Low-x and Diffraction

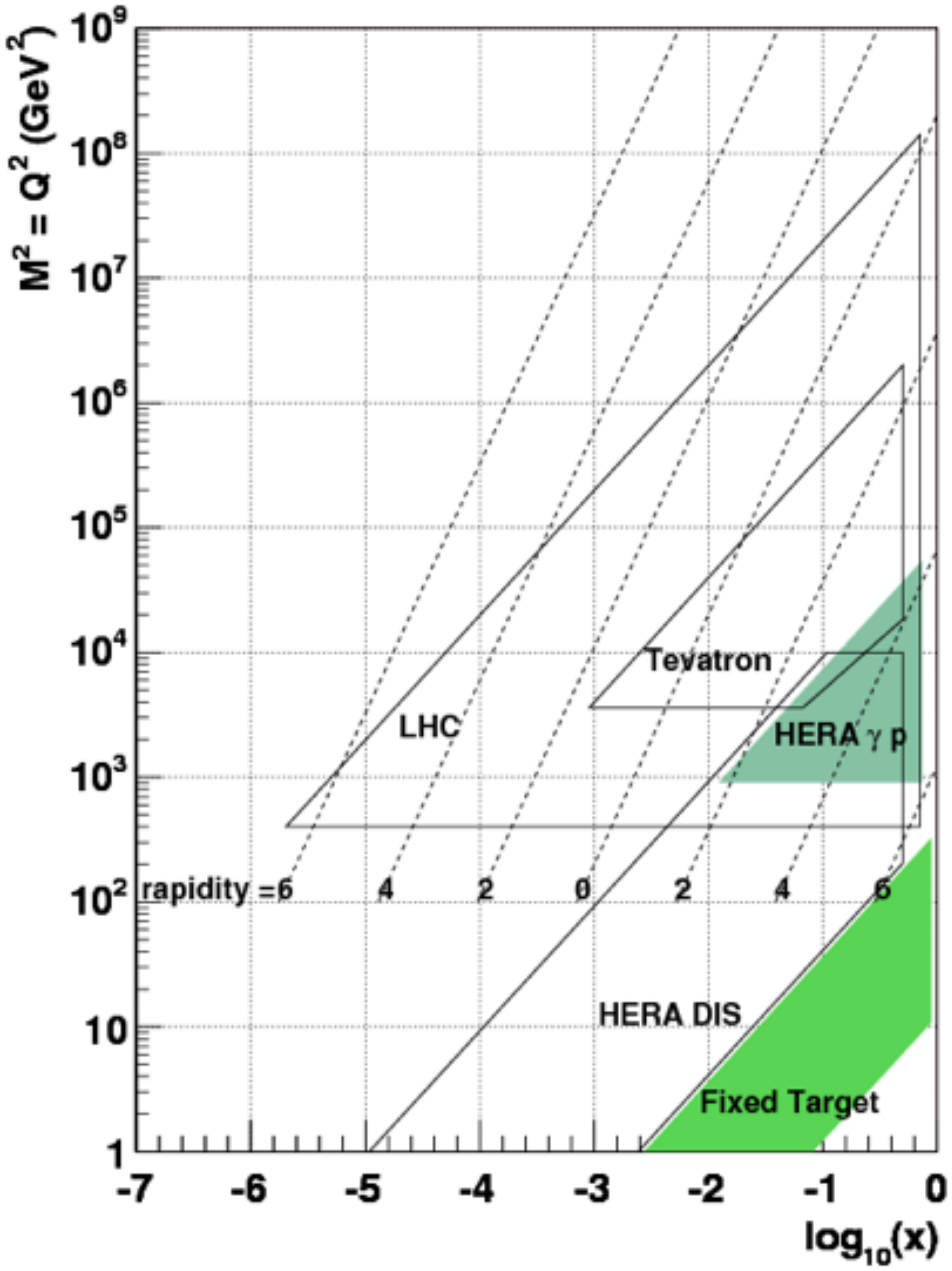
L. Favart

Université Libre de Bruxelles

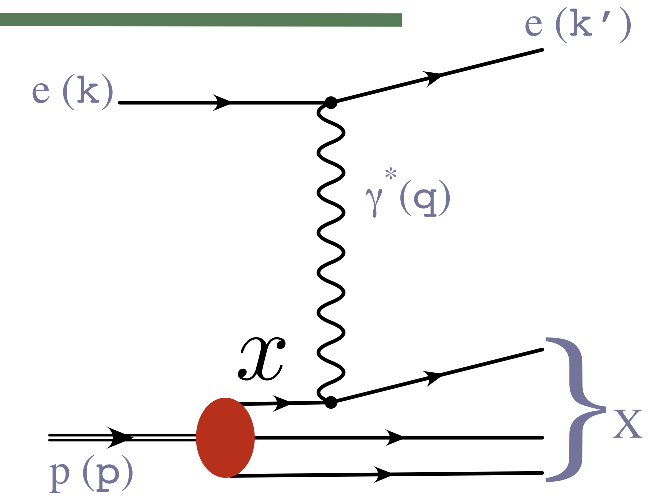
DIS16

Hamburg 11-15 April 2016

DIS: kinematics

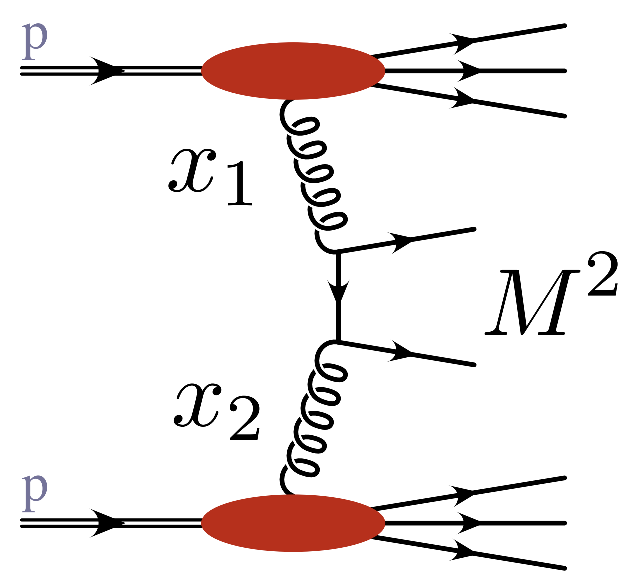


HERA



$$Q^2 = sxy \qquad x \in [0,1] \qquad y \in [0,1]$$

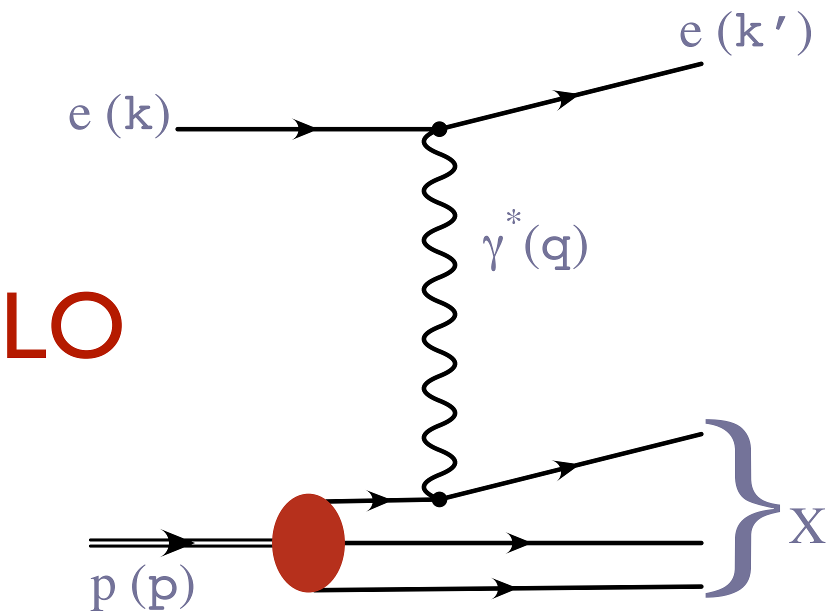
LHC
Tevatron



rapidity Y: $x_{1,2} = \frac{M}{\sqrt{S}} e^{\pm Y}$

low x physics ≈ forward physics

DIS: dynamics in collinear factorisation



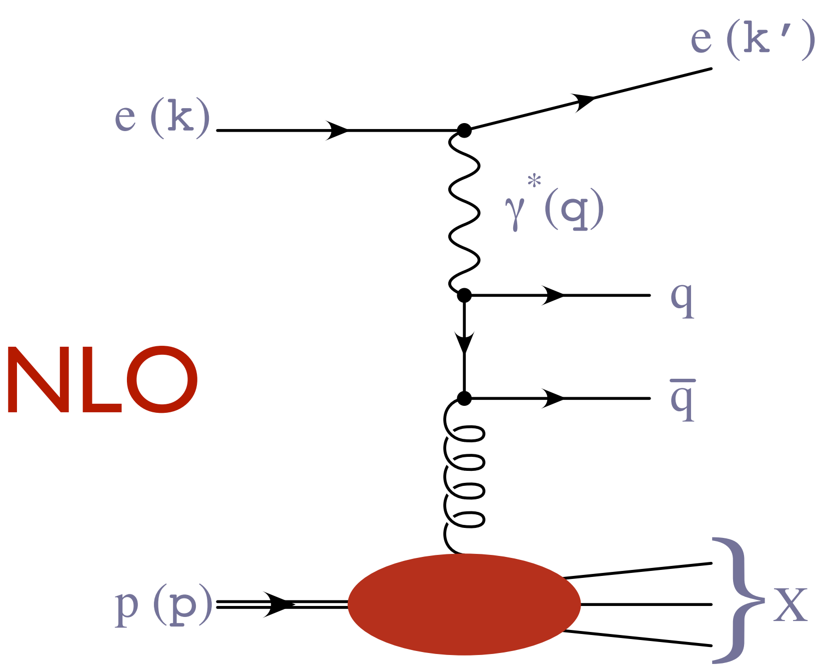
Usually in infinite momentum frame:

– p: made of partons carrying a fraction of the p longitudinal (large) momentum
⇒ access to quark densities

– interaction between the γ* and a parton over short time
⇒ factorisation

$$\frac{d^2\sigma}{dx\,dQ^2} \simeq \frac{2\,\pi\,\alpha^2}{x\,Q^4}\left(1+(1-y)^2\right) F_2(x,Q^2)$$

$$F_2(x,Q^2) = \sum_{quarks} e_q^2\, x\,(q+\bar{q})$$

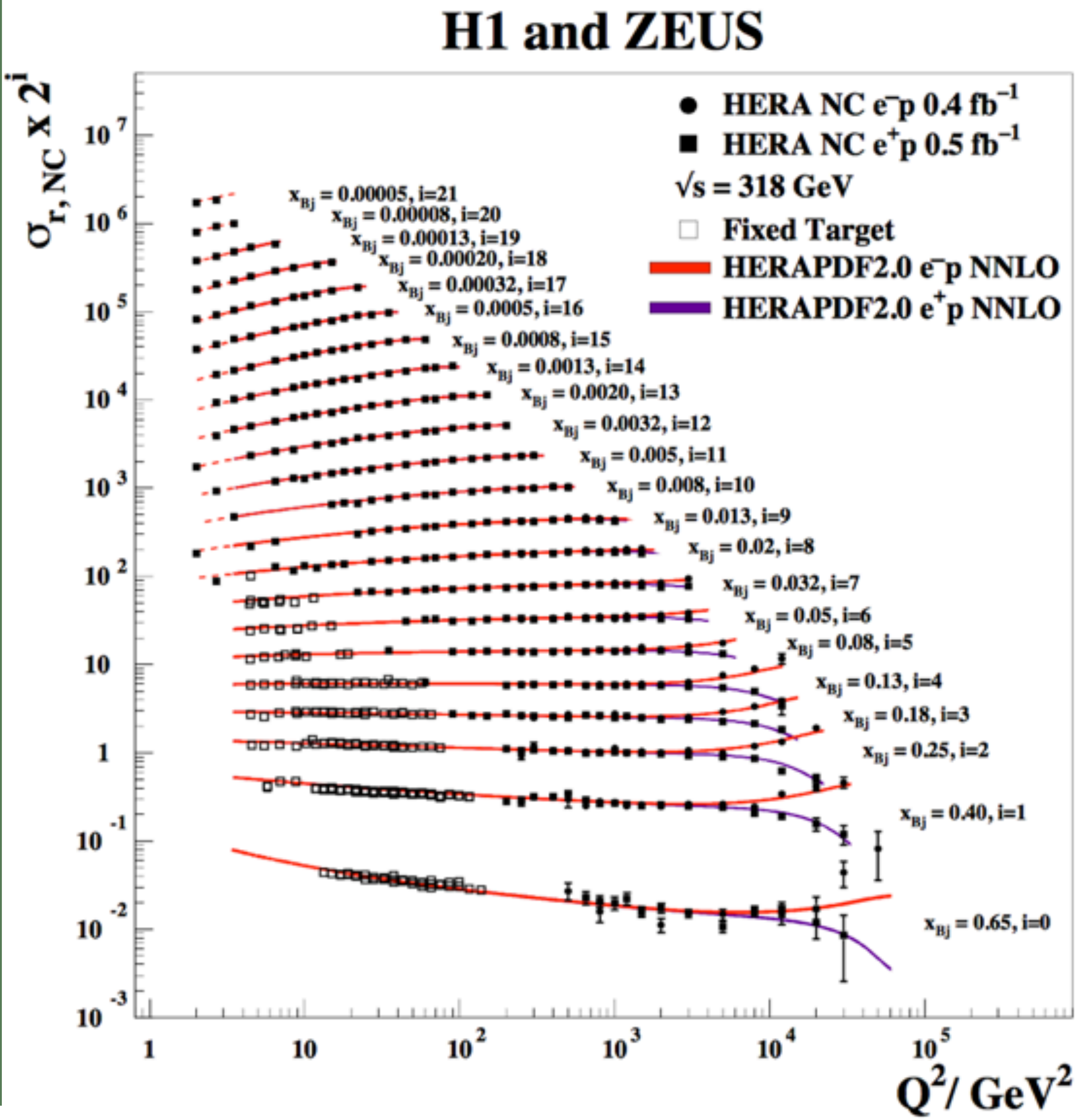


at NLO (α_s order):
- DGLAP evolution in log(Q^2)

