Low-x QCD with protons and nuclei at the LHC

1st ECFA-CERN LHeC Workshop

Divonne les Bains, 1st – 3rd Sept. 2008

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Overview

- Introduction:

  - Parton structure & evolution at low-x, gluon saturation
  - Measurements of low-x PDFs: processes, kinematic domains, ...

- Experimental tests:

  - Saturation hints at HERA (proton)
  - Saturation hints at RHIC (nucleus)
  - Low-x perspectives at the LHC (proton & nucleus):

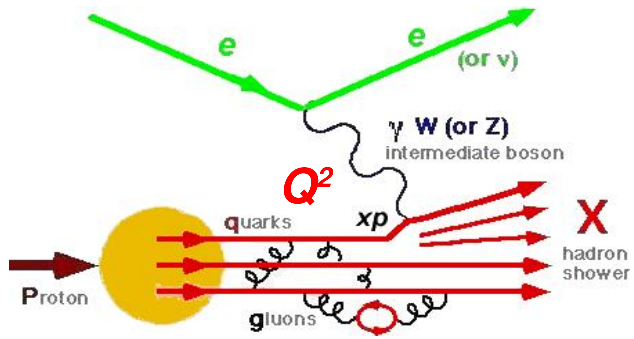
    pp @ 14 TeV: forward (di)jets, QQbar, heavy-Q ...

    PbPb @ 5.5 TeV: $dN_{ch}/d\eta$, Υ photo-production

- Summary & Outlook (LHeC).

Parton densities at low-x

- DIS e-p collisions probe distributions of partons in the proton:



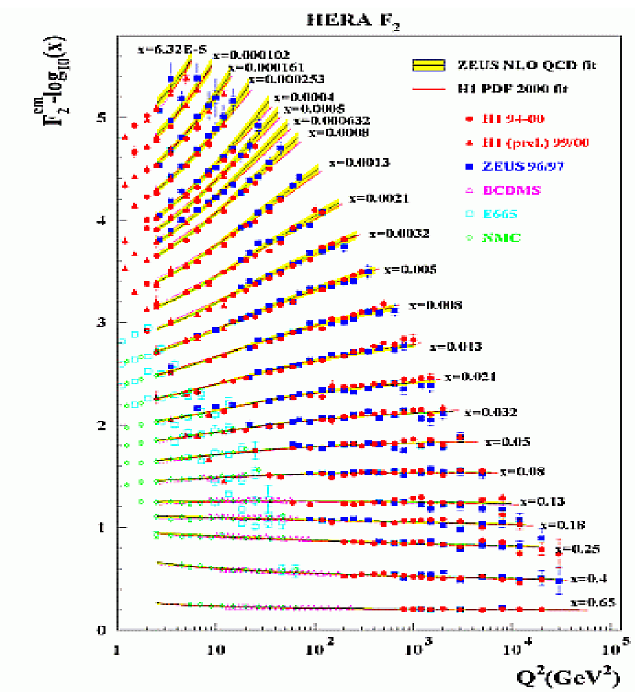
Q^2 = "resolving power"

Bjorken x = momentum fraction carried by parton

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

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

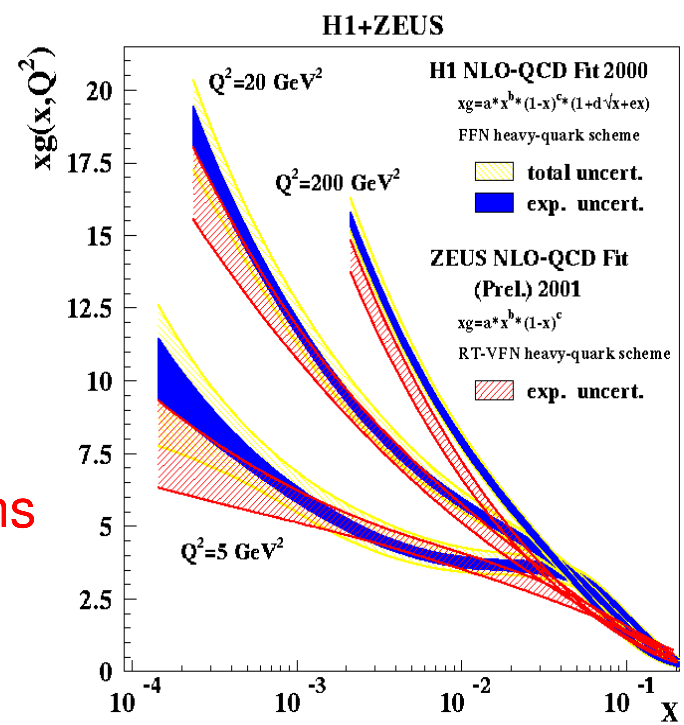
- HERA: strong rise of $F_2(x,Q^2)$ at low-x:



γ couples directly only to (sea) quarks

⇒

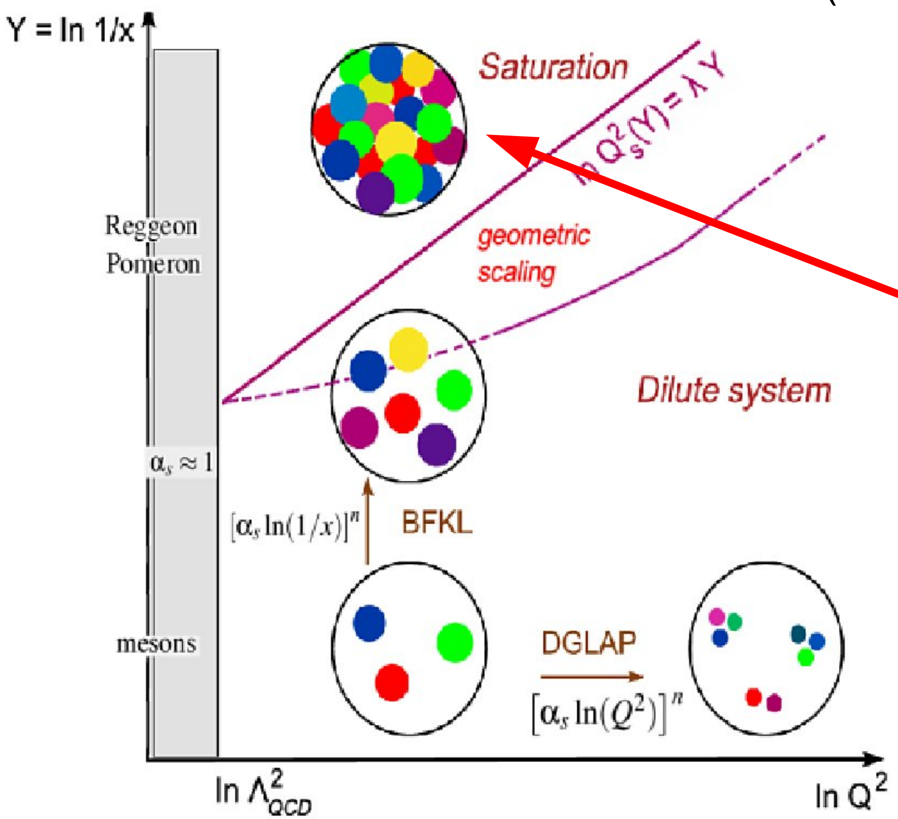
$\partial \ln F_2 / \partial \ln Q^2 \propto$ gluons



(x,Q^2) evolution of PDFs

- **Q^2 - DGLAP** (k_T-order'd emission): $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ 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 (even less for multi-parton systems = nuclei):



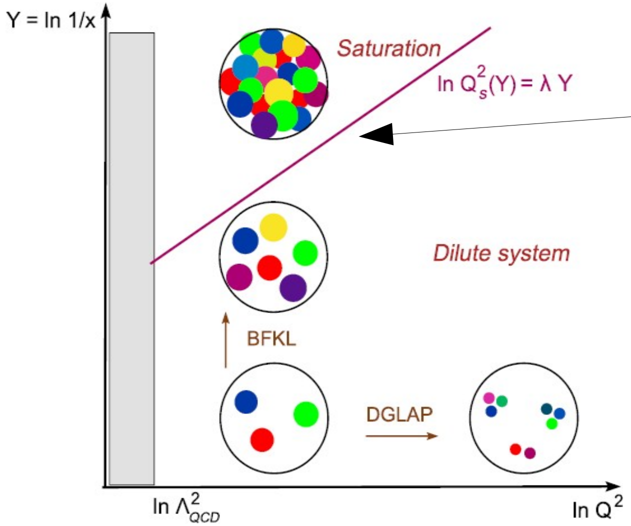
(i) Too high gluon density: nonlinear gluon-gluon fusion balances branchings

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

(iii) Violation of unitarity even for $Q^2 >> \Lambda^2$ (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:



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

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

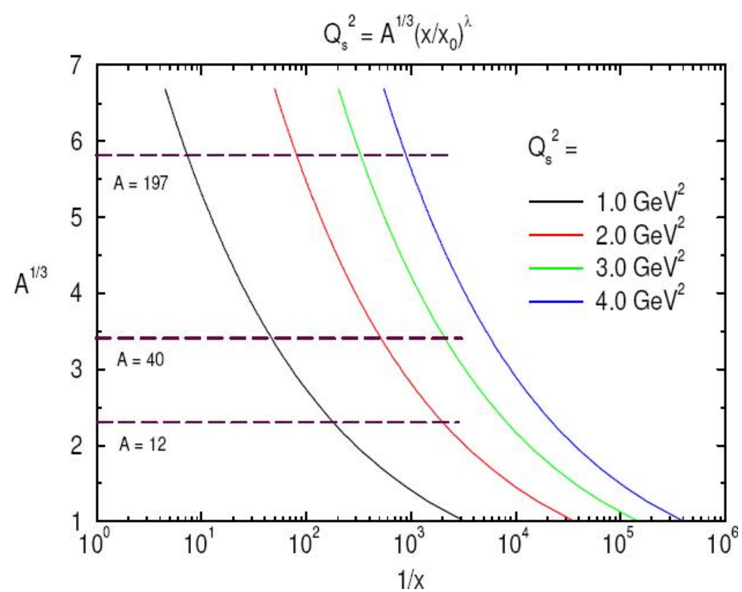
Saturation for: low x, large s, large y, large A

- Nucleus (larger parton tranverse density) amplifies saturation effects:

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

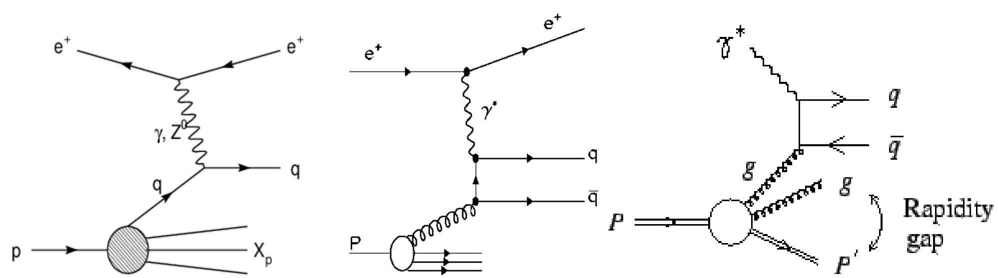
Q_s^2~1 GeV^2 (HERA,p)

Q_s^2~2 GeV^2 (e)RHIC (Au),5 GeV^2 (LHC,Pb)

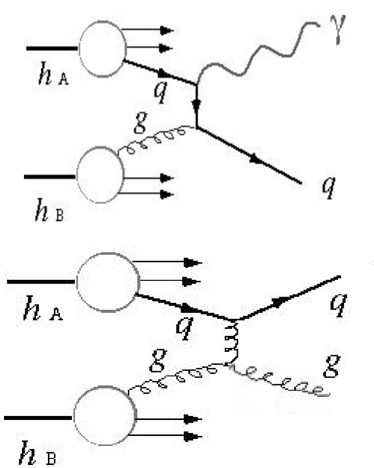


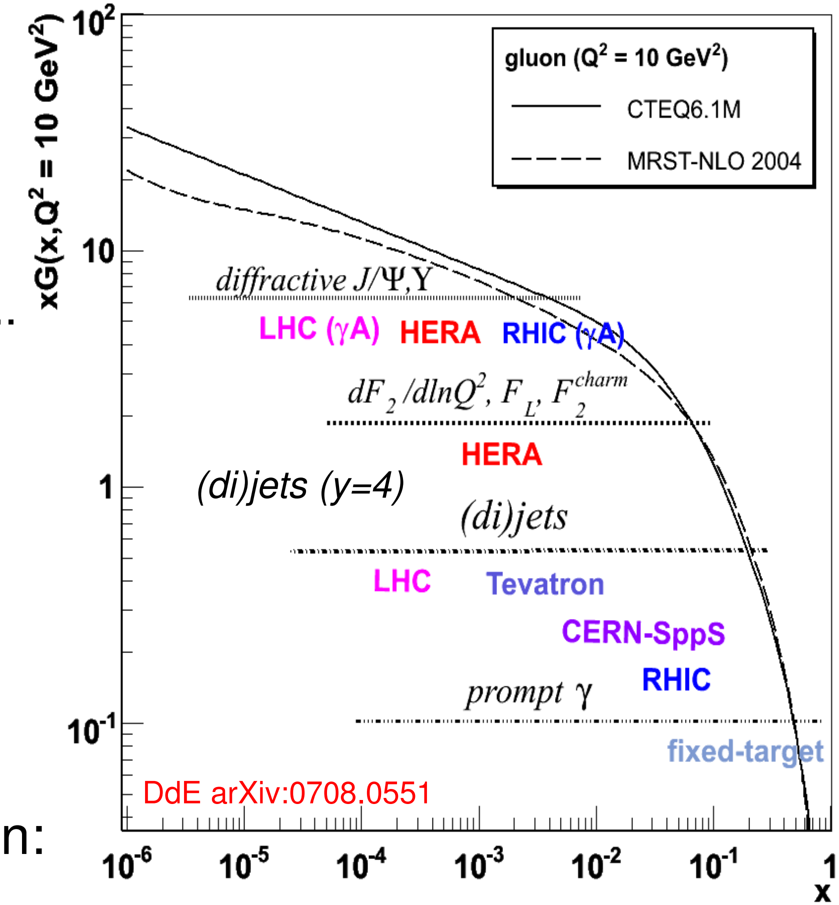
Experimental access to low-x gluon PDF

- Perturbative processes:
  - e-p: $\partial \ln F_2 / \partial \ln Q^2$, F_L, heavy-Q, diffractive $Q\bar{Q}$: ...

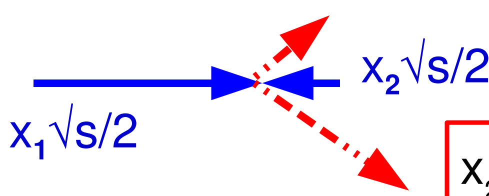


  - p-p, A-A: prompt γ , (di)jets:





  - Forward production:

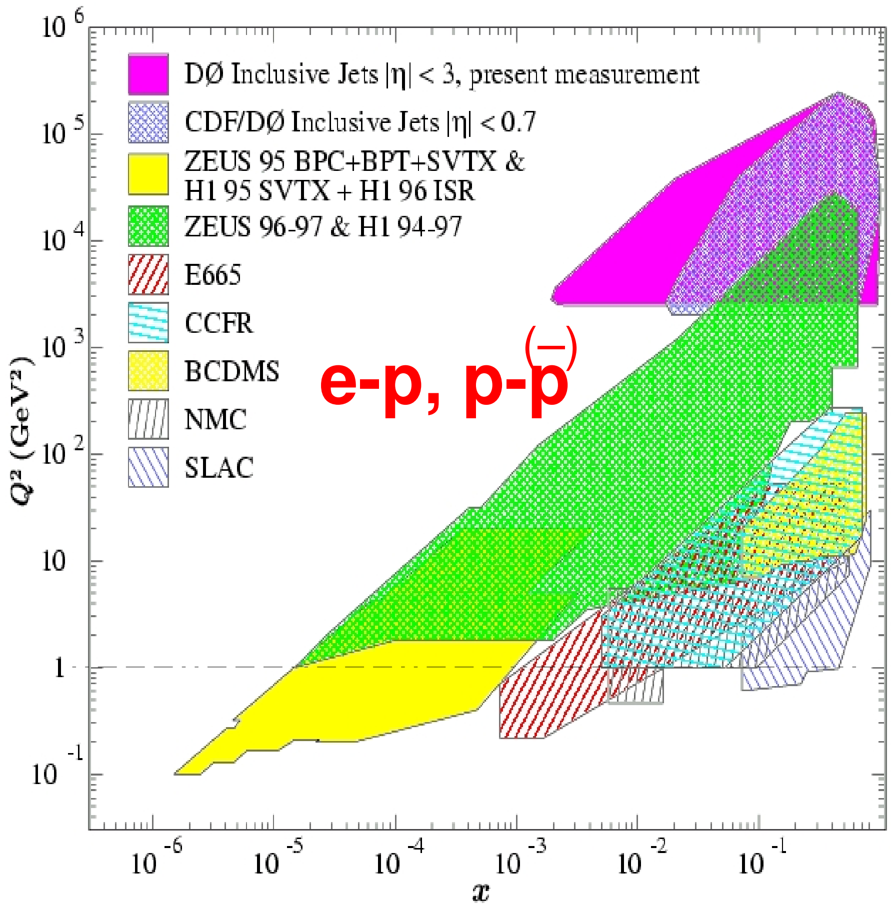


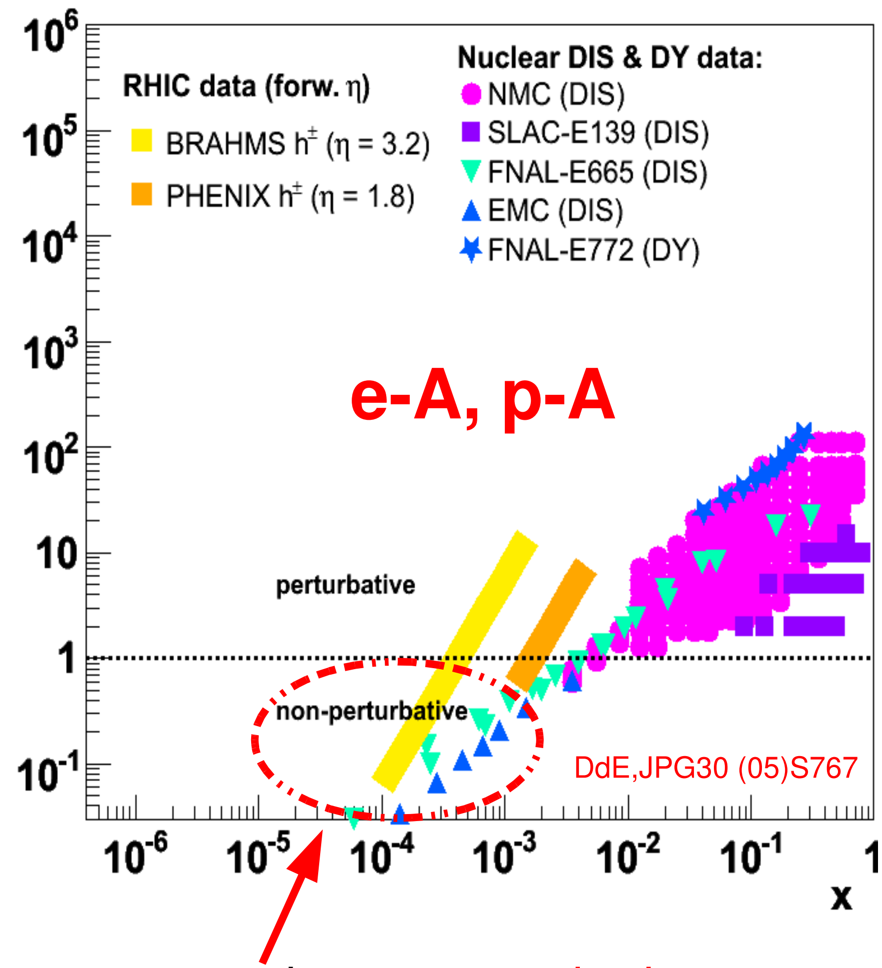
$$x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$$

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

(x,Q²) experimental domains: proton, nucleus

- Kinematical (x,Q²) domains covered experimentally:





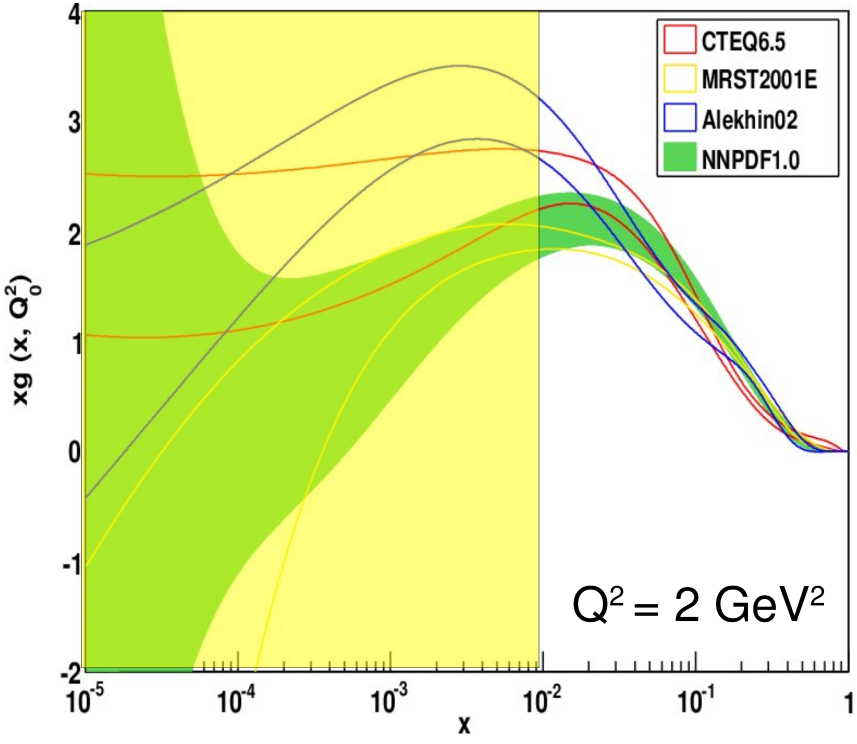
- Note: most existing low-x nPDFs measurements in non-perturbative range

