Beauty physics with heavy ions (and prospects)

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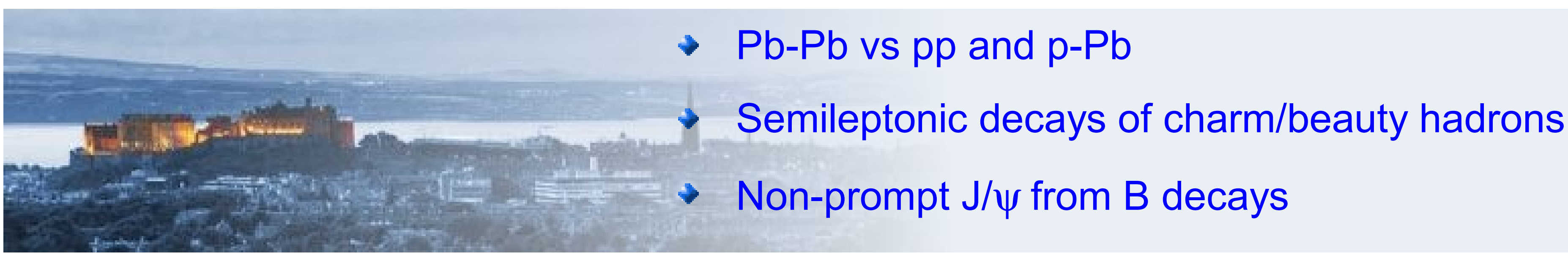
Outline:

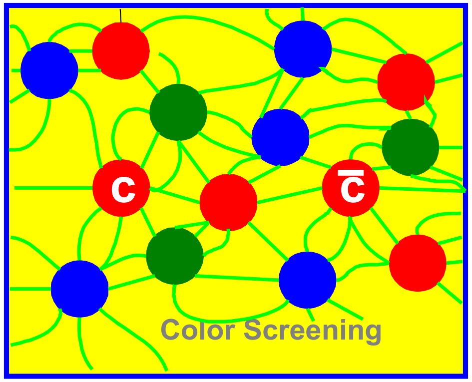
- Why beauty and bottomonia in heavy-ion collisions
- Pb-Pb vs pp and p-Pb
- Semileptonic decays of charm/beauty hadrons
- Non-prompt J/ψ from B decays
- Υ(ns) suppression
- Future prospects



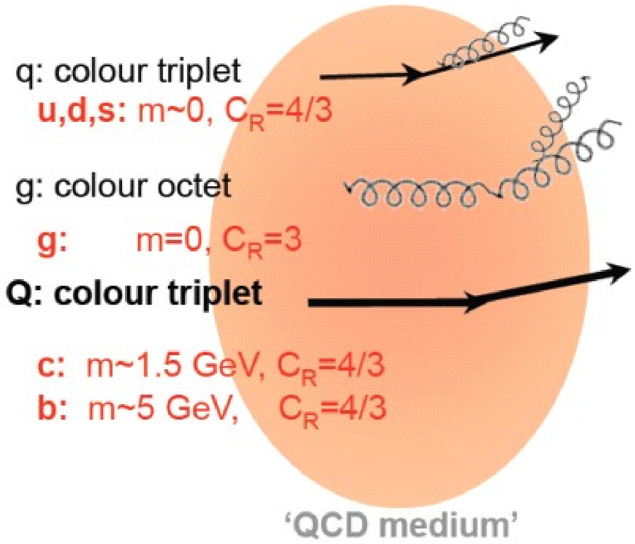
Beauty 2014
Edinburgh, 14-18/7/2014

Relativistic heavy ion collisions and heavy flavours

- Relativistic heavy ion collisions at RHIC and LHC energies provide the conditions to form a state of matter where quarks and gluons are deconfined, the Quark-Gluon Plasma (QGP)



- Quarkonia: melt due to colour screening sensitive to the QGP temperature



- Open heavy flavours: probe the energy density of the QGP

Heavy flavours in heavy ion collisions

- Heavy quarks ($m_q >> \Lambda_{QCD}$) are produced in the early stages of heavy-ion collisions
- Short formation time ($t_{charm} \sim 0.1$ fm/c << $\tau_{QGP} \sim 10$ fm/c)
- Uniqueness of heavy quarks: abundance basically conserved in the medium
  - Transported through the full system evolution
- Probe of the hot and dense medium produced in HI collisions
- Energy loss in the medium:
  - elastic scattering
  - gluon radiation
- How does energy loss depend on path-length, medium density, parton mass and color charge?
  - Medium density and path length: $\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$
  - Color charge and mass ("dead cone"): $\Delta E_{quark} < \Delta E_{gluon}$

$$\Delta E_b < \Delta E_c < \Delta E_{light\ quarks}$$

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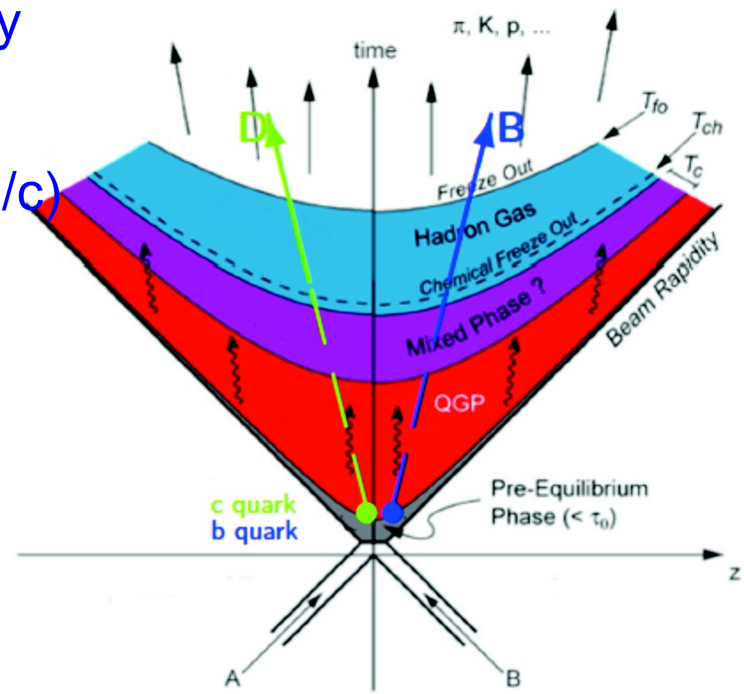


Heavy quarks in pp and p-A collisions

- **pp: reference for A-A**
  - effects related to the hot and dense medium created in HI are highlighted through the comparison with the pp reference
- Nuclear modification factor: used to compare the particle production in Pb-Pb to pp

$$R_{AA}(p_T) = \frac{\frac{dN_{AA}}{dp_T}}{\langle T_{AA}\rangle \frac{d\sigma_{pp}}{dp_T}}$$

Yield in Pb-Pb collisions (dN_{AA}/dp_T)

cross section in pp collisions ($d\sigma_{pp}/dp_T$)

Nuclear overlap function ($\langle T_{AA}\rangle$)

$R_{AA}=1$ ⇒ Pb-Pb collisions are a trivial superposition of pp collisions

$R_{AA}\neq 1$ ⇒ Binary scaling broken
Nuclear effects present

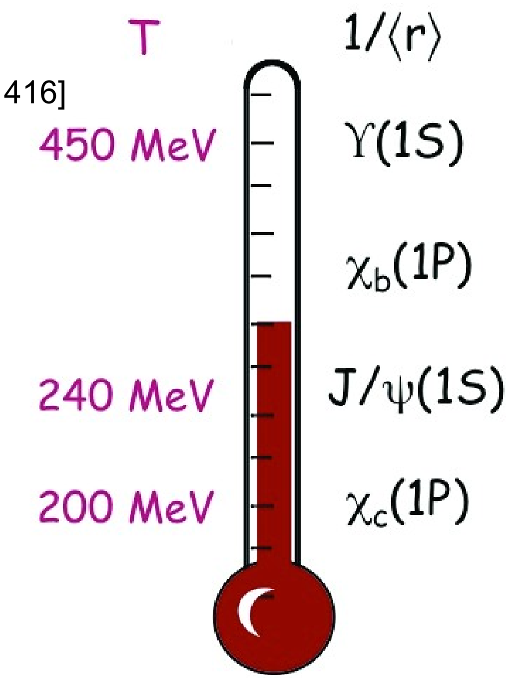
- LHC is the ideal place to measure heavy quark production

$$\sigma_c(LHC) \approx 5-10\,\sigma_c(RHIC)$$
$$\sigma_b(LHC) \approx 50\,\sigma_b(RHIC)$$

- Disentangle effects related to the hot medium from cold nuclear matter effects
- **p-A collisions:** no QGP created ⇒ **reference for cold nuclear matter**

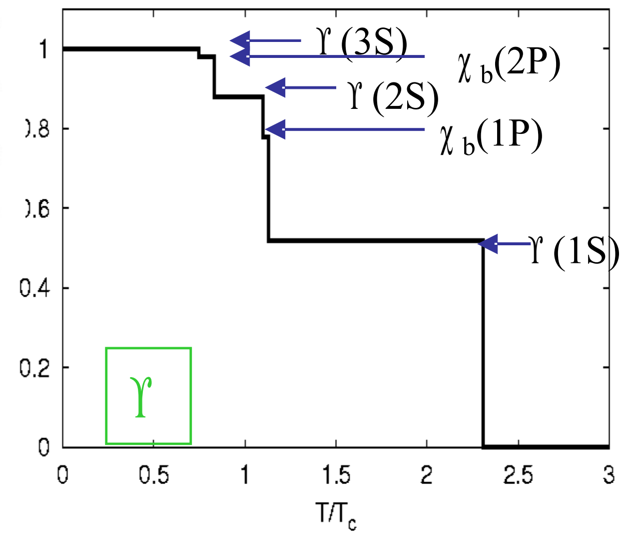
Quarkonia in heavy ion collisions

- Produced in the initial hard-scattering process
- Melting of quarkonia due to Debye screening [PLB 178 (1986) 416] (at LHC, recombination for charmonium is another possible mechanism) Phys. Lett. B 652, 259 (2007)...
- Depending on the binding energy, different states melt at different temperature → sequential suppression [Phys. Rev. D 64 (2001) 094015]



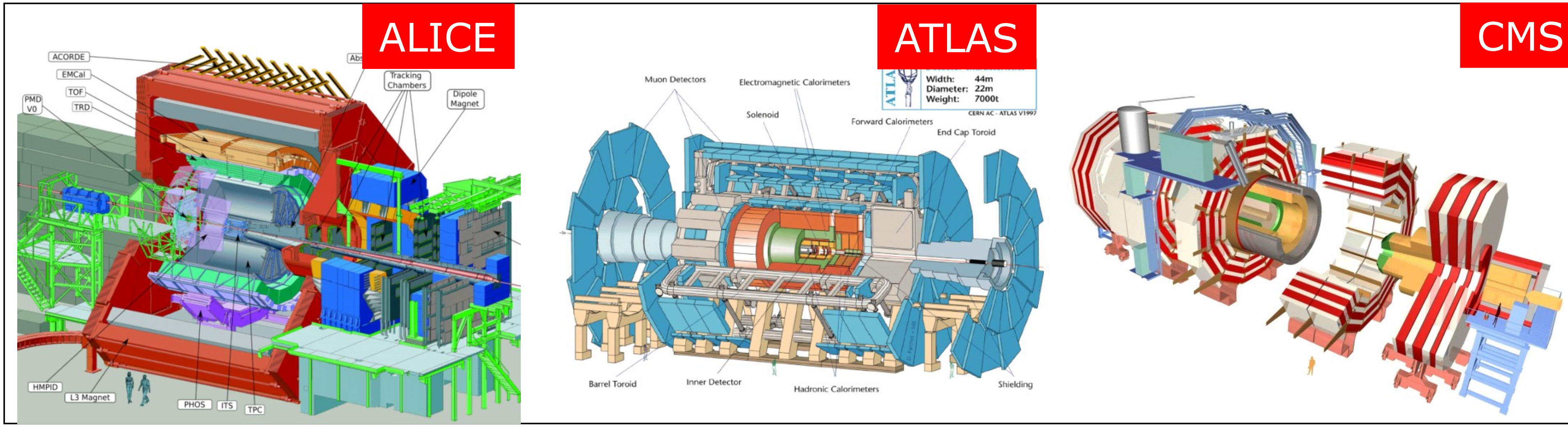
State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

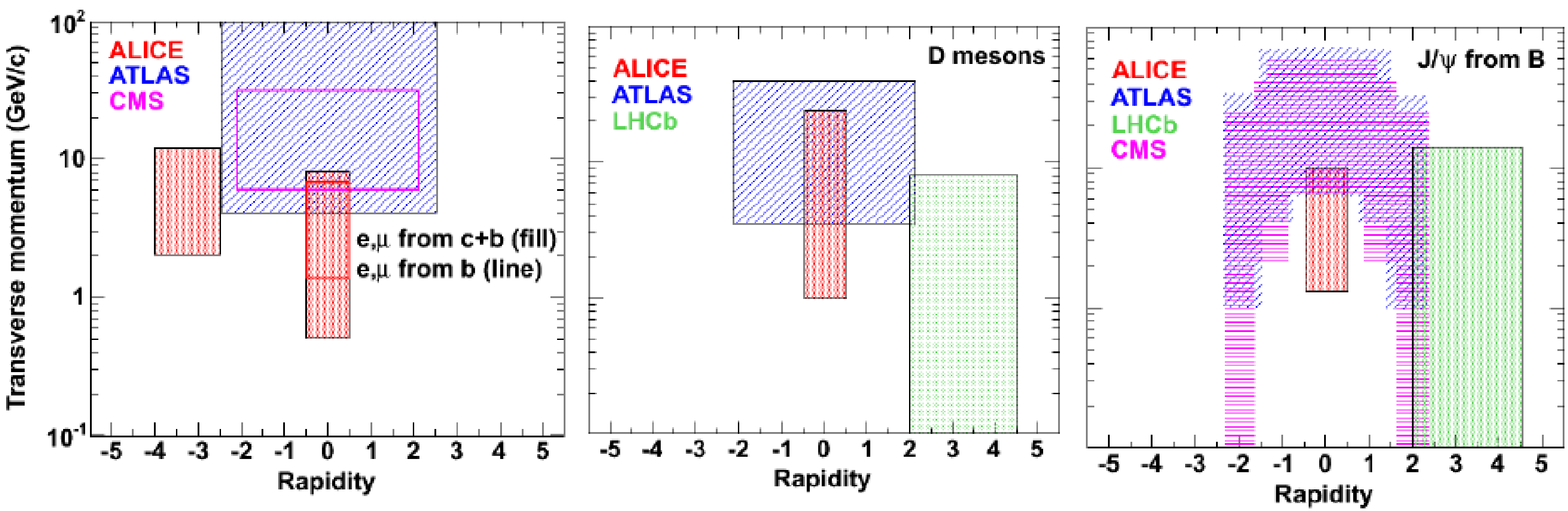
Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



