Diffraction and forward physics at HERA and the LHC

International Workshop on Forward Physics
and Forward Calorimeter Upgrade in ALICE

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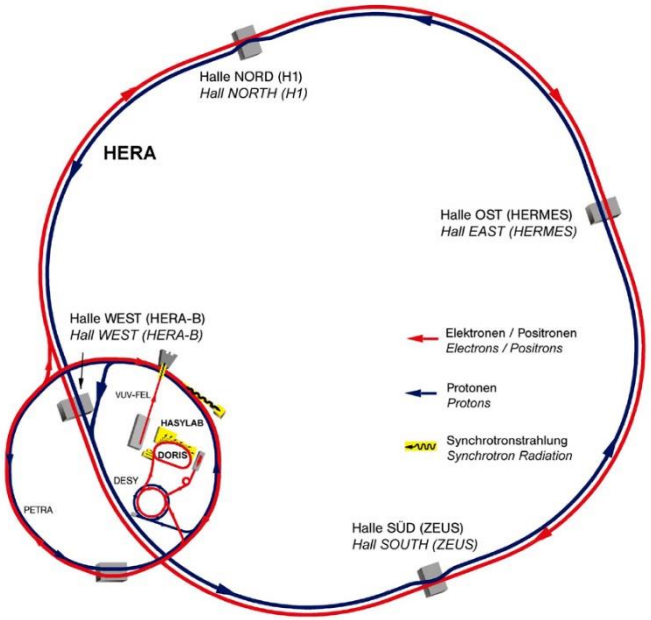
HERA and the LHC

- HERA 1992-2007 ($e^{\pm}p$)
  - CM energy ~ 314 GeV
  - Run1: ~100 pb^{-1}, run2: 400 pb^{-1}
- LHC 2010 – (pp, pA, AA)
  - Run1: 7/8 TeV, 20fb^{-1}
  - Run2: 13 TeV, 150fb^{-1}
  - Run3 from 2021,
    then run4 with High-lumi option (3000 fb^{-1})
- Both equipped with …
  - Good calorimetry coverage $|\eta| \lesssim 5 - 7$
  - Roman pots
  - Forward neutron (and neutral pion by LHCf)



Today's subjects

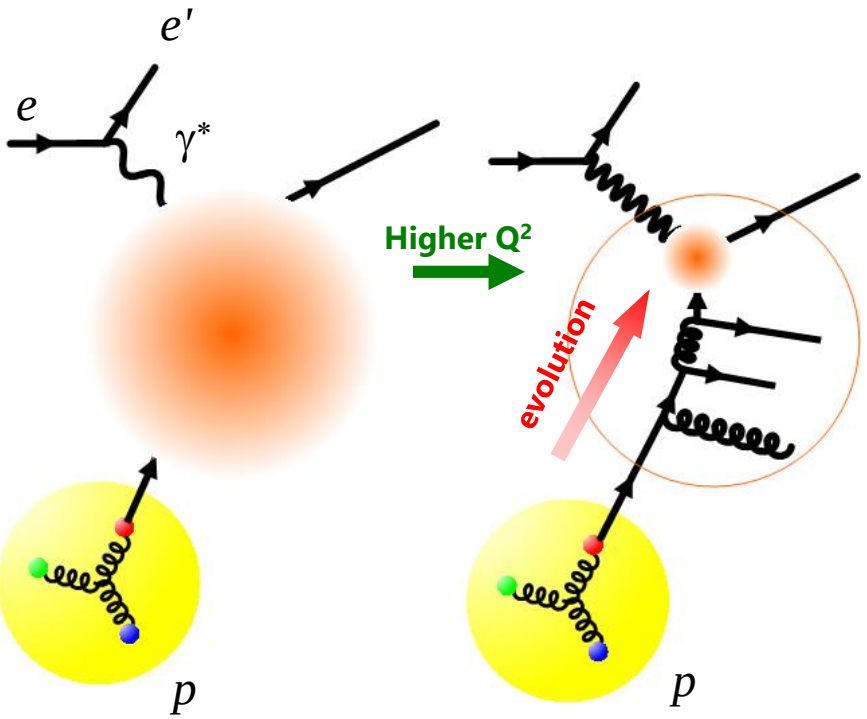
- Introduction: where is soft – hard transition between forward and hard vertex?

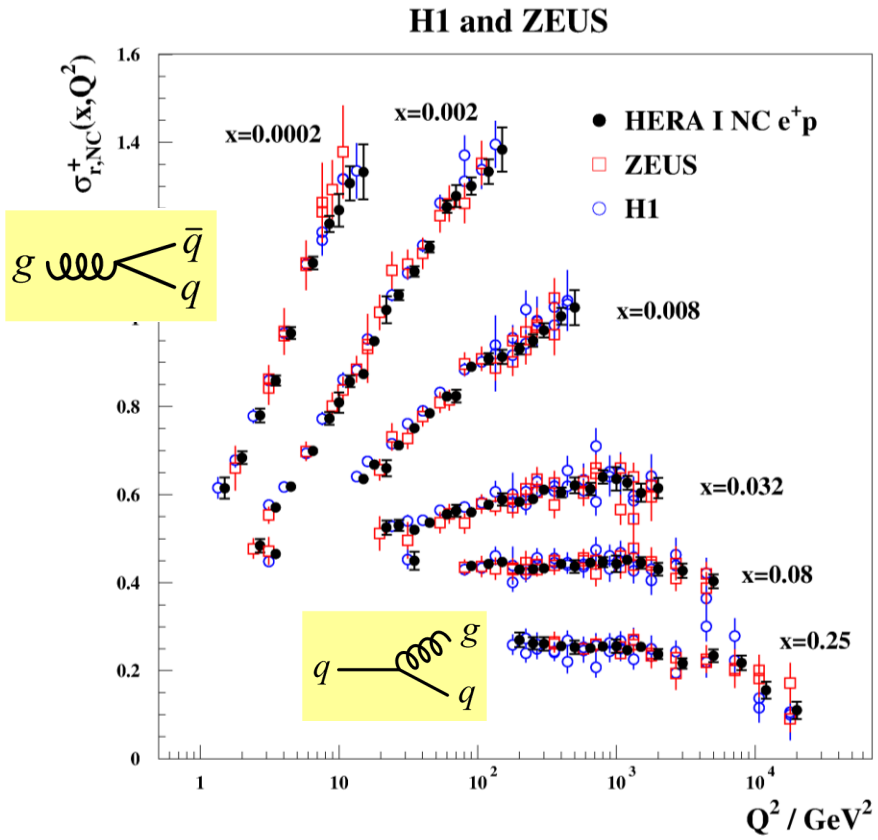
- Diffraction at HERA and the LHC
  - from measurements using central detectors
  - multi-parton interaction and gap-survival
  - measuring the forward-going proton

- Forward-going baryons in inclusive processes

Most of the results from 1-2 decades ago
Contents are rather pedagogical
... asking for patience (especially for old people)

DIS: fast rise of partons towards low-x

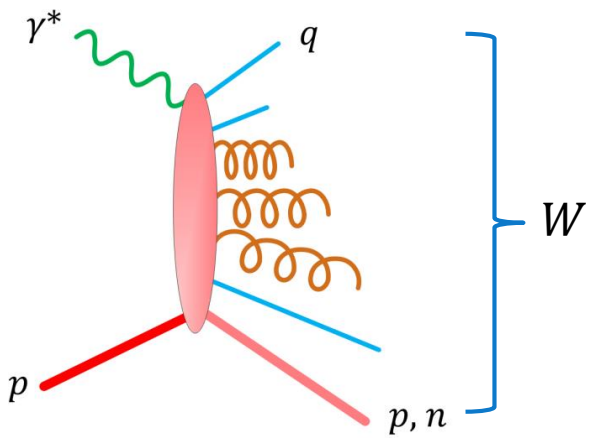


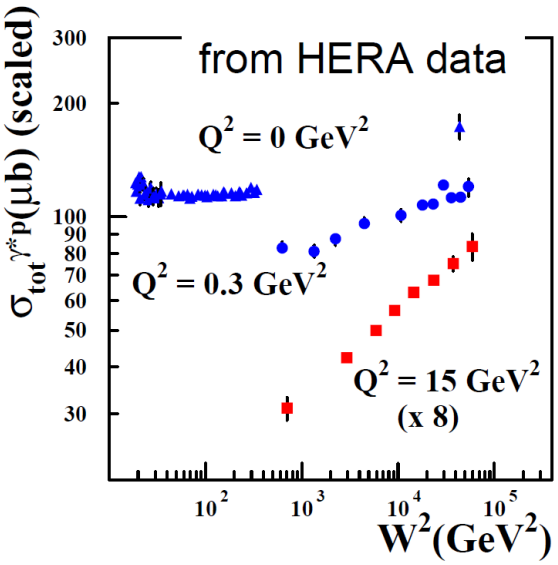


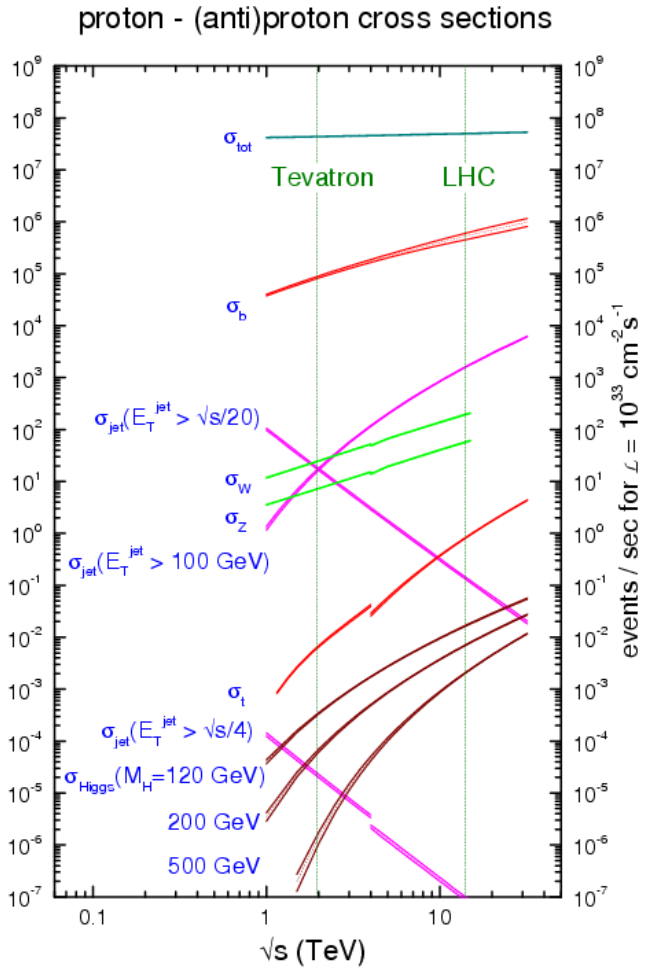
Q^2 : virtuality of the exchanged photon x: momentum fraction

- Finer resolution: individual partons visible
  - Strong **positive** scaling violation in low-x

DIS as hadron-hadron scattering





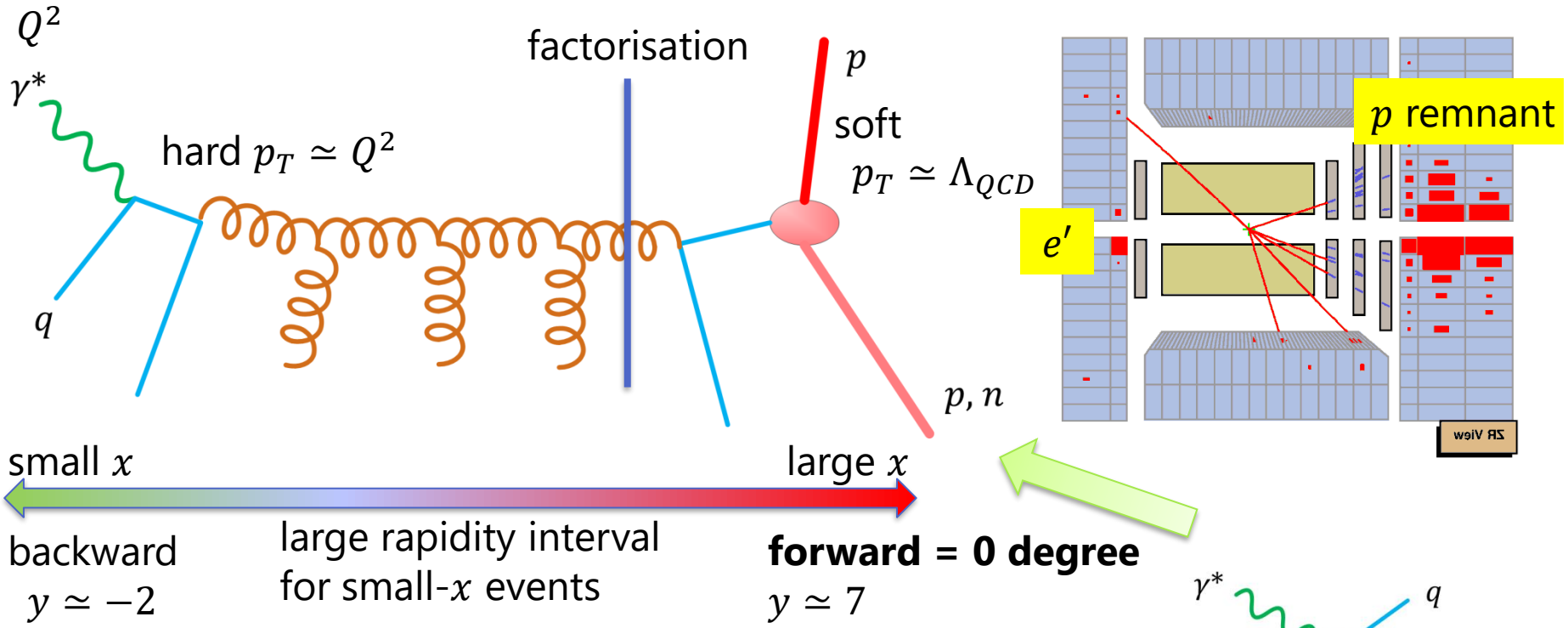


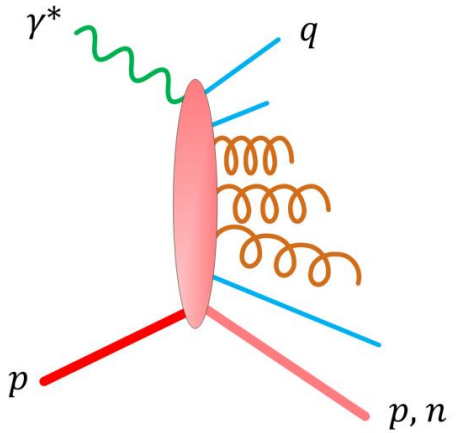
- For low-Q^2 processes, photon regarded as hadron
  - The lower x, the higher W ($\gamma^* p$ centre-of-mass energy)

    $$W^2 = \left(\frac{1}{x} - 1\right) Q^2 \approx \frac{Q^2}{x} \quad (x \ll 1)$$

  - Fast rise: partons visible
    Evidence of hard processes – so as for the LHC

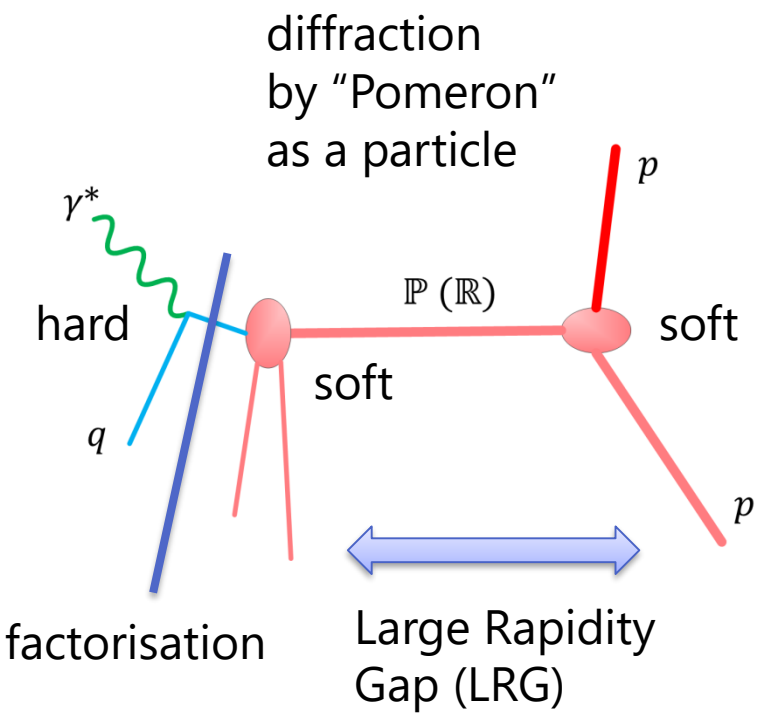
Forward physics of high-energy DIS

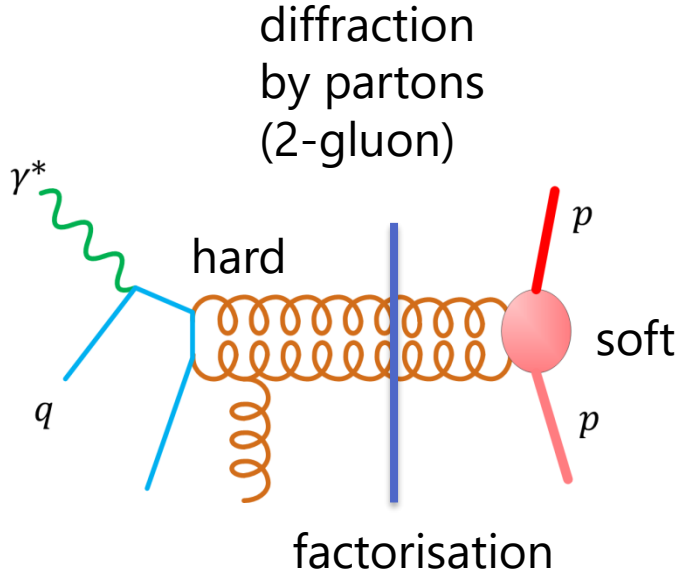




- where is the transition from hard to soft?
  - Inclusive DIS: pQCD assumes factorisation
    - collinear (soft) below there
  - for all the processes?

Example: diffraction

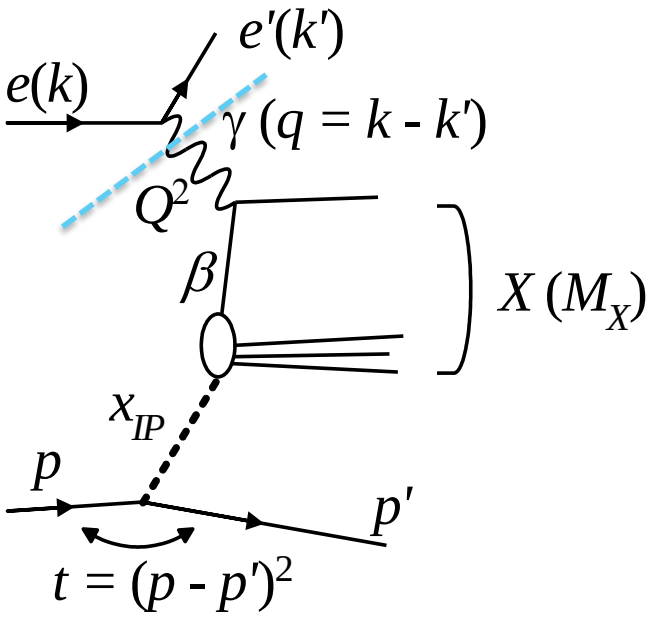




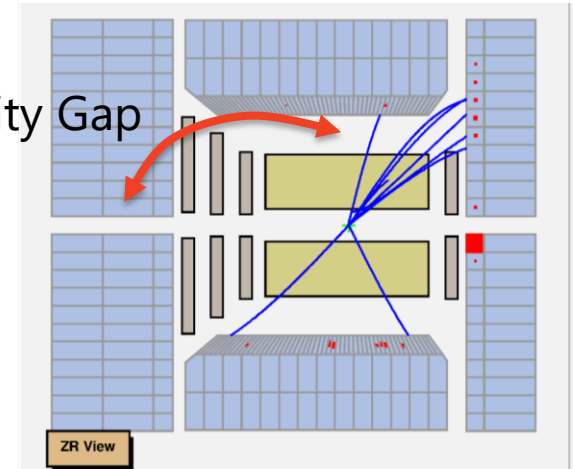
- Where is the transition from long-range physics to pQCD?
  - precise test with DIS at HERA

Diffractive DIS and diffractive PDFs

- partonic structure of diffractive exchange (Pomeron) by γ^*
- what to measure: $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$
  - Structure function of diffractive process
  - Extracting diffractive PDFs (DPDFs) through scaling violation, using jets … (assuming factorisation theorem would work for diffractive DIS)



Large Rapidity Gap (LRG)

