Heavy Ion Collisions in the LHC Era
Quy Nhon, Vietnam, July 17th 2012

Physics at low x_{Bj} and in eA at the LHeC

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Contents:

1. Status and motivation.

2. The Large Hadron Electron Collider.

3. Physics case at low x_{Bj} and in eA:
    - Inclusive measurements and small-x glue.
    - Inclusive diffraction.
    - Exclusive diffraction.
    - Final states: dynamics of QCD radiation and hadronization.

4. Summary and outlook.

CDR, arXiv:1206.2913, J. Phys. G 39 (2012) 075001;
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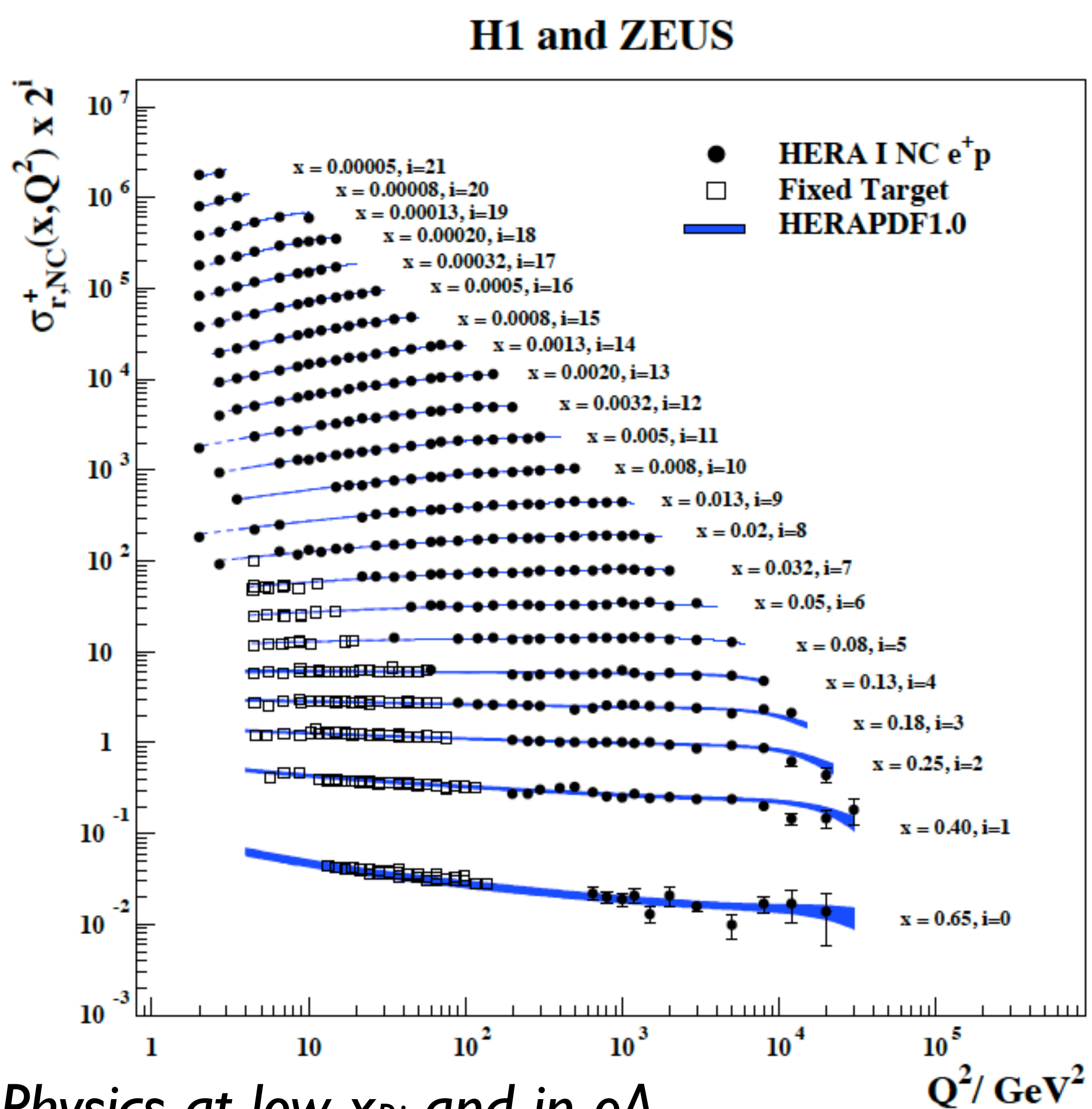
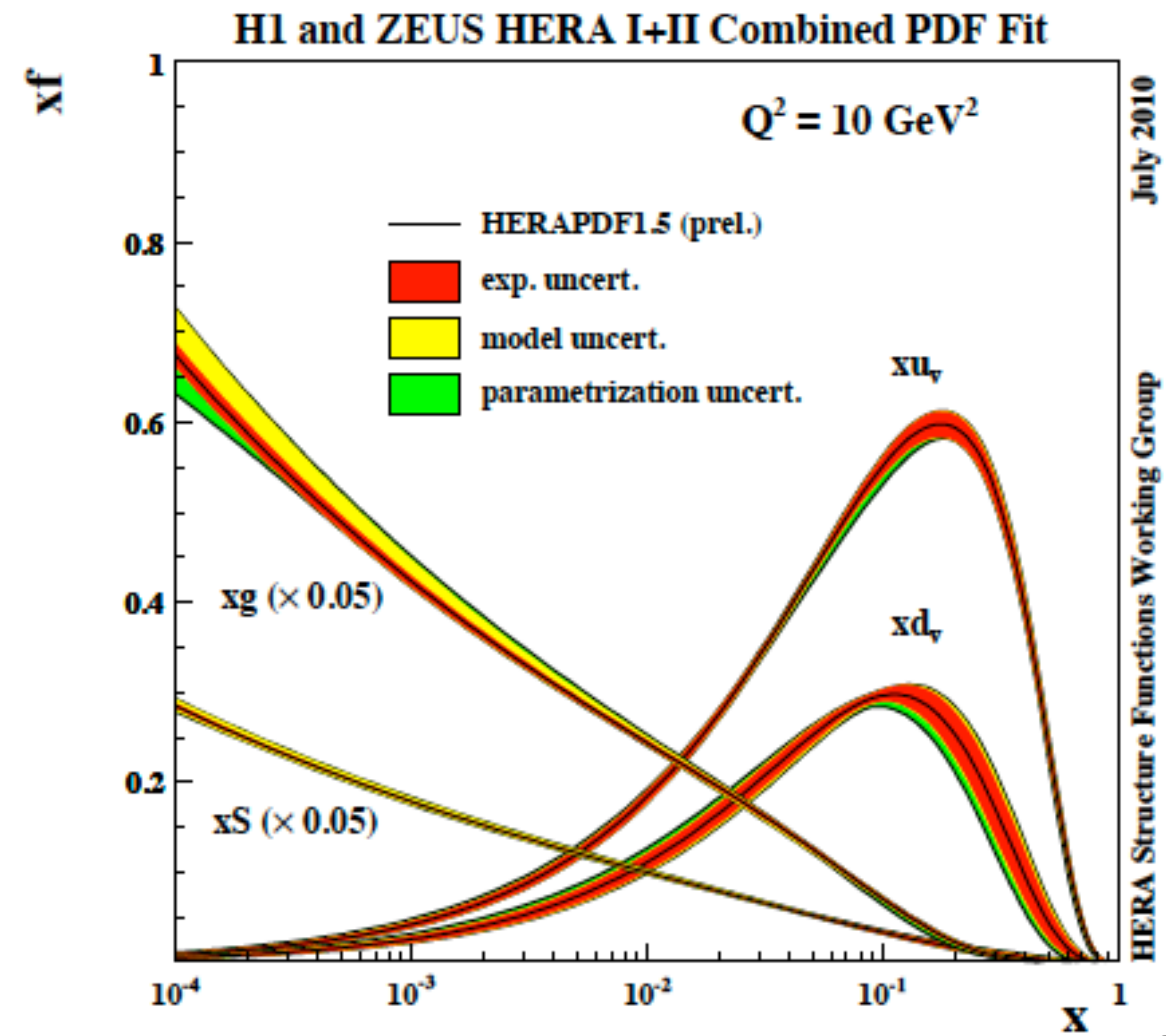
Legacy from HERA:

- Structure functions in an extended x-Q^2 range, xg $\propto 1/x^\lambda$, $\lambda>0$.
- Large fraction of diffraction $\sigma_{diff}/\sigma_{tot}\sim 10\%$.
- But: no eA/eD, kinematical reach at small x, luminosity at high x / for searches (odderon,...), flavour decomposition, TMDs,...





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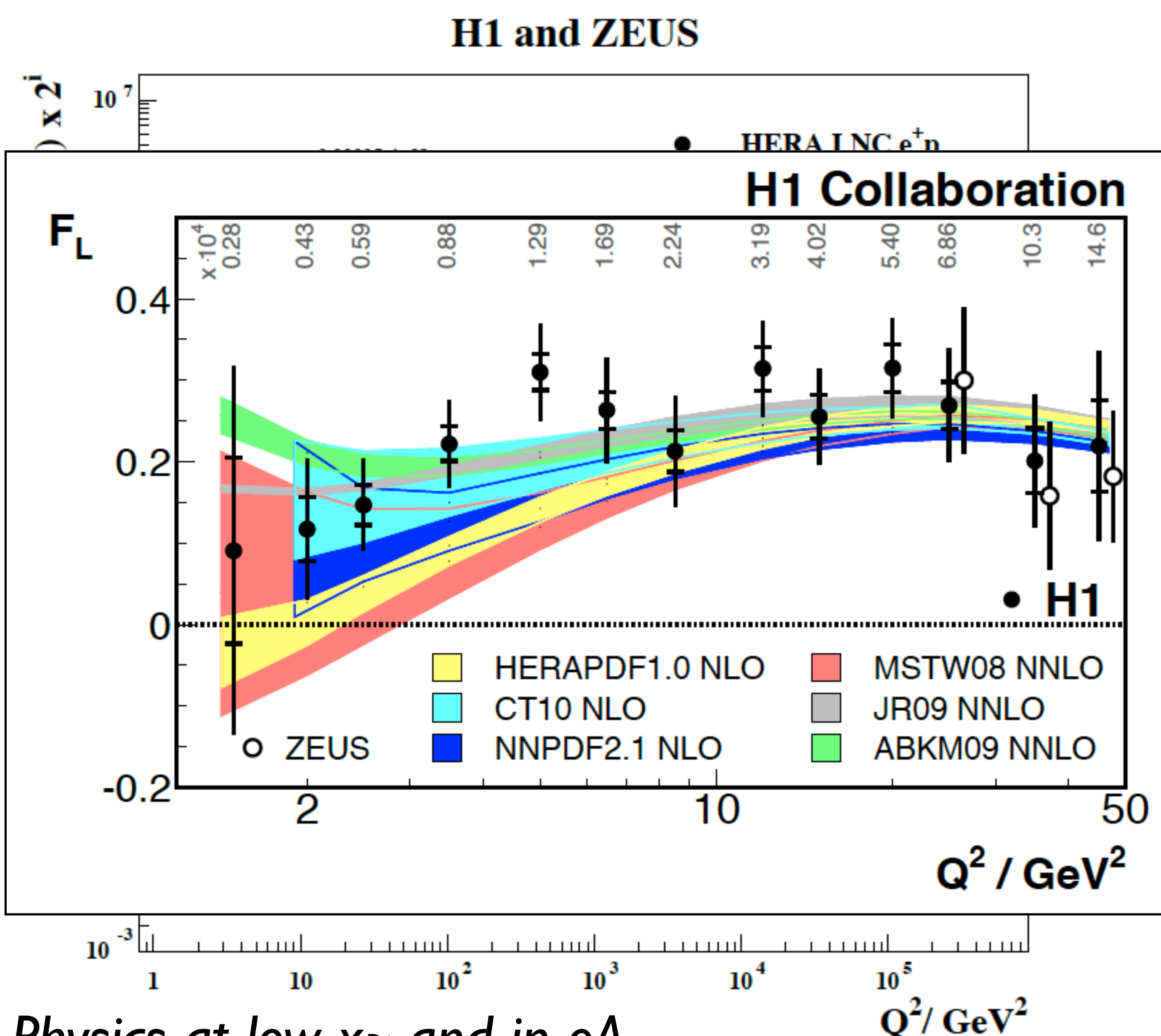

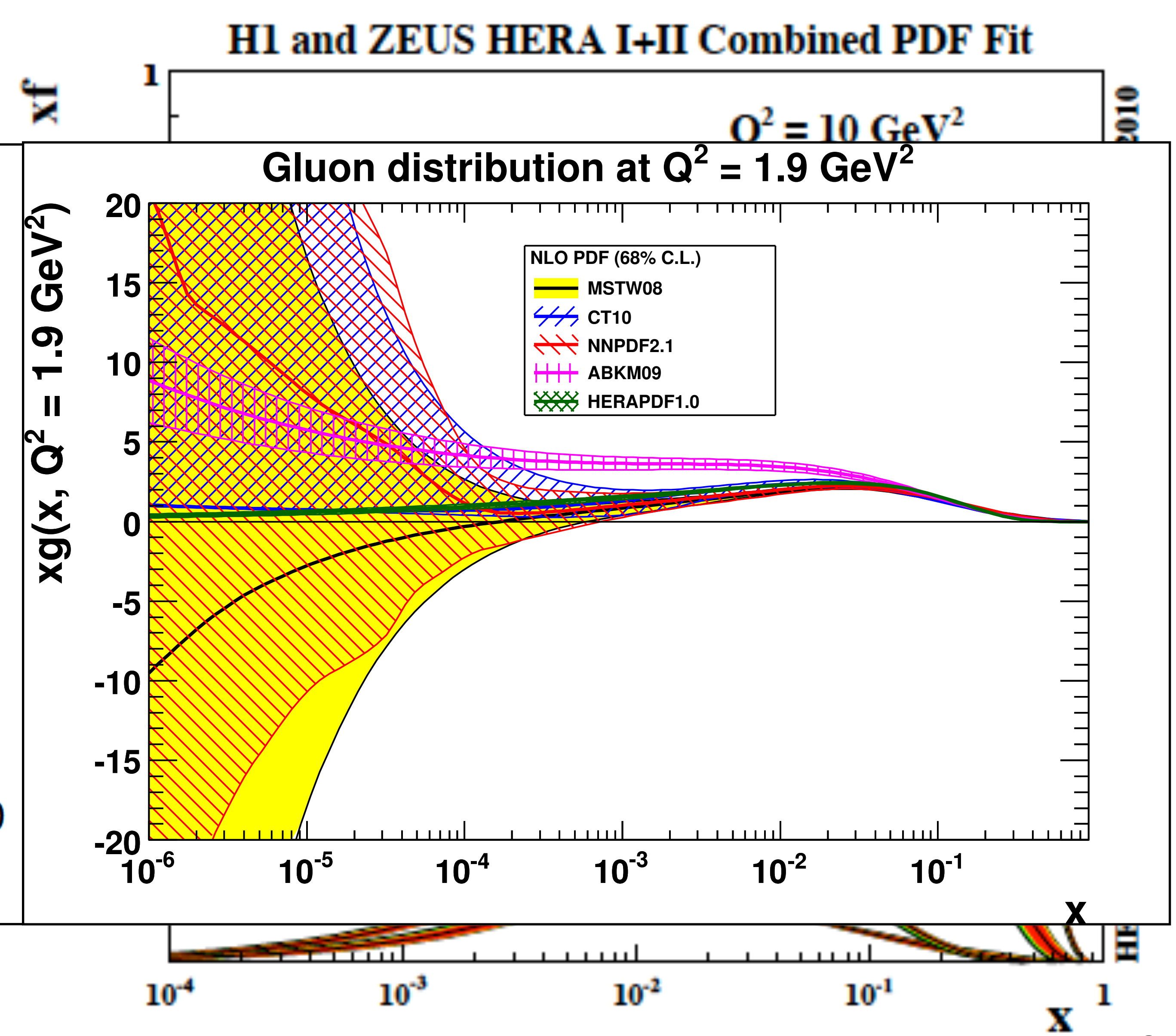

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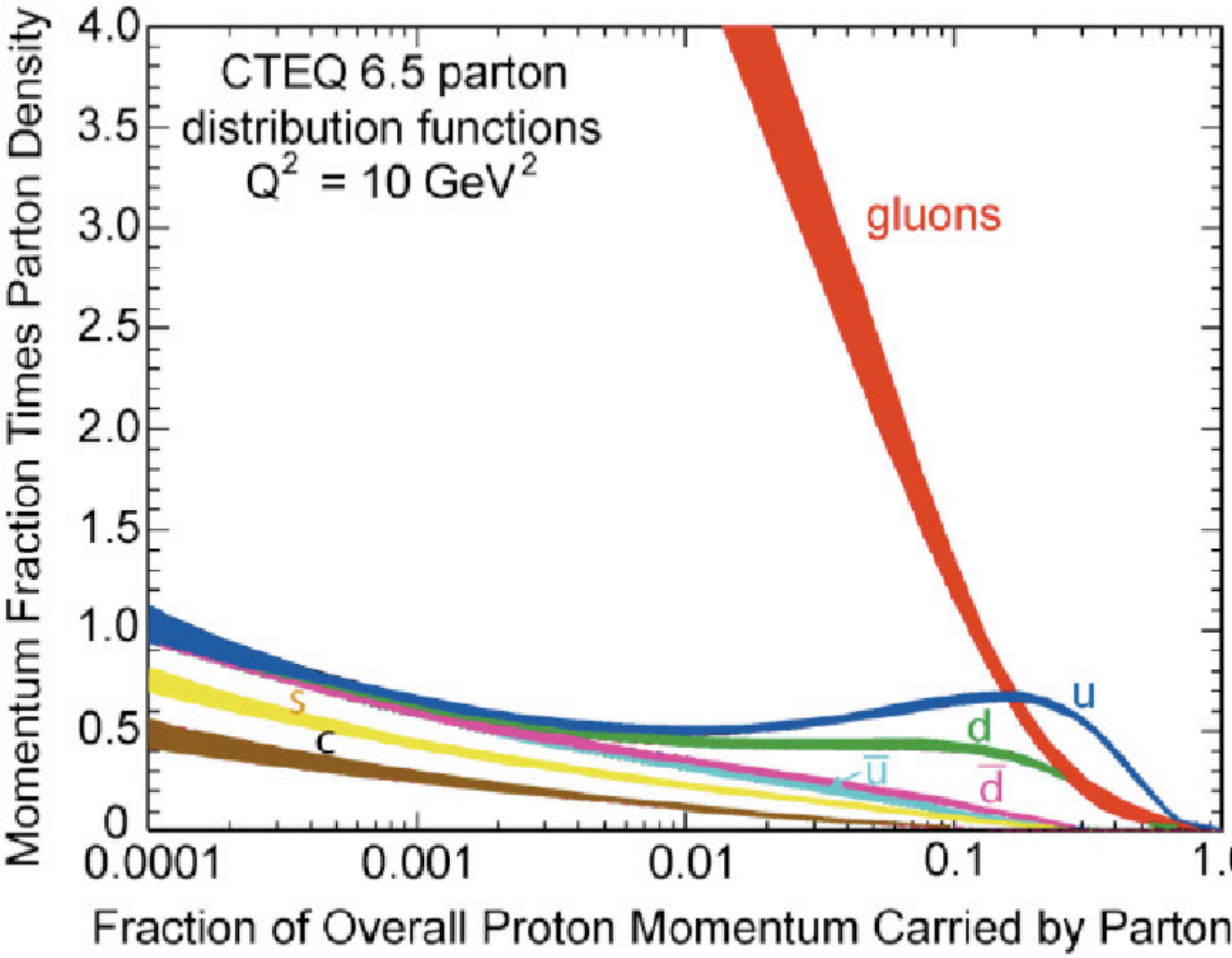

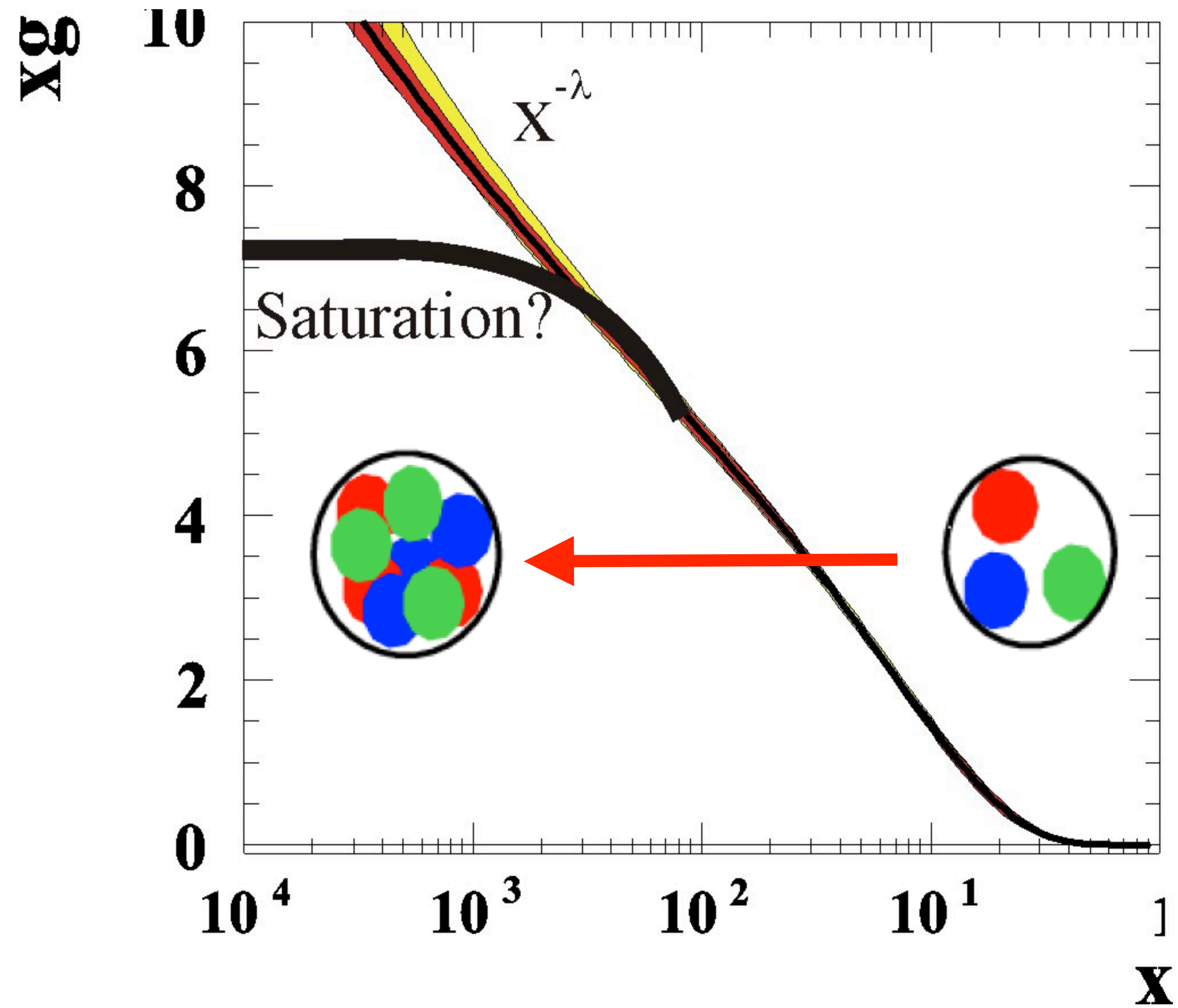

- QCD radiation of partons when x decreases leads to a large number of partons (gluons), provided each parton evolves independently (linearly, $\Delta[xg] \propto xg$).
- This independent evolution breaks at high densities (<u>small x or high mass number A</u>): non-linear effects ($g \leftrightarrow gg$, $\Delta[xg] \propto xg - k(xg)^2$).

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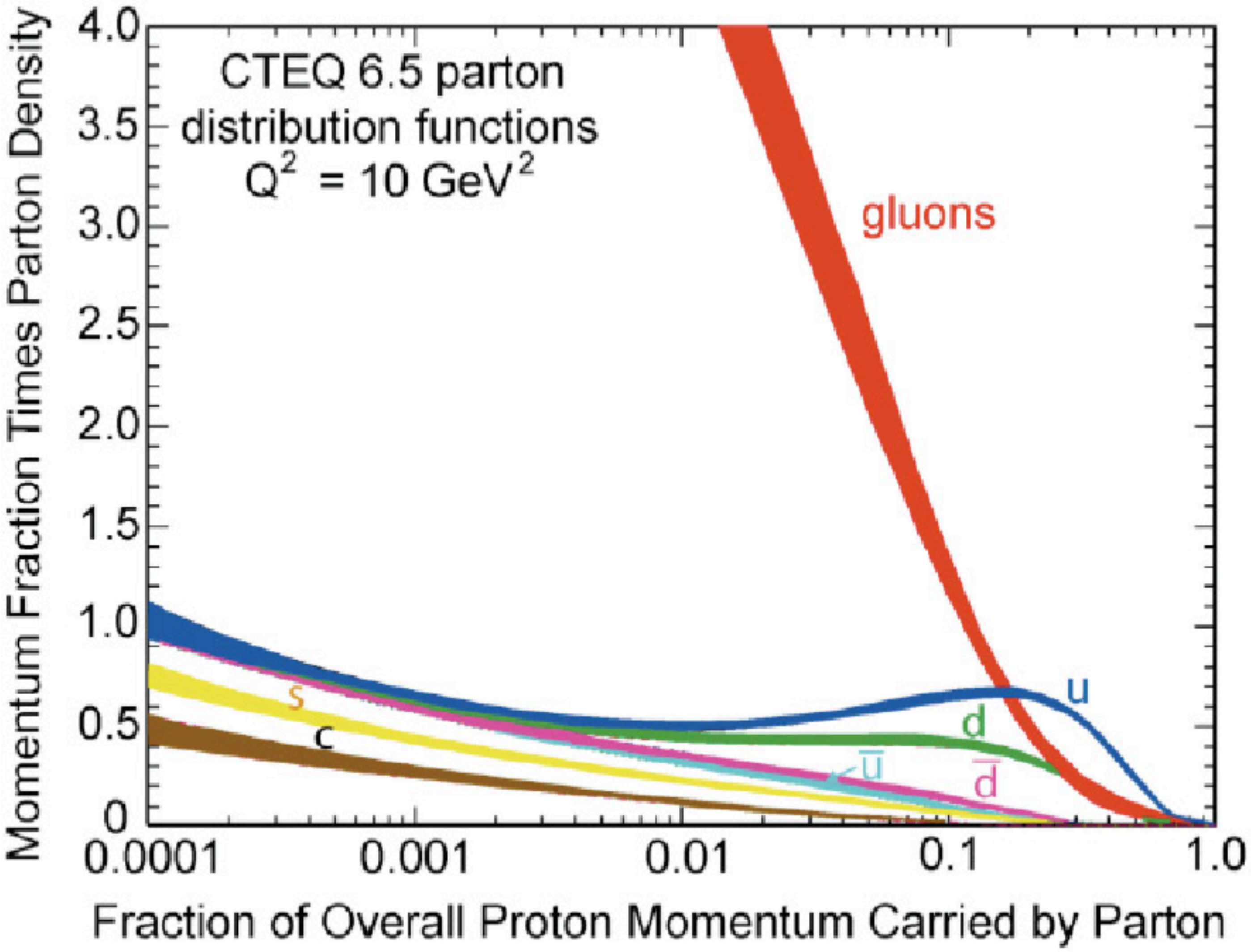

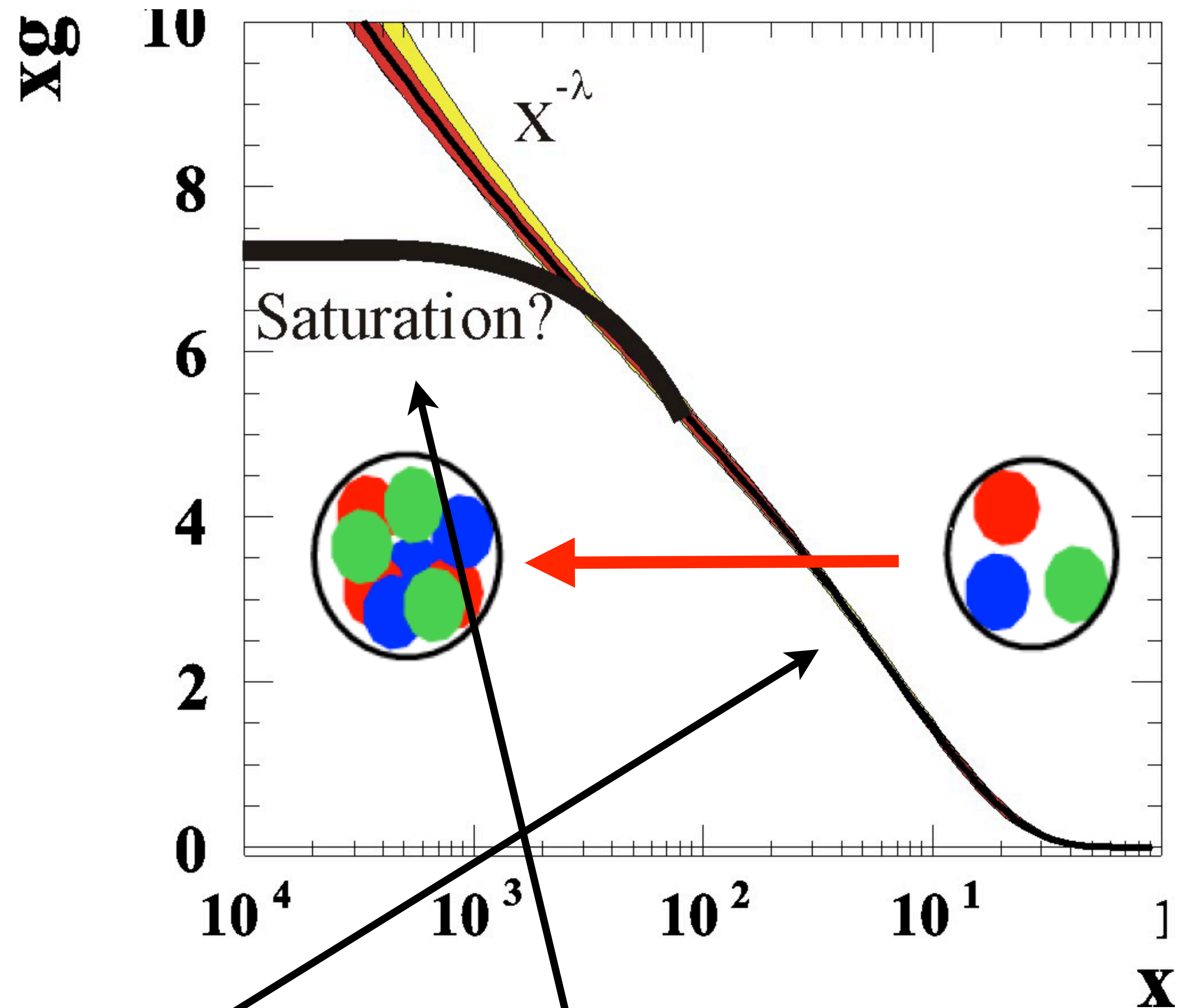

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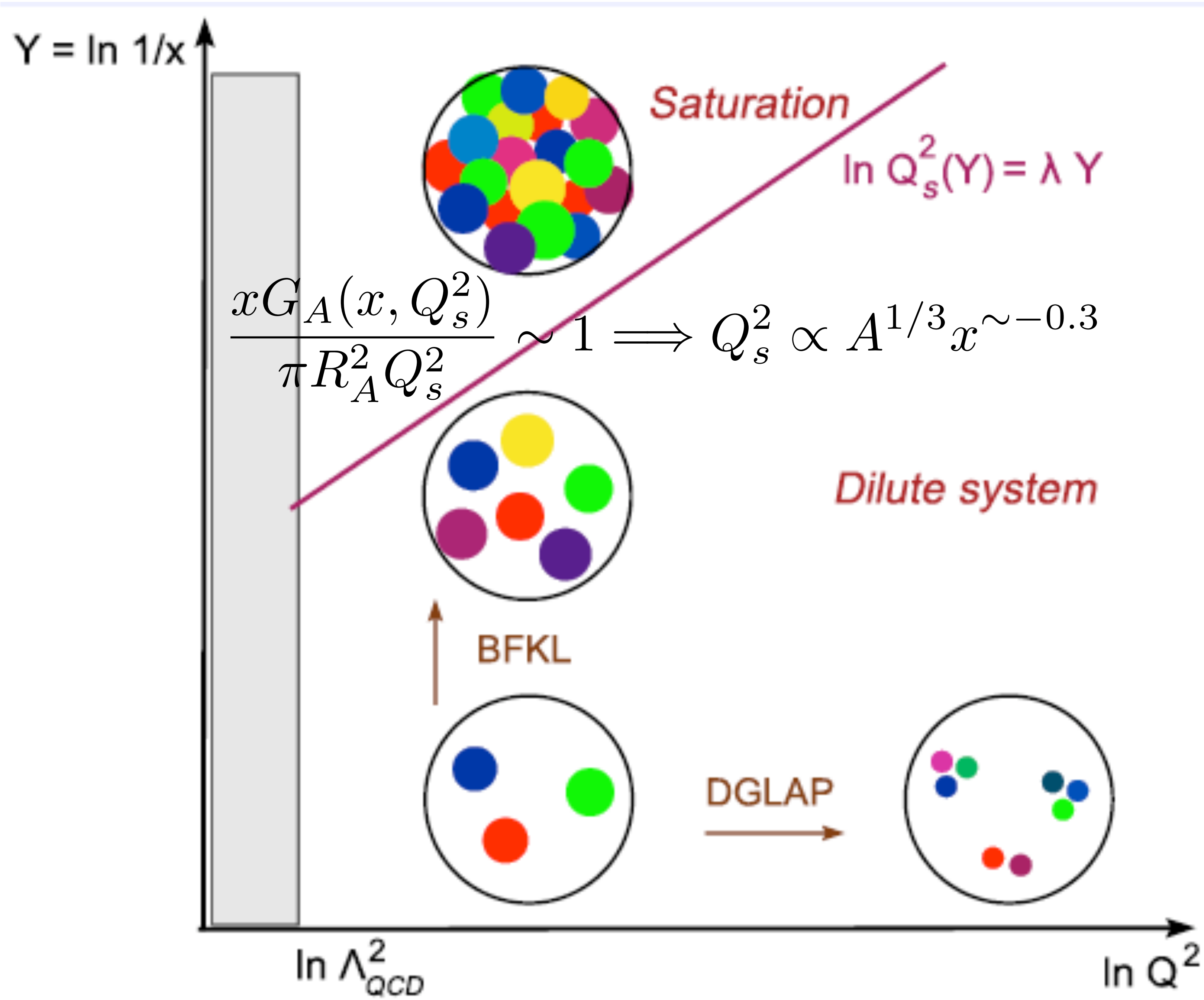

Origin in the early 80's: GLR, Mueller et al, McLerran-Venugopalan.

Our aims: understanding

- The implications of unitarity in a QFT.
- The behaviour of QCD at large energies.
- The hadron wave function at small x.
- The initial conditions for the creation of a dense medium in heavy-ion collisions.

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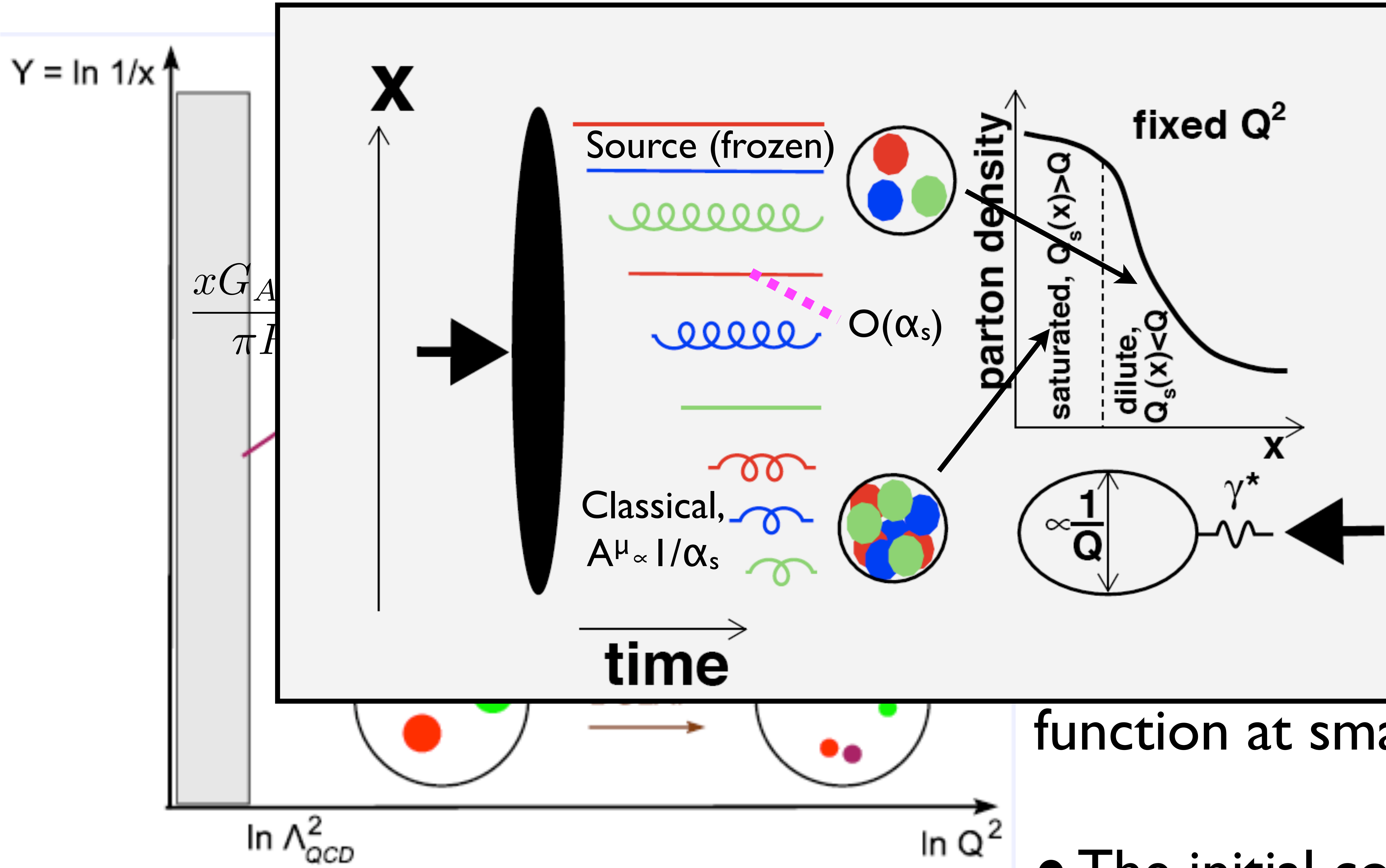

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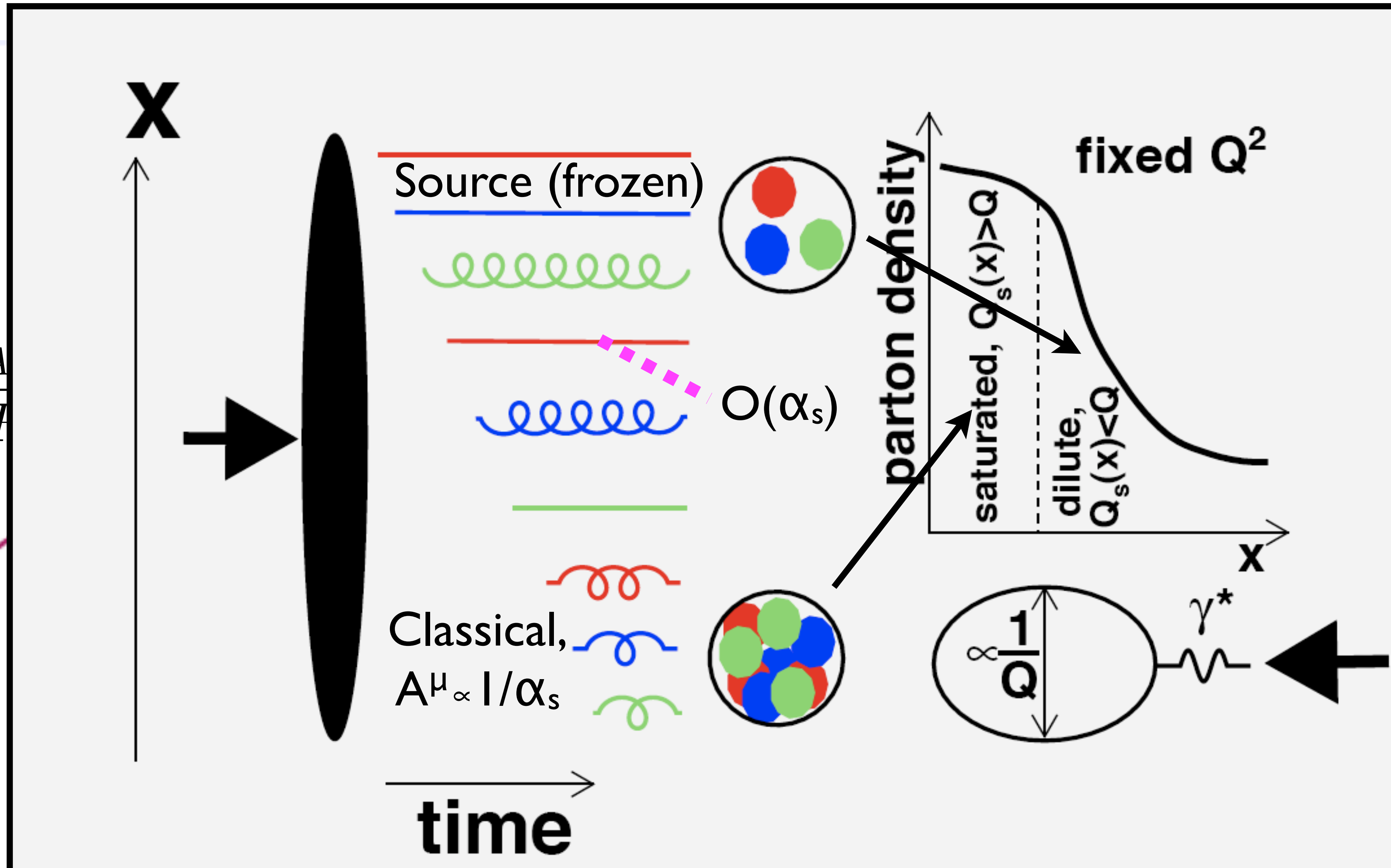


Questions:

- Theory: can the dense regime be described using pQCD techniques? Or non-perturbative - Regge, AdS/QCD,...? Which factorisation is at work?
- Experiment: where do present/future experimental data lie?

Status of small-x physics:

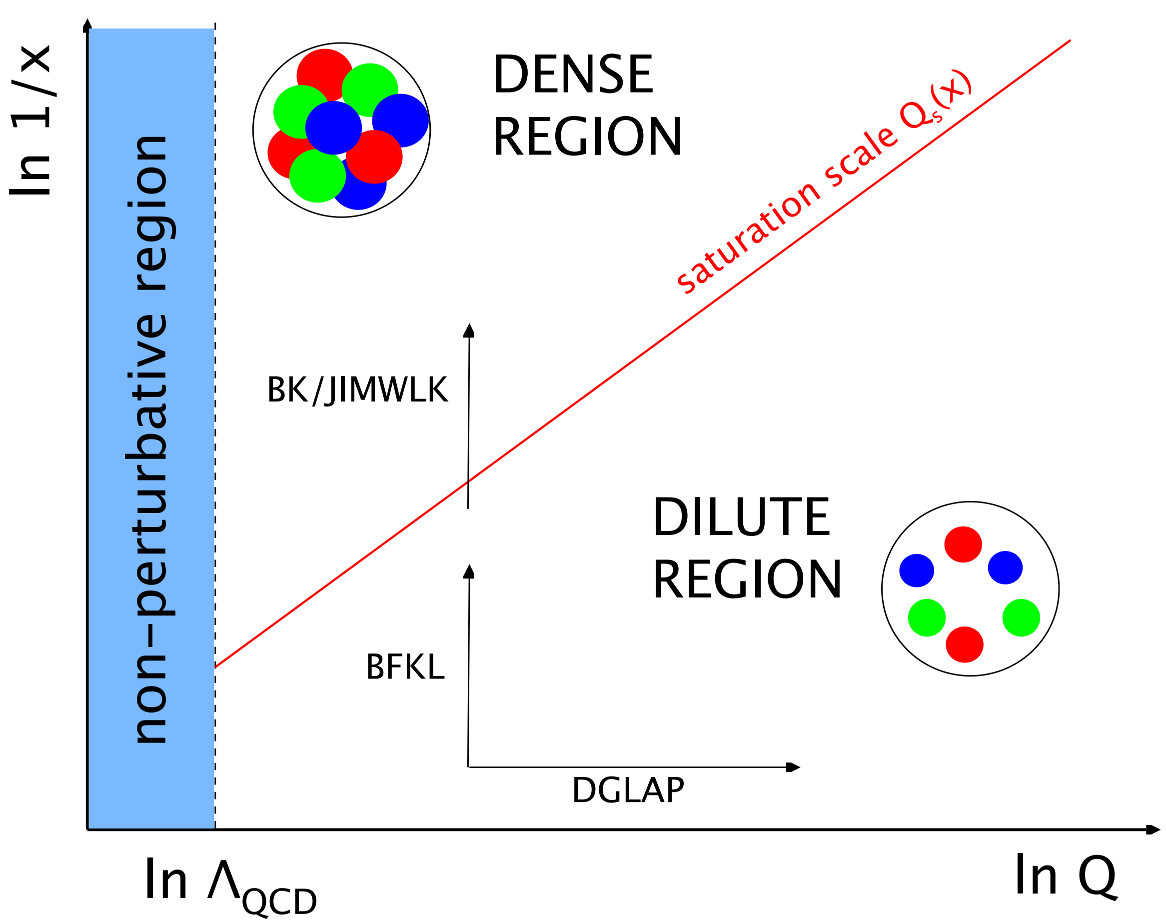
• Three pQCD-based alternatives to describe small-x ep and eA data (differences at moderate $Q^2(>\Lambda^2_{QCD})$ and small x):

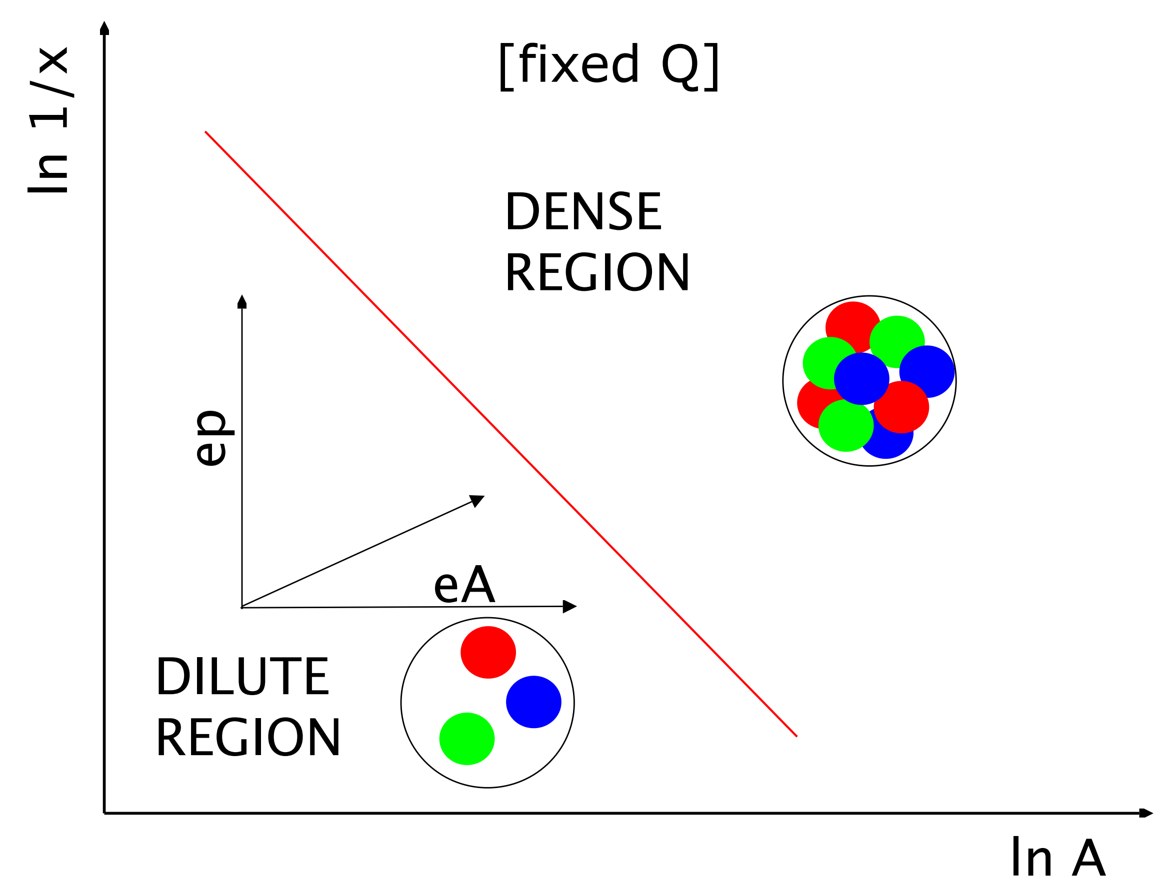
→ DGLAP evolution (fixed order PT).

→ Resummation schemes.

