Ultraperipheral collisions at the LHC

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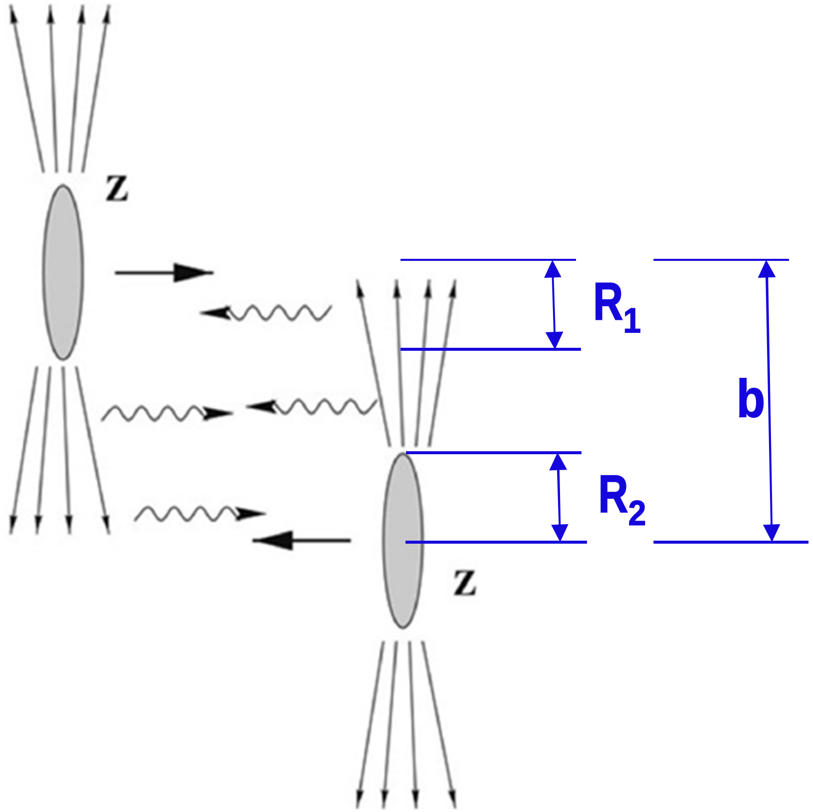
28 November 2017

LHC as a γγ, 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)

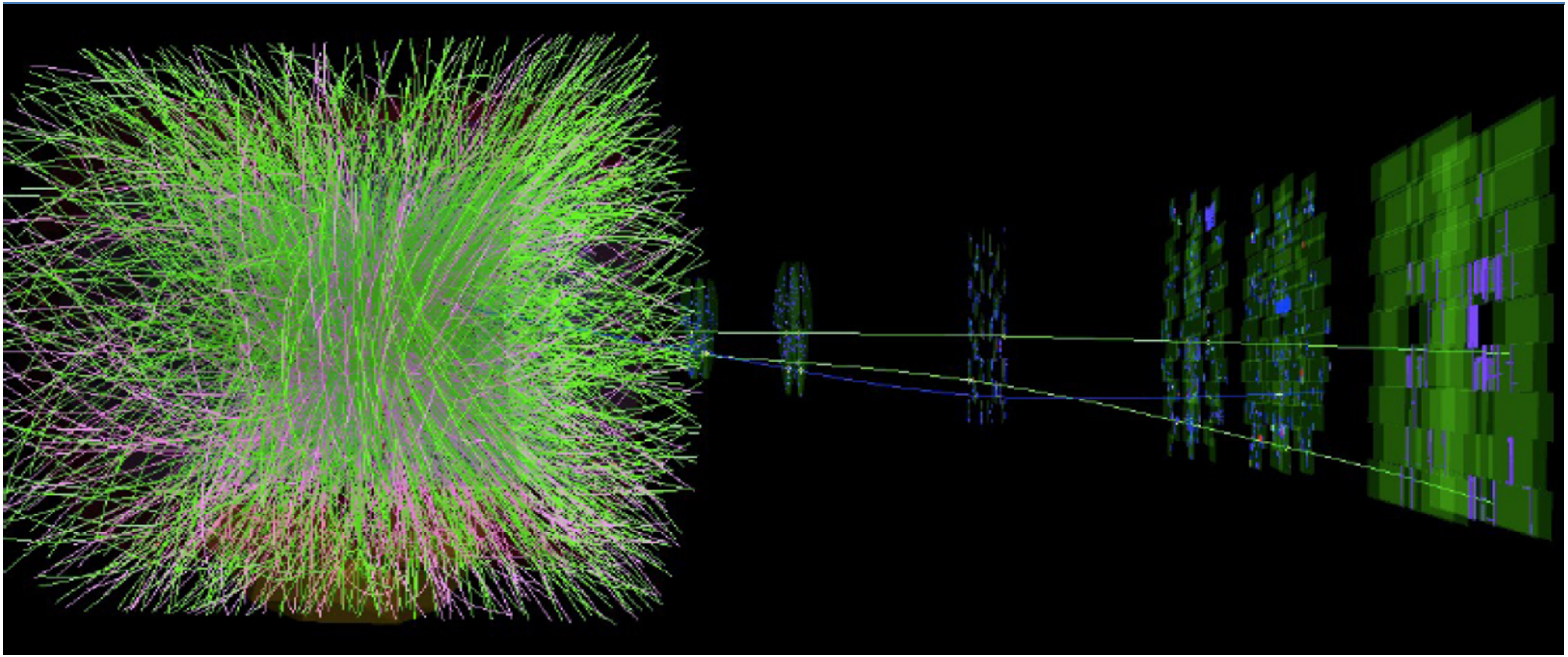
→ flux proportional to Z^2

→ high cross section for γ-induced reactions

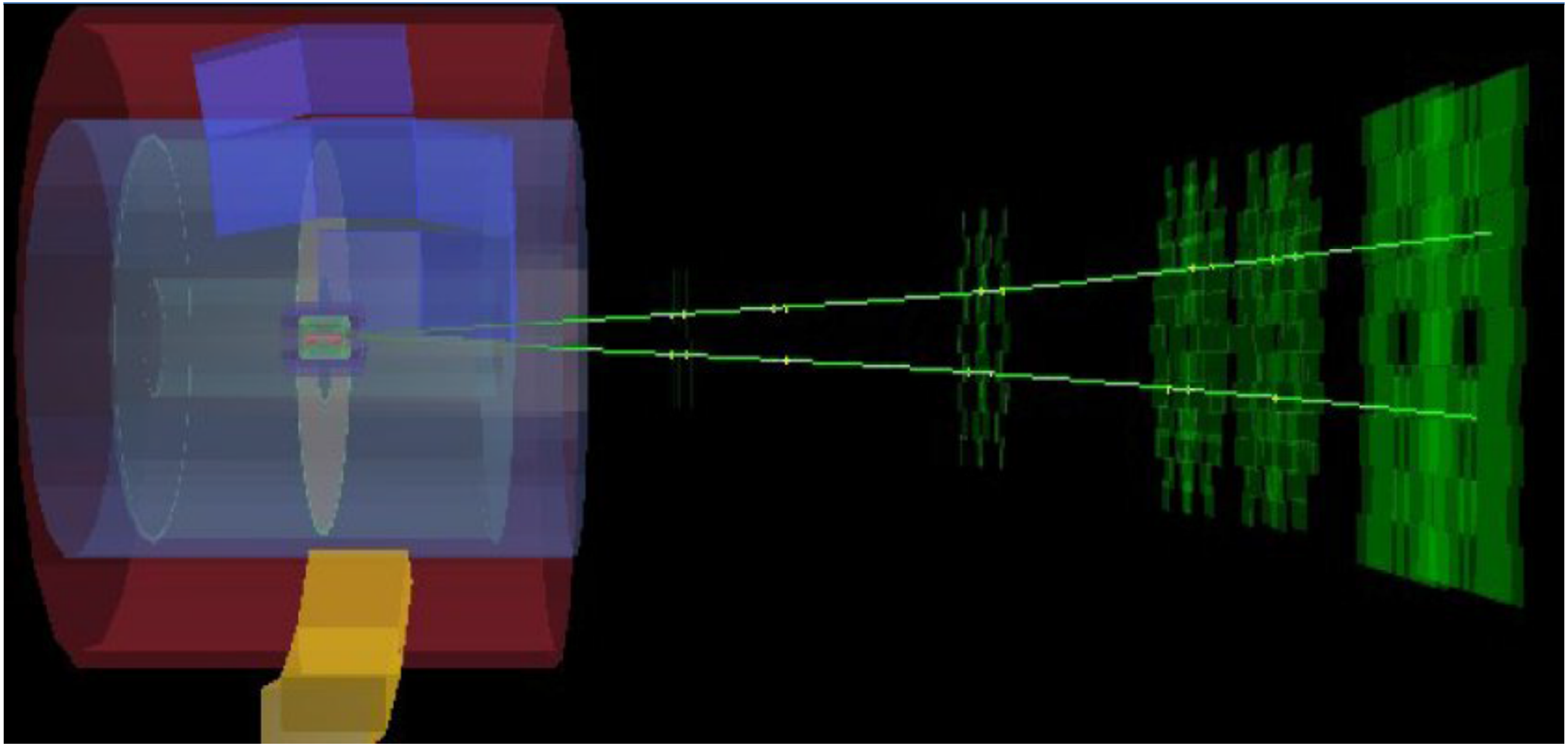
Pb-Pb UPC at LHC can be used to study γ- γ, γ-p, γ-Pb interactions at higher center-of-mass energies than ever before

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

From typical hadronic interaction...

