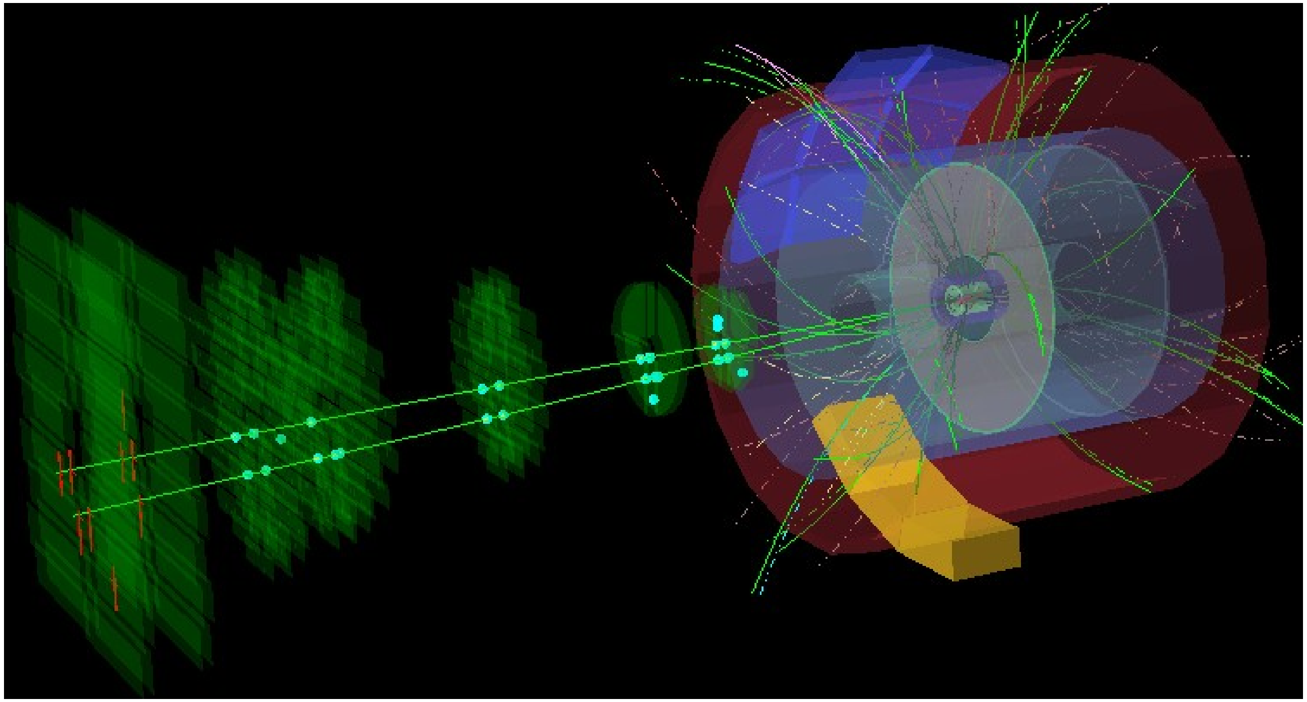
Heavy-quark and quarkonia production

in pp and heavy-ion collisions



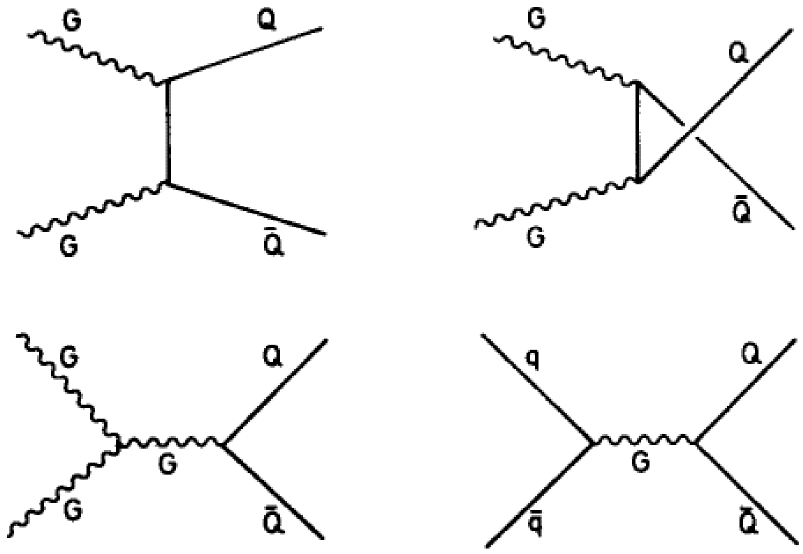
Outlook

- Heavy quarks in pp collisions
  - Charmonium
  - Bottomonium
  - Open Charm/Beauty

- Heavy-Ion collisions
  - Charmonium R_{AA}
  - Heavy Quark energy loss
  - Elliptic Flow
  - J/ψ in ultra-peripheral collisions

Heavy quarks in pp

- charm (≈ 1.5 GeV/c²)
- bottom (≈ 5 GeV/c²)
- top (≈ 175 GeV/c²)
- heavy quark pairs produced in hard partonic scattering → perturbative QCD

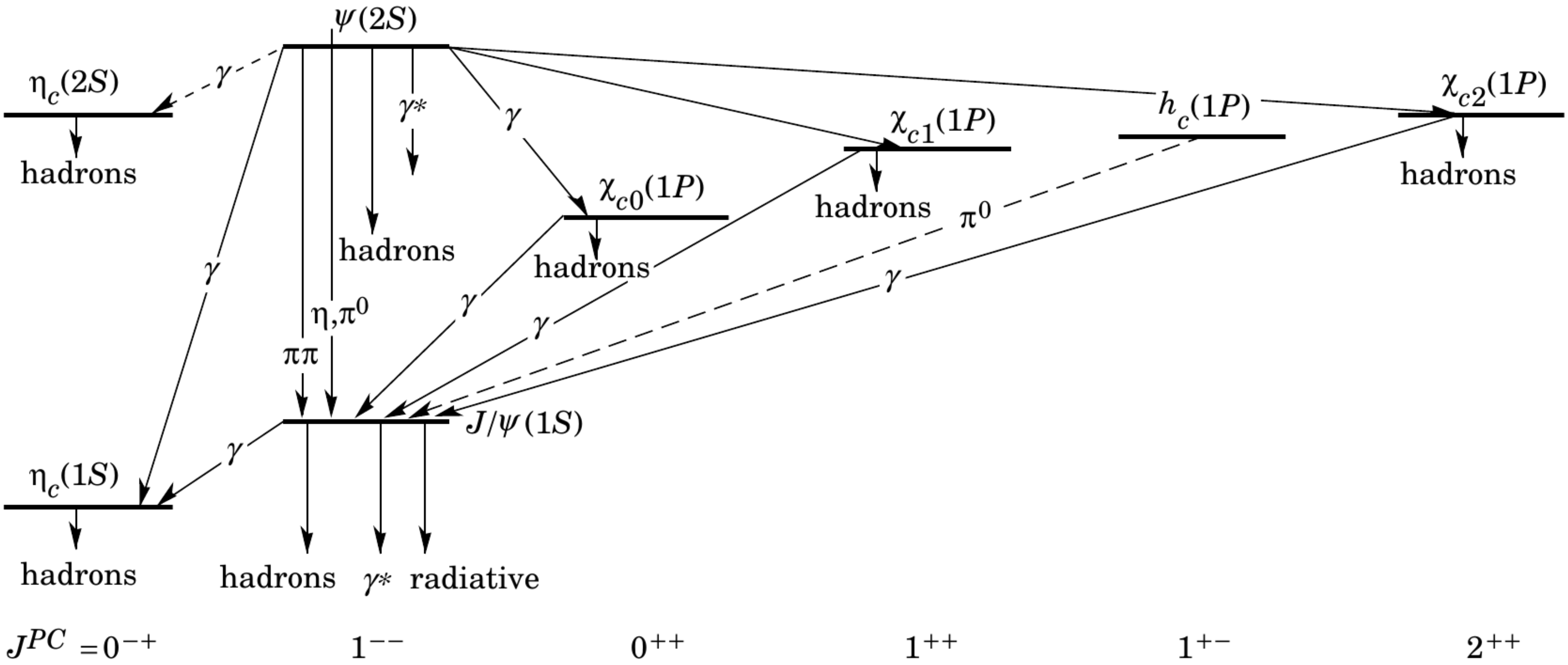


- to get production cross sections, convolute three terms:
  1. parton distribution function of incoming protons
  2. partonic hard scattering cross sections (perturbative QCD)
  3. hadronization into specific hadron → nonperturbative models

Heavy quarks in pp

- Quarkonium production models
  - **CSM**: $Q\overline{Q}$ pair in color-singlet state with same quantum numbers as quarkonium. → Successful at low energies, large corrections needed at higher, infrared divergences for P (and higher)-wave quarkonia
  - **CEM**: $Q\overline{Q}$ pair evolves to quarkonium if invariant mass less than threshold for pair of open-flavor mesons. Probability for specific state energy and momentum independent. → Rough description of data
  - **NRQCD factorization**: most sound theoretically and most successful phenomenologically. Probability for $Q\overline{Q}$ to evolve to quarkonium as matrix elements of NRQCD operators (expansion in α_s and v) → many successes in describing data, remaining discrepancies
  - **Fragmentation functions**: convolution of parton production cross section and light-cone fragmentation functions.

Charmonium

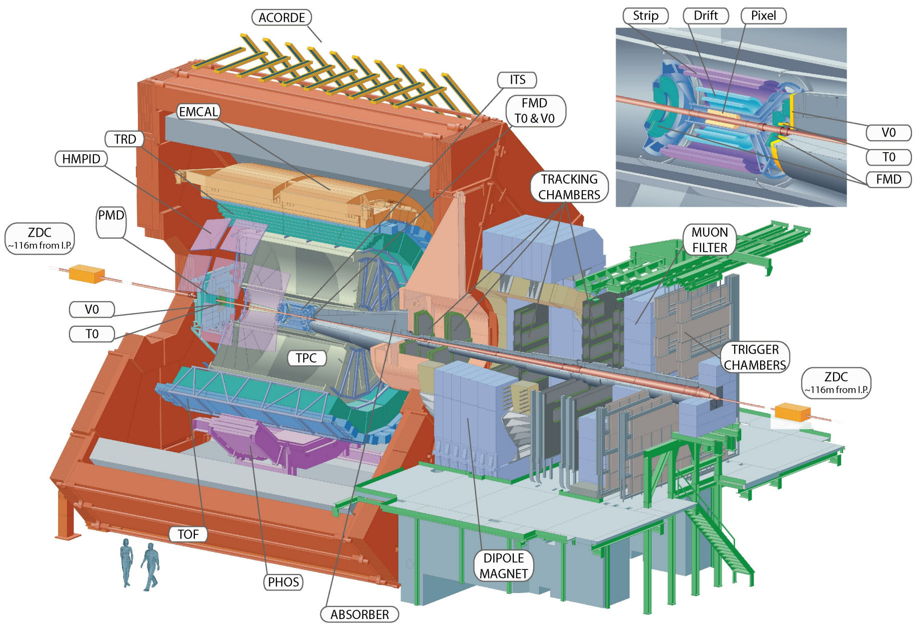


S. Eidelman et al., Review of Particle Physics, Phys. Lett. B592:1+, 2004

J/ψ decay modes

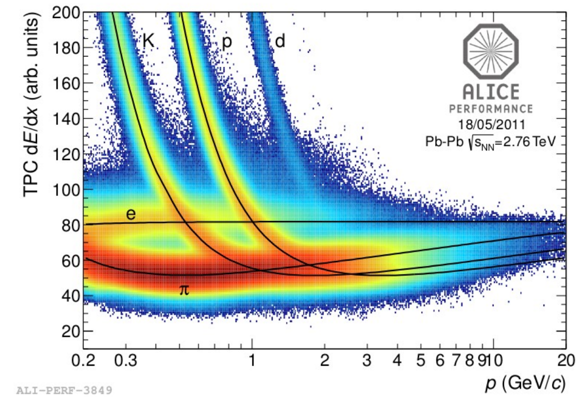
- mass below threshold for production of two D mesons
- hadronic decay modes strongly suppressed due to OZI rule
- → narrow width: 93 keV/c^2
- → electromagnetic decays become relevant
- BR $J/\psi \rightarrow e^+e^-/\mu^+\mu^-$: 6% each

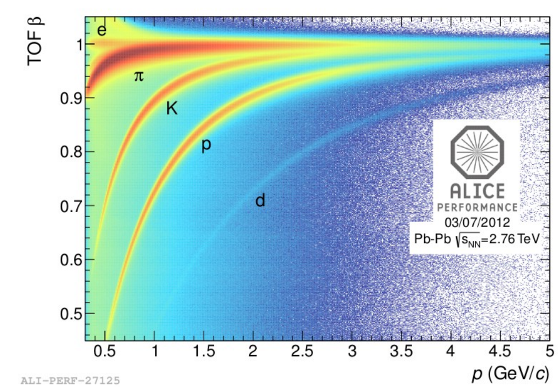
J/ψ in ALICE



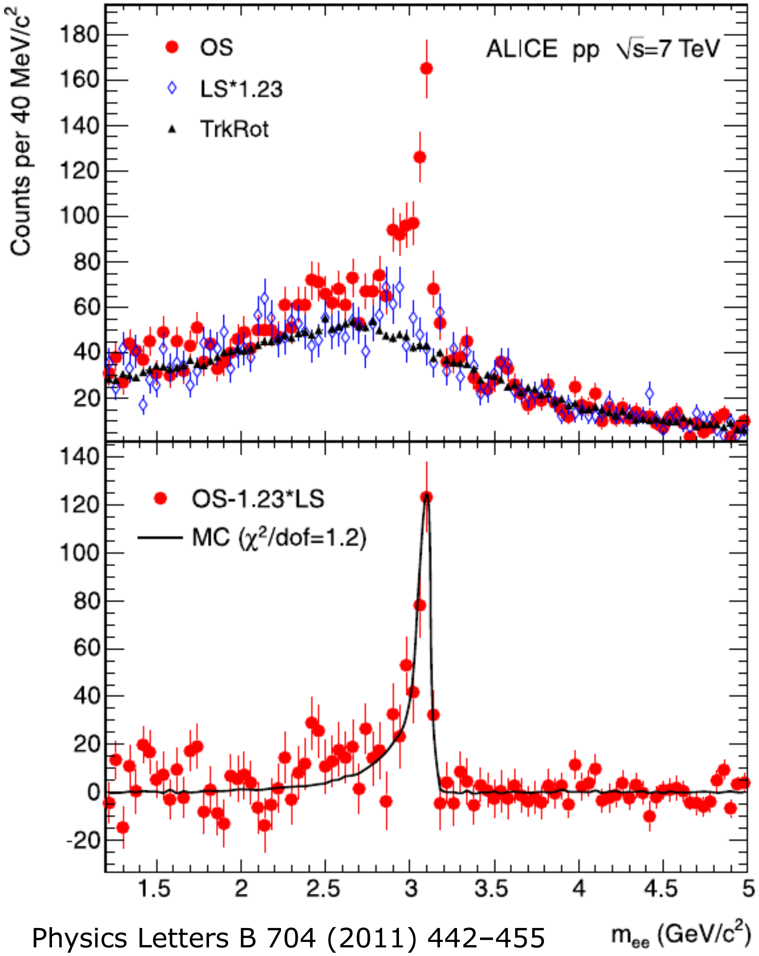
- dielectron channel at midrapidity
- dimuon channel at forward rapidity

electron identification:





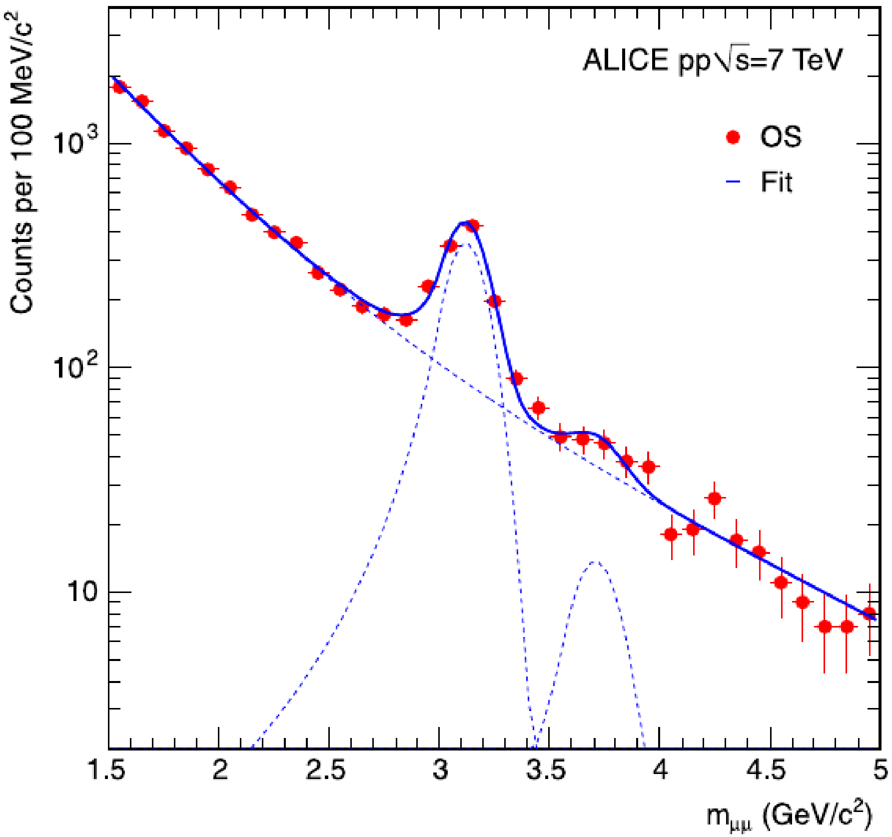
J/ψ → ee



Physics Letters B 704 (2011) 442–455

- mass spectrum of oppositely charged electrons
- background description
  - **like-sign pairs**
  - **track rotation**
  - event mixing
  - fitting

J/ψ →μμ



Physics Letters B 704 (2011) 442–455

- mass spectrum of oppositely charged muons
- background description
  - like-sign pairs
  - track rotation
  - event mixing
  - **fitting**