- Bottomonia:
  - More tightly bound: $T_D > T_C$ and 3 different T_D
  - Less regeneration: clearer signature of suppression

Measurements at the LHC

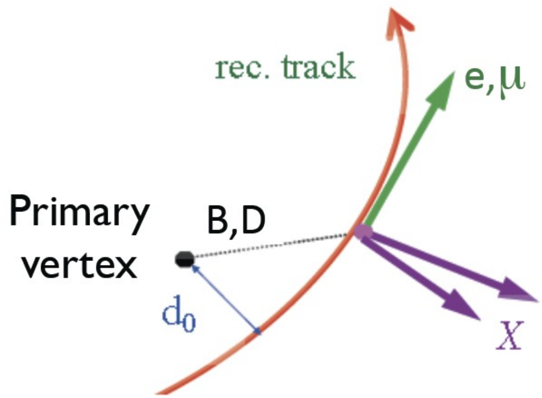


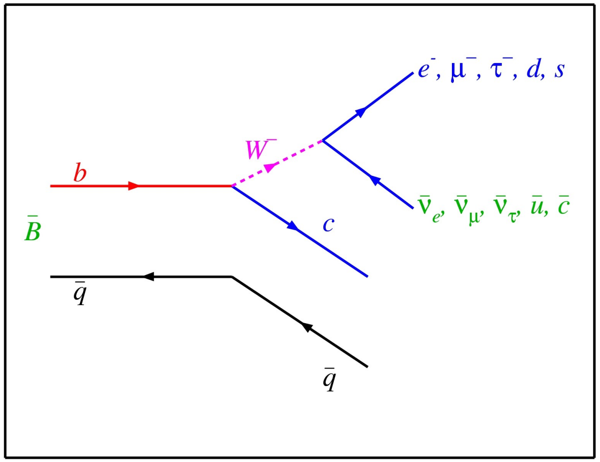


no LHCb measurement in Pb-Pb collisions

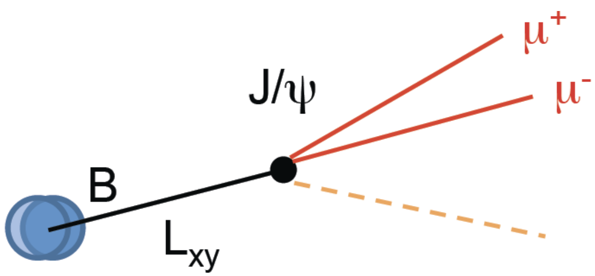
Physics channels for HF in heavy-ion collisions

- Semileptonic decays of B/D mesons



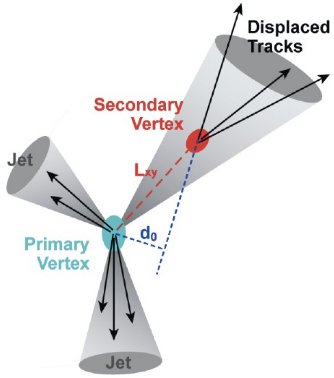


- J/ψ from B decays
  Decay is displaced from primary vertex

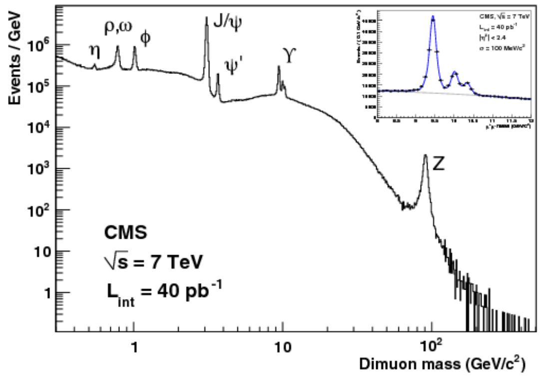


- Jet b-tagging

  (not covered by this presentation)

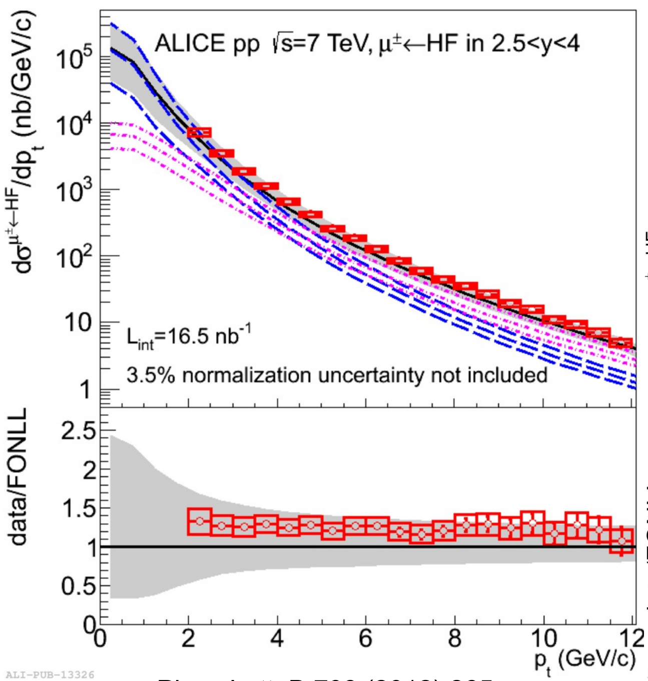


- Quarkonia: decays into dileptons

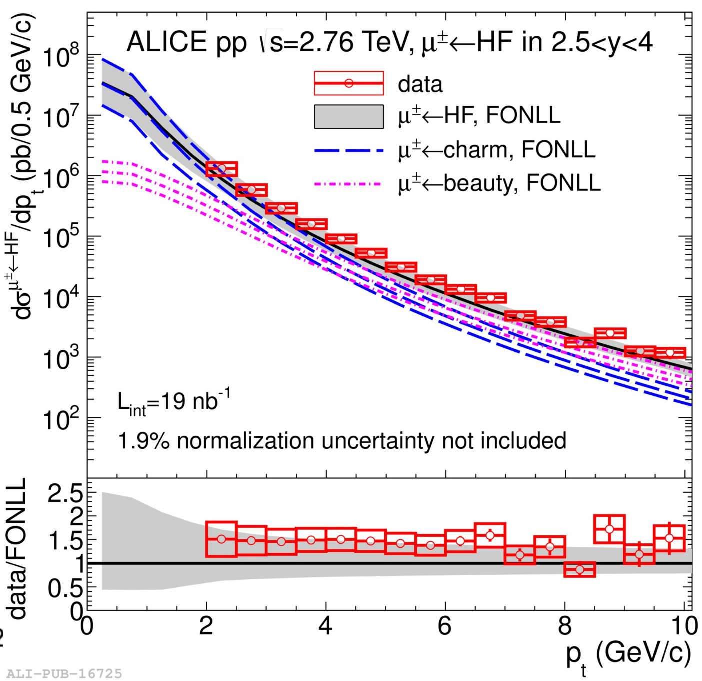


Semileptonic decays of charm/beauty hadrons: pp collisions

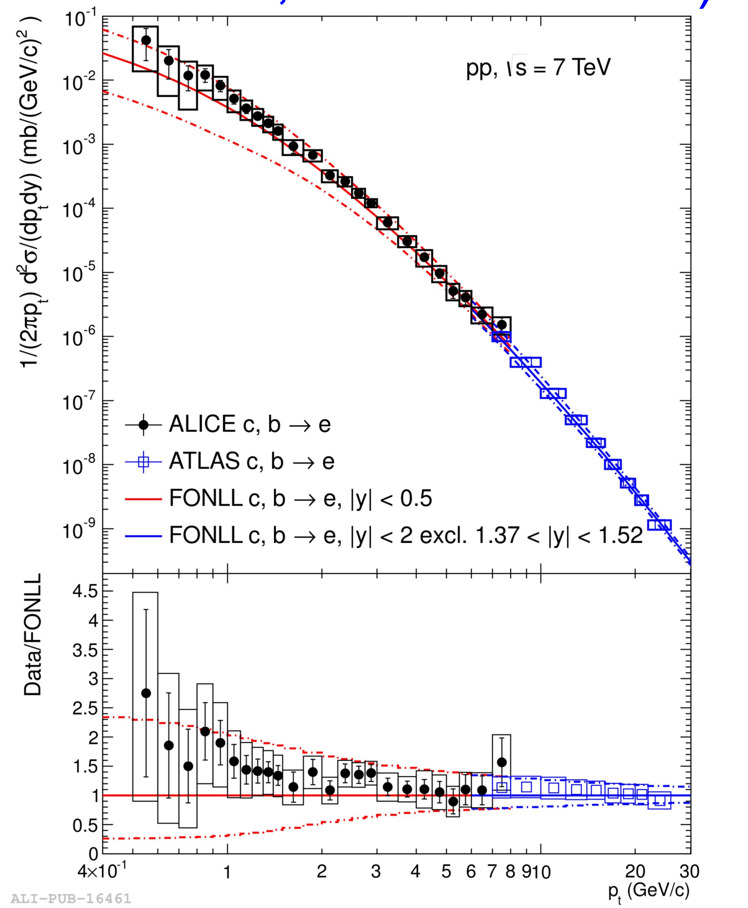
- Measurements at both forward (muons) and mid rapidity (electrons)
- Single muon p_T spectra
- Background, concentrated at low p_T, subtracted by means of simulations
- No charm/beauty separation (b/c separation possible for e, see next slides)
- Results in agreement with FONLL calculations



Phys. Lett. B 708 (2012) 265



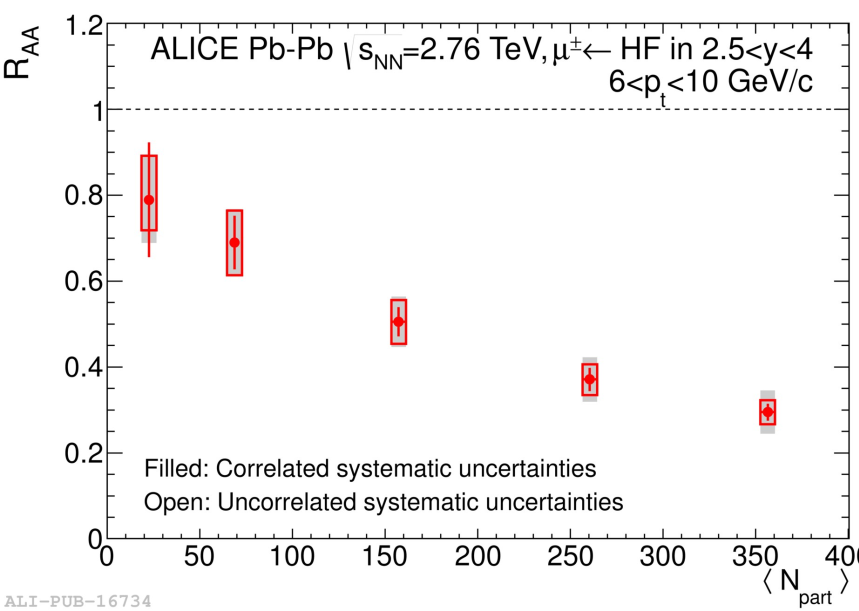
Phys. Rev. Lett. 109, 112301 (2012)



Phys. Rev. D 86, 112007 (2012)

Semileptonic decays of charm/beauty hadrons: Pb-Pb collisions at 2.76 TeV

- No significant dependence of R_{AA} on p_T both in central and peripheral collisions
- Strong suppression of the yield for p_T>3 GeV/c in central collisions
- Similar suppression at forward and midrapidity



