Photon-nucleus collisions at the LHC

Daniel Tapia Takaki
The University of Kansas

APS GHP workshop
Baltimore, April 10, 2015

Plan of this talk

Ultra-**P**eripheral (pp, pA and AA) **C**ollisions

- What are UPCs
- Why at LHC

Recent results

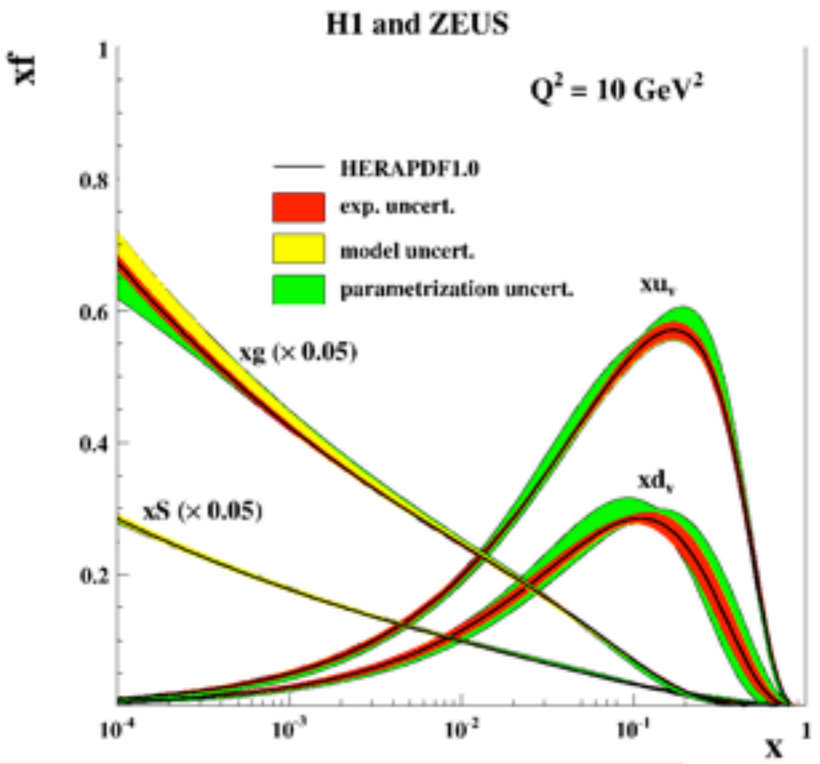
Future directions

Forward HI physics

the nature of the initial state is one of the most important questions in relativistic heavy-ion physics.

UPCs are cleaner probes of nPDFs

Low-x regime dominated by gluons



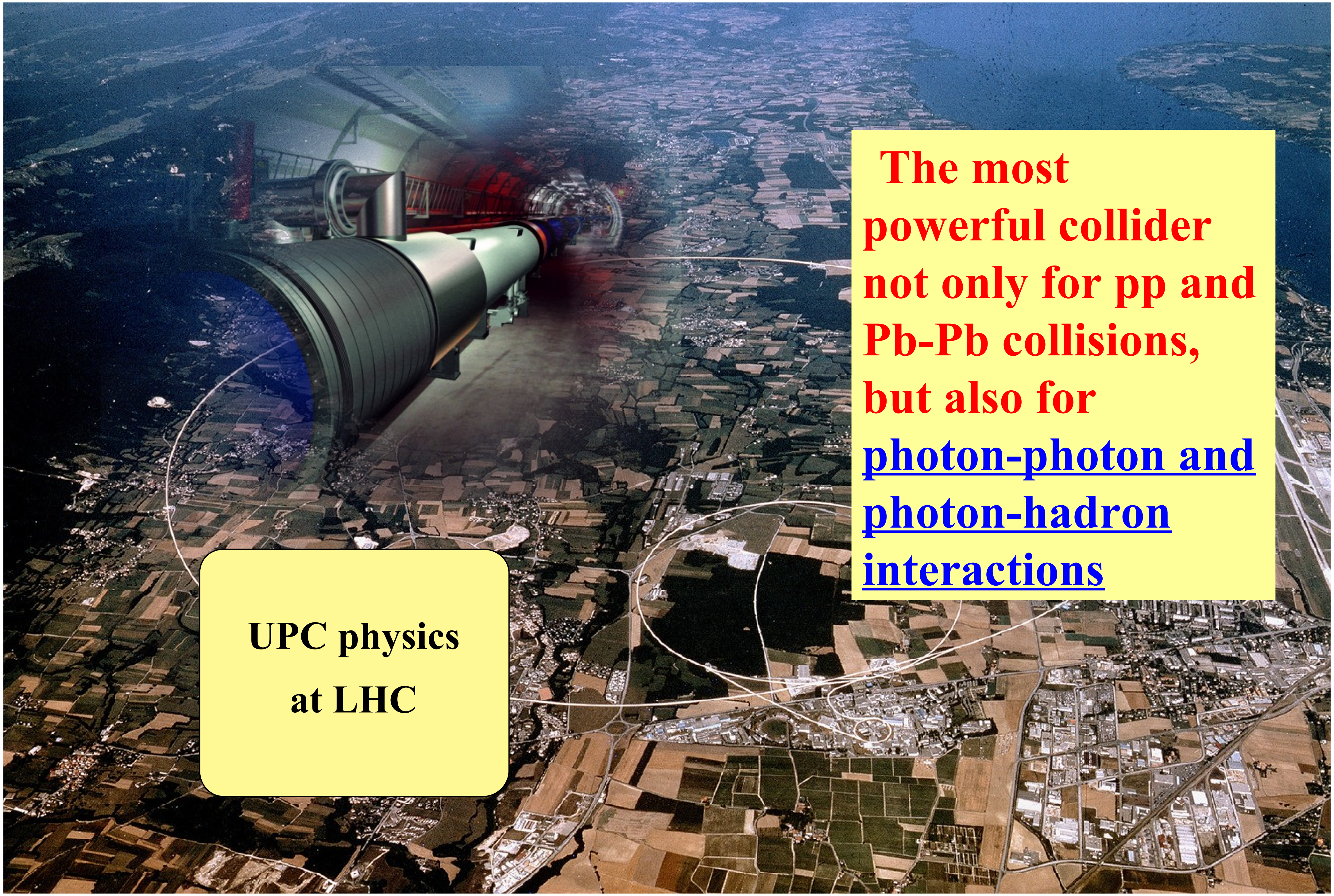
UPC at LHC can be seen as the precursor of part of the EIC physics

UPC described in the two recent White Papers:

EIC white paper: arXiv:1212.1701 [nucl-ex]

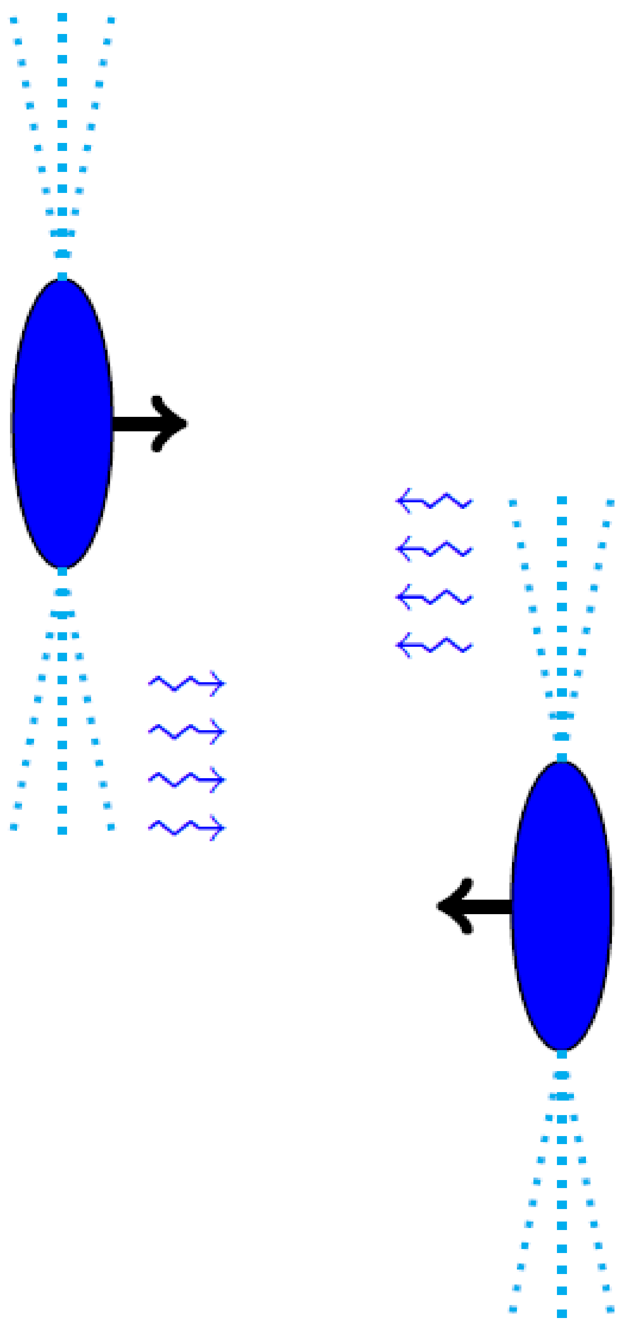
HI White paper: arXiv:1502.02730 [nucl-ex]

Using the LHC as a $\gamma\gamma$, γPb, γp collider



UPCs in Pb-Pb

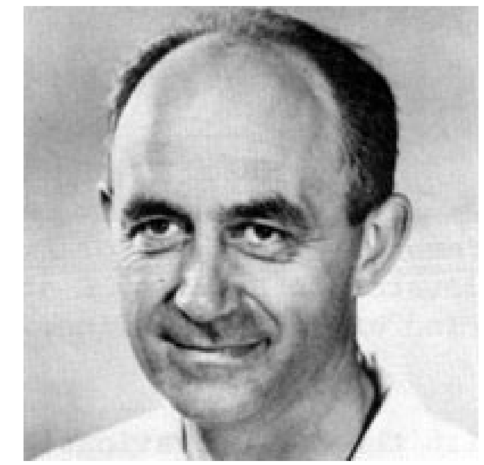
Why Ultra-Peripheral collisions



Nuovo Cim.,2:143-158,1925

http://arxiv.org/abs/hep-th/0205086

Therefore, we consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.



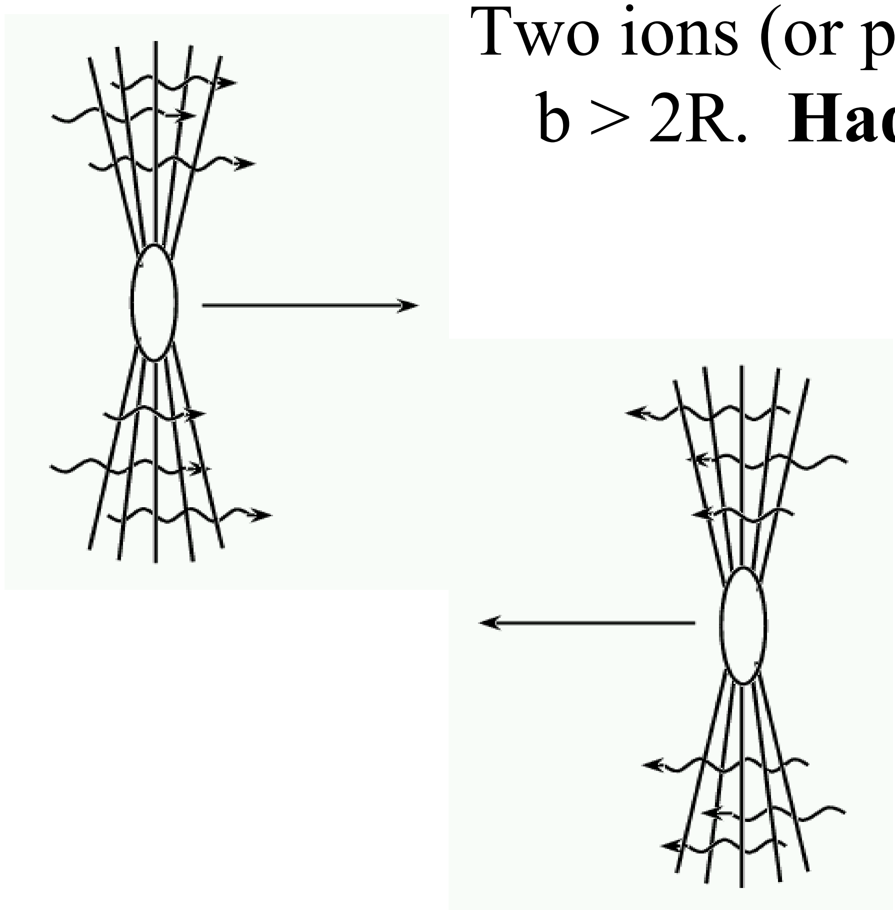
Enrico FERMI

The electromagnetic field surrounding these protons/ions can be treated as a beam of quasi real photons

High photon flux ~ Z^2
→ well described by the Weizsäcker-Williams approximation

Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

Why ultra-peripheral heavy-ion collisions

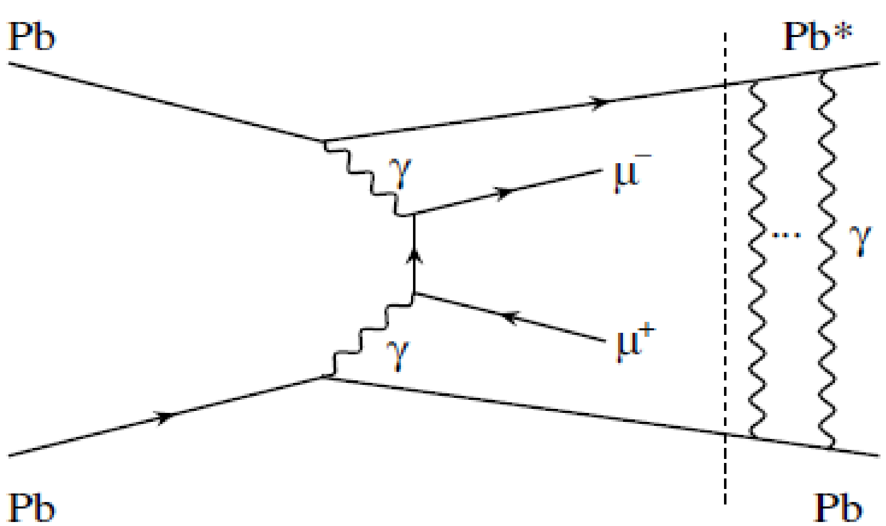


Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

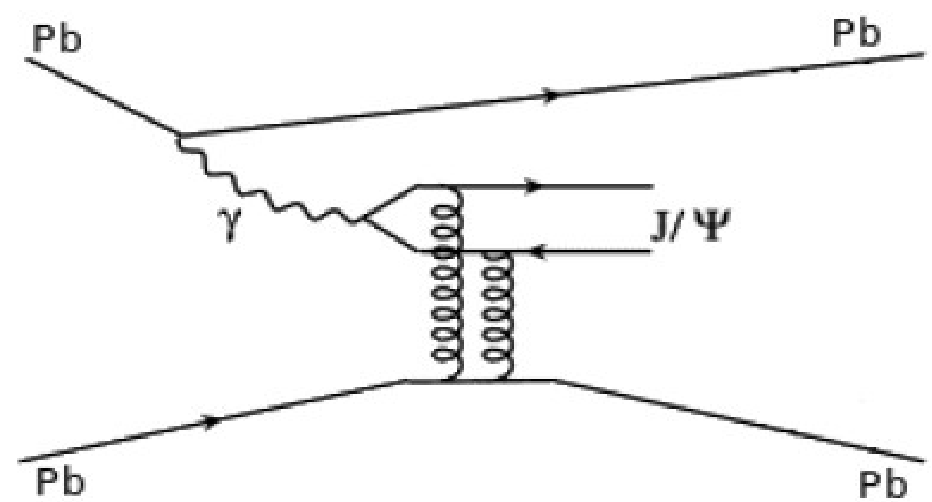
Number of photons scales like Z^2 for a single source ⇒ exclusive particle production in heavy-ion collisions dominated by electromagnetic interactions.

The virtuality of the photons → 1/R ~ 30 MeV/*c*

Photon-induced reactions



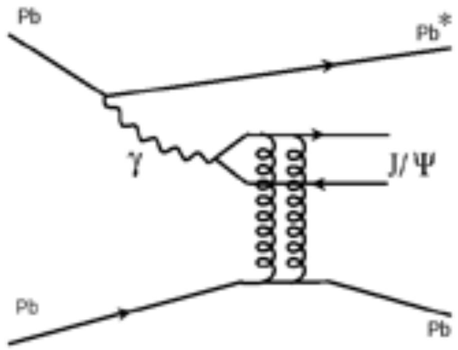
Two-photon production



γ + p → J/ψ + p

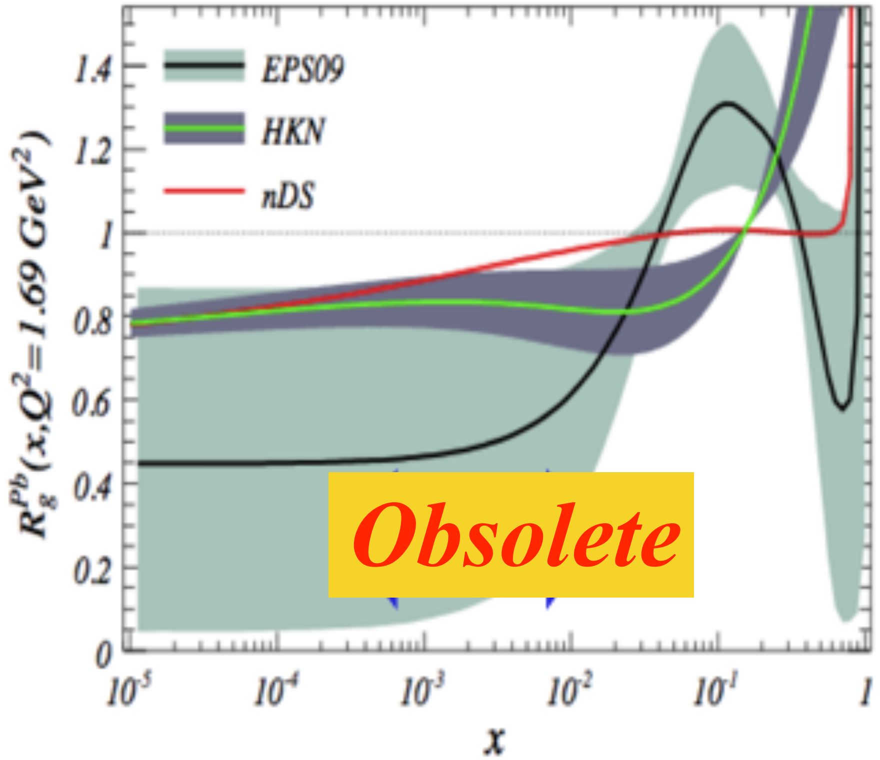
modelled in pQCD: exchange of two gluons with no net-colour transfer

UPC Quarkonia Probe Nuclear Glue



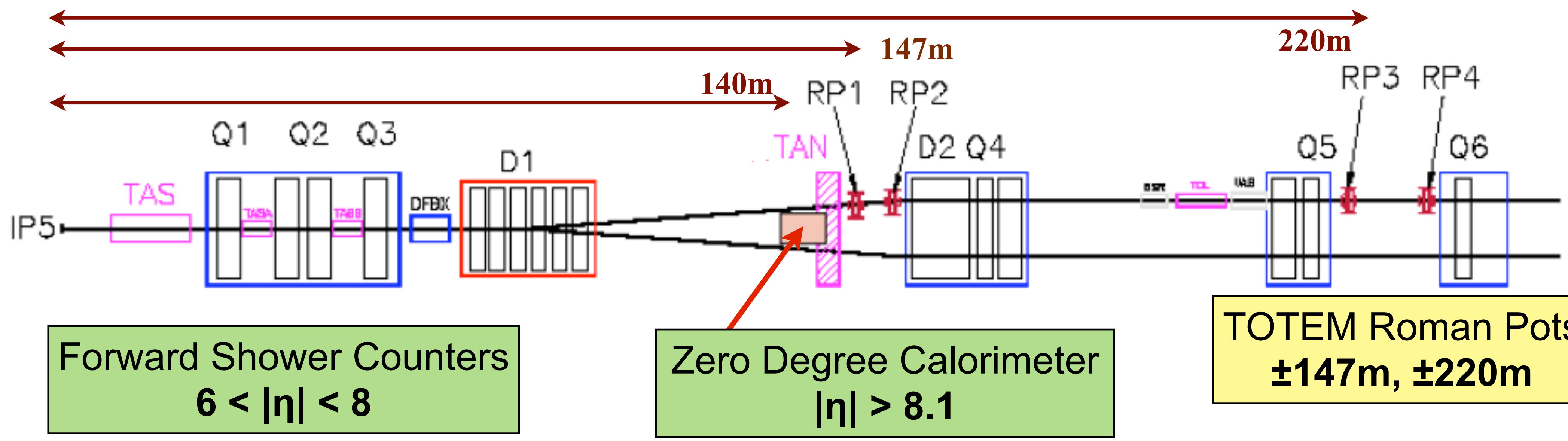
$$\left.\frac{d\sigma_{\gamma A\to J/\Psi A}}{dt}\right|_{t=0} = \xi_{J/\Psi}\left(\frac{16\pi^3\alpha_s^2\Gamma_{l^+l^-}}{3\alpha M_{J/\Psi}^5}\right)[xG_A(x,\mu^2)]^2$$

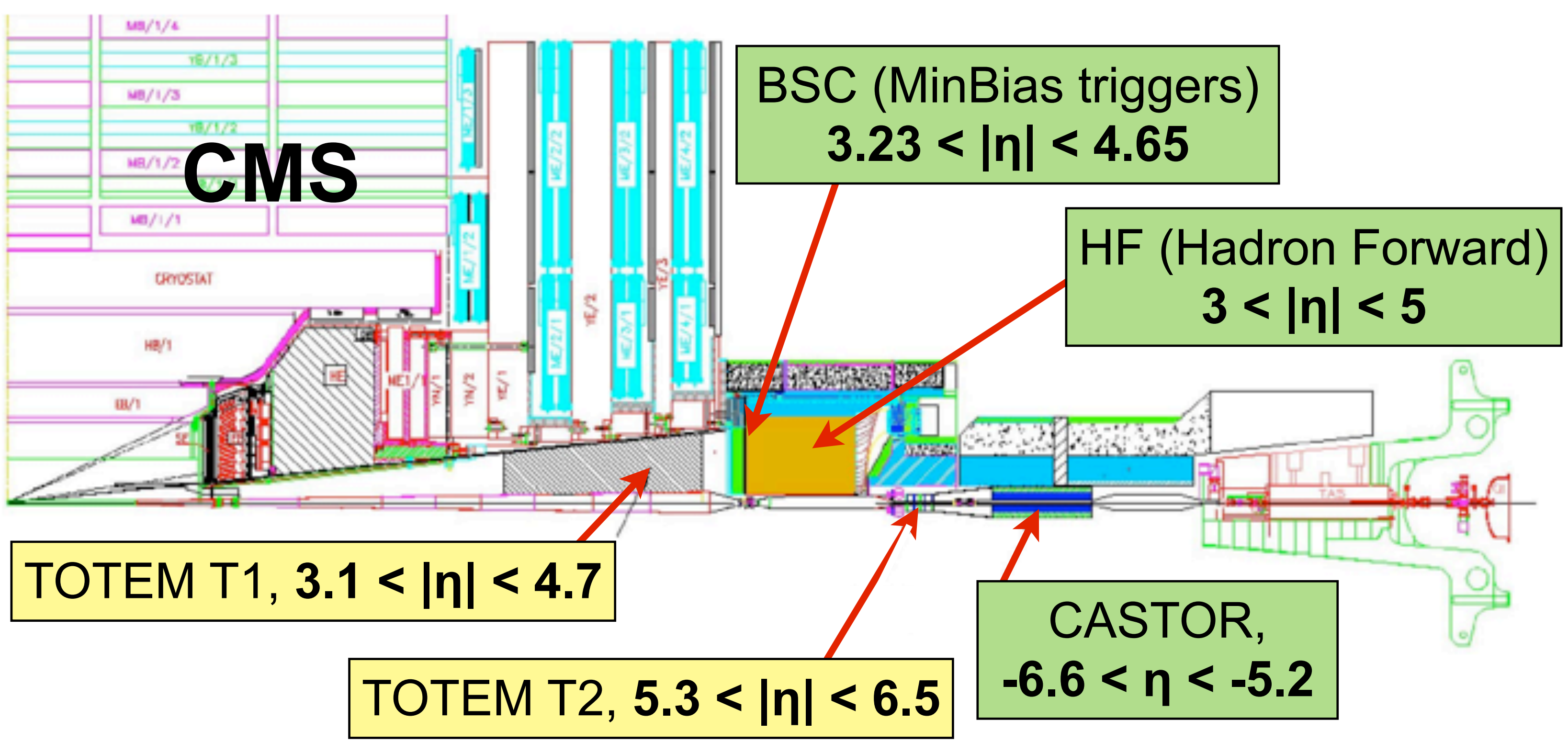
The ultra-peripheral coherent J/ψ photoproduction cross section depends on the **nuclear gluon density squared**

