Diffraction, ultra-peripheral collisions, low x physics at the LHC and connection to EIC

- intro
- gluons, low x phenomena, and saturation
- diffraction and deep inelastic scattering at HERA
- diffraction at the LHC
- UPC and low x physics
- forward charm and low x gluons
- connection to EIC physics

talk pbm
POETIC8
March 19-23, 2018
Regensburg, Germany

EMMI

HUAZHONG UNIVERSITY

GSI

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

recent reference on the physics of saturation:

IOP Publishing Reports on Progress in Physics

Rep. Prog. Phys. **80** (2017) 032301 (33pp) doi:10.1088/1361-6633/aa5435

Key Issues Review

High gluon densities in heavy ion collisions

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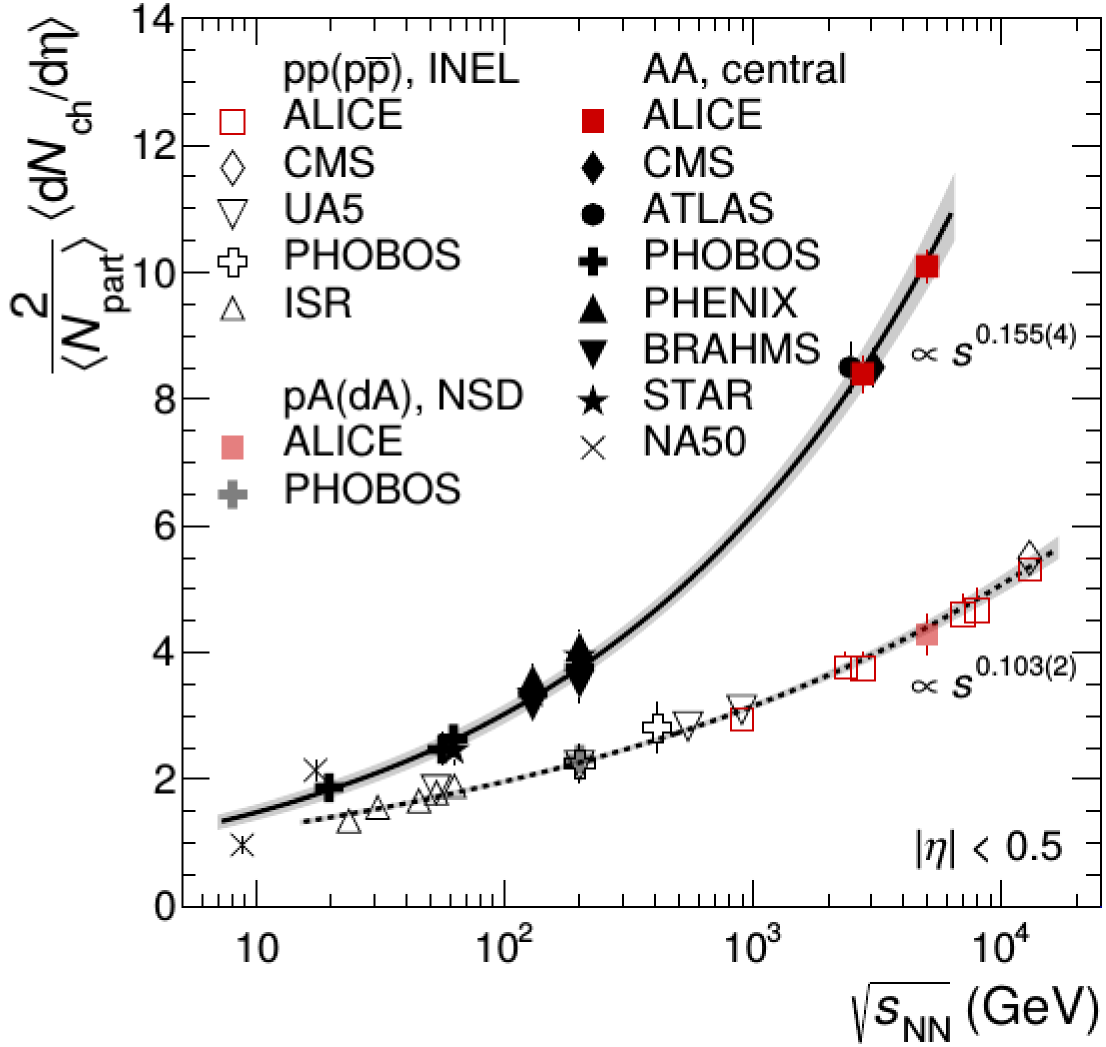
can one see saturation effects in particle production experiments?

energy dependence of hadron production in central Pb-Pb (Au-Au) collisions

total number of hadrons produced

2.76 TeV
N_had = 25800

5.02 TeV
N_had = 32300



data from LHC run1 and run2

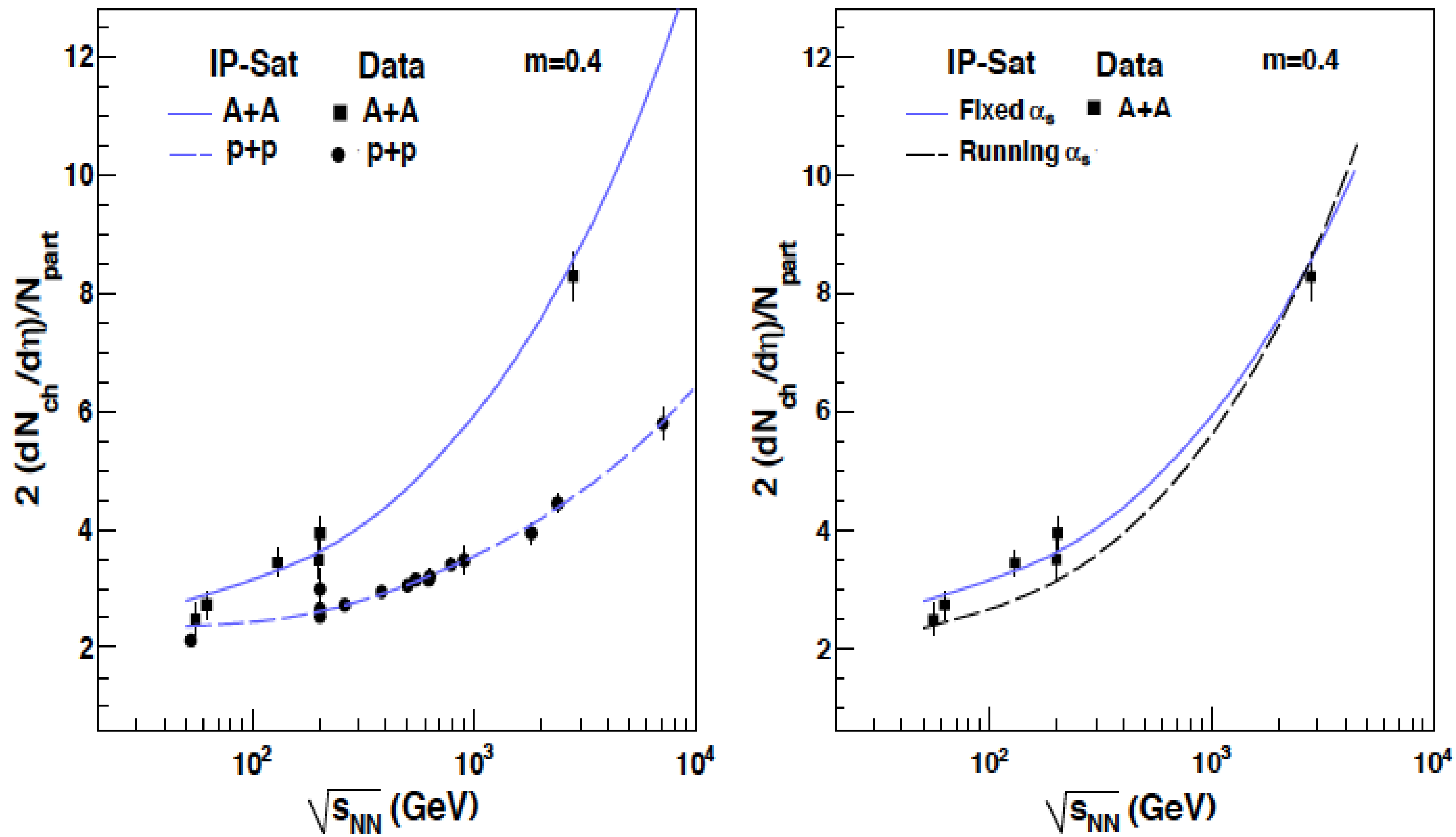
ALICE coll., Phys.Rev.Lett. 116 (2016) no.22, 222302

note: exponent in energy dependence is different for pp and PbPb; not anticipated but now explained in saturation models

energy dependence of particle production in Pb-Pb collisions at LHC

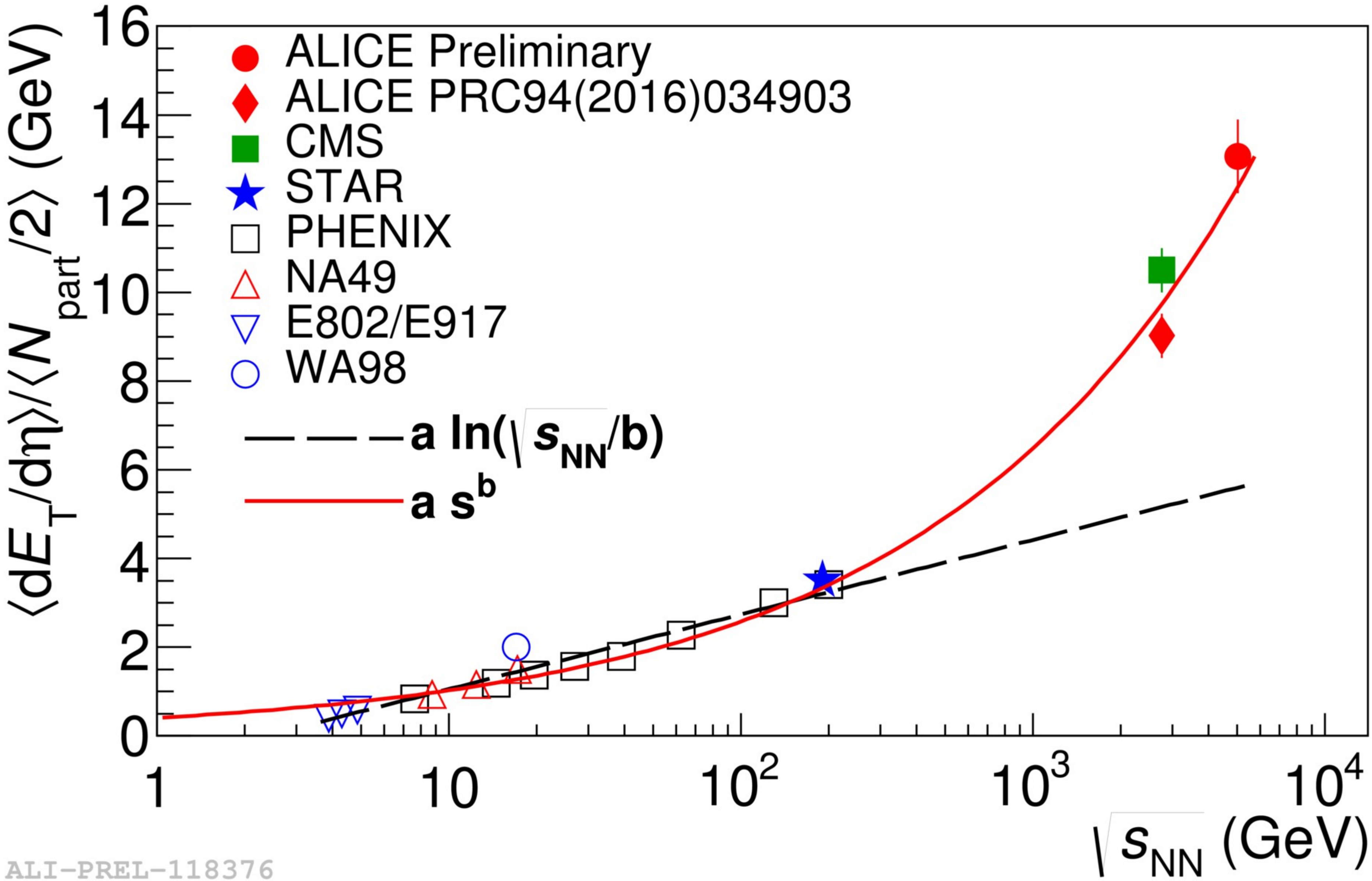
QCD saturation at the LHC: comparisons of models to p+p and A+A data and predictions for p+Pb collisions

