Small-x physics at the LHC

3rd CERN-ECFA-NuPECC Workshop on the LHeC

Chavannes-de-Bogis, 11th Nov. 2010

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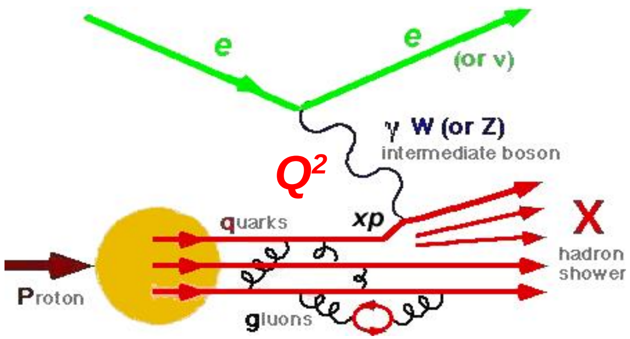
CERN

Overview

- Introduction:
  - Uncertainties on parton structure & evolution at low-*x*.
  - Measurements of (n)PDFs: processes, kinematic domains, ...
- Perspectives of low-x PDF constraints at the LHC:
  - ▷ p-p @ 14 TeV (forward): γ, DY, (jets, W, Z)
  - ▷ γ-Pb in ultraperipheral Pb-Pb colls @ 5.5 TeV: $Q\bar{Q}$
  - ▷ p-Pb colls. @ 8.8 TeV: γ, $Q\bar{Q}$, (jets, W,Z)
- Summary

Motivation (I): Low-*x* PDFs

- DIS collisions probe distributions of partons inside hadrons:



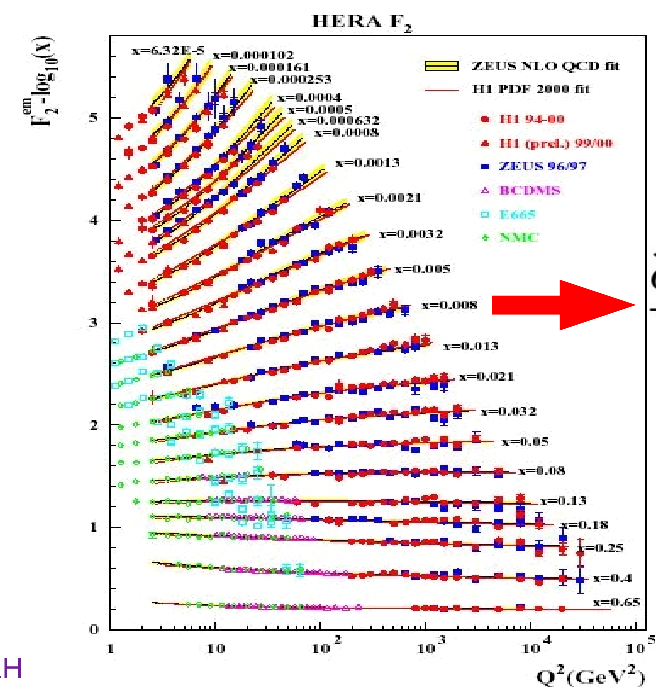
Q^2 = "resolving power"

Bjorken x = momentum fraction carried by parton

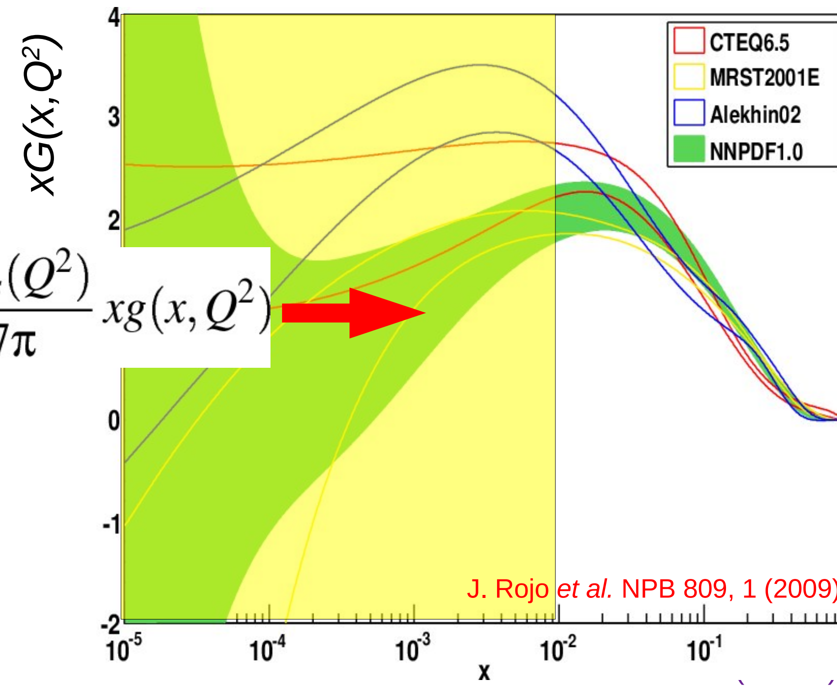
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ \cdot F_2 \mp Y_- \cdot xF_3 - y^2 \cdot F_L\right]$$

F_2, F_3, F_L = proton structure functions, (*y* = inelasticity).

- Gluons dominate but only <u>indirectly constrained</u> via F_2 "scaling violations":



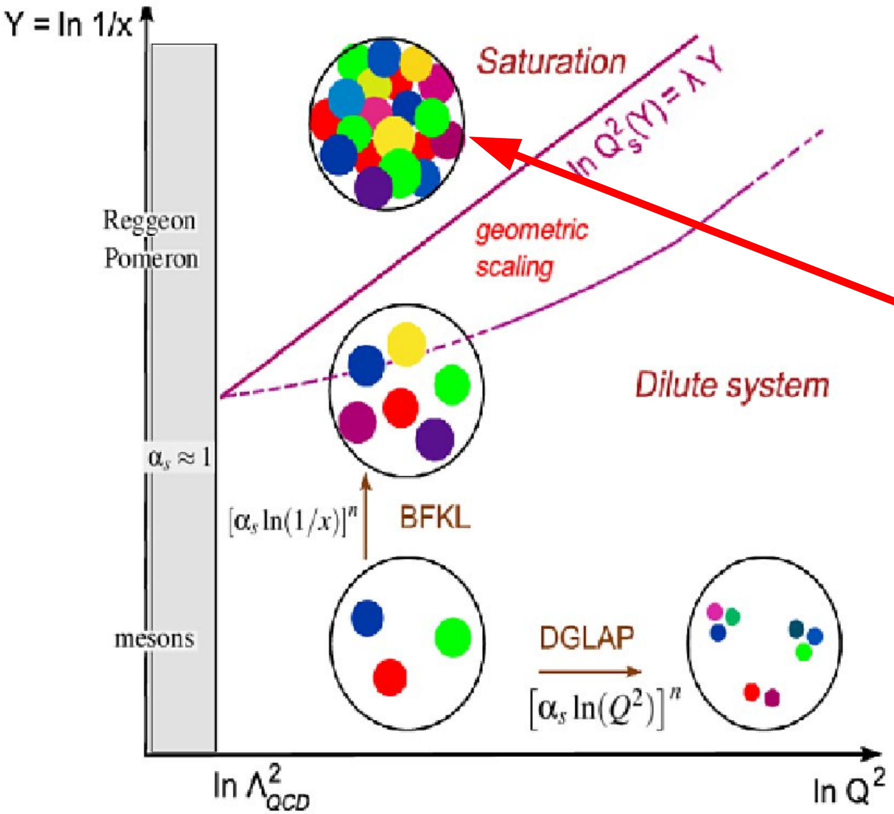
$$\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi}\, xg(x,Q^2)$$



J. Rojo *et al.* NPB 809, 1 (2009)

Motivation (II): low-x QCD evolution

- **Q² - DGLAP** (k_T-order'd emission): $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n, Q_0^2 \sim 1$ GeV² [LT,coll.factoriz.]
- **x - BFKL** (p_L-ordered emission): $F_2(x) \sim \alpha_s \ln(1/x)^n$ [uPDFs, k_T-factoriz.]
- Linear equations (single parton radiation/splitting) cannot work at low-x:



(i) Too high gluon density: nonlinear gluon-gluon fusion balances branchings

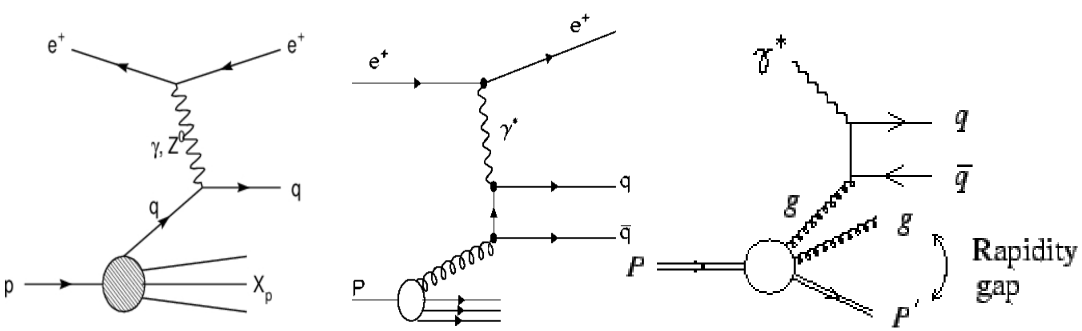
(ii) pQCD (collinear & k_T) factorization assumptions invalid (HT, no incoherent parton scatt.)

(iii) Violation of unitarity even for $Q^2 >> \Lambda^2$ (too large perturbative cross-sections)

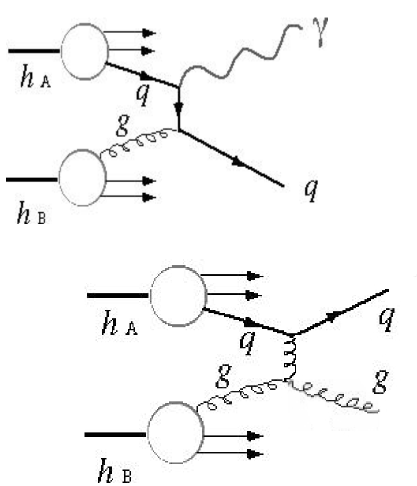
- Saturation enhanced in multi-parton systems (nuclei): $Q_s^2 \sim A^{1/3} \sim 6$

Experimental access to low-x gluon PDF

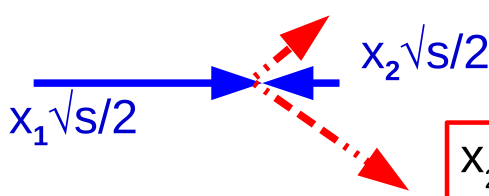
- Perturbative processes:
  - e(γ)-p, e(γ)-A → F_2, F_L, F_2^c, excl. QQ



  - p-p, p-A → γ, γ*, heavy-Q, jets:



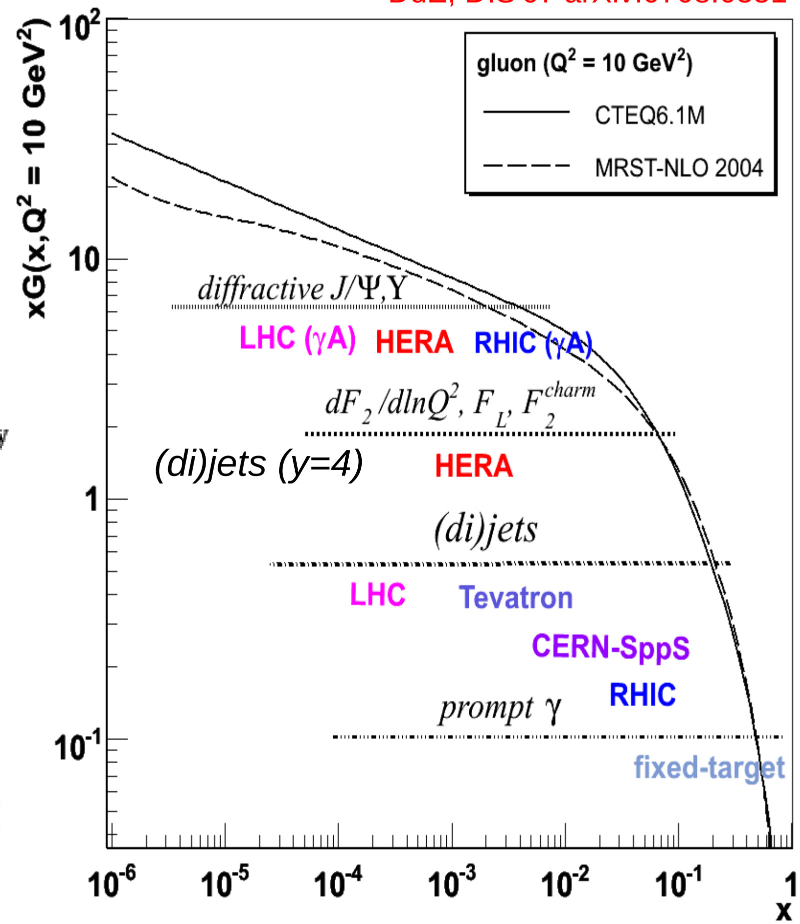
  - Forward production:



$x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$

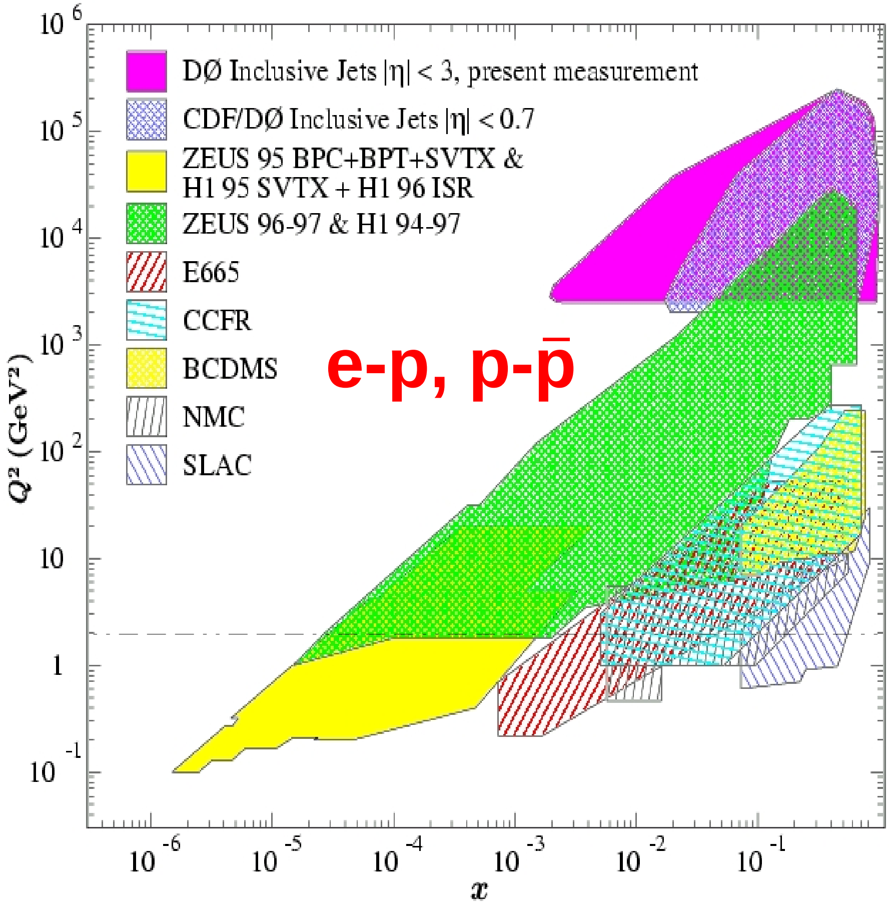
Every 2-units of y, x^{min} decreases by ~10

DdE, DIS'07 arXiv:0708.0551



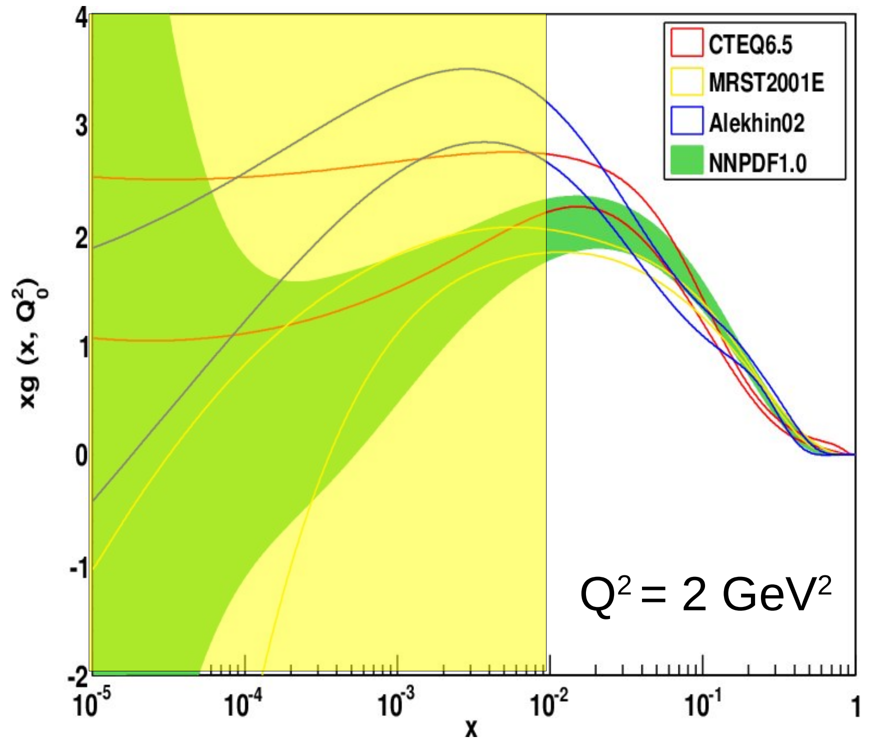
Low-x gluon PDF (proton)

- Kinematical (*x*,Q^2) domain covered so far experimentally:



- Low-x gluons mostly indirectly from F_2 "scaling violations".

R.D. Ball *et al.* arXiv:0808.1231

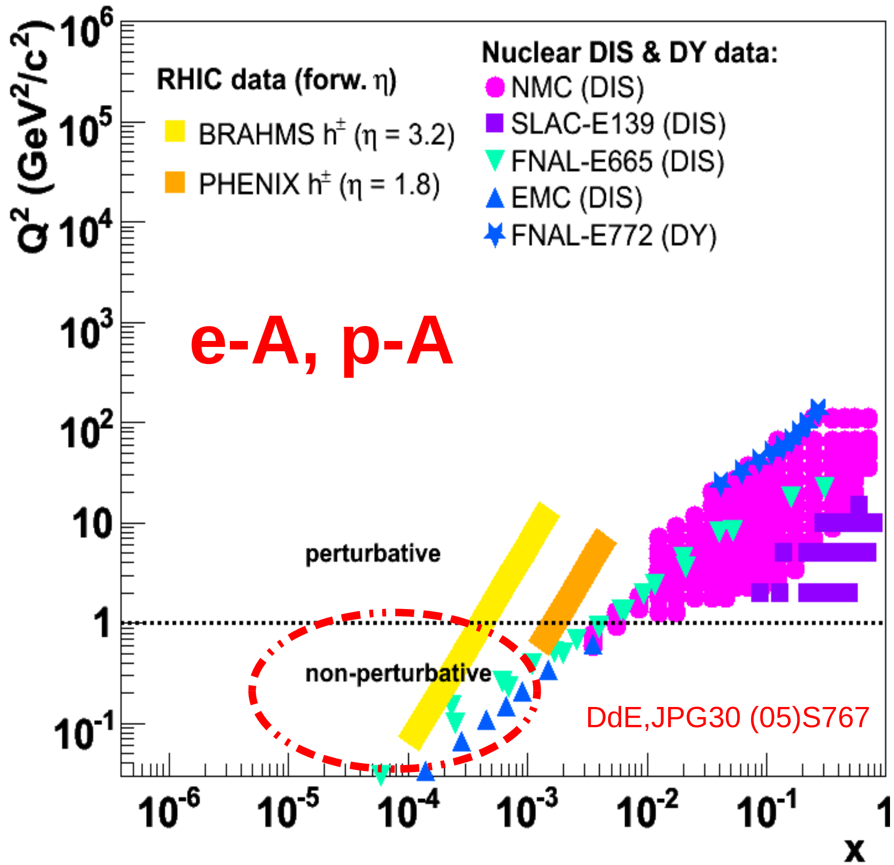


- Large uncertainties below $x \sim 10^{-2}$ at moderate Q^2

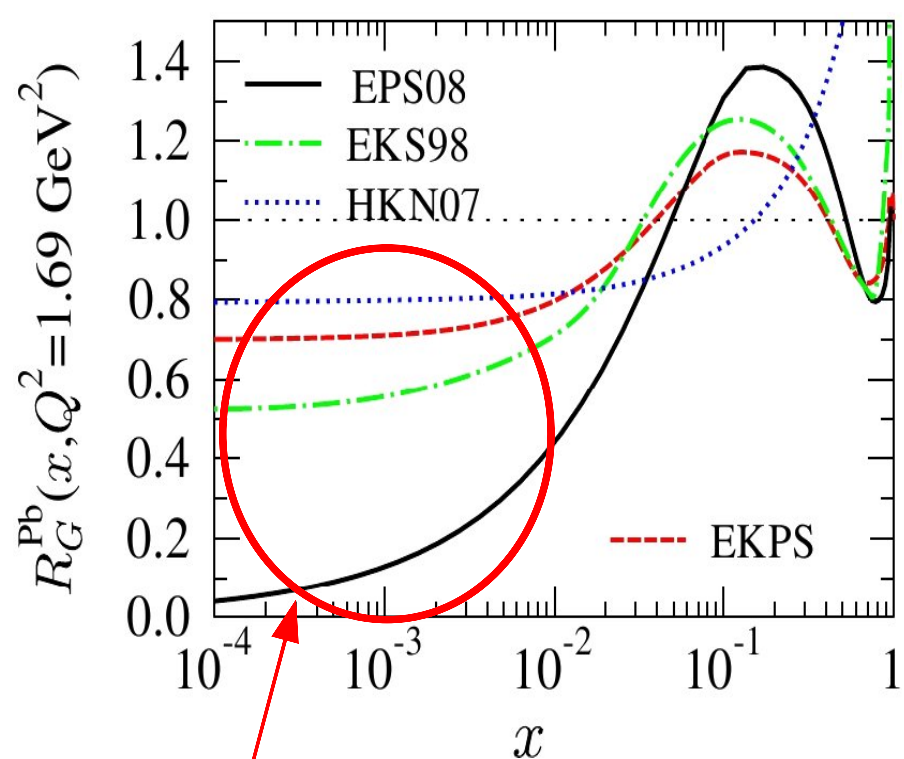
Low-x gluon PDF (nucleus)

[see C.Salgado's talk]

- Current knowledge of low-x gluons from:
  F_2 (e,ν-A), Drell-Yan (p-A), high-p_T hadrons (d-Au).
- x<0.01: very few measurements (non-perturbative): huge uncertainties !

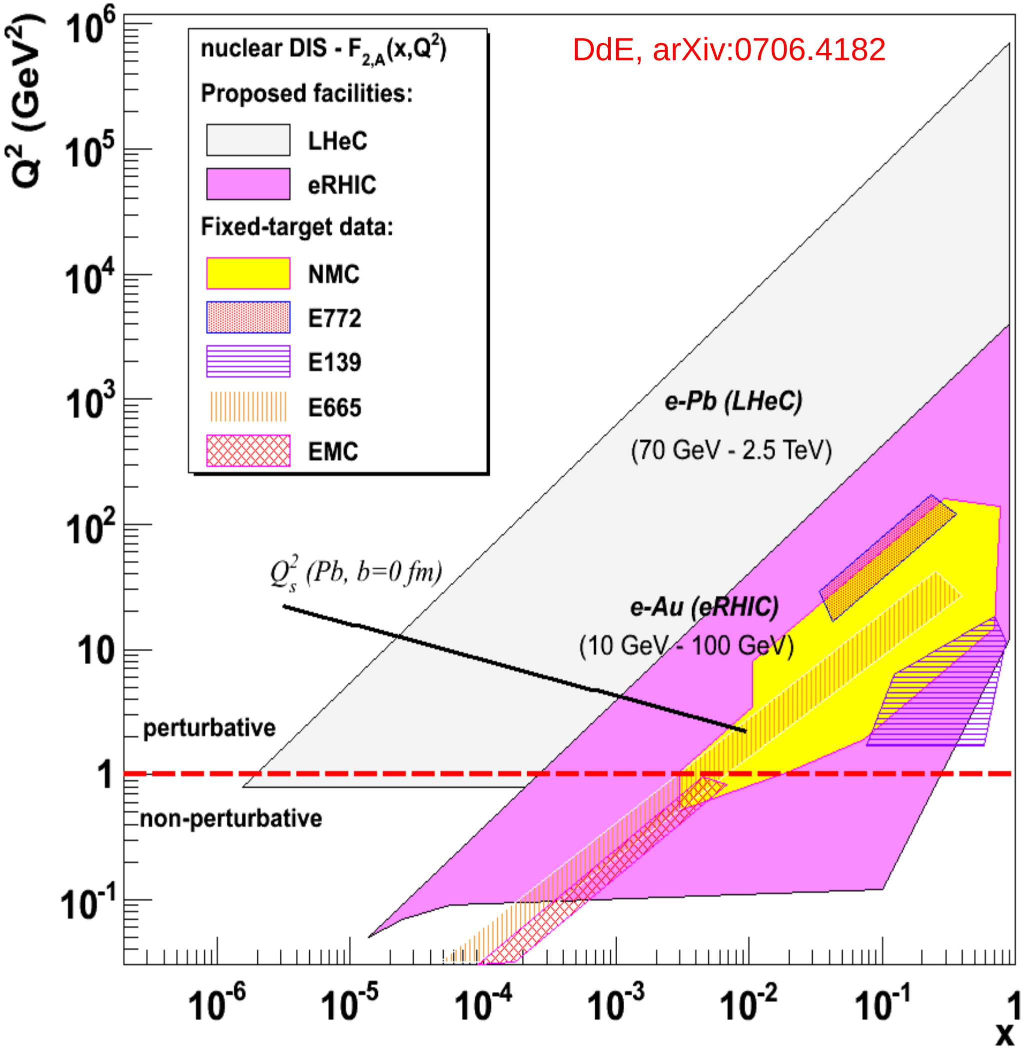


Eskola-Kolhinen-Salgado JHEP 0807 (08)102



$xG(x,Q^2)$ virtually unknown below x~10^{-2} !

Improvements before future nDIS facilities ?



Ultimately: F_2^A, $F^A_{2,charm}$, F_L^A, ...

- eRHIC:
  (e⁻) 20 GeV – (A) 100 GeV
  $\sqrt{s}$~60 GeV, $\mathcal{L}$~10^{33} $cm^{-2}s^{-1}$

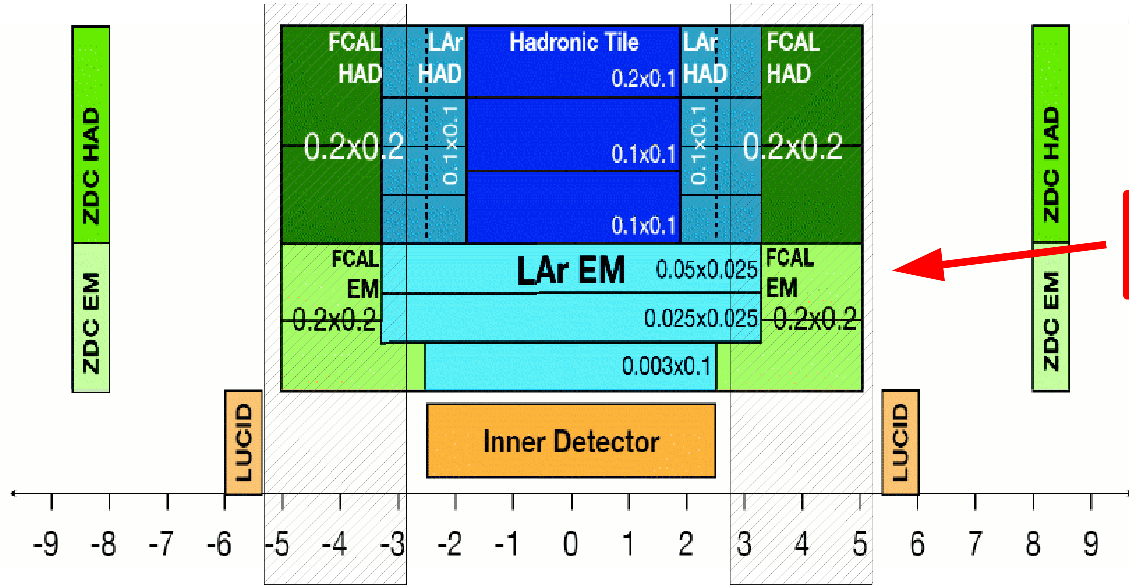
- LHeC:
  (e⁻) 70 GeV – (p,A) 2.75, 7 TeV
  $\sqrt{s}$~0.9,1.4 TeV, $\mathcal{L}$~10^{33} $cm^{-2}s^{-1}$

Huge increase in nuclear (x,Q^2) kinematical reach !

