Forward physics at the LHC: QCD, electroweak & Higgs

QCD-School Les Houches

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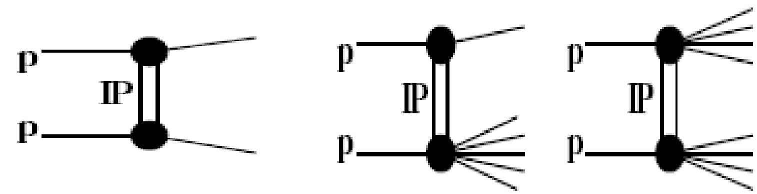
CERN

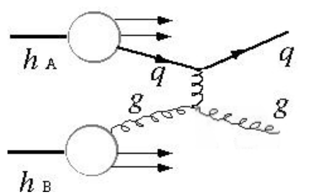
Forward physics: why ?

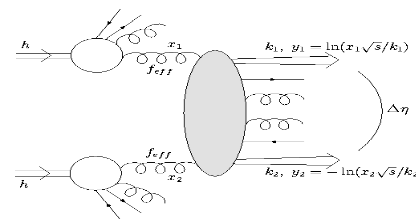
- Many interesting (mostly color-singlet exchange) scatt. processes at the LHC are characterized by forward particle production:

QCD:
- elastic/diffractive interactions:



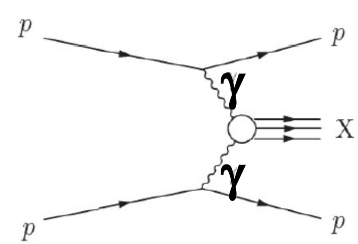
- low-x:

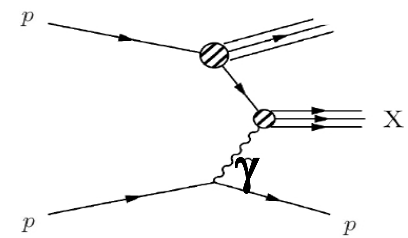




- cosmic-rays MCs

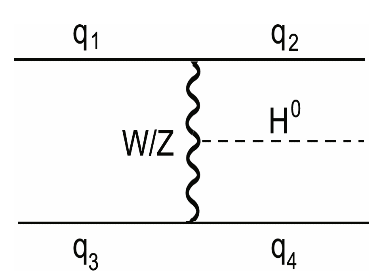
EWK: two-photon, photon-proton colls.

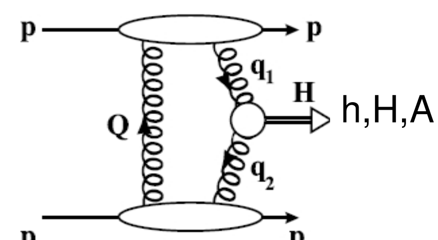




Higgs: VBF, central exclusive,

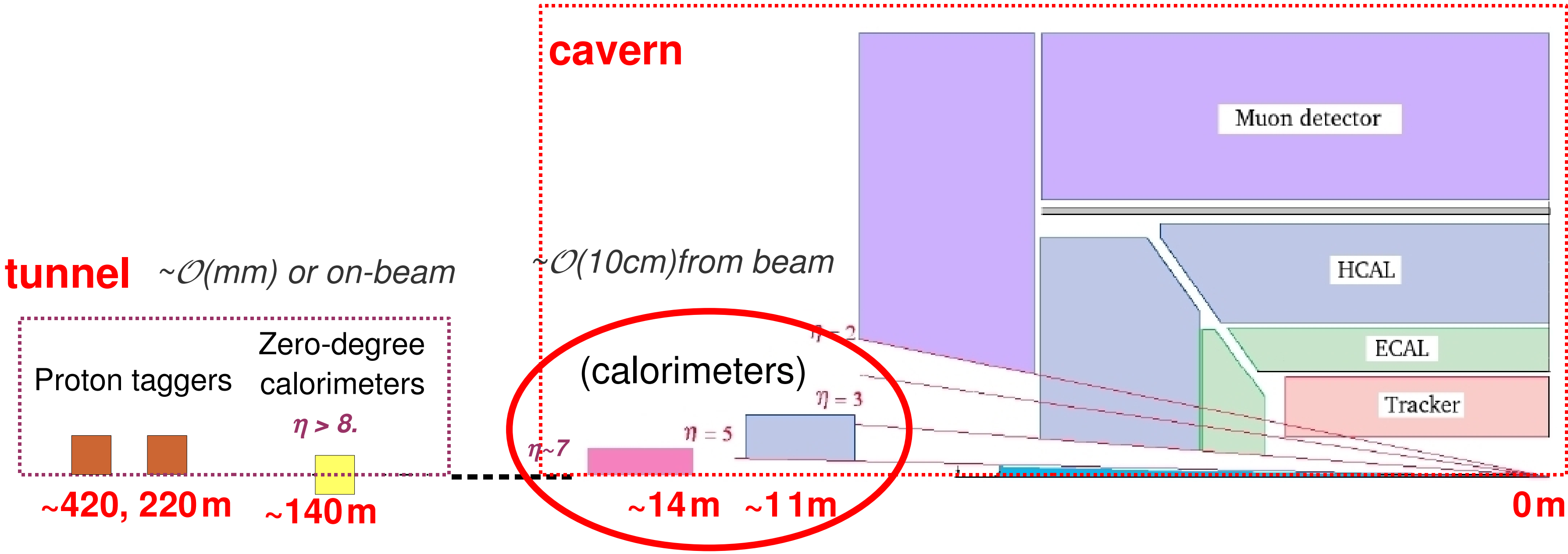
MSSM Higgs, ...





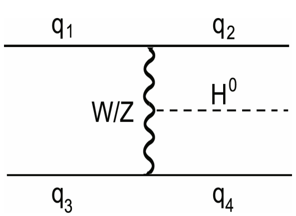
Forward detectors: where ?

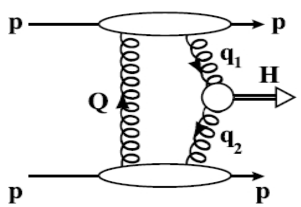
■ Near-beam detectors (CMS/ATLAS): $|\eta| = \ln\tan(\theta/2) > 3$



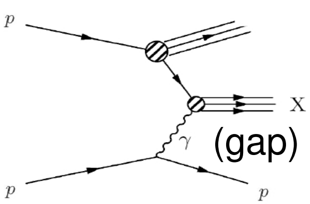
1) p,n tagging devices

2) Direct particle measurements: fwd. jets, ...





3) Hadron “vetoing” devices: rapidity gaps



Lectures – Programme

1st

0. Introduction
1. Forward **detectors** at the LHC
2. **QCD** physics with forward detectors:
   - Diffractive/Elastic scattering.
   - UHE cosmic-rays MCs.

2nd

   - **Low-x QCD**

3th

3. **EWK** physics with forward detectors:
   - photon-photon, photon-proton collisions
4. **Higgs** physics with forward detectors
   - VBF Higgs, central-exclusive Higgs, ...

Lecture II: Experimental tests of low-x QCD

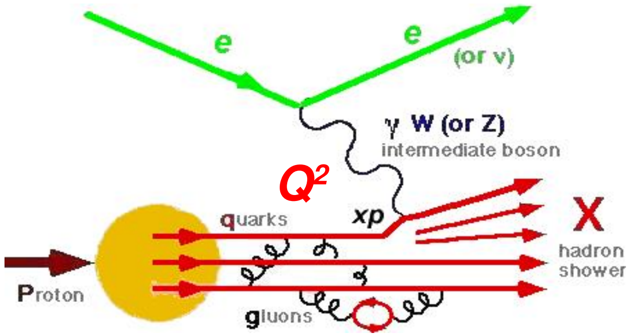
- Introduction:
  - Parton structure & evolution at low-*x*, gluon saturation.
  - Measurements of low-x PDFs: processes, kinematic domains, ...
- Experimental tests:
  - Saturation hints at HERA (proton)
  - Saturation hints at RHIC (nucleus)
  - Low-*x* perspectives at the LHC (p,A)

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

    PbPb @ 5.5 TeV case-studies: $dN_{ch}/d\eta$, Y photo-production
- Summary

Parton densities at low-*x*

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



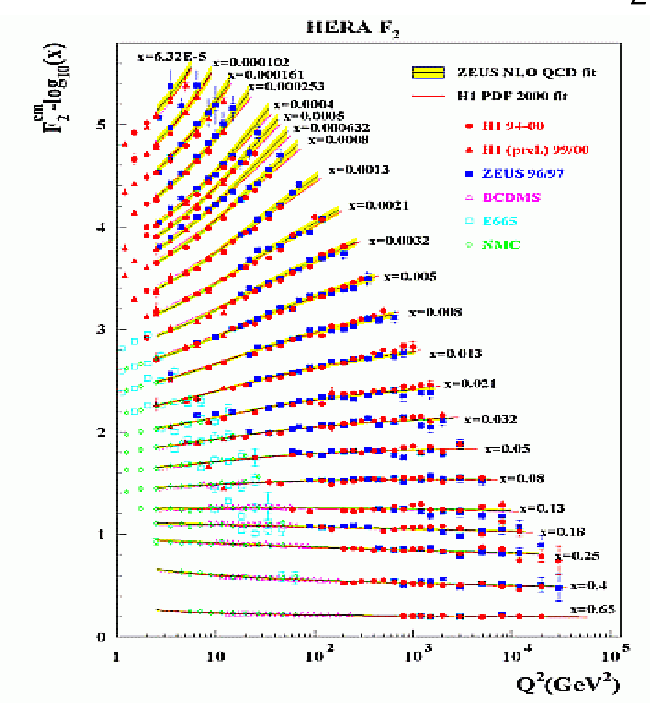
Q ² = "resolving power"

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).

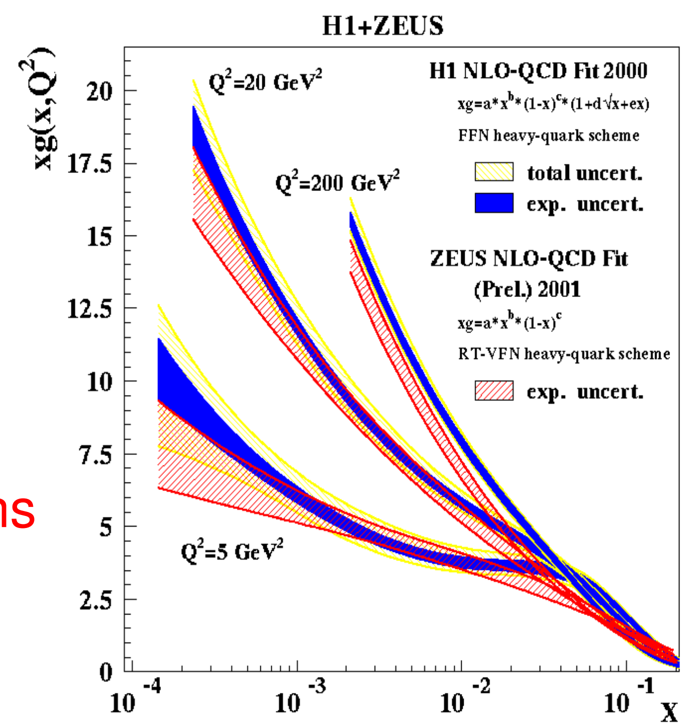
- HERA: strong rise of $F_2(x,Q^2)$ at low-x:



γ couples directly only to (sea) quarks

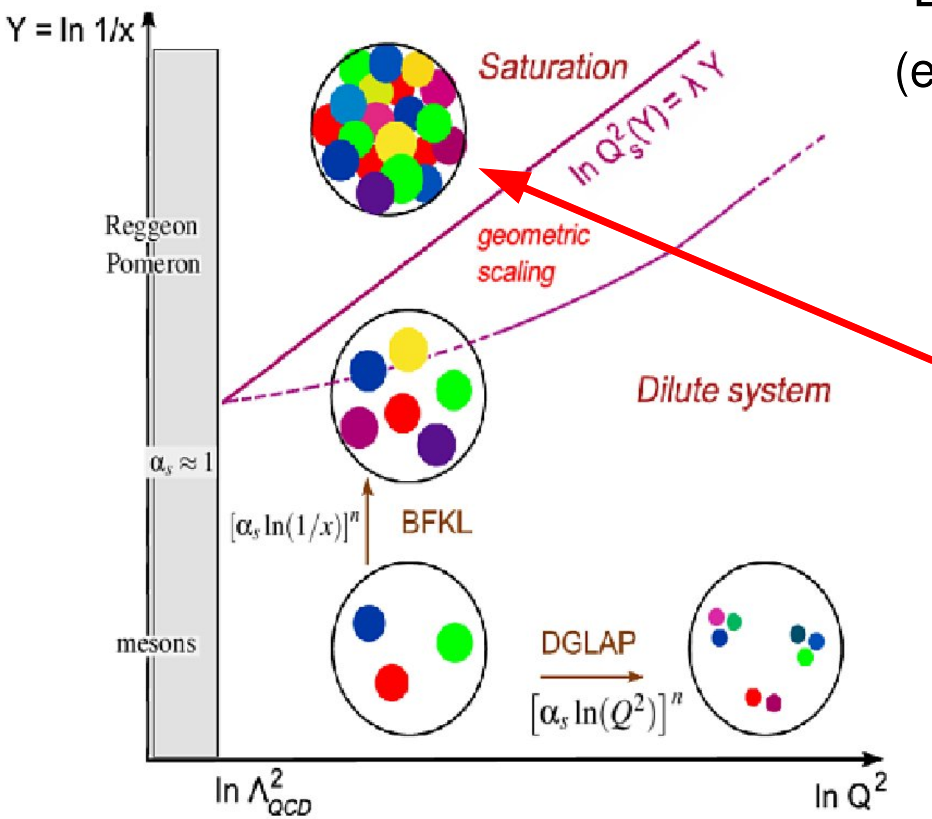
⇒

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



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

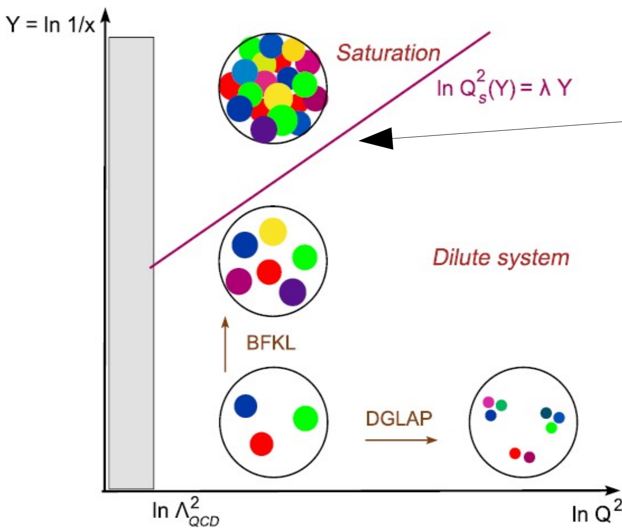
(i) Too high gluon density: nonlinear gluon-gluon fusion balances branchings

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

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

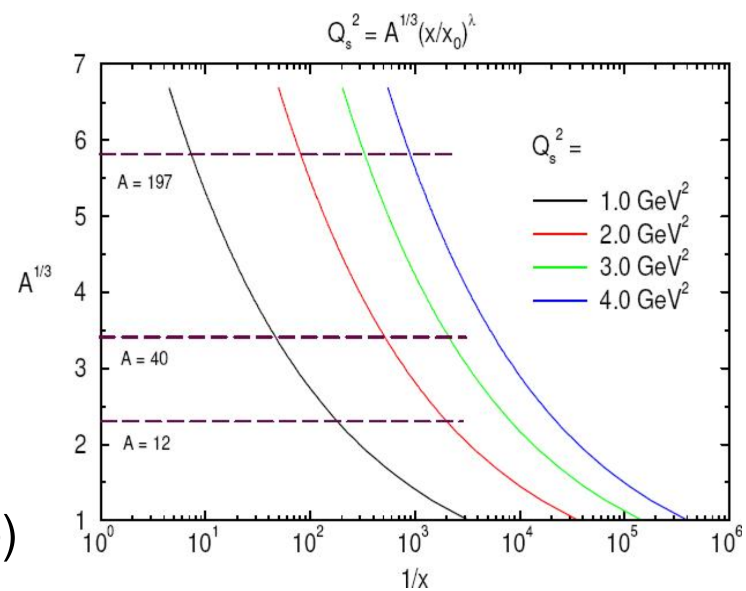
Saturation for: low x, large s, large y, large A

- 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)

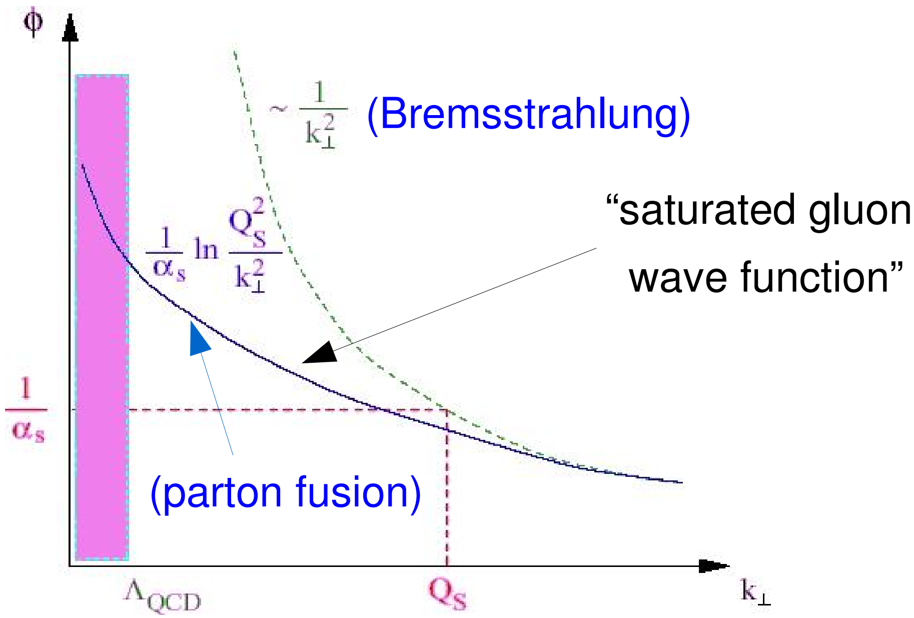


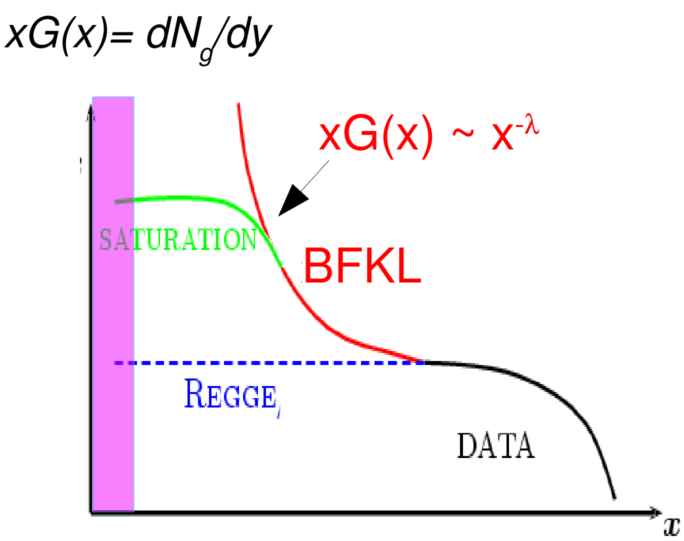
Color Glass Condensate (CGC)

