QCD at forward rapidity, in ultra-peripheral collisions, and multi-parton interactions

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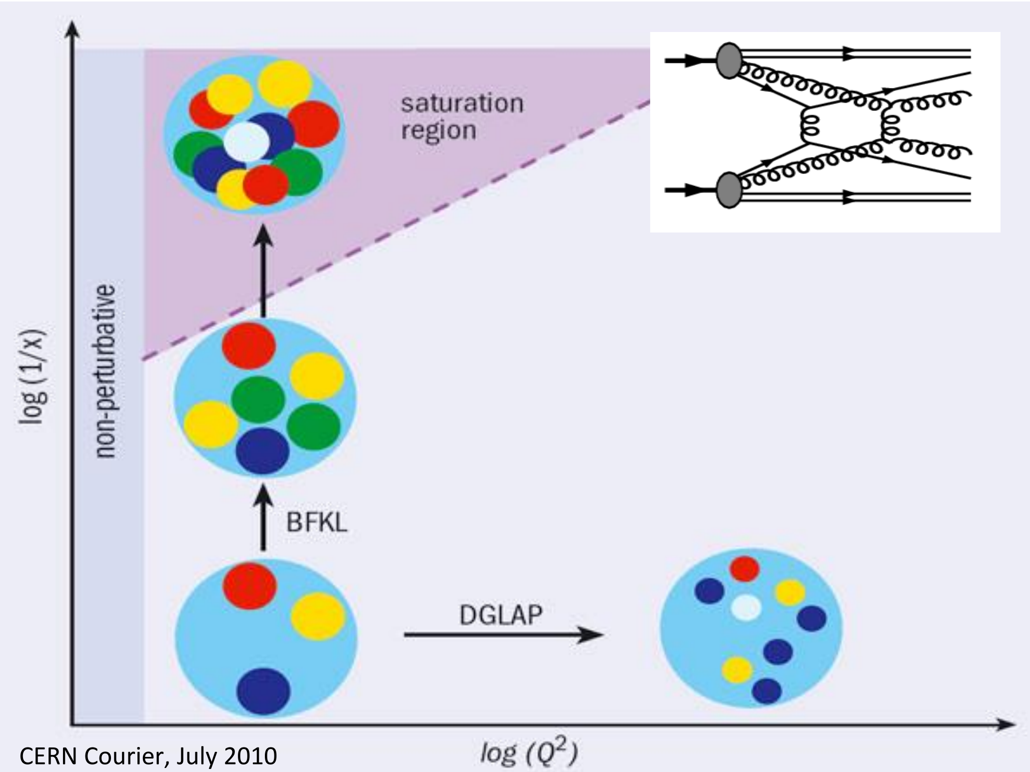
on behalf of ALICE, ATLAS, CMS and LHCb collaborations

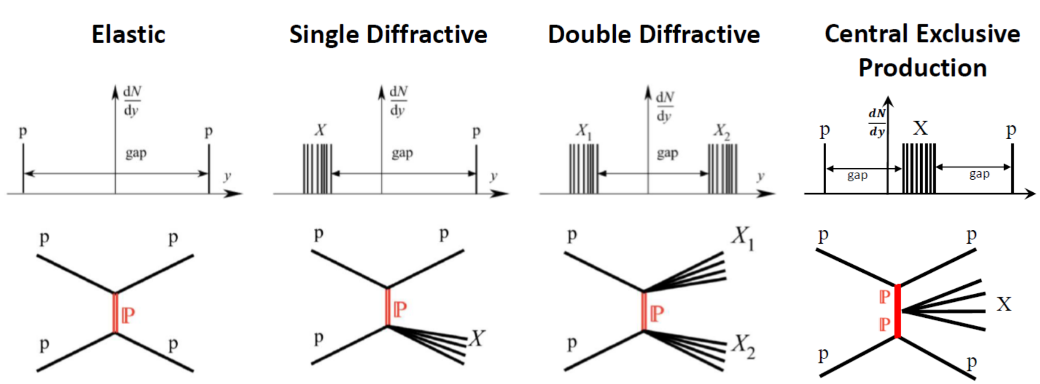
LHCP Bologna
5 June 2018

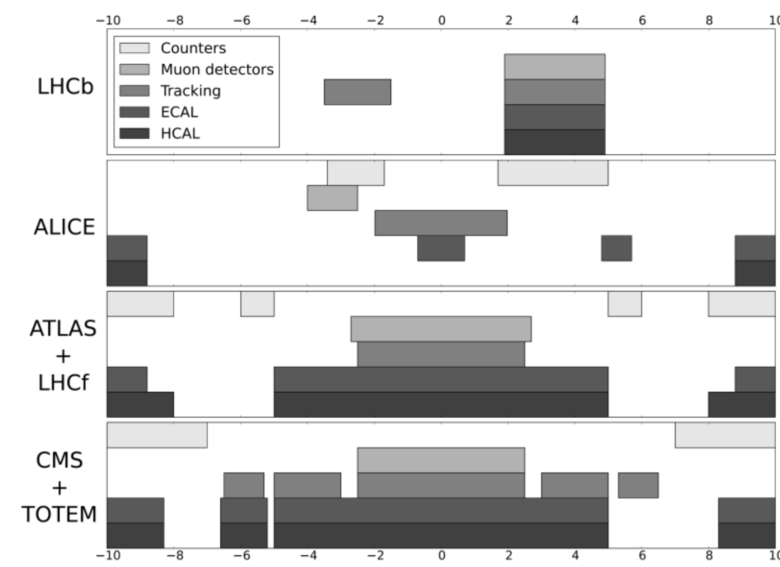
Introduction



CERN Courier, July 2010

- **Forward physics:**
  - Diffraction
  - BFKL effects
- **Ultra-peripheral collisions (UPC)**
  - PDF and nPDFs at low-x
  - anomalous gauge couplings
- **Multi-parton interactions (MPI):**
  - Minimum bias and high-multiplicity measurements
  - Underlying events
  - Double-parton scattering





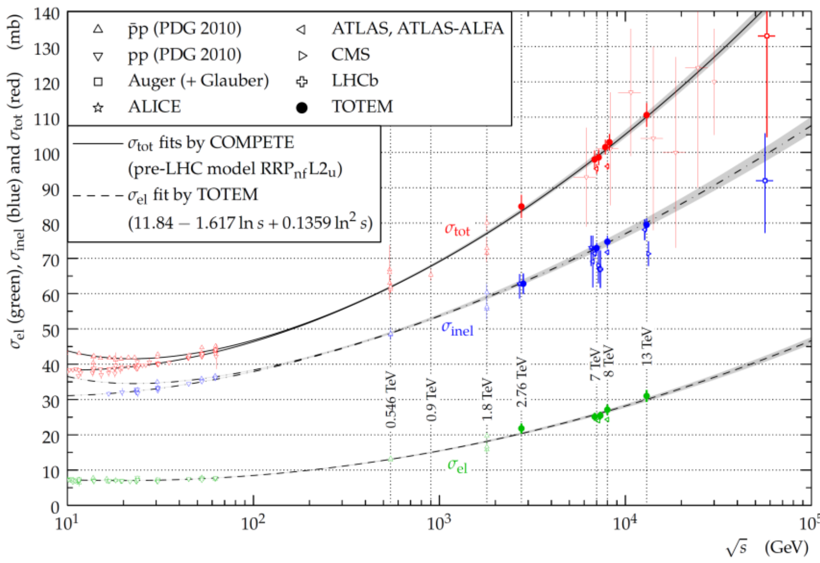
Courtesy: C. Baus

Latest TOTEM results

Luminosity-independent total cross section:

$$\sigma_{\mathrm{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_{t=0}}{N_{\mathrm{el}} + N_{\mathrm{inel}}}$$

$$\rho = \frac{\mathrm{Re}\,A^N}{\mathrm{Im}\,A^N}$$



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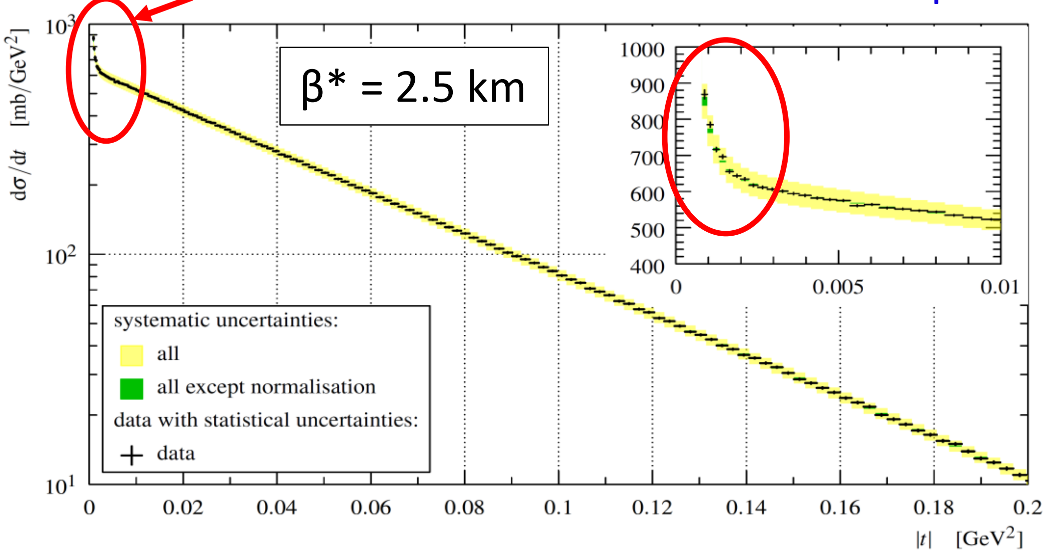
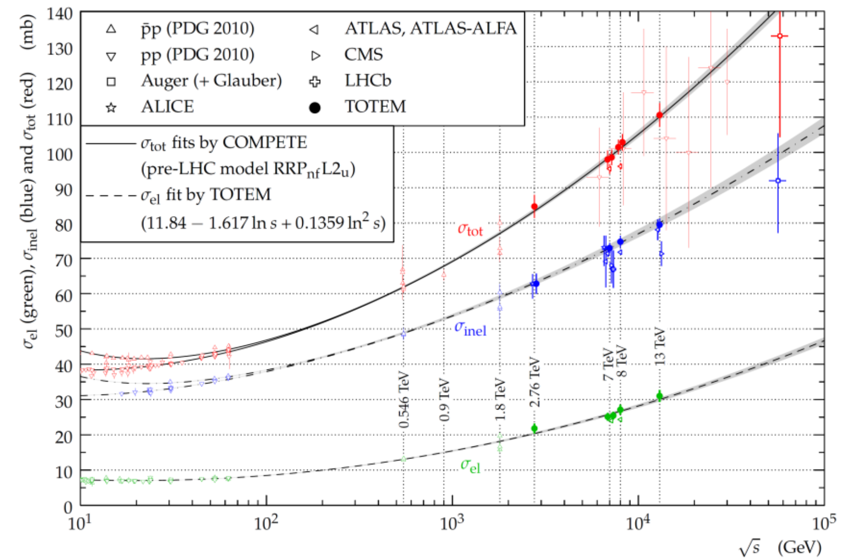
ρ from Coulomb-nuclear interference:

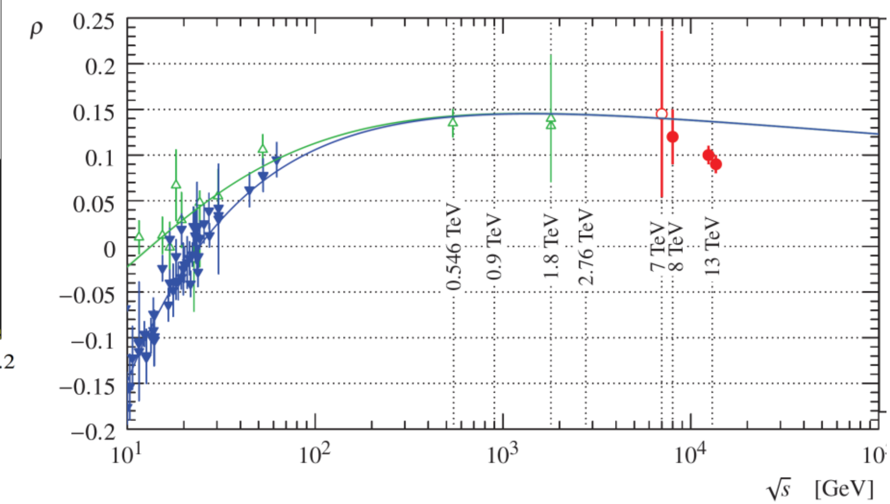
$$\frac{\mathrm{d}\sigma^{\mathrm{C+N}}}{\mathrm{d}t} = \frac{\pi(\hbar c)^2}{s p^2}\left|\frac{\alpha s}{t}\mathcal{F}^2 + \mathcal{A}^{\mathrm{N}}\left[1 - \mathrm{i}\alpha G(t)\right]\right|^2$$

Coulomb

nuclear elastic amplitude







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Luminosity-independent total cross section:

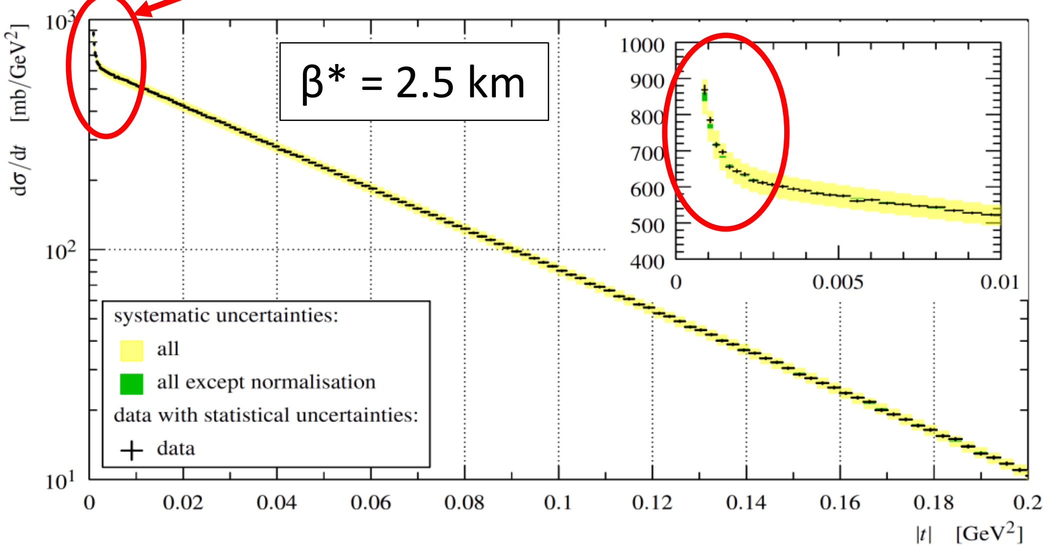
$$\sigma_{\mathrm{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_{t=0}}{N_{\mathrm{el}}+N_{\mathrm{inel}}} \qquad \rho = \frac{\mathrm{Re}\, A^N}{\mathrm{Im}\, A^N}$$

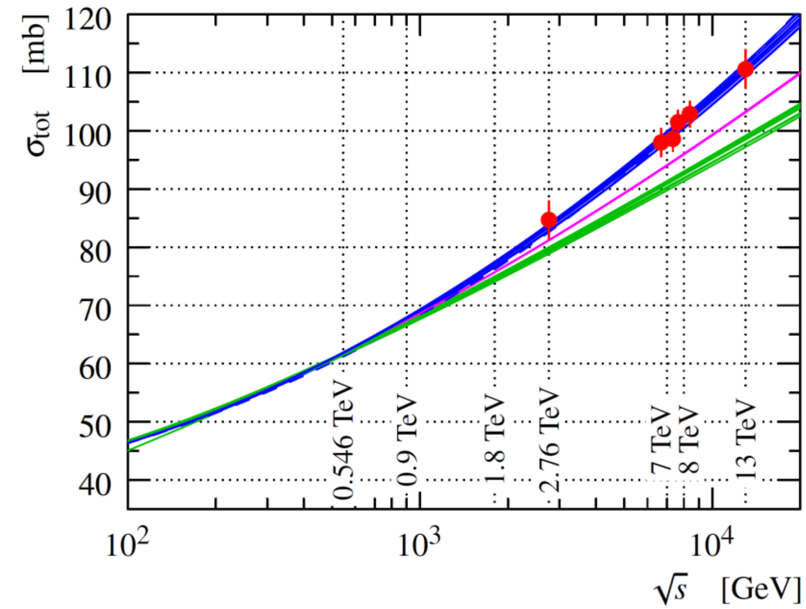
ρ from Coulomb-nuclear interference:

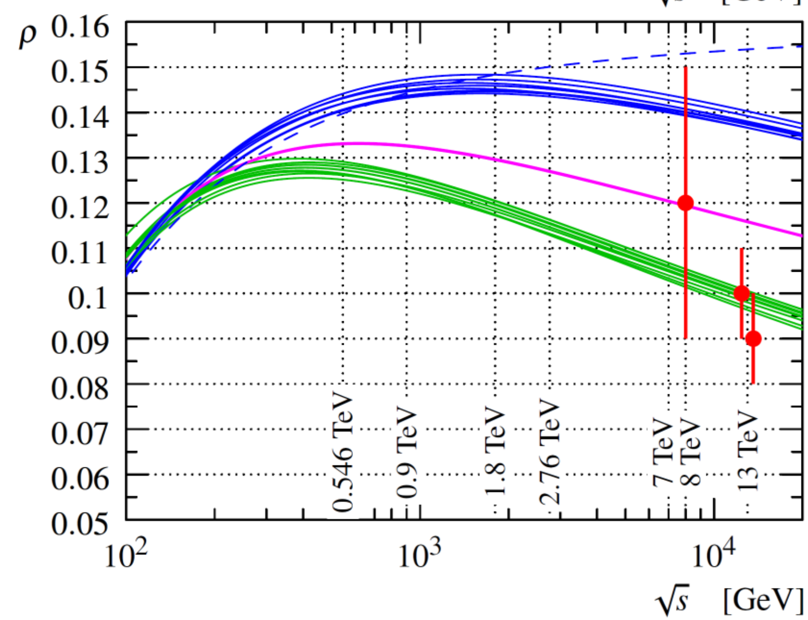
$$\frac{\mathrm{d}\sigma^{C+N}}{\mathrm{d}t} = \frac{\pi(\hbar c)^2}{sp^2}\left|\frac{\alpha s}{t}\mathcal{F}^2 + \mathcal{A}^N\left[1 - i\alpha G(t)\right]\right|^2$$

Coulomb

nuclear elastic amplitude







- COMPETE model fails to describe σ_{tot} and ρ measurements simultaneously.
- Contribution from Odderon exchange?

