Rapidity dependence of coherent J/ψ

Daniel Tapia Takaki

IPN Orsay – Université Paris-sud

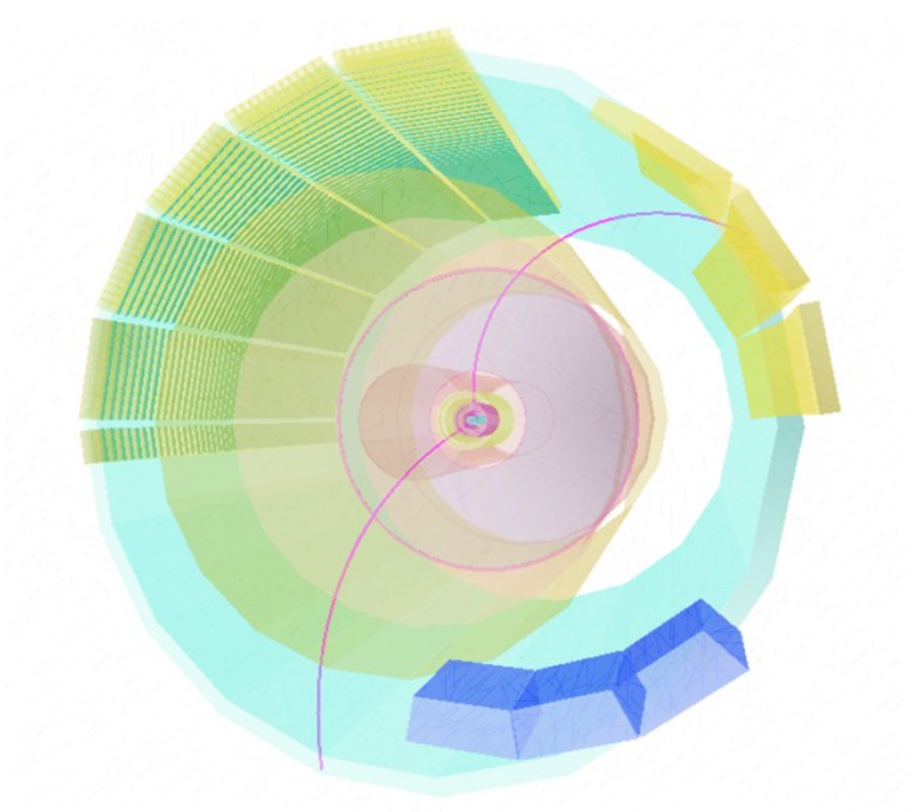
Rencontres Ions Lourds

Saclay, 21 February 2013

Plan of this talk

Ultra-Peripheral collisions (UPC)

- lead-lead
- proton-lead



Summary

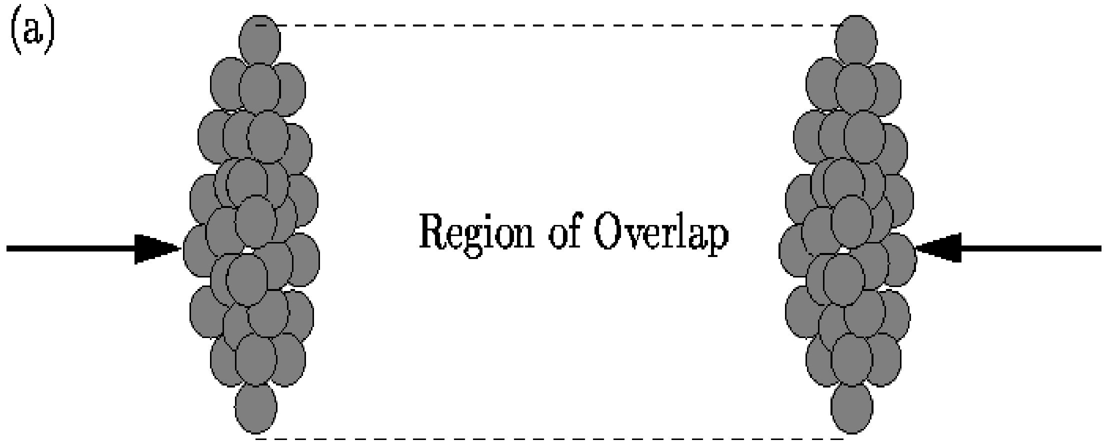
Using the LHC as a $\gamma\gamma$, γPb, γp collider

The most powerful collider not only for pp and Pb-Pb collisions, but also for <u>photon-photon and photon-hadron interactions</u>

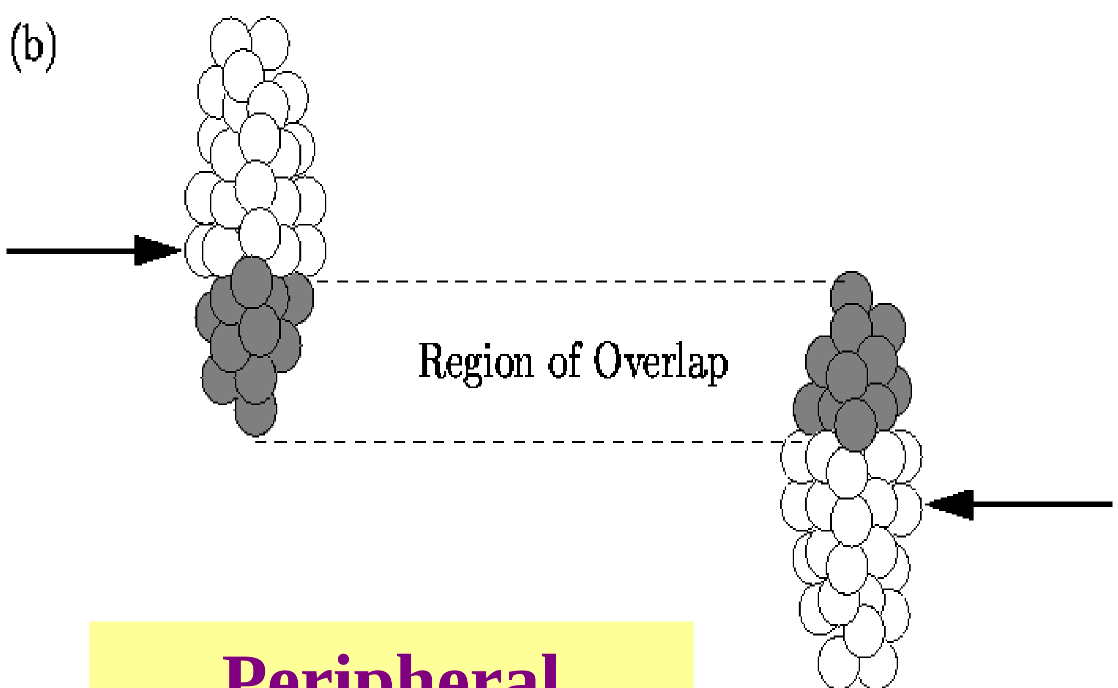
Using the LHC as a γγ, γPb, γp collider

UPCs in Pb-Pb

Terminology in heavy-ion collisions



Central collision



Peripheral collision

Collision Centrality

- Describes the overlap of two incoming ions at the point at which they collide
- The more central the collision, the greater number of participating nucleons (N_{part} or N_{wound})
- Energy of system increases with collision centrality

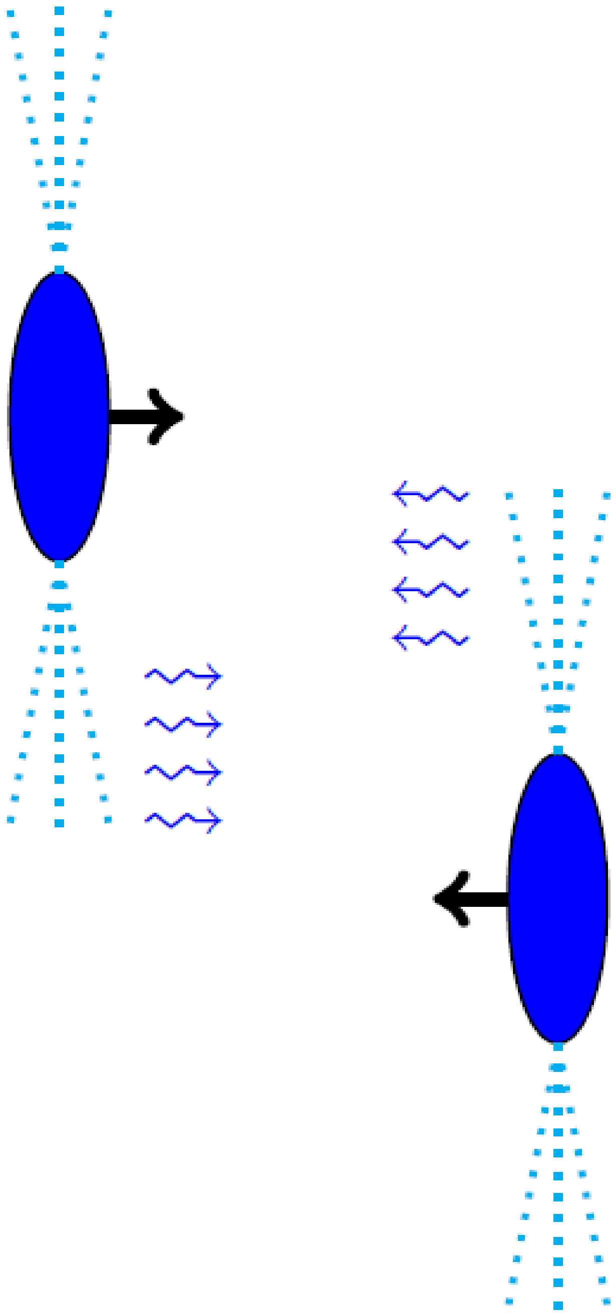
Multiplicity

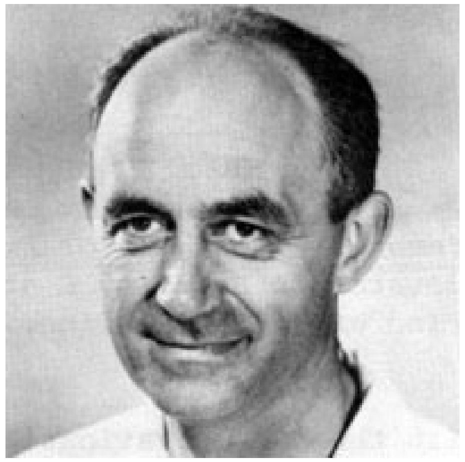
- Number of charged particles produced in the collision

If this is a peripheral collision ….

Here is a ultra-peripheral collision ...

Why Ultra-Peripheral collisions



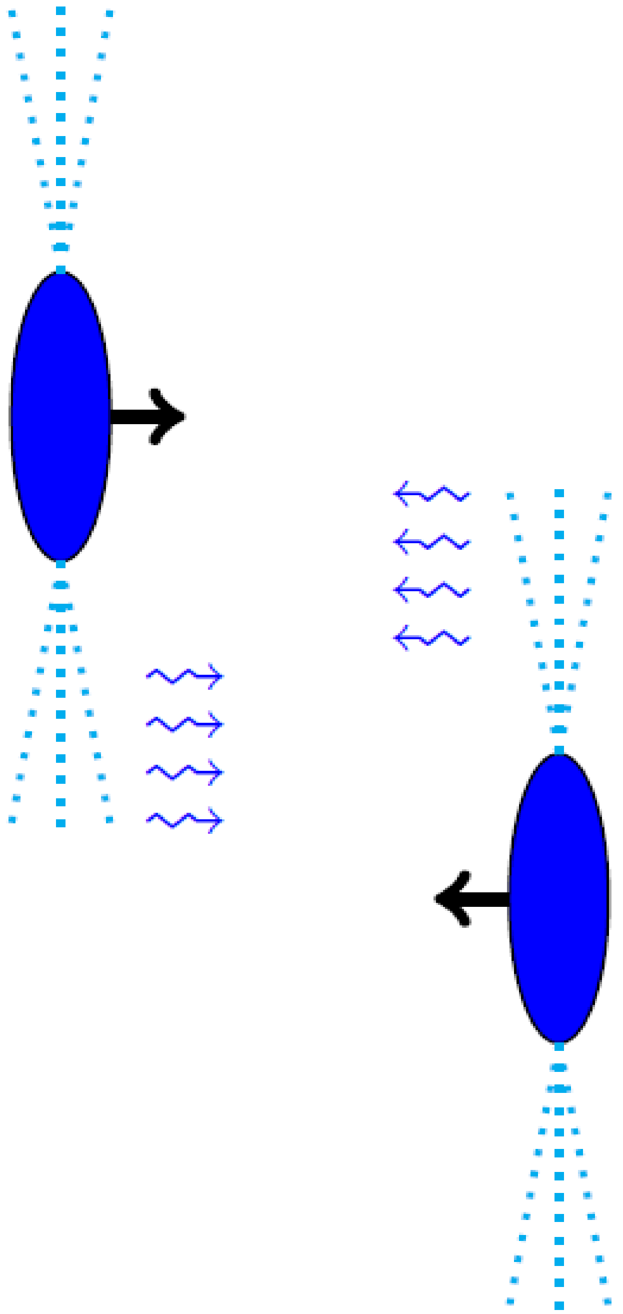


Enrico FERMI

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

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

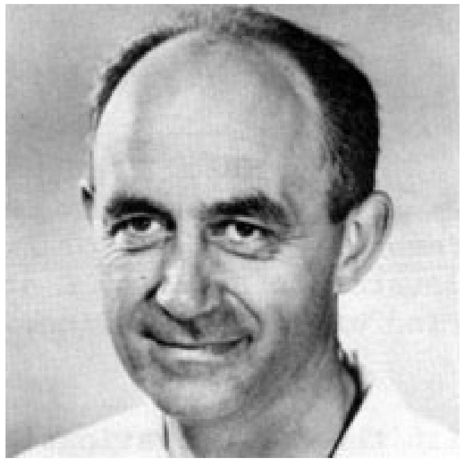
Why Ultra-Peripheral collisions



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.

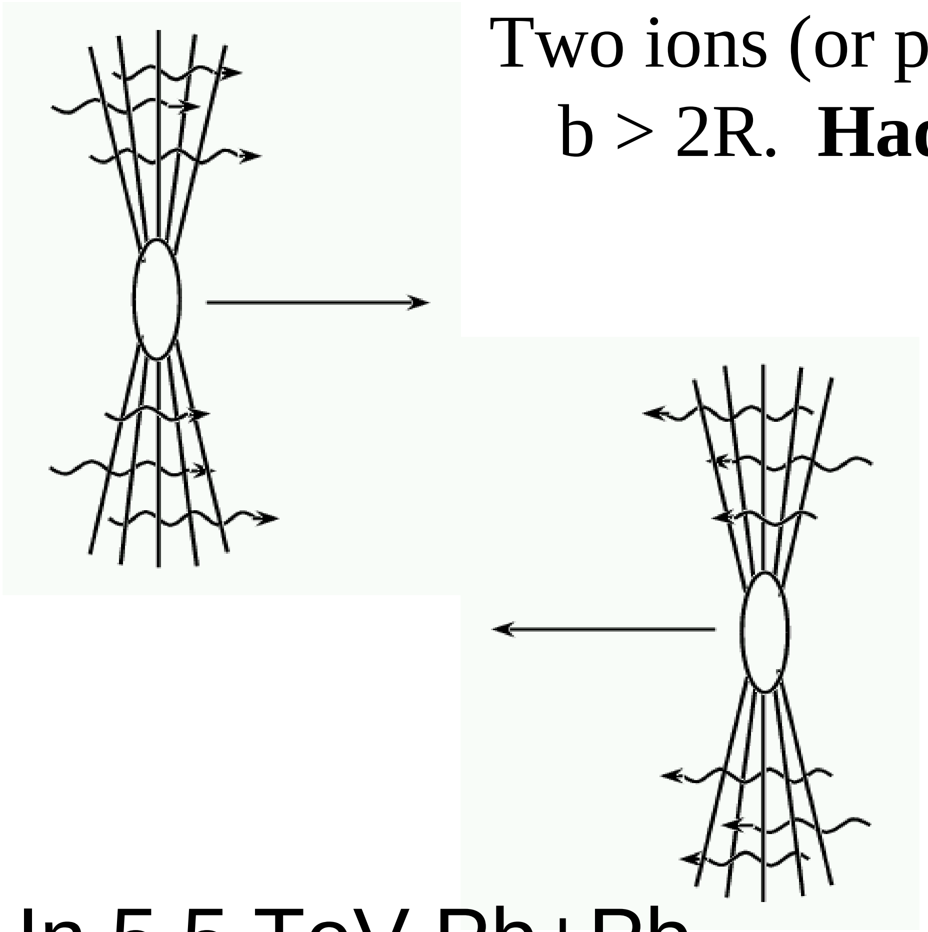


Enrico FERMI

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

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*

In 5.5 TeV Pb+Pb

R. Bruce et al., Phys.Rev. 12 071002 (2009)

σ(hadronic) ~ 8b; σ(e^+e^-) ~ 281 b

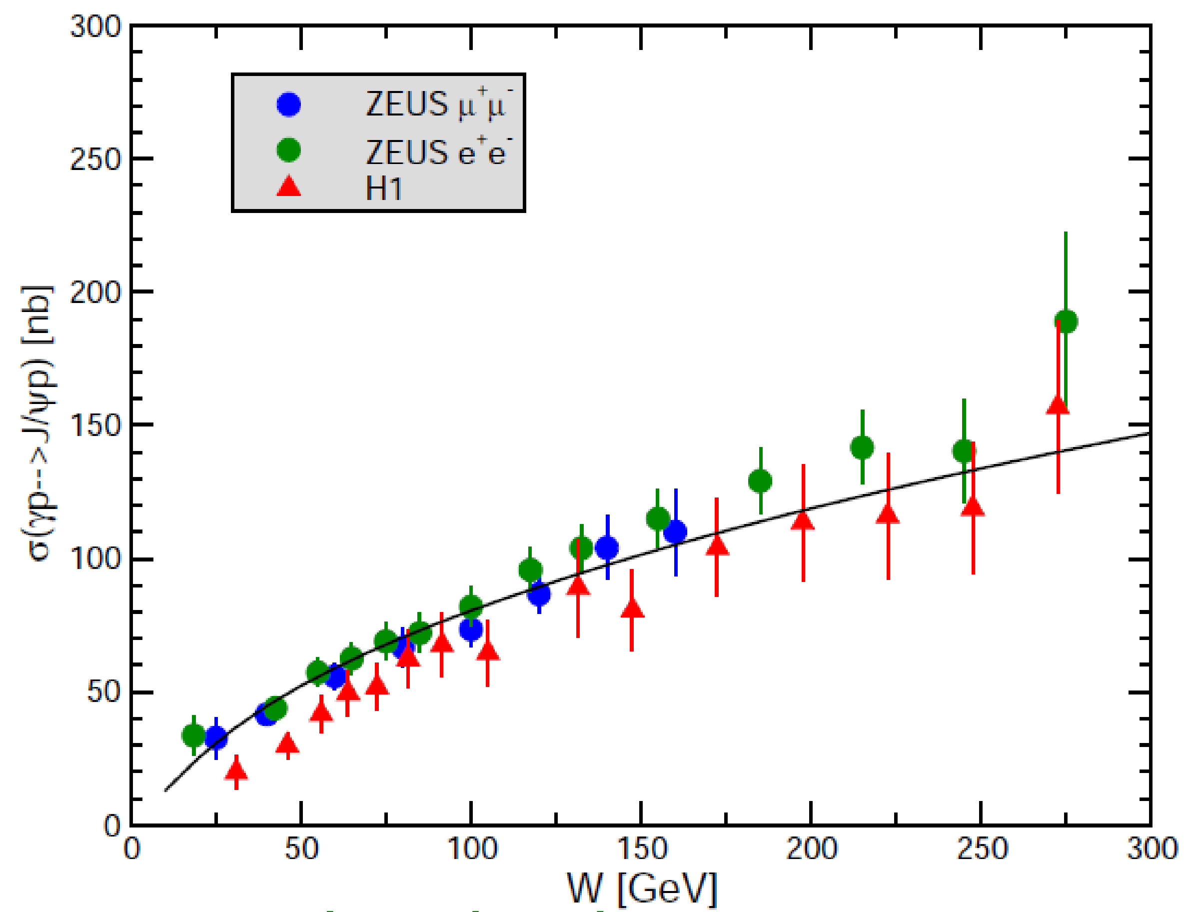
σ(EMD) ~ 226 b

A big jump in energy ...

RHIC: $W_{\gamma N,max}$ ~ 34 GeV

HERA: $W_{\gamma N,max}$ ~ 300 GeV

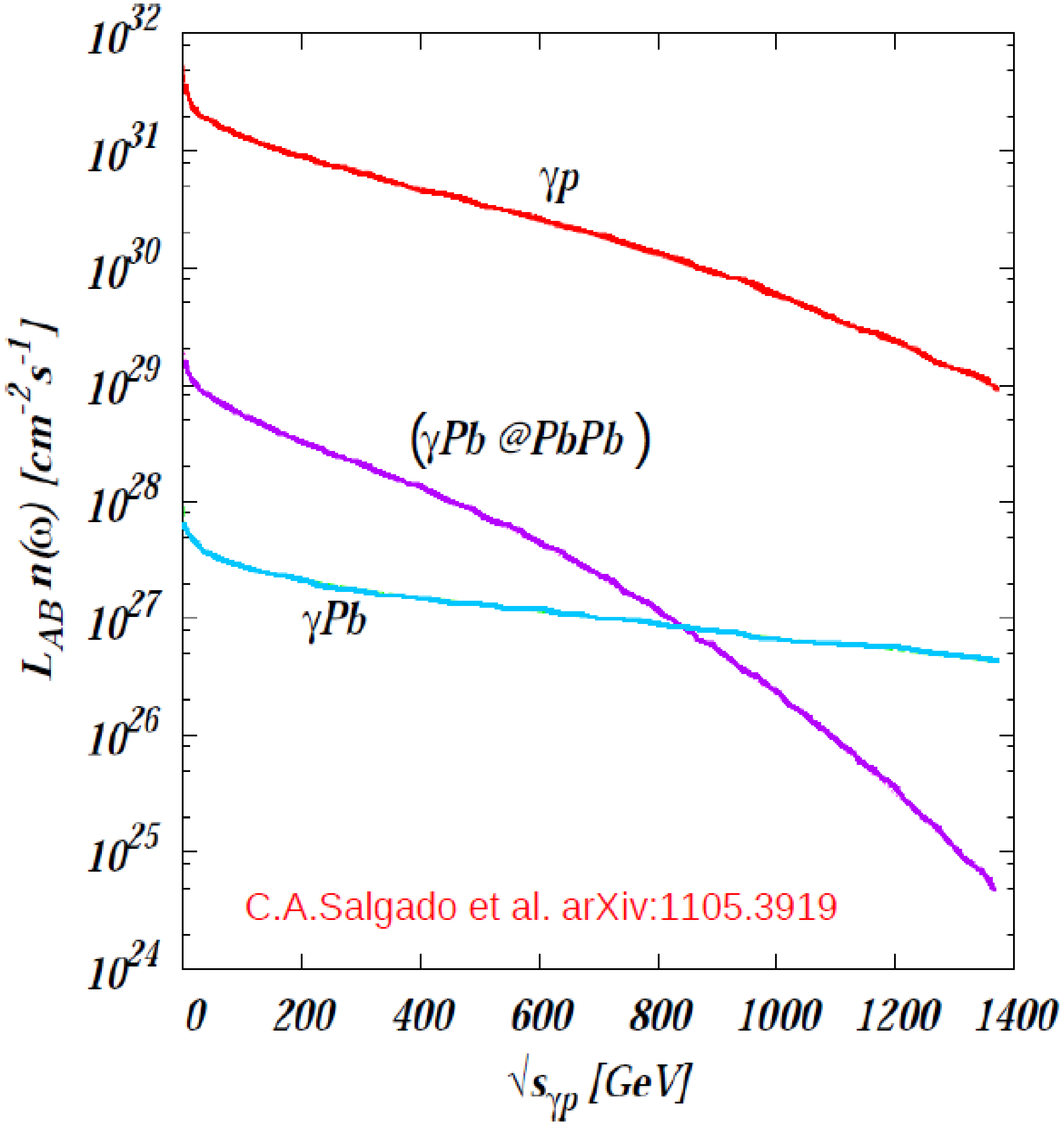
LHC: $W_{\gamma N,max}$ reaches up to 950 GeV !



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

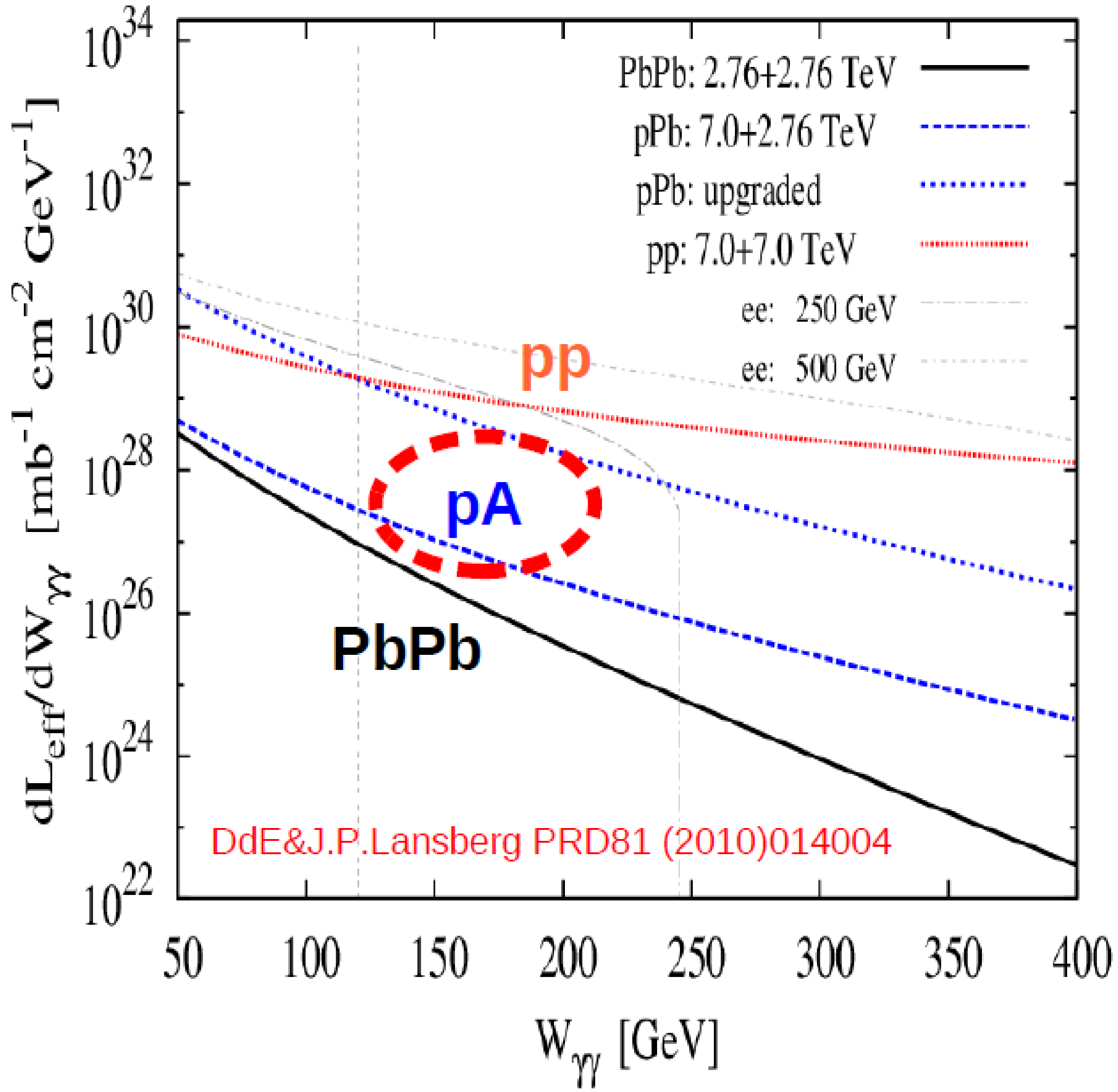
Effective luminosities in UPC

p-Pb @ 8.8 TeV



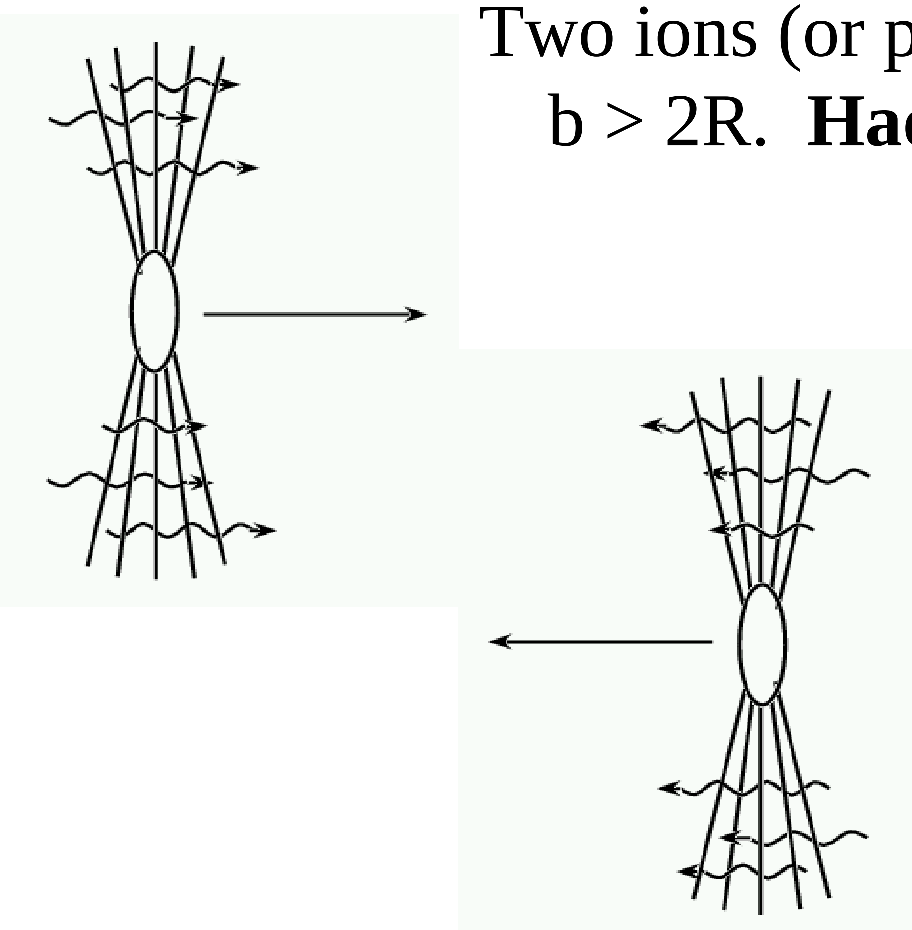
Beyond ~1 TeV scale

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



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

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*

Coherent production:

Photon couples coherently to all nucleons

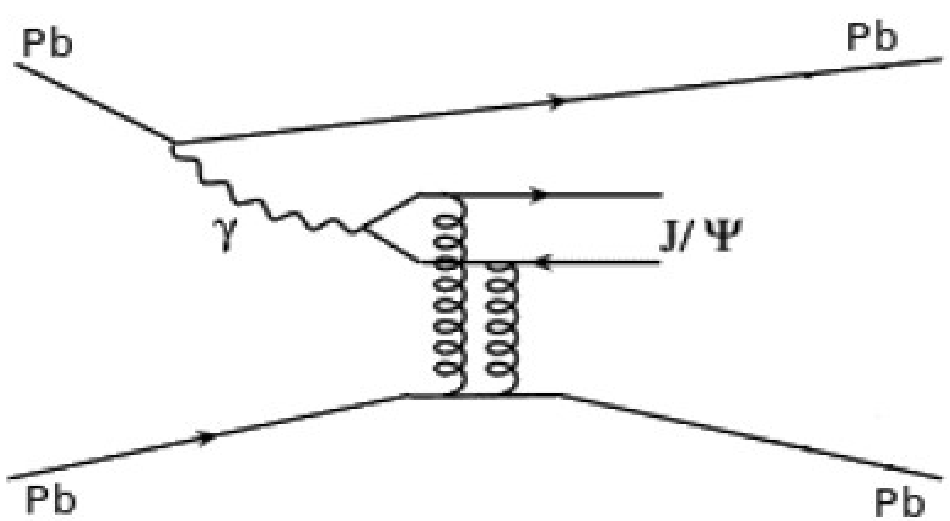
$\langle p_T \rangle$~60MeV/*c;* target nucleus normally does not break up

Incoherent production

Photon couples to a single nucleon

Quasi-elastic scattering off a single nucleon

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



$\gamma + p \rightarrow J/\psi + p$

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

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...

