

Perspectives in low-x QCD with protons & heavy-ions at the LHC

6th Small-x & Diffraction Workshop

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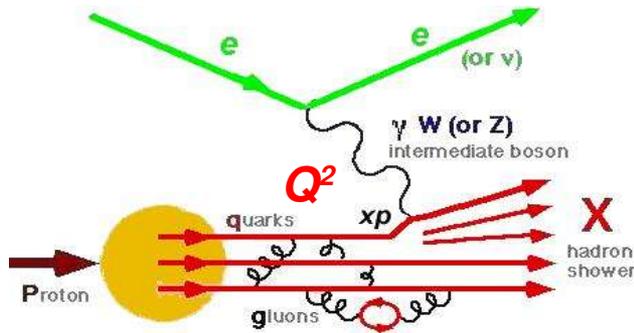
CERN, PH/EP

Overview

- Introduction:
 - Parton structure & evolution at low- x
 - Gluon saturation: Color Glass Condensate (CGC), non-linear QCD evolution (BK/JIMWLK) equations
 - Measurements of low- x PDFs: processes, kinematic domains, ...
- Experimental tests:
 - Signatures at HERA (proton) & RHIC (nucleus)
 - Low- x perspectives at the LHC (p,A)
 - PbPb @ 5.5 TeV case-studies: $dN_{\text{ch}}/d\eta$, Y photo-production
 - pp @ 14 TeV case-studies: forward (di)jets, QQbar, DY ...
- Summary

Parton structure at low-x

- DIS ep collisions probe **partonic distributions** in the proton:



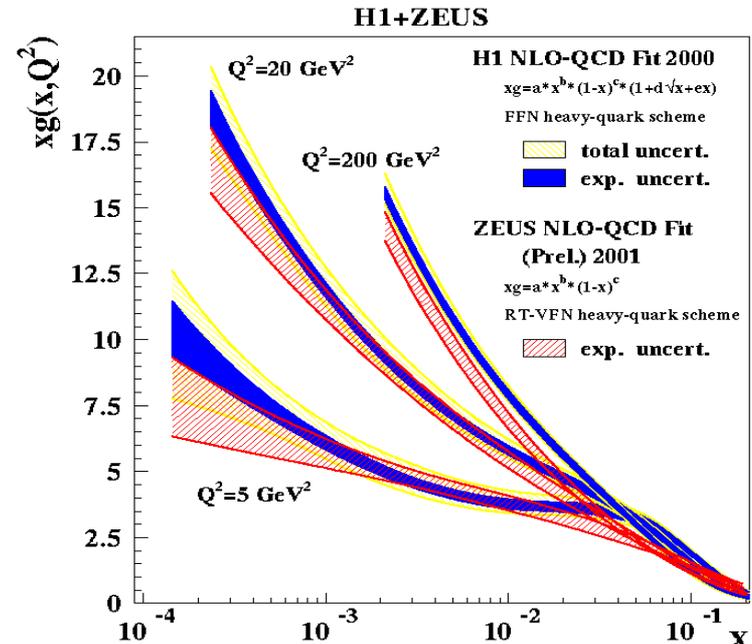
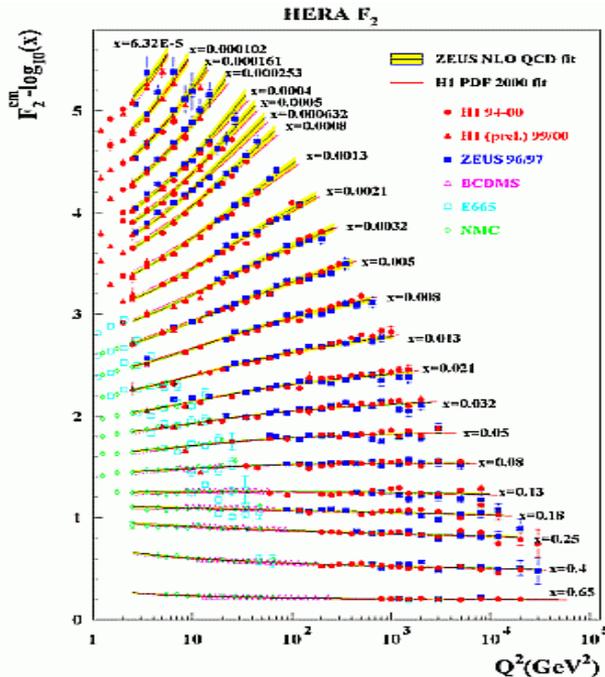
Q^2 = “resolving power”

Bjorken x = momentum fraction carried by parton

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [2xy^2 F_1 + 2(1-y)F_2]$$

F_1, F_2 = proton structure functions, (y = inelasticity).

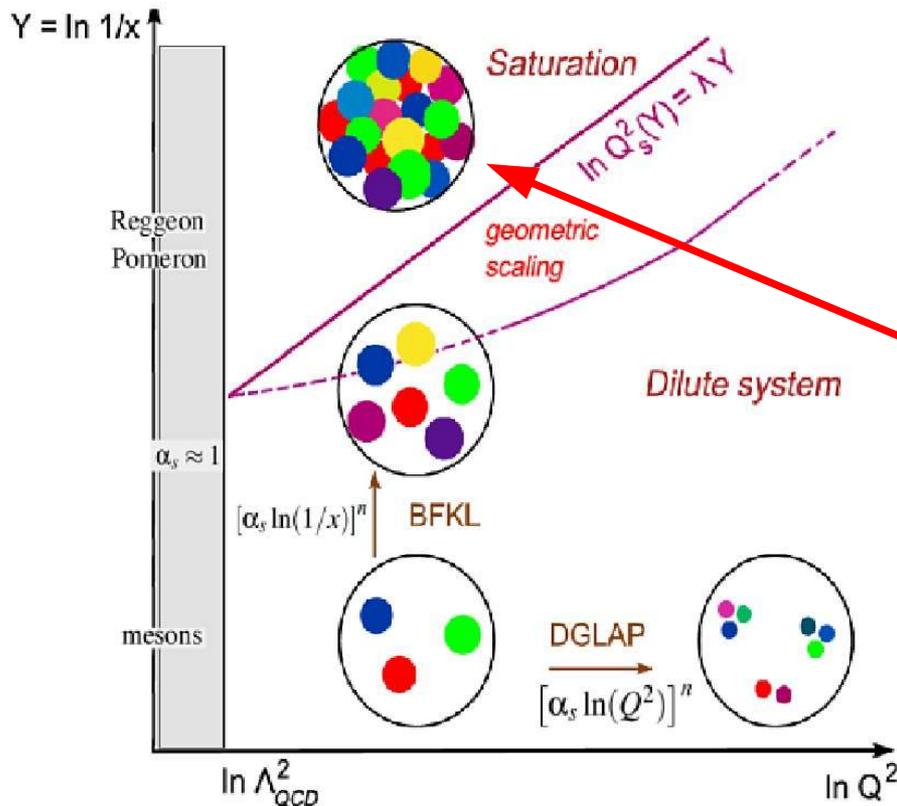
- HERA: **strong rise at low-x** of $F_2(x, Q^2) \propto$ sea-quarks, $\partial \ln F_2 / \partial \ln Q^2 \propto$ **gluons**



(x, Q^2) evolution of PDFs

- **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 (as a function of Q^2 , x)

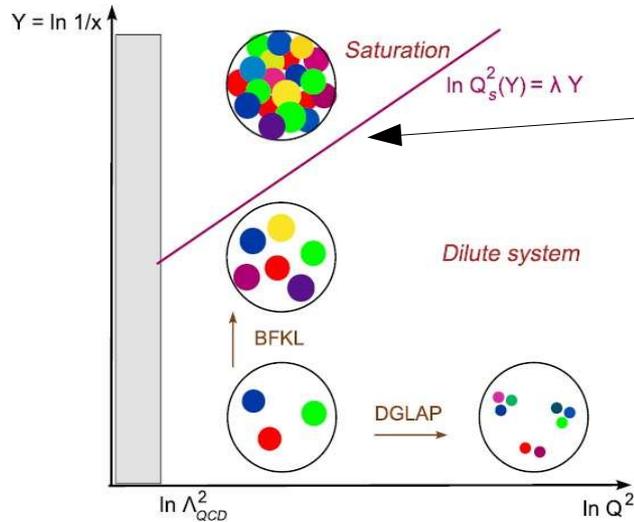
- DGLAP/BFKL cannot work at low- x (even less for multi-parton systems = nuclei):



- (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 scale” (Q_s)

- **Onset** of non-linear QCD when **gluons** are numerous enough (low-x) & “large” enough (low- Q^2) to **overlap**:



$$Q_s^2 \sim \alpha_s \frac{x G_A(x, Q_s^2)}{\pi R_A^2}$$

$$\sim A^{1/3} x^{-\lambda} \sim A^{1/3} (\sqrt{s})^\lambda \sim A^{1/3} e^{\lambda y} \quad \lambda \sim 0.3$$

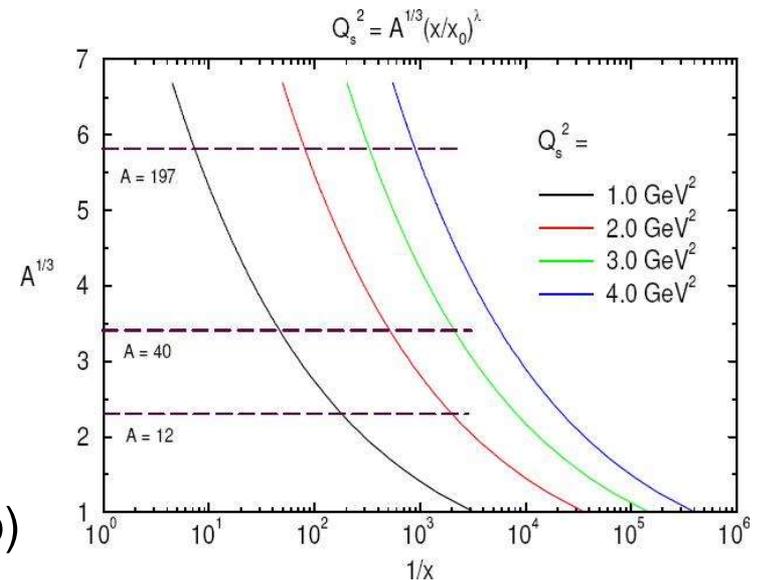
Saturation for: **low x, large s, large y, large A**

- **Nucleus** (larger parton transverse density) **amplifies saturation** effects:

$$Q_s^2 \sim A^{1/3} \sim 6$$

$$Q_s^2 \sim 1 \text{ GeV}^2 \text{ (HERA, p)}$$

$$Q_s^2 \sim 2 \text{ GeV}^2 \text{ (e)RHIC (Au), } 5 \text{ GeV}^2 \text{ (LHC, Pb)}$$

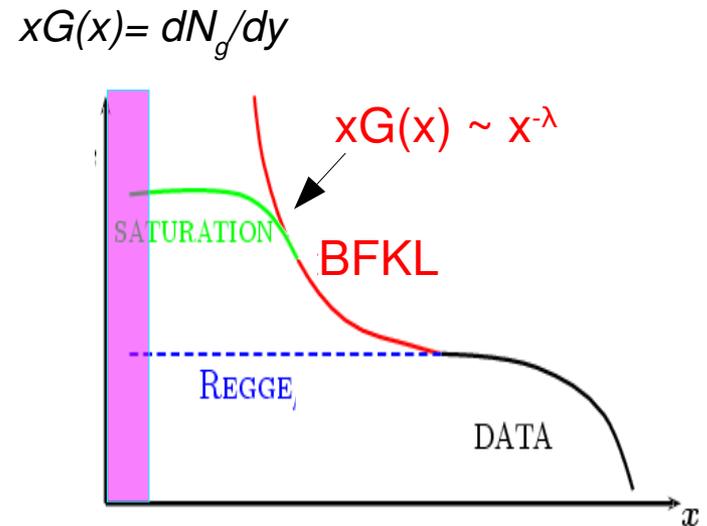
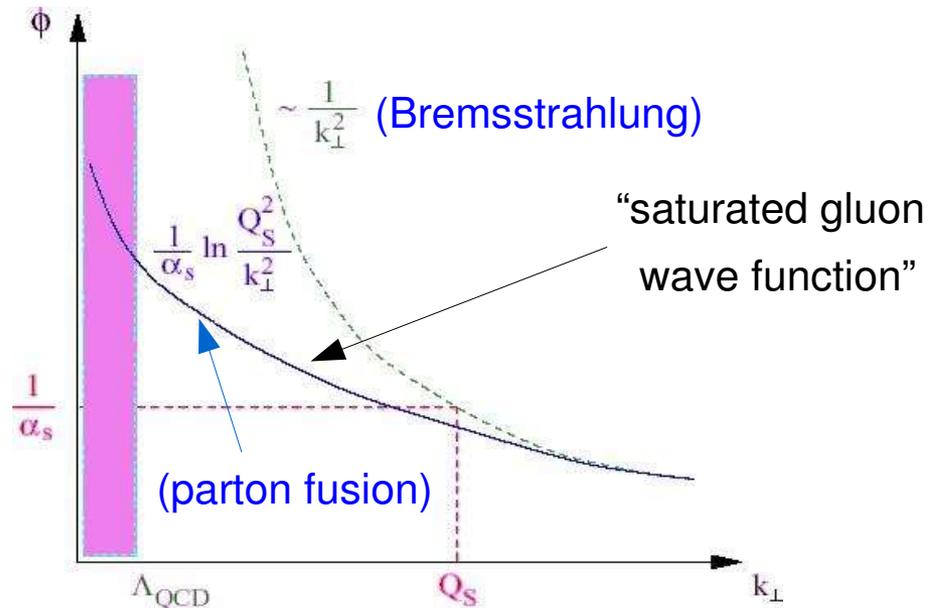


Color Glass Condensate (CGC)

[McLerran, Venugopalan, Kharzeev, Levin, Kovchegov, Jalilian-Marian, Mueller, Iancu, Gelis, Tuchin, Iakura, Dumitru, ...]

➤ CGC = EFT in high-energy (small-x) QCD limit:

- **C**olor (obvious) **G**lass ($q \sim$ “frozen” sources) **C**ondensate (high gluon occup.)
- Hadrons = **C**lassical fields below/around Q_s :



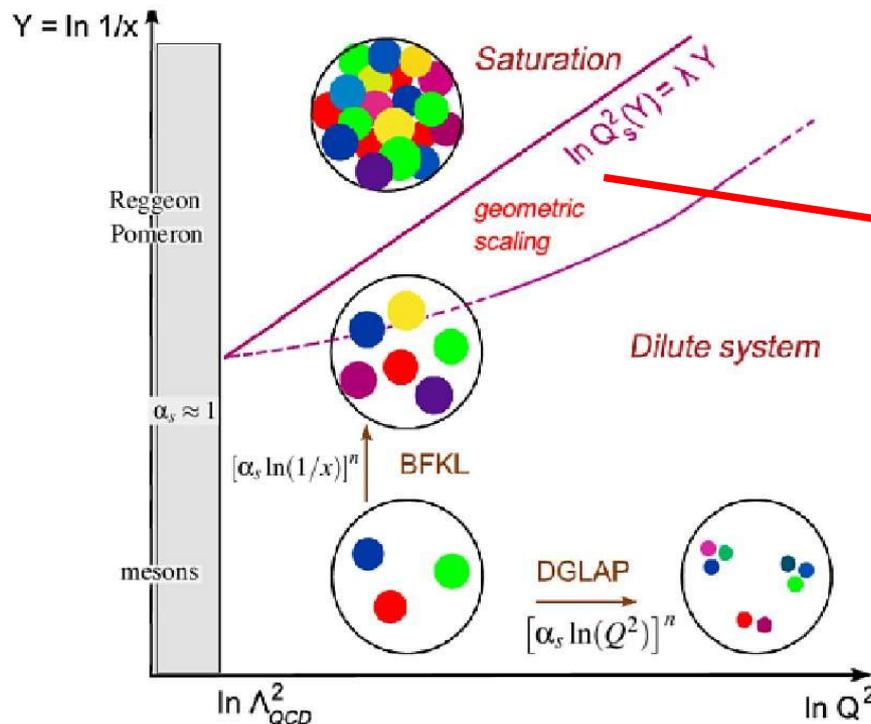
- Q_s hard \Rightarrow perturbative calculations (strong $F_{\mu\nu}$, weak coupling): $\alpha_S(Q_s^2) \ll 1$
- pA, AA \equiv collisions of gluon wave function(s) “resum” all multiple scatts.

Non-linear QCD evolution equations

➤ Gluon evolution at low-x: classical stochastic process of splitting & merging governed by **BK-JIMWLK** eqs.

- **Non-linear, all-twist** equations in saturation regime
- Generalized Fokker-Planck eq. (wave-function **diffusion**)
- **JIMWLK** → large N_c limit → **BK** → low-density limit → **BFKL**

[Balitsky, Kovchegov, Jalilian-Marian, Iancu, McLerran, Kovner, Leonidov, Weigert, ...]



Additional quantum corrections:
lead to anomalous dimension
in "extended scaling" region:

$$\frac{1}{Q^2} \rightarrow \left(\frac{1}{Q^2}\right)^\gamma \quad \gamma \simeq 1/2$$

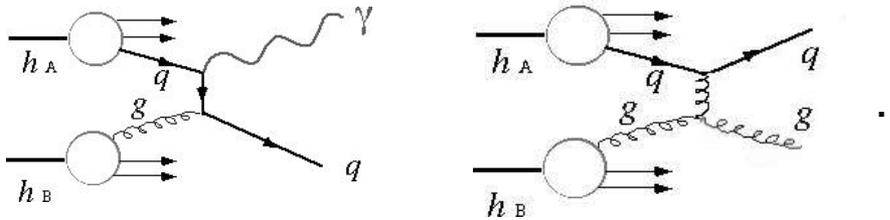
$$Q_s^2 < Q^2 < Q_s^4/\Lambda^2$$

extended window of
applicability **outside CGC** !

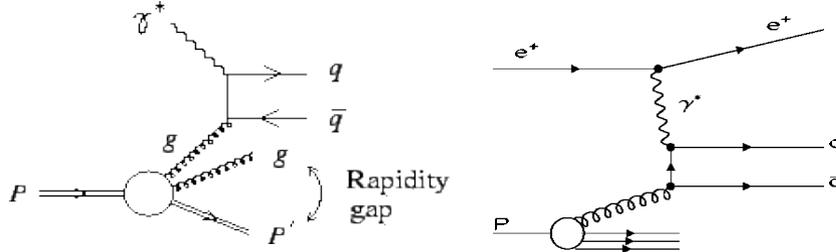
Experimental probes of gluon PDF ($\gamma^*p, pp, \gamma^*A, AA$)

➤ Perturbative processes:

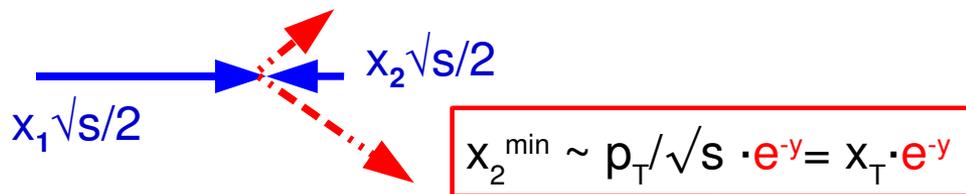
▶ Prompt γ , (di)jets (γ^*p, pp, AA):



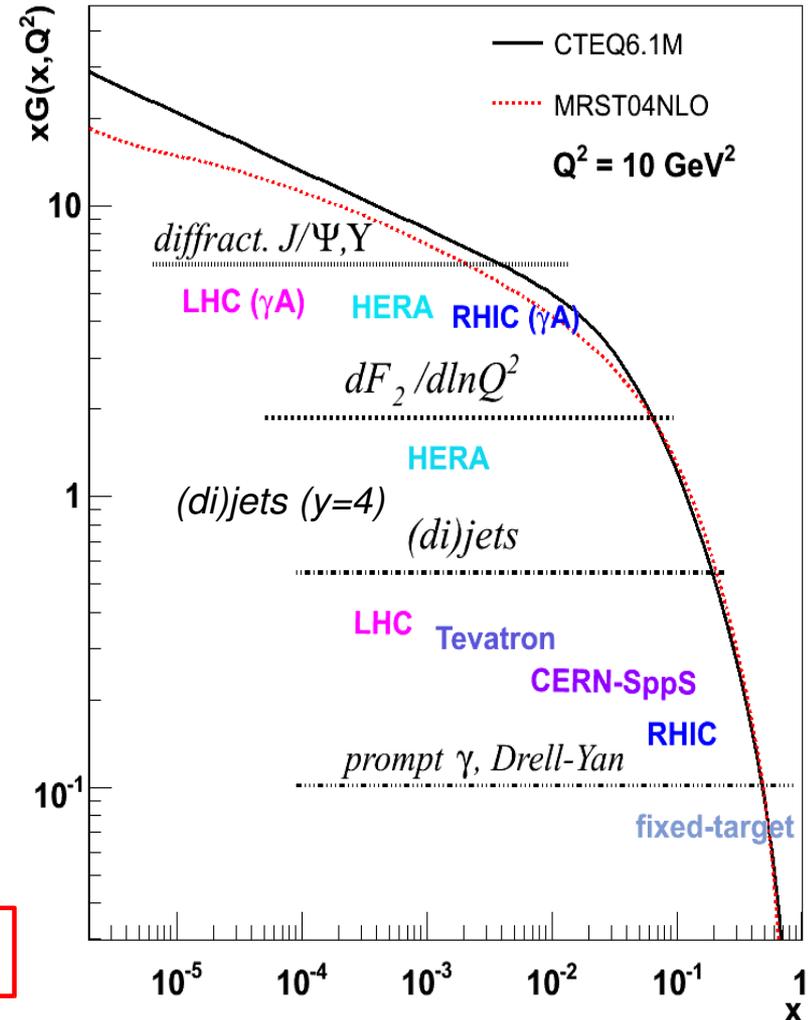
▶ Diffractive $Q\bar{Q}$, heavy-Q (γ^*p, γ^*A):



