Charmonium production with ALICE at the LHC

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EMMI Physics Days
GSI Darmstadt

Outline

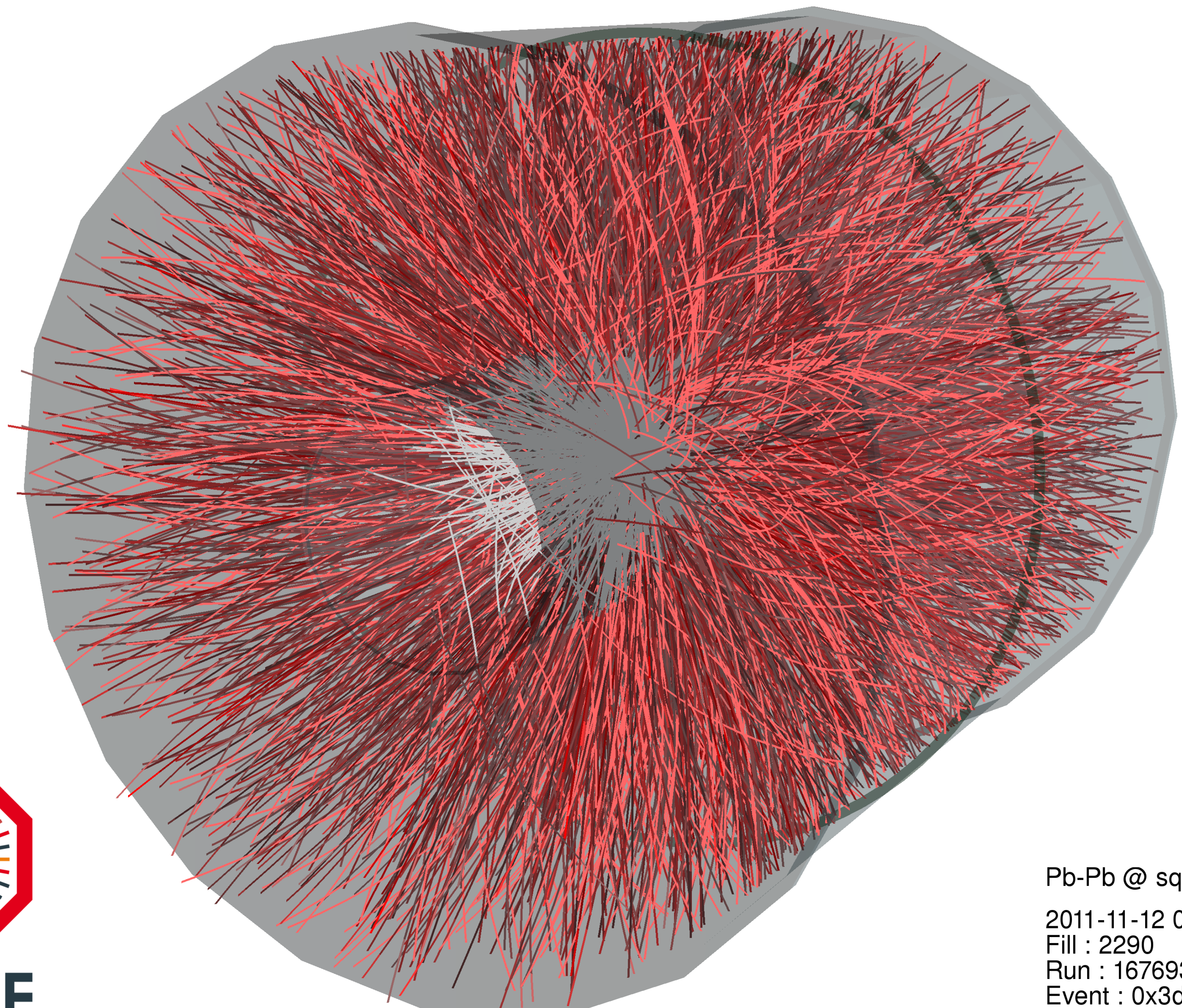
1) Charmonium in Pb-Pb collisions at the LHC

- Motivation
- Measurements by ALICE

2) Charmonium in p-Pb collisions at the LHC

- Motivation
- Measurements by ALICE

3) Conclusion and Outlook



Pb-Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

ALICE
A JOURNEY OF DISCOVERY

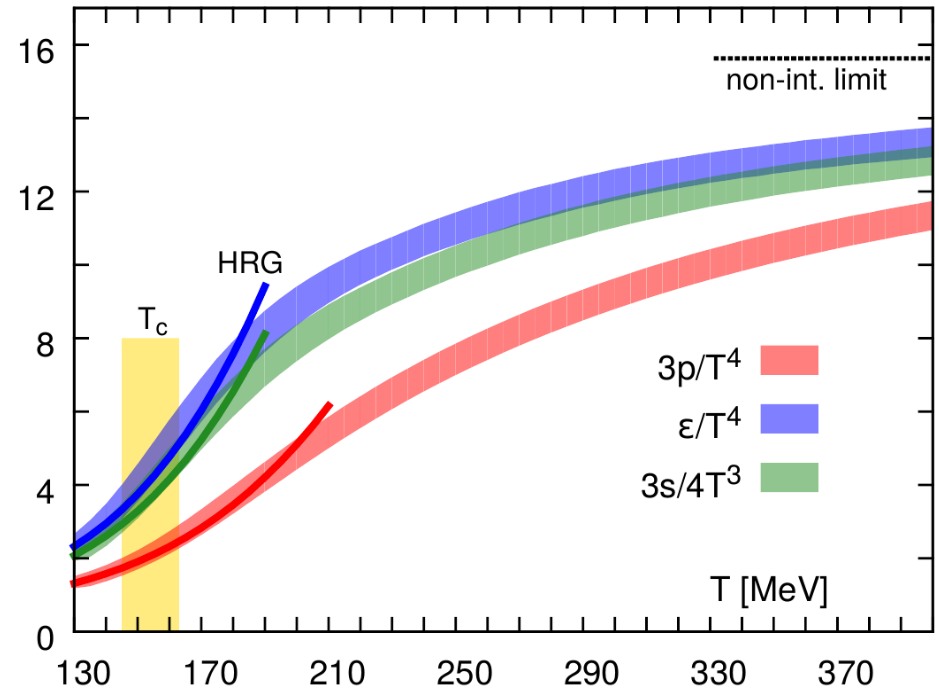
Heavy-ion collisions: Quark-Gluon Plasma Physics

- Heavy-ion collisions: experimental access to many-body physics governed by **Q**uanten**C**hromo**D**ynamics

- Lattice QCD:

  at vanishing baryochemical potential at close to realistic quark masses

  cross-over from Hadron Resonance Gas (HRG) to **Quark-Gluon Plasma**



link: arXiv:1407.6387 (HotQCD), consistent results in phenom. relevant region from Wuppertal-Budapest link: arXiv:1309.5258, **Phys. Lett. B 370 (2014) 99-104**

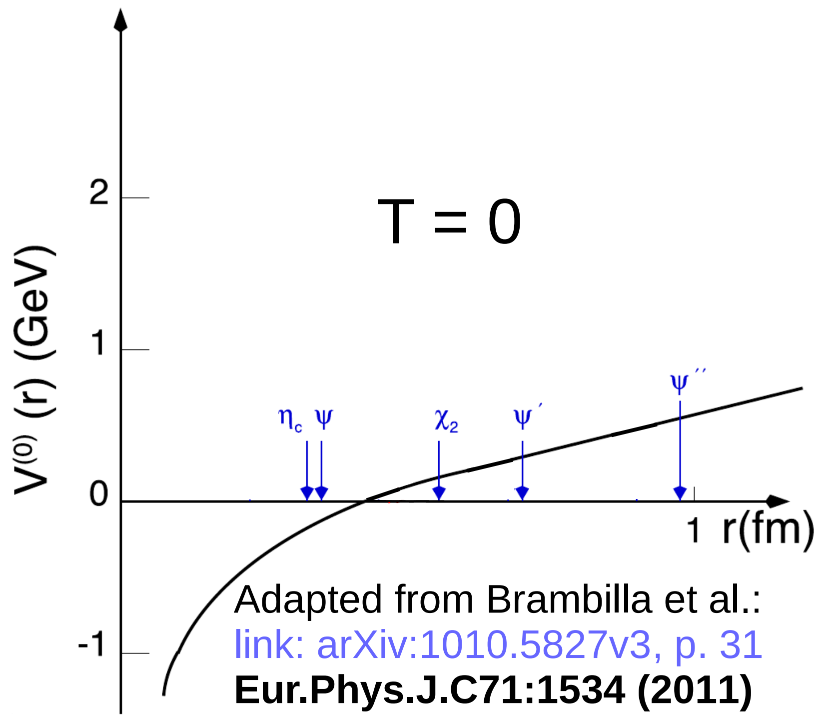
→ tested by ultra-relativistic heavy-ion collisions at the LHC

Quark-Gluon Plasma: heavy quarkonia as a tool

- Key measurement:
  direct experimental
  signature for deconfinement

- **Heavy quarkonia:**
  bound states of $c\bar{c}$/$b\bar{b}$-quark pairs

  model systems for interaction
  of color charges at T=0 and finite T



Adapted from Brambilla et al.:
link: arXiv:1010.5827v3, p. 31
Eur.Phys.J.C71:1534 (2011)

→ color screening and thermal width influencing bound states
first discussed as sign of deconfinement in heavy-ion collisions by Matsui & Satz
Phys.Lett.B 178 (1986) link: DOI: 10.1016/0370-2693(86)91404-8

→ theory effort towards quantitative understanding
review about quarkonia theory at finite T: A. Mocsy, P. Petreczky, M. Strickland
Int. J. of Mod. Phys. A, Vol. 28, 1340012 (2013) link: arXiv:1302.2180

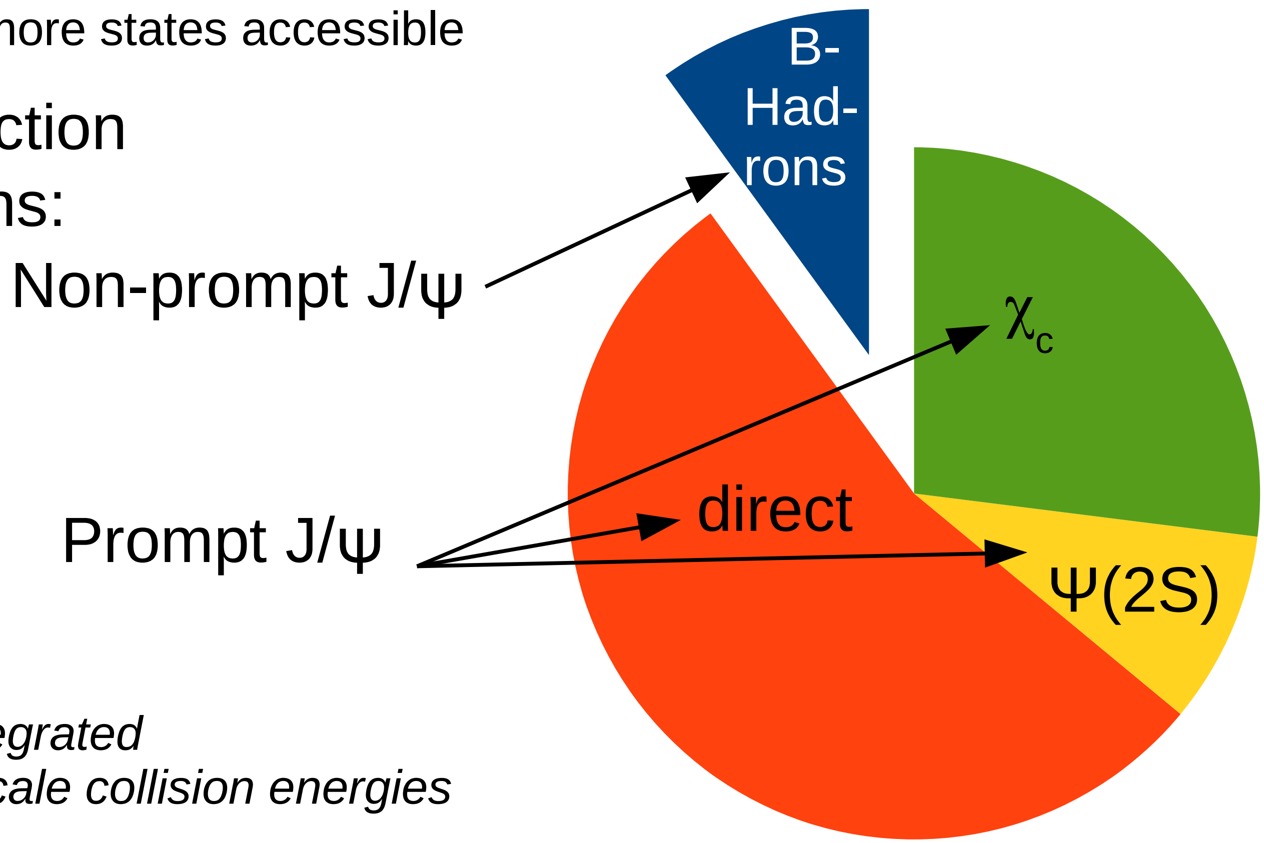
Heavy-ion collisions and charmonium detection

- Charmonium ($c\bar{c}$) bound vector states **J/ψ and ψ(2S)**

  $BR(J/\psi \rightarrow e^+e^-/\mu^+\mu^-) \approx 6\ \%$
  $BR(\psi(2S) \rightarrow e^+e^-/\mu^+\mu^-) \approx 0.8\ \%$

  → **accessible in nucleus-nucleus collisions**
  in pp/p-Pb collisions more states accessible

- **Inclusive** J/ψ production
  in hadronic collisions:



Approx. production fractions integrated over p_T in pp-collisions at TeV-scale collision energies

Charmonium in heavy-ion collisions: 'melting' as initial idea

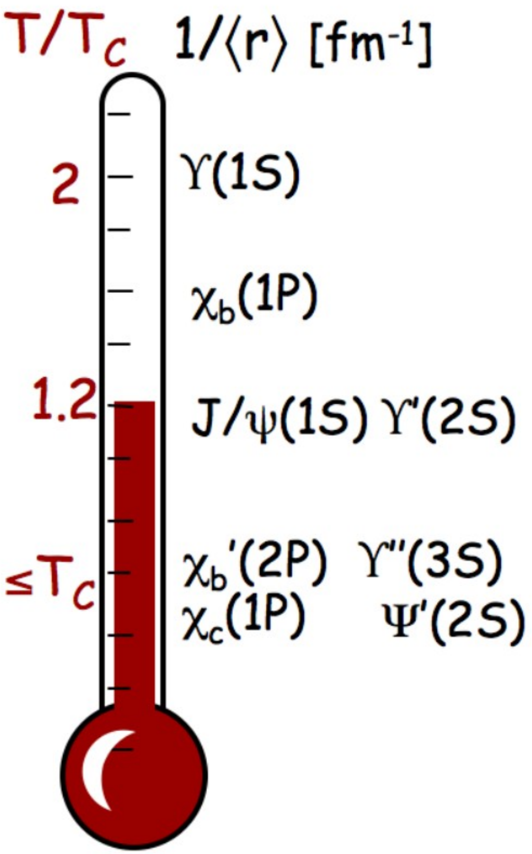
- **Suppression of J/ψ production** via color screening as a probe of deconfinement in heavy-ion collisions since 1986

  T. Matsui and H. Satz, **Phys.Lett.B 178 (1986)**
  link: DOI: 10.1016/0370-2693(86)91404-8

- **Sequential suppression** of quarkonia as a function of temperature:
  → quarkonia as thermometer

  F.Karsch, H. Satz, **Z.Phys. C51 (1991)**
  link: DOI: 10.1007/BF01475790

- Underlying picture:
  charmonia produced before QGP formation
  → subsequent 'melting' in fireball

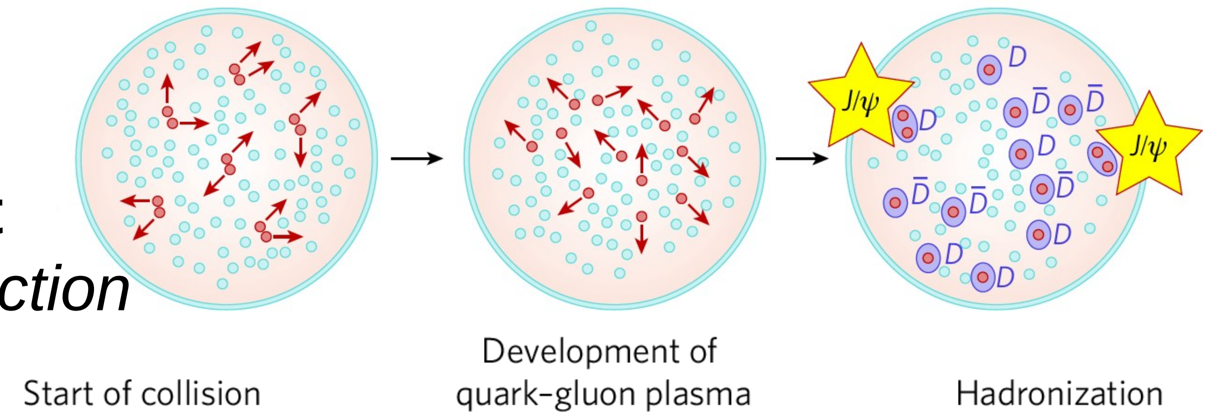


Taken from A. Mocsy:
link: arXiv:0811.0337
Eur.Phys.J.C61:705-710 (2009)

Charmonium in heavy-ion collisions at the LHC: new effects

- Large charm quark densities & charm conserved: new mechanism beyond 'melting'

  → **late stage production: sign of deconfinement** by *non-primordial production*



P. Braun-Munzinger and J.Stachel, Nature 448 (2007)

- 2 scenarios:

