

“Famous plots” I

Initial-state, parton structure

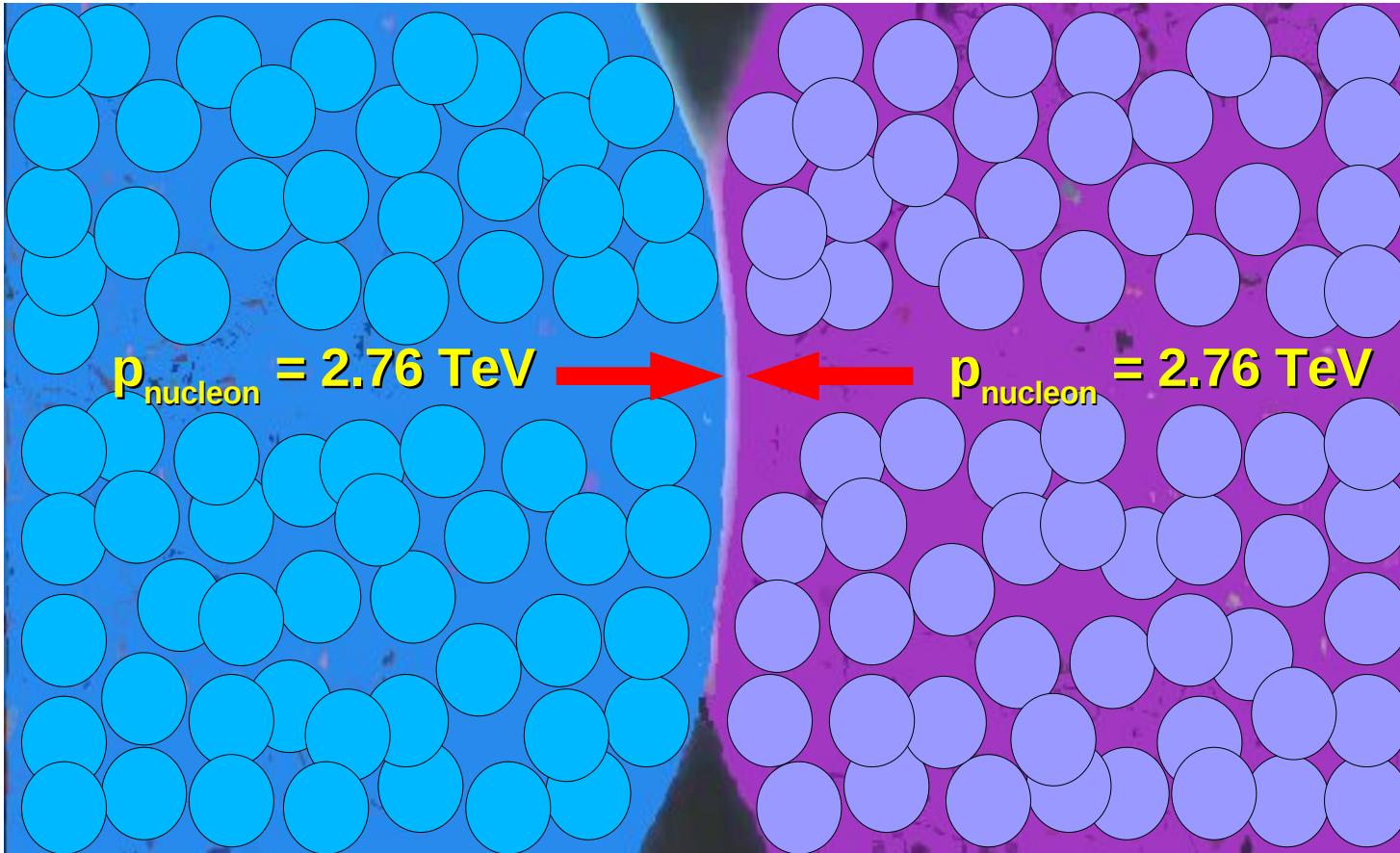
Quark-Matter'11 Student Lectures

Annecy, 22nd May 2011

David d'Enterria
CERN

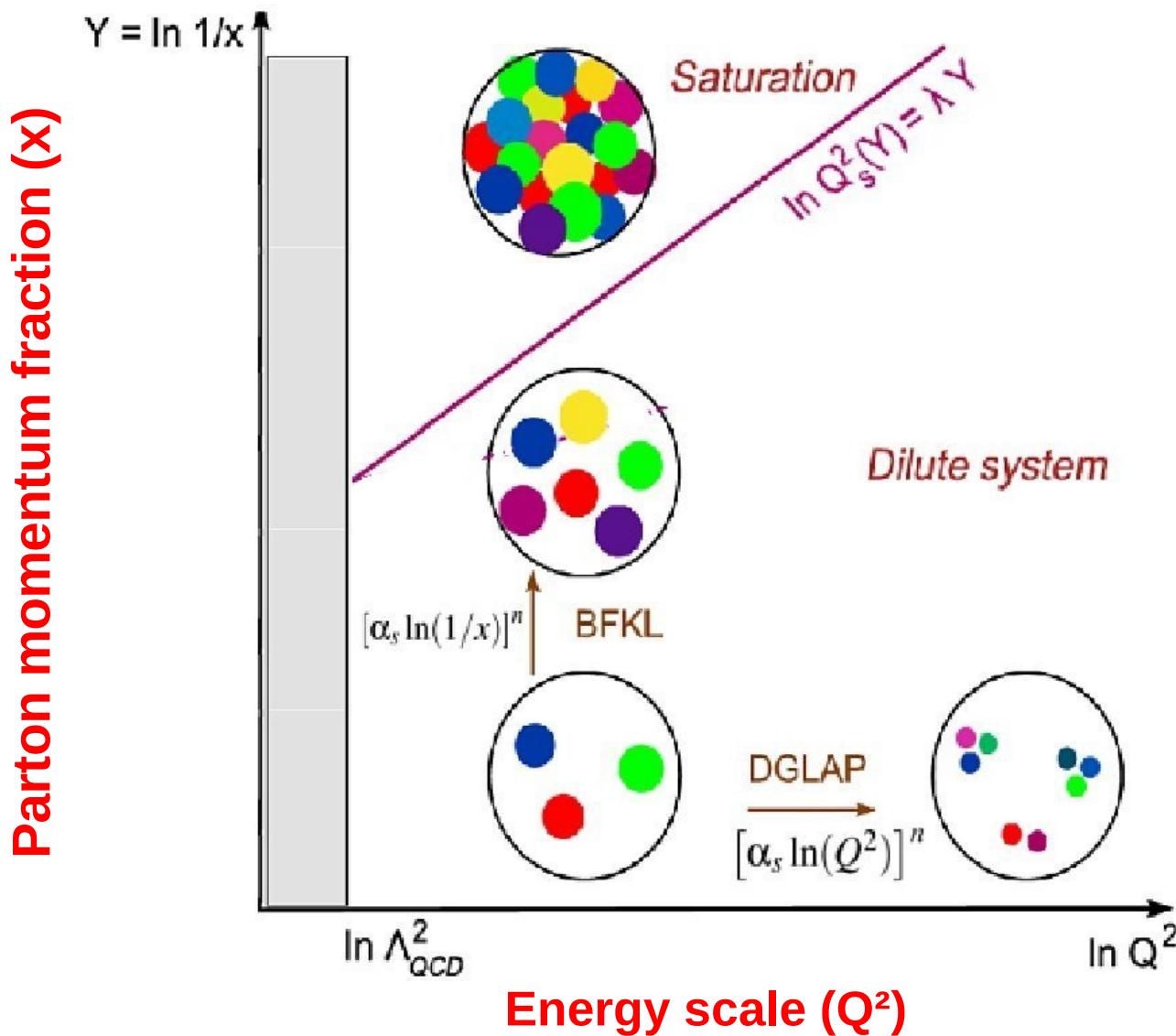
Nucleus-nucleus at the LHC: the initial-state

- Two **nuclei** coming against each other.
 - Each nucleon has a momentum of $p_{\text{nucleon}} = 2.76 \text{ TeV}$

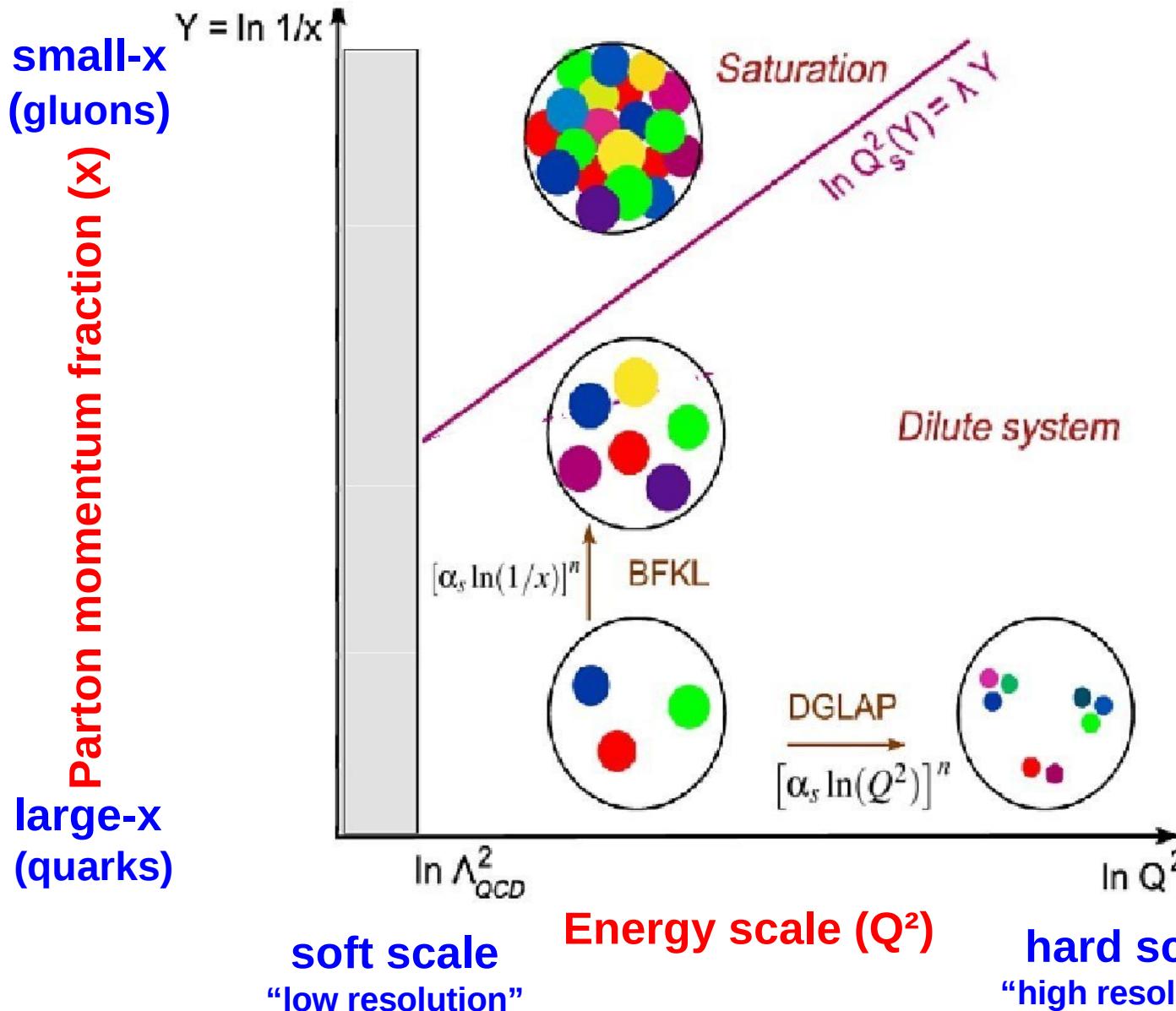


- What is the **structure** of this initial-state ?

Bjorken-x versus Q^2 plot



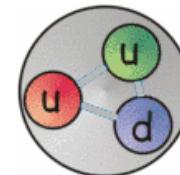
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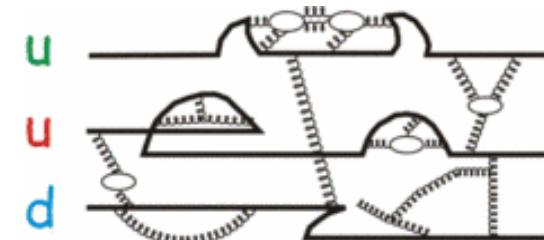
Partonic structure of hadrons

- A hadron (proton, neutron) accelerated at high energies is seen as a composite object made of **constituents partons**:

- valence quarks (uud,udd): ~50% momentum
Give global quantum numbers (Q, B, I_3, \dots)



- gluons (g): ~50% hadron momentum
“everywhere”, exchanged among partons



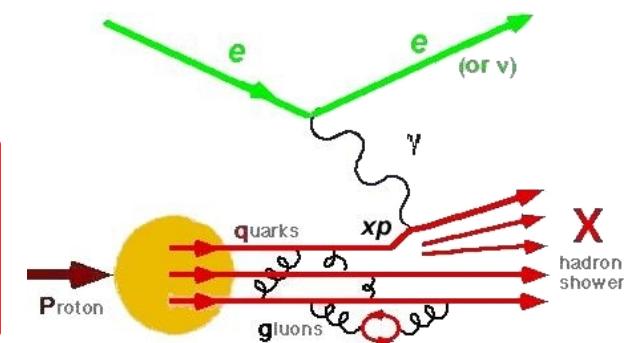
- sea quarks ($q\bar{q}$):
gluon fluctuations $g \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}$



(virtual $q\bar{q}$ pairs)

- Hadron **composition** in terms of
of quarks or gluons depends on:

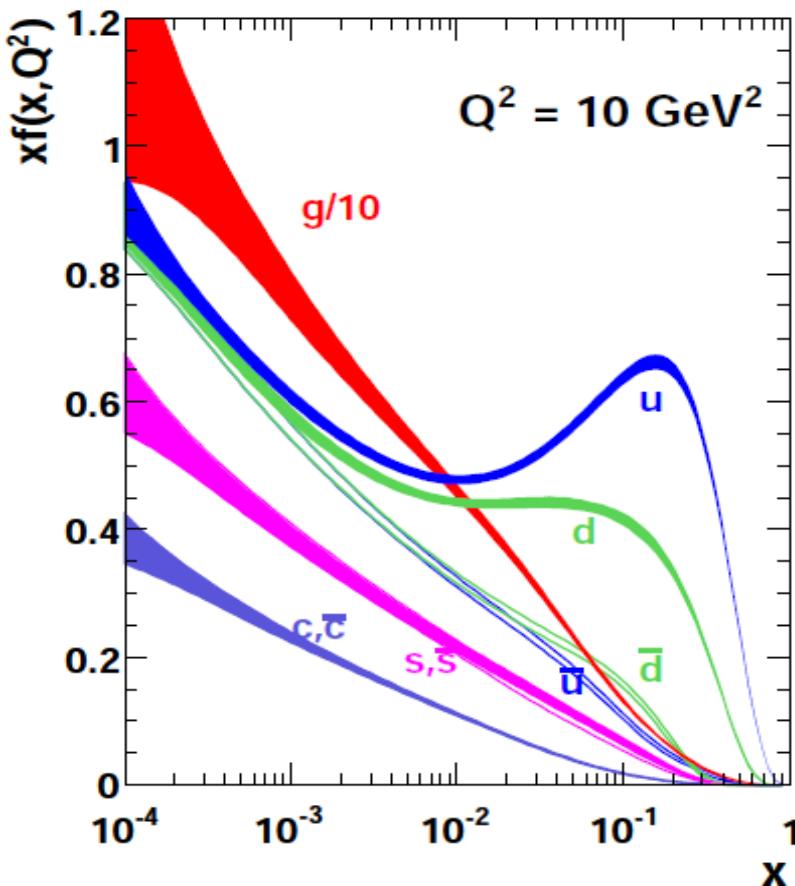
- Energy scale (Q^2): hardness of “**projectile**” probe
- Bjorken-x fraction = $p_{\text{parton}}/p_{\text{nucleon}}$ of parton “**target**”



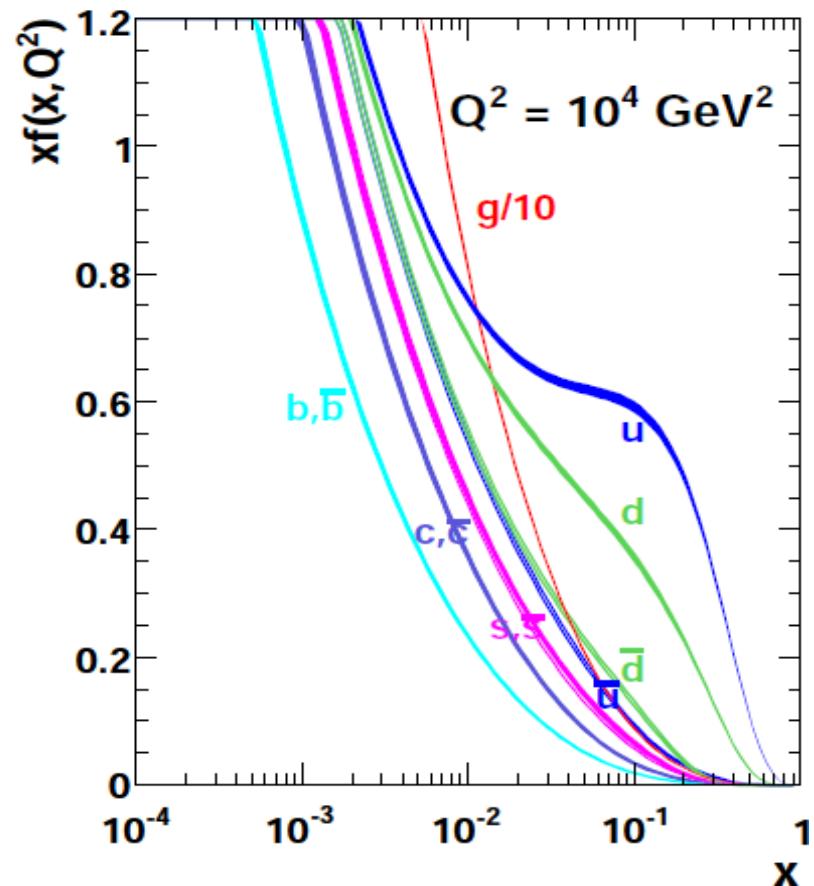
Partonic structure of hadrons: $f(Q^2)$

- Parton distribution functions (PDF) vs. energy scale:

(moderate Q^2 energy scale)



