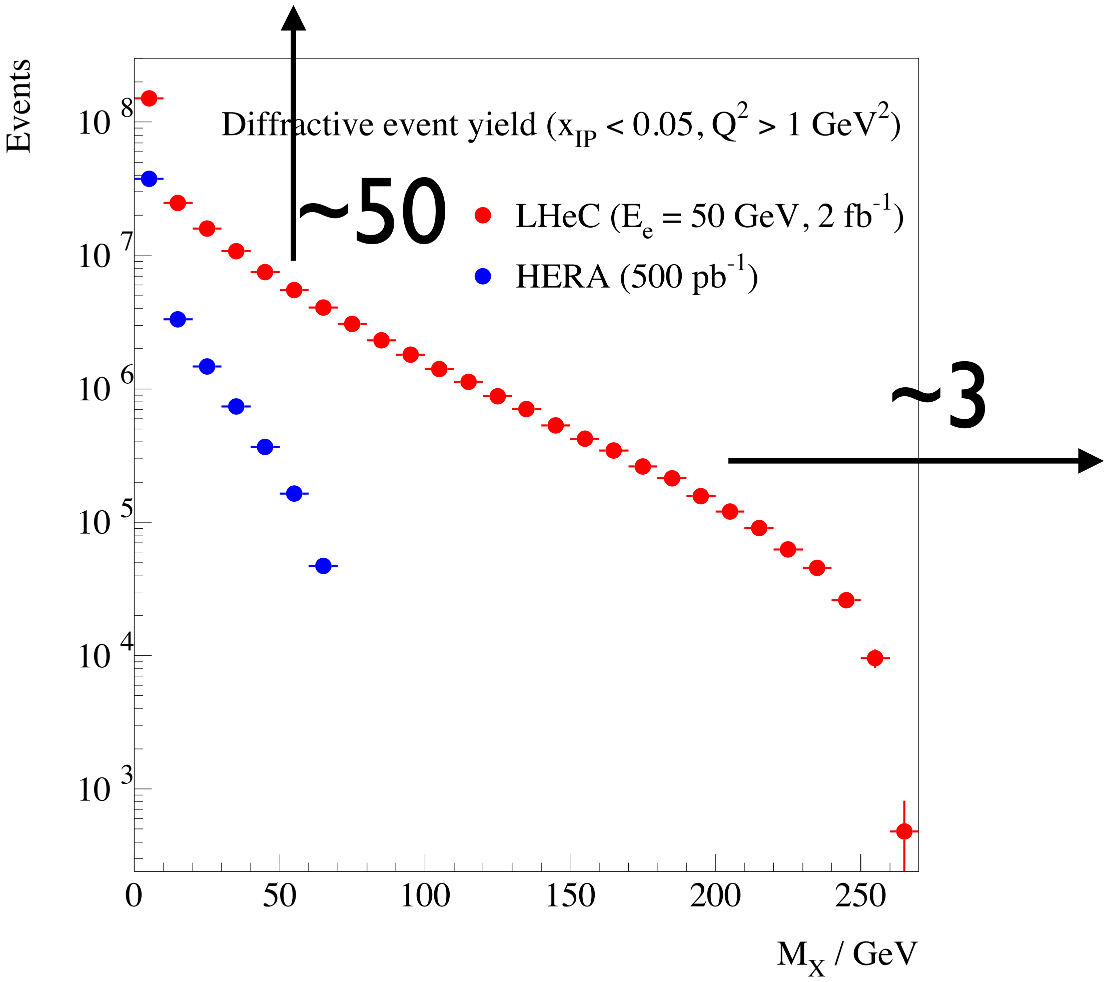
Diffraction in ep:









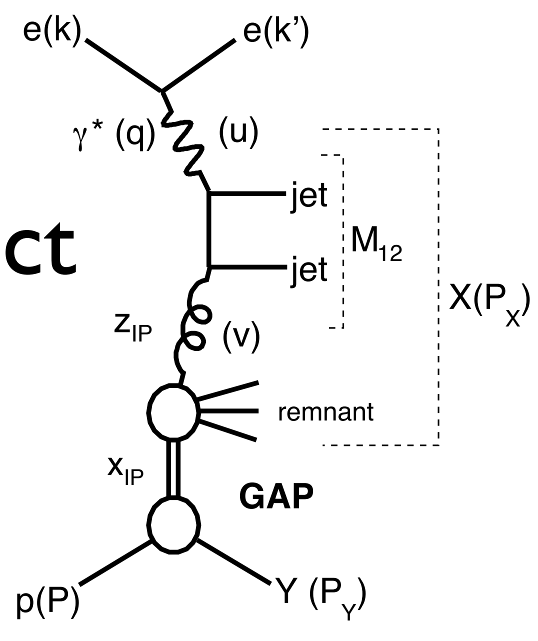


Diffractive dijets in ep:

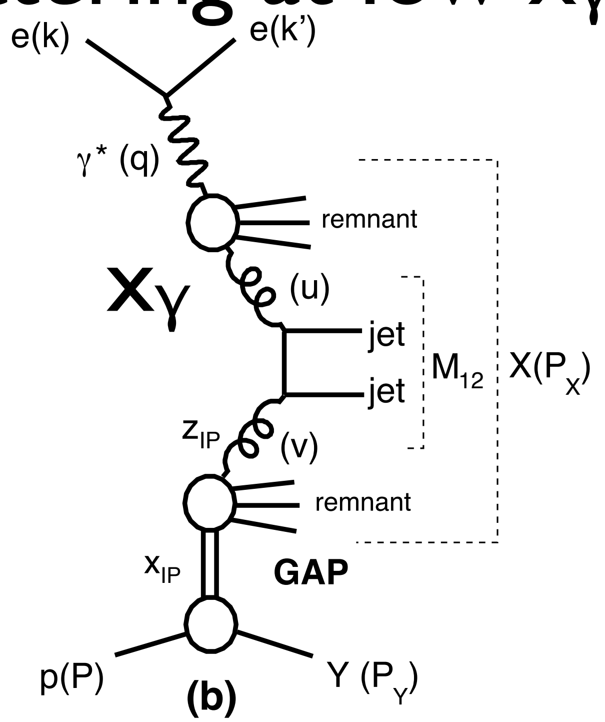
resolved:

rescattering at low x_γ?

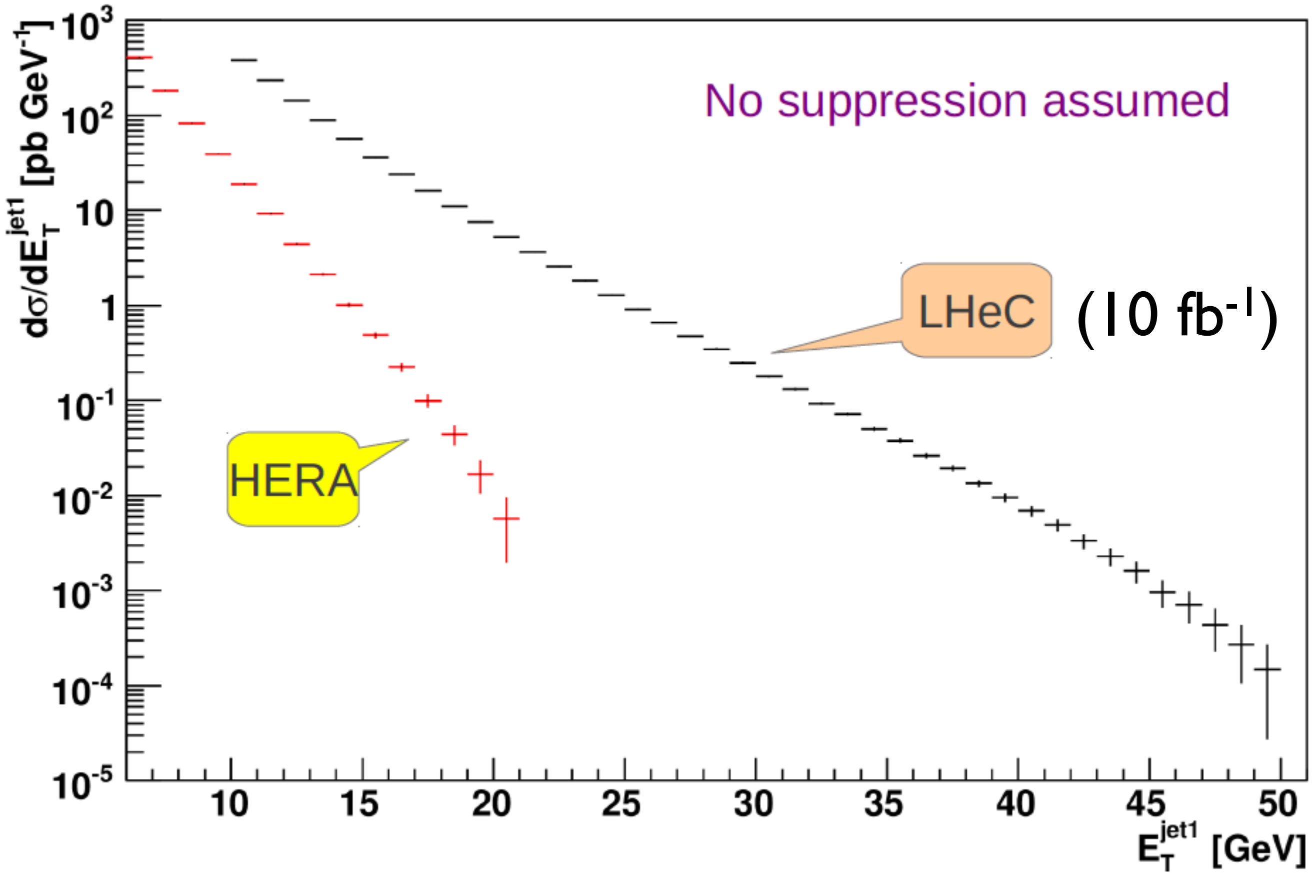
direct



(a)



(b)



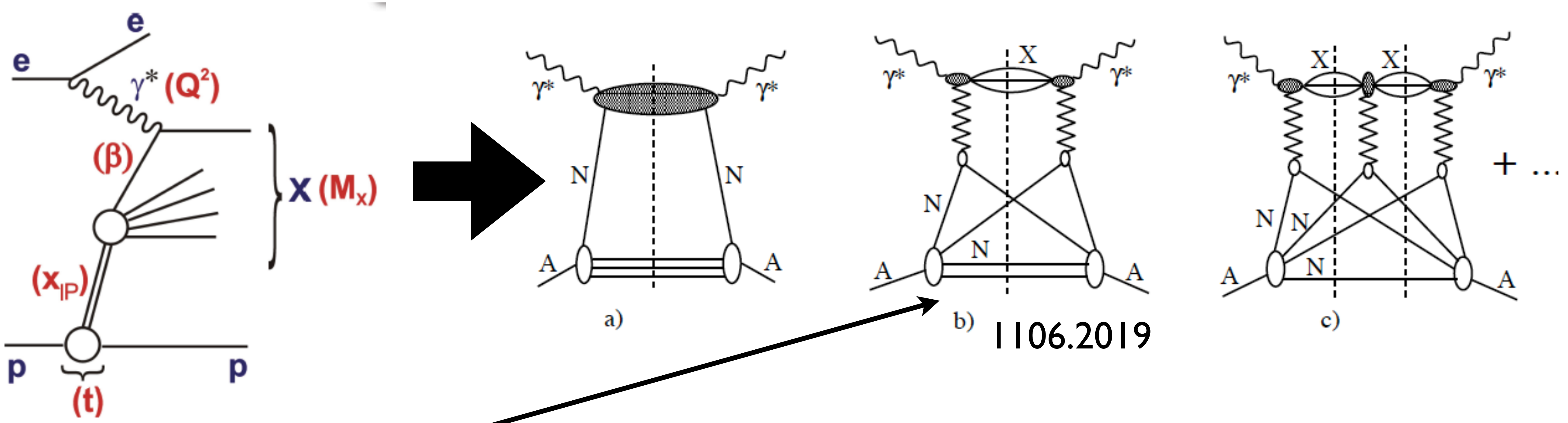
(10 fb^{-1})

- Diffractive dijet and open heavy flavour production offer large possibilities for:
  - ➜ Checking factorization in hard diffraction.
  - ➜ Constraining DPDFs.

- Large yields up to large p_T^{jet}.

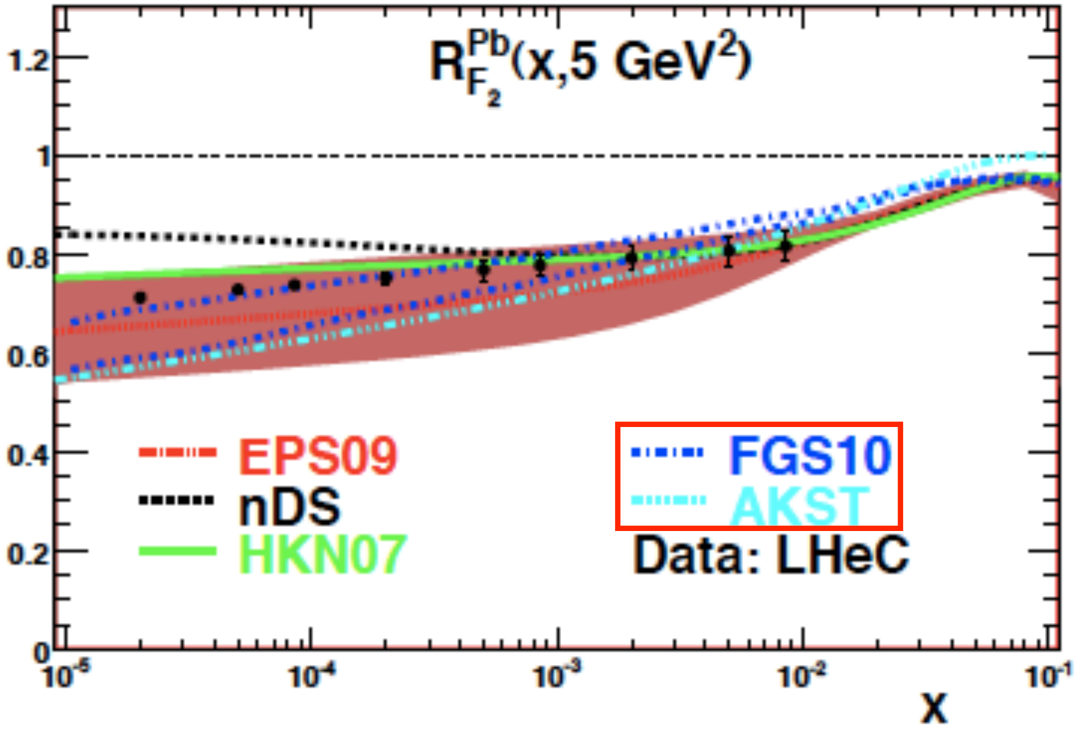
- Direct and resolved contributions: photon PDFs.

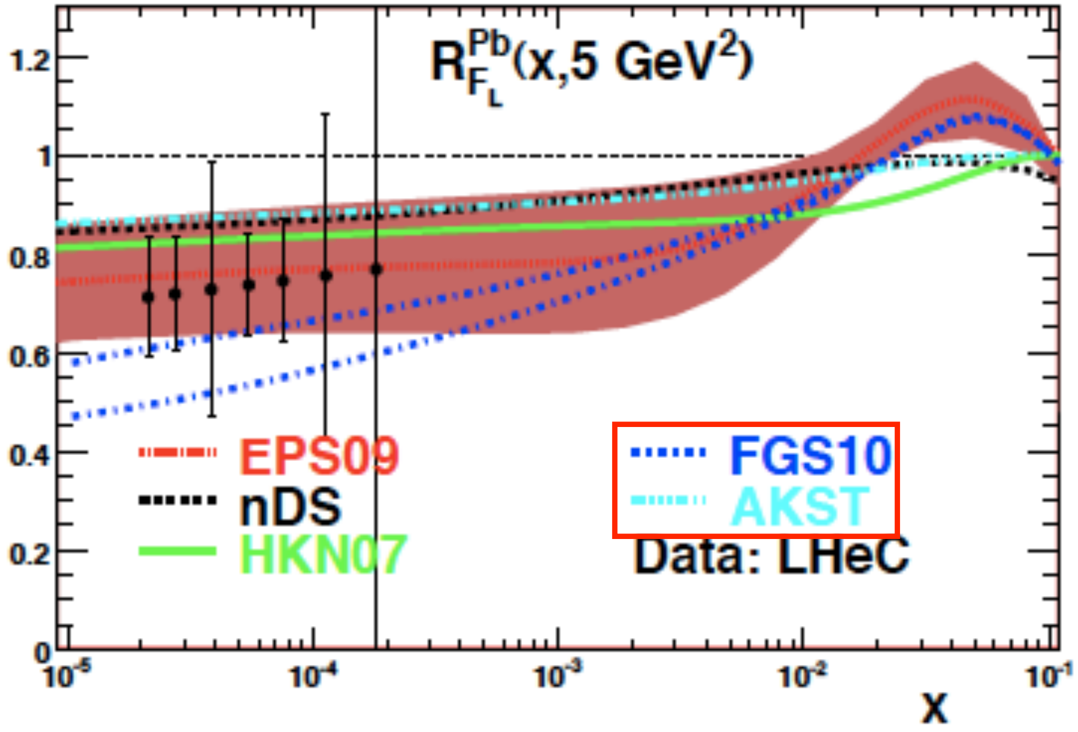
Diffraction in ep and shadowing:



1106.2019

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





Contents:

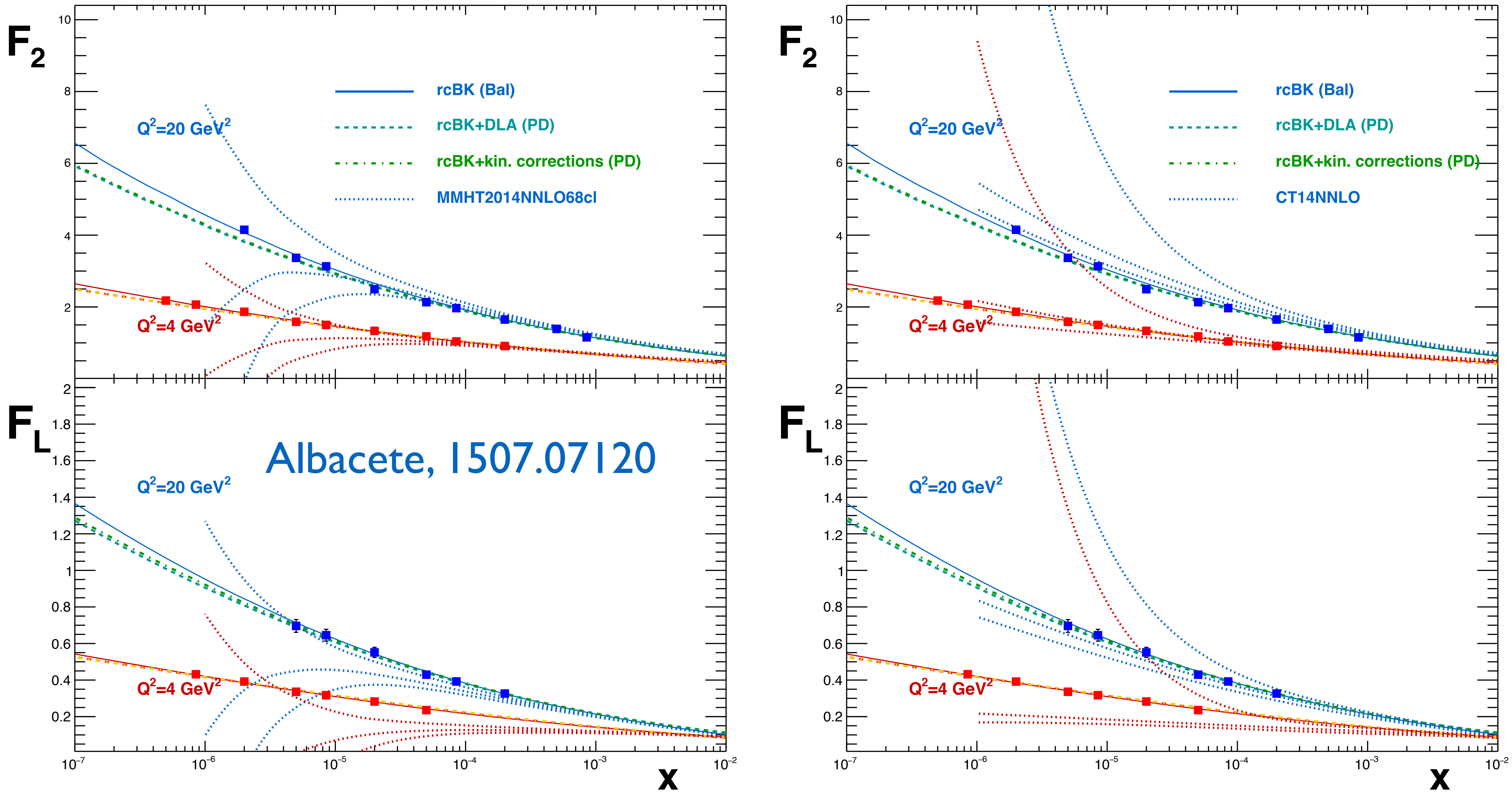
1. Introduction.

2. Determining the small-x PDFs.

3. Searching for physics beyond DGLAP:
    - ➜ Inclusive observables.
    - ➜ Diffraction.
    - ➜ Particle production and correlations.

4. Summary.

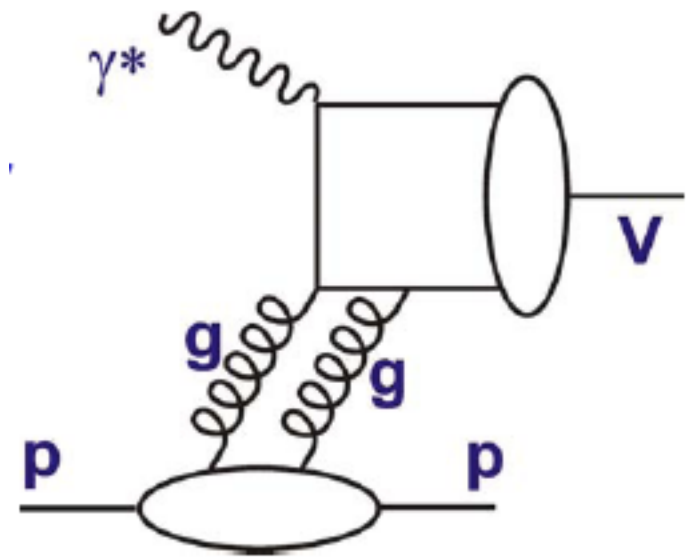
Structure functions:

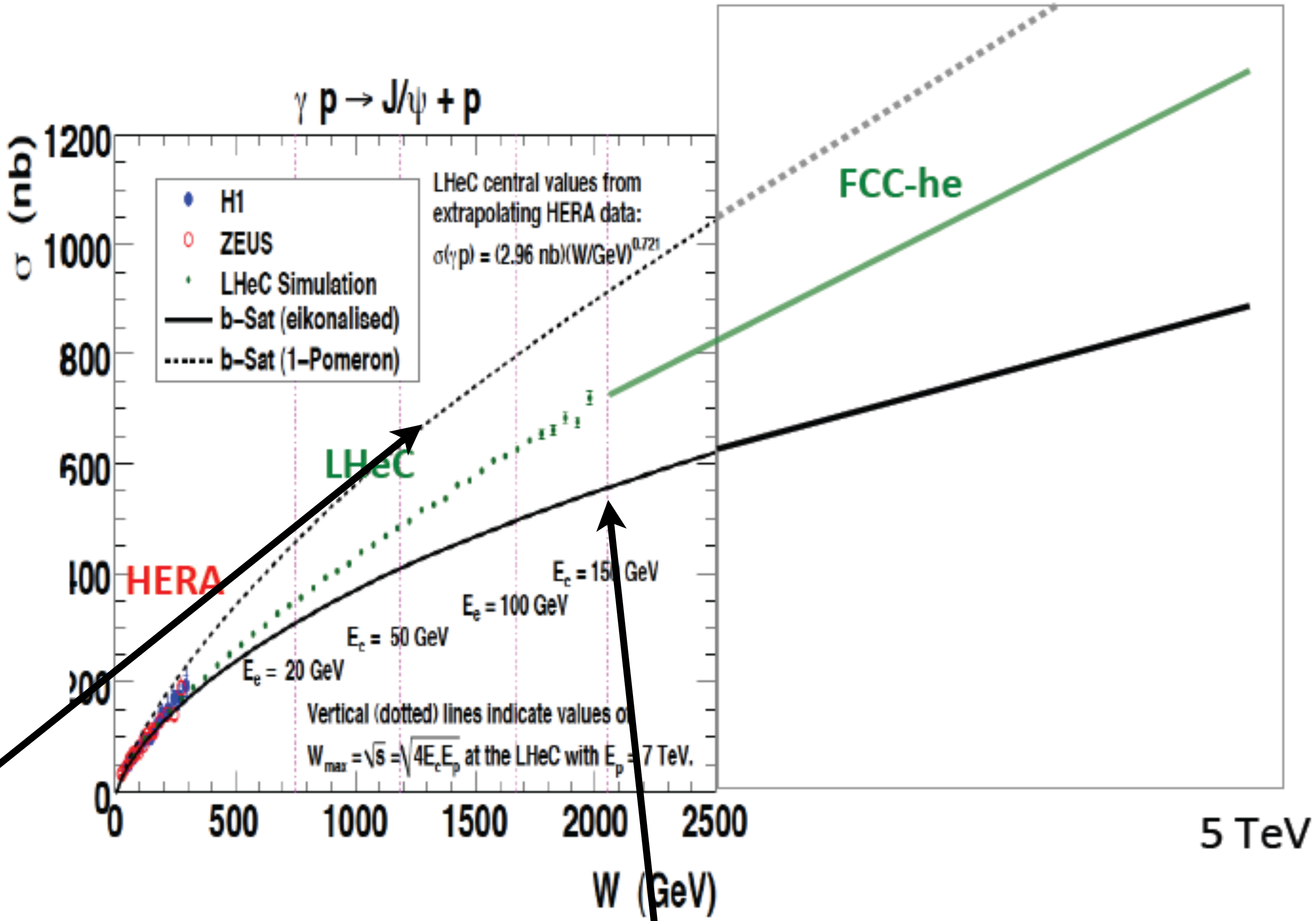


Albacete, 1507.07120

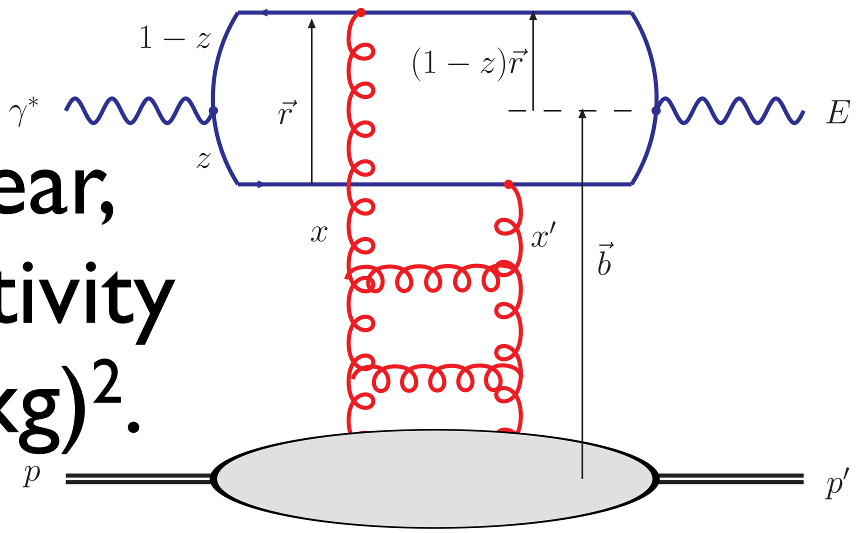
- F_2 and F_L at the FCC will provide a decisive test of small-x QCD (DGLAP cannot accommodate both if saturation is included), FCC reaching nearly $x=10^{-7}$ in DIS - much beyond HERA and the LHeC.