TOTEM: CERN-EP-2017-335 + arXiv: 1712.06153

=> QCD parallel session: A. Tricomi, June 7, 12:06

Inelastic cross section at 13 TeV

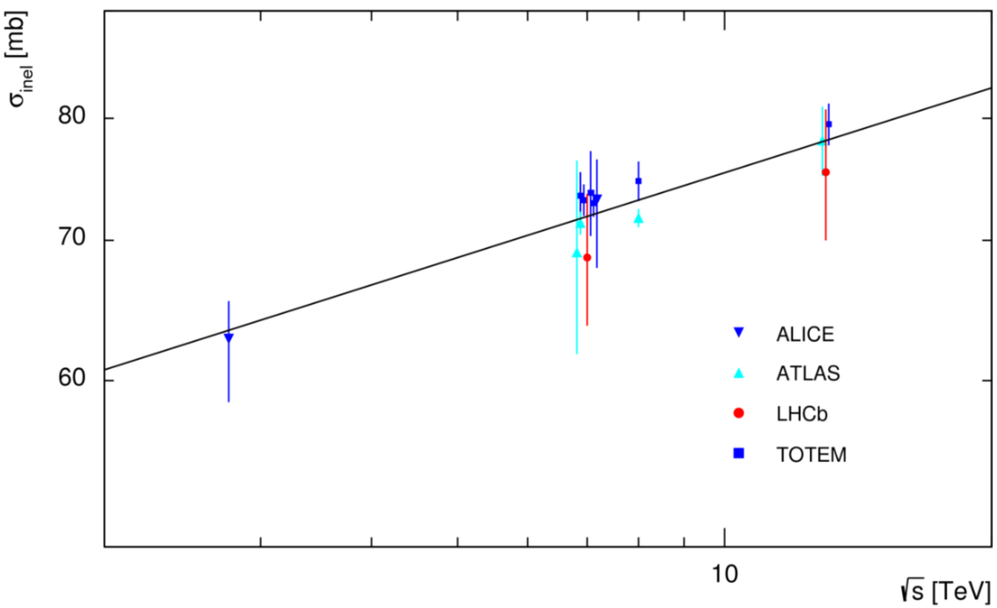
TOTEM: σ_{tot} = 110.6 ± 3.4 mb, N_{el}/N_{inel} = 0.390 ± 0.017 => σ(INEL) = 79.5 ± 1.8 mb

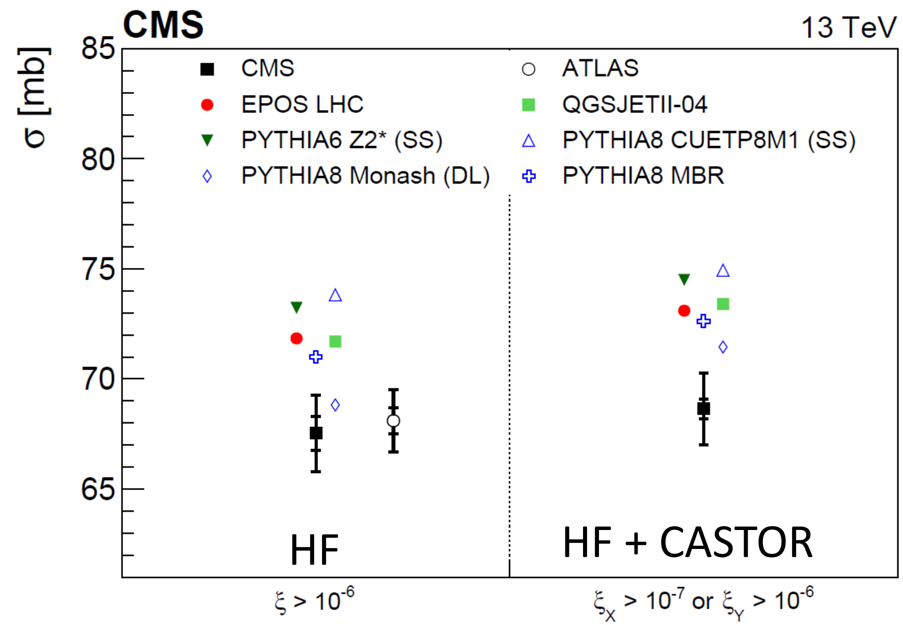
LHCb: σ(acc) = 62.2 ± 0.2 (syst) ± 2.5 (lumi) mb => σ(INEL) = 75.4 ± 3.0(exp) ± 4.5(extr) mb

ATLAS: $\sigma(\xi>10^{-6})$ = 68.1 ± 0.6 (syst) ± 1.3 (lumi) mb => σ(INEL) = 78.1 ± 0.6(exp) ± 1.3(lumi) ± 2.6(extr) mb

CMS: $\sigma(\xi>10^{-6})$ = 67.5 ± 0.8 (syst) ± 1.6 (lumi) mb

$\sigma(\xi_X>10^{-6}$ or $\xi_Y>10^{-7})$ = 68.6 ± 0.5 (syst) ± 1.6 (lumi) mb



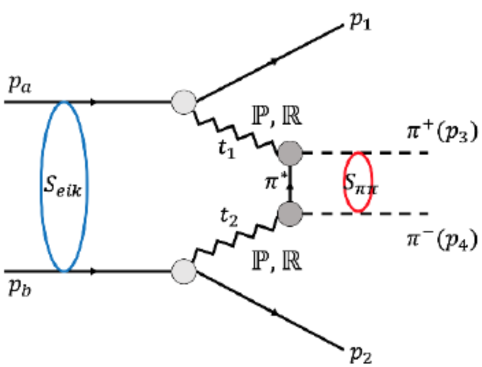


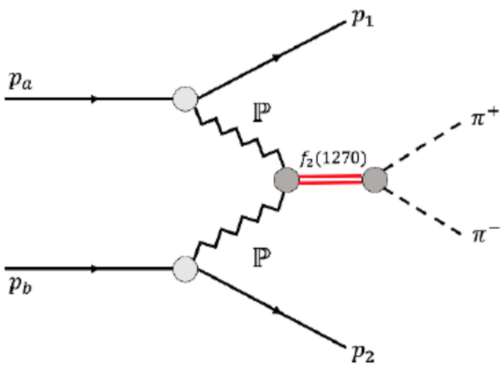
- INEL cross section measurements consistent in all experiments
- CAVEAT: models overestimate diffractive contribution in visible cross sections

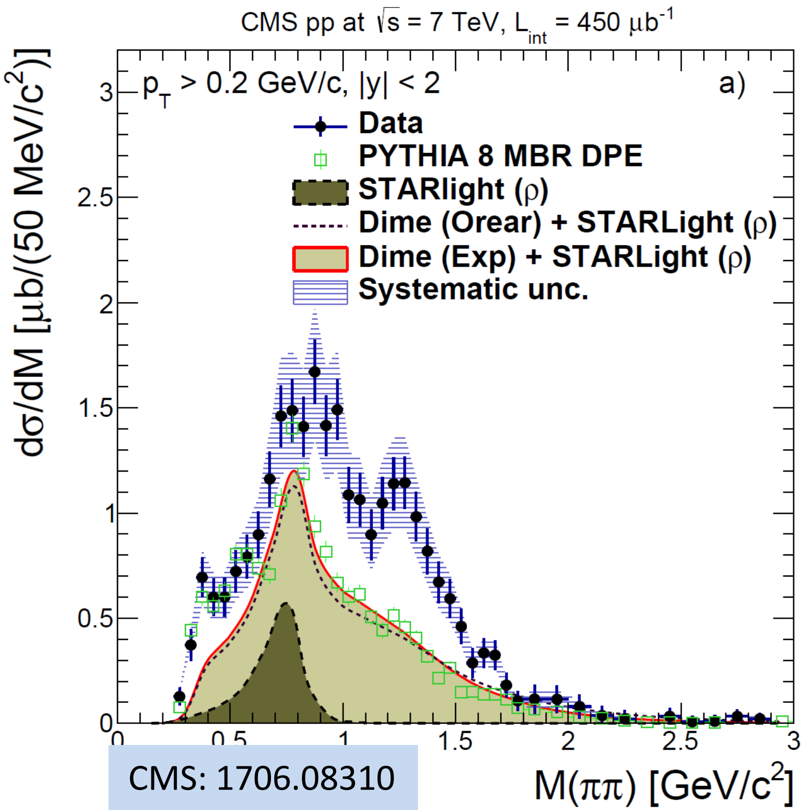
ATLAS: PRL 117 (2016), 182002
CMS: arXiv:1802.02613
LHCb: arXiv:1803.10974
TOTEM: arXiv: 1712.06153

=> QCD parallel session: O. Kuprash, June 7, 12:44

Central exclusive production





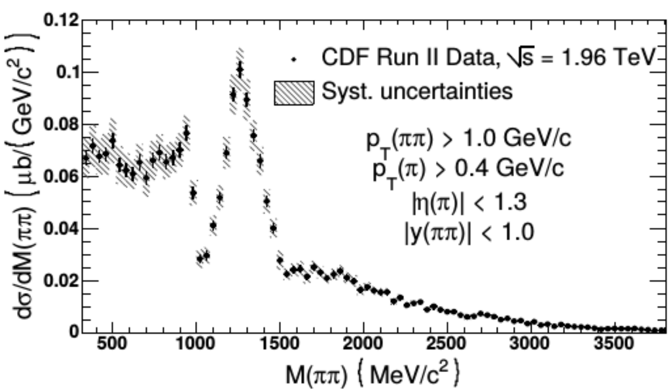


CMS: 1706.08310

- Dominated by pomeron-pomeron interactions => Enhanced production of 0^{++}, 2^{++} resonances
- Measured cross section 50% larger than model predictions (resonances and low-mass proton dissociation not included in models)

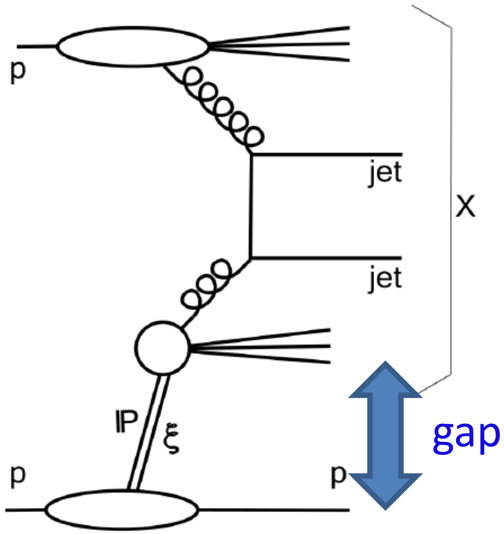
Prospects:

- Determination of pomeron-meson effective couplings
- Hadron spectroscopy (e.g ππ,KK,4π,2π2K channels) including charm sector
- Glueball and oddball searches



CDF: PRD 91 (2015) 091101

Diffractive dijet production

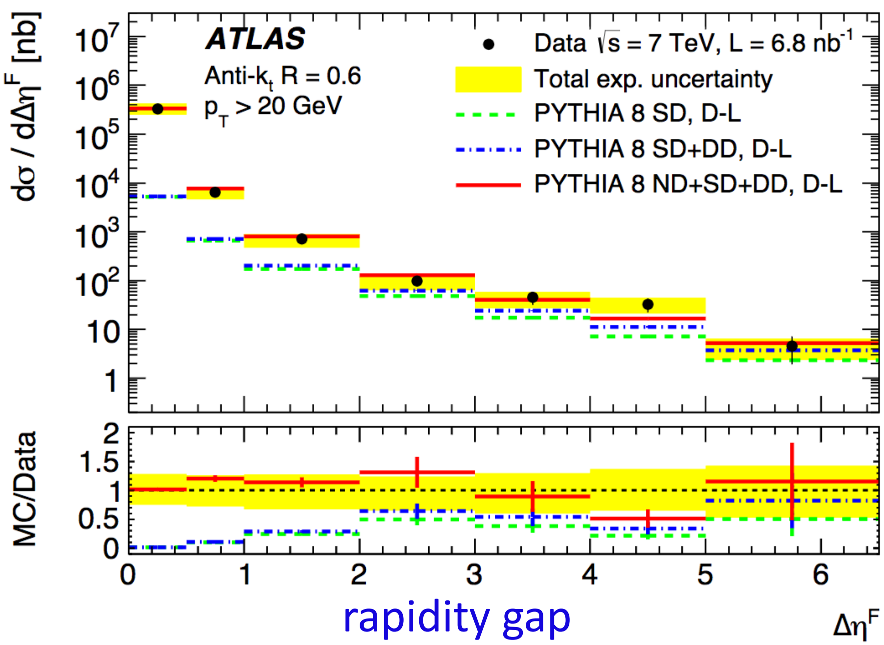


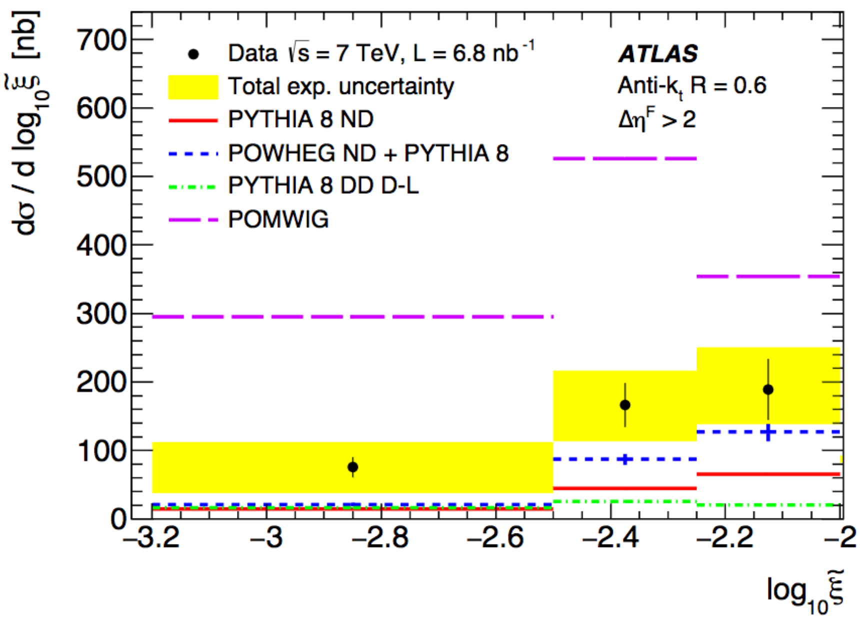
- Extensively studied in ep at HERA => diffractive PDFs
- In pp rapidity gap is spoiled by additional exchanges
- Diffraction dominant at Δη > 2

Strong absorptive effects:

- ATLAS: S^2 = **0.16** ± 0.04(stat.) ± 0.08 (syst.)
- CMS: S^2 = **0.12** ± 0.05 (LO)

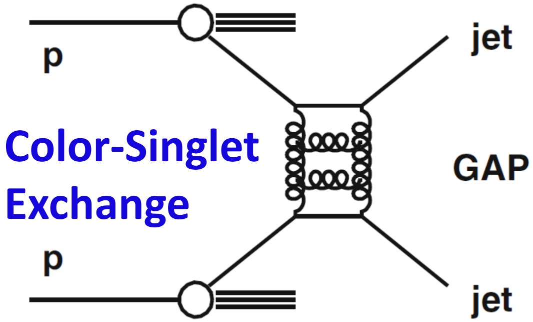
$S^2(\sqrt{s})$ dependence not yet established