STARLIGHT
http://starlight.hepforge.org

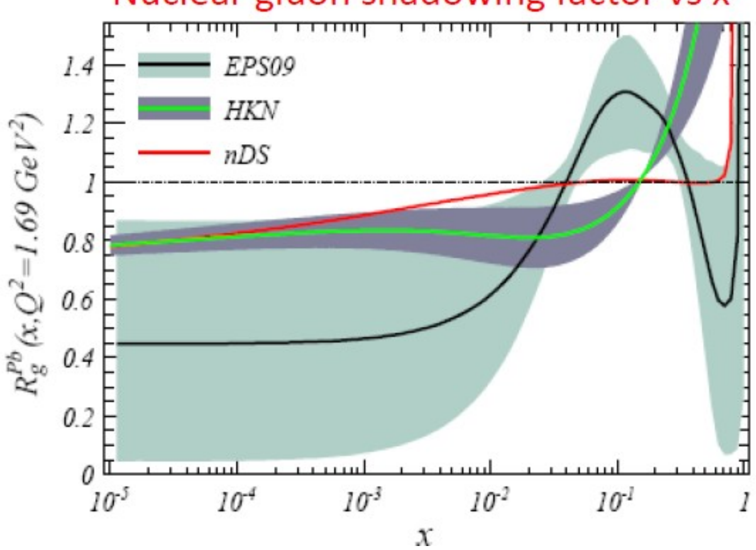
Adeluyi and Bertulani (AB)
Phys. ReV. C 85 (2012) 044904

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

Nuclear gluon shadowing factor vs x



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

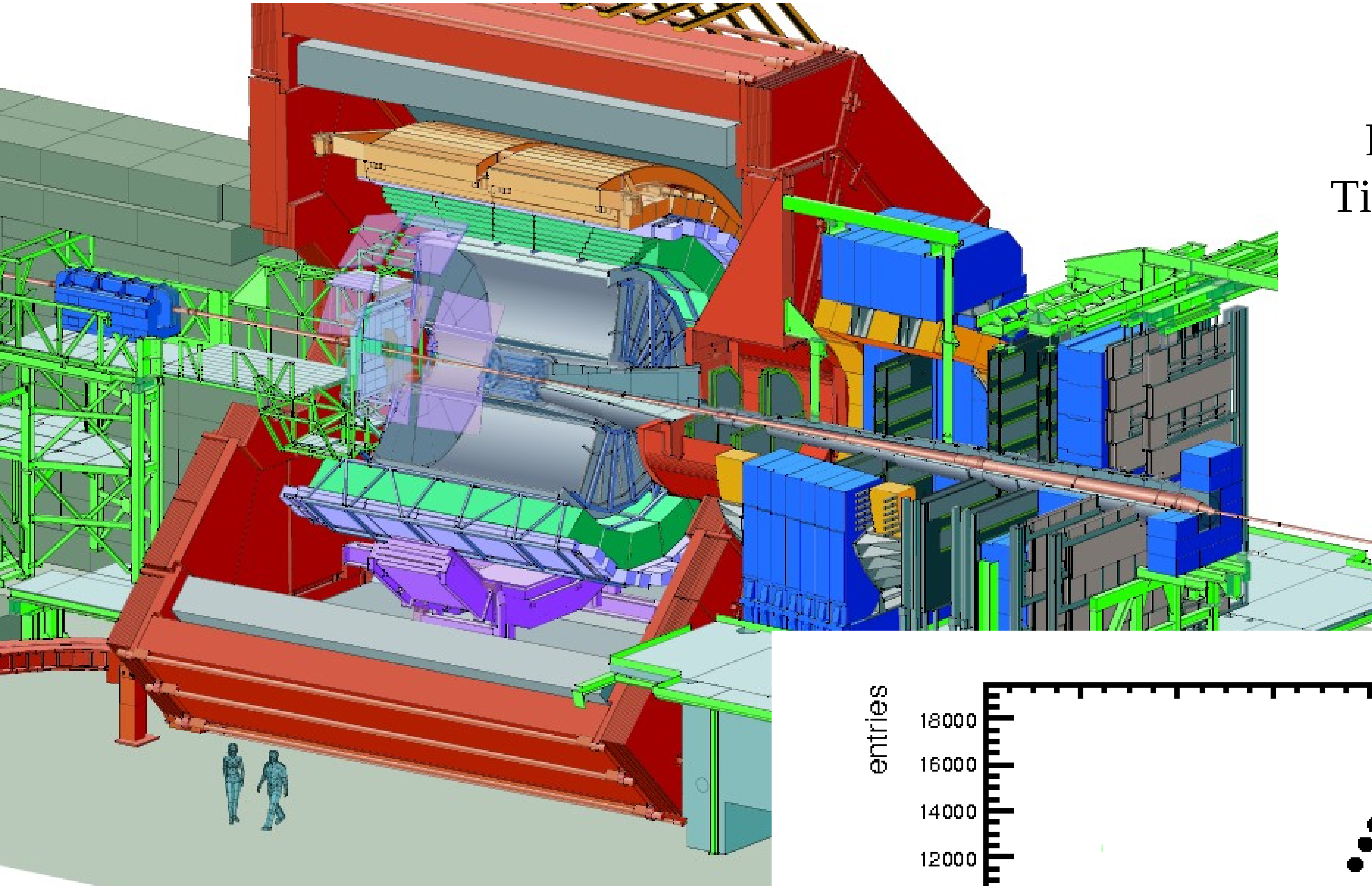
$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3\left[xg\left(x,\frac{M_V^2}{4}\right)\right]^2$$ Ryskin 1993

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

Also a more recent calculation

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

The ALICE experiment at LHC



Central rapidity

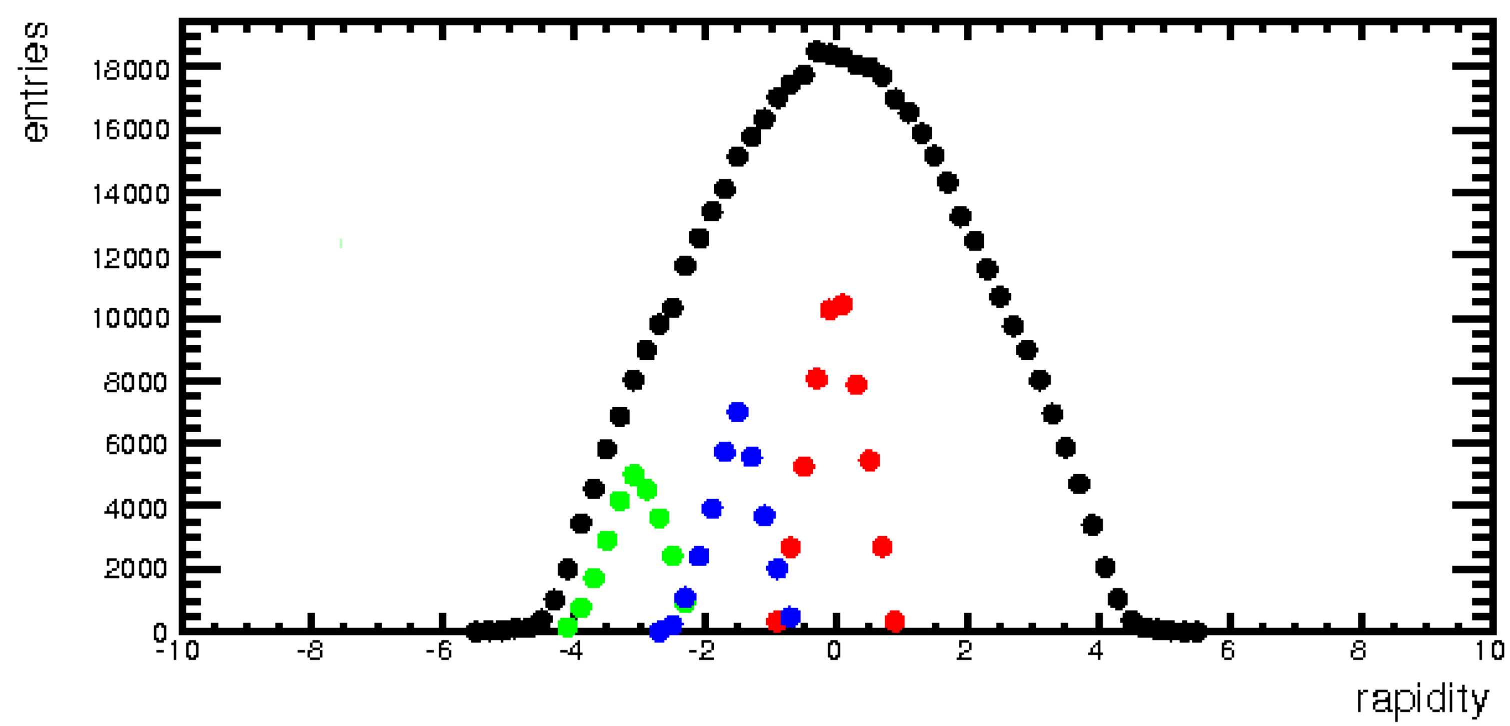
Inner Tracking (ITS), Time Projection Chamber (TPC), Time-of-Flight, TRD, EMCAL

$|\eta| < 0.9$

Forward rapidity

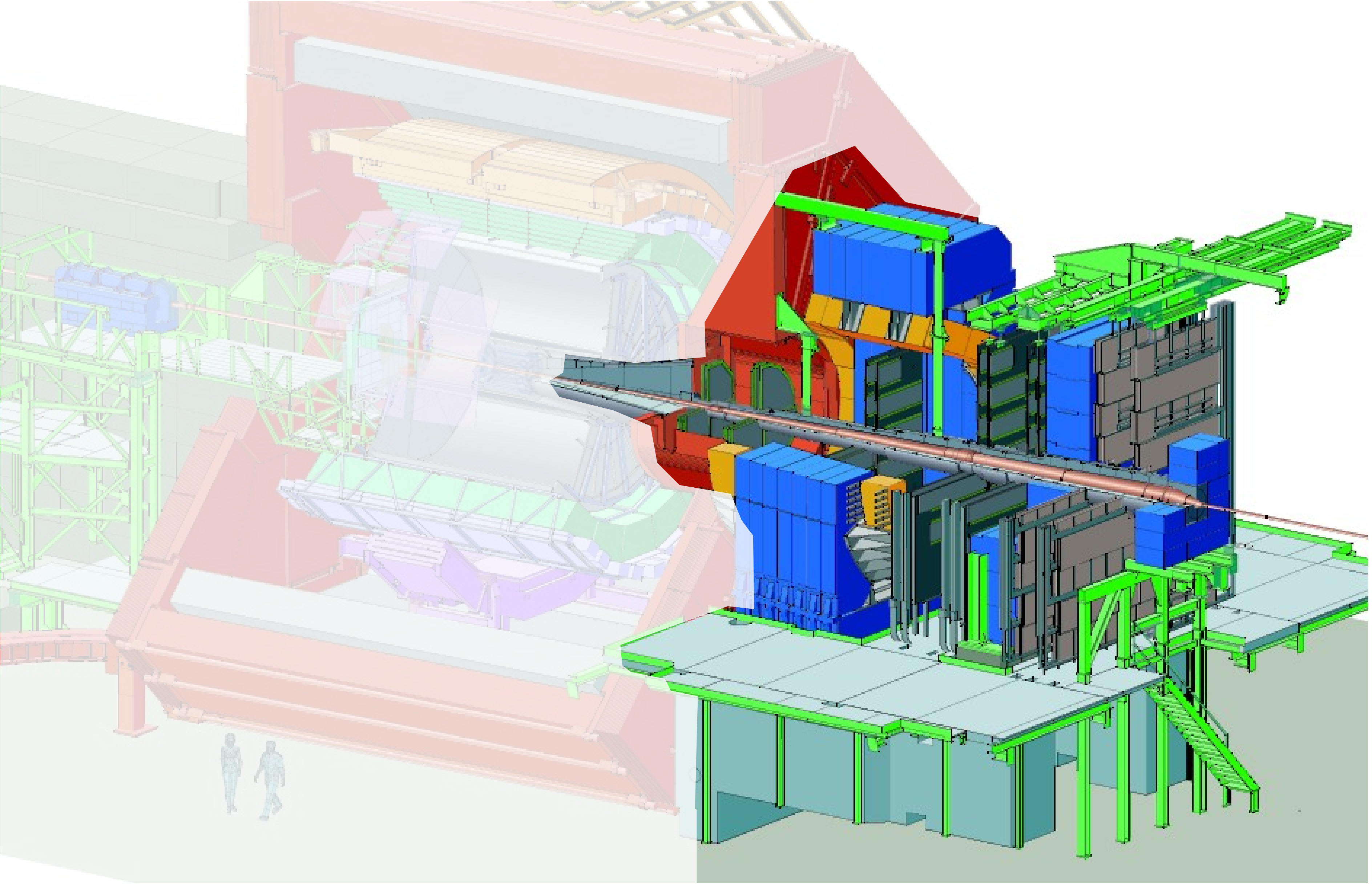
Muon Spectrometer

$-4 < \eta < -2.5$



ALICE can measure J/ψ mesons down to zero p_T

The ALICE experiment at LHC



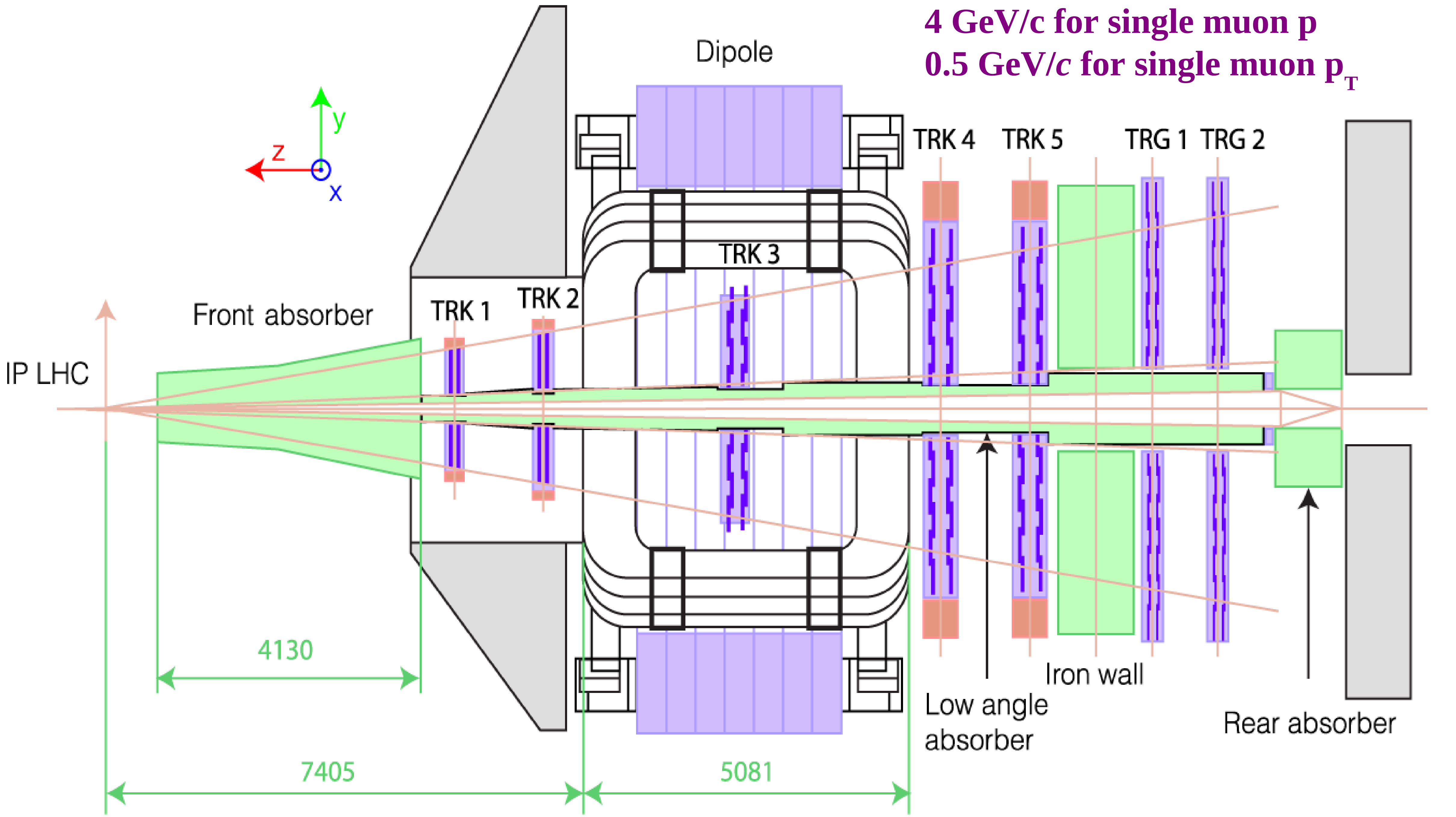
Forward rapidity

Muon Spectrometer

$-4 < \eta < -2.5$

Muon spectrometer

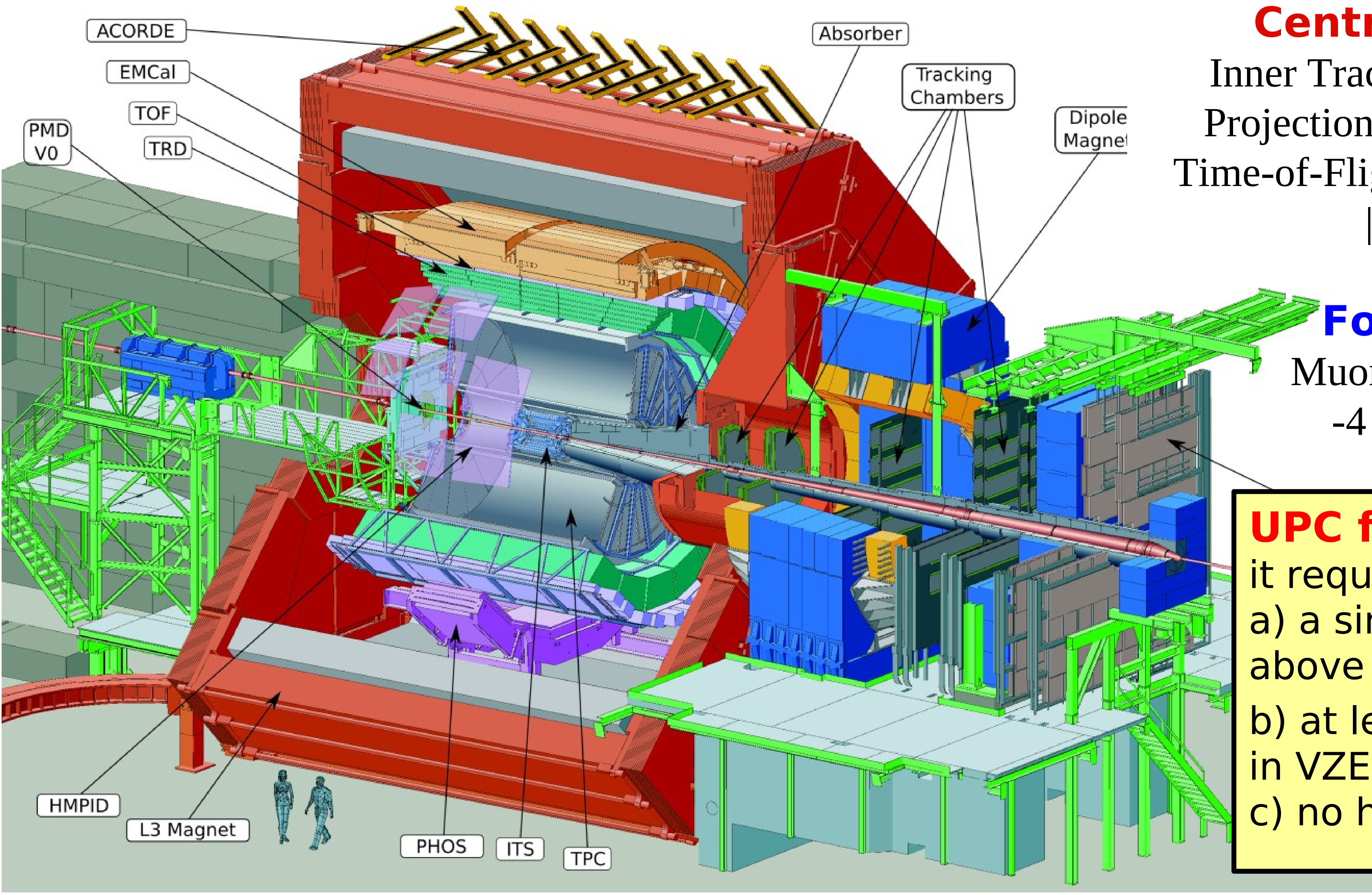
Hardware cut
4 GeV/c for single muon p
0.5 GeV/*c* for single muon p_T



5 tracking stations (10 planes of MWPC) . 70 μm resolution in the bending plane

2 trigger stations (4 planes of RPCs) ~ 2ns response

Quarkonia measurements at ALICE



Central rapidity

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

$|\eta| < 0.9$

Forward rapidity

Muon Spectrometer

$-4 < \eta < -2.5$

UPC forward trigger

it requires

a) a single muon trigger above 1 GeV/c p_T

b) at least one hit in VZERO-C

c) no hits in VZERO-A

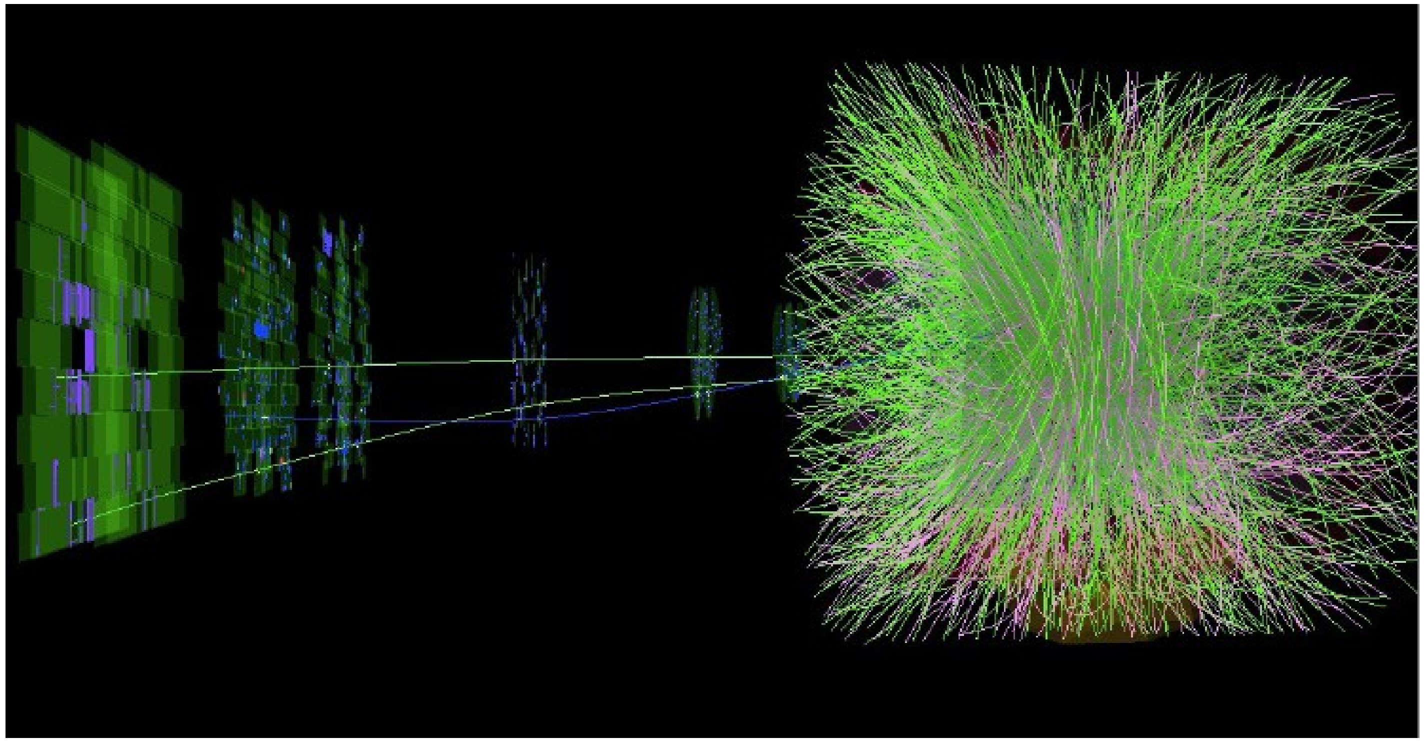
Forward detectors used in this analysis:

VZERO-A: $2.8<\eta<5.1$; VZERO-C: $-3.7<\eta<-1.7$

ZDC: 116 m on either side of the IP

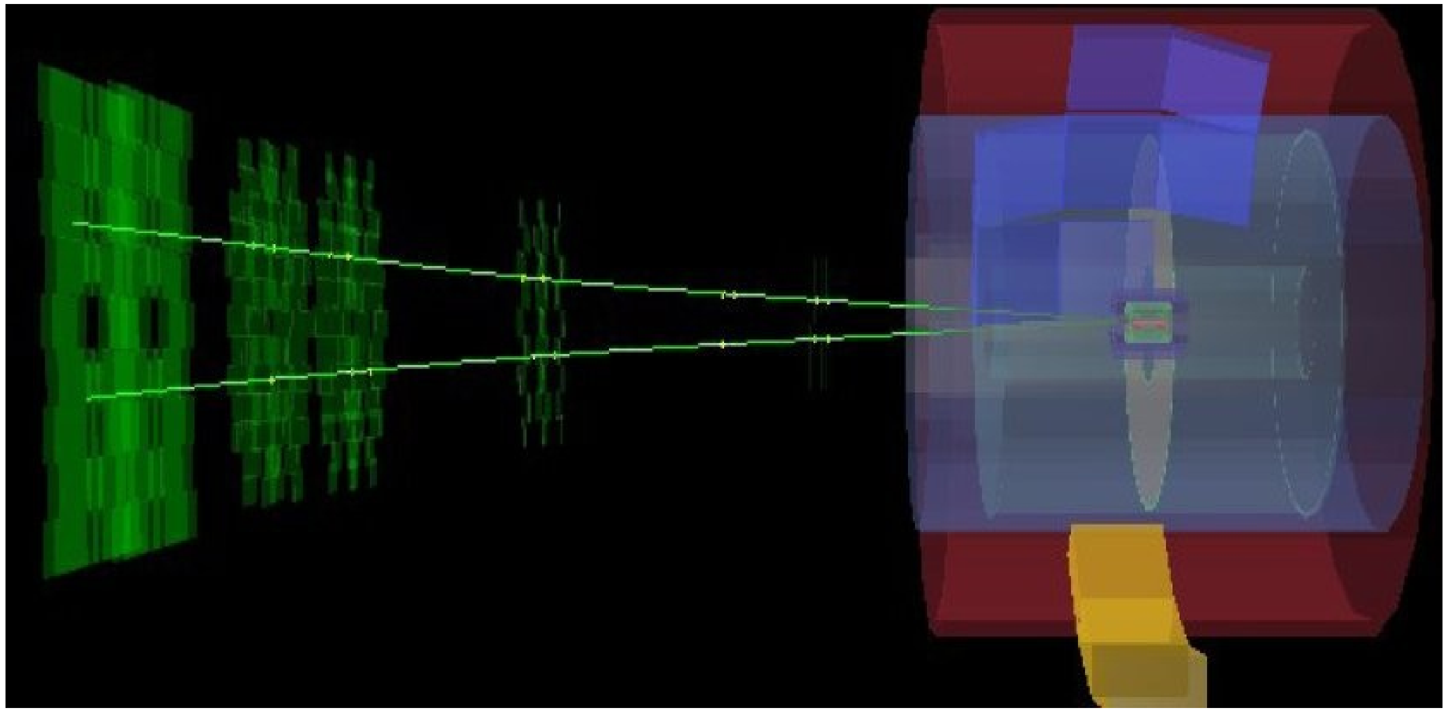
ALICE can measure J/ψ mesons down to zero p_T