➤ Forward production:

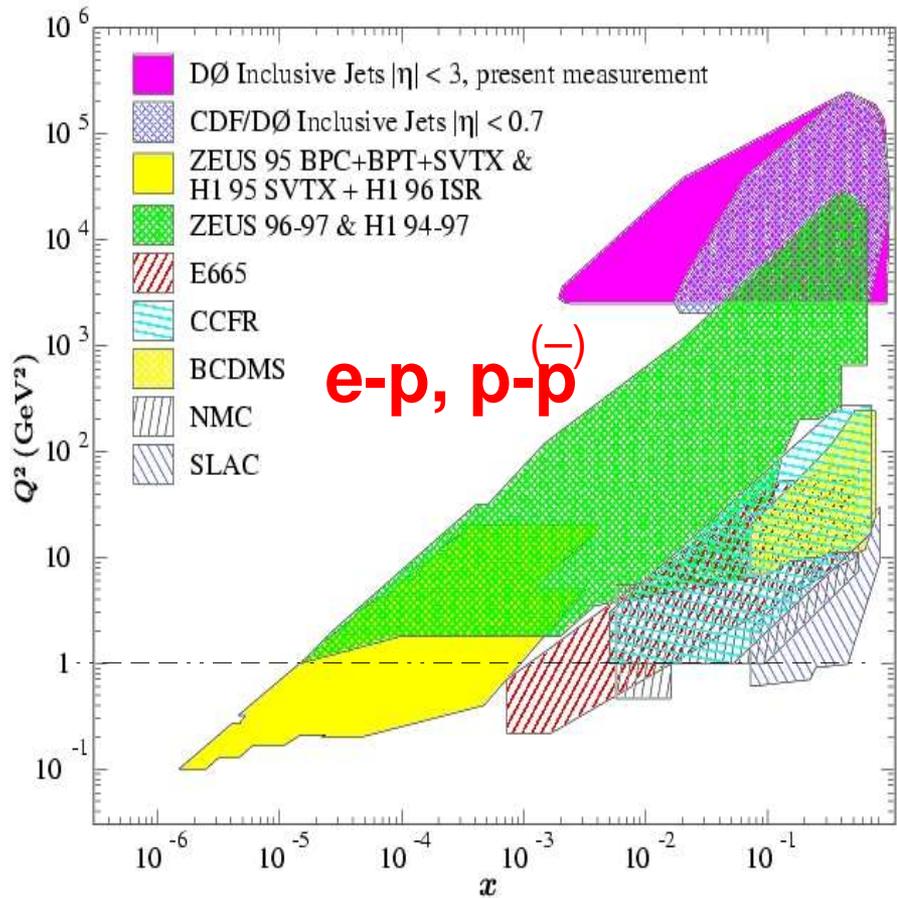


Every 2-units of y , x^{\min} decreases by ~ 10

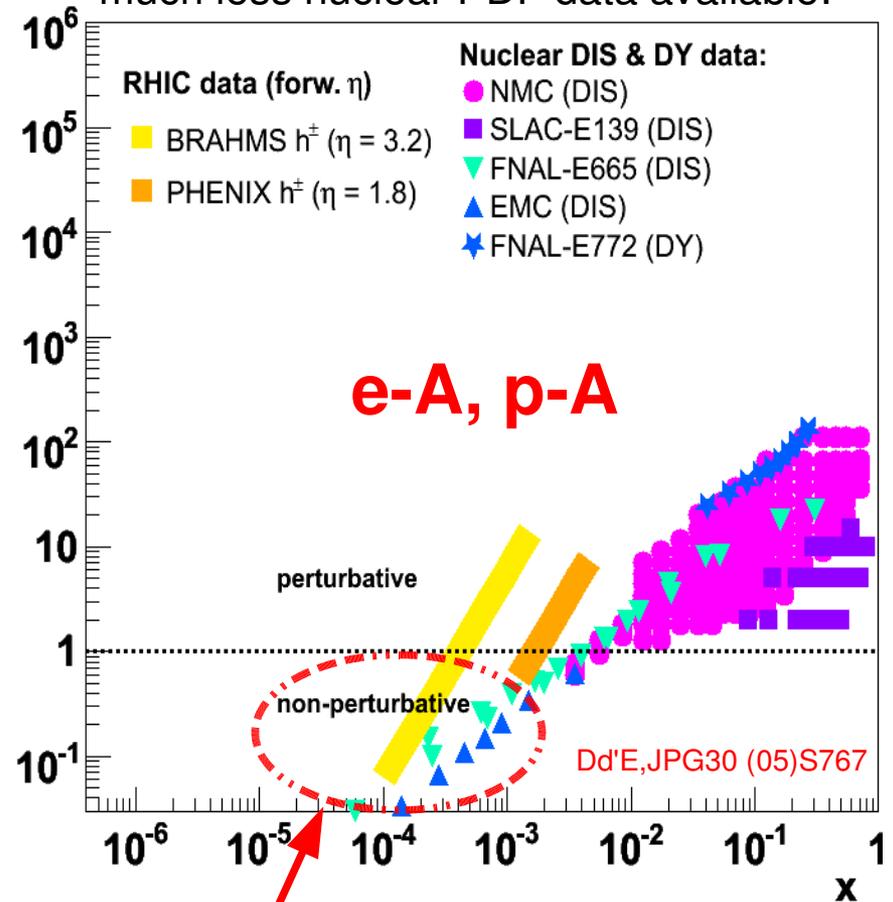


PDF (x, Q^2) exp. domains: proton, nucleus

➤ Kinematical (x, Q^2) domains covered experimentally:



much less nuclear PDF data available:

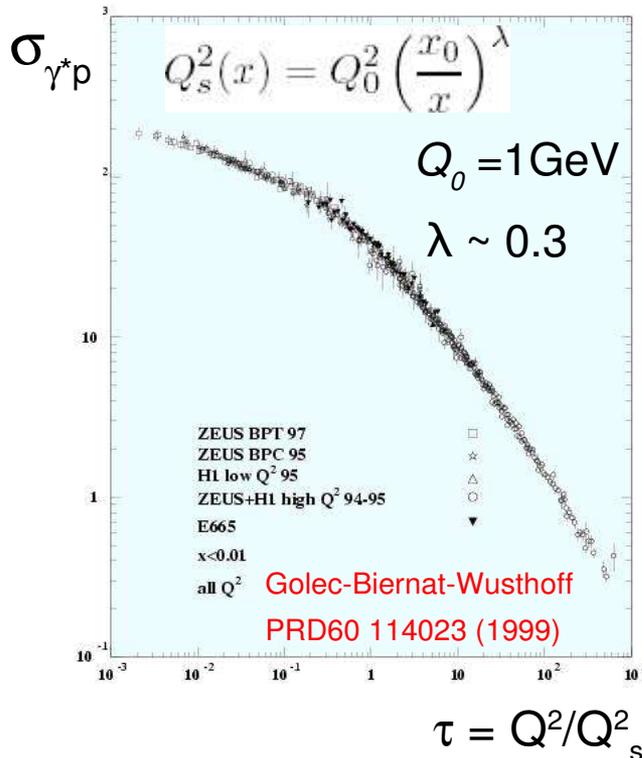


➤ Note: most existing **low-x nPDFs** measurements in the **non-perturbative** range

Saturation hints at HERA ?

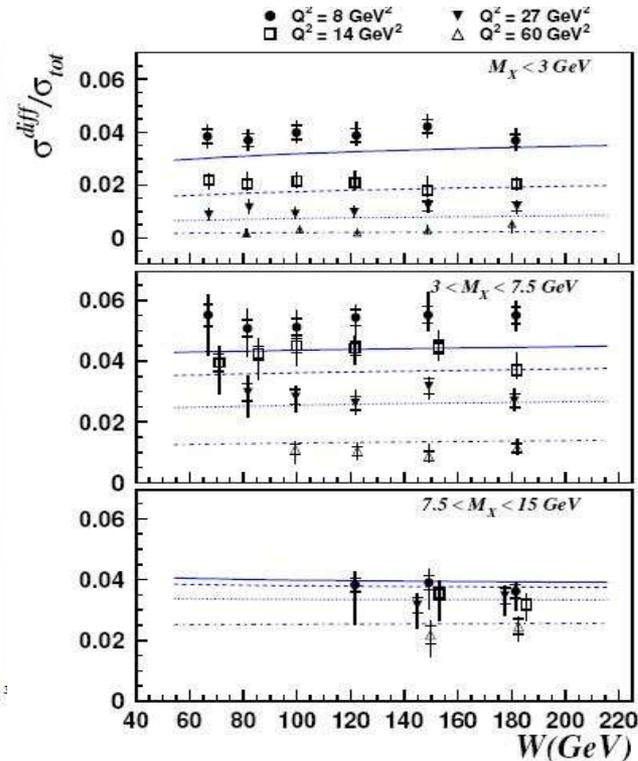
➤ DGLAP fits most of ep data ... Saturation models explain better a few cases:

“Geometric scaling”



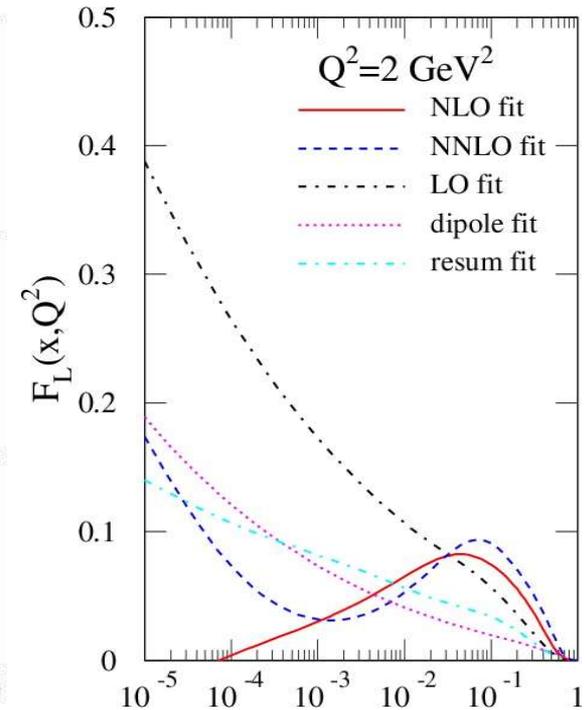
Inclusive DIS x-section depends on **single scale** Q^2/Q_s^2 for $x < 0.01$

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



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

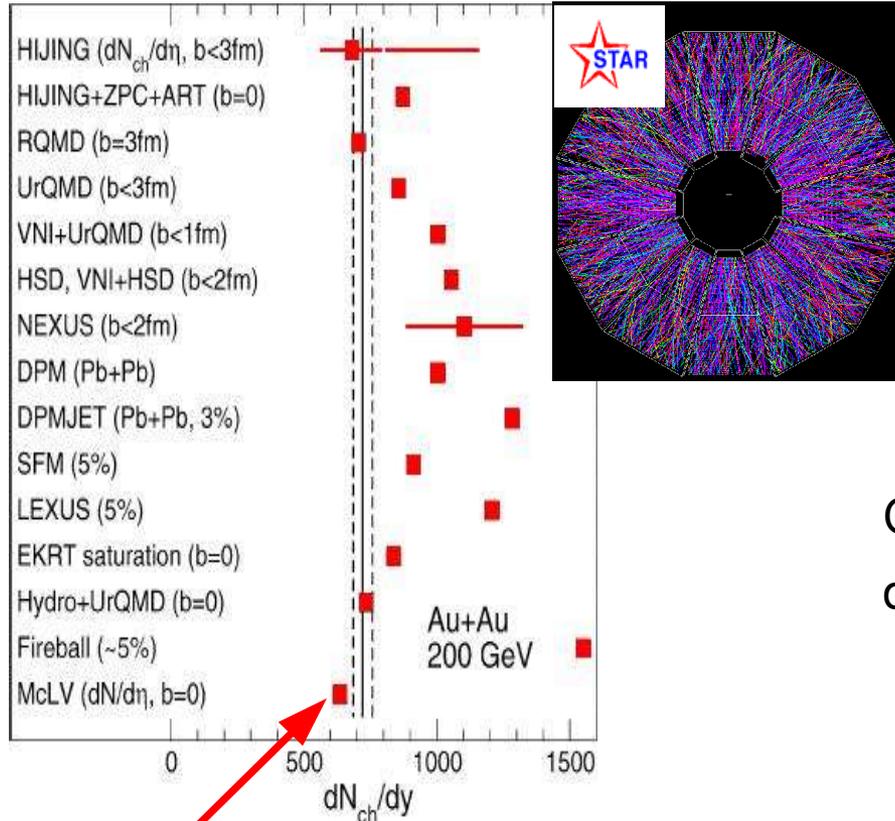
Longitudinal struc. funct.



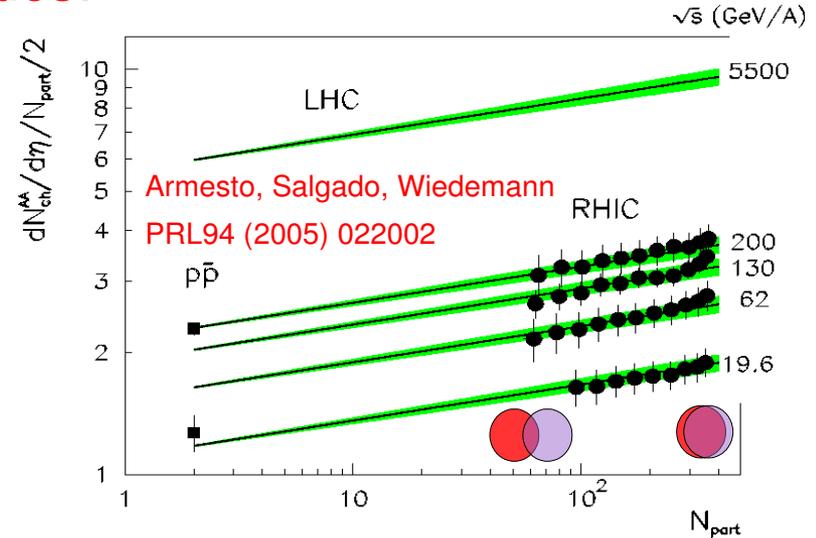
Gluon (F_L) at NLO becomes **negative** for $Q^2 \sim 2 \text{ GeV}^2$ at low- x

Saturation hints at RHIC ? (AuAu @ 200 GeV)

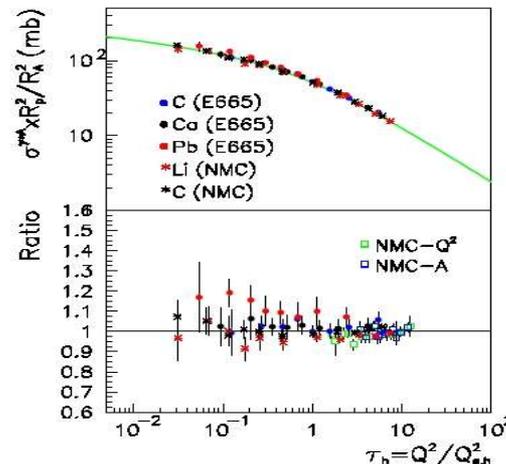
➤ “Reduced” total AuAu hadron multiplicities:



$dN_{ch}/d\eta \sim 650$ at $\eta=0$ described by CGC
(or models which include **reduced incoming parton flux**)



Centrality & sqrt(s) dependence of $dN/d\eta$ described by **geometric-scaling** models

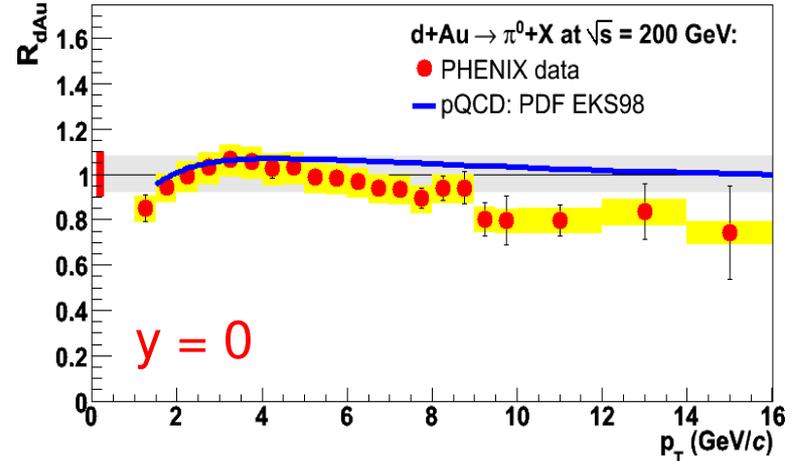
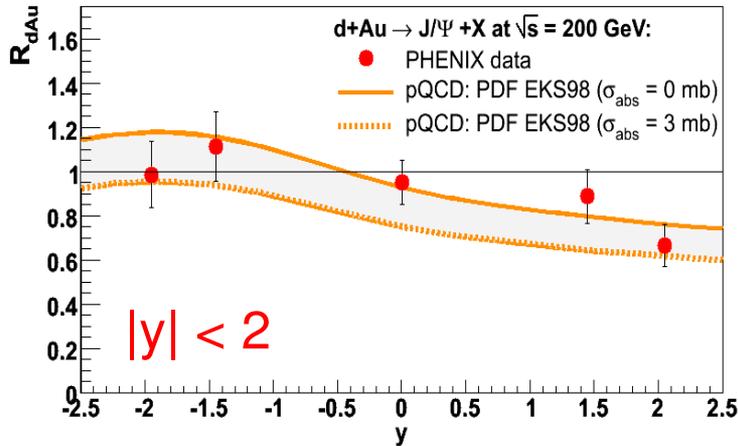


Confirms approx:

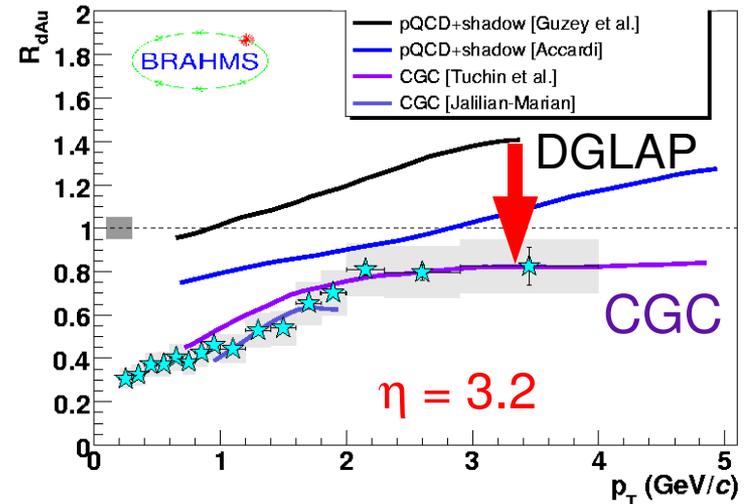
$$Q_s^2 \sim A^{1/3}$$

Saturation hints at RHIC ? (dAu @ 200 GeV)

➤ $y \sim 0$ ($x \sim 10^{-2}$): **Hard** hadroprod. described by **NLO pQCD** + mild LT shadowing:



➤ $\eta = 3.2$ ($x \sim 10^{-3}$): **Suppressed hadron production** ($p_T \sim 2 - 4$ GeV/c) better described by **CGC** than NLO pQCD: reduced partonic flux in Au at low-x



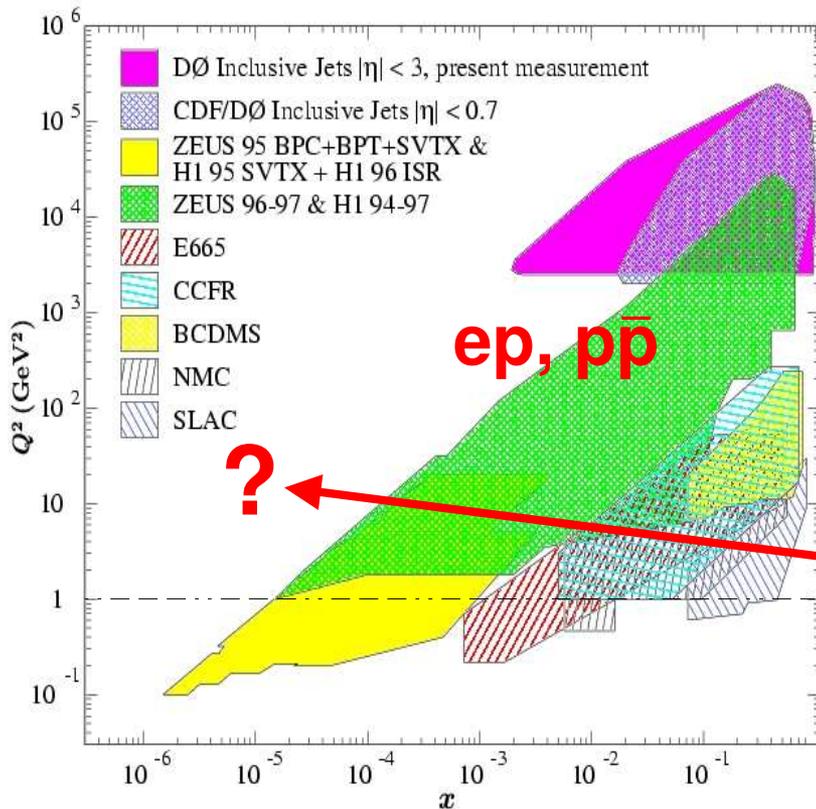
LHC: low- x proton PDF studies

➤ pp @ 14 TeV :

(i) At $y=0$, $x=2p_T/\sqrt{s} \sim 10^{-3}$ (domain probed at HERA, Tevatron). Go fwd. for $x < 10^{-4}$

(ii) Saturation momentum: $Q_s^2 \sim 1 \text{ GeV}^2$ ($y=0$), 3 GeV^2 ($y=5$)

(iii) **Very large perturbative** cross-sections:



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

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

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

$$p(p_1) + p(p_2) \rightarrow Q + \bar{Q} + X \quad \text{Heavy flavour}$$

$$p(p_1) + p(p_2) \rightarrow W/Z + X \quad \text{W,Z production}$$

LHC **forward** rapidities:

e.g. $y \sim 6$, $Q \sim 10 \text{ GeV}$

x down to 10^{-6} !