Elastic VM production in ep (I):

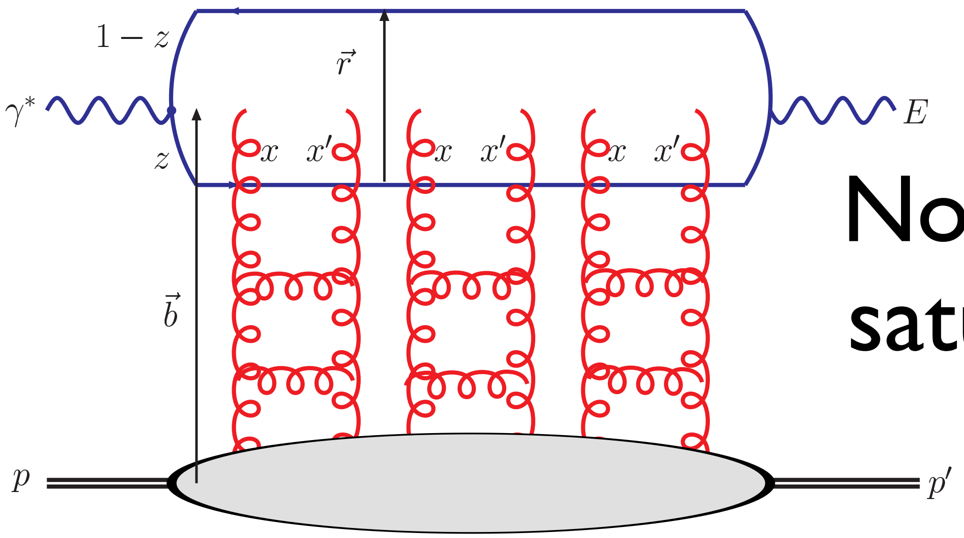




- Elastic J/ψ production may be a candidate to signal saturation effects at work.



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

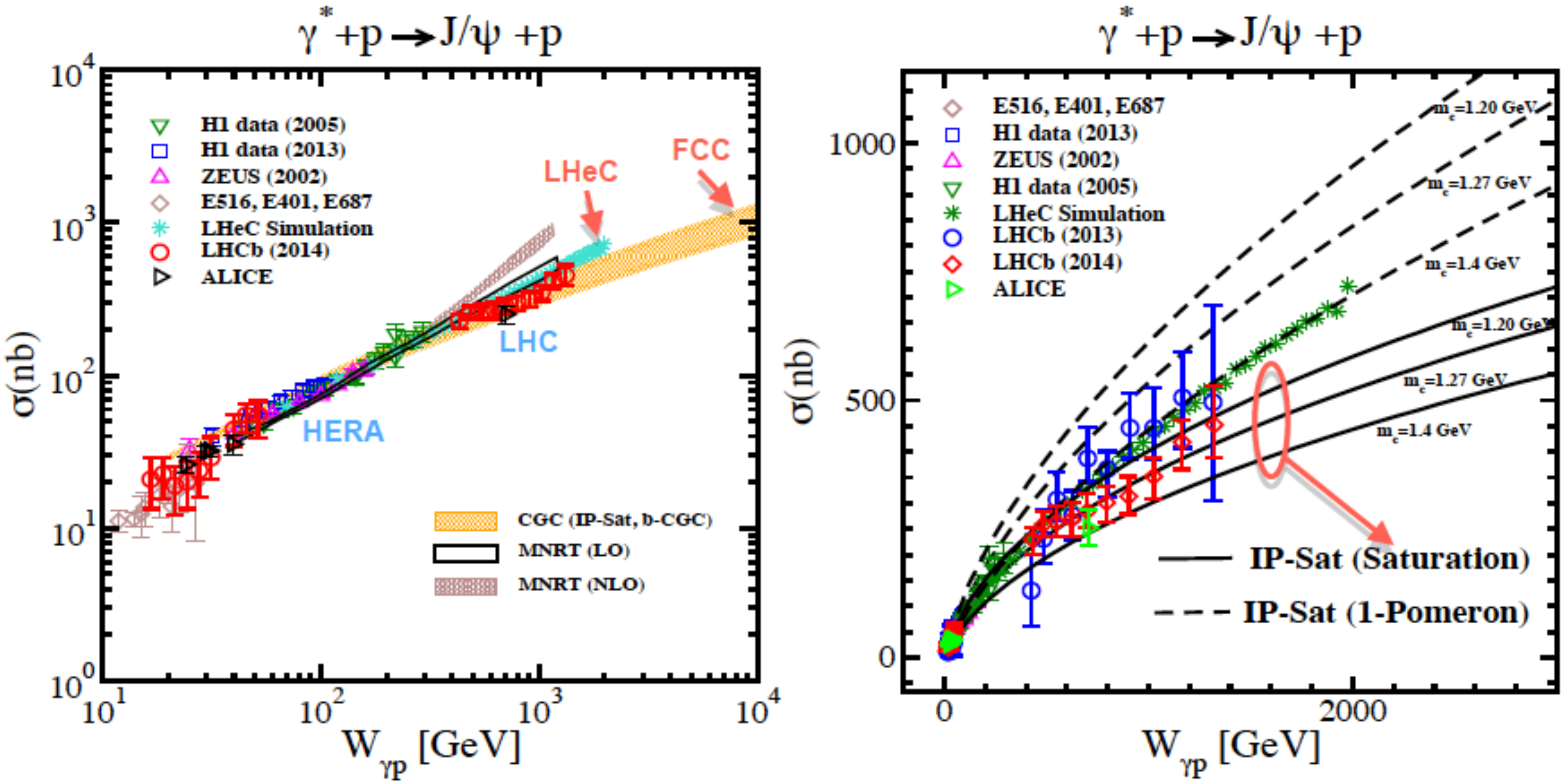


Non-linear, saturation.

Elastic VM production in ep (I):

- UPCs are an alternative, though less precise.

Armesto and Rezaeian, arXiv:1402.4831

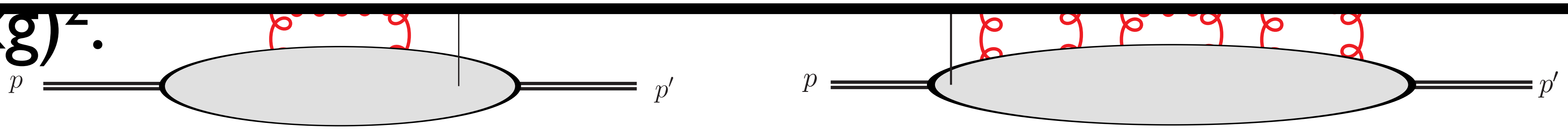


eV

r,

n.

to $(xg)^2$.



Elastic VM production in ep (I):

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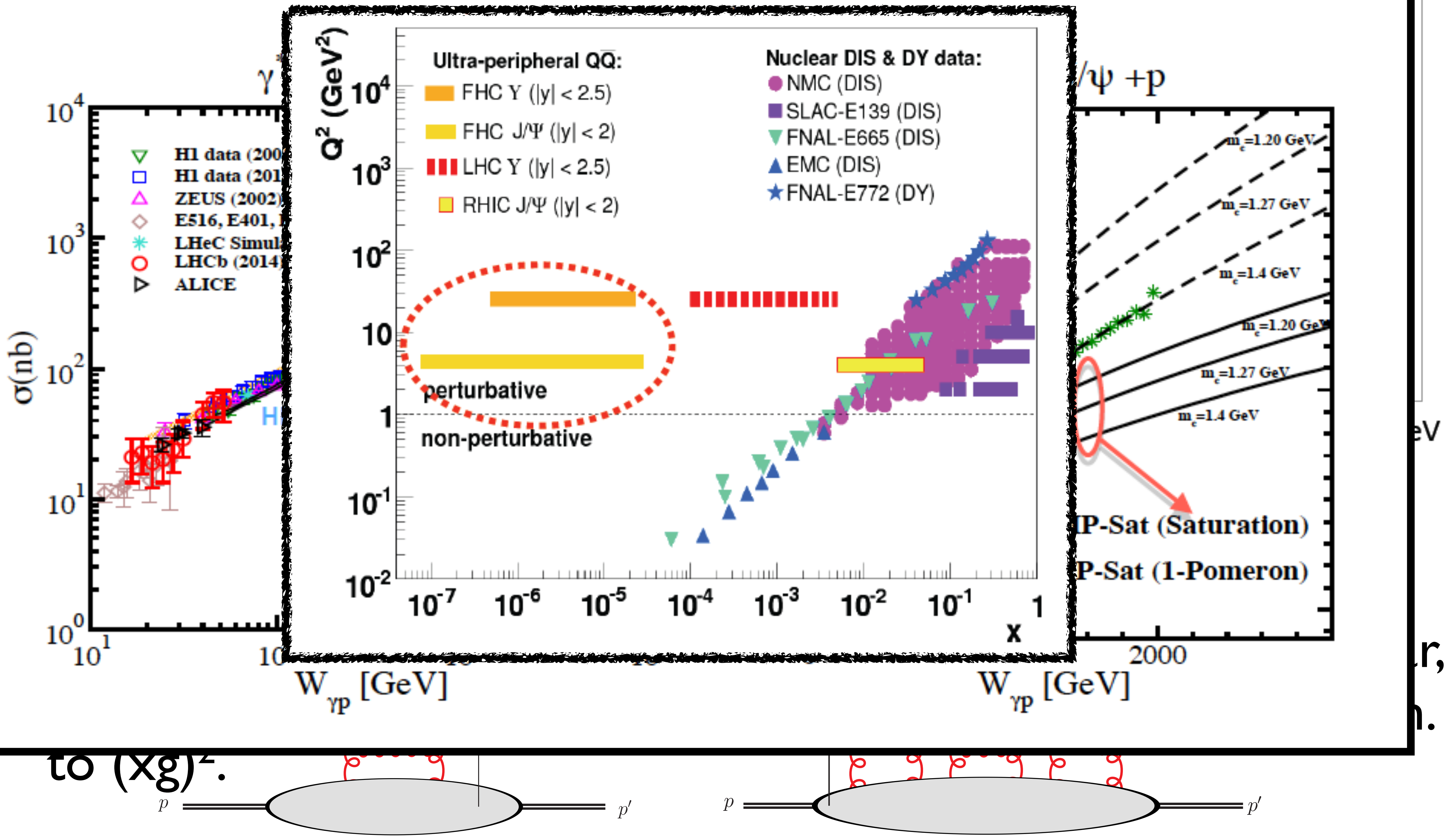
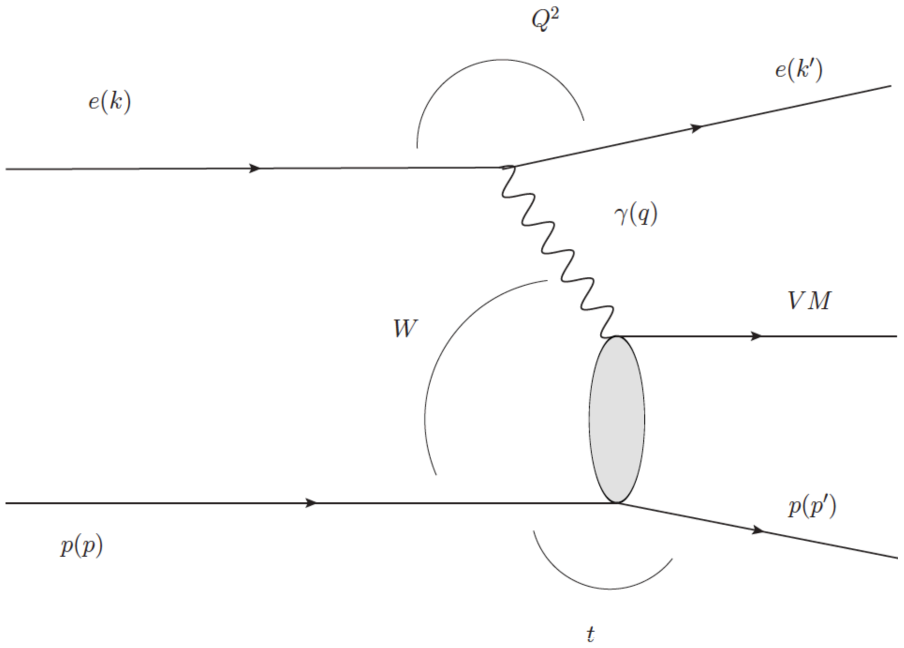
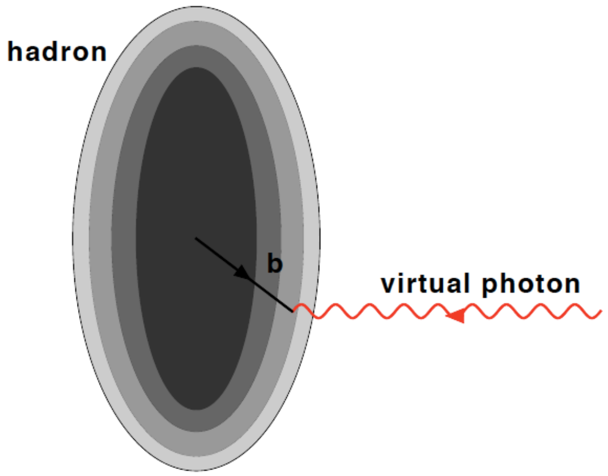
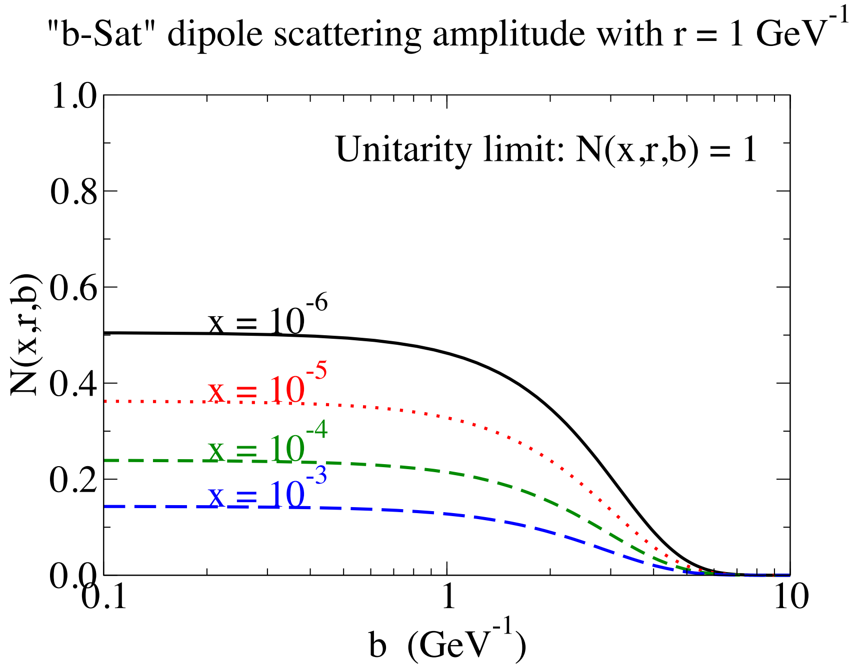


to $(xg)^2$.

Elastic VM production in ep (II):

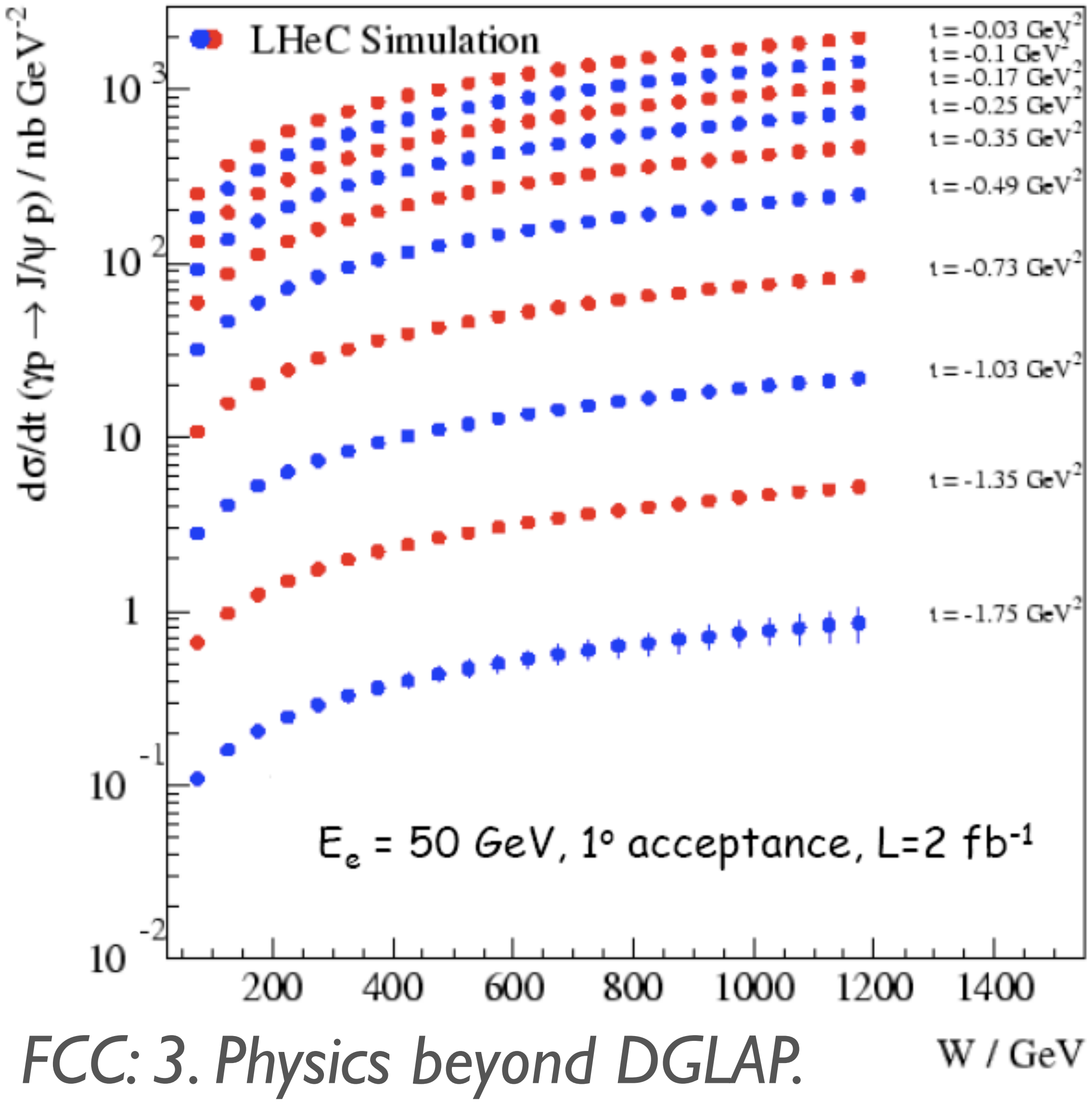




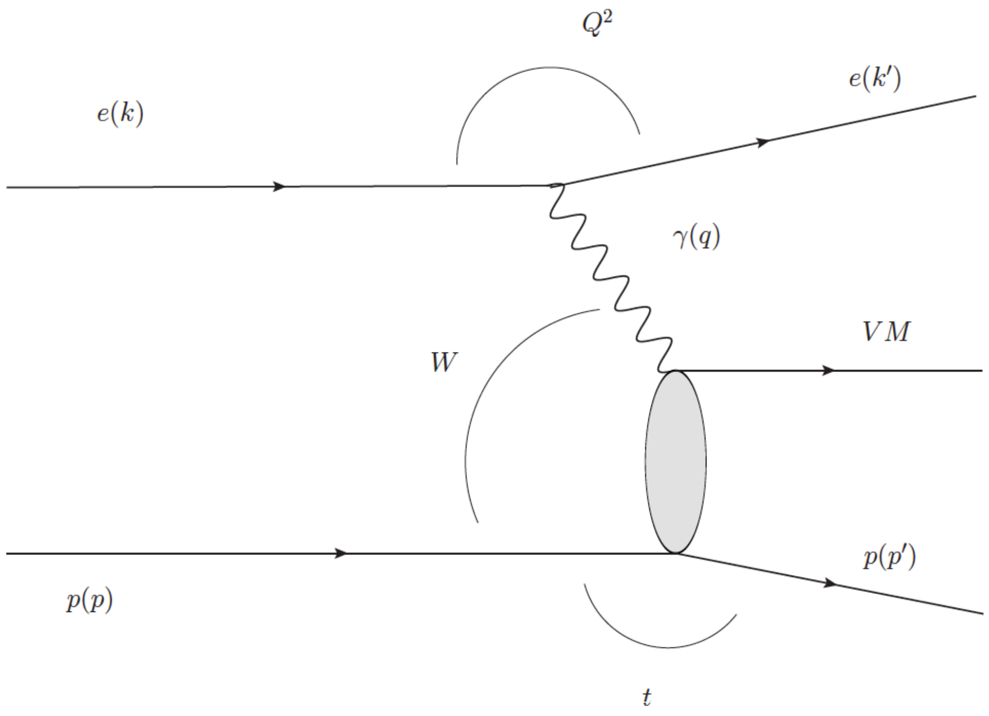


- t-differential measurements give a transverse mapping of the glue in the hadron/nucleus (gluon GPD; quark GPDs accesible through DVCS).

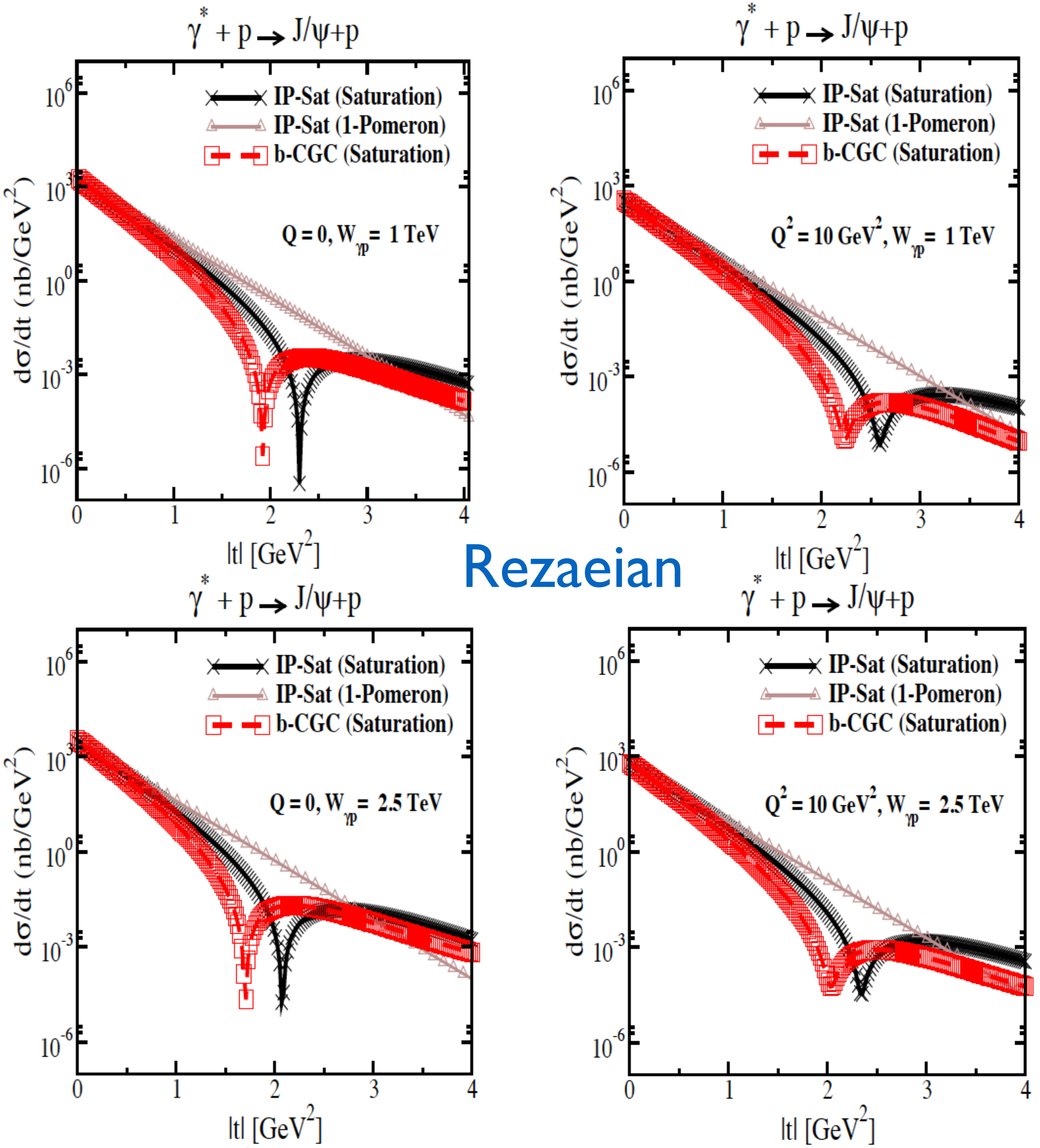
- Large acceptance, up to |t|=2 GeV^2, achievable at the FCC-eh.



Elastic VM production in ep (III):

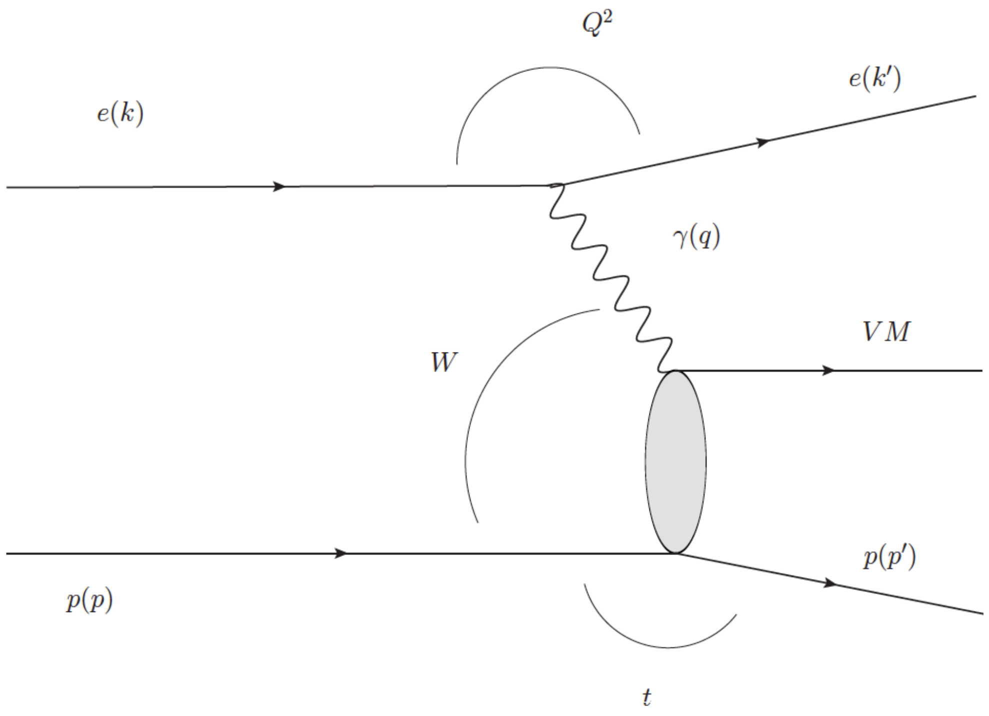


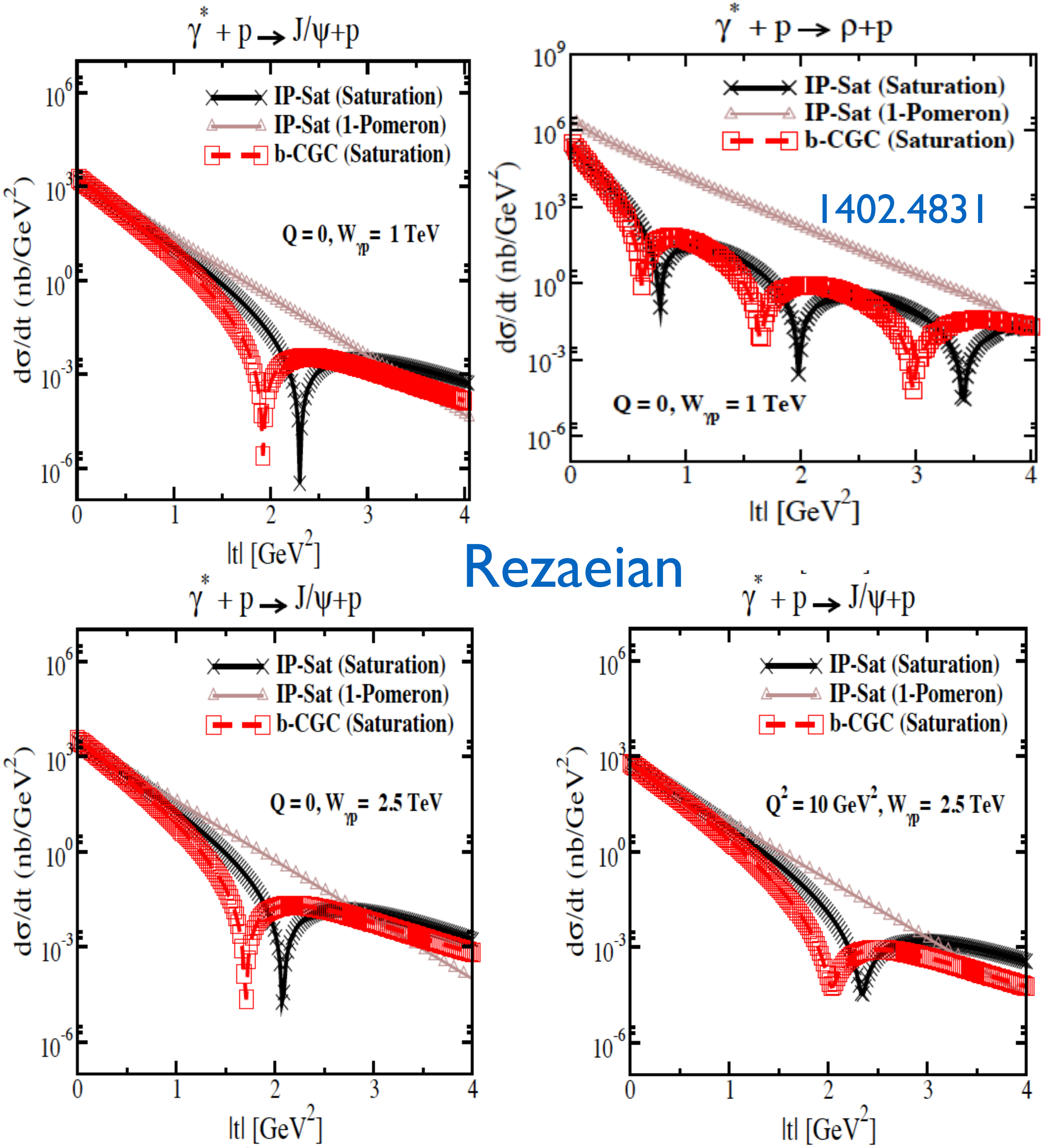
- Position of the dip and its evolution determined by the transverse structure of proton/nuclei; its shrinking is natural in non-linear evolution towards the black disk (unitarity) limit.