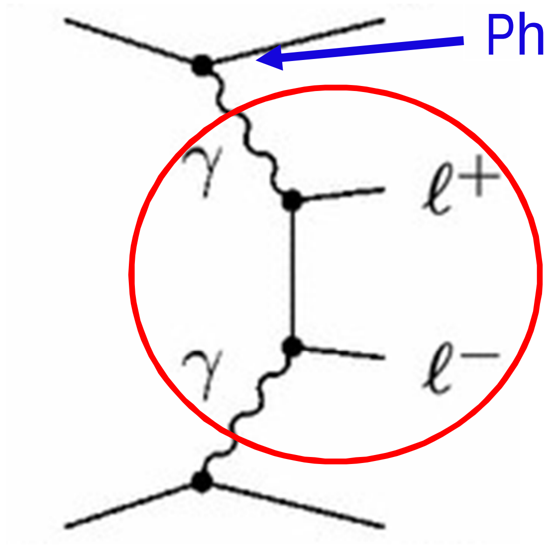


to ultraperipheral collisions



- Experimental signature: few signal tracks in an otherwise empty detector
- Wide acceptance coverage is important to ensure event emptiness
- Zero degree calorimeters (ZDC) serve to veto hadronic interactions

$\gamma\gamma \to$ dileptons



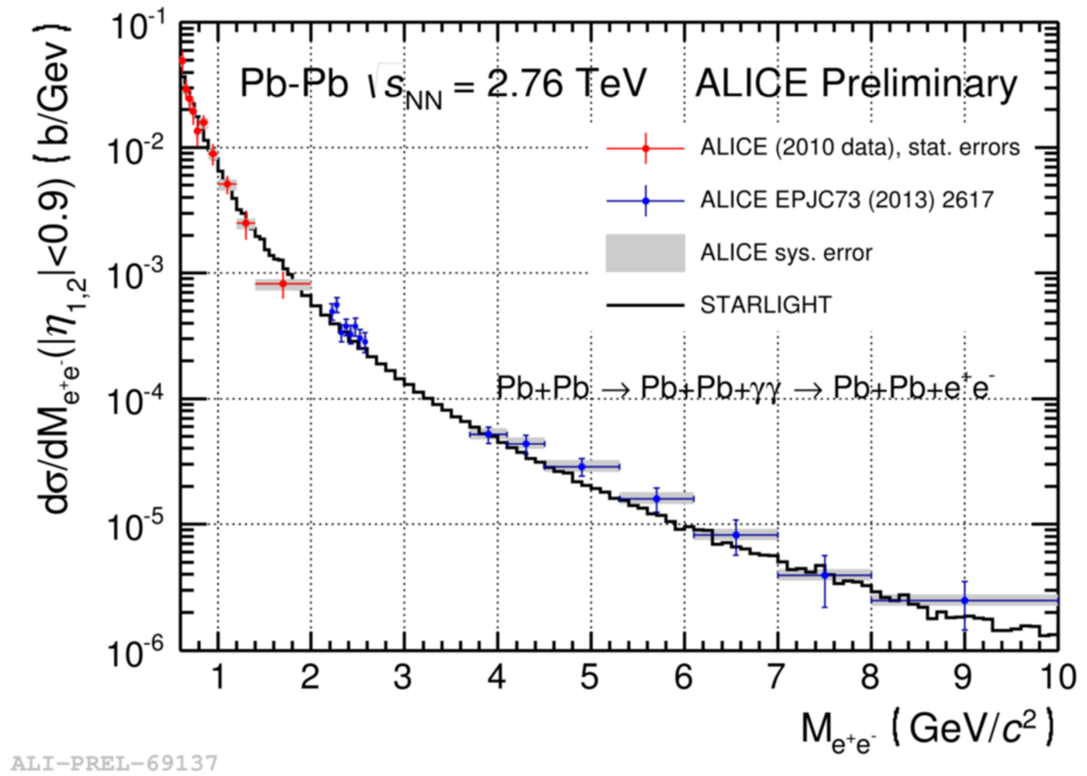
Photon flux in equivalent photon approximation (~ Z^2)

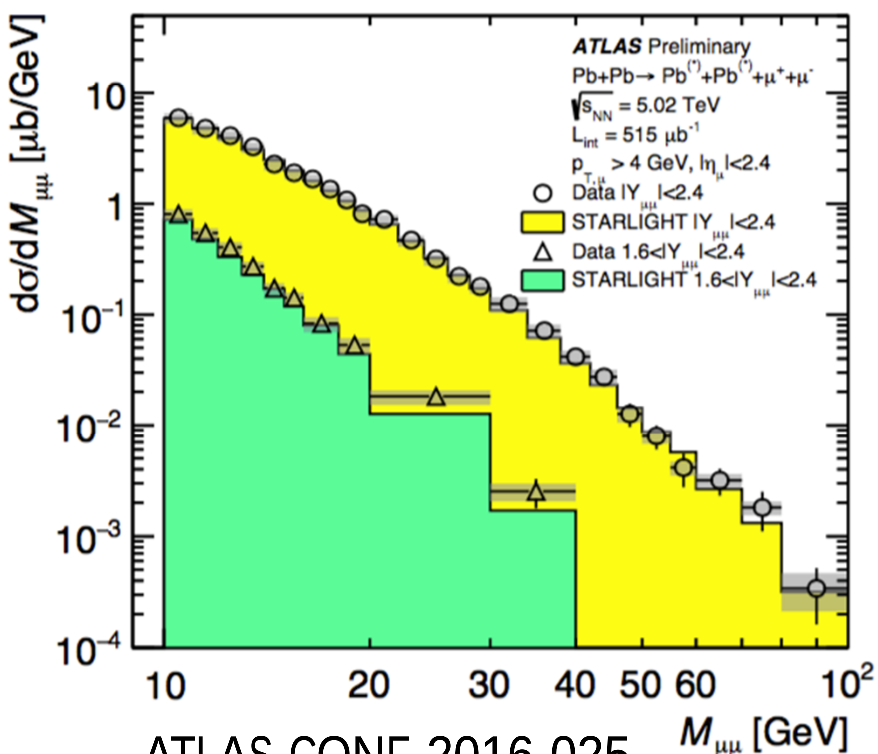
$$N_{\gamma/Z}(k) = \frac{2Z^2\alpha_{\rm em}}{\pi}[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}(K_1^2(\zeta) - K_0^2(\zeta))]$$

$$\zeta = k(2R_A/\gamma_L)$$

Leading order QED (Landau & Lifshitz,1934)

