LHCP 2016 Lund

Soft QCD physics in pp collisions at the LHC

A selection

O. Villalobos Baillie
University of Birmingham

Plan of Talk

- d*N*/dη at 13 TeV
- σ_{inel} at 13 TeV
- Ultra Peripheral Collisions
- Two aspects of Multi Parton Interactions (MPI)
- Summary

dN/dη at 13 TeV

$dN/d\eta$ Distributions at 13 TeV

- ATLAS, ALICE and CMS have all shown $dN/d\eta$ distributions at this new energy.
- Significant development in Monte Carlo generators since beginning of 7 TeV era.
- Time to check whether things are going better.

d*N*/dη Distributions at 13 TeV

- ATLAS, ALICE and CMS have all shown dN/dη distri
- Signif gene
- Time better.

CAVEAT

Sounds simple, but…

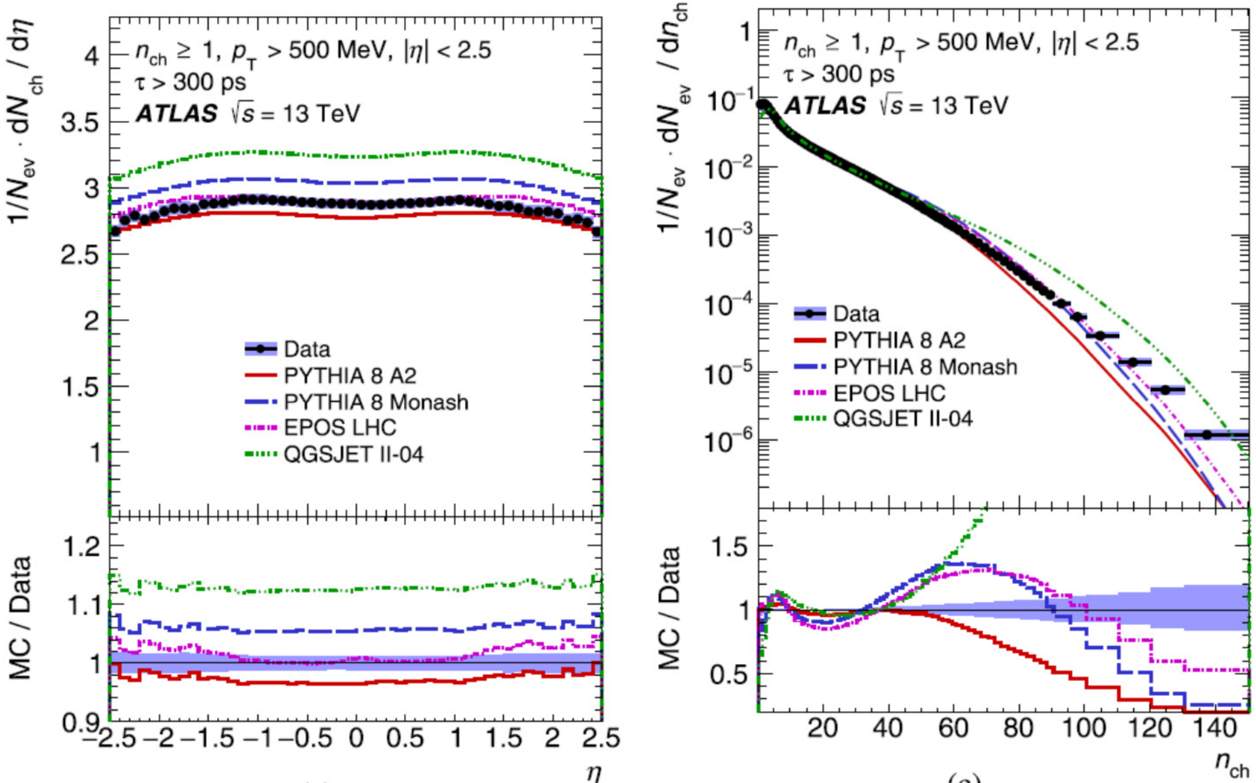
$$\frac{\mathrm{d}N}{\mathrm{d}\eta} = \left.\frac{N_{\mathrm{tracks}}}{N_{\mathrm{events}}}\right|_{\Delta\eta}$$

- What is a track?
- What is an event?

Problems

- **Tracks**. Measuring a track properly implies a p_T cutoff. Where it goes is experiment-dependent. To compare experiments, need either to have common threshold (not necessarily possible) or use a *model* to extrapolate to p_T=0 GeV/c
- **Events.** Selecting events implies a choice on what *kind* of events. Some events (especially single diffractive events), which for low diffractive masses have tracks only at very forward rapidities, are difficult to detect, and may be missed, yet should be included in an N_{inel} measurement. The options are
  - Try to correct, for which some knowledge of the diffractive contribution is needed,
  - Choose an event definition, e.g. one with at least some minimum number of tracks at mid-rapidity, which essentially excludes single diffraction altogether.

ATLAS dN/dη



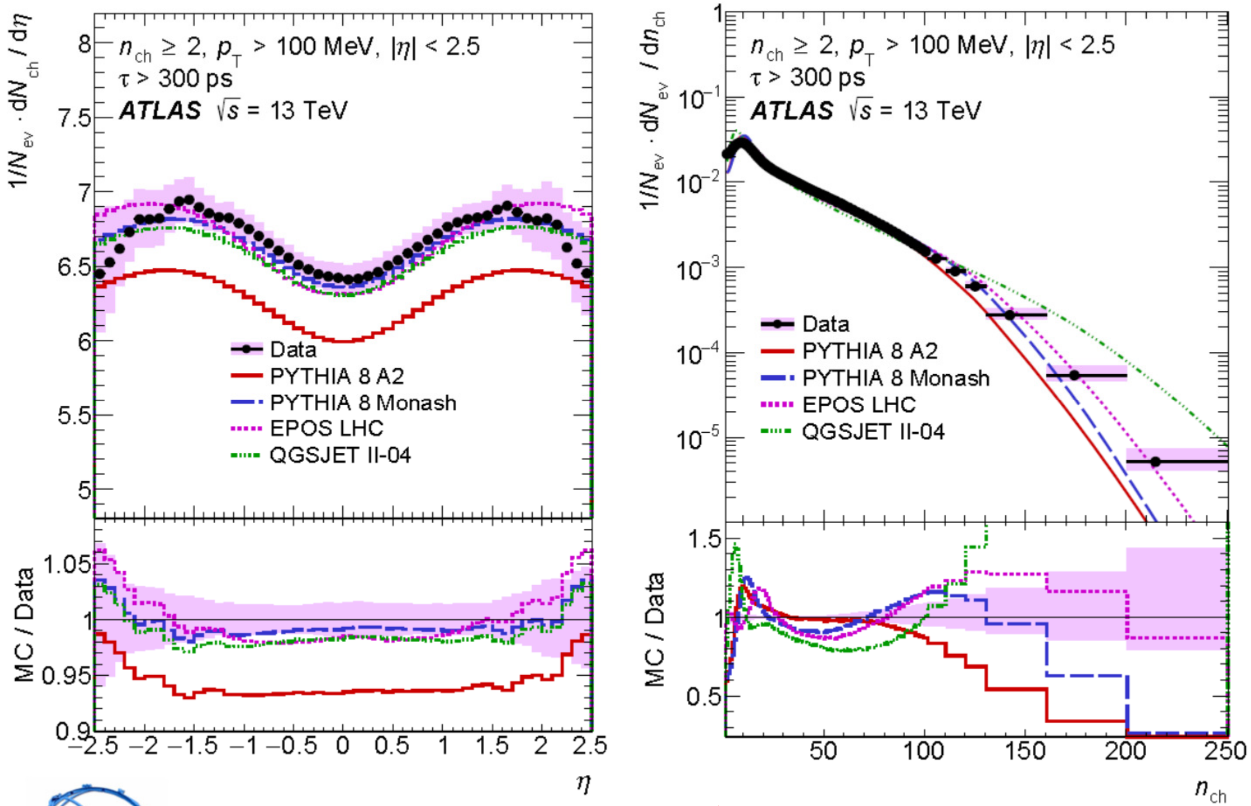
(a) (c)

- ATLAS have chosen the options of
  - $p_T > 500$ MeV/c
  - $N_{ch} \geq 1$
- *i.e.* options that inhibit single diffraction.

$$\frac{dN}{d\eta} = 2.874 \pm 0.001(\text{stat.}) \pm 0.033(\text{sys.})\Big|_{n_{ch} \geq 2,\, p_T > 500\ \text{MeV}/c,\, |\eta| < 0.2}$$