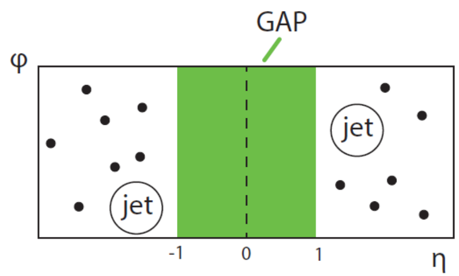


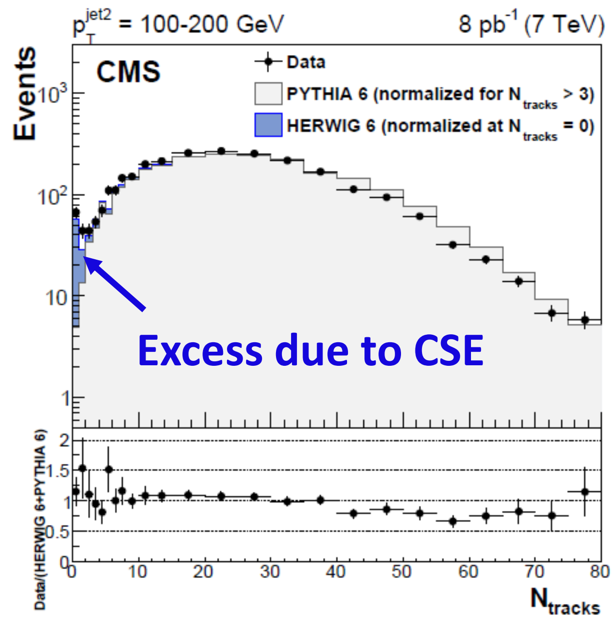


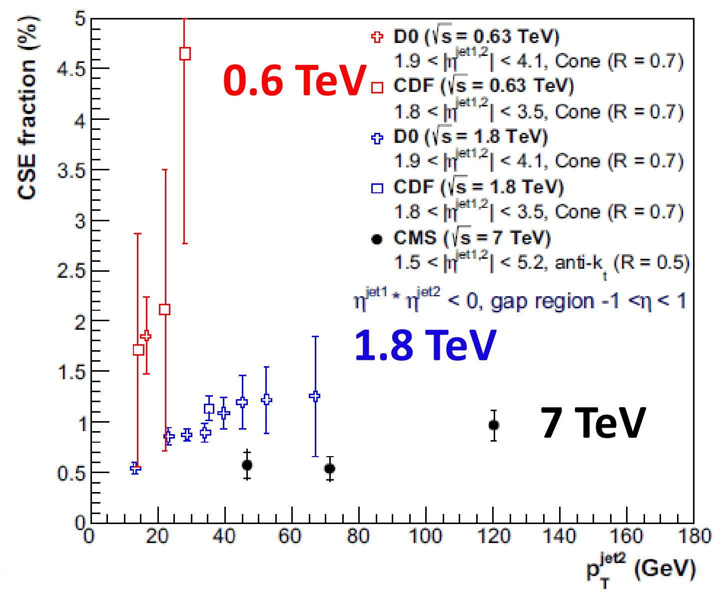
CMS: PRD87 (2013) 012006, ATLAS: PLB754 (2016) 214 + Recent review on gap survival: KMR, J.Phys. G45 (2018) 053002

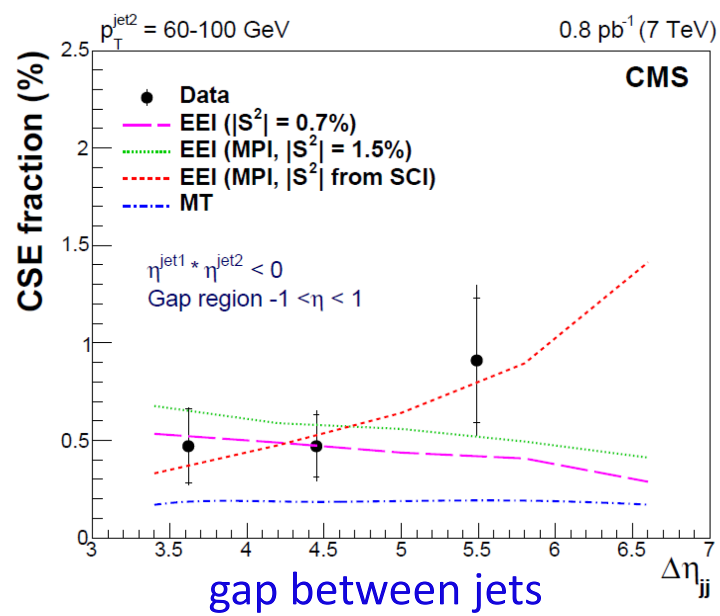
First jet-gap-jet measurements at LHC











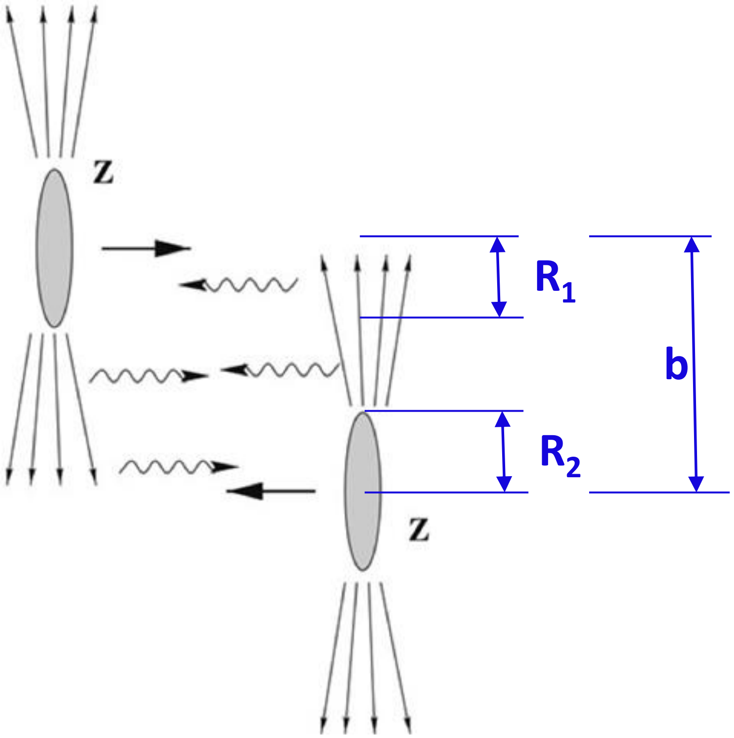
- Jet-gap-jet events are driven by hard pomeron exchange => sensitive to BFKL dynamics
- Strategy:
  - select dijet events with $|\eta_{jet}|$>1.5
  - study track activity in the "gap" region: $|\eta|$<1

- **Clear excess at N_{tracks} = 0**
- **Qualitatively described by LL BFKL** (HERWIG)
- CSE fraction is very sensitive to soft rescattering (gap survival probability)

CMS: EPJC 78 (2018) 242

=> QCD parallel session: O. Kuprash, June 7, 12:44

LHC as a $\gamma\gamma$, γp and γPb collider



Ultra-peripheral (UPC) collisions: b > R_1+R_2

→ hadronic interactions strongly suppressed

High photon flux

→ well described in Weizsäcker-Williams approximation (quasi-real photons)

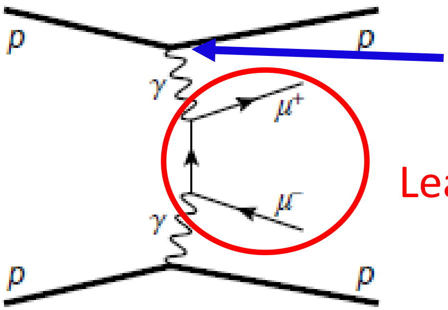
→ flux proportional to Z^2

→ high cross section for γ-induced reactions

Pb-Pb UPC at LHC can be used to study γ- γ, γ-p, γ-Pb interactions at higher center-of-mass energies than ever before

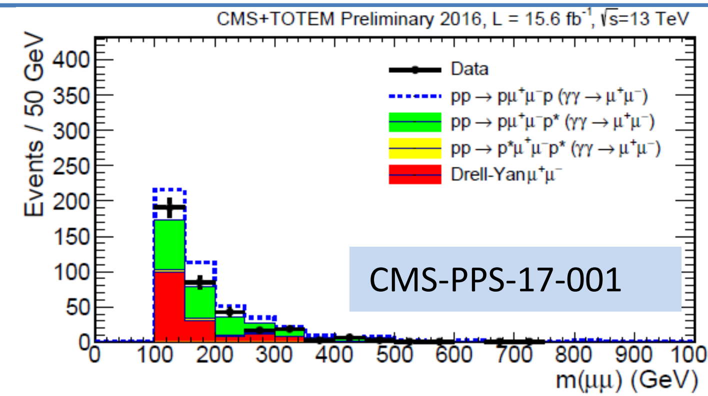
Recent reviews on UPC physics:
A.J. Baltz et al, Phys. Rept. 458 (2008) 1
J.G. Contreras, J.D. Tapia Takaki. Int.J.Mod.Phys. A30 (2015) 1542012

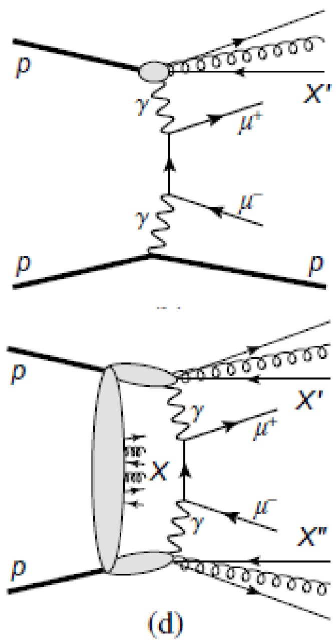
γγ → dileptons in pp

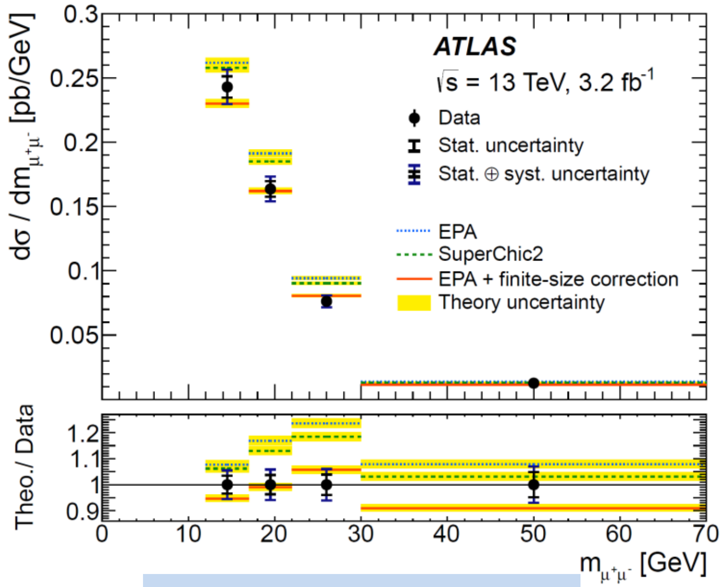


Photon flux in equivalent photon approximation (EPA)

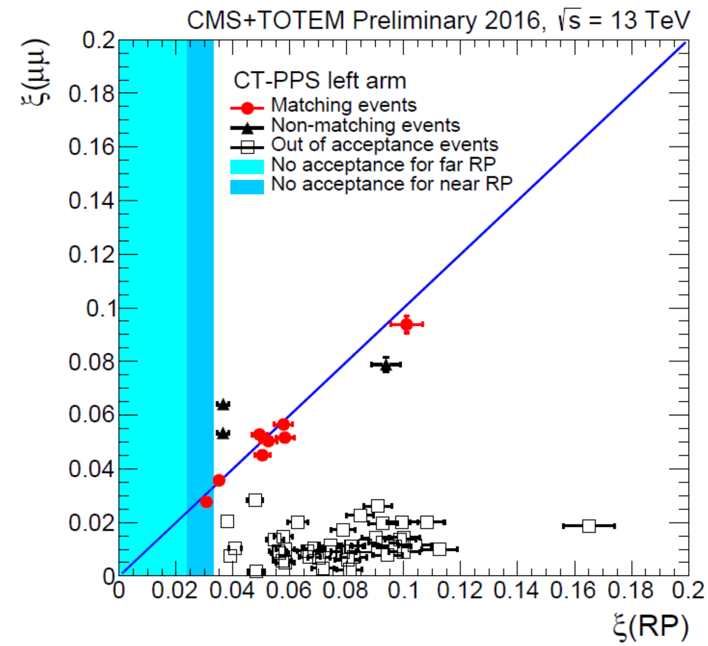
Leading order QED





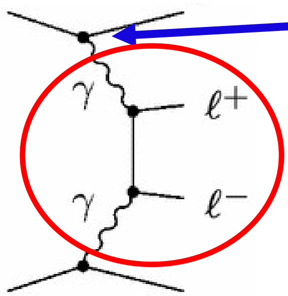


ATLAS: PLB777 (2018) 303



- 10-20% suppression wrt EPA due to extra hadronic interactions
- Absorptive corrections tend to increase with dimuon mass
- Uncertainties can be improved with proton tagging => first CMS+TOTEM measurements

$\gamma\gamma \rightarrow$ dileptons in Pb-Pb

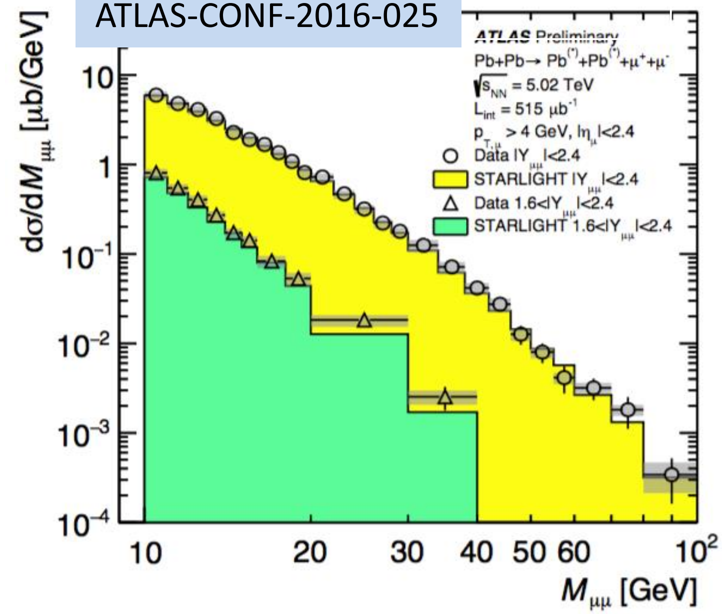


Photon flux proportional to Z^2

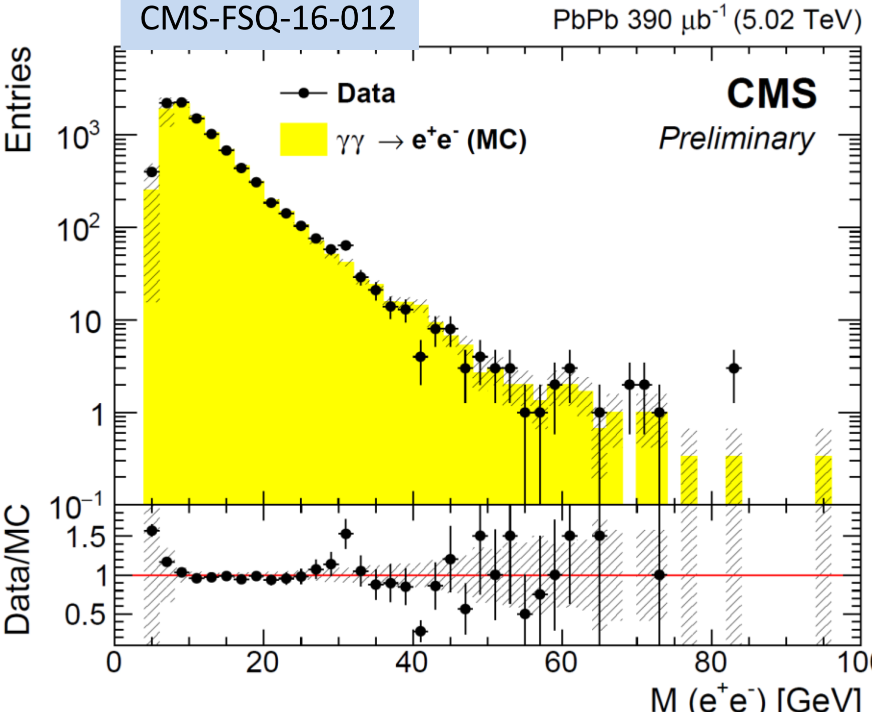
Leading order QED

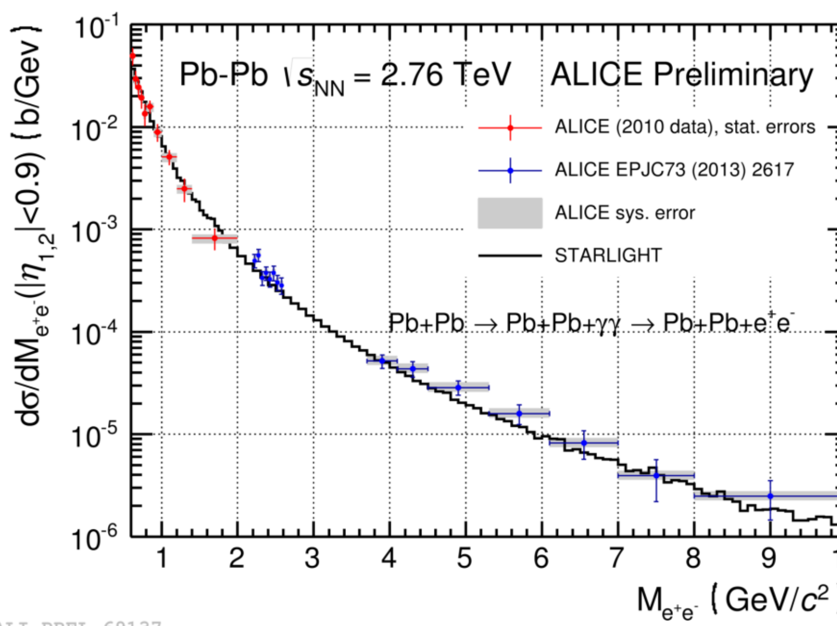
Good agreement between LHC data and LO QED predictions (STARLIGHT)