Rezaeian

Elastic VM production in ep (III):





1402.4831

Rezaeian

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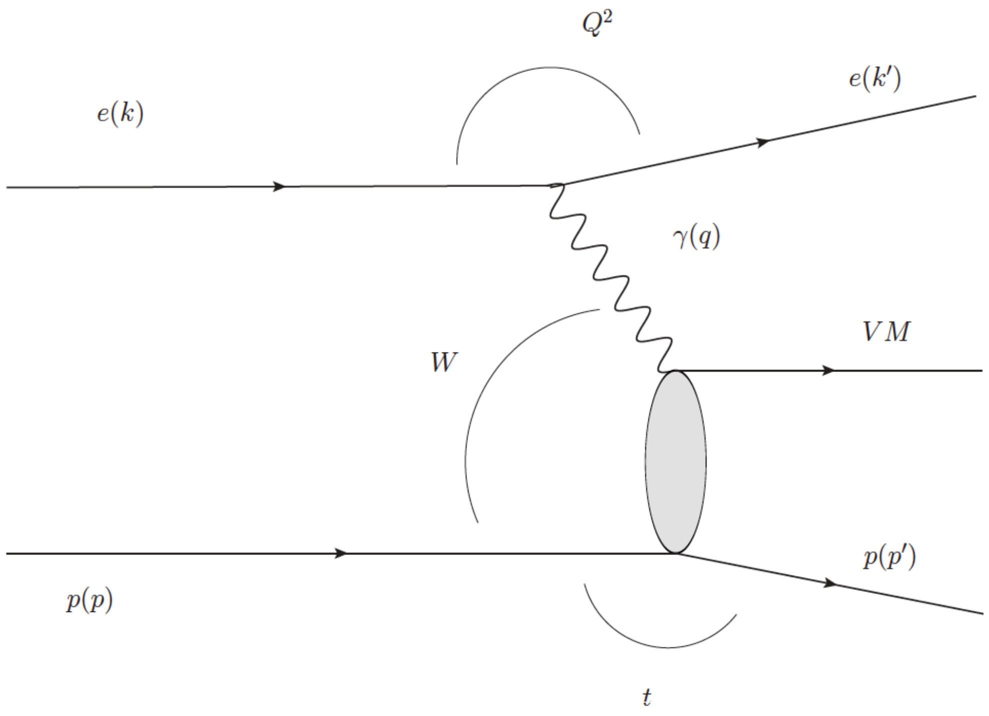
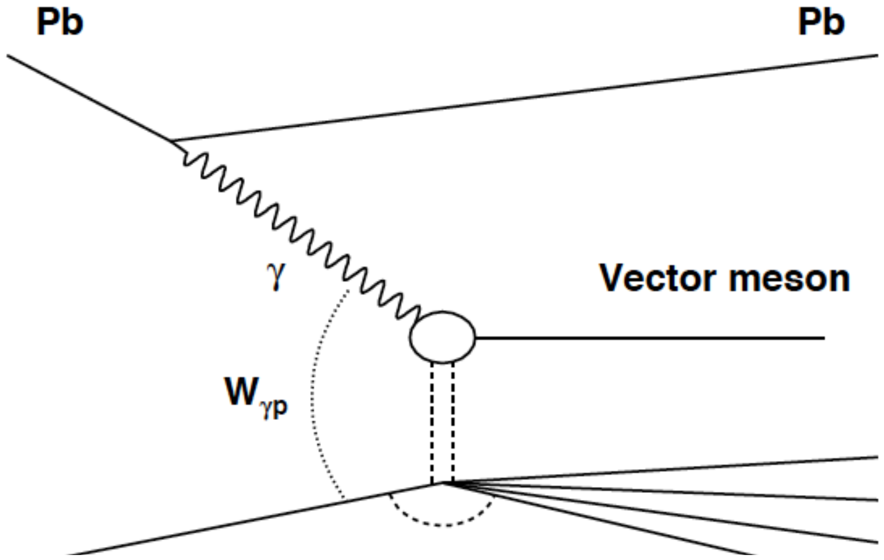
Elastic VM production in ep (III):

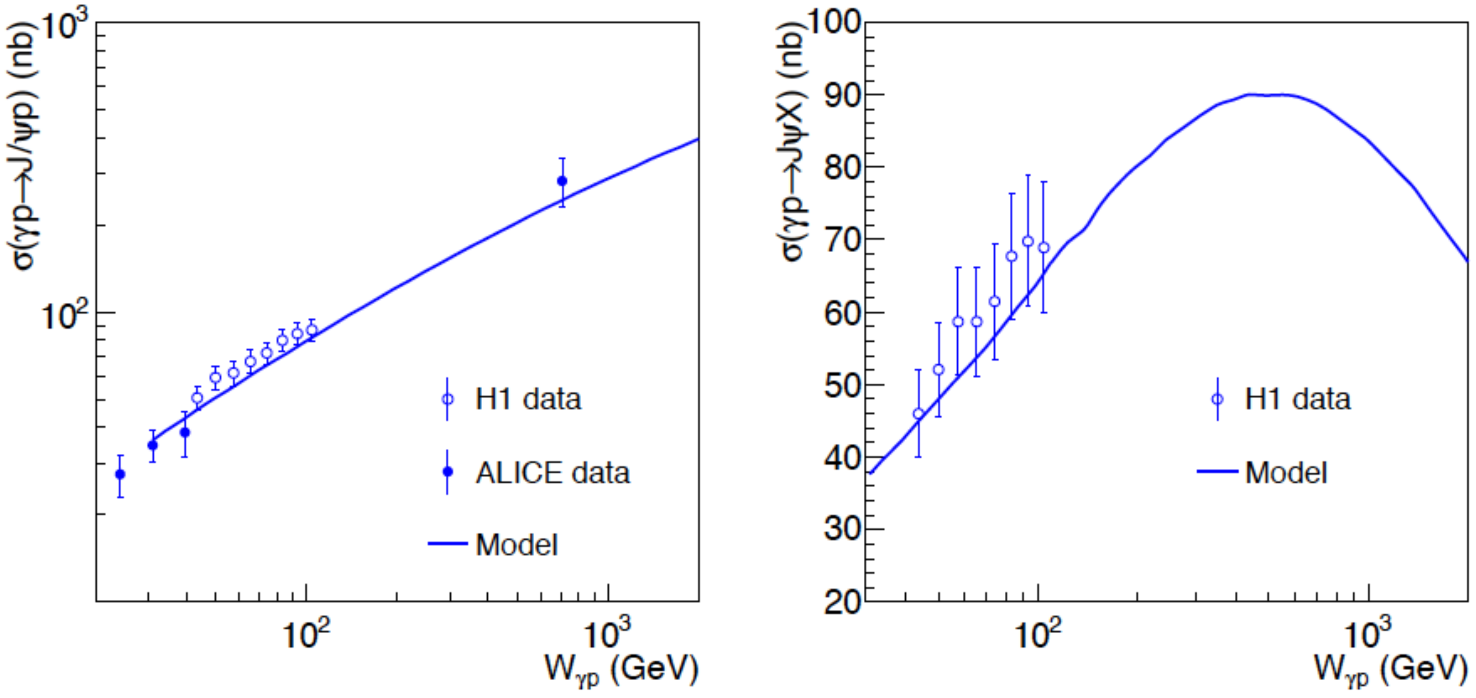


- Position of the dip and its evolution determined by the transverse structure of proton/nuclei; its shrinking is natural in non-linear evolution towards the black disk (unitarity) limit.

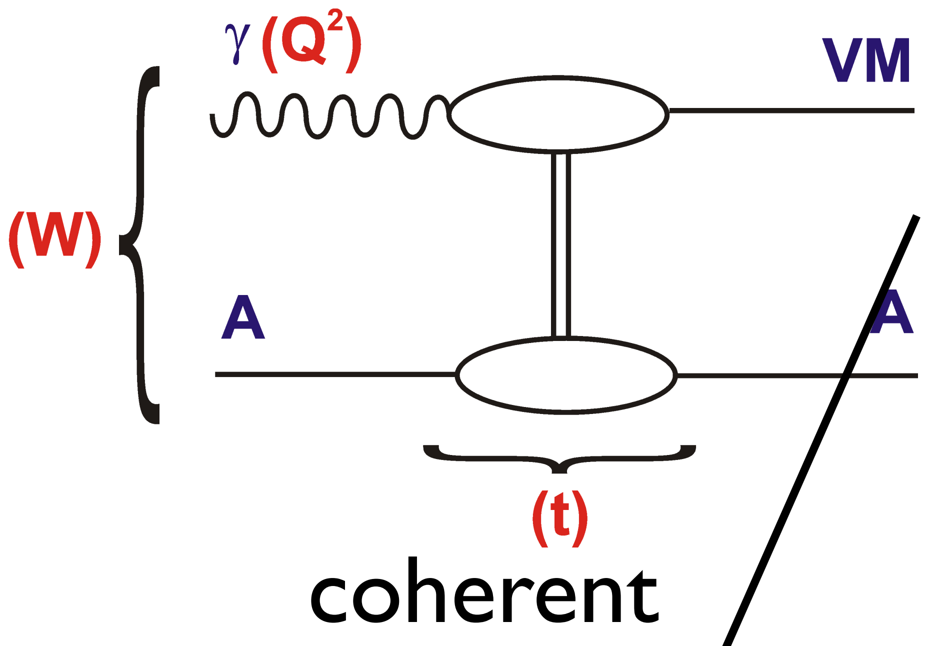
- For incoherent diffraction, sensitivity to the proton transverse structure: homogeneous versus lumpy.



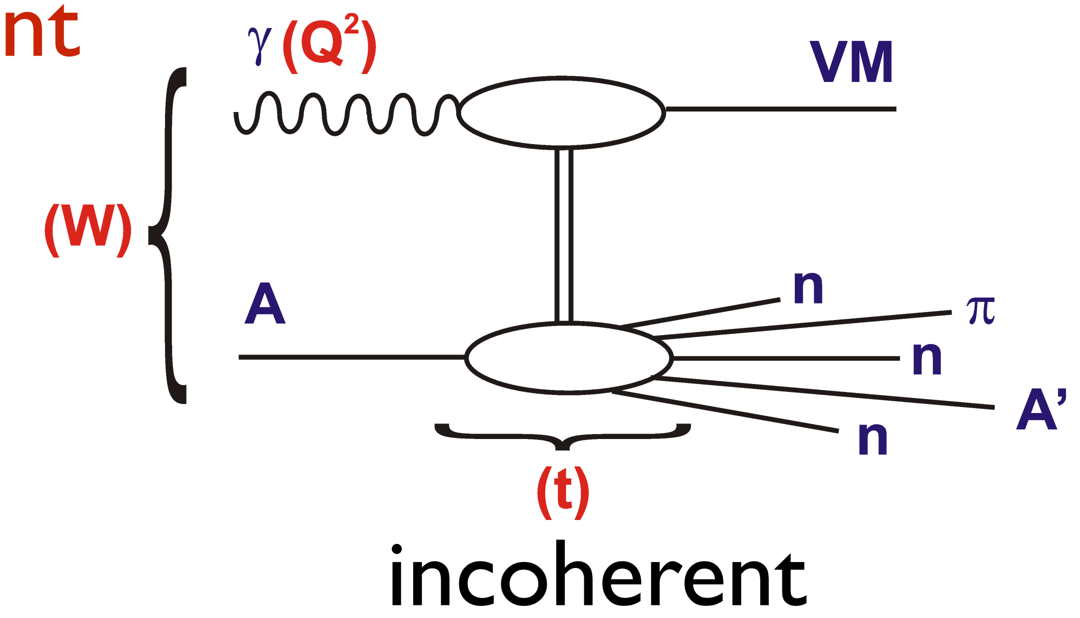
1608.07559

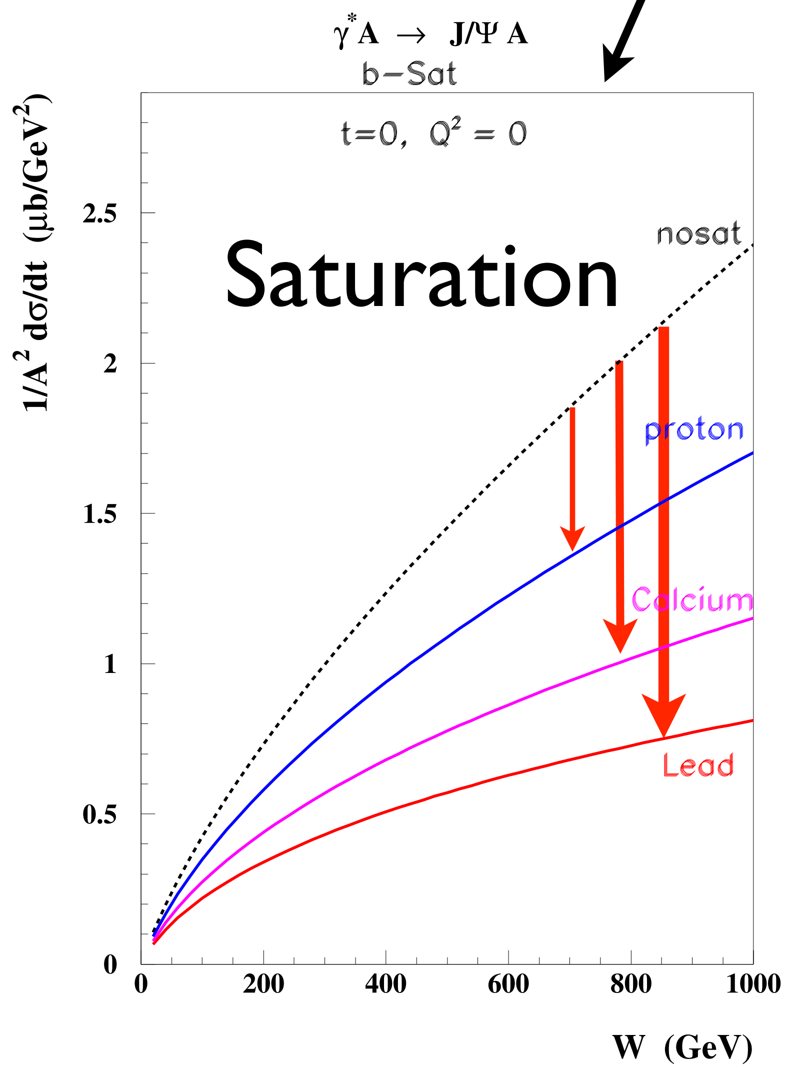


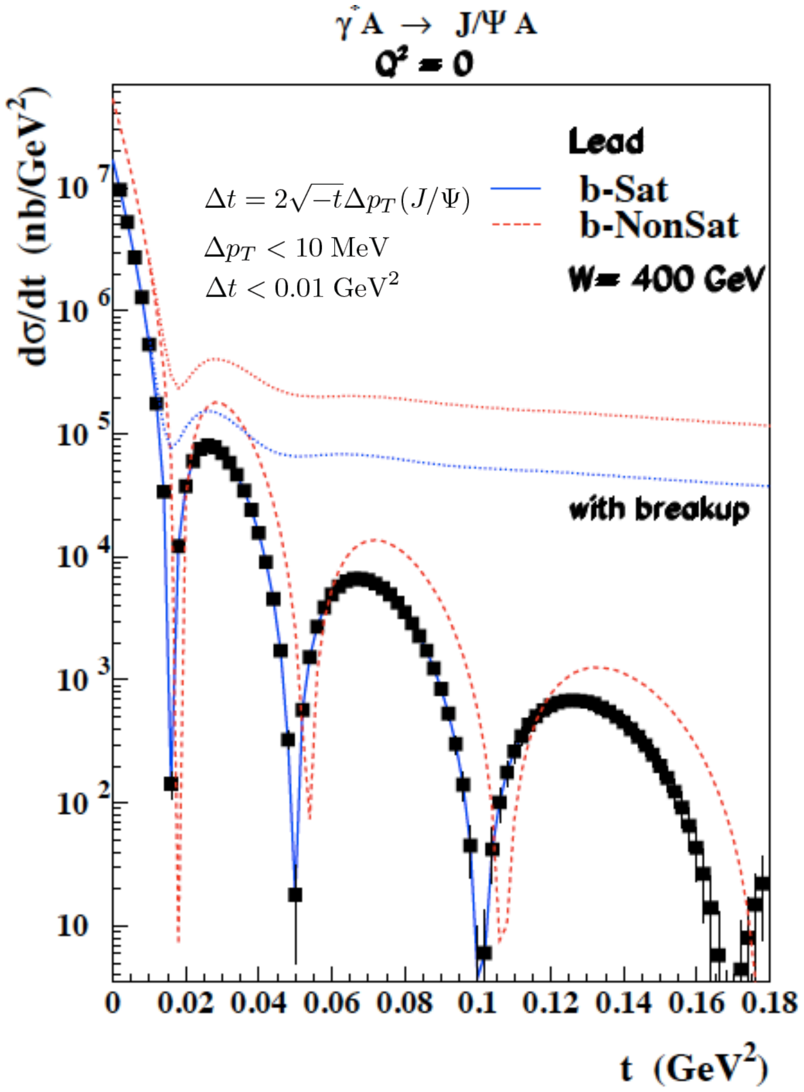
Elastic VM production in eA:



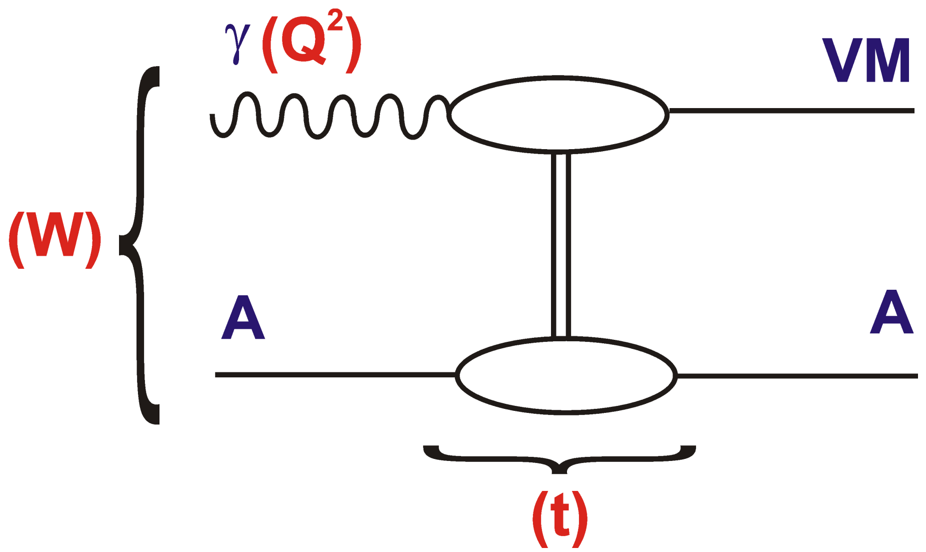
- For the coherent case, predictions available.
- Challenging experimental problem.







Elastic VM production in eA:



coherent

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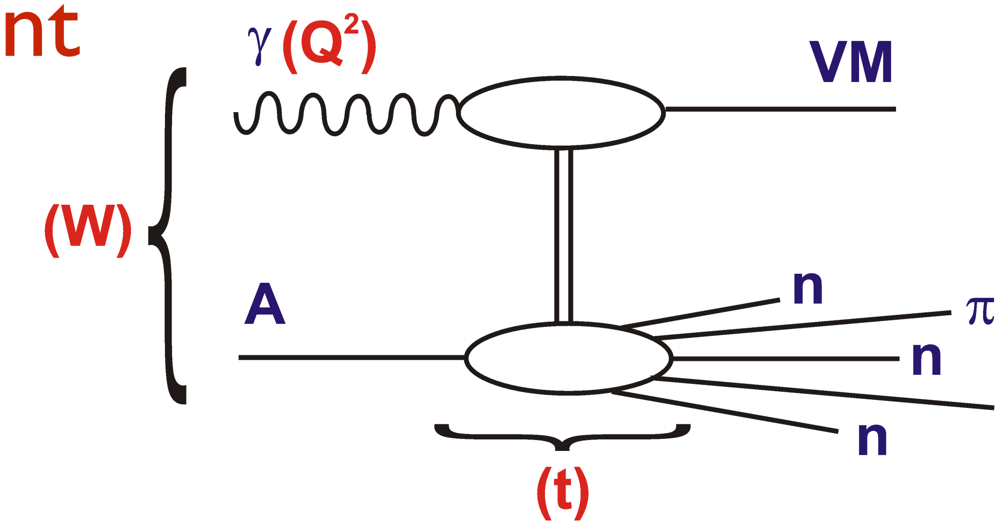
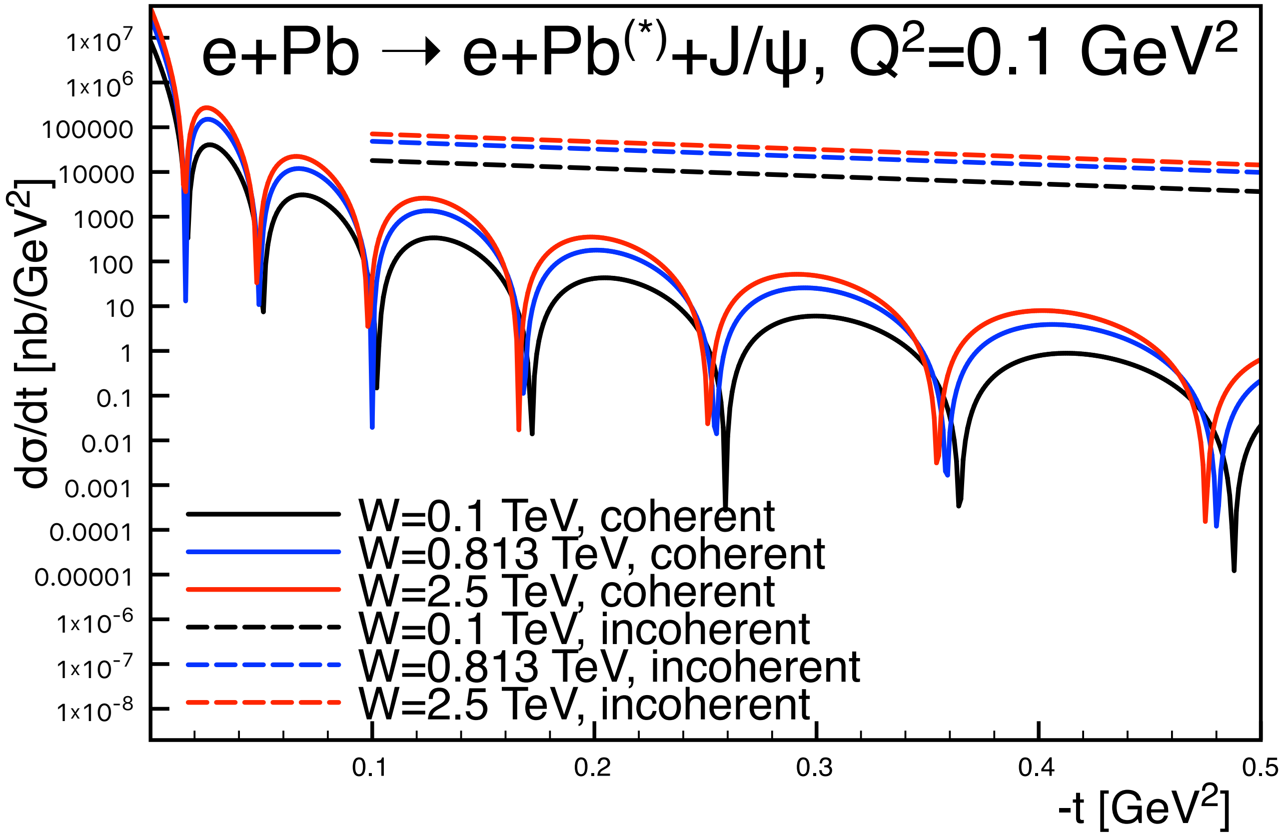
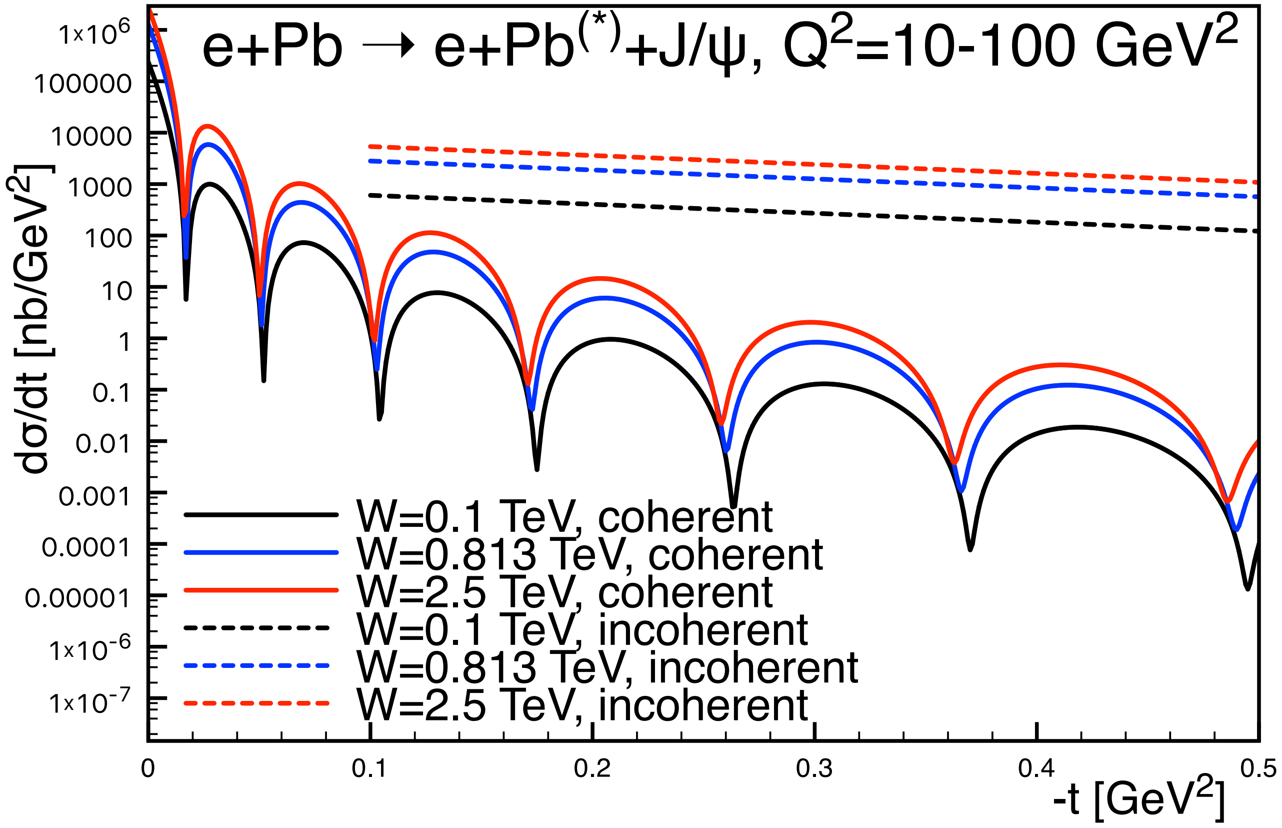
- Challenging experimental problem.