Phys. Lett. B758 (2016) 67

ATLAS dN/dη

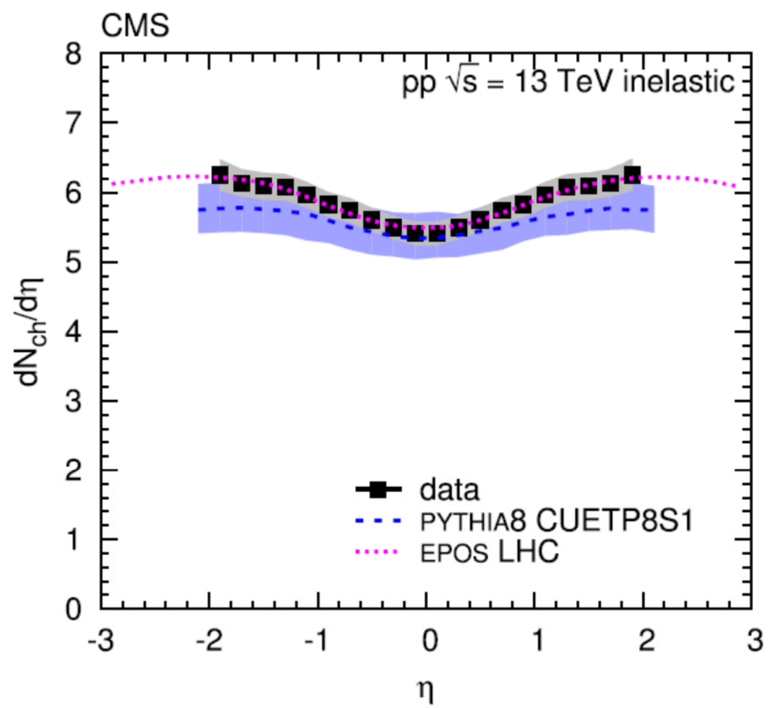


- New ATLAS analysis uses
  - $p_T >$ 100 MeV/c
  - $N_{ch} \geq 2$
- Single diffraction is inhibited, and p_T cut allows direct comparison with other experiments.

$$\frac{dN}{d\eta} = 6.50 \pm 0.01 \Big|_{n_{ch} \geq 2,\, p_T > 100\ \mathrm{MeV}/c,\, |\eta| < 0.2}$$

ArXiv:1606.01133v1

CMS dN/dη



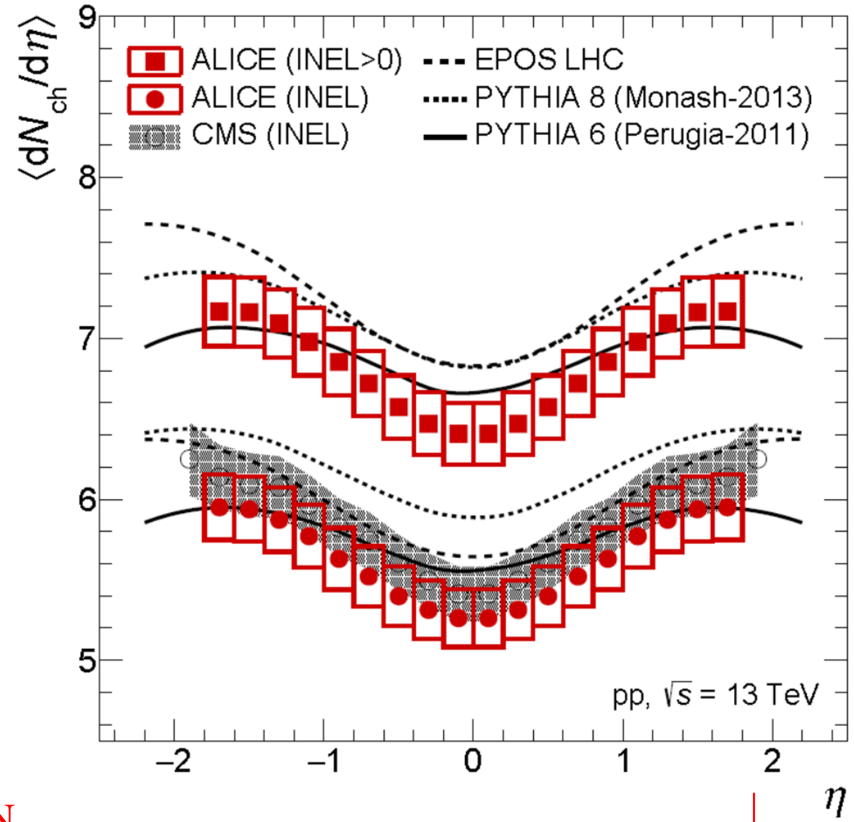
The CMS multiplicity measurement is based on *tracklets*, with an effective threshold of 40 MeV/*c*, but extrapolated to $p_T > 0$ GeV/c

No minimum tracklet number requirement.

$$\frac{dN}{d\eta} = 5.49 \pm 0.01 \pm 0.17 \Big|_{p_T > 40\ \mathrm{MeV}/c, |\eta| < 0.5}$$

Phys. Lett. B751 (2015) 143

ALICE dN/dη



ALICE use tracklets with a p_T onset of ~ 50 MeV/c,
and two different multiplicity requirements:

INEL no minimum demand on tracklet multiplicity

INEL>0 at least one tracklet in |η|<1.

$$\frac{dN}{d\eta} = 5.31 \pm 0.18 \text{ (INEL)}; \ 6.46 \pm 0.19 \text{ (INEL>0)}\Big|_{p_T > 50 \text{ MeV}/c, |\eta|<0.5}$$

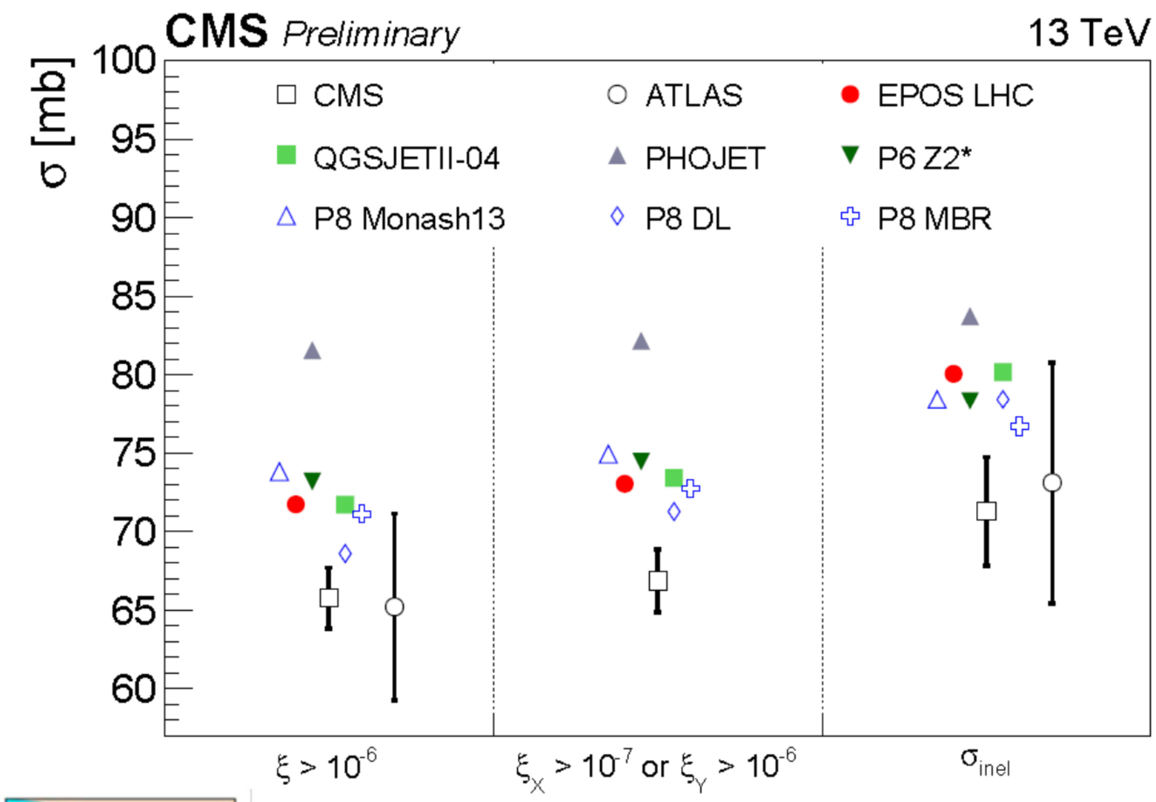
J. Adam et al. Phys. Lett. B753 (2015) 319

Inelastic cross section at 13 TeV

Inelastic cross section

- Measure Minimum Bias (MB) interactions over range of available trigger detectors
  - ATLAS $2.07 < |\eta| < 5.9$ Measurement restricted to $M_X^2/s = \xi > 10^{-6}$.
  - CMS $-6.6 < \eta < -3.0$, $3.0 < \eta < 5.2$ Measurement for $\xi > 10^{-6}$ and $\xi > 10^{-7}$
- Both experiments can measure in $\xi > 10^{-6}$, but extrapolation needed to go to full inelastic cross section.