ATLAS-CONF-2016-025



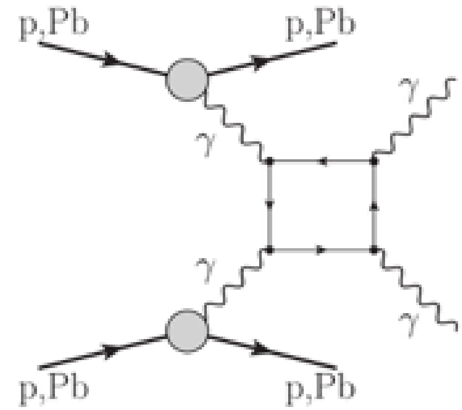
CMS-FSQ-16-012





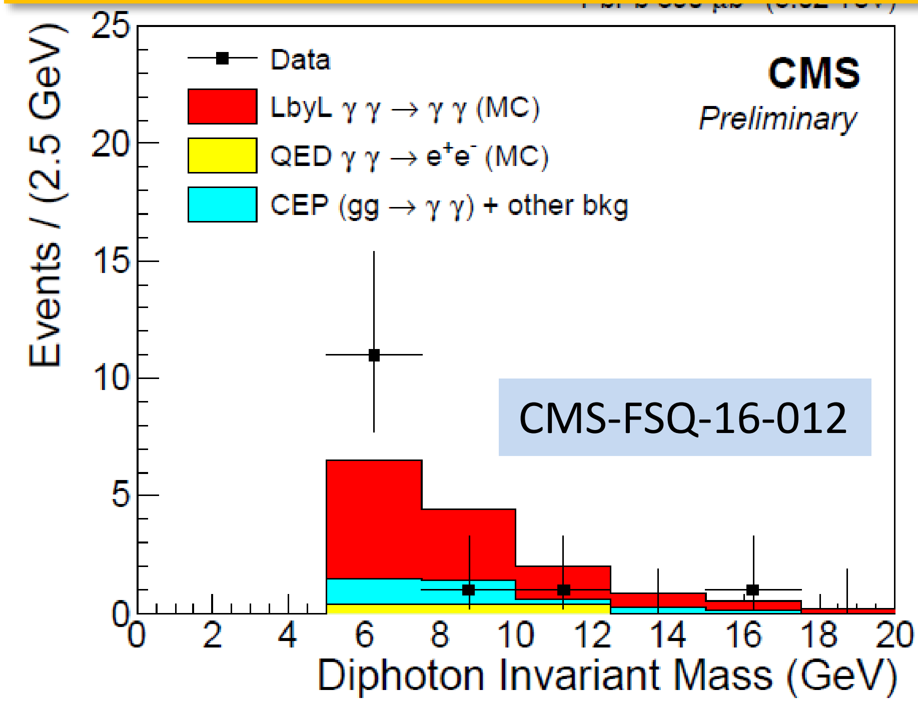
Light-by-light scattering

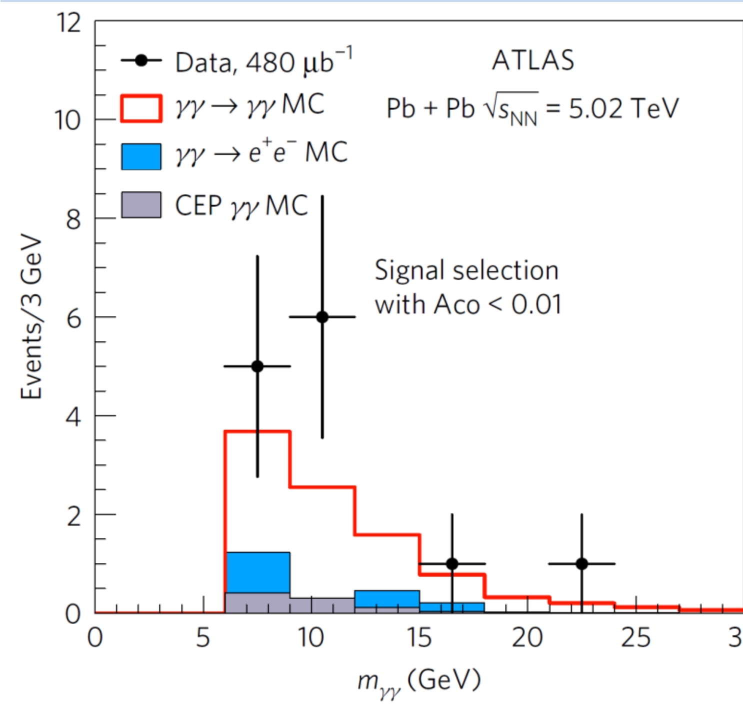
- Forbidden in classical electrodynamics
- Tested indirectly in g-2 measurements, Delbruck scattering and photon splitting processes at low-energies
- Possible channel to study anomalous gauge couplings and contributions from BSM particles



Evidence for light-by-light scattering in UPCs in agreement with SM predictions
4.1σ (CMS) and 4.4σ (ATLAS) significance

ATLAS, Nature Physics 13, 852 (2017)



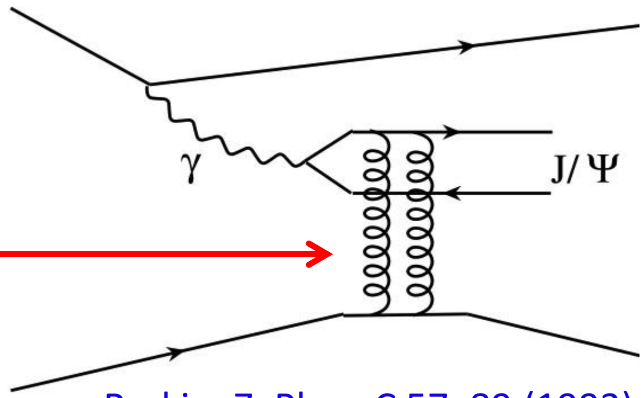


See also $\gamma\gamma \rightarrow W^+W^-$ by ATLAS, PRD 94 (2016) 032011 and CMS, JHEP 08 (2016) 119

J/ψ photoproduction in UPC

- LO pQCD: exclusive J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**:

$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$



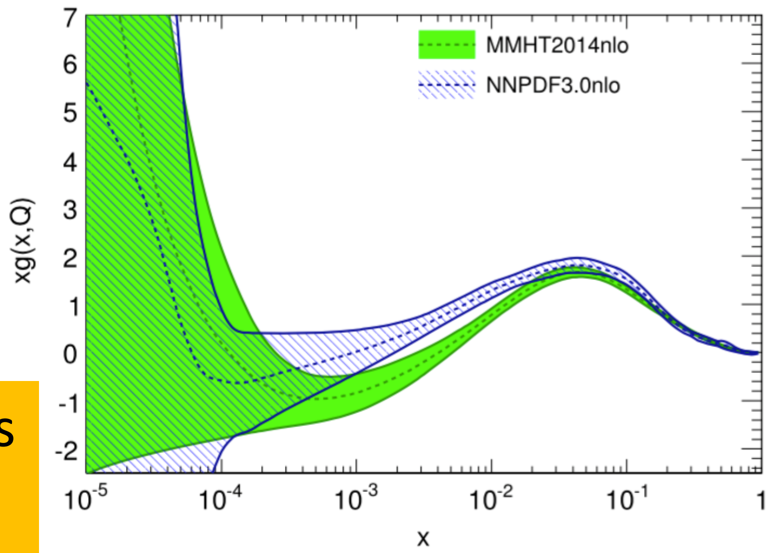
Ryskin: Z. Phys. C 57, 89 (1993)

- J/ψ mass serves as a hard scale:

$$Q^2 \sim \frac{M_{J/\psi}^2}{4} \sim 2.5\ \mathrm{GeV}^2$$

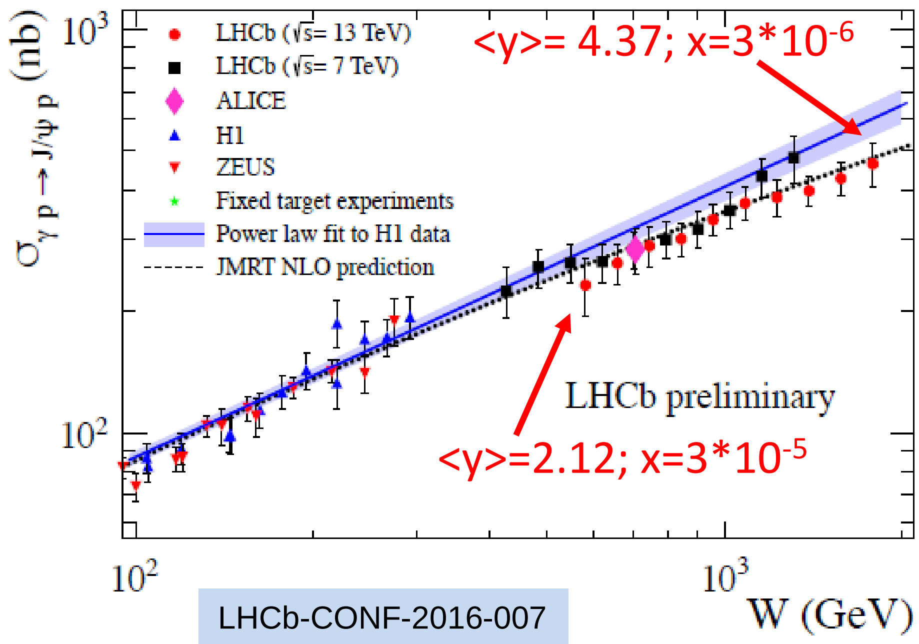
- Bjorken x ~ 10^{-2} – 10^{-5} accessible at LHC:

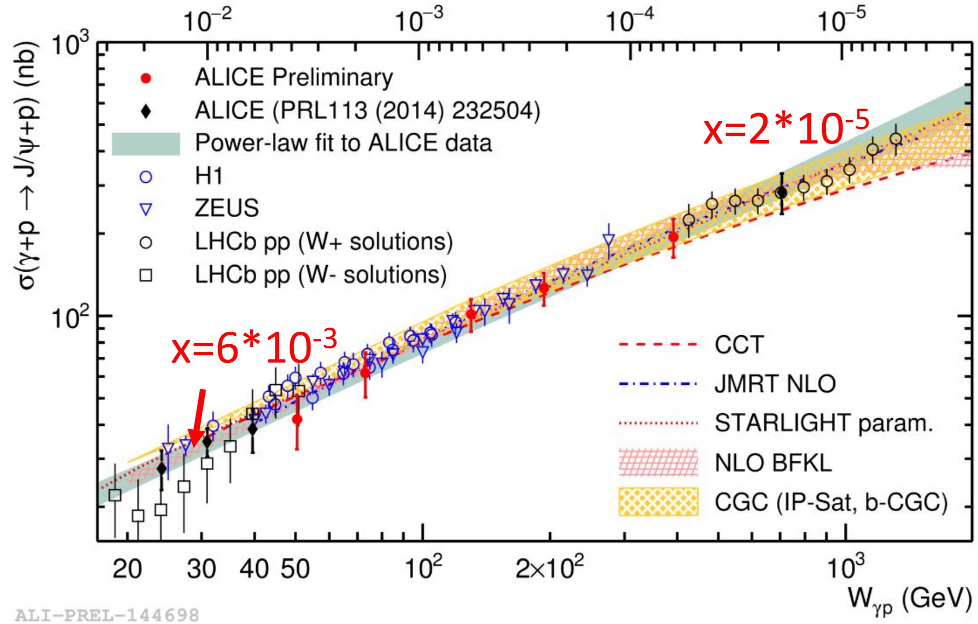
$$x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2} = \frac{M_{J/\psi}}{2E_p}\exp(\pm y)$$



Vector meson photoproduction in UPC allows one to probe poorly known **gluon distributions at low *x***

J/ψ photoproduction off proton

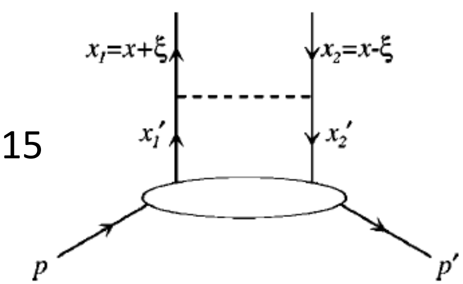




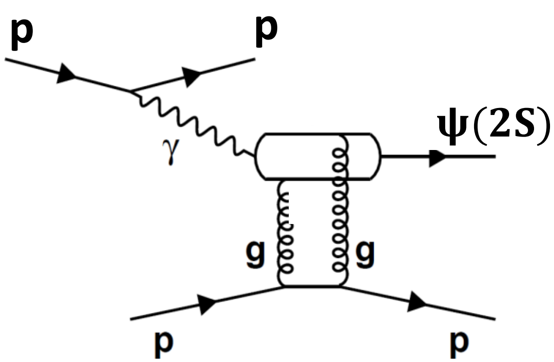
Can we use this data to constrain gluon PDFs?

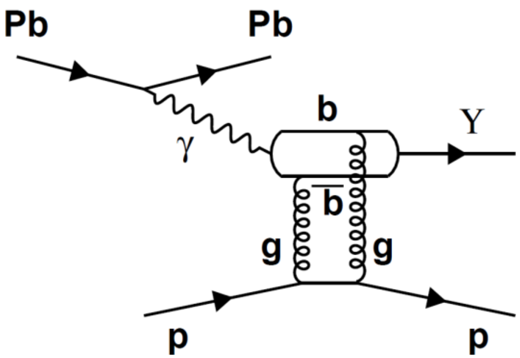
Caveats:

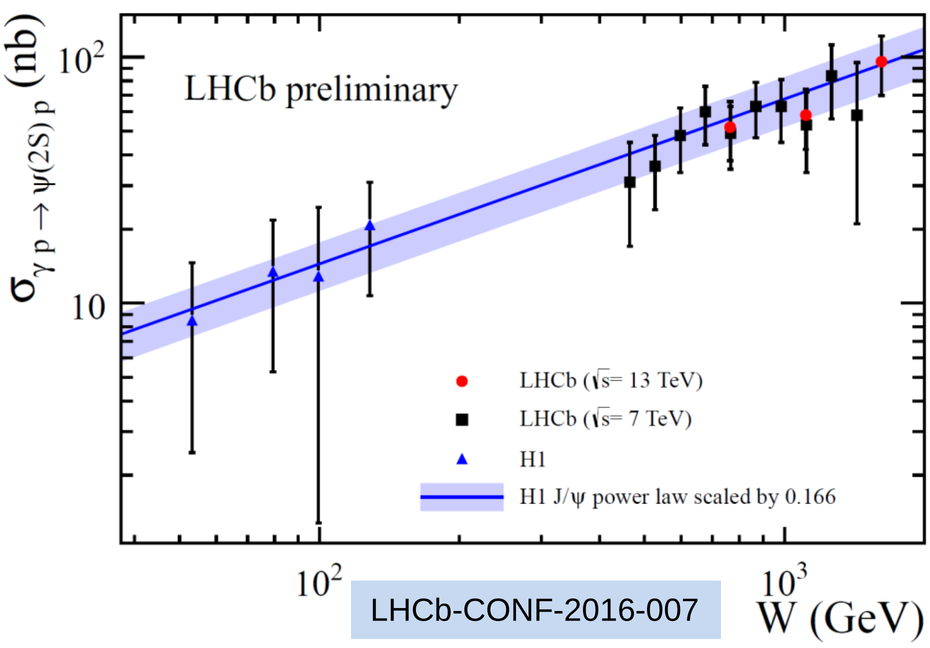
- J/ψ photoproduction probes generalized gluon distributions (two gluons have different x values):
  - Connected with collinear PDFs via Shuvaev transform: PRD 60 (1999) 014015
- Scale uncertainty (μ^2 ~ 2.4-3 GeV^2 is a reasonable choice)
- Large NLO contributions



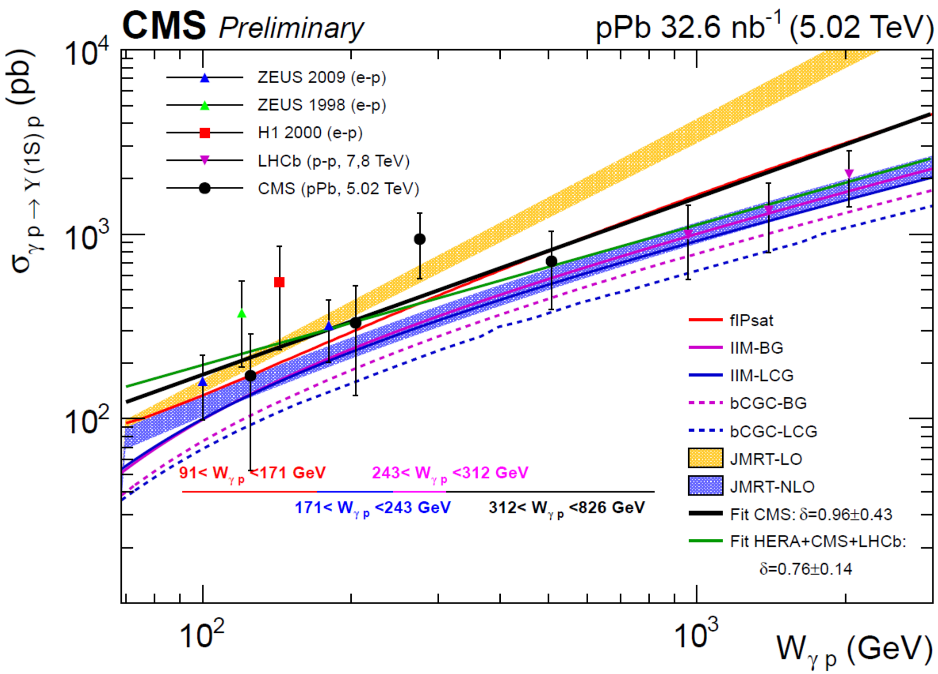
ψ(2S) and Υ(1S) photoproduction off proton







