Quarkonia Measurements with ALICE at the LHC

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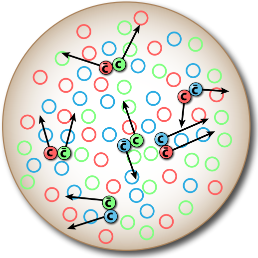
Introduction

Physics Motivation: J/ψ in Heavy-Ion Collisions

Quark-Gluon Plasma (QGP): Deconfined state of strongly interacting matter

QGP induced effects: $\rightarrow$ **AA**

- Melting due to Debye screening $\downdownarrows$
- Recombination of uncorr. $Q\bar{Q}$ $\upuparrows$
- Thermal production (at LHC) $\upuparrows$



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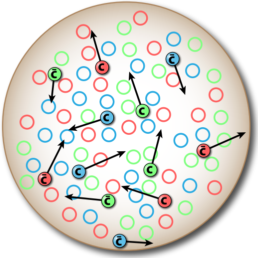

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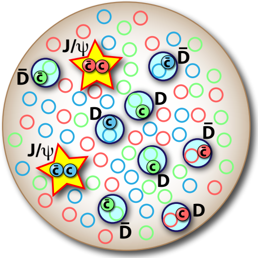

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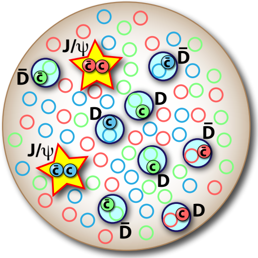
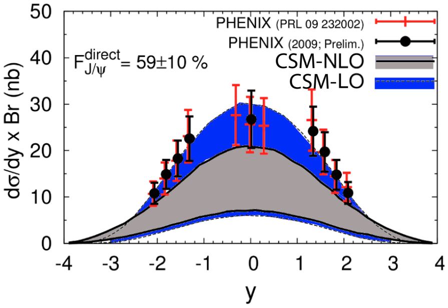


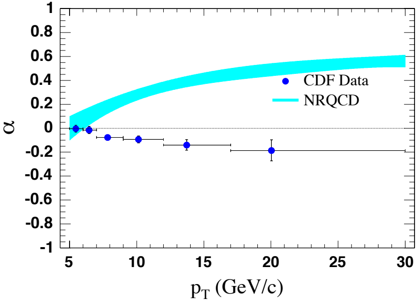
- Cold nuclear matter effects: $\rightarrow$ **pA**
  - Nuclear absorption (small at LHC) $\downdownarrows$
  - Shadowing (depending on x) $\downdownarrows\upuparrows$
- Direct Quarkonia production + feed down (J/ψ) $\rightarrow$ **pp**

Quarkonia in heavy-ion collisions - probe of deconfinement

Physics Motivation: J/ψ in pp Collisions



[J.P.Lansberg: Phys. Lett. B 695 (2011) 149]



[A.Abulencia: Phys. Rev. Lett. 99(13) (2007) 132001]

Competing models:

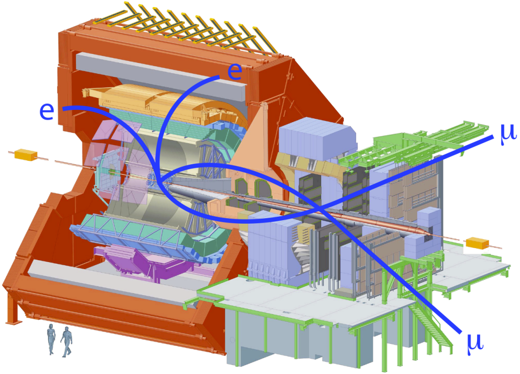
- Colour Singlet Model (CSM)
- Non-Relativistic QCD approach (NRQCD)
- Colour Evaporation Model (CEM)

- Polarization parameter $\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$

Elementary production mechanisms not well understood
pp: crucial baseline for Pb-Pb

The ALICE Experiment

$\sim$ 1000 members
116 institutes, 33 countries



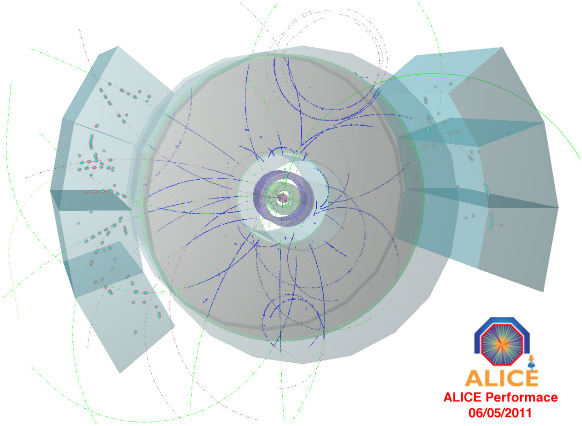
$J/\psi \to e^+e^-$

$|y| < 0.9 \quad p_t > 0$
TPC, ITS

$J/\psi \to \mu^+\mu^-$

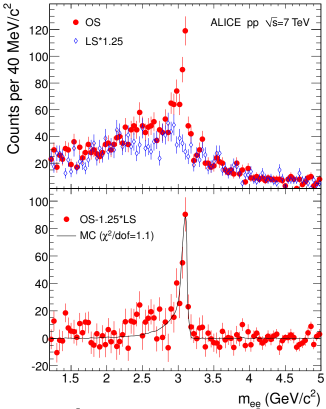
$2.5 < y < 4.0 \quad p_t > 0$
Muon Spectrometer