CMS σ_{inel}



- Cross sections obtained for $\xi > 10^{-6}$, ($\xi > 10^{-7}$), and full kinematics.
- Quite large error for extrapolation
- Diffractive mass according to PYTHIA Schuler-Sjöstrand parameterization.

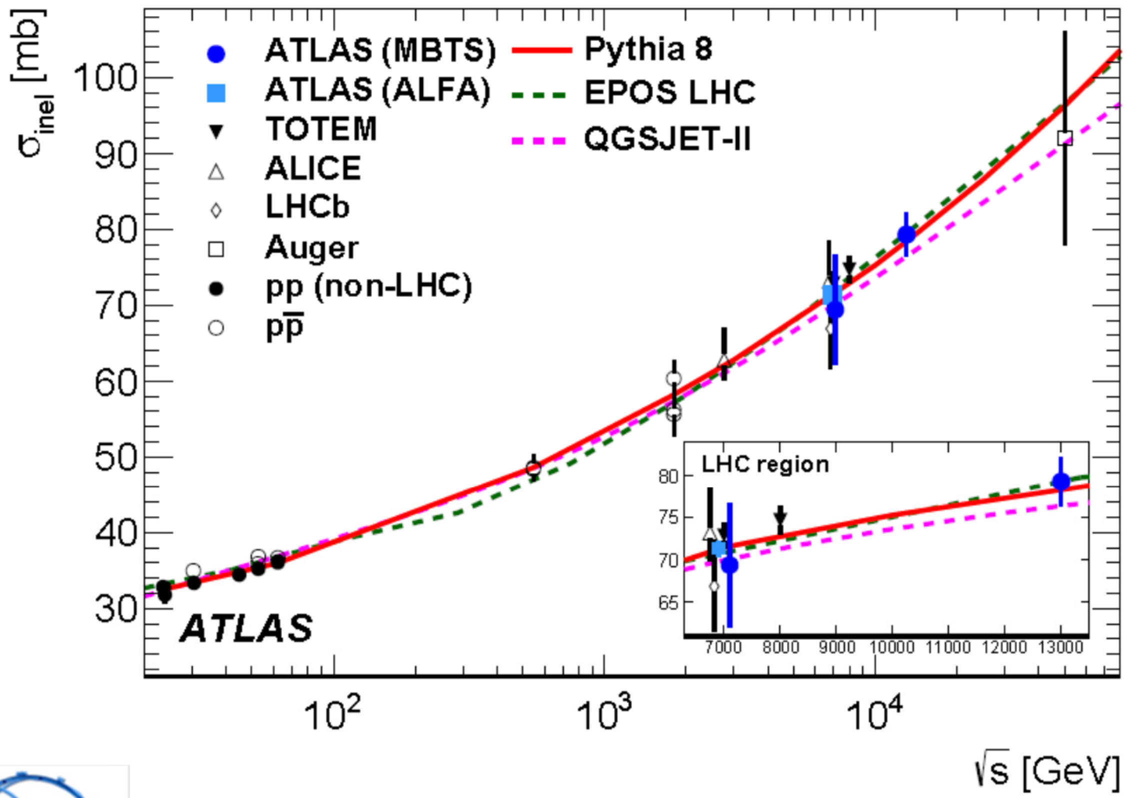
CMS PAS FSQ-15-005

$\sigma_{\xi>10^{-6}}$= 65.77±0.06±0.44±1.96 mb

σ_{inel} = 71.26±0.06±0.47±2.09 ±2.72 mb

ATLAS σ_{inel}

- Cross sections obtained for $\xi > 10^{-6}$, and full kinematics.
- Quite large error for extrapolation
- Diffractive mass according to PYTHIA Donnachie-Landshoff parameterization.



ArXiV:1606.0265

$\sigma_{\xi>10^{-6}}$= 68.2±0.08±1.3 mb

$$f_D = \frac{\sigma_{SD} + \sigma_{DD}}{\sigma_{inel}} = 28\%$$

σ_{inel} = 79.3±0.08±1.3 ±2.5 mb

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ATLAS σ_{inel}

- Cross sections obtained for ξ > … full … cs. … ge error … polation … e mass … to … e- … f … erization.

Extrapolation errors need some revisiting.

For ATLAS, extrapolation is 79.3 - 68.2 = **11.1** ± 2.5 mb

For CMS, it is 71.26 - 65.77 = **5.83** ± 2.72 mb

Difference is twice quoted extrapolation error for same extrapolation

Different diffractive models (Schuler-Sjöstrand (CMS) vs tuned Donnachie-Landshoff+7 TeV optical theorem result (ATLAS)) used for diffractive mass distribution

…265

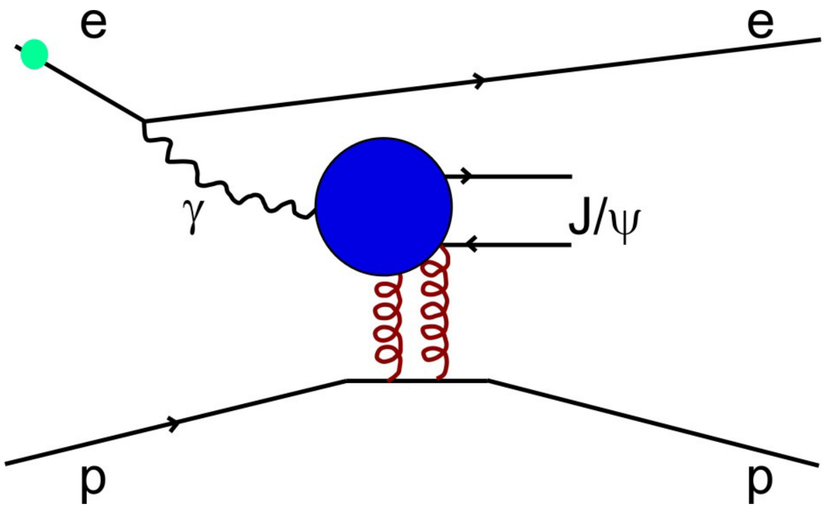
$\sigma_{\xi>10^{-6}}$= 68.2±0.08±1.3 mb

$$f_D = \frac{\sigma_{SD} + \sigma_{DD}}{\sigma_{inel}} = 28\%$$

σ_{inel} = 79.3±0.08±1.3 ±2.5 mb

Ultra-Peripheral Production

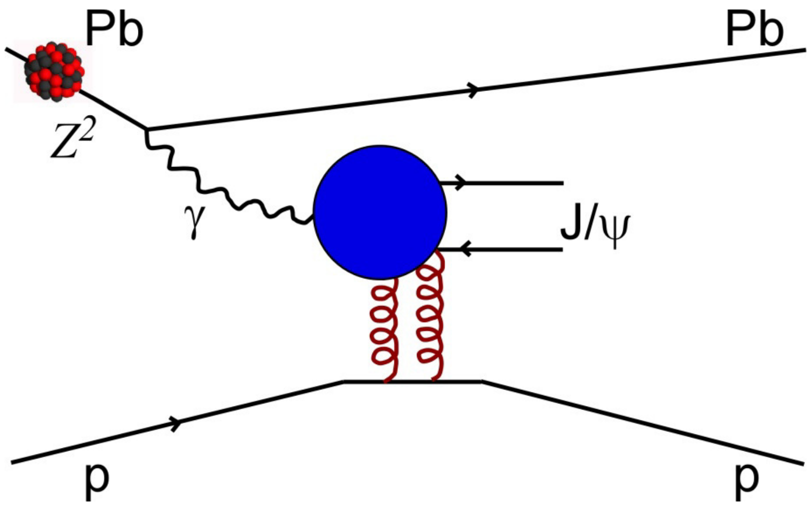
Vector Meson Photoproduction



- Extensively studied at HERA for (e.g.) ρ and J/ψ mesons.
- As seen from leading order diagram, sensitive to gluon structure functions.