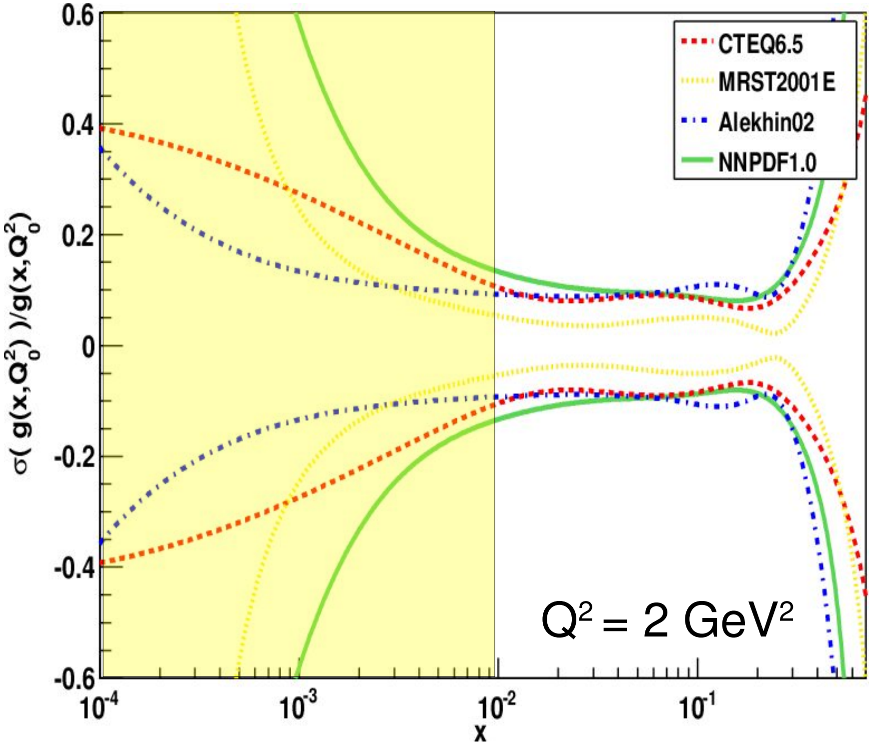
Low-x gluon PDF (proton)

- Most of our current knowledge of low-x gluons comes indirectly from F_2 scaling violations : $\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi} xg(x,Q^2)$

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

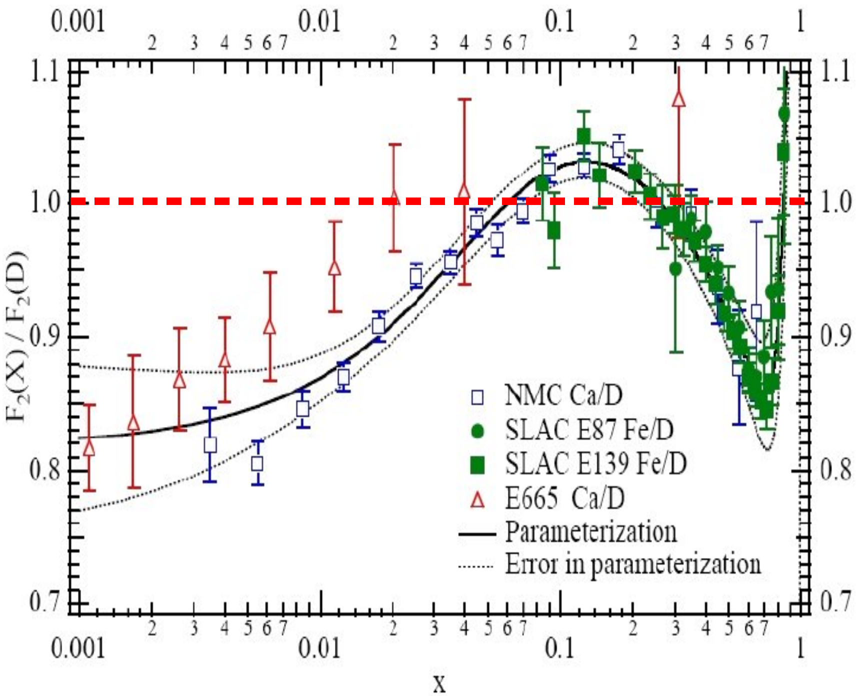
R.D. Ball *et al.* arXiv:0808.1231





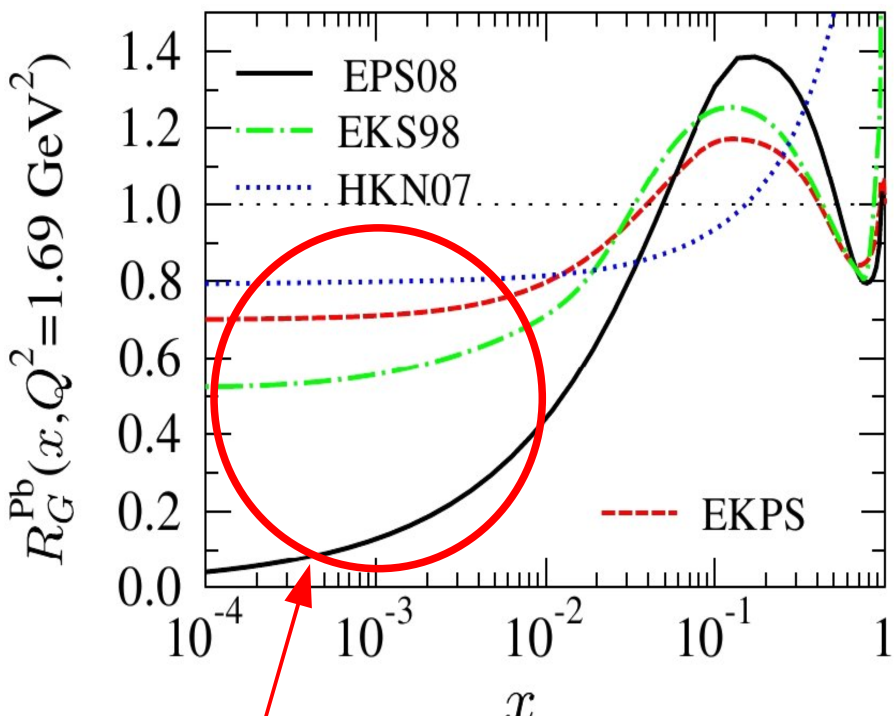
Low-x gluon PDF (nucleus)

- Current knowledge of low-x gluons from:
  nuclear F_2, nuclear Drell-Yan (p-A), high-p_T hadrons (d-Au, RHIC).
- Increasing nuclear shadowing below x~0.1



See e.g. M.Arneodo
Phys. Rept. 240 (94) 301

K.Eskola et al. JHEP 0807 (08)102

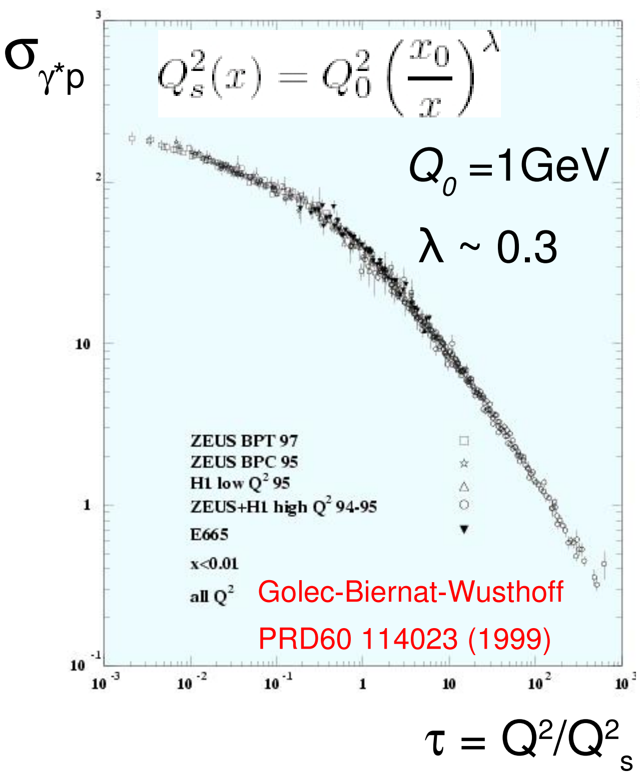


- Nuclear $xG(x,Q^2)$ virtually unknown below x~10^{-3} !

Saturation hints at HERA: proton

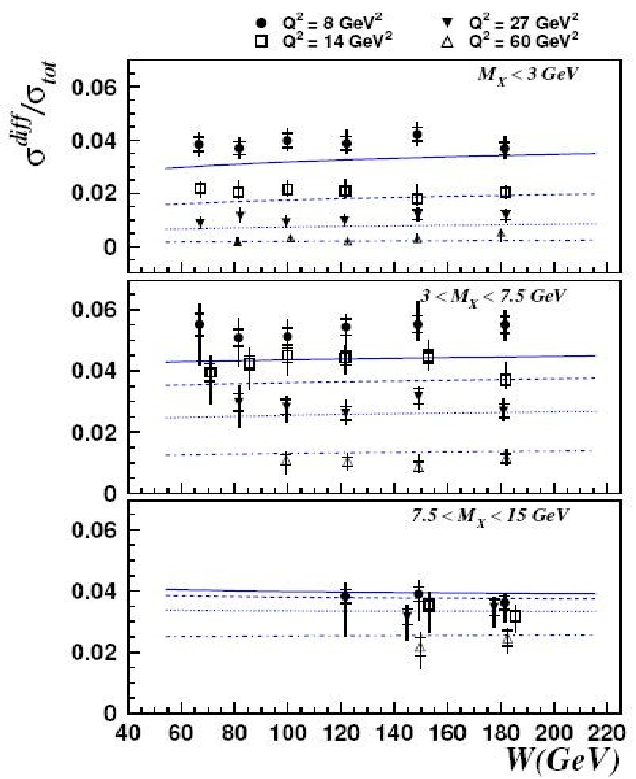
- DGLAP fits most of e-p data. Saturation models explain better a few cases:

(1) "Geometric scaling"



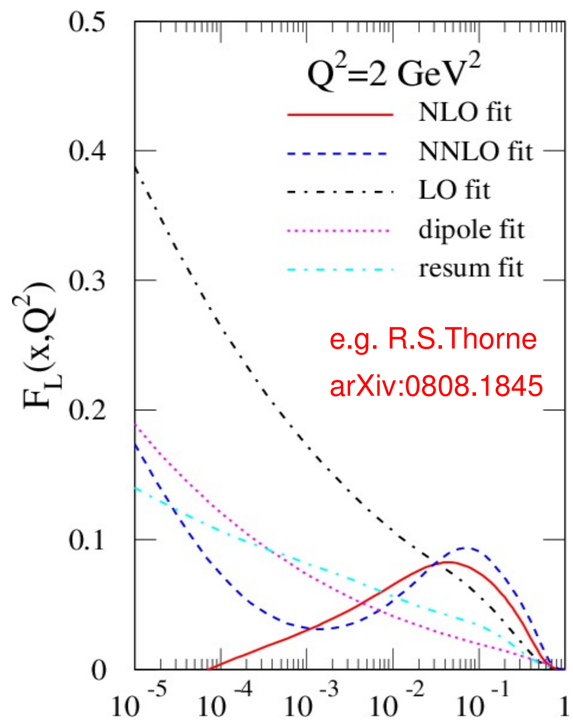
Inclusive DIS x-section depends on single scale Q^2/Q_s^2 for $x < 0.01$

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



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

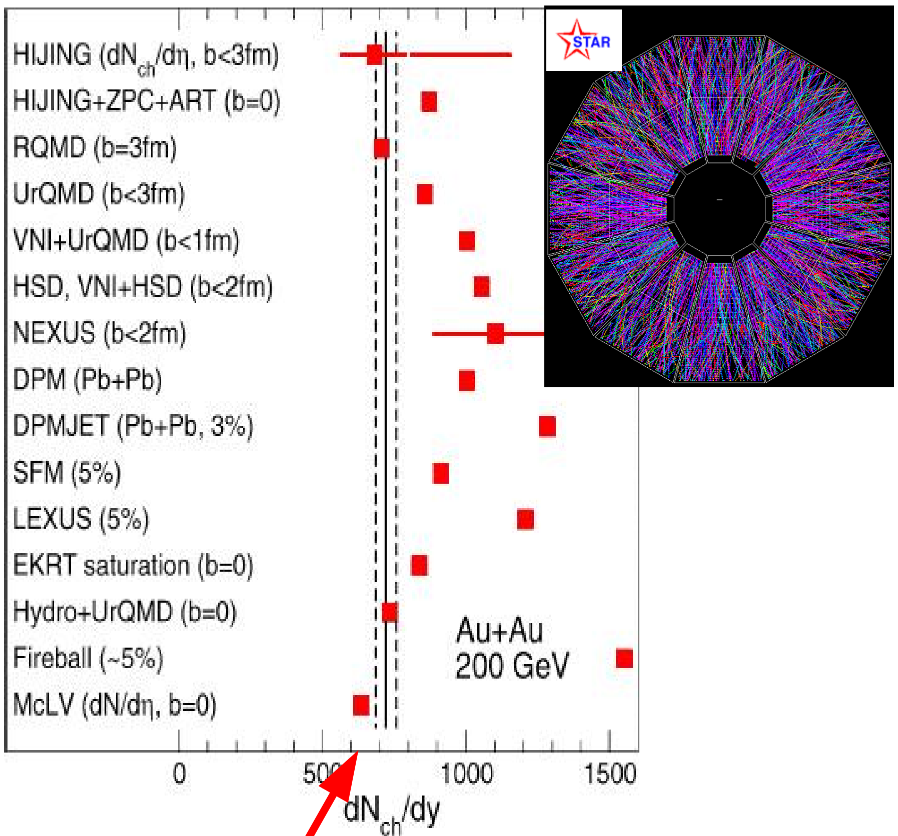
(3) Long. struc. function



Gluon (F_L) at NLO becomes negative for Q^2~2 GeV^2 at low-x

Saturation hints at RHIC: nucleus

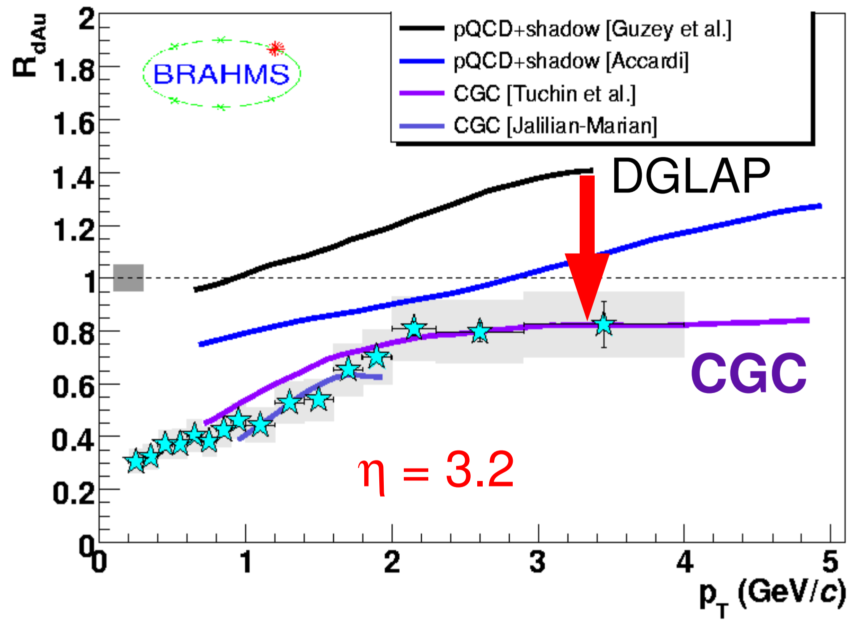
(1) Reduced Au-Au hadron multiplicities:



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

(2) Suppressed forward hadrons

(η = 3.2, p_T~3 GeV/c, i.e. $x \sim 10^{-3}$):



R_{dAu}~0.8 better described by CCG-models than NLO pQCD: reduced partonic flux in Au at low-x

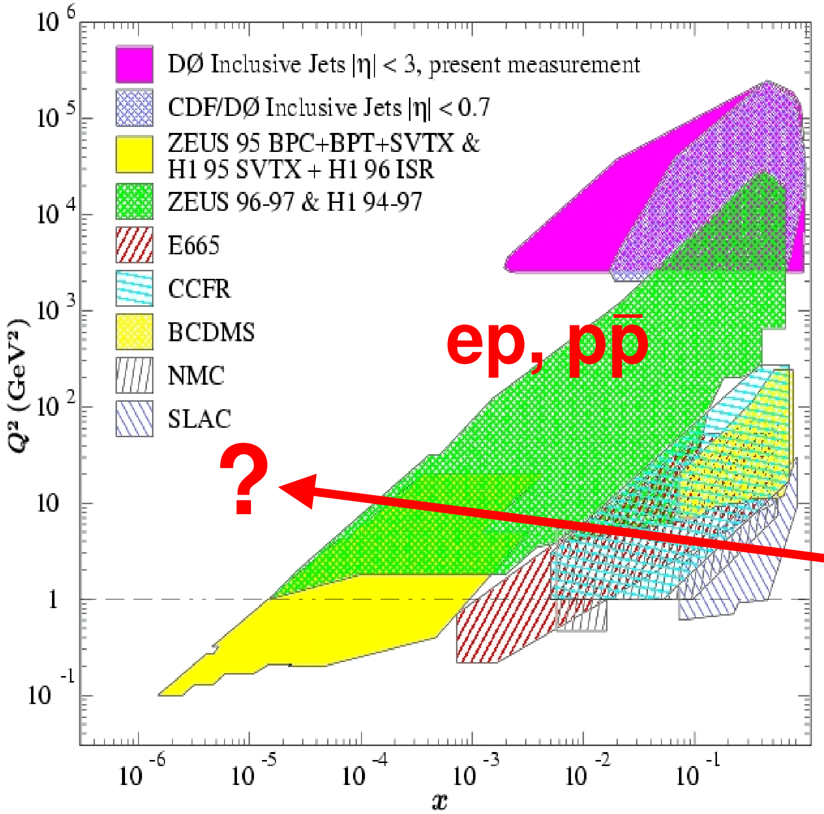
Low-*x* studies at the LHC: proton

- p-p @ 14 TeV :

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

(2) Saturation momentum: $Q_s^2\sim$ 1 GeV² (y=0), 3 GeV² (y=5)

(3) Very large perturbative cross-sections:



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

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

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

$$p(p_1)+p(p_2)\to Q+\bar{Q}+\ X$$ Heavy flavour

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

LHC forward rapidities:

e.g. y ~ 6, Q ~ 10 GeV

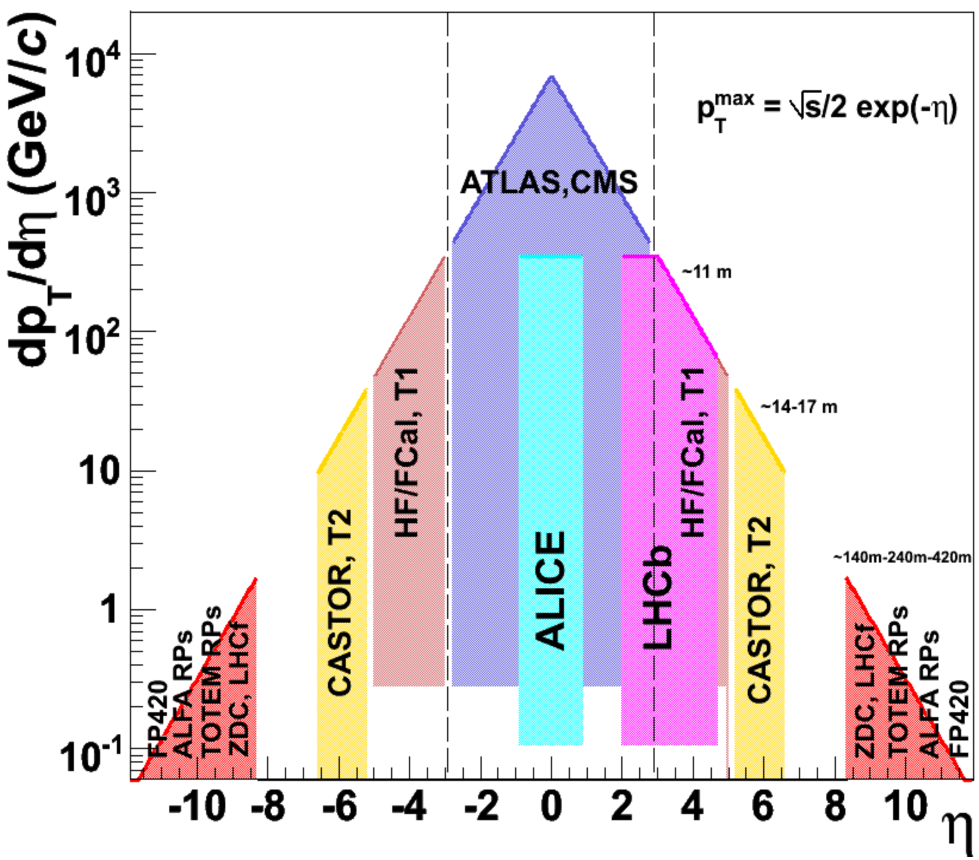
x down to 10^{-6} !

Forward detectors at the LHC

- Most of phase-space $\Delta y \sim 2\times\ln(\sqrt{s})/m_p \sim 20$ covered:

  1^{st} time in a collider !