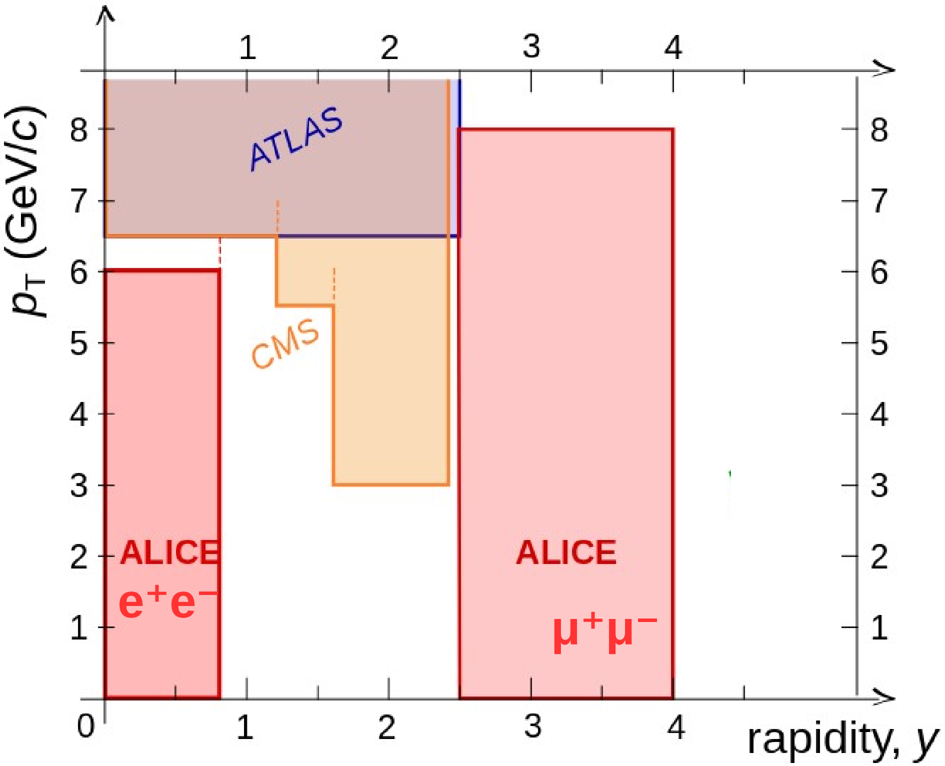
1) **The Statistical Hadronization Model**

charmonium production exclusively at phase boundary
P. Braun-Munzinger and J. Stachel, Phys.Lett.B, 490 (2000) link: arXiv:0007059

2) **Kinetic Models**

J/ψ production and destruction during lifetime of deconfined phase from initially uncorrelated and from same hard-scattering $c\bar{c}$ pairs
R. L. Thews, M. Schroeder, J. Rafelski, **Phys.Rev.C, 63 (2001)**, link:arXiv:0007323

J/ψ measurements at the LHC



Acceptance of p_T-differential inclusive J/Ψ measurements in Pb-Pb collisions (picture by A. Maire)

ALICE high p_T reach statistics llimited, for $\mu^+\mu^-$ limit from from pp reference, not from Pb-Pb
→ reach will be extended in RUN 2

CMS/ATLAS low p_T reach instrumental
Rapidity limits all instrumental

- Only ALICE down to p_T = 0 GeV/c in Pb-Pb collisions:

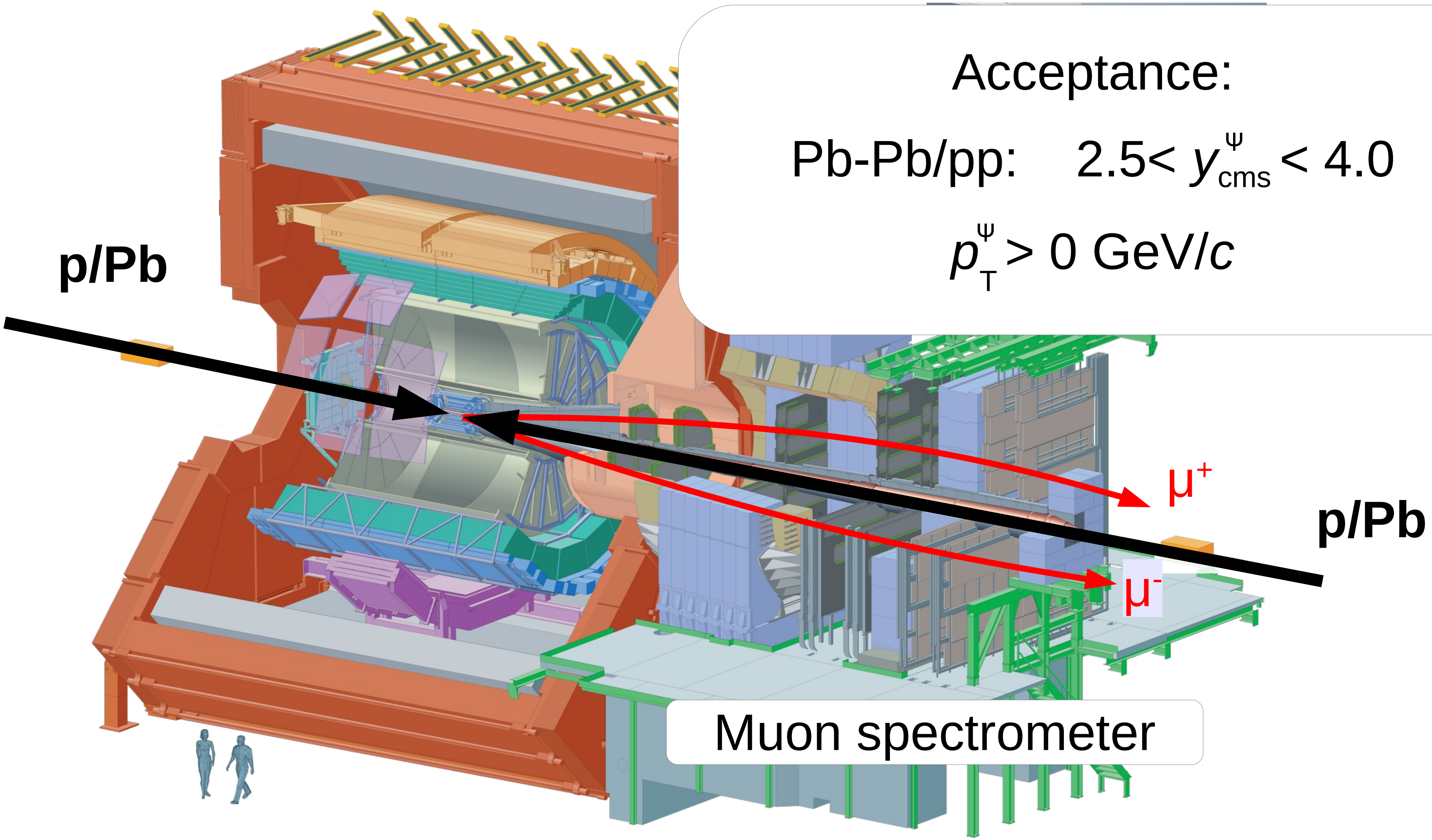
→ low-p_T region most crucial for non-primordial production and charm thermalization aspects

Charmonium with ALICE at the LHC

Acceptance:

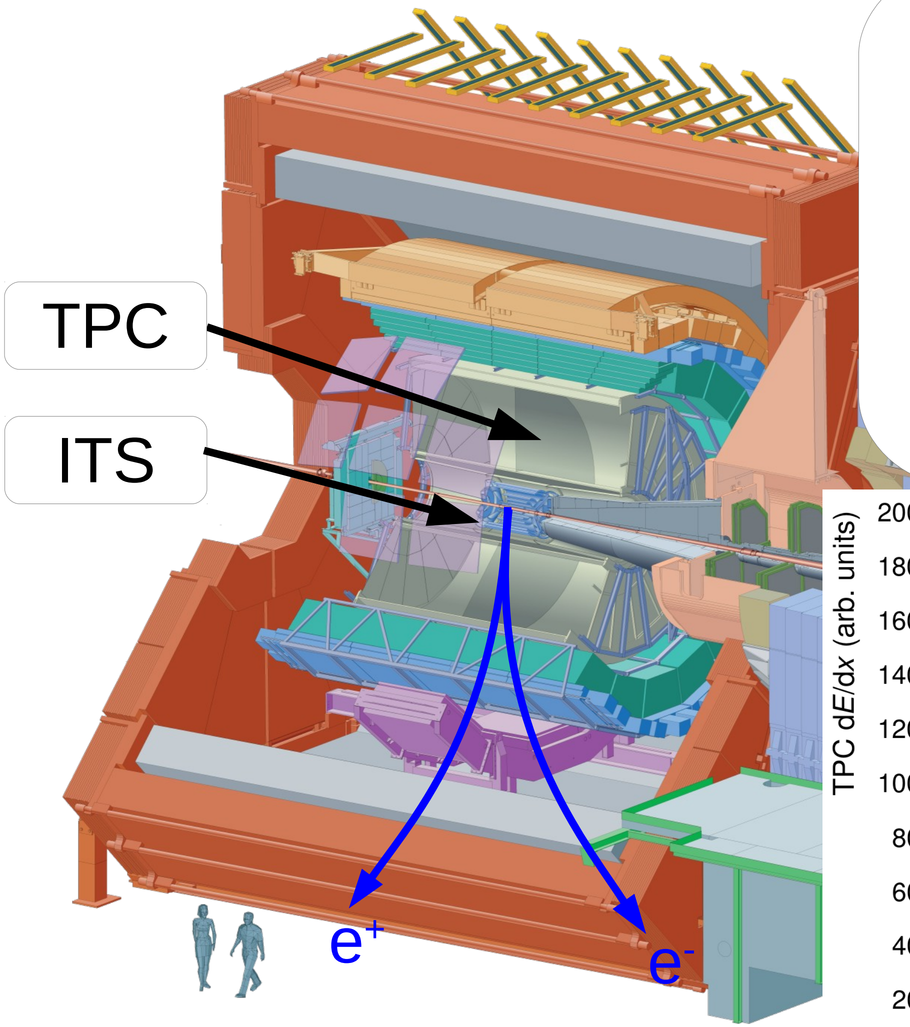
Pb-Pb/pp: $2.5 < y^{\psi}_{cms} < 4.0$

$p^{\psi}_{T} > 0$ GeV/c



Inclusive J/ψ and ψ(2S) down to $p_T = 0$ GeV/c at forward rapidity

Charmonium with ALICE at the LHC



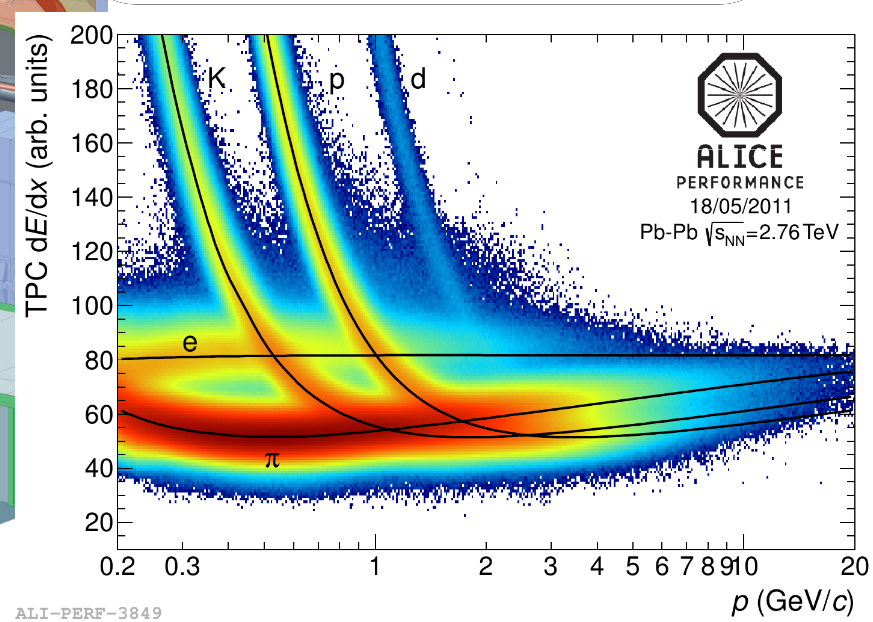
Acceptance in Pb-Pb:

$|\, y^{\Psi}_{cms} \,| < 0.8$

Acceptance in pp:

$|\, y^{\Psi}_{cms} \,| < 0.9$

$p^{\Psi}_{T} > 0$ GeV/c



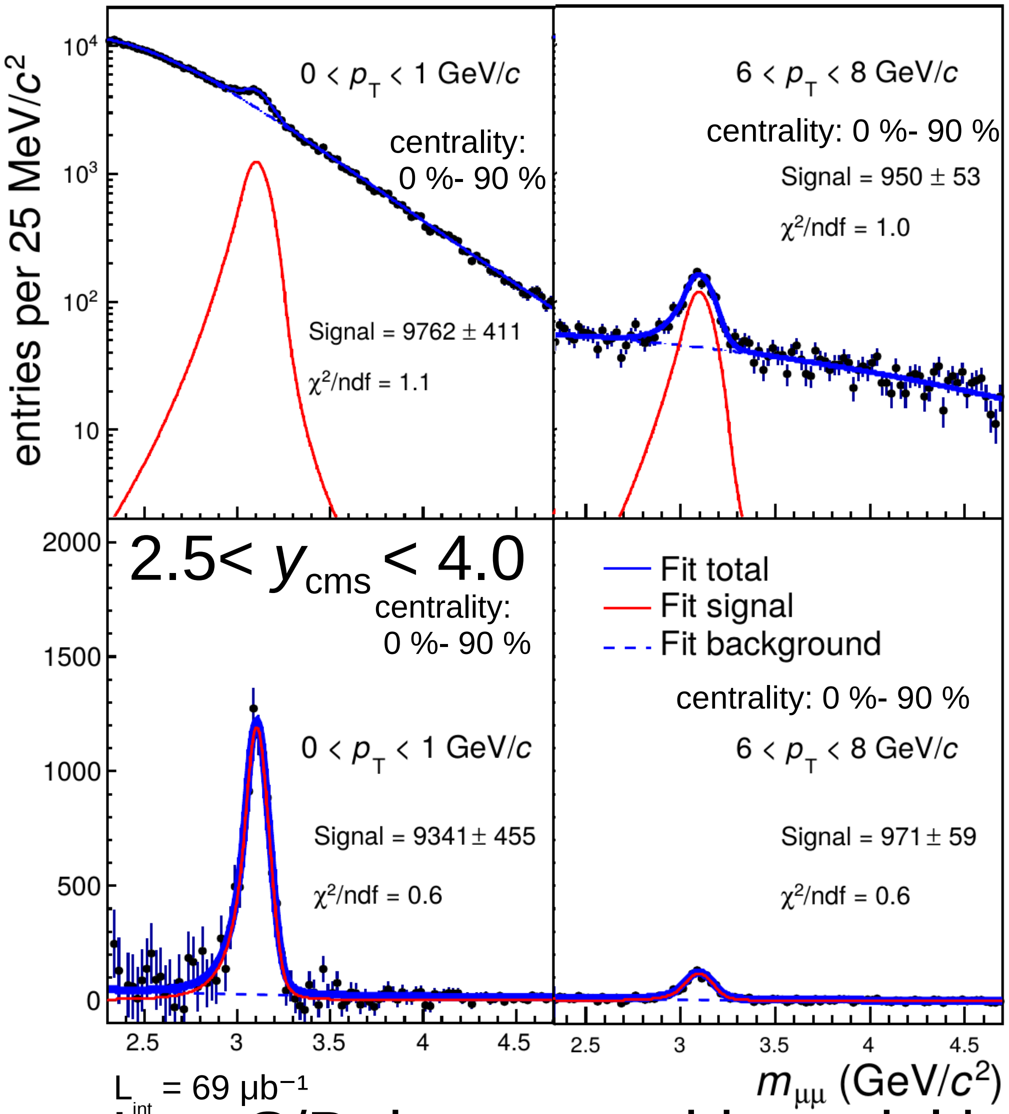
Inclusive J/ψ down to p_T = 0 GeV/c at midrapidity