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



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

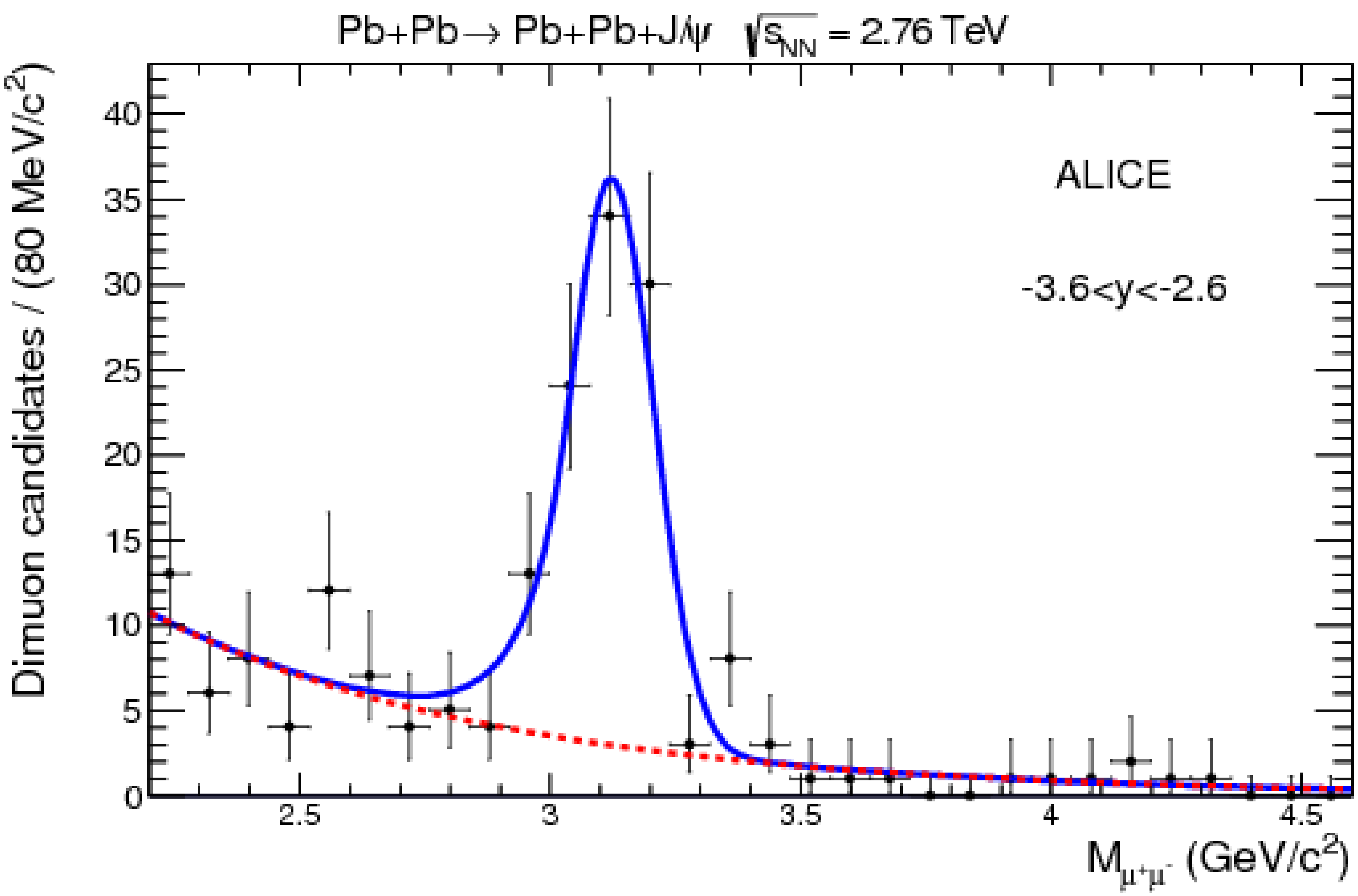
....to an exclusive J/ψ candidate



First UPC measurement at LHC carried out by ALICE
Phys.Lett. B718 (2013) 1273-1283
CERN Courier; Nov issue

Signal yield extraction

Exactly two oppositely charged muons



Only two like-sign pairs → Combinatorial background <2% at 90% CL around J/ψ mass

Fitting functions: Crystal Ball and exponential

$$N_{\mathrm{yield}} = 96 \pm 12(\mathrm{stat}) \pm 6(\mathrm{syst})$$

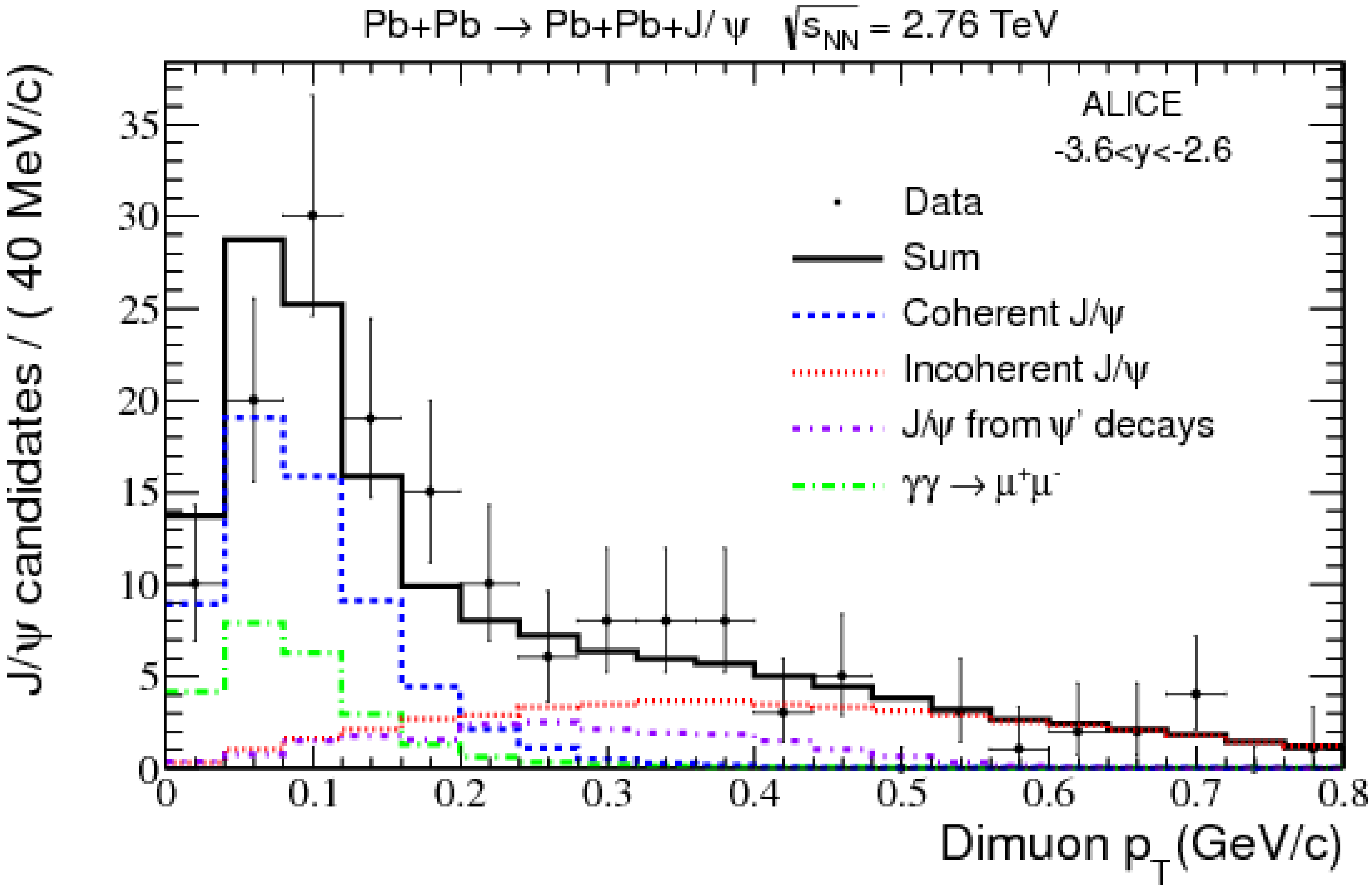
Exponential slope parameter

Data: -1.40 +/- 0.20 $GeV^{-1}c^2$

MC($\gamma\gamma \to \mu^+\mu^-$): -1.39 +/- 0.01 $GeV^{-1}c^2$

→ An additional indication that background is under control in this kinematic region

p_T distribution for J/ψ candidates



Four physics processes:

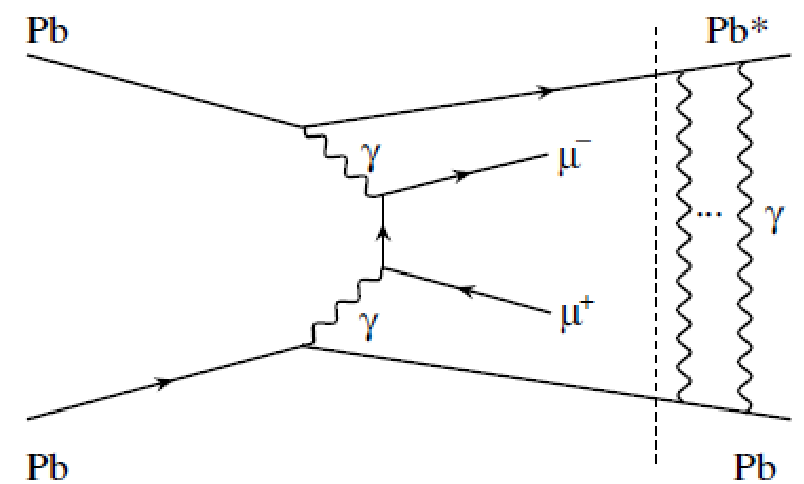
- Coherent J/ψ
- Incoherent J/ψ
- J/ψ from ψ' decays
- $\gamma\gamma \rightarrow \mu^+\mu^-$

The coherent J/ψ signal is clearly visible

$$N^{coh}_{J/\psi} = 78 \pm 10(\mathrm{stat})^{+7}_{-11}(\mathrm{syst})$$

Coherent J/ψ differential cross section

We use the QED continuum pair production ($\gamma+\gamma \rightarrow \mu^+\mu^-$) for normalisation



$$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{1}{BR(J/\psi \rightarrow \mu^+\mu^-)} \cdot \frac{N^{coh}_{J/\psi}}{N_{\gamma\gamma}} \cdot \frac{(Acc \times \varepsilon)_{\gamma\gamma}}{(Acc \times \varepsilon)_{J/\psi}} \cdot \frac{\sigma_{\gamma\gamma}}{\Delta y}$$

Standard QED process,but there are some caveats...

1. Uncertainty from higher order terms :

Photon coupling to the nuclei is $Z\alpha^{1/2}$ rather than $\alpha^{1/2}$. Here Z=82
Either negligible effect or a 16% reduction in the $\gamma+\gamma$ cross section

2. Uncertainty on minimum momentum transfer and nuclear form factor

3. Previous experimental results:

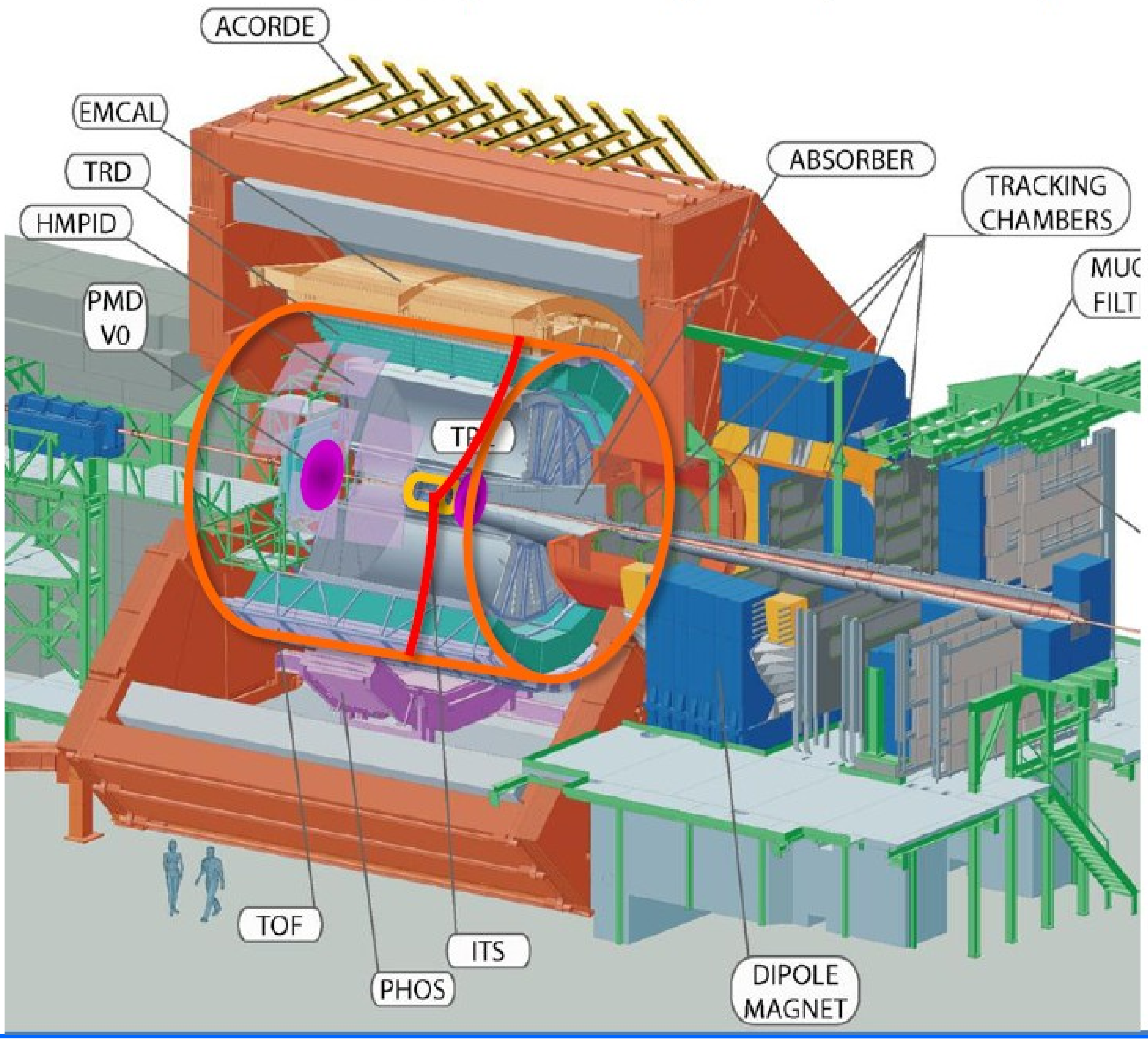
STARLIGHT predictions in good agreement to STAR/PHENIX measurements, but their experimental results have uncertainties between 20-30%

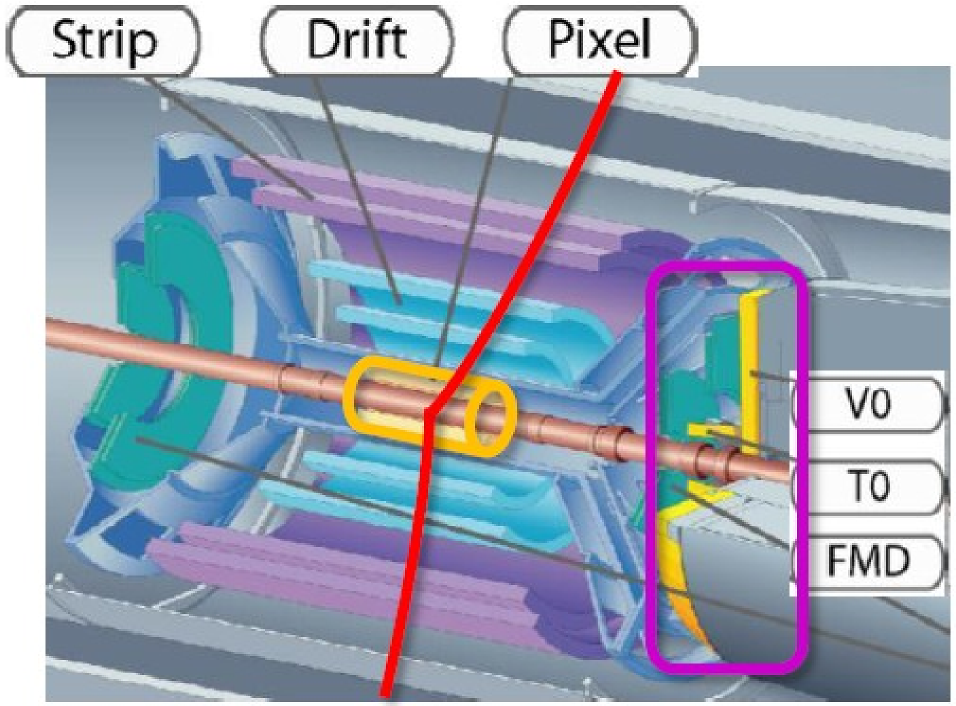
Theoretical uncertainty on $\gamma+\gamma \rightarrow \mu^+\mu^-$ is 20%

Central barrel measurements

UPC central barrel trigger:

- $2 \leq$ **TOF** hits ≤ 6 ($|\eta| < 0.9$)
  + back-to-back topology ($150° \leq \varphi \leq 180°$)
- ≥ 2 hits in **SPD** ($|\eta| < 1.5$)
- no hits in **VZERO** (C: $-3.7 < \eta < -1.7$, A: $2.8 < \eta < 5.1$)





Integrated luminosity ~ 20 μb^{-1}

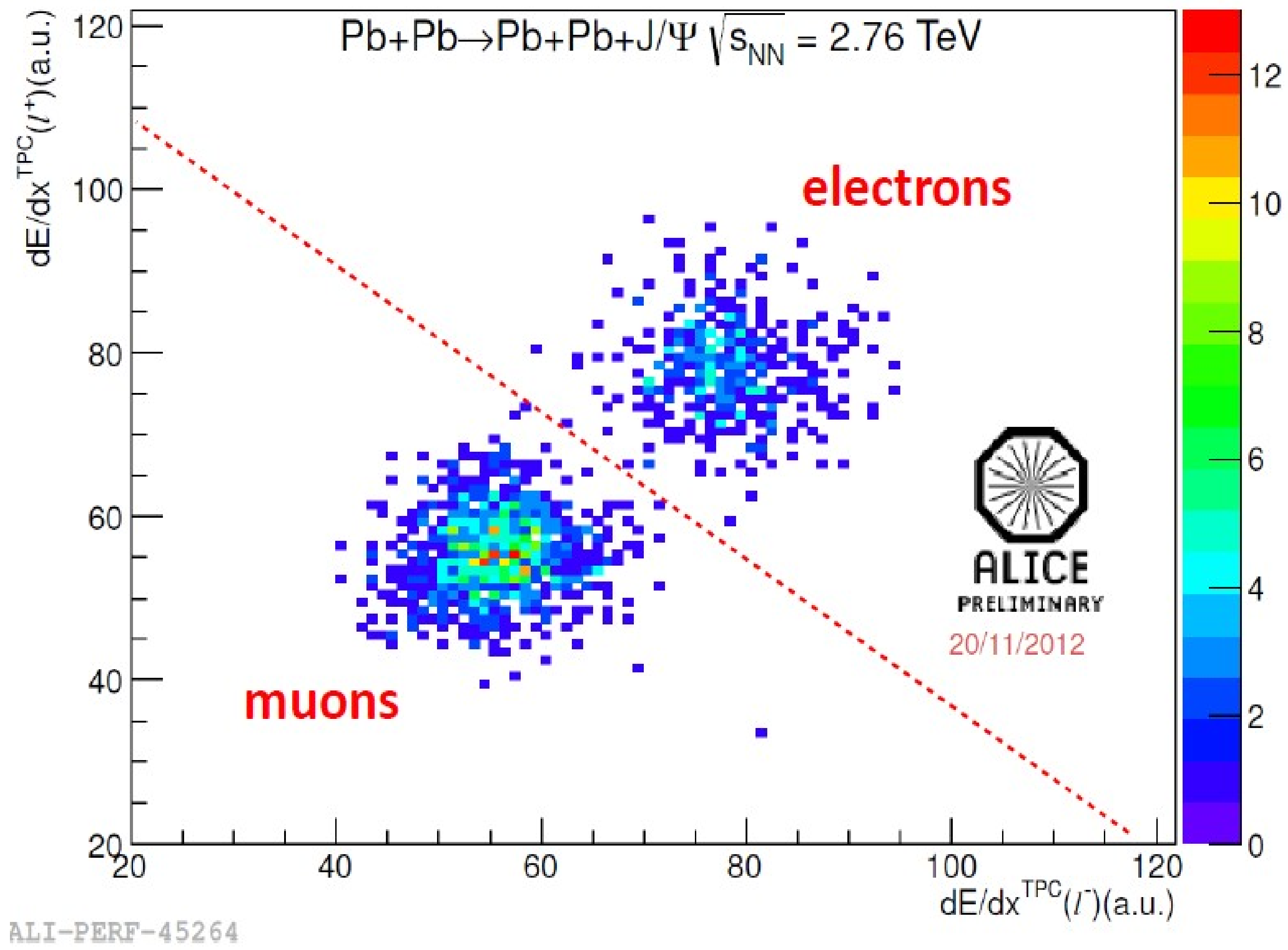
Offline event selection:

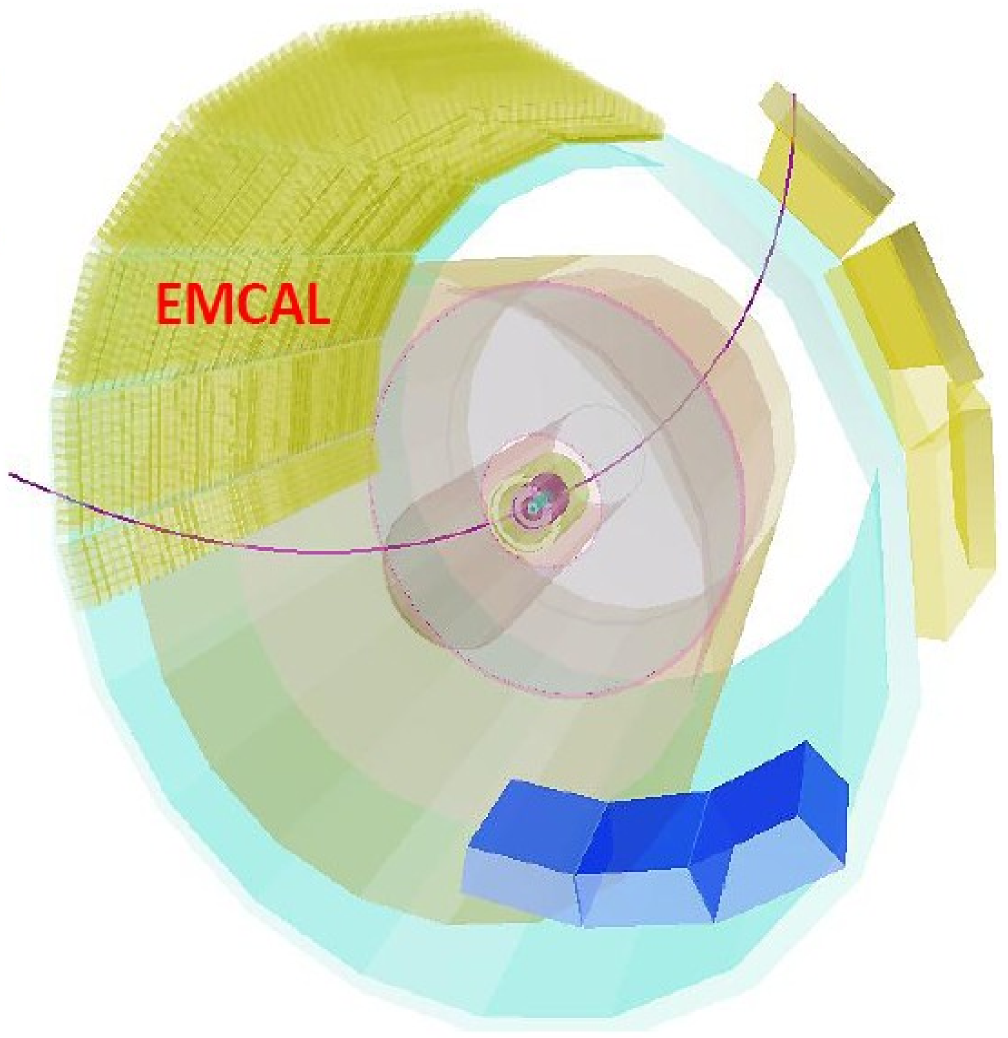
- Offline check on VZERO timing
- Hadronic rejection with ZDC

Track selection:

- Two tracks: $|\eta| < 0.9$
- ≥ 70 TPC clusters, ≥ 1 SPD clusters
- p_T dependent DCA cut
- opposite sign dilepton
  $|y| < 0.9$, $2.2 < M_{inv} < 6$ GeV/c^2
- dE/dx in TPC compatible with e/μ

Central barrel measurements

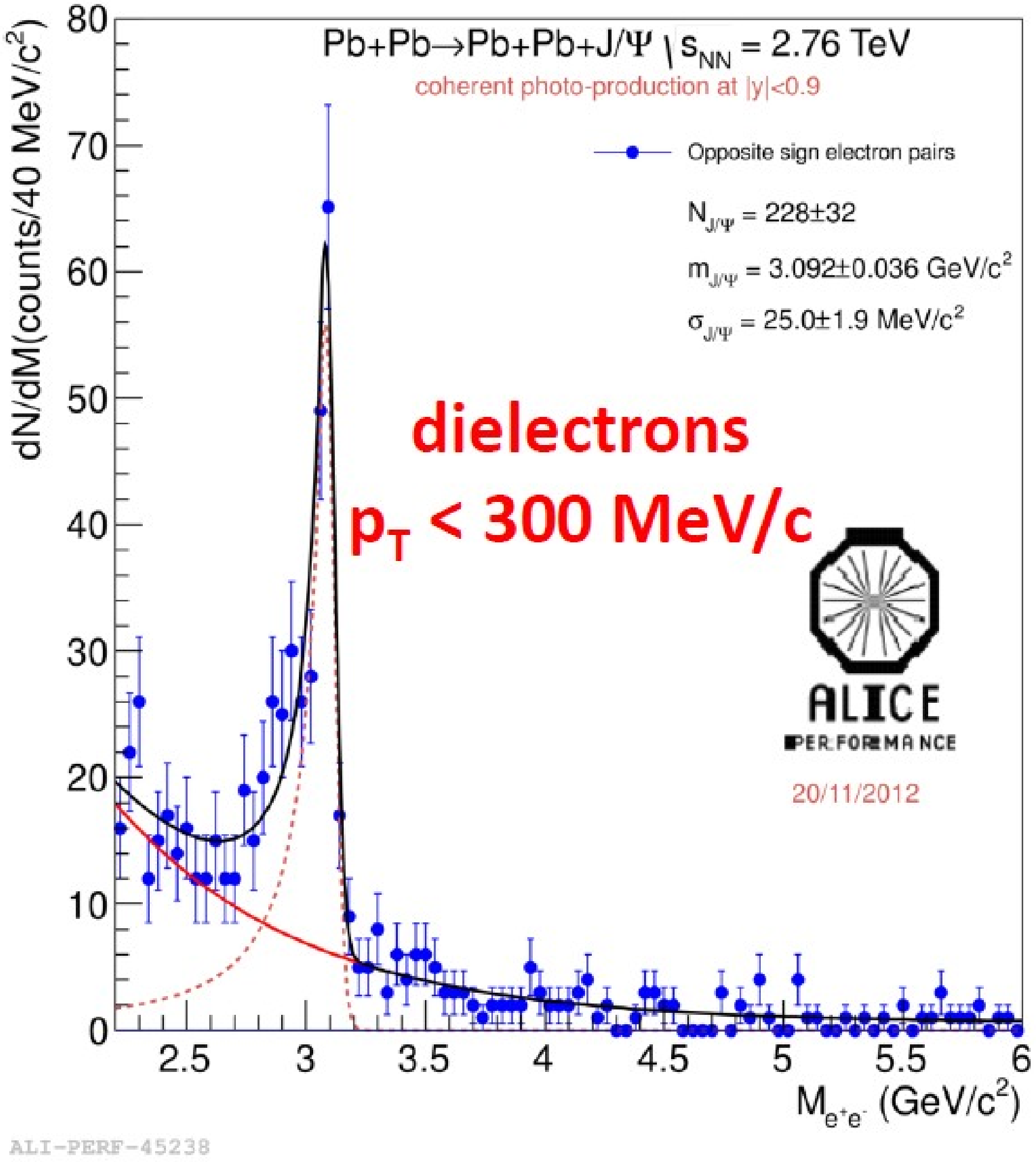


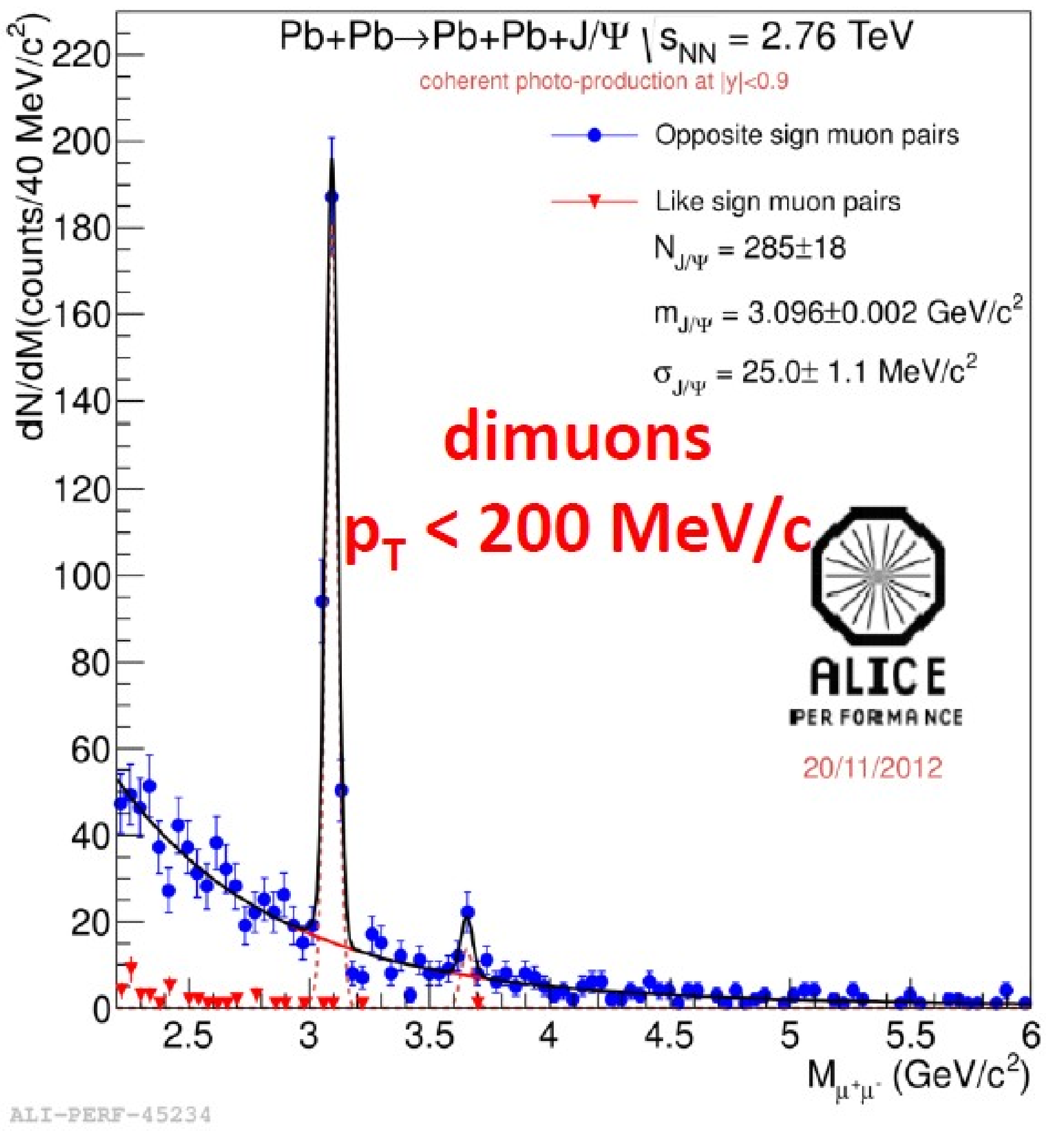


- dE/dx in TPC compatible with e/μ energy loss
- Cross-checked with E/p in EMCAL
- ±2% systematics due to e/μ separation