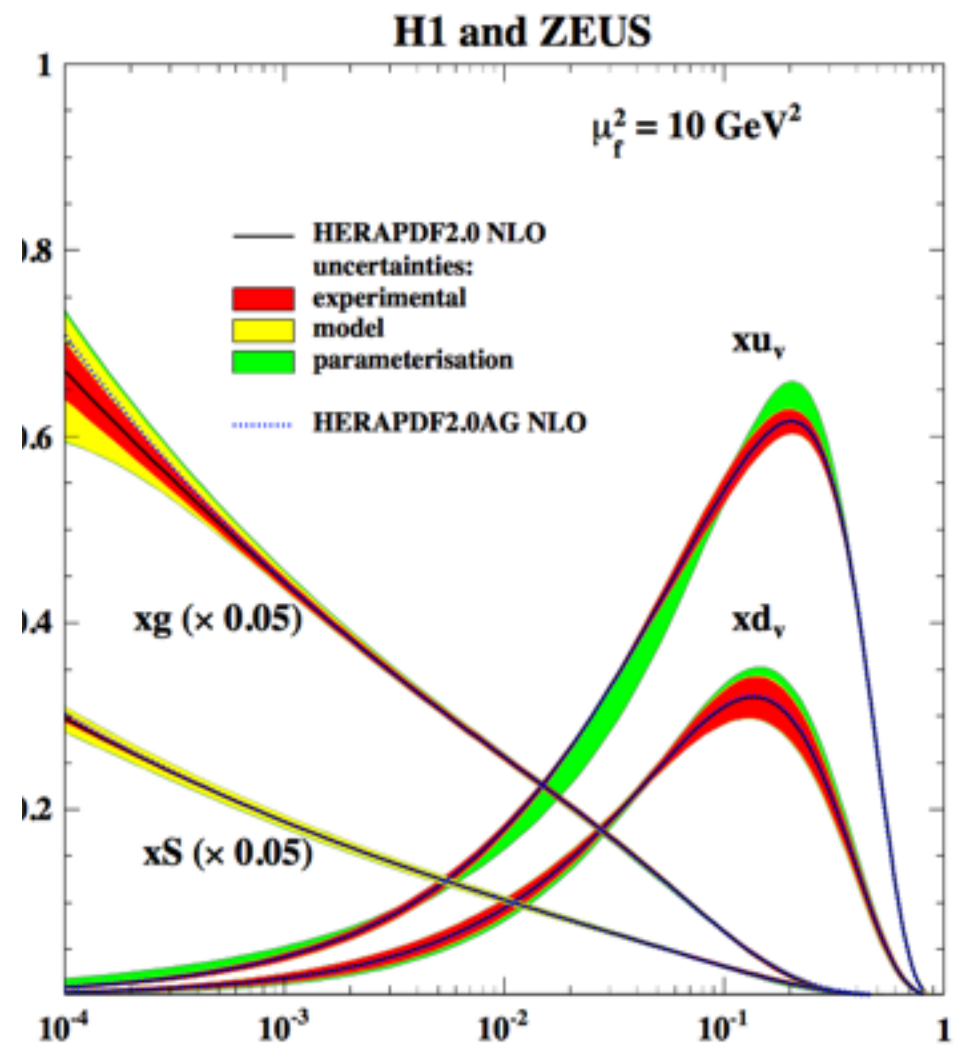
⇒ access to gluon densities

⇒ non-perturbative physics parametrised in PDFs

DIS: collinear factorisation - PDFs



From HERA (and other) cross section measurements, using DGLAP eq.
⇒ extraction of quark and gluon dencities (PDFs)



[arxiv:1506.06042]

⇒ High gluon (and sea) densities at low-x

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DGLAP

Integro(x)–differential(Q²) eq. for integrated gluon dist. g:

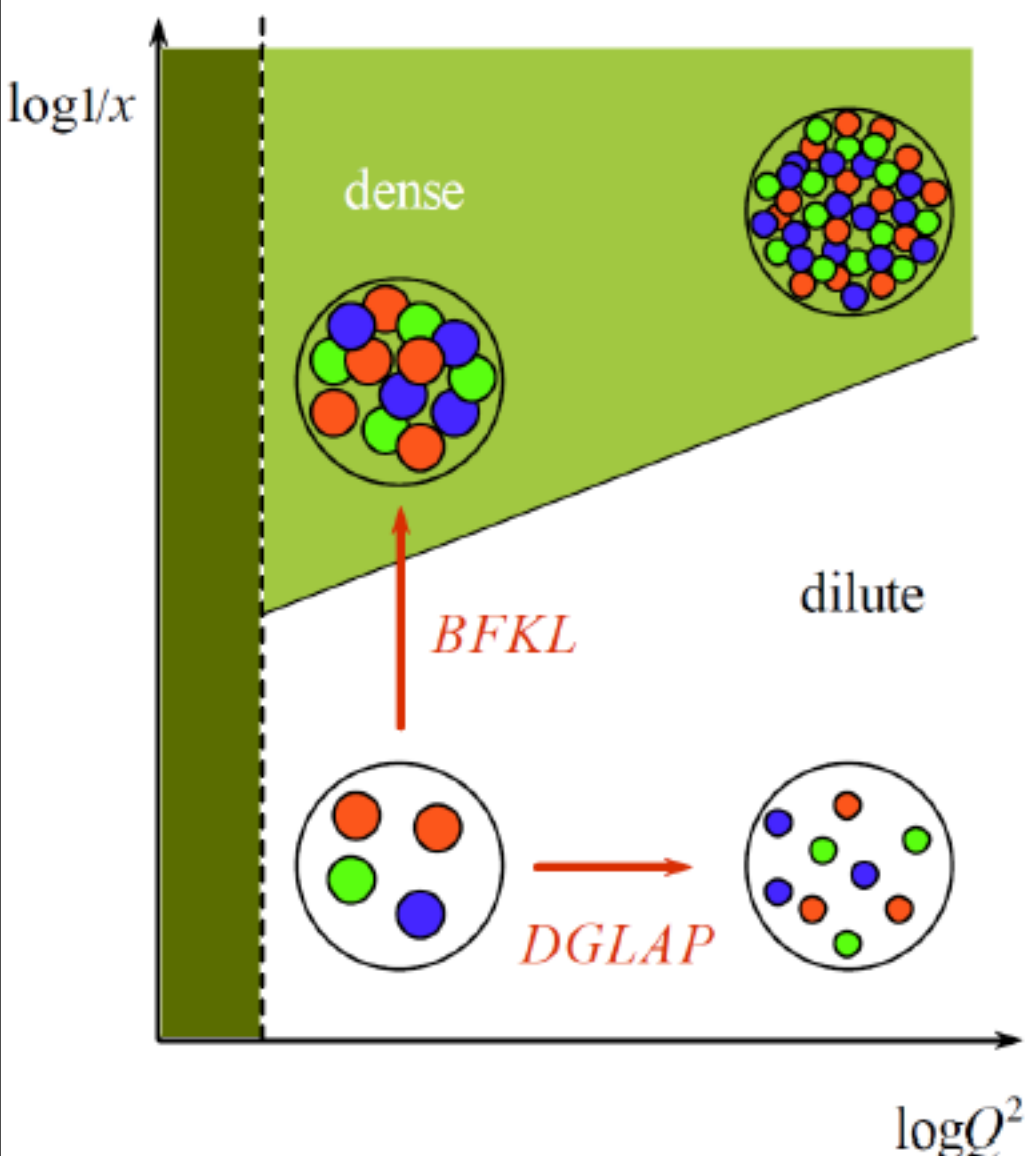
$$\frac{\mathrm{d}g(x,Q^2)}{\mathrm{d}\ln Q^2} \sim \alpha_S \int \frac{\mathrm{d}z}{z} P_{gg}(\frac{x}{z}) g(z,Q^2)$$

BFKL

Integro(k)–differential(x) eq. for unintegrated gluon dist. G:

$$\frac{\mathrm{d}G(x,k^2)}{\mathrm{d}\ln 1/x} \sim \alpha_S \int \frac{\mathrm{d}k'^2}{k'^2} K(\frac{k}{k'}) G(x,k'^2)$$

$$g(x,Q^2) = \int^Q \mathrm{d}^2k \; G(x,k^2)$$



Both eq. relate ⊥ and longitudinal structures

- given long. struc. DGLAP gives the ⊥ structure evol.

- given the ⊥ struct. BFKL gives you the long. evol.

If all orders are computed, they should be equivalent

If not: DGLAP valid at medium-large x, large Q^2

BFKL valid at low x, medium Q^2

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DGLAP

Integro(x)–differential(Q²) eq. for integrated gluon dist. g:

$$\frac{\mathrm{d}g(x,Q^2)}{\mathrm{d}\ln Q^2} \sim \alpha_S \int \frac{\mathrm{d}z}{z} P_{gg}(\frac{x}{z}) g(z,Q^2)$$

BFKL

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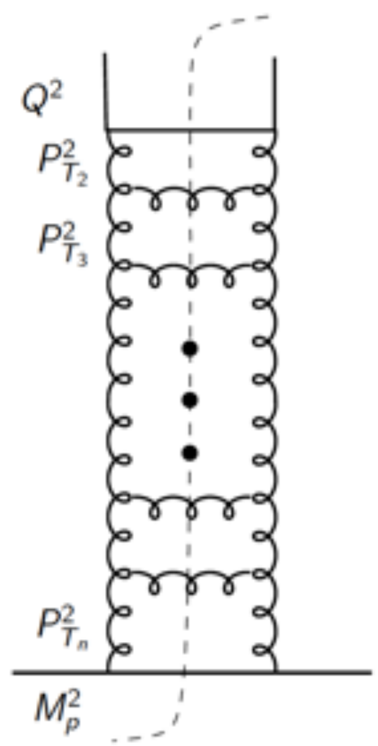
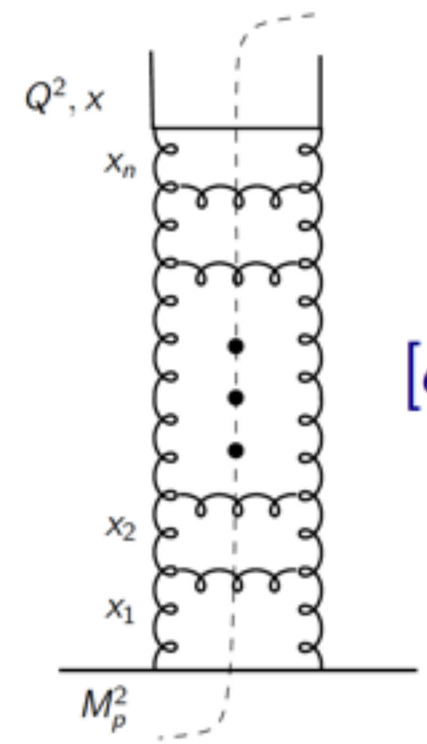
Evolution equations ⇒ gluon ladder diagrams (at cross section level)



$$[\alpha_S(Q^2)\ln(\frac{Q^2}{Q_0^2})]^n$$

$$Q^2 \simeq p^2_{T1} \gg p^2_{T2} \gg p^2_{T3} \gg \ldots$$

strong ordering



$$[\alpha_S(Q^2)\ln(\frac{1}{x})]^n$$

$$x_1 \gg x_2 \gg x_3 \gg \ldots \gg x$$

strong ordering

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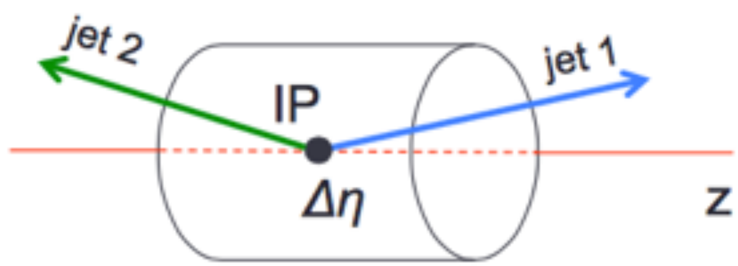
BFKL: applicability window

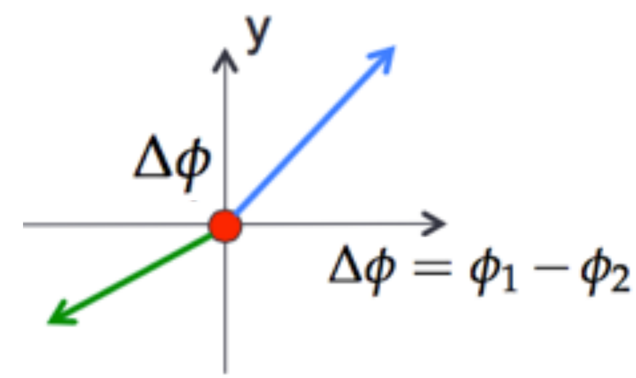
- We know the fantastic success of DGLAP

To demonstrate the need of BFKL evolution at low x, several observables are studied which enhance BFKL w.r.t. DGLAP

- enhance BFKL $\Rightarrow$ separated objects (jet, particle) by a large rapidity
- supress DGLAP $\Rightarrow$ similar P_T objects

Mueller-Navelet jets





$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}}) \cos(n(\pi - \Delta\phi))\right]$$

where Fourier coefficients correspond to average cosines of decorrelation :

$$C_n(\Delta y, p_{\mathrm{Tmin}}) = \langle \cos(n(\pi - \Delta\phi)) \rangle$$

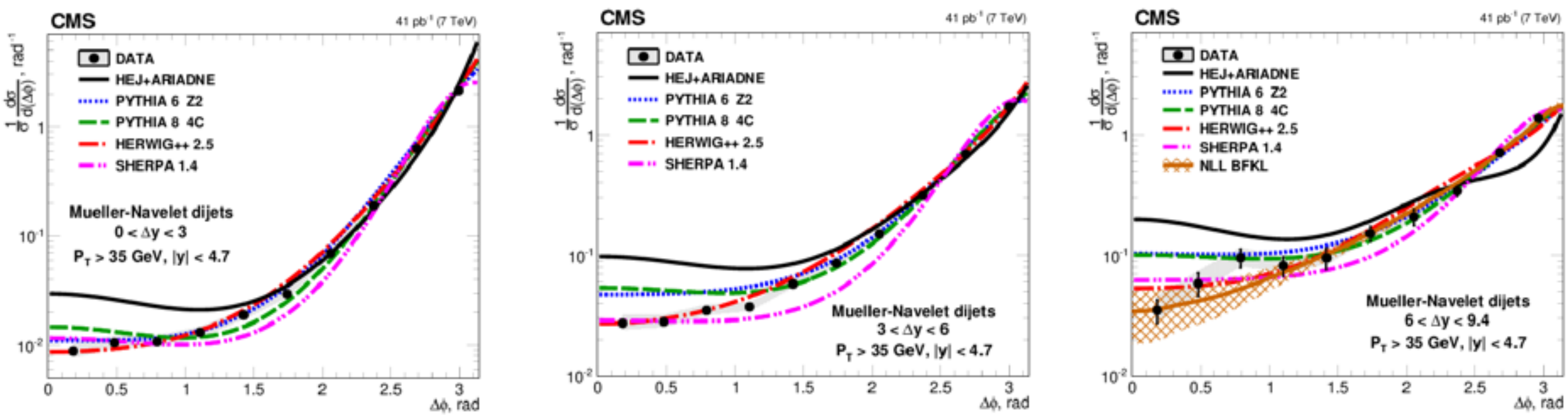
- for back-to-back jets: <cos> = 1
- BFKL dynamics enhance cross section at low <cos>