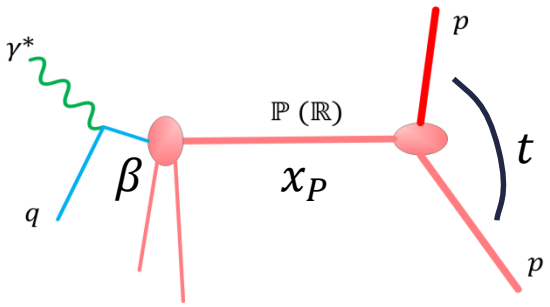


β: long. momentum fraction of the parton in the exchange

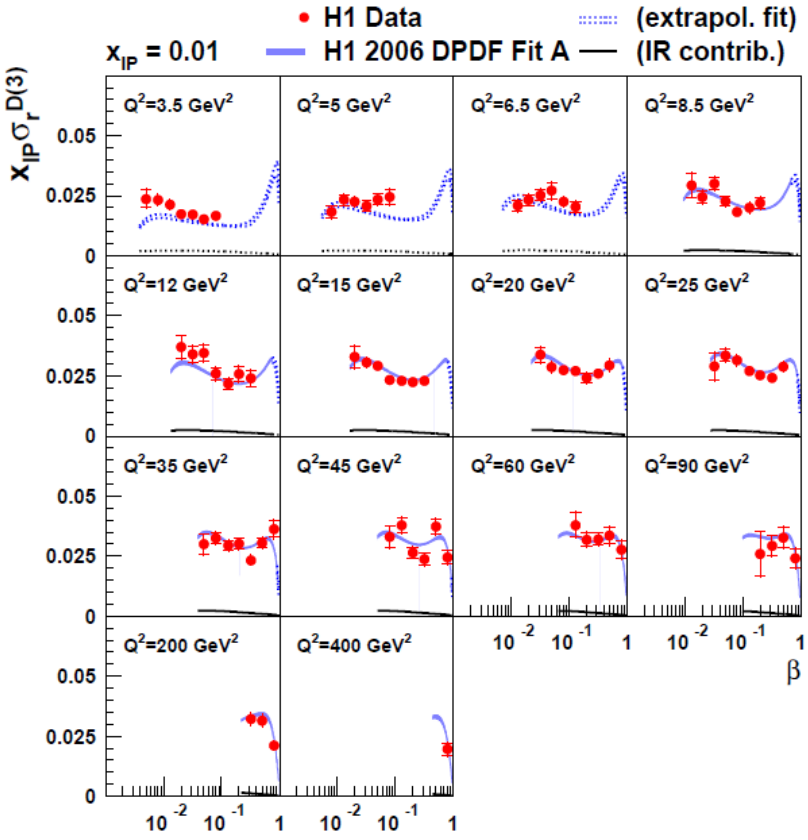
$x_{\mathbf{P}}$: long. momentum fraction of the exchange in the proton

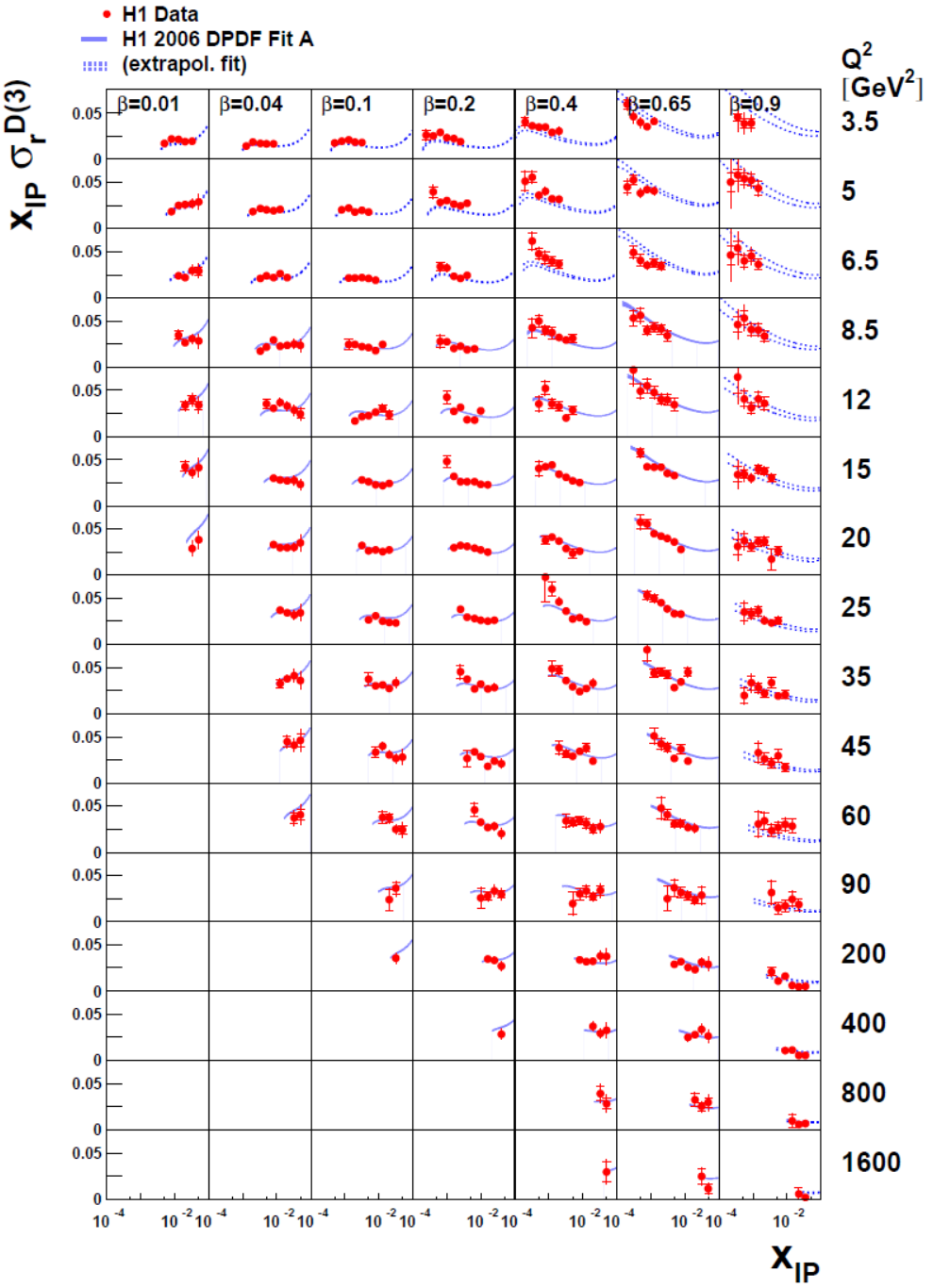
$Q^2 = -q^2 = -(k - k')^2$: negative of momentum transfer squared

$F_2^{D(3)}$ from H1, ZEUS

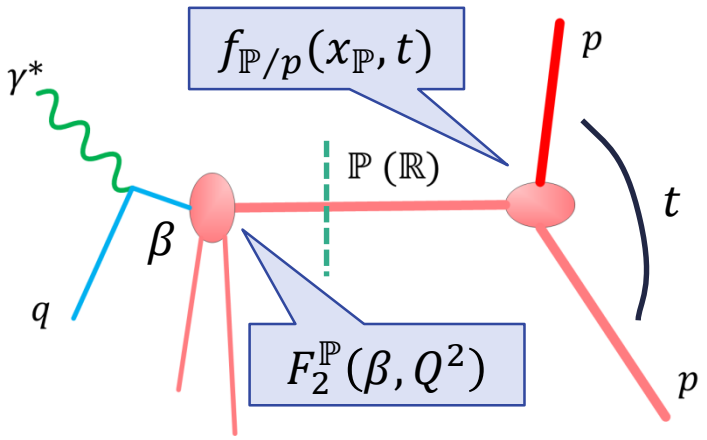


$$\beta = x/x_{\mathbb{P}}$$

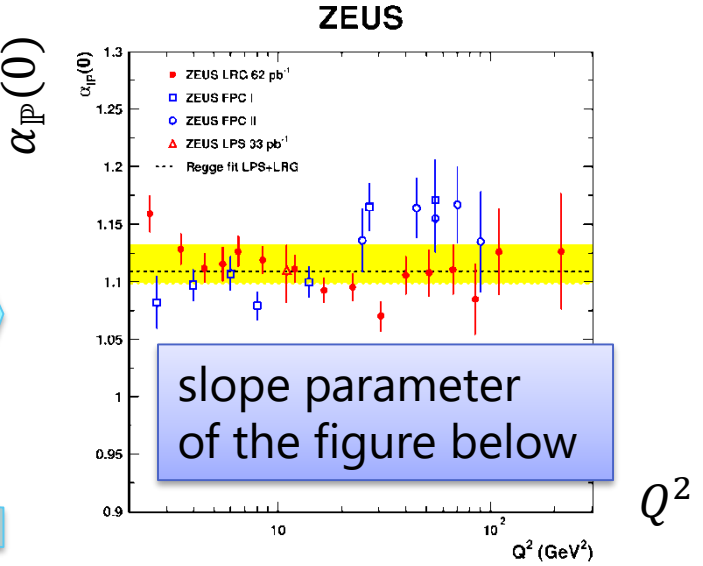




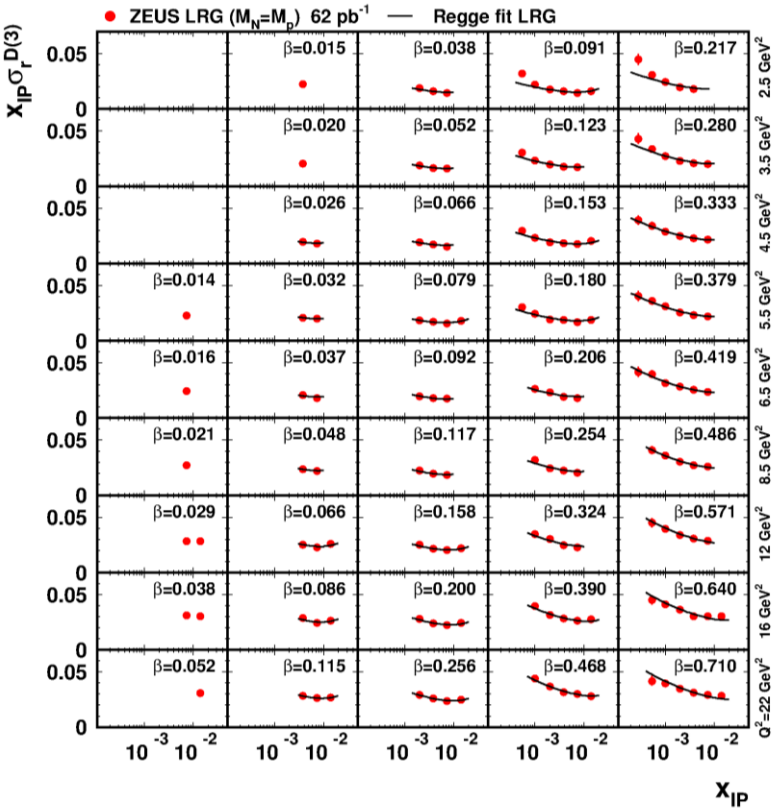
Is Pomeron a "particle" ?



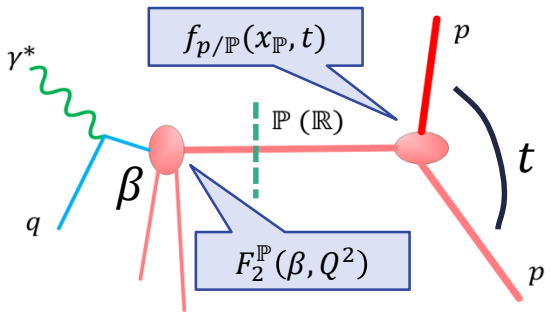
Fit by $\frac{1}{x_P^{2\overline{\alpha_P}-1}}$



- Check if the cross section can be factorised into:
  - the Pomeron flux $f_{p/\mathbb{P}}(x_{\mathbb{P}}, t)$ and
  - the upper part $F_2^{\mathbb{P}}(\beta, Q^2)$
- This holds pretty well: cross section shape in x_P is independent of β and Q^2
  - If 2-glu: depends on $x = \beta \times x_{\mathbb{P}}$
    $\rightarrow x_{\mathbb{P}}$ dependence steeper with Q^2



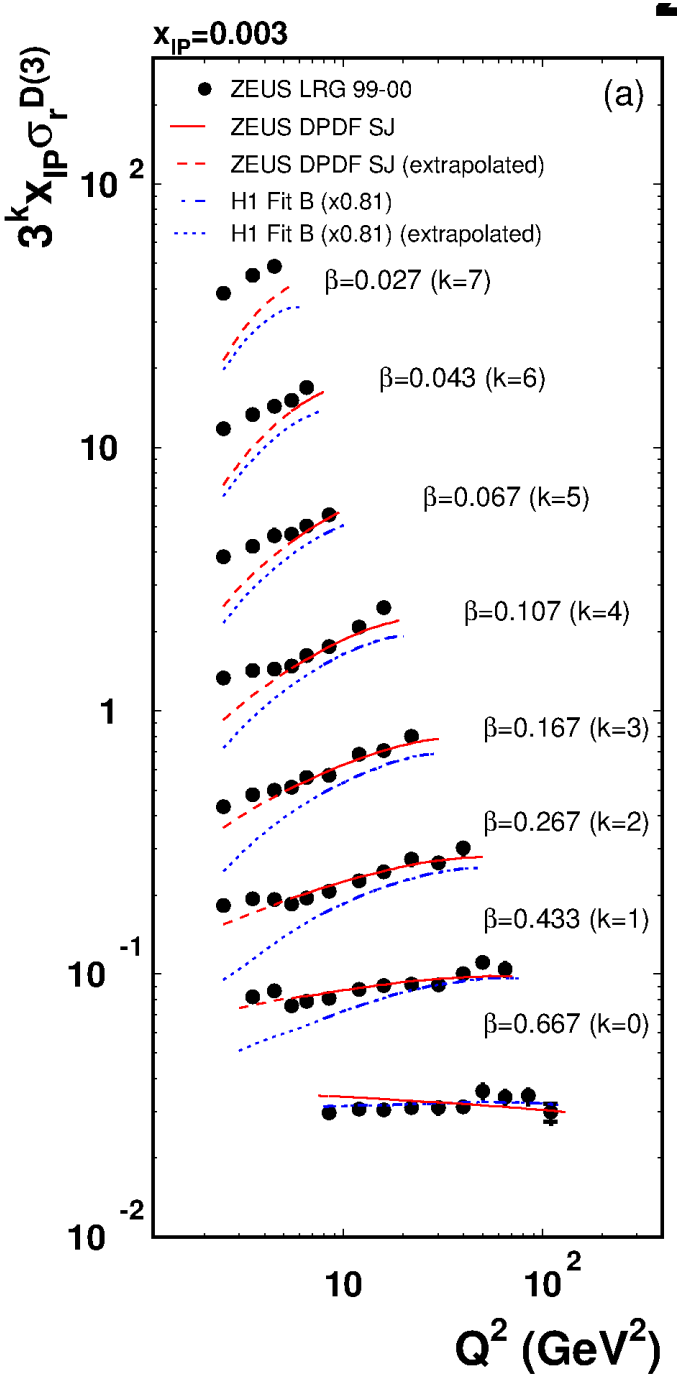
Scaling violation analysis for $g(\beta, Q^2)$ in DPDF



$$\beta = x/x_{\mathbb{P}}$$

- Positive scaling violation in almost all β values
  - Quarks dynamically produced through gluons
  - **The exchanged object is gluon-rich consistent with naïve 2-gluon picture**

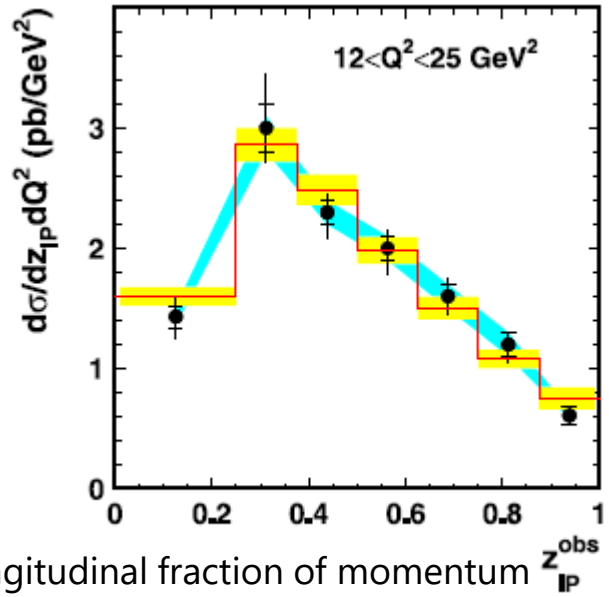
- some excess at low-Q^2 (higher twist!): I will come to this point later



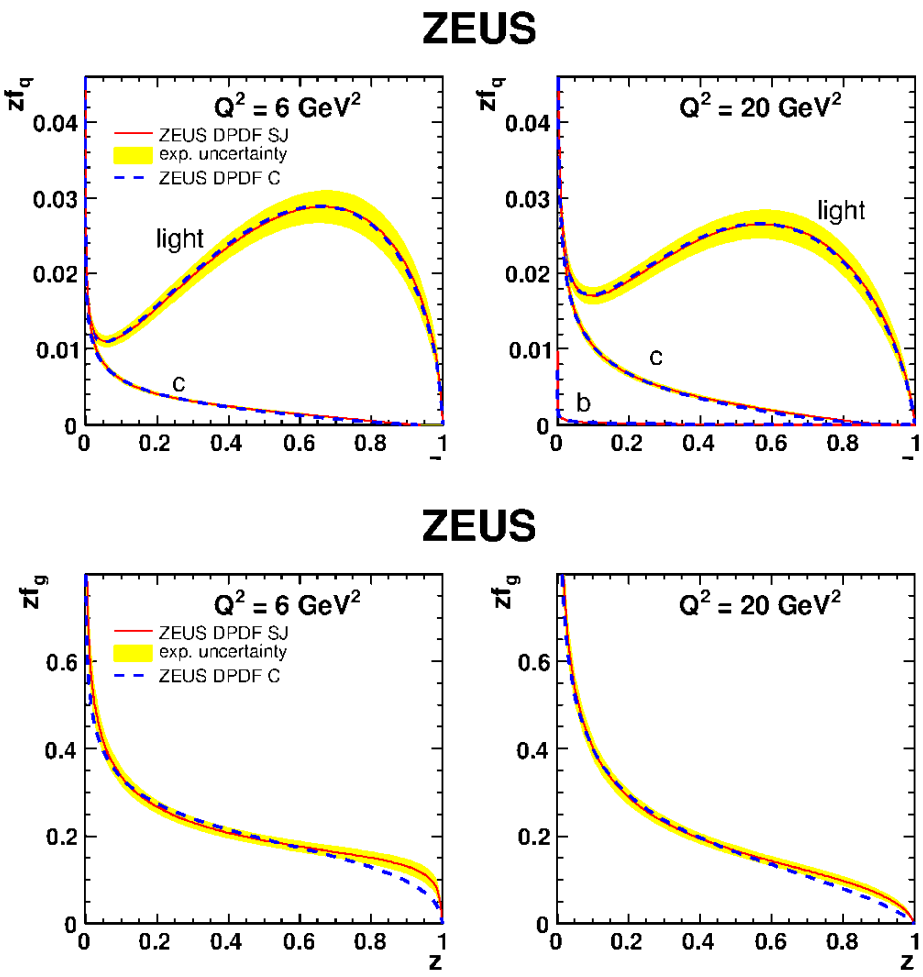
Extracted diffractive parton densities

- Gluons are not strongly constrained in diffractive DIS
- Jet cross sections are used to constrain gluons
- 63% is gluon at $Q^2 = 10$ GeV

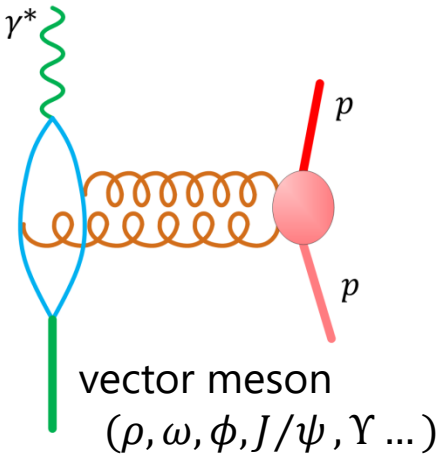
ZEUS dijet cross section and DPDF SJ

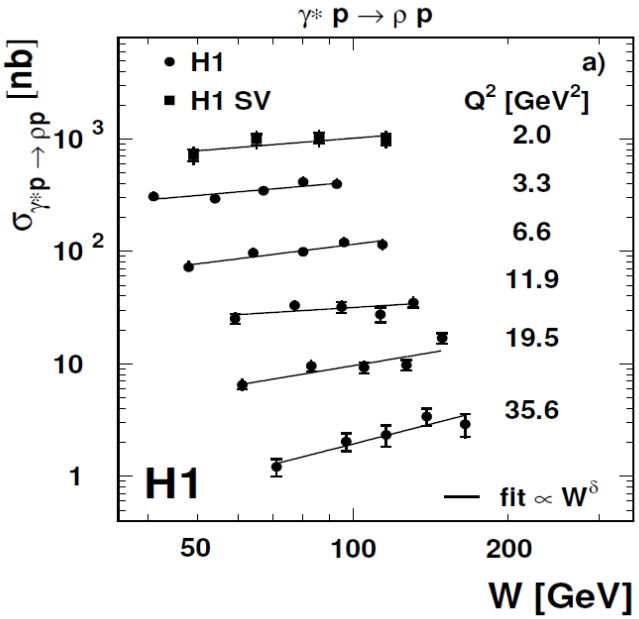


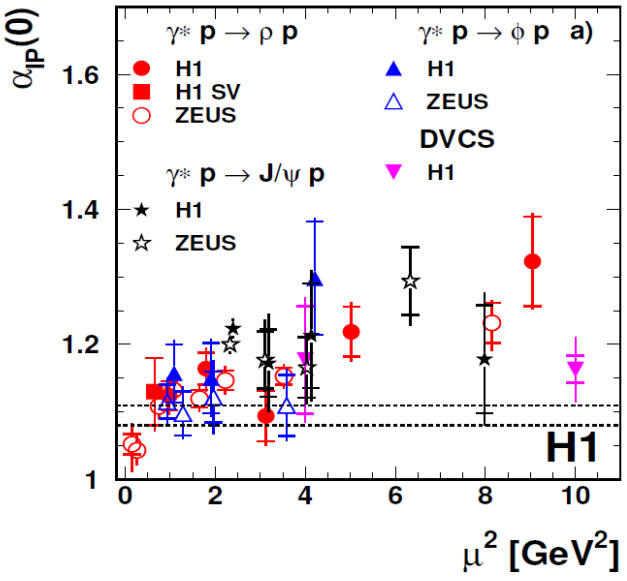
Longitudinal fraction of momentum carreid by the dijet system, wrt Pomeron



