Exclusive Vector Meson Production at HERA and the LHC

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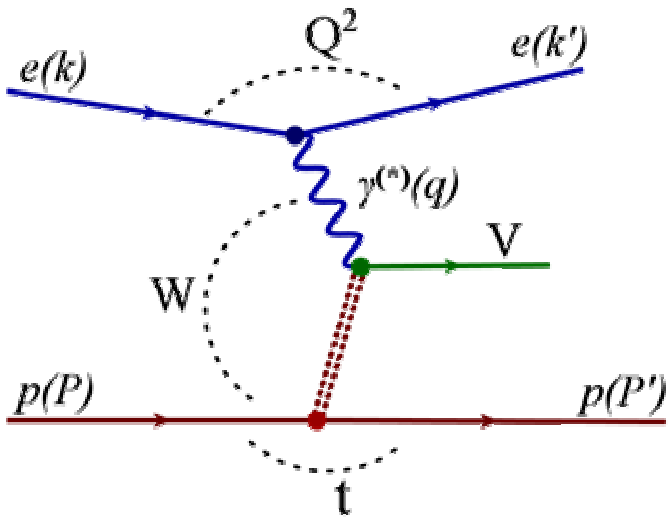
- **Exclusive VM production at HERA : transition from soft to hard regime**
- **Exclusive photoproduction of J/Ψ at HERA**
- **Exclusive production of J/Ψ in p-p and heavy-ion ultra-peripheral collisions at the LHC**
- **Summary**

3rd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society

Various Faces of QCD

Świerk, October 8-9, 2016

Vector meson production extensively studied at HERA



$V\ (J^{PC} = 1^{--}) = \rho, \omega, \phi, J/\Psi, \Psi', \Upsilon$

Q^2	virtuality of the exchanged boson
W	γ-p centre – of – mass energy
t	(4-momentum transfer)^2 at the proton vertex

$Q^2 >> 1\ GeV^2$ deep inelastic scattering (DIS)

$Q^2 \approx 0\ GeV^2$ photoproduction

Diffractive vector meson production : t-channel exchange of a colourless object with vacuum quantum numbers (Pomeron, IP)

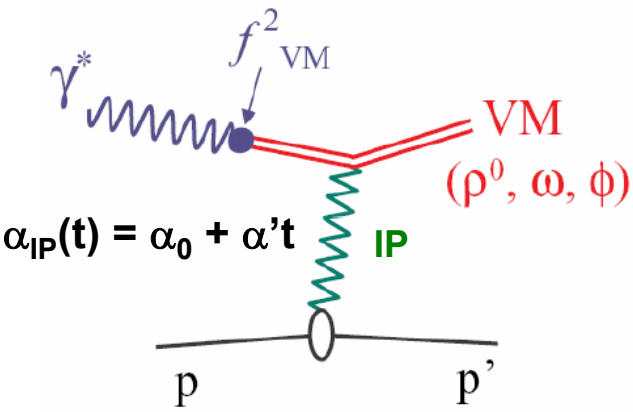
$|t| < 1\ GeV^2$: the proton stays intact, high |t|: proton dissociates to a low mass excited state

Experimental signature :

- Notably two-prong decays via charged decay products ($\rho^0 \to \pi^+\pi^-$, $\phi \to K^+K^-$, $J/\Psi \to e^+e^-$/ $\mu^+\mu^-$)
- No additional activity beyond the noise level in the detector
  (except that associated with the scattered electron)
- Proton dissociative processes: activity in forward detectors

Soft and hard Pomeron exchange

Soft Pomeron exchange



Vector Dominance Model + Regge phenomenology

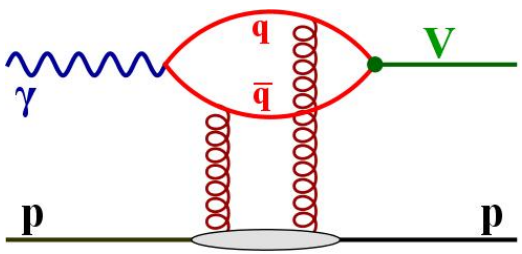
$\alpha_0 = 1.08$, $\alpha' = 0.25$ GeV^{-2} (Donnachie&Landshoff)

$$\sigma^{\gamma p \to Vp} \propto W^{4(\alpha_{IP}-1)} \propto W^{\delta}, \qquad \delta \approx 0.22$$

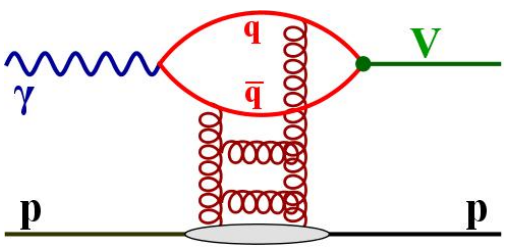
$d\sigma/dt \sim \exp(-b(W)|t|) \rightarrow$

transverse size of the interaction region : $b \sim R_{int}^2 \approx 10$ GeV^{-2}

Hard Pomeron diagrams



LO: 2-gluon exchange



LL 1/x – BFKL Pomeron

Perturbative QCD

Hard scales: Q^2, M_{VM}, t → small $q\bar{q}$ dipoles

Proton rest frame – dipole approach

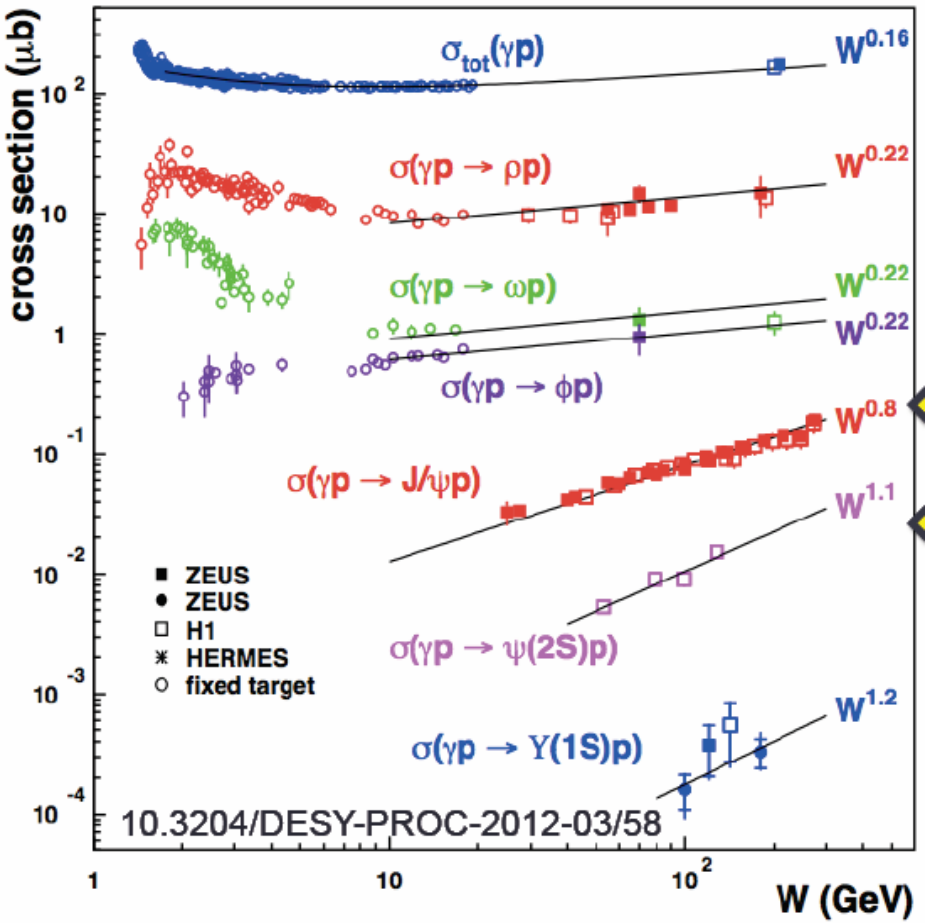
- The virtual photon fluctuates into a $q\bar{q}$ pair
  → a colour dipole of transverse size $r_\perp \sim 1/\sqrt{Q^2}$
- The dipole scatters elastically from the proton
  (dipole cross section)
- The outgoing dipole hadronises to VM
  (non-perturbative VM wavefunction)

► LO : $\sigma^{\gamma p \to Vp} \sim (xg(x))^2 \sim W^{\delta}$ (skewing effects neglected)
cross section sensitive to gluon density !