→ 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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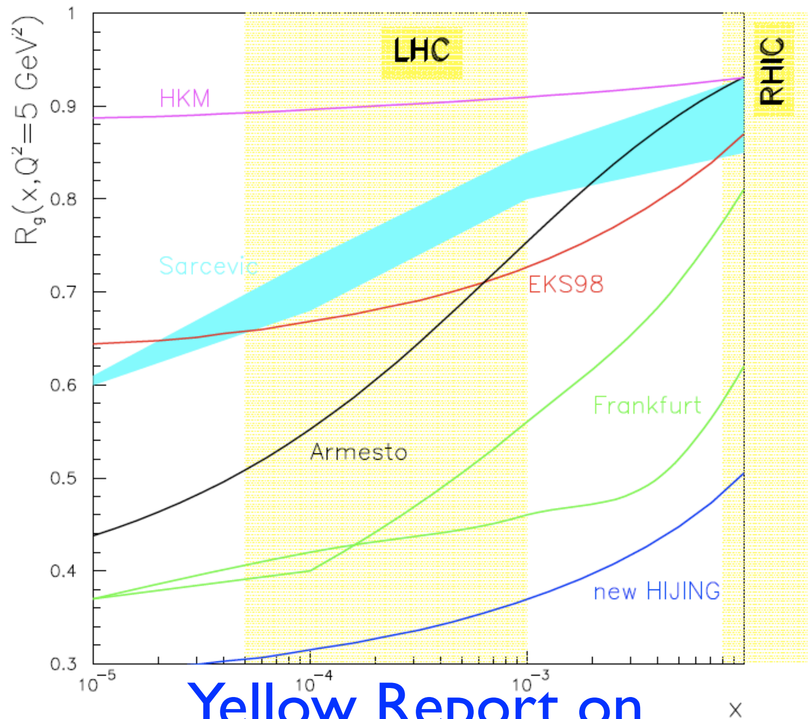
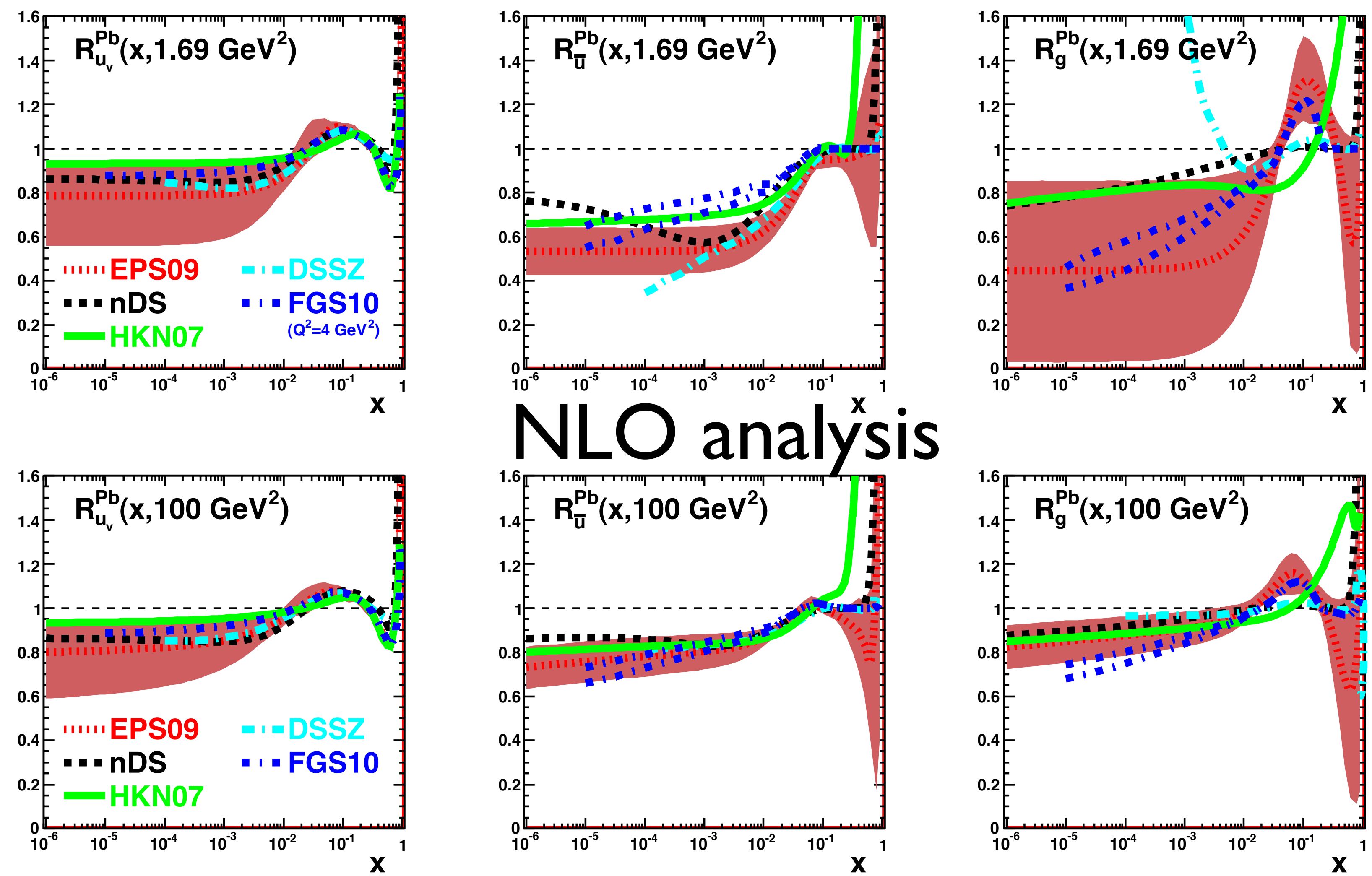


Yellow Report on Hard Probes, 2004

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

- Available DGLAP analysis at NLO show large uncertainties at small scales and x.
- eA colliders not available before ~ 2020: EIC, LHeC?



NLO analysis

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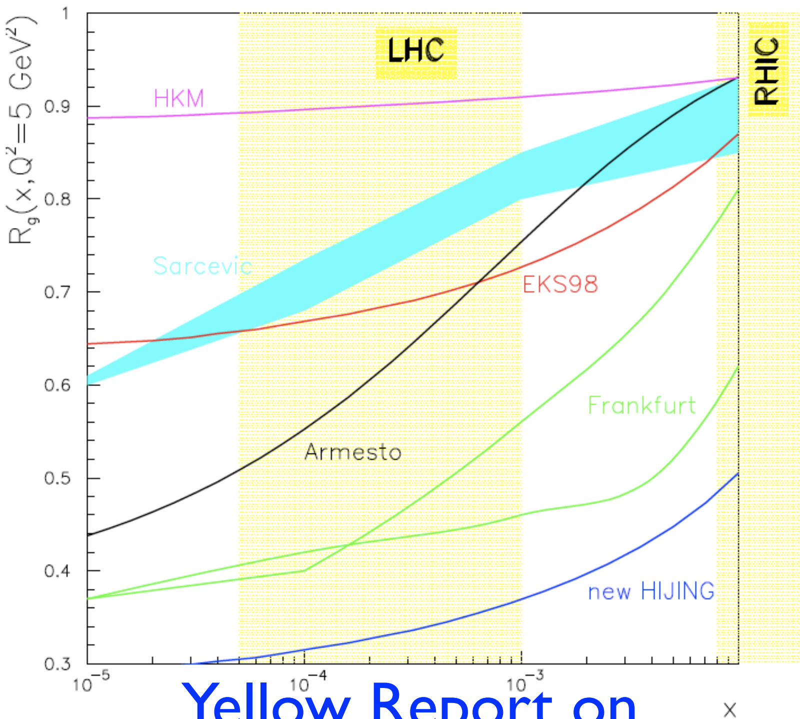

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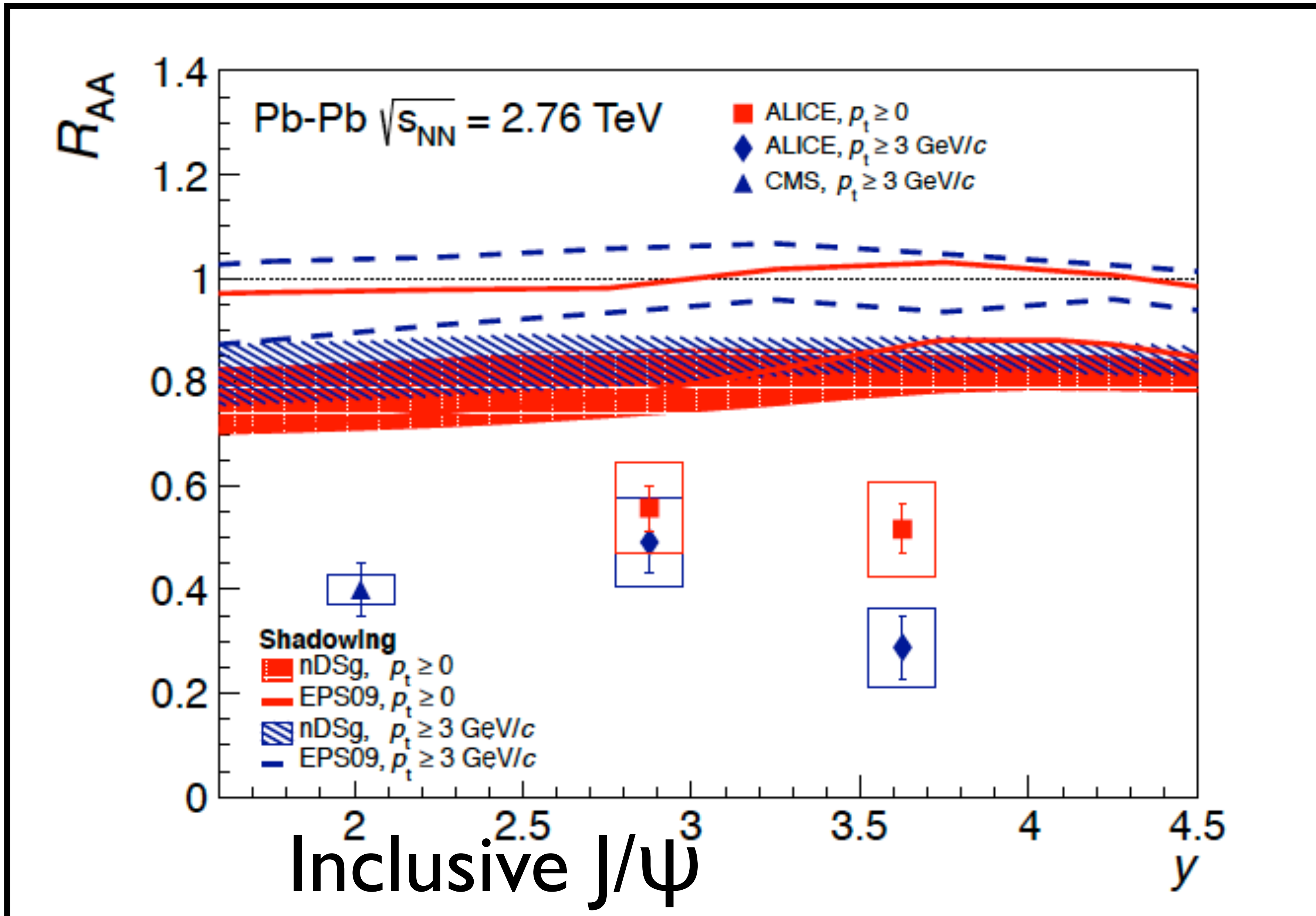

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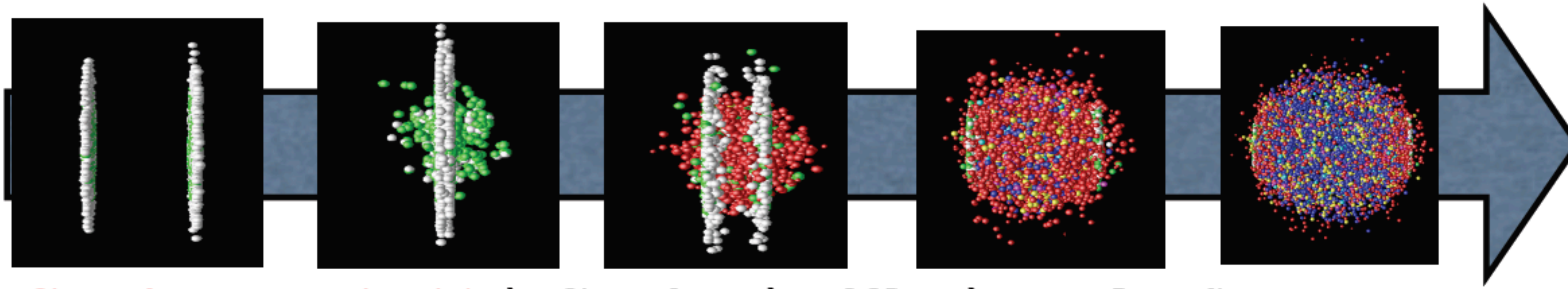
Relevance for the HI program:



- 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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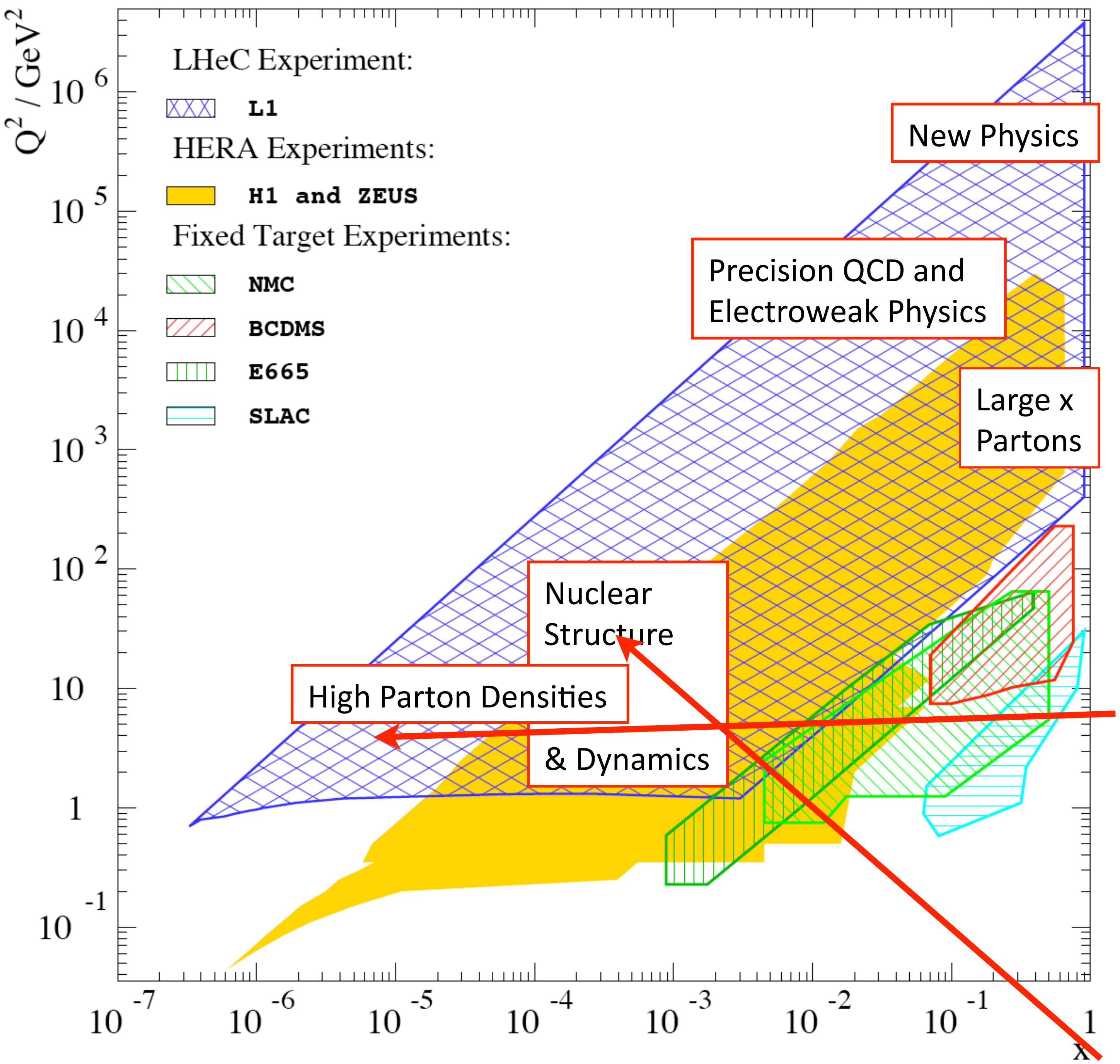
Project:

- **LHeC@CERN** → ep/eA experiment using p/A from the LHC: E_p=7 TeV, E_A=(Z/A)E_p=2.75 TeV/nucleon for Pb.
- New e^+/e^- accelerator: $E_{cm}\sim$1-2 TeV/nucleon (E_e=50-150 GeV).
- Compatible with pp/pA/AA LHC operation, power < 100 MW.

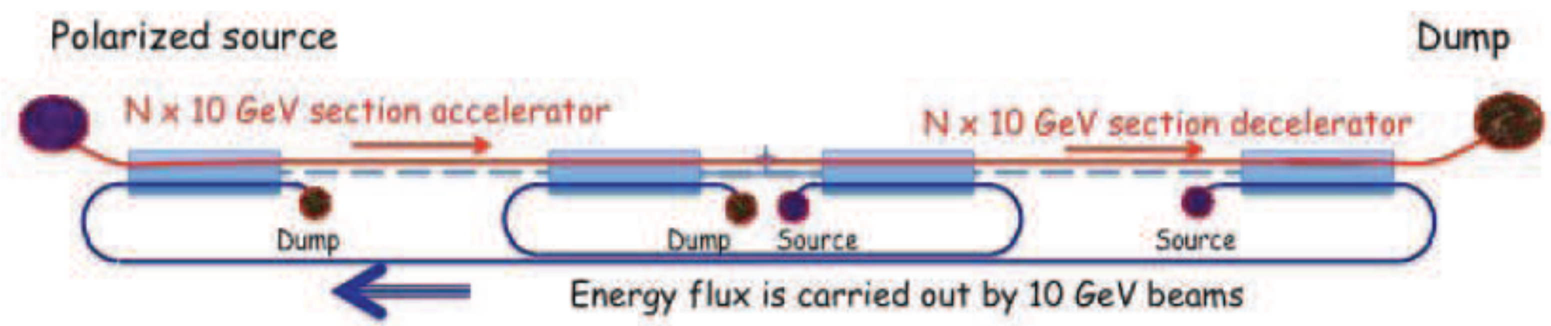
Requirements	LHeC	HERA	How?
high lumi for high x and Q^2	10^33	$1\text{-}5\times10^{31}$	
large acceptance	1-179 deg.	7-177 deg.	kinematic coverage
tracking	0.1 mrad	0.2-1 mrad	modern Si
EMcal	0.1 %	0.2-0.5 %	kinematic reconstruction
Hcal	0.5 %	1 %	tracking + calo e/h
accurate lumi/pol	0.5 %	1 %	demanding



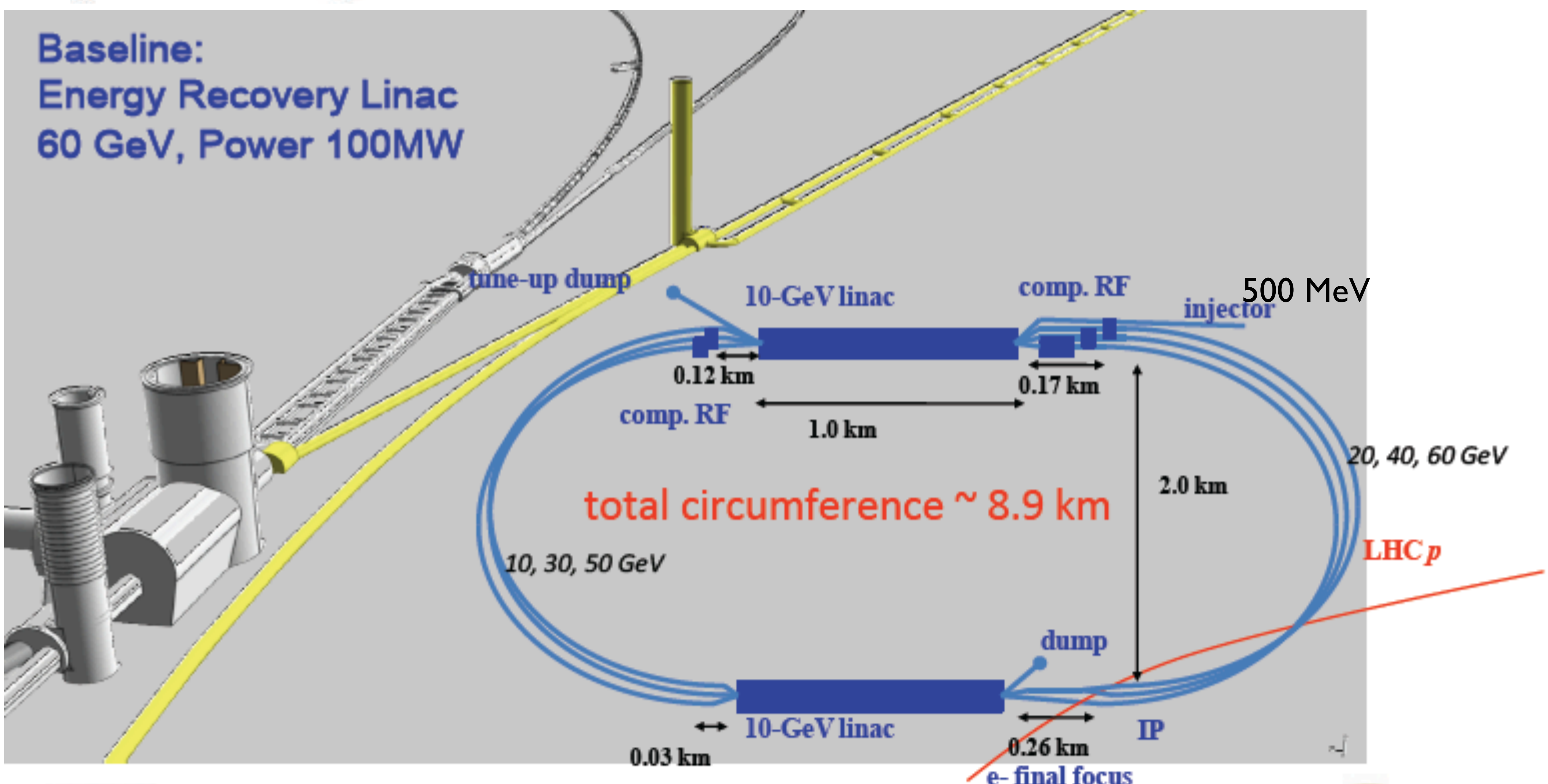
- Proton structure to a few 10^{-20} m: Q^2 lever arm.
- Precision QCD/EW physics.
- High-mass frontier (leptoquarks, excited fermions, contact interactions).
- Unambiguous access, in ep and eA, to a qualitatively novel regime of matter predicted by QCD.
- Substructure/parton dynamics inside nuclei with strong implications on QGP search.

Option A: Linac-Ring

HE LR, 140 GeV



HE LR, ER, 140 GeV



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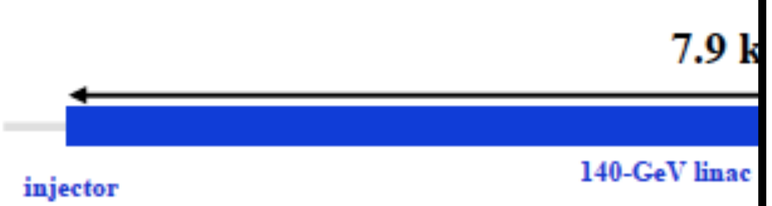

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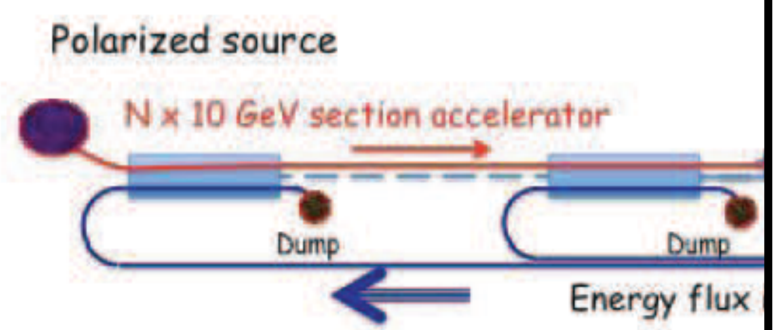
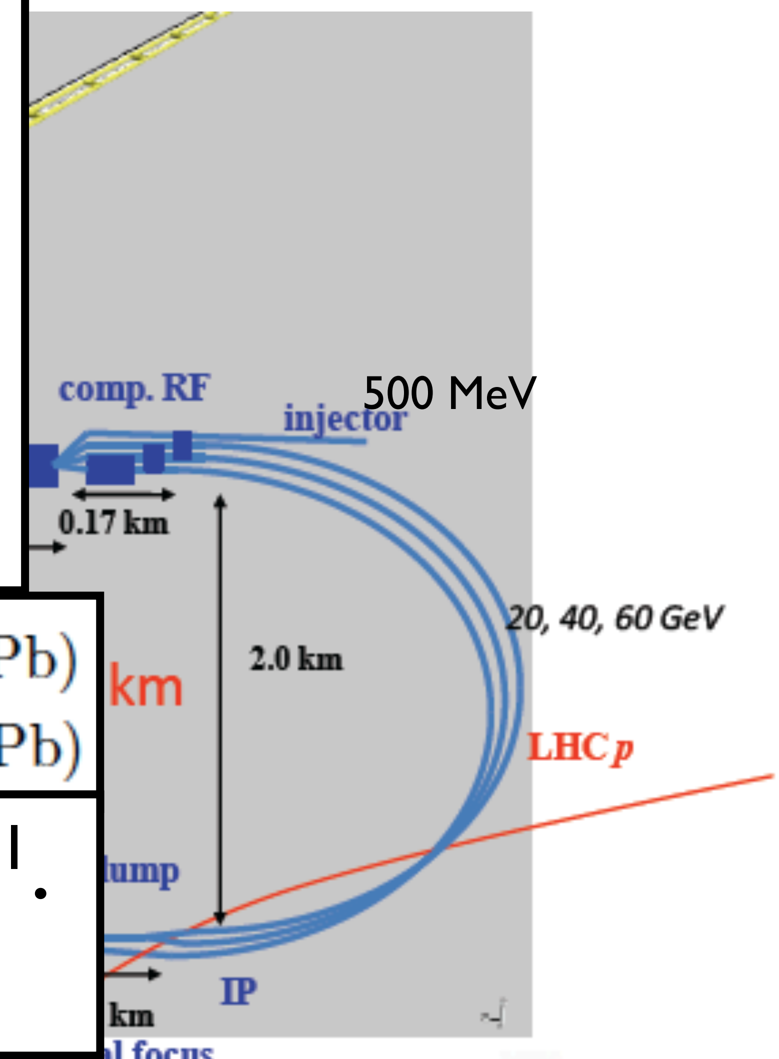


R, ER, 140 GeV

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

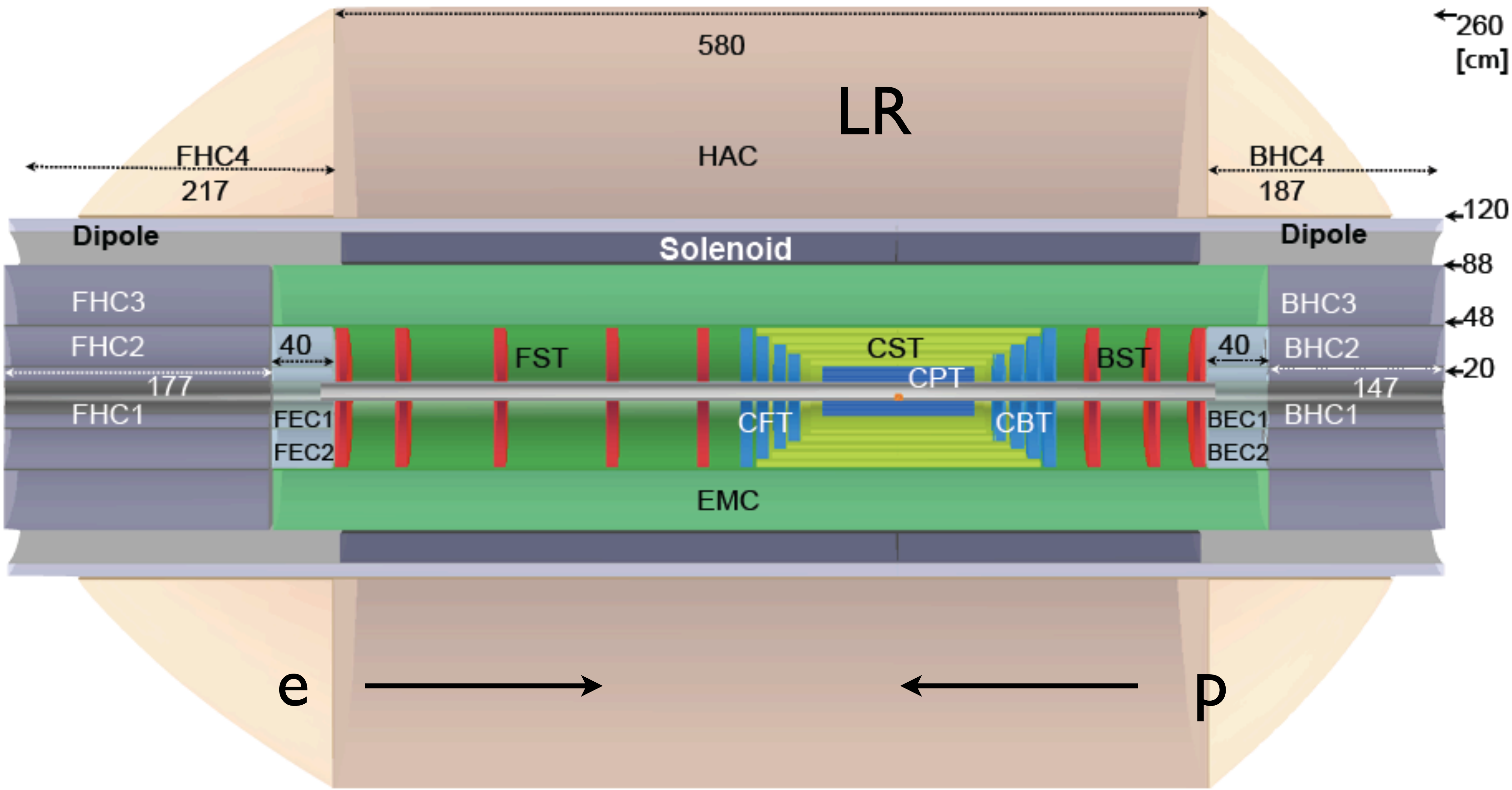


$$L_{eN} = \begin{cases} 9 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1} & \text{(Nominal Pb)} \\ 1.6 \times 10^{32}\ \text{cm}^{-2}\text{s}^{-1} & \text{(Ultimate Pb)} \end{cases}$$

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

Large L for e$^+$ challenging.

The detector: low-x/eA setup



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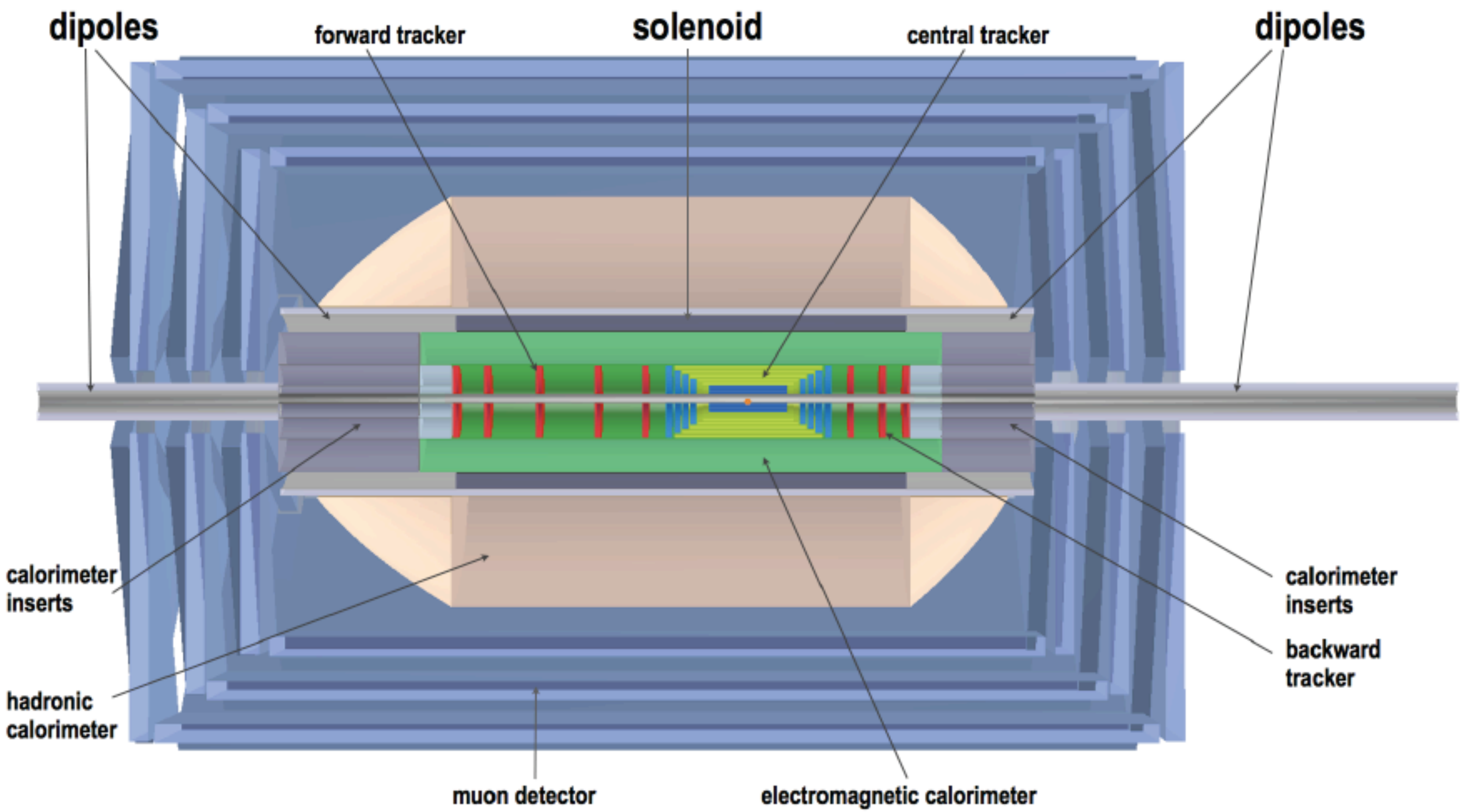

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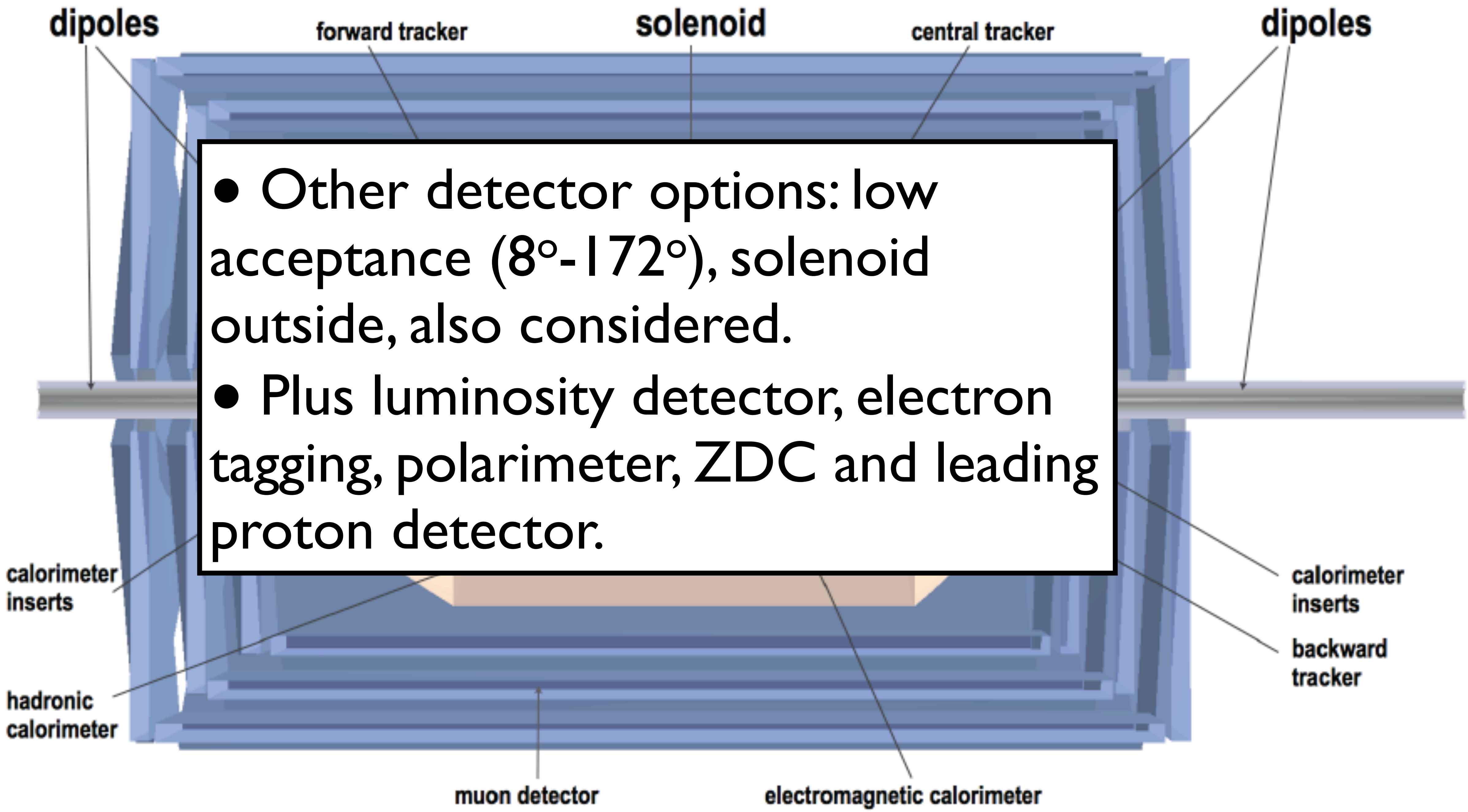
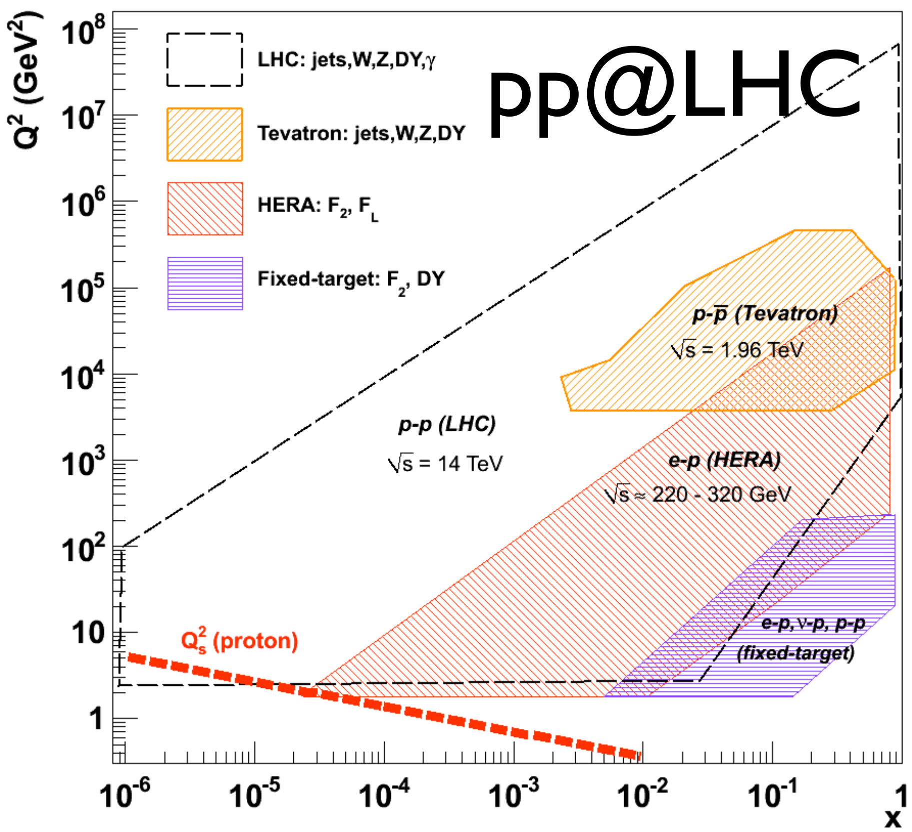
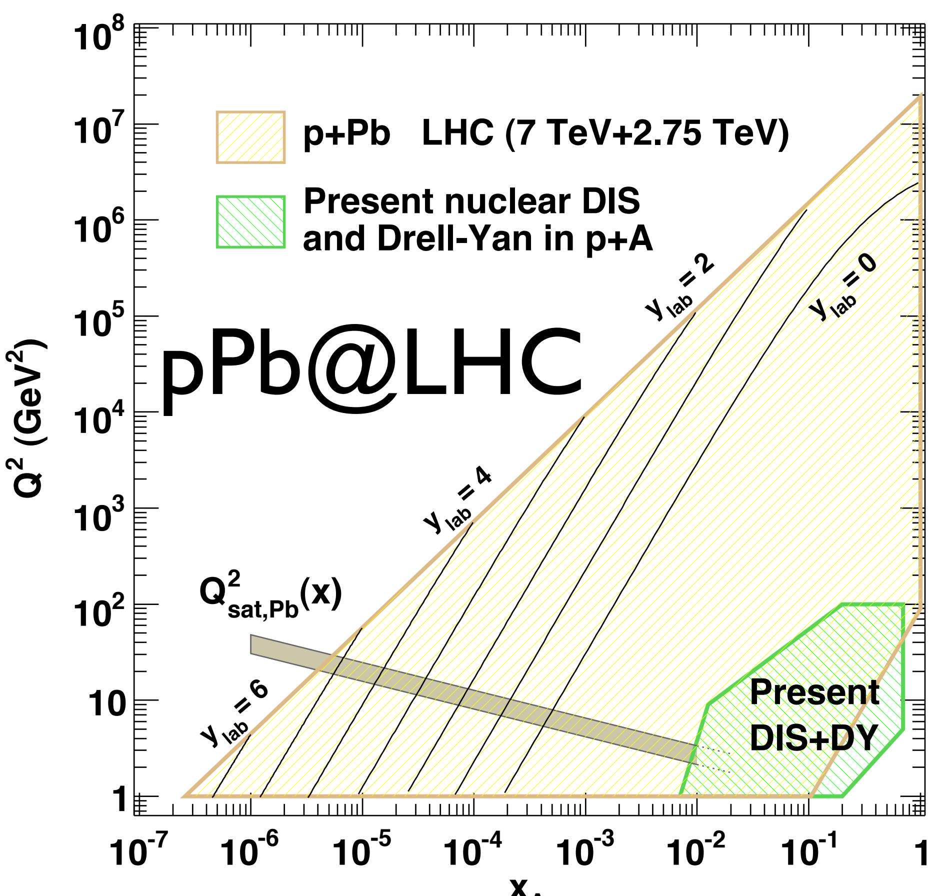


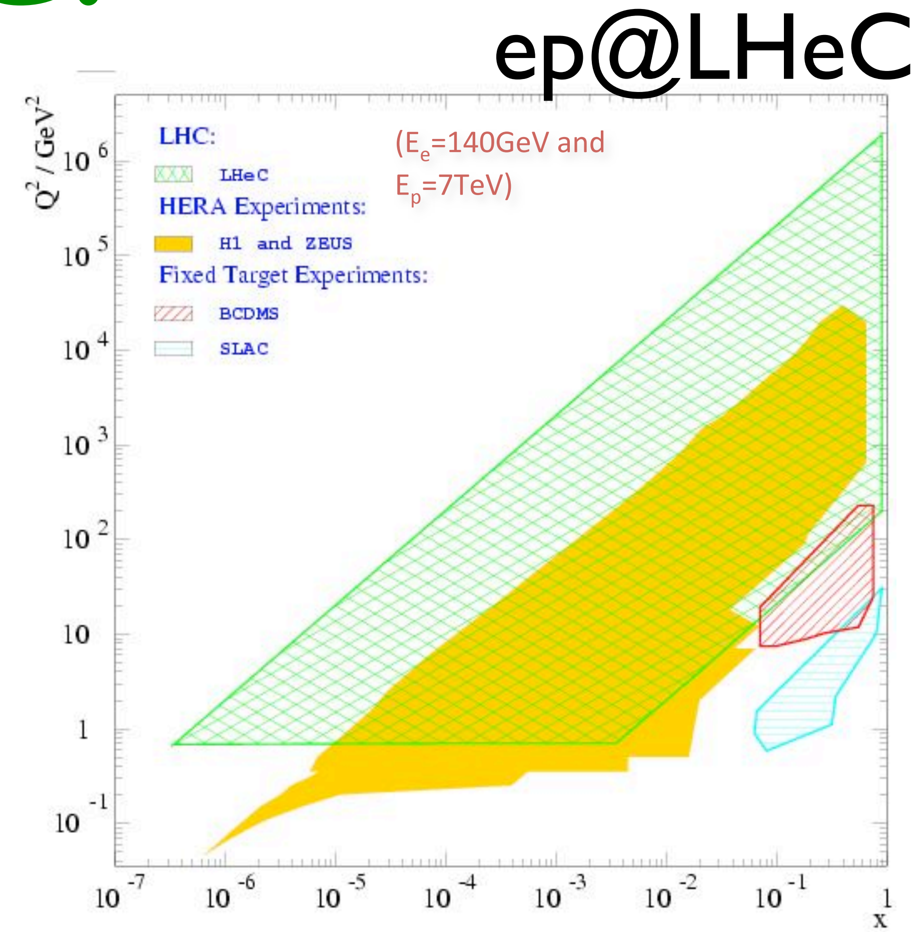
- Other detector options: low acceptance (8°-172°), solenoid outside, also considered.
- Plus luminosity detector, electron tagging, polarimeter, ZDC and leading proton detector.

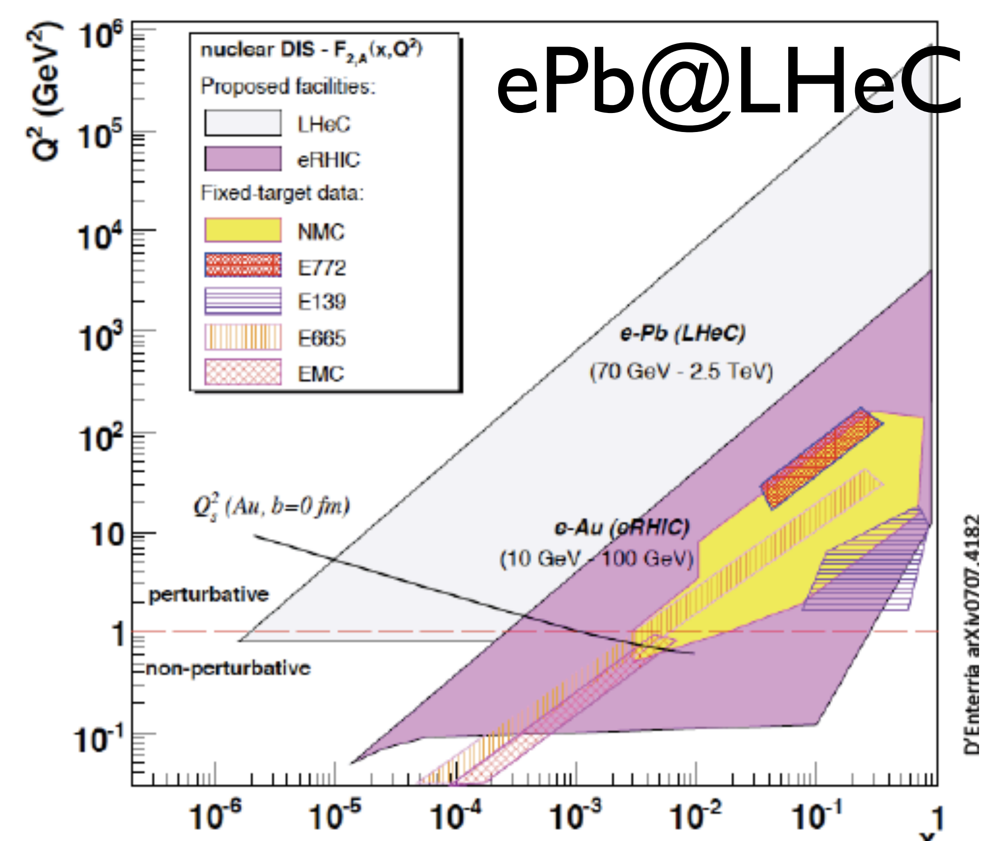
LHC vs. LHeC:





- The LHeC will explore a region overlapping with the LHC but in a much cleaner manner.