Separation of Prompt & non-prompt J/ψ down to low p_T

J/ψ analyses in Pb-Pb collisions

link: arXiv:1311.0214

Phys.Lett. B734 (2014) 314-327

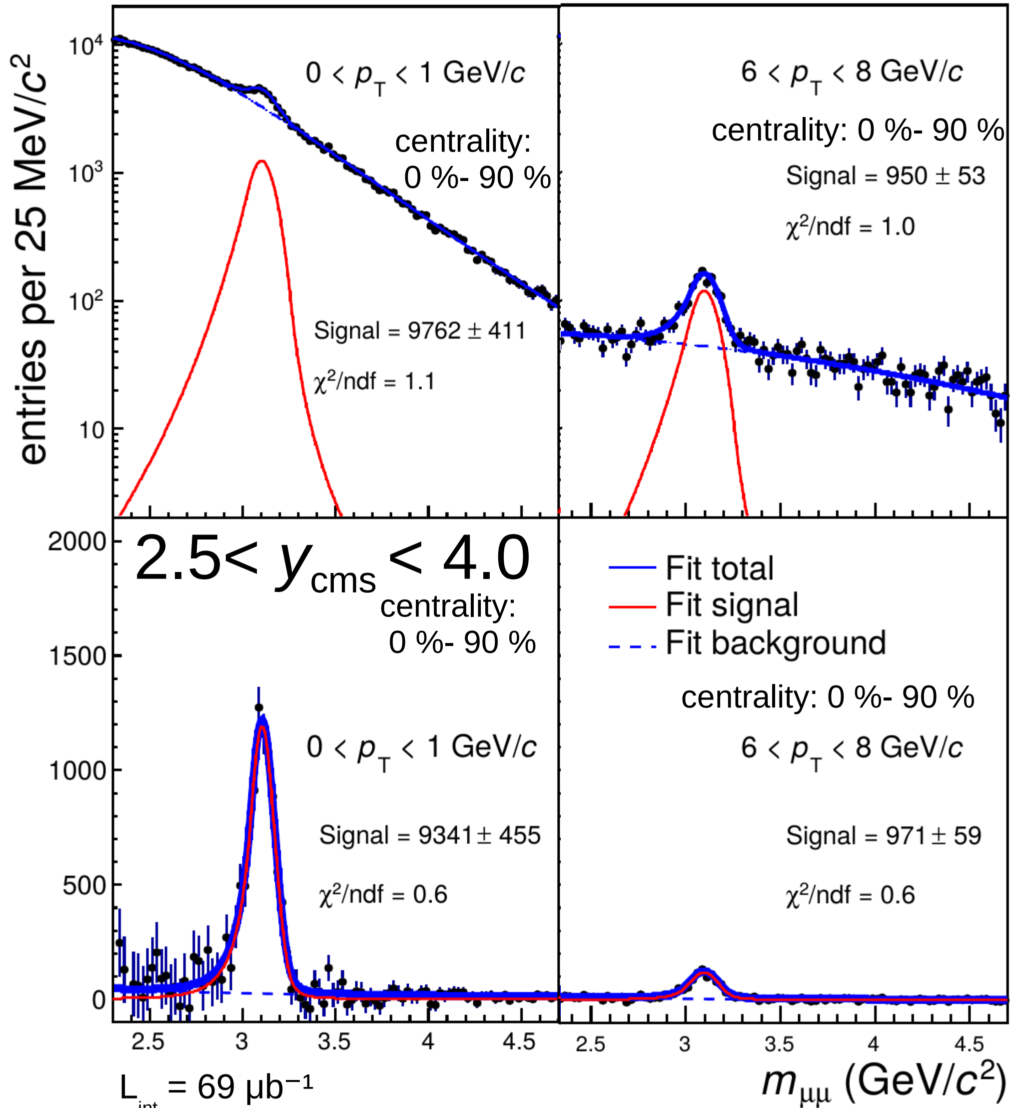


- Low S/B due to combinatorial background

  → relying on data-driven mixed-event technique, for $\mu^+\mu^-$ also direct fit

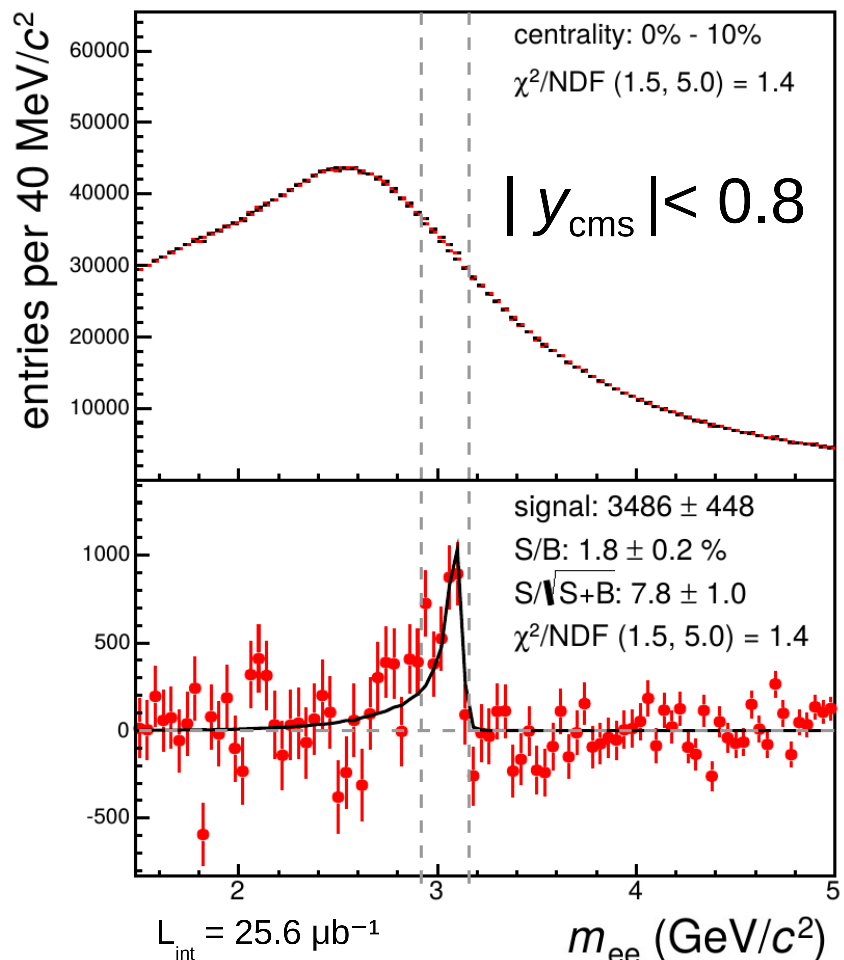
  limitations: $\mu^+\mu^-$: tracking eff. unc. & pp reference; e^+e^-: statistics & pp reference

J/ψ analyses in Pb-Pb collisions



link: arXiv:1311.0214

Phys.Lett. B734 (2014) 314-327



- Low S/B due to combinatorial background
  → relying on data-driven mixed-event technique, for $\mu^+\mu^-$ also direct fit

  limitations: $\mu^+\mu^-$: tracking eff. unc. & pp reference; e^+e^-: statistics & pp reference

Nuclear modification factor observables

$$R_{AA} = \frac{N_{J/\psi \text{ in } AA}}{\langle T_{AA} \rangle \cdot \sigma_{J/\psi \text{ in } pp}}$$

Pb-Pb collisions

$$R_{pA} = \frac{N_{J/\psi \text{ in } pA}}{\langle T_{pA} \rangle \cdot \sigma_{J/\psi \text{ in } pp}}$$

p-Pb collisions

$$\langle T_{AA} \rangle = \langle N_{coll\ AA} \rangle / \sigma_{NN}$$

$$\langle T_{pA} \rangle = \langle N_{coll\ pA} \rangle / \sigma_{NN}$$

$N_{J/\psi \text{ in } AA(pA)}$: measured yield in A-A/p-A

- In absence of nuclear effects:

  $R_{AA} = 1$ and $R_{pA} = 1$
  for high-Q^2 processes

Nuclear modification factor observables

$$R_{AA} = \frac{N_{J/\psi \text{ in AA}}}{\langle T_{AA} \rangle \cdot \sigma_{J/\psi \text{ in pp}}}$$

Pb-Pb collisions

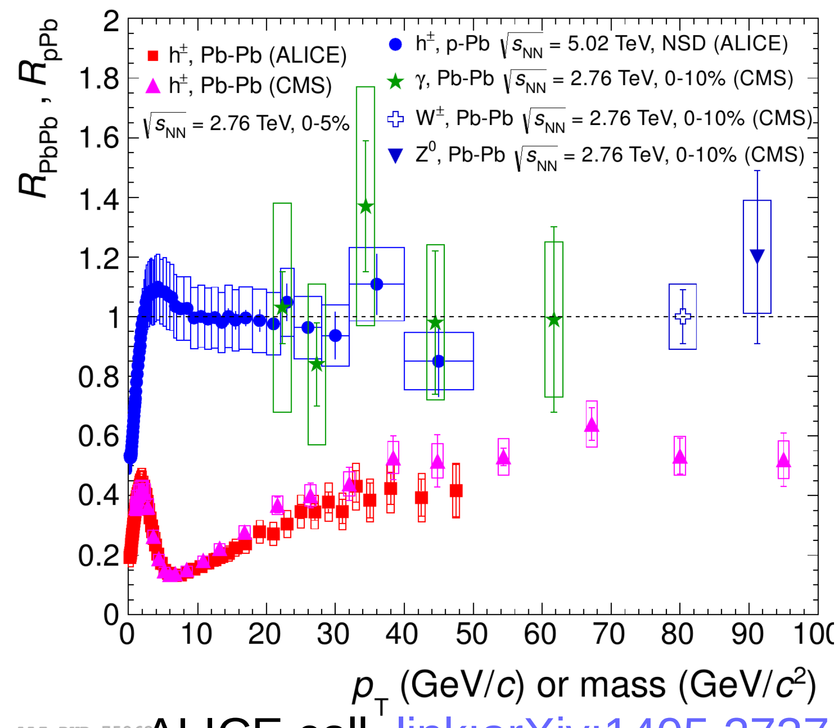
$$R_{pA} = \frac{N_{J/\psi \text{ in pA}}}{\langle T_{pA} \rangle \cdot \sigma_{J/\psi \text{ in pp}}}$$

p-Pb collisions

$$\langle T_{AA} \rangle = \langle N_{\text{coll AA}} \rangle / \sigma_{NN}$$

$$\langle T_{pA} \rangle = \langle N_{\text{coll pA}} \rangle / \sigma_{NN}$$

$N_{J/\psi \text{ in AA(pA)}}$: measured yield in A-A/p-A



ALICE coll. link:arXiv:1405.2737

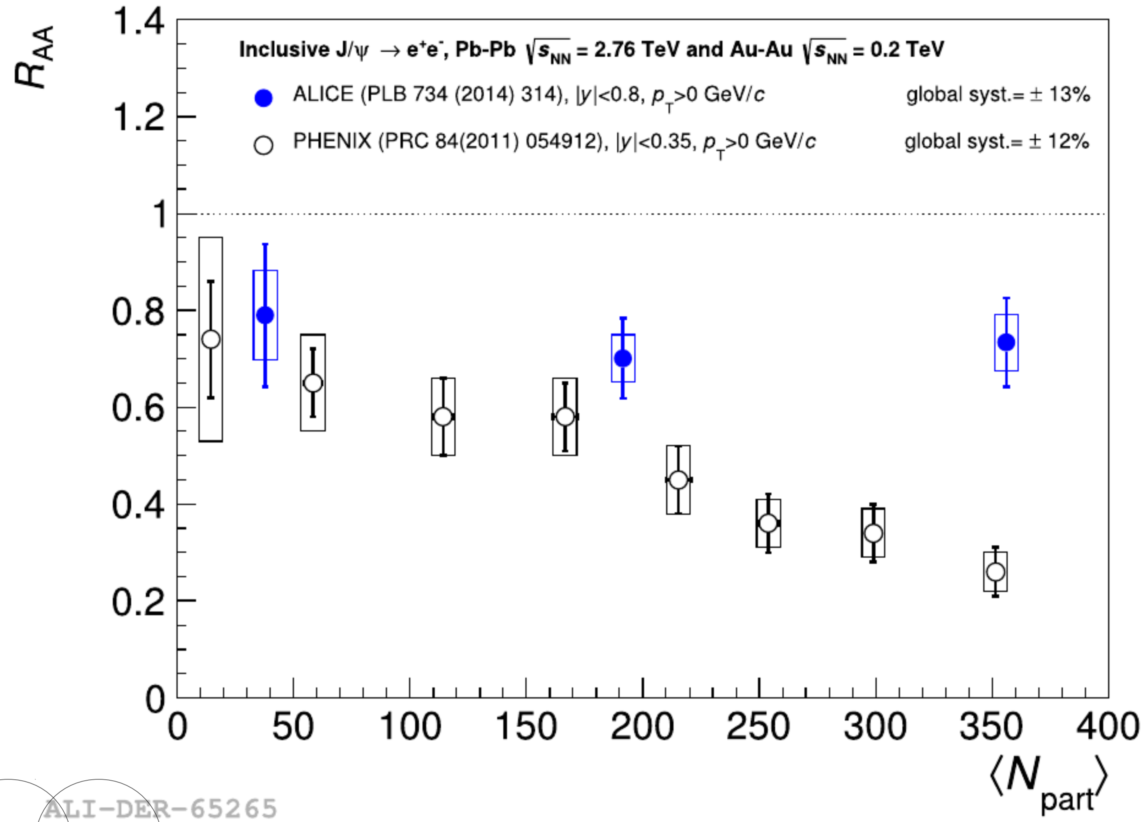
Eur. Phys. J. C 74 (2014) 3054

- In absence of nuclear effects:

  $R_{AA} = 1$ and $R_{pA} = 1$

  for high-Q² processes

J/ψ results in Pb-Pb: centrality dependence



link: arXiv:1311.0214

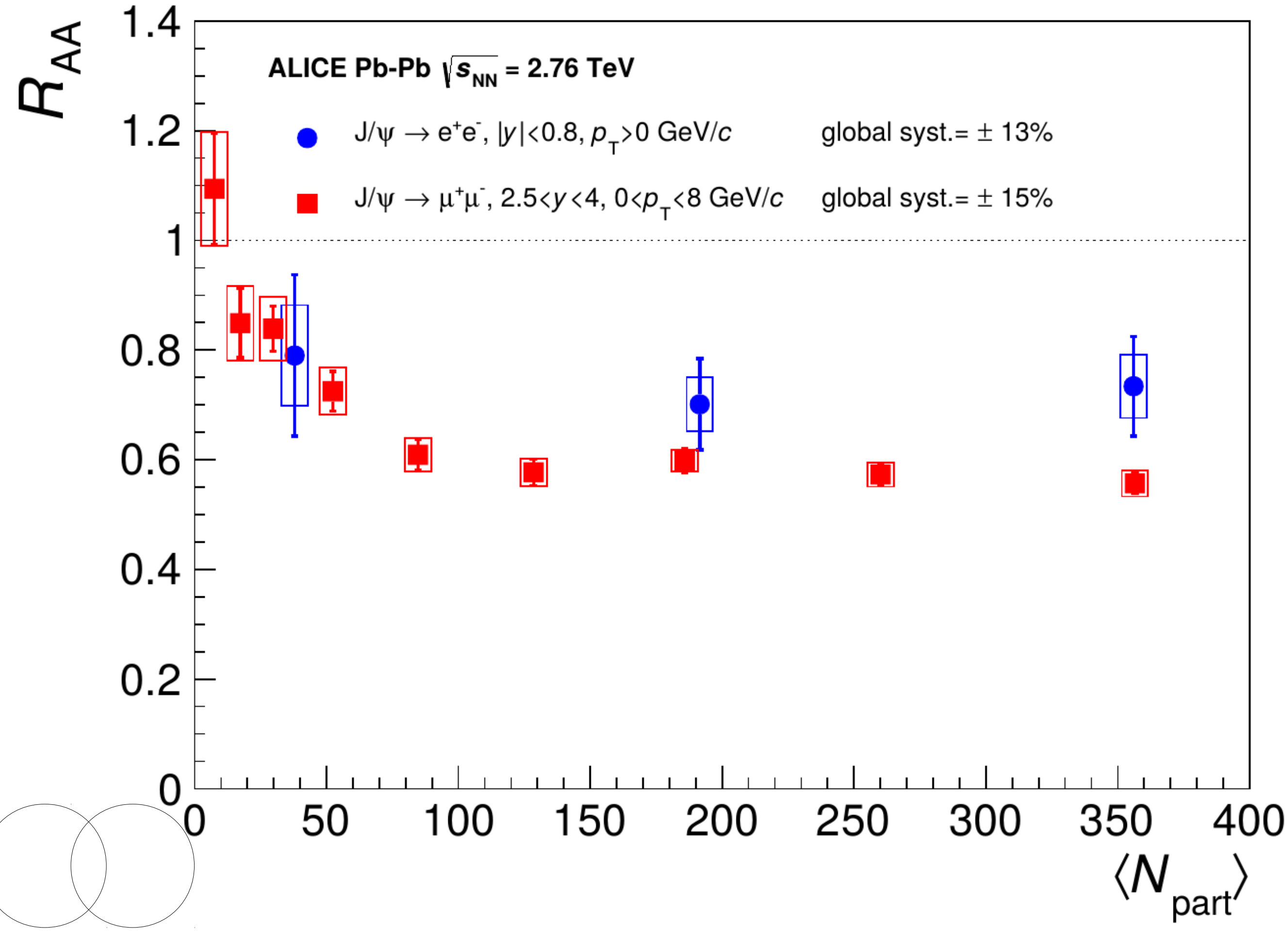
Phys.Lett. B734 (2014) 314-327
& indicated PHENIX reference

$\sqrt{s}_{NN}$ = 2.76 TeV: | y_{cms} |< 0.8

$\sqrt{s}_{NN}$ = 0.2 TeV: | y_{cms} |< 0.35

- Qualitatively different behavior at LHC compared to RHIC
- **Predicted by models including non-primordial J/ψ production**

J/ψ results in Pb-Pb: centrality dependence



link: arXiv:1311.0214

Phys.Lett. B734 (2014) 314-327

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

| y_{cms} |< 0.8

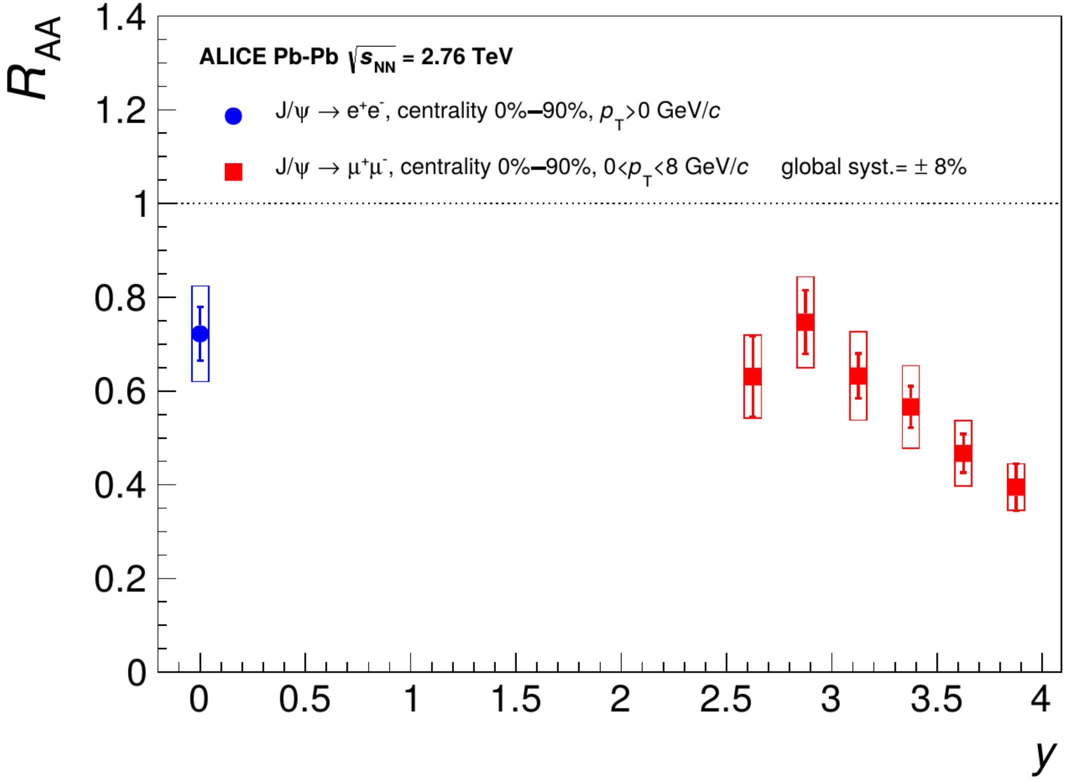
2.5 < y_{cms} < 4.0

- No significant centrality dependence beyond <N_{part}>=70
- Hint for less suppression at midrapidity than at forward rapidity expected in statistical model/transport models

J/ψ results in Pb-Pb: rapidity dependence

link: arXiv:1311.0214

Phys.Lett. B734 (2014) 314-327



$\sqrt{s}_{NN}$ = 2.76 TeV

$|y_{cms}| < 0.8$

$2.5 < y_{cms} < 4.0$

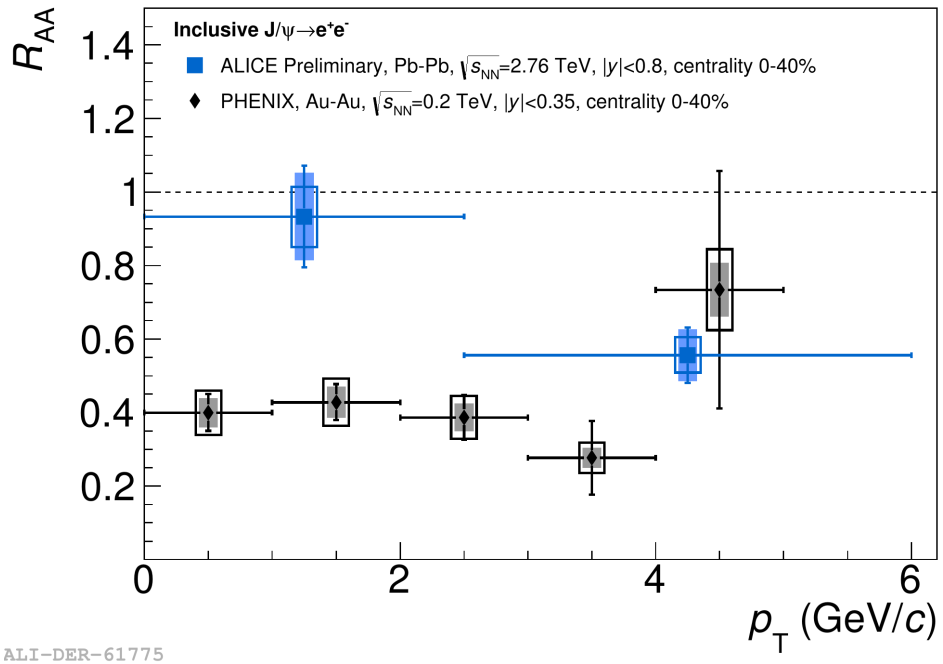
- Clear rapidity dependence visible

  - in contrast to expectation in melting scenario
  - in accordance with expectation from non-primordial production