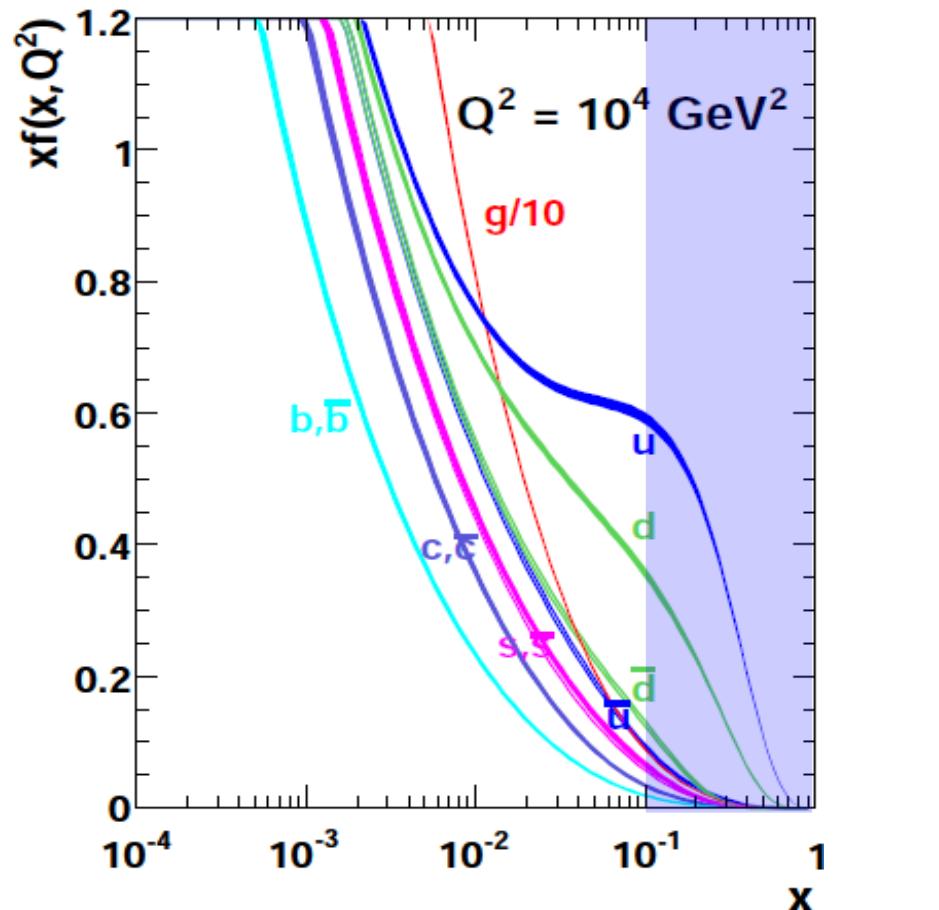
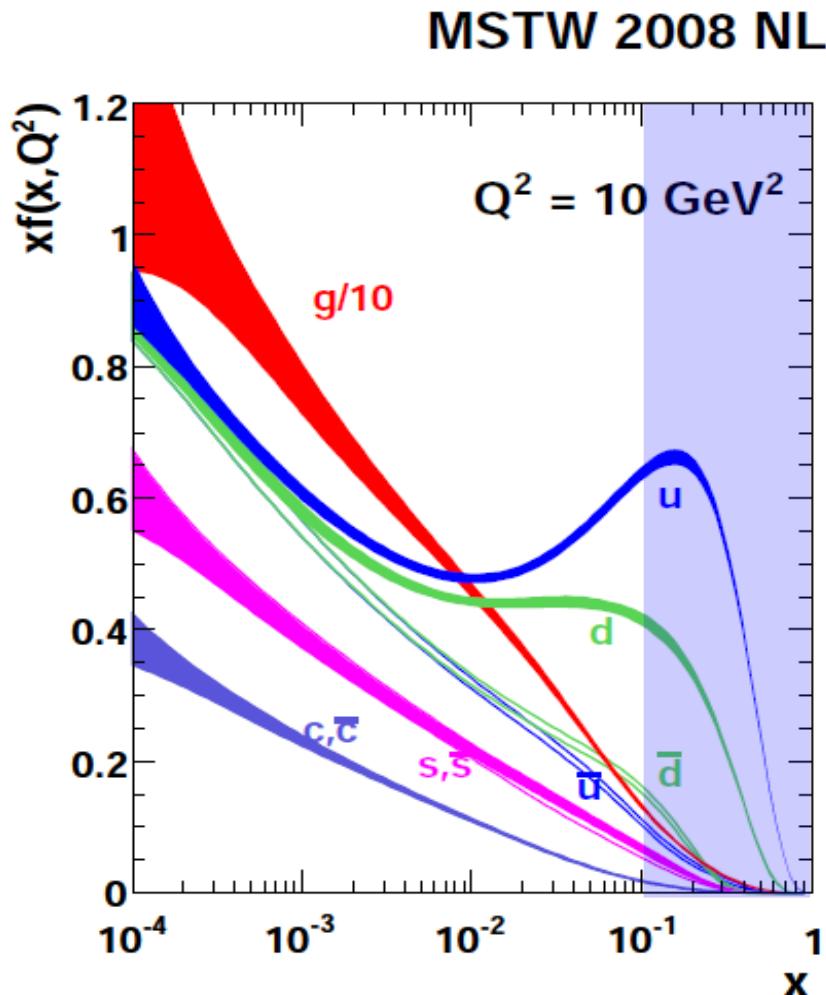
(large Q^2 energy scale)



- Higher scale \rightarrow plus energy available \rightarrow more gluons (sea-q) radiated
PDF evolution as a fct. of Q^2 : described by DGLAP equations

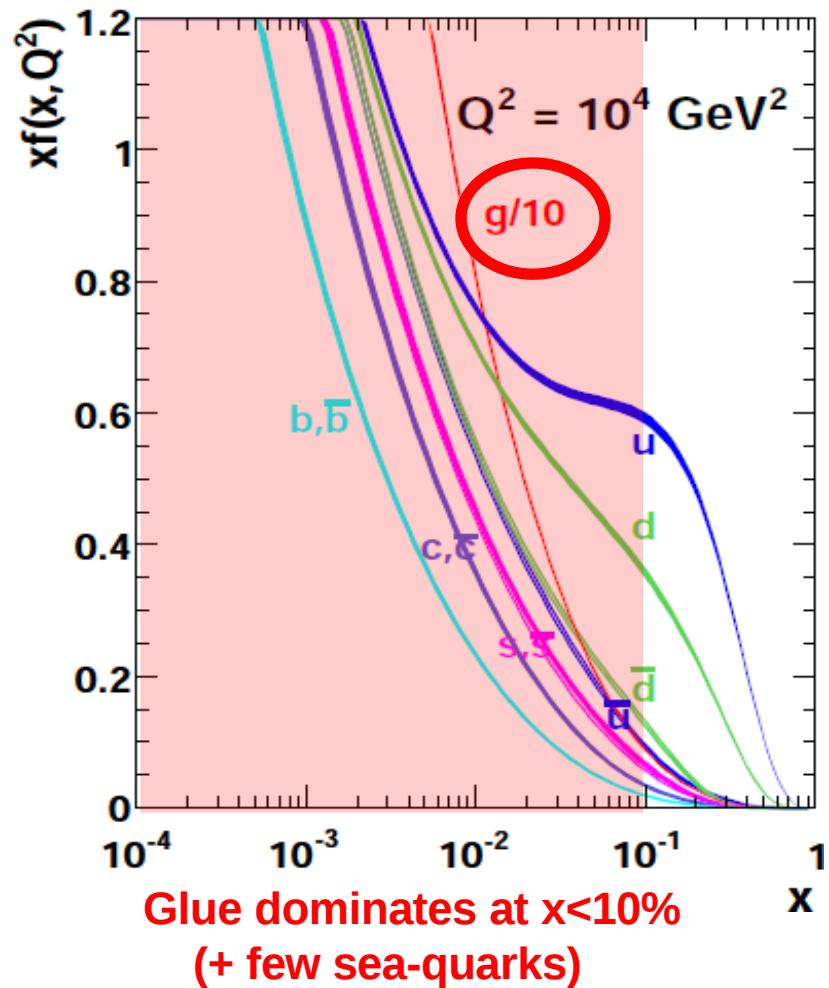
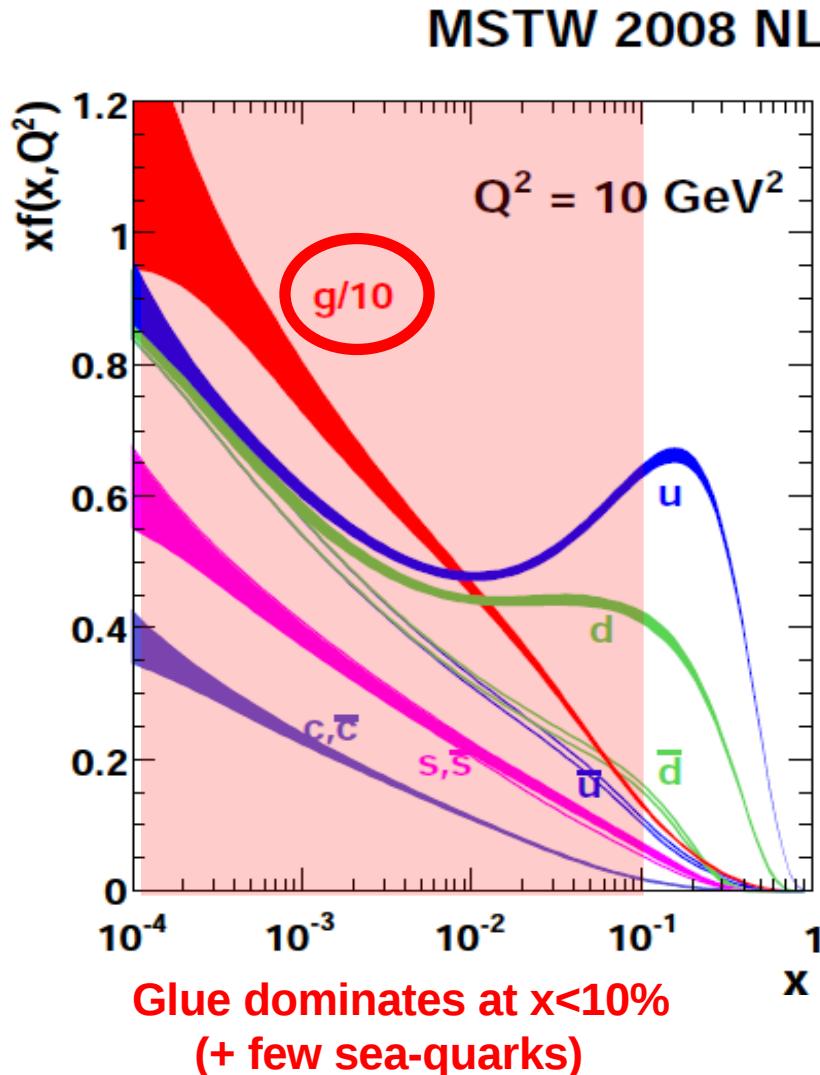
Partonic structure of hadrons: $f(x)$

- Parton distribution functions (PDF) vs. momentum fraction:

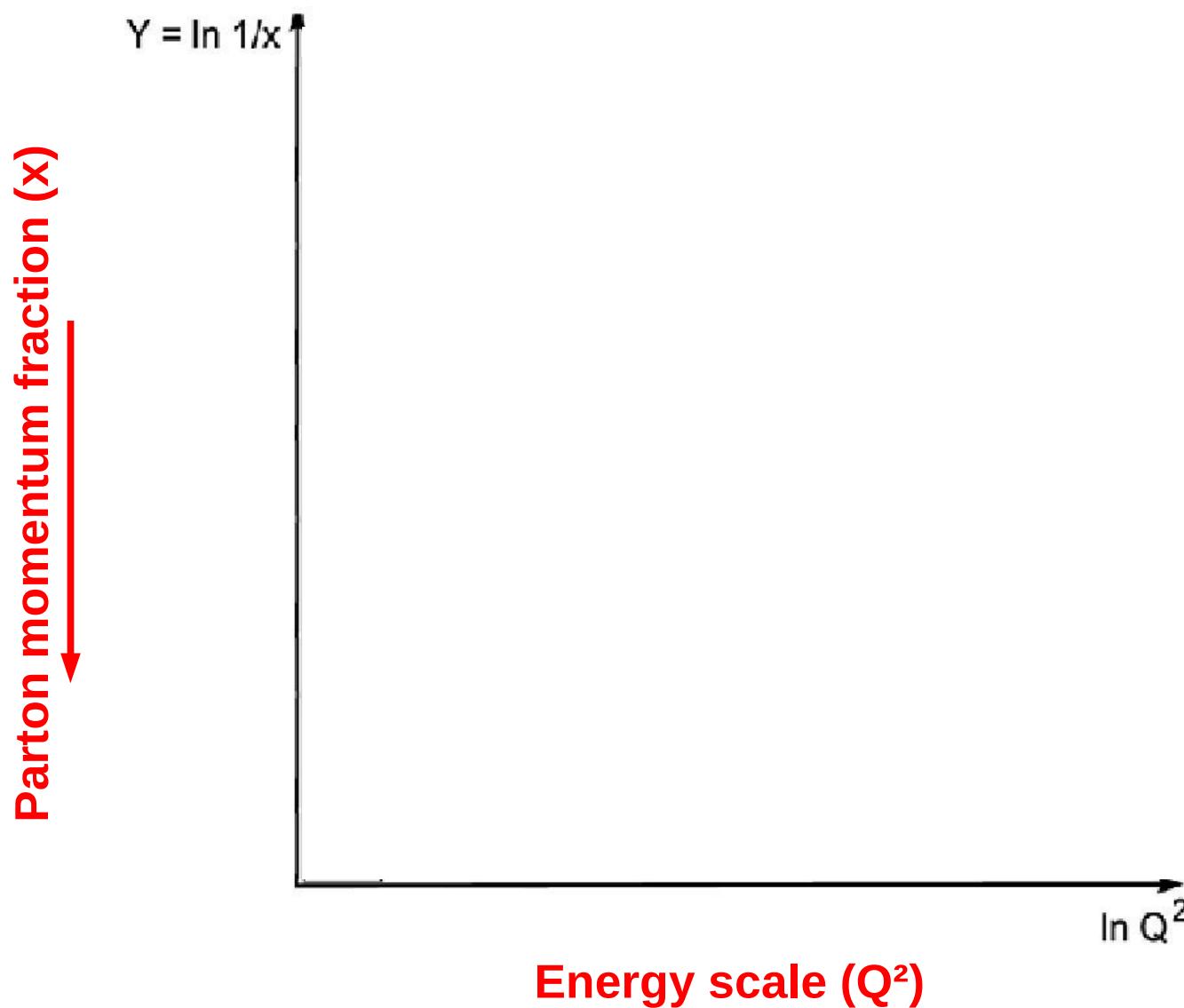


Partonic structure of hadrons: $f(x)$

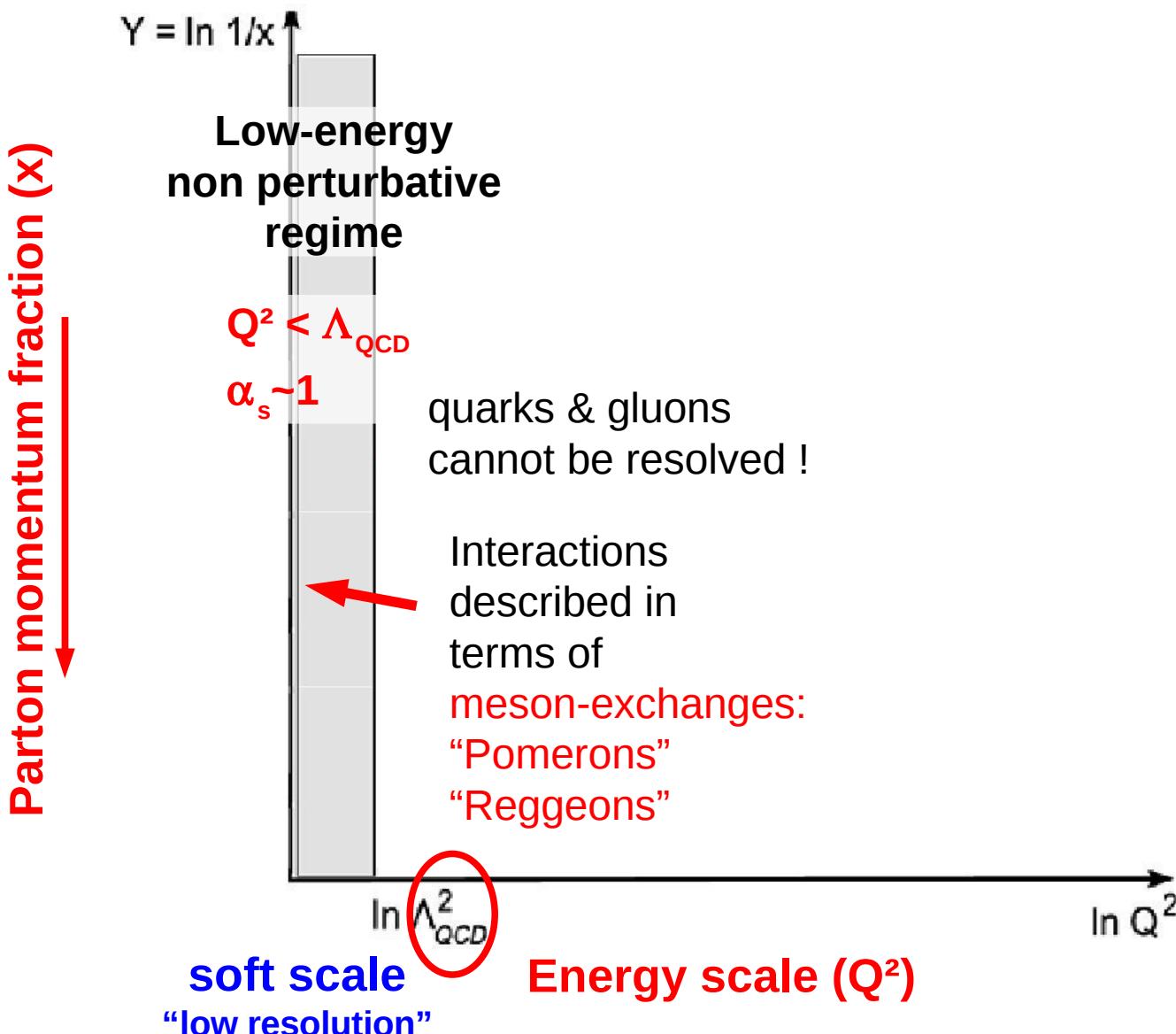
- Parton distribution functions (PDF) vs. momentum fraction:



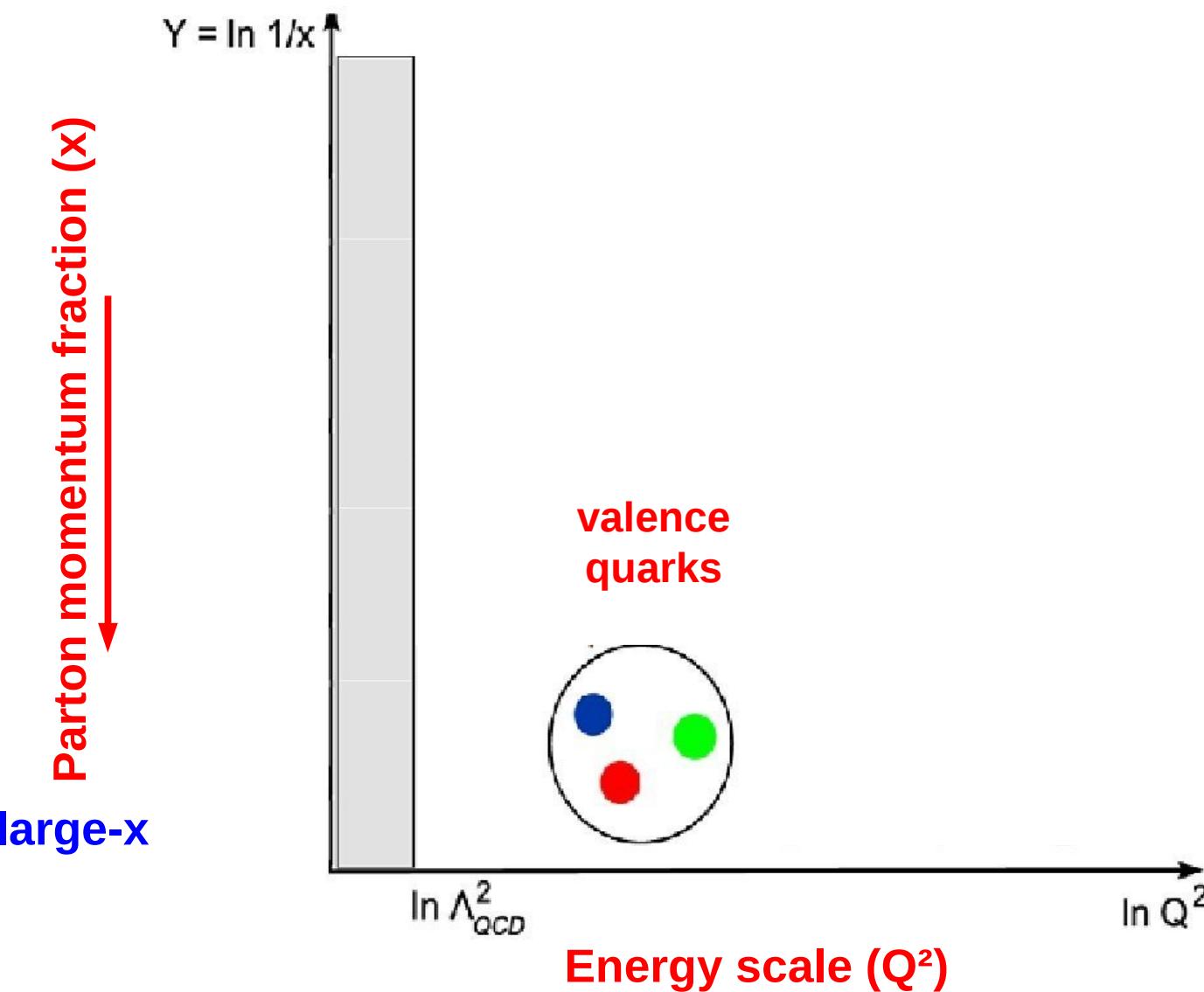
Bjorken-x versus Q^2 plot



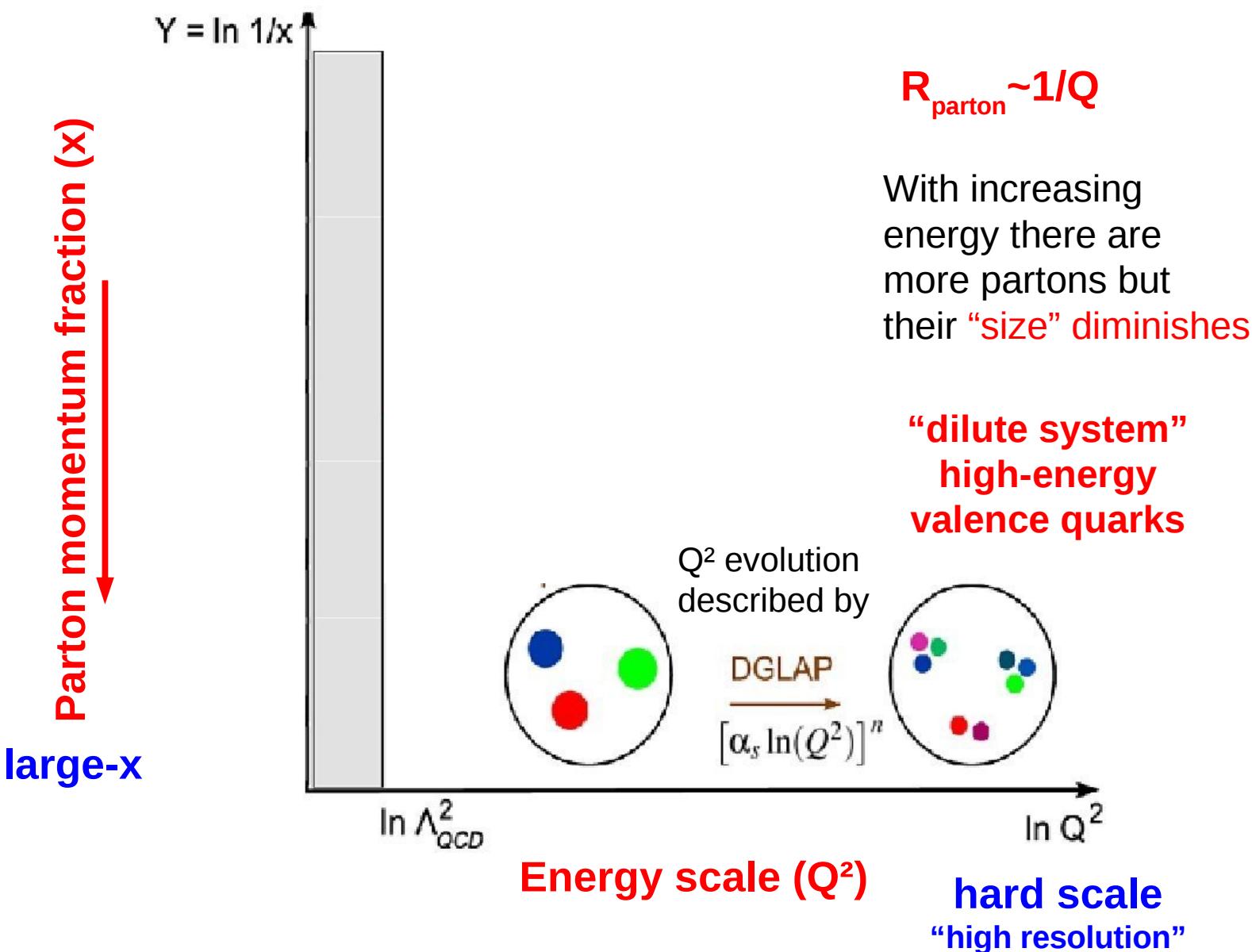
Bjorken-x versus Q^2 : low Q^2



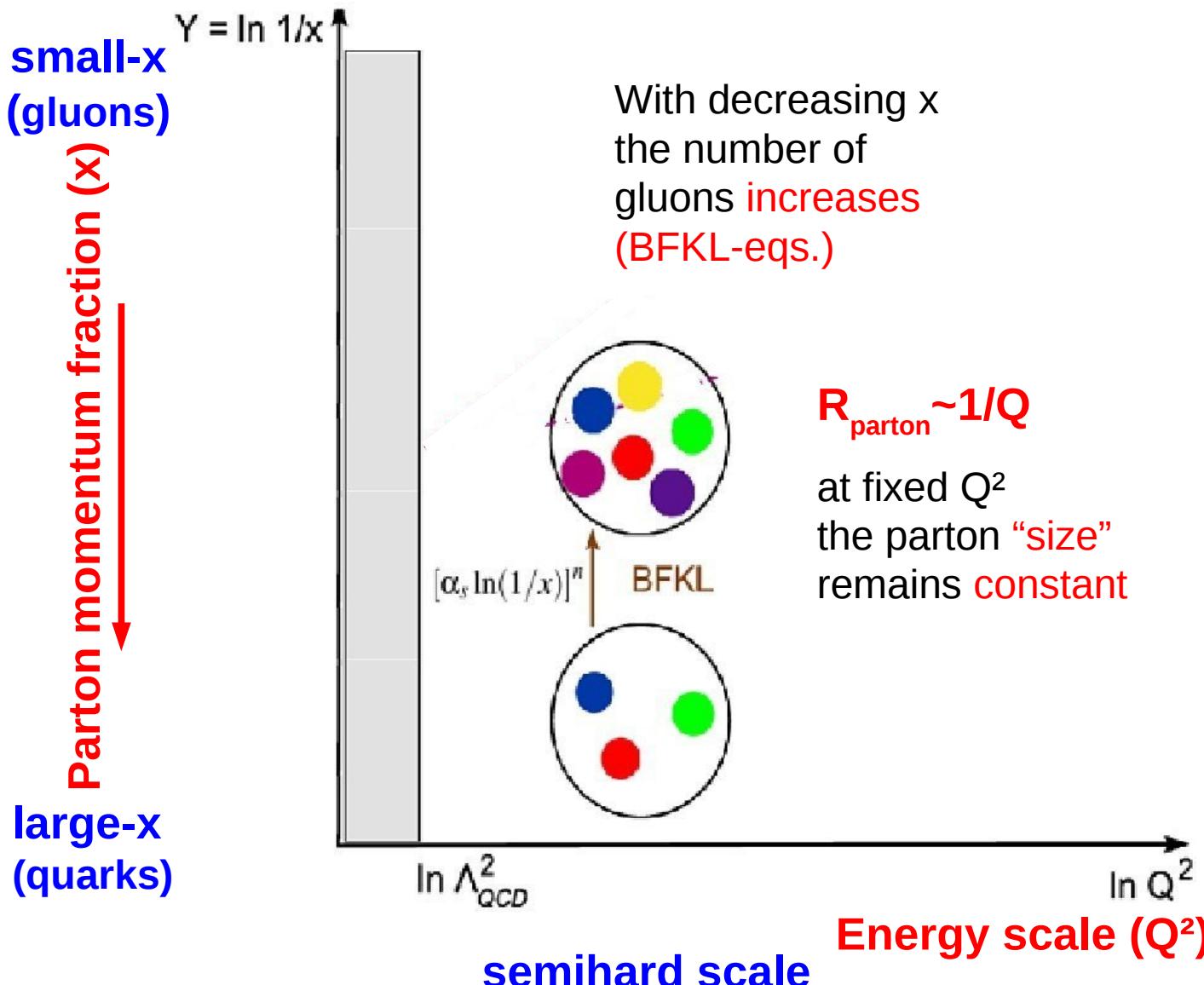
Bjorken-x versus Q^2 : large-x



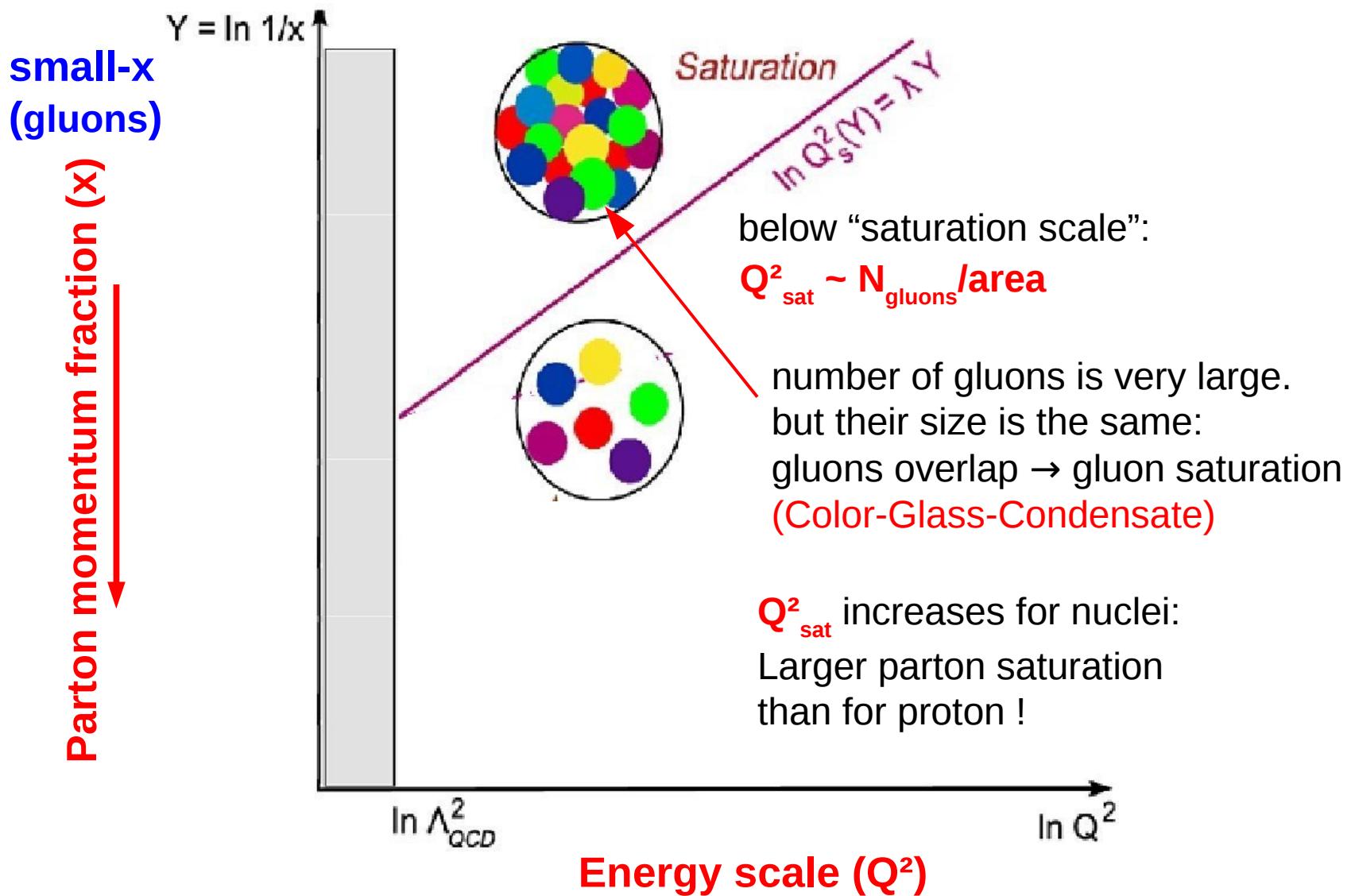
Bjorken-x versus Q^2 : large-x, high- Q^2



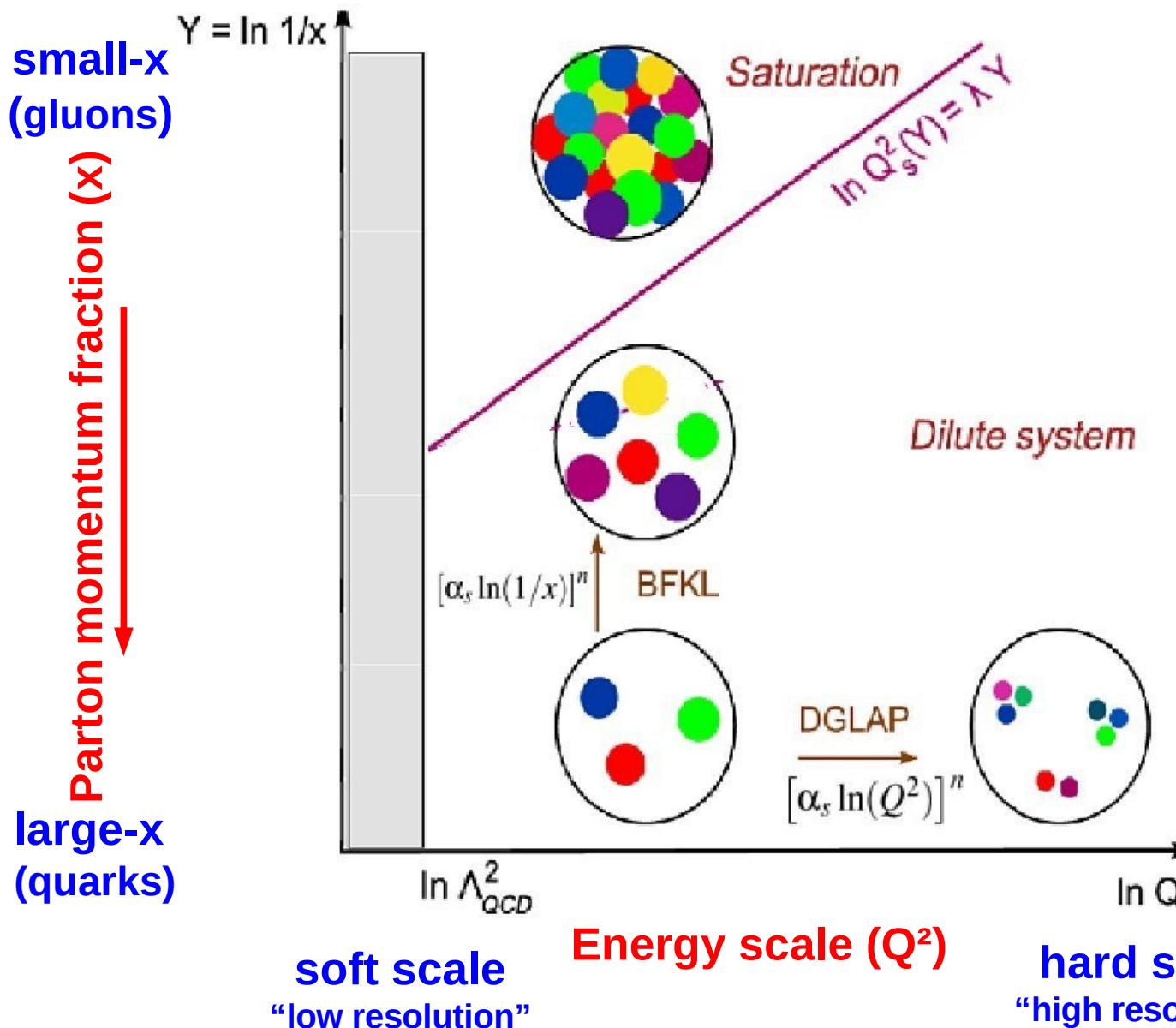
Bjorken-x versus Q^2 : intermediate- Q^2