BFKL: applicability window

talk WG2 Wed PM:
Gabor Veres

Mueller-Navelet jets: CMS measurement at 7 TeV [arXiv:1601.06713]

$\Delta y < 3$ $\quad$ $3 < \Delta y < 6$ $\quad$ $6 < \Delta y < 9.4$

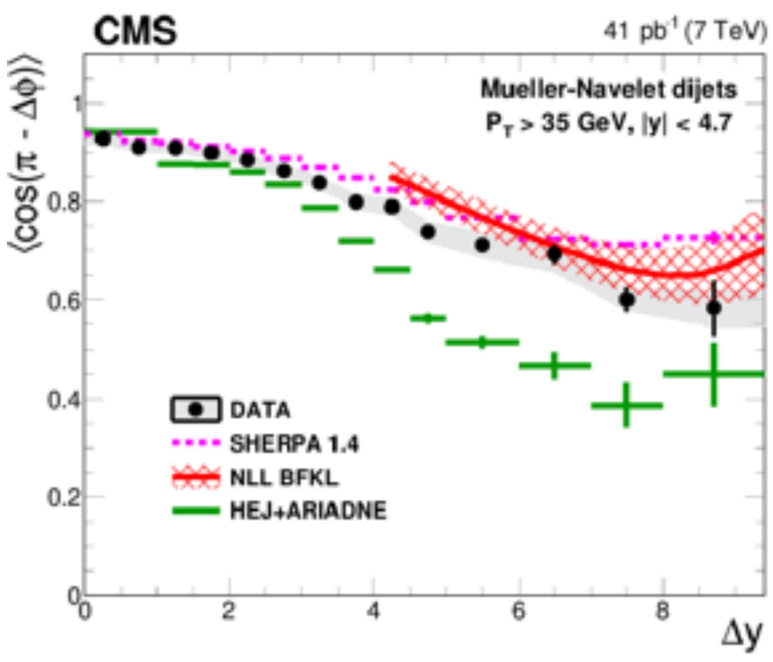


- the decorrelation increases with the rapidity interval
- DGLAP models (HERWIG, PYTHIA, SHERPA) give reasonable description
- BFKL inspired MC (HEJ) overestimates the decorrelation
- NLL BFKL (*) prediction describes well the data at large rapidity interval

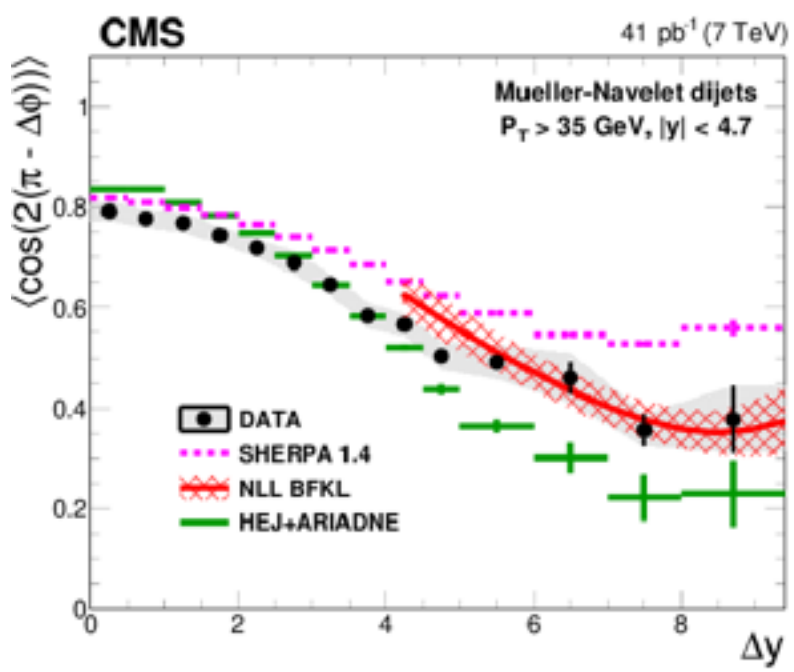
(*) B. Ducloué, S.Szymanowski and S. Wallon (2013)

BFKL: applicability window

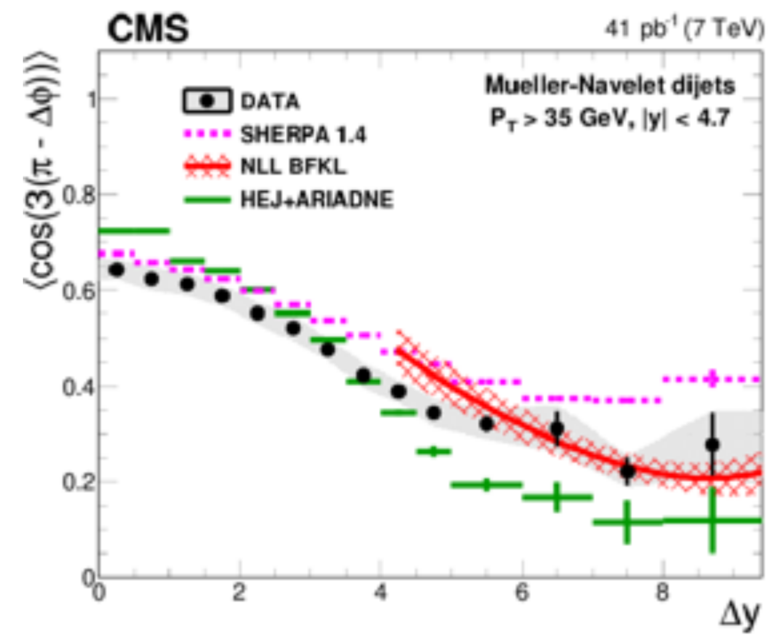
$< \cos(\pi - \Delta\phi) >$



$< \cos 2(\pi - \Delta\phi) >$

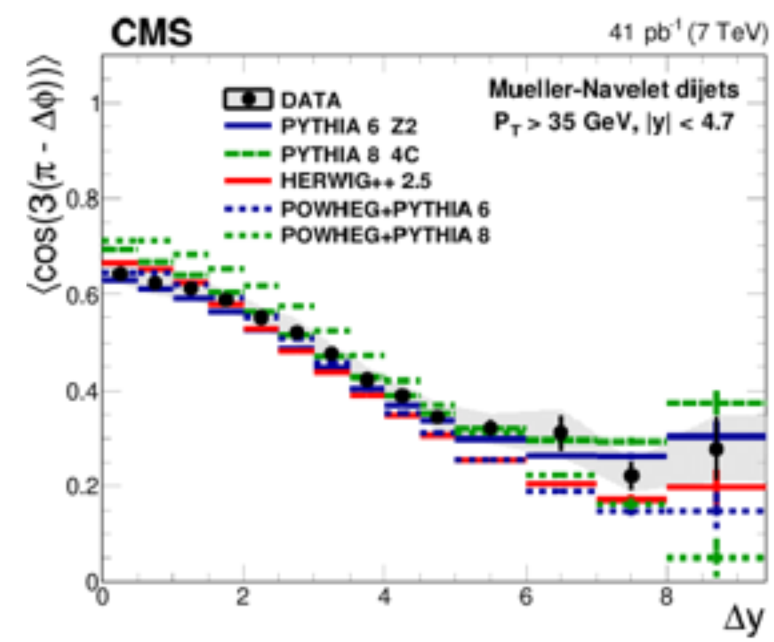


$< \cos 3(\pi - \Delta\phi) >$



DGLAP-based approach HERWIG satisfactory in general
- including NLO ME does not improve the description
- including MPI does not neither

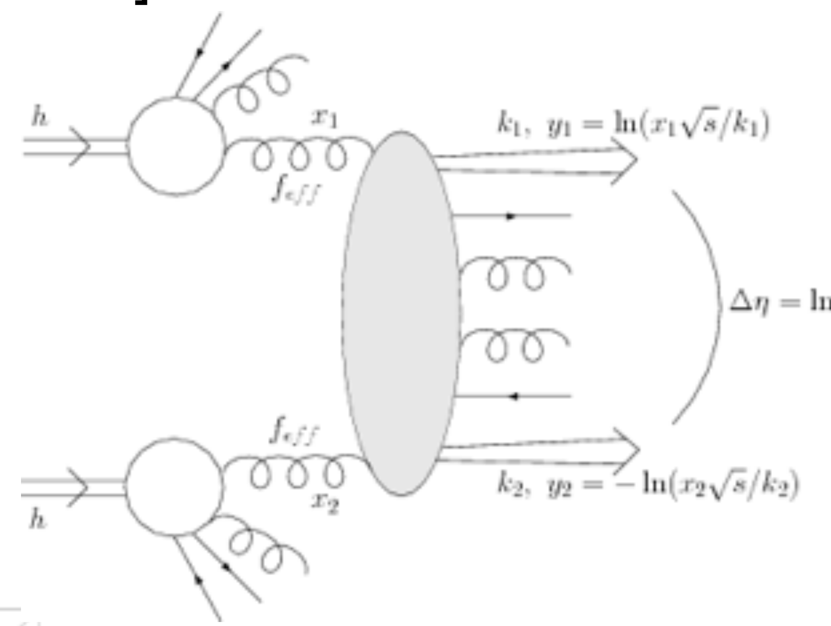
NLL BFKL prediction describes well the data at large rapidity interval of the Fourier coefficients 2 and 3.

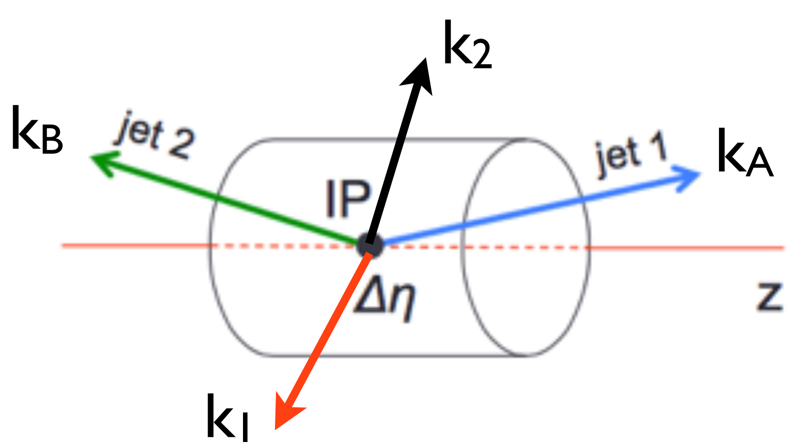


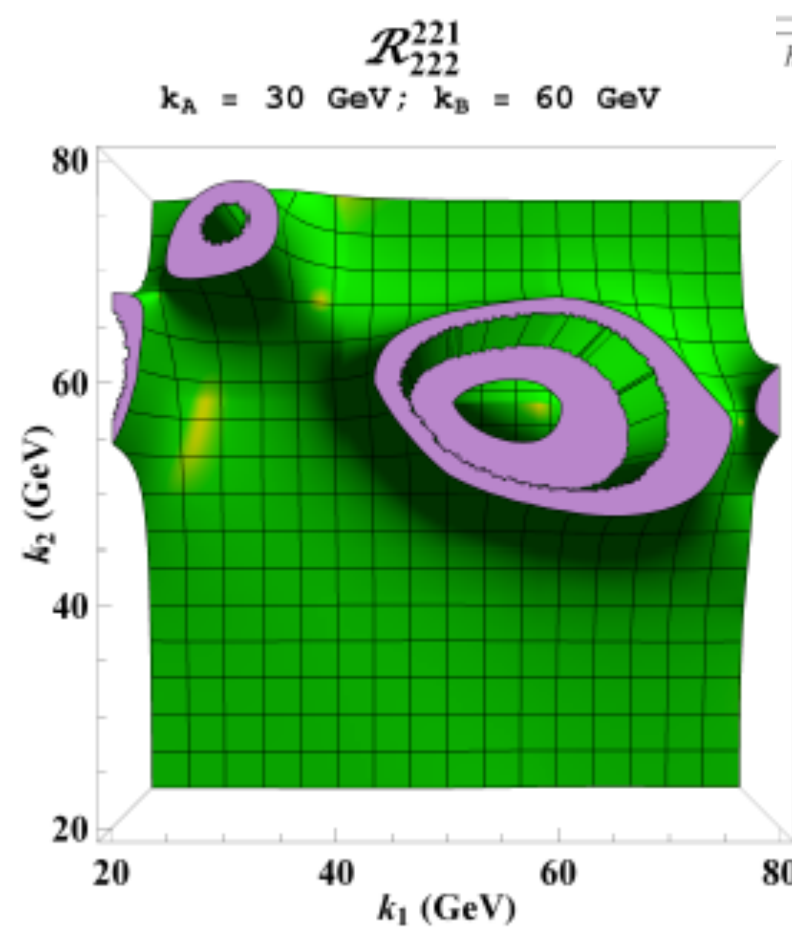
BFKL: applicability window

related theory talks
WG5 Tue PM

- Mueller-Navelet jets the LHC [2 talks: F. Celiberto & G.Chachamis]
- J/Ψ and one jet [R.Boussarie]
- BFKLex: MC in multi-Regge* limit [G.Chachamis]
- 4 jets - LHC 2fwd/bwd + 2 central [F. Celiberto]







dependences on the transverse momenta and rapidity of the two central jets can be a distinct signal of the onset of BFKL dynamics

(*) multi-Regge limit: keeping only LL in BFKL ⇒ strong ordering in rapidity

Low-x related experimental results

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WG5 related
exp. talks

Thu AM

- ATLAS: tot, el. and inelastic cross sections 7 & 13 TeV [M. Trzebinski]
- ATLAS: very low pt charged particle distribution [W. Lukas]
- CMS inelastic cross section at 13 TeV [H. Van Haevermaet]
- CMS: very fwd energy distr. and jets [A. Van Spilbeek]
- CMS: fwd energy density [I. Katkov]
- CMS: charged part. distrib. for ND, SD, DD at 13 TeV [B. Roland]
- TOTEM-CMS: combined results [S. Sen]