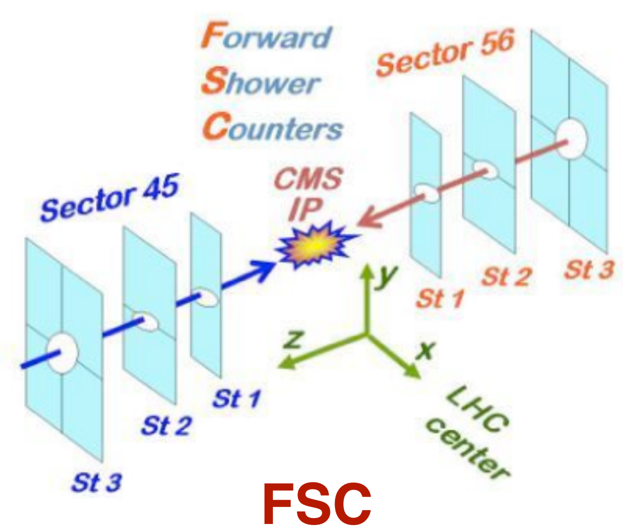


C. A. Salgado et al 2012 J. Phys . G : Nucl. Part. Phys . 39 015010

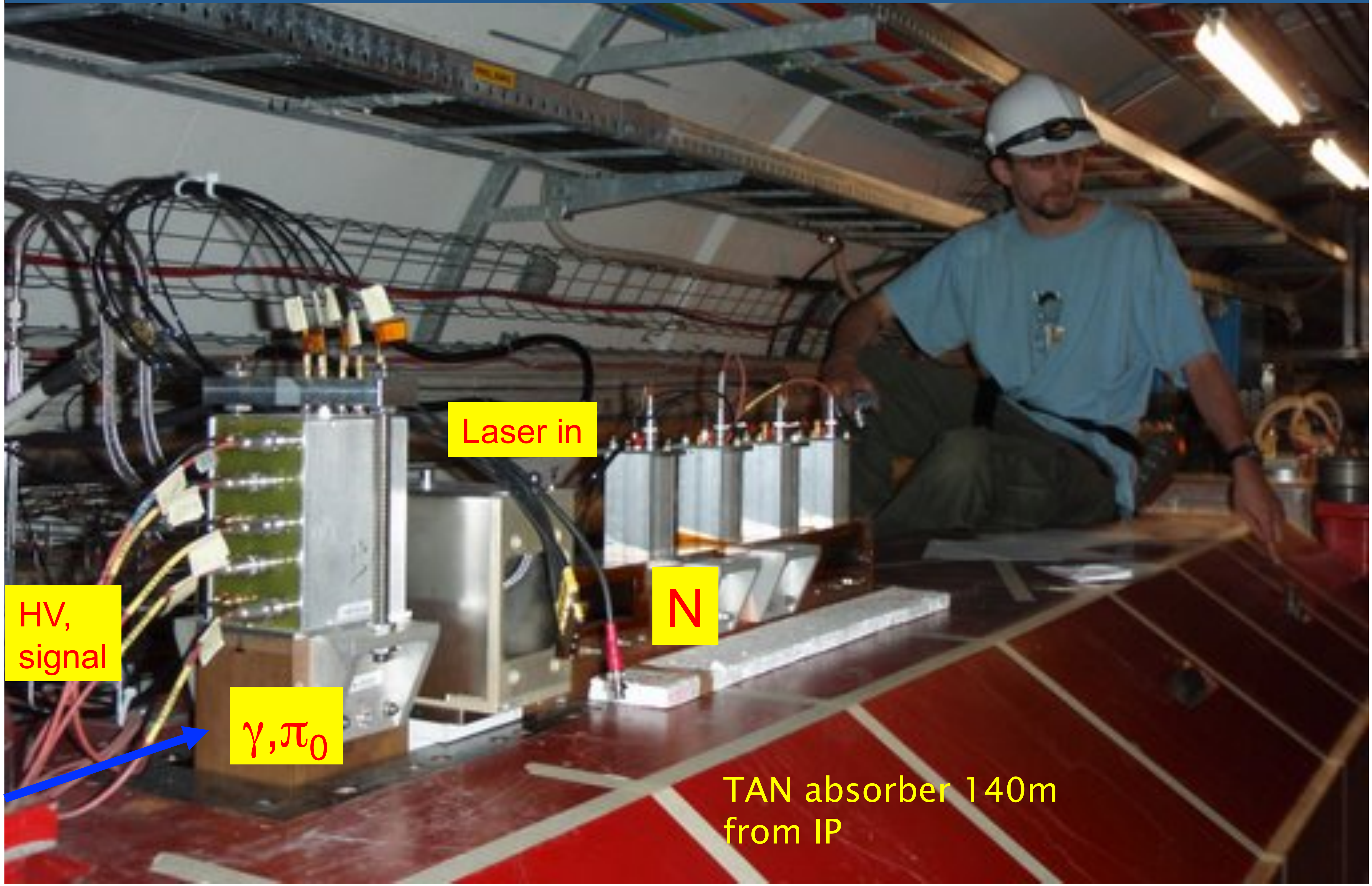
Forward detectors at CMS



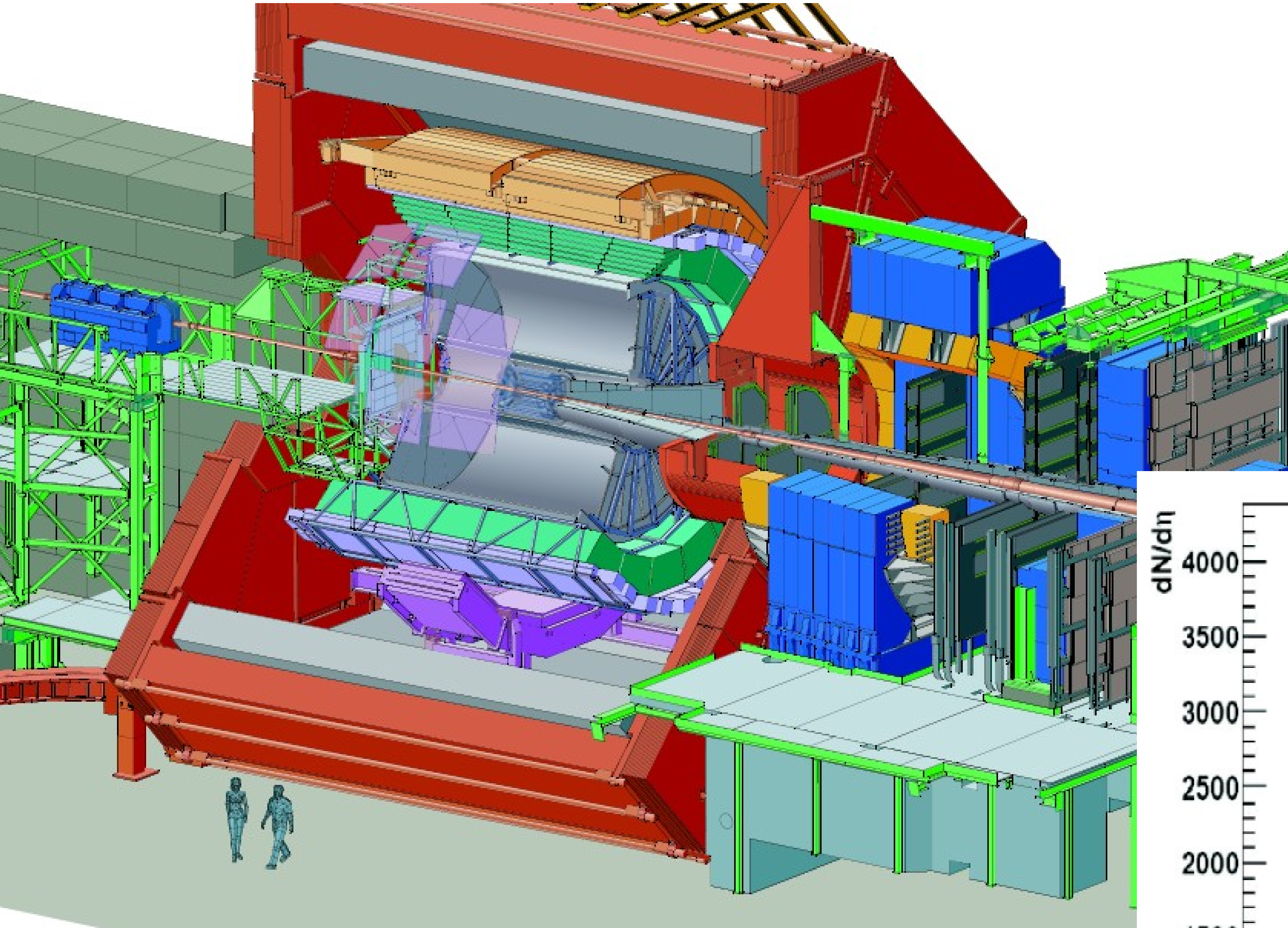




Zero Degree Calorimeters



The ALICE experiment at LHC



Central rapidity

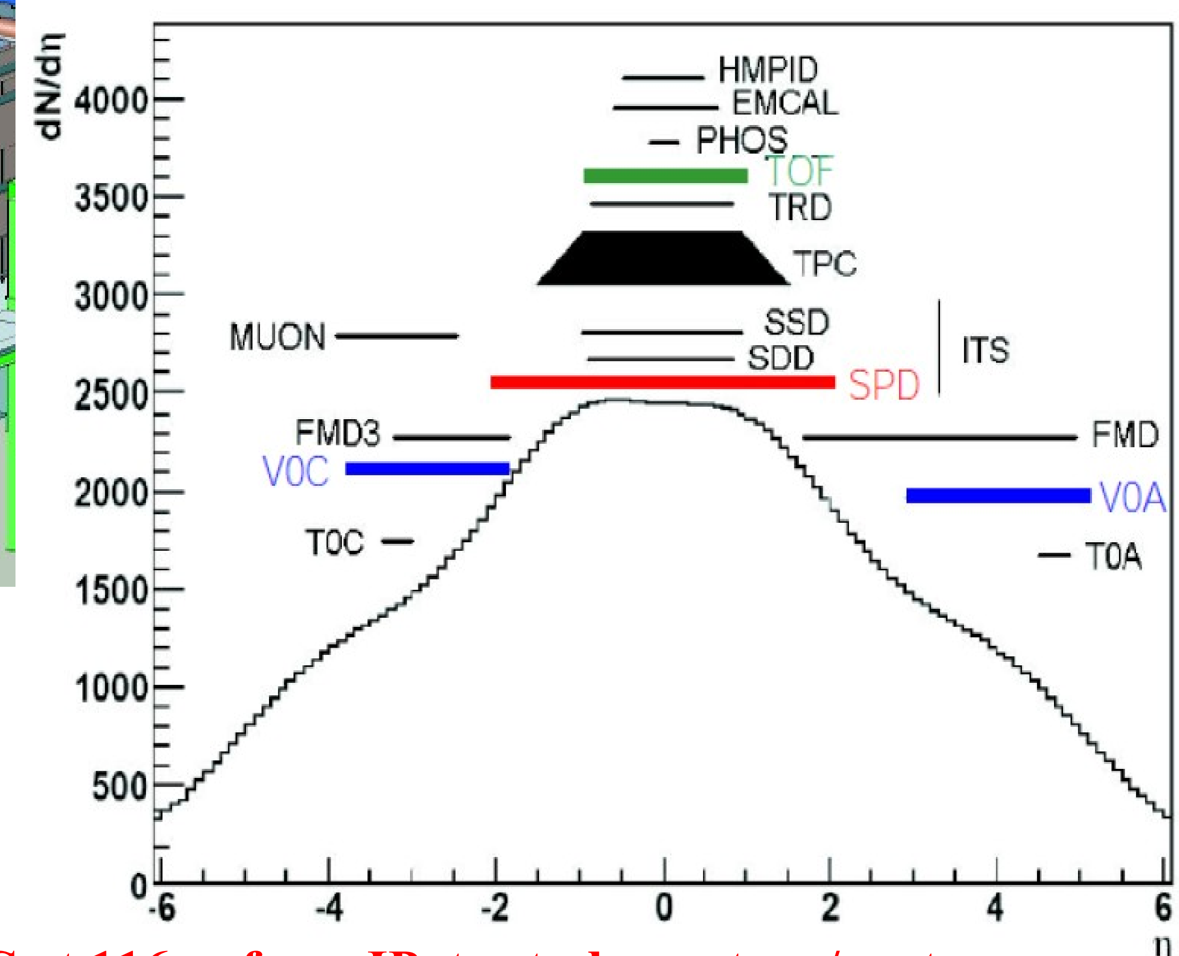
Inner Tracking (ITS), Time Projection Chamber (TPC), Time-of-Flight, TRD, EMCAL

$|\eta| < 0.9$

Forward rapidity

Muon Spectrometer

$-4 < \eta < -2.5$

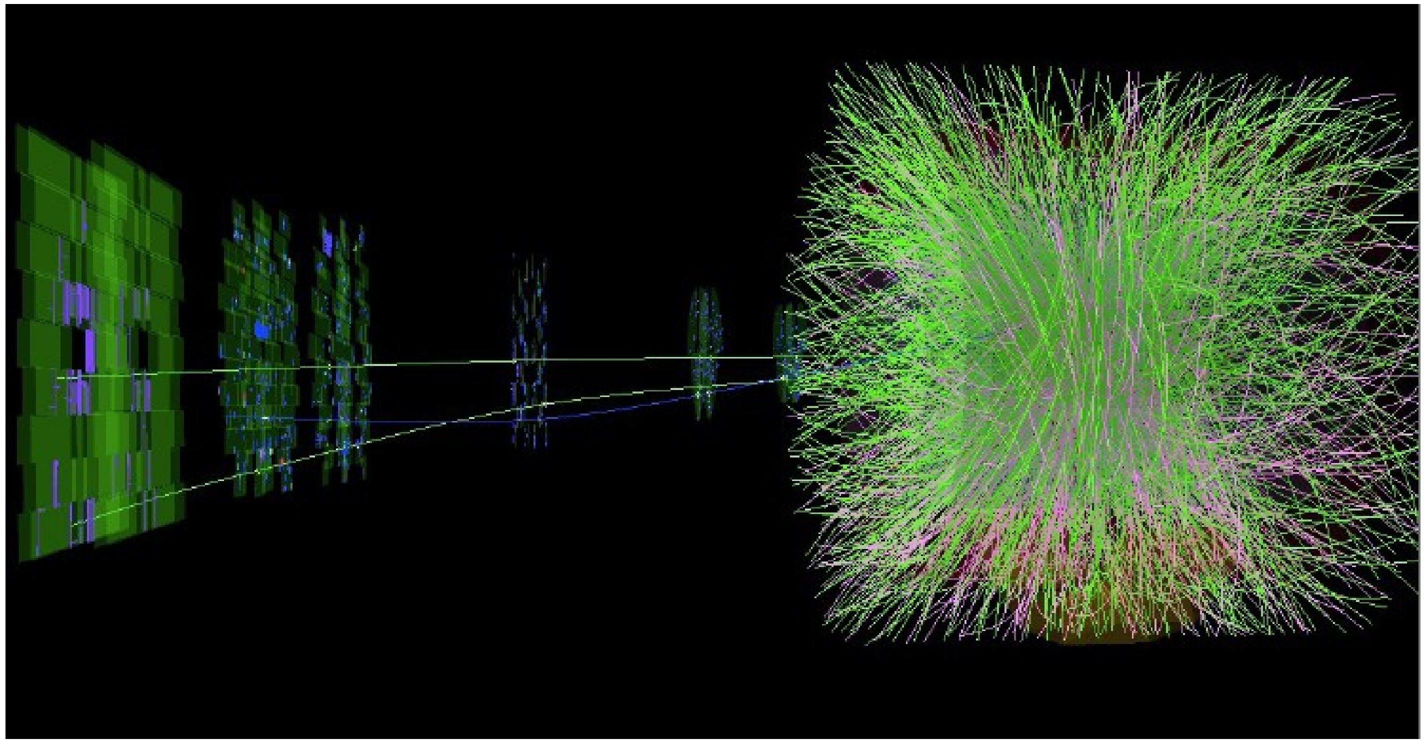


Dedicated triggers for UPC, using VZERO forward detectors for vetoing And MUON, TOF and SPD

ALICE can measure J/ψ mesons down to zero p_T

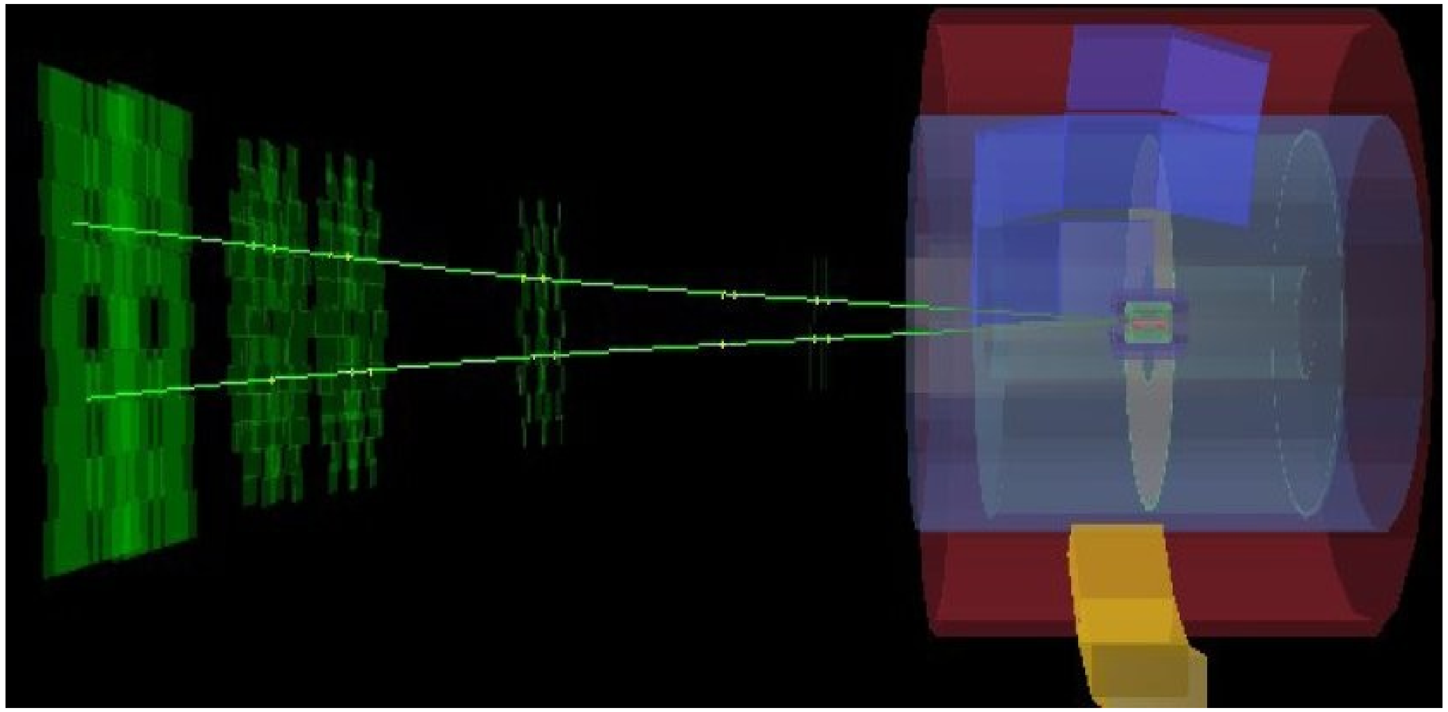
ZDC at 116 m from IP, to study neutron/proton emitted at the very forward region

Exclusive J/ψ analysis at **forward rapidity**



From a typical inclusive J/ψ candidate in Pb-Pb collisions...

....to an exclusive J/ψ candidate

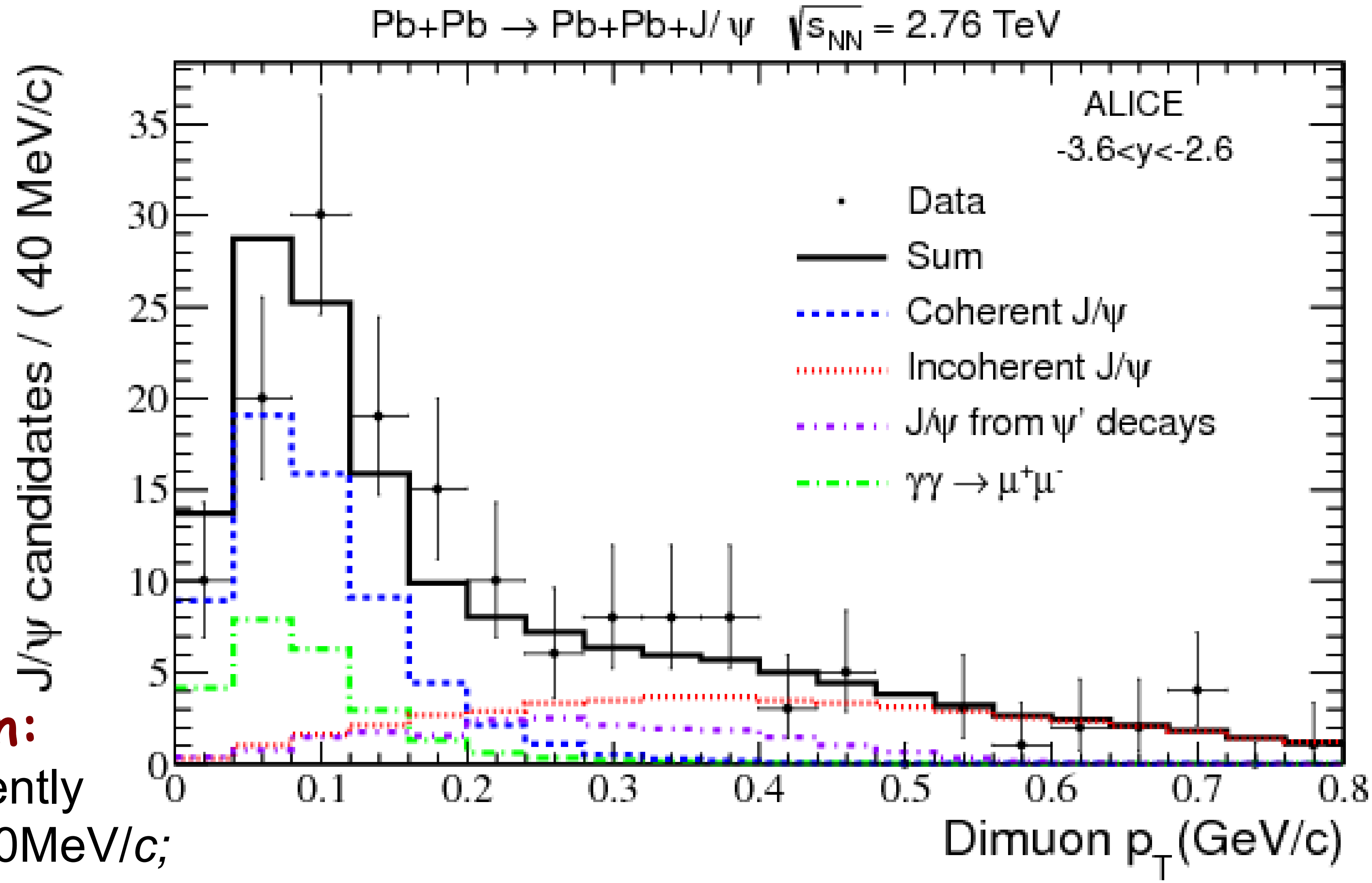


Two UPC publications by ALICE

Phys.Lett. B718 (2013) 1273-1283

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

p_T distribution for J/ψ candidates



Coherent production:

Photon couples coherently to all nucleons $\langle p_T \rangle$~60MeV/*c*;

target nucleus does not break up, in most cases

Incoherent production

Photon couples to a single nucleon

Quasi-elastic scattering off a single nucleon

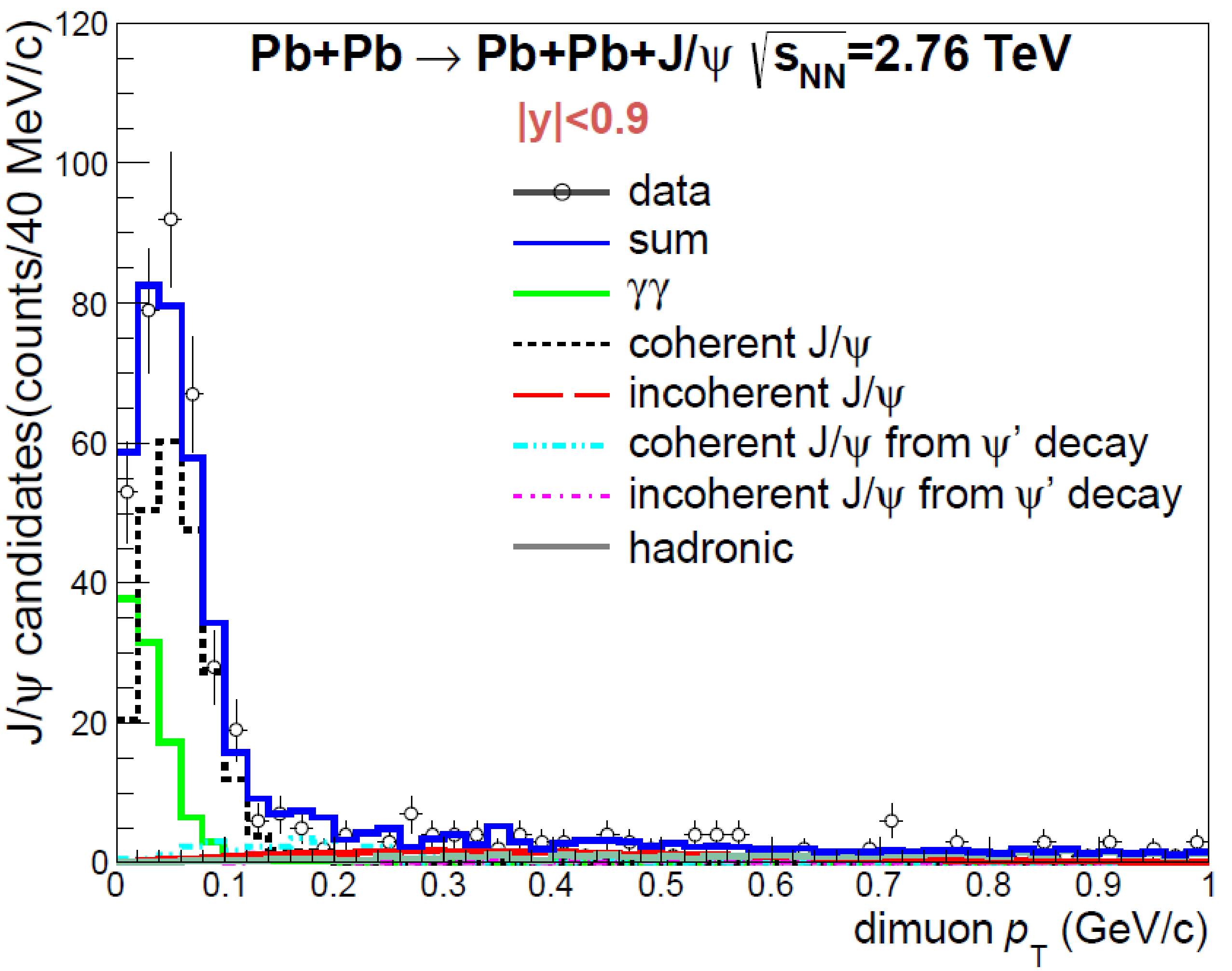
$\langle p_T \rangle$~500 MeV/*c*

Four physics processes:

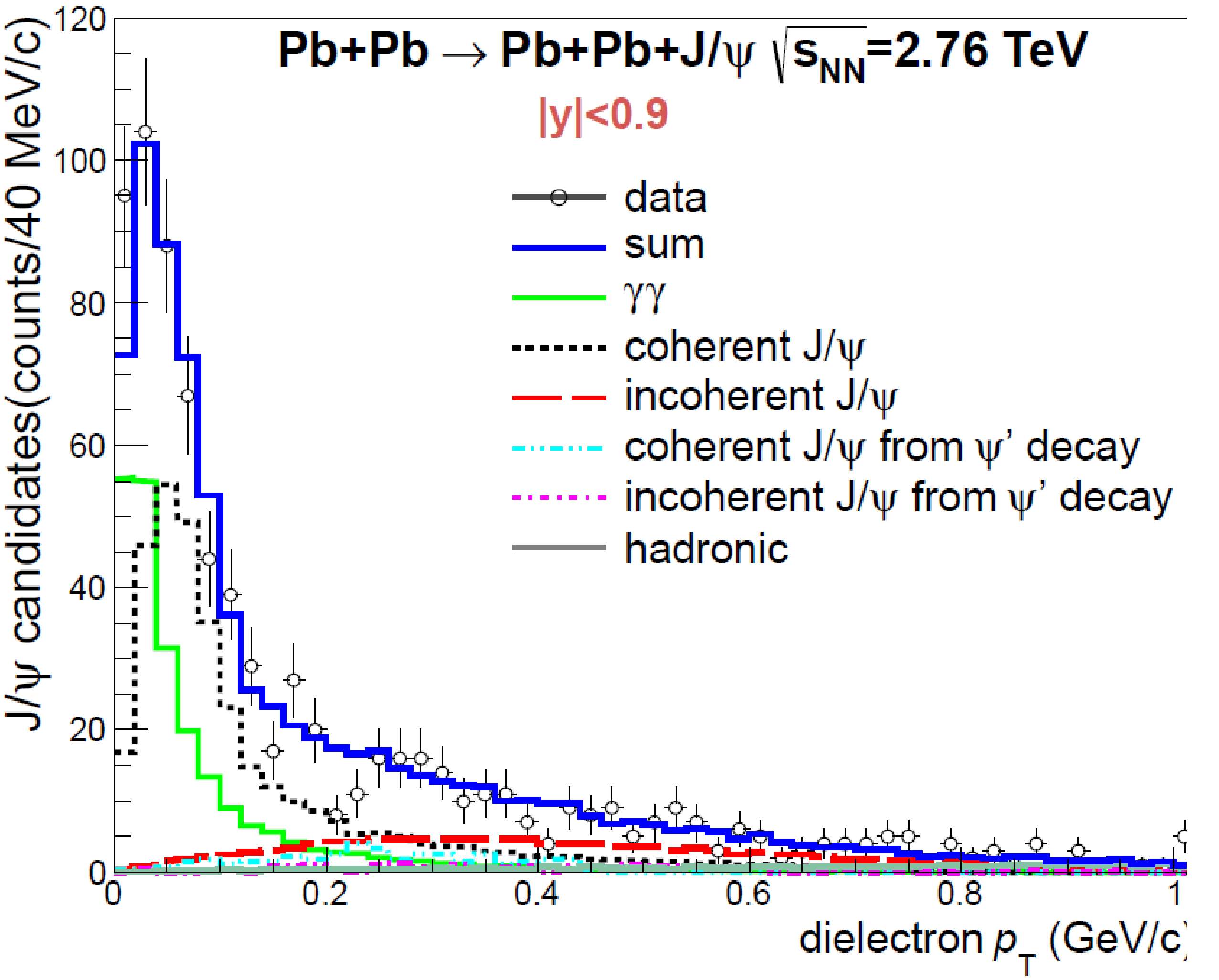
- Coherent J/ψ
- Incoherent J/ψ
- J/ψ from ψ' decays
- $\gamma\gamma \rightarrow \mu^+\mu^-$