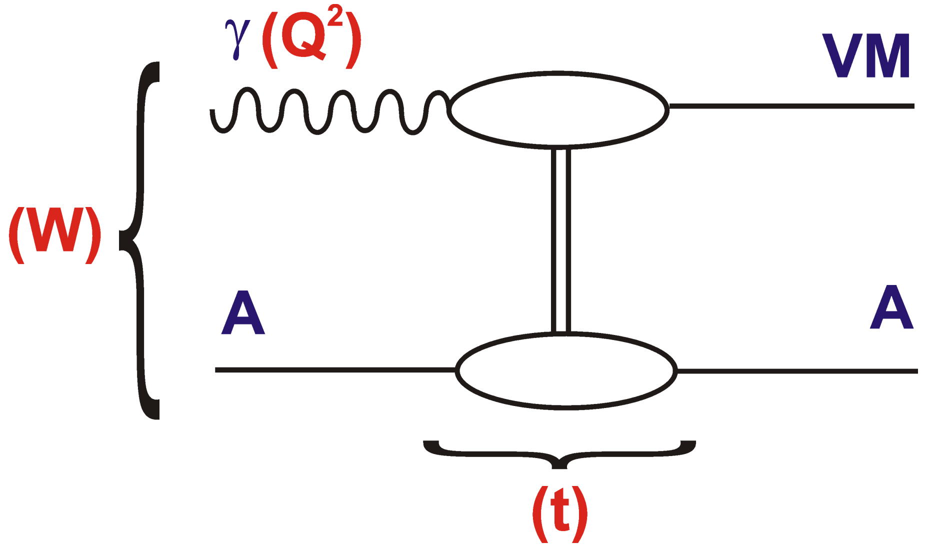
incoherent





Mantysaari, 1011.1988, IPsat

Elastic VM production in eA:



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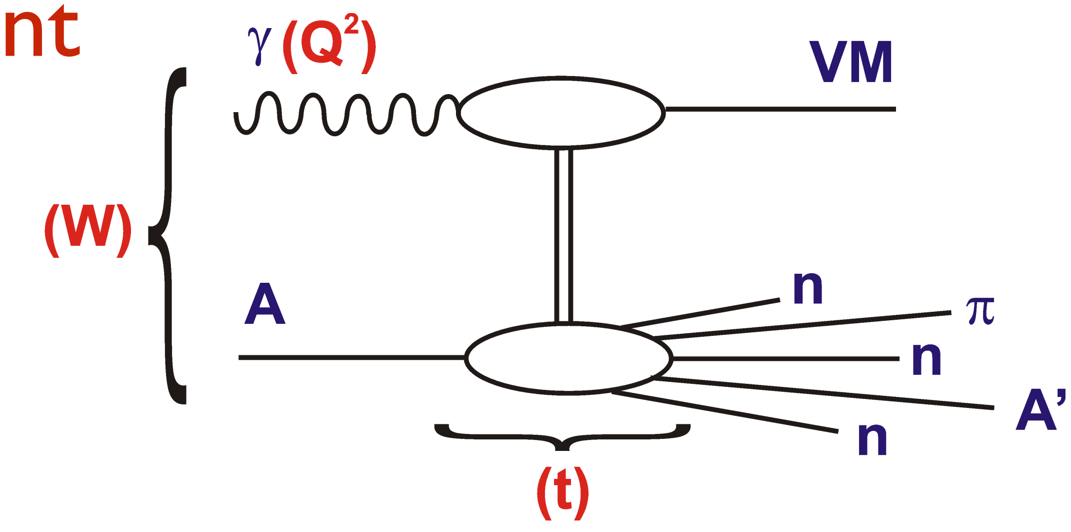

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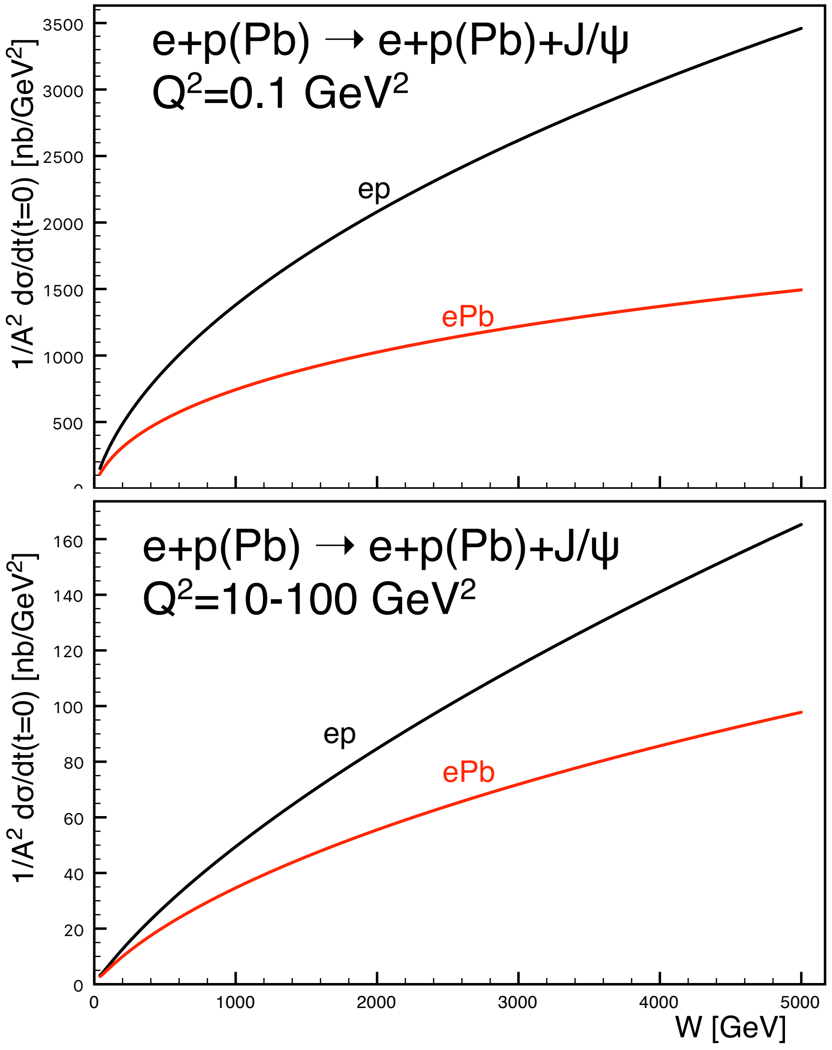
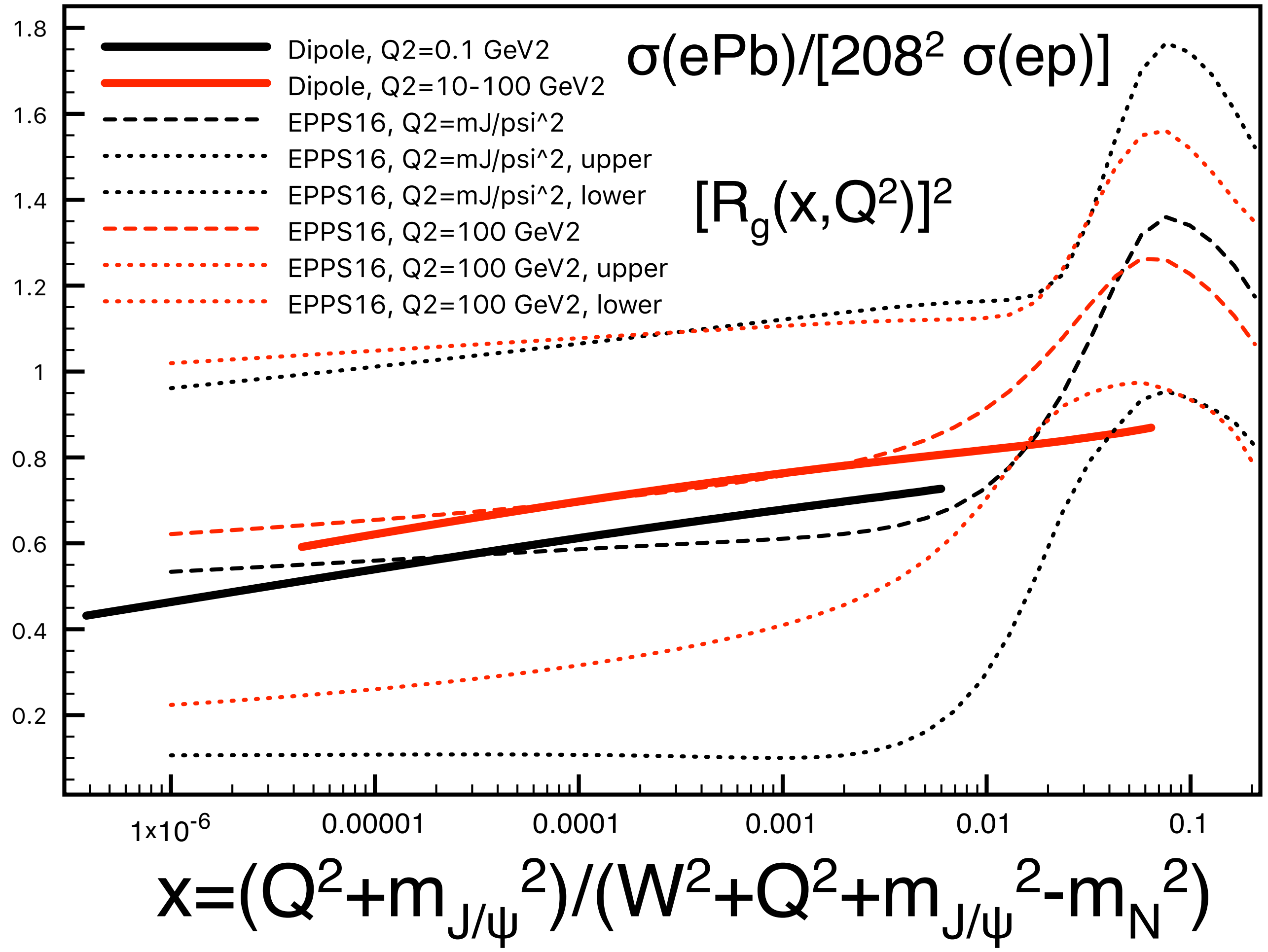
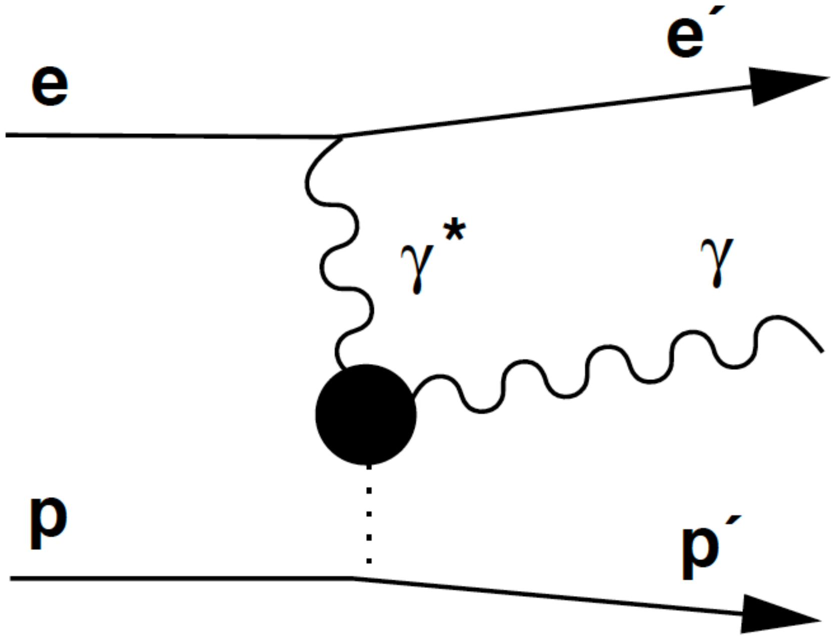




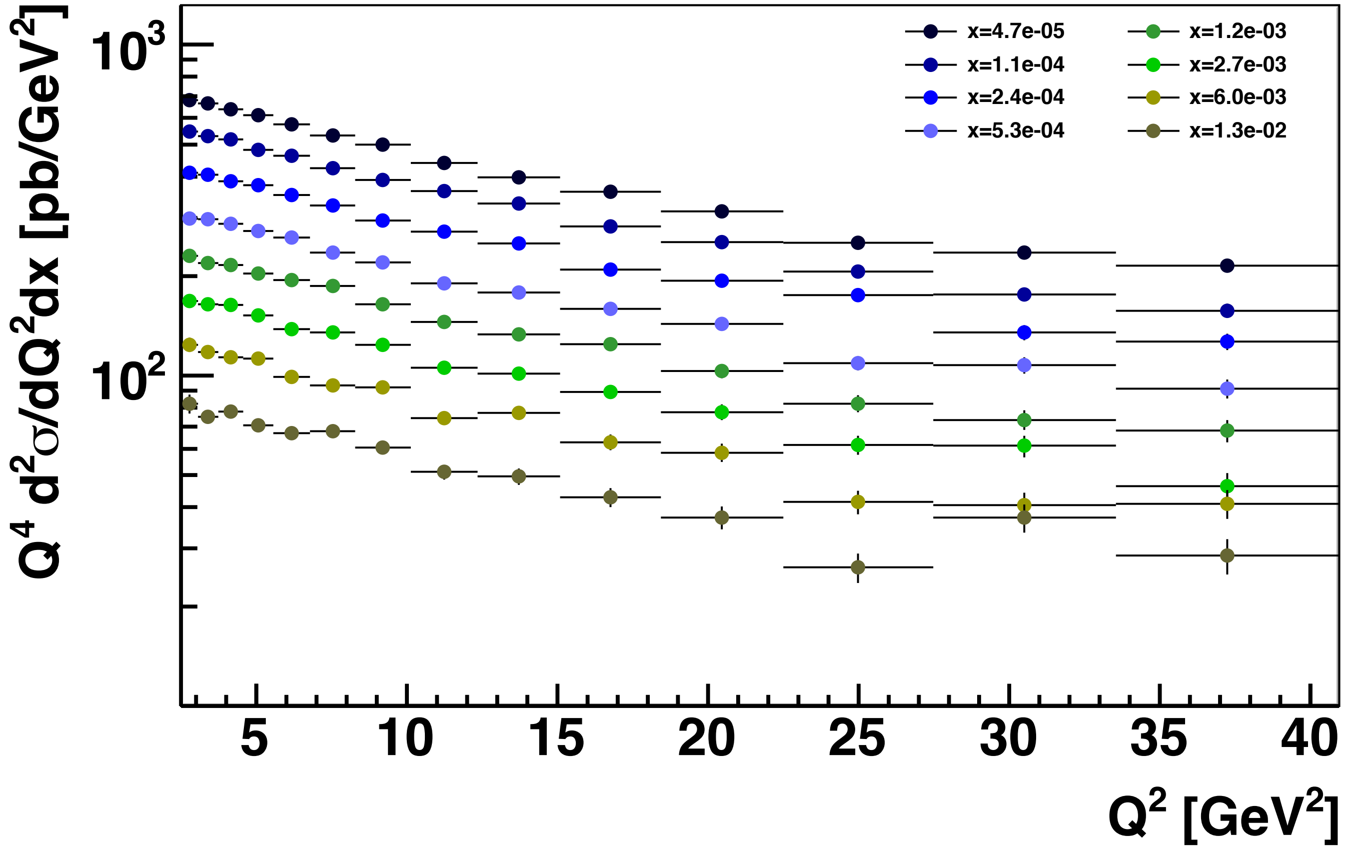
Mantysaari, Paukkunen

DVCS:

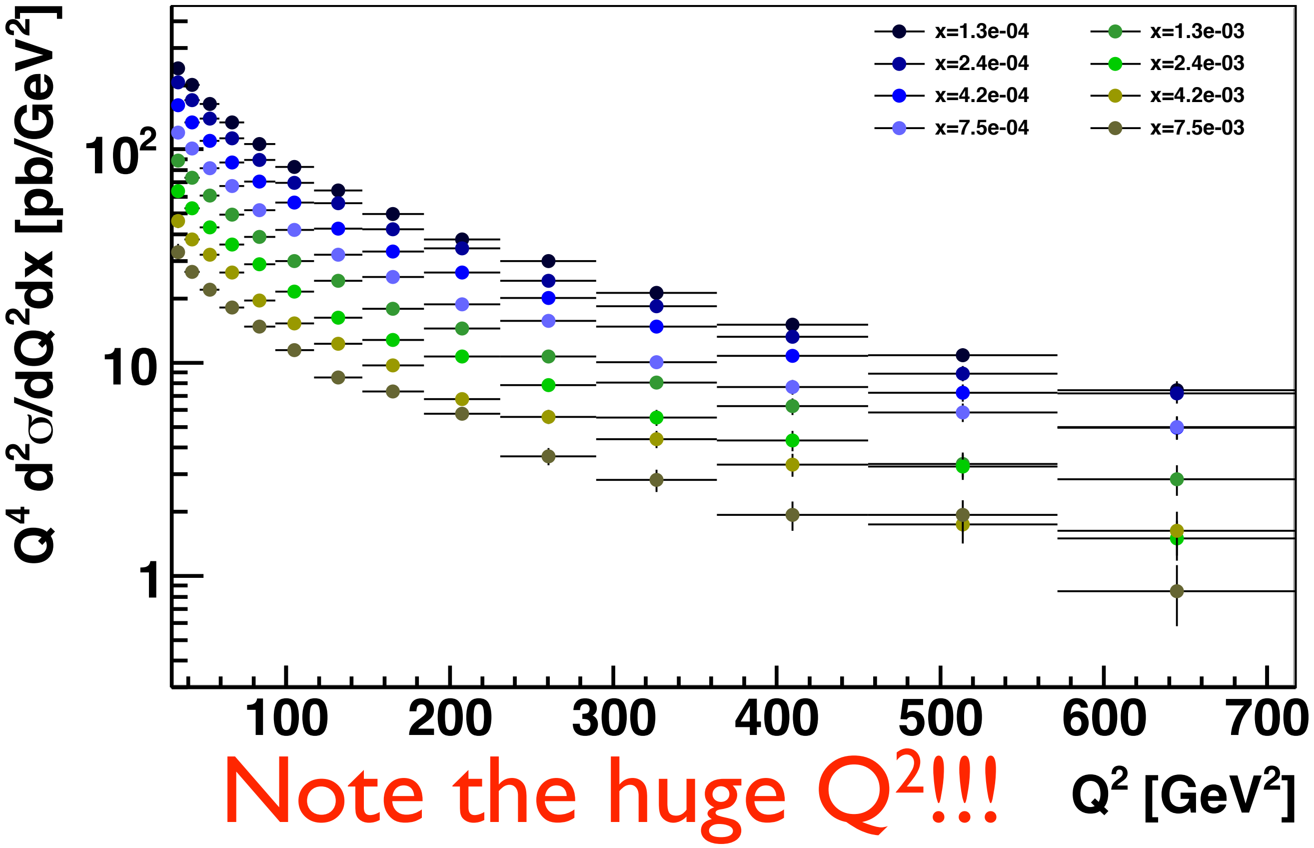
- Exclusive processes give information about GPDs, whose Fourier transform gives a tranverse scan of the hadron: DVCS sensitive to the singlet.
- Sensitive to dynamics e.g. non-linear effects.



DVCS, E_e=50 GeV, 1°, $p_T^{\gamma,cut}$=2 GeV, 1 fb^{-1}



DVCS, E_e=50 GeV, 10°, $p_T^{\gamma,cut}$=5 GeV, 100 fb^{-1}



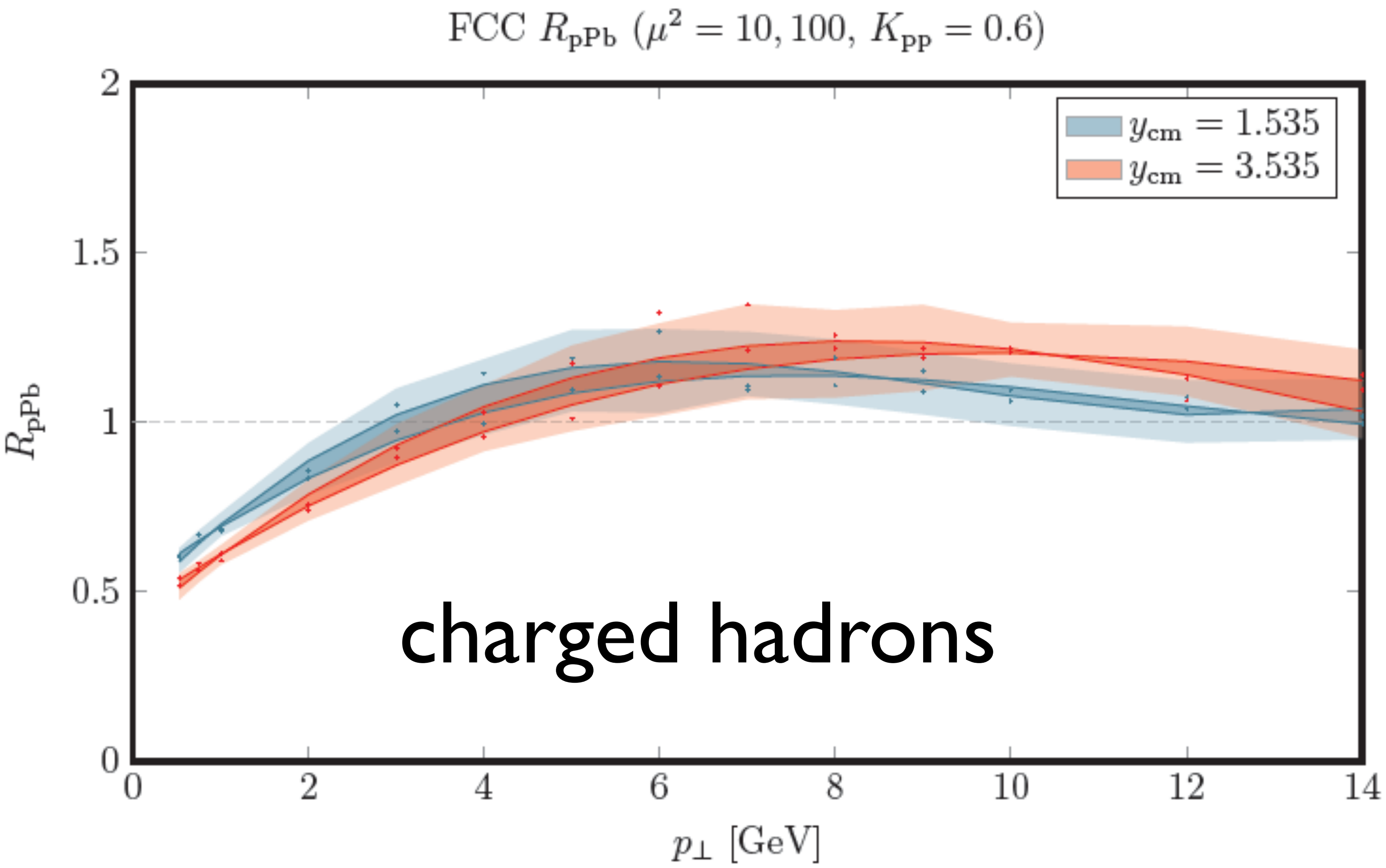
Note the huge Q^2!!!

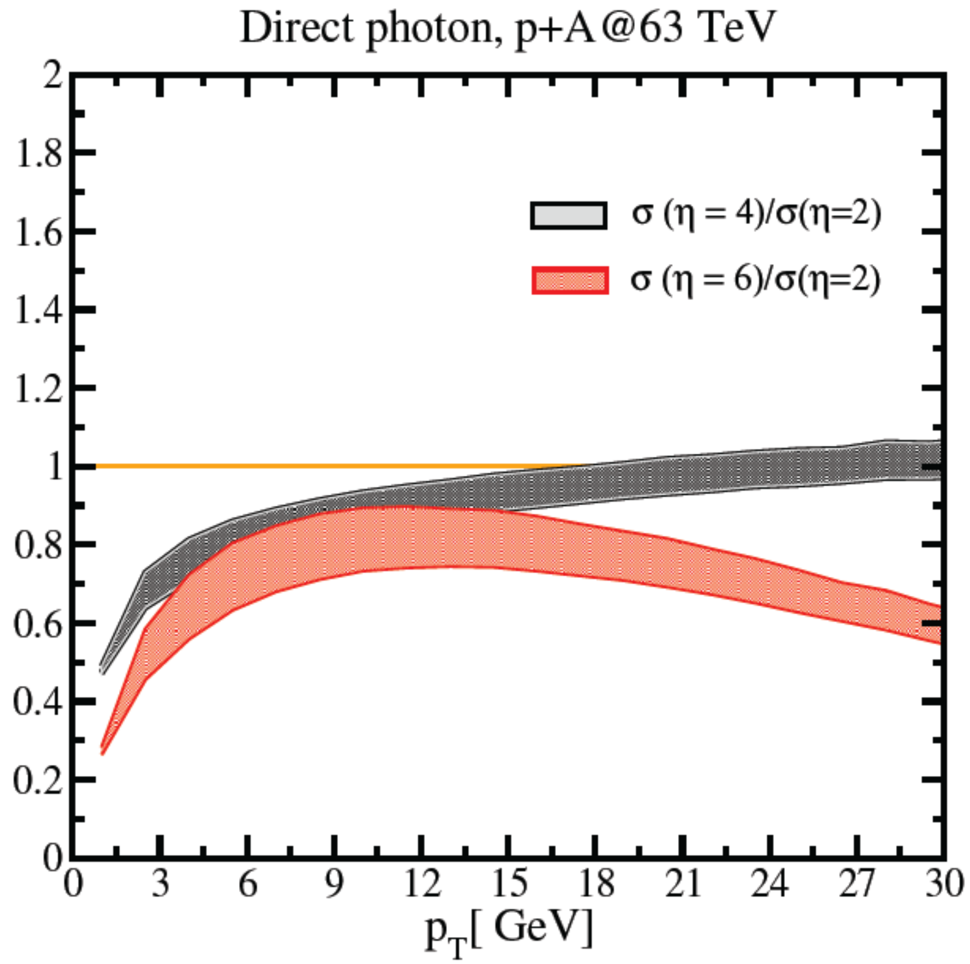
Single particle suppression in pA:

- Single particle suppression increasing with rapidity was proposed as a signal of saturation.

$$\boxed{R_{\mathrm{pA}} = \frac{\text{yield in eA/pA}}{\text{scaled yield in ep/pp}}}$$

- To be contrasted with an extraction of PDFs in collinear factorisation: tensions?