Gluon saturation

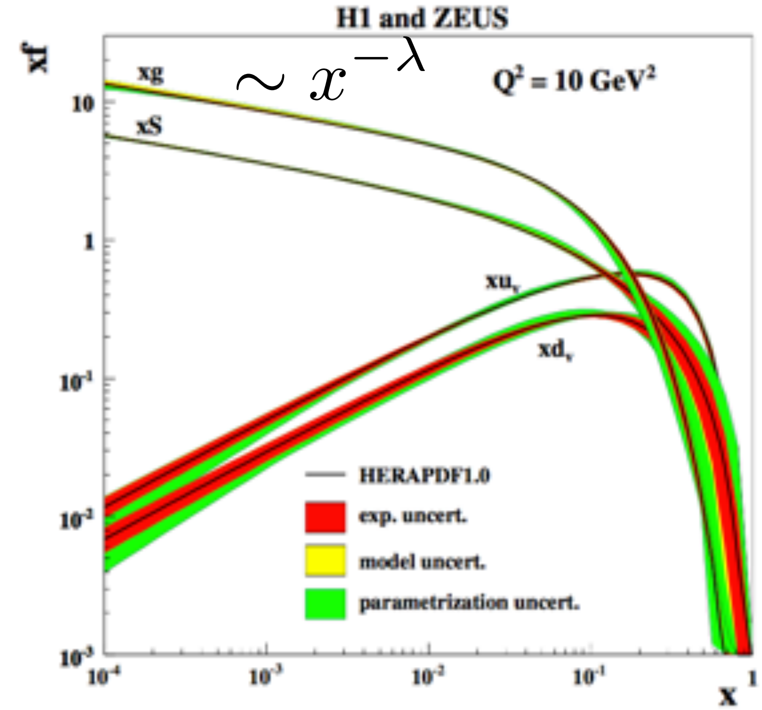
- What happens at even lower x?
- Evolution with Q^2 or x: cascade of gluons
- At some point the density of gluon is so large

  ⇒ recombine ⇒ saturate

  ⇒ nonlinear interactions

⇒ BK (Balitsky-Kovchegov) equation

& JIMWLK evol. of multiparton correlators

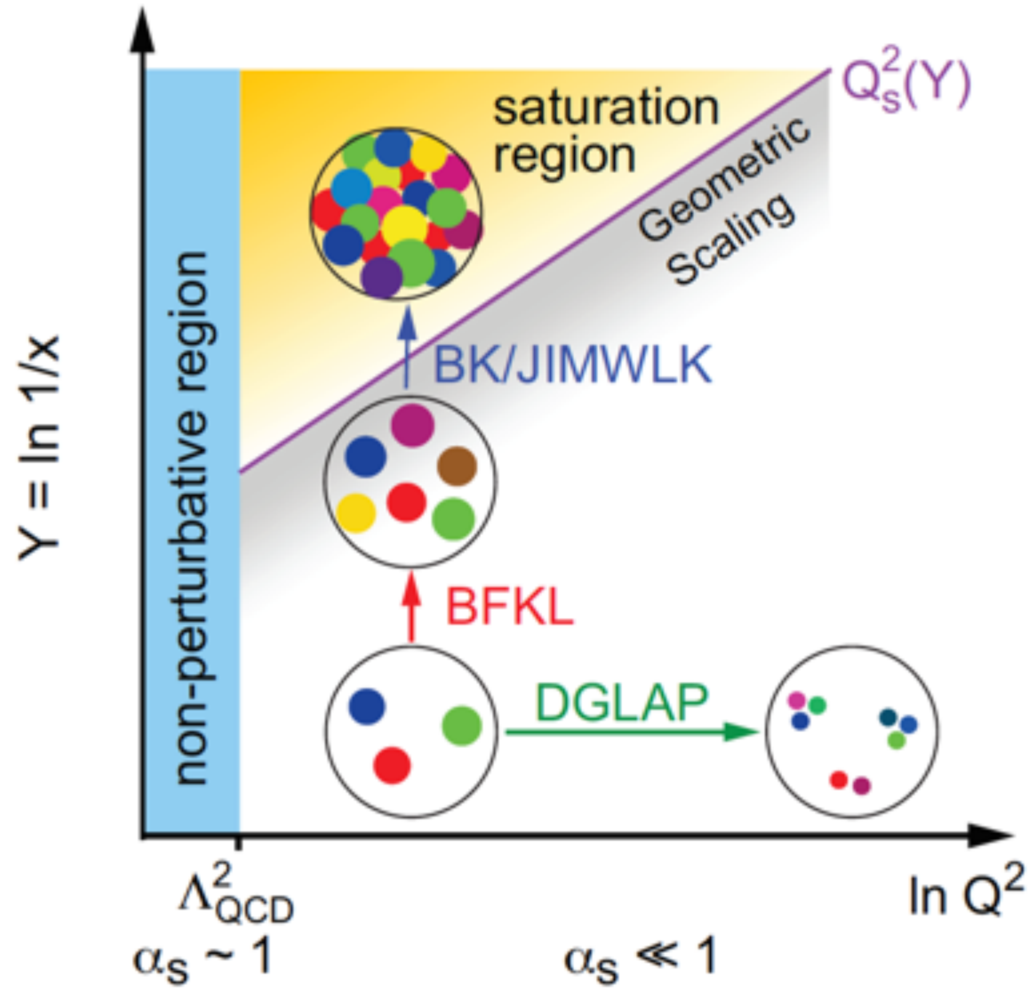


- When saturation? Depends on:

  → size of the gluon ~ $1/Q^2$

$$\frac{\text{density}}{\text{unit transverse area}} \sim 1 \quad \Rightarrow \quad \frac{xg(x,Q_s^2)}{Q_s^2} \sim 1$$

$$\Rightarrow \quad Q_s^2 \sim Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$$



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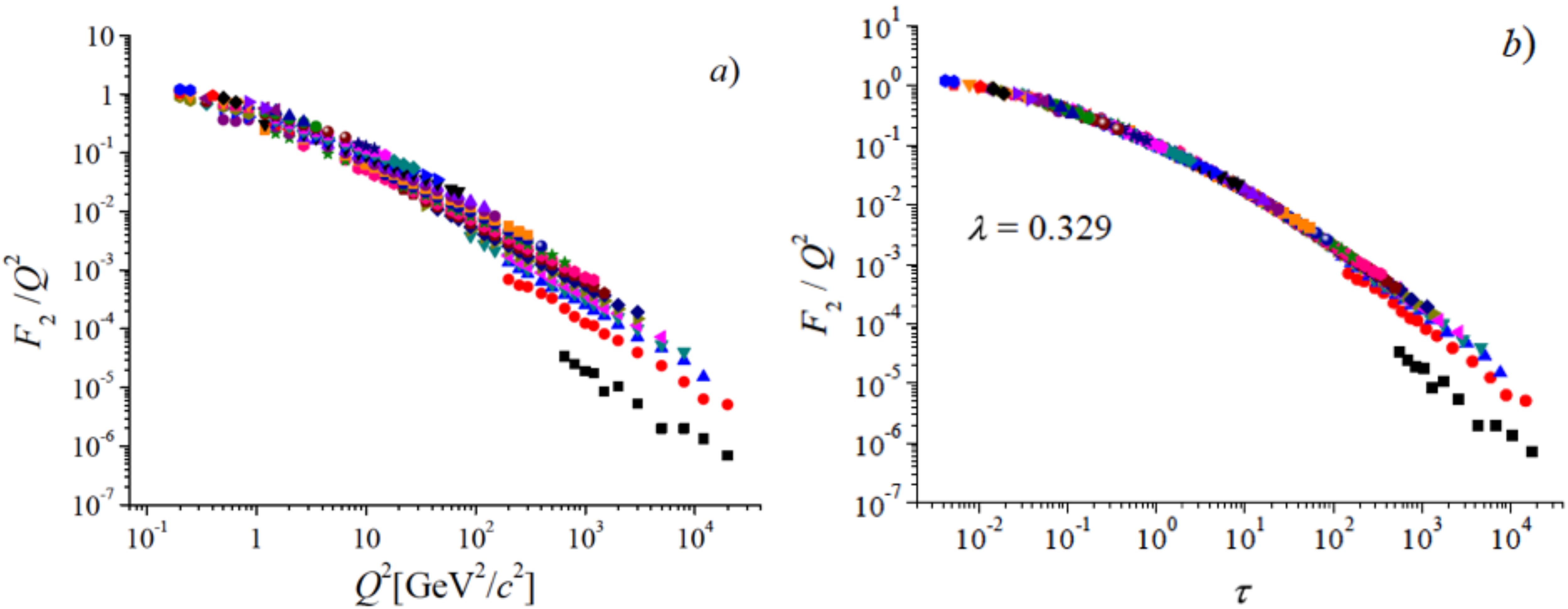
Geometric Scaling



Praszalowicz, Stebel [arXiv:1211.5305]

The cross section depend only on one variable: τ

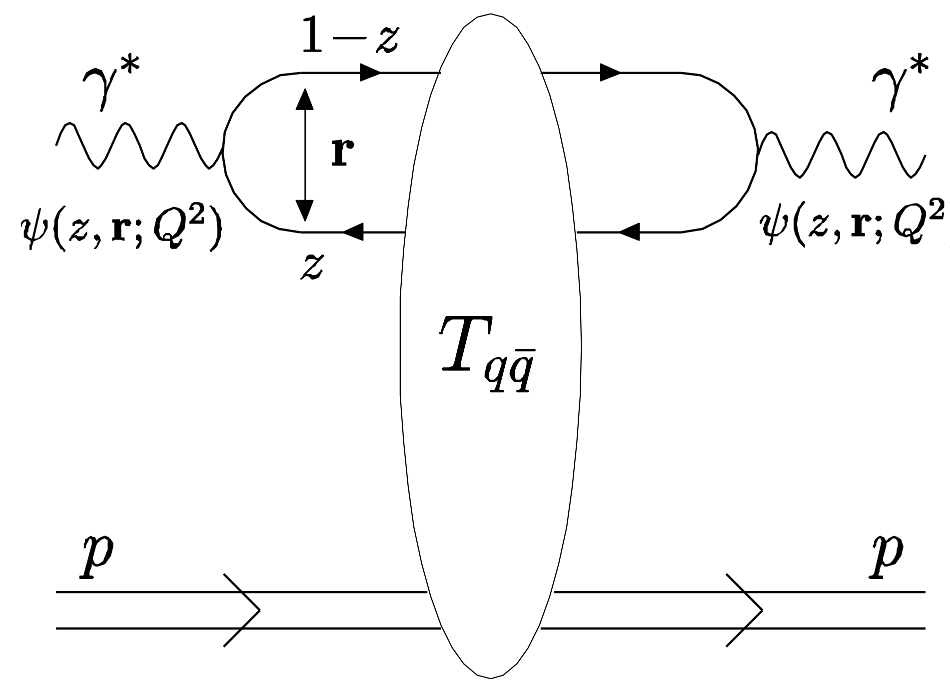
up to x= 0.08 !

$$\tau = \frac{Q^2}{Q^2_{\rm sat}(x)} \quad Q^2_{\rm sat}(x) = Q^2_0 \left(\frac{x}{x_0}\right)^{-\lambda} \quad \lambda = 0.29$$

Easier to be understood in the dipole approach

Colour dipole approach

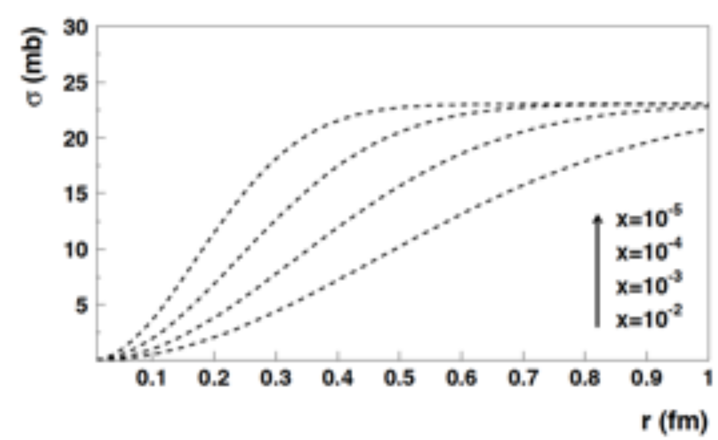
- In the proton rest frame
- The virtual photon fluctuates in a qq pair interacting with the proton
- dipole size r~1/Q
- Dipole cross section σ_{qq} is related to gluon distribution



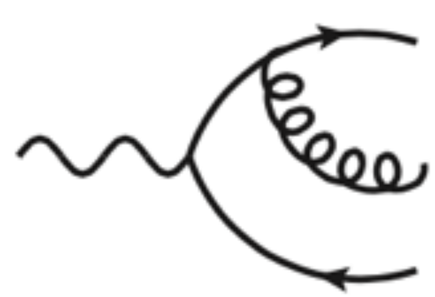
$$\sigma_{T,L}(x,Q^2) = \int \mathrm{d}^2 r \int_0^1 \mathrm{d}z |\Psi_{T,L}(r,z,Q^2)|^2 \sigma_{q\bar{q}}(x,r)$$

- Several models include a saturating dipole cross section

$$\sigma_{q\bar{q}}(x,r) = \sigma_0(1 - e^{-r^2 Q_s^2(x)})$$



- explain nicely the geometrical scaling
- reproduces well measured σ_{diff} / σ_{inc}
- NLO: perturbative expansion of photon wave function (qqg)

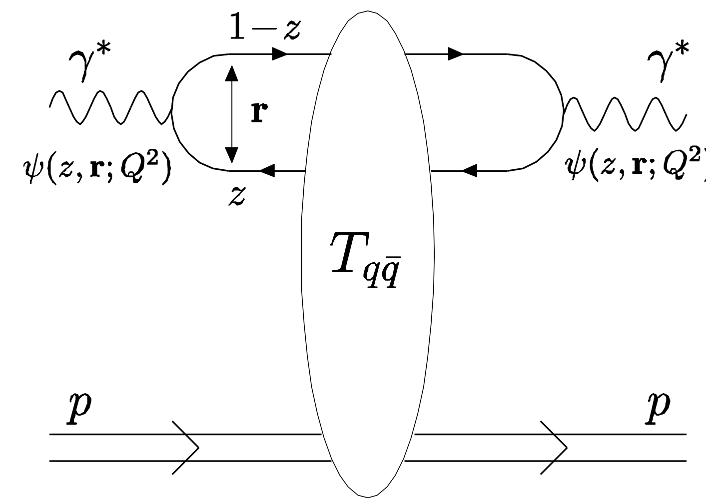


related theory talks

	WG5 related theory talks
• NLO Balitsky-Kovchegov equation with resummation [H. Mäntysaari]	Tue AM
• Forward J/Ψ production at LHC to probe gluon saturation [B. Ducloué]	Wed AM
• Single inclusive forward hadron production at NLO [B. Ducloué]	Thu AM
• Forward Drell-Yan at LHC in kt-factorization: saturation? [A. Szczurek]	Thu AM