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

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

  - **C**olor (obvious) **G**lass (q ~ "frozen" sources) **C**ondensate (high gluon occup.)
  - Hadrons = Classical fields below/around Q_s:



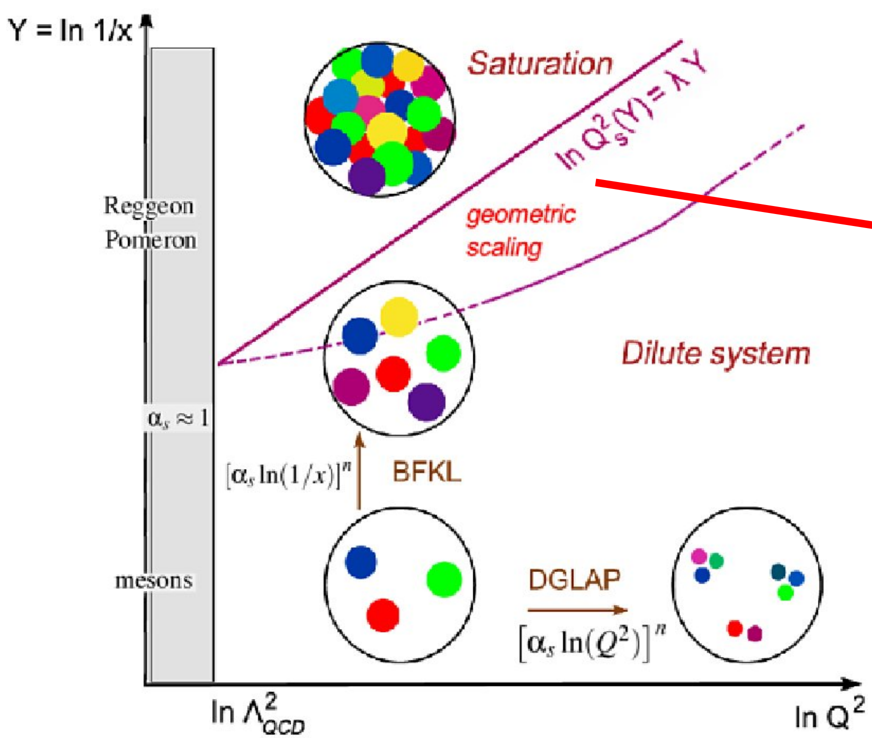


  - Q_s hard ⇒ perturbative calculations (strong $F_{\mu\nu}$, weak coupling): $\alpha_S(Q_s^2) << 1$
  - pA,AA ≡ collisions of gluon wave function(s) "resum" all multiple scatts.

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 diffussion)
  - 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:

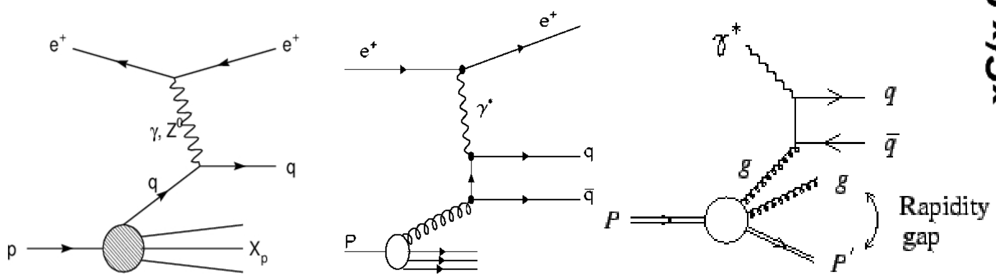
$$\frac{1}{Q^2} \rightarrow \left(\frac{1}{Q^2}\right)^\gamma \quad \gamma \simeq 1/2$$

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

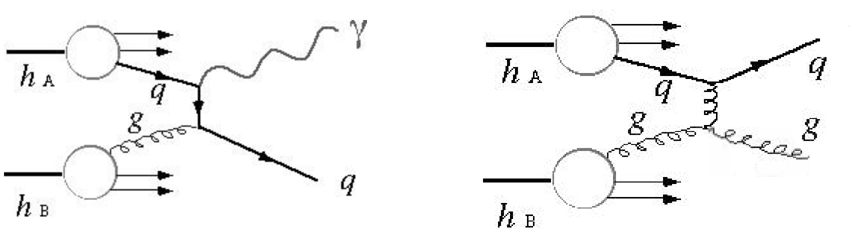
extended window of applicability outside CGC !

Experimental access to low-x gluon PDF

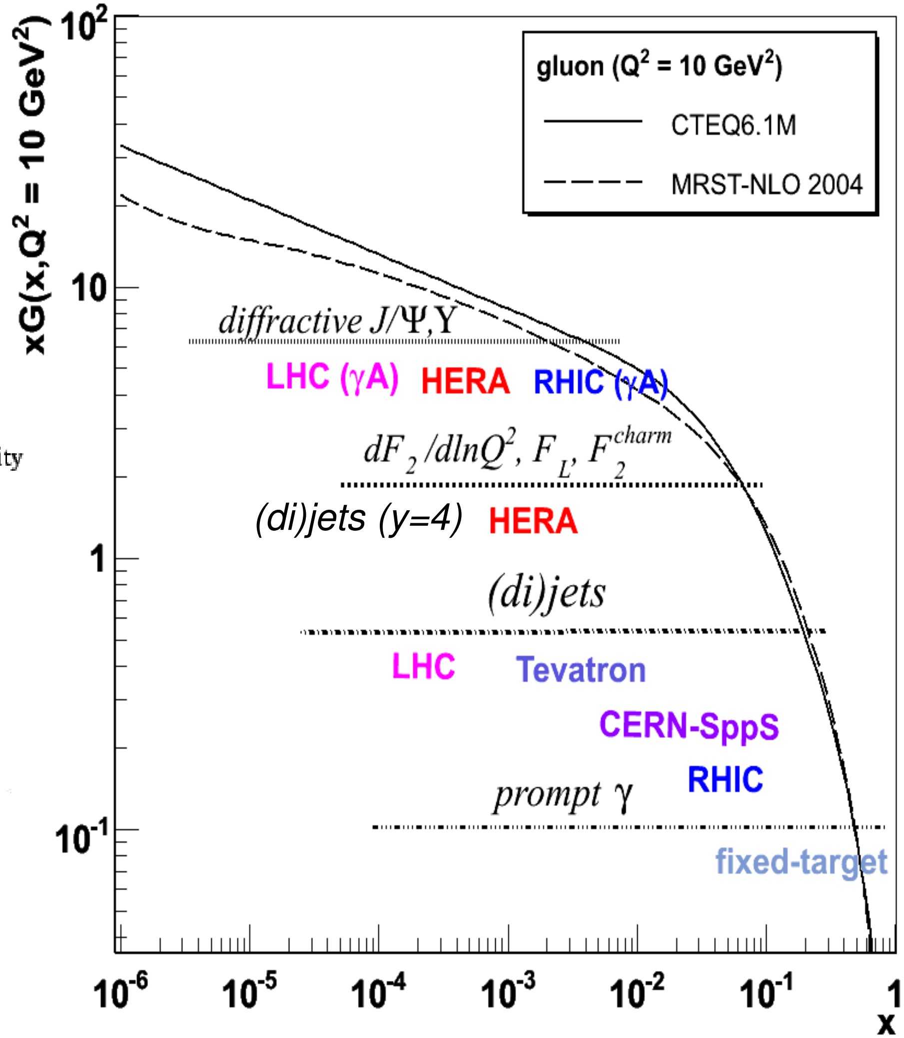
- Perturbative processes:
  - e-p: $\partial \ln F_2/\partial \ln Q^2$, F_L, heavy-Q, diffractive $Q\bar{Q}$:



  - p-p, A-A: prompt γ , (di)jets:

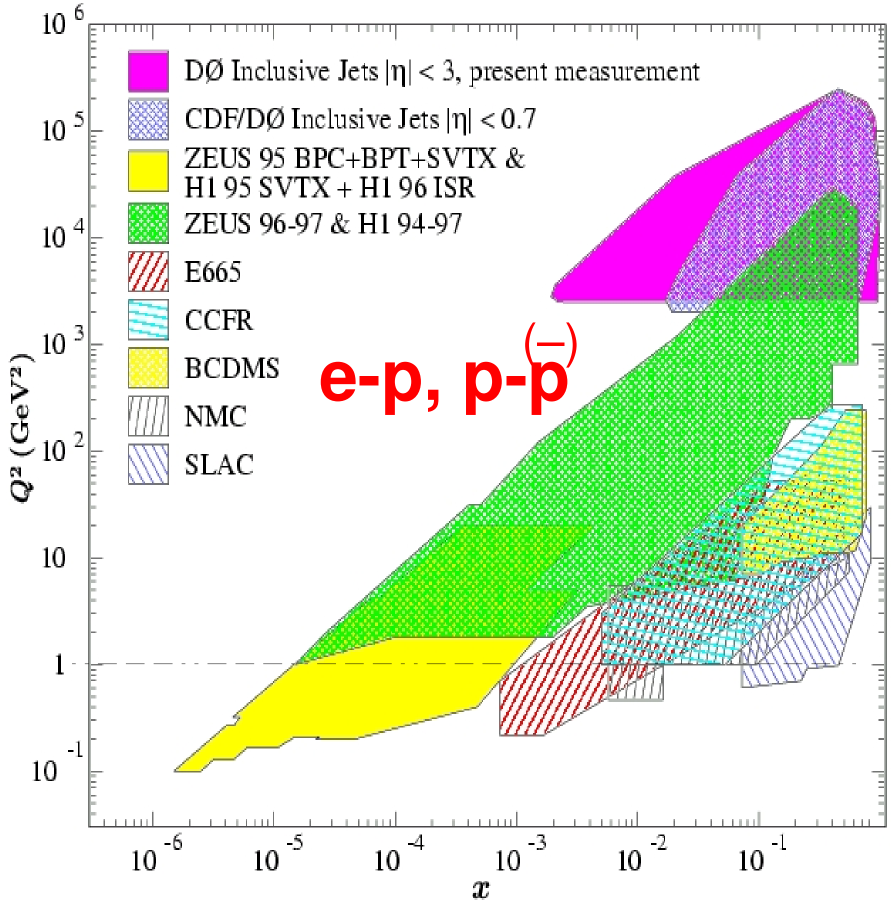


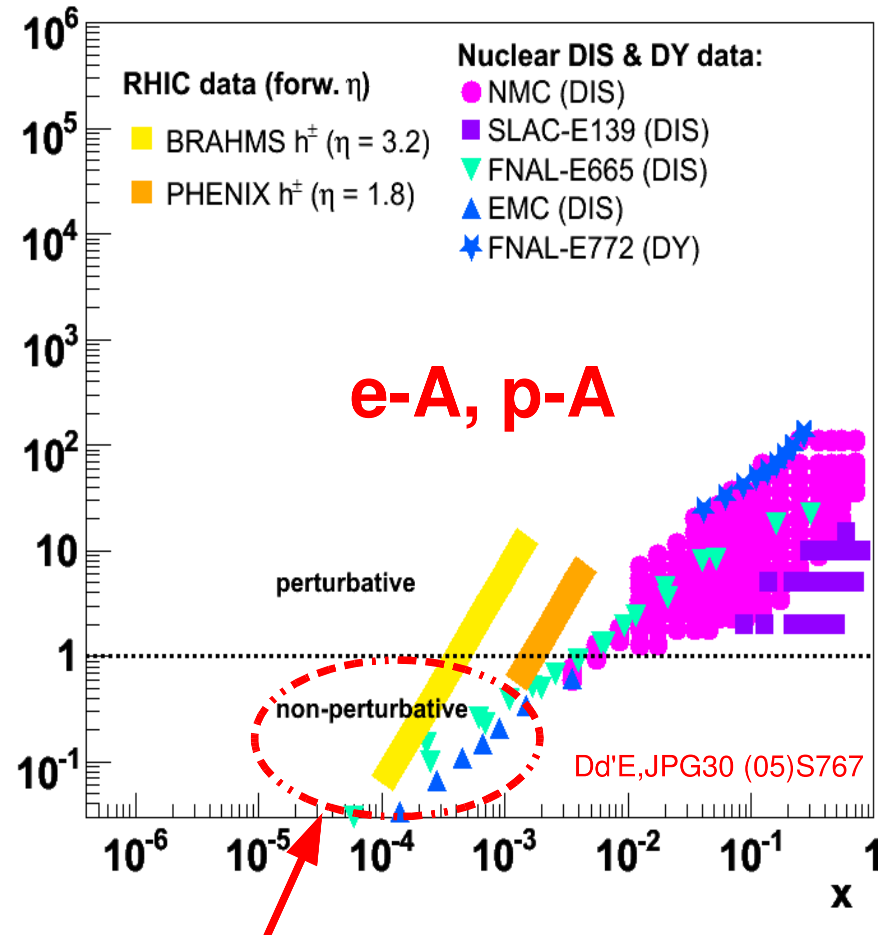
[DdE arXiv:0708.0551]



(x,Q^2) experimental domains: proton, nucleus

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



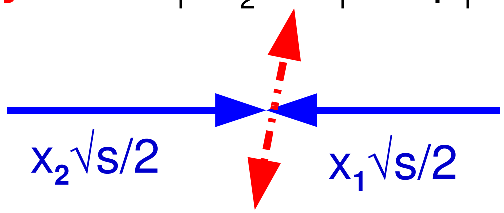


- Note: most existing low-x nPDFs measurements in the non-perturbative range

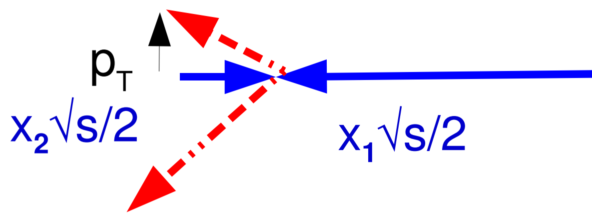
Small-x → Forward rapidities

- 2 → 2 parton kinematics:

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



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



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

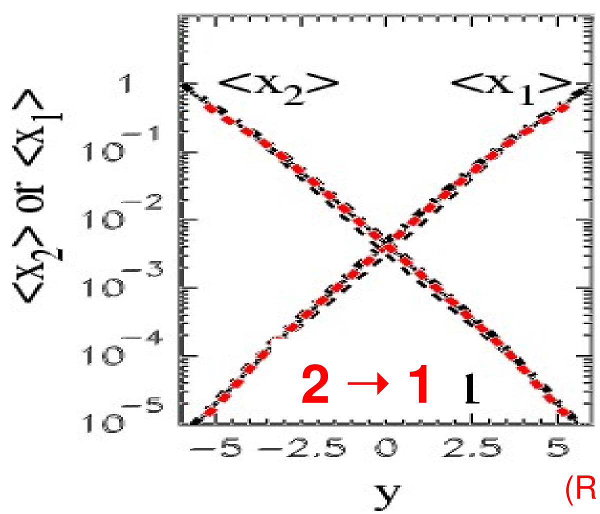
$x_T \sim 10^{-3}$ ($\eta \sim 6$): $x_{min} \sim 10^{-6}$

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

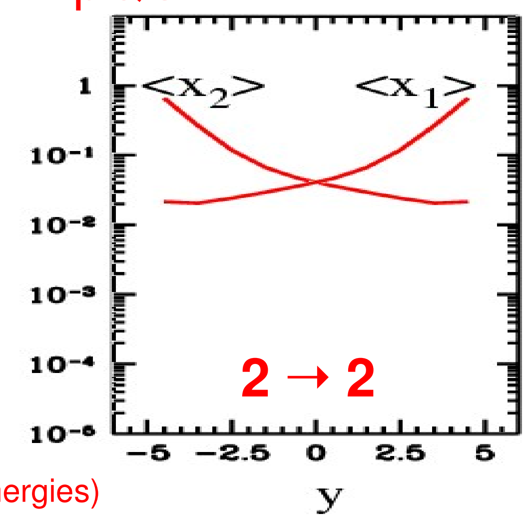
$$x_{1,2}^{2\to 1} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y}\right)$$

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

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



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



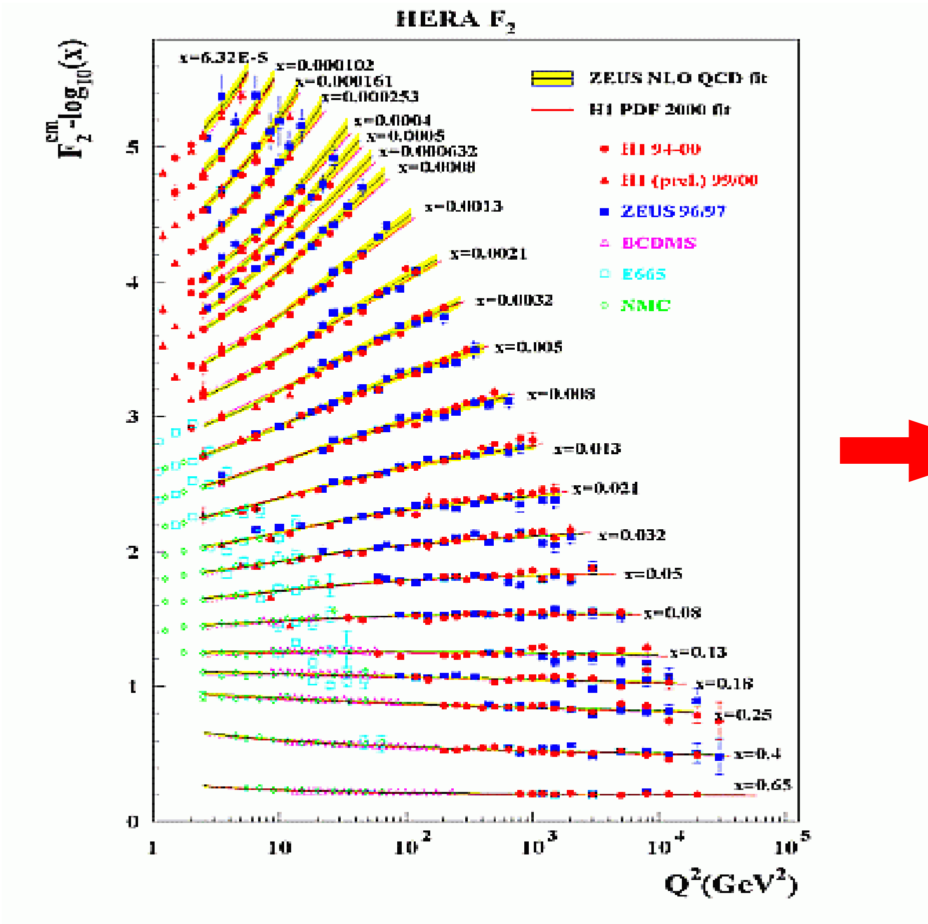
(RHIC energies)