J/ψ in pp Collisions



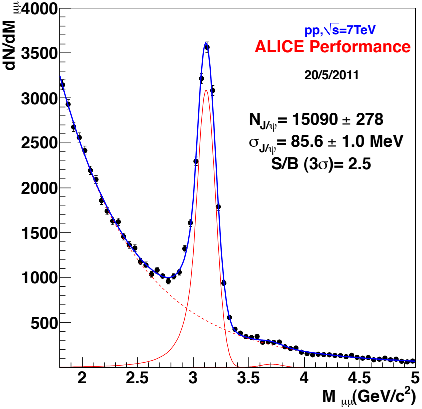
J/ψ in pp Collisions - Invariant Mass Spectra at 7 TeV

$J/\psi \to e^+e^-$



[ALICE: arXiv:1105.0380]

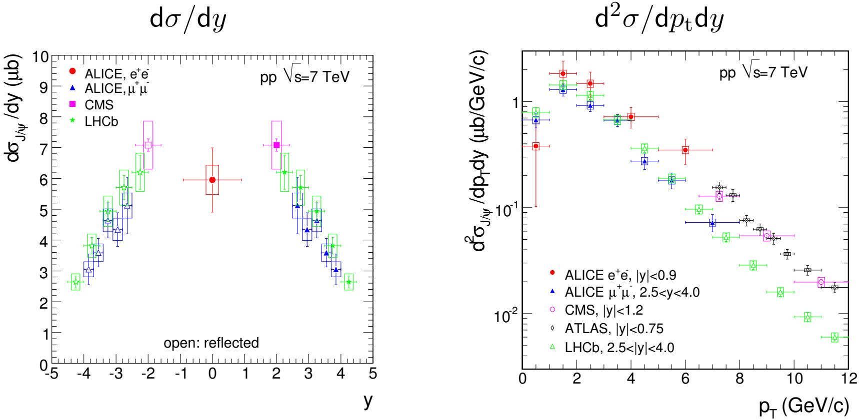
$J/\psi \to \mu^+\mu^-$



- Background: Subtraction of like-sign spectrum
- Signal: Bin counting

- Fit of Crystal-Ball function (signal) + 2 exponentials (background)

Differential Cross Sections - 7 TeV

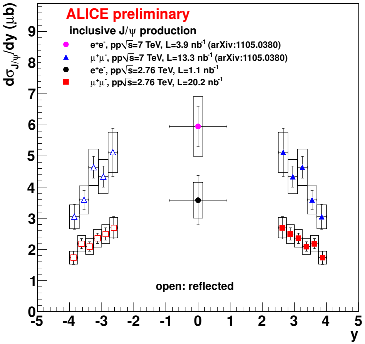


[ALICE: arXiv:1105.0380], [CMS: arXiv:1011.4193], [ATLAS: arXiv:1104.3038], [LHCb: arXiv:1103.0423]

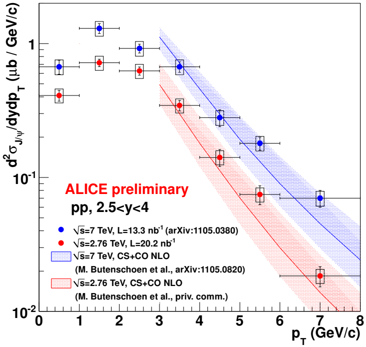
p_{t} spectra in good agreement with other LHC experiments

Differential Cross Sections - 2.76 & 7 TeV

$d\sigma/dy$

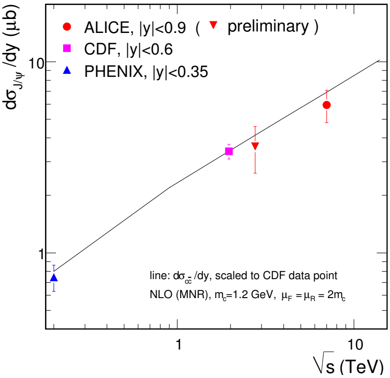


$d^2\sigma/dp_t dy$

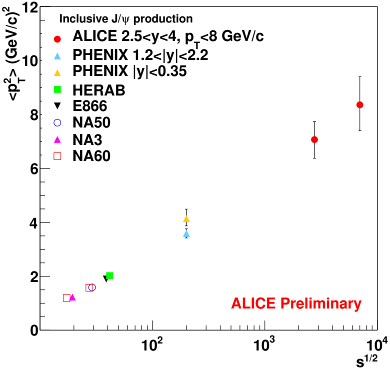


Good agreement of $d^2\sigma/dp_t dy$ with NLO NRQCD calculations

Inclusive J/ψ Production vs. Collision Energy



[M.L.Mangano: Nucl. Phys. B373 (1992) 295]