Bjorken-x versus Q^2 : small-x

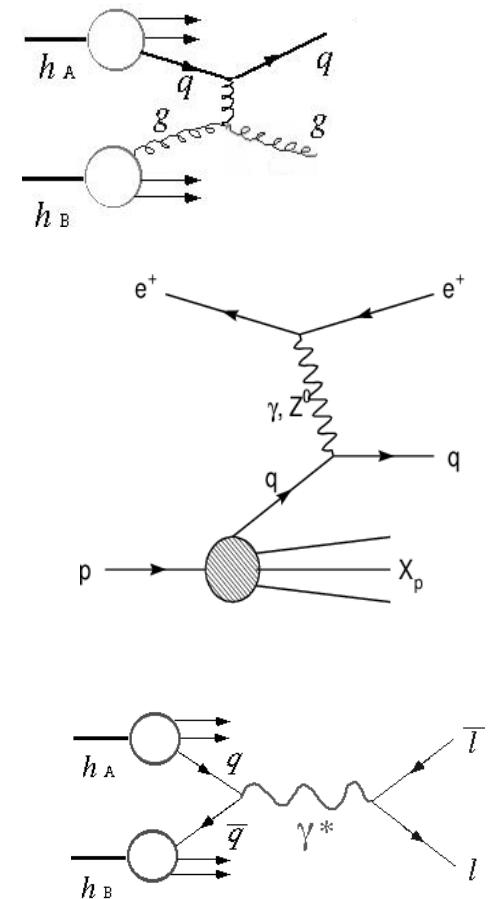
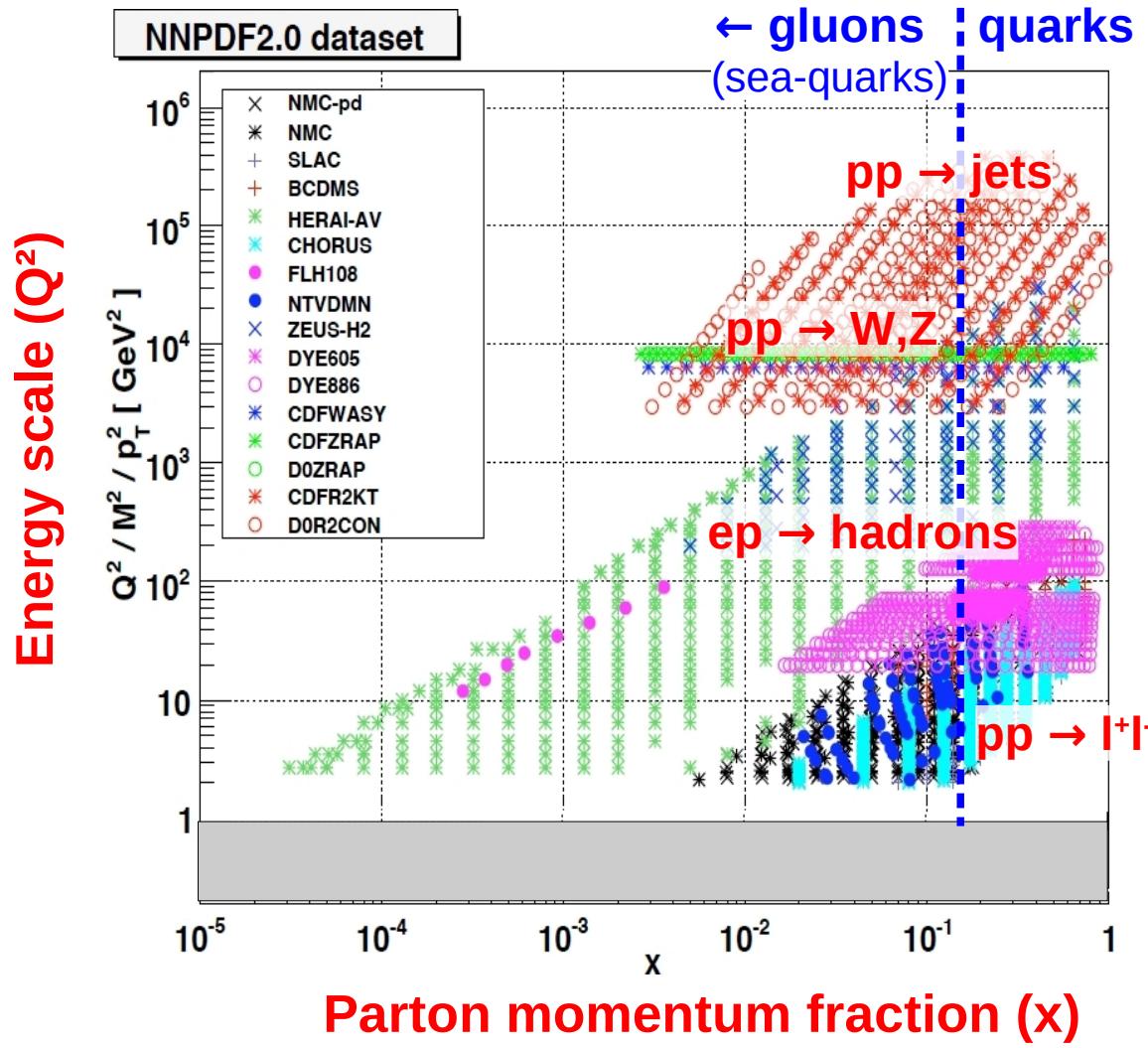


Bjorken-x versus Q^2 (summary)



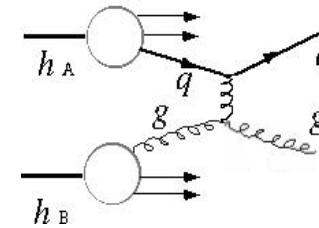
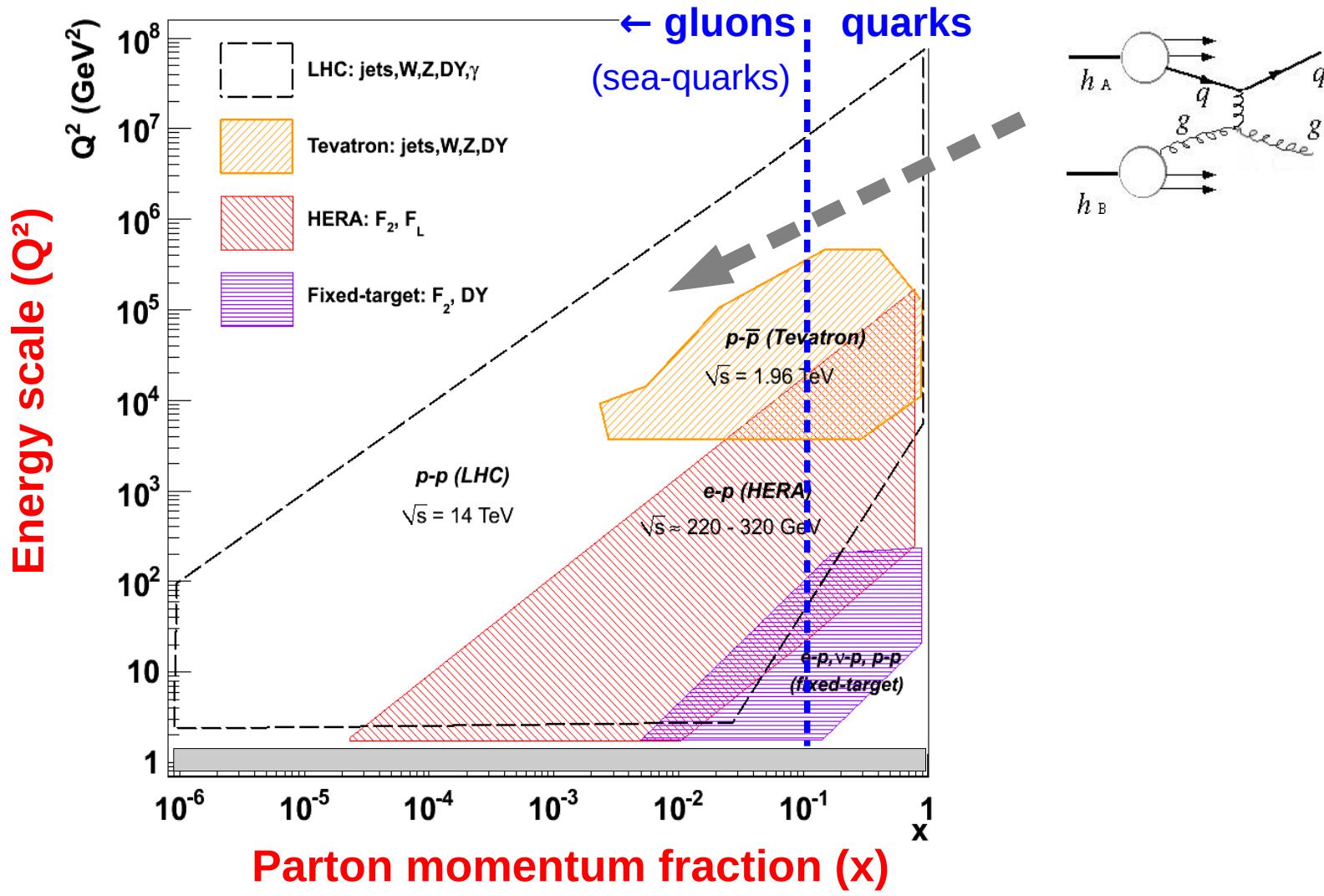
Q^2 versus Bjorken-x (experiment, pre-LHC)

- Deep-inelastic-scattering (ep), fixed-target (pp), collider (pp)



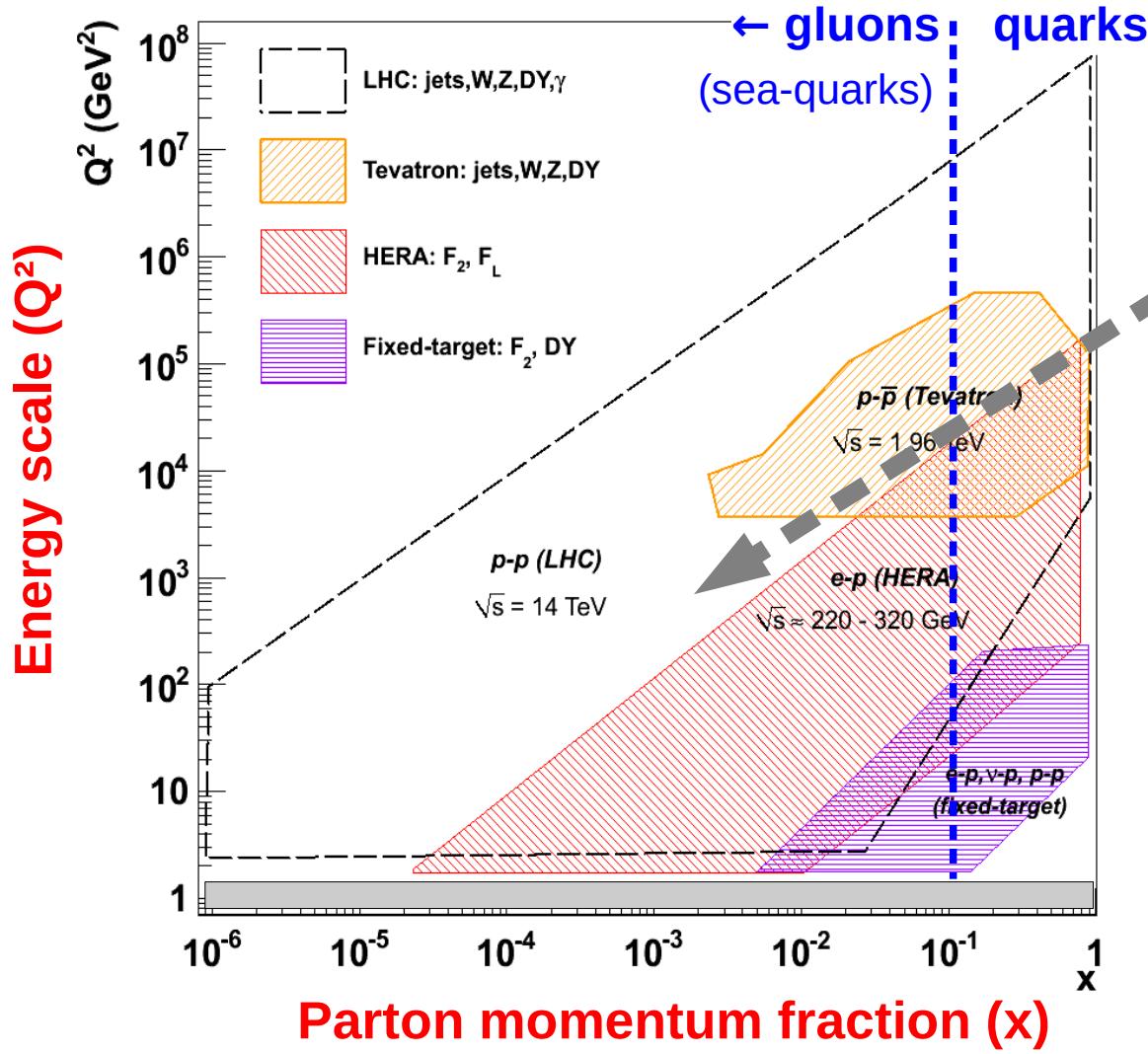
Q^2 versus Bjorken-x (experiment, LHC)

- (x, Q^2) increased significantly !



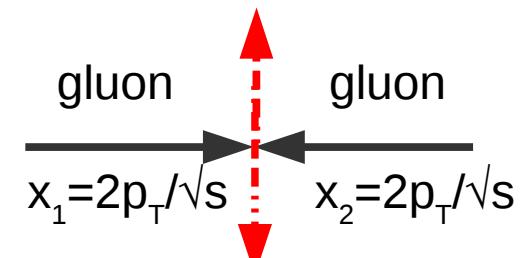
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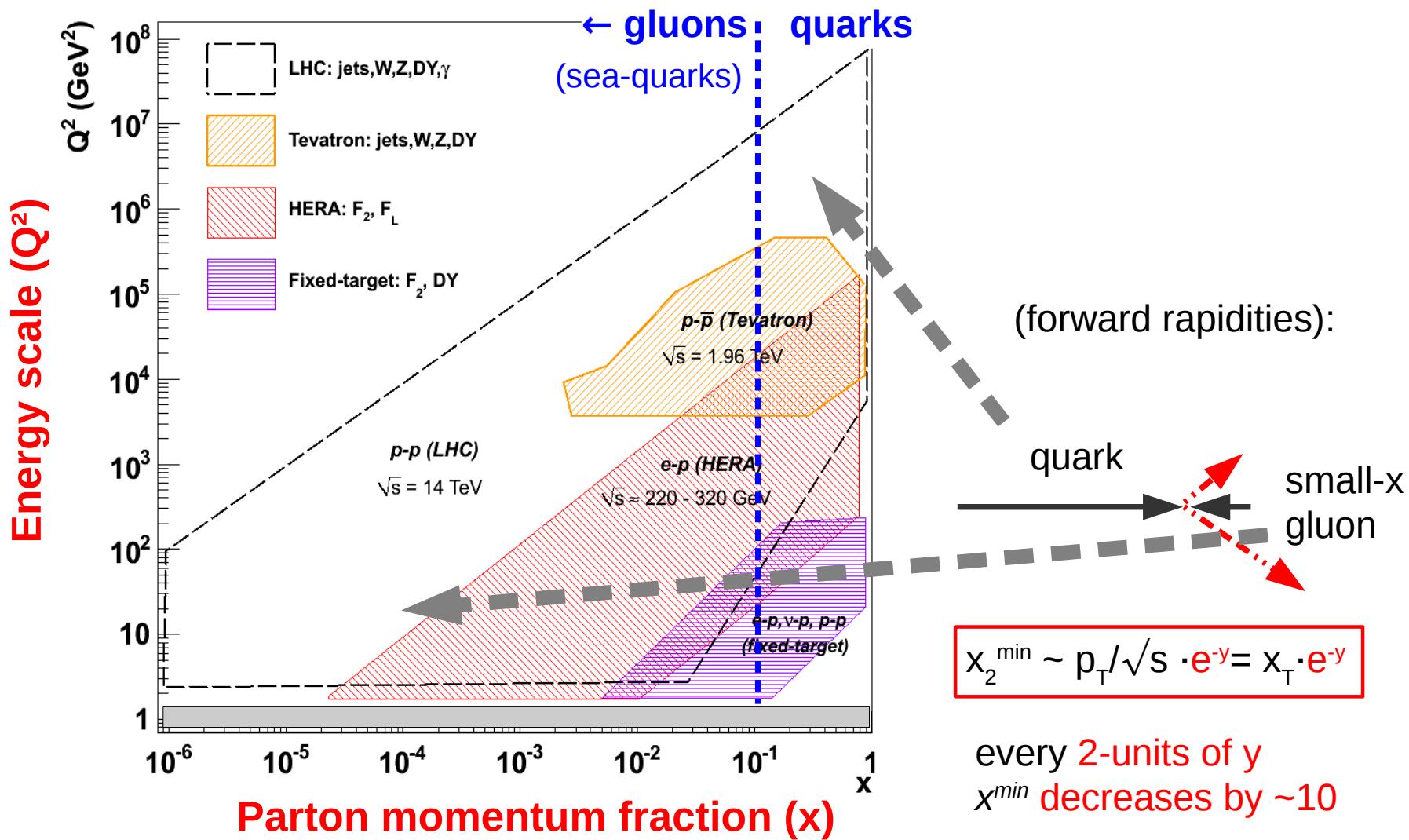
- parton-parton collision:

(mid-rapidity, 90°):