Central barrel measurements in UPC

J/ψ in the dimuon channel



J/ψ in the dielectron channel

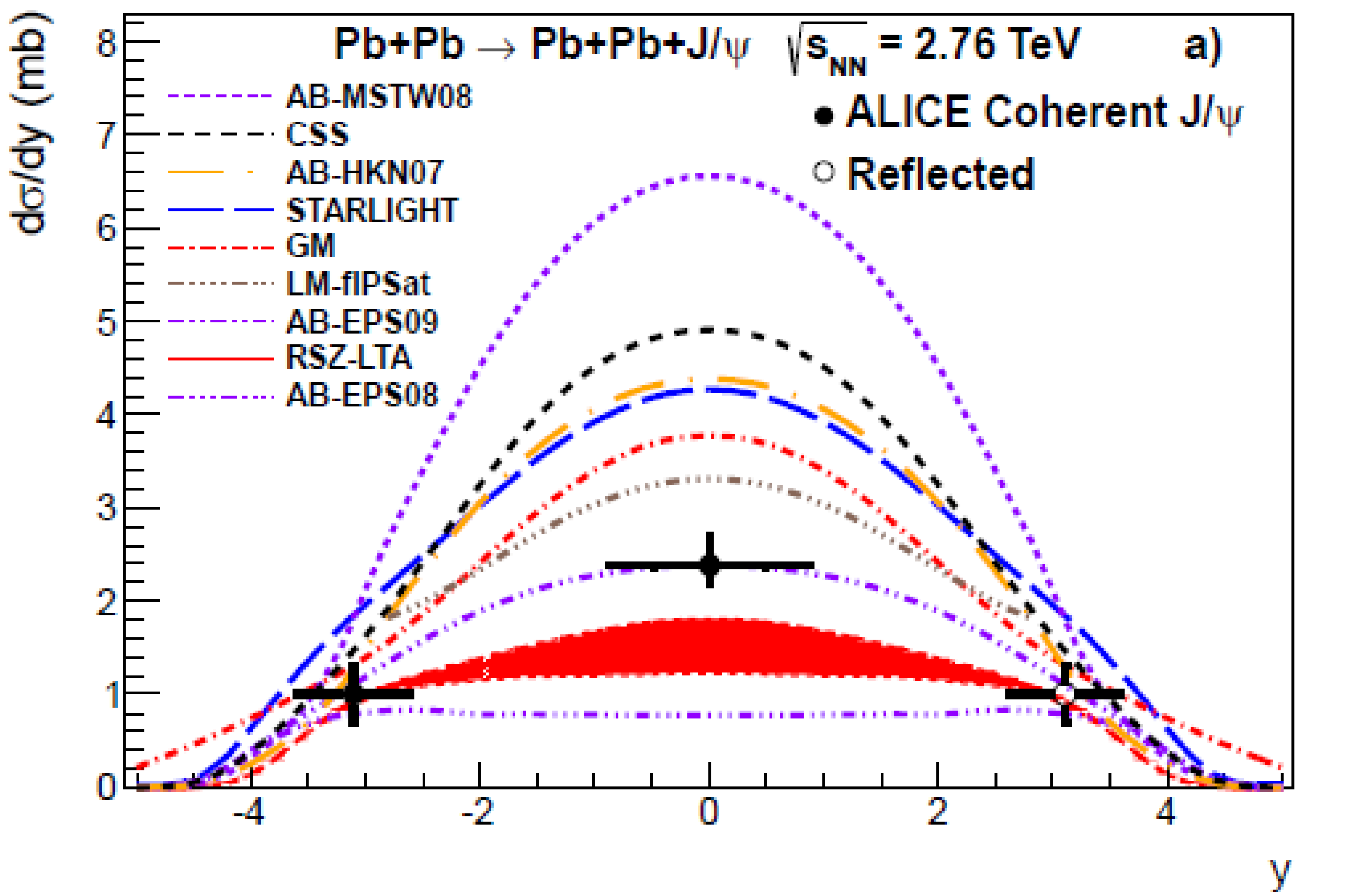


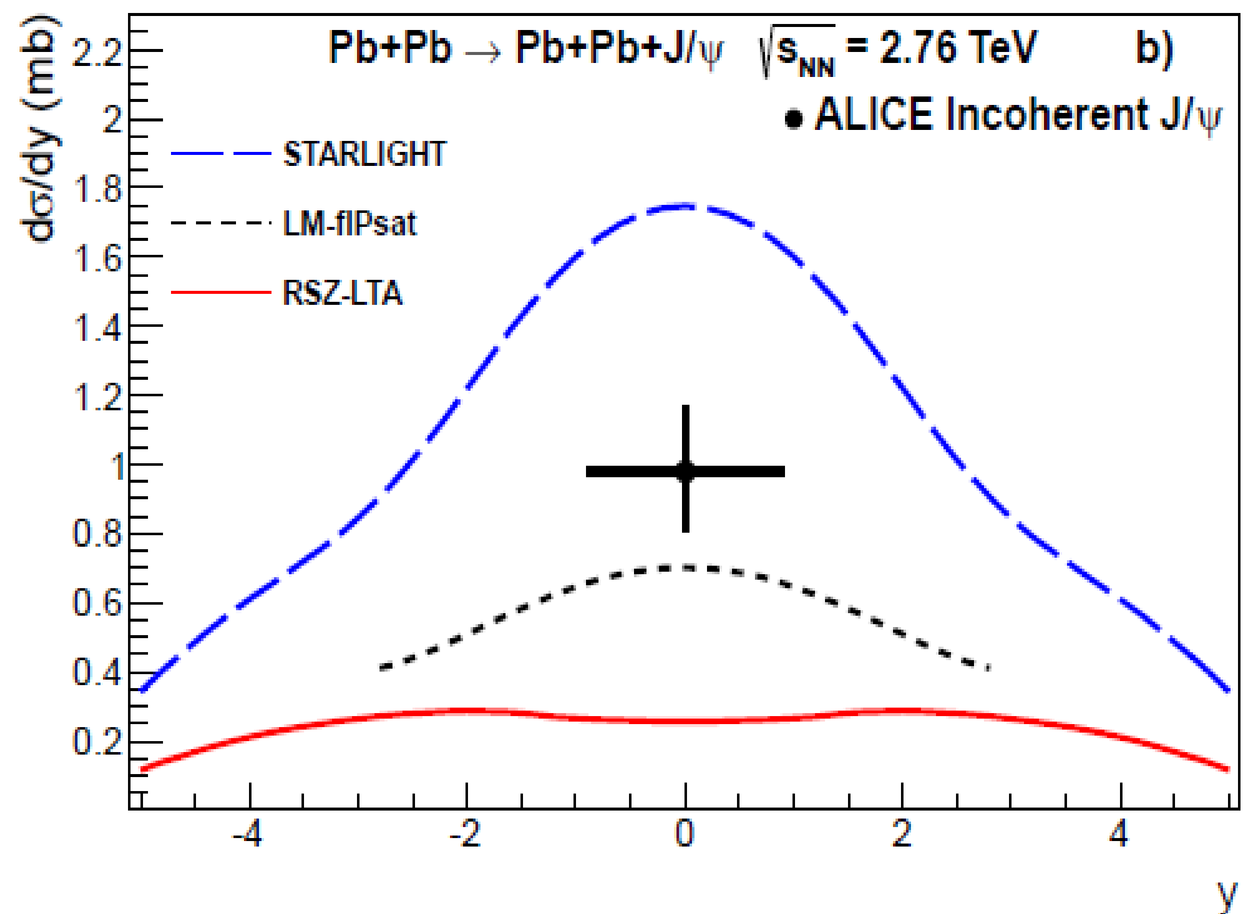
Data is well described by signals/backgrounds expected in UPC

Data *and* theoretical predictions

Coherent J/ψ

Incoherent J/ψ





Direct evidence of nuclear gluon shadowing

At mid-rapidity, Bjorken-*x* ~ 10^{-3}

ALICE shows that the distribution in $x \approx 10^{-2} - 10^{-3}$ range is consistent with the EPS09 parameterization

Two UPC publications by ALICE

Phys.Lett. B718 (2013) 1273-1283

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

Nuclear gluon shadowing from ALICE data

V. Guzei, E. Kryshen, M. Strikman, M. Zhalov. Phys. Lett. B726 (2013) 290

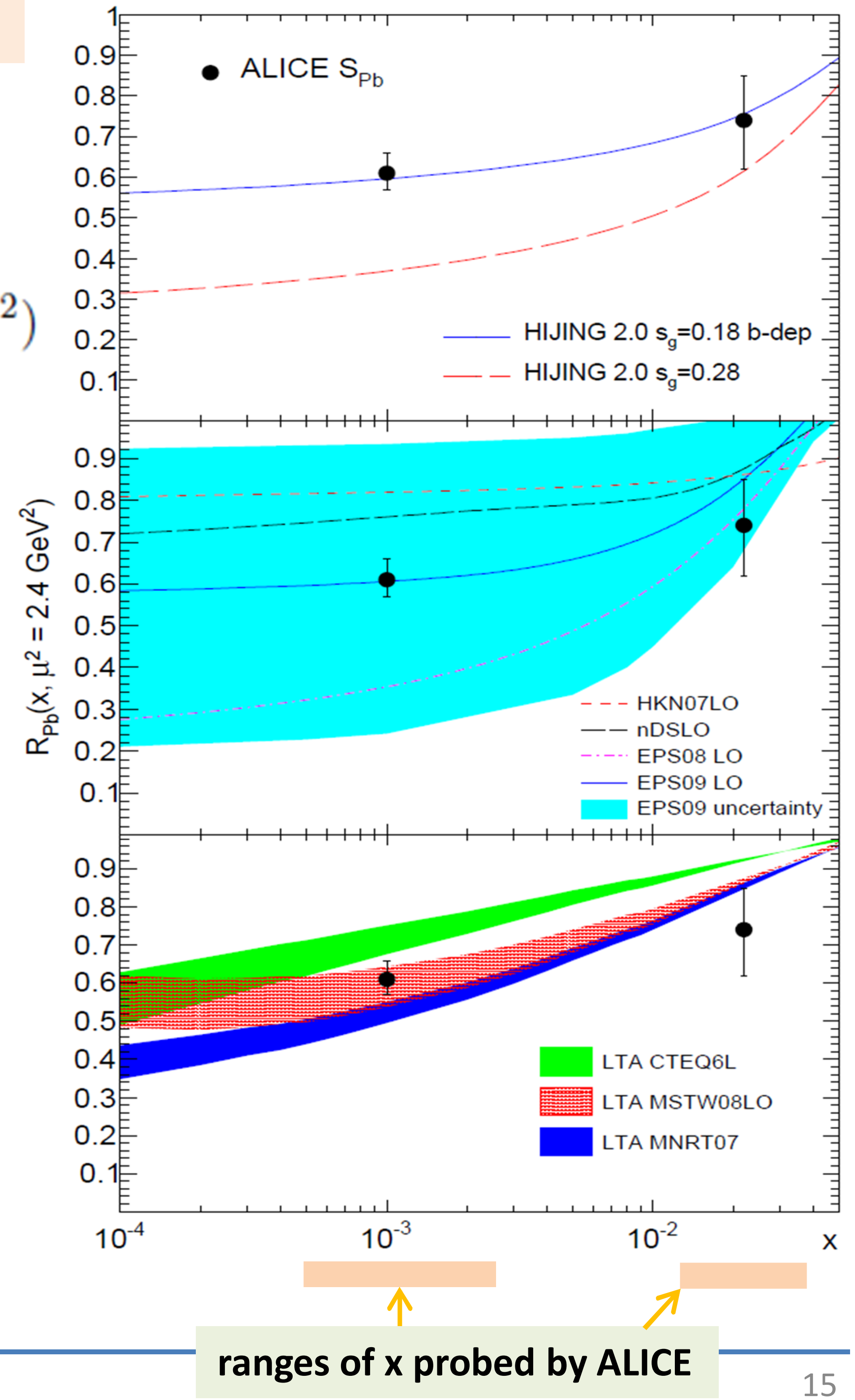
Nuclear suppression factor in J/ψ photoproduction:

ALICE data corrected for photon flux

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(W_{\gamma p})}\right]^{1/2} \Rightarrow R(x, \mu^2 = 2.4\ \mathrm{GeV}^2)$$

Impulse Approximation: J/ψ photoproduction cross section from HERA corrected for the integral over squared Pb form-factor

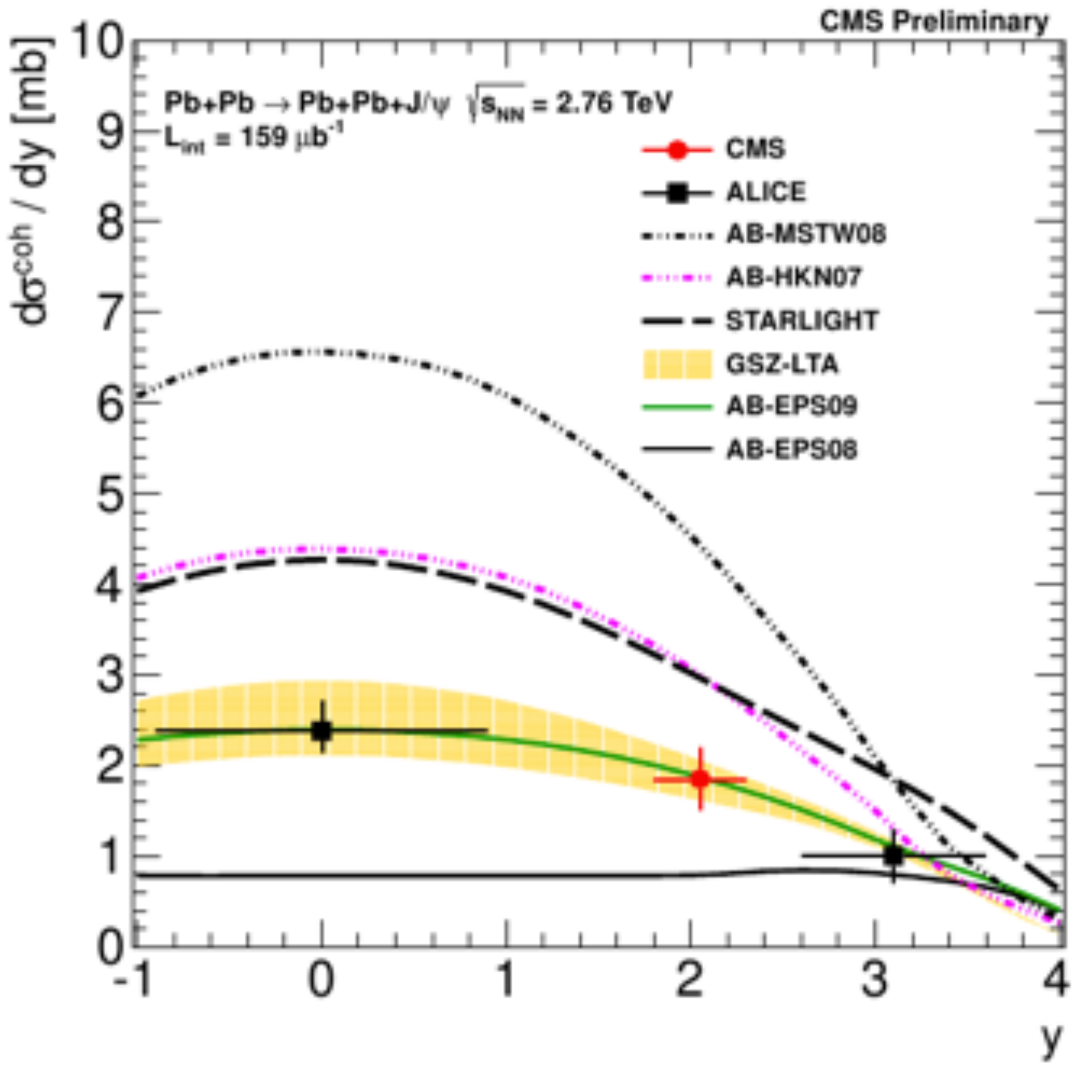
- **Hijing:** scale-independent gluon shadowing, characterized by parameter s_g
- **Shadowing parametrizations (EPS,nDS,HKN07)** use DIS and Drell-Yan data + π^0 data from RHIC (EPS) – gluon shadowing essentially unconstrained at low x
- **Leading twist approximation:** propagation of color dipoles in nuclei via intermediate diffractive states (Gribov-Glauber shadowing theory). Incorporates diffractive parton distributions in proton (from HERA)



Coherent J/y Cross Section in PbPb UPC

NEW

- Cross section for X_n0_n is scaled up to the total cross section using STARLIGHT
- CMS and ALICE results favor the same theoretical models
- ALICE and CMS measurements favor models containing moderate gluon shadowing



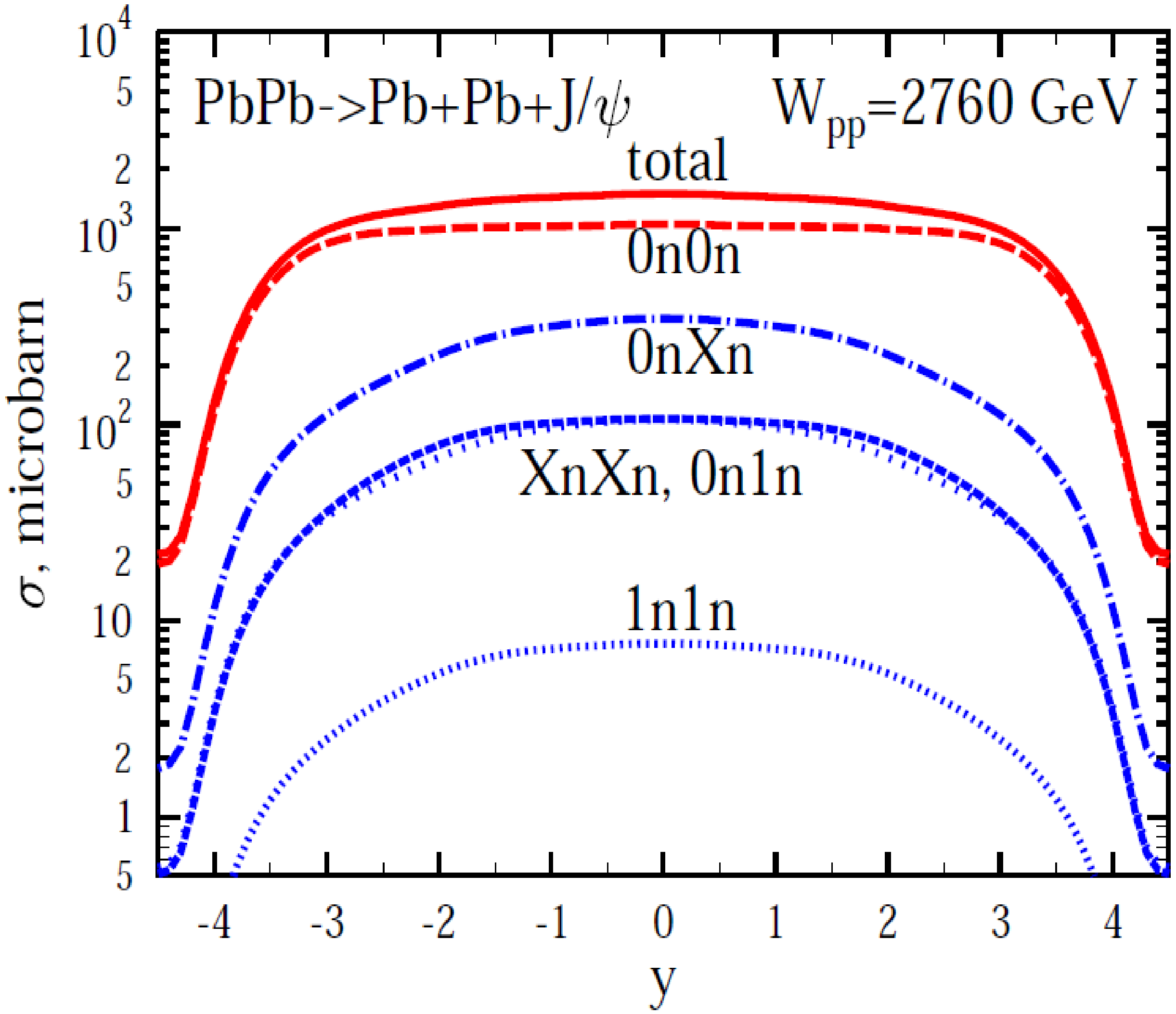
CMS: HIN-12-009: http://cds.cern.ch/record/1971267

ALICE: Eur.Phys.J. C73 (2013) 2617 Phys.Lett. B 718 (2013) 1273-1283

P. Kenny
IS conference. Dec 2014

New at the LHC: Dependence on neutron emission

Using Zero Degree Calorimeters (ZDC) it is possible to select coherent production with ion excitation, where neutrons are emitted from at least one of the nuclei



Different configurations:

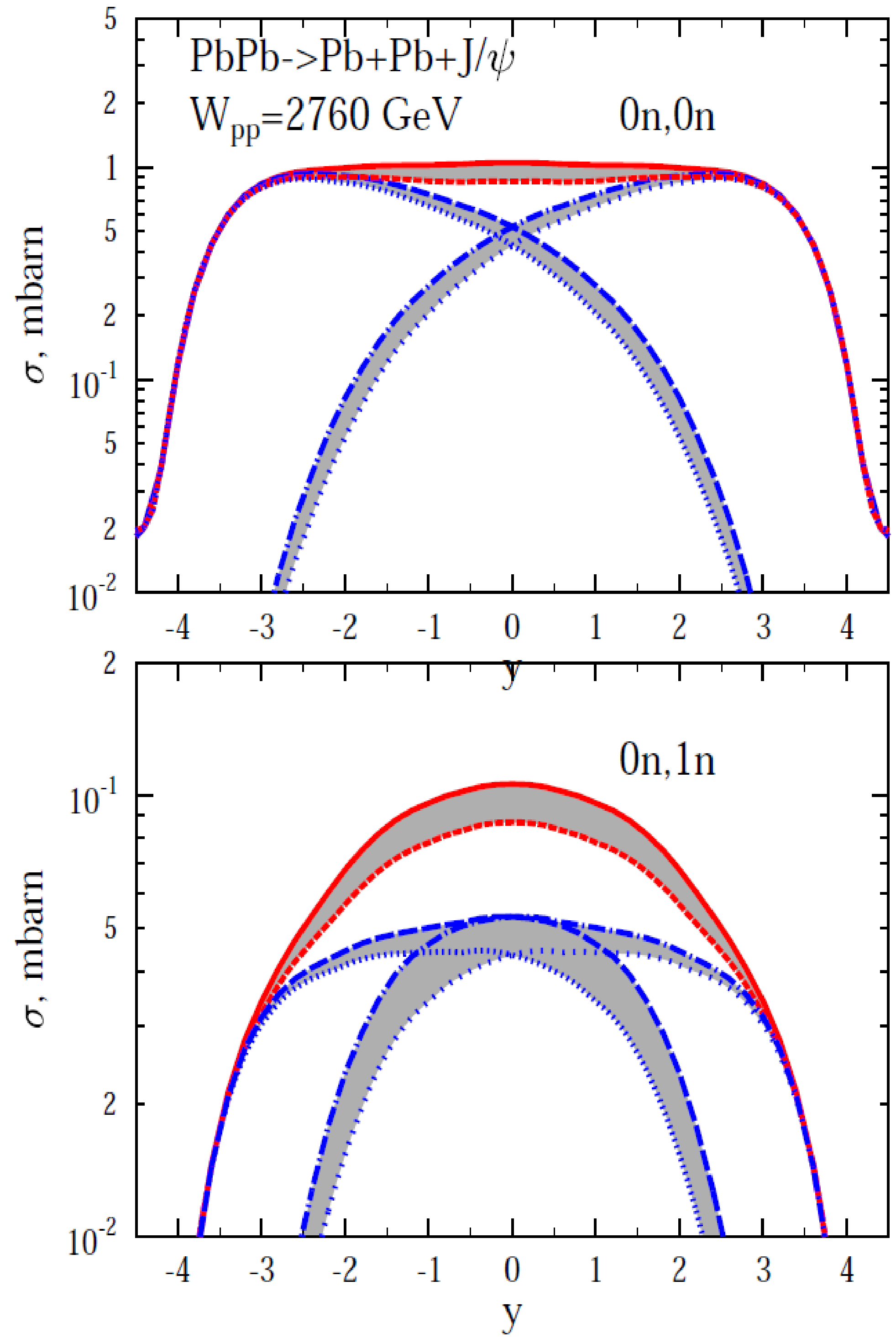
1n1n: one neutron emission by each ion;

XnXn: emission of several neutrons;

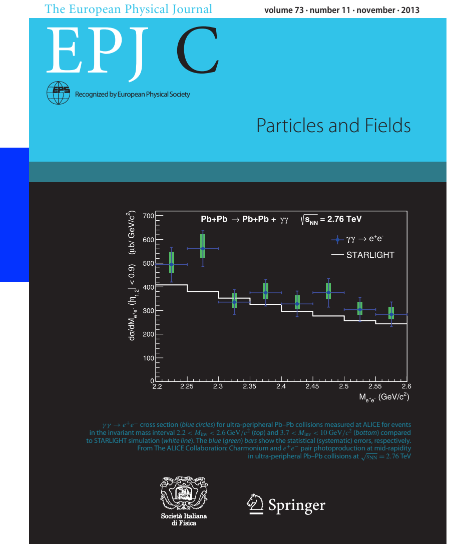
0n1n and 0nXn: excitation and decay of one of the ions, and