Central barrel measurements

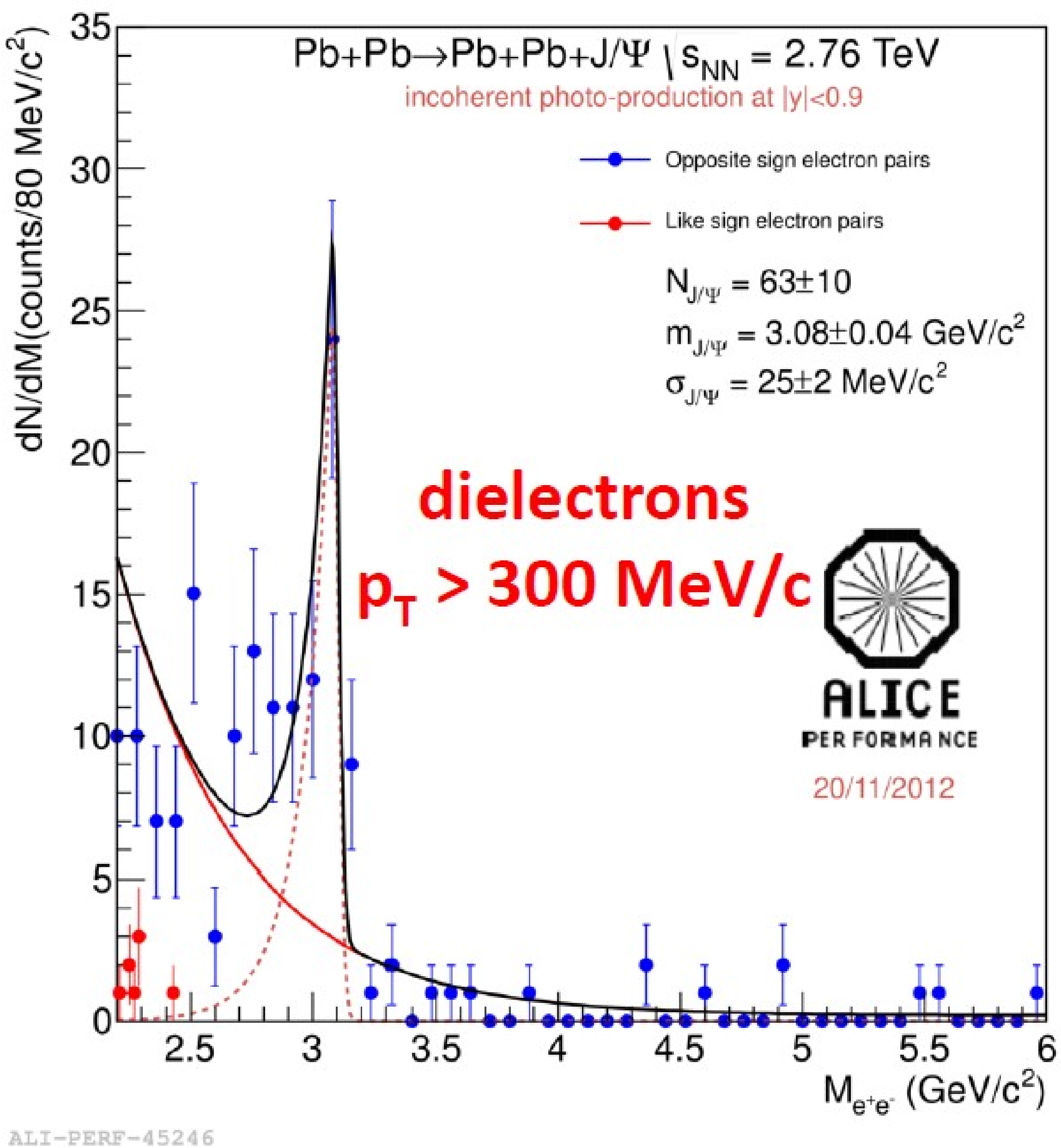
coherent enriched sample

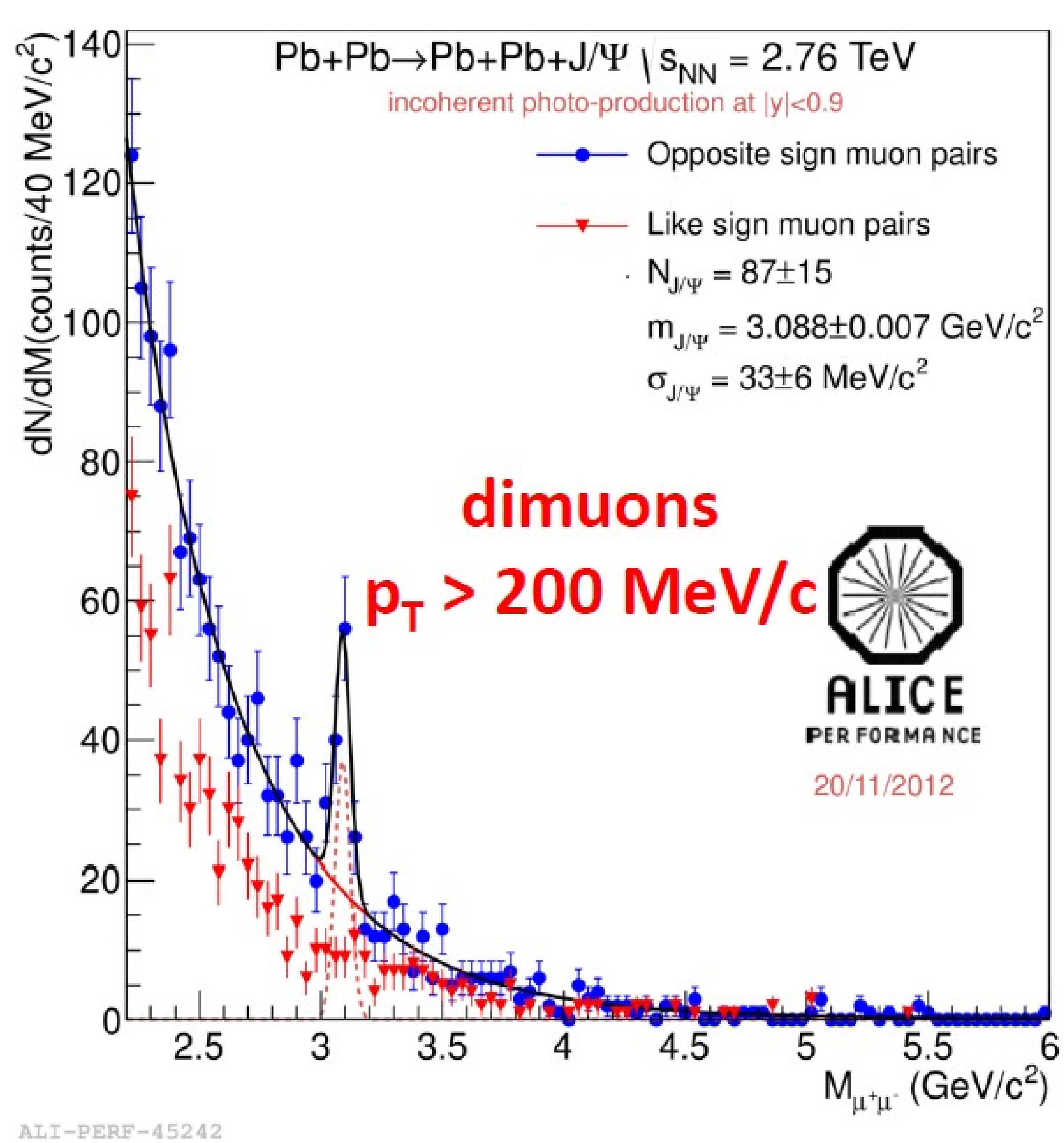




Central barrel measurements

incoherent enriched sample





Theoretical predictions

1. AB-MSTW08 - No nuclear effects
All nucleons contribute to the scattering $d\sigma/dt$ at $t=0$ scales with A^2

2. STARLIGHT, CM and CSS Glauber approach to calculate the number of nucleons contributing to the scattering. Dependence on total J/ψ-nucleon cross section

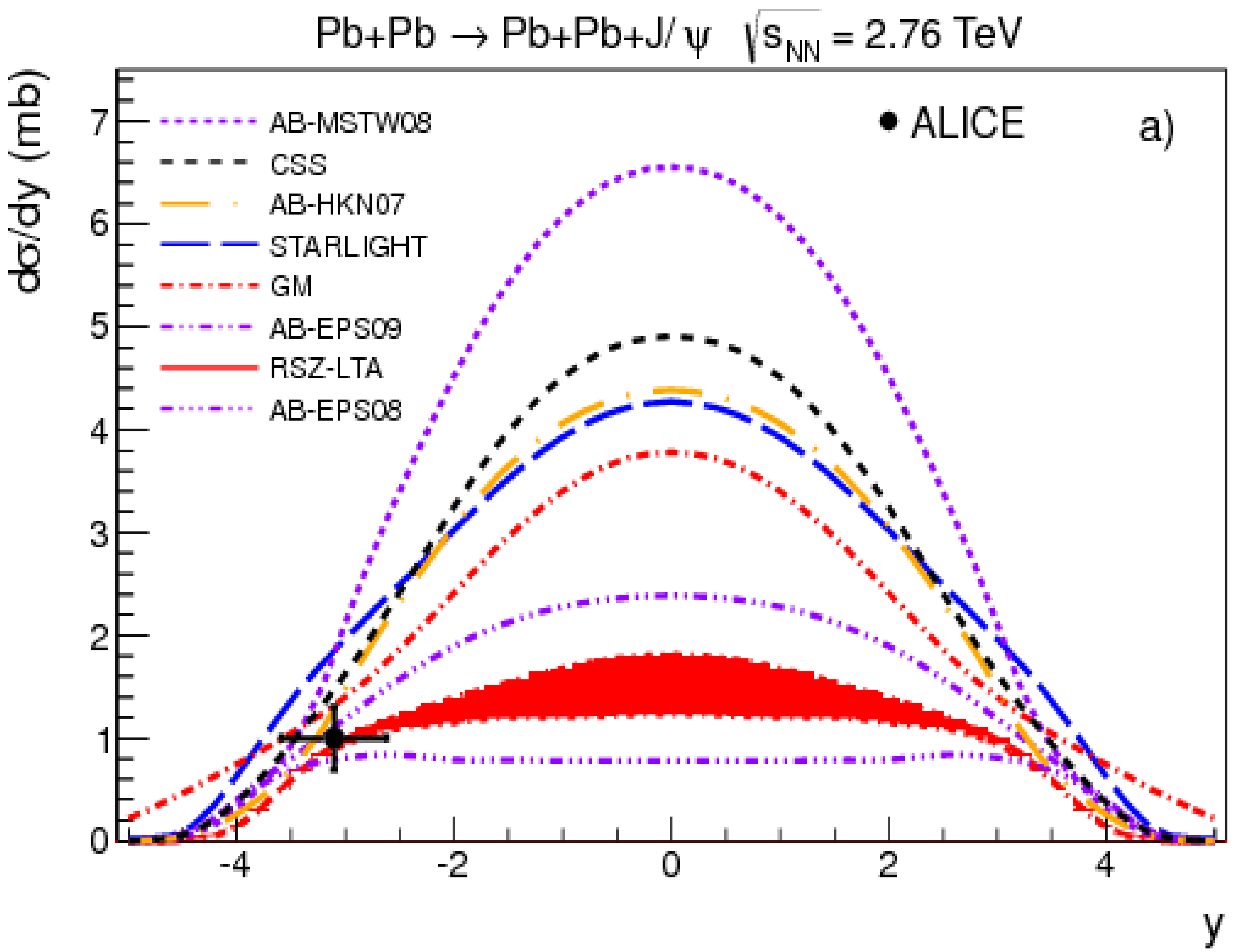
3. Partonic models (AB-EPS08, AB-EPS09, AB-HKN07, RSZ-LTA)
Cross section proportional to the nuclear gluon distribution squared

Data *vs* theoretical predictions

1. AB-MSTW08 - No nuclear effects
All nucleons contribute to the scattering $d\sigma/dt$ at $t=0$ scales with A^2

2. STARLIGHT, CM and CSS Glauber approach to calculate the number of nucleons contributing to the scattering. Dependence on total J/ψ-nucleon cross section

3. Partonic models (AB-EPS08, AB-EPS09, AB-HKN07, RSZ-LTA)
Cross section proportional to the nuclear gluon distribution squared



Most forward J/ψs in UPC Pb-Pb at LHC are from low photon-proton c.m.s. energy

Either nucleus can serve as photon emitter or photon target, at forward rapidity (-3.6<y<-2.6), x~10^{-2} and x~10^{-5}

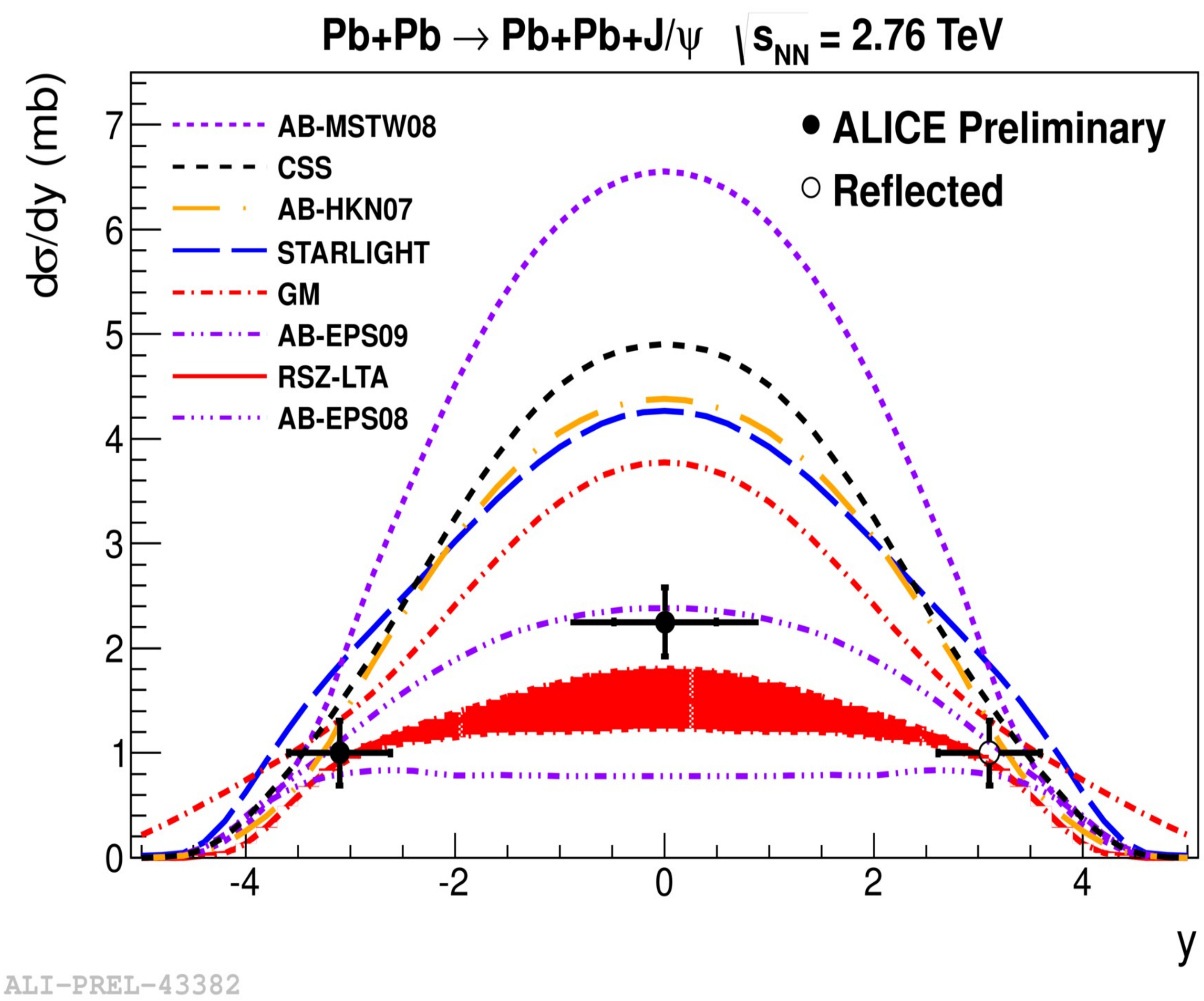
The error is the quadratic sum of the statistical and systematic errors

Data *vs* theoretical predictions

1. AB-MSTW08 - No nuclear effects
All nucleons contribute to the scattering dσ/dt at t=0 scales with A^2

2. STARLIGHT, CM and CSS Glauber approach to calculate the number of nucleons contributing to the scattering. Dependence on total J/ψ-nucleon cross section

3. Partonic models (AB-EPS08, AB-EPS09, AB-HKN07, RSZ-LTA)
Cross section proportional to the nuclear gluon distribution squared



Published forward J/ψ measurement
Preliminary central J/ψ measurement

Best agreement with EPS09 shadowing

Shadowing factor ~0.6 at $x \sim 10^{-3}$, $Q^2 = 2.5\ GeV^2$

Summary: Rapidity dependence coherent J/ψ

- **ALICE** has made the first LHC measurement on J/ψ photoproduction in ultra-peripheral Pb-Pb collisions at 2.76 TeV, per nucleon pair

- **Coherent J/ψ differential cross section**

$$\boxed{d\sigma^{coh}_{J/\psi}/dy = 1.00 \pm 0.18(\text{stat})^{+0.24}_{-0.26}(\text{syst})\ \text{mb}}$$

-3.6<y<-2.6
p_T<0.3 GeV/*c*

- AB-MSTW08 is strongly disfavoured. It assumes that the forward scatting cross section scales with the number of nucleons squared. STARLIGHT cross section is also disfavoured

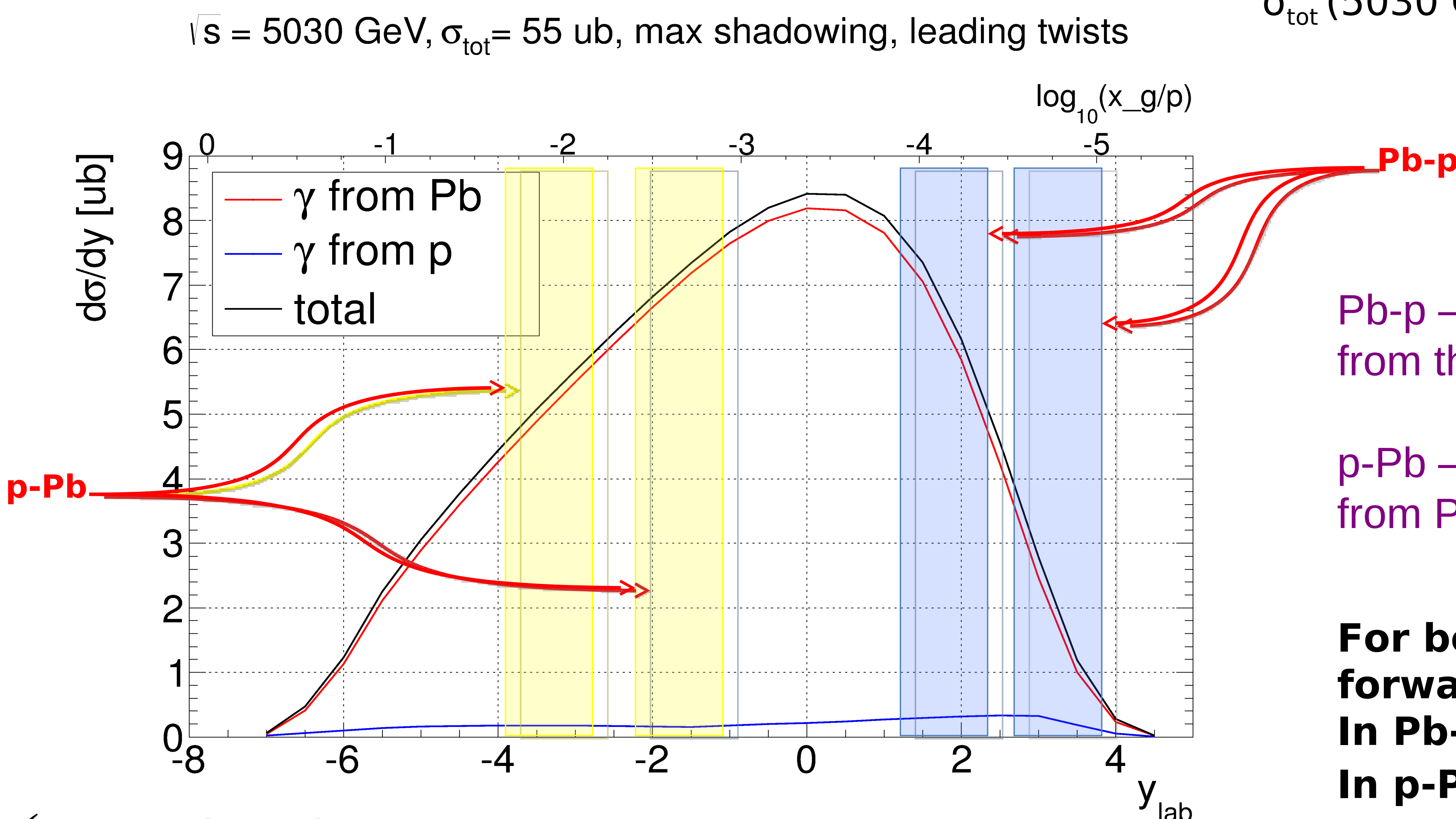
Phys.Lett. B718 (2013) 1273-1283

- Best agreement is found with models that include nuclear gluon shadowing (AB-EPS09)

One more thing…

Rapidity coverage using MUON

σ_{tot} (5030 GeV) = 55 μb



Pb-p – low-x gluons from the proton

p-Pb – low-x gluons from Pb

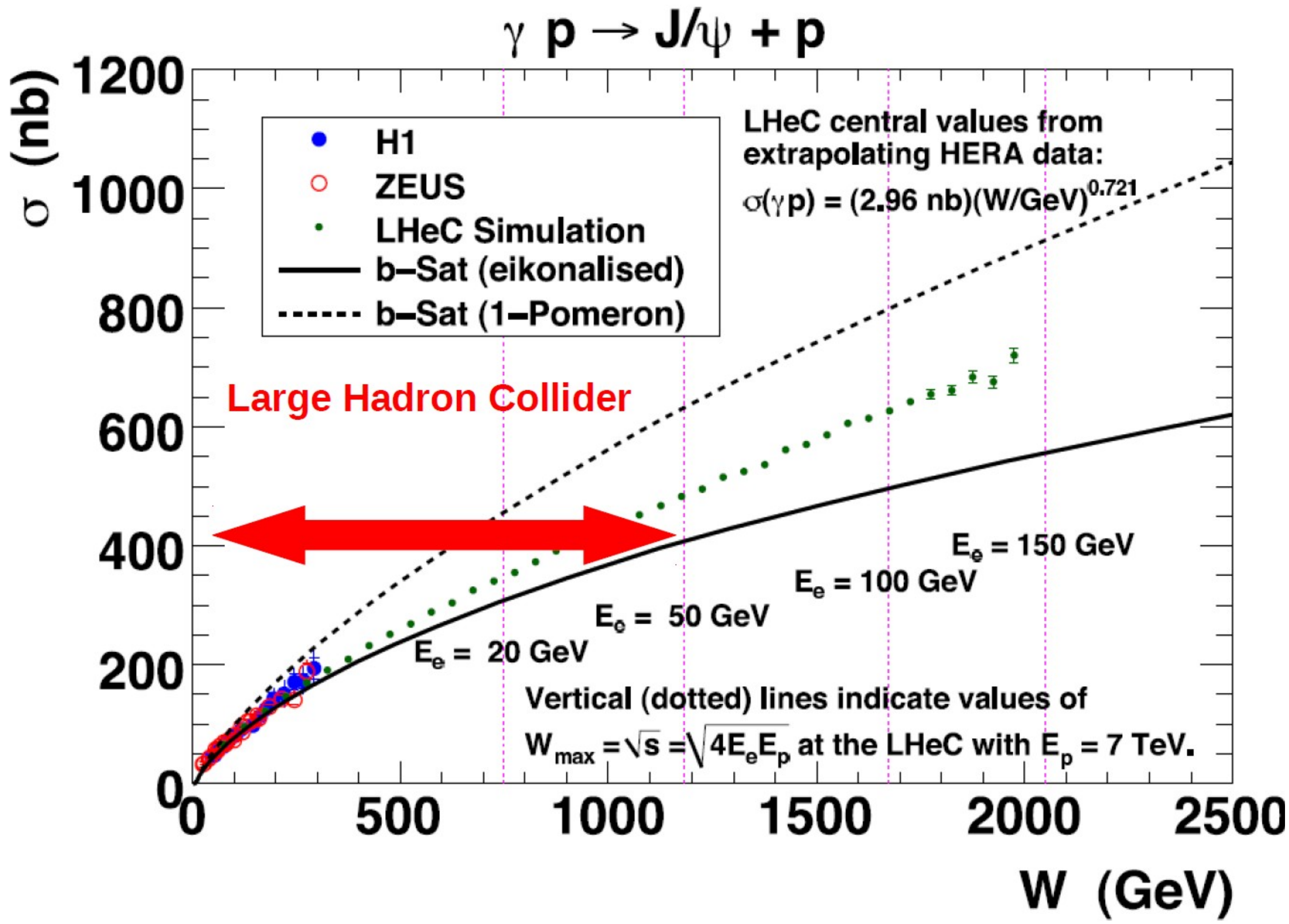
For both muons forward
In Pb-p ->x_p~10^{-5}
In p-Pb ->x_p~10^{-2}

- ✓ ALICE is unique at LHC
- ✓ Unexplored kinematic regime

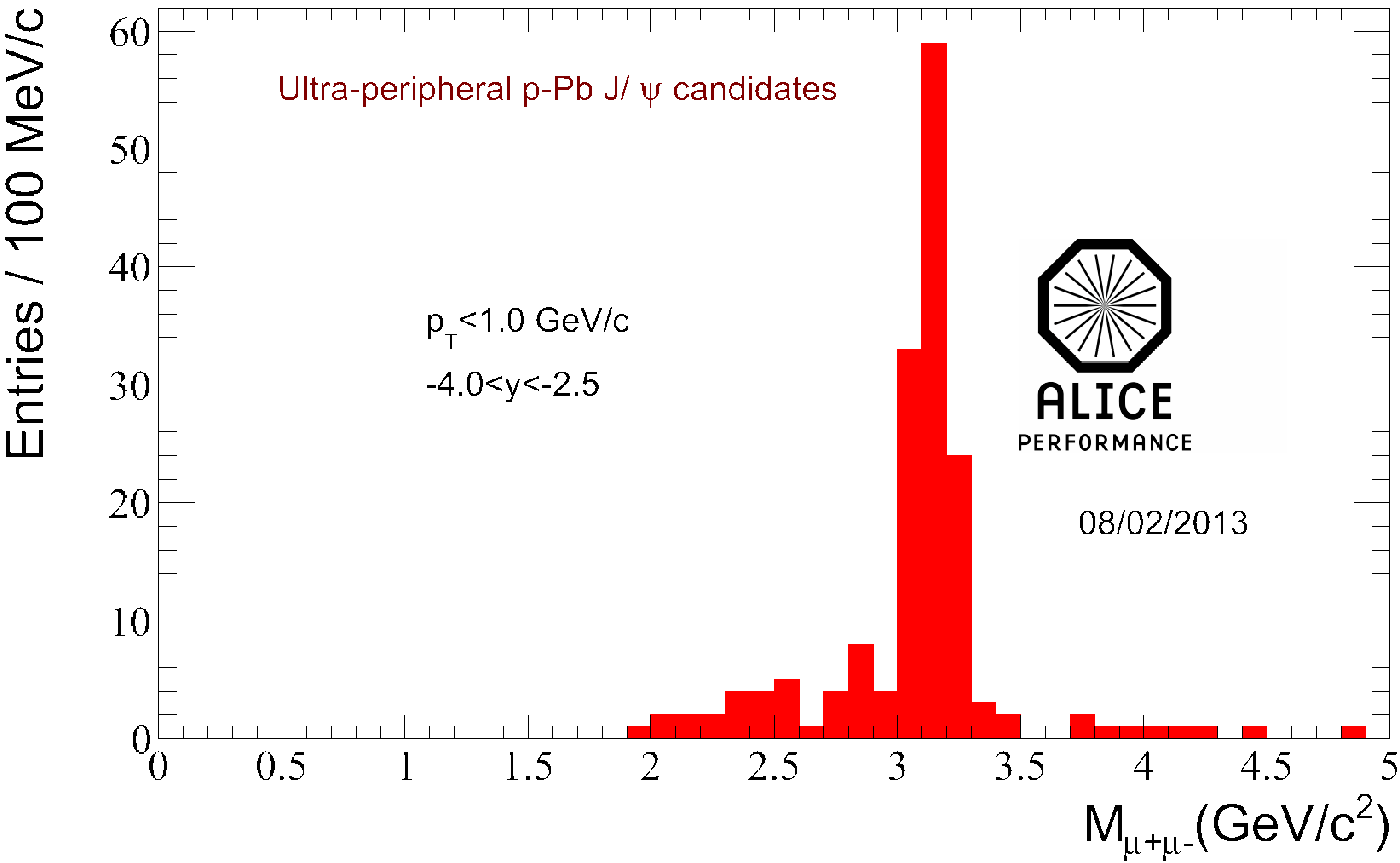
For semi-forward

In Pb-p ->x_p~10^{-4}
In p-Pb ->x_p~10^{-3}

J/ψ photoproduction in γ+p



UPC J/ψ candidates in p-Pb



Summary on UPC analyses at ALICE

UPC Pb-Pb

- Coherent J/ψ at forward rapidity → **Phys.Lett. B718 (2013) 1273-1283**
- Coherent/Incoherent J/ψ at mid-rapidity → analysis ongoing
- Other ongoing analyses
  - ρ^0 photoproduction at mid-rapidity → analysis ongoing
  - Incoherent J/ψ photoproduction

UPC Ppb and pPb

- Data collected in in early 2013

Additional slides

2. Model predictions

The center–of–mass energy per nucleon in Pb–Pb collisions at the LHC is $\sqrt{s_{NN}} = 2.76$ TeV. This corresponds to a Lorentz factor of $\gamma_L = 1470$. The invariant mass of the ρ^0 is $M_{\rho^0} = 775$ MeV. At mid–rapidity, $y = 0$, this gives a photon energy of $E_\gamma = 775$ MeV$/2 = 338$ MeV. The equivalent γ–proton center–of–mass energy is then

$$W_{\gamma p} = \sqrt{4E_\gamma m_p \gamma_L} = 43.2 \text{ GeV}. \tag{1}$$

This is three times higher than at RHIC, and higher than in any fixed–target experiment.