Efficiencies and uncertainties

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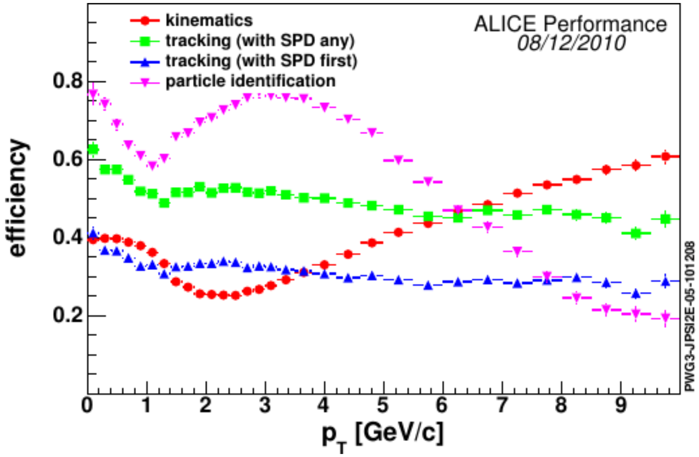
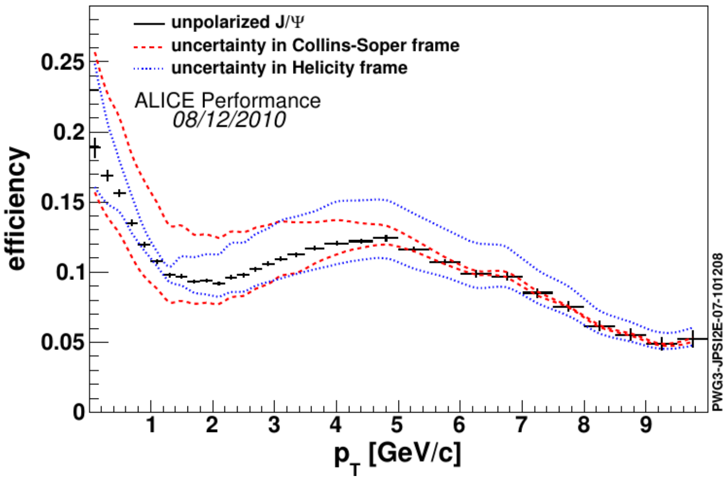
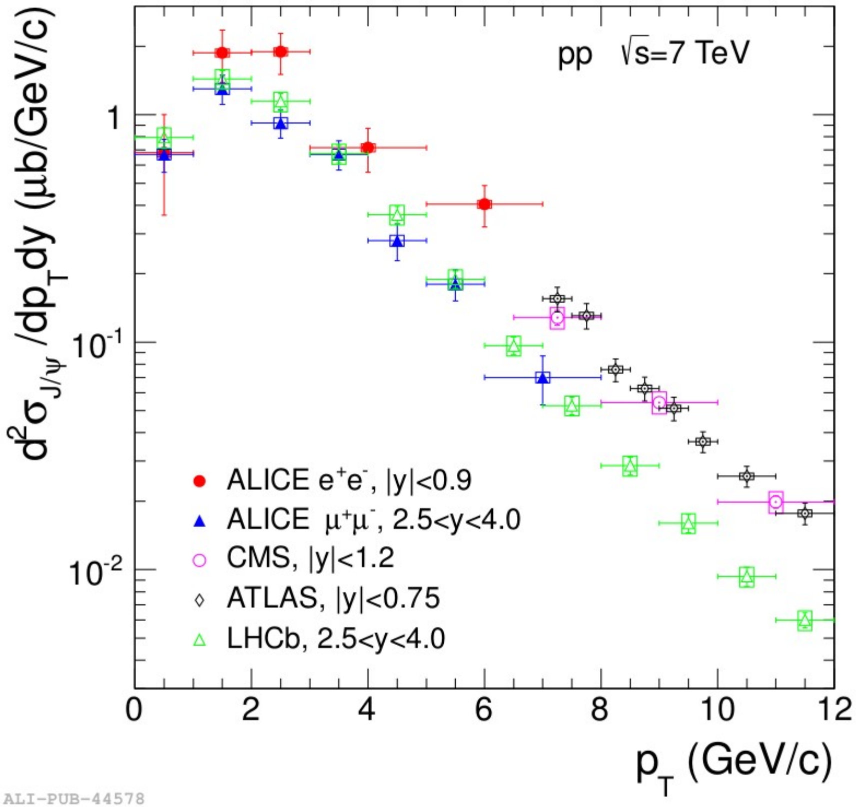


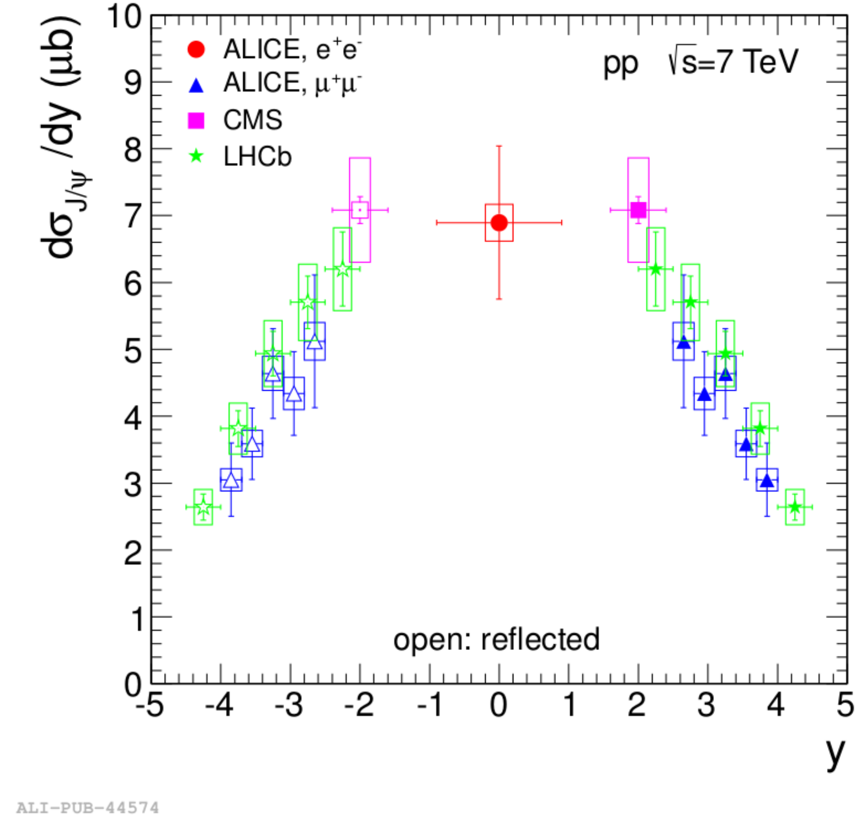
Channel	e^+e^-		$\mu^+\mu^-$	
Signal extraction	8.5		7.5	
Acceptance input	1.5		5	
Trigger efficiency	0		4	
Reconstruction efficiency	11		3	
R factor	–		3	
Luminosity	4		5.5	
B.R.		1		
Polarization	$\lambda = -1$	$\lambda = 1$	$\lambda = -1$	$\lambda = 1$
CS	+19	−13	+31	−15
HE	+21	−15	+22	−10



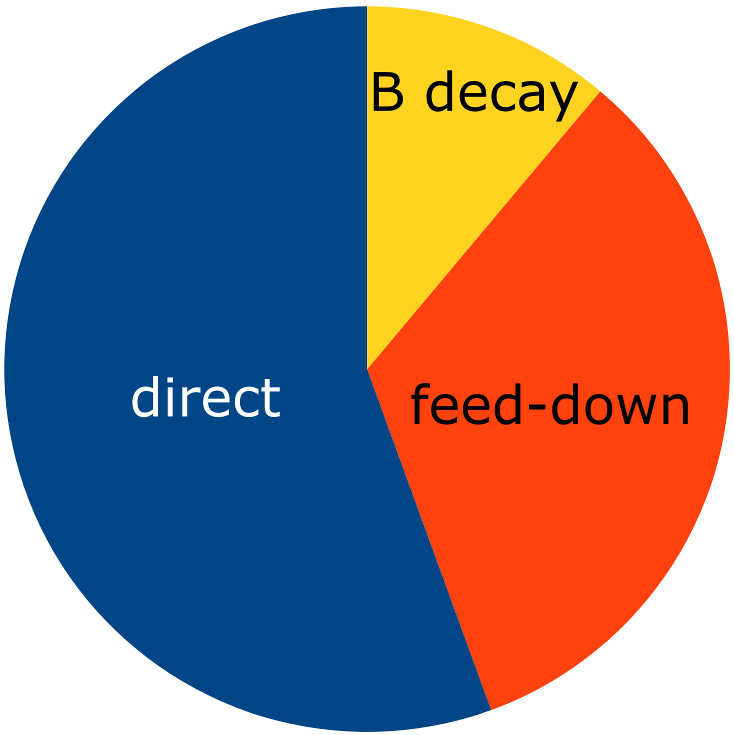
- take efficiencies into account to extract inclusive cross section
- systematic errors mainly due to unknown J/ψ polarization

Inclusive J/ψ cross section





Sources of inclusive J/ψ

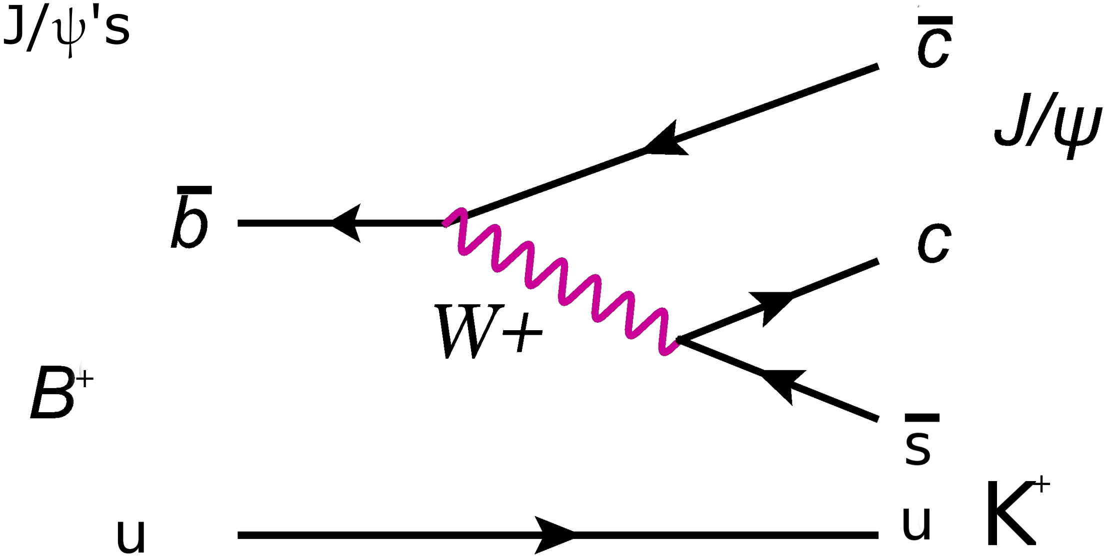


- Prompt
  - **Direct production**: 50-60%
  - **Feed-down** from heavier charmonia ($\psi(2s)$, χ_c): 30-40%
- Non-prompt
  - **B meson decay**: ~10%, p_T dependent

(numbers for LHC energies)

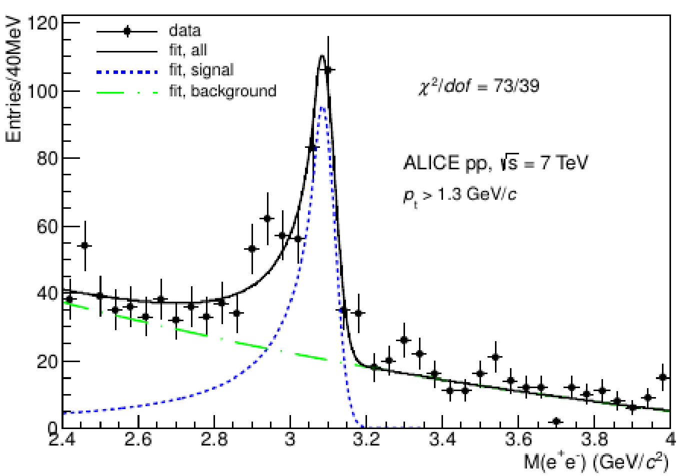
B mesons

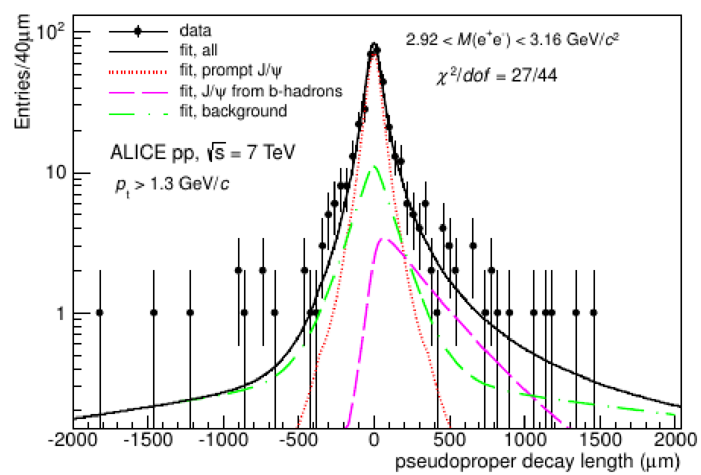
- mesons with 1 b (anti-) quark and one light quark
- masses > 5280 MeV/c²
- weak decay to charmonium
- $c\tau \approx 450 - 500\,\mu m$ → can be used to disentangle prompt from non-prompt J/ψ's



J/ψ from B decay

- for each J/ψ candidate:
  - find primary vertex and J/ψ decay vertex, connect by vector $\vec{L}$
  - project on J/ψ p_T → $L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{p_T}$
  - → **pseudoproper decay length** $l_{J/\psi} = \frac{c \cdot L_{xy} \cdot m_{J/\psi}}{p_T}$





JHEP 11 (2012) 065

J/ψ from B decay

- fit simultaneously mass spectrum and $l_{J/\psi}$ distribution by log-likelihood function

$$\ln L = \sum_{i=1}^{N} \ln F(l_{J/\psi}, m_{ll})$$

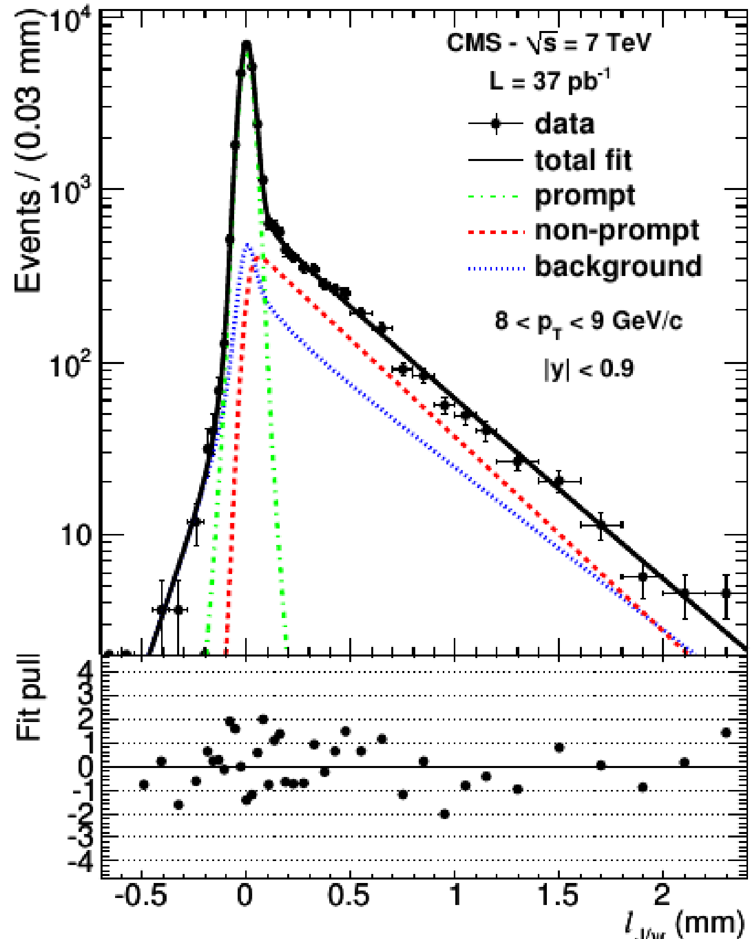
- contributions from signal and background

- signal $l_{J/\psi}$ shape:

$$F_{Sig}(l_{J/\psi}) = f_B \cdot F_B(l_{J/\psi}) + (1 - f_B) \cdot F_p(l_{J/\psi})$$

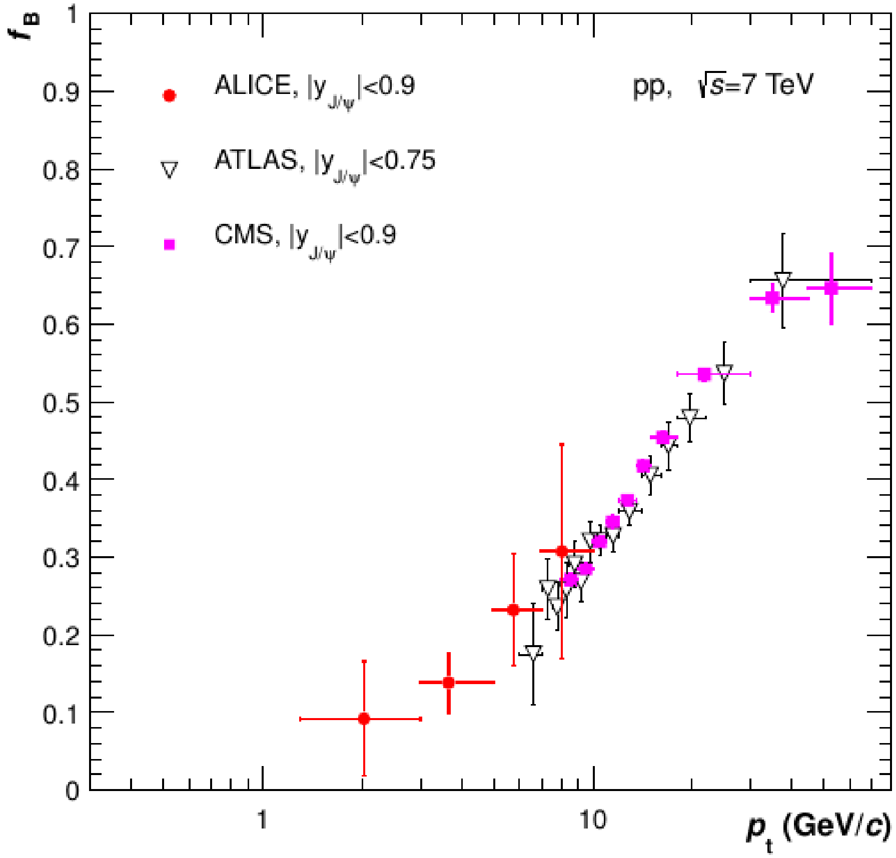
$F_p(l_{J/\psi})$: resolution function

$F_p(l_{J/\psi})$: res. fnc. + true $l_{J/\psi}$ distribution



JHEP 02 (2012) 011

J/ψ from B decay



JHEP 11 (2012) 065

- consistent results from different LHC experiments
- amount of J/ψ from B decay rises with transverse momentum