0n0n: no neutron emission

V. Rebyakova, M. Strikman and M. Zhalov
ArXiv:1109.0737, Sept 2011

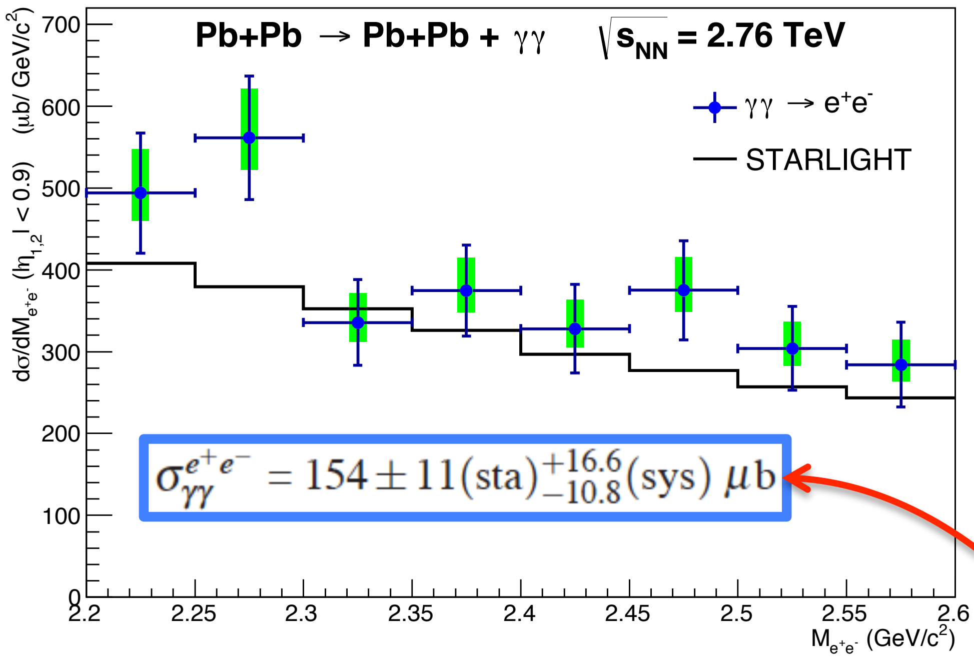


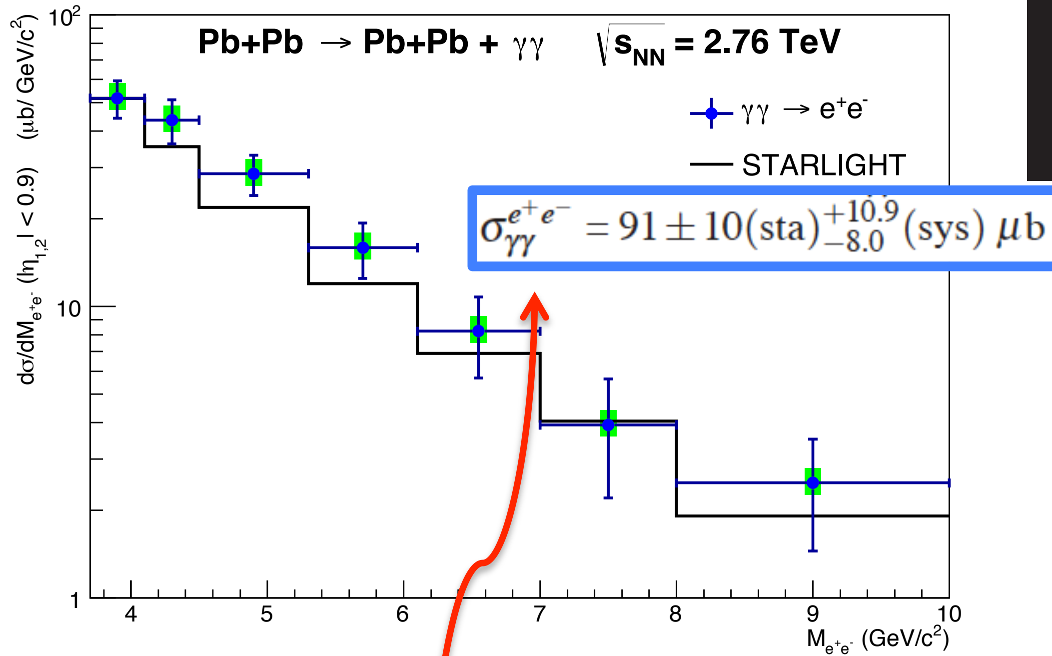
Shaded area: Uncertainty on nuclear gluon shadowing



$\gamma+\gamma \rightarrow e^{+}+e^{-}$ production in Pb-Pb (Central Barrel)

Eur. Phys. J. C (2013) 73:2617





- ✓ QED process … but uncertainties due to
  - ➢ Higher order corrections because the coupling is enhanced by a factor of Z
  - ➢ Nuclear form factor and the minimum momentum transfer in the interaction
- → Different models predict a reduction of the LO cross section up to 30%
- → (see for example: A. J. Baltz, Phys. Rev. C 80 (2009) 034901; Phys. Rev. Lett. 100 (2008) 062302)

- ✓ Measurement in two different mass ranges: [2.2,2.6] and [3.7,10] GeV/c^2
- ✓ Precision of 12% and 16% respectively
- ✓ Data slightly above STARLIGHT, a LO prediction

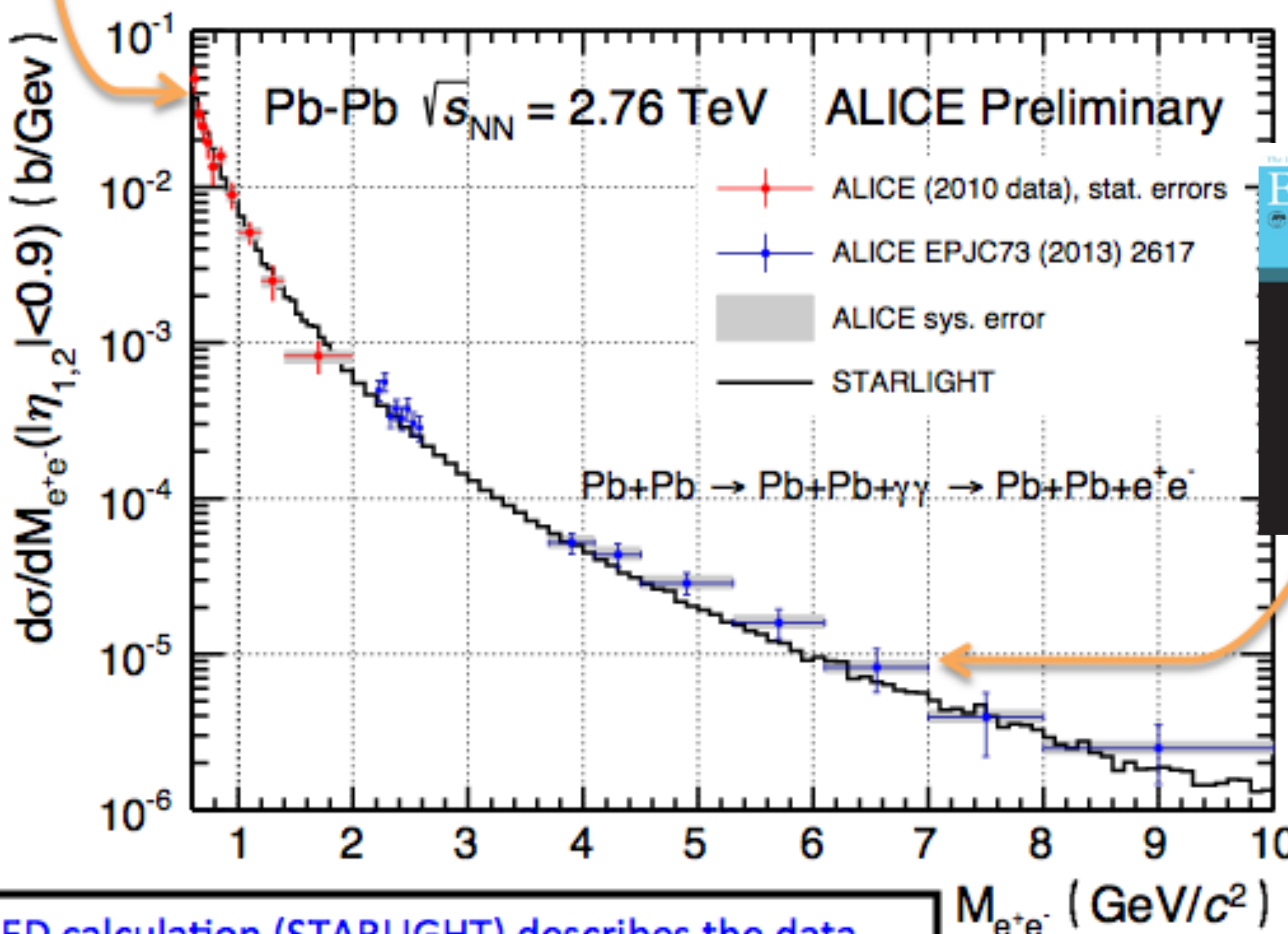
ALICE data sets stringent limits on the contribution from high order terms

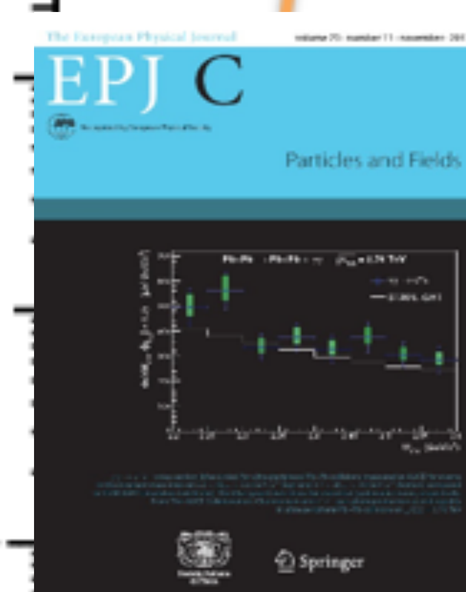
Eur. J. Phys. C73, 2617 (2013)

Eur. Phys. J. C73 (2013) 2617

2010: Low luminosity, but trigger allows to cover the low mass region

2011: High luminosity, measurement to higher masses possible





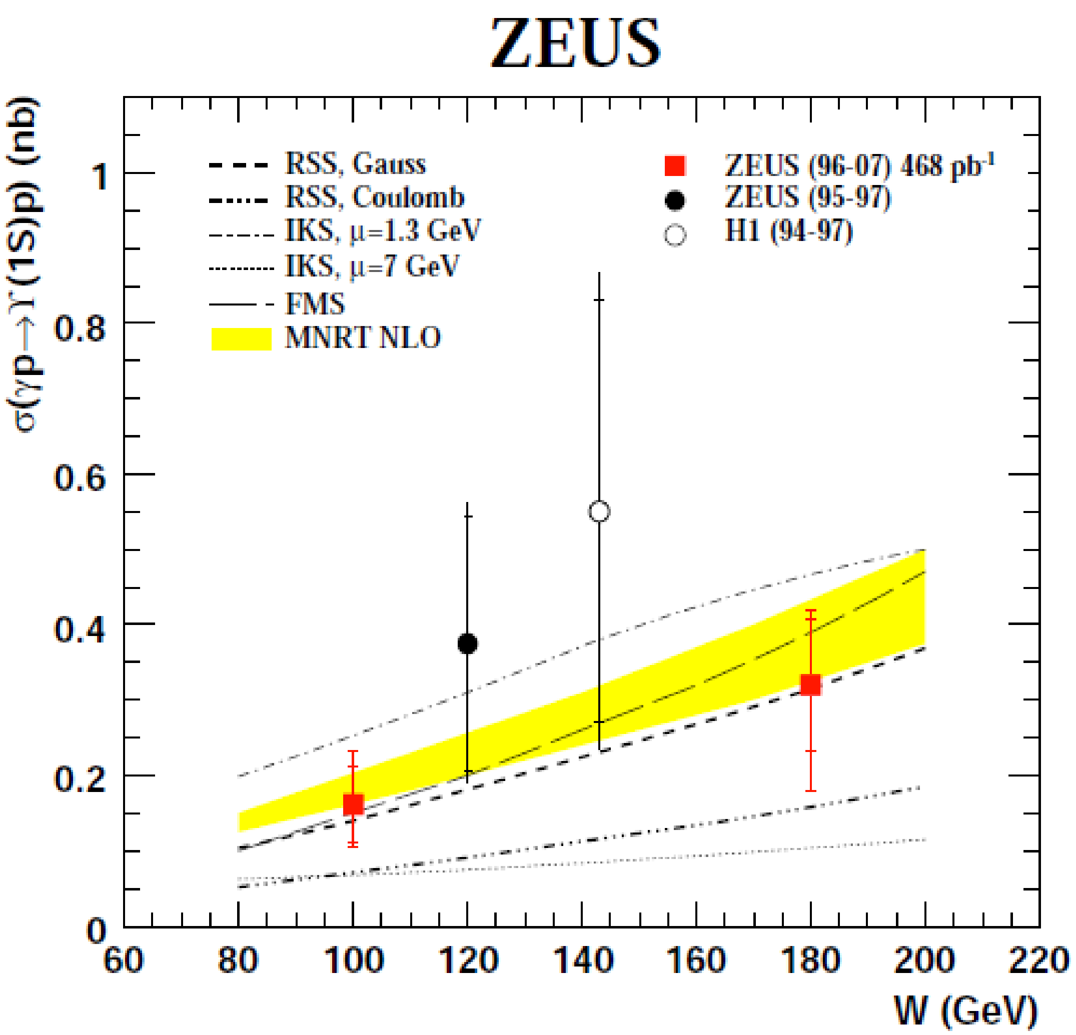
A LO QED calculation (STARLIGHT) describes the data
Strong constraint on NLO contributions

Upsilon photoproduction

$\gamma + p \rightarrow Y + p$: possible thanks to strong photon flux of the proton hitting the Pb nuclues

Very limited statistics from HERA (H1 and ZEUS) ~ 100 candidates

Uncertainty in measured cross section larger than a factor 3

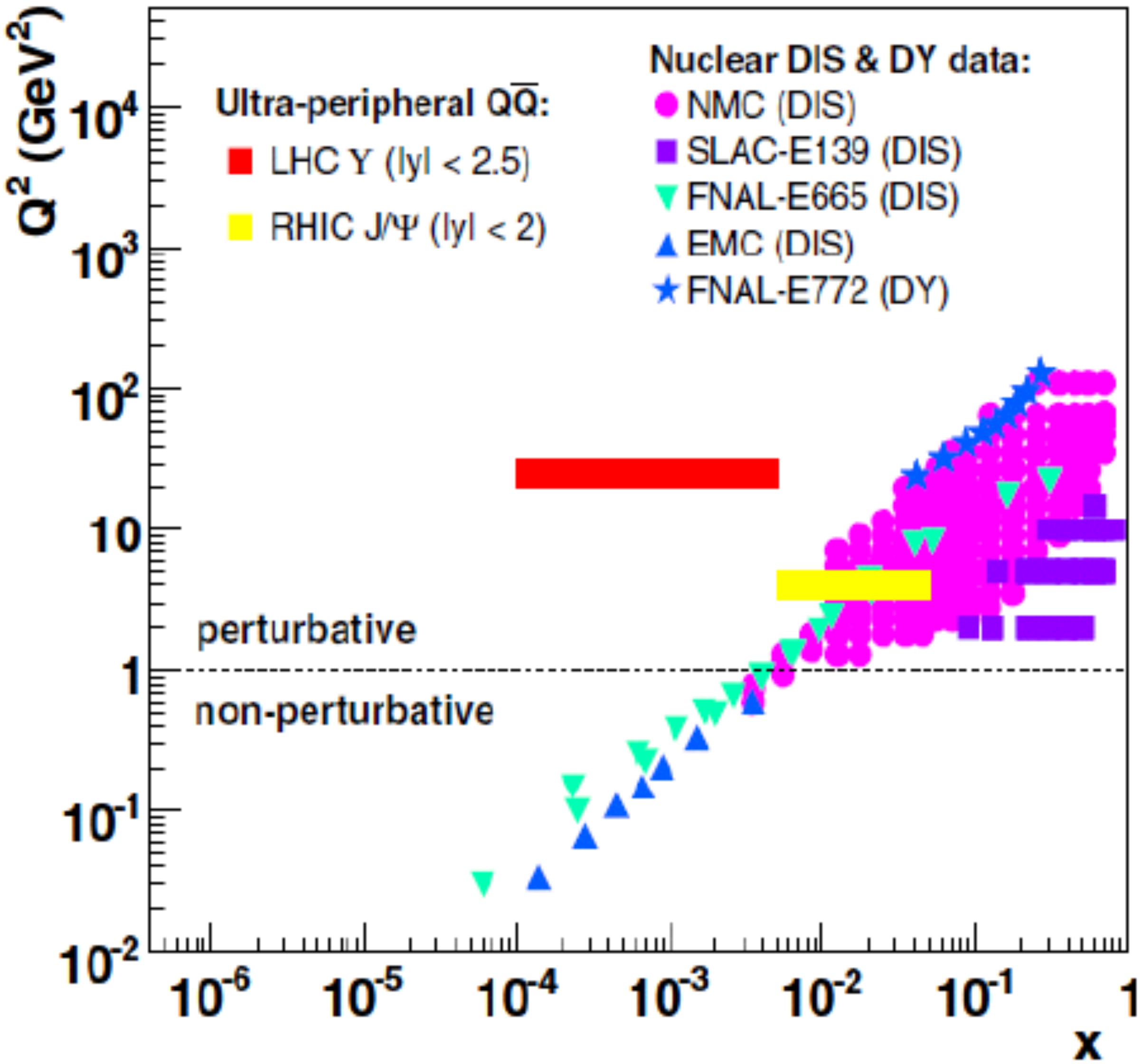


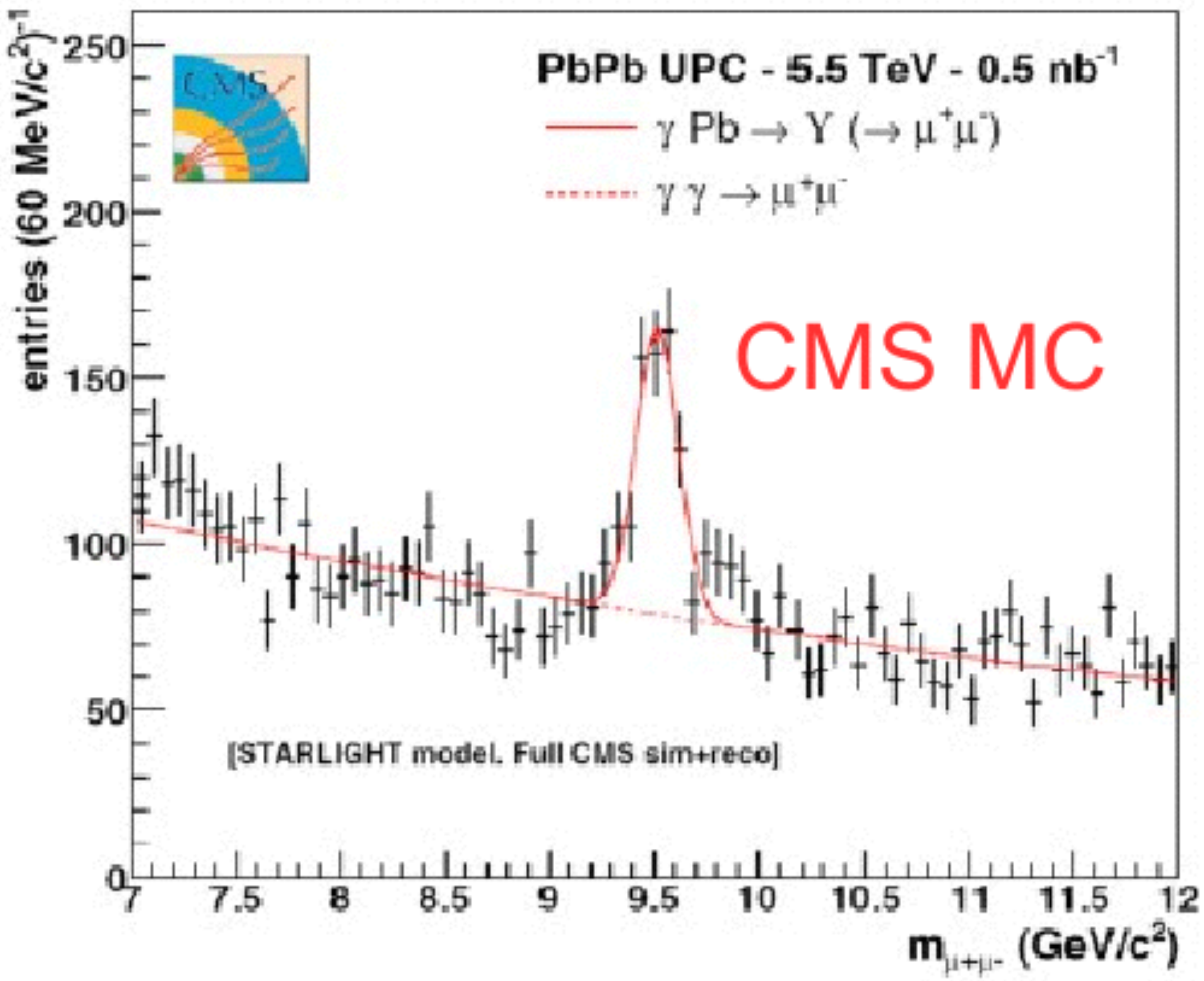
Ideal way to measure this process at LHC

Needed to have a baseline for

$\gamma + Pb \rightarrow Y + Pb$

Here CMS is very competitive as Upsilon acceptance is down to zero transverse momenta





2011: 150 mb^{-1}

at $\sqrt{s_{NN}}$ = 2.76 TeV

2015 Pb-Pb run with CMS

- Between 200-1000 Upsilon candidates expected

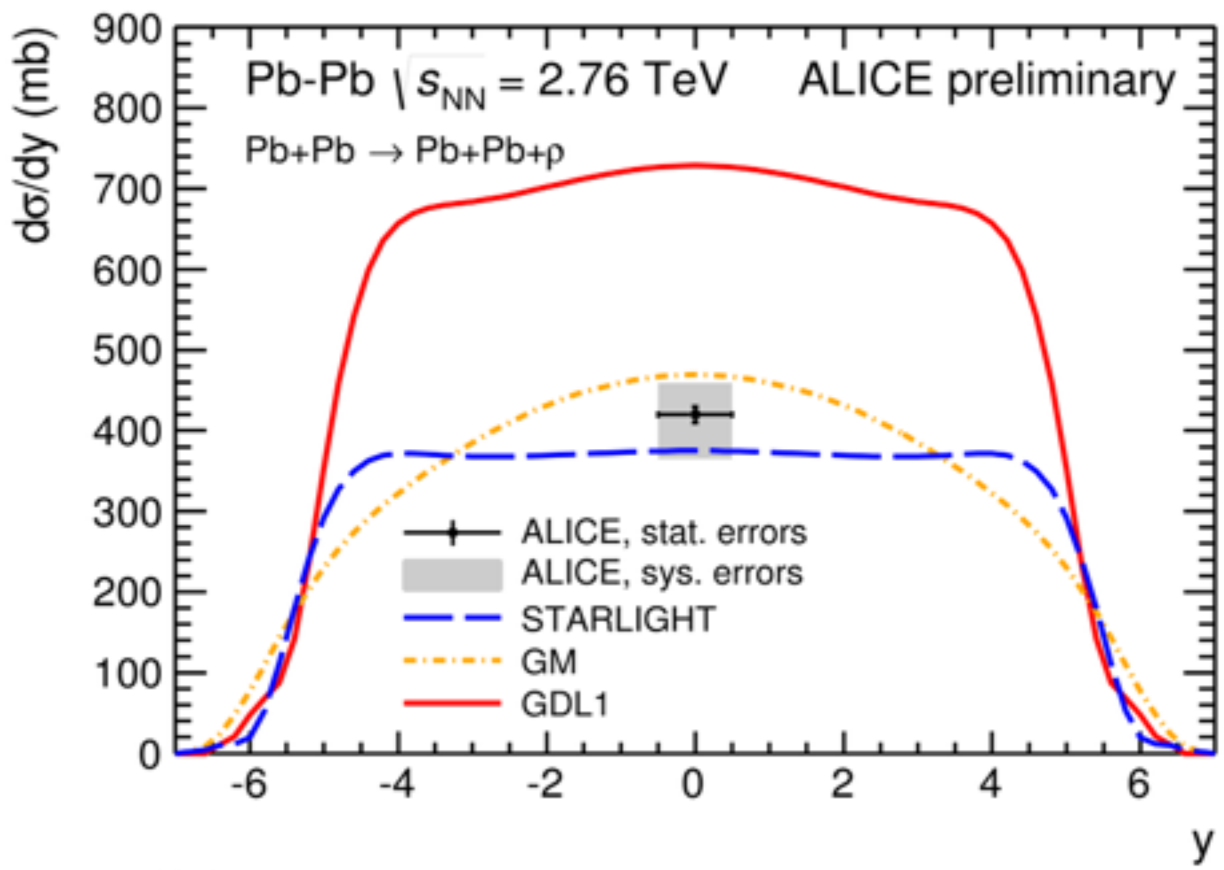
2015: 0.5-1.5 nb^{-1}

at $\sqrt{s_{NN}}$ = 5.1 TeV

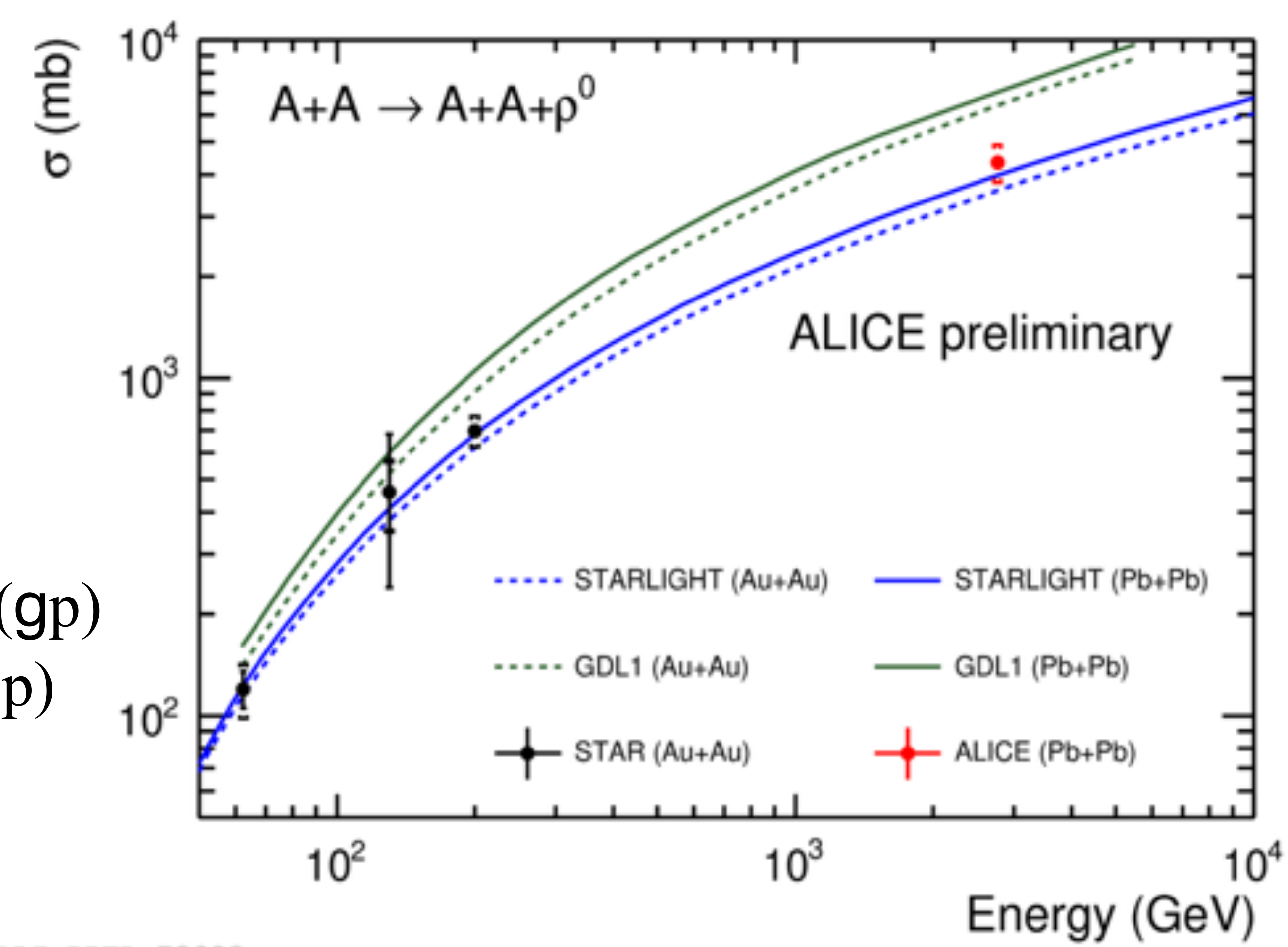
Coherent rho^0 photoproduction in Pb-Pb

$$\left.\frac{d\sigma(\rho^0)^{coh.}}{dy}\right|_{y=0} = \left(420 \pm 10(\text{stat.})\,^{+39}_{-55}(\text{sys.})\right)\ \text{mb}$$

arXiv:1503.09177 [nucl-ex]
Put on Arxiv last week



Energy dependence



GDL: proper QM Glauber calculation for scaling s(gp) → s(gA), uses Donnachie-Landshoff model for s(gp)