Vector meson production in $\gamma^* p$



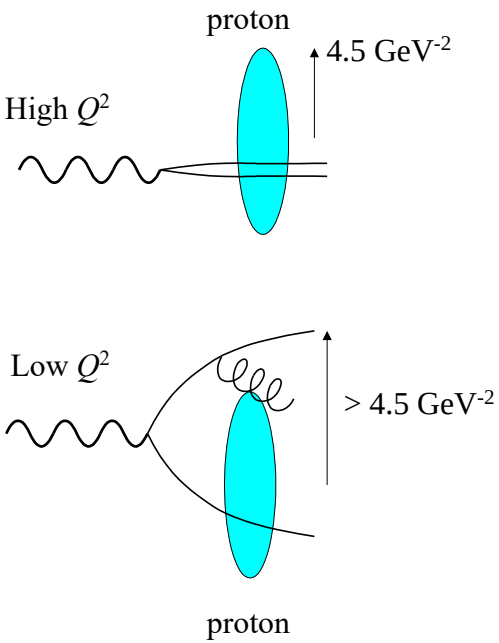


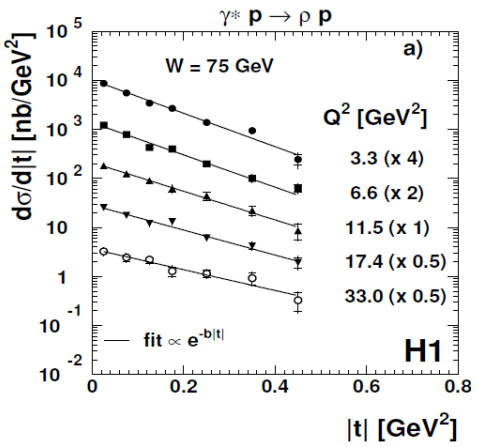


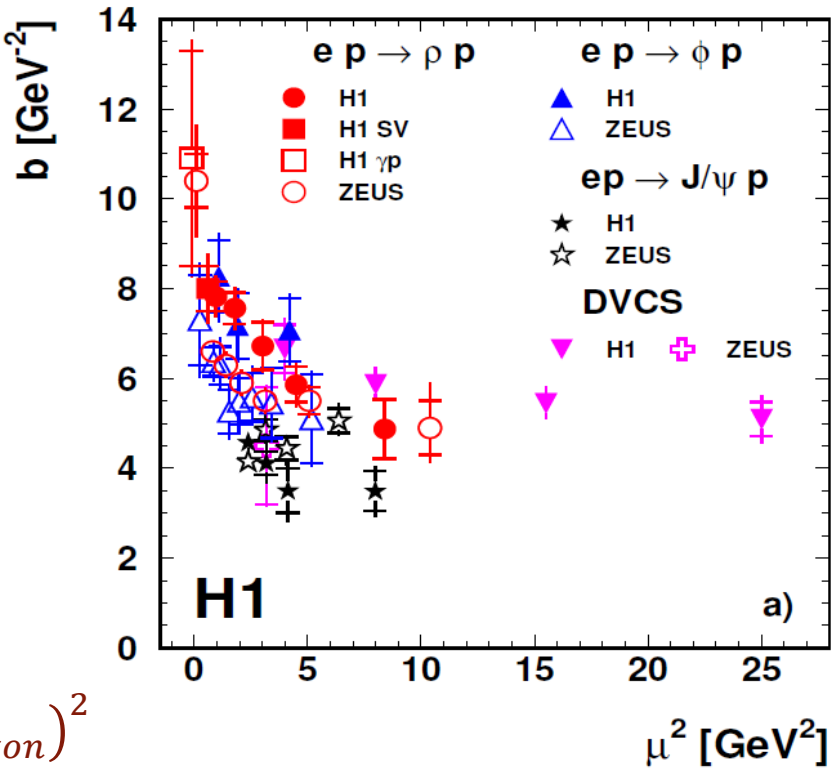
$\mu^2 = (Q^2 + M_V^2)/4$

- Vector meson is higher twist (vector-meson dominance model)
- Observing rapid rise of cross section in W if a hard scale exists i.e.
  - if the VM is produced from **a very virtual photon** ($Q^2 \gg \Lambda_{QCD}$)
  - or if the **VM is heavy** (J/ψ, Υ)
- **Well explained by the 2-gluon picuture: $\sigma_{VM} \propto |g(x)|^2$**
  - $\alpha_{\mathbb{P}}(0) \sim 1.25$ corresponds to $g(x) \propto x^{0.25}$

Forward vertex: t-dependence of VMs







- Measuring proton recoil $t = \left(p_{proton} - p'_{proton}\right)^2$
- If steep, the process is peripheral
  - parameterised by $e^{-b|t|}$
- Observation: b approaches to ~ 4 GeV^{-2}
  - the interaction becomes point-like
  - supporting the "hard" picture of VM production

$\mu^2 = (Q^2 + M_V^2)/4$

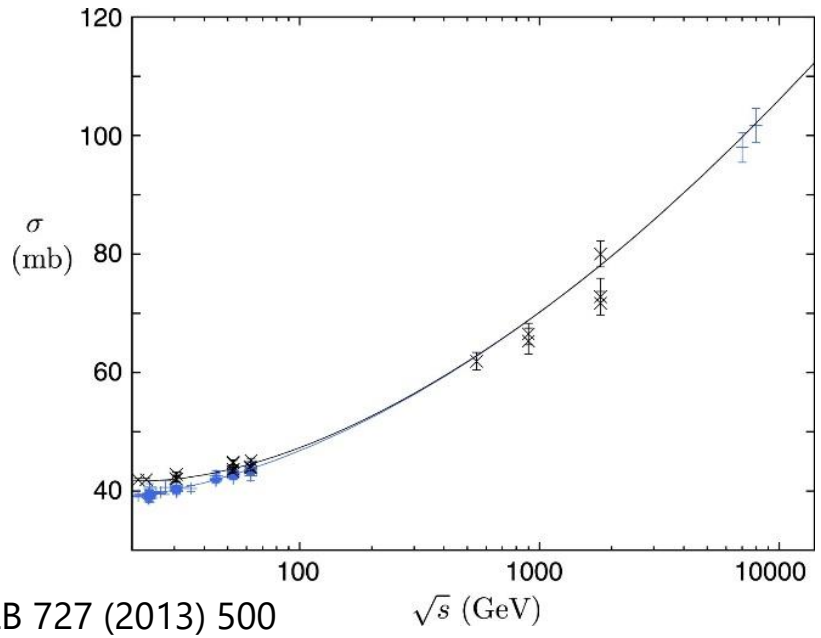
Diffractive cross sections at the LHC

Is the diffraction with the same mechanism?

- "Pomeron Intercept" α_P: rise of the cross section with $\sqrt{\hat{s}}$
  - diffraction at HERA: $\sigma(x_P = \xi) \propto \frac{1}{x_P^{2\overline{\alpha_P}-1}}$ with $\overline{\alpha_P} - 1 \equiv \epsilon \simeq 0.104$
  - at the LHC: $\frac{d\sigma}{d\log\xi} \propto \log^{\epsilon}\xi$ or $\frac{d\sigma}{d\eta_{gap}} \propto \eta_{gap}^{\epsilon}$

$$\alpha(t) = 1 + \epsilon + \alpha' t$$

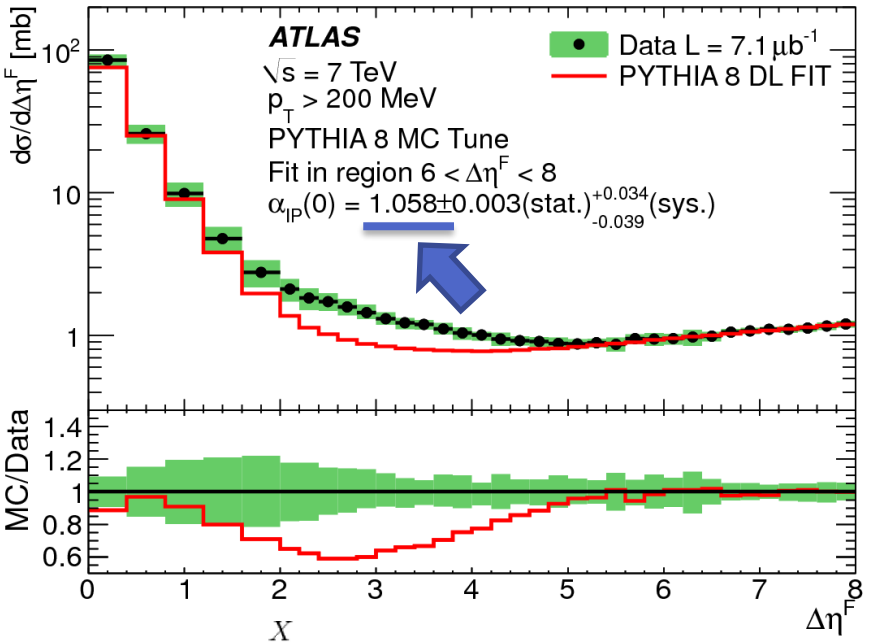
- Is Pomeron universal?
  - from hadron-hadron total cross section:
    $\epsilon = 0.08$ (fit up to 62 GeV)
    $= 0.110$ (including LHC*)
  - from HERA diffraction:
    $\epsilon = 0.104$

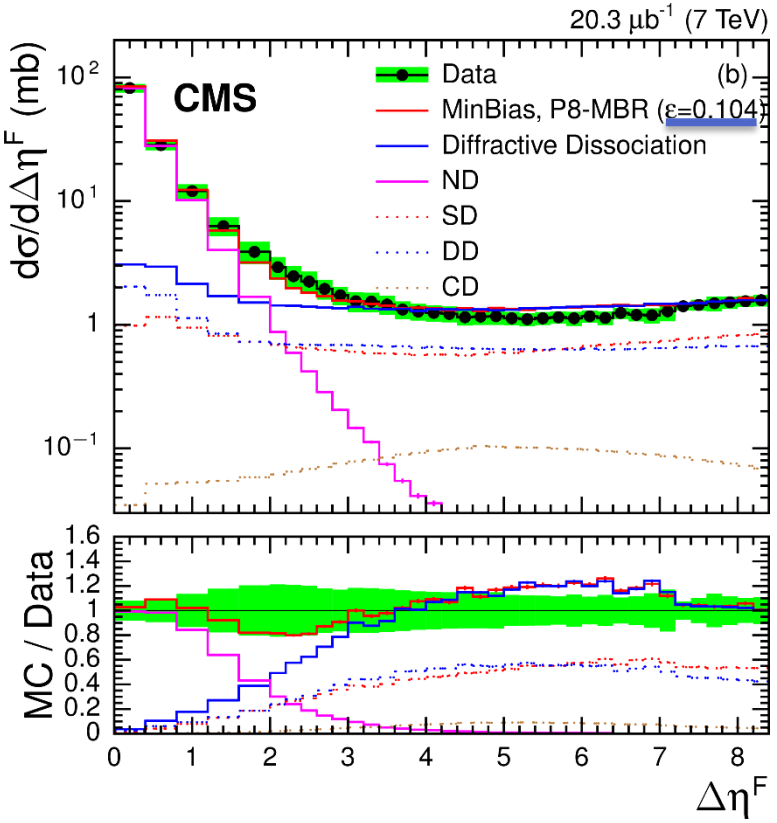


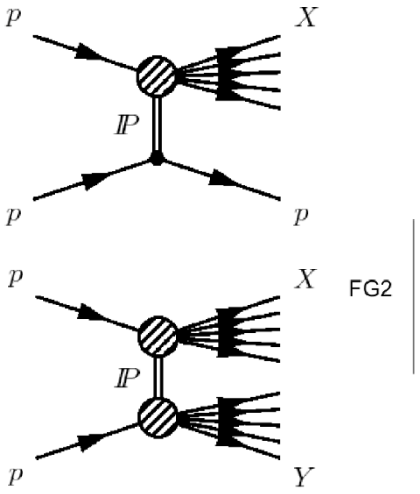
* A. Donnachie and P.V. Landshoff, PLB 727 (2013) 500

Cross sections vs rapidity gap $\Delta\eta^F$

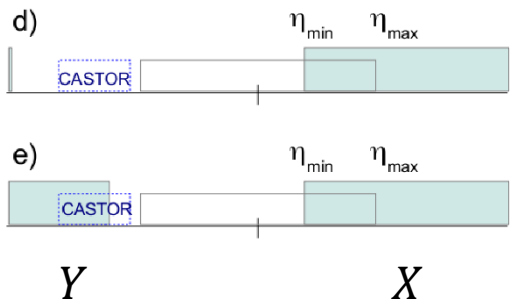
$\Delta\eta^F$ (rapidity gap from the forward edge of the detector)





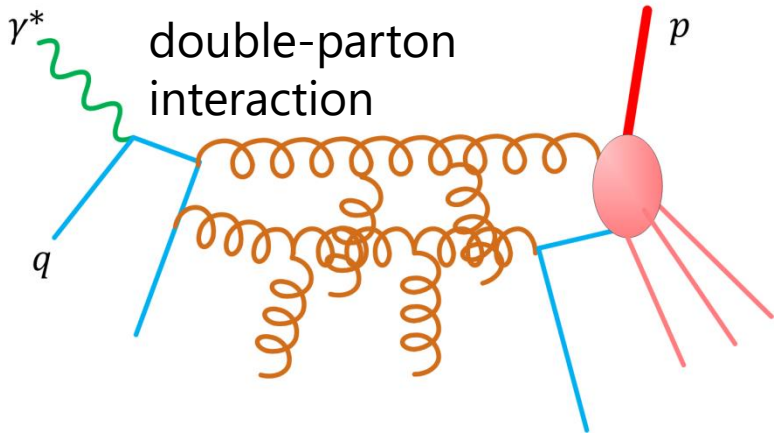


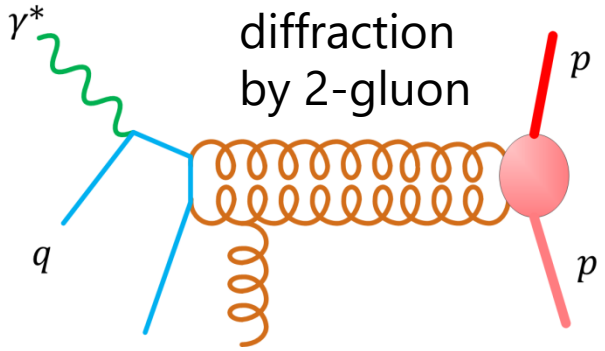
FG2

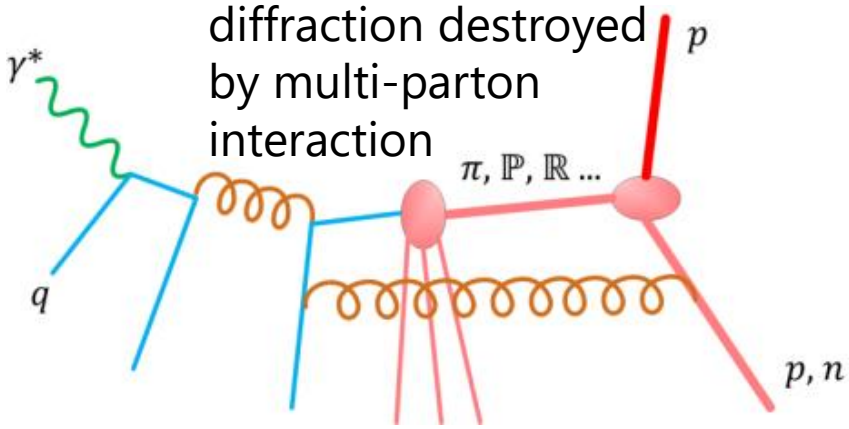


- Intercepts from slope with large rapidity gap
- Consistent with DL universal Pomeron intercept

Multi-parton phenomena







- Diffractive exchange is one variation of multi-partonic interaction
- Similar diagrams with coloured state: double-parton interaction
- Colour-neutral state may be destroyed by additional exchange
  - Gap-survival probability S^2: to have no additional exchange in diffraction

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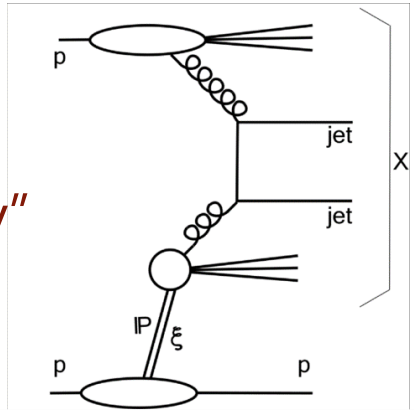
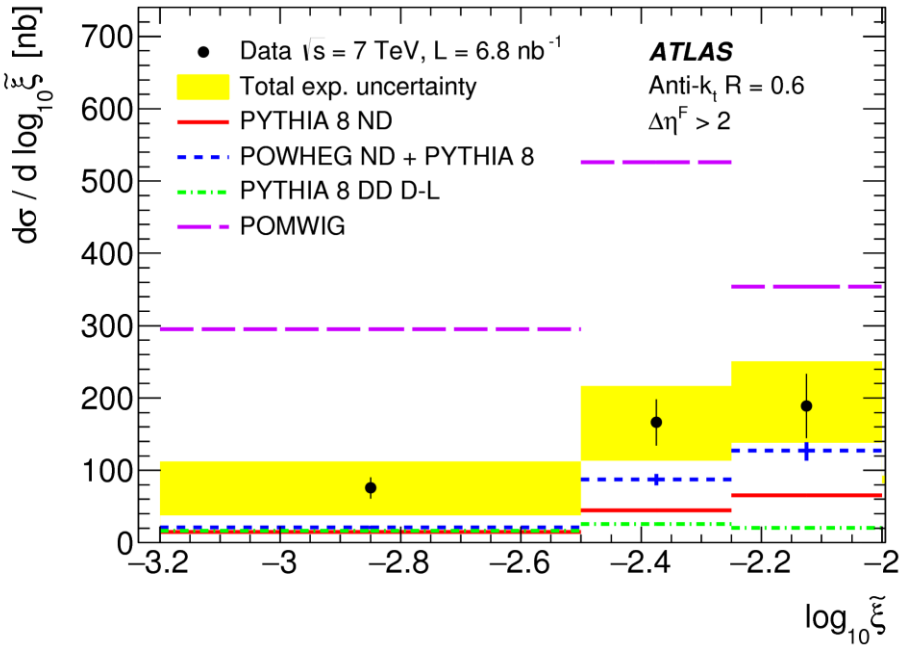
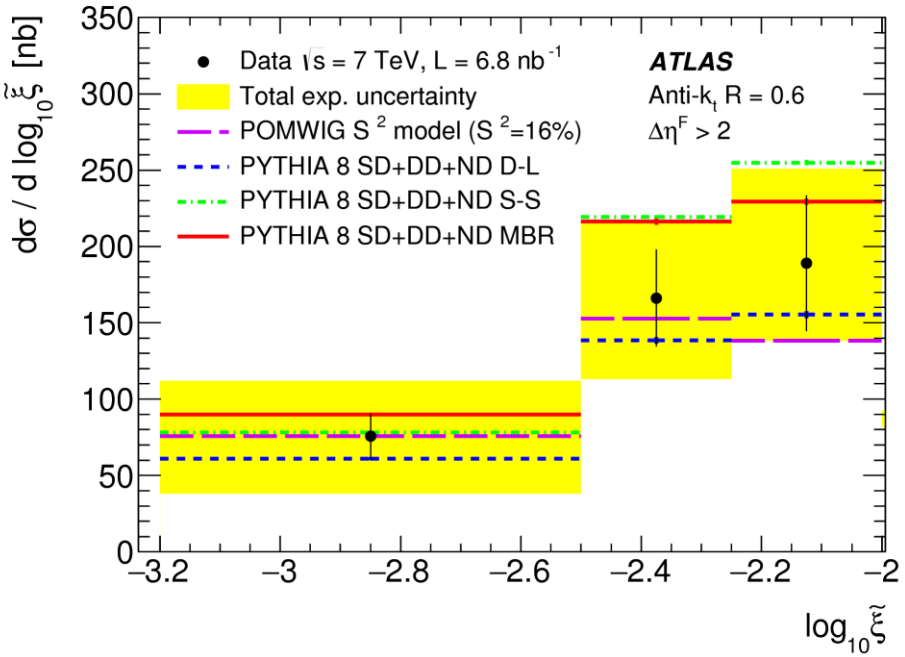
Diffractive dijet cross sections



- Main objective: to obtain the "survival probability"
- Rapidity gap selection $\Delta\eta^F > 2.4$

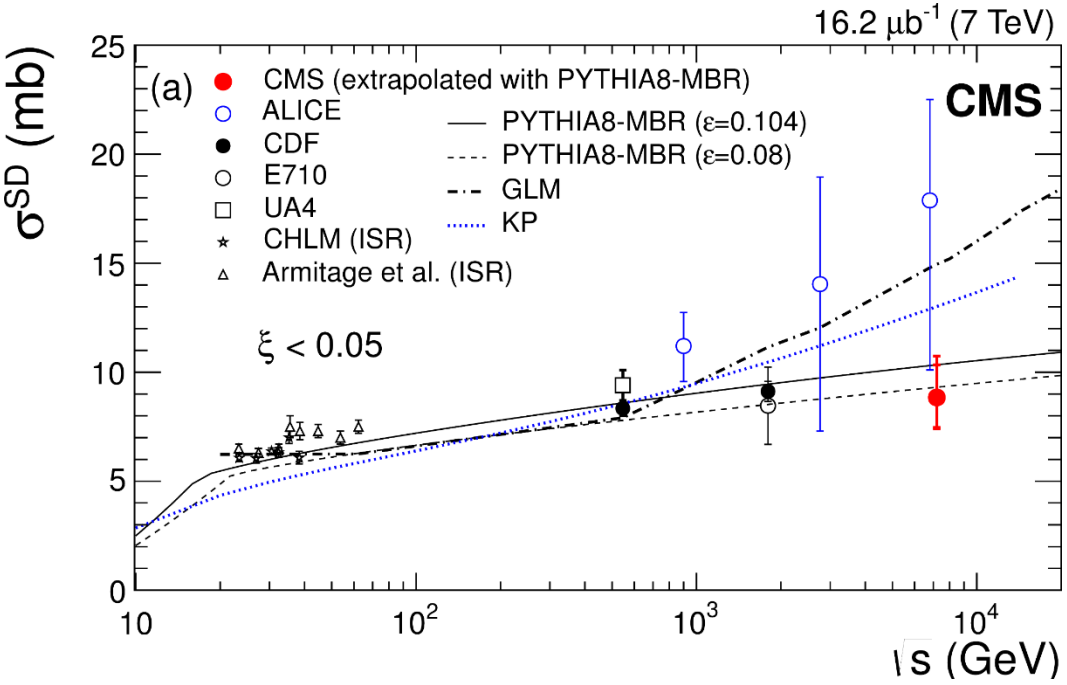




- POMWIG too high, giving $S^2 = 0.16 \pm 0.04(stat.) \pm 0.08(exp.syst.)$
- PYTHYA8 SD+DD explains the data without suppression factor
  - for various "Pomeron flux" models

Suppression or not?