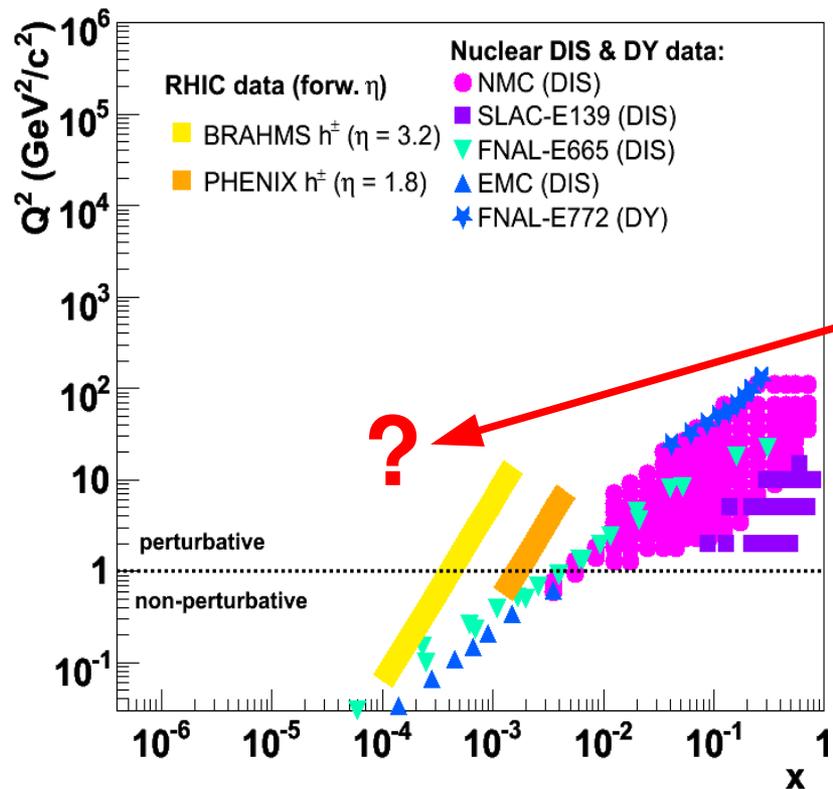
LHC: low- x nuclear PDF studies

➤ PbPb @ 5.5 TeV, pPb @ 8.8 TeV:

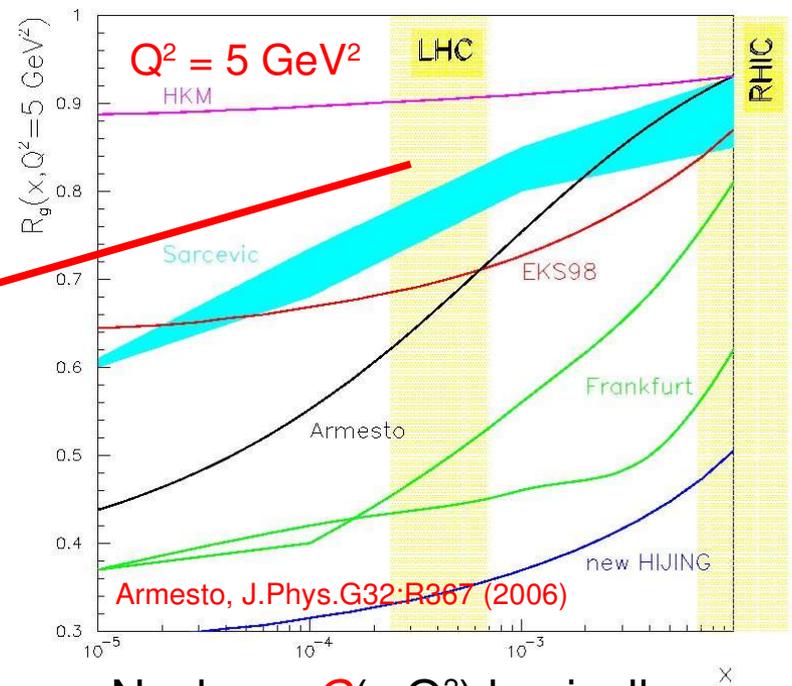
(i) Very high $\sqrt{s} \Rightarrow$ Bjorken $x=2p_T/\sqrt{s} \sim 30\text{-}45$ times lower than AuAu,dAu @ RHIC !

(ii) Saturation momentum ($A^{1/6} \sim 6$) : $Q_s \sim [5 \text{ GeV}^2]e^{(0.3y)}$

(iii) Very large perturbative cross-sections.



Ratio of Pb/p gluon densities:



Nuclear $xG(x, Q^2)$ basically unknown for $x < 10^{-3}$!

Forward Detectors in CMS & ATLAS

➤ CMS + TOTEM:



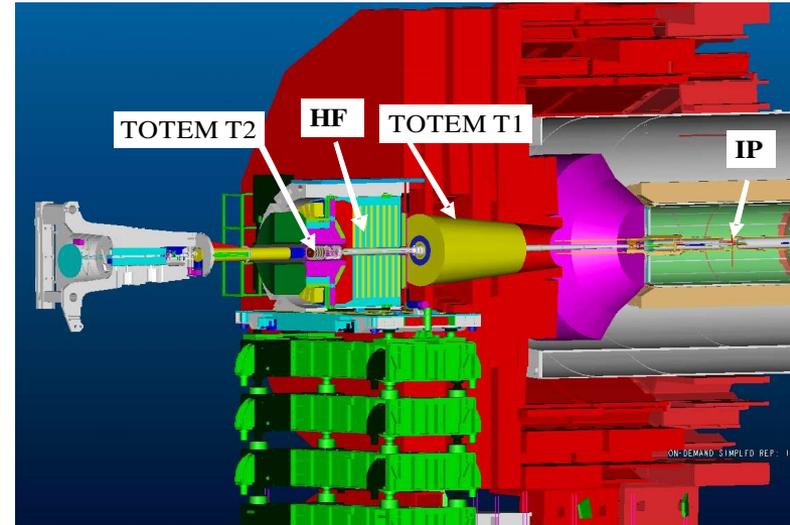
HF (Iron-Q-fiber calo): $3 < \eta < 5$

TOTEM-T1 (CSC telescope): $3.1 < \eta < 4.7$

TOTEM-T2 (GEM telescope): $5.3 < \eta < 6.7$

CASTOR (W/-Q-fiber calo): $5.3 < \eta < 6.5$

ZDC (W/Q-fiber calo): $\eta > 8.3$ (neutral)



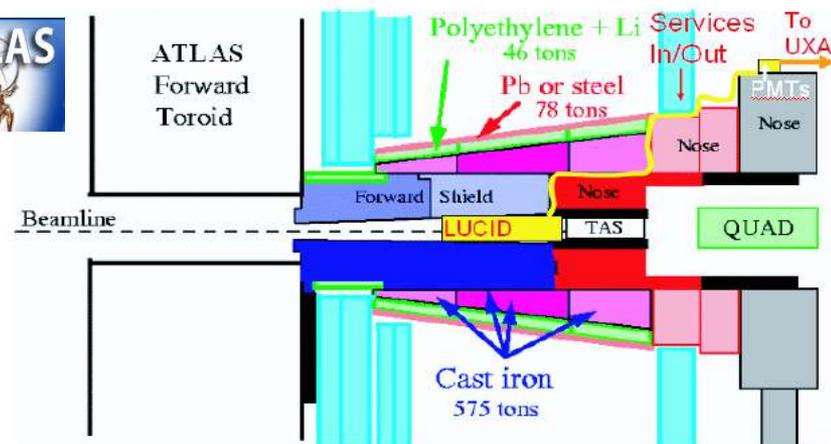
➤ ATLAS:



FCal.: $3 < \eta < 5$

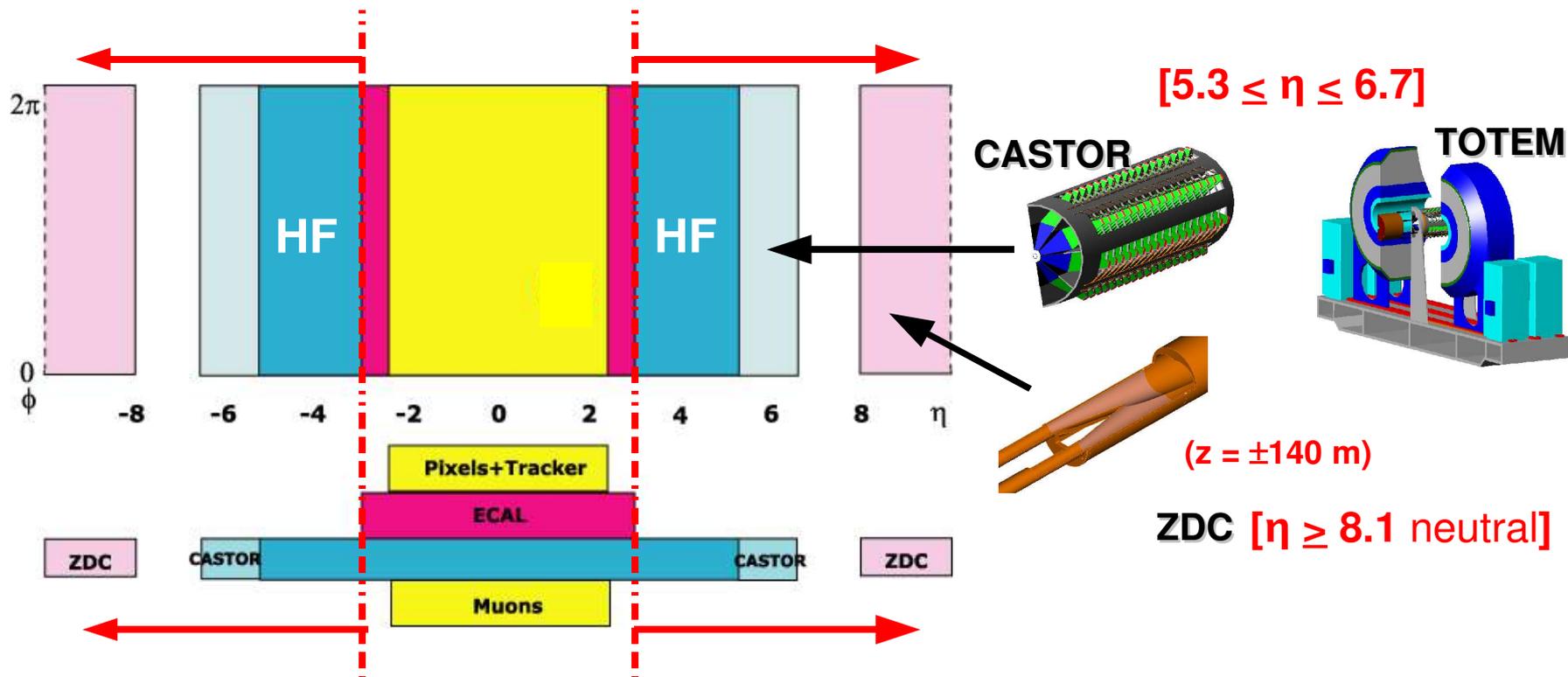
LUCID (Cerenkov Counter): $5.4 < \eta < 6.1$

ZDC (W/Q-fiber calo): $\eta > 8.3$ (neutral)



CMS/TOTEM at the LHC

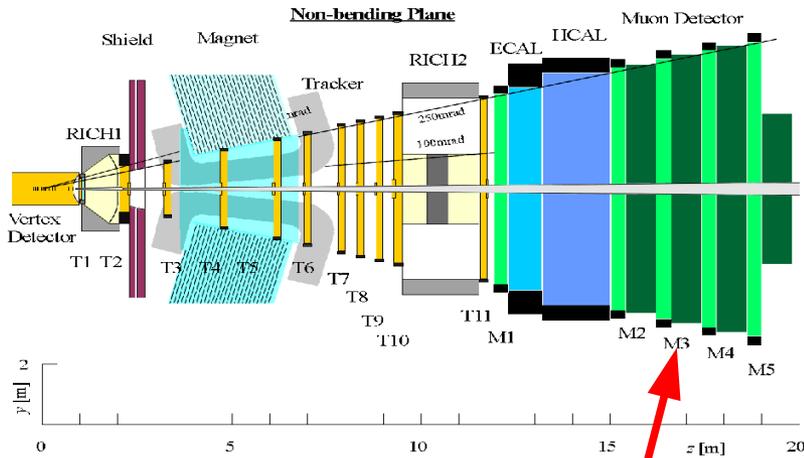
- HF, CASTOR, ZDC + TOTEM: Quasi-full acceptance at LHC:



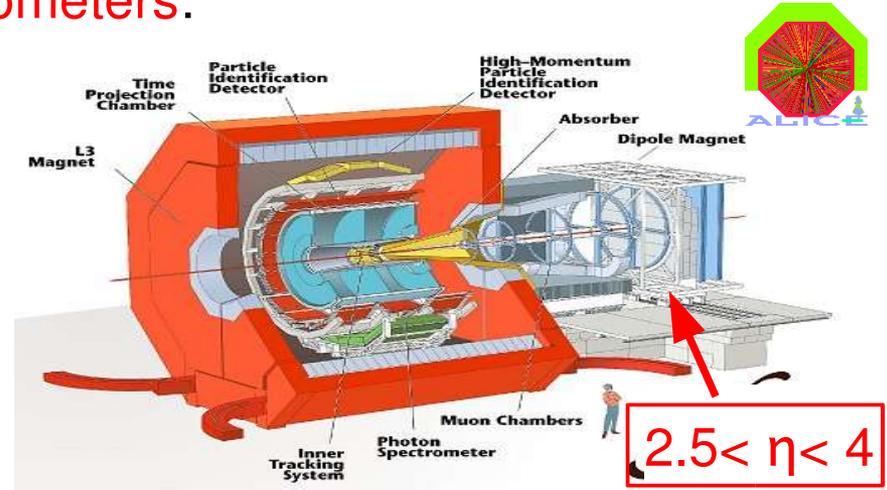
- Detection capabilities within $\eta \leq 6.7$ (and $\eta \geq 8.1$, neutral).
- Hard scattering measurements (jets, high- p_T hadrons, DY) possible down to $x \sim 10^{-6}$ in pp, pA, AA at LHC.

Forward Detectors in ALICE & LHCb

➤ ALICE, LHCb forward muon spectrometers:

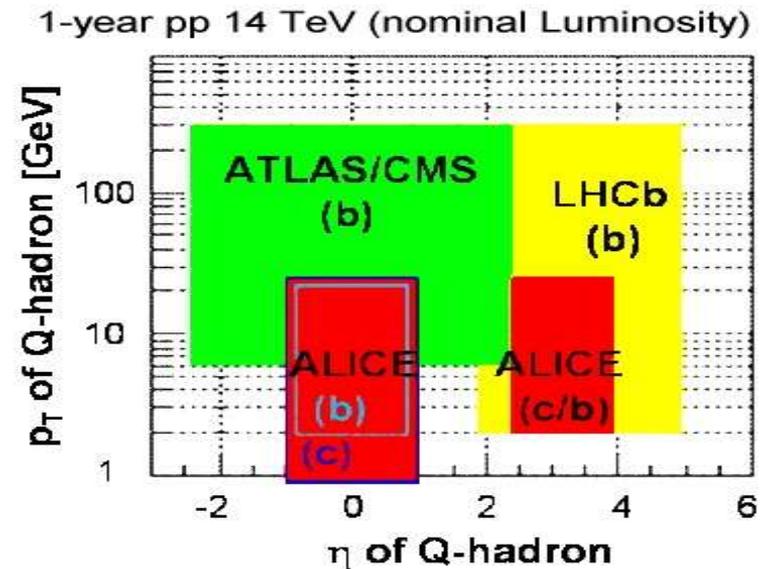


$2 < \eta < 5$



$2.5 < \eta < 4$

➤ Excellent capabilities for heavy-Q, QQbar fwd. measurements at low-x:

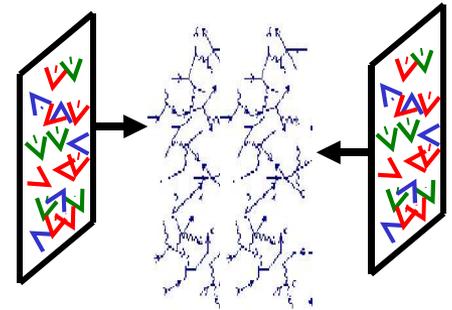


Case-study I: Total PbPb hadron multiplicity

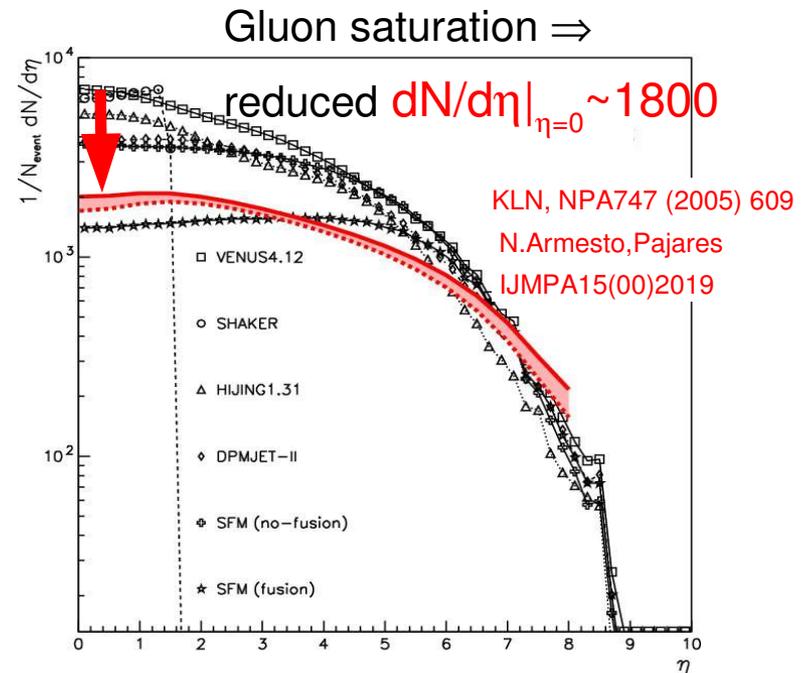
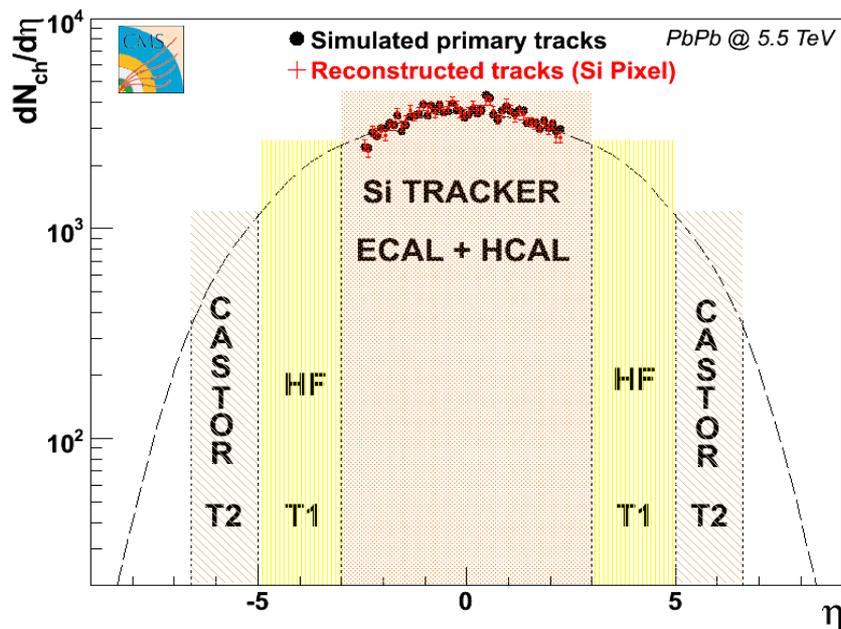
- Final A+A multiplicity \propto Initial number of released gluons :