GM: Based on color dipole model with saturation implementation by the CGC formalism

STARLIGHT: scales the experimentally measured gp cross section using a Glauber model, neglecting the elastic nuclear cross section

$$\sigma(\rho^0)^{coh.} = \left(4.3 \pm 0.1(\text{stat.})\,^{+0.6}_{-0.5}(\text{sys.})\right)\ \text{b}$$

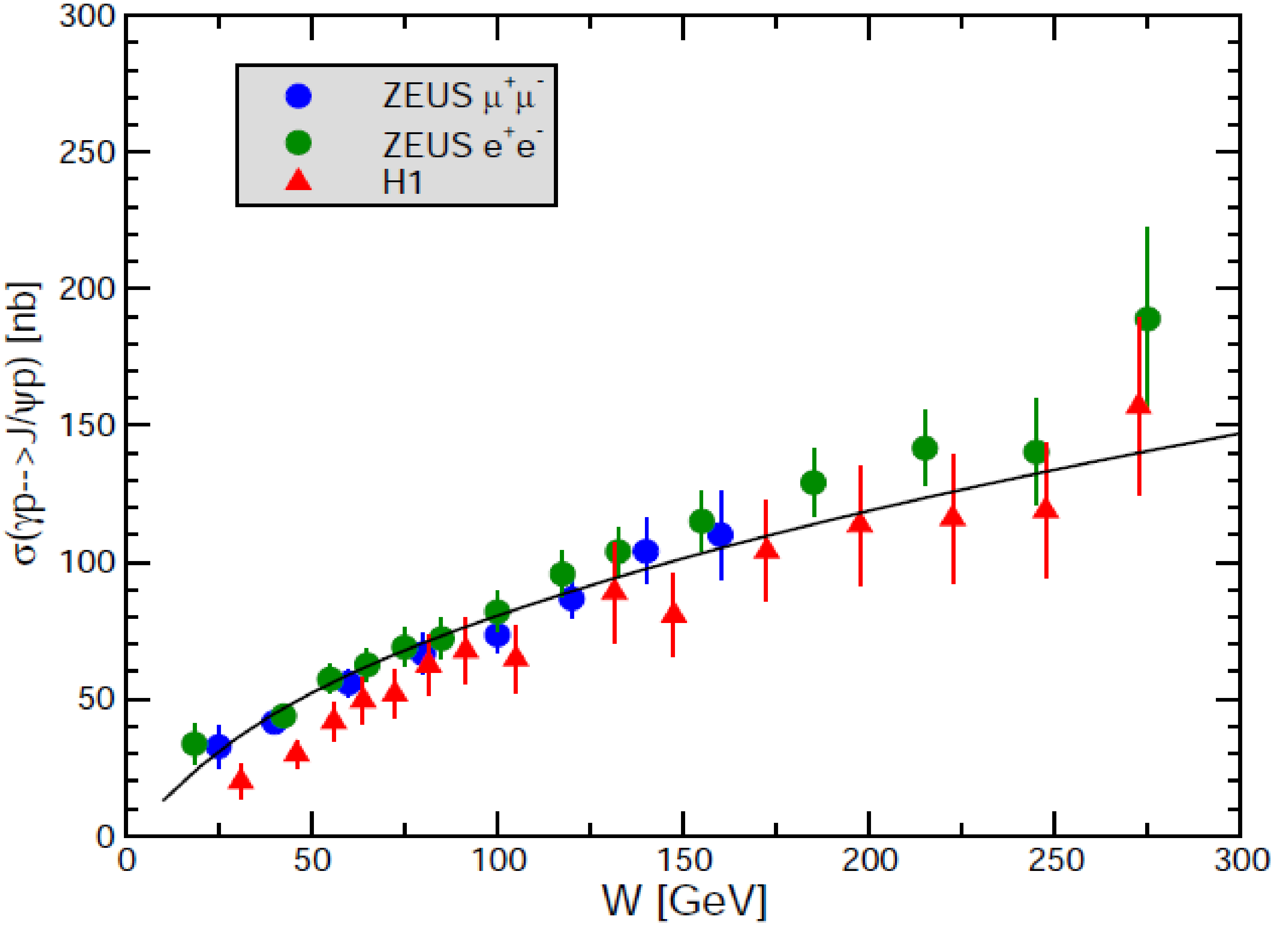
p

UPCs in Pb-Pb

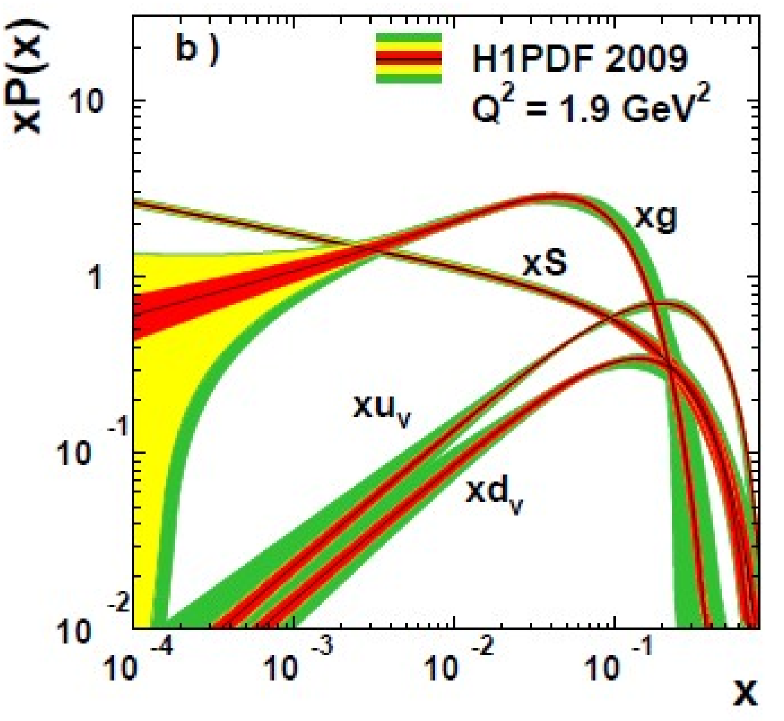
J/ψ photoproduction in γp

$$\frac{d\sigma_{\gamma p \to pJ/\psi}}{dt} = \frac{\Gamma_{ee} M^3_{J/\psi} \pi^3}{48\alpha_{em}} \cdot \frac{\alpha_S^2(\bar{Q}^2)}{\bar{Q}^8} \left[x g_N(x, \bar{Q}^2) \right]^2 \exp[B_{J/\psi}(s)t]$$

The Pb nucleus acts as photon emitter (enhanced flux by factor $Z^2 \approx 7000$ compared to the photon flux from the proton

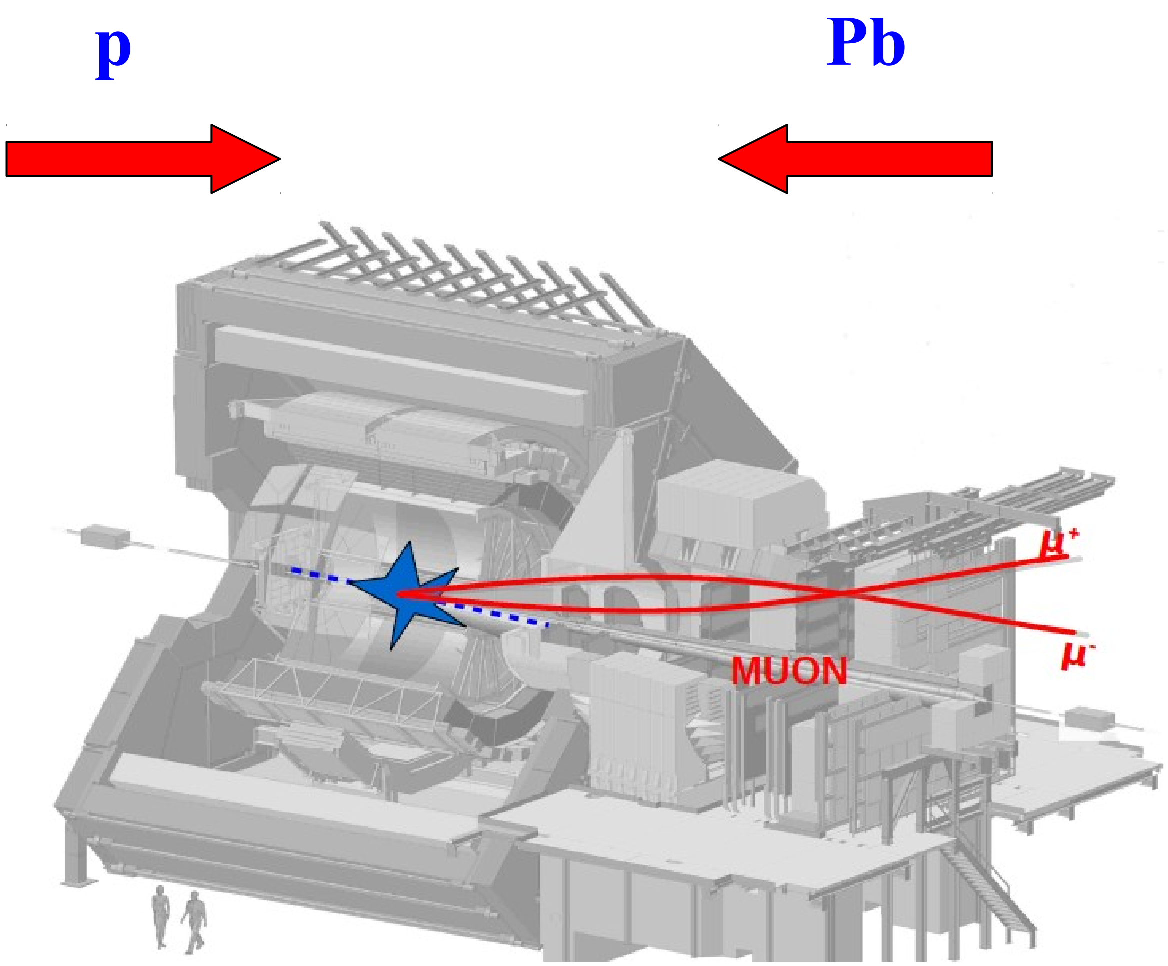


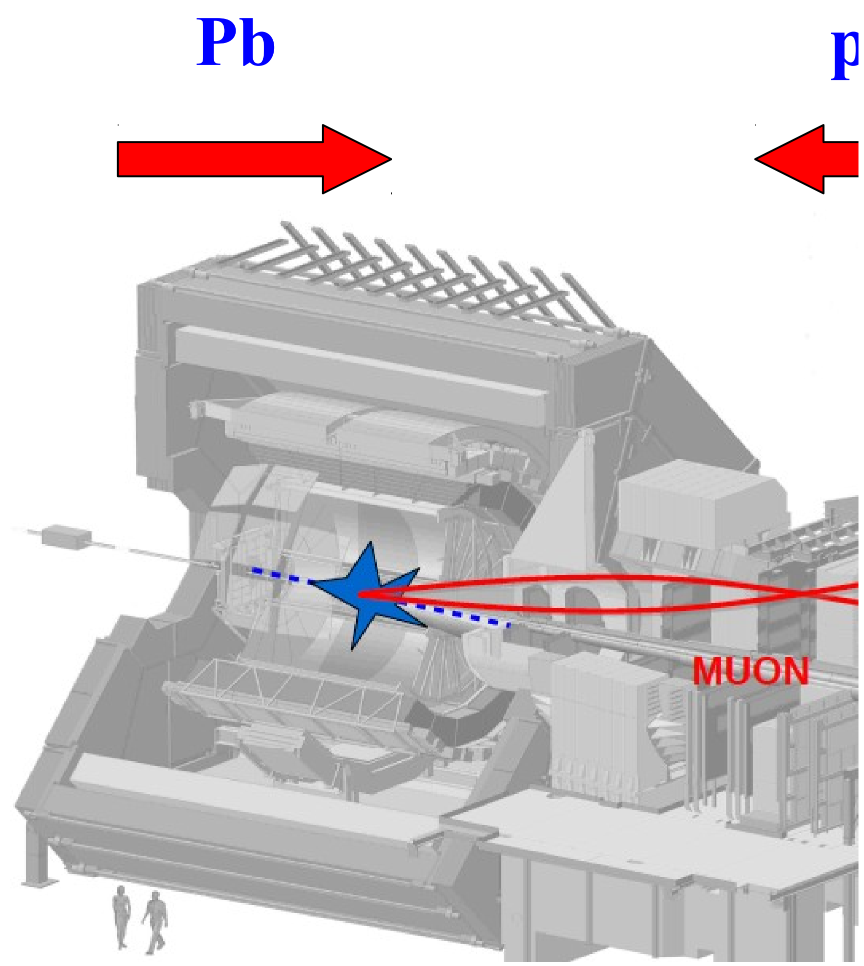
H1: A. Aktas *et al.* Eur.Phys. J.C46:585-603,2006
ZEUS:S. Chekanov et al., Nucl. Phys. B695 (2004) 3.
A. Martin et al. Phys.Lett. B 662:252-258, 2008



At LHC Bjorken-*x* down to 10^{-5}

γp centre-of-mass energies at the 1 TeV energy scale





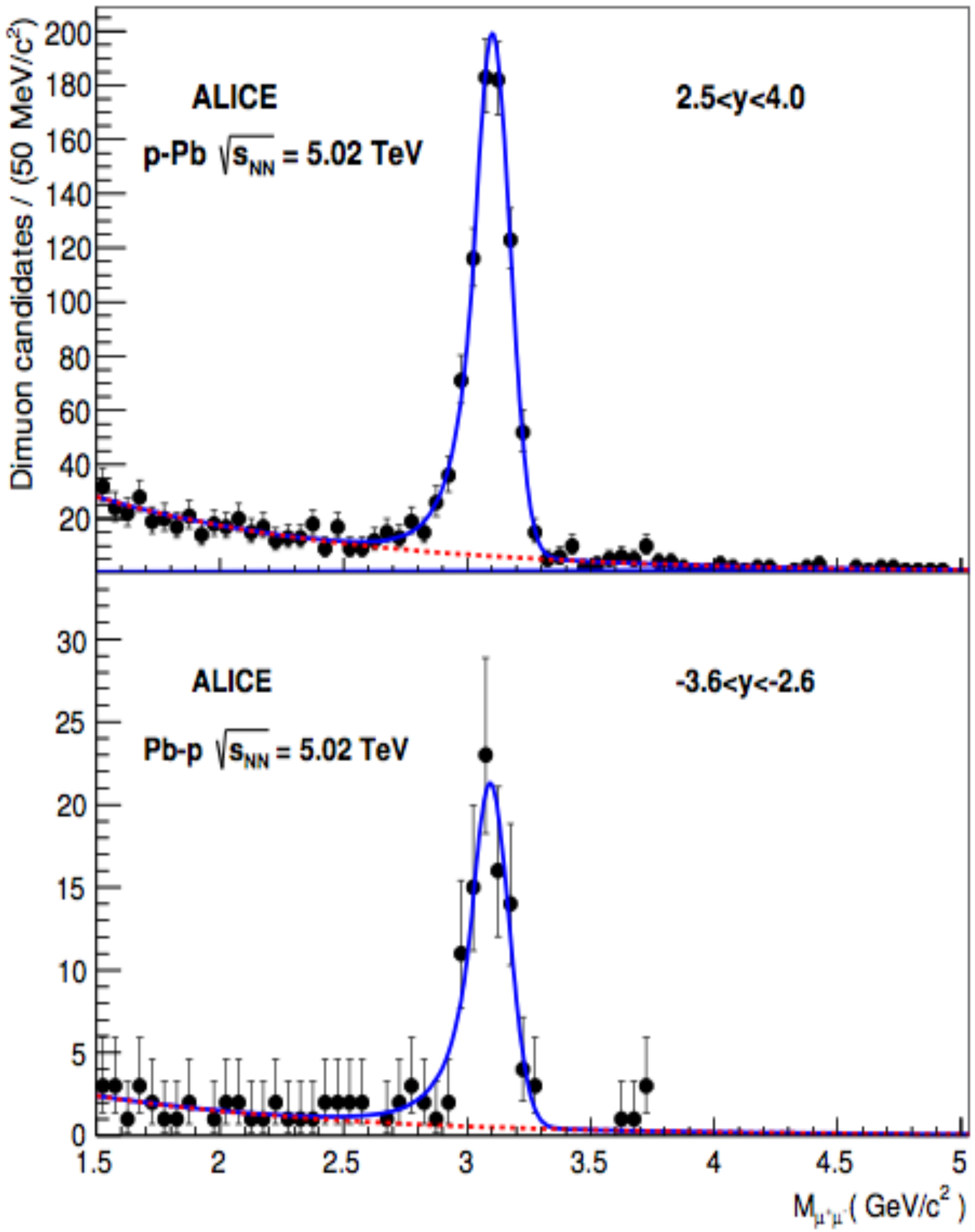
$21 < W_{\gamma p} < 45$ GeV

$549 < W_{\gamma p} < 1163$ Ge

- The fact that the Pb nucleus is the dominant photon emitter allows us to separate the two $W_{\gamma p}$ regimes unambiguously.
  - "p-Pb" (*) corresponds to the lower energy range
  - "Pb-p" corresponds to the higher energy range.

$$x = \left(M_{J/\psi} / \sqrt{s_{NN}}\right)\exp(\pm y)$$

Exclusive J/psi in p-Pb



$<W_{gp}> \sim 30$ GeV

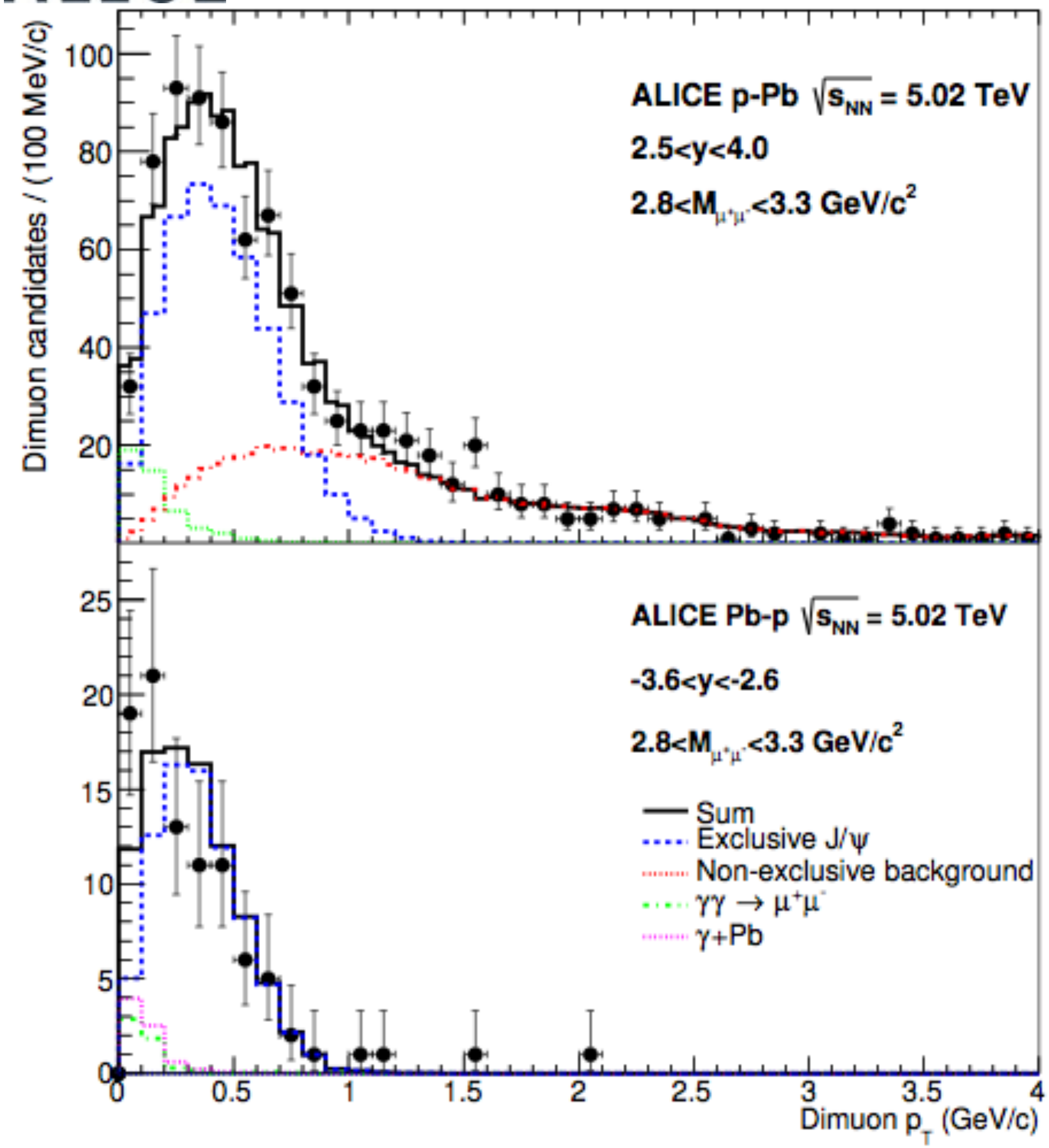
$<W_{gp}> \sim 700$ GeV

Phys.Rev.Lett. 113 (2014) 23, 232504

DTT
ICHEP 2014

Exclusive J/psi in p-Pb

Phys.Rev.Lett. 113 (2014) 23, 232504



Data well described by templates

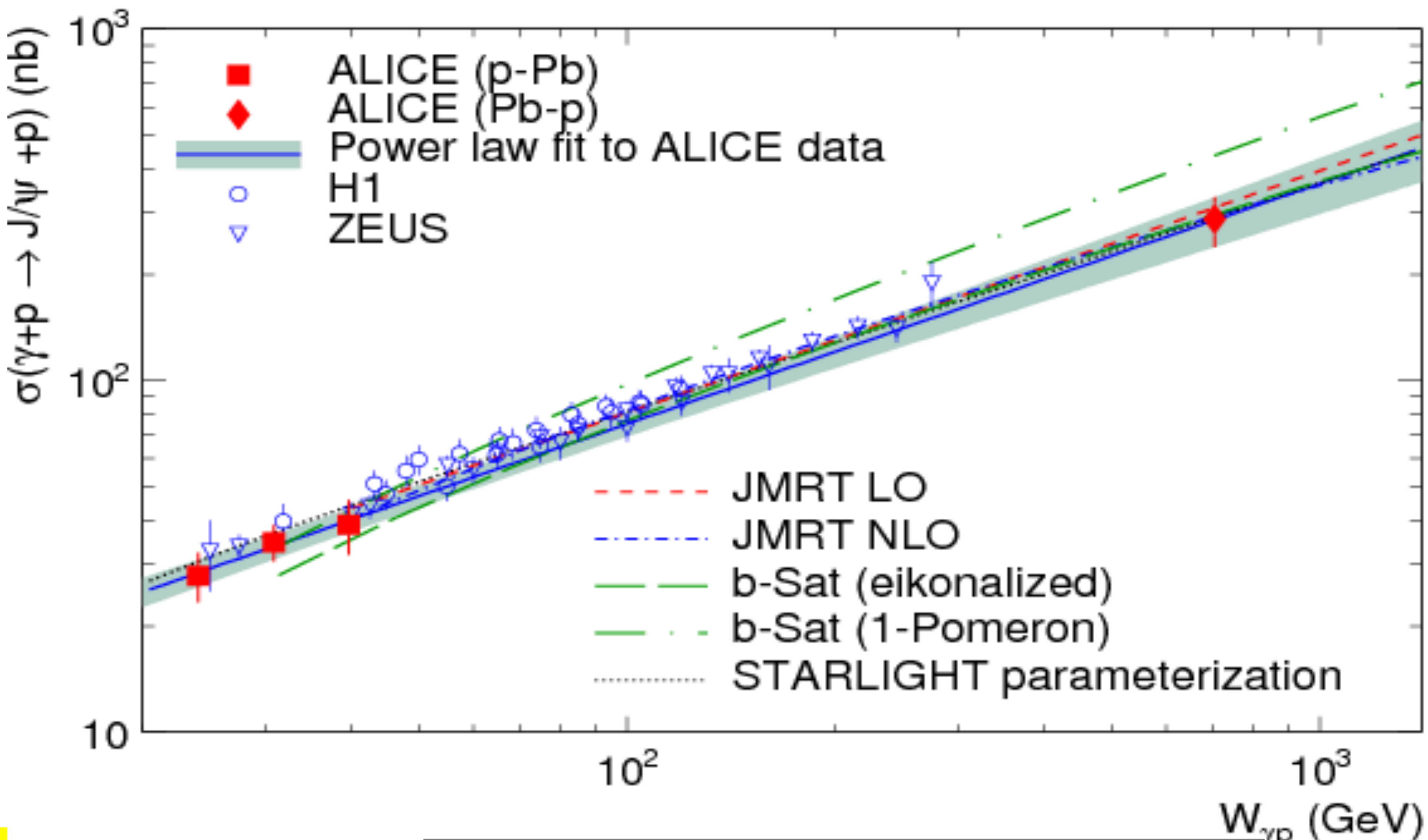
Energy dependence is clearly visible

Low W_{gp} energy point
$\langle W_{gp} \rangle \sim 30$ GeV

High W_{gp} energy point
$\langle W_{gp} \rangle \sim 700$ GeV

Exclusive J/psi in p-Pb

Phys.Rev.Lett. 113 (2014) 23, 232504



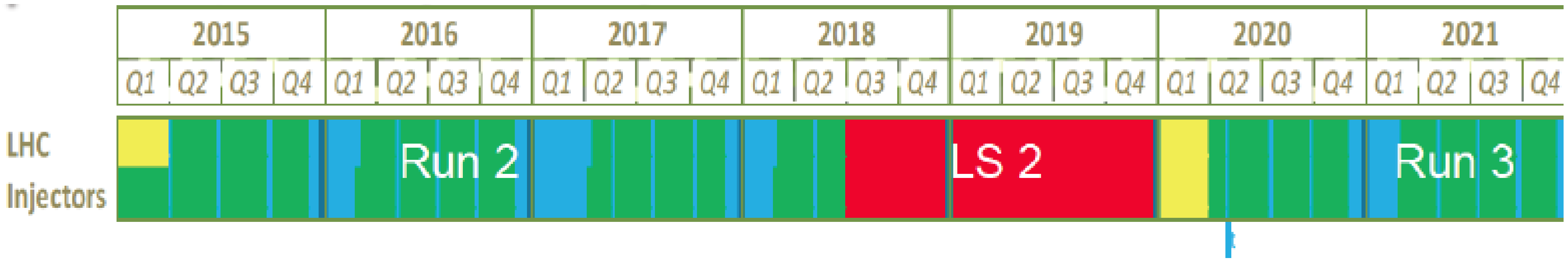
- Our knowledge of the photon emitter allows us to solve for $\sigma(W_{\gamma p})$ using the measured $d\sigma/dy$
- A power law fit ($\sigma(W) \sim W^{\delta}$) to ALICE data points gives δ=0.68±0.06.