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

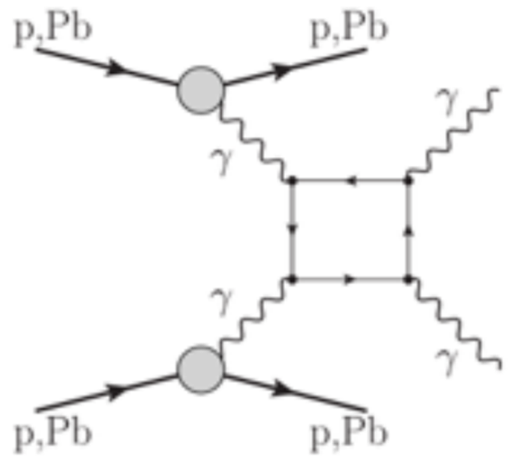




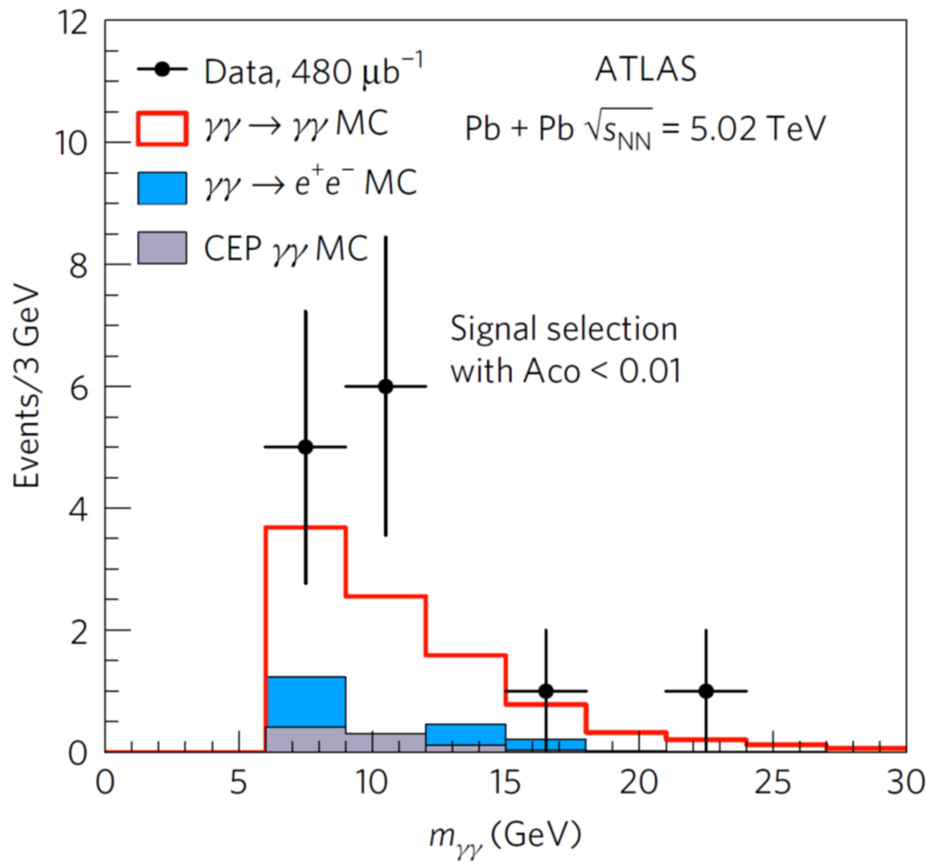
ATLAS-CONF-2016-025

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, see PRL 111 (2013) 080405

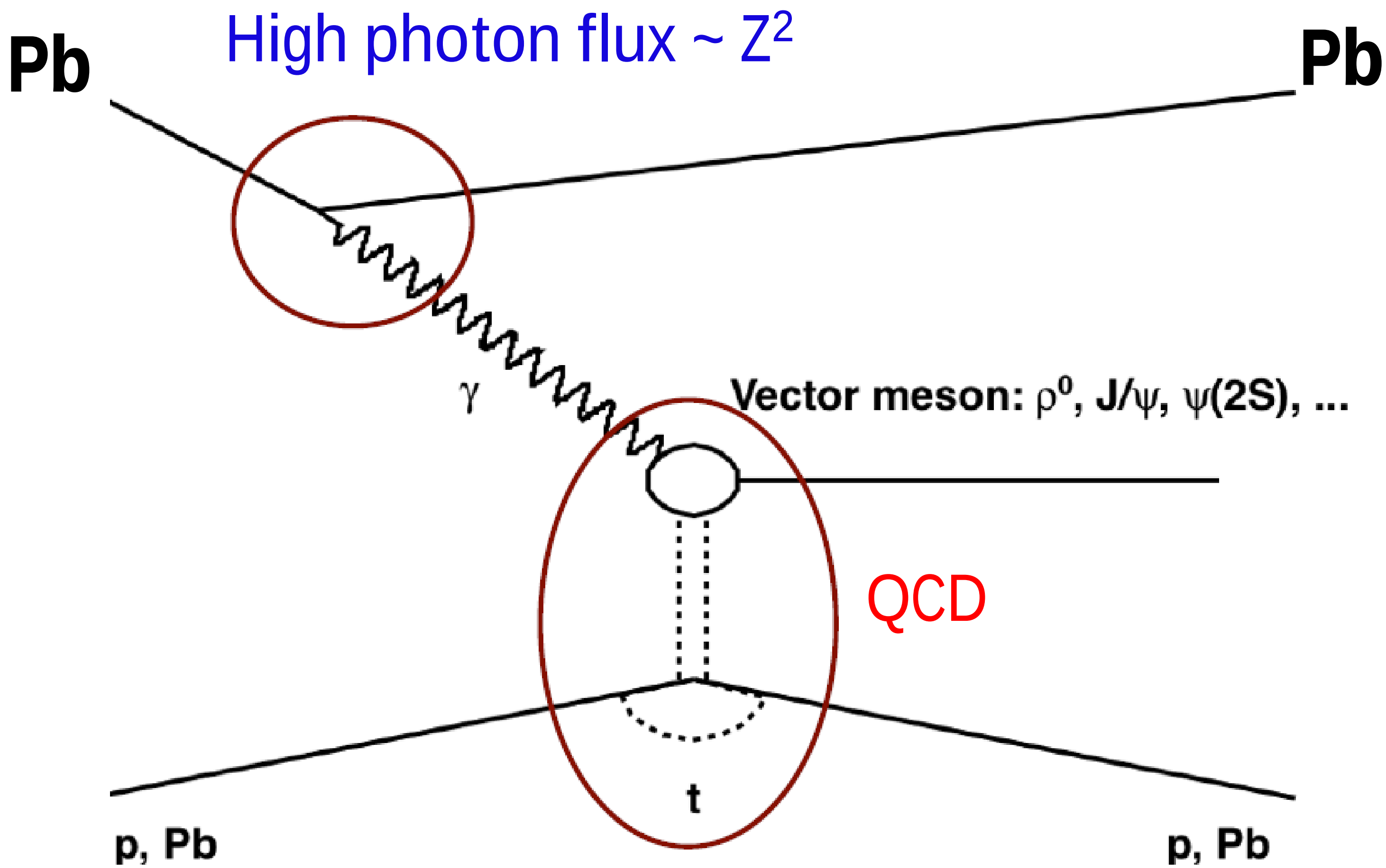


ATLAS: evidence for light-by-light scattering in UPCs in agreement with SM predictions (4.4σ significance)



ATLAS, Nature Physics 13, 852 (2017)

Vector meson photoproduction in UPC



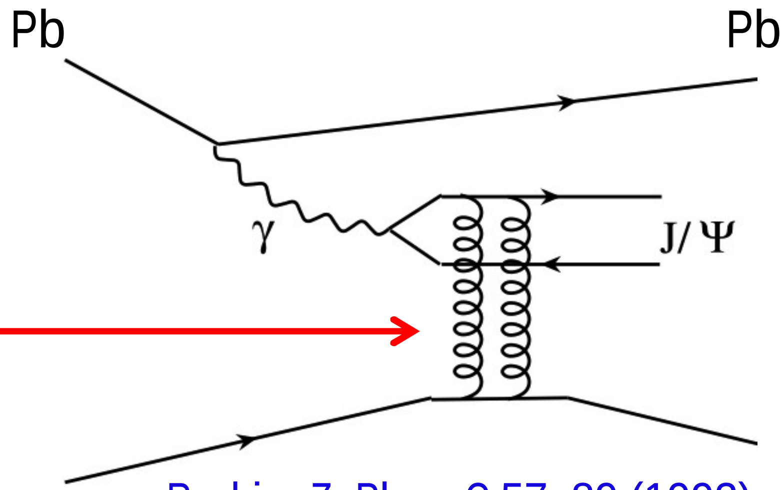
Exclusive vector meson production cross section in UPC can be factorized in two parts:

- QED: photon flux: $dN/d\omega$
- QCD: vector meson photoproduction: $\sigma(W_{\gamma p})$

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**:

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



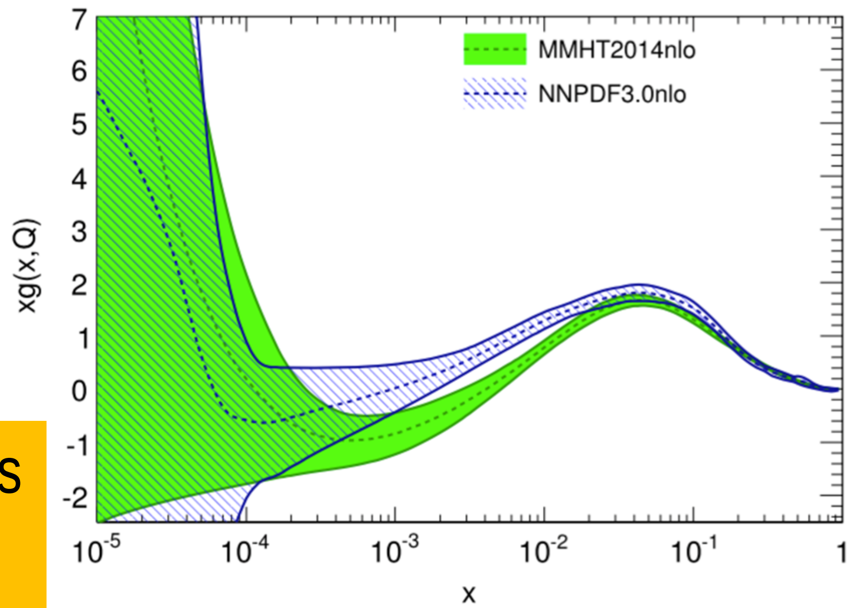
Ryskin: Z. Phys. C 57, 89 (1993)

- J/ψ mass serves as a hard scale:

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

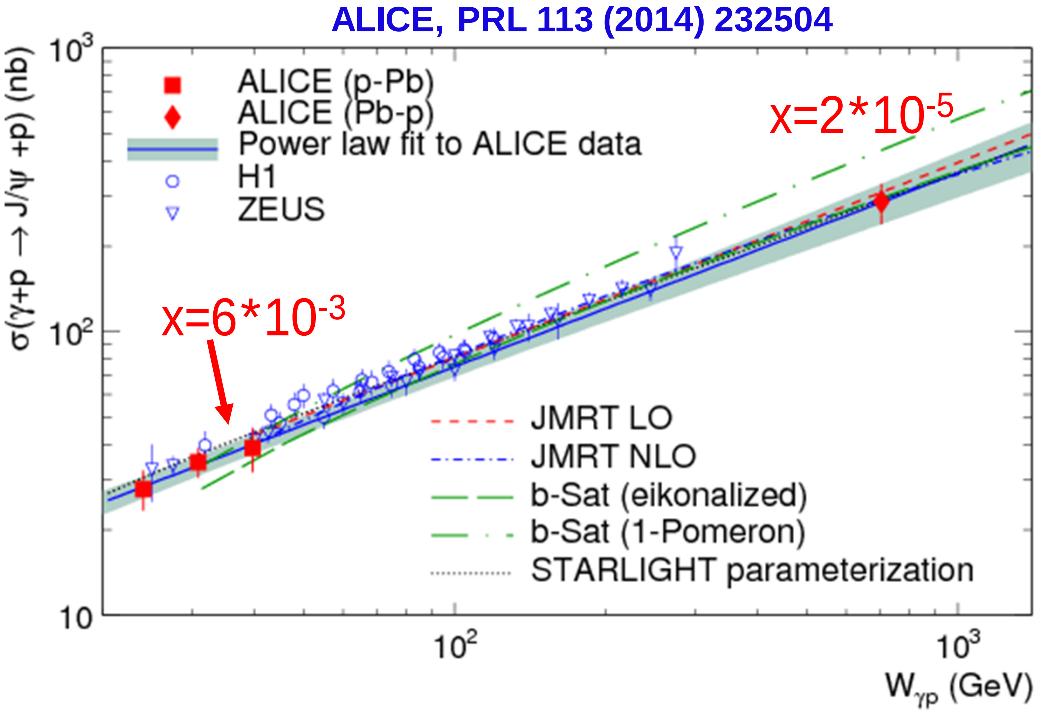
- Bjorken x ~ 10^{-2} – 10^{-5} accessible at LHC:

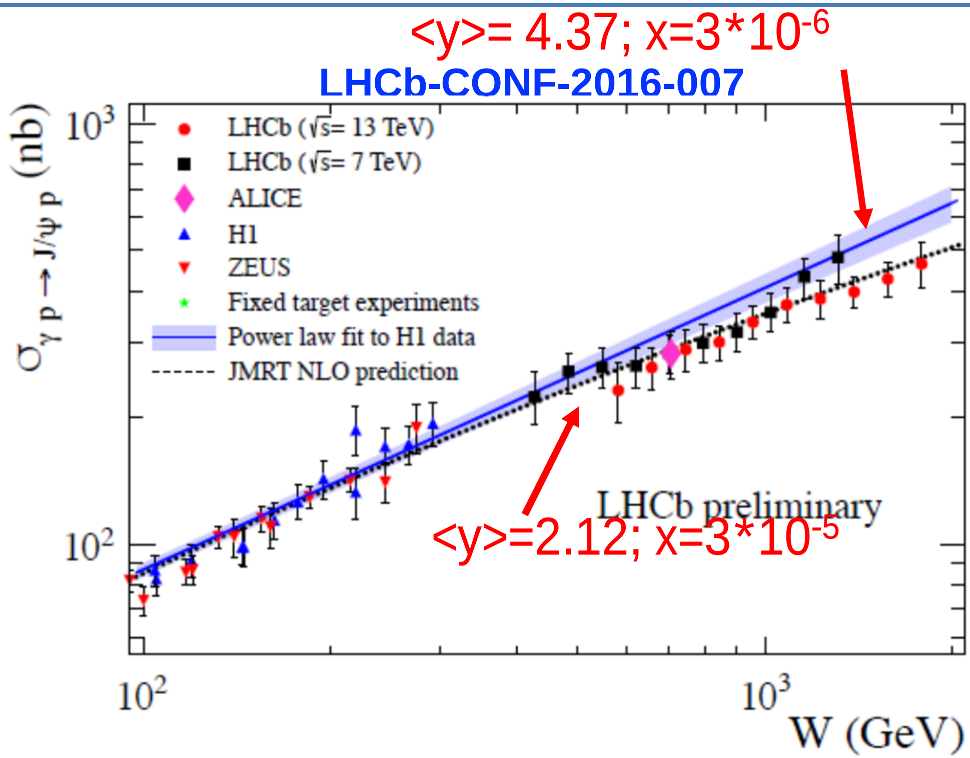
$$x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}} = \frac{M_{J/\psi}}{2E_p}\exp(\pm y)$$