Prompt J/ψ cross section

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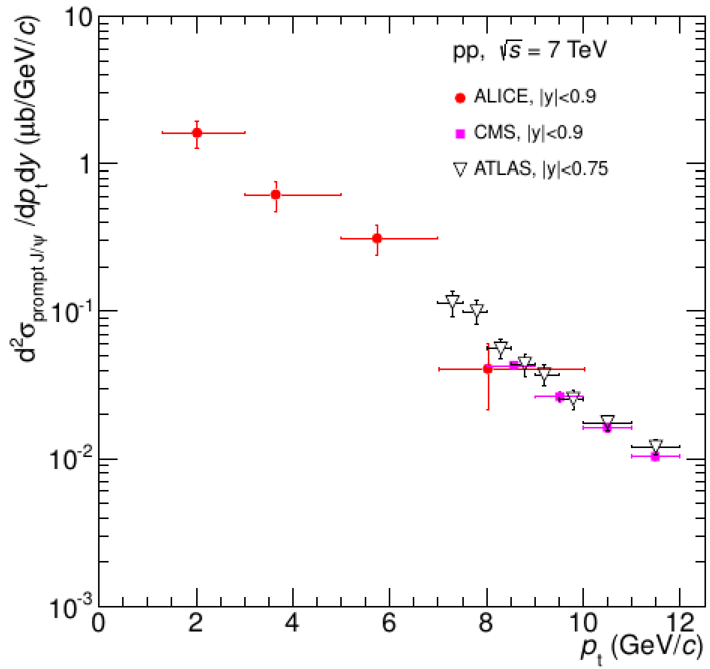
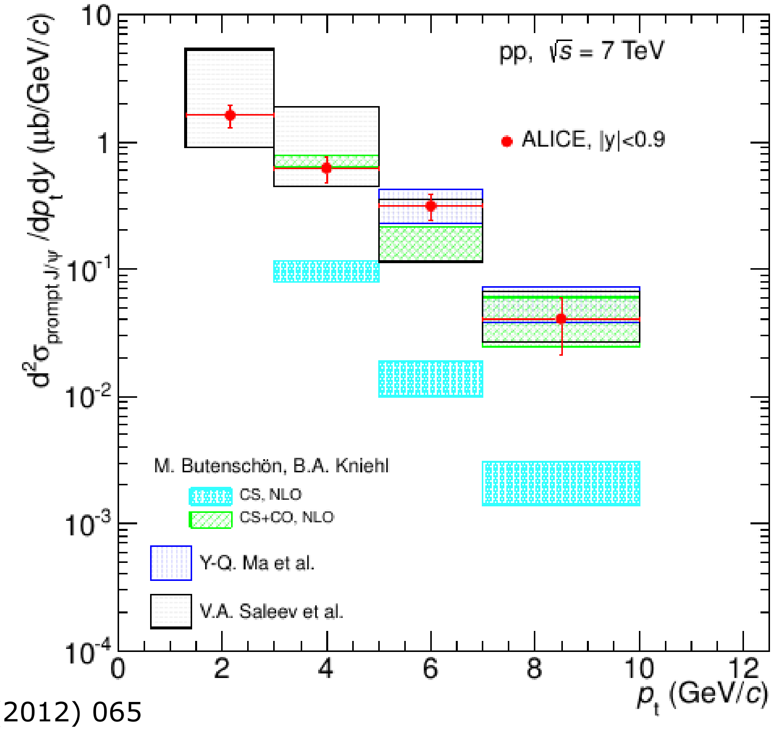
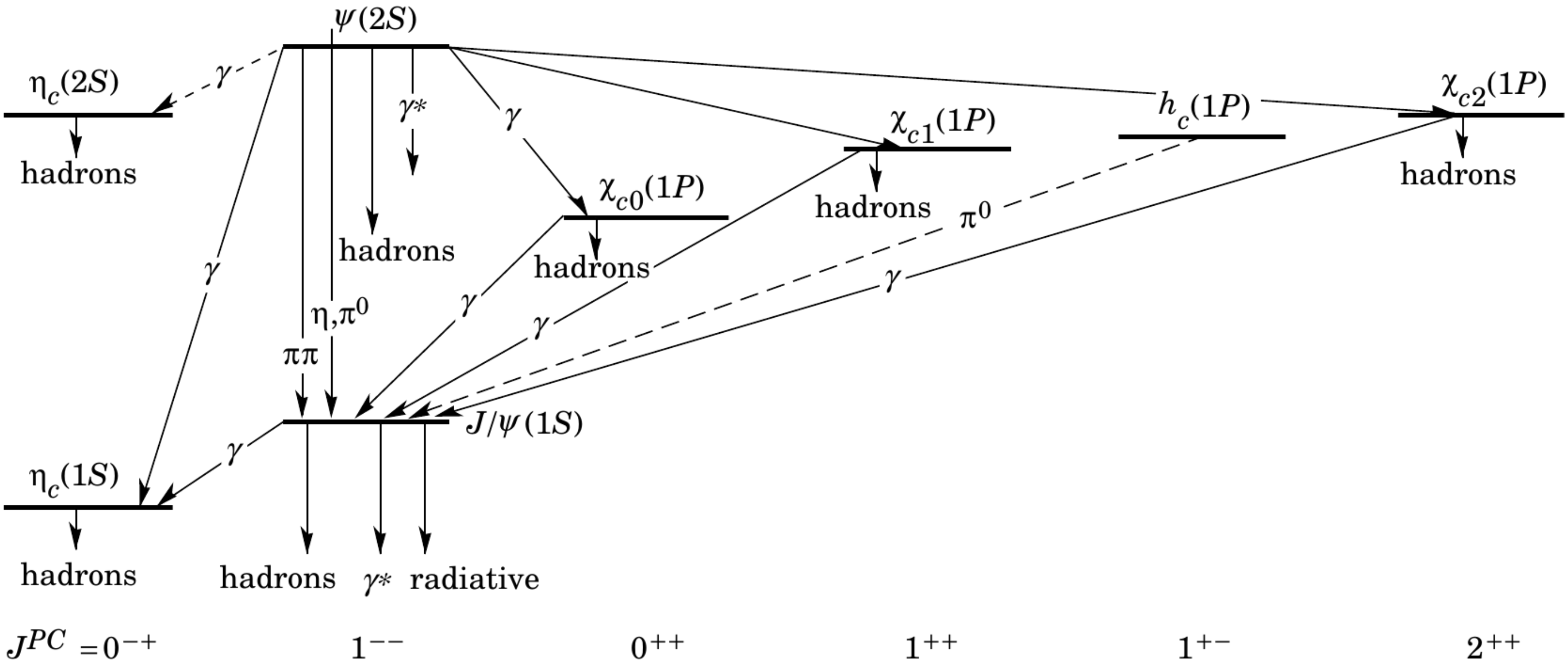




JHEP 11 (2012) 065

- obtain prompt cross section
- comparison with models shows importance of color octet contributions

Higher charmonia states



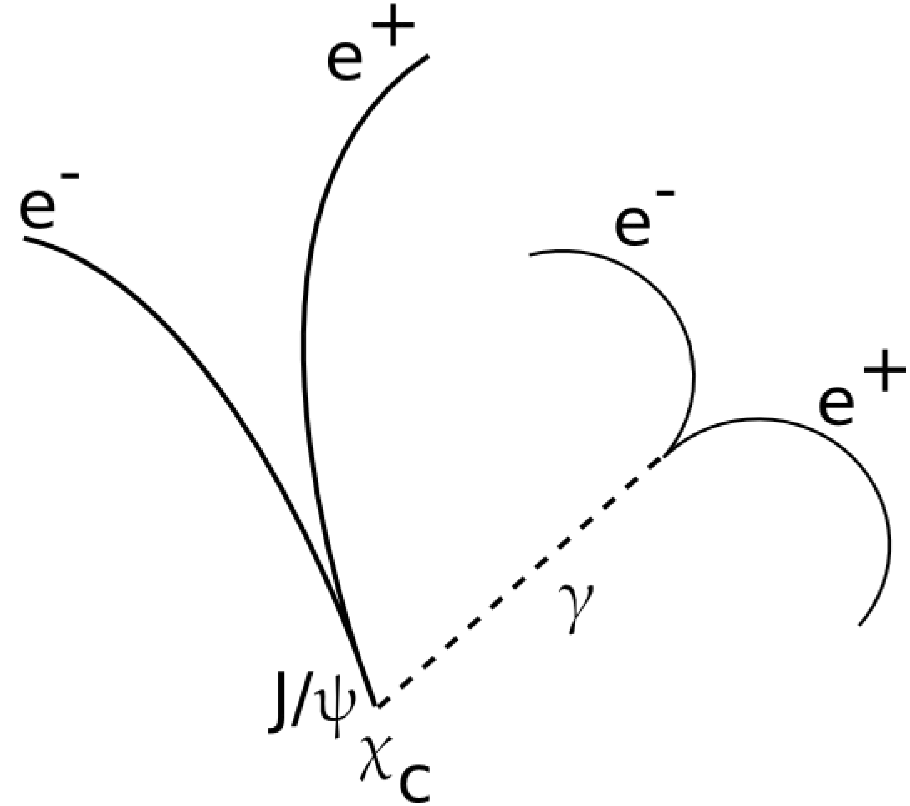
χ_{cJ}

- BR $\chi_{c1} \rightarrow \gamma$ J/ψ: 35%
- BR $\chi_{c2} \rightarrow \gamma$ J/ψ: 20%

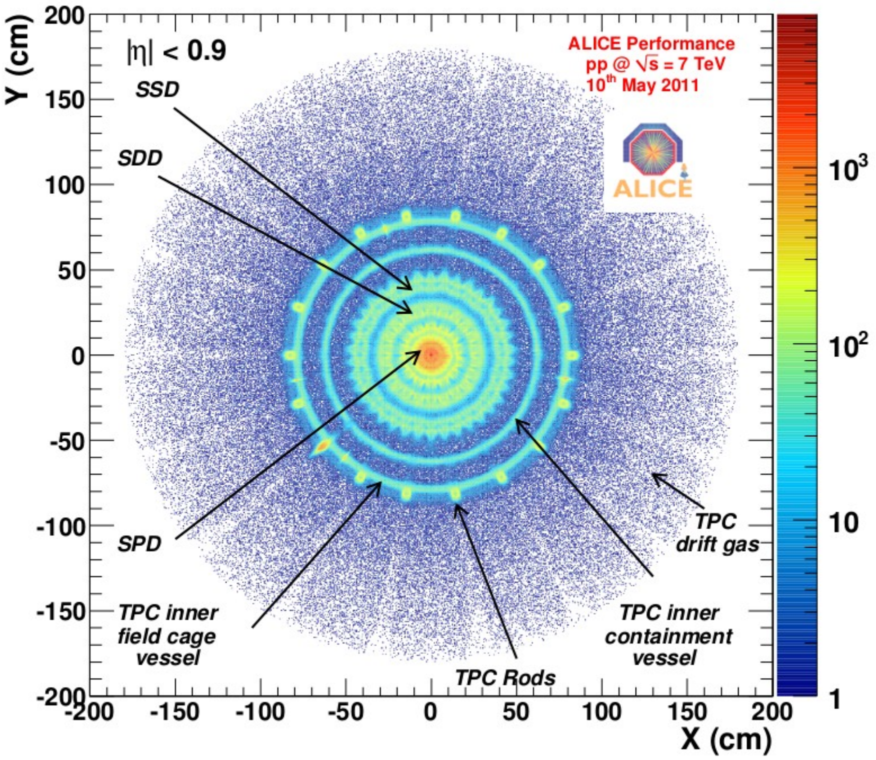
- mass difference between J/ψ and χ_{cJ} : 500 MeV/c² → low momentum γ

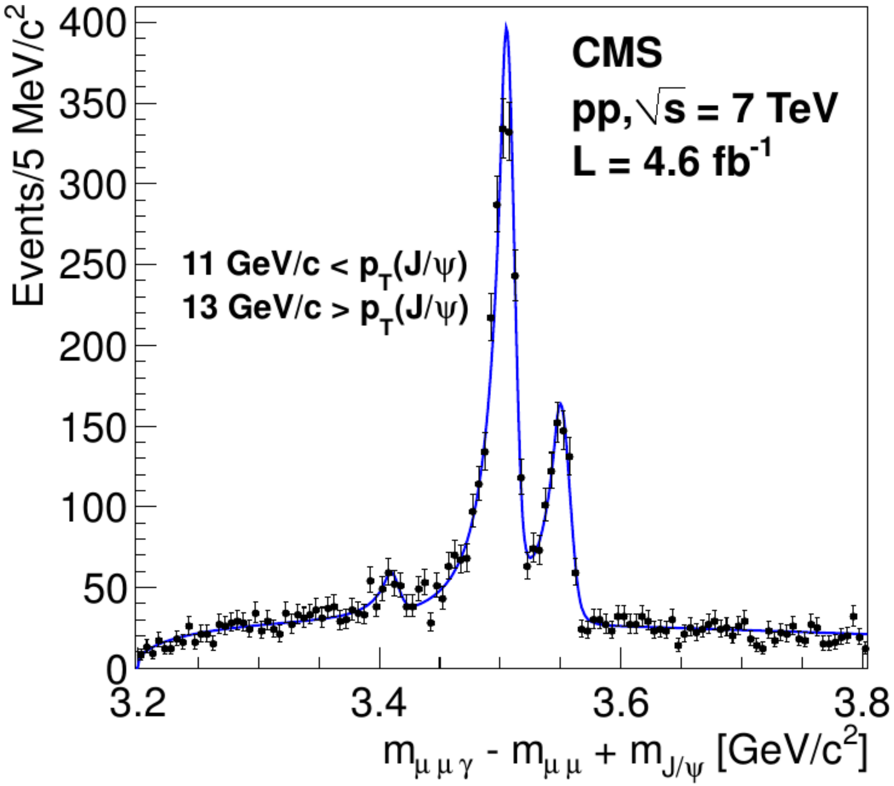
- mass difference between χ_{c1} and χ_{c2} : 45 MeV/c² → high momentum resolution necessary to distinguish states

- often used: conversion $\gamma \rightarrow e^+e^-$



χ_{cJ}

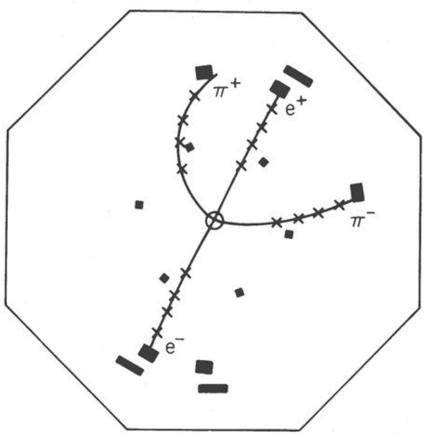




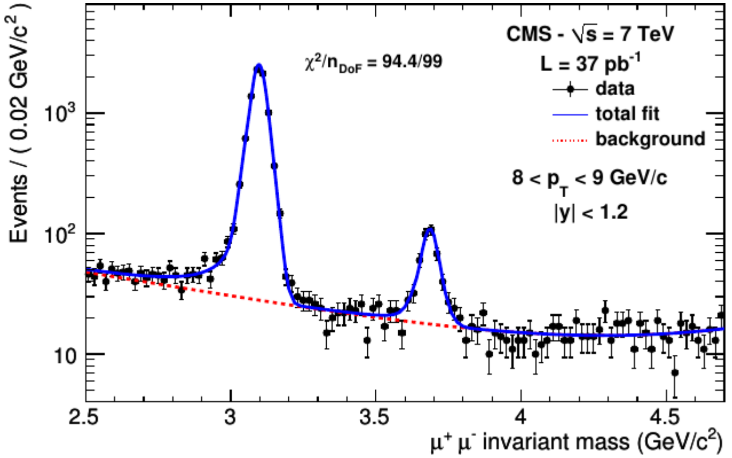
Eur. Phys. J. C 72 (2012) 2251

ψ(2S)

- BR ψ(2S) → J/ψ + anything: 60%
  - BR ψ(2S) → J/ψ + $\pi^+\pi^-$: 34%
  - also ψ(2S) → e^+e^- / $\mu^+\mu^-$: 0.8% each