Prithwish Tribedy[1] and Raju Venugopalan[2]



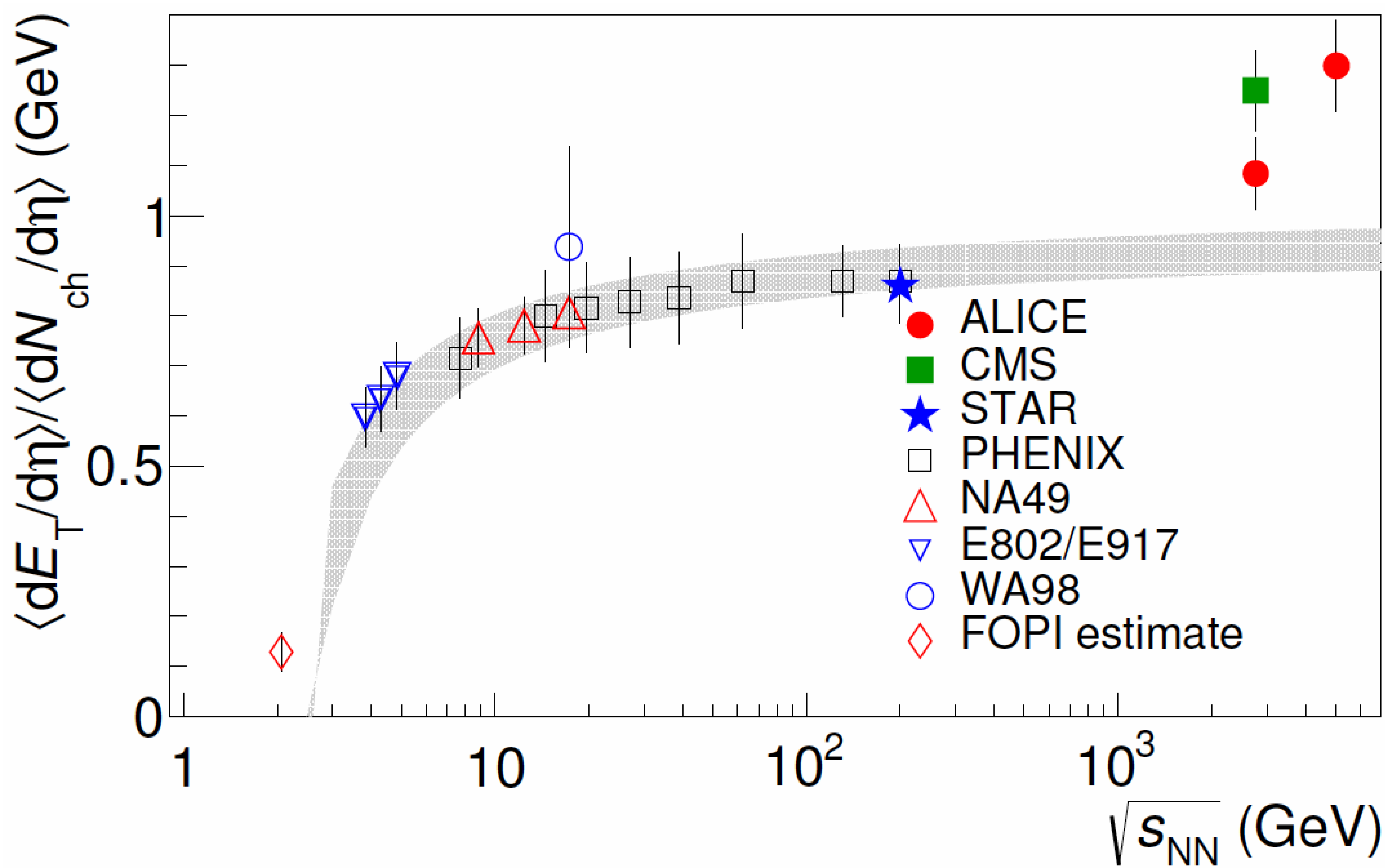
The difference between pp and Pb-Pb is explained as due to the larger scaling violations in a large nucleus compared to the pp case, arXiv:1112.2445

energy dependence of transverse energy distribution



note: a s^b = 0.4 s^0.2

energy dependence of transverse energy/particle production – Pb-Pb (Au-Au)



indication of anomalous energy dependence?

N_{ch} and E_T cannot directly be obtained in a perturbative approach

look for other observables:
charmonium production in diffractive and ultra-peripheral collisions

charmonium production in diffractive events at HERA

1[st] order perturbation theory,
Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085,

including higher orders,
J.Phys. G43 (2016) no.3, 035002, Eur.Phys.J. C76 (2016) no.11, 633

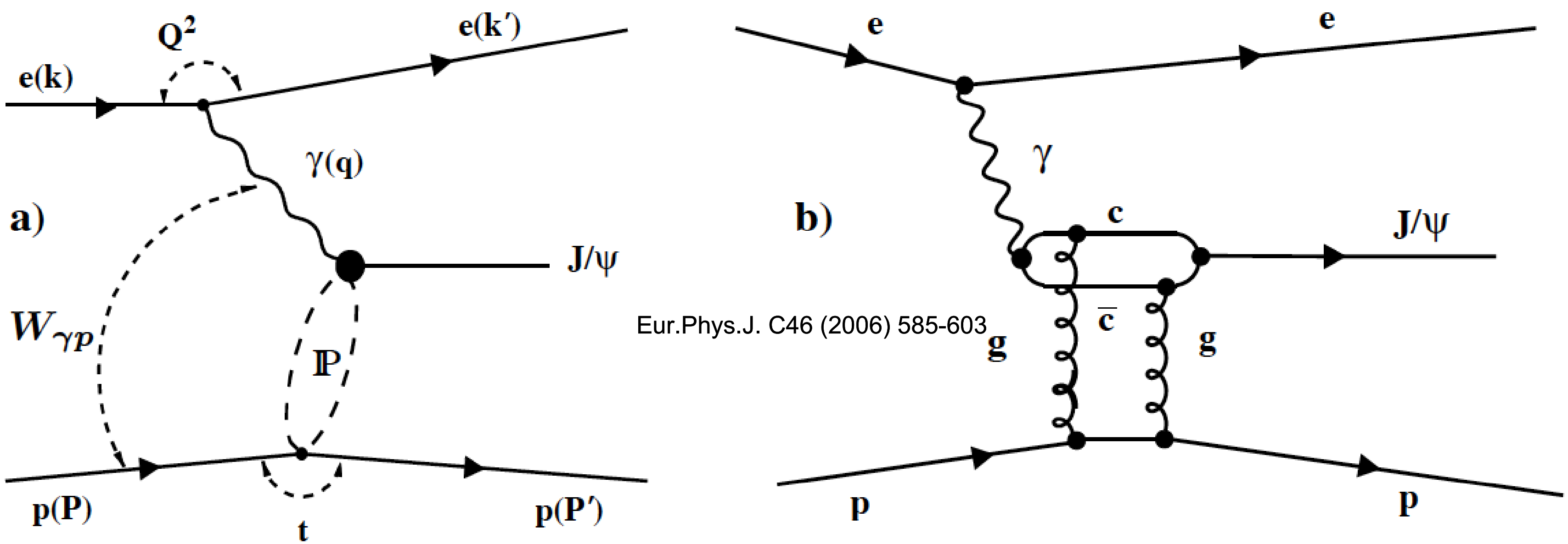
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right).$$

Here Γ_{ee} is the electronic width of the J/ψ, and

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4\,, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)\,.$$

because of the large mass of the J/psi, the scale Q_bar is large → perturbative approach

2 options, option a not consistent with measured energy dependence



Eur.Phys.J. C46 (2006) 585-603

Figure 1: Elastic J/ψ production, a) in an approach based on Pomeron ($\mathbb{P}$) exchange and b) in a pQCD approach via two gluon exchange. The kinematic variables are indicated in a).

Hera H1 publication, hep-ex/0510016, Eur.Phys.J. C46 (2006) 585-603

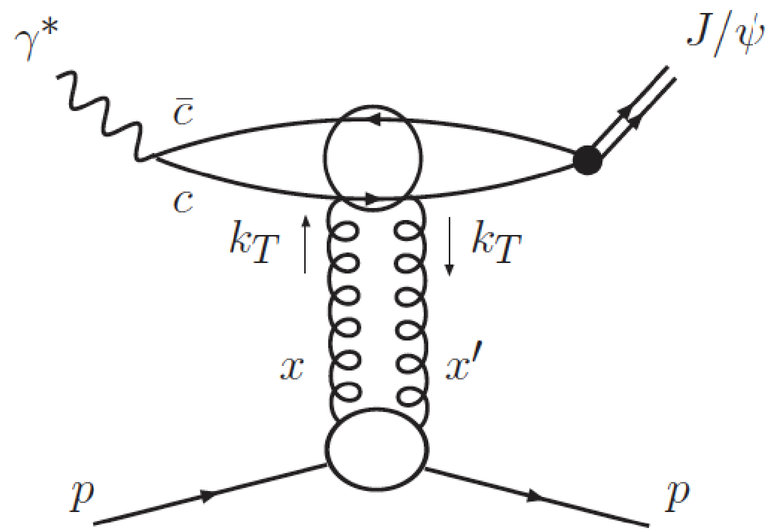


Figure 1: Schematic picture of high energy exclusive J/ψ production, $\gamma^* p \to J/\psi\, p$. The factorised form follows since, in the proton rest frame, the formation time $\tau_f \simeq 2E_\gamma/(Q^2+M^2_{J/\psi})$ is much greater than the $c\bar{c}$-proton interaction time $\tau_{\rm int}$. In the case of the simple two-gluon exchange shown here, $\tau_{\rm int} \simeq R_p$, where R_p is the radius of the proton.