Summary

The LHC is the most powerful photon-photon and photon-hadron collider

Photoproduction of Heavy quarkonium production in UPC was discussed → study nuclear gluon density

At LHC, the following analysis can be done

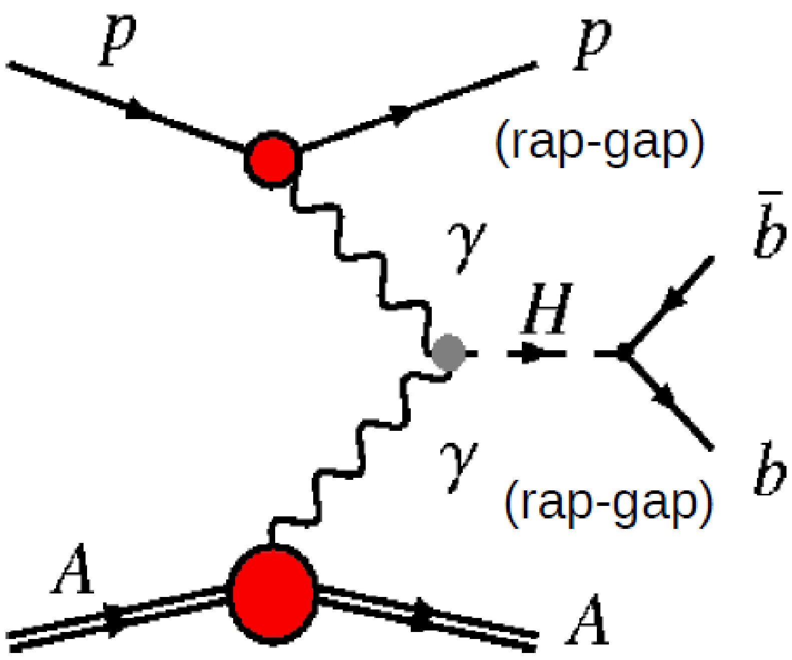
- Energy dependence
- Rapidity dependence
- Collidying systems (pp, PbPb, pPb, Pbp)

First time measurements on photon-proton are expected. A yet unexplored kinematic regime!

Exclusive Higgs in photon-photon

DdE&J.P.Lansberg PRD81 (2010)014004

- Exclusive electromagnetic Higgs production:



- Photons emitted by p & A.
- Proton & nucleus survive interaction
  (proton dissociation also considered)
- Two rapidity gaps (p & A sides).

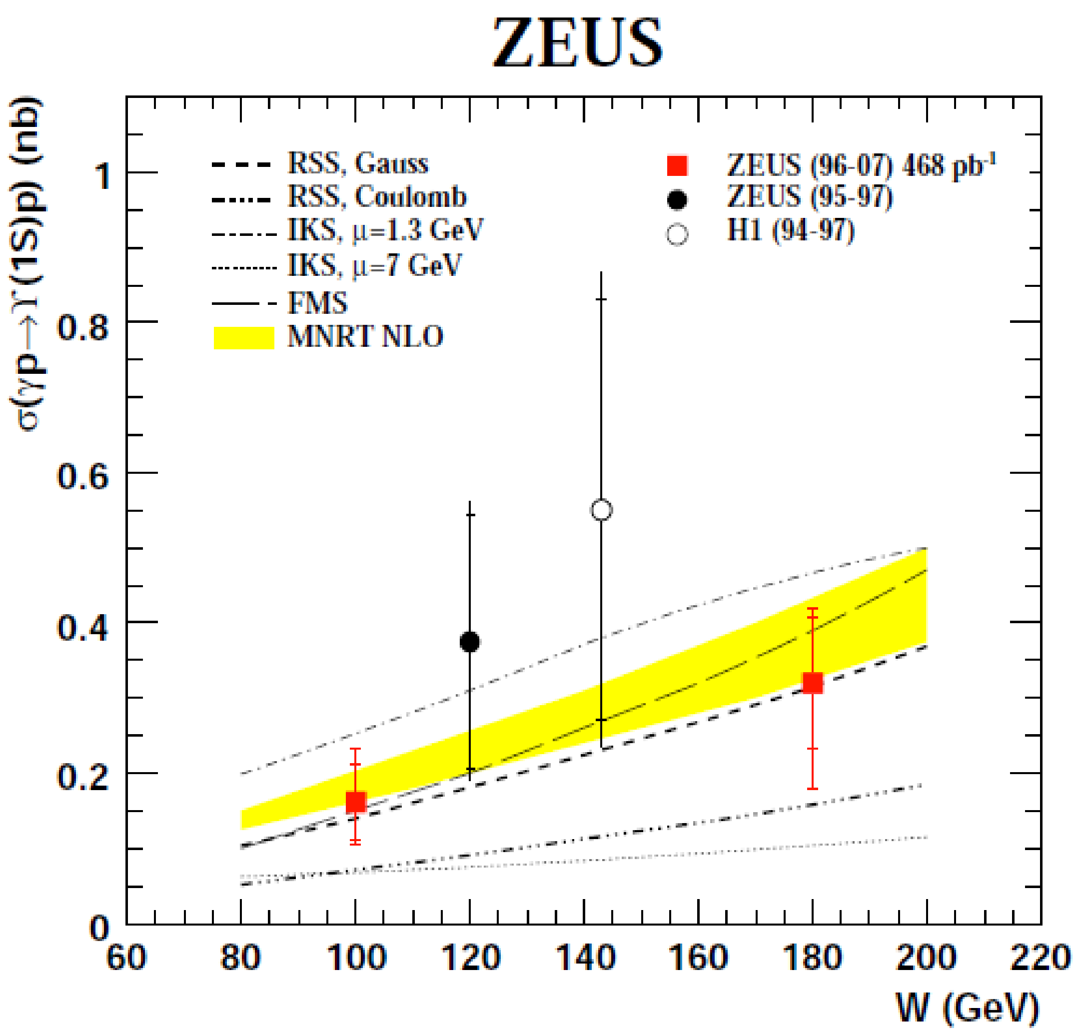
They calculated
3-sigma
observation with
300 pb-1

Upsilon photoproduction

γ + p → Υ + p : possible thanks to strong photon flux of the proton hitting the Pb nuclues

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

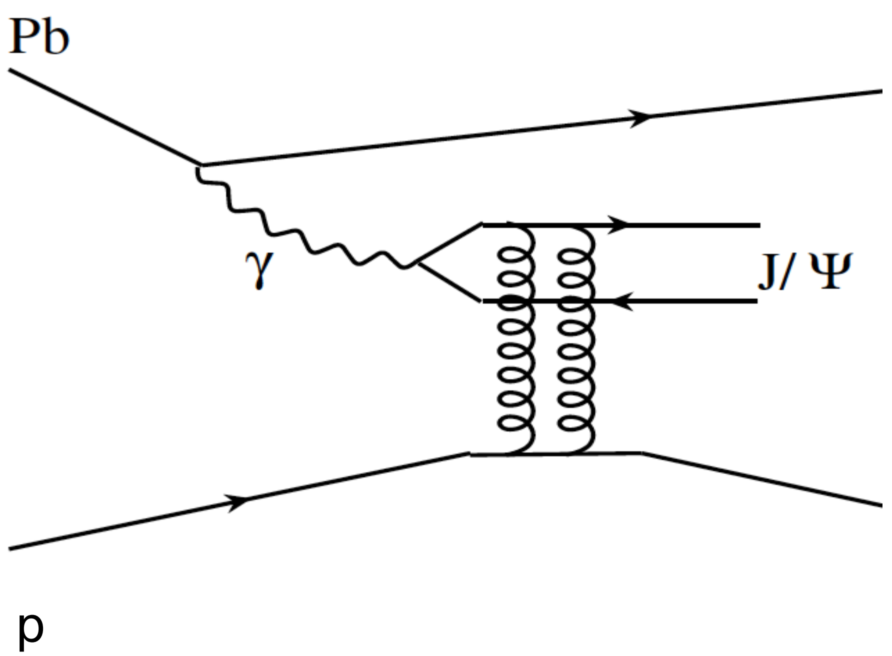
Uncertainty in measured cross section larger than a factor 3

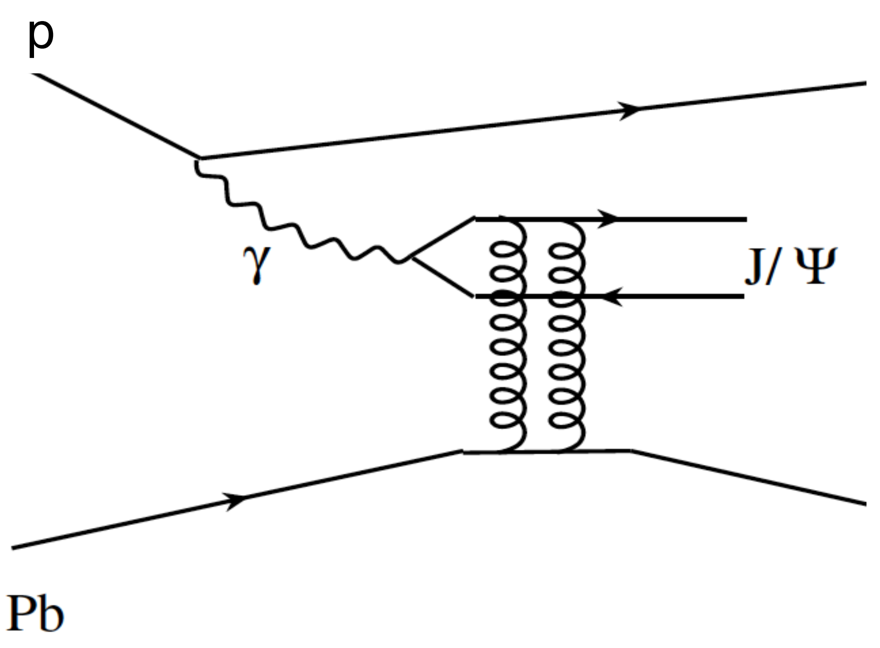


Ideal way to measure this process at LHC

Needed to have a baseline for

γ + Pb → Υ + Pb



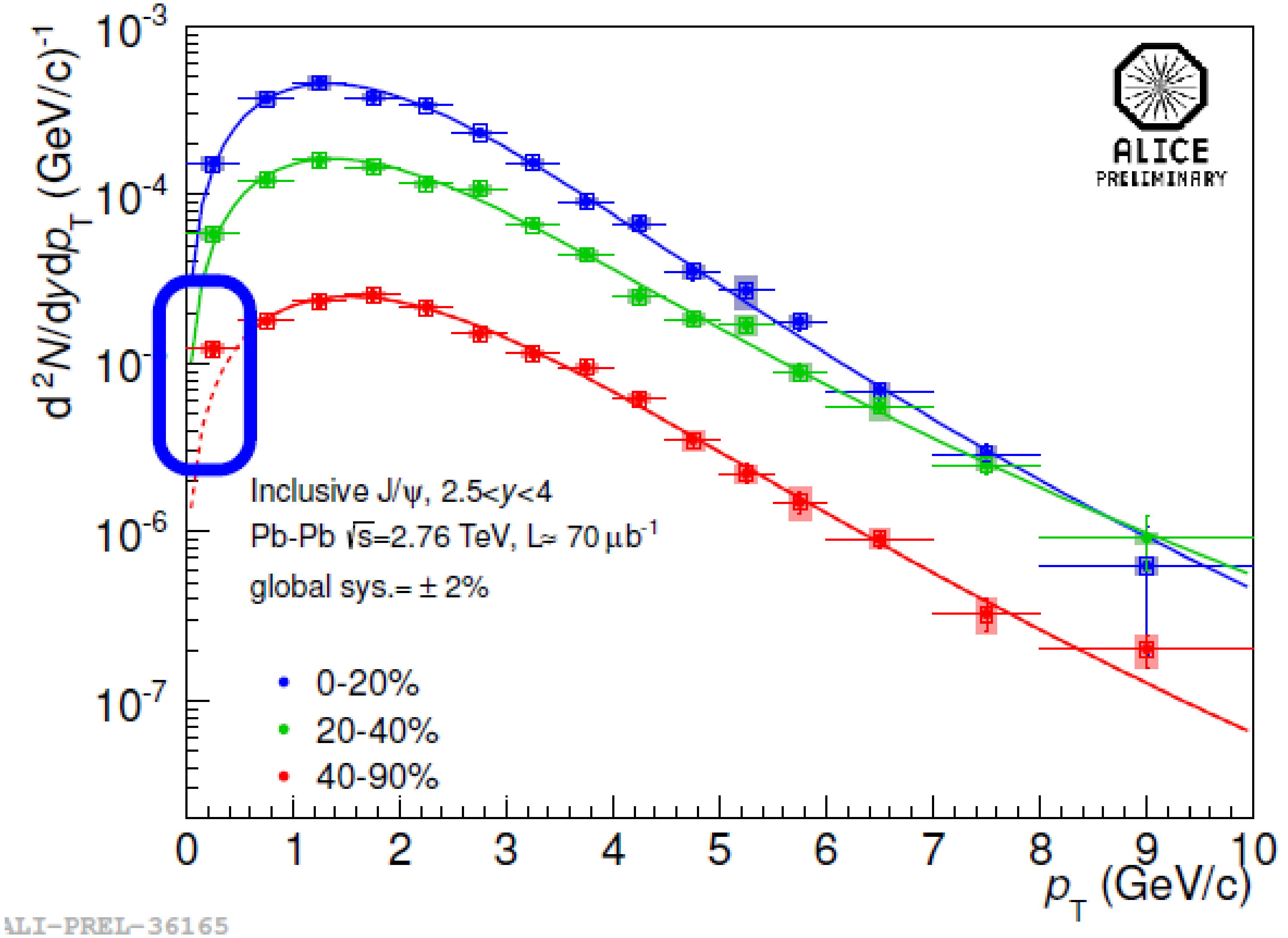


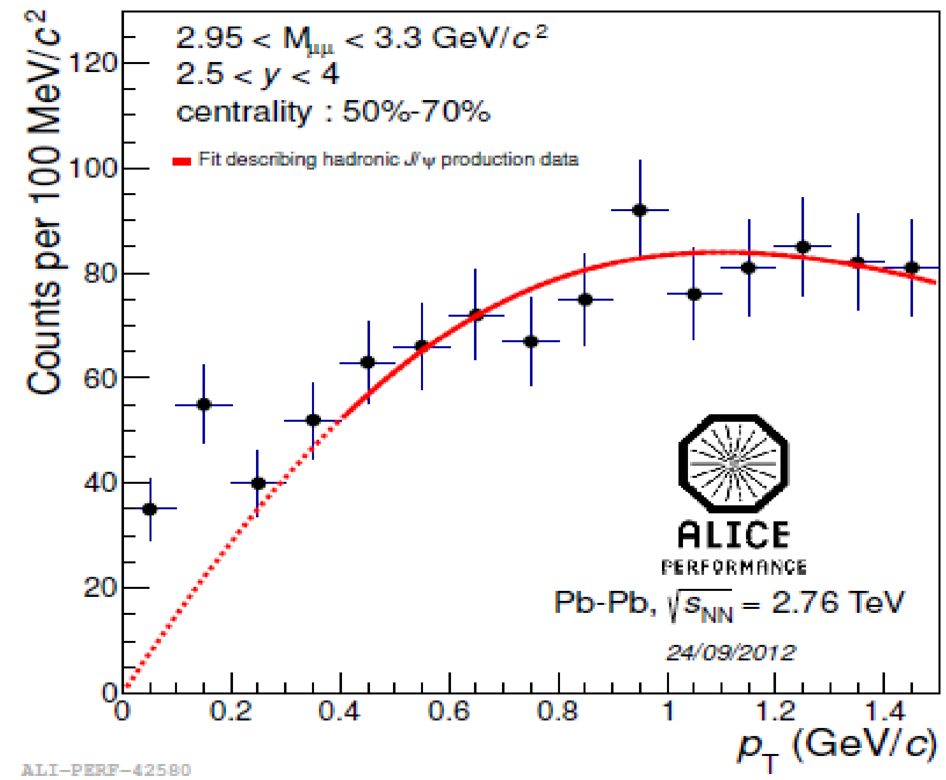
UPC in pPb and Pbp

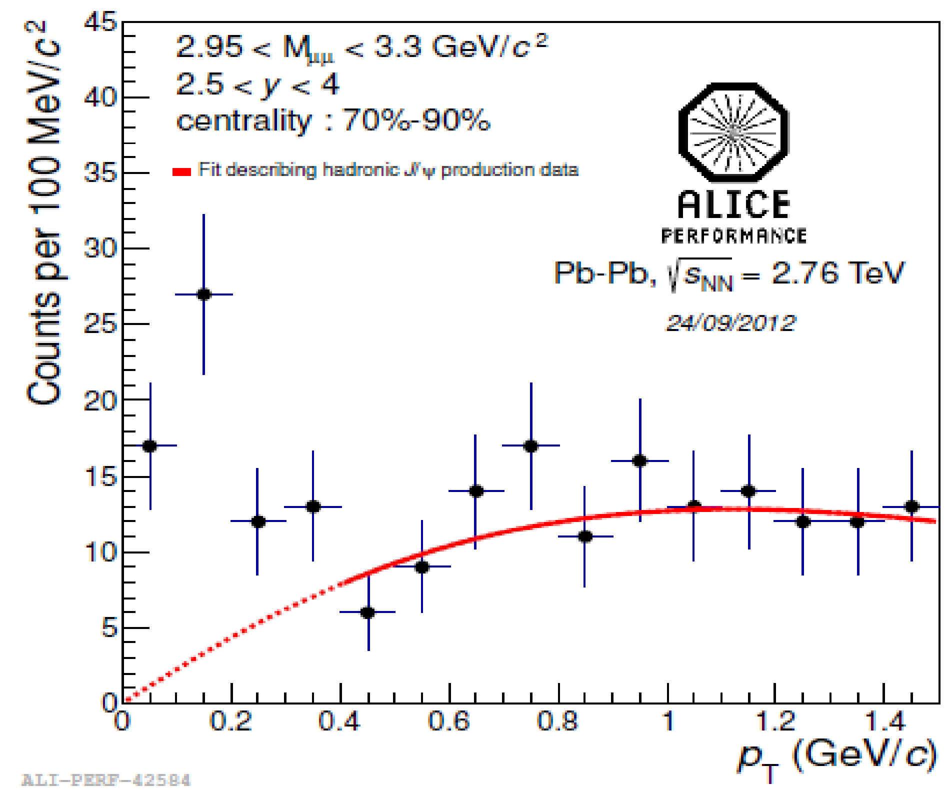
Photon flux scale $\rightarrow Z^2$ Target scale $\rightarrow A^{2/3}$

Then, flux/target scale ~200

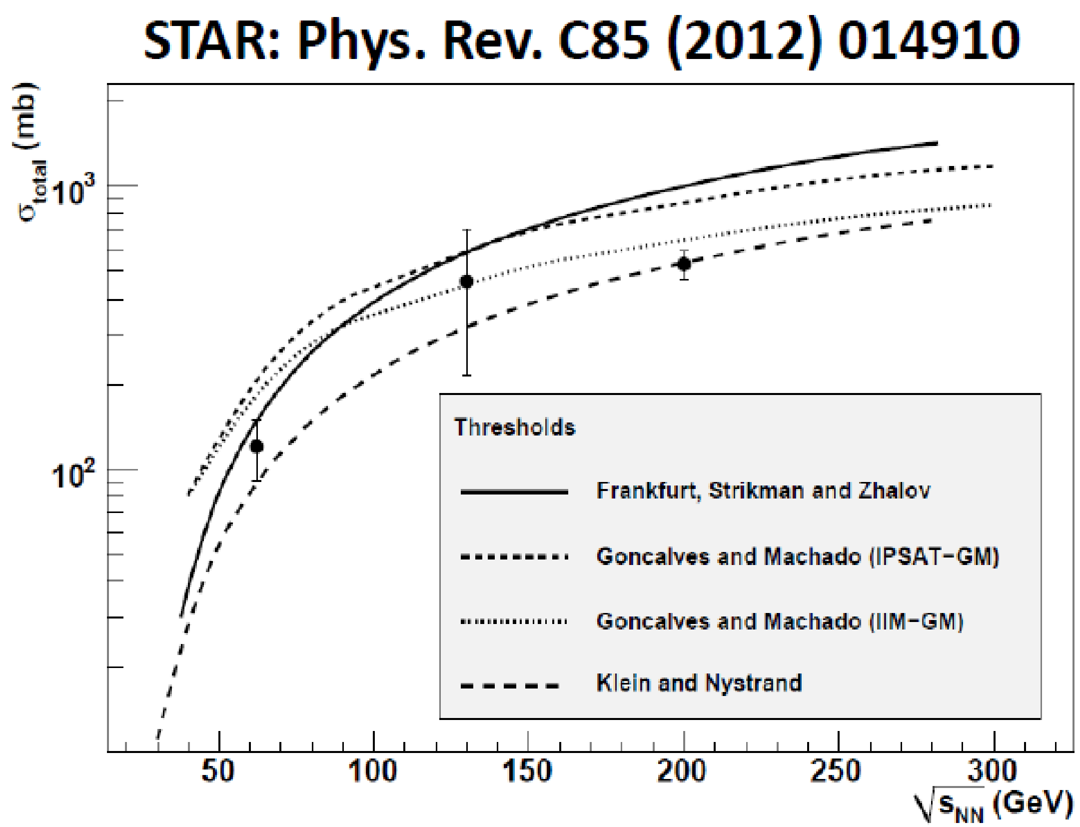
UPC in inclusive peripheral Pb-Pb at forward rapidity?!

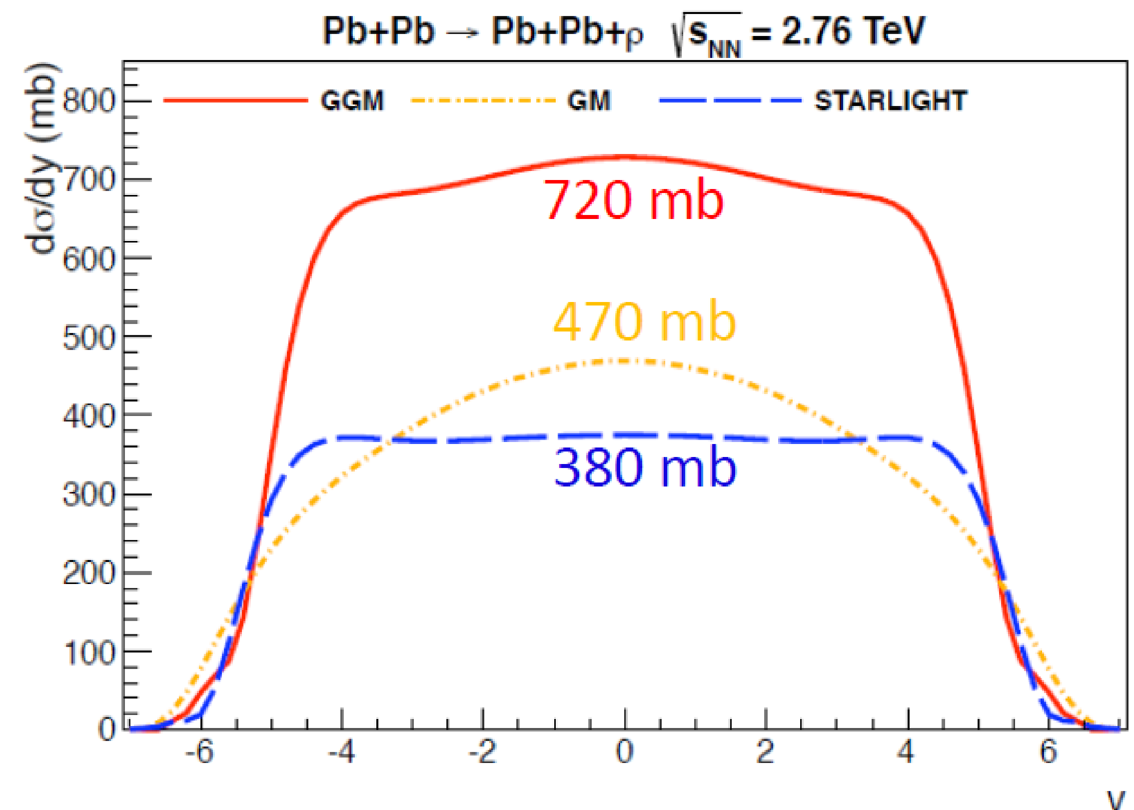






ρ^0 photo-production at central rapidity





GGM: Frankfurt, Strikman, Zhalov, Phys. Lett. B 537 (2002) 51; Phys. Rev. C 67(2003) 034901

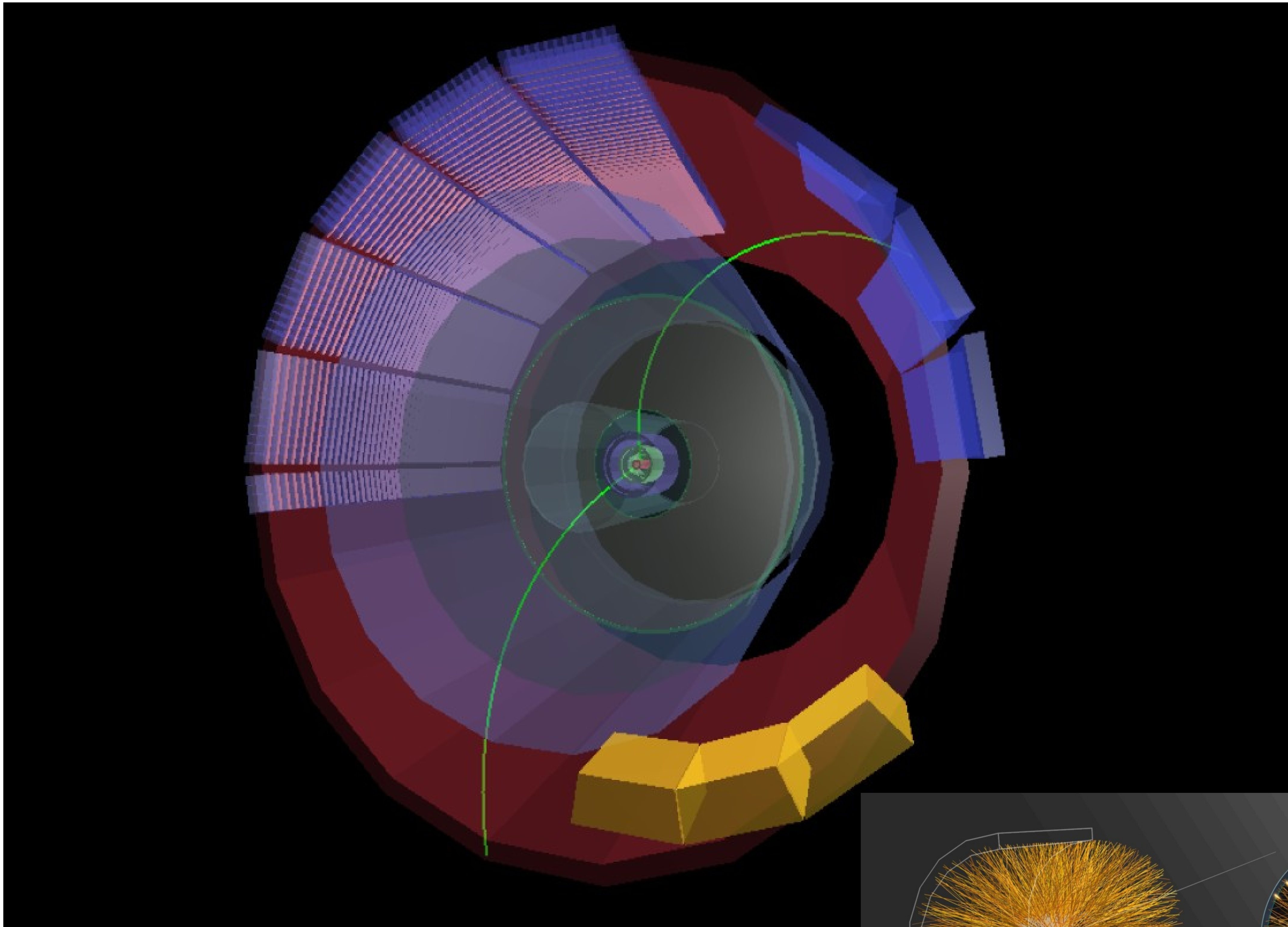
- Generalized Vector Meson Dominance Model in the Gribov-Glauber approach.
- Includes nondiagonal transitions $\gamma \rightarrow \rho' \rightarrow \rho$
- $\sigma_{\rho N}$ from Donnachie-Landshoff model, in agreement with HERA and lower energy data.