See (e.g.) P.R. Newman and M. Wing, Rev. Mod. Phys. **86** (2014) 1037

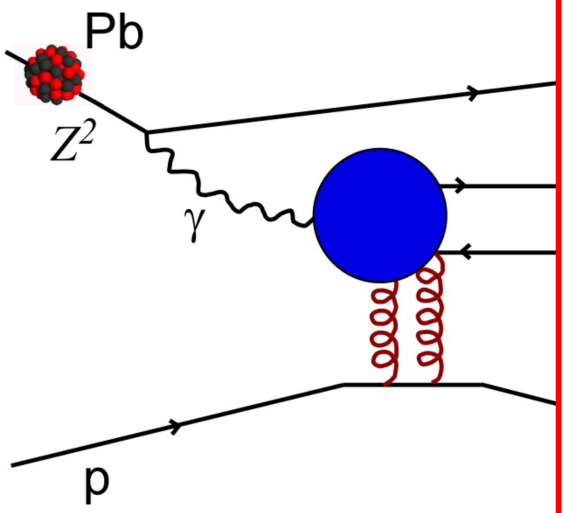
UltraPeripheral production



- Essentially the same process, except that the photon is emitted by a proton or *a nucleus.*
- Asymmetric proton-nucleus case has some advantages, as
  - flux is increased by factor Z^2,
  - As a result, Pb ion is tagged as photon emitter, while proton structure function is probed.

Exclusive process: we go to very *low* multiplicities

UltraPeripheral production



All Experiments now involved!

ALICE	**p-Pb, PbPb**
ATLAS	**PbPb**
CMS	**pPb, PbPb**
LHCb	**pp**

Expect more soon…

- Essentially the same ...ess, except that the ...on is emitted by a ...on or *a nucleus.*
- ...nmetric proton-...eus case has some ...ntages, as
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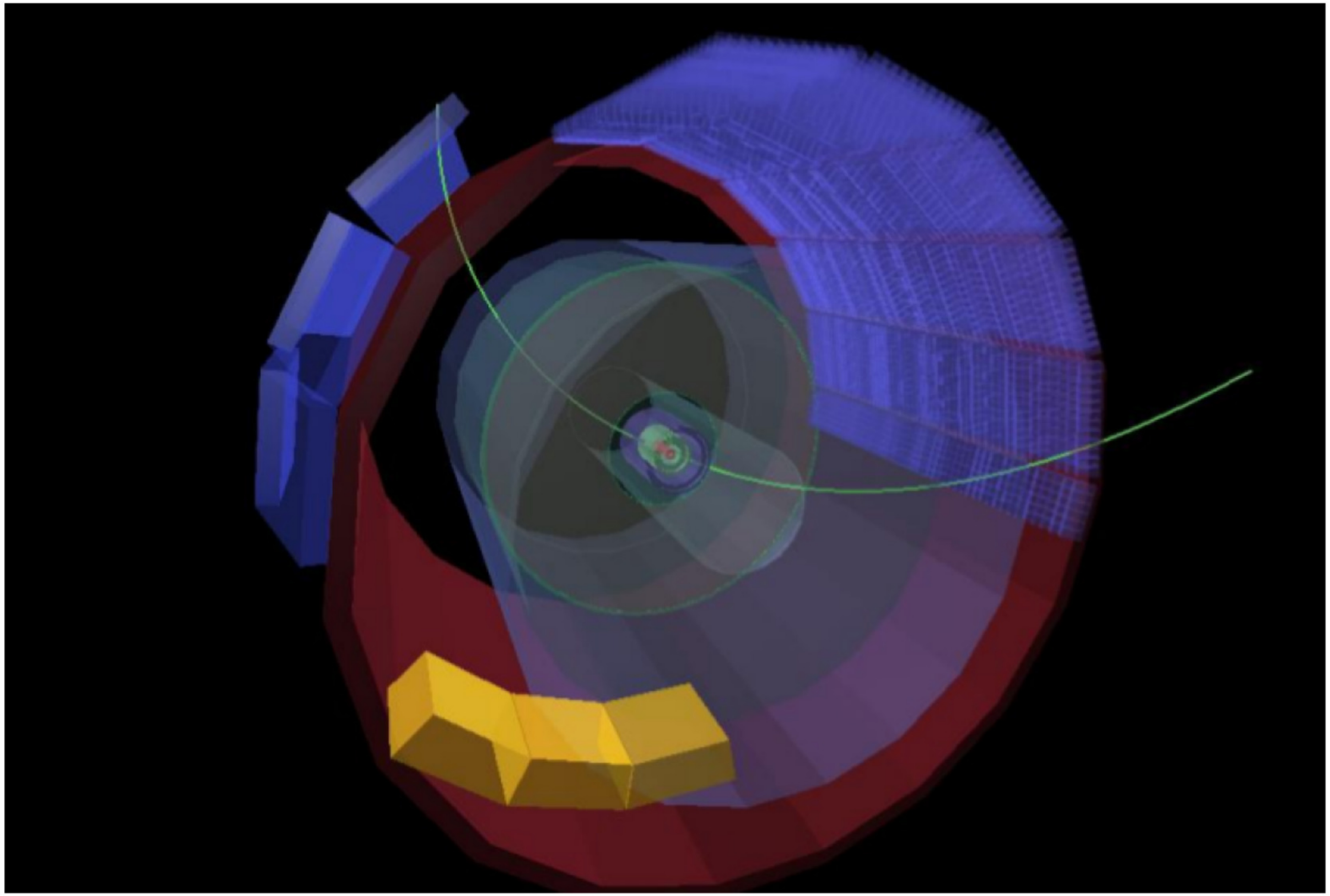
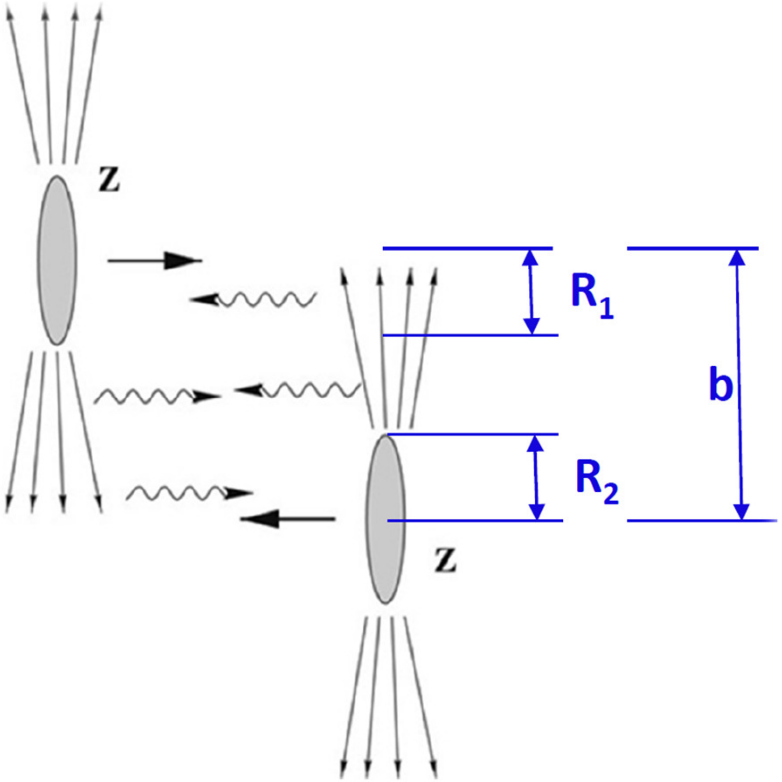
Exclusive process: we go to very *low* multiplicities

p-Pb event



"Just two tracks in an otherwise empty detector"

In more Detail…

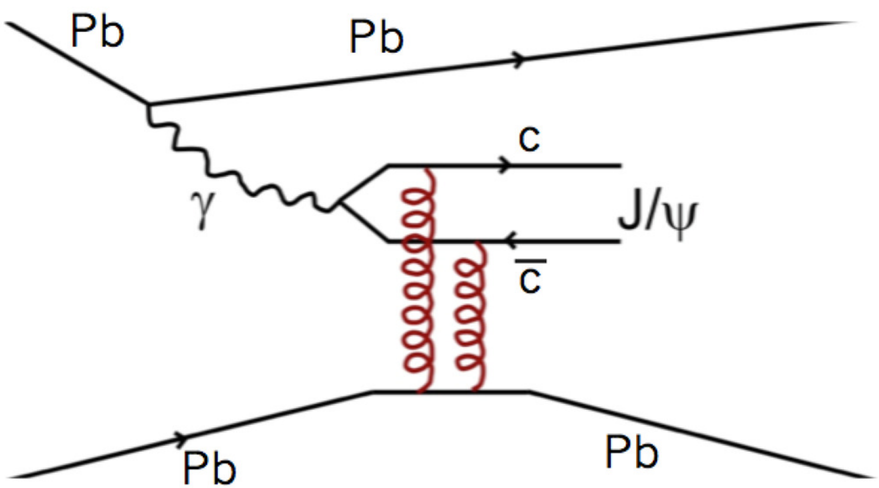


- In UPC, the projectiles (Pb-Pb, p-Pb or pp) are at large impact parameters, $b > R_1 + R_2$, and so hadronic processes are greatly suppressed
- Photon flux $\propto Z^2$
- Photon virtuality $Q^2 = (\hbar c/R)^2 \approx (35\ \mathrm{MeV})^2$ for γ from Pb