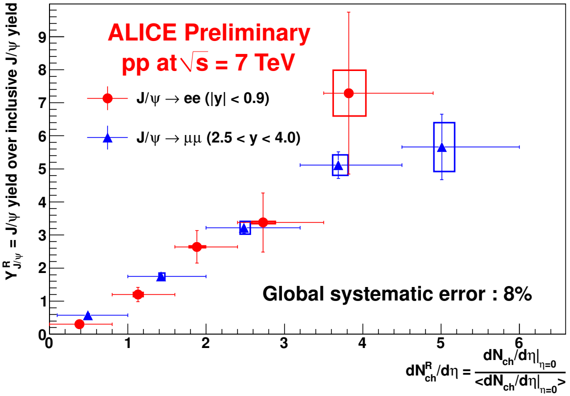


- ALICE mid-rapidity data follows trend of cross section vs. $\sqrt{s}$
- NLO pQCD $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ prediction scaled to match CDF data

- $\langle p_\mathrm{t}^2 \rangle$ extracted from fits to the p_t differential distributions
- Approximately logarithmic increase with $\sqrt{s}$

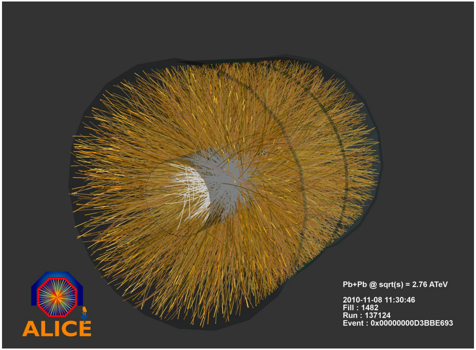
Multiplicity Dependence

$Y^R_{\mathrm{J}/\psi}$: Yield in multiplicity bin over yield per inelastic pp collision



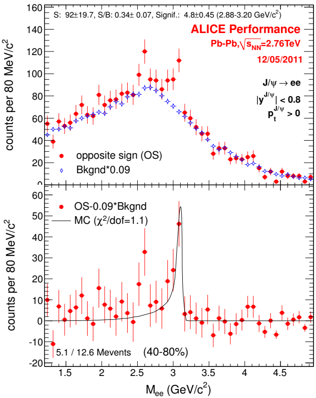
Approximately linear increase with charged particle density
Indication for multiple parton interactions

J/ψ in Pb-Pb Collisions

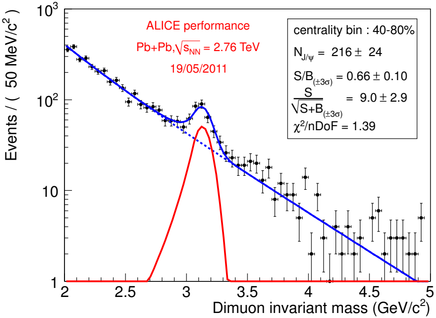


J/ψ in Pb-Pb Collisions - Invariant Mass Spectra at 2.76 TeV

$J/\psi \rightarrow e^+e^-$



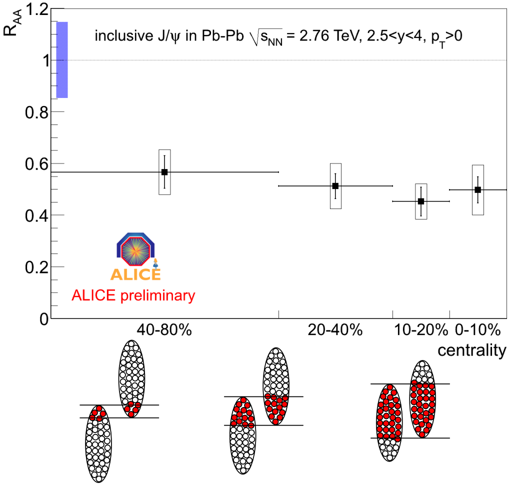
$J/\psi \rightarrow \mu^+\mu^-$



- Background: Track rotation
  - Rotate one track by a random angle around ϕ
- Signal: Bin counting

- Fit of Crystal-Ball function (signal) + 2 exponentials (background)

Inclusive J/ψ R_{AA}

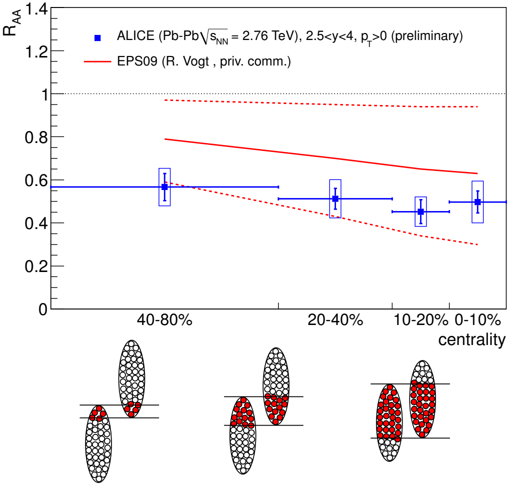


$$R_{AA} = \frac{Y_{Pb-Pb}}{\langle N_{coll} \rangle \cdot Y_{pp}}$$

- Bars: Statistical errors
- Boxes: Centrality-dependent systematic uncertainties
- Filled box: Common systematic uncertainties
- Not corrected for feed-down from B decay

