

Measuring low-x nuclear PDFs at the LHC: a wish list

Workshop on nuclear Parton Distrib. Functions

Annecy, 22nd - 23rd Feb. 2010

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Overview

■ Introduction:

- Uncertainties on parton structure & evolution at low-x.
- Measurements of nuclear PDFs: processes, kinematic domains, ...

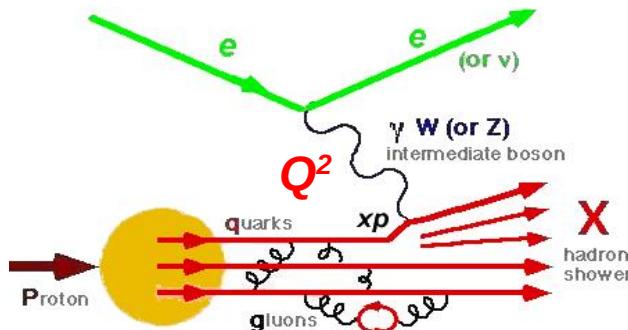
■ Perspectives (wish-list) of low-x PDF constraints at the LHC:

- ▷ γ -Pb in ultraperipheral Pb-Pb colls @ 5.5 TeV: $Q\bar{Q}$, jets
- ▷ p-Pb colls. @ 8.8 TeV: forward jets, γ , DY, heavy-Q, $Q\bar{Q}$, W,Z

■ Summary

Motivation (I): Low- x PDFs

- DIS collisions probe **distributions of partons** inside hadrons:



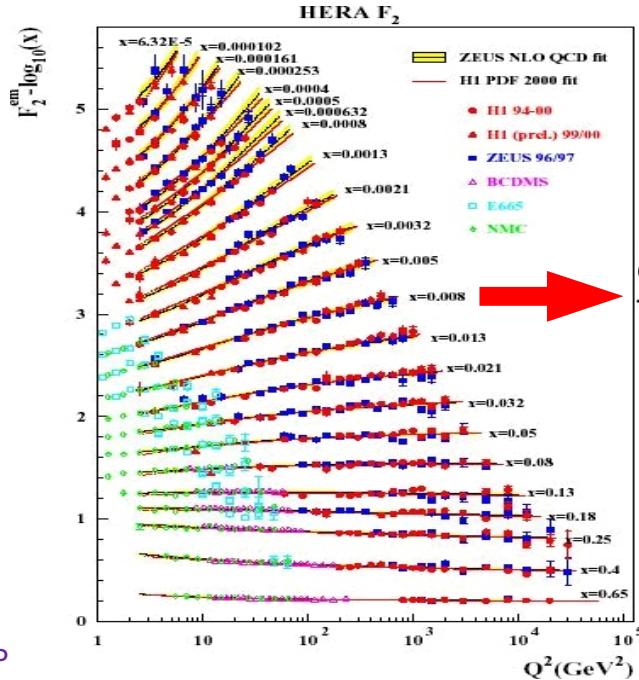
Q^2 = “resolving power”

Bjorken x = momentum fraction carried by parton

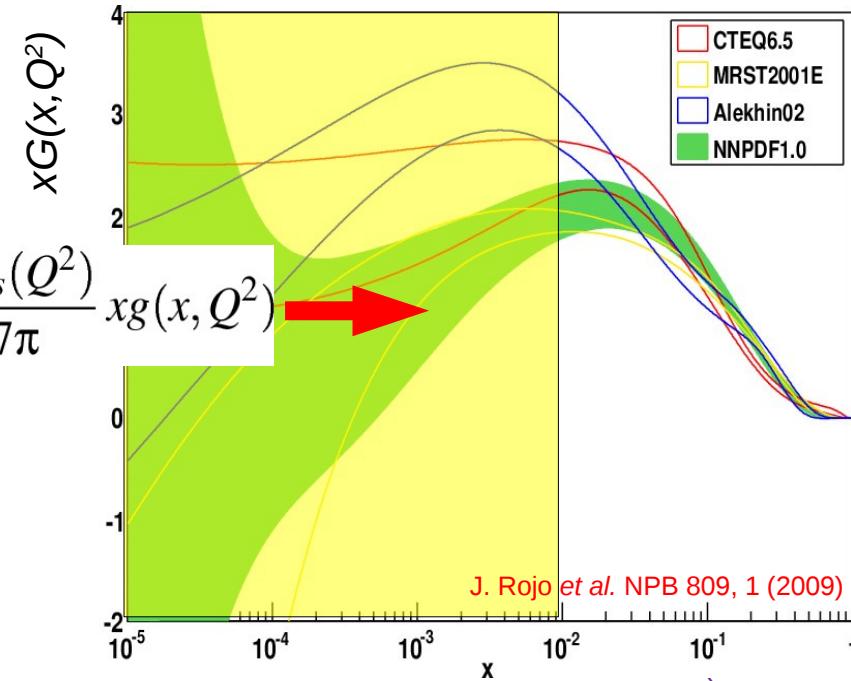
$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [Y_+ \cdot F_2 \mp Y_- \cdot xF_3 - y^2 \cdot F_L]$$

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

- Gluons dominate but only indirectly constrained via F_2 “scaling violations”:



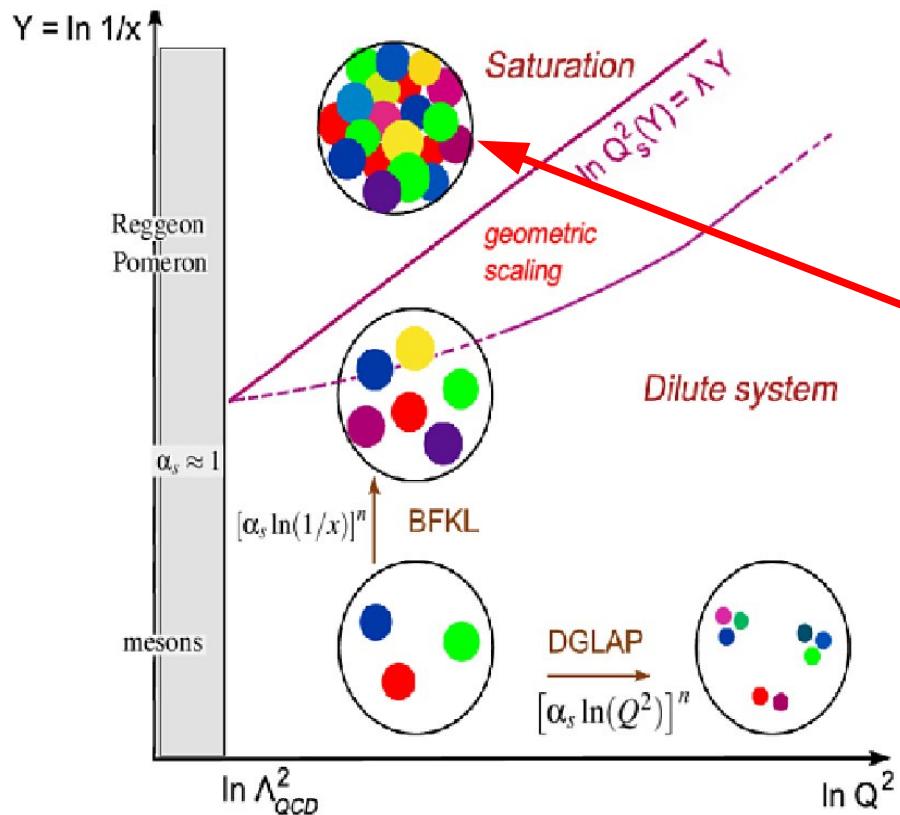
$$\frac{\partial F_2(x, Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi} xg(x, Q^2)$$



Motivation (II): low- x QCD evolution

[cf. F.Gelis' talk]

- **Q^2 - DGLAP** (k_T -order'd emission): $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n, Q_0^2 \sim 1 \text{ GeV}^2$ [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 :

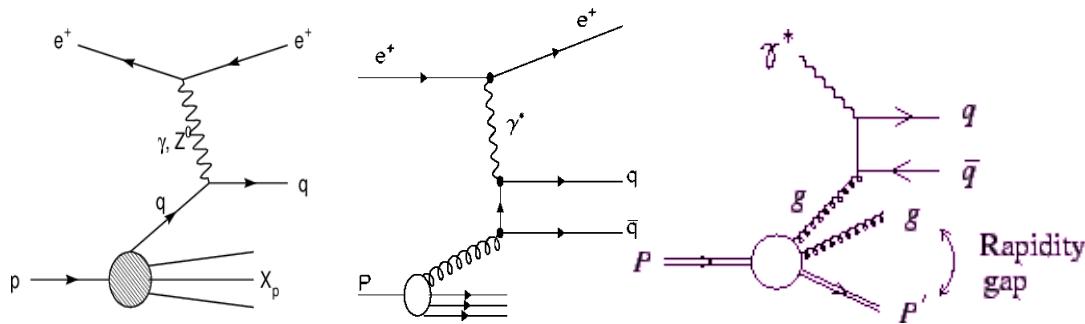


- (i) Too high gluon density: **nonlinear gluon-gluon fusion** balances branchings
- (ii) pQCD (collinear & k_T) **factorization** assumptions invalid (HT, no incoherent parton scatt.)
- (iii) **Violation of unitarity** even for $Q^2 \gg \Lambda^2$ (too large perturbative cross-sections)
- Saturation enhanced in multi-parton systems (nuclei): $Q_s^2 \sim A^{1/3} \sim 6$

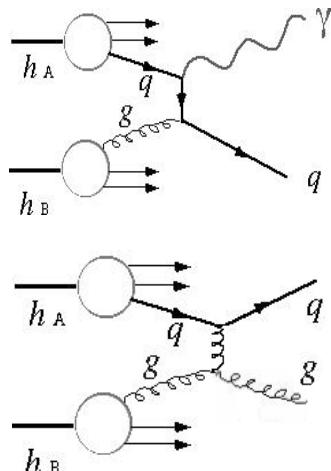
Experimental access to low-x gluon PDF

■ Perturbative processes:

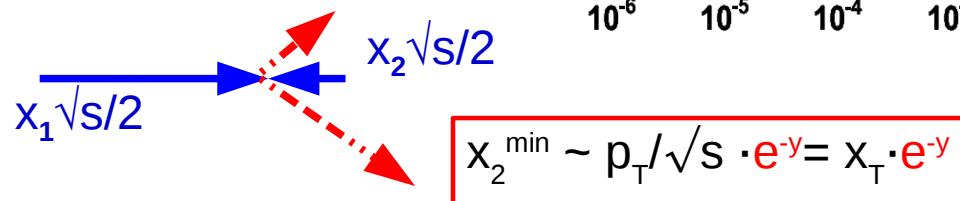
- $e(\gamma)\text{-}p, e(\gamma)\text{-}A: F_2, F_L, F_2^{\text{charm}}, \text{ excl. } Q\bar{Q}, \dots$



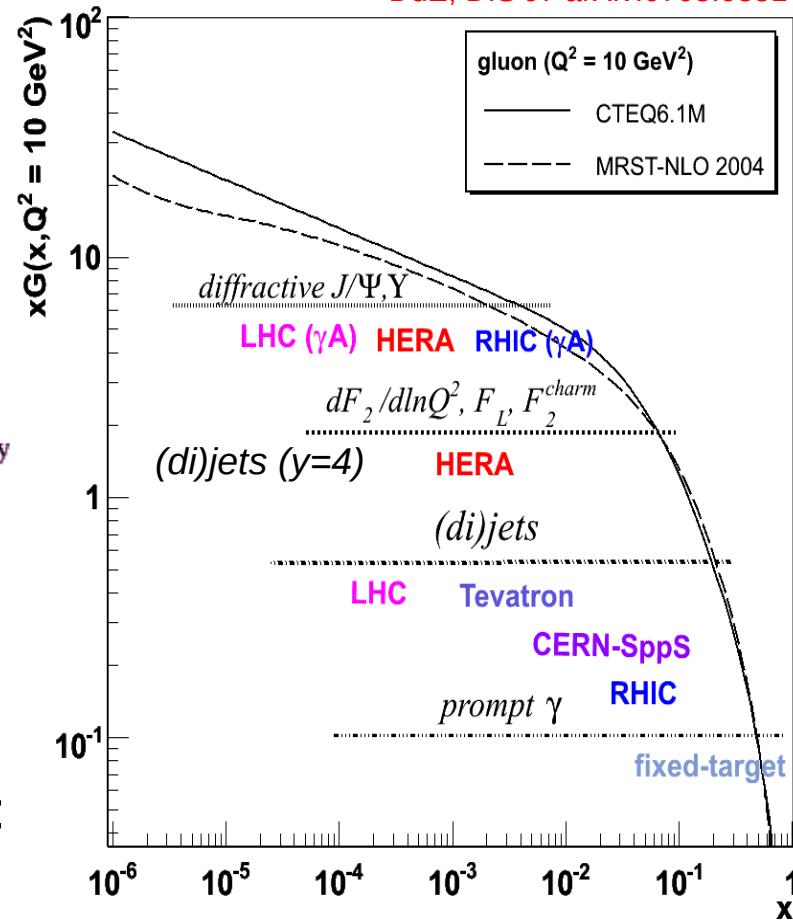
- $p\text{-}p, p\text{-}A: \text{direct } \gamma, \gamma^* \text{ (DY), heavy-Q, jets:}$