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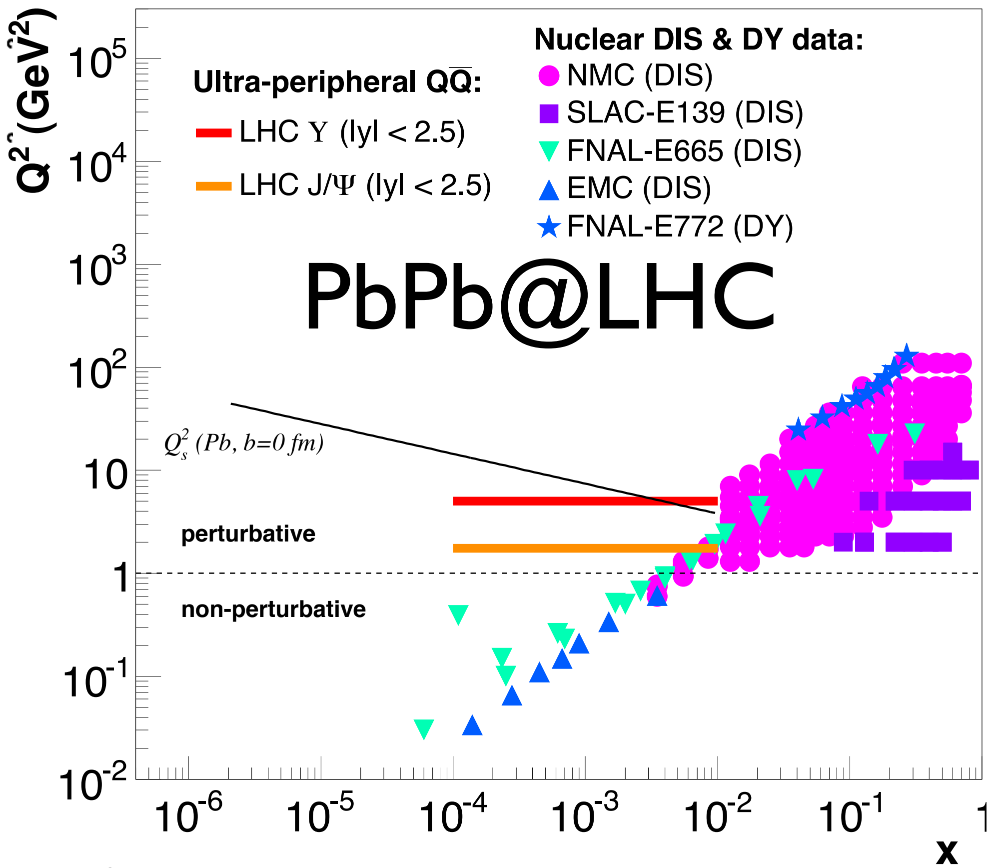

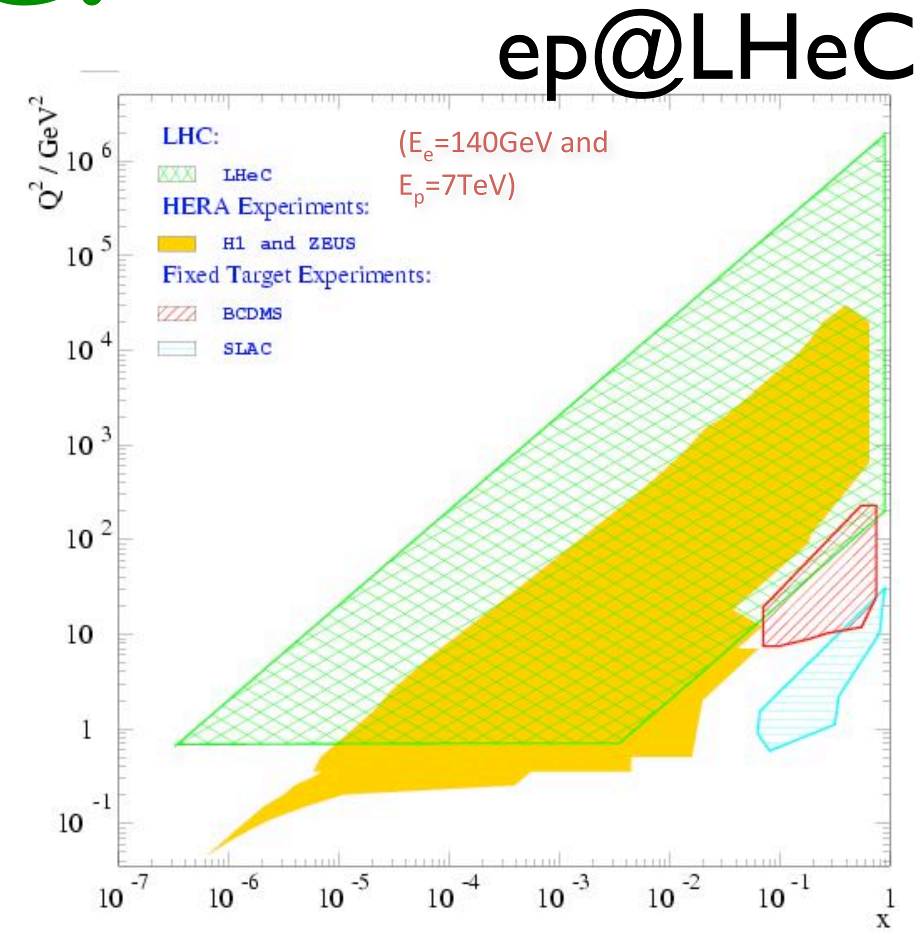

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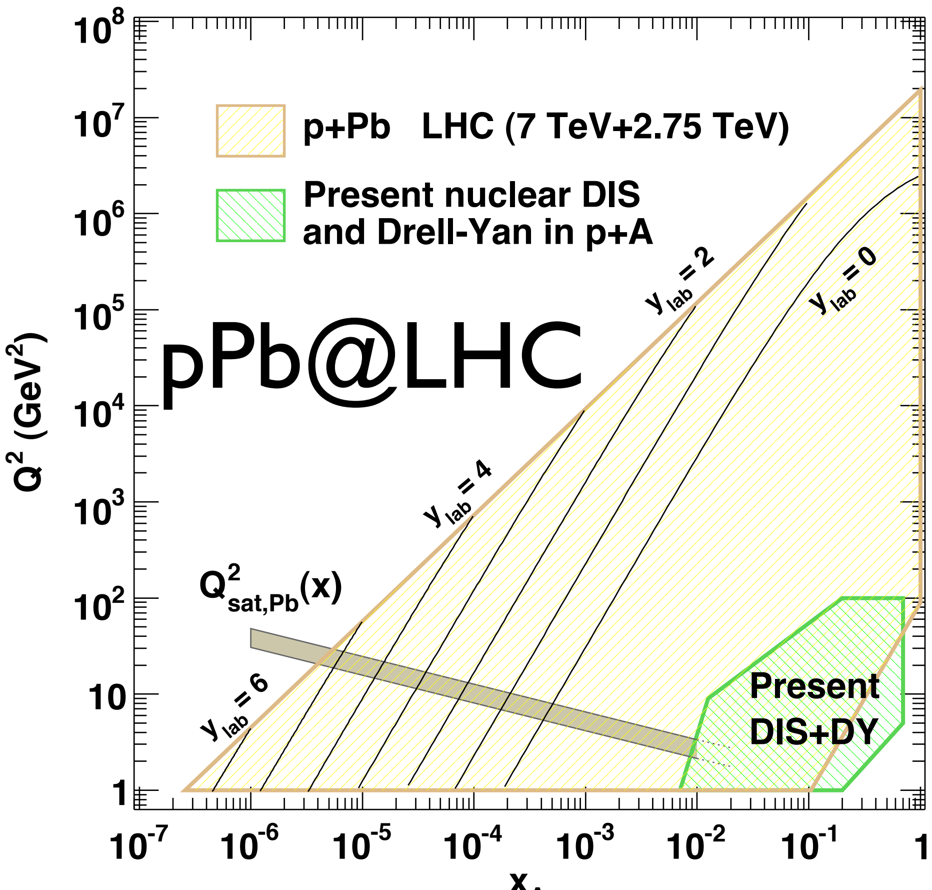

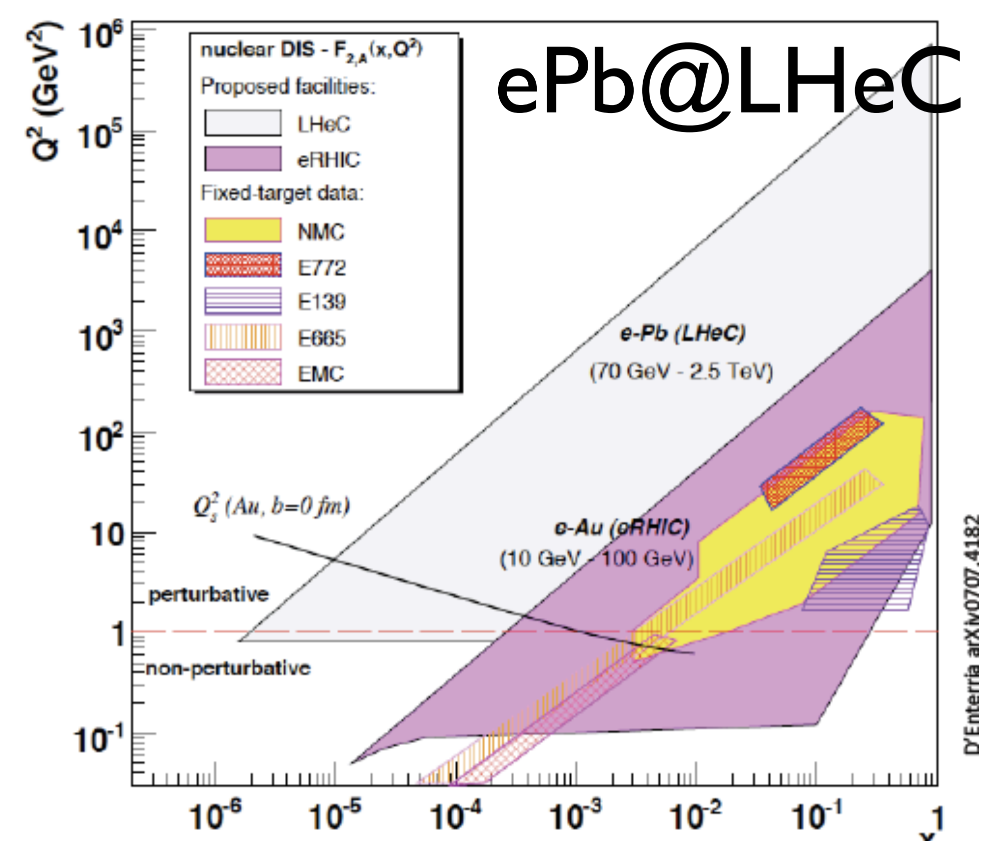

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- Parton densities poorly known at small x and small to moderate Q^2: uncertainties in predictions.
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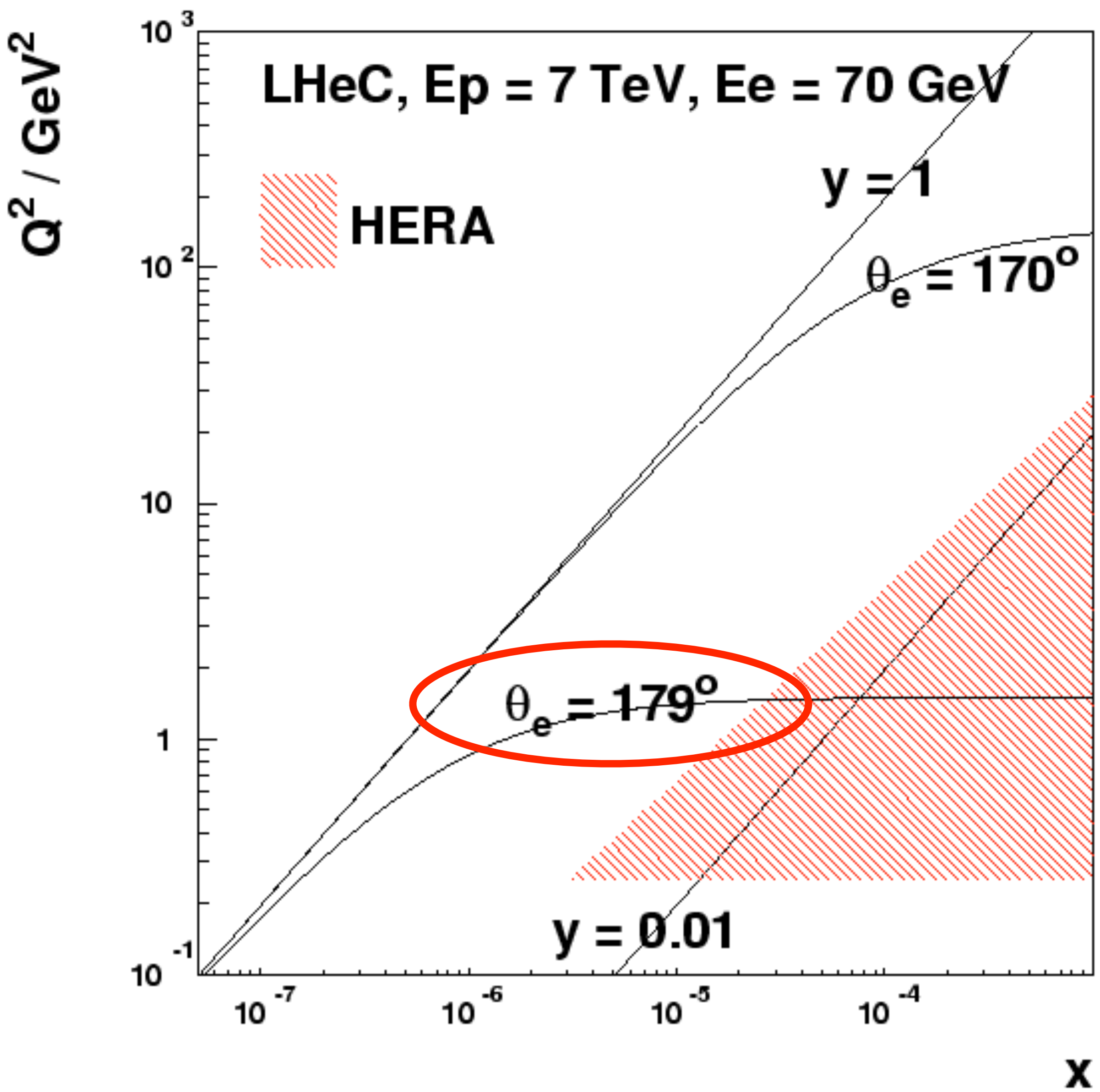

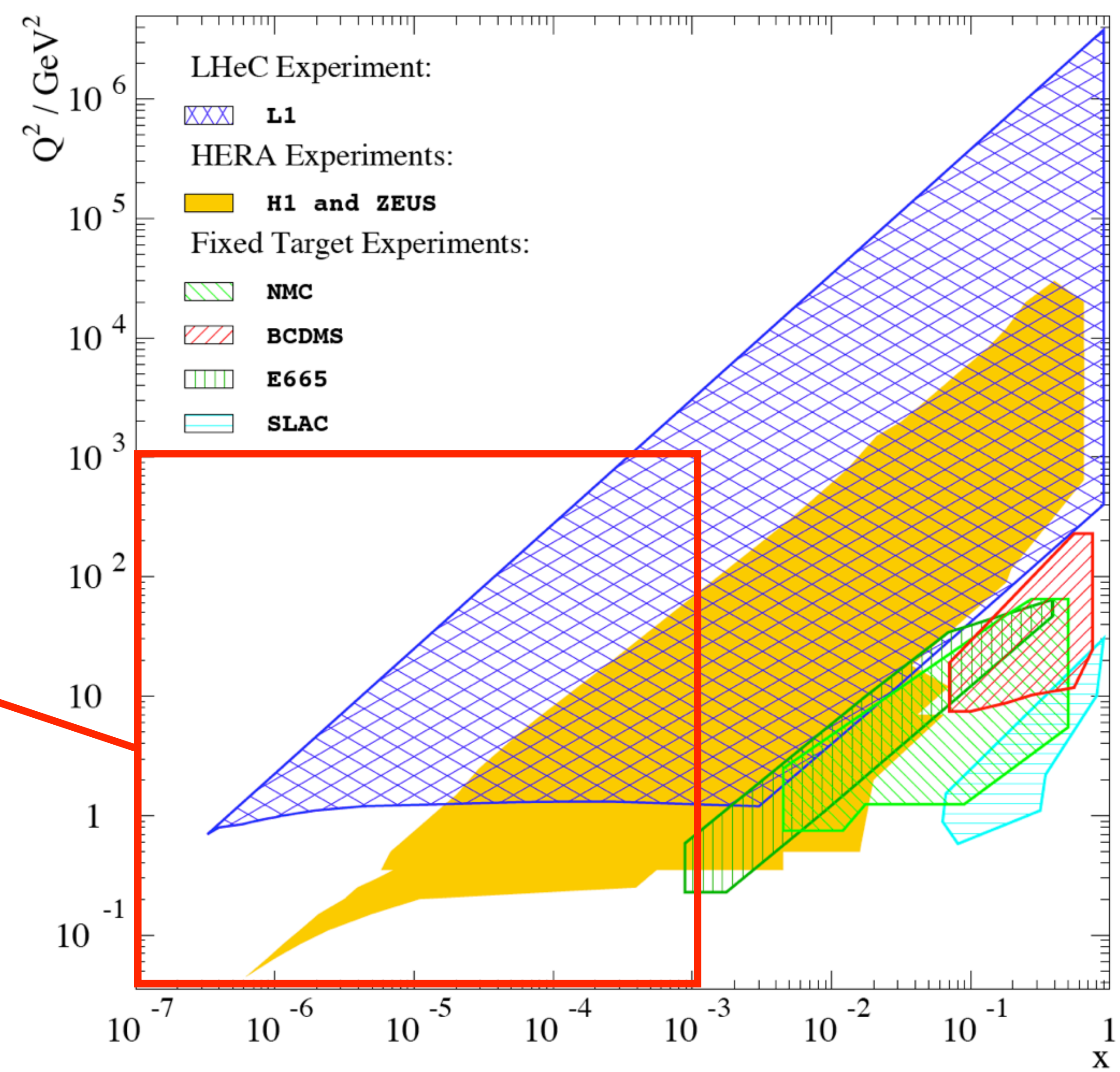

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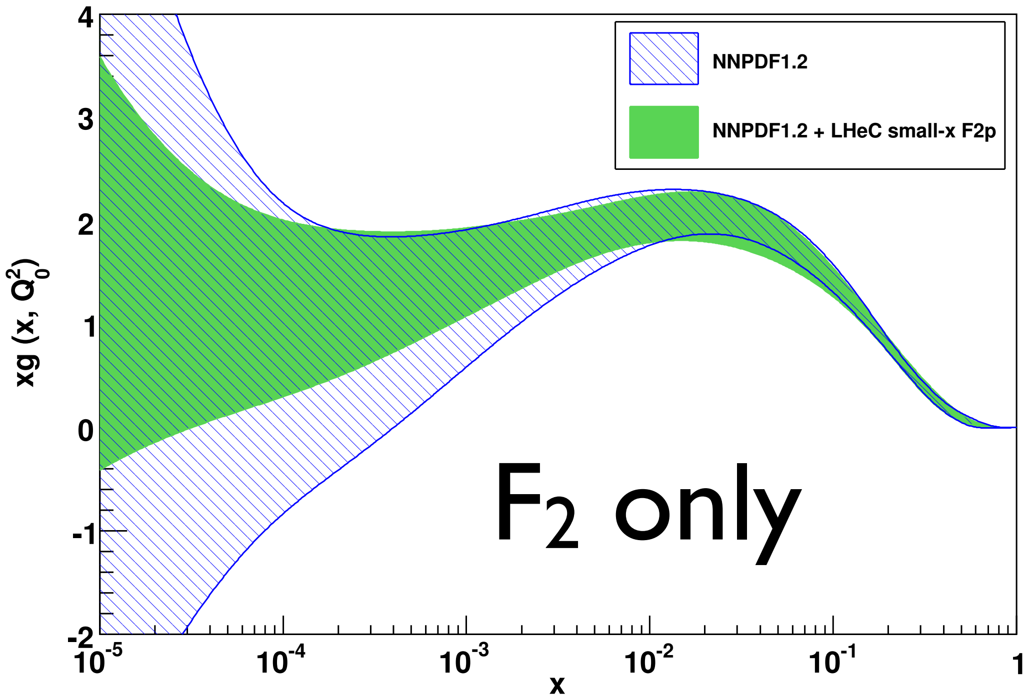
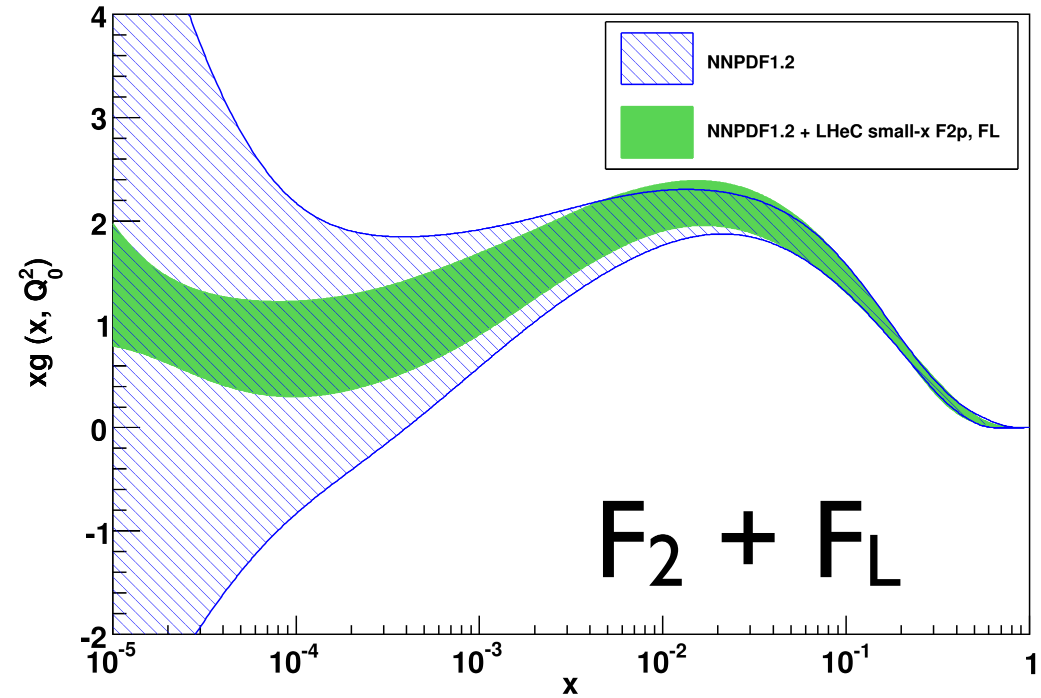
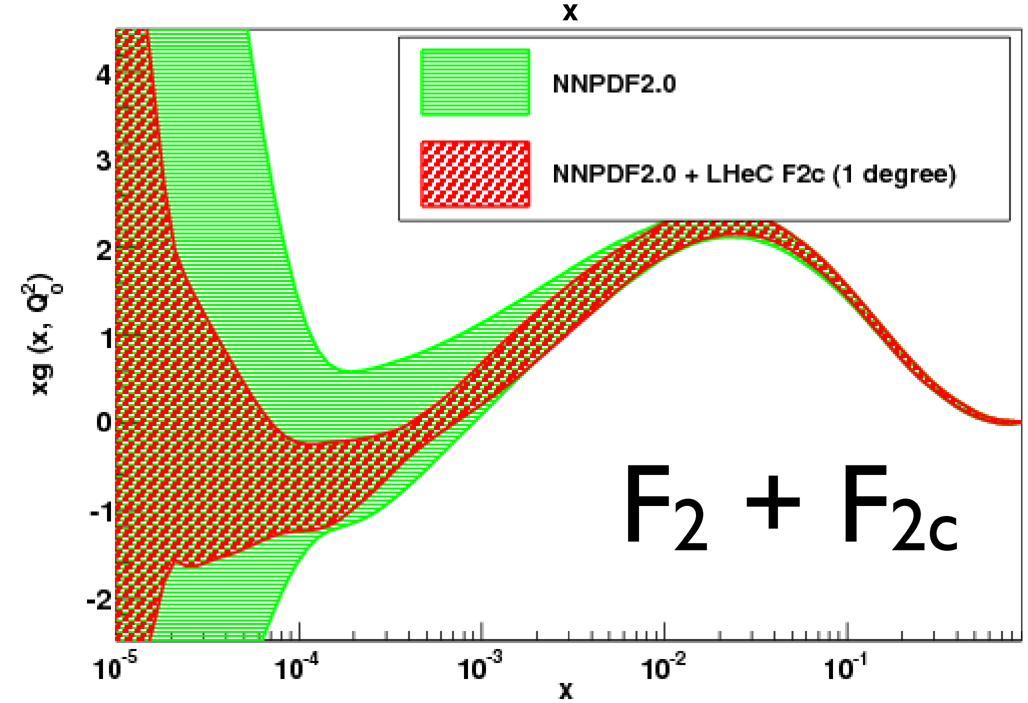




$Q_0^2 = 2$ GeV^2



Nuclear PDFs at small x:

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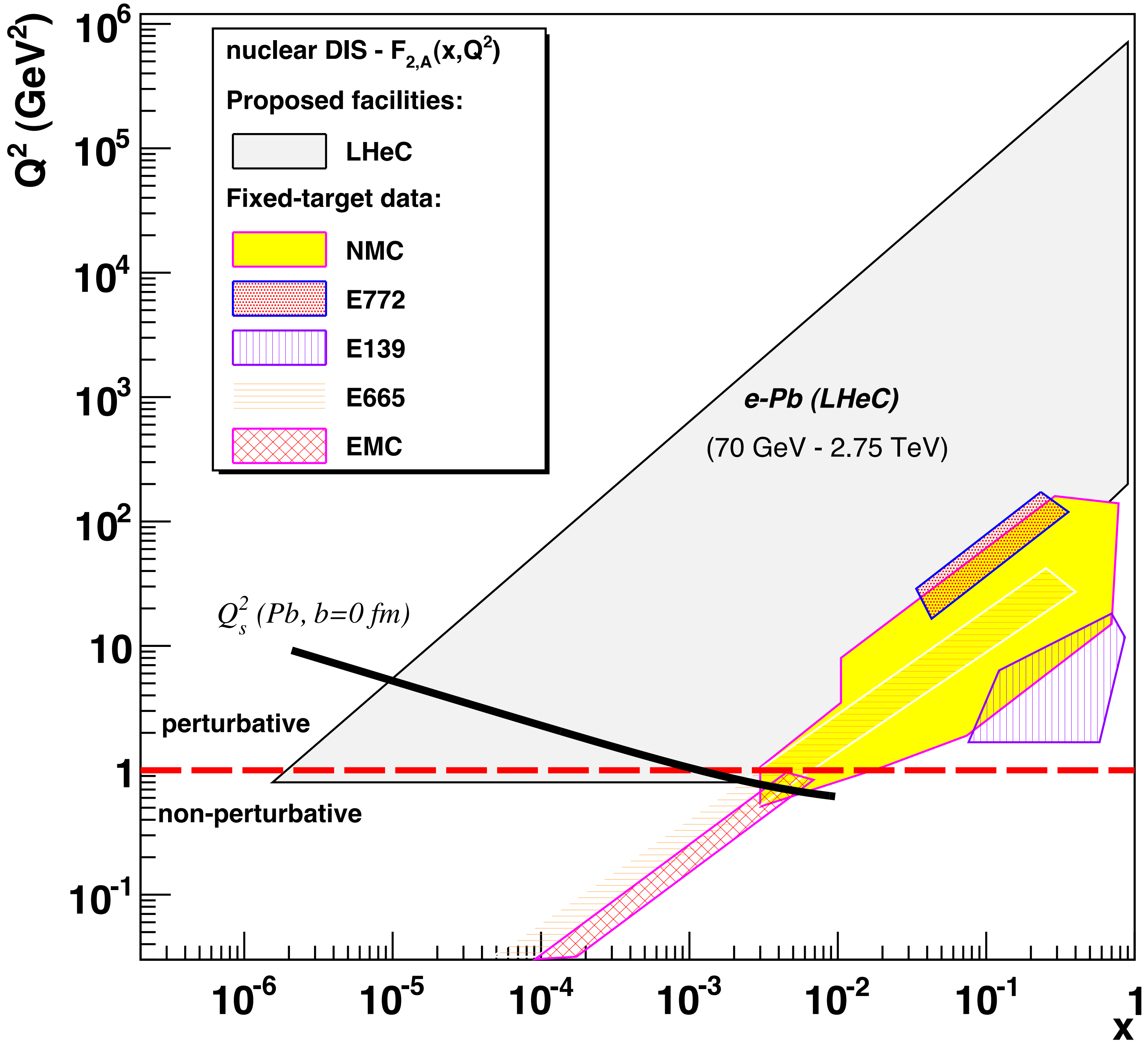

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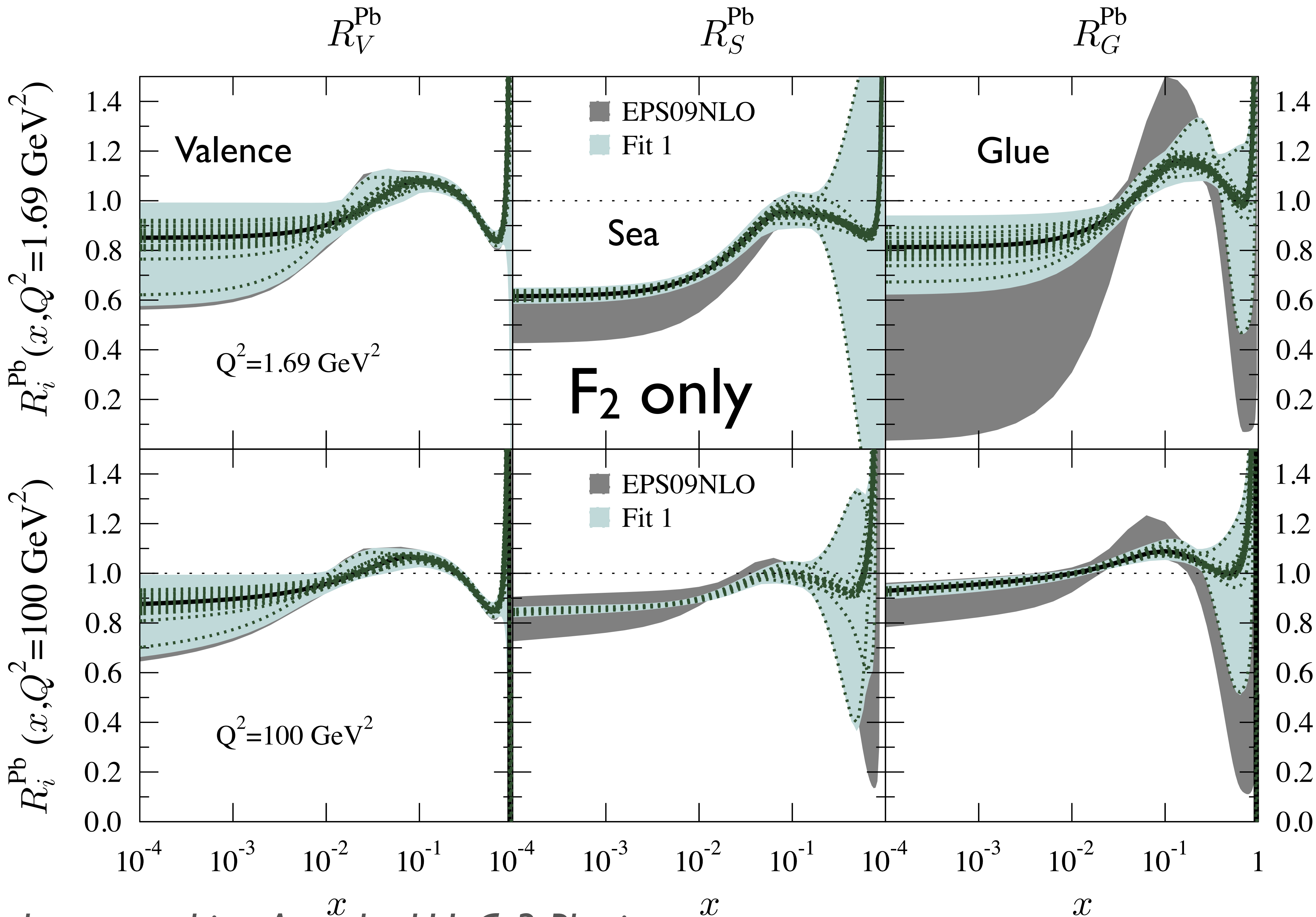

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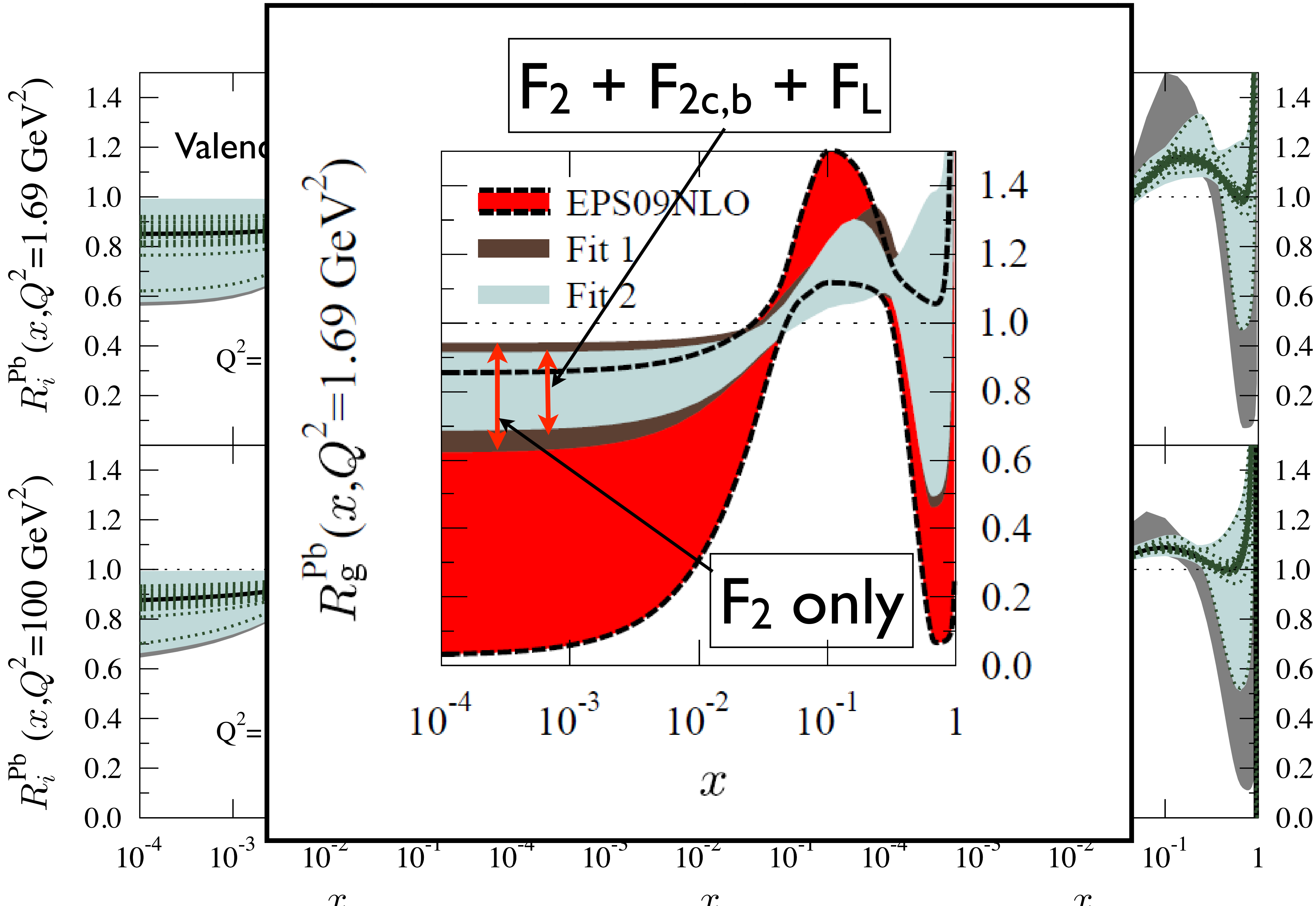

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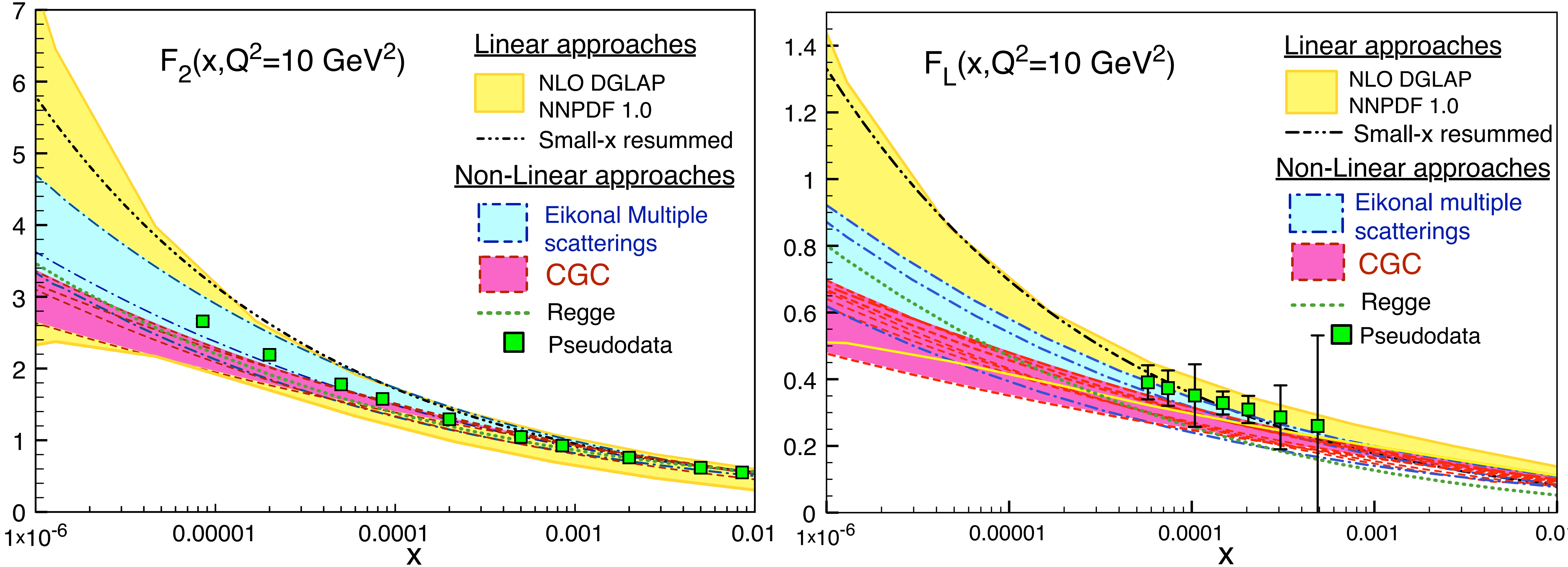
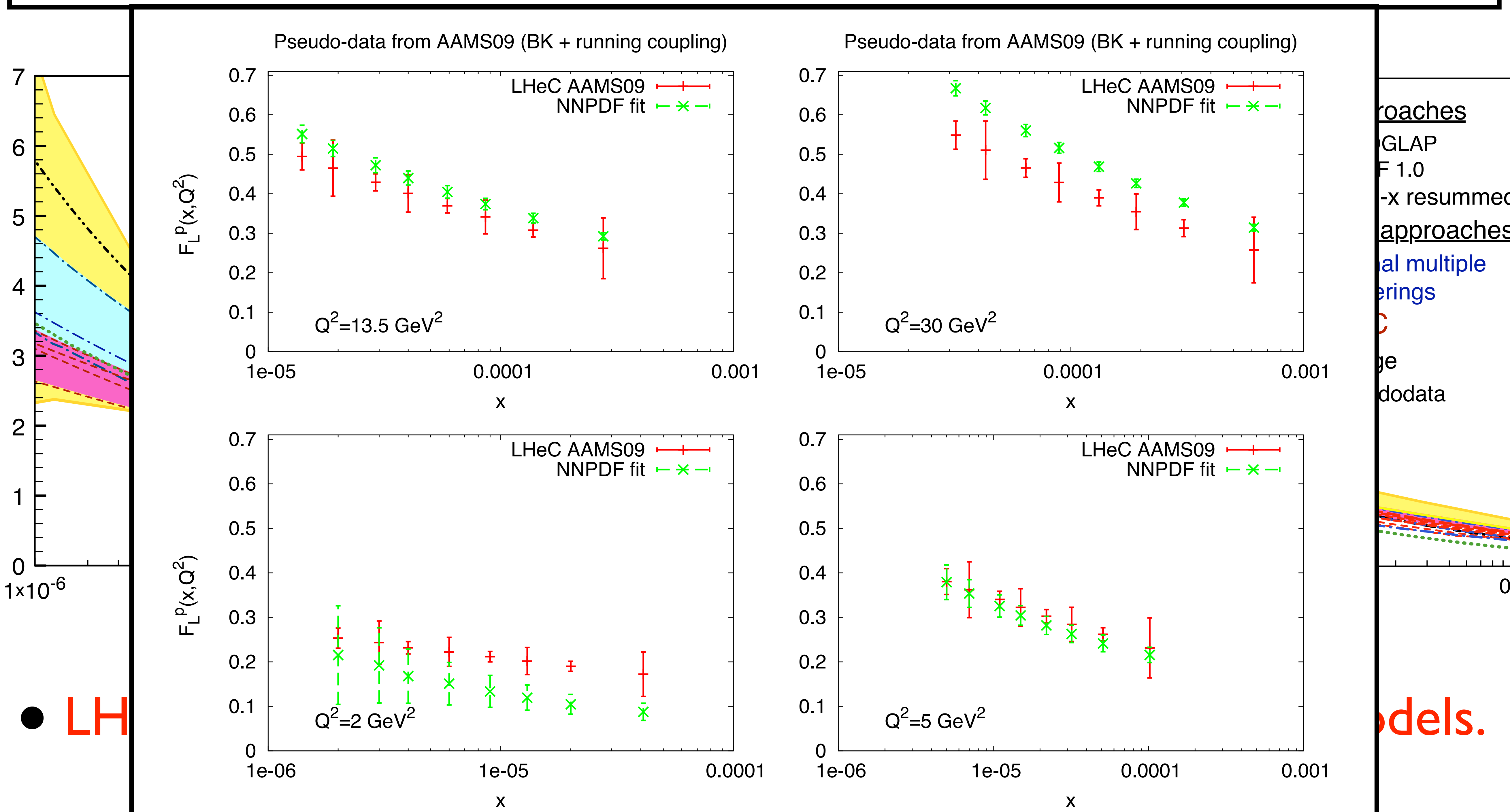


- LHeC F_2 and F_L data will have discriminatory power on models.

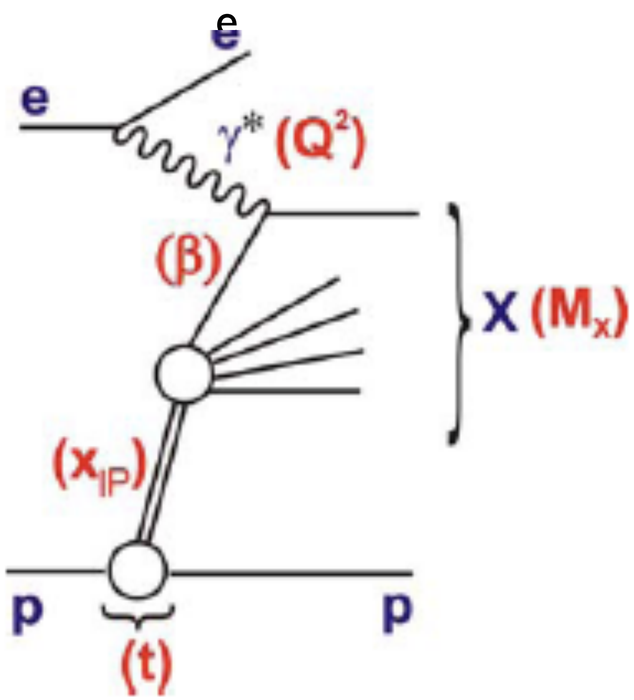
Effects beyond DGLAP?:

NLO DGLAP cannot simultaneously accommodate LHeC F_2 and F_L data if saturation effects included according to current models.

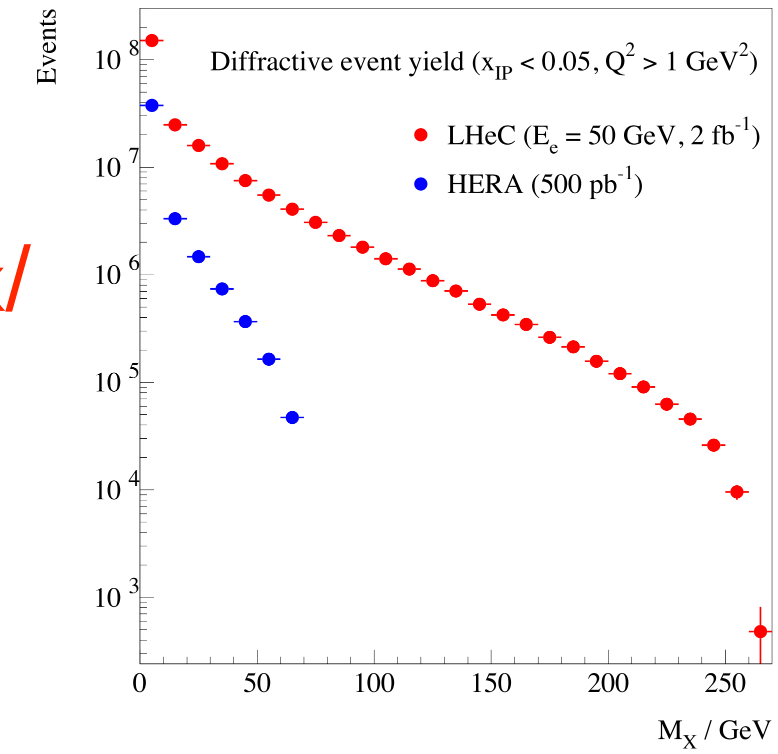


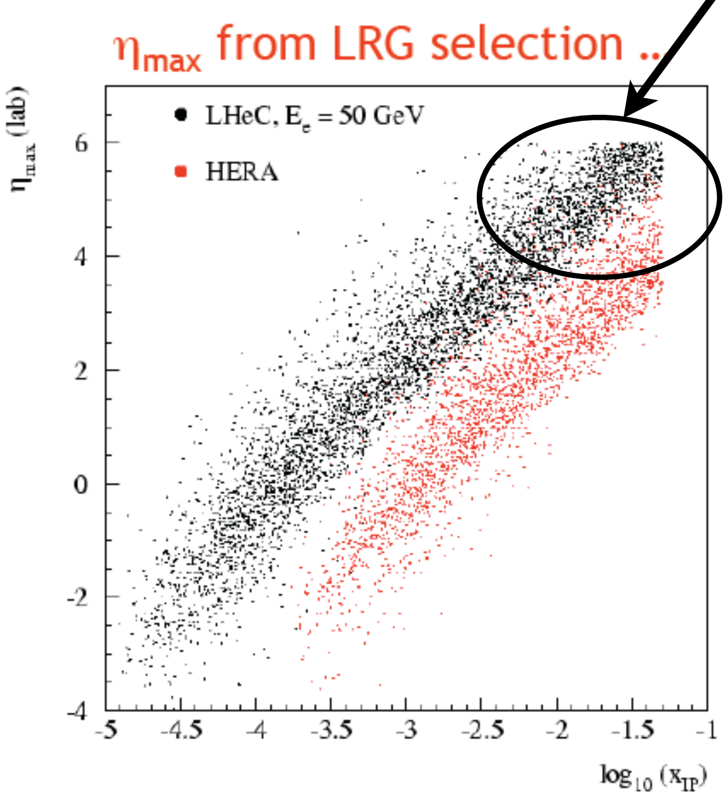
- LH … odels.