In more detail

$$\frac{d\sigma_{\gamma^{*}p/Pb}(t=0)}{dt}=\frac{16\Gamma_{ee}\pi^{3}}{3\alpha_{em}M^{5}_{J/\psi}}\left\{\alpha_{s}\left(Q^{2}\right)G_{p/Pb}\left(x,Q^{2}\right)\right\}^{2}$$

LEADING ORDER



- The photon emitted by one nucleus couples to a vector meson
- At LO, the cross-section is proportional to the gluon PDF squared
- Hard scale for the J/ψ of Q^2 ~ $(M_{J/\psi}^2/4)$ ~ 2.5 GeV^2
  - Model dependence for lighter particles (e.g. ρ)

Q^2 ~ 22.4 GeV^2 for ϒ

Two Energies…

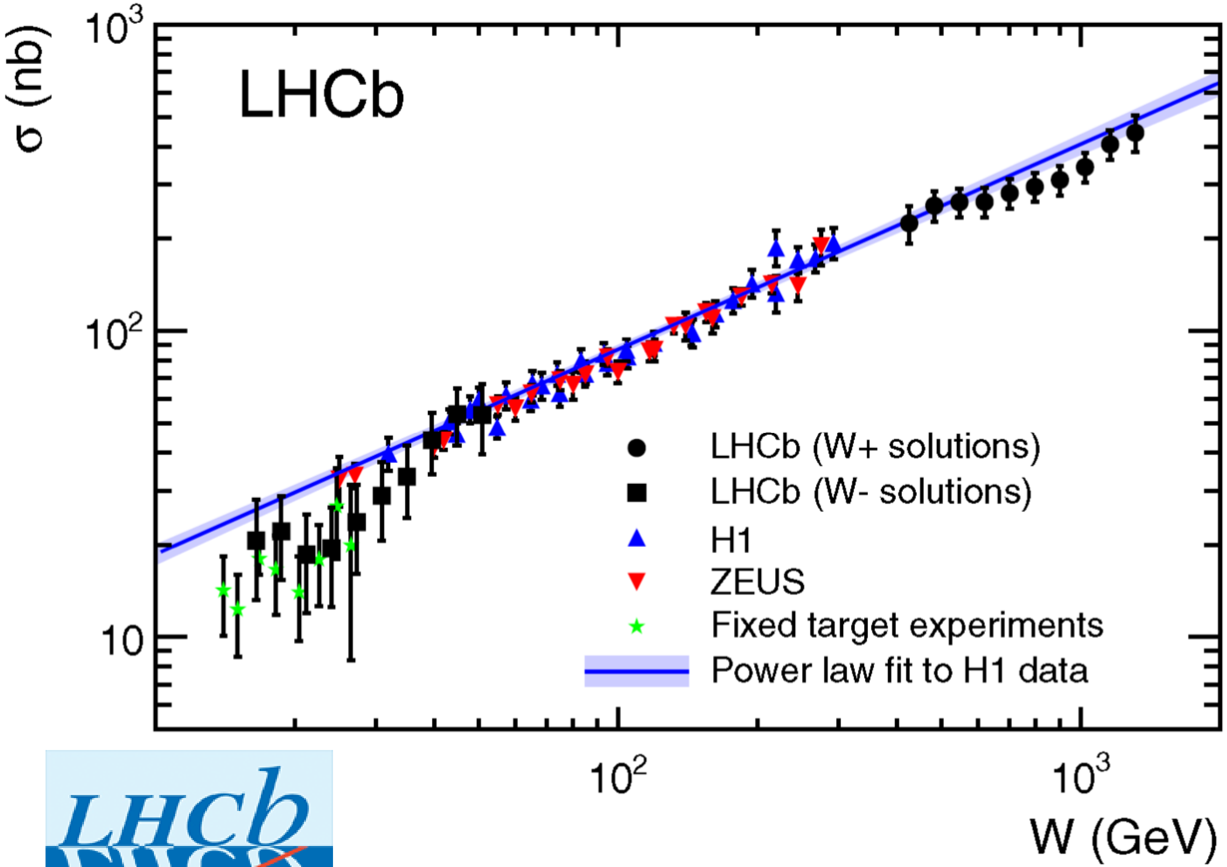
- Result of measurement is to obtain d*N*/d*y* distribution.
- To move to dσ/d*W*, need to know energy of photon, given by

$$W_{\gamma p}^2 = 2E_p M_{J/\psi} \exp(\pm y)$$

- Two solutions, according to whether J/ψ travels in direction of photon source or not.

$$x = (M_{J/\psi} / W_{\gamma p})^2$$

LHCb J/ψ in pp

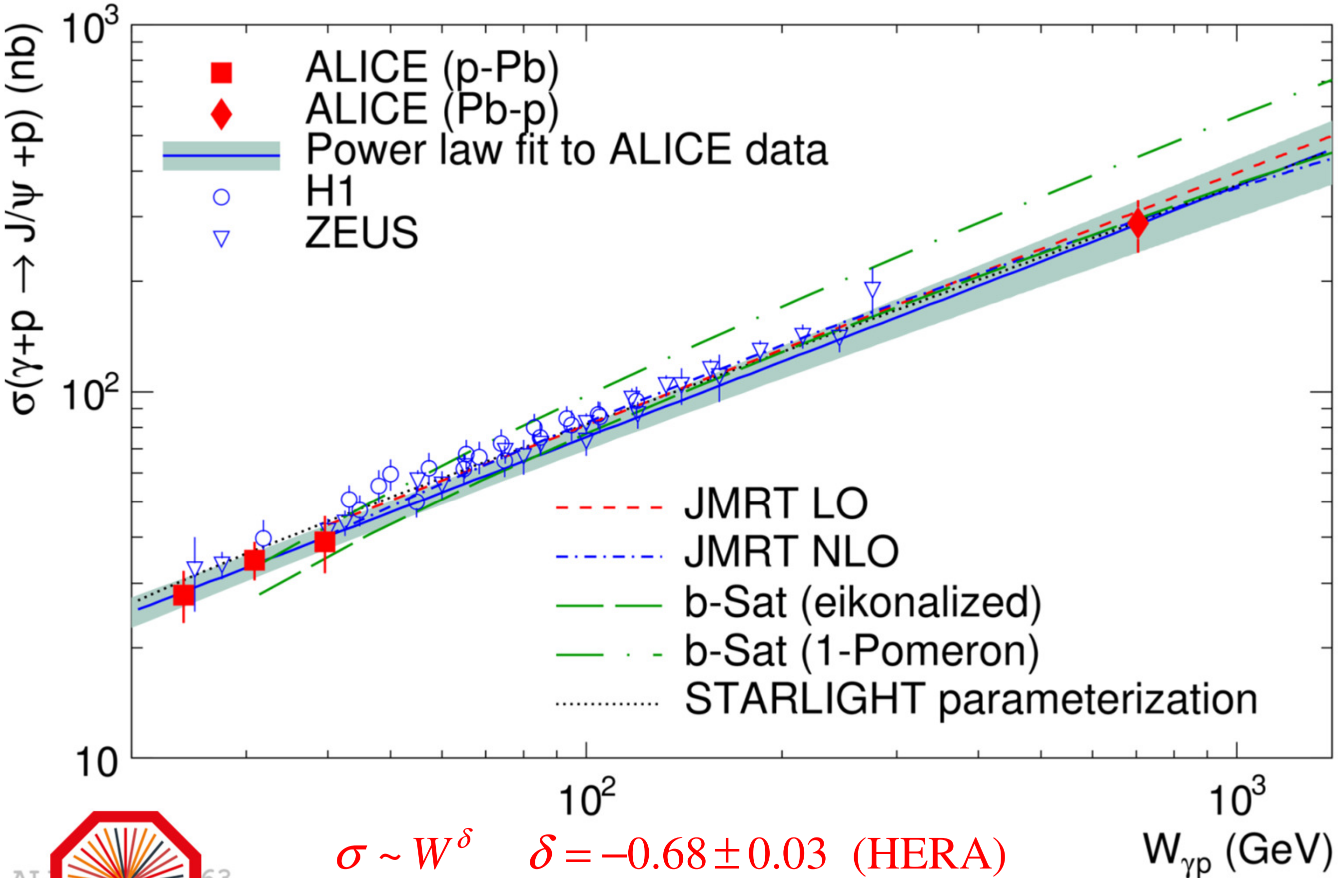


- Energy reach to ~1.3 TeV
- Energy ambiguity means that two solutions come from one set of measurements.