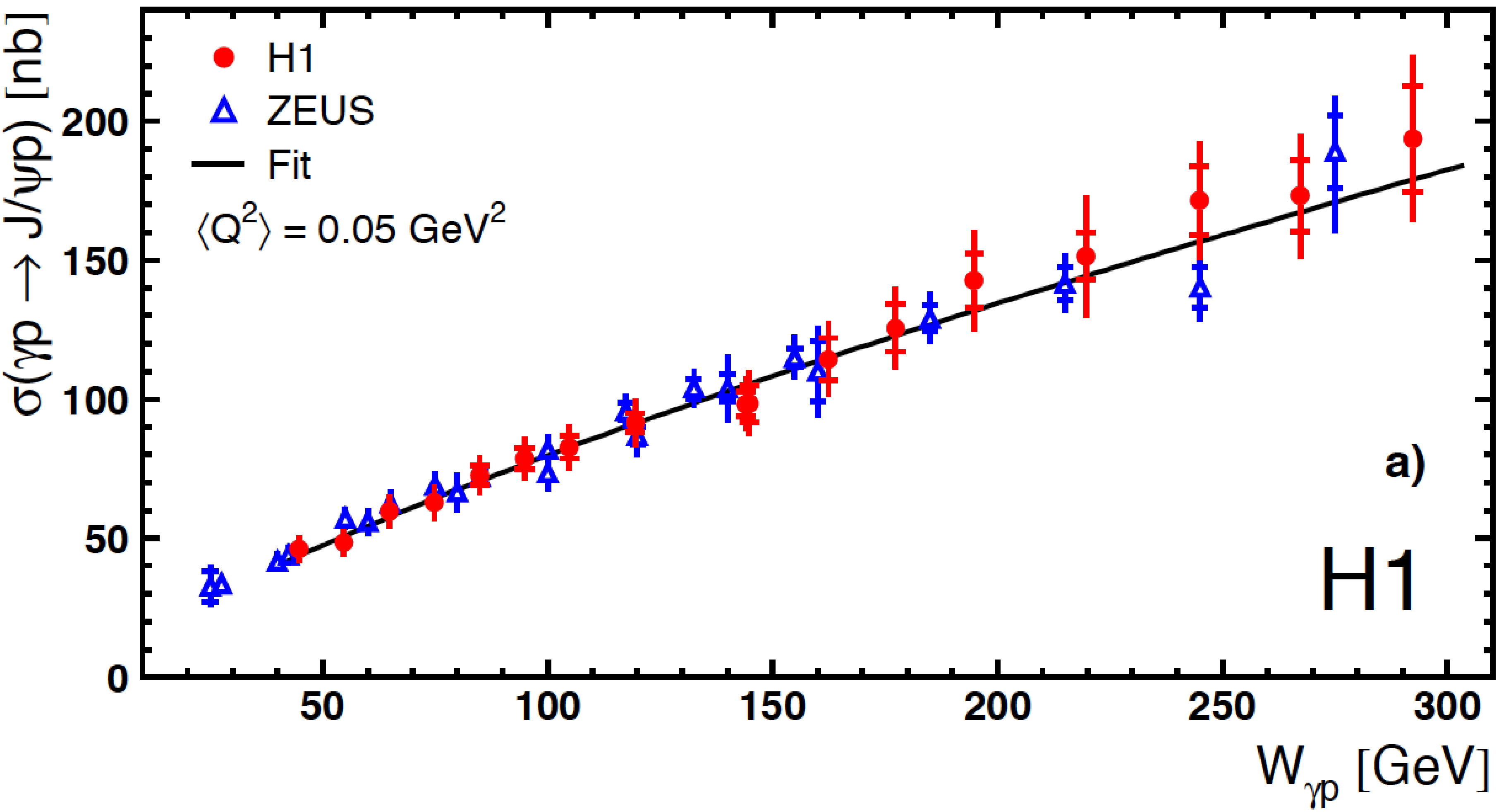
correction for higher orders, see Jones et al.

$$\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right] \longrightarrow \int_{Q_0^2}^{(W^2-M_{J/\psi}^2)/4} \frac{\mathrm{d}k_T^2\,\alpha_s(\mu^2)}{\bar{Q}^2(\bar{Q}^2+k_T^2)} \frac{\partial\left[xg(x,k_T^2)\sqrt{T(k_T^2,\mu^2)}\right]}{\partial k_T^2} + \ln\left(\frac{\bar{Q}^2+Q_0^2}{\bar{Q}^2}\right) \frac{\alpha_s(\mu_{\mathrm{IR}}^2)}{\bar{Q}^2 Q_0^2}\, xg(x,Q_0^2)\sqrt{T(Q_0^2,\mu_{IR}^2)}\,.$$

Hera results from H1 and Zeus

here, $Q^2 = p_t^2$

data parametrized as $\sigma \propto W_{\gamma p}^{\delta}$
W is photon proton cm energy



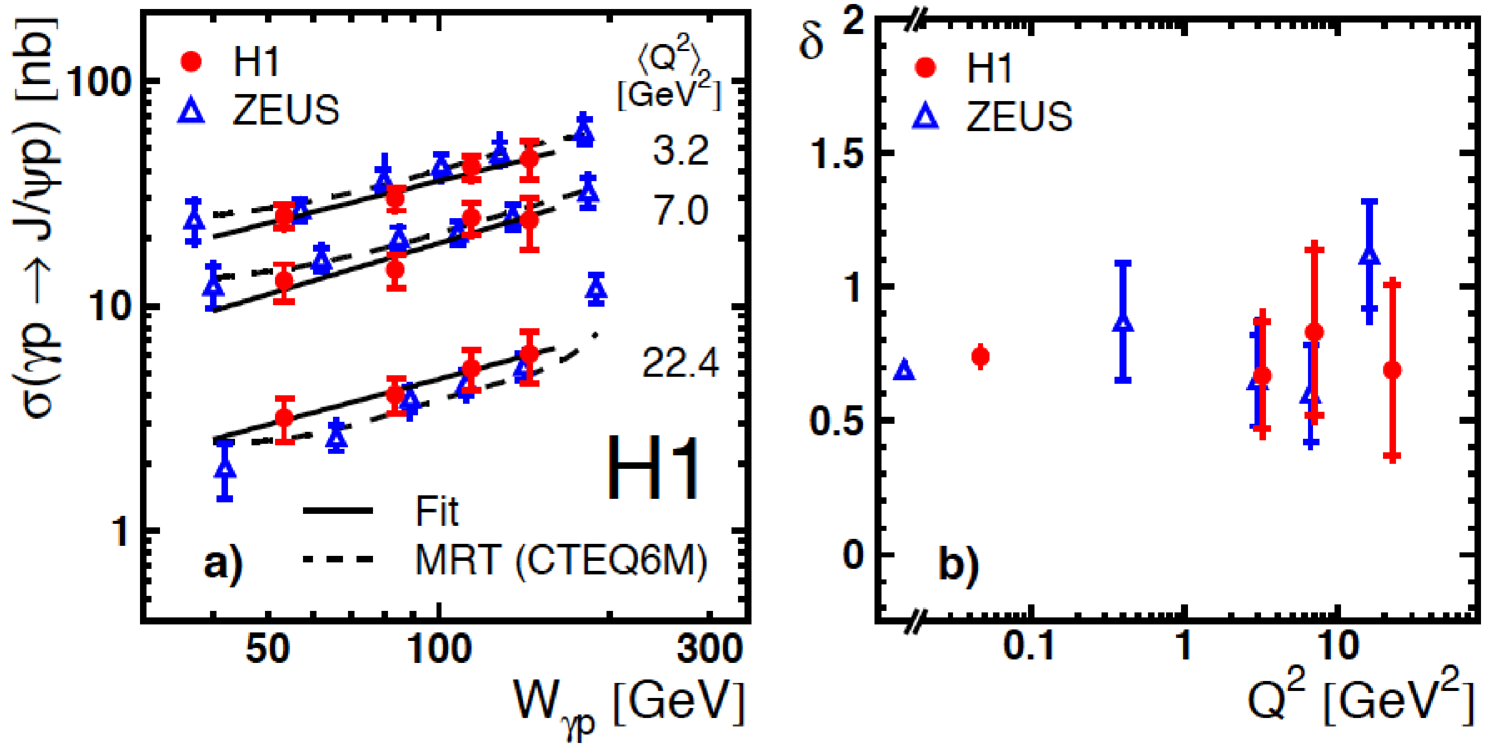


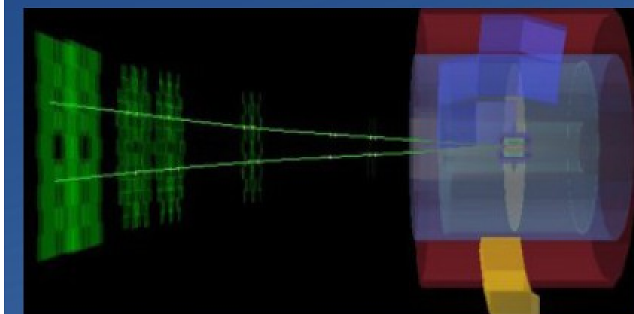
Figure 6: a) Total cross sections for elastic J/ψ production as a function of $W_{\gamma p}$ in the range $|t| < 1.2\,\mathrm{GeV}^2$ in electroproduction in three bins of Q^2. $\langle Q^2 \rangle$ indicates the bin centre value in the Q^2 range considered. The solid lines show fits to the H1 data of the form $\sigma \propto W_{\gamma p}^{\delta}$. The dashed curves show the MRT QCD prediction based on the gluon distribution CTEQ6M [48] with the normalisation factors from the fit to the Q^2 distribution. Results from the ZEUS experiment [16] in a similar kinematic range are also shown. They have been scaled to the given $\langle Q^2 \rangle$ values using the Q^2 dependence measured by ZEUS. b) The fit parameter δ as a function of Q^2. The inner error bars show the statistical error, while the outer error bars show the statistical and systematic uncertainties added in quadrature.

data well described by 'conventional' pQCD calculations

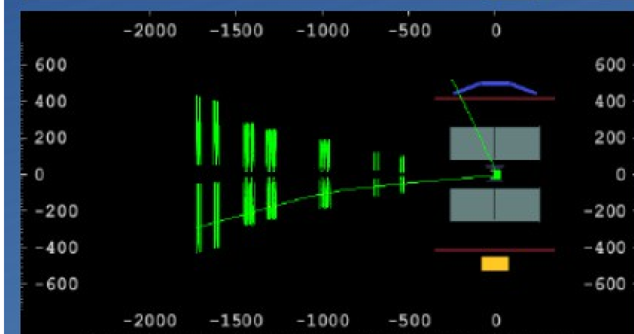
now to ultra-peripheral collisions

Some remarks on ultra-peripheral collisions in p-Pb and Pb-p

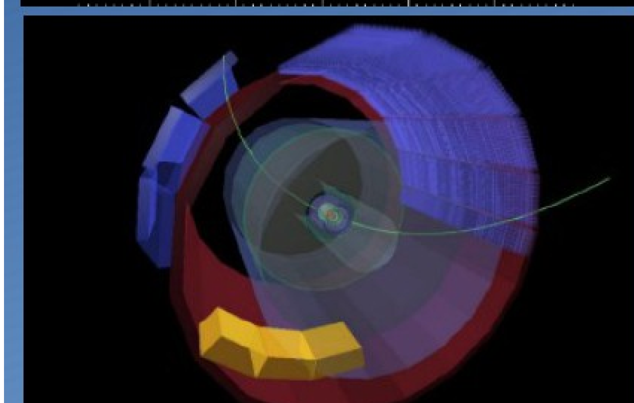
3 possibilities in ALICE: Forward, Semi-forward, and Central



Both muons in muon arm
J/ψ rapidity: $-4.0 < y < -2.5$
γ+p CM energies:
$21 \le W_{\gamma p} \le 45$ GeV (p+Pb)
$550 \le W_{\gamma p} \le 1160$ GeV (Pb+p)