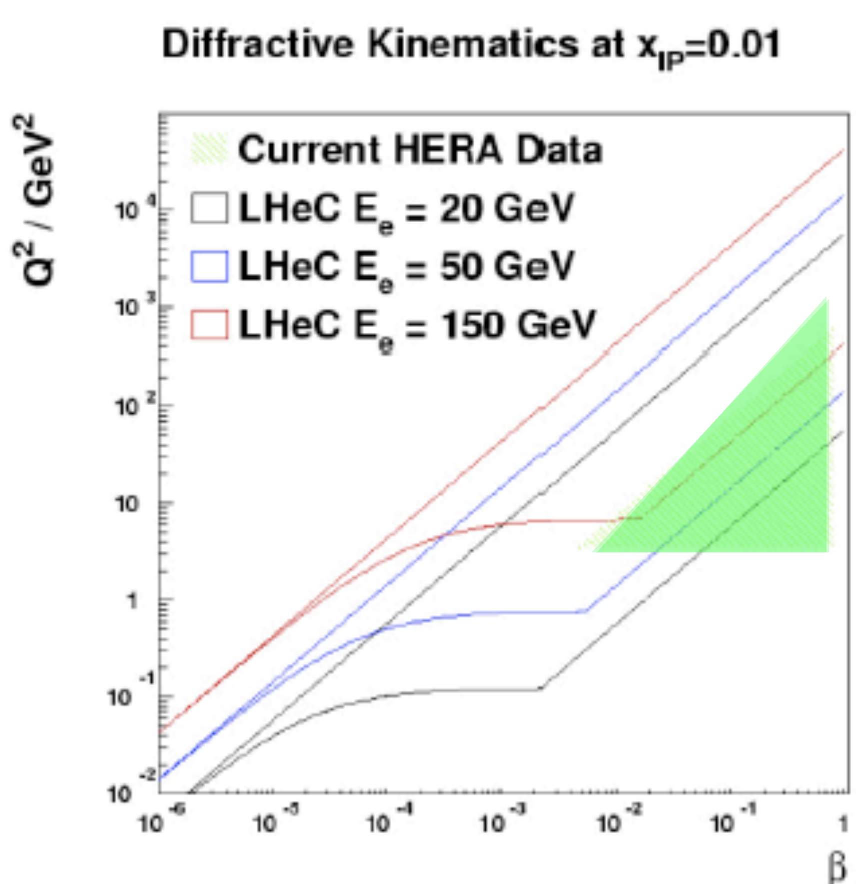
ep diffractive pseudodata:

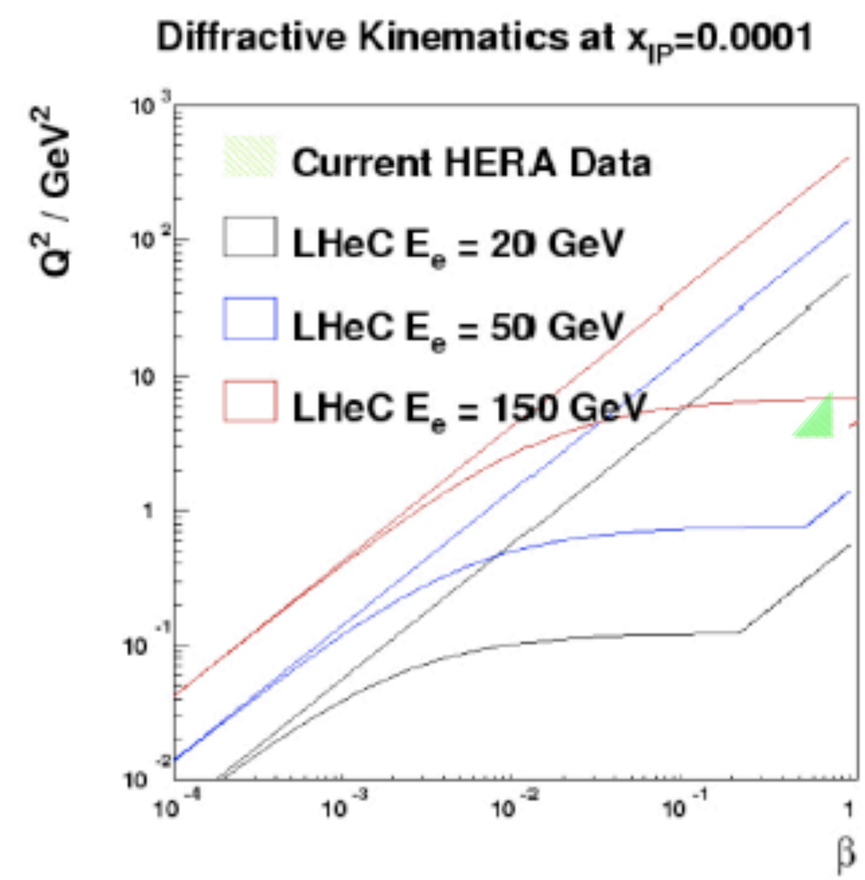


- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.
- Possibility to combine LRG and LPS.

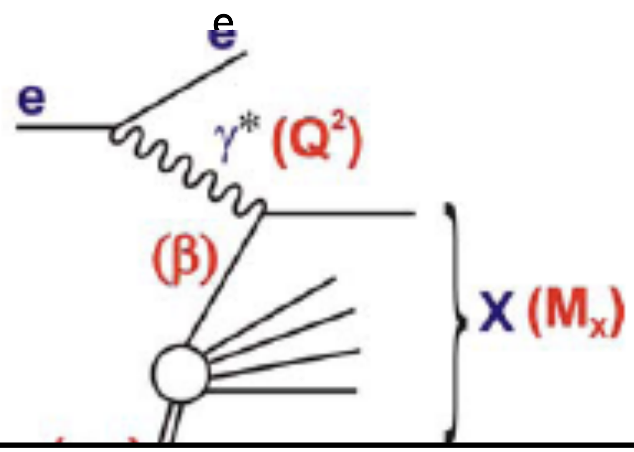




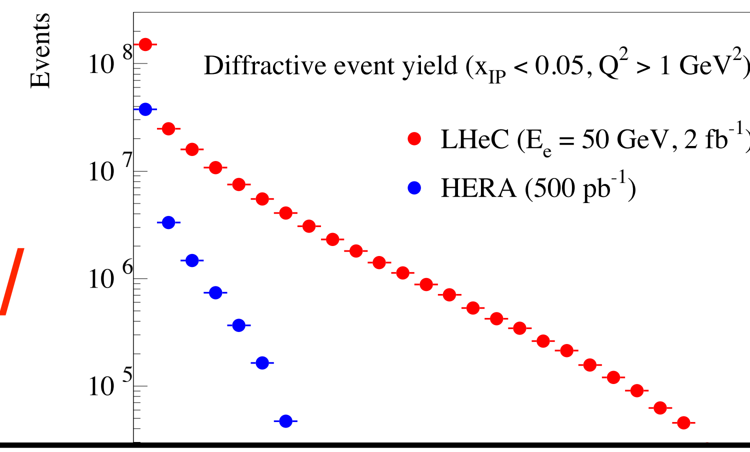




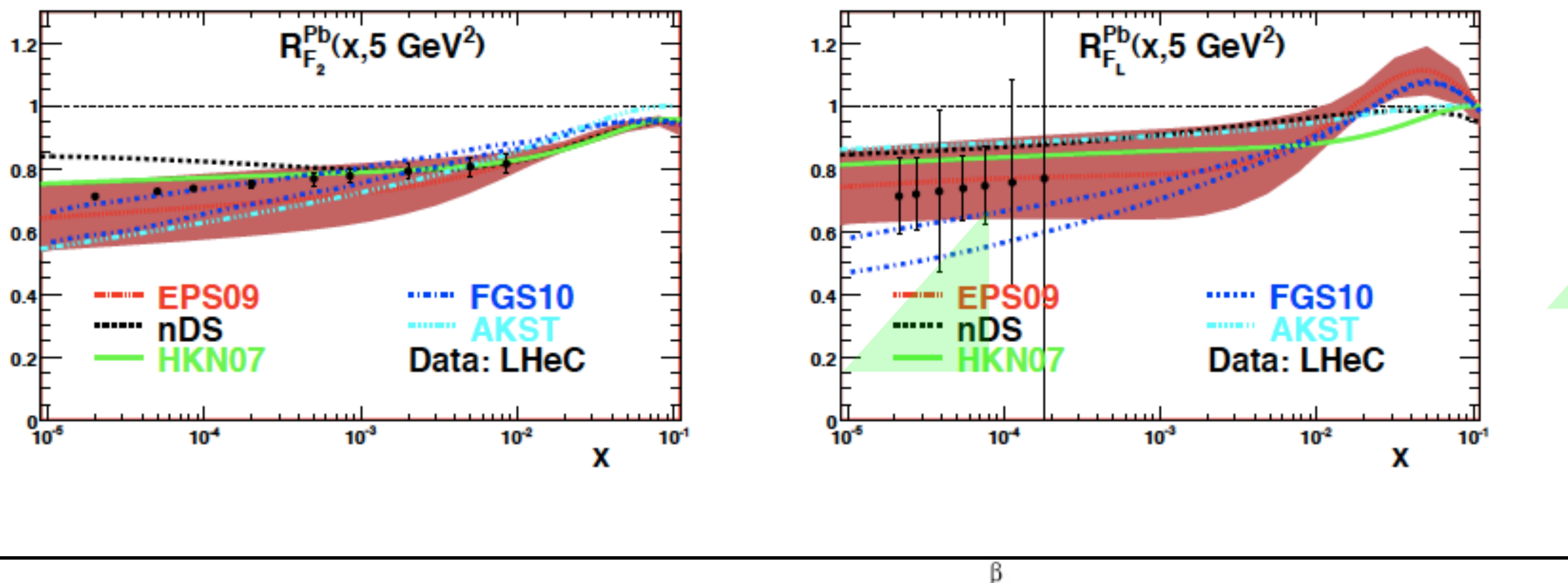
ep diffractive pseudodata:



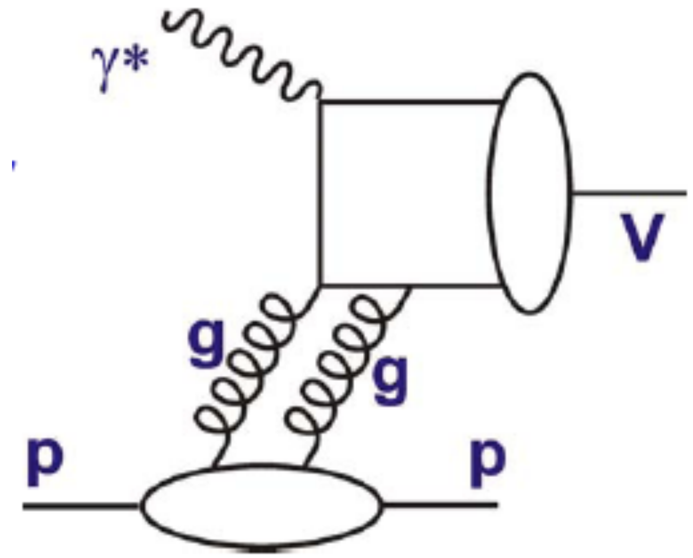
- Large increase in the M^2, $x_P=(M^2-t+Q^2)/(W^2+Q^2)$, $\beta=x/x_P$ region studied.

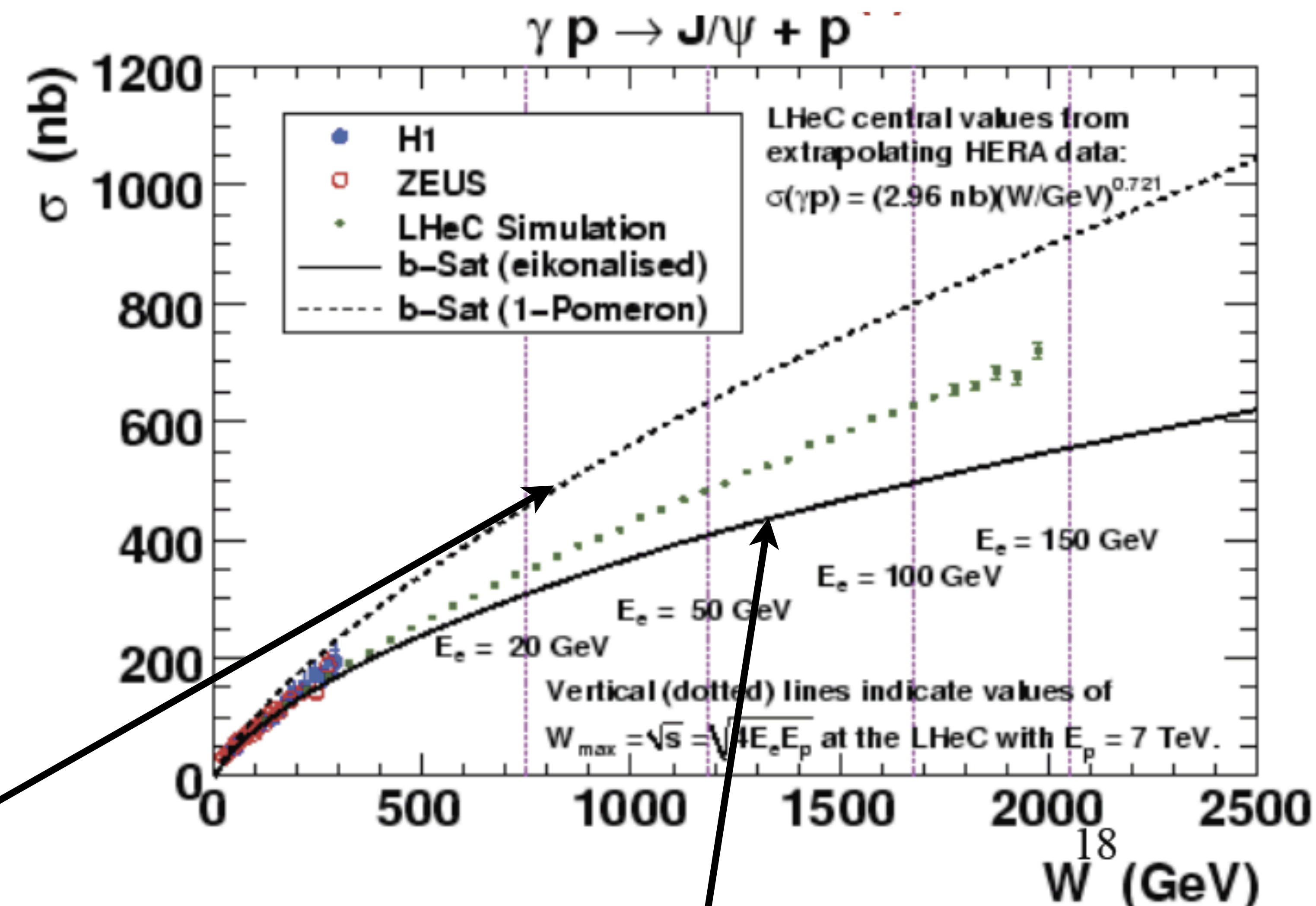


Note: diffraction in ep is linked to shadowing in eA (Gribov): FGS, Capella-Kaidalov et al,...



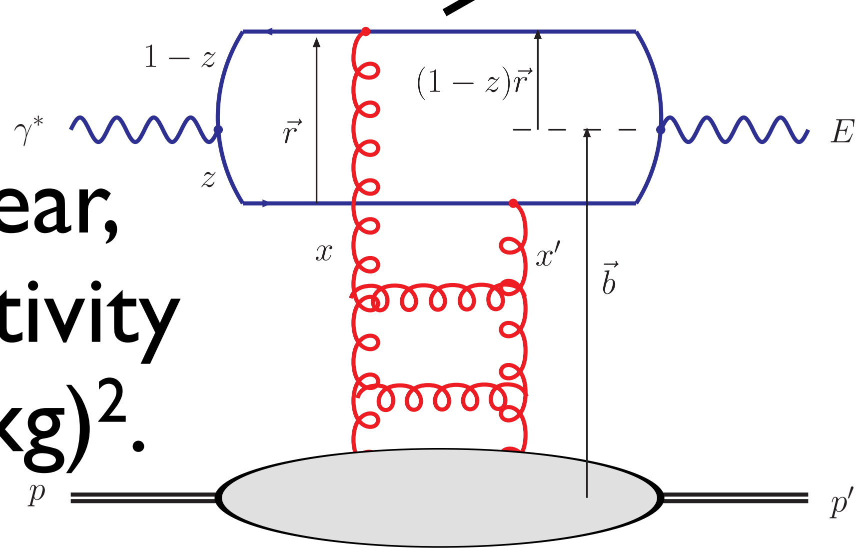
Elastic VM production in ep:

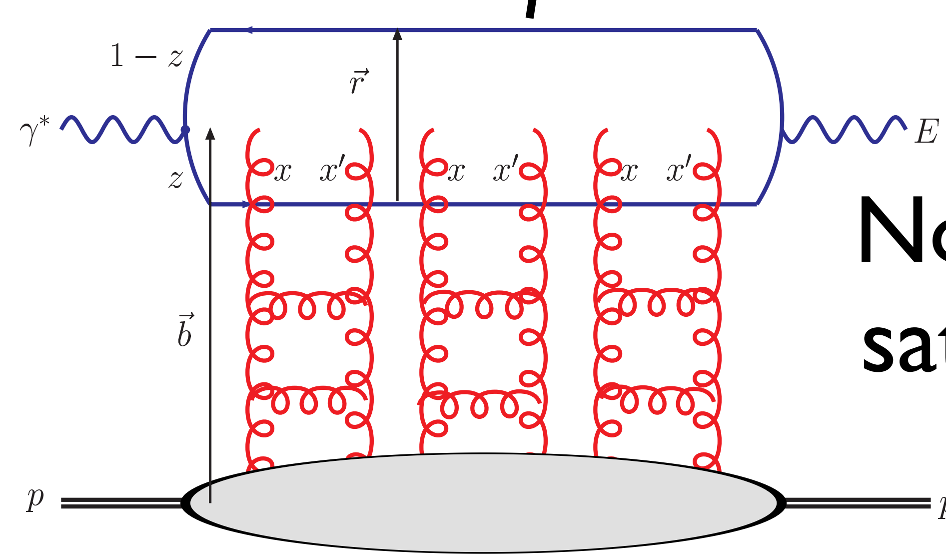




- Elastic J/ψ production appears as a candidate to signal saturation effects at work!!!

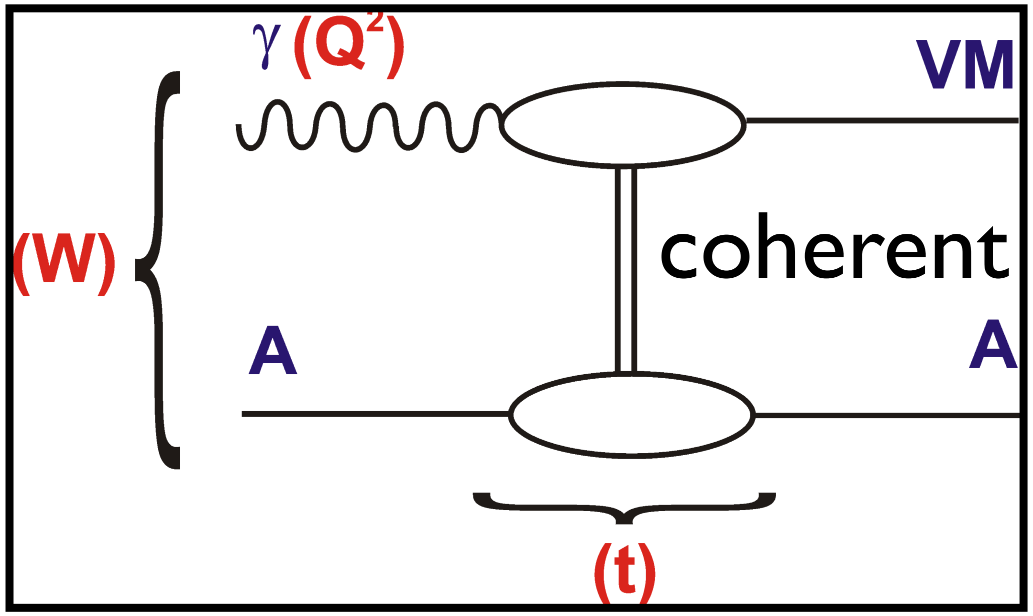
Linear, sensitivity to $(xg)^2$.





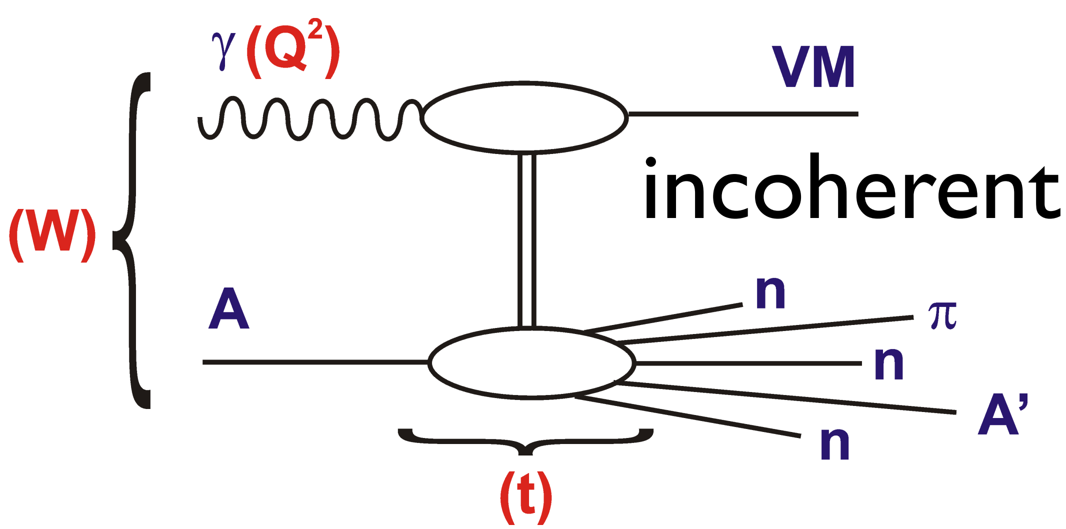
Non-linear, saturation.

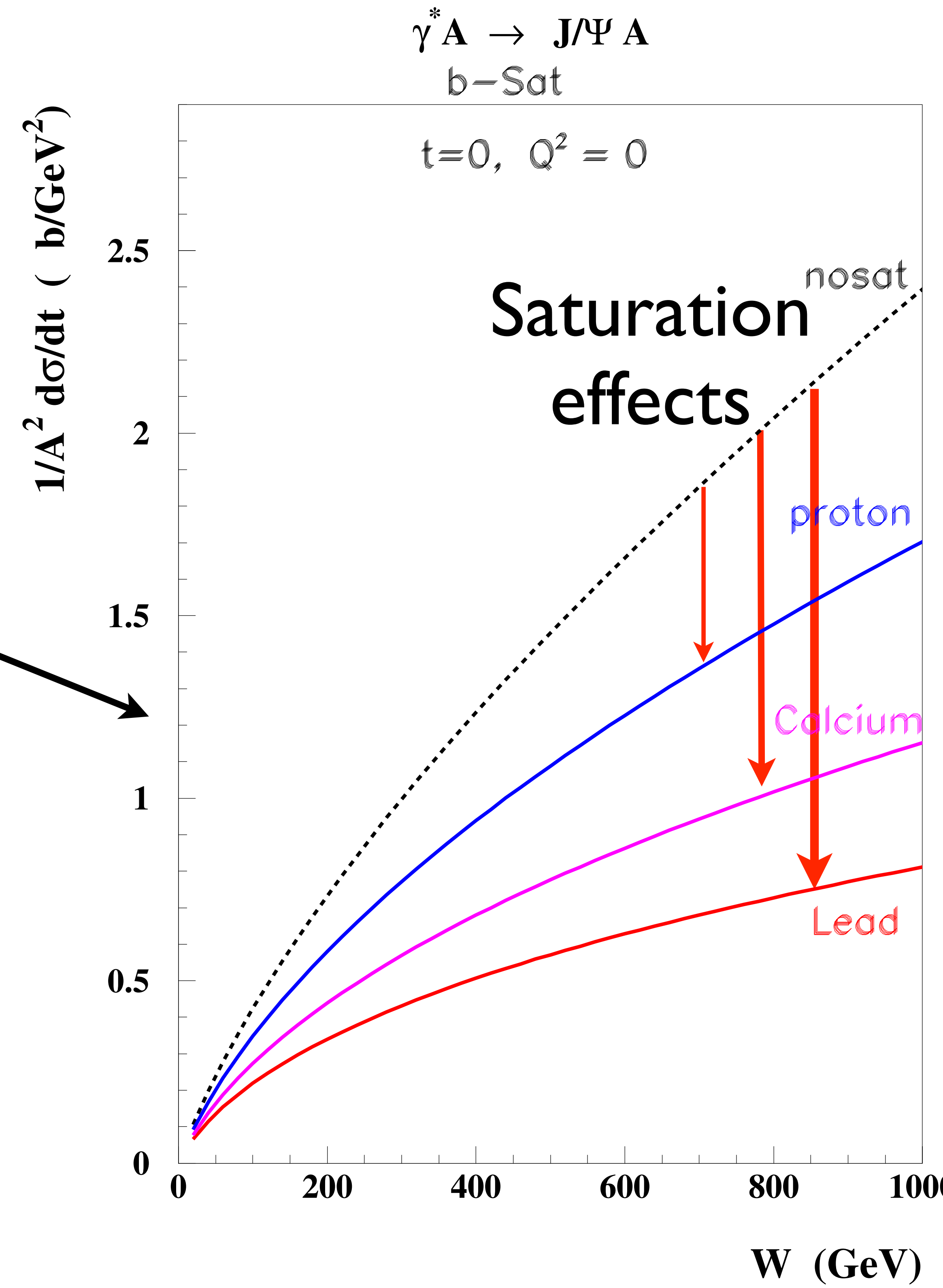
Elastic VM production in eA:



- For the coherent case, predictions available.

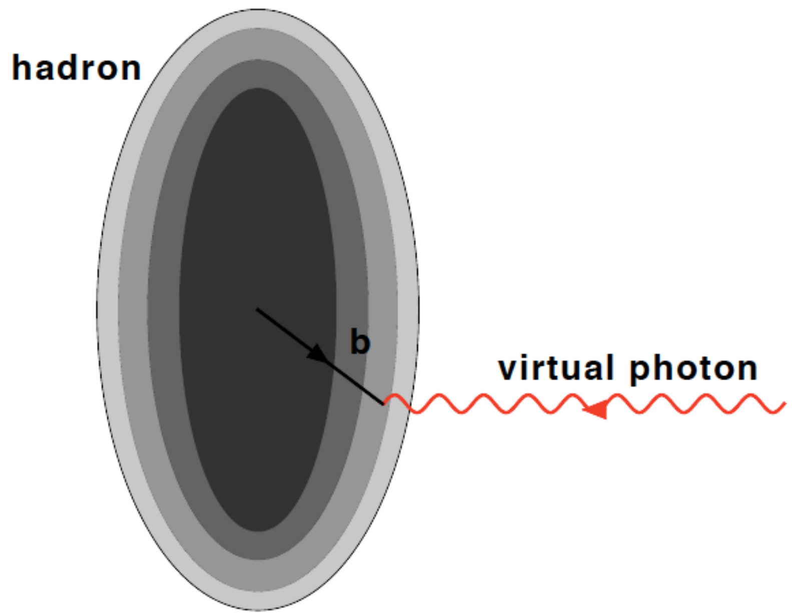
- Challenging experimental problem.

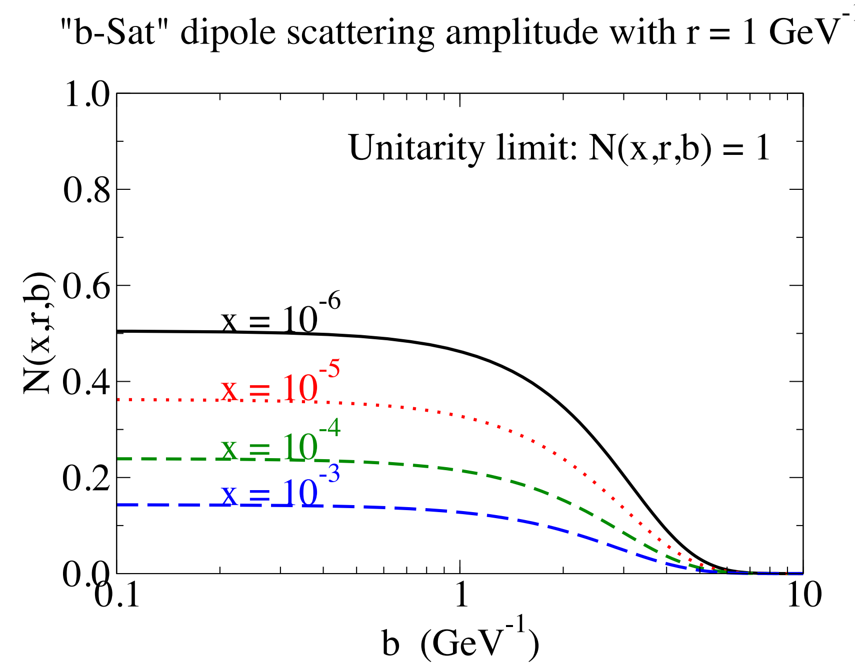


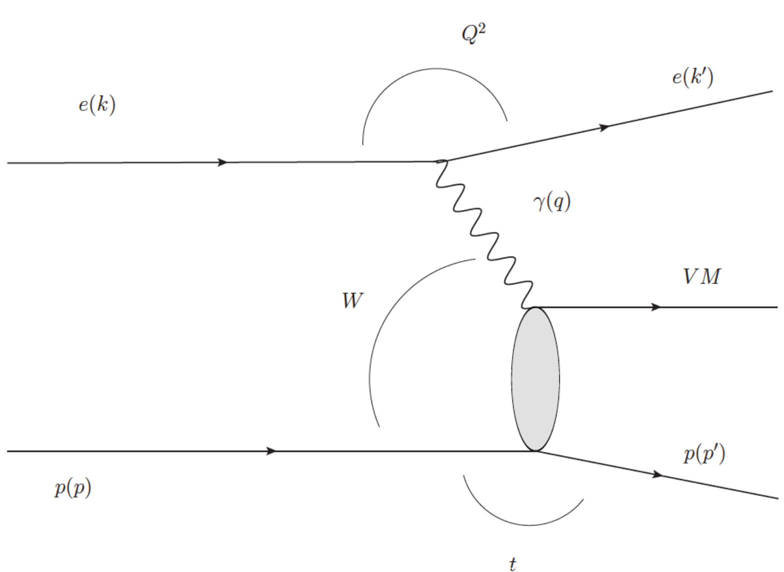


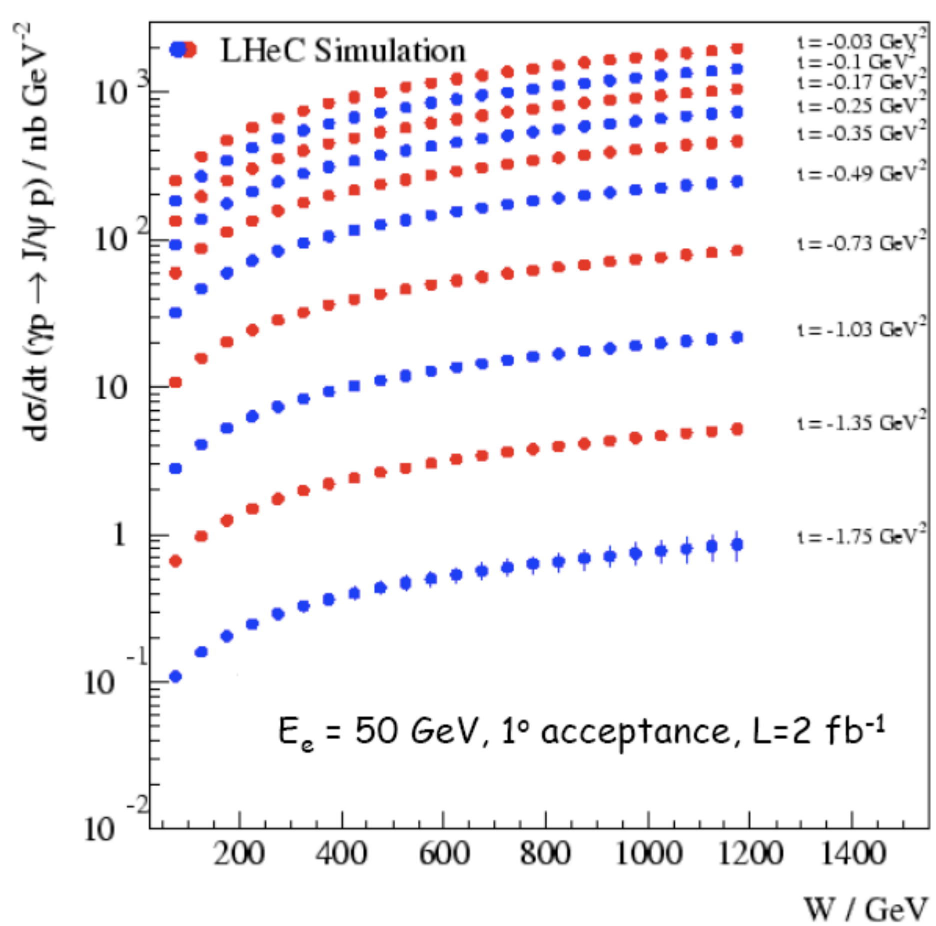
Transverse scan: elastic VM

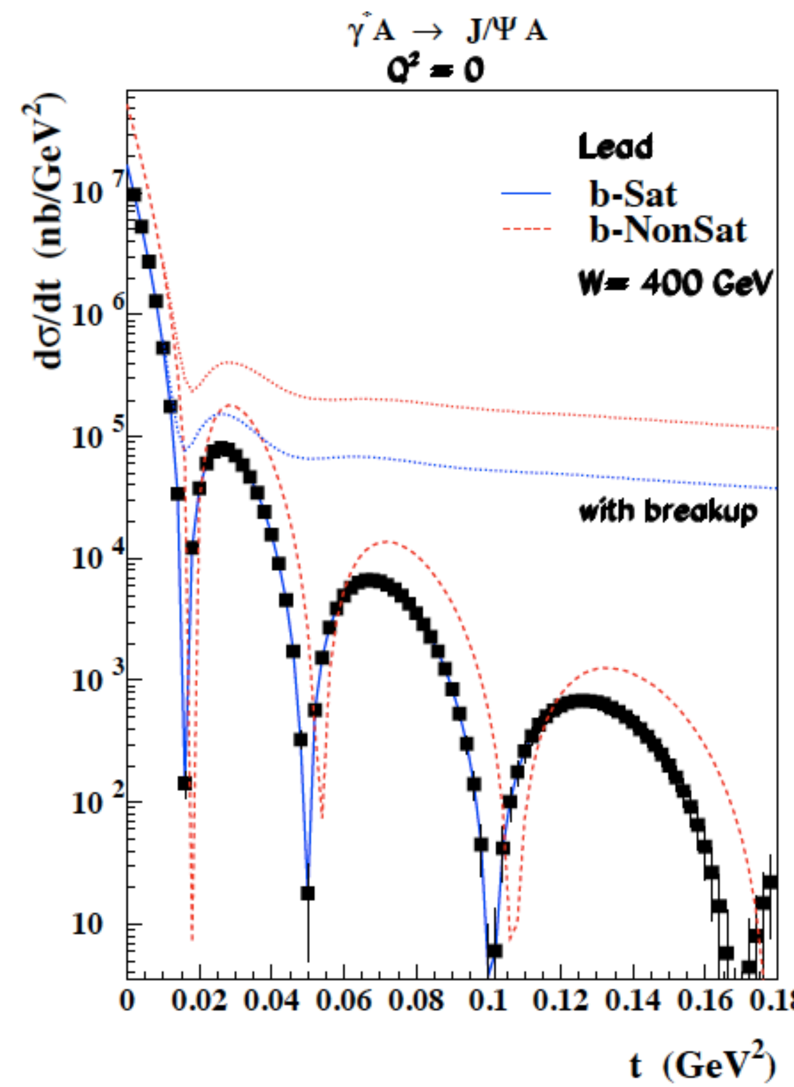
- t-differential measurements give a gluon tranverse mapping of the hadron/nucleus.





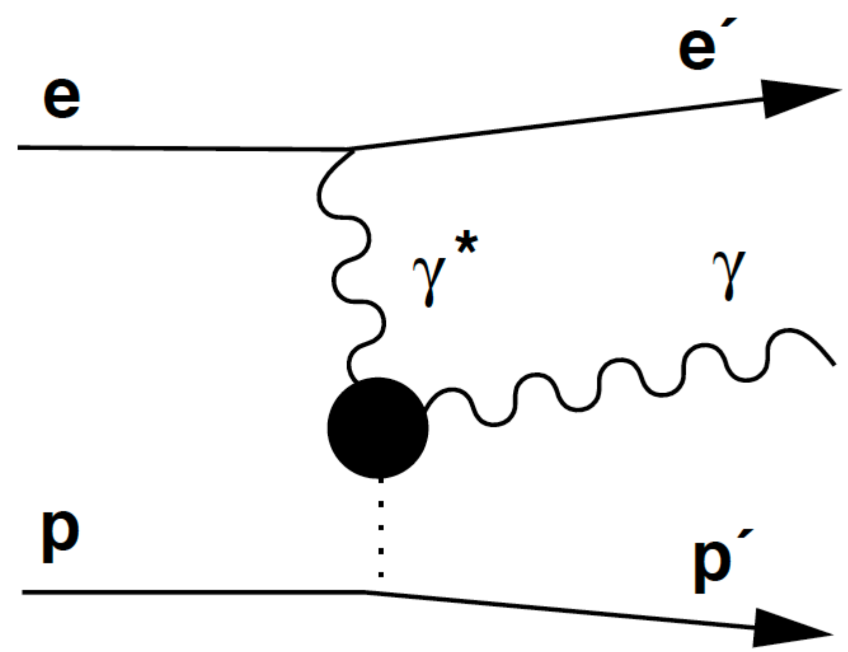




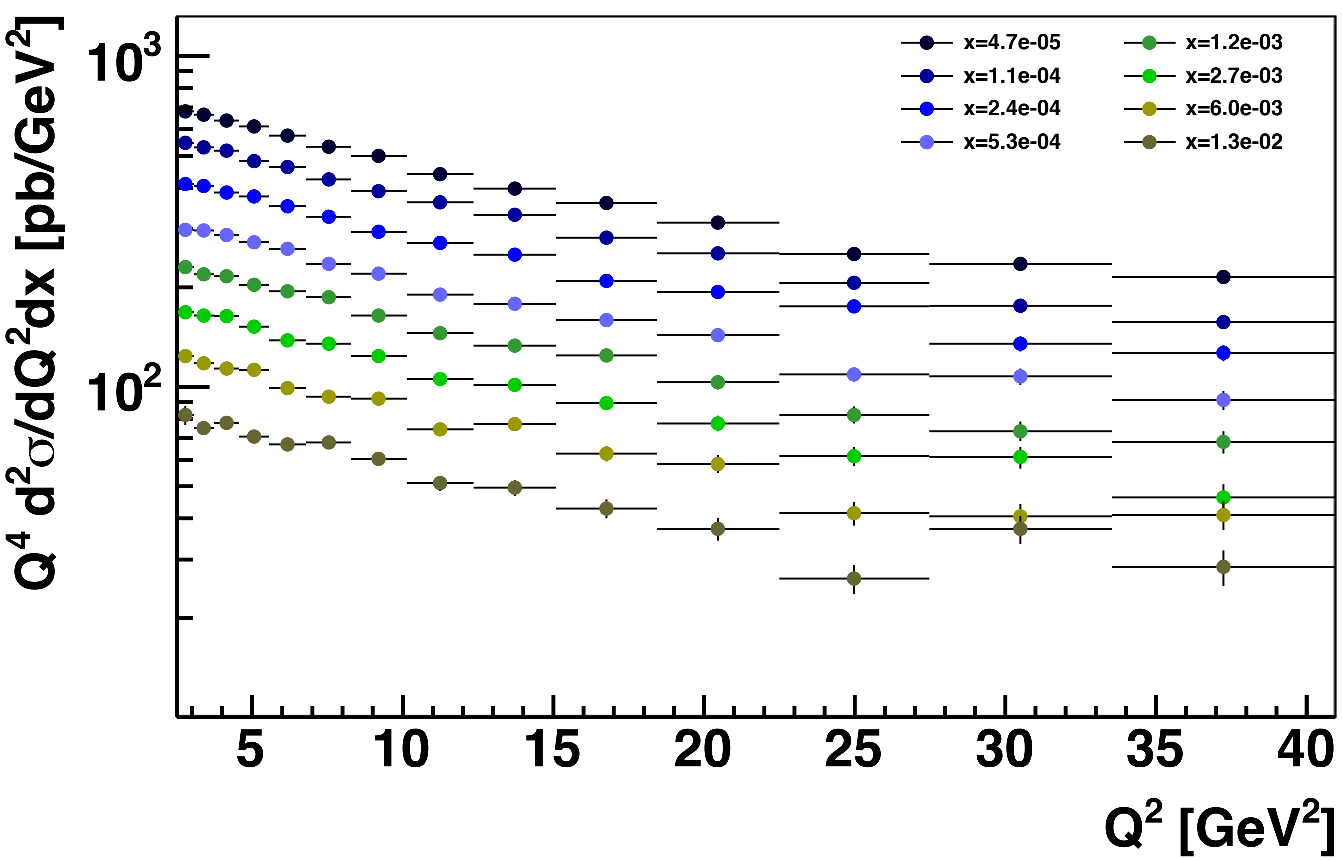


DVCS:

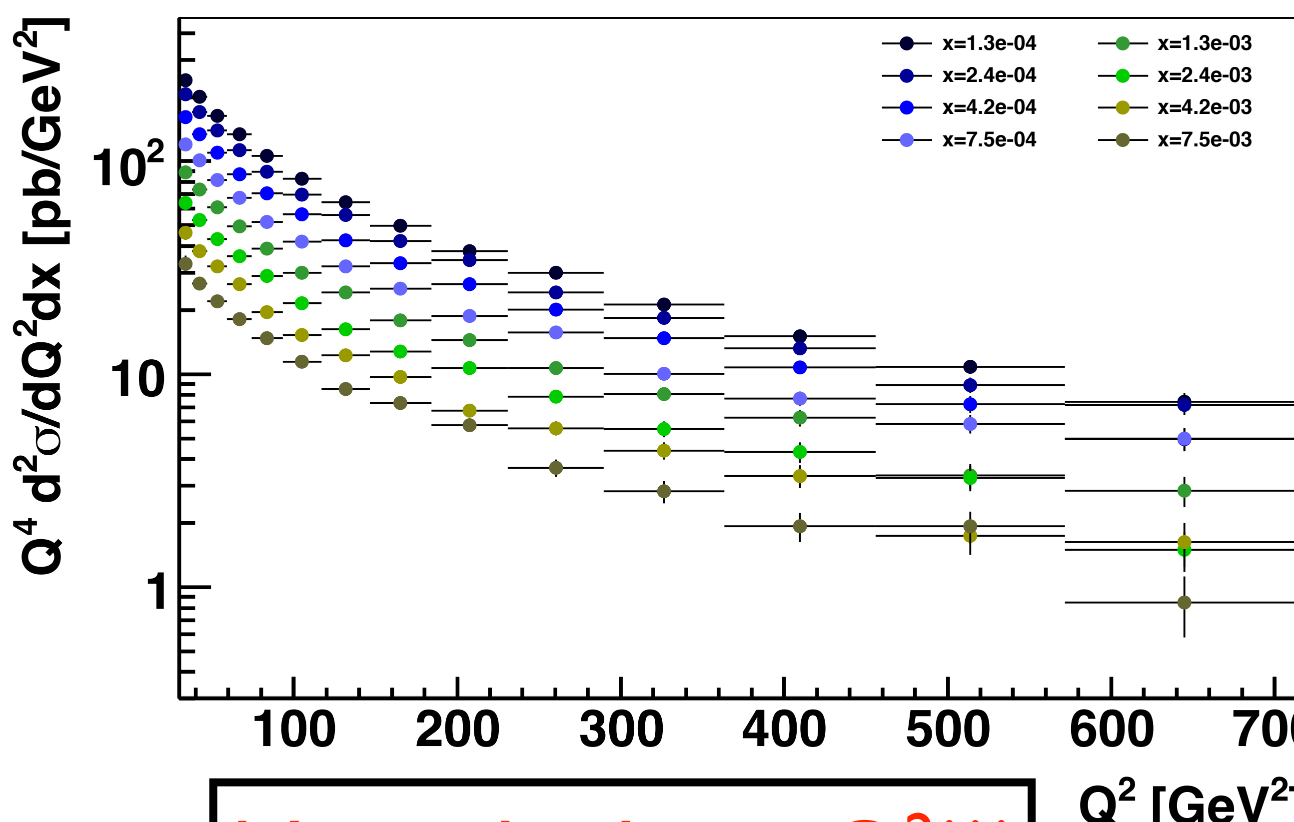
- Exclusive processes give information about GPDs, whose Fourier transform gives a tranverse scan of the hadron: DVCS sensitive to the singlet.
- Sensitive to dynamics e.g. non-linear effects.



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}

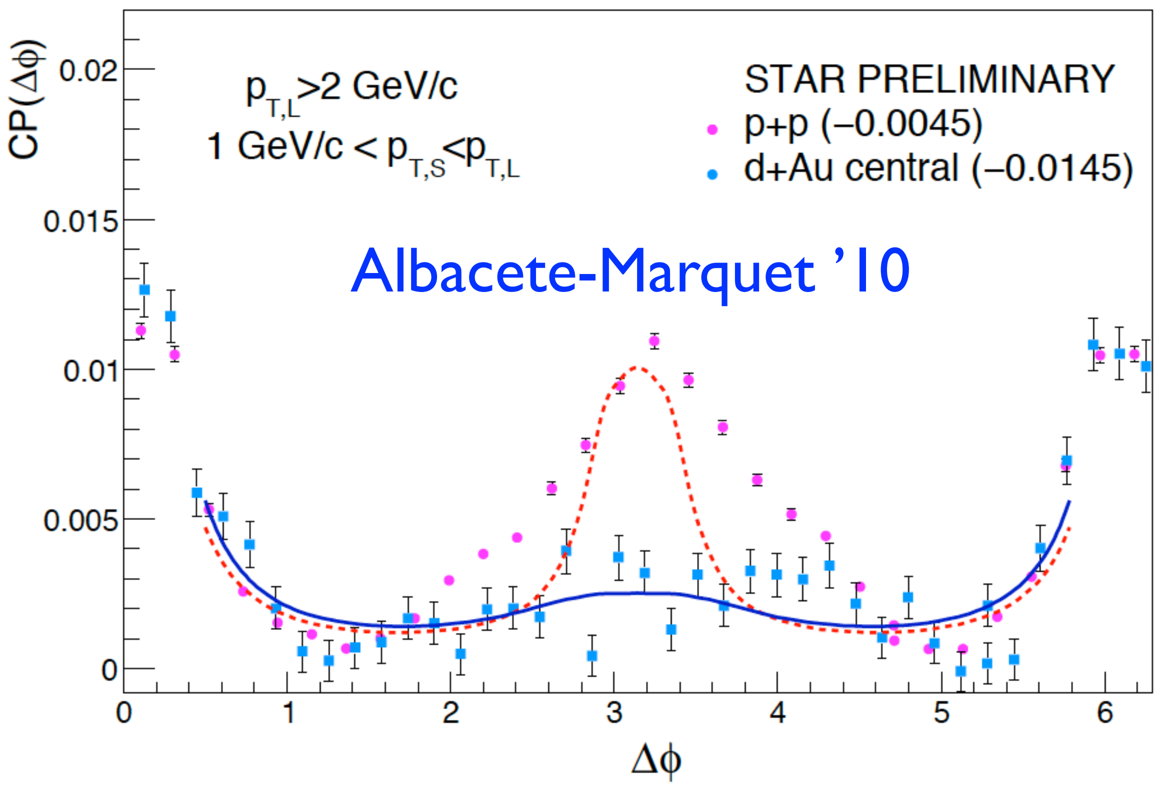


Note the huge Q^2!!!

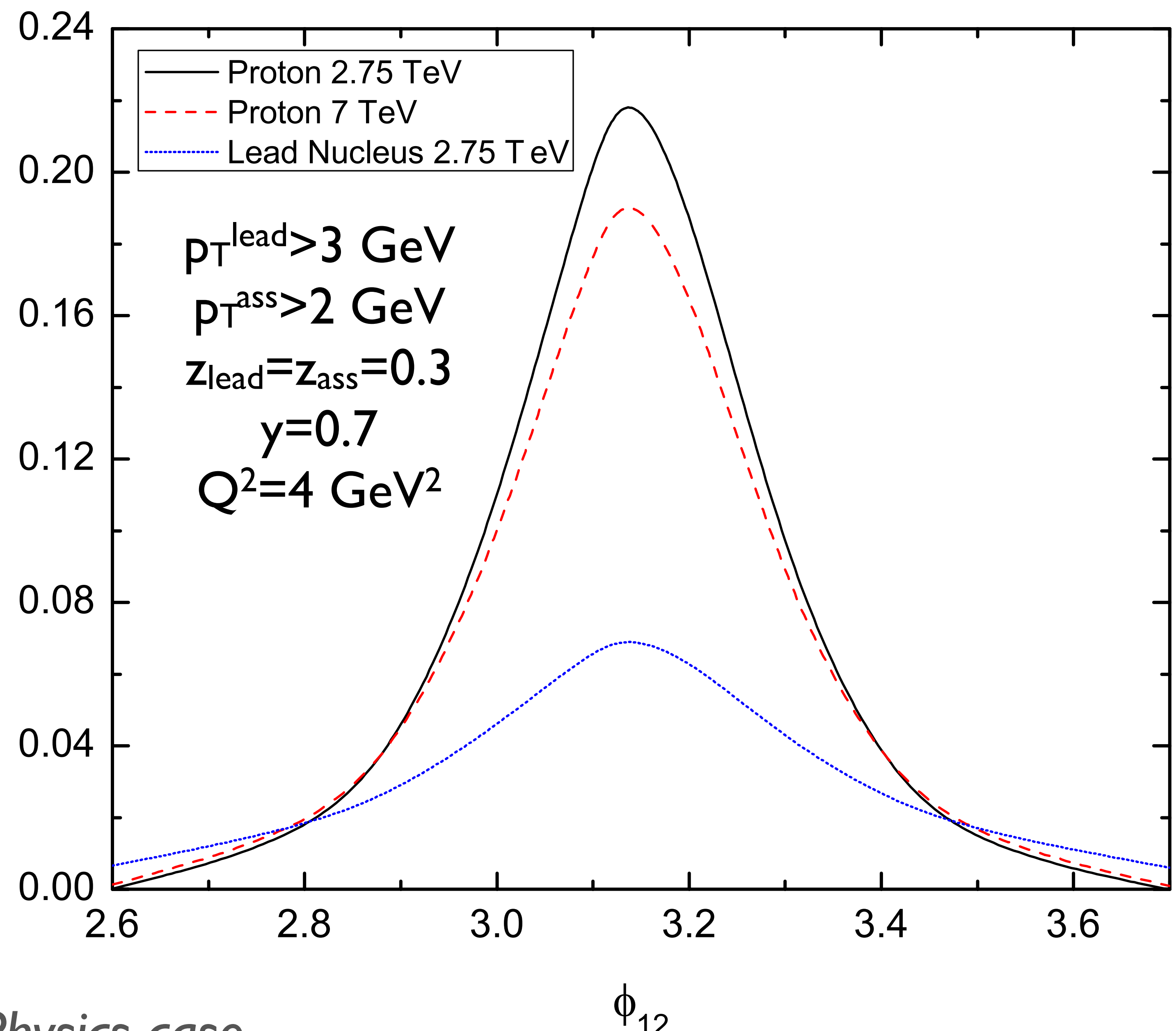
Dihadron azimuthal decorrelation:

- Dihadron azimuthal decorrelation is currently discussed at RHIC as one of the most suggestive indications of saturation.