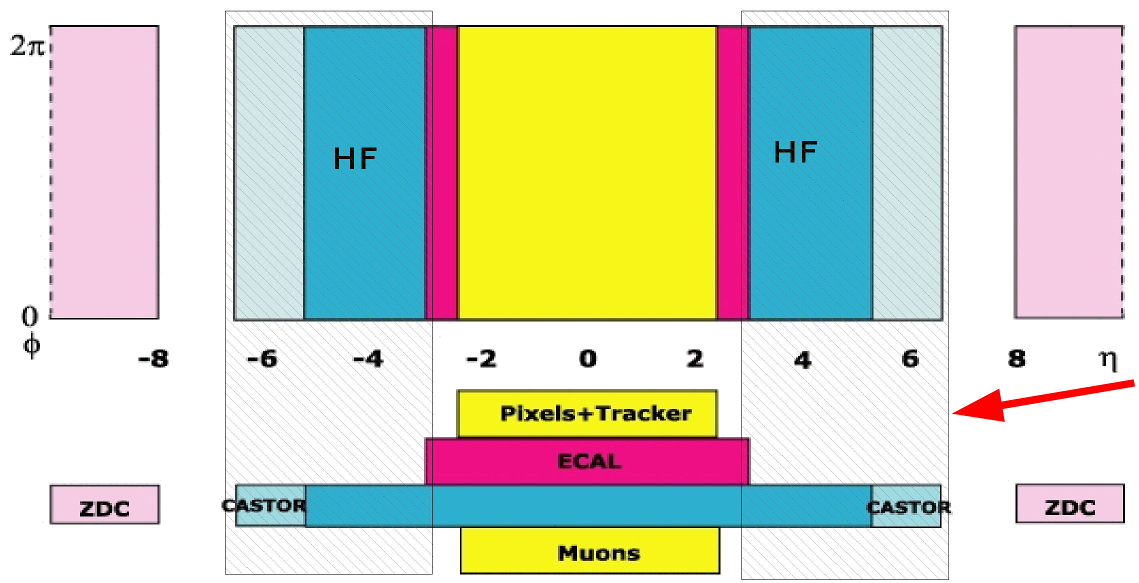
Q^2 ~ 1 -10^6 GeV^2

x down to ~10^{-6} .

Jets & γ : ATLAS/CMS calorimeters



$|\eta| < 5$



$|\eta| < 5$, $5 < \eta < 6.6$

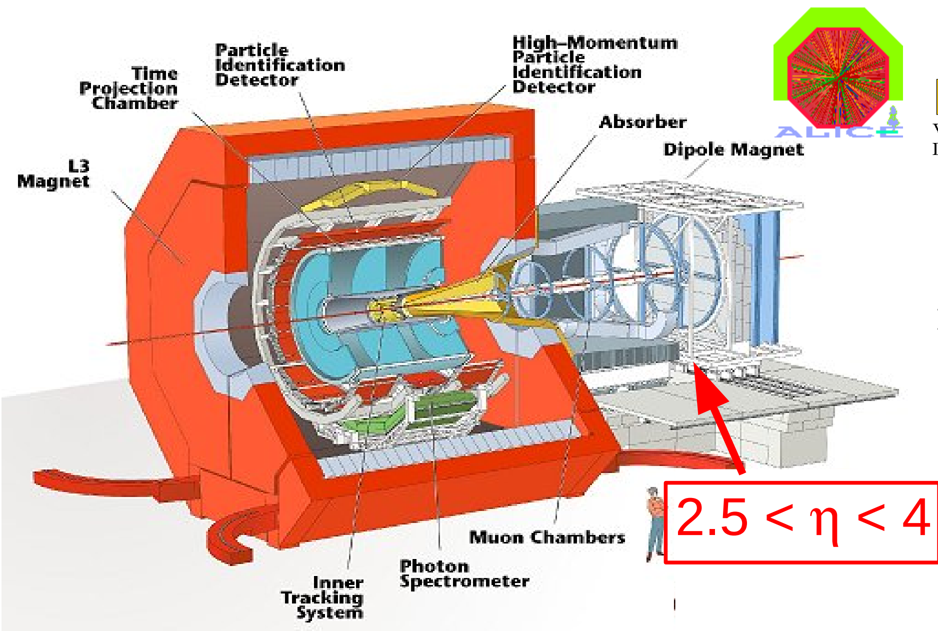
Note: also LHCb calos within $2 < \eta < 5$ but limited p_T range

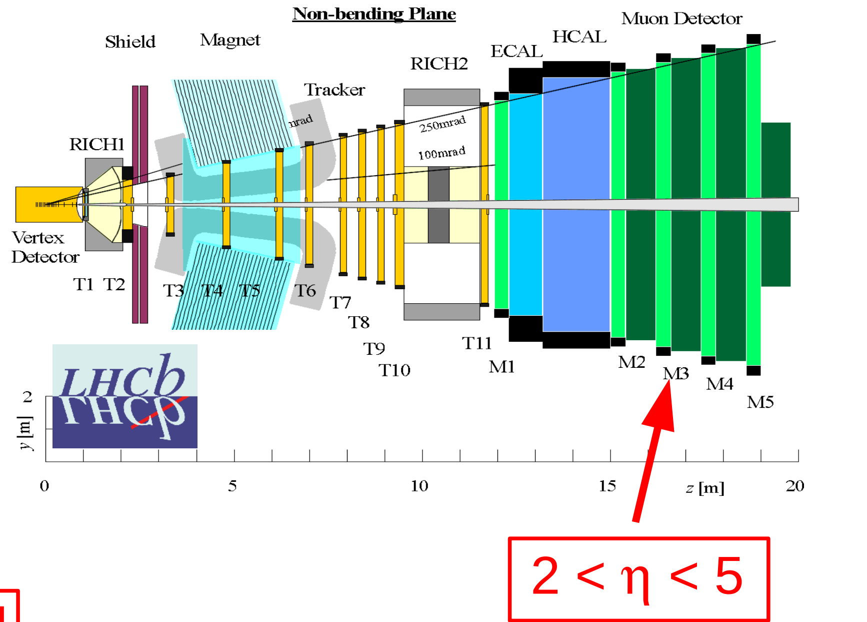
p_T (γ) < 15 GeV/c

p_T (jets) < 50 GeV/c

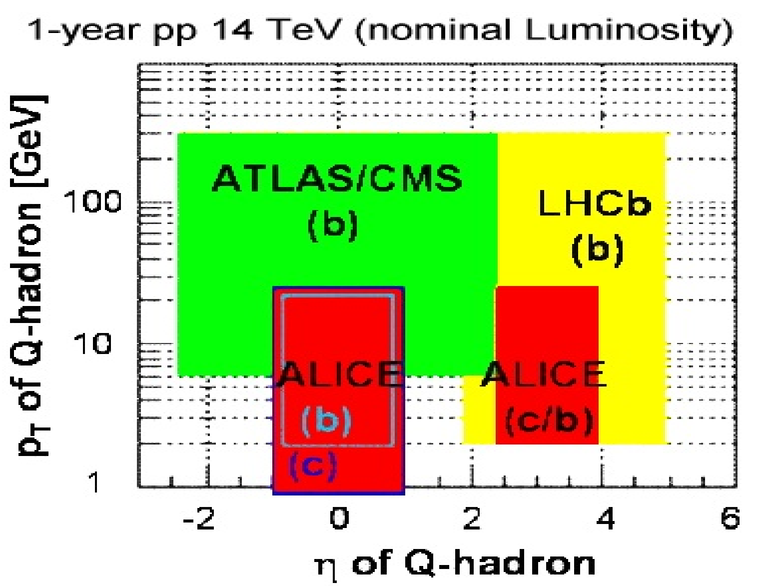
Heavy-flavour & DY: LHCb & ALICE

- Forward muon spectrometers:





- Excellent capabilities for heavy-Q, $Q\bar{Q}$, DY fwd. measurements at low-x:



(It would be very interesting if LHCb runs p-A)

Low-x proton PDFs from p-p collisions at the LHC

LHC forward detectors

- Measurements exploiting forward detectors:

  $x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$ (every 2-units of y, x^{min} decreases by ~10)

DdE, arXiv:0806.0883

- Jets, photons in fwd. calorimeters:

  CMS/ATLAS: within $|\eta|<5$

  LHCb: $2 < \eta < 5$ ($p_T < 15,50$ GeV)

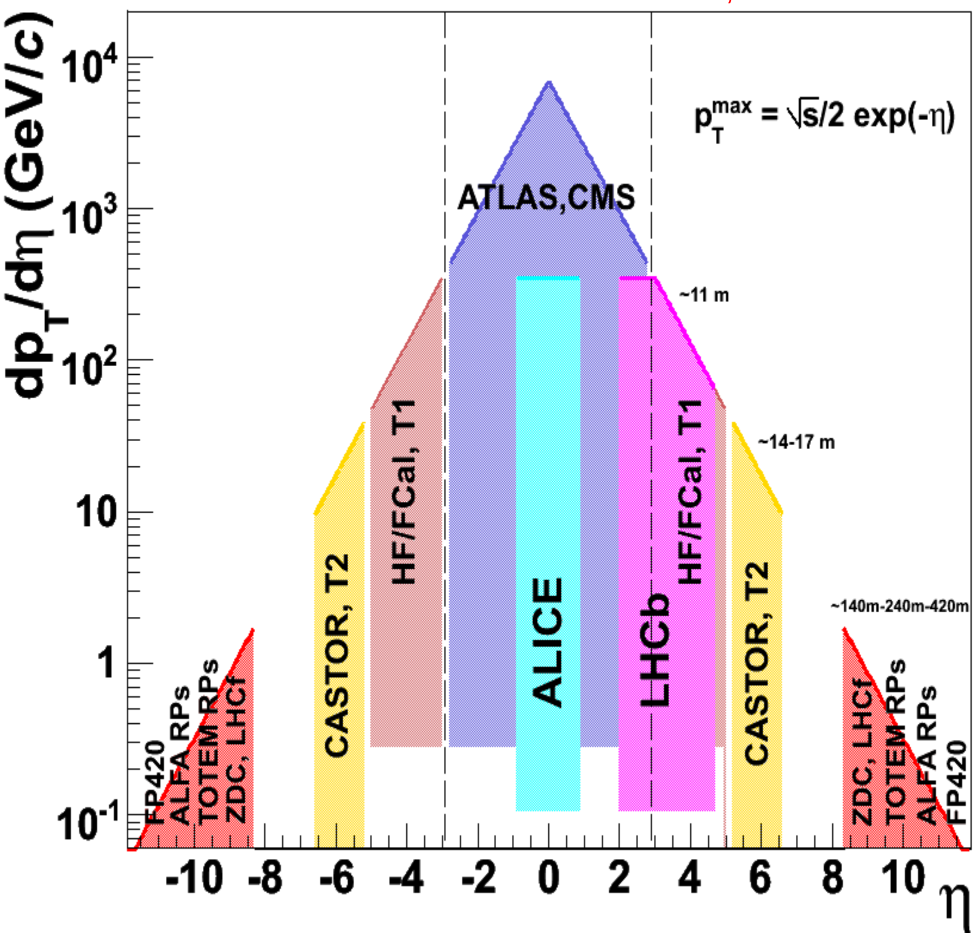
- Muons (DY, heavy-Q, $Q\bar{Q}$) in fwd. μ-spectrometers:

  ALICE: $2.5 < \eta < 4$ (but no 2[nd] vtx.)