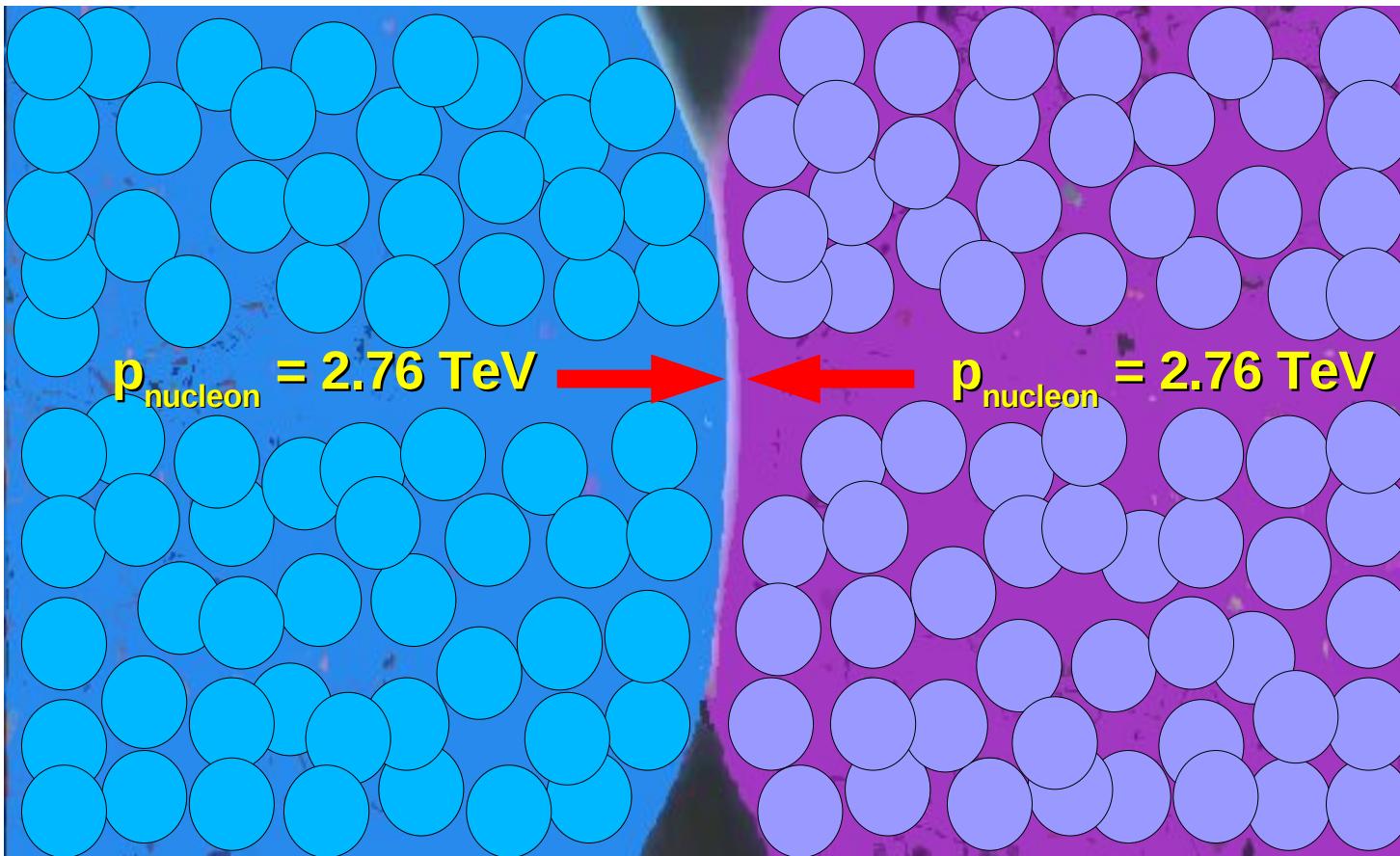
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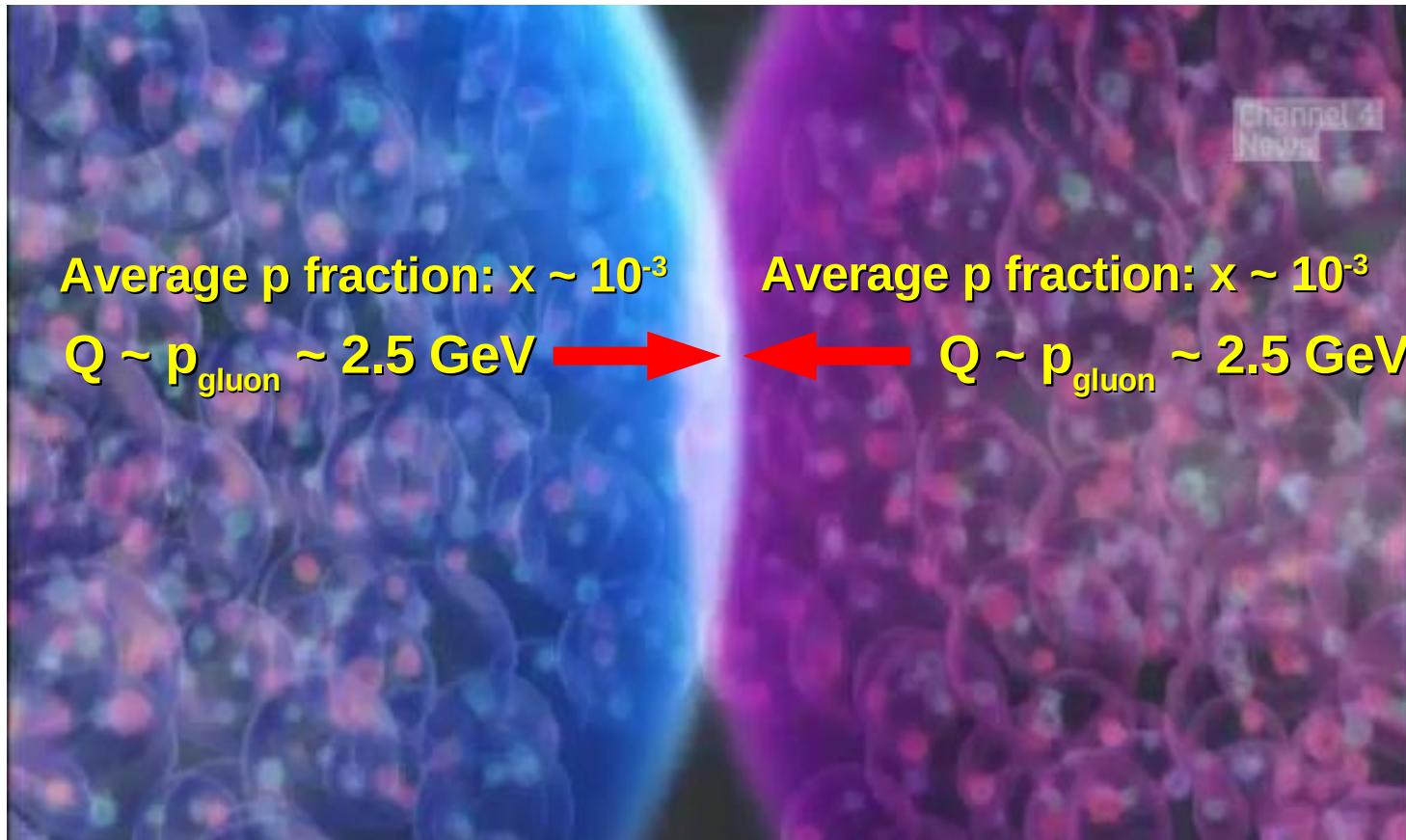
Nucleus-nucleus at the LHC: the initial-state

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 - Each nucleon has a momentum of $p_{\text{nucleon}} = 2.76 \text{ TeV}$



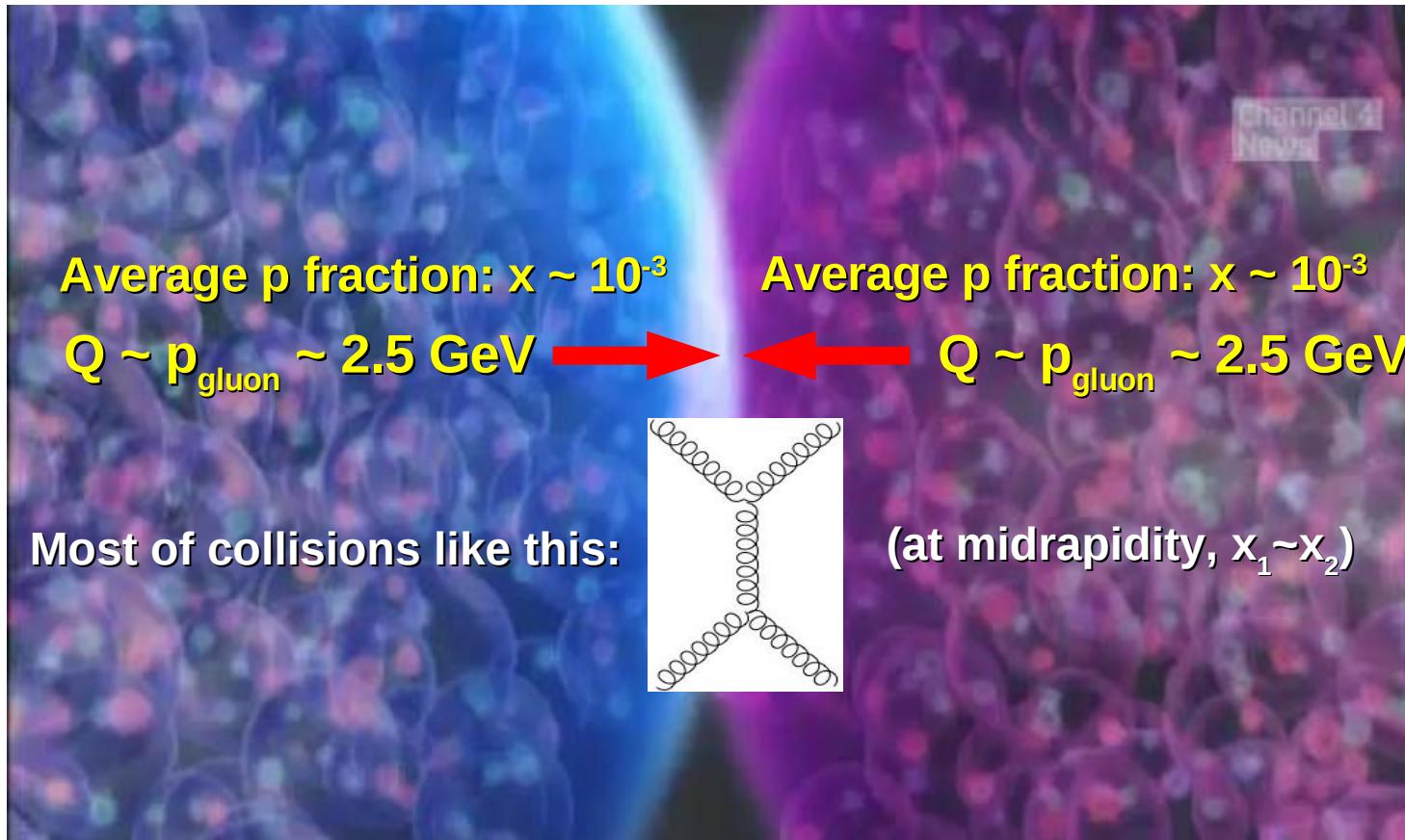
Nucleus-nucleus at the LHC: the initial-state

- Two “parton balls” coming against each other.
 - Parton “targets” with typical momentum fraction: $x \sim 0.1\%$ (gluons !)
 - Parton “projectiles” with typical energy scale: $Q \sim 2.5 \text{ GeV}$

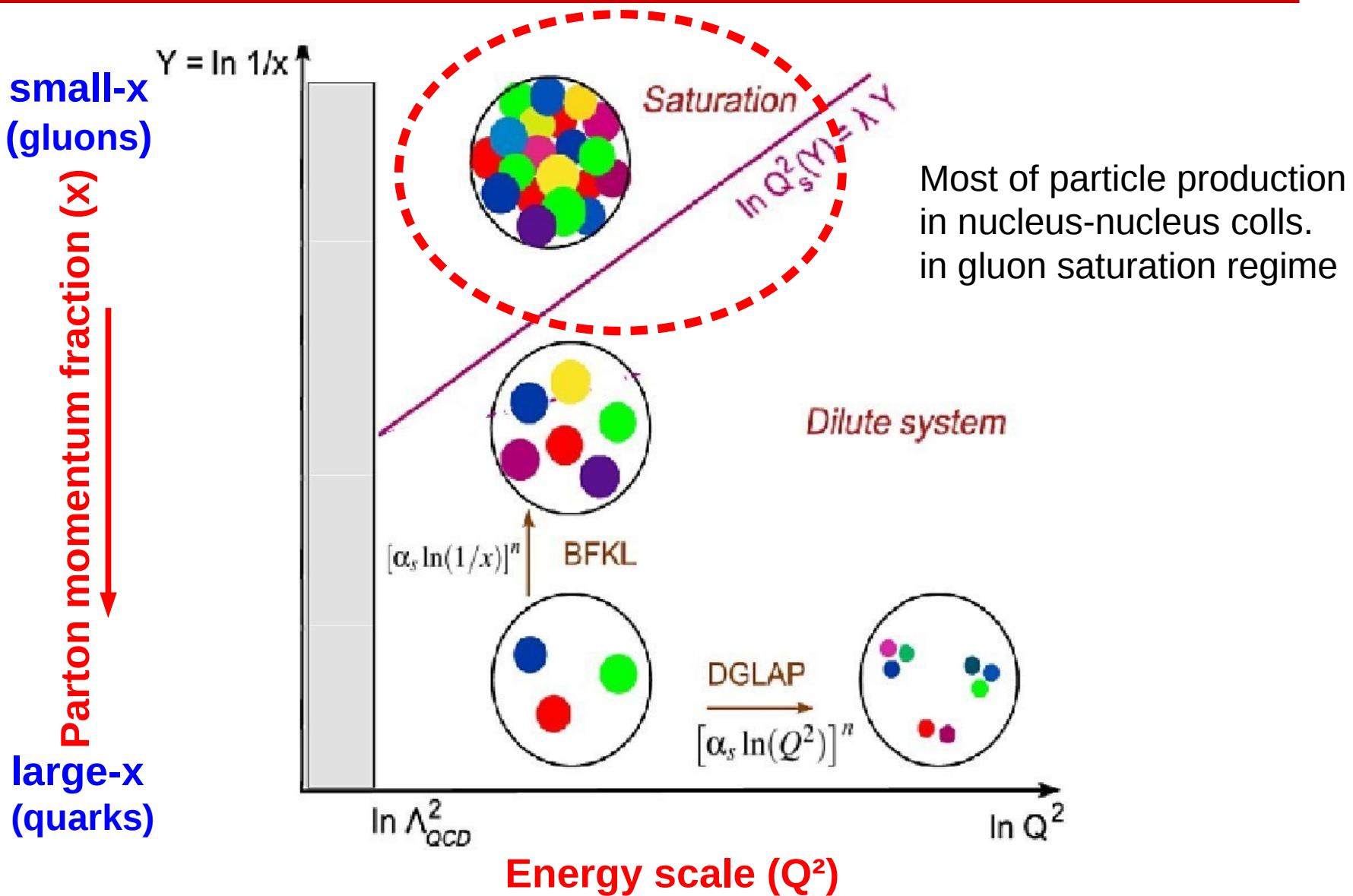


Nucleus-nucleus at the LHC: g-g collisions

- Two “gluon balls” coming against each other.
 - Gluon “targets” with typical momentum fraction: $x \sim 0.1\%$
 - Gluon “projectiles” with typical energy scale: $Q \sim 2.5 \text{ GeV}$



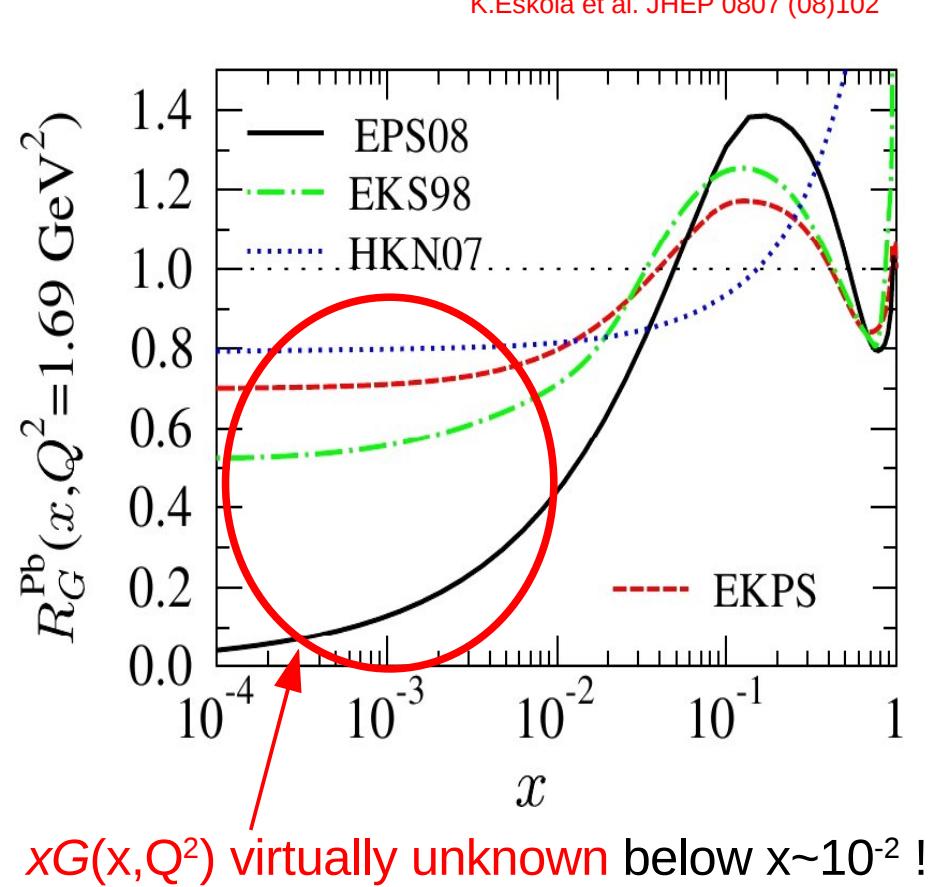
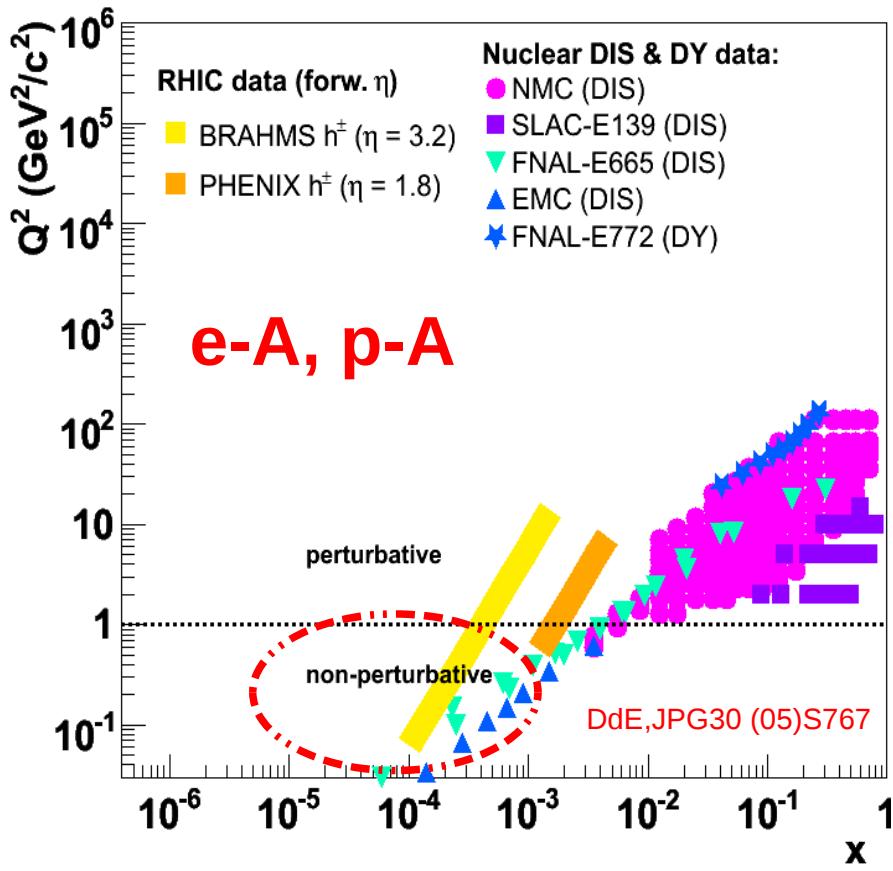
Initial-state at the LHC: saturated g-g collisions



Backup slides

Low-x gluon nuclear densities

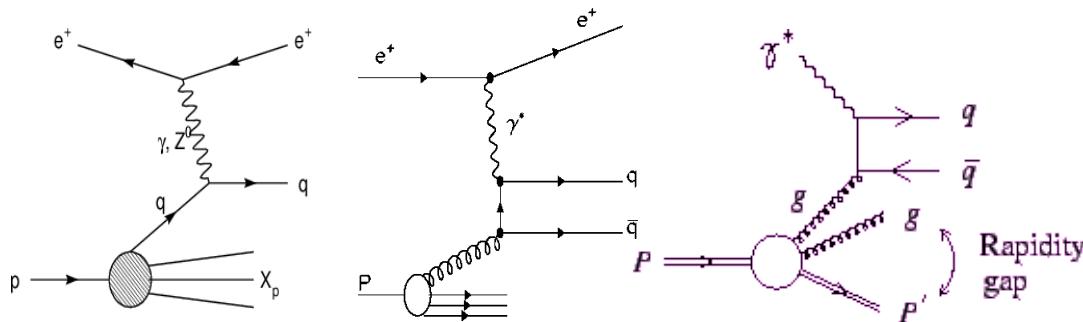
- Current knowledge of low-x gluons from:
 F_2 (e-A), Drell-Yan (p-A), high- p_T hadrons (d-Au).
- $x < 0.01$: very few measurements (non-perturbative): huge uncertainties !