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



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

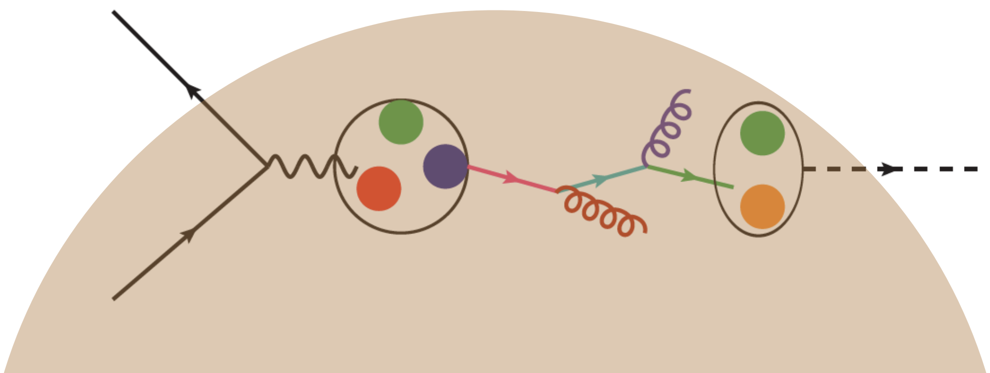


Radiation and hadronization:

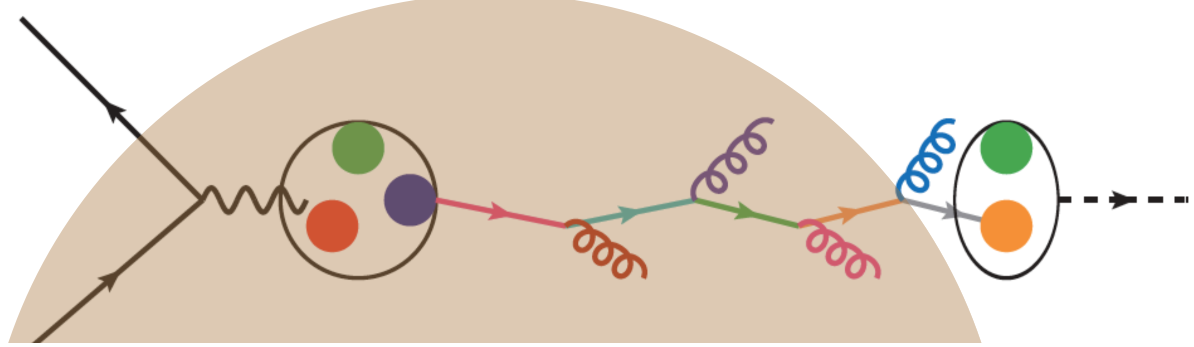
- LHeC: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

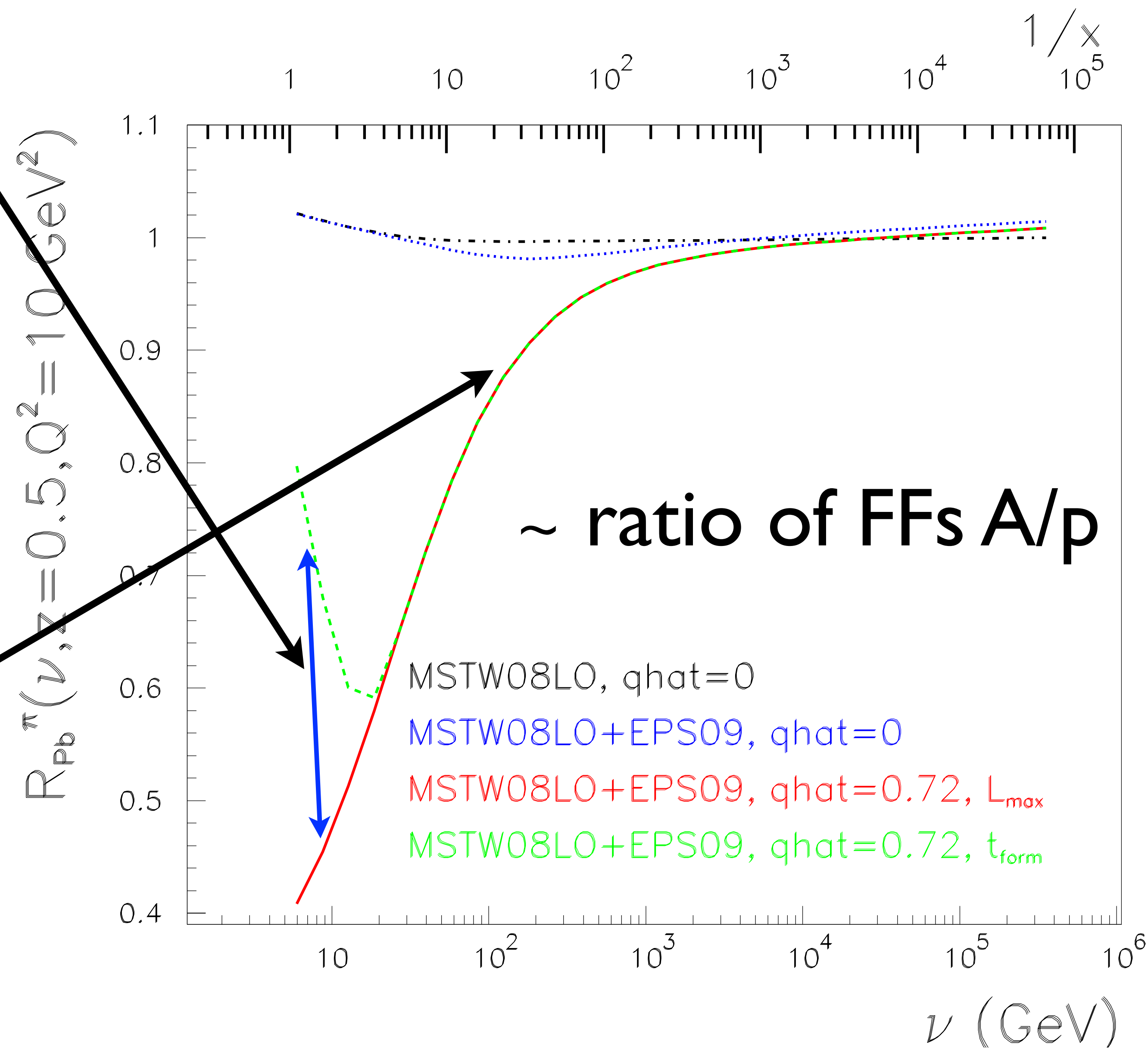
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Big/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$

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



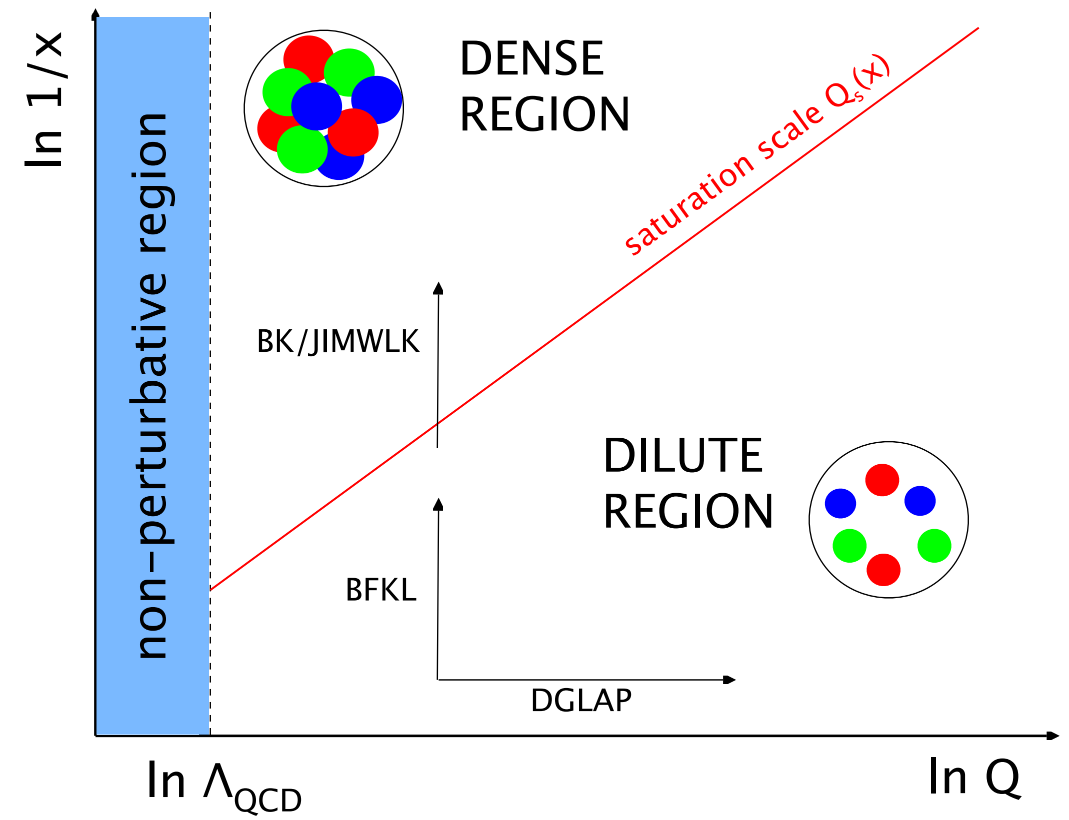
- High energy: partonic evolution altered in the nuclear medium.

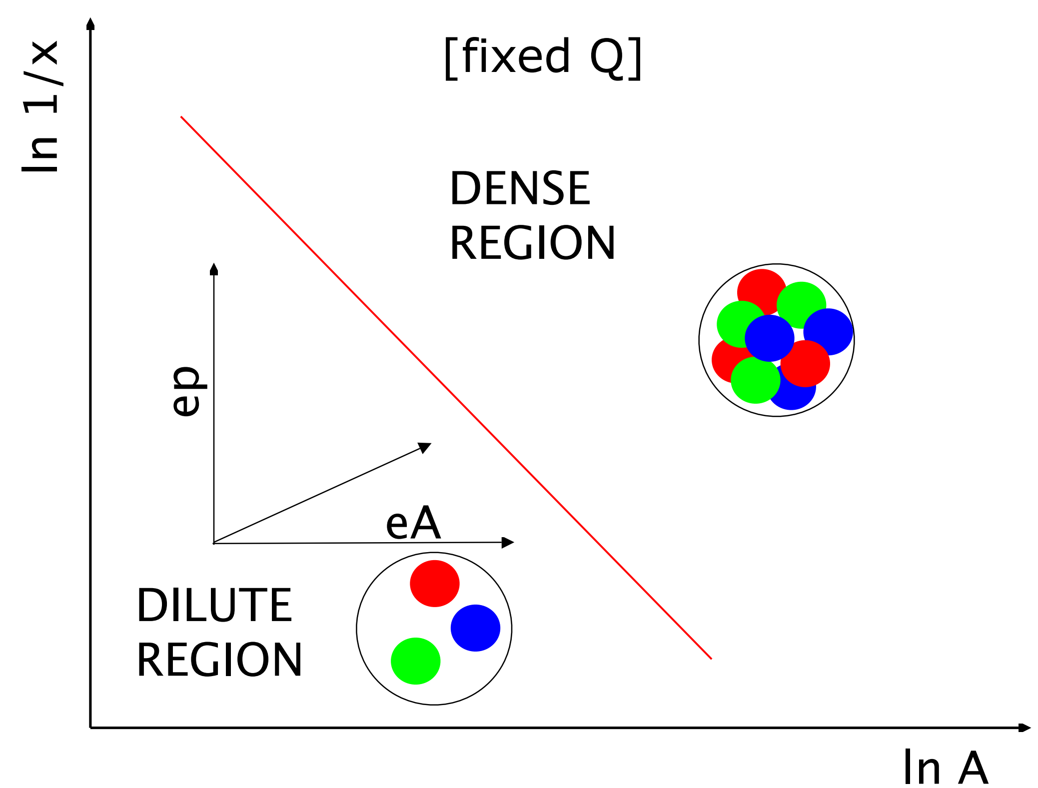




Summary:

- ***At an LHeC@CERN***:
  - ➜ Unprecedented access to small x in p and A for PDFs.
  - ➜ Novel sensitivity to physics beyond standard pQCD.
  - ➜ Stringent tests of QCD radiation and hadronization.
  - ➜ High precision tests of collinear factorization(s).
  - ➜ Transverse scan of the hadron at small x.
  - ➜ ...
- **The LHeC will answer the question of saturation/ non-linear dynamics. For that, ep AND eA essential!!!**





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2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept

Report

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http://cern.ch/lhec

2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)

2009: 2nd CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

2010: Report to CERN SPC (June)
3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
NuPECC puts LHeC to its Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11)
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New workshop June 14-15 2012

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Thanks to the organizers for the invitation!!!

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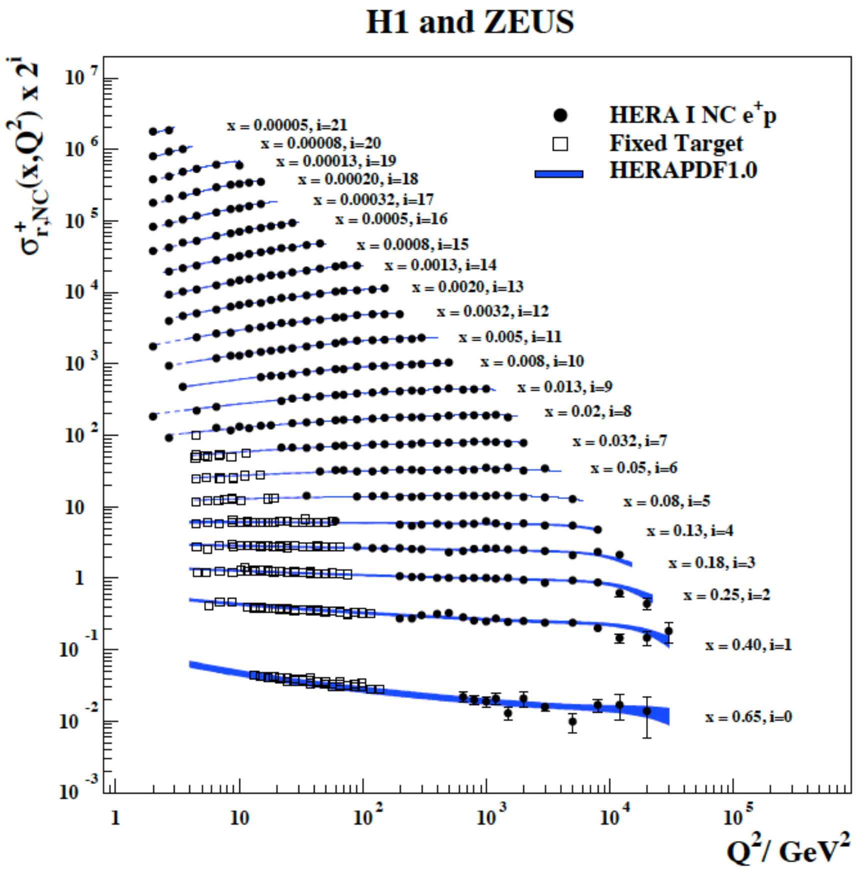
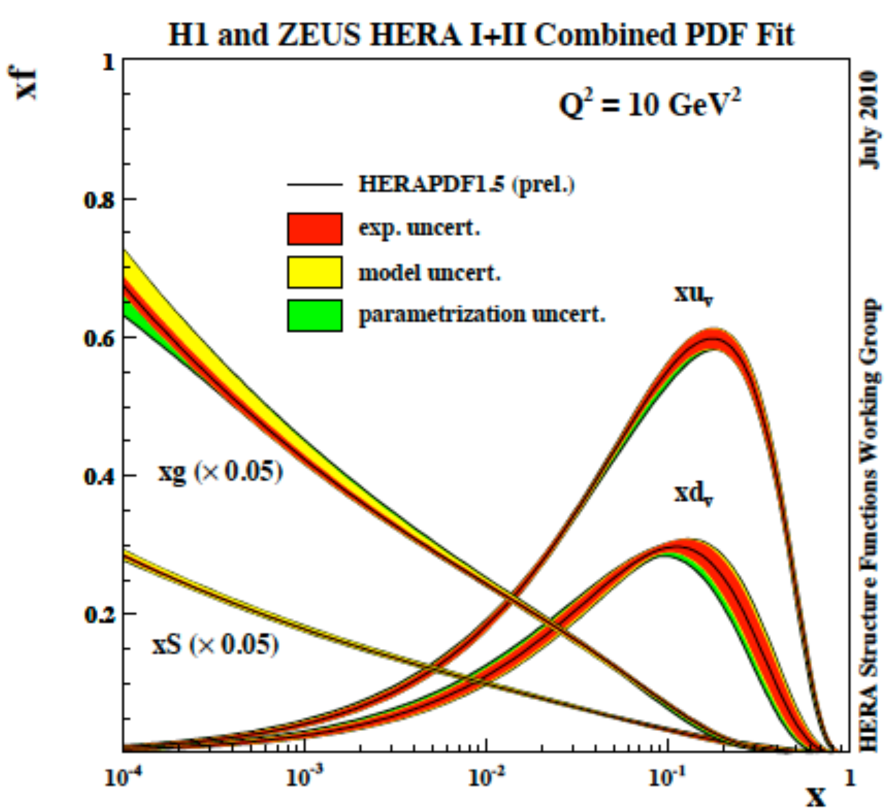
Backup:

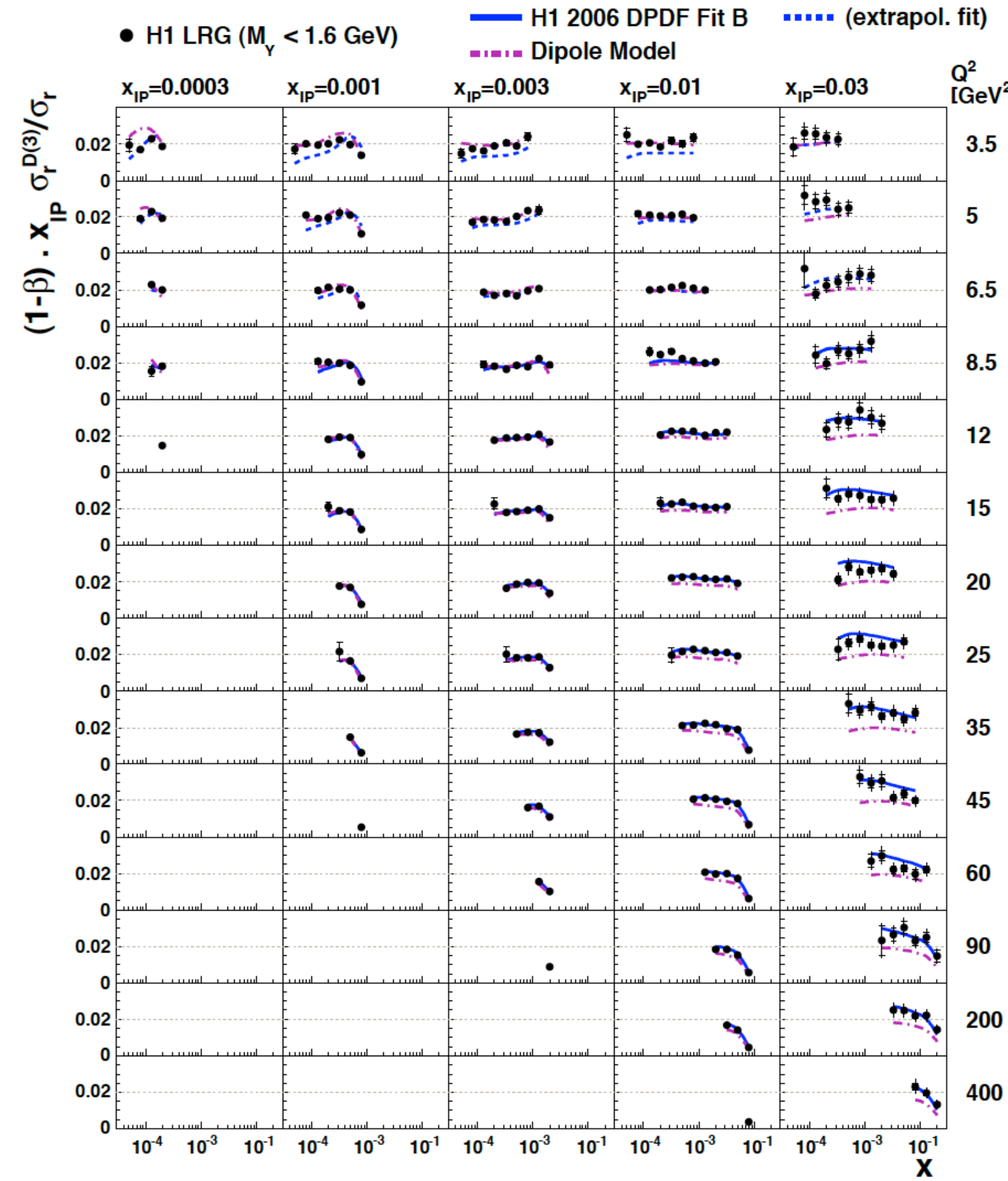
Messages from HERA:

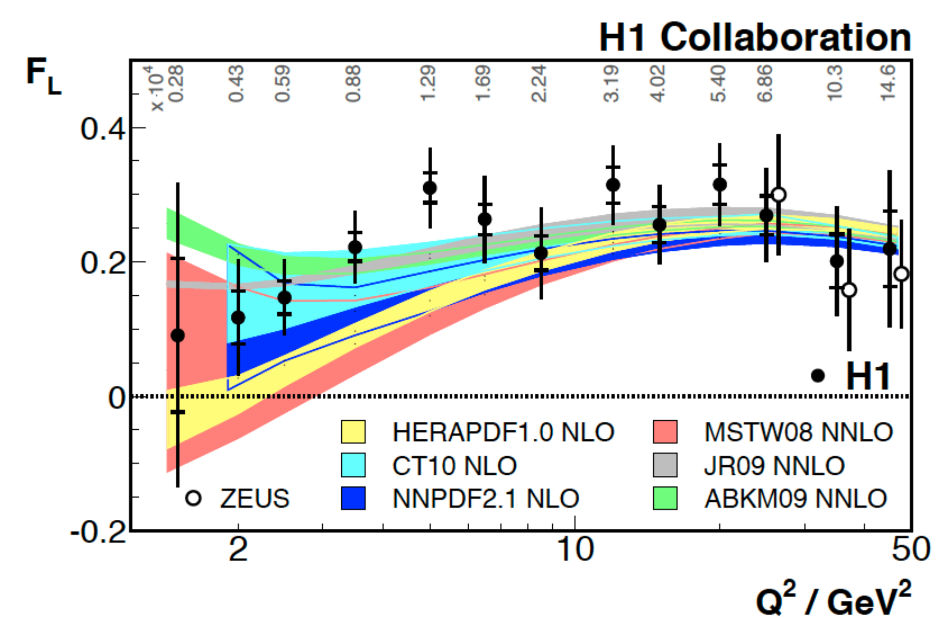
- Very good description of $F_{2(c,b)}$ (F_L?) within DGLAP, steep gluon in $1/x$.

- Large fraction of diffraction $\sigma_{diff}/\sigma_{tot}\sim 10\%$ (Cooper-Sarkar, 1206.0984).

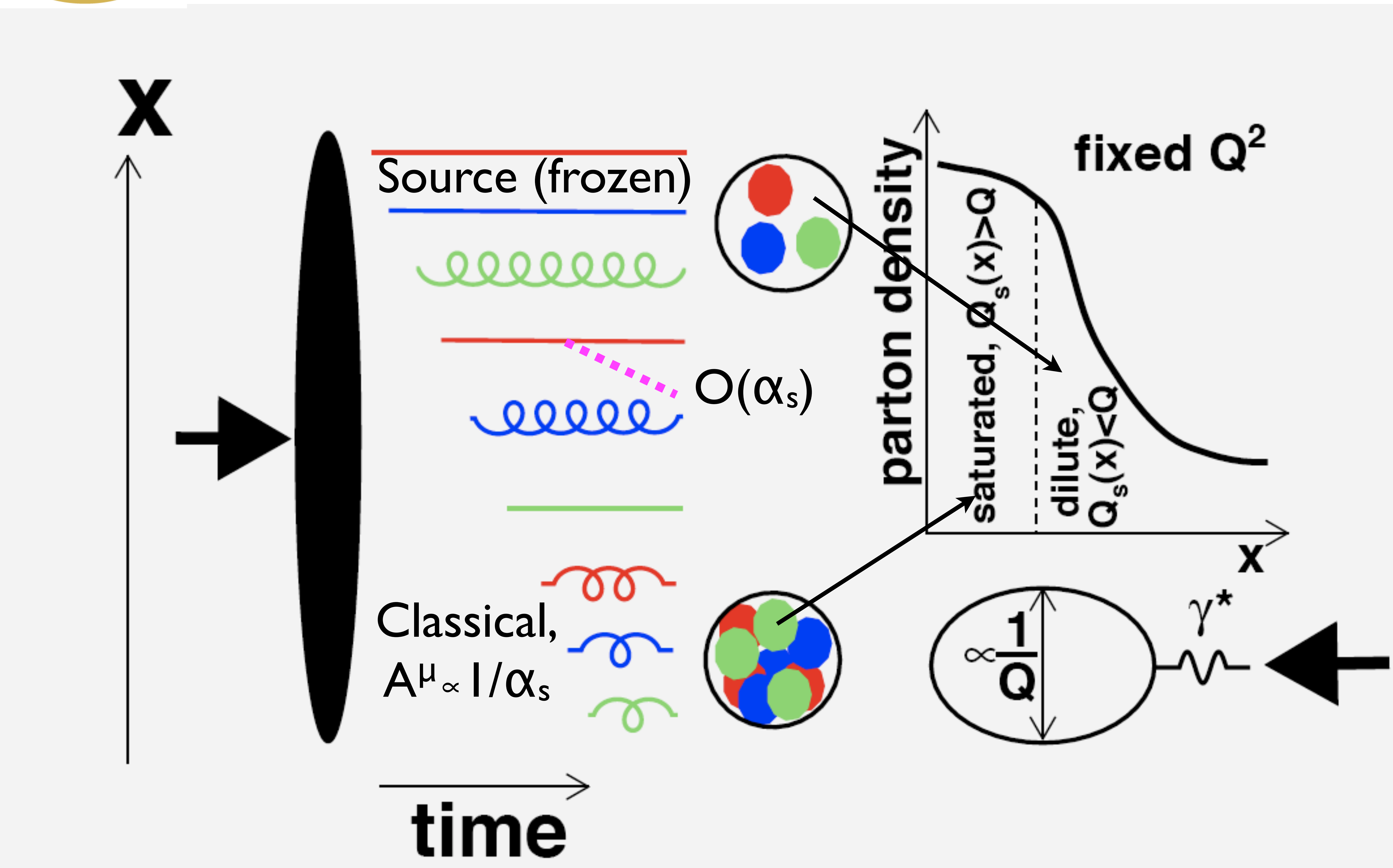




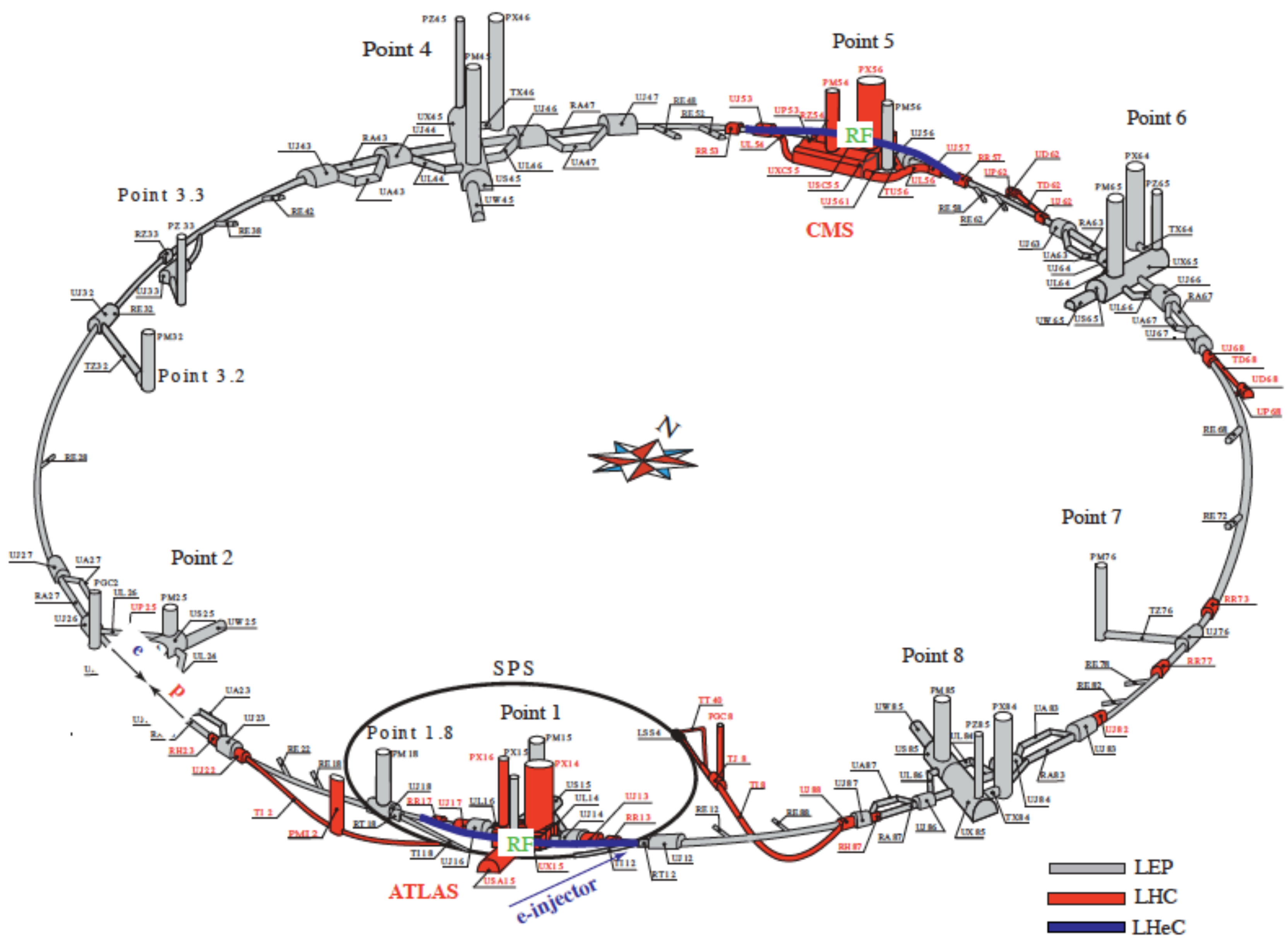


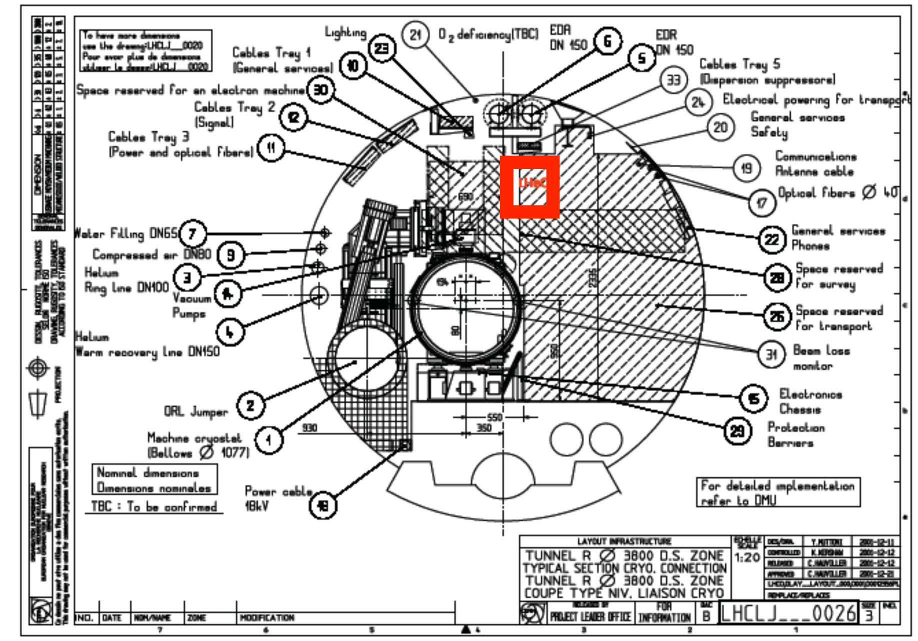


Saturation ideas: CGC

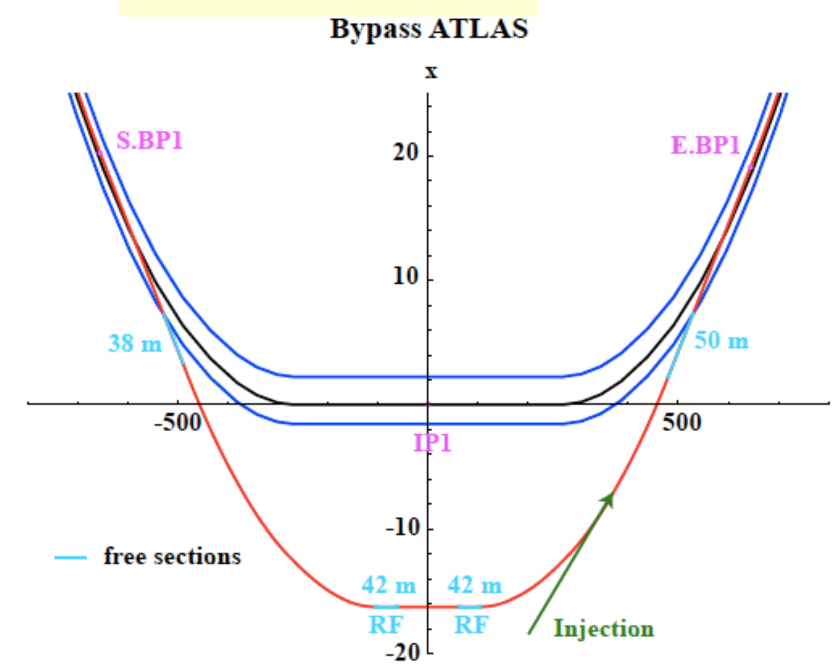


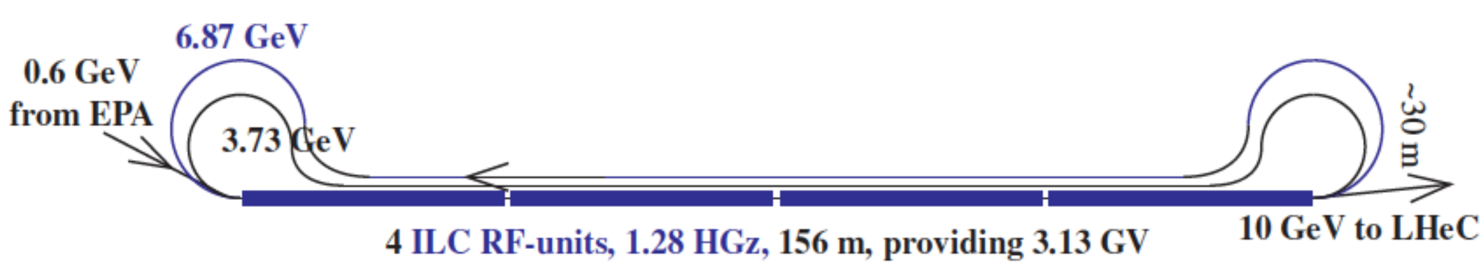
Machine: Ring-Ring option



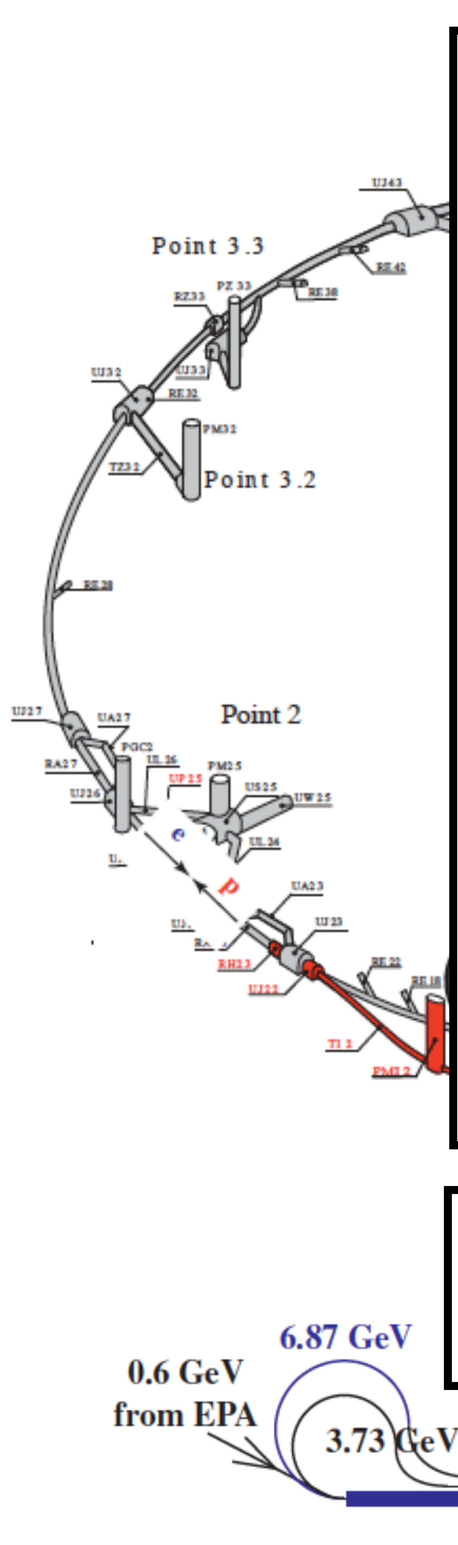


BYPASS

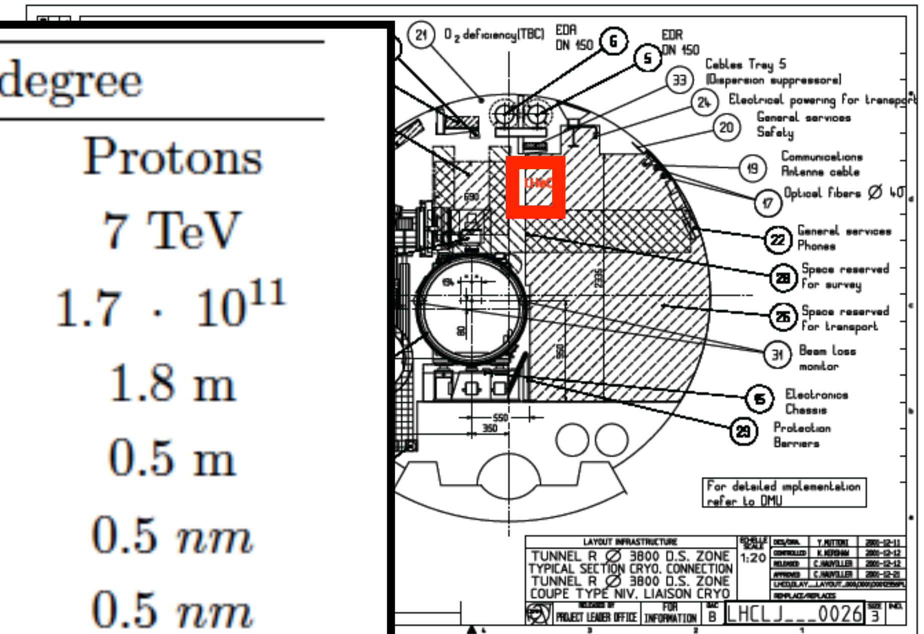


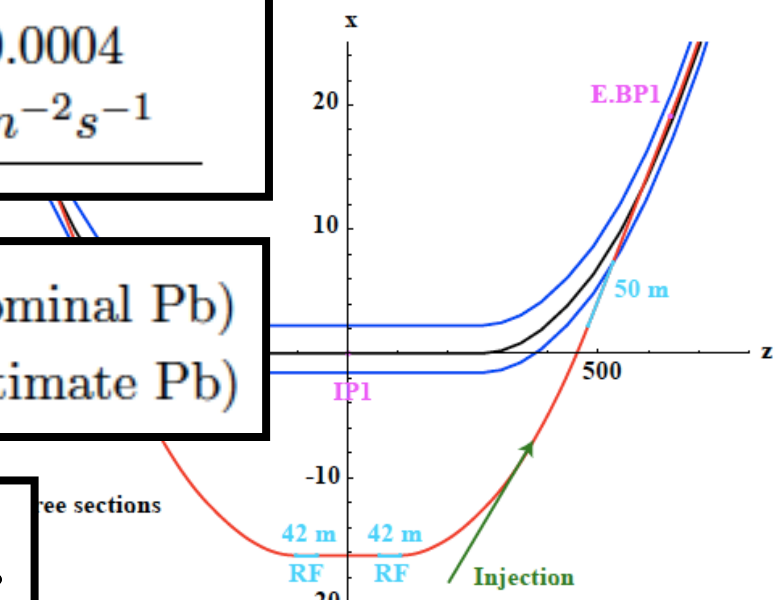


Machine: Ring-Ring option



IR Option	1 degree		10 degree	
Beams	Electrons	Protons	Electrons	Protons
Energy	60 GeV	7 TeV	60 GeV	7 TeV
Intensity	$2 \cdot 10^{10}$	$1.7 \cdot 10^{11}$	$2 \cdot 10^{10}$	$1.7 \cdot 10^{11}$
β_x^*	0.4 m	4.05 m	0.18 m	1.8 m
β_y^*	0.2 m	0.97 m	0.1 m	0.5 m
ϵ_x	5 nm	0.5 nm	5 nm	0.5 nm
ϵ_y	2.5 nm	0.5 nm	2.5 nm	0.5 nm
σ_x	$45\mu m$		$30\mu m$	
σ_y	$22\mu m$		$15.8\mu m$	
Cross angle	1 mrad		1 mrad	
$\xi_{bb,x}$	0.086	0.0008	0.085	0.0008
$\xi_{bb,y}$	0.088	0.0004	0.090	0.0004
Luminosity	$7.33 \cdot 10^{32}\ cm^{-2}s^{-1}$		$1.34 \cdot 10^{33}\ cm^{-2}s^{-1}$	

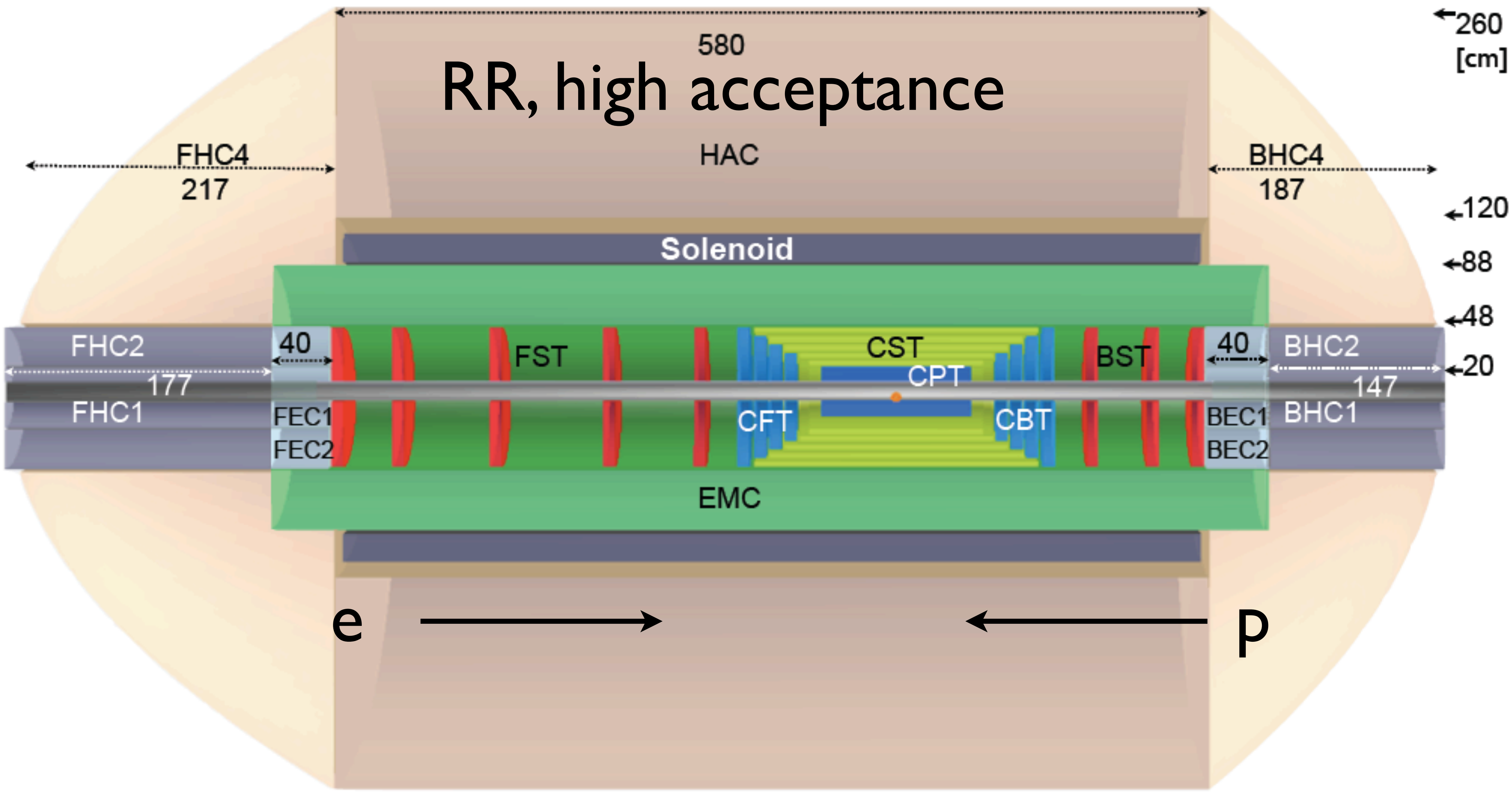




$$L_{eN} = \frac{n_b f_0 N_e (A N_{Pb})}{4\pi\sqrt{\beta_{xe}^*\varepsilon_x}\sqrt{\beta_{ye}^*\varepsilon_y}} = \begin{cases} 2.6 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Nominal Pb)} \\ 4.5 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Ultimate Pb)} \end{cases}$$

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

The detector: low-x/eA setup



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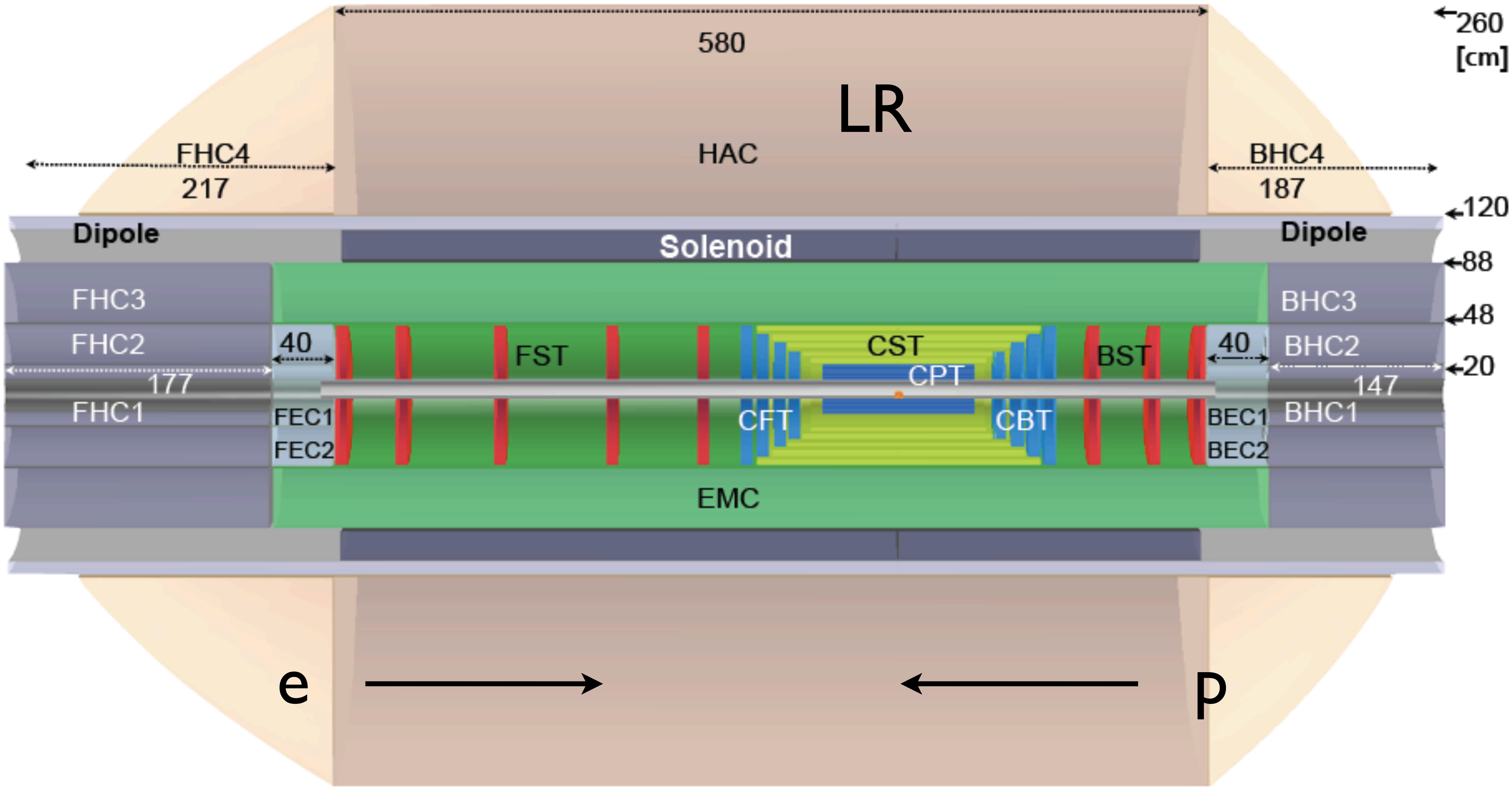