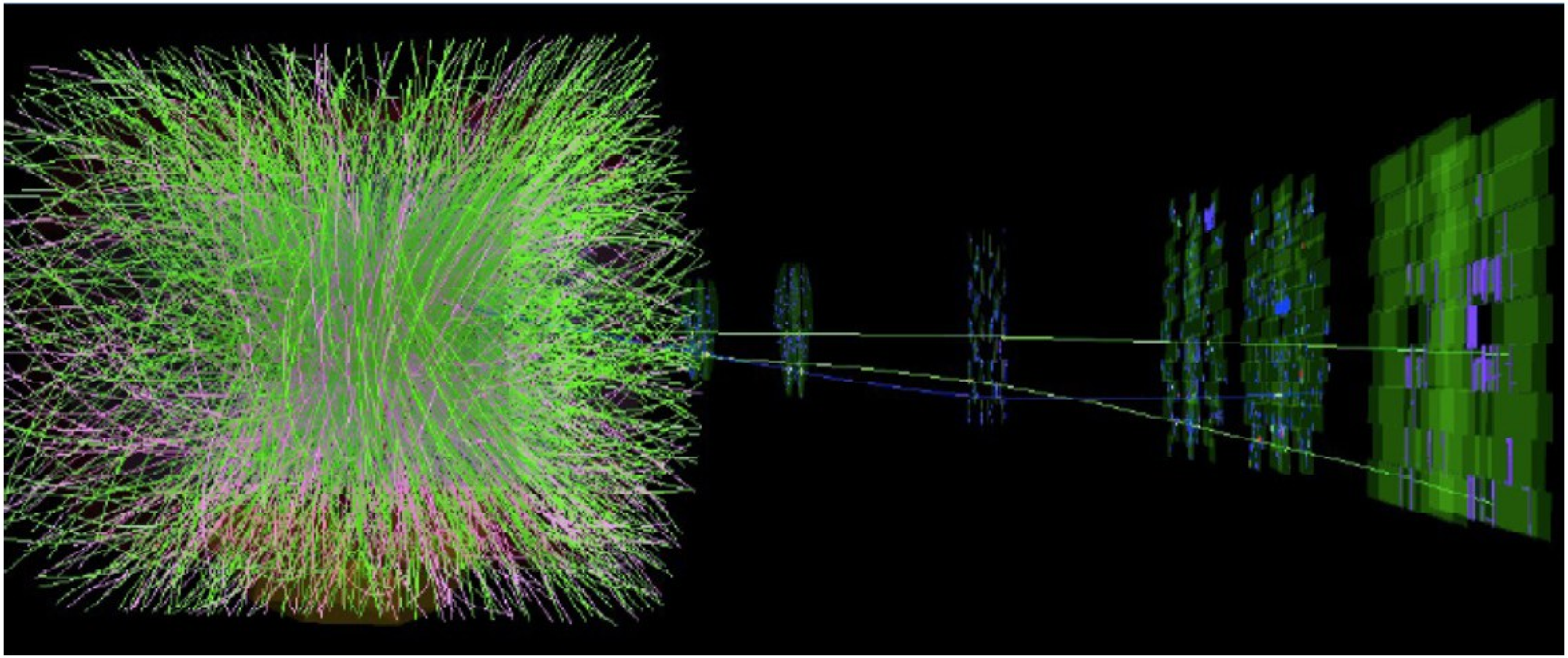
One muon in muon arm, one in central barrel
J/ψ rapidity: $-2.5 < y < -1.3$
γ+p CM energies:
$45 \le W_{\gamma p} \le 82$ GeV (p+Pb)
$300 \le W_{\gamma p} \le 550$ GeV (Pb+p)



Both muons/electrons in central barrel
J/ψ rapidity: $-0.9 < y < 0.9$
γ+p CM energies:
$100 \le W_{\gamma p} \le 250$ GeV (p+Pb/Pb+p)

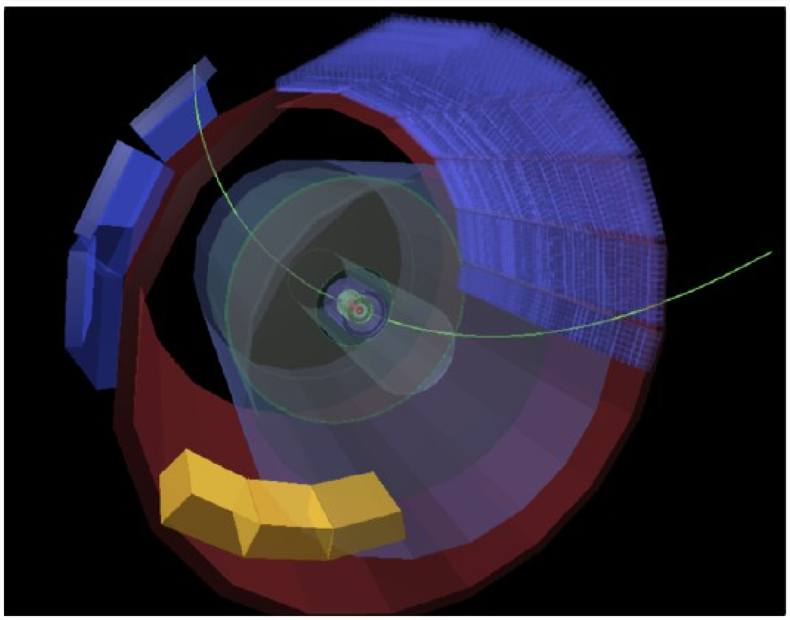
$W_{\gamma p}$ - γ-p center of mass energy

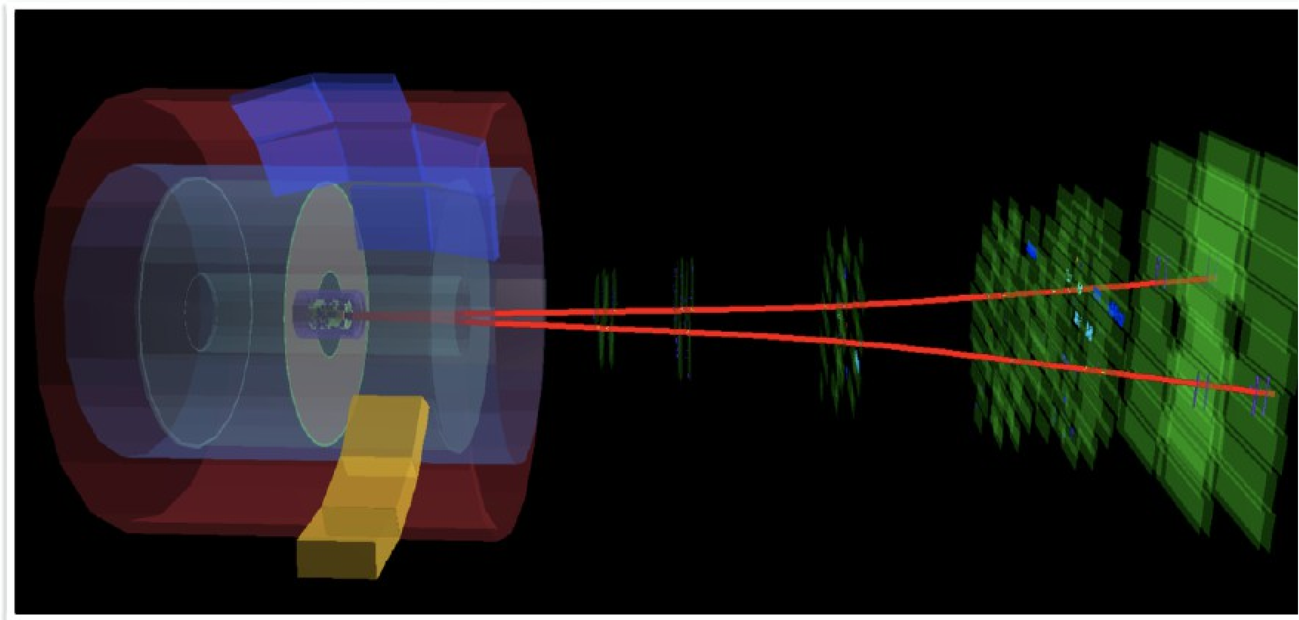
From typical hadronic interaction…



...to ultra-peripheral colisions

2 Pb nuclei collide at 2.76 TeV/nucleon without breaking apart and only 1 lepton pair with invariant mass of the J/psi is produced!





data from the ALICE collaboration

UPC in ALICE p-Pb

For symmetric systems (Pb+Pb/p+p) and $y \neq 0$, one has two contributions:

high E_γ - low x   or   low E_γ - high x

Not straight forward to separate the two.

⇒ Advantage in p-Pb, photon is almost always emitted by Pb-nucleus.

⇒ Can study γ+p interactions at unprecedented energies at forward rapidities.

$$\omega_{1,2} = \frac{1}{2} M_V e^{\pm y}$$

ultra-peripheral collisions -some selected aspects

Ultra-peripheral collisions (UPCs)

- Heavy nuclei carry strong electric and magnetic fields
  - Fields are perpendicular -> treat as nearly-real virtual photons
    - $E_{max} = \gamma hc/b$
  - Photonuclear interactions
  - Two-photon interactions
- Visible when $b>\sim 2R_A$, so there are no hadronic interactions;
  - STAR & ALICE also see photon interactions in peripheral nuclear collisions

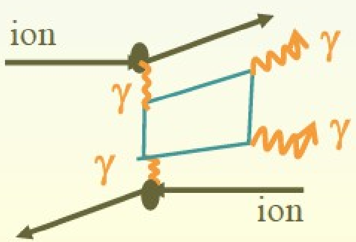
Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy $W_{\gamma p}$	24 GeV	~80 GeV	700 GeV	~3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1400 GeV

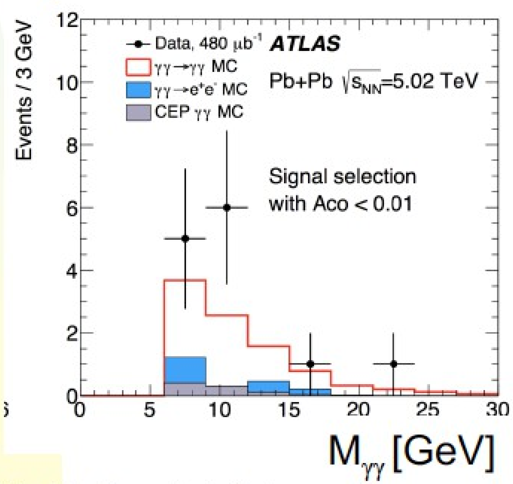
*LHC at full energy $\sqrt{s}$=14 TeV/5.6 TeV

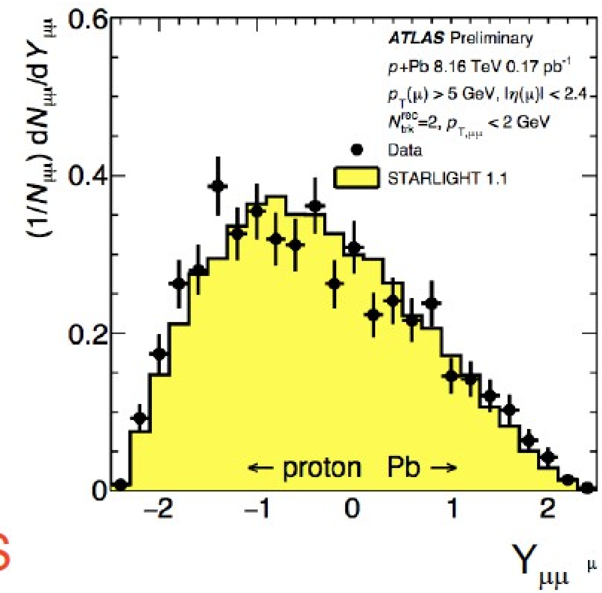
next 4 slides from Spencer Klein, talk at QM2017, Chicago, see also arXiv:1704.04715