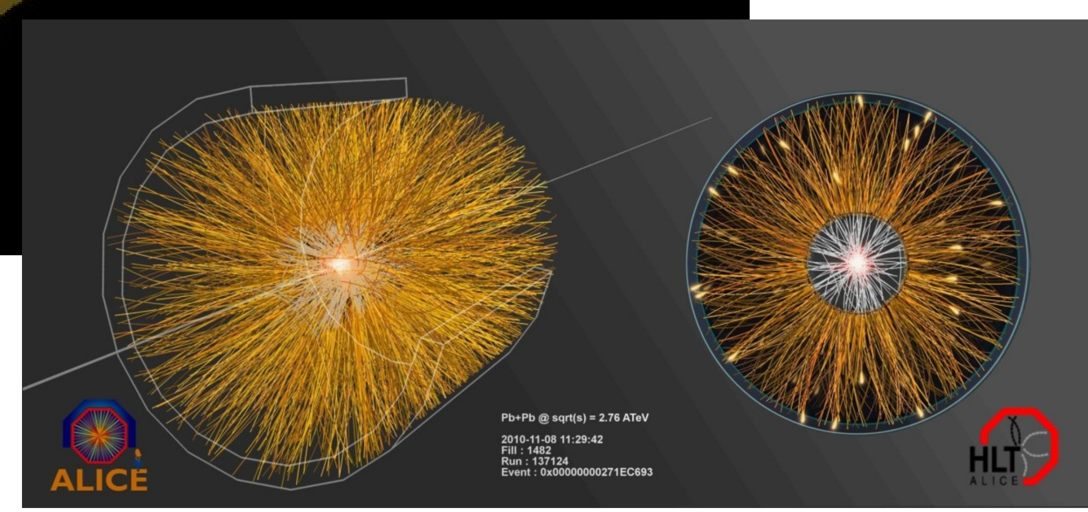
GM: Gonçalves, Machado, Phys. Rev. C 84 (2011) 011902

- Based on the color dipole model in combination with saturation from a CGC model.

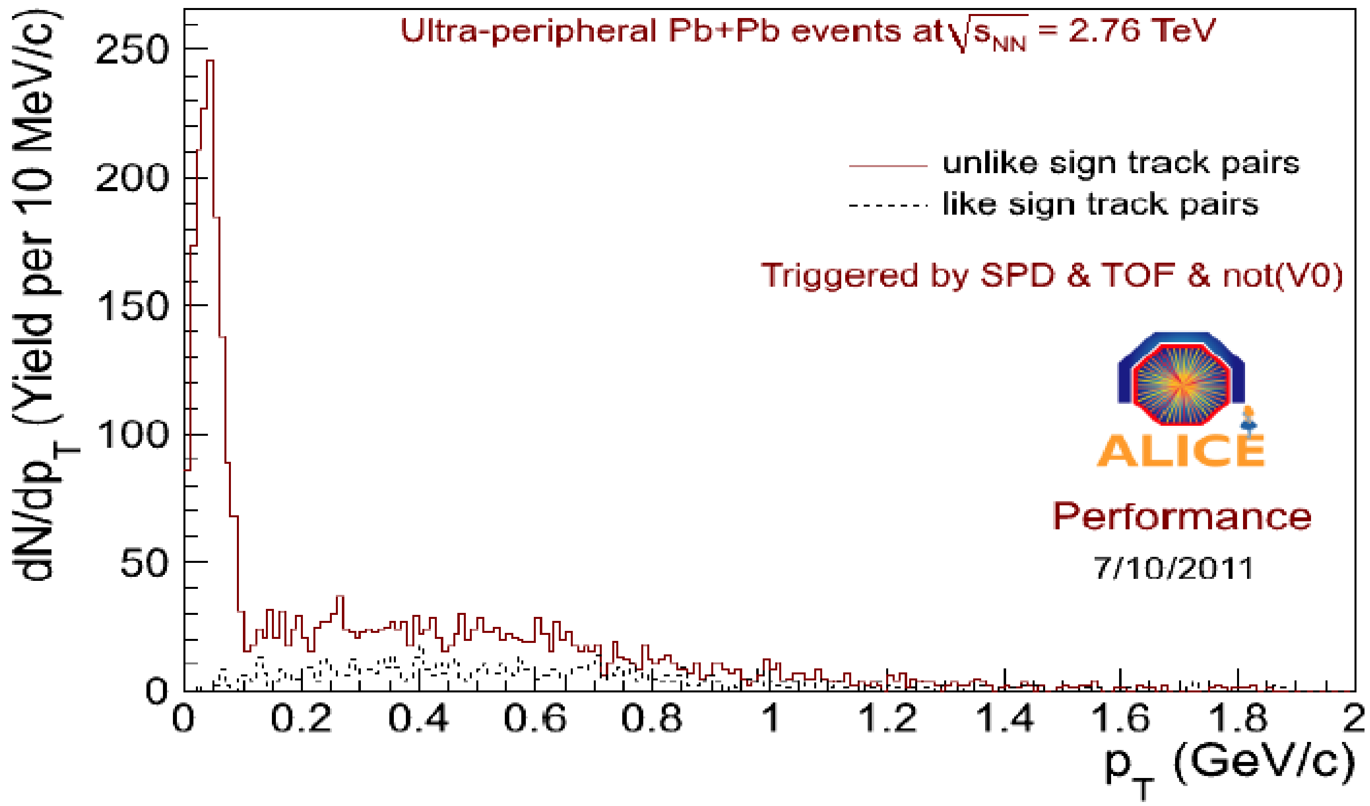
STARLIGHT: Klein, Nystrand, Phys. Rev. C 60 (1999) 014903, http://starlight.hepforge.org/

- Uses experimental data on $\sigma_{\rho N}$ cross section.
- Glauber model neglecting the elastic part of total cross section.

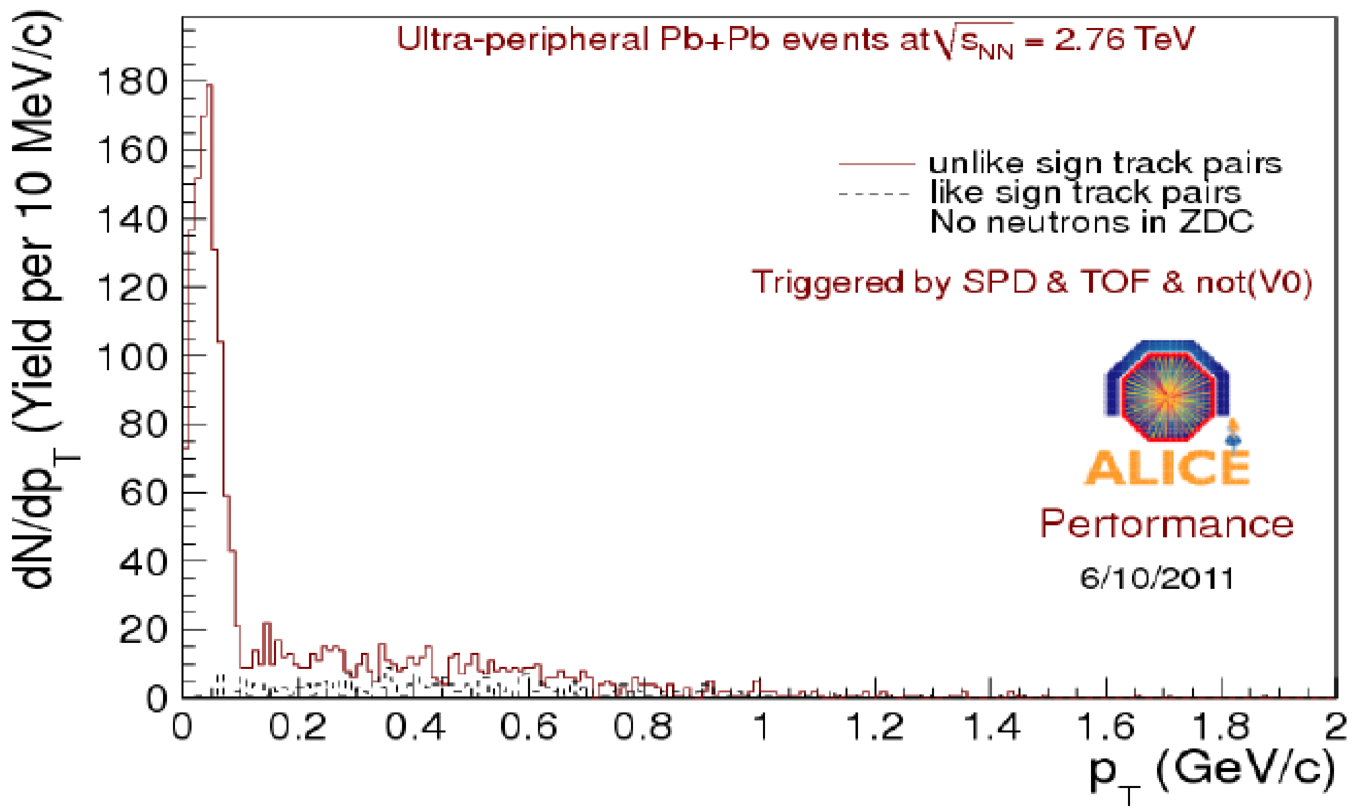



Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x00000000271EC693
ALICE
HLT

ρ^0 photo-production at central rapidity



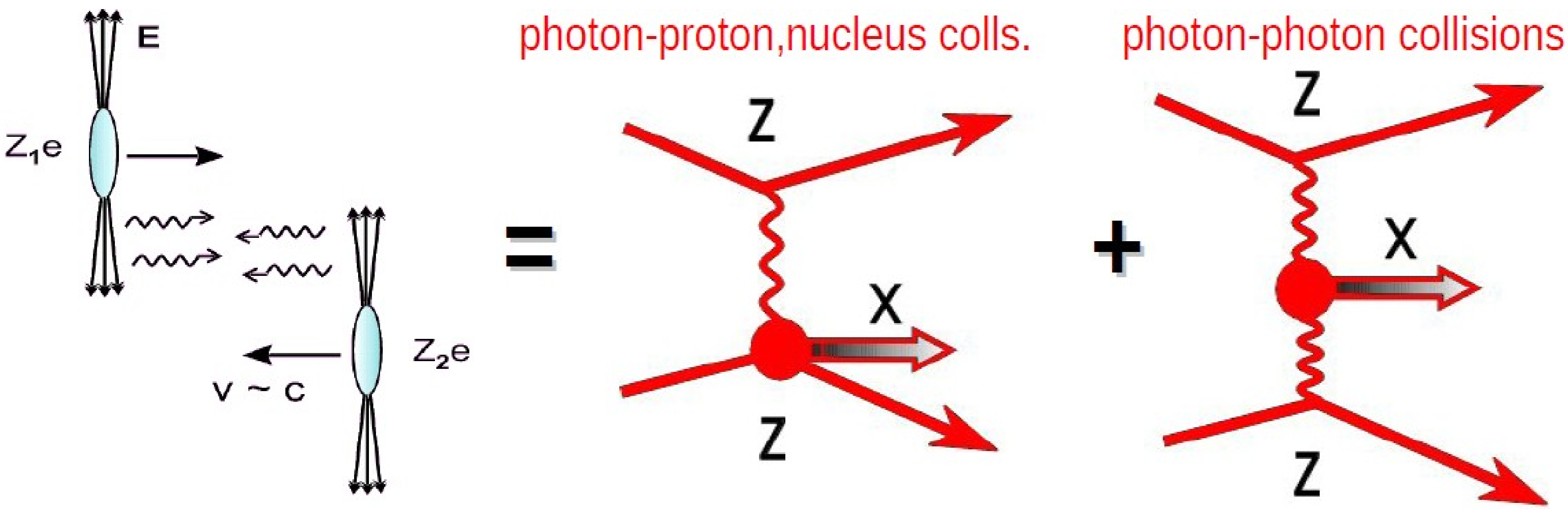
- Coherent production characterised by low transverse momentum of the final state, determined by the nuclear form factor, $p_T < \approx 100$ MeV/c.



- Results after requiring no neutron emission using ZDCs, *i.e.* No neutron break-up

- Next step: Determine ρ^0 photoproduction cross section

Why Ultra-Peripheral collisions

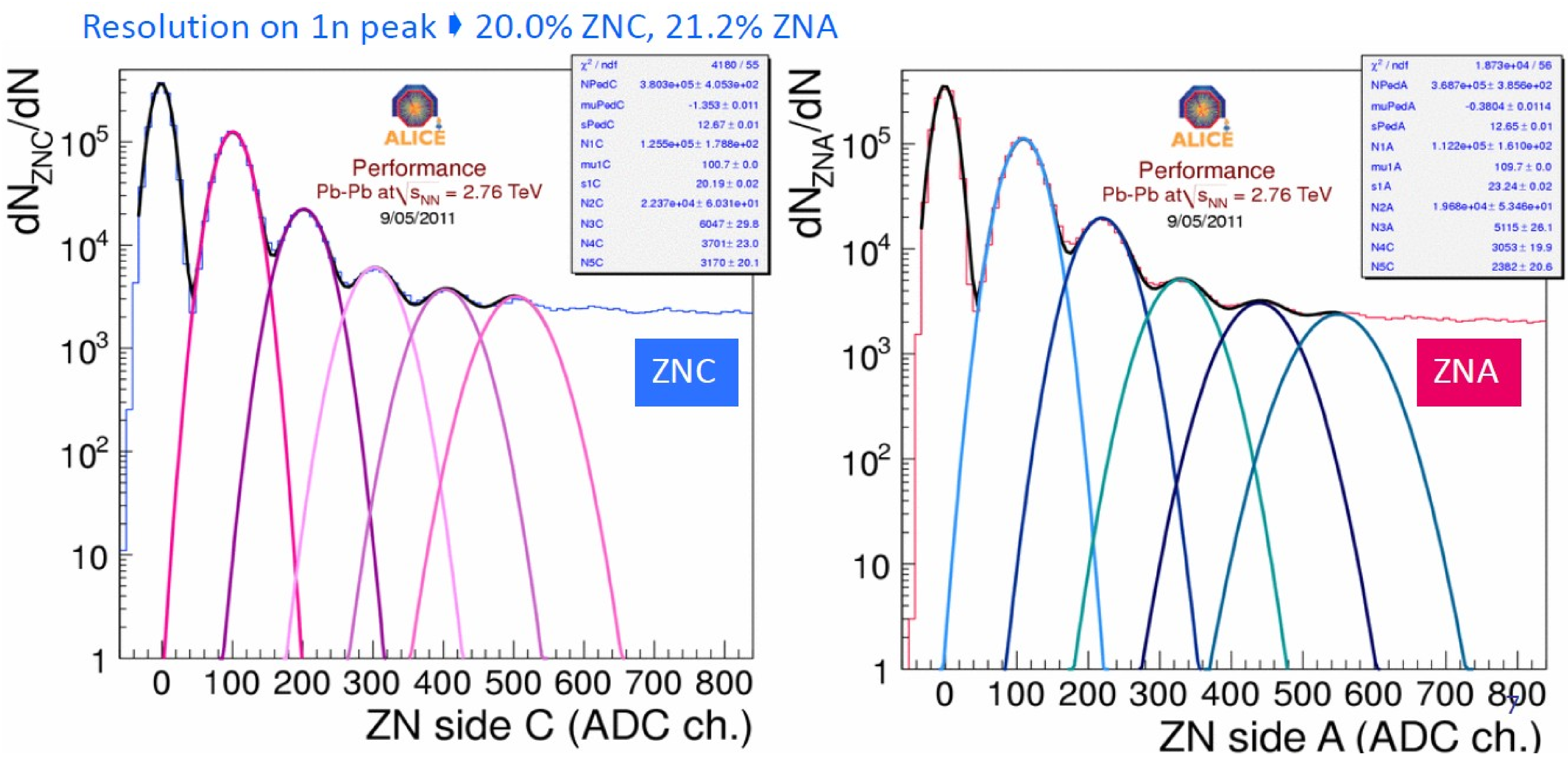


- Max. LHC γ energies: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb-beam), ~ 2.5 TeV (p-beam)
- Max. LHC $\gamma\gamma$ c.m. energies: PbPb: $\boxed{\sqrt{s_{\gamma\gamma}} \approx 160\text{ GeV} \approx \sqrt{s_{\gamma\gamma}}\text{ (LEP)}}$
  pPb: $\boxed{\sqrt{s_{\gamma\gamma}} \approx 260\text{ GeV} \approx 2 \times m_H}$

ZDC analysis

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

→ See C. Oppedisano's talk at Quark Matter 2011, Annecy, France



Plots for single electromagnetic dissociation

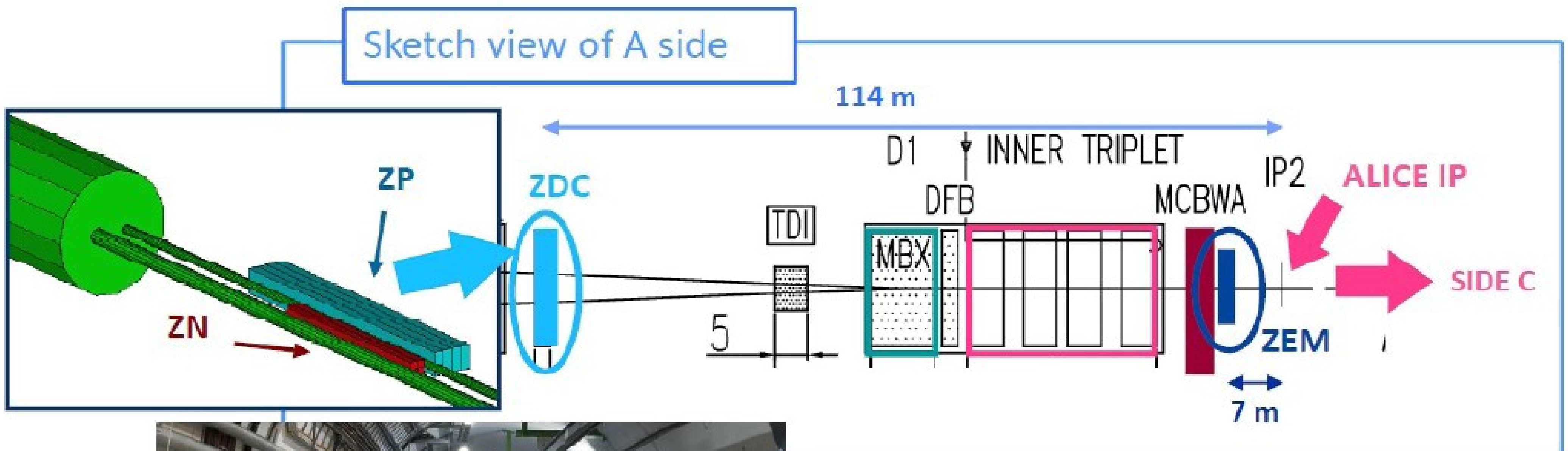
ALICE ZDCs

ALICE neutron ZDCs (ZNs) ➡ placed at 0° w.r.t LHC axis, ~114 m far from IP on both sides (ZNC on C side, ZNA on A side), "spaghetti" calorimeters, dimensions (7x7x100) cm^3

The ZDC system is completed by:

- 2 proton calorimeters placed at ~114 m from the IP external to the beam pipe
- 2 small (7x7x21) cm^3 EM calorimeters (ZEM1, ZEM2) placed at ~7.5 m from the IP, at ±8 cm from LHC axis, only on A side covering the range $4.8<\eta<5.7$

ZN acceptance for neutrons emitted in EMD of Pb nuclei at $\sqrt{s}$ = 2.76 A TeV ➧ 99 %



DATA

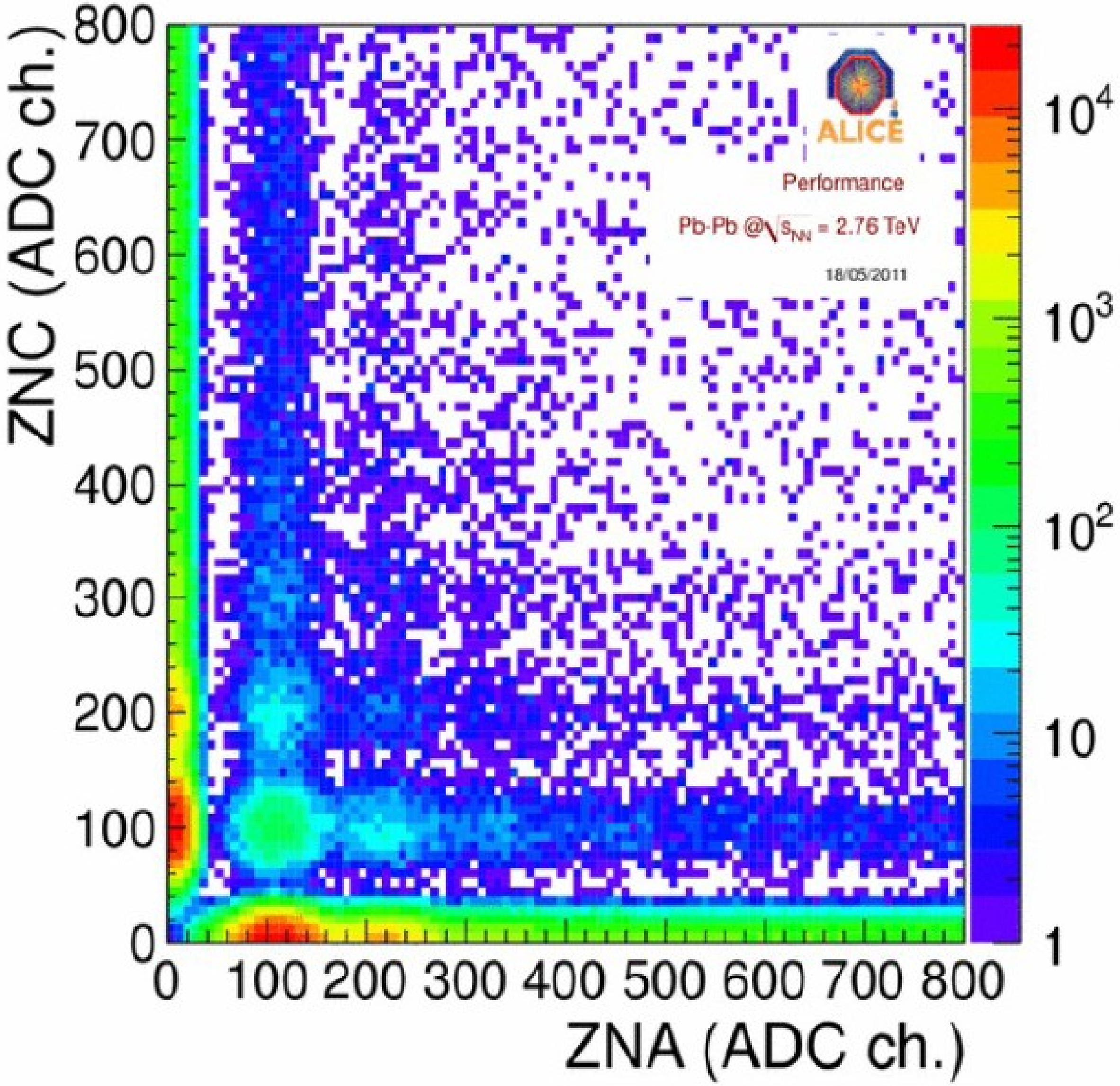
Sample ➧ dedicated RUN, $2.8 \cdot 10^6$ events collected

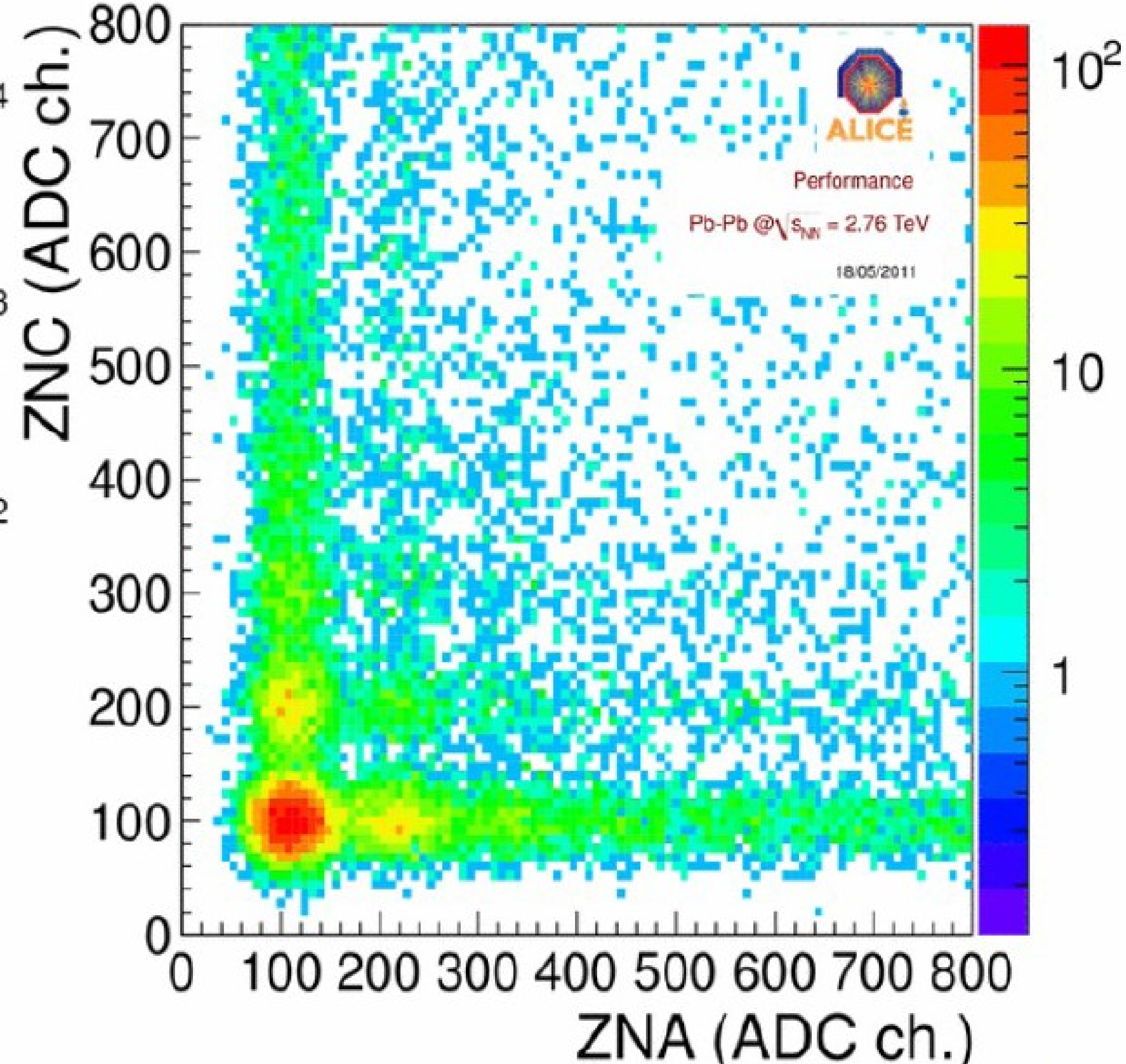
Trigger ➧ OR of the ZNs ➧ same input sent to Van der Meer scan scalers

Energy thresholds ➧ ZNC~500 GeV, ZNA~450 GeV (3σ below 1n mean value)

➡ ZNC vs. ZNA signal

- ➧ single EMD processes
- ➧ mutual EMD processes





6

Coherent production?!