DdE, arXiv:0806.0883



- ATLAS/CMS:

  forward calorimeters

  (up to $|\eta|\sim 6.6$)

- ALICE/LHCb:

  forward muon spectrometers

  (up to $\eta=5$)

- TOTEM:

  forward trackers

  (up to $|\eta|=6.4$)

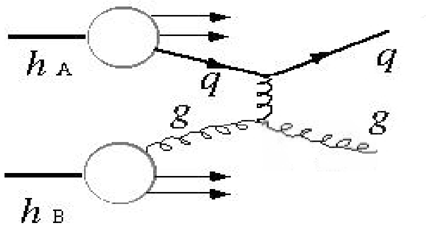
$$x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$$

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

Case-study I: Forward jets in CMS (3 <|η |< 6.6)

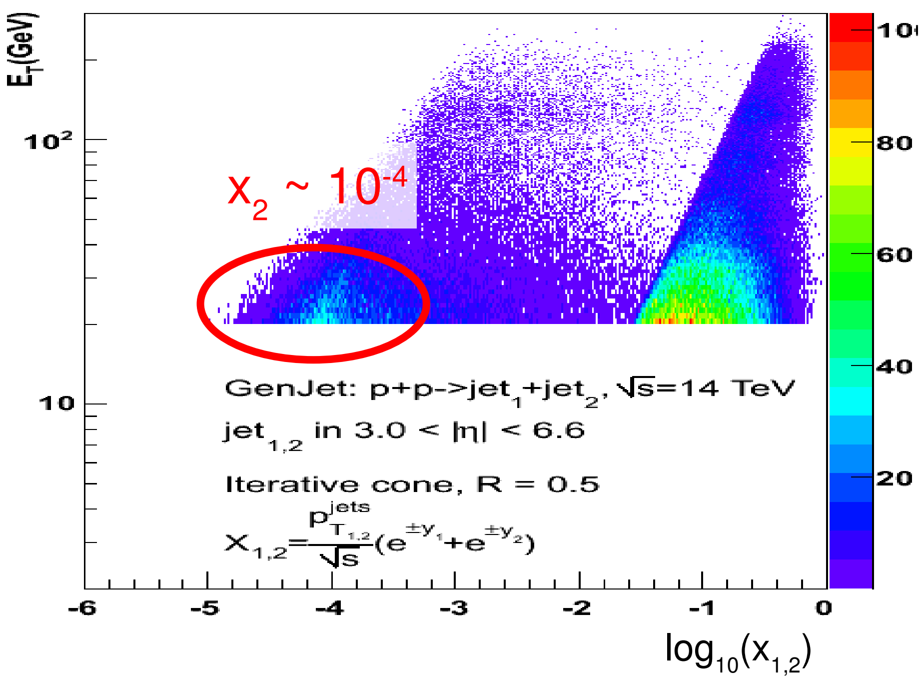
[S.Cerci, D.d'E, CMS]

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

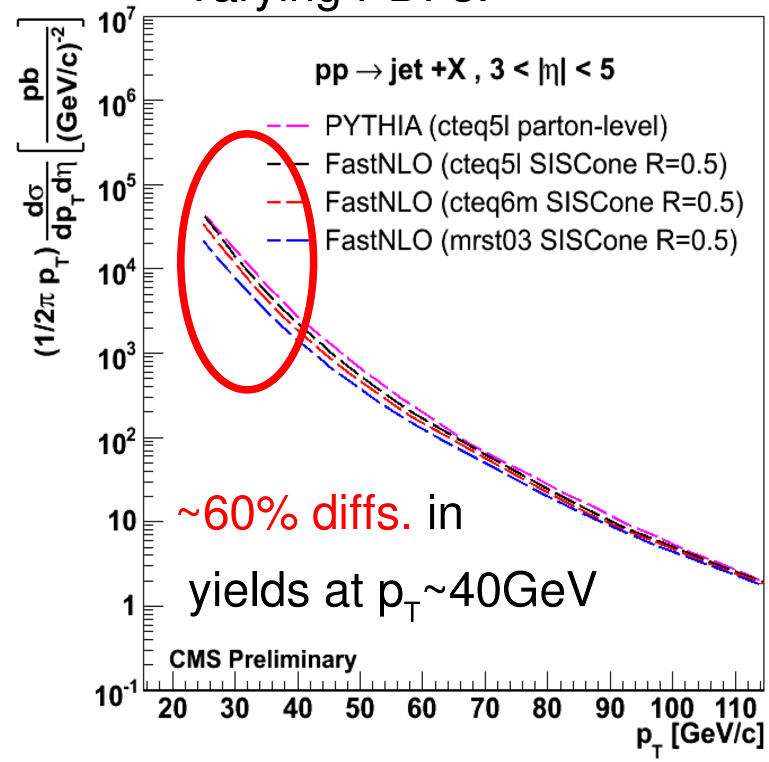


Jets in HF (3<|η|<5) probe: $x_2 \sim 10^{-4}$

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



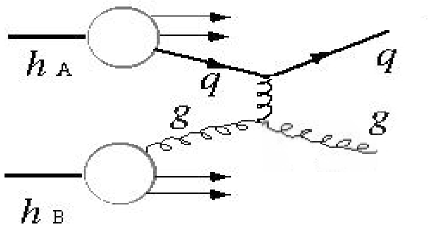
varying PDFs:



Case-study I: Forward jets in CMS ($3 < |\eta| < 6.6$)

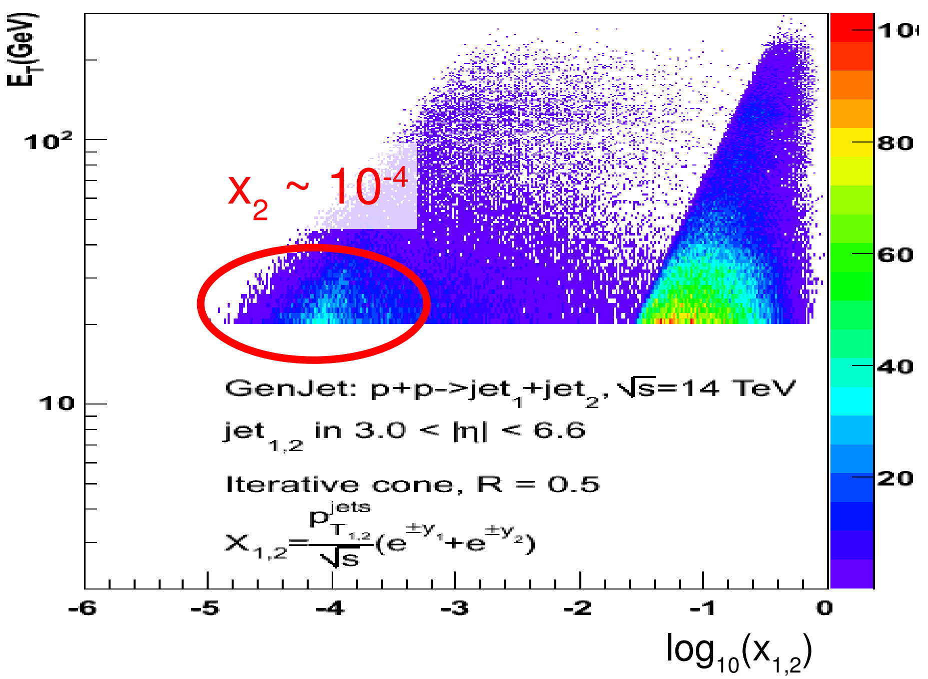
[S.Cerci, D.d'E, CMS]

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

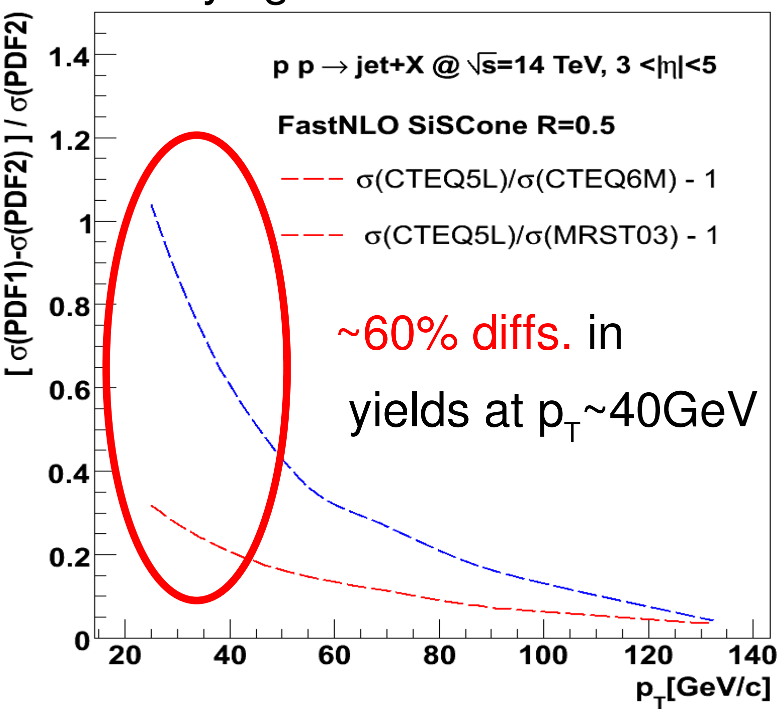


Jets in HF ($3<|\eta|<5$) probe: $x_2 \sim 10^{-4}$

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



varying PDFs:



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

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

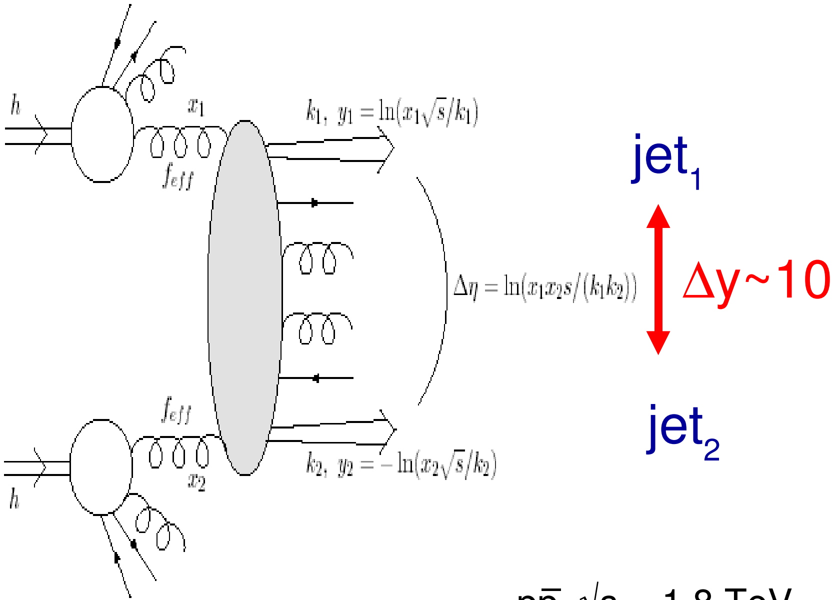
BFKL: extra radiation between the 2 jets will smooth out back-to-back topology

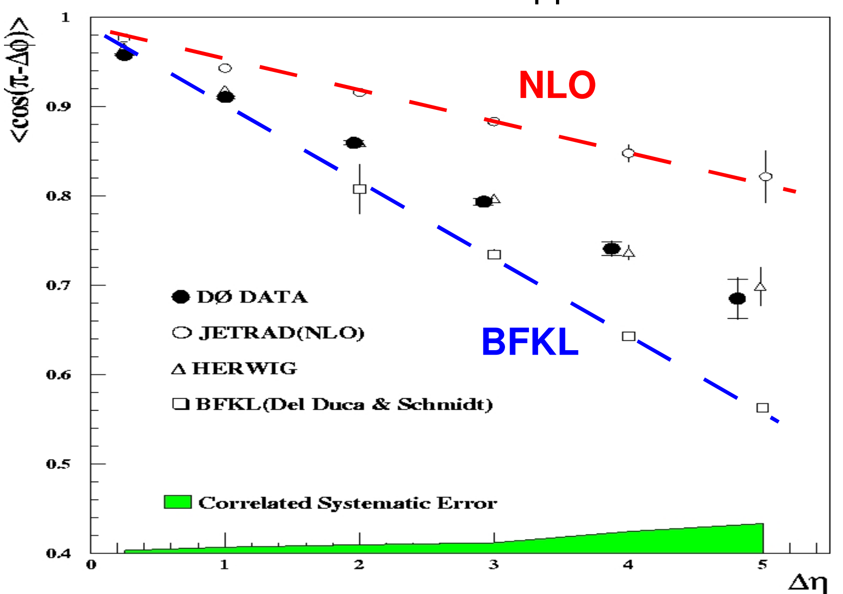
A.H.Mueller, H.Navelet, NPB282 (1987)727

(partially compensated by gluon saturation ?)

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

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





[D0 Collab, PRL77(97)595]

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):

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

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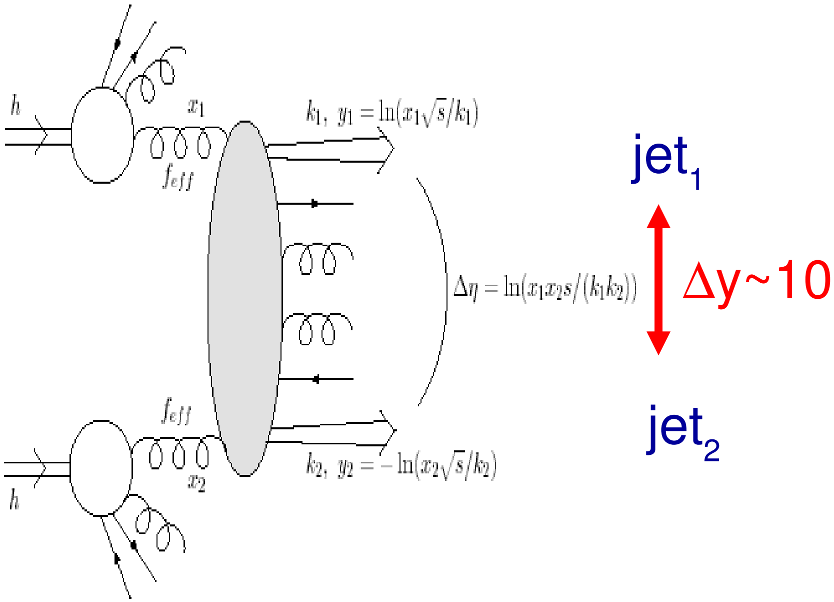

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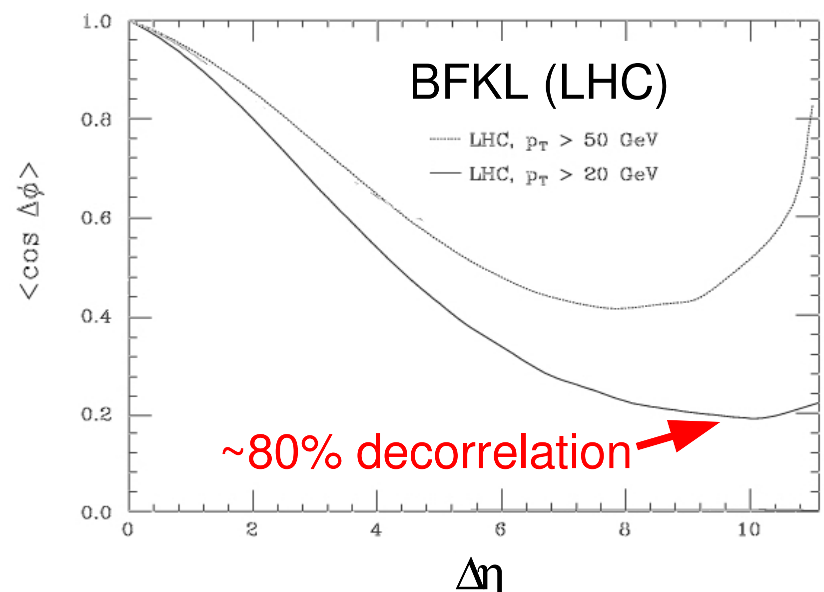

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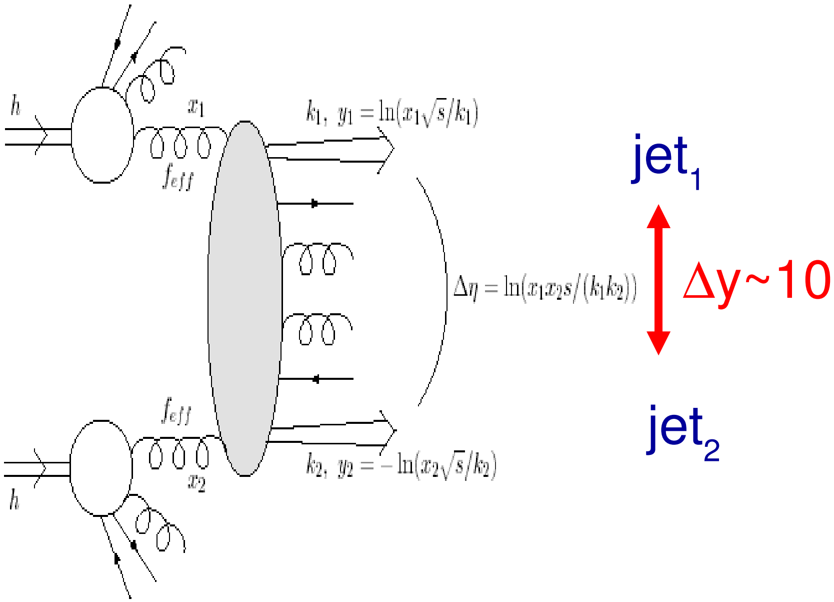

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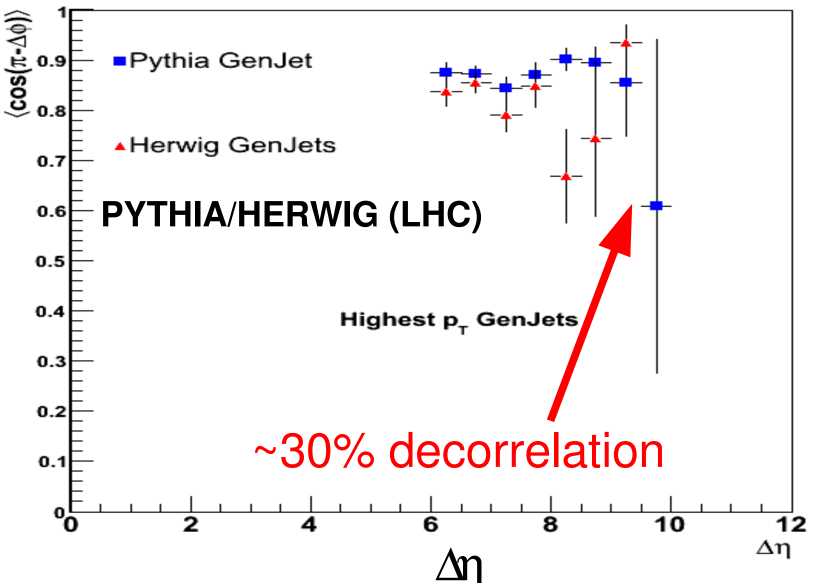
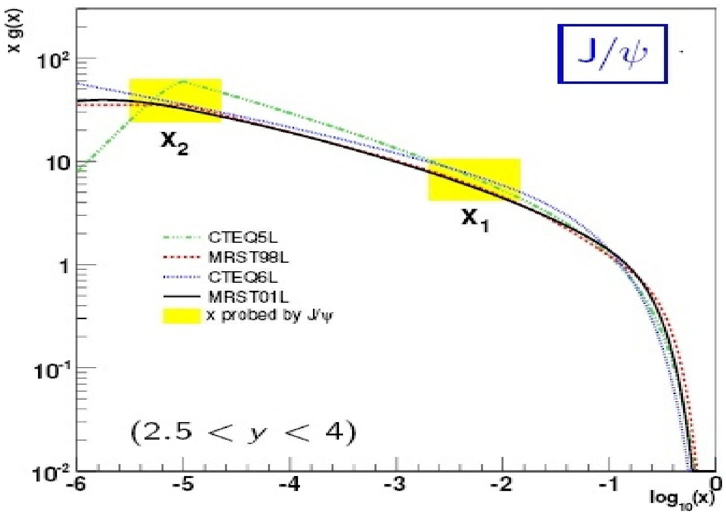
[S.Cerci, D.d'E, CMS]

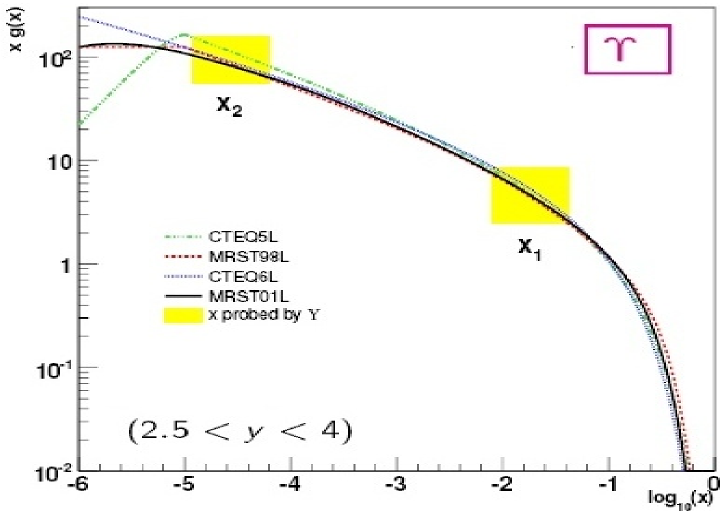


[DelDuca, Schmidt], [Orr, Stirling]
[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon] [E. Iancu et al.]

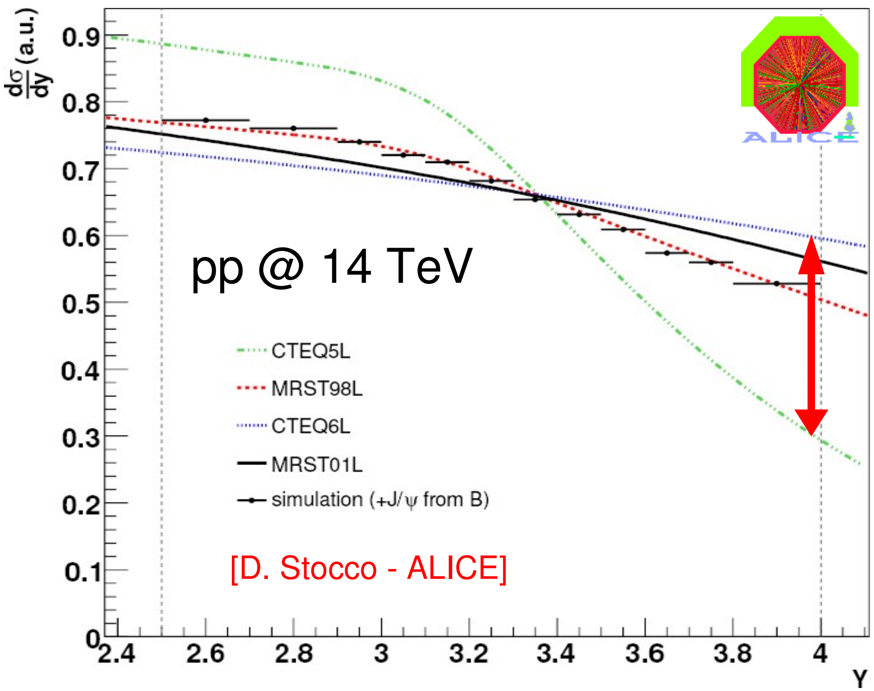
Case-study III: Forward $Q\bar{Q}$ in ALICE ($2.5 < |\eta| < 4$)

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





dσ/dy J/ψ: NLO CEM w/ varying PDFs



QQbar: Sensitive to diff. PDFs and DGLAP versus CGC predictions

(Note: $m_{J/\psi} \sim Q_s$ at the LHC)

Low-x studies at the LHC: nucleus

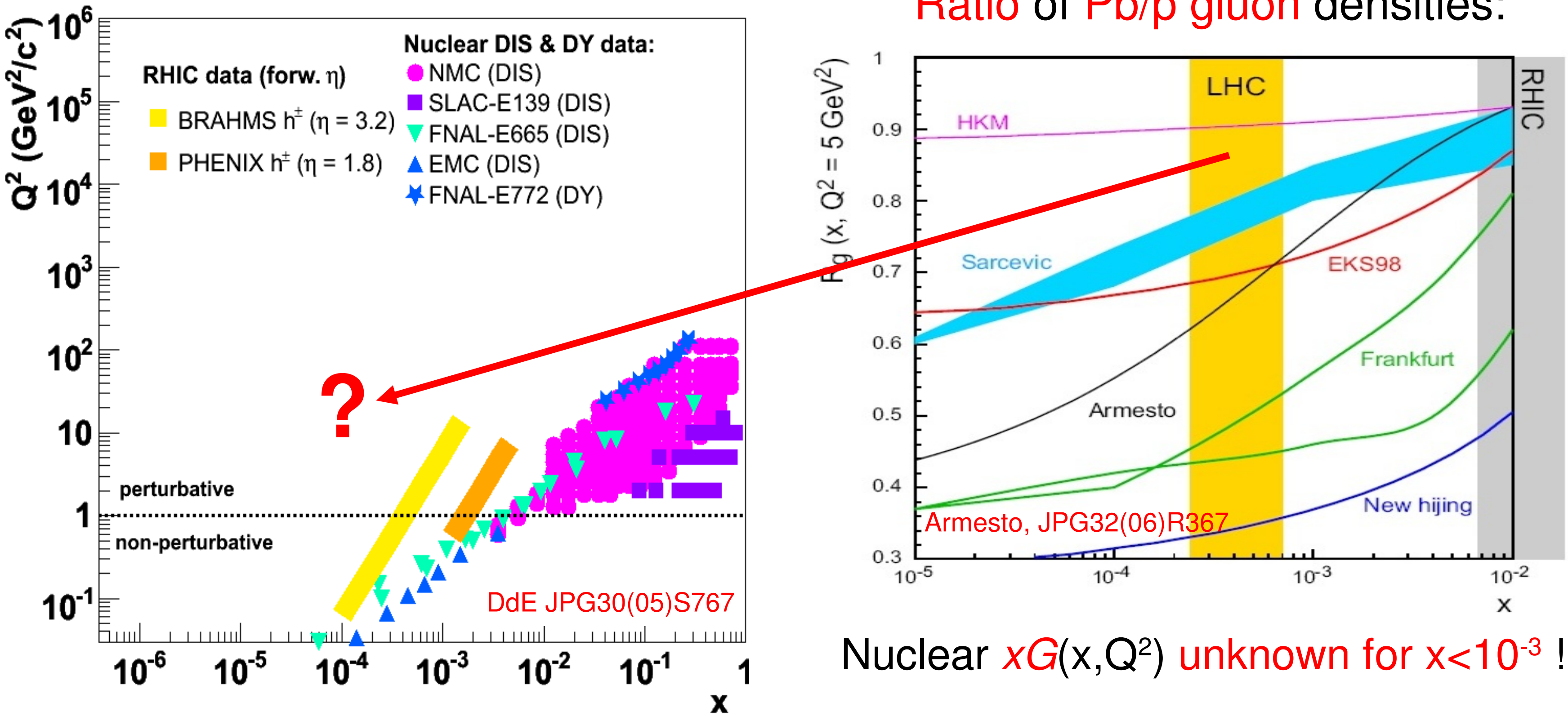
- Pb-Pb @ 5.5 TeV, p-Pb @ 8.8 TeV:

  (1) Bjorken $x=2p_T/\sqrt{s}$~30-45 times lower than Au-Au,d-Au @ RHIC !