Colour dipole approach

$$\sigma^{\rm DIS}(x,Q^2) = \int {\rm d}^2 r \int_0^1 {\rm d}z |\Psi(r,z,Q^2)|^2 \sigma_{q\bar q}(x,r)$$

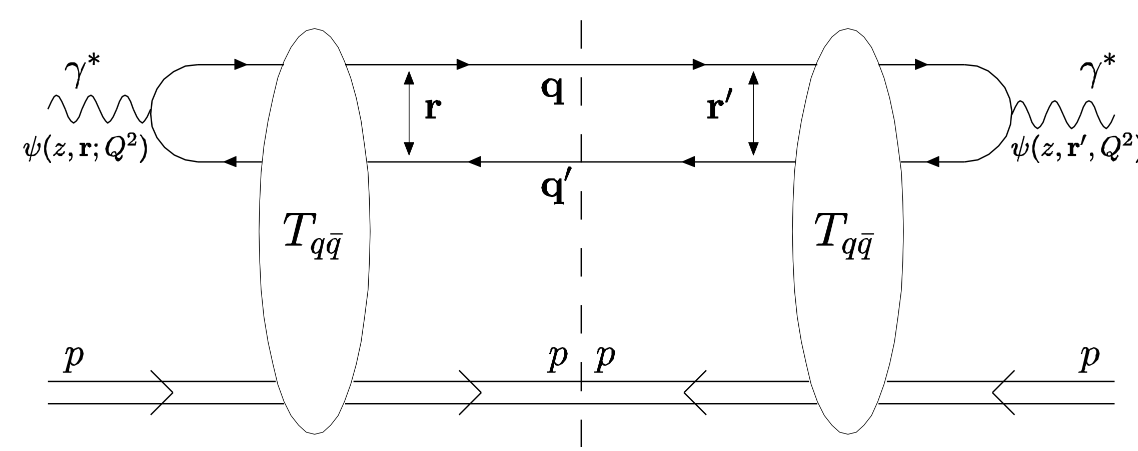


- using the optical theorem:

$$\sigma^{q\bar q + p \to X} \sim \mathcal{I}m\, A^{q\bar q + p \to q\bar q + p}|_{t=0}$$

- we obtain the diffractive cross section in DIS regime

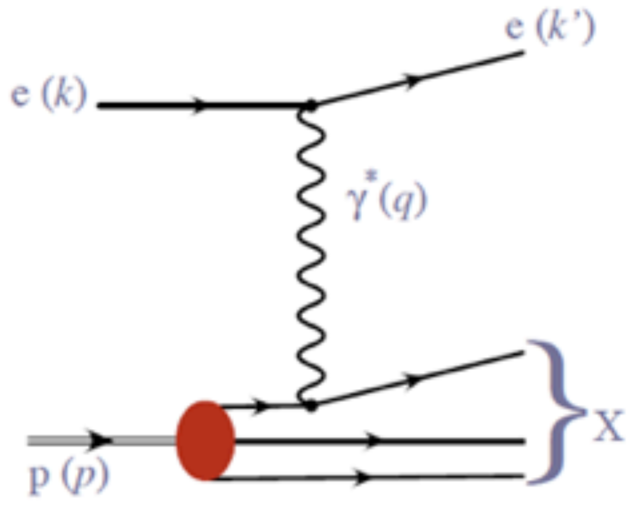
$$\frac{{\rm d}\sigma^{\rm DDIS}(x,Q^2)}{{\rm d}t}|_{t=0} = \frac{1}{16\pi} \int {\rm d}^2 r \int_0^1 {\rm d}z |\Psi(r,z,Q^2)|^2 \sigma^2_{q\bar q}(x,r)$$

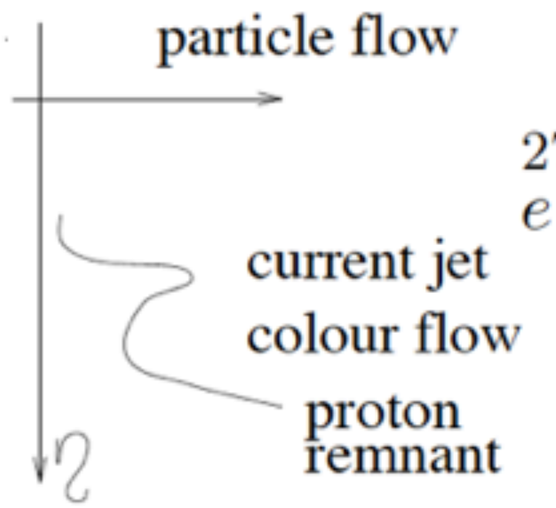


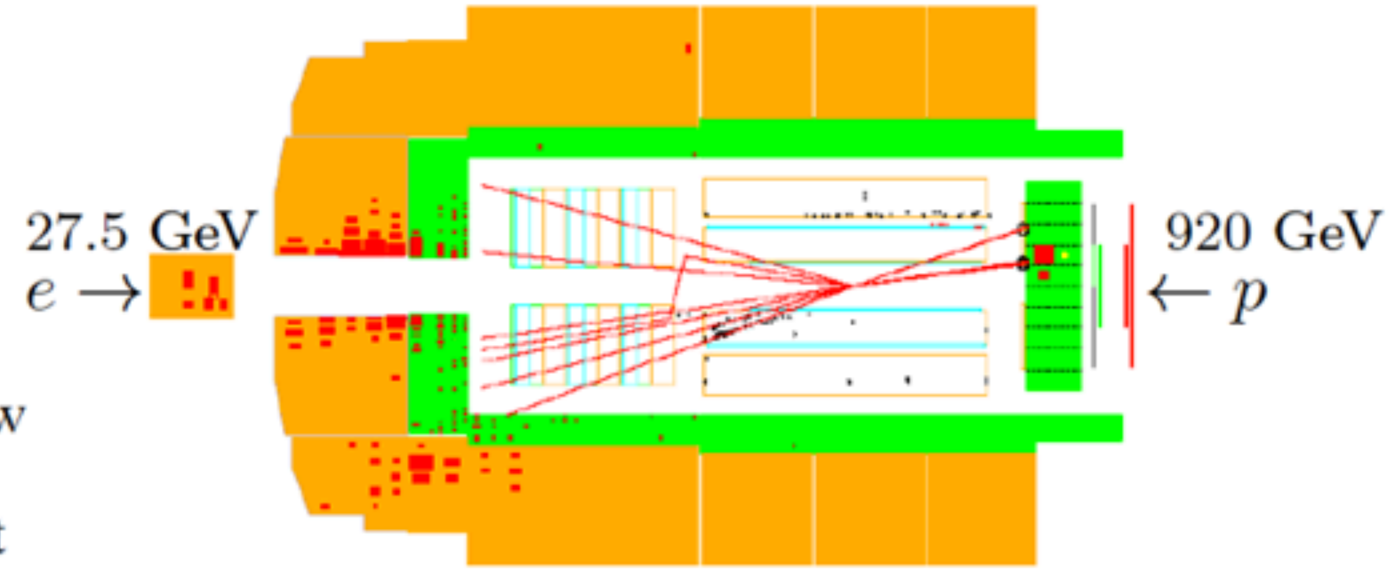
What is diffraction?

DIS and DDIS

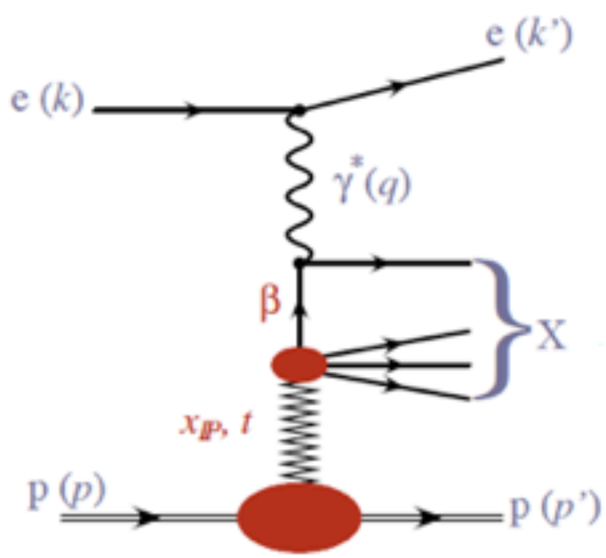
Deep Inelastic Scattering (DIS)

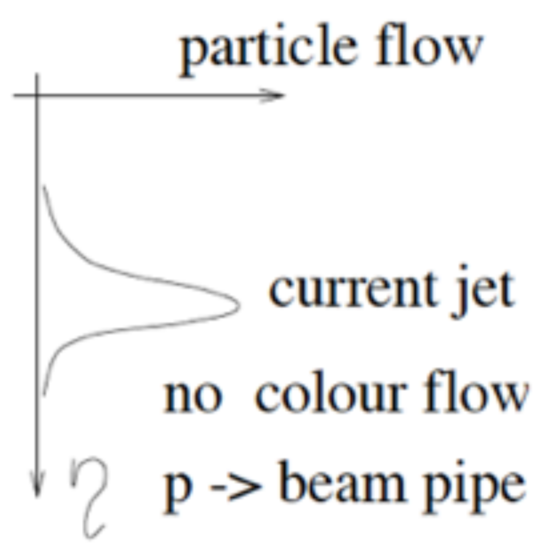


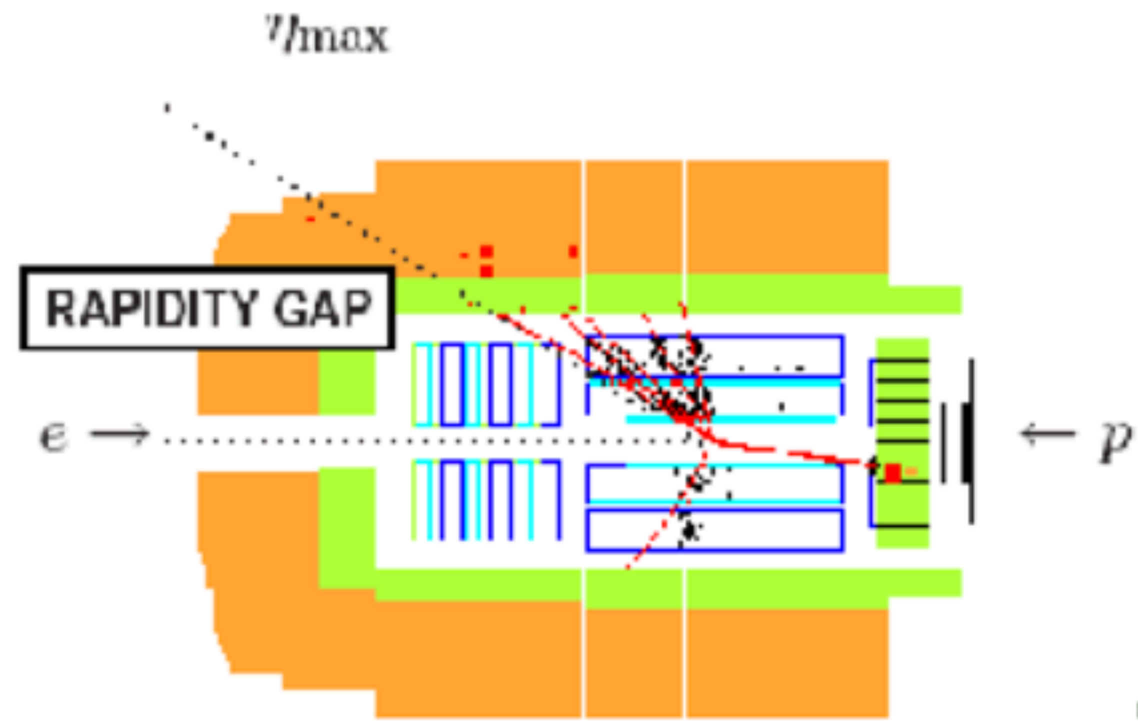




Diffractive Scattering (DDIS)







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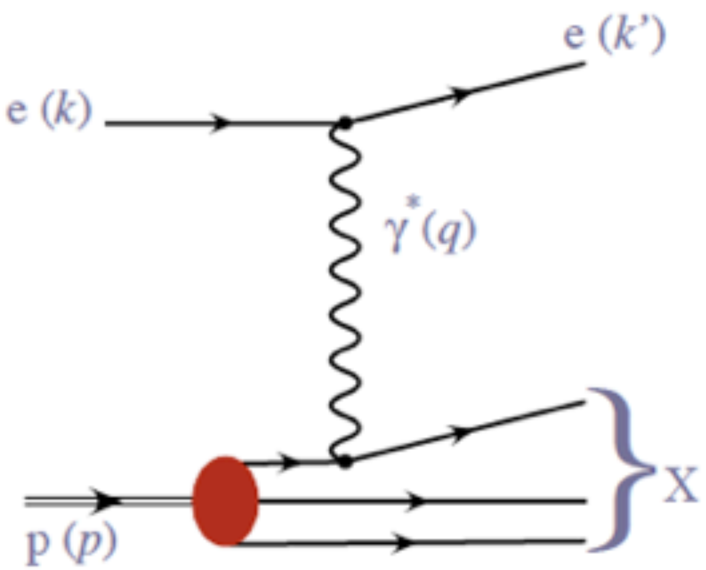
DIS and DDIS