J/ψ results in Pb-Pb: p_T dependence

link: DOI: 10.1016/j.nuclphysa.2014.09.082

prelim. e^+e^-: QM' 14



$\sqrt{s}_{NN}$ = 2.76 TeV: | y_{cms} |< 0.8

$\sqrt{s}_{NN}$ = 0.2 TeV: | y_{cms} |< 0.35

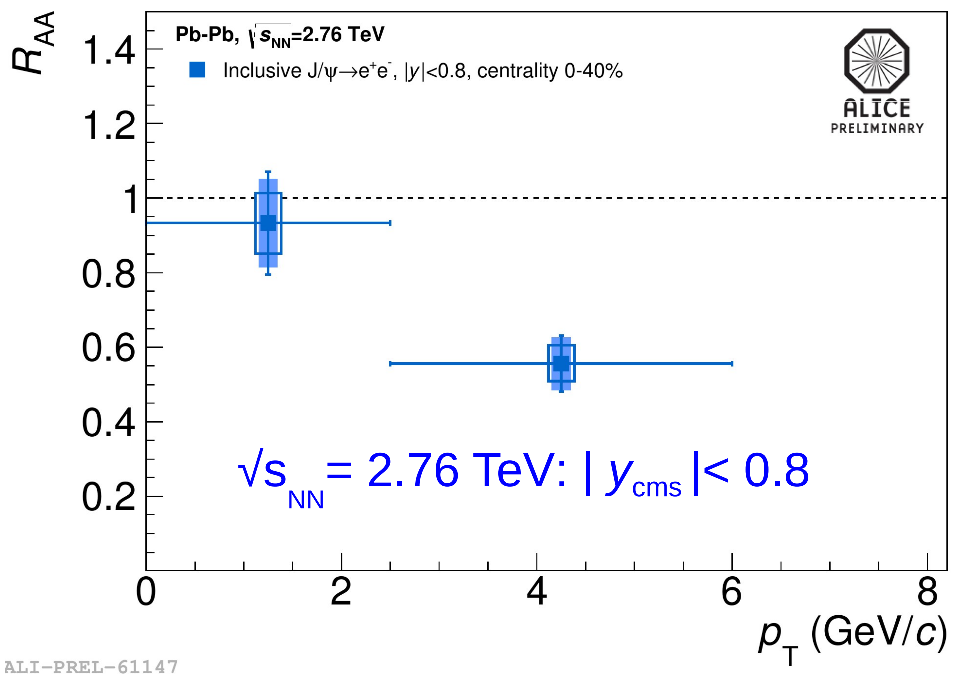
- p_T dependence of suppression in constrast to RHIC observation
- Observed pattern in accordance with increased non-primordial production

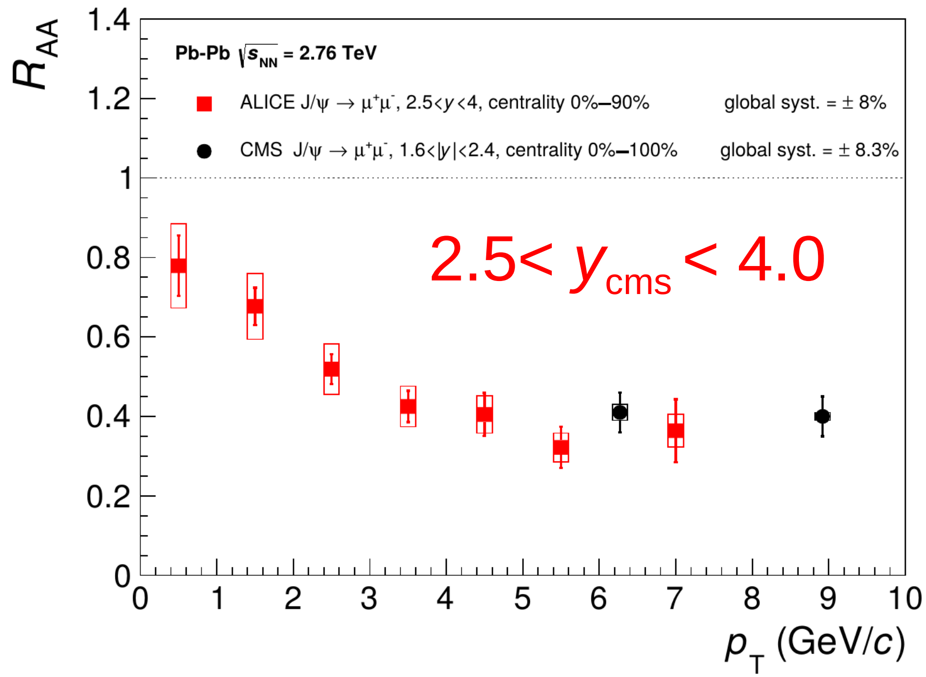
→ **support for late stage 'combination' pictures at low p_T**

J/ψ results in Pb-Pb: p_T dependence

link: DOI: 10.1016/j.nuclphysa.2014.09.082
prelim. e^+e^-: QM' 14

link: arXiv:1311.0214
Phys.Lett. B734 (2014) 314-327



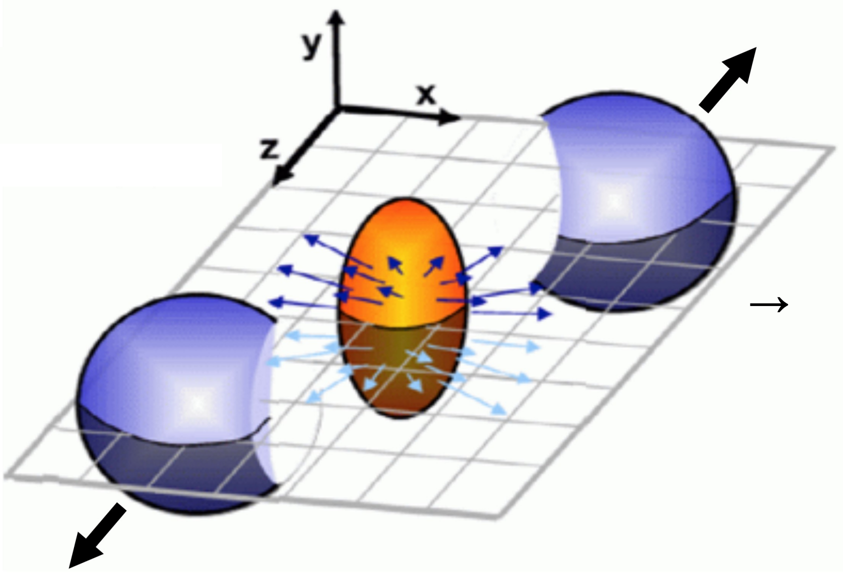


- Strong p_T dependence of suppression
- Good agreement with CMS at high p_T
- At high p_T potentially different physics at work (energy loss)

  → **support for late stage 'combination' pictures at low p_T**

- Simplified picture of elliptic flow:
  sufficient for the following discussion

  initial coordinate space asymmetry → **momentum space asymmetry in final state**



- Finite elliptic flow for charmonium:

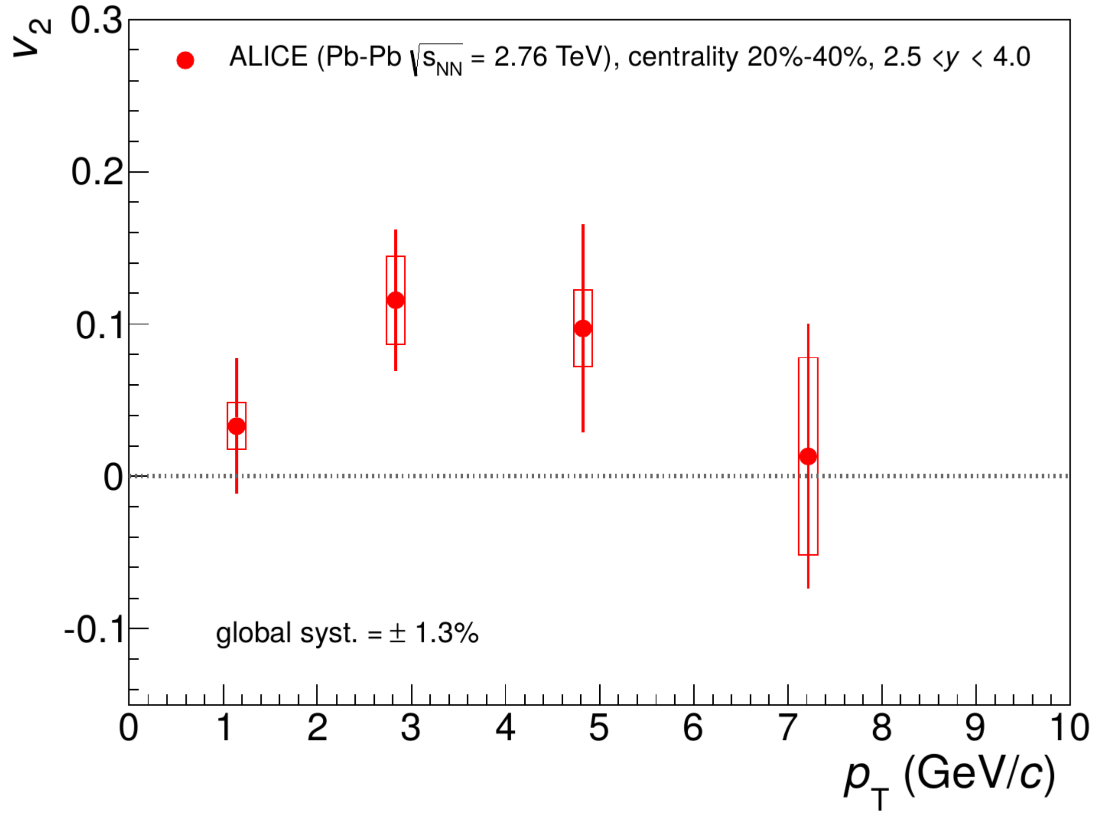
  pointing to (partial) **thermalization**

→ **challenging analysis: first result at the LHC by ALICE**

applying innovative analysis technique

link: arXiv:1303.5880
Phys.Rev.Lett. 111 (2013) 162301

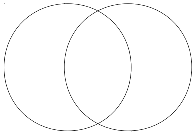
J/ψ results in Pb-Pb: elliptic flow



link: arXiv:1303.5880

Phys.Rev.Lett. 111 (2013) 162301

2.5< y_{cms} < 4.0

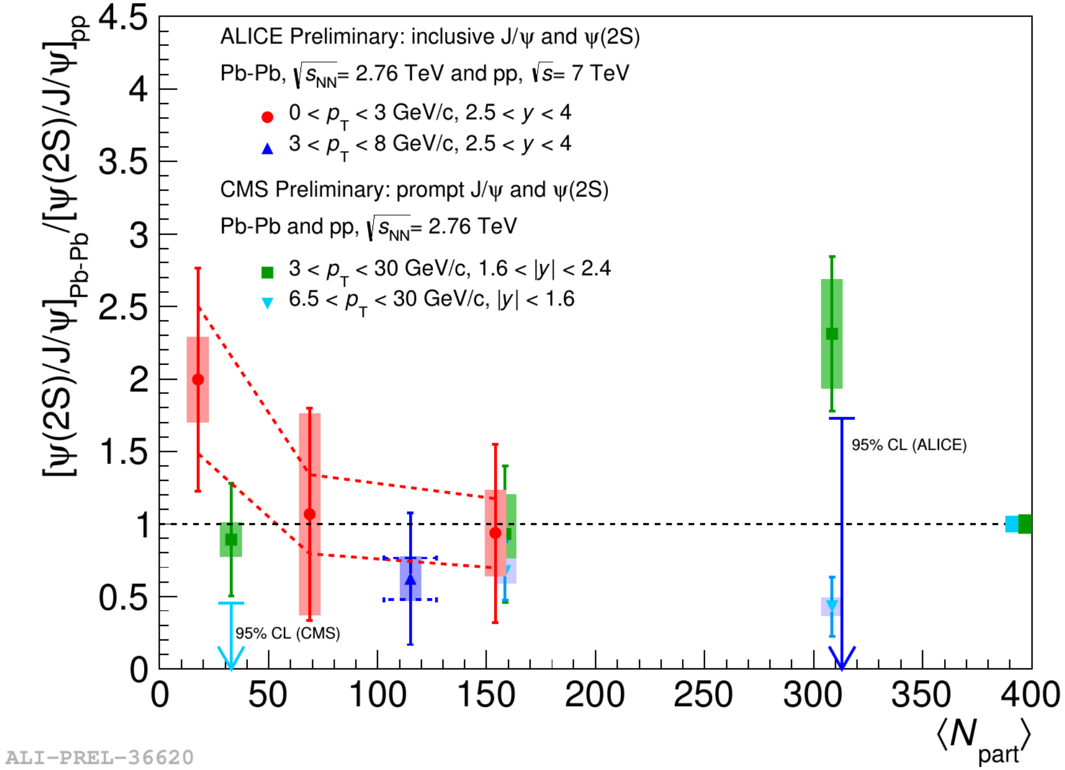


- 2.7σ significance in 20-40% centrality for 2 < p_T < 6 GeV/c

→ indication for non-zero flow: support for thermalization
→ more statistics for conclusions needed

subsequent observation by CMS of large v_2(link: HIN-12-001) at higher p_T in slightly different rapidity windows (preliminary result)

ψ(2S) results in Pb-Pb



taken from QM '14 review by A. Andronic: link: arXiv:1409.5778

Final ALICE result to be published very soon

CMS result (very close to prelim.) submitted to PRL link: arXiv:1410.1804 see also back-up

- Important measurement to disentangle between transport models & statistical model
- Reconciliation between ALICE and CMS difficult, but acceptance not overlapping
- Lowest p_T in most central collisions not yet accessible
  → additional statistics in Pb-Pb required

Displaced J/ψ at mid-rapidity in Pb-Pb

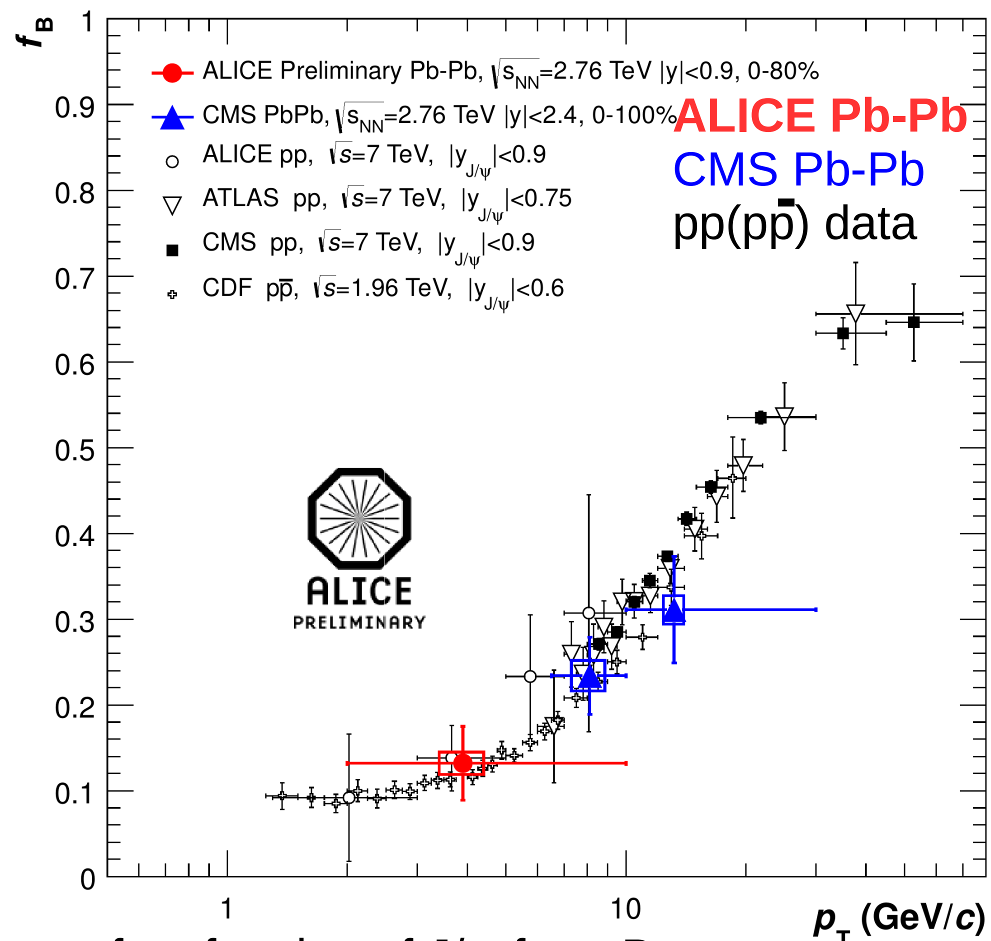
Preliminary SQM '13:
link: arXiv:1311.7269

