Charm production at LHC: an overview

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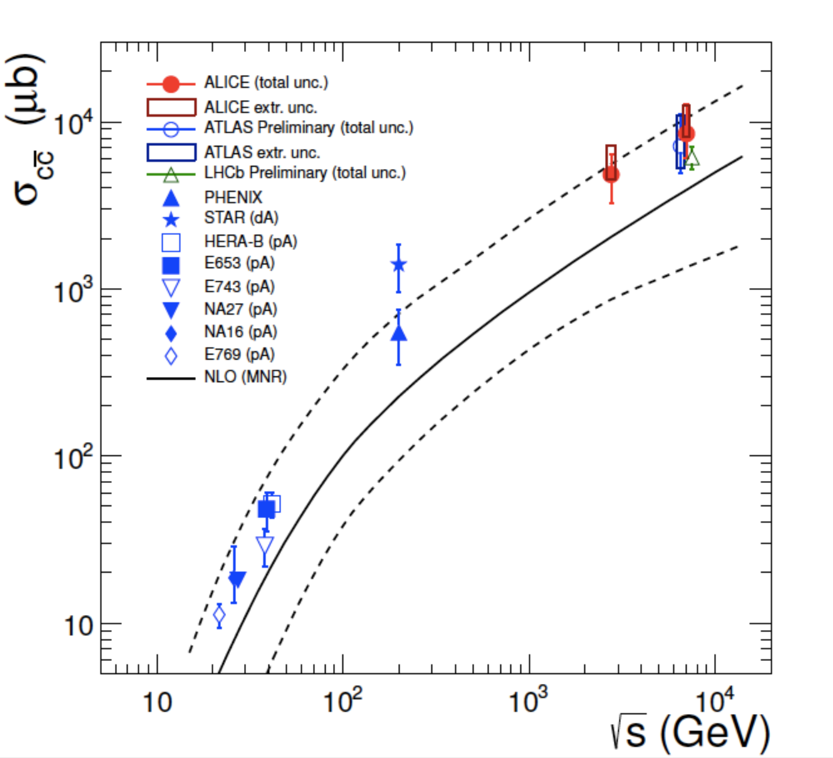
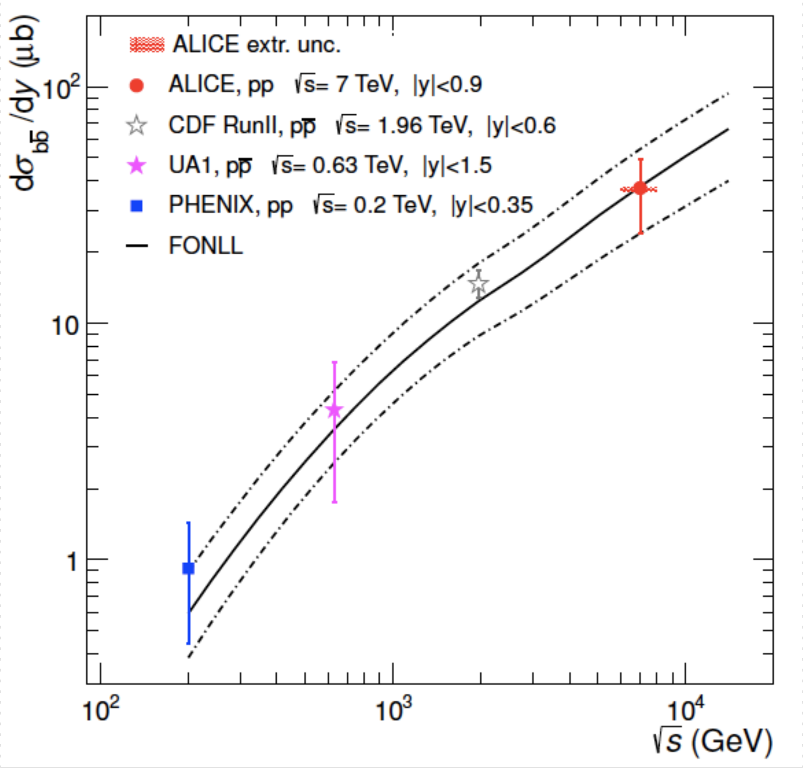
Outline:

- The actual title of my talk is: "***HF* production at LHC: an *experimental* overview**"
- open heavy flavour / hidden heavy flavour
  - a glance to pp, focus on Pb-Pb

LHC is *the* place to study HF

- Large production cross-sections
  (now measured in pp)



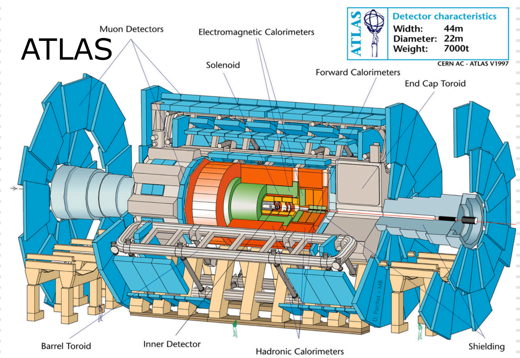


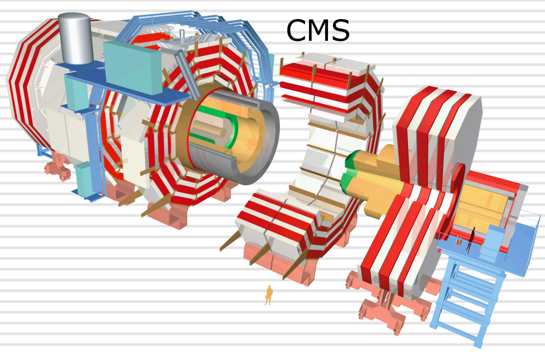
- Expected in 1 Pb-Pb collision at $\sqrt{s_{NN}}$=2.76 TeV:
  ≈ 60 $c\bar{c}$ ≈ 2 $b\bar{b}$

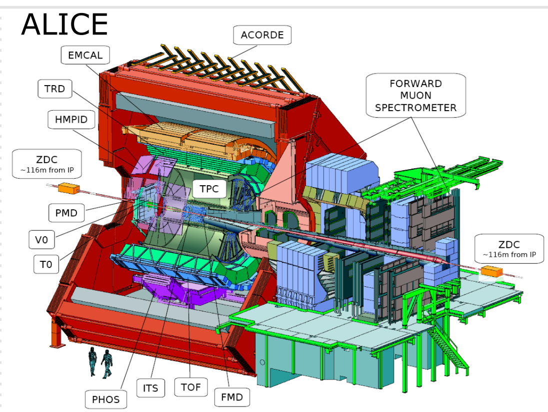
(MNR, shadowing: EKS98, EPS08. Factor 2 uncertainty)

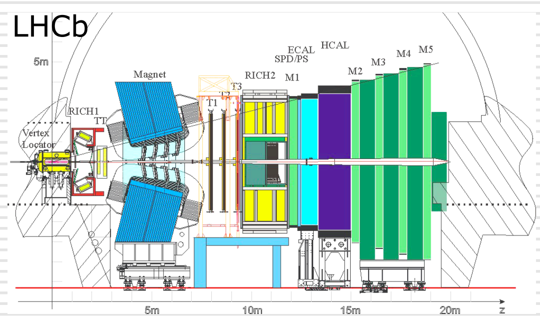
The LHC experiments

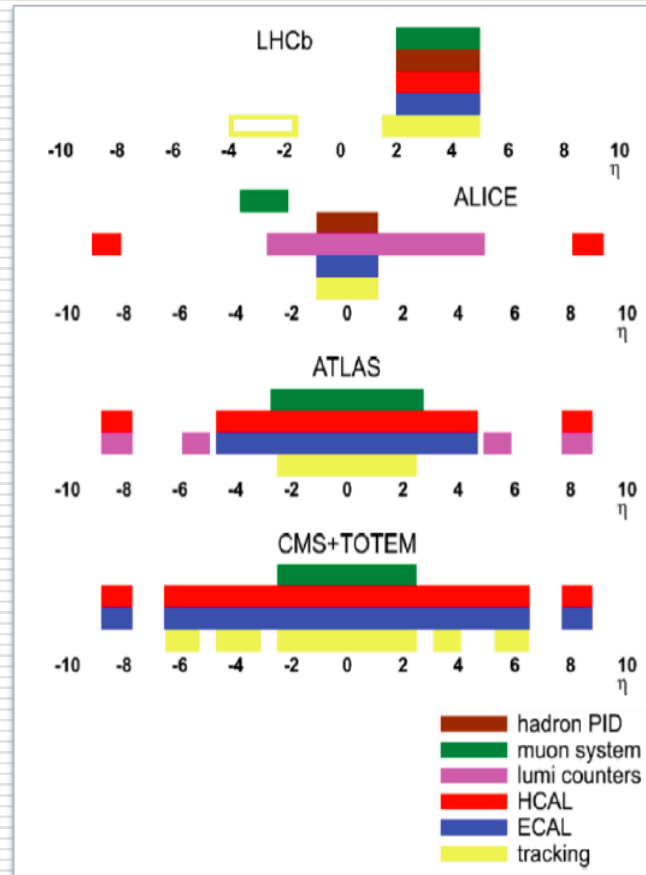
- complementary capabilities:
  - high pt, high rate, jets: the realm of CMS and ATLAS
  - low pt coverage, low material budget, excellent PID: ALICE
  - LHCb is *designed* for HF studies, but has not a heavy ion program









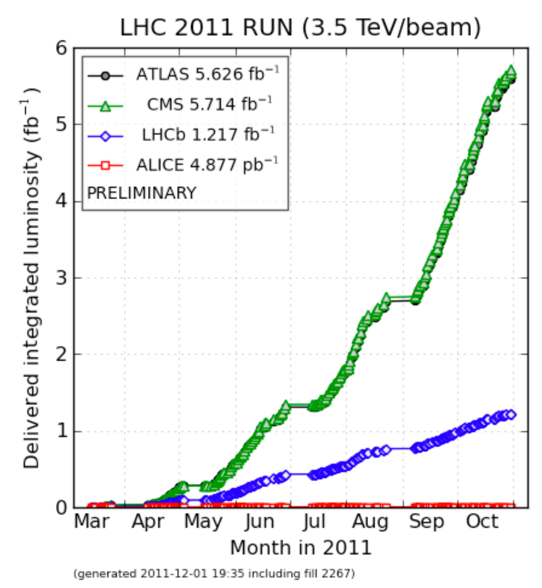


pp: the baseline

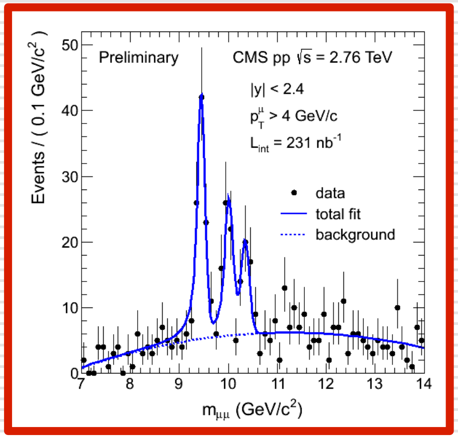
- good pp 'baseline' is crucial
  - MC tuning
  - where & how much to trust QCD calculations
  - where & how much to trust detector & analysis
  - comparison to AA

- At SPS (and initially also at RHIC) experiments have suffered for low quality pp data

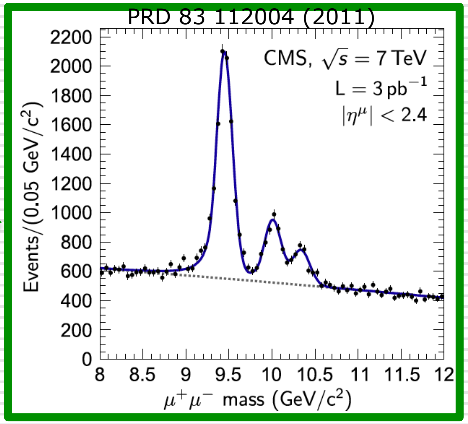
- LHC: more pp at the *correct* energy
  - 'R_{AA}' error has large contribution from pp statistics
  - months of AA, only days of pp@2.76TeV



$<1/10^3$ of L_{int}



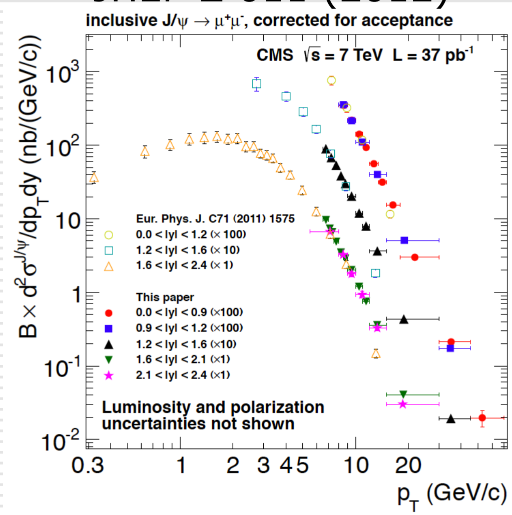
2.76 TeV vs. 7 TeV



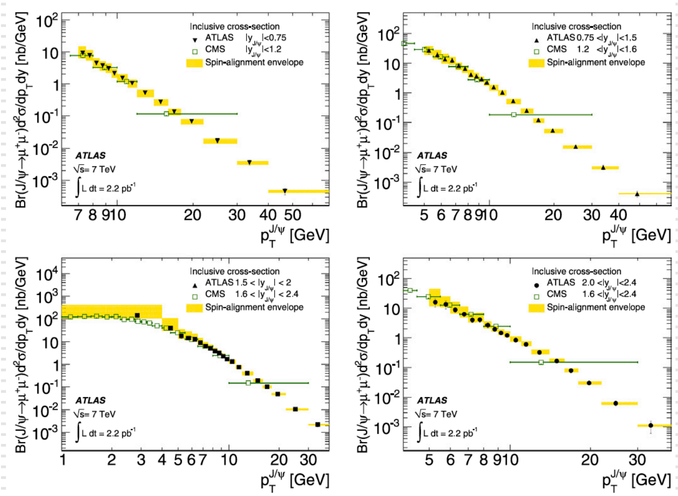
pp at 7 TeV: hidden HF

J/ψ

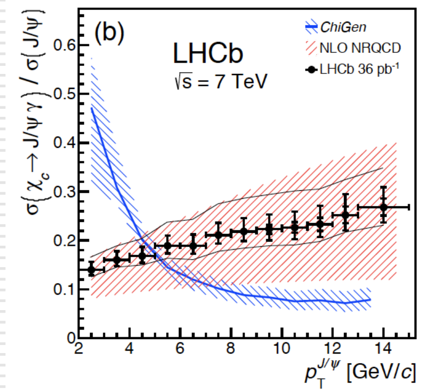
JHEP **2** 011 (2012)



NP**B 850** 387 (2011)



arXiv:1204.1462



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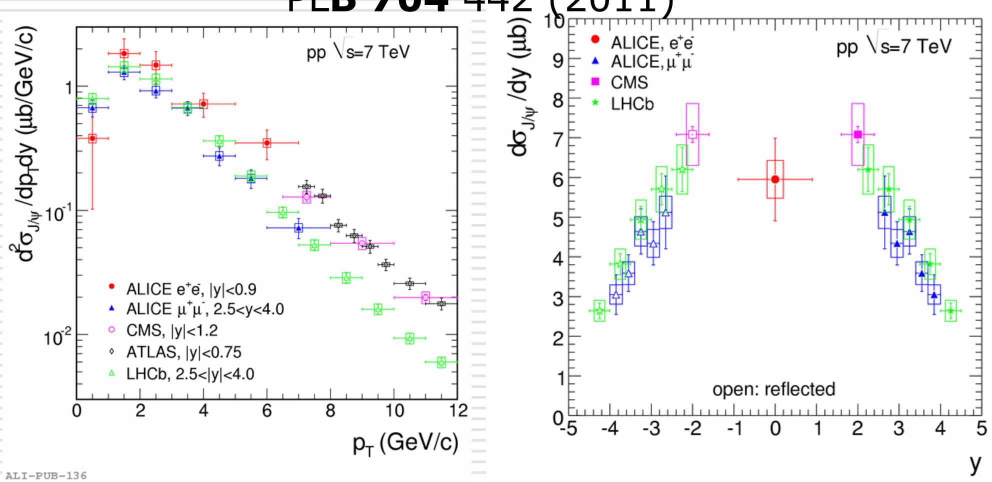
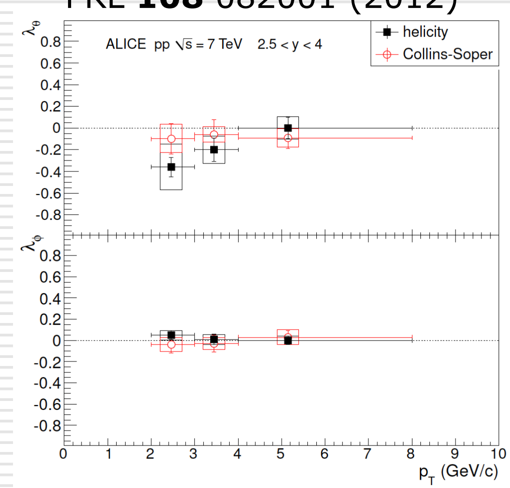


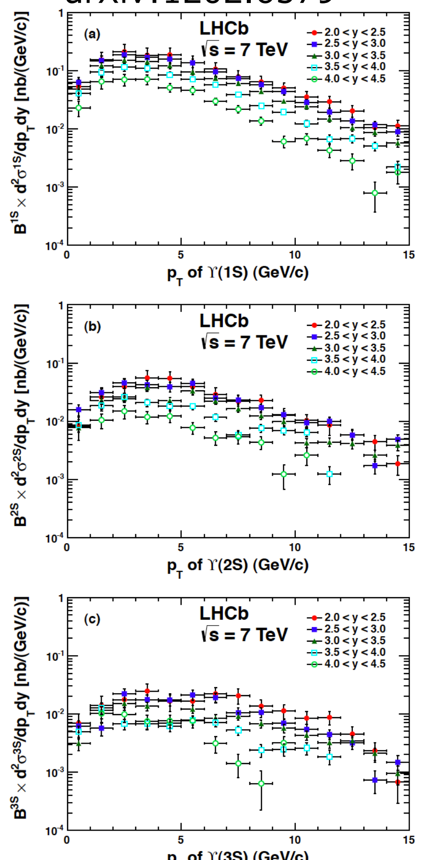
PRL **108** 082001 (2012)