CGC:
$$\frac{dN}{d^2bd\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x, Q_s^2) \cdot A^{1/3}$$

+ “local parton-hadron duality” (1 gluon = 1 final hadron)



- CMS $dN_{ch}/d\eta$ ($|\eta| < 2.5$) via hit counting in Si pixel layers:



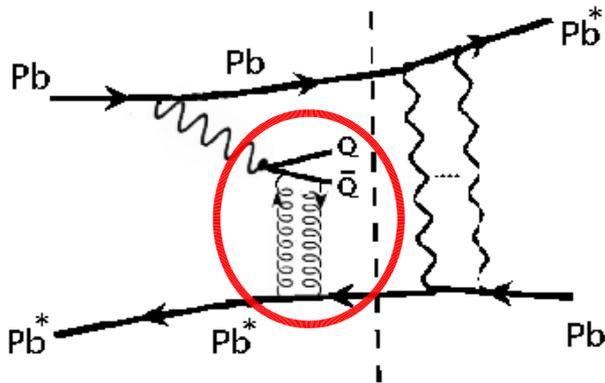
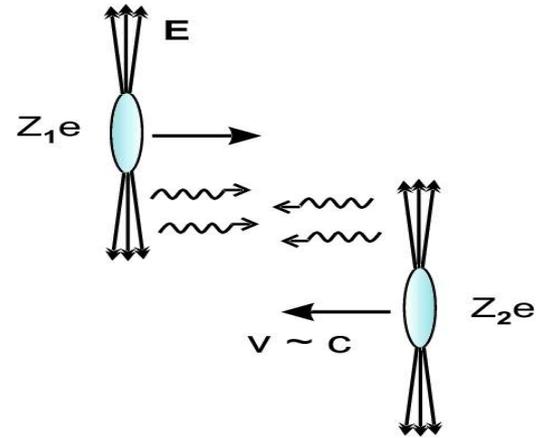
Case-study II: Υ photoprod. (γ Pb) in UPC PbPb

- High energy heavy-ions produce **strong electromagnetic fields** due to the coherent action of $Z = 82$ protons:
- Equivalent **flux of photons** in EM (aka. Ultra-Peripheral, $b_{\min} \sim 2R_A \sim 20$ fm) AA colls.:

Max. γ energy: $E_{\gamma_{\max}} \sim 80$ GeV (PbPb-LHC)

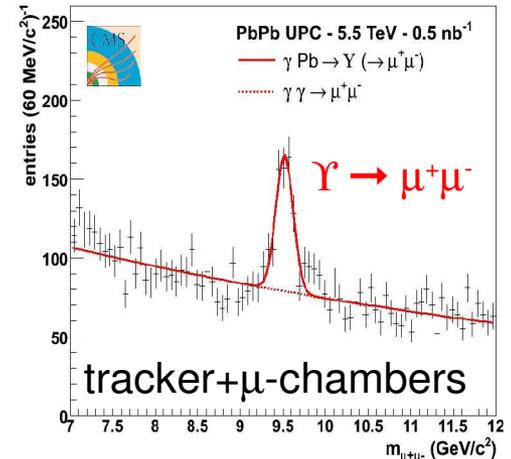
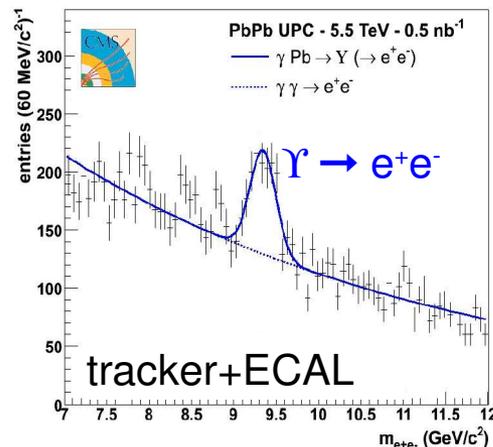
γ Pb: max. $\sqrt{s}_{\gamma\text{Pb}} \approx 1$ TeV \approx **3. - 4. $\times \sqrt{s}_{\text{p}}(\text{HERA})$**

- QQ diffract. photoprod. sensitive to **gluon density squared**:



$$y=0 : x(\Upsilon) = 2 \cdot 10^{-3}$$

$$y \sim 2 : x(\Upsilon) \sim x(y=0) \cdot e^{-y} \sim 10^{-4}$$

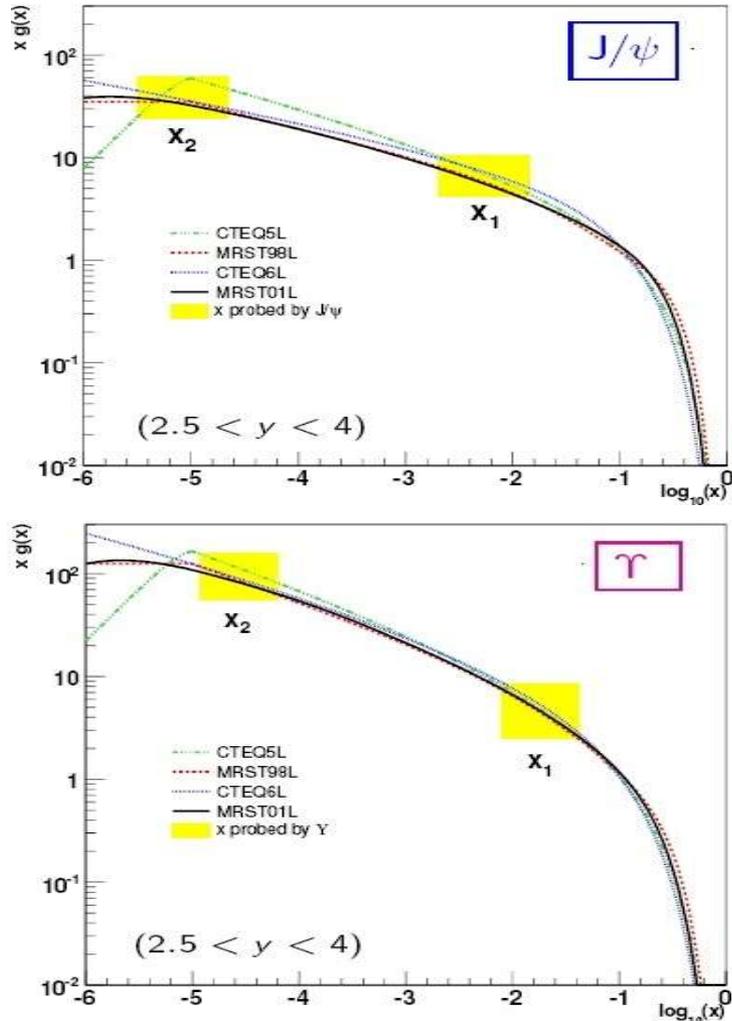


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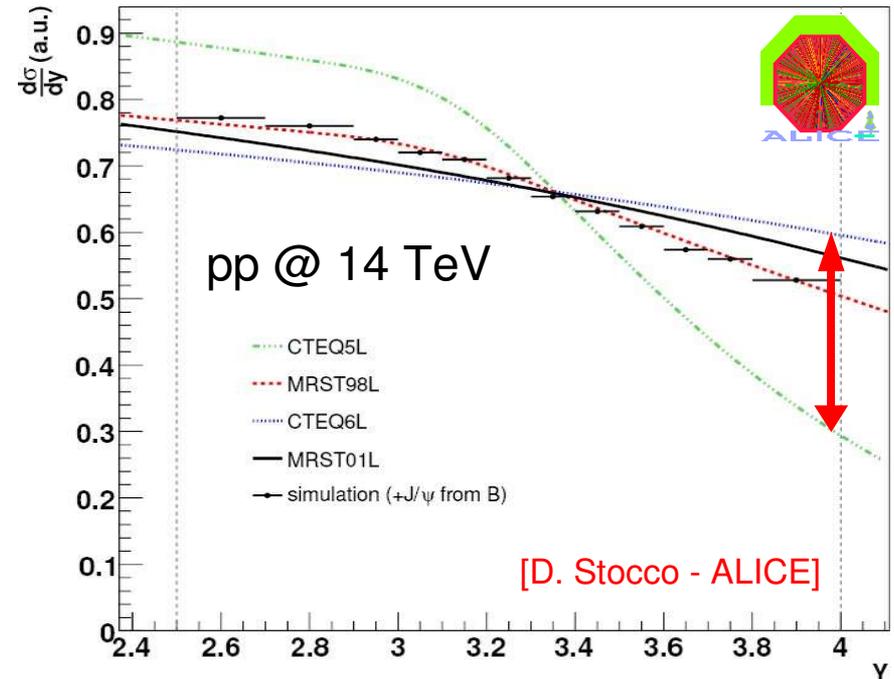
~ 500 Υ expected (0.5 nb^{-1}): unexplored $xG_A(x, Q^2)$

Case-study III: Forward $Q\bar{Q}$ in ALICE ($2.5 < |\eta| < 4$)

➤ J/ψ measurement in μ spectrometer: $xg(x)$ in the proton at $x_2 \sim 10^{-5}$:



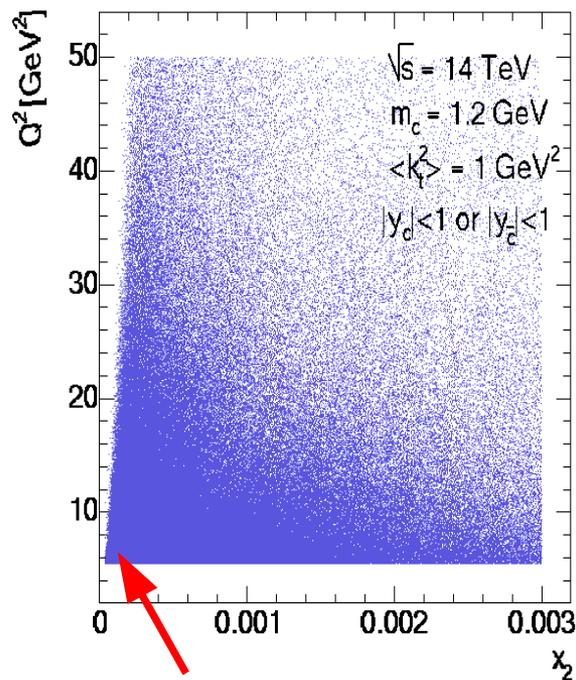
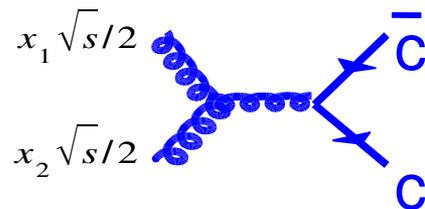
$d\sigma/dy$ J/ψ : NLO CEM w/ varying PDFs



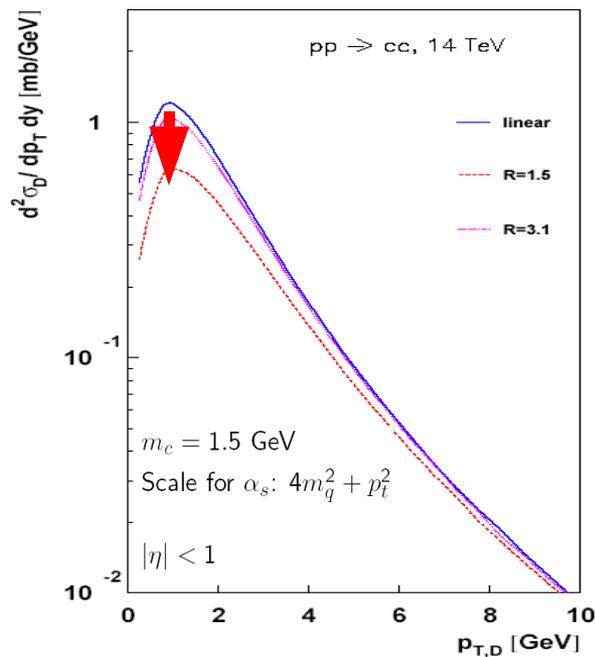
$Q\bar{Q}$ bar: Sensitive to diff. PDFs and
DGLAP versus CGC predictions

Case-study IV: Low- p_T charm in ALICE ($|\eta| < 1$)

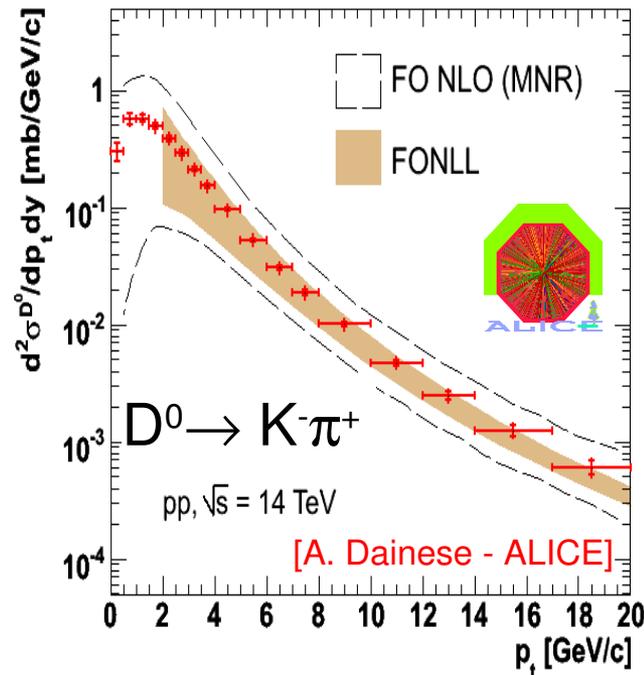
➤ Open charm measurement in TPC+TRD ($y=0$):



$xg(x)$ in the proton
at $x_1 \sim x_2 \sim m_c / \sqrt{s} \sim 10^{-4}$



Charm suppression
due to non-linear QCD
effects



Good reco capabilities
(displaced vtx. + e^\pm PID)
down to $p_T = 0$ GeV/c

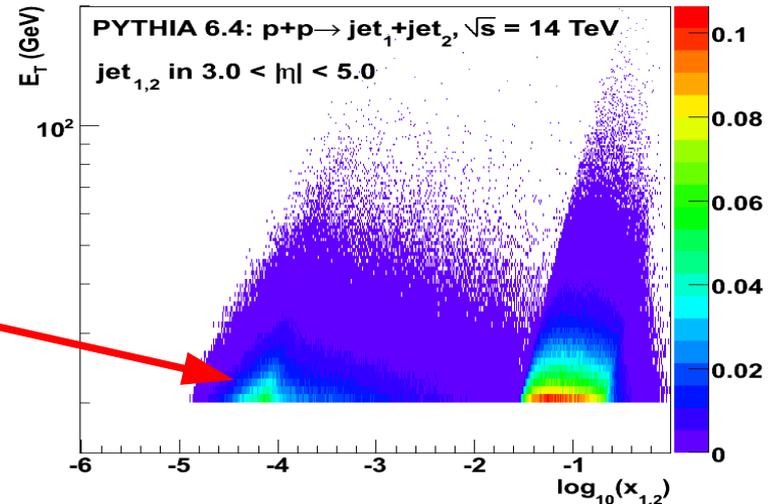
Case-study V: Forward jets in CMS ($3 < |\eta| < 5$)

➤ Forward “soft” jets ($E_T \sim 20\text{-}100$ GeV):

$p + p \rightarrow jet1 + jet2 + X$ (VBF-Higgs trigger)

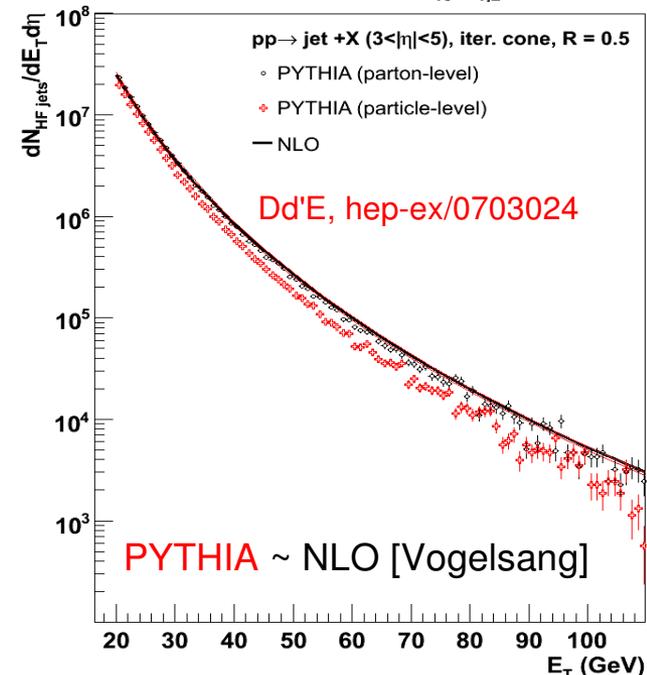
Sensitive to partons with: $x_2 \sim 10^{-4}$

Jets in CASTOR ($5.3 < |\eta| < 6.6$): $x_2 \sim 10^{-6}$



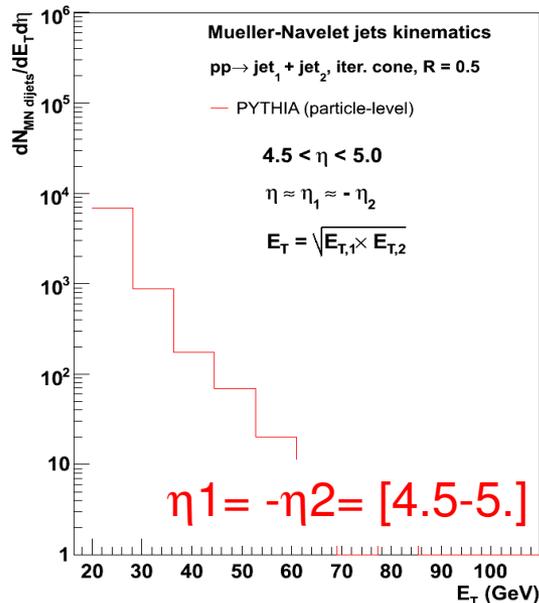
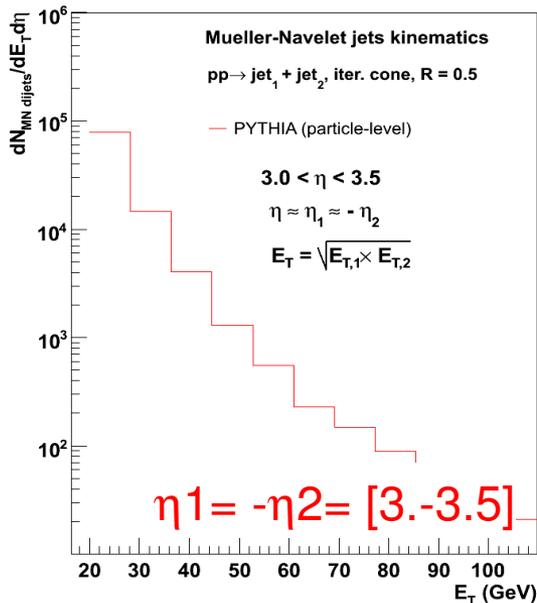
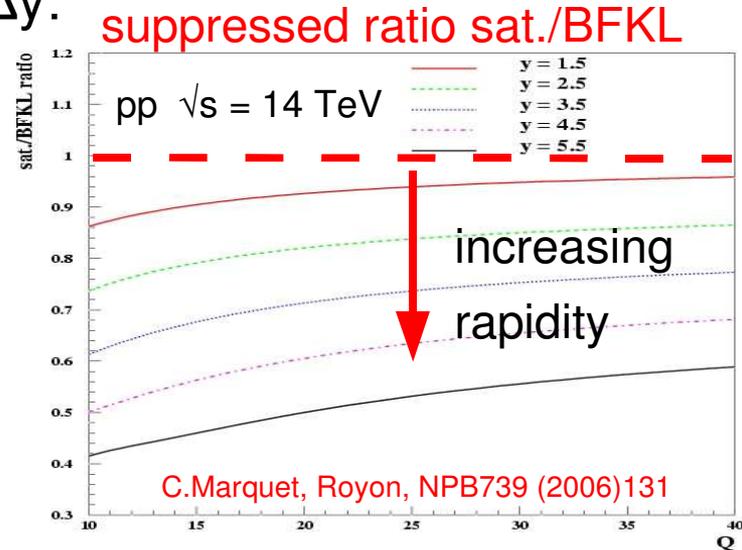
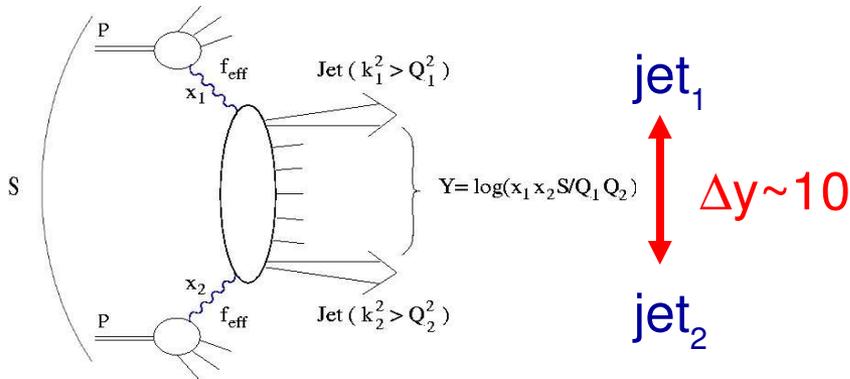
➤ Inclusive fwd. jet reconstruction (HF):

- PYTHIA 6.4. min-bias (hard&soft QCD)
- MC-level proof-of-principle only
- HF grid: $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$
- Iterative cone, $R=0.5$, $E_{\text{thresh}}=10$ GeV, $E_{\text{seed}}=3$ GeV
- Missing important corrections: underlying-evt.
(PYTHIA CMS-Tune), hadronization (cluster vs. Lund)
- Large yields. Low- E_T uncertainties to be determined.