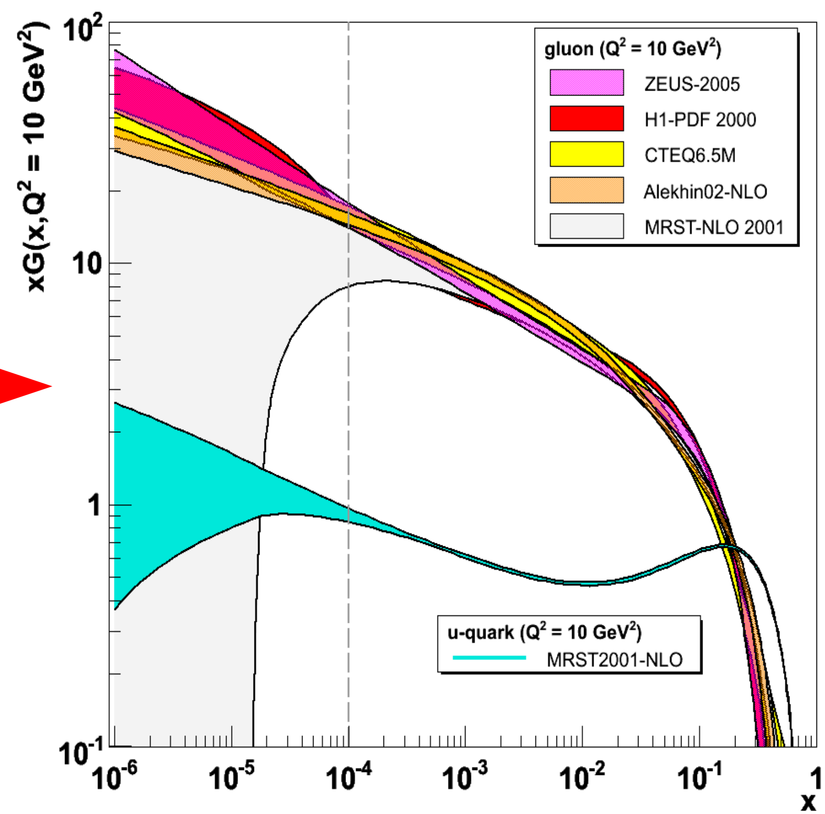
[Accardi,nucl-th/0405046]

Low-x QCD at HERA

Low-x gluon PDF at HERA

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





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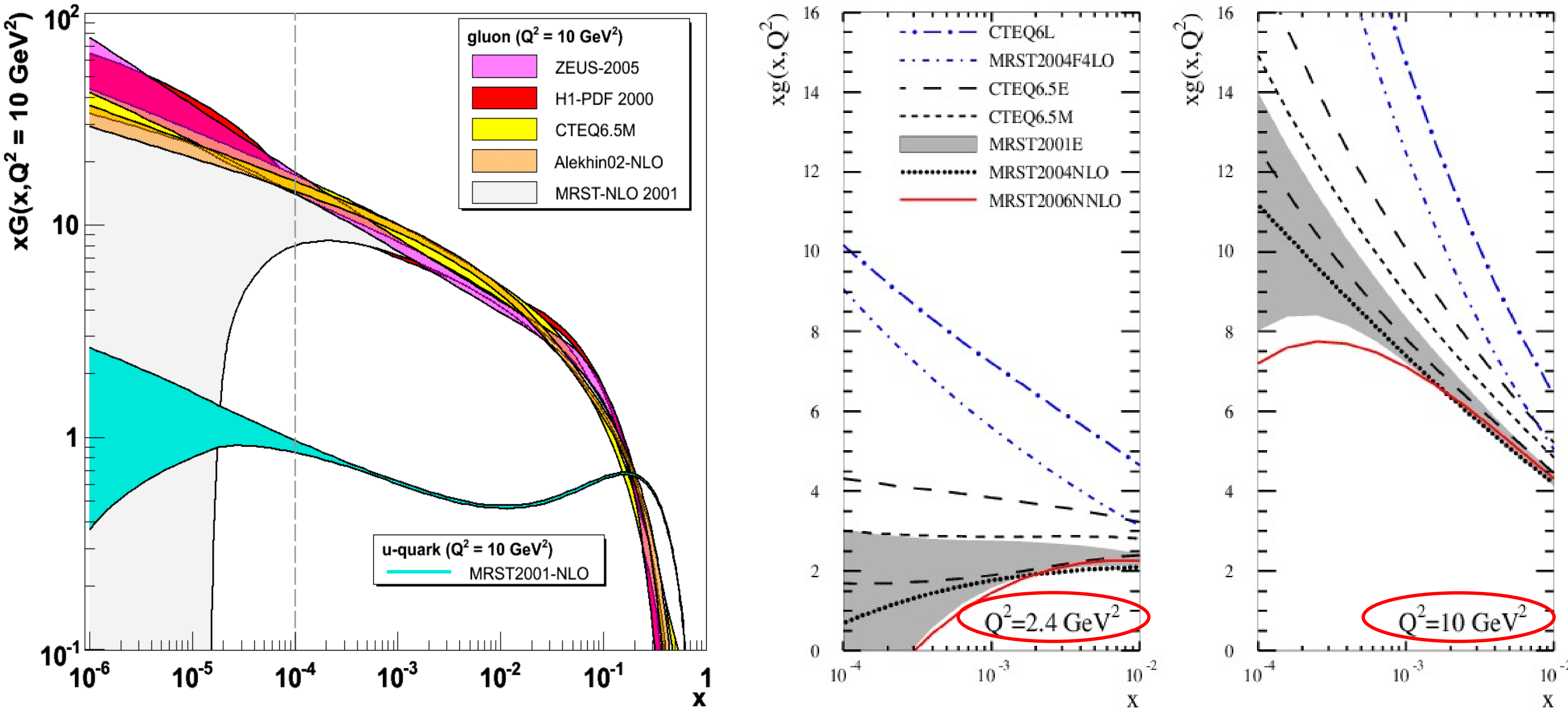
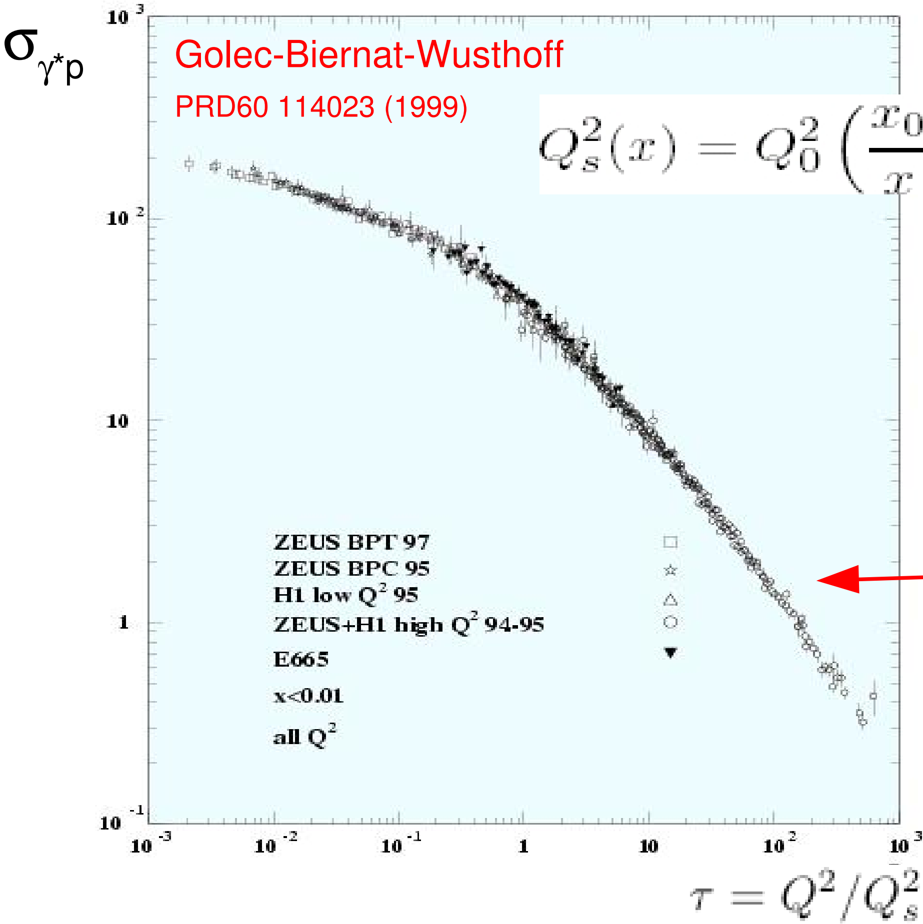
$$\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \approx \frac{10\,\alpha_s(Q^2)}{27\pi}\, xg(x,Q^2)$$

- Large uncertainties (esp. at moderate Q^2):



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

- Saturation predicts low-x structure depends 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

σ_{γ^*p} described by dipole model:
particular realization of CGC
where $\sigma_{\text{dipole-p}}$ ~ 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*]

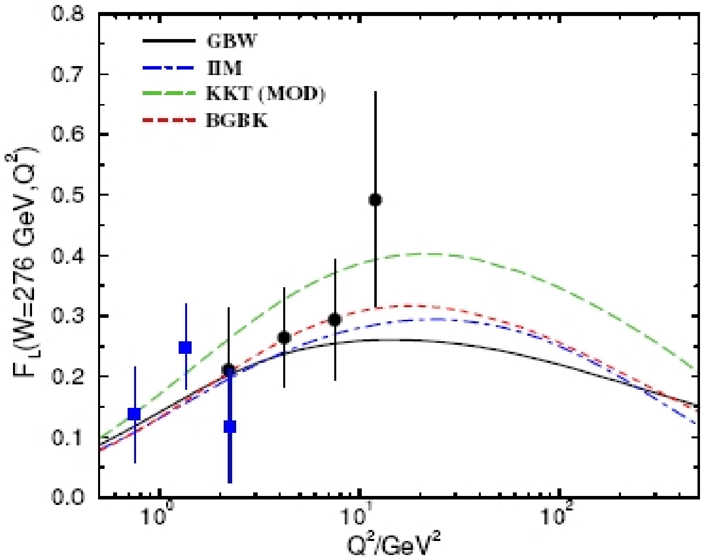
Saturation hints at HERA (II): F_L at low-x

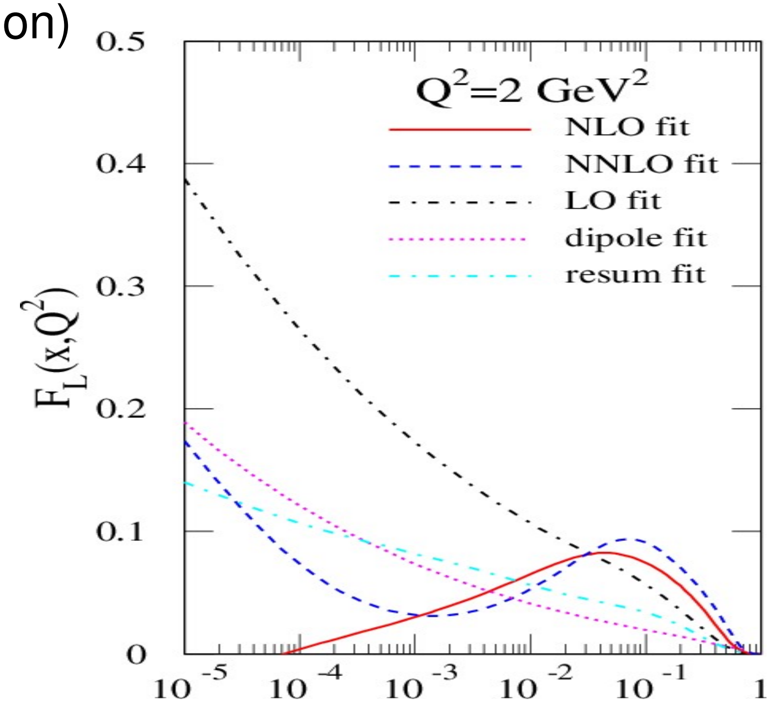
- F_L directly depends on gluon PDF: $F_L \propto \alpha_s \, xg$

  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 √s

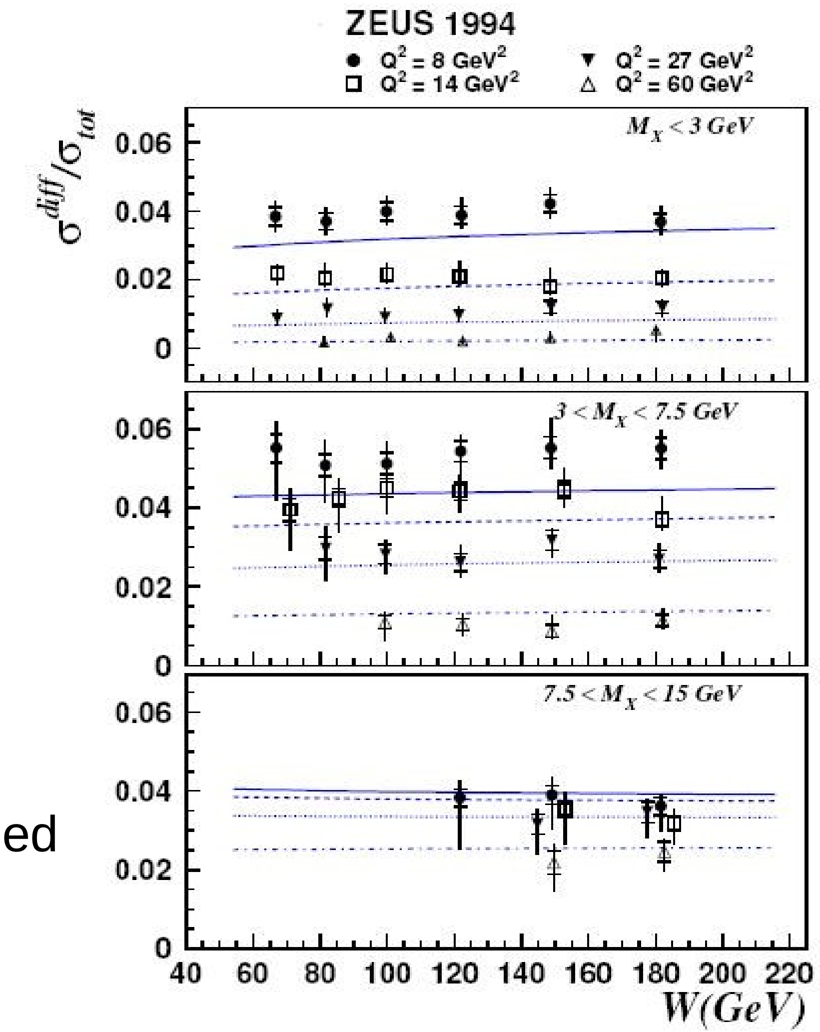
Saturation hints at HERA (III): $\sigma_{diffract}/\sigma_{tot}$ ratio

- 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:

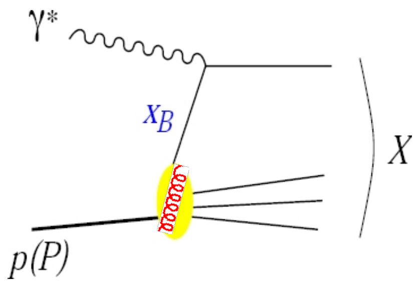
$$\sigma_{\rm diff}/\sigma_{\rm tot} \propto |xg(x,Q^2)|^2/xg(x,Q^2)$$
$$\sim W^{4\lambda}/W^{2\lambda} \sim W^{2\lambda}$$

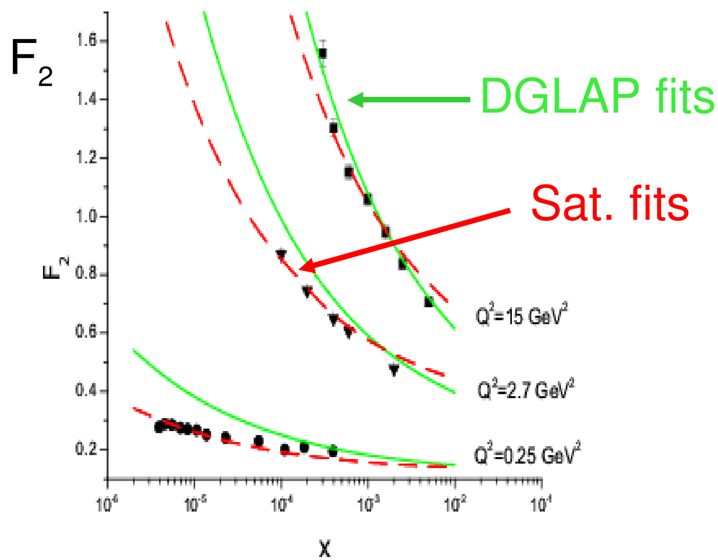
... constant dependence naturally described by saturation models.