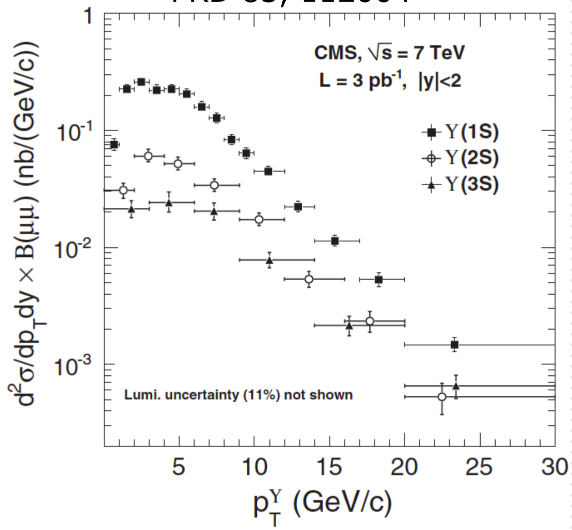
pp at 7 TeV: hidden HF

- Upsilon and χ_b

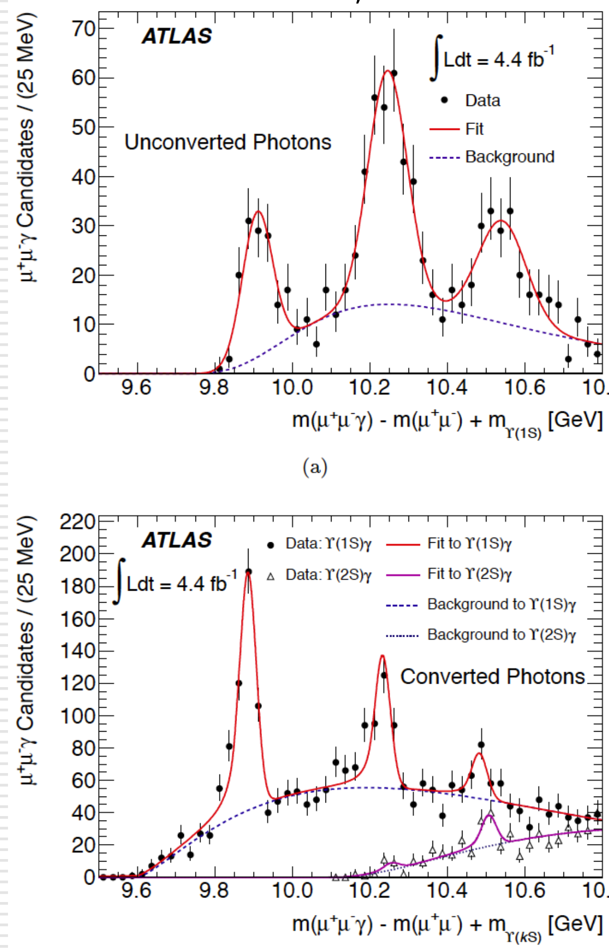
arXiv:1202.6579



PRD 83, 112004



PRL 108, 152001



pp at 7 TeV: open HF

- D mesons

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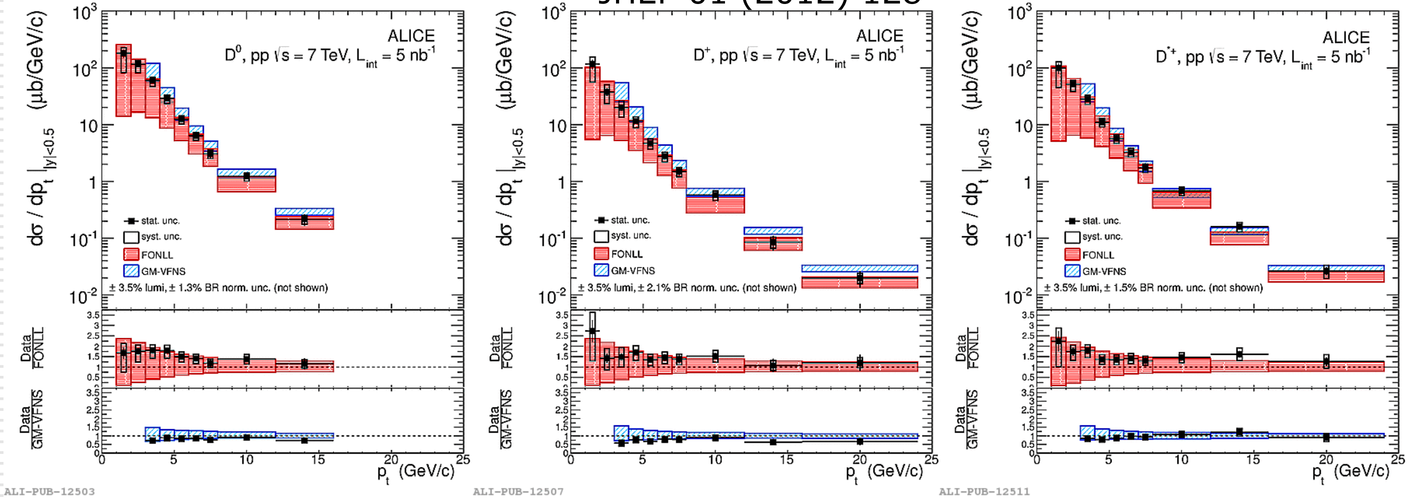

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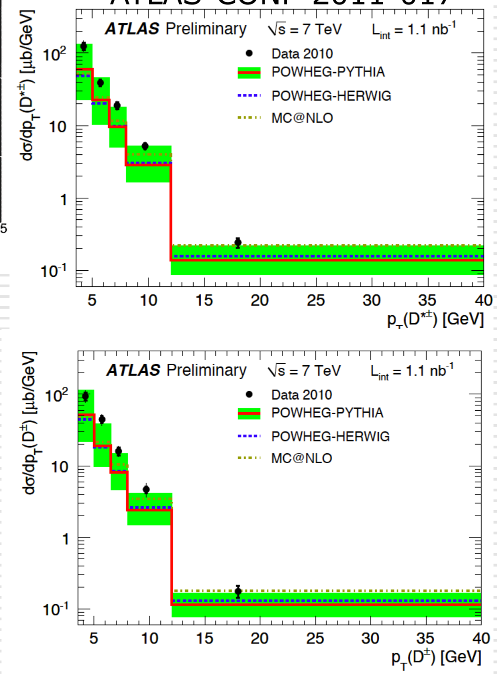
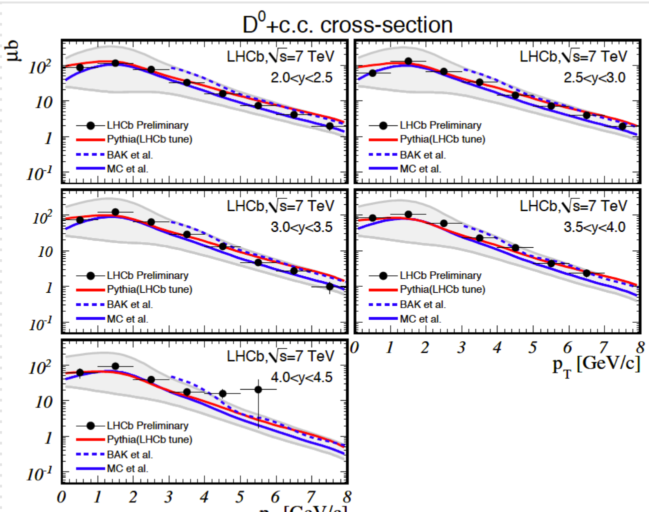
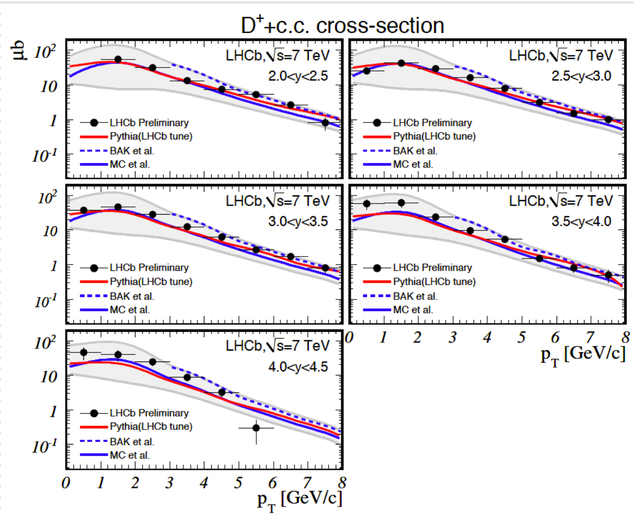


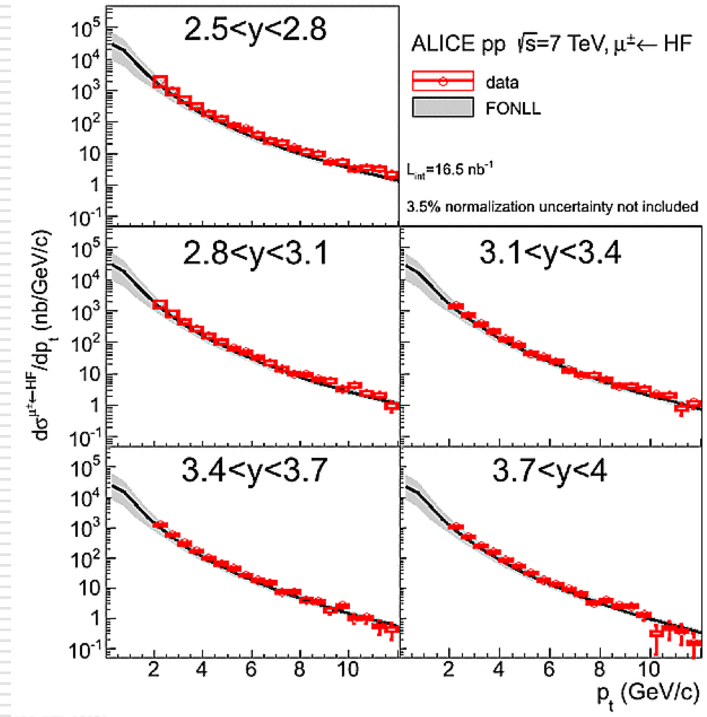




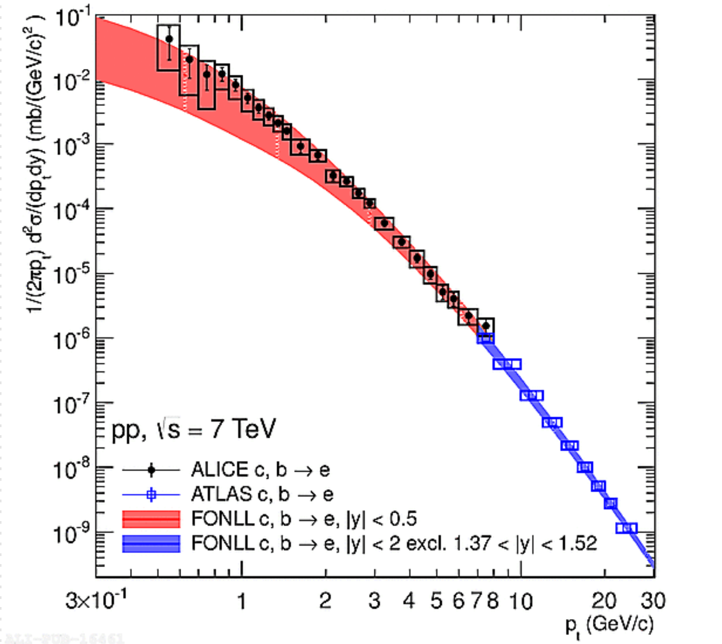
pp at 7 TeV: open HF

- single leptons

arXiv:1201.3791

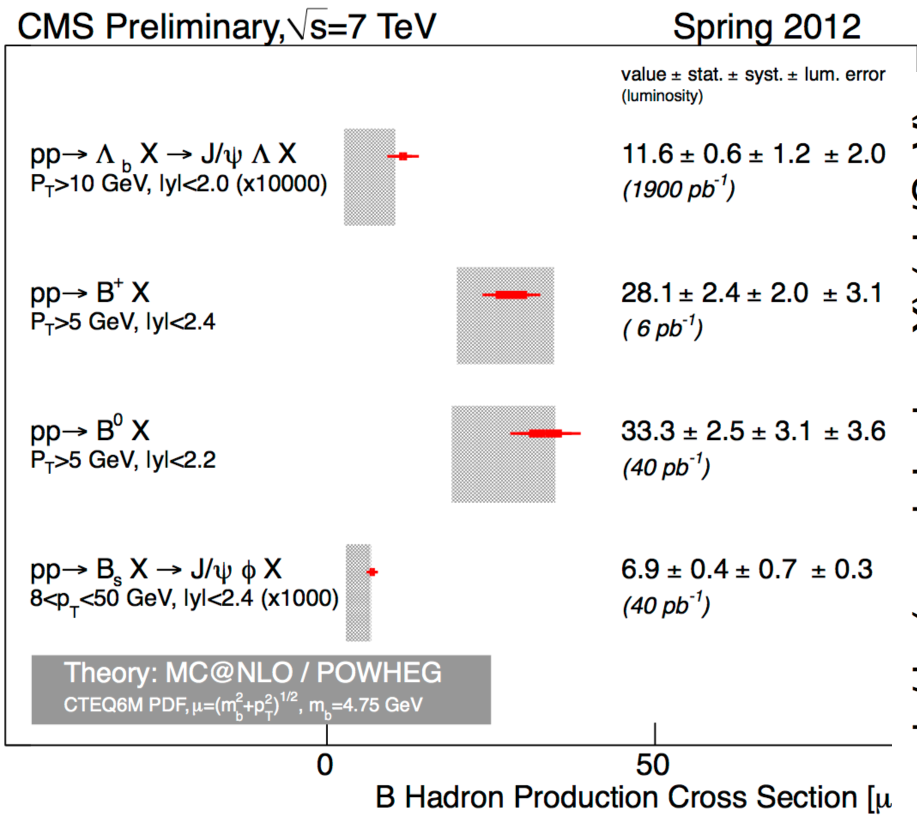


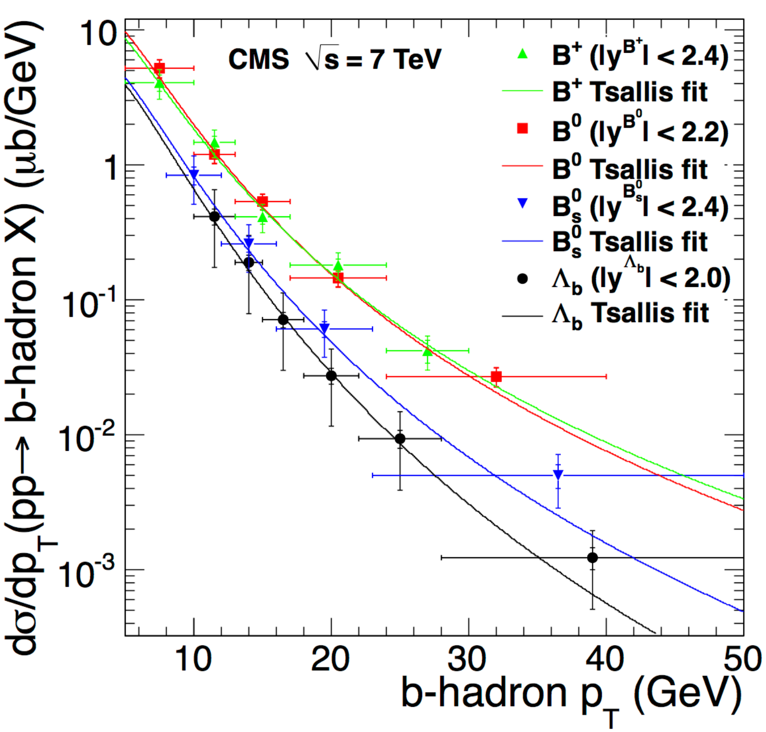
arXiv:1205.5423



pp at 7 TeV: open HF

- open beauty, exclusive decays



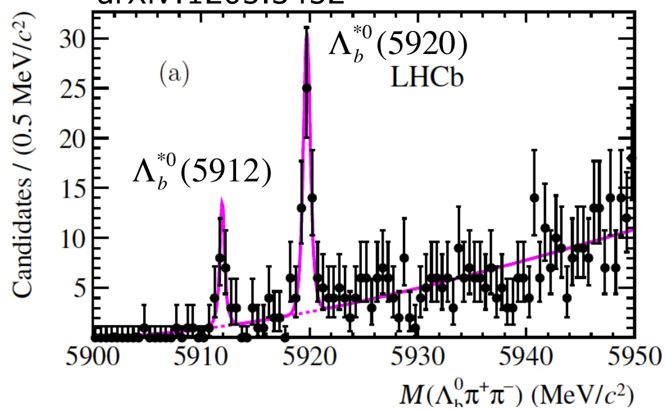


pp at 7 TeV: open HF

- open beauty, new particles and decay channels

orbitally-excited Λ_b^0 baryons

arXiv:1205.3452



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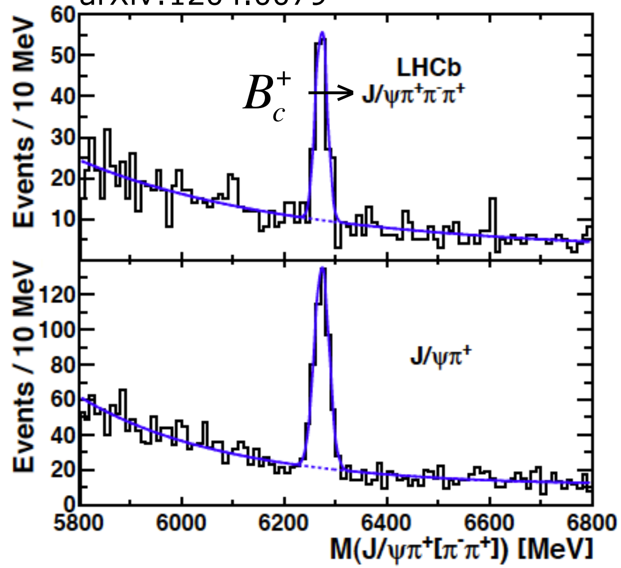
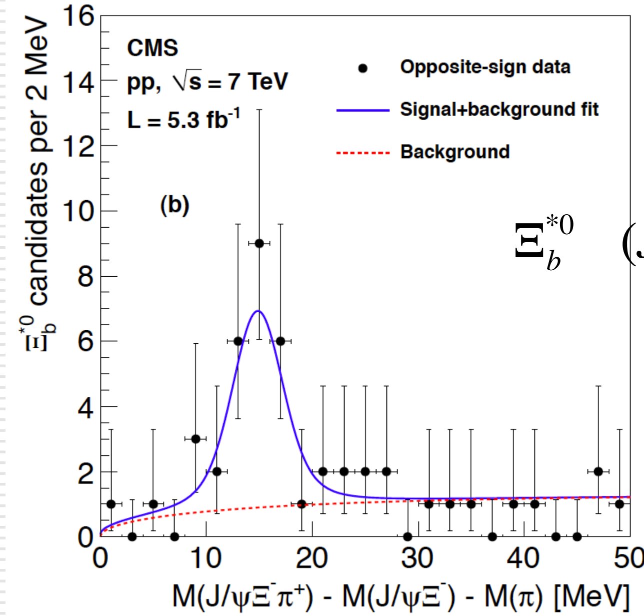


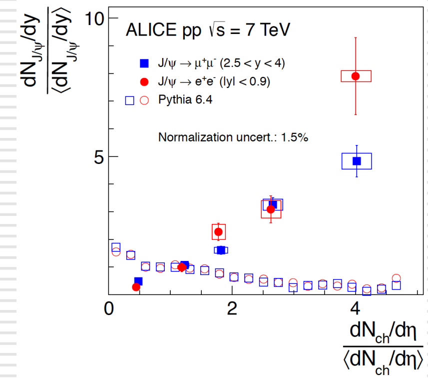
arXiv:1204.5955



Ξ_b^{*0} $(J^P = 3/2^+)$?