► Forward production:

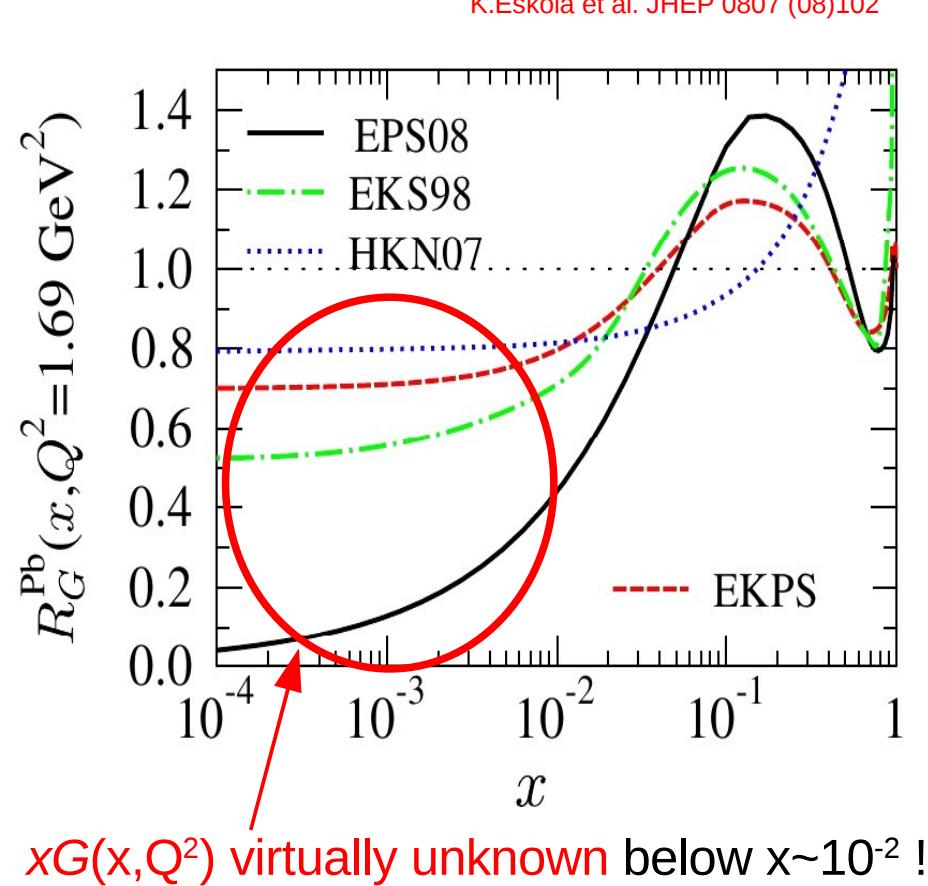
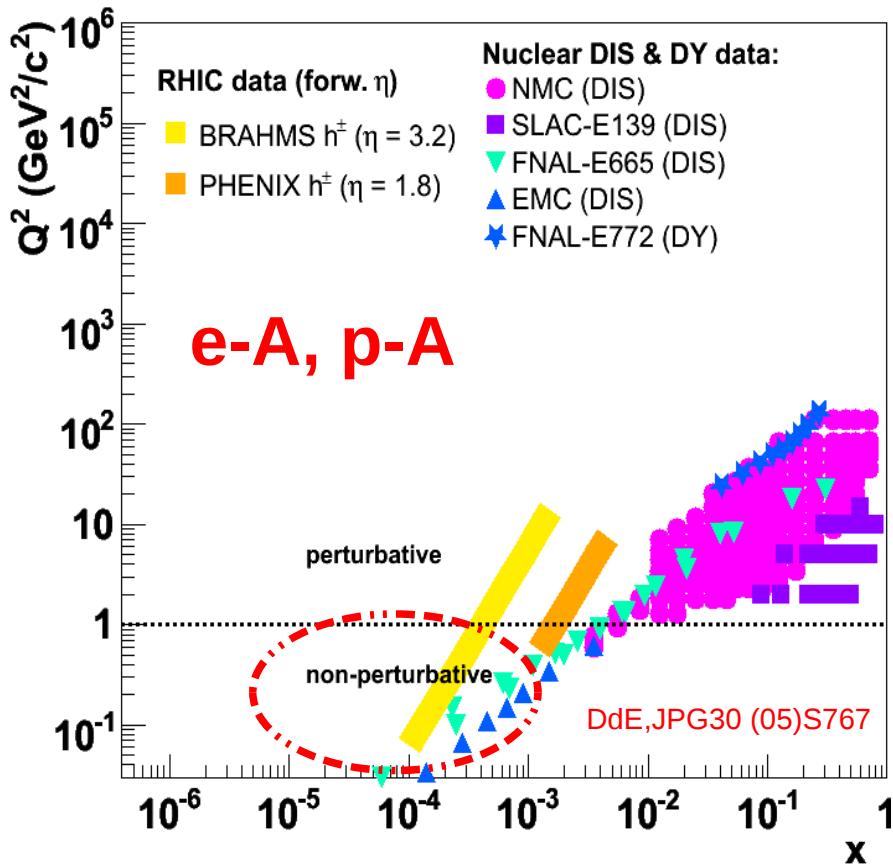


Every 2-units of y , x^{\min} decreases by ~ 10



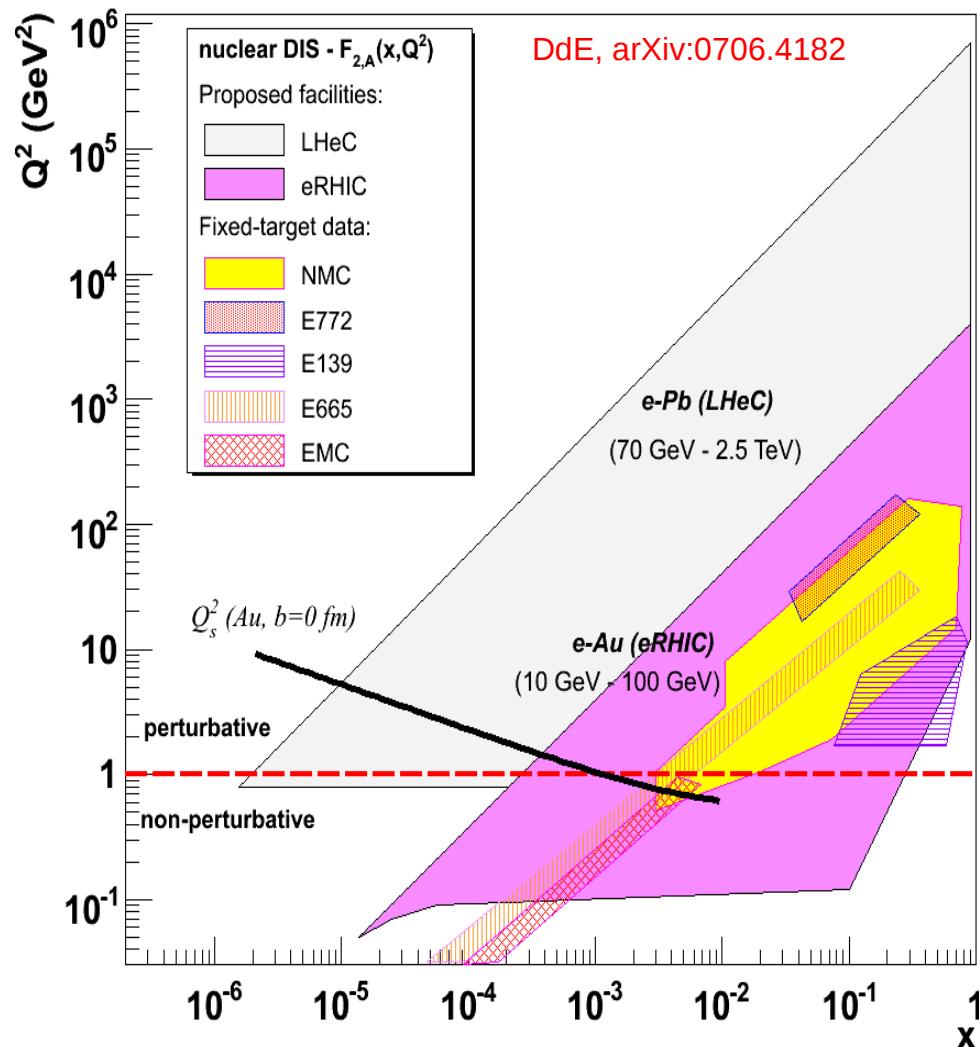
Low-x gluon nuclear densities

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



What to do before future(?) nDIS facilities ?

[cf. N.Arnesto's talk]



Ultimately: F_2^A , $F_{2,\text{charm}}^A$, F_L^A , ...

■ eRHIC:

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

■ LHeC:

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

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

$Q^2 \sim 1 - 10^6$ GeV 2

$x \sim 10^{-6} - 1$.

LHC: Forward detectors for low-x PDFs

■ Key measurements:

γ -A (UPC A-A) $\rightarrow Q\bar{Q}$, jets

p-A $\rightarrow \gamma, \gamma^*,$ heavy-Q, $Q\bar{Q}$, jets, W, Z

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

(every 2-units of y,
 x^{\min} decreases by ~ 10)

■ Jets, photons in fwd. calorimeters:

CMS/ATLAS: up to $|\eta| < 5$.

LHCb: $2 < \eta < 5$ ($p_T < 20, 50$ GeV)

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

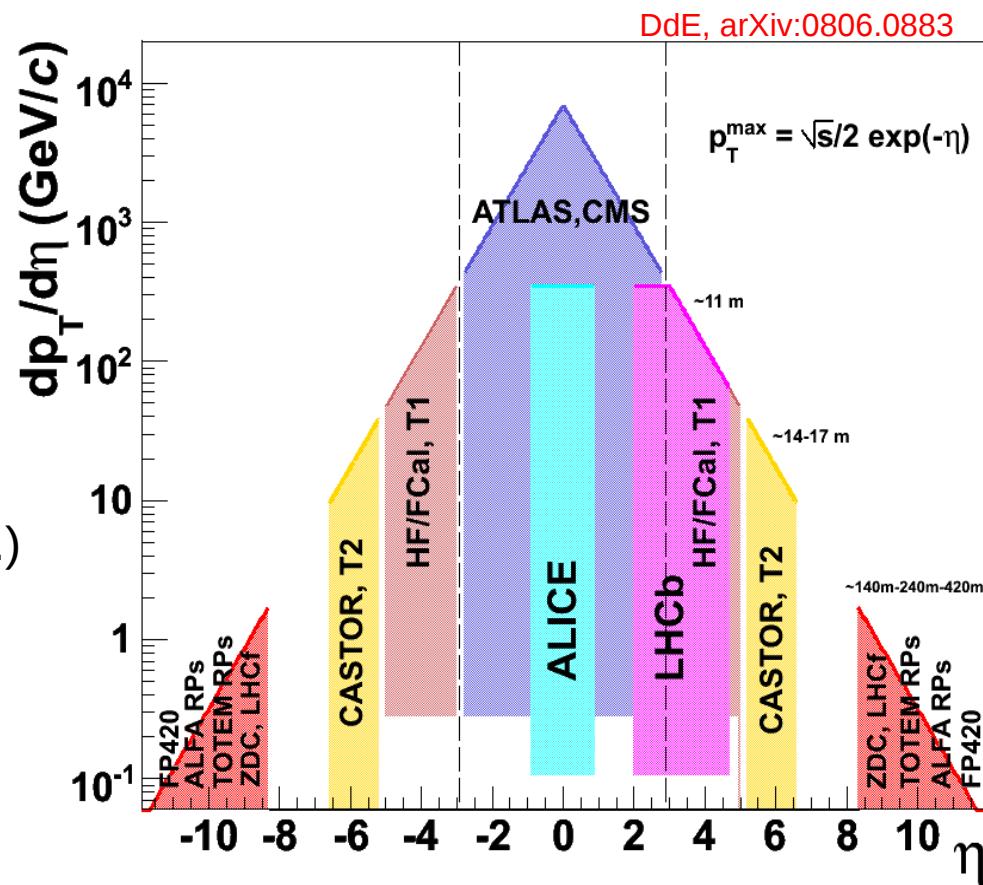
ALICE: $2.5 < \eta < 4$ (but no 2nd vtx.)