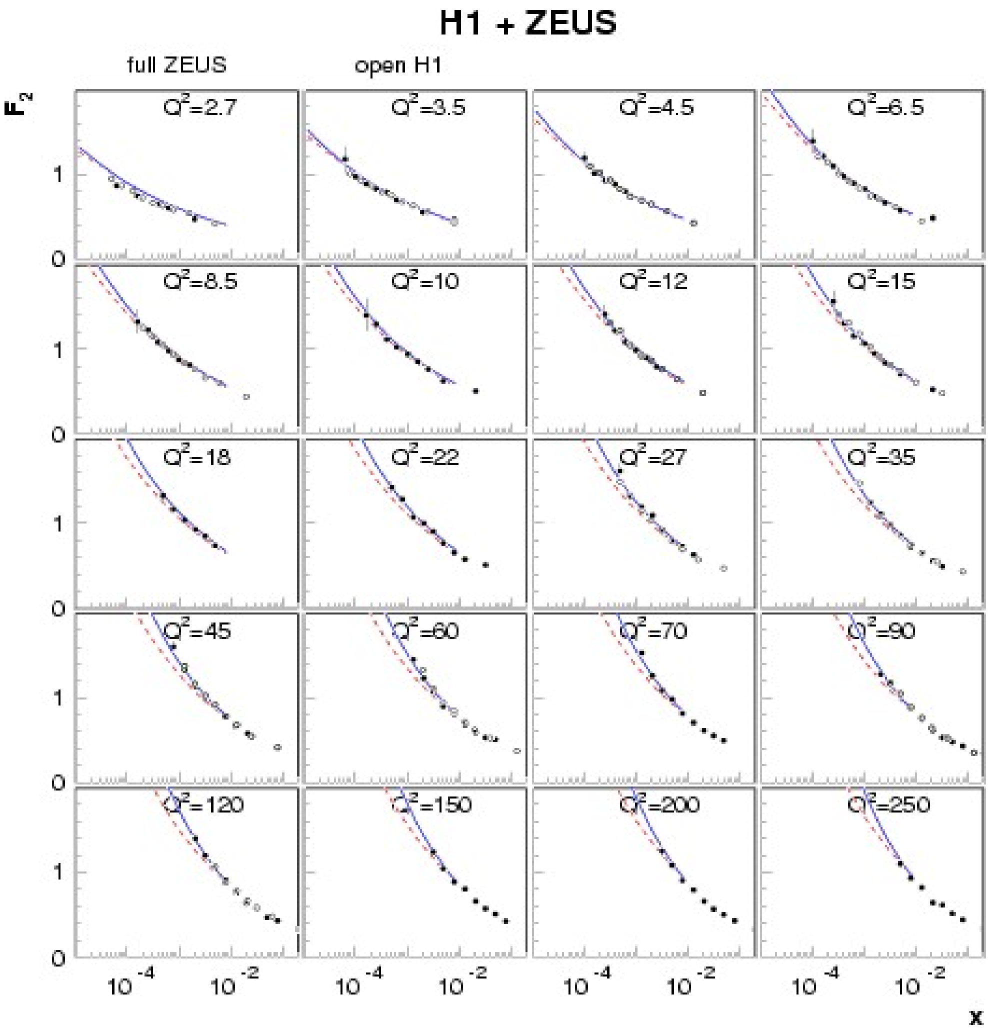
HERA data vs. saturation models: $F_2(x,Q^2)$

- 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)*





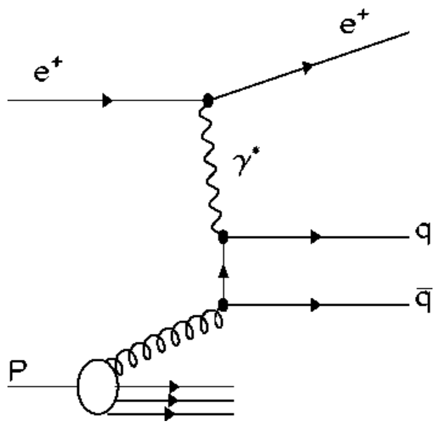
[Forshaw,Shaw, hep-ph/0411337]



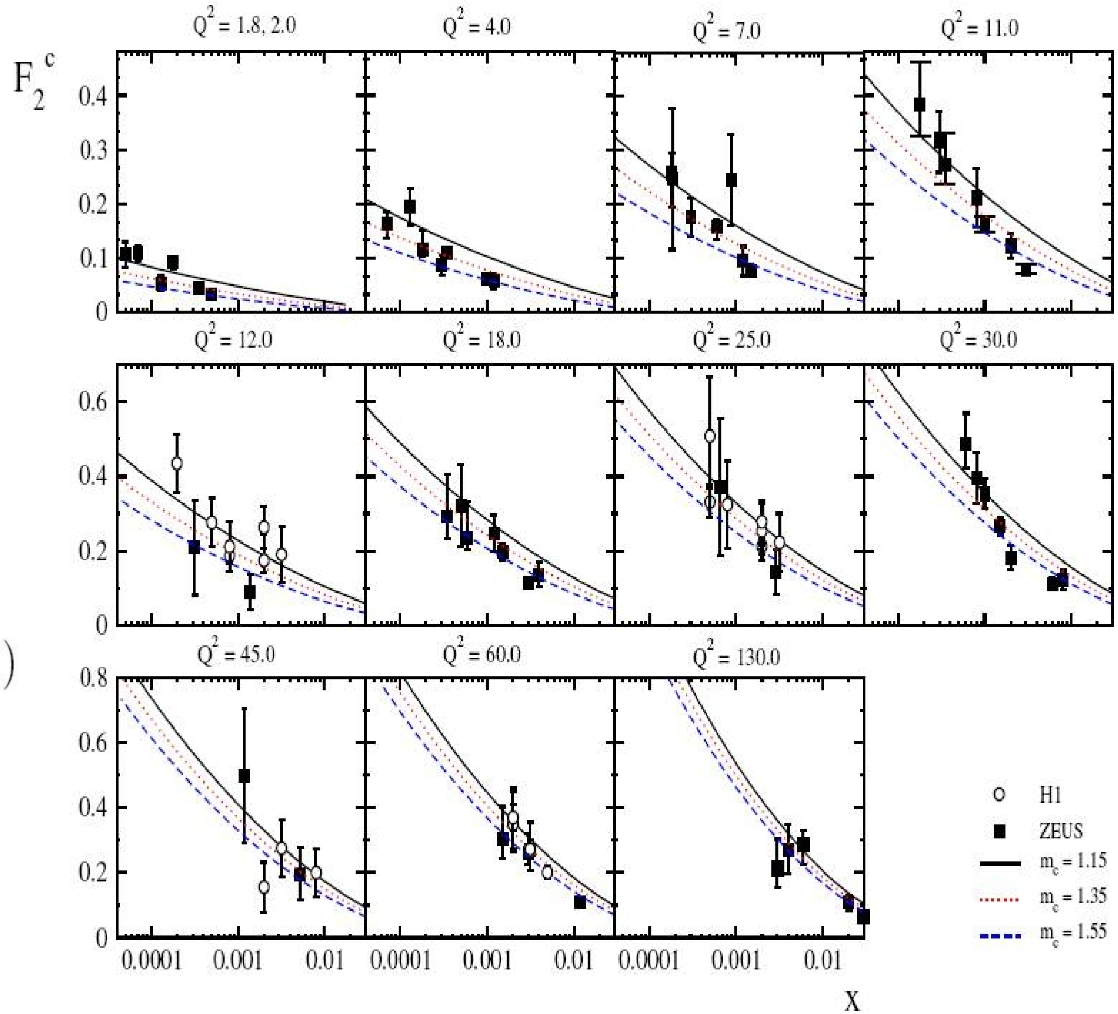
HERA data vs. saturation models: $F_2^{charm}(x,Q^2)$

- Saturation models describe well F_2 for charm:

  (Note: also DGLAP models)



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

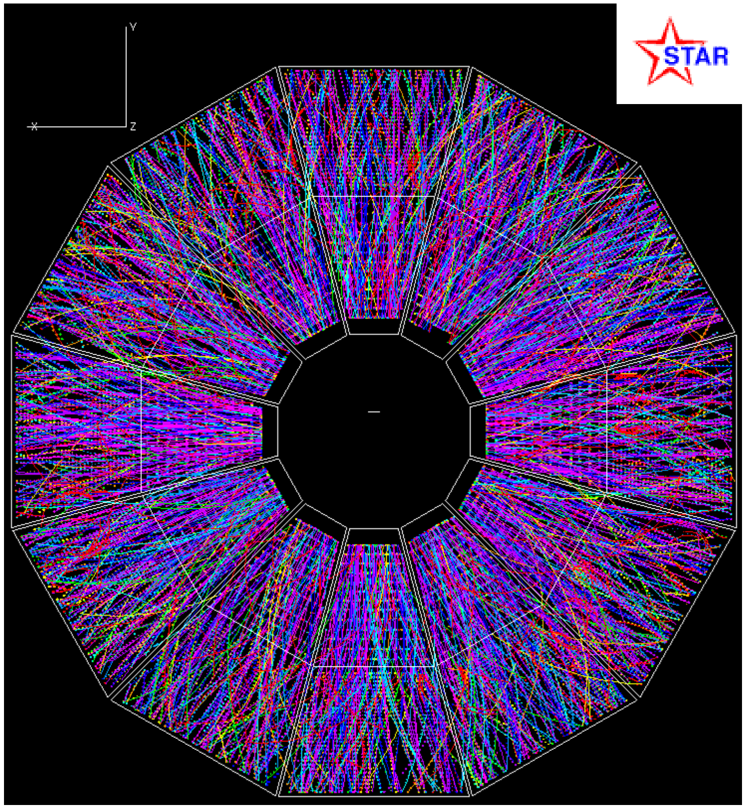


[Machado-Goncalves, EPJC 30 (2003)]

Low-x QCD at RHIC

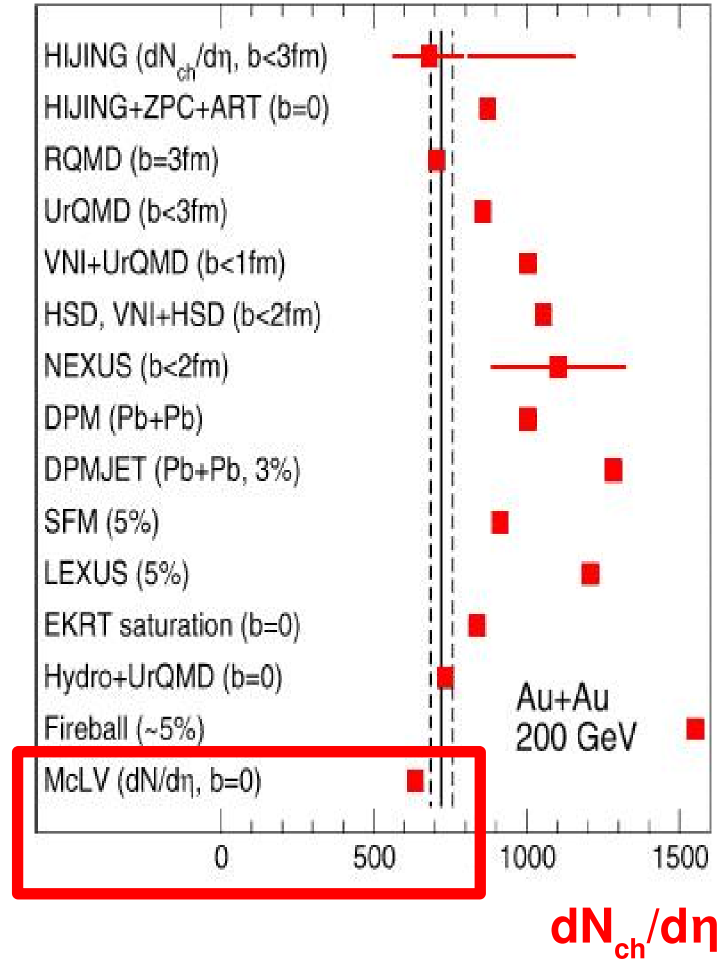
Saturation hints at RHIC (I): hadron multiplicity

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



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

Predicted multiplicites:



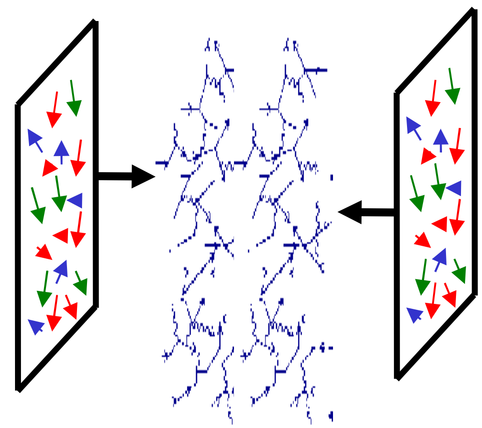
- Reduced multiplicity predicted by saturation models: gluon recombination reduces incoming parton flux.

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

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

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

Collision of 2 classical (saturated) fields

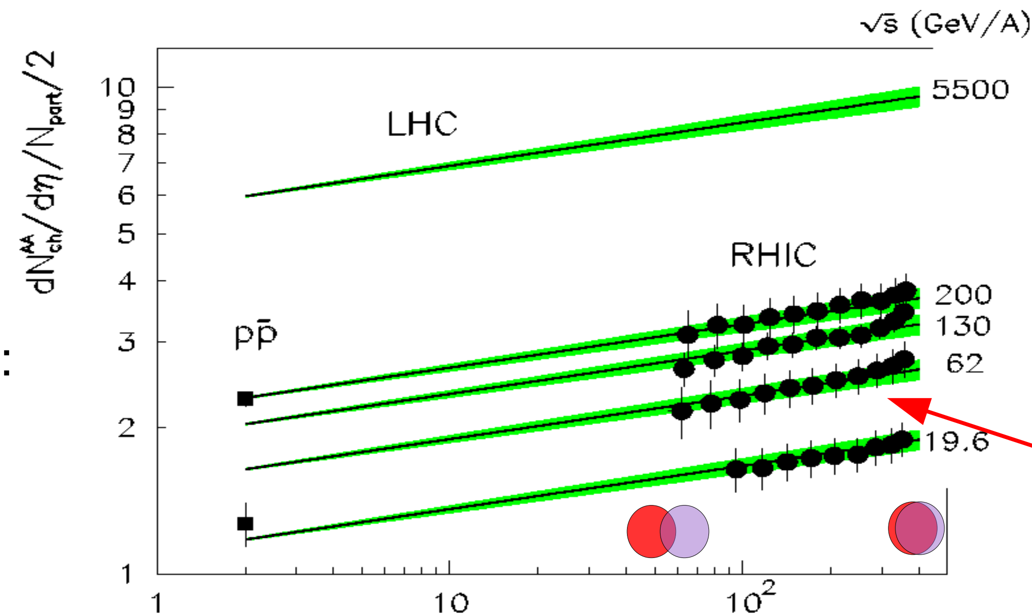


+ "local parton-hadron duality" (*1 gluon = 1 final hadron*)

- Centrality & √s dependence well described:

pprox:

$1/3$



Armesto, Salgado, Wiedemann PRL94 (2005) 022002

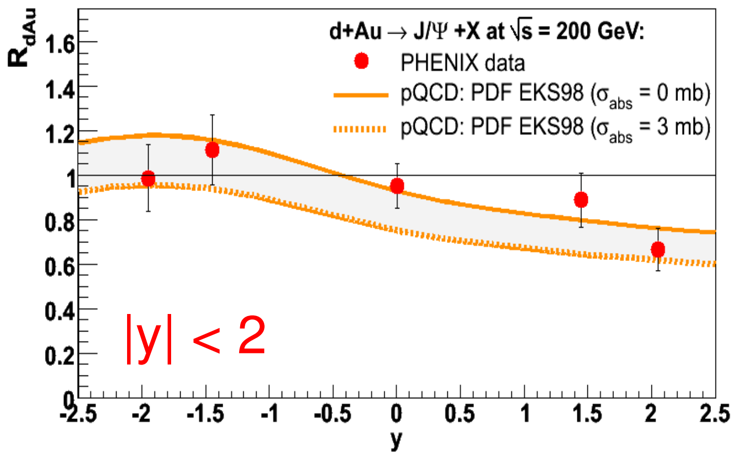
Q_s dependence on transv. area

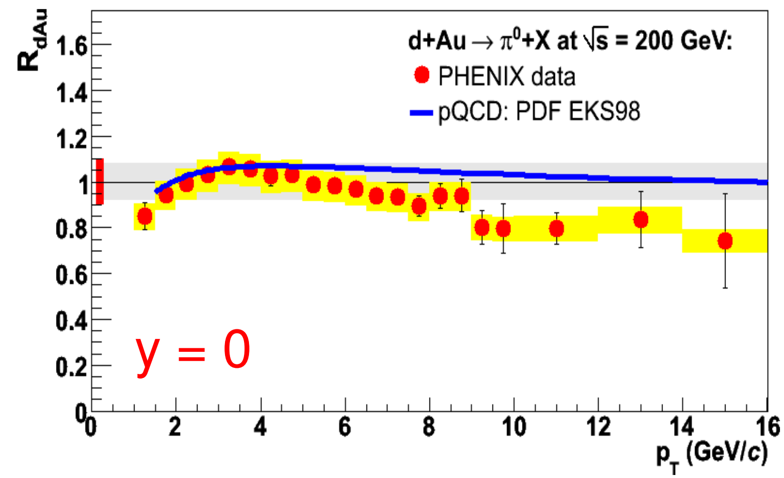
$$\sim \frac{1}{\alpha_s(Q_s^2)}$$

Kharzeev-Levin-Nardi, PLB507 (2001) 121

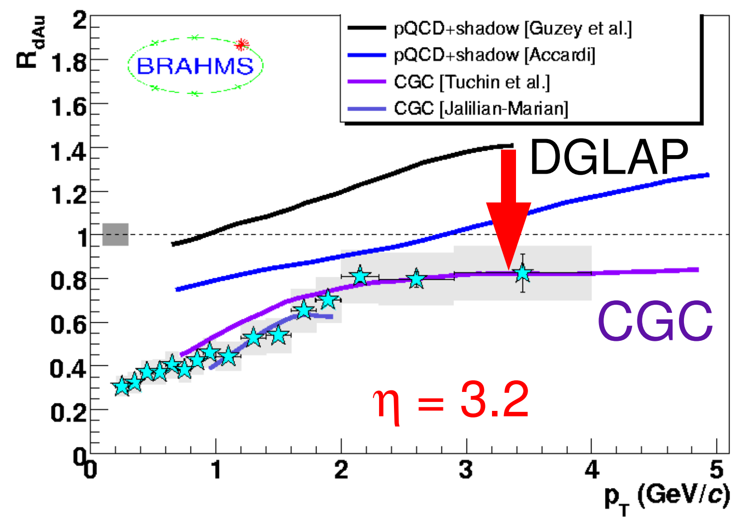
Saturation hints at RHIC (III): fwd. hadron suppression

- 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



Low-x QCD at the LHC

- RHIC & HERA saturation signals are more “hints” than “evidences”: low-x range probed is too close to non-perturbative domain (Q_s^2~1 GeV^2)
- Much better conditions @ the LHC (Q_s^2 ~5 GeV^2, lower x, larger y)

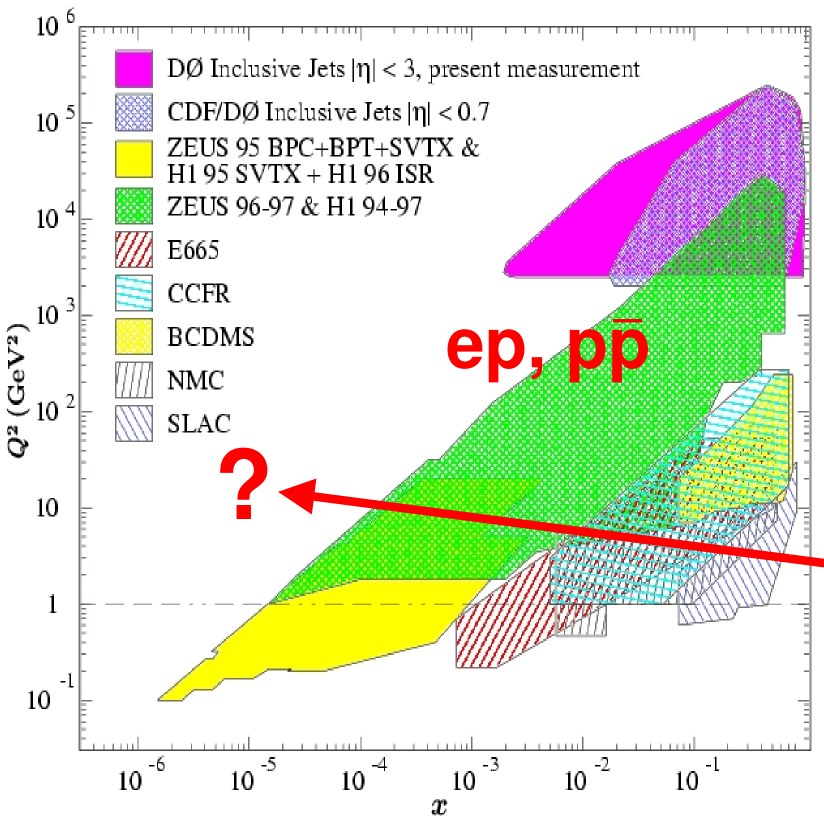
Low-*x* studies at the LHC: proton

- p-p @ 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 GeV² (y=0), 3 GeV² (y=5)

  (iii) 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

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

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

LHC forward rapidities:

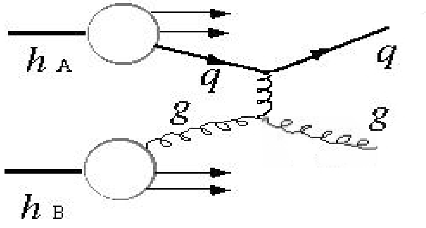
e.g. y ~ 6, Q ~ 10 GeV

x down to 10^{-6} !