- Access to prompt J/ψ and to Beauty hadrons

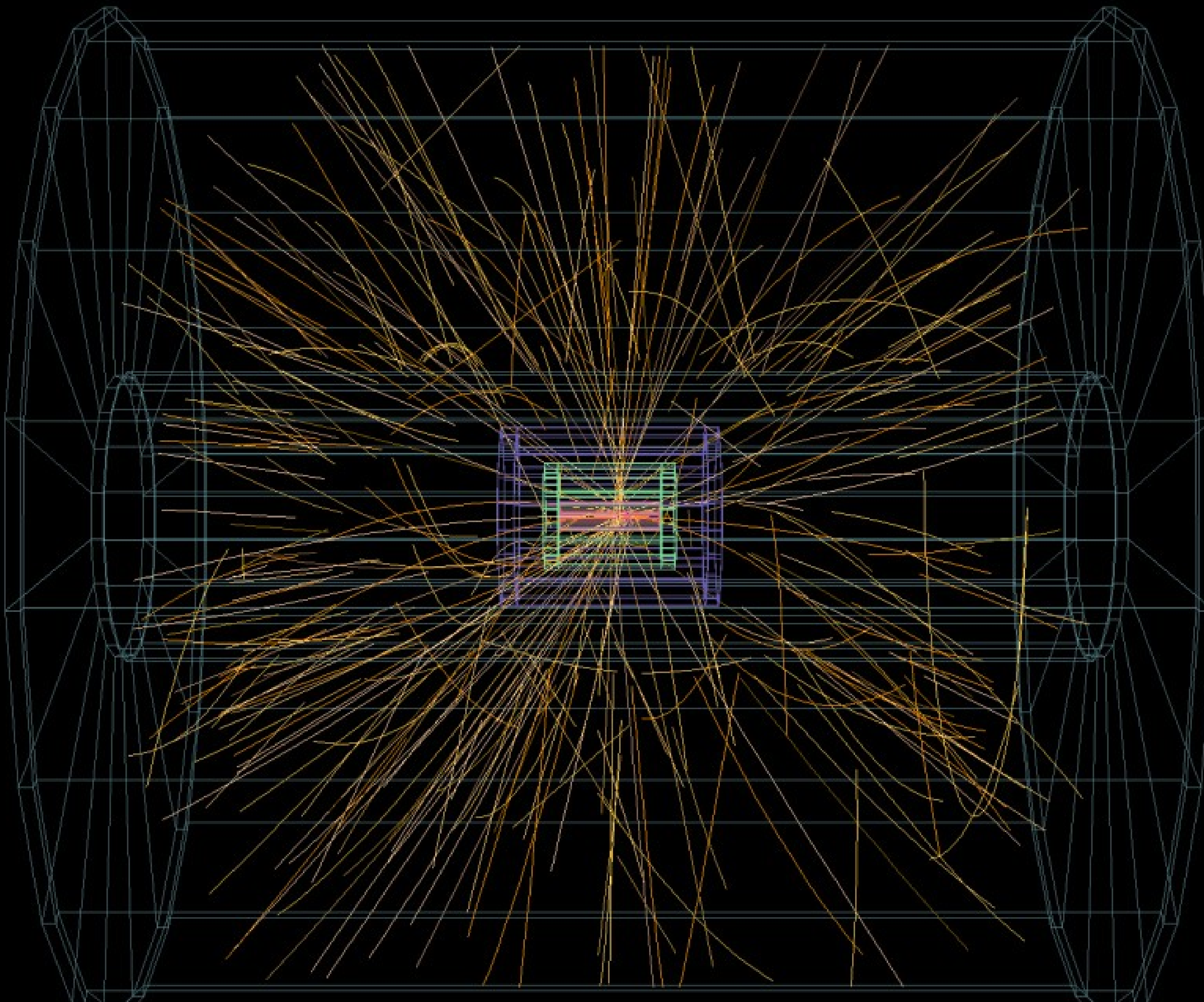
- Unique low p_T capability complementary to CMS

→ interpretation of inclusive J/ψ not altered by Beauty feed-down

→ first constraints on beauty hadrons at low p_T at LHC



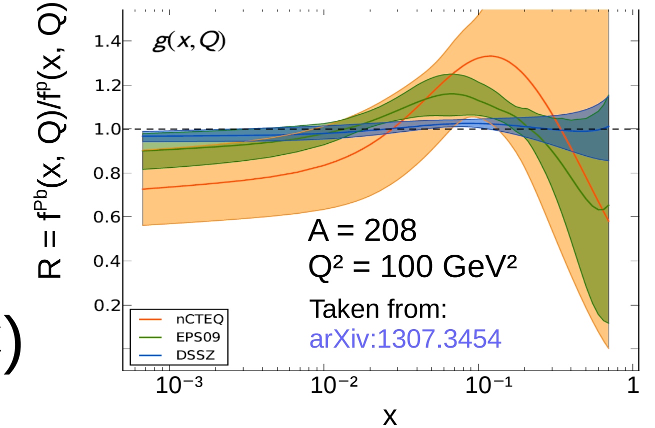
f_B = fraction of J/ψ from Beauty



Predicted J/ψ modifications in p-Pb at the LHC

- Leading twist gluon shadowing

  Color Evaporation Model (CEM) R. Vogt, , link: arXiv:1003.3497 Phys.Rev.C 81 (2010)
  Color Singlet Model (CSM) E. Ferreiro et al., link: arXiv:1305.4569 Phys.Rev.C 88 (2013)

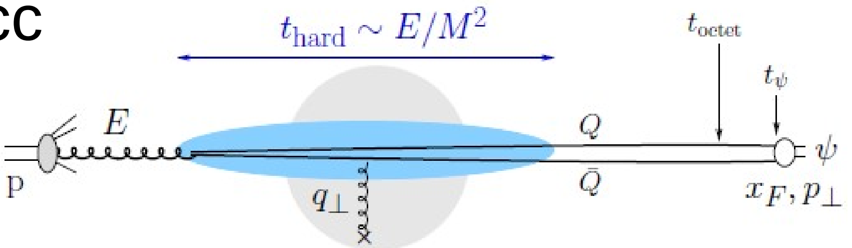


- Saturation via Colour Glass Condensate (CGC)

  H. Fujii et al., arXiv:1304.2221 Nucl.Phys. A915 (2013)

- Coherent energy loss of pre-resonant $c\bar{c}$

  Arleo et al., link: arXiv:1212.0434 JHEP 1303 (2013)



JHEP 1303 (2013)

- Charm shadowing & dipole break-up

  Kopeliovich et al., link: arXiv:1012.5648 Nucl. Phys.A 864 (2011)

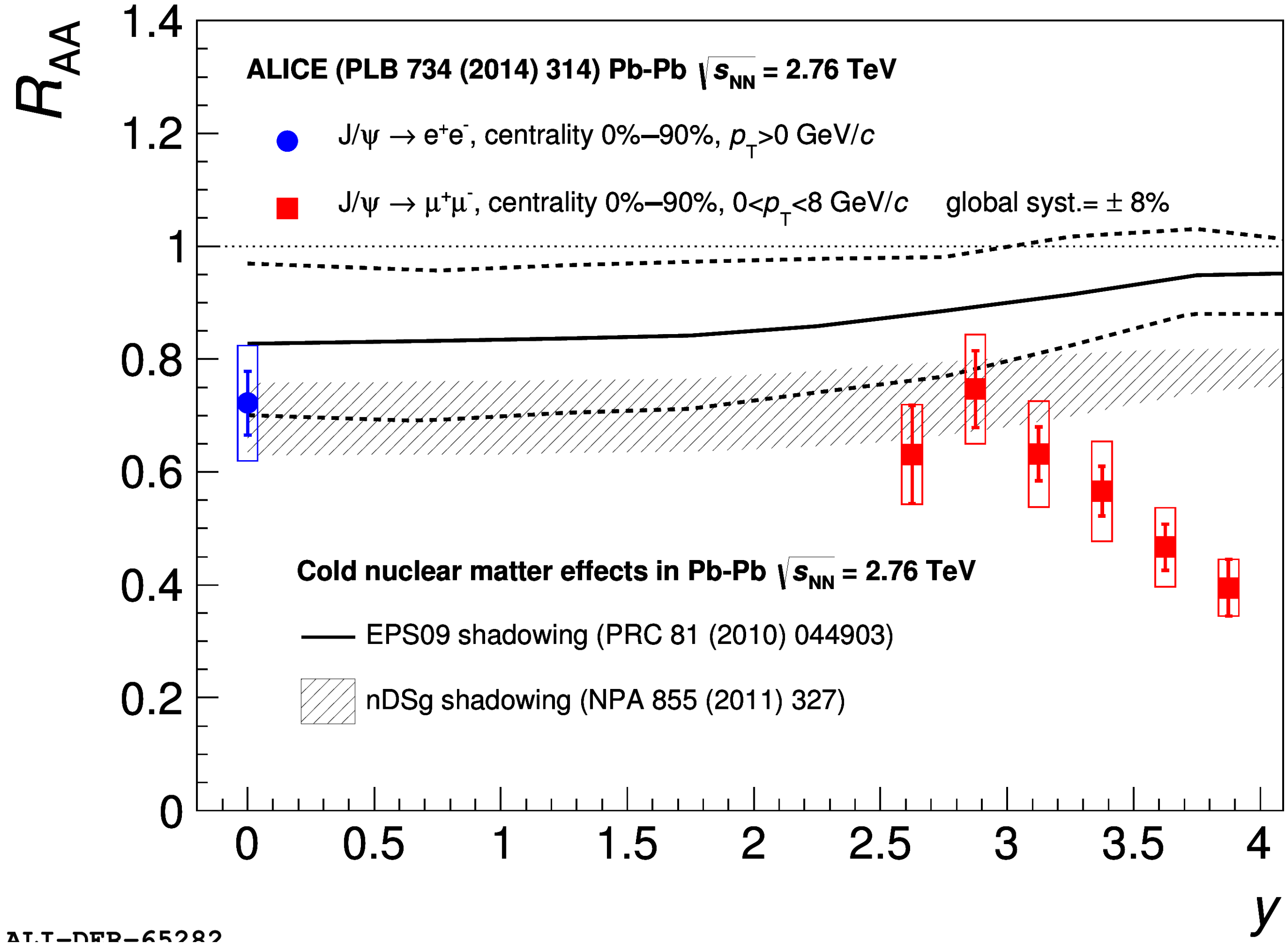
- Hot medium effects

  Y. Liu et al., link: arXiv:1309.5113, Phys. Lett. B 728 (2014))

- negligible/small nuclear absorption expected

Caveats:
- no consensus about pp production mechanism
- besides direct J/ψ: feed-down from B hadrons, ψ(2S) and χ_c

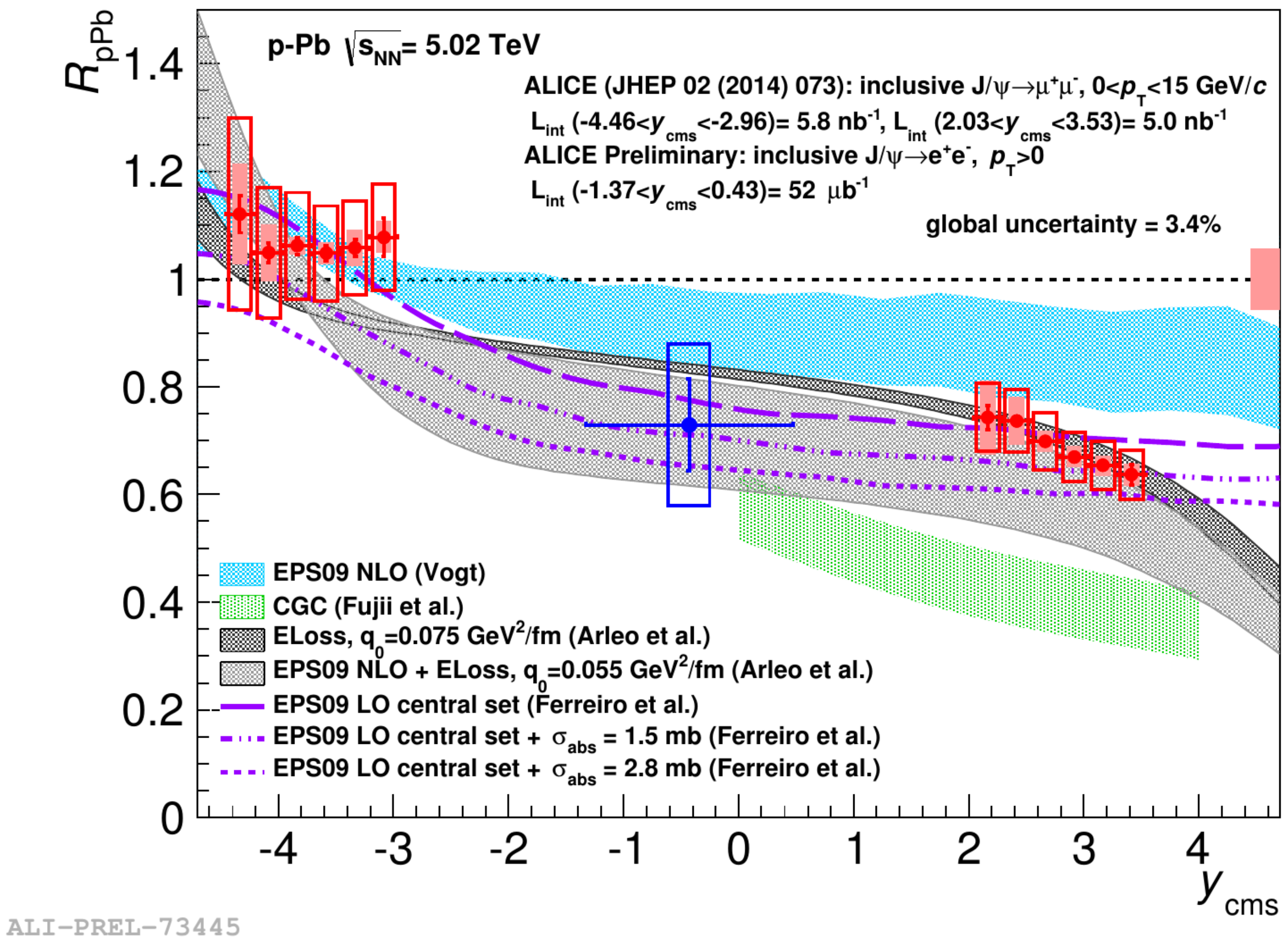
Impact of shadowing on nuclear modification factor in Pb-Pb



- Large influence on Pb-Pb result and its interpretation
- Large uncertainties in parametrizations and different results

→ measurement in p-Pb essential

p-Pb results: rapidity dependence



$\mu^+\mu^-$: link: arXiv:1308.6726

JHEP 1402 (2014) 073

Prelim. HP' 13 e^+e^-:
link: arXiv:1404.1615

to appear in Nucl. Phys. A (Hard-Probes '13)

Red muon channel results consistent with LHCb

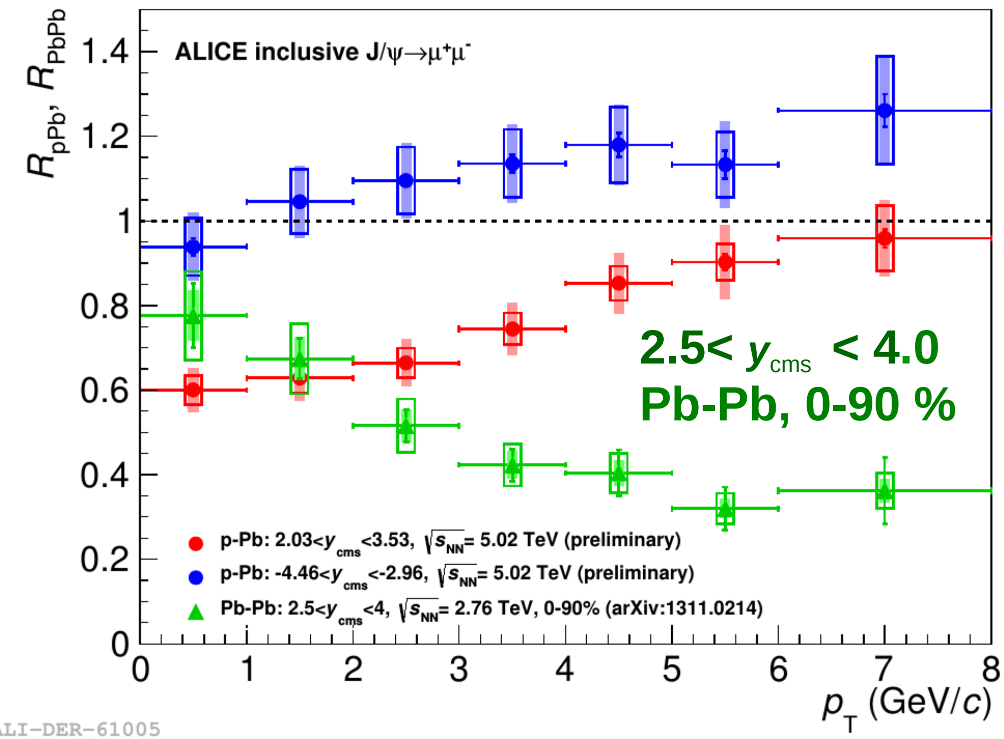
- Consistent with shadowing and/or coherent energy loss model
- Specific Color Glass Condensate model based on CEM discarded

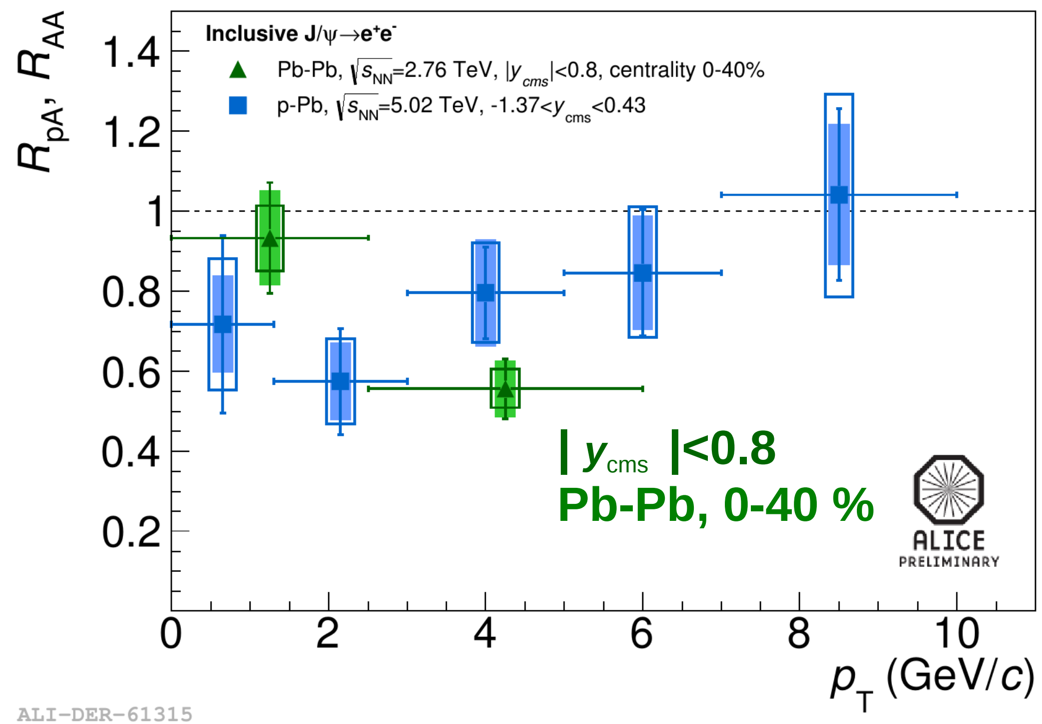
Prelim. HP' 13: link: arXiv:1404.1615
to appear in Nucl. Phys. A