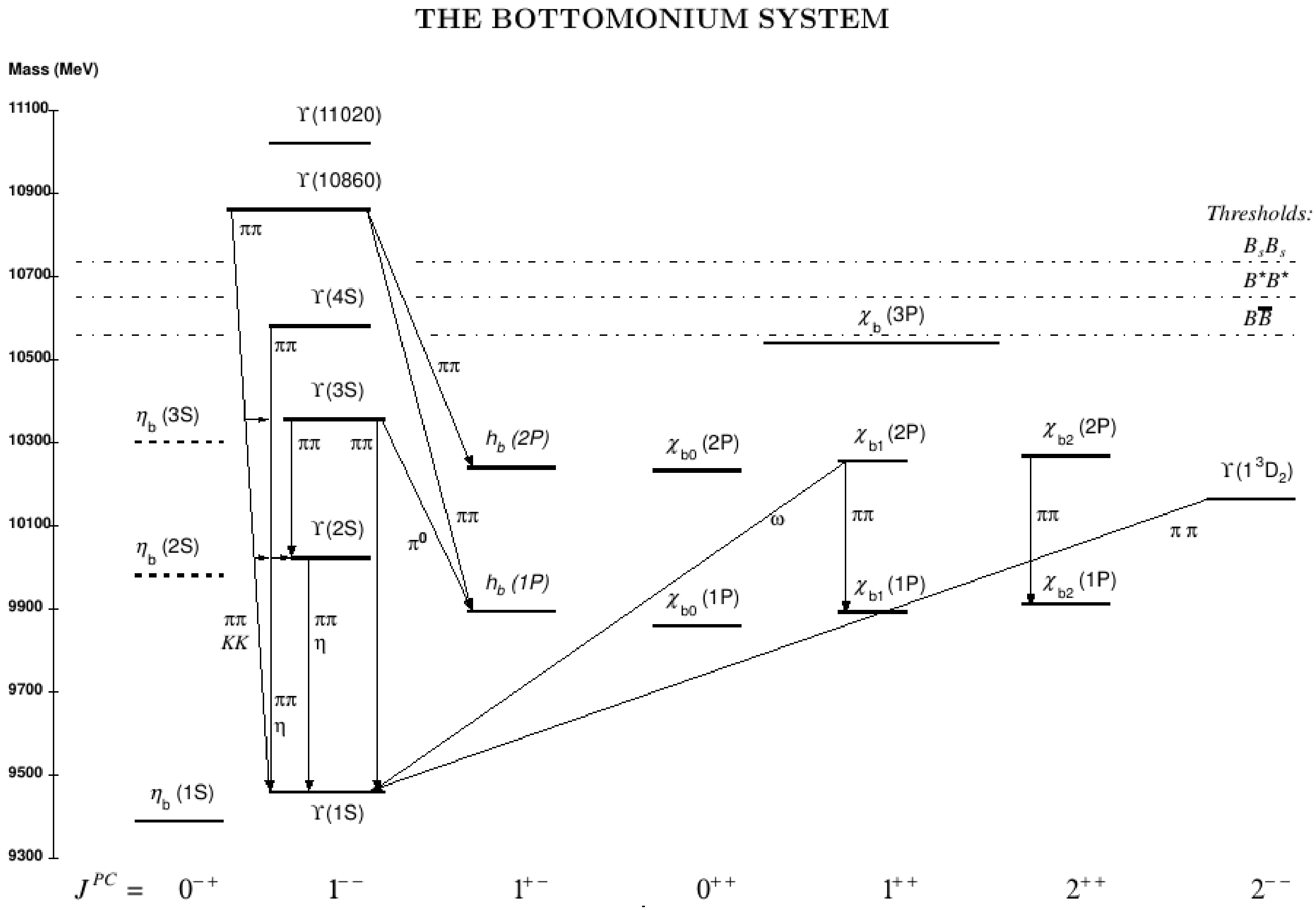


SLAC

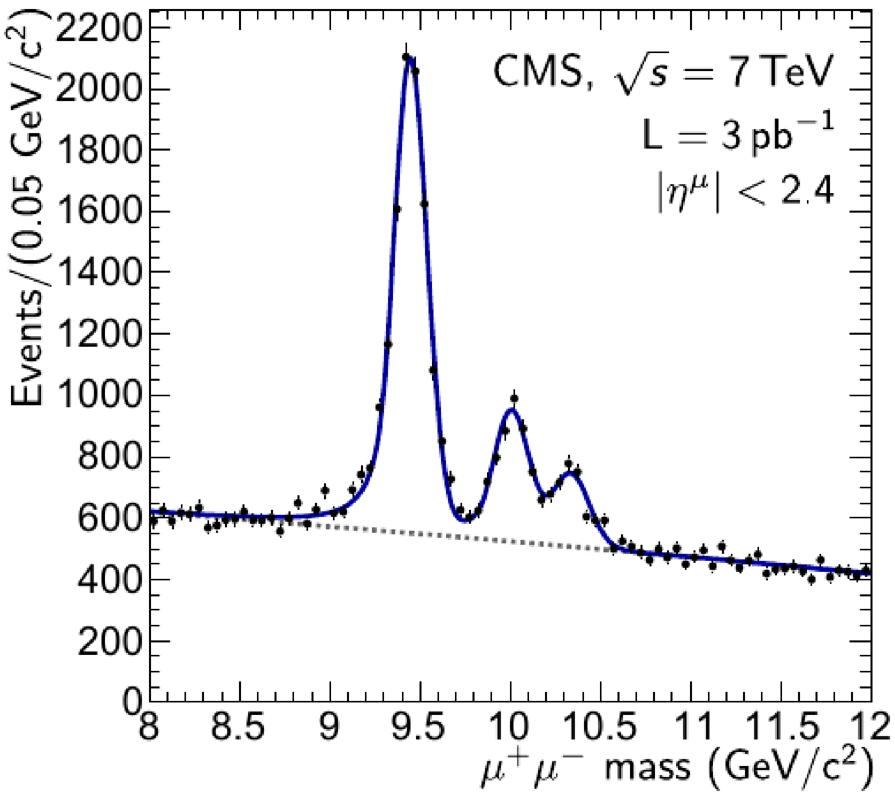


JHEP 02 (2012) 011

Bottomonium



Υ(nS)

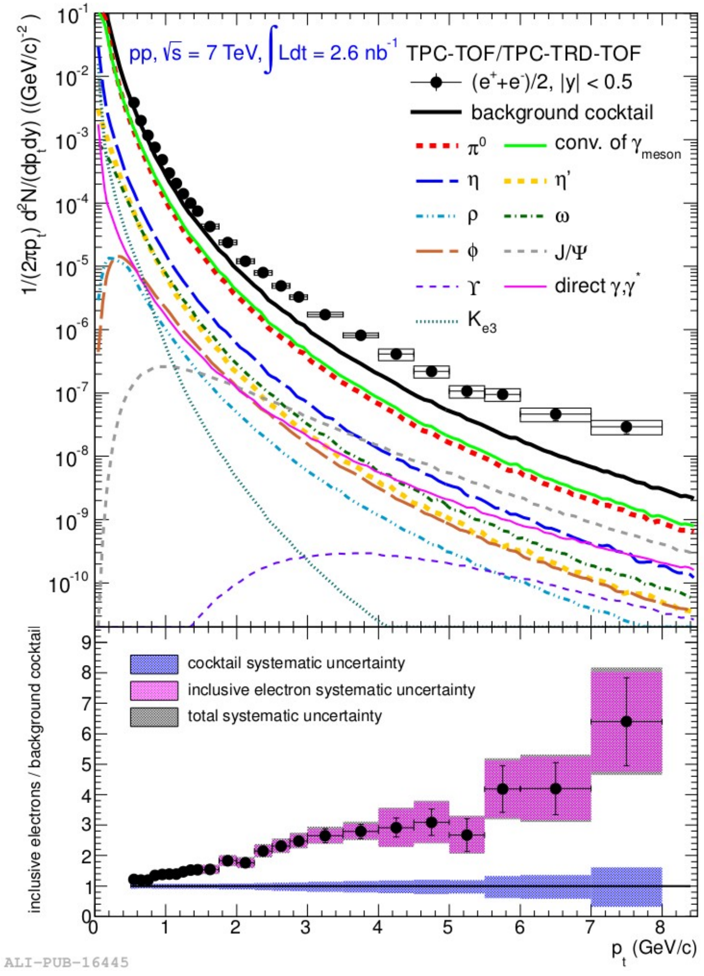


Phys.Rev. D83 (2011) 112004

- as for J/ψ, relatively large BR to dilepton channel: ~5% for Υ(1S)
- Υ(nS) → Υ(1S) + $\pi^+\pi^-$
- …

Open heavy flavor in pp
Semileptonic decays

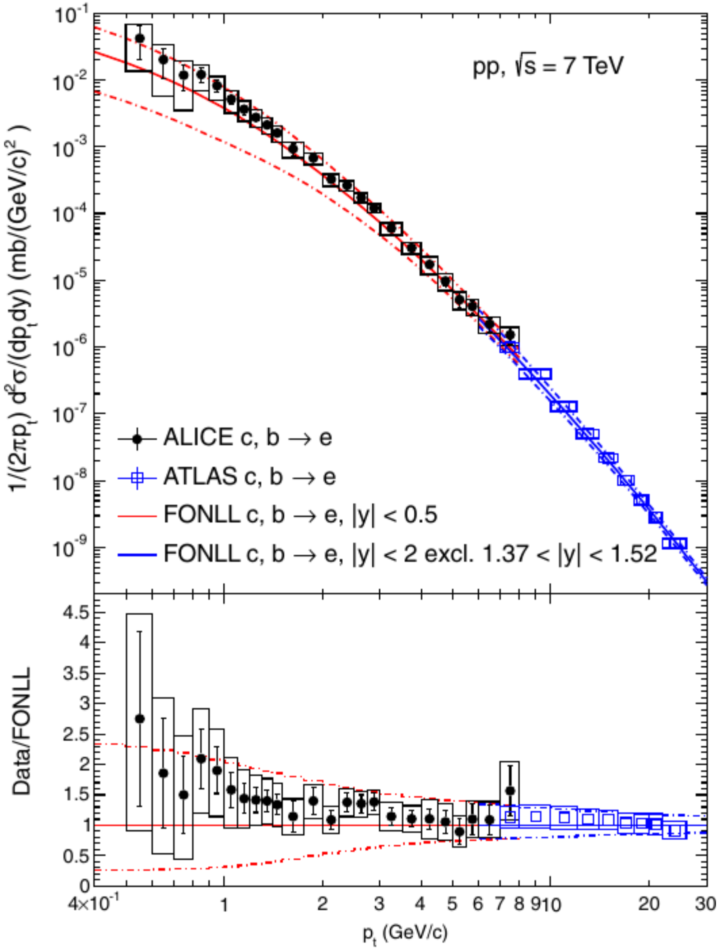
- $D^+ = c\bar{d}\,,\, D^0 = c\bar{u}\,,$ $\bar{D}^0 = \bar{c}u\,,\, D^- = \bar{c}d$ $\qquad c\tau \approx 120 - 310\,\mu m$
- B similar $\qquad c\tau \approx 450 - 500\,\mu m$
- measurement: either electrons from **semileptonic decays:** measure inclusive electron spectrum, subtract electrons from other sources



Open heavy flavor in pp

Semileptonic decays

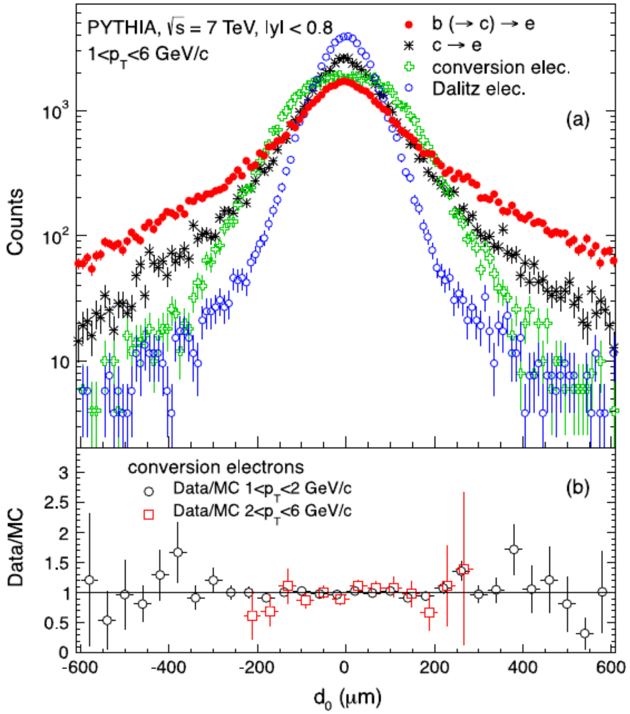
- $D^{+}=c\bar{d}\,,D^{0}=c\bar{u}\,,$
  $\bar{D}^{0}=\bar{c}u\,,D^{-}=\bar{c}d$ $\quad c\tau\approx 120-310\,\mu m$
- B similar $\quad c\tau\approx 450-500\,\mu m$
- measurement: either electrons from **semileptonic decays:** measure inclusive electron spectrum, subtract electrons from other sources
- agreement with FONLL calculations



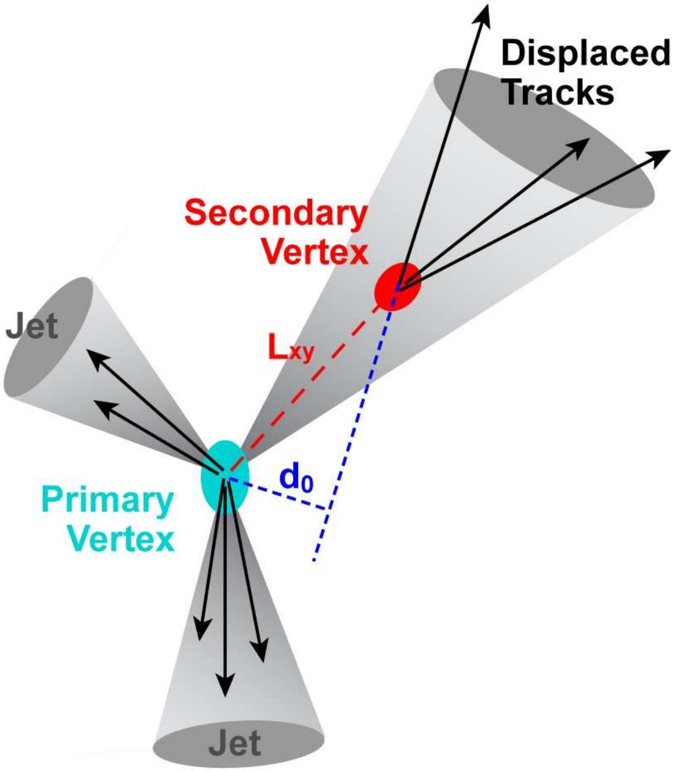
Phys. Rev. D 86, 112007 (2012)

b and c

- use impact parameter to disentangle feed-down from beauty

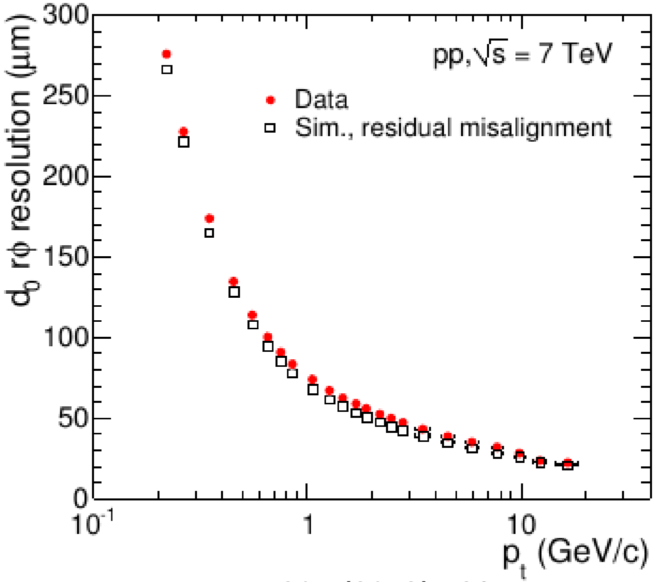


Physics Letters B 721 (2013) 13–23

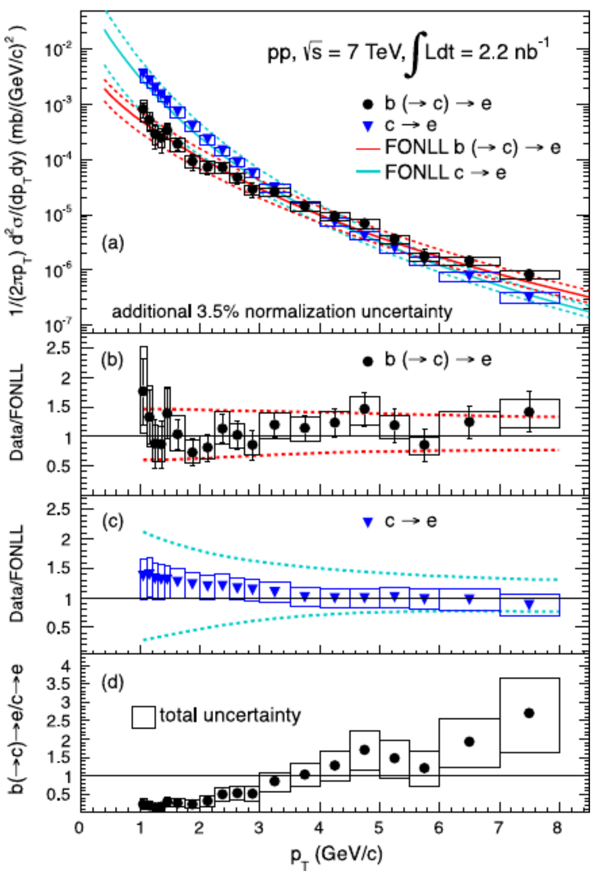


b and c

- use impact parameter to disentangle feed-down from beauty
- high resolution in ALICE:



JHEP 1201 (2012) 128



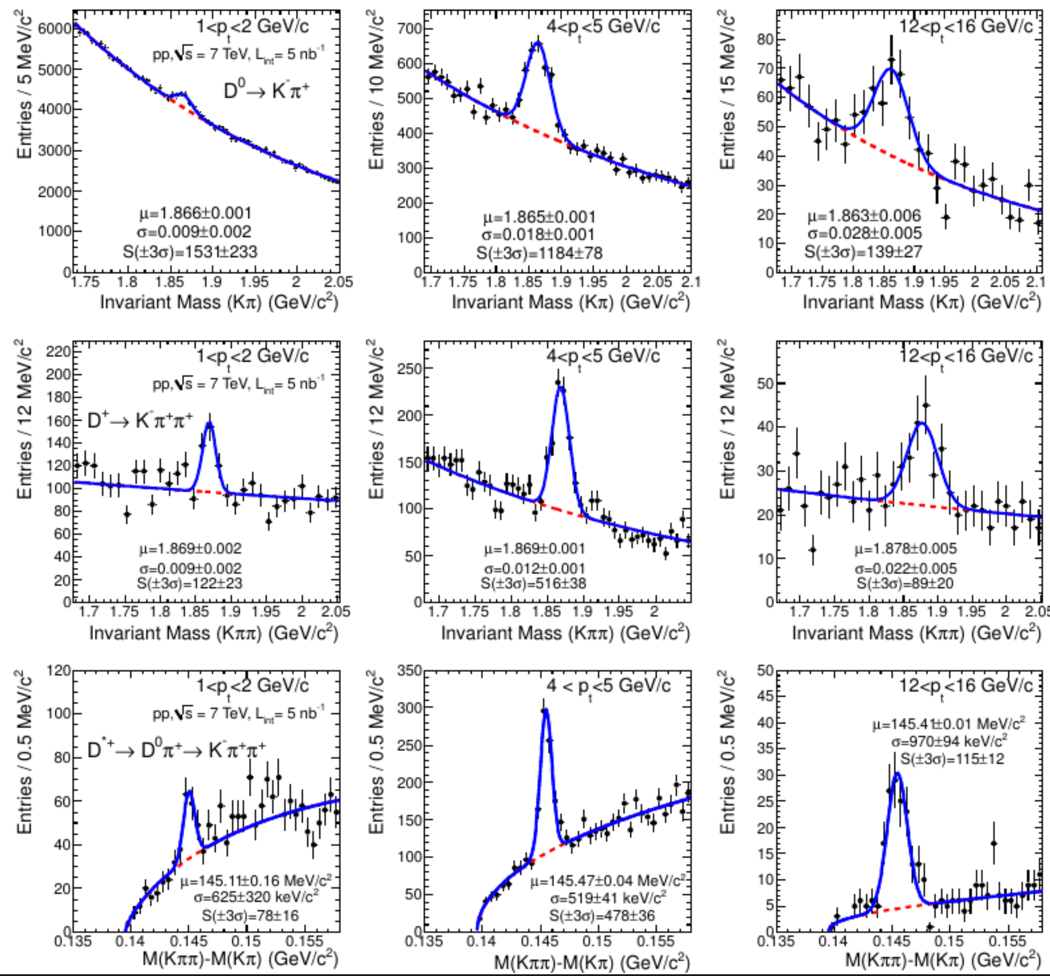
Physics Letters B 721 (2013) 13–23

Open heavy flavor in pp

Hadronic decays

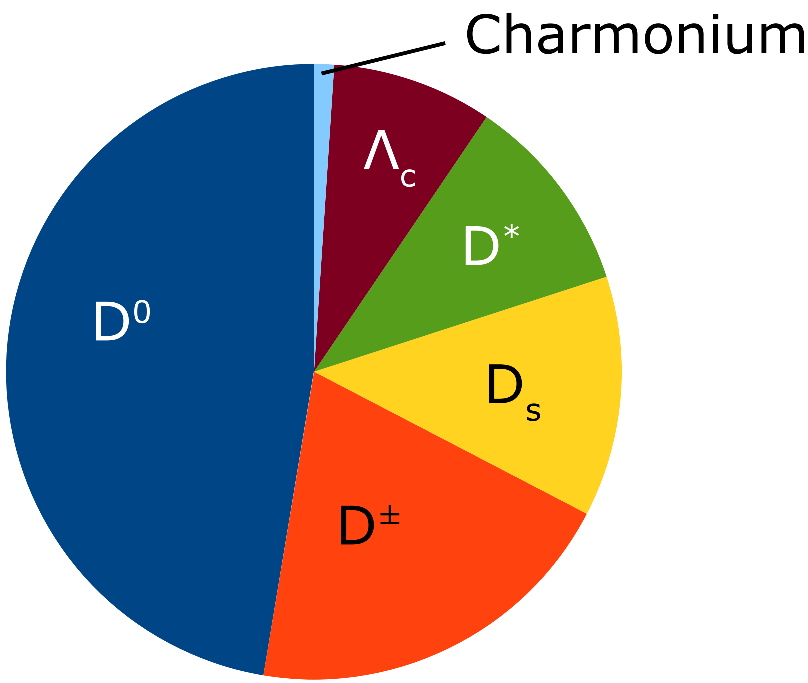
- measurement:
  or **reconstruction** of decay products from hadronic decays

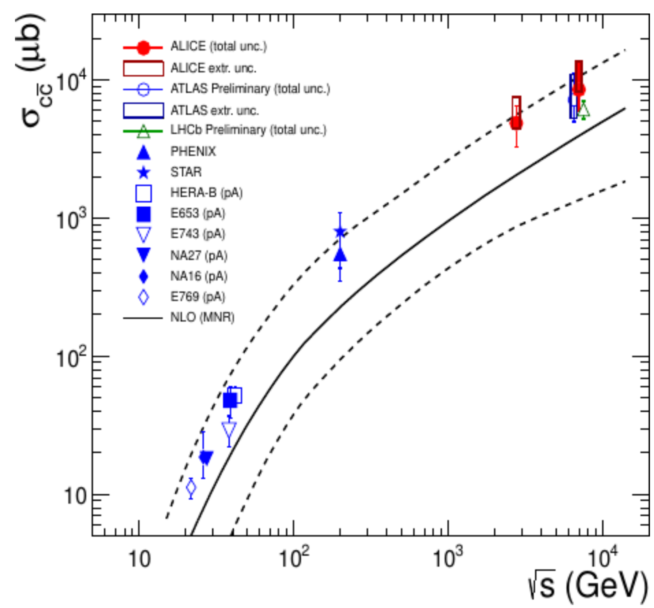
- require minimum impact parameter to reduce background



JHEP 1201 (2012) 128

Total charm cross section

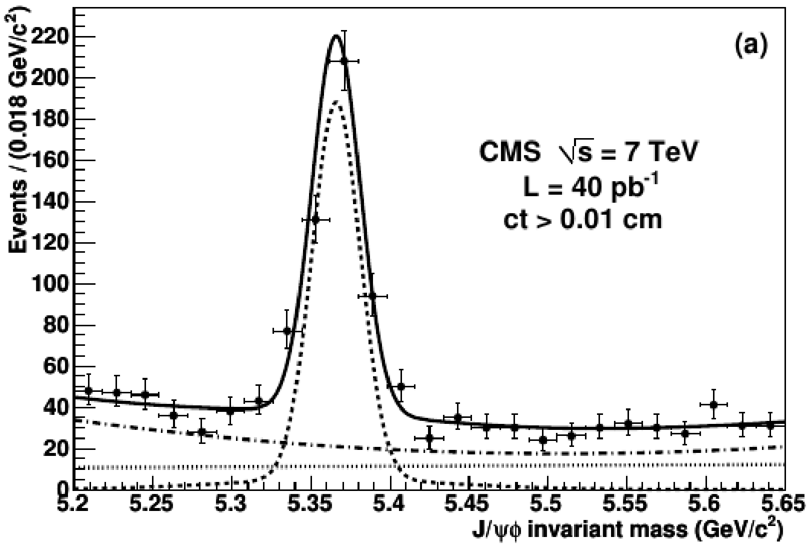




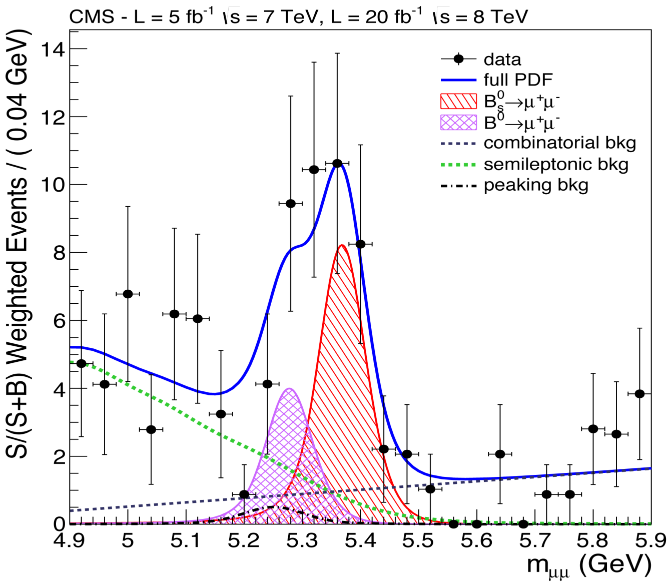
JHEP 1201 (2012) 128

- divide cross section for measured D mesons by fragmentation ratio to obtain total charm cross section

B meson reconstruction



Phys.Rev. D84 (2011) 052008



Phys. Rev. Lett. 111 (2013) 101804

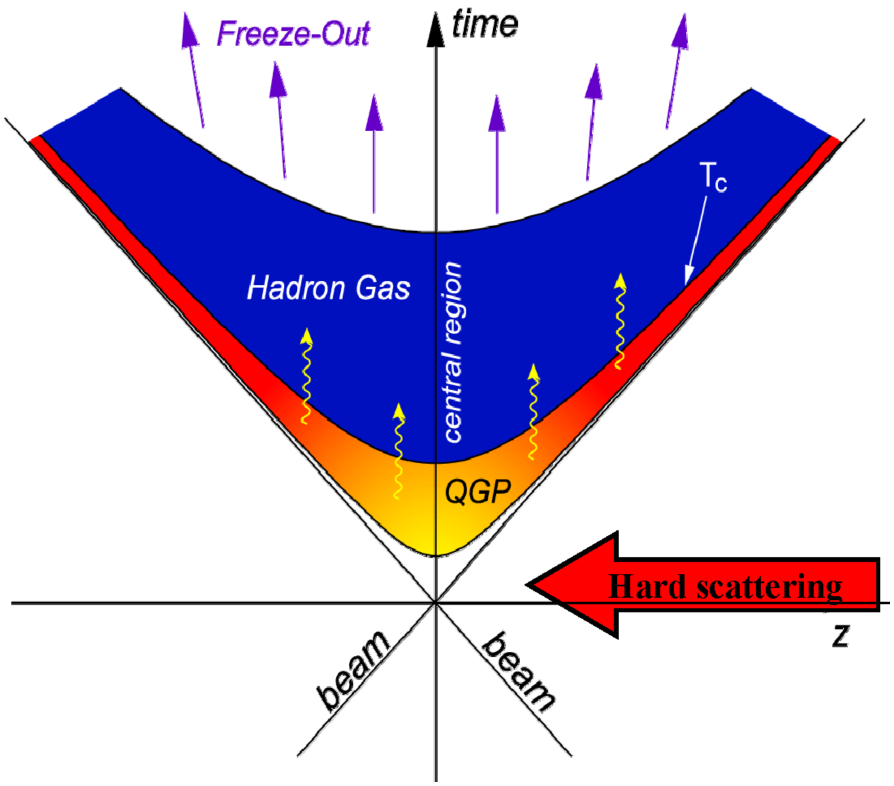
$B_s^0 \rightarrow J/\psi\phi$, BR ~10^{-3}

$B_s^0 \rightarrow \mu\mu$, BR~10^{-9}

- indirect search for physics beyond the standard model
- probes CP violation

Heavy quarks in heavy-ion collisions

- heavy quarks are produced early on in the collision ($m_c \gg T_c$ → thermal production strongly suppressed)
- maintain their identity throughout all stages of the collision
- → ideal probe for the medium created in the collision

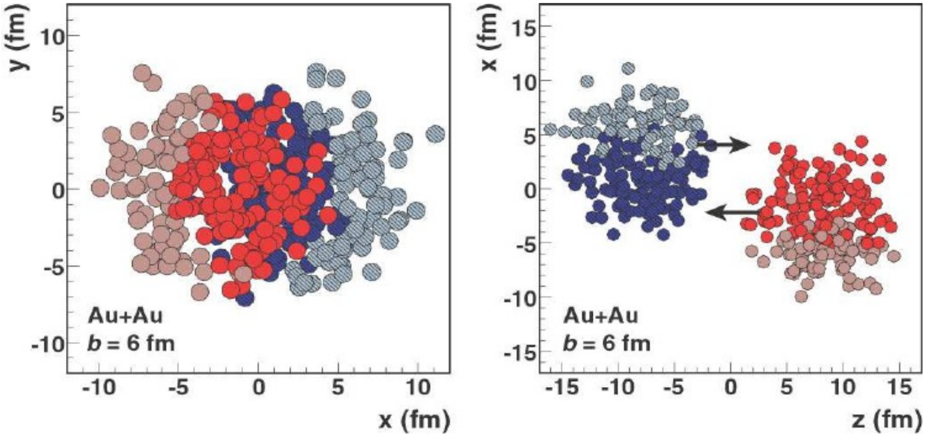


Charmonium suppression

- Quantified by nuclear modification factor:

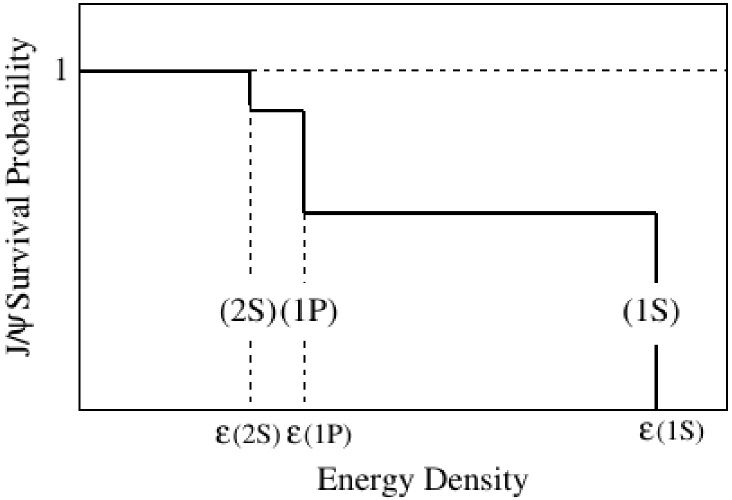
$$R_{AA} = \frac{d^2 N_{AA} / dp_T\, dy}{\langle N_{coll} \rangle d^2 N_{pp} / dp_T\, dy}$$

- compare yield in heavy-ion and proton-proton collisions
- hard probes → scale by mean number of collisions for given centrality → Glauber Monte Carlo calculations

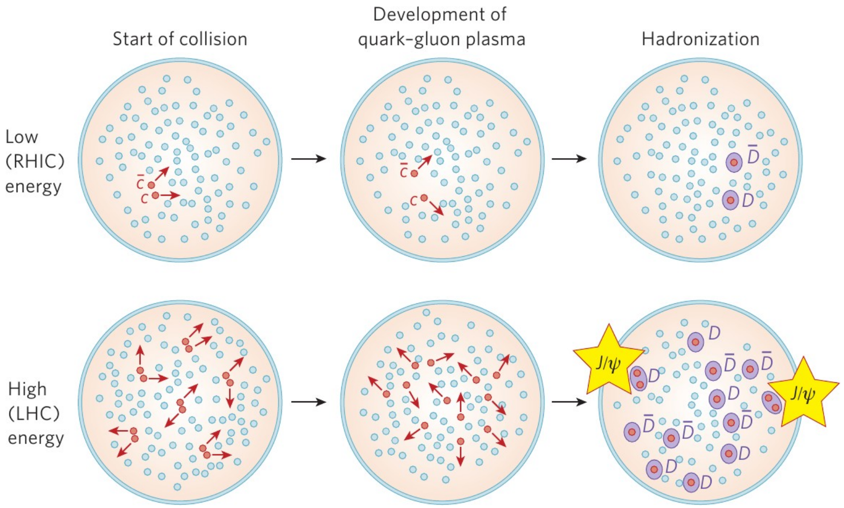


Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243

Charmonia melting & (re)combination



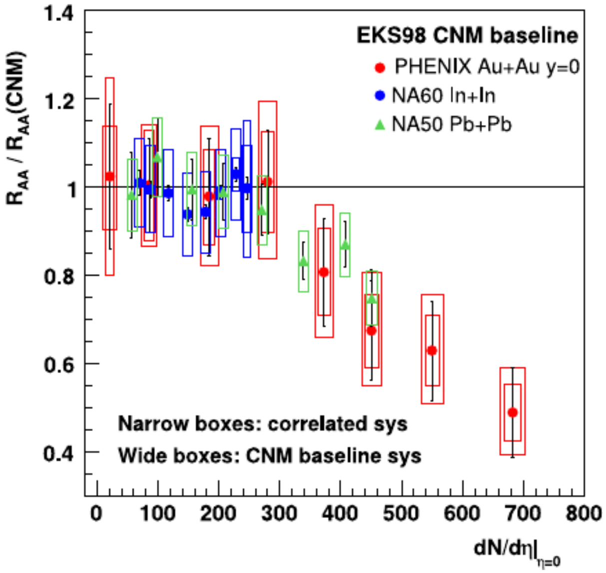
Nucl.Phys. A783 (2007) 249-260



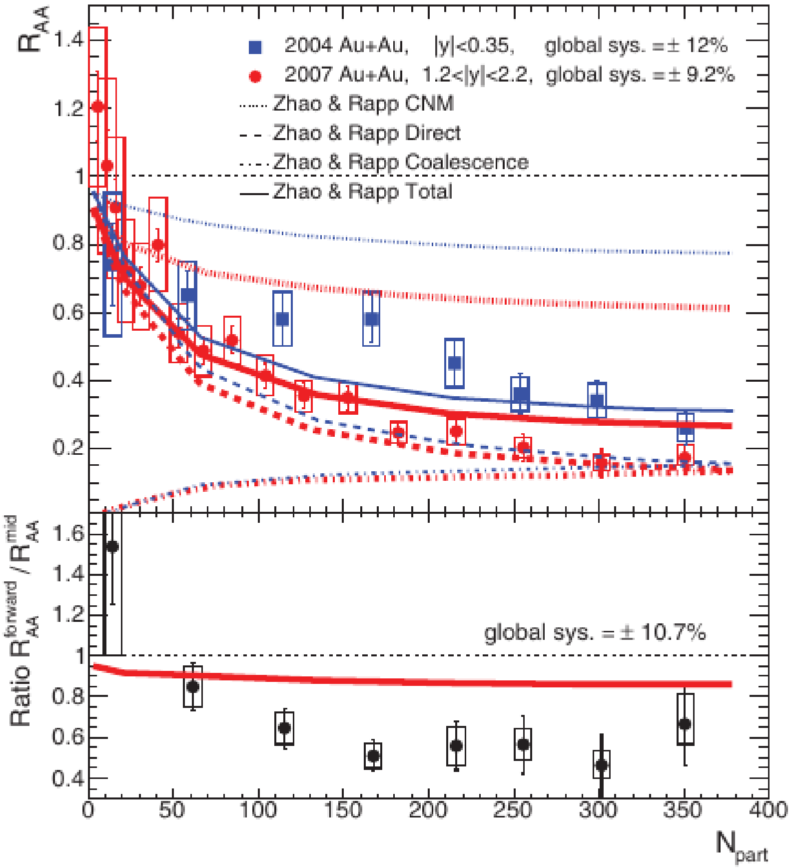
Nature 448, 302-309

- potential between c and $\bar{c}$ quark is screened by free color charges in QGP → "melting" of charmonia states with increasing T
- at higher (LHC) energies, $c\bar{c}$ are abundantly produced → (re)combination to charmonia at phase boundary (Statistical Hadronization Model) or continuous creation and dissociation during hot phase (transport models)