LHCb-CONF-2016-007



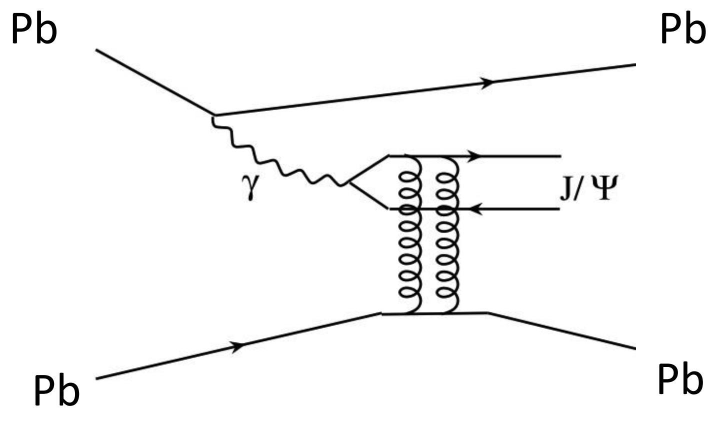
- ψ(2S) and Υ(1S) cross sections compatible with power law
- LHCb measurements reveal importance of NLO effects

CMS-PAS-FSQ-13-009
LHCb: JHEP 09 (2015) 084

J/ψ photoproduction on Pb target

Coherent J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**

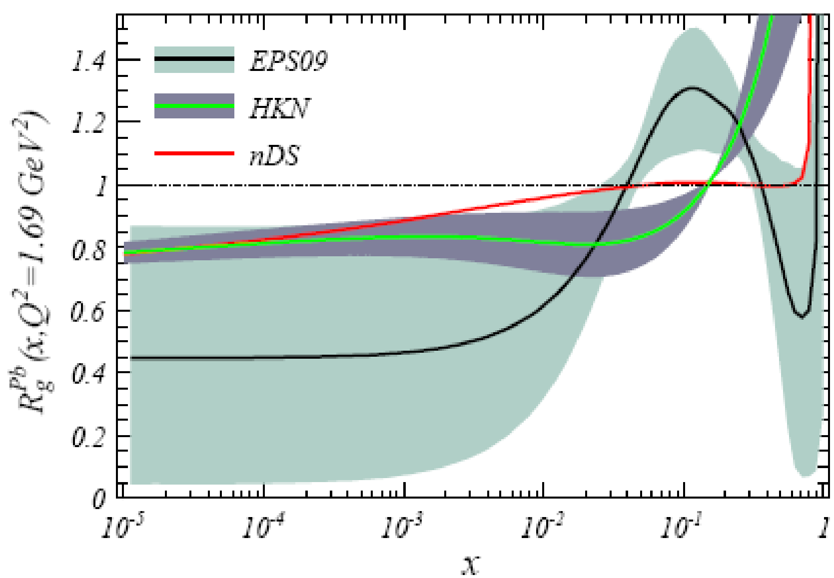
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{\rm em}Q^8}\left[xg_A(x,Q^2)\right]^2$$



J/ψ photoproduction in Pb-Pb UPC (lead target) provides information on **gluon shadowing in nuclei at low x**

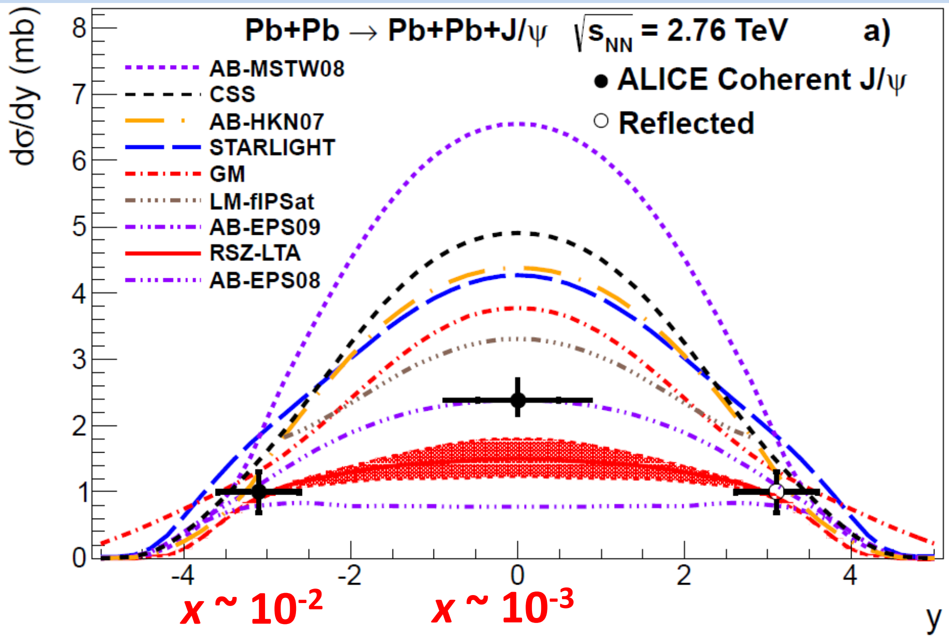
$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$

– gluon shadowing factor

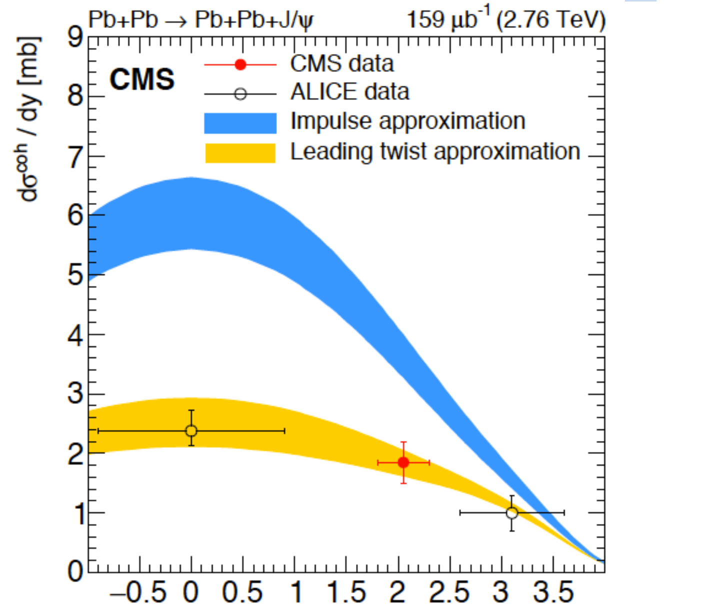


Results from Run 1

ALICE: Phys. Lett. B718 (2013) 1273, Eur. Phys. J. C73 (2013) 2617



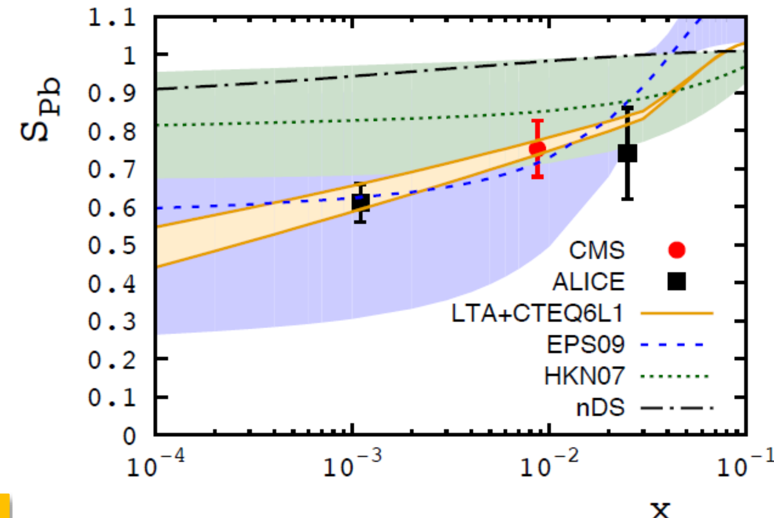
CMS: Phys.Lett. B772 (2017) 489-511



Experimental cross section in Pb-Pb UPC divided by the photon flux

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(W_{\gamma p})}{\sigma^{IA}_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(W_{\gamma p})} \right]^{1/2}$$

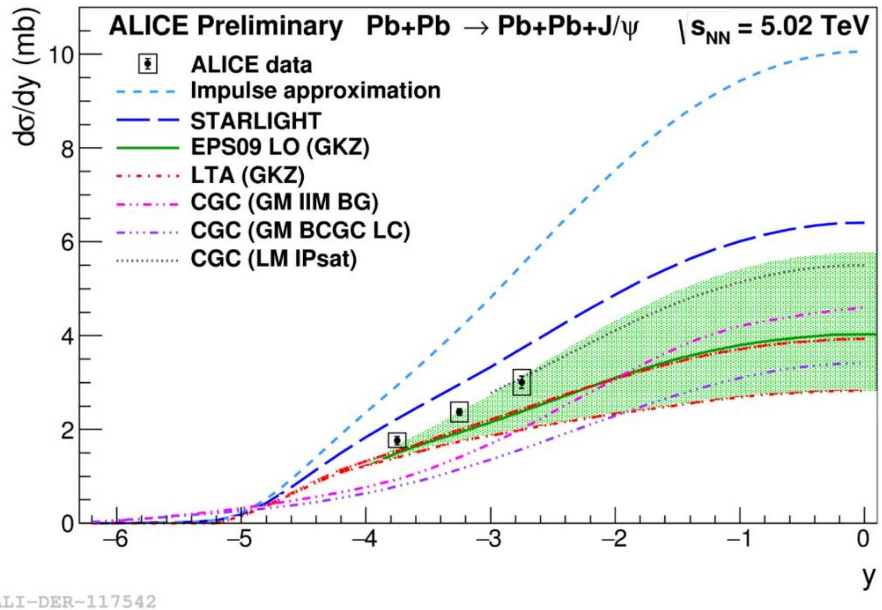
Impulse approximation (derived from forward photoproduction cross section on proton)

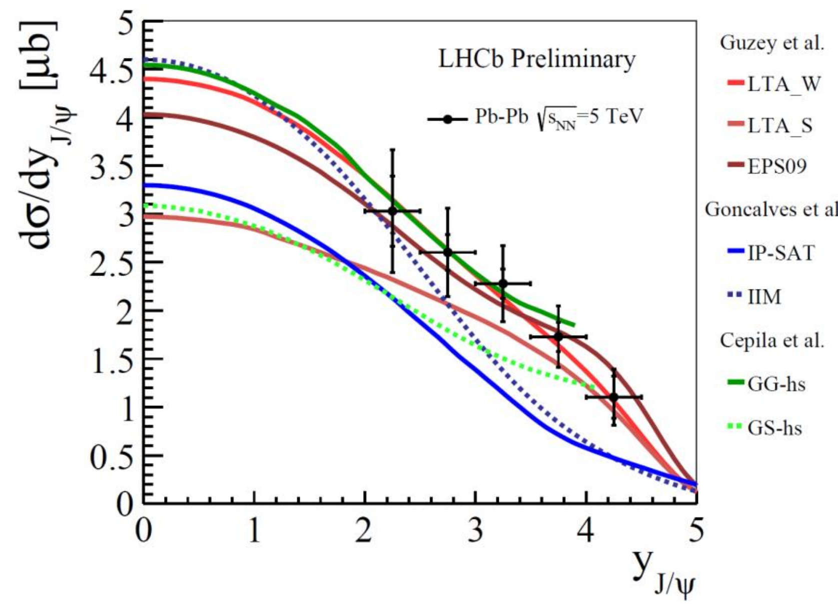


Good agreement with EPS09 and LTA shadowing

Guzey, EK et al. PLB726 (2013) 290

First run 2 results

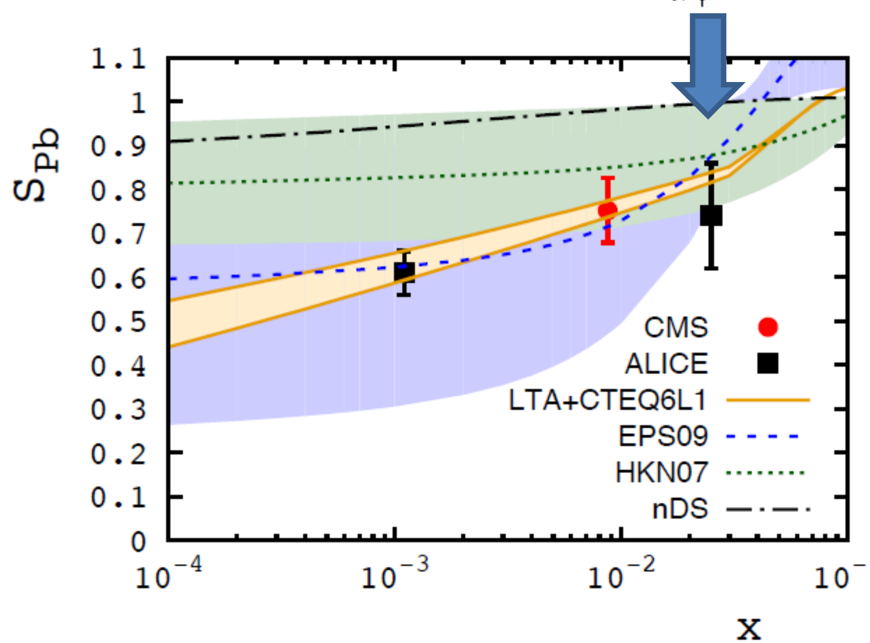




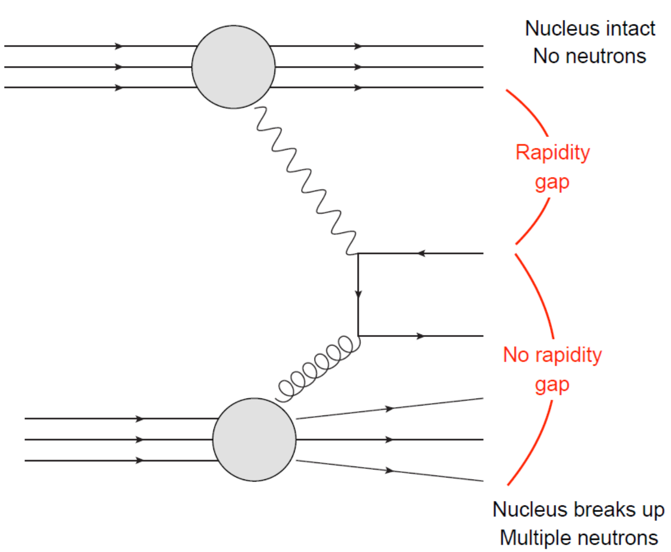
- 90-95% contribution of high-x: 0.7-3 x 10^{-2}
- Back-of-the-envelope calculation (neglect low-x):

Data/Impulse approximation ~ 0.6

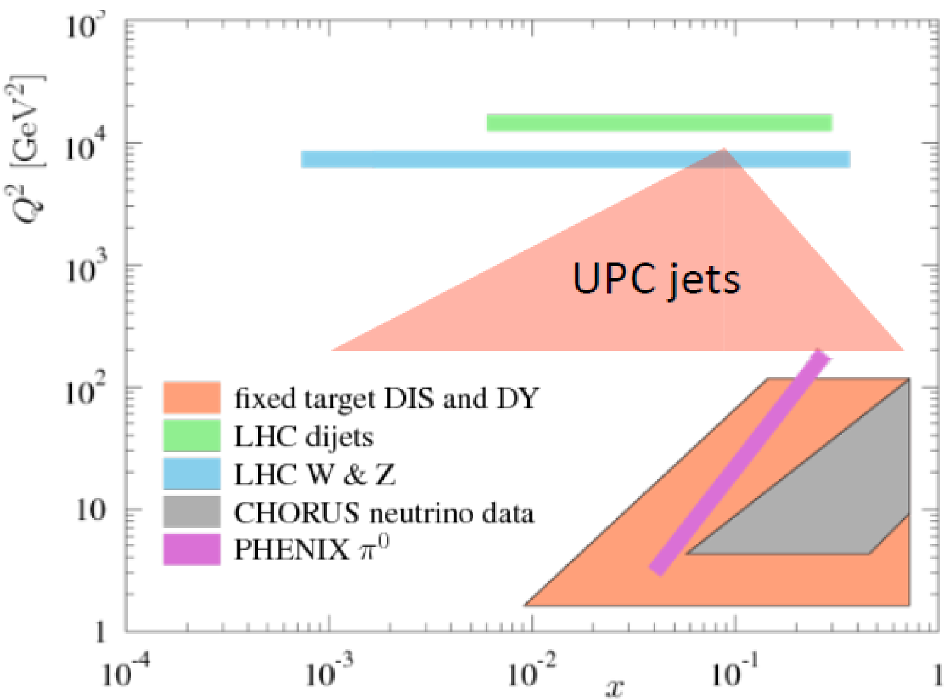
=> shadowing factor ~ $\sqrt{0.6}$ ~ 0.8