Deep Inelastic Scattering $ep \to eX$

Q^2 $= -q^2$ - virtuality of the exchanged photon

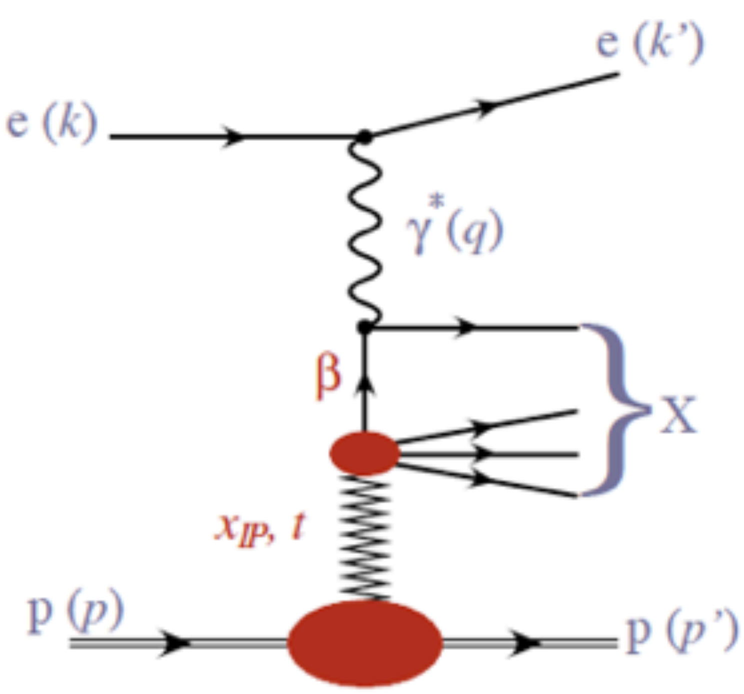
W $\gamma^* - p$ system energy

x Bjorken-x: fraction of proton's momentum carried by the struck quark

y γ^* inelasticity : $y = Q^2/s\,x$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\,\pi\,\alpha^2}{x\,Q^4} Y_+ F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

$Y_+ = 1 + (1-y)^2$



Diffractive Scattering $ep \to eXp$

$x_{I\!P}$ fraction of proton's momentum of the colour singlet exchange

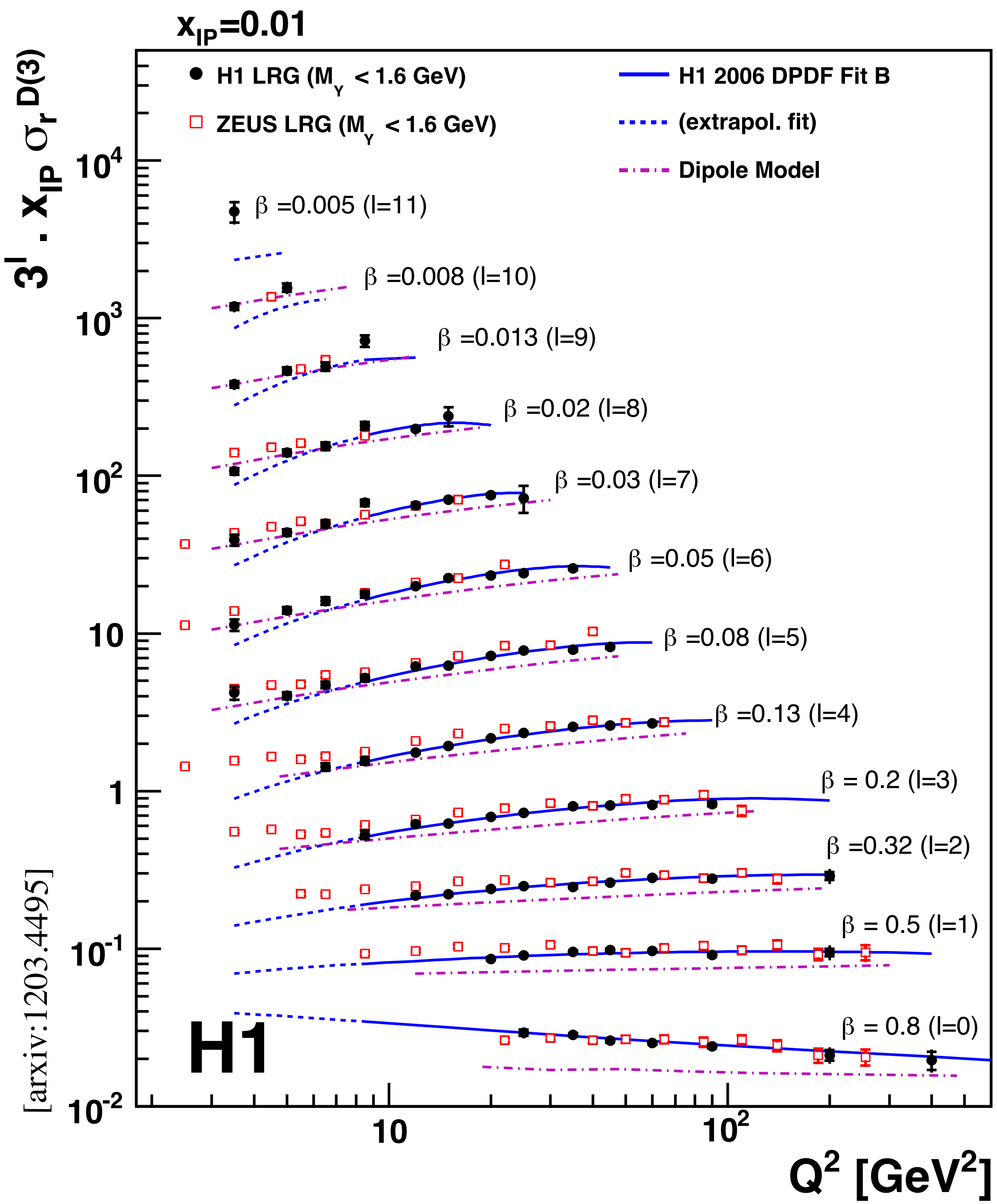
$$x_{I\!P} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

β fraction of $I\!P$ carried by the quark "seen" by the γ^* $\beta = x/x_{I\!P}$

t $= (p - p')^2$, 4-momentum squared at the p vertex

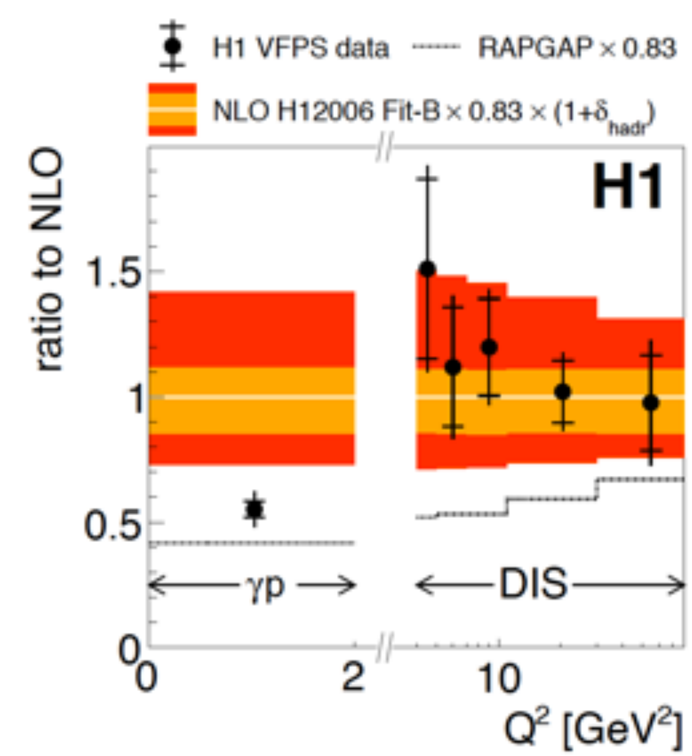
$$\frac{d^4\sigma^D}{d\beta\; dQ^2\; dx_{I\!P} dt} = \frac{2\pi\alpha^2}{\beta Q^4}\; Y_+ F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t) - \frac{y^2}{Y_+} F_L^{D(4)}$$

Diffractive PDF



pert. QCD predict. in DDIS

- Fact. theorem for γ*p int. at large Q^2
- DGLAP from Diff. SF ⇒ DPDF
- largely dominated by gluon
- use DPDF ⇒ e.g. dijet predictions



- OK in DIS but not at Q^2 =0 !
- D* at HERA [K. Cerny]

WG5 talk
Wed PM

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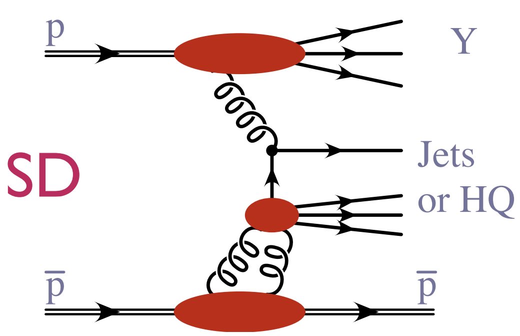
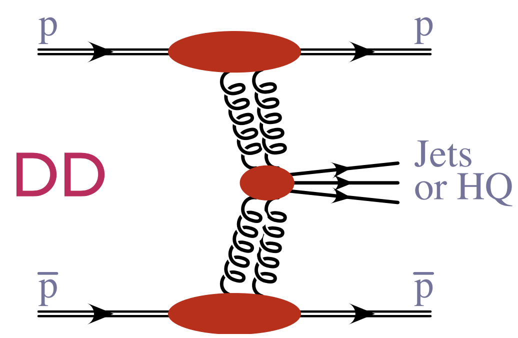
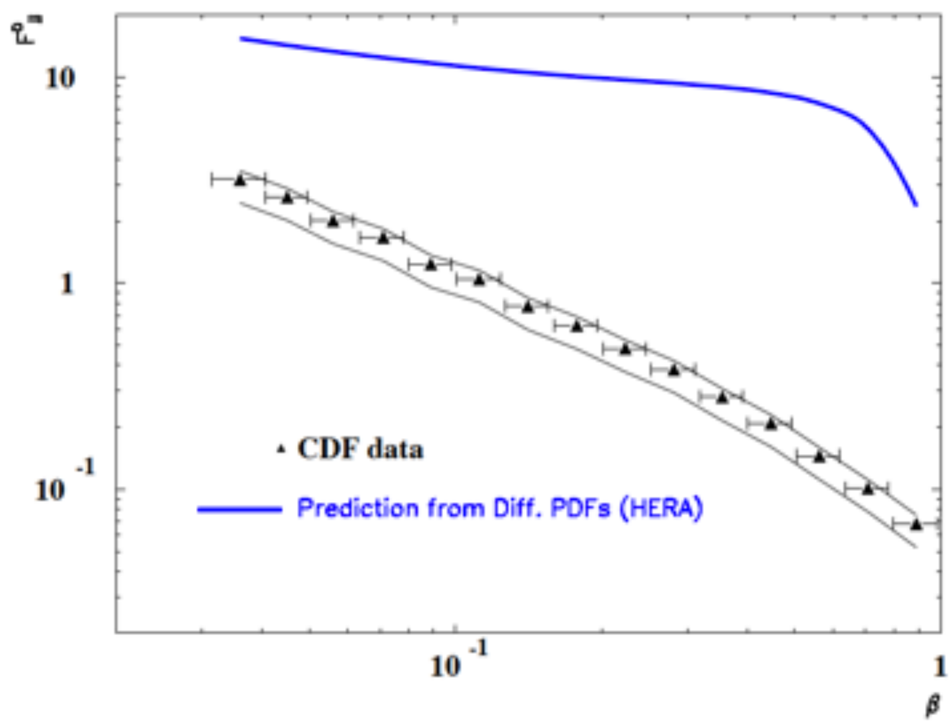
Export DPDF to p-p ?





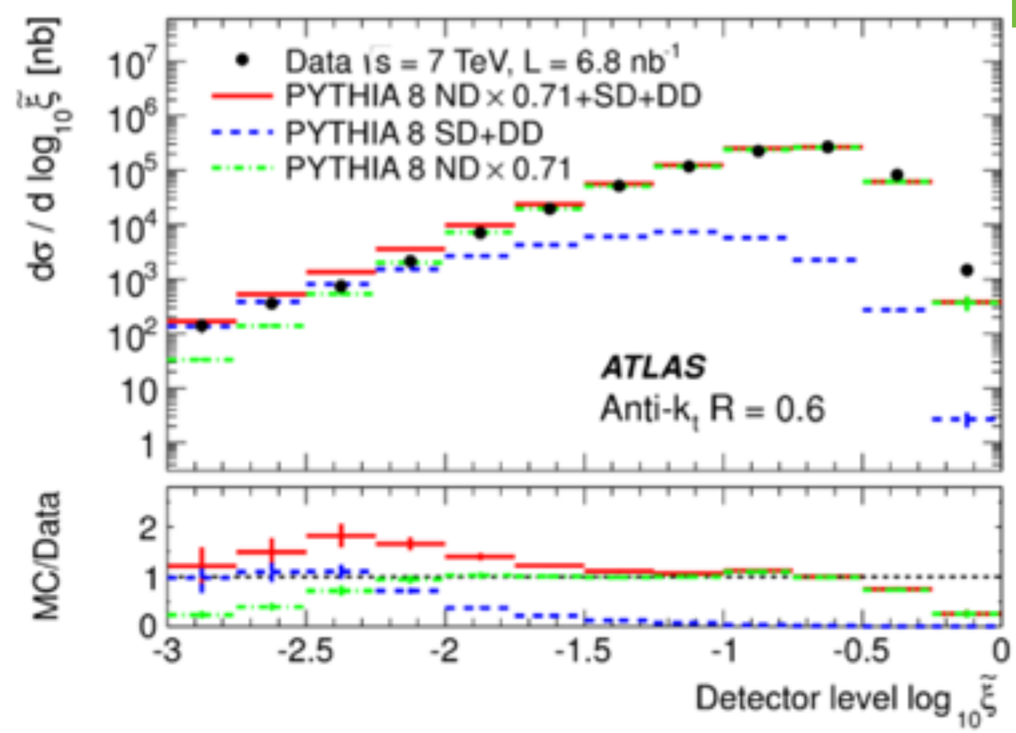
- DPDF ⇒ do **not lead to correct** predictions in p-p
- because of (soft) interactions between spectator partons of beam particles
- filling the rap. gap
- need phenom. models to quantify them (gap survival prob.)



factorisation is broken in pp !