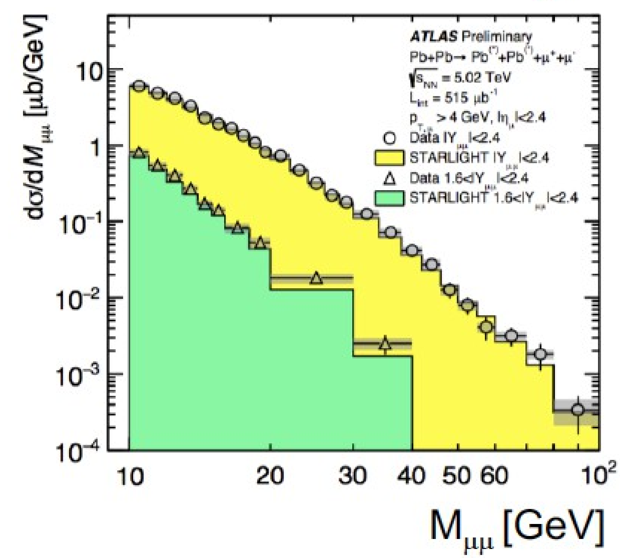
$\gamma\gamma$ -> Dileptons

- Large samples from ALICE, ATLAS & STAR
- Data is in excellent agreement with lowest order QED
  - STARlight Monte Carlo
  - $Z\alpha$ ~ 0.6, so perturbation theory might fail
- Light-by-light scattering seen by ATLAS
  - Sensitive to new particles



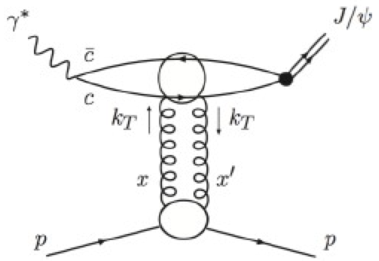






ATLAS: arXiv:1702.01625; M. Dyndal, this conference

VM photoproduction in pQCD



- In 2-gluon model, leading order pQCD

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right).$$

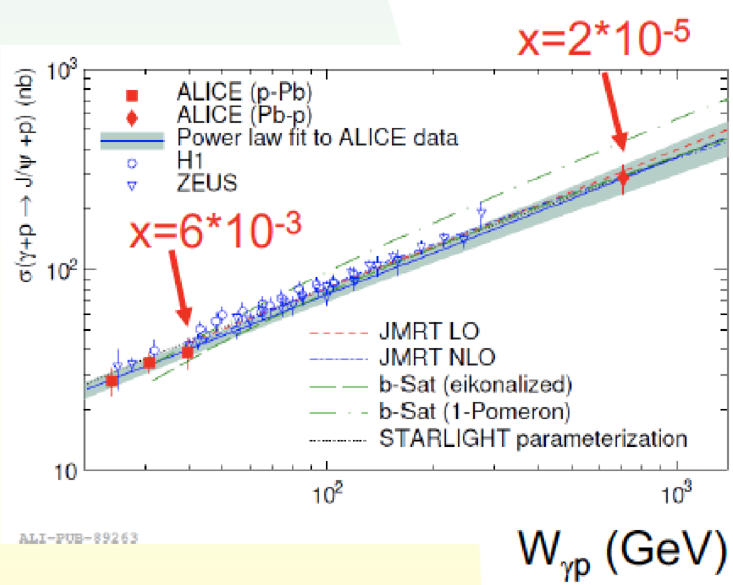
- With $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2+Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - pQCD factorization does not strictly hold
    - Two gluons have different x values (with x' ≪ x ≪ 1)
      - Use generalized (skewed) gluon distributions – smallish correction.
      - Can do exactly with Shuvaev transform
  - Photon is not pure $q\bar{q}$ dipole
  - Choice of scale μ
  - "Absorptive corrections" for pp akin to $b>R_A+R_b$

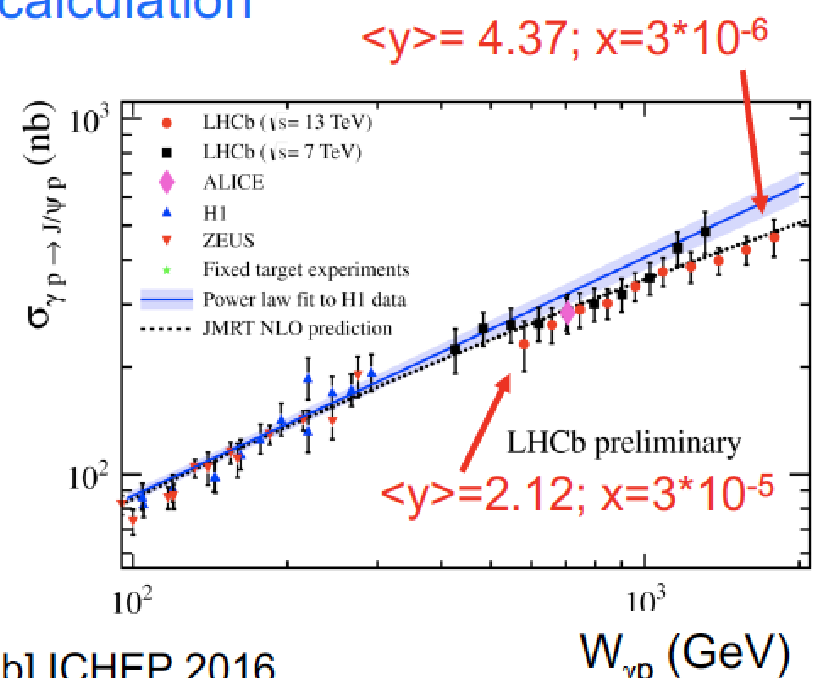
Jones, Martin, Ryskin and Teubner ("JMRT"), JHEP 1311, 085 (2013); and others

11

$\sigma(\gamma p \to J/\psi\, p)$

- Data up to $W_{\gamma p}$= 1.5 TeV -5 times the HERA maximum
- ALICE sees good pA agreement with HERA data
- LHCb 13 TeV-beam data somewhat below 7 TeV data?
  - LHCb uses bootstraps from HERA range for 2-fold ambiguity
- NLO calculation predicts a small down-turn from power law prediction at energies above ~ 300 GeV
  - 13 TeV data agrees well with NLO calculation

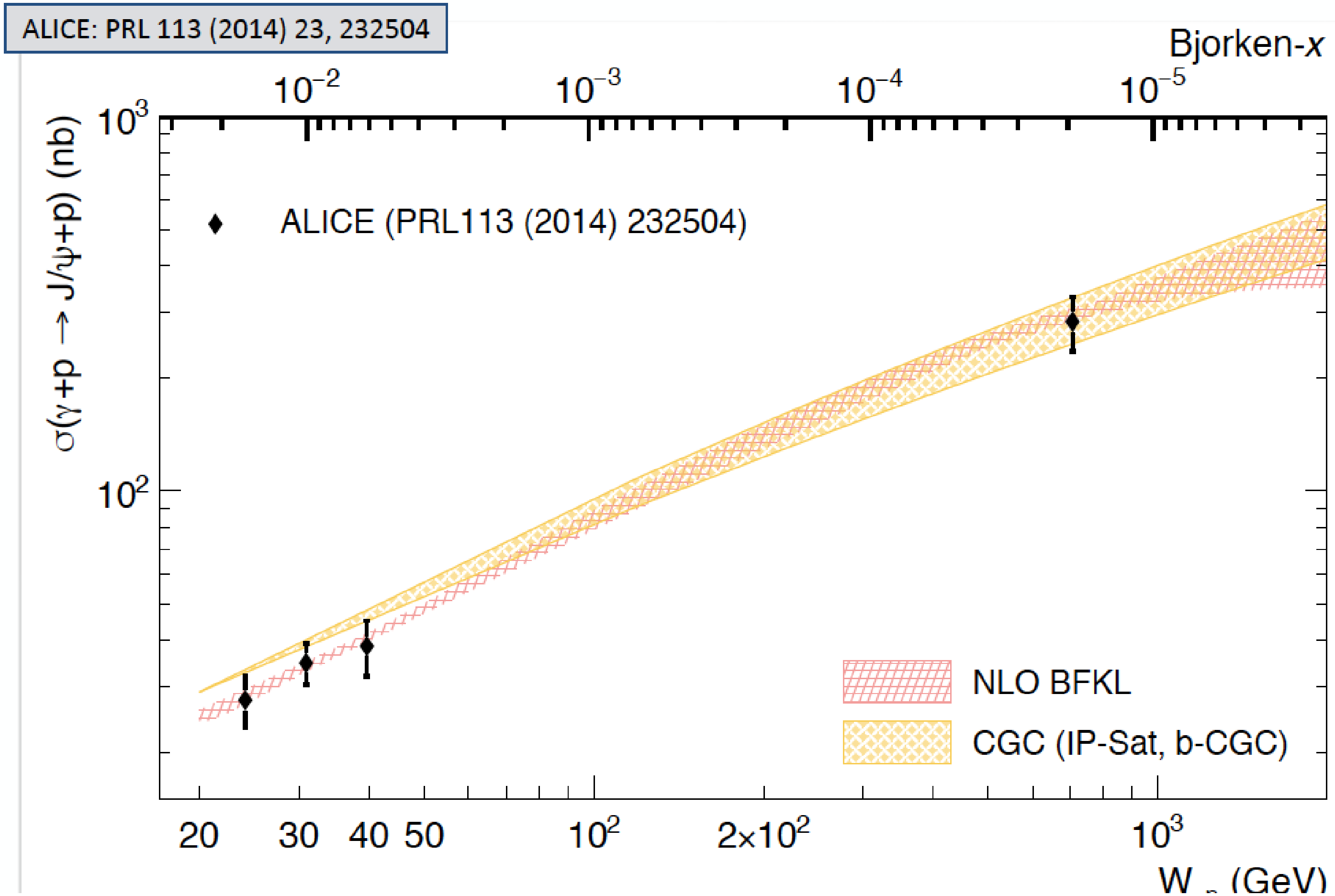




J. Adams [ALICE], DIS 2016; R. McNulty [LHCb] ICHEP 2016

power law exponent delta essentially unchanged down to x = 3*10^{-6}
no evidence yet for anomalous W dependence over full x range