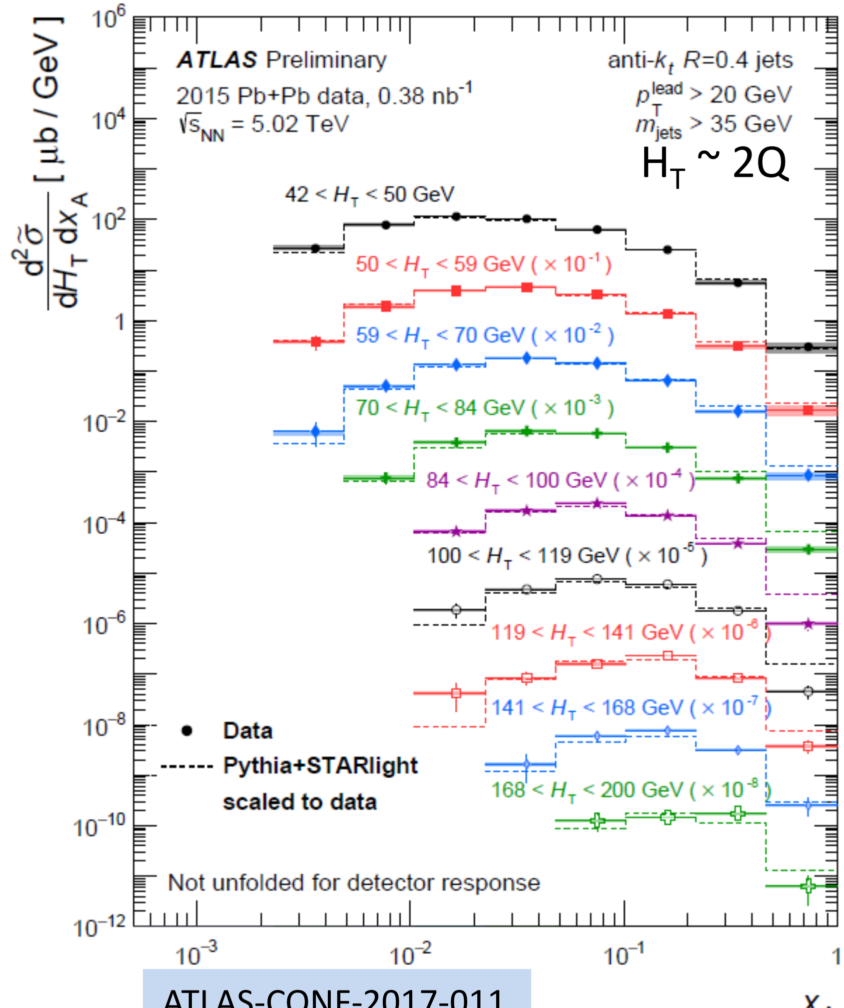


Photonuclear dijet production



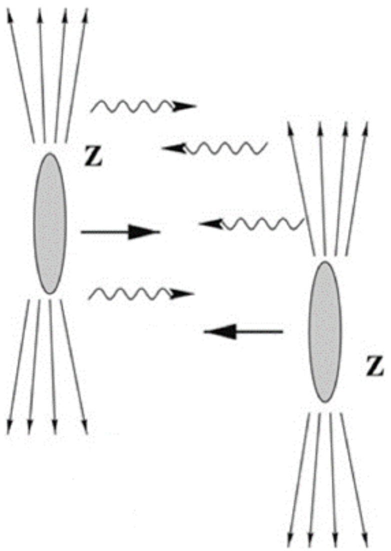
- Single gluon exchange: theoretically clean
- Experimentally studied in events with rapidity gap and one intact nucleus (no neutrons in ZDC)
- Unfolding in progress

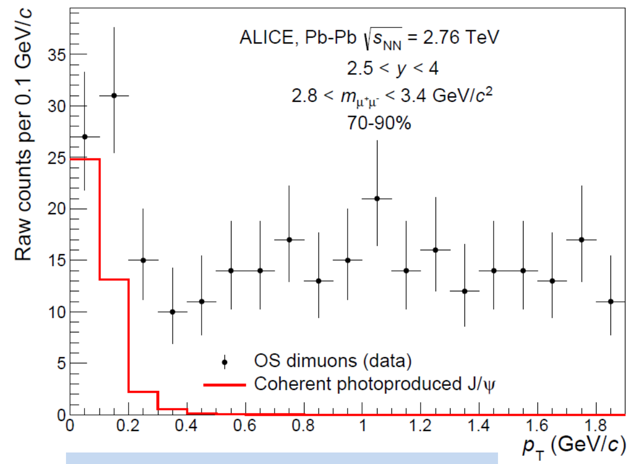




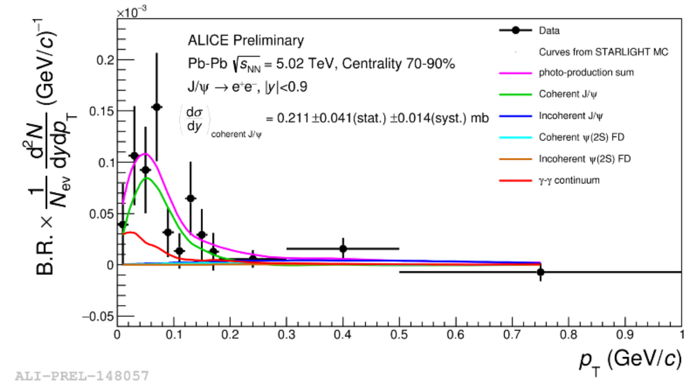
ATLAS-CONF-2017-011

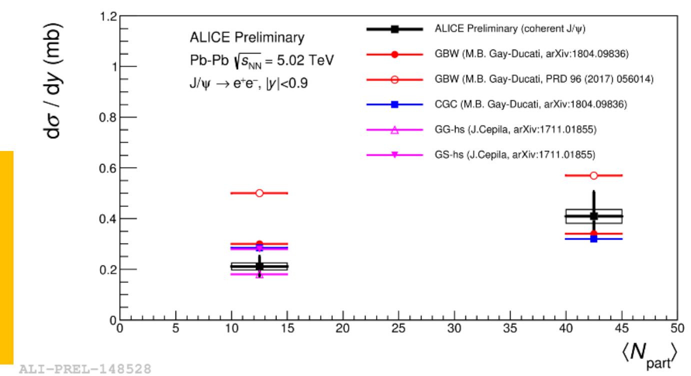
Photon-induced processes at b<2R



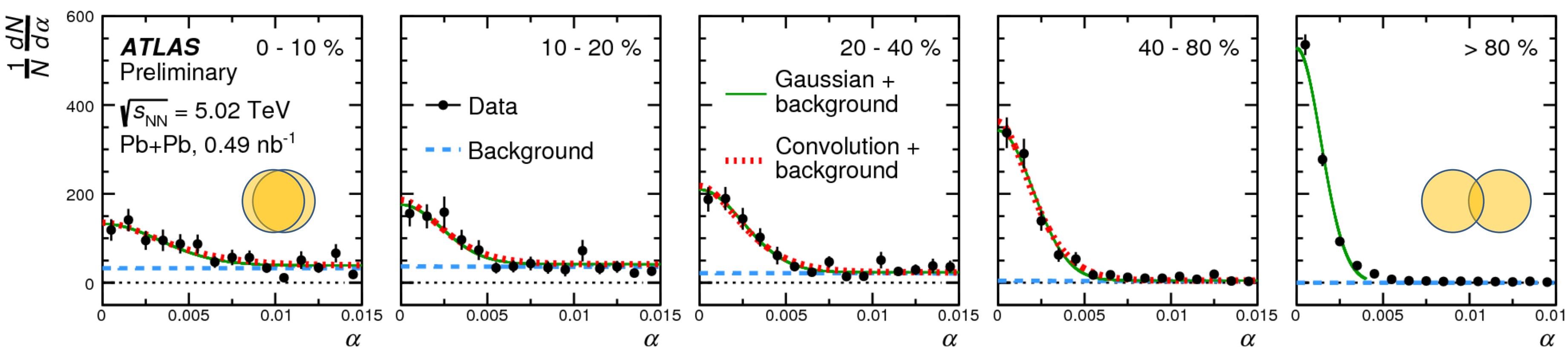


ALICE: PRL 116 (2016) 222301





- J/ψ excess at low-pt – coherent photoproduction?
- Acomplanarity of photoproduced dimuons as a probe for QGP?



ATLAS: HION-2018-11

Acomplanarity of photoproducted dimuons

Multi-parton interactions (MPI)

- MPI has become increasingly important in MC modelling of soft particle production
- Correlations and colour reconnection effects are essential in understanding of MPI

Review on MPI: Mod.Phys.Lett. A28 (2013) 1330010.

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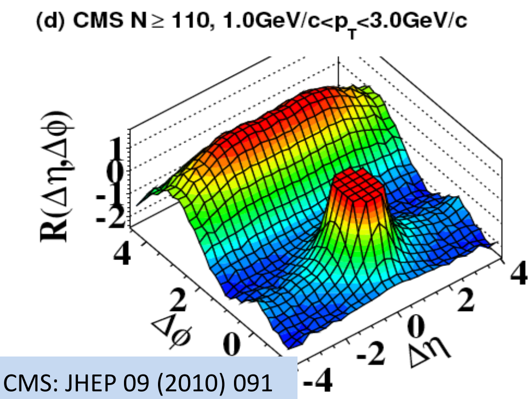
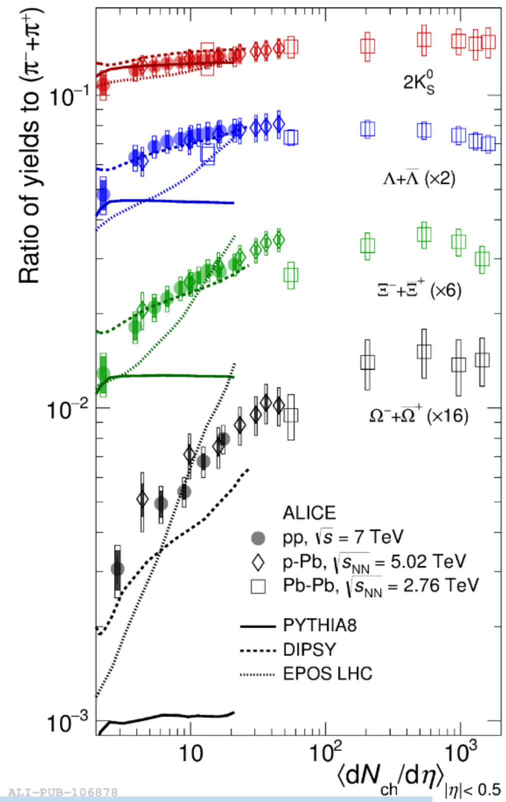


CMS: JHEP 09 (2010) 091



ALICE: Nature Phys. 13 (2017) 535

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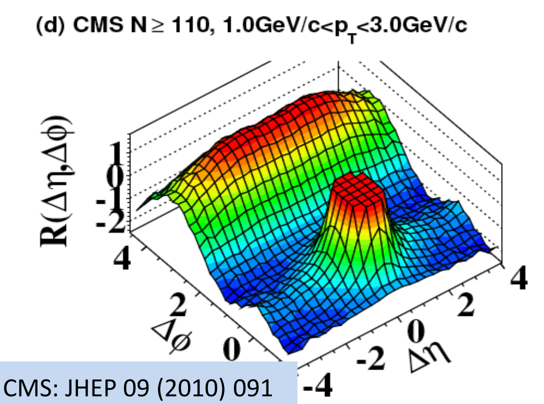

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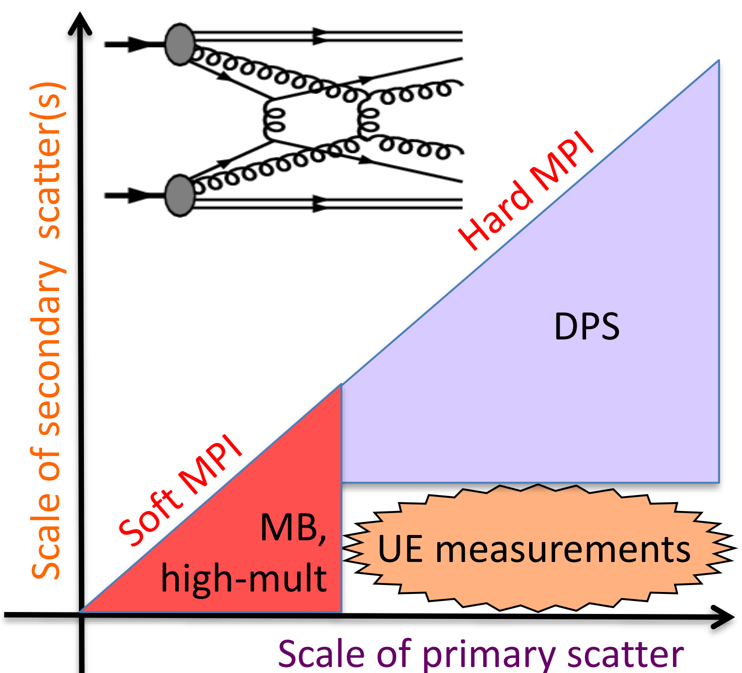

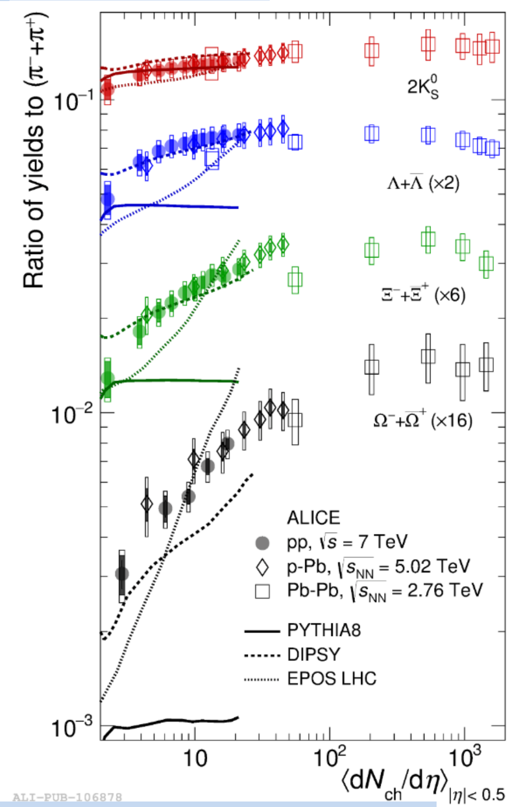

Credits: Paolo Bartalini

Review on MPI: Mod.Phys.Lett. A28 (2013) 1330010.