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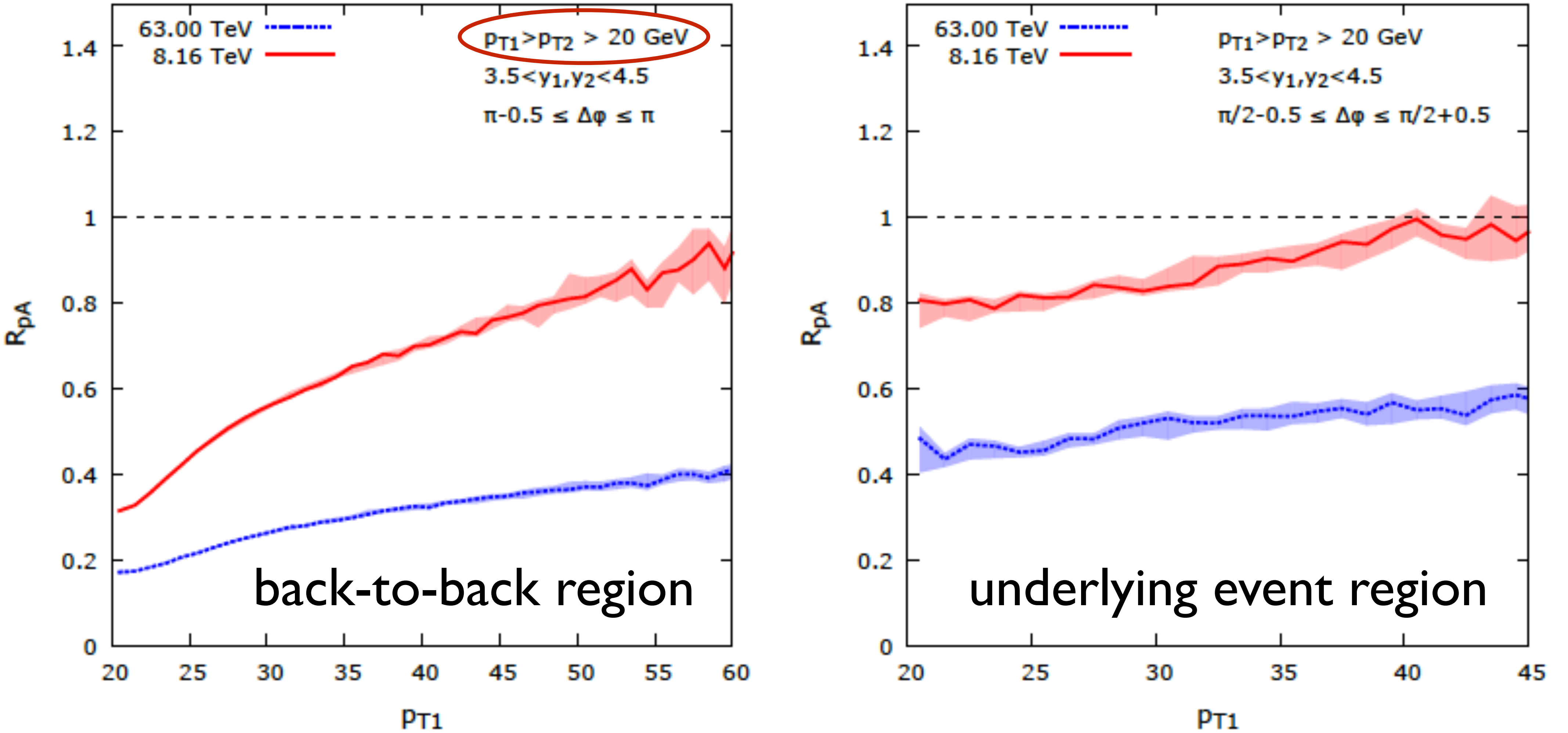
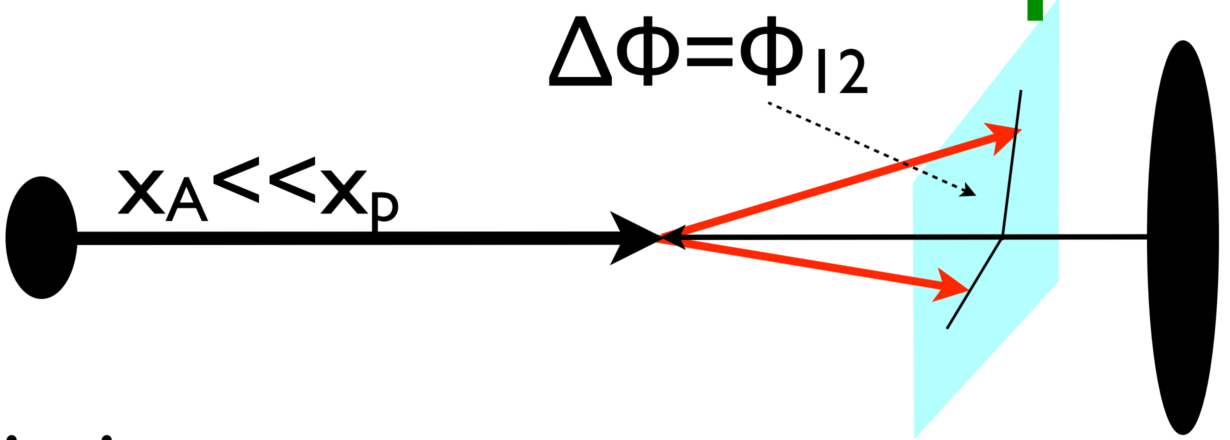


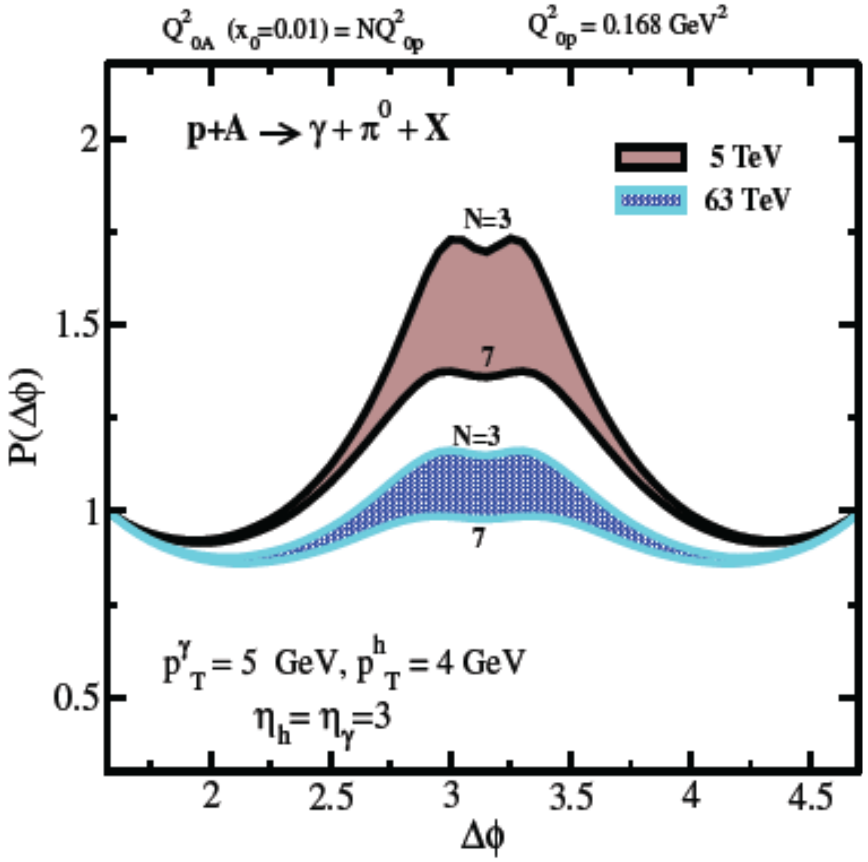
dijet yield modification pPb/pp, anti-k_T, R=0.5

Azimuthal decorrelation in eA/pA:

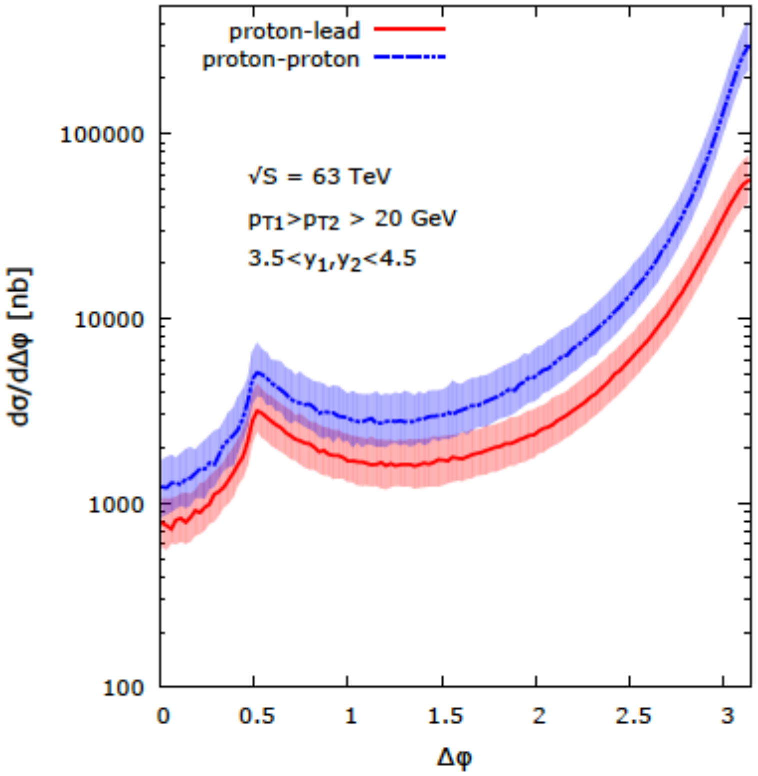
- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- To be studied far from kinematical limits.



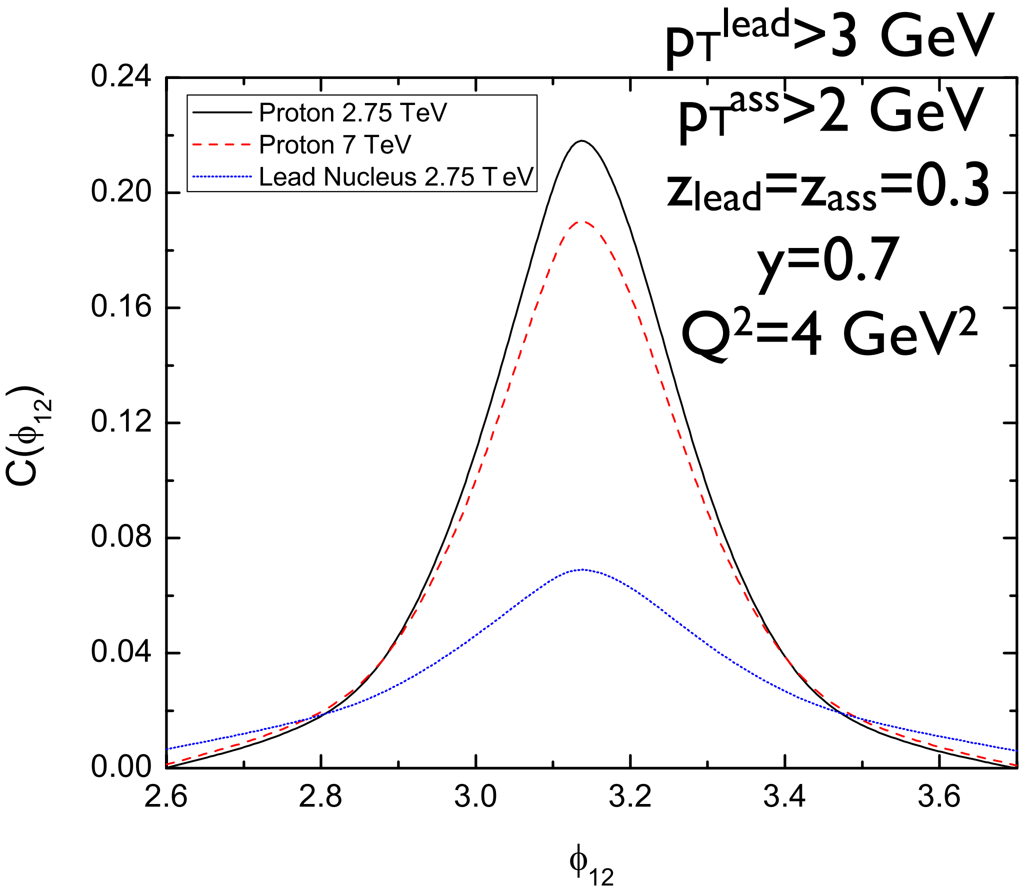
$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N\to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N\to h_1 h_2 + X}}{dz_{h1}\, dz_{h2}\, d\phi_{12}}$$



γ-π^0 in pPb



jet-jet in pPb



h-h in ePb

Azimuthal decorrelation in eA/pA:

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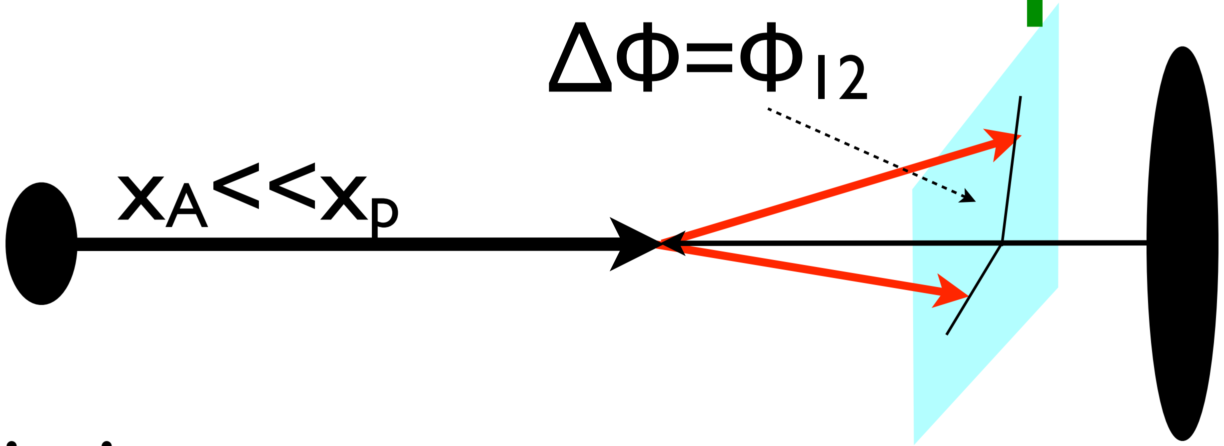
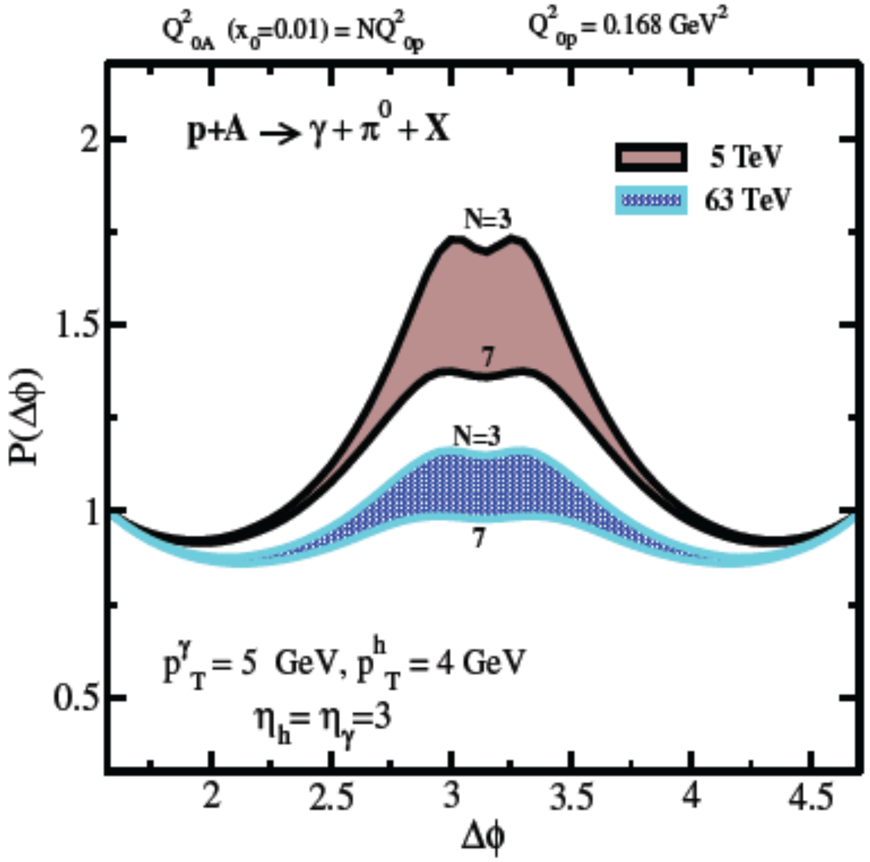
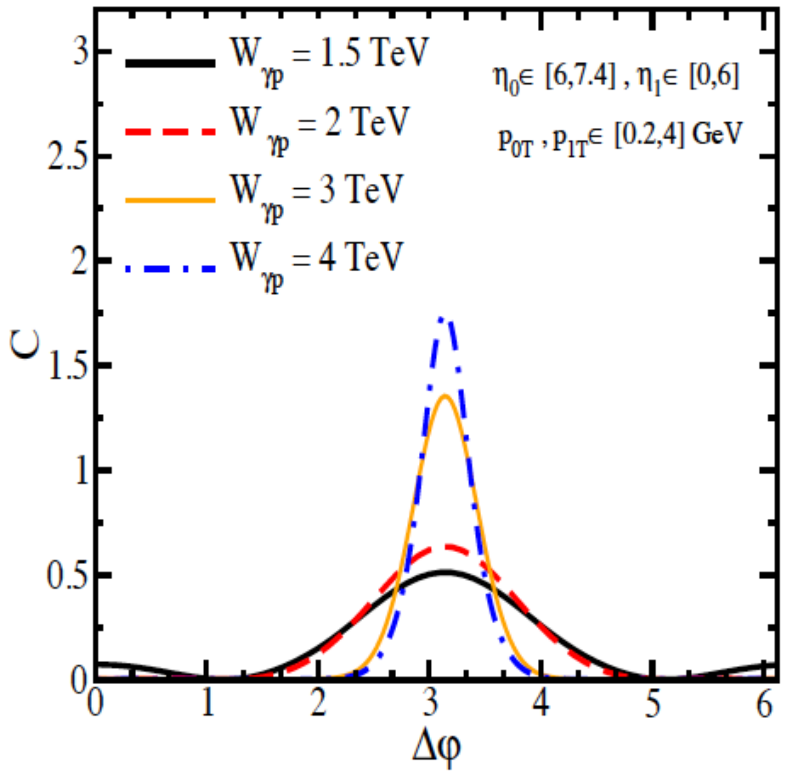


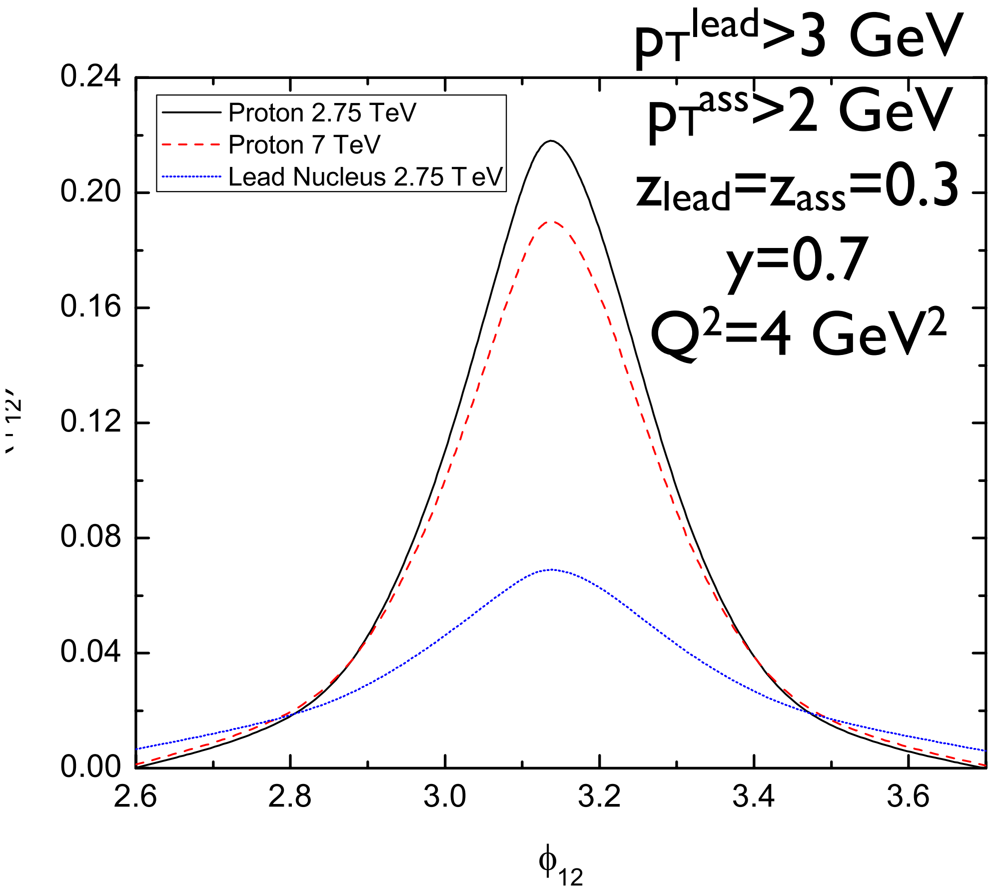
$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N\to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N\to h_1 h_2+X}}{dz_{h1}dz_{h2}d\phi_{12}}$$



γ-π^0 in pPb



central-forward exclusive dijets in ep/eA, 1511.07452



p_T^{lead}>3 GeV
p_T^{ass}>2 GeV
$z_{lead}=z_{ass}$=0.3
y=0.7
Q^2=4 GeV^2

h-h in ePb

Summary (I):

- In ep/eA/pA collisions at the FCC:

  ➜ High-precision tests of collinear factorization(s) and determination of PDFs.

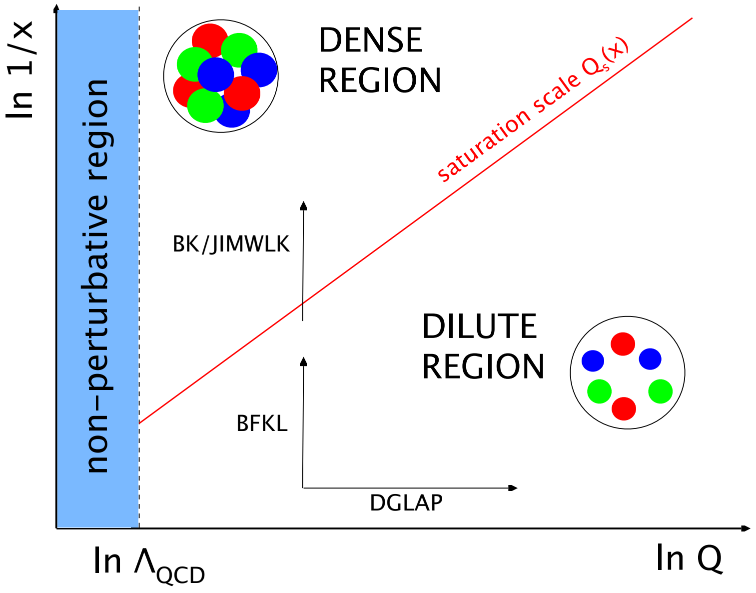
  ➜ Unprecedented access to small x in p and A (extension of 4-5 o.f.m.) in the perturbative Q^2 region.

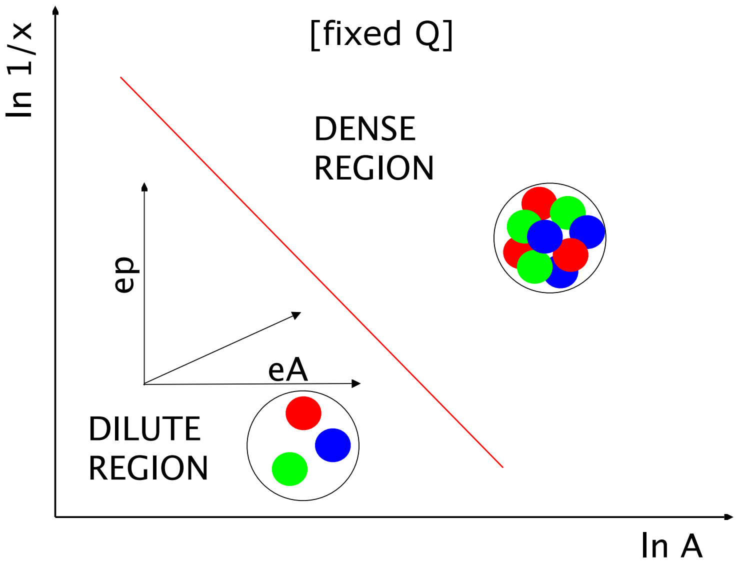
  ➜ Novel sensitivity to physics beyond standard pQCD.

  ➜ Transverse scan of the hadron/nucleus at small x; …

  Detectors should have large rapidity acceptance and, for pA, γ, h and jet ID.

- **Unique capabilities**, with strong implications for precision in pp/AA.
- The FCC will address the question of saturation/non-linear dynamics. **For that, e, p and A are crucial.**





Summary (II):

- **ep/eA and pp/pA are complementary:**
  ➜ DIS offers fully constrained kinematics and a cleaner theoretical and experimental environment.
  ➜ Hadron collisions extend the kinematic region and test factorisation.
- ***To be done***: we must
  ➜ Extend more LHeC studies to the FCC-eh (synergies with the EIC?).
  ➜ Consider the LHC findings and the HL-LHC possibilities.
  ➜ With emphasis on **those aspects that are exclusive of the FCC**: diffraction, GPDs, nPDFs, tensions in the standard collinear framework when non-linear dynamics appears,…, at very small x and perturbative Q^2.

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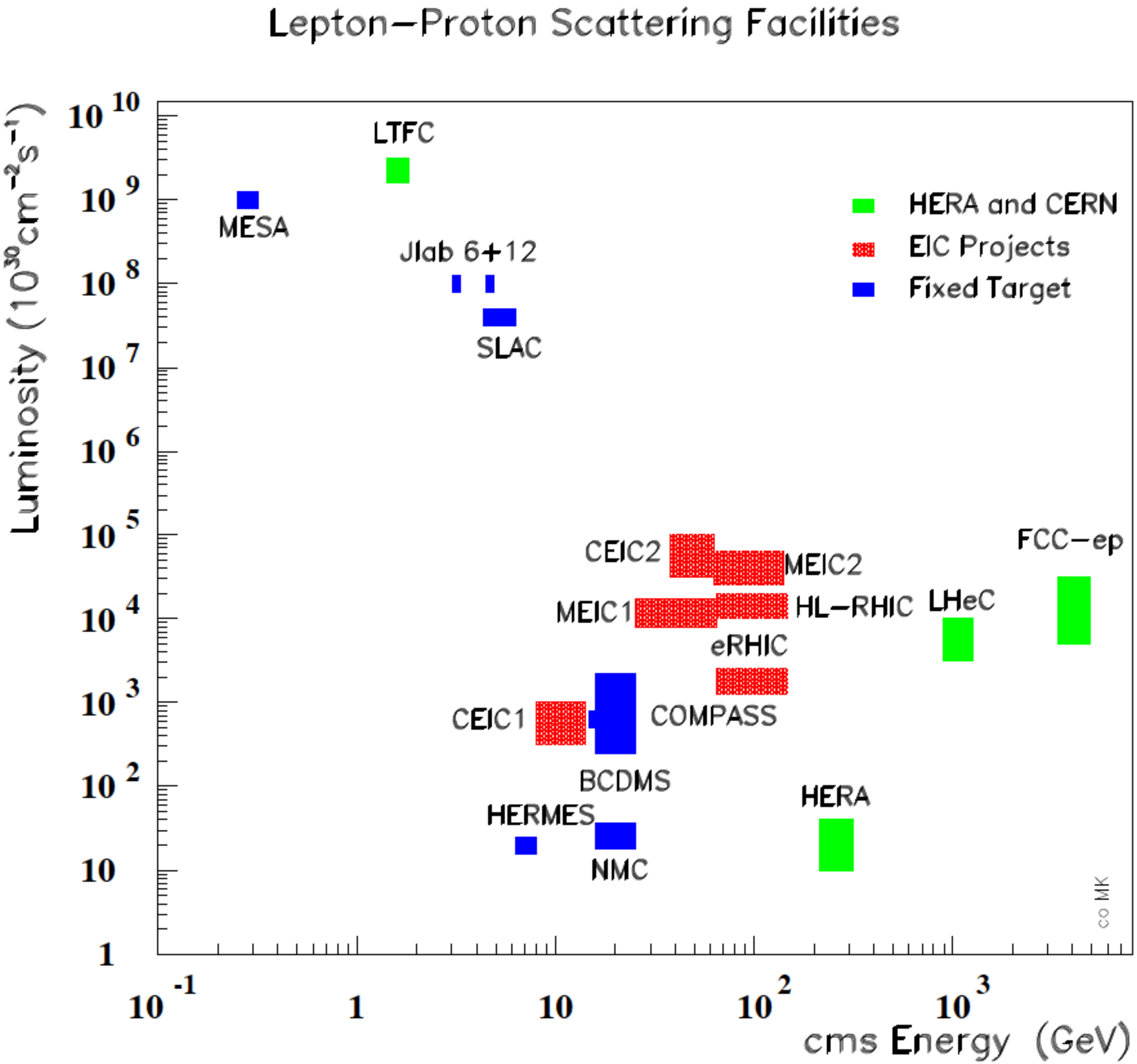
➜ Many thanks to Javier Albacete, Max and Uta Klein, Heikki Mantysaari, Hannu Paukkunen and Amir Rezaeian for sending new calculations, and Paul Newman for suggestions.
➜ Many thanks to the organisers for the invitation!