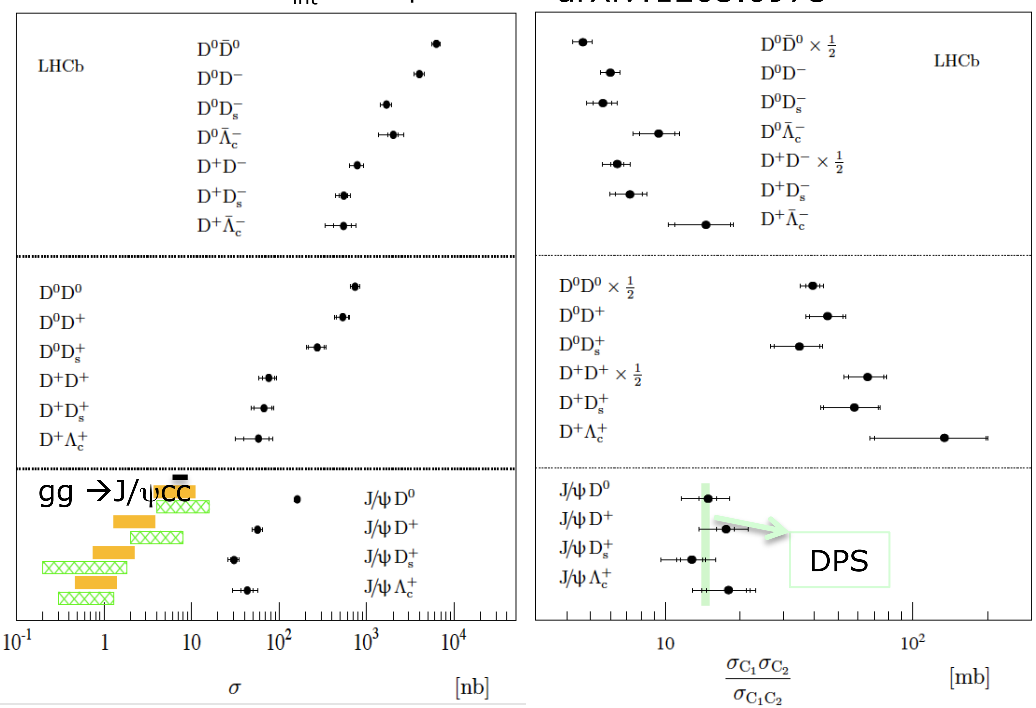
pp at 7 TeV: new observables

- multiplicity dependence (→ C. Blume)



- double charm production
  - cross sections >> gg fusion predictions
  - better agreement is found with the DPS model
    - moreover, absence of azimuthal or rapidity correlations
  - but CC data do not fit well this scheme
    - if DPS dominates → $\sigma_{CC}^{eff} \approx 2\text{-}3\sigma_{CJ/\psi}$
  - $C\bar{C}$ events → sizeable contribution from the gluon splitting process to charm quark production

L_{int}=355 pb^{-1} arXiv:1205.0975



Theoretical description of HF production in pp at LHC: executive summary

- Open HF
  - good agreement between pQCD based calculations and data
    - main theoretical uncertainties from factorization and renormalization scales

- Quarkonia
  - NRQCD with CSM and COM (including $^3P_j^{[8]}$ channels) does a good job in describing present observables:

    $d^2N/dydpt$ and polarization of J/ψ,
    $d^2N/dydpt$ of ψ', Upsilon family and χ_c

- no firm conclusions on double charm production and multiplicity dependence

Theoretical description of HF production in pp at LHC

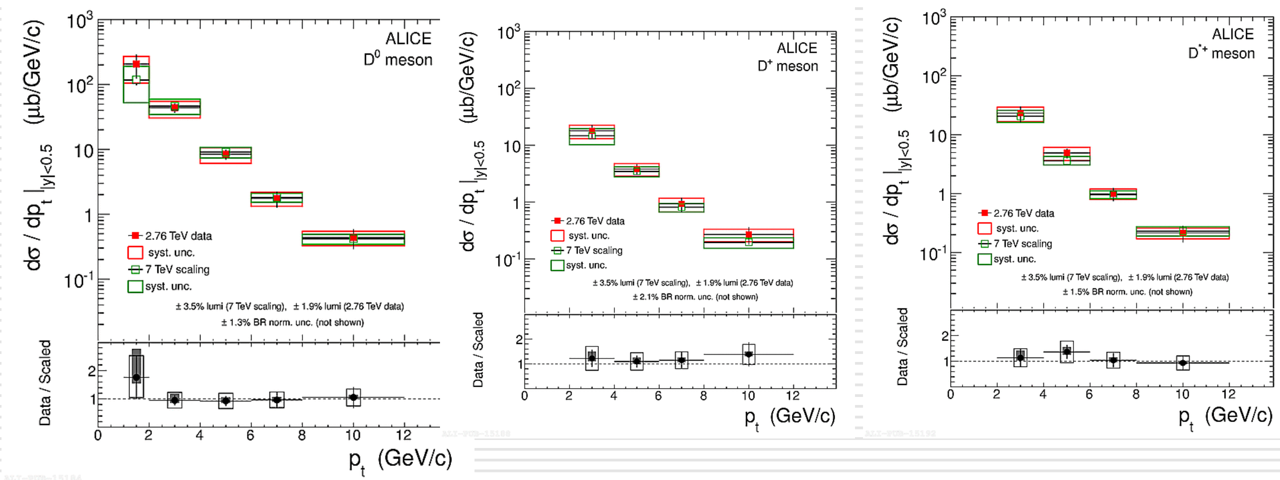
- e.g., beauty vs. FONLL

Expt	Observable (p_T in GeV)	σ^{exp}	σ^{FONLL}	Comments
1: LHCb [56]	$\sigma(H_b, 2 \le \eta \le 6)$	$75.3 \pm 11.4\ \mu$b	$70.8\ ^{+33.3}_{-24.4}\ \mu$b	average $b + \bar{b}$
2: LHCb [57]	$\sigma(B^{\pm}, p_T < 40, 2 < y < 4.5)$	$41.4 \pm 3.4\ \mu$b	$40.1\ ^{+19.0}_{-14.5}\ \mu$b	$f(b \to B^-) = 0.403$
3: CMS [55]	$\sigma(B^0,\ p_T^B > 5,\ \lvert y^B \rvert < 2.2)$	$33.2 \pm 4.3\ \mu$b	$25.5\ ^{+10.5}_{-7.1}\ \mu$b	$f(b \to B^0) = 0.403$
4: CMS [54]	$\sigma(B^+,\ p_T^B > 5,\ \lvert y^B \rvert < 2.4)$	$28.1 \pm 4.4\ \mu$b	$27.2\ ^{+11.2}_{-7.5}\ \mu$b	$f(b \to B^-) = 0.403$
5: CMS [58]	$\sigma(B_s^0,\ 8 < p_T^B < 50,\ \lvert y^B \rvert < 2.4)$ $\times \text{BR}(B_s^0 \to J/\psi\, \phi)$	6.9 ± 0.8 nb	$4.5\ ^{+2.3}_{-1.9}$ nb (includes BR uncertainty)	$f(b \to B_s^0) = 0.11$ $\text{BR}(B_s^0 \to J/\psi\, \phi) = (1.4 \pm 0.5) \times 10^{-3}$
6: LHCb [64]	$\sigma(H_b \to J/\psi, p_T^{\psi} < 14, 2 < y_{\psi} < 4.5)$	$1.14 \pm 0.16\ \mu$b	$1.16\ ^{+0.55}_{-0.42}\ \mu$b	$\text{BR}(b \to J/\psi) = 0.0116$
7: ALICE [66]	$\sigma(H_b \to J/\psi, p_T^{\psi} > 1.3, \lvert y_{\psi} \rvert < 0.9)$	$1.26 \pm 0.16\ \mu$b	$1.33\ ^{+0.59}_{-0.48}\ \mu$b	$\text{BR}(b \to J/\psi) = 0.0116$
8: CMS [73]	$\sigma(H_b \to \mu,\ p_T^{\mu} > 6,\ \lvert y^{\mu} \rvert < 2.1)$	$1.32 \pm 0.34\ \mu$b	$0.855\ ^{+0.28}_{-0.19}\ \mu$b	$\text{BR}(b \to \ell) = 0.0108$ $\text{BR}(b \to c \to \ell) = 0.096$

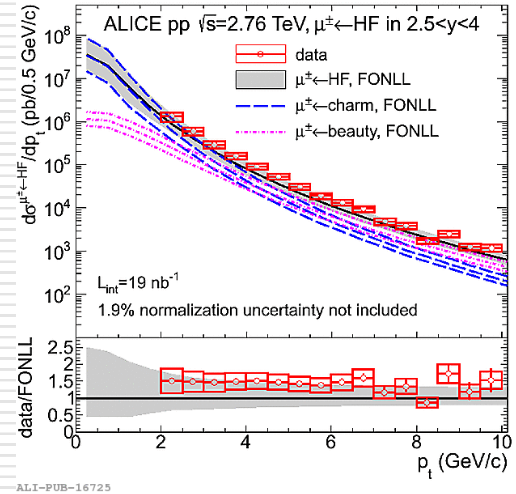
the baseline: pp at 2.76 TeV

- remarkably lower quality than at 7 TeV

arXiv:1205.4007



arXiv:1205.6443



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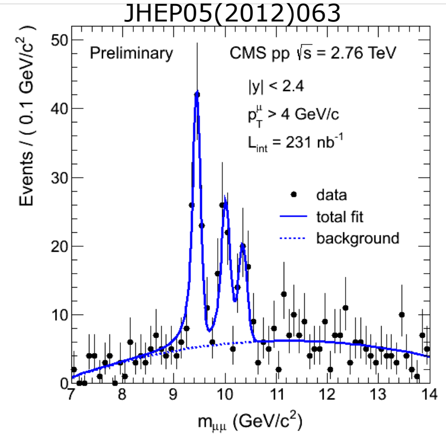

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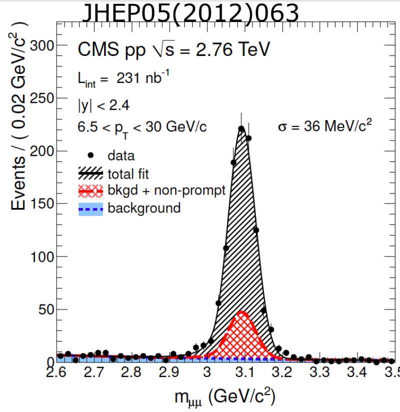
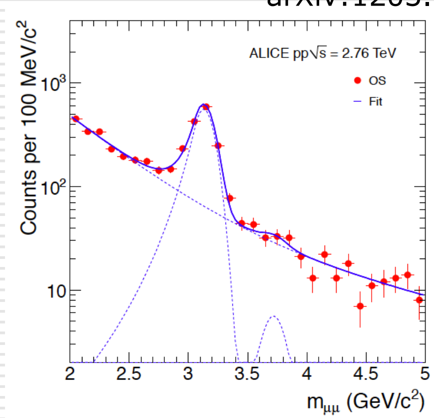
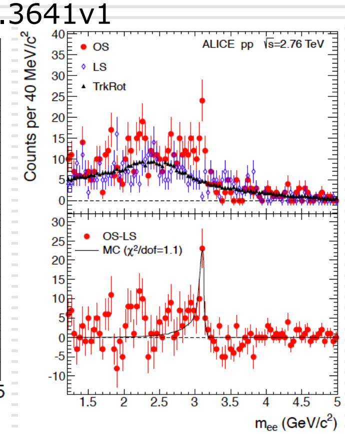


arXiv:1203.3641v1





Pb-Pb collisions

Questions:

- How do c and b quarks loose energy ?
  - naïve picture: $\Delta E(g) < \Delta E(c) < \Delta E(b)$?
- do c and b thermalize ?
- sequential melting of quarkonia ?
  - charmonium: is there a regeneration mechanism at work?

Observables:

- R_{AA} of open Heavy Flavour
  - $R_{AA}(D)/R_{AA}(\pi) > 1$: colour charge and mass effect ?
  - $R_{AA}(b)/R_{AA}(c) > 1$: mass effect ?
- R_{AA} of quarkonia
- V_2 of open/hidden HF

Additional question: pA measurement ?

Charm & beauty as probes

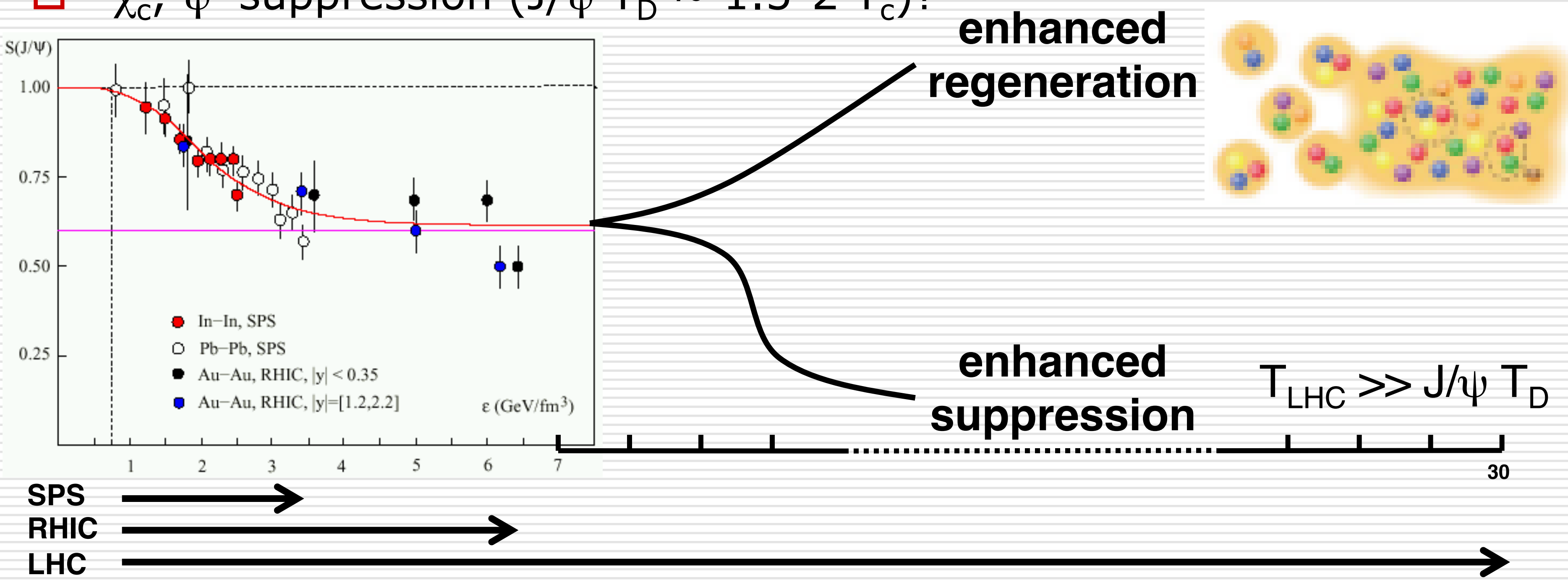
- calculable in pQCD; calibration measurement from pp
  - → rather solid ground
    - caveat: modification of initial state from pp to AA
      - shadowing ~ 20 %
      - saturation?
    - pA reference fundamental!

- produced essentially in initial impact
  - → probes of high density phase

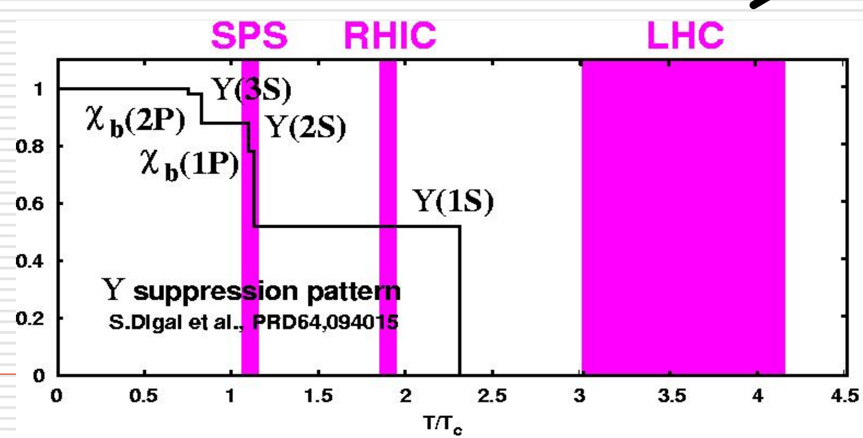
- no extra production at hadronization
  - → probes of fragmentation
    - e.g.: independent string fragmentation vs recombination

Quarkonium production in Pb-Pb collisions

- J/ψ suppression & regeneration?
- χ_c, ψ′ suppression (J/ψ T_D ~ 1.5-2 T_c)?