  (2) Saturation enhanced ($A^{1/3}\sim6$) : $Q_s^2 \sim 5\ GeV^2$

  (3) Very large perturbative cross-sections.

Ratio of Pb/p gluon densities:

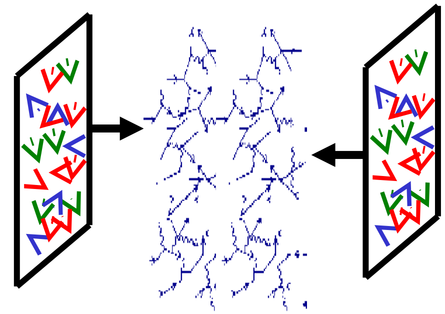


Nuclear $xG(x,Q^2)$ unknown for $x<10^{-3}$!

Case-study I: Total Pb-Pb hadron multiplicity

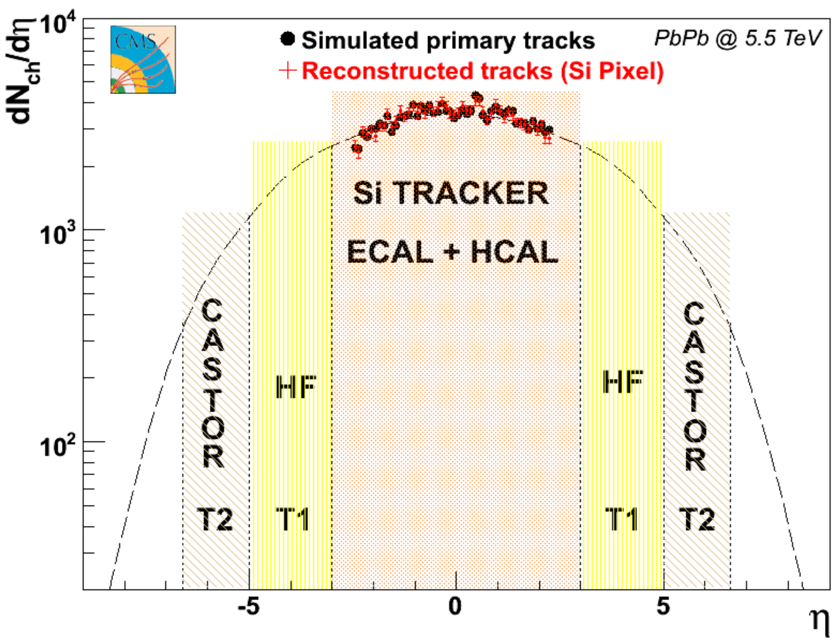
- Final A+A multiplicity ∝ Initial number of released gluons :

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

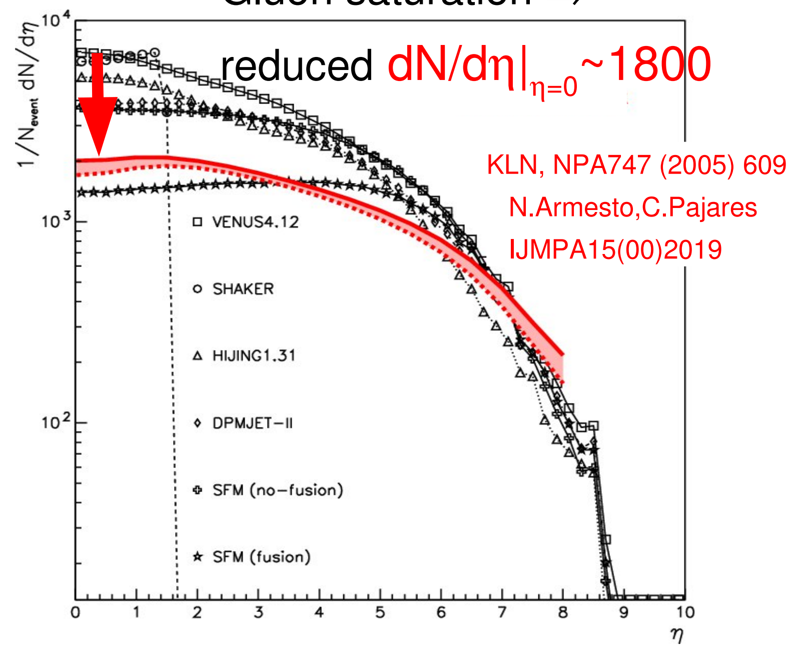


+ "local parton-hadron duality" (*1 gluon = 1 final hadron*)

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



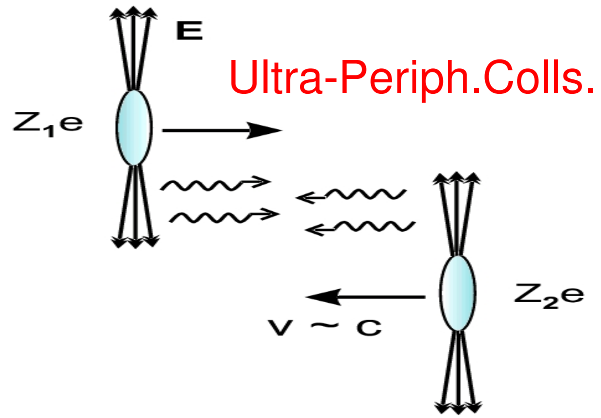
Gluon saturation ⇒ reduced $dN/d\eta|_{\eta=0}$~1800



Case-study II: Υ photoproduction in UPCs (γ Pb)

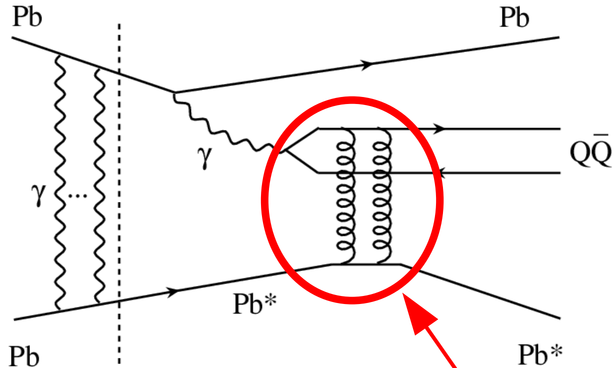
[DdE, hep-ex/0703024]

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

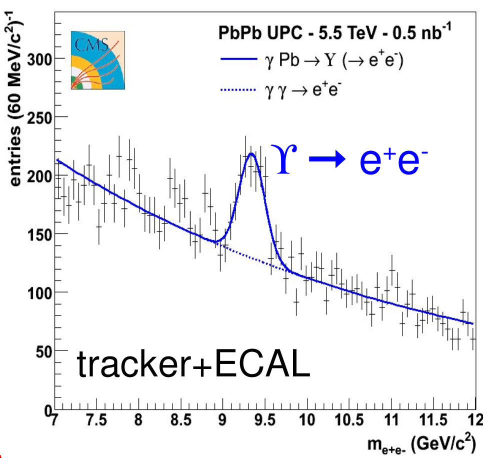


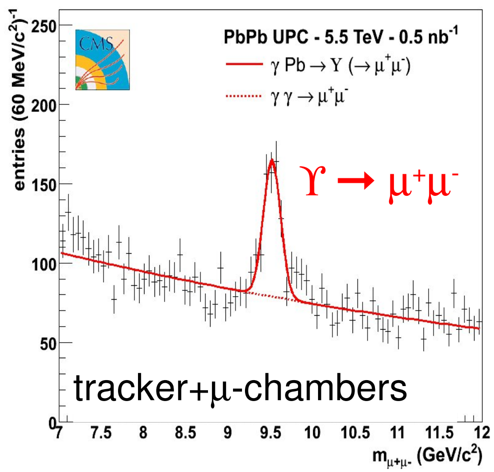
- Equivalent photon flux:
  E_γ^{max} ~ 80 GeV (PbPb-LHC)
  γ Pb: max. $\sqrt{s_{\gamma Pb}} \approx$ 1. TeV ≈ 3. - 4. × $\sqrt{s_{\gamma p}}$(HERA)

- $Q\bar{Q}$ diffractive photoproduction (ZDC neutron-tagging) sensitive to $|xG|^2$



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





~500 Υ/0.5 nb^{-1} expected in CMS

Outlook: proposed nuclear DIS facilities

- eRHIC:

  (e⁻) 20 GeV – (A) 100 GeV

  $\sqrt{s}$~60 GeV, $\mathcal{L}$~10^{33} $cm^{-2}s^{-1}$

- LHeC:

  (e⁻) 70 GeV – (p,A) 2.75, 7 TeV

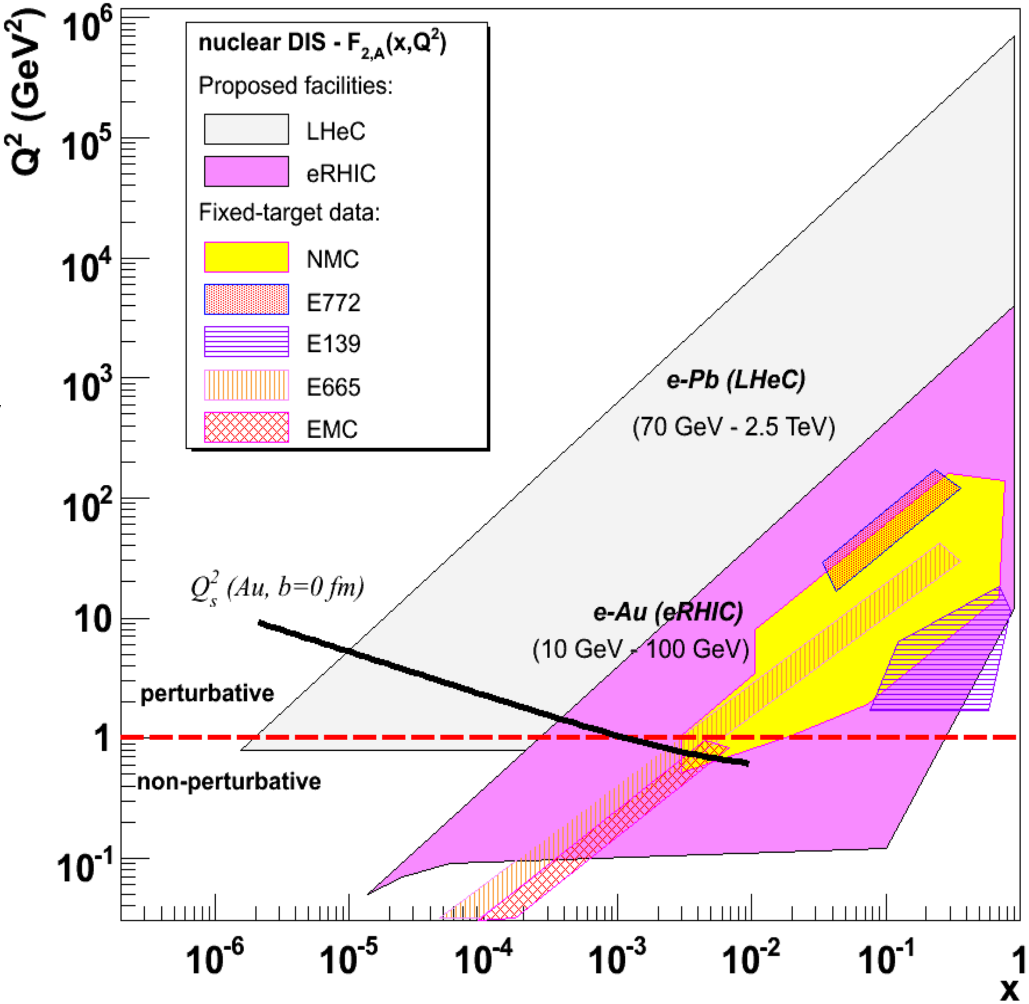
  $\sqrt{s}$~0.9,1.4 TeV, $\mathcal{L}$~10^{33} $cm^{-2}s^{-1}$

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

Q^2~10^6 GeV^2

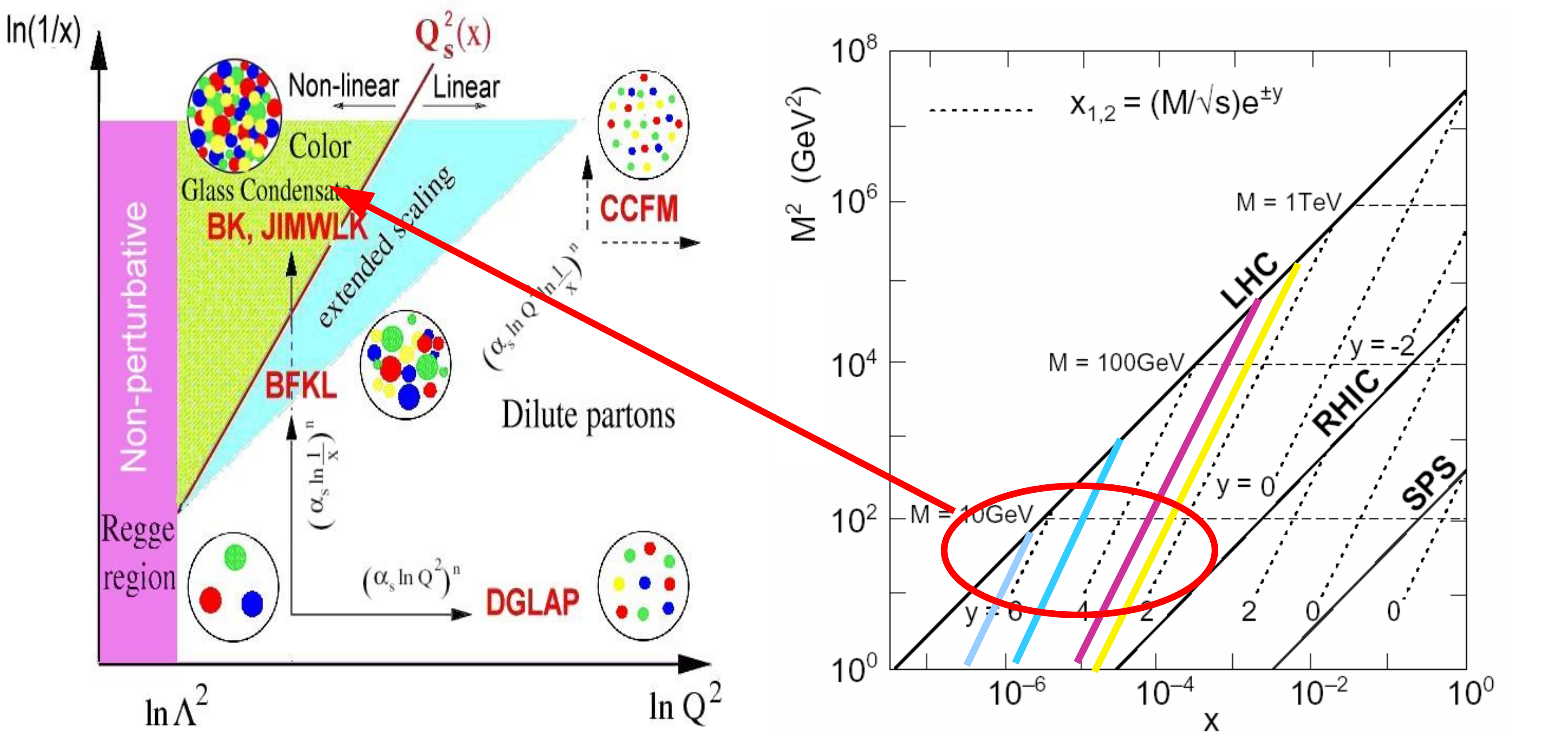
x~10^{-6}

DdE, arXiv:0706.4182



Summary

- Gluon saturation & non-linear evolution must set-in at (some) low-x in the hadrons → Basic info on high-energy limit of QCD
- Hints of non-linear QCD dynamics in *e-p* (HERA) and d-A,A-A (RHIC)
- LH(e)C = unique lab to study high parton density /evolution in p,Pb down to $x \sim 10^{-6}$ using fwd. detectors & perturbative processes: (di)jets, QQbar,...

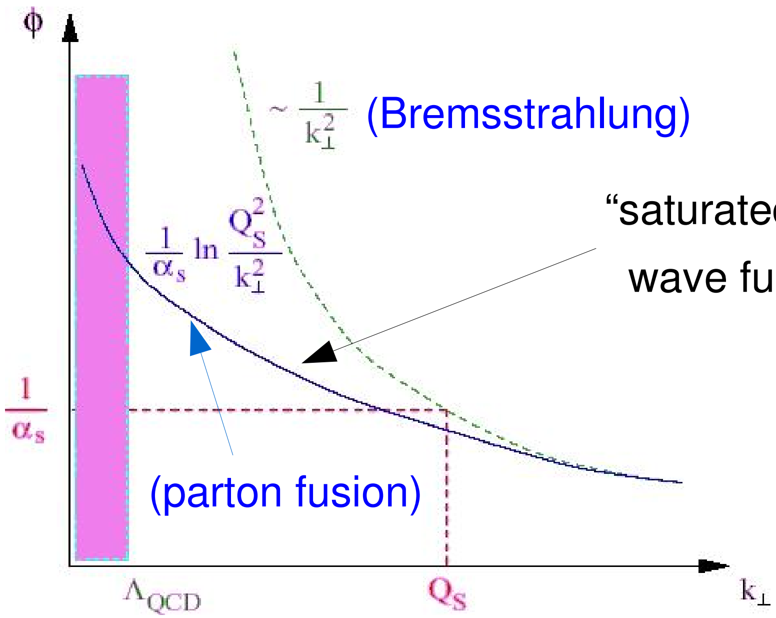


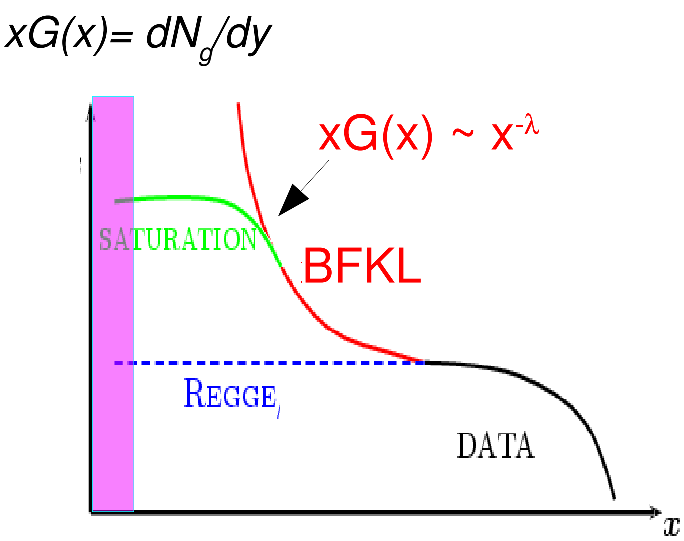
Backup slides

Color Glass Condensate (CGC)

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

- CGC = EFT in high-energy (small-x) QCD limit:
  - **C**olor (obvious) **G**lass (q ~ "frozen" sources) **C**ondensate (high gluon occup.)
  - Hadrons = Classical fields below/around Q_s:



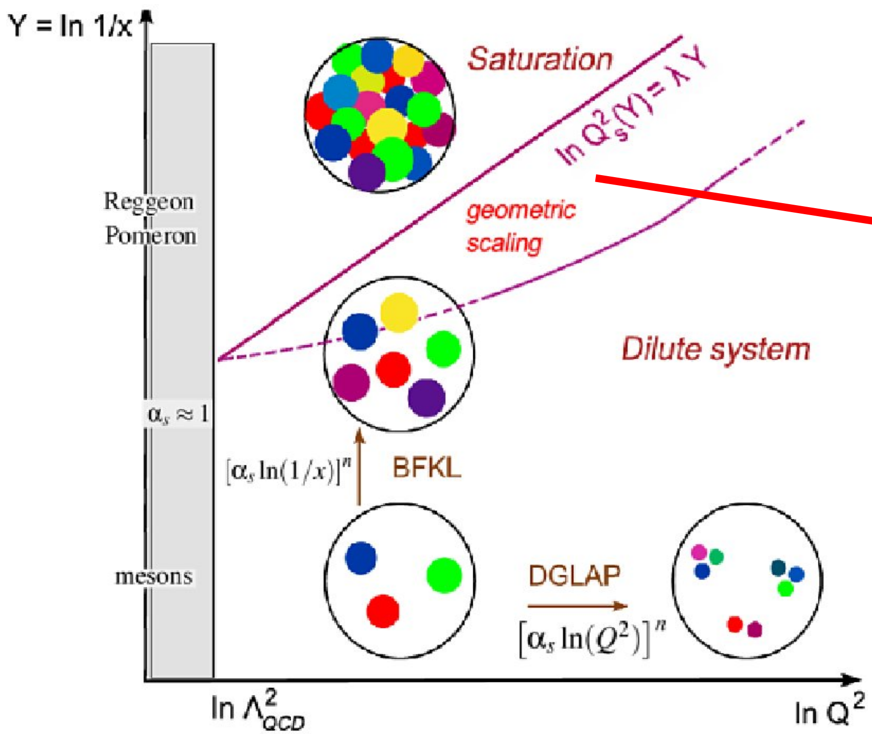


  - Q_s hard ⇒ perturbative calculations (strong $F_{\mu\nu}$, weak coupling): $\alpha_S(Q_s^2) << 1$
  - pA,AA ≡ collisions of gluon wave function(s) "resum" all multiple scatts.