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

J/ψ photoproduction of proton

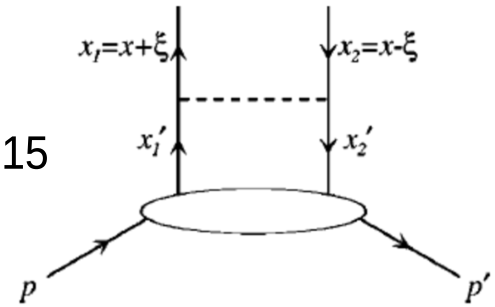




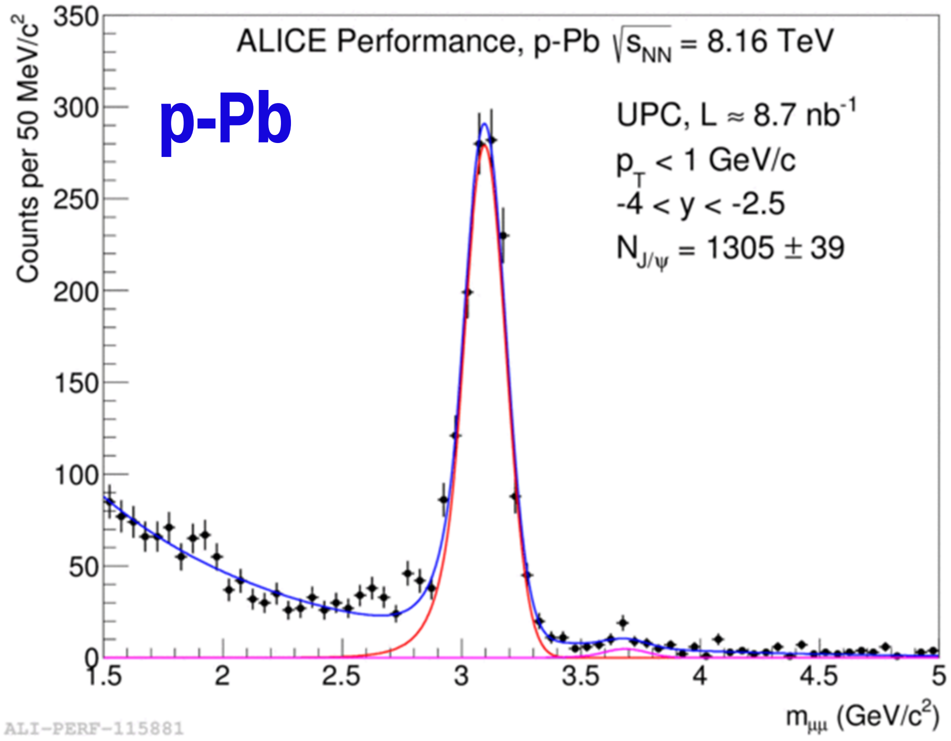
Can we use this data to constrain gluon PDFs?

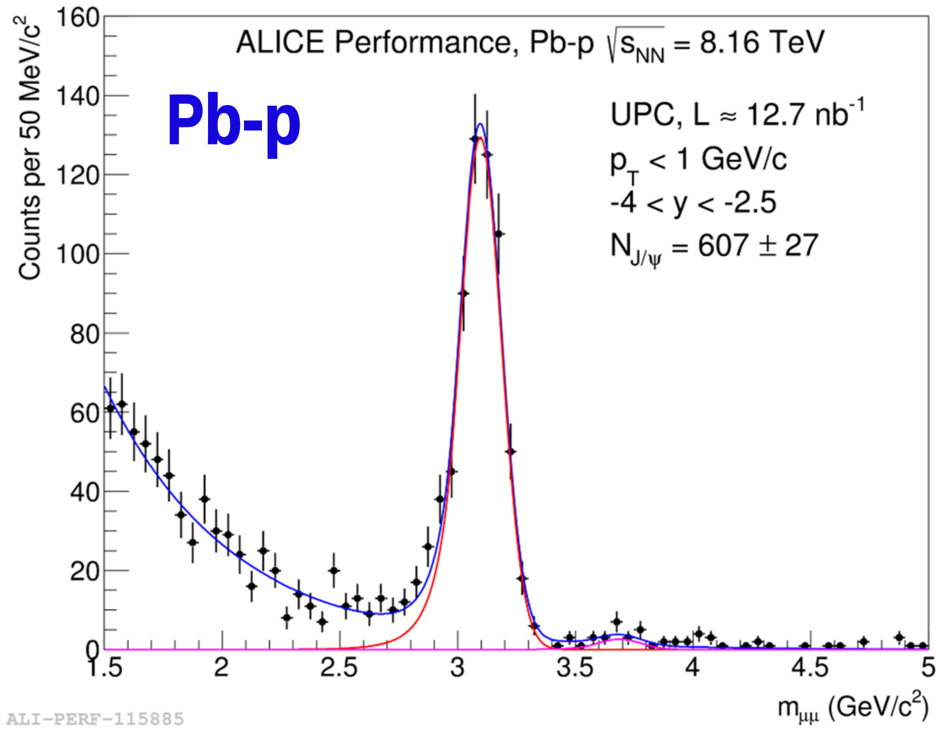
Caveats:

- 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

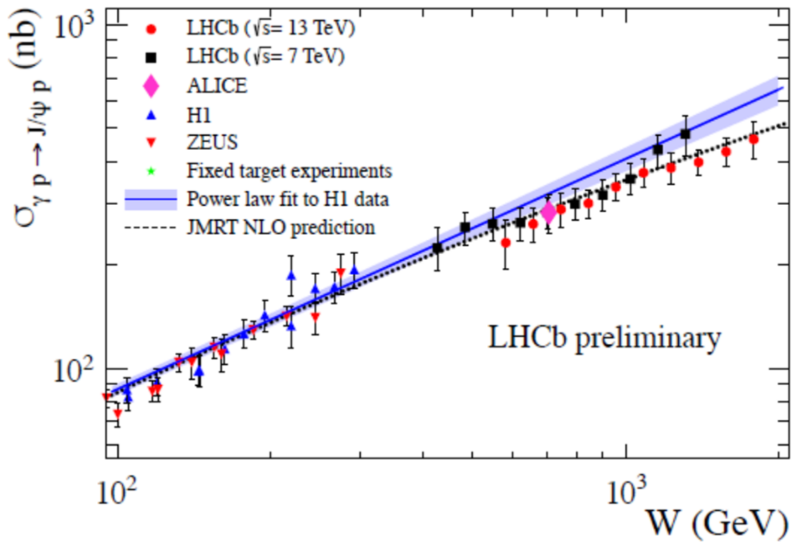


Run 2: p-Pb @ 8.16 TeV



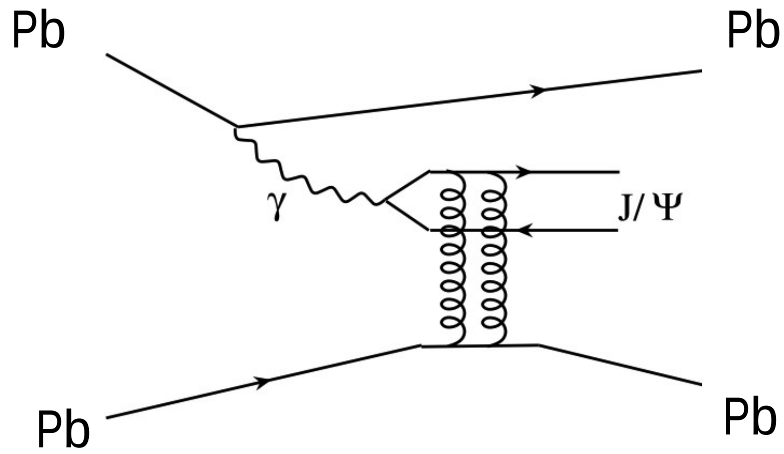


- x10 more stat at high $W_{\gamma p}$ ~ 0.7-1.4 TeV
- search for gluon saturation effects in p at low x~10^{-5}
- study proton-dissociative cross section behaviour at high $W_{\gamma p}$



J/ψ photoproduction on Pb target

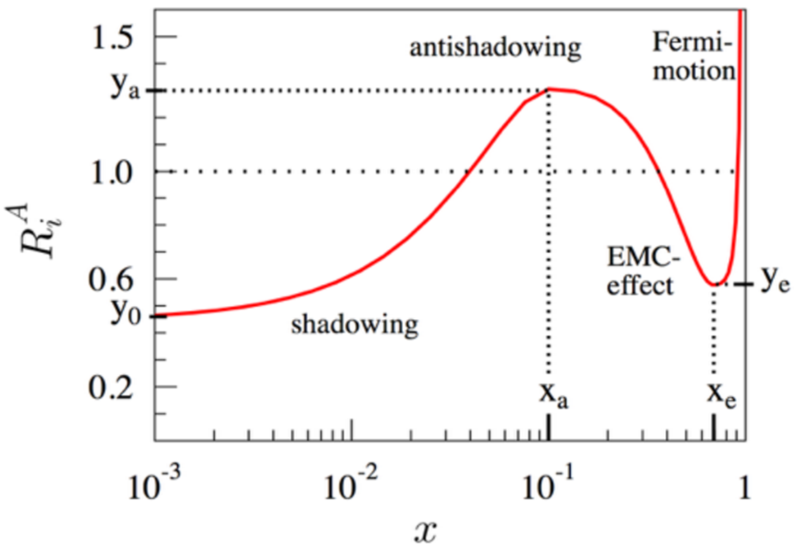
Coherent J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**