Cross-section behaviour vs $\sqrt{s}$

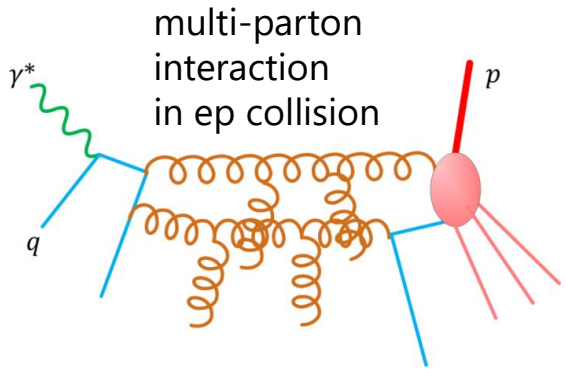


- Diffractive cross section rises weakly (CMS)
  - Diffraction rises faster than total xs according to Regge theory that means: still some suppression at high energies?

Multi-parton interaction at the LHC

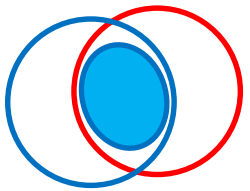
$\sigma_{parton} > \sigma_{inelastic}$
at high $\sqrt{s}$ and low p_T

- multiple parton collision unavoidable
- observed in Tevatron, evidences at HERA



Double-parton interaction cross section is expressed as:

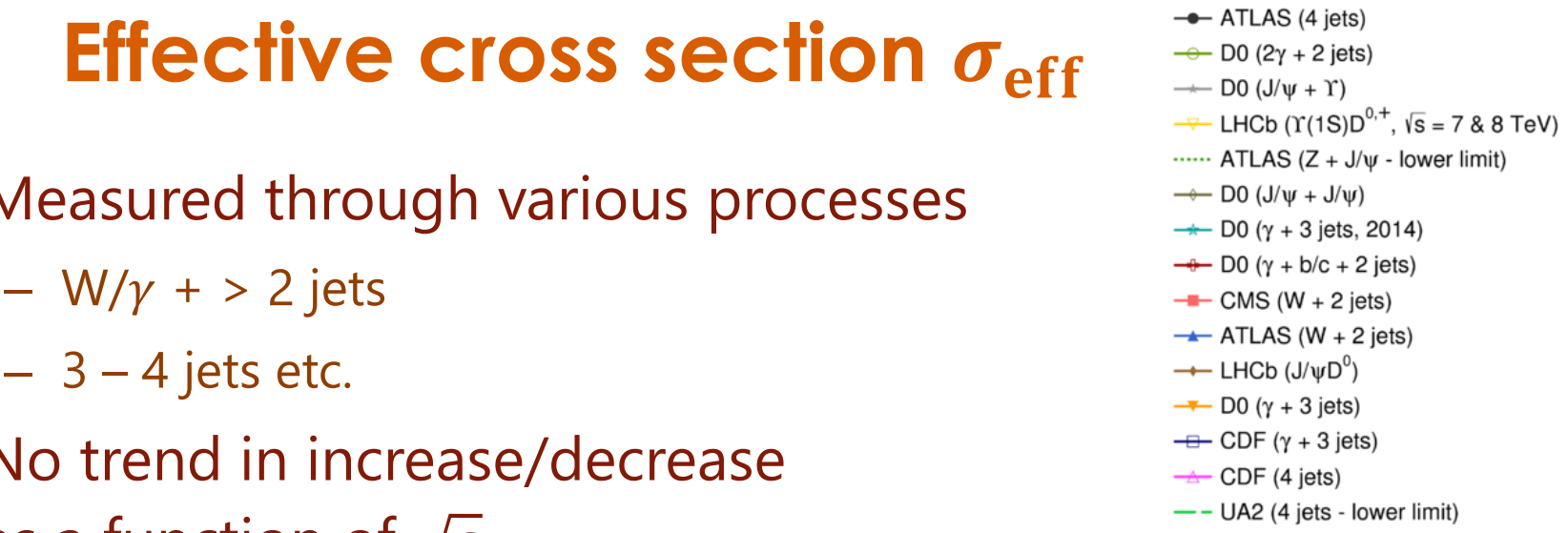
$$\sigma_{DPI}(A,B) = \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{eff}}}$$

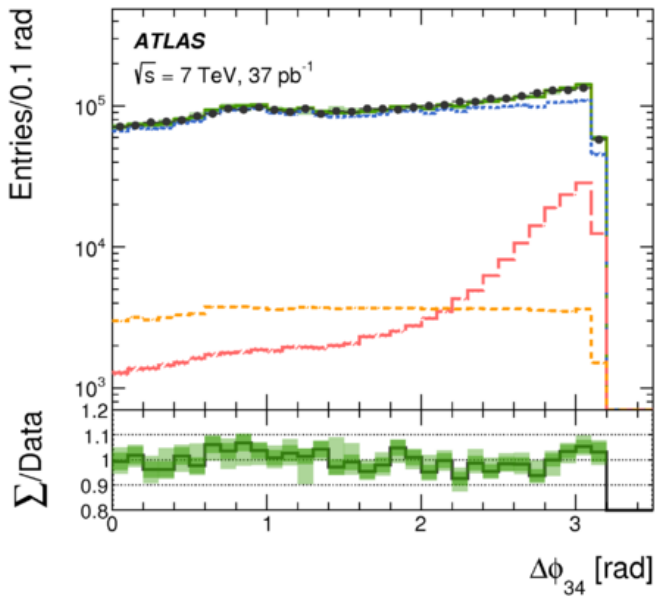


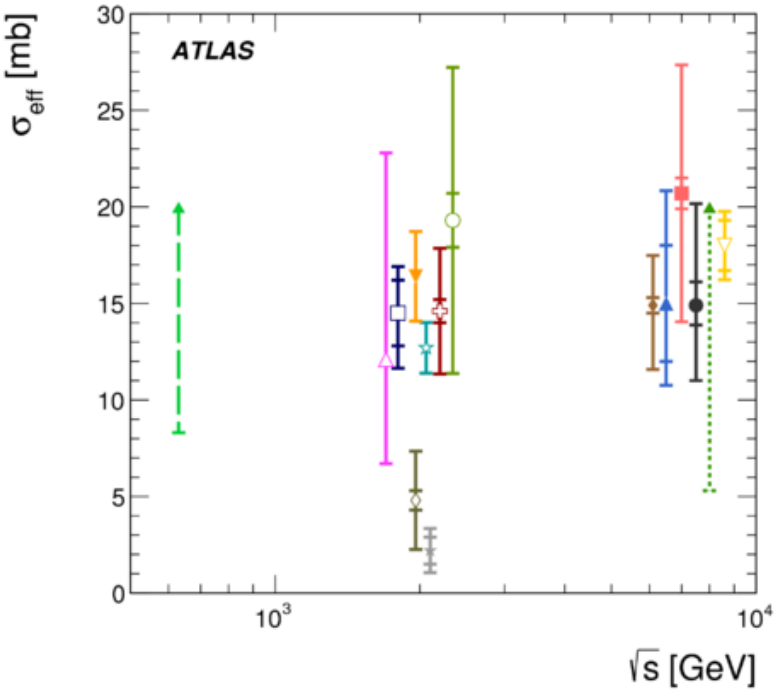
- σ_A, σ_B : cross sections of the two particles, which increase slowly with $\sqrt{s}$
- σ_{eff} : effective overlapping area of partons
  Smaller the σ_{eff}, more squeezed the partons, thus higher σ_{DPI}

Effective cross section σ_{eff}

- Measured through various processes
  - W/γ + > 2 jets
  - 3 – 4 jets etc.
- No trend in increase/decrease as a function of $\sqrt{s}$

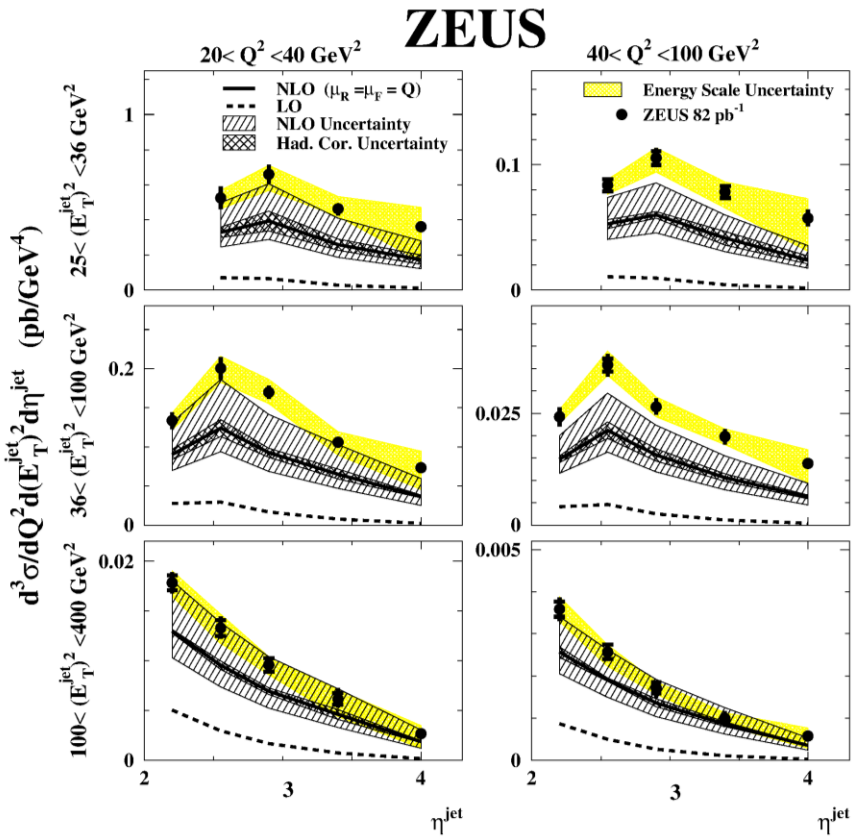


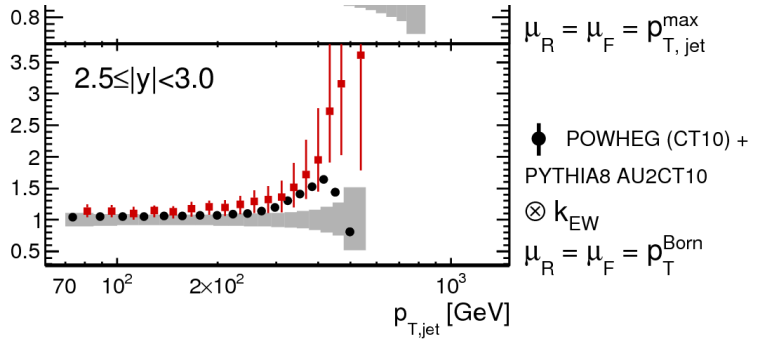




Not very forward region ($2 < \eta < 4$)

- H1 and ZEUS have been using calorimeter for jets up to $\eta \simeq 3$
  - Reconstructing DIS kinematics using hadrons
    (this is the only way for charged current!)
  - Dijets to reconstruct initial state parton's momentum
- ZEUS tried up to 4
  H1 to 6 using plug calorimeter
- ATLAS and CMS: up to 3 for cross section measurements

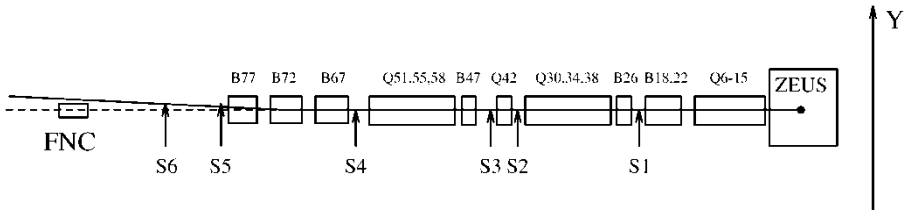




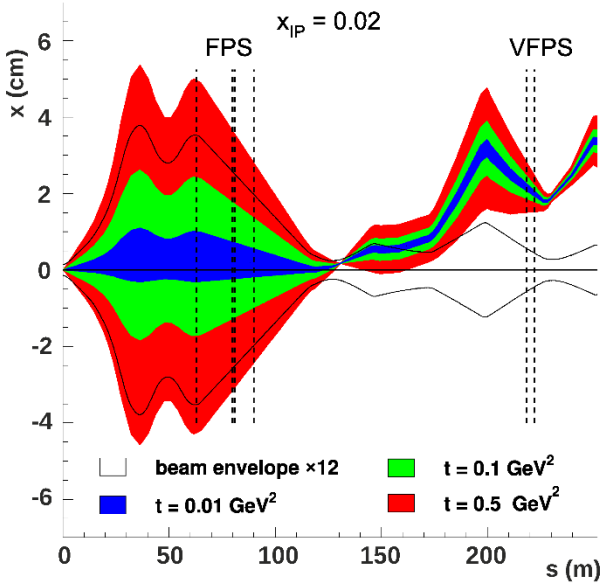
From an ATLAS paper

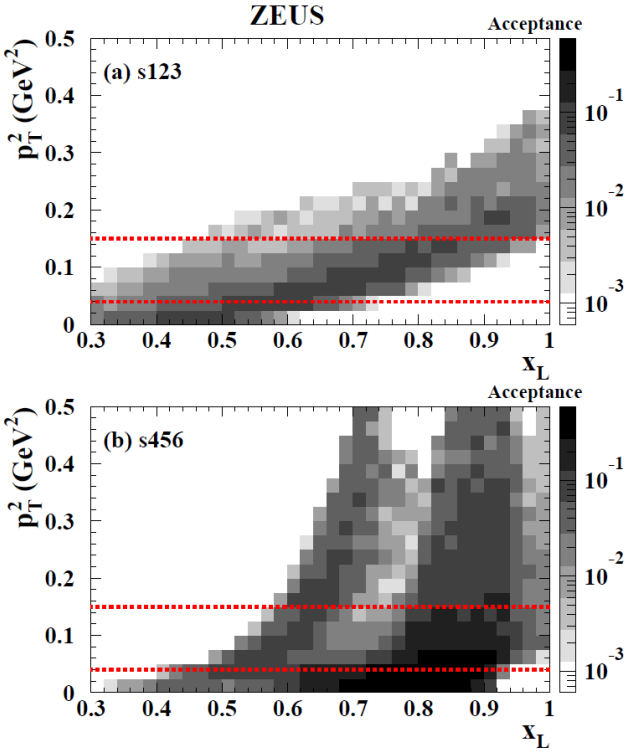
Forward proton detectors at HERA

- H1 FPS / ZEUS LPS :
  - rather complicated acceptance but still covers:
    - some acceptance at the diffractive peak ($x_L \sim 1$)
    - $p_T = 0$ at $0.3 < x_L < 0.9$ etc.



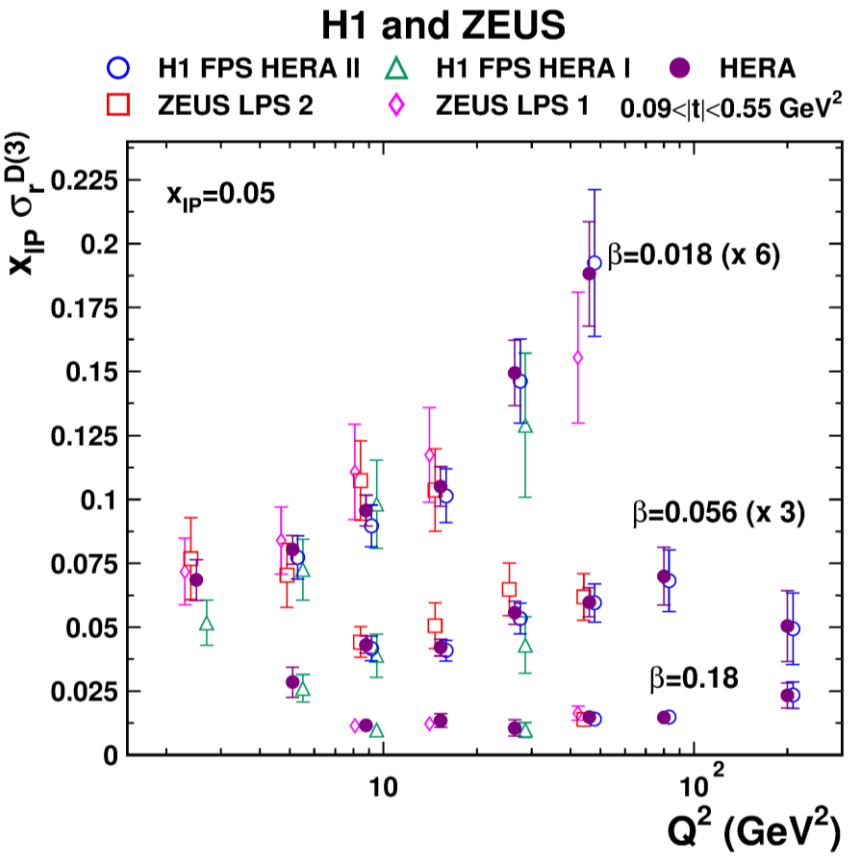
- H1 VFPS
  - very high acceptance for $0.9 < x_L < 0.97$
  - Detectors in the cold section of SC magnets





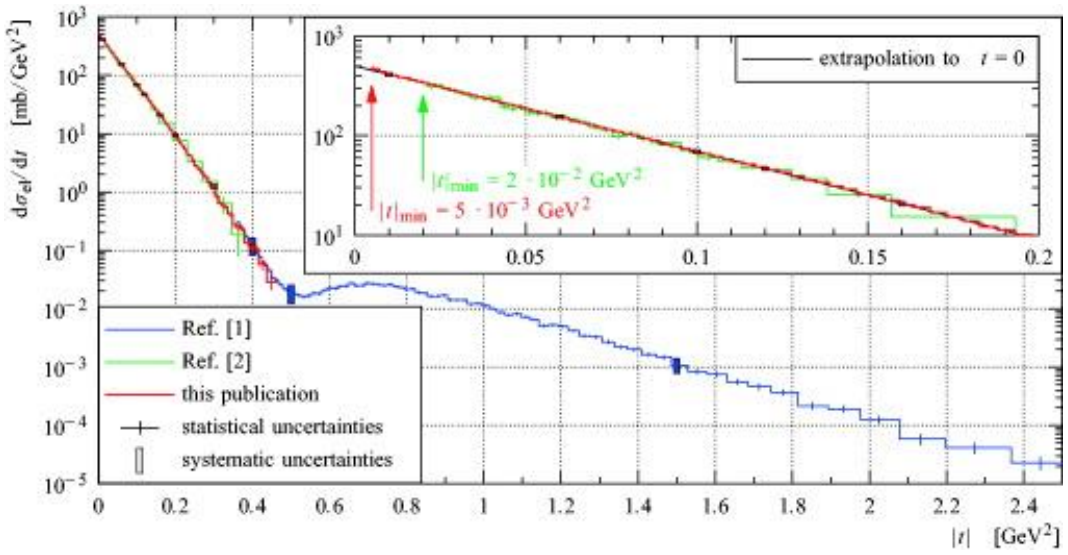
Diffractive XSs using proton spectrometers

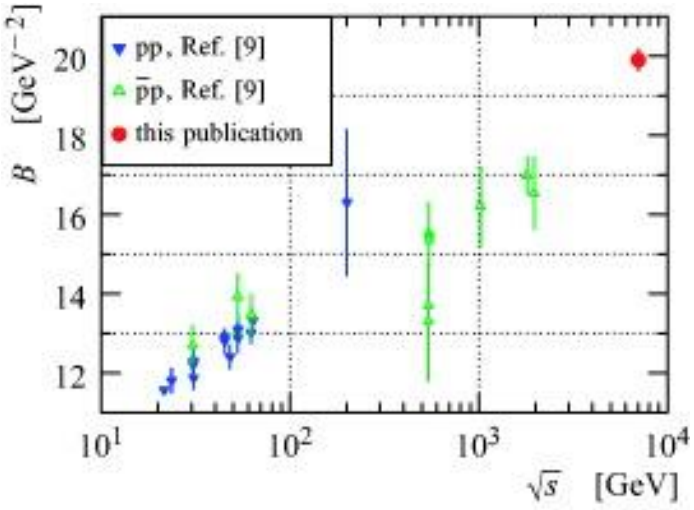
- Consistent results with different detectors
- Strong positive scaling violation at high β
  - $\beta = x/x_P$: Bjorken x for Pomeron
  - Diffractive exchange is gluonic