Non-linear QCD evolution equations: BK/JIMWLK

- 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:

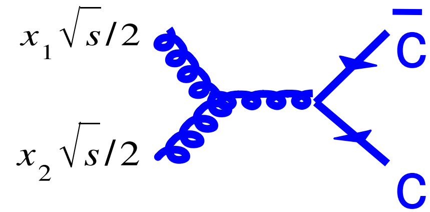
$$\frac{1}{Q^2} \to \left(\frac{1}{Q^2}\right)^\gamma \quad \gamma \simeq 1/2$$

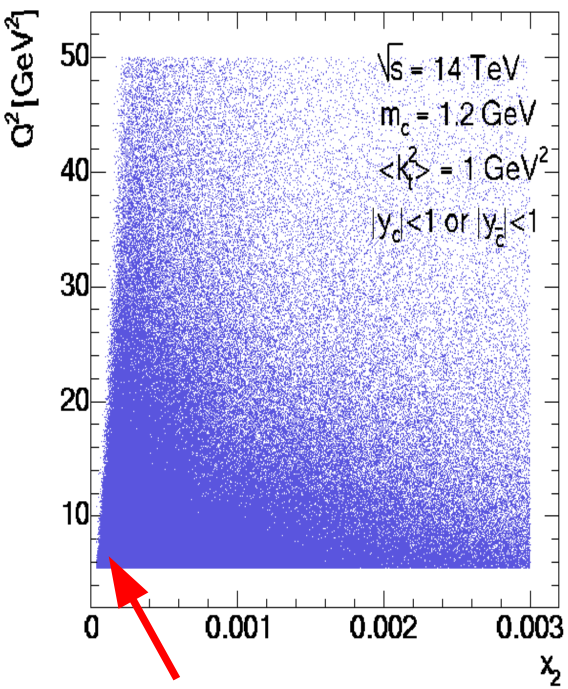
$$Q_s^2 < Q^2 < Q_s^4/\Lambda^2$$

extended window of applicability outside CGC !

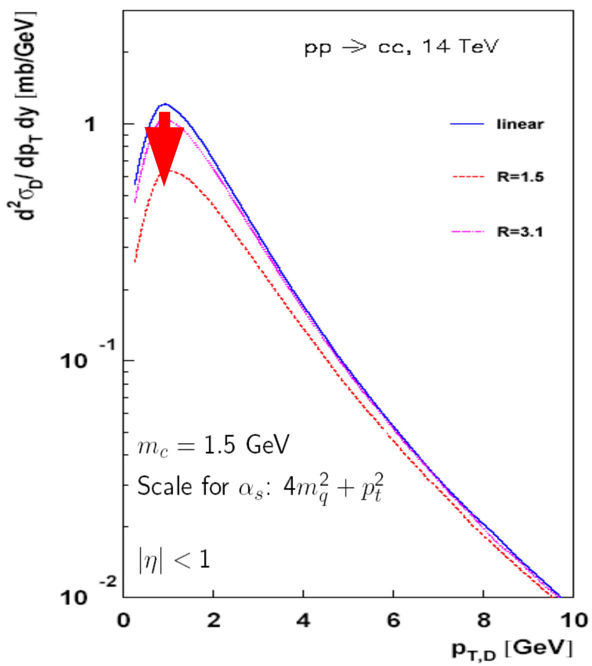
Case-study IV: Low-p_T charm in ALICE ($|\eta|<1$)

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

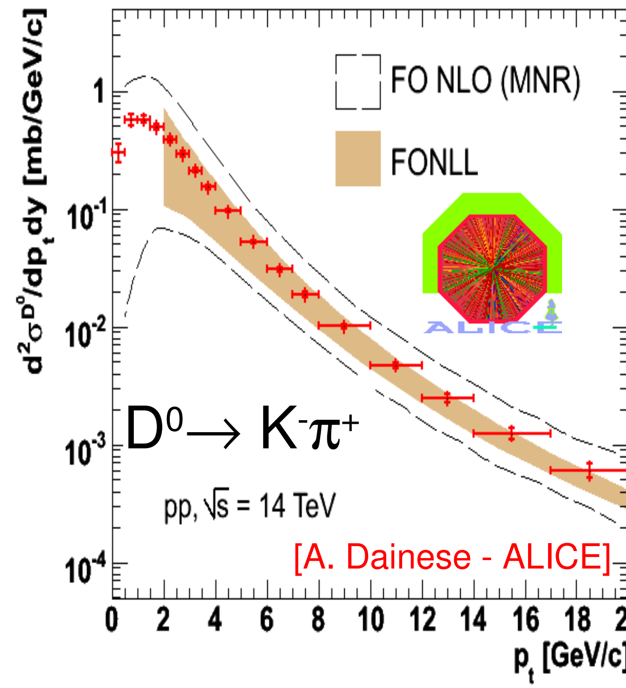




xg(x) in the proton at $x_1 \sim x_2 \sim m_c/\sqrt{s} \sim 10^{-4}$



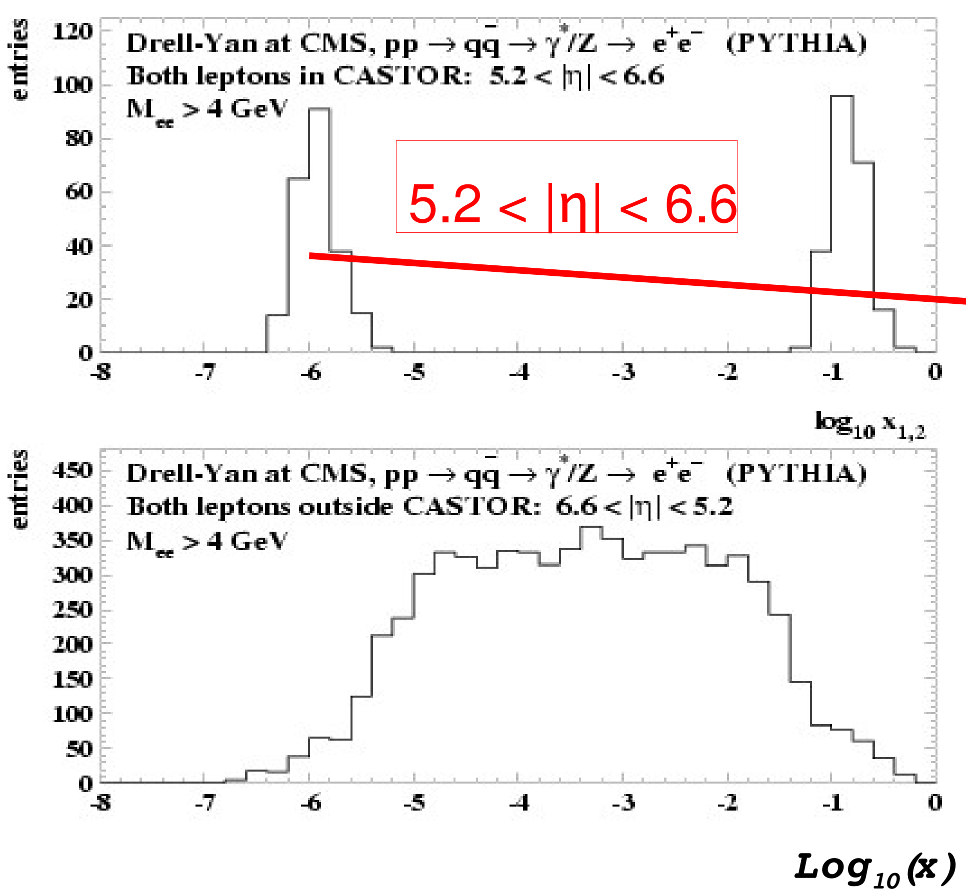
Charm suppression due to non-linear QCD effects



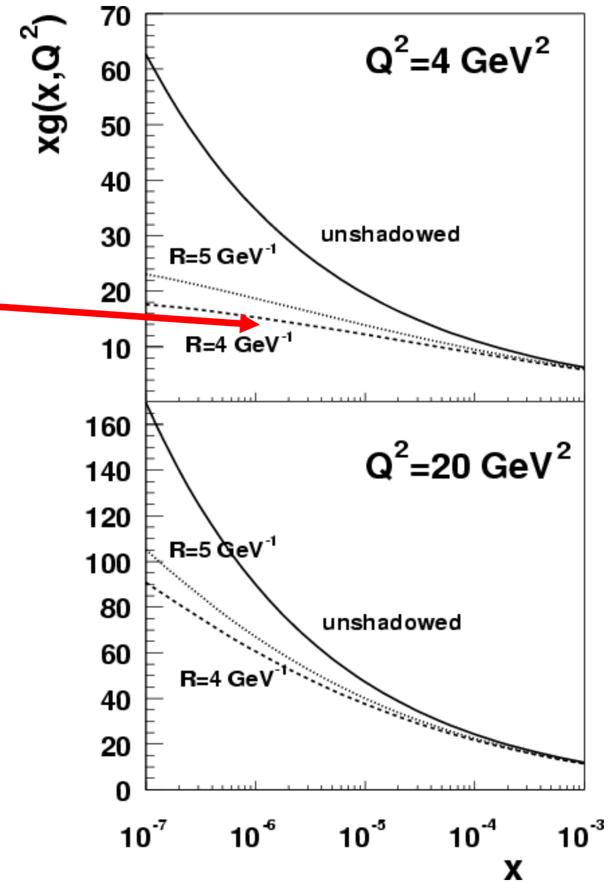
Good reco capabilities (displaced vtx.+ $e^\pm$ PID) down to p_T = 0 GeV/c

Case-study VII: DY in CASTOR-T2 (5.2 <|η|< 6.6)

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



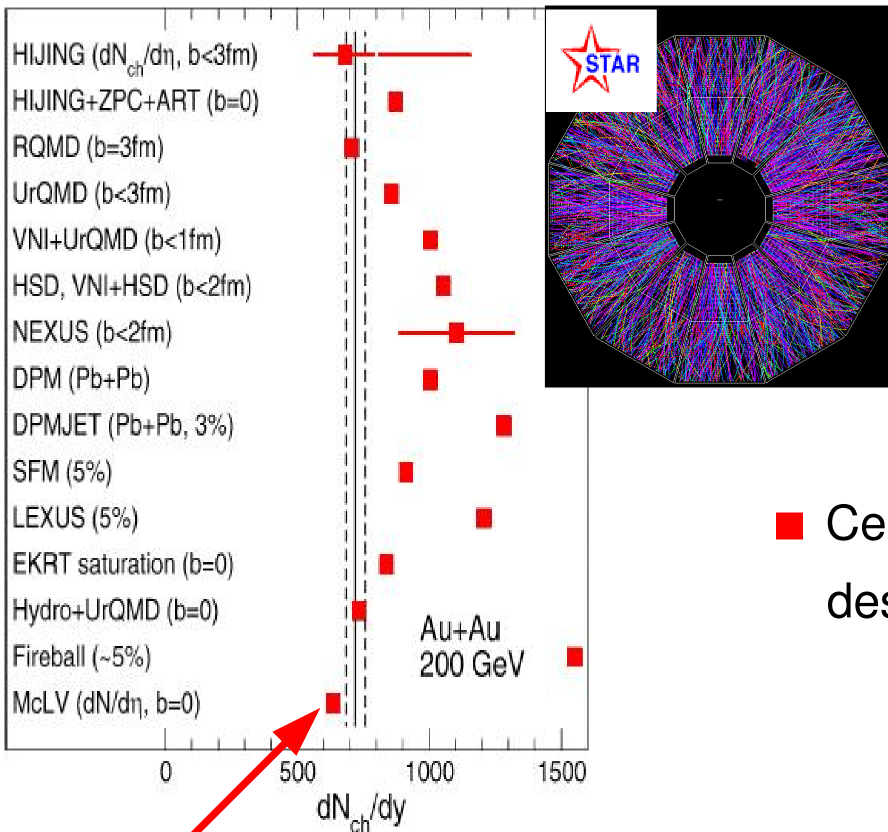
PDF parametrizations

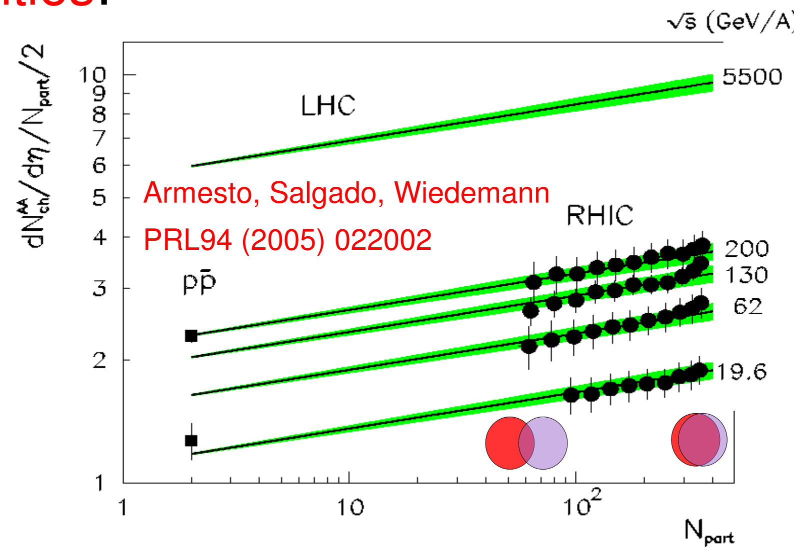


TOTEM T2 tracker+ CASTOR needed to deal w/ large QCD (& QED) bckgd.

Saturation hints at RHIC ? (AuAu @ 200 GeV)

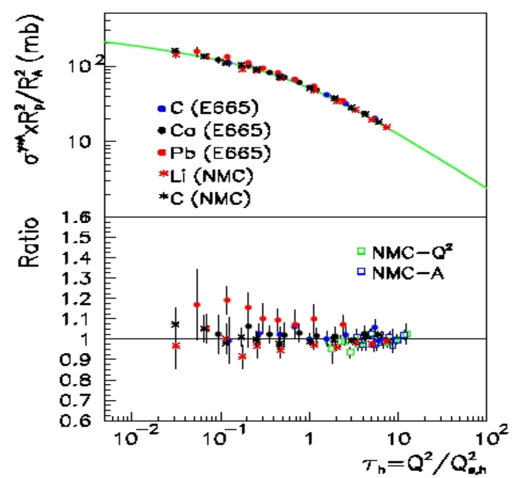
- "Reduced" total AuAu hadron multiplicities:





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

- Centrality & sqrt(s) dependence of dN/dη described by geometric-scaling models.

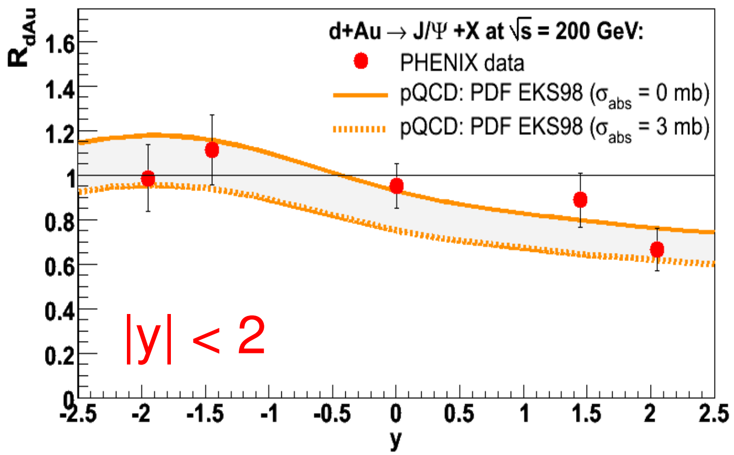


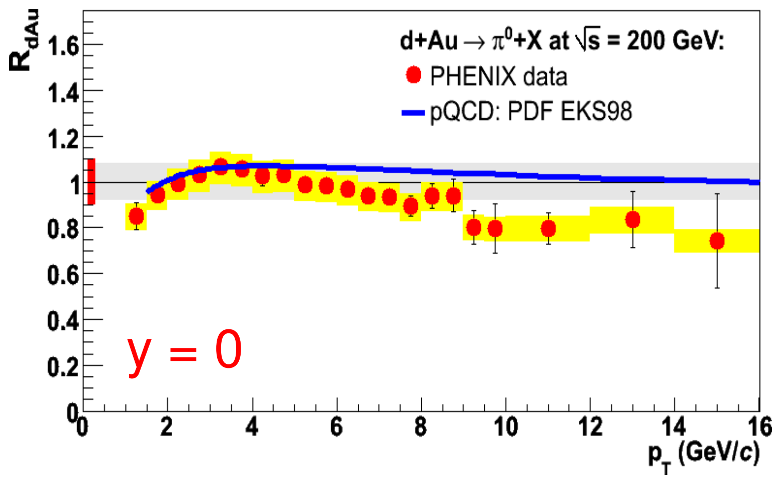
Confirms approx:

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

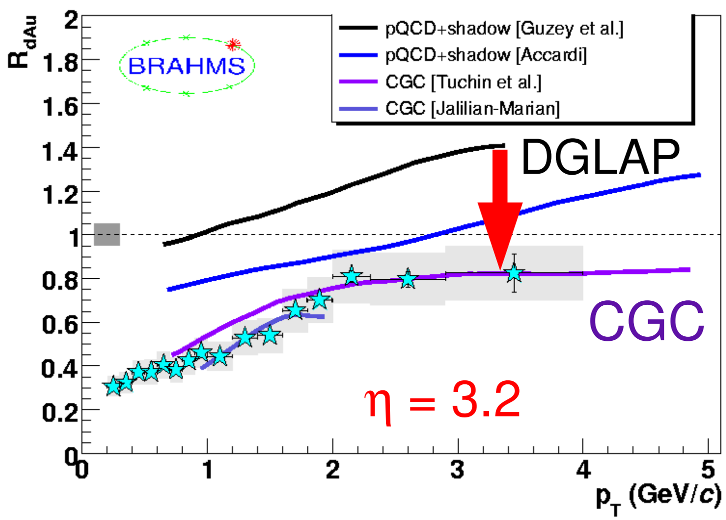
Saturation hints at RHIC ? (dAu @ 200 GeV)

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





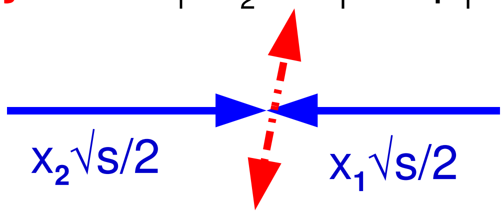
- η = 3.2 ($x \sim 10^{-3}$): Suppressed hadron production (p_T ~ 2 – 4 GeV/c) better described by CGC than NLO pQCD: reduced partonic flux in Au at low-x



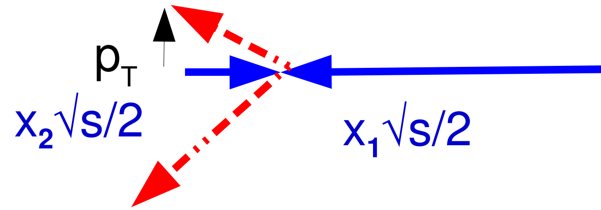
Small-x → Forward rapidities

- $2 \rightarrow 2$ parton kinematics:

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



$$x_{1,2}^{2\to2} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y} + e^{\pm y'}\right) \Rightarrow x_2^{min} = \frac{x_T\, e^{-\eta}}{2 - x_T\, e^{\eta}}$$



e.g. LHC, p_T = 10 GeV/c

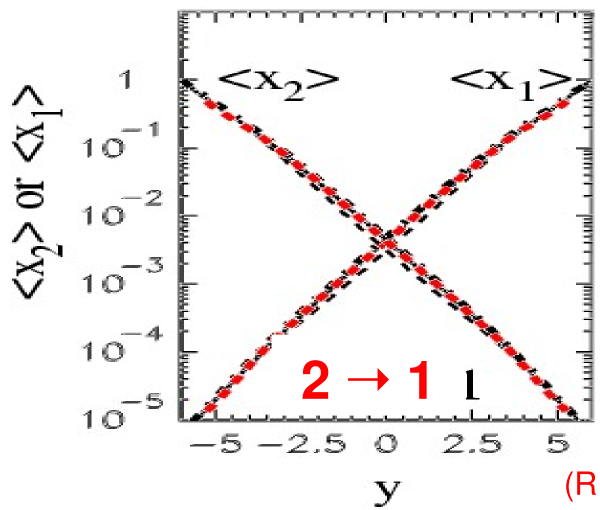
$x_T \sim 10^{-3}$ ($\eta \sim 6$): $x_{min} \sim 10^{-6}$

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

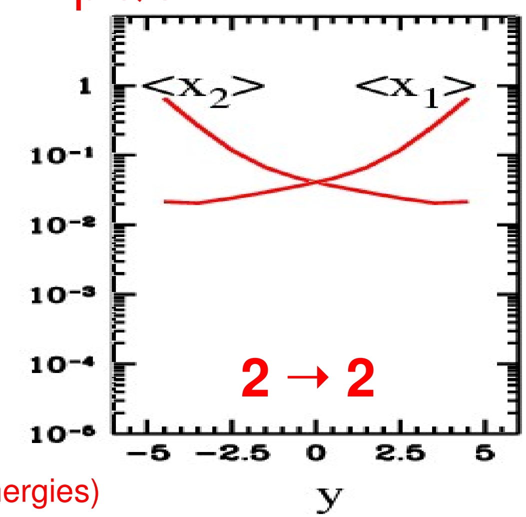
$$x_{1,2}^{2\to1} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y}\right)$$

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

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



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



(RHIC energies)

[Accardi,nucl-th/0405046]