See talk by G. Passaleva

A. Aaij et al. J. Phys. G **41 (2014) 055002**

ALICE J/ψ in p-Pb

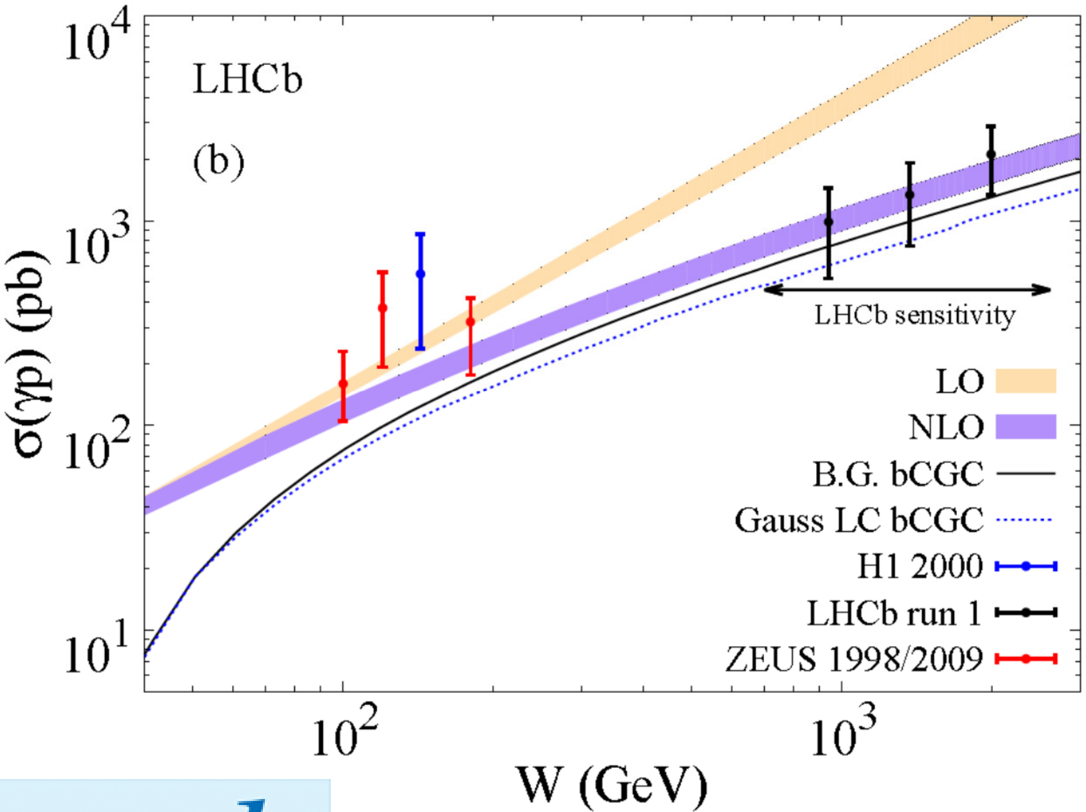


$\sigma \sim W^{\delta}$ $\quad \delta = -0.68 \pm 0.03$ (HERA)

$\delta = -0.68 \pm 0.06$ (ALICE)

- p-Pb resolves ambiguity, so low and high energy points distinct.
- Lower max. energy in pPb.
- Precision on slope of energy curve similar to HERA

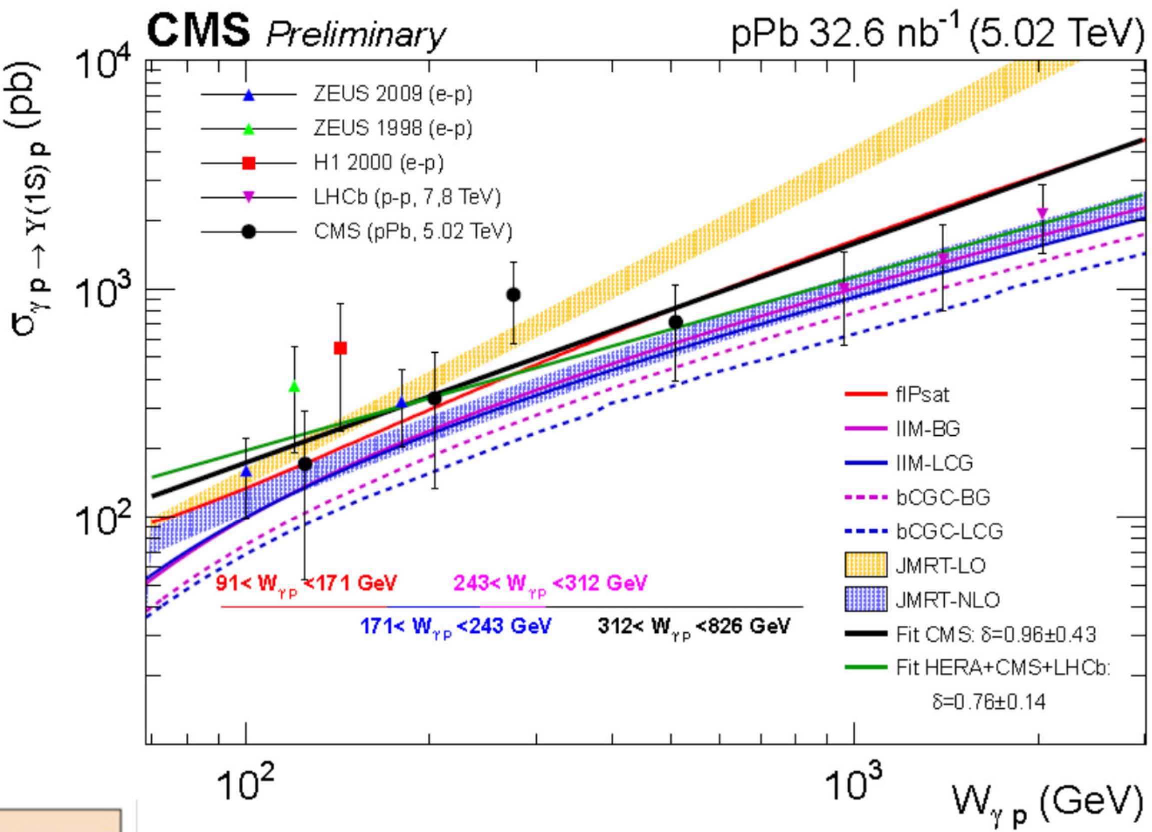
LHCb ϒ in pp



A. Aaij et al. JHEP **09** (2015) 084

- First UPC measurement of ϒ
- In good agreement with NLO
  - JHEP **1311** 085
- Larger Q^2 scale provides useful independent validation of UPC. However, for low-*x* studies, range covered is correspondingly less.

CMS Υ in pPb



CMS PAS FSQ-13-009

First UPC measurement of Υ in pPb

In good agreement with NLO

– JHEP **1311** 085

Larger Q^2 scale provides useful independent validation of UPC. However, for low-*x* studies, range covered is correspondingly less.

Multi-Parton Interactions

MPI from Heavy Flavour

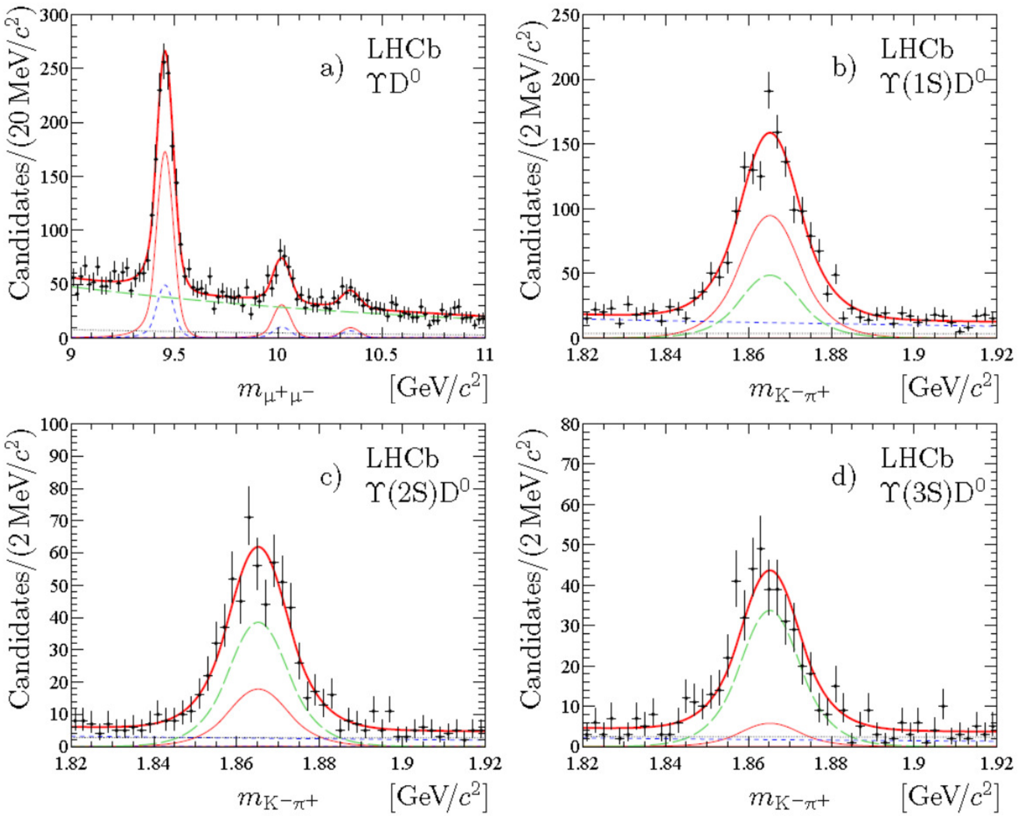
- Heavy flavour production has been proposed as a probe for MPIs, both
  - Singly, through an increase in (e.g.) inclusive charm production with multiplicity