SPS + RHIC



Eur. Phys. J. C71 (2011) 1534

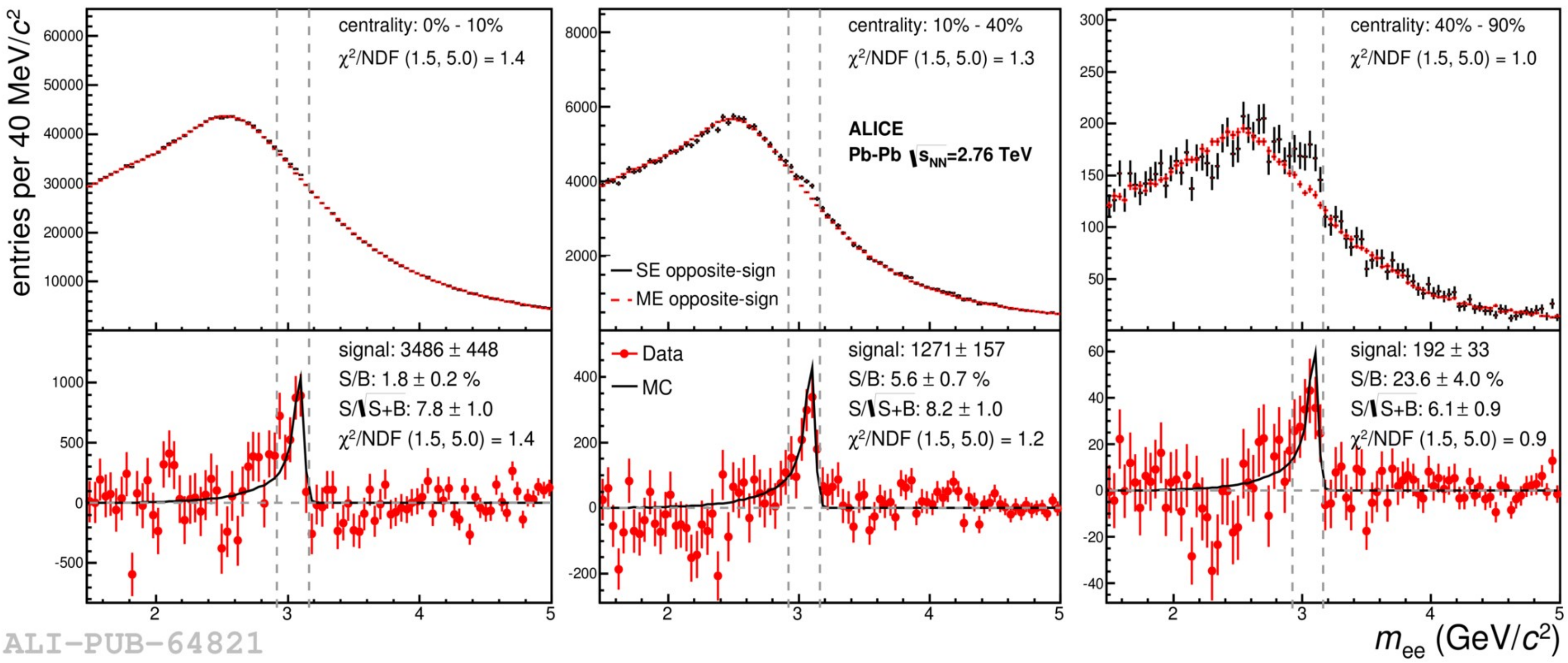


Phys. Rev. C 84, 054912 (2011)

- agreeing results
- BUT: at RHIC less suppression at midrapidity → hint for (re)combination?

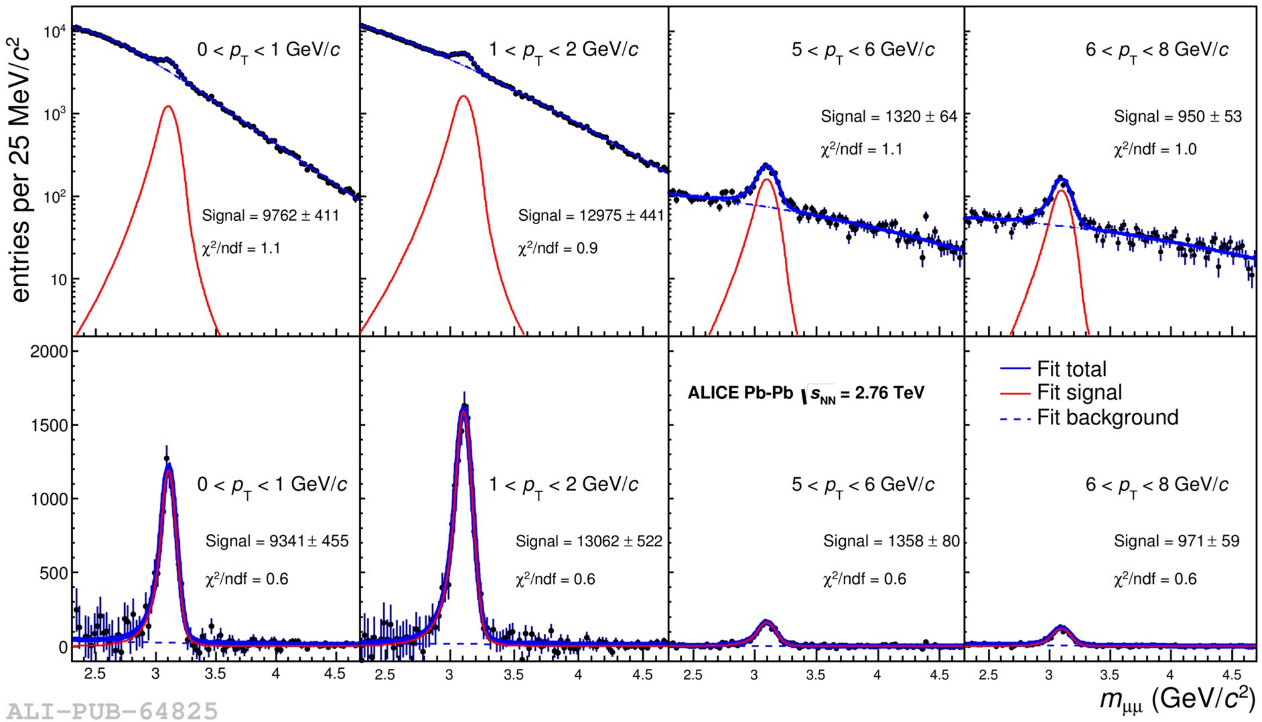
ALICE measurements

- J/ψ → ee
- reminder: in pp: S/B ~ 1

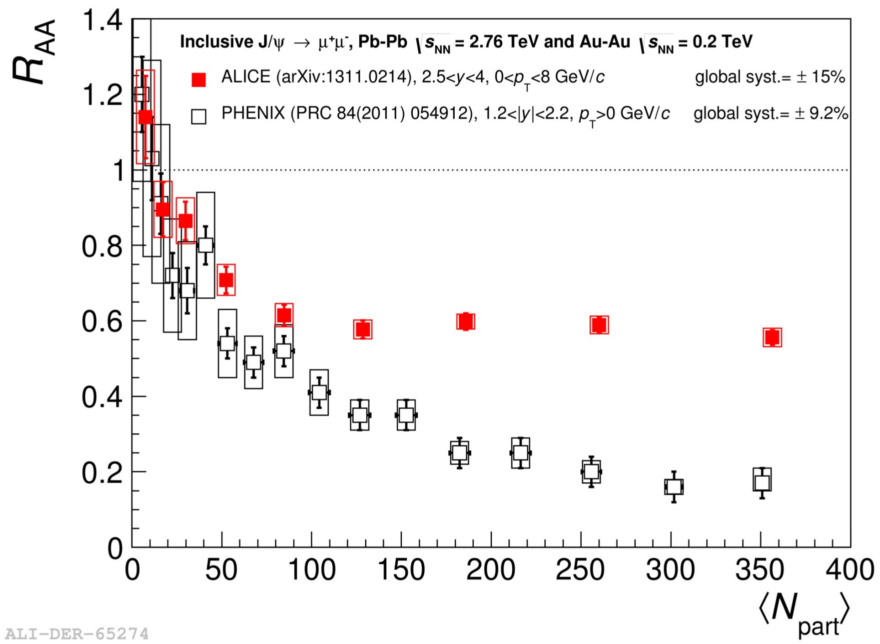


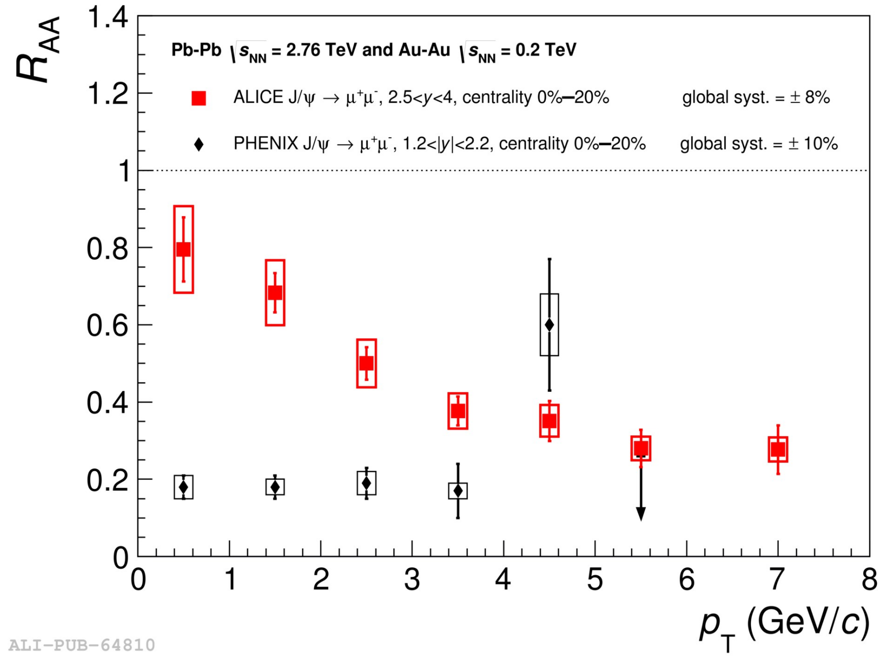
ALICE measurements

- J/ψ →μμ
- reminder: in pp: S/B ~ 2-3



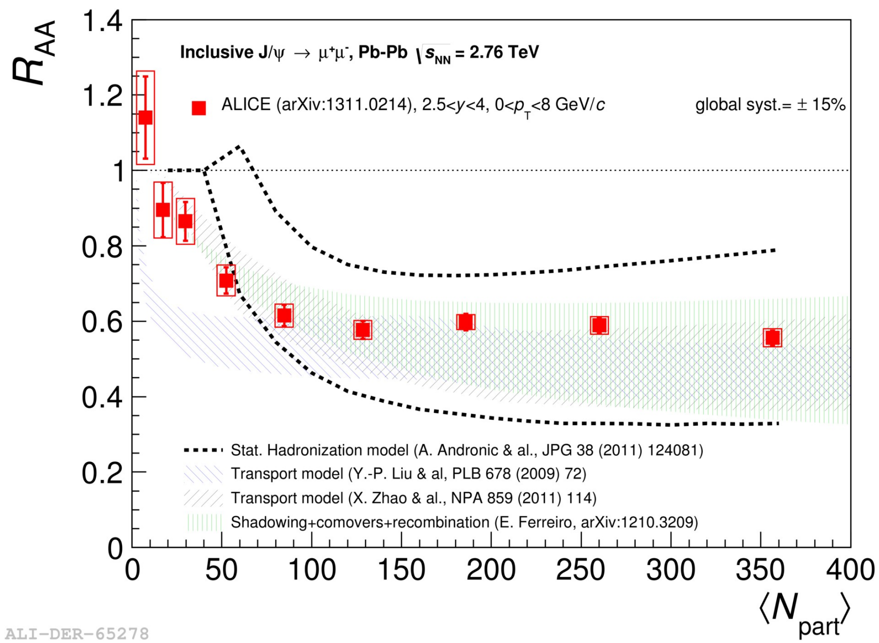
J/ψ R_{AA} at LHC energies

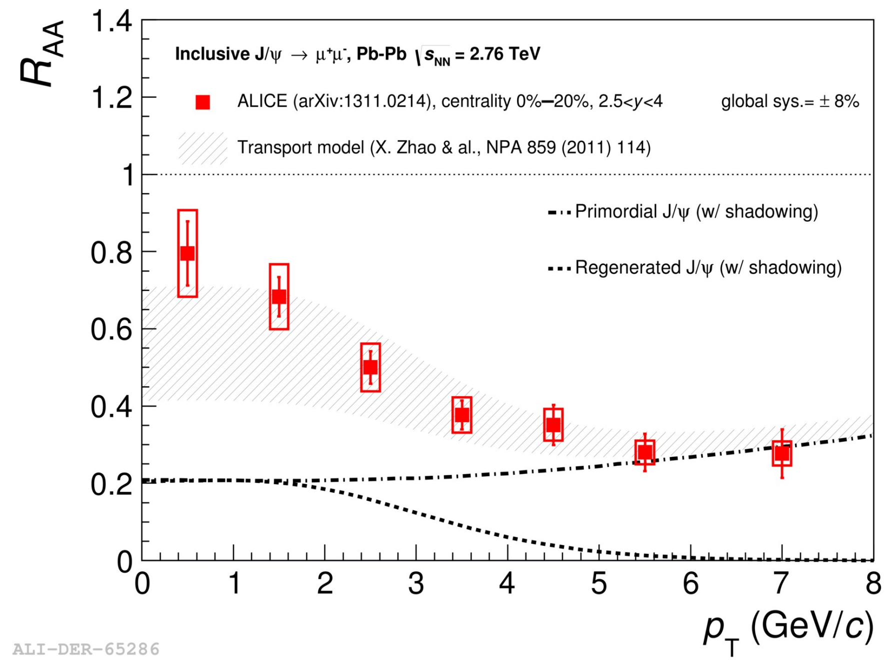




- less suppression in central collisions and at low p_T than at RHIC

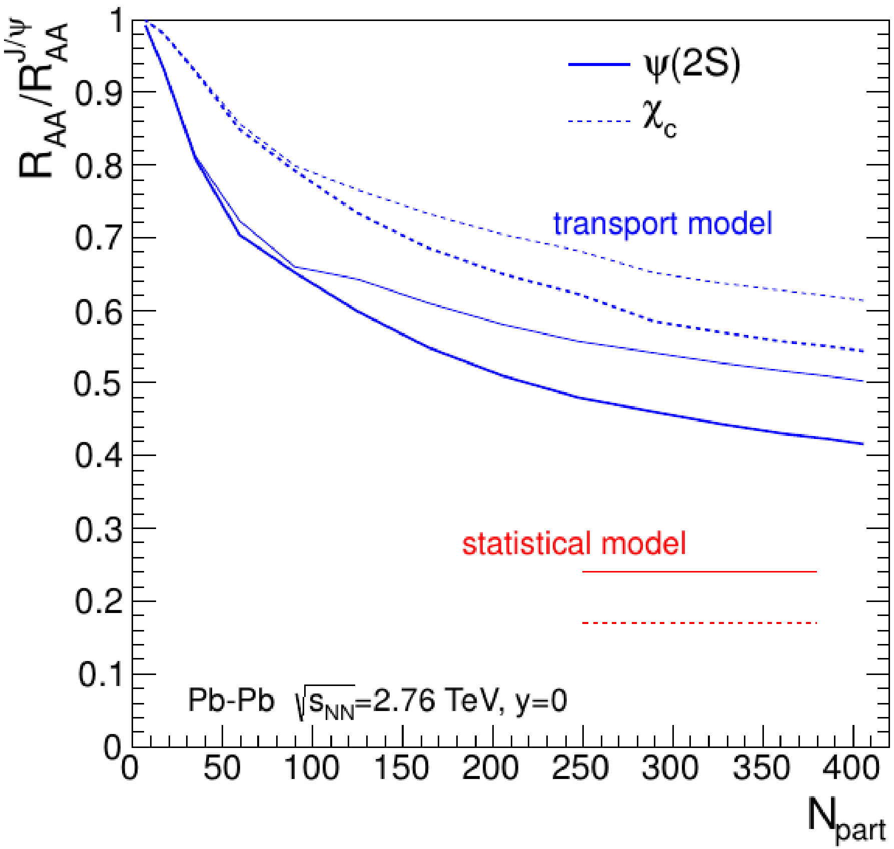
J/ψ R_{AA} at LHC energies: models





- data reasonably well described by models
- models based on very different physical assumptions perform comparably well in describing the data