Typical b-slopes for hadron-hadron collisions

- parameterised by e^{-Bt}
- "shrinkage": nucleon becomes larger with collision energy
- at 100 GeV (HERA energy): ~14 GeV^{-2}
  - elastic scattering i.e. peripheral

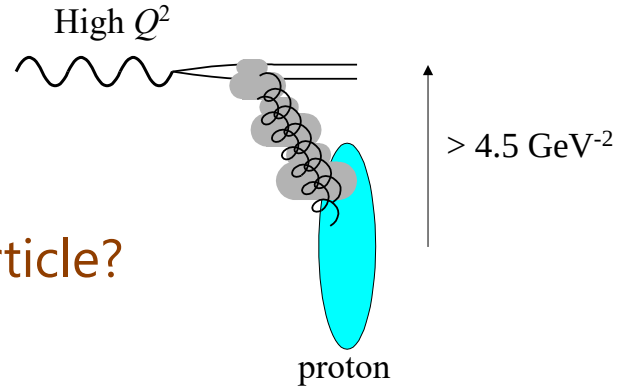


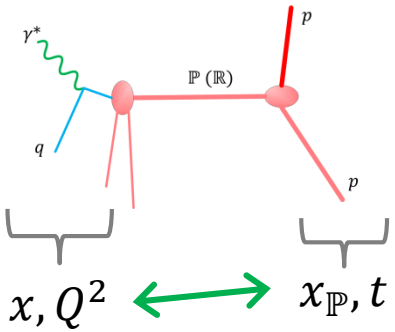


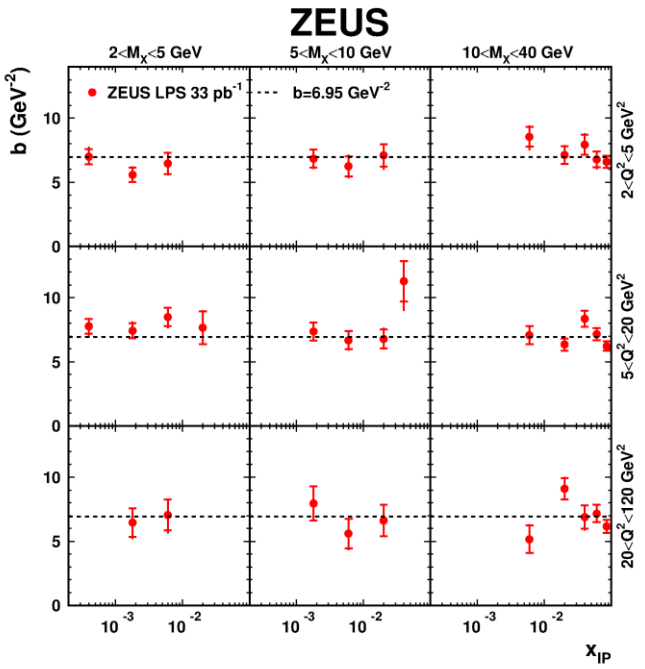
TOTEM collaboration
EPL 101 (2013) 21002

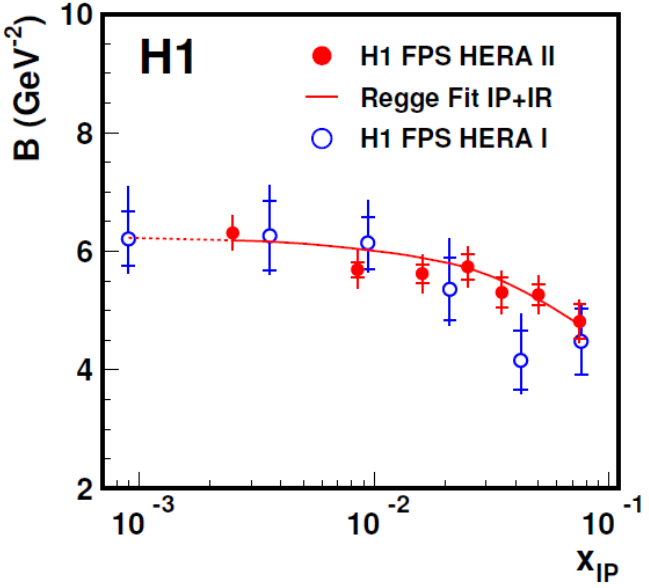
Is inclusive diffraction peripheral?

- $b \simeq 6 - 7\ \mathrm{GeV}^{-2}$
  - Not completely peripheral, not completely point-like
  - Pomeron is perhaps not completely a particle?





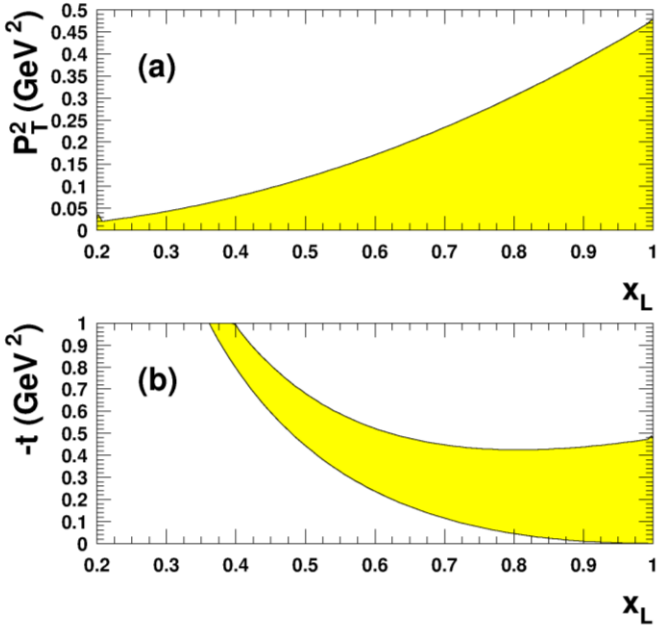


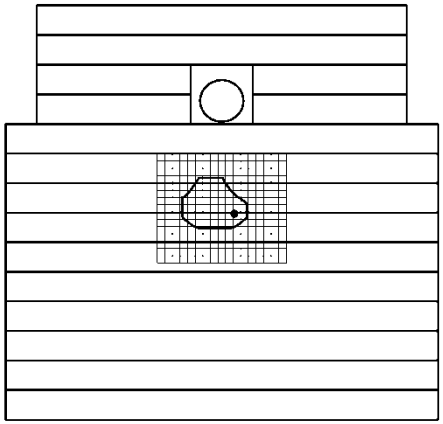


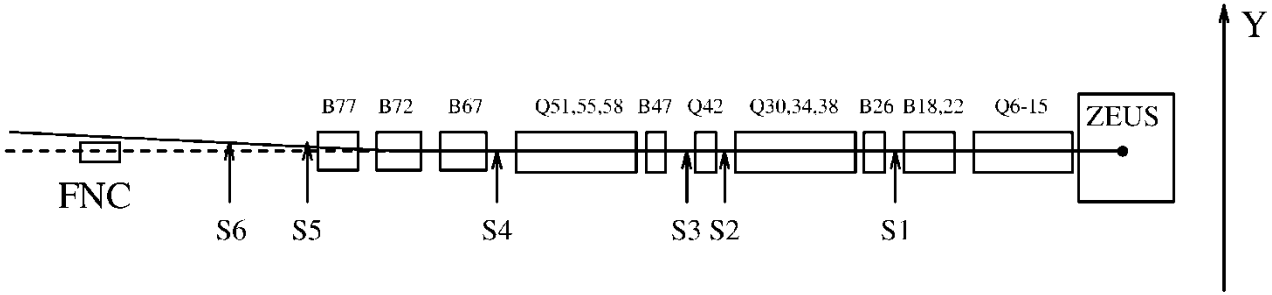
… but the slope is independent of Q^2 (unlike vector meson)

Forward baryon properties for inclusive processes

- H1/ZEUS have equipped forward neutron calorimeters
  - Big space, big calorimeter proton beam was bent upward
  - aperture limited by magnets
  - with scintillator tracker for position reconstruction

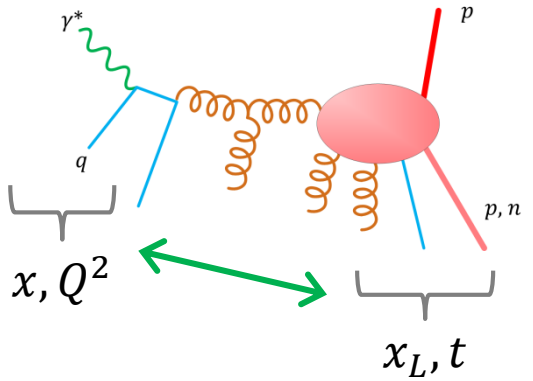


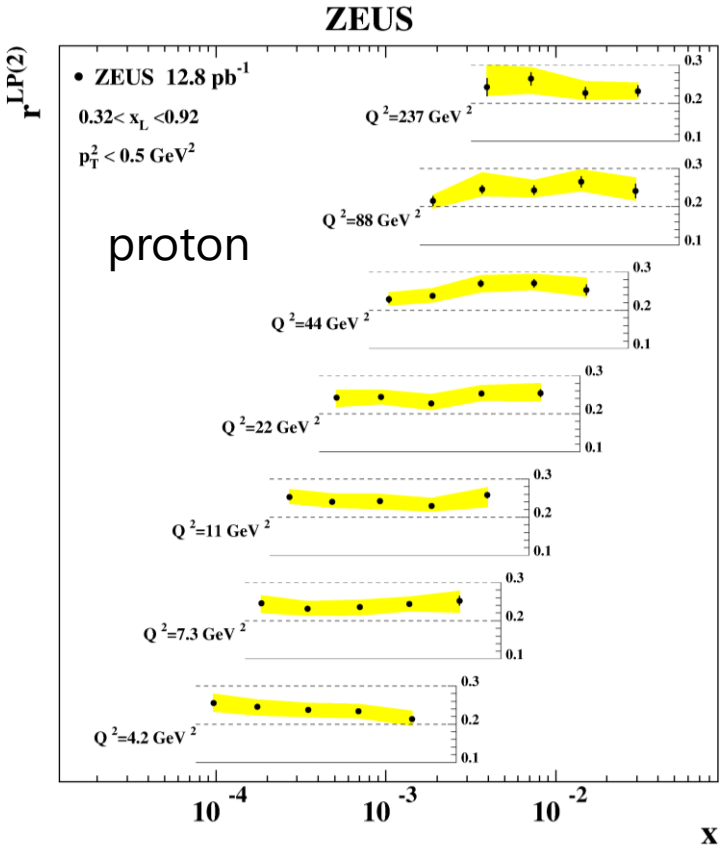


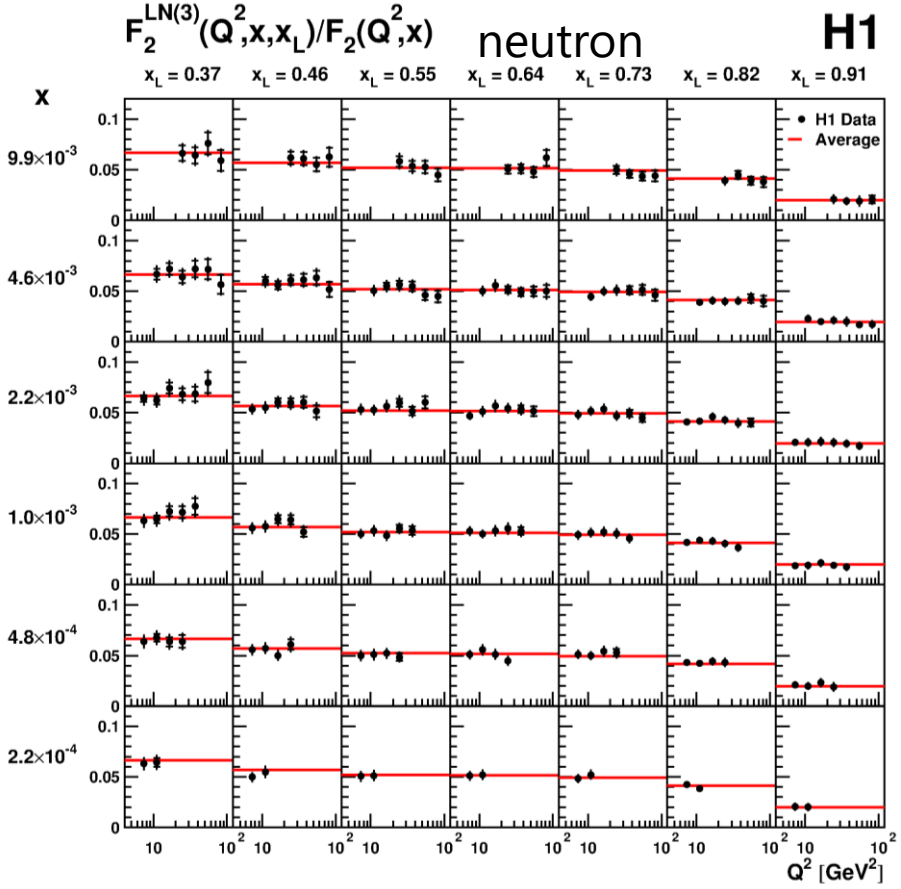


Does baryon talk to virtual photon?

- The answer is basically no!
  - No yield dependence on x, Q^2 "limiting fragmentation"





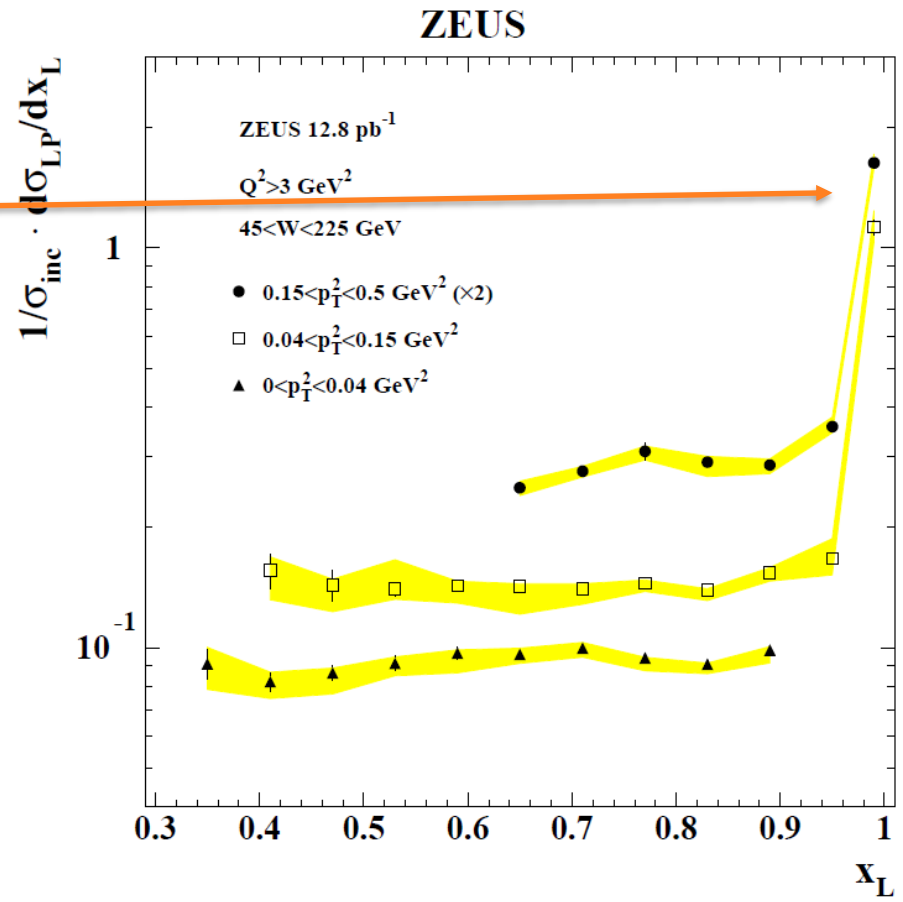


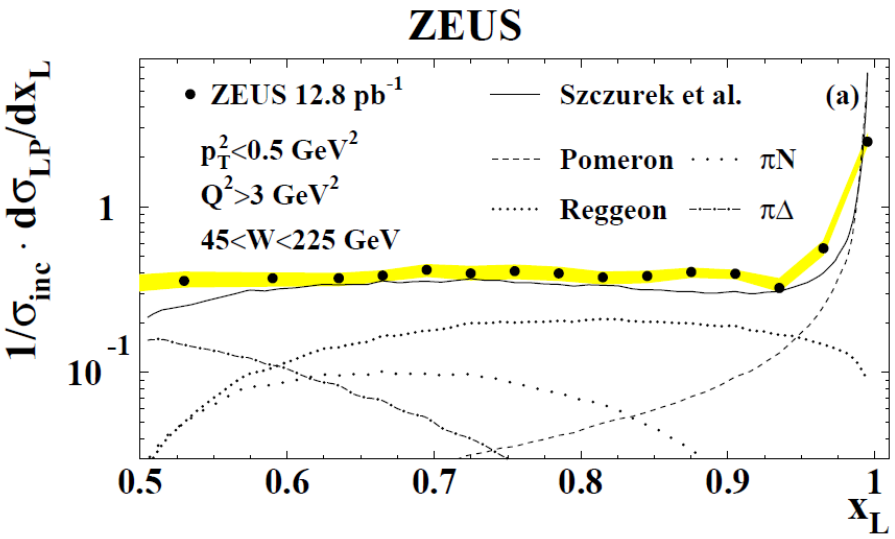
The left and right vertices are way separated

Longitudinal spectrum of forward proton

- $x_L = p_Z^{LB}/p_{beam}$
- Very flat

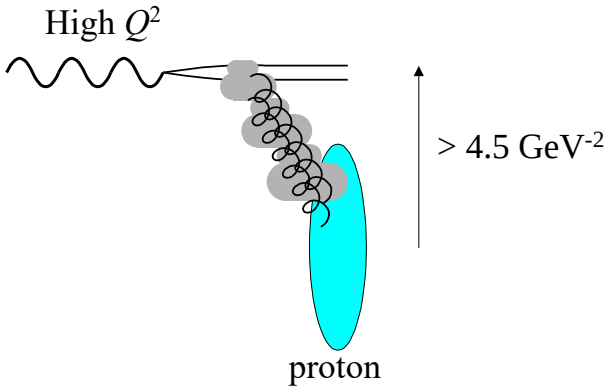
  (except for diffractive peak)
  - Limited fragmentation, or
  - pariticle exchange model (Regge poles superimposed)



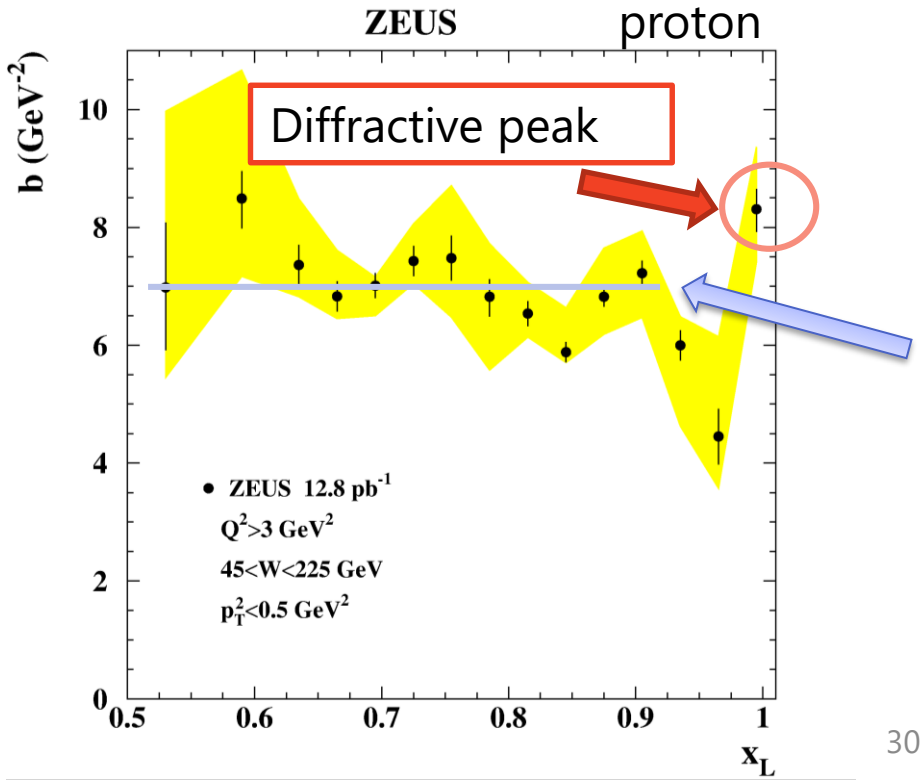


b-slope of the forward proton

- $b \sim 7\ \mathrm{GeV}^{-2}$ ($\sigma \propto e^{-bp_T^2}$) , constant
- Slightly larger than proton size
  - Somewhat peripheral?
    Semi-soft, not directly probing proton

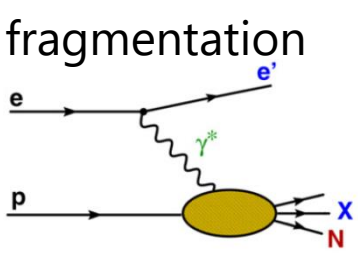


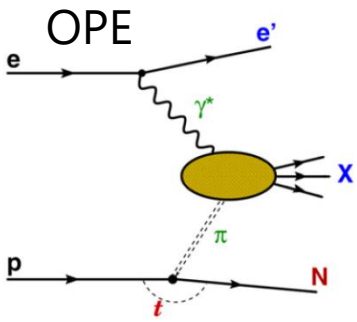
- How about
  forward neutron?