- ϒ melts only at LHC
- ϒ′ T_D ~ J/ψ T_D
- Small ϒ regeneration
  - ◊ ϒ′ can unravel J/ ψ suppression VS regeneration



R_{CP} of HF leptons

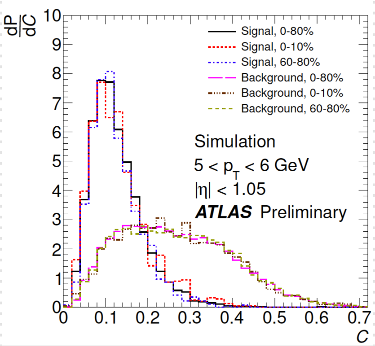
- ATLAS

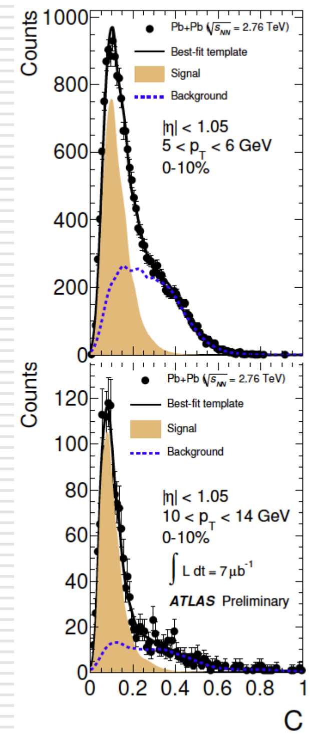
Fraction of momentum lost in detector compared to expectation

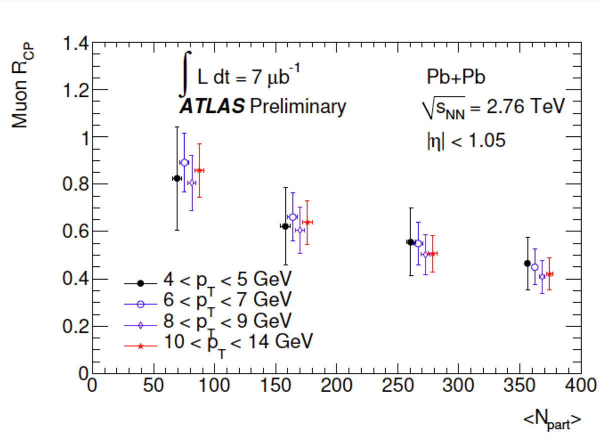
$$C = \left|\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}}\right| + rS$$

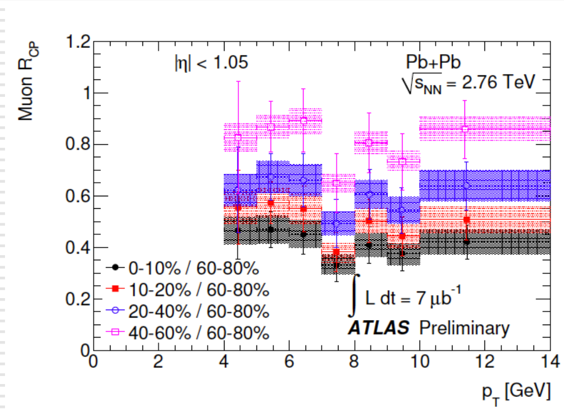
Composite of two discriminants
r=0.07 chosen for optimal separation

***S*≡Scattering significance**
Measure of angular deflection compared to expectation from multiple scattering
Identifies muons from decay in flight







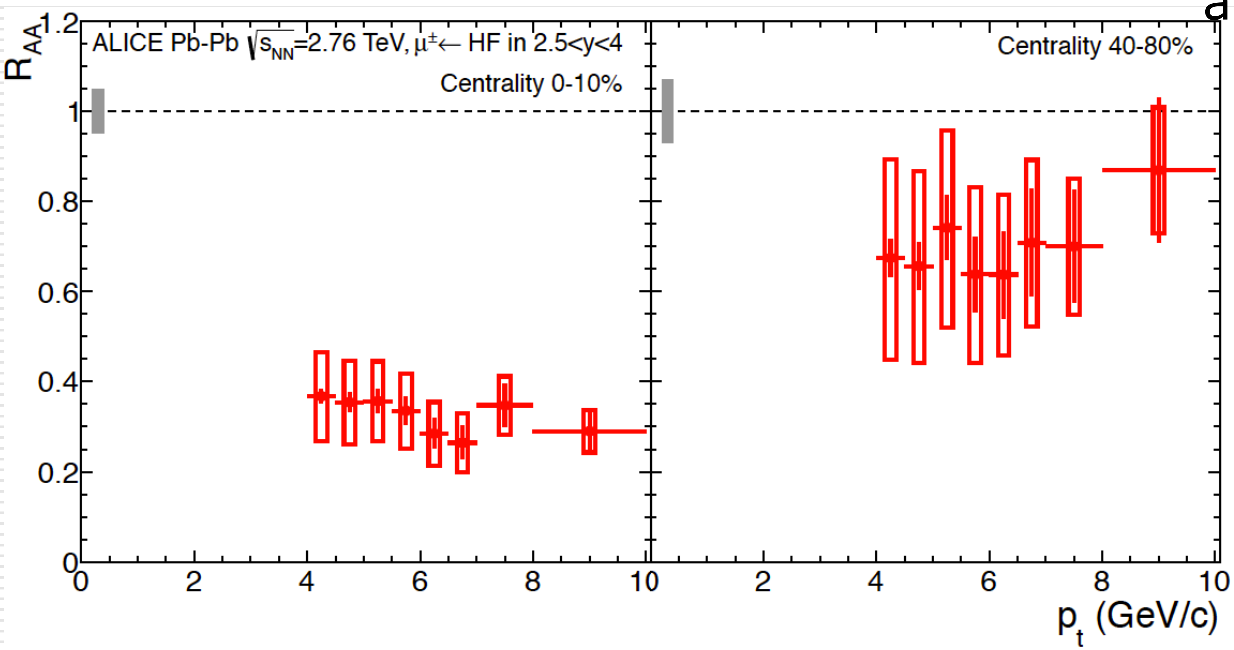


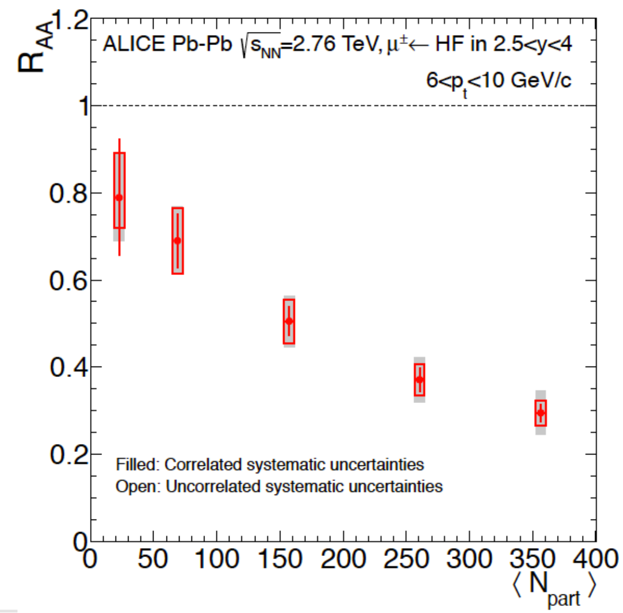
- less suppressed than charged hadrons
- No significant p_t dependence

better: R_{AA} of HF leptons

- Track selection
  - Match track with segments in the trigger chambers → reject punch-through hadrons
  - Distance of Closest Approach to primary cut rejects tracks from beam-gas interactions
- Background subtraction: π, K decays
  - pp: using as input MC simulations
  - PbPb: using ALICE data at mid rapidity

arXiv.1205.6443





Strong suppression in central collisions
No significant p_t dependence

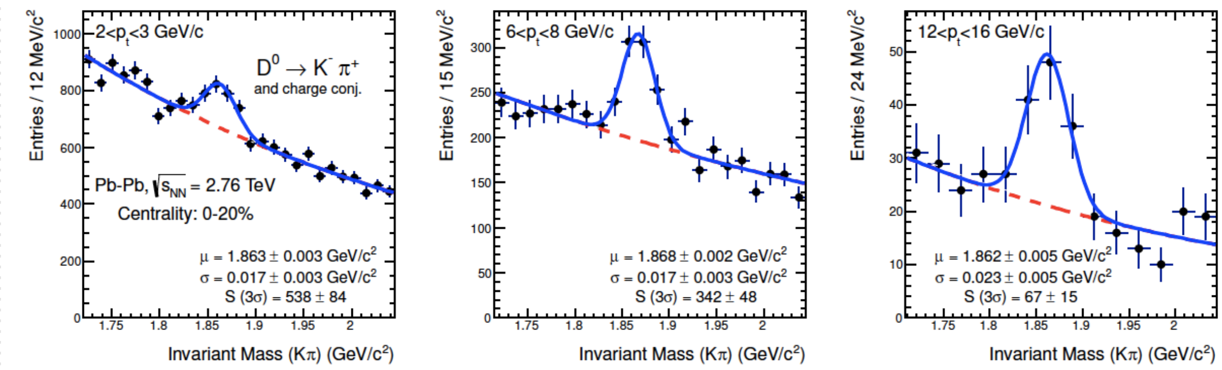
next talk by S. Lapointe

more directly: exclusive meson or semi-inclusive B channels

- D mesons (ALICE)
  - $D^0 \rightarrow K\pi$
  - $D^+ \rightarrow K\pi\pi$
  - $D^* \rightarrow D^0\pi$

talk by S. Lapointe

arXiv:1203.2160



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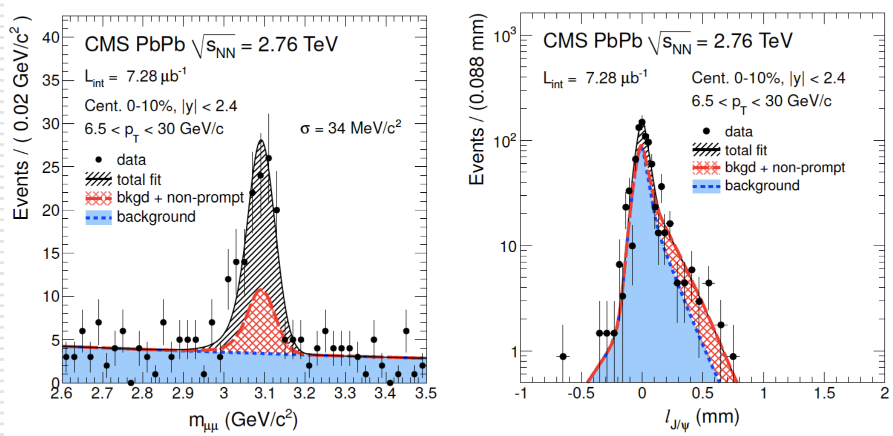
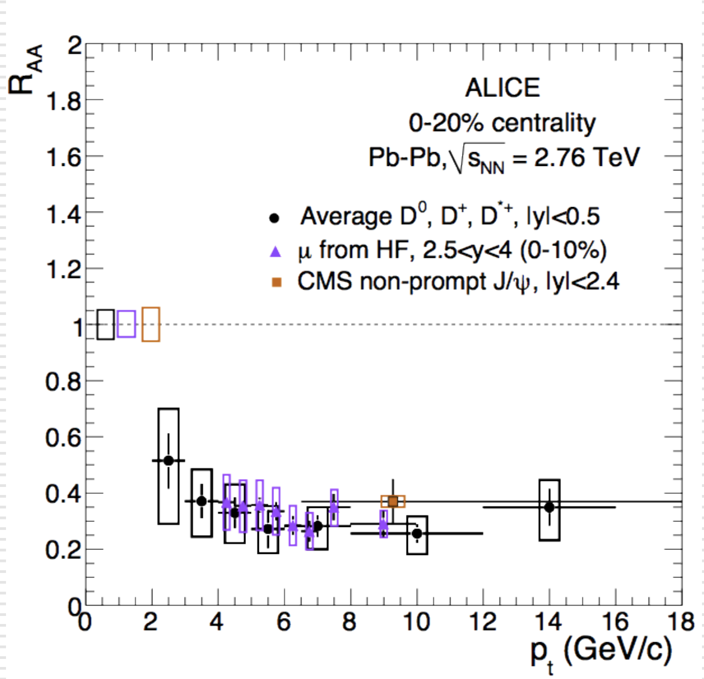
- B hadrons (CMS)
  - $B \rightarrow J/\psi + X$



R_{AA} of open HF

next talk by S. Lapointe

- $H_{c,b} \rightarrow$ muons
- D mesons
- $B \rightarrow J/\psi$



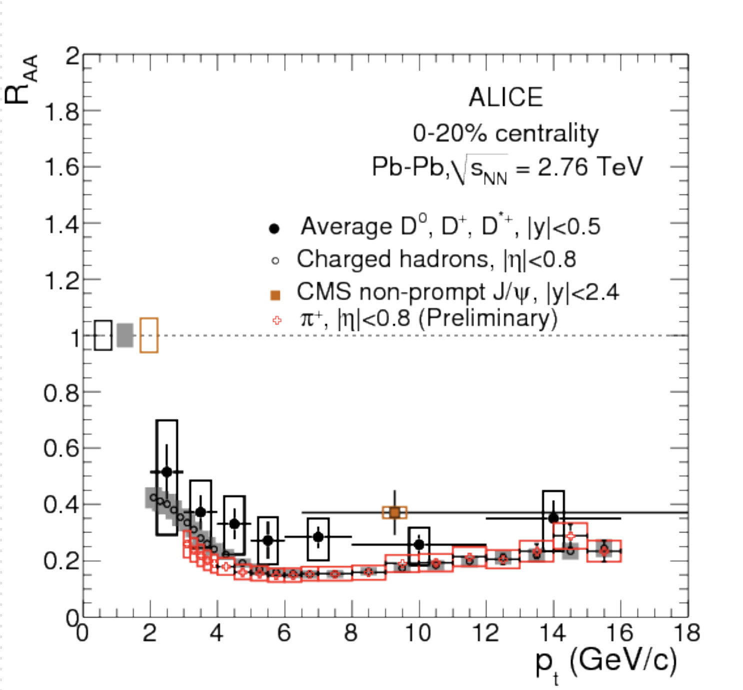
$B \rightarrow J/\psi + X$

- charm vs beauty: no evidence of mass effects

R_{AA} of open HF

next talk by S. Lapointe

- Charged hadrons
- Identified pions
- D mesons
- B → J/ψ

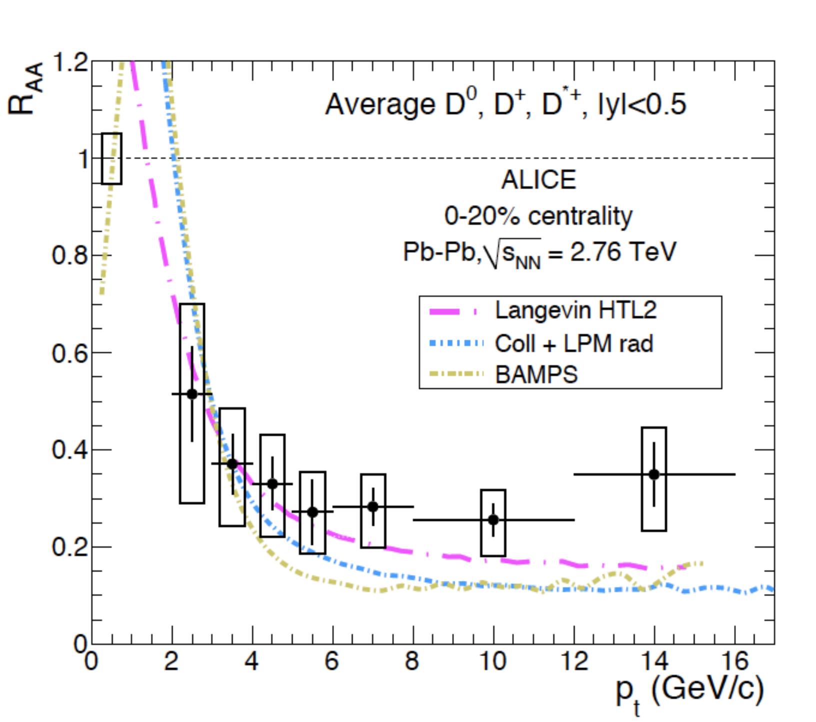


B→J/ψ +X

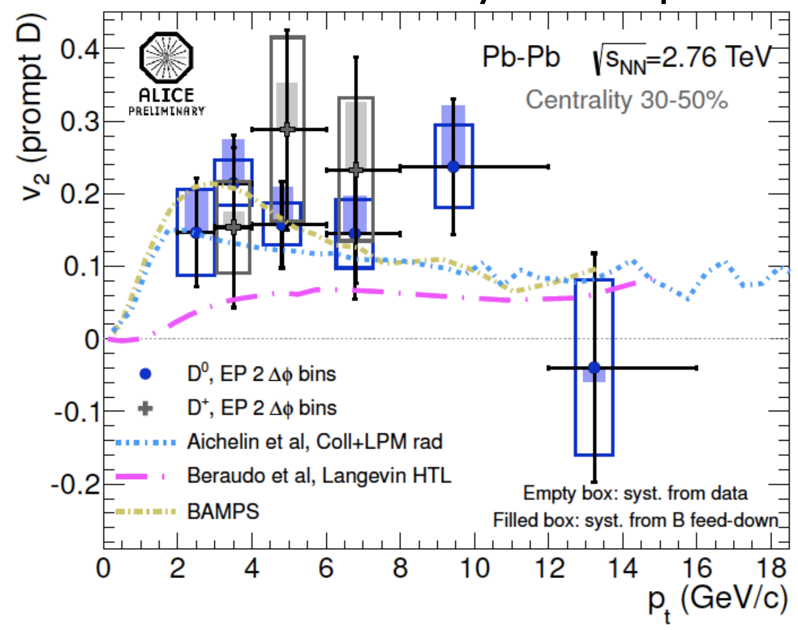
- Charm vs beauty: no evidence of mass effects
- HF vs pion: hint of a hierarchy

model discrimination:

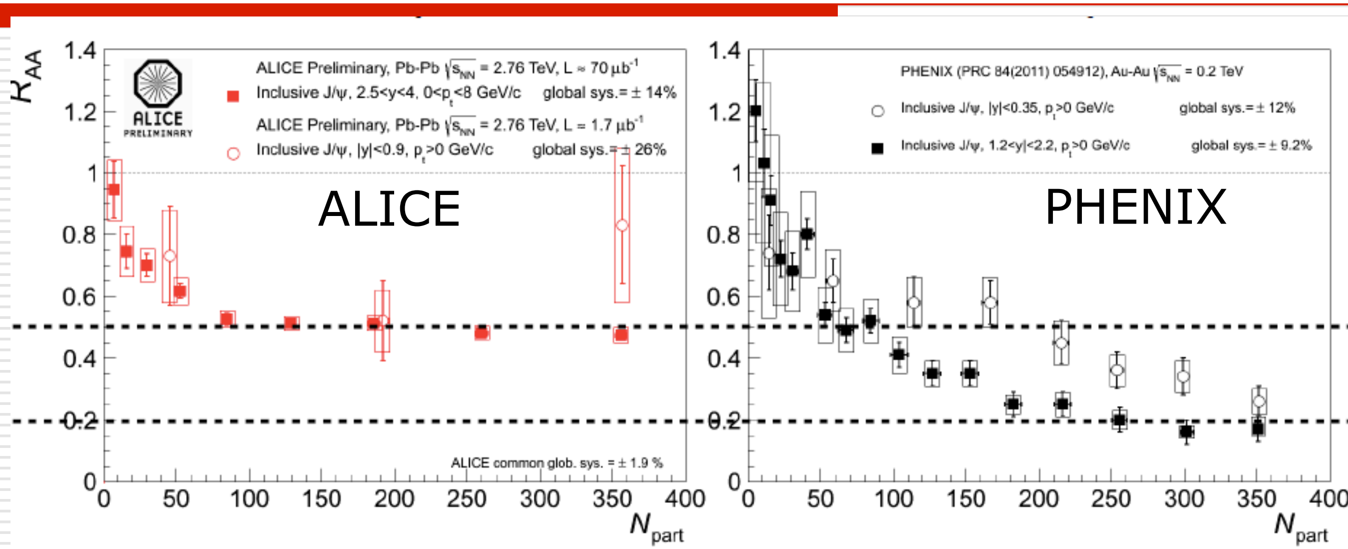
- describe both R_{AA} and v_2



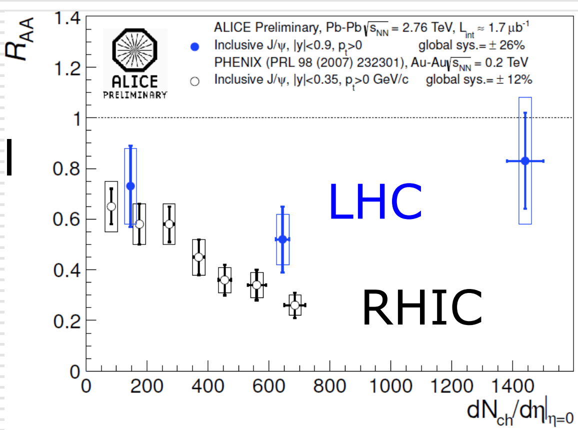
next talk by S. Lapointe

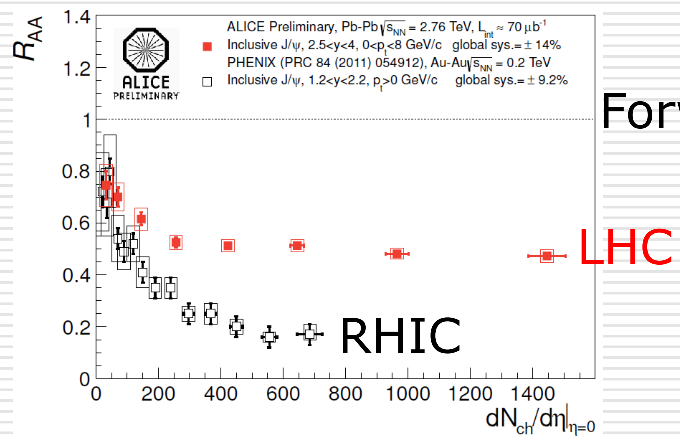


Quarkonia: J/ψ



Central

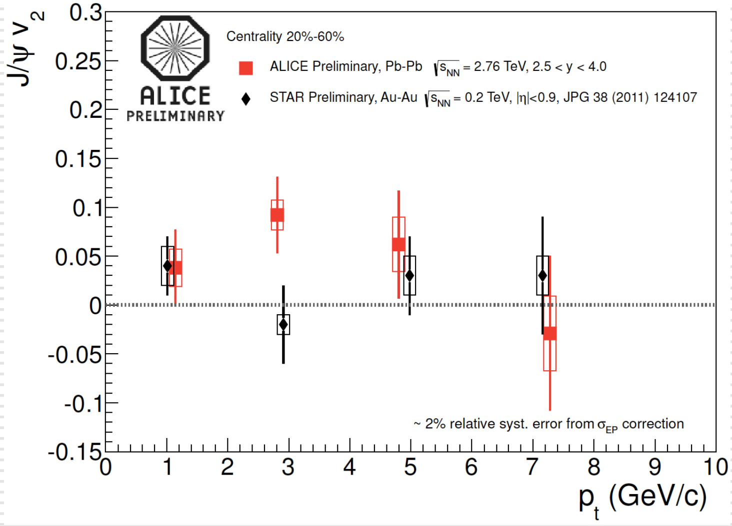


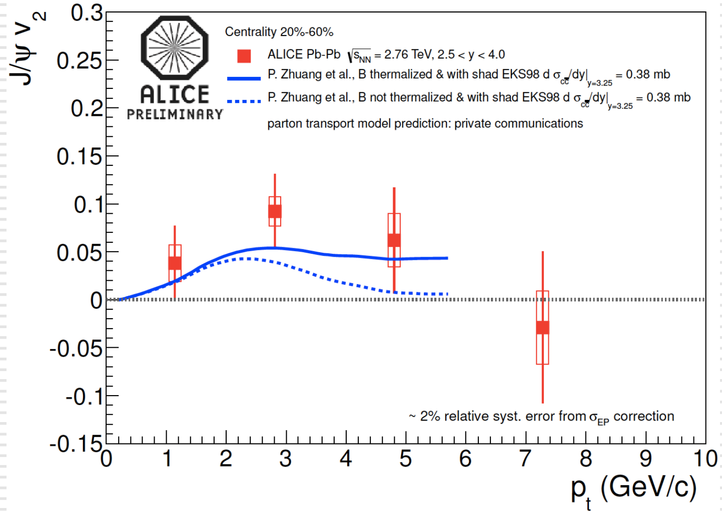


Forward

- J/Ψ suppression is *finally* different @ LHC
  - unless CNM plays very dirty, unexpected tricks
- much more in the talk by C. Blume

Quarkonia: J/ψ



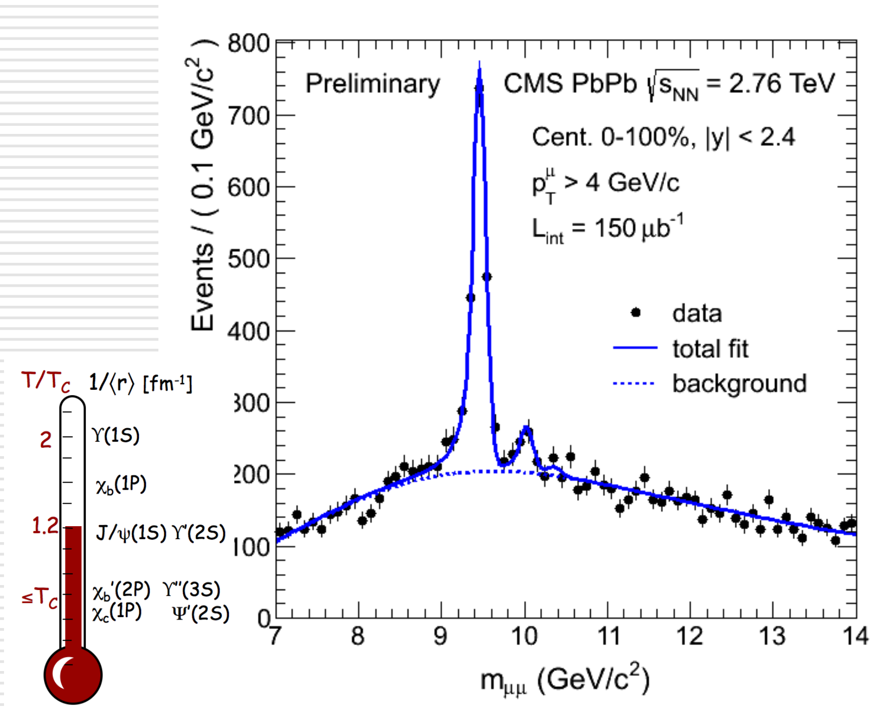


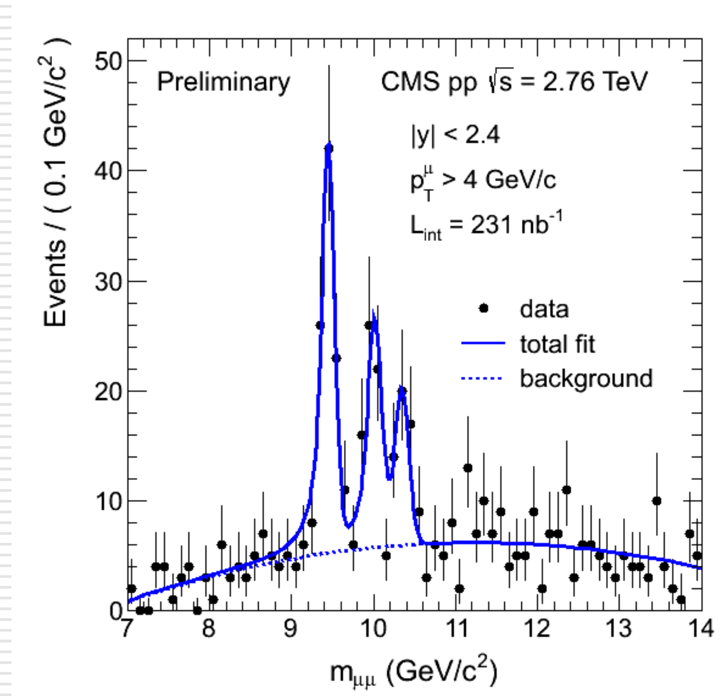
- Indication for $v_2 > 0$ in the range $2 < p_t < 4$ GeV/c
  - significance ~ 2.2σ deviation from 0 for ALICE
  - the presence of flow would fit well in the reco. picture

- J/Ψ suppression is *finally* different @ LHC
  - unless CNM plays very dirty, unexpected tricks
- much more in the talk by C. Blume

Quarkonia: Υ

- The Upsilon family



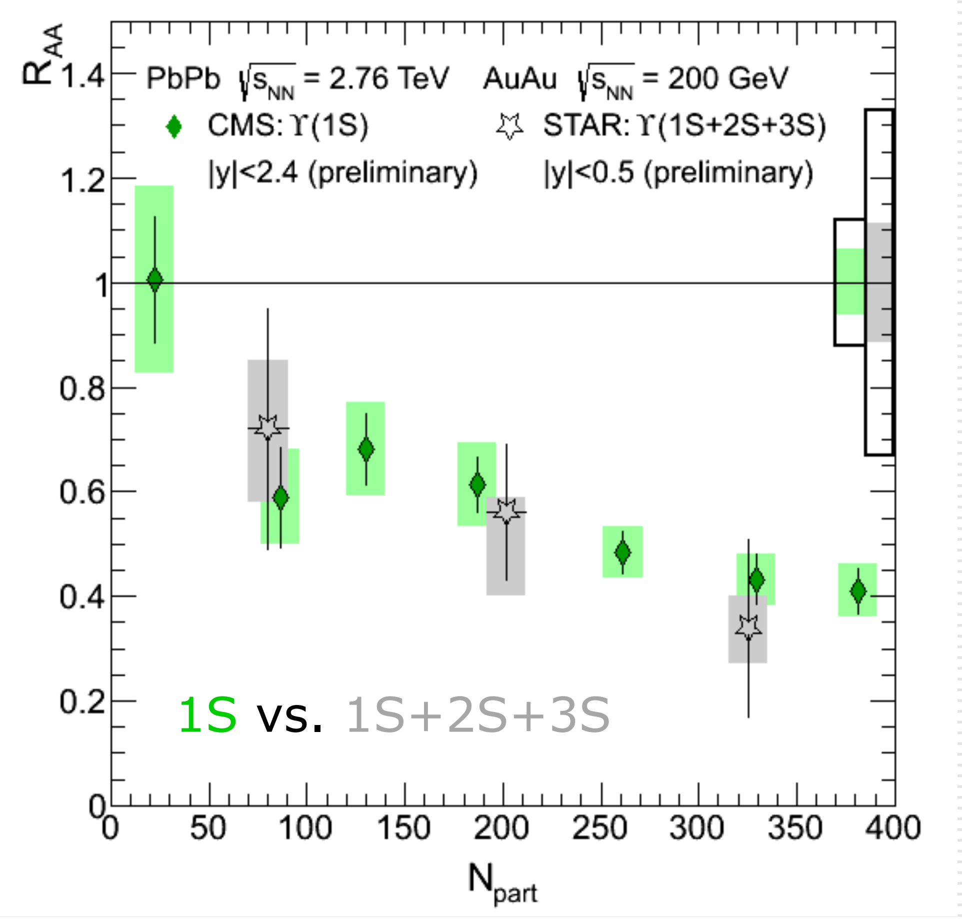


Sequential suppression can be seen already in inv. mass distributions

Quarkonia

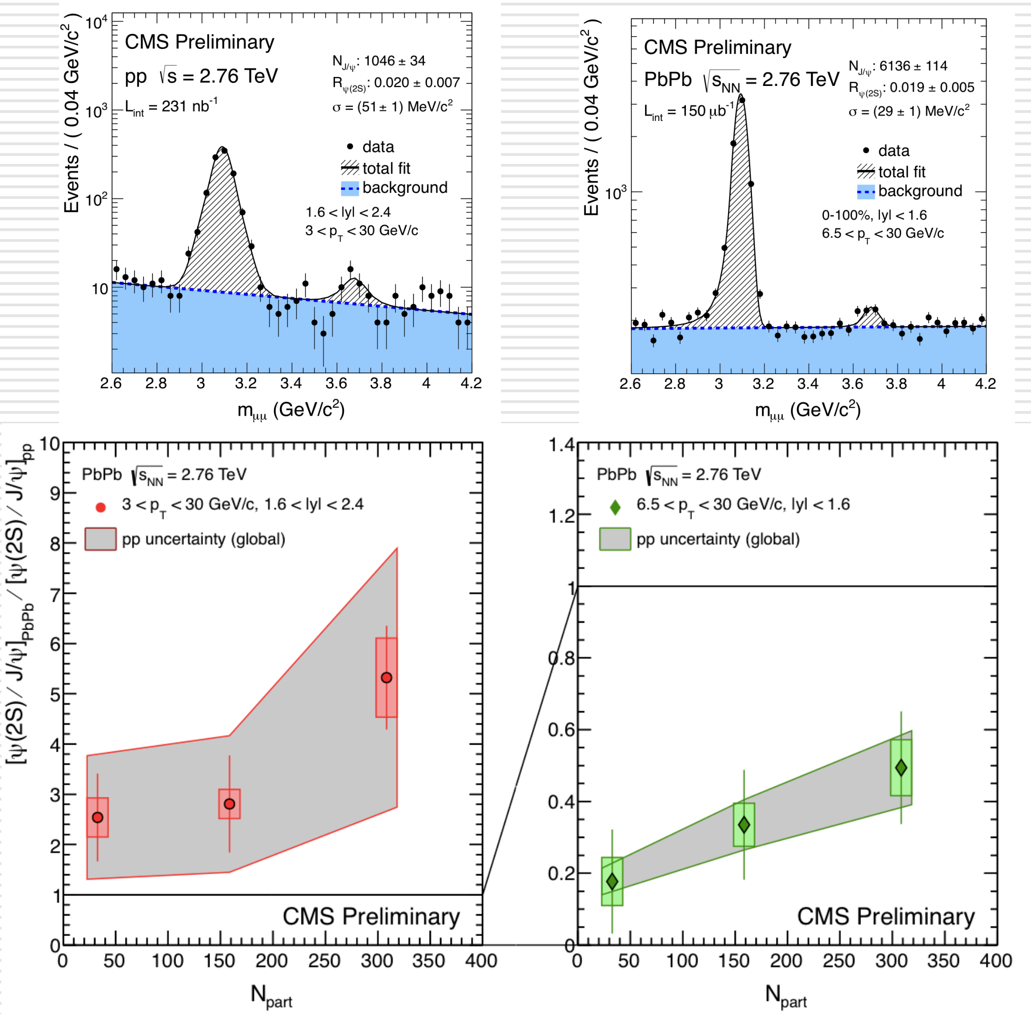
- first results on Υ(2S) R_{AA}
- clear suppression of Υ(2S)
- Υ(1S) suppression consistent with excited state suppression (~50% feed-down)
- RHIC vs. LHC
  - STAR R_{AA}(1+2+3) = **$0.56^{+0.22}_{-0.26}$**
  - CMS RAA(1+2+3) = **0.32**

consistent within 1σ



CMS ψ(2S)

CMS-HIN-12-007



- For p_T>6.5 GeV/c and |y|<1.6: ψ(2S) are more suppressed than J/ψ
- For p_T>3 GeV/c and 1.6<|y|<2.4: indication of ψ(2S) being less suppressed than J/ψ
- better pp reference needed
  - extrapolate 7 TeV data?