ALICE: Nature Phys. 13 (2017) 535

Multi-parton interactions (MPI)

- MPI has become increasingly important in MC modelling of soft particle production
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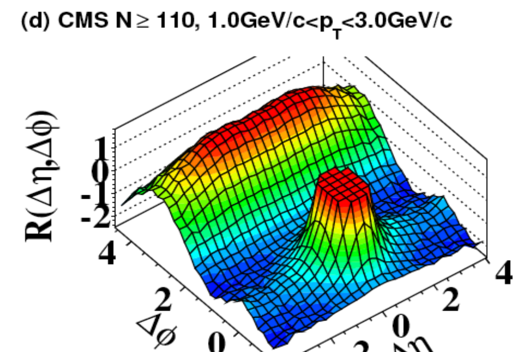
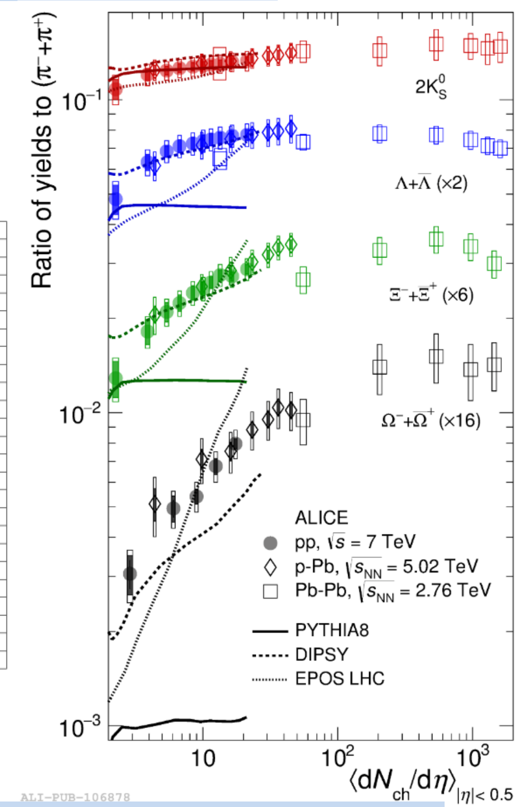
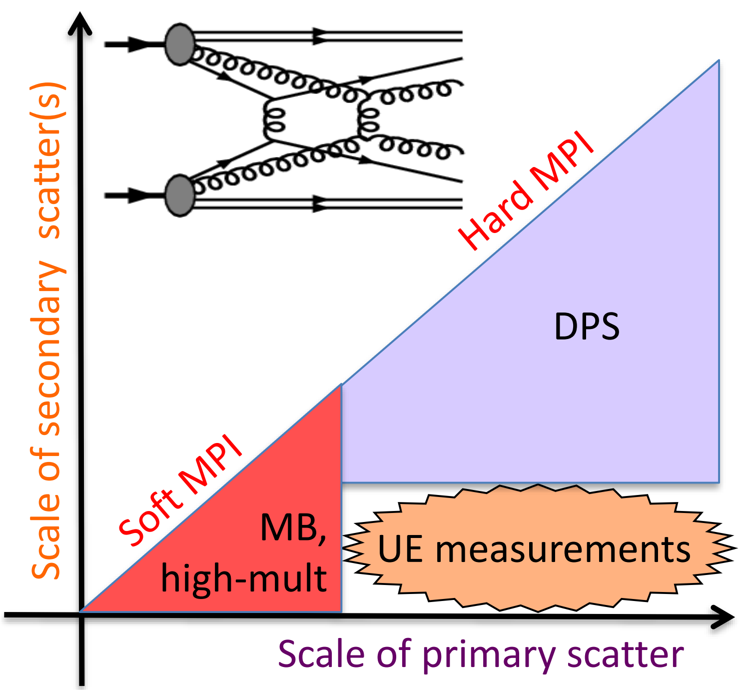
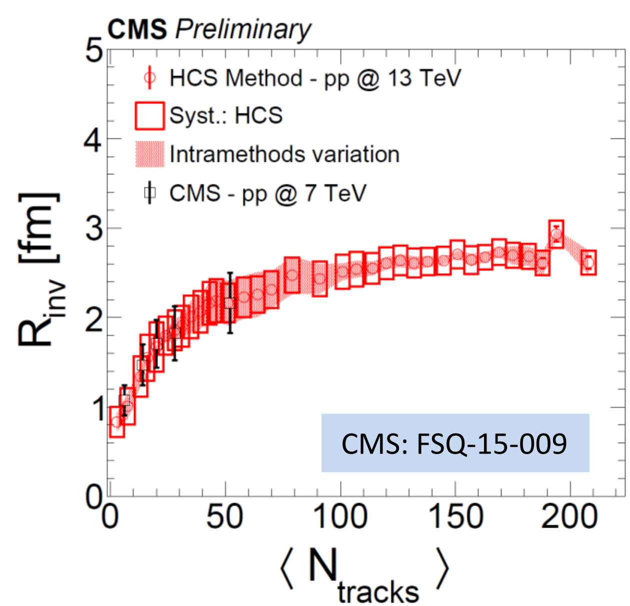
- MPIs are considered to be at the origin of collectivity in small systems => dedicated HI session at 11:30 today
- Femtoscopic measurements may provide complementary information on MPI and related collective effects



CMS: JHEP 09 (2010) 091







CMS: FSQ-15-009

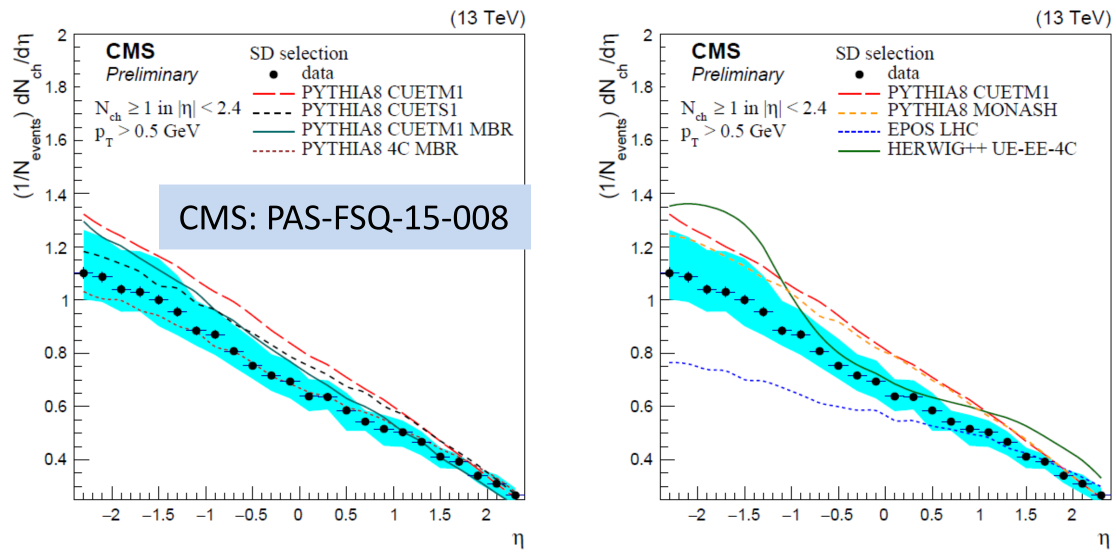
Credits: Paolo Bartalini

Review on MPI: Mod.Phys.Lett. A28 (2013) 1330010.

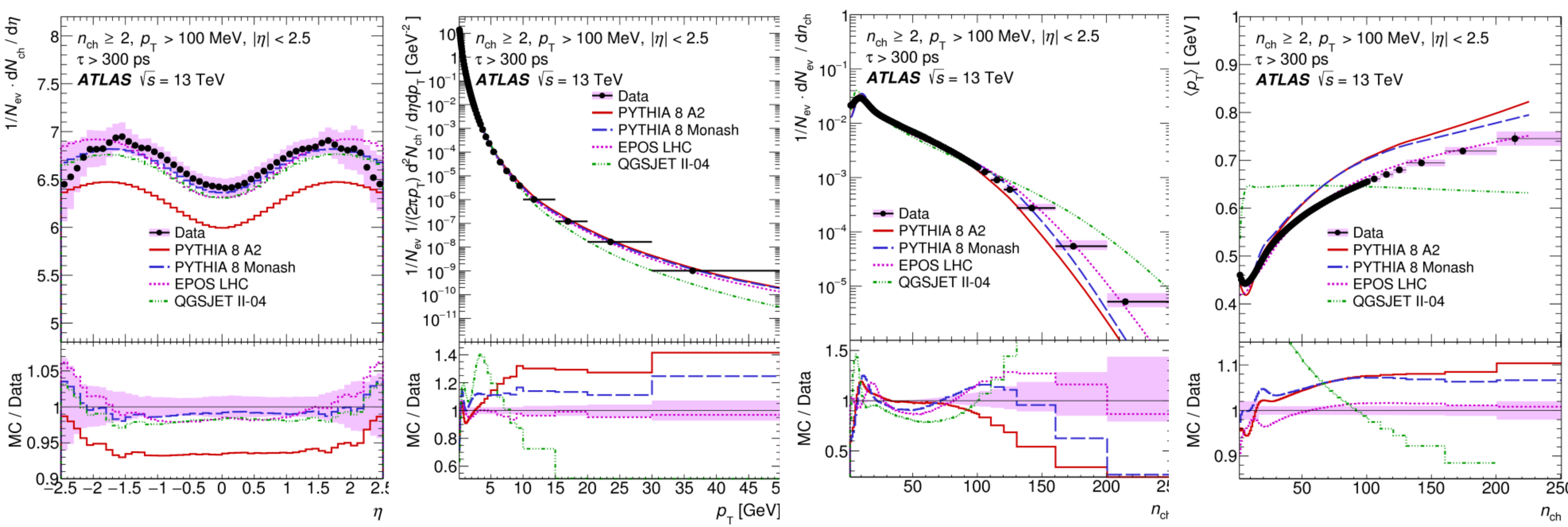
ALICE: Nature Phys. 13 (2017) 535

Charged particle distributions at 13 TeV

- Basic measurements: dN/dη, p_T and N_{ch} spectra, mean p_T vs N_{ch}
- EPOS provides best description for dN/dη and p_T spectra
- None of the models reproduces multiplicity distributions
- Pythia 8 overestimates <p_T> (sensitive to colour reconnection)



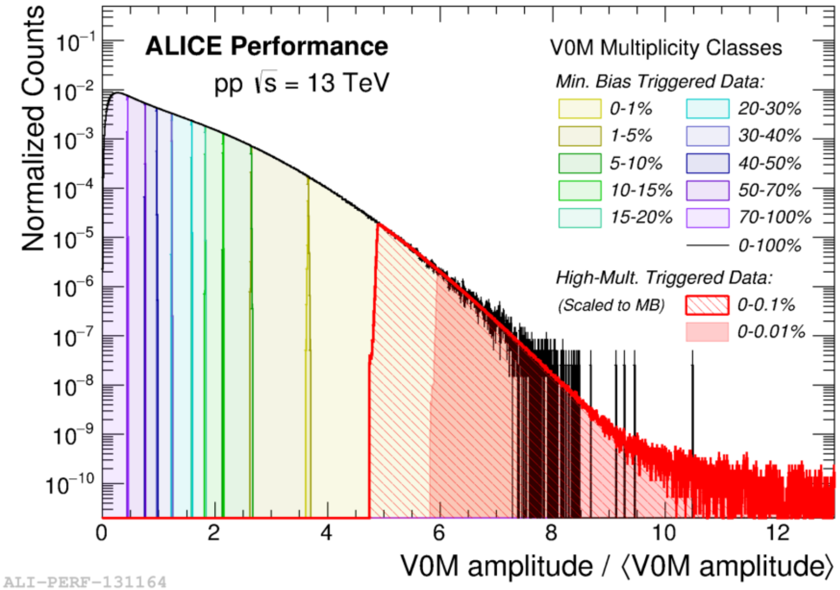
CMS: PAS-FSQ-15-008



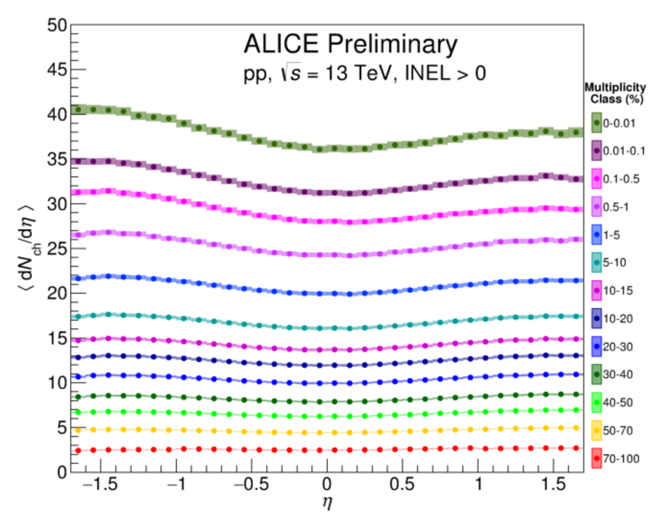
ATLAS: (pt>100 MeV): EPJ C76 (2016) 502, (pt>500 MeV): PLB 758 (2016) 67

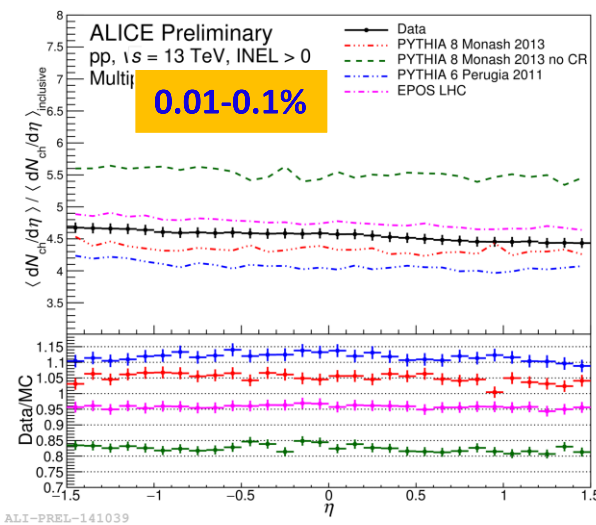
Multiplicity-dependent studies

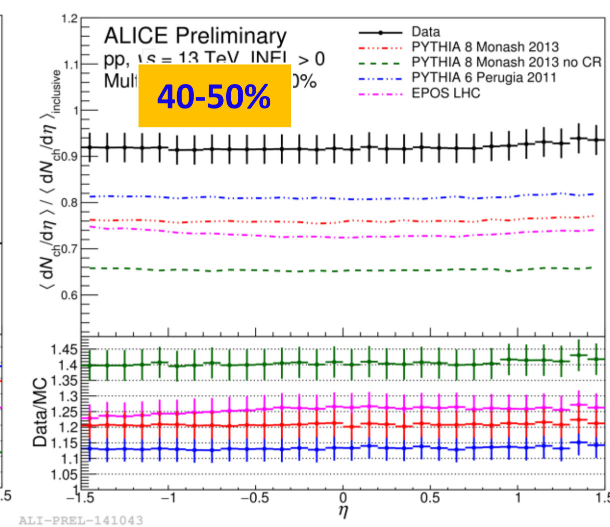
- Extending multiplicity reach with high-multiplicity triggers
- High forward multiplicity: Pythia 8 and EPOS LHC are close to data
- Moderate forward multiplicity: all models underestimate central dN/dη



Multiplicity in the forward region

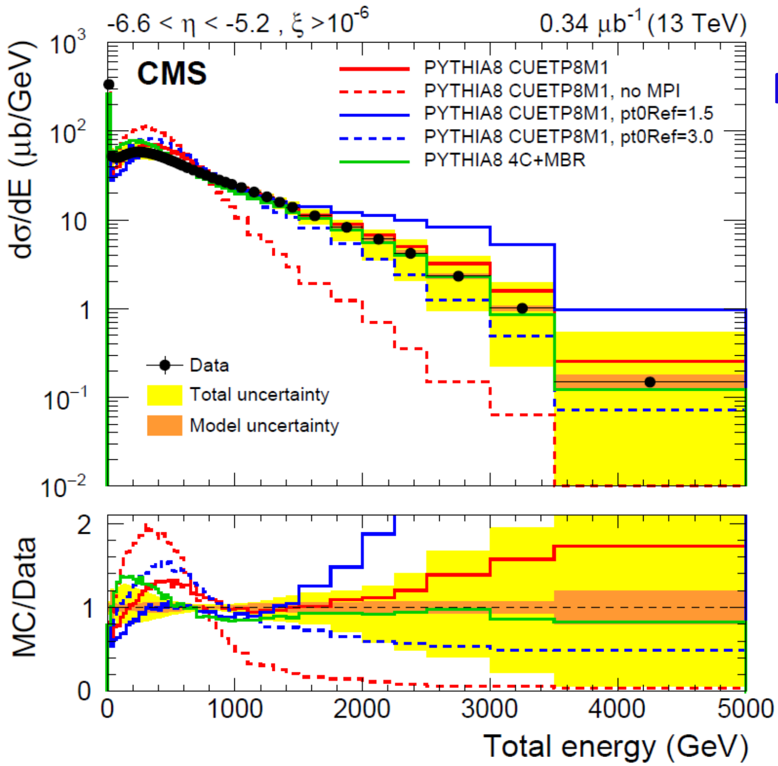




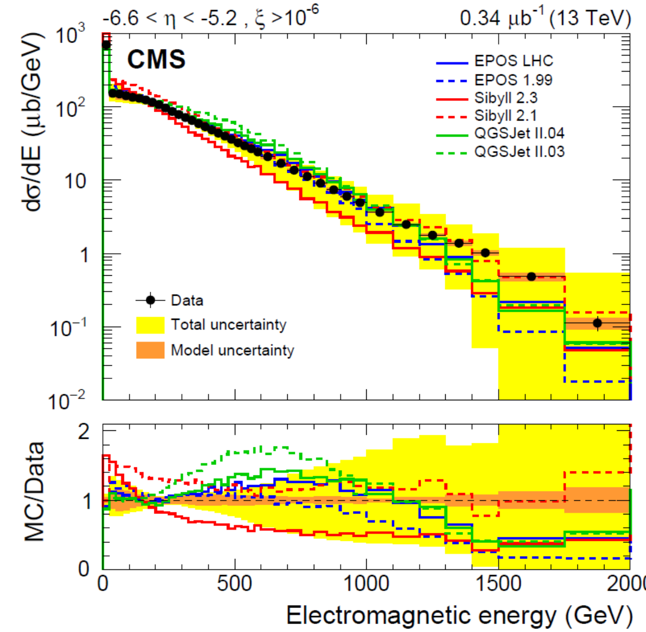


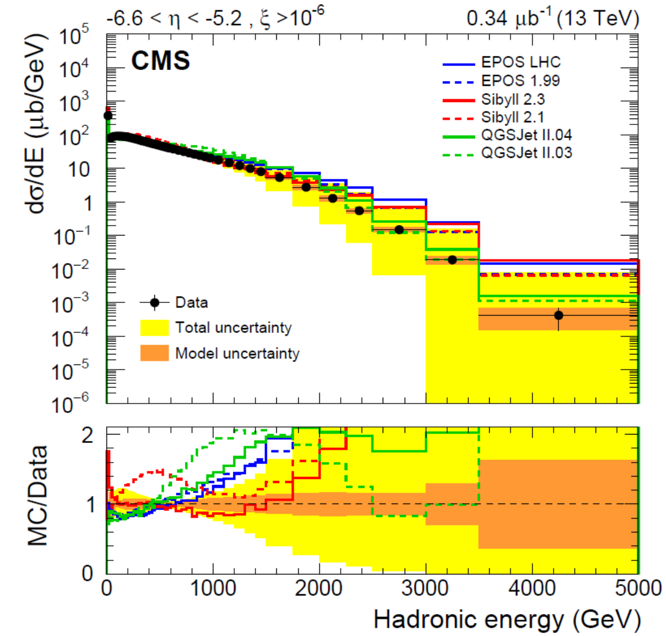
Forward energy flow

- EM and hadronic energy measured with CASTOR at 0T field
- kinematics relevant for cosmic ray showers: $-6.6 < \eta < -5.2$