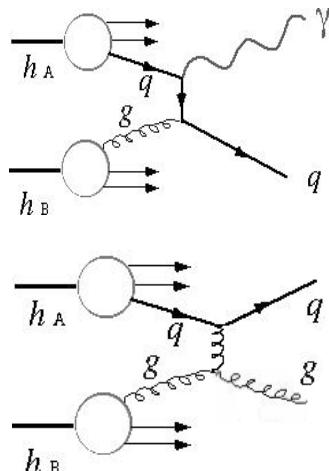
Experimental access to low-x PDFs

■ Perturbative processes:

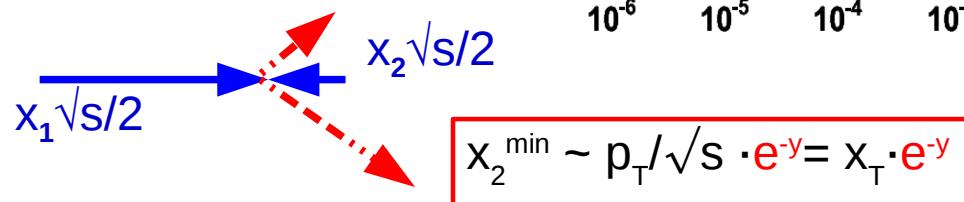
- $e(\gamma)\text{-}p, e(\gamma)\text{-}A: F_2, F_L, F_2^{\text{charm}}, \text{ excl. } Q\bar{Q}, \dots$



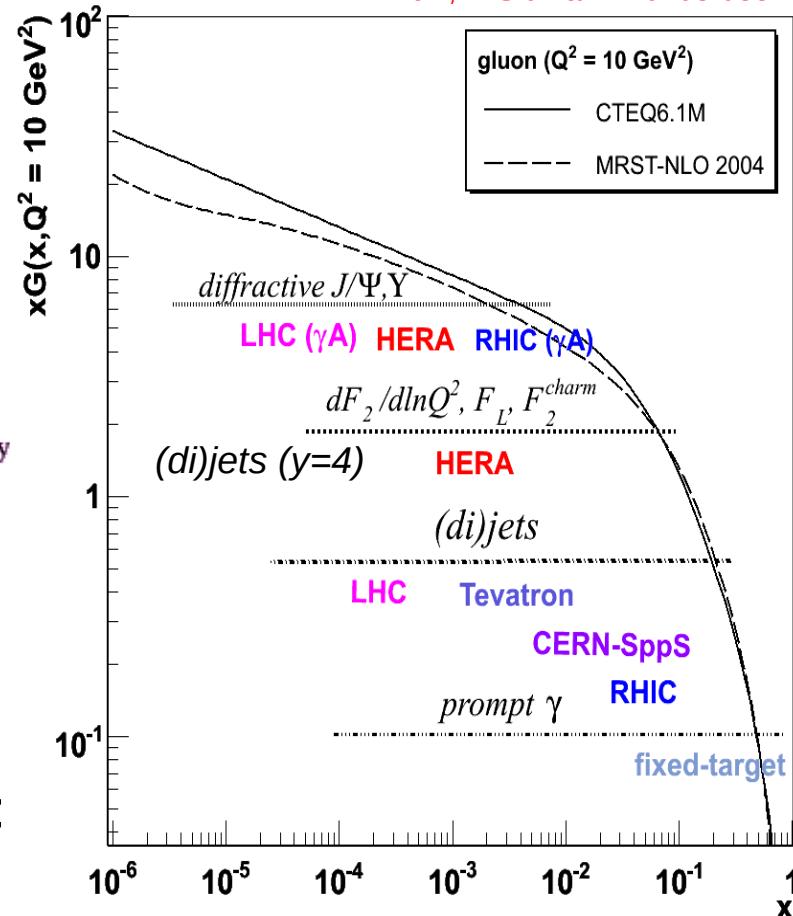
- $p\text{-}p, p\text{-}A: \text{jets, direct } \gamma, \gamma^* \text{ (DY), heavy-Q:}$



► Forward production:

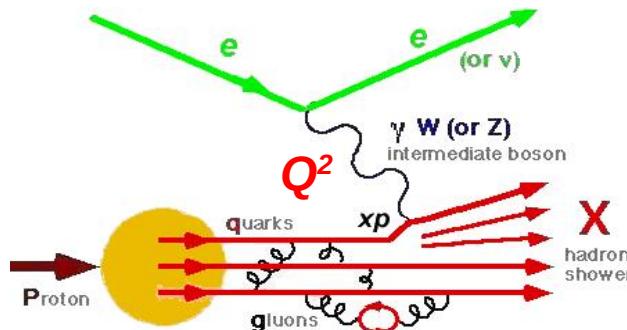


Every 2-units of y , x^{\min} decreases by ~ 10



Low-x PDFs

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



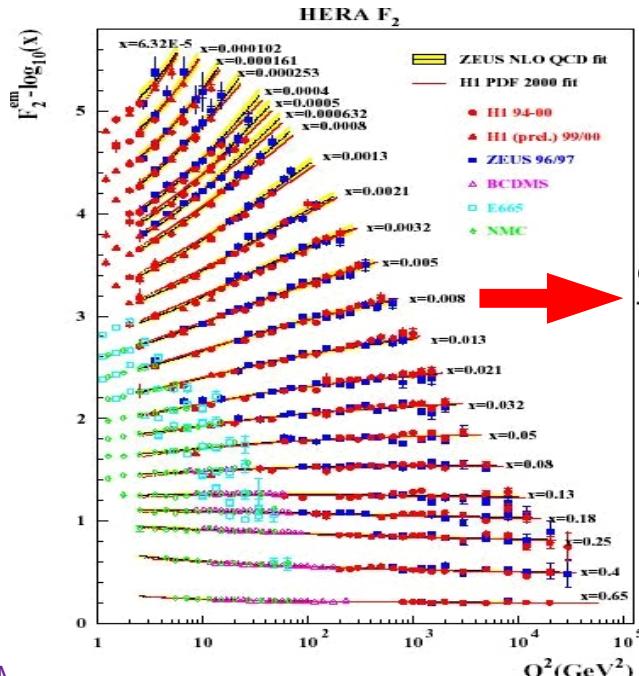
Q^2 = “resolving power”

Bjorken x = momentum fraction carried by parton

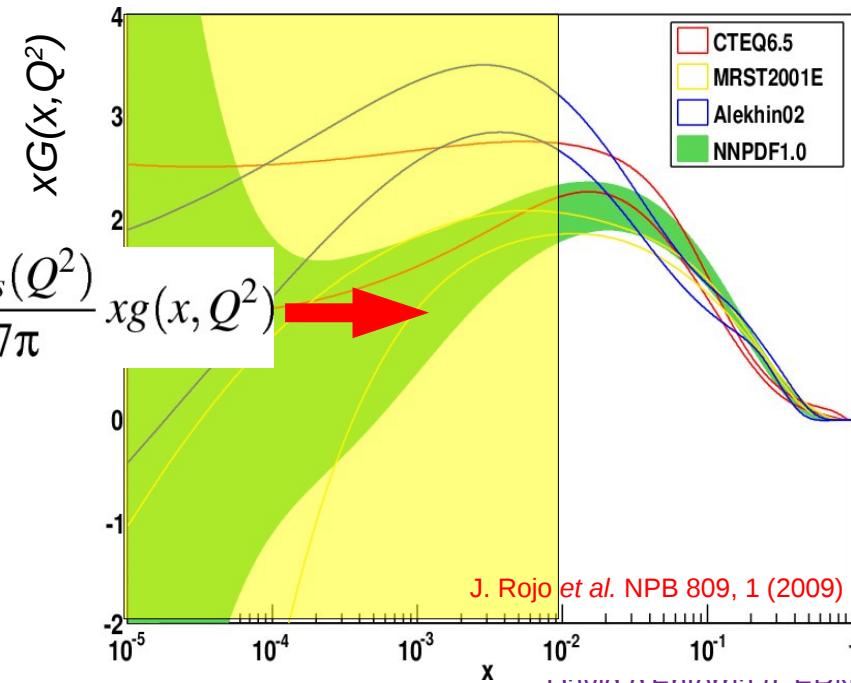
$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [Y_+ \cdot F_2 \mp Y_- \cdot xF_3 - y^2 \cdot F_L]$$

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

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



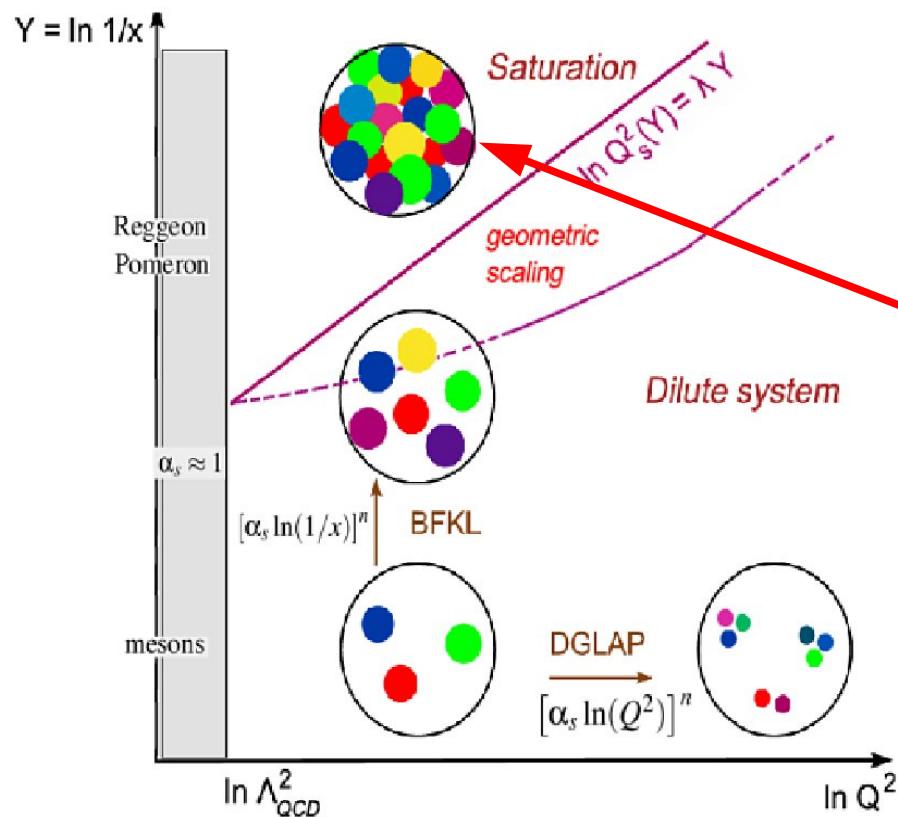
$$\frac{\partial F_2(x, Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi} xg(x, Q^2)$$



QCD evolution equations

[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 :



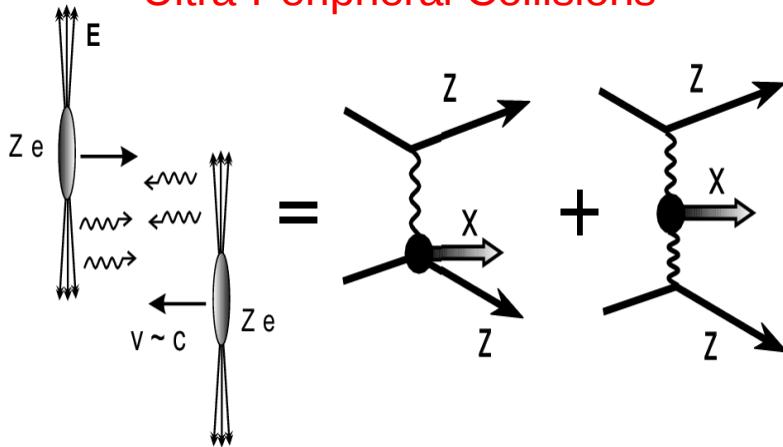
- (i) Too high gluon density: **nonlinear gluon-gluon fusion** balances branchings
- (ii) pQCD (collinear & k_T) **factorization** assumptions invalid (HT, no incoherent parton scatt.)
- (iii) **Violation of unitarity** even for $Q^2 \gg \Lambda^2$ (too large perturbative cross-sections)
- Saturation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

Photoproduction in A-A collisions at the LHC

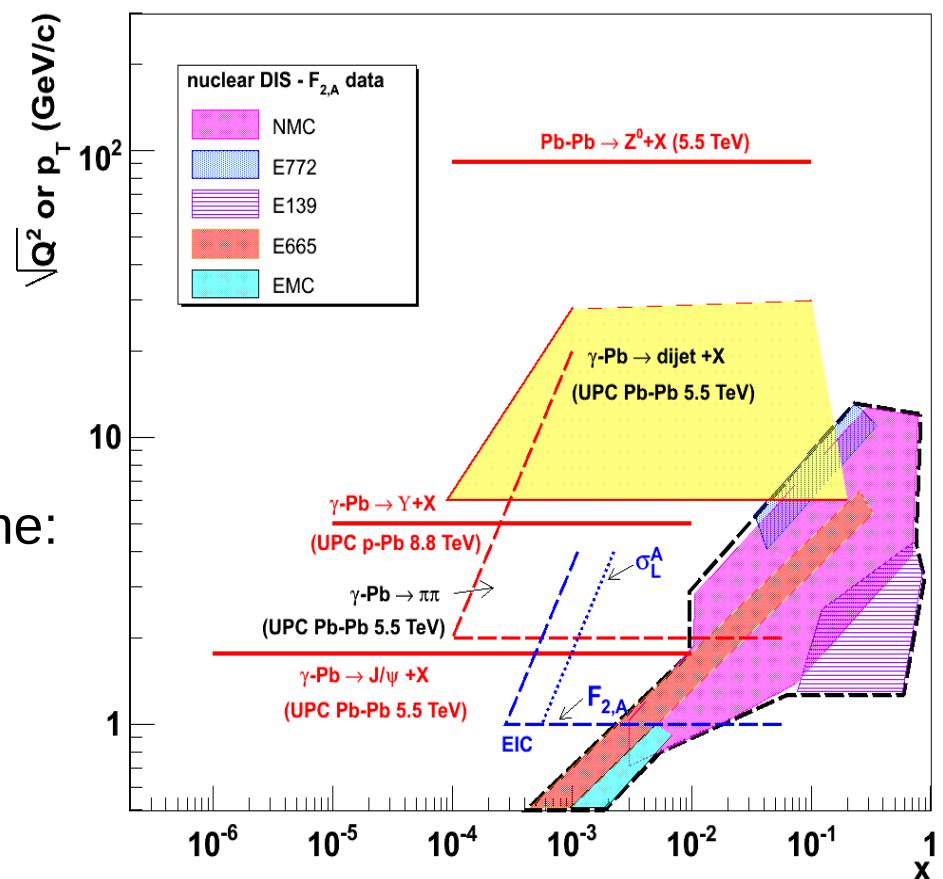
- High-energy heavy-ions produce **strong E.M. fields** due to coherent action of $Z_{\text{Pb}} = 82$ protons:
- UPCs in Pb-Pb @ 5.5 TeV: $E_{\gamma}^{\max} \sim 80 \text{ GeV} \Rightarrow$

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

Ultra-Peripheral Collisions



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

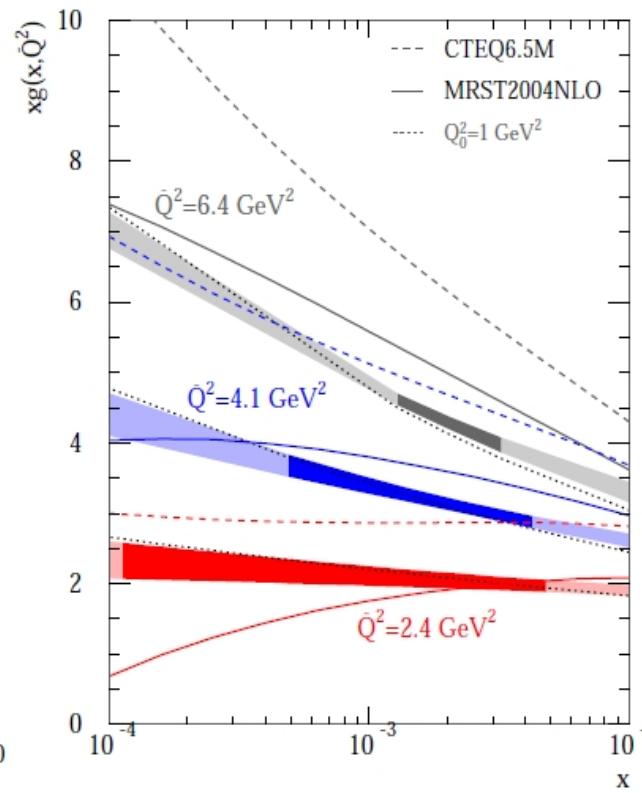
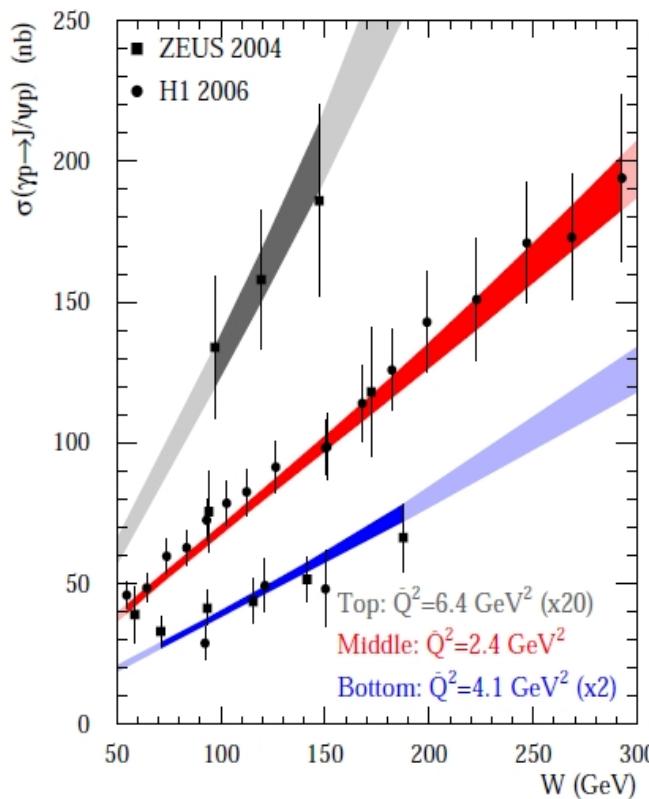
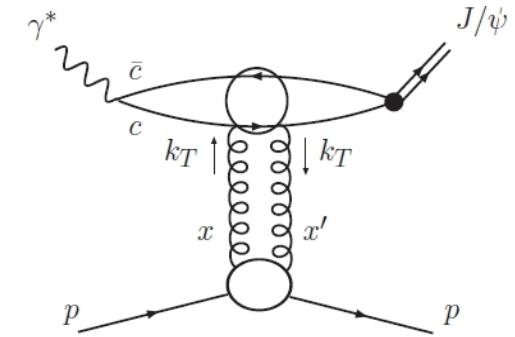