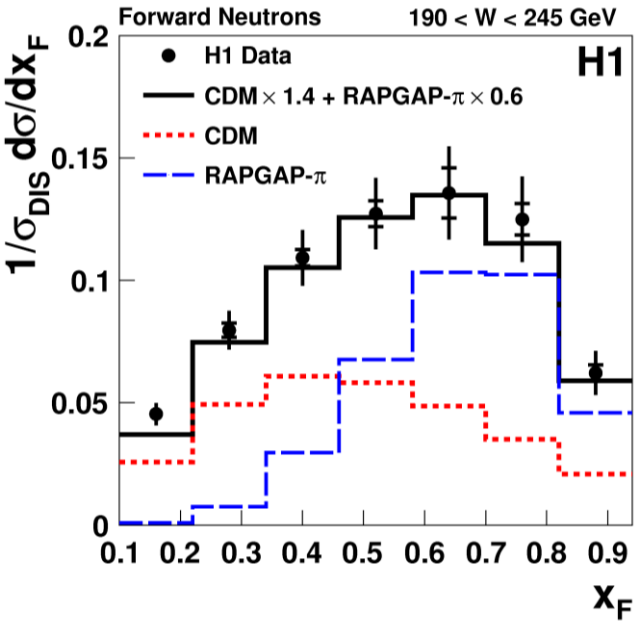
Longitudinal spectrum of leading neutron

- DIS, $Q^2 > 2$ (ZEUS) or 6 (H1) GeV^2
- large x_L $(0.6 < x_L < 0.9)$ can be explained by OPE (one-pion exchange)
  - Fragmentaion a la Pythia is not enough

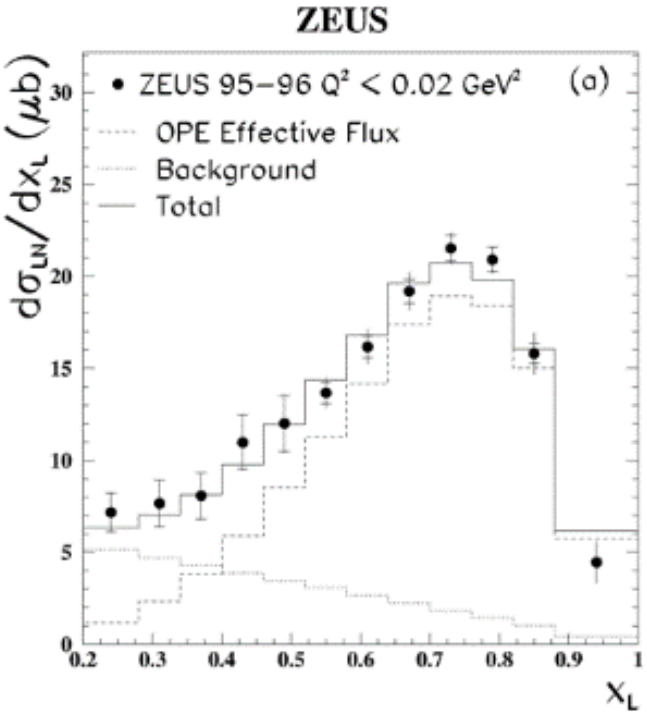




DESY-14-035

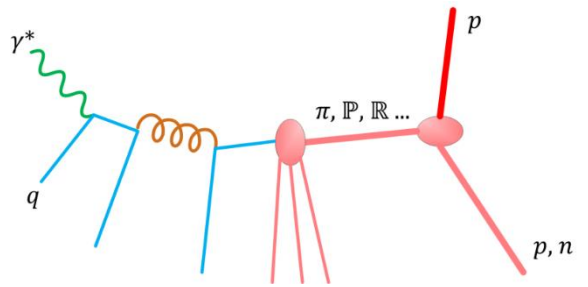


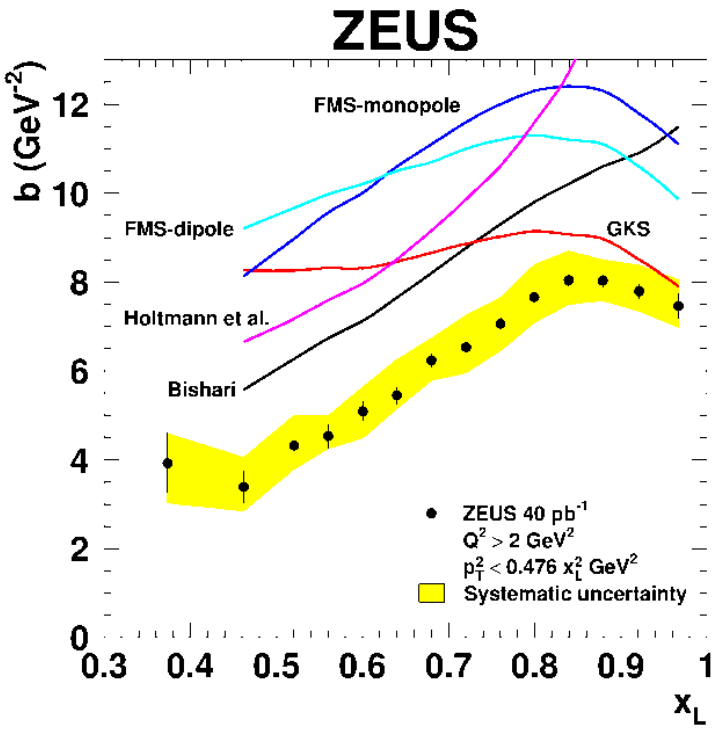
Nucl.Phys.B637(2002)3

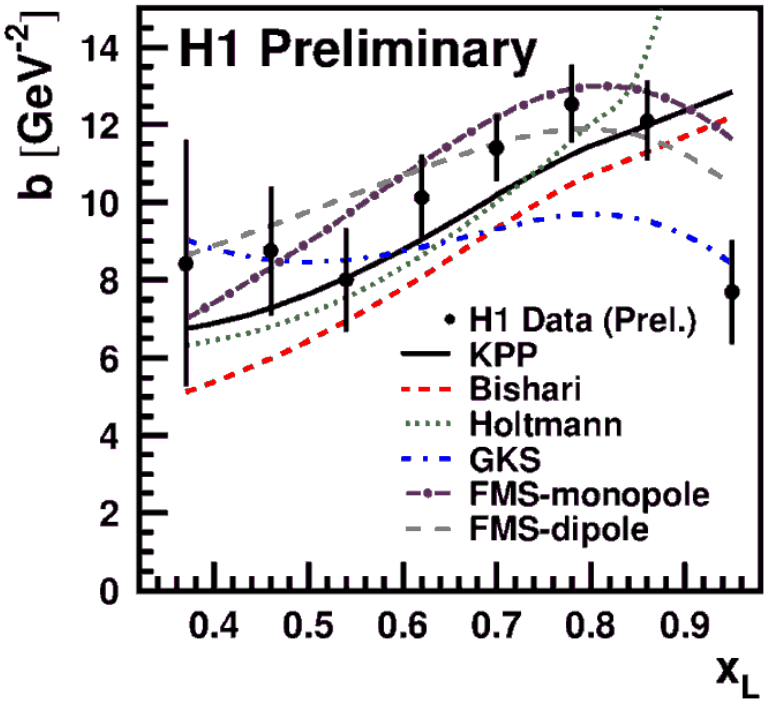


b-slope vs x_L for forward neutron

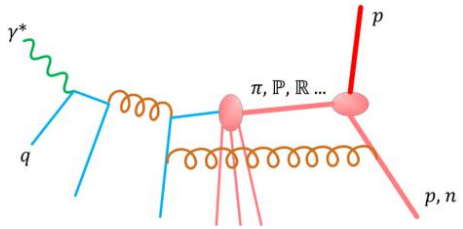
- $b \sim 7\ \mathrm{GeV}^{-2}$ on average: similar to proton
- but: strong x_L dependence
  - consistent with predictions based on pion flux $f_{\pi/p}$, supporting OPE hypothesis

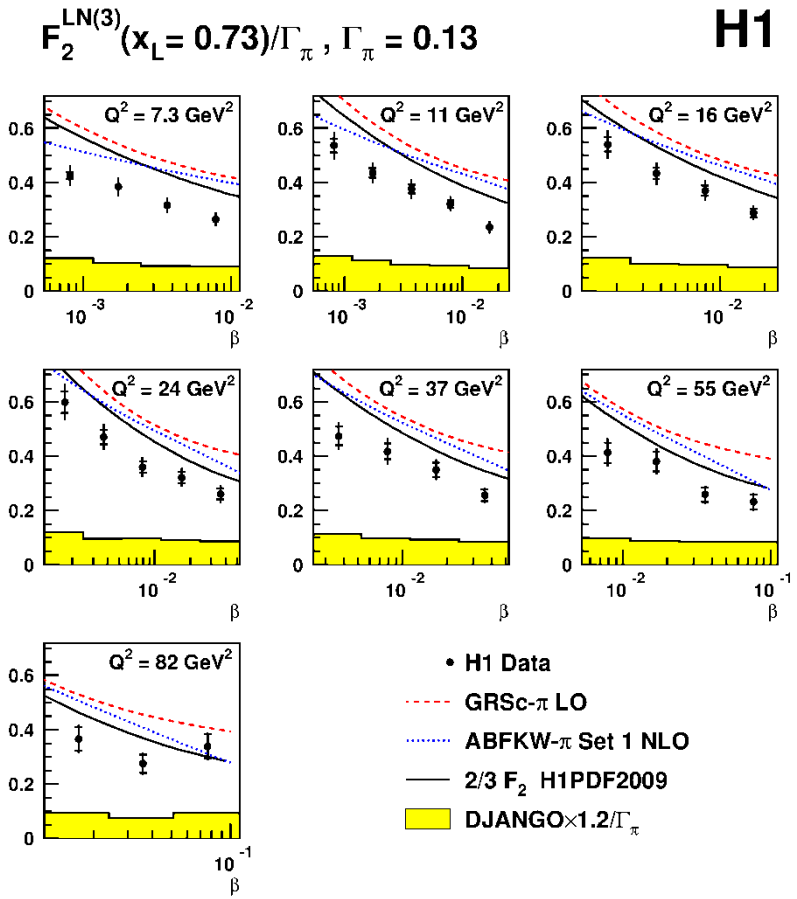


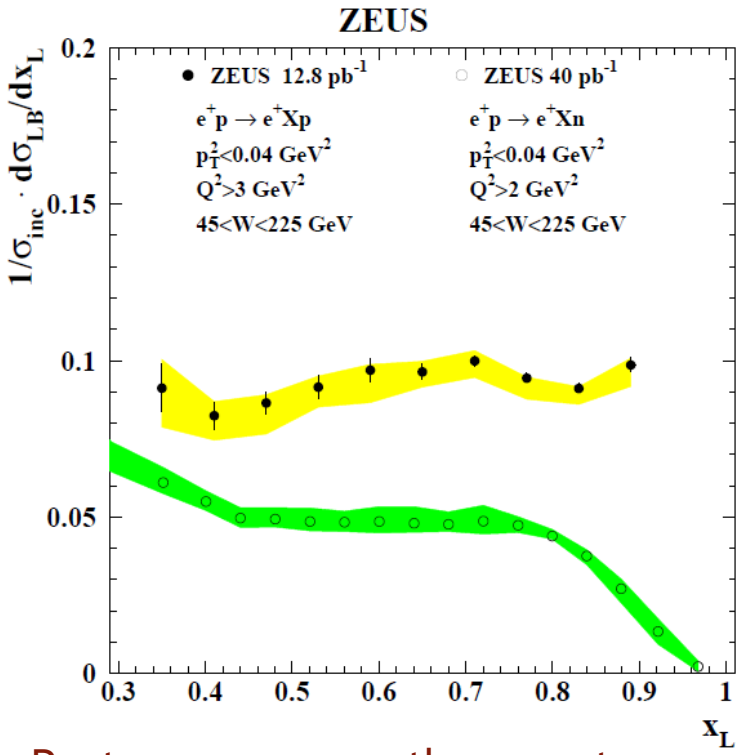




Proton and neutron yield in DIS







- Neutron yield is 20-30% fewer than naïve prediction of $p : n = 1 : 2$ expected from isovector exchange
- Absorbtion? Rescattering?

- Protons are more than neutron
  - .. at least in very forward region $p_T < 0.04$ GeV^2
  - Not consistent with isovector exch.

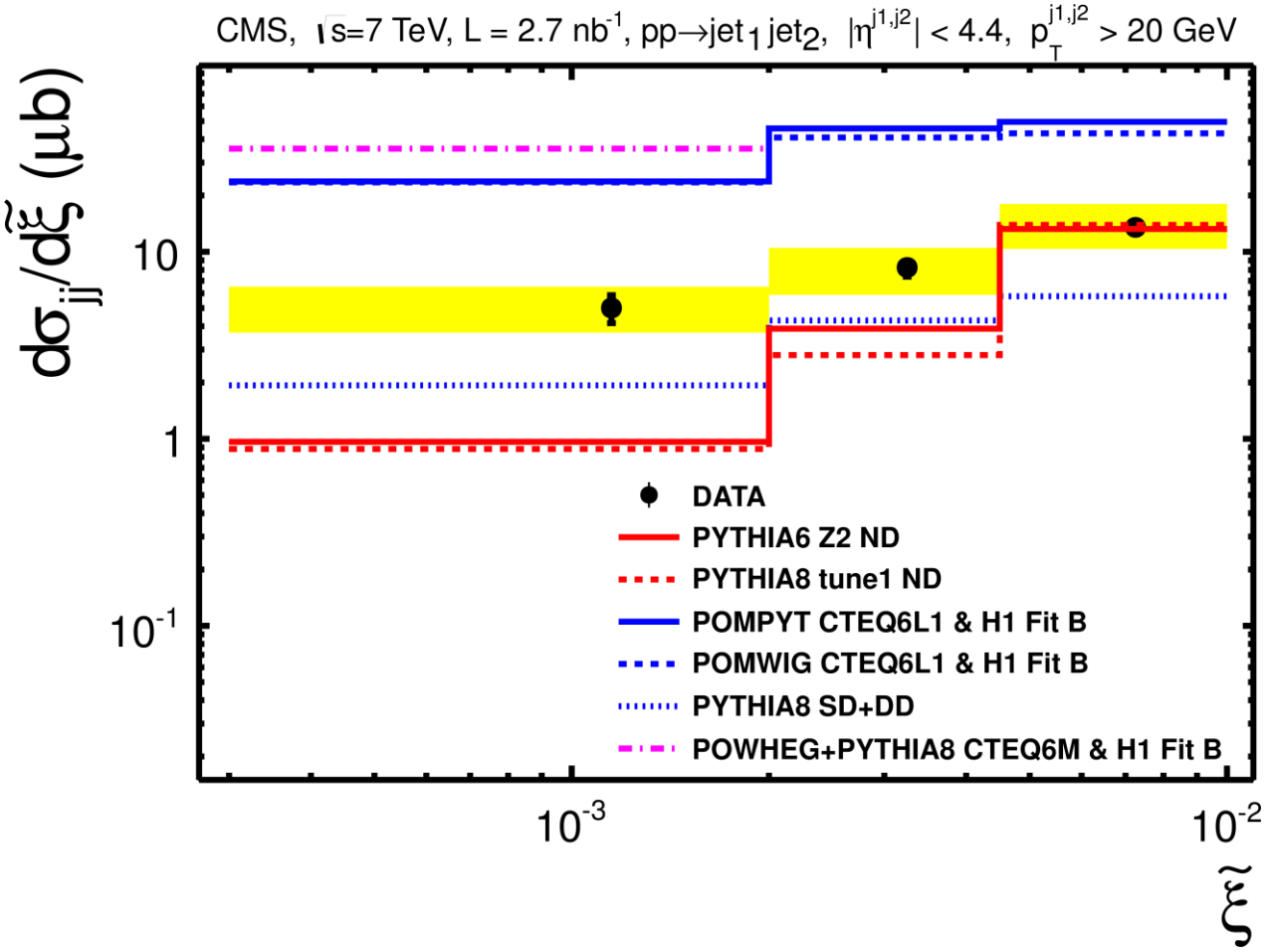
Where did neutron disappear?

Summary

- Diffraction: ~ long-range physics
  - semi-soft b-slope
  - consistent with (universal) Pomeron exchange, which has partonic structure
  - exception: vector meson production with hard scale
  - suppression at high energies? Perhaps.
- Leading (forward) baryons: also via long-range process
  - semi-soft b-slope
  - γ^* and proton are well separated
  - neutron suppressed
    - absorptive effect? Where did they go? A new measurement in different environment is awaited

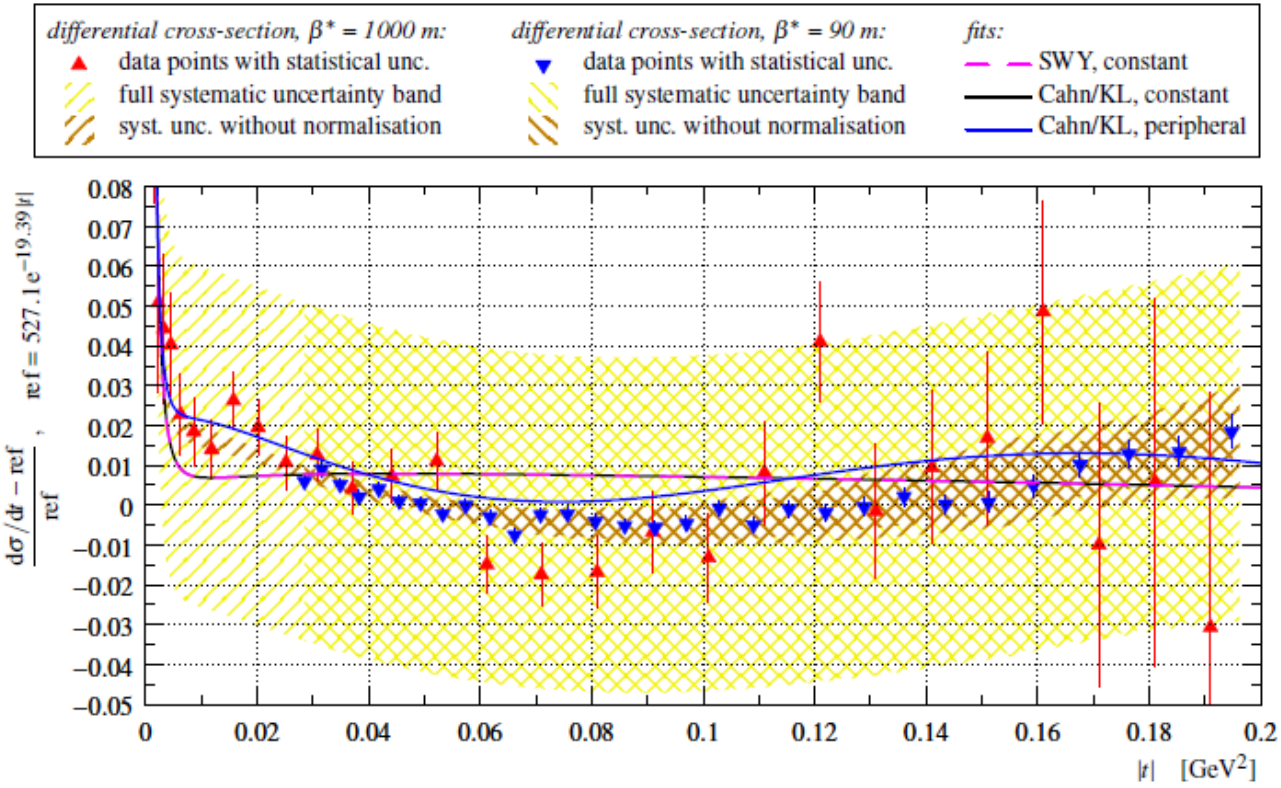
BACKUP

cf. CMS result



- You see a bit of excess over Pythia8 ND+SD+DD, in fact

Effect of Coulomb scattering

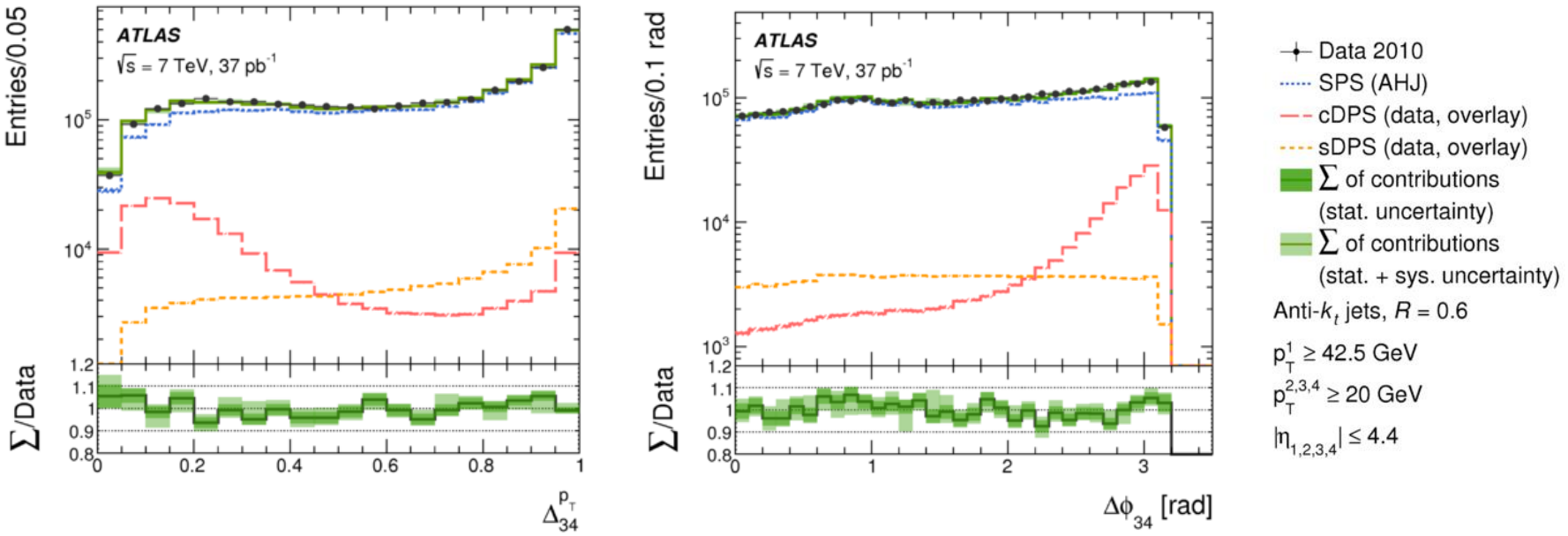


- Total cross section determined by extrapolating to t=0
  - need to take into account the Coulomb scattering and non-exponential slope
- interference around $|t|\sim 0.01$
- cross section only important below this range (not measured by ATLAS)