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

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



Nuclear shadowing = suppression of cross section on a nucleus compared to sum of cross sections on individual nucleons. Explained by destructive interference among amplitudes for interaction with 1, 2 and more nucleons

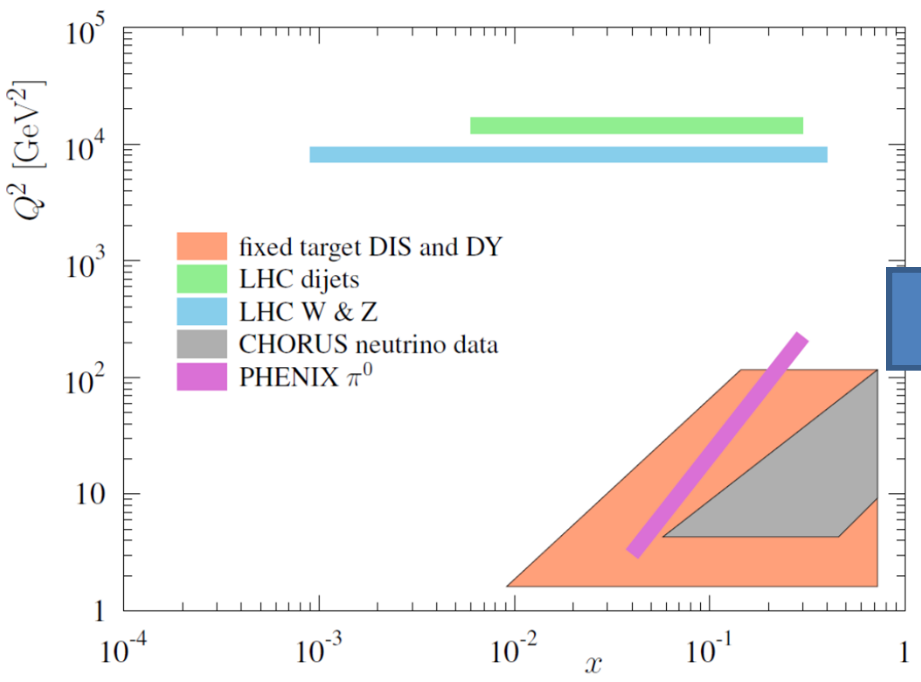
Parton distributions in nuclei (nPDFs)

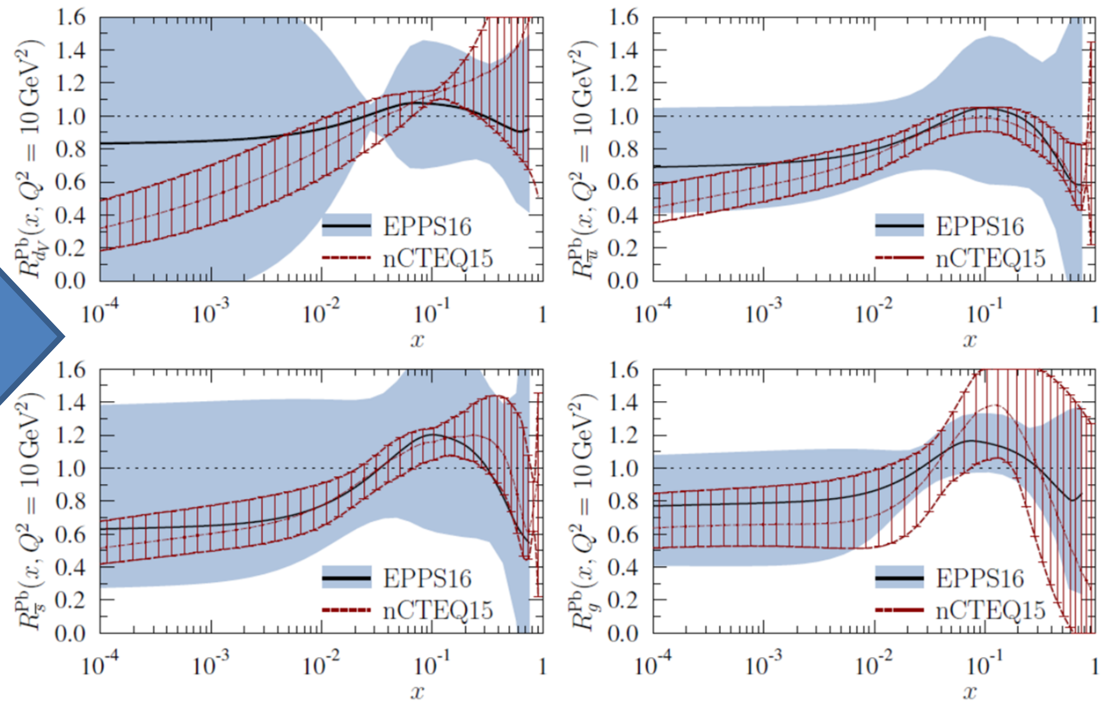
nPDFs are fundamental QCD quantities for the description of DIS, pA, AA collisions

- determine initial state in heavy ion collisions
- required for quantitative estimates for the onset of saturation

Determination of nPDFs:

EPPS16 : EPJ C (2017) 77

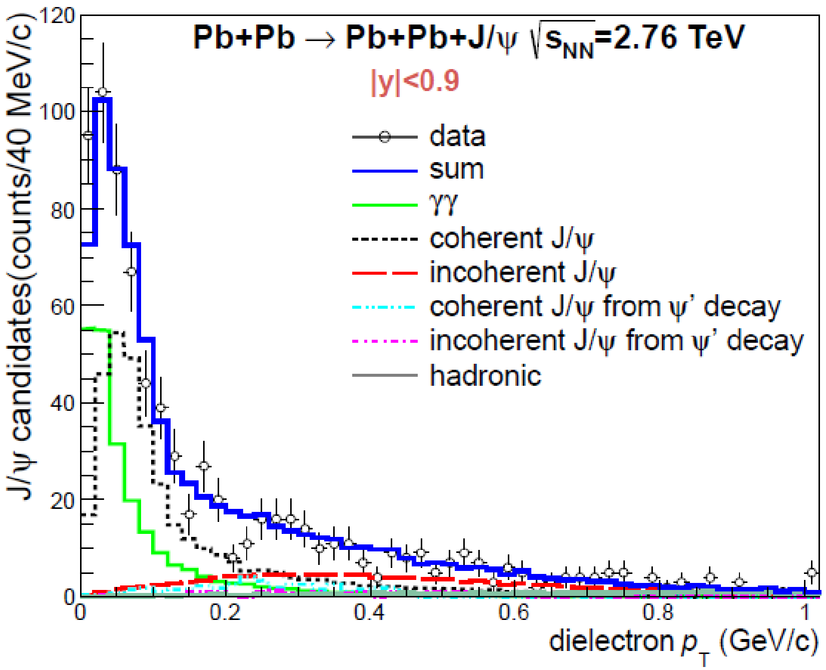




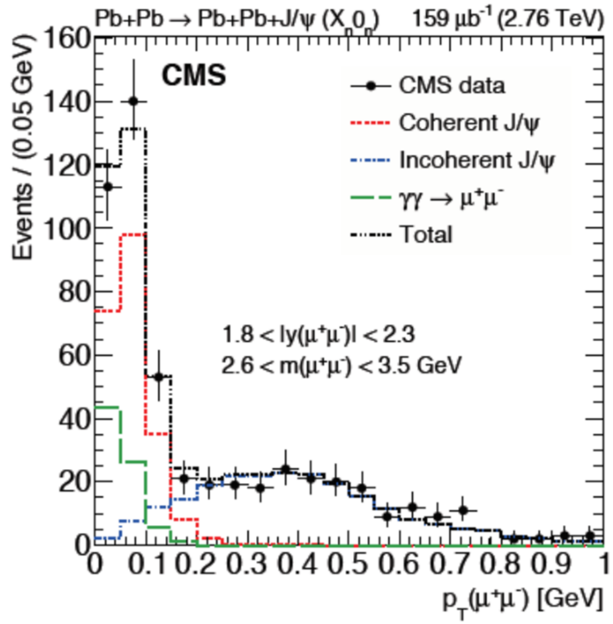
Resulting nPDFs have rather **large uncertainties, especially for small-x gluons** due to:

- Limited kinematics
- Indirect extraction of gluons via Q^2 evolution

Coherent and incoherent photoproduction



ALICE. Eur. Phys. J. C73 (2013) 2617



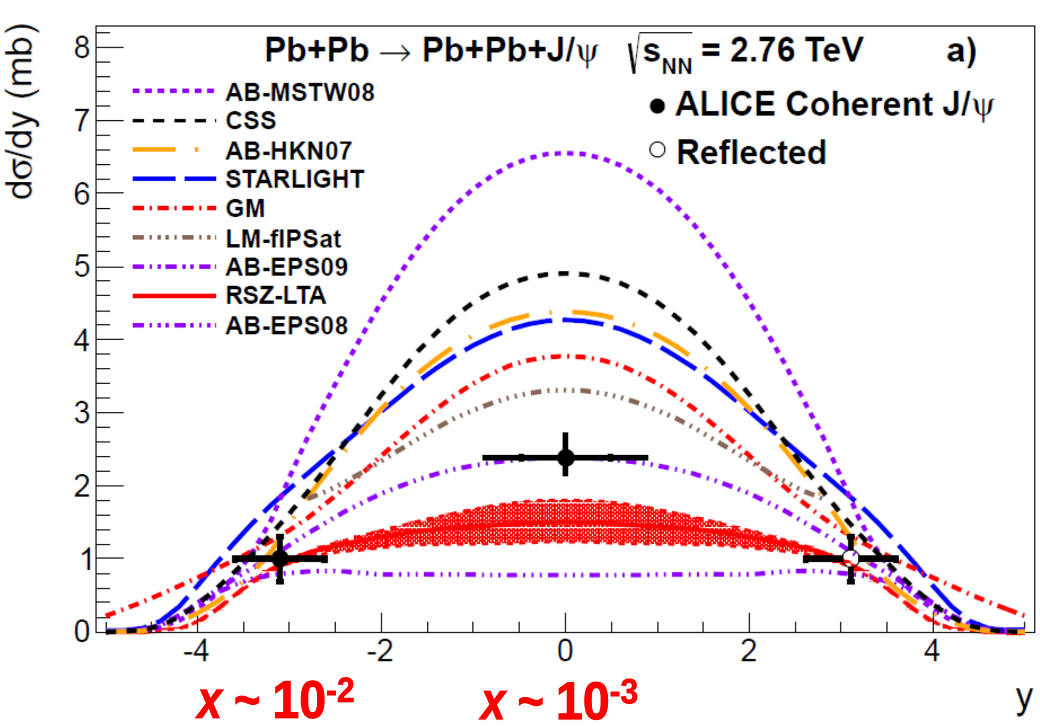
CMS: Phys.Lett. B772 (2017) 489-511

Two types of photoproduction processes:

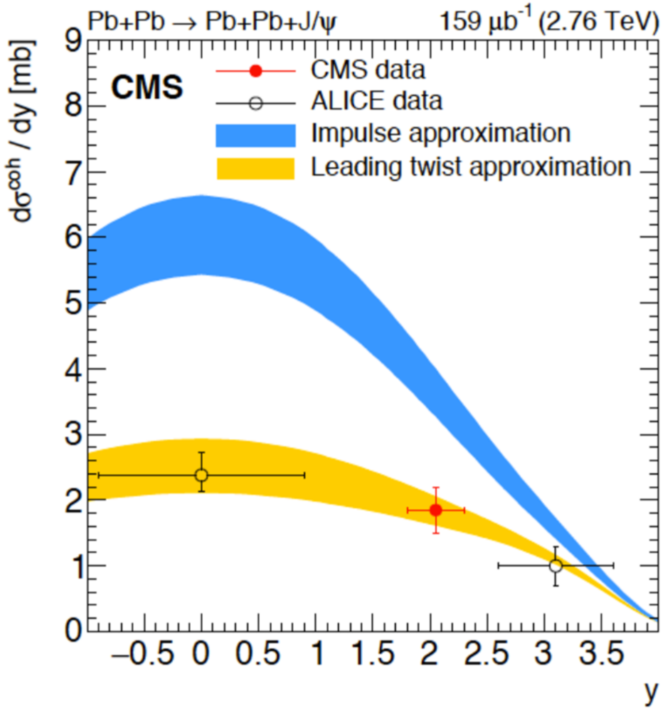
- **Coherent:**
  - photon couples coherently to all nucleons
  - $\langle p_T \rangle \sim 1/R_{Pb} \sim 60$ MeV/c
- **Incoherent:**
  - photon couples to a single nucleon
  - $\langle p_T \rangle \sim 1/R_p \sim 450$ MeV/c
  - usually accompanied by neutron emission
- Other contributions: J/ψ from coherent and incoherent ψ' decays and $\gamma\gamma \rightarrow ll$

Results from Run 1

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



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



Several competing approaches:

- Empirical shadowing parameterizations: AB, PRC85 (2012) 044904
- Shadowing in leading twist approximation (LTA): RSZ, PLB 710 (2012) 252
- Color dipole model + saturation: GM: PRC84 (2011) 011902, CSS: PRC86 (2012) 014905, LM: PRC87 (2013) 032201

Good agreement with **EPS09 and LTA shadowing**

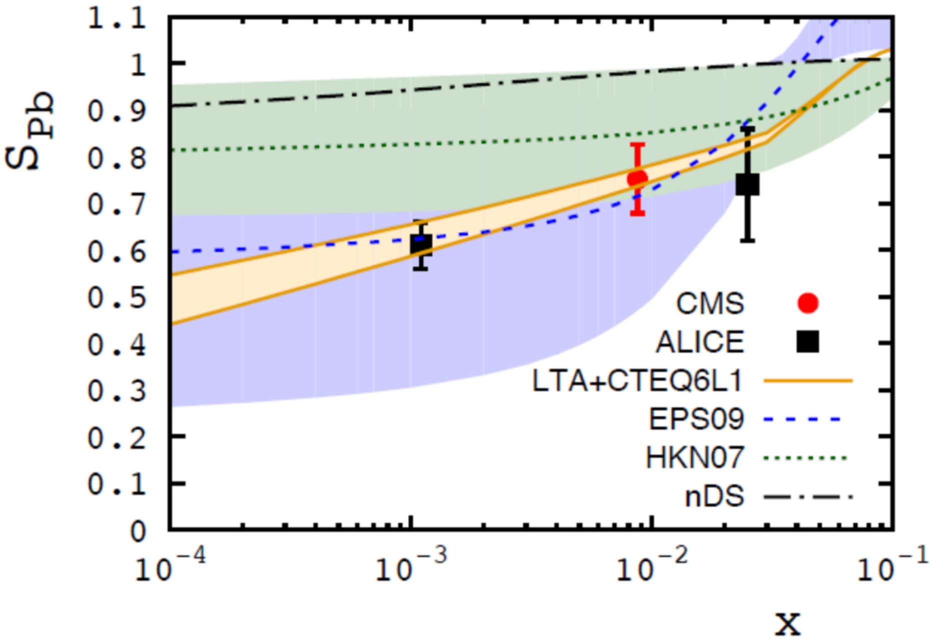
Gluon shadowing from photoproduction data

Nuclear suppression factor:

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

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

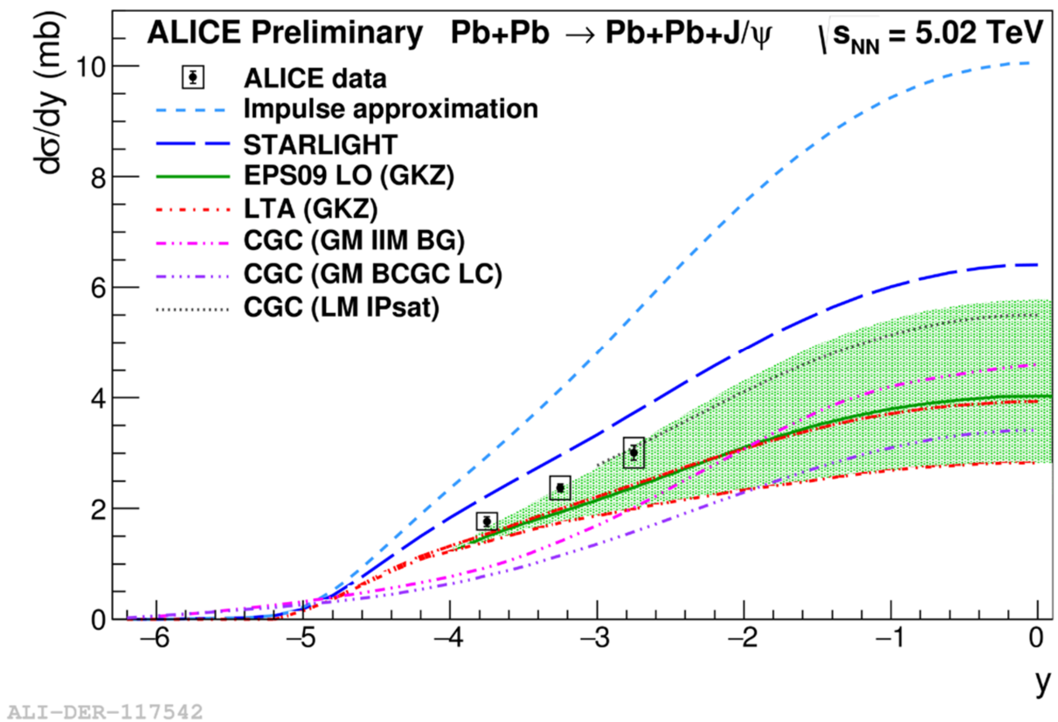
Impulse approximation:
forward photoproduction cross section on proton (HERA) times integral over squared Pb form-factor



Guzey, EK et al. Phys. Lett. B726 (2013) 290
Guzey, Zhalov JHEP 1310 (2013) 207

- Nuclear suppression factor S gives direct access to $R_g(x,\mu\sim2.4$ GeV)
- First direct evidence of large gluon nuclear shadowing: $R_g(x,\mu\sim2.4$ GeV) ~ 0.6
- Many complications (skewness, NLO, scale uncertainty and higher-twist corrections) are likely minimized – S factor can be used in global nPDF fits

First run 2 results



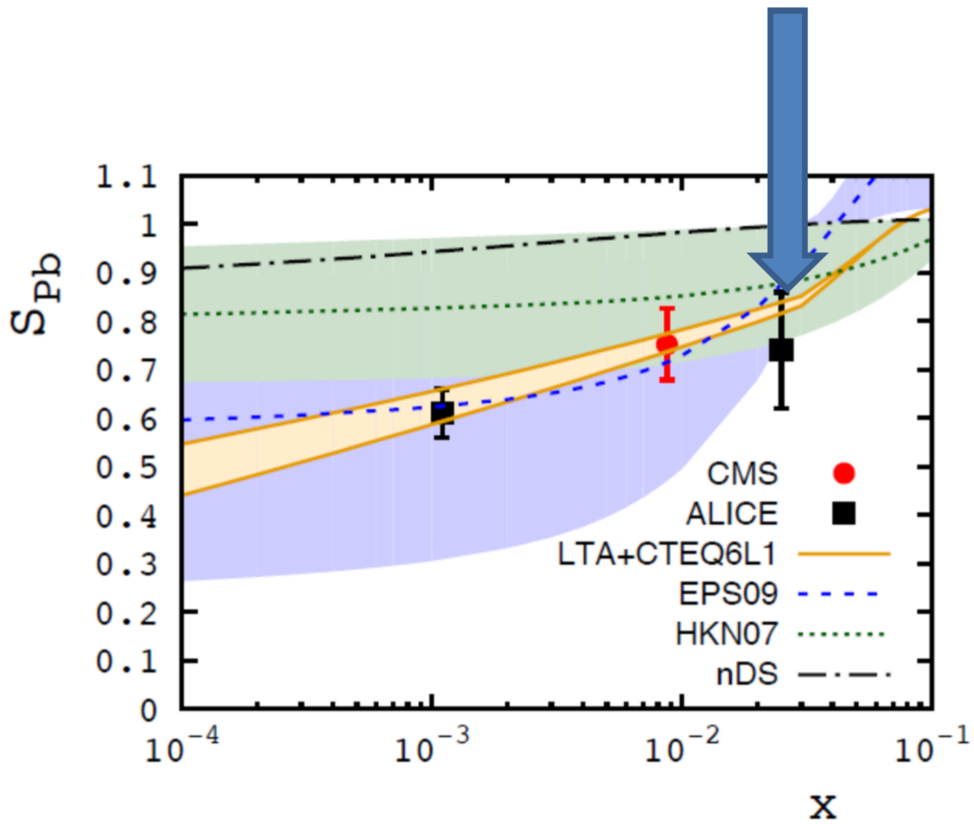
$$\frac{d\sigma_{UPC}}{dy} = n(\omega_1)\sigma_{\gamma T}(\omega_1) + n(\omega_2)\sigma_{\gamma T}(\omega_2)$$