SD and DD at LHC [Trzebinski]

WG5 talk
Thu AM



[arXiv:1511.00502]

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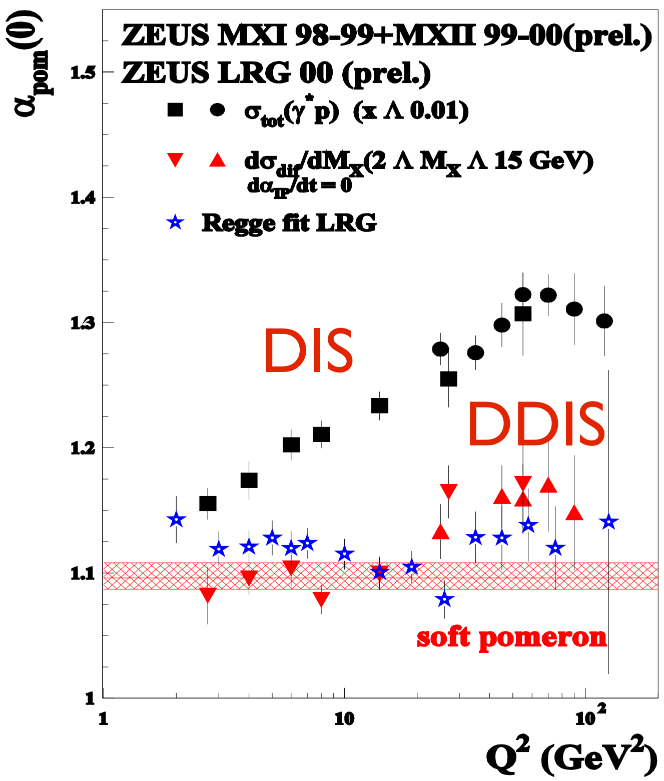
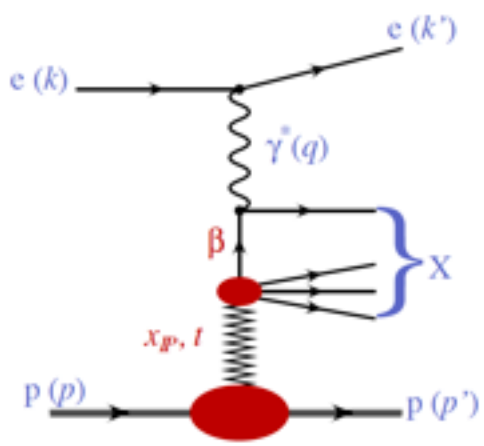
Perturbative Pomeron ?



- partons from IP can be treated in perturb.

way to predicted dijet cross section in γ*p int. at large Q^2

- amazingly the Pomeron stays non-pert. even at high Q^2 !
- No rise typical of gluon density evolution
- hard scale is diluted before reaching the IP or in the IP
- Will LHC data see a start of pert. evolution ?

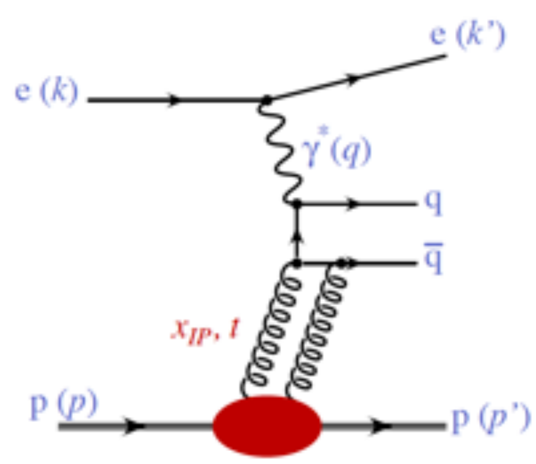


$\beta \simeq Q^2/(Q^2 + M_X^2)$

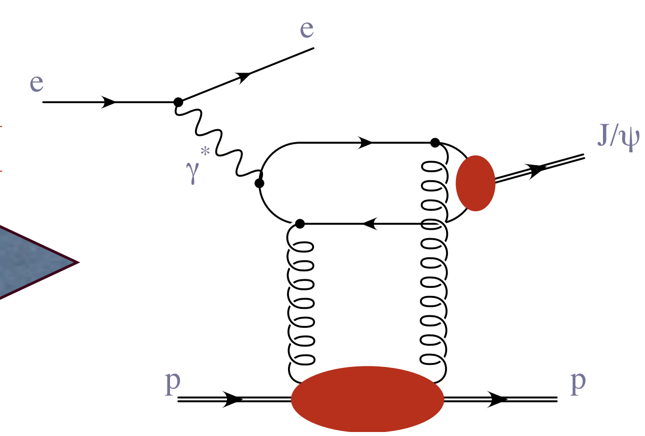
For $M_X^2 \ll Q^2$

Large β

The photon “sees” the full Pomeron



if qq=VM



$\sigma \sim W^\delta \sim |xg(x, Q^2)^2|$

if in pert. regime only valid at small x

- **Different possible hard scales:** M_X (heavy quarks)
Q^2
-t (not covered here)

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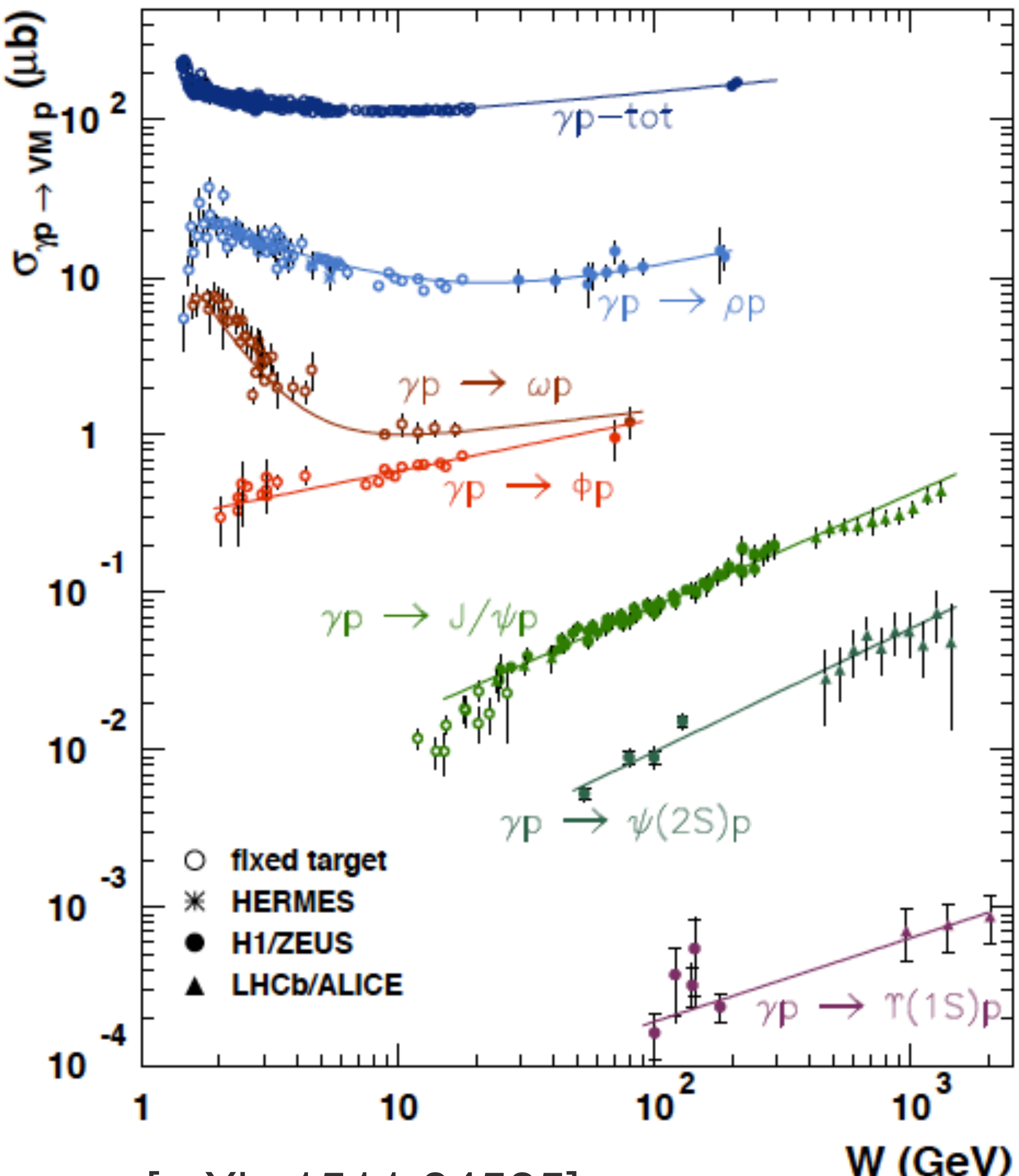
Exclusive VM photoproduction

$Q^2 = 0$



[arXiv:1511.04535]

-recent world data compilation

-transition soft ⇒ hard regime with masses

-Fit $\sigma \sim N_1 W^{\delta_1} + N_2 W^{\delta_2}$

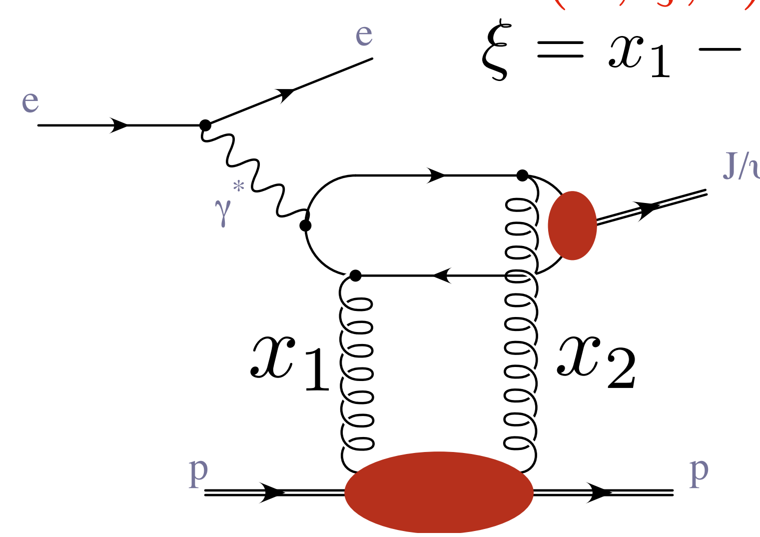
-high W (=low x) rises similarly to $|x\, g(x,Q^2)|^2$

-low W: dipole model not valid

⇒ coll. fact.: Generalized Parton Distr.

GPDs: $H(x,\xi,t),\ E(x,\xi,t)$

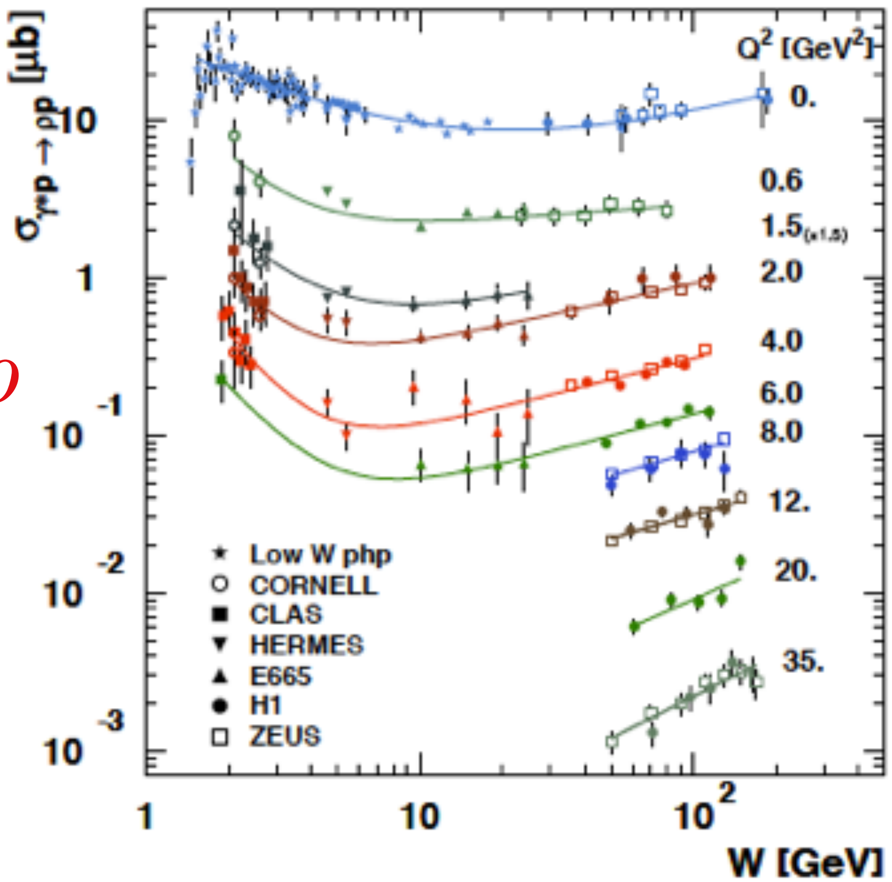
$\xi = x_1 - x_2$



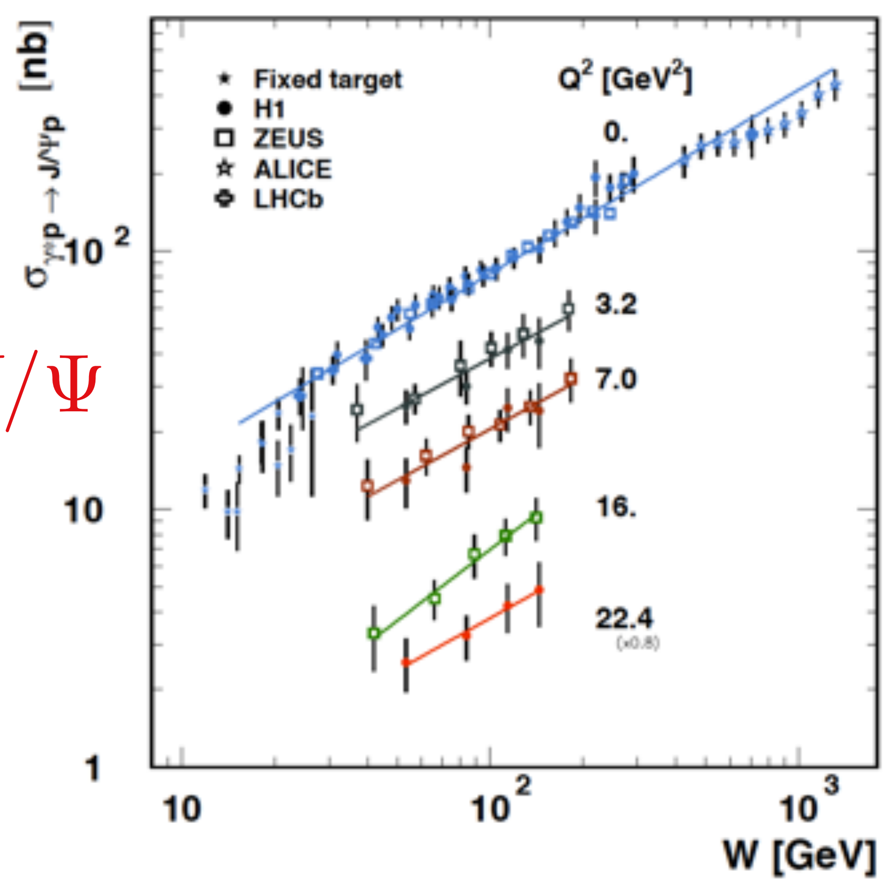
-for heavy VM, skewing effect important: $x_1 \neq x_2$