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

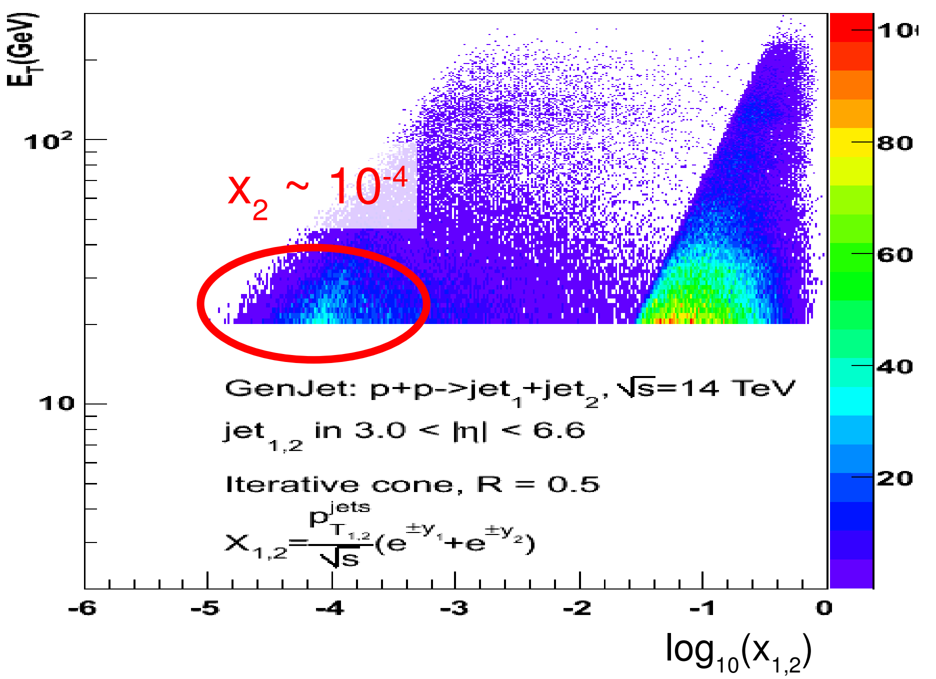
[S.Cerci, D.d'E, this School]

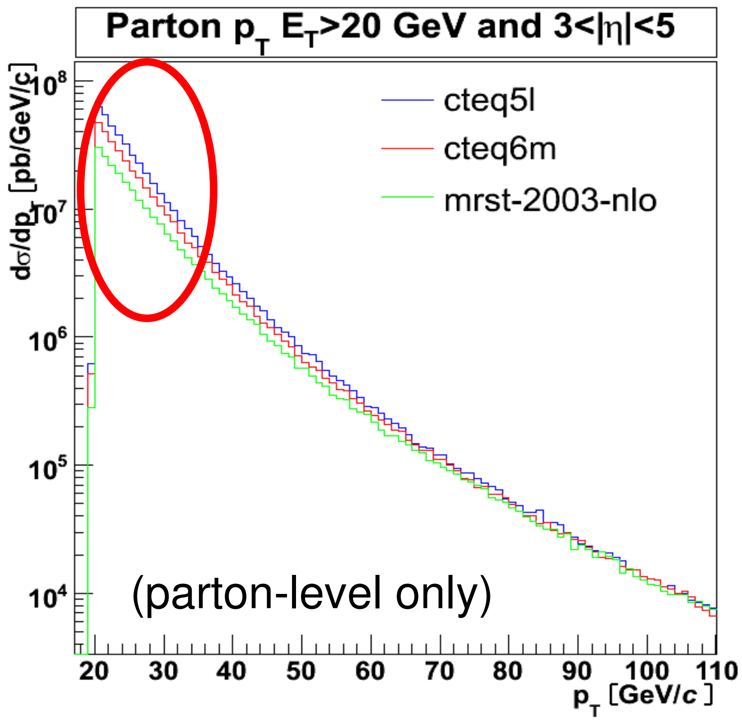
- Forward jets (E_T ~20-100 GeV) sensible to low-x PDFs:



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

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





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

[S.Cerci, D.d'E, this School]

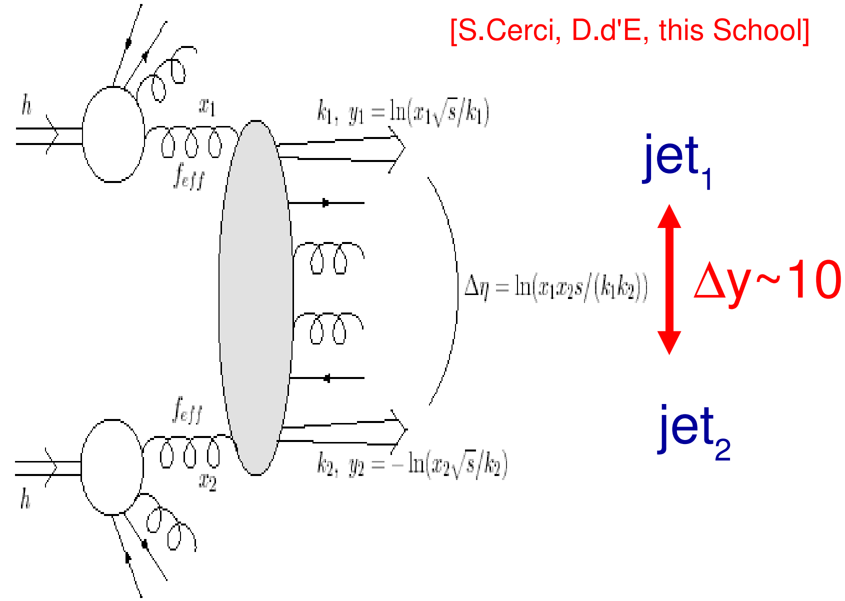
- Mueller-Navelet dijets with large y separation very sensitive to low-x QCD evolution (testing ground for BFKL):

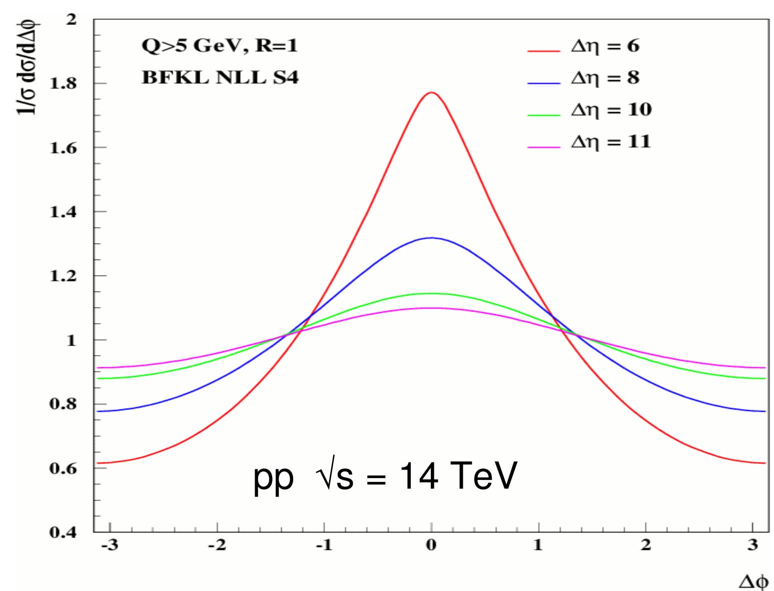
  BFKL: extra radiation between the 2 jets will smooth out back-to-back topology

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

  (enhanced radiation partially compensated by gluon saturation ?)

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

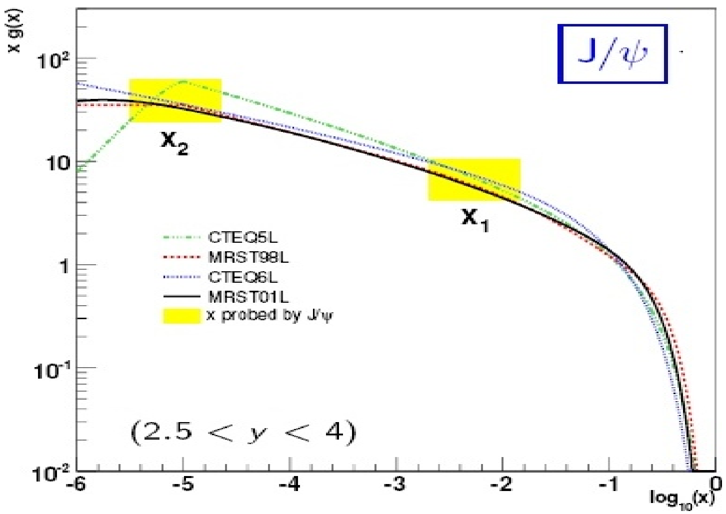


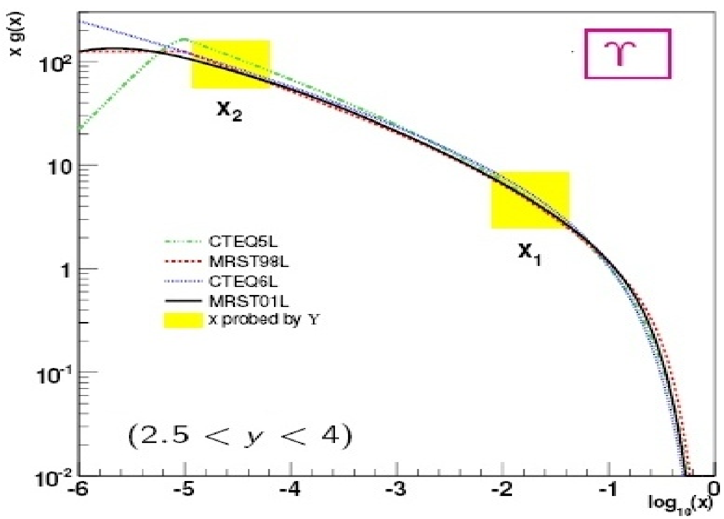


[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon]
[E. Iancu et al.]

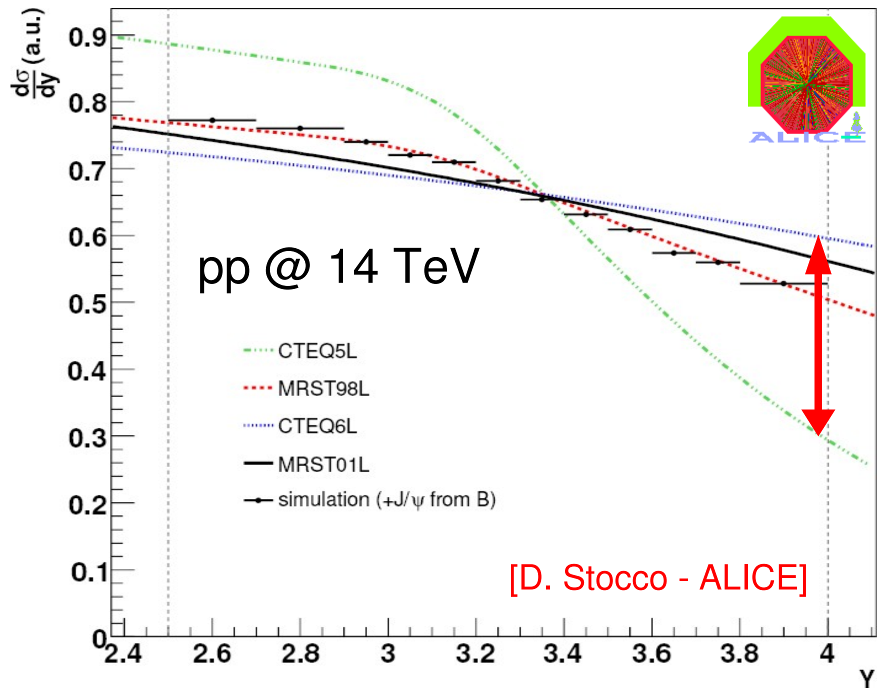
Case-study III: Forward $Q\bar{Q}$ in ALICE ($2.5 < |\eta| < 4$)

- 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



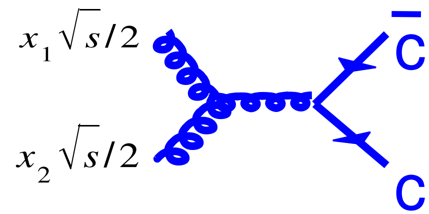
QQbar: Sensitive to diff. PDFs and DGLAP versus CGC predictions

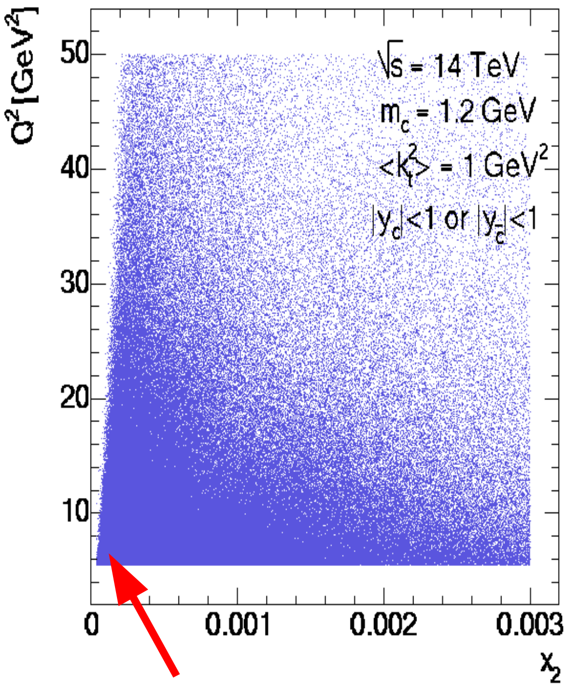
(Note: $m_{J/\psi} \sim Q_s$ at the LHC)

Case-study IV: Low-p_T charm in ALICE

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

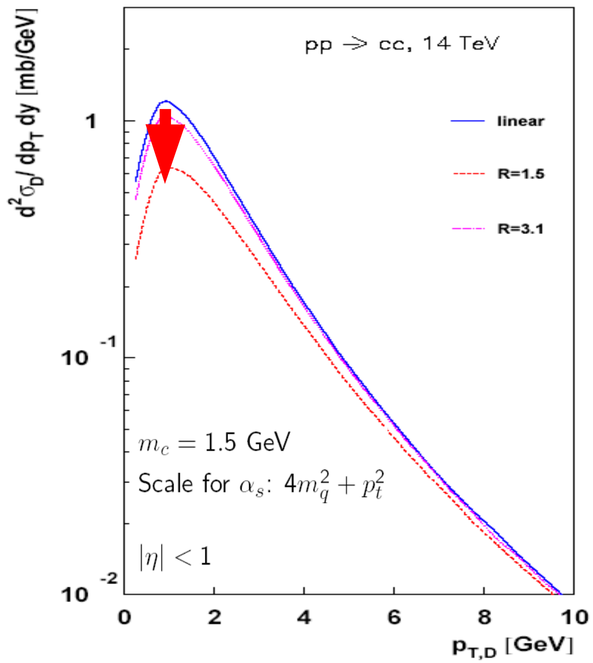
(indirect measurements also in fwd. μ-spectrometer)