► $\delta \approx 0.7$ (J/Ψ prod.), $b \ll 10$ GeV^{-2} (~ 4-5 GeV^{-2})

Vector mesons at HERA : energy dependence

Various VM photoproduction cross sections as a funcion of $W_{\gamma p}$: $\sigma \sim W_{\gamma p}^{\delta}$



- VM mass sets the QCD scale

- small M_{VM} (~ 1 GeV) :
  transverse size of dipole ~ size of proton

- large M_{VM} : small dipole size,
  dipole resolves partons in the proton:
  $\sigma \sim (xg)^2 \rightarrow$ large δ

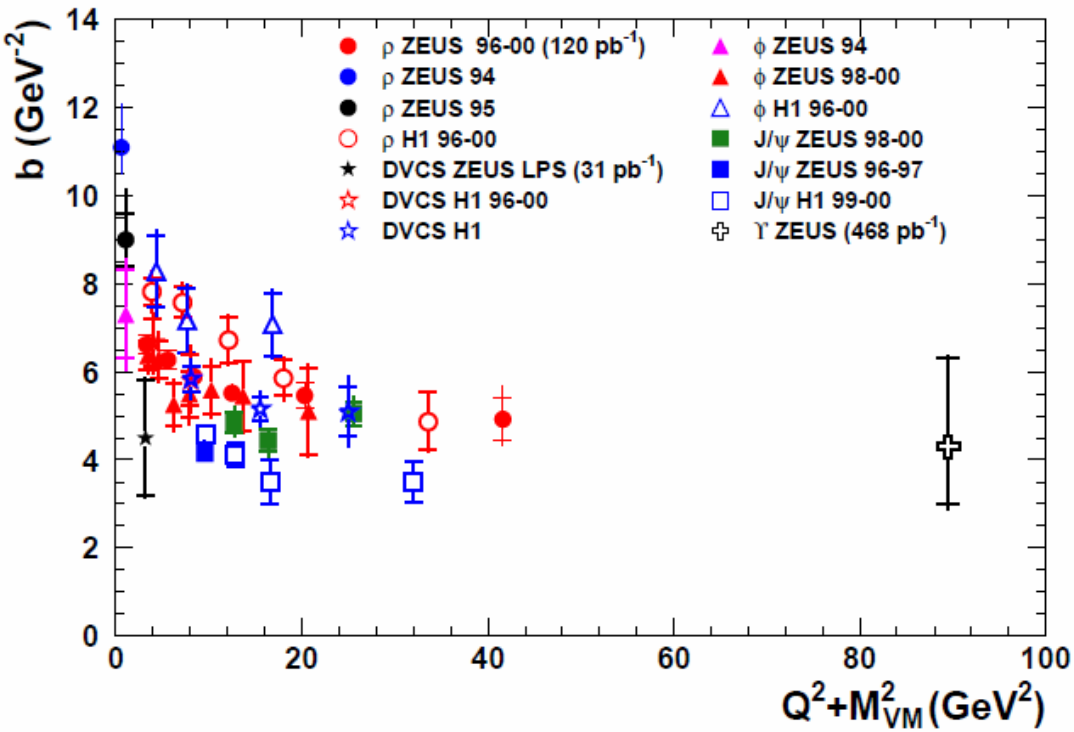
Increasing gluon density with decreasing x
→ the rapid rise of cross section with W
($x \sim 1/W_{\gamma p}^2$)

- Large parton densities at low x

→ phenomena of parton saturation
and non-linear evolution
may become important

VM production at HERA: transition from soft hadronic to perturbative behaviour

Vector mesons at HERA : t dependence



$d\sigma/dt \sim e^{-b|t|}$

$b = b_{VM} + b_p$

$b_{VM} = 1/(Q^2 + M_{VM}^2)$

⇒ **Convergence towards an asymptotic value of b ~ 5 GeV^{-2} measuring the proton size**

$b_p \rightarrow$ size of the gluons area

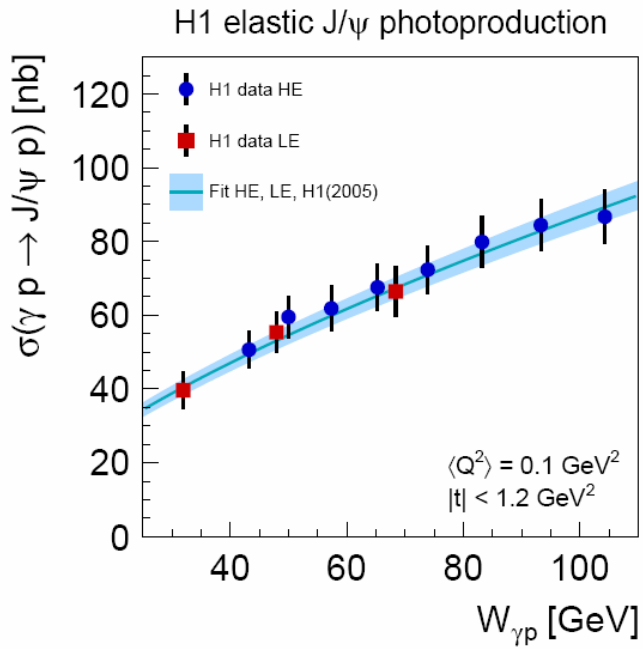
$\langle r^2 \rangle = 2b_p \cdot (\hbar c)^2 \sim 0.6$ fm

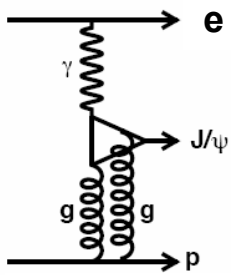
$r_{em} \sim 0.8$ fm

- Decreasing slope (and interaction size) with rising scale $Q^2 + M_{VM}^2$
  → transition from soft and hard regime
- The gluon radius of the proton may be smaller than its quark radius

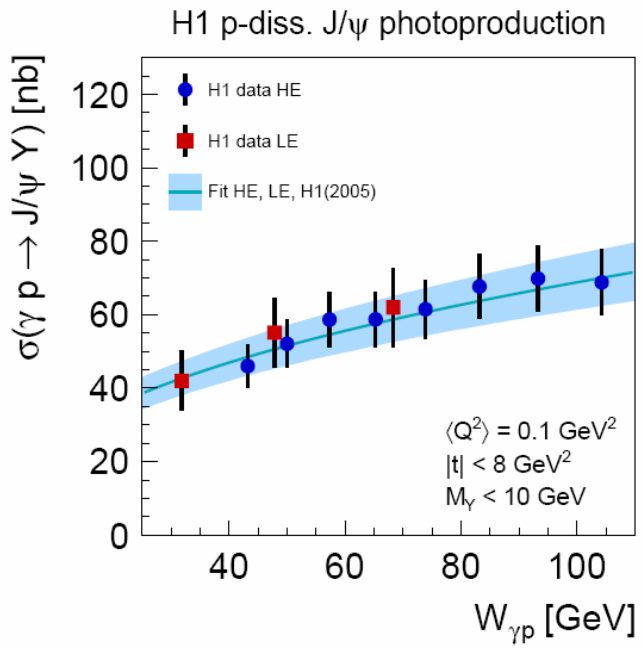
Photoproduction of J/Ψ mesons at HERA

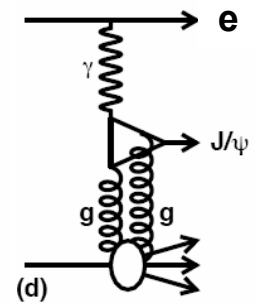
H1 [EPJ **C73** (2013) 2466], **HE: $\sqrt{s} \approx 318$ GeV, LE: $\sqrt{s} \approx 225$ GeV**