See e.g. S. Porteboeuf and R. Granier de Cassagnac, Nucl. Phys. B Proc. Supp. **214** 181

  - In pair production, where yields can be compared against pQCD calculations.

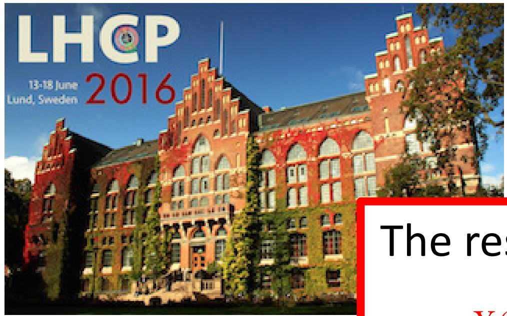
See e.g. C.H. Kom, A. Kulesza, and W.J. Stirling PRL (2011) 082002

LHCb Υ+ charm



- Measurement in 7 TeV and 8 TeV data of
  - $\Upsilon(1S)D^0$, $\Upsilon(2S)D^0$, $\Upsilon(1S)D^+$, $\Upsilon(2S)D^+$, $\Upsilon(1S)D_s^+$
- Using known fragmentation functions, obtain

$\Upsilon c\bar{c}$



LHCb ϒ+ charm

The result of this yields

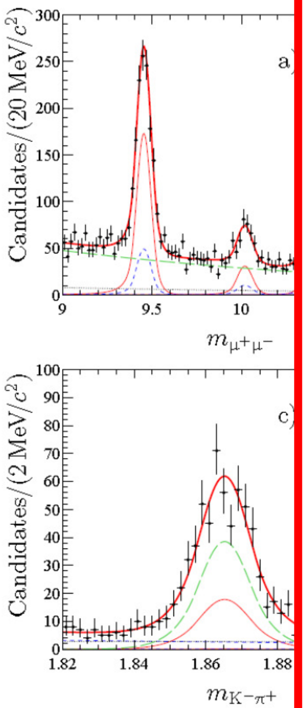
$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{7\mathrm{TeV}} = (5.5 \pm 1.7)\%$$

$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{8\ \mathrm{TeV}} = (6.2 \pm 0.7)\%$$

While Single Parton Scattering (SPS) predictions give

$$\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}} = (0.2 - 0.6)\%$$

So results are substantially above SPS prediction,
and are consistent with Double Parton Scattering (DPS).



ent in 7
eV data

(2S)D^0,
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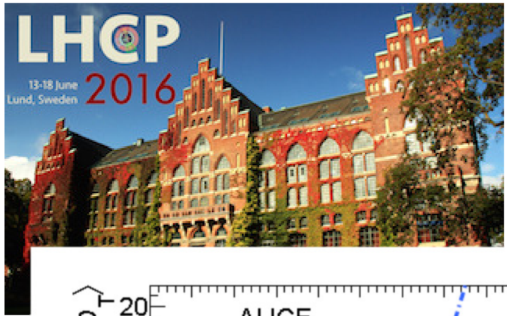
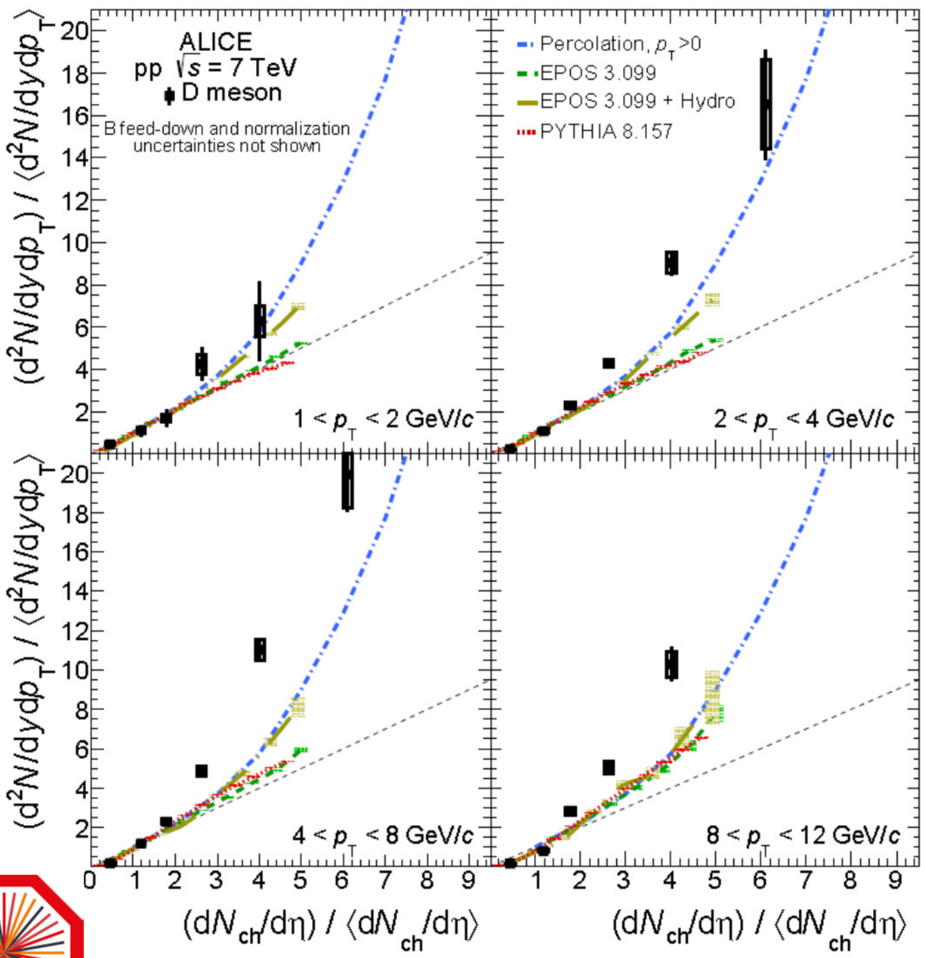
R. Aaij et al. ArXiV:1510.05949



ALICE Charm and multiplicity

pp



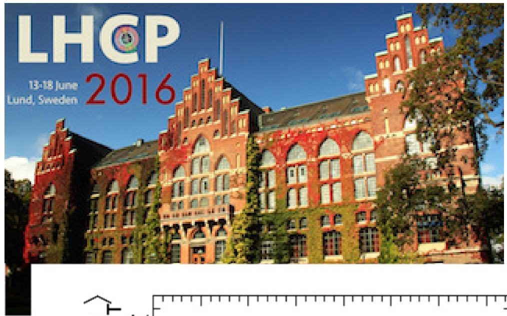
- Results show increase in relative yield of D mesons as a function of relative multiplicity.
- Faster than linear increase!
- Percolation works best (*); increase even *too* rapid for MPI, as represented in PYTHIA.