$-4.46 < y_{cms} < -2.96$

$2.03 < y_{cms} < 3.53$

$-1.37 < y_{cms} < 0.43$

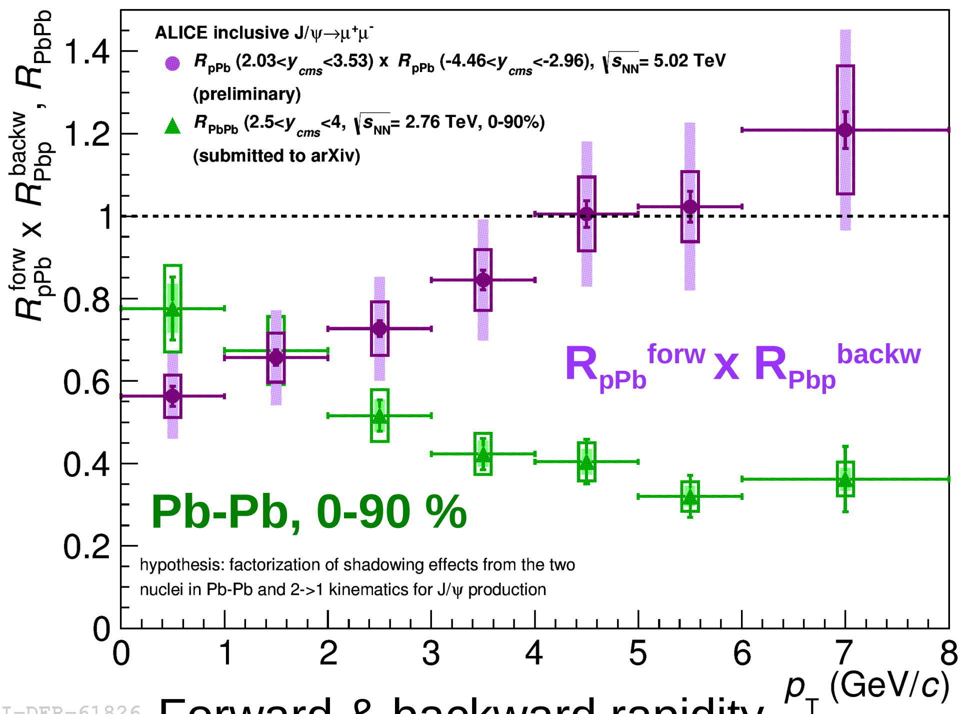




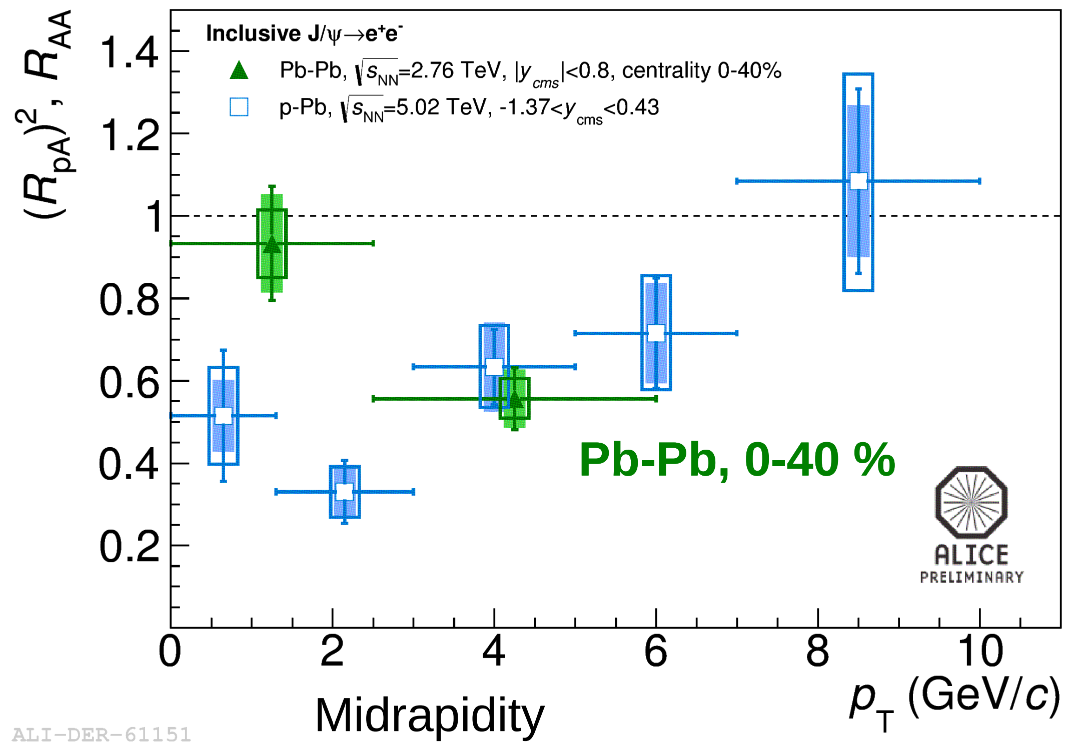
- Different p_T dependencies of nuclear modification factor in Pb-Pb and p-Pb/Pb-p

p-Pb results: p_T dependence compared to Pb-Pb

Prelim. HP' 13: link: arXiv:1404.1615



Forward & backward rapidity



Midrapidity

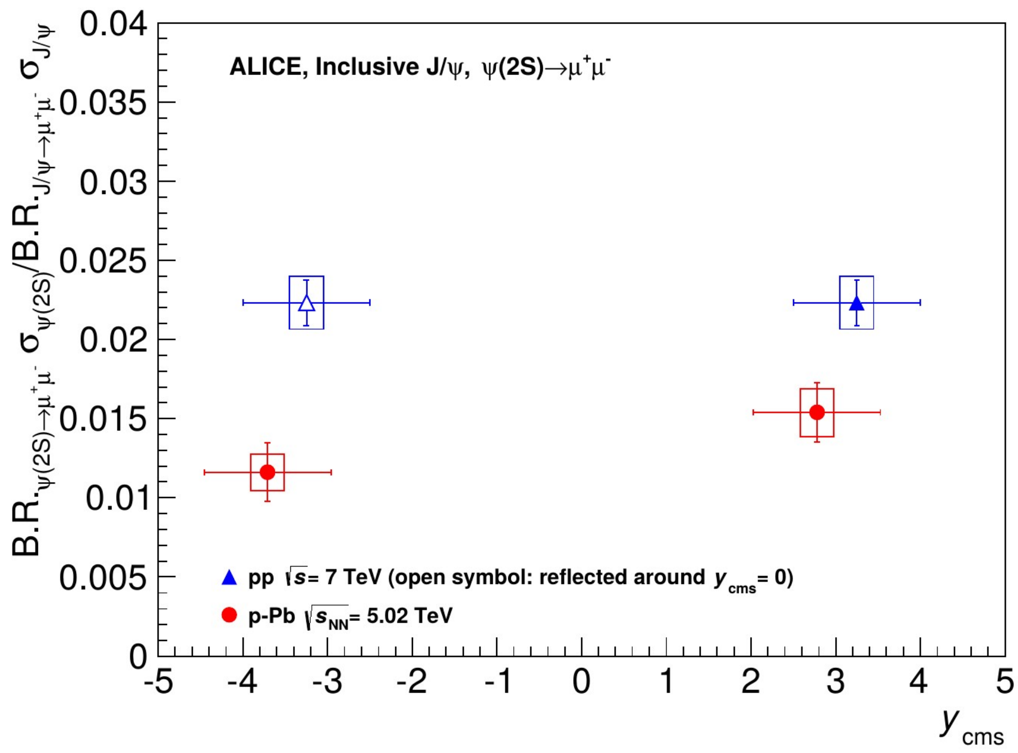
- **Assuming**: 2→1 kinematics (e.g. LO CEM) + factorization of nuclear effects (e.g. only nPDF as nucl. effects in pA)
  approx. matching of x ranges in p-Pb and Pb-Pb run

  → hint of enhancement at low p_T + suppression at high-p_T in Pb-Pb

- **Strengthening support for non-primordial production**

ψ(2S) results in p-Pb

link: arXiv:1405.3796
Submitted to JHEP



pp

p-Pb

- Expectation from shadowing/CGC/coherent energy loss: nuclear modification of ψ(2S) very similar to J/ψ

→ behavior not explained by standard nuclear modifications

Conclusion

Charmonia at the LHC: the observable for deconfinement

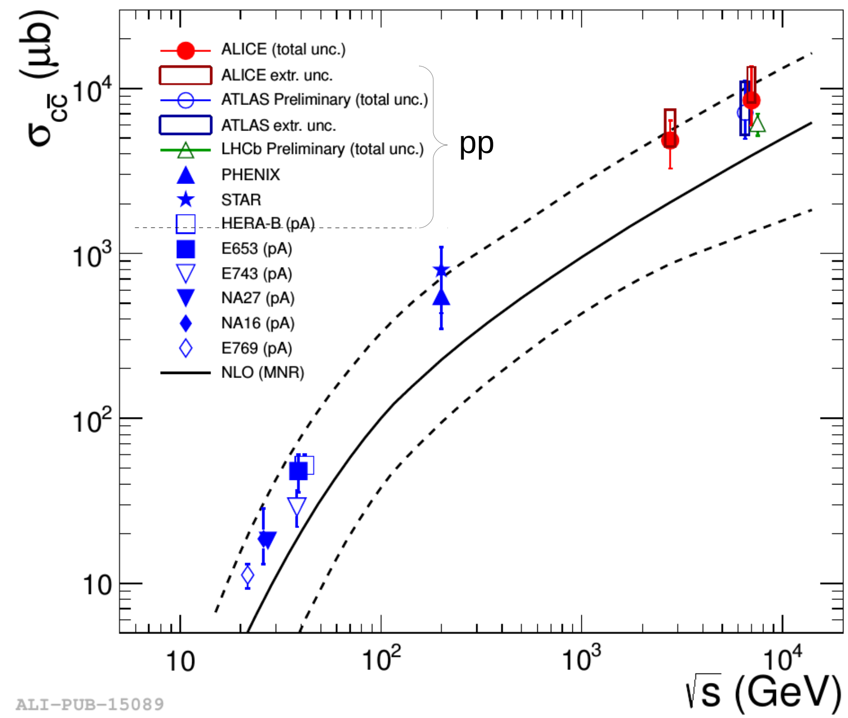
- ALICE in key position
  unique low p_T capability for J/ψ and ψ(2S) in Pb-Pb and in p-Pb collisions in two different rapidity ranges
- Predictions of transport and statistical hadronization model confirmed based on RHIC experience

  → **non-primordial J/ψ production at the LHC**

- Interpretation of J/ψ elliptic flow still premature
  more statistics required
- ψ(2S) results in Pb-Pb and p-Pb lacking coherent explanation
  more statistics (Pb-Pb) and theory effort (p-Pb) needed for conclusions

Outlook 2015+

- Additional final ALICE results on J/ψ and ψ(2S) in p-Pb and in Pb-Pb close to publication



Taken from: ALICE coll., **JHEP 1207 (2012) 191**
Link: arXiv:1205.4007

- **Looking forward eagerly to Run 2**:

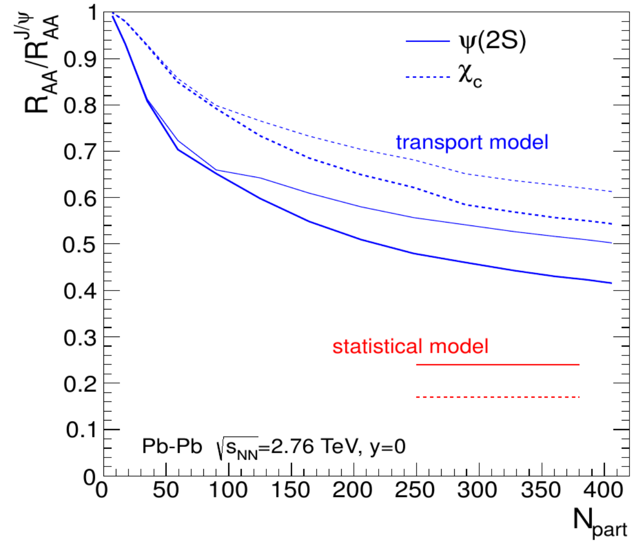
  - generic predicition for transport and statistical model:

    increase of $R_{AA}^{J/\psi}$ with larger $\sqrt{s_{NN}}$

  - larger event statistics

  - full acceptance Transition Radiation Detector: better electron identification in all systems and triggering in pp/p-Pb at mid-rapidity to acquire better references for Pb-Pb

Back-up: Outlook 2018+



taken from QM '14 review by A. Andronic: link: arXiv:1409.5778

- Run 3: high luminosity upgrade of ALICE
- New 7-layer Silicon Tracker (lower mat. Budget, higher gran.)
- New TPC read-out with GEMs without gating grid

→ **50 kHz Pb-Pb at continuous read-out**

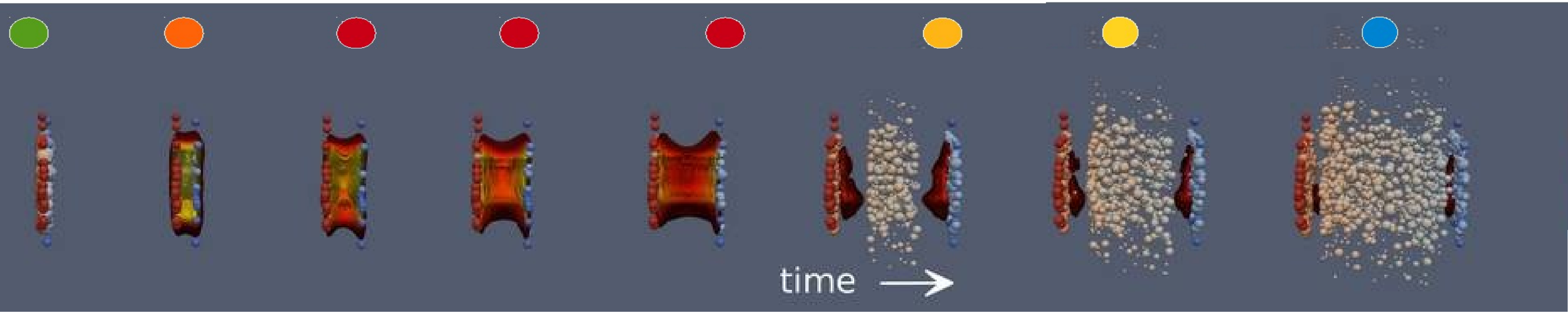
→ **collect 10 nb^{-1}, equiv. to 8 • 10^{10} events**

- Precision measurements of ψ(2S) at forward and mid-rapidity:

→ disentangle between transport and Statistical Hadronization Model

- Measurement of total open charm cross section in Pb-Pb collisions (Λ_c, D^0 down to p_T=0...):

→ fix most crucial loosly constrained parameter by experiment!



Initial conditions

Pre-equilibrium stage

Quark-Gluon Plasma phase

Chemical freeze-out
Hadronic rescattering
kinetic freeze-out

Free-streaming particles

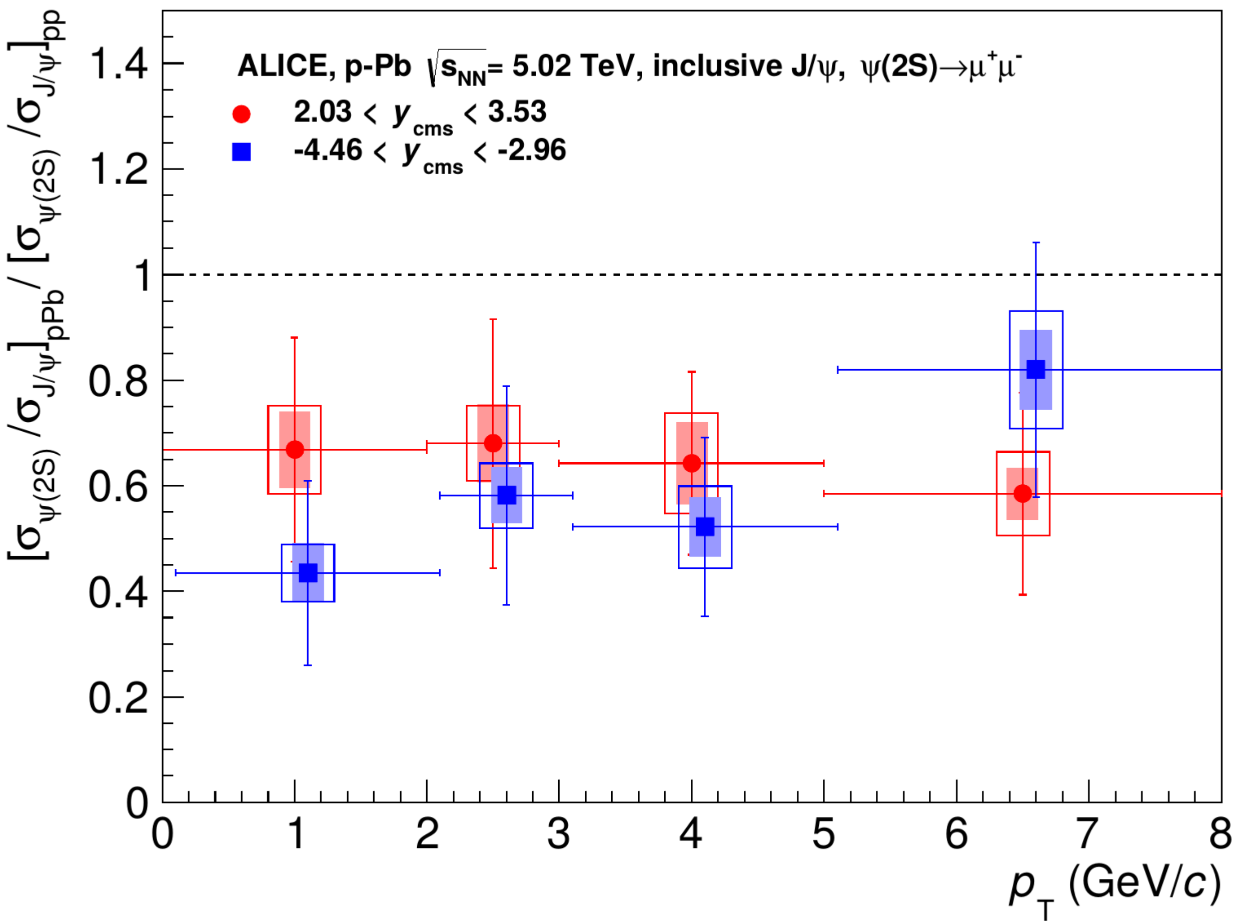
A standard picture of ultra-relativistic heavy-ion collisions