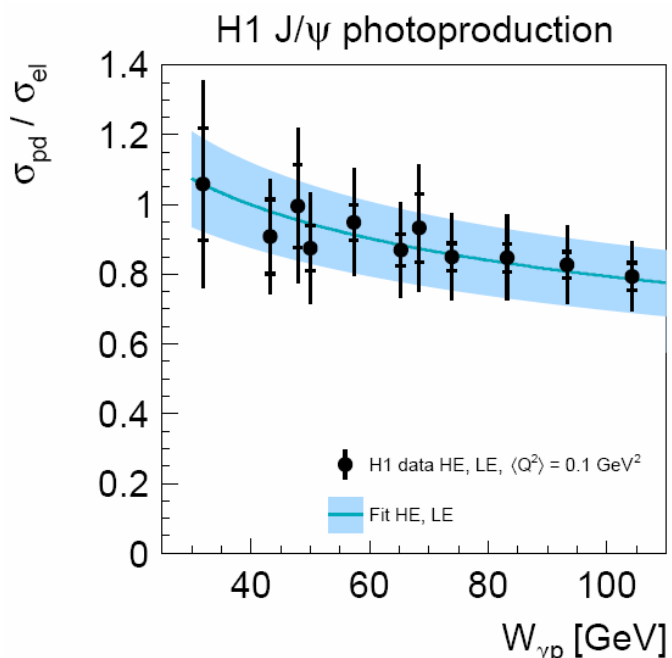




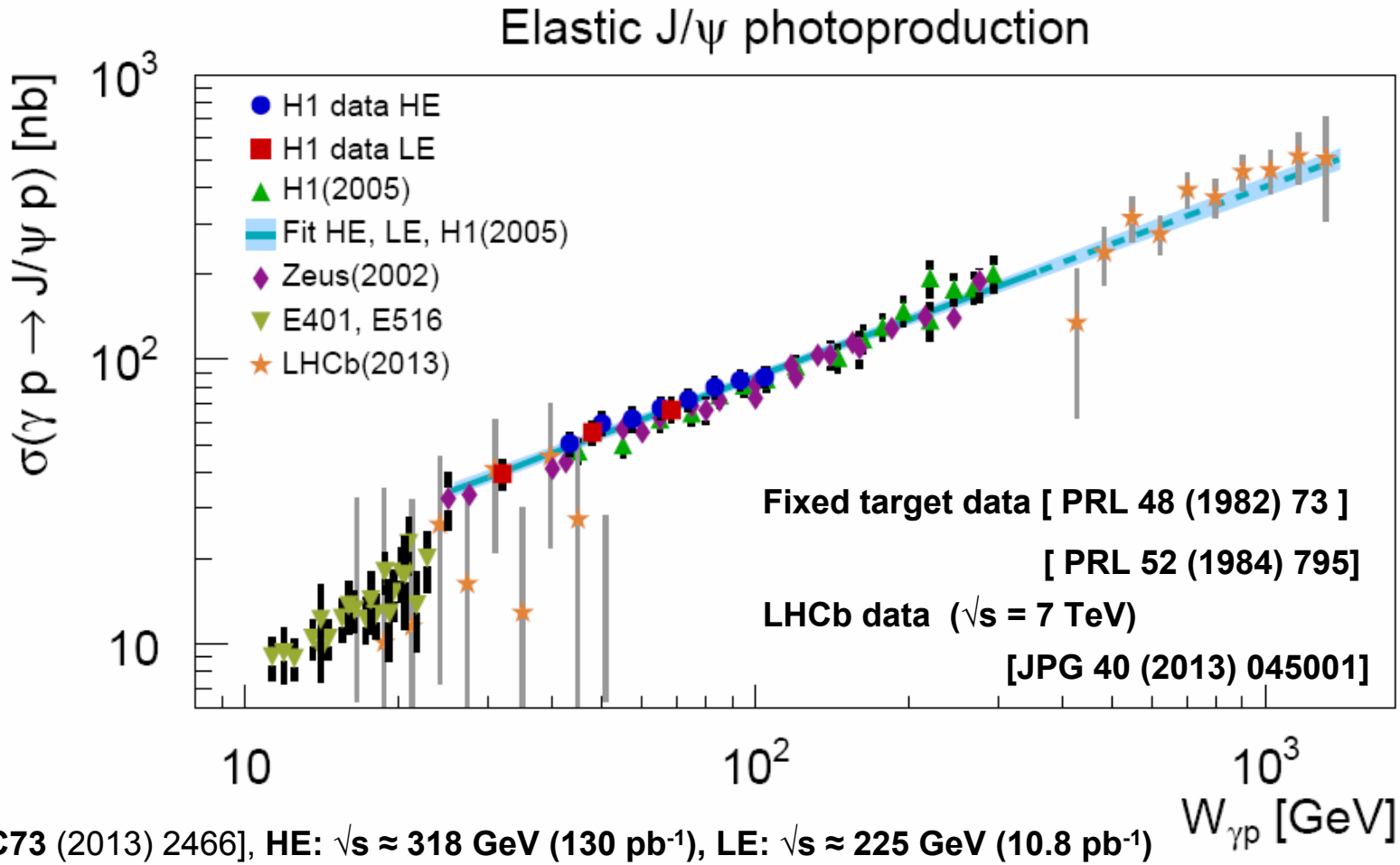
- **Simultaneous unfolding of elastic and proton-dissociative channels**
- **Both e^+e^- and $\mu^+\mu^-$ decay channels**
- **Energy dependence: $\sigma \sim W_{\gamma p}^{\delta}$**
  $\delta_{el} = 0.67 \pm 0.03$, $\delta_{p\text{-}diss} = 0.42 \pm 0.05$
- **Ratio of the p-diss to elastic J/Ψ cross section decreases with increasing $W_{\gamma p}$ (E. Gotsman et al. : $W_{\gamma p}$ dependent survival probablity for the p-diss process)**







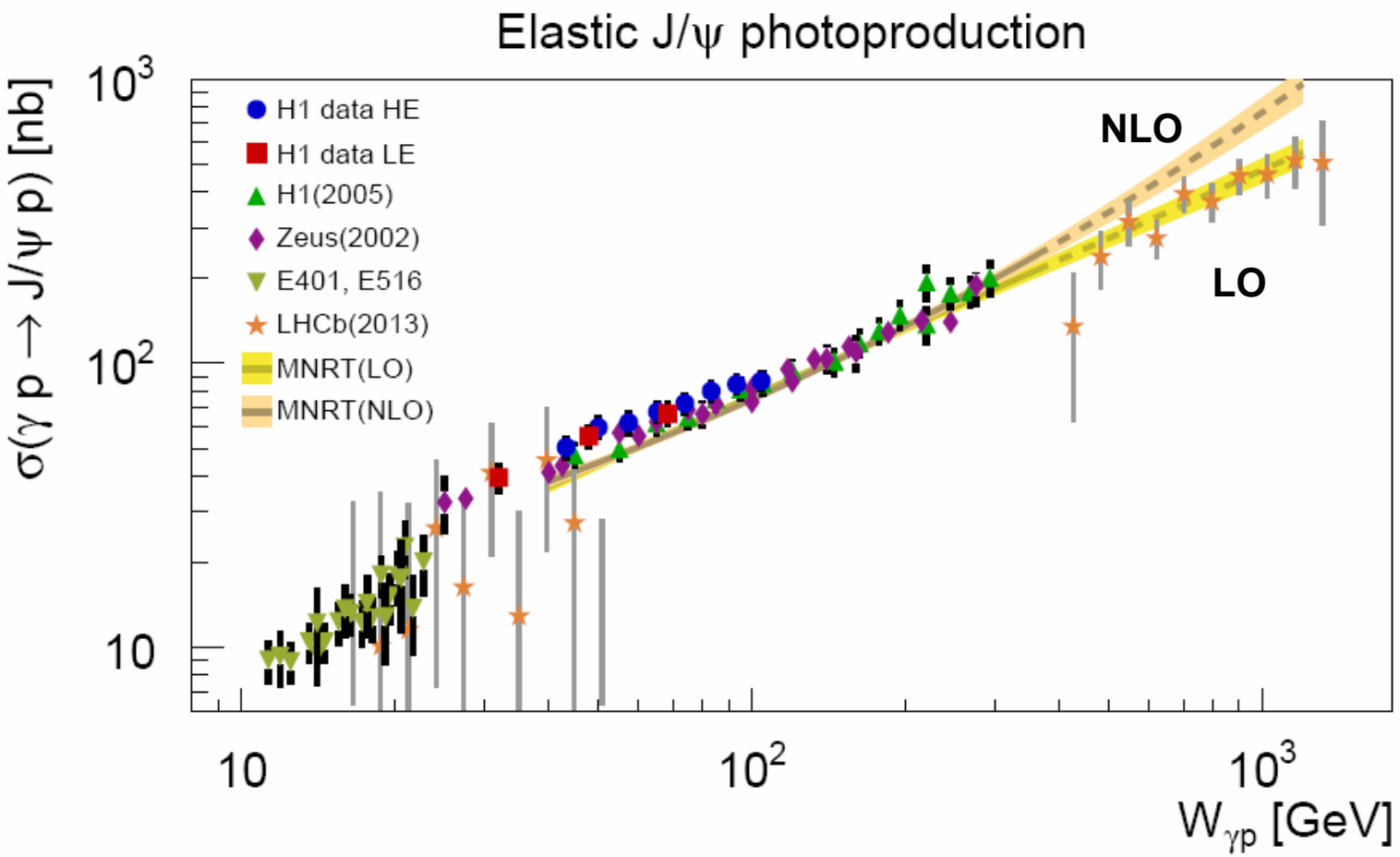
Exclusive photoproduction of J/Ψ mesons



[EPJ **C73** (2013) 2466], **HE: √s ≈ 318 GeV (130 pb^{-1}), LE: √s ≈ 225 GeV (10.8 pb^{-1})**