Higher charmonia states



CERN-LHCC-2012-012 ; LHCC-I-022

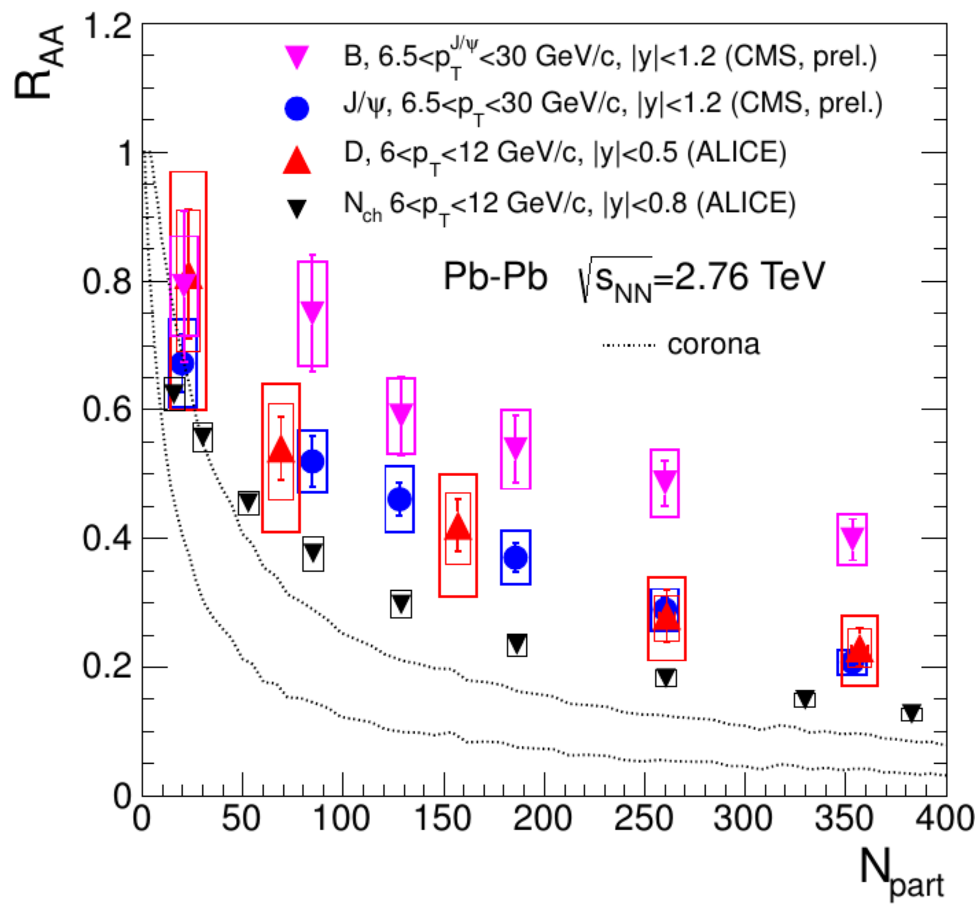
- different models make different predictions for R_{AA} of higher mass charmonia with respect to J/ψ
- measurements can help to discriminate between competing models

Heavy quark energy loss

- smaller loss expected than for light quarks → **dead cone effect**: gluon radiation suppressed at $\theta_0 < m/E$

- measurements in favor of this assumptions

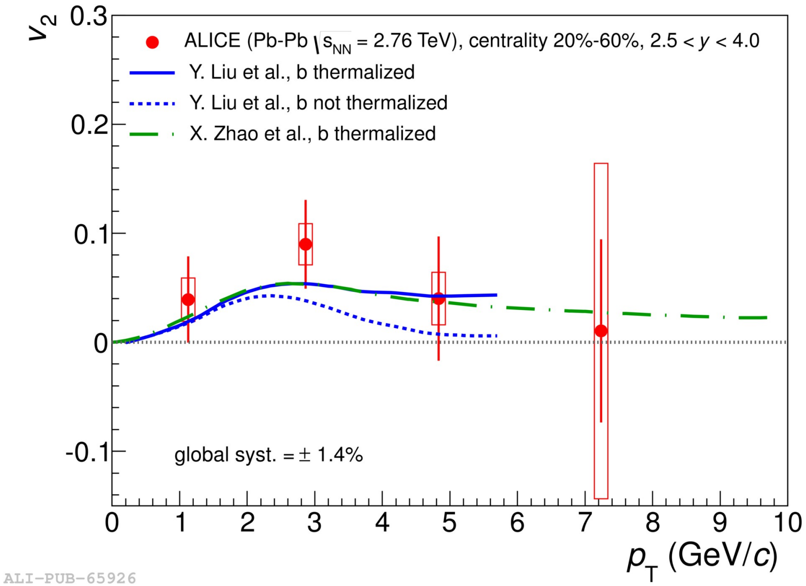
  (**Caution**: different p_T and y ranges)

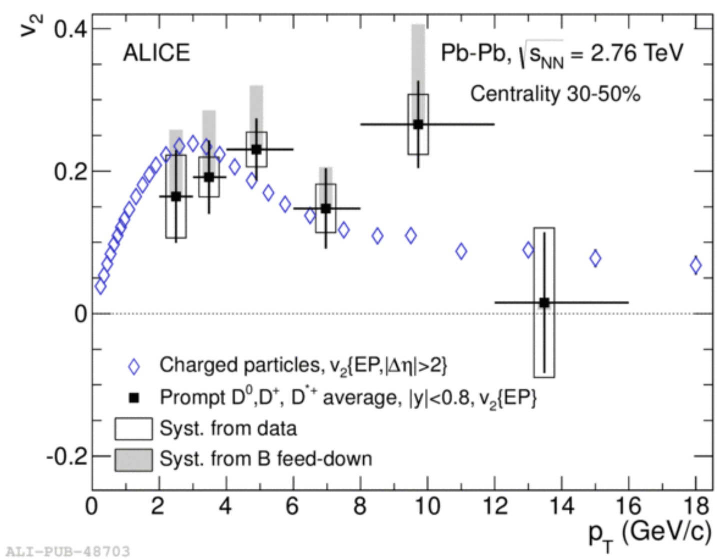


Elliptic flow

- anisotropic (almond shaped) overlap region in non-central collisions →(interaction in medium) → momentum anisotropy

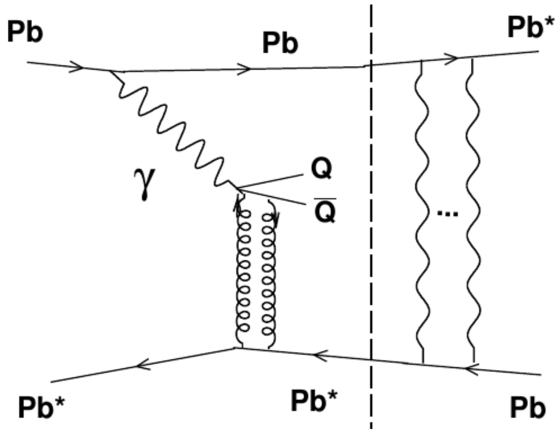
- non-zero elliptic flow seen in both charmonium and open charm

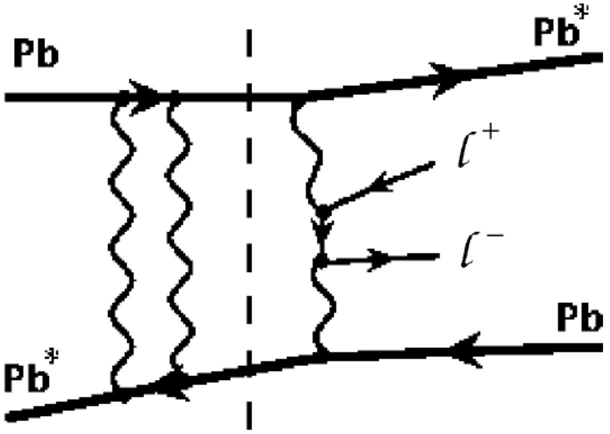




J/ψ in ultra-peripheral collisions

- impact parameter larger than size of nuclei
- strong electromagnetic field between heavy-ion nuclei
- exclusive vector meson production: exchange of two gluons with no net color transfer
- either coherent: photon couples to whole nucleus
  or incoherent: photon couples to single nucleon

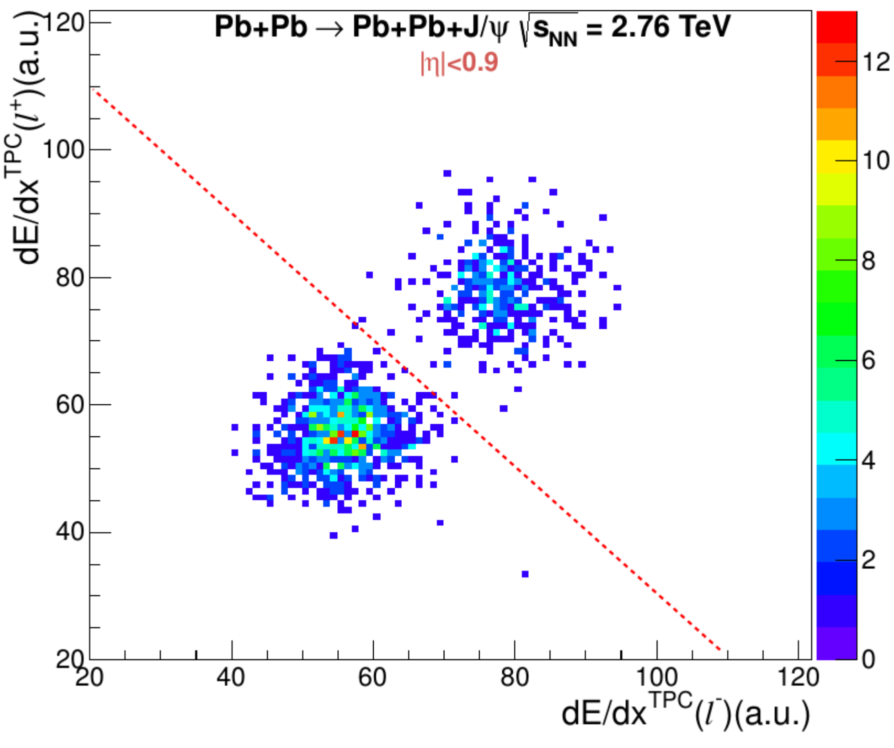


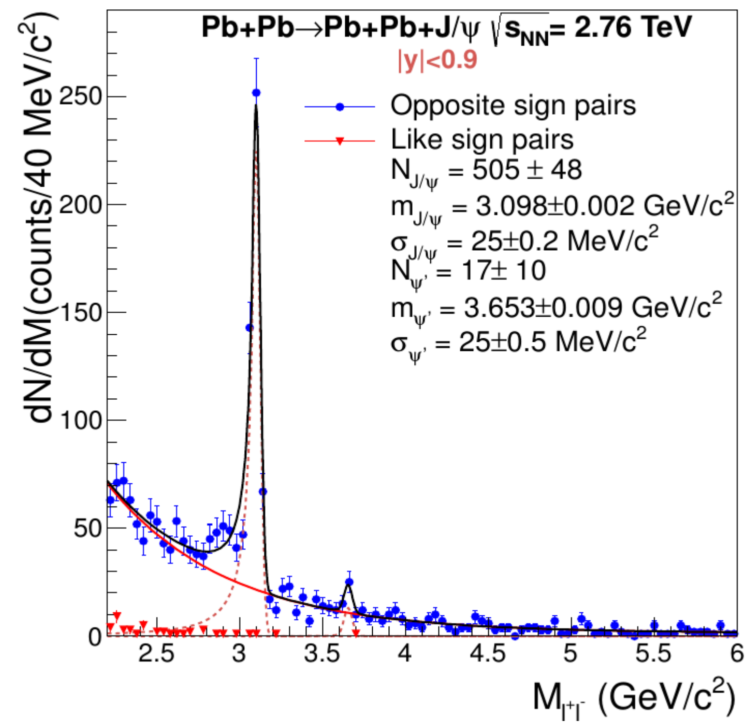


Phys. Rept. 458 (2008) 1-171

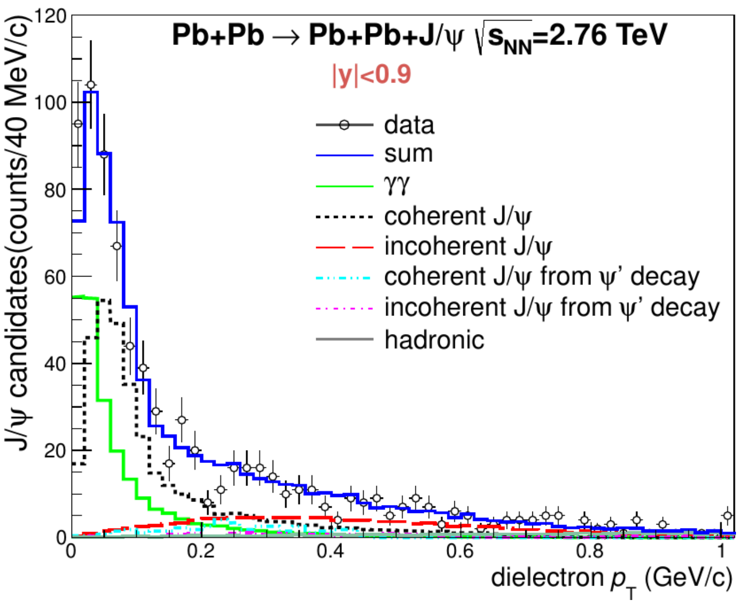
J/ψ in ultra-peripheral collisions

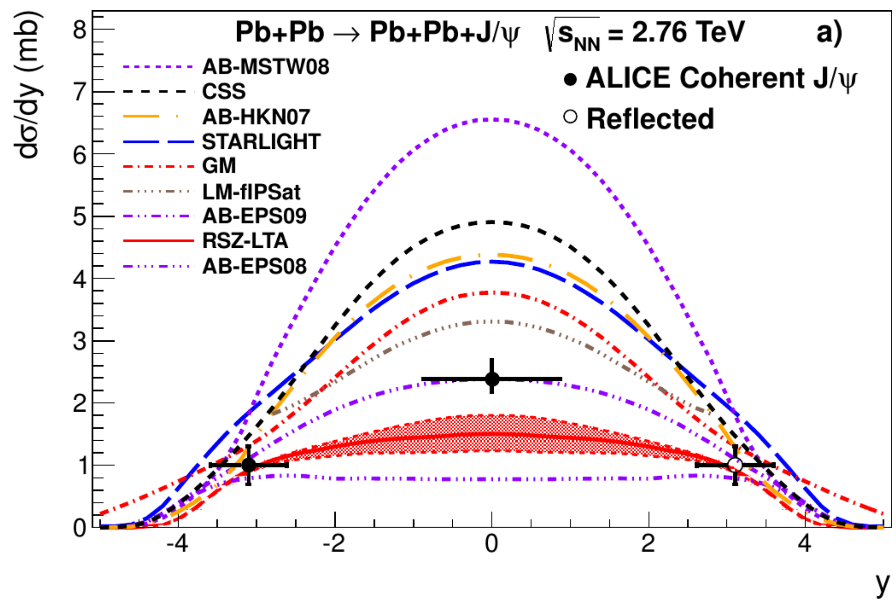
- select event with ≤ 10 tracks
- two tracks compatible with being dilepton pair





J/ψ in ultra-peripheral collisions





- allows investigation of gluon distribution at Bjorken-x around 10^{-3}
- model predictions wide spread, mainly differ in how they treat nuclear effects (gluon shadowing)

Summary and Conclusion

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- Heavy quarks are important tool
  - in pp to test pQCD
  - in heavy-ion collisions to investigate deconfined medium

- Charmonium no longer “thermometer” for QGP, but it remains an important probe
  - either for medium itself (transport models),
  - or for phase transition (statistical hadronization model)

- Ultra-peripheral collisions can be used to investigate gluon distributions in nuclei

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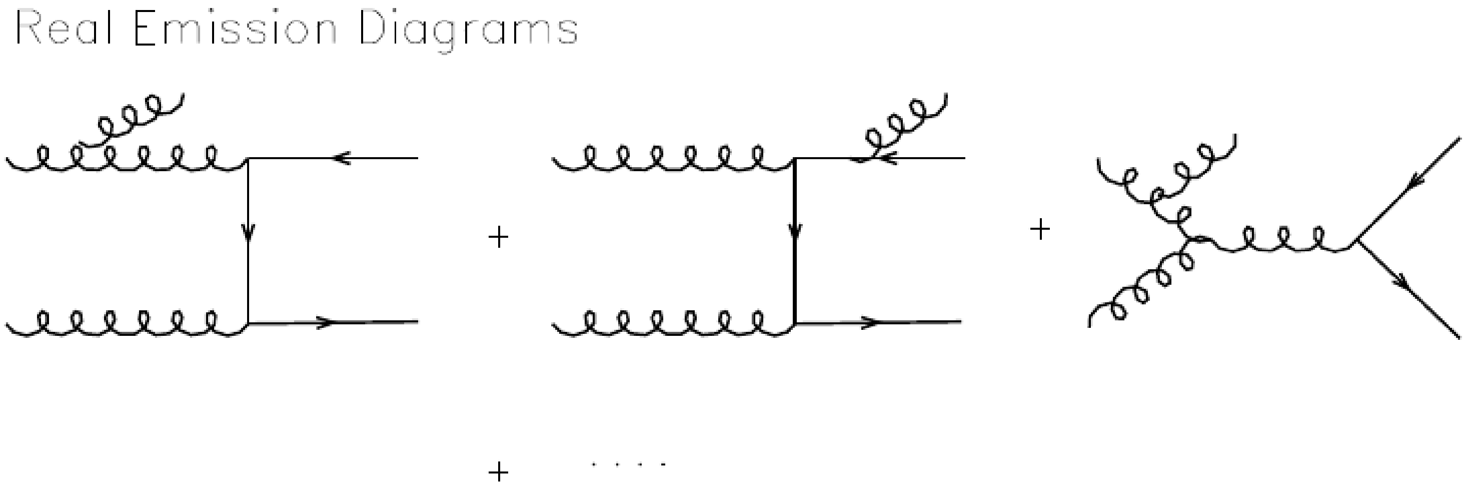
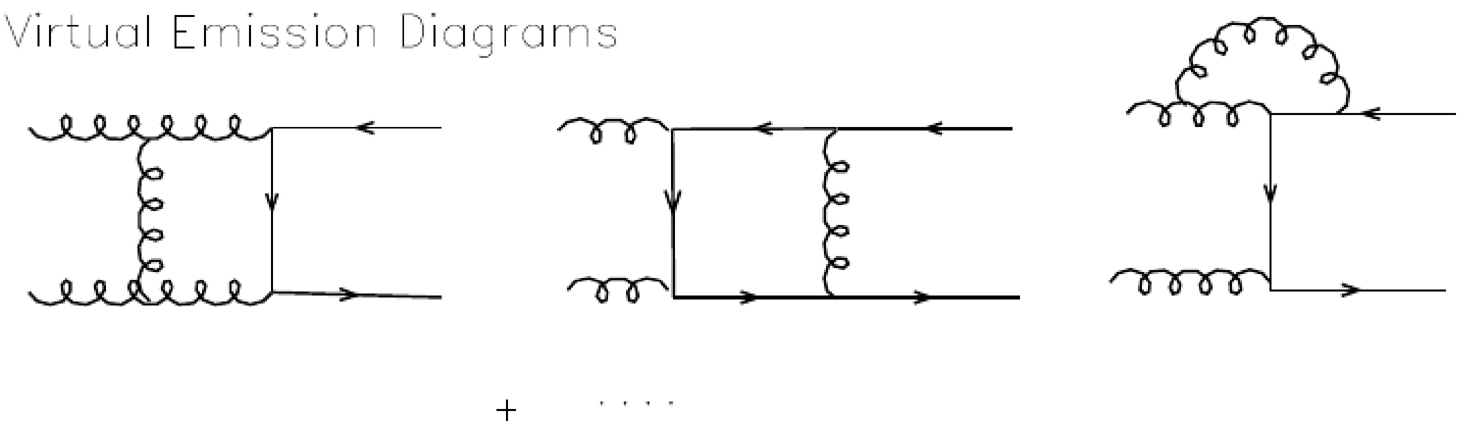
Backup