taken from H. Petersen, QM' 14 studen session link, Courtesy of Madai: link

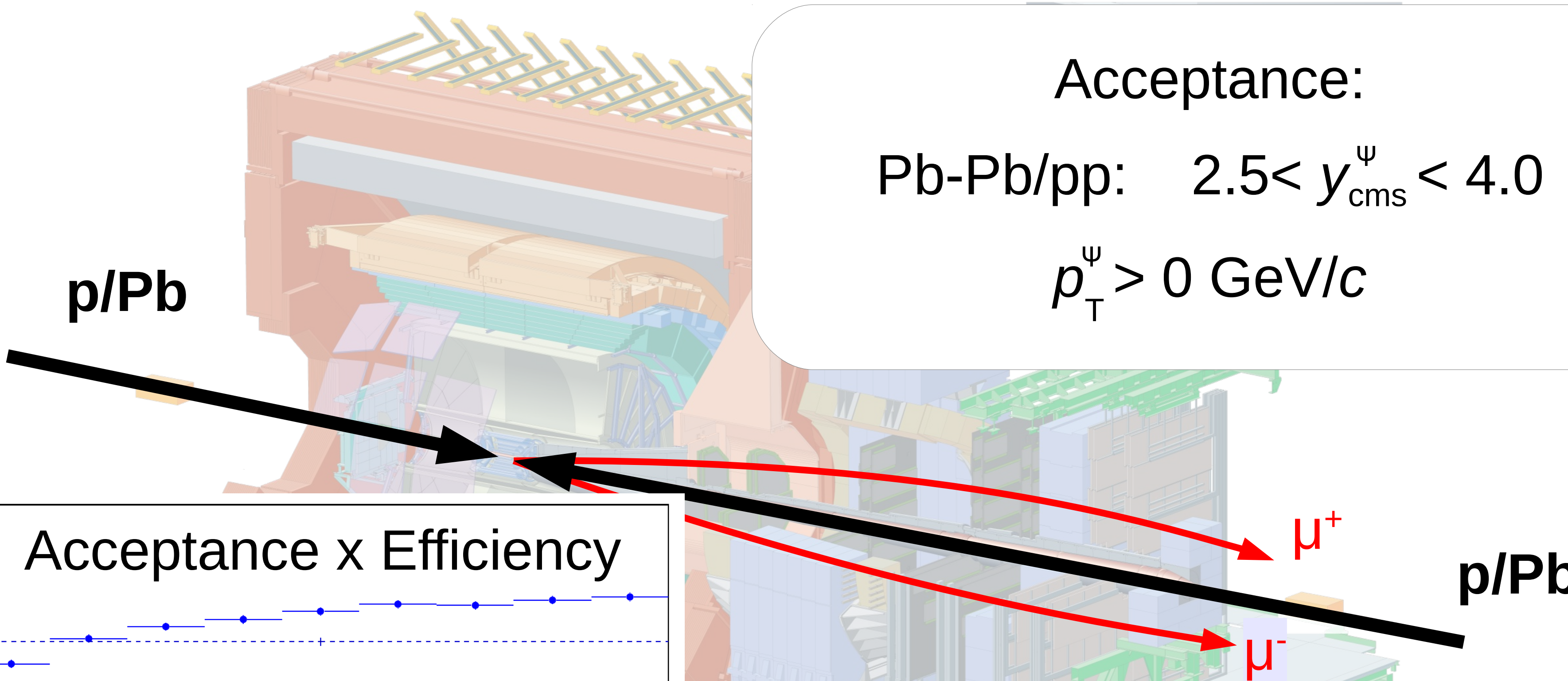
Back-up: ψ(2S) in p-Pb

link: arXiv:1405.3796

Submitted to JHEP



Within uncertainties no p_T dependence of double ratio observed

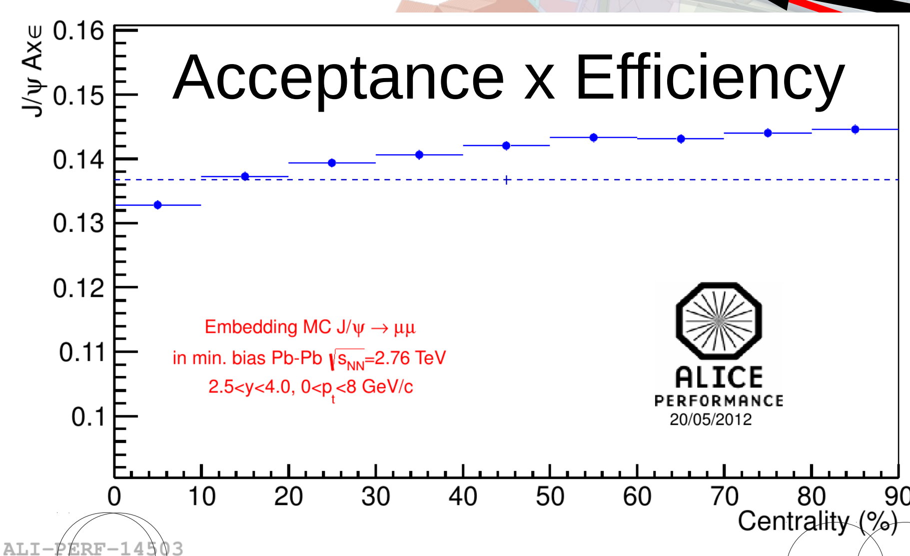


Acceptance:

Pb-Pb/pp: $2.5 < y^{\psi}_{cms} < 4.0$

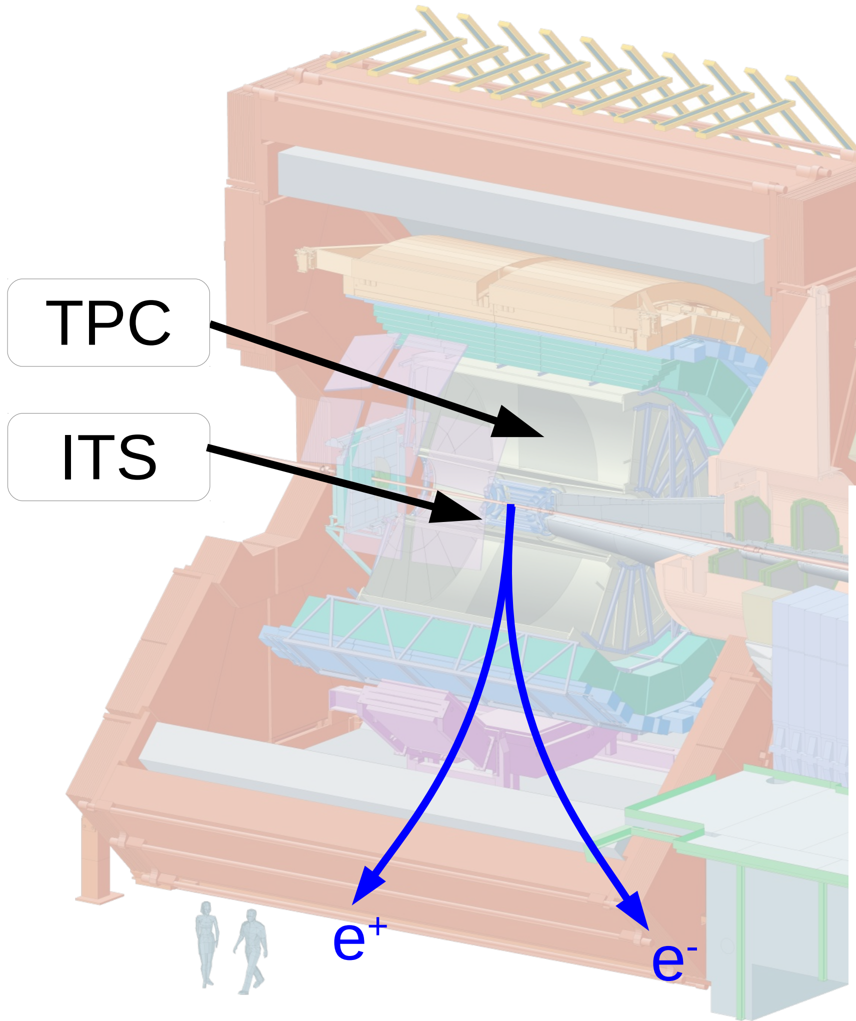
$p^{\psi}_{T} > 0$ GeV/c

Muon spectrometer



Inclusive J/ψ and ψ(2S) down to p_T= 0 GeV/c at forward rapidity

Back-up: Charmonium with ALICE at the LHC



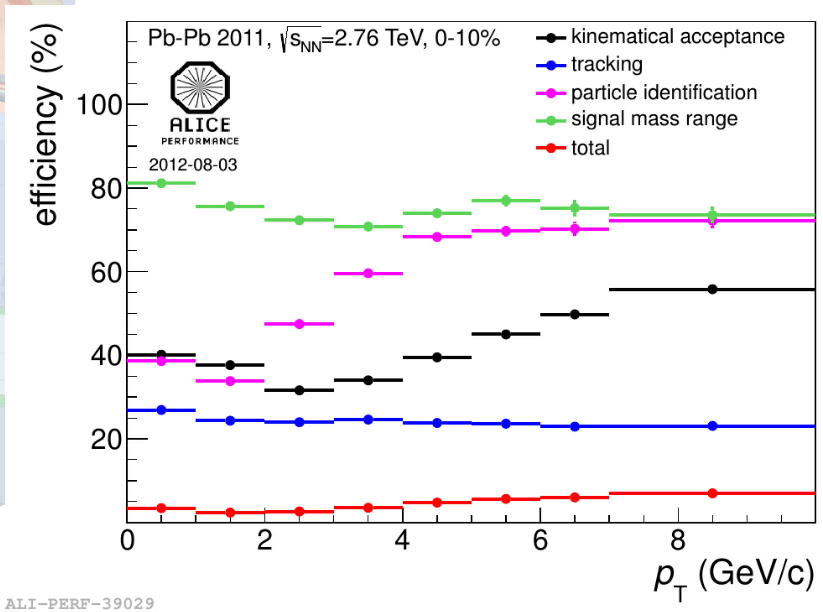
Acceptance in Pb-Pb:

$|y^{\psi}_{cms}| < 0.8$

Acceptance in pp:

$|y^{\psi}_{cms}| < 0.9$

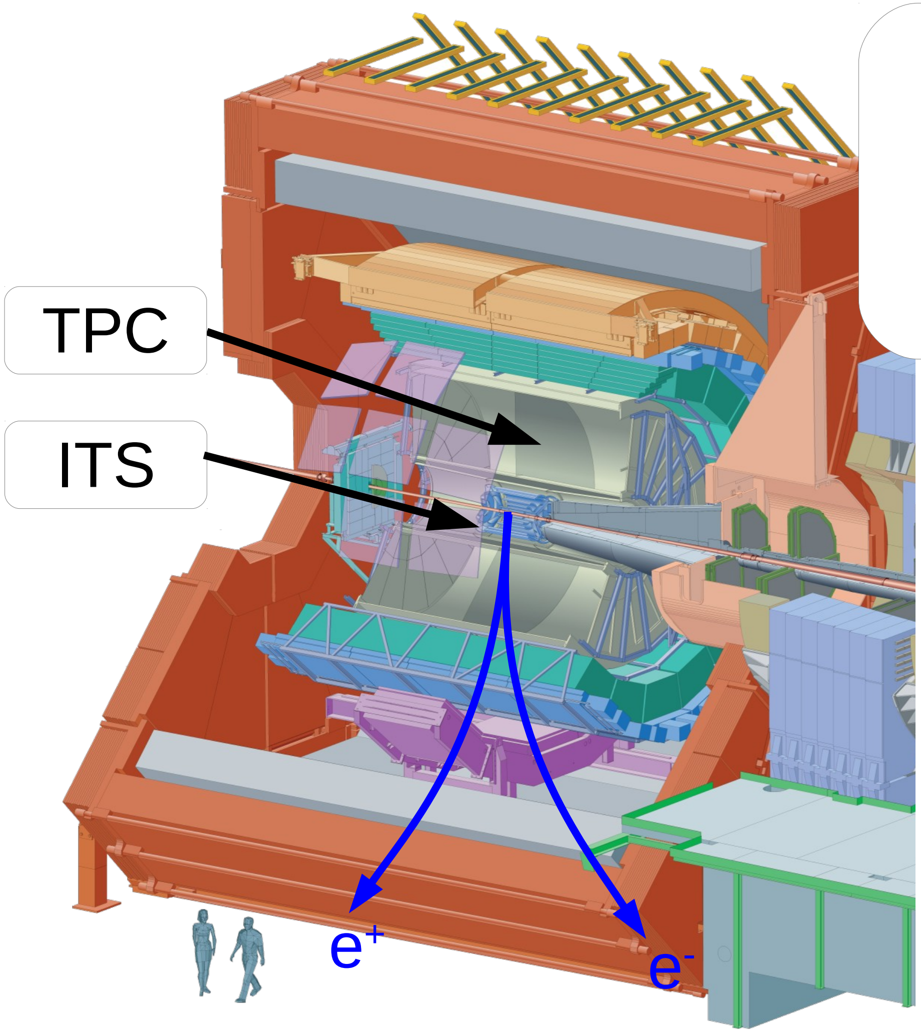
$p^{\psi}_{T} > 0$ GeV/c



Inclusive J/ψ down to p_T = 0 GeV/c at mid-rapidity

Separation of prompt and non-prompt J/ψ down to low p_T

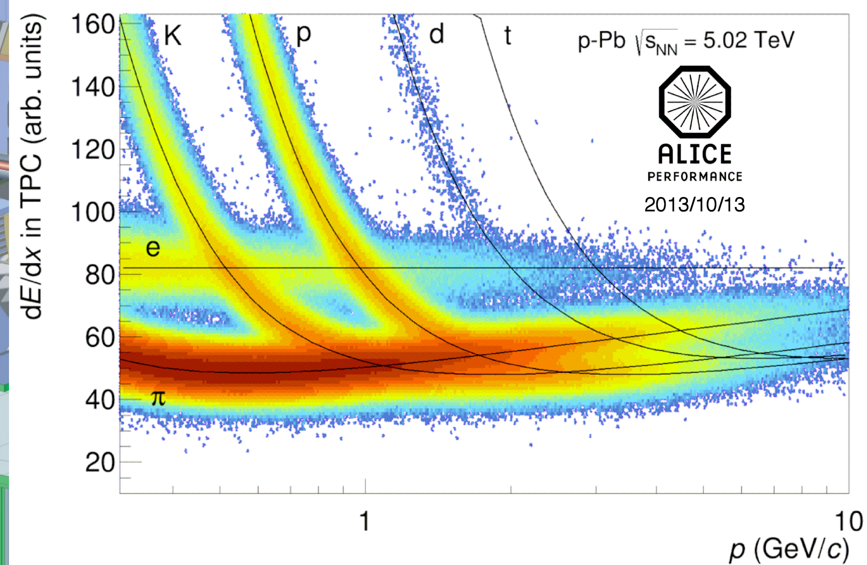
Back-up: Charmonium with ALICE at the LHC



Acceptance in p-Pb:

$-1.37 < y^{\psi}_{cms} < 0.43$

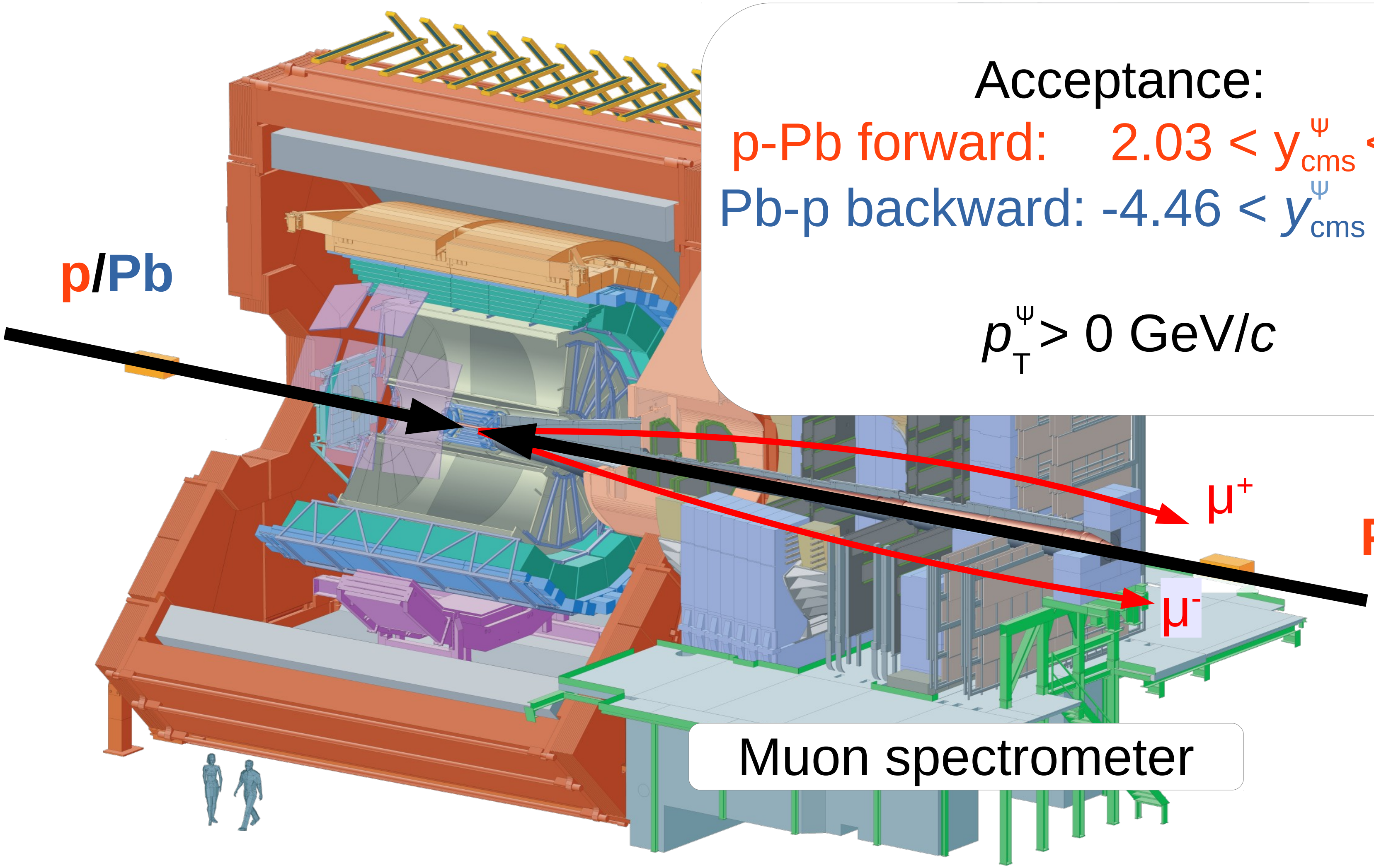
$p^{\psi}_{T} > 0$ GeV/c



Inclusive J/ψ down to $p_T = 0$ GeV/c at mid-rapidity

Separation of prompt and non-prompt J/ψ down to low p_T

Back-up: Charmonium with ALICE at the LHC



Acceptance:

p-Pb forward: $2.03 < y^{\psi}_{cms} < 3.53$

Pb-p backward: $-4.46 < y^{\psi}_{cms} < -2.96$

$p^{\psi}_{T} > 0$ GeV/c

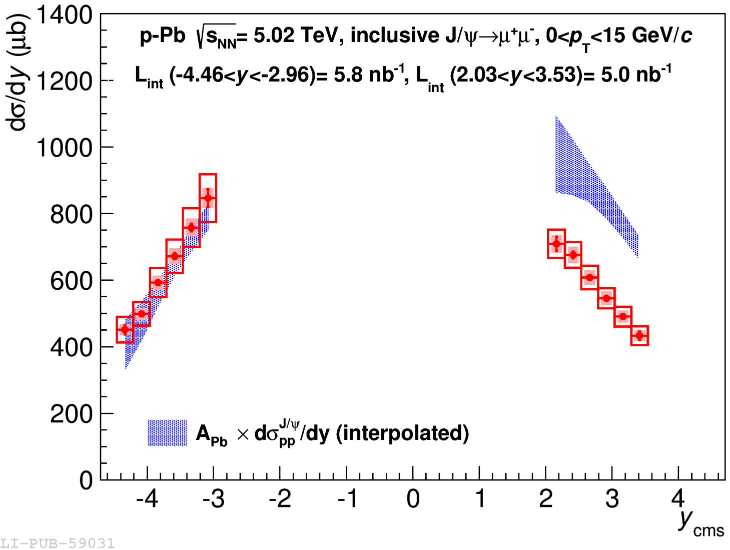
Inclusive J/ψ and ψ(2S) down to $p_T = 0$ GeV/c at forward rapidity

p-Pb: forward and backward rapidity via beam direction inversion

Back-up: pp-reference at $\sqrt{s}$ = 5.02 TeV & 2.76 TeV

Dimuons:

- $\sqrt{s}$ = 2.76 TeV: measurement in pp
- $\sqrt{s}$ = 5.02 TeV: interpolation of ALICE results in pp at $\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 7.0 TeV in bins of y, p_T
- extrapolation in y, where necessary
  y-ranges only partially overlapping between pp and p-Pb
  cross-checked with approach chosen for the dielectrons



Dielectrons:

- dσ/dy via interpolation of results (PHENIX, CDF, ALICE) at y≈0:

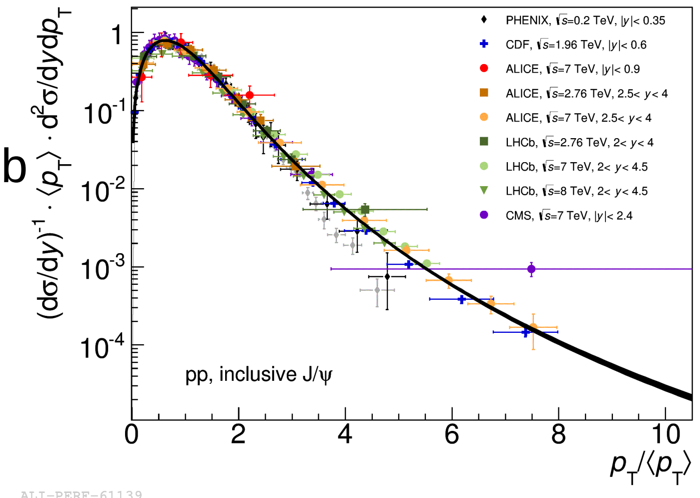
BR(J/ψ→ee)xdσ/d$y_{pp,y≈0}$($\sqrt{s}$ = 5.02 TeV) = 368 ± 91 nb

effect of rapidity shift negligible w.r.t. total uncertainty

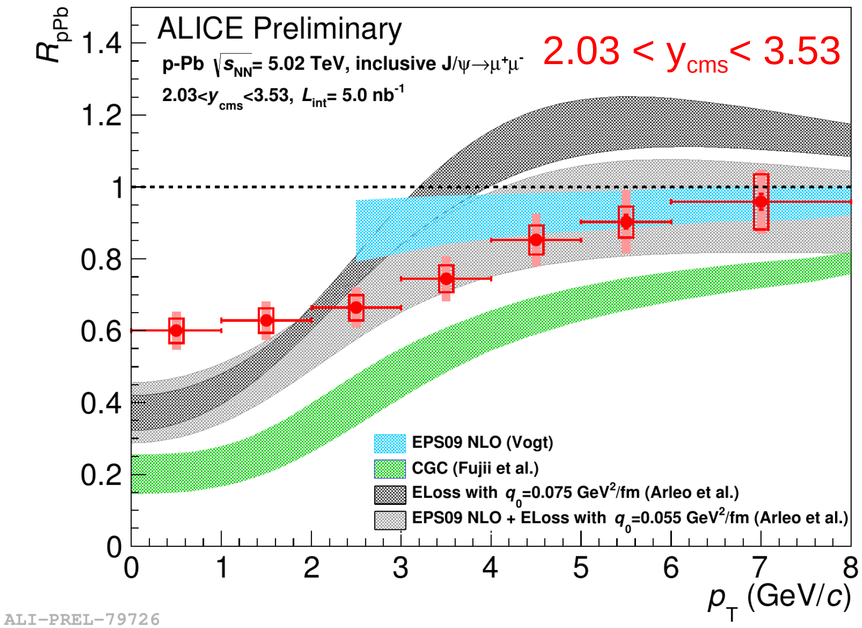
BR(J/ψ→ee)xdσ/d$y_{pp,y≈0}$($\sqrt{s}$ = 2.76 TeV) = 252.57 ± 31 nb

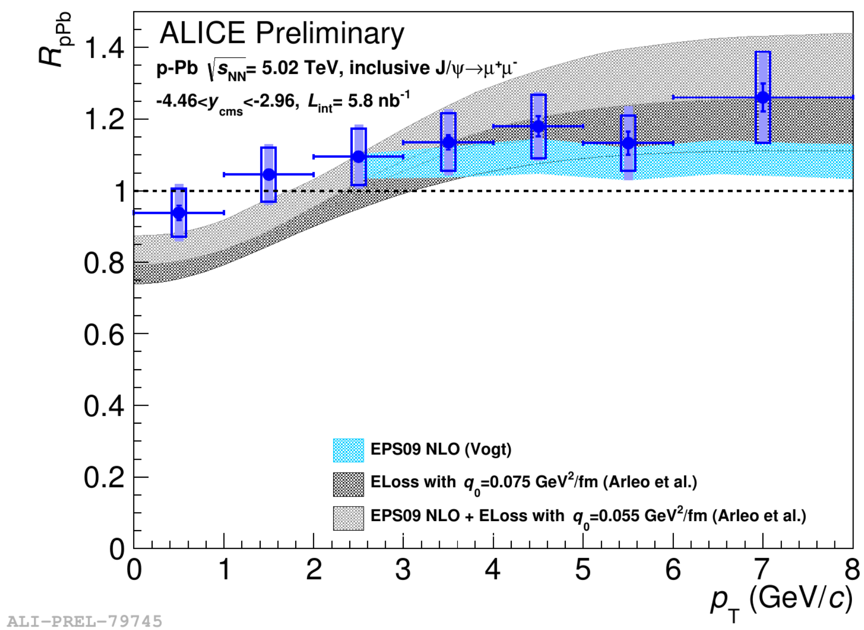
effect of rapidity shift negligible w.r.t. total uncertainty

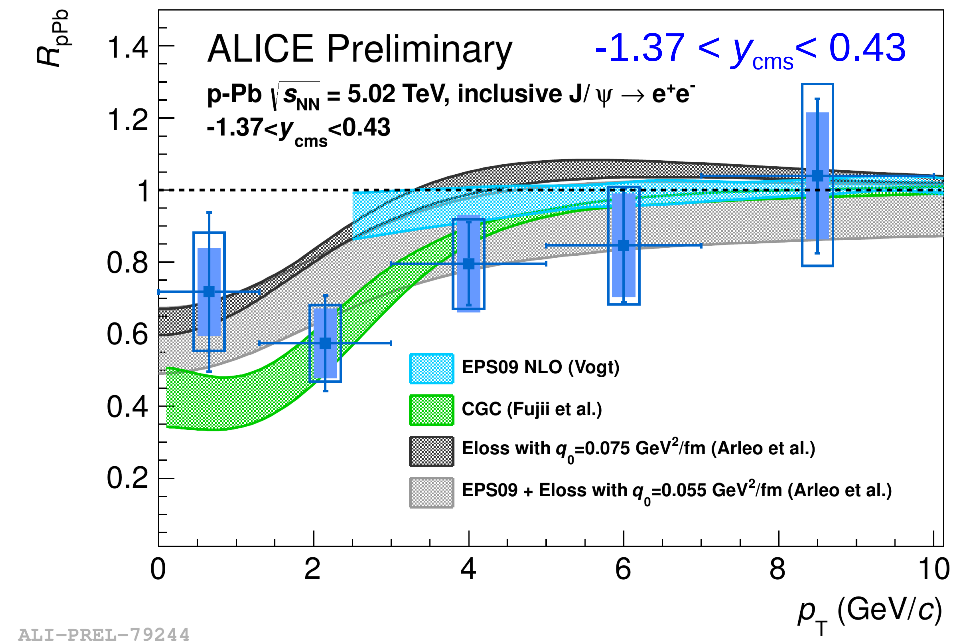
- p_T-dependence from phenomenological scaling
  inspired by arXiv:1103.2394



Back-up: p-Pb results: p_T-dependence







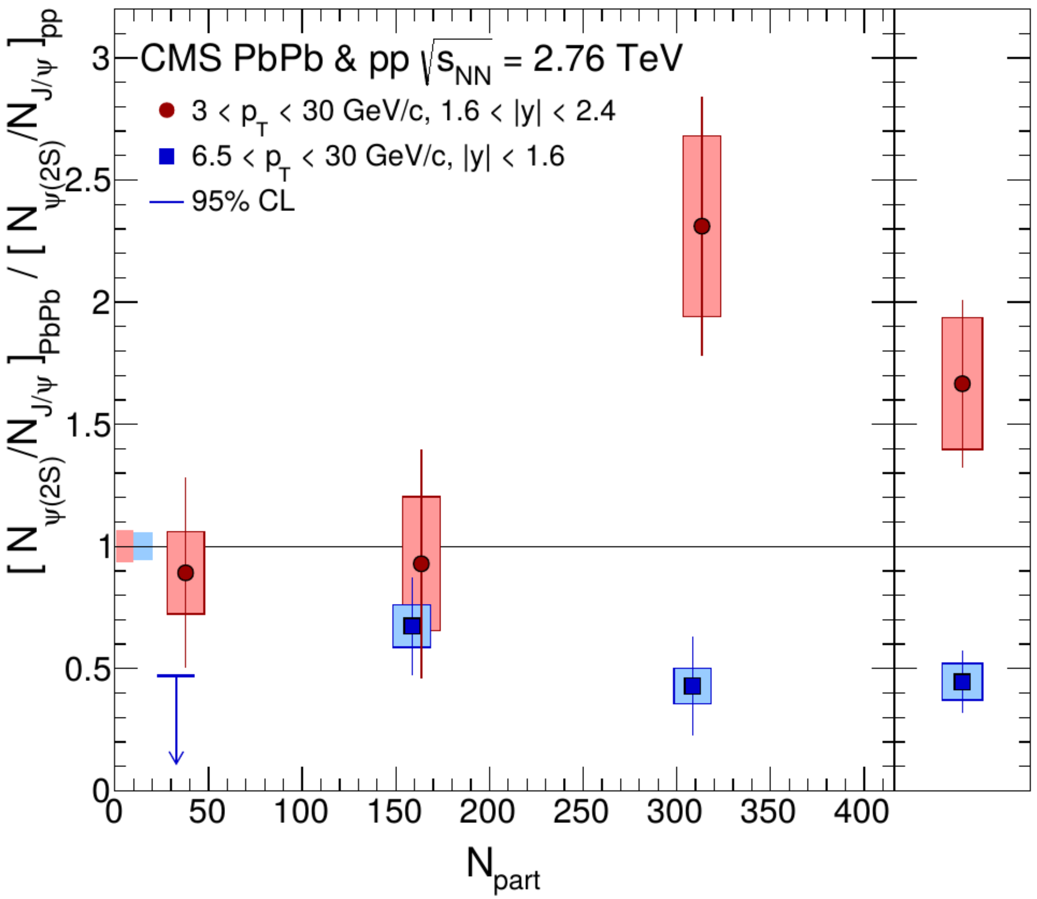
Shadowing and/or coherent energy loss picture capture basic features of data

Low p_T data not described by energy loss model

Theory uncertainties sizeable

Back-up: ψ(2S) in Pb-Pb by CMS

link: arXiv:1410.1804
CMS psi(2S)



Not same kinematic regime as ALICE preliminaries
Nevertheless:
reconciliation with ALICE findings at forward rapidity difficult
→ need higher statistics for better understanding: crucial Run 2 measurement

Back-up: original sequential melting

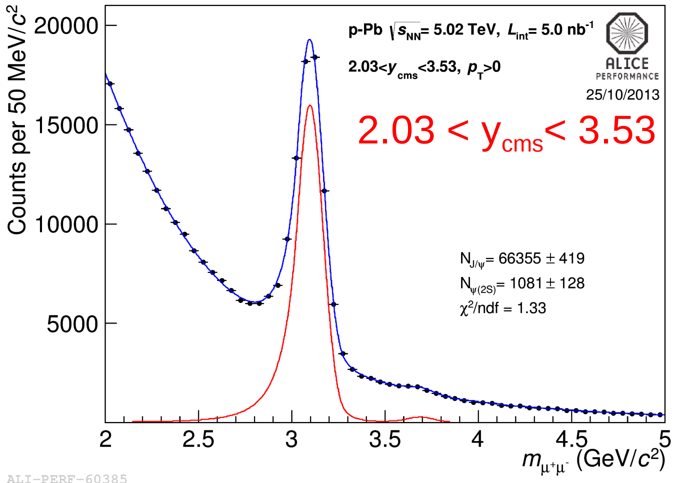
F. Karsch, H. Satz, **Z.Phys. C51 (1991) 209-224**
link: DOI: 10.1007/BF01475790

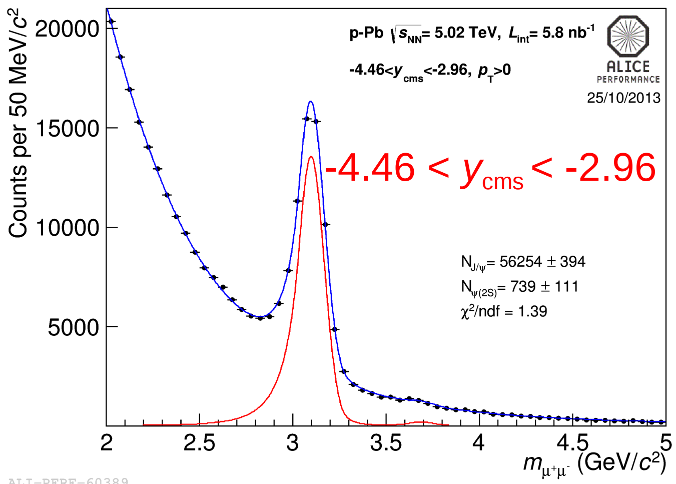
Both approaches: nuclear absorption and color screening

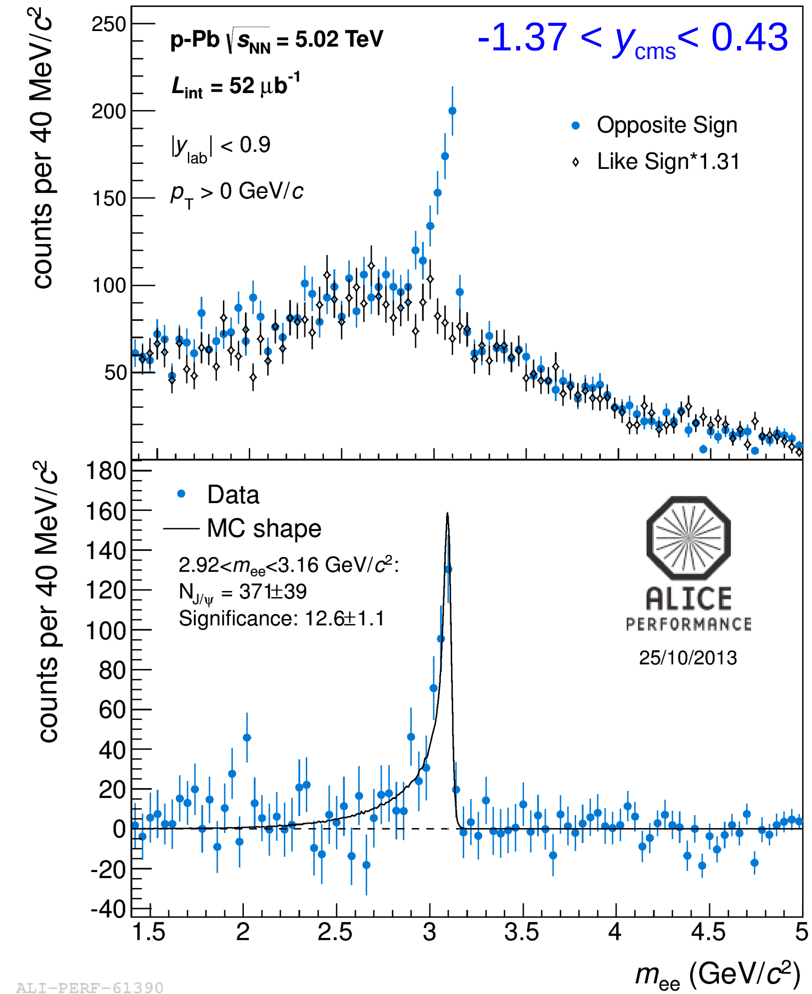
In both cases, we have assumed a well-defined bound state "formation time" [23, 28], governing the onset of deconfinement or absorption; this is clearly on oversimplification. Screening will have an effect on the evolution of the bound state even before it has reached its full size [29–31], and a "pre-hadronic" bound state can also interact already with the constituents of a dense hadronic medium [32]. The inclusion of such effects will lead to earlier and stronger suppression. To keep our arguments as simple and transparent as possible, we shall nevertheless retain the idea of a definite formation time and return later to the consequences of a more detailed description.

The abrupt onset of suppression in ε, and its abrupt end in P_T, as obained from colour screening, is a consequence of the sharp formation time of the bound states in question. If the deconfining medium were present already at time $t=0$, then we would have to study the evolution of the bound state for a screened potential, and this considerably softens both the ε and the P_T distributions [29–31]. On the other hand, it will take some time before the $c\bar{c}$ or $b\bar{b}$ pair can experience an effect of the medium, and even longer time for the plasma to become established. Hence the distributions we have shown should given an indication of the expected behaviour, even though they will be softened somewhat.

Back-up: J/ψ analyses in p-Pb collisions







Dimuons: dedicated trigger

L_{int}=5.0 nb^{-1} (forward)

L_{int}=5.8 nb^{-1} (backward)

Limited by tracking eff. & pp reference

Dielectrons: Minimum Bias

L_{int}= 52 μb^{-1}

Limited by statistics & by pp reference