$xg(x, Q^2)$ from exclusive $Q\bar{Q}$ photoprod. at HERA

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

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

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



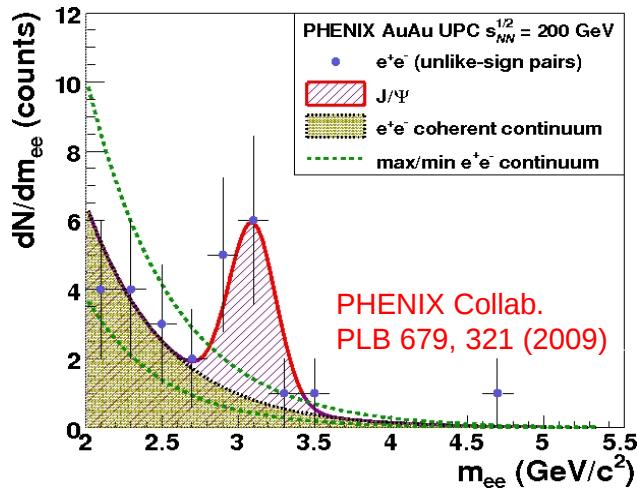
NLO pQCD analysis:

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

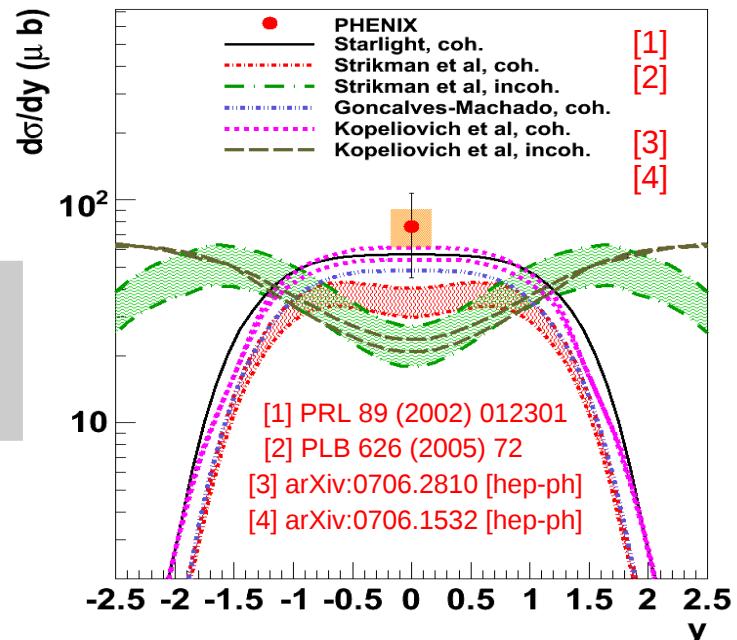
Martin, Nockles,
Ryskin, Teubner
PLB 662, (2008)252

$xg(x, Q^2)$ 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:

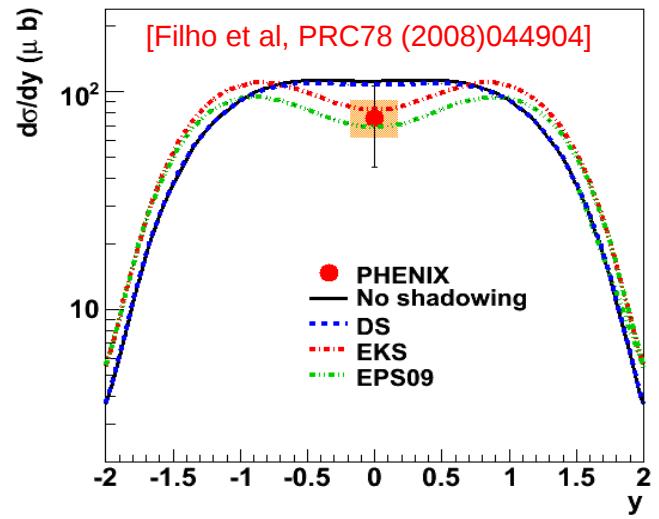
Starlight: coherent, HERA data parametrization

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

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

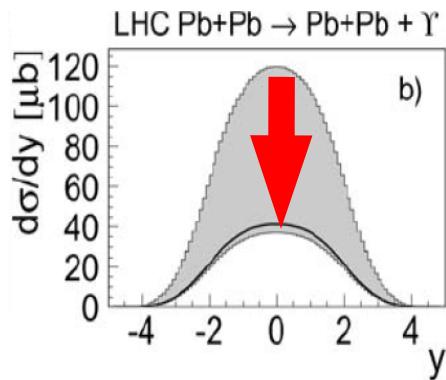
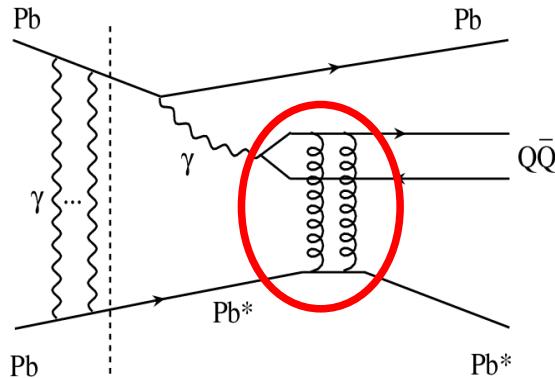
Kopeliovich et al:
coherent & incoherent, color-dipole + gluon saturation

Filho, Gonçalves, Griep:
coherent, DGLAP nuclear PDFs

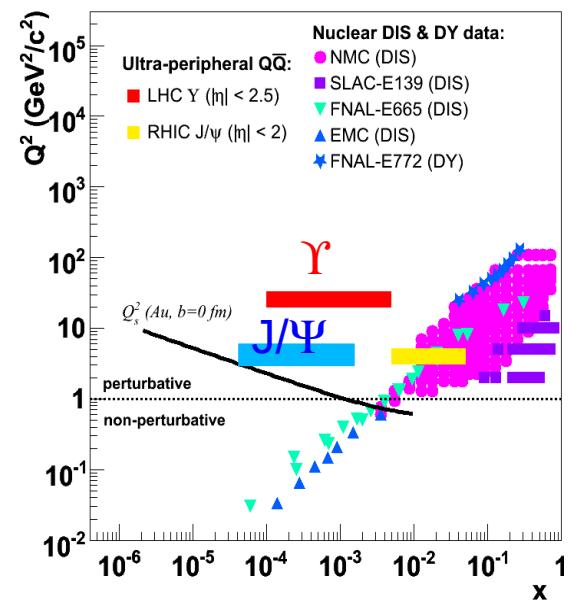


LHC example I: Pb-Pb $\rightarrow \gamma$ Pb $\rightarrow J/\Psi, \Upsilon$ Pb

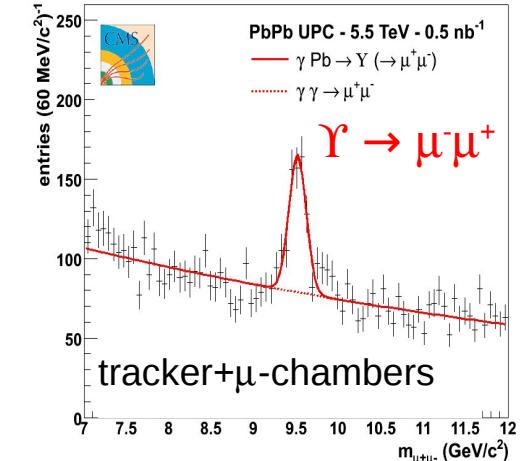
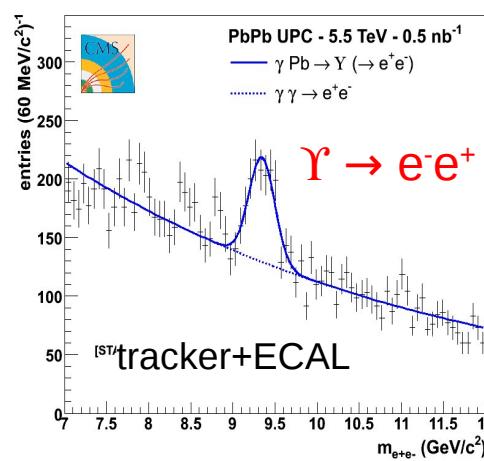
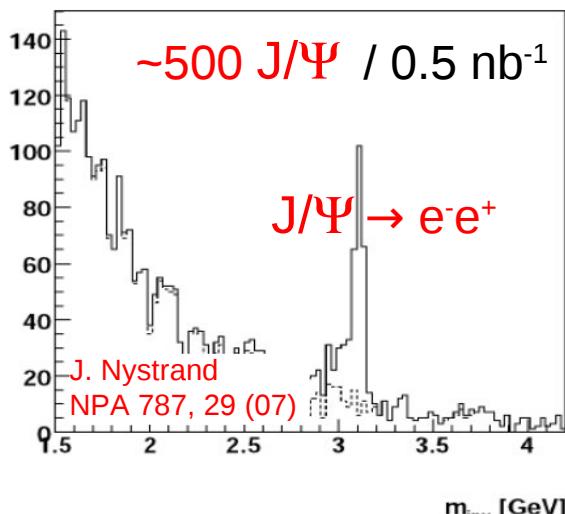
Theoretical predictions:



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



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

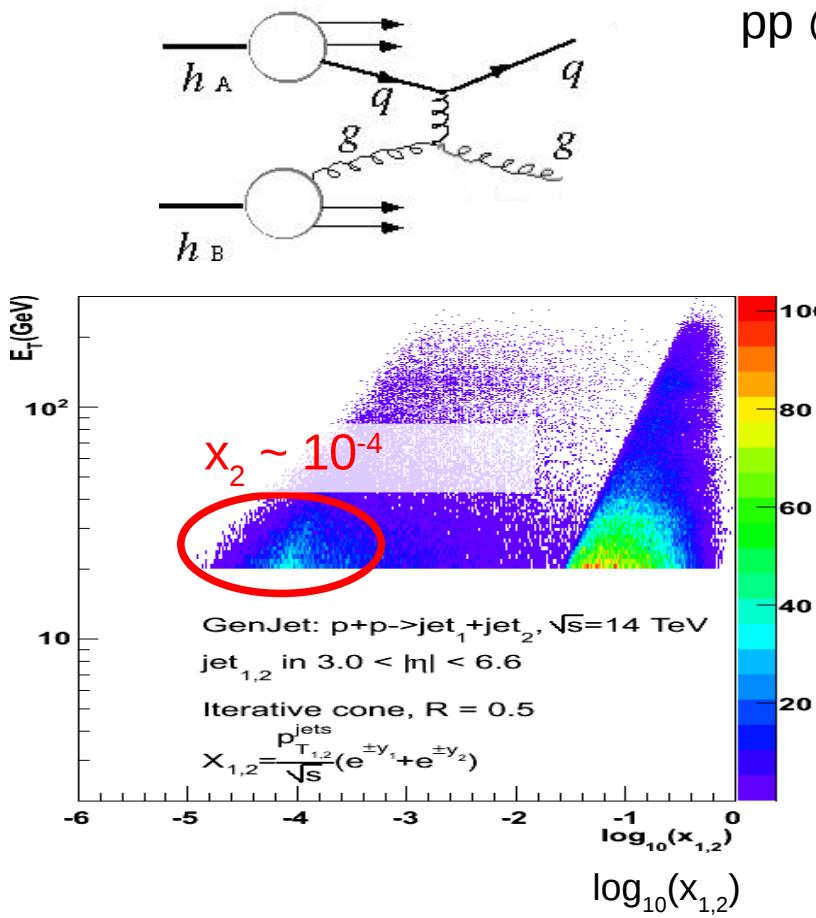


$\sim 500 \Upsilon / 0.5 \text{ nb}^{-1}$

DdE, NPB 184, 158 (08)

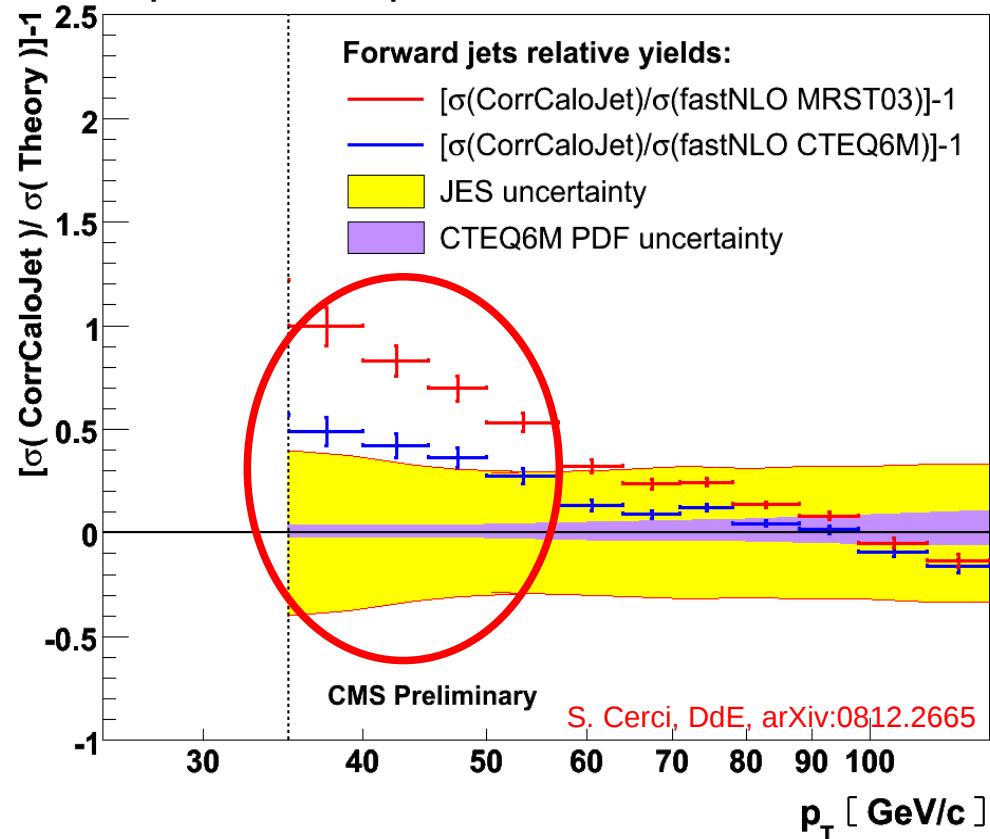
LHC example II: Forward jets in CMS ($3 < |\eta| < 6.6$)

- 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

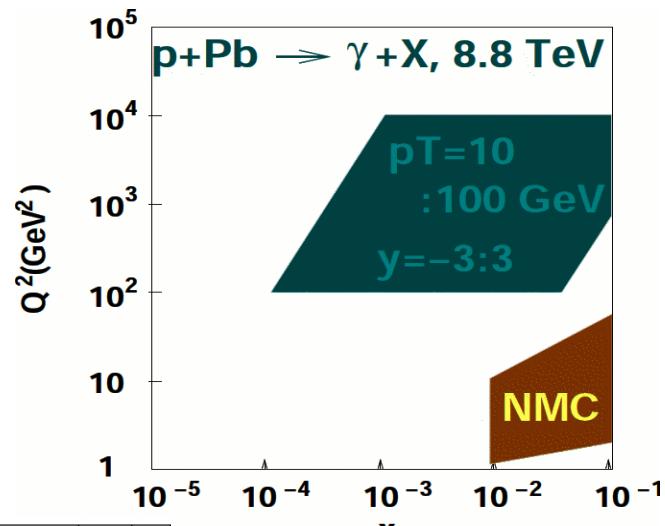
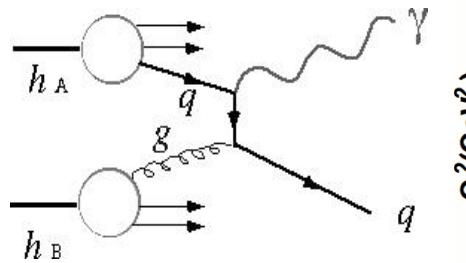
Spectrum dependence on PDF choice:



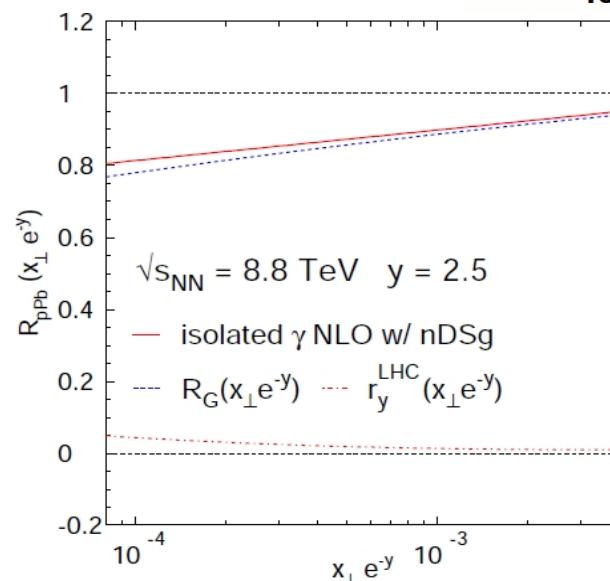
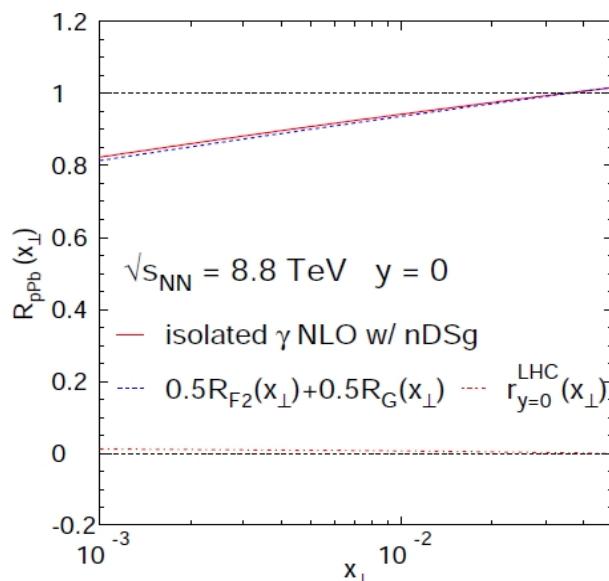
- Warning: p-p analysis. Jet reconstruction performances in p-Pb ?