  LHCb: $2 < \eta < 5$

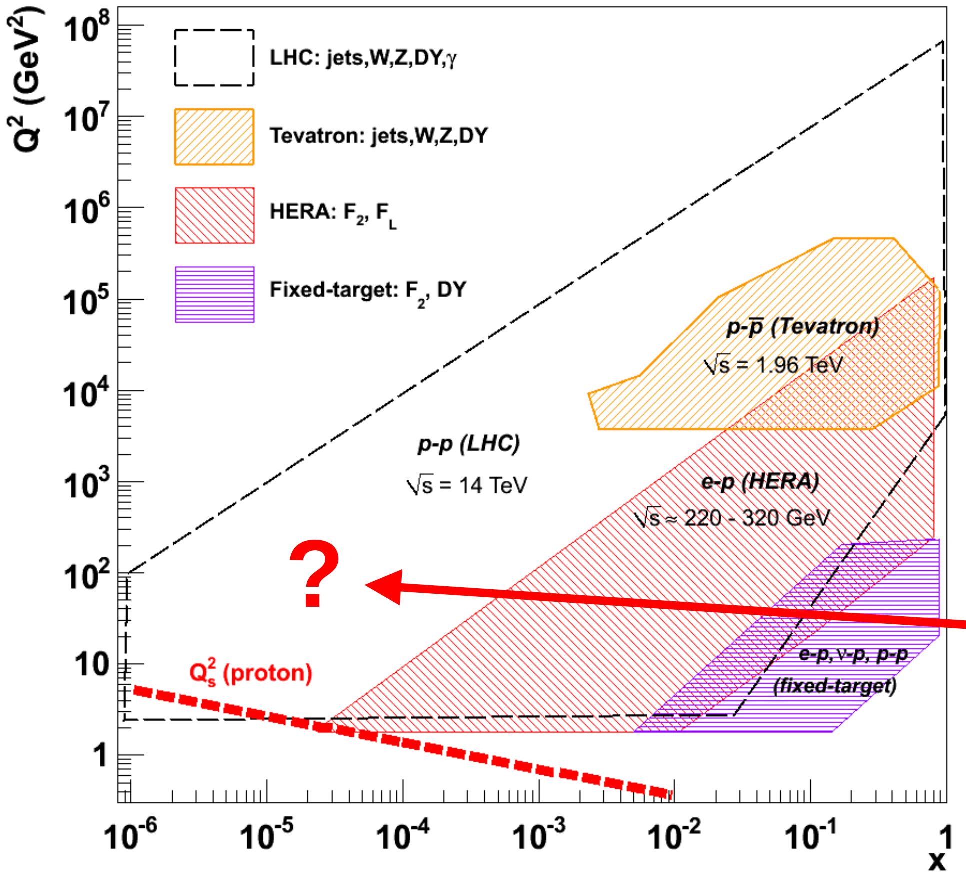
- Fwd. trackers/PID:

  LHCb: $2<\eta<5$



Low-x studies at the LHC: proton

- At y=0, $x=2p_T/\sqrt{s}\sim10^{-3}$ (probed at HERA,Tevatron). Go fwd. for $x<10^{-4}$
- Very large pQCD cross-sections:



$$p(p_1)+p(p_2)\rightarrow \text{jet}+\gamma+\ X$$ Prompt γ

$$p(p_1)+p(p_2)\rightarrow l\bar{l}+\ X$$ Drell-Yan

$$p(p_1)+p(p_2)\rightarrow \text{jet}_1+\text{jet}_2+\ X$$ Jets

$$p(p_1)+p(p_2)\rightarrow Q+\bar{Q}+\ X$$ Heavy-Q

$$p(p_1)+p(p_2)\rightarrow W/Z+\ X$$ W,Z

Forward rapidities:
(e.g. y~5, M~2.5 GeV)

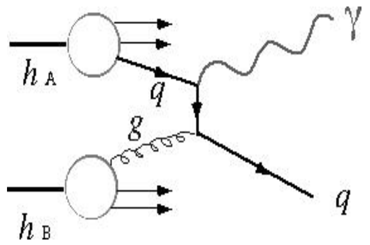
x down to 10^{-6} !

- But barely touching sat. momentum: $Q_s^2\sim0.6$ GeV^2 (y=0), 3 GeV^2 (y=5)

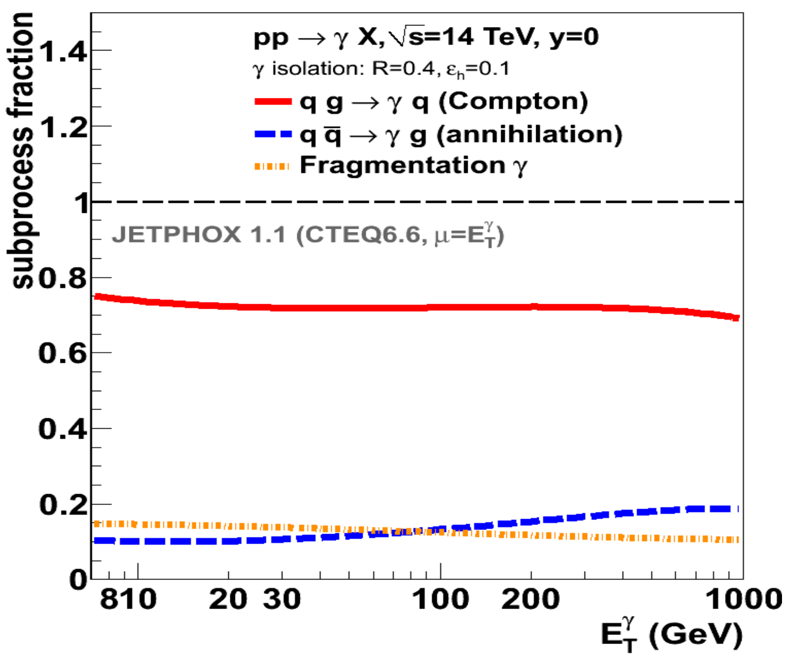
Example I: Forward γ in LHCb (2 <η< 5)

R. Ichou-DdE, PRD82, 014015 (2010)

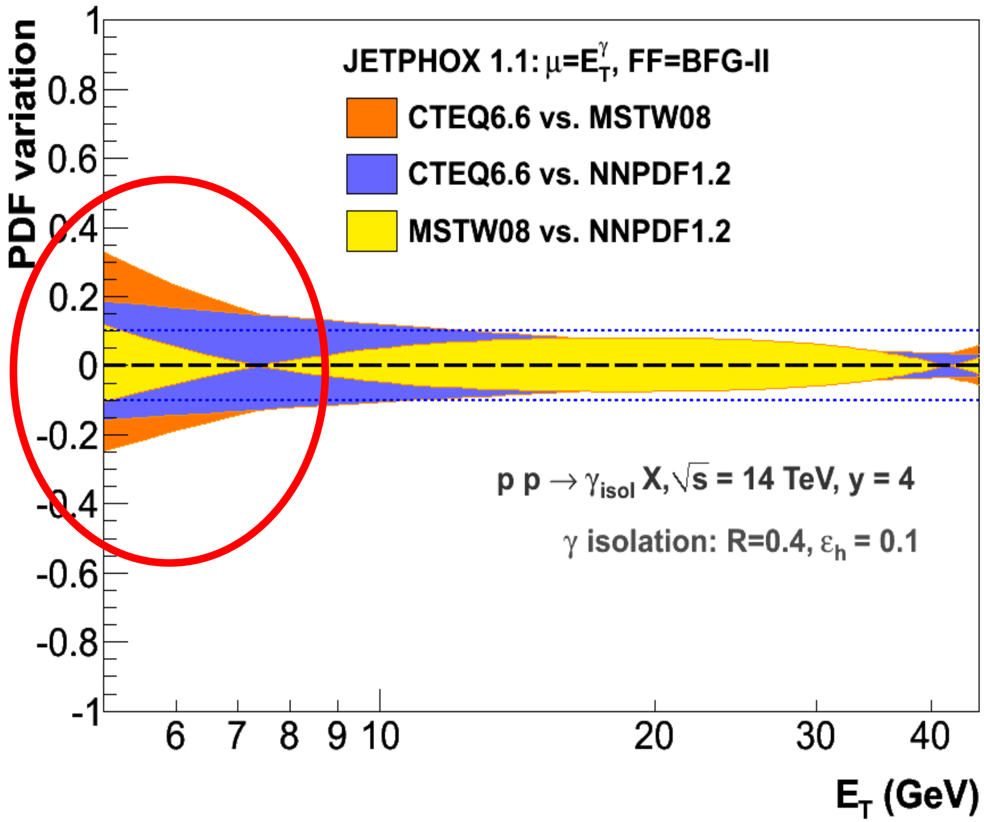
- Isolated photons (E_T ~5-15 GeV) ~80% from quark-gluon Compton:



x probed down to ~10^{-5}



Spectrum dependence on PDF choice:

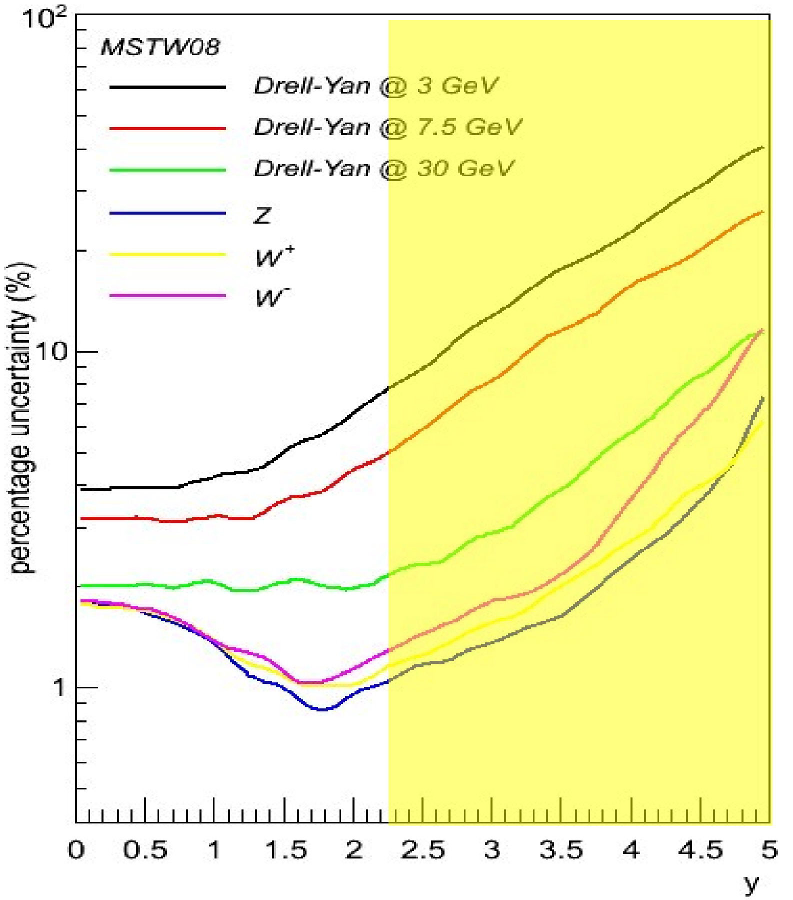


Example II: fwd EWK in LHCb (2 < η < 5)

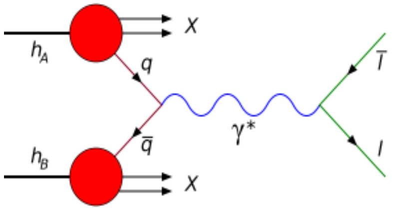
[de Lorenzi, DIS'10]

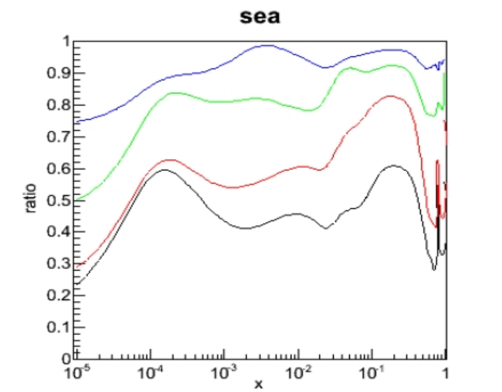
- PDF uncertainty on forward EWK x-sections:

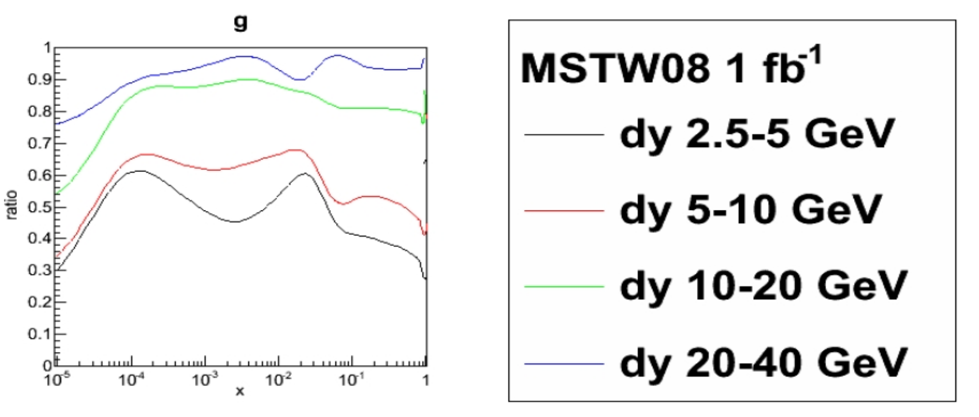
~3% (Z), ~30% (low-mass DY)



- Impact of 1 fb^{-1} DY data on sea, glue (after/before):







Improvement of up to ~70%

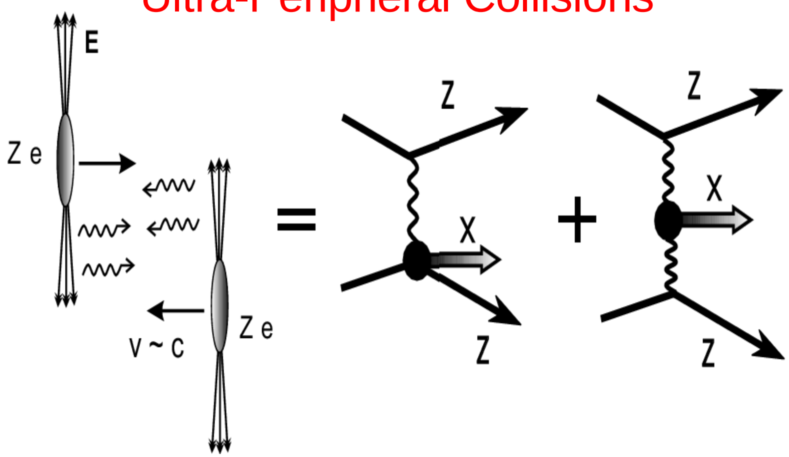
Low-x nuclear PDFs from A-A collisions at the LHC

γ-Pb (UPC Pb-Pb at 5.5 TeV) $\rightarrow Q\bar{Q}$

Photoproduction in A-A collisions at the LHC

- High-energy heavy-ions produce strong E.M. fields due to coherent action of $Z_{Pb} = 82$ protons:

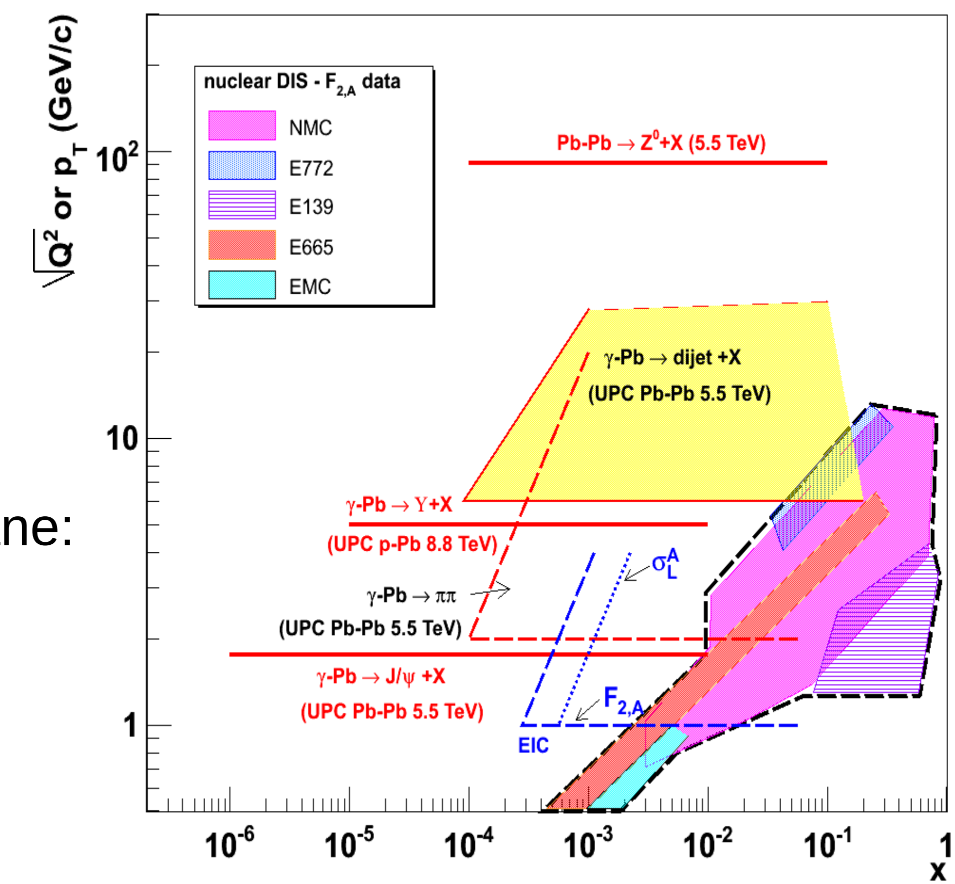
Ultra-Peripheral Collisions



- UPCs in Pb-Pb @ 5.5 TeV:

$E_{\gamma}^{max} \sim 80$ GeV $\Rightarrow$

γ-Pb max. $\sqrt{s_{\gamma Pb}} \approx 1$ TeV $\approx 3\sqrt{s_{\gamma p}}$ (HERA)



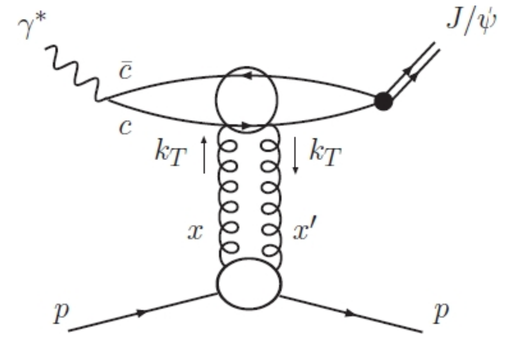
- Various processes in (x,$\sqrt{Q^2}$) plane:
  - γ-Pb → $Q\bar{Q}$
  - γ-Pb → dijets

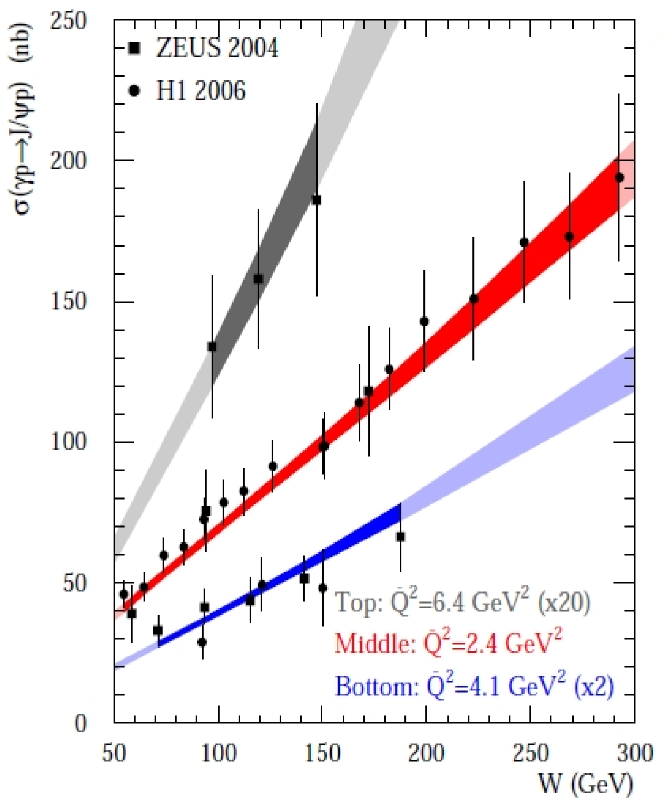
$xg(x,Q^2)$ from exclusive $Q\bar{Q}$ photoprod. at HERA

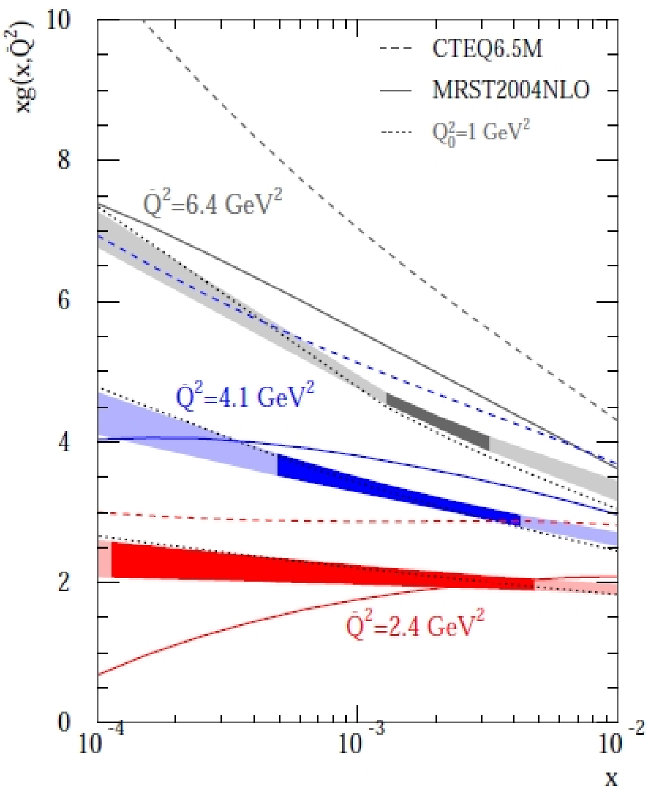
- $\gamma\ p \rightarrow J/\Psi,\Upsilon + p$ is sensitive to gluon distribution squared:

$$\left.\frac{d\sigma(\gamma p \to V p)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG(x,Q^2)\right]^2, \text{ with } Q^2 = M_V^2/4$$

$$x = M_V^2 / W_{\gamma p}^2$$







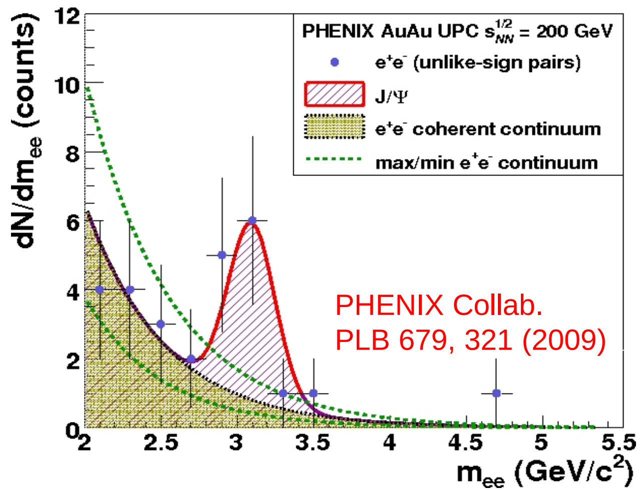
NLO pQCD analysis:

Discrimination of different $xg(x,Q^2)$ parametrizations

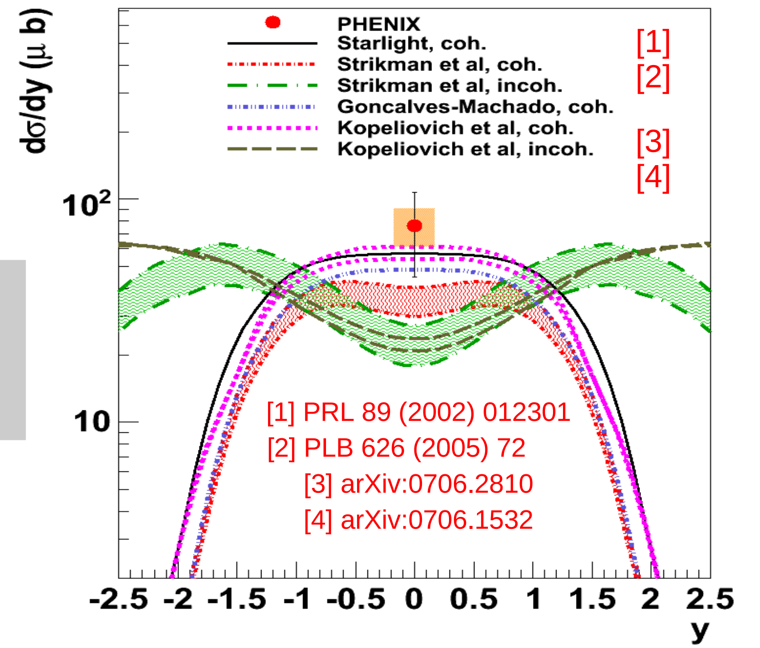
Martin, Nockles, Ryskin, Teubner PLB 662, (2008) 252

xg(x,Q^2) from exclusive $Q\bar{Q}$ photoprod. at RHIC

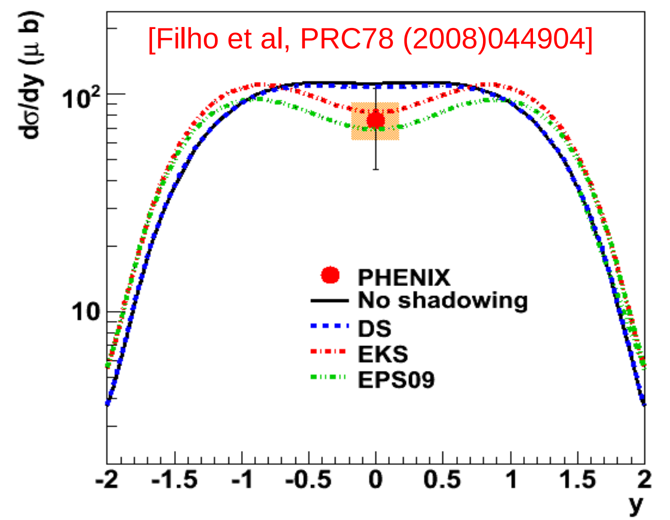
- γ Au → J/Ψ + Au at $W_{\gamma A}$~24 GeV



$d\sigma/dy|_{y=0}$ =
76± 31 (stat)
± 15 (syst) μb

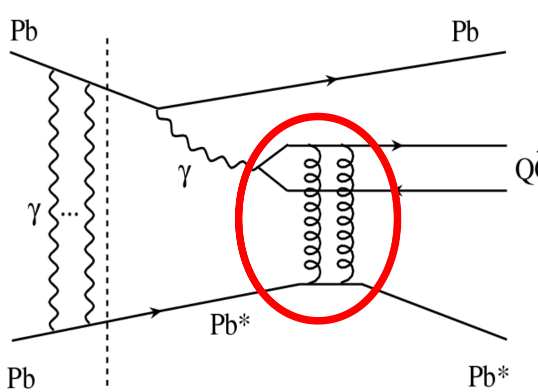


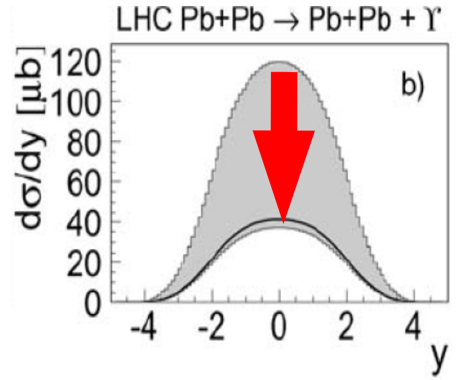
- Model comparisons:
  - Starlight (coherent): HERA data parametrization
  - Strikman et al (coherent & incoherent):
    color-dipole + $\sigma_{J/\psi N}$ = 3mb
  - Gonçalves-Machado (coherent):
    color-dipole + Glauber-Gribov shadowing
  - Kopeliovich et al. (coherent & incoherent):
    color-dipole + gluon saturation
  - Filho, Gonçalves, Griep (coherent):
    DGLAP nuclear PDFs



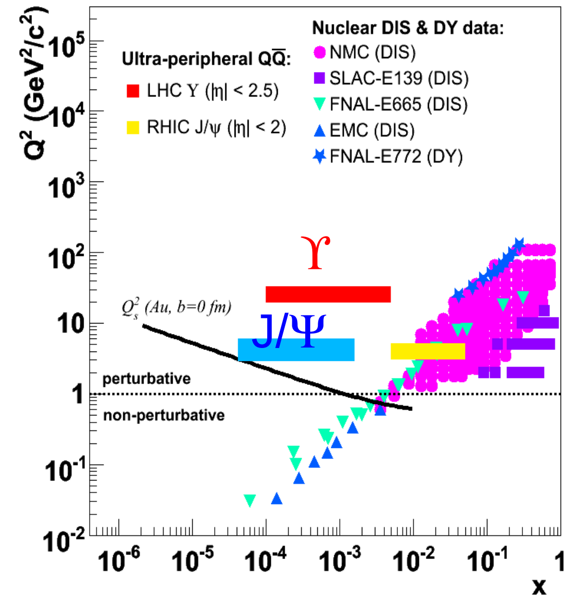
Example: Pb-Pb → γ Pb → J/Ψ,ϒ Pb

- Theoretical predictions:





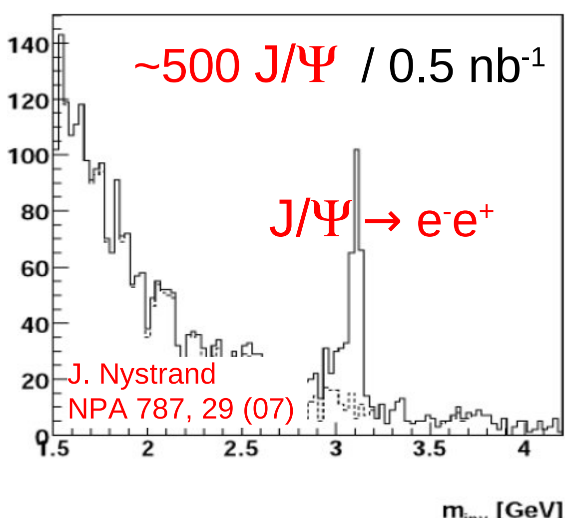
Impulse: σ = 133 mb
LT shadowing: σ = 78 mb
CGC: σ ~ 40 mb

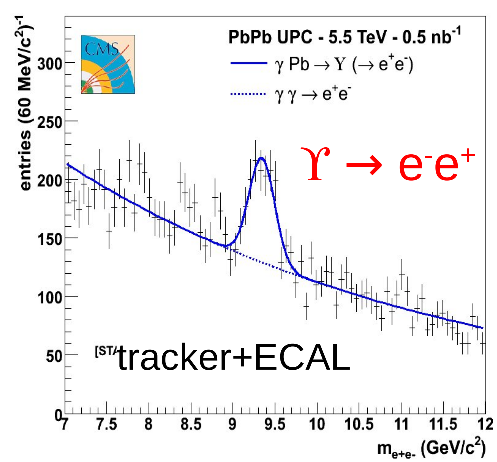


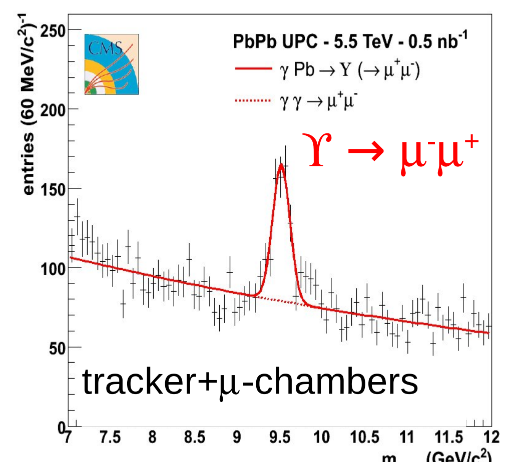
- γ Pb → J/Ψ,ϒ + Pb in ALICE, CMS:

~500 ϒ / 0.5 nb^{-1}

DdE, NPB 184, 158 (08)







Low-x nuclear PDFs from p-A collisions at the LHC

p-Pb at 8.8 TeV → jets, γ, γ^*, heavy-Q, W/Z

(x,Q^2) coverage in p-A at the LHC

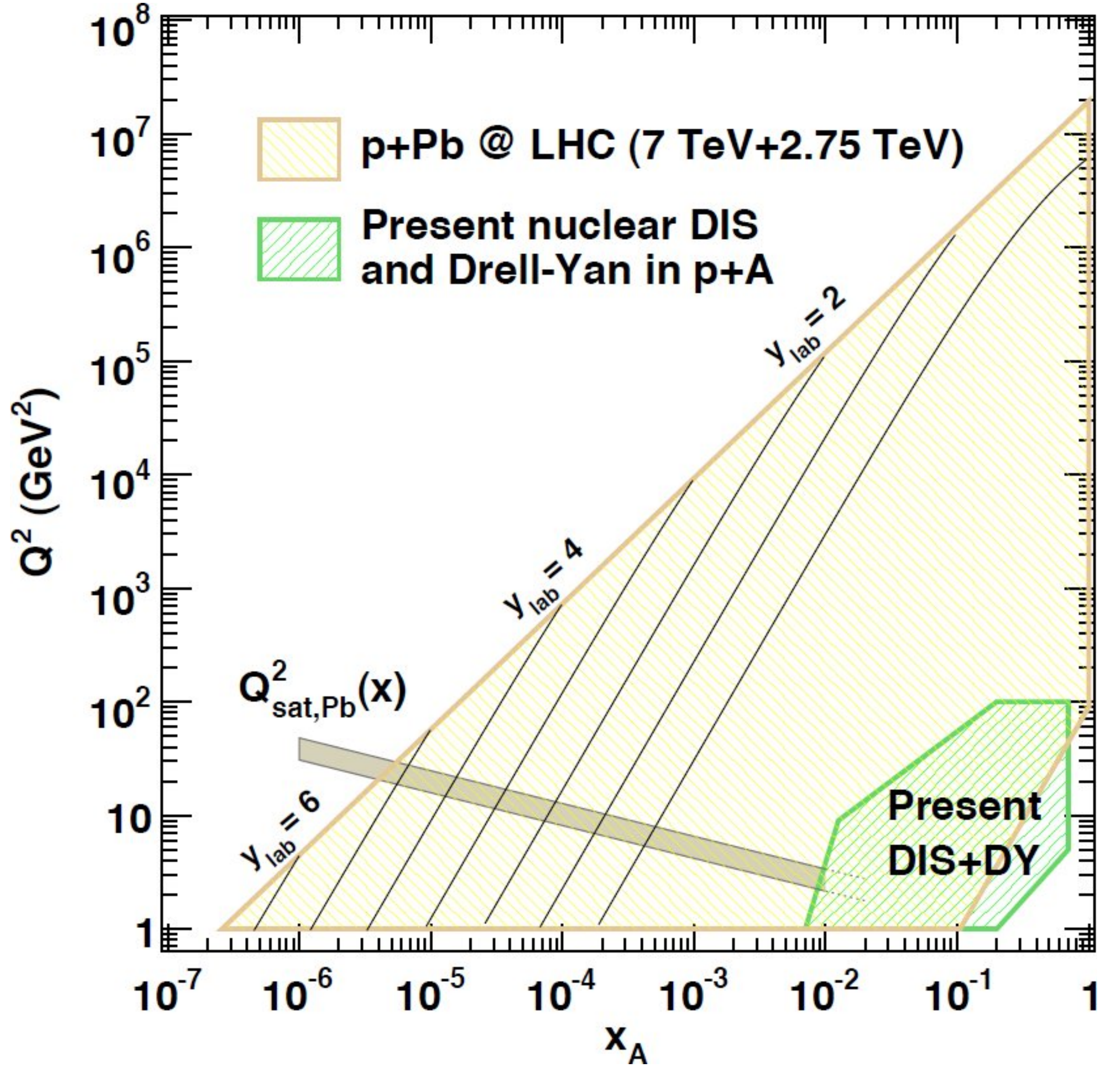
[see C.Salgado's talk]

- Central rapidities:

  jets, γ, $h^{\pm}$, heavy-Q

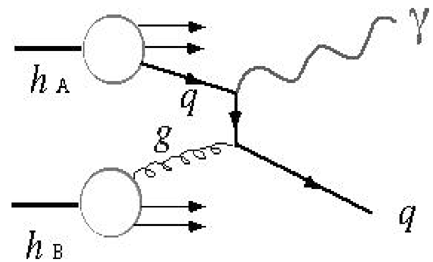
- Forward rapidities:

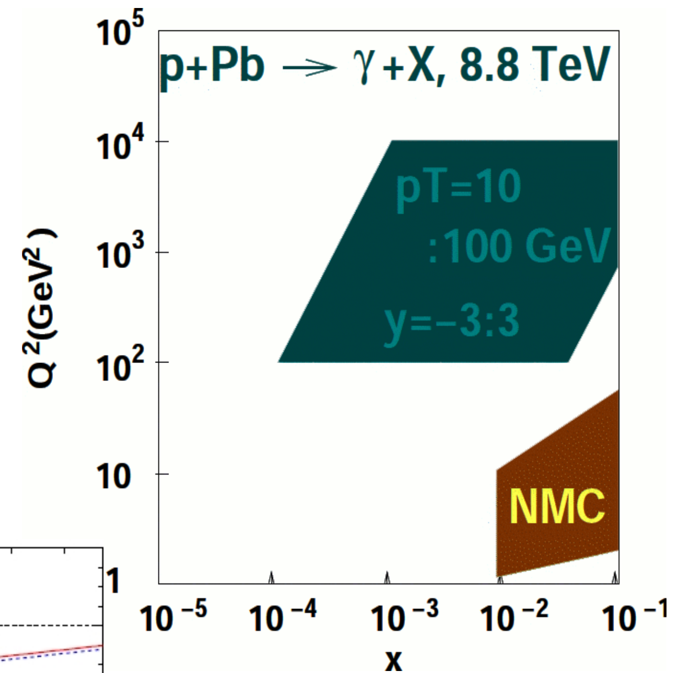
  Heavy-quarks (D,B)



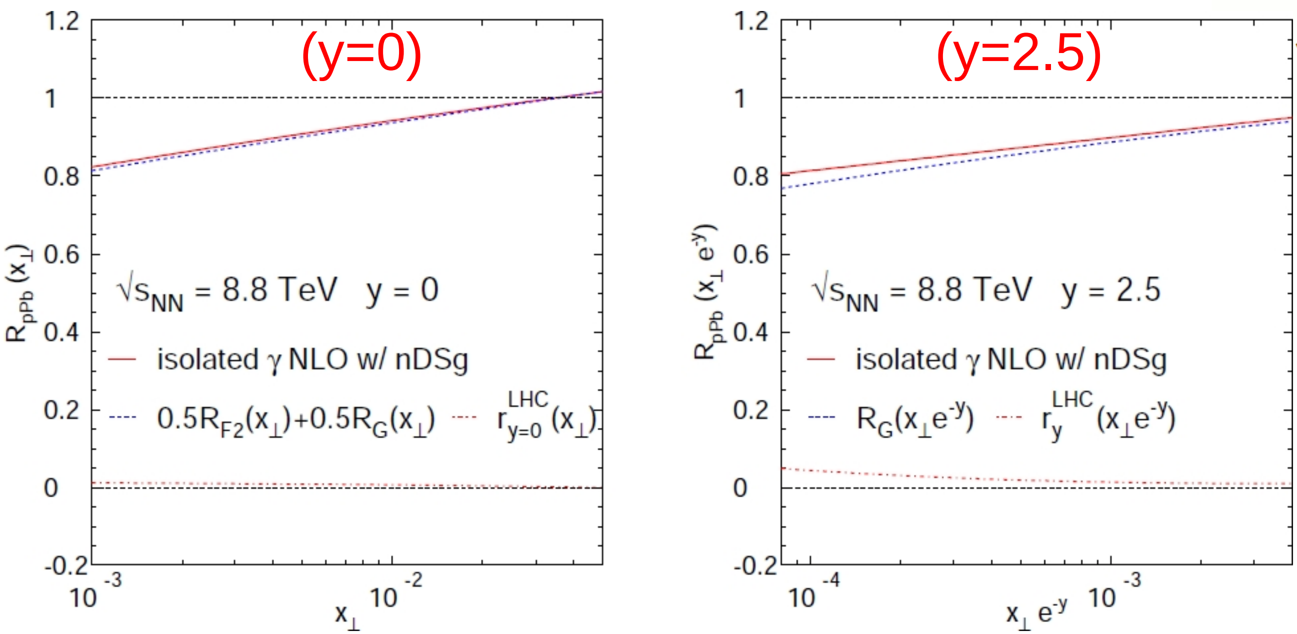
Example I: Isolated γ in ATLAS/CMS (|η| < 3)

- p-A → γ X at 8.8 TeV, p_T ~10-100 GeV/c at |η|<3 probe glue at $x_2 \sim 10^{-3}$





- Nuclear modification factor $R_{pPb}(x_T)$:

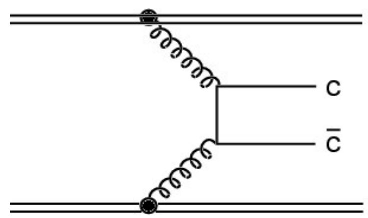


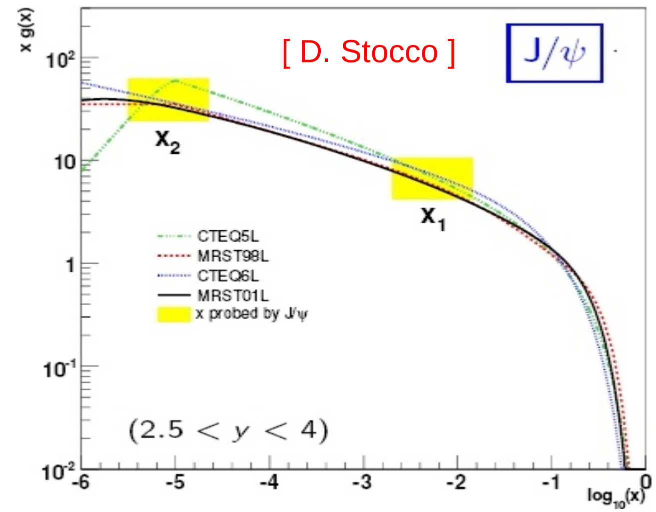
[Arleo-Gousset, PLB2008]

Example II: Forward $Q\bar{Q}$ in ALICE ($2.5 < \eta < 4$)

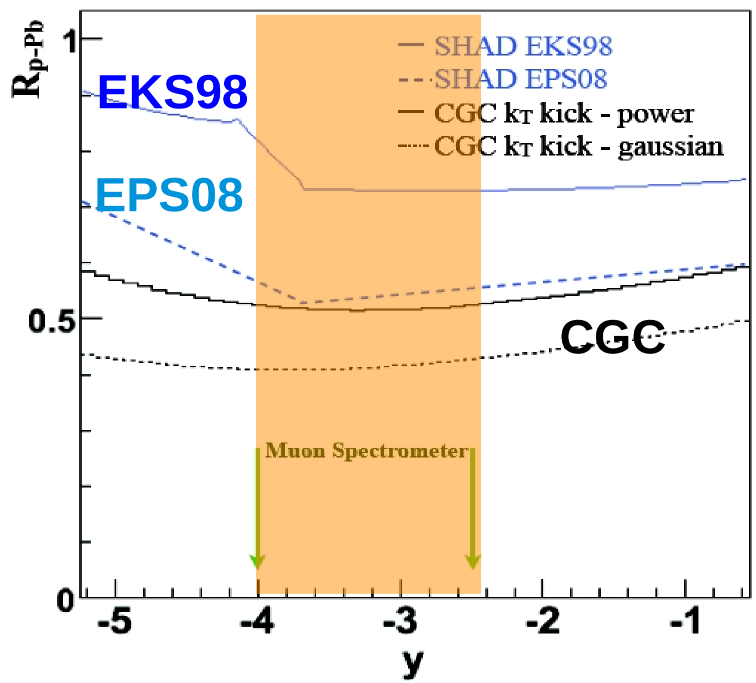
- J/ψ measurement in fwd μ-spectrometer:

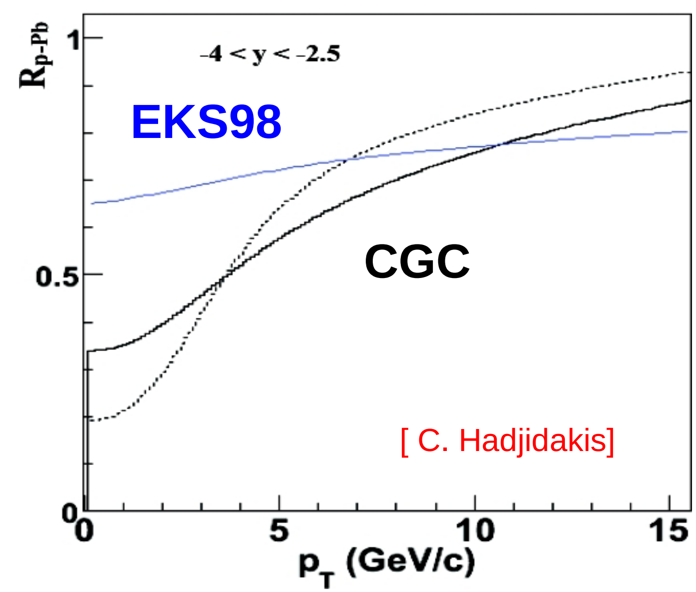
  Sensitive to xg(x)
  down to $x_2 \sim 10^{-5}$





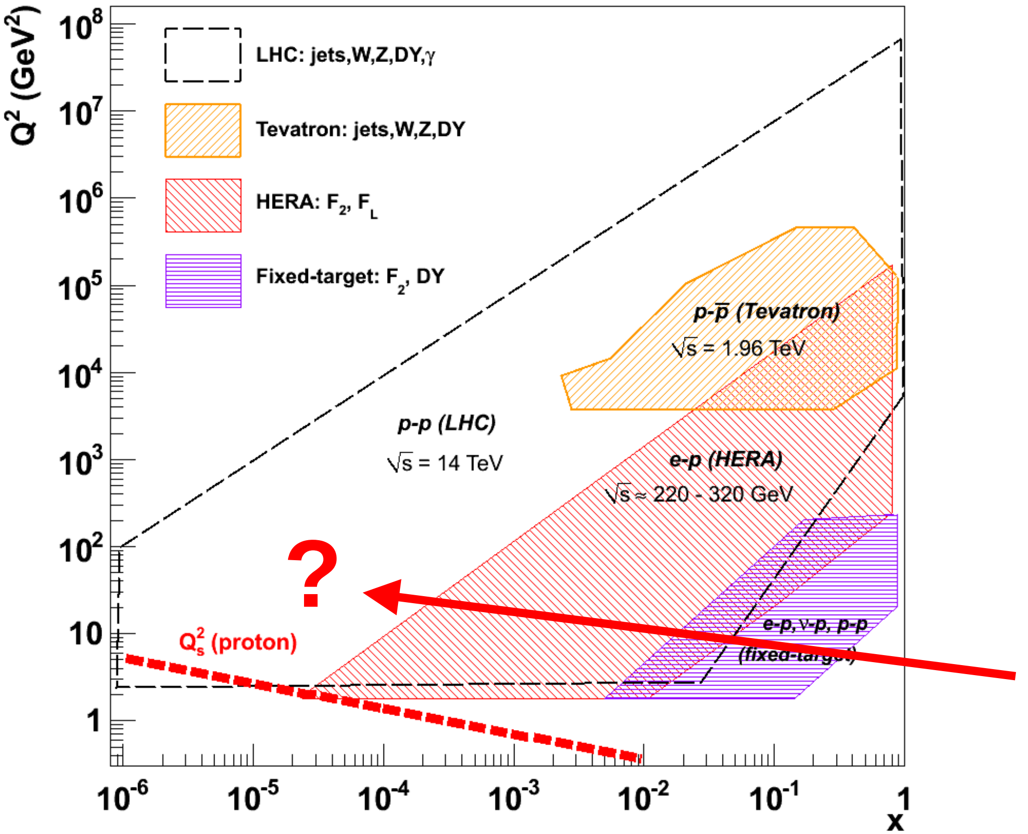
- Expected $R_{pPb}(y,p_T)$ in p-Pb at 8.8 TeV :

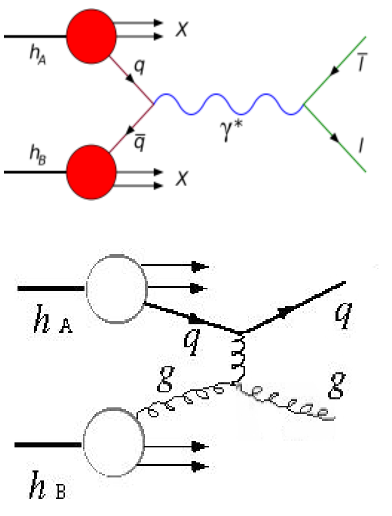




Summary: low-x QCD with protons

- Improvements of low-x PDFs expected using forward detectors:



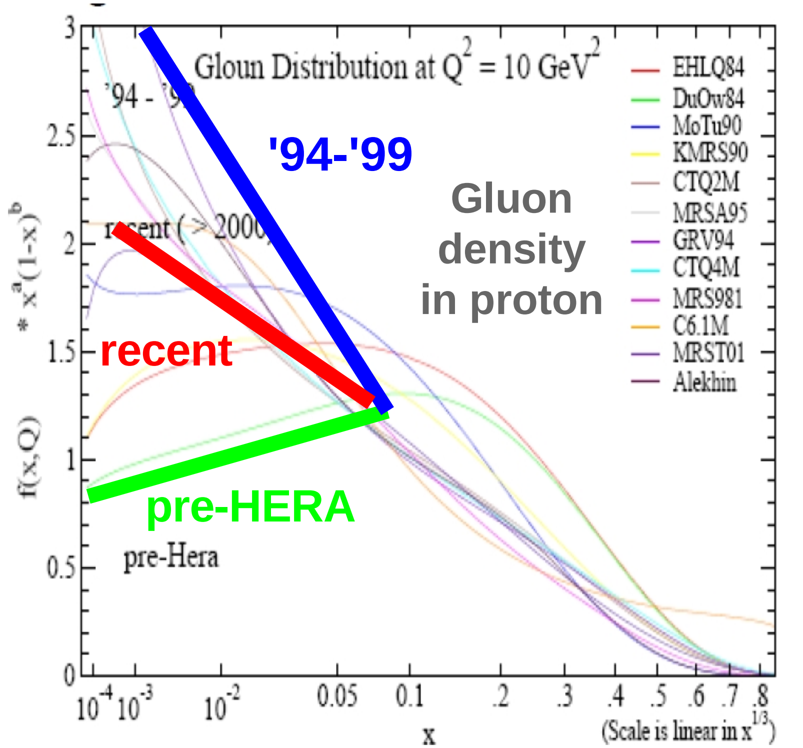


In particular, low mass DY (y~5, M~2.5 GeV): Reduction of sea/glue uncertainty by up to 70%.

- But LHC barely touches $Q_s^2(x)$.
- LHeC needed for non-linear evolution studies in proton.

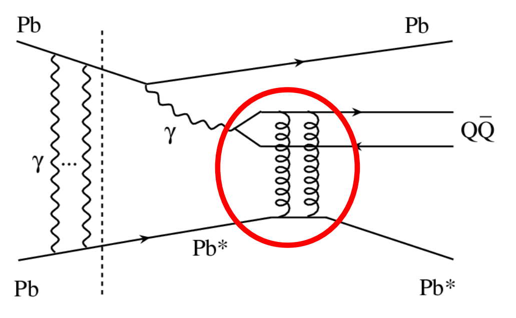
Summary: low-x QCD with nuclei

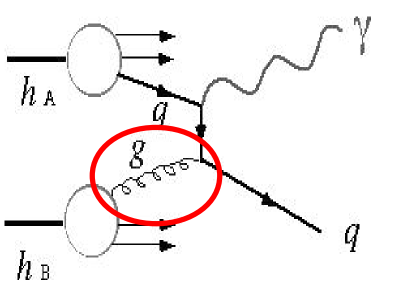
- Current knowledge of low-x nuclear gluon density (& evolution?) is as bad or worst! than for the proton ~15 years ago (pre-HERA).



- In order to reach present-day proton PDF precision we would need a machine like LHeC.

- LHC $xG(x,Q^2)$ constraints:
  - ▷ γ-Pb (Pb-Pb) @ 5.5 TeV
  - ▷ p-Pb @ 8.8 TeV





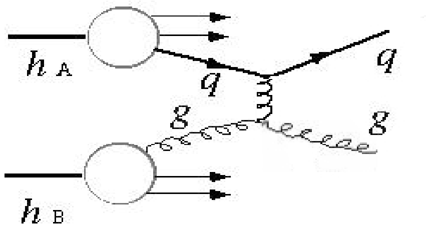
- Plus, lots of low-x (saturation) dynamics studies possible too at the LHC

Backup slides

Example: Forward jets in CMS (3 <|η| < 6.6)

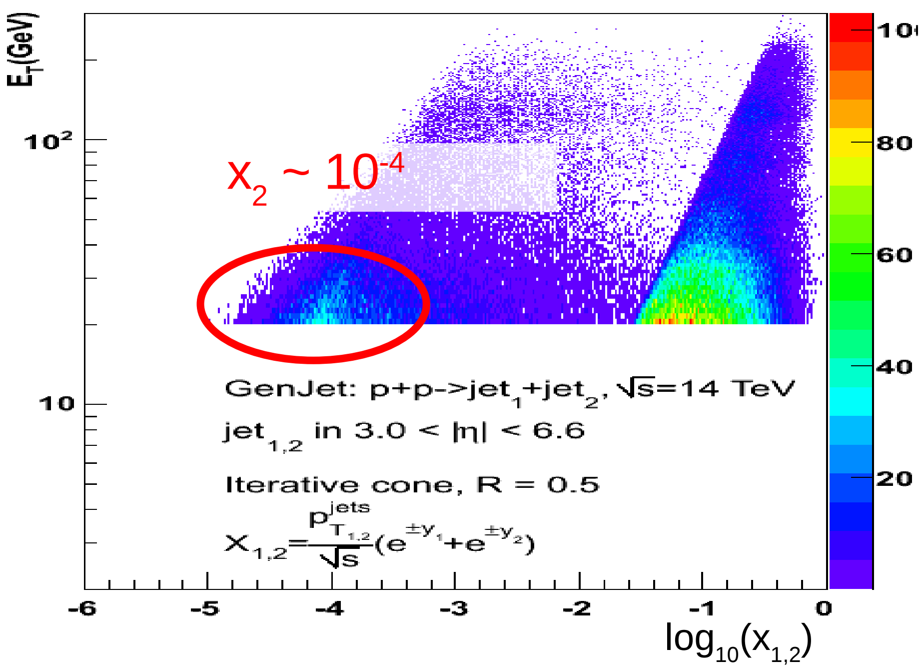
[S.Cerci-DdE, arXiv:0806.0091]

- Forward jets (E_T ~20-100 GeV) sensitive to low-x PDFs:

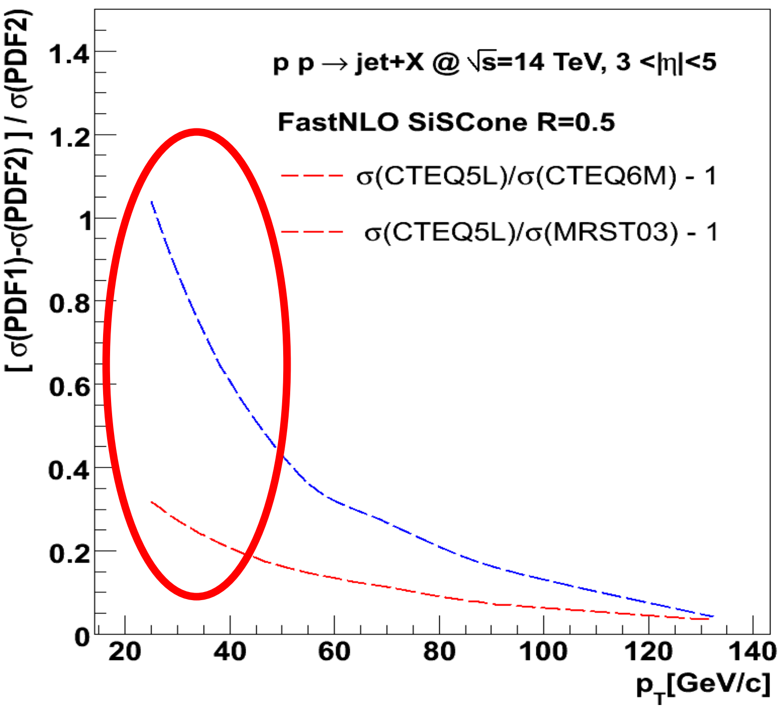


Jets in HF (3<|η|<5) probe: $x_2 \sim 10^{-4}$

Jets in CASTOR (5.1<|η|< 6.6): $x_2 \sim 10^{-5}$

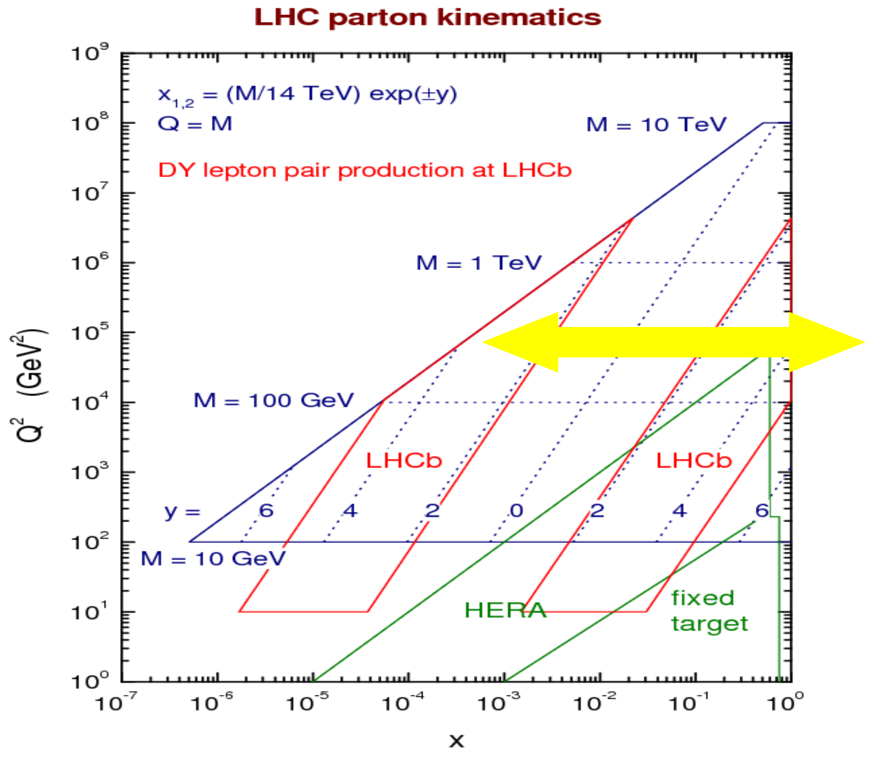


varying PDFs:



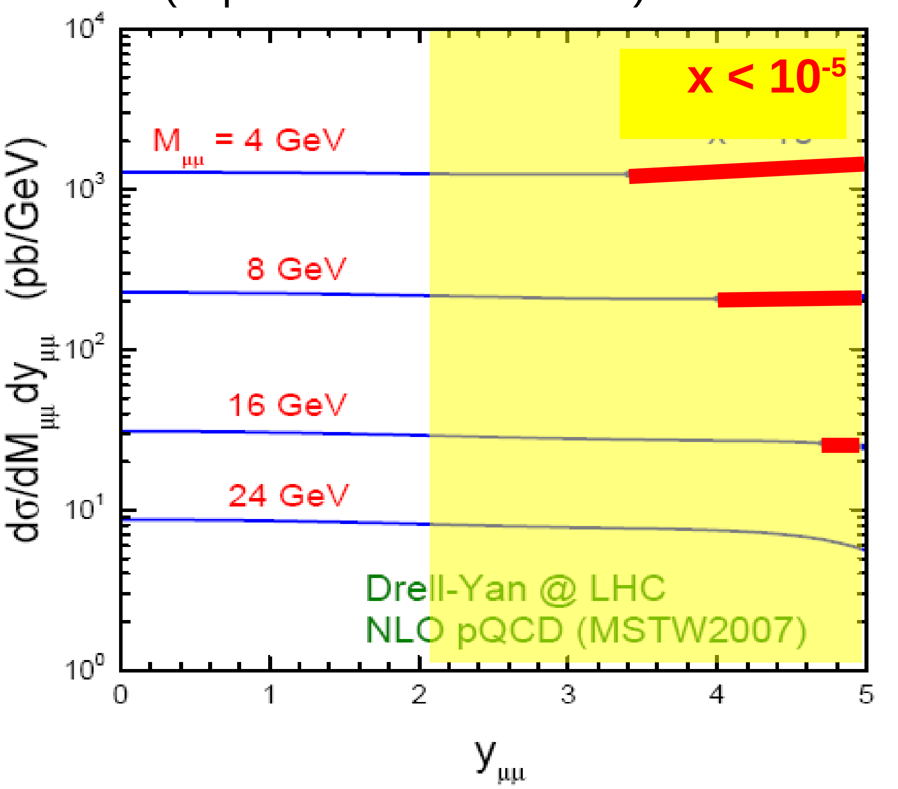
Example: Forward γ* in LHCb (2 < η < 5)

- Drell-Yan forward μ: $q\bar{q} \to \mu^+\mu^-$ (trigger on low-p muons: p>8GeV, p_T>1GeV)
- Sensitive to low-x quark densities



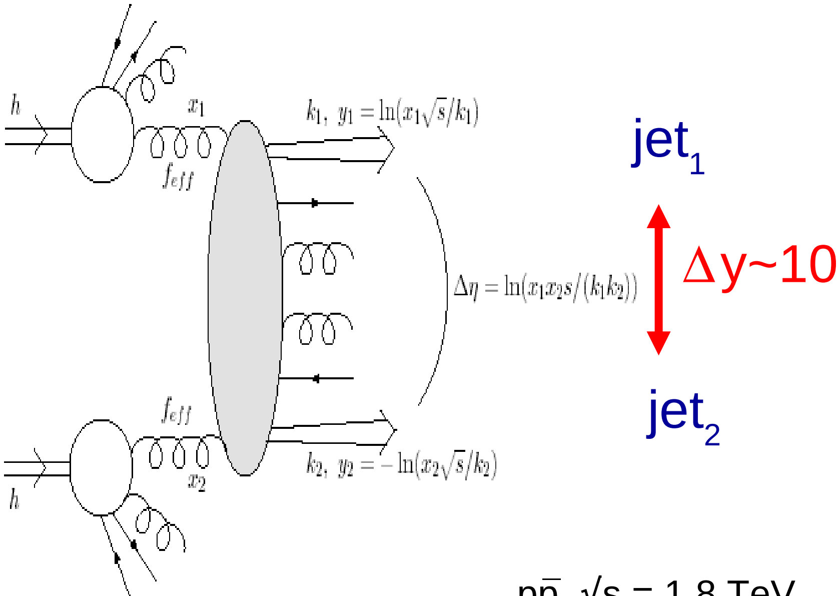
pp @ 14 TeV

(expected cross sections)



Example: Mueller-Navelet dijets in CMS ($\Delta\eta$ ~10)

- Mueller-Navelet dijets with large y separation very sensitive to low-x QCD evolution (testing ground for BFKL):



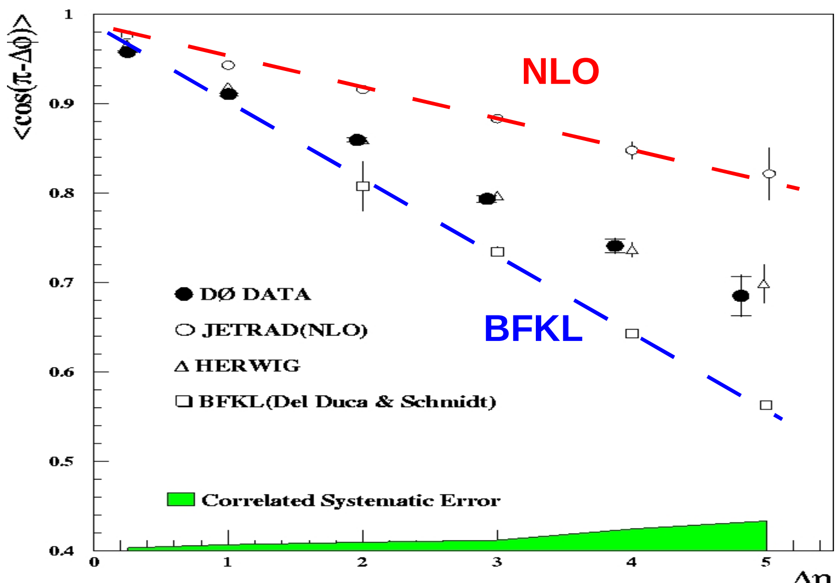
BFKL: extra radiation between the 2 jets will smooth out back-to-back topology

A.H.Mueller, H.Navelet, NPB282 (1987)727

(partially compensated by gluon saturation ?)

- Increased azimuthal decorrelation with increasing Δy (w.r.t. DGLAP collinear-factorization):

$p\bar{p}$ $\sqrt{s}$ = 1.8 TeV



[D0 Collab, PRL77(97)595]

[DelDuca, Schmidt], [Orr, Stirling]
[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon] [E. Iancu et al.]

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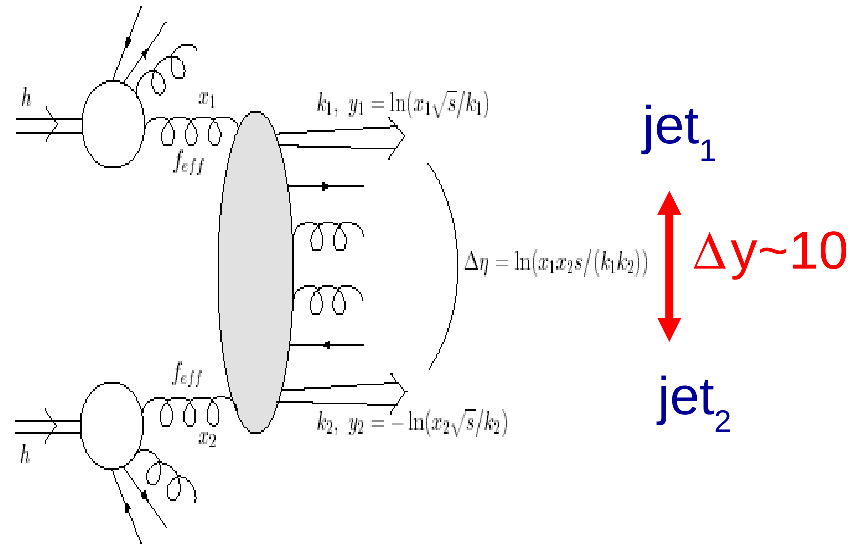

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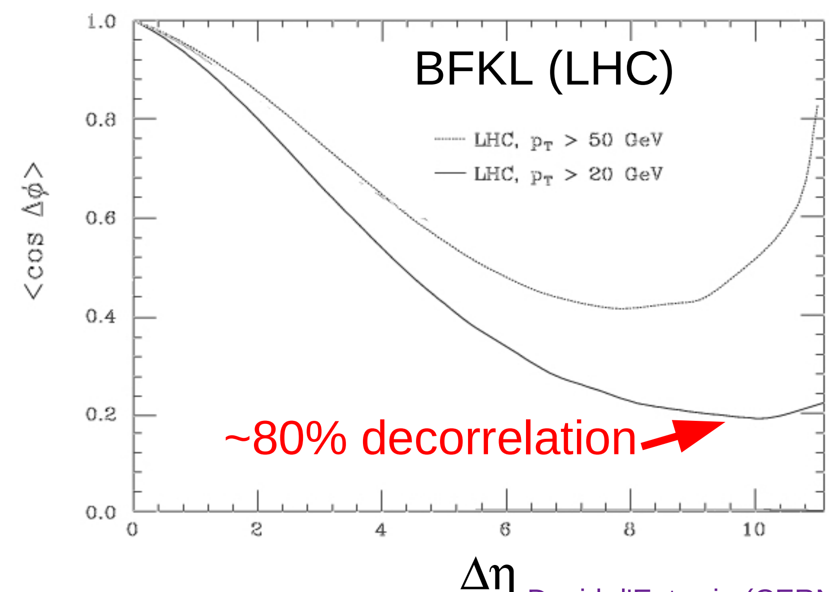

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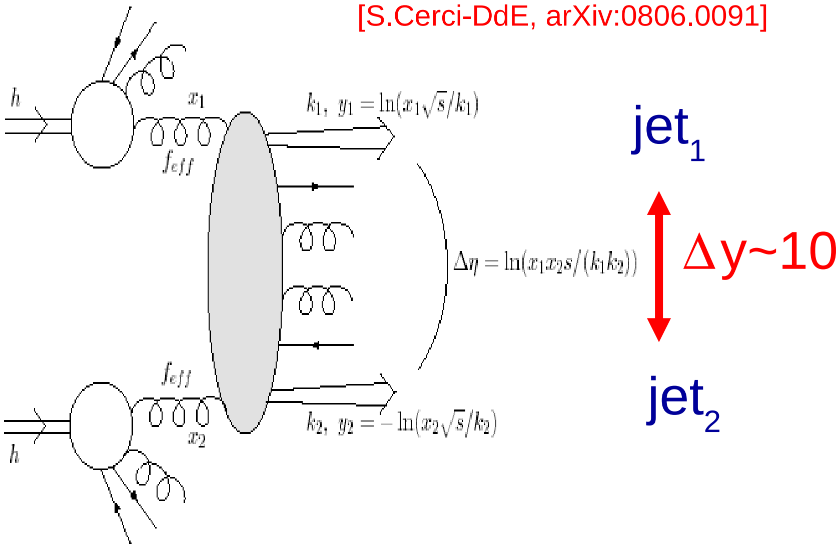

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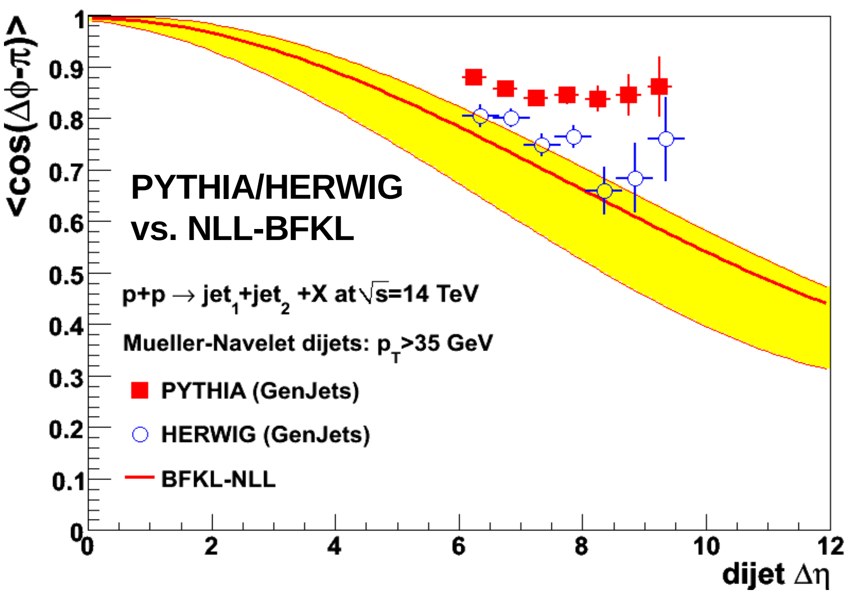

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