Low energy (high-x) High energy (low-x)

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

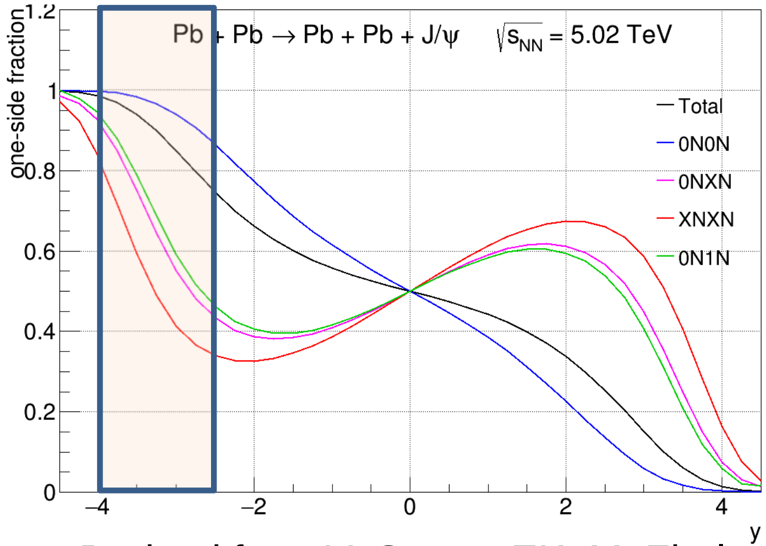
ALICE/Impulse approximation ~ 0.6

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



Next...

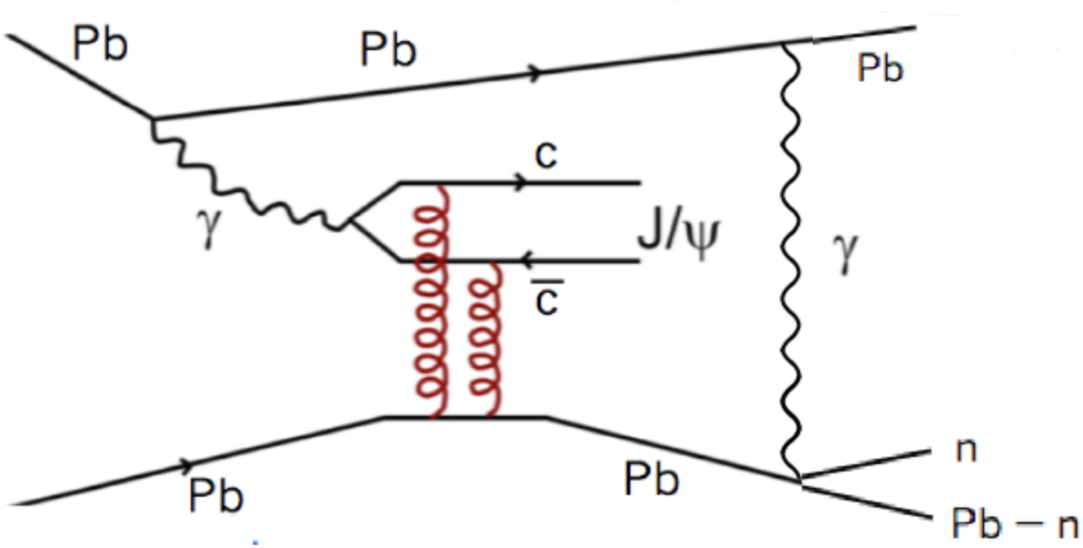
- Study J/ψ photoproduction accompanied by neutron emission (measured with Zero Degree Calorimeters) => access x~10^{-5}

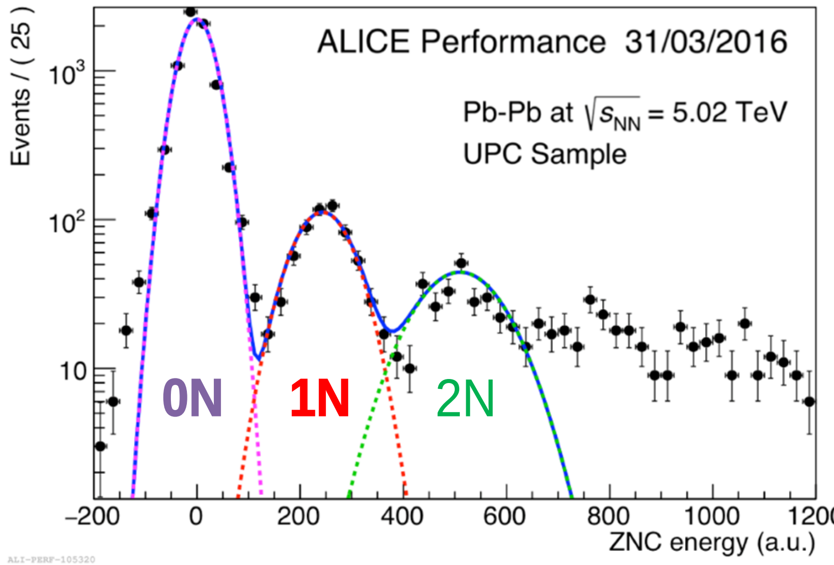


Derived from V. Guzey, EK, M. Zhalov, **PRC93 (2016), 055206**

$$\frac{d\sigma_{UPC}}{dy} = n(\omega_1)\sigma_{\gamma T}(\omega_1) + n(\omega_2)\sigma_{\gamma T}(\omega_2)$$

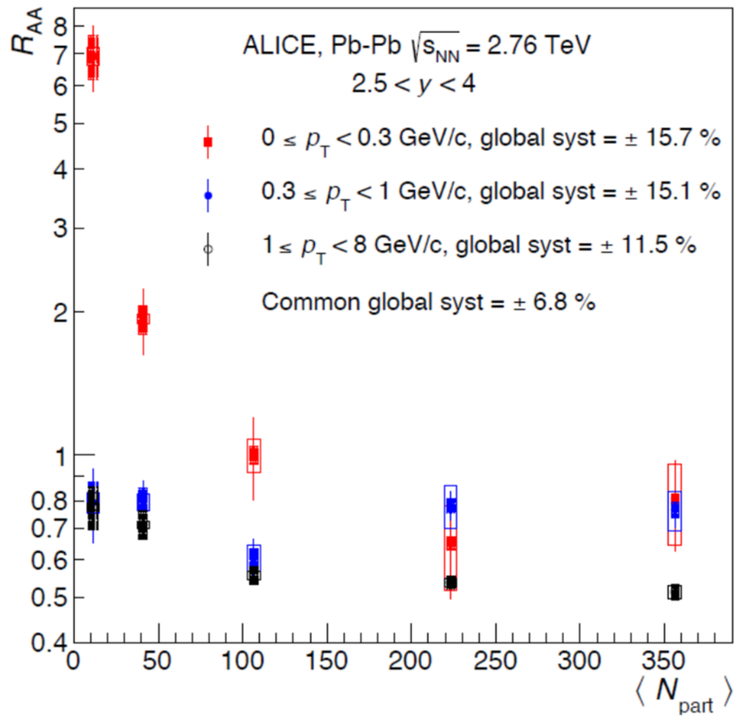
Low energy (high-x) High energy (low-x)