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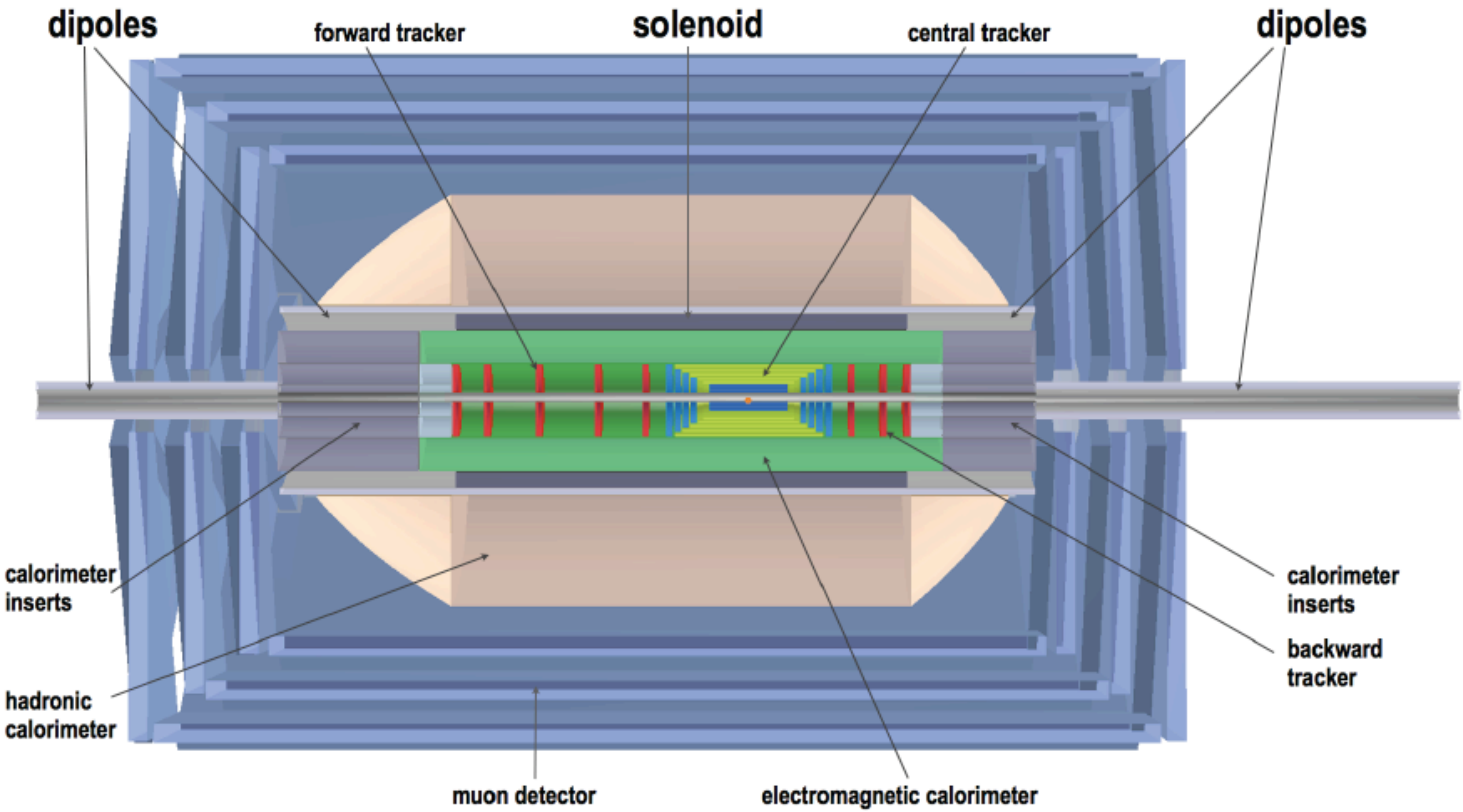

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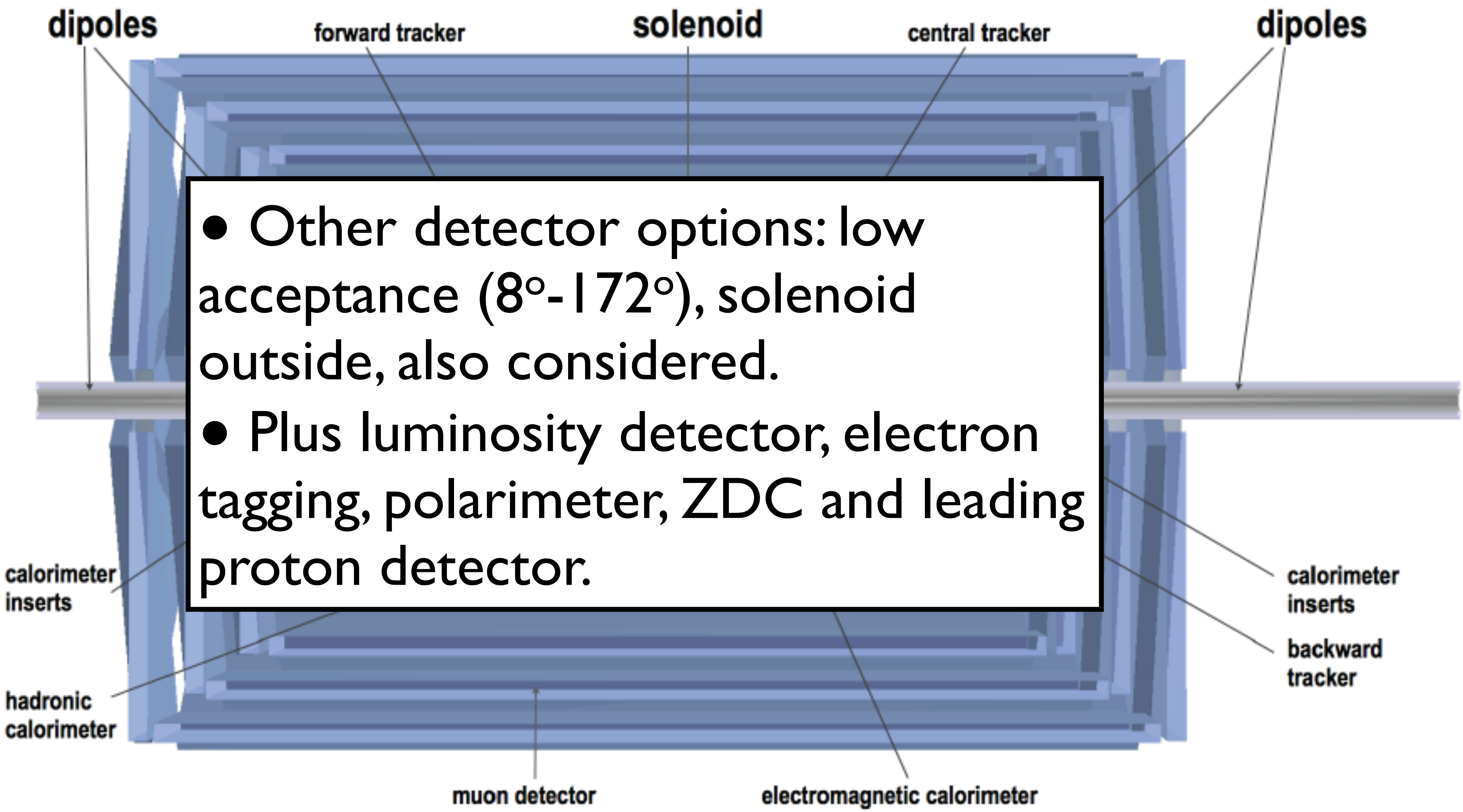
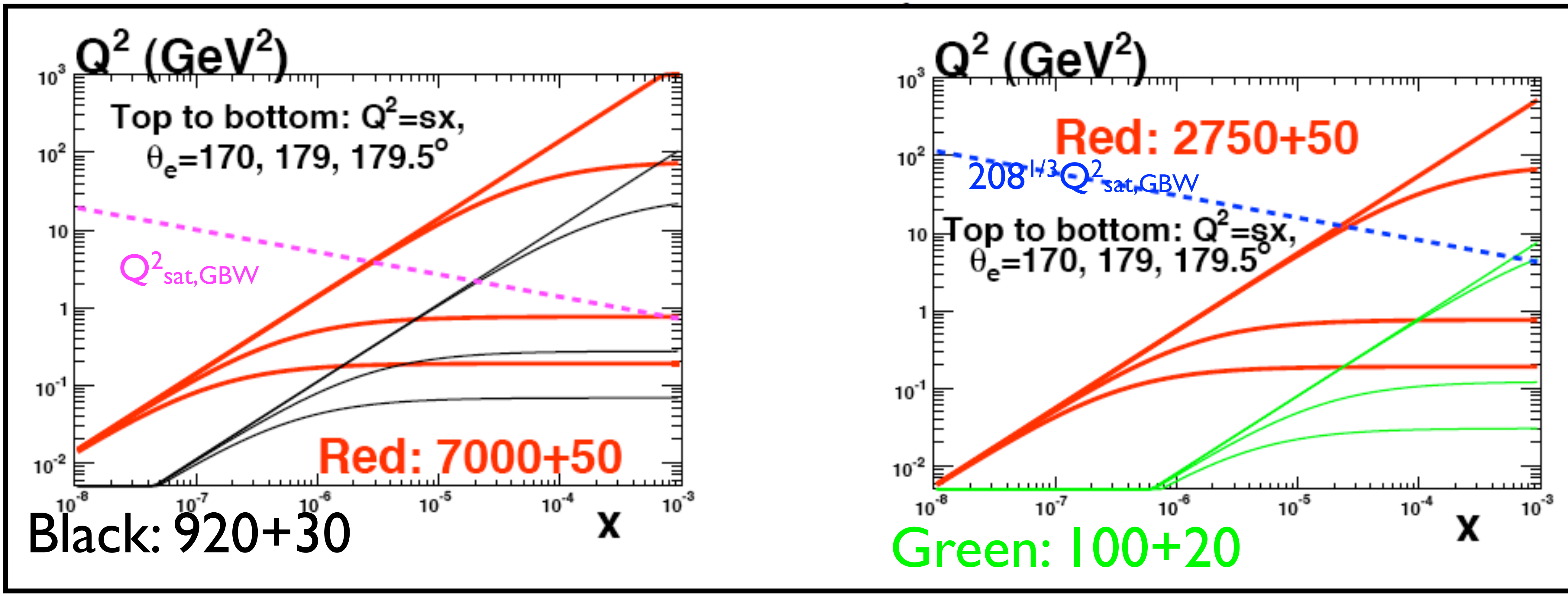


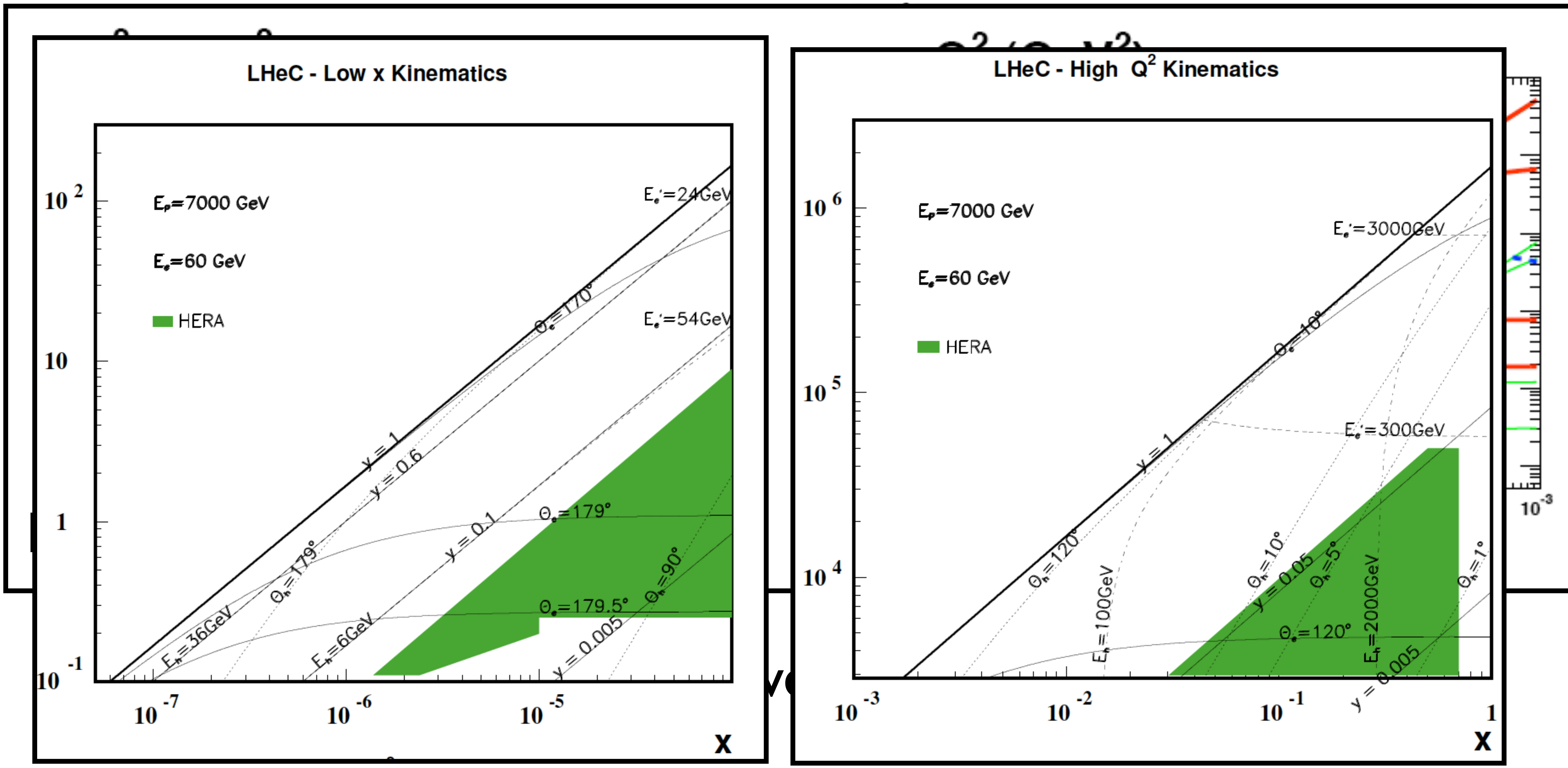
- Other detector options: low acceptance (8°-172°), solenoid outside, also considered.
- Plus luminosity detector, electron tagging, polarimeter, ZDC and leading proton detector.

Kinematics:



- ep: access to the perturbative region below x ~ a few 10^{-5}.
- eA: new realm.
- No small-x physics without ~ 1 degree acceptance.

Kinematics:



- eA: new realm.
- No small-x physics without ~ 1 degree acceptance.

LHeC scenarios:

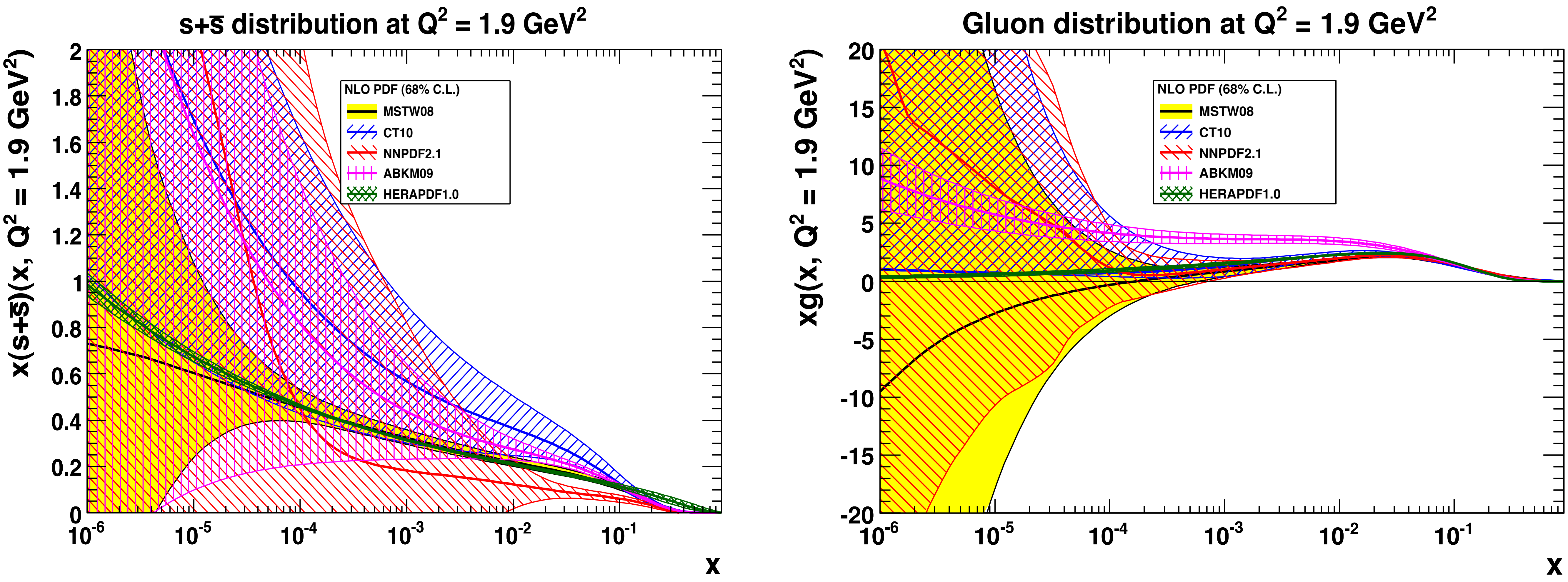
For F_2

config.	E(e)	E(N)	N	∫L(e⁺)	∫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^{-4}	10^{-4}	0.4	10^{-3}	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp
I	50	3.5	Ca	$5 \cdot 10^{-4}$		?	$5 \cdot 10^{-3}$	?	?	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.

Proton PDFs at small x:

- Parton densities poorly determined at small x and small to moderate Q^2 $\Rightarrow$ uncertainties in the predictions for observables within collinear factorisation.



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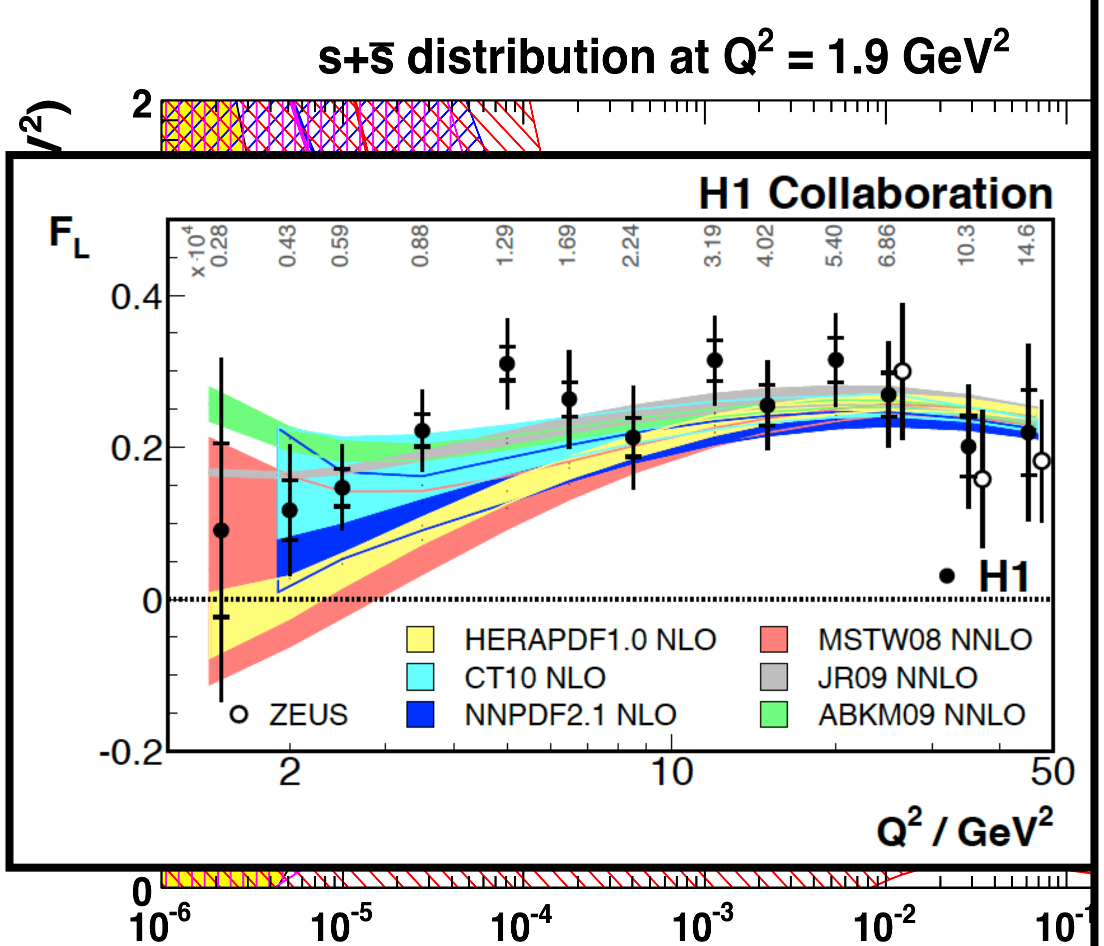
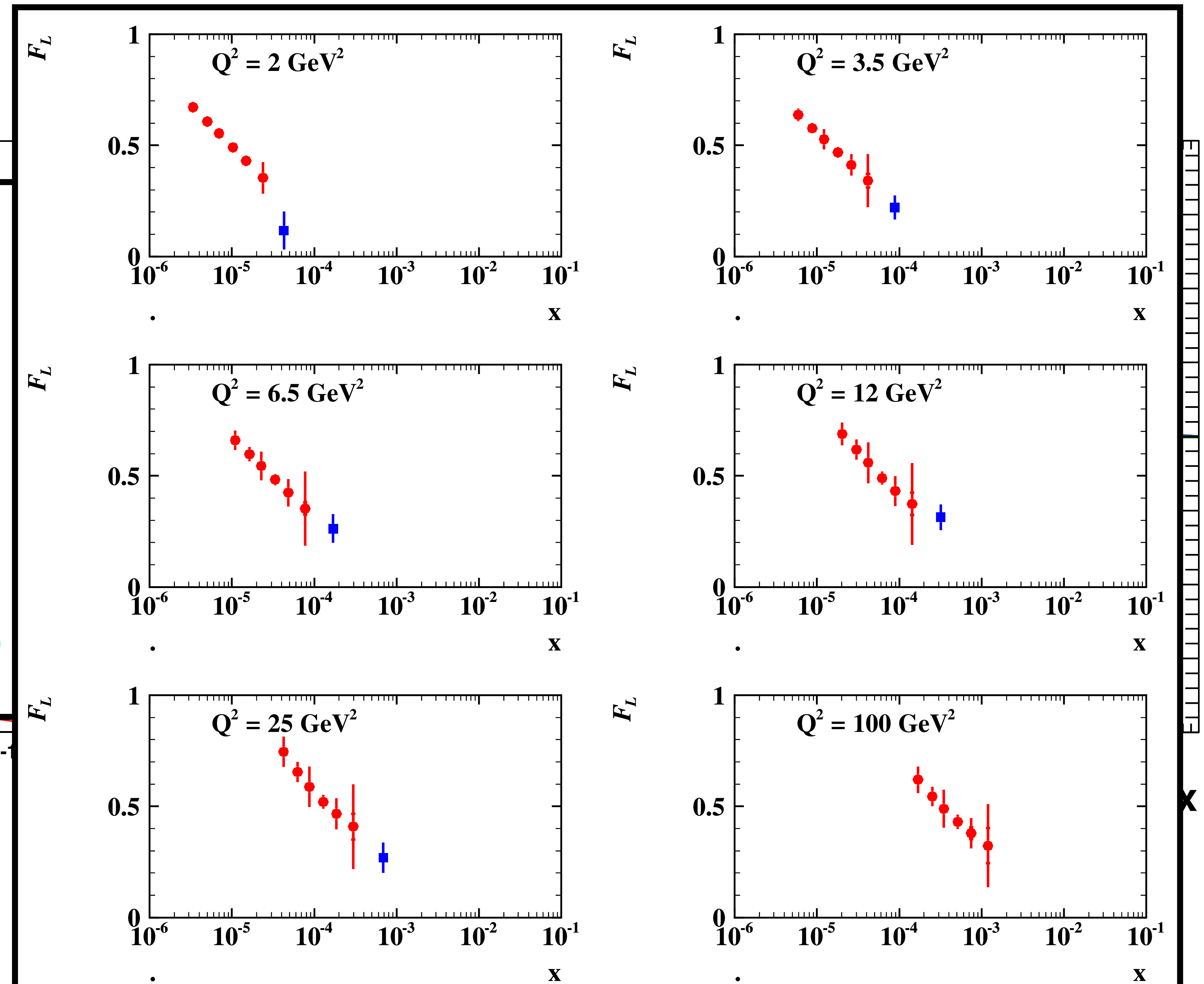
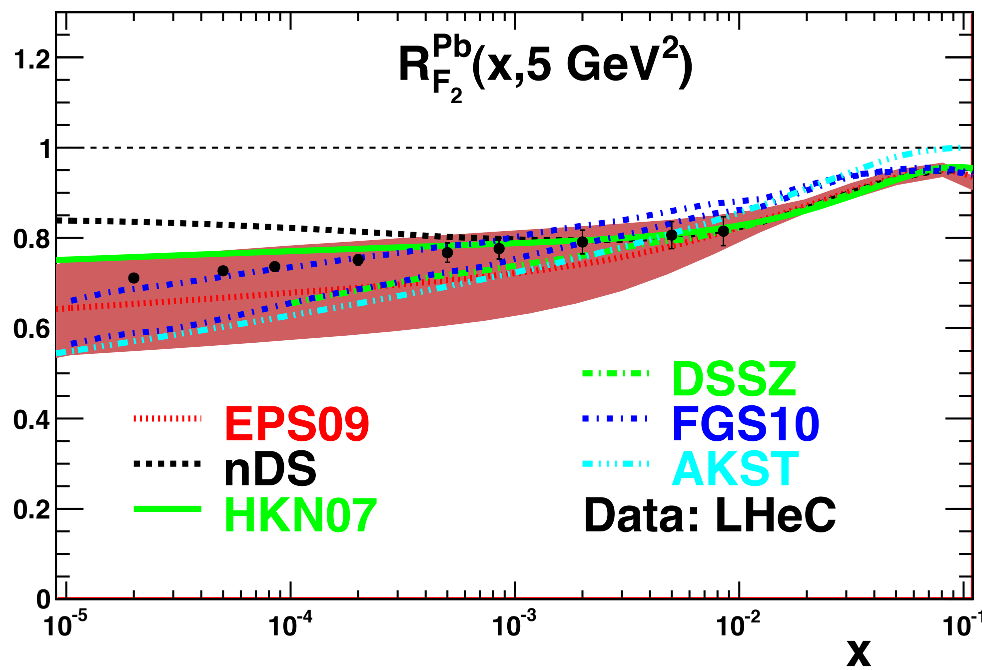


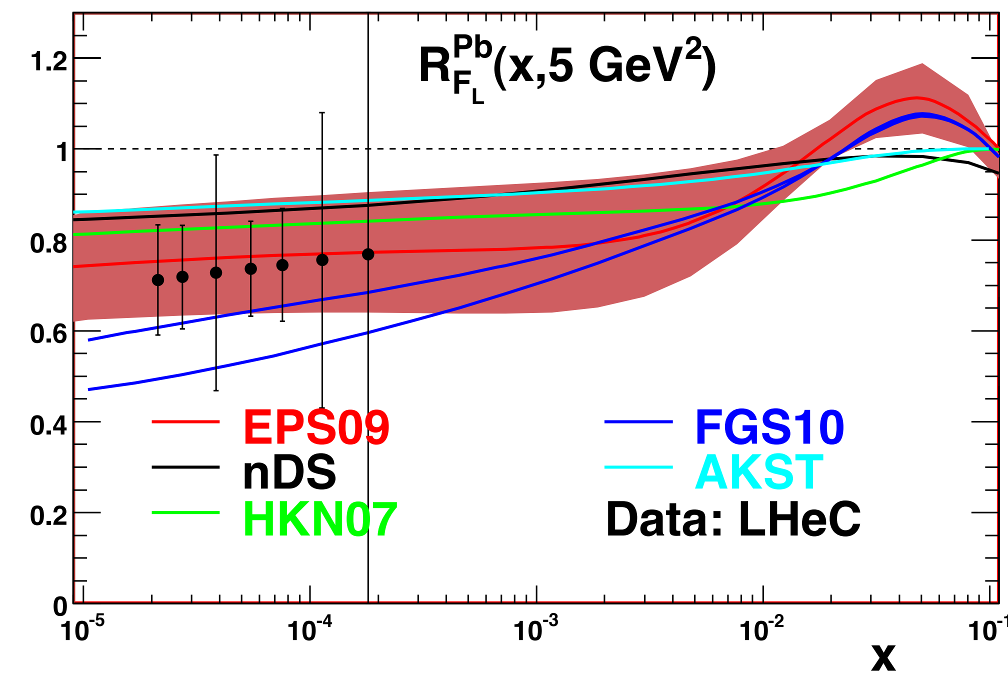


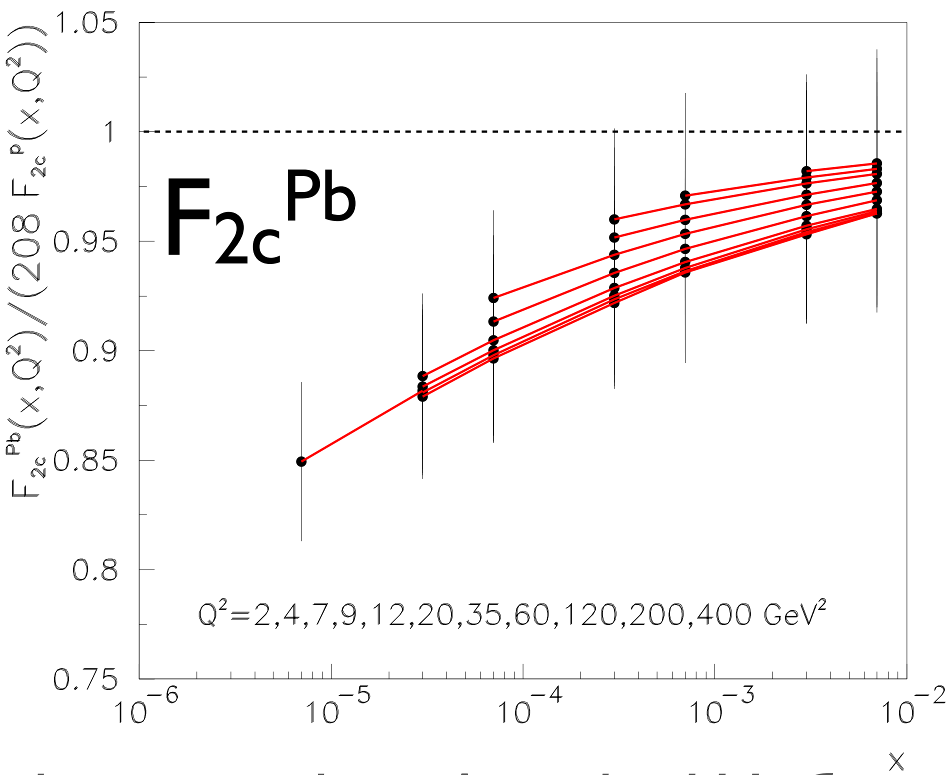
eA inclusive: comparison

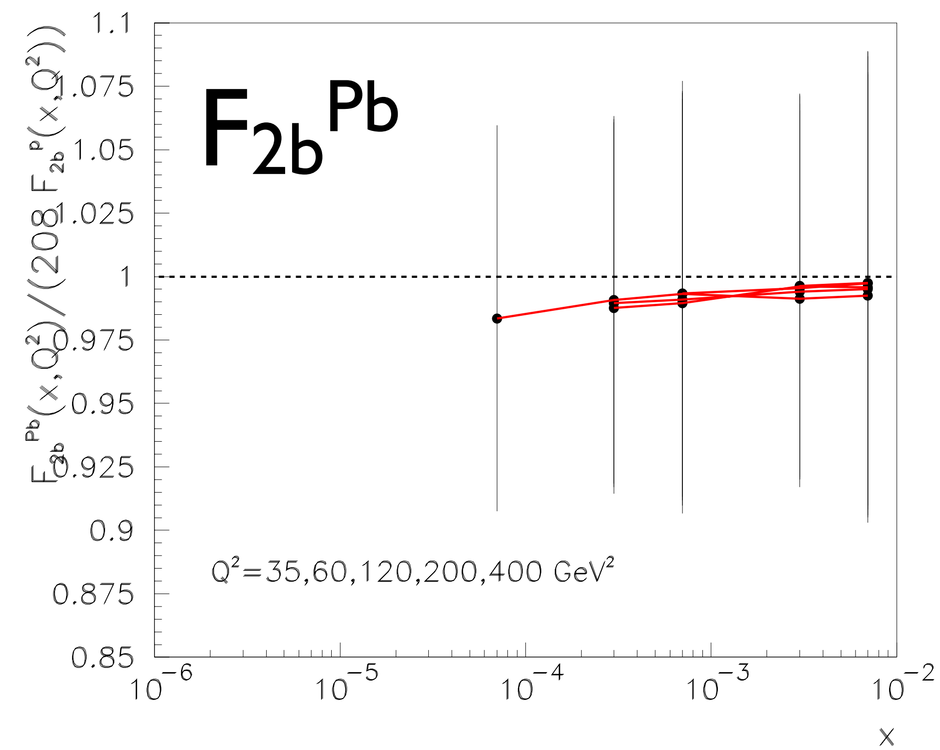
- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x

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









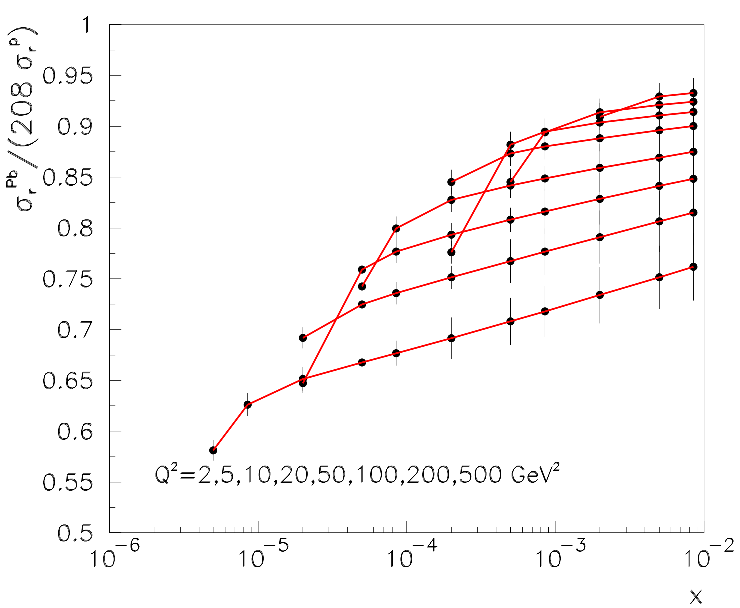
Note: F_L in eA

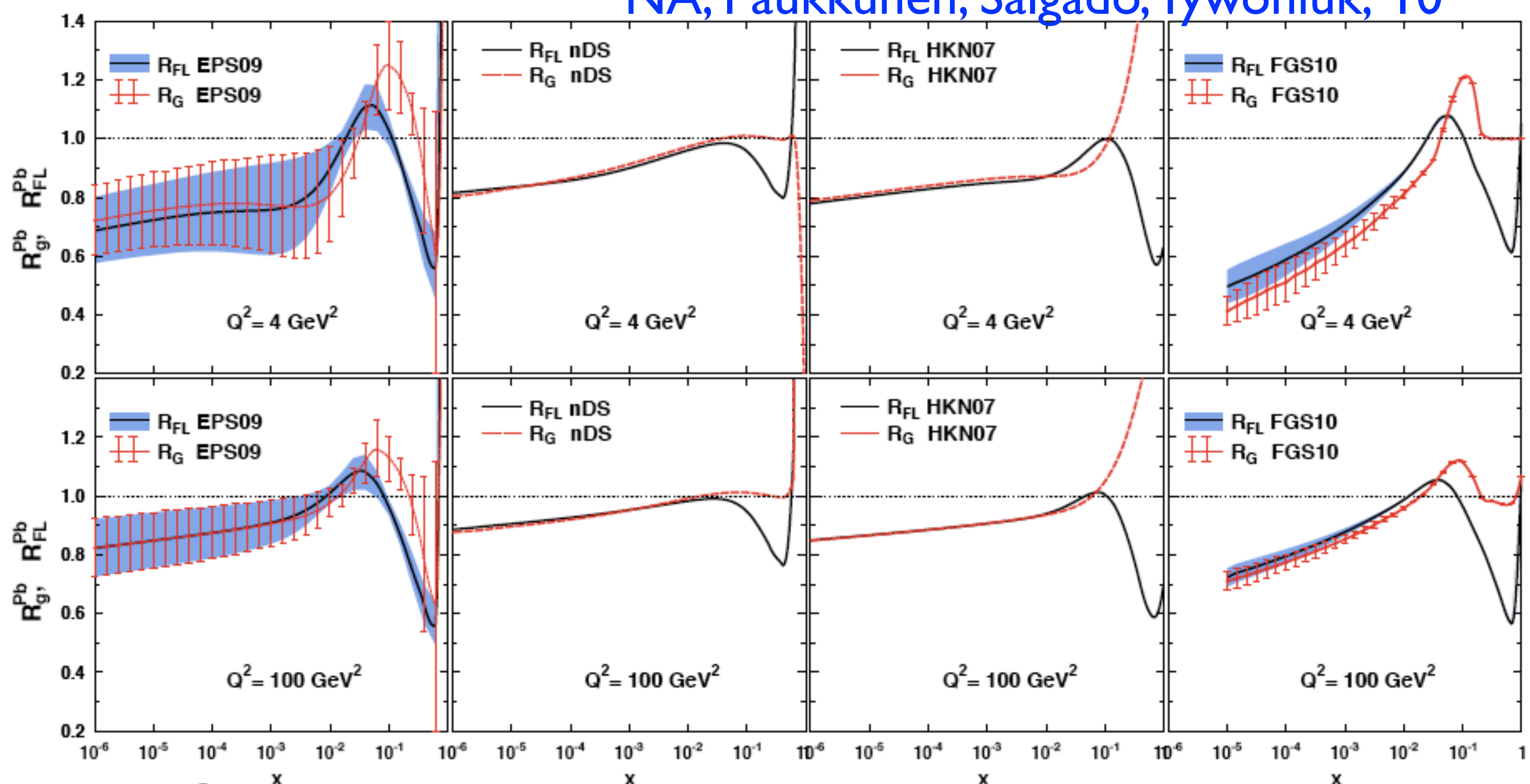
$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+}\frac{F_L}{F_2}\right], \qquad Y_+ = 1 + (1-y)^2$$

- 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

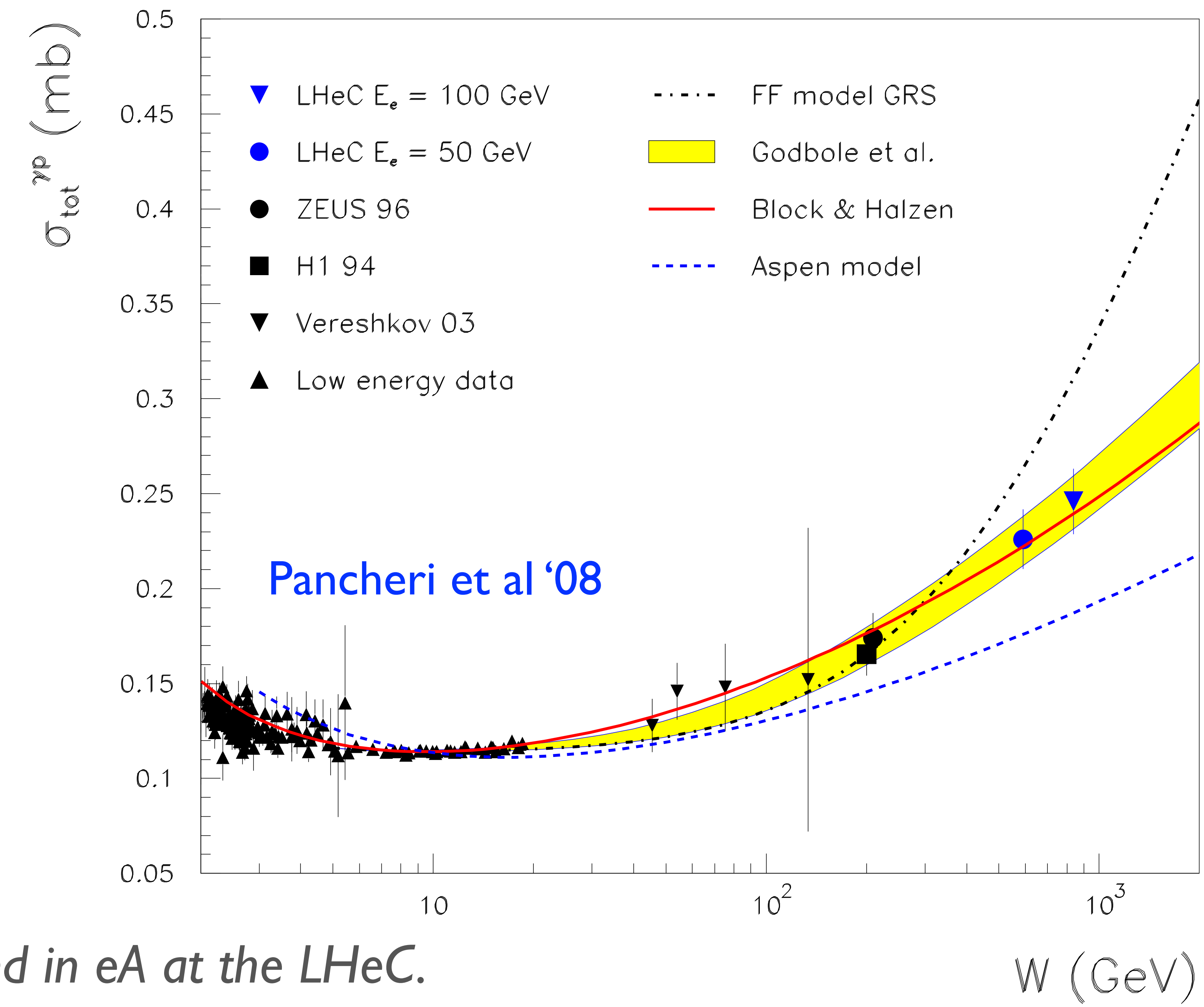




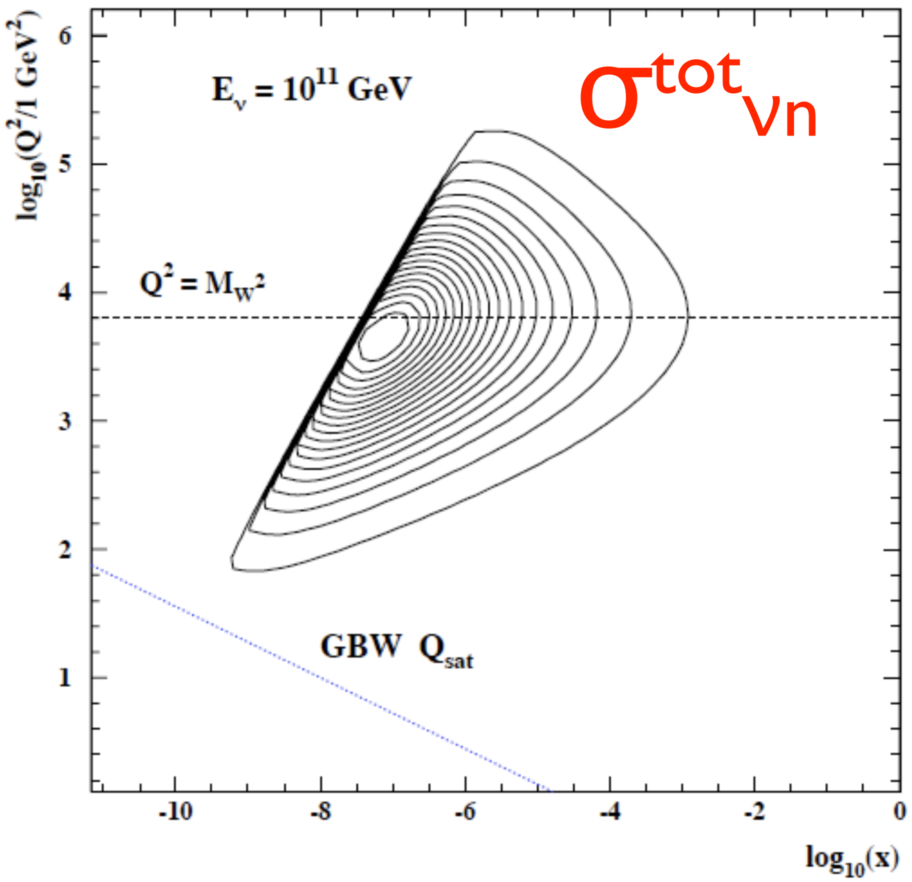
Photoproduction cross section:

- Small angle electron detector 62 m far from the interaction point: $Q^2<0.01$ GeV, $y\sim0.3 \Rightarrow W\sim0.5\ \sqrt{s}$.

- Substantial enlarging of the lever arm in W.