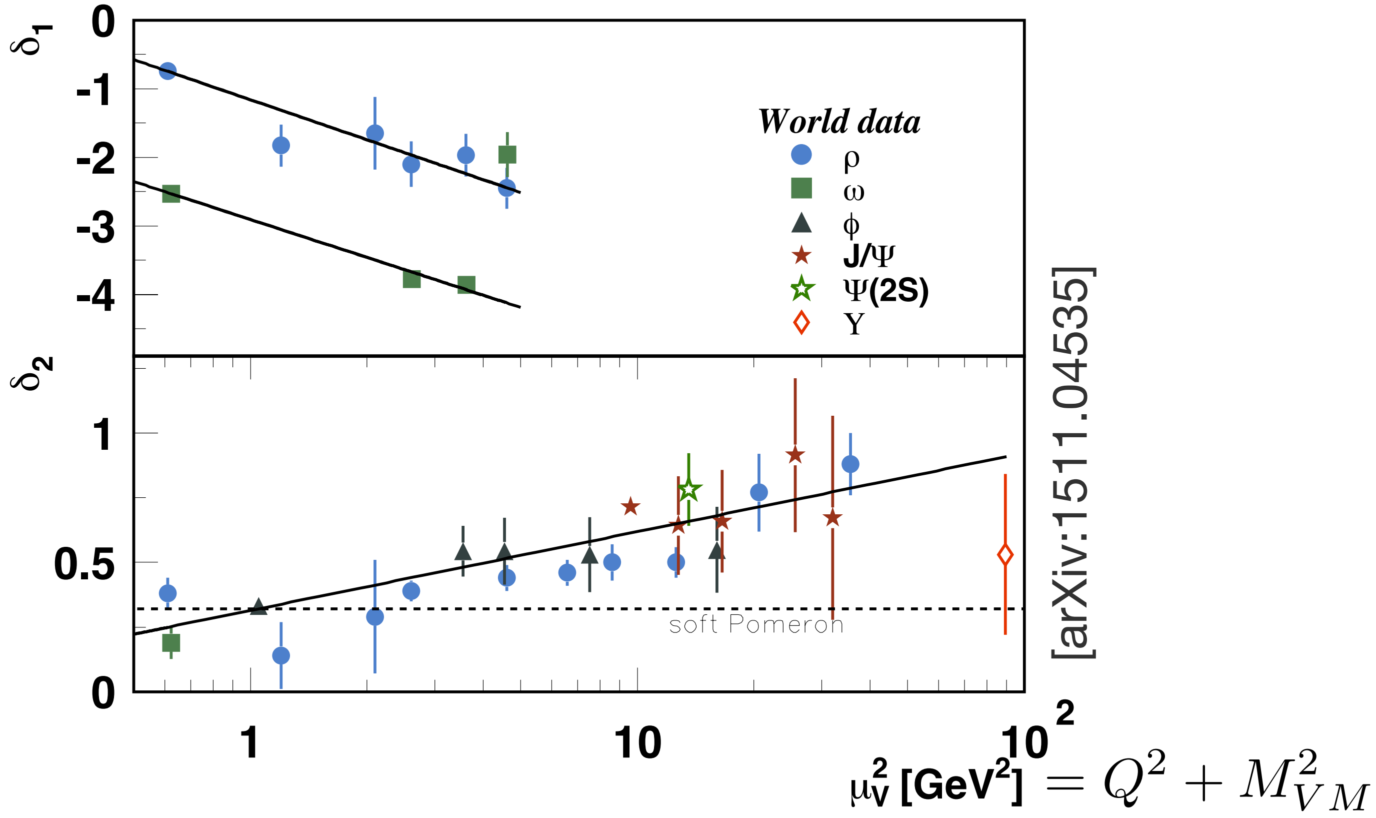
Exclusive VM electroproduction

ρ



J/Ψ





High W:

- slope increases with Q^2+M^2
- universal behaviour vs scale (for all VM)
- dominated by gluons

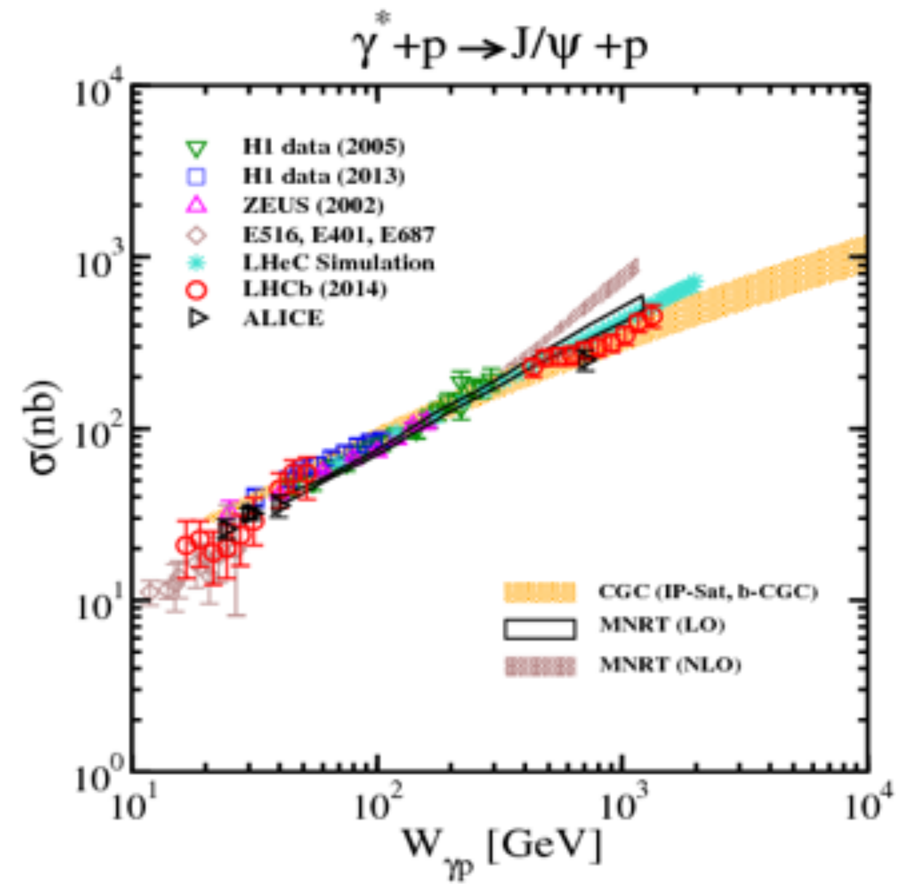
Low W:

- |slope| increases with Q^2+M^2
- different behaviour for ρ and ω
- role of valence quarks

Exclusive VM production

High W:

- access to gluon density
- recent LHC J/Ψ favours models with gluon saturation



[arXiv:1402.4831]

11 WG5 related exp. talks

Tue & Wed

- CMS: ϒ - from p-Pb [R. Chudasama]
- CMS: J/Ψ - from Pb-Pb [D. Takaki]
- CMS: exclusive $\pi^+\pi^-$ [M. Khahzad]
- LHCb: J/Ψ and Ψ' [R. McNulty]
- ALICE: J/Ψ from p-Pb [J. Adam]
- ALICE: J/Ψ from Pb-Pb [K. Graham]
- ALICE: VM from Pb-Pb [G. Contreras]
- STAR: exclusive $\pi^+\pi^-$ from Au [S. Klein]
- STAR: J/Ψ from Au [W. Schmidke]
- ZEUS: Ψ(2S)//Ψ(1S) ratio [N. Kovalchuk]
- H1: ρ leading neutron [S. Levonian]

6 WG5 related theory talks

Tue & Wed

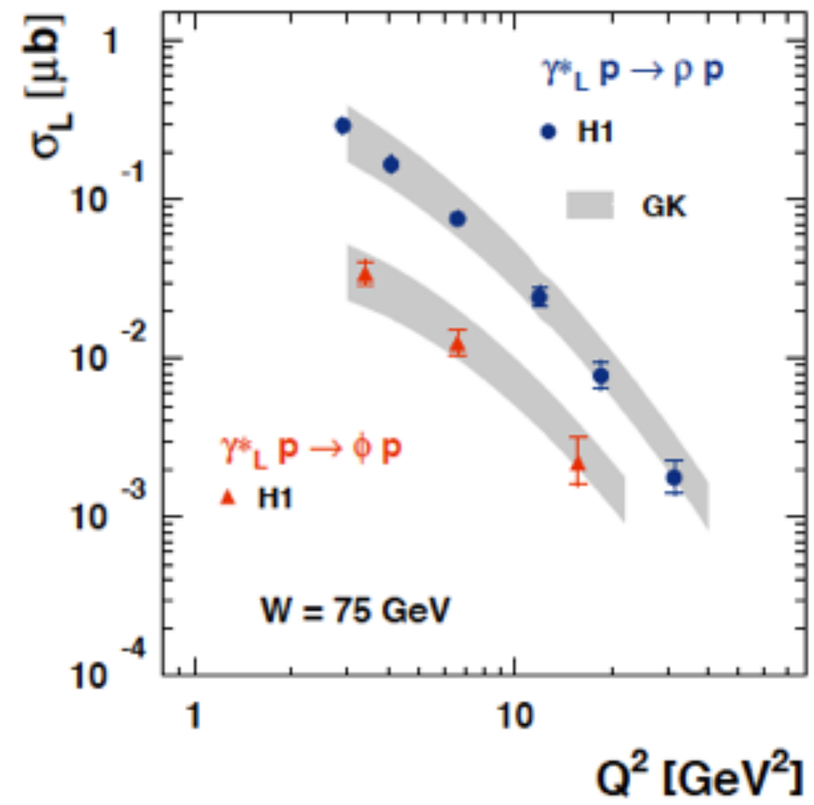
- J/Ψ and ϒ in pQCD kt-fact [W. Schafer]
- CGC: VM provides evidence for strong geometric fluctuations in p [H. Mäntysaari]
- AdS/QCD prediction for φ [M. Ahmadi]
- Sub-femtoscopic with VM [J. Dainton]
- exclusive $\pi^+\pi$ with tensor Pomeron approach [P. Lebiedowicz]
- dipole: VM with leading neutrons and leading p - saturation [V. Goncalves]

Exclusive VM electroproduction-GPDs

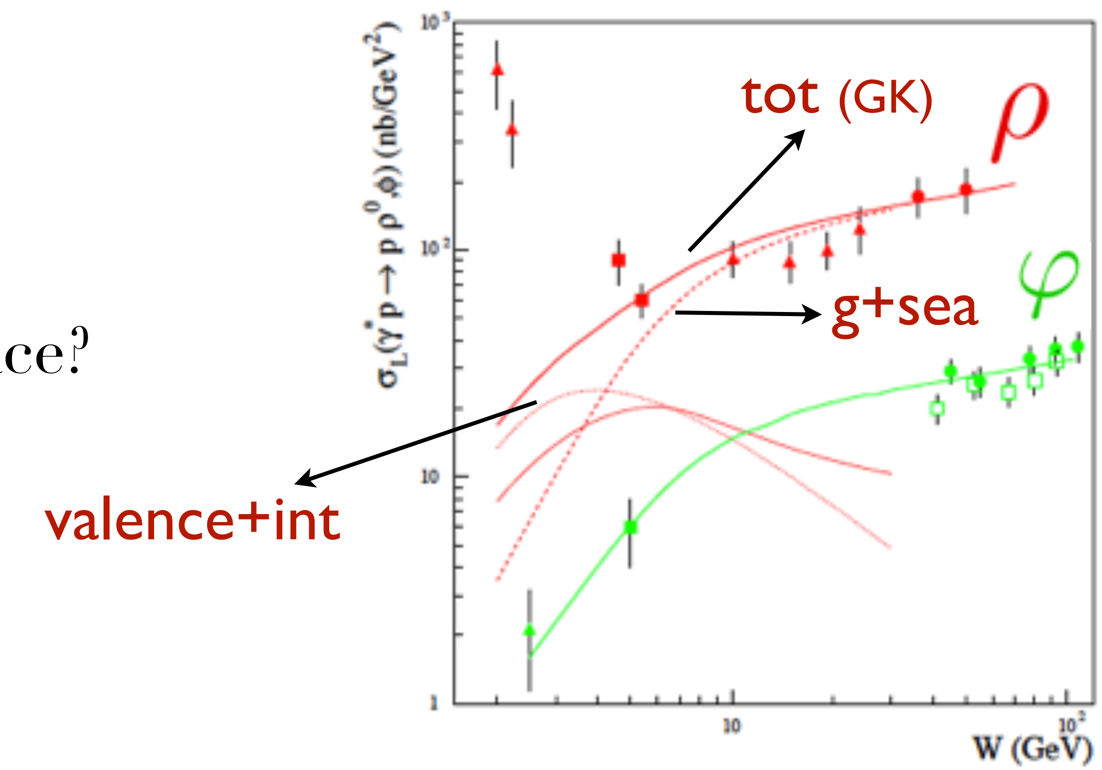
GPD: important approach
- meas. of where the partons are
- their kinematic correlation
- access to orbital ang. momentum

High W:
- also well described by GPDs based prediction
- separately for σ_L et σ_T
- if higher twist part added (at HERA Q^2)

Low W:
- predictions based on GPDs:
  - describes well the ϕ
  - does not reproduce ϱ the at low W
- is there another mechanism taking place?
- while DVCS is well described



[arXiv:1511.04535]



Much more details and results on, VM, DVCS, GPDs,... in Spin session

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Conclusion

- Low-x and diffraction are related by many aspects

- They provide a particularly challenging phenomenology to be described by QCD

- where factorisation between pert. and non-pert. aspects plays a major role

- very active field both in theory and experimentally for many successes and still many open questions

- while waiting for the EIC and LHeC, interesting data from
    - hadron/ion colliders
    - final HERA results
    - soon: CLAS II and COMPASS (DVCS run)

- disclaimer: for all non covered aspects: ions, large t diffraction,...