CERN-EP-2016-183 arXiv:1608.01857

Double-parton interactions through 4-jets

- two types of double-parton scattering signal in 4-jet events
  - "cDPI": complete-DPI, 2-jet ⊗ 2-jet
  - "sDPI": semi-DPI, 3-jet ⊗ 1-jet
    - 1jet missing from detection for the "second" scattering
  - and generic 4-jet events from single parton-scattering

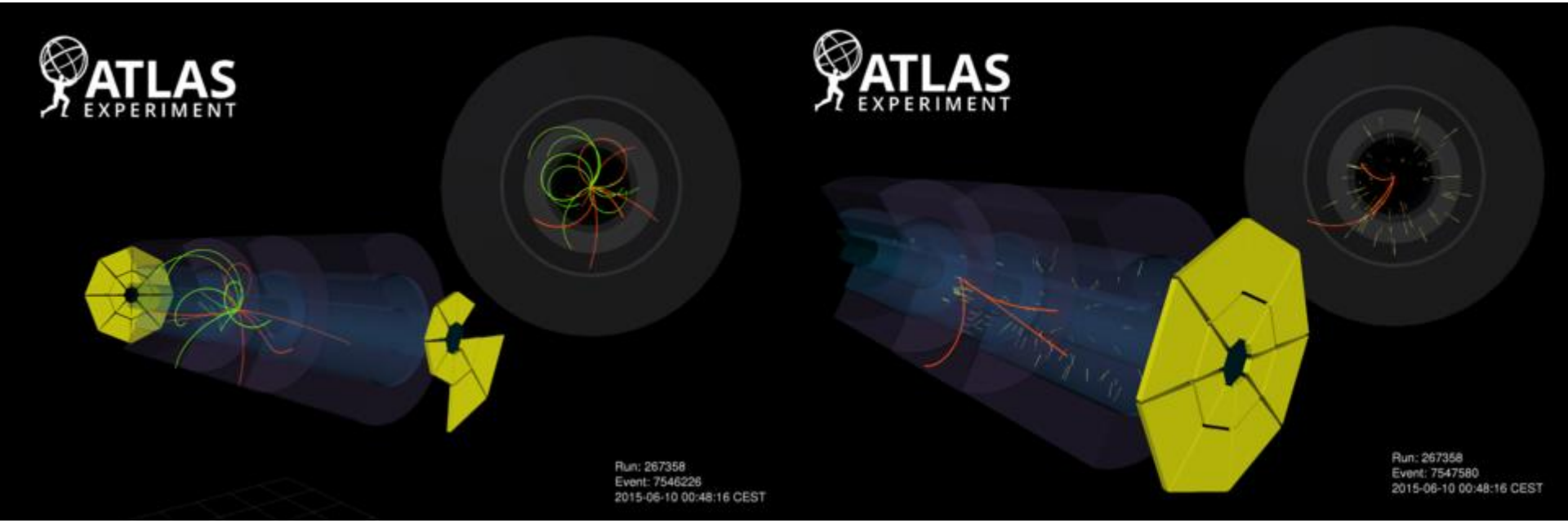


cDPI can be distinguished from the SPI, but sDPI not quite

CERN-EP-2016-140 arXiv:1606.02625

Inelastic cross section @ 13 TeV

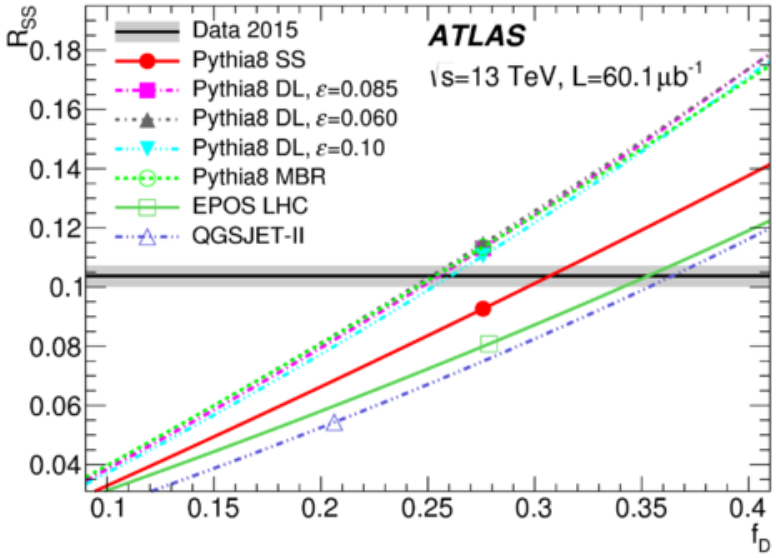
- MBTS (Minimum-bias trigger scintillators) to tag inelastic, SD (single-diffractive) and DD (double-) events
  - Covering $2.07 < |\eta| < 3.86$, corresp. to $\xi = M_X/s > 5 \times 10^{-6}$
- Other detectors including LHCf are used to calibrate the trigger efficiency MBTS



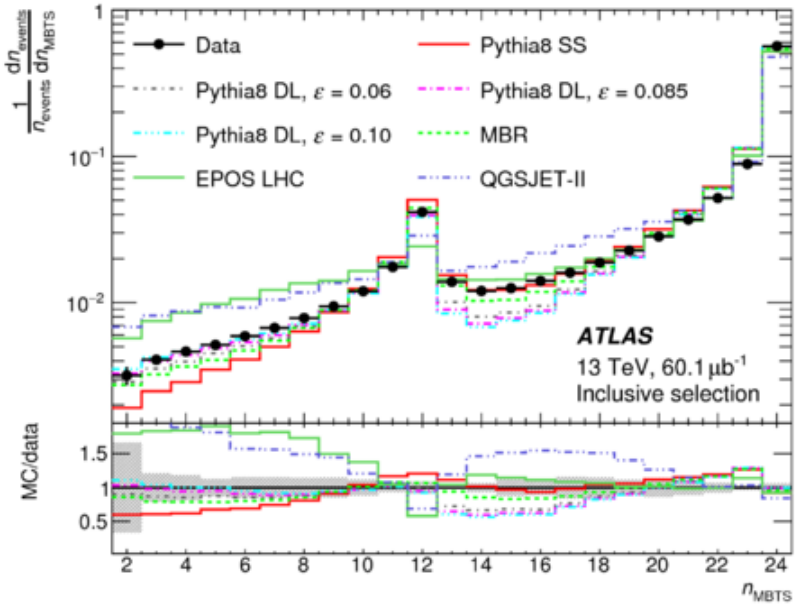
Inclusive events

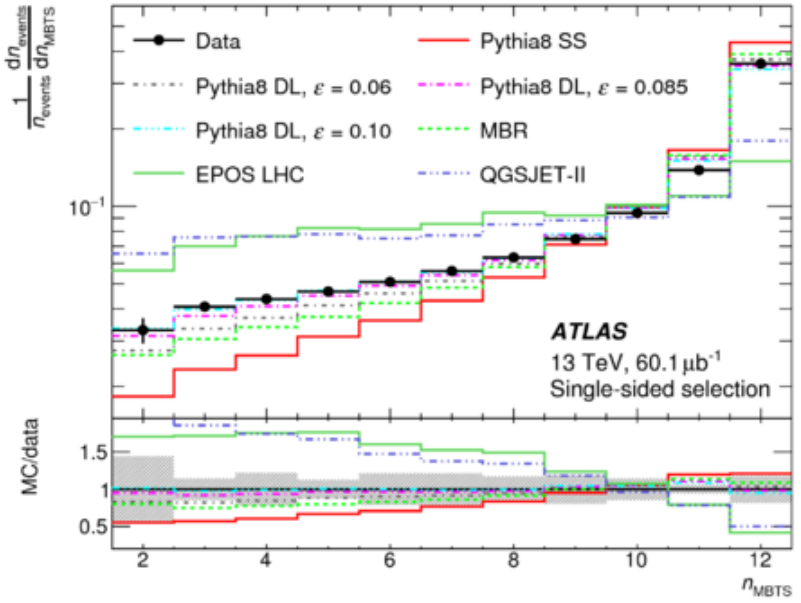
Single-sided events (mostly SD)

Diffractive fraction and MBTS hits

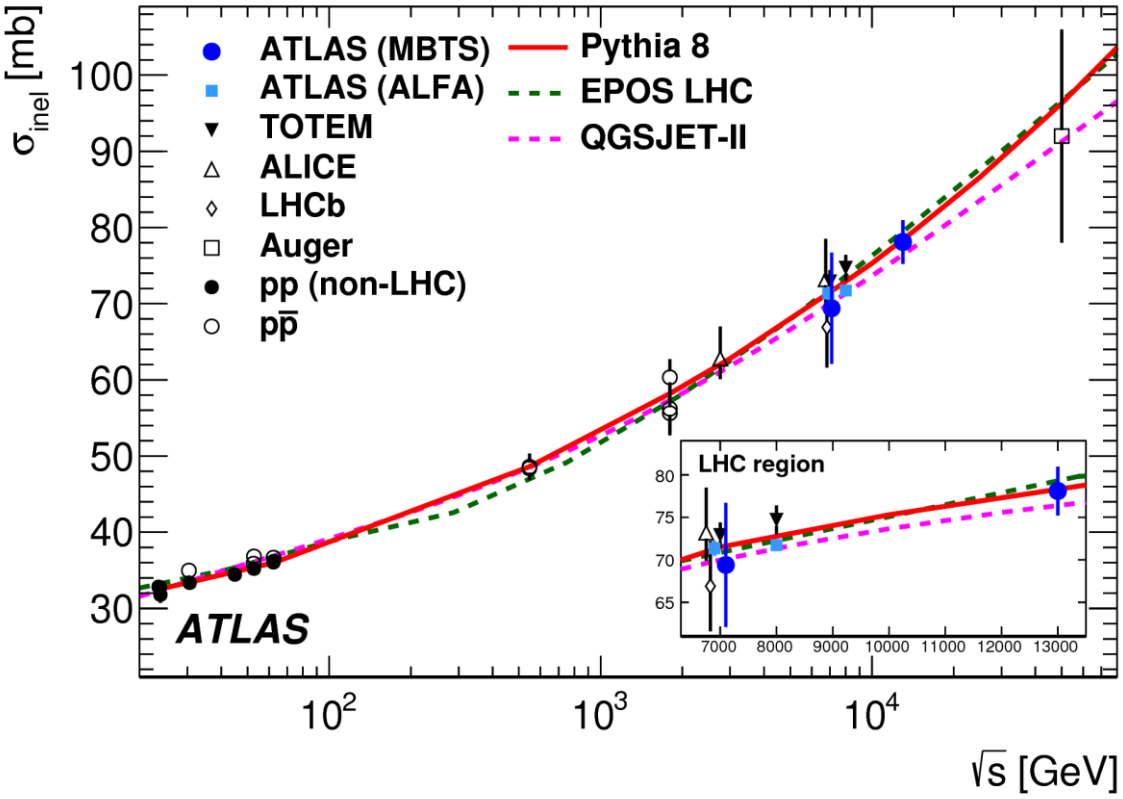


- R_{SS} = (single-sided)/inclusive
  - EPOS/QGSJET needs large diffractive fraction for explaining the observed R_{SS}
  - Mainly because of large multiplicity in the MBTS i.e. in forward rapidity





13 TeV inelastic cross section σ_{inel}



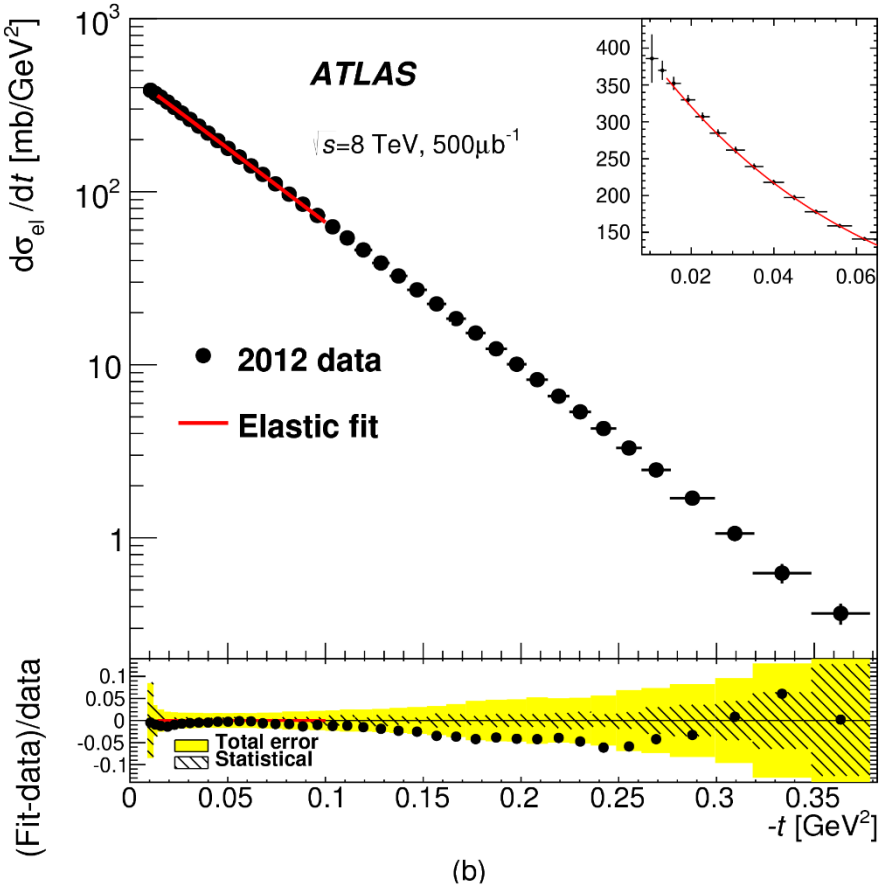
- Uncertainty due to the diffractive fraction f_D is small
- Extrapolation for $\xi < 5 \times 10^{-6}$: 9.9 ± 2.4 mb
  - "total" inelastic: $\sigma_{\mathrm{inel}} = 78.1 \pm 0.6(\mathrm{exp}) \pm 2.4(\mathrm{extrap.})$ mb

Phys. Lett. B (2016) 158

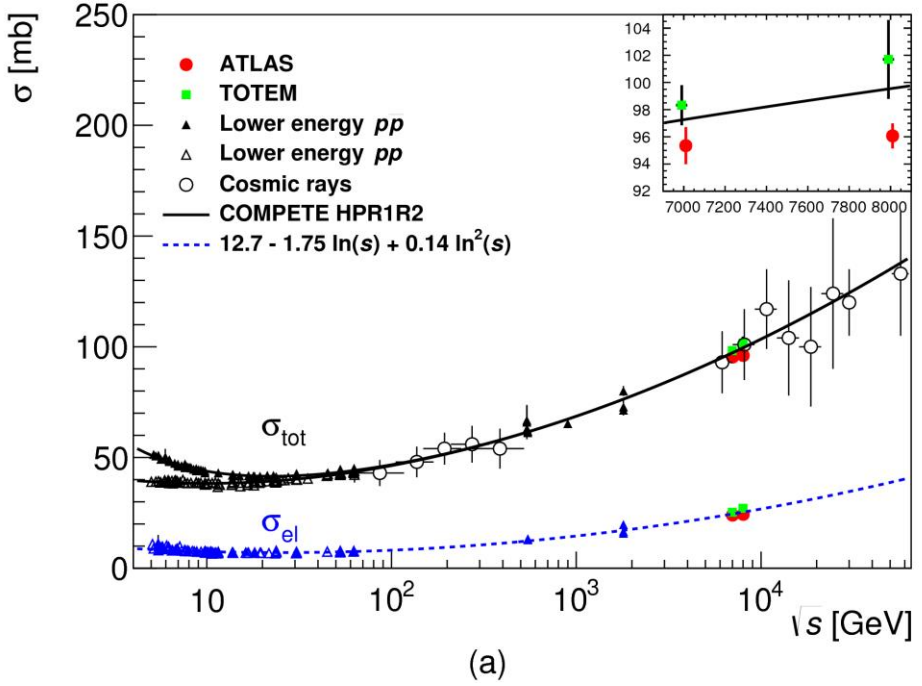
Total cross section from optical theorem

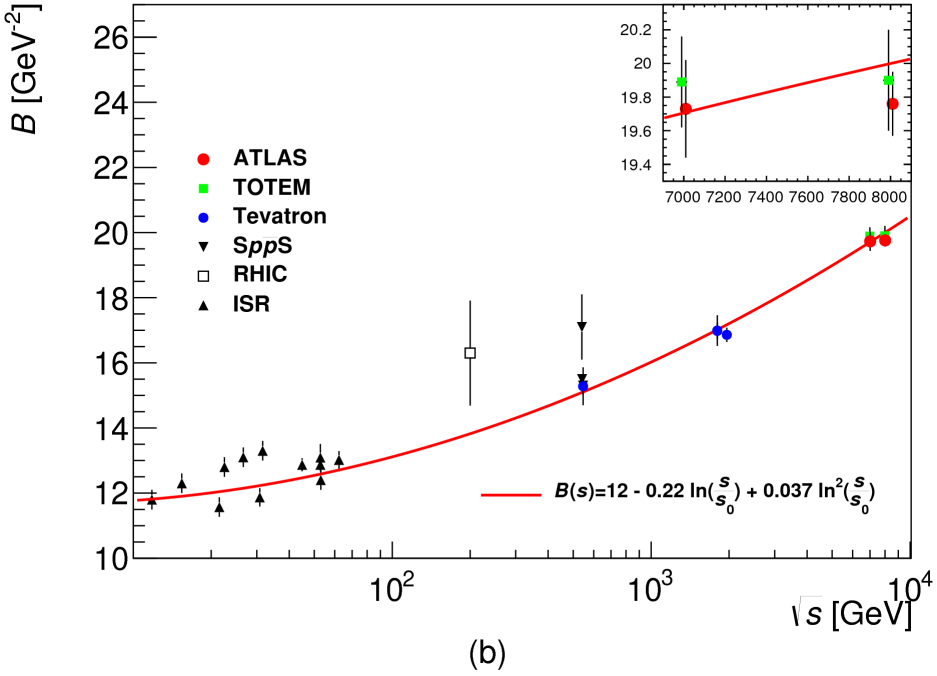
- t –distribution measured by double-arm Roman pots
  - ALFA scintillating fibres by ATLAS
  - TOTEM around the CMS IP
- ALFA uses luminosity for absolute cross section
- TOTEM does not depend on luminosity measurement

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{\left(\frac{dN_{el}}{dt}\right)\Big|_{t=0}}{(N_{el}+N_{inel})}$$



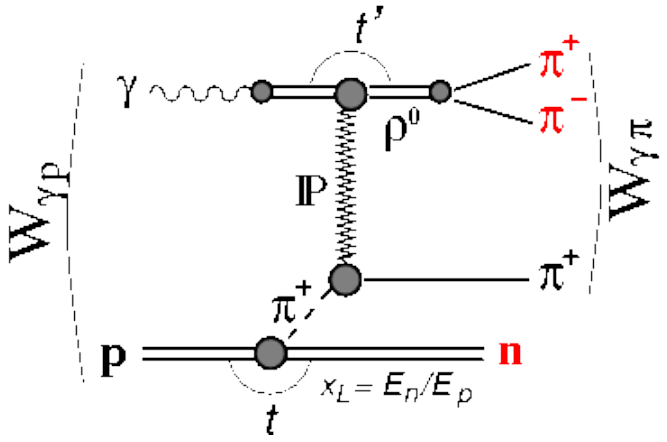
Results



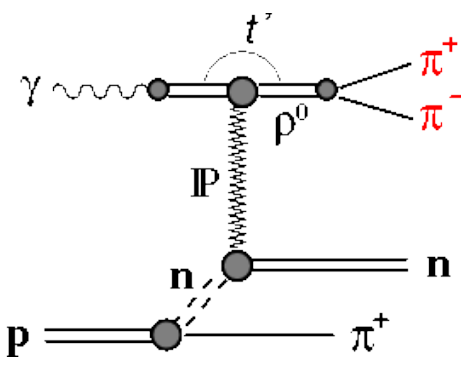


- Some tension between two results
  - slope results agree, though

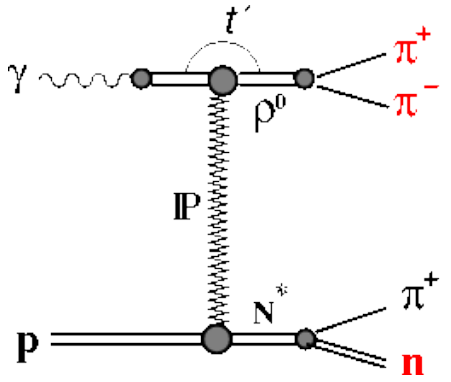
ρ^0 photoproduction with a neutron



(One-) Pion Exchange (OPE) dominant at high x_L



neutron exchange

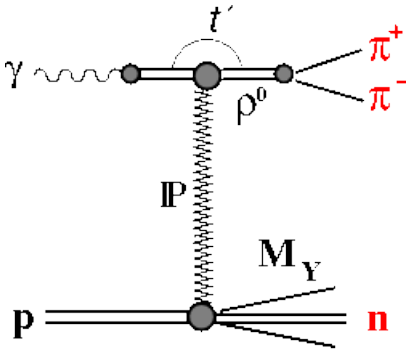


through decay of N*

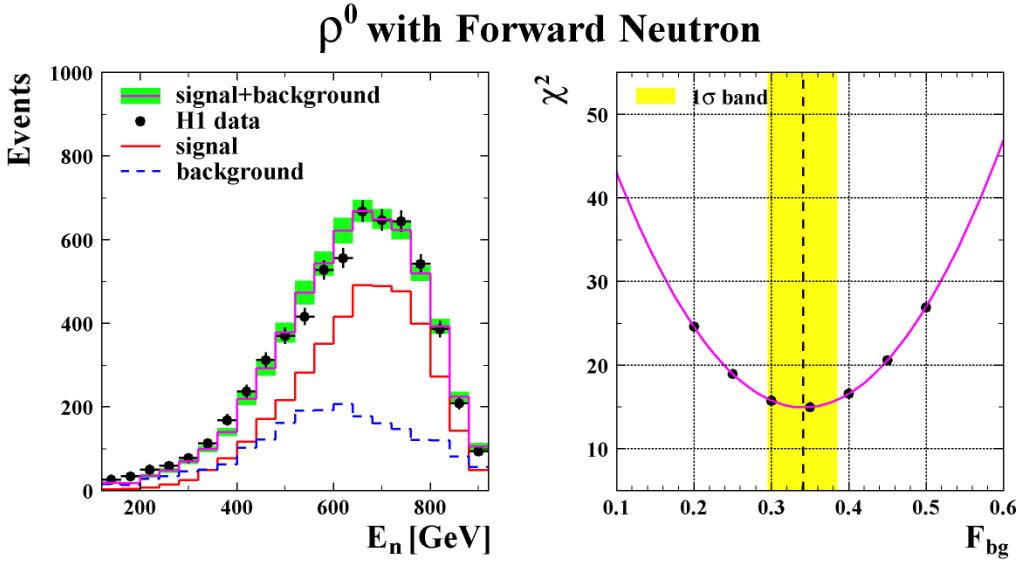
cancelling (opposite sign in amplitude)