Summary: HF production at LHC

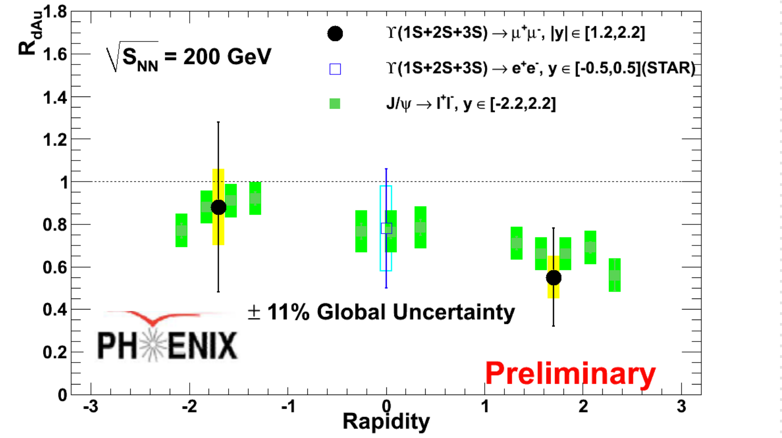
- HF in pp:
  - excellent measurements, theory does a good jobs
  - data at "reference energy" have to be improved
- Open HF in Pb-Pb
  - "indications" of:
    - $R_{AA}(D)/R_{AA}(\pi) > 1$ → colour charge and mass effect ?
    - $R_{AA}(b)/R_{AA}(c) > 1$? → mass effect ?????
  - "wish list" (besides smaller errors):
    - lower p_t => stronger m effect
    - dN_{HF}/dy in AA => J/Ψ normalisation, thermal production?
    - HF baryons ? => Λ_c/D
    - pPb => shadowing corrections at small pt

  Talk by C. Kuhn
- Quarkonia in Pb-Pb
  - J/ψ suppression
    - it is definitely different @ LHC
    - overall picture favors recombination scheme
  - Upsilon suppression: beautiful data … and make sense !
  - ψ'→ give theorists time to digest
- HF in pPb
  - check cold nuclear matter effect, this year

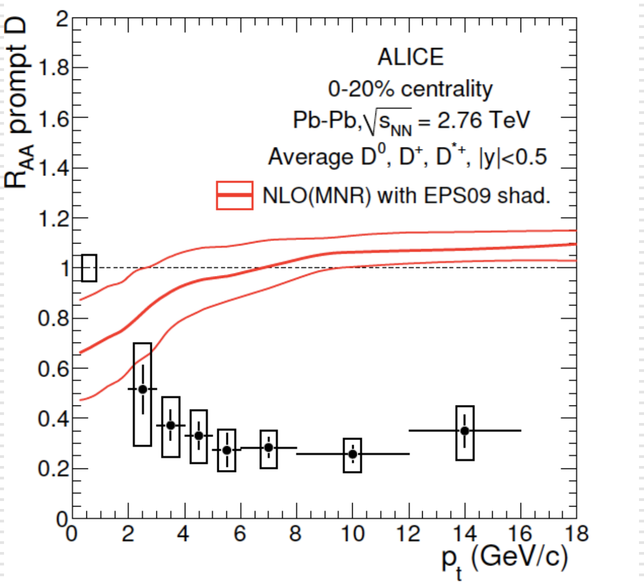
Spares

CNM effects: always tricky

- e.g. Phoenix
  - one would expect nuclear absorption for Υ << than for J/Ψ
  - but large error



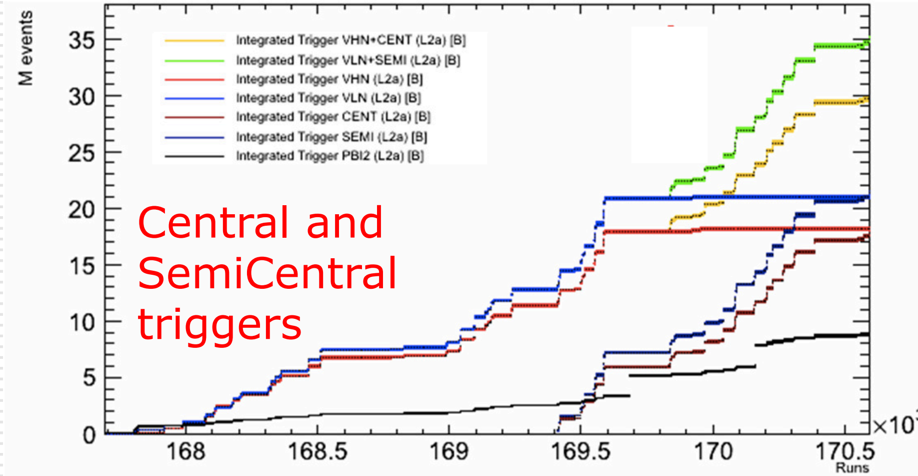
- Expected shadowing for D meson at LHC
  - sizeable at low p_t
  - a measurement is always better than even the best guess

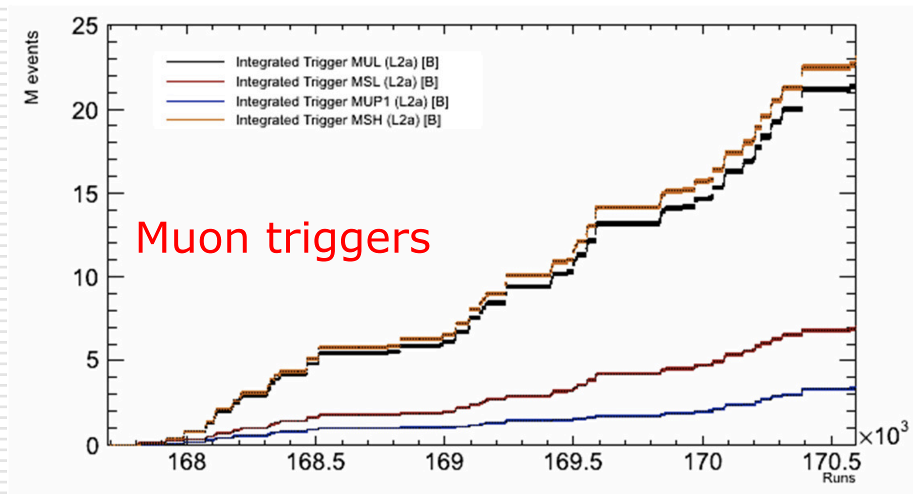


Pb-Pb 2011 run statistics

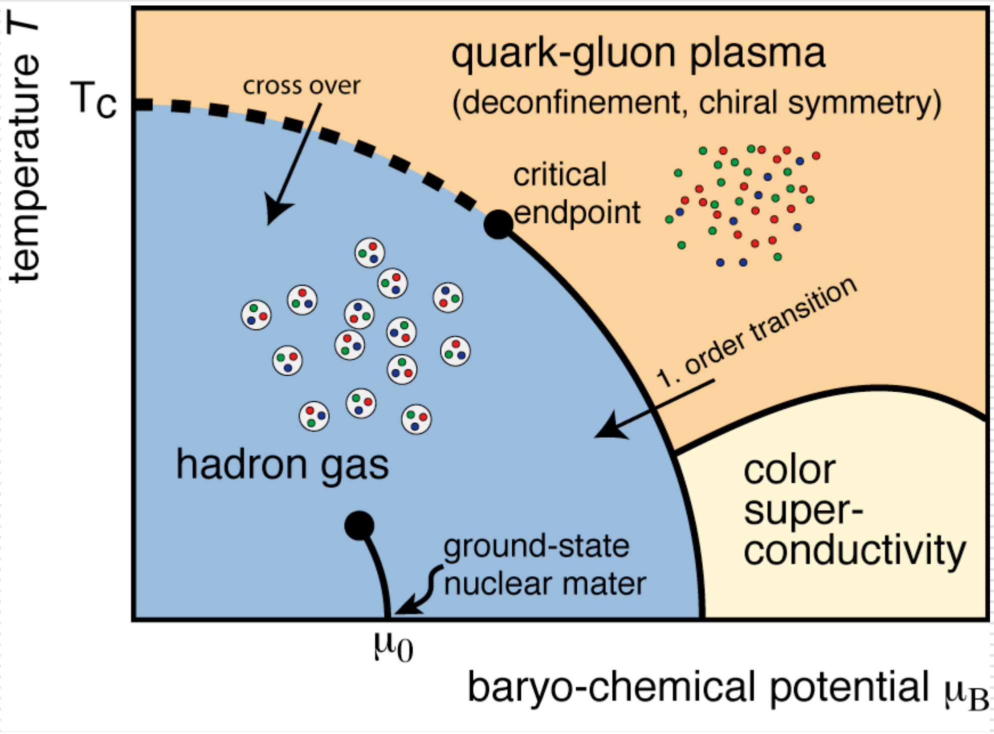
- Collected events:
  - 132.4M physics events
  - 7.7M calibration events

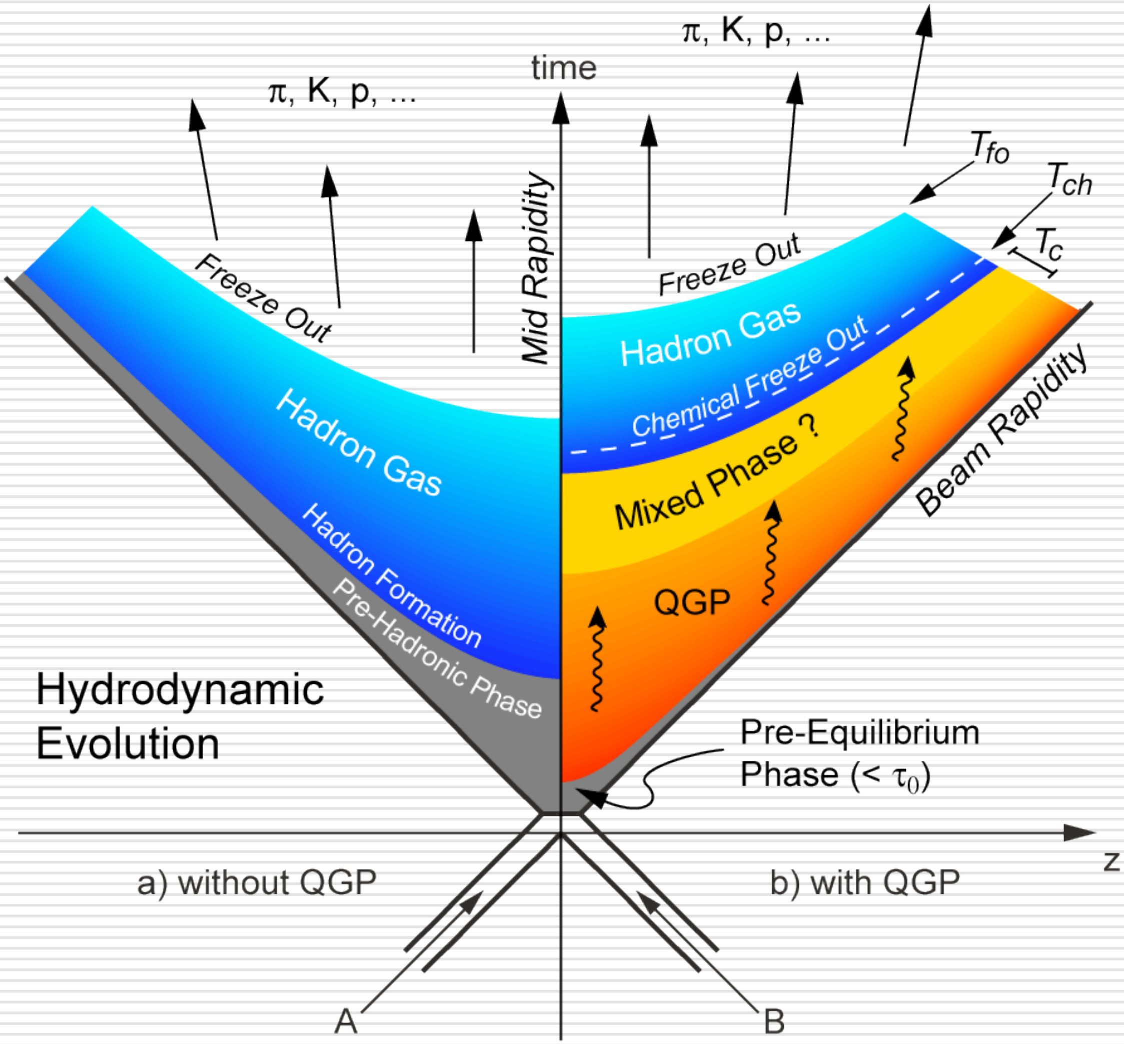
Physics	L2a Counts
MinBias	8798.8 k events
Central	29985.4 k events
SemiCentral	35020.4 k events
EMCAL Jet	10765.1 k events
EMCAL Gamma	7928.3 k events
Barrel UPC (SPD)	7880.7k events
Barrel UPC (EMCAL)	18.4 k events
PHOS	948.6 k events
MUON Single Low	6947.0 k events
MUON Single High	22978.3 k events
MUON UPC	3368.8 k events
DiMUON unlike	21634.2 k events





The Phase Diagram of QCD Matter




π, K, p, ...
time
π, K, p, ...
T_{fo}
T_{ch}
T_c
Freeze Out
Mid Rapidity
Freeze Out
Hadron Gas
Chemical Freeze Out
Hadron Gas
Mixed Phase ?
Beam Rapidity
Hadron Formation
Pre-Hadronic Phase
QGP
Hydrodynamic
Evolution
Pre-Equilibrium
Phase (< τ_0)
z
a) without QGP
b) with QGP
A
B

Charm & Beauty as probes

- calculable in pQCD; calibration measurement from pp
  - → rather solid ground
    - caveat: modification of initial state from pp to AA
      - shadowing (for pt <5-7 GeV/c)
      - saturation?
    - pA reference fundamental!

- produced essentially in initial impact
  - → probes of high density phase

- no extra production at hadronization
  - → probes of fragmentation
    - e.g.: independent string fragmentation vs recombination

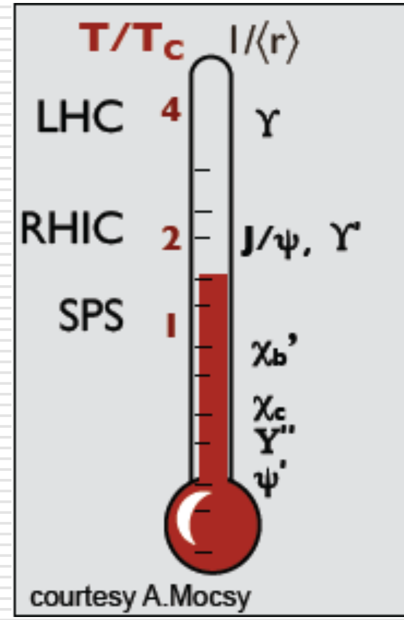
Probing the medium

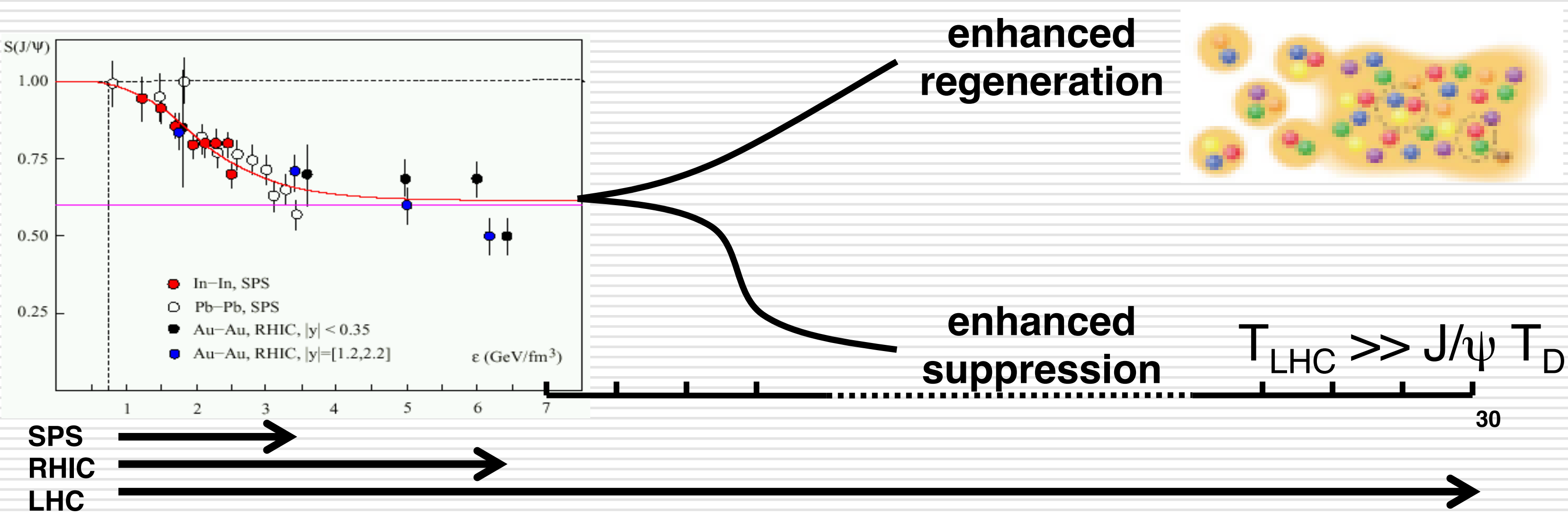
- quenching vs colour charge
  - heavy flavour from quark (C_R = 4/3) jets
  - light flavour from (p_T-dep) mix of quark and gluon (C_R = 3) jets

- quenching vs mass
  - heavy flavour predicted to suffer less energy loss
    - gluonstrahlung
    - collisional loss
  - beauty vs charm

Quarkonia at LHC

- Quarkonia dissociation due to colour screening
- Dissociation pattern depends on binding energy T_D and medium temp. T → quarkonia as a thermometer
  - Υ would dissociate only at LHC
  - $\Upsilon' T_D \sim J/\psi T_D$
- Expected regeneration for charmonia due to in-medium coalescence of charm quarks