- **Fixed target data : lower normalisation and steeper slope than HERA data**
- **H1 fit extrapolation for the elastic J/Ψ cross section describes the LHCb data at high $W_{\gamma p}$** (~ 1.5 TeV)
  LHCb (36 pb^{-1}): p + p → p + J/Ψ + p

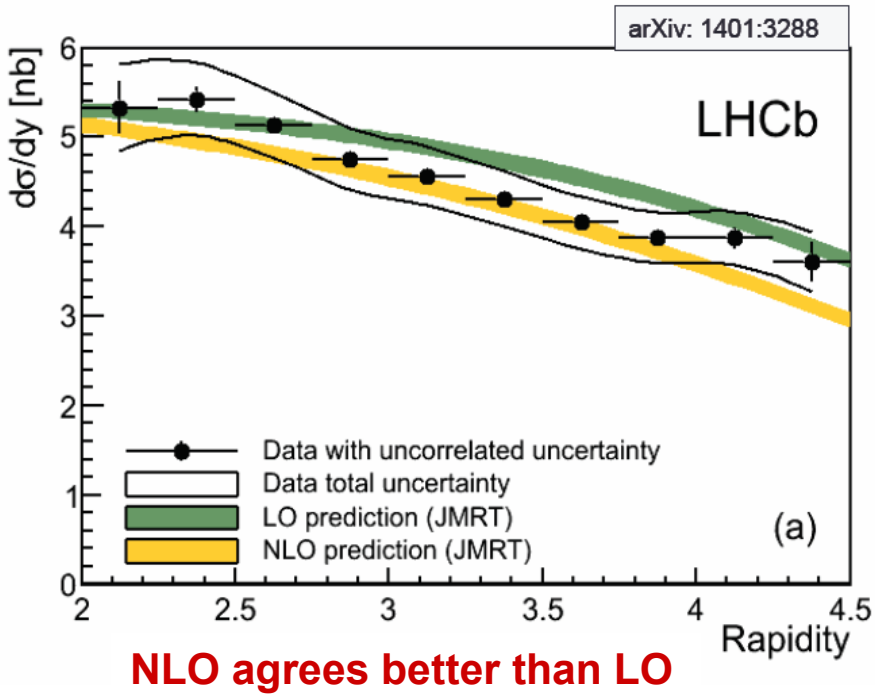
Exclusive photoproduction of J/Ψ mesons



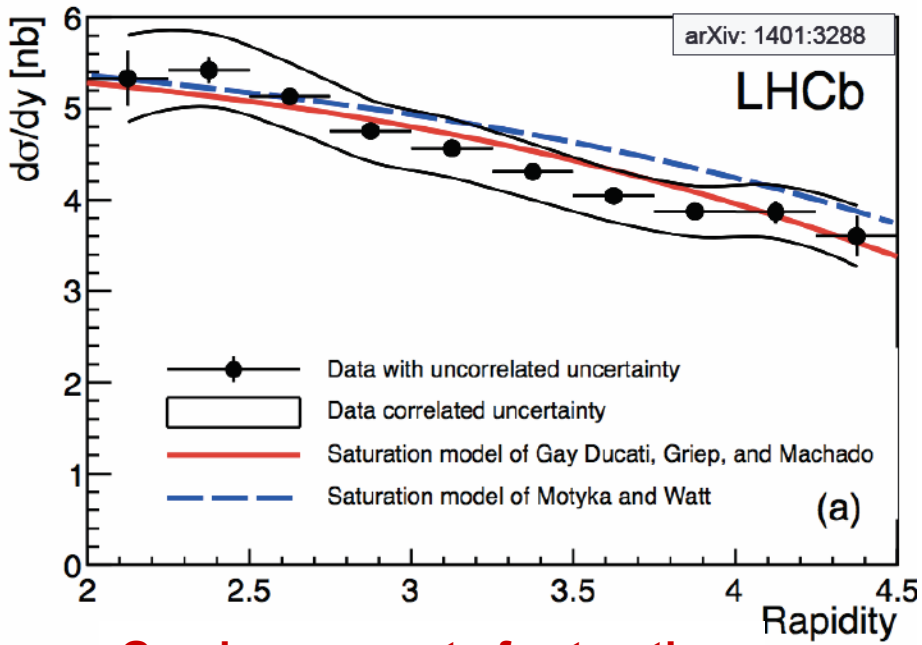
- **LO and NLO low x gluon density** ($10^{-4} \leq x \leq 10^{-2}$) **derived from fits to previous J/Ψ data at HERA** (A. Martin et al., PLB 662 (2008) 252)
- **Both fits extrapolated to higher $W_{\gamma p}$** (~ 1.5 TeV)
- **LO fit describes the LHCb data at $\sqrt{s}$ = 7 TeV well, NLO fit is too steep**

$d\sigma(pp \rightarrow p + J/\Psi + p) / dy$

Updated LHCb measurements (930 pb^{-1}) at $\sqrt{s}$ = 7 TeV [J. Phys. G41 (2014) 055002]



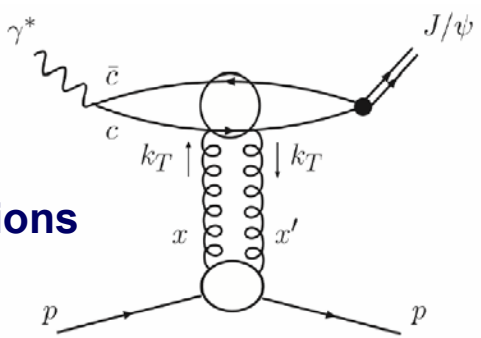
NLO agrees better than LO



Good agreement of saturation models with the LHCb data

New QCD analysis

Jones, Martin, Ryskin&Teubner (JMRT)
JHEP 1311 (2013) 085



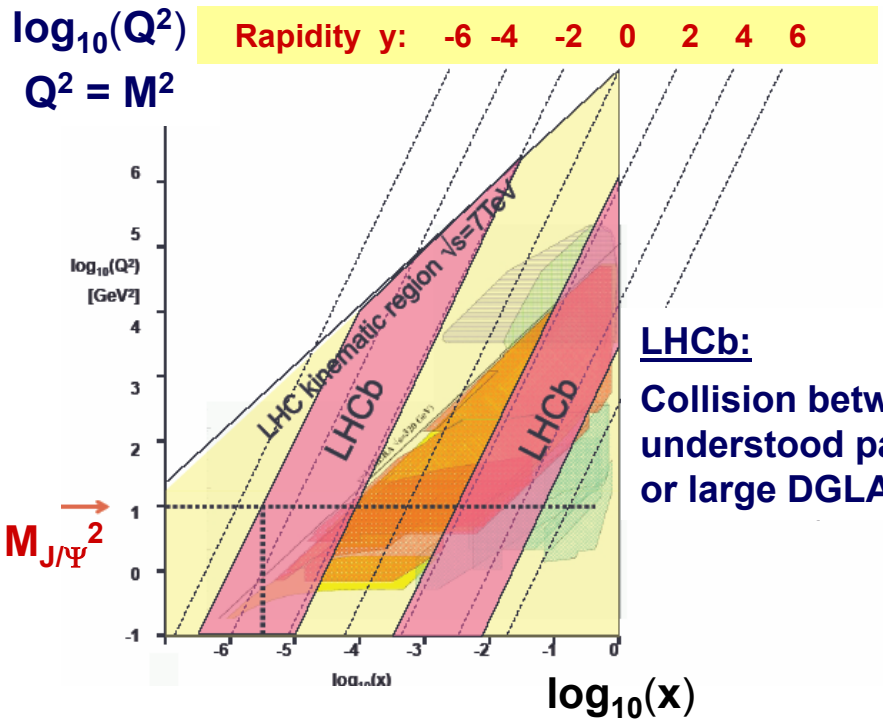
Skewed g(x, x', k_T)