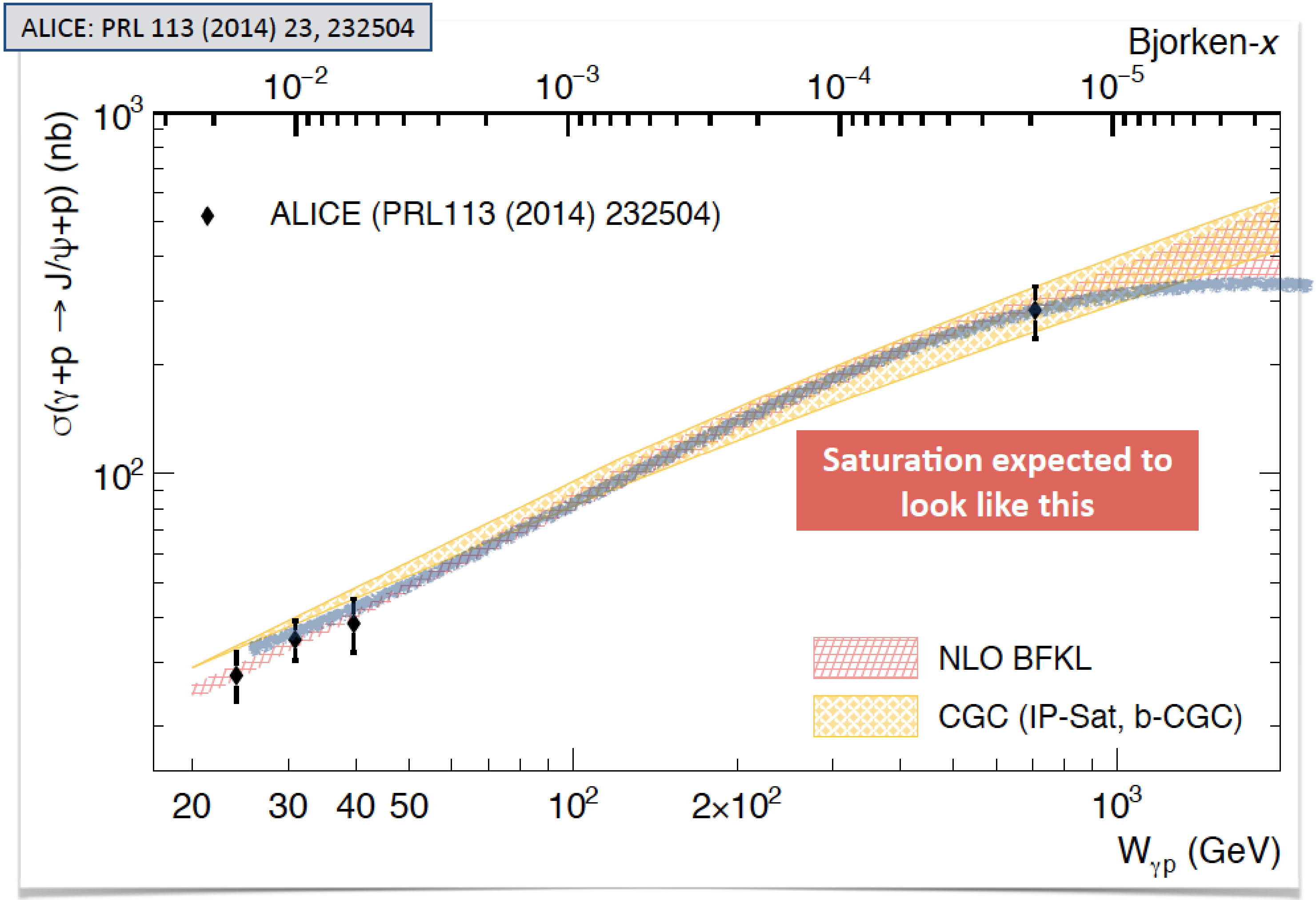
ALICE: PRL 113 (2014) 23, 232504



- ALICE data are also correctly described by recent calculations using:
  - CGC by Armesto and Rezaeian Phys.Rev. D90 (2014) 054003,
  - NLO BFKL by Bautista et el Phys.Rev. D94 (2016) 054002.

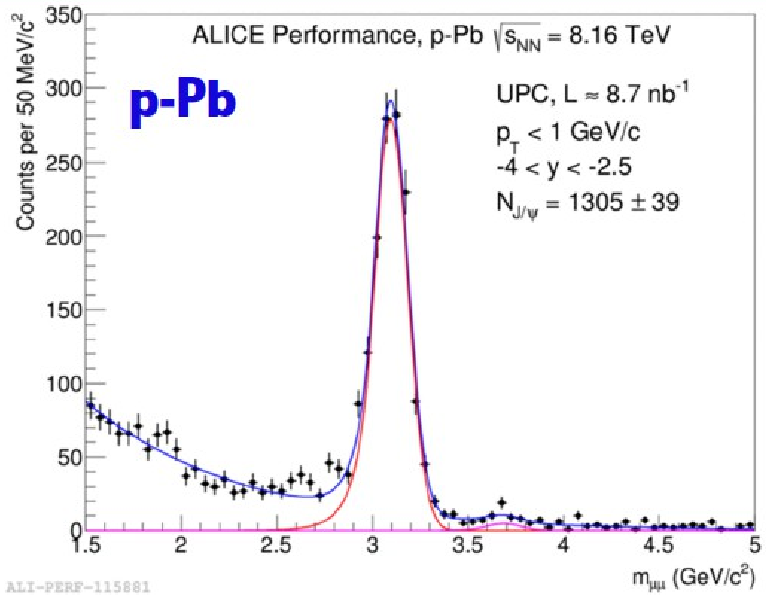
Figure from J.G. Contreras, EMMI workshop, Krakow, Poland, Sep. 2017

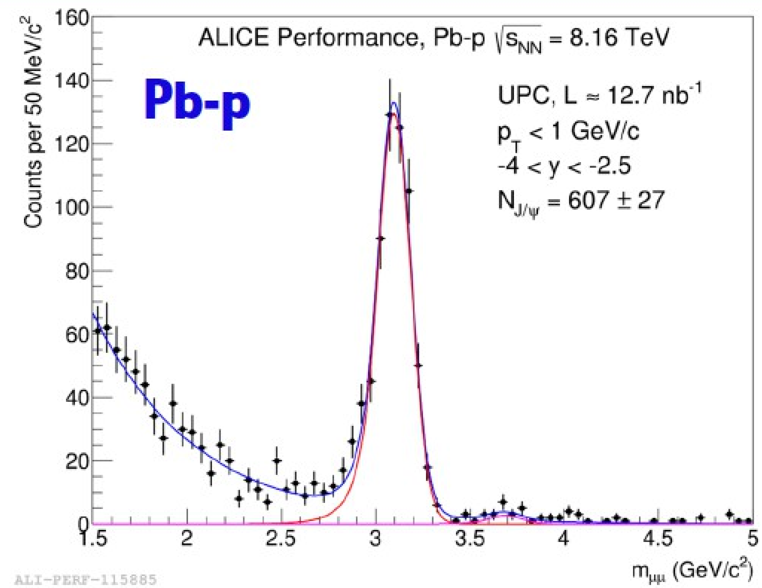
ALICE: PRL 113 (2014) 23, 232504



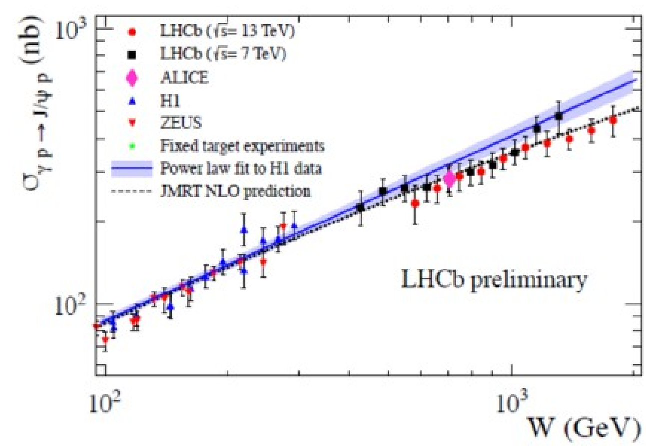
newest ALICE results, exploring $x = 3\ 10^{-6}$

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 $W_{\gamma p}$



Energy dependence of dissociative J/ψ photoproduction as a signature of gluon saturation at the LHC

J. Cepila, J.G. Contreras (Prague, Tech. U.),
J. D. Tapia Takaki (Kansas U.). Aug 26, 2016. 6 pp.

Published in Phys.Lett. B766 (2017) 186-191

... developed a model in which the quantum fluctuations of the proton structure are characterised by hot spots, whose number grows with decreasing Bjorken- x . model reproduces the F2(x,Q2) data from HERA at the relevant scale, as well as the exclusive and dissociative J/ψ photoproduction data from H1 and ALICE. model predicts that for $W\gamma p \approx 500$ GeV , the dissociative J/ψ cross section reaches a maximum and then decreases steeply with energy, which is in qualitatively good agreement to a recent observation that the dissociative J/ψ background in the exclusive J/ψ sample measured in photoproduction by ALICE decreases as energy increases.

signature for gluon saturation at LHC energies?

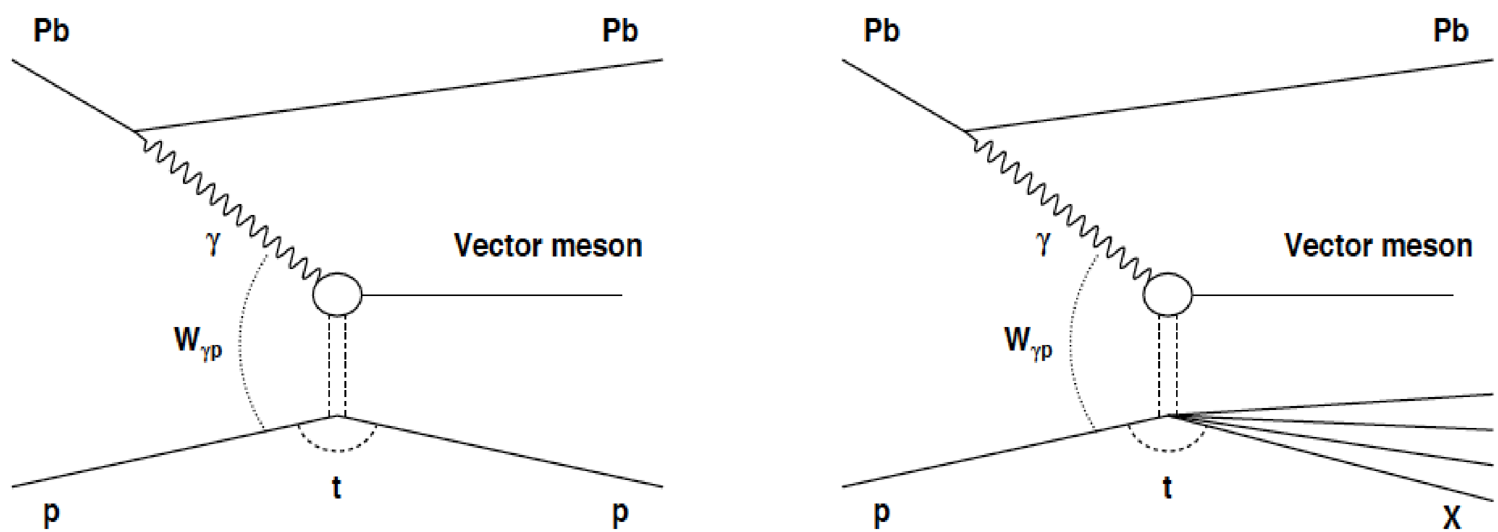


Figure 1: Diagrams for exclusive (left) and dissociative (right) vector meson photo-production. The source of photons is a lead nucleus as in p-Pb collisions at the LHC. For the case of HERA, the source of photons was either an electron or a positron.

the model

the color dipole interacts with the nucleus according to the Golec-Biernat/Wuesthoff 'saturation model

$$N(x, r, b) = \sigma_0 N(x, r) T(\vec{b})$$

$$N(x, r) = \left(1 - e^{-r^2 Q_s^2(x)/4}\right),$$

with the saturation scale given by

$$Q_s^2(x) = Q_0^2 (x_0/x)^\lambda,$$

new approach: the proton profile function T(b) contains regions of 'hot spots' which are introduced according to:

$$N_{hs}(x) = p_0 x^{p_1} (1 + p_2 \sqrt{x})$$

this x dependence introduces an implicit W dependence!