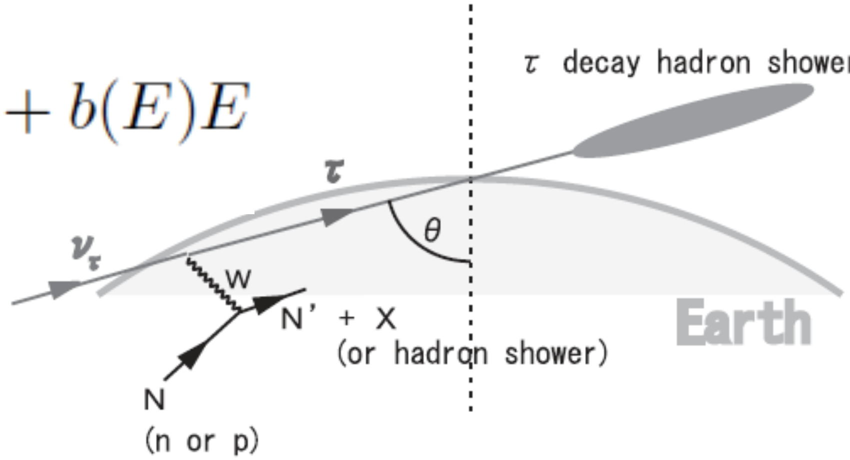


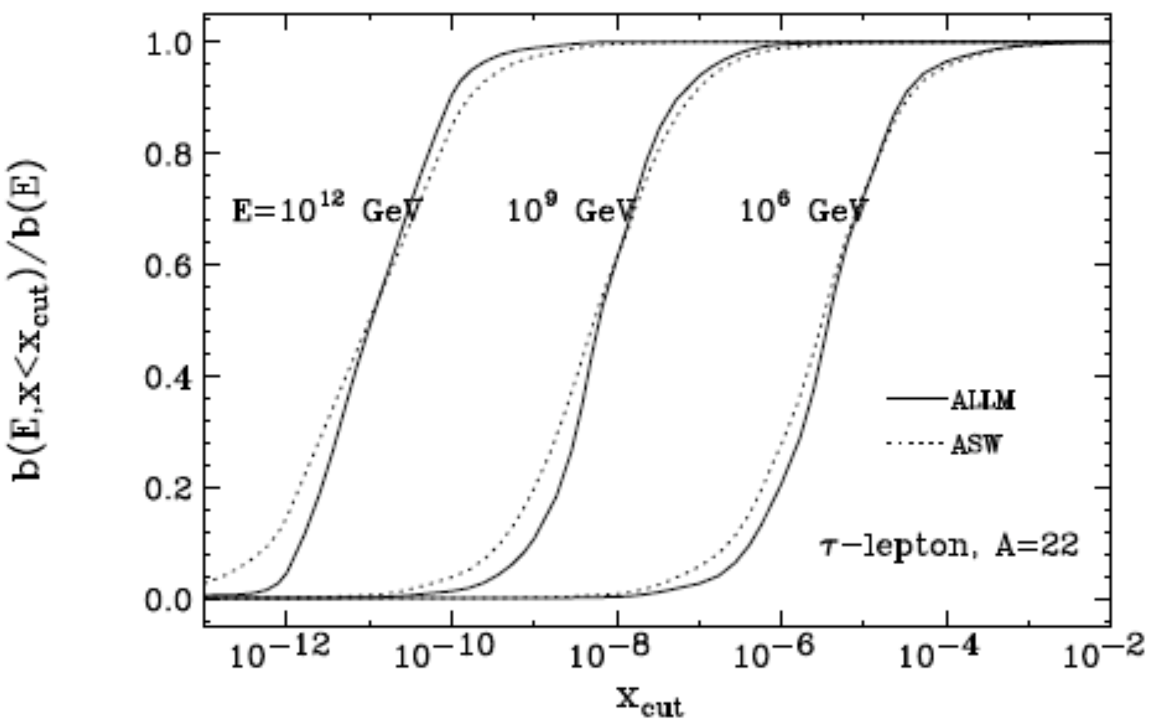
Implications for UHEν's:

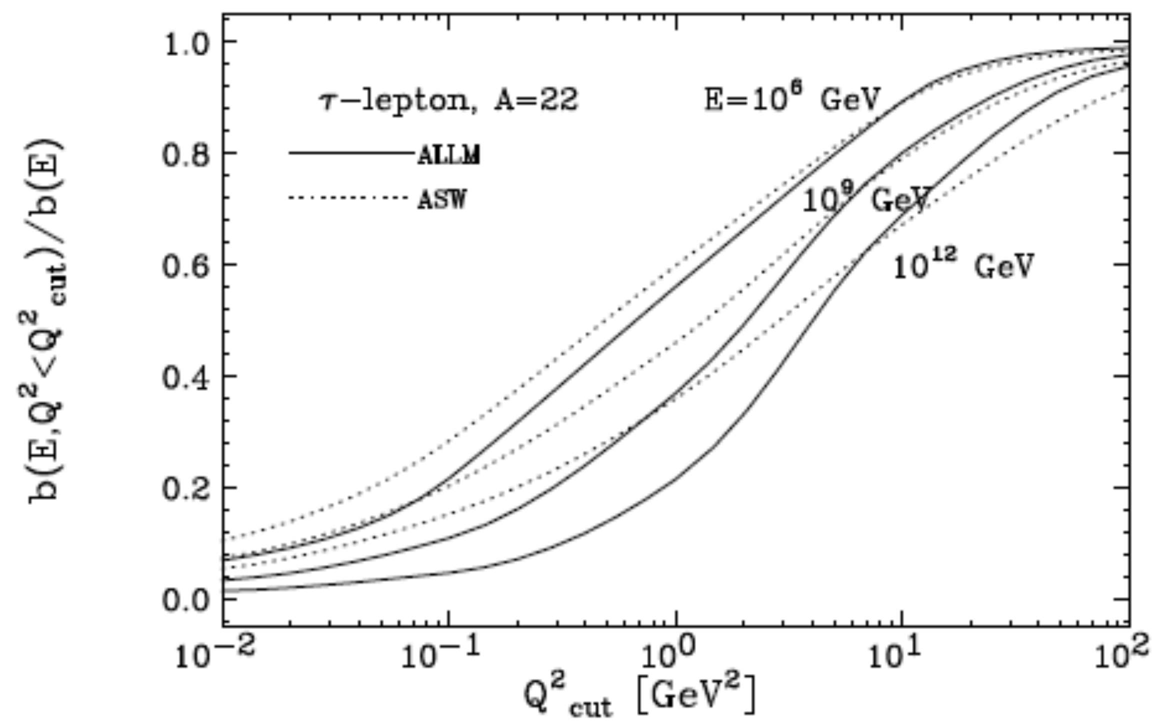


- ν-n/A cross section (τ energy loss) dominated by DIS structure functions / (n)pdfs at small-x and large (small) Q^2.
- Key ingredient for estimating fluxes.

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

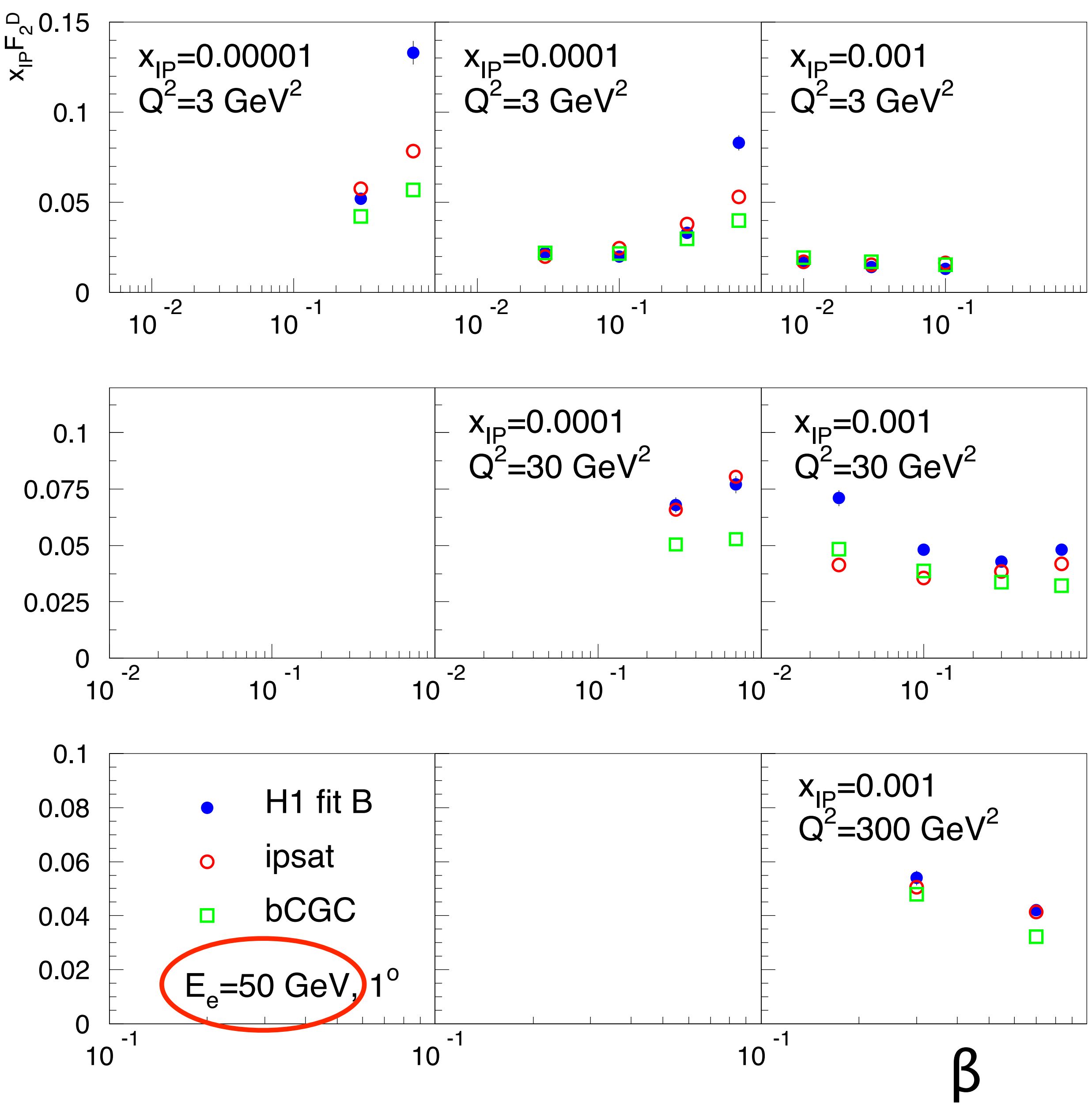


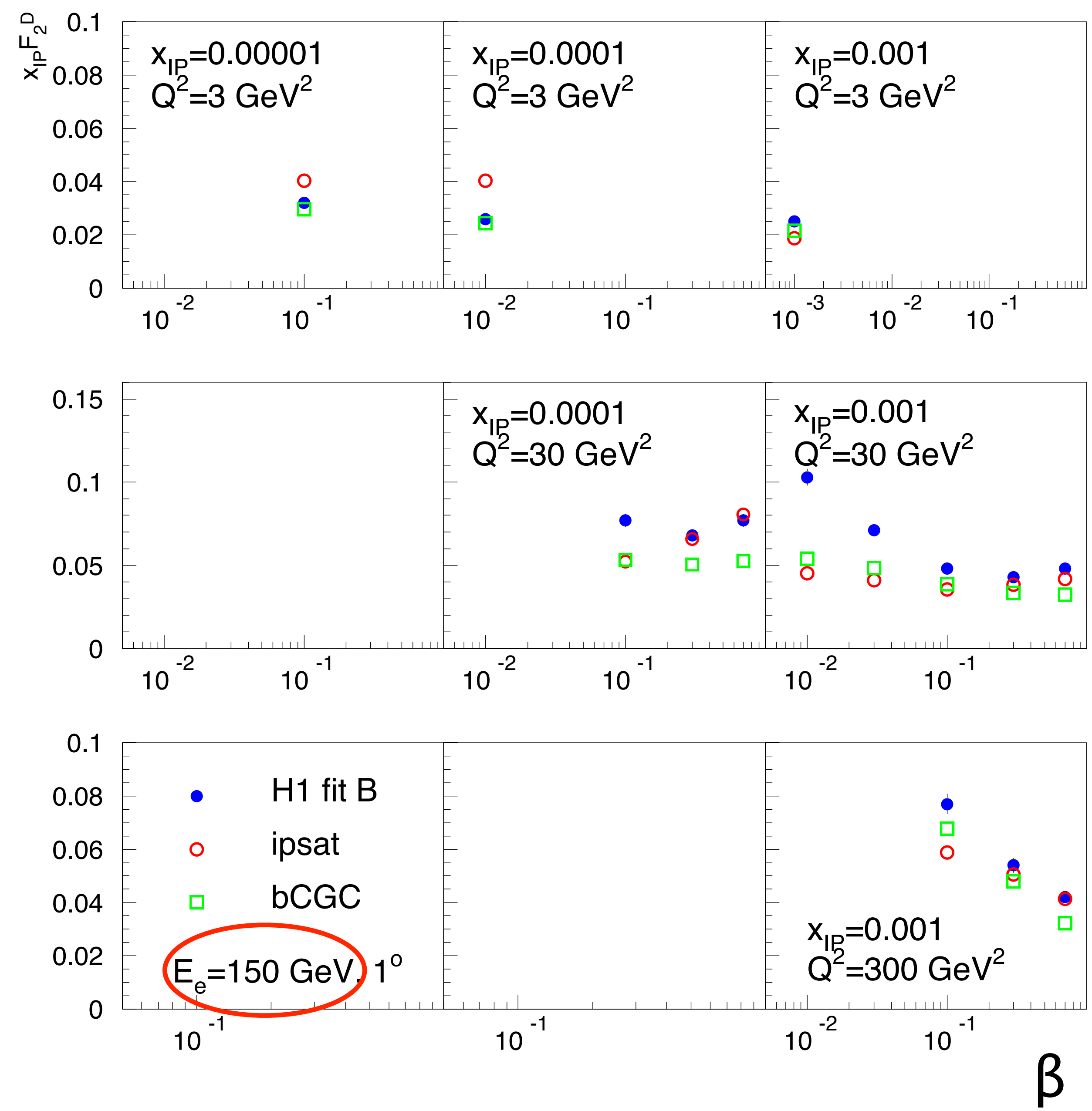




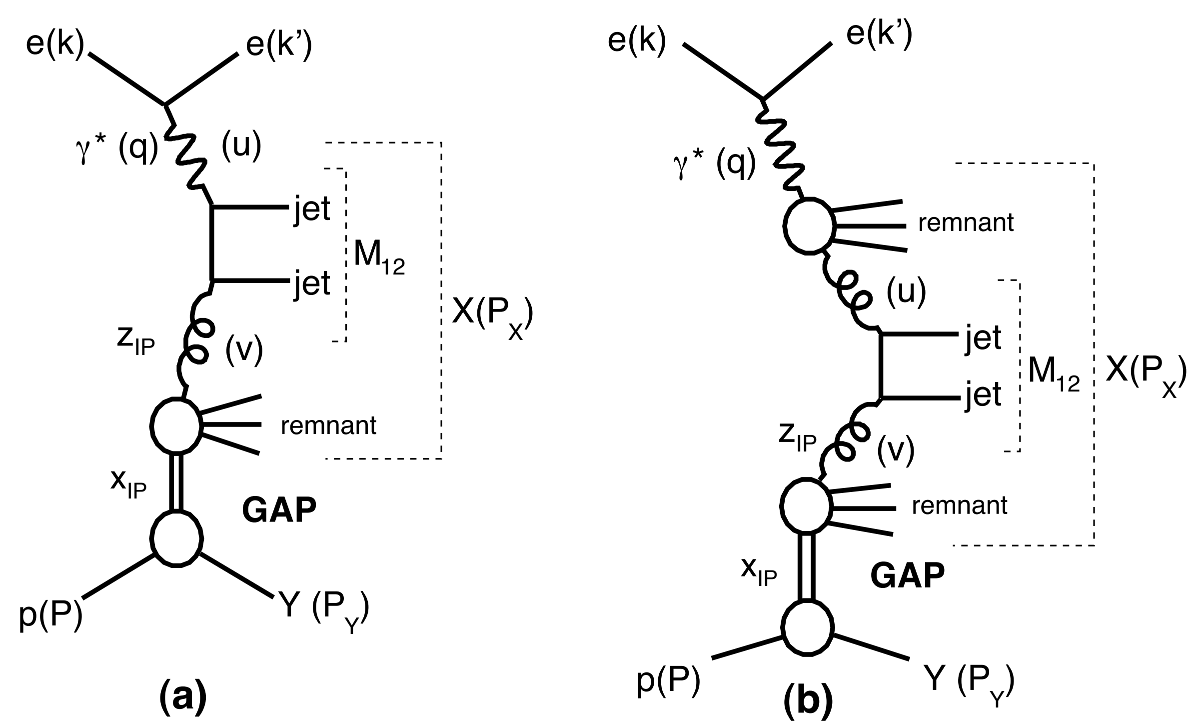
Diffraction and non-linear dynamics:

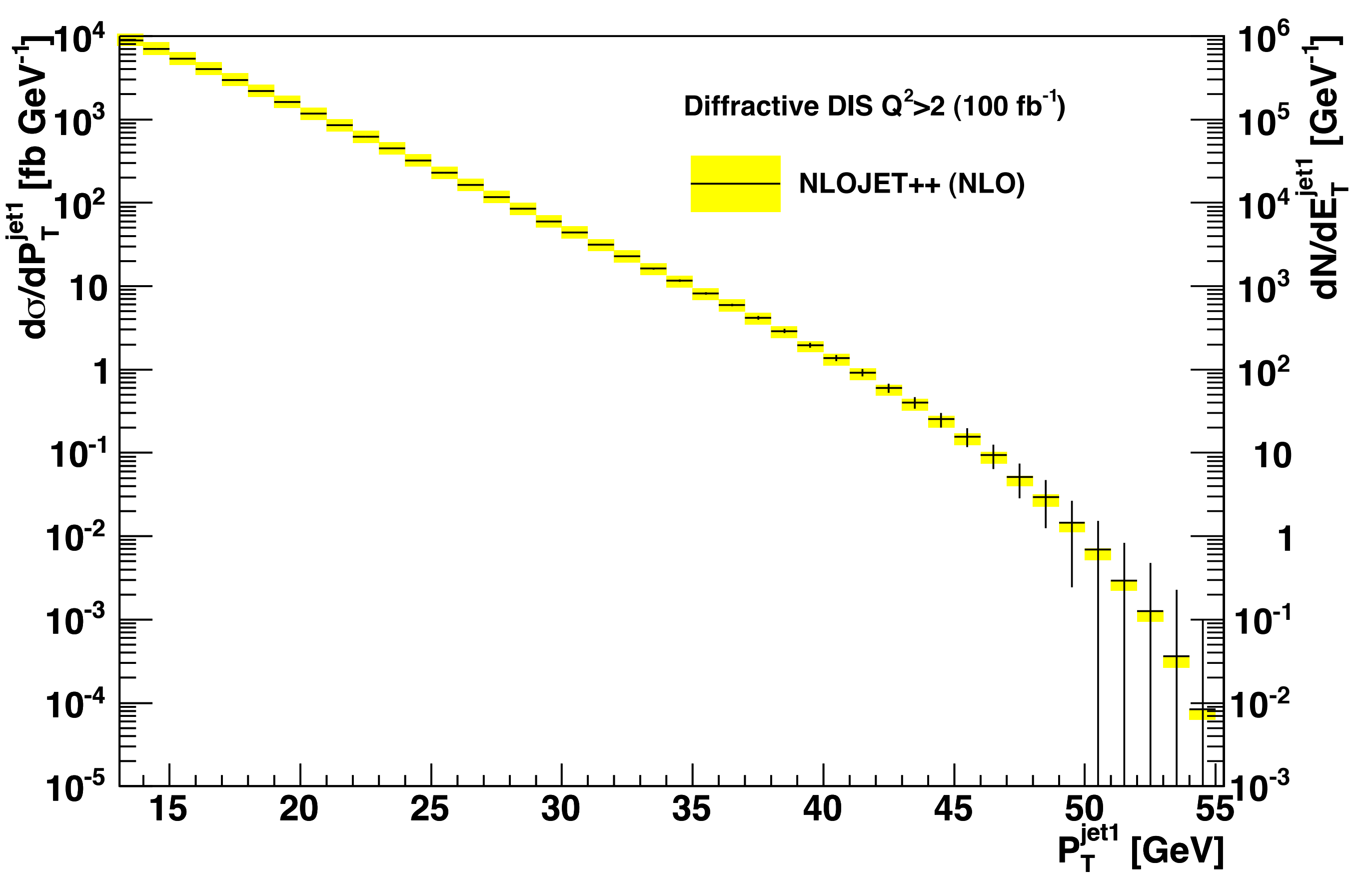
- Dipole models show differences with linear-based extrapolations (HERA-based dpdf's) and among each other: possibility to check saturation and its realization.





Diffractive dijets:



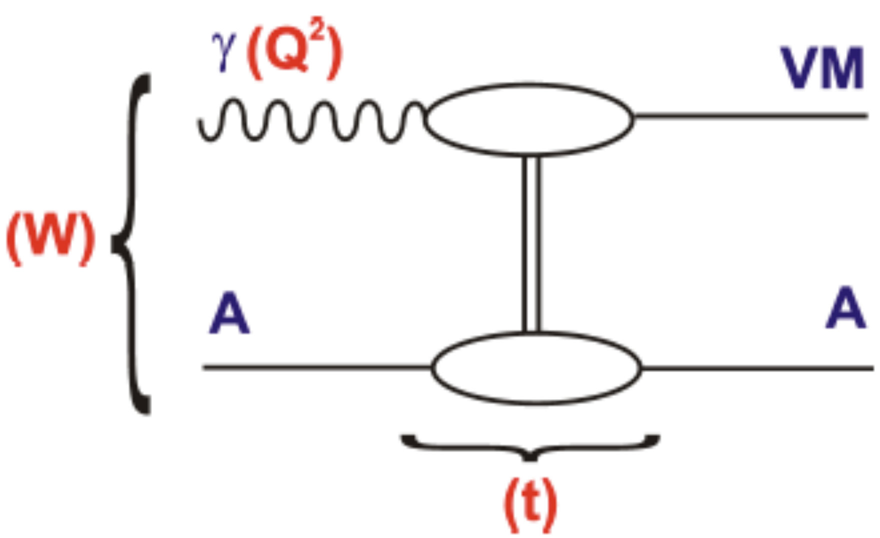


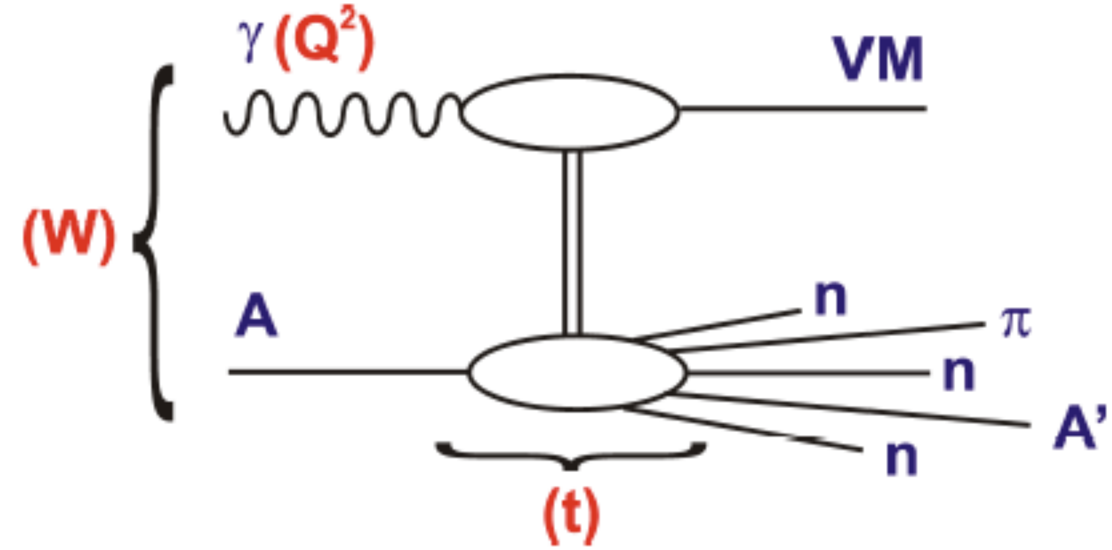
- Diffractive dijet and open heavy flavour production offer large possibilities for:
  → Checking factorization in hard diffraction.
  → Constraining DPDFs.

- Large yields upto large p_T^{jet}.

- Direct and resolved contributions: photon PDFs.

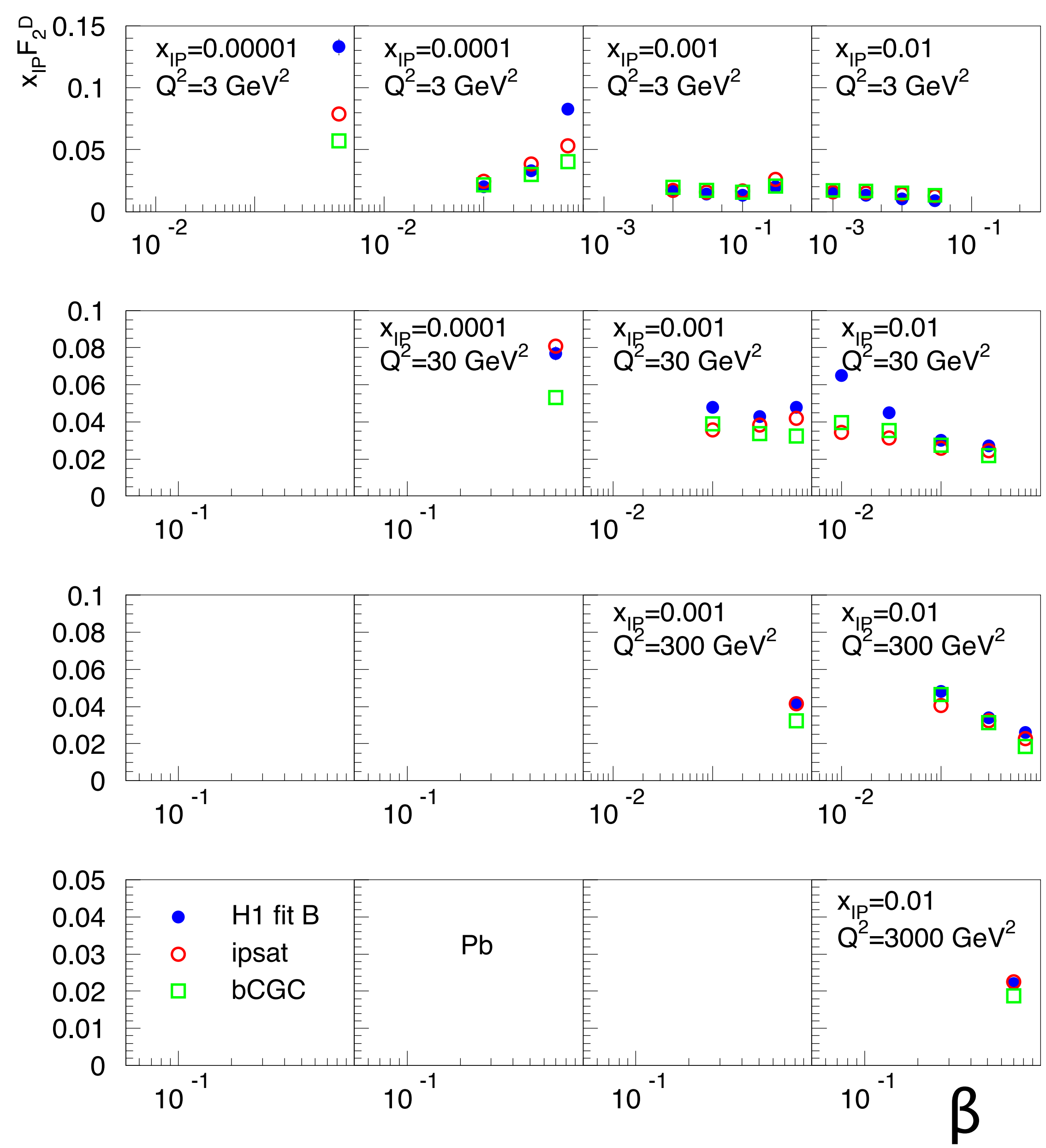
Diffractive DIS on nuclear targets:





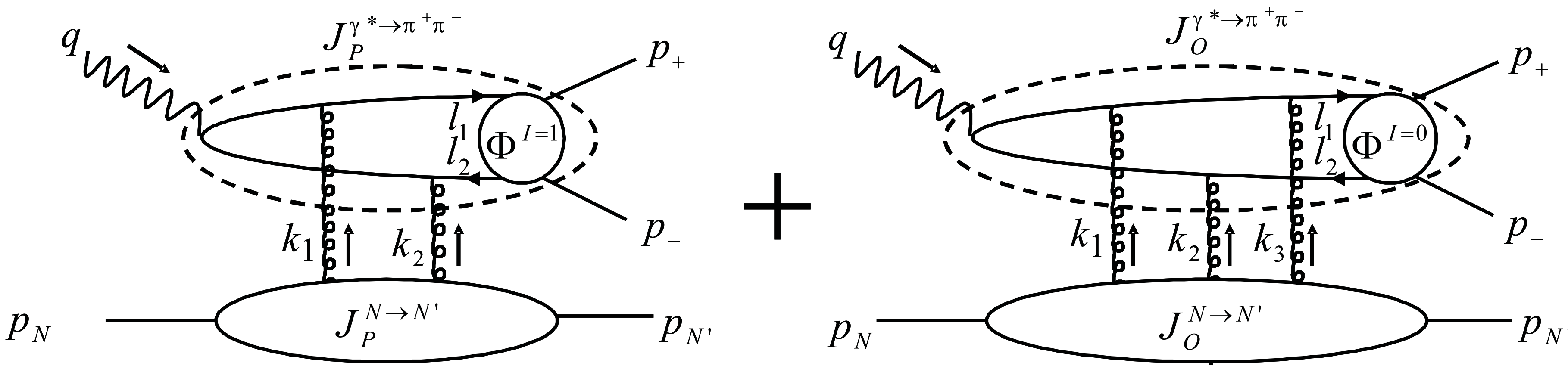
- Challenging experimental problem, requires Monte Carlo simulation with detailed understanding of the nuclear break-up.

- For the coherent case, predictions available.



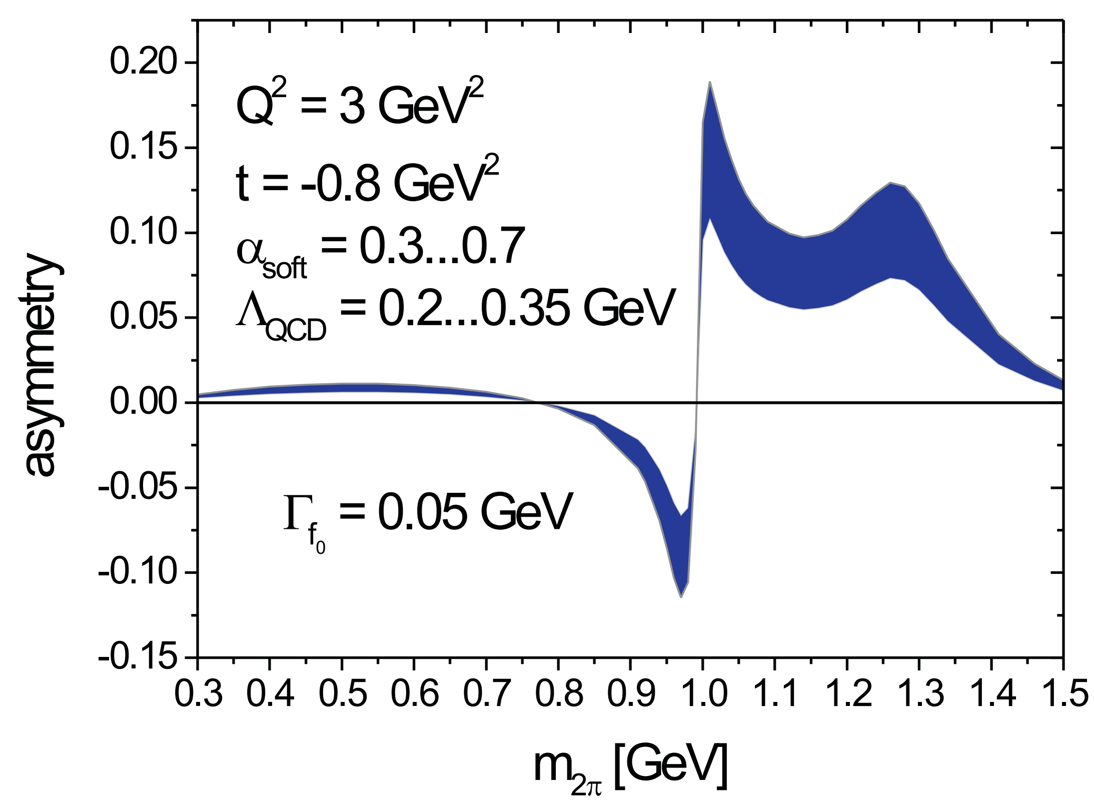
Odderon:

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



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

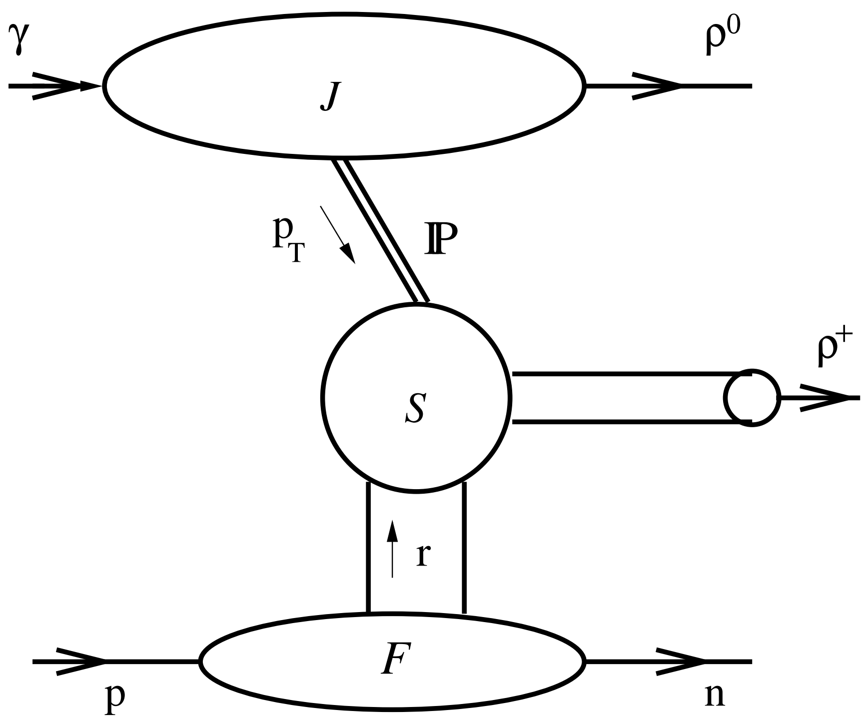
- Sizable charge asymmetry, yields and reconstruction pending.



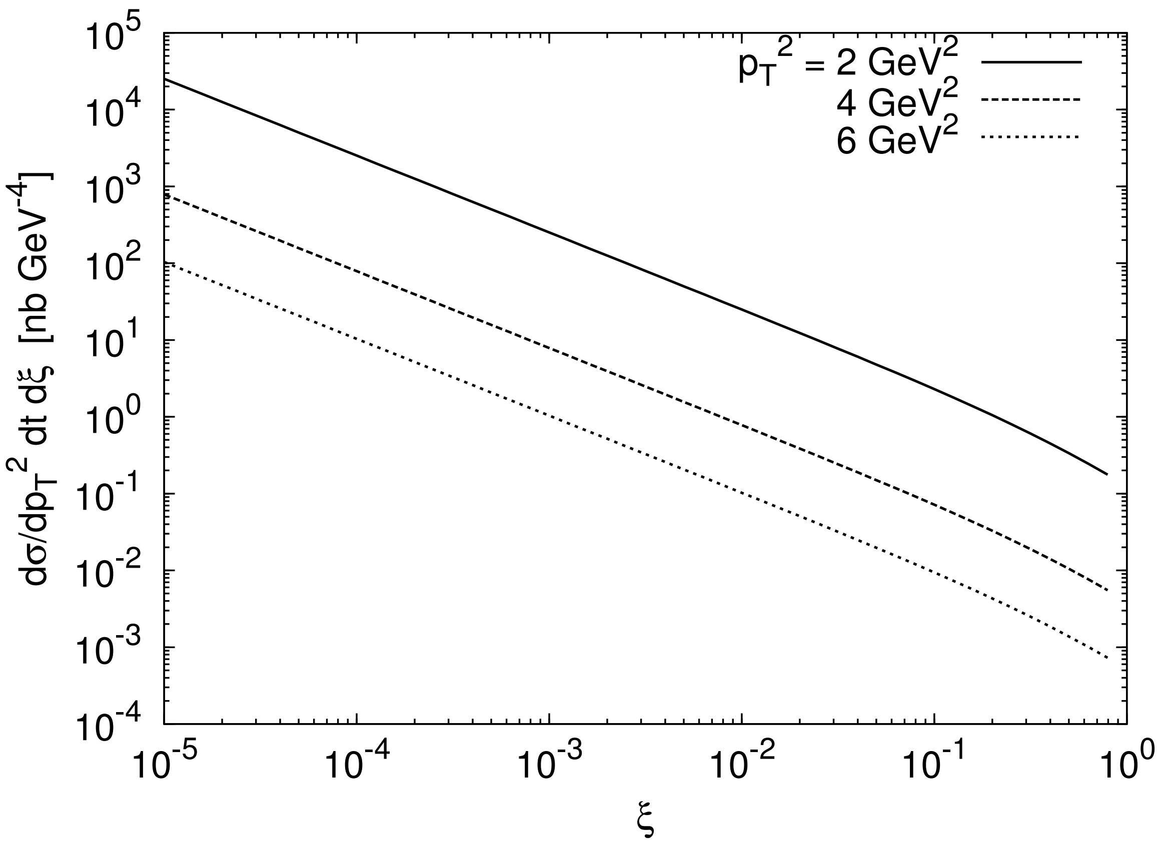
Transversity GPDs:

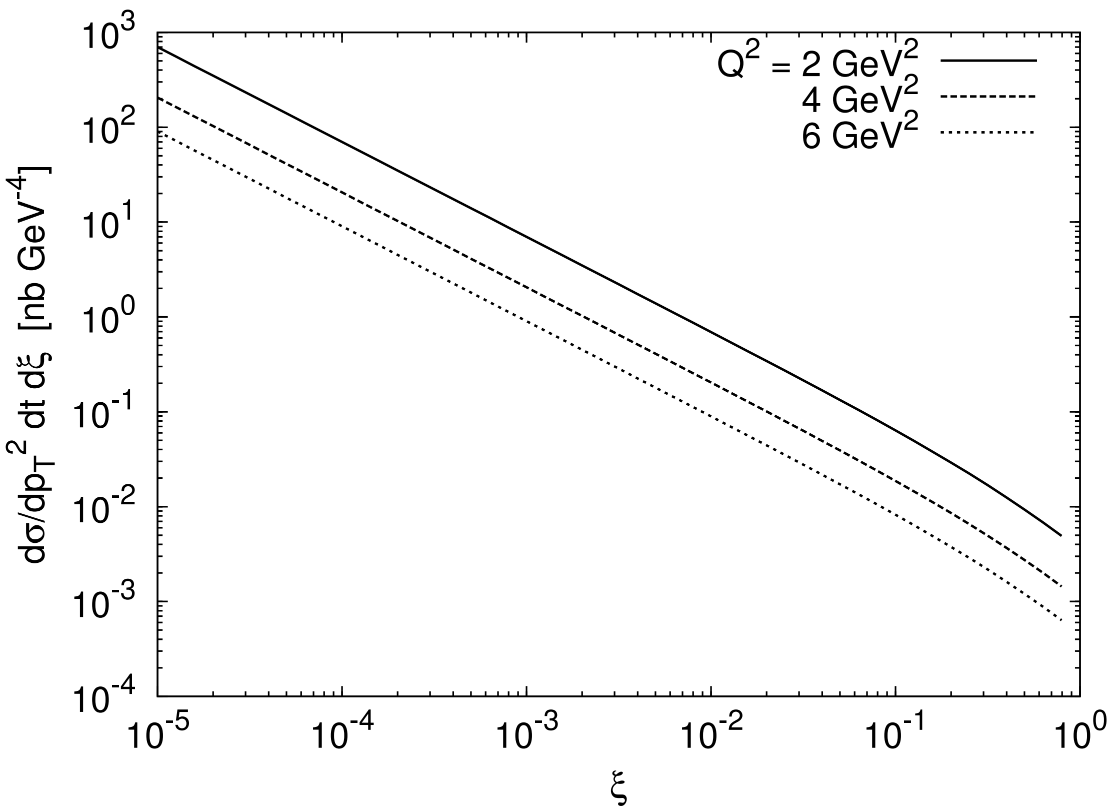
- Chiral-odd transversity GPDs are largely unknown.

- They can be accessed through double exclusive production:



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





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

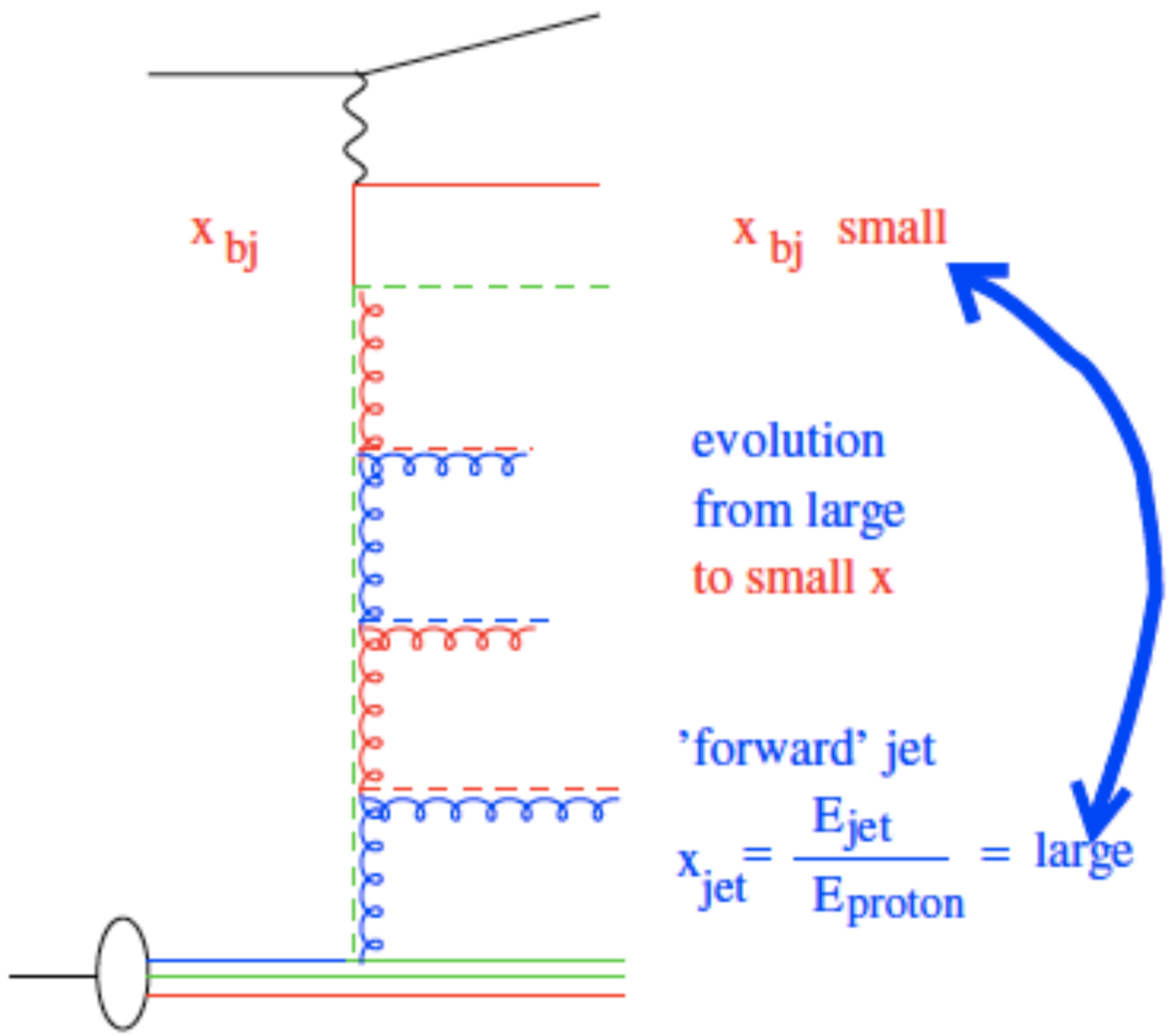
Dynamics of QCD radiation:

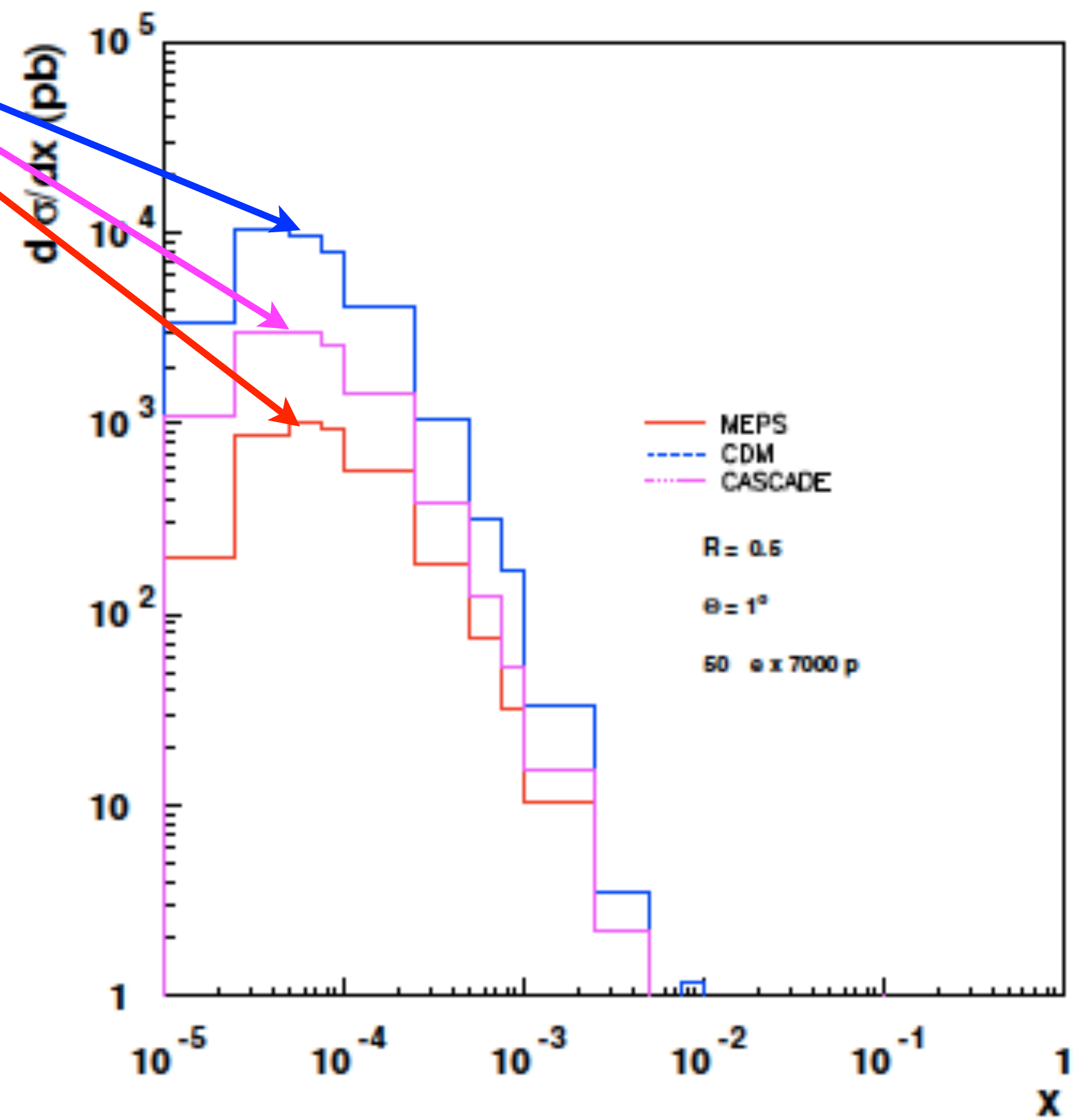
- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:

→ k_T-ordered: DGLAP.

→ k_T-disordered: BFKL-like.

→ Saturation?





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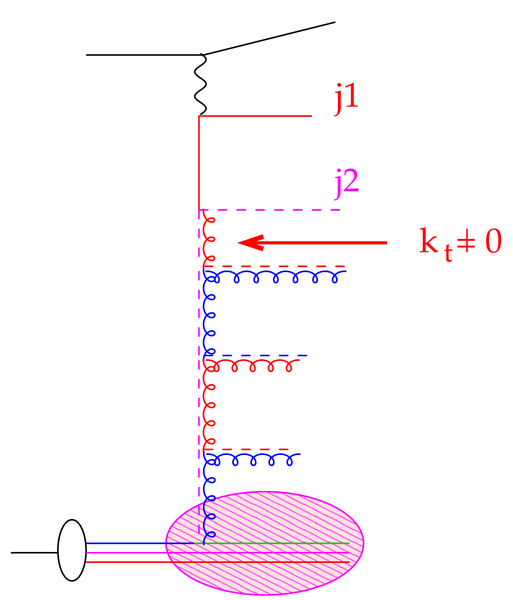
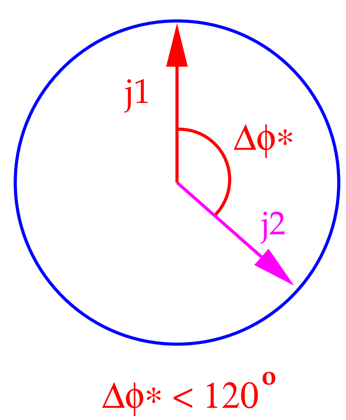
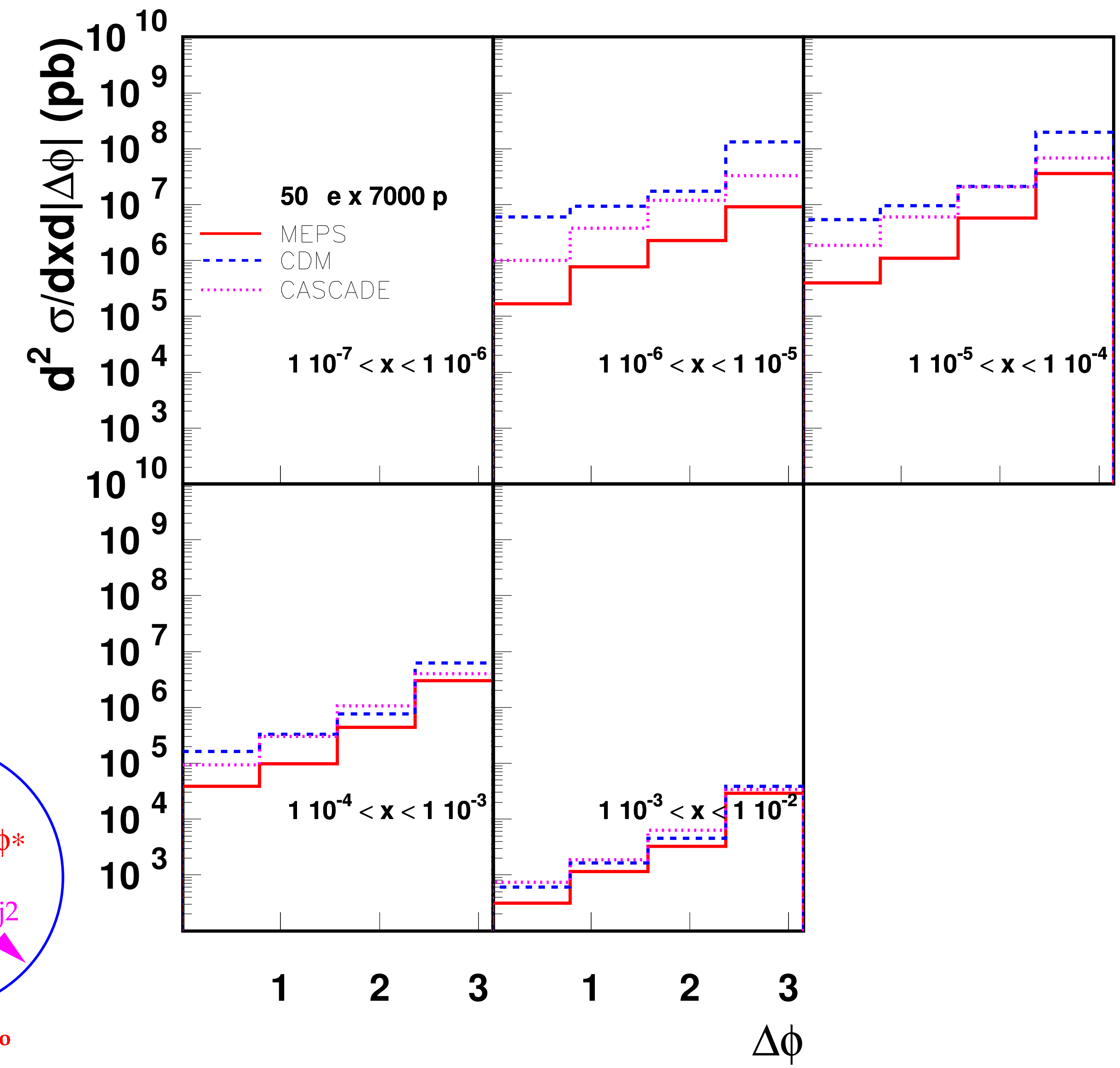
- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.