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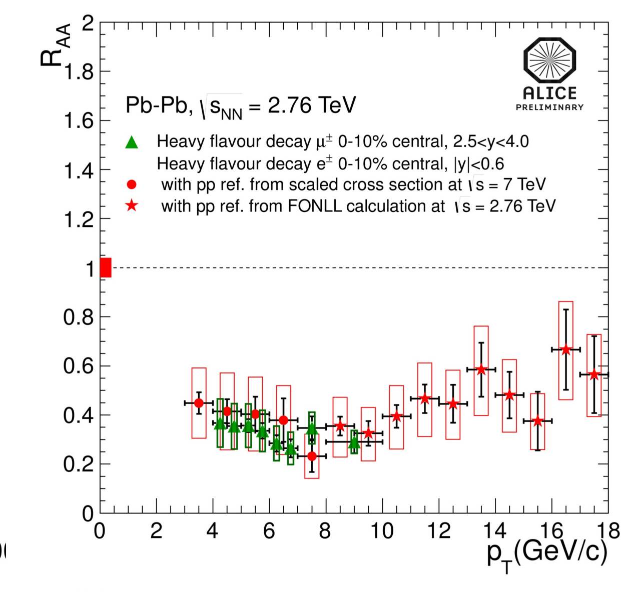
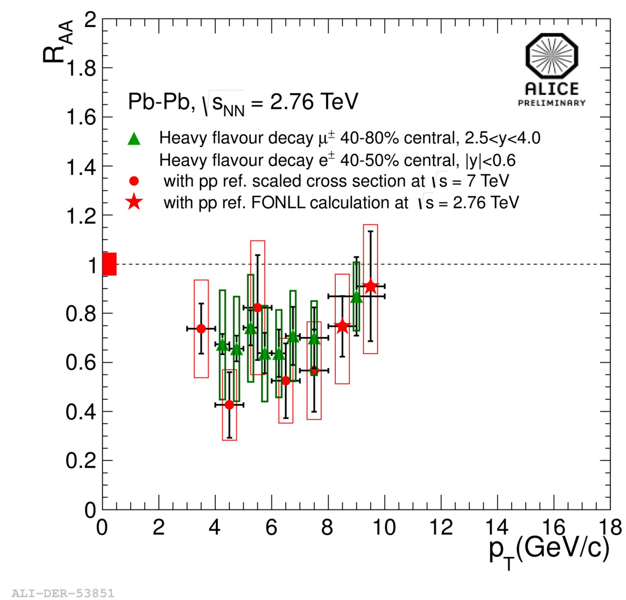
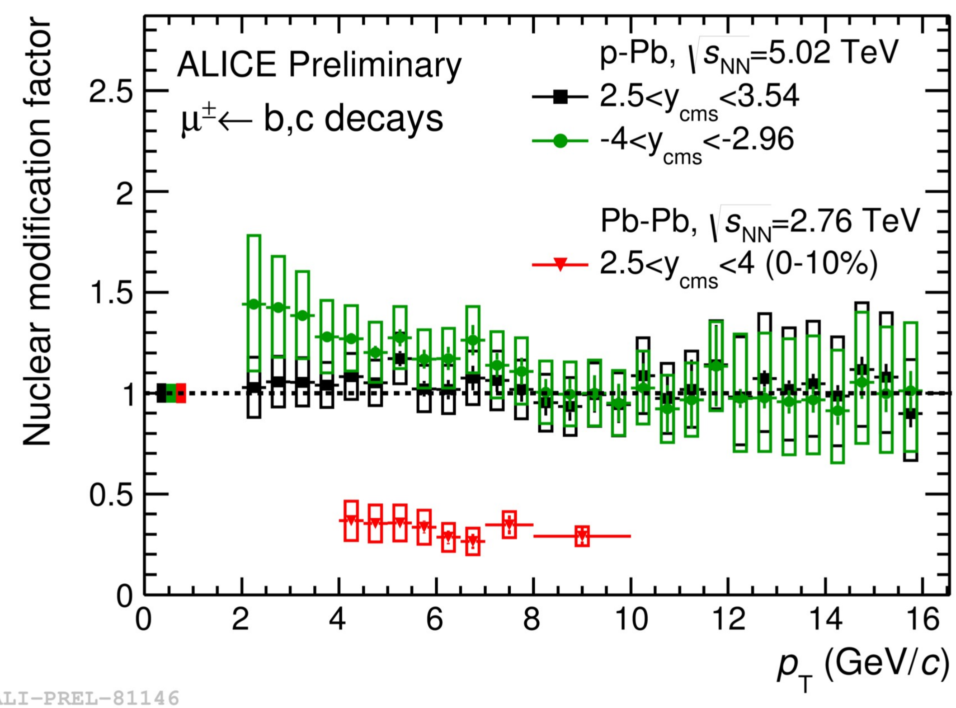
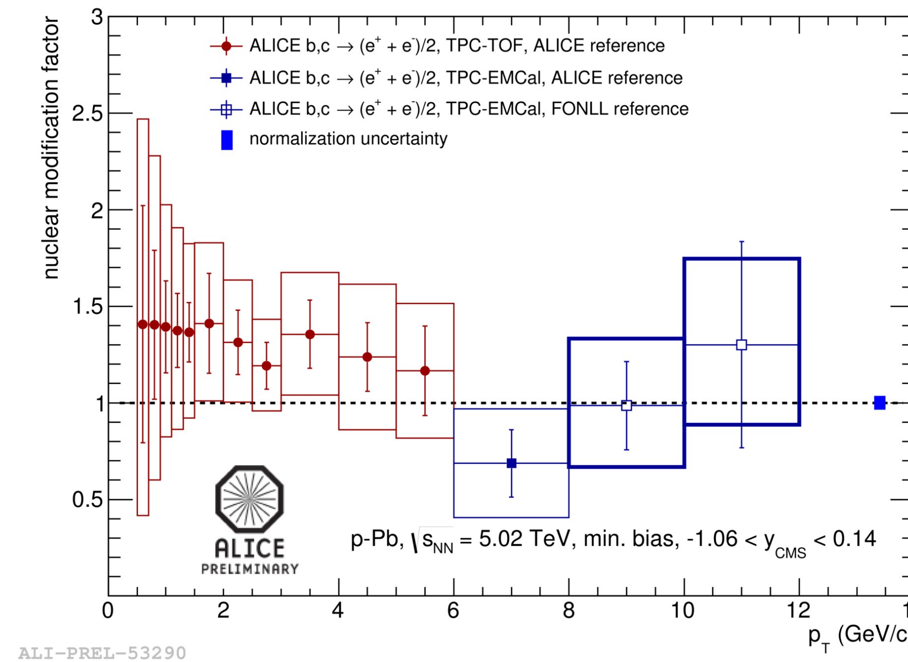




Semileptonic decays of HF: CNM effects

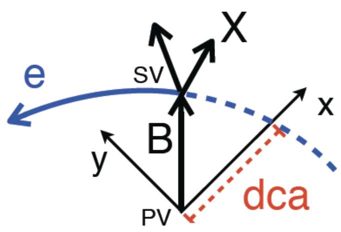
- Data taken in p-Pb (forward y) and Pb-p (backward y). y_{CMS}= +- 0.465
- No data in pp at 5.02 TeV. σ_{pp} used for R_{pPb} calculated scaling the measured cross sections at 2.76 and 7 TeV using the ratios predicted by FONLL
- At forward rapidity: R_{pPb} consistent with unity within uncertainties
- At backward rapidity: slightly larger than unity in $2<p_T<4$ GeV
- At mid rapidity (b,c e): R_{pPb} compatible with unity within uncertainties
- Suppression in Pb-Pb due to final state effects



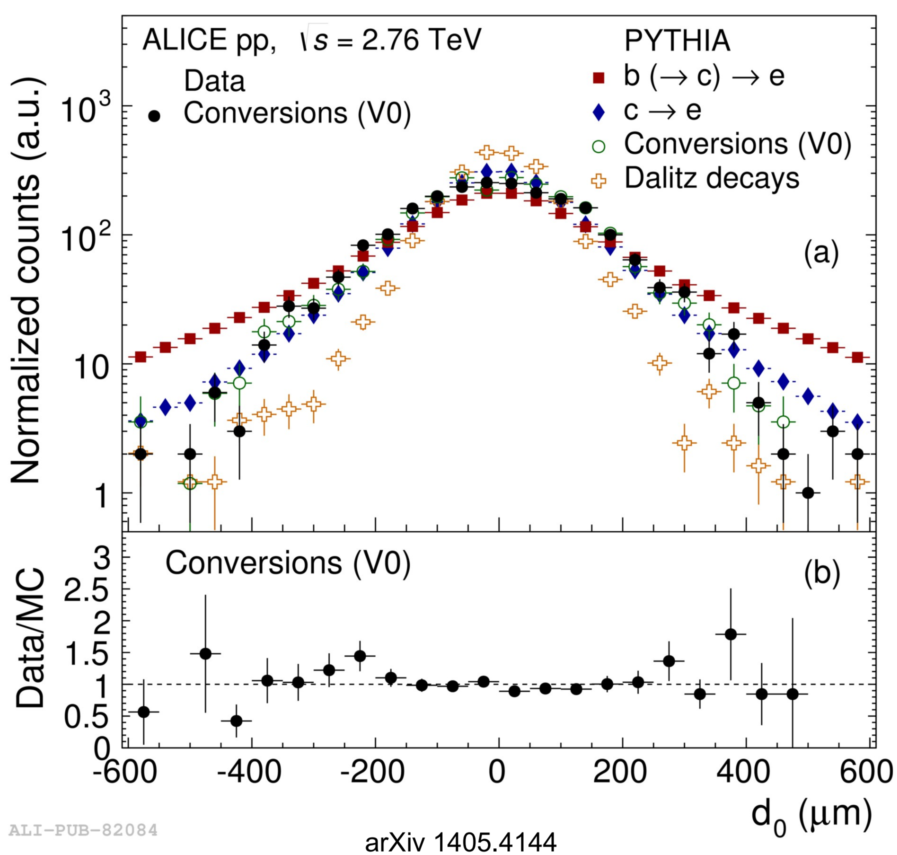


Beauty from semileptonic decays of electrons

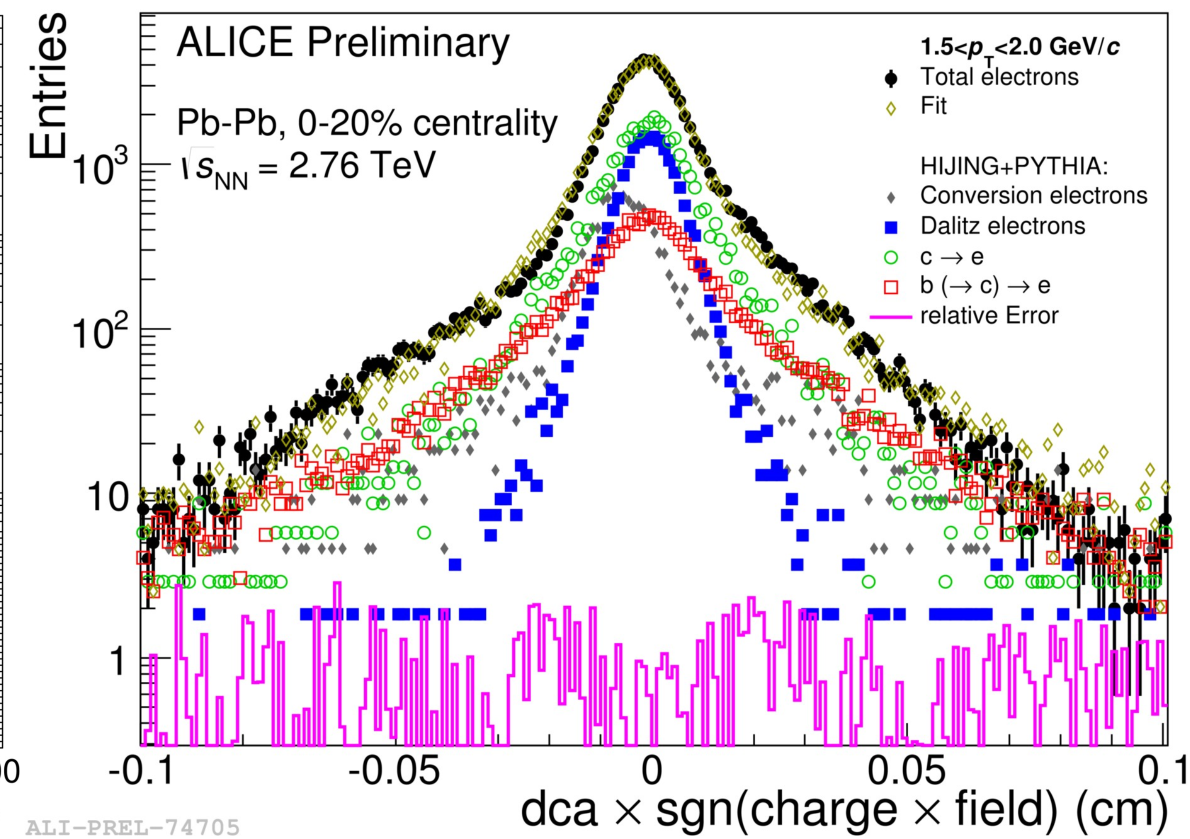
- Analysis based on the electron impact parameter distribution
- Broad dca distribution of electrons from B decays
- dca resolution properly reproduced by simulations



(results in pp at sqrt(s)=7 TeV in Phys Lett B 721 (2013) 13)