Case-study VI: Mueller-Navelet dijets in CMS-HF

- Mueller-Navelet dijets separated by large Δy : very sensitive to non-DGLAP evolution

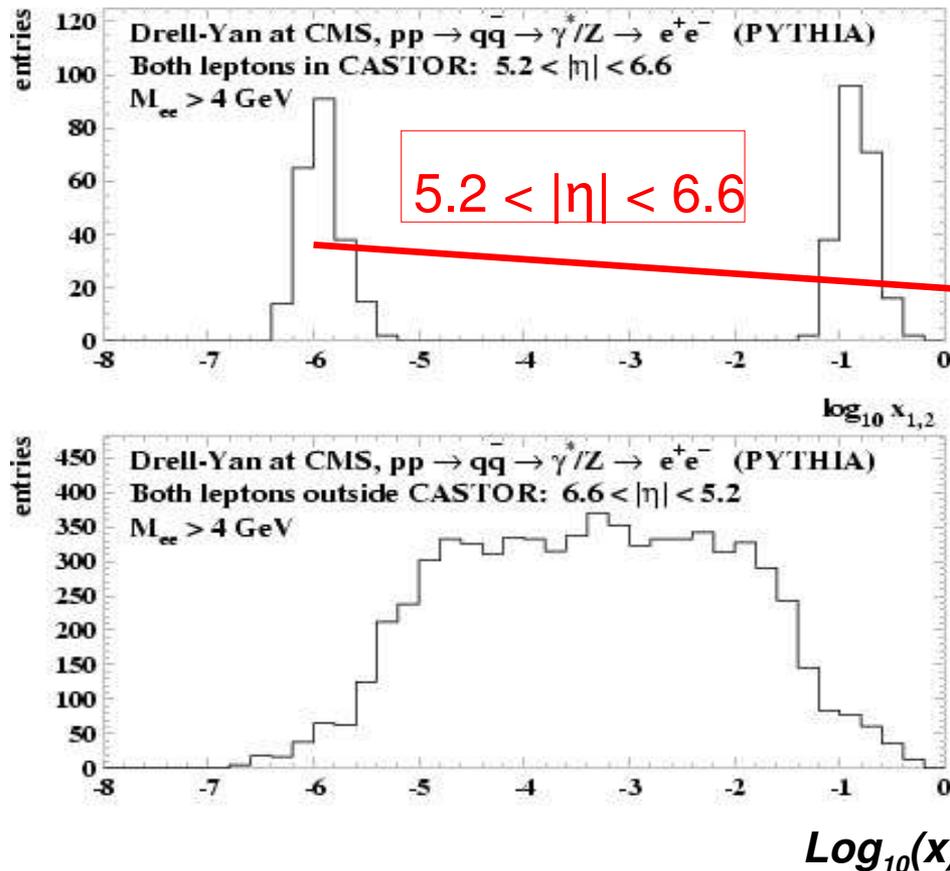


PYTHIA rates with M-N kin.
cuts: $\sim 10^4$ dijets [$E_T \sim 30$ GeV]
in $\mathcal{L} \sim 1 \text{ pb}^{-1}$ (low luminosity run): enough stats. for detailed studies of Δy -evolution.

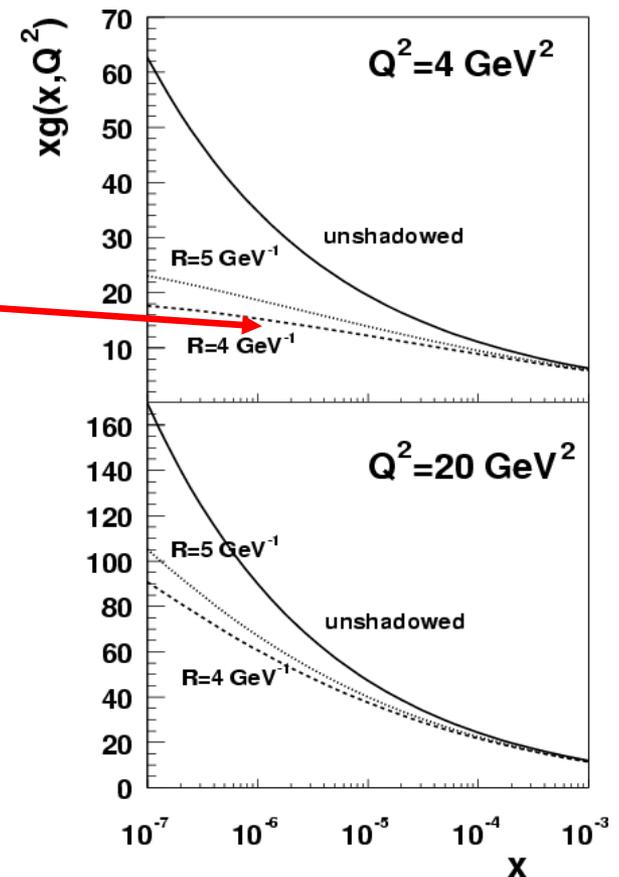
Dd'E, hep-ex/0703024

Case-study VII: DY in CASTOR-T2 ($5.2 < |\eta| < 6.6$)

- Drell-Yan **feasibility** studies with CMS (CASTOR) + TOTEM (T2):
- Sensitive to low-x **quark** densities



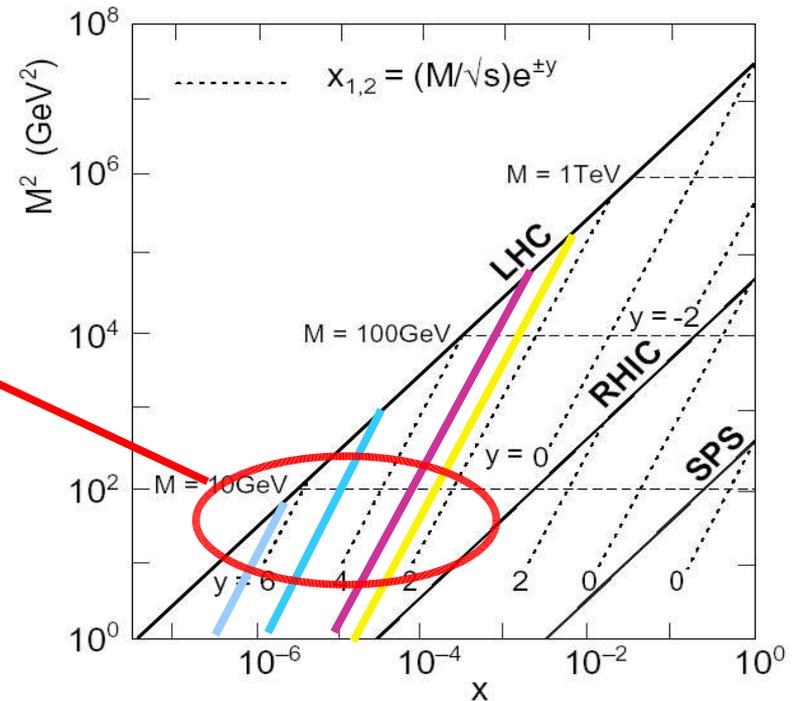
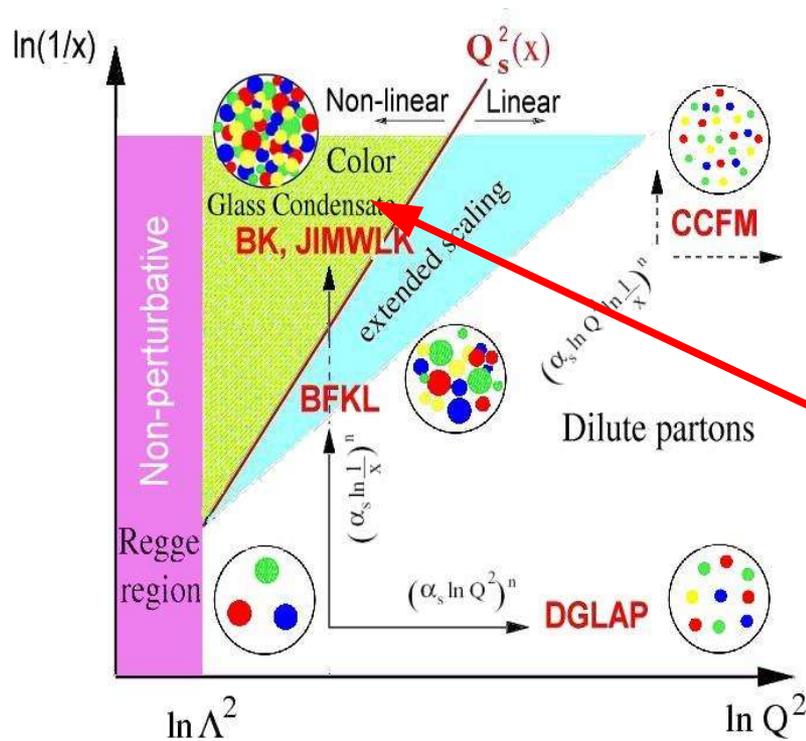
PDF parametrizations



TOTEM T2 tracker+ CASTOR needed to deal w/ **large QCD (& QED) bckgd.**

Summary

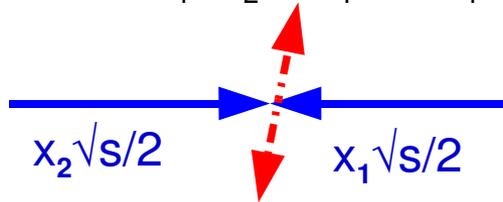
- **Gluon saturation & non-linear evolution** must set-in at (some) low-x in hadronic wave-functions → Fundamental info on **high-energy limit of QCD**
- **Hints** of non-linear QCD dynamics in *ep* (**HERA**) and dA,AA (**RHIC**)
- **LHC = unique lab** to study **high parton density**/evolution in p,Pb down to $x \sim 10^{-6}$ using **fwd. detectors** and **perturbative** processes: (di)jets, QQbar, DY, ...



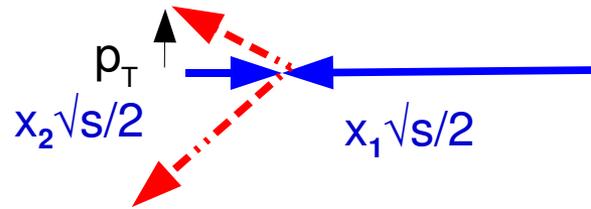
Backup slides

Small-x \rightarrow Forward rapidities

- $2 \rightarrow 2$ parton kinematics:
 $y = 0$: $x_1 \sim x_2 \sim x_T = 2p_T/\sqrt{s}$



$$x_{1,2}^{2 \rightarrow 2} = \frac{p_T}{\sqrt{s}} (e^{\pm y} + e^{\pm y'}) \Rightarrow x_2^{\min} = \frac{x_T e^{-\eta}}{2 - x_T e^{\eta}}$$



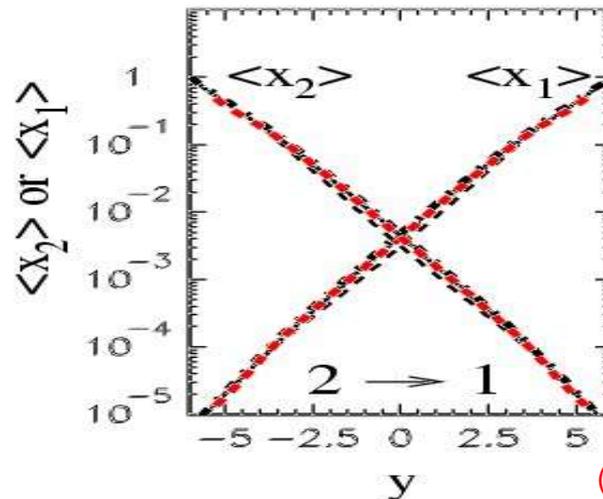
e.g. LHC, $p_T = 10$ GeV/c
 $\theta \sim 10^{-3}$ ($\eta \sim 7$): $x_{\min} \sim 10^{-6}$

- $2 \rightarrow 1$ (gluon fusion) CGC kinematics: much lower x allowed ($x_2 \sim x_2^{\min}$)

$$x_{1,2}^{2 \rightarrow 1} = \frac{p_T}{\sqrt{s}} (e^{\pm y})$$

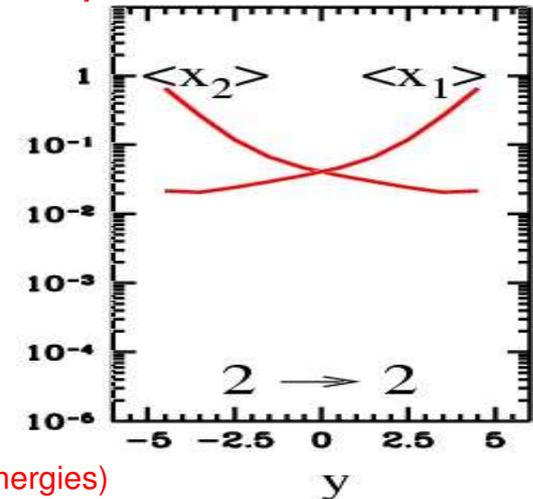
Every 2-units of y ,
 x_2 decreases by ~ 10

CGC: $x(y=4) \sim 10^{-4}$



(RHIC energies)

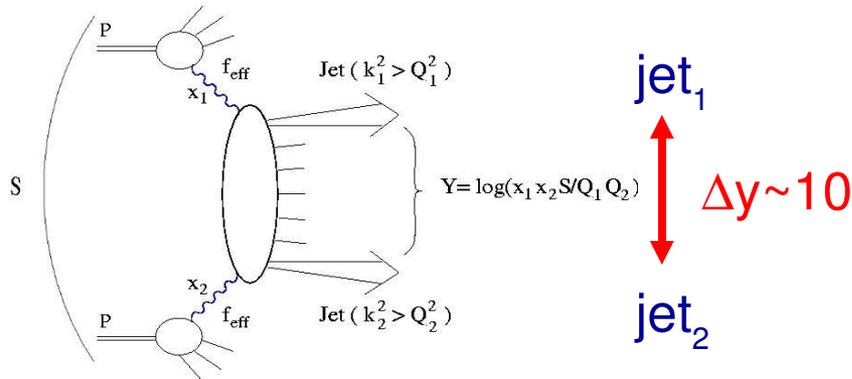
pQCD: $x(y=4) \sim 10^{-2}$



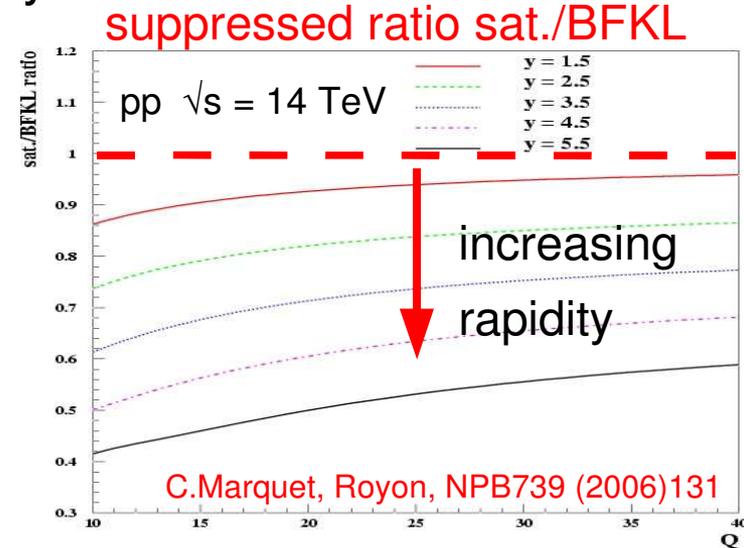
[Accardi,nucl-th/0405046]

Case-study V: Mueller-Navelet dijets in CMS-HF

- **Mueller-Navelet dijets** separated by large Δy :
very **sensitive to non-DGLAP evolution**



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



- Proof-of-principle study in CMS: MC-level dijet reconstruction applying **MN kinematics cuts** to PYTHIA pp-14 TeV:

- $E_{T,i} > 20 \text{ GeV}$
- $|E_{T,1} - E_{T,2}| < 2.5 \text{ GeV}$ (similar virtuality, to minimise DGLAP-evolution)
- $3 < |\eta_{1,2}| < 5$ (both jets in HF)
- $\eta_1 \cdot \eta_2 < 0$ (each jet in a different HF)
- $|\eta_1| - |\eta_2| < 0.25$ (almost back-to-back in pseudo-rapidity)

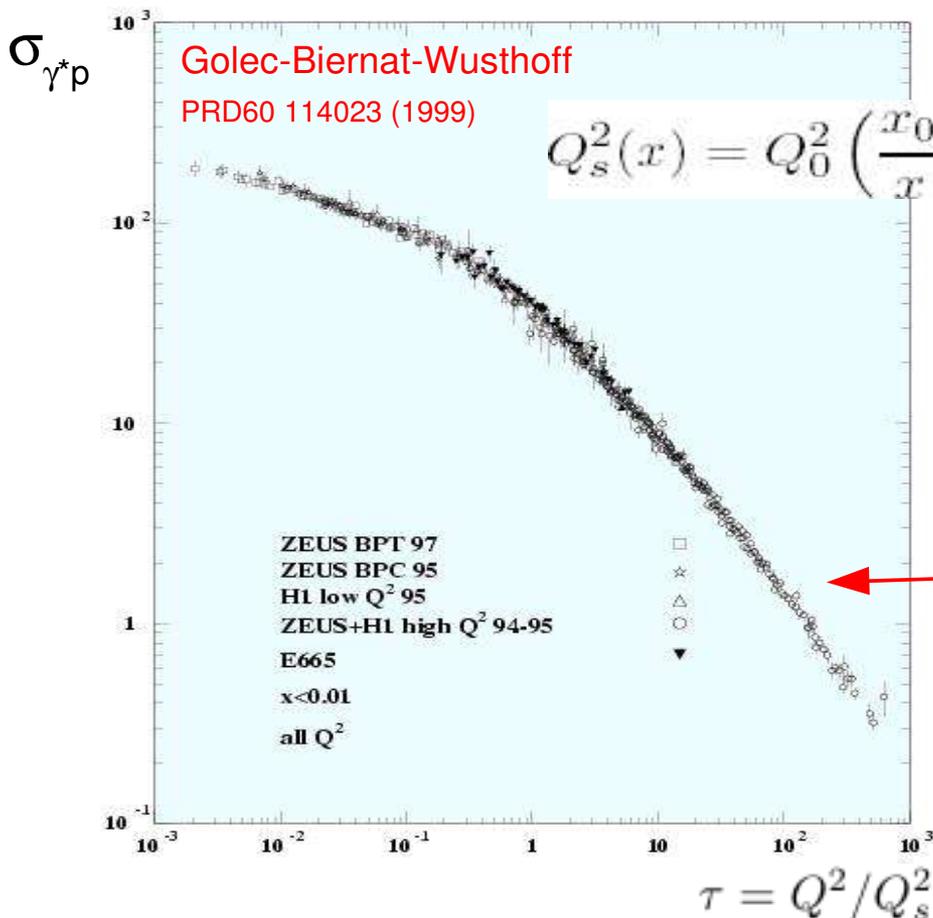
$$\frac{d^2\sigma}{d\eta dQ} = \frac{N_{jets}}{\Delta\eta\Delta Q} \int \mathcal{L} dt$$

$$Q \equiv \sqrt{E_{T,1} \cdot E_{T,2}}$$

HERA (incl. DIS): “Geometric scaling” of σ_{γ^*p} at low- x

- Saturation predicts low- x structure depends on single scale $Q_s^2(x)$

Inclusive DIS cross-section scales with Q^2/Q_s^2 for $x < 0.01$ ($0.045 < Q^2 < 450 \text{ GeV}^2$)



σ_{γ^*p} described by **dipole model**:
particular realization of CGC
where $\sigma_{\text{dipole-p}} \sim f(G(x)) \sim f(Q_s)$