Four physics processes:

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

$$N^{\mathrm{coh}}_{\mathrm{J}/\psi} = \frac{N_{\mathrm{yield}}}{1 + f_I + f_D}$$

Feed-down (f_D):
for example, ψ' decays to J/ψ $\pi^+\pi^-$

$$f_D^P = \frac{\sigma_{\psi'} \cdot BR(\psi' \rightarrow \mathrm{J}/\psi + \mathrm{anything}) \cdot (\mathrm{Acc} \times \varepsilon)^P_{\psi' \rightarrow \mathrm{J}/\psi}}{\sigma_{\mathrm{J}/\psi} \cdot (\mathrm{Acc} \times \varepsilon)_{\mathrm{J}/\psi}}$$

Three polarisation scenarios for ψ' decays were considered:

- No polarisation (NP)
- Full longitudinal polarisation (L)
- Full transverse polarisation (T)

According to STARLIGHT

$$f_D^{NP} = 11.9\%,\ f_D^T = 9.3\%,\ f_D^L = 16.8\%$$

According to RSZ

$$f_D^{NP} = 5.5\%,\ f_D^T = 4.3\%,\ f_D^L = 7.9\%$$

Thus, we took as the best estimate

f_D=(11±6)%

J/ψ Incoherent fraction (f_I)

According to STARLIGHT

$$f_I = 0.12$$

According to RSZ

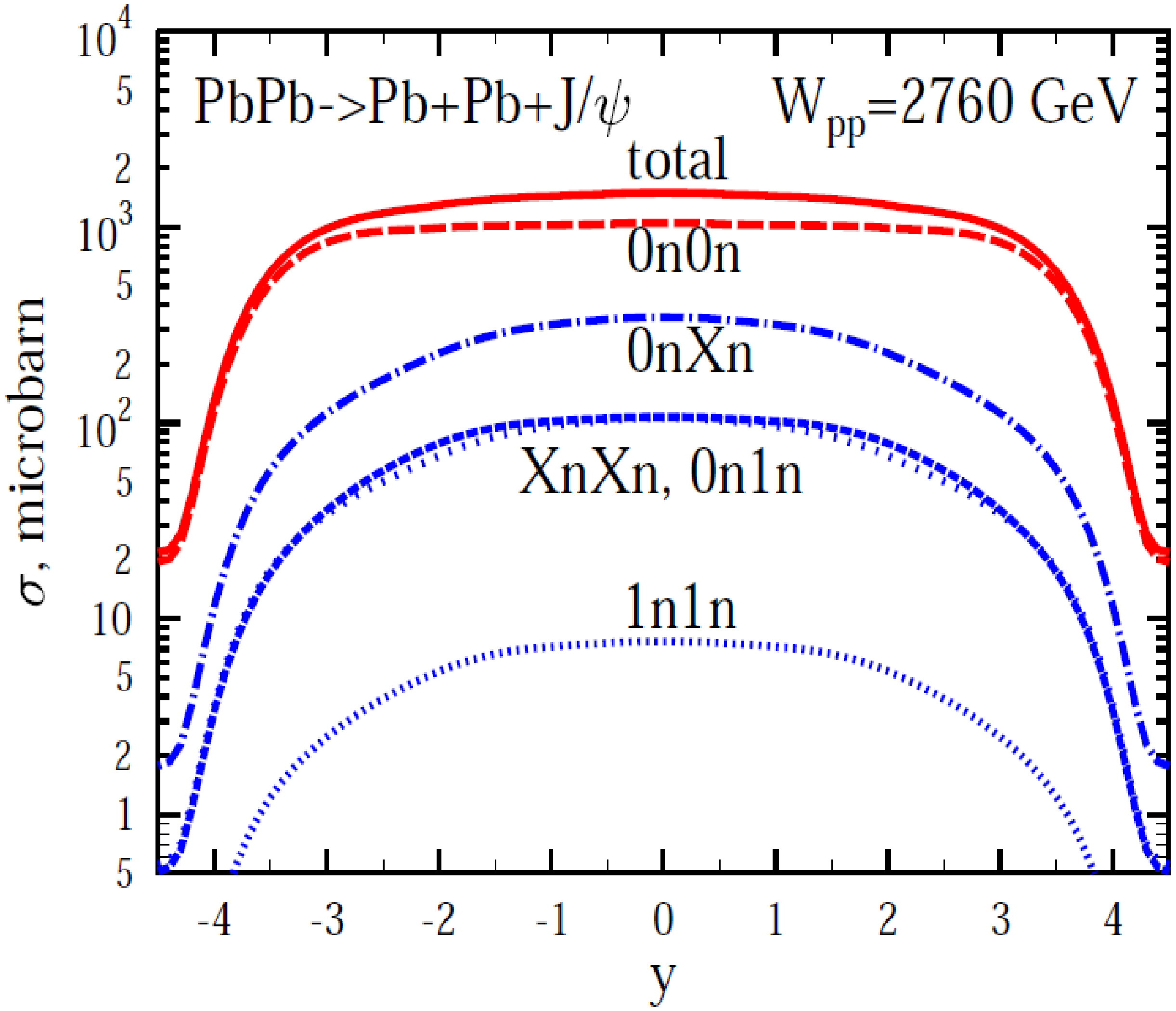
$$f_I = 0.08$$

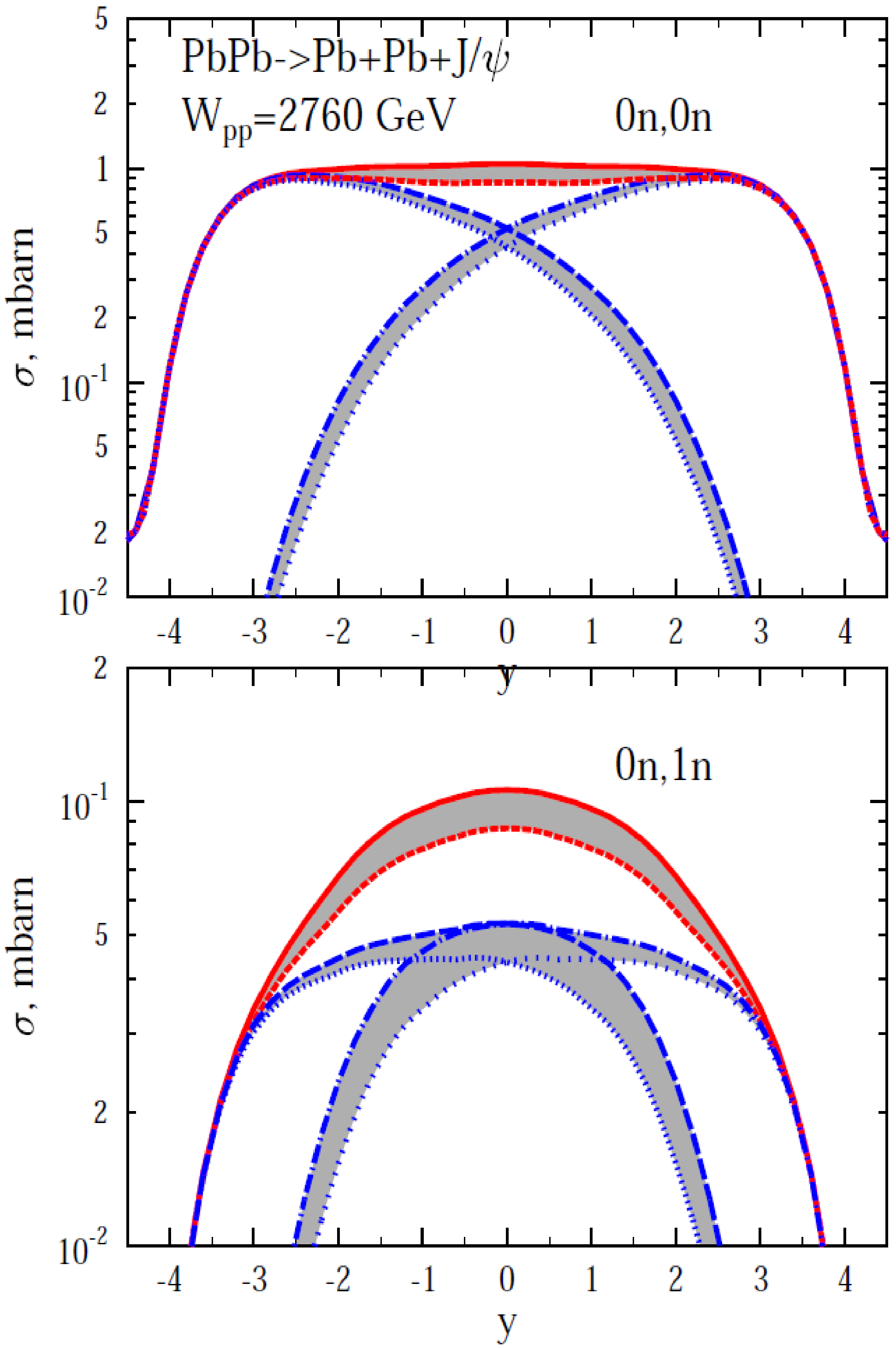
Using data ...

$$f_I = 0.26 \pm 0.05 \Rightarrow f_I = 0.12^{+0.14}_{-0.04}$$

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

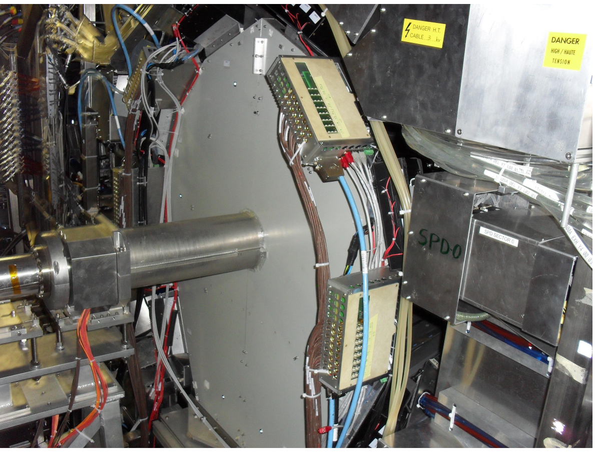
0n0n: no neutron emission

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

Shaded area: Uncertainty on nuclear gluon shadowing

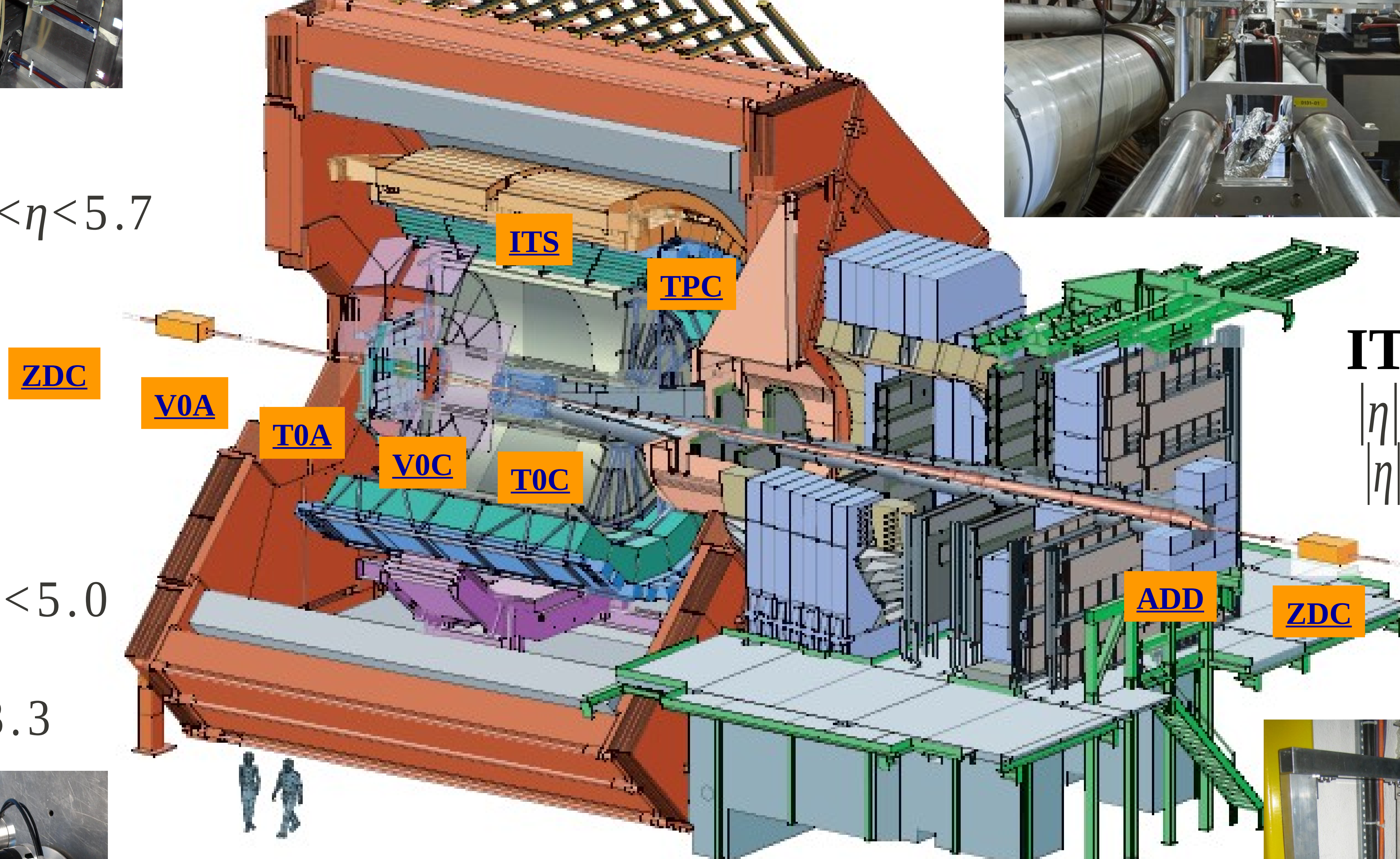
Diffractive Physics Today

V0A $2.8<\eta<5.1$



ZN $|\eta|>8.7$ **ZP** $|\eta|>8.4$

TPC $|\eta|<0.9$



ZEM $4.8<\eta<5.7$

ITS $|\eta|<1.4$ $|\eta|<2.0$

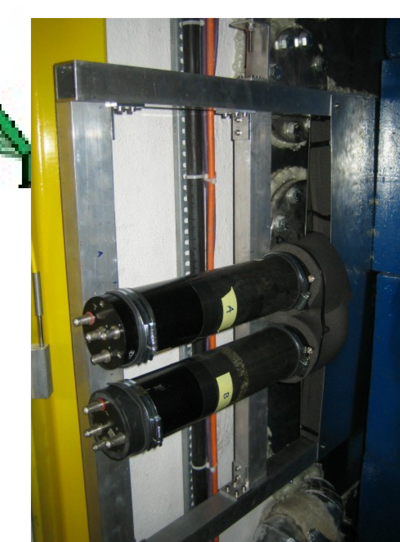
T0A $4.5<\eta<5.0$

T0C $-2.9<\eta<-3.3$

V0C $-1.7<\eta<-3.7$

FMD $1.7<\eta<5.0$ $-3.4<\eta<-1.7$

ADD $-4.9<\eta<-6.0$



Odderon production

Exclusive J/Ψ and Υ hadroproduction

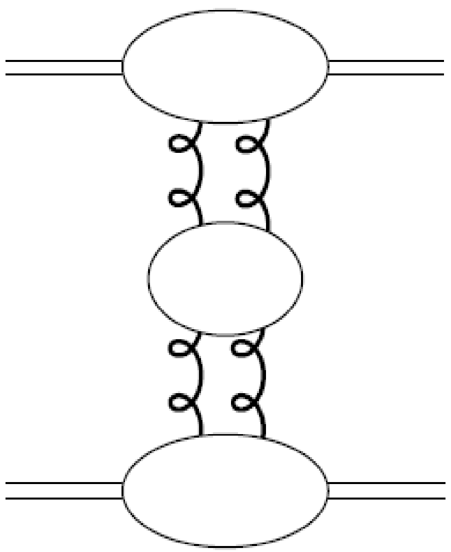
and the QCD odderon

Lech Szymanowski

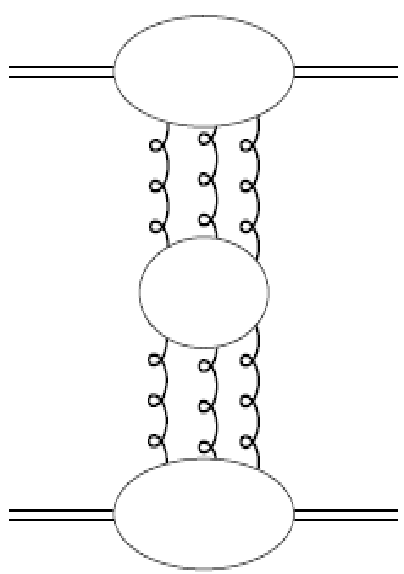
Ecole Polytechnique, Palaiseau,

Soltan Inst. for Nucl. Studies, Warsaw

Lech et al.
Phys Rev D. 75. 094023



16 July 2011



- Puzzle:

QCD $\rightarrow$

TWO colour singlet reggeons with intercepts around 1:

POMERON ($C = 1$) $\sigma_{AB} + \sigma_{\bar{A}B}$

ODDERON ($C = -1$) $\sigma_{AB} - \sigma_{\bar{A}B}$

which still escapes experimental verification

Odderon was introduced more than 30 years ago

L. Lukaszuk and B. Nicolescu, Lett. Nuovo Cim. **8** (1973) 405

it was often considered as a "heretic and doubtful concept"

C. Ewerz

naive Pomeranchuk thm: $\Delta\sigma = \sigma_T^{\bar{p}p} - \sigma_T^{pp} \rightarrow 0$, for $s \rightarrow \infty$

too strong assumptions in the proof (no odderon)

LHCb - Exclusive χ_c

	$\sigma(pp \to pp(J/\psi + \gamma))$ LHCb (pb)	SuperCHIC prediction (pb)
χ_{c0}	9.3 ± 4.5	14
χ_{c1}	16.4 ± 7.1	10
χ_{c2}	28 ± 12.3	3

[2] See LHL, V. A. Khoze, M. G. Ryskin, W. J. Stirling, Eur. Phys. J. **C69** (2010) 179-199.
[3] LHCb-CONF-2011-022

L.A. Harland-Lang (University of Cambridge) 4 / 19

CDF - Phys. Rev. Lett. 102, 242001 (2009)

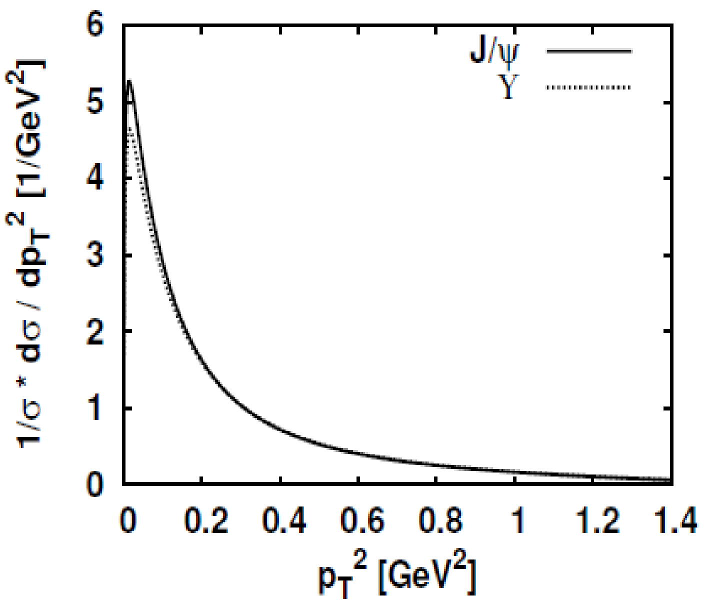
Our observation of exclusive χ_{c0} production implies that exclusive Higgs boson production should occur at the LHC [9] and imposes constraints on the $p+p \to p+H+p$ cross section.

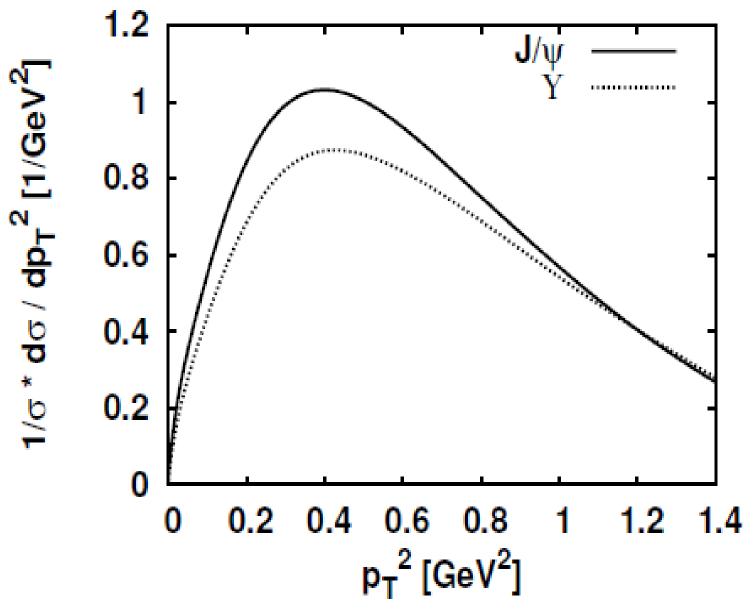
***Challenging measurement at the LHC**

***Large theoretical errors**

***Could be used as a standard central diffraction candle, useful for exclusive Higgs production**

Odderon production





Lech et al.
Phys Rev D. 75. 094023

$\frac{d\sigma}{dyd\mathbf{p}^2}\Big|_{norm}$ for $p\bar{p} \to p\bar{p}V$ and $pp \to ppV$.

$d\sigma^{corr}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

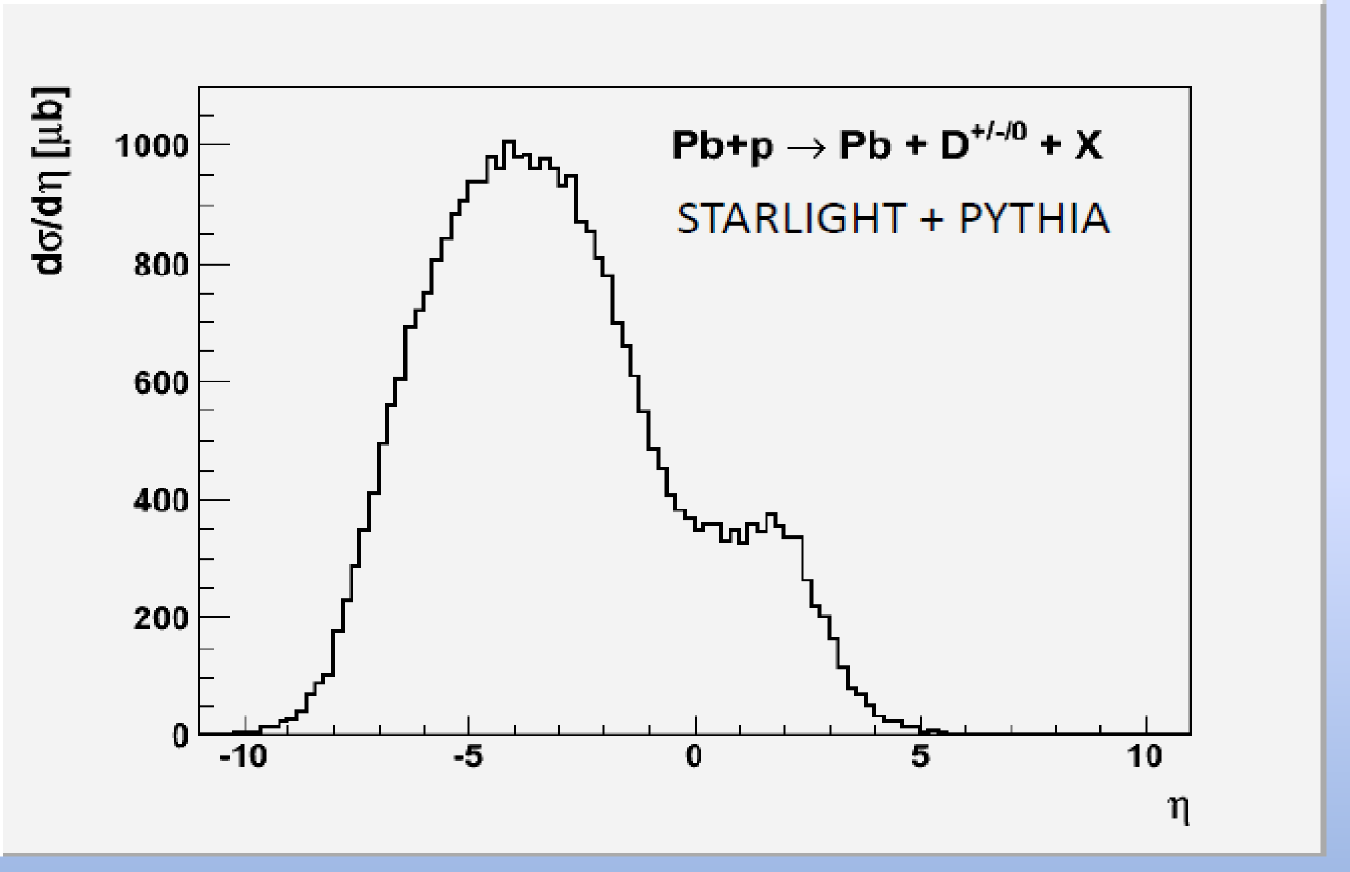
- γ-P and P-O ampl. do not interfere in our approx. $\to$ they can be treated independently

CDF - Phys. Rev. Lett. 102, 242001 (2009)

If the J/ψ and $\psi(2S)$ cross sections were larger than expected for photoproduction, it would be evidence for odderon exchange. If we assume a theoretical value of $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.0\pm0.3$ nb for photoproduction ($\gamma I\!P \to J/\psi$), compatible with the predictions, we can place a 95% C.L. upper limit $\frac{d\sigma}{dy}|_{y=0}(J/\psi) < 2.3$ nb for odderon exchange ($O I\!P \to J/\psi$).

Ultra-Peripheral Collisions – Proton-nucleus collisions

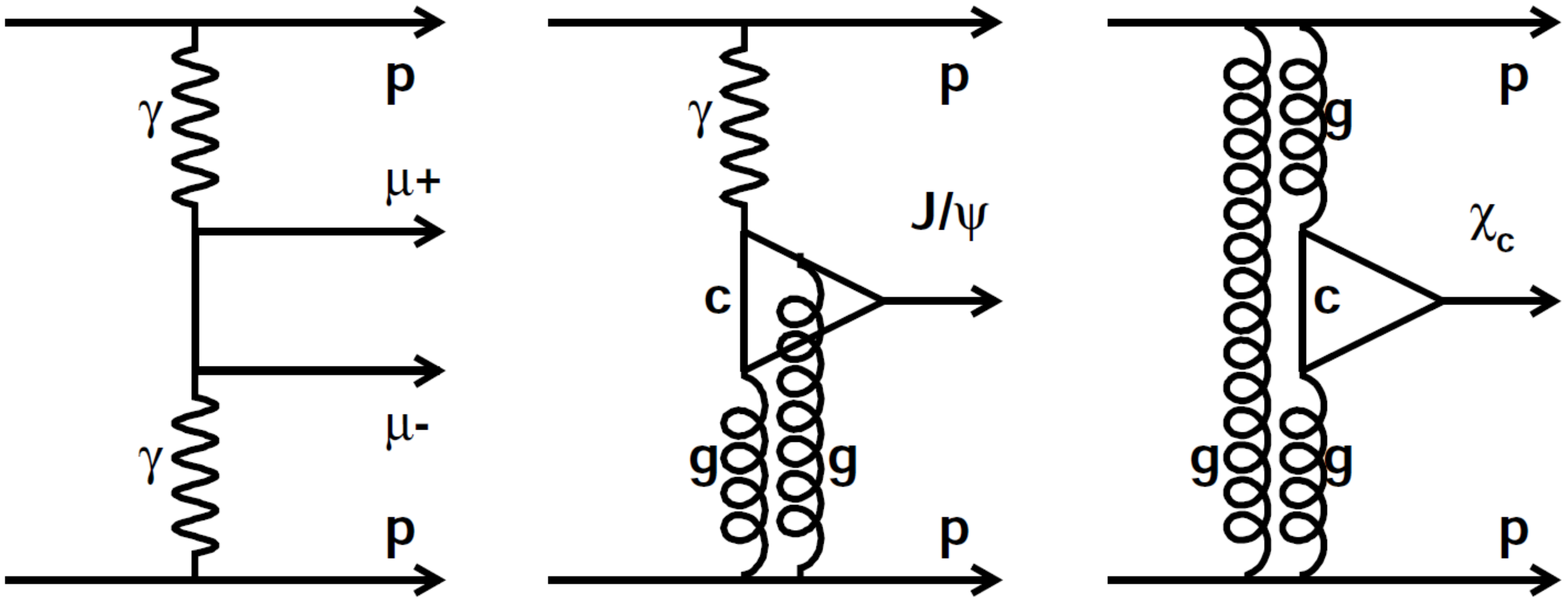
Example: photoproduction of open charm in p+Pb collisions.



- Cross section for photoproducing D mesons around mid-rapidity $d\sigma/dy \approx 400\ \mu b$.
- Plateau in forward direction from γ fluctuating to a ccbar-pair.