Absorptive corrections for pp

Motyka&Watt, Phys. Rev. D78 (2008) 014023

Gay Ducati et al., Phys. Rev. D88 (2013) 017504

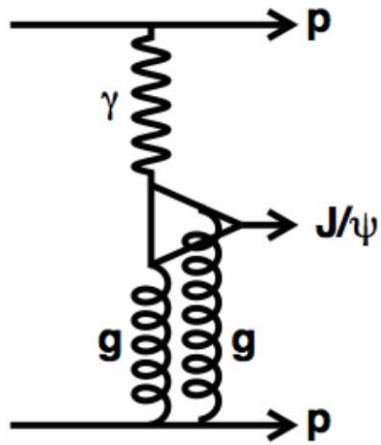
Central exclusive J / Ψ production at LHC

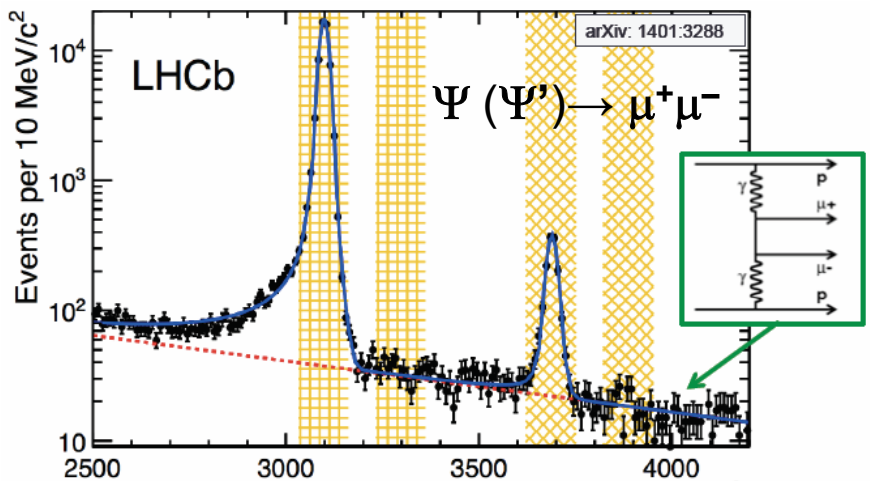


LHCb:

Collision between one well understood parton and one unknown or large DGLAP-evolved parton

$pp \rightarrow p + J/\Psi + p$



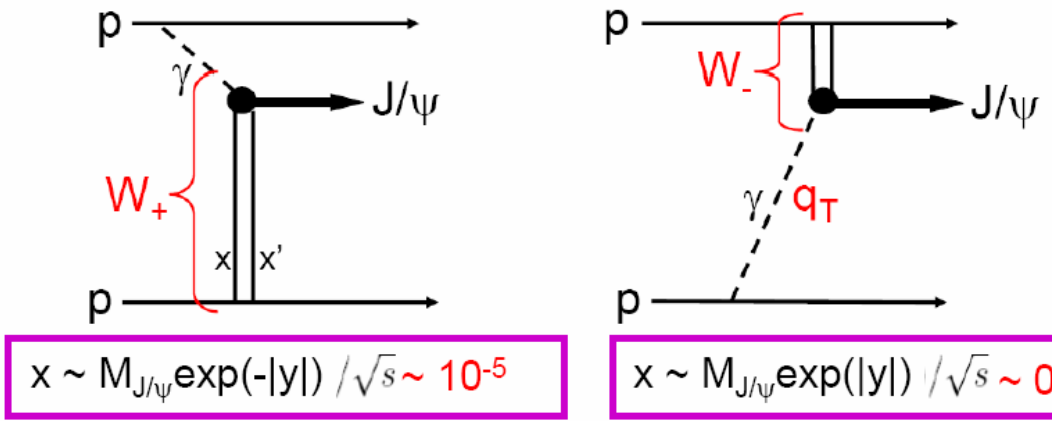


Central Exclusive Production of J/Ψ:

- low-multiplicity in a small rapidity interval + large rapidity gaps (LRG) on either side
- selection of LRG events + fitting p_T of J/Ψ (exclusive process ≡ small p_T)
- Test of QCD and Pomeron
- Sensitive to gluon density at v. low x (down to about 10^{-5} for $2 < y < 4$ at $\sqrt{s} = 13$ TeV)
- Search for saturation effects

$pp \rightarrow p + J/\Psi + p$: exclusive J/Ψ production described by the sum of 2 diagrams → for each measured rapidity bin there are 2 solutions for $W_{\gamma p}$

γp, $p\gamma$ ambiguity



$$W_{\pm}^2 = M_{J/\psi}\sqrt{s}\; e^{\pm|y|}$$

W_+ diagram – main contribution to J/Ψ x-sec for J/Ψ produced at large rapidity y

$|y|=4$

$x \sim M_{J/\psi}\exp(-|y|)/\sqrt{s} \sim 10^{-5}$

$x \sim M_{J/\psi}\exp(|y|)/\sqrt{s} \sim 0.02$

LHCb data points for $W_+(W_-)$ determined assuming the H1 derived power – law fit for $W_-(W_+)$ and using relation of exclusive production of J/Ψ in pp to photoproduction :

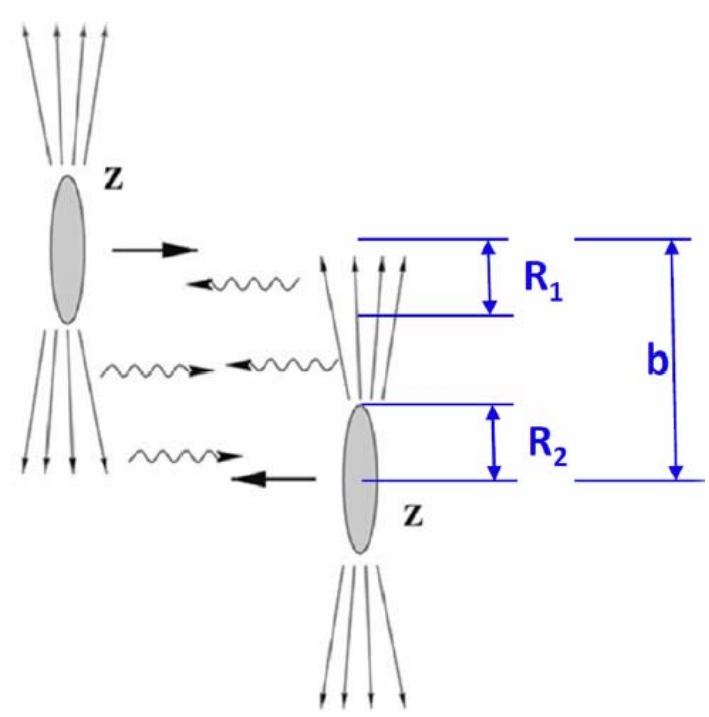
measure → plot → HERA

$$\frac{d\sigma_{pp\rightarrow pJ/\psi p}}{dy} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\rightarrow pJ/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\rightarrow pJ/\psi p}(W_-)$$

$dn/dk_{\pm}$: photon fluxes for photons of energy $k_{\pm}$

$r_{\pm}$: absorptive corrections [Schäfer & Szczurek PRD 76 (2007) 094014]

Ultra - peripheral collisions at the LHC (UPC)



- UPC – the projectiles (Pb-Pb, p-Pb or pp) are at large impact parameters :

  $b > R_1 + R_2$

- hadronic processes are greatly suppressed
- nucleus is an intensive source of photons

  photon flux ~ Z^2

  $\Rightarrow$ large cross sections for photon induced reactions
- photon virtuality restricted by the nuclear form factor

  $Q^2 = (\hbar c/R)^2 \approx (35\ \text{MeV})^2$ for γ from Pb
- exclusive VM production in γA