Forward jets:

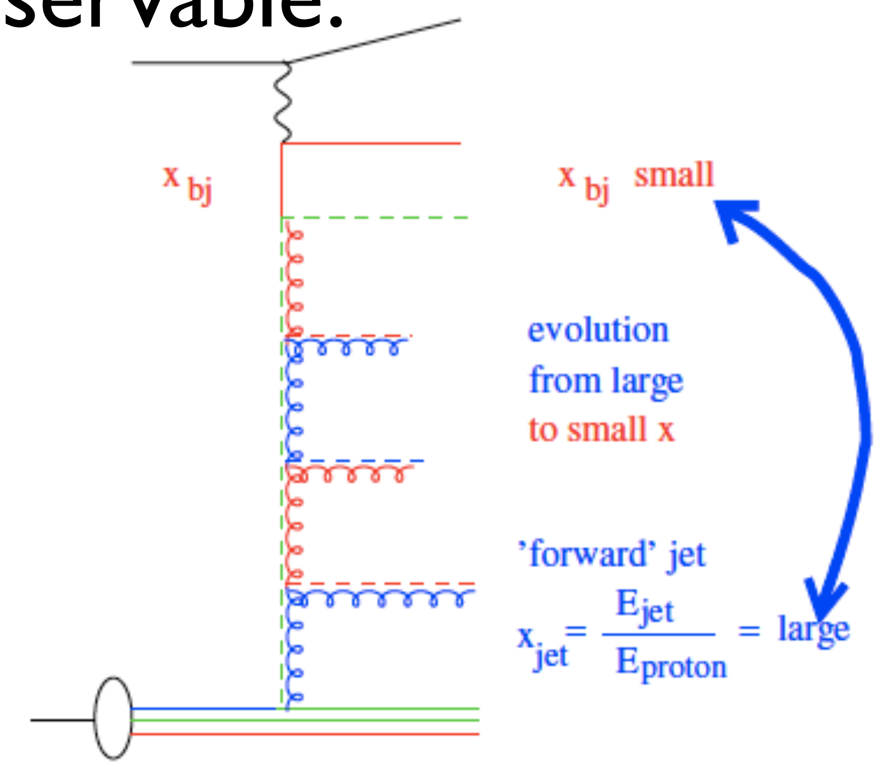
- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:

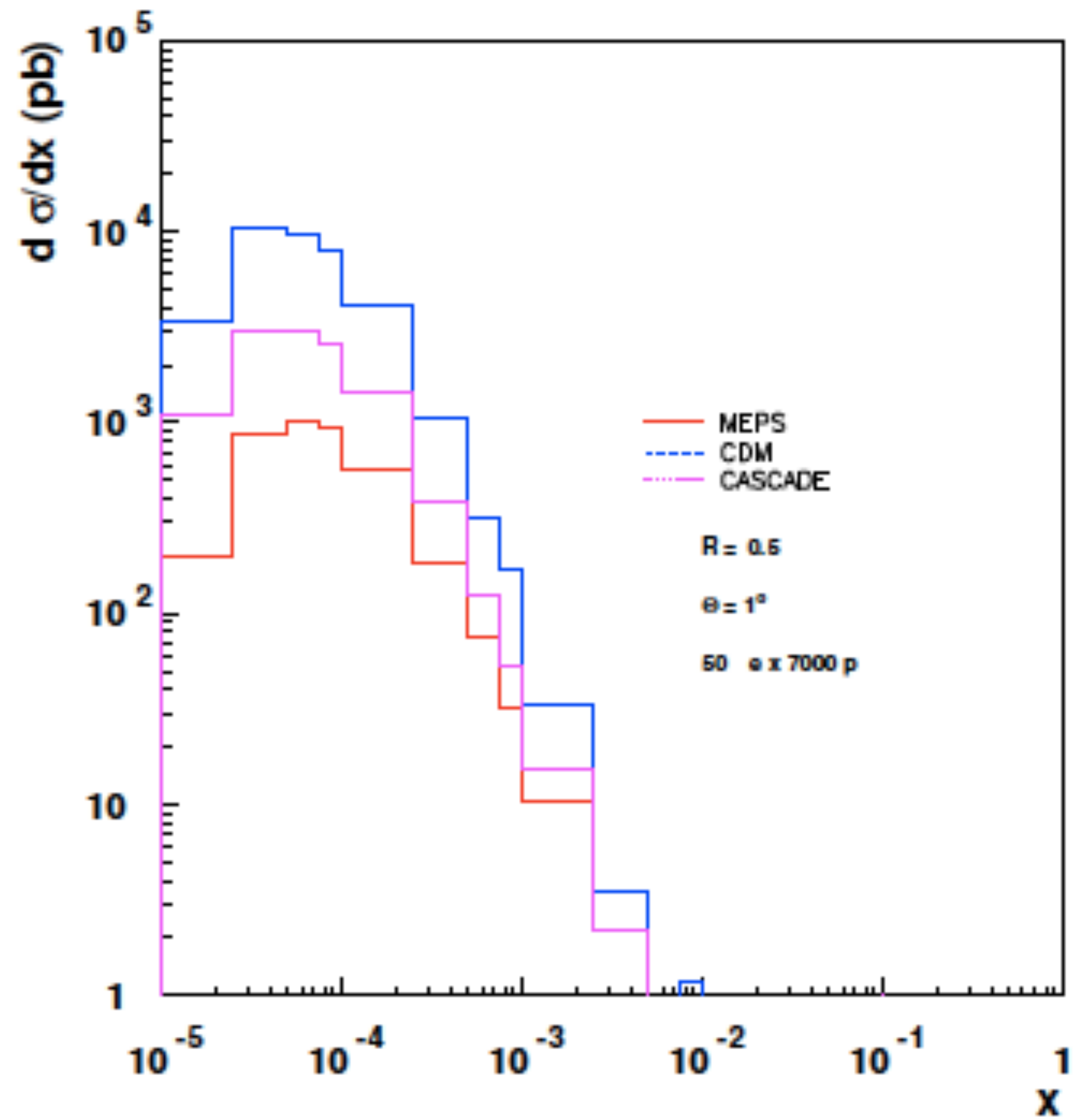
→ k_T-ordered: DGLAP.

→ k_T-disordered: BFKL.

→ Saturation?

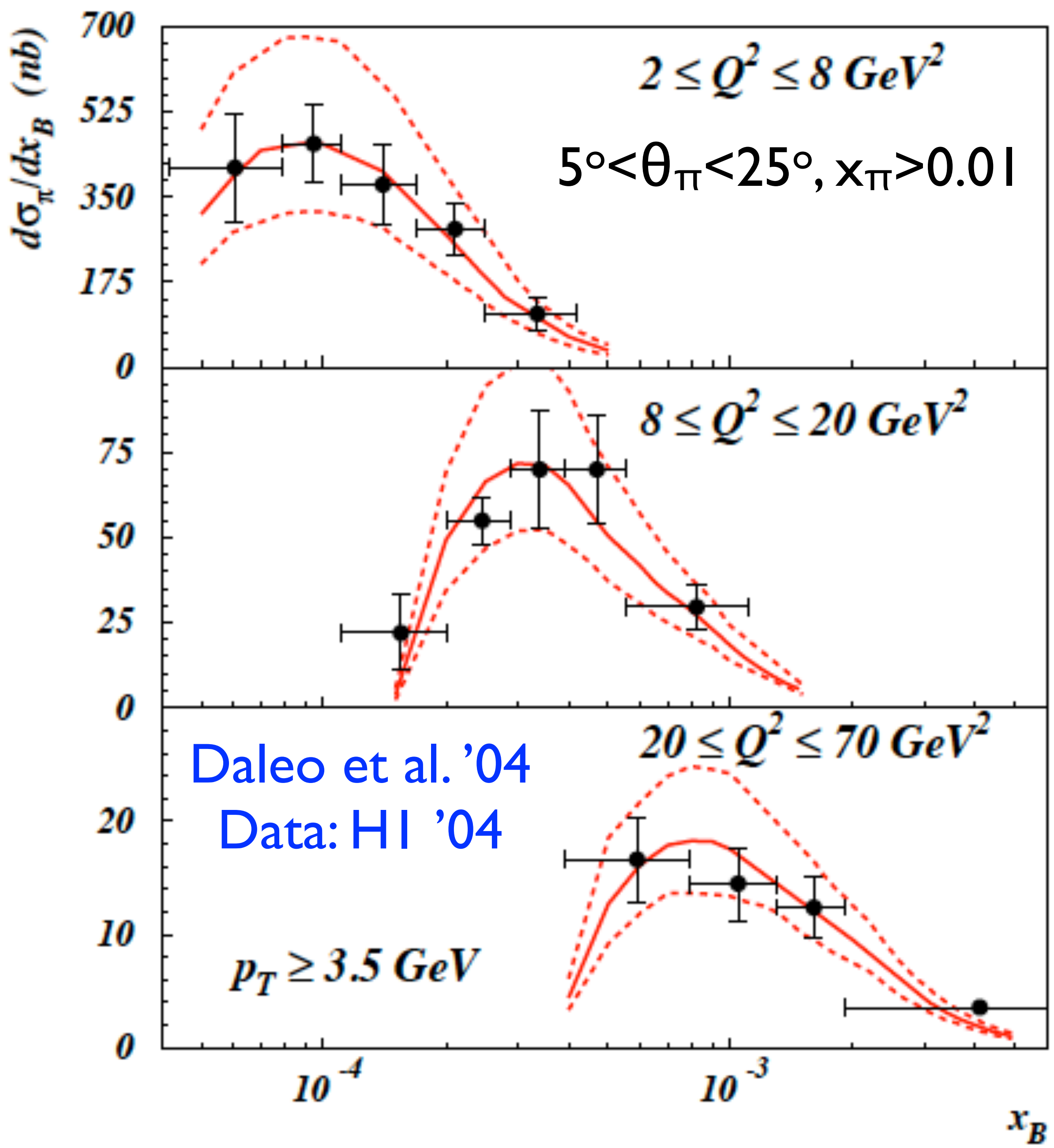
- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.



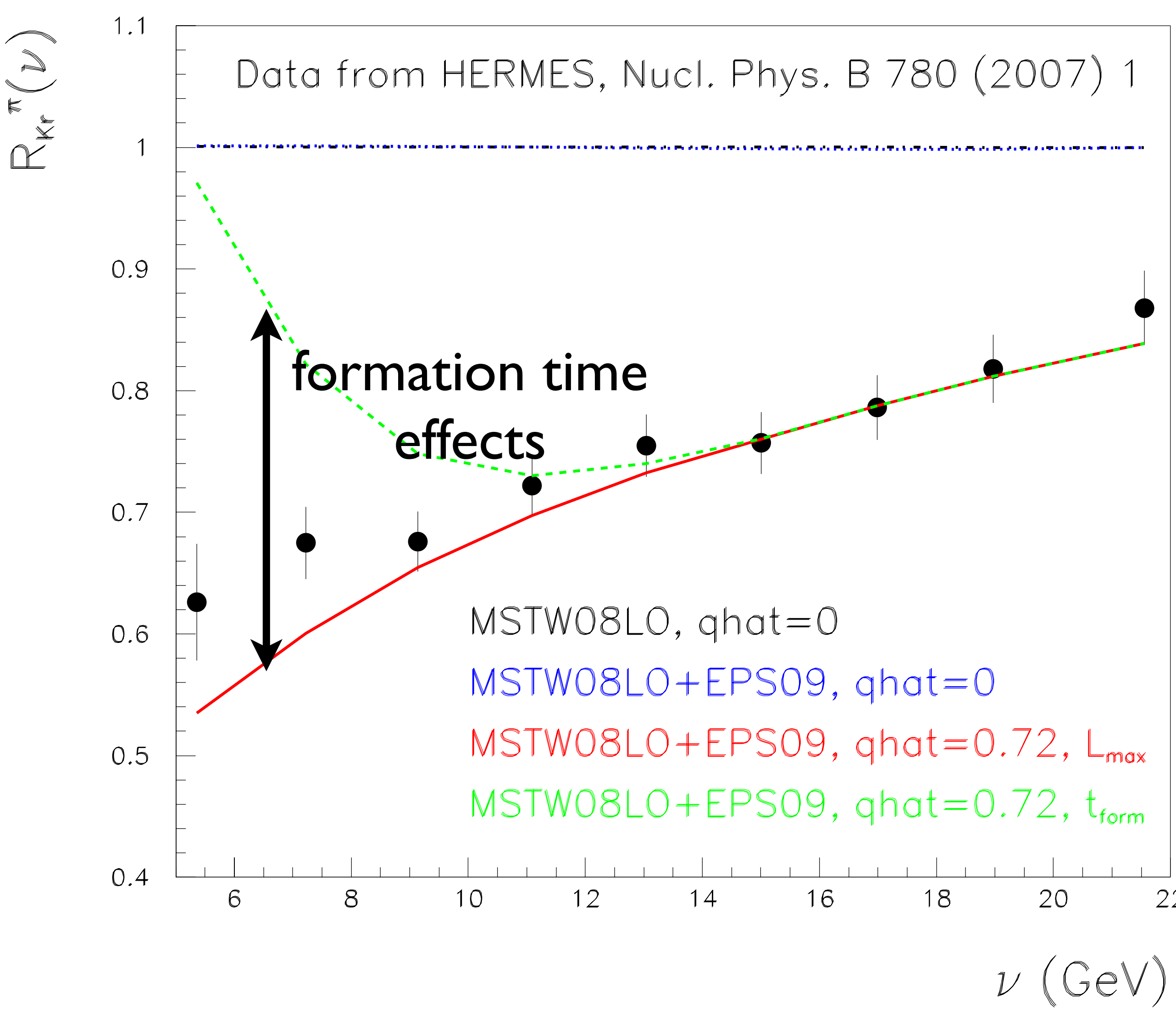


Radiation and hadronization:

- 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).



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



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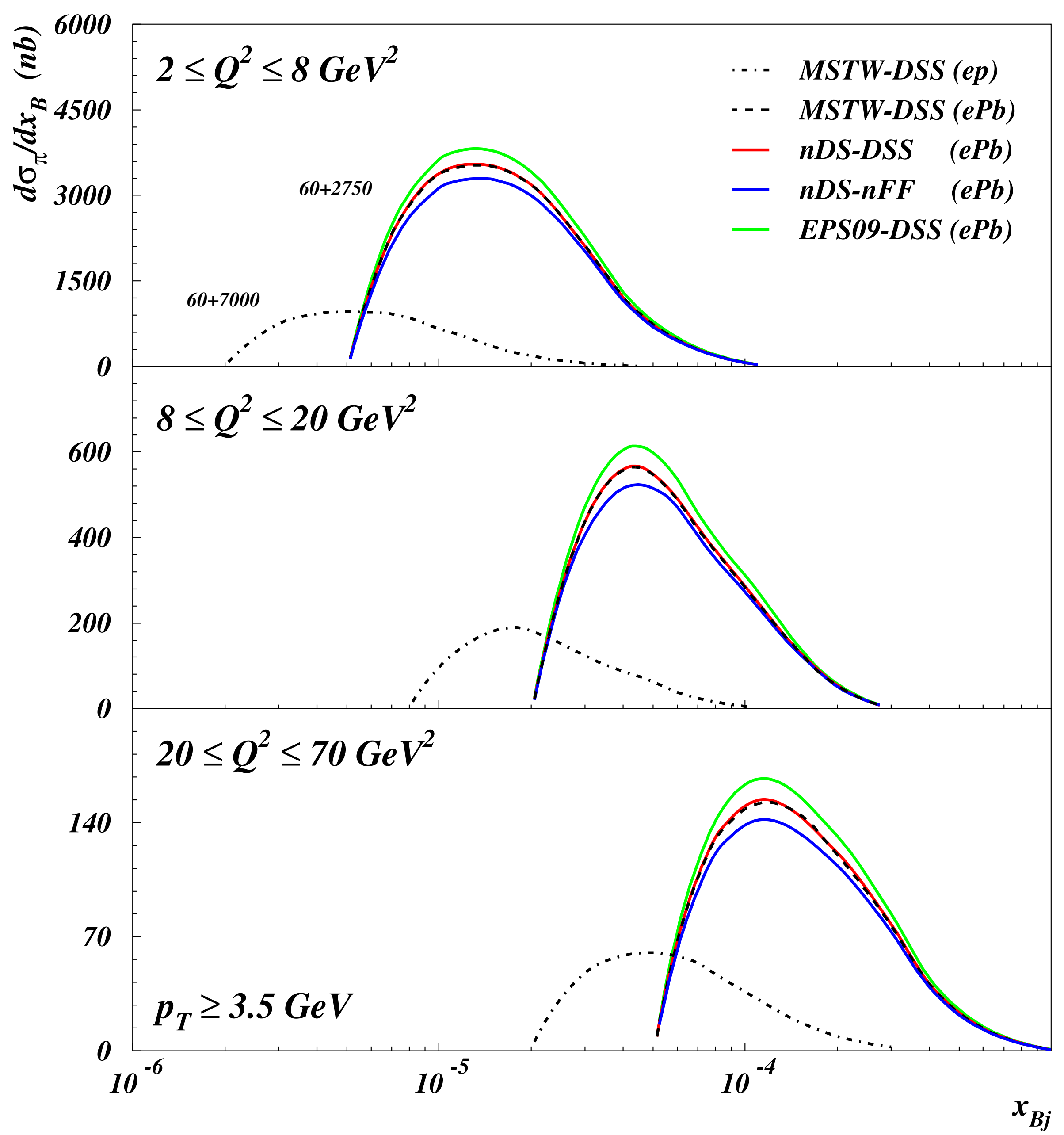

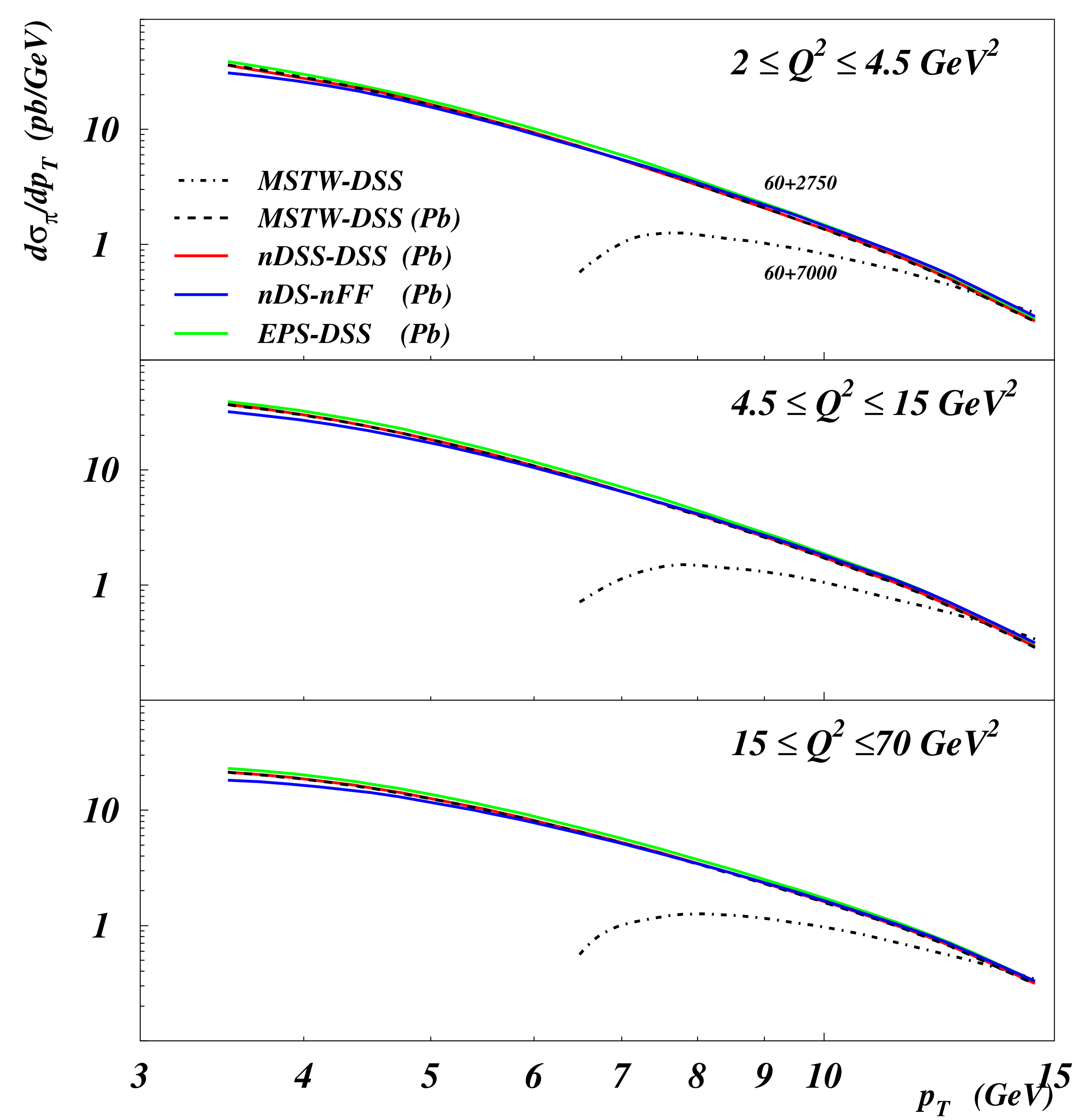

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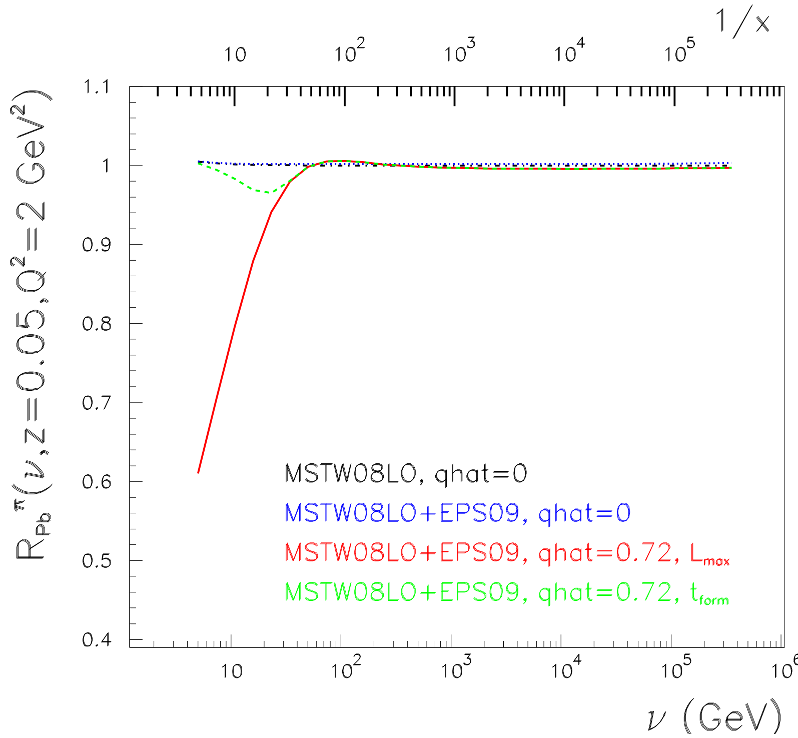

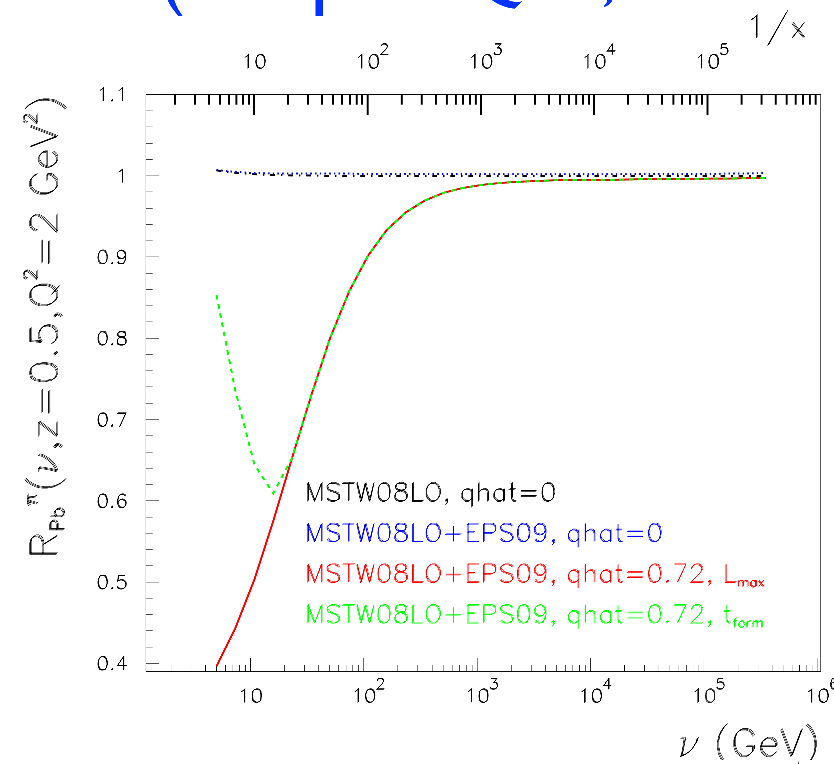

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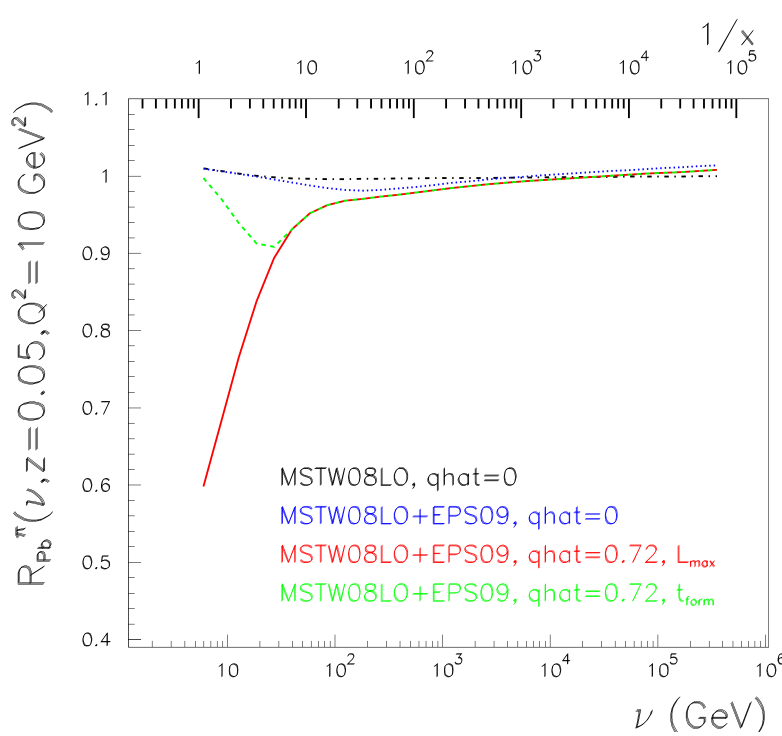
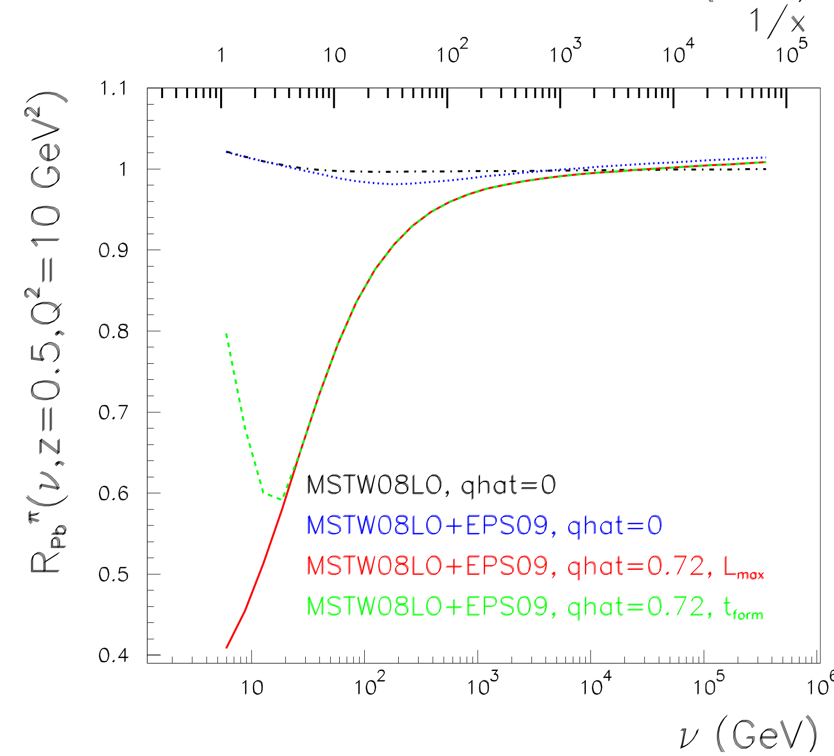
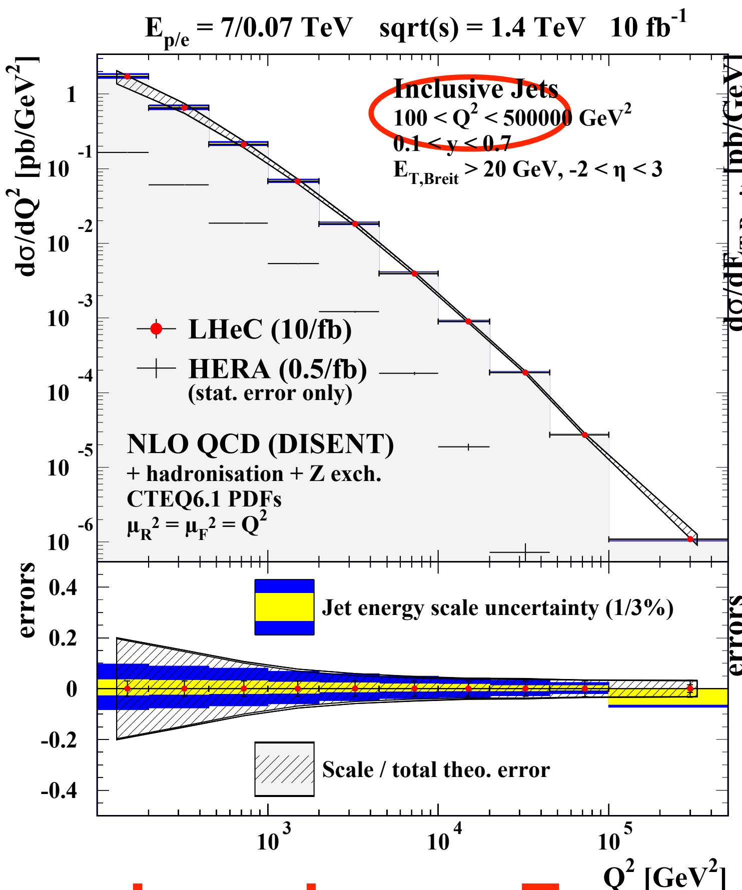
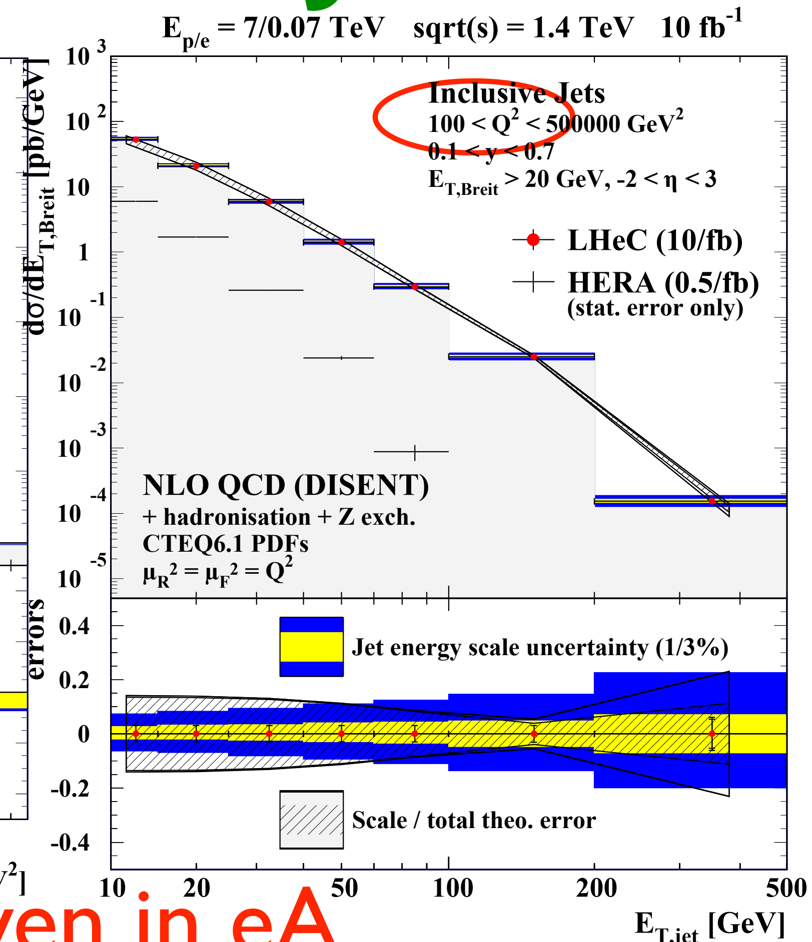
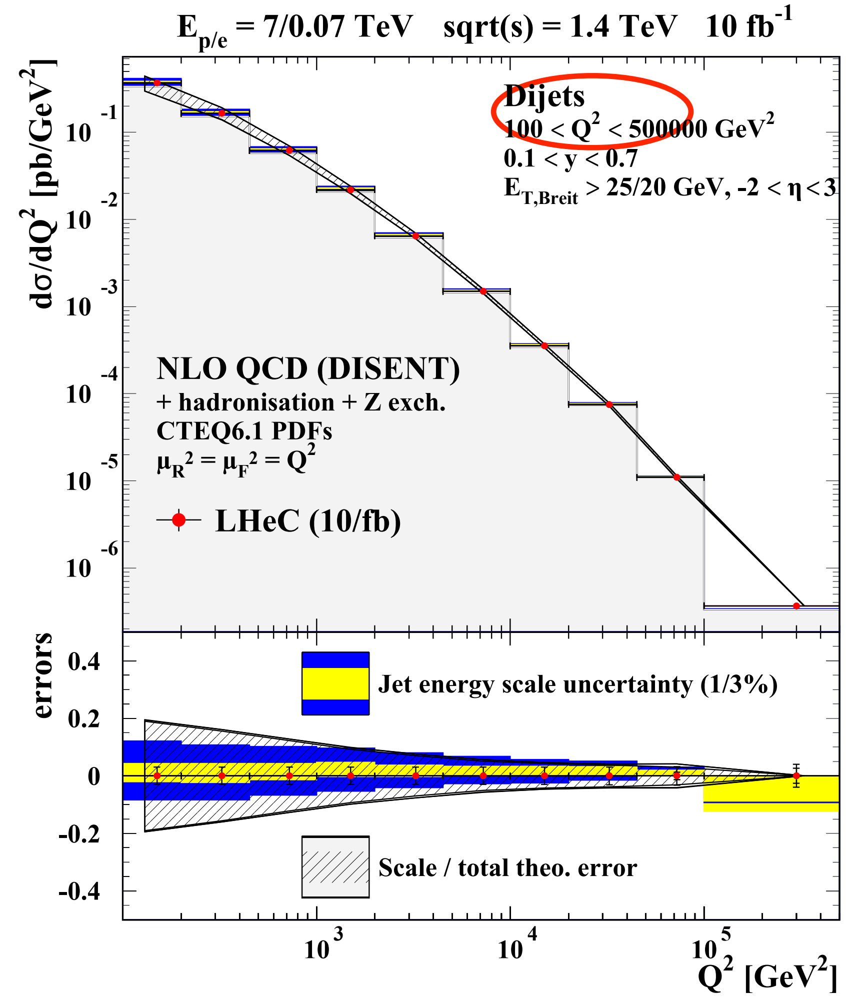




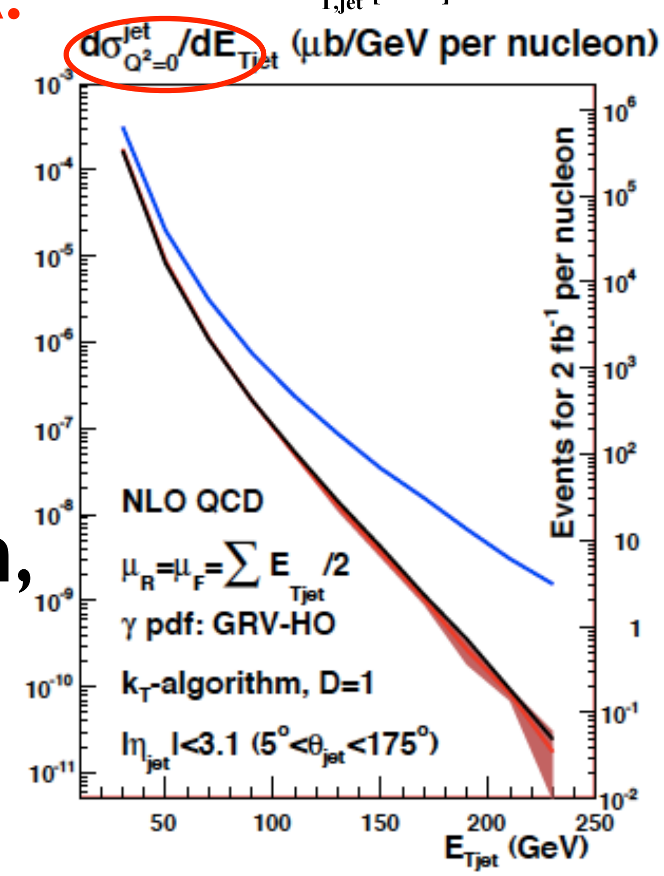
Jets:

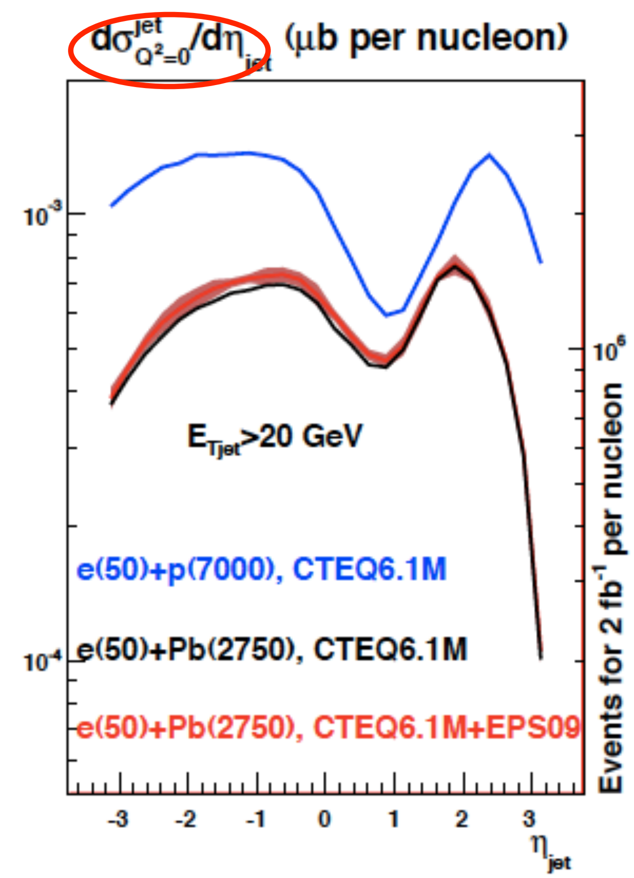






- Jets: large E_T even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.

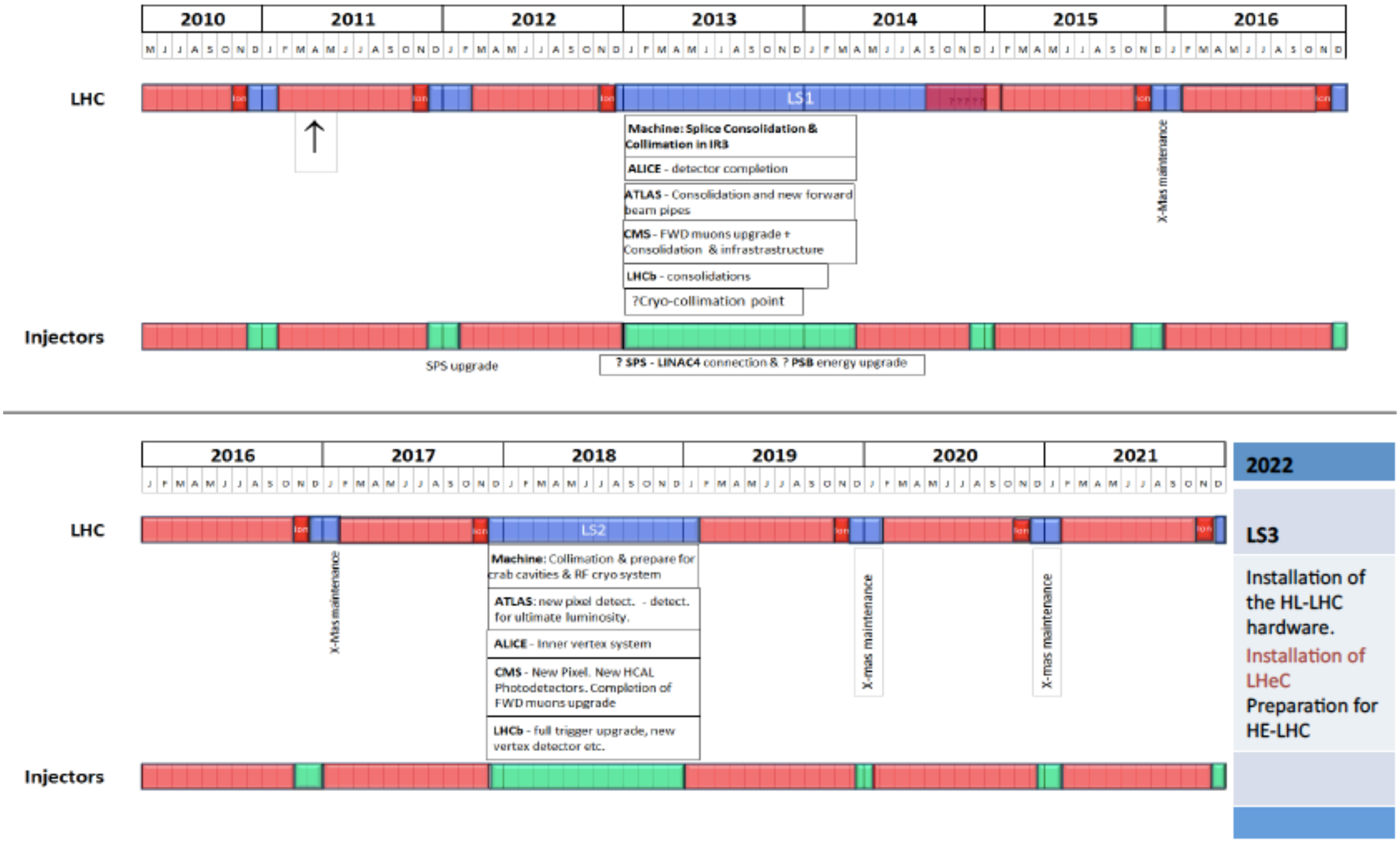




Tentative timeline:

New rough draft 10 year plan

Not yet approved!



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Tentative timeline:

New rough draft 10 year plan

Not yet approved!

2010	2011	2012	2013	2014	2015	2016

→ LHC death by radiation damage estimated by 2030-2035.

→ LHeC should work for ~ 10 years.

→ No disturbance to LHC operation: built on surface, installation during LS3.

$\Rightarrow$

Injectors

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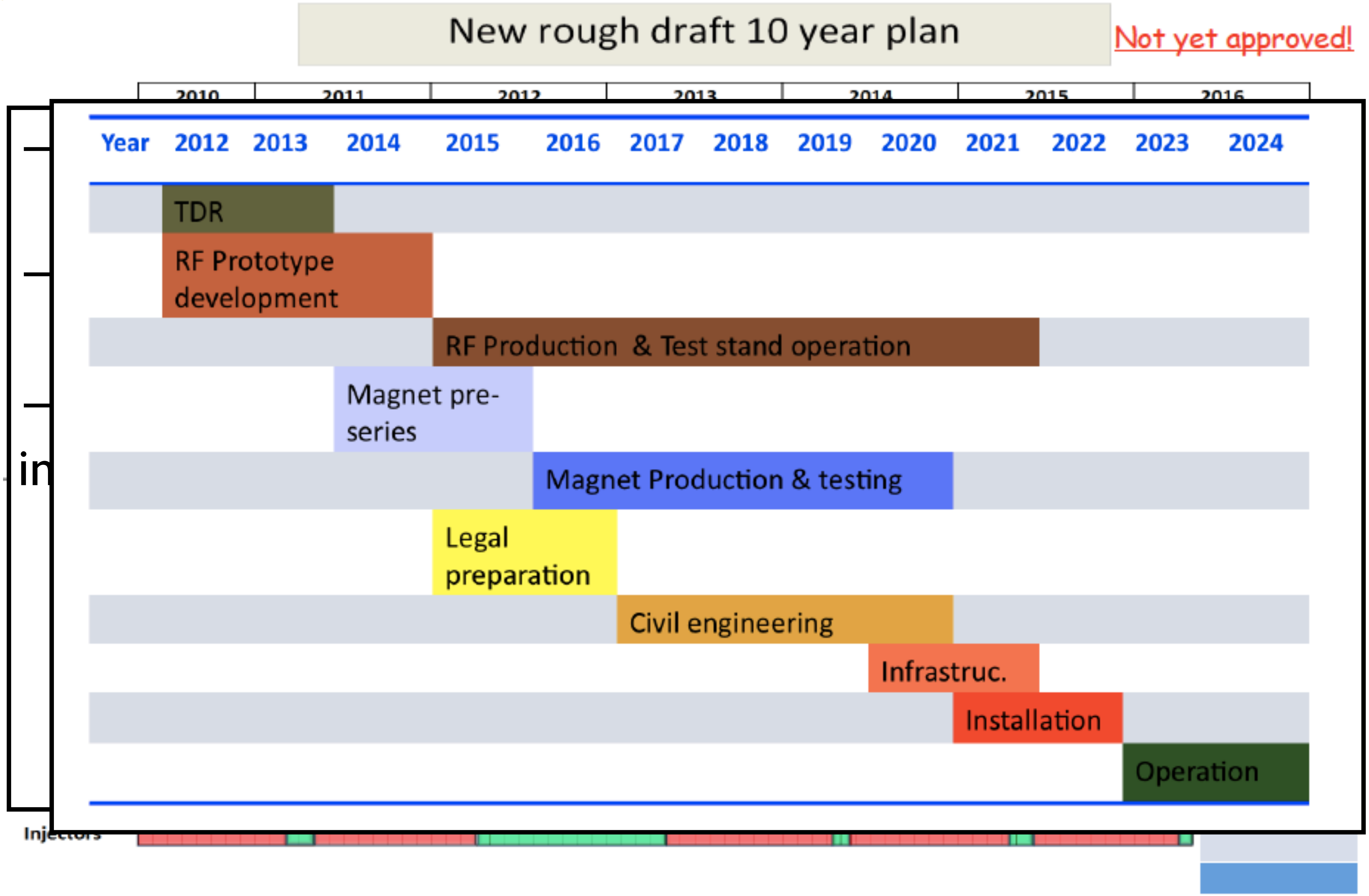
Tentative timeline:



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