

Recent ALICE quarkonium study highlight

Run 2 latest results & new Run 3 measurements

Maxime Guilbaud⁽¹⁾

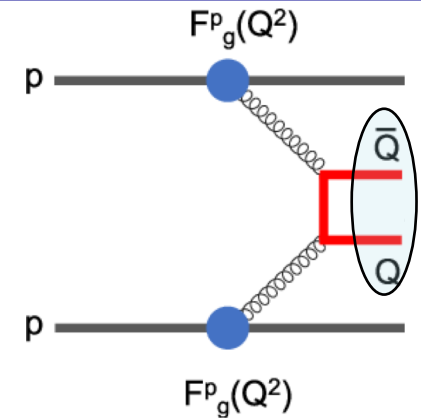
on behalf of the ALICE Collaboration



Quarkonia as a probe in small systems

Quarkonia: $c\bar{c}/b\bar{b}$ weakly bound states

- Varieties of excited states: J/ψ , $\psi(2S)$, $\Upsilon(nS)$, ...
- Production of heavy quarks at early time
 - pQCD
- Bound state formation
 - non-perturbative QCD

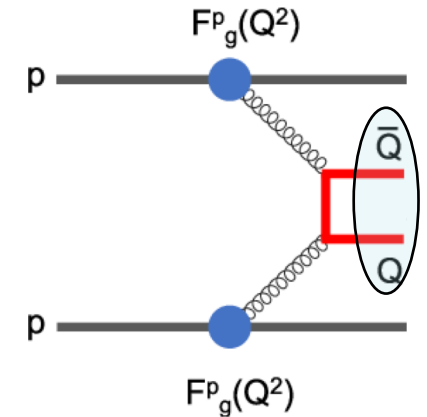


[Phys. Report \(2020\) 858 02.006](#)

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In “vacuum” production

- Measured differentially and quite precisely calculated
- Access to PDF
- Used as reference

High-multiplicity environment

- multiparton Interaction (MPIs)
- Collectivity

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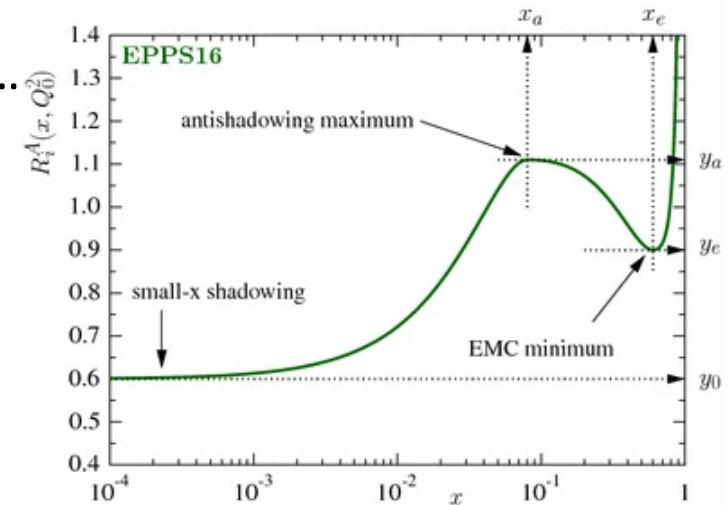
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Eur. Phys. J C 77 (2017) 3, 163

In “cold-medium” production:

- nPDF: PDF modification
- Coherent energy loss
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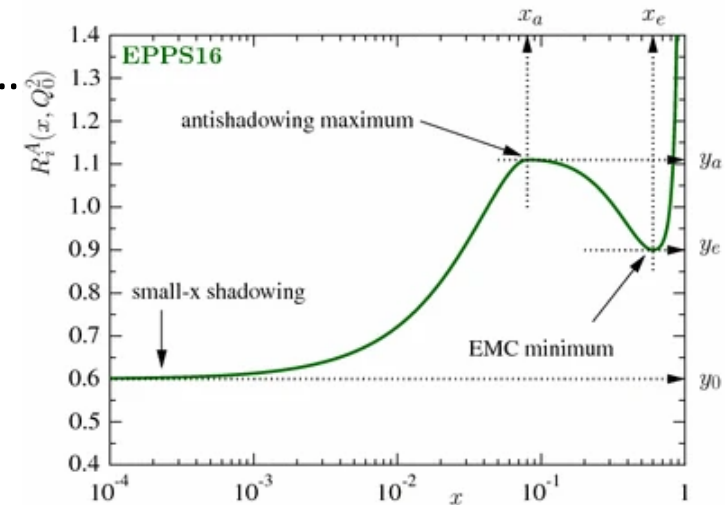
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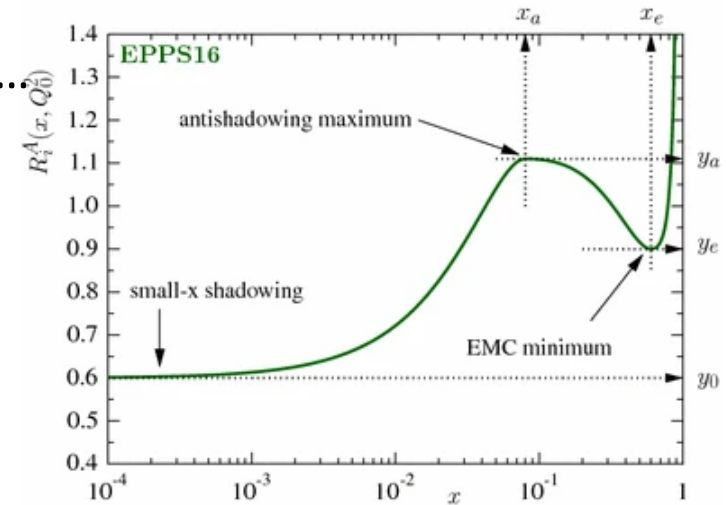
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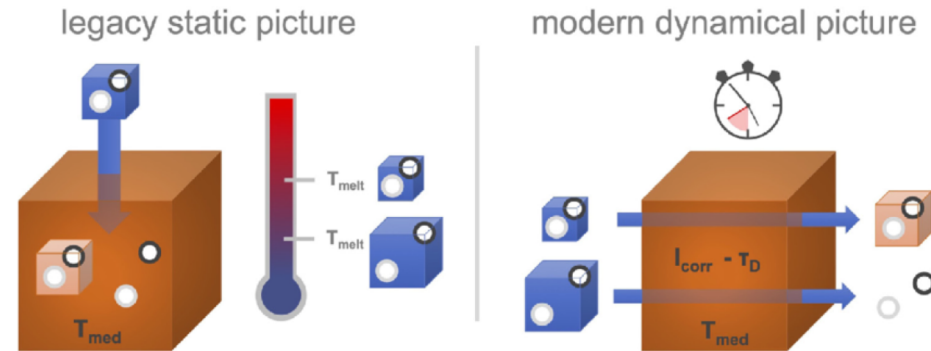
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p-Pb collisions

Quarkonia as a probe in Pb–Pb

In "hot-medium" production: Quark-Gluon Plasma (QGP)

- Quarkonia suppression
 - Depend on bounding energies
 - Picture moved from static to dynamical nowadays



Phys. Report (2020) 858 02.006

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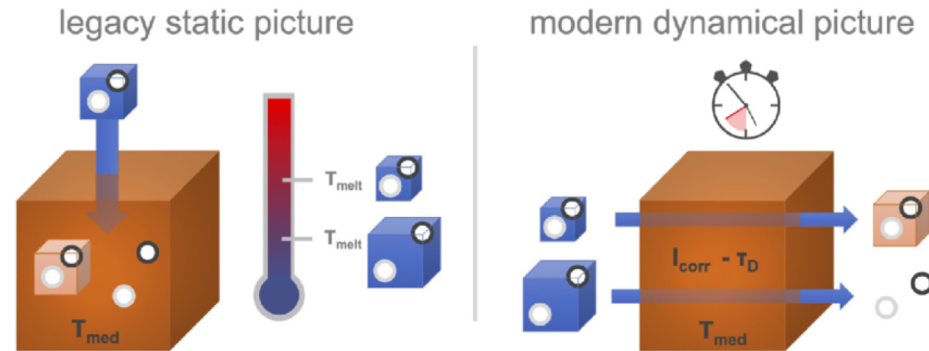
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$$\frac{d}{dt} N_Q(t) = -\Gamma_Q(T(t)) [N_Q(t) - N_Q^{eq}(T(t))]$$

NPA 943 (2015) 147-158
PLB 749 (2015) 98-103

TAMU, comover, ...



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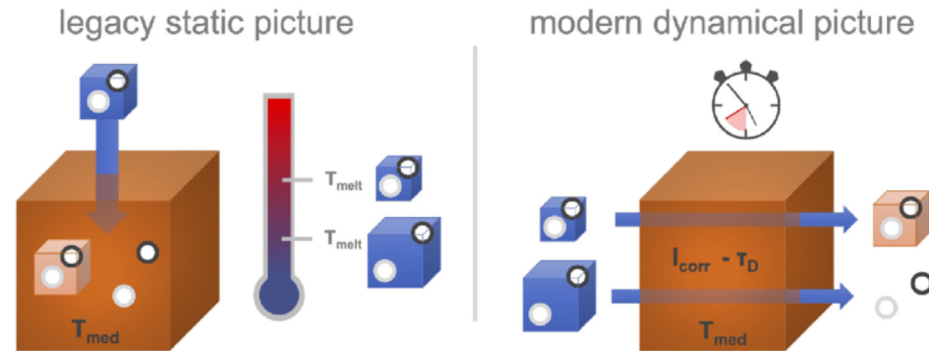
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- At phase boundary??

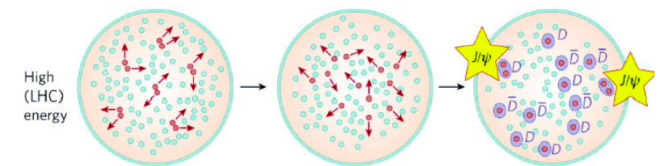
$$N_{c\bar{c}}(t) = \frac{1}{2} g_c V \sum_i [n_{D_i}^{th} + n_{\Lambda_i}^{th} + \dots] + \frac{1}{2} g_c^2 V \sum_i [n_{\psi_i}^{th} + n_{\chi_i}^{th} + \dots] + \dots$$

PLB 797 (2019) 134836

Statistical hadronization model



Phys. Report (2020) 858 02.006



Nature (2007) 448, 302-309

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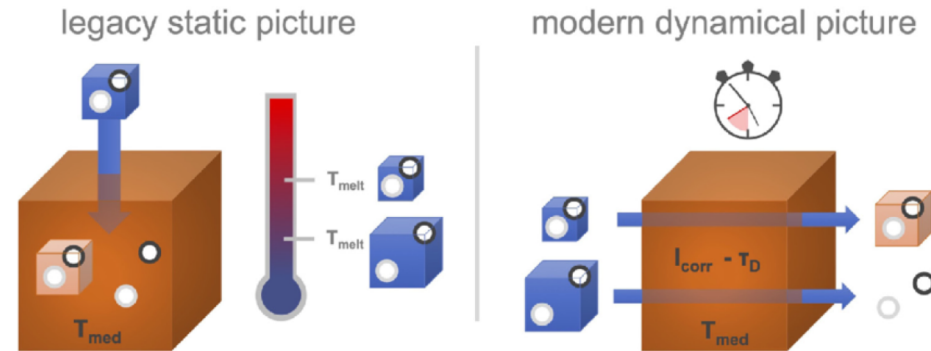
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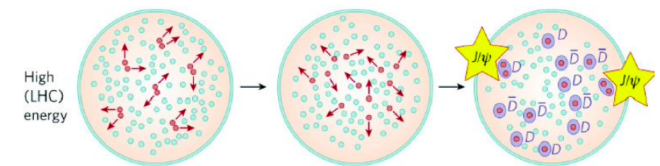
PLB 797 (2019) 134836

Statistical hadronization model

- Parton energy loss at high transverse momentum



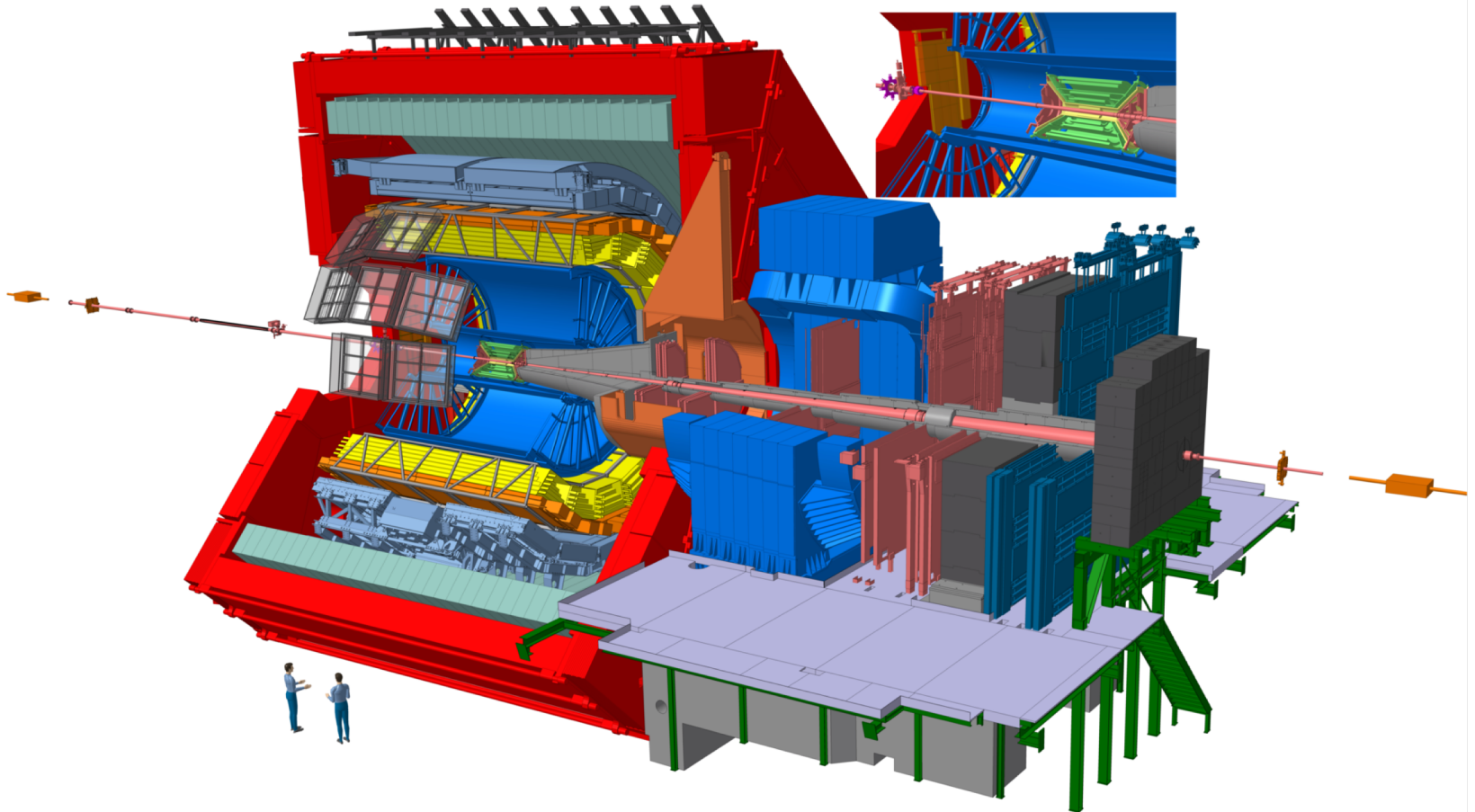
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Nature (2007) 448, 302-309

The ALICE detector:

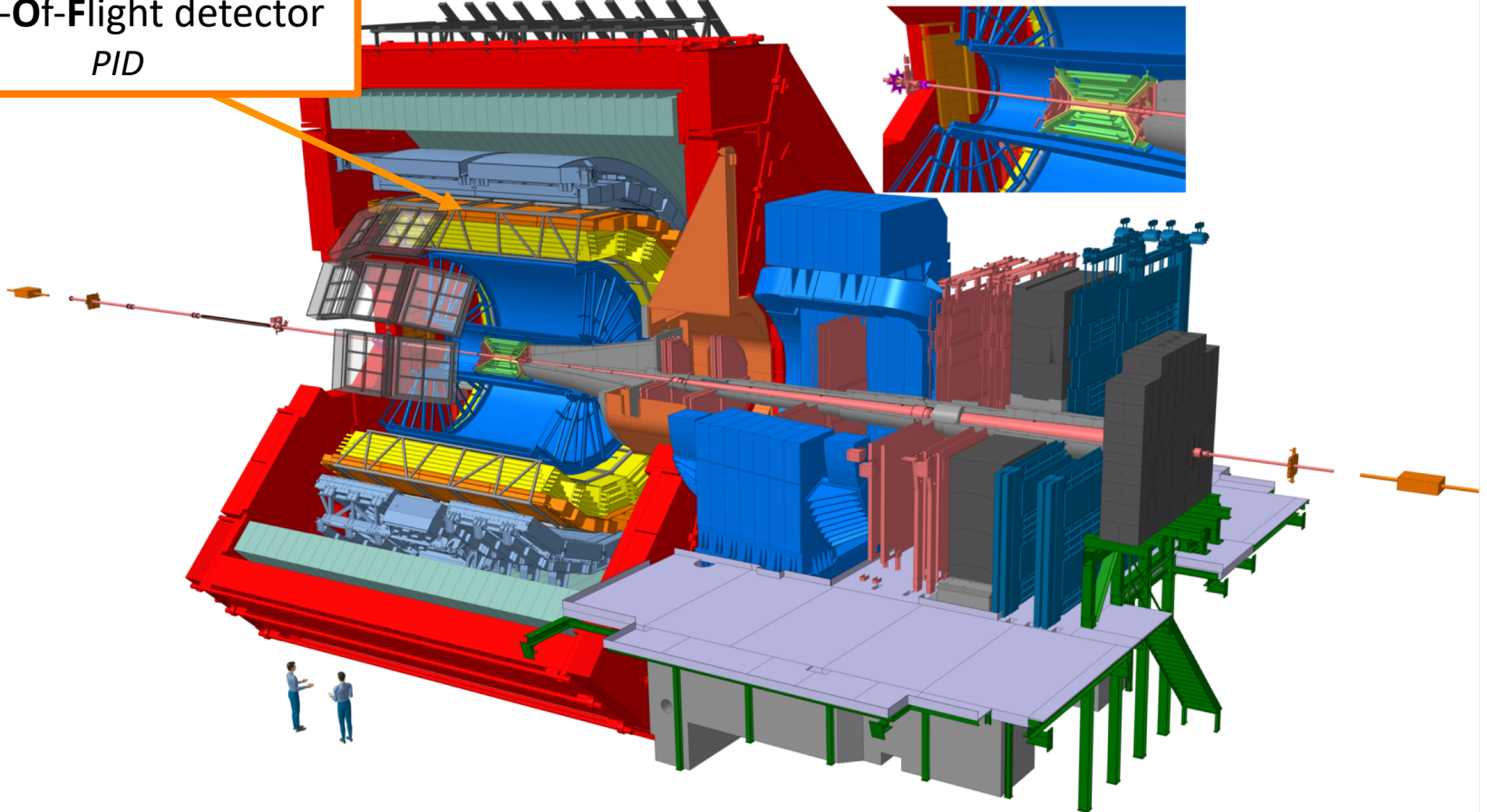
Run 2 setup



The ALICE detector:

Run 2 setup

Time-Of-Flight detector
PID

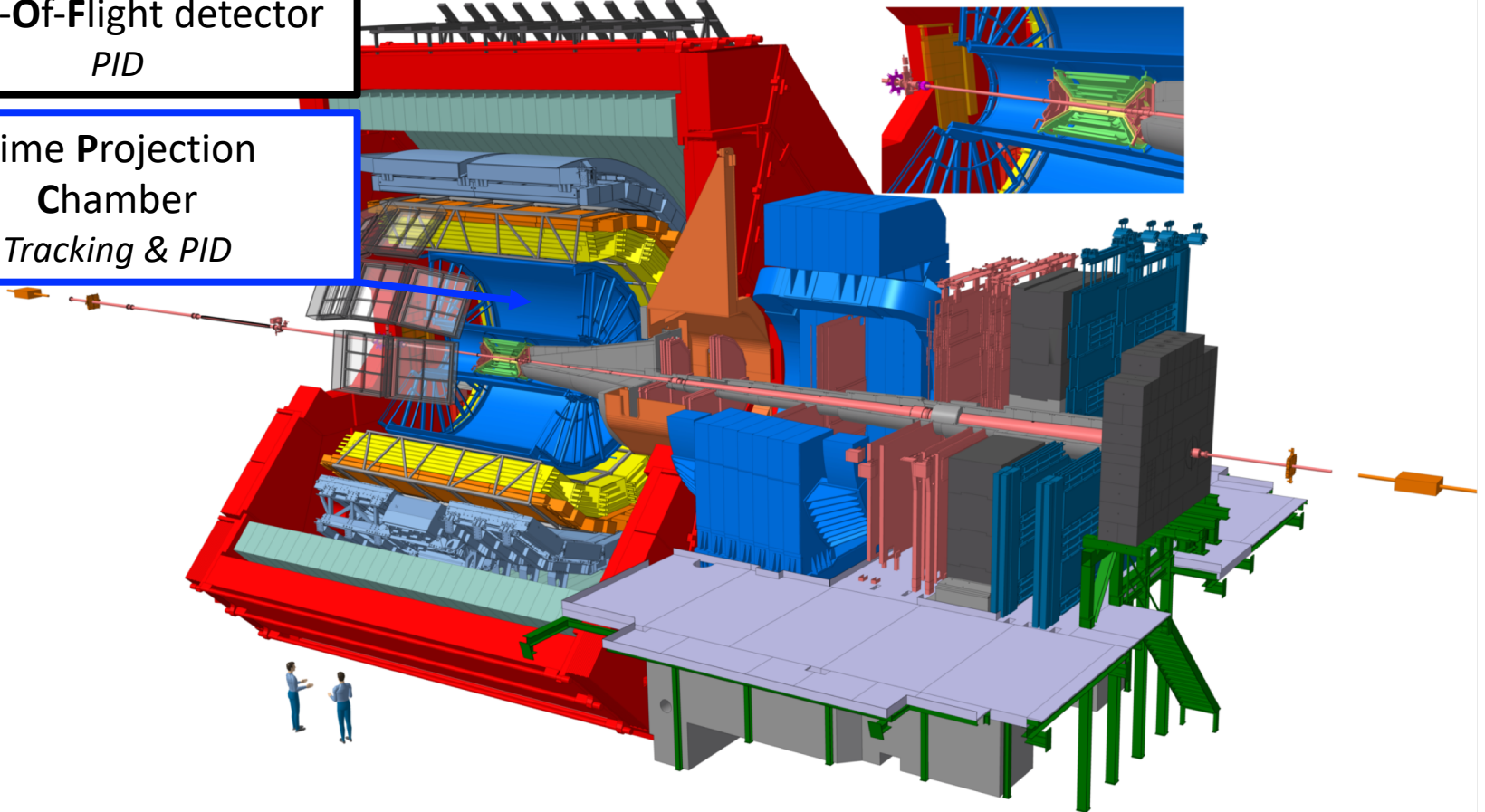


The ALICE detector:

Run 2 setup

Time-Of-Flight detector
PID

Time Projection
Chamber
Tracking & PID



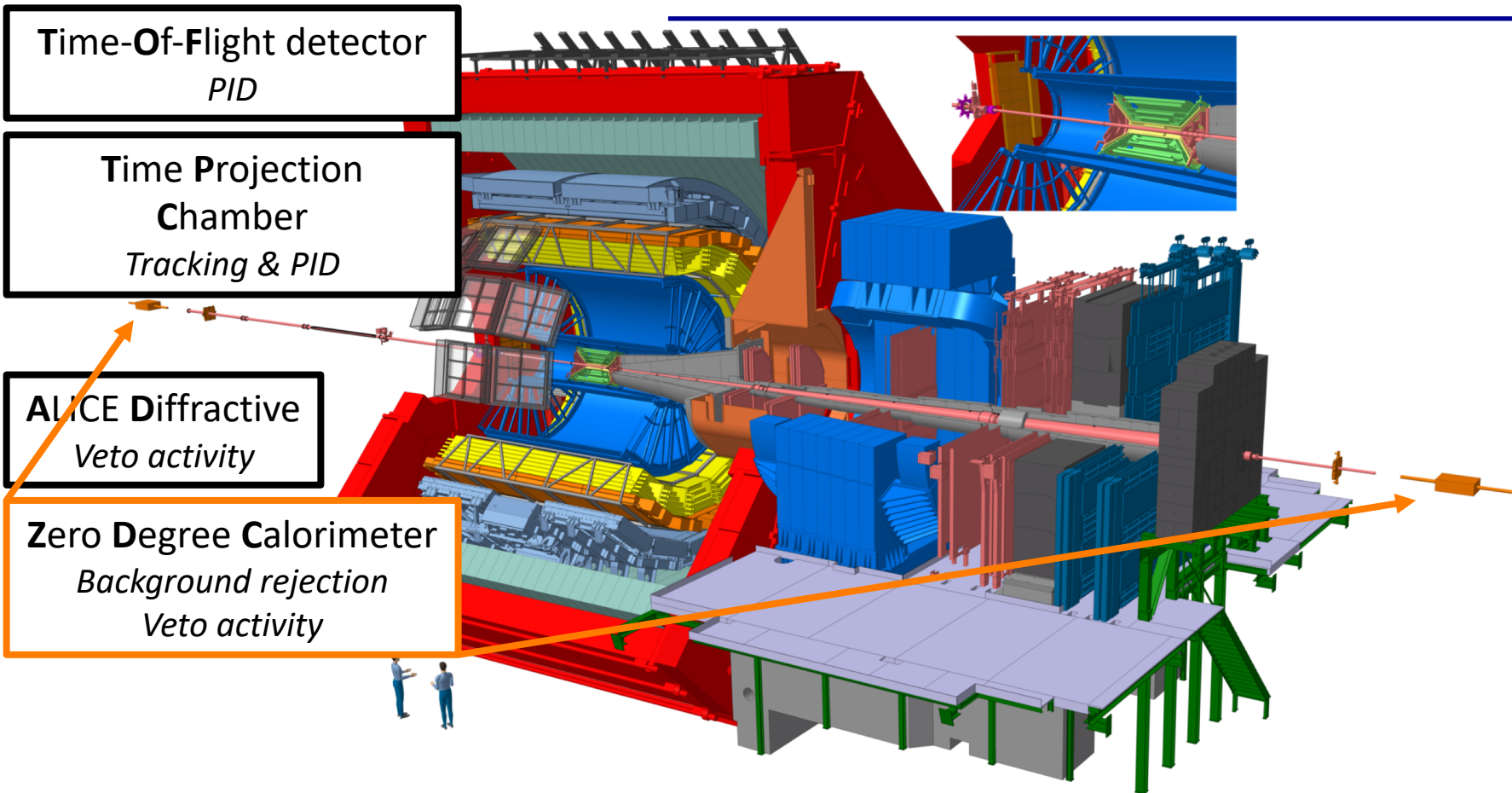


ALICE Diffractive *Veto activity*



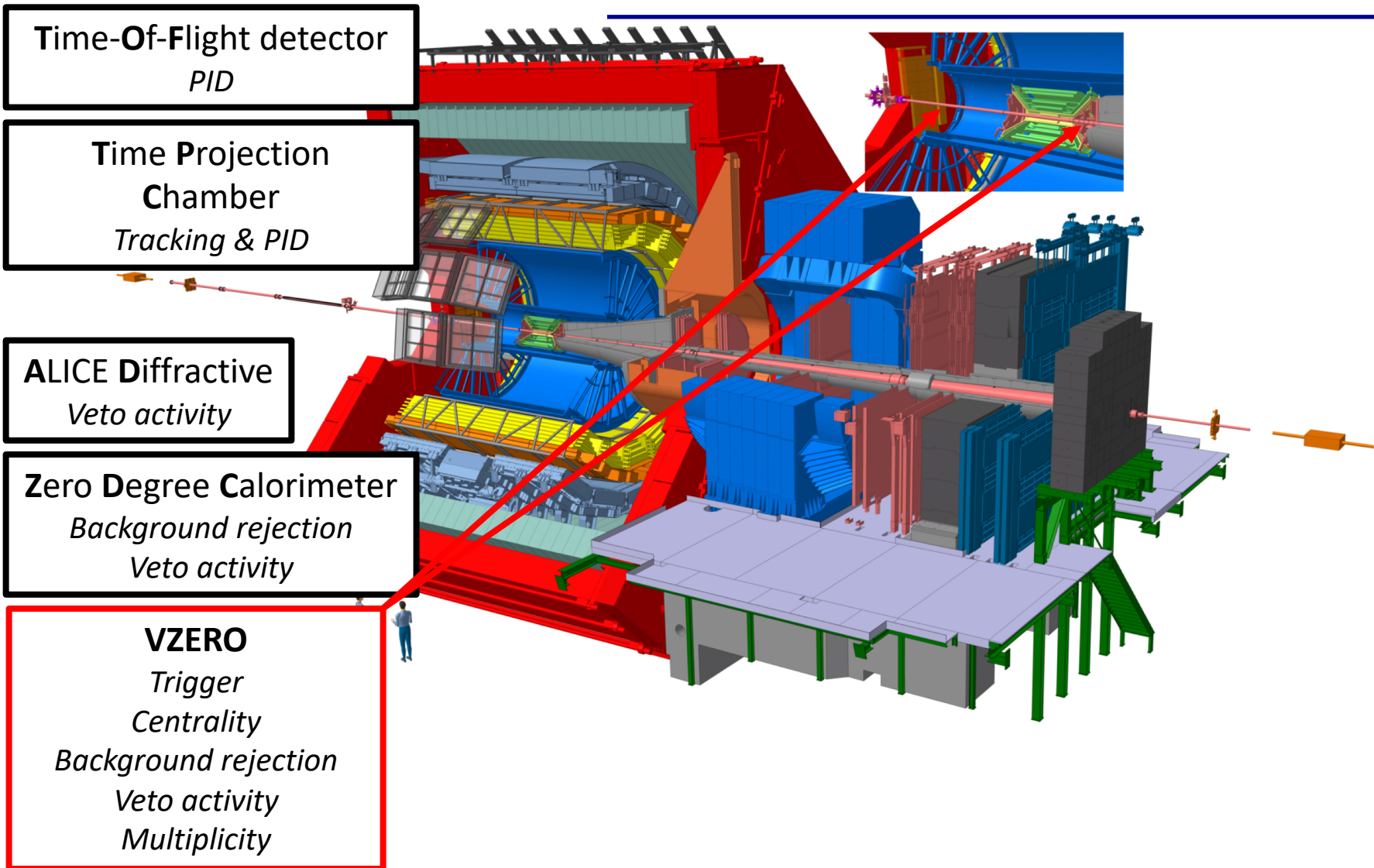
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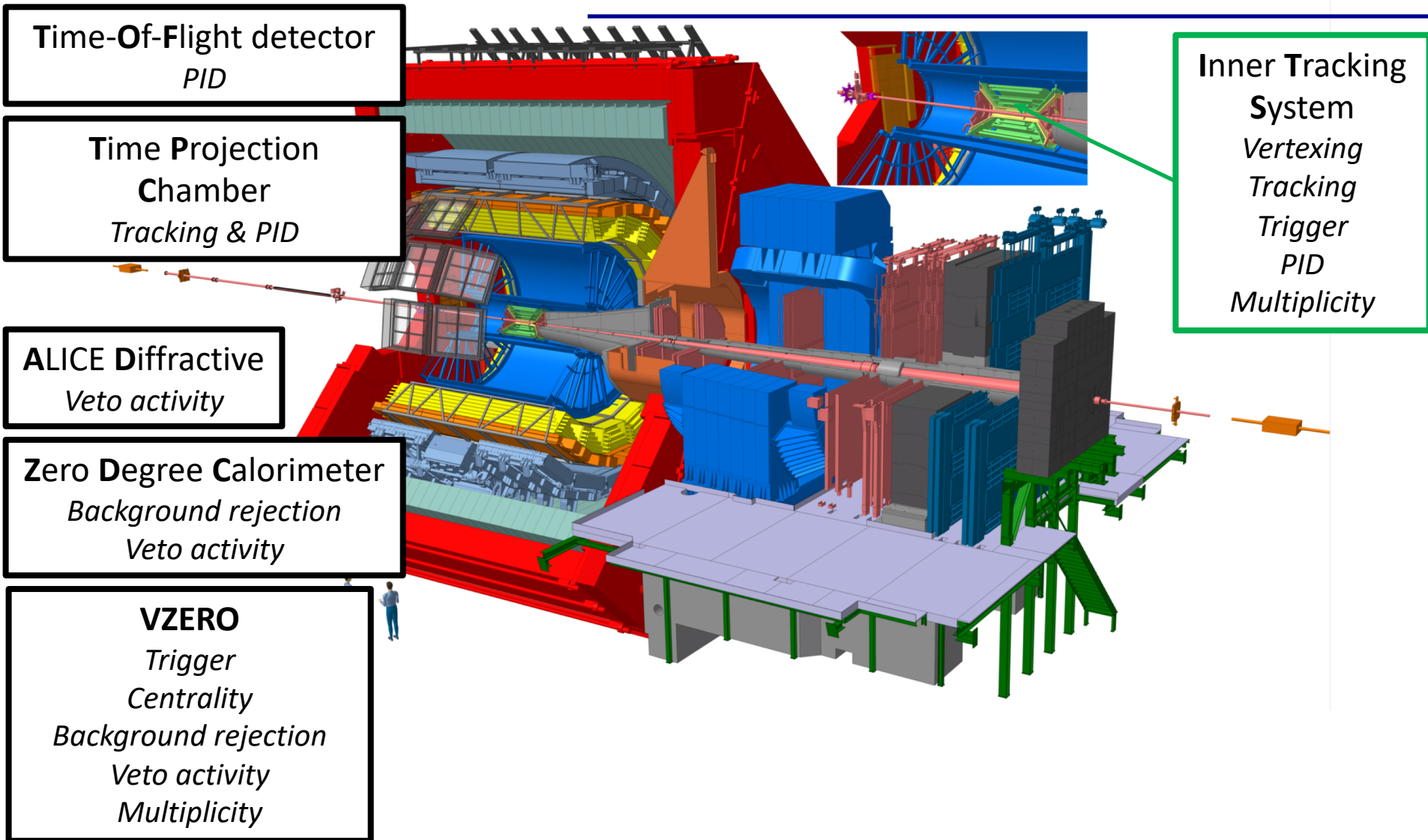
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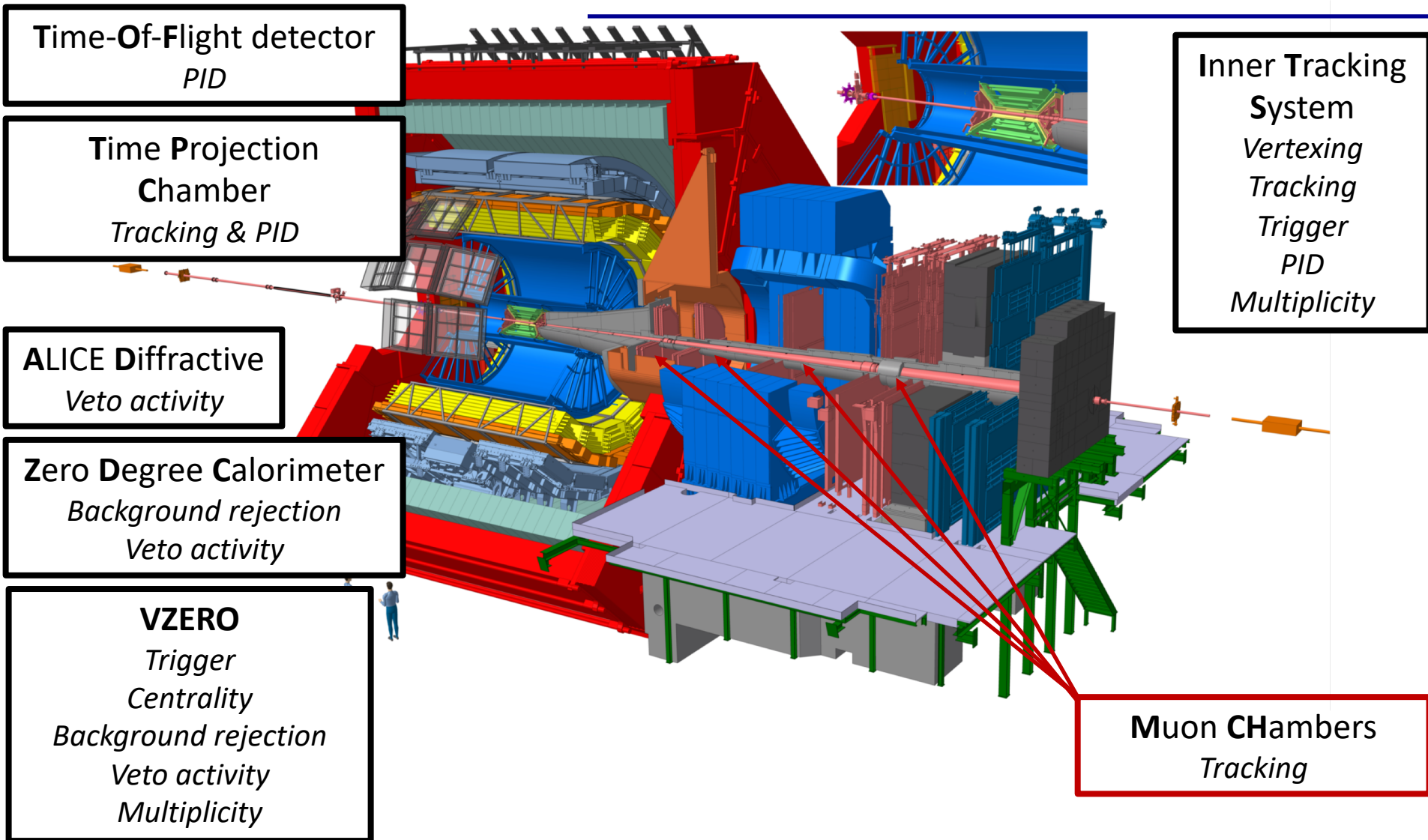
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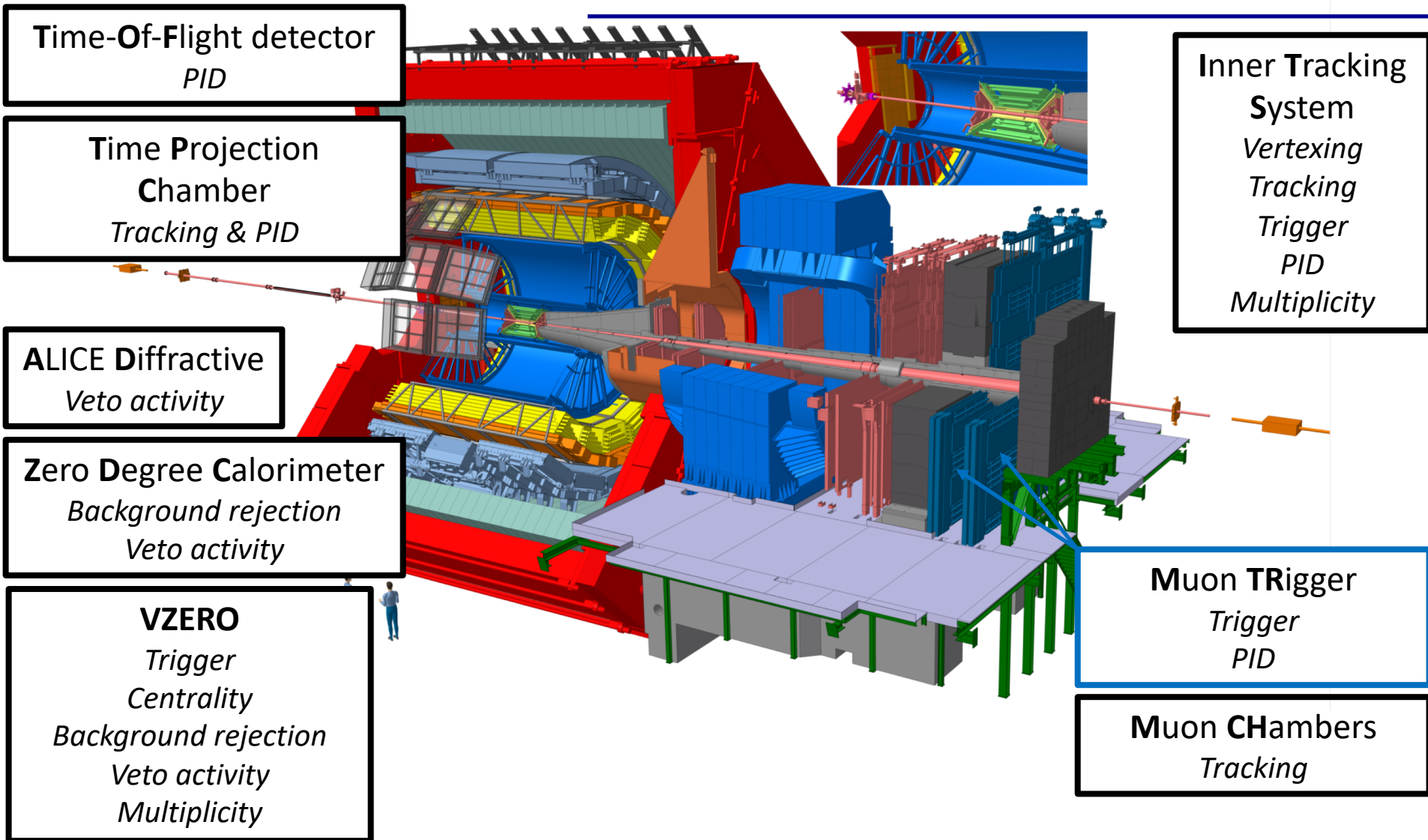
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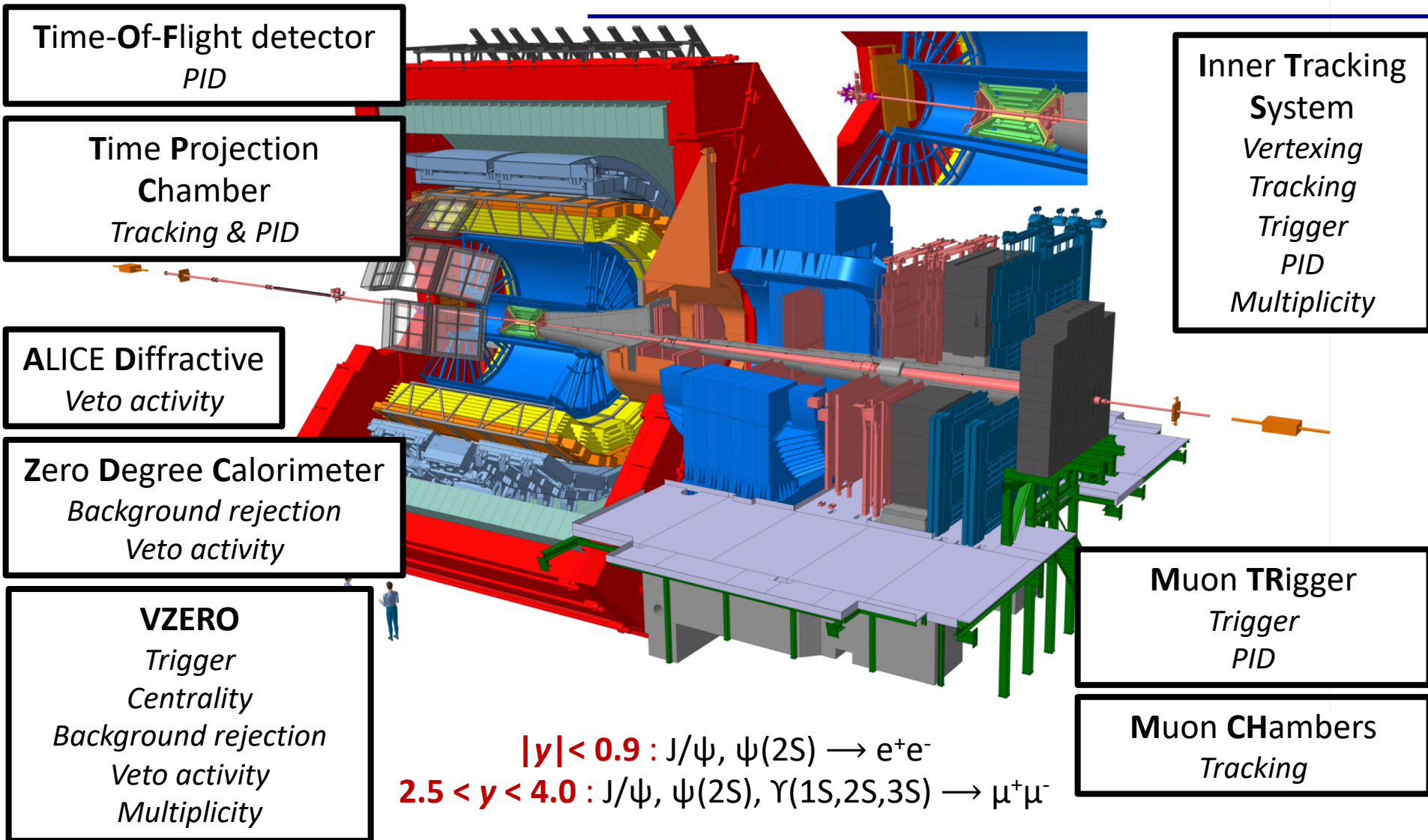
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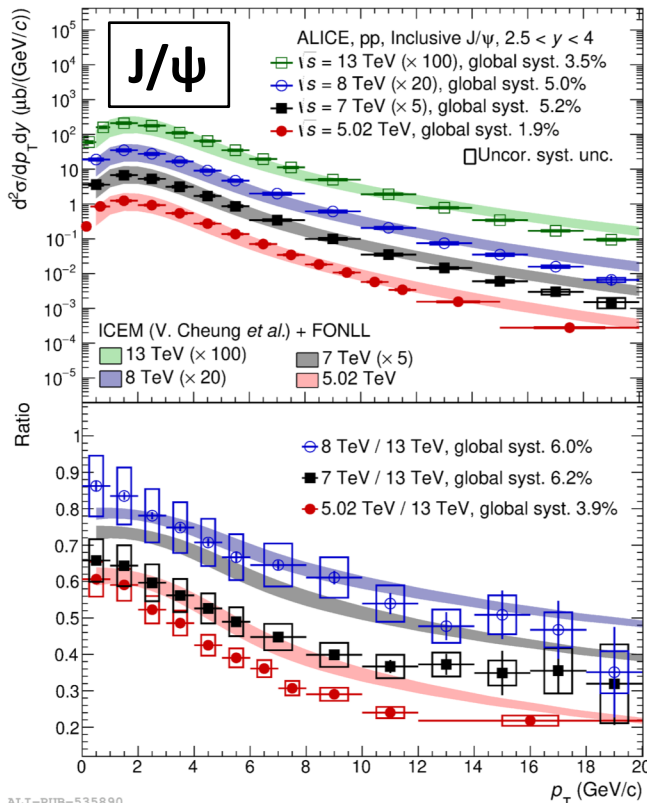
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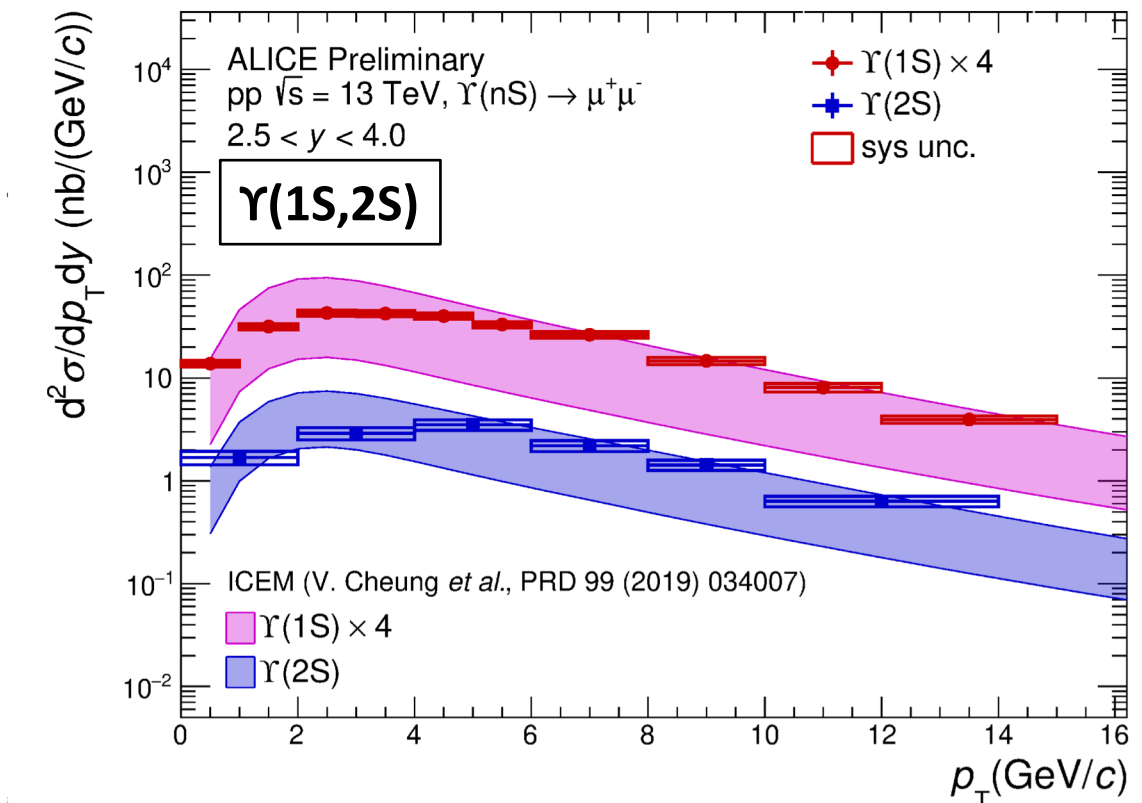
Quarkonium production in pp collisions

Cross sections

Eur. Phys. J C 83 (2023) 61



ICEM: PRD 98 (2018) 11, 114029

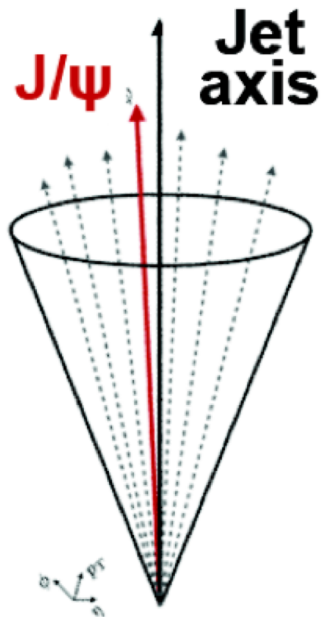


Precise p_T -differential measurement for various $\sqrt{s}$ energies

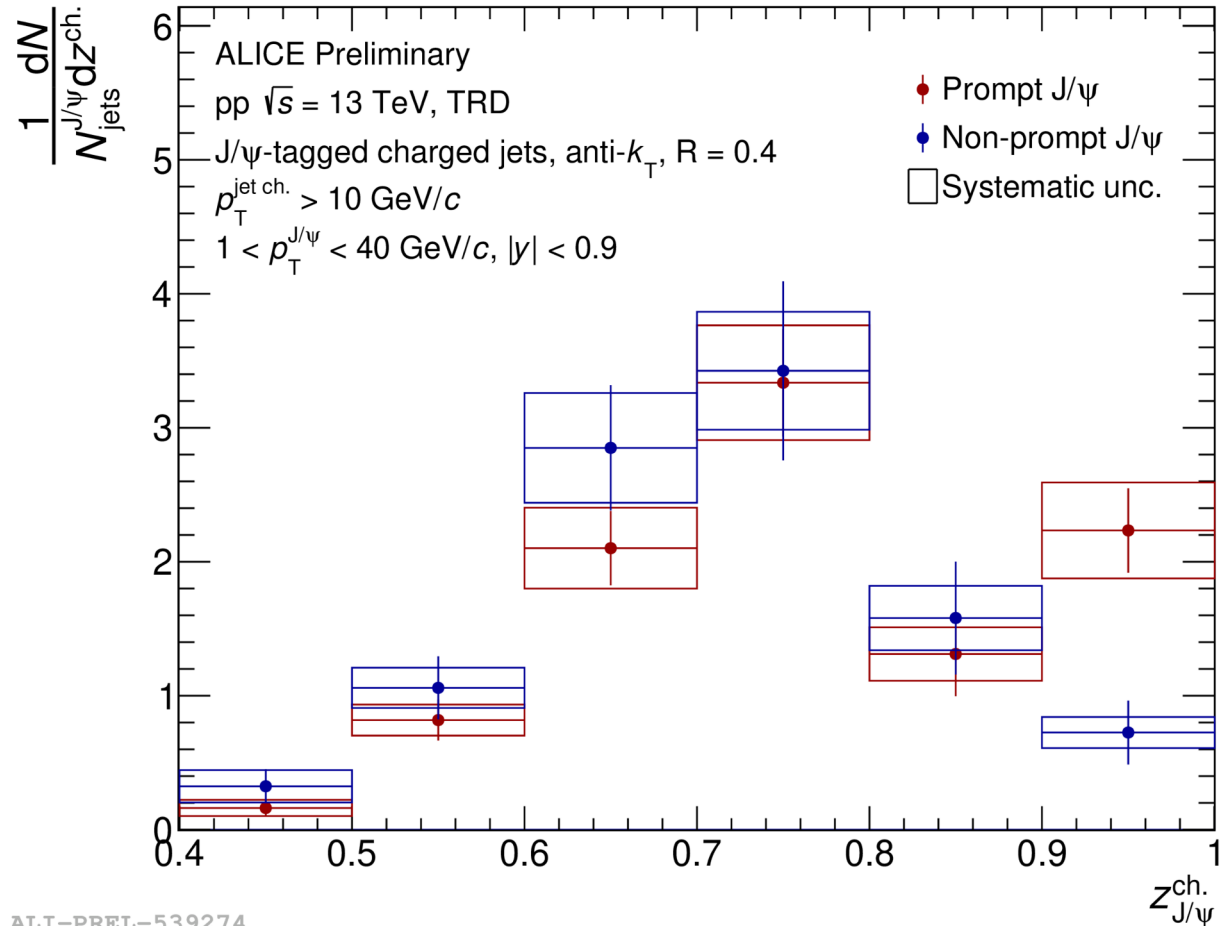
- Models qualitatively well describe cross sections
- Tensions observed in the ratios

Quarkonium production in pp collisions

J/ψ in jets



$$z_{J/\psi}^{ch} = \frac{p_T^{J/\psi}}{p_T^{jet,ch}}$$

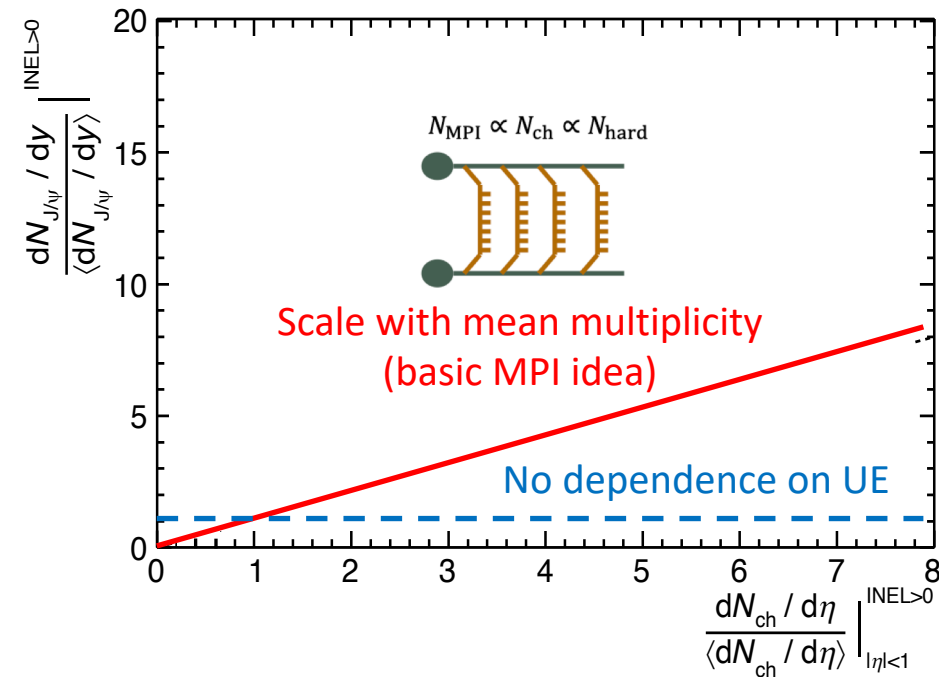


(Non-)prompt J/ψ fragmentation function

- Similar within uncertainties for most of z values

Constraining MPI scenarios:

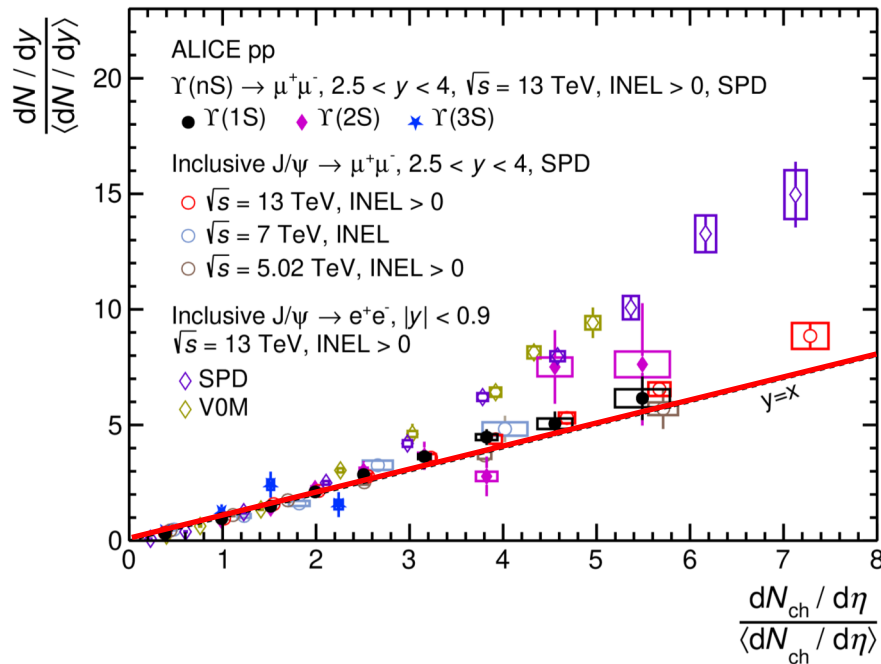
quarkonia production as a function of multiplicity



Constraining MPI scenarios:

quarkonia production as a function of multiplicity

arxiv:2209.04241



ALI-PUB-526565

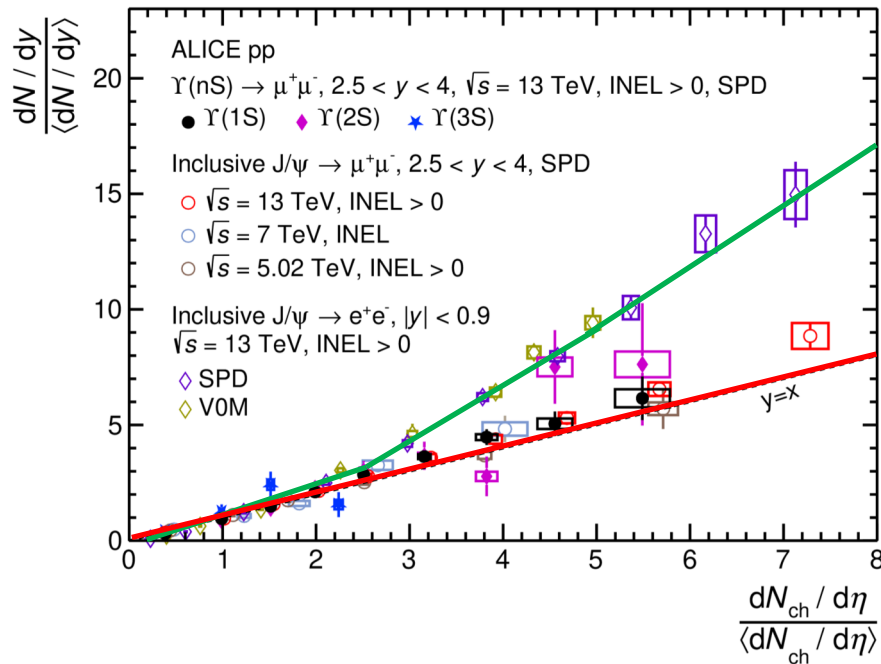
Production vs charged-particle multiplicity:

- Simple MPI scenario at **forward y**

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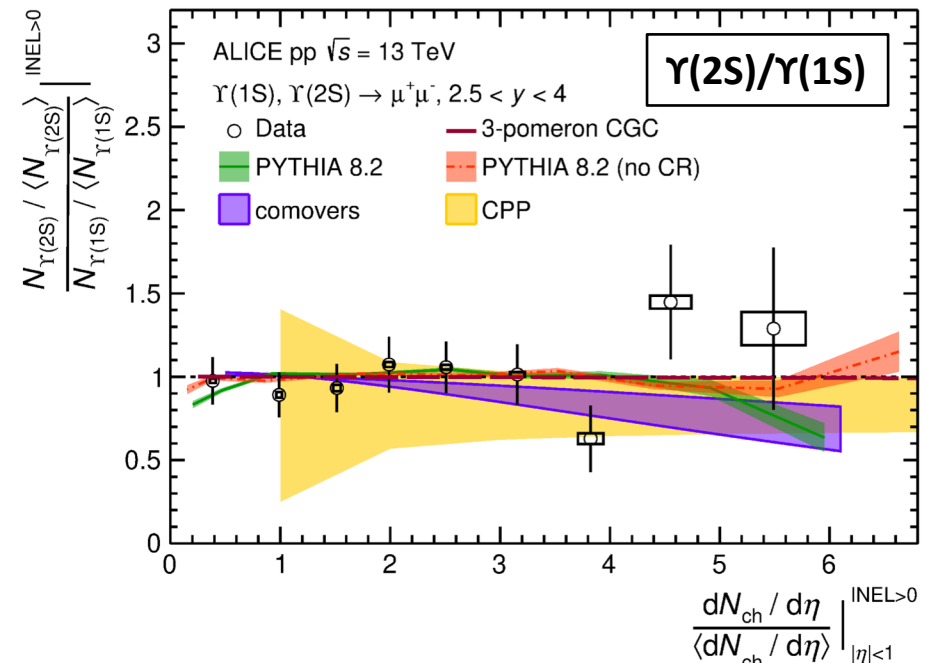
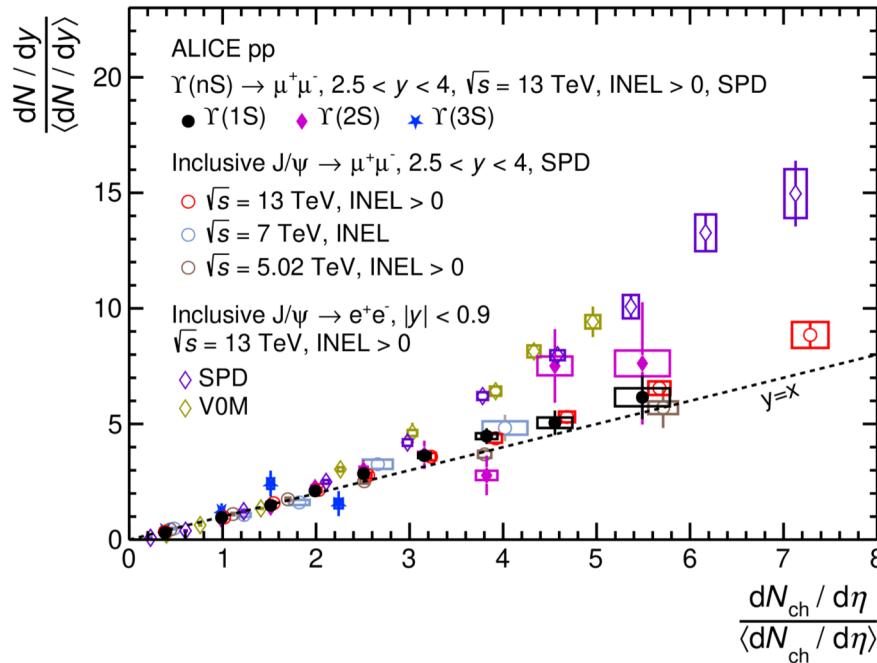
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- Non-linear increase at **midrapidity**
 - Qualitatively reproduced by models

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ALI-PUB-526565

ALI-PUB-526555

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3-pomeron: [Eur. Phys. J C 80 \(2020\) 6, 560](#)

CPP: [PRD 101 \(2020\) 5, 054023](#)

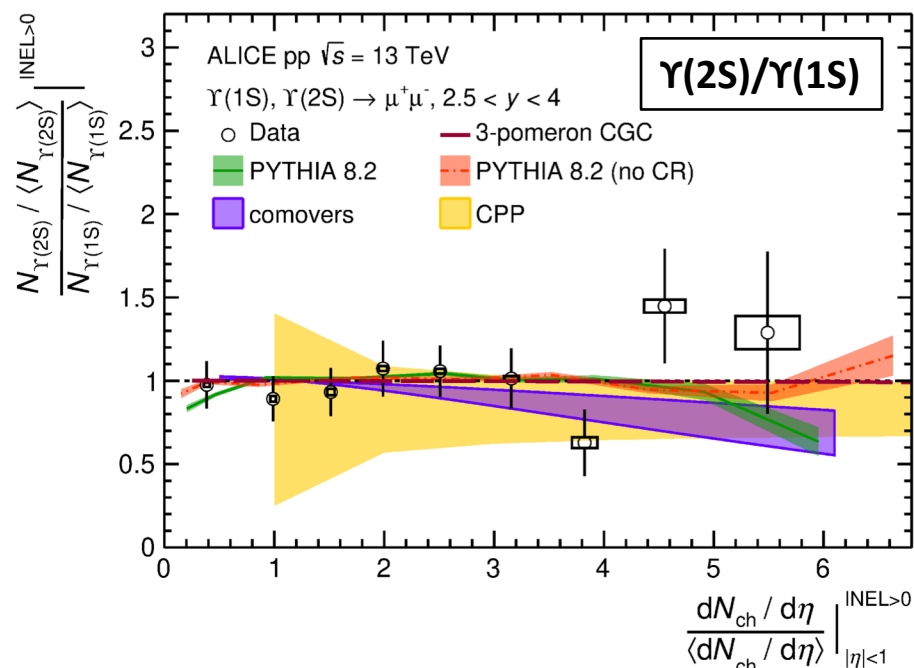
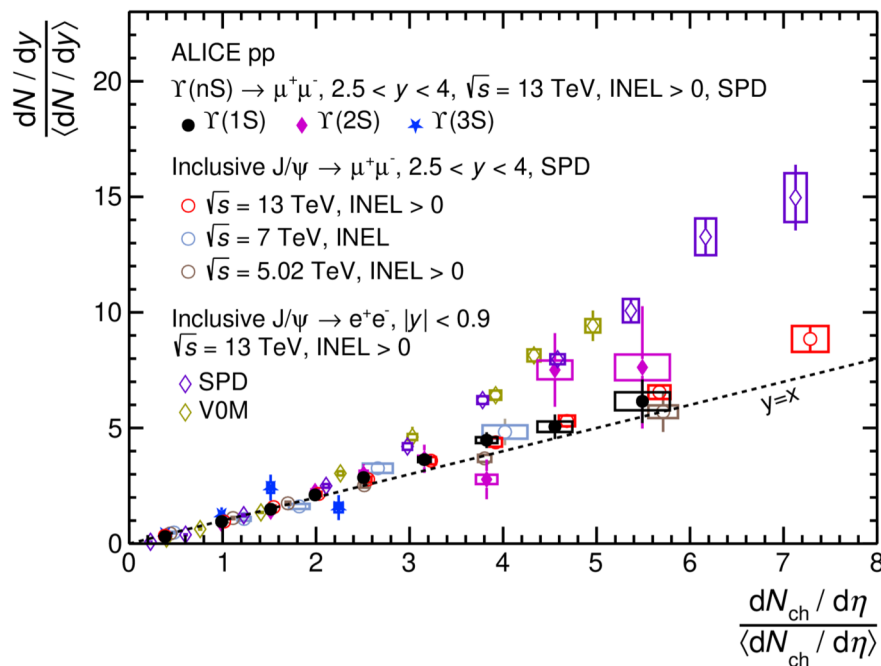
Pythia 8.2: [Comput.Phys.Commun. 191 \(2015\) 159-177](#)

Comovers: [PLB 749 \(2015\) 98-103](#)

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ALI-PUB-526565

ALT-PUB-526555

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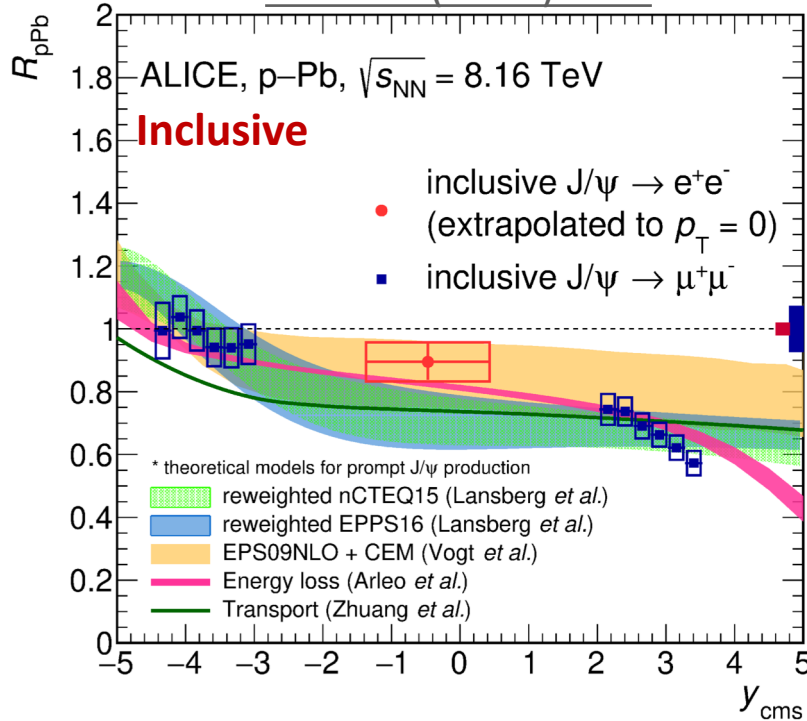
Pythia 8.2: Comput.Phys.Commun. 191 (2015) 159-177

Comovers: PLB 749 (2015) 98-103

We also have some DPS results for J/ψ – see backup

nPDF model constraints: J/ψ production in p -Pb collisions

JHEP 07 (2023) 137



nCTEQ15HQ: [PRD 105 \(2022\) 11, 114043](#)

EPPS16: [Eur. Phys. J C 77 \(2017\) 1, 1](#)

EPS09NLO+CEM: [Int. J. Mod. Phys. E 22 \(2013\) 1330007](#)

Transport: [JHEP 03 \(2019\) 015](#)

FONLL+EPPS16: [Eur. Phys. J C 77 \(2017\) 3, 163](#)

Coherent energy loss: [JHEP 05 \(2013\) 155](#)

Transport: [PLB 765 \(2017\) 323-327](#)

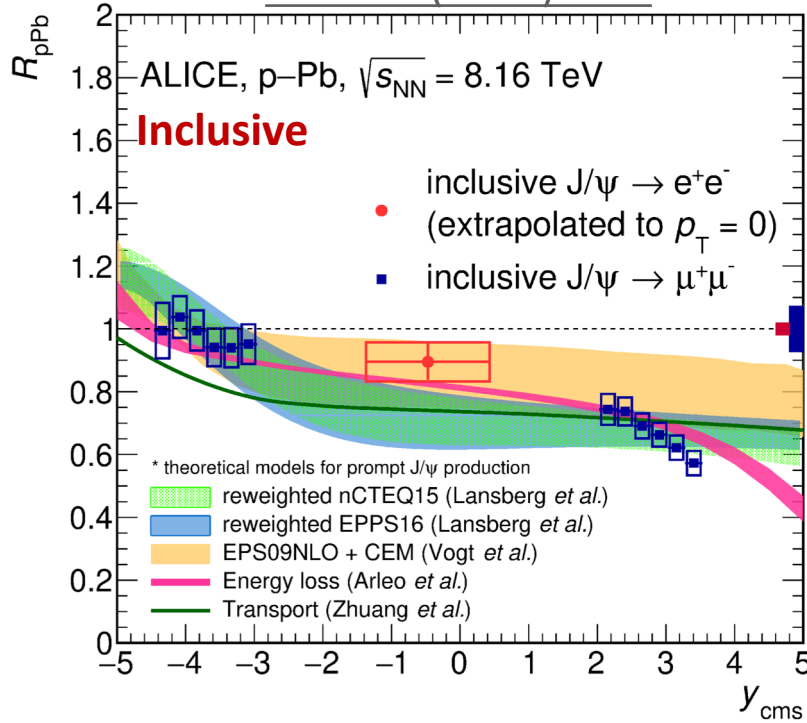
ALI-PUB-561226

Hints on gluon shadowing & energy loss

- Larger suppression in p-going direction

nPDF model constraints: J/ψ production in p -Pb collisions

JHEP 07 (2023) 137



ALI-PUB-561226

Hints on gluon shadowing & energy loss

- Larger suppression in p-going direction
- J/ψ more suppressed at low- p_T

nCTEQ15HQ: PRD 105 (2022) 11, 114043

EPPS16: Eur. Phys. J C 77 (2017) 1, 1

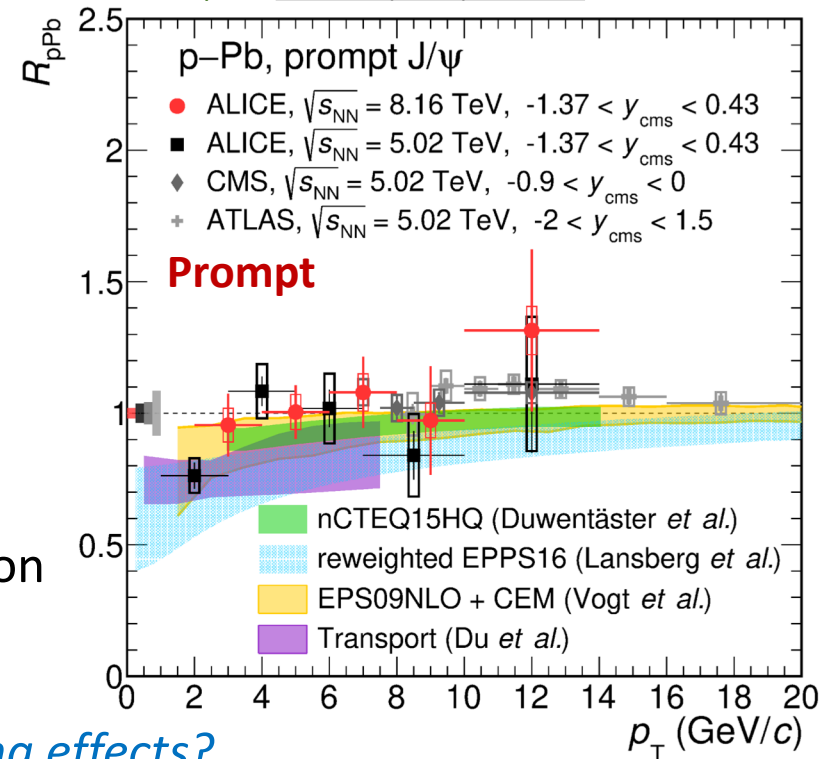
EPS09NLO+CEM: Int. J. Mod. Phys. E 22 (2013) 1330007

Transport: JHEP 03 (2019) 015

FONLL+EPPS16: Eur. Phys. J C 77 (2017) 3, 163

Coherent energy loss: JHEP 05 (2013) 155

Transport: PLB 765 (2017) 323-327



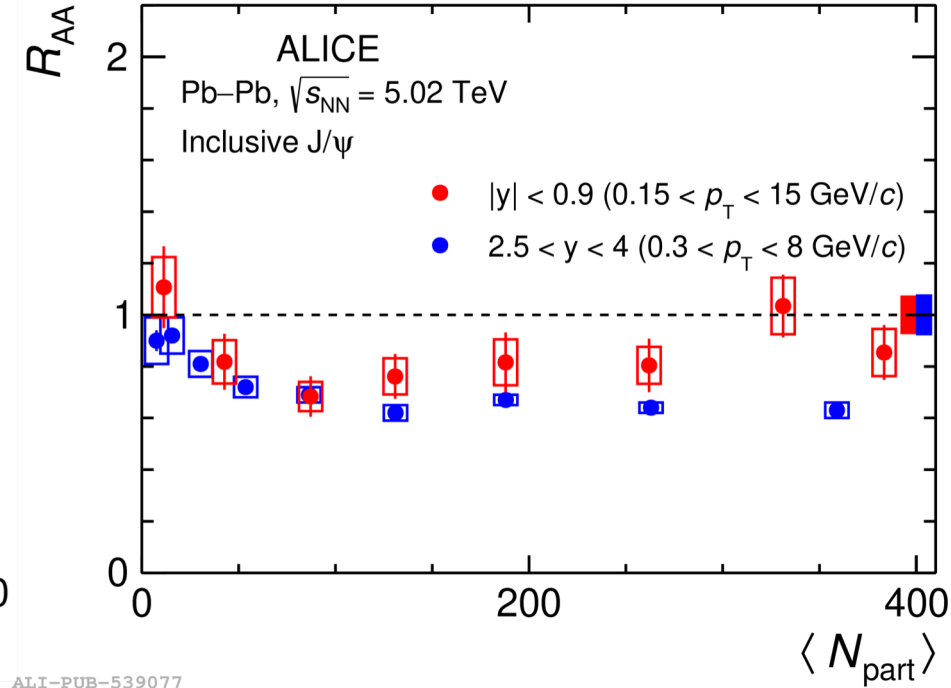
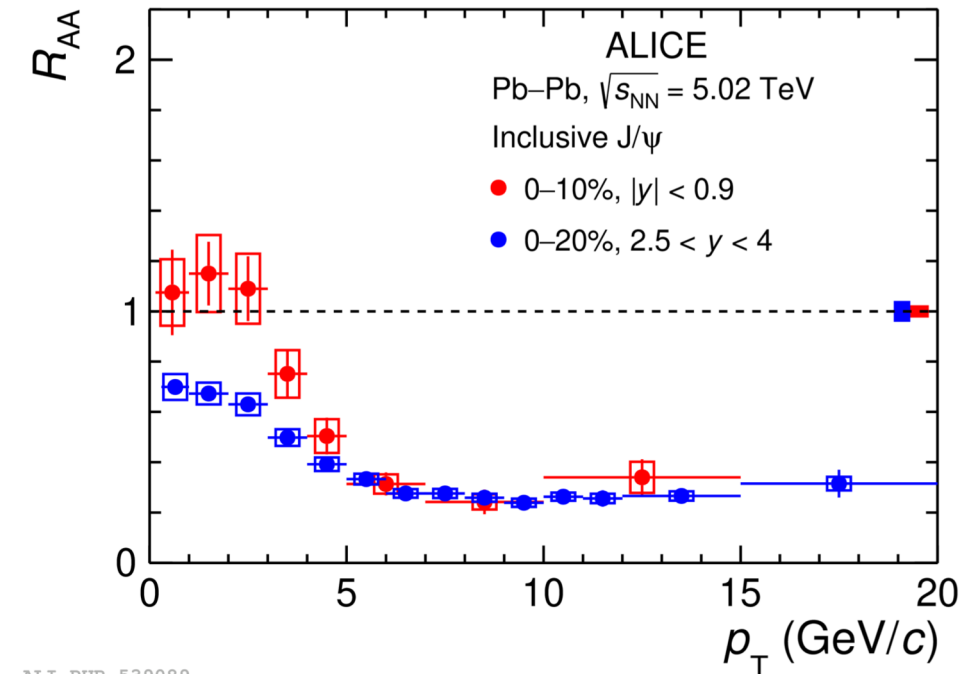
ALI-PUB-561246

Are gluon shadowing & energy loss competing effects?

Charm production in Pb–Pb:

inclusive J/ψ R_{AA}

arxiv:2303.13361



Charmonia regeneration at low p_T

- R_{AA} measurement is consistent with J/ψ flow measurement

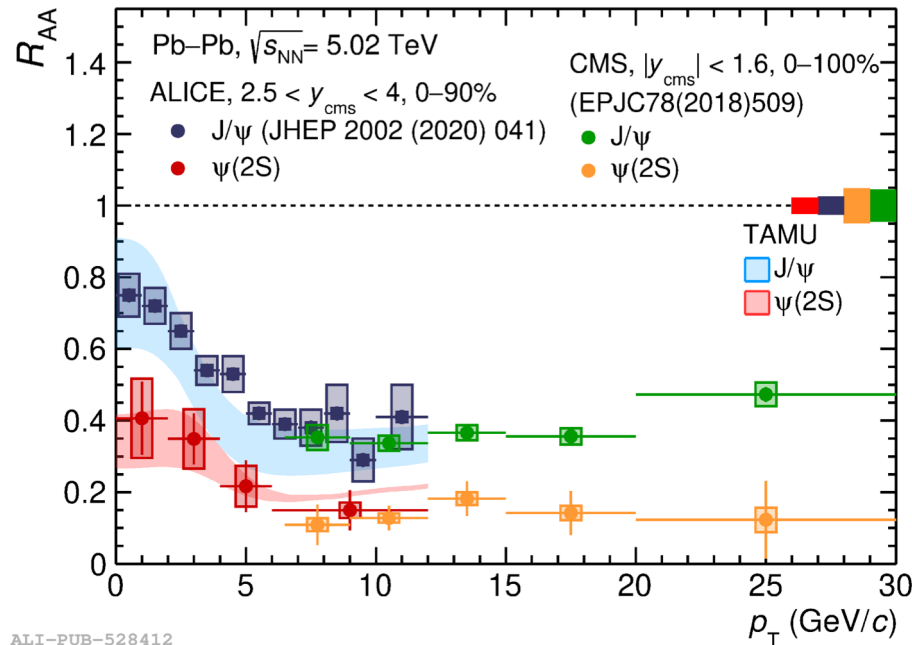
Regeneration at **midrapidity** > regeneration at **forward rapidity**

- Heavily depends on the local charm quark density

Charm production in Pb–Pb:

inclusive $\psi(2S)$ R_{AA}

arxiv:2210.08893



ALI-PUB-528412

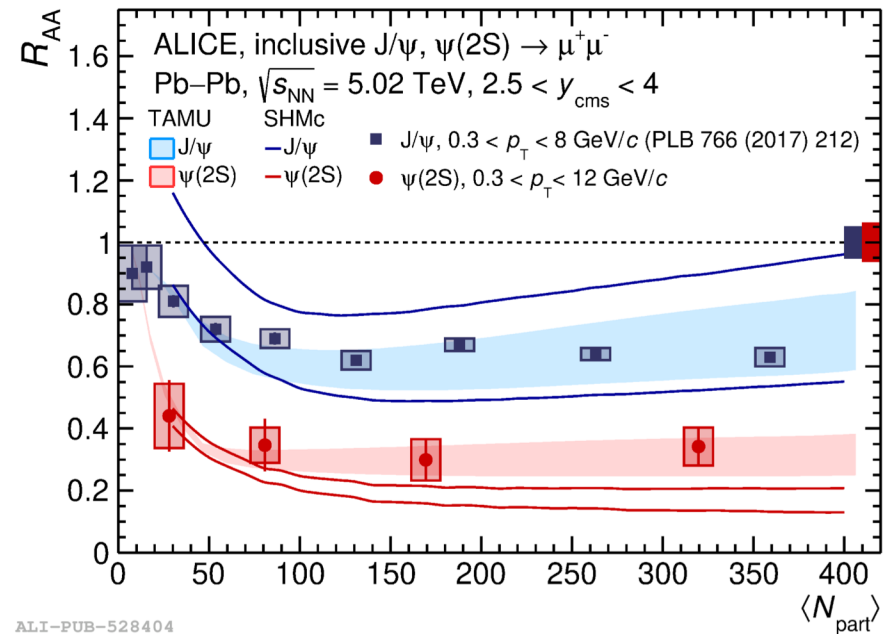
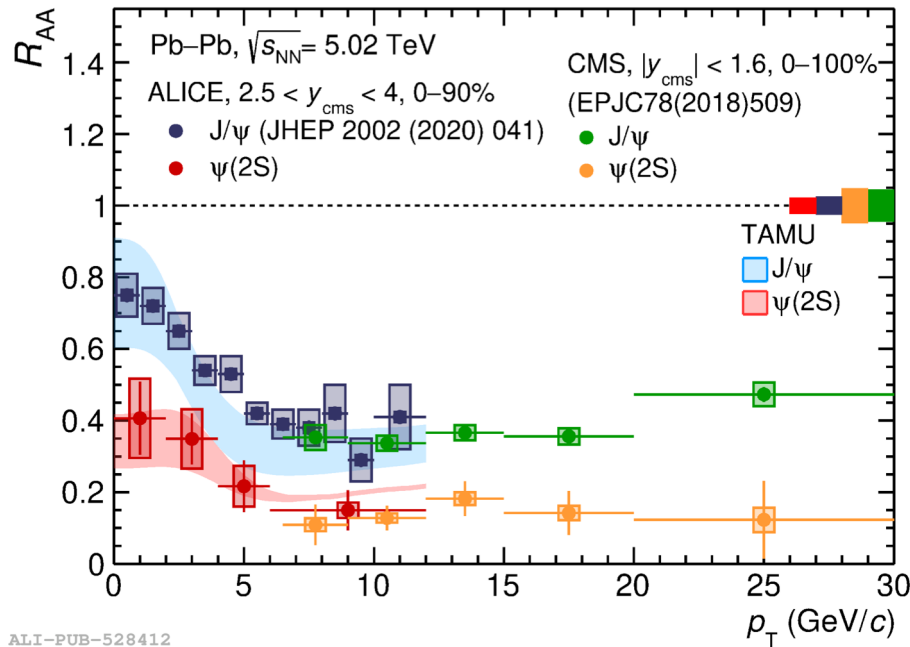
$\psi(2S)$ as a tool to test regeneration scenario

- $\psi(2S)$ more suppressed than J/ψ
- Hint of $\psi(2S)$ regeneration at low p_T

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arxiv:2210.08893



TAMU: [NPA 943 \(2015\) 147-158](#)

SHMc: [PLB 797 \(2019\) 134836](#)

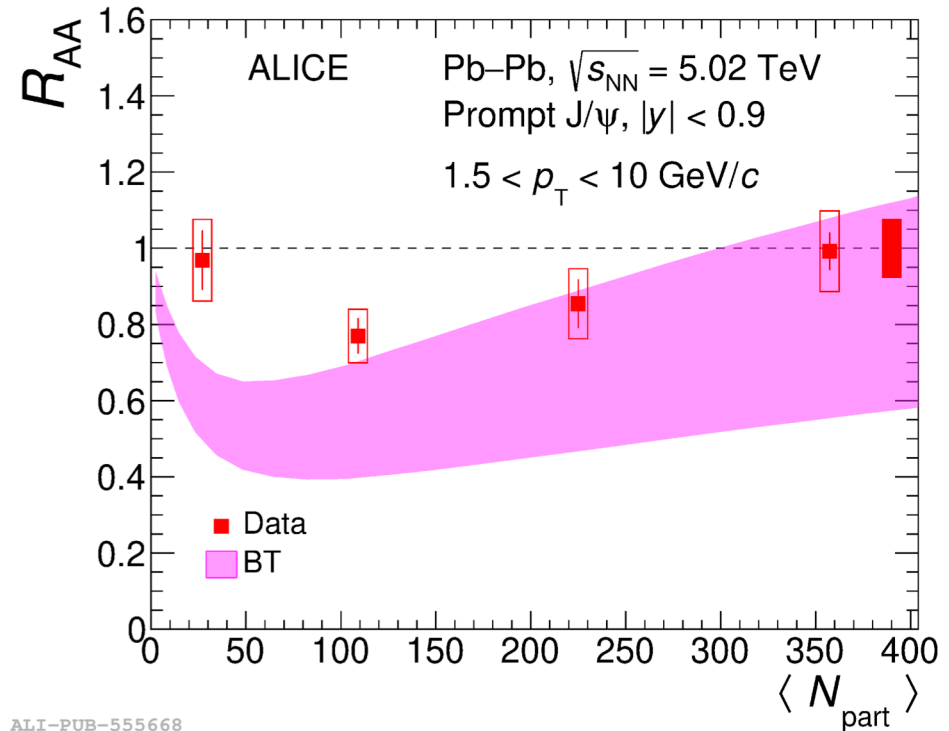
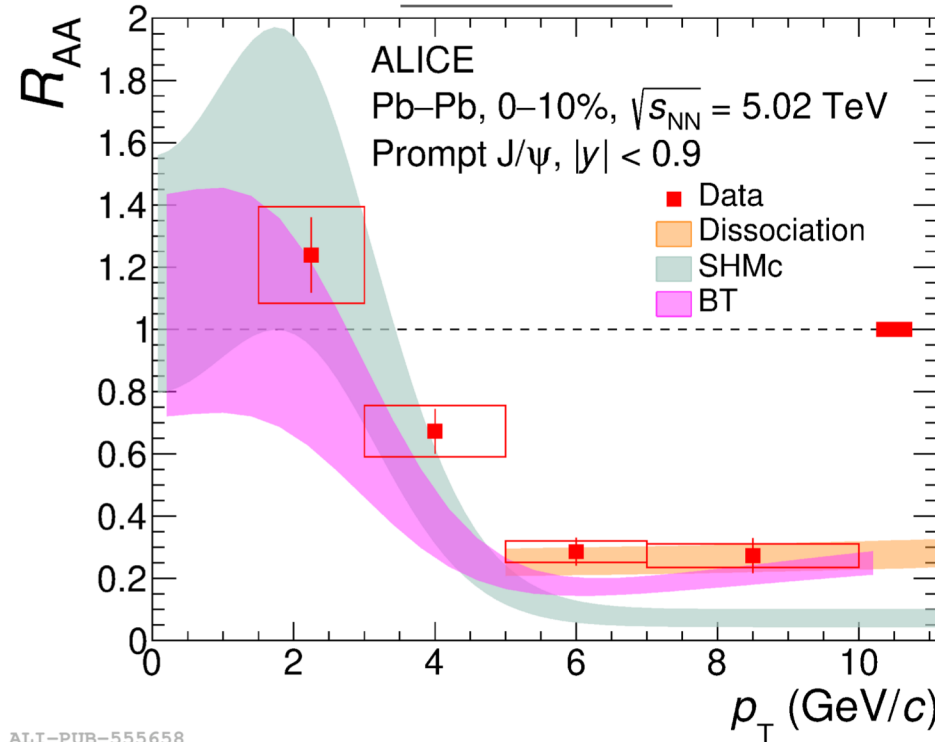
ψ(2S) as a tool to test regeneration scenario

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Theoretical model uncertainties still large BUT ψ(2S) data better described by Transport model

Charm production in Pb–Pb: *prompt J/ψ at midrapidity*

arxiv:2308.16125



ALI-PUB-555658

ALI-PUB-555668

Looking at prompt production (charm) only at midrapidity

- Consistent with regeneration + suppression scenarios

Dissociation: [PLB 778 \(2018\) 384-391](#)

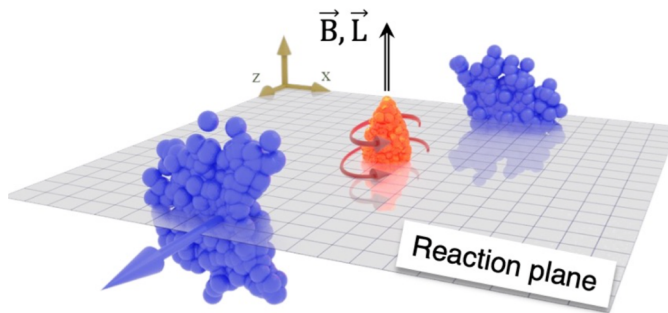
SHMc: [PLB 797 \(2019\) 134836](#)

BT: [PRC 43 \(2019\) 12, 124101](#)

Quarkonium polarization

Related to spin alignment of a particle w.r.t a given axis :

- Very intense magnetic field generated, highly vortical fluid:



- For a vector meson ($\mathbf{v}$), the total angular momentum (J, J_z) is :

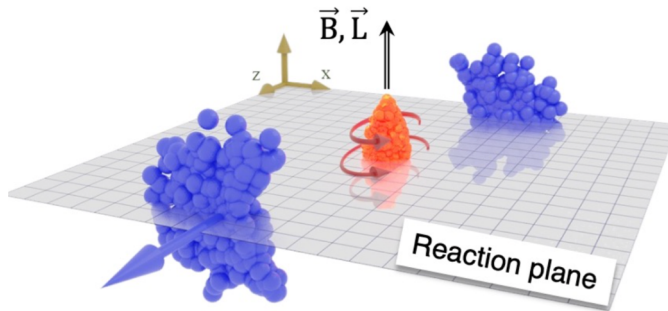
$$|\mathbf{v}; J, J_z\rangle = b_{+1}|1, +1\rangle + b_0|1, 0\rangle + b_{-1}|1, -1\rangle$$

- Quarkonium polarization via polarized $q\bar{q}$ recombination and polarized $q(\bar{q})$ fragmentation

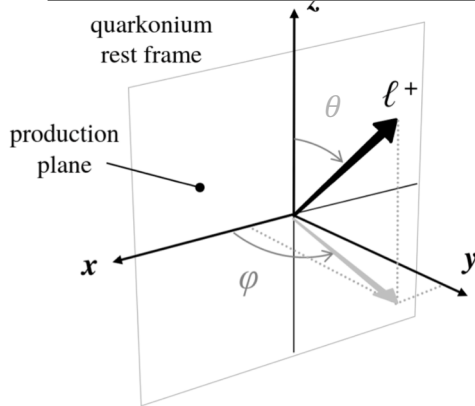
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Eur. Phys. J. C 69 (2009) 657-673



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$$|\mathbf{v}; J, J_z\rangle = b_{+1}|1, +1\rangle + b_0|1, 0\rangle + b_{-1}|1, -1\rangle$$

- Quarkonium polarization via polarized $q\bar{q}$ recombination and polarized $q(\bar{q})$ fragmentation
- The angular distribution of the decay products is linked to the spin alignment

$$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0) \Rightarrow \text{no polarization}$$

$$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1, 0, 0) \Rightarrow \text{pure transverse}$$

$$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0) \Rightarrow \text{pure longitudinal}$$

$$W(\cos\theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi)$$

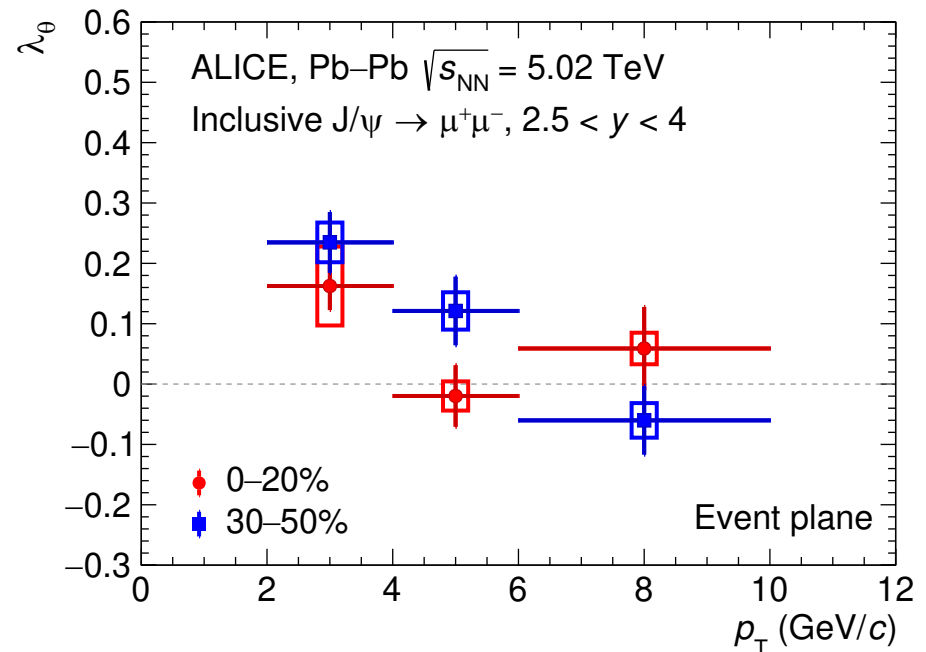
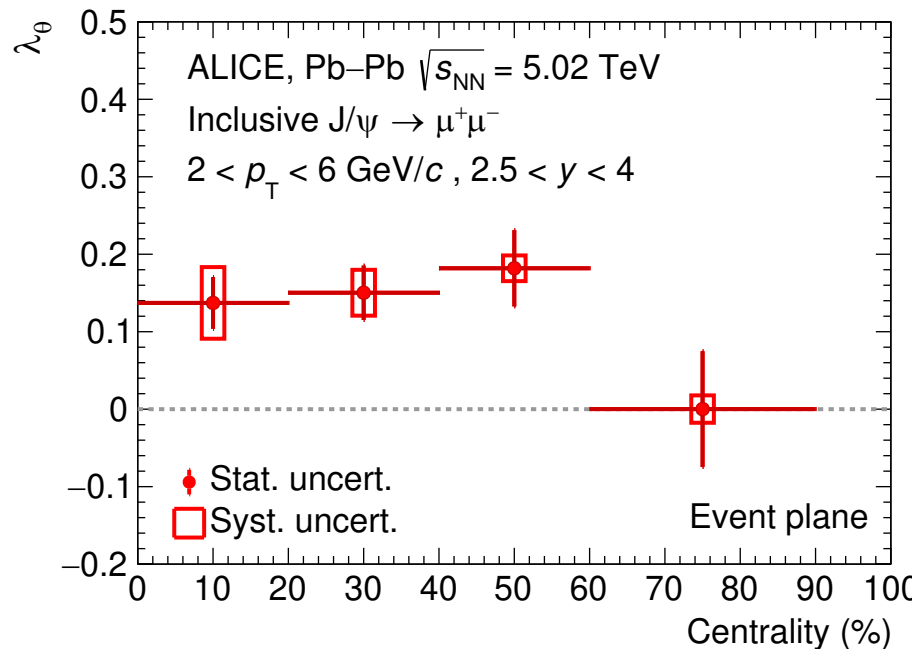
Quarkonium polarization:

Results in Pb-Pb wrt. event plane

New measurement using an Event Plane (EP) based frame

- Axis orthogonal to the Event Plane in the collision center-of-mass frame
- $> 3.5 \sigma$ deviation from 0 observed in 40-60% centrality range
- $> 3.9 \sigma$ deviation from 0 observed at low p_T in 30-50% centrality range
- Full theoretical description needed

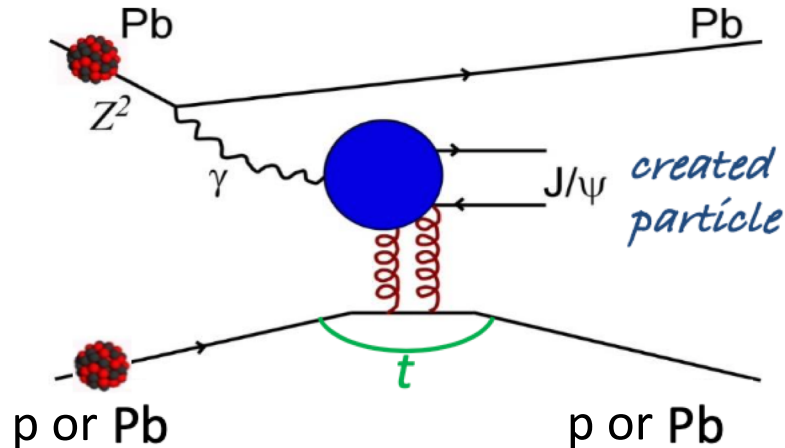
PRL 131 (2023) 4, 042303



UPC in p-Pb:

probing the gluon PDF

Probing nuclear/proton gluon density



- Cross section sensitive to gluon distribution function

$$\frac{d\sigma_{XA}}{dy} = n_{\gamma,1}(y)\sigma_{\gamma A}(y) + n_{\gamma,2}(-y)\sigma_{\gamma X}(-y)$$

Photon flux

Photonuclear cross section

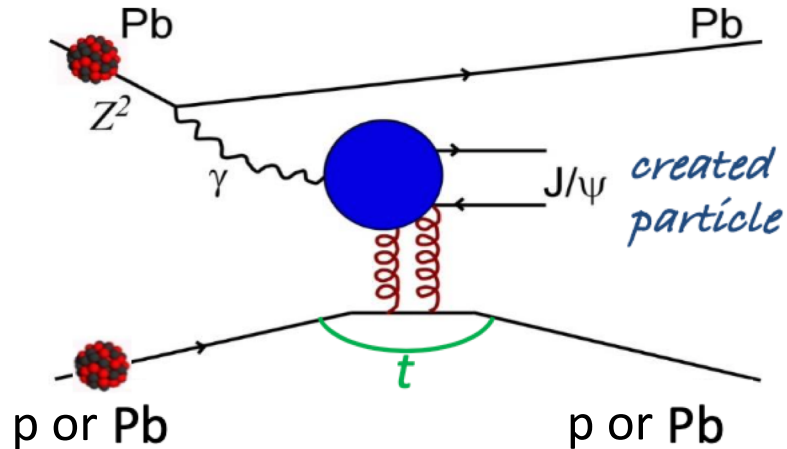
- Low x : $x = \frac{M_{VM}}{\sqrt{s}} e^{\pm y} \Rightarrow 10^{-5} < x < 10^{-2}$ at LHC energies

- VM transverse polarization expected

UPC in p-Pb:

probing the gluon PDF

Probing nuclear/proton gluon density

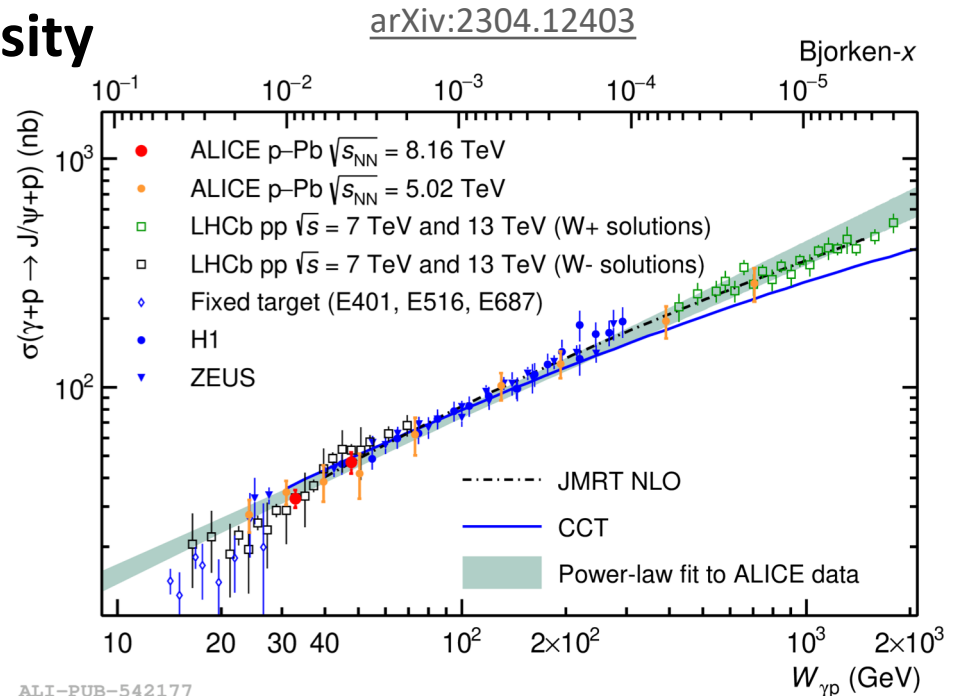


- Cross section sensitive to gluon distribution function

$$\frac{d\sigma_{XA}}{dy} = n_{\gamma,1}(y)\sigma_{\gamma A}(y) + n_{\gamma,2}(-y)\sigma_{\gamma X}(-y)$$

- Low x : $x = \frac{M_{VM}}{\sqrt{s}} e^{\pm y} \Rightarrow 10^{-5} < x < 10^{-2}$ at LHC energies

- VM transverse polarization expected



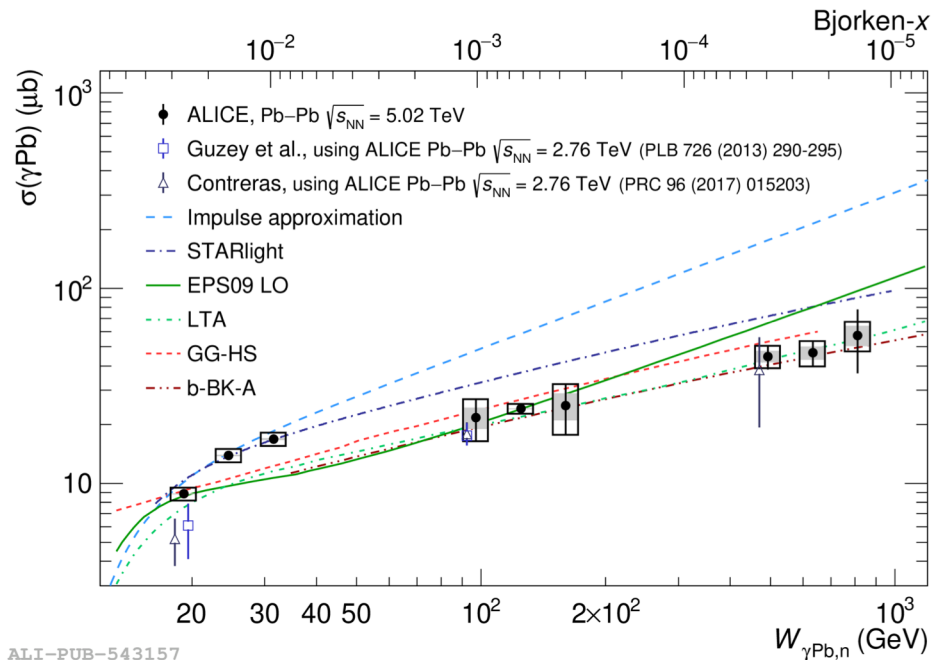
ALI-PUB-542177

proton gluon PDF do not change as a function of energy

UPC in Pb–Pb:

cross-section & polarization

arXiv:2305.19060



1st energy dependence measurement down to $x \sim 10^{-5}$

- Favor saturation and shadowing

IA: [Phys. Rev. 85 \(1952\) 4, 636](#)

STARlight: [Comput. Phys. Commun. 212 \(2017\) 258-268](#)

EPS09 LO: [JHEP 04 \(2009\) 065](#)

LTA: [Phys. Rept. 512 \(2012\) 255-393](#)

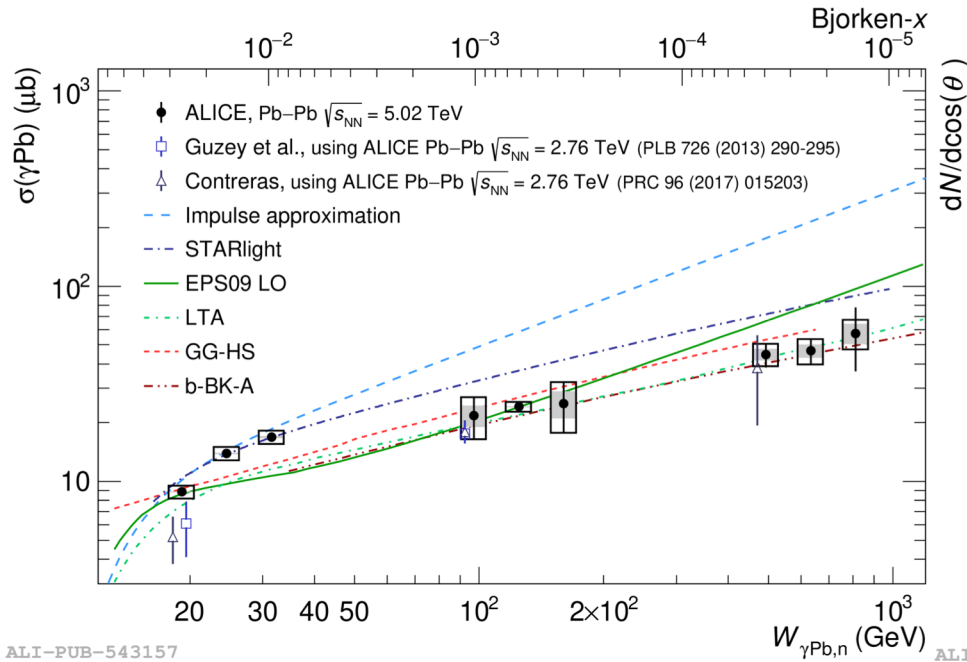
GG-HS: [PRC 97 \(2018\) 2, 024901](#)

b-BK-A: [PLB 817 \(2021\) 136306](#)

UPC in Pb–Pb:

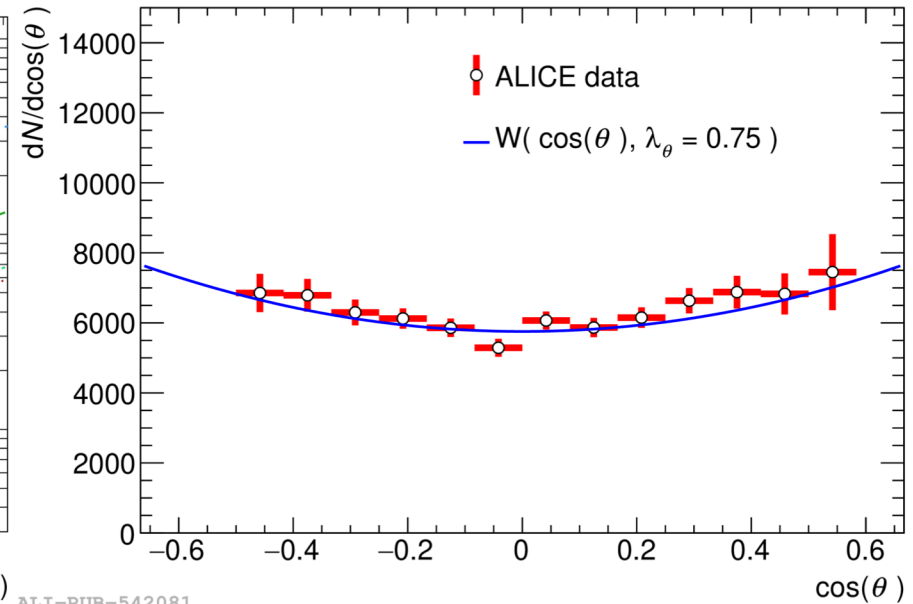
cross-section & polarization

arXiv:2305.19060



arxiv:2304.10928

ALICE, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV, Coherent J/ψ



1st energy dependence measurement down to $x \sim 10^{-5}$

- Favor saturation and shadowing

1st coherent J/ψ polarization measurement

- Compatible with transverse polarization

IA: [Phys. Rev. 85 \(1952\) 4, 636](#)

STARlight: [Comput. Phys. Commun. 212 \(2017\) 258-268](#)

EPS09 LO: [JHEP 04 \(2009\) 065](#)

LTA: [Phys. Rept. 512 \(2012\) 255-393](#)

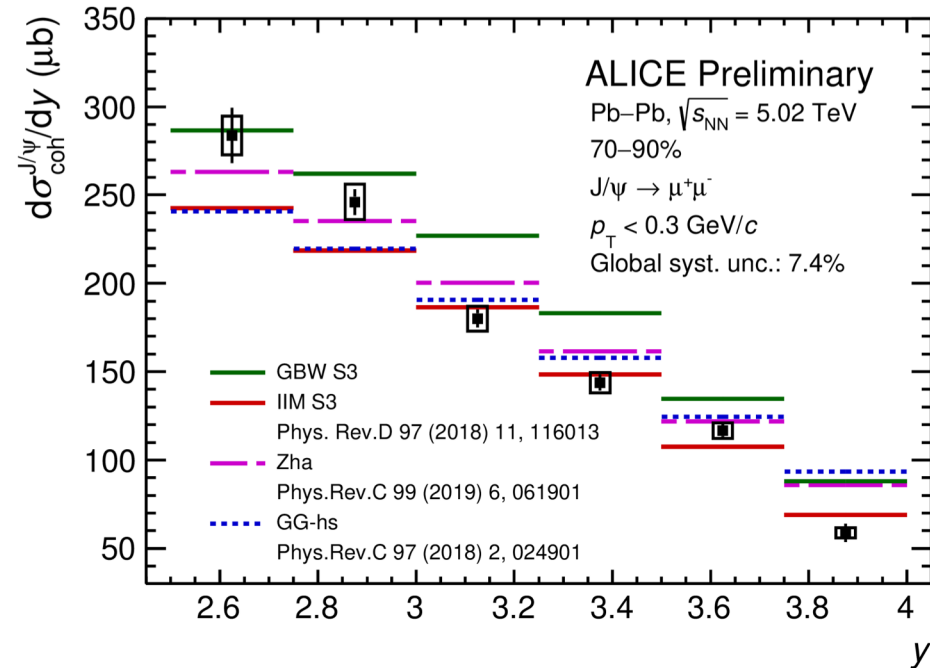
GG-HS: [PRC 97 \(2018\) 2, 024901](#)

b-BK-A: [PLB 817 \(2021\) 136306](#)

J/ψ Photoproduction in peripheral Pb–Pb collisions

Coherent J/ψ photoproduction

- Observed as a yield excess at low- p_T by ALICE in peripheral events
- As in UPC, models fail to reproduce the rapidity distribution

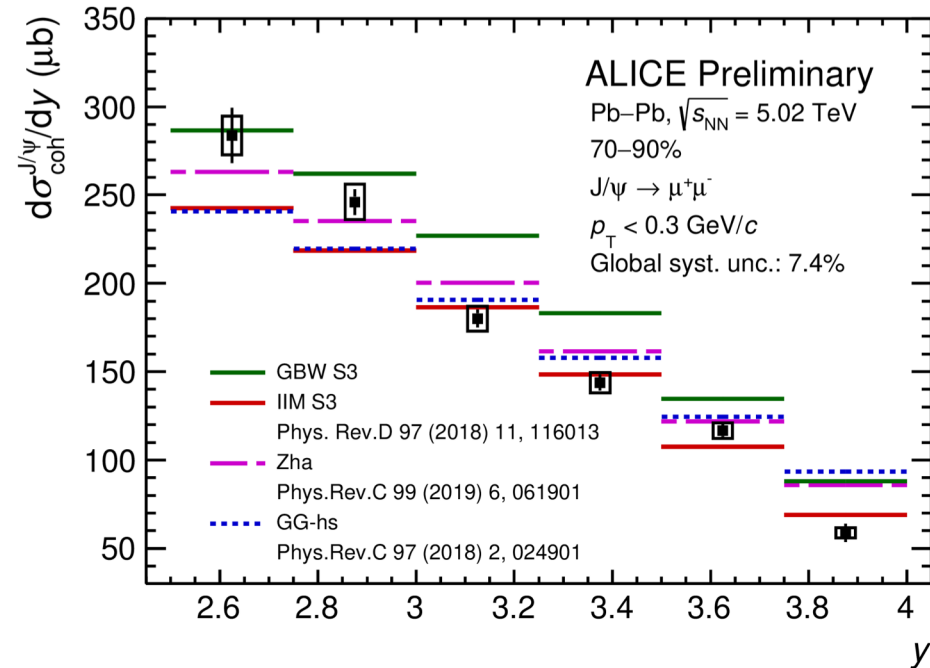
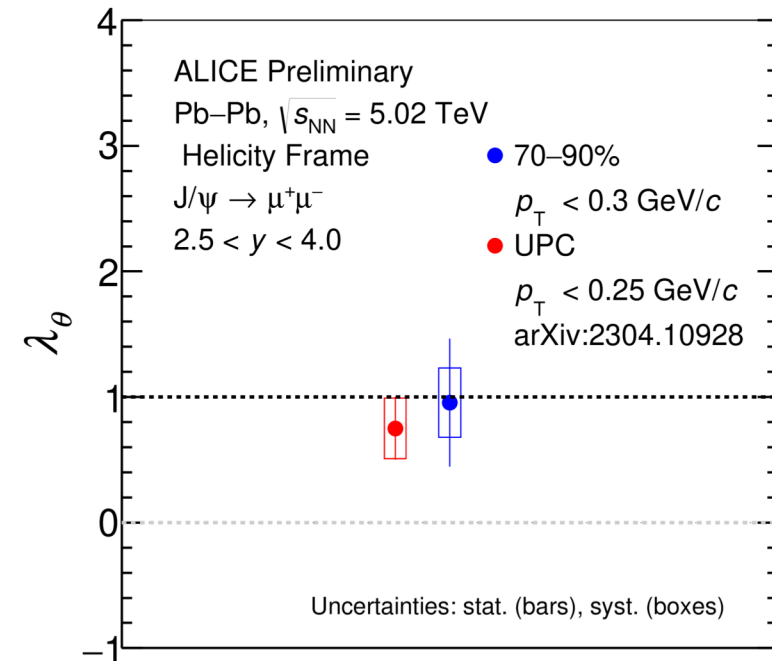


ALI-PREL-547942

J/ψ Photoproduction in peripheral Pb–Pb collisions

Coherent J/ψ photoproduction

- Observed as a yield excess at low- p_T by ALICE in peripheral events
- As in UPC, models fail to reproduce the rapidity distribution

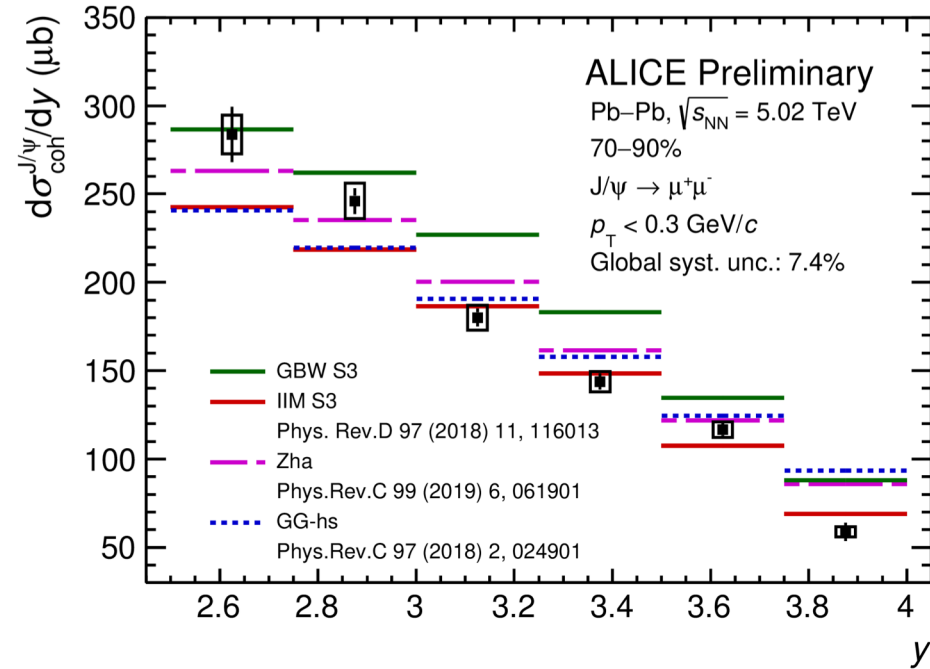
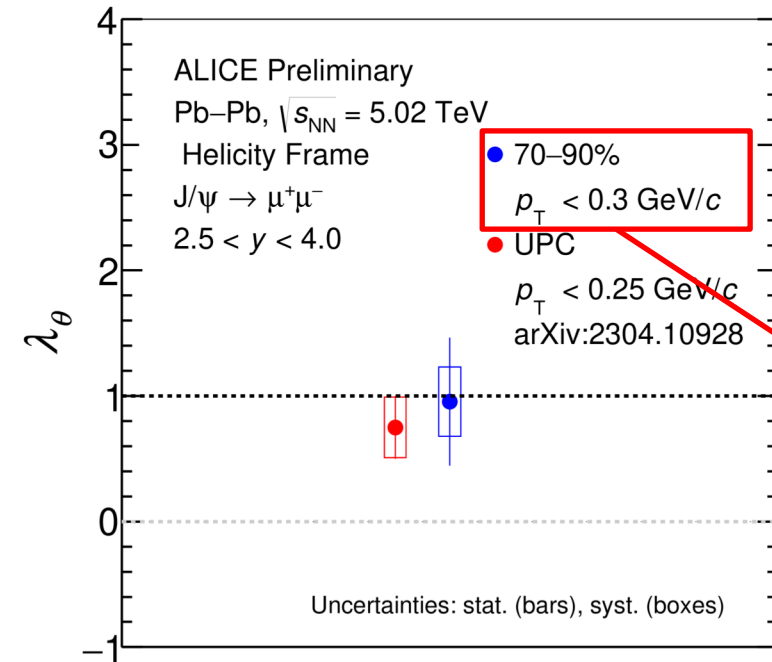


Inclusive J/ψ polarization at low p_T

J/ψ Photoproduction in peripheral Pb–Pb collisions

Coherent J/ψ photoproduction

- Observed as a yield excess at low- p_T by ALICE in peripheral events
- As in UPC, models fail to reproduce the rapidity distribution



Inclusive J/ψ polarization at low p_T

- $p_T < 0.3$ GeV/c dominated by J/ψ photoproduction
- Compatible with transverse polarization & UPC results

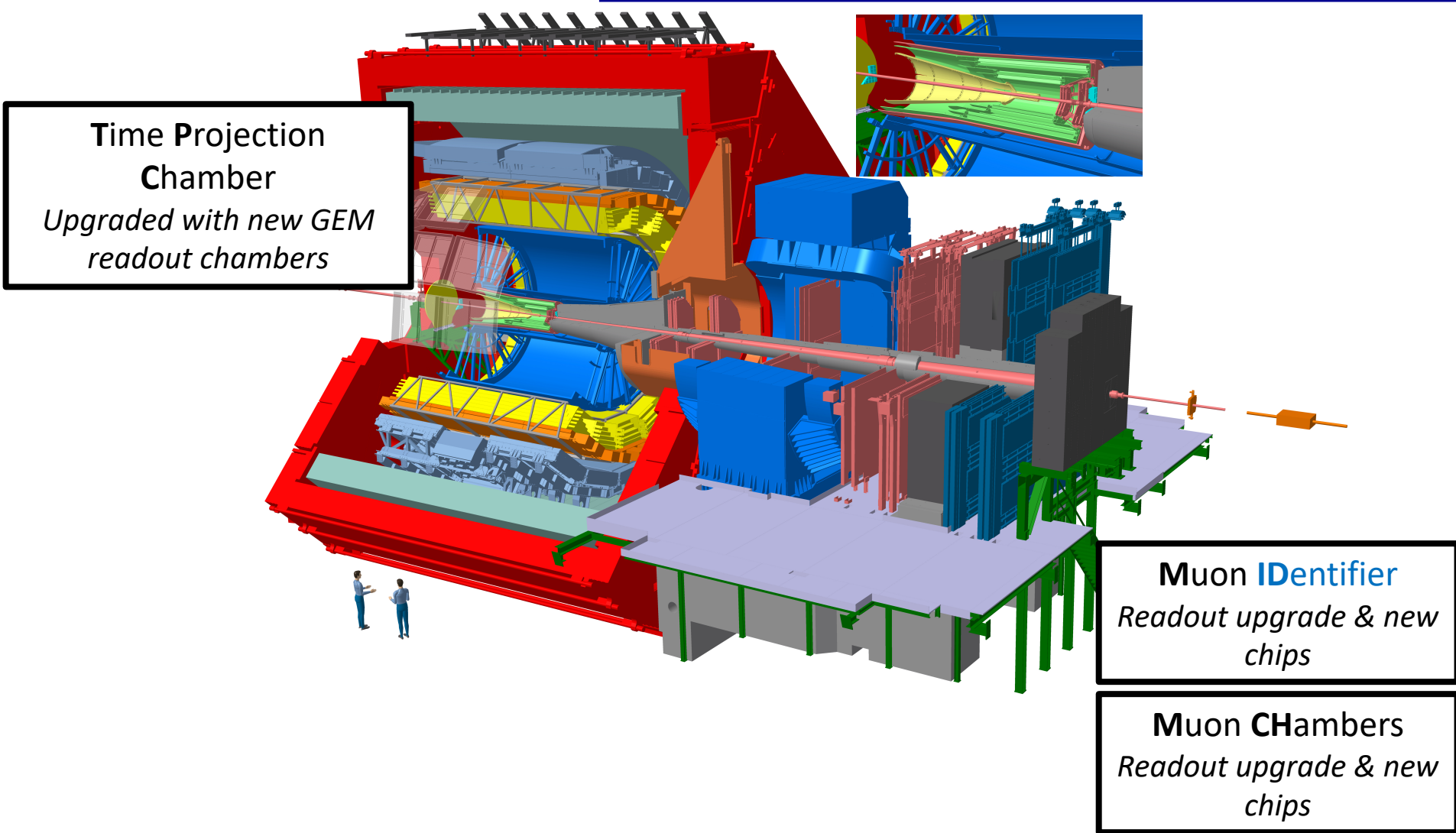
Summary

ALICE has produced a variety of precise quarkonium measurements

- *pp collisions:*
 - Good understanding at the moment but more precise calculation may help
- *High multiplicity in small colliding systems:*
 - Models implementing MPI scenario seems to qualitatively reproduce the data
- *p–Pb collisions:*
 - Low p_T suppression described by gluon shadowing
 - Larger suppression in the p-going direction → gluon shadowing/energy loss
- *Pb–Pb collisions:*
 - Charmonia production → interplay between suppression & regeneration
 - Underlying mechanism of regeneration studied with excited states
 - Significant polarization measured: *magnetic field? vorticity?*
- *UPC & photoproduction in peripheral events*
 - Transverse polarization of J/ψ measured
 - UPC model cannot well described the y -dependence of data in peripheral events

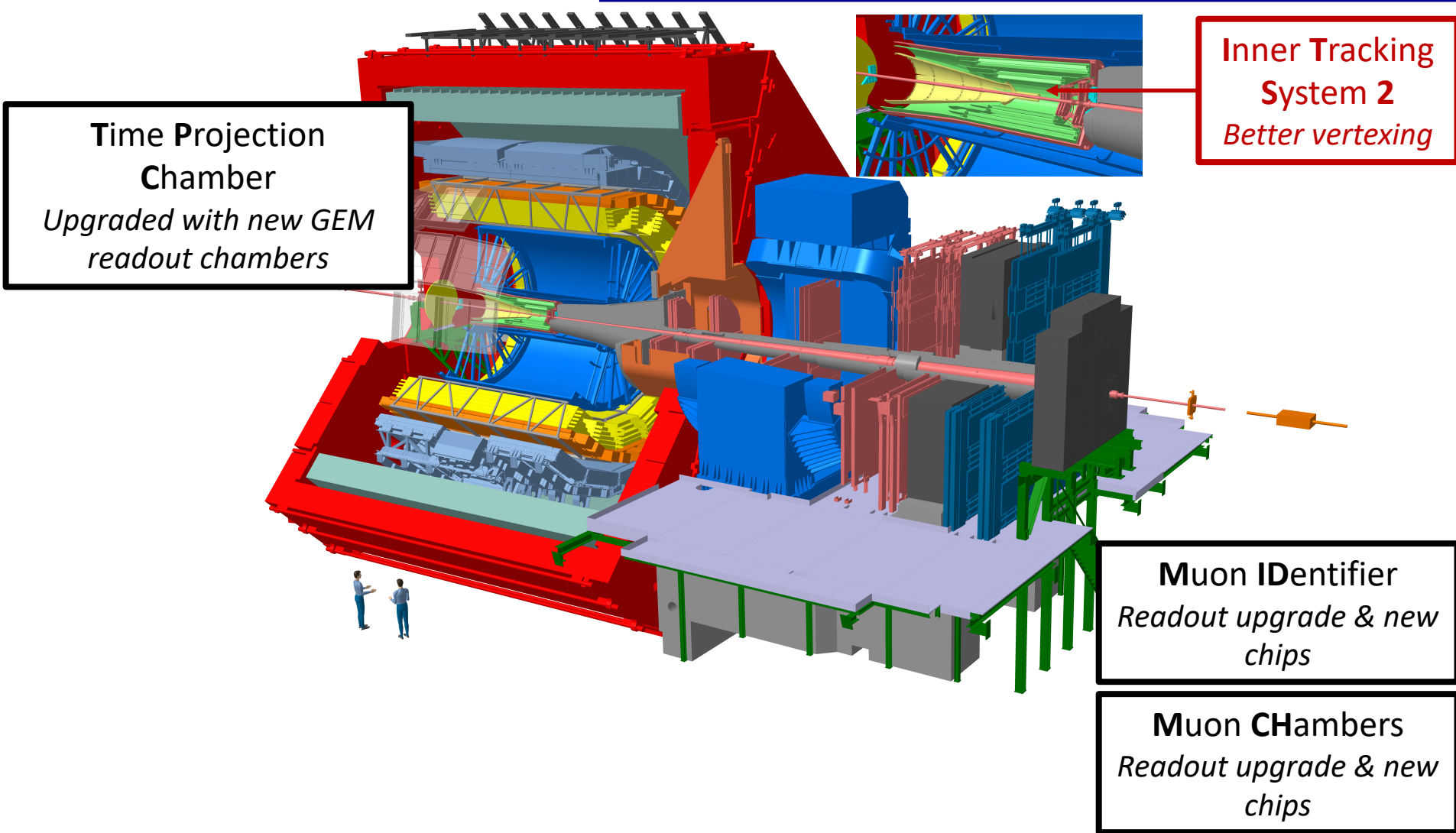
The ALICE detector:

Run 3 setup



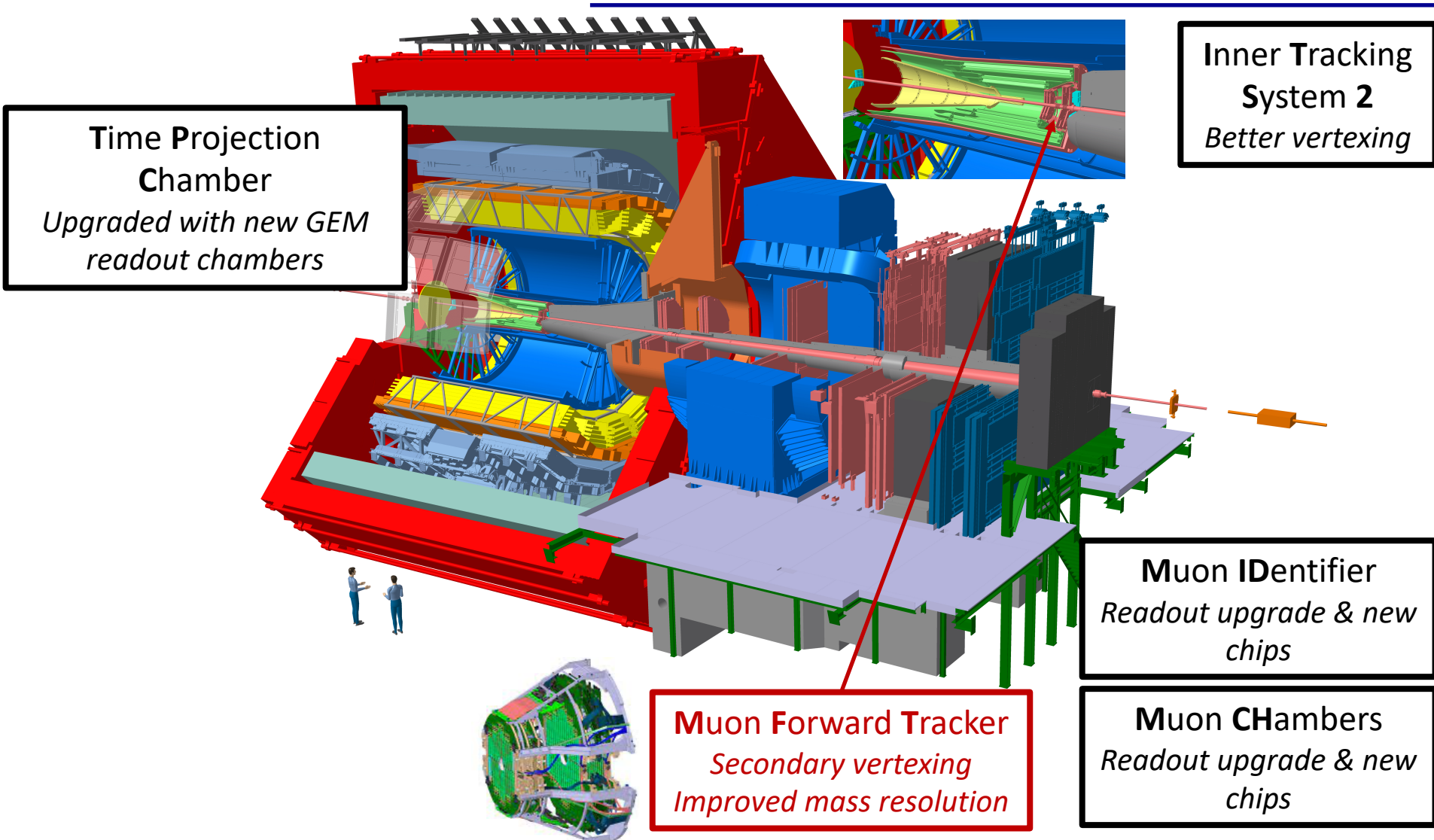
The ALICE detector:

Run 3 setup



The ALICE detector:

Run 3 setup



The ALICE detector:

Run 3 setup

Time Projection Chamber
Upgraded with new GEM readout chambers

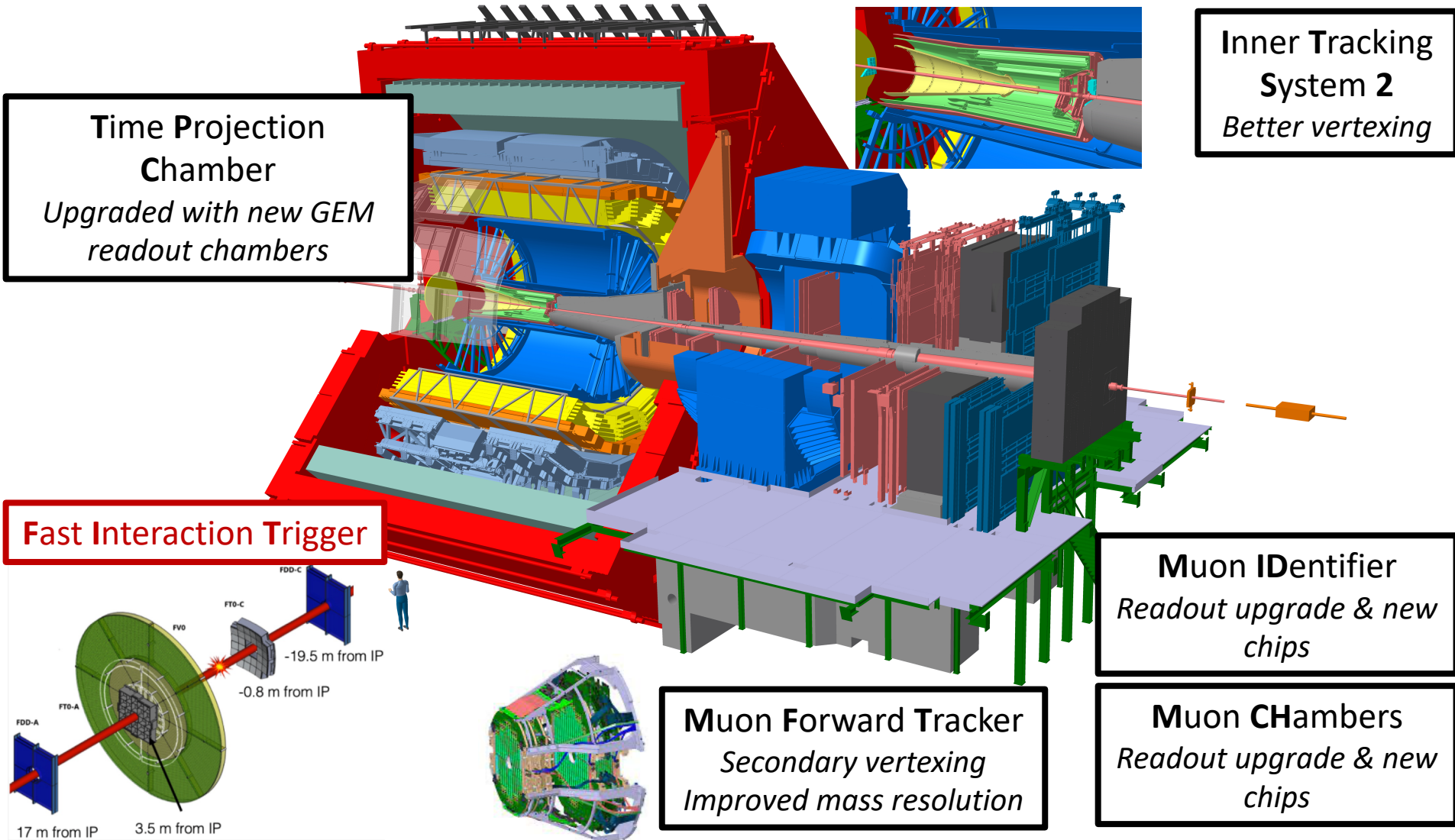
Inner Tracking System 2
Better vertexing

Fast Interaction Trigger

Muon Identifier
Readout upgrade & new chips

Muon Chambers
Readout upgrade & new chips

Muon Forward Tracker
*Secondary vertexing
Improved mass resolution*



The ALICE detector:

Run 3 setup

Time Projection Chamber
Upgraded with new GEM readout chambers

Inner Tracking System 2
Better vertexing

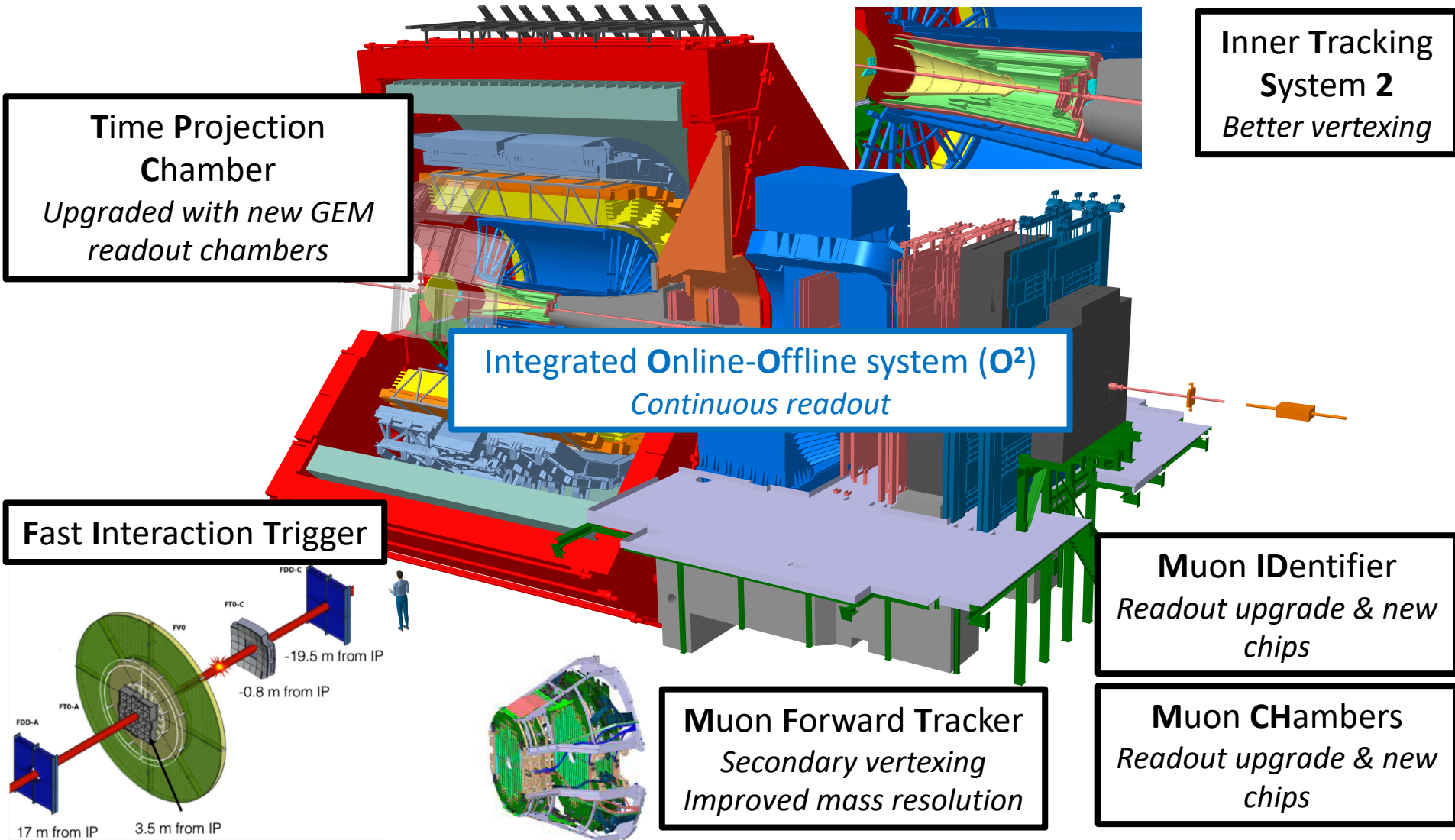
Integrated Online-Offline system (O²)
Continuous readout

Fast Interaction Trigger

Muon Identifier
Readout upgrade & new chips

Muon Chambers
Readout upgrade & new chips

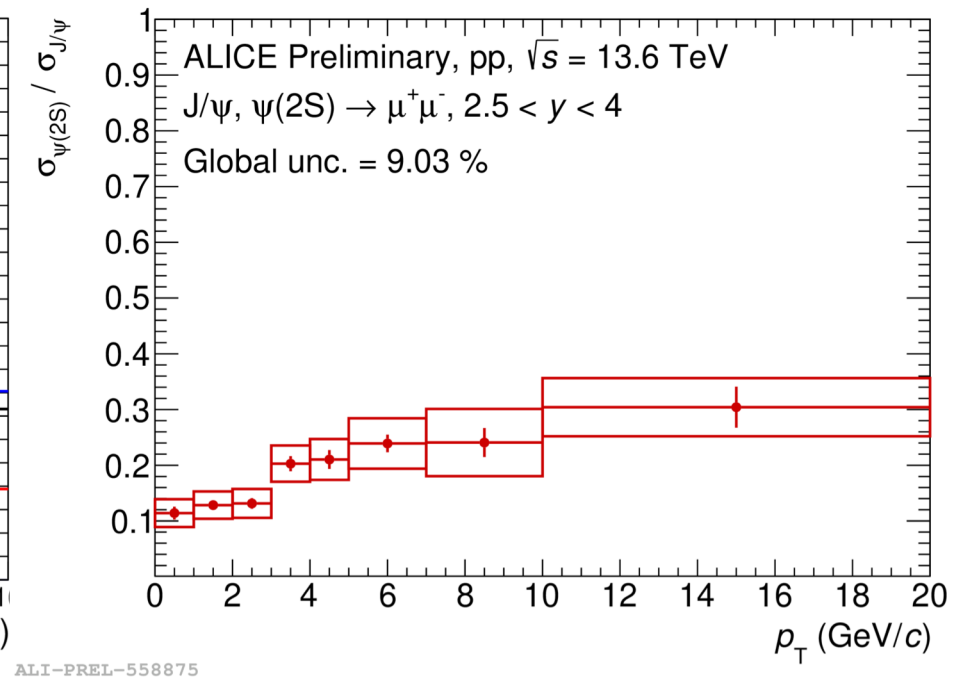
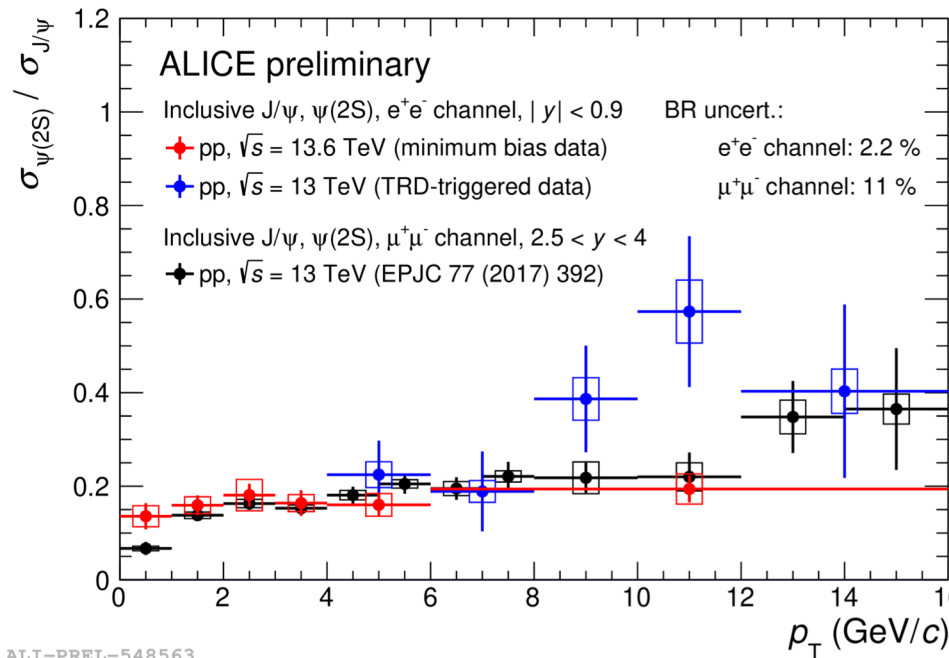
Muon Forward Tracker
*Secondary vertexing
Improved mass resolution*



Some Run 3 results coming...

New results with the upgraded ALICE experiment are coming!

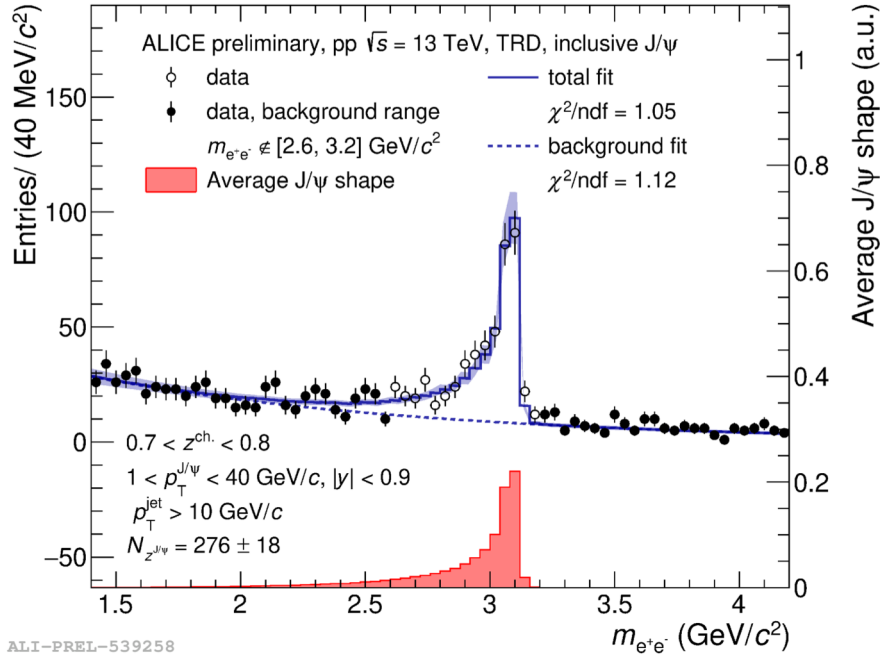
- First “standard candle” measurement obtained
- Still need to collect more data
- Better performances expected (smaller systematic uncertainties)
- Charm/Beauty separation at forward rapidity



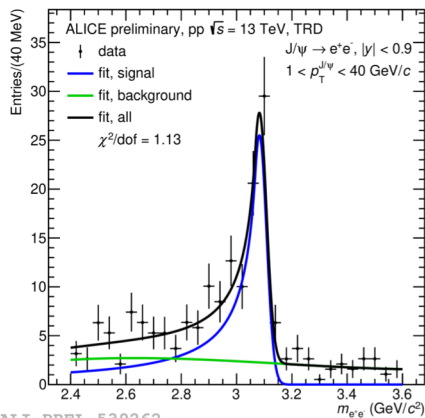


Thanks!

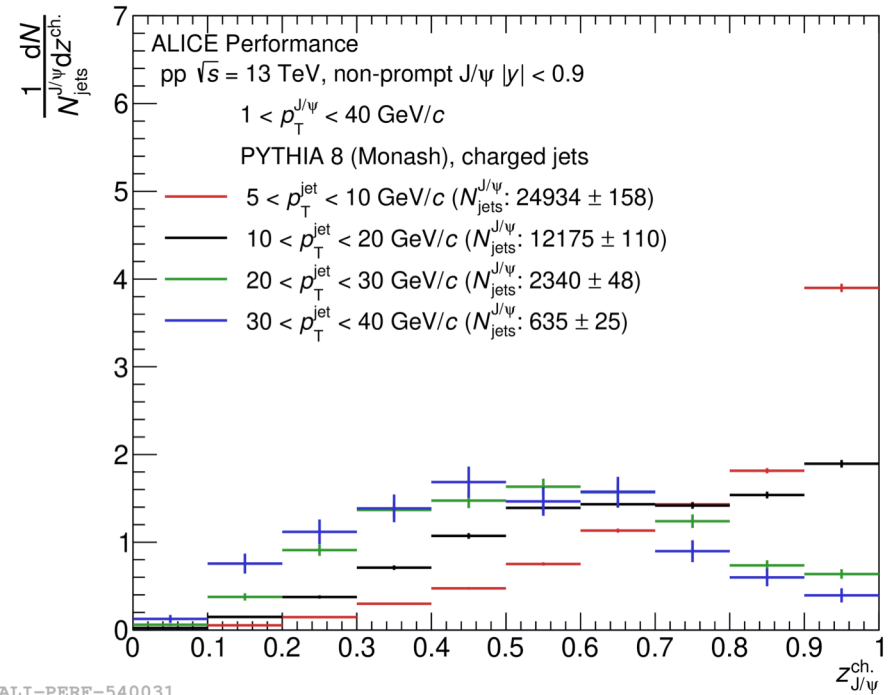
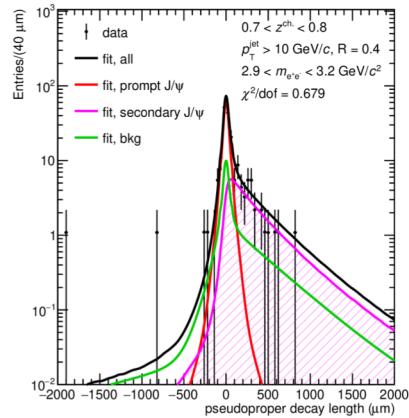
Backup



ALI-PREL-539258

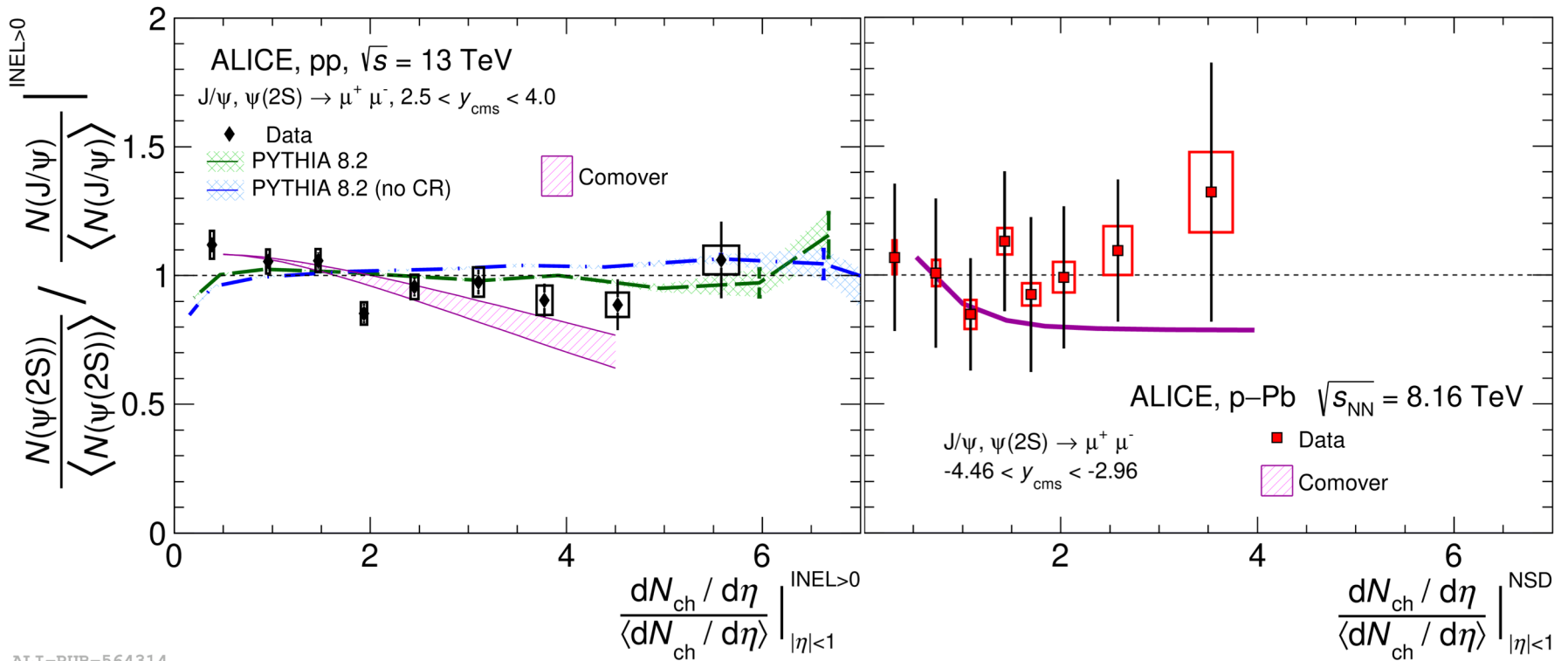


ALI-PREL-539262



ALI-PERF-540031

Backup



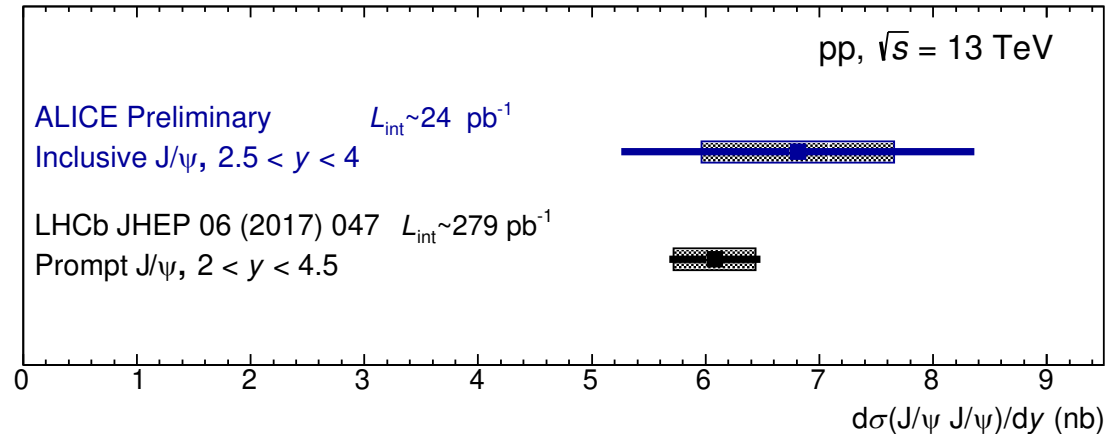
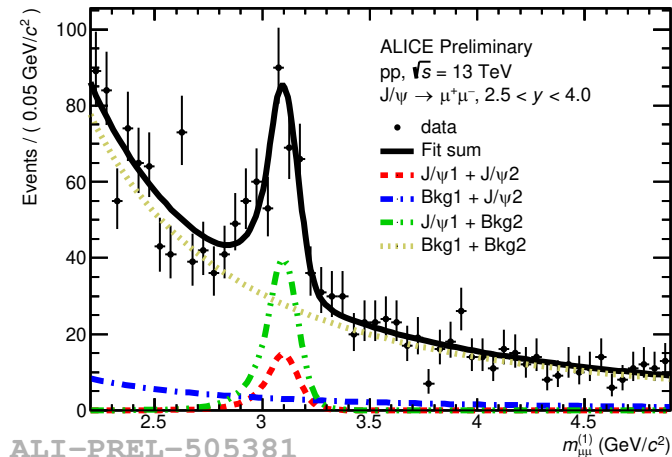
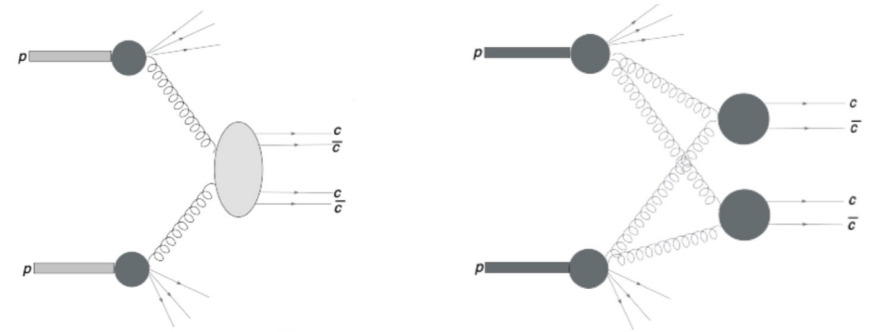
ALI-PUB-564314

J/ψ pair production

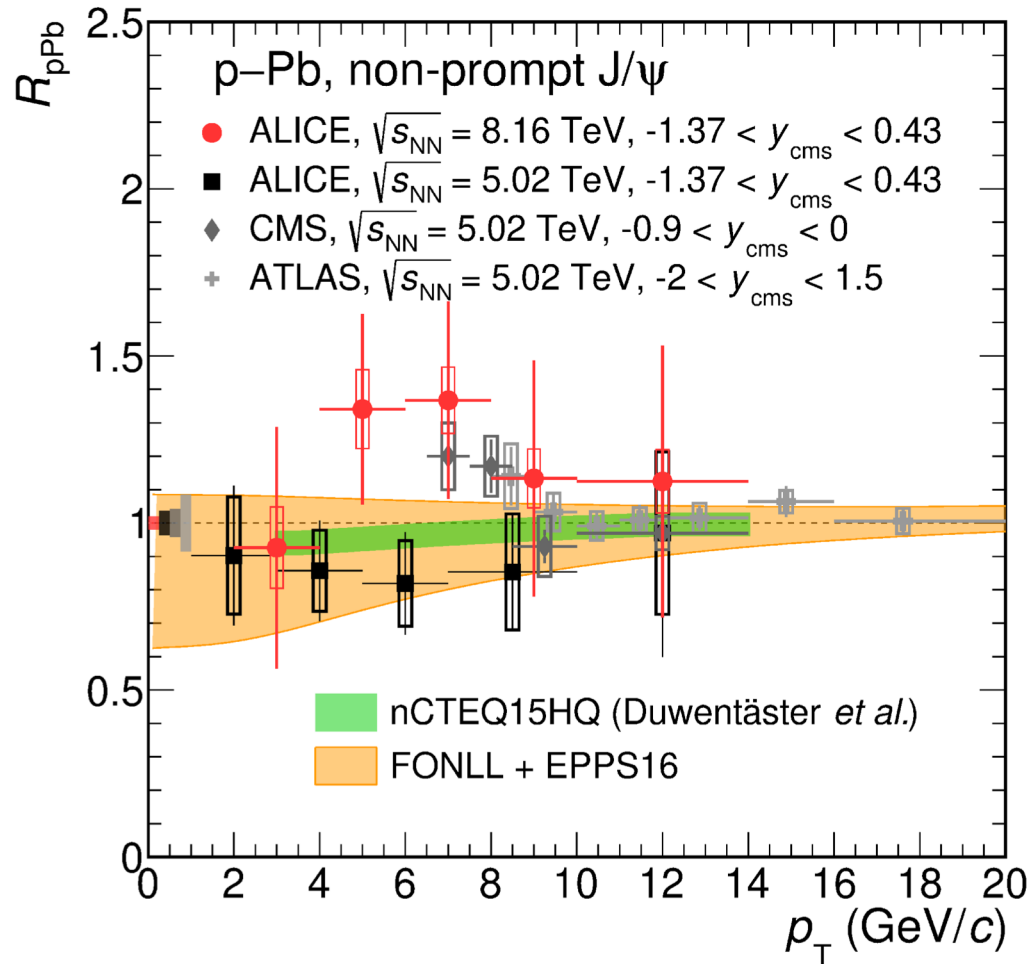
Non trivial correlation in ALICE central barrel

- Constraint on:
 - DP scattering
 - J/ψ production, NRQCD
- Good agreement w/ LHCb
 - ALICE is inclusive
 - $\neq$ acceptances

AIP, 1523 (2013) 1

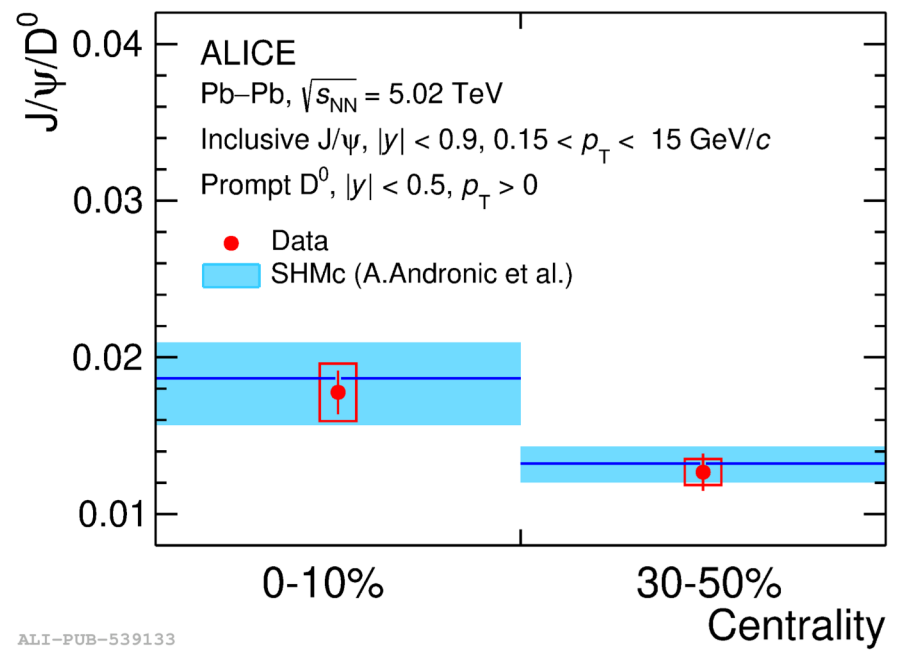
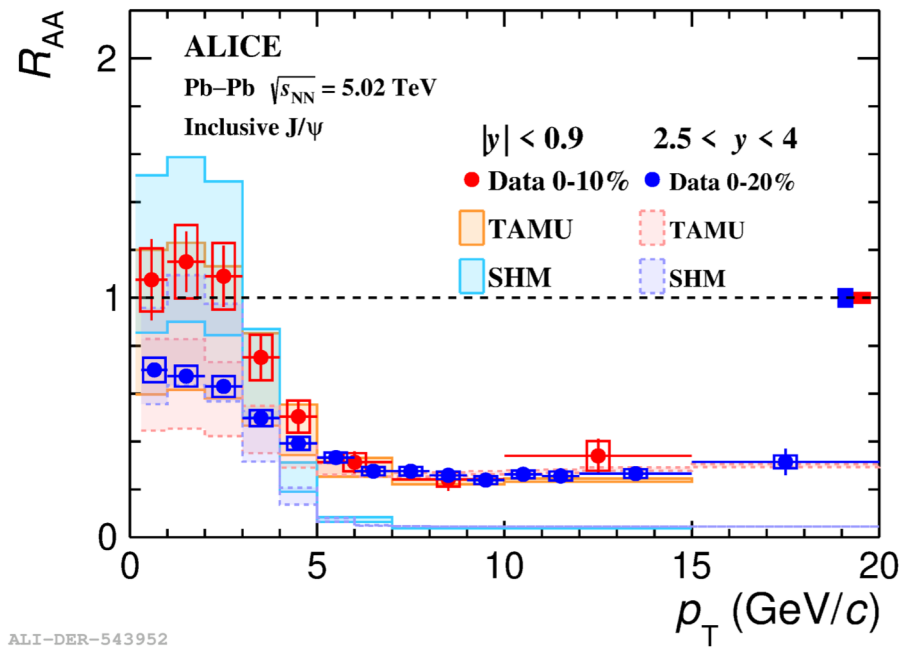


Backup

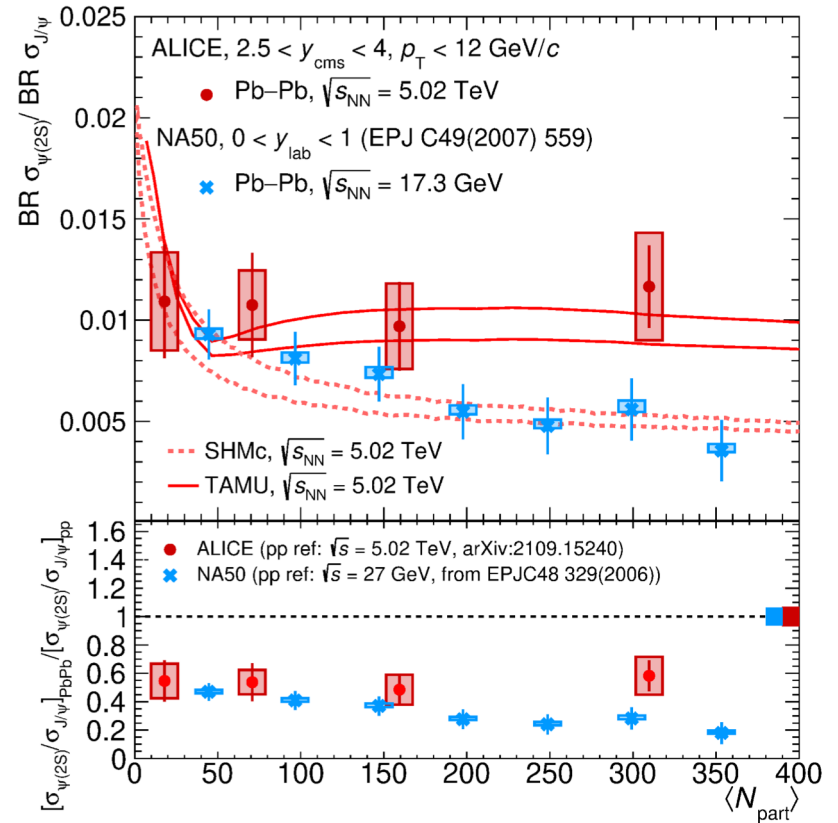
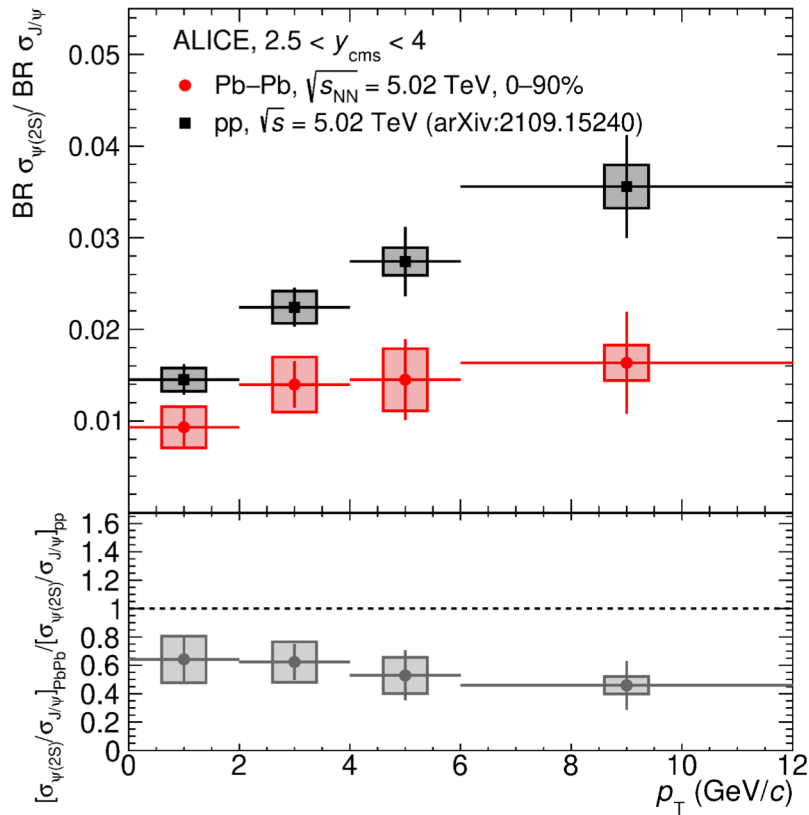


ALI-PUB-561251

Backup



Backup



ALI-PUB-528408

UB-528400

EPS09 LO (GKZ): parameterization of nuclear shadowing
 data PRC 93 (2016) 055206

LTA: Leading Twist Approximation of nuclear shadowing
 PRC 93 (2016) 055206

IIM BG, IPsat, BGK-I: color dipole approach coupled to the
 Color Glass Condensate formalism with different
 assumptions on the dipole-proton scattering amplitude
 PRC 90 (2014) 015203, PRC 83 (2011) 065202,
 PRC 99 (2019) 044905, J. Phys. G 42 (2015) 105001
 PRC 87 (2013) 032201

GG-HS: color dipole model with hot-spots nucleon
 structure
 PRC 97 (2018) 024901, PLB 766 (2017) 186-191

b-BK: Color dipole approach coupled with impact-
 parameter dependent Balitsky-Kovchegov equation
 PLB 817 (2021) 136306