HERA Measurements
H1 δ=0.67±0.03
ZEUS δ=0.69±0.02

No change on the proton gluon density between HERA and LHC energies

DTT
ICHEP 2014

Run 2 and beyond



5.1 TeV for the 2015 Pb-Pb run

1 nb-1 for CMS/ATLAS

Next heavy-ion run in 2016 and 2017

Heavy Ion Preparations for Run 2

- The 2015 Ion Period will be the first high luminosity Pb run in the LHC Ion program
  - Peak Lumi: 3.7 x 10^{27} $cm^{-2}s^{-1}$, interaction rate ~30kHz
  - 8 times higher than the 2011 PbPb interaction rate, and 4 times higher than the LHC design value!

Summary

Forward Heavy-Ion Physics at LHC is exploring QDC phenomena at novel x-values

Many new interesting topics still there to study QCD and New Physics at high energies/ luminosities: nuclear shadowing, saturation, excited states of vector mesons, Higgs production …

UPC physics can be seen as the precursor for the Electron-Ion Collider

Recent workshop on Forward HI physics

LHC WG meeting on difraction and forward physics & Future directions heavy-ion physics in the forward region

http://cern.ch/lawrence2014

September 3-6, 2014

Lawrence and Kansas City

CERN Yellow Report on Forward physics, in preparation

Additional slides

Why J/ψ photo-production at LHC

Total J/ψ cross section: 23 mb (STARLIGHT) *vs* 10.3 mb Rebyakova, Strikman and Zhalov

Models differ by the way photo-nuclear interaction is treated...

Five model predictions available
- published in the last two years-

STARLIGHT
http://starlight.hepforge.org

Adeluyi and Bertulani (AB)
Phys. ReV. C 85 (2012) 044904

Goncalves and Machado (GM)
Phys. ReV C 84 (2011) 011902

Cisek, Szczurek, Schafer (CSC)
Phys. ReV. C 86 (2012) 014905

Rebyakova, Strikman and Zhalov (RSZ)
Phys. Lett. B 710 (2012) 252

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3\left[xg\left(x,\frac{M_V^2}{4}\right)\right]^2$$

Ryskin 1993

$$\frac{\left.\frac{d\sigma(\gamma A\to VA)}{dt}\right|_{t=0}}{\left.\frac{d\sigma(\gamma N\to VN)}{dt}\right|_{t=0}} = \left[\frac{G_A(x,M_V^2/4)}{G_N(x,M_V^2/4)}\right]^2$$

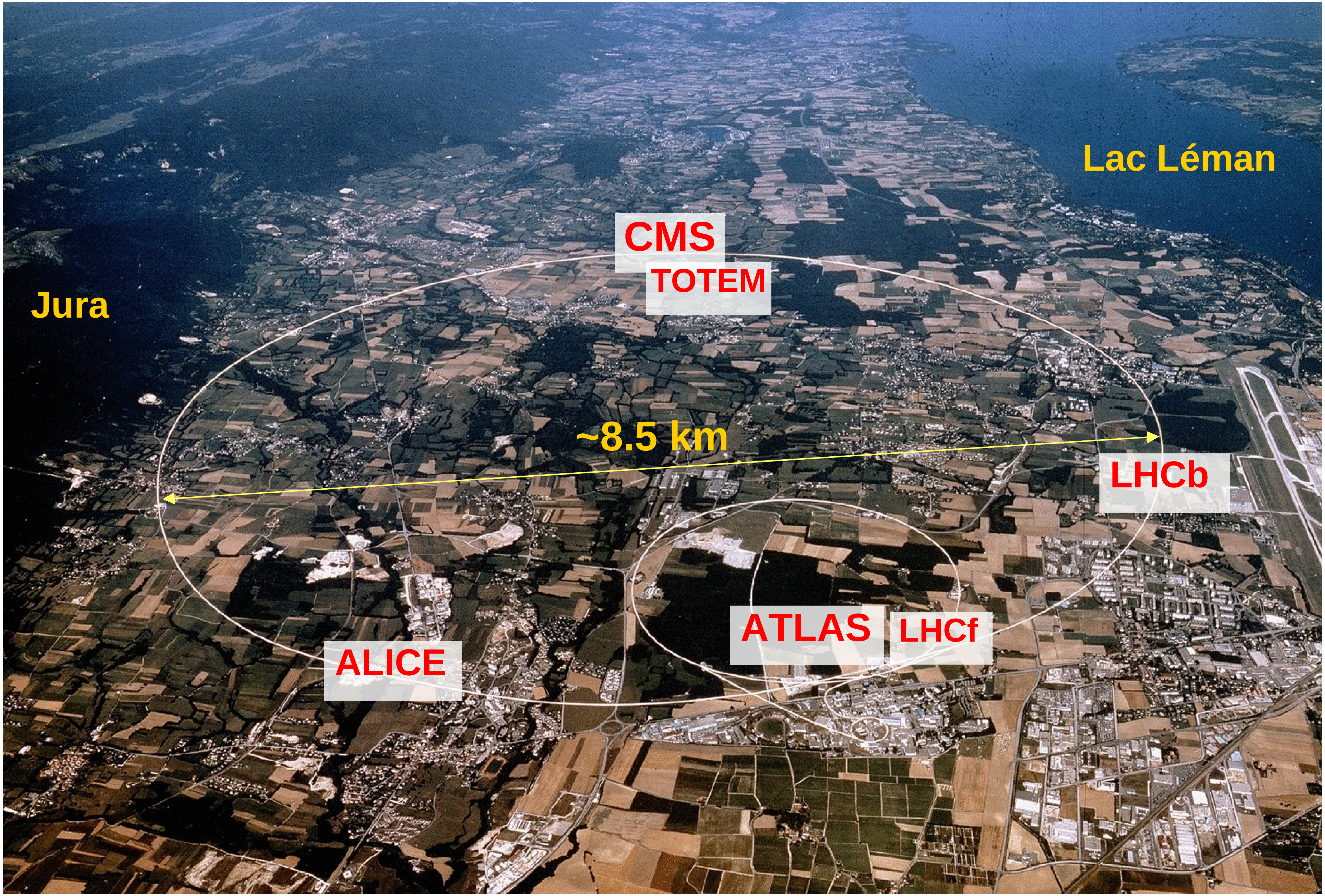
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{\rm em}Q^8}\left[xG_A(x,Q^2)\right]^2$$

Mass of J/ψ 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: $x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2}$

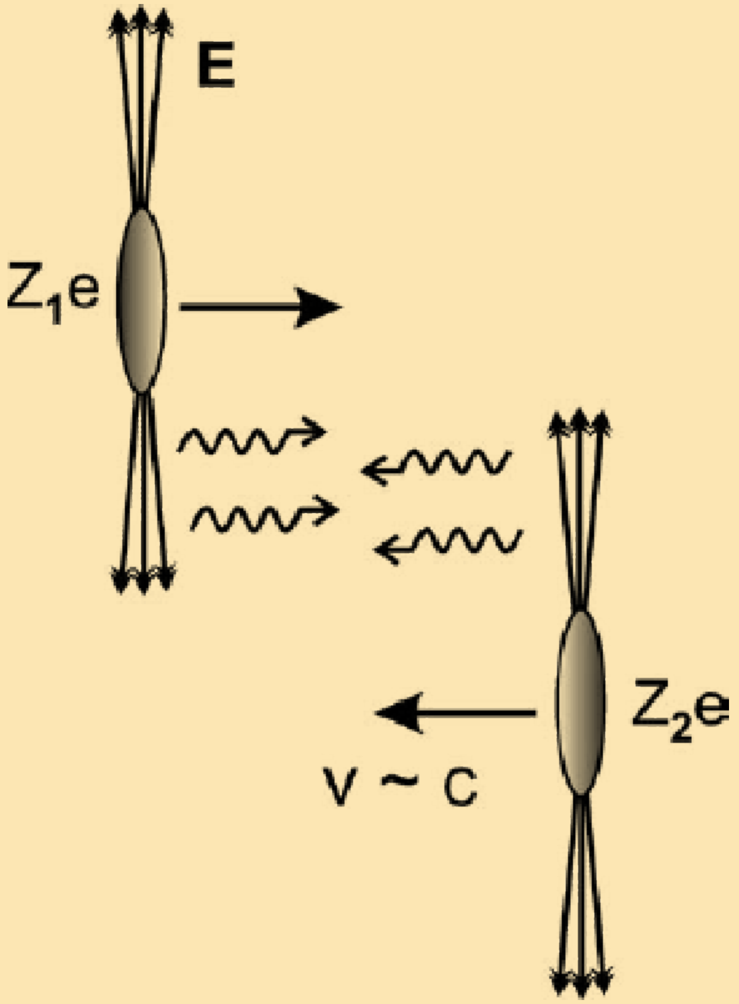
Also a more recent calculation

T. Lappi, H. Mäntysaari
http://arxiv.org/abs/1301.4095


Lac Léman
CMS
TOTEM
Jura
~8.5 km
LHCb
ATLAS
LHCf
ALICE

What is an UPC?

- Range of strong interaction $\sim 1/m_\pi \sim 1\text{fm}$
- Range of electromagnetic force ∞
- Impact parameter $b > 2R_A$
  $\Longrightarrow$ **photon-nucleus** collision
  $\Longrightarrow$ Just like DIS, only $Q^2 = 0$
- Look for **exclusive** events: A intact
- Signature: “two muons in an otherwise empty detector”



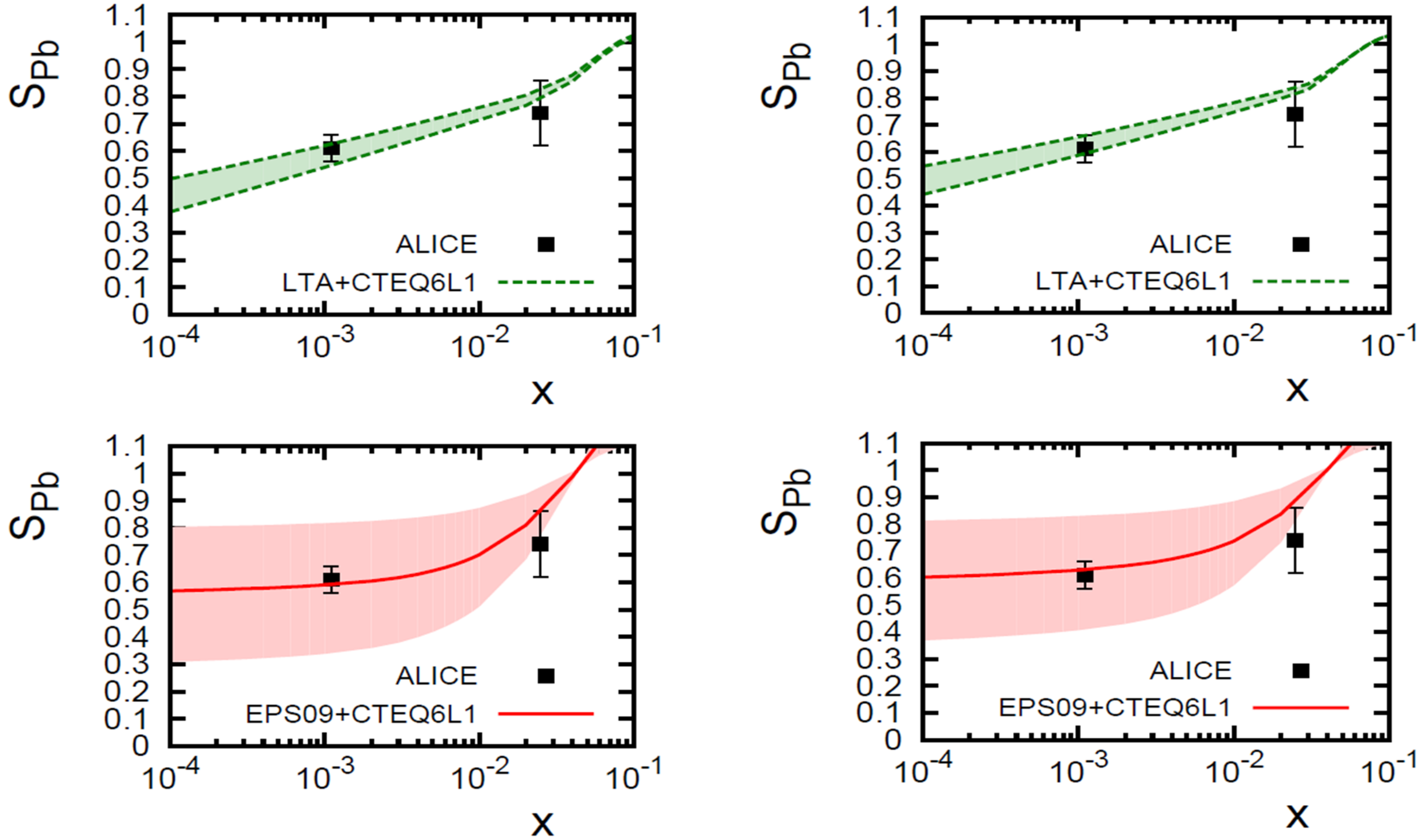
- In DIS: Q^2 provides hard scale $\Longrightarrow$ QCD perturbation theory
- In UPC: hard scale e.g. from heavy quark $\Longrightarrow$ quarkonia

T. Lappi
IS conference. Dec 2014

Scale dependence

- Studied in detail in Guzey, Zhalov: JHEP 1310 (2013) 207.
- Scale of 3 GeV^2 found to be most appropriate for the description of J/ψ photoproduction data

2.4 GeV^2 3 GeV^2



EPS09, variation of scale by factor 4:

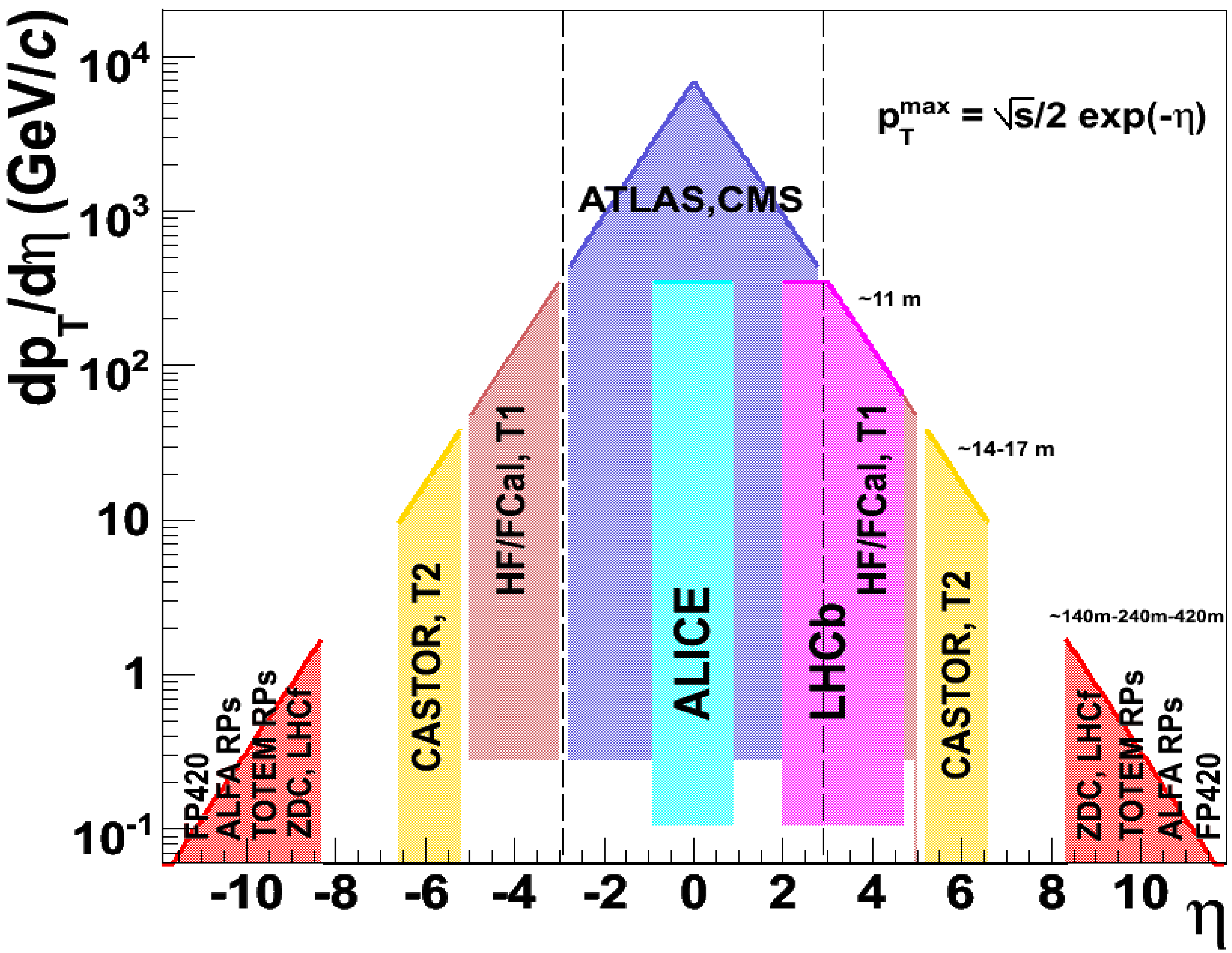
$R(x=0.011, Q^2 = 2.4\ GeV^2) = 0.569$

$R(x=0.011, Q^2 = 9.6\ GeV^2) = 0.671$

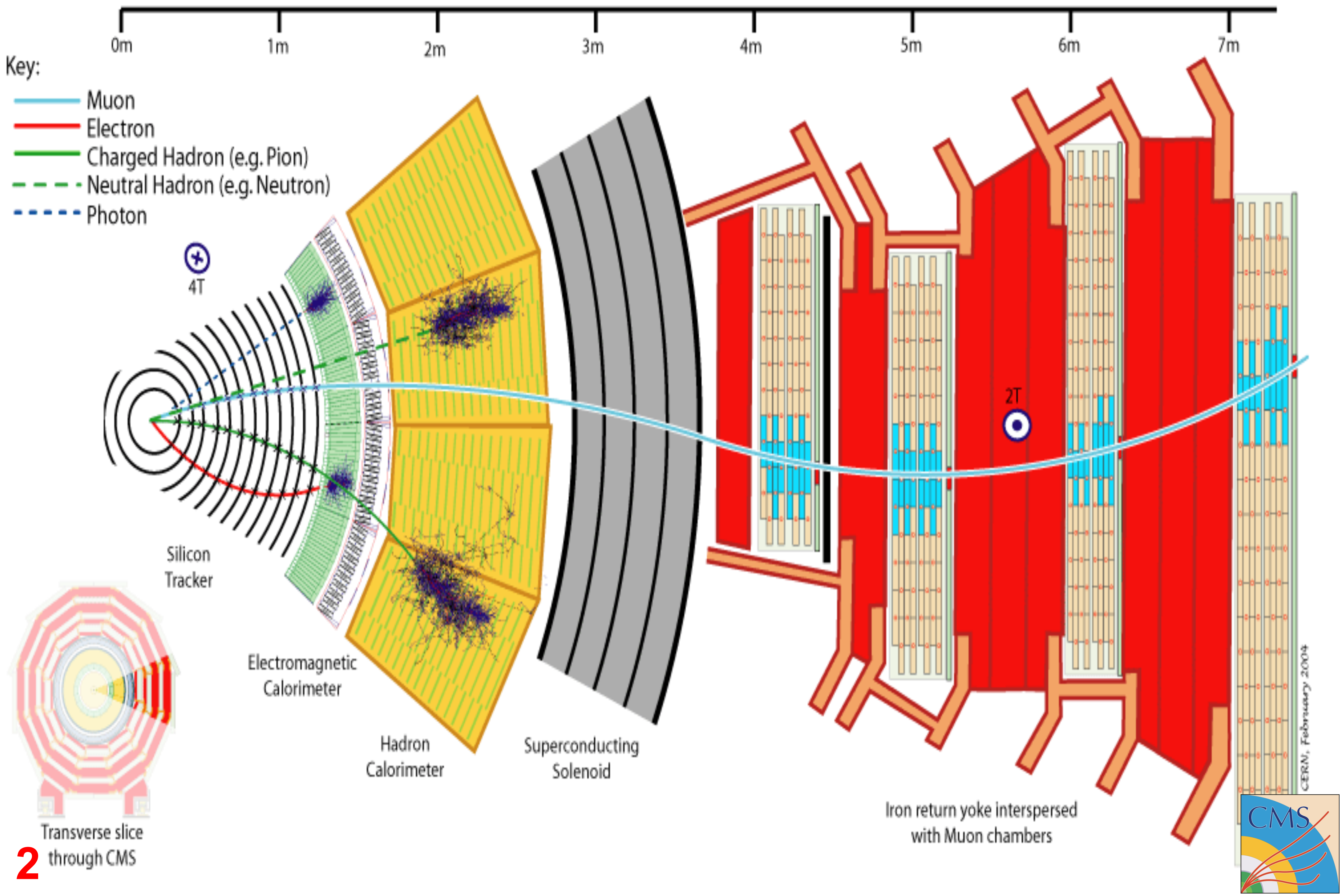
Future measurements of heavier vector mesons (ψ', Υ) will further elucidate the importance of the scale

Forward physics at LHC

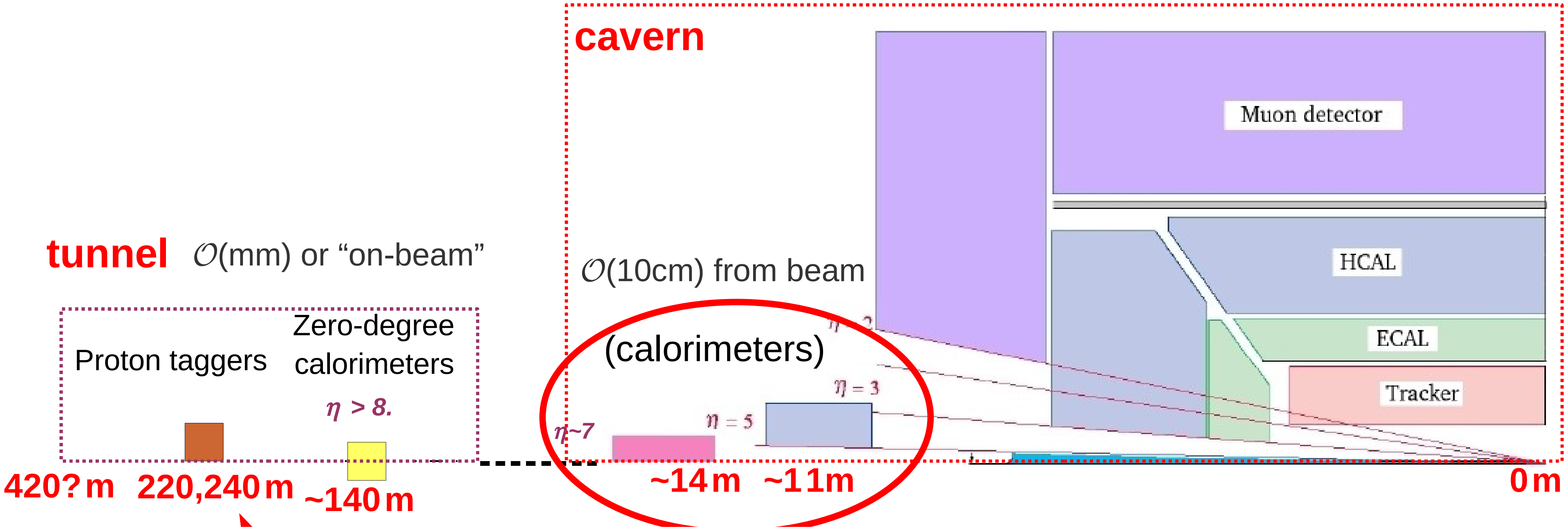
DdE, arXiv:0708.0551



A transverse slice through CMS

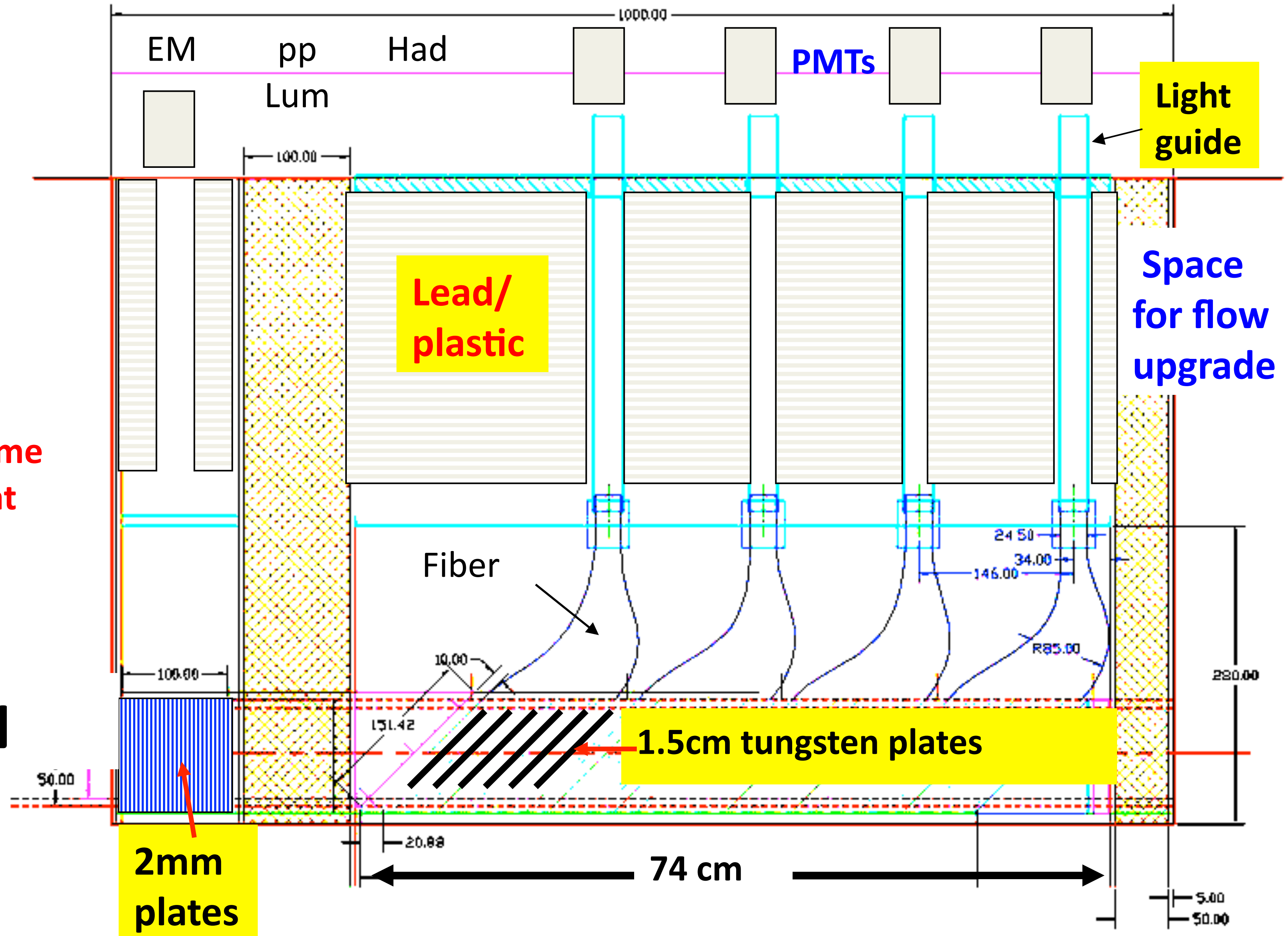


Forward physics at CMS



Side View of ZDC

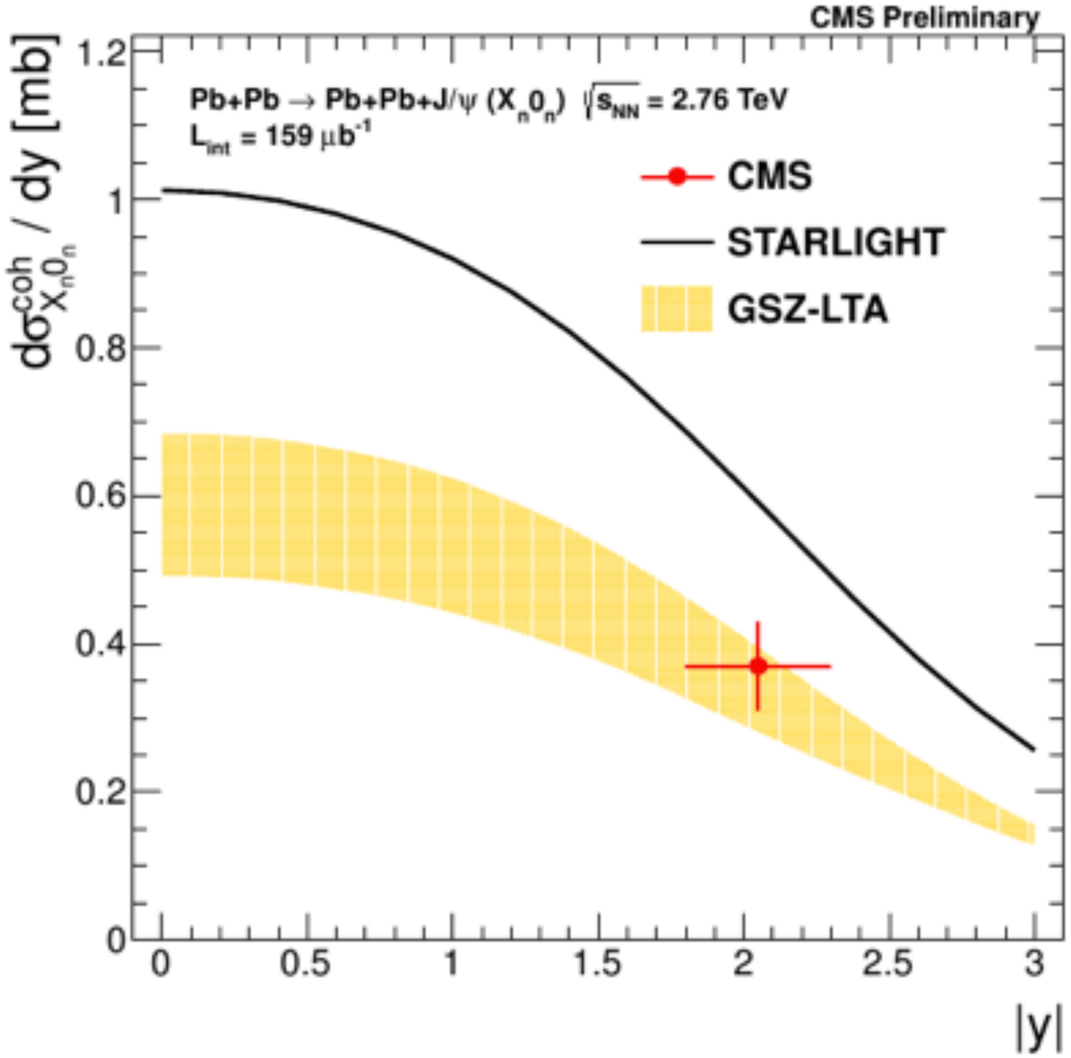
- Quartz fibers and tungsten absorber Cherenkov detectors
- 140 meters from interaction point on either side
- Total of 18 channels
  - 5 electromagnetic sections each segmented transverse to the beam
  - 4 hadronic sections segmented longitudinally