Proton-proton collisions

Feynman diagram; exclusive dimuon final states



Diphoton production

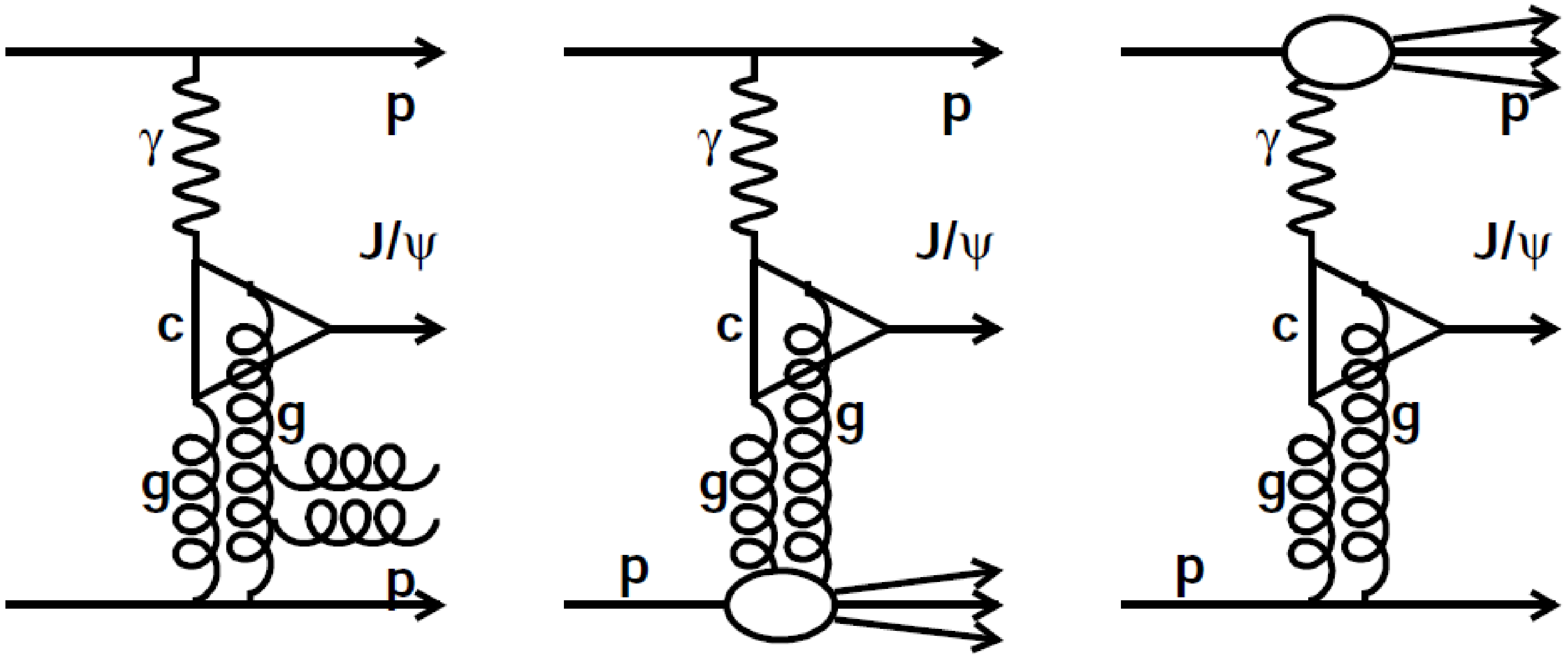
Photon-pomeron fussion

Double pomeron exchange

p+p → p + X + p

First LHC studies by LHCb-CONF-2011-022

Non-exclusive J/ψ

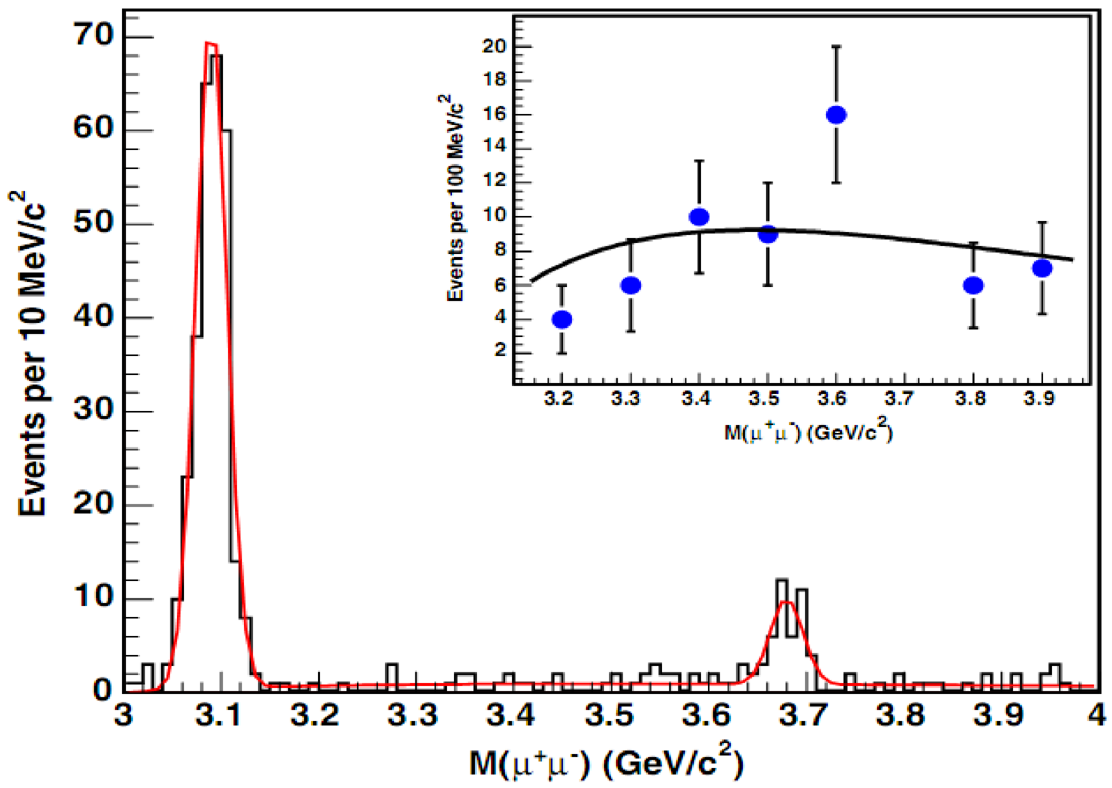


Additional final states particles due to proton dissociations or additional gluon radiations

CDF results

CDF - Phys. Rev. Lett. 102, 242001 (2009)

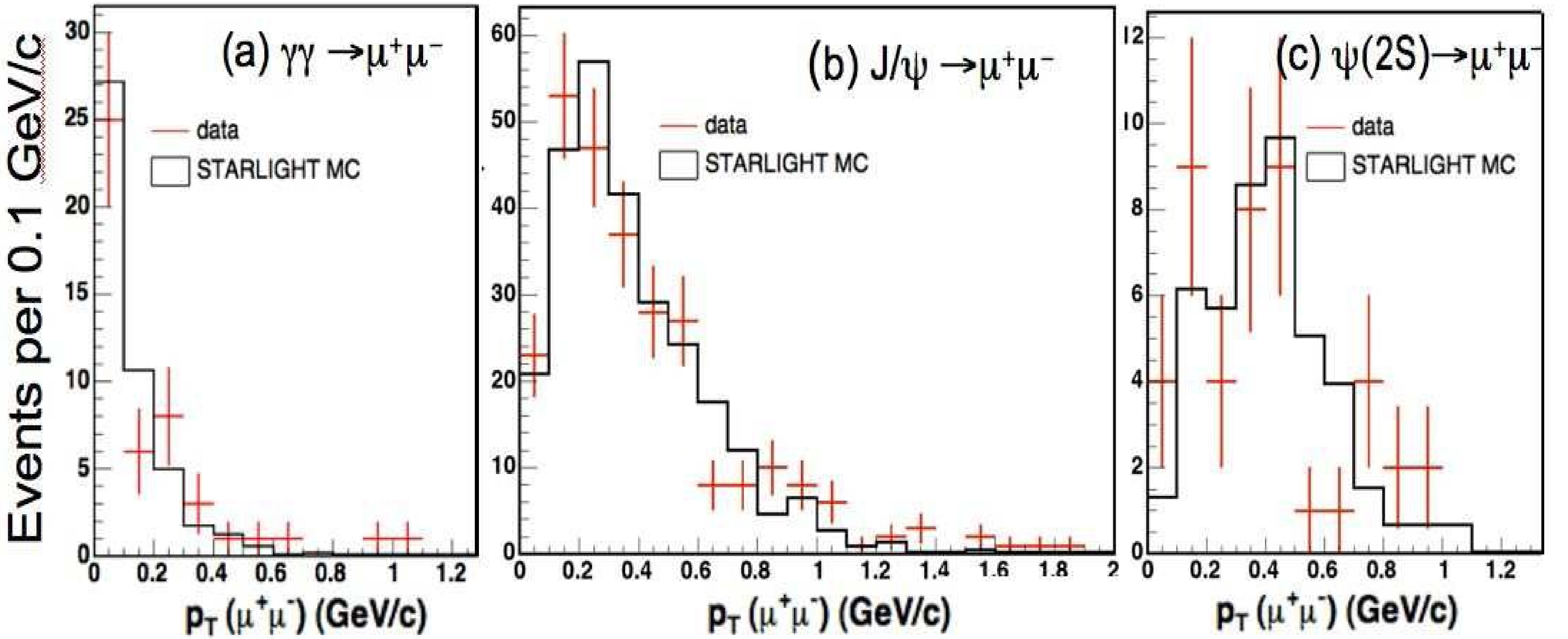
- Integrated luminosity: 1.48 fb^{-1}
- Total μμ events: 402
- μμ in the barrel (y=0): |η|<0.6
- η coverage:
  - |η|<3.6 - EM calorimeter
  - 3.6<|η|<5.2 – lead liquid scintillator calorimeter
  - 3.4<|η|<4.7 – Cherenkov counters
  - |η|<7.4 – Beam shower scintillator counters
- Good η coverage allowed to reject background contributions.
- Good calorimetry allowed to separate χ_{c0} contribution
- y=0 → x~10^{-3} – consistent with HERA results
-
- γ + p ~ 100 GeV centre-of-mass energy



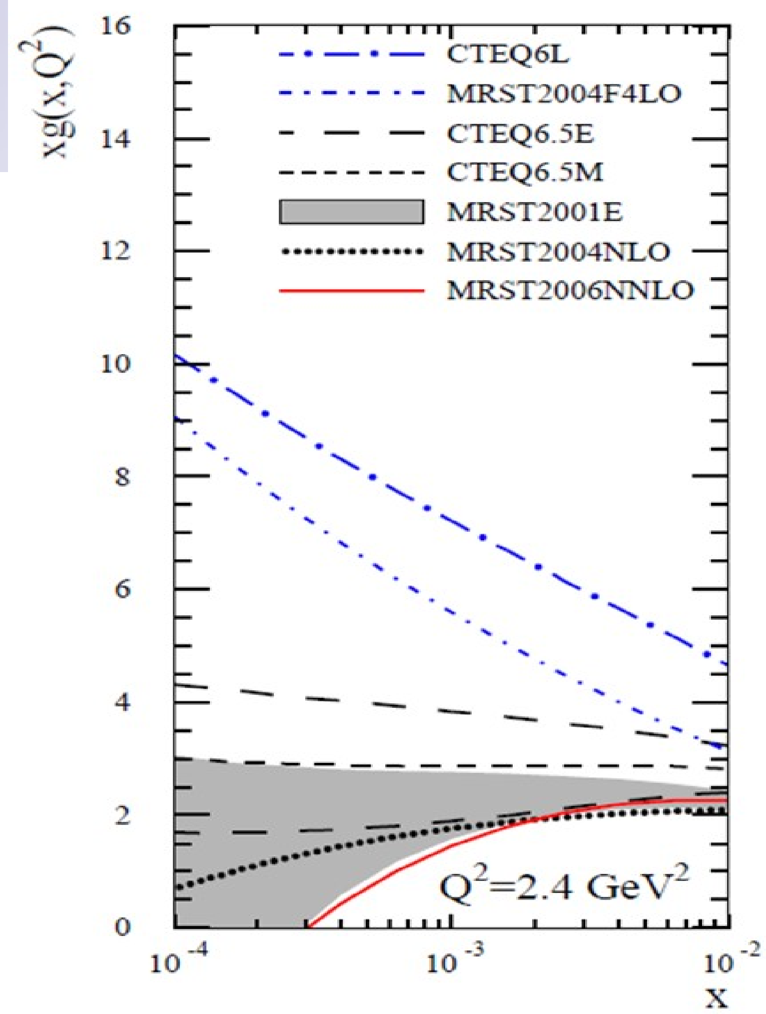
Channel	# Events	dσ/dy (y=0), nb
J/ψ	286	3.92 ± 0.25 ± 0.52
ψ'	39	0.53 ± 0.09 ± 0.10
χ_{c0}	65	76 ± 10 ± 10

CDF results

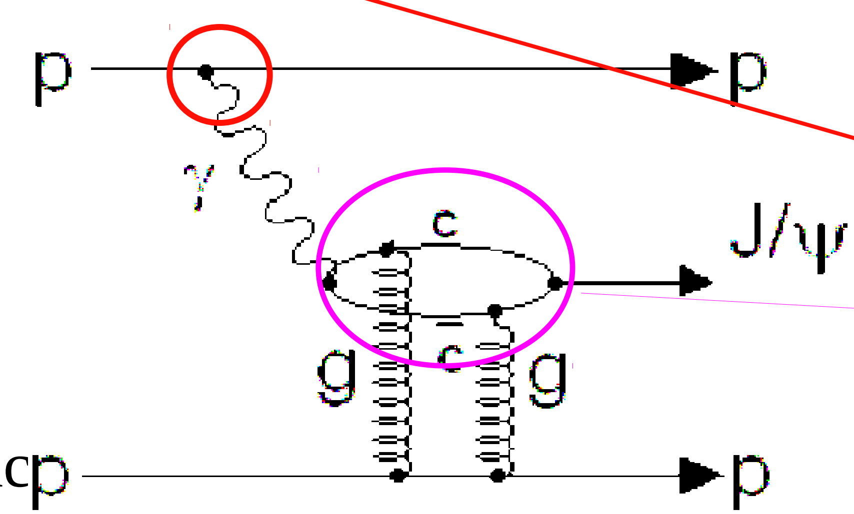
CDF - Phys. Rev. Lett. 102, 242001 (2009)



Small x gluon physics



- V. Rebyakova, Phys. Rev. D81, 031501(R) (2010)
- Coherent J/ψ production: pp → ppJ/ψ:



- Extrac -5.
  In the leading order:

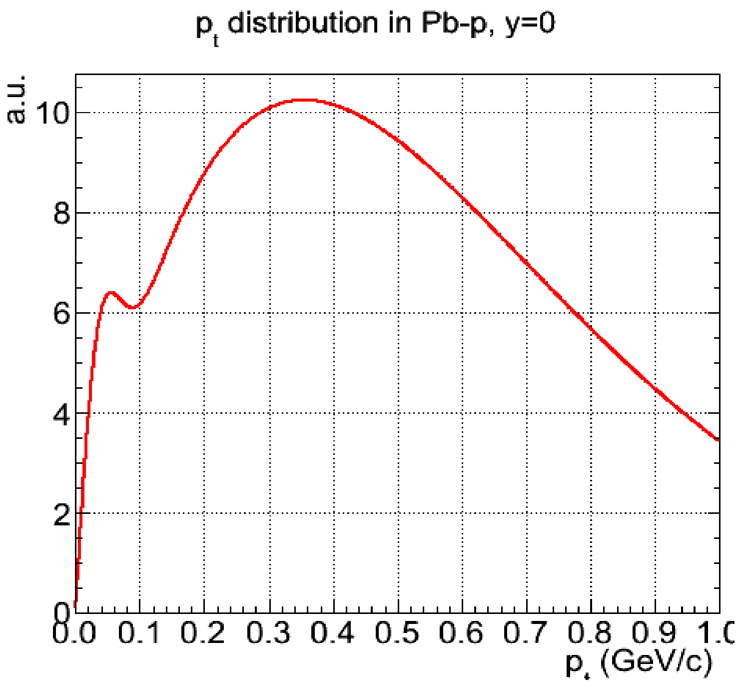
$$\frac{d\sigma_{pp\to ppJ/\psi}}{dtdy} = \frac{dN_{\gamma/p}(y)}{dy}\cdot\frac{d\sigma_{\gamma p\to ppJ/\psi}(y,t)}{dt} + \frac{dN_{\gamma/p}(-y)}{dy}\cdot\frac{d\sigma_{\gamma p\to ppJ/\psi}(-y,t)}{dt}$$

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

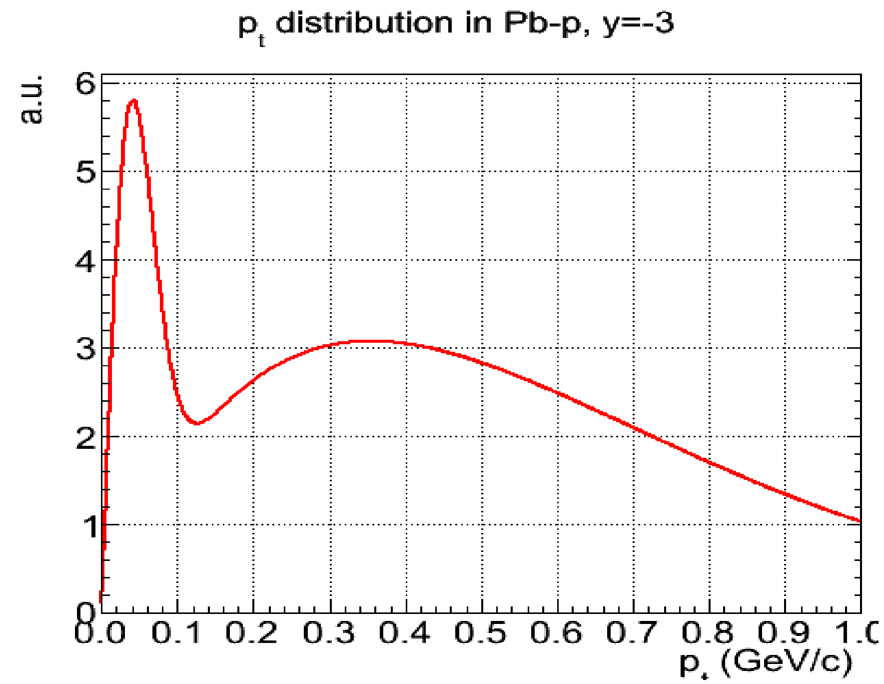
J/ψ photoproduction - p_T

Recent Calculations by E. Kryshen and M. Zhalov, private communication

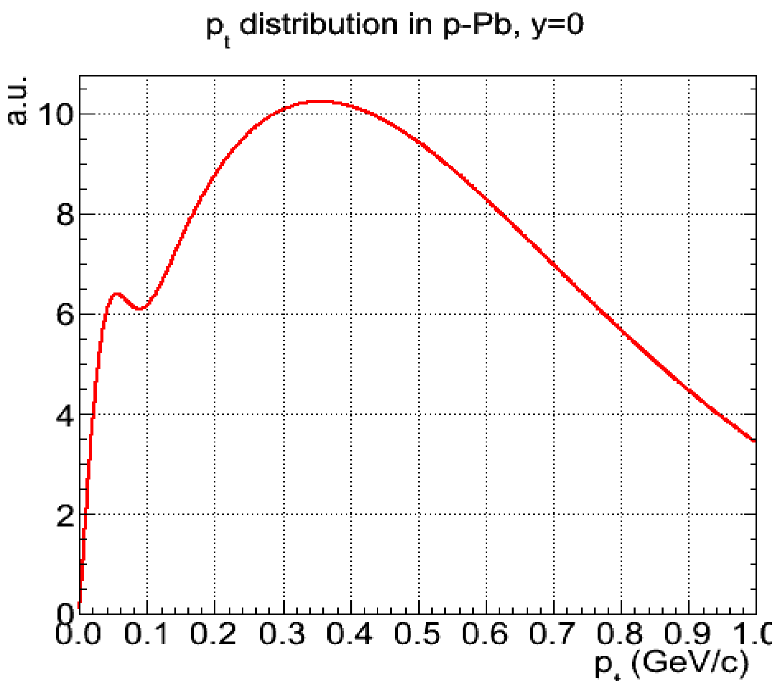
Pb-p **Central**

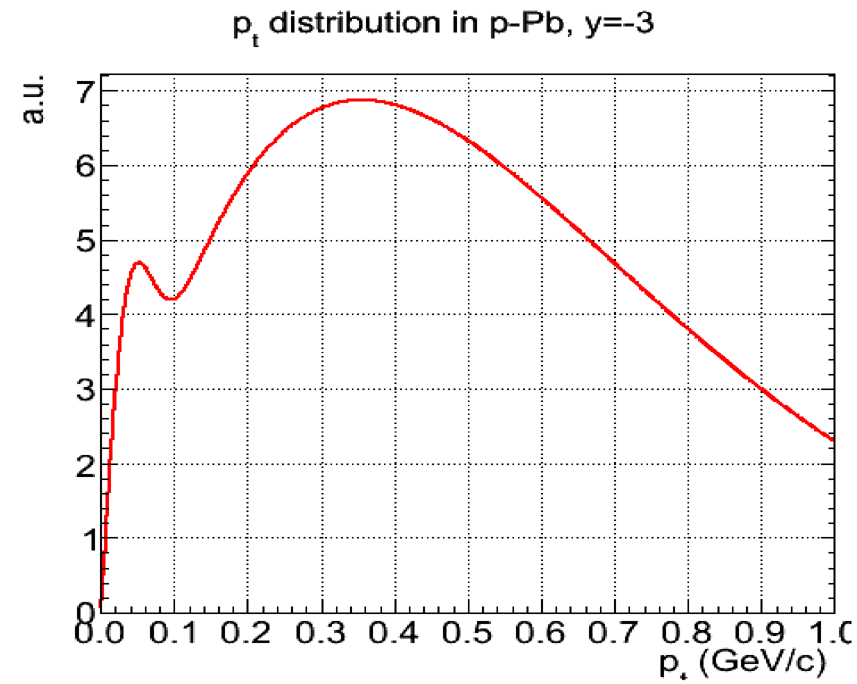


Forward



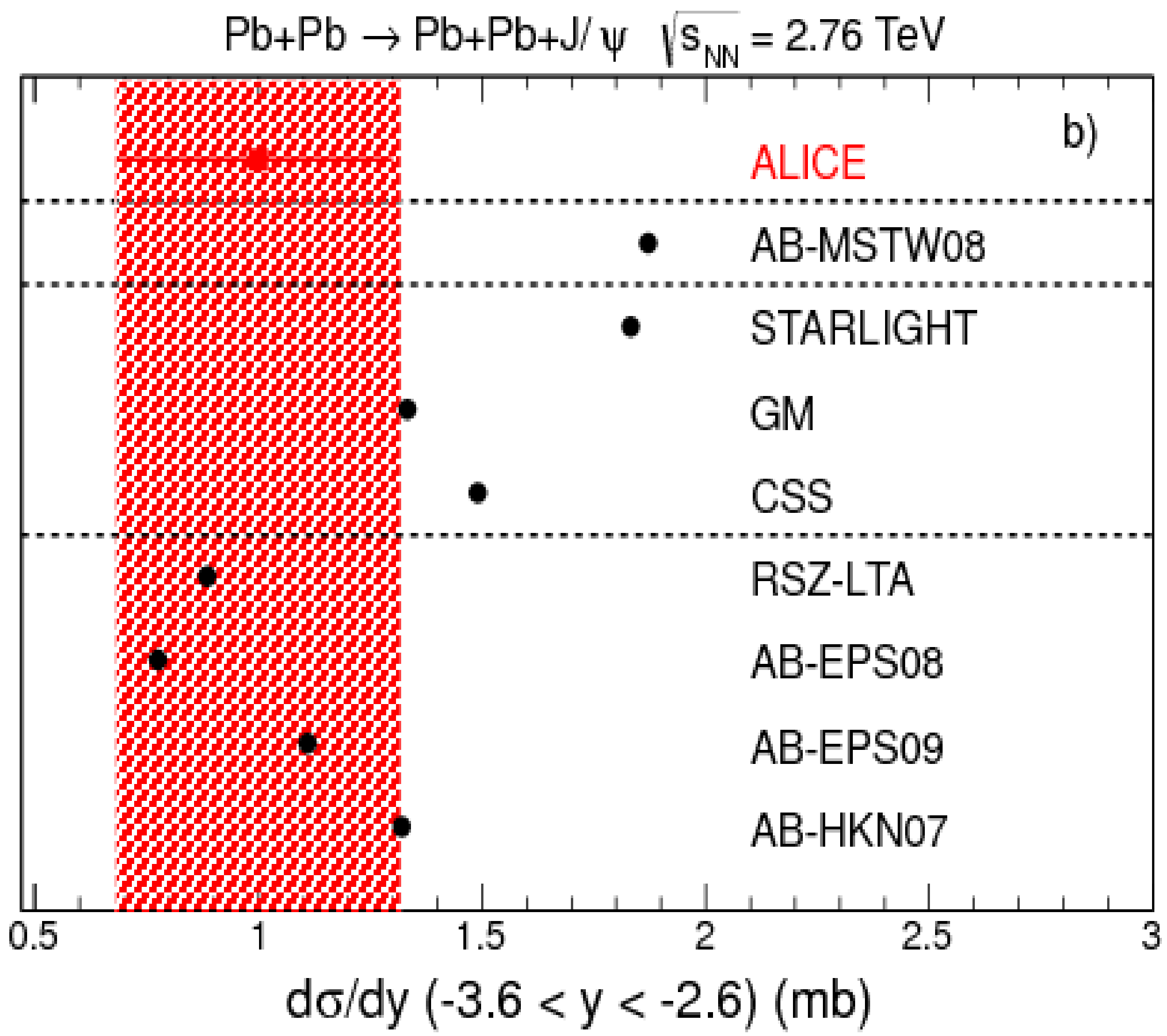
p-Pb





Data *vs* theoretical predictions

Integrated cross section

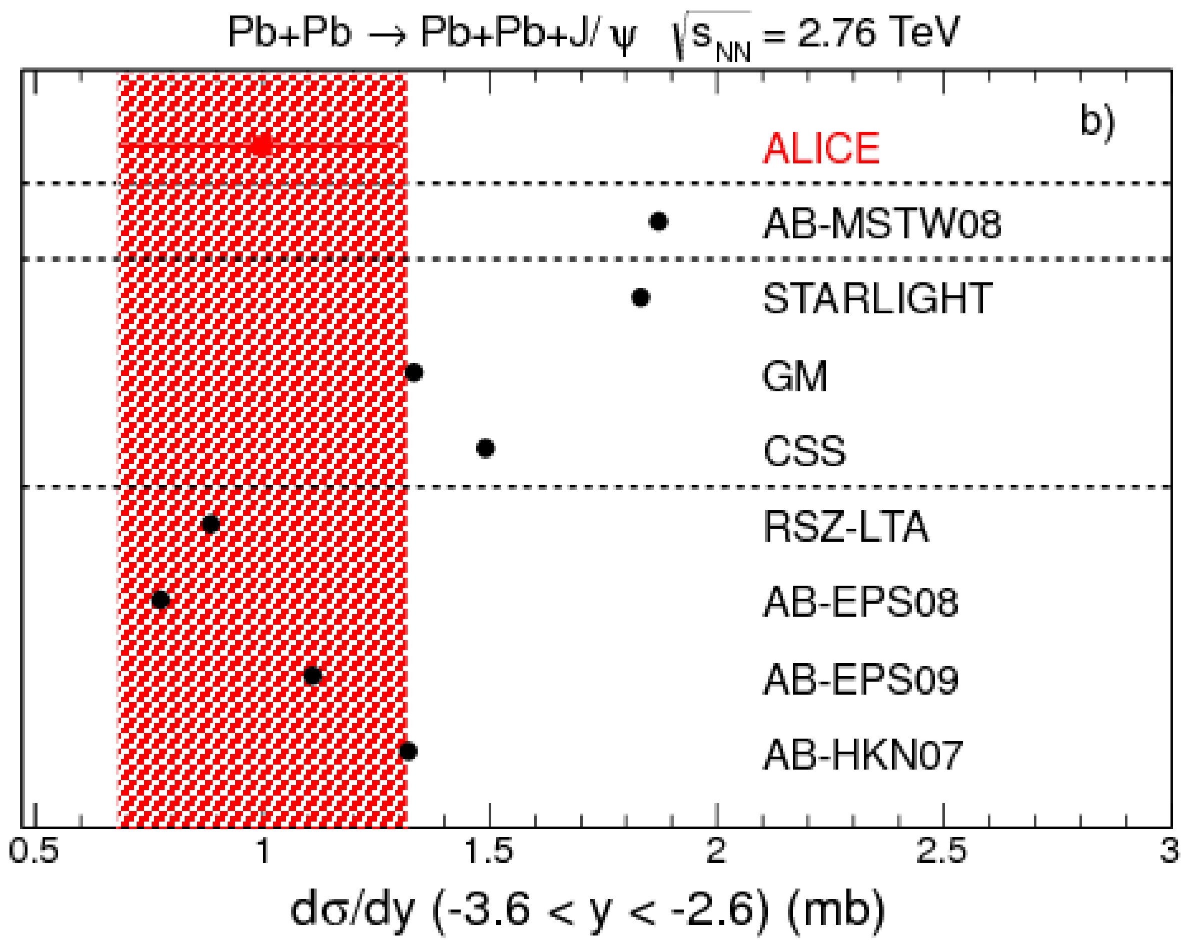


Largest deviations (3σ):
STARLIGHT and AB-MSTW08

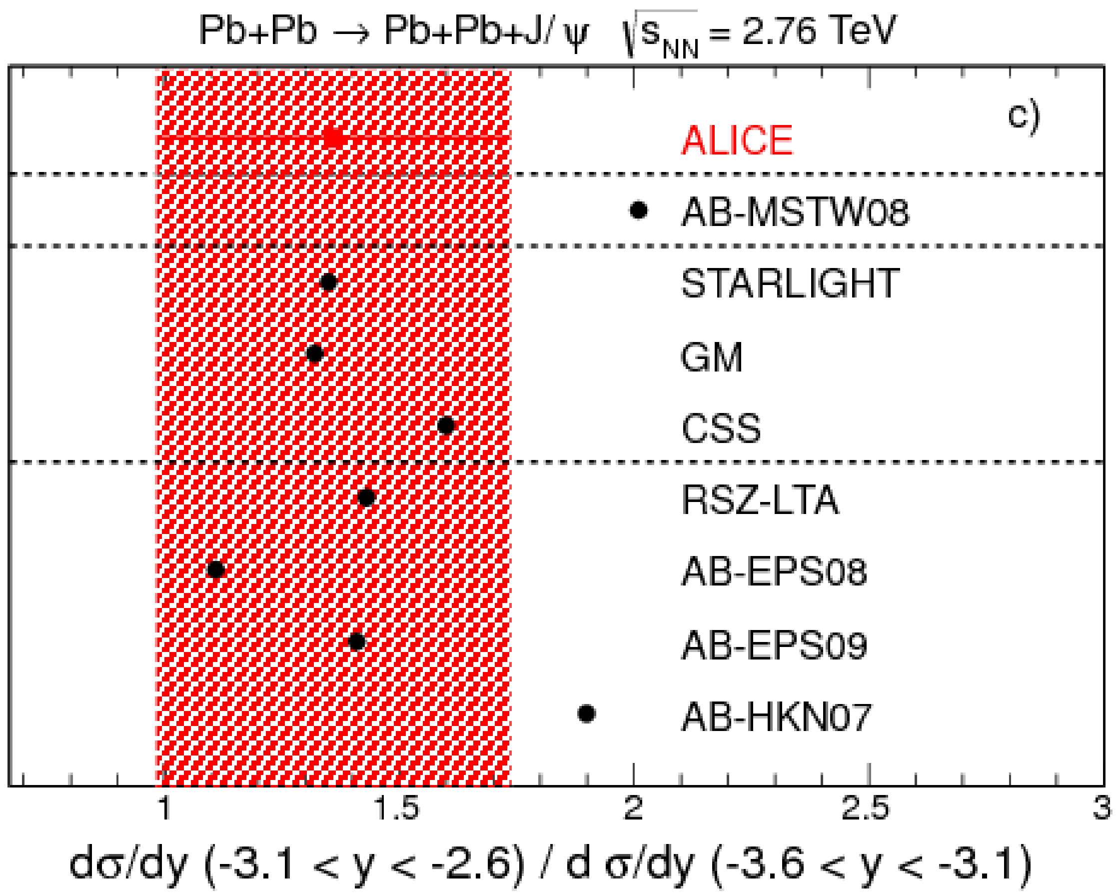
Best agreement (1σ):
RSZ-LTA, AB-EPS08 and AB-EPS09

Data *vs* theoretical predictions

Integrated cross section



Ratio of dσ/d*y*



$$R = \sigma(-3.1 < y < -2.6)/\sigma(-3.6 < y < -3.1) = 1.36 \pm 0.36(\mathrm{stat}) \pm 0.19(\mathrm{syst})$$

Largest deviations (3σ):
STARLIGHT and AB-MSTW08

Best agreement (1σ):
RSZ-LTA, AB-EPS08 and AB-EPS09

More than 1.5σ deviations:
AB-MSTW08 and AB-HKN07