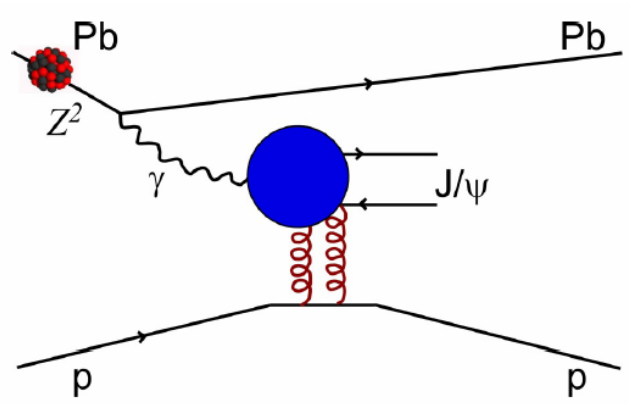
  coherent:

  γ couples coherently to all nucleons, low $p_{T,VM}$, nucleus does not break up

  incoherent:

  quasi-elastic scattering off a single nucleon, higher $p_{T,VM}$, nucleus breaks up (activity in v. forward region)

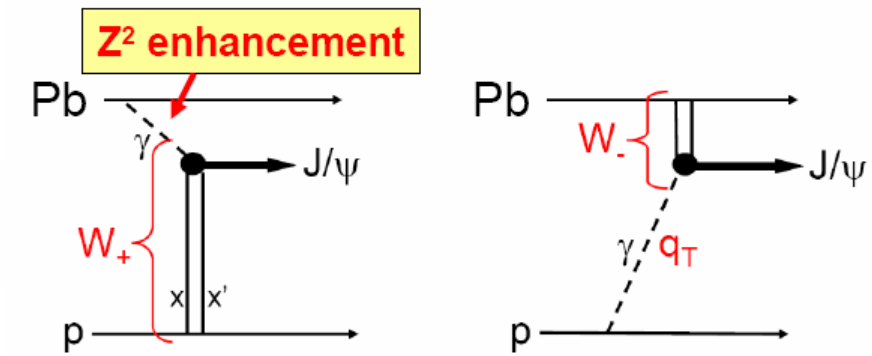
p + Pb → p + J/Ψ + Pb



Asymmetric proton-nucleus collisions

⇒ **dominant contribution from the amplitude where Pb emits the photon (strong Z^2 enhancement of photon flux)**

⇒ **proton structure is probed – extraction of the small x gluon**



$$\frac{d\sigma}{dy}(p+Pb \to p+Pb+J/\psi) = k\frac{dn}{dk}\sigma(\gamma+p \to J/\psi+p)$$

photon flux from MC STARLIGHT

ALICE

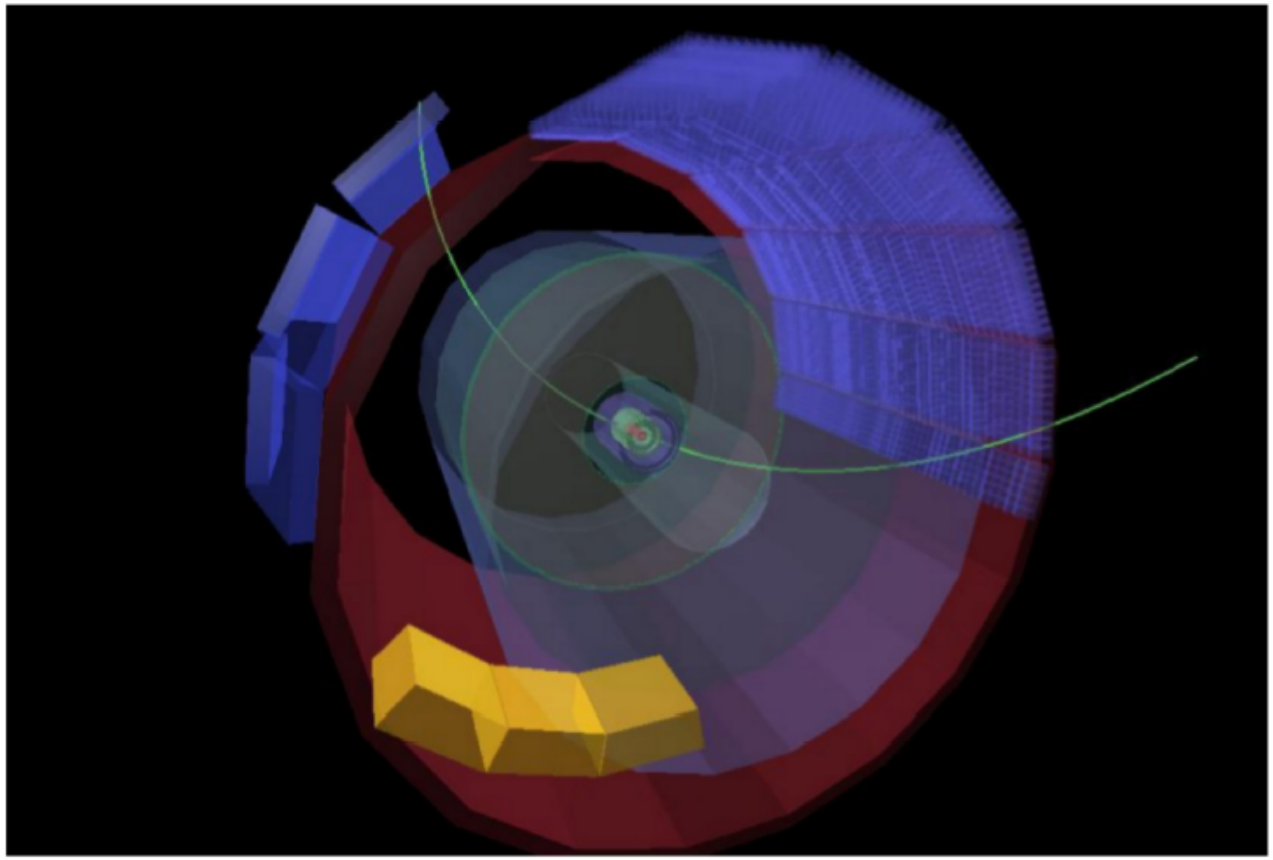
Exclusive photoproduction of J/Ψ

- **p- Pb UPCs at $\sqrt{s_{NN}}$ = 5.02 TeV**
- **Pb-Pb UPCs at $\sqrt{s_{NN}}$ = 2.76 TeV**

J/Ψ photoproduction in Pb – Pb

- **dominant contribution from the W_- amplitude**
  - → **effective γN energy not so large**
  - → **probe nuclear effects on gluon PDF (gluon shadowing)**

p – Pb event



2 tracks in an otherwise empty detector

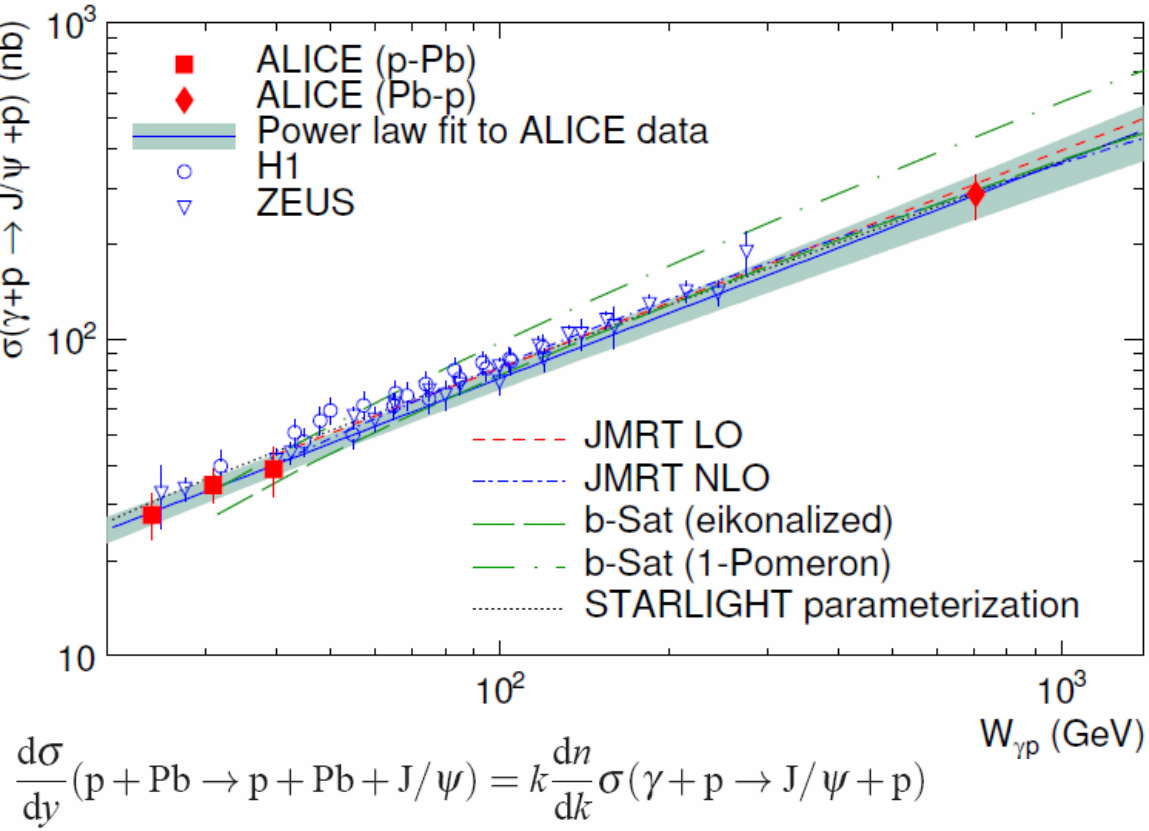
PRL 113 (2014) 232504, Exclusive J/Ψ photoproduction off protons in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