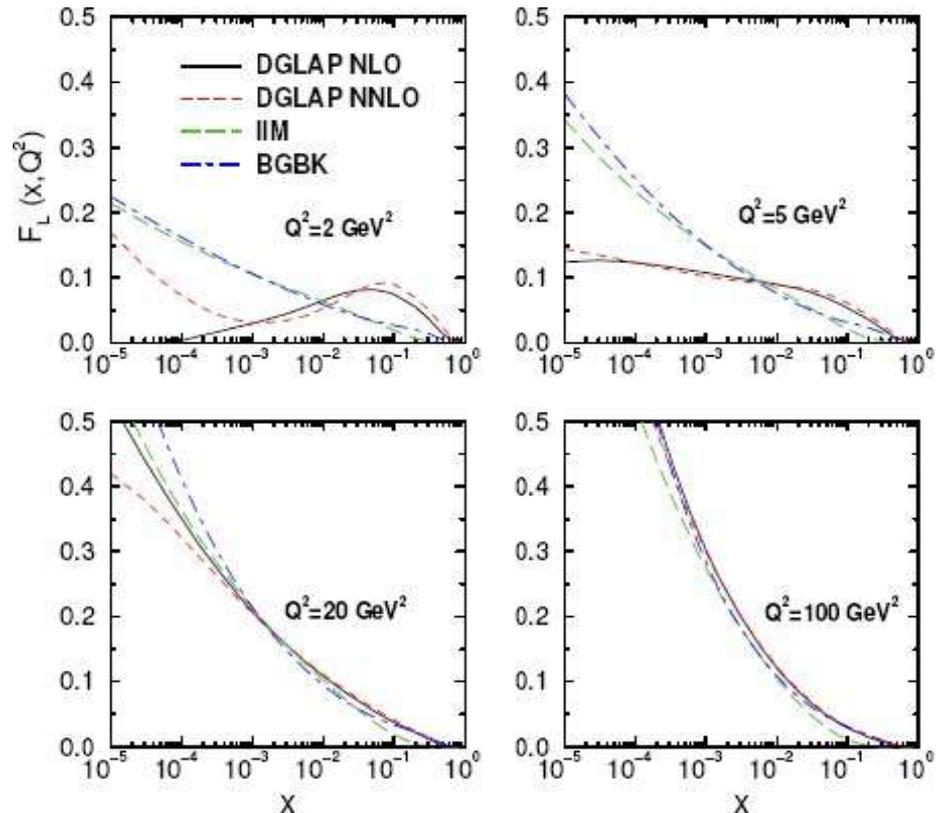
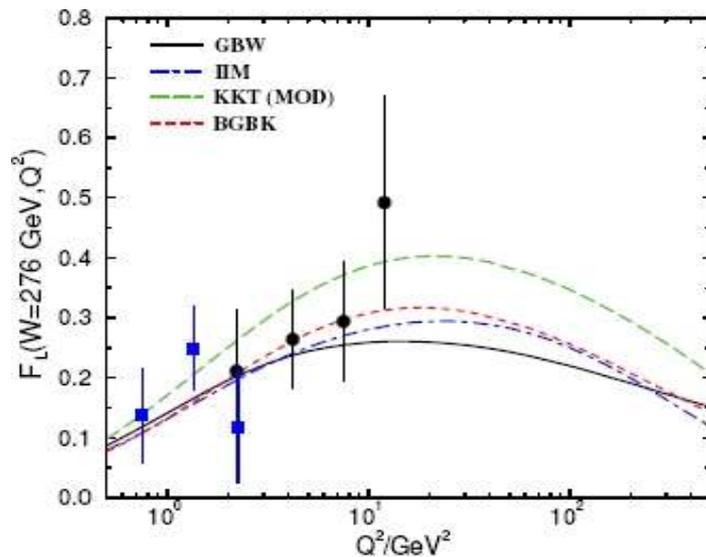
Scaling valid up to large Q^2
 (“**extended scaling**” region):

$$Q_s^2 < Q^2 < Q_s^4/\Lambda^2$$

[Note: DGLAP also shows this property but much more sensitive on $xG(Q^2)$ fit chosen]

HERA (DIS): F_L at low- x

- F_L **directly** depends on **gluon PDF**. DGLAP predicts $F_L < 0$ for $Q^2 \sim 2 \text{ GeV}^2$!
- F_L much more sensitive to saturation corrections than F_2 scaling violat.
- Direct **measurement** of F_L expected at HERA in June'07 (**ep at lower \sqrt{s}**)



HERA: $\sigma_{\text{diffract}}/\sigma_{\text{tot}}$ ratio

Inclusive hard diffraction

[K. Golec-Biernat and M. Wüsthoff]

Naively, in perturbative (or Regge) approach

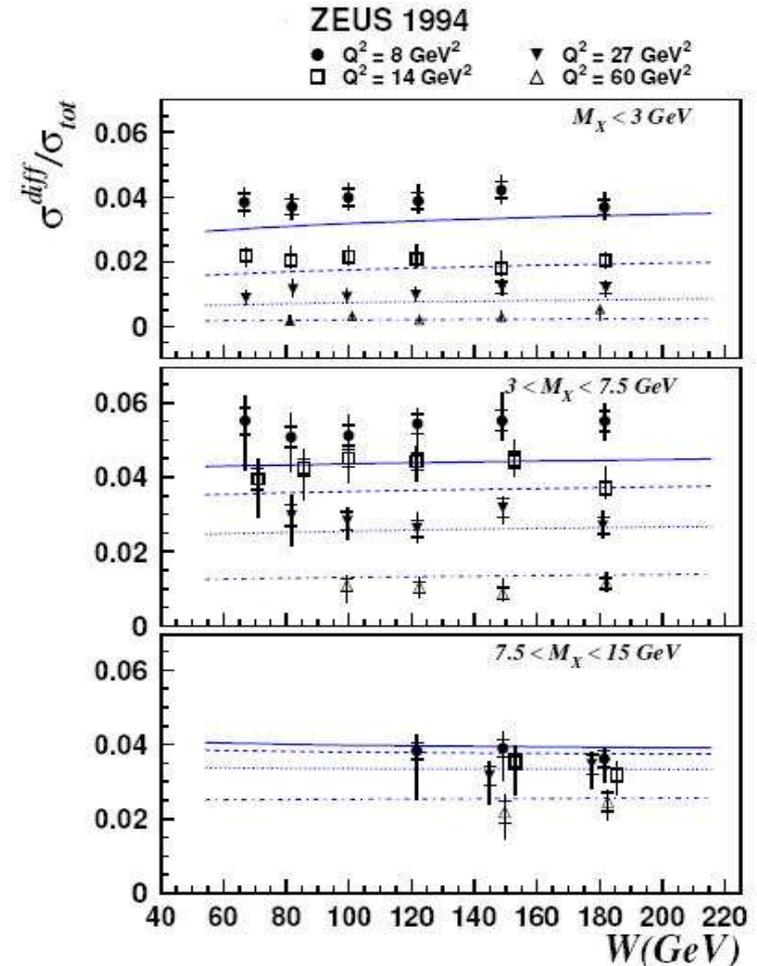
$$\sigma_{\text{tot}}(W^2, Q^2) \sim \text{Im}\mathcal{T} \sim (W^2)^\lambda$$

$$\sigma_{\text{diff}}(W^2, Q^2) \sim |\mathcal{T}|^2 \sim (W^2)^{2\lambda}$$

At HERA $\lambda \simeq 0.25$ for large Q^2 but

$\sigma_{\text{diff}}/\sigma_{\text{tot}}$ is flat!

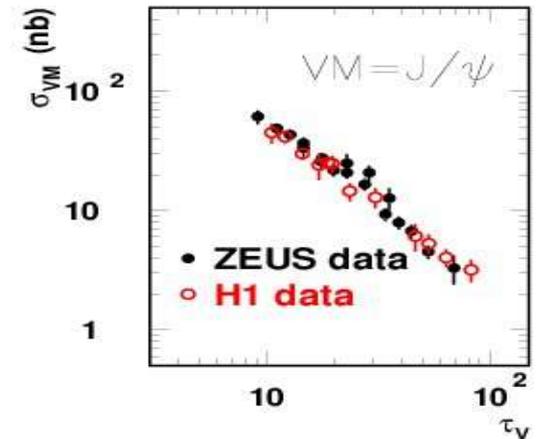
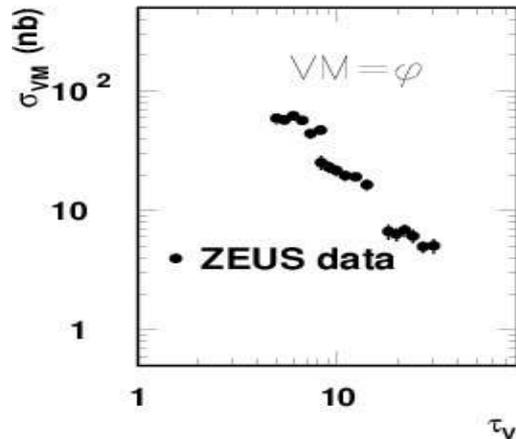
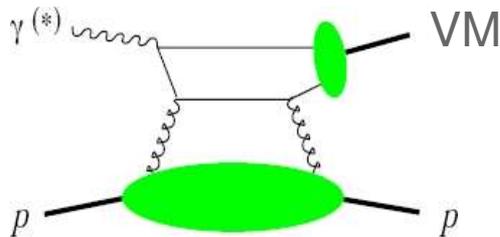
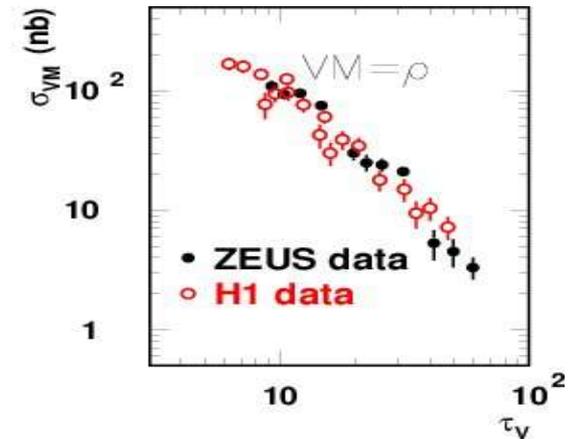
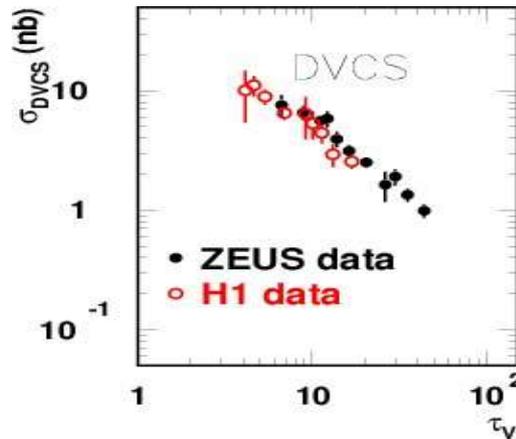
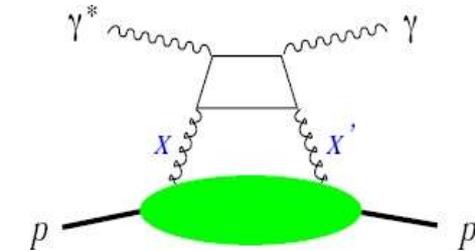
The flat ratio $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ is obtained only if the lower momentum cut-off scale grows as a power of W^2



HERA (diffract. DIS): “Geometric scaling” of σ_{VM} , σ_{DVCS}

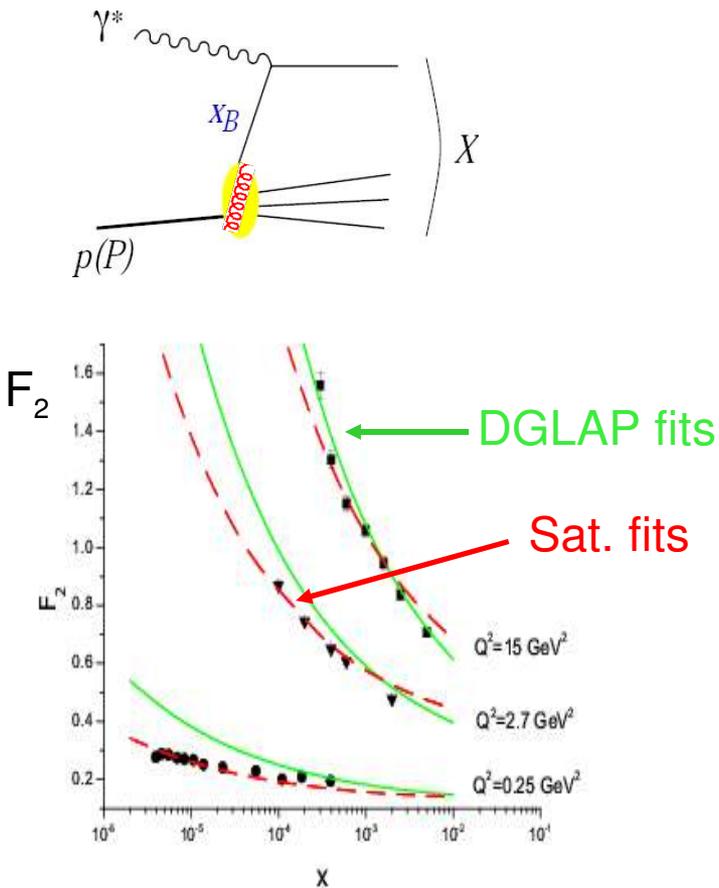
- Geometric scaling also observed in diffractive observables (DVCS, exclusive vector-meson production):

C.Marquet, L. Schoeffel
hep-ph/0606079

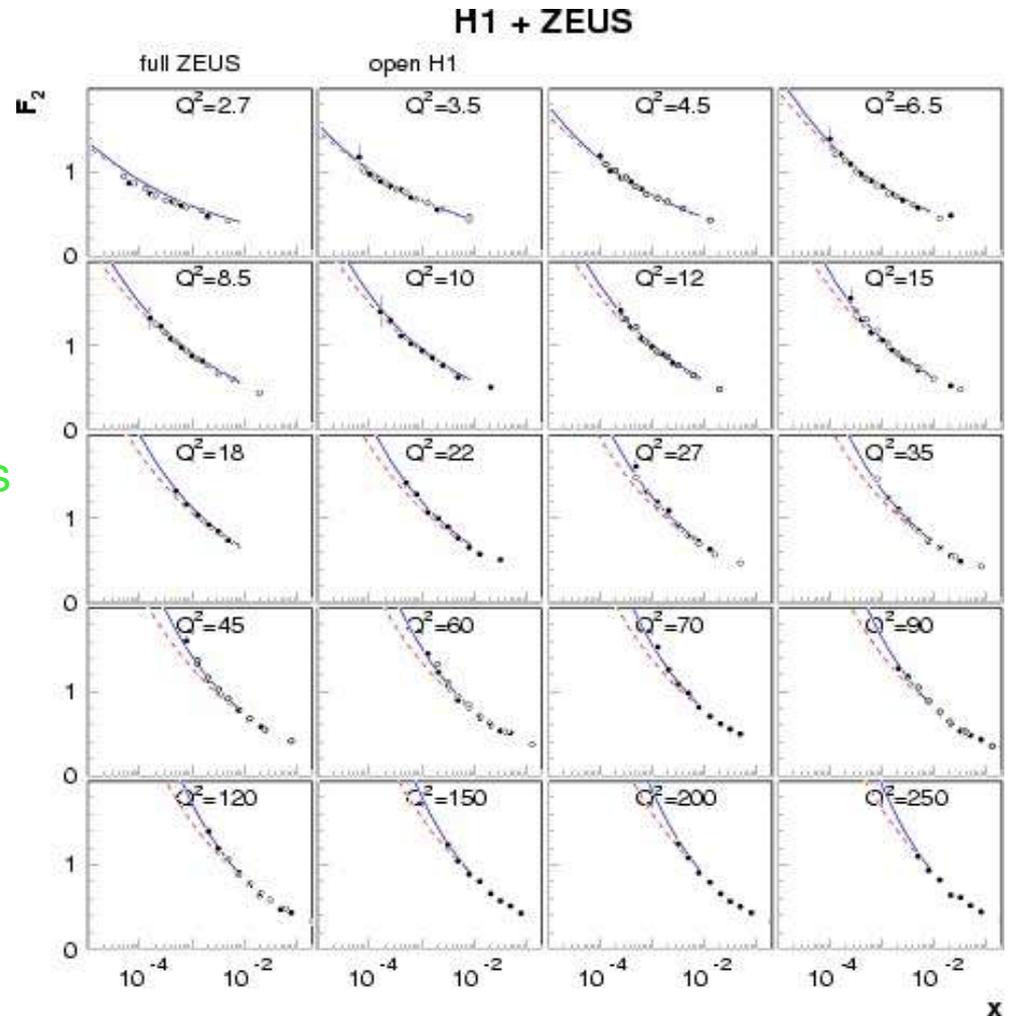


HERA (inclusive DIS): $F_2(x, Q^2)$ at moderate Q^2

- Saturation models describe well $F_2(x, Q^2)$ in “transition region” of moderate/low Q^2 (Note: also DGLAP though at limit of applicability)



Forshaw, Shaw, hep-ph/0411337

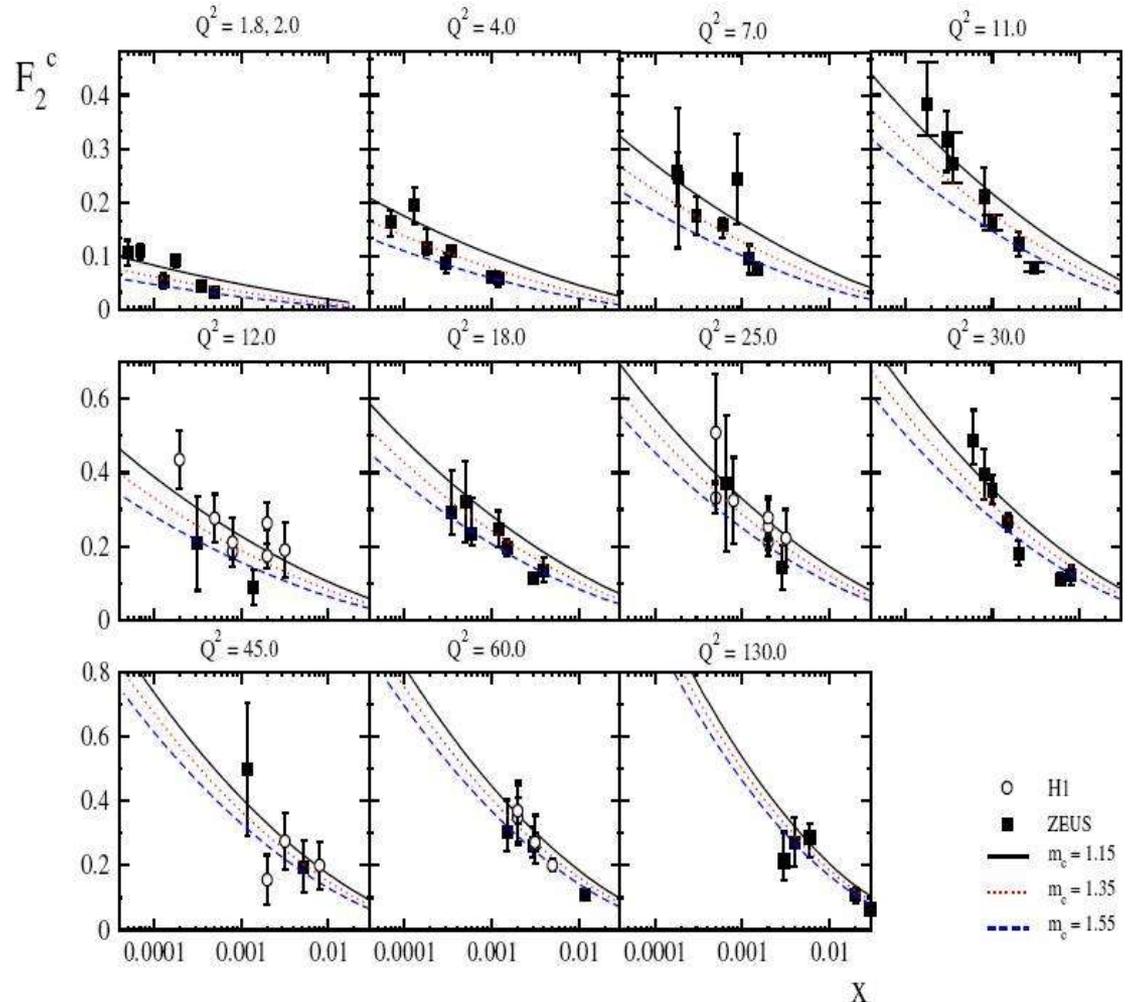
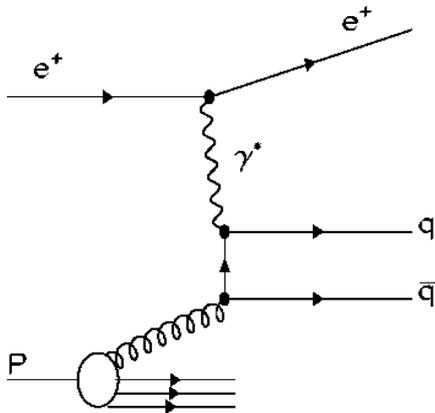


x

HERA (DIS): $F_2(x, Q^2)$ for charm described

- Saturation models describe well F_2 for charm:
 (Note: also DGLAP models)