Strong suppression already at peripheral collisions

Inclusive J/ψ R_{AA}



$$R_{AA} = \frac{Y_{Pb-Pb}}{\langle N_{coll}\rangle \cdot Y_{pp}}$$

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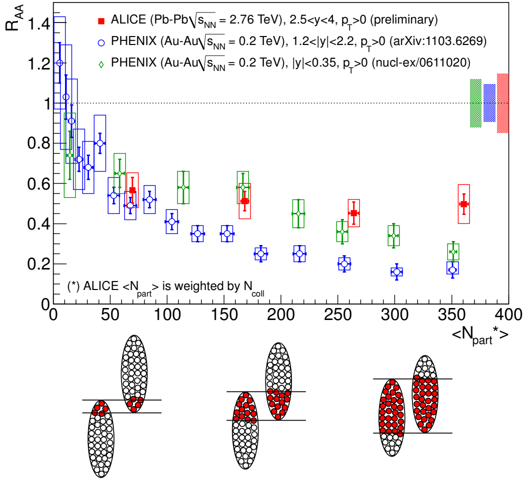
Large uncertainties of shadowing prediction - pA data crucial

Inclusive J/ψ R_{AA}



$$R_{AA} = \frac{Y_{Pb-Pb}}{\langle N_{coll} \rangle \cdot Y_{pp}}$$

- Bars: Statistical errors
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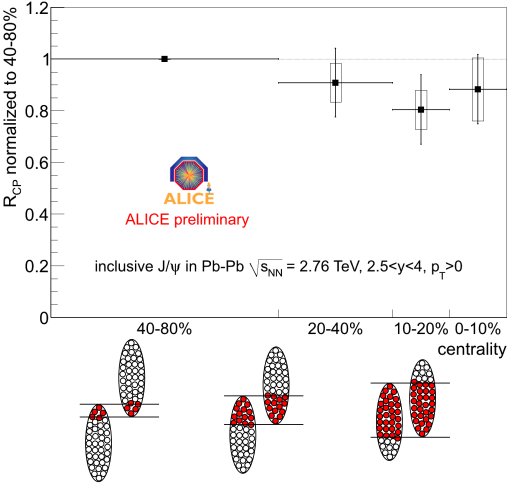
Less suppression in central events at LHC than at RHIC

Inclusive J/ψ R_{CP}

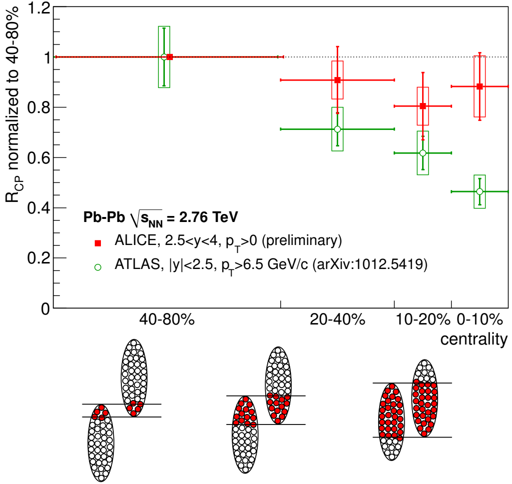


$$R_{\mathrm{CP}} = \frac{\left\langle N_{\mathrm{coll}}^{\mathrm{periph.}} \right\rangle \cdot Y_{\mathrm{Pb-Pb}}^{\mathrm{cent.}}}{\left\langle N_{\mathrm{coll}}^{\mathrm{cent.}} \right\rangle \cdot Y_{\mathrm{Pb-Pb}}^{\mathrm{periph.}}}$$

- Systematic uncertainties of the reference (40-80%) propagated to the ratio

Weak centrality dependence of R_{CP}

Inclusive J/ψ $R_{\rm CP}$

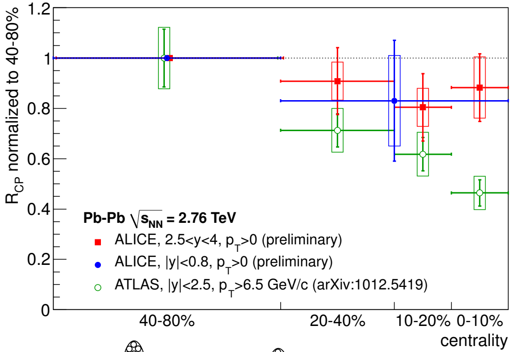


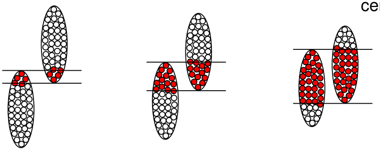
$$R_{\rm CP} = \frac{\left\langle N_{\rm coll}^{\rm periph.} \right\rangle \cdot Y_{\rm Pb-Pb}^{\rm cent.}}{\left\langle N_{\rm coll}^{\rm cent.} \right\rangle \cdot Y_{\rm Pb-Pb}^{\rm periph.}}$$

- Systematic uncertainties of the reference (40-80%) propagated to the ratio

$R_{\rm CP}$ of most central collisions larger at forward rapidities (ALICE) than at central rapidity & high $p_{\rm t}$ (ATLAS)