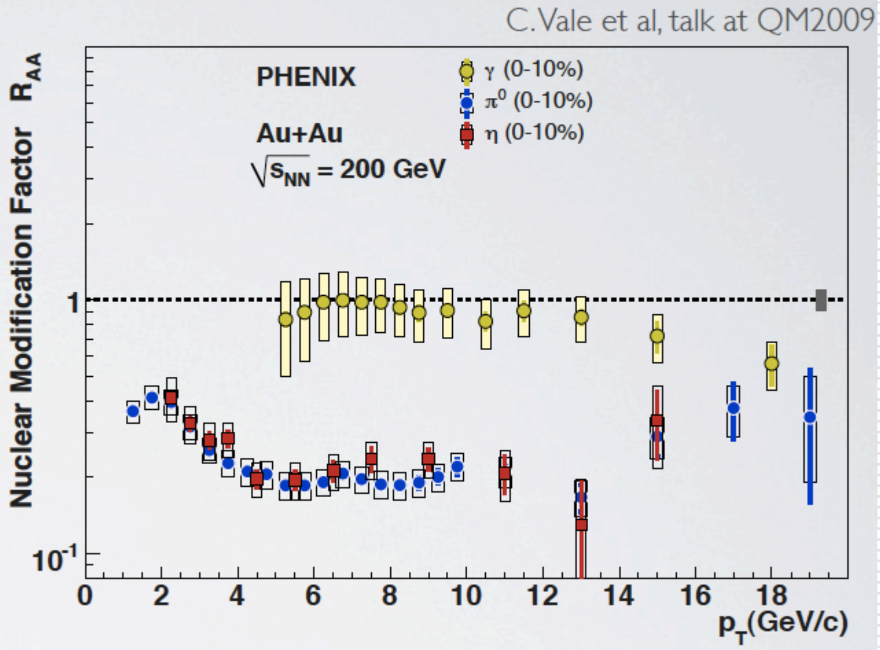




Jet quenching at RHIC

- high p_T hadrons strongly suppressed in central Au+Au
- nuclear modification factor

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{<N_{coll}> d^2N^{pp}/dydp_T}$$



- final state effect due to strong interaction
- photons not suppressed
- parton energy loss in dense medium

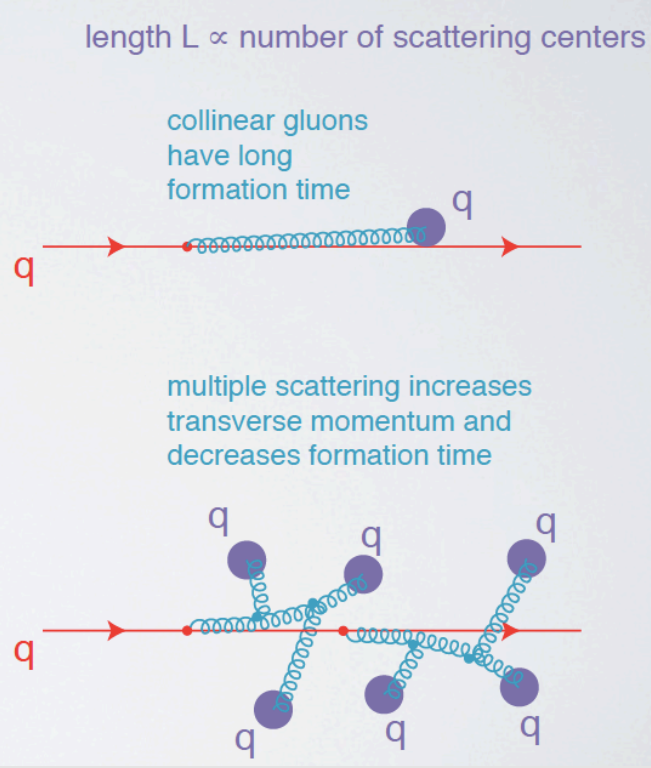
Parton energy loss

- partons produced in hard (high Q^2) scattering
  - traverse matter and loose energy
    - gluon radiation and collisions
    - amount of energy loss characteristic for medium density
    - non-linear effects from interference
      - Landau-Pomeranchuk-Migdal

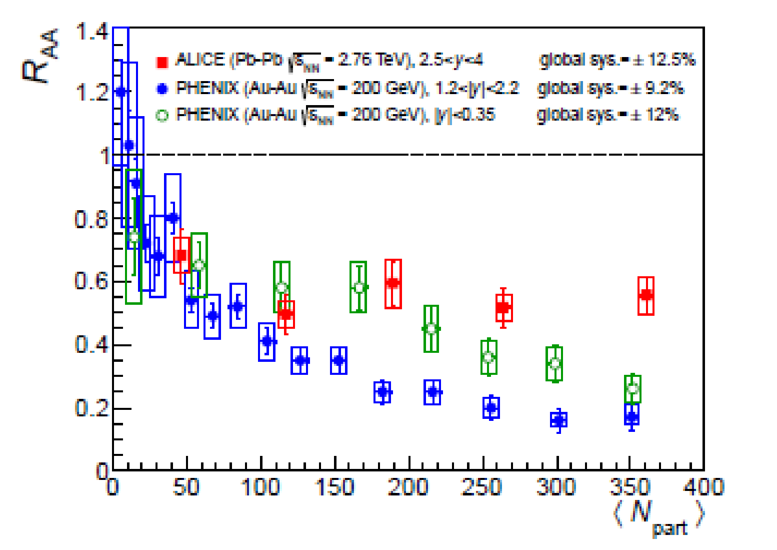
$$\Delta E \propto \alpha_s \hat{q} L^2$$

      - with transport coefficient:

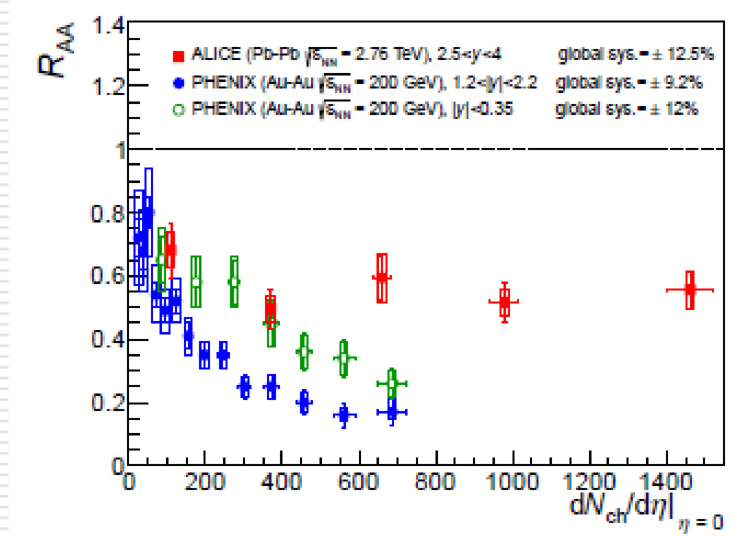
$$\hat{q} \equiv \left\langle p_T^2 \right\rangle / \lambda \approx \rho_{\text{gluons}}$$



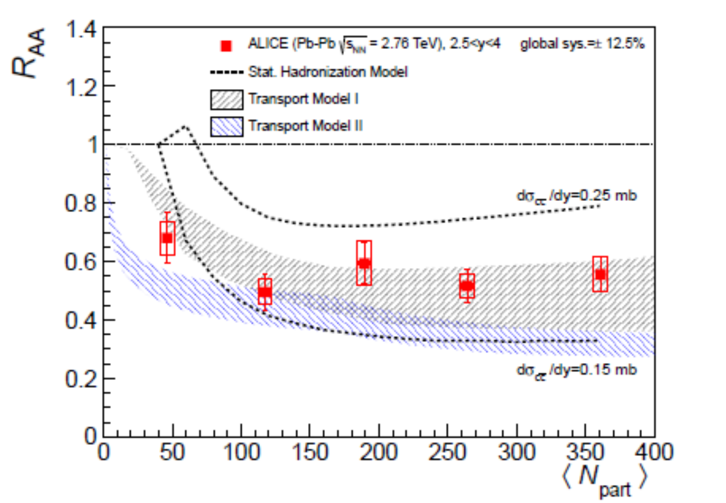
  - finally fragment into jets of hadrons
    - measured effect: jet quenching



R_{AA}
ALICE (Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV), 2.5<y<4 global sys.= ± 12.5%
PHENIX (Au-Au $\sqrt{s_{NN}}$ = 200 GeV), 1.2<|y|<2.2 global sys.= ± 9.2%
PHENIX (Au-Au $\sqrt{s_{NN}}$ = 200 GeV), |y|<0.35 global sys.= ± 12%
$\langle N_{part} \rangle$

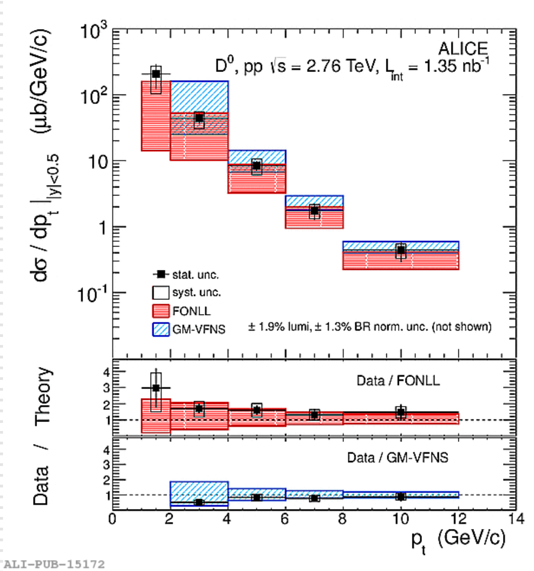


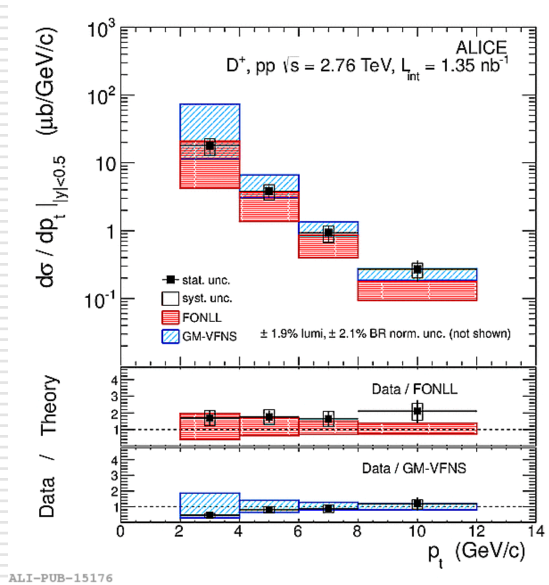
R_{AA}
ALICE (Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV), 2.5<y<4 global sys.= ± 12.5%
PHENIX (Au-Au $\sqrt{s_{NN}}$ = 200 GeV), 1.2<|y|<2.2 global sys.= ± 9.2%
PHENIX (Au-Au $\sqrt{s_{NN}}$ = 200 GeV), |y|<0.35 global sys.= ± 12%
$dN_{ch}/d\eta|_{\eta=0}$

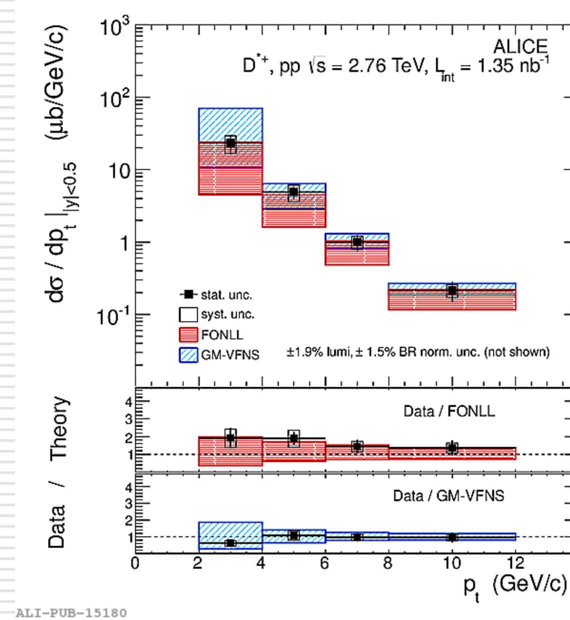


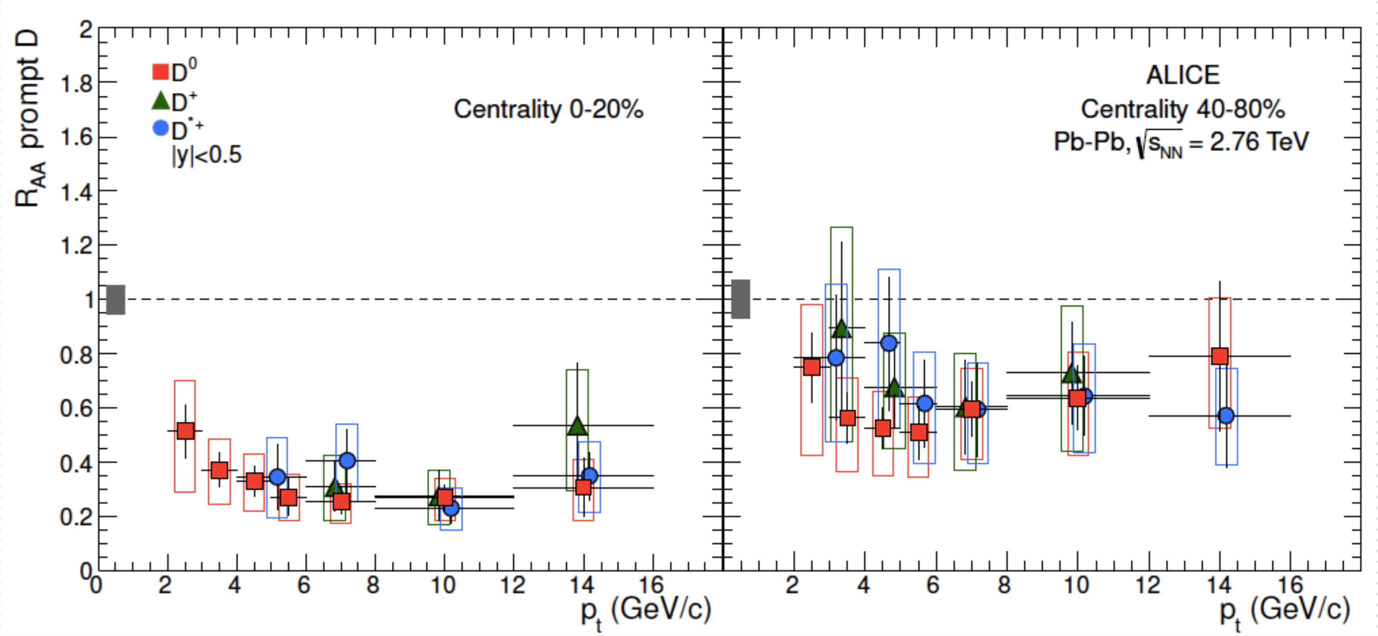
R_{AA}
ALICE (Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV), 2.5<y<4 global sys.=± 12.5%
Stat. Hadronization Model
Transport Model I
Transport Model II
$d\sigma_{c\bar{c}}/dy$=0.25 mb
$d\sigma_{c\bar{c}}/dy$=0.15 mb
$\langle N_{part} \rangle$