Thank you very much for your attention!!!

Backup:

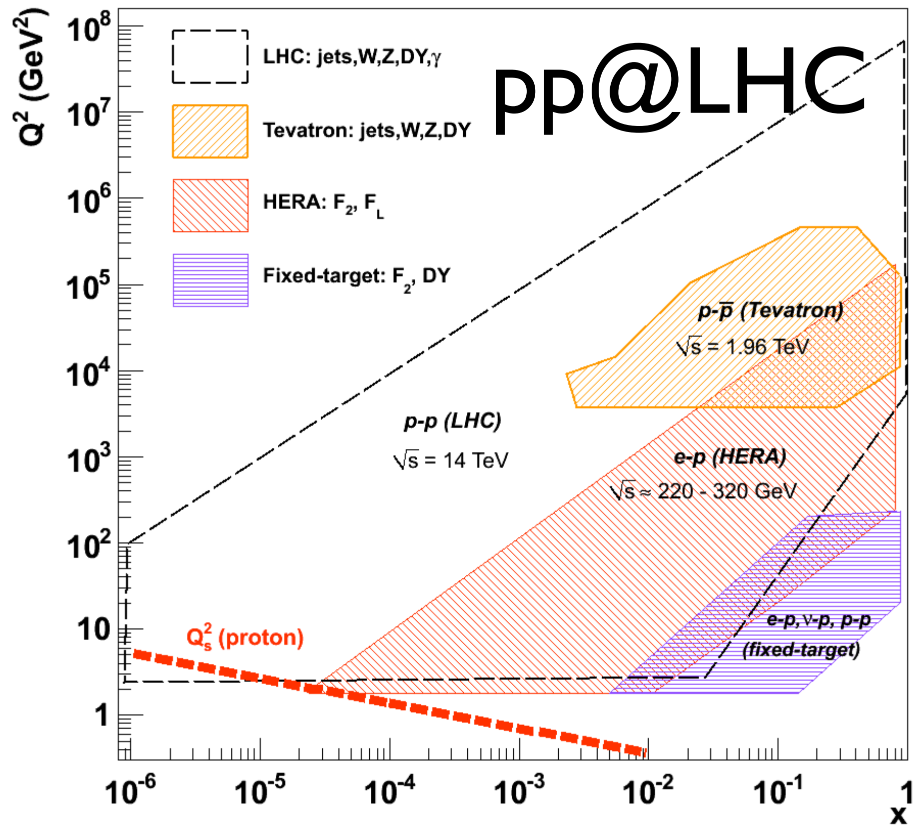
DIS landscape:



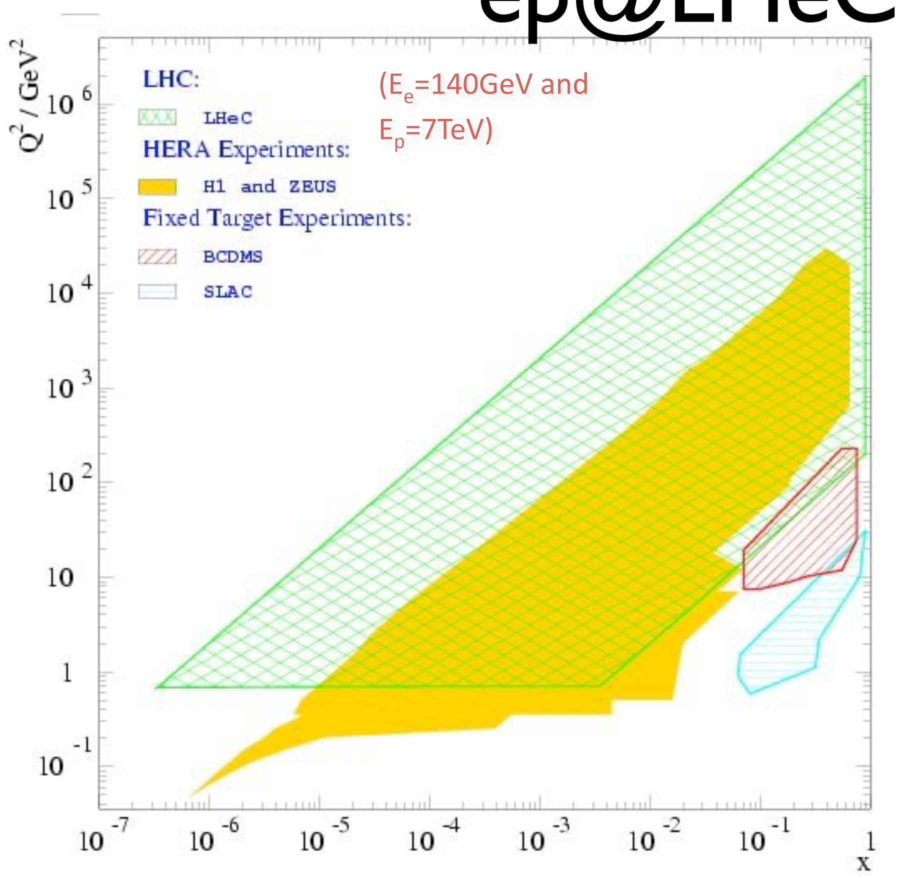
Theory in the non-linear regime:

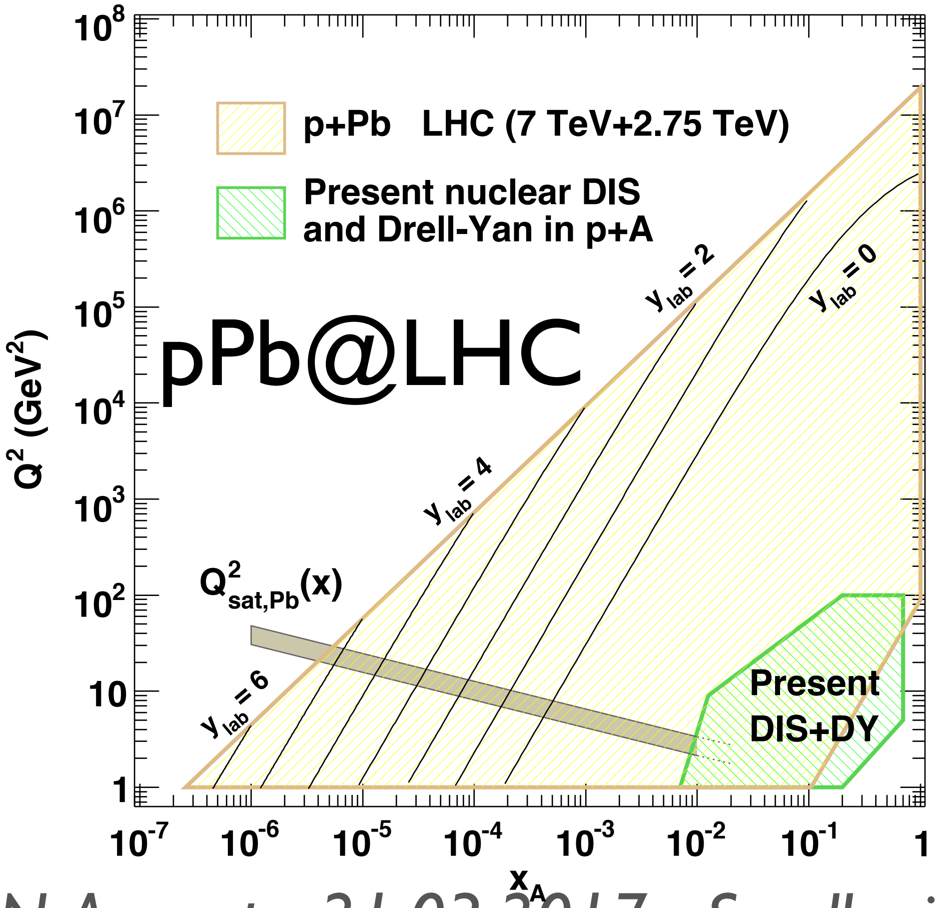
Item	Order	Theory	Pheno-menology	Comments
Evolution eqns.	NLO	✔	~	rcBK and resummations; dilute-dense approx.
DIS impact factor	NLO	✔	✘ at NLO	dilute-dense approx.
Hadrons at y~0	LO	✔	✔	q and Q , dilute-dense approx.
Forward hadrons	NLO	✔	✔	q and Q, hybrid formalism
Quarkonium at y~0	LO	✔	✔	dilute-dense approx.+NRQCD
Forward quarkonium	LO	✔	✔	hybrid formalism
$\gamma^{(*)}$ at y~0	NLO	✔	✘ at NLO	dilute-dense approx., not yet DY at NLO
Forward $\gamma^{(*)}$	LO	✔	✔	hybrid formalism
Dijets at y~0	LO	✔	✔	dilute-dense approx., partial NLO
Forward dijets	LO	✔	✔	hybrid formalism and high-energy factorisation, partial NLO
Diffractive dijets	NLO	✔	✘ at NLO	dilute-dense approx.
g-g/q-q correlations	LO	✔	✔/✘	glasma graph approx.

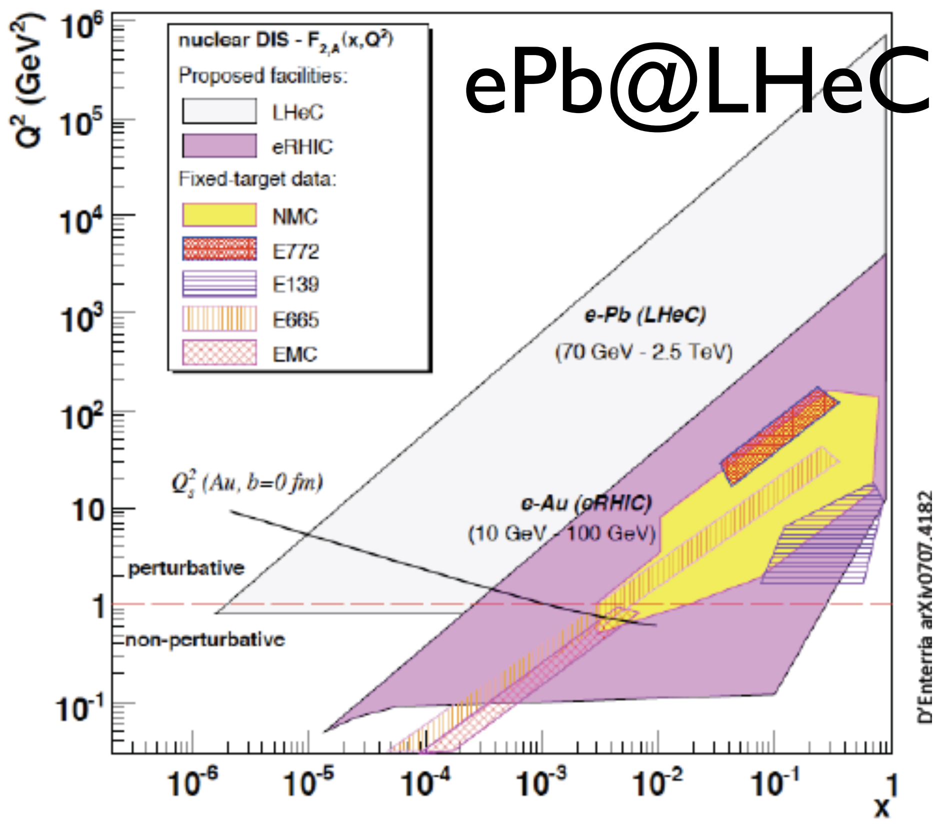
LHC vs. LHeC:



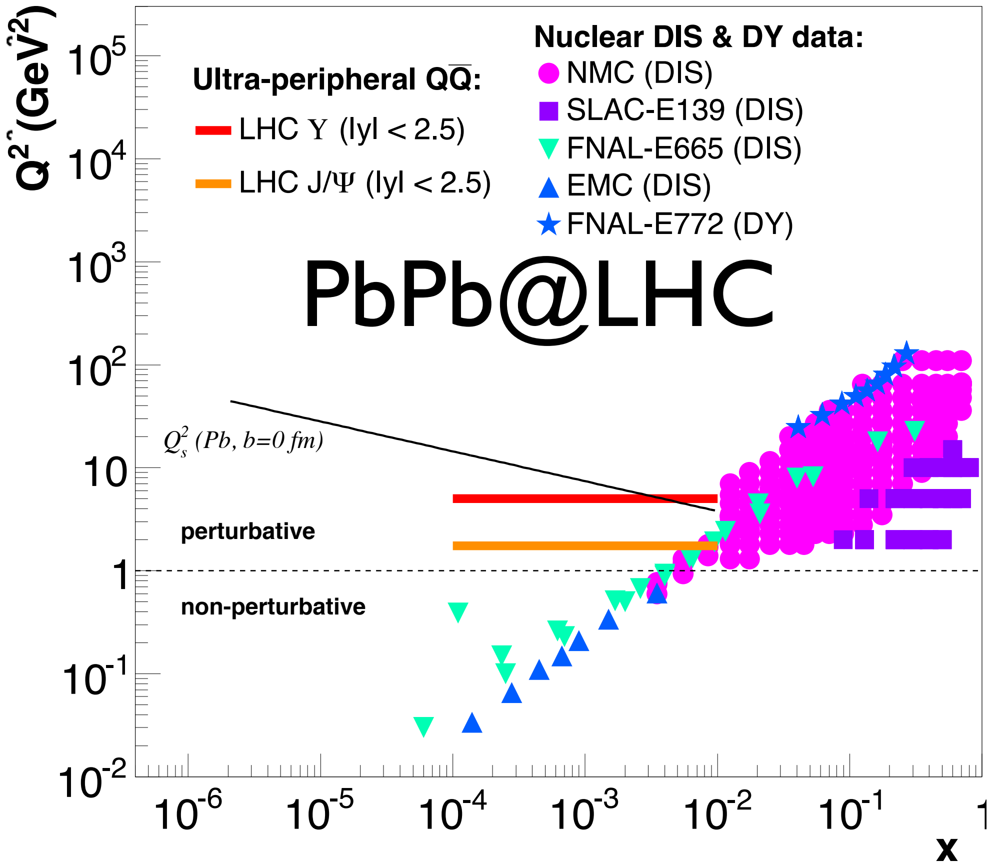
ep@LHeC



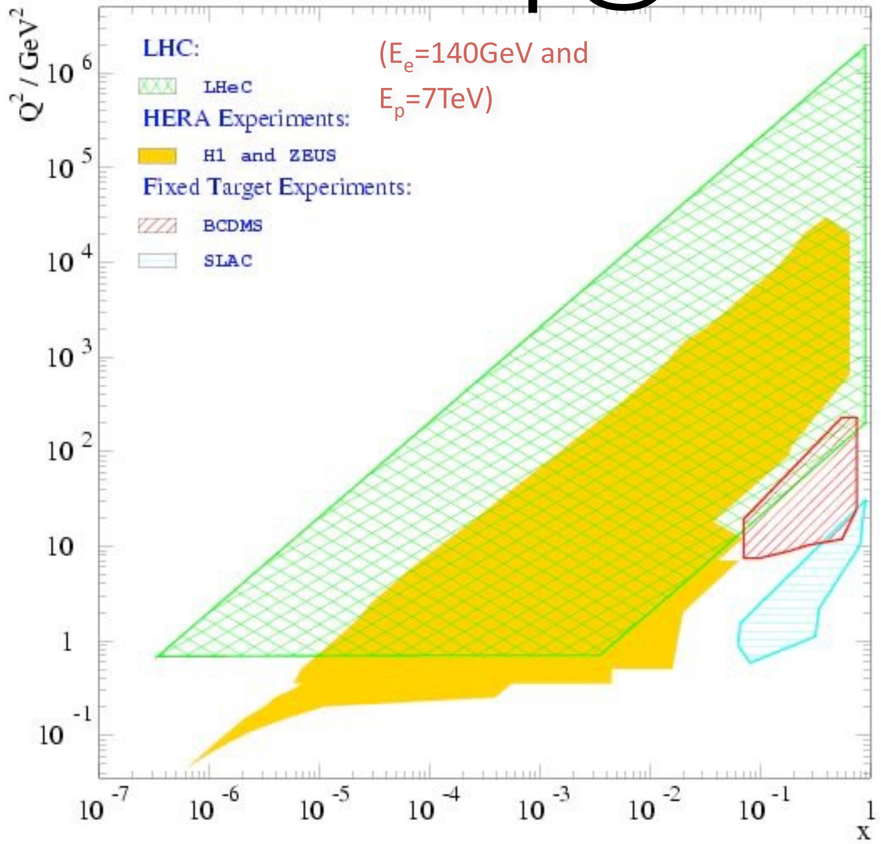


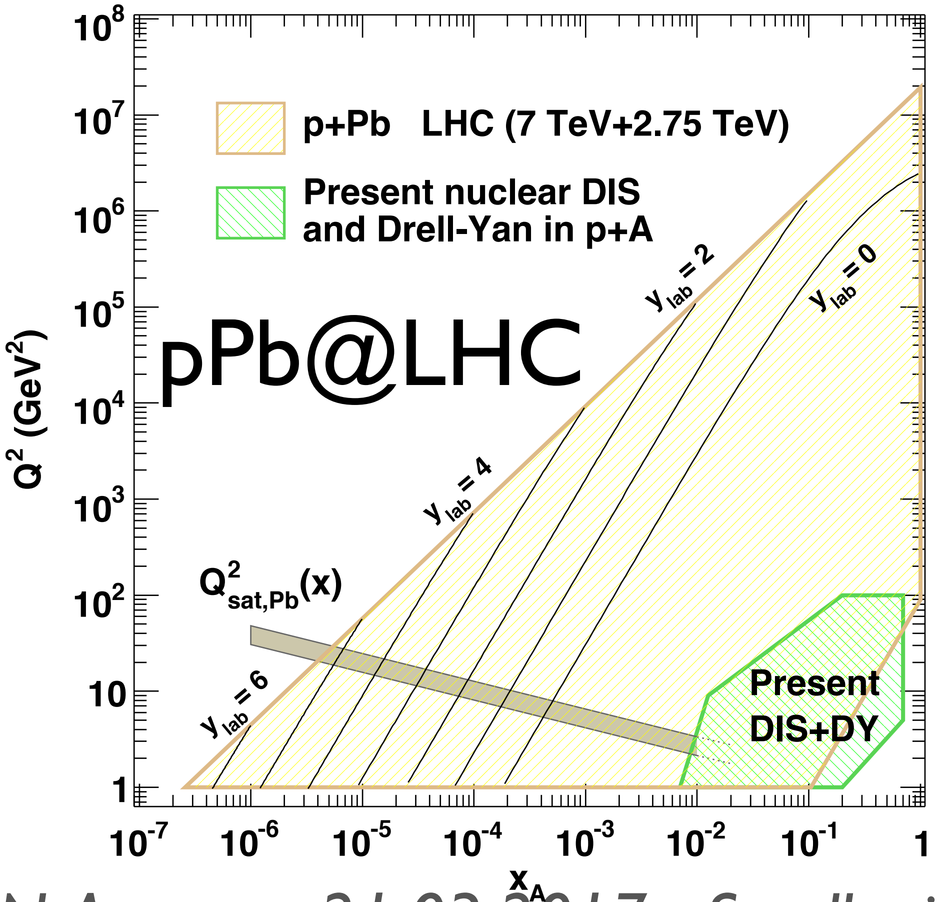


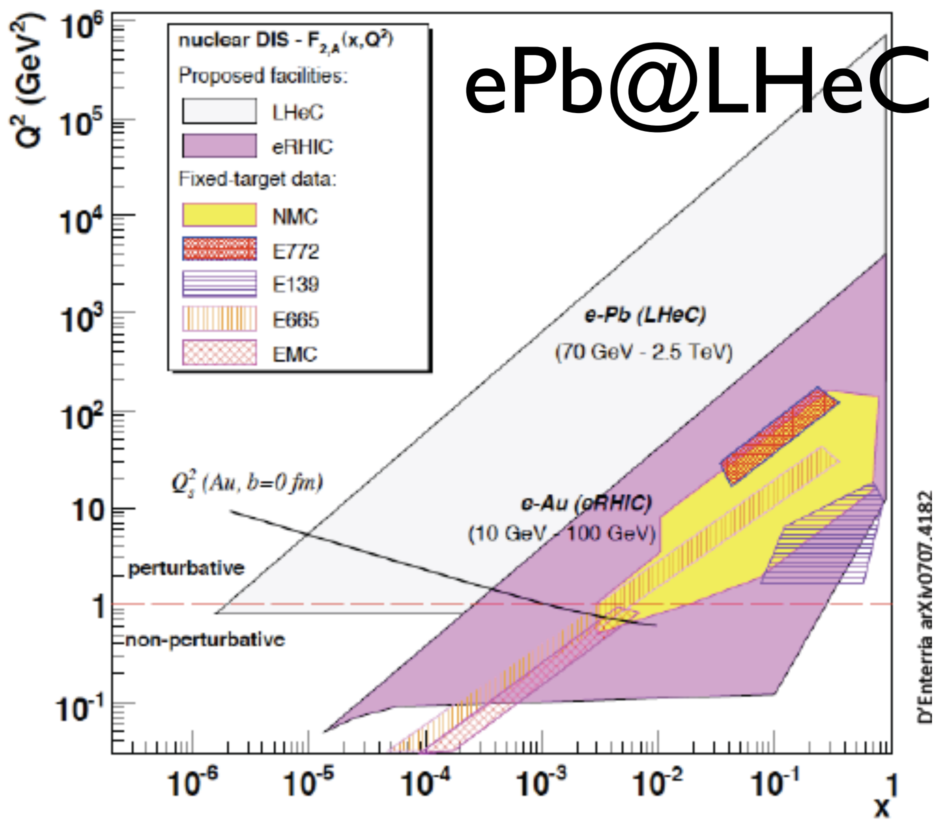
LHC vs. LHeC:



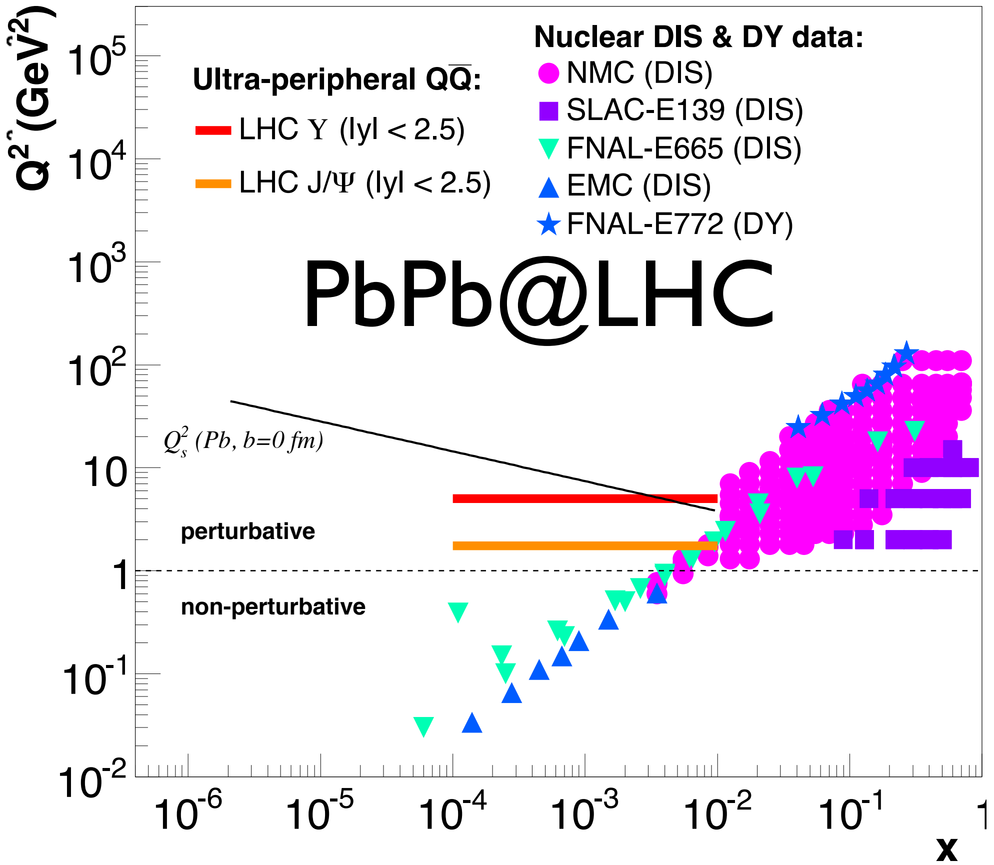
ep@LHeC

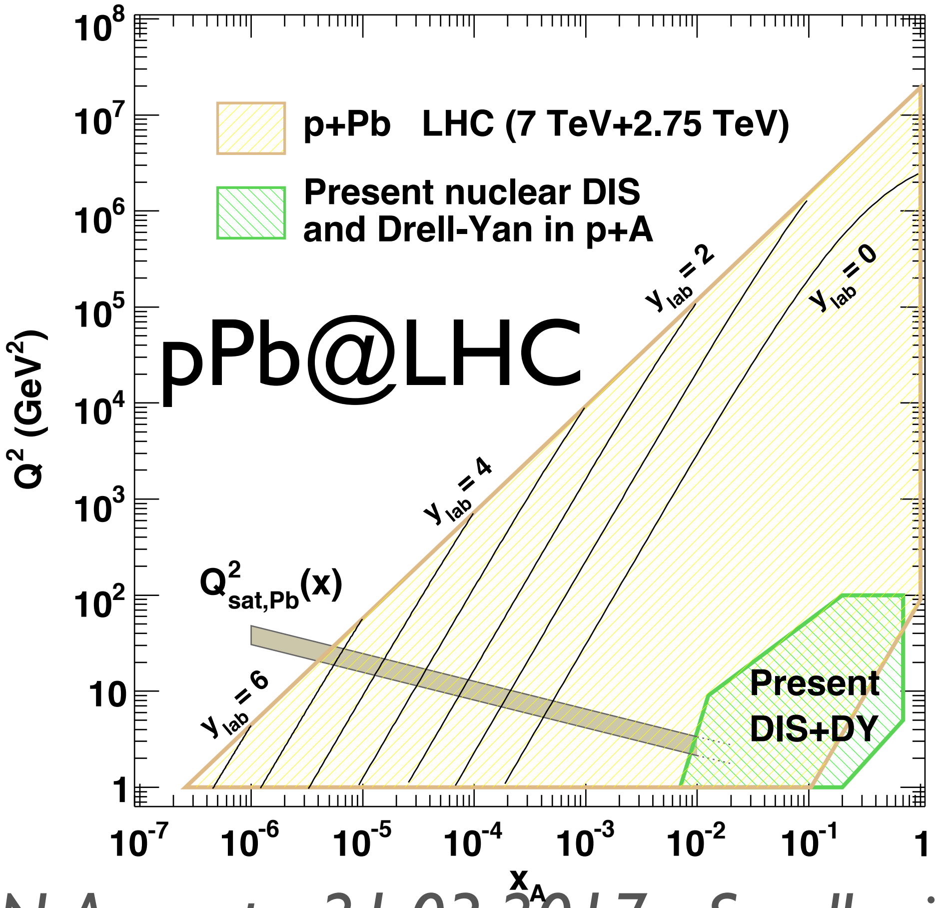






LHC vs. LHeC:



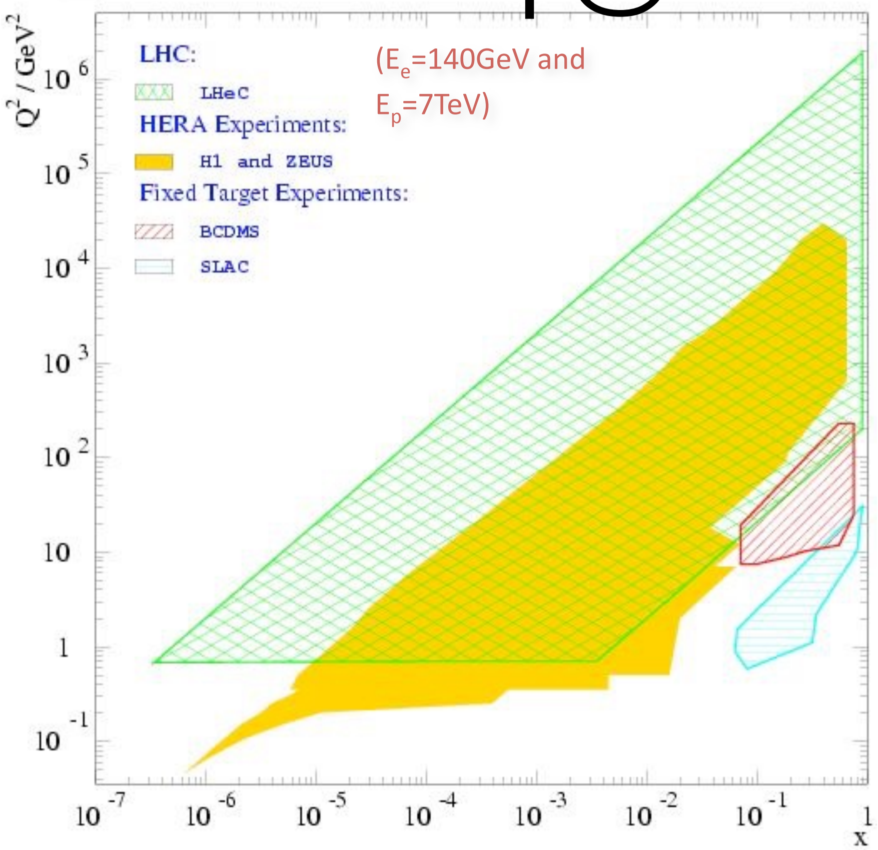


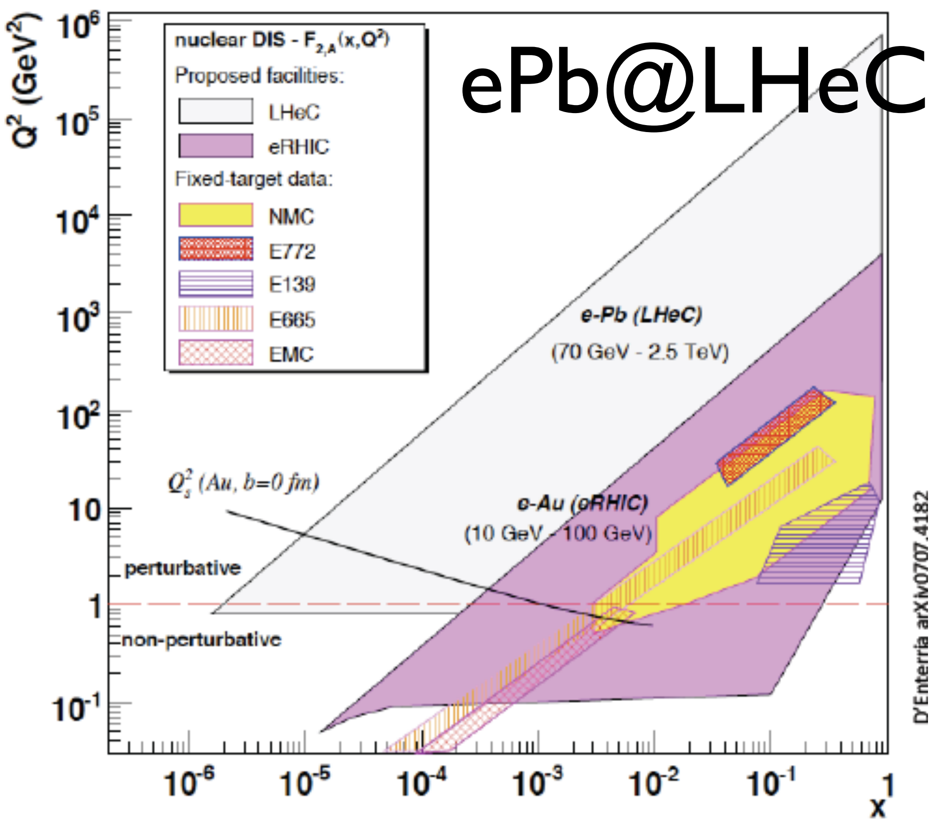
- The LHeC will explore a region overlapping with the LHC:

➜ in a cleaner experimental setup;

➜ on firmer theoretical grounds.

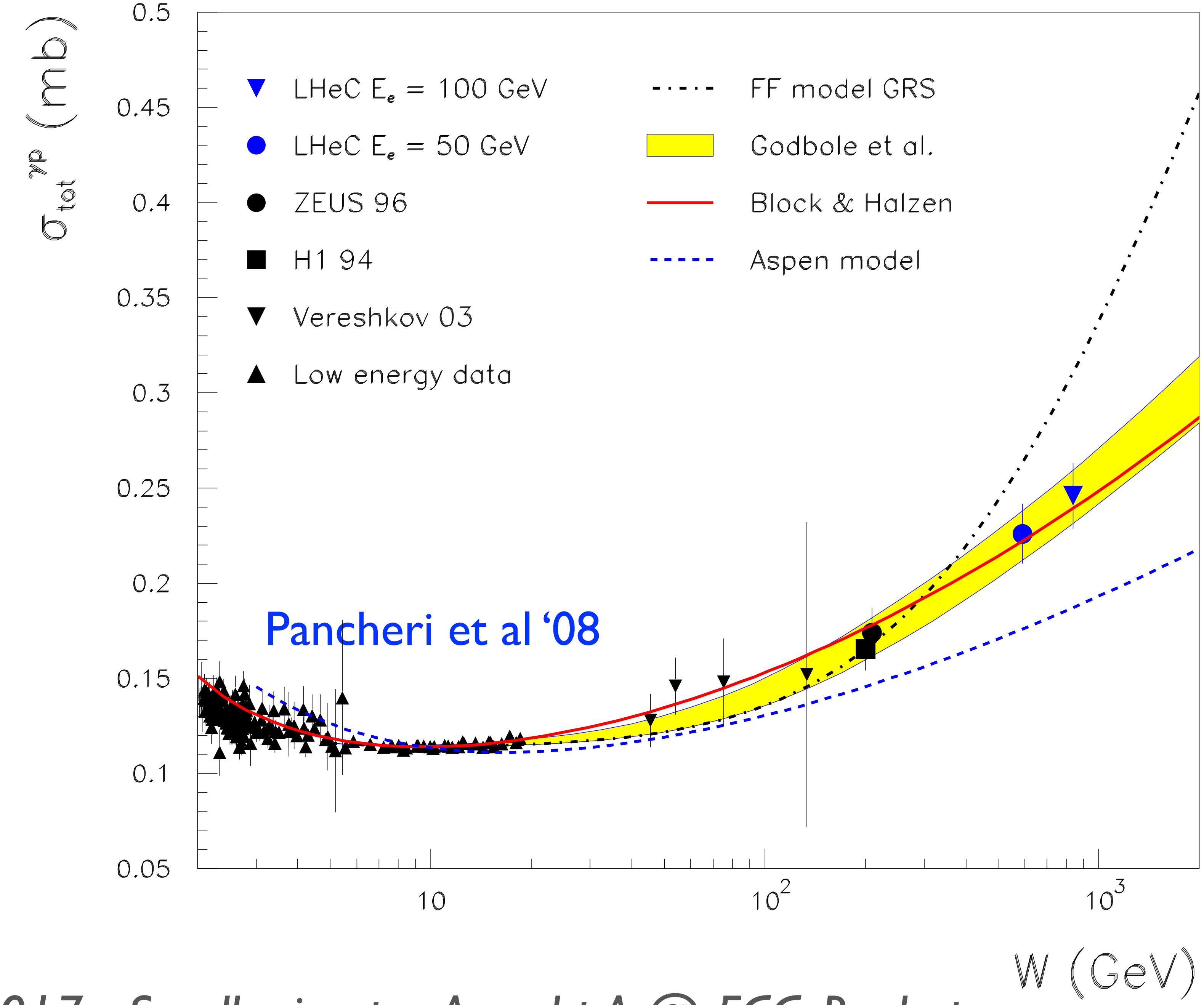
ep@LHeC



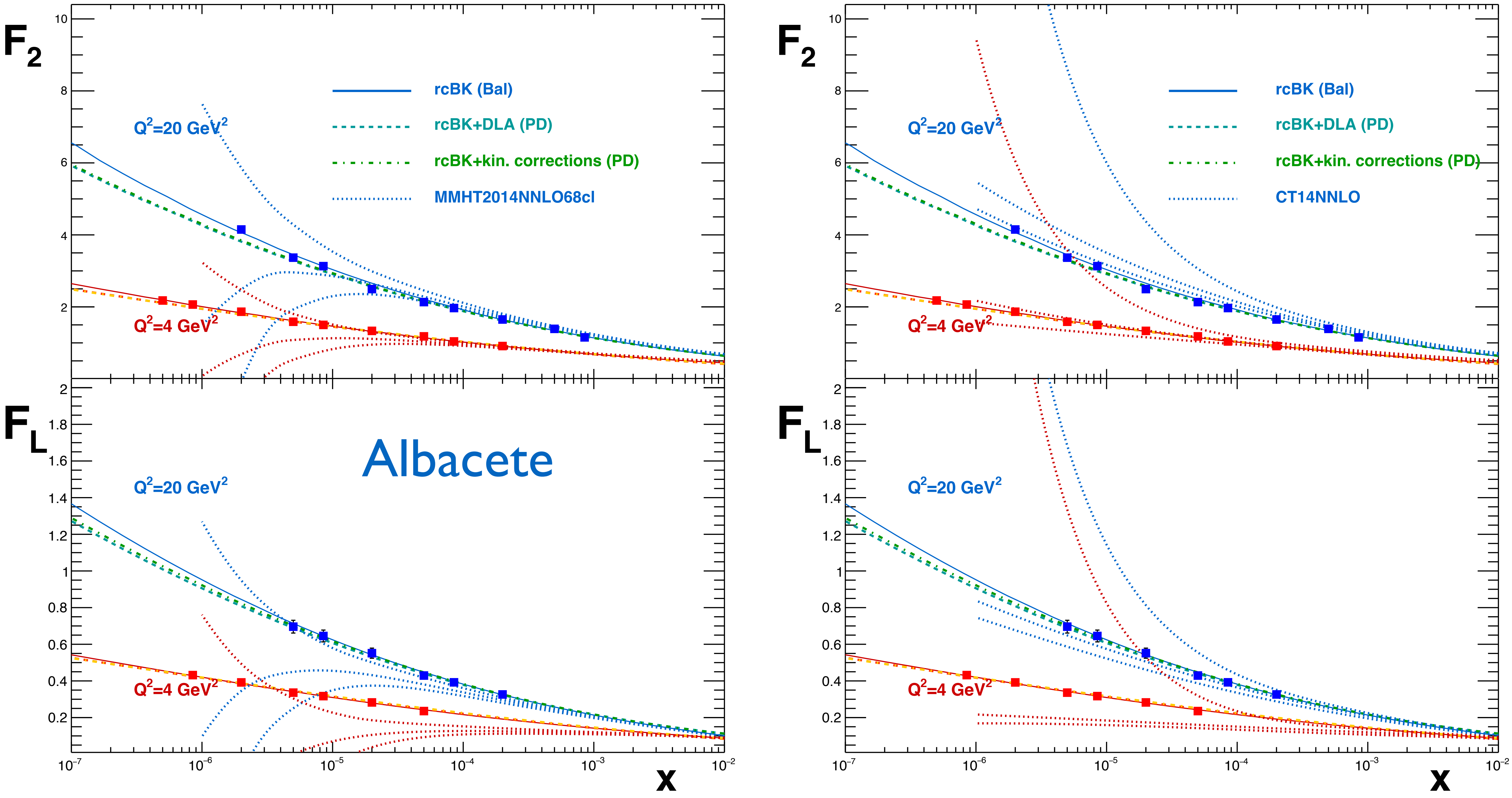


Photoproduction cross section:

- Small angle electron detector 62 m far from the interaction point: $Q^2<0.01$ GeV, y~0.3 ⇒ W~0.5 $\sqrt{s}$.
- Substantial enlarging of the lever arm in W.



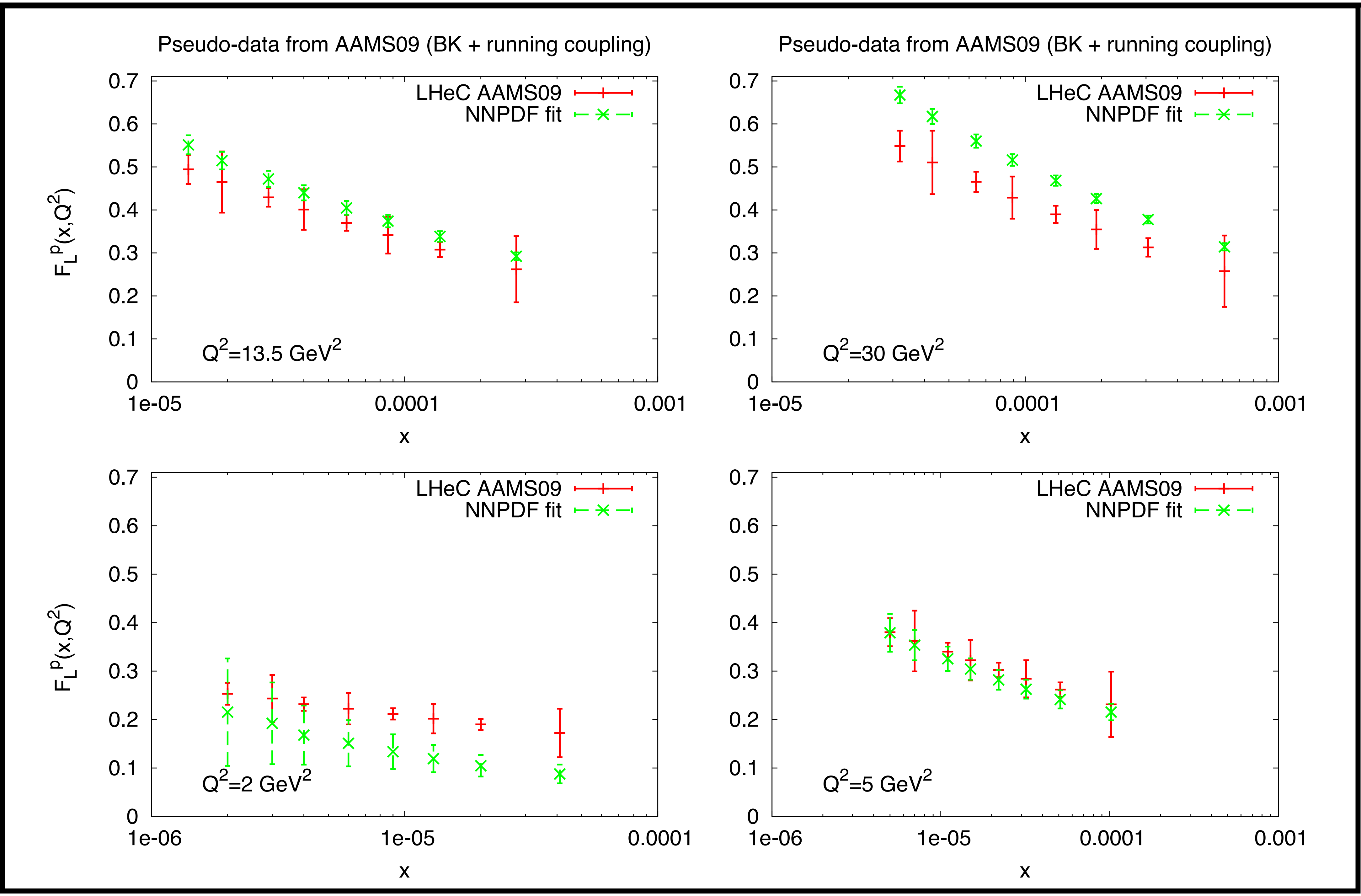
Structure functions:



- F$_2$ and F$_L$ data will have discriminatory power on models.

Structure functions:

DGLAP cannot simultaneously accommodate F_2 and F_L data if saturation effects are included according to current models: F_2 and F_L at the FCC will provide a decisive test of small-x QCD.



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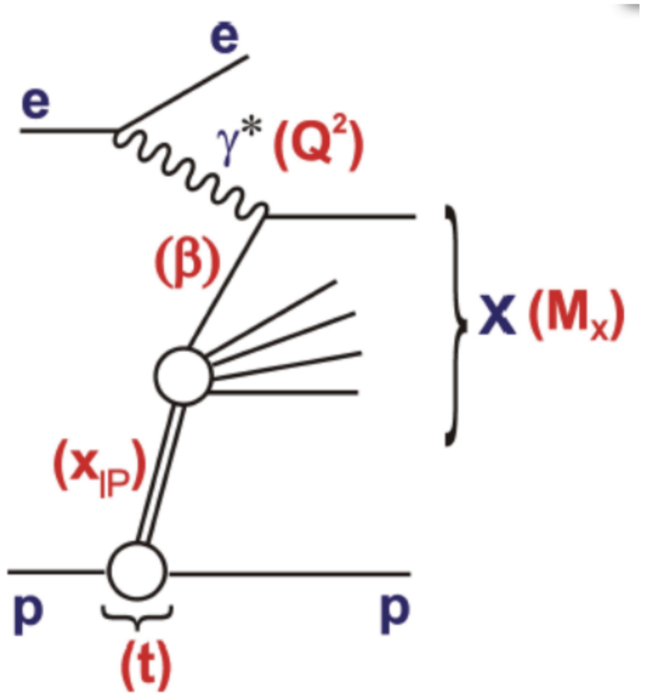
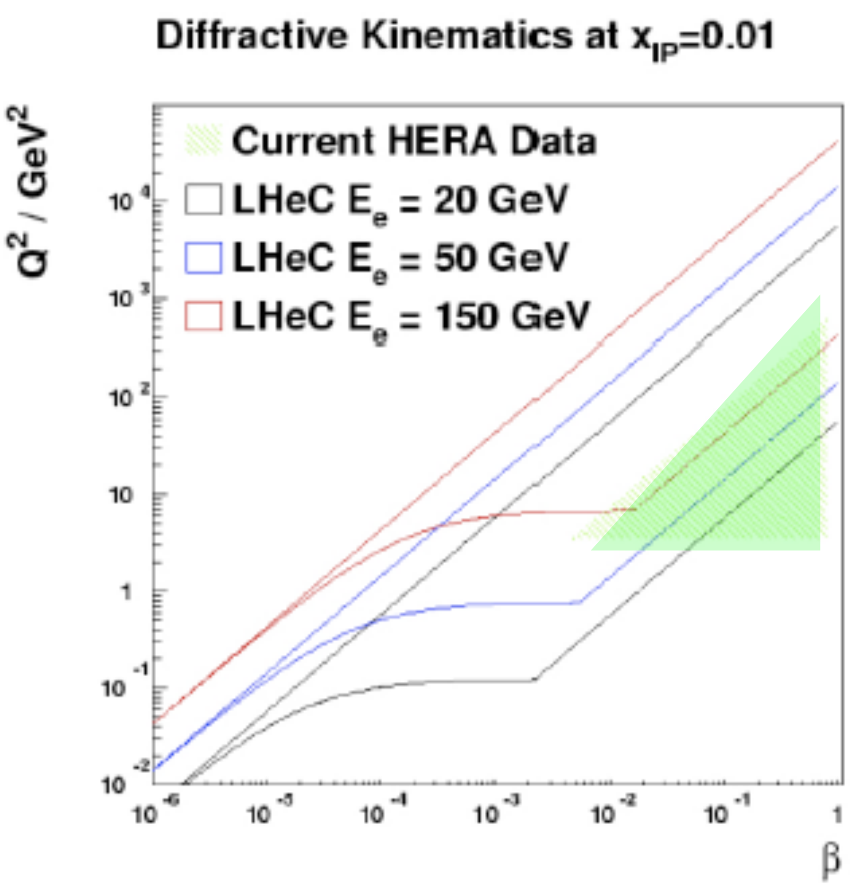
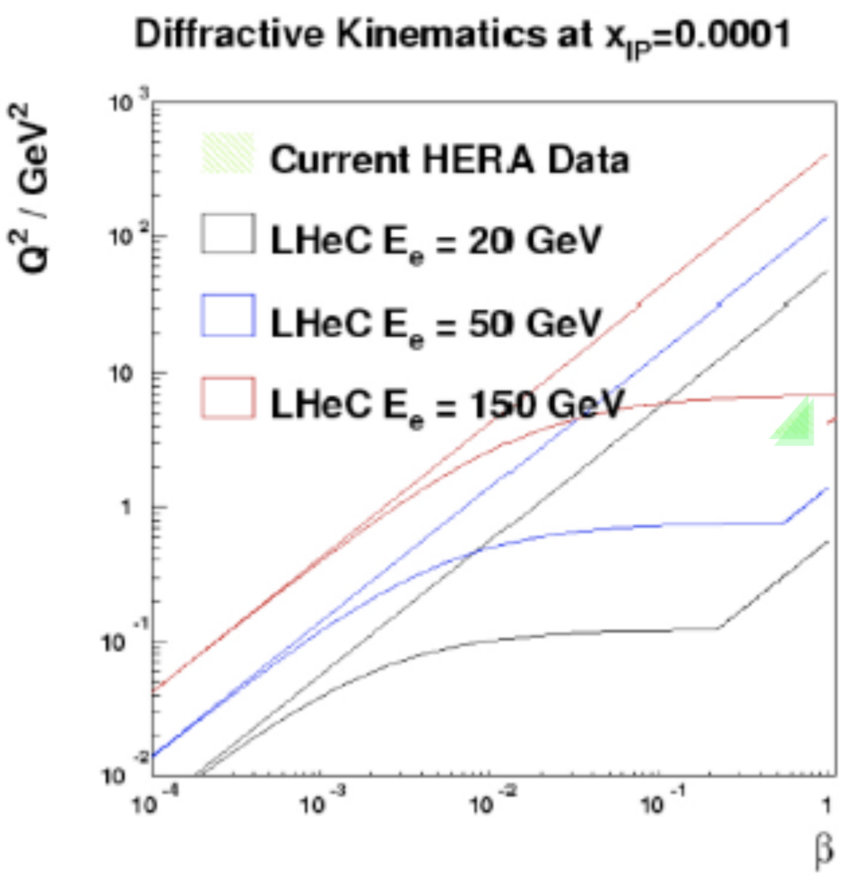
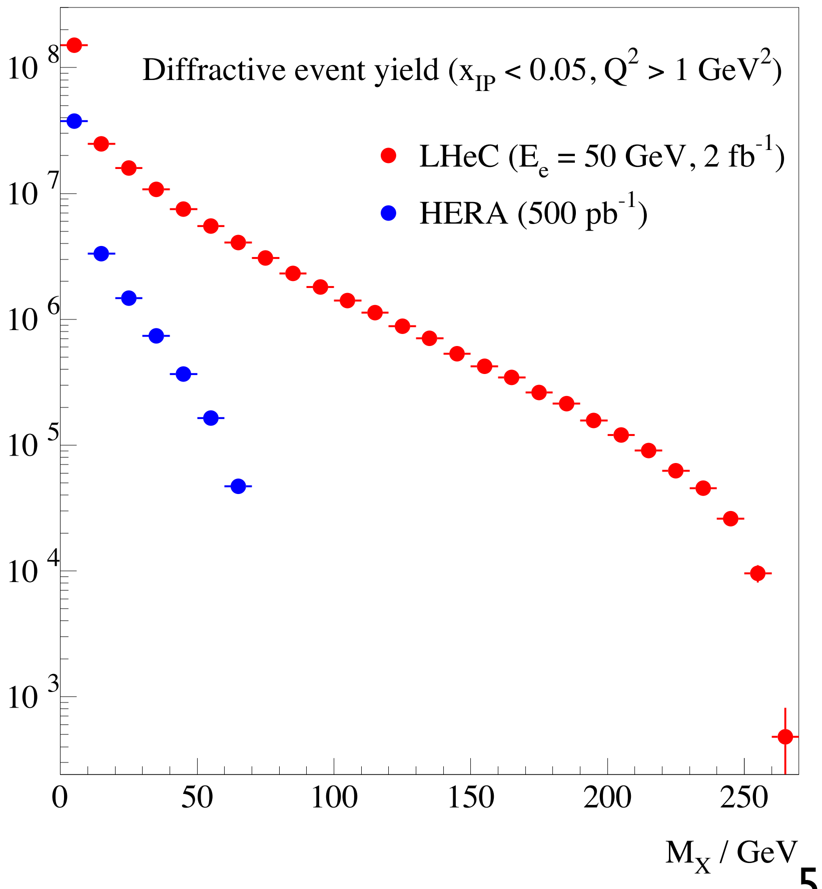
Diffraction in ep:



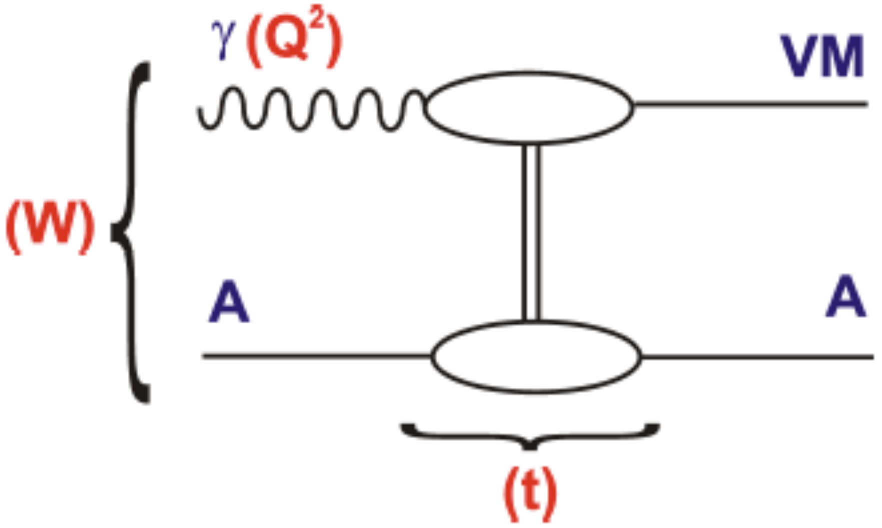
- Large increase in the M^2 (diffractive heavy states up to ~0.5 TeV), $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.
- Possibility to combine rapidity gap and proton tagging.
- Precise determination of DPDFs.