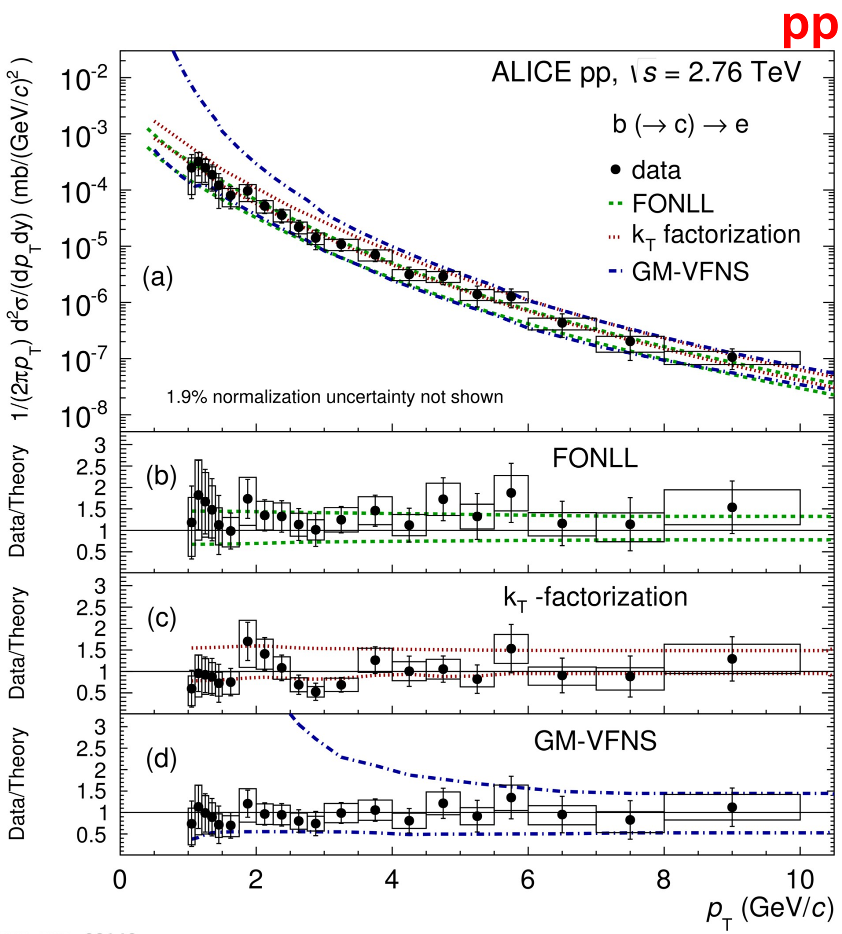


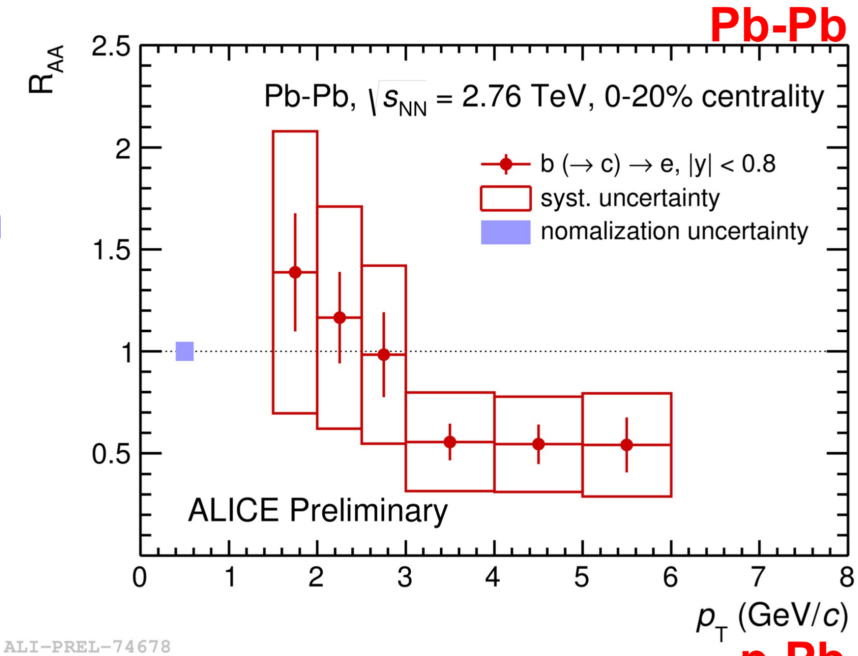
arXiv 1405.4144

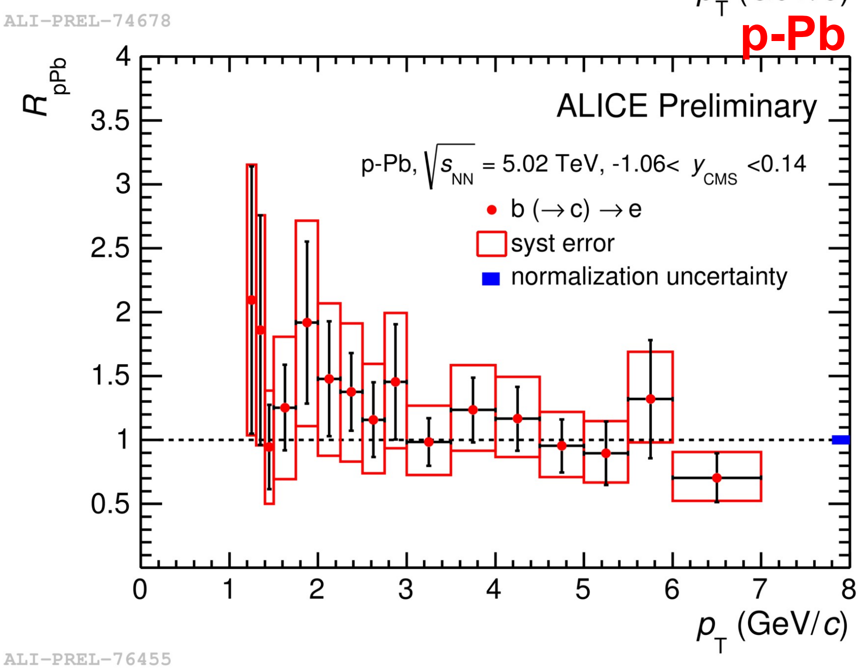


Electrons from beauty decays

- pp cross section well reproduced by FONLL
- Pb-Pb: within large uncertainties, R_{AA}~0.5 for p_T>3 GeV/c
- R_{pPb} consistent with unity: suppression due to final state effects



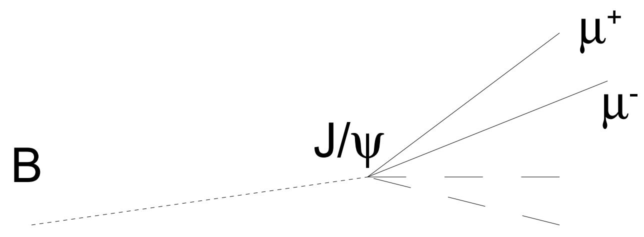


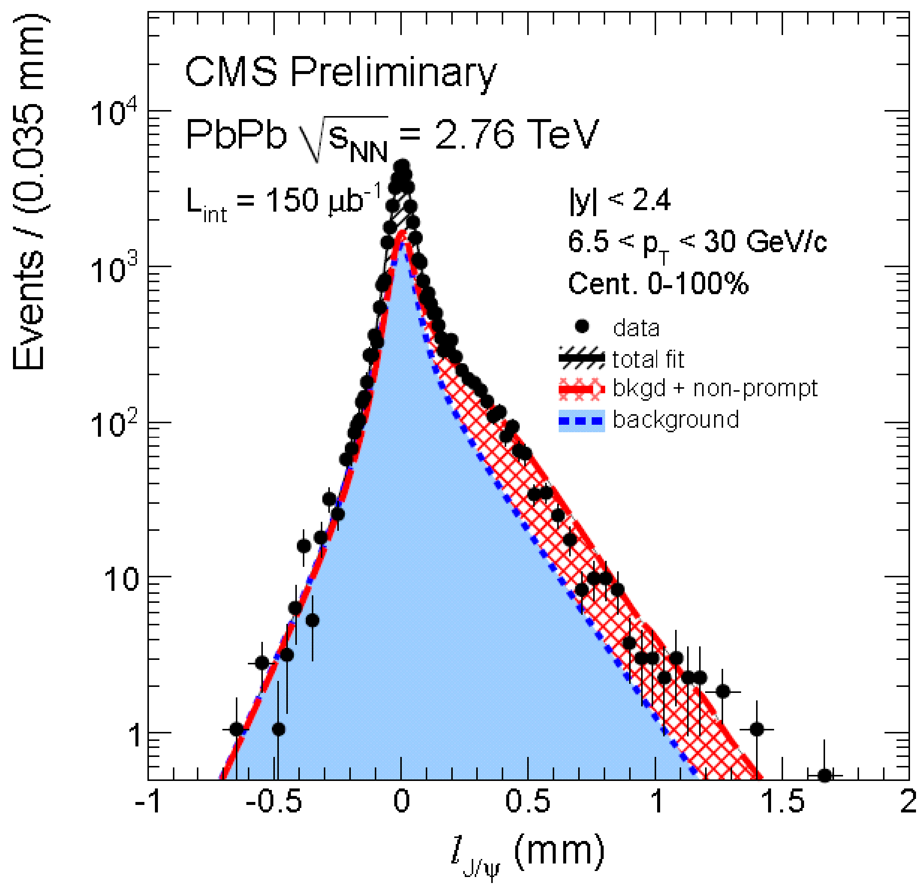


Beauty: detection through its decay to J/ψ

- Non-prompt J/ψ from B decays: simultaneous fit of dimuon invariant mass spectrum and pseudo-proper decay length

$$l_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$





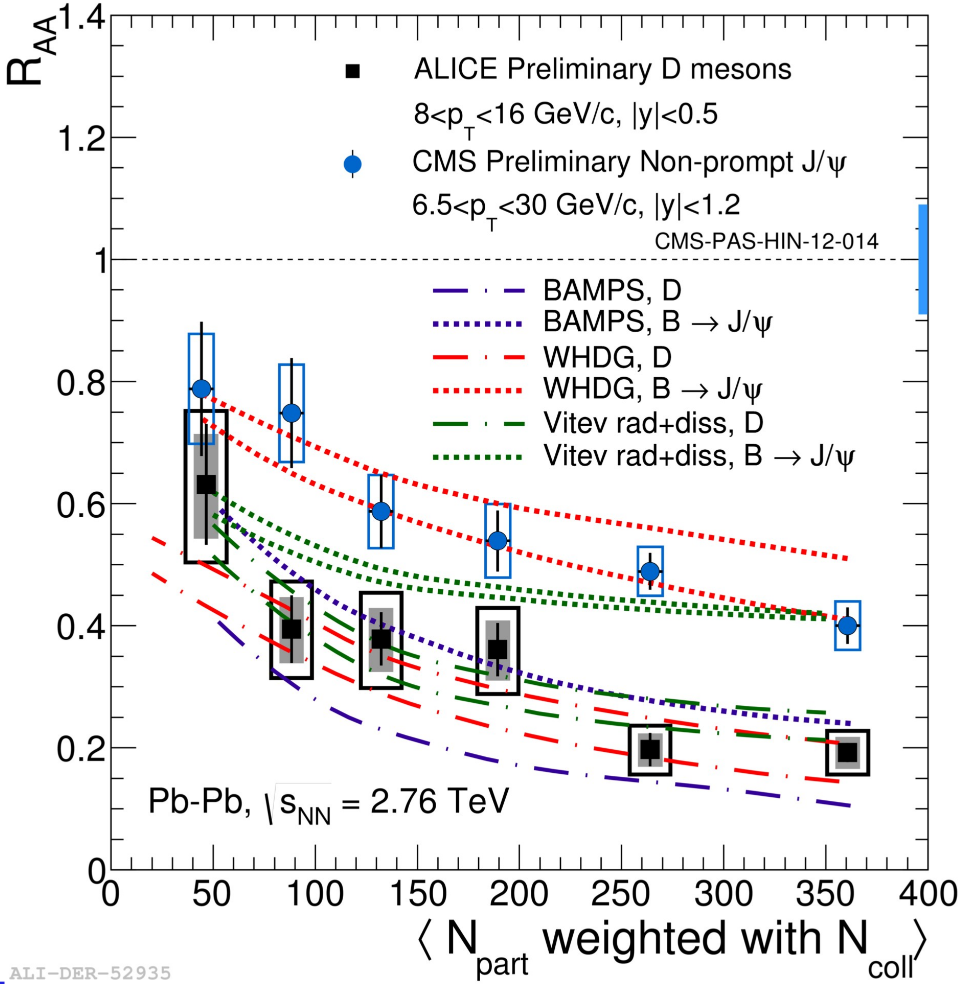
Non-prompt J/ψ: Pb-Pb collisions

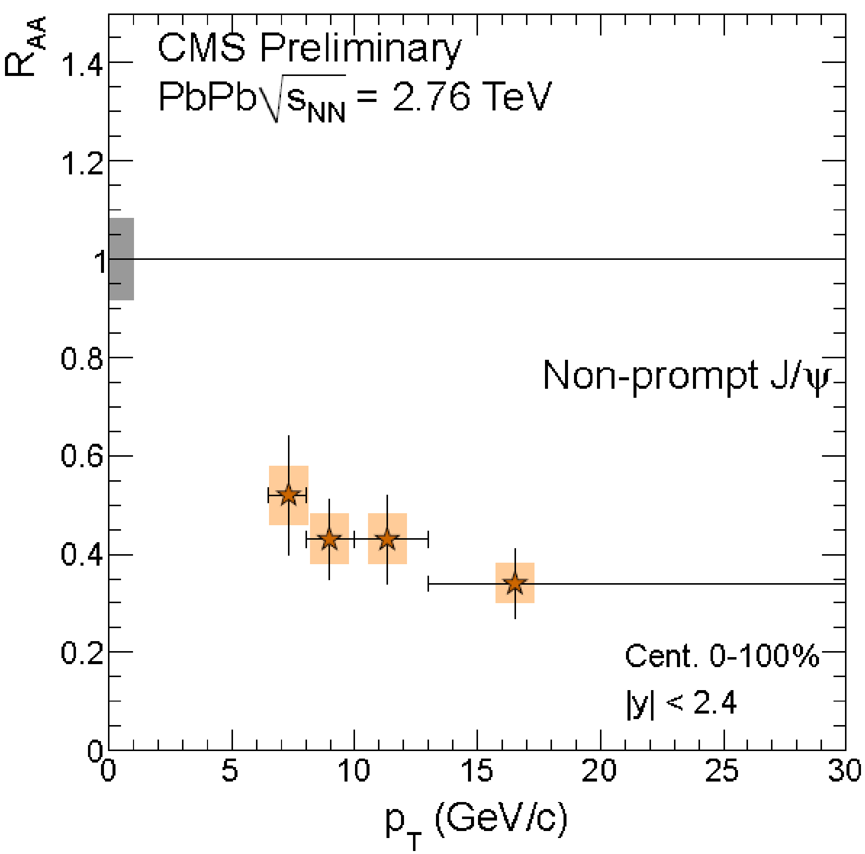
D suppression vs centrality stronger than B, as expected