NLO corrections





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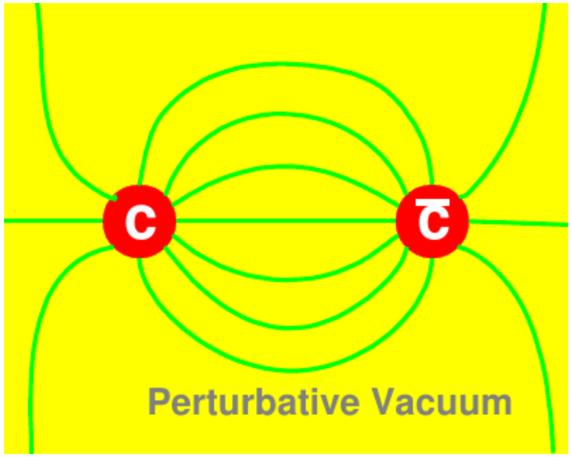
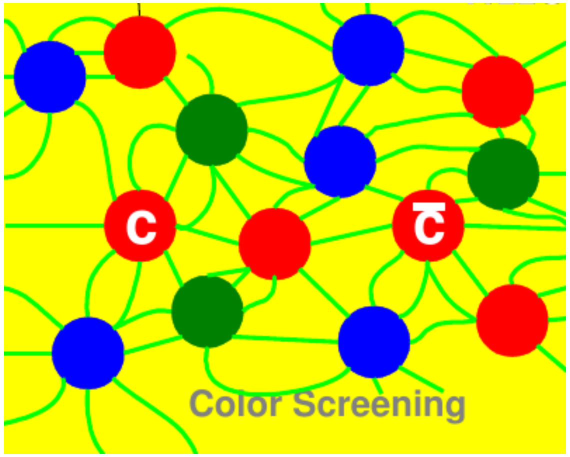
Charmonia melting



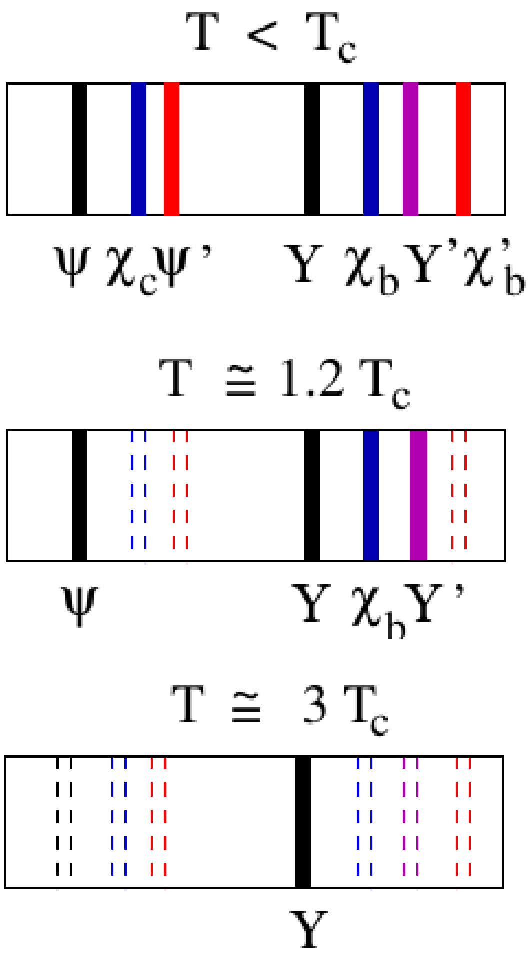


- potential between c and $\bar{c}$ quark is screened by presence of free color charge in QGP

$$V(r, T=0) = \sigma r - \frac{\alpha_{eff}}{r} \quad \longrightarrow \quad V(r, T \gg T_c) = \frac{\alpha_{eff}}{r} \exp[-r/\lambda_D(T)]$$

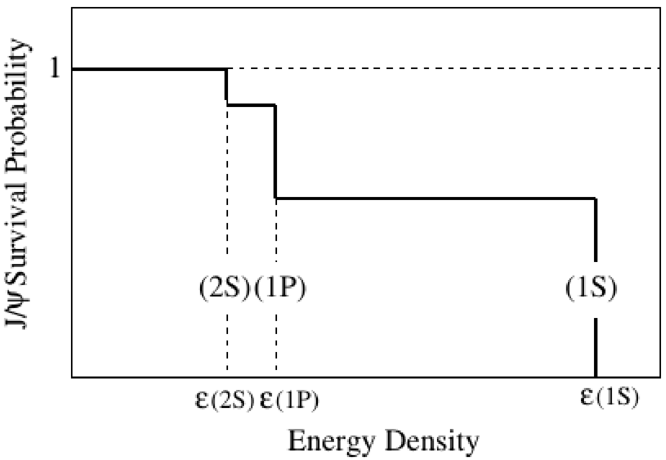
- “melting”, if screening length smaller than size of hadron

Sequential suppression



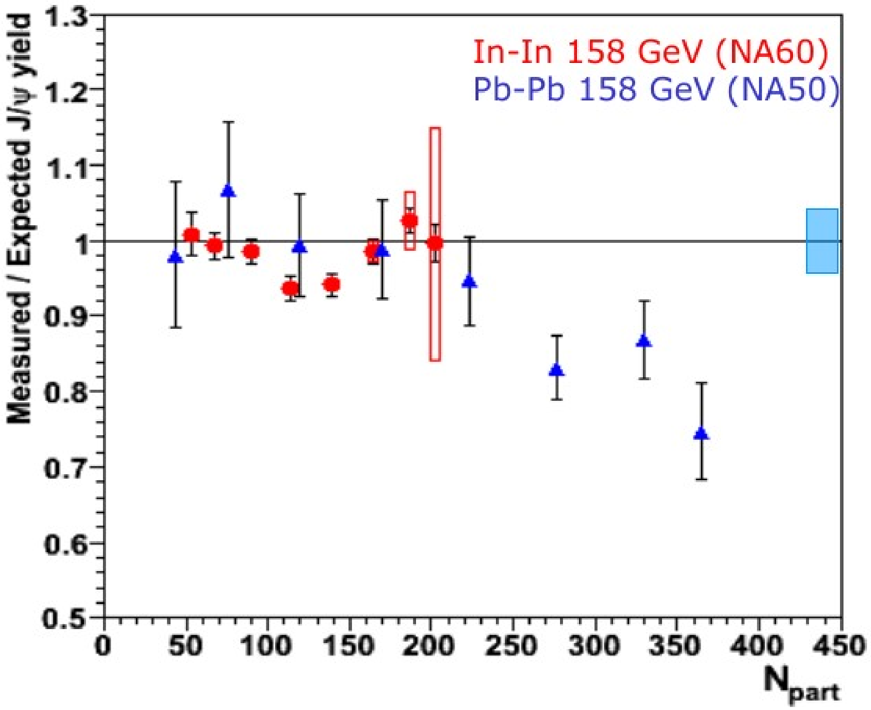
- Charmonia states have different radii, they melt at different temperatures

- their feed-down to J/ψ vanishes
  → stepwise decline of J/ψ yield
  → thermometer for the QGP



SPS

- NA38, NA50, NA51, NA60: fixed target experiments, $\sqrt{S_{NN}} \approx 20\,GeV$



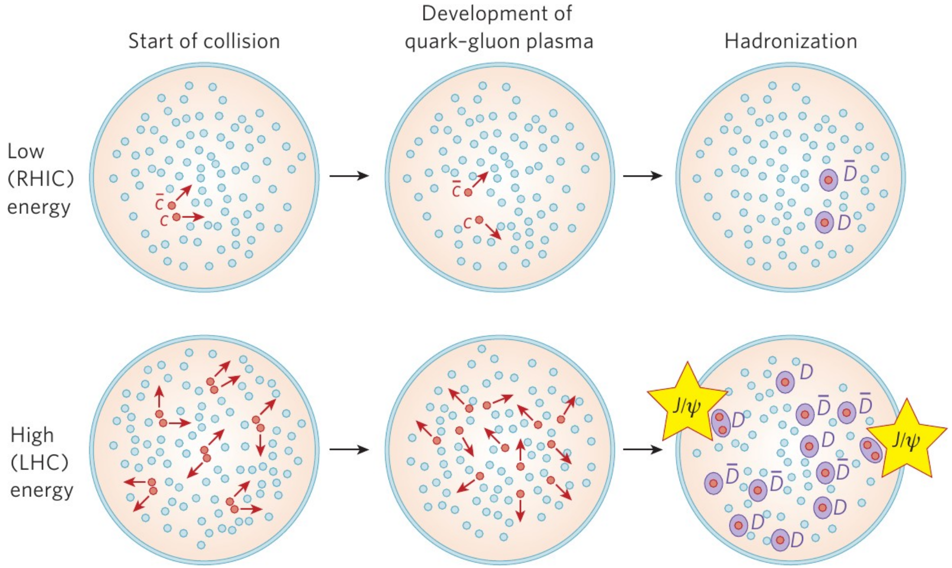
- agreement between NA50 and NA60 in common region
- "anomalous suppression" beyond cold nuclear matter effects
- compatible with melting of χ_c and ψ(2S), i.e. sequential suppression scenario

Higher energies: (Re)combination

- at higher energies, $c\bar{c}$ pairs are abundantly produced → can recombine to charmonia

most central AA	SPS (20GeV)	RHIC (200GeV)	LHC (2.76TeV)
$N_{c\bar{c}}$/event	~0.2	~10	~60

- **Statistical hadronization**:
  - no charmonia production before QGP
  - $c,\bar{c}$ quarks distributed to hadrons according to thermal model at hadronization
- **alternative**: continuous destruction and recreation of charmonia in QGP



R_{AA} vs. p_T

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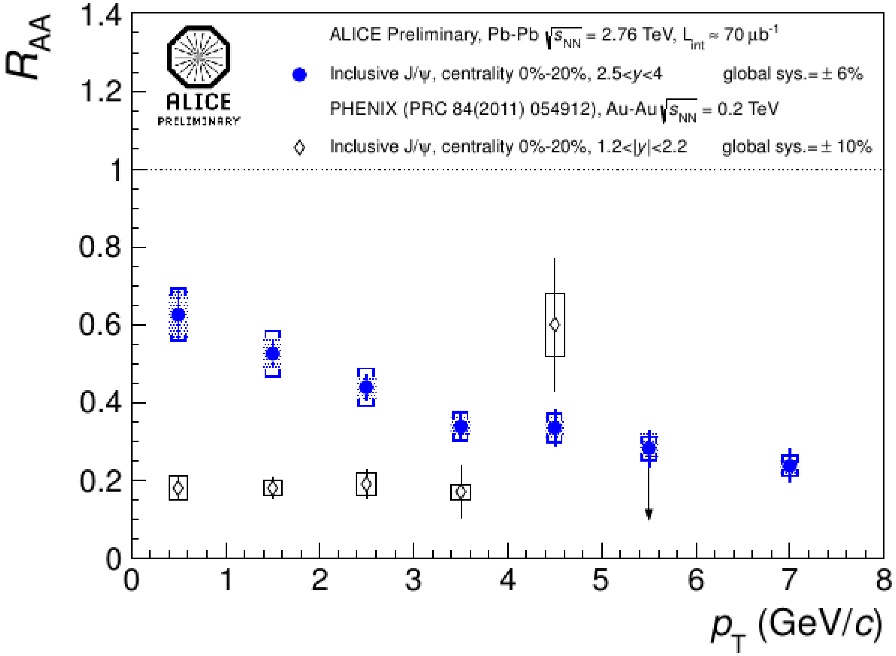
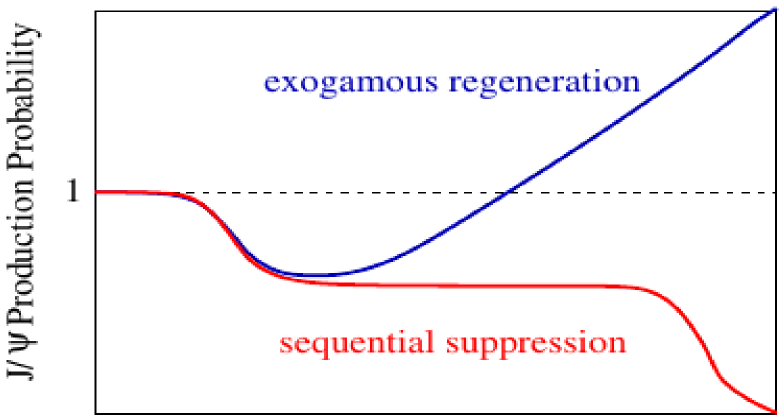
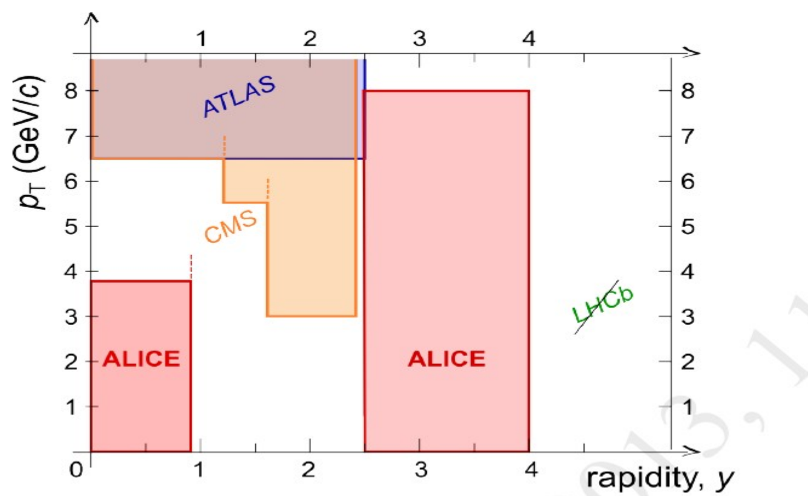


- R_{AA} p_T dependence very different from RHIC
- at low p_T suppression is significantly reduced

LHC: expectation



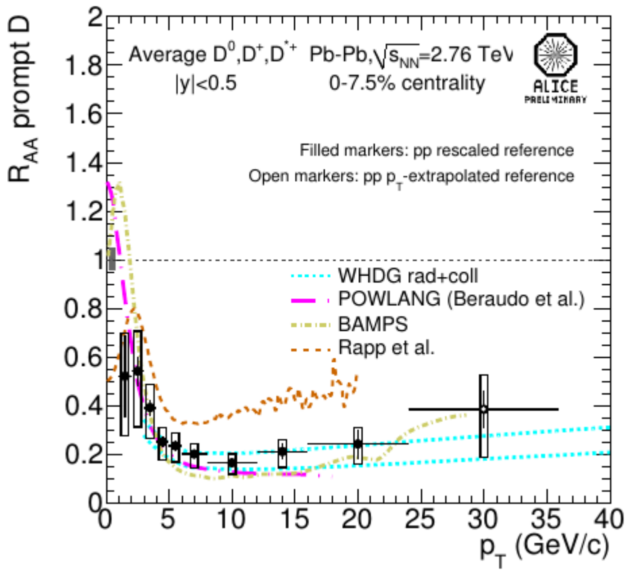


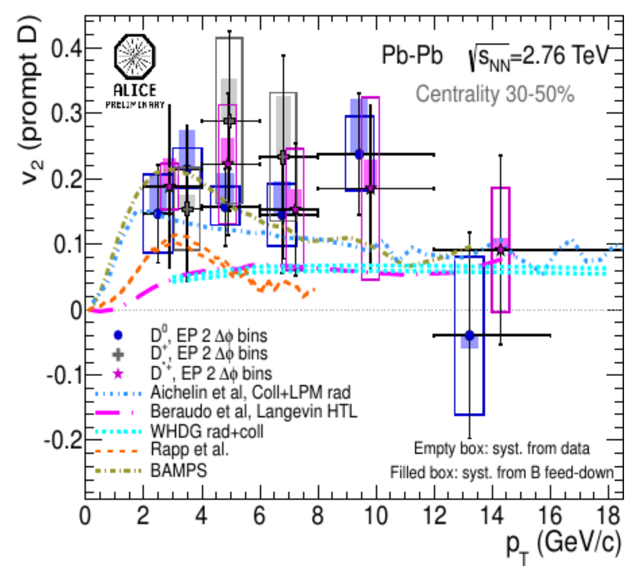
- another order of magnitude increase in $\sqrt{S_{NN}}$ → further suppression or (re)combination?

- different detectors cover different kinetic regions → complementary measurements

Open heavy flavor in Heavy-Ion collisions

- do heavy quarks take part in collective motion in deconfined stage → elliptic flow





Elliptic Flow

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$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left[n\left(\phi-\psi_R\right)\right]\right)$$

v_1 directed flow

v_2 elliptic flow

Ultra-peripheral