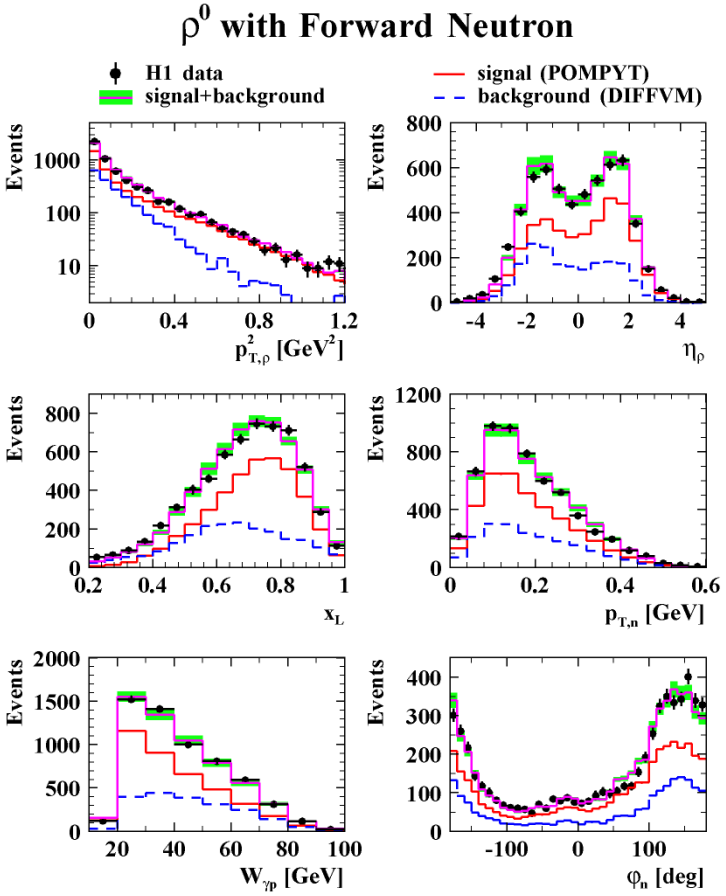
- Difference from inclusive neutron production
- Accessing $\gamma\pi$ diffraction

Background: neutron from proton-dissociated system Y



$\rho^0 + n$: Background subtraction



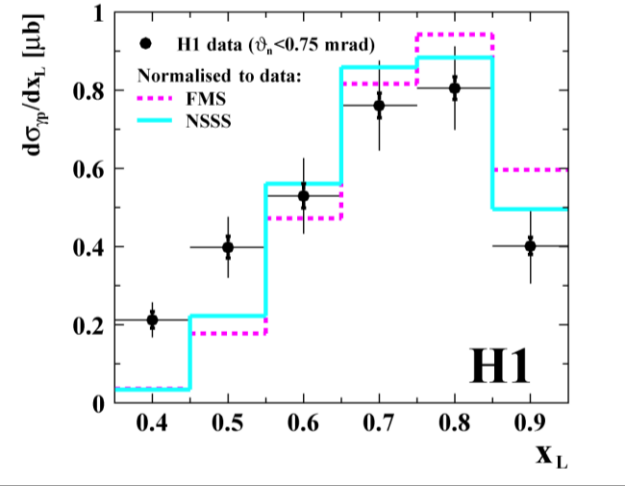


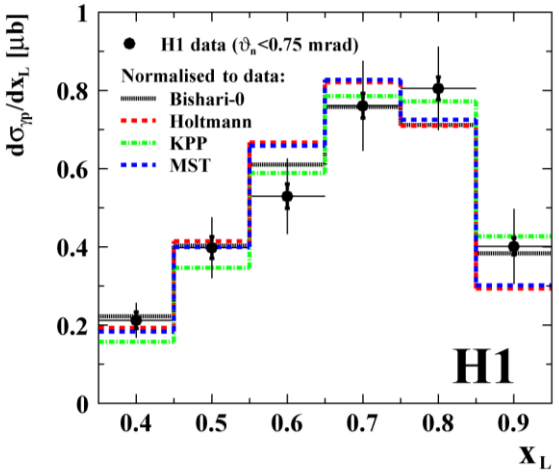
- Using shape difference in x_L
  - OPE is dominant at high x_L $(0.65 < x_L < 0.95)$
- Proton dissociative background is subtracted hereafter

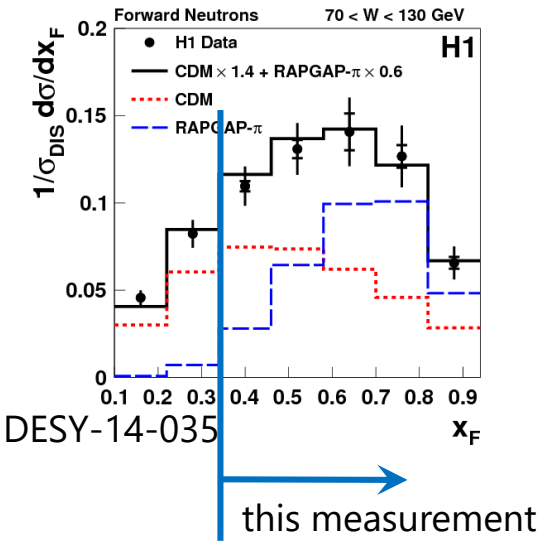
Good description of data with thus determined background fraction

$\rho^0 + n$: γp cross sections

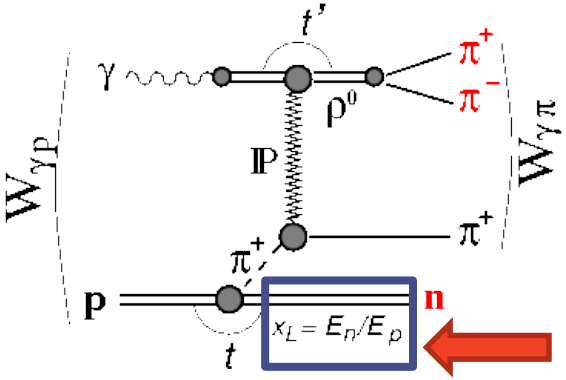
inclusive spectrum in DIS (blue-dashed: OPE contribution)





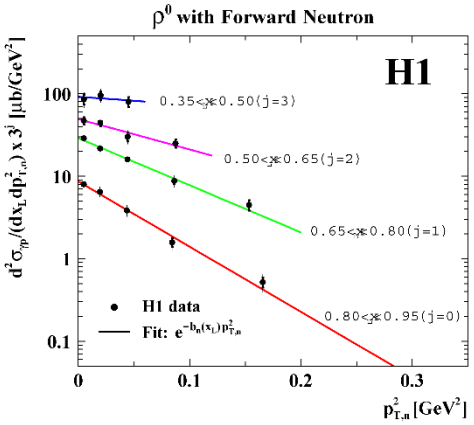


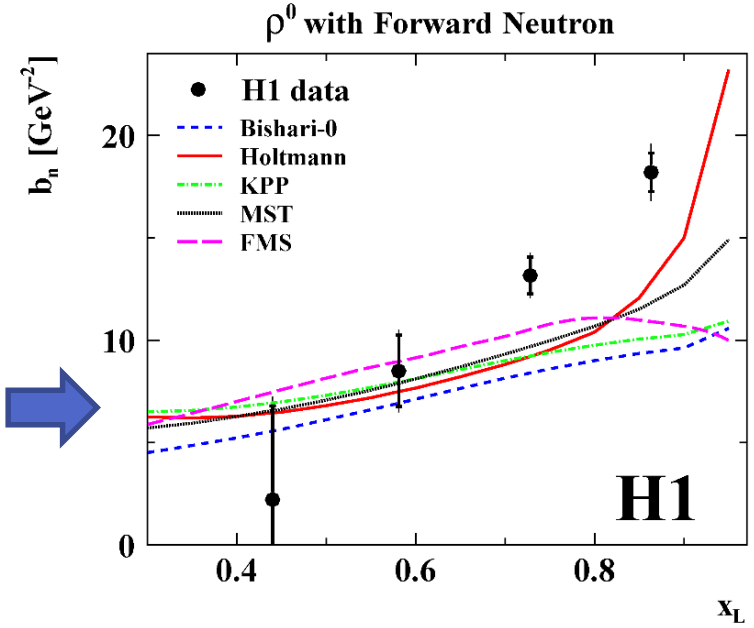
$20 < W_{\gamma p} < 100$ GeV
$0.35 < x_L < 0.95$
$t' < 1\ \mathrm{GeV}^2$

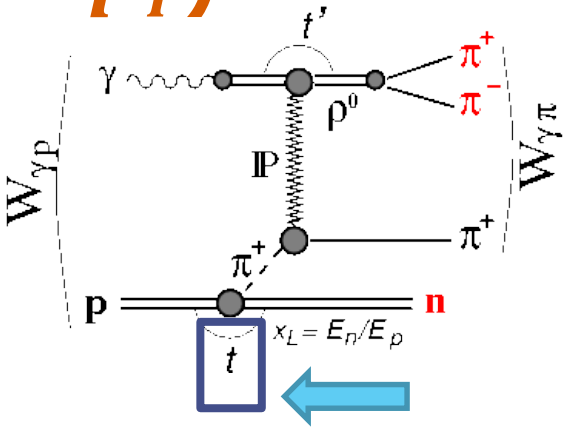


- Similar shape as the inclusive neutron
  - factorisation at proton-neutron vertex
- Well described by many of models
  - except for FMS and NSSS
- **Absolute cross section: $\sigma_{\gamma\pi}/\sigma_{\gamma p} = 0.25 \pm 0.06$**
  - **smaller than additive quark model ($\simeq 0.6$)**
  - **absorption?**

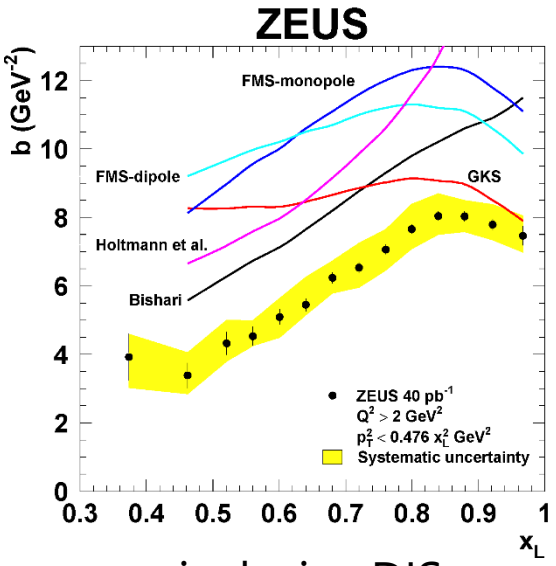
$\rho^0 + n$: t-distribution (neutron p_T)





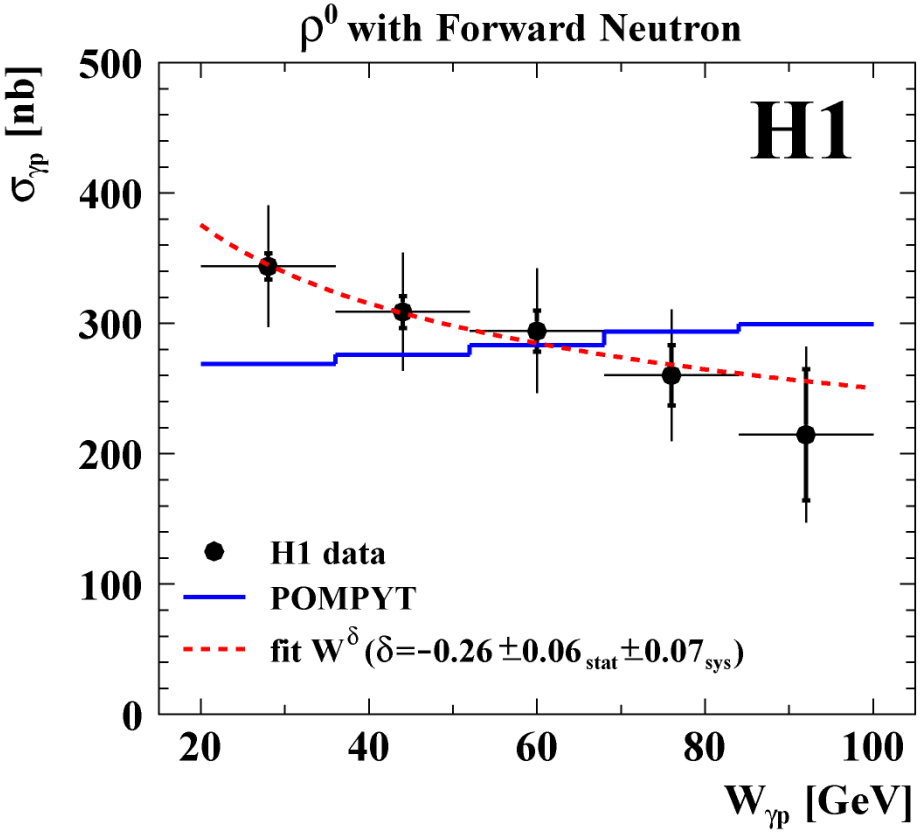


- Steeply falling (i.e. high b parameter) at very high x_L
  - Not observed in inclusive neutron production
  - Absorption of "large configuration" ?
  - Some models predicted qualitatively



inclusive DIS

$\rho^0 + n$: W-dependence



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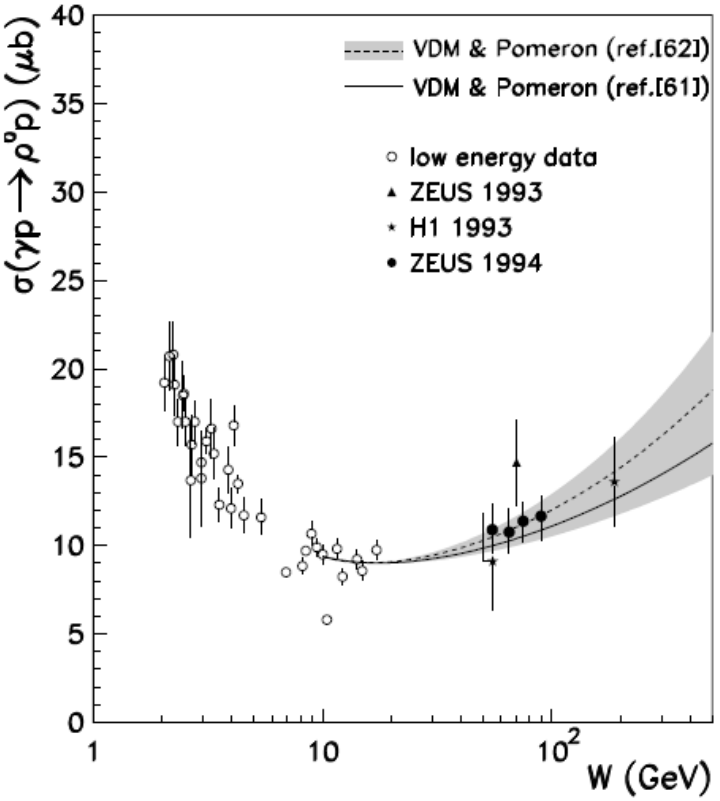
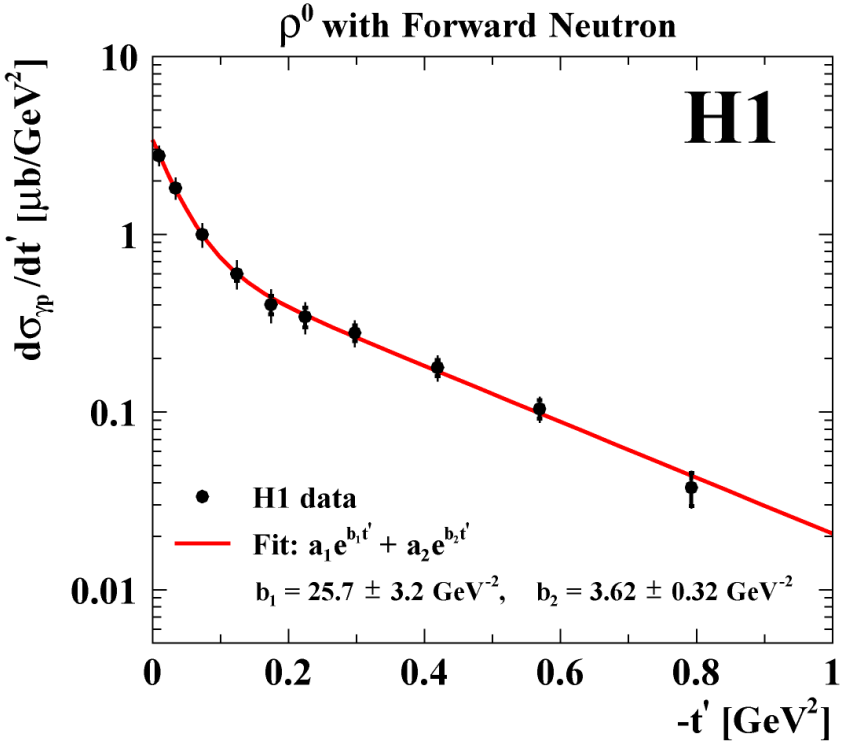
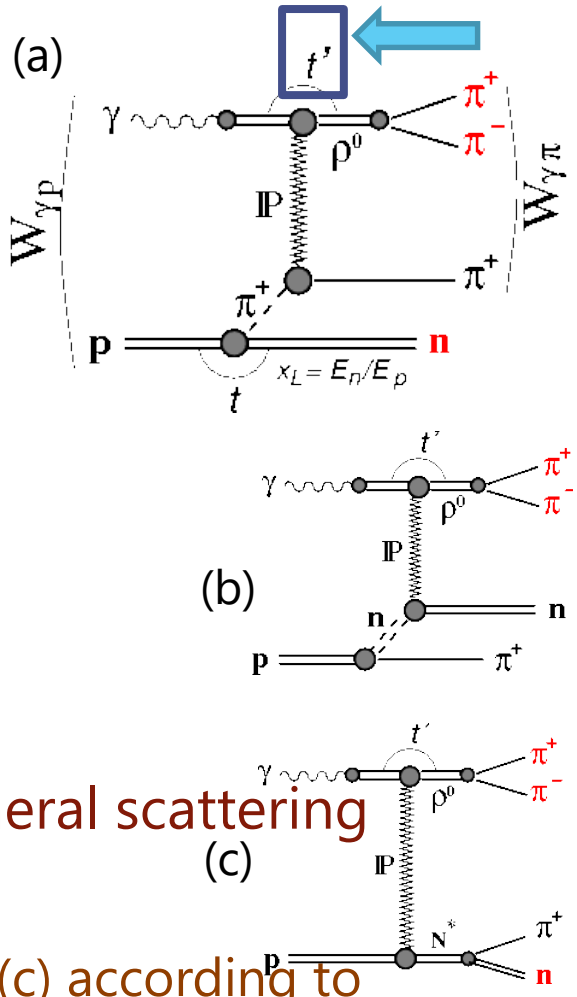


- Pomeron trajectory: $\delta \simeq 0.08$
- $\gamma p \to \rho^0 p$ at HERA prefers to increase with W
- Different for $\gamma\pi \to \rho^0\pi$?

t'-dependence ($\gamma\pi$ scattering mom. transf.)





- $b_1 \sim 25\ \mathrm{GeV}^{-2}$: diffractive peak - very peripheral scattering
- $b_2 \sim 3.5\ \mathrm{GeV}^{-2}$:
  - Interference between various diagrams (a)–(c) according to double-peripheral process (π, $\mathbb{P}$) ?
  - "Pion dissociation" component?