Models in qualitative agreement with data

BAMPS (collisional Eloss in expanding medium),
WHDG (collisional + radiative Eloss),
Vitev (radiative + collisional Eloss + D mesons dissociation)

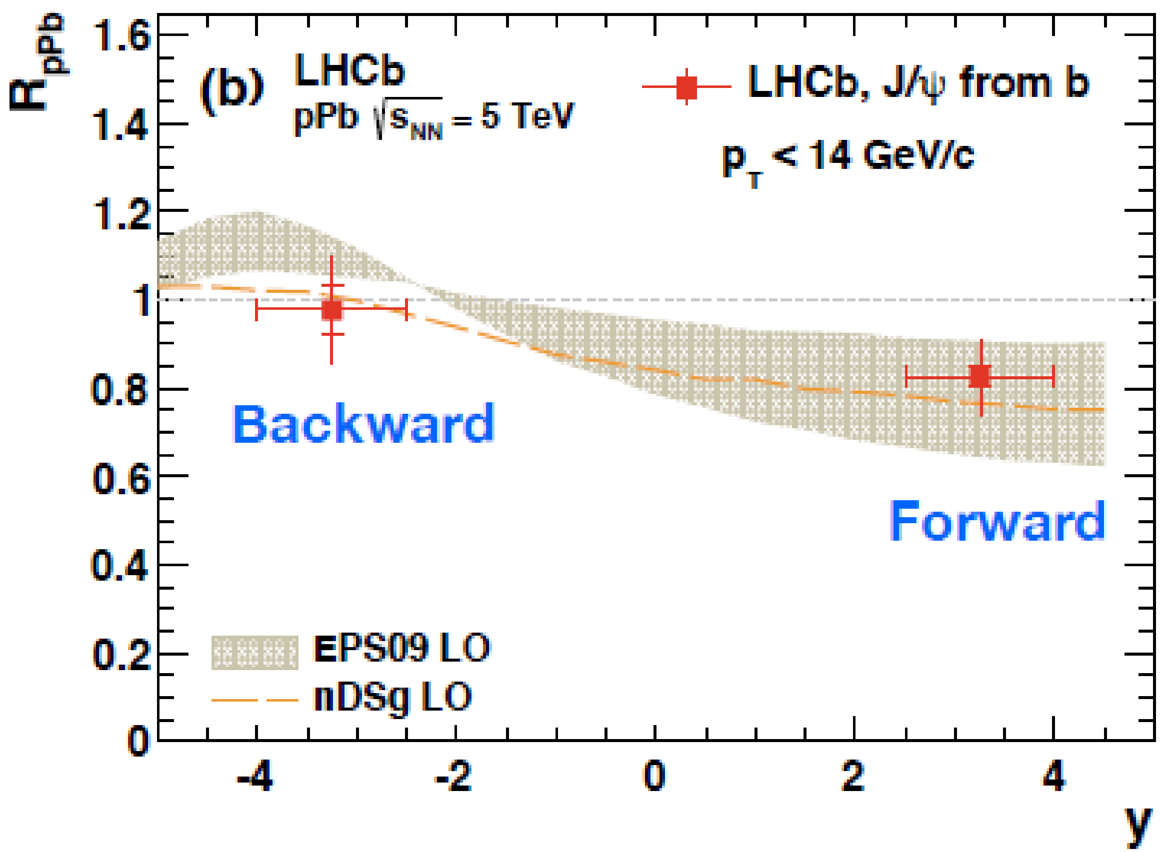
B suppression seems to increase with increasing p_T in the measured momentum range





Non-prompt J/ψ: p-Pb collisions

- Slight rapidity dependence
- Modest suppression at forward rapidity
- Consistent with unity at backward rapidity
- Small CNM effects: observed suppression in Pb-Pb due to hot medium effects

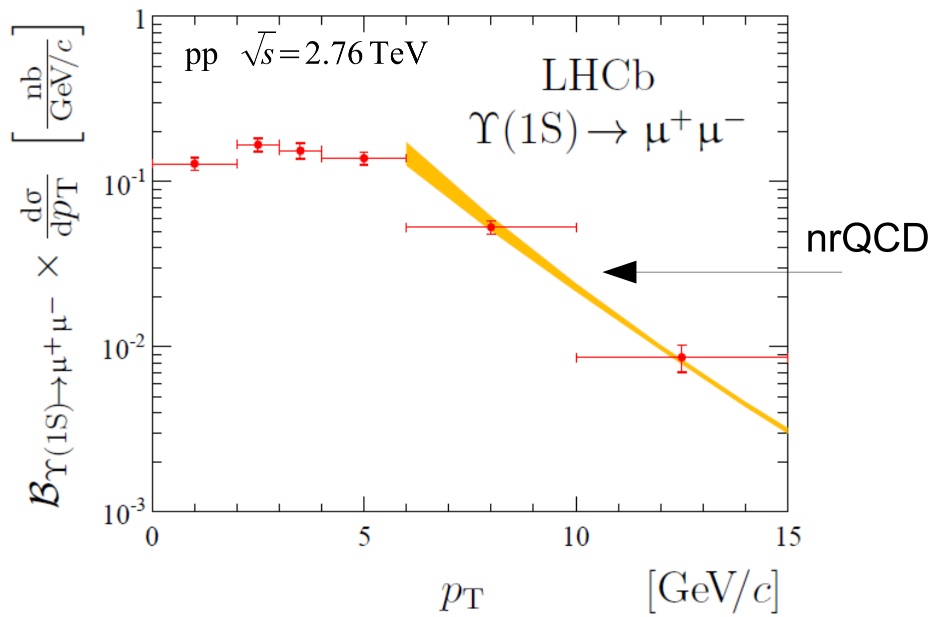


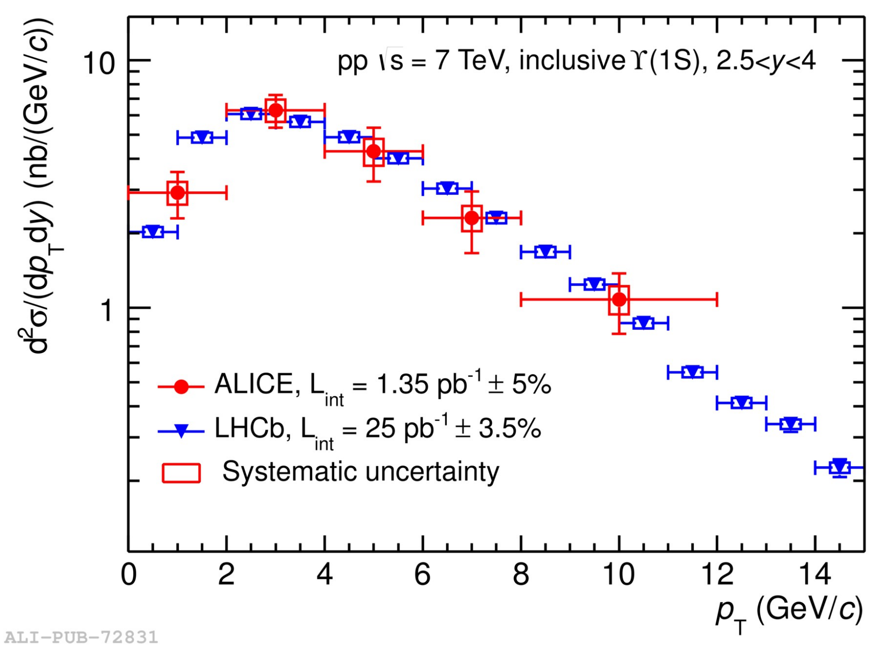
Υ production in pp collisions at forward y

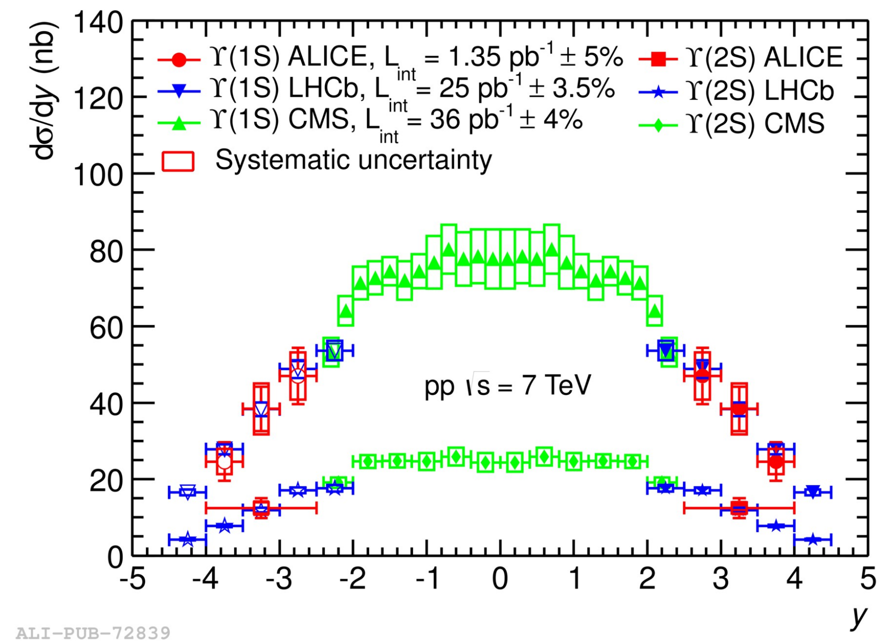
- Results on Υ at forward rapidity from ALICE and LHCb
- Good agreement at 7 TeV between the two experiments
- Fraction of Υ(1S) from Υ(2S):

$$f^{\Upsilon(1S)} = 0.090 \pm 0.027 \pm 0.005$$

- At midrapidity: see CMS talk







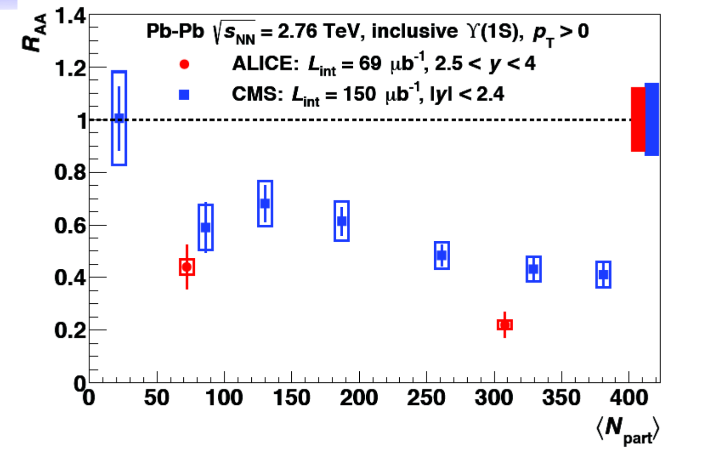
Inclusive Υ(1S) R_{AA} in Pb-Pb (forward y)

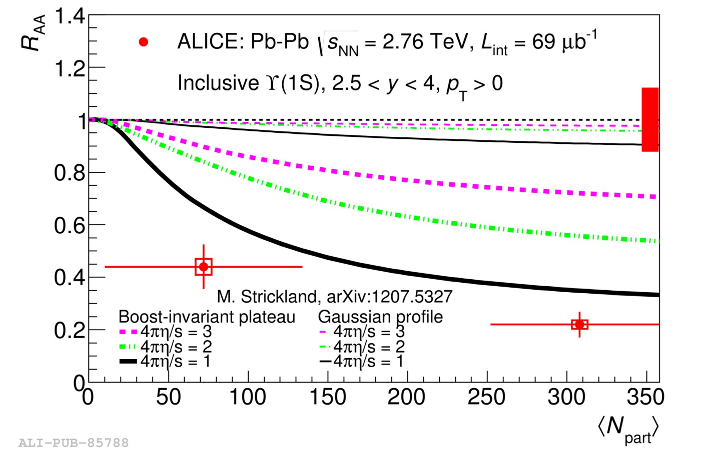
- Stronger suppression at forward y w.r.t. mid y
- Dynamical model [Strickland, arXiv 1207.5327]
  - -Thermal suppression of bottomonia
  - -Anisotropic hydro model
  - -No CNM, no regeneration

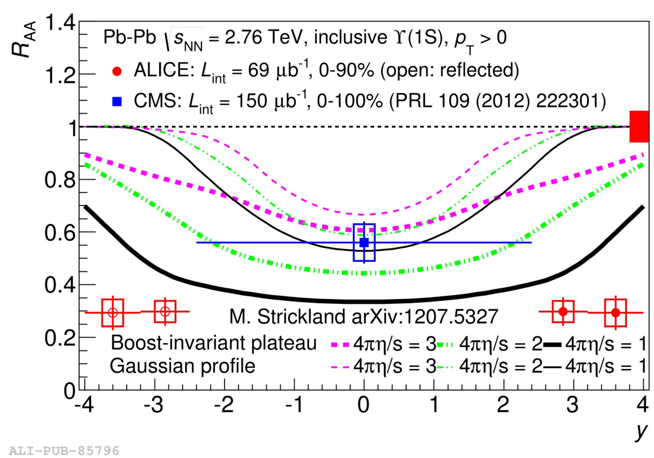
  Underestimates the measured Υ(1S) at forward y
- Transport model [Emerick et al, EPJ A48(2012) 72]
  - -Υ(nS) suppression by QGP (mainly of higher mass states)
  - -Small regeneration
  - -CNM included via an 'effective' σ_{ABS}=0-2 mb