Forward Detectors in CMS & ATLAS

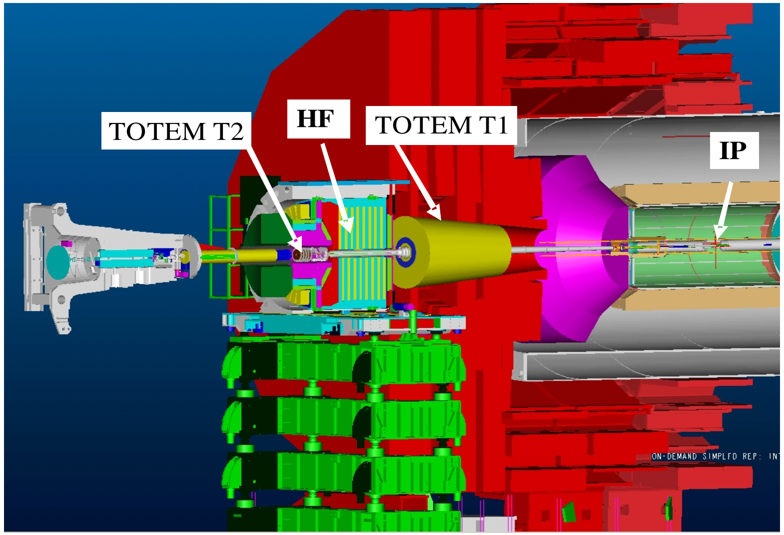
- CMS + TOTEM:

  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)

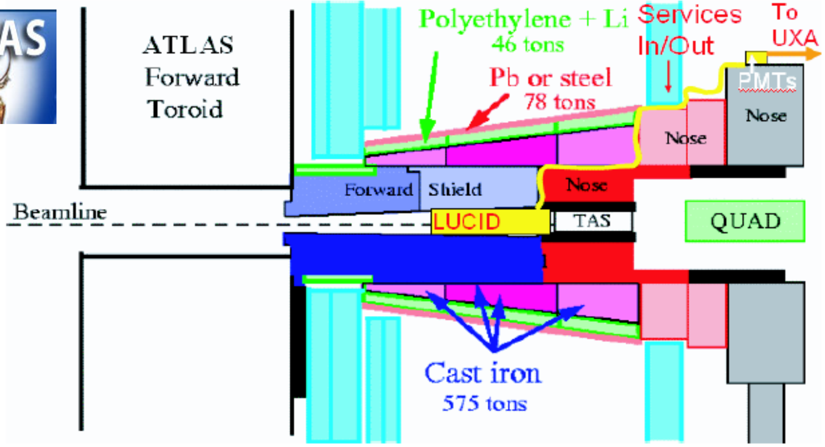


- ATLAS:

  FCal.: $3 < \eta < 5$

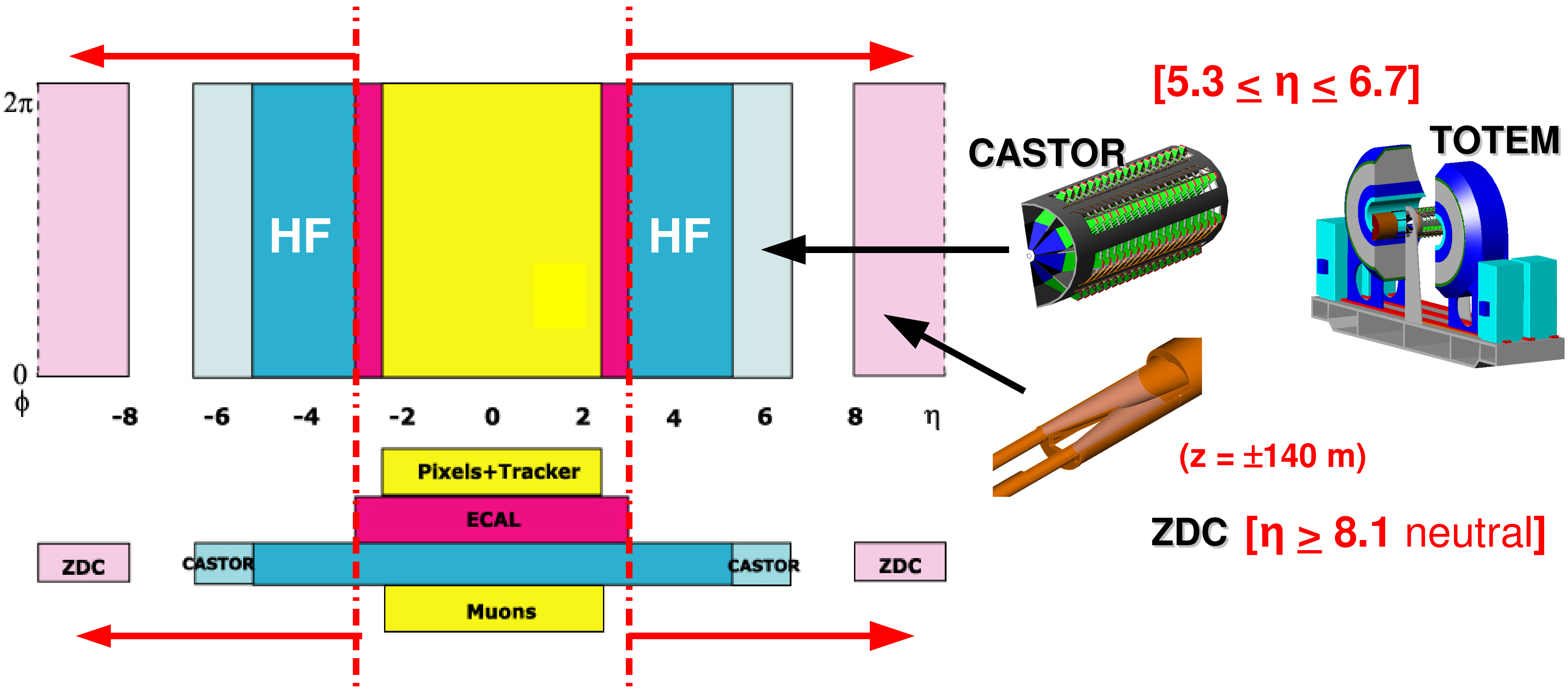
  LUCID (Cerenkov Counter): $5.4 < \eta < 6.1$

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



CMS/TOTEM at the LHC

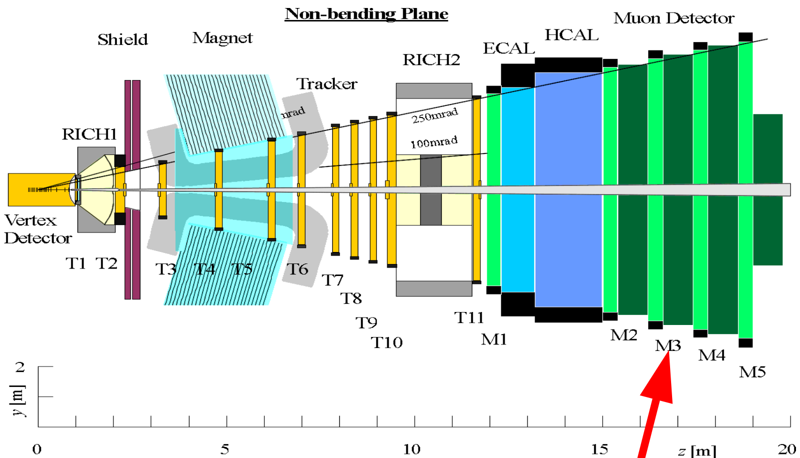
- HF,CASTOR,ZDC + TOTEM: Quasi-full acceptance at LHC:



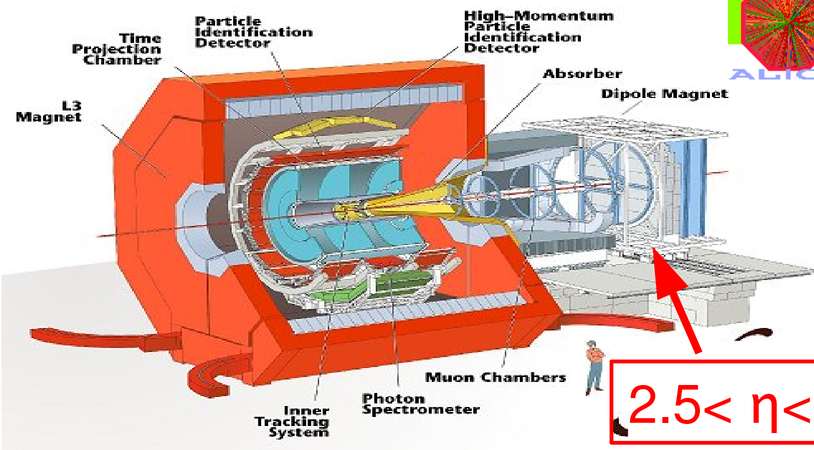
- Detection capabilities within $\eta \leq 6.7$ (and $\eta \geq 8.1$, neutral).
- Hard scattering measurements (jets, high-p_T hadrons, DY) possible down to $x \sim 10^{-6}$ in pp, pA, AA at LHC.

Forward Detectors in ALICE & LHCb

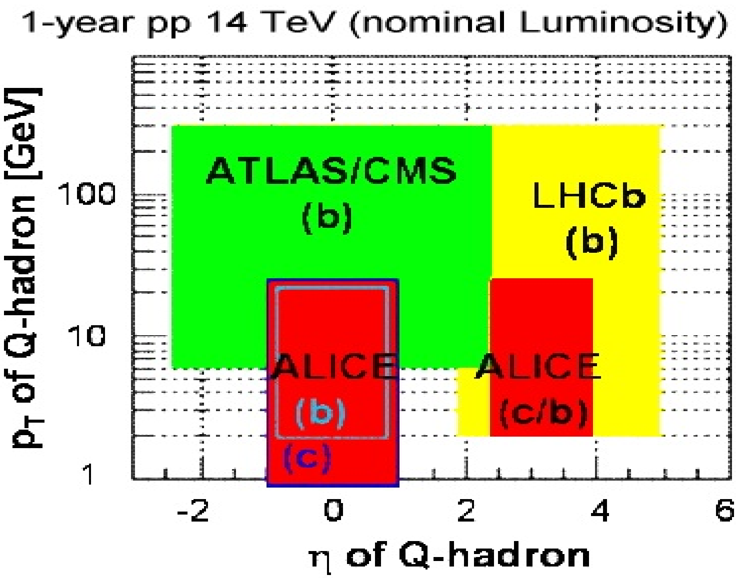
- ALICE, LHCb forward muon spectrometers:



2 < η < 5



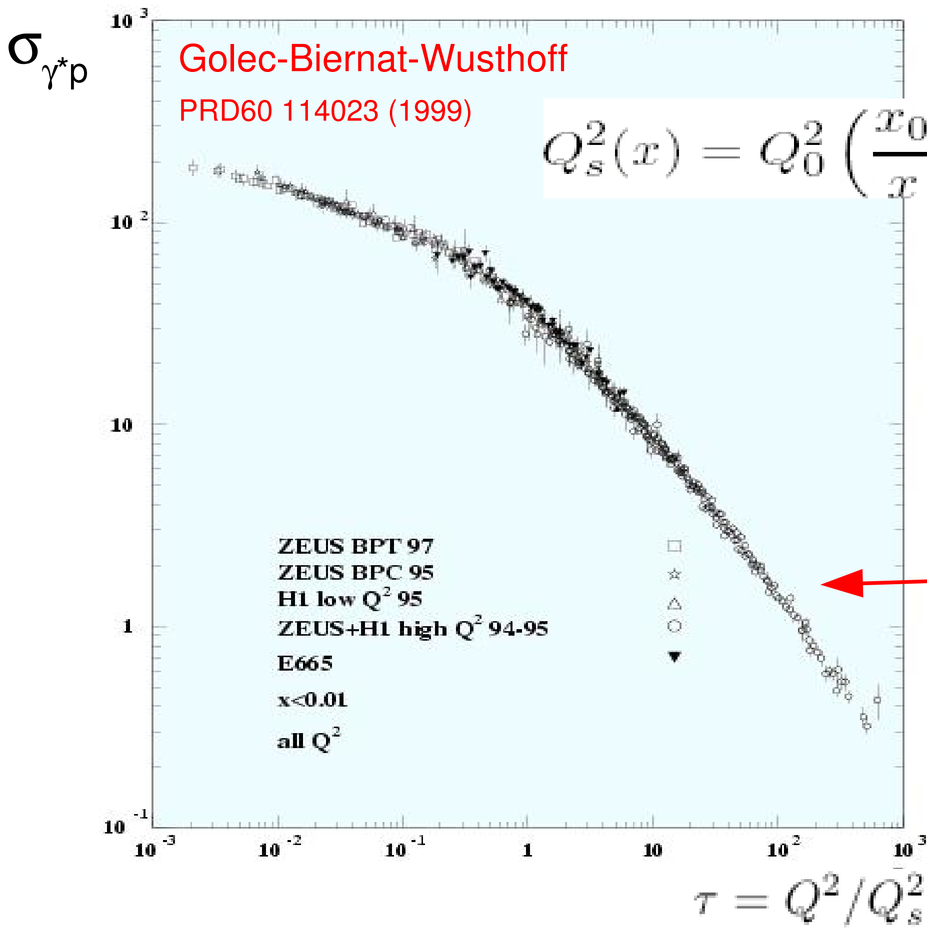
2.5< η< 4



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

Saturation hints at HERA (I): "Geometric scaling"

- Saturation predicts low-x structure dependence on single scale $Q^2_s(x)$
- Inclusive $\sigma_{\gamma^* p}$ seen to scale with Q^2/Q_s^2 for **x < 0.01**:



$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$, Q_0 = 1 GeV, λ~ 0.3

$\sigma_{\gamma^* p}$ described by dipole model:
particular realization of CGC
where $\sigma_{dipole\text{-}p}$ ~ f(G(x)) ~ 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 to $xG(Q^2)$ fit chosen*]

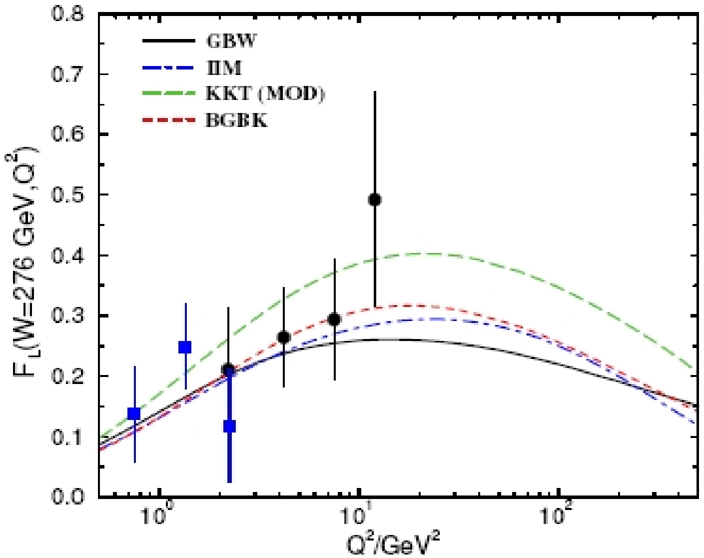
Saturation hints at HERA (II): F_L at low-x

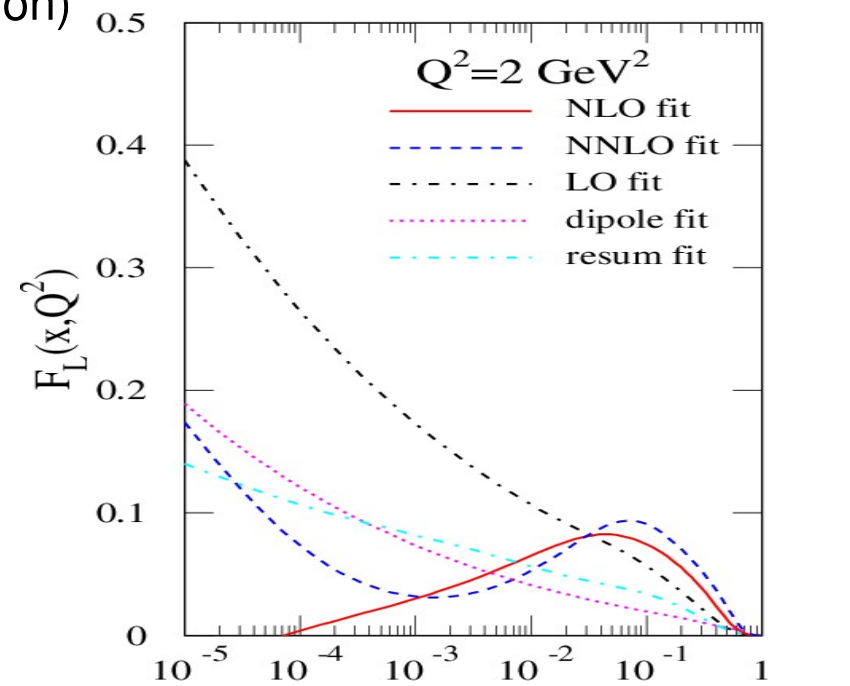
- F_L directly depends on gluon PDF: $F_L \propto \alpha_s xg$

  but F_L is a small correction to $\sigma_{\gamma p}$: $$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ \cdot F_2 \mp Y_- \cdot xF_3 - y^2 \cdot F_L\right]$$

- F_L derived from NLO DGLAP analysis, is negative for Q^2~2 GeV^2 !?

  (indicates "tension" with std. DGLAP evolution)





- Direct measurement of F_L carried out at HERA in Jun'07: e-p at lower $\sqrt{s}$

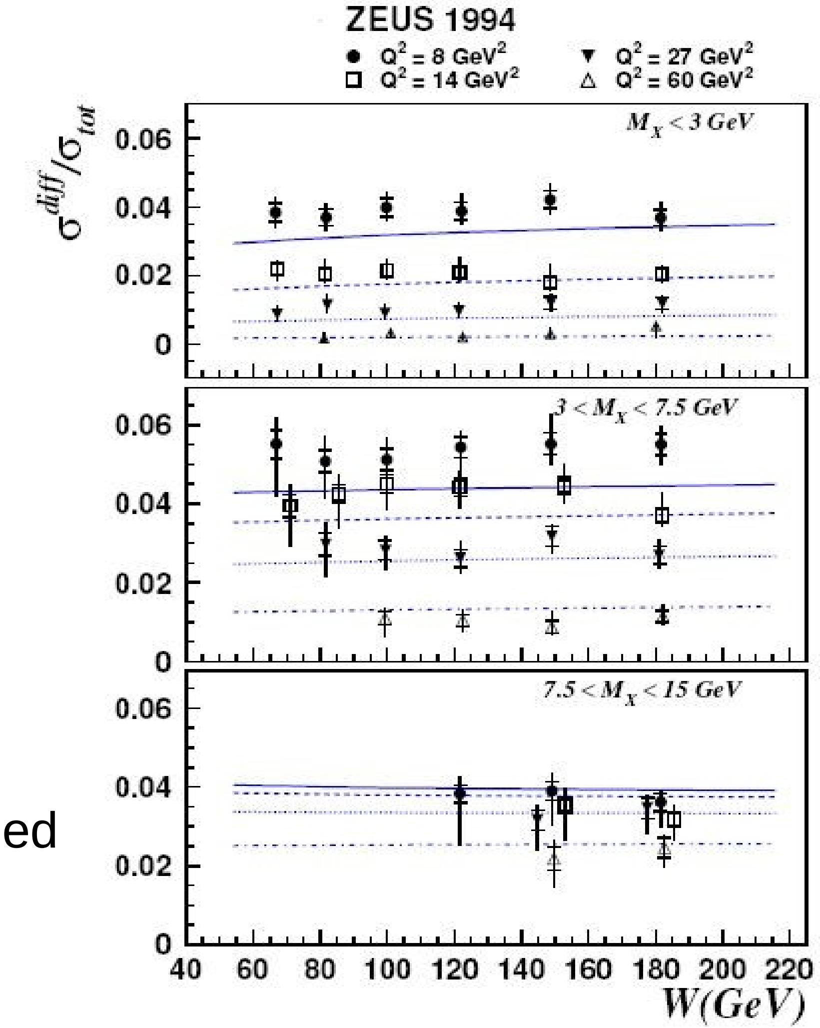
Saturation hints at HERA (III): $\sigma_{diffract}/\sigma_{tot}$ ratio

- Hard diffraction x-sections & total x-sections observed to have similar energy dependence.

- Flat $\sigma_{diffract}/\sigma_{tot}$ vs energy is at variance with expected rise behaviour in standard pQCD:

$$\sigma_{\rm diff}/\sigma_{\rm tot} \propto |xg(x,Q^2)|^2/xg(x,Q^2)$$
$$\sim W^{4\lambda}/W^{2\lambda} \sim W^{2\lambda}$$

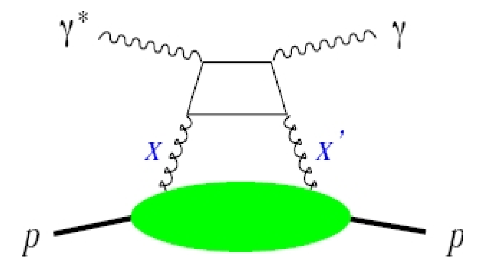
... constant dependence naturally described by saturation models.