arXiv:1205.4007



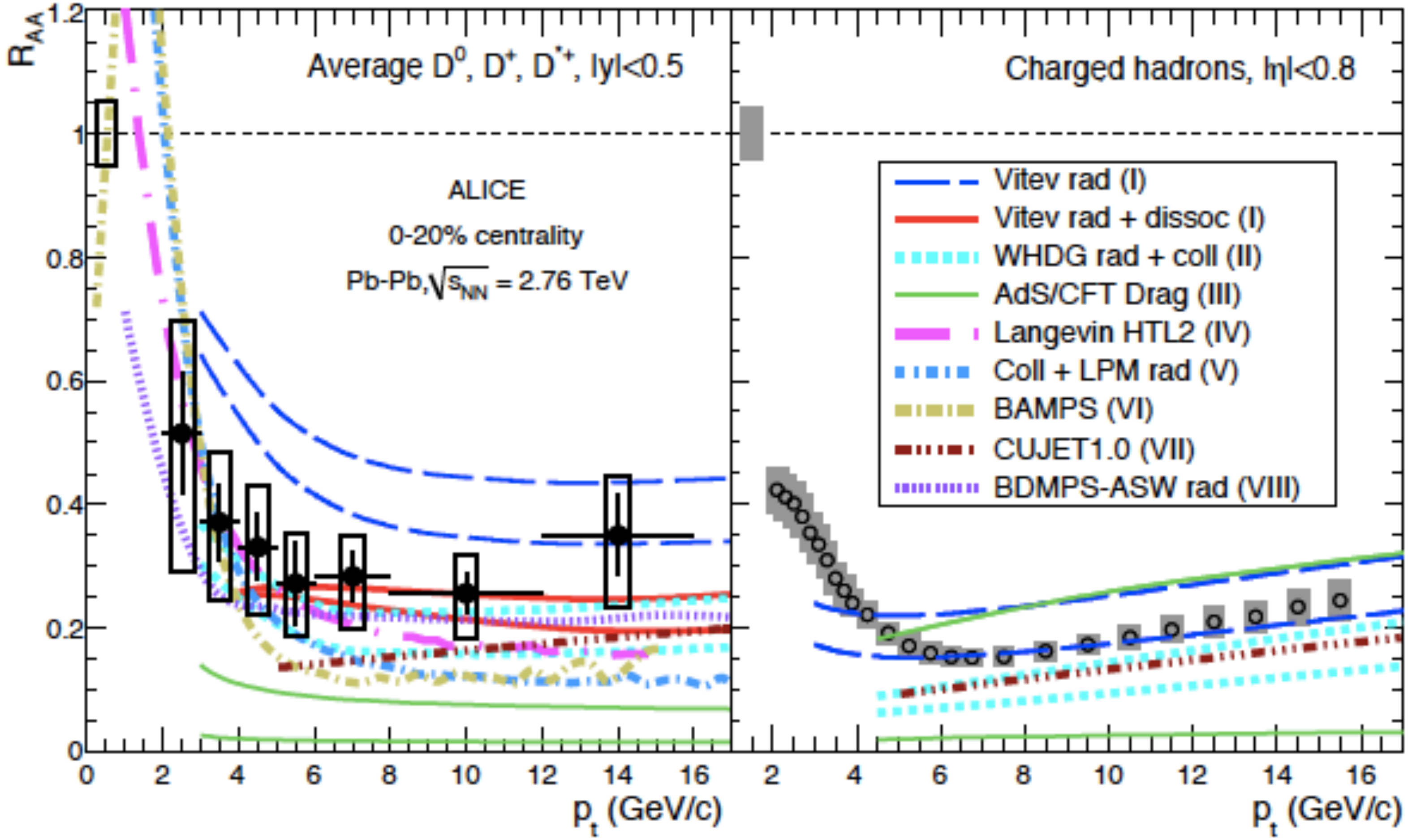




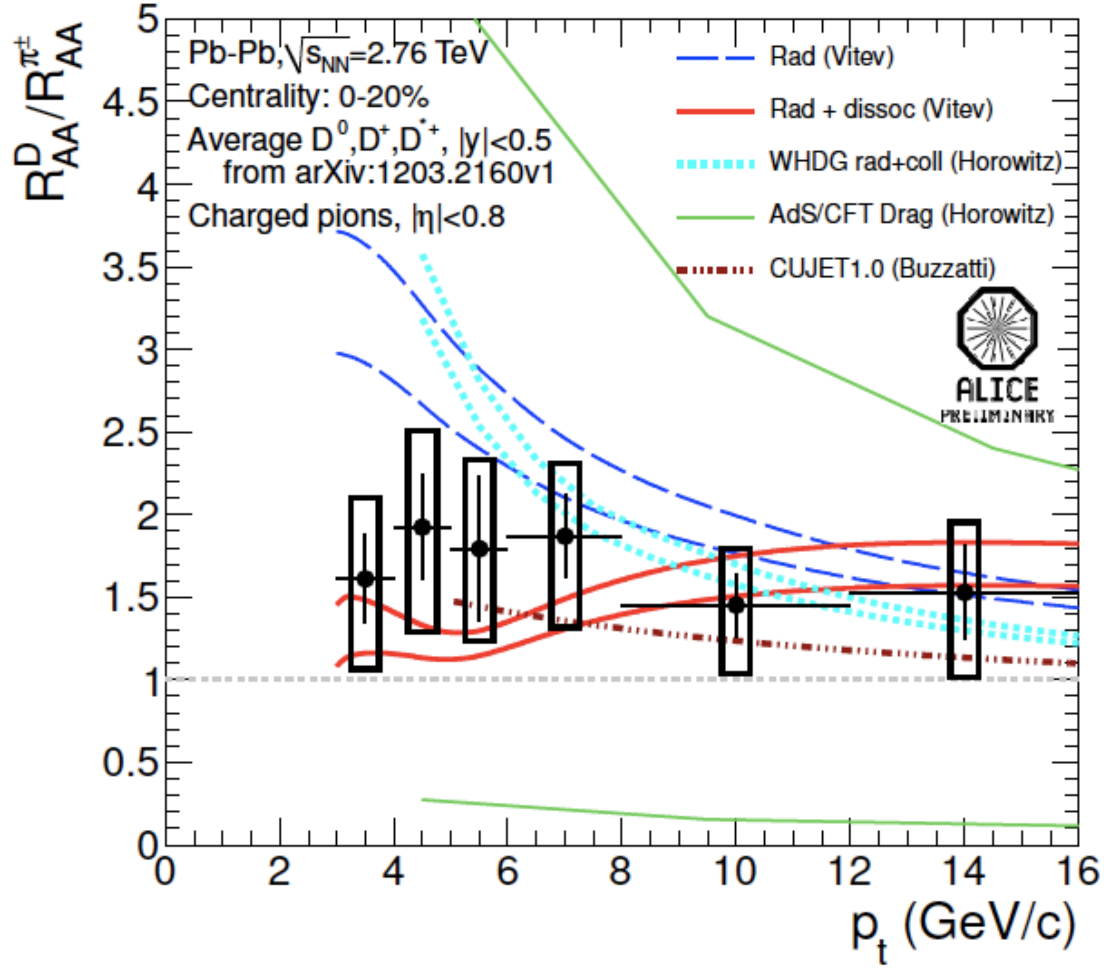


R_{AA} prompt D
D0
D+
D*+
|y|<0.5
Centrality 0-20%
ALICE
Centrality 40-80%
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
p_t (GeV/c)
p_t (GeV/c)

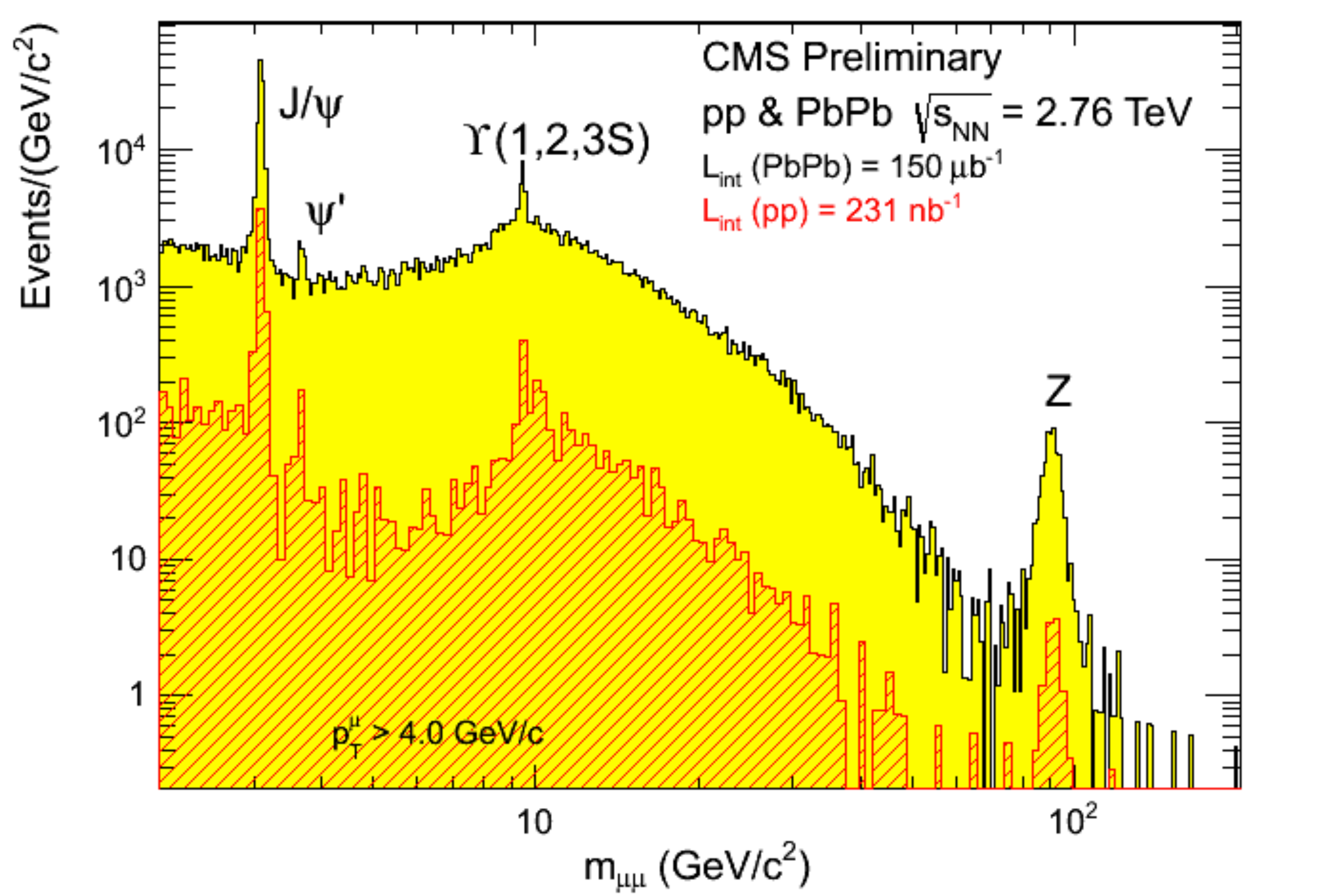
R_{AA} of D mesons vs. theory



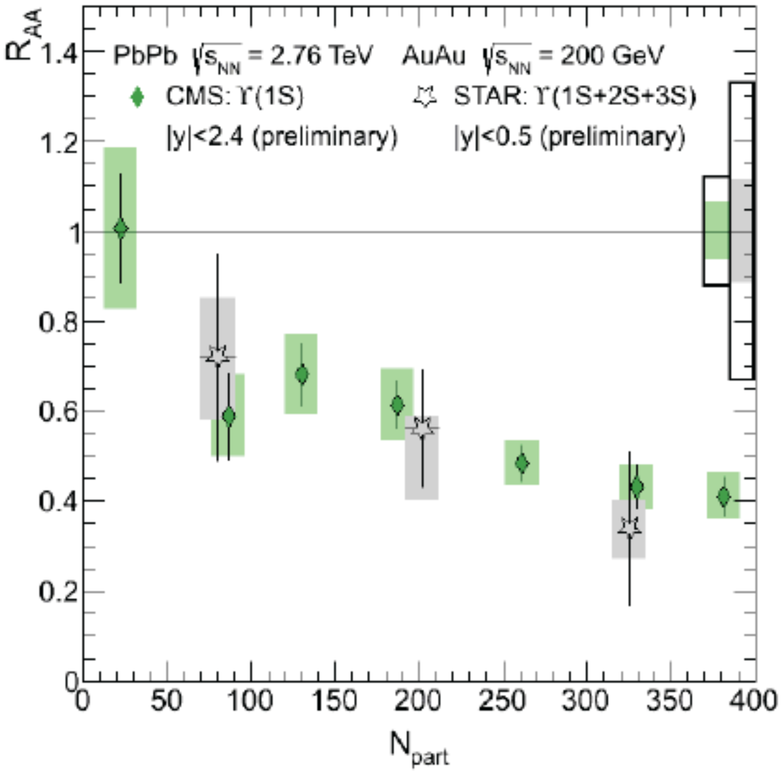
$R_{AA}(D) / R_{AAa}(\pi) > 1$?



pp vs Pb-Pb statistics at 2.76 TeV per nucleon pair



Comparison to RHIC



- STAR measured R_{AA} of Υ(1S+2S+3S) combined
  - arXiv:1109.3891
  - min. bias value:

$$R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$$

- CMS: separate R_{AA} for Υ(1S) and Υ(2S)
  - can calculate min. bias R_{AA} of Υ(1S+2S+3S):

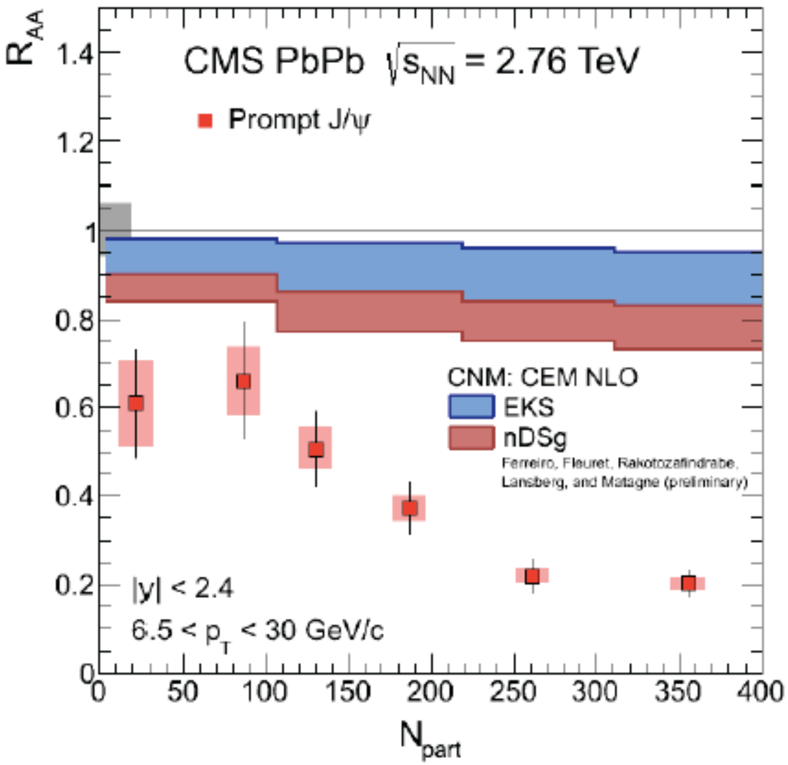
$$R_{AA}(\Upsilon(1S+2S+3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}}$$

$$= 0.53 \times \frac{1+0.19}{1+0.97} \approx 0.32$$

CMS-HIN-11-011

Hard Probes 2012, Calgiari, 27 May – 1 June 2011 14

Prompt J/ψ: CNM Effects

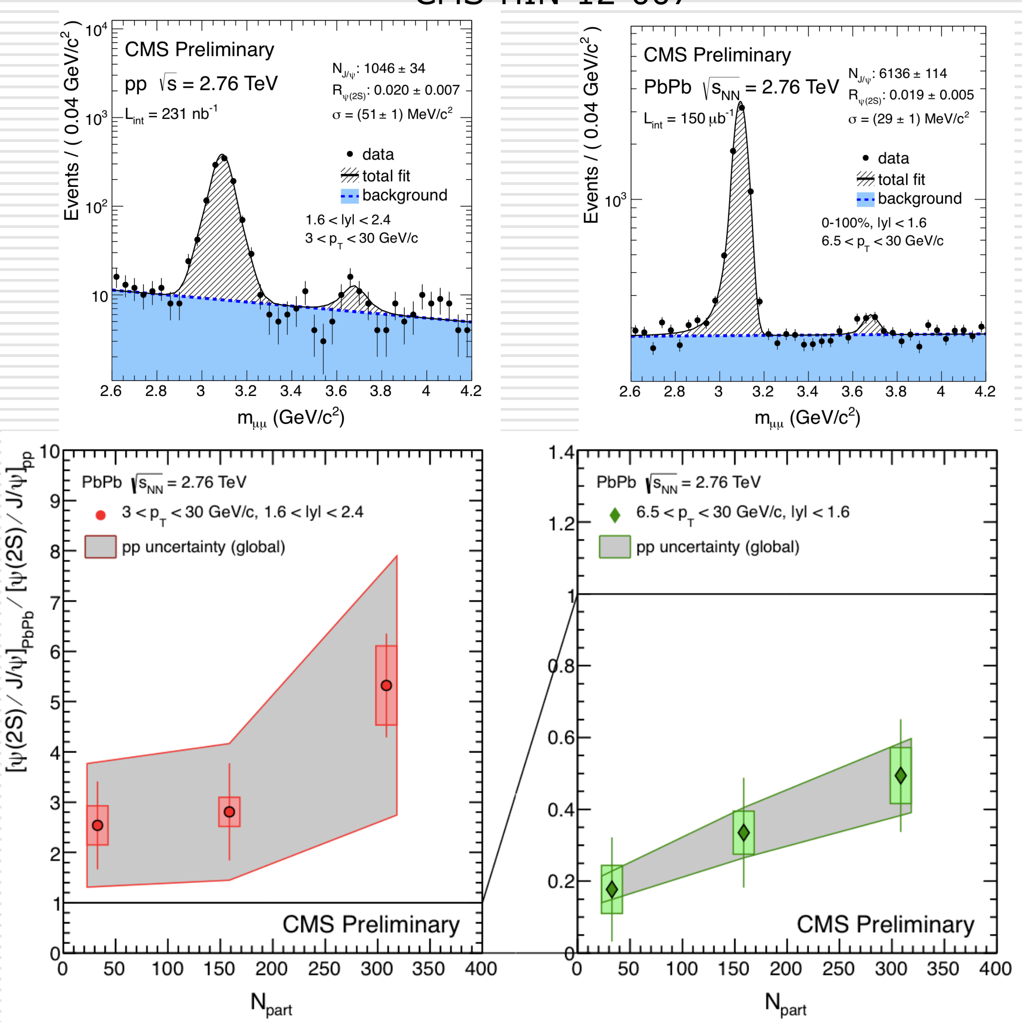


Ferreiro et al. (preliminary)

- Prompt J/ψ
  - p_T > 6.5 GeV/c:
  - in 0–10% centrality: suppressed by factor 5
  - in 50–100%: suppressed by factor ~1.6
- Cold nuclear matter effects
  - work in progress to estimate (anti)shadowing contributions
  - relatively small at high p_T

CMS $\psi(2S)$

CMS-HIN-12-007



Measured yield double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$ as a function of centrality. The p_T and rapidity bins are $6.5<p_T<30$ GeV/c and $|y|<1.6$ (left), and $3.0<p_T<30$\GeVc and $1.6<|y|<2.4$ (right). The error bars and boxes stand for the PbPb statistical and systematic uncertainties, respectively. The shaded band is the uncertainty on the pp measurement, common to all double-ratio points.

double charm production

Table 1: Estimates for the production cross-sections of the J/ψ C and CC modes in the LHCb fiducial range given by the leading order gg → J/ψ $c\bar{c}$ matrix element, σ_{gg} [13,14,17], the double parton scattering approach, σ_{DPS} and the intrinsic charm model, σ_{IC}.

Mode	σ_{gg} [13,14]	σ_{gg} [17]	σ_{DPS}	σ_{IC}
			[nb]	
J/ψ D^0	10 ± 6	7.4 ± 3.7	146 ± 39	220
J/ψ D^+	5 ± 3	2.6 ± 1.3	60 ± 17	100
J/ψ D_s^+	1.0 ± 0.8	1.5 ± 0.7	24 ± 7	30
J/ψ Λ_c^+	0.8 ± 0.5	0.9 ± 0.5	56 ± 22	
			[μb]	
D^0D^0			2.0 ± 0.5	1.5
D^0D^+			1.7 ± 0.4	1.4
$D^0D_s^+$			0.65 ± 0.15	0.4
$D^0\Lambda_c^+$			1.5 ± 0.5	1.4
D^+D^+			0.34 ± 0.09	0.3
$D^+D_s^+$			0.27 ± 0.07	0.2
$D^+\Lambda_c^+$			0.64 ± 0.23	

These LO α_s^4 pQCD results have a factor of two uncertainties due to selection of the scale for α_s.

double charm production

$$\sigma_{\mathrm{DPS}}(\mathrm{C_1C_2}) = \begin{cases} \frac{1}{2}\frac{\sigma(\mathrm{C_1}) \times \sigma(\mathrm{C_1})}{\sigma_{\mathrm{eff}}^{\mathrm{DPS}}}, & \text{for } \mathrm{C_1} = \mathrm{C_2} \\ \frac{\sigma(\mathrm{C_1}) \times \sigma(\mathrm{C_2})}{\sigma_{\mathrm{eff}}^{\mathrm{DPS}}}, & \text{for } \mathrm{C_1} \neq \mathrm{C_2}. \end{cases}$$

effective cross-section measured in multi-jet events at the Tevatron:
$\sigma^{DPS}_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

σ_{DPS}