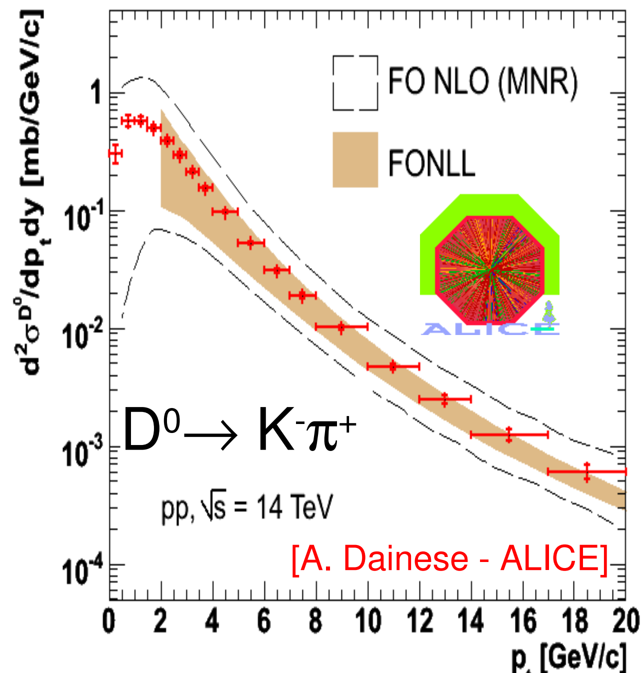


xg(x) in the proton

at $x_1 \sim x_2 \sim m_c/\sqrt{s} \sim 10^{-4}$



Charm suppression due to non-linear QCD effects



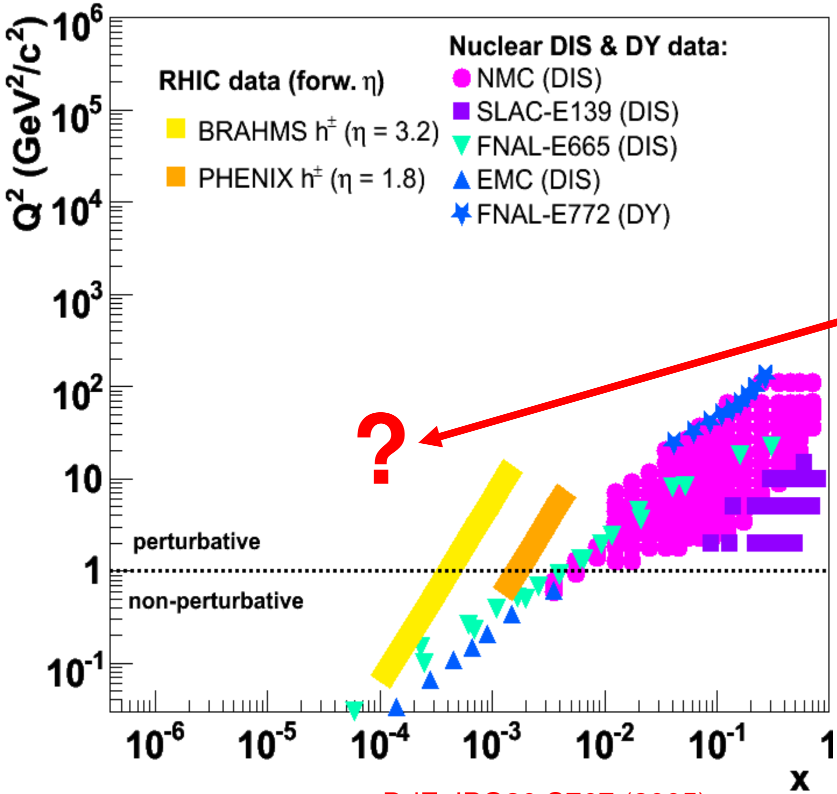
Good reco capabilities

(displaced vtx.+ $e^{\pm}$ PID)

down to p_T = 0 GeV/c

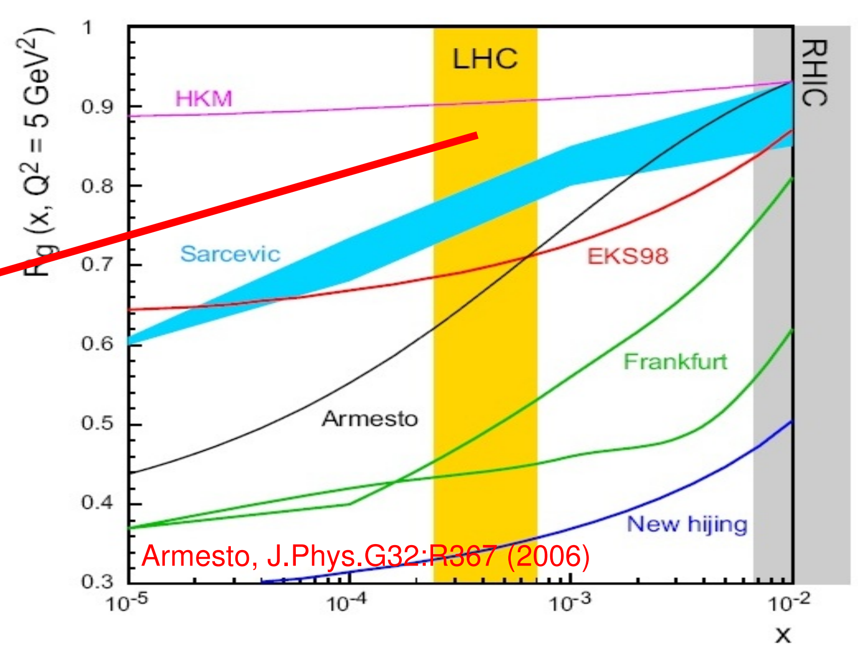
Low-*x* studies at the LHC: nucleus

- Pb-Pb @ 5.5 TeV, p-Pb @ 8.8 TeV:
  - (i) Bjorken $x=2p_T/\sqrt{s}$~30-45 times lower than Au-Au,d-Au @ RHIC !
  - (ii) Saturation enhanced ($A^{1/3}$~6) : Q_s^2 ~ 5 GeV^2
  - (iii) Very large perturbative cross-sections.



DdE JPG30:S767 (2005)

Ratio of Pb/p gluon densities:

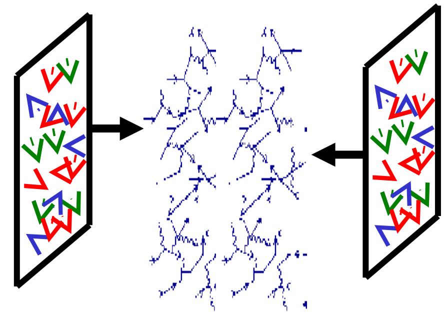


Nuclear $xG(x,Q^2)$ unknown for $x<10^{-3}$!

Case-study I: Total Pb-Pb hadron multiplicity

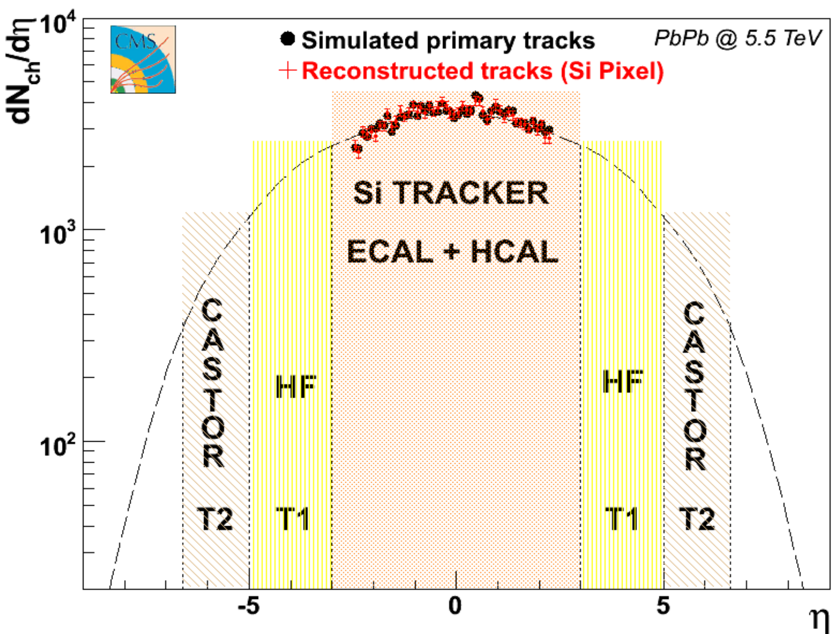
- Final A+A multiplicity ∝ Initial number of released gluons :

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

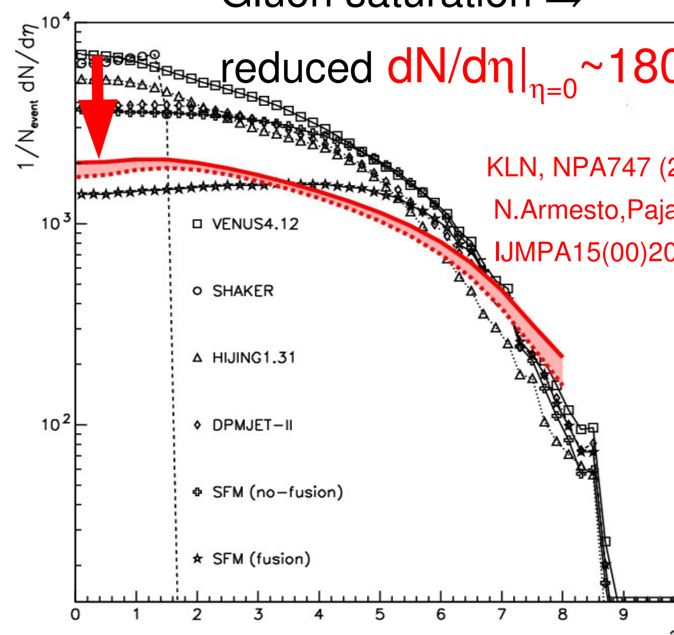


+ "local parton-hadron duality" (*1 gluon = 1 final hadron*)

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



Gluon saturation ⇒



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

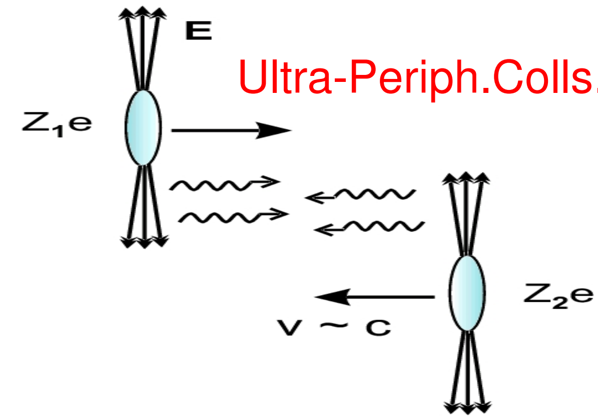
KLN, NPA747 (2005) 609

N.Armesto,Pajares IJMPA15(00)2019

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

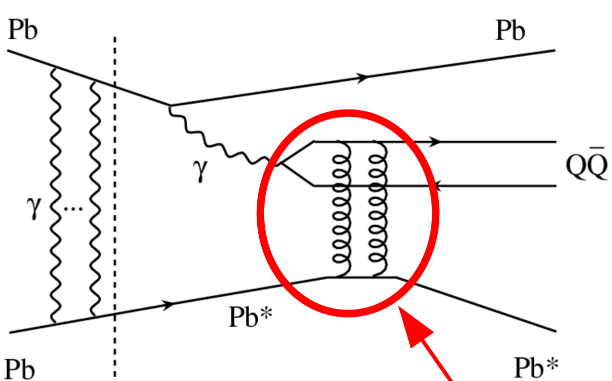
[Dd'E, hep-ex/0703024]

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

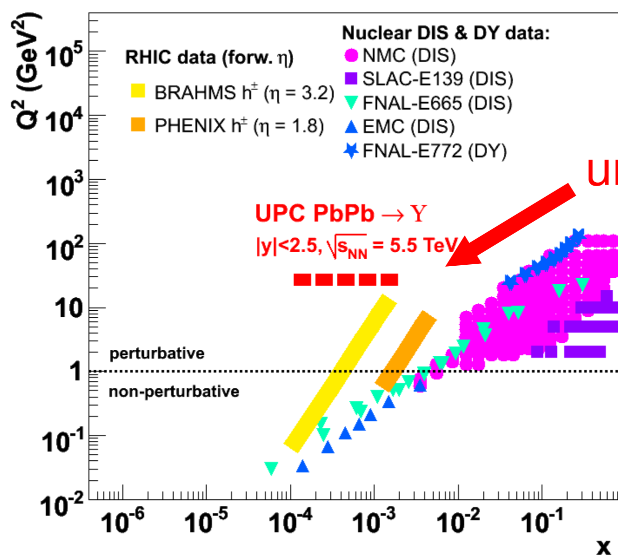


- Equivalent photon flux:
  - E_γ^{max} ~ 80 GeV (PbPb-LHC)
  - γ Pb: max. $\sqrt{s_{\gamma Pb}} \approx$ 1. TeV $\approx$ 3. - 4. × $\sqrt{s_{\gamma p}}$(HERA)

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



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



unexplored $xG_A(x,Q^2)$

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

y~2: $x(\Upsilon) \sim 10^{-4}$

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

[Dd'E, hep-ex/0703024]

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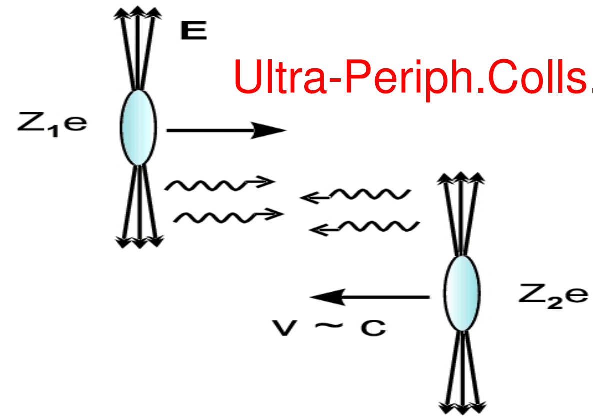

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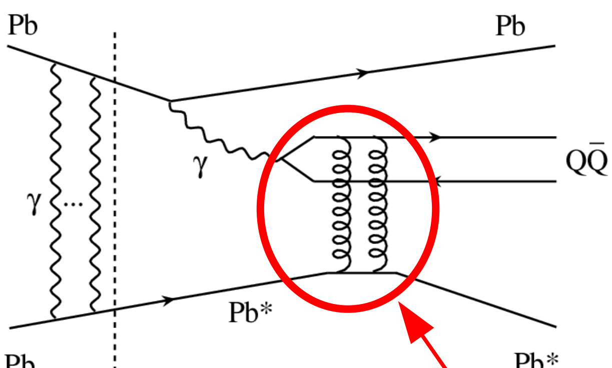
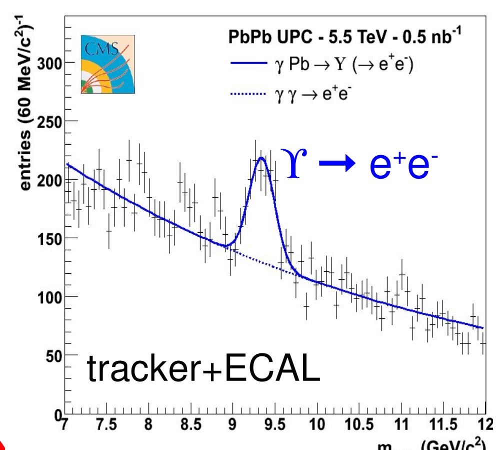
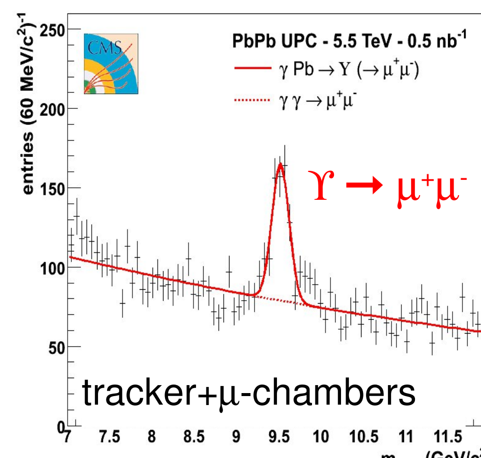


$$\left.\frac{d\sigma_{\gamma p,A\to V\,p,A}}{dt}\right|_{t=0} = \frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3\left[xG(x,Q^2)\right]^2$$

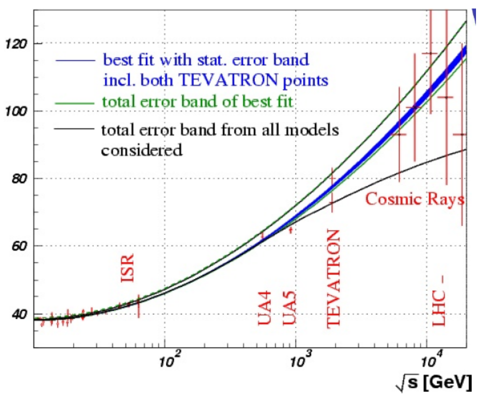




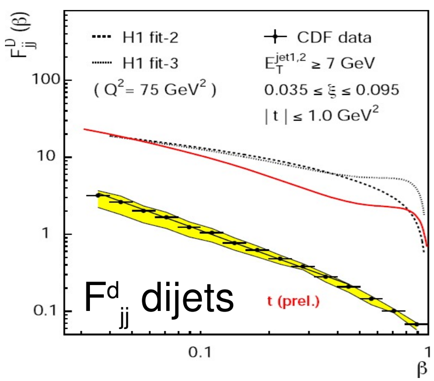
~500 ϒ/0.5 nb^{-1} expected in CMS

Summary Lecture-I: forward physics @ LHC

p-p σ_{tot}, elastic scatt.



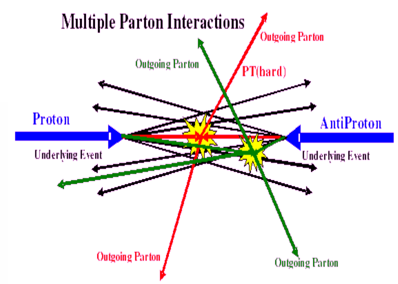
hard diffraction



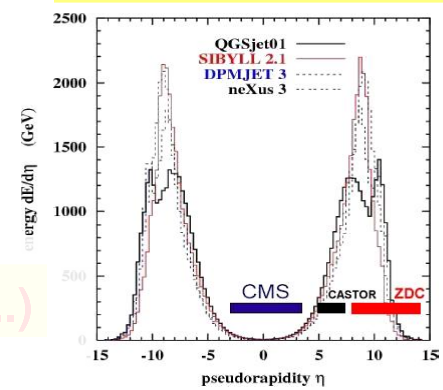
VM photoprod.

(B)SM Higgs

MB/UE/MPI



UHE cosmic-rays



gluon saturation, CGC

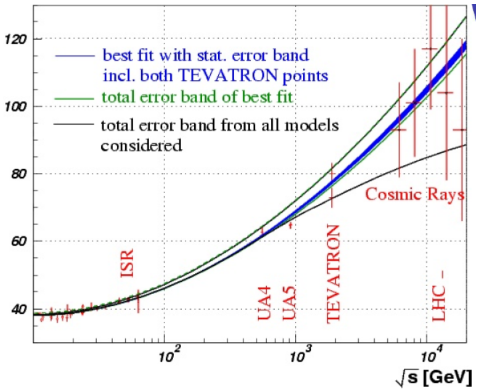
low-x PDFs

BFKL

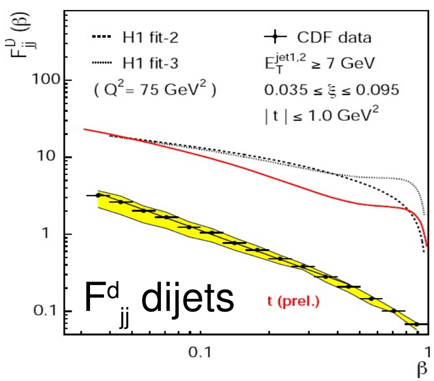
EWK (γ-γ,γ-W,...)

Summary Lecture-II: forward physics @ LHC

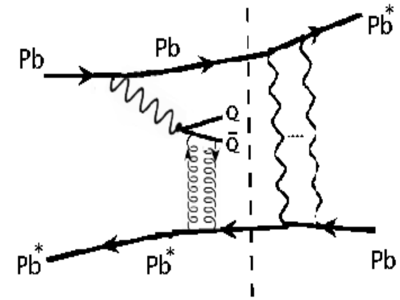
p-p σ_{tot}, elastic scatt.



hard diffraction

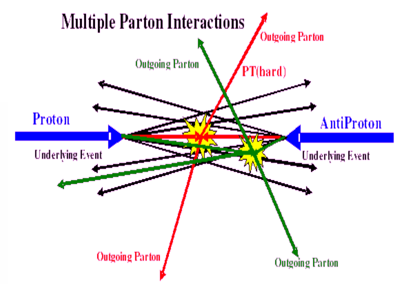


VM photoprod.