LHCb: $2 < \eta < 5$

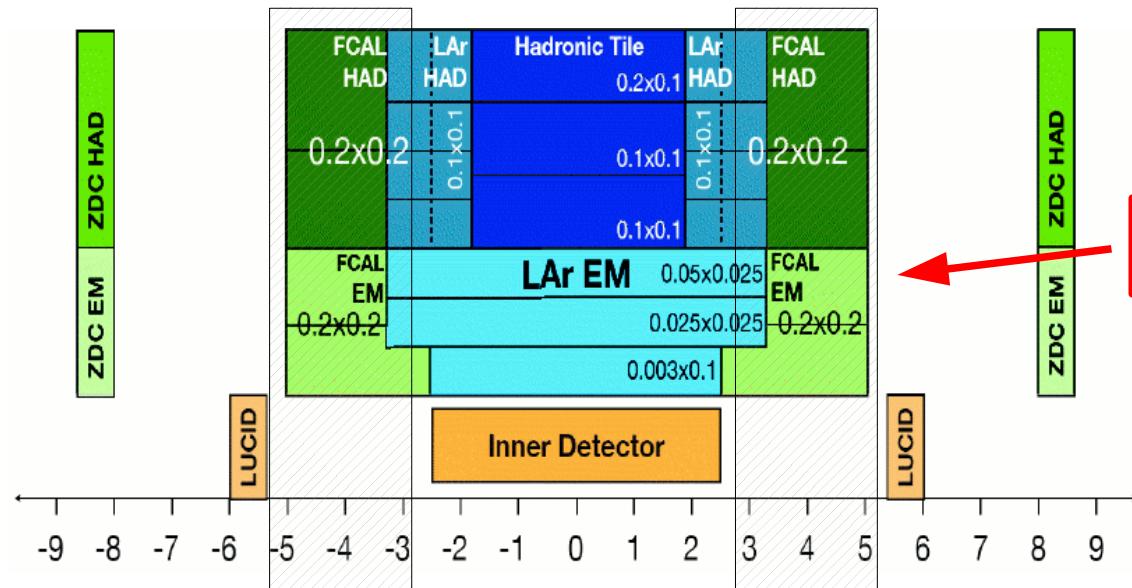
■ Trackers/PID:

LHCb: $2 < \eta < 5$

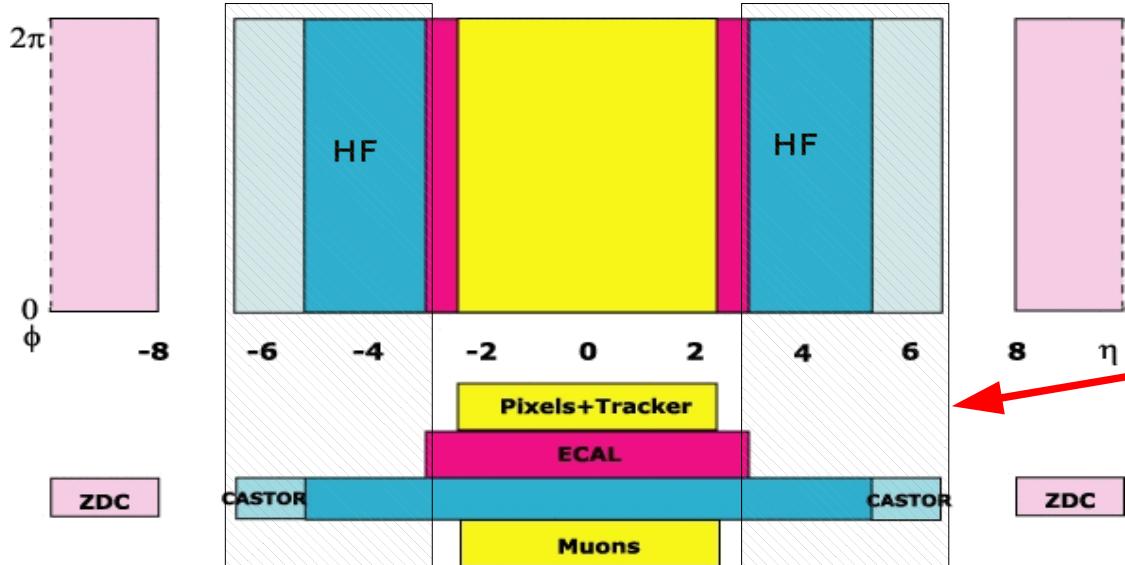
(TOTEM partially)



Forward jets & γ : ATLAS/CMS calorimeters



$3 < |\eta| < 5$



$3 < |\eta| < 6.6$

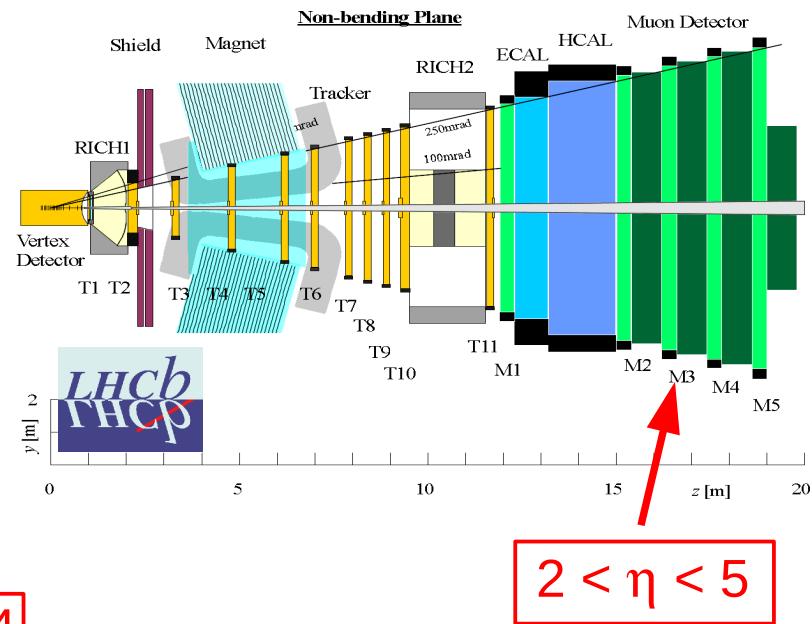
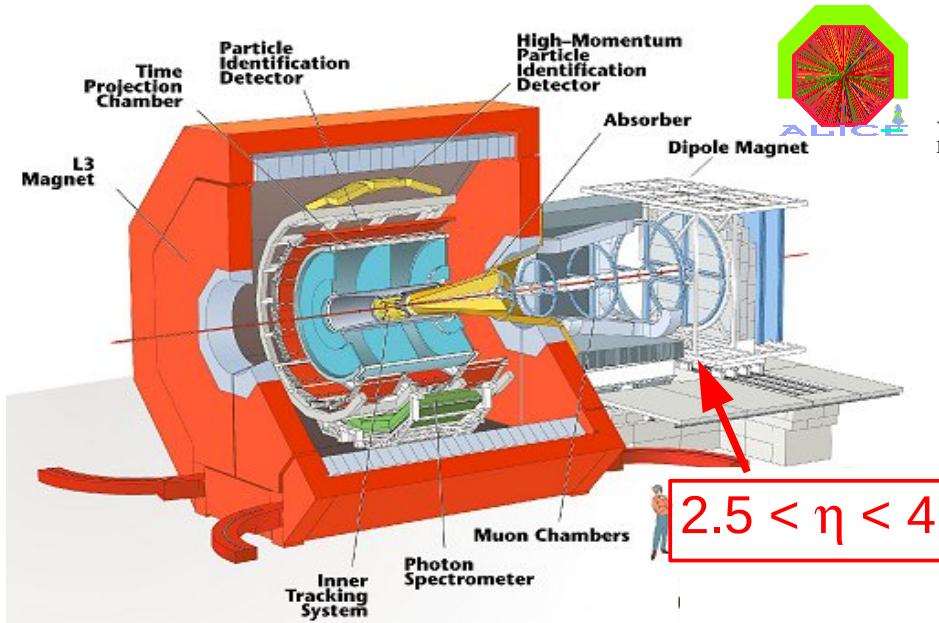
Note: also LHCb
calos in $2 < \eta < 5$
but limited p_T range

$p_T(\gamma) < 15 \text{ GeV}/c$

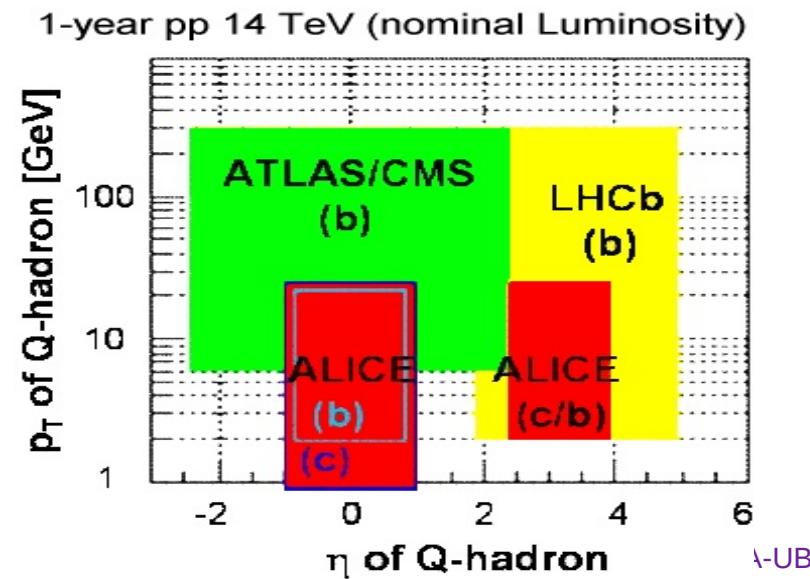
$p_T(\text{jets}) < 50 \text{ GeV}/c$

Open/close heavy-flavour: LHCb & ALICE

■ Forward muon spectrometers:



- Excellent capabilities for **heavy-Q**, $Q\bar{Q}$ fwd. measurements at low- x :
- I will assume that LHCb will run p-A



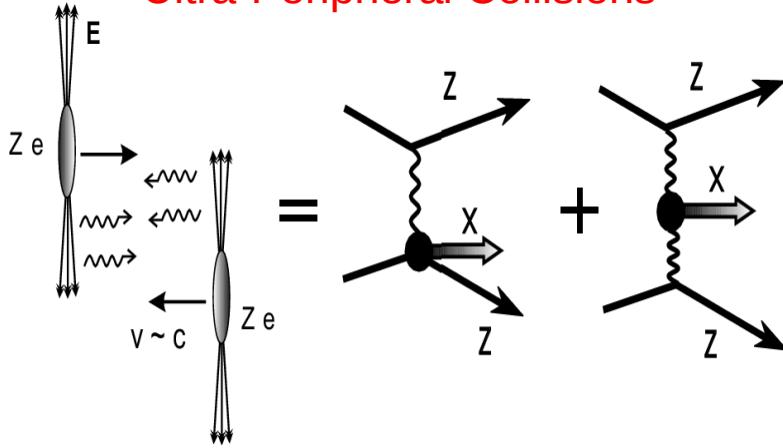
Low-x nuclear PDFs from A-A collisions at the LHC