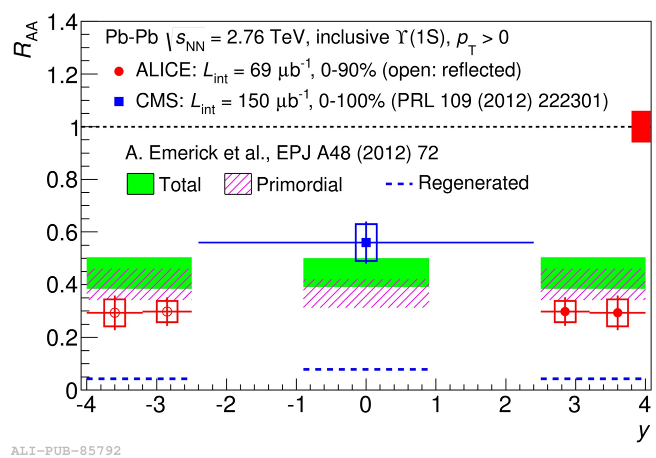
  Underestimates the measured Υ(1S) at forward y

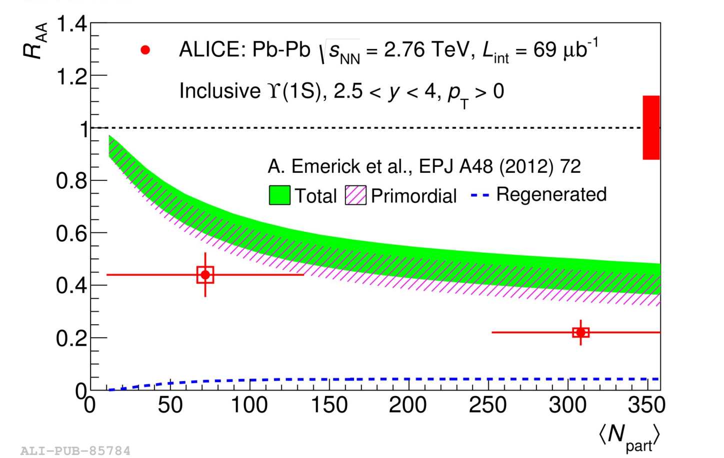
  R_{AA} vs y is not reproduced







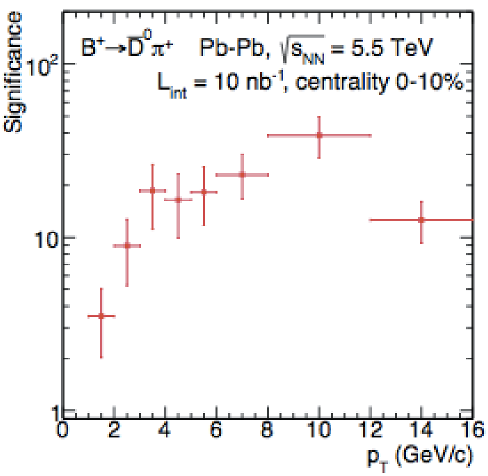


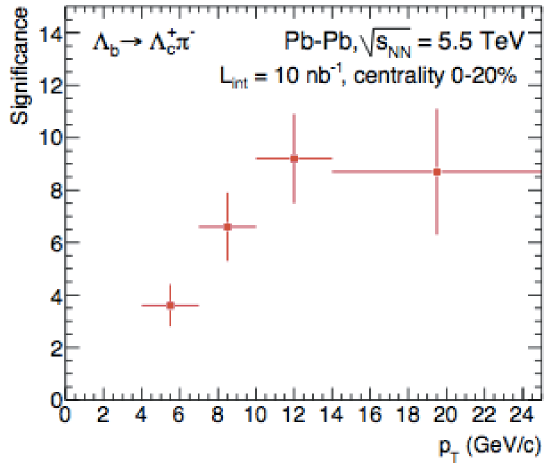


Future beauty measurements in heavy ions

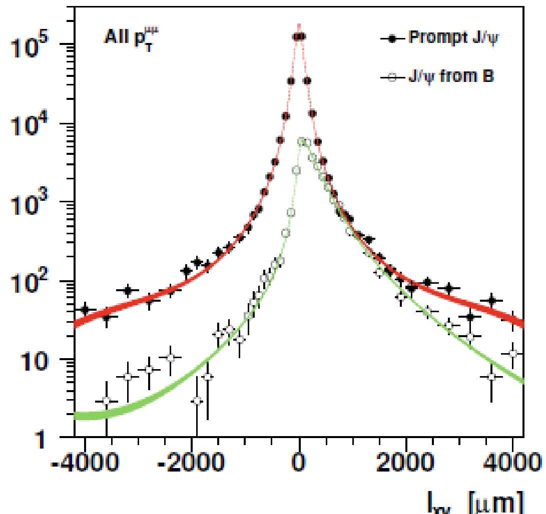
- Run 2: higher sqrt(s) and 5-10 times more integrated luminosity in Pb-Pb
- Run 3:

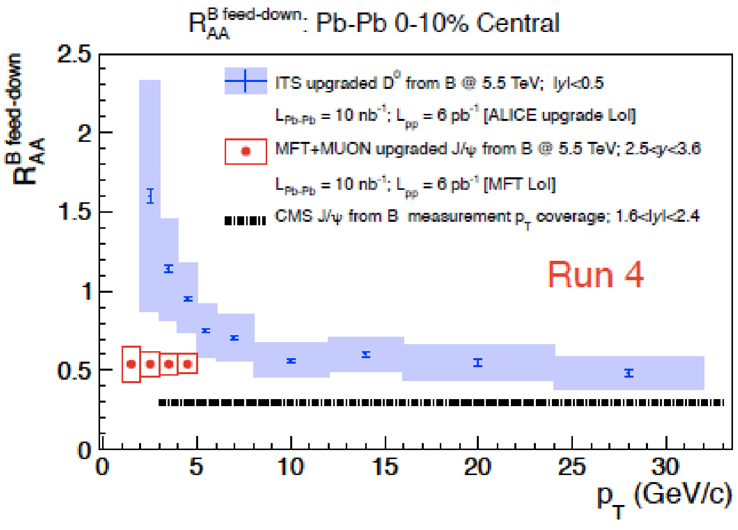
ALICE ITS upgrade:
-Improved track precision and higher L_{INT}
-Fully reconstructed beauty decays





ALICE MFT: separation of prompt and non-prompt J/ψ down to p_T=1 GeV/c in Pb-Pb





Summary

- Clear suppression of heavy flavours, stronger for central collisions
- Similar at forward and mid rapidity
- Small cold nuclear matter effects in p-Pb collisions
- p-Pb collisions appear as a superposition of binary pp collisions: suppression in Pb-Pb is a final state effect
- D suppression stronger than B: consistent with the expectation based on the "dead cone effect" $\Delta E_b < \Delta E_c < \Delta E_{\text{light quarks}}$
- Combined information on D and B can constrain predictions on energy loss and lead to the understanding of Eloss mechanism and transport coefficients of the medium
- Υ suppression:
  - stronger at forward rapidity than at midrapidity
  - models do not reproduce the trend vs y and underestimate the suppression at forward rapidity
- Future beauty measurements in heavy ions
  - ALICE upgrades: ITS and MFT

  Main items on beauty:
  - fully reconstructed beauty decays
  - Separation of prompt and non-prompt J/ψ in Pb-Pb down to p_T=1 GeV/c

Backup slides

Dead cone effect

- Dead cone effect: suppression of gluon radiation by heavy quarks at low angles
- Guon radiation for a (massive) quark is **suppressed for angles θ_0<M/E**

$$\theta_0 \equiv \frac{M}{E}$$

$$dP_{\mathrm{HQ}} = dP_0 \cdot \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2} \qquad dP_0 \simeq \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk_\perp^2}{k_\perp^2} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

distribution of soft gluons radiated by a heavy quark

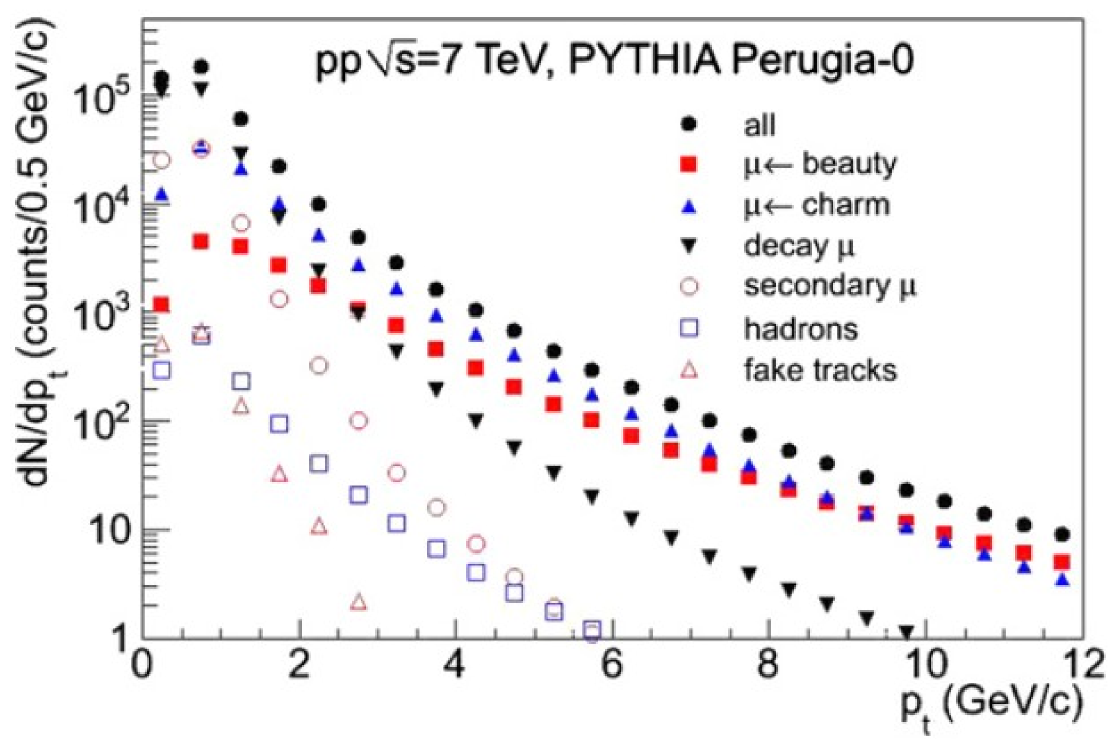
standard bremmstrahlung spectrum

Y.L. Dokshitzer, D. E. Kharzeev, *Phys. Lett.* B 519 (2001) 199

- Suppression pattern thus depends on mass, the more massive being the less suppressed

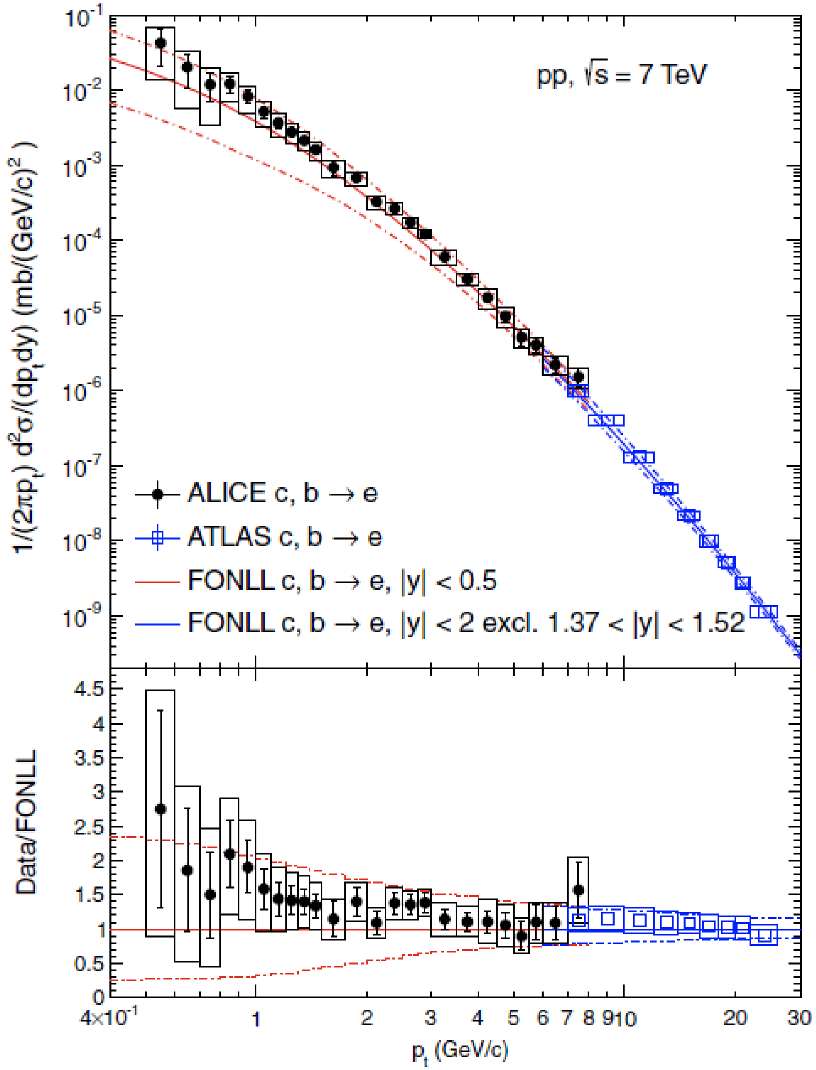
Semileptonic decays of charmed/beauty hadrons: pp collisions, forward rapidity