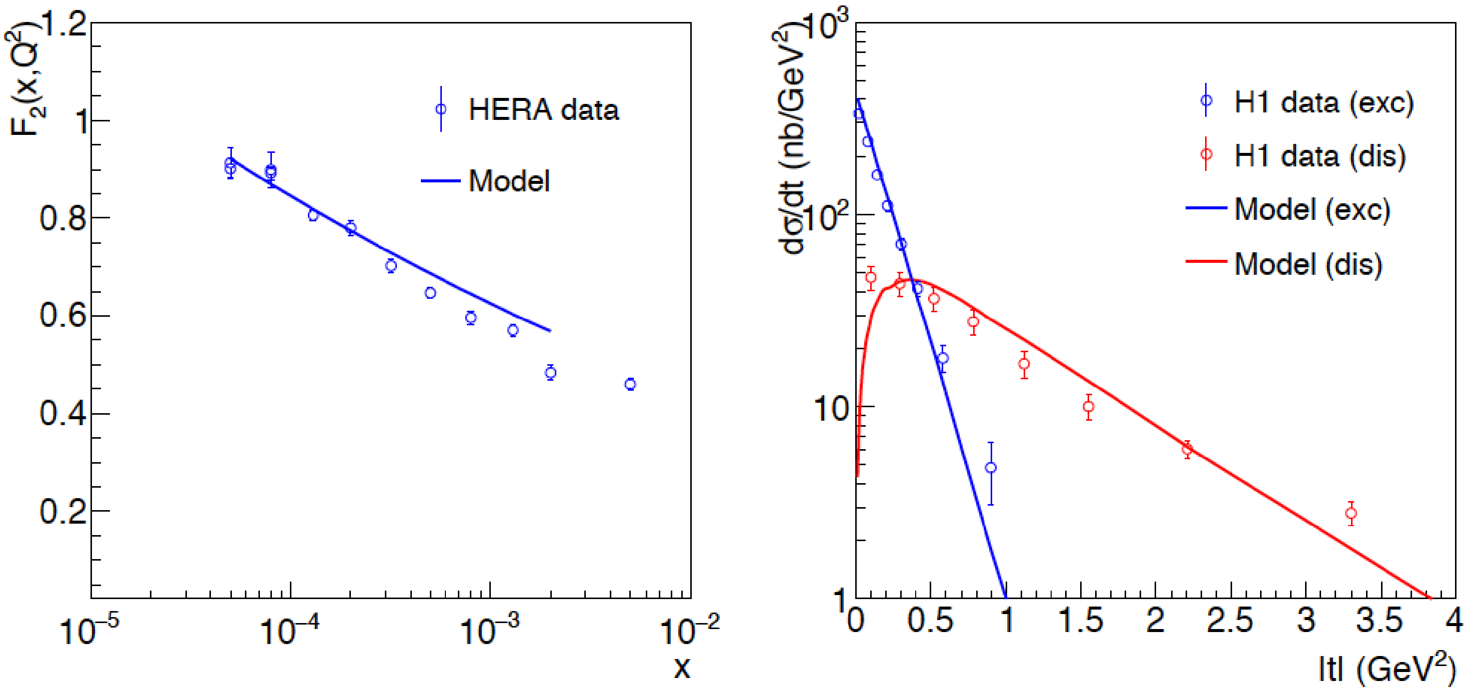


Figure 2: Comparison of the model (solid lines) to data (open bullets) on (left) the structure function of the proton $F_2(x, Q^2)$ at $Q^2 = 2.7$ GeV^2 as measured by H1 and Zeus [26] and (right) the $|t|$ distribution of exclusive (blue) and dissociative (red) photoproduction of J/ψ as measured by H1 [11] at $\langle W_{\gamma\mathrm{p}}\rangle = 78$ GeV.

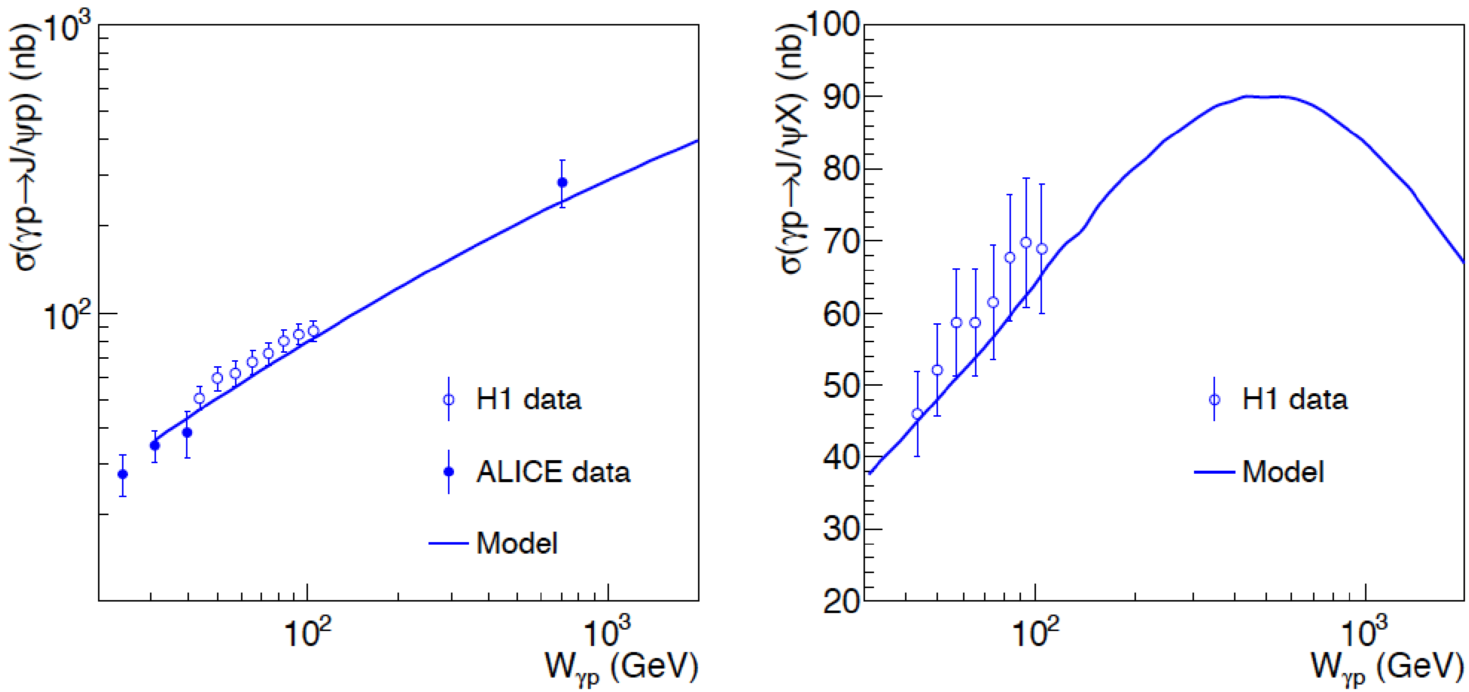
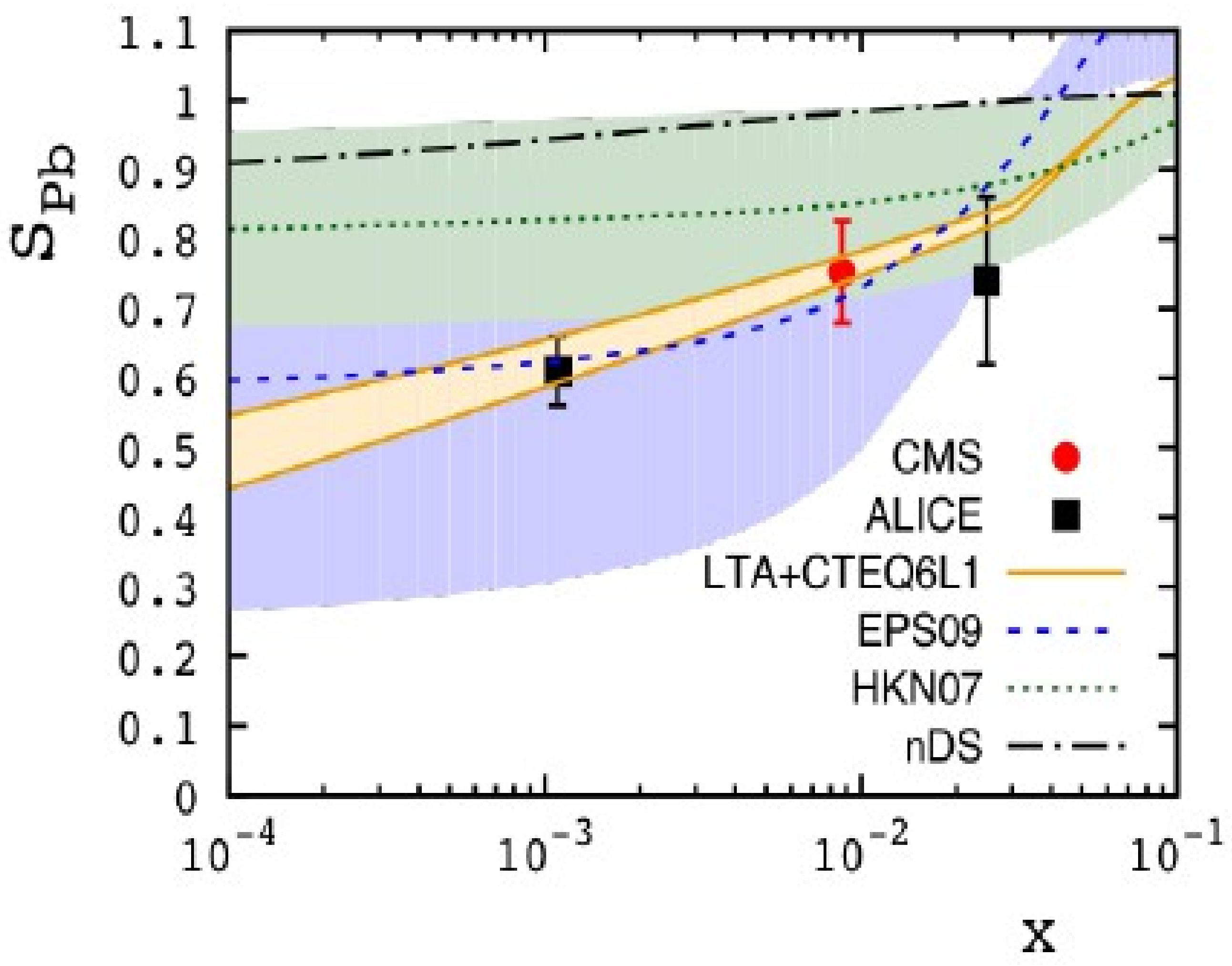


Figure 3: Comparison of the model (solid lines) to data on the $W_{\gamma p}$ dependence of the cross section for exclusive (left) and dissociative (right) photoproduction of J/ψ as measured by H1 [11] and ALICE [6] (open and solid bullets, respectively).