Pythia tunes



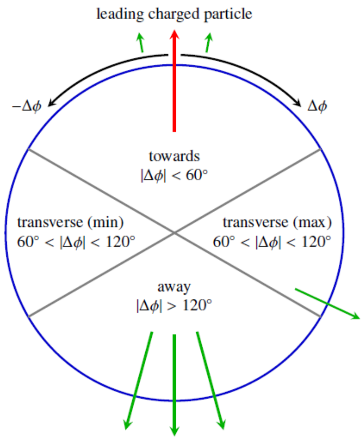


- Energy spectrum very sensitive to MPI settings in PYTHIA
- Cosmic shower generators underestimate muon production rate

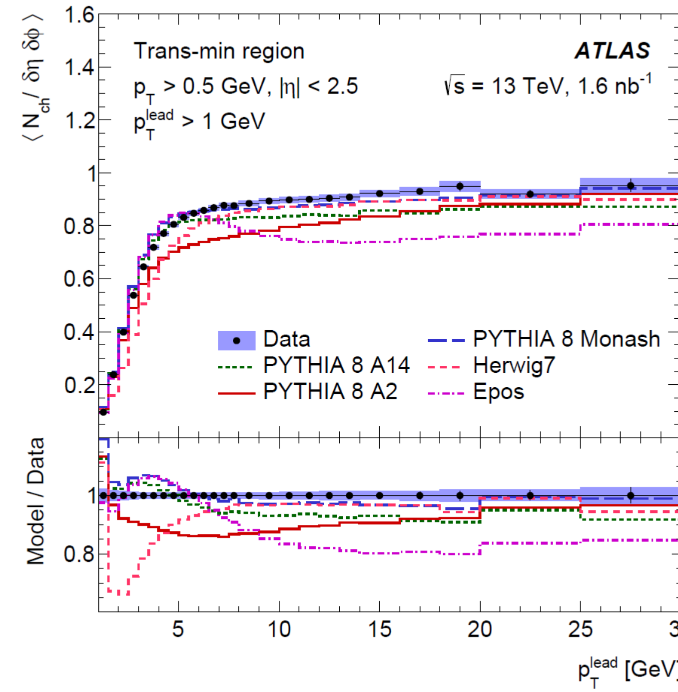
CMS: JHEP 08 (2017) 046

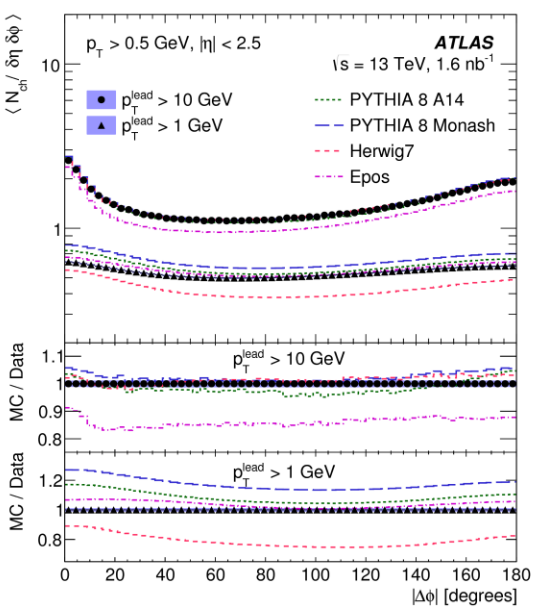
Underlying event measurements at 13 TeV

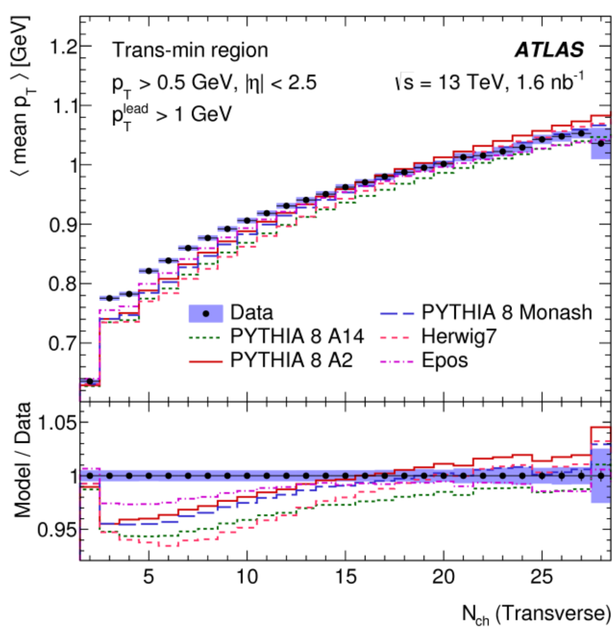
<N_{ch}>, <Σp_T>, mean p_T studied vs p_T^{lead}, N_{ch}, $|\Delta\phi|$

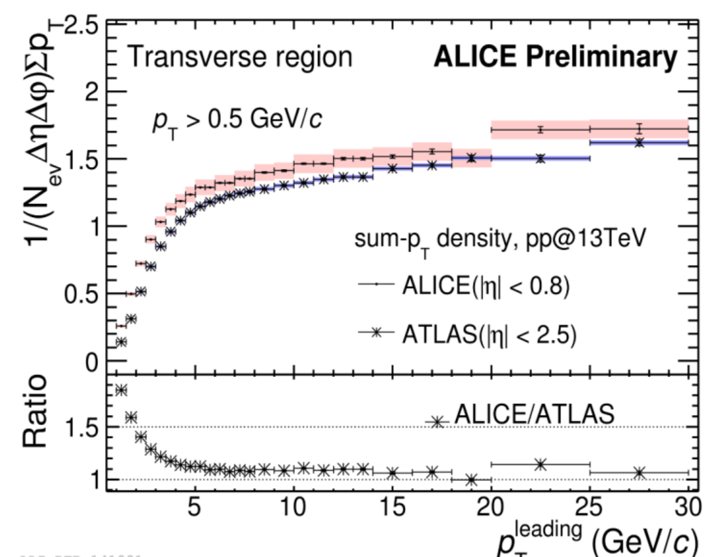


- 13TeV UE data in reasonable agreement with Run1 tunes
- Tension with MB tunes
- Mean p_T underestimated at low multiplicities (sensitive to CR)









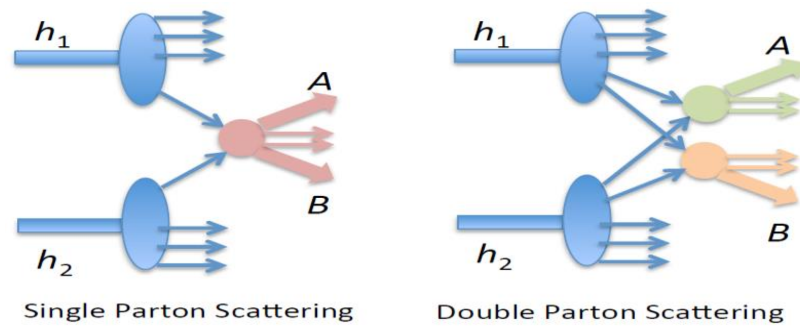
ATLAS: JHEP 03 (2017) 157

Double parton scattering (DPS)

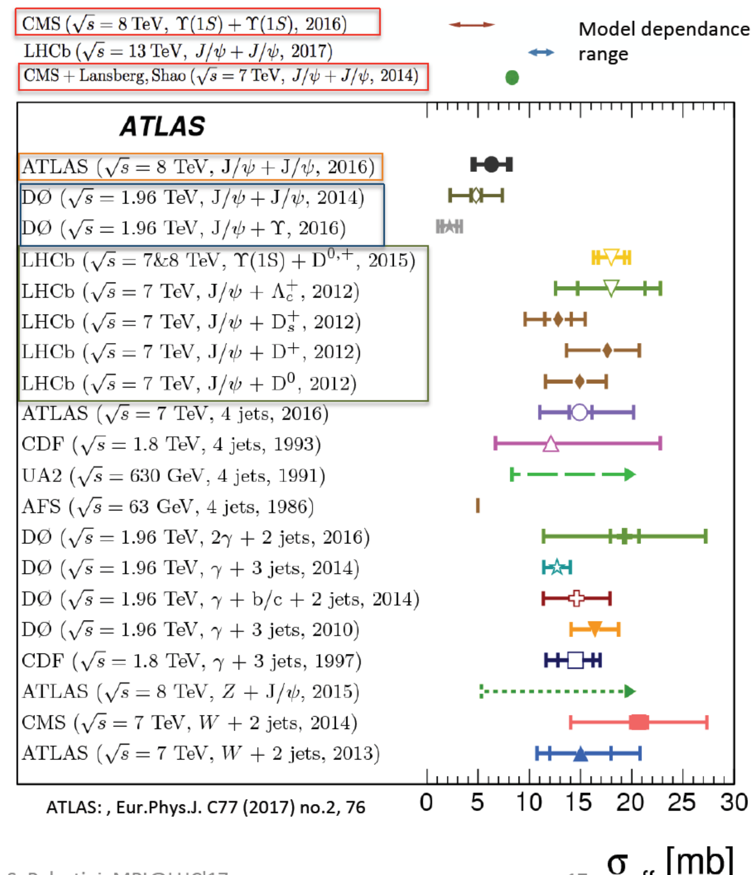
- Double Parton Scattering (DPS) = two hard scatterings in a single pp collision
- A simple model that ignores correlation between partons:

$$\sigma_{AB}^{\mathrm{DPS}} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}}$$

m = 1: different pairs
m = 2: identical pairs
σ_i: 2 ⟶ 2 cross section



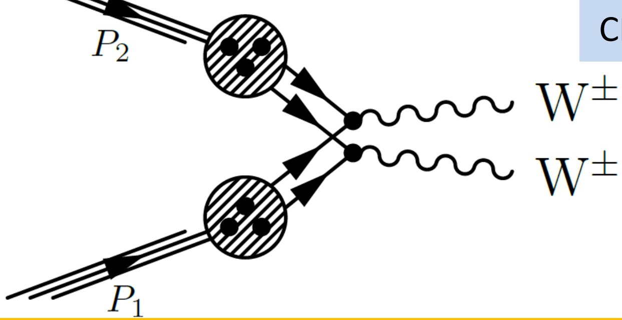
- DPS may provide valuable information on:
  - transverse parton profile of the proton
  - the role of many-parton correlations
- σ_{eff} studied in 4jets, γ+3jets, W+2jets, J/ψ+J/ψ,D+J/ψ,DD etc.



- typical σ_{eff} ~ 15-20 mb
- Indications of non-universality of σ_{eff} in J/ψ+J/ψ and J/ψ+Y measurements

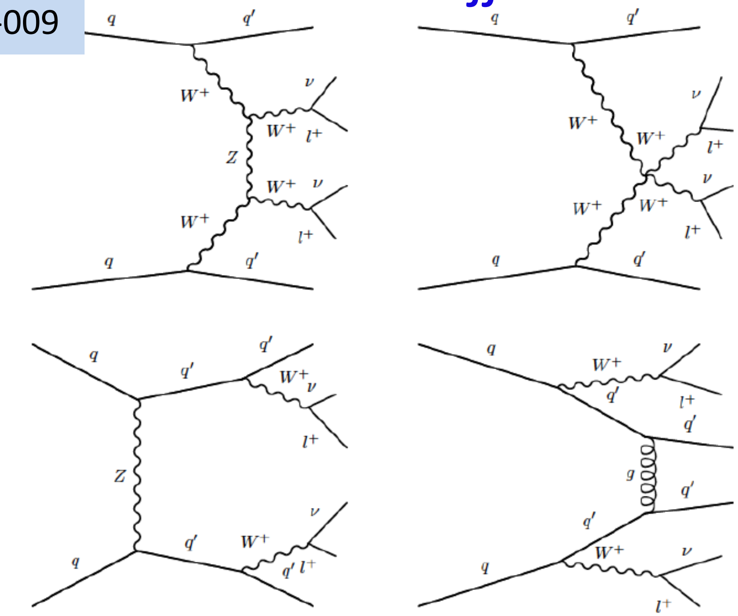
DPS with same-sign WW

DPS: $W^{\pm}W^{\pm}$



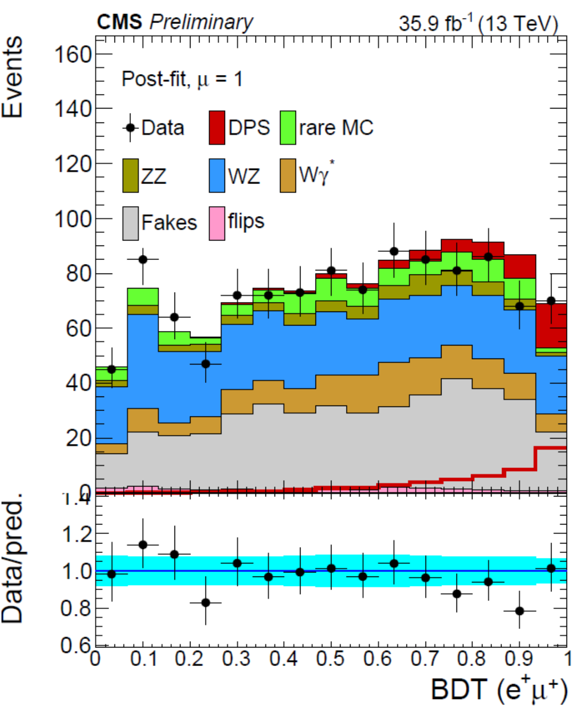
CMS (WW 8 TeV): JHEP 1802 (2018) 032
CMS (WW 13TeV): CMS-PAS-FSQ-16-009

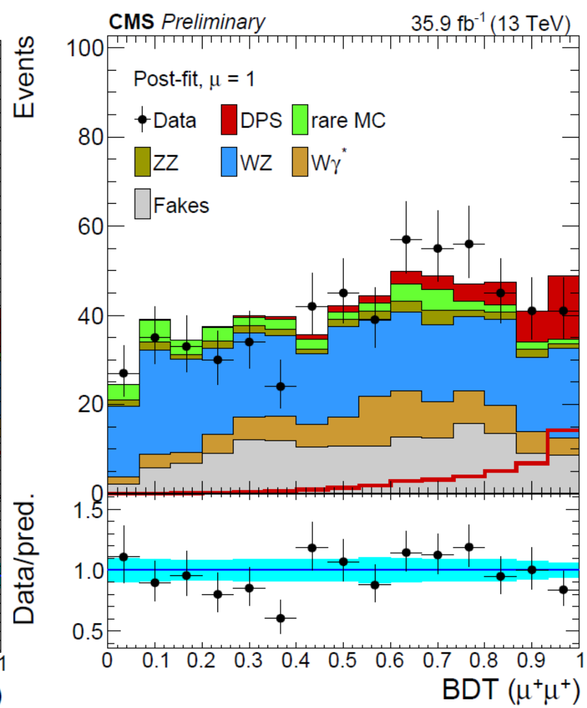
SPS: $W^{\pm}W^{\pm}jj$

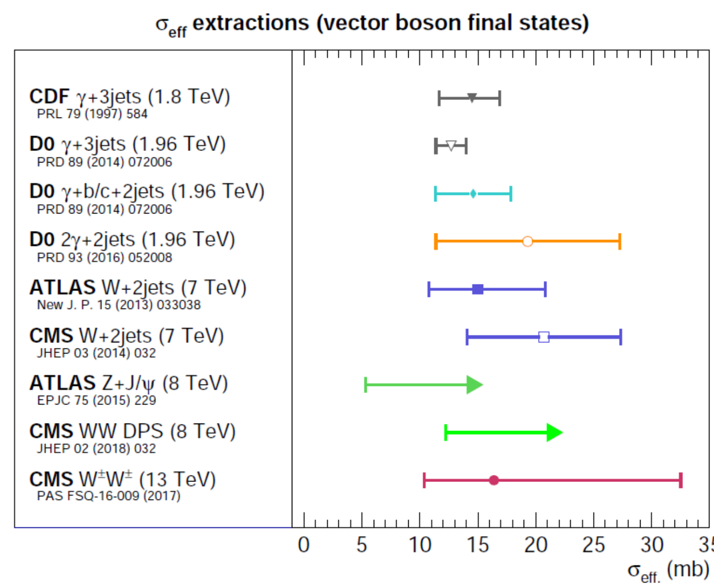


Very clean channel for DPS studies:

- SPS process is accompanied by two high-pt jets
- Two high-pt leptons from W decays in the final state







Summary

- Hints of odderon contribution in total cross section measurements
- First observation of color-singlet exchange in jet-gap-jet events at LHC
- First $\gamma\gamma \rightarrow \gamma\gamma$ measurements compatible with SM predictions
- Vector meson photoproduction in UPC at unprecedently high energies => info on gluon PDFs and nuclear shadowing effects
- Multi-differential measurements on MPI-related effects at 13TeV => new constraints on MC models