γ-Pb (UPC Pb-Pb at 5.5 TeV) → Q \bar{Q} , jets

Photoproduction in A-A collisions at the LHC

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

Ultra-Peripheral Collisions

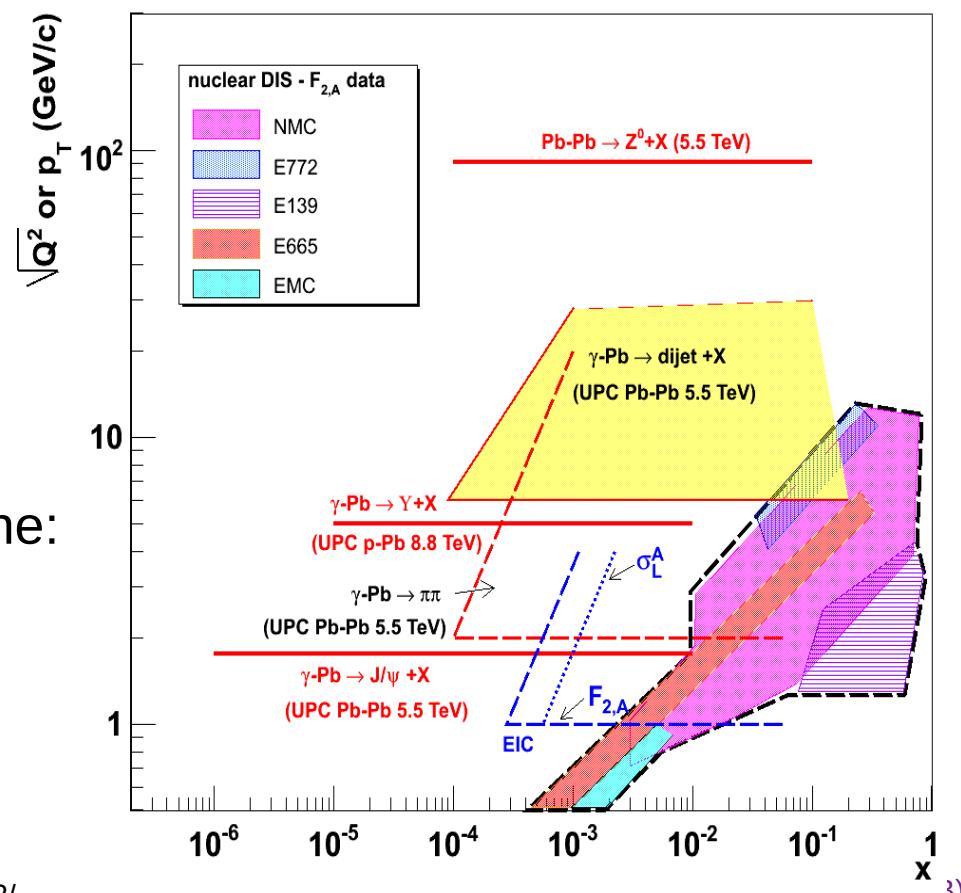


- UPCs in Pb-Pb @ 5.5 TeV:

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

$\gamma\text{-Pb max. } \sqrt{s}_{\gamma\text{Pb}} \approx 1 \text{ TeV} \approx 3\sqrt{s}_{\gamma p}$ (HERA)

- Various processes in $(x, \sqrt{Q^2})$ plane:
 - ▶ $\gamma\text{-Pb} \rightarrow Q\bar{Q}$
 - ▶ $\gamma\text{-Pb} \rightarrow \text{dijets}$

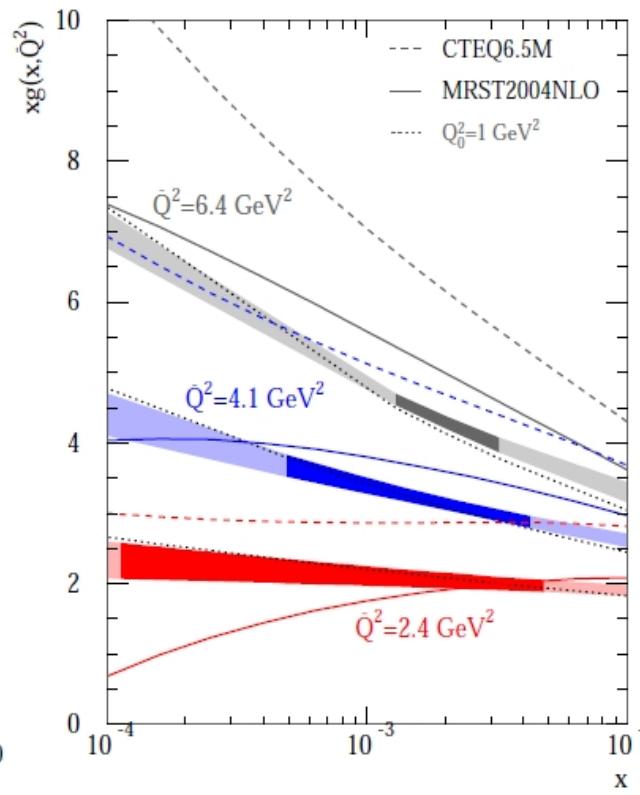
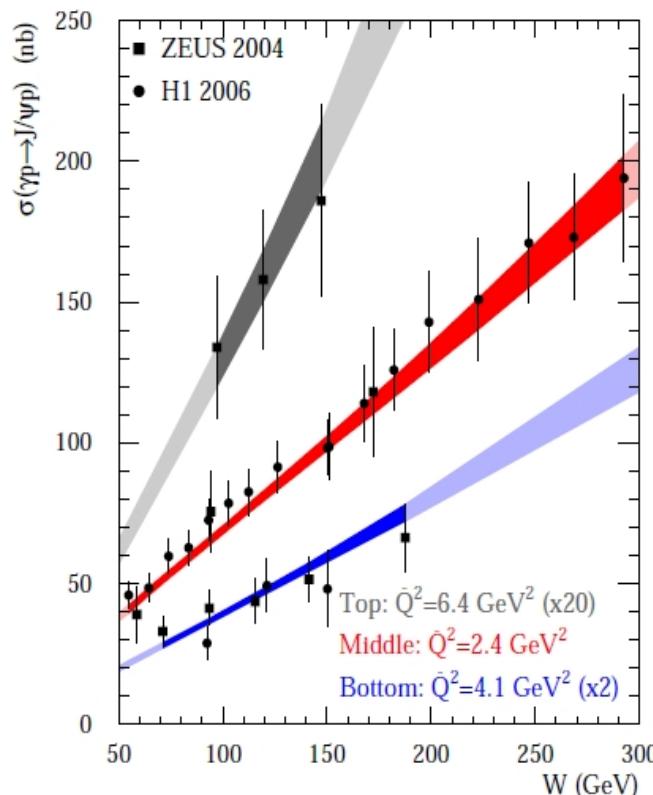
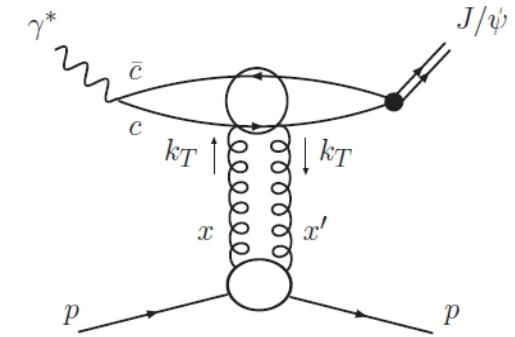


$xg(x, Q^2)$ from exclusive $Q\bar{Q}$ photoprod. at HERA

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

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

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



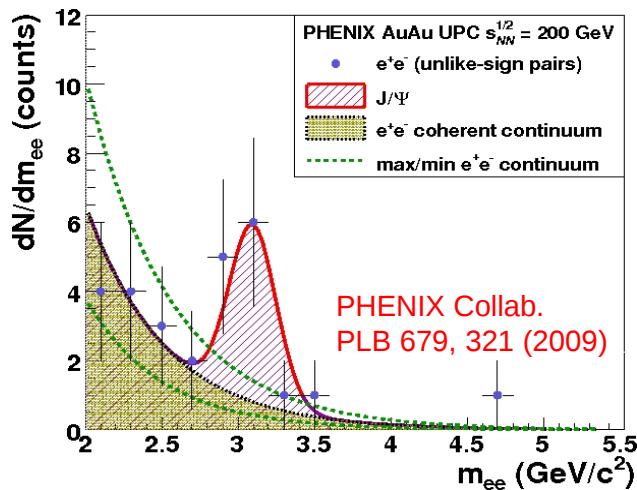
NLO pQCD analysis:

Discriminates between different $xg(x, Q^2)$ parametrizations

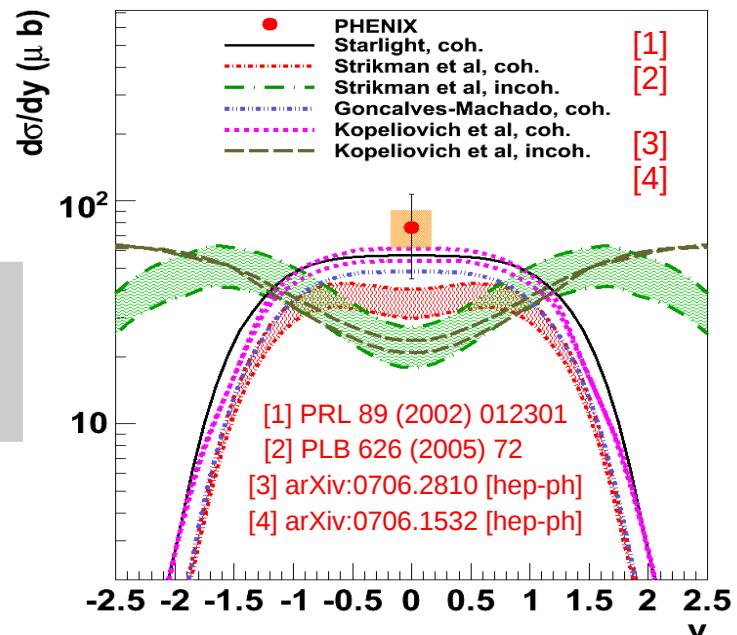
Martin, Nockles,
Ryskin, Teubner
PLB 662, (2008)252

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

■ γ Au \rightarrow J/ Ψ + Au at $W_{\gamma A} \sim 24$ GeV



$$d\sigma/dy|_{y=0} = 76 \pm 31 \text{ (stat)} \pm 15 \text{ (syst)} \mu\text{b}$$



■ Model comparisons:

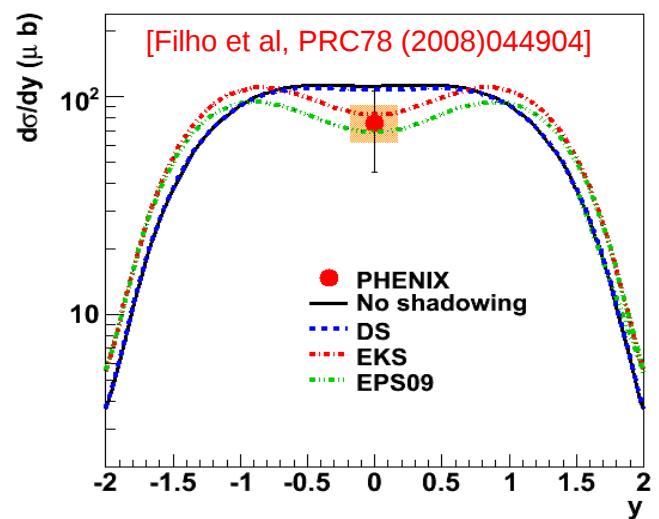
Starlight: coherent, HERA data parametrization

Strikman et al:
coherent & incoherent, $\sigma_{J/\psi N} = 3\text{mb}$

Gonçalves-Machado:
coherent only, color-dipole + Glauber-Gribov shadow

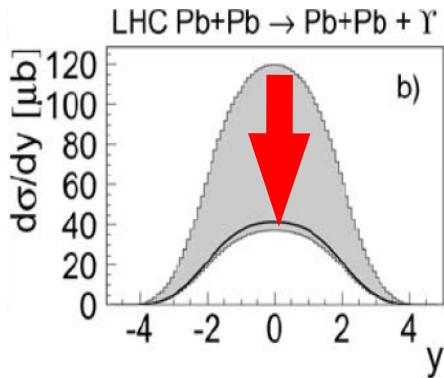
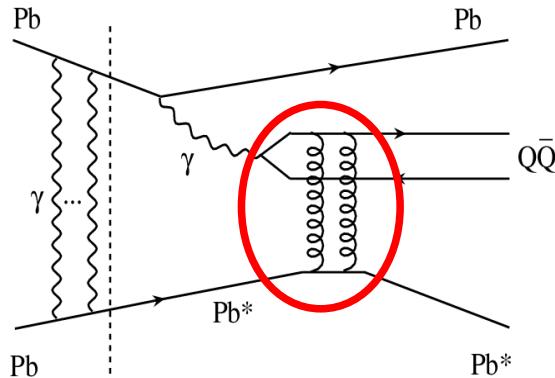
Kopeliovich et al:
coherent & incoherent, color-dipole + gluon saturation