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 ($y=0$, $y=2.5$):



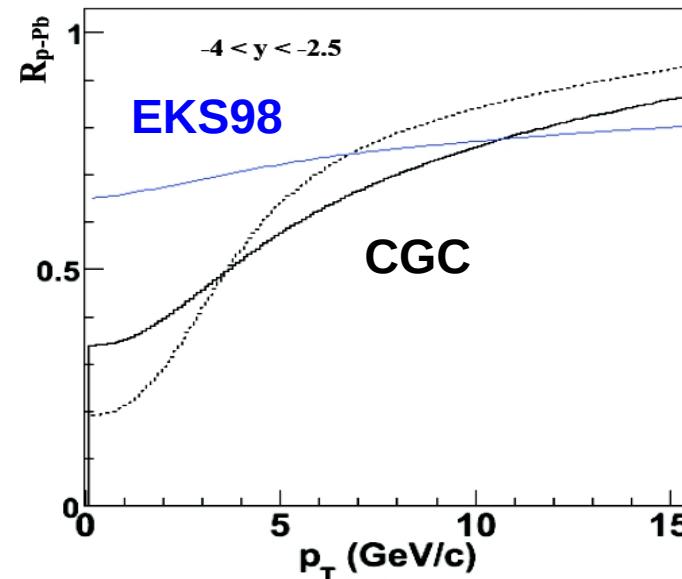
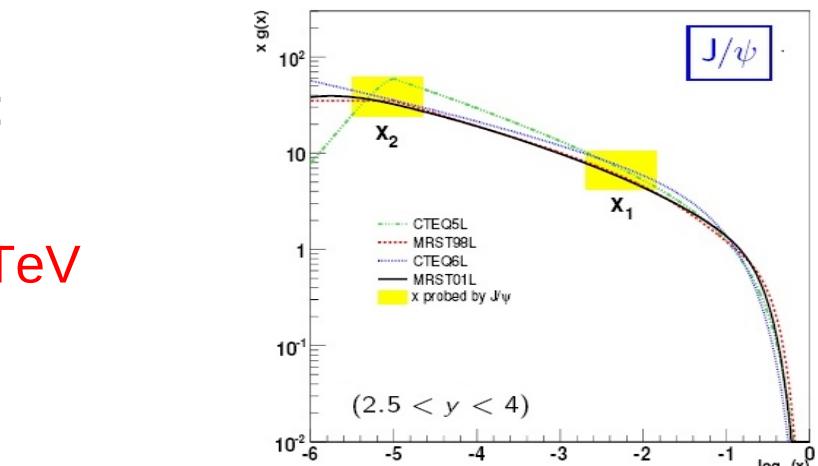
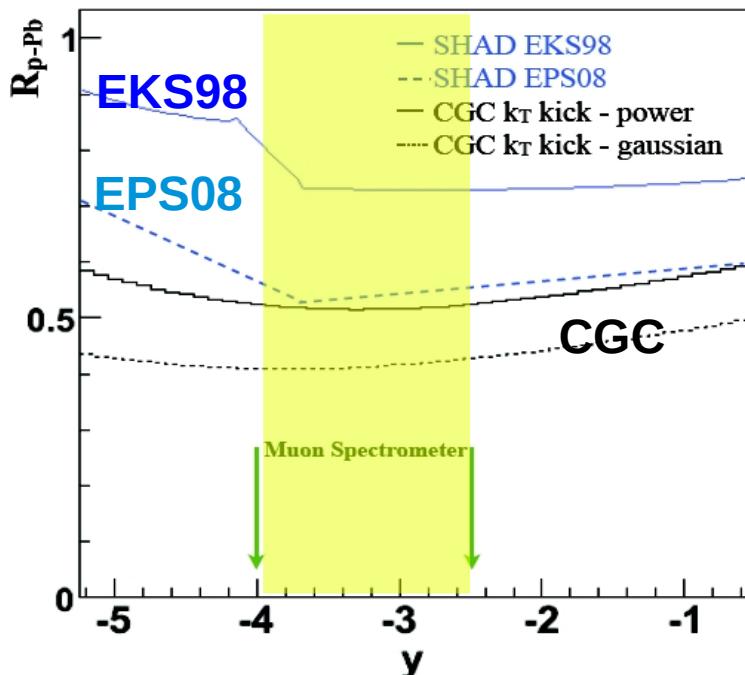
[cf. T. Gousset talk]

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

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

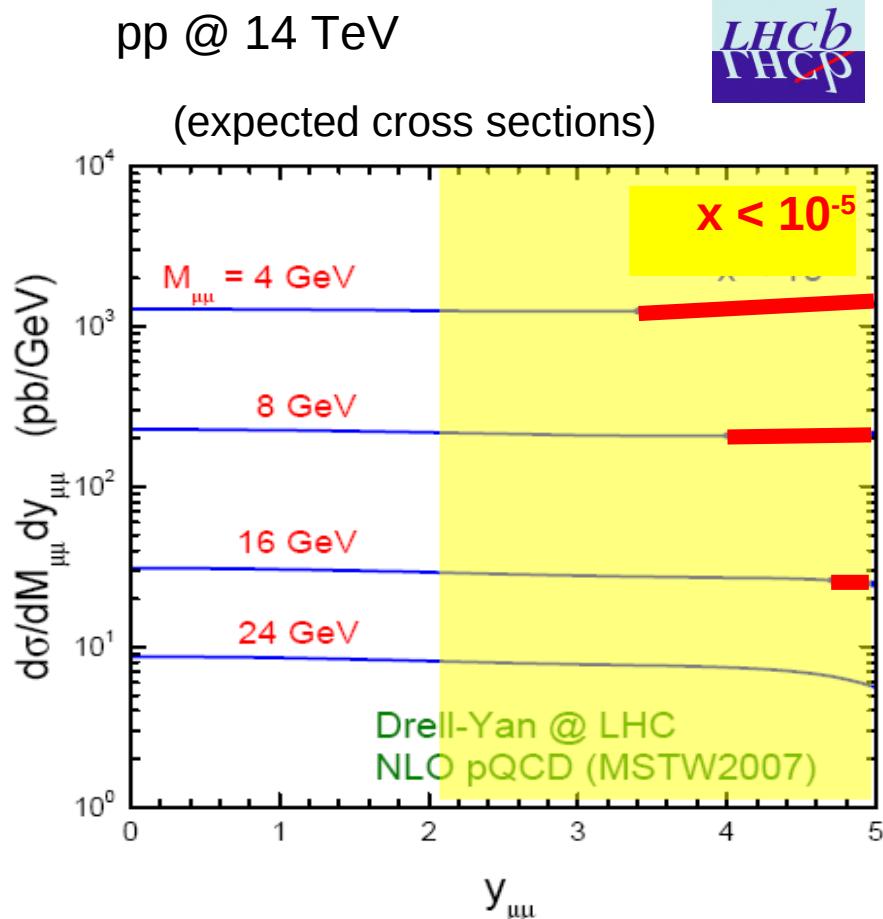
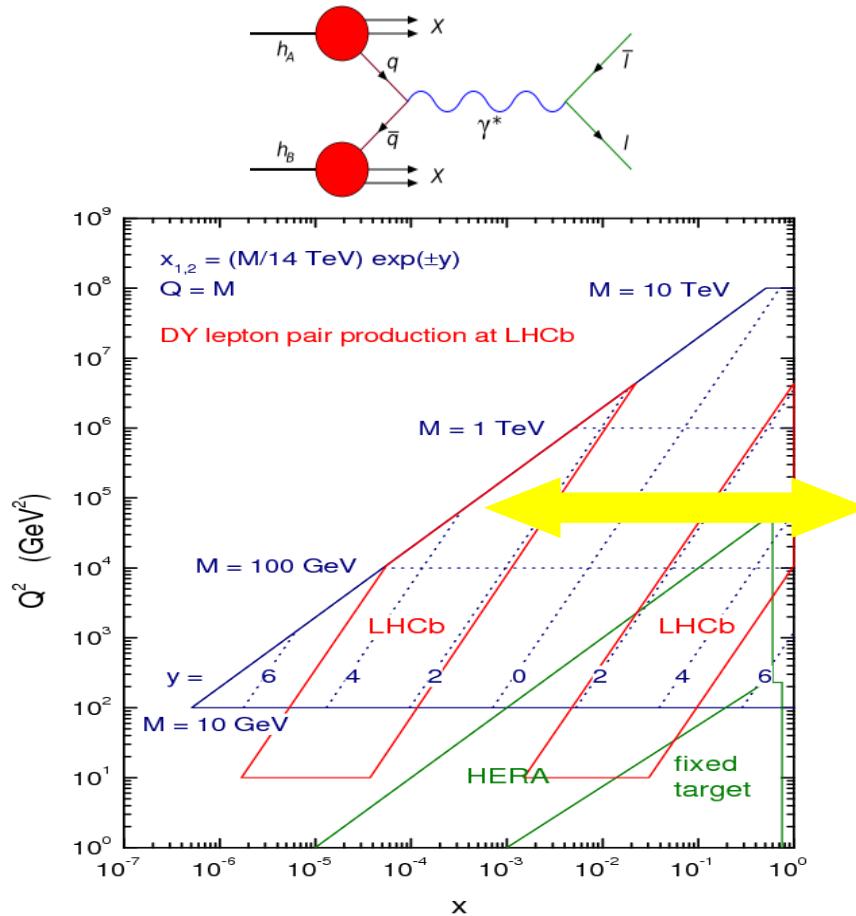
[cf. C.Hadjidakis talk]

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



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

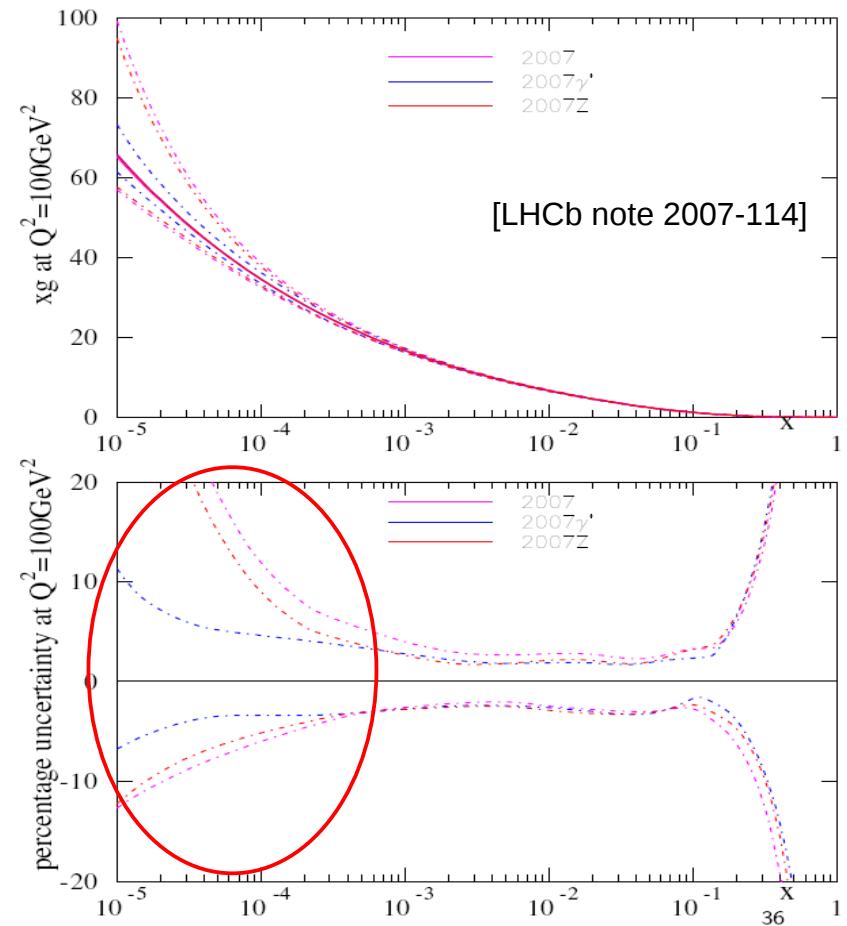
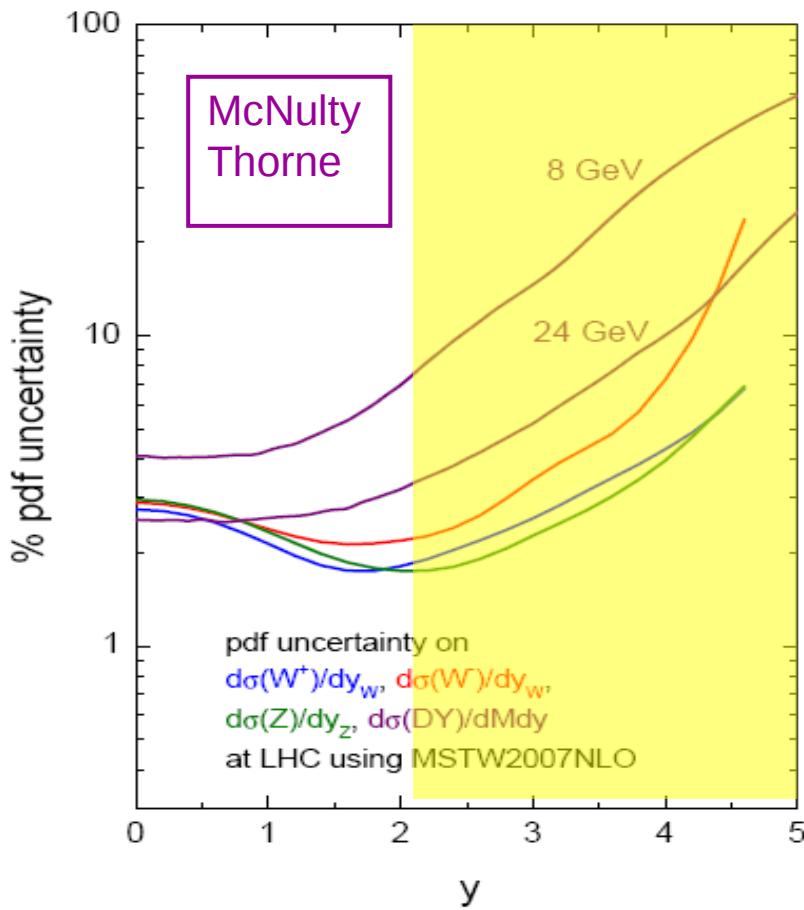
- Drell-Yan forward μ : $q\bar{q} \rightarrow \mu^+ \mu^-$ (trigger on low- p muons: $p>8\text{GeV}$, $p_T>1\text{GeV}$)
- Sensitive to low- x quark densities



- 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: $>20\% \rightarrow <10\%$

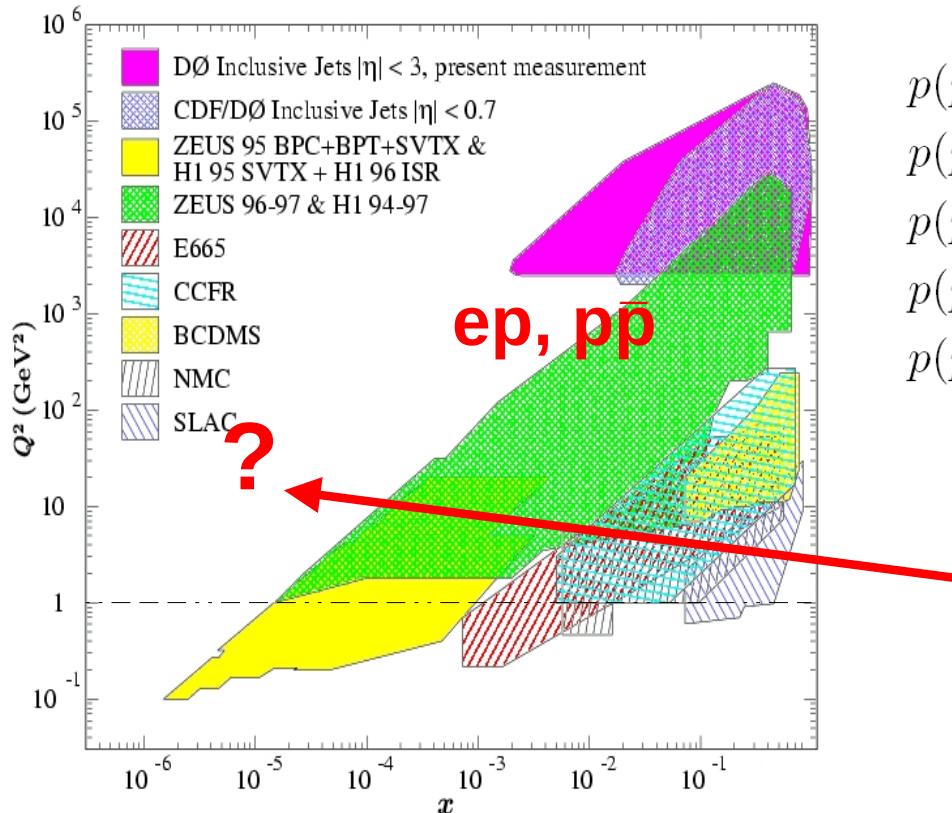


- Warning: p-p analysis. Reconstruction performances in p-Pb ?

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} !~~

Summary

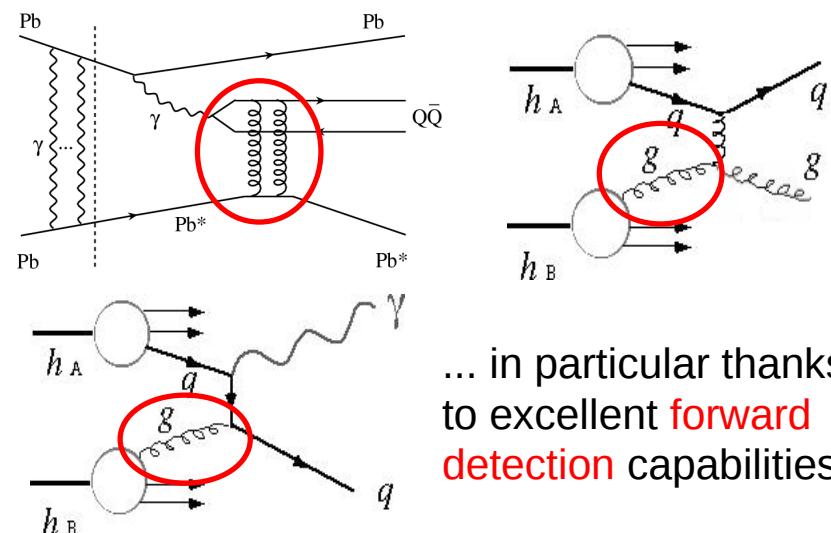
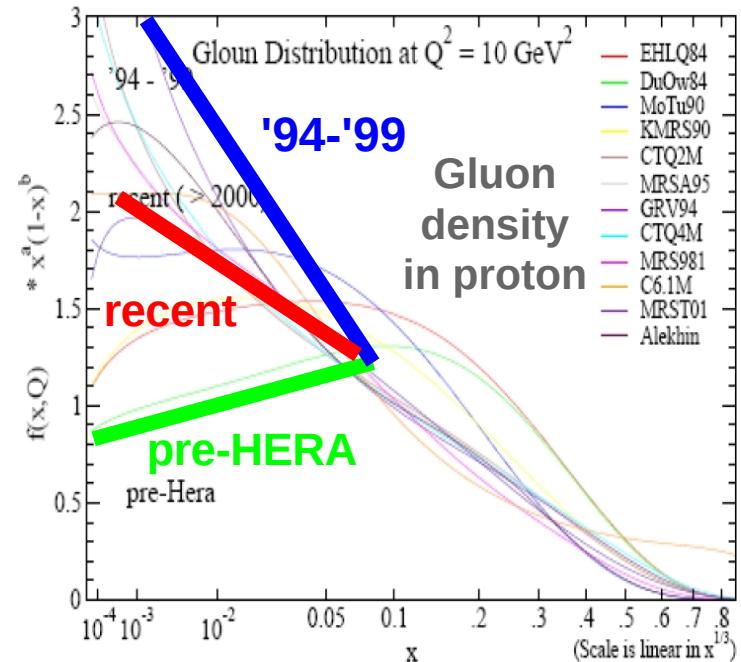
- Current knowledge of low- x nuclear gluon density (& evolution?) is as bad or worst! than for the proton ~15 years ago (pre-HERA).

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