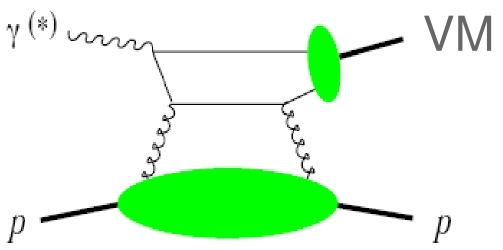


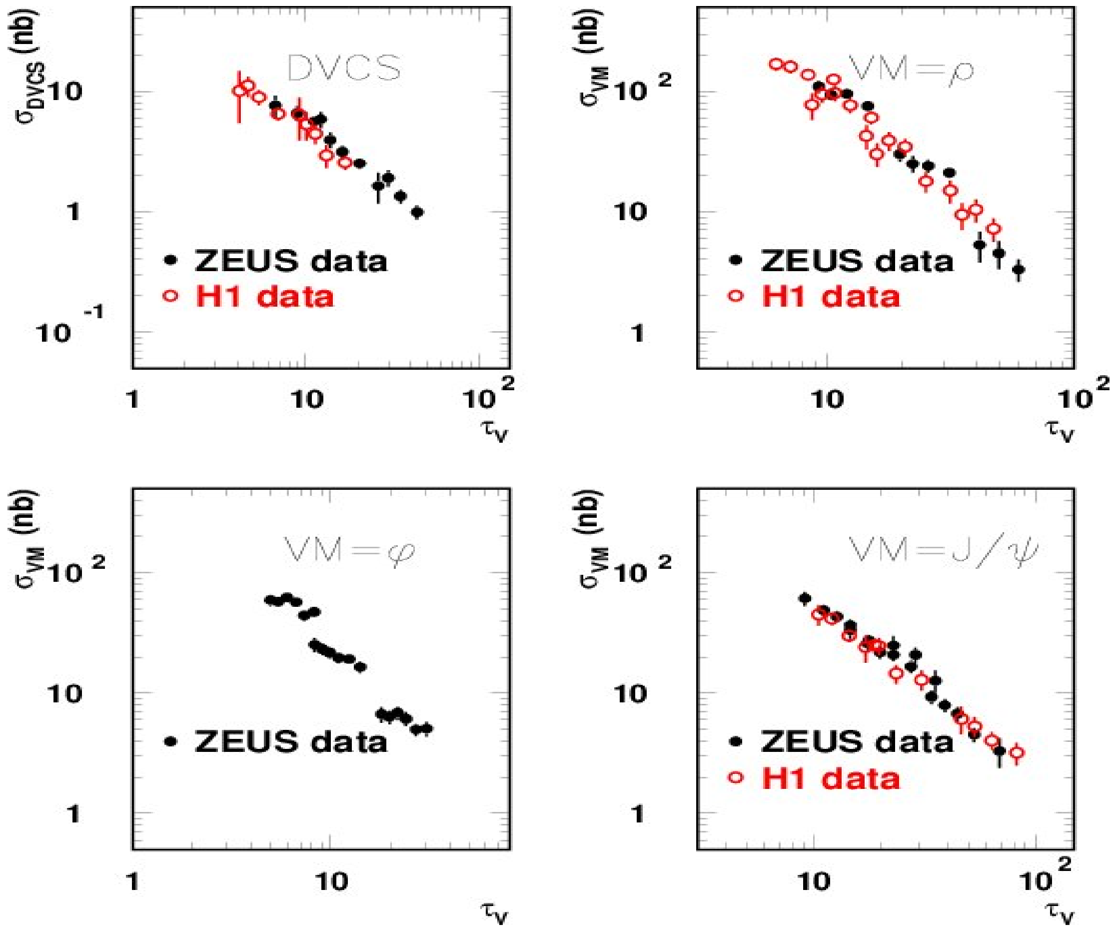
HERA (diffract. DIS): "Geometric scaling" of σ_{VM}, σ_{DVCS}

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

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

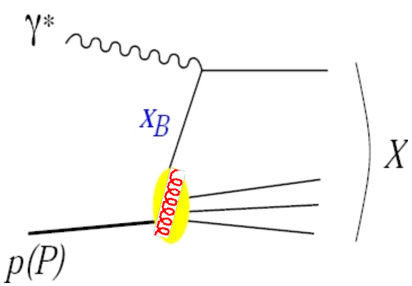


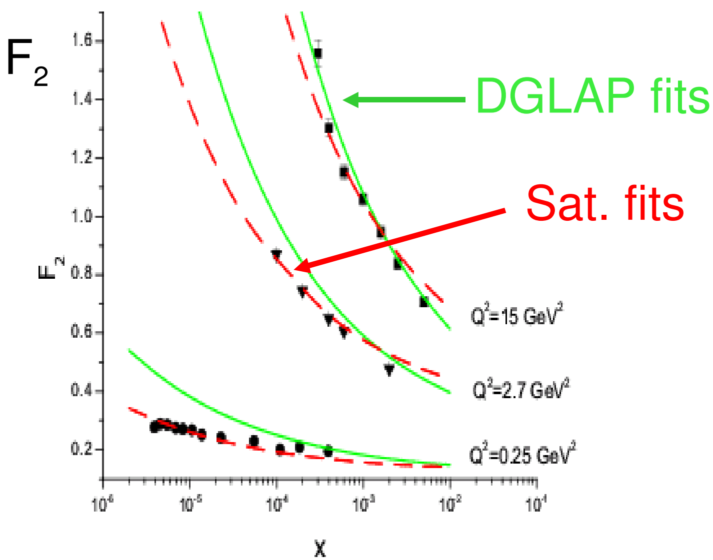




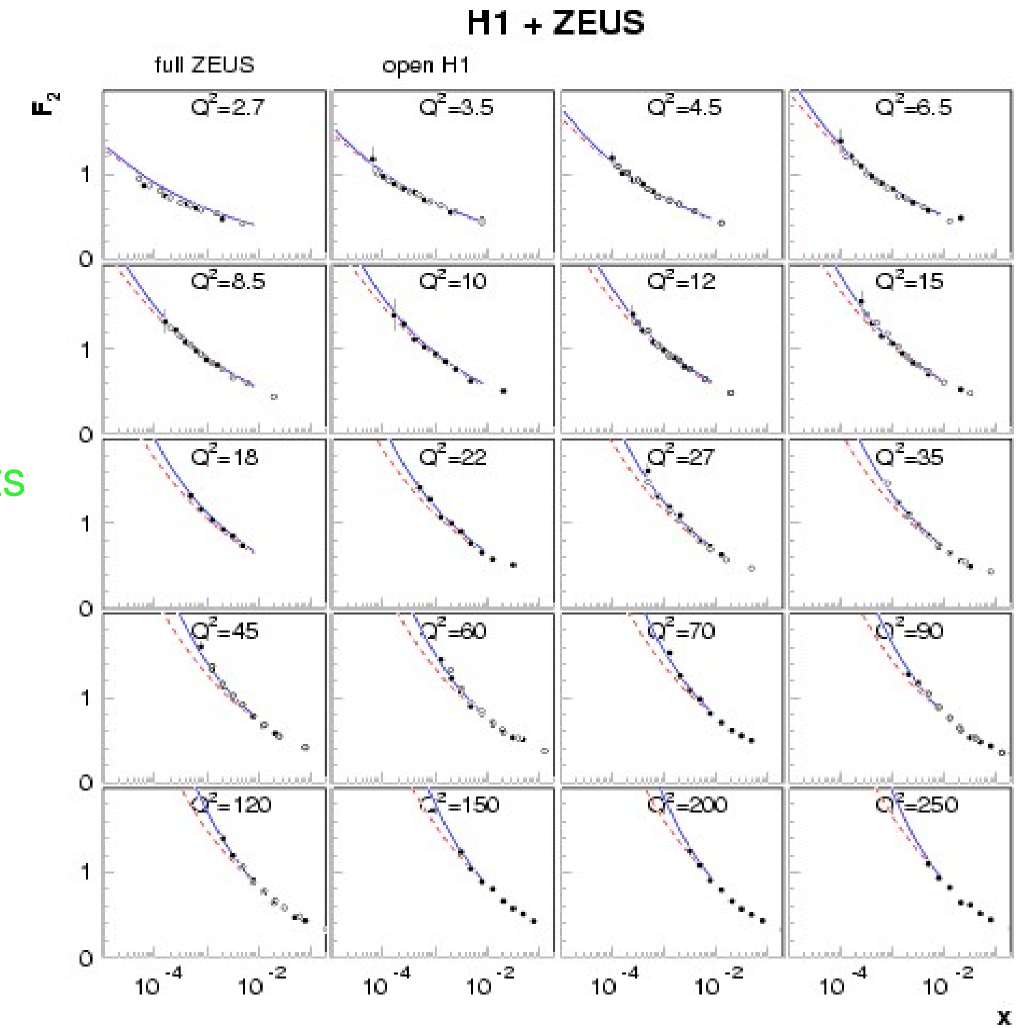
HERA data vs. saturation models: $F_2(x,Q^2)$

- 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)*





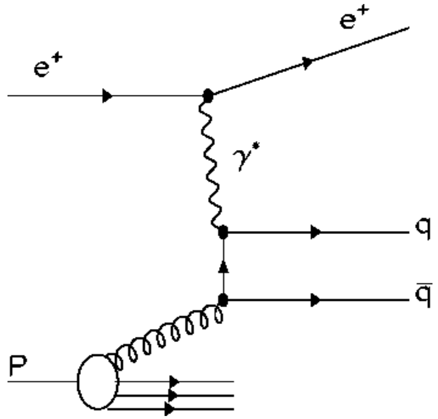
[Forshaw,Shaw, hep-ph/0411337]



HERA data vs. saturation models: $F_2^{charm}(x,Q^2)$

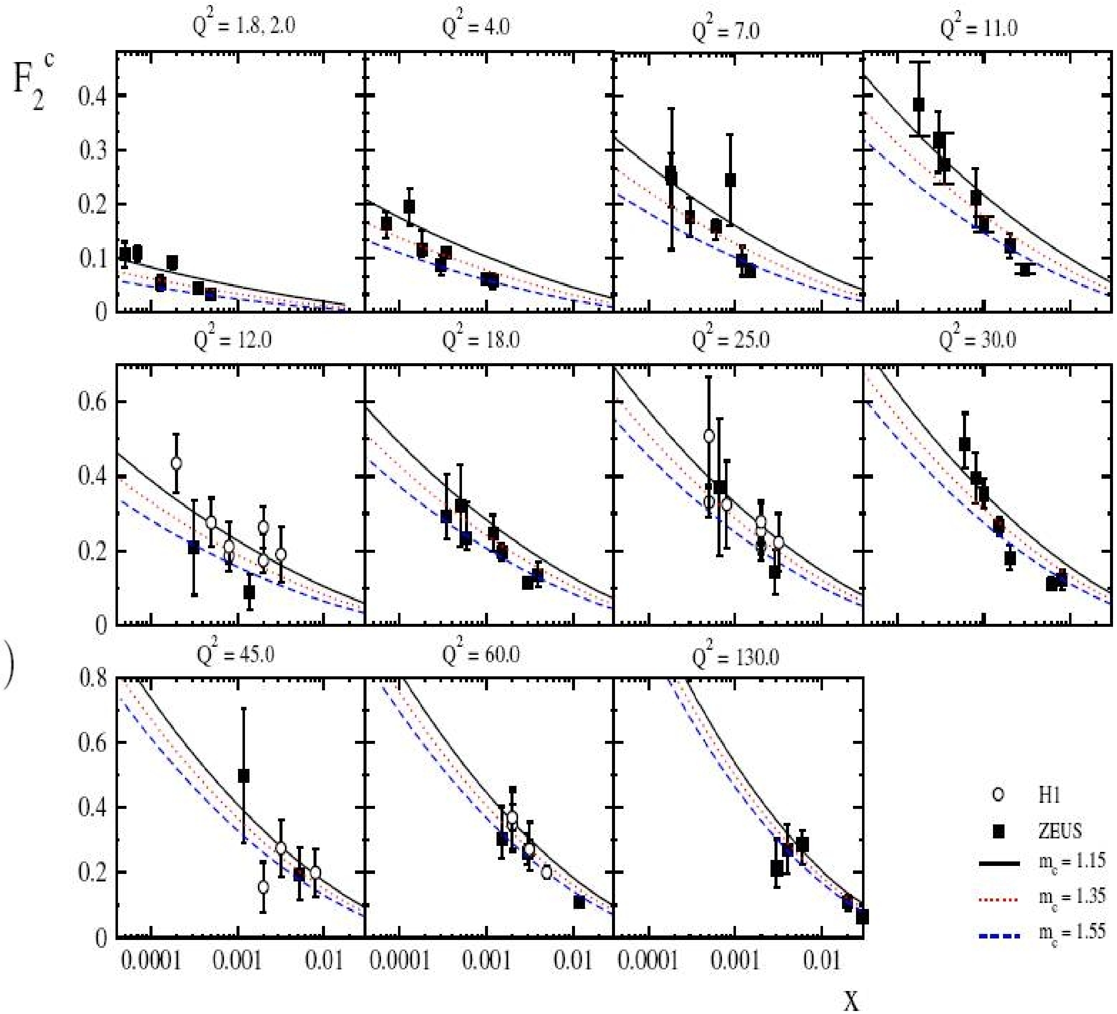
- Saturation models describe well F_2 for charm:

  (Note: also DGLAP models)



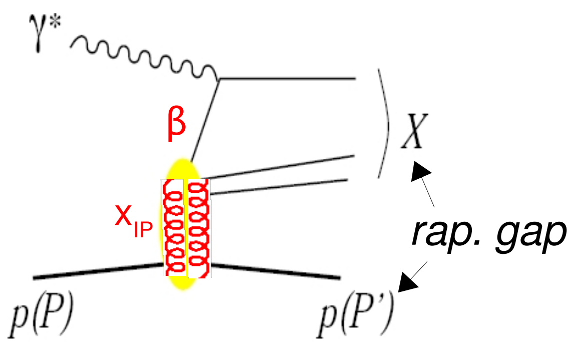
$$F_2^{c\bar{c}}(x,Q^2) = \frac{Q^2}{4\pi\alpha}\sigma_{tot}(\gamma p \to c\bar{c}X)$$

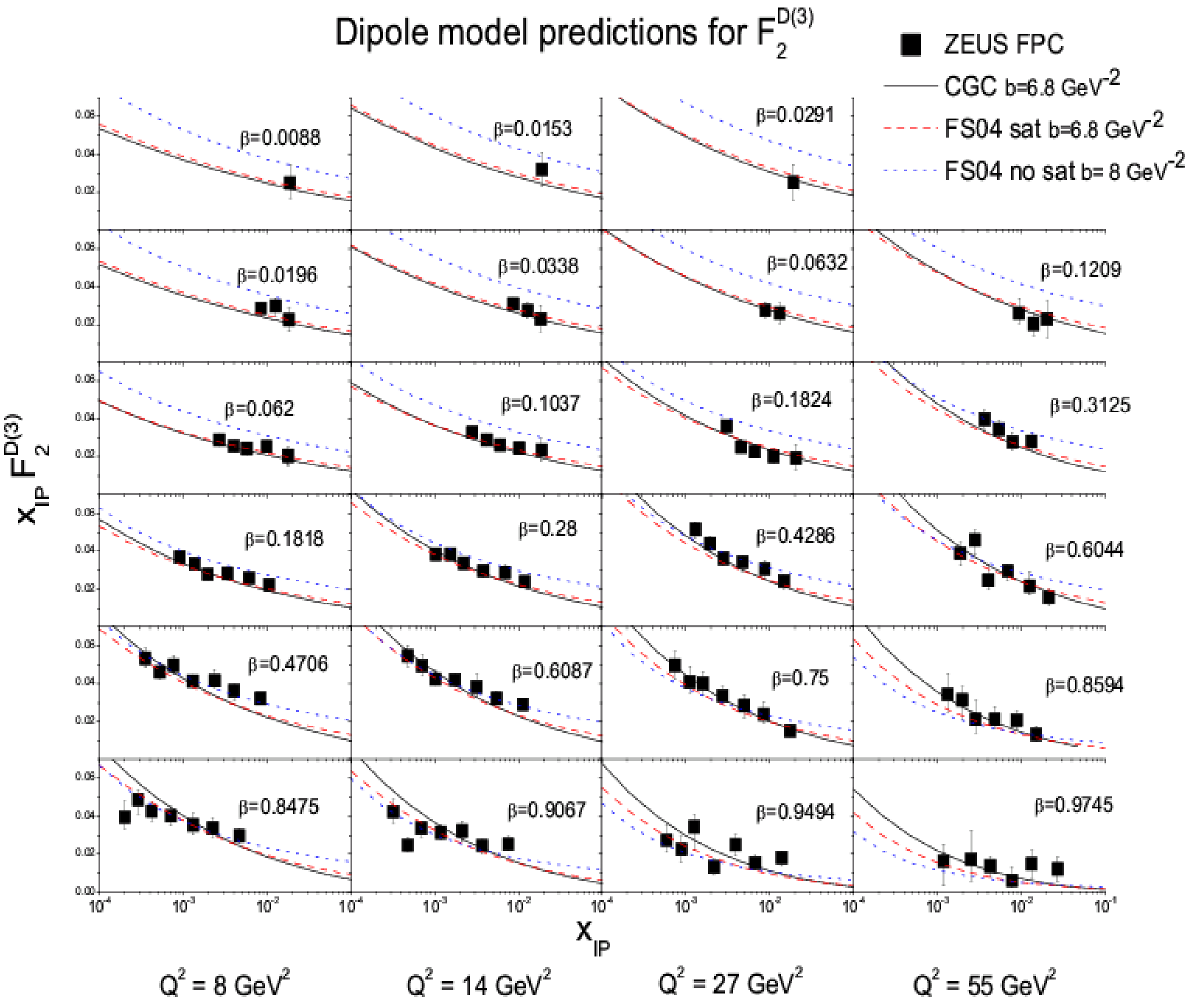
[Machado-Goncalves, EPJC 30 (2003)]



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

- Saturation models provides framework to describe consistently total $\gamma^* p$ 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

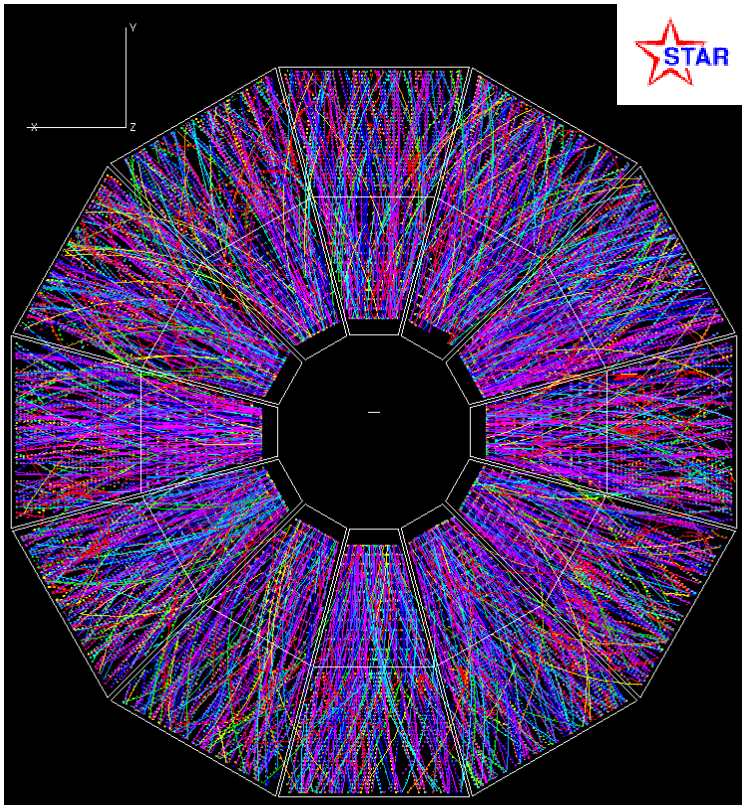
carried by struck parton

Forshaw,Shaw

hep-ph/0411337

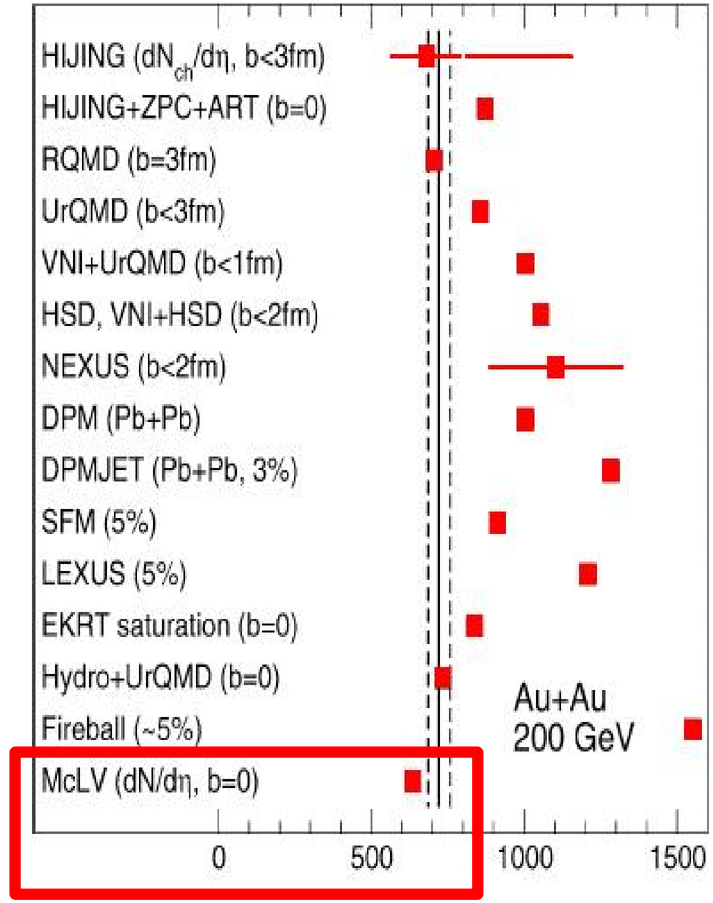
Saturation hints at RHIC (I): hadron multiplicity

- AuAu (200 GeV) 0-5% most central colls.:



$dN_{ch}/d\eta$~ 650 charged particles at y=0

Predicted multiplicites:



$dN_{ch}/d\eta$

- Reduced multiplicity predicted by saturation models: gluon recombination reduces incoming parton flux.