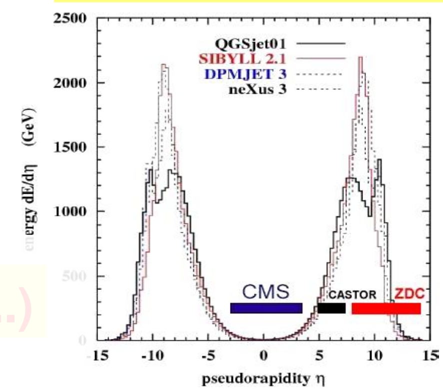


(B)SM Higgs

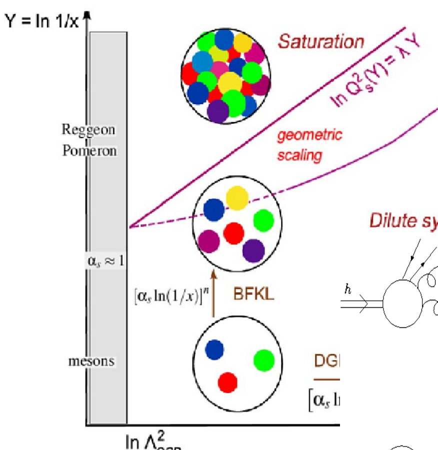
MB/UE/MPI



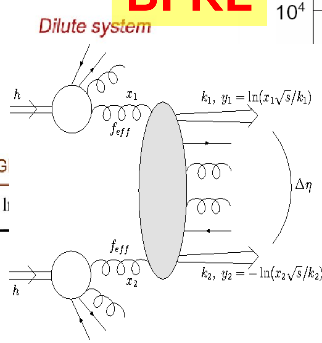
UHE cosmic-rays



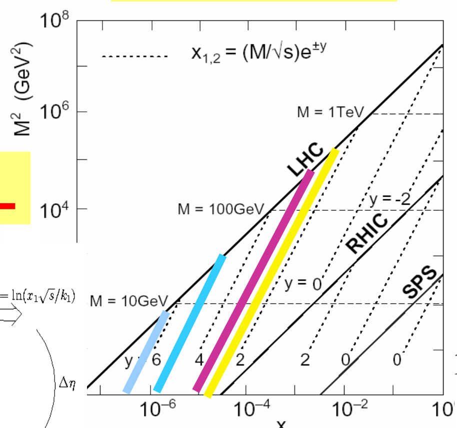
gluon saturation, CGC



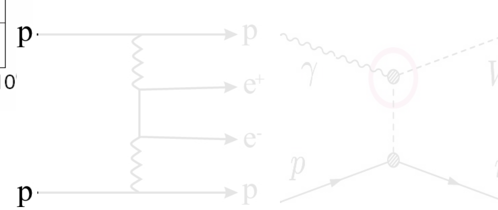
BFKL



low-x PDFs



EWK (γ-γ,γ-W,...)



Forward measurements at the LHC

1. Diffractive & elastic p-p collisions:
   - Total cross-sections, elastic scattering.
   - Soft & hard diffraction.
2. UHE Cosmic-rays physics:
   - Forward energy & particle flows (p-p, p-A, A-A).
   - CR “exotica”.
3. Low-x QCD:
   - Parton saturation, non-linear QCD evolution,
   - Proton: fwd. jets, fwd. QQbar, fwd. DY
   - Nucleus: $dN_{ch}/d\eta$, QQbar photoproduction

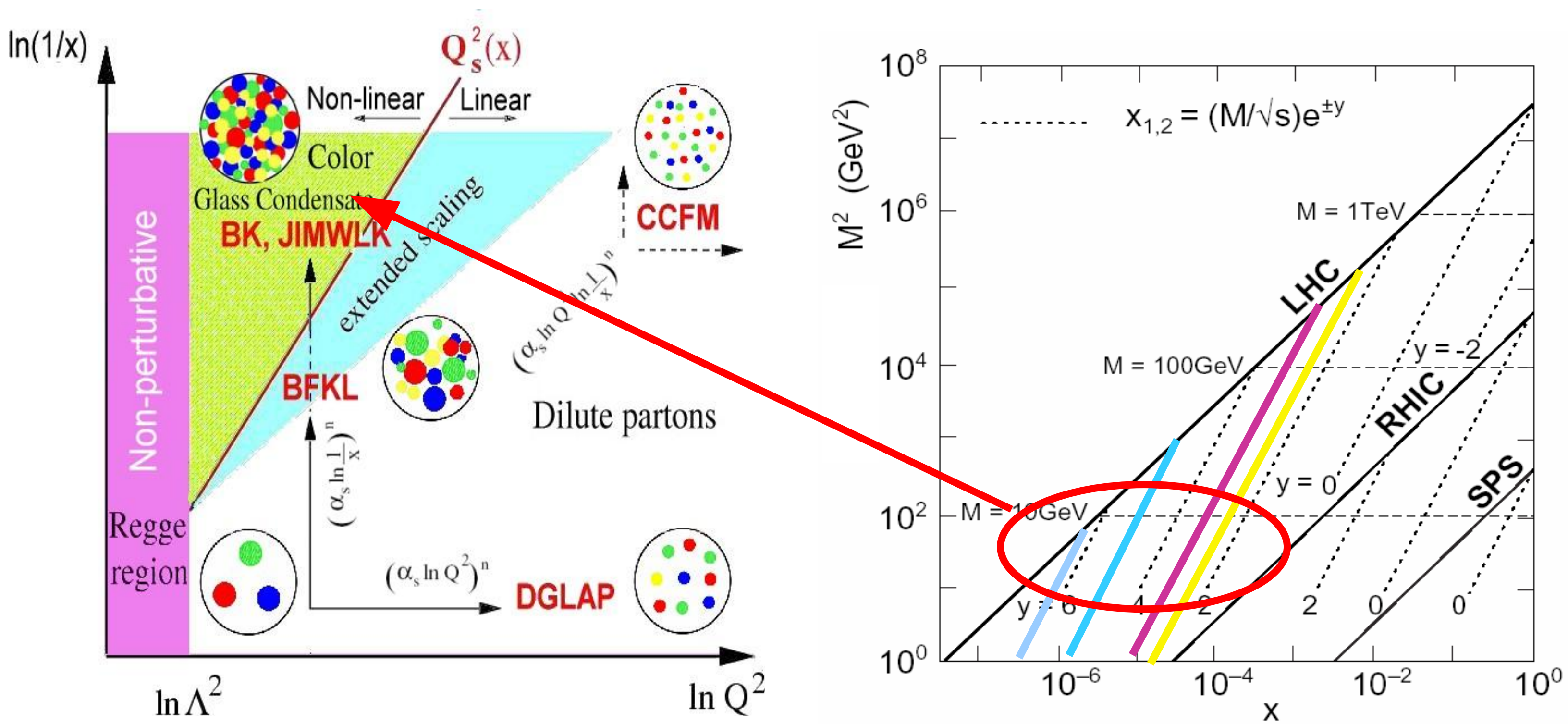
3[d] lecture

4. EWK: two-photon, γ–proton interactions:
   - Absolute luminosity via: $pp \to \gamma\gamma \to p\,\ell^+\ell^-\,pp$
   - Triple/Quartic gauge boson couplings via: $pp \to \gamma p \to pnW$, $\gamma\gamma \to WW,ZZ$
5. Higgs & beyond SM:
   - Vector-Boson-Fusion Higgs tagging
   - Central exclusive (SM, MSSM) Higgs

Backup slides

Summary

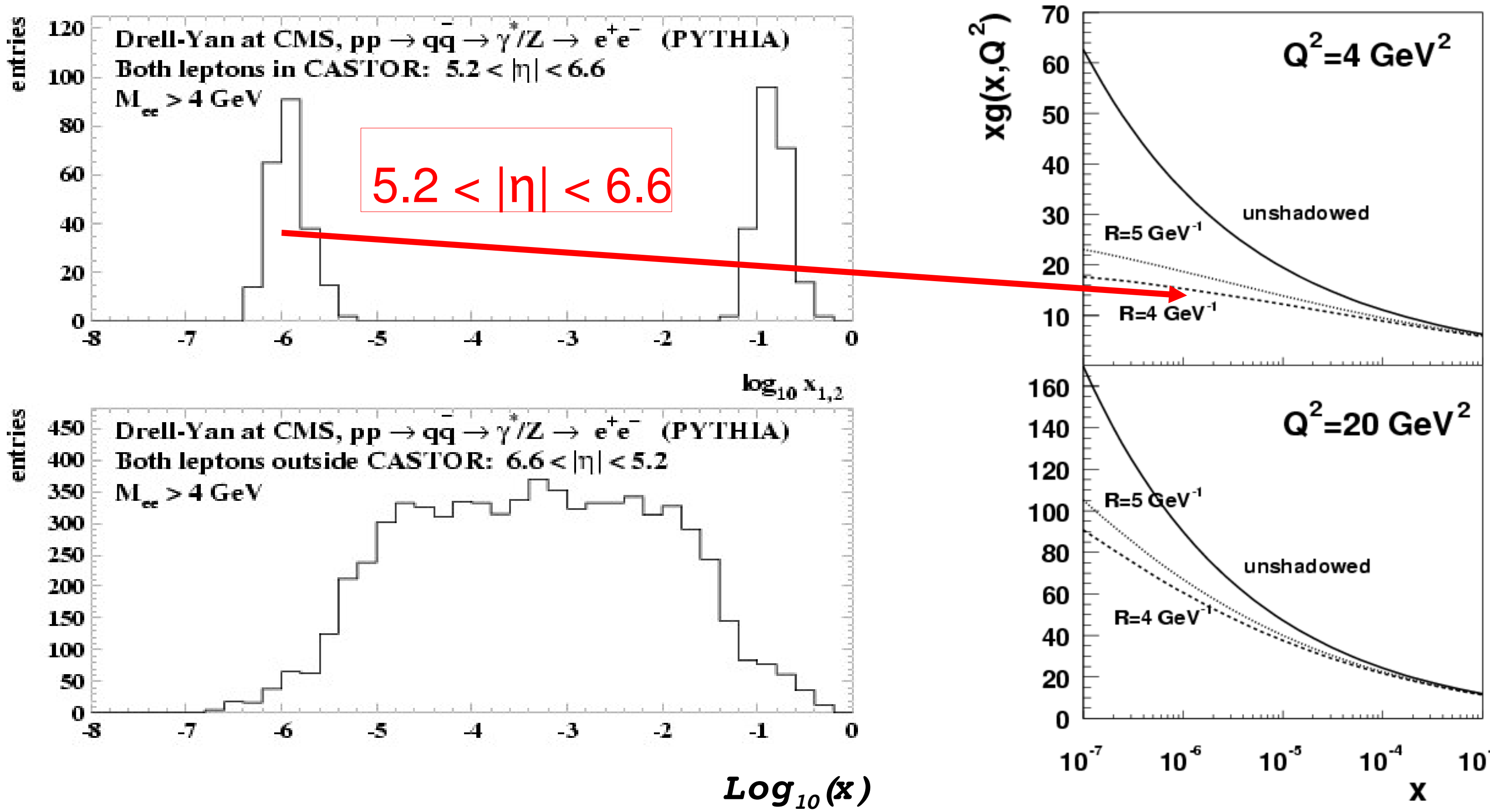
- Gluon saturation & non-linear evolution <u>must</u> set-in at (some) low-x in hadronic wave-functions → Fundamental info on high-energy limit of QCD
- Hints of non-linear QCD dynamics in *ep* (HERA) and dA,AA (RHIC)
- LHC = unique lab to study high parton density /evolution in p,Pb down to $x\sim10^{-6}$ using fwd. detectors and perturbative processes: (di)jets,QQbar,DY,...



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

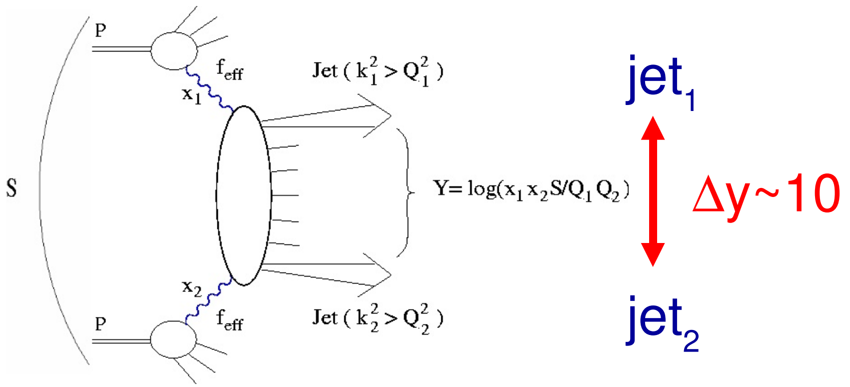


TOTEM T2 tracker+ CASTOR needed to deal w/ large QCD (& QED) bckgd.

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

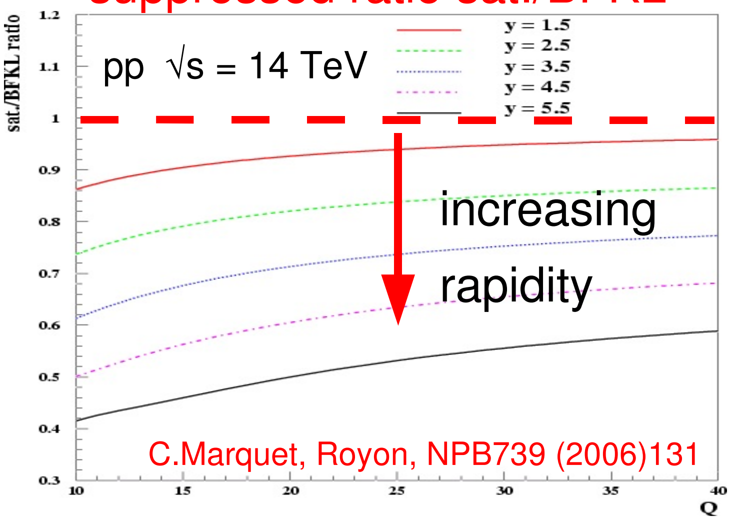
- Mueller-Navelet dijets separated by large Δy:

very sensitive to non-DGLAP evolution



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

suppressed ratio sat./BFKL



C.Marquet, Royon, NPB739 (2006)131

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

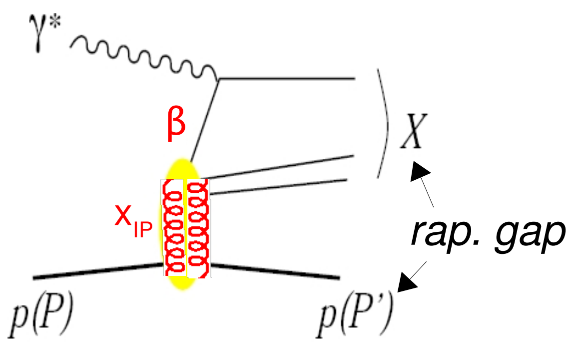
  - $E_{T,i} > 20\,\mathrm{GeV}$
  - $|E_{T,1} - E_{T,2}| < 2.5\,\mathrm{GeV}$ (similar virtuality, to minimise DGLAP-evolution)
  - $3 < |\eta_{1,2}| < 5$ (both jets in HF)
  - $\eta_1 \cdot \eta_2 < 0$ (each jet in a different HF)
  - $|\eta_1| - |\eta_2| < 0.25$ (almost back-to-back in pseudo-rapidity)

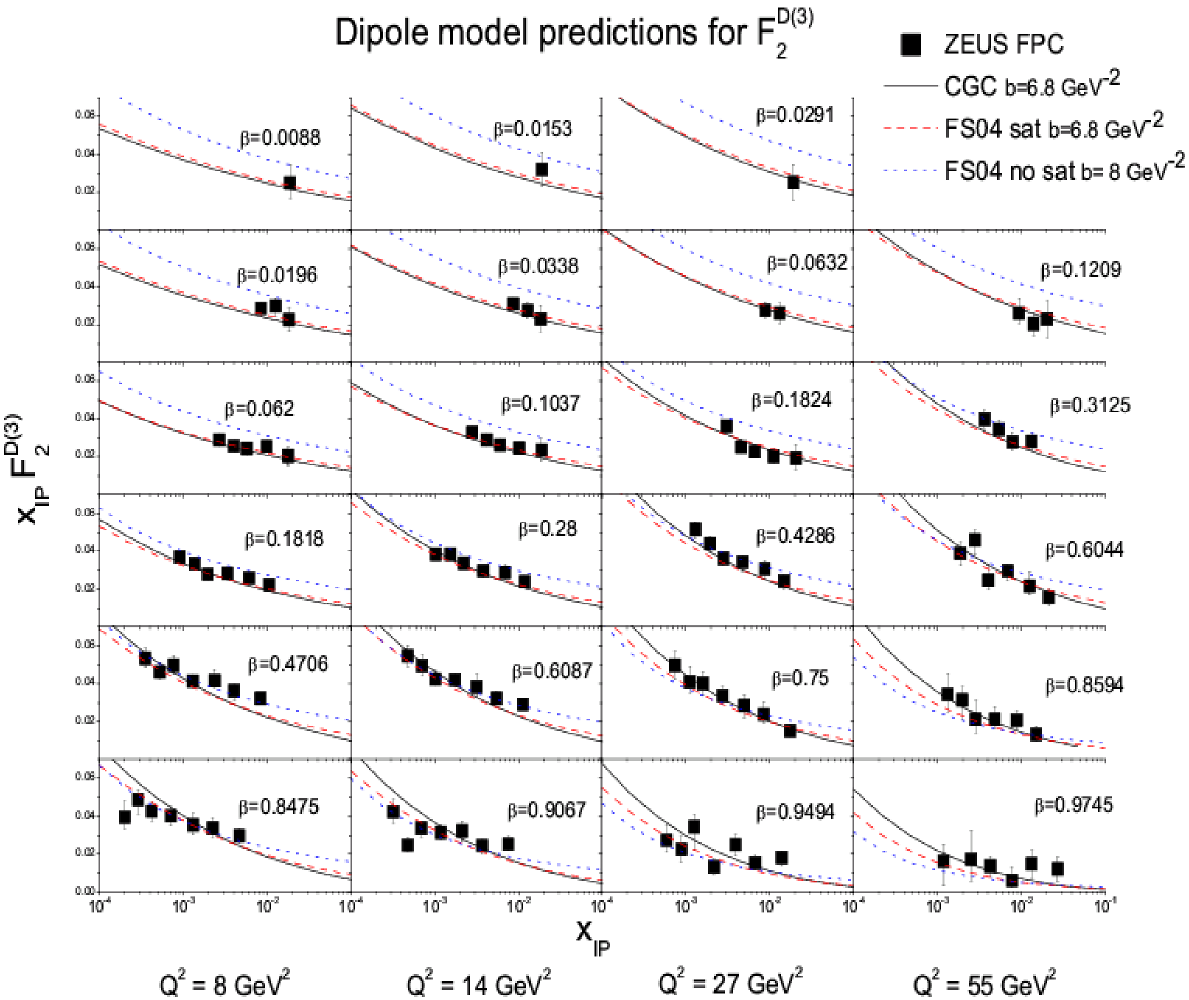
$$\frac{d^2\sigma}{d\eta dQ} = \frac{N_{jets}}{\Delta\eta\Delta Q}\frac{1}{\int \mathcal{L}dt}$$