(*) E.G. Ferreiro and C. Pajares PRC (2012)034903, ArXiV:1501.03381

J. Adam et al. JHEP **09** (2015) 148

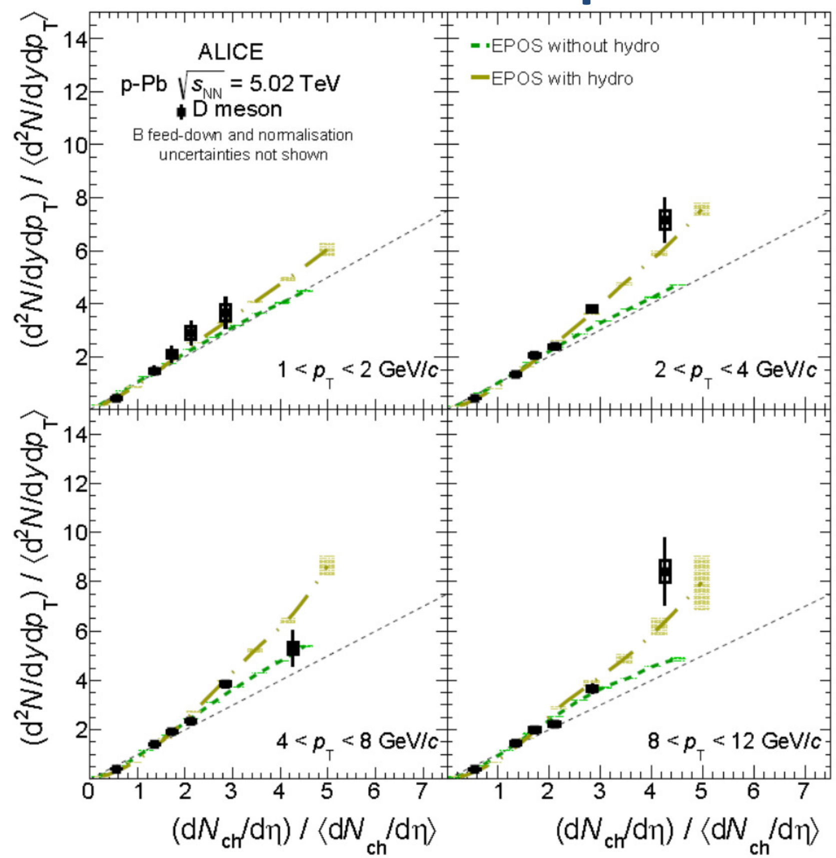
See talk by **C. Zampolli**

ALICE



ALICE Charm and multiplicity

pPb

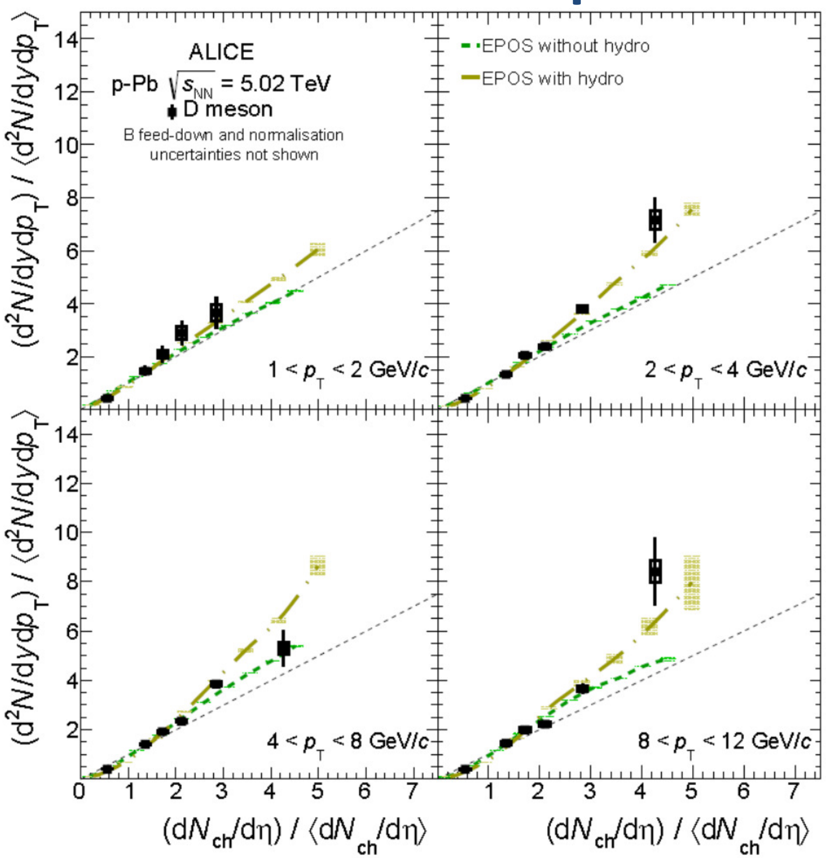


- Similar faster than linear increase!
- In this case, EPOS (shown) can or MPI (not shown) could describe increase.

J. Adam et al. ArXiv:1602.072

ALICE Charm and multiplicity

pPb



- Similar faster than linear increase!
- In this case, EPOS (shown) can or MPI (not shown) could describe increase.

…and similar things seen (even in pp!) in behaviour of multistrange production with multiplicity in pp. See talk by **V. Vislavicius**

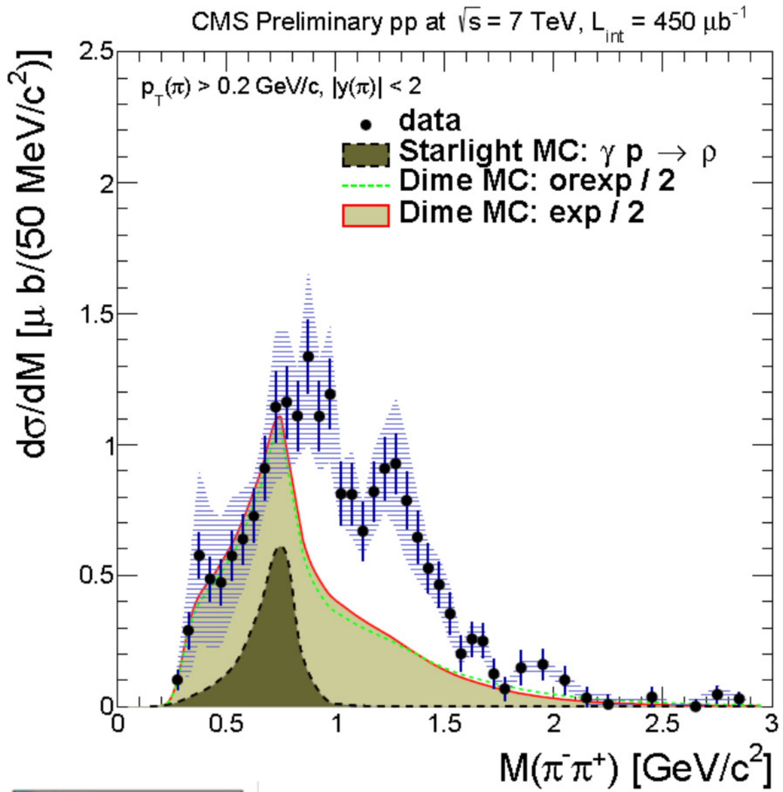
J. Adam et al. ArXiv:1602.072

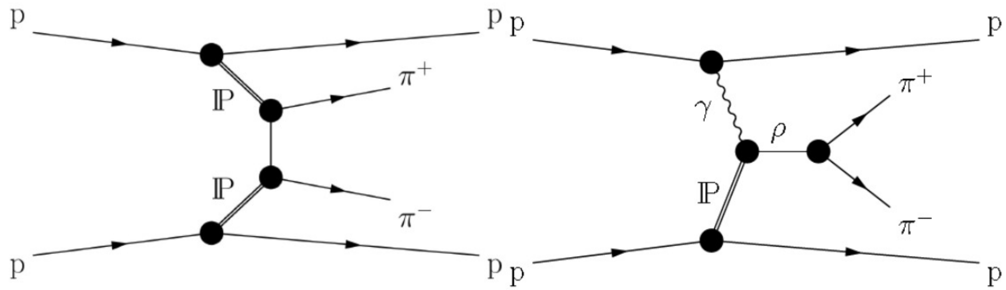
Summary

- Good consistency obtained between experiments on d*N*/dη in pp at 13 TeV
  - Two p_T thresholds available with different properties
  - Well described by PYTHIA 8 (Monash) or EPOS-LHC at low pt threshold
- At *very low* multiplicity, UPC, now studied by *all* LHC experiments, provides a new tool for studying pdfs (and their modification in nuclear matter)
- Heavy flavour gives new access to MPI, e.g. with new production ratios with beauty
- As multiplicity *increases*, interesting previously unseen effects emerge, e.g. in heavy flavour
- Much more needs to be done to explore and explain these phenomena.

BACKUP

Similar Process: Double Pomeron Exchange





- Double Pomeron Exchange also gives rise to large rapidity gaps – similar event topologies to UPC (photon-Pomeron)
- Mechanism selects even parity states, while UPC favours vector states.
- Long-standing interest because of potential as glueball filter (ISR-AFS, SPS-WA102, COMPASS)