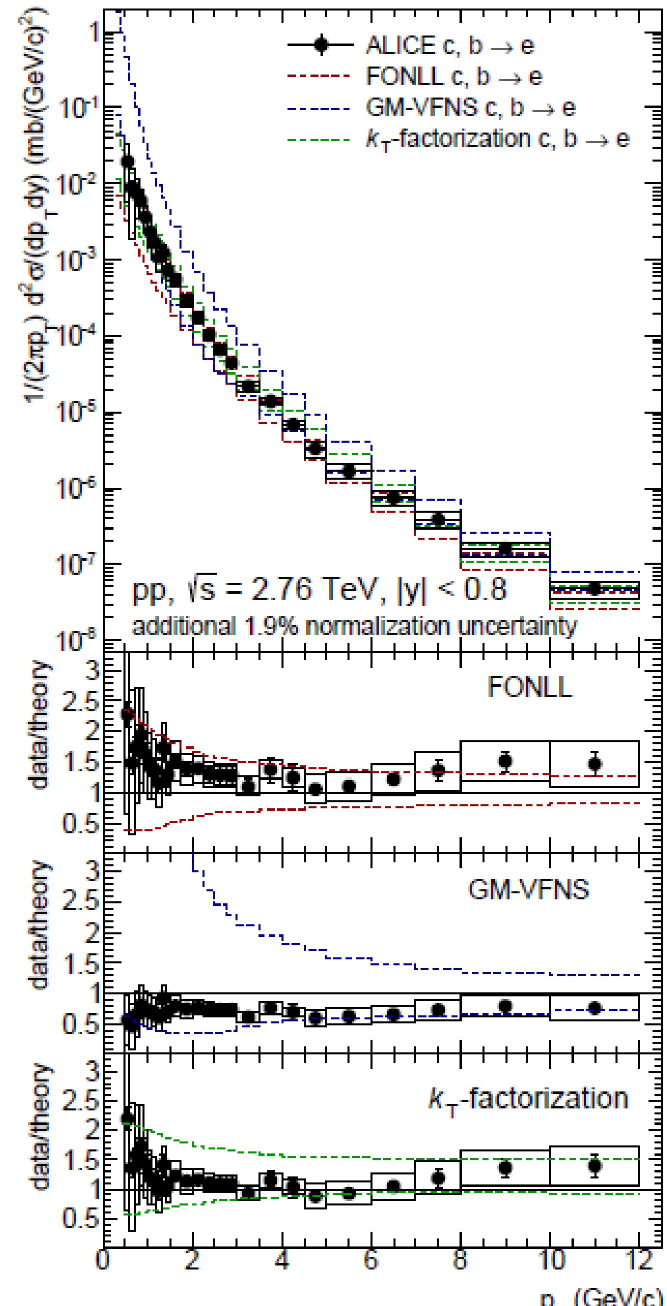
- Muons at forward rapidity (2.5<y<4)
- p_T spectrum of single muons
- No separation of charm and beauty
- Background from π,K decays mainly concentrated at low p_T, subtracted by means of simuations with PYTHIA and PHOJET
- Systematic uncertainty due to BKG subtraction from ~ 5% (3.7<y<4) to a maximum of 35% (2.5<y<2.8, p_T=2 GeV/c)



Semileptonic decays of HF at midrapidity: pp

- Similar procedure for electrons at mid rapidity
- Within uncertainties, FONLL reproduces the measurements

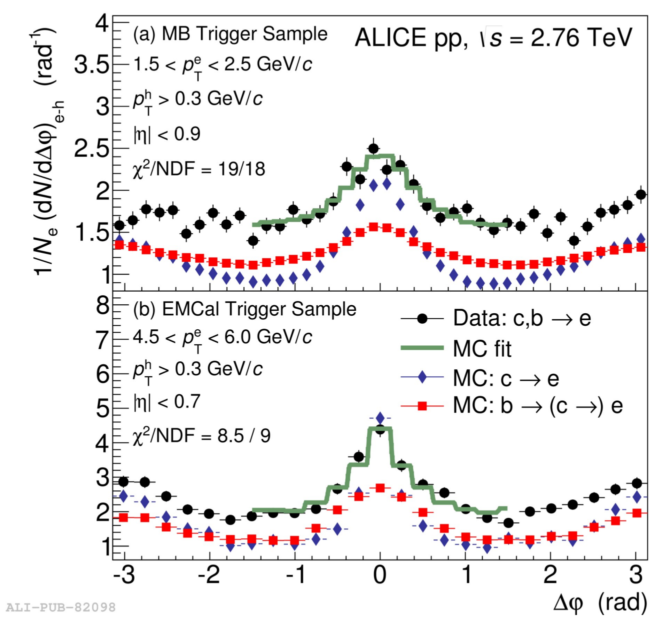


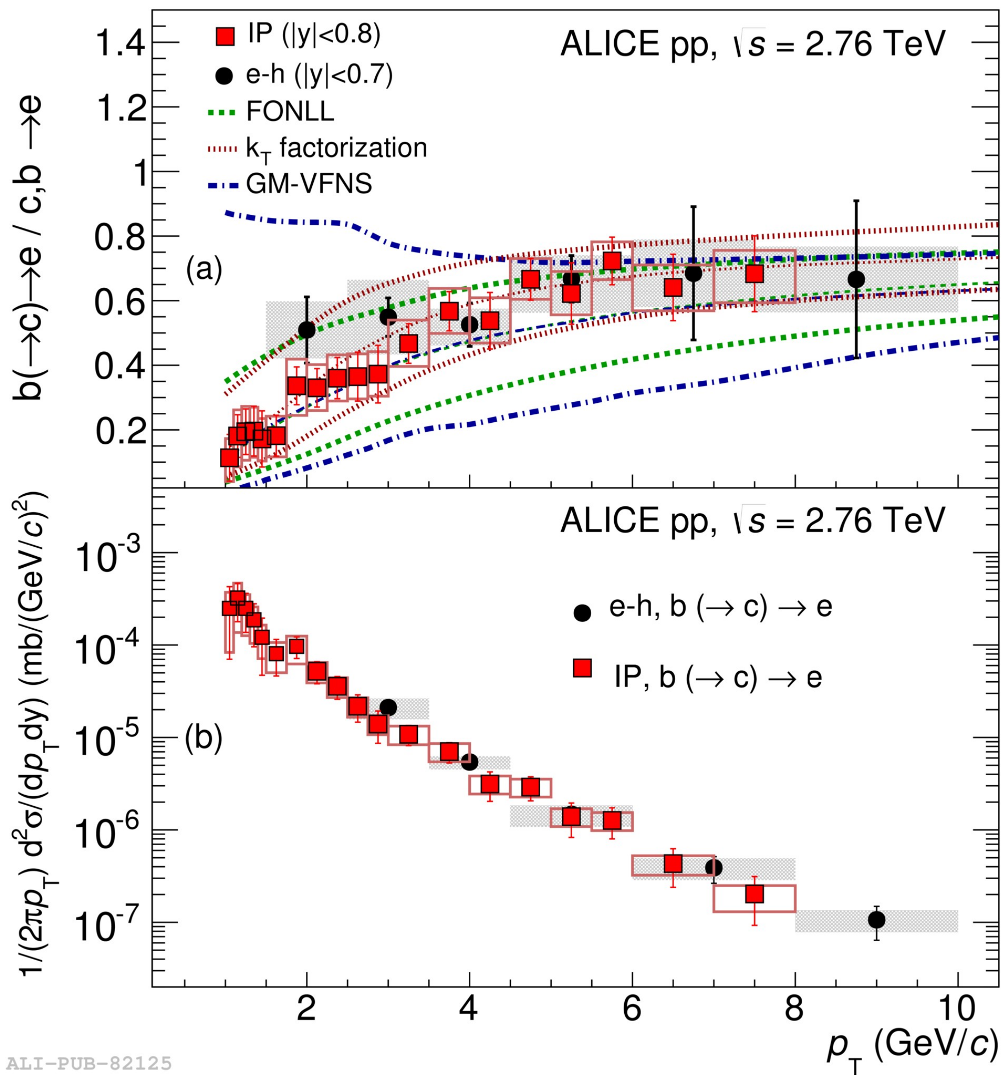


Electrons from beauty/electrons from HF

- Red squares: method based on track impact parameter
- Black circles: based on the azimuthal correlations between heavy-flavour decay electrons and charged hadrons

Due to the different decay kinematics of charm and beauty hadrons, the width of the near-side peak is larger for beauty than for charm hadron decays

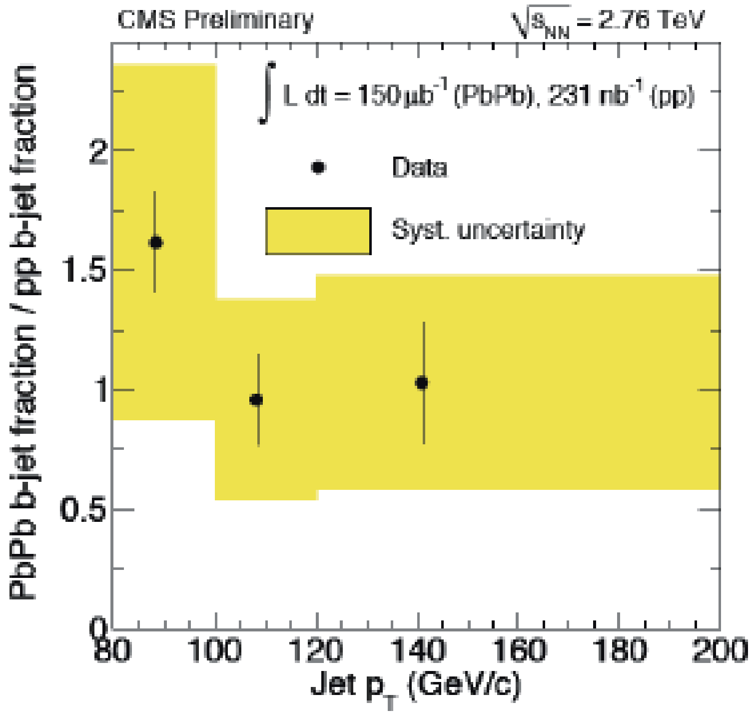




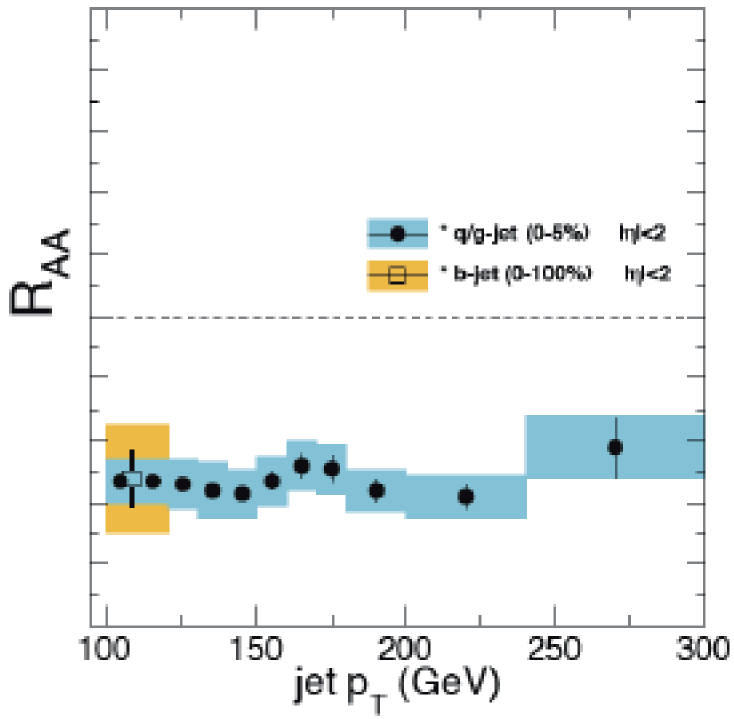
Δϕ: difference in azimuth between electrons and hadrons

b-jets

double ratio:
b-jet fraction PbPb / b-jet fraction pp

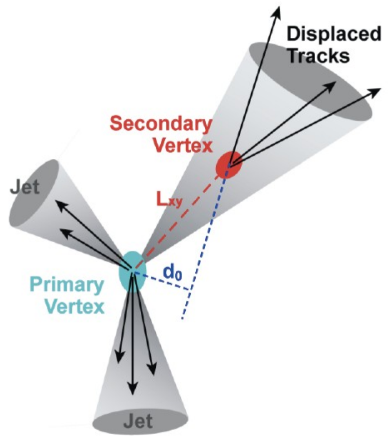


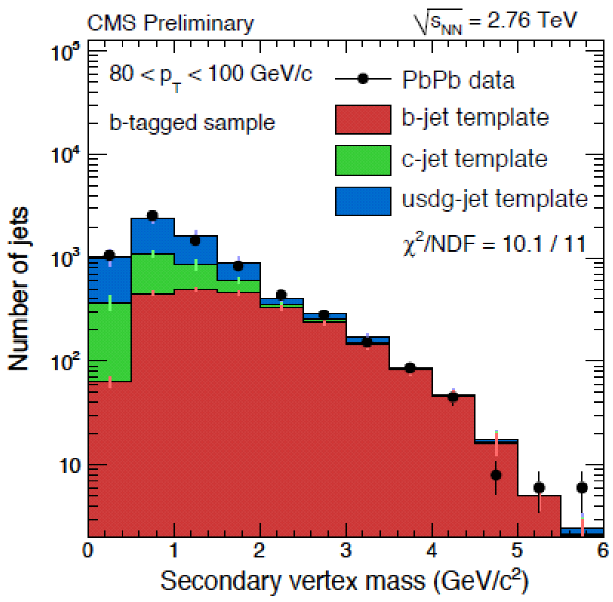
b-jet R_{AA}:
inclusive jet R_{AA} * double ratio