5 5 Jan 201

Coherent J/y Cross Section in PbPb UPC

NEW



- Cross section measured for events with single sided neutron emission, the Xn0n break-up mode
- X_n0_n is the largest cross section available given ZDC trigger requirement

$ds/dy(coh/X_n0_n) = 0.37\pm0.04(stat)\pm0.04(syst)mb$

P. Kenny
IS conference. Dec 2014

Break-up Modes Ratios

NEW

J/ψ with $p_T < 0.15$ GeV/c	X_nX_n/X_n0_n	$1_n0_n/X_n0_n$	$1_n1_n/X_n0_n$
Data	0.36 ± 0.04	0.26 ± 0.03	0.03 ± 0.01
STARLIGHT	0.37	N/A	0.02
GSZ	0.32	0.30	0.02

First measurement of break-up ratios for UPC J/y

X_n0_n single-sided neutron emission with any number of neutrons

X_nX_n double-sided neutron emission with any number of neutrons

1_n0_n single-sided neutron emission with only one neutron

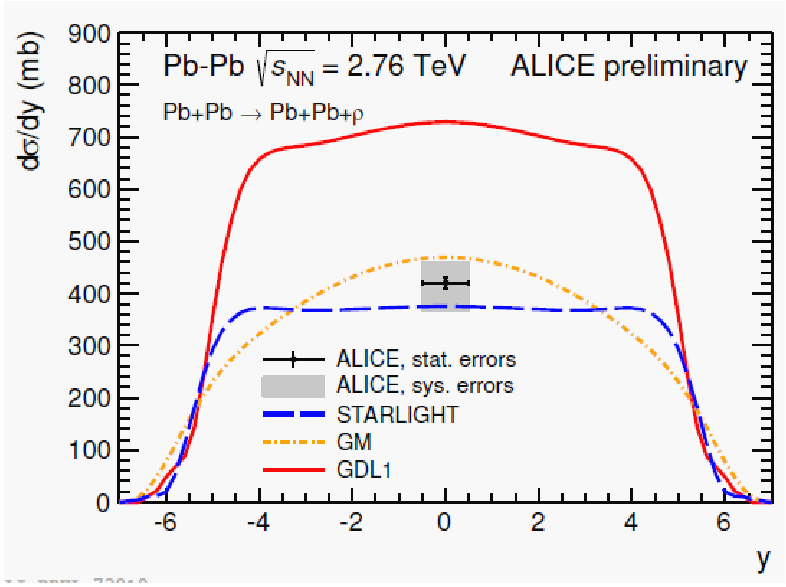
1_n1_n double-sided neutron emission with only one neutron on each side

The multiple photon-exchange model of nuclear break-up in coherent interactions describes the data reasonably well

P. Kenny
IS conference. Dec 2014

Cross-sections below Quantum Glauber?

- σ(γA->ρA) should be calculable by a quantum Glauber calculation, with input from σ(γA->ρA)
  - σ(γA->ρA) fixed (or checked) by HERA
- Both ALICE & 62 & 200 GeV STAR measurements find σ's ~40% lower
- Quantum Glauber approach should be straightforward
  - Works OK at lower (fixed target, k~10 GeV) energies
- Evidence that nuclei do not behave like individual nucleons?
  - Is pQCD applicable at low Q^2
    - Shadowing??



ALICE data presented by C. Mayer at the Wkshp. on Photon induced collisions at the LHC (2014).

S. Klein
IS conference. Dec 2014

LHC schedule

LHC goal for **2015 and for Run 2 and 3**

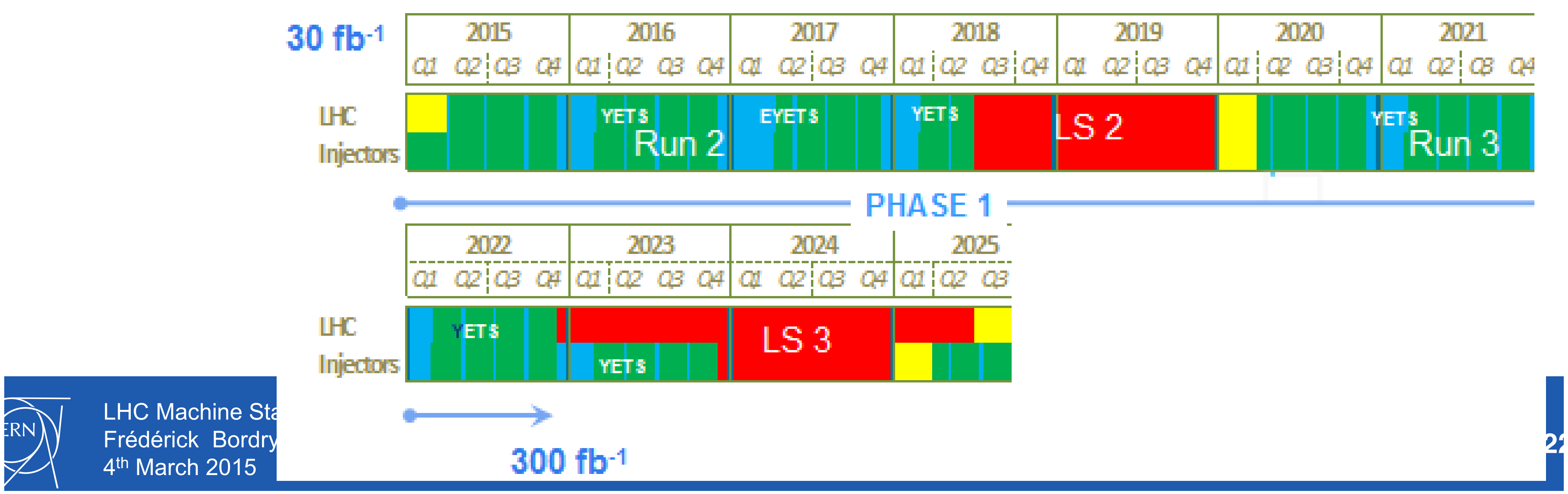
Integrated luminosity goal:

2015 : 10 fb^{-1}

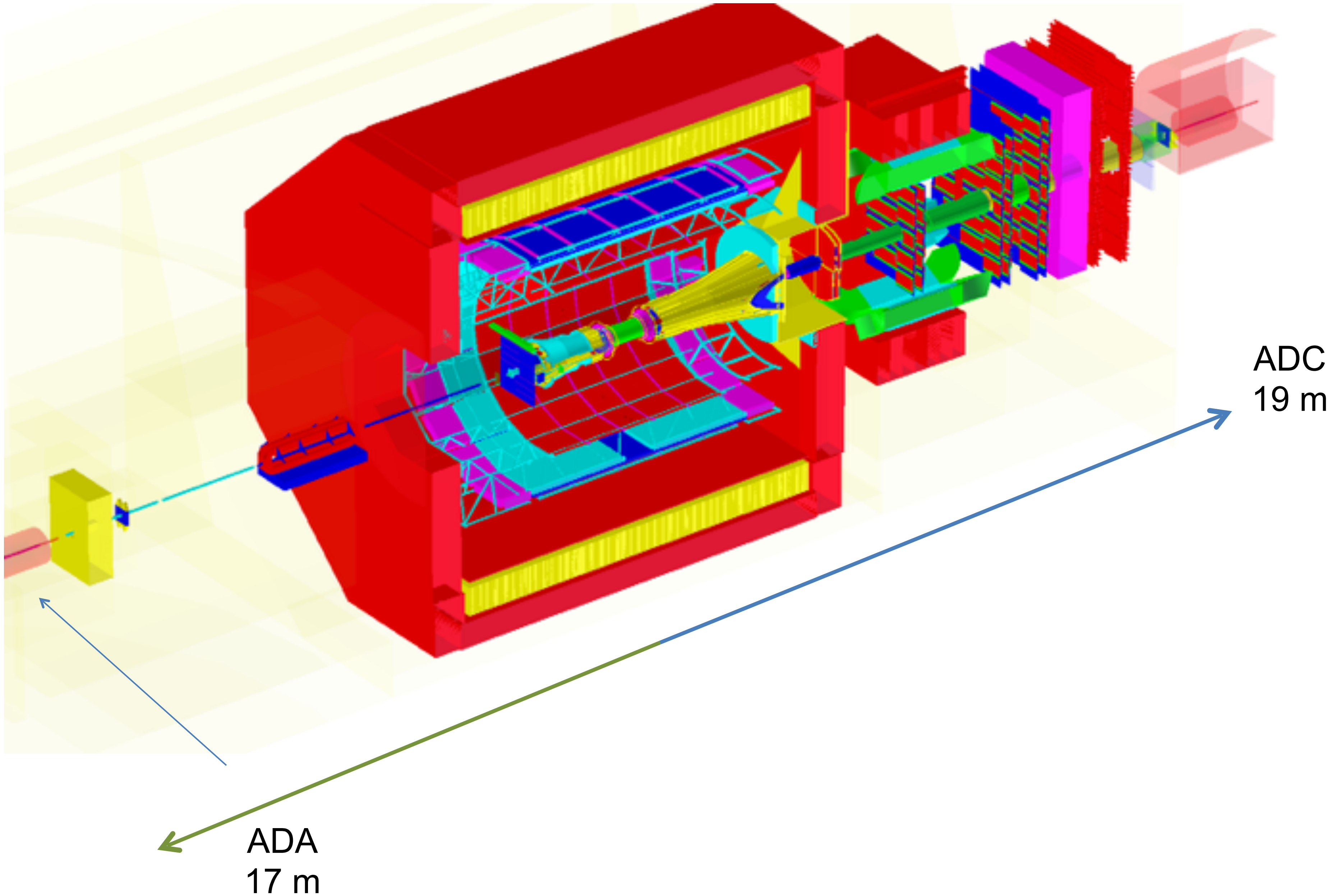
Run2: ~100-120 fb^{-1}

(better estimation by end of 2015)

300 fb^{-1} before LS3

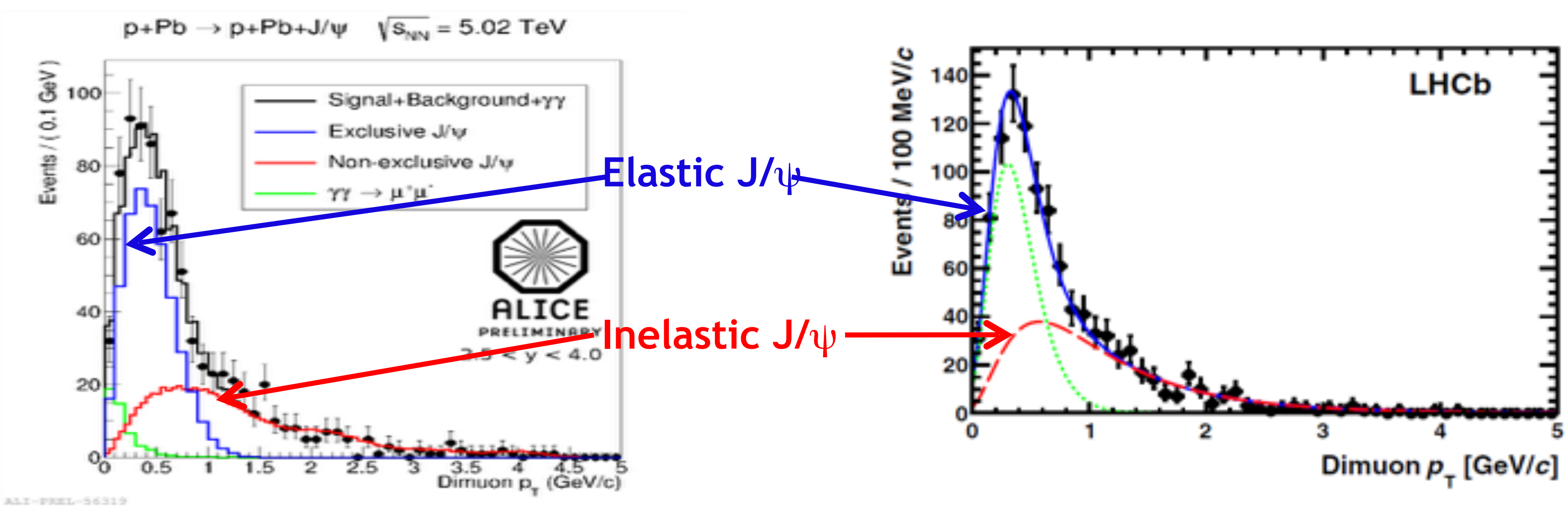


Ongoing projects at ALICE: ADA/ADC

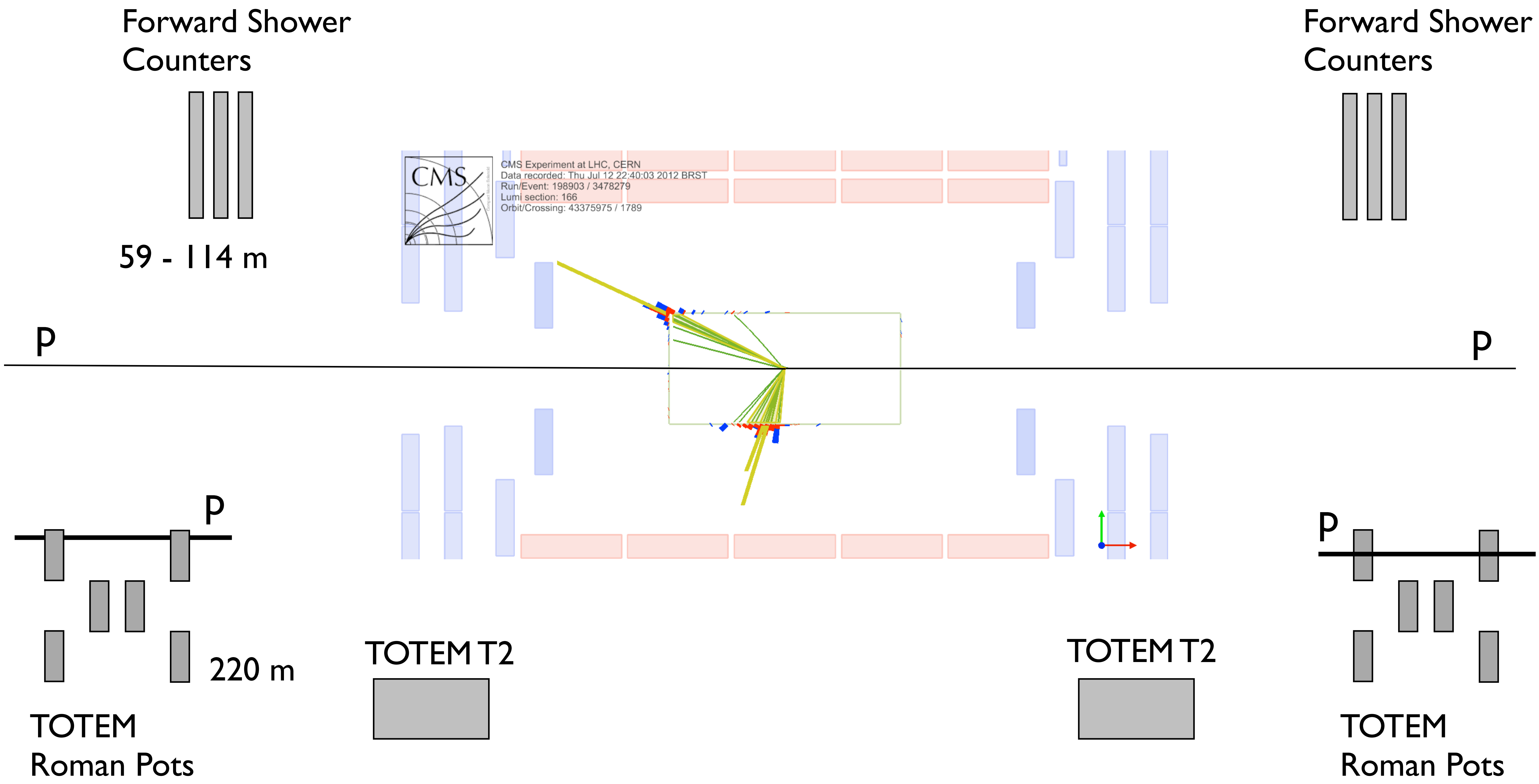


J/ψ in ultra-peripheral pp and p-Pb collisions

- Exclusive J/ψ photoproduction measured by ALICE in p-Pb (Pb as a source of photons) and by LHCb in pp. ALICE can also measure J/ψ photoproduction in pp in run2 ($\sqrt{s}$ = 13 TeV)
- Experimentally events with only two muons are selected by applying vetos on central and forward detector activity
- Inelastic J/ψ are characterized by broader pt distribution, but separation of inelastic and elastic contributions is a delicate task
- **ADA and ADC detectors will help to suppress inelastic contribution**



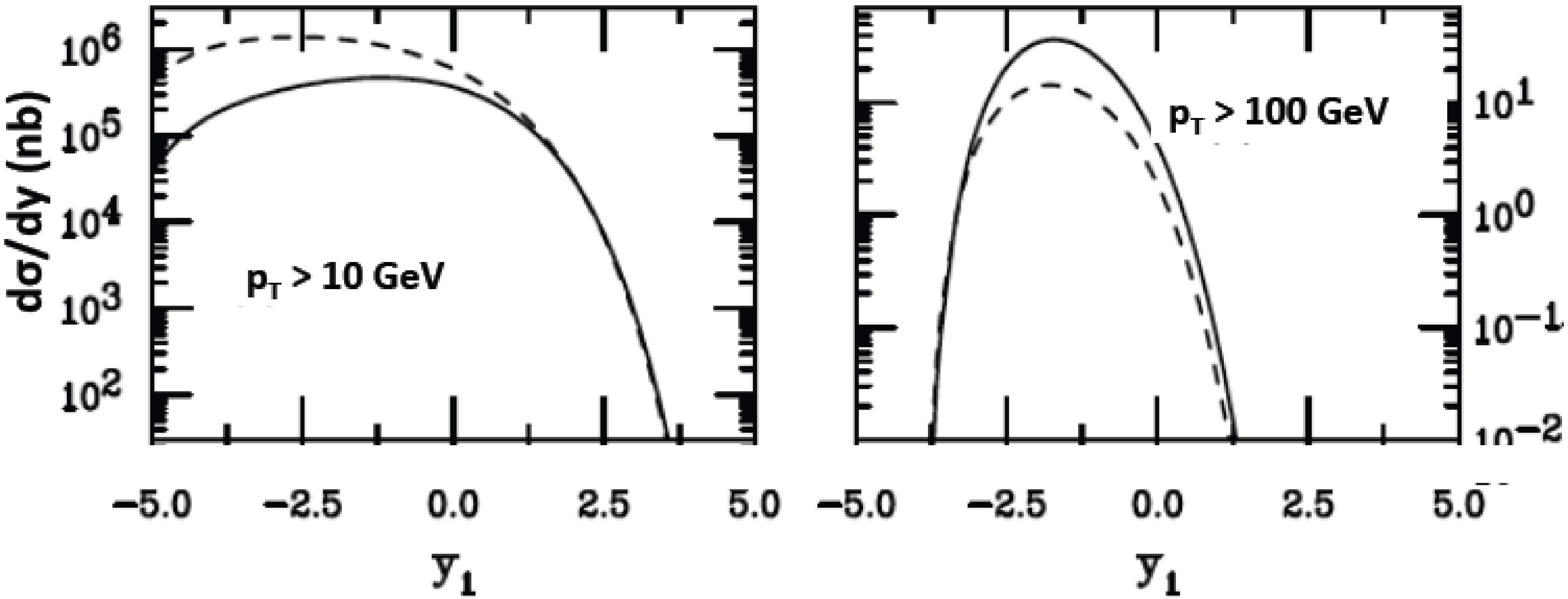
Dijet: CMS+TOTEM



CMS: |η| < 5 **T2: 5.3 < |η| < 6.5** **FSC: 6 < |η| < 8** **TOTEM RP**

very large rapidity coverage !

Dijet production in UPC



The photon is coming from the left and its direction can be resolved by the correlation with neutrons in the ZDCs.

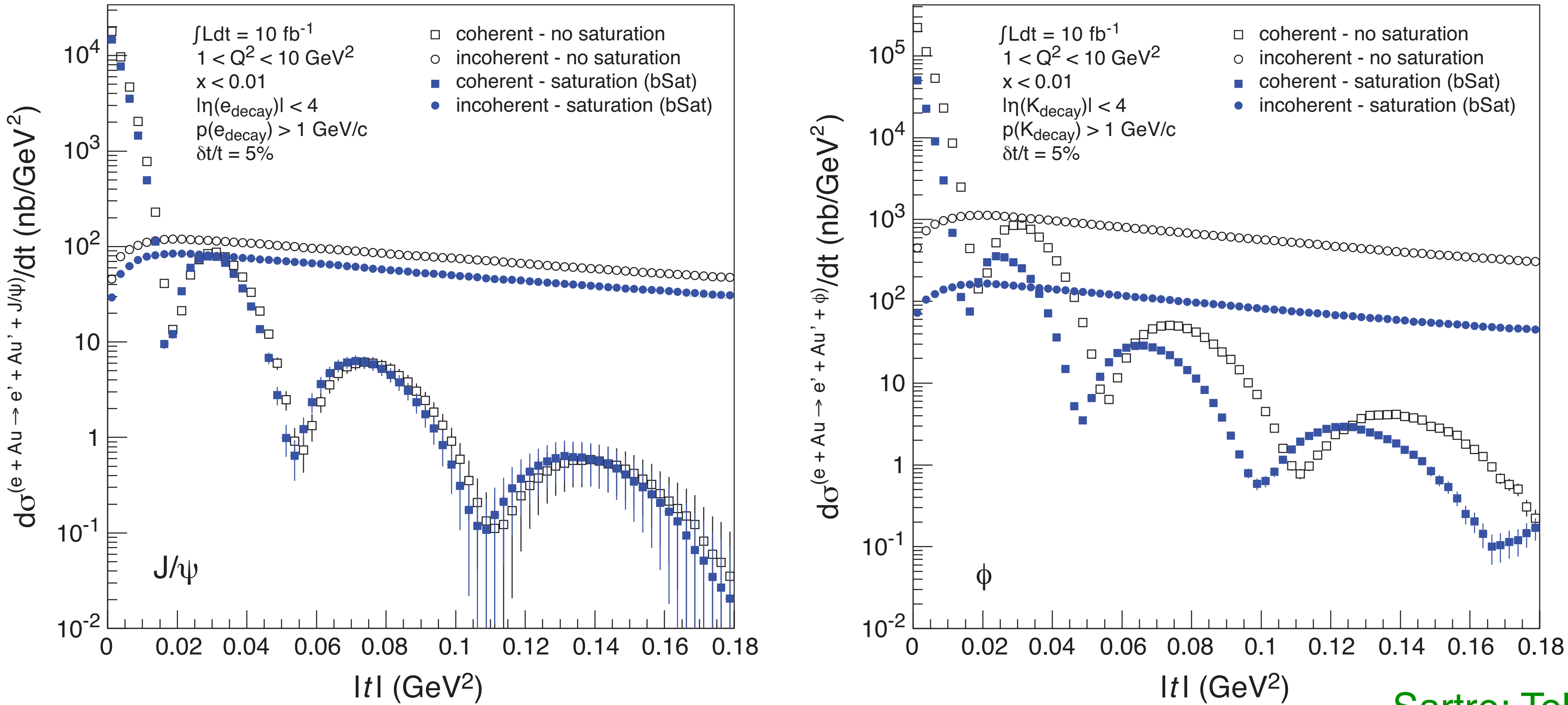
In the direct process (solid), the entire photon energy contributes to the hard process while in the resolved case (
part does.