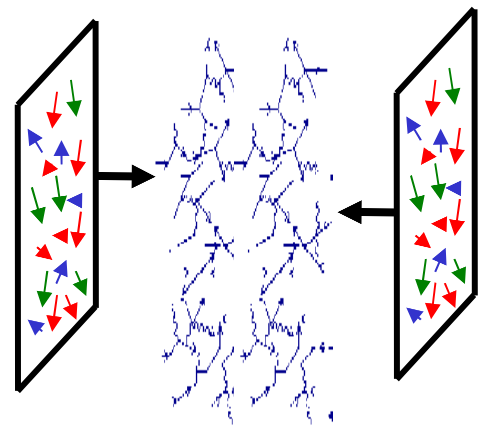
Saturation hints at RHIC (II): $dN_{ch}/d\eta$ vs. centrality

- CGC: Final hadron multiplicity ∝ Initial number of released gluons ∝ Q_s^2

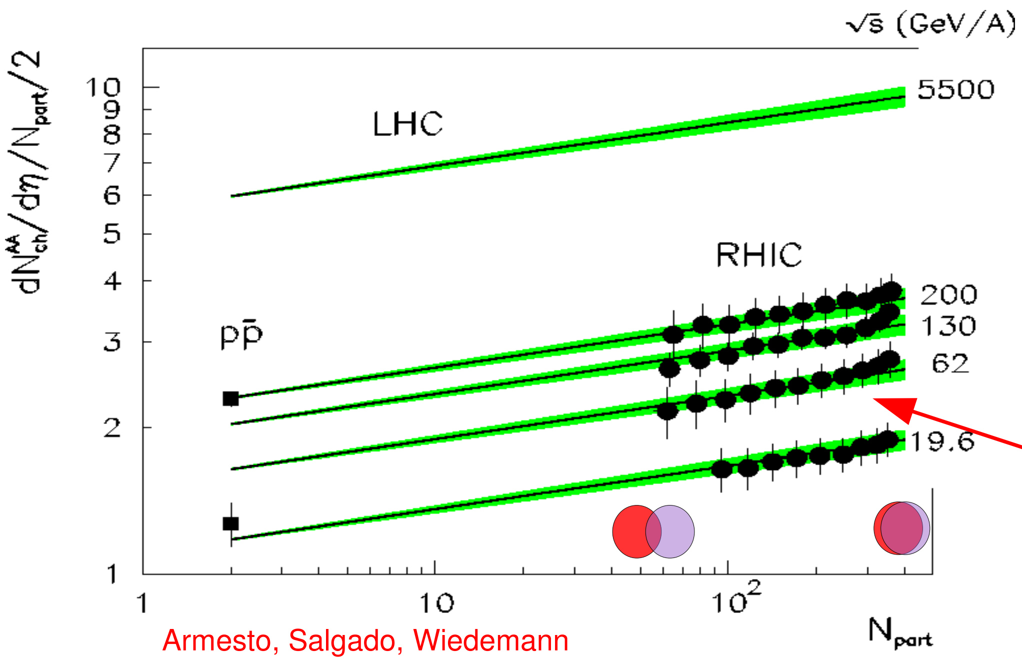
$$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x,Q_s^2)\cdot A^{1/3}$$

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

Collision of 2 classical (saturated) fields



- Centrality & √s dependence well described:



Armesto, Salgado, Wiedemann PRL94 (2005) 022002

pprox:

1/3

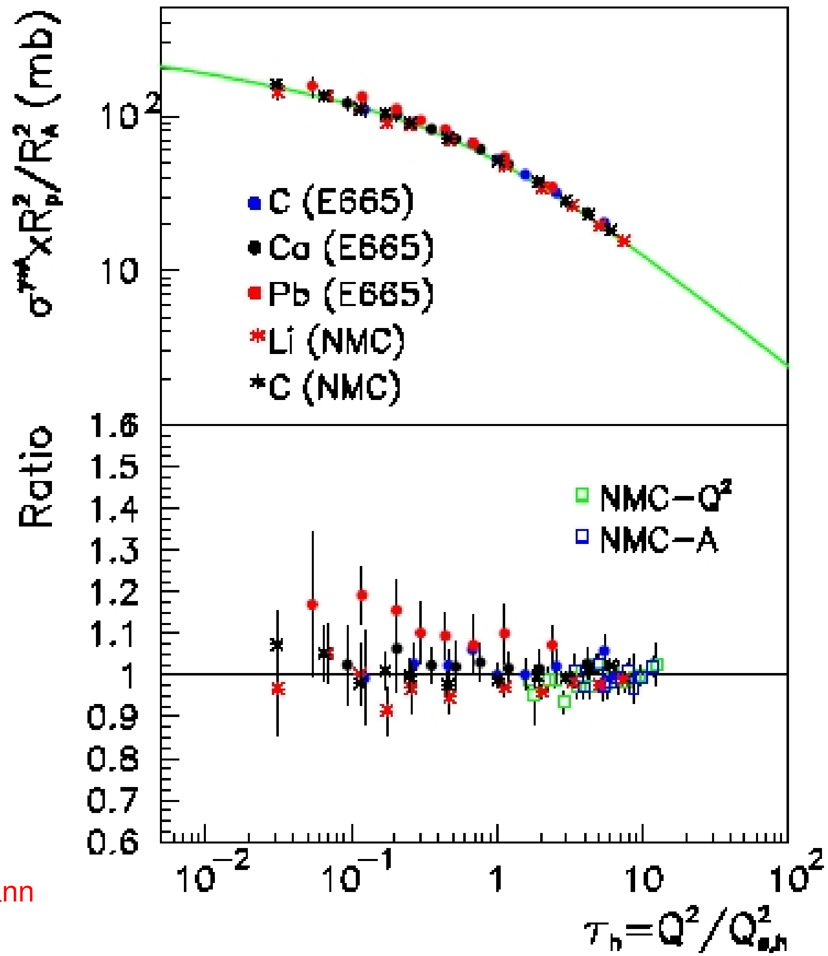
Q_s dependence on transv. area

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

Kharzeev-Levin-Nardi, PLB507 (2001) 121

nuclear DIS: "Geometric scaling" at low-x

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



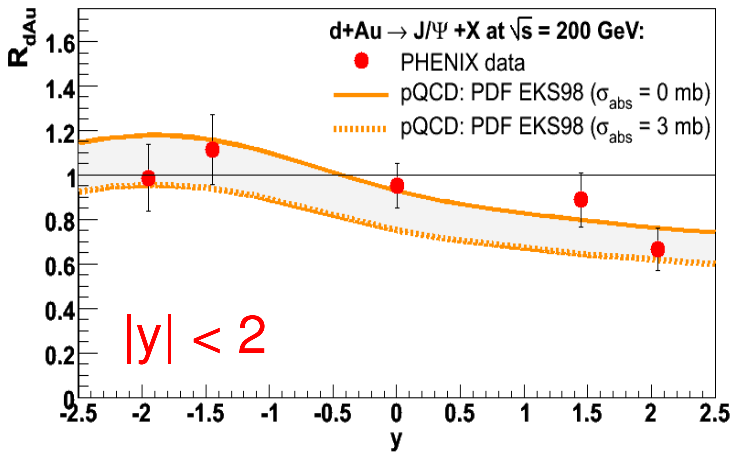
Confirms approx:

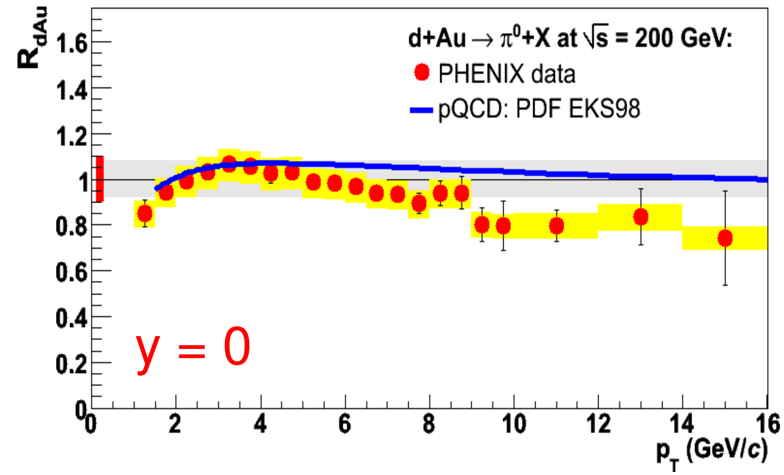
$$Q_s^2 \sim A^{1/3}$$

Armesto, Salgado, Wiedemann
PRL94 (2005) 022002

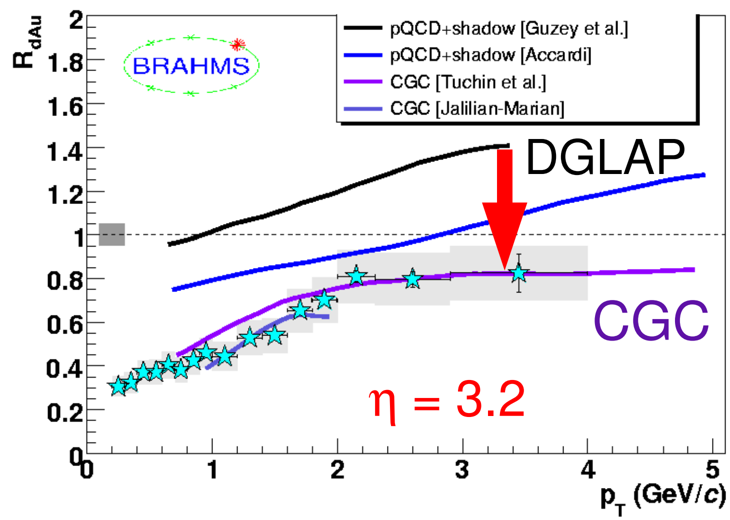
Saturation hints at RHIC (III): fwd. hadron suppression

- y~0 (x~10^{-2}): Hard hadroprod. described by NLO pQCD (+mild LT shadowing):





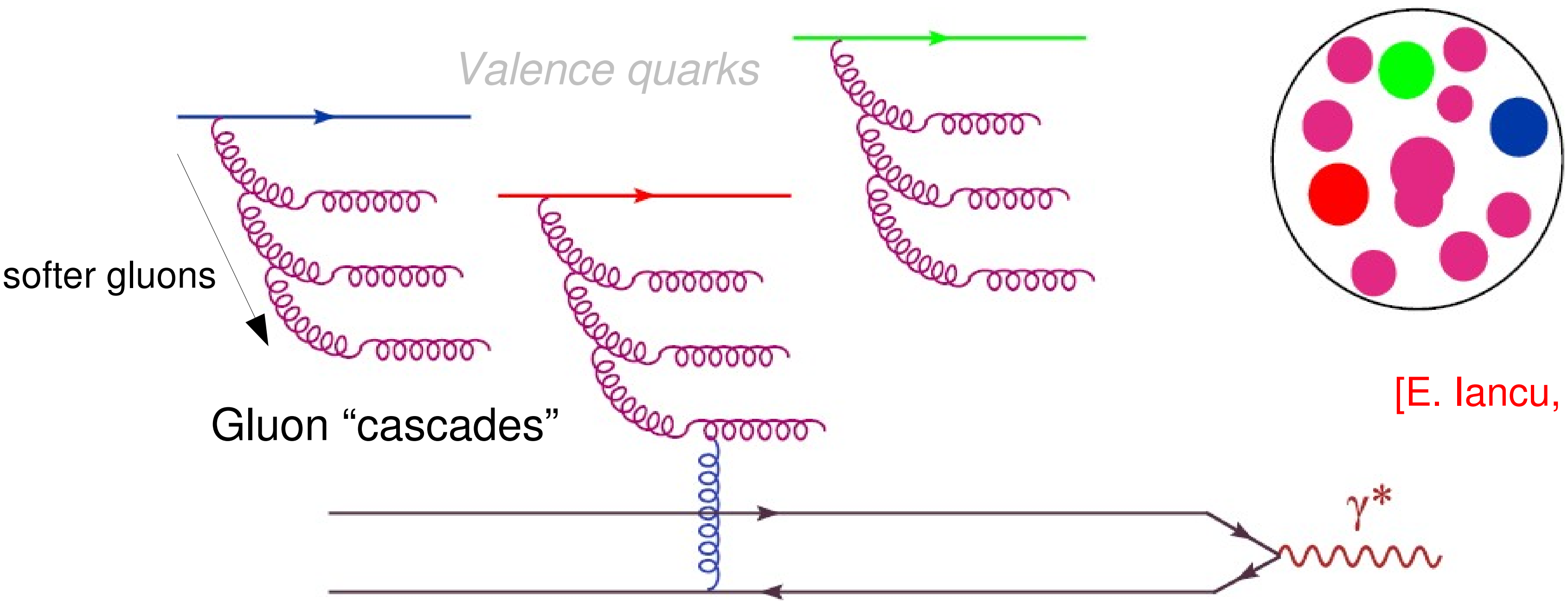
- η = 3.2 (x~10^{-3}): Suppressed hadron production (p_T ~ 2 – 4 GeV/c) better described by CGC than NLO pQCD: reduced partonic flux in Au at low-x



BFKL linear evolution equations

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

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

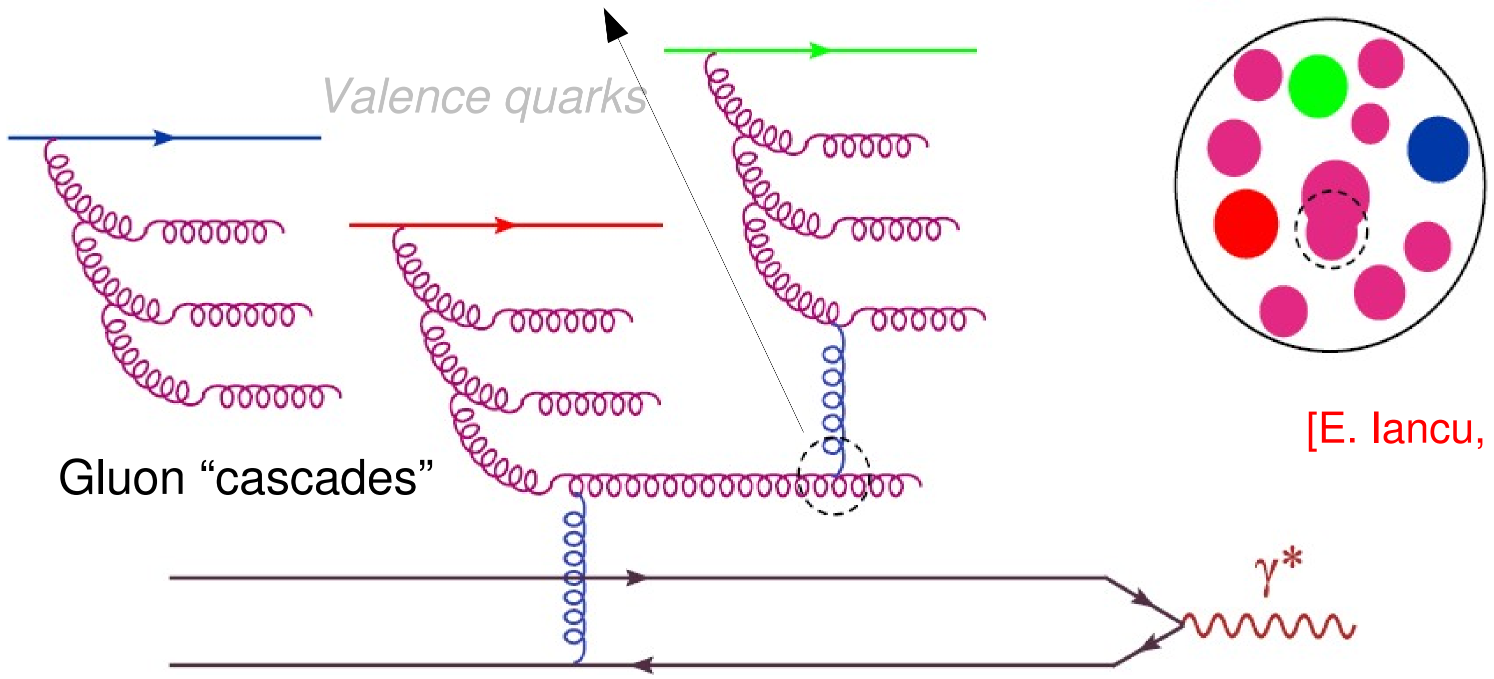


[E. Iancu, ECT*-07]

Non-linear QCD evolution equations

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

$$\frac{\partial n}{\partial Y} \simeq \alpha_s n - \alpha_s^2 n^2 = 0 \quad \text{when} \quad n \sim \frac{1}{\alpha_s} \gg 1$$

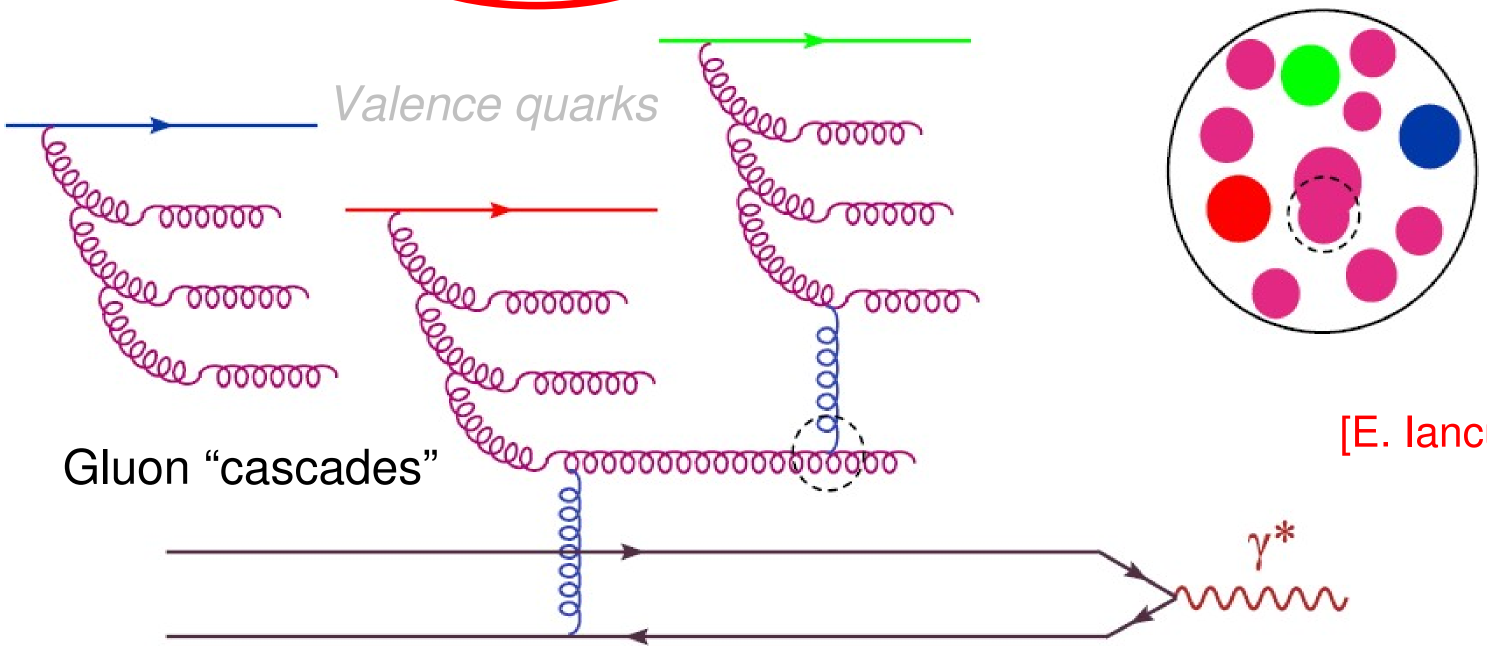


[E. Iancu, ECT*-07]

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")

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



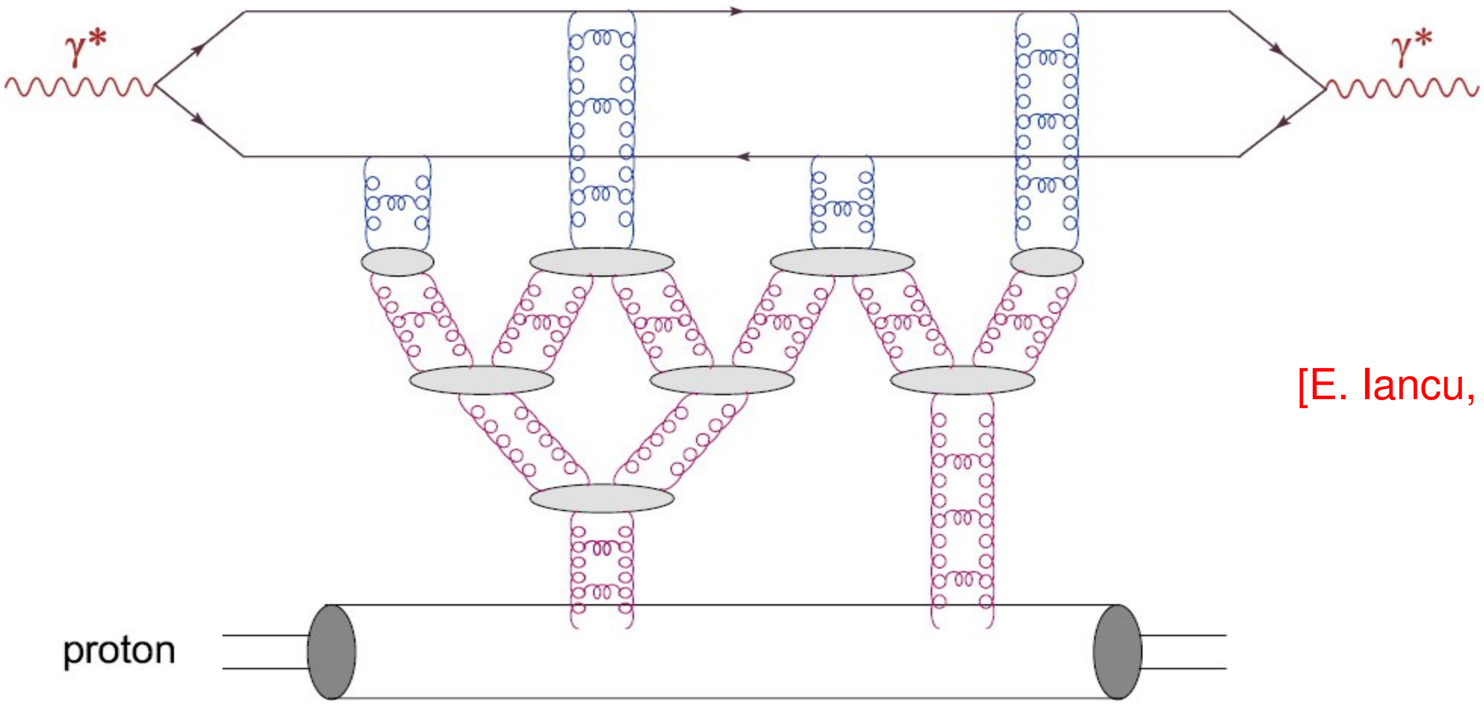
[E. Iancu, ECT*-07]

- 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):

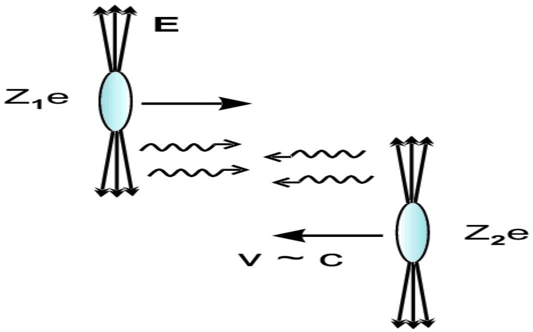
$$\frac{\partial n}{\partial Y} = \alpha_s \partial_\rho^2 n + \alpha_s n - \alpha_s^2 n^2 + \sqrt{\alpha_s^2 n}\,\nu \qquad \langle \nu(Y_1)\nu(Y_2)\rangle = \delta(Y_1 - Y_2)$$



[E. Iancu, ECT*-07]

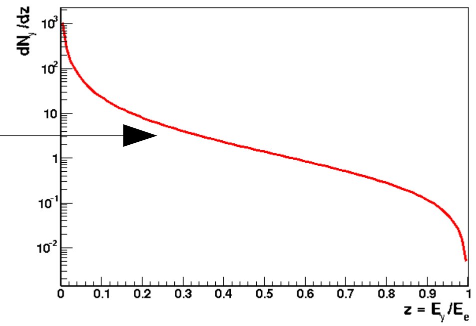
- Stochastic FKKP equation: full reaction-diffusion process in stat. phys.

Photoproduction (γ A) 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 :

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



- Photon beams:
  - **Flux ~ Z^2** (~$7 \cdot 10^3$ for Pb).
  - "Coherence condition" : γ wavelength > nucleus size

    Maximum γ energy: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 – 160 GeV (Pb,Ca)
  - Center of mass-energies (LHC): **$\sqrt{s_{\gamma A}} \approx$ 0.7 – 2. TeV $\approx$ (3 – 10) × $\sqrt{s_{\gamma p}}$(HERA)**
  - Bjorken x range in nucleus: (y=0): x(J/Ψ) ~$3 \cdot 10^{-3}$, x(ϒ)~10^{-2}

    (y=3): x(J/Ψ) ~ $2 \cdot 10^{-5}$, x(ϒ)~10^{-4}
- Forward neutron-tagging (ZDC): ~50% UPC colls. lead to nuclear breakup.