Filho, Gonçalves, Griep:
coherent, DGLAP nuclear PDFs

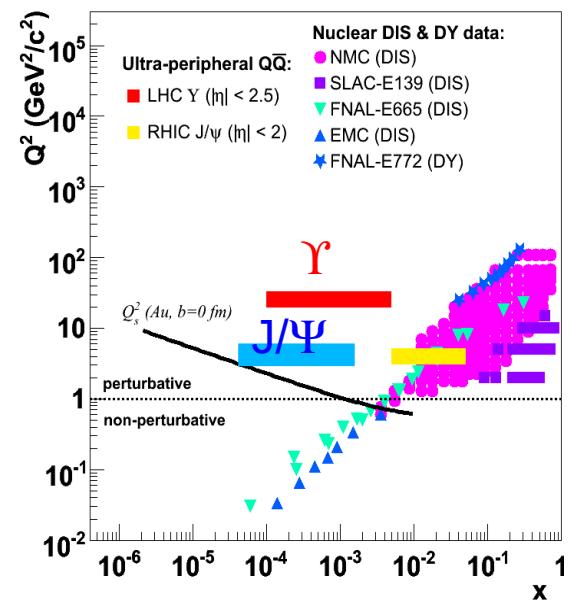


LHC example I: Pb-Pb $\rightarrow \gamma$ Pb $\rightarrow J/\Psi, \Upsilon$ Pb

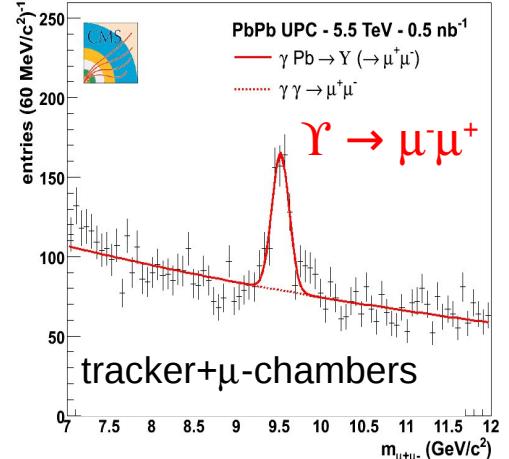
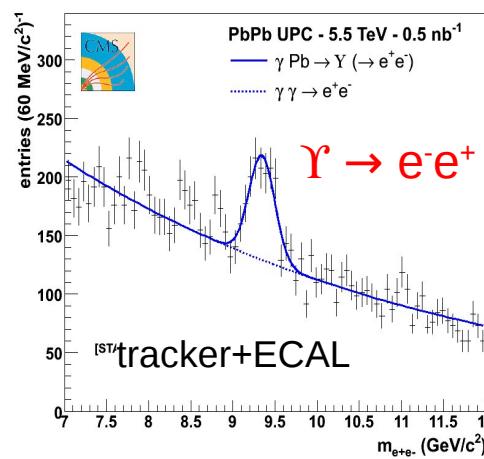
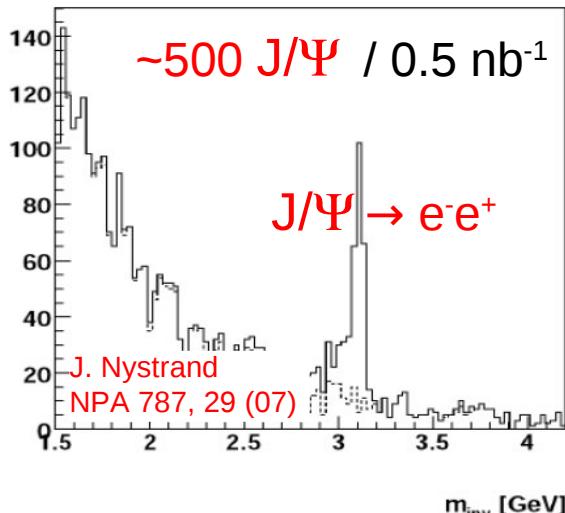
Theoretical predictions:



Impulse: $\sigma = 133$ mb
LT shadowing: $\sigma = 78$ mb
CGC: $\sigma \sim 40$ mb



γ Pb \rightarrow $J/\Psi, \Upsilon$ + Pb in ALICE, CMS:



$\sim 500 \Upsilon / 0.5 \text{ nb}^{-1}$

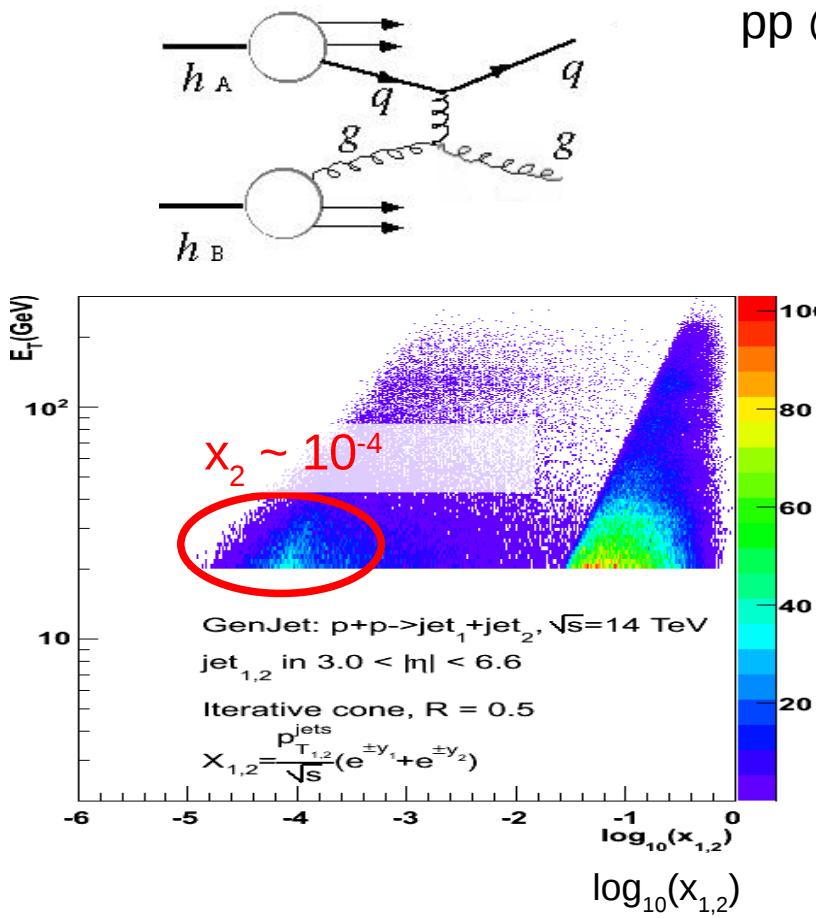
DdE, NPB 184, 158 (08)

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

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

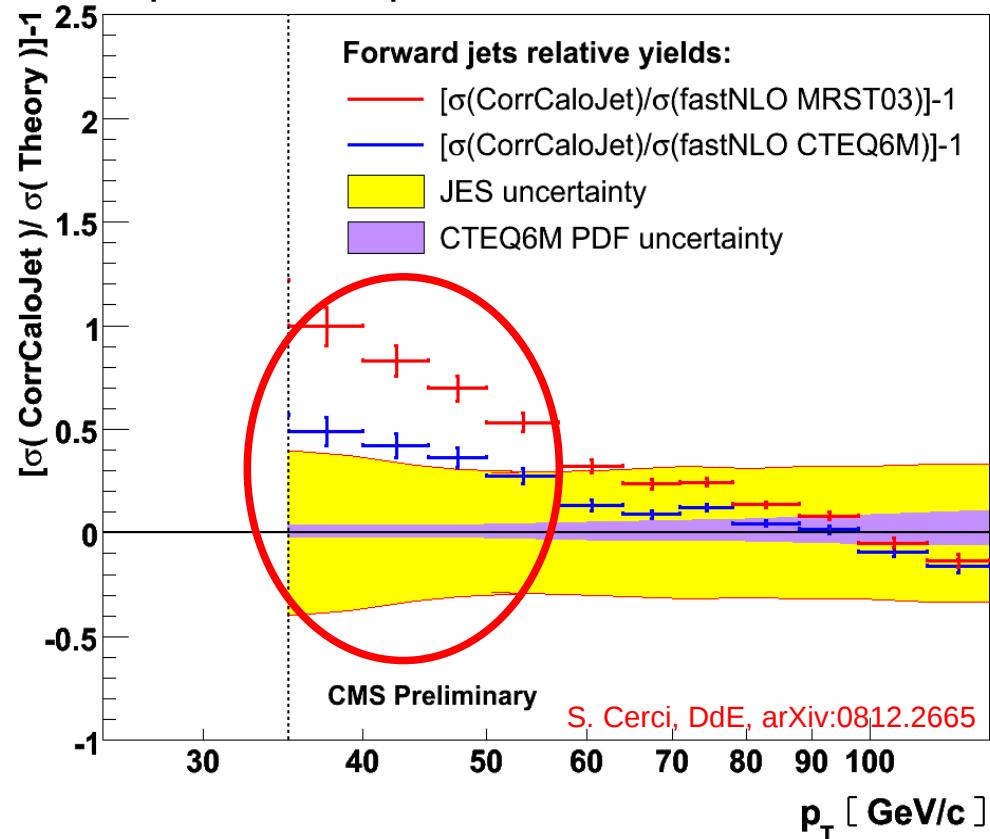
LHC example II: Forward jets in CMS ($3 < |\eta| < 6.6$)

- Jets with $p_T \sim 20-100 \text{ GeV}/c$ at forward rapidities ($3 < |\eta| < 5$) probe $x_2 \sim 10^{-4}$:



pp @ 14 TeV

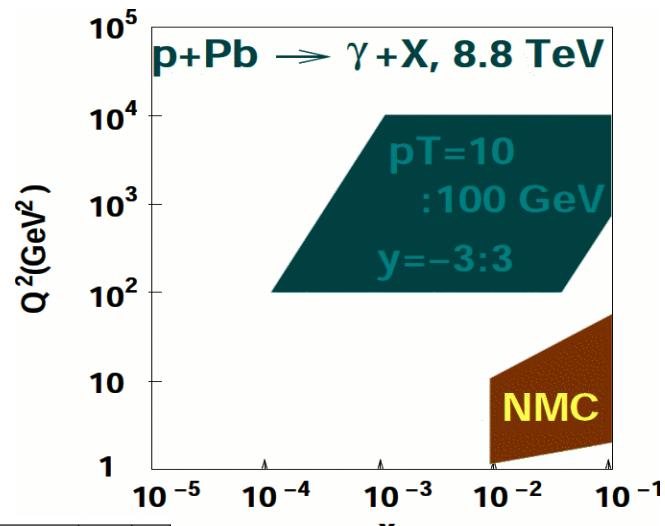
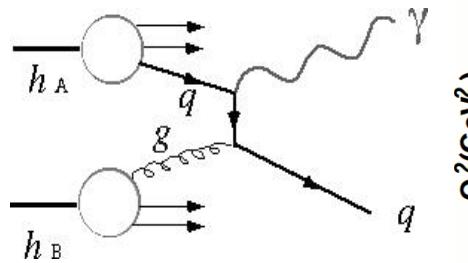
Spectrum dependence on PDF choice:



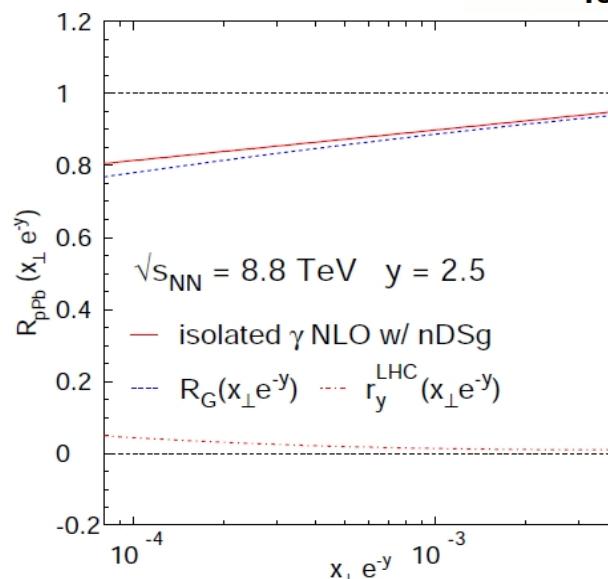
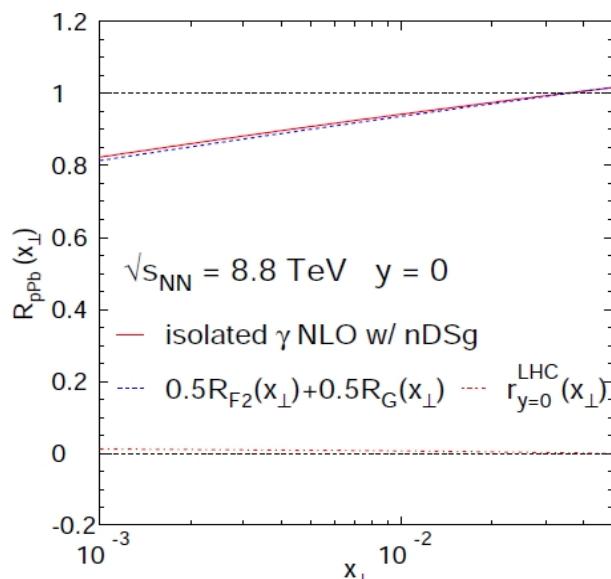
- Warning: p-p analysis. Jet reconstruction performances in p-Pb ?