LAB : forward / backward produced J/Ψ → $\mu^+\mu^-$, 2.5 < y < 4 (p-Pb), -3.6 y < -2.6 (P -p)

$W_{\gamma p}$ between 20 – 700 GeV; Bjorken-x between ~2 · 10^{-2} to 2 · 10^{-5}

ALICE : J/Ψ in p-Pb

Energy dependence of σ(γ + p → J/Ψ + p)



$$\frac{d\sigma}{dy}(p + Pb \to p + Pb + J/\psi) = k\frac{dn}{dk}\sigma(\gamma + p \to J/\psi + p)$$

JMRT (Durham group)
Skewed g(x, x', Q^2), abs. corr.

STARLIGHT MC
Klein, Nystrand
Glauber Model + fit to HERA data

Dipole models:

b-Sat (eikonalized) with saturation
Kowalski, Motyka, Watt
PRD 74 (2006) 074016

b-Sat (1-Pomeron) without saturation
J. L. Abelleira Fernandez et al.
arXiv:12114831

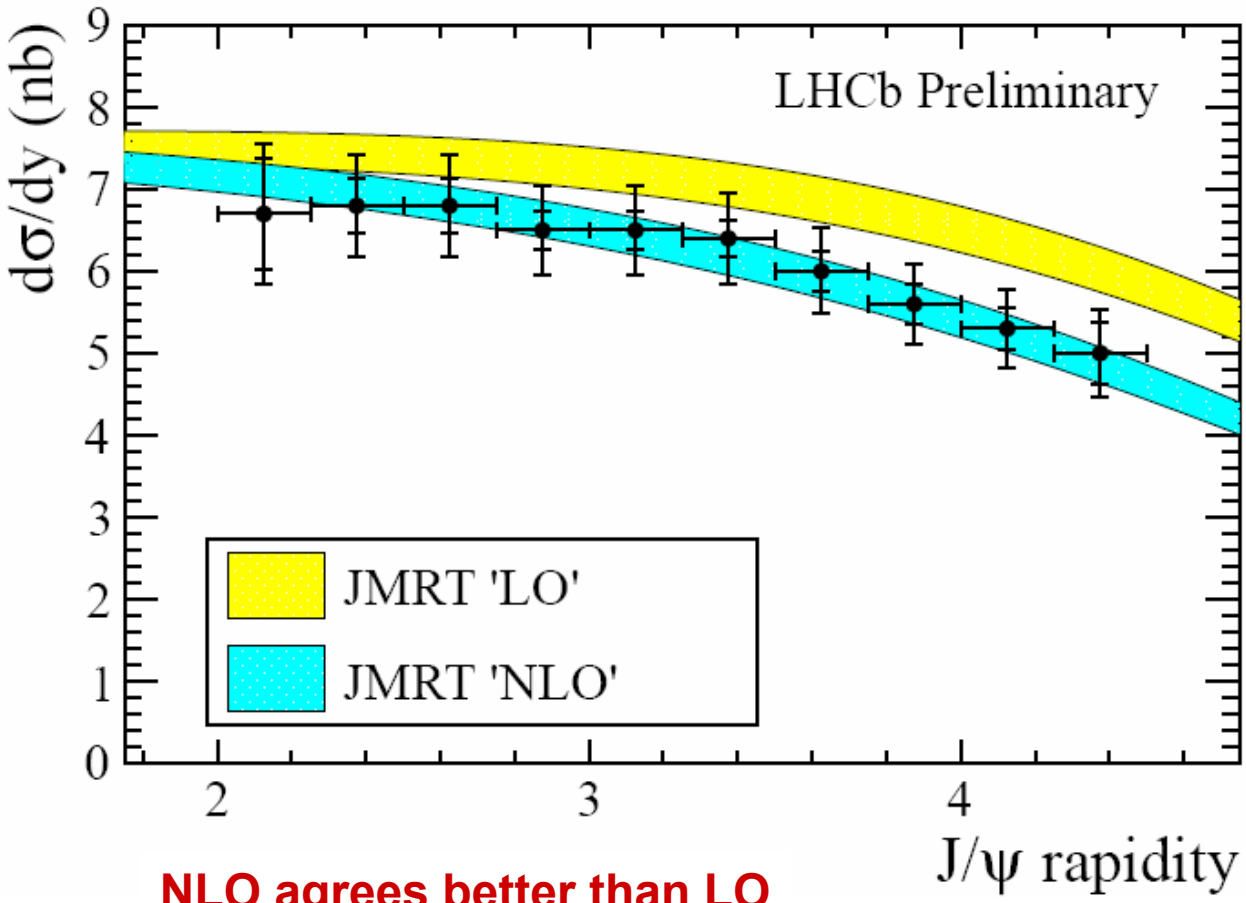
- **Precision on slope of energy curve similar to HERA**
  $\sigma \sim W^{\delta}$, δ = - 0.68 ± 0.03 (HERA), δ = - 0.68 ± 0.06 (ALICE)
  $\Rightarrow$ no deviation from a power law up to ~ 700 GeV
- **Theoretical predictions within one sigma of the ALICE data [except b-Sat (1-Pomeron)]**

Preliminary LHCb measurements: pp → p + J/Ψ + p at √s = 13 TeV (204 pb^{-1})

New forward shower counters (HERSCHEL) improve the exclusivity of events
Silicon strip vertex detector + HERSCHEL cover pseudorapidity regions:

$-10 < \eta < -5$, $-3.5 < \eta < -1.5$, $1.5 < \eta < 10$

LHCb-CONF-2016-007

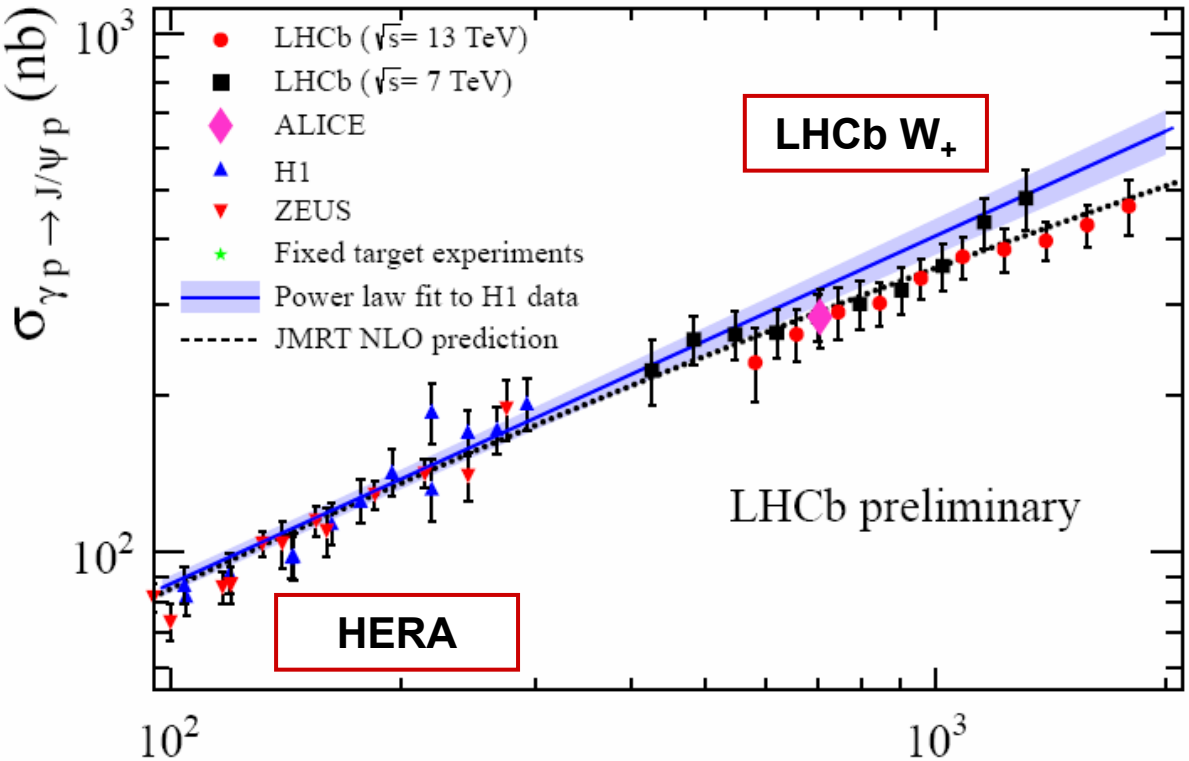


NLO agrees better than LO

$W_{\gamma p}$ up to 2 TeV

→ $x \approx 2 \cdot 10^{-6}$

Preliminary LHCb measurements: pp → p + J/Ψ + p at √s = 13 TeV (204 pb^{-1})



Comparison of LHCb data at √s = 7 TeV and √s = 13 TeV to HERA and ALICE data at lower W

$$\frac{d\sigma_{pp\to pJ/\psi p}}{dy} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to pJ/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to pJ/\psi p}(W_-)$$

- **W_ term fixed (HERA parametrisation), modified photon flux and gap survival factors**
- **The 13 TeV LHCb data in agreement with recalculated 7 TeV results**
- **Deviation from a pure power-law extrapolation of HERA (missing HO or saturation effects ?)**
- **Data in agreement with JMRT NLO predictions**

Summary

- **Exclusive production of vector mesons at HERA illustrates the transition from soft hadronic to hard partonic regions**

- **Exclusive VM measurements stimulate development of QCD-based models**

- **Exclusive J/Ψ photoproduction data from HERA and the LHC have the potential to produce constraints on the gluon density at very low-x**

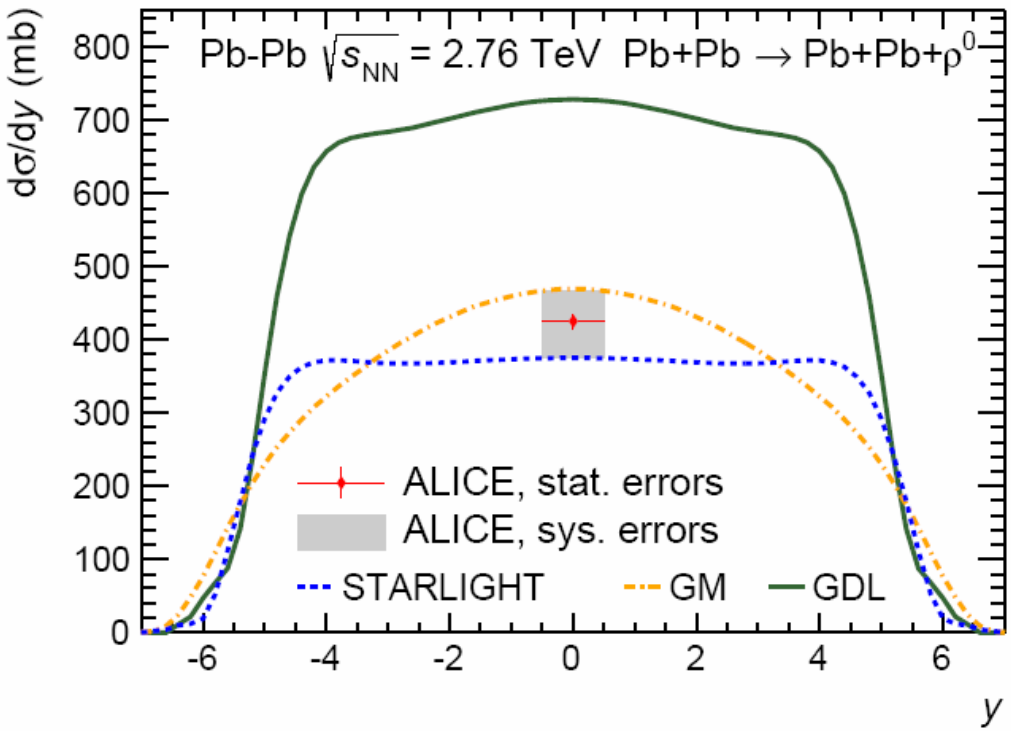
backup

Coherent ρ^0 production in ultra-peripheral Pb-Pb collisions

L. Frankfurt, M. Strikman, M. Zhalov (GDL) : QM Glauber + DL fit to HERA data

V. P. Goncalves, M.V.T. Machado (GM): Color dipole model with CGC-like saturation

S.R. Klein, J. Nystrand (STARLIGHT): Classical Glauber model + fit to HERA data

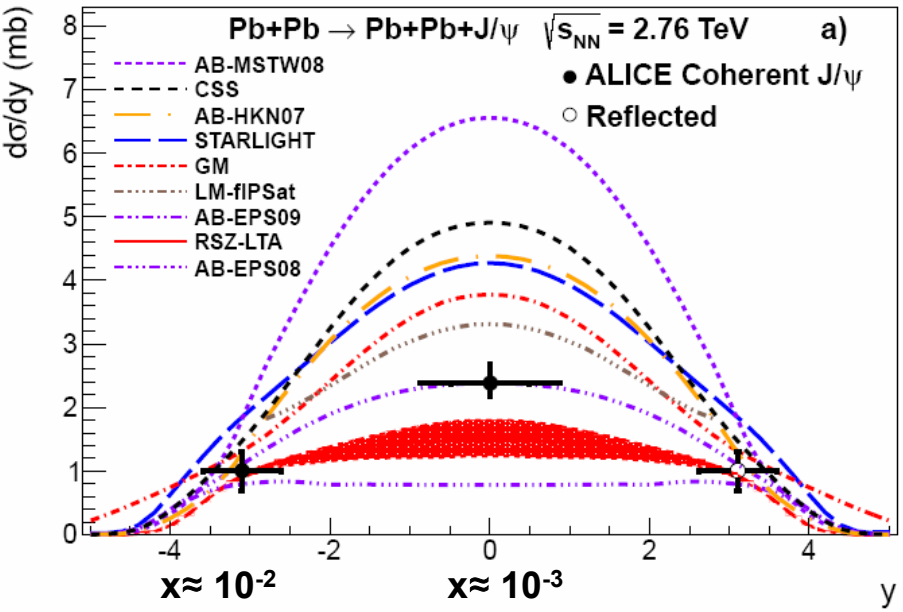


JHEP 1509 (2015) 095

- **Agreement with STARLIGHT**
- **Disagreement with the GDL model may be explained by inelastic nuclear shadowing [see PLB 752 (2016) 51]**

Coherent J/Ψ production in ultra-peripheral Pb-Pb collisions

PLB 718 (2013)1273
EPJ C73 (2013) 261



Agreement is best for models incorporating nuclear gluon shadowing

STARLIGHT: Klein, Nystrand, PRC60 (1999) 014903
VDM + Glauber approach where J/ψ+p cross section is obtained from a parameterization of HERA data

- **GM: Gonçalves, Machado, PRC84 (2011) 011902**
color dipole model, dipole nucleon cross section taken from the IIM saturation model

- AB: Adeluyi and Bertulani, PRC85 (2012) 044904
LO pQCD calculations: AB-MSTW08 assumes no nuclear effects for the gluon distribution, other AB models incorporate gluon shadowing effects according to the EPS08, EPS09 or HKN07 parameterizations

- **CSS: Cisek, Szczurek, Schäfer, PRC86 (2012) 014905**
Glauber approach accounting $c\bar{c}g$ intermediate states

- **RSZ: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252**
LO pQCD calculations with nuclear gluon shadowing computed in the leading twist approximation

- Lappi, Mäntysaari, PRC87 (2013) 032201: color dipole model + saturation