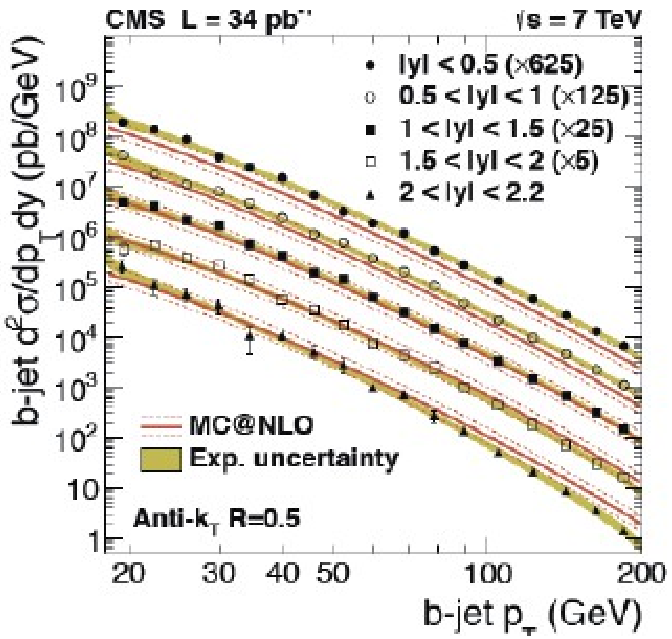


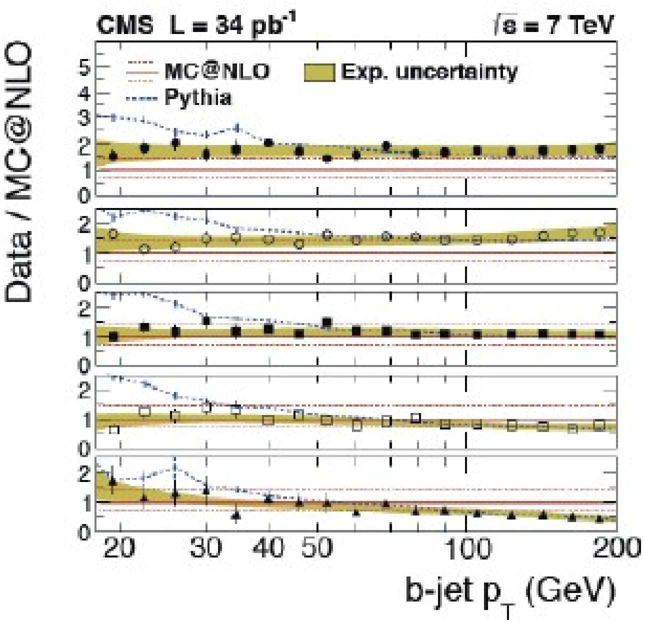
b-jet measurements

- Search of secondary vertices
- Cuts based on the flight distance
- b contribution from template fits to the secondary vertex mass distribution



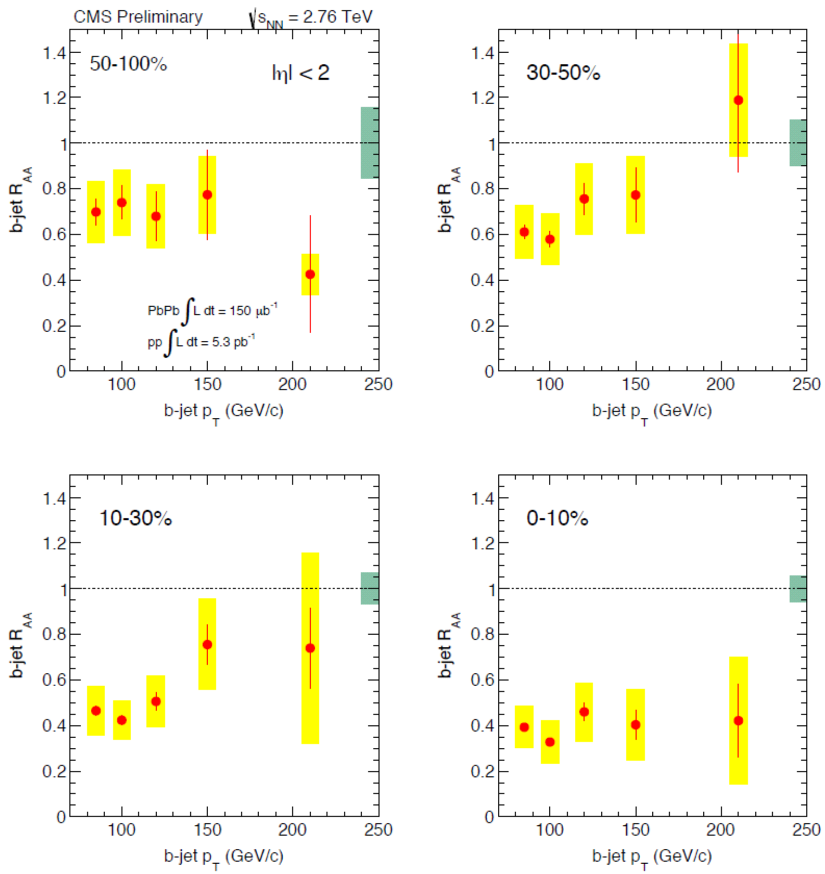


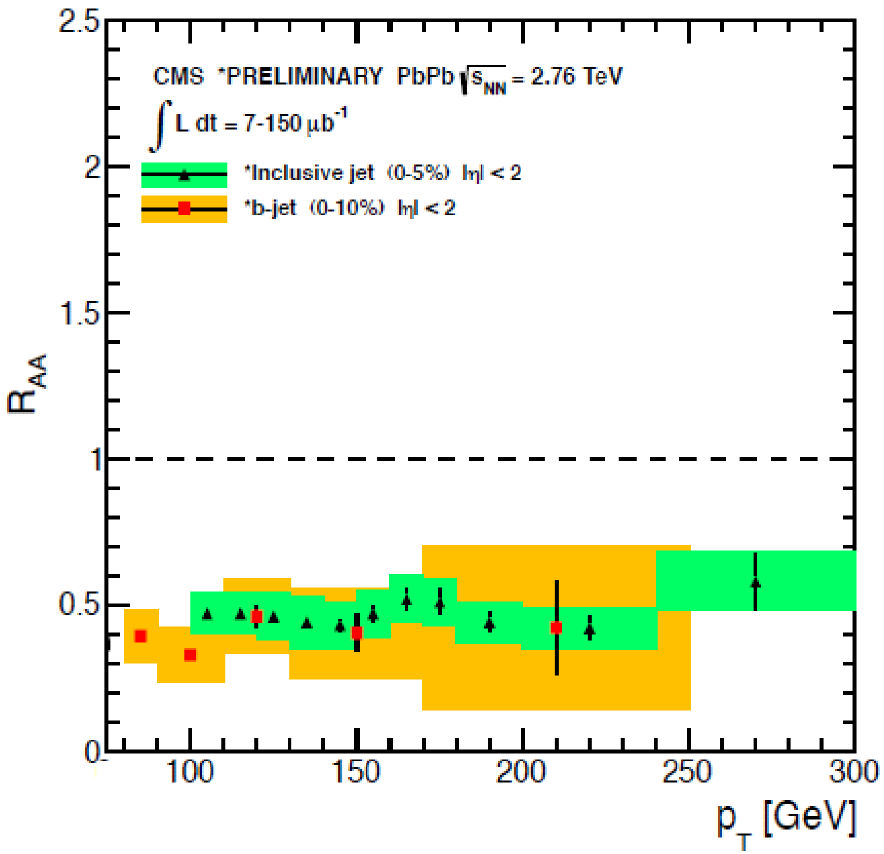




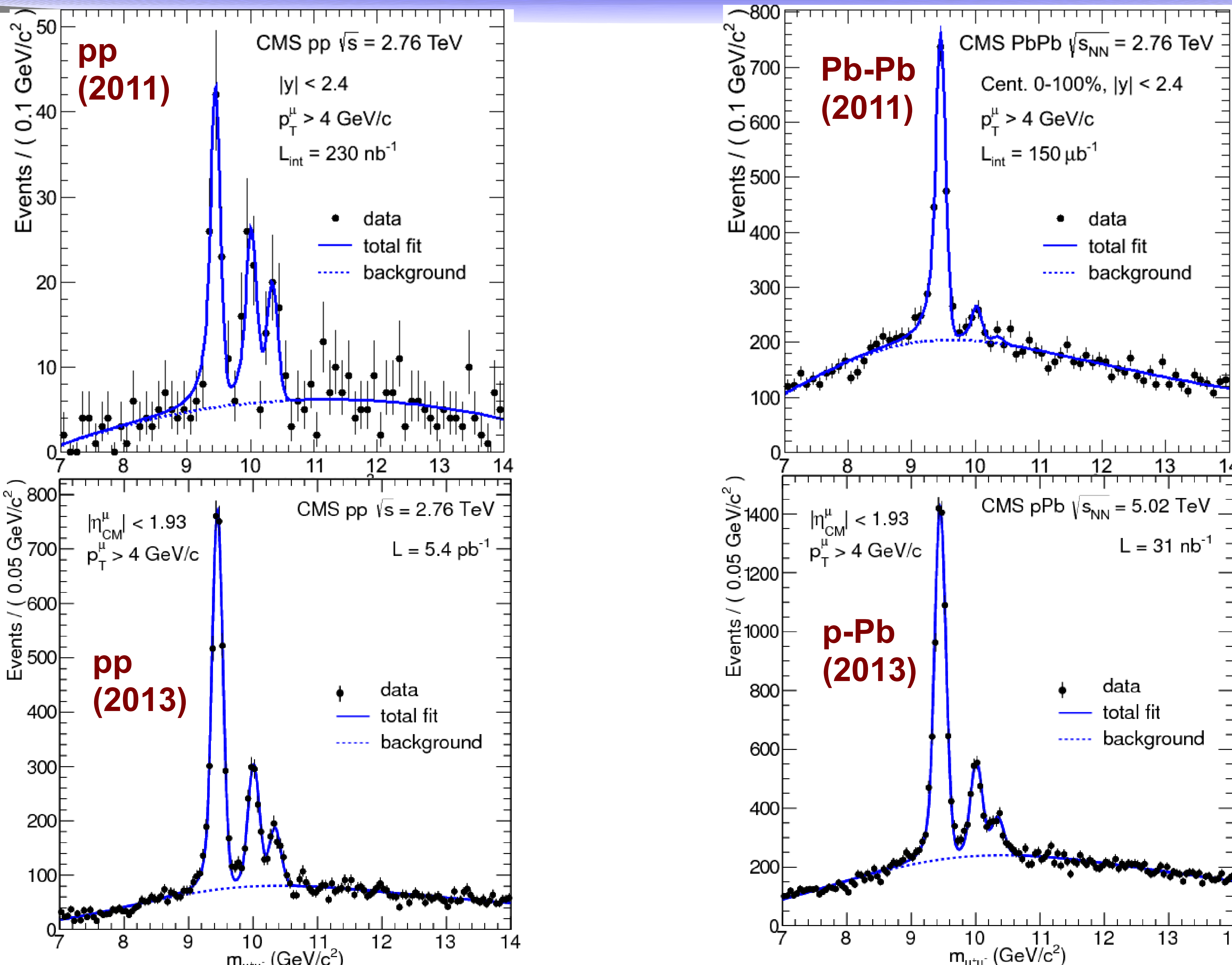
b-jet suppression

- Clear b-jet suppression up to large p_T
- Suppression similar to the one of light flavours at high p_T, as expected (effects related to quark mass become negligible)



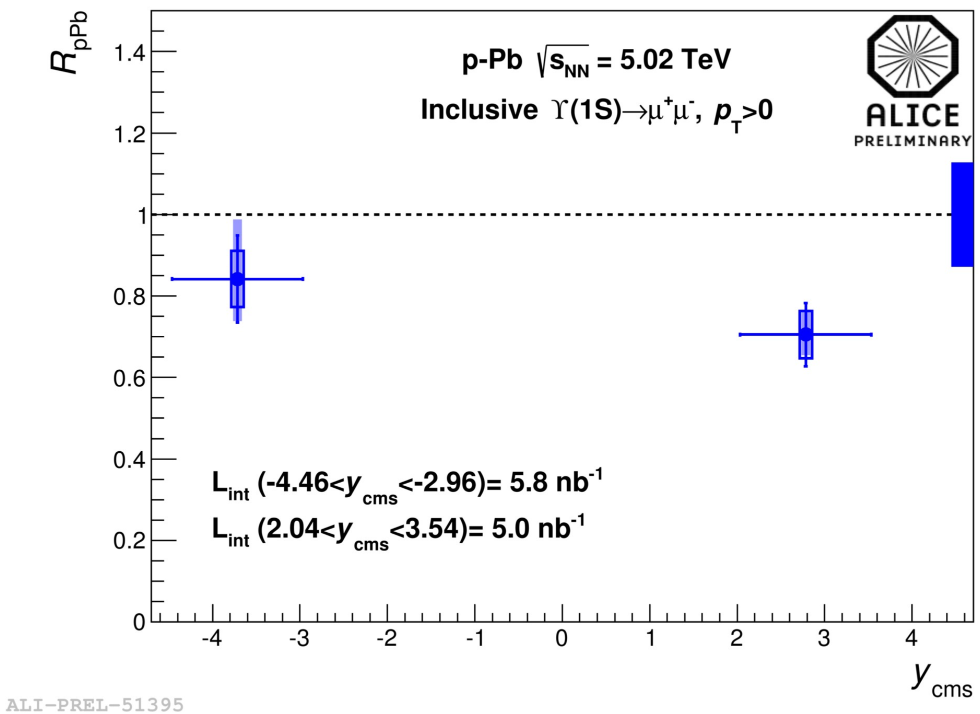