LHC example III: γ in ATLAS/CMS ($|\eta| < 3$)

- p-A $\rightarrow \gamma X$ at 8.8 TeV w/ $p_T \sim 10\text{-}100 \text{ GeV}/c$ at $|\eta| < 3$ probe glue at $x_2 \sim 10^{-3}$:



- Nuclear modification factor ($y=0$, $y=2.5$):



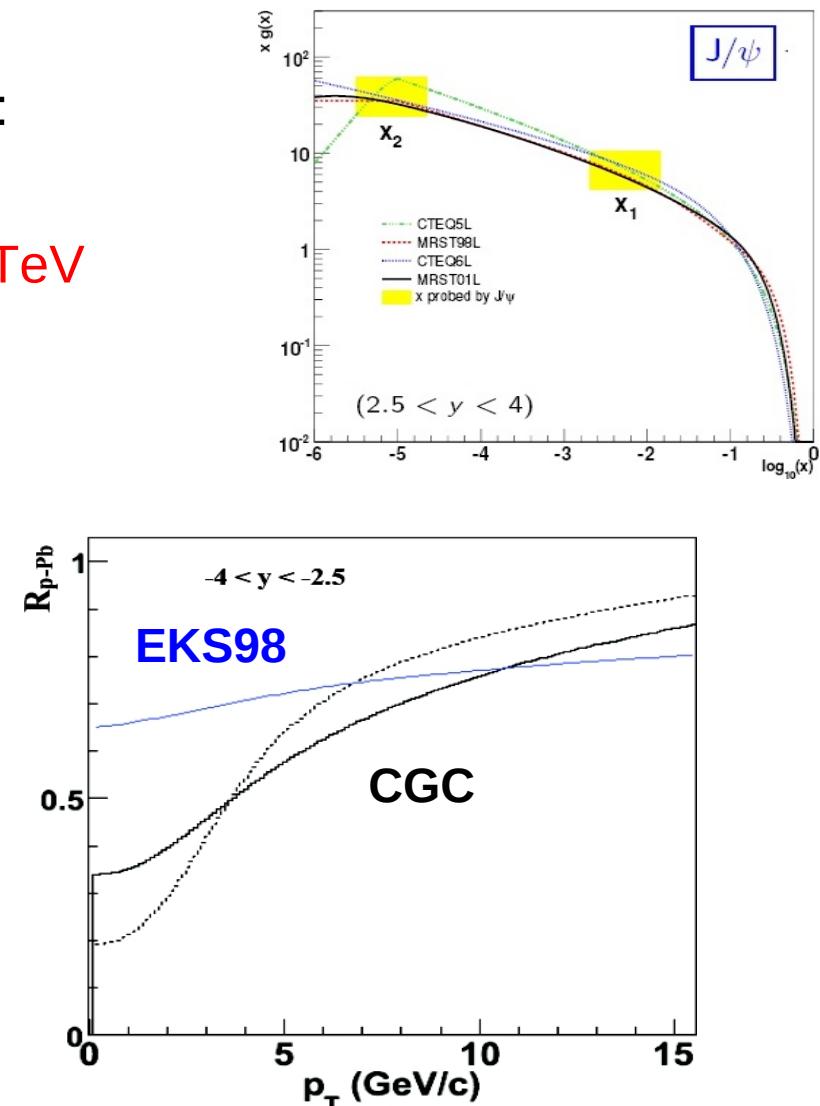
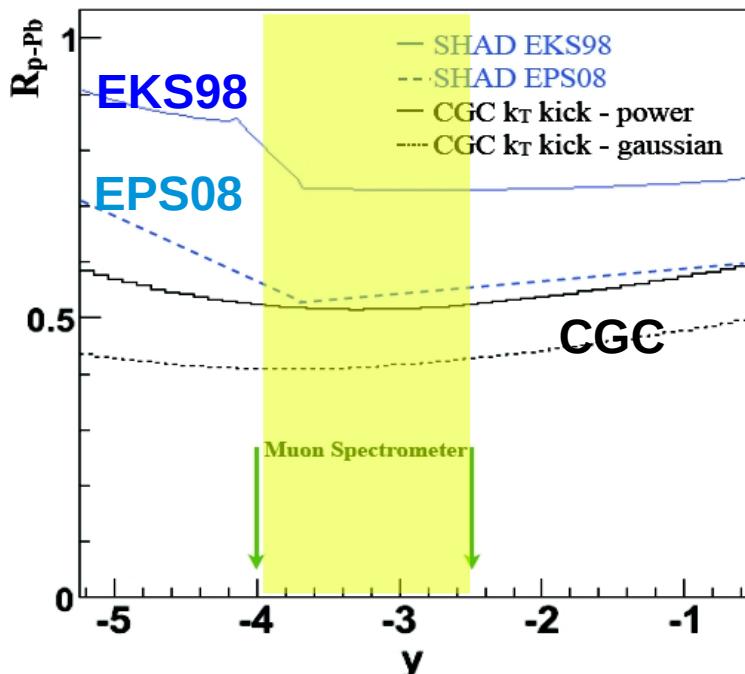
[cf. T. Gousset talk]

- Note: theoretical analysis. Photon reco performances in p-Pb ?

LHC example IV: Forward $Q\bar{Q}$ in ALICE ($2.5 < \eta < 4$)

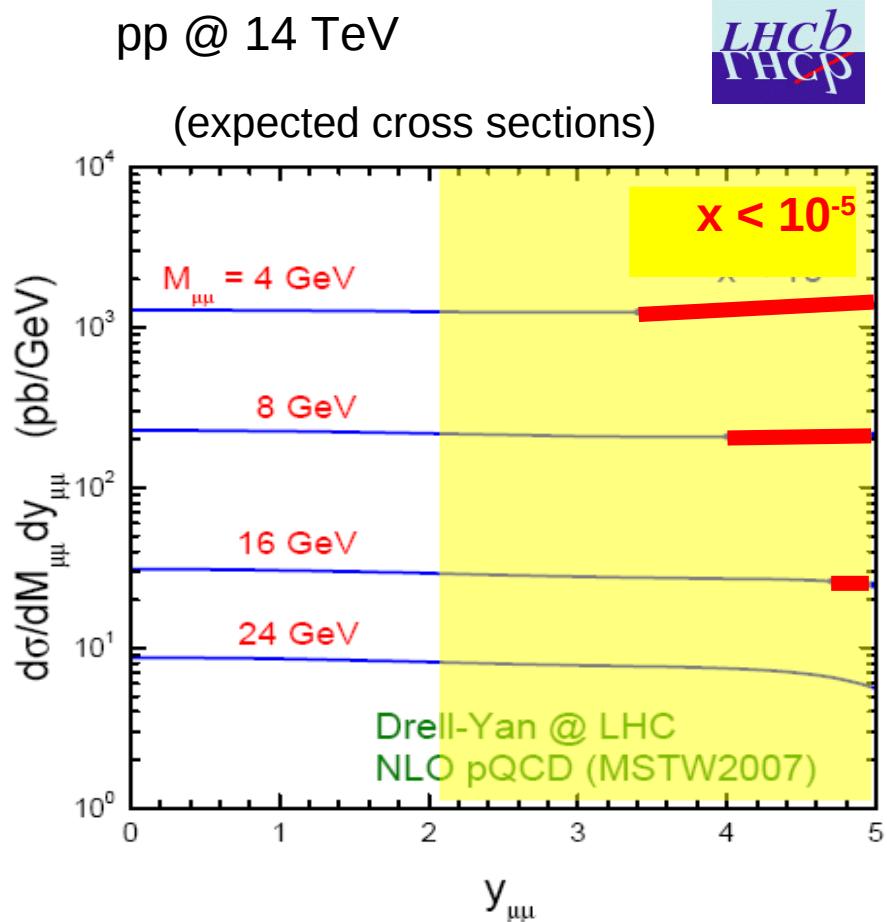
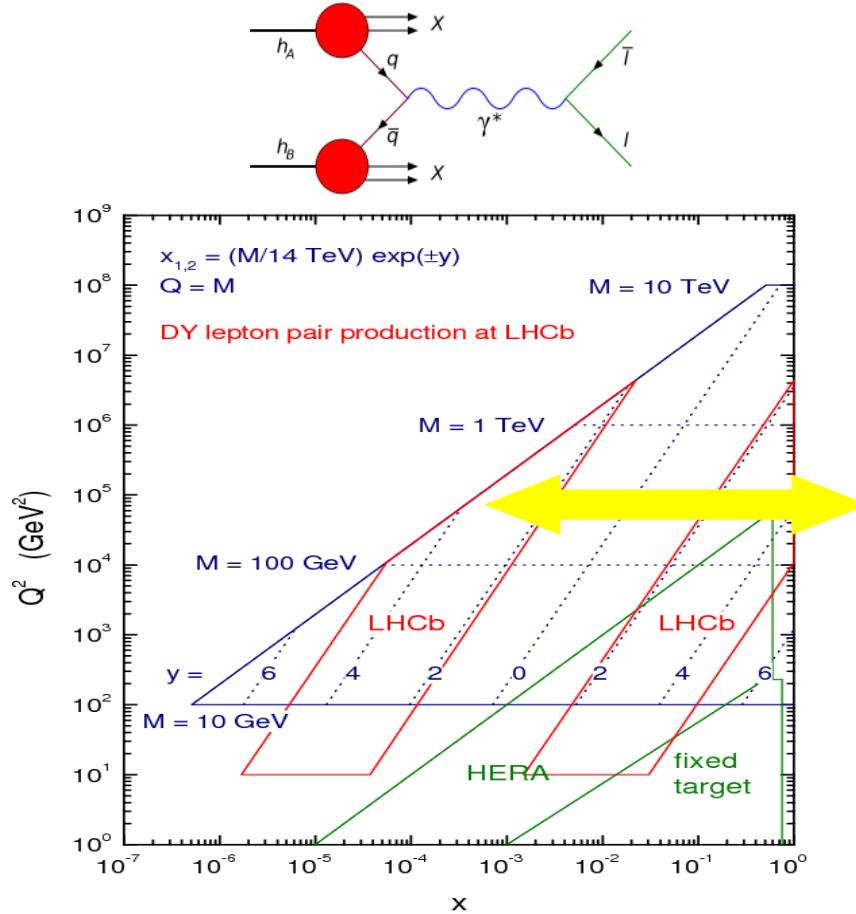
[cf. C.Hadjidakis talk]

- J/ψ measurement in $2.5 < \eta < 4$:
Sensitive to $xg(x)$ down to $x_2 \sim 10^{-5}$:
- Expected $R_{pPb}(y, p_T)$ in p -Pb at 8.8 TeV
in μ -spectrometer:



LHC example V: Forward γ^* in LHCb ($2 < \eta < 5$)