Inclusive J/ψ R_{CP}





$$R_{CP} = \frac{\left\langle N_{coll}^{periph.} \right\rangle \cdot Y_{Pb-Pb}^{cent.}}{\left\langle N_{coll}^{cent.} \right\rangle \cdot Y_{Pb-Pb}^{periph.}}$$

- Systematic uncertainties of the reference (40-80%) propagated to the ratio

Challenging analysis in e^+e^- at mid-rapidity: Still large errors

Summary & Outlook

Summary

- pp collisions:
  - ALICE has measured the inclusive J/ψ production in $\sqrt{s} = 7$ and 2.76 TeV pp collisions in e^+e^- and $\mu^+\mu^-$
  - Results are in good agreement with NLO NRQCD calculations
  - The inclusive J/ψ yield shows a linear increase with the multiplicity
- Pb-Pb collisions:
  - The inclusive J/ψ R_{AA} and R_{CP} have been presented as a function of collision centrality
  - J/ψ R_{AA} larger at LHC $(2.5 < y < 4.0)$ than at RHIC in $1.2 < y < 2.2$; closer to RHIC at $|y| < 0.35$
  - J/ψ R_{CP} larger at ALICE $(2.5 < y < 4.0)$ than at ATLAS ($|y| < 2.5$, $p_{\mathrm{t}} > 6.5 GeV$) in central collisions
- Unique at LHC for ALICE: $p_{\mathrm{t}}^{\mathrm{J}/\psi}$ reach down to 0 GeV/c

Outlook

- Polarization measurements
- Measurement of secondary J/ψ
- Transition Radiation Detector as trigger and to improve PID

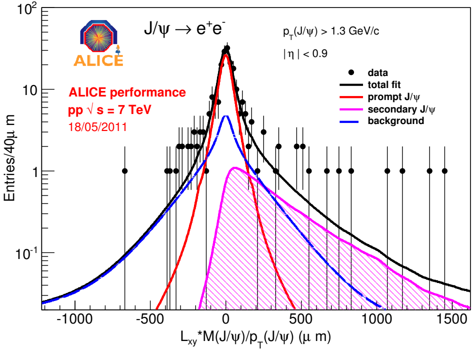
Backup

Backup - J/ψ from B Decay

$c\tau \sim 500\mu\mathrm{m} \rightarrow$ likely to have a displaced vertex

B fraction: Simultaneous fit of inv. mass + pseudo proper decay length

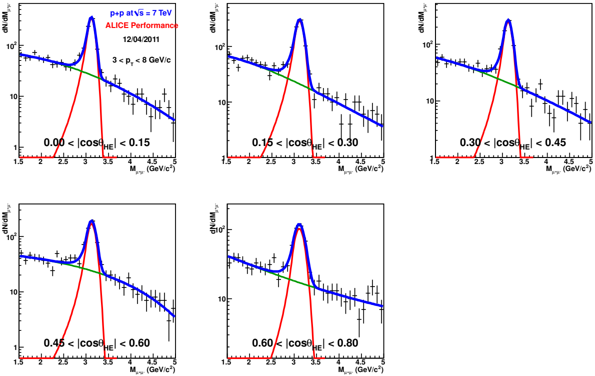
$$x = L_{\mathrm{xy}} \frac{M_{\mathrm{J}/\psi}}{p_{\mathrm{t}}}$$



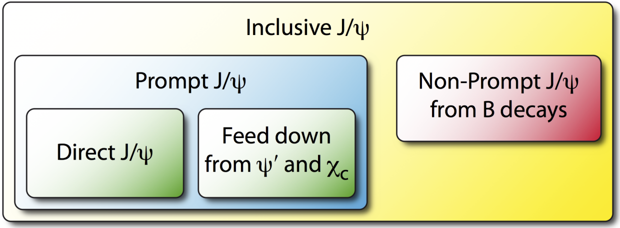
- Measurement possible at central rapidity due to excellent impact parameter resolution ($\sigma_{\mathrm{r}\phi} < 75\mu m$ for $p_{\mathrm{t}} > 1\mathrm{GeV}/c$)
- First estimation ongoing, high statistics sample collected in 2011 should allow for a precise measurement

Backup - J/ψ Polarization

- Important observable to test theory
- 2010 7 TeV pp statistics allow determination of full angular distribution of J/ψ decay muons
- Expected statistical error of the polarization parameter < 0.2 for 3 $p_{\rm t}$ bins