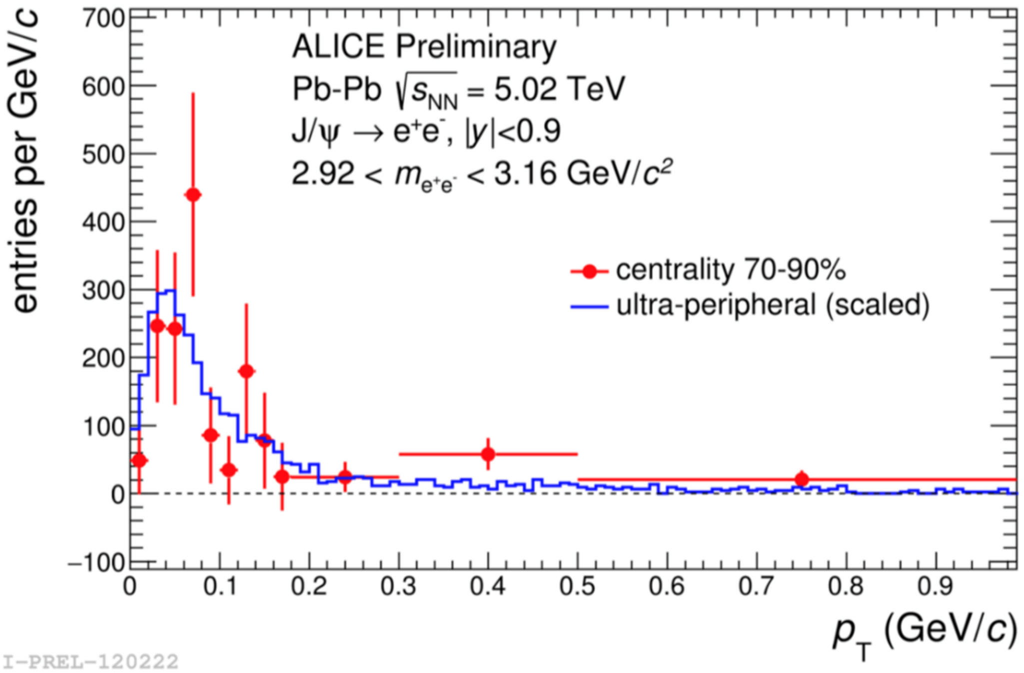


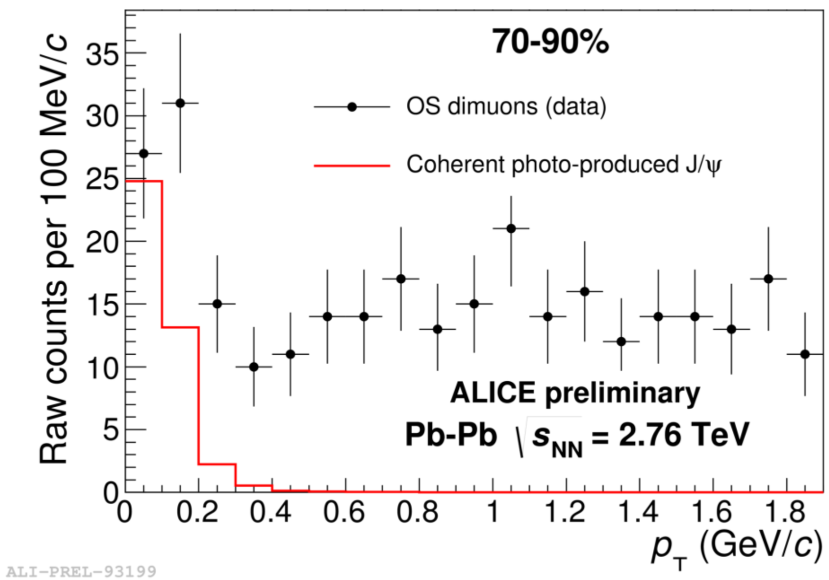


J/ψ production in peripheral Pb-Pb

- Data shows an excess of J/ψ at low p_T < 100 MeV/c (R_{AA} ~ 7)
- Possible interpretation: coherent photoproduction on nuclear fragments



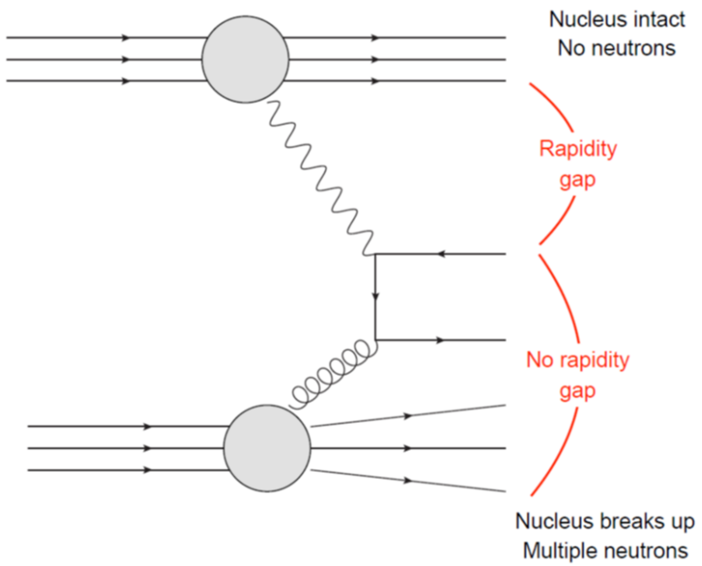


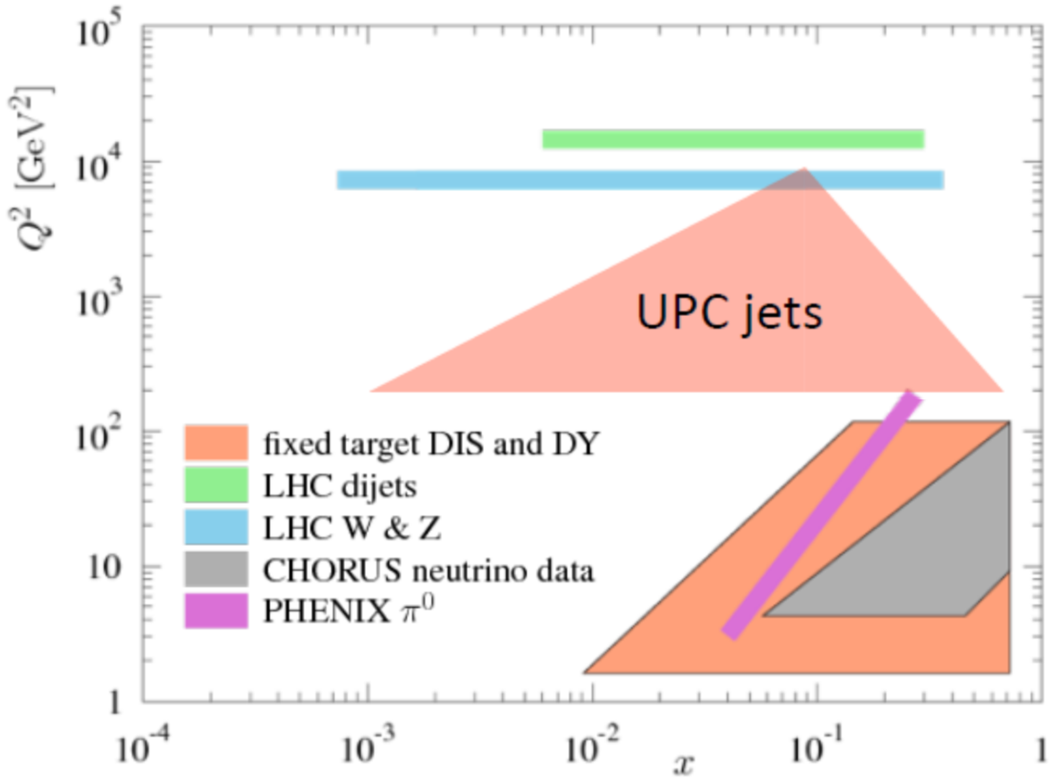


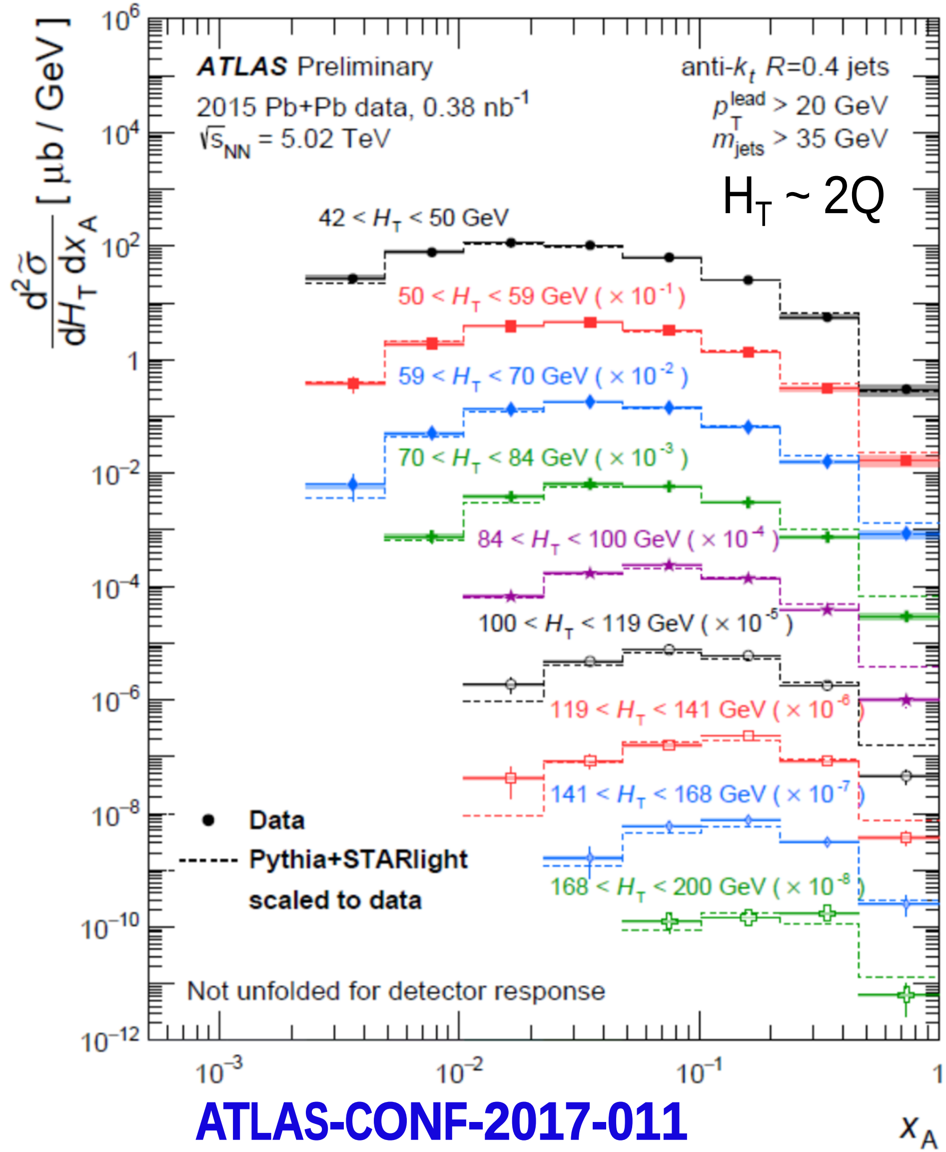
ALICE: PRL 116 (2016) 222301

Photonuclear dijet production

- Single gluon exchange: theoretically clean
- Experimentally studied in 0NXN events with rapidity gap
- Unfolding in progress







ATLAS-CONF-2017-011

Summary and outlook

- LHC is an effective γγ, γp and γPb collider
- Continuum γγ → l+l- cross sections consistent with LO predictions
  - Validate photon fluxes obtained with EPA
- Evidence for SM γγ → γγ production (significance of 4.4σ)
- Photoproduction of vector mesons in UPC at LHC allows one to study gluon distributions at unprecedently high energies
- Coherent J/ψ photoproduction cross sections in UPC shows direct evidence of large gluon shadowing R(x=0.001) ~ 0.6
- Expect lots of new data on photoproduction of vector mesons and dijets in UPC