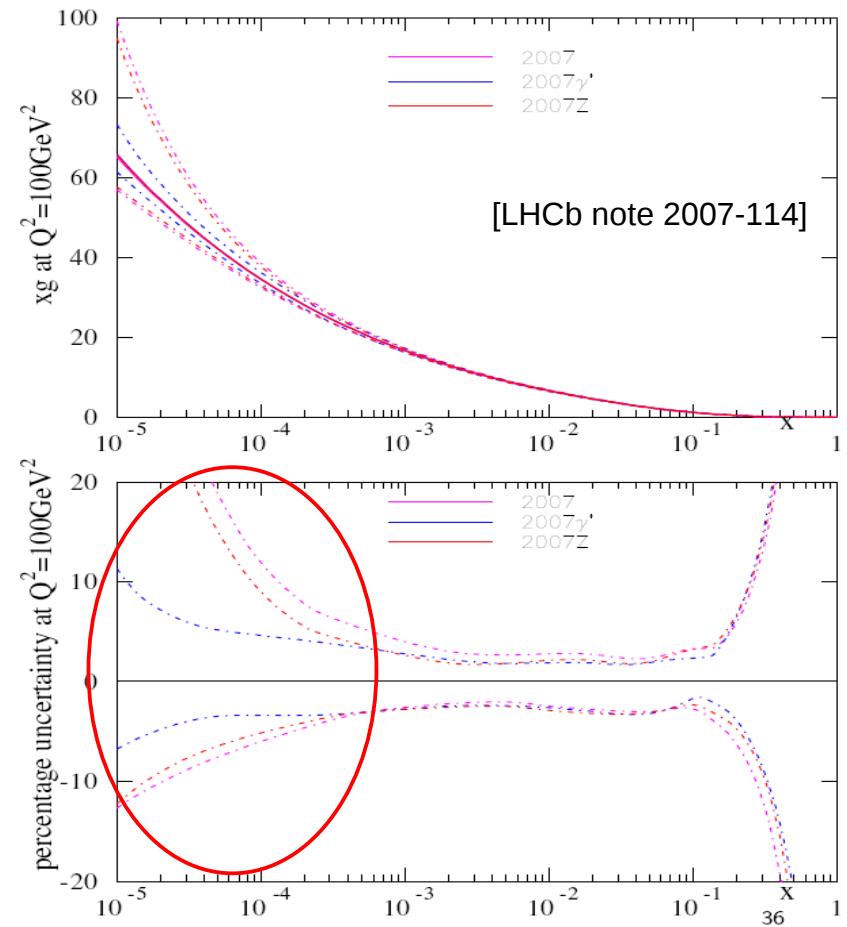
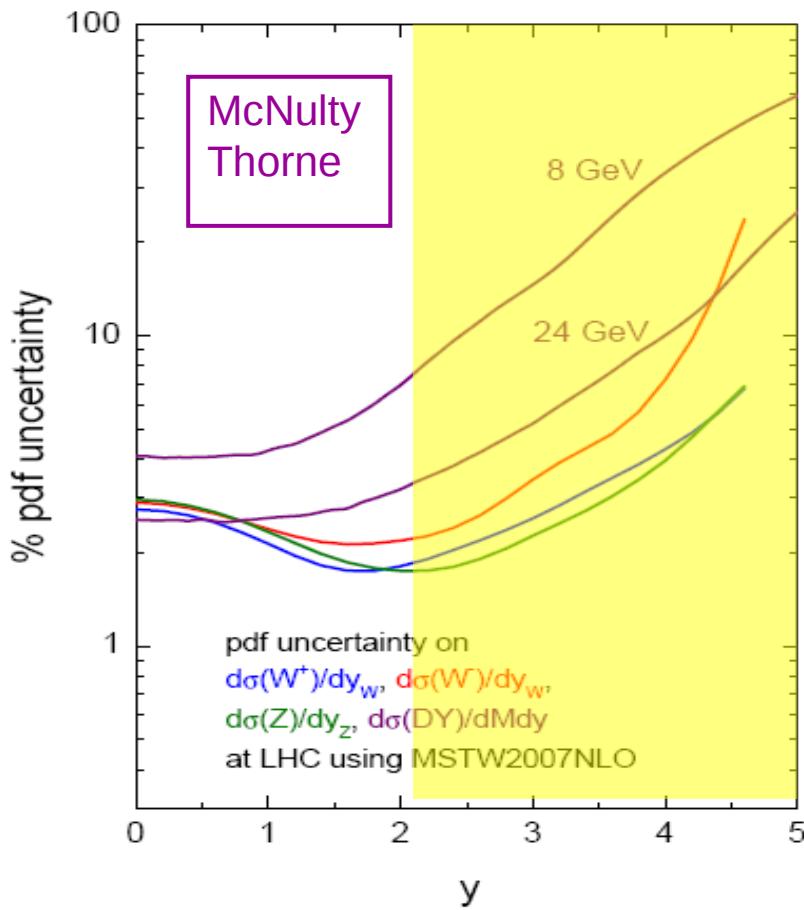
- Drell-Yan forward μ : $q\bar{q} \rightarrow \mu^+ \mu^-$ (trigger on low- p muons: $p>8\text{GeV}$, $p_T>1\text{GeV}$)
- Sensitive to low- x quark densities



- Warning: p-p analysis. Reconstruction performances in p-Pb ?

LHC example VI: fwd DY,Z,W in LHCb ($2 < \eta < 5$)

- Impact of 1 fb^{-1} LHCb data for forward DY,W,Z (<5% error) production on the gluon PDF uncertainty: $>20\% \rightarrow <10\%$



- Warning: p-p analysis. Reconstruction performances in p-Pb ?

Summary

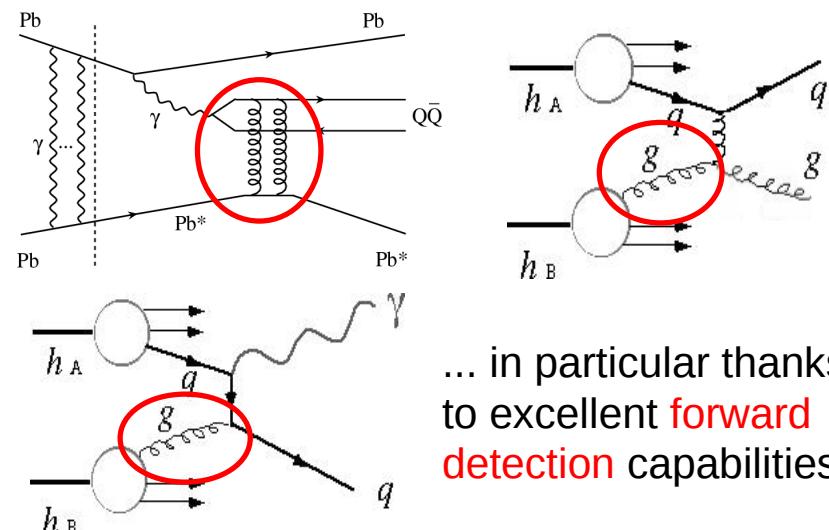
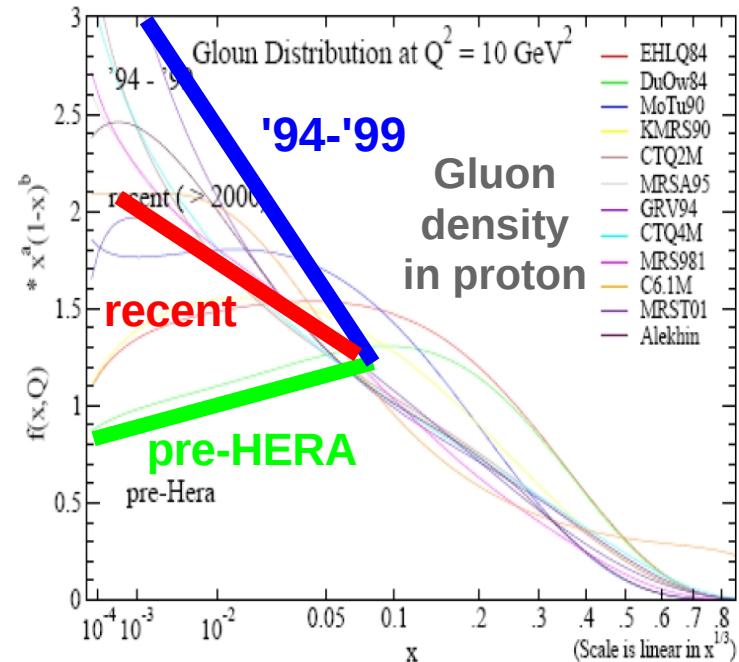
- Current knowledge of low- x nuclear gluon density (& evolution?) is as bad or worst! than for the proton ~15 years ago (pre-HERA).

Large impact on genuine physics (saturation) & on interpretation of QGP data (e.g. J/ψ suppr.).

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

- Hopefully, we can constrain $xG(x, Q^2)$ with coming LHC data:

- ▷ γ -Pb (Pb-Pb) @ 5.5 TeV
- ▷ p-Pb @ 8.8 TeV



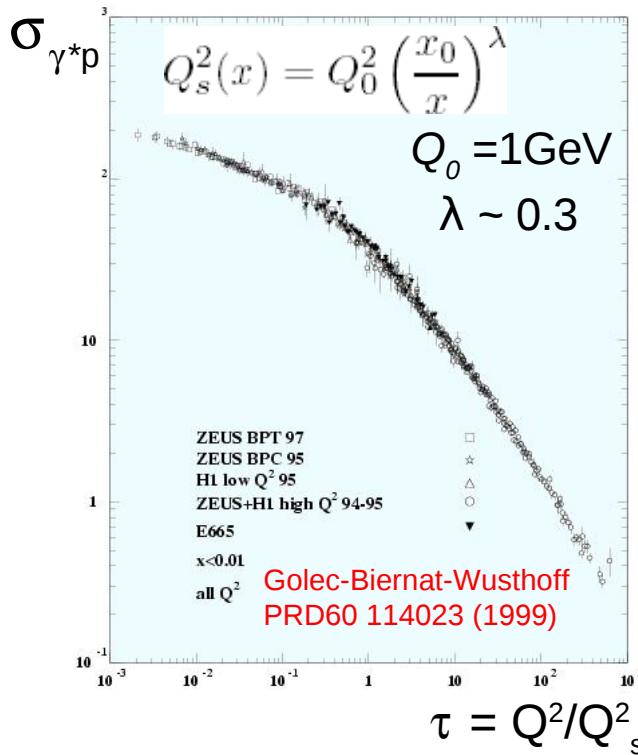
... in particular thanks to excellent forward detection capabilities

Backup slides

Saturation hints at HERA: proton

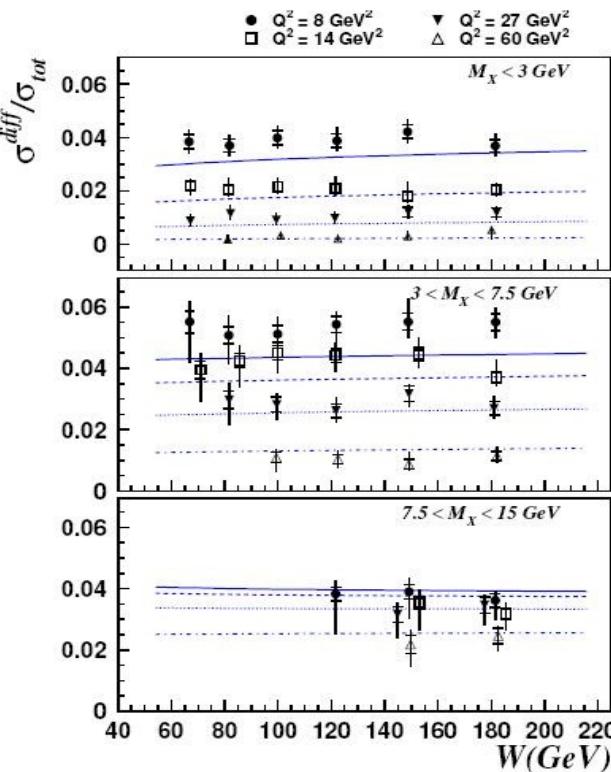
■ DGLAP fits most of e-p data. Saturation models **explain better** a few cases:

(1) “Geometric scaling”



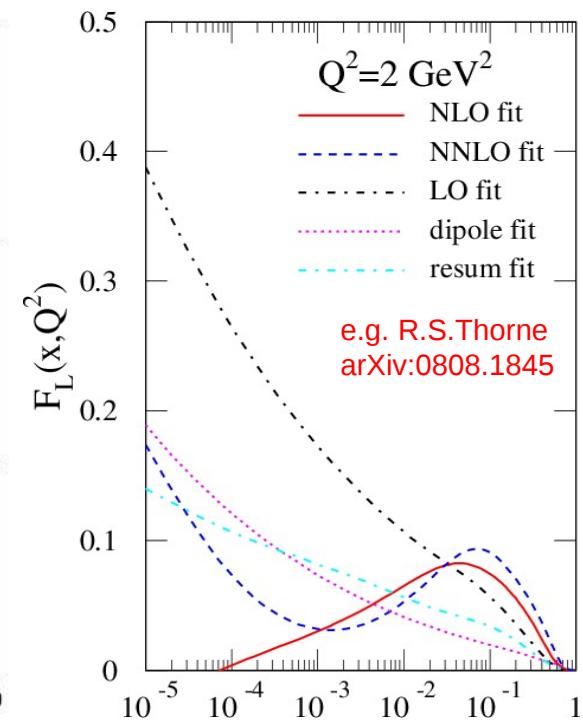
Inclusive DIS x-section depends on **single scale** Q^2/Q_s^2 for $x < 0.01$