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

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

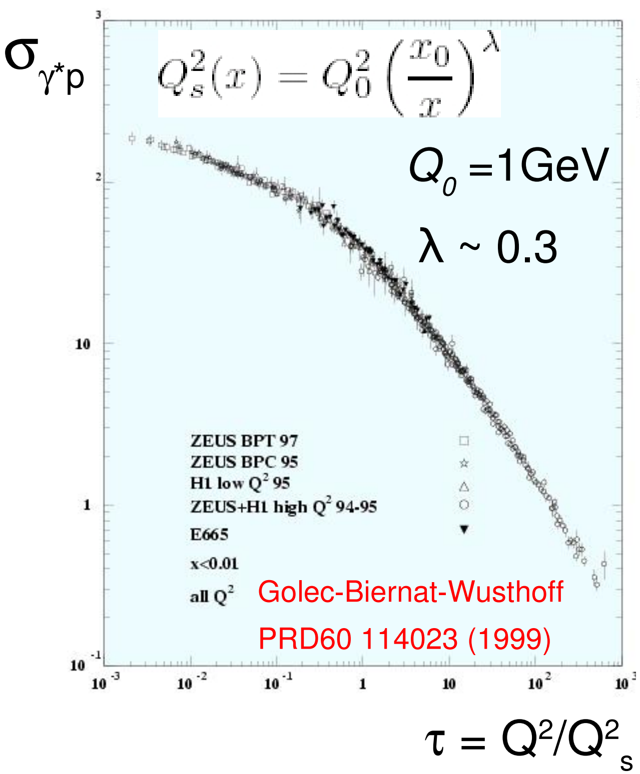
β = fraction of IP momentum carried by struck parton

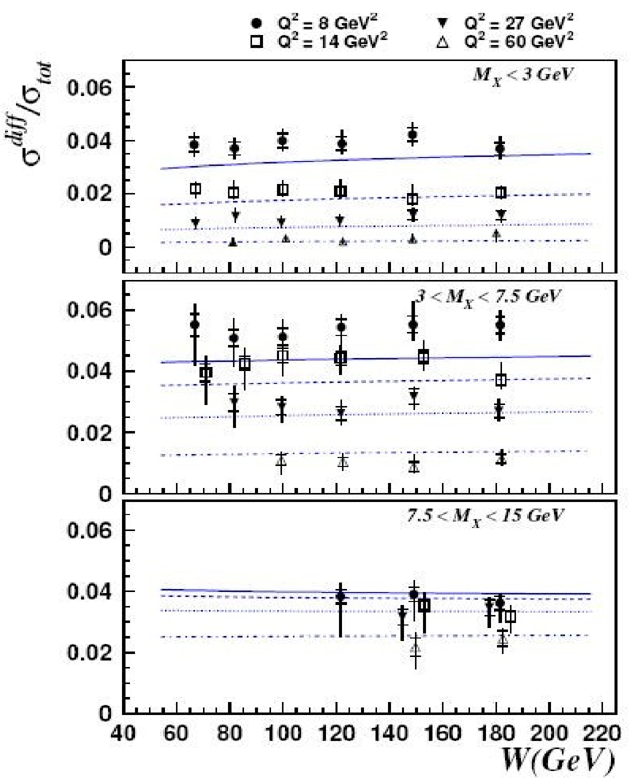
Forshaw,Shaw
hep-ph/0411337

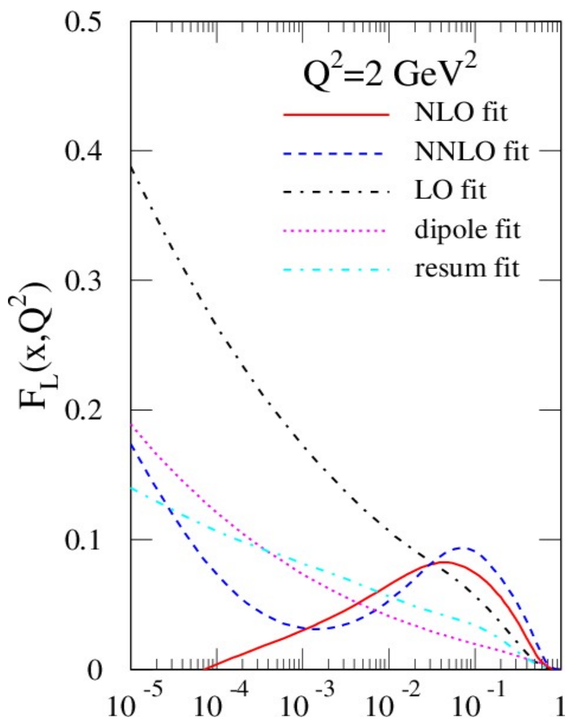
Saturation hints at HERA

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

"Geometric scaling" | flat $\sigma_{diffract}/\sigma_{tot}$ vs energy | Longitudinal struc. funct.







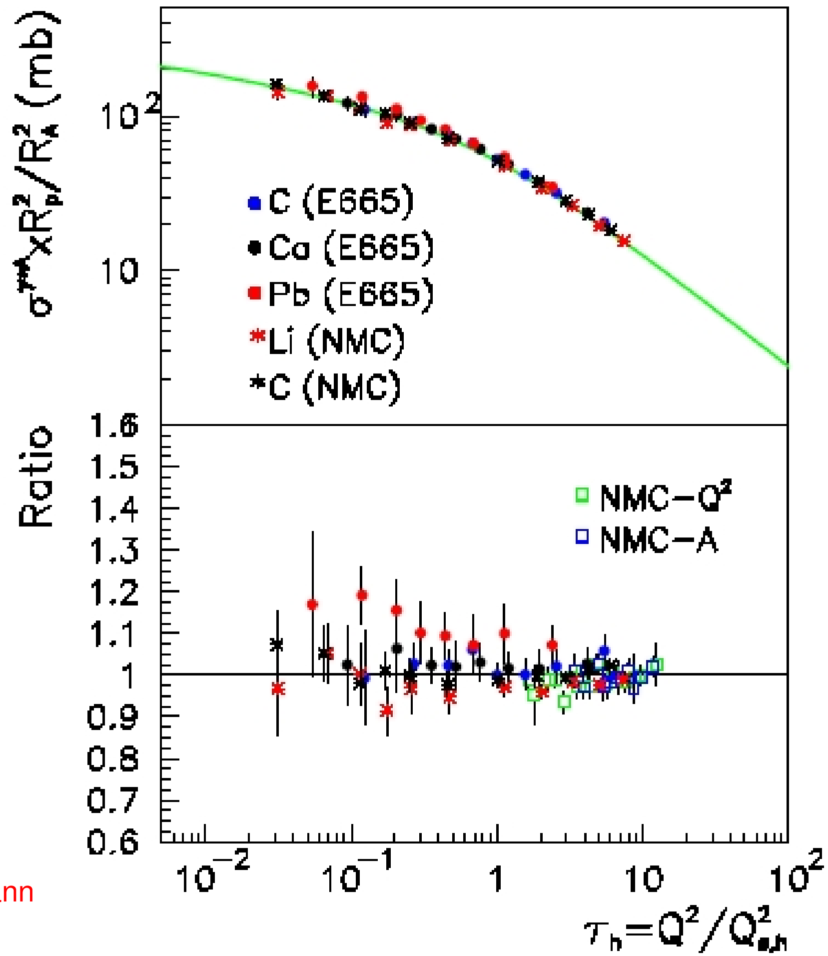
Inclusive DIS x-section depends on single scale Q^2/Q_s^2 for $x < 0.01$

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

Gluon (F_L) at NLO becomes negative for $Q^2 \sim 2$ GeV² at low-x

Incl. DIS nuclear: "Geometric scaling" at low-x

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



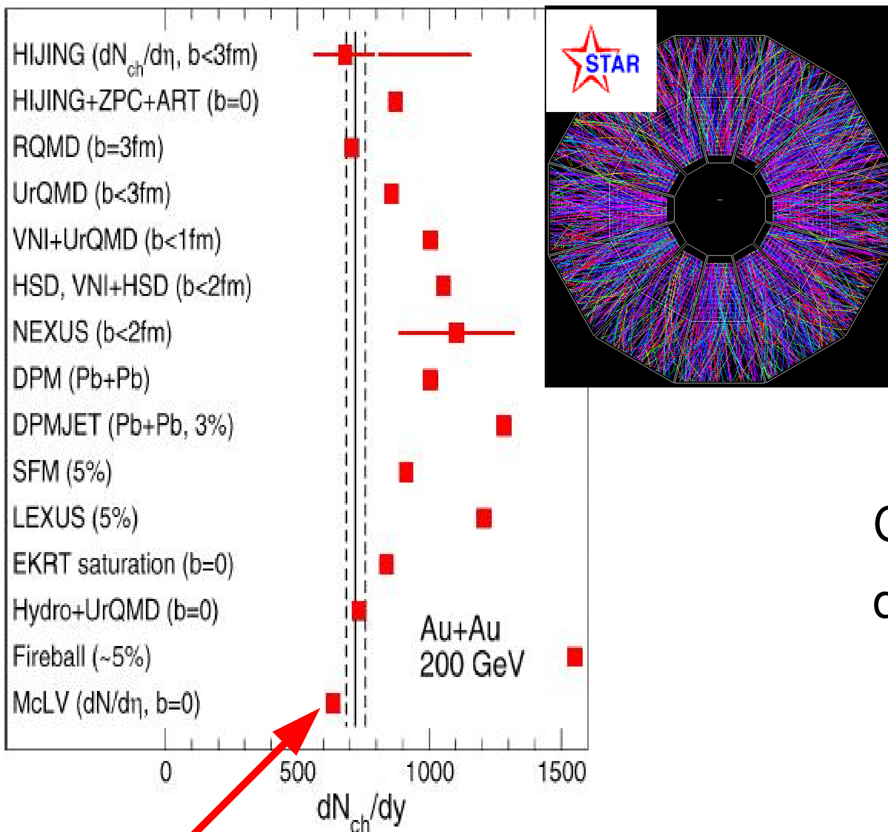
Confirms approx:

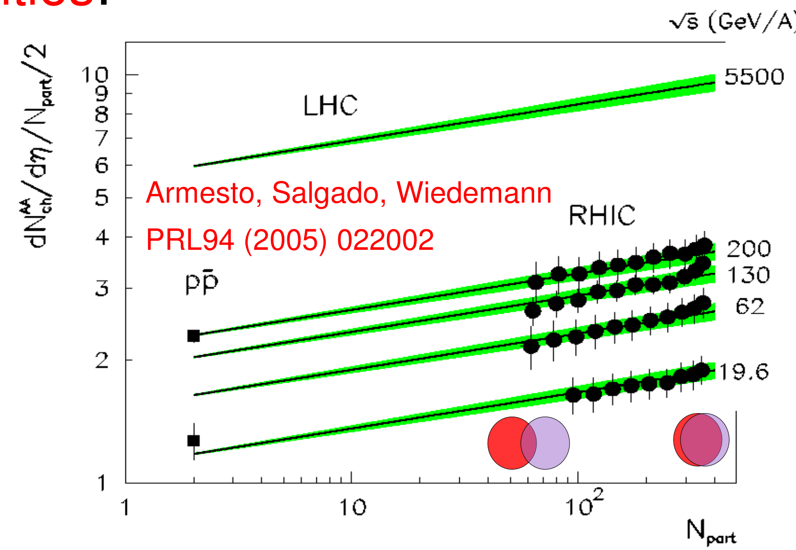
$$Q_s^2 \sim A^{1/3}$$

Armesto, Salgado, Wiedemann
PRL94 (2005) 022002

Saturation hints at RHIC ? (AuAu @ 200 GeV)

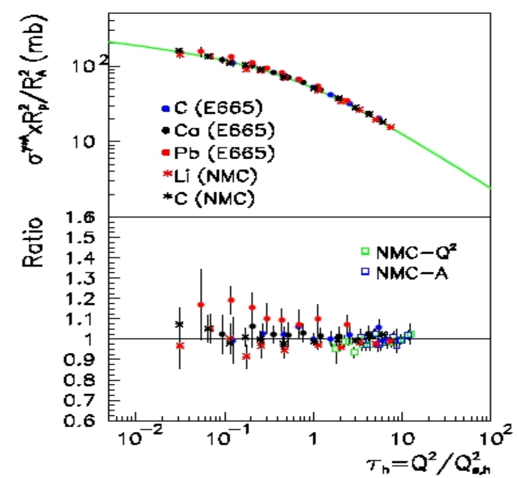
- “Reduced” total Au-Au hadron multiplicities:





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

dN$_{ch}$/dη~ 650 at η=0 described by CGC (or models which include reduced incoming parton flux)



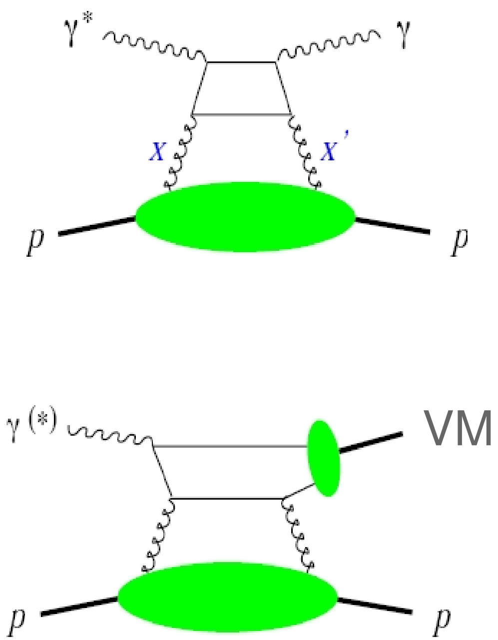
Confirms approx:

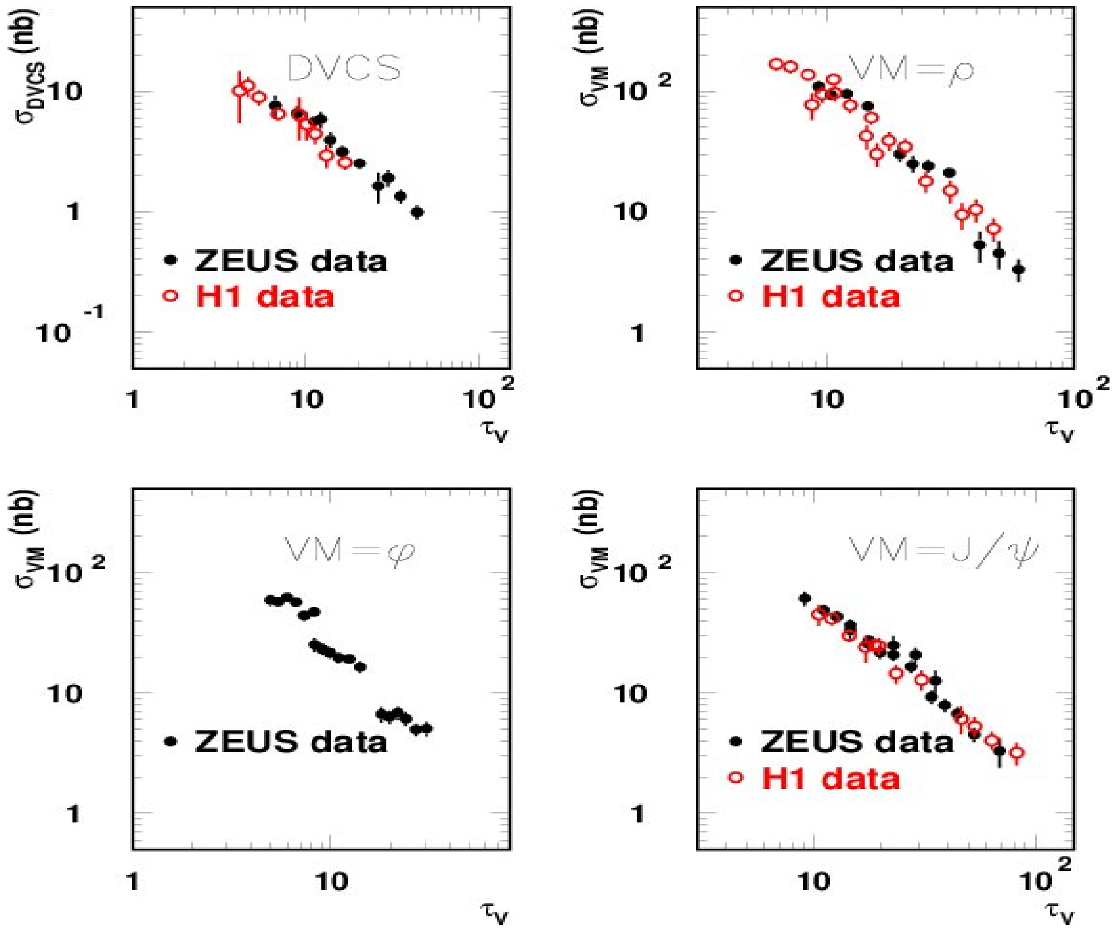
$$Q_s^2 \sim A^{1/3}$$

Saturation hints at HERA (IV): diffract. geom. scaling

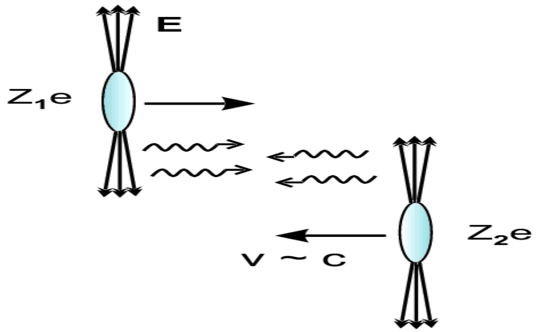
- Geometric scaling also observed in diffractive observables (DVCS, exclusive vector-meson production):

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





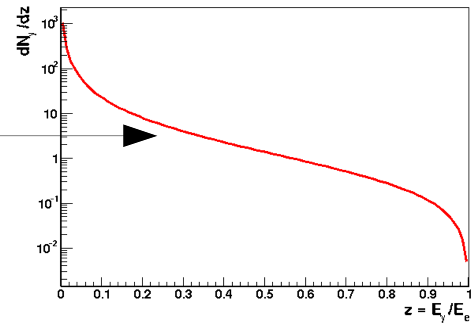
Photoproduction (γ A) in UPC AA collisions



- 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 :

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

(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.