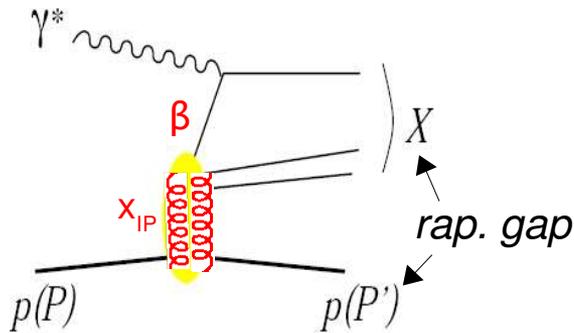
$$F_2^{c\bar{c}}(x, Q^2) = \frac{Q^2}{4\pi\alpha} \sigma_{tot}(\gamma p \rightarrow c\bar{c}X)$$



Machado-Goncalves, EPJC 30 (2003)
 Gay-Ducati

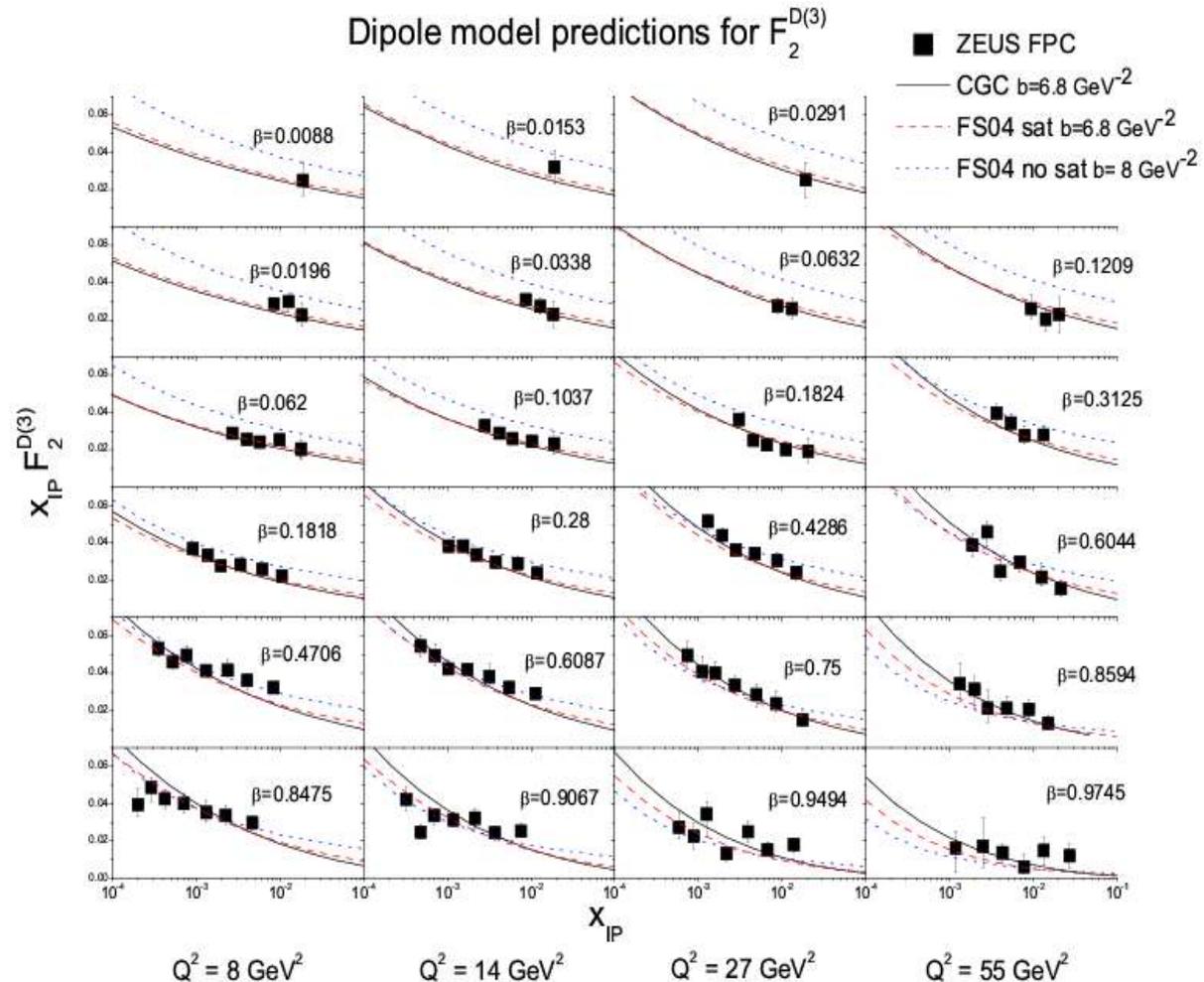
HERA (diffractive DIS): $F_2^D(x,\beta)$ described

- Saturation models provides framework to describe consistently total γ^*p x-section (F_2) and **DDIS** ($x_{IP}F_2^{D(3)}$, Pomeron) & **DVCS** forward amplitudes:



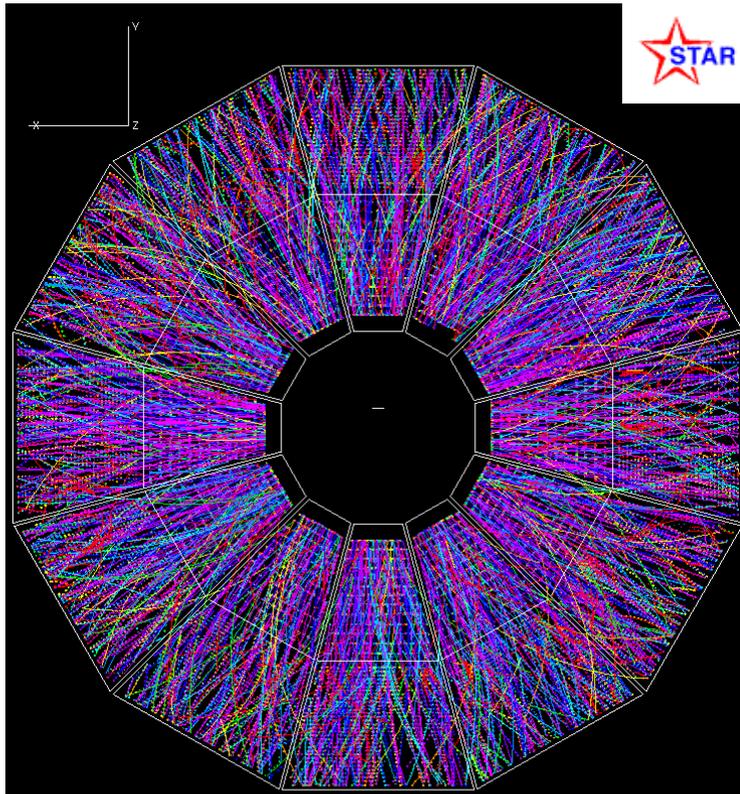
x_{IP} = fraction of p momentum carried by Pomeron
 β = fraction of IP momentum carried by struck parton

Forshaw, Shaw
 hep-ph/0411337



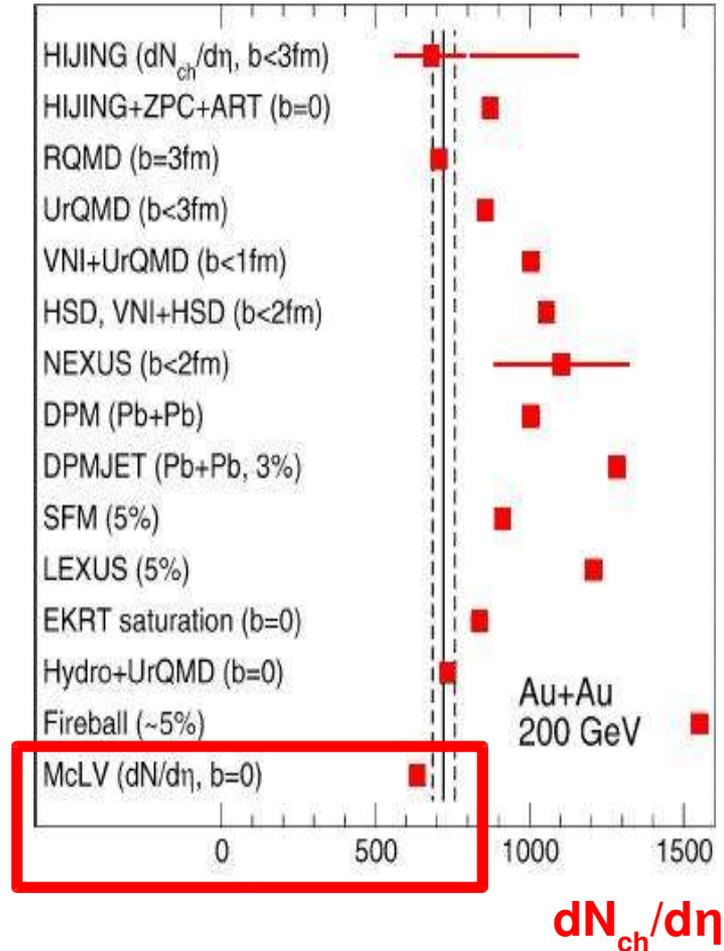
RHIC: Total AA hadron multiplicity (I)

➤ AuAu (200 GeV) 0-5% most central collis.: Predicted multiplicites:



~ 650 charged particles per unit rapidity at $y=0$

➤ **Reduced multiplicity** predicted by saturation models ("gluon recombination" reduces incoming parton flux).



$dN_{ch}/d\eta$

RHIC: Total AA hadron multiplicity (II)

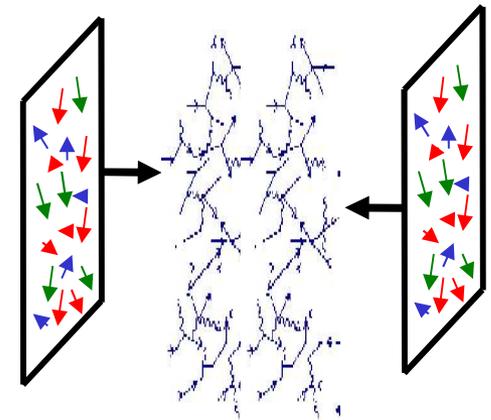
- **CGC**: Final hadron multiplicity \propto Initial number of released gluons $\propto Q_s^2$

$$\frac{dN}{d^2bd\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x, Q_s^2) \cdot A^{1/3}$$

+ "local **parton-hadron duality**" (1 gluon = 1 final hadron)

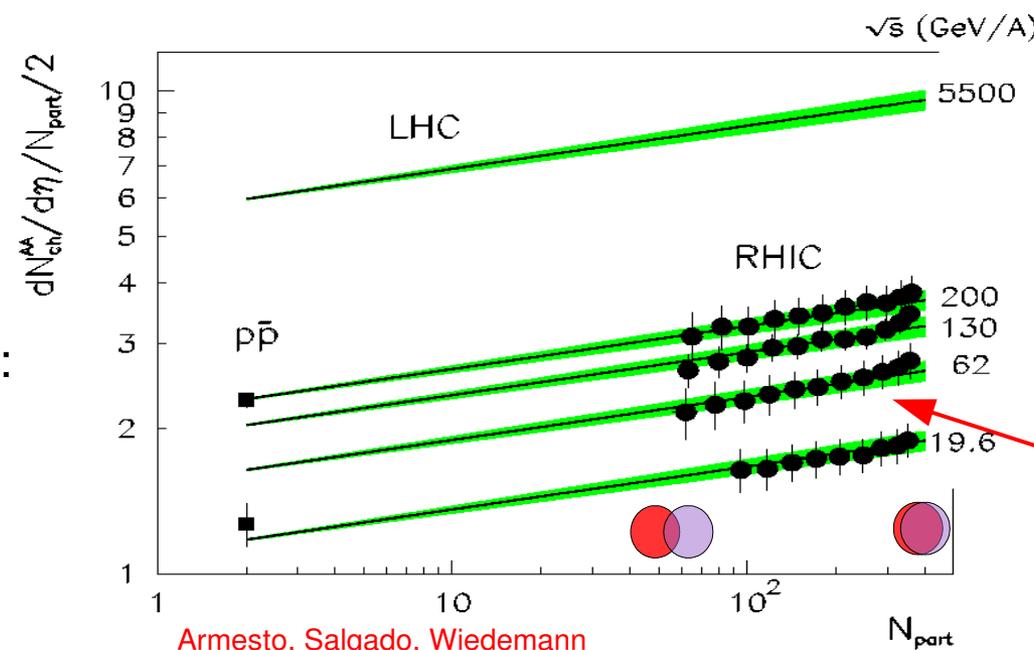
- **Centrality & \sqrt{s} dependence well described:**

Collision of 2 classical (saturated) fields



Q_s dependence on transv. area

$$\sim \frac{1}{\alpha_s(Q_s^2)}$$



Armesto, Salgado, Wiedemann

PRL94 (2005) 022002

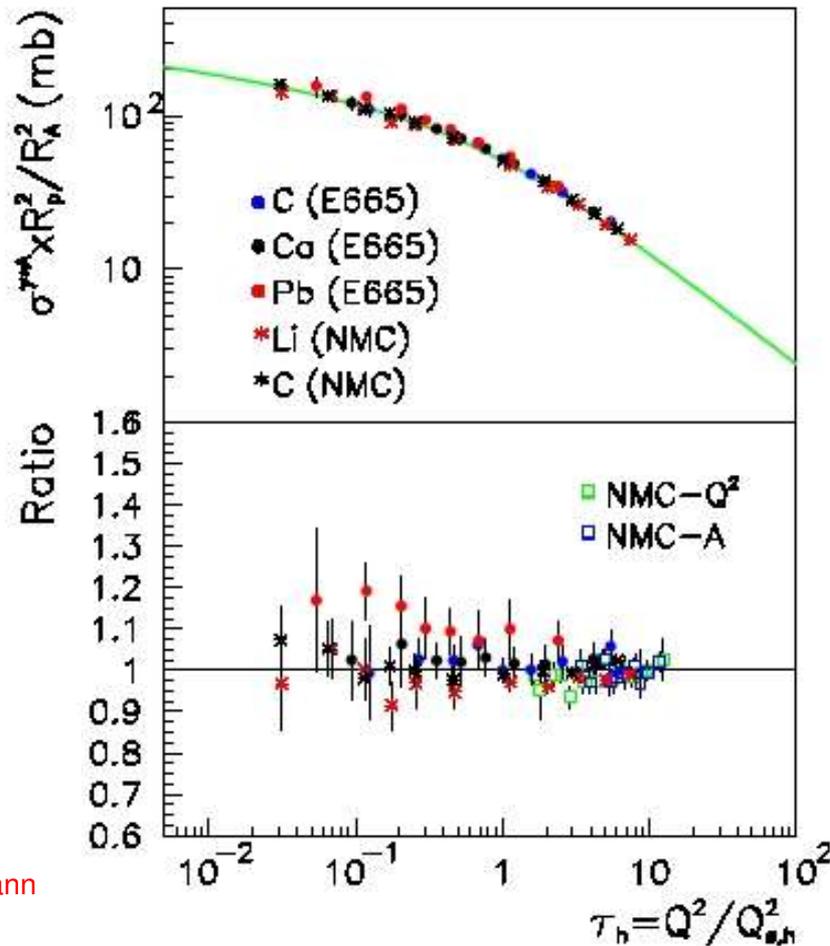
Kharzeev-Levin-Nardi, PLB507 (2001) 121

approx:

1/3

Incl. DIS nuclear: “Geometric scaling” at low-x

- Geometric scaling also in nuclear DIS $\sigma_{\gamma A}$ data (E665, NMC) for $x < 0.01$



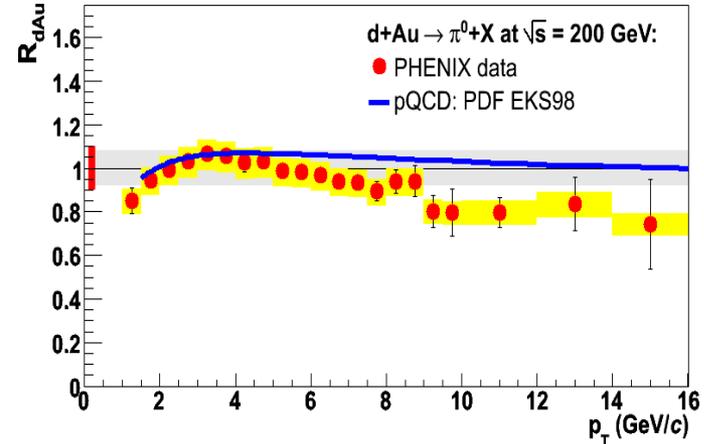
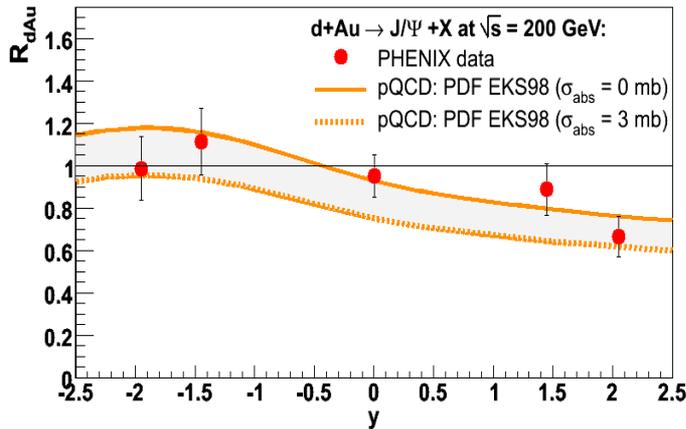
Confirms approx:

$$Q_s^2 \sim A^{1/3}$$

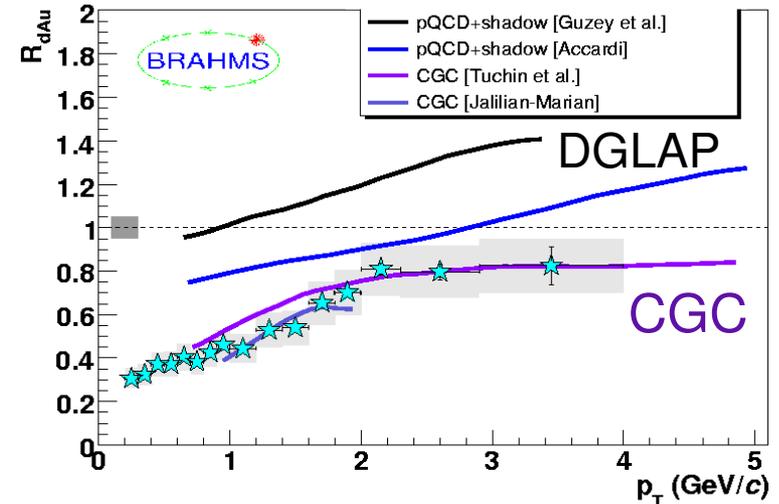
Armesto, Salgado, Wiedemann
PRL94 (2005) 022002

RHIC: suppressed forward dAu p_T spectra

- **Hard** hadrons at $y=0$ ($x \sim 10^{-2}$) described by **coll. factoriz.+mild** LT shadowing:



- At $\eta = 3.2$ ($x \sim 10^{-3}$) **suppressed hadron spectrum** $p_T \sim 2 - 4$ GeV/c not described by std. pQCD but **by CGC**:
 reduced partonic flux in Au at low-x