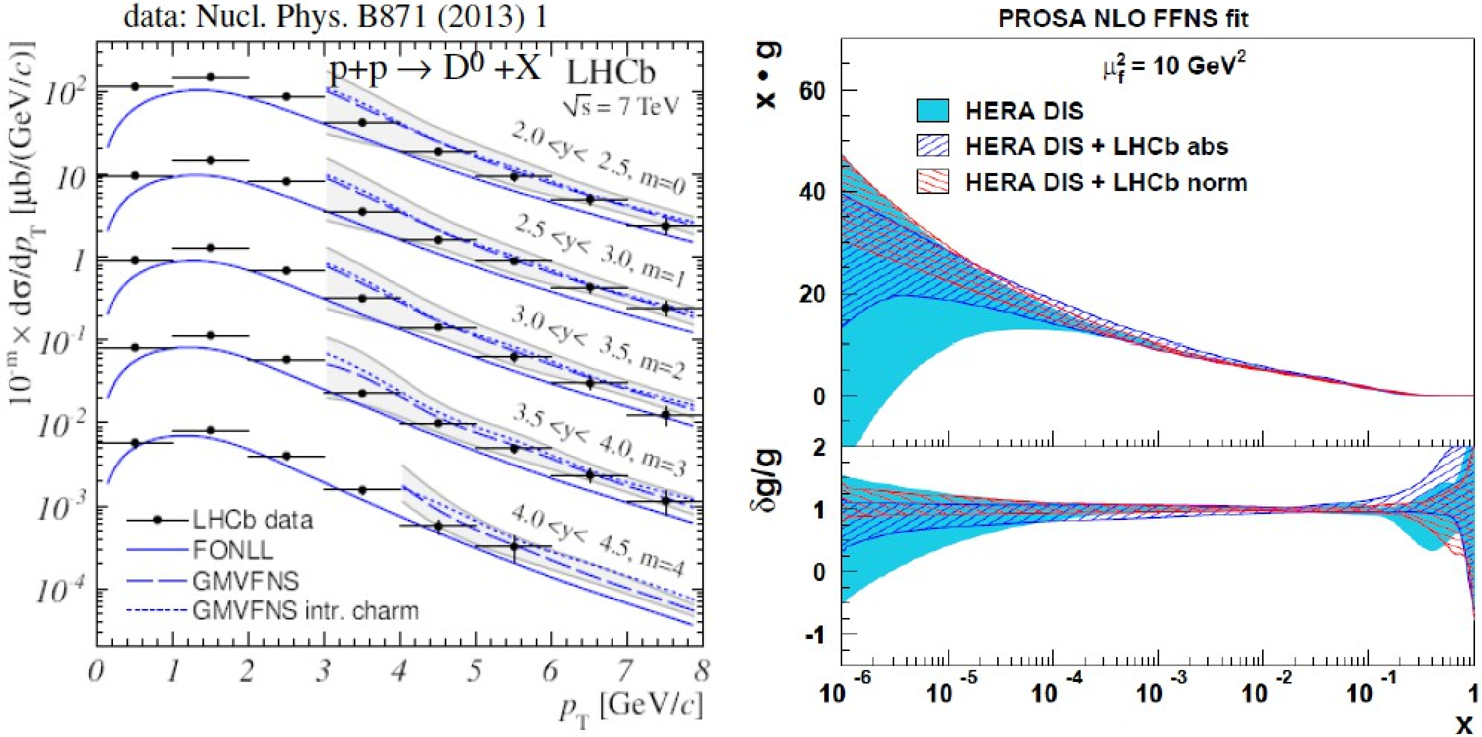
observation of this peak would be, in this model, a consequence of saturation – is this unique?

Shadowing extracted from J/psi production in UPC Pb-Pb vs pp



Results constrain EPS09 shadowing calculations and agree with recent leading twist (LTA) calculations. Fig. Taken from Vadim Guzey V. Guzey and M. Zhalov, JHEP **1310**, 207 (2013)

precision measurement of open charm production by LHCb measurement at forward rapidity provides input on low-x gluon PDFs



for a recent summary of data and pQCD predictions see:
Guzzi, Geiser, Rizatdinova, 1509.04582 and Beraudo, 1509.04530
additional constraint of gluon PDF in particular at low x (down to 5 10^{-6})

new analysis by Gauld, Rojo and Slate, arXiv:1705.04217

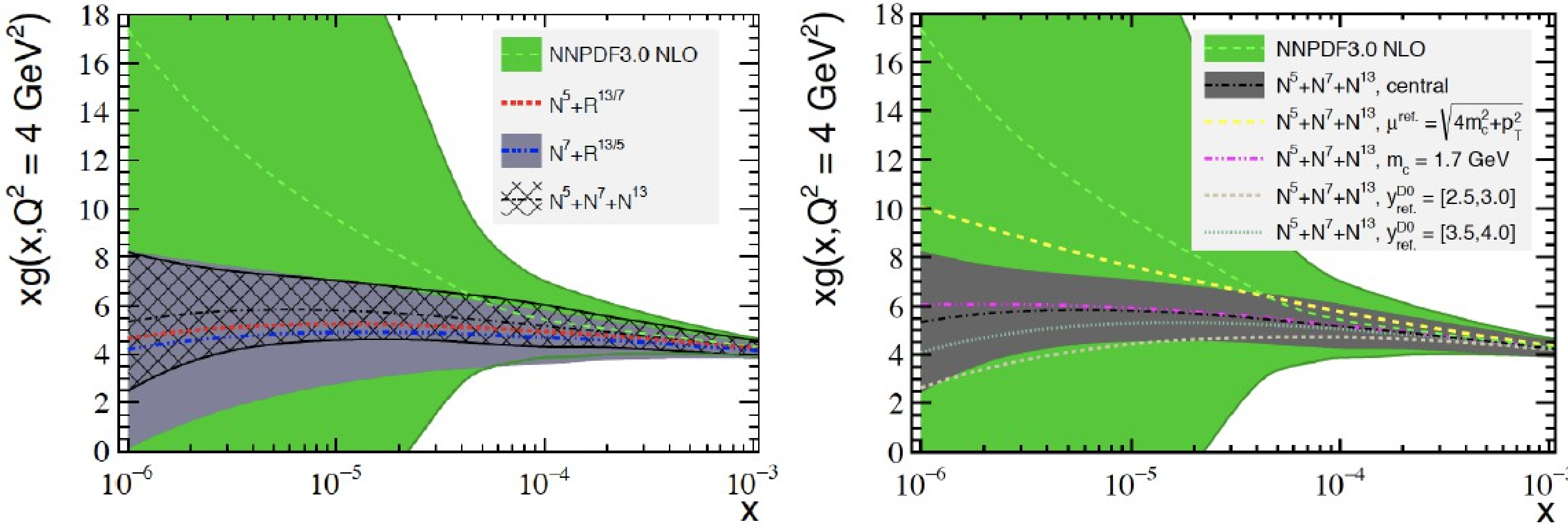


Figure 1: Left plot: the small-x gluon PDF in NNPDF3.0 compared with the results when various combinations of LHCb D meson production data are included in the fit. Right plot: the impact of variations of the input theoretical settings in the $N^5+N^7+N^{13}$ NNPDF3.0+LHCb fit.

good constraints down to x = 10^{-6} by analysis of LHCb pp ► D at 5, 7, 13 TeV data

outlook

no clear signatures for saturation effects in present LHC data

data consistent with phenomenology established at HERA

down to $x \sim 10^{-5}$ but analysis not model independent

next steps:

- psi' and Y production
- dissociative charmonium production
- forward production of direct photons
- open charm
- forward jet production....

huge increase in statistics expected for Run3 backup slides

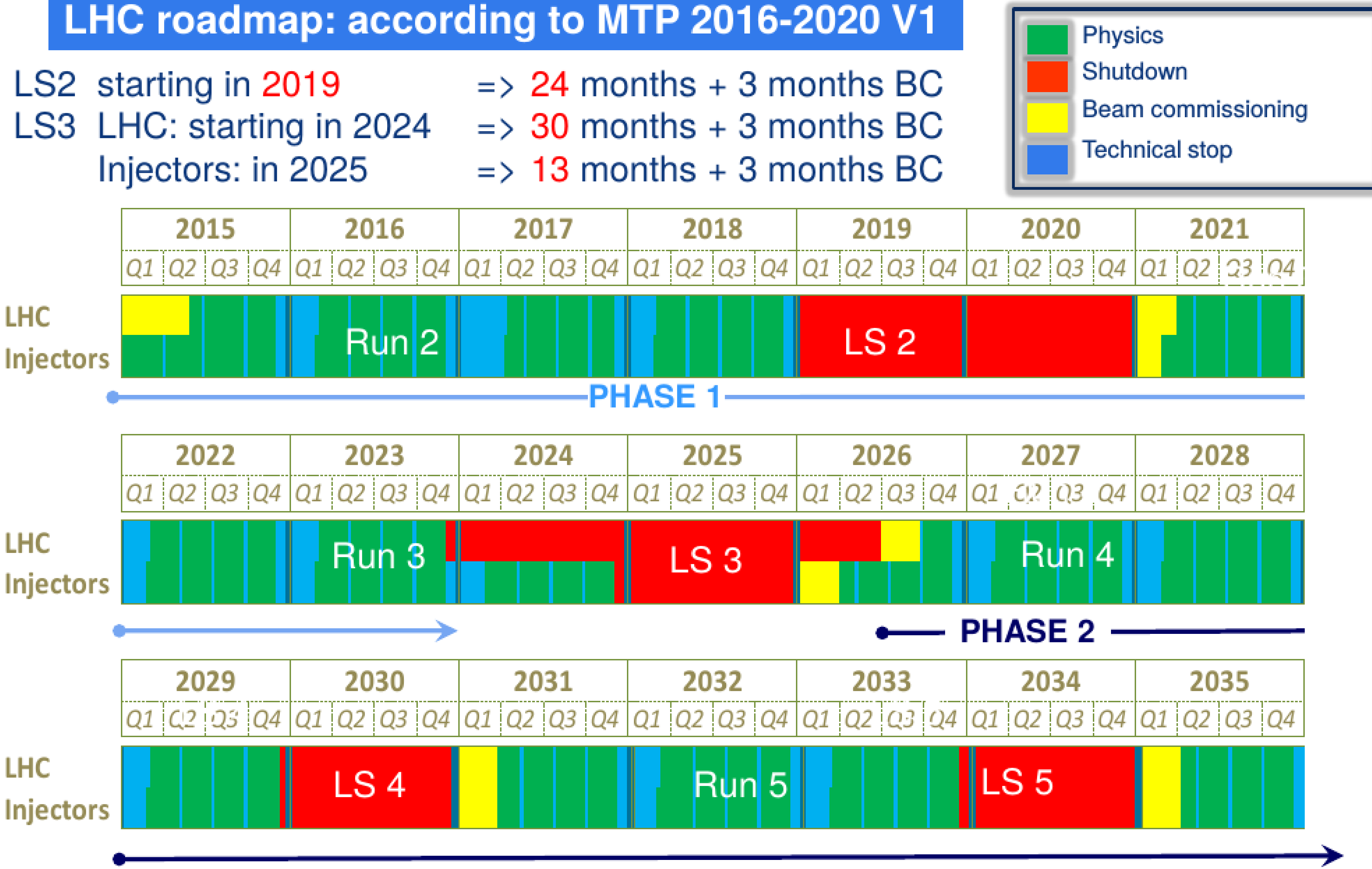
LHC ion program for Run3 and Run4

Main conclusion of the '2013 European Strategy for Particle Physics' process

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics ***and the quark-gluon plasma."***

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



approved ALICE program up to and including LHC Run4

ALICE Upgrade Strategy

High precision measurements of rare probes at low $p_{T,}$ which cannot be selected with a trigger, require a large sample of events recorded on tape

Target

- Pb-Pb recorded luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events
- pp (@5.5 Tev) recorded luminosity $\geq 6\ pb^{-1}$ ➡ 1.4×10^{11} events

Gain a factor **100** in statistics over approved programme

... and significant improvement of vertexing and tracking capabilities

I. Upgrade the ALICE readout systems and online systems to

- read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6 \times 10^{27}\ cm^{-1}s^{-1}$), with a minimum bias trigger → NEW GEM TPC Readout Planes
- Perform online data reduction based on reconstruction of clusters and tracks (tracking used only to filter out clusters not associated to reconstructed tracks)

II. Improve vertexing and tracking at low p_T ➔ NEW ITS

ALICE upgrade: main physics topics for Run3 and Run4

rare probes at low p_T:

- heavy flavor hadrons
- quarkonia
- di-leptons at low and intermediate mass
- light anti-matter and exotic clusters
- jet physics
- event-by-event fluctuations of conserved quantum numbers
- ultra-peripheral collisions , low x physics, photon-photon collisions