UPCs and the EIC

- UPCs are a 'limiting case' of EIC physics
  - Almost real photons
  - No tagging
- UPC data for many channels are available now
  - No need to wait
  - Other channels can be studied with improved triggering
- At the very least, this is a good testbed for EIC physics

S. Klein
IS conference. Dec 2014

Exclusive Vector Meson Production in e+A



Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations

➡Need good breakup detection efficiency to discriminate between the two scenarios

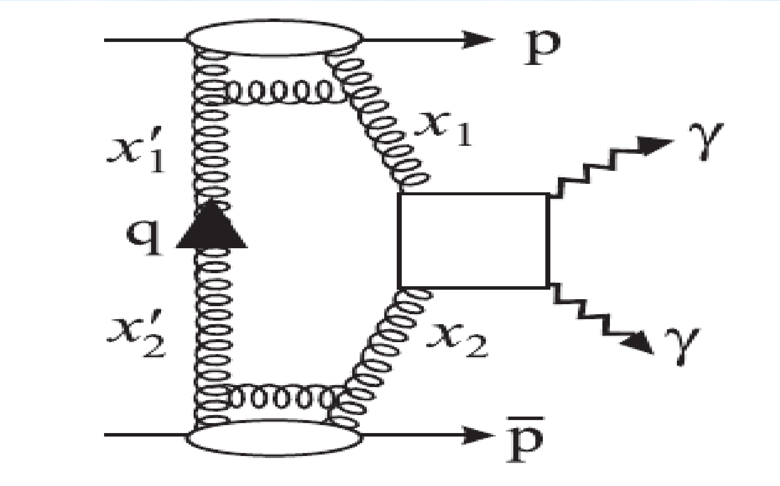
- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

IS2014: macl@bnl.gov 29

Exclusive production in pp vs. AA

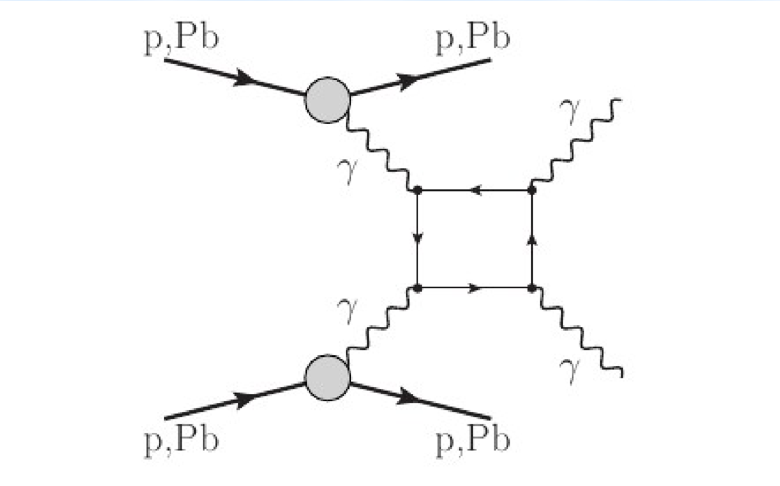
Different production mechanisms may dominate. Consider exclusive $\gamma\gamma$ (or Higgs) production:

p-p



V. A. Khoze, A.D. Martin, M.G. Ryskin, W.J. Stirling, Eur. Phys. J C 38 (2005) 475.

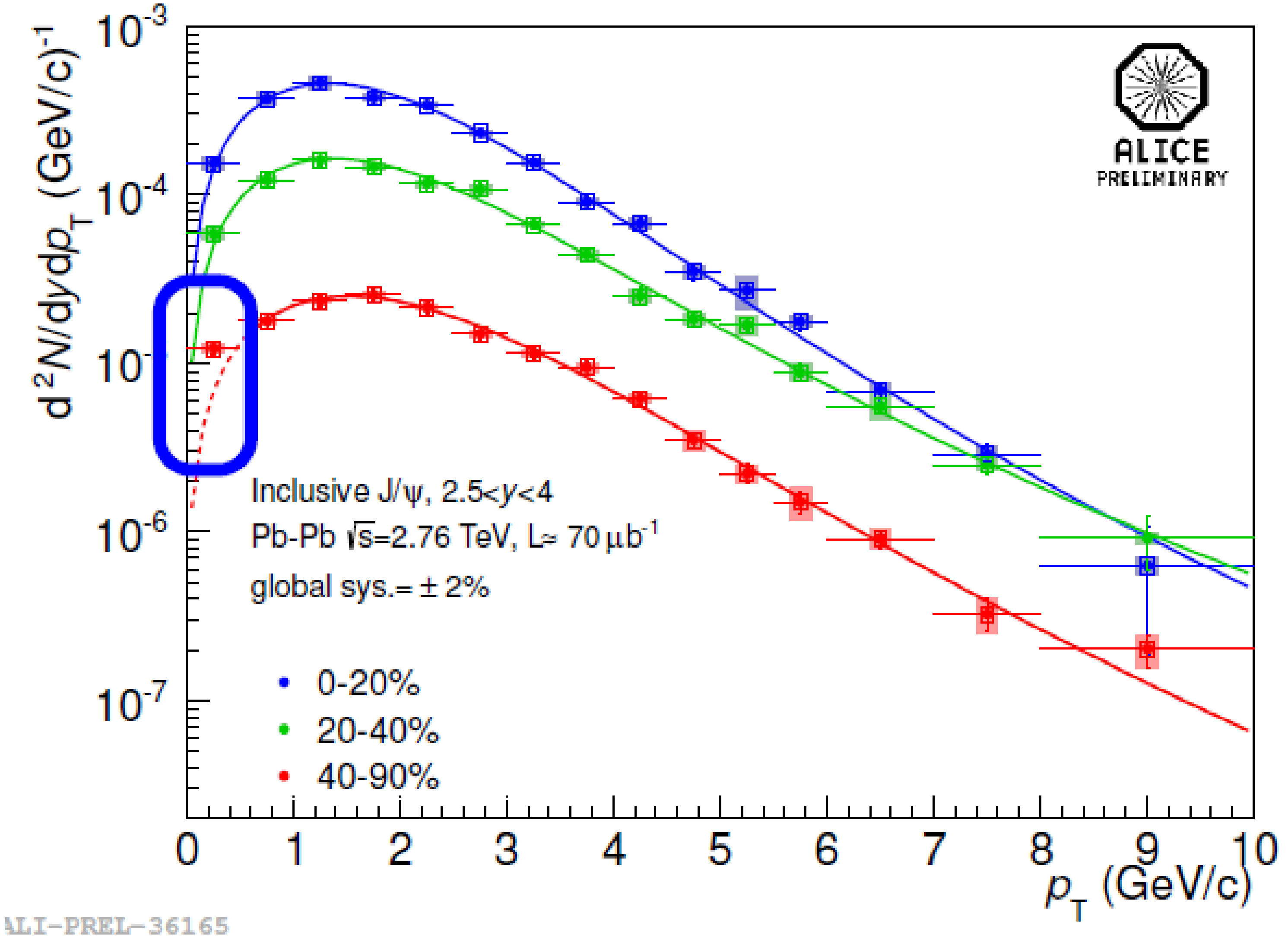
Pb-Pb

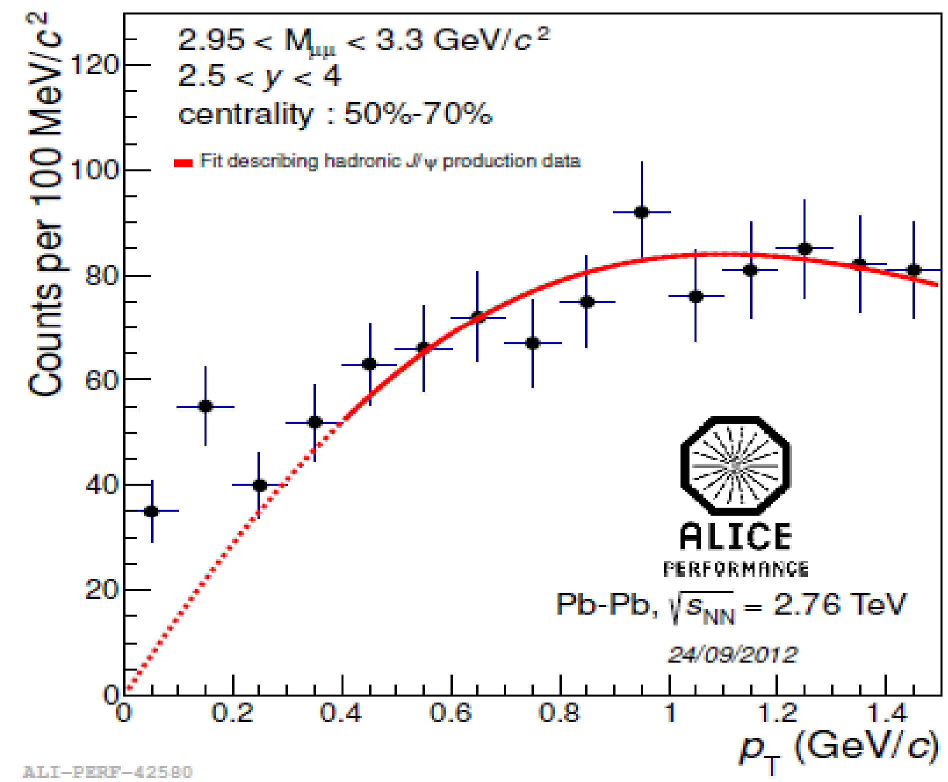


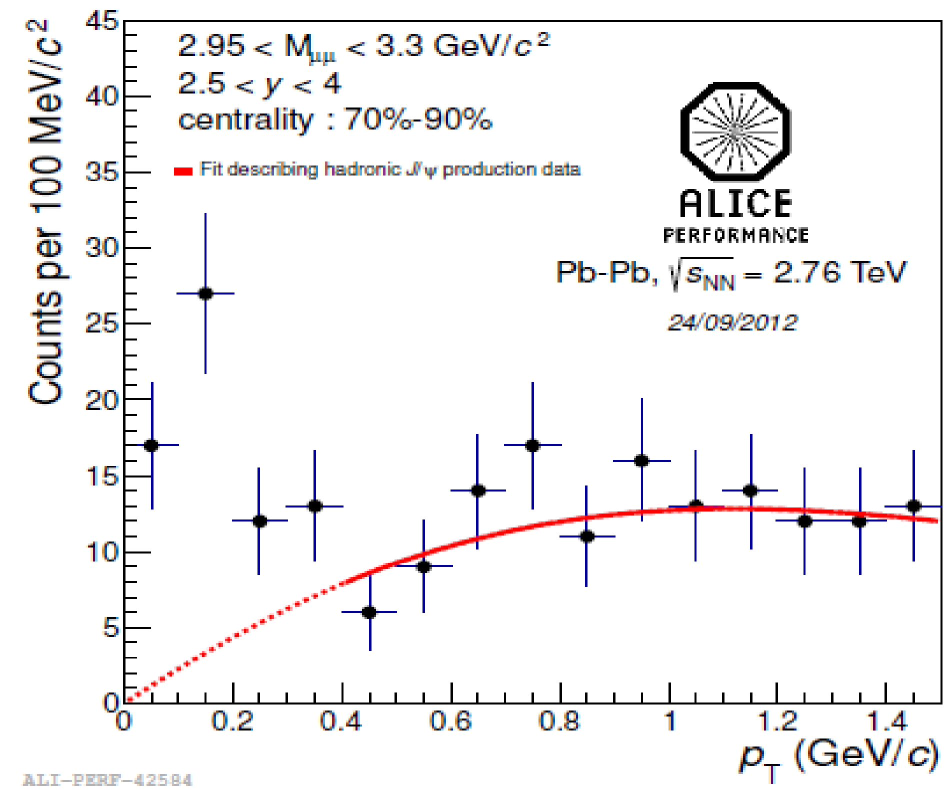
D. d'Enterria, G.G. Silveira, PRL 111 (2013) 080405.

In p-p collisions, 3 (or more) gluon exchange dominate, whereas for heavy-ion collisions, $\gamma\gamma\rightarrow\gamma\gamma$ dominate.

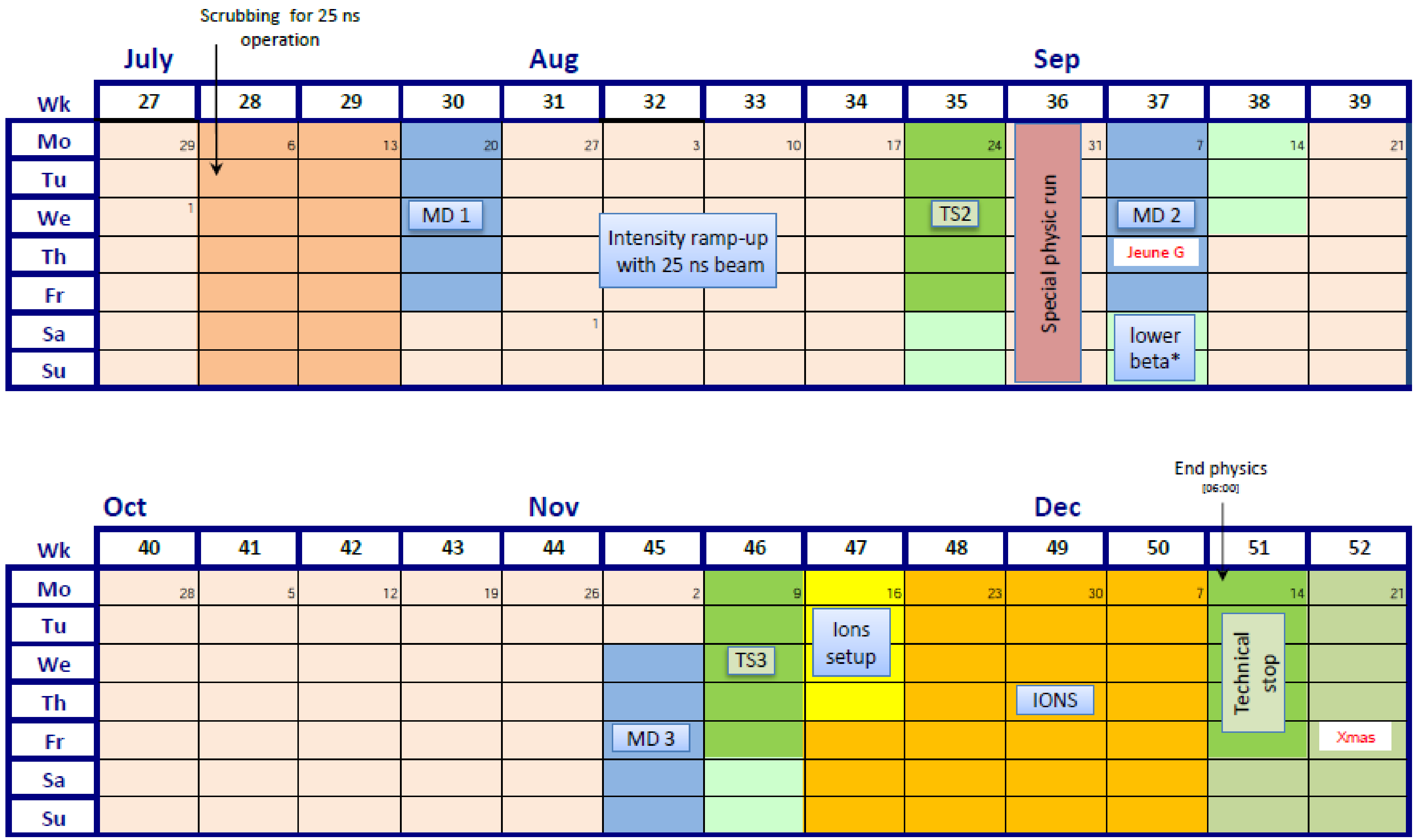
UPC in inclusive peripheral Pb-Pb at forward rapidity?!



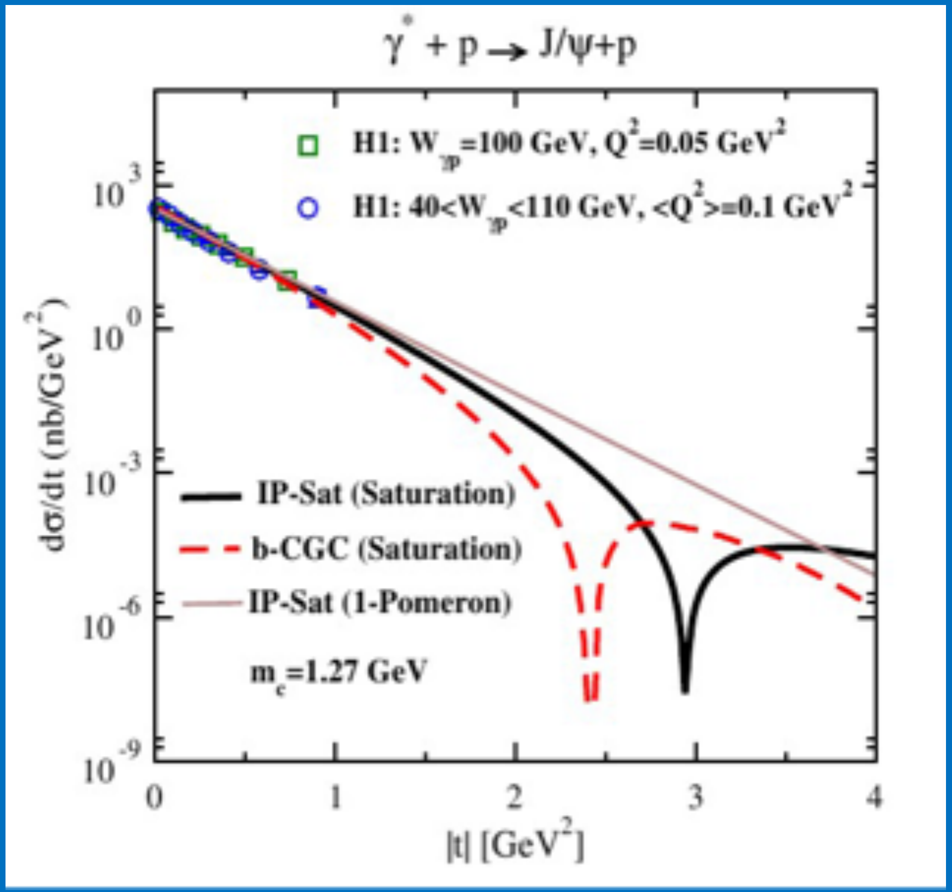




HI and special pp runs in 2015



- 4 day floating MD removed
- Otherwise as was



J/Ψ with high statistics

N. Armesto, A.H. Rezaeian, Phys. Rev. D 90 (2014) 054003:

t (=p_T^2) distribution of differential cross sections of photo-production of vector mesons may discriminate among saturation and non-saturation models.
→ dip (or multiple dips) in the t distribution of diffractive photoproduction of vector mesons"

J/Ψ rapidity tag

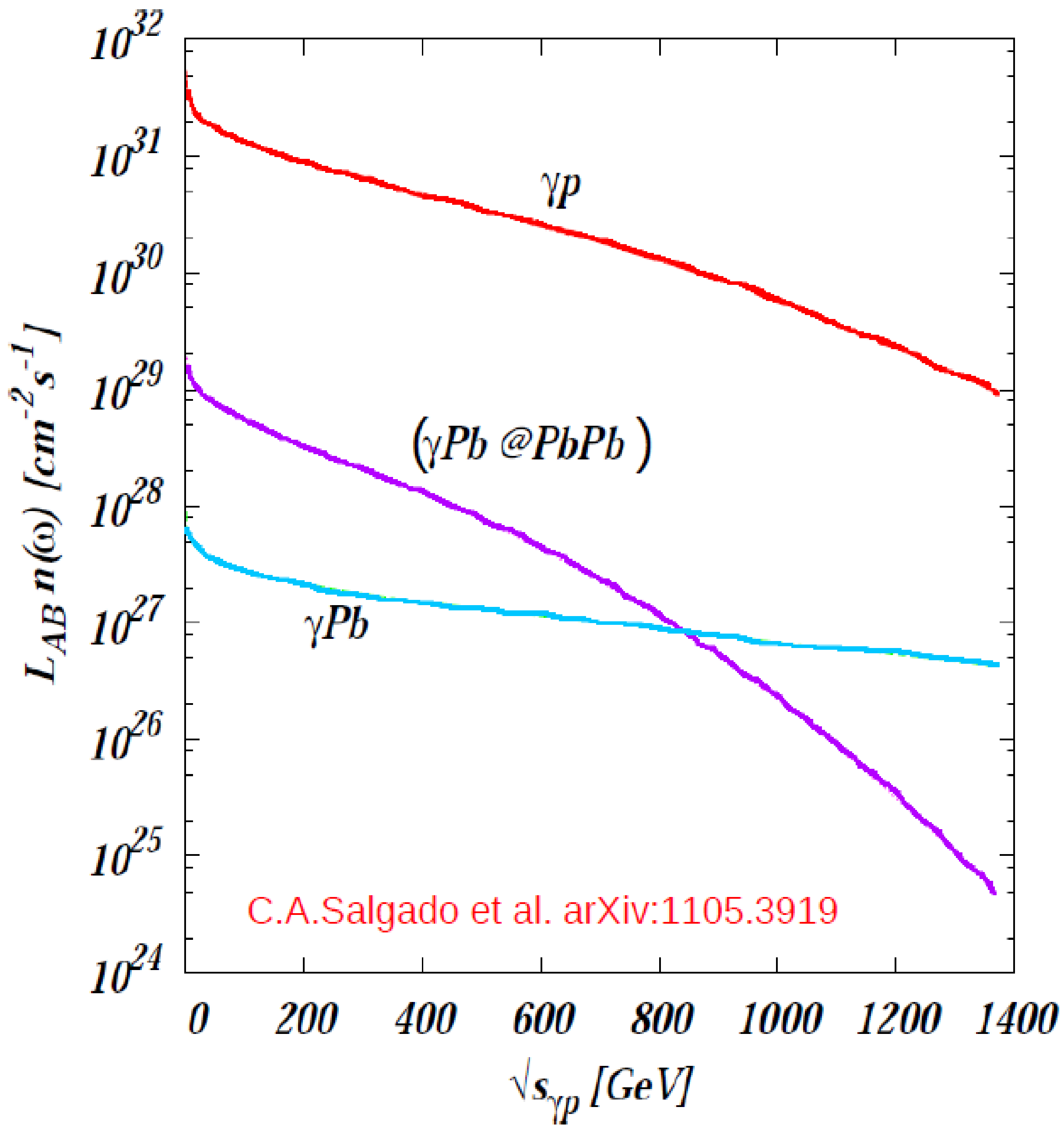
- At forward rapidity we have contributions both from x ~10^{-2} (95%) and 10^{-4} (5%), depending on the Pb nucleus emitting the photon.
  → tagging by using ZDC activity, see arXiv:1109.0737 → Gluon shadowing at 10^{-4} feasible !

→ Run2: 2,500 J/Ψ * 5 % * 30 % ~ 40 tagged J/Ψ at x ~10^{-4} (1 nb^{-1})

E. Scapparone
IS conference. Dec 2014

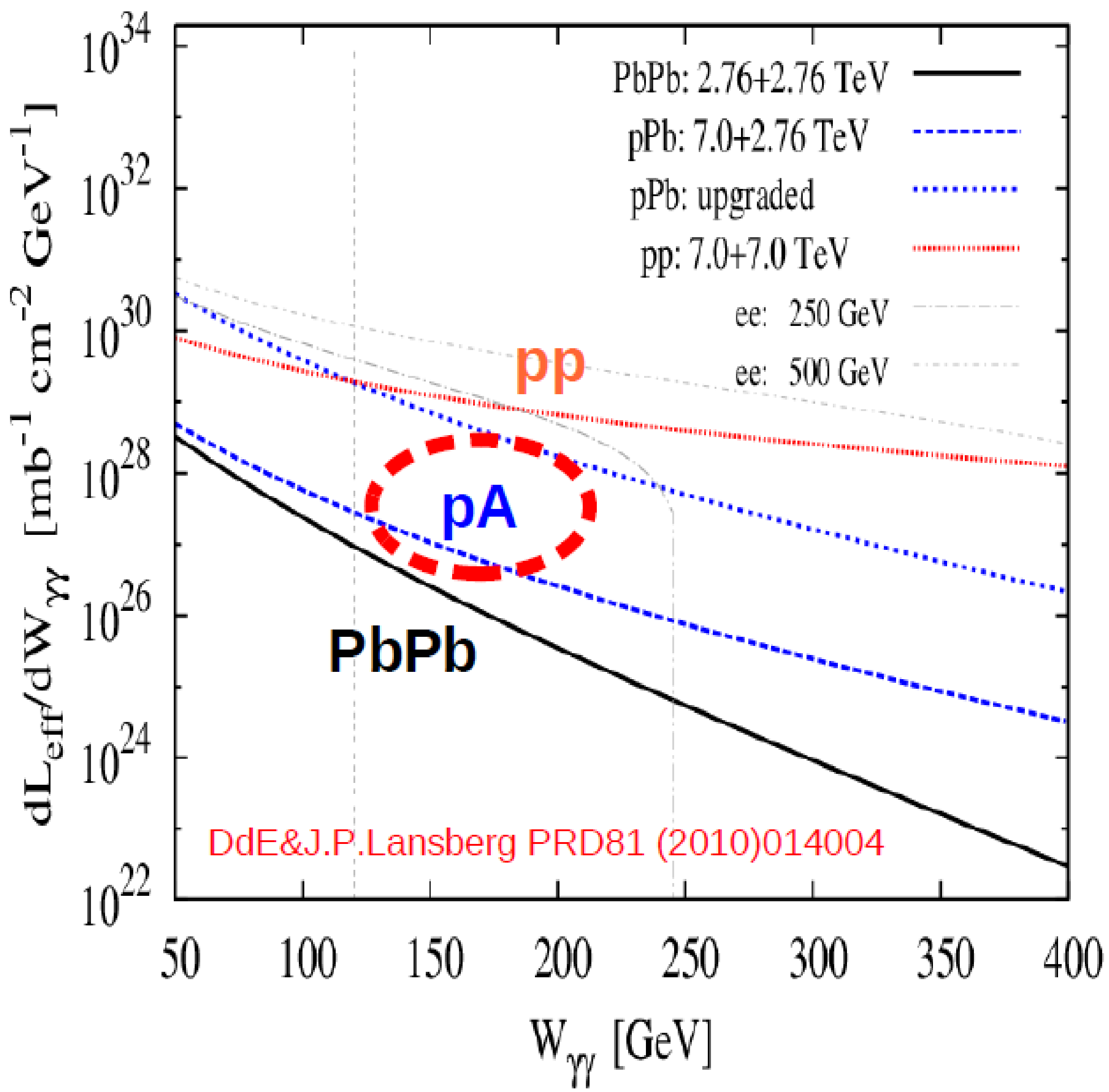
Effective luminosities in UPC

p-Pb @ 8.8 TeV



Beyond ~1 TeV scale

p-Pb vs p-p,Pb-Pb,e^+e^-



$$\mathcal{L}^{eff}_{\gamma\gamma} \equiv \mathcal{L}_{AB}\, d\mathcal{L}_{\gamma\gamma}/dW_{\gamma\gamma}$$

Photon-induced interactions in eA vs. in pA or AA

- Energy reach very favorable in UPC:

LHC: $W_{\gamma N} \leq 500$ GeV for γA (Pb-Pb collisions)

$W_{\gamma N} \leq 1500$ GeV for γp (p-Pb collisions)

MEIC: $W_{\gamma N} \sim 15\text{-}70$ GeV

eRHIC: $W_{\gamma N} \sim 50\text{-}100$ GeV

LHeC: $W_{\gamma N} \sim 1300$ GeV (γp); 800 GeV (γA) [$E_e = 60$ GeV]

- UPC restricted to photoproduction ($Q^2 \approx 0$) because of the Form Factor.

Joakim Nystrand, Poetic V, New Haven, Connecticut 22-26 September 2014. 4