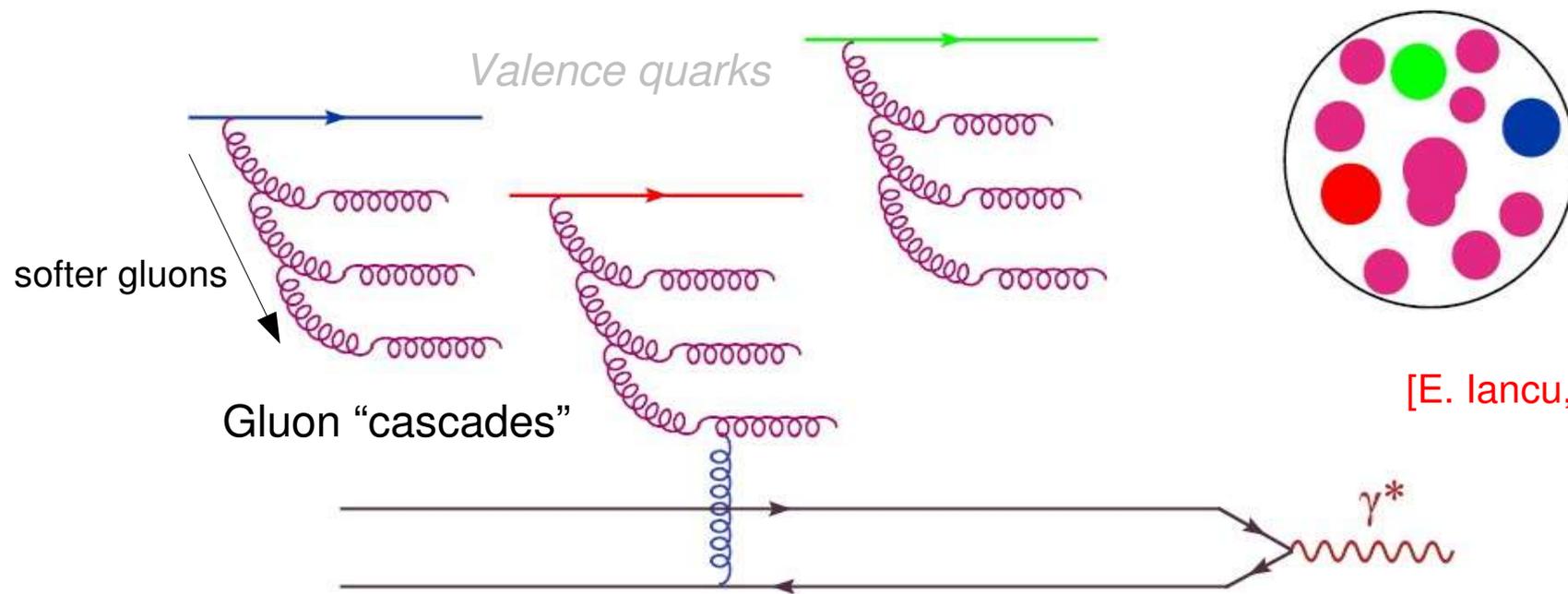


- But RHIC & HERA saturation “evidences” **too close to non-perturbative range** ($Q_s^2 \sim 1$ GeV²). Much better conditions @ LHC ($Q_s^2 \sim 5$ GeV², lower x, larger y)

BFKL linear evolution equations

- **Malthusian growth** of gluon density (n) w/ increasing- Y (decreasing- x):

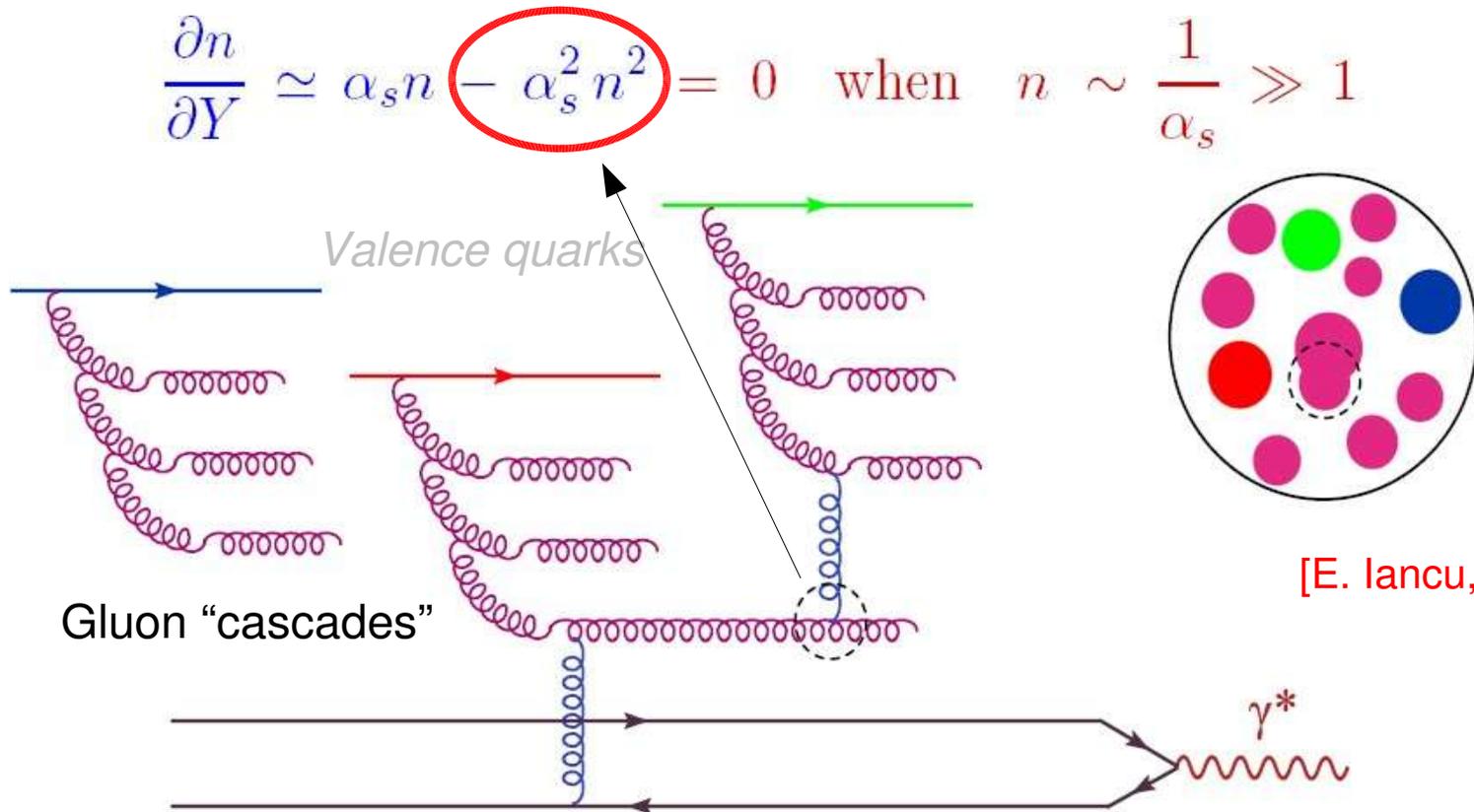
$$\frac{\partial n}{\partial Y} \simeq \alpha_s n \quad \Rightarrow \quad n(Y) \propto e^{\omega \alpha_s Y}, \quad Y = \ln(1/x)$$



[E. Iancu, ECT*-07]

Non-linear QCD evolution equations

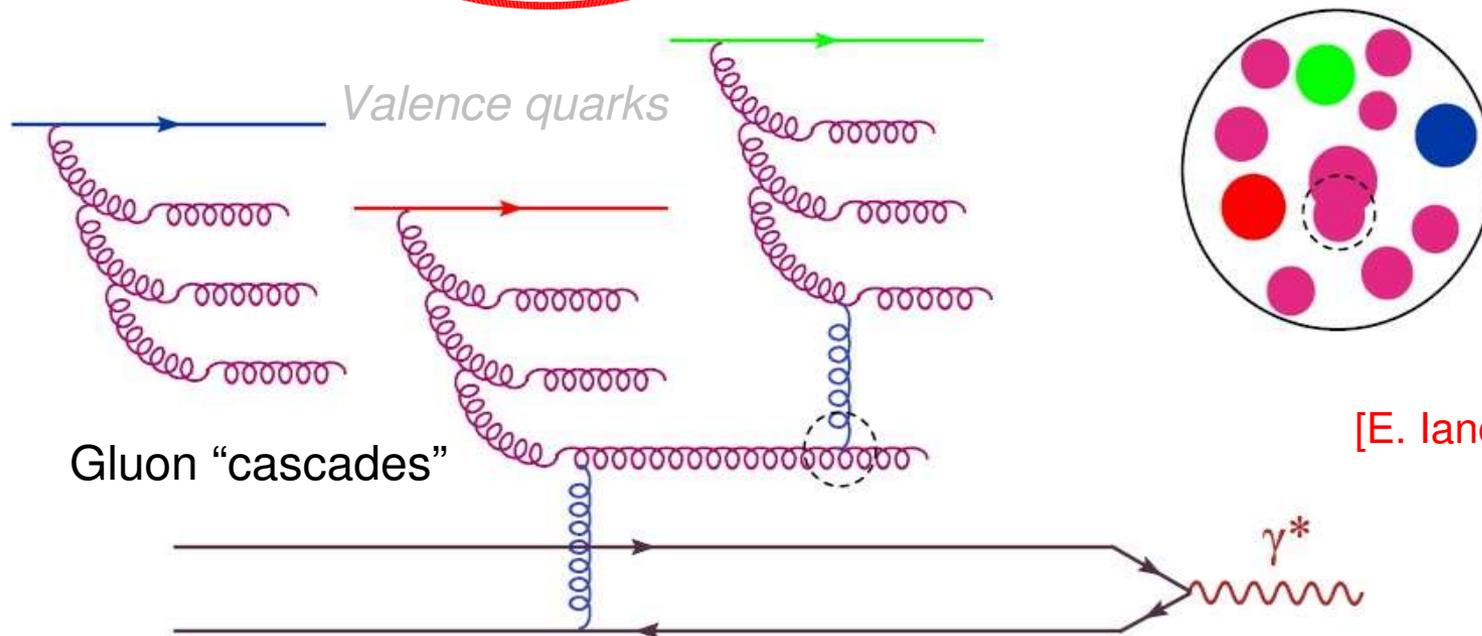
- Growth of gluon density (n) compensated by **gluon fusion** ($-n^2$):



BK-JIMWLK non-linear QCD equations

- Full evolution (non-locality) requires additional **diffusion term**: saturation “spills out” into the dilute regime **above Q_s** (“geometric scaling”)

$$\partial_Y n(\rho, Y) = \alpha_s \partial_\rho^2 n(\rho, Y) + \alpha_s n(\rho, Y) - \alpha_s^2 n^2(\rho, Y)$$

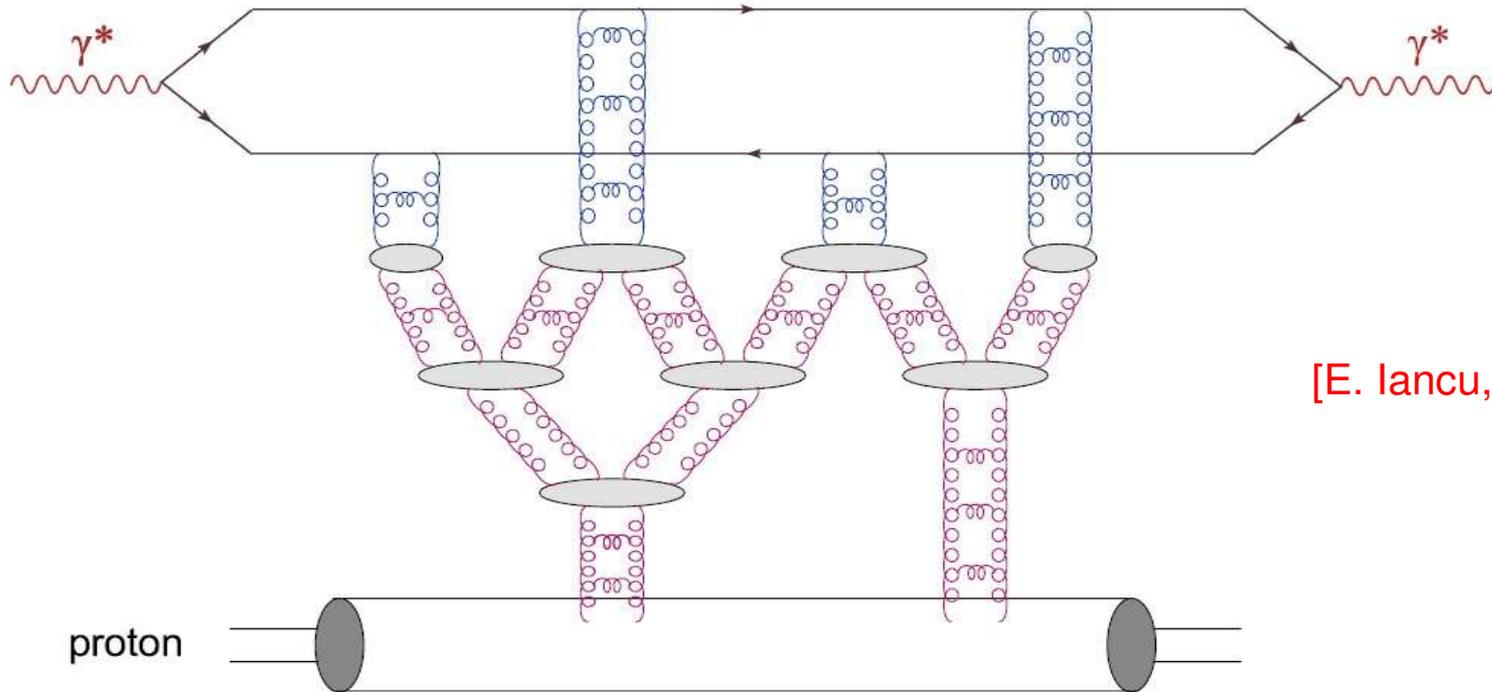


- Same class as **FKPP eq.** (stat. phys.): **diffusion+growth+recombination**

BK-JIMWLK + “Pomeron loops”

- Full non-linear evolution needs to take into account also **gluon-number fluctuations** (“hot spots” inside hadron):

$$\frac{\partial n}{\partial Y} = \alpha_s \partial_\rho^2 n + \alpha_s n - \alpha_s^2 n^2 + \sqrt{\alpha_s^2 n} \nu \quad \langle \nu(Y_1) \nu(Y_2) \rangle = \delta(Y_1 - Y_2)$$

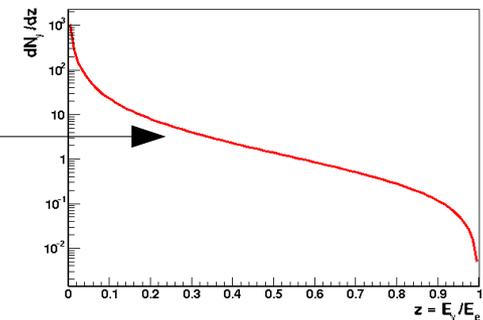
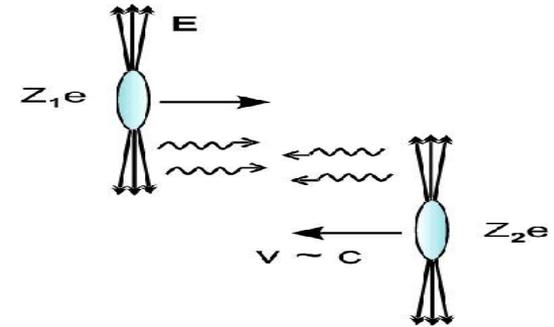


[E. Iancu, ECT*-07]

- **Stochastic FKKP** equation: full reaction-diffusion process in stat. phys.

Photoproduction (γA) in UPC AA collisions

- Heavy-ions (charge Z) produce **strong EM fields** (coherent action of all protons):
- Equivalent **flux of photons** in electromagnetic (aka. Ultra-Peripheral, $b_{\min} \sim 2R_A$) $A+A$:



$$\frac{dN_\gamma}{dE} (b > b_{\min}) \propto \frac{\alpha_{em} Z^2}{\pi} \frac{1}{E} \quad (\text{soft bremsstrahlung } \gamma \text{ spectrum})$$

- Photon beams:

- **Flux $\sim Z^2$** ($\sim 7 \cdot 10^3$ for Pb).

- “**Coherence condition**” : γ wavelength $>$ nucleus size

Maximum γ energy: $\omega < \omega_{\max} \approx \left(\frac{\gamma}{R}\right) \sim 80 - 160 \text{ GeV}$ (Pb,Ca)

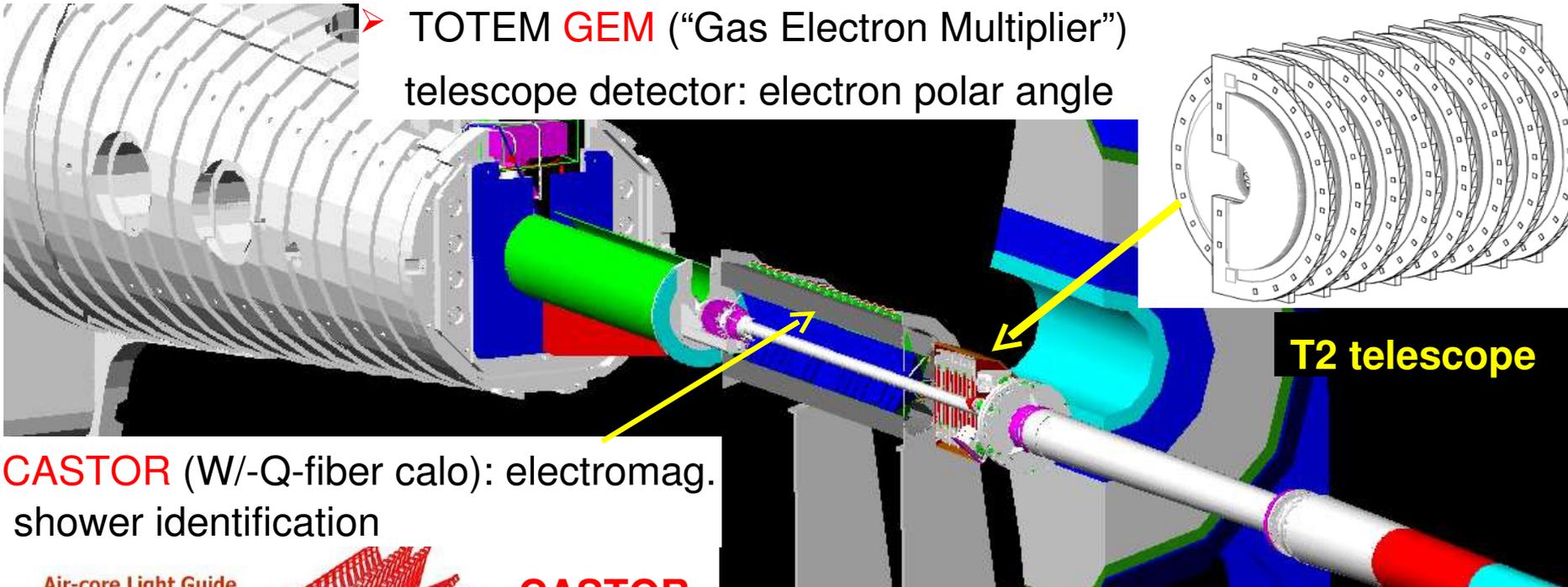
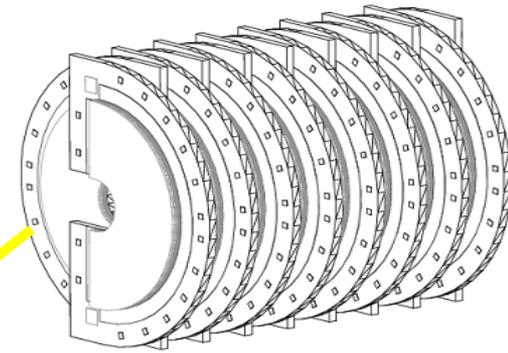
- Center of mass-energies (LHC): $\sqrt{s}_{\gamma A} \approx 0.7 - 2. \text{ TeV} \approx (3 - 10) \times \sqrt{s}_{\gamma p}$ (HERA)

- Bjorken x range in nucleus: $(y=0): x(J/\Psi) \sim 3 \cdot 10^{-3}$, $x(\Upsilon) \sim 10^{-2}$
 $(y=3): x(J/\Psi) \sim 2 \cdot 10^{-5}$, $x(\Upsilon) \sim 10^{-4}$

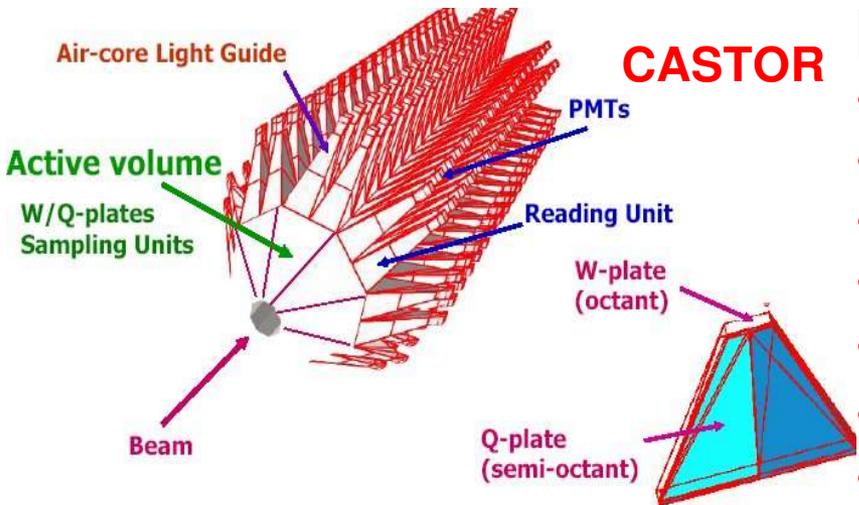
- Forward **neutron-tagging (ZDC)**: $\sim 50\%$ UPC colls. lead to nuclear breakup.

CMS: TOTEM-2 and CASTOR ($5.2 < |\eta| < 6.6$)

➤ TOTEM **GEM** (“Gas Electron Multiplier”) telescope detector: electron polar angle



CASTOR (W/-Q-fiber calo): electromag. shower identification



T2 telescope

- Tungsten plates + **quartz** fibres
- **Cherenkov** sampling calorimeter
- Light-guides + **APDs** readout
- **Azimuth** segmented (8 octants)
- **EM** section: 11.2 cm $\sim 19 X_0$
- **HAD**+EM sections: 136 cm $\sim 10 \lambda_1$
- 192 channels