(2) flat $\sigma_{\text{diffract}}/\sigma_{\text{tot}}$ vs energy



Diffract. & total x-sections similar W dependence \neq pQCD: $\sigma_{\text{tot}} \sim W^{2\lambda} \neq \sigma_{\text{diff}} \sim W^{4\lambda}$

(3) Long. struc. function

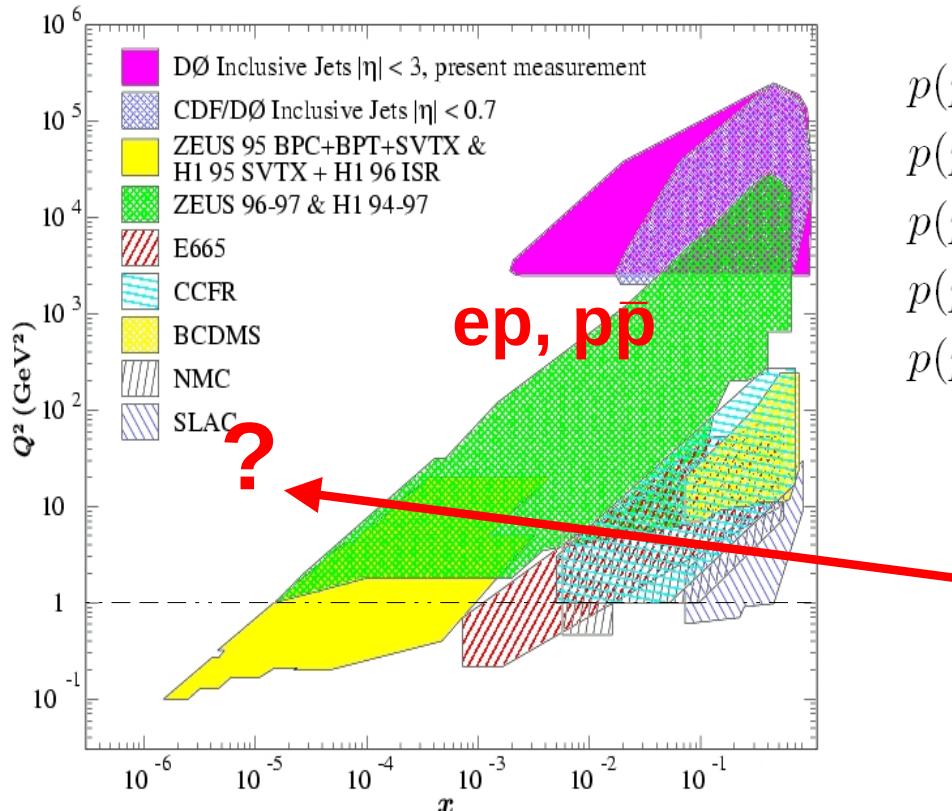


Gluon (F_L) at NLO becomes **negative** for $Q^2 \sim 2 \text{ GeV}^2$ at low- x

Low- x studies at the LHC: proton

■ p-p @ 14 TeV :

- (1) At $y=0$, $x=2p_T/\sqrt{s} \sim 10^{-3}$ (domain probed at HERA, Tevatron). **Go fwd.** for $x < 10^{-4}$
- (2) Saturation momentum: $Q_s^2 \sim 1 \text{ GeV}^2$ ($y=0$), 3 GeV^2 ($y=5$)
- (3) **Very large perturbative** 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 flavour**
 $p(p_1) + p(p_2) \rightarrow W/Z + X$ **W,Z production**

LHC **forward** rapidities:
e.g. $y \sim 6$, $Q \sim 10 \text{ GeV}$

~~* down to 10^{-6} !~~

Case-study II: Mueller-Navelet dijets in CMS ($\Delta\eta \sim 10$)

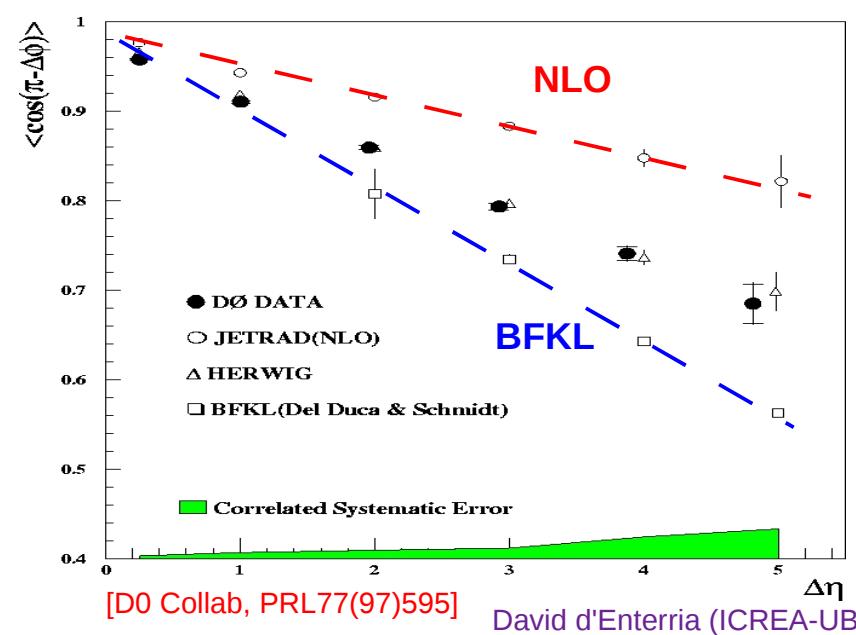
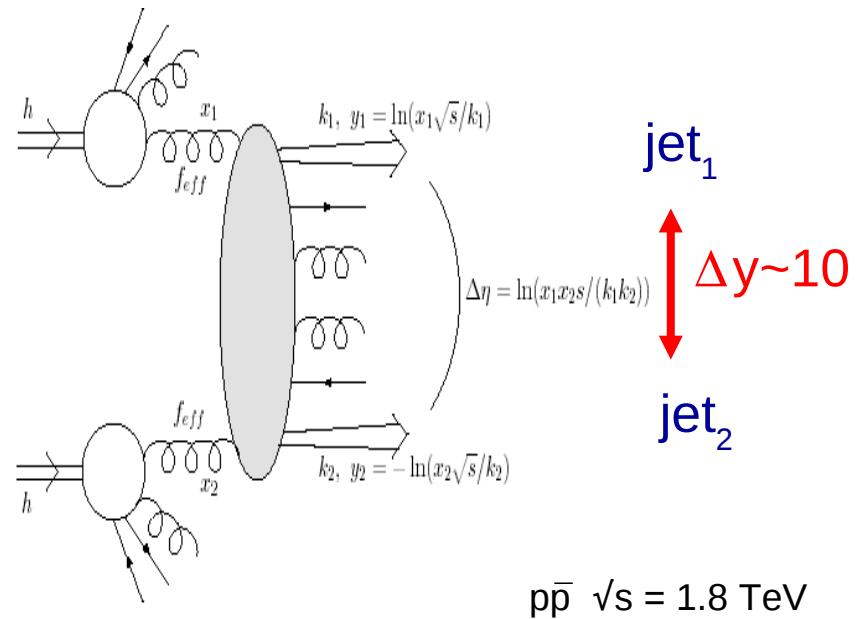
- Mueller-Navelet dijets with large y separation very sensitive to low- x QCD evolution (testing ground for BFKL):

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):

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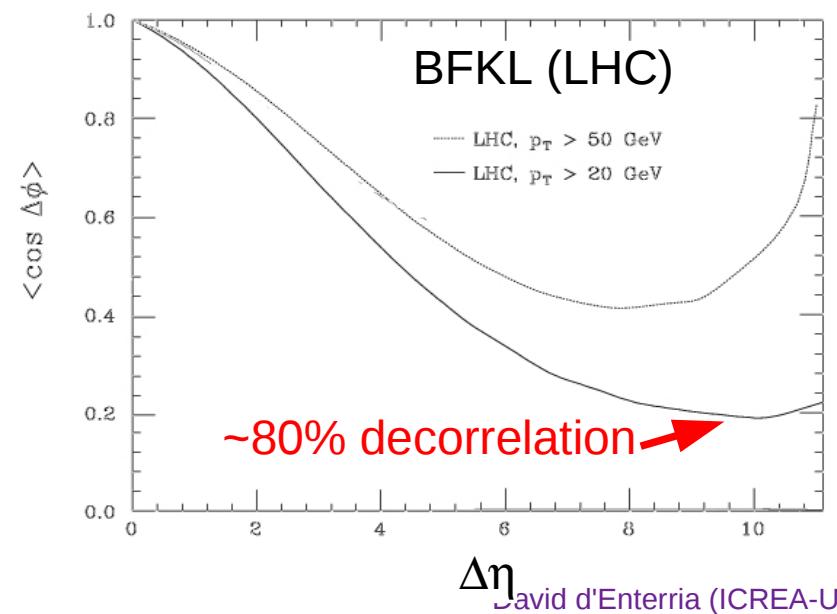
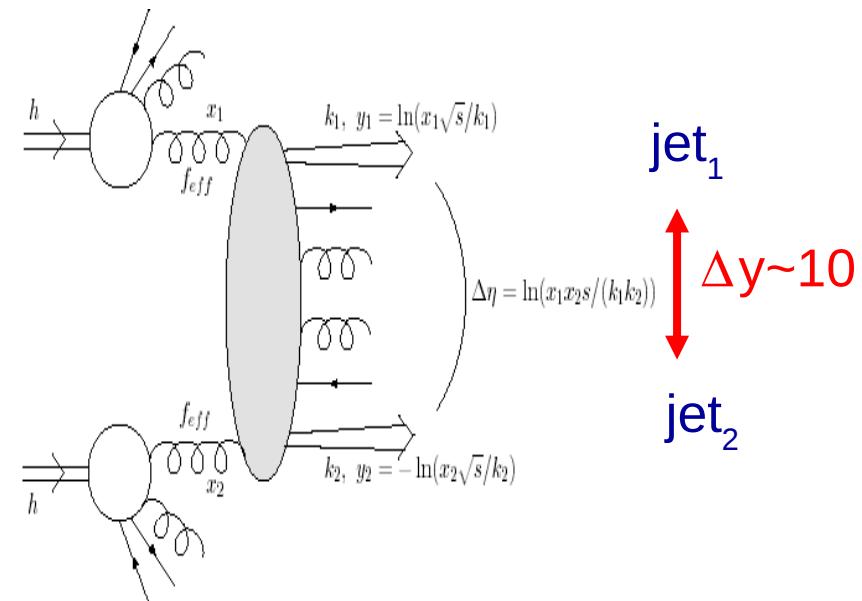
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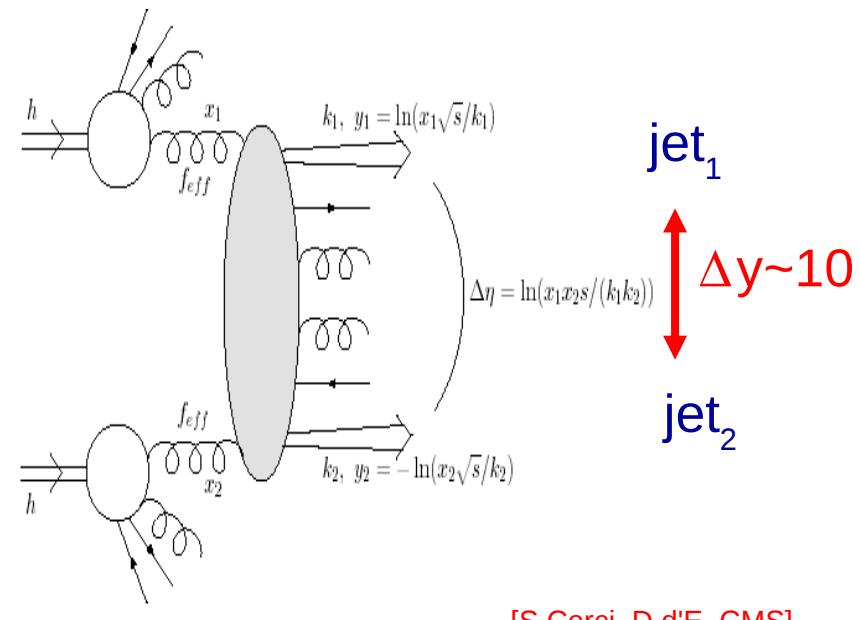
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[S.Cerci, D.d'E, CMS]