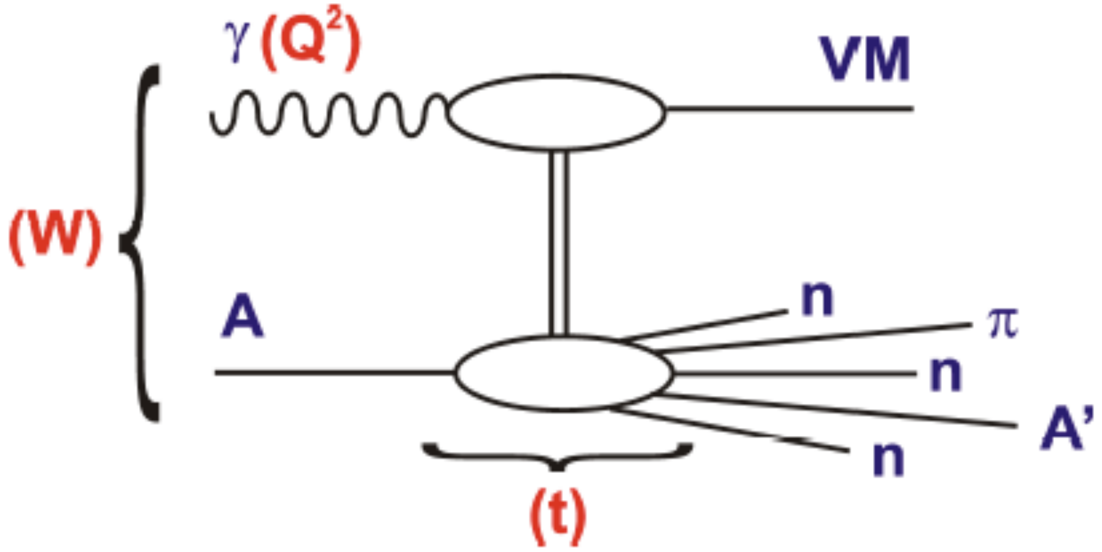






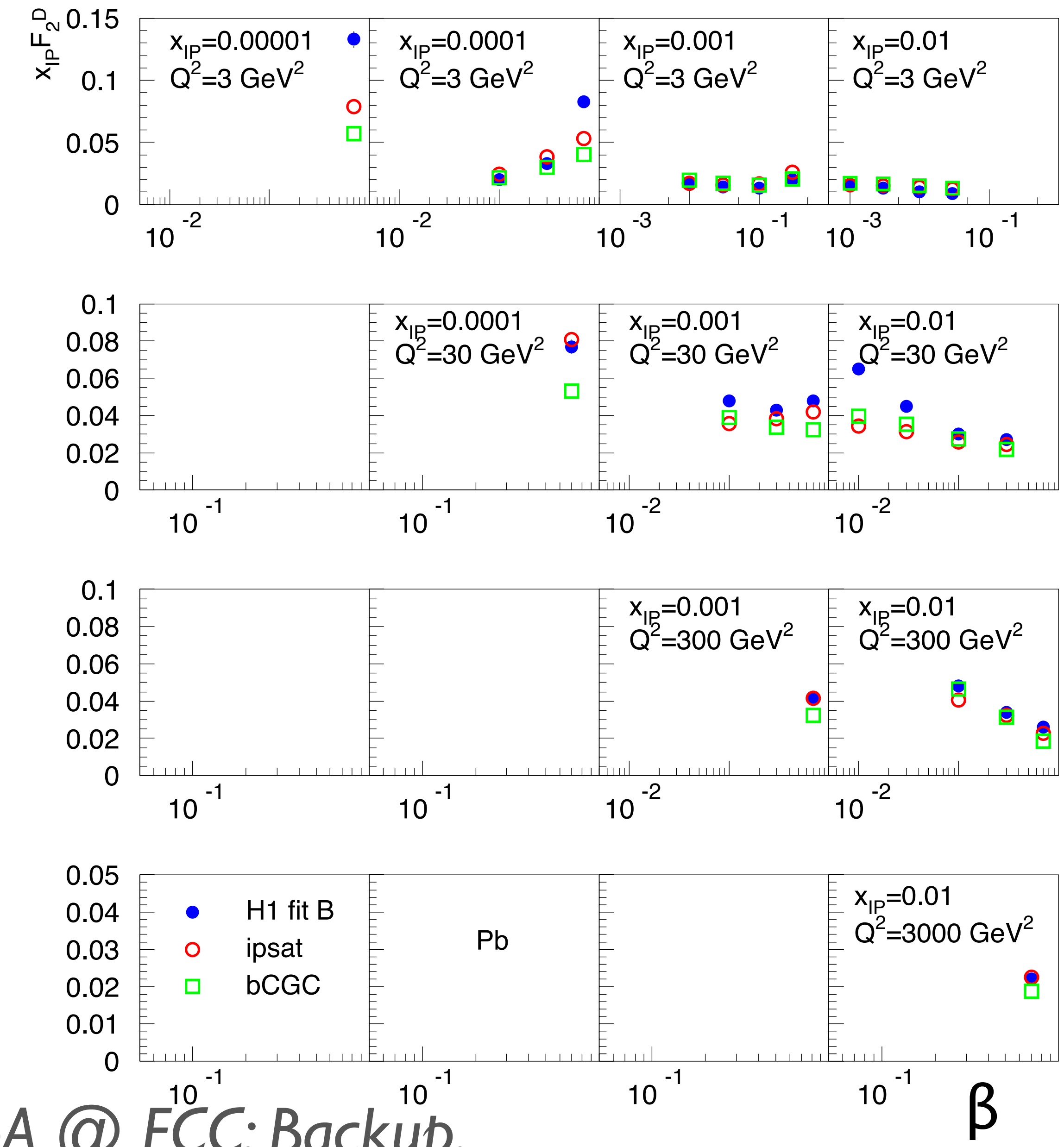
Diffractive DIS on nuclear targets:





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

- For the **coherent case**, predictions available.



Dijet azimuthal decorrelation:

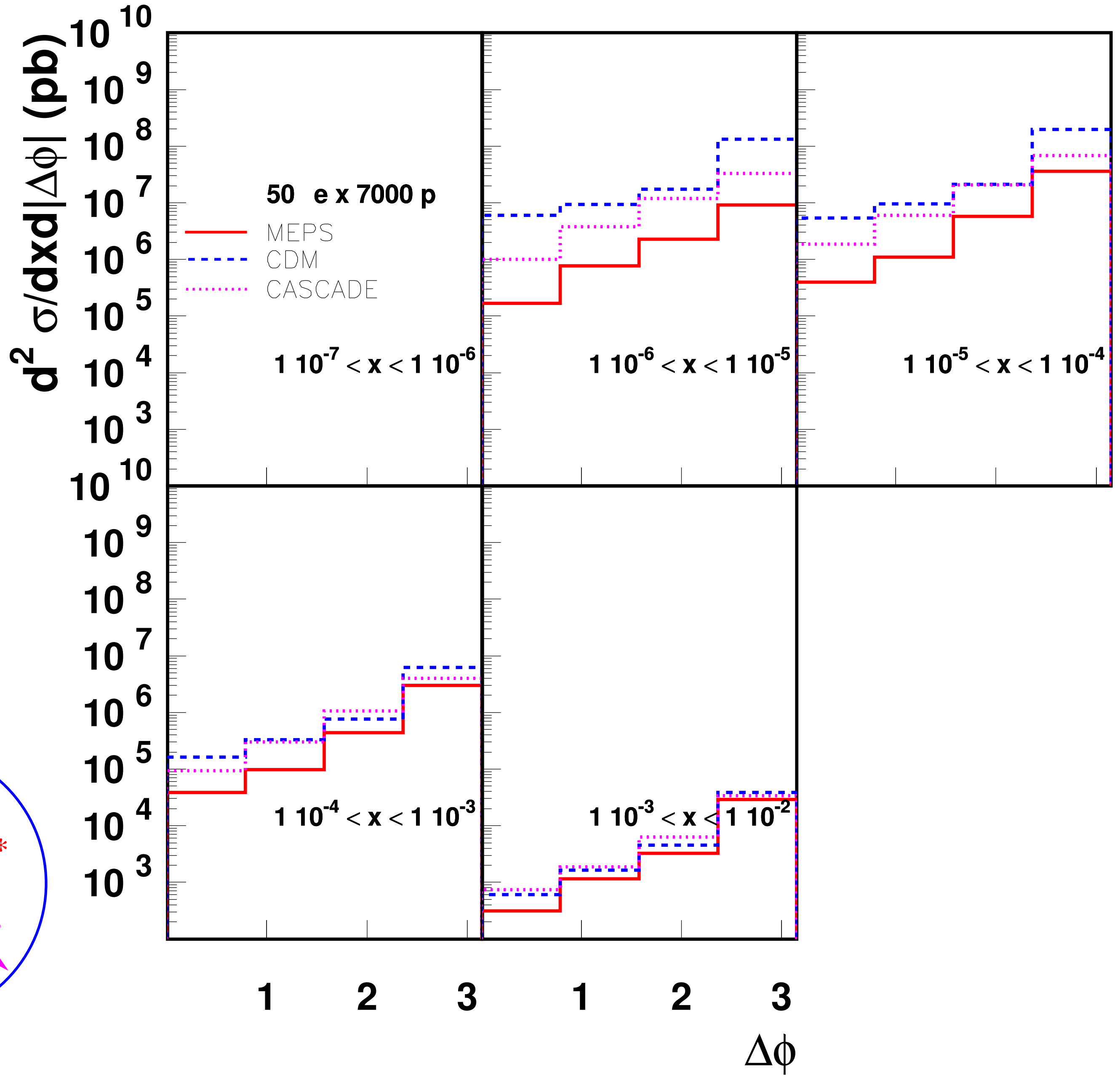
- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:

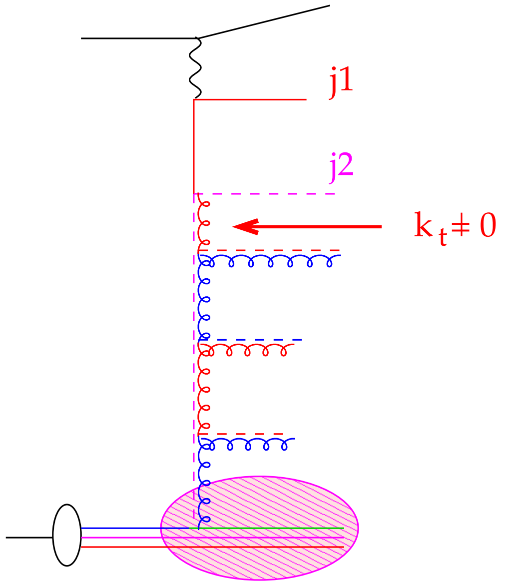
➜ k_T-ordered: DGLAP.

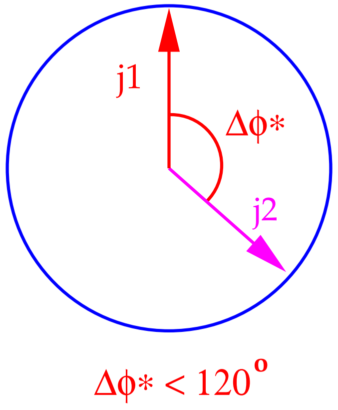
➜ k_T-disordered: BFKL.

➜ Saturation?

- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.







Forward jets:

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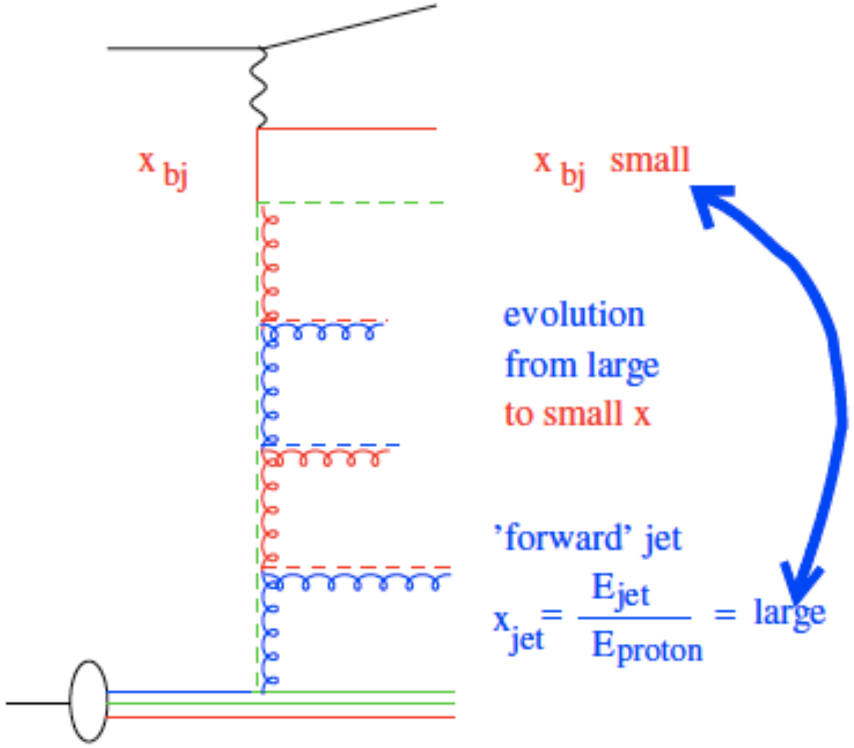
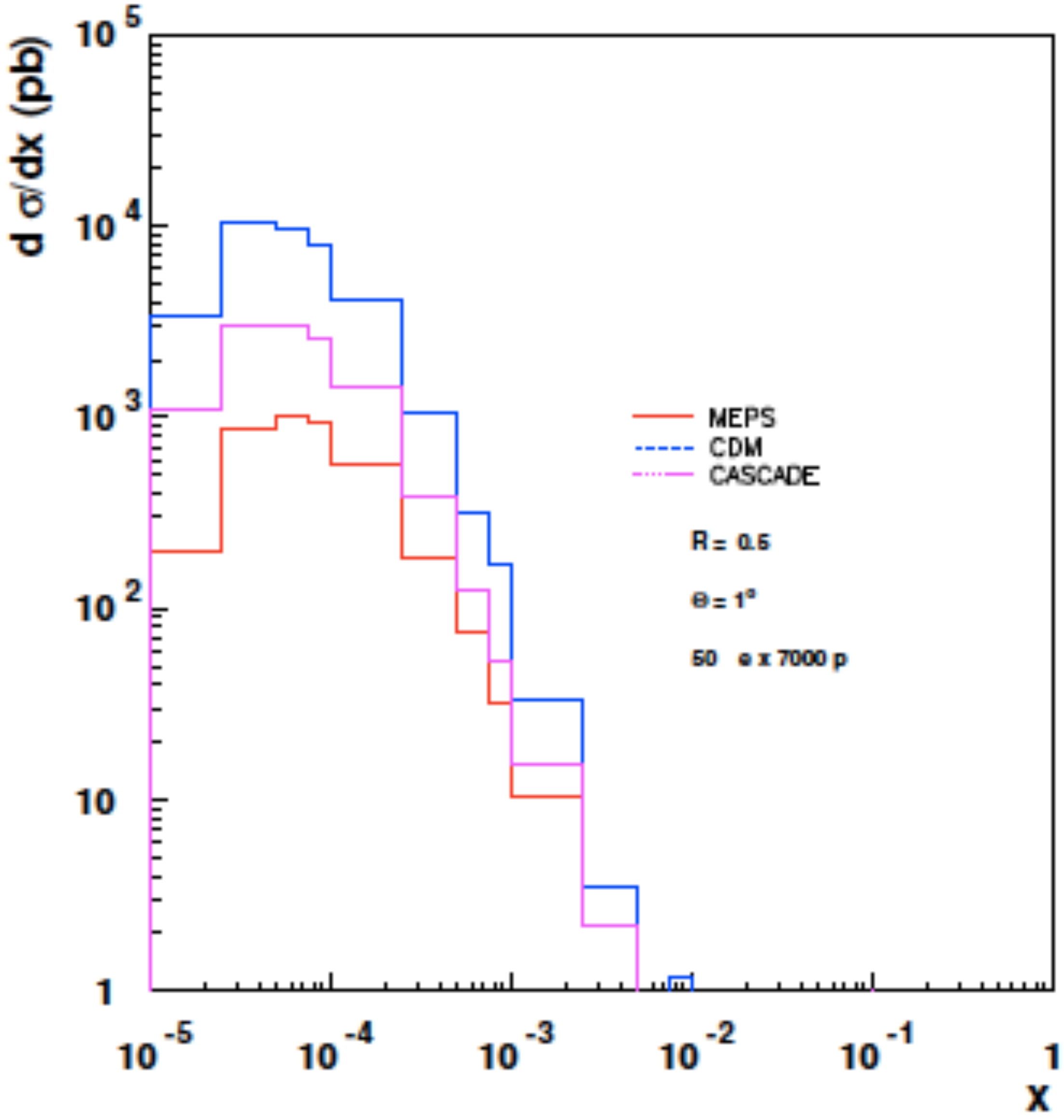
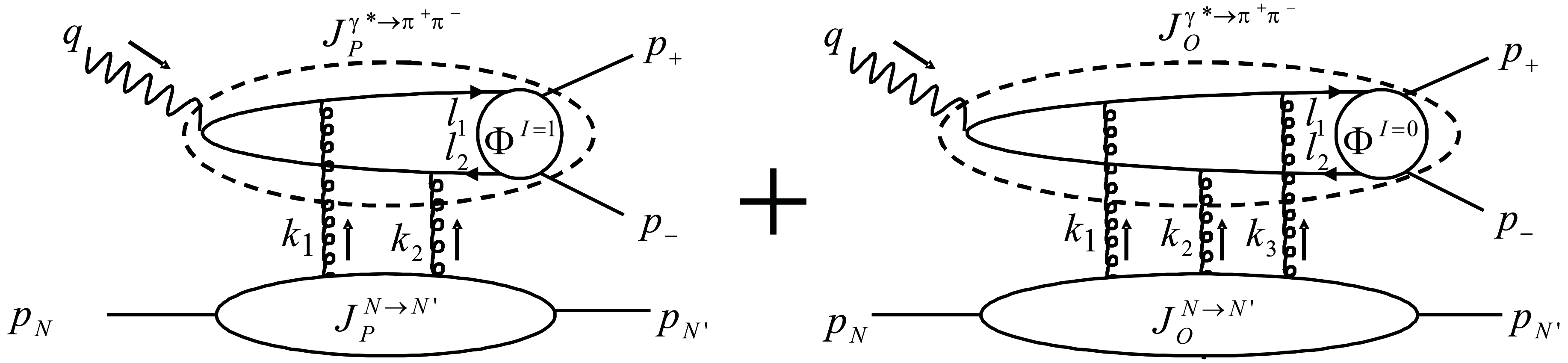




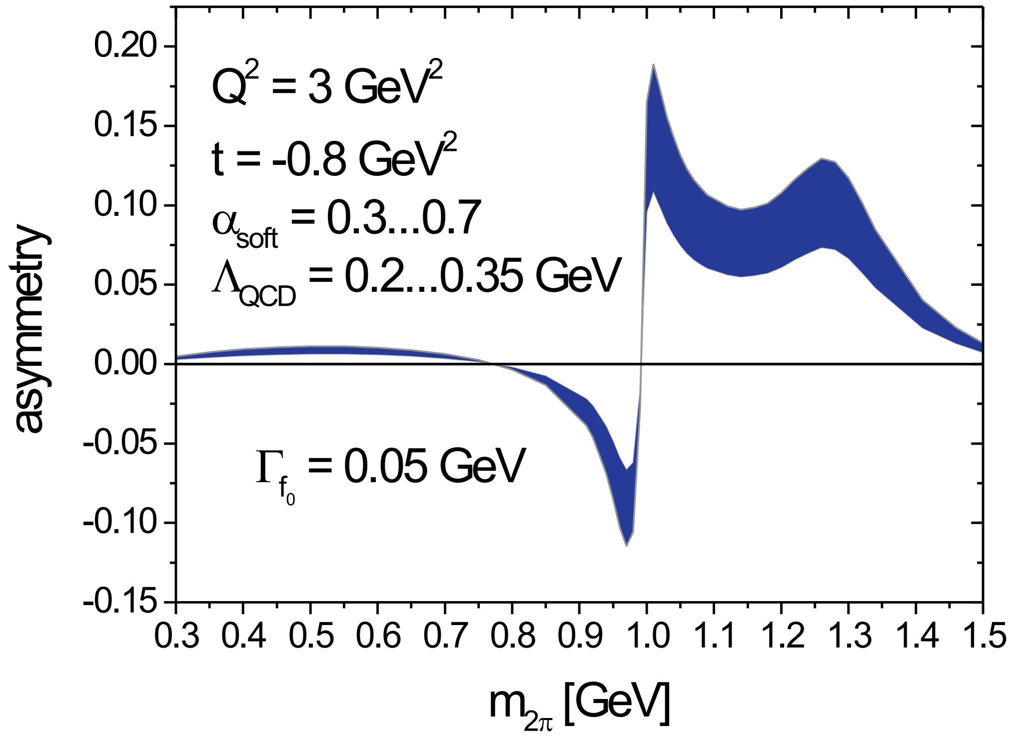
Odderon:

- Odderon (C-odd exchange contributing to particle-antiparticle difference in cross section) seached in $\gamma^{(\star)}p \to Cp$, where $C = \pi^0, \eta, \eta', \eta_c \ldots$ or through O-P interferences.



$$A(Q^2,t,m_{2\pi}^2) = \frac{\int \cos\theta \, d\sigma(W^2,Q^2,t,m_{2\pi}^2,\theta)}{\int d\sigma(W^2,Q^2,t,m_{2\pi}^2,\theta)} = \frac{\int_{-1}^{1} \cos\theta \, d\cos\theta \, 2 \, \mathrm{Re}\left[\mathcal{M}_P^{\gamma_L^*}(\mathcal{M}_O^{\gamma_L^*})^*\right]}{\int_{-1}^{1} d\cos\theta \left[|\mathcal{M}_P^{\gamma_L^*}|^2 + |\mathcal{M}_O^{\gamma_L^*}|^2\right]}$$

- Sizable charge asymmetry, yields and reconstruction pending.

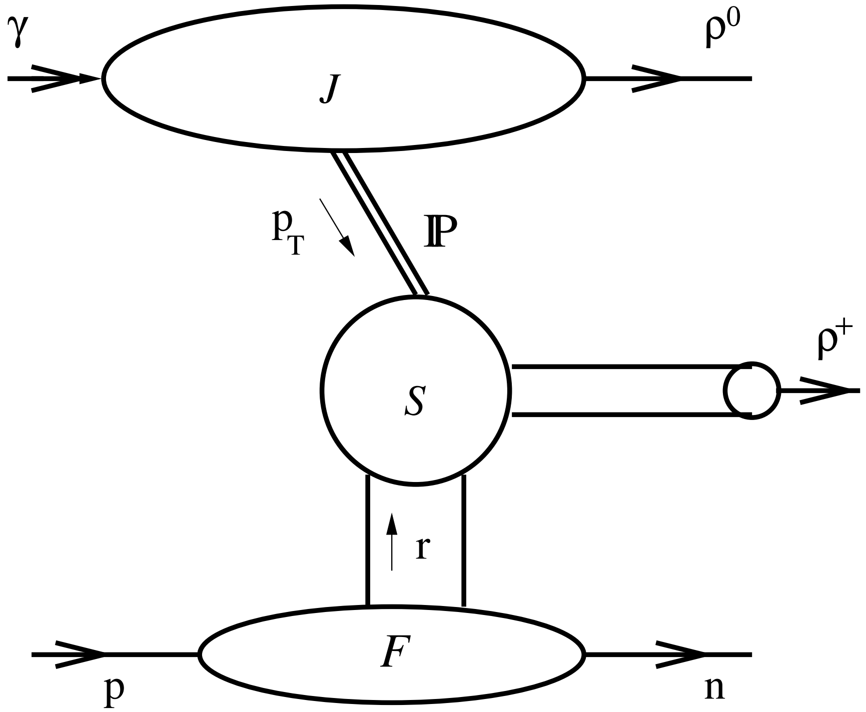


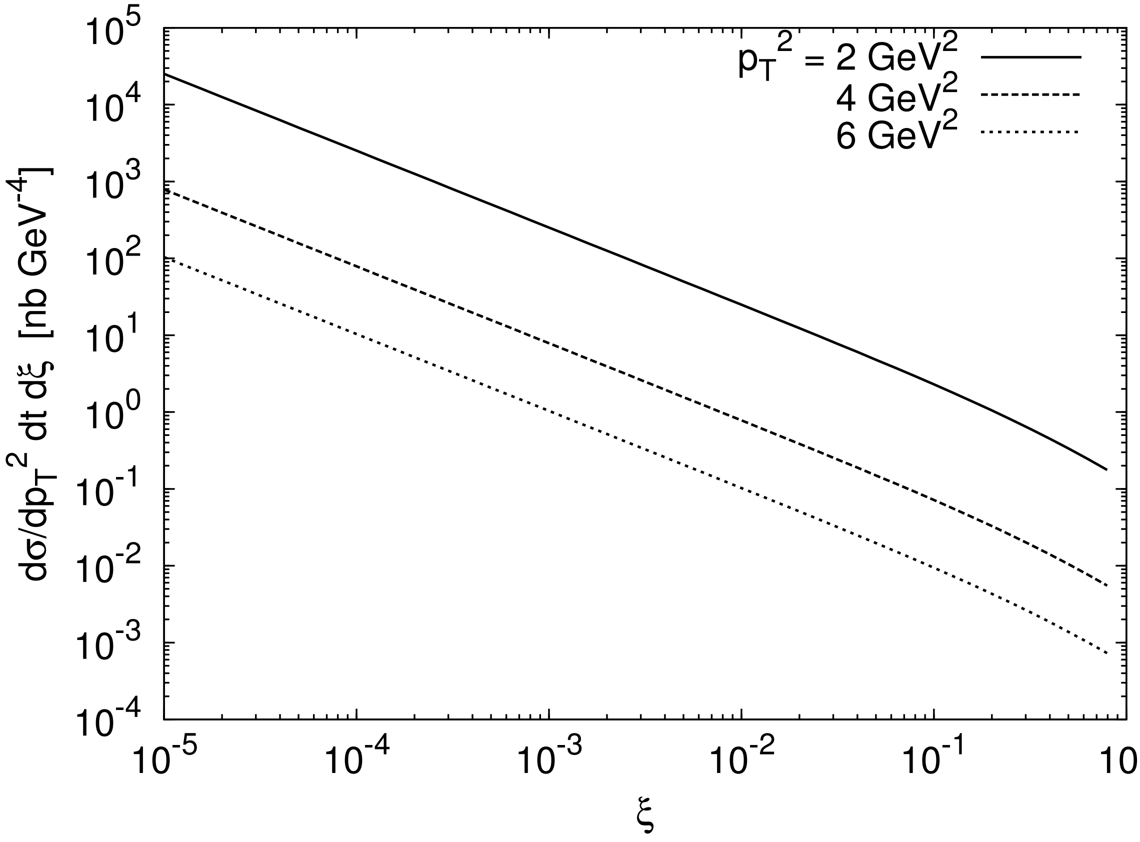
Transversity GPDs:

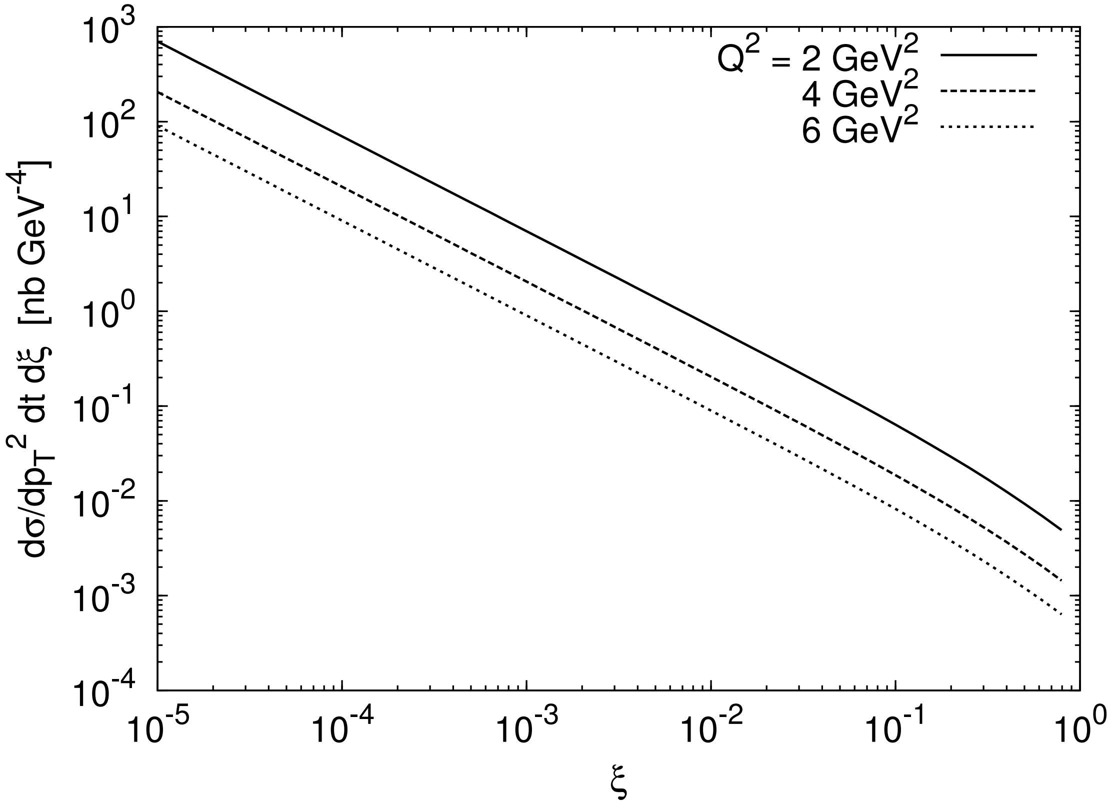
- Chiral-odd transversity GPDs are largely unknown.

- They can be accessed through double exclusive production:

$$e p(p_2) \to e' \gamma^{(*)}_{L/T}(q)\ \ p(p_2) \to e' \rho^0_{L,T}(q_\rho)\ \ \rho_T(p_\rho)\ N'(p_{2'})$$







$$\xi \approx x_B/(2-x_B)$$