Backup - Contributions to J/ψ Yield



The ALICE Experiment

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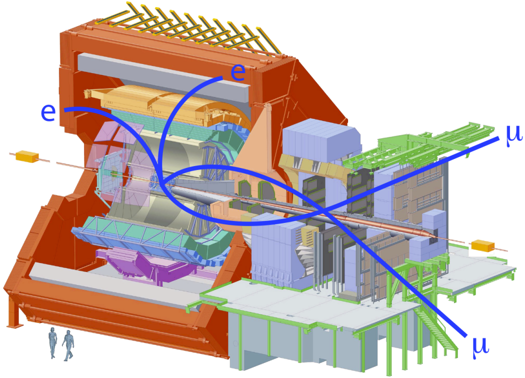
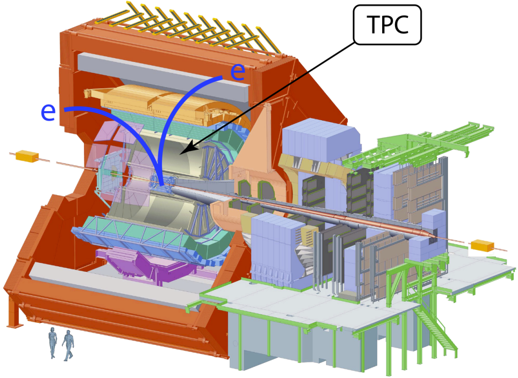
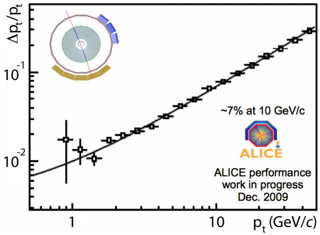
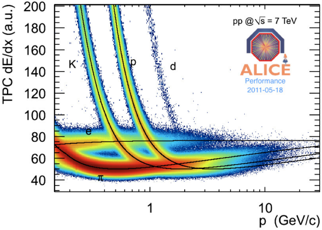


The ALICE Experiment

Time Projection Chamber







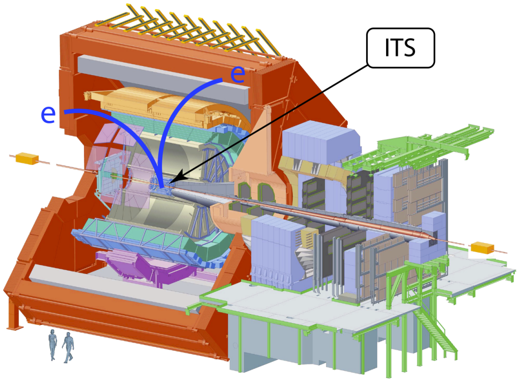
$J/\psi \rightarrow e^+e^-$

$|y| < 0.9 \quad p_t > 0$

- Main tracking device
- PID of charged particles

The ALICE Experiment

Inner Tracking System



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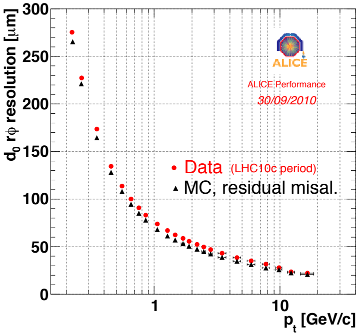
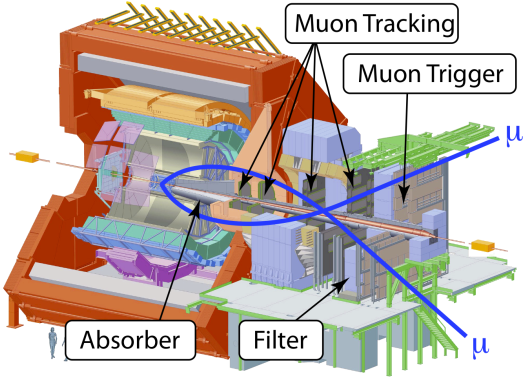


- 3×2 layers of silicon detectors: pixel, drift, strip
- Primary + secondary vertices
- Improve momentum measurement

The ALICE Experiment

Forward Muon Spectrometer



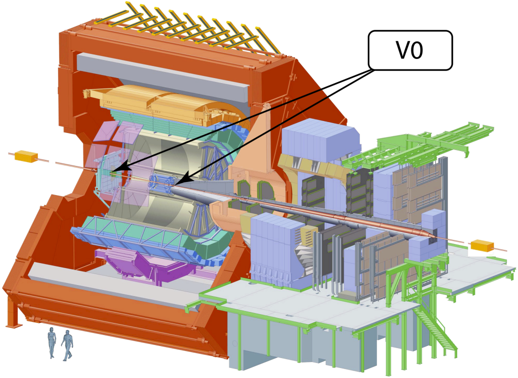
- Absorber
  + beam shield
  + filter
  protect from hadrons
- 10 plane tracking system
- 4 plane trigger system
- Dipole magnet: momentum determination

$J/\psi \to \mu^+\mu^-$

$2.5 < y < 4.0 \quad p_t > 0$

The ALICE Experiment

V0



- Minimum bias trigger together with the ITS
- V0 amplitude: Centrality selection in Pb-Pb

J/ψ in pp Collisions - Run Statistics

Triggers:

- e^+e^-: minimum bias interaction trigger
- $\mu^+\mu^-$: forward muon in coincidence with minimum bias trigger

Results are based on:

Energy (TeV)	LHC period	Integrated Luminosity (nb^{-1})	
		J/$\psi \to e^+e^-$	J/$\psi \to \mu^+\mu^-$
7	2010	3.9	15.6
2.76	2011	1.1	20.2

J/ψ in Pb-Pb Collisions - Run Statistics

Trigger:

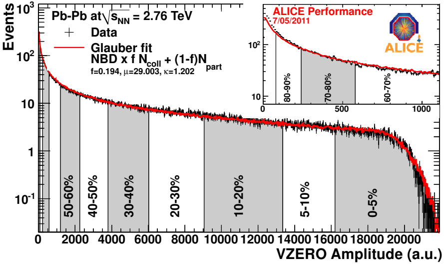
- Minimum bias interaction trigger

Results are based on:

Energy (TeV)	LHC period	Integrated Luminosity (μb^{-1})
2.76	2011	2.7

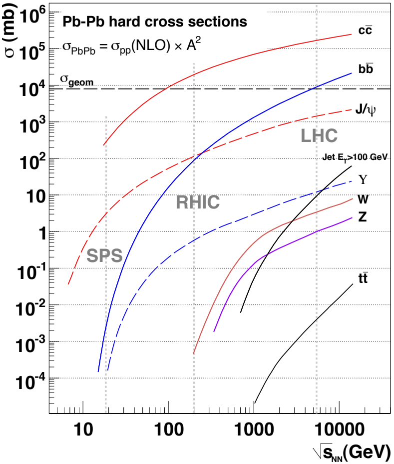
Centrality selection:

- Based on a geometrical Glauber-model fit to the V0 amplitude



Backup - Cross Section vs. Energy

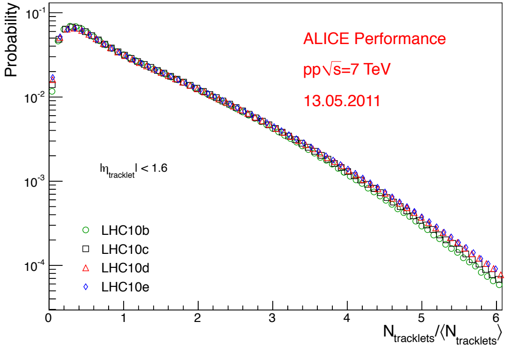
- High precision data needed
- Data in new energy regime further constrains models
- **pp data: crucial baseline for AA**

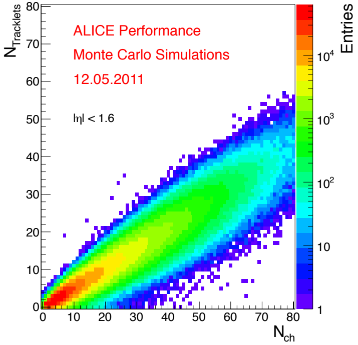


[D.d'Enterria: Nucl. Part. Phys. 35(10) (2008) 104039]

LHC will deliver excellent statistics for quarkonia measurements

Backup - Relative Yield, Multiplicity





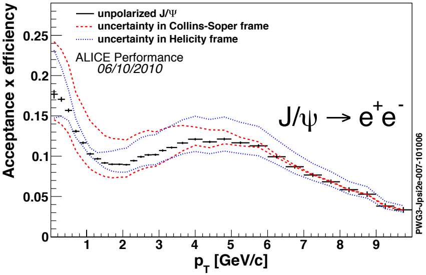
Relative Yield

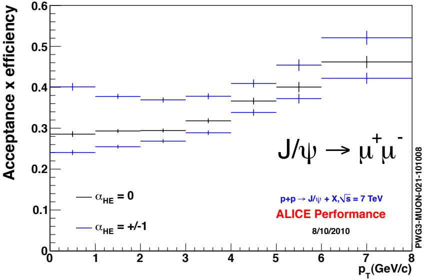
$$Y^R_{J/\psi} = \frac{Y^{bin}_{J/\psi}}{Y^{inel}_{J/\psi}} = \frac{N^{bin}_{J/\psi}/N^{bin}_{CINT1B}}{N^{inel}_{J/\psi}/N_{inel}}$$

Relative Multiplicity

$$dN^R_{ch}/d\eta = \frac{dN_{ch}/d\eta|_{\eta=0}}{\langle dN_{ch}/d\eta|_{\eta=0}\rangle}$$

Backup - Corrections pp





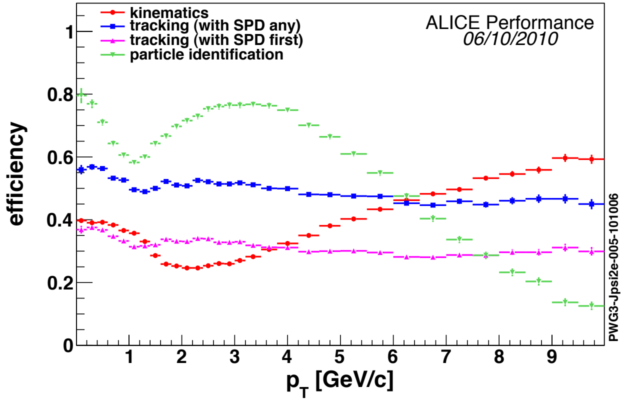
Analysis in e^+e^- (10.0%)

1. Kinematical acceptance
   - $|y^{J/\psi}| < 0.9$
   - $|\eta^{e^+,e^-}| < 0.9$
   - $p_t^{e^+,e^-} > 1.0$ GeV$/c$
2. Reconstruction efficiency
3. Particle identification
4. Mass integration limits

Analysis in $\mu^+\mu^-$ (32.9%)

1. Kinematical acceptance
   - $-4.0 < y^{J/\psi} < -2.5$
   - $p^{\mu^+,\mu^-} > 4.0$ GeV$/c$
2. Reconstruction efficiency

Backup - Partial Efficiencies pp



Backup - Systematic Error Estimation pp

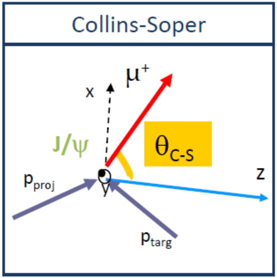
Channel	e^+e^-		$\mu^+\mu^-$	
Trigger efficiency	0%		4%	
Acceptance input	1%		2%	
Reconstruction efficiency	11%		3%	
Signal extraction	8.5%		7.5%	
R factor	0%		3%	
Luminosity	8%			
Branching ratio	1%			
Total sys. error	**16.1%**		**12.6%**	
Polarization	$\alpha = -1$	$\alpha = 1$	$\alpha = -1$	$\alpha = 1$
Collins-Soper	+19%	-13%	+31%	-15%
Helicity	+21%	-15%	+22%	-10%

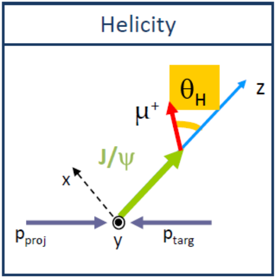
- Largest contribution: (yet) unknown polarization

Backup - Systematic Error Estimation Pb-Pb

Source	e^+e^-centrality				common
	0-10%	10-20%	20-40%	40-80%	
$N_{\mathrm{J/psi}}$	19%	14%	17%	14%	
$N_{\mathrm{J/psi}}/N_{\mathrm{J/psi}}^{40-80\%}$	12%	8%	7%		
Acceptance input					3%
Tracker efficiency	4%	2%	1%	0%	5%
Trigger efficiency					4%
Reconstruction eff.					2%
Branching ratio					1%
Cross section					13%
$\langle T_{\mathrm{AA}} \rangle$	4%	4%	4%	6%	
$\langle T_{\mathrm{AA}} \rangle^{\mathrm{i}} / \langle T_{\mathrm{AA}} \rangle^{40-80\%}$	6%	5%	4%		
Total for R_{AA}	20%	15%	17%	15%	15%
Total for R_{CP}	14%	10%	8%		

Backup - Polarization Reference Frames





Collins-Soper (CS):
bisector of the angle between proj. and (-) target in the quarkonium C.M. frame.

Helicity (HE):
Direction of the quarkonium in the C.M. frame of the collision.

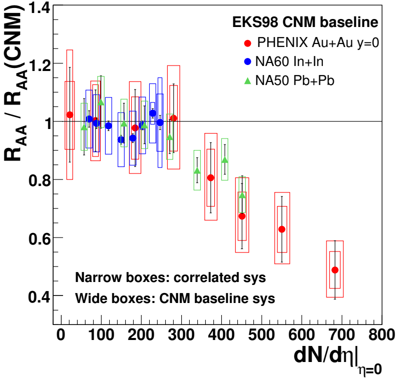
Backup - Polarization Reference Frames

Characterization of the Quark-Gluon Plasma

- Direct Quarkonia production + feed down (J/ψ) $\rightarrow$ **pp**
- Cold nuclear matter effects: $\rightarrow$ **pA**
  - Nuclear absorption (small at LHC) $\downdownarrows$
  - Shadowing (depending on x) $\downdownarrows\upuparrows$

QGP induced effects: $\rightarrow$ AA

- Melting due to Debye screening $\downdownarrows$
- Recombination of uncorr. $\mathrm{Q\bar{Q}}$ $\upuparrows$
- Thermal production (at LHC) $\upuparrows$



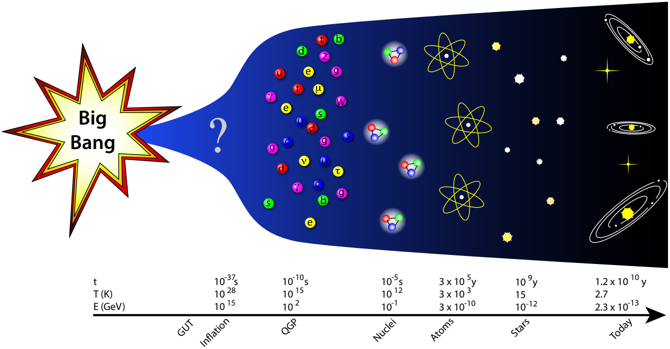
[N.Brambilla: arXiv:1010.5827v3/hep-ph]

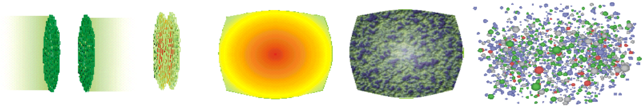
$$R_{\mathrm{AA}} = \frac{Y^{\mathrm{J}/\psi}_{\mathrm{Pb-Pb}}}{\langle N_{\mathrm{coll}}\rangle \cdot Y^{\mathrm{J}/\psi}_{\mathrm{pp}}}$$

Fit to p_{t} Spectra

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{t}}} \sim \frac{p_{\mathrm{t}}}{\left(1 + \left(\frac{p_{\mathrm{t}}}{p_0}\right)^2\right)^x} \tag{1}$$

Physics Motivation: Quark-Gluon Plasma





before collision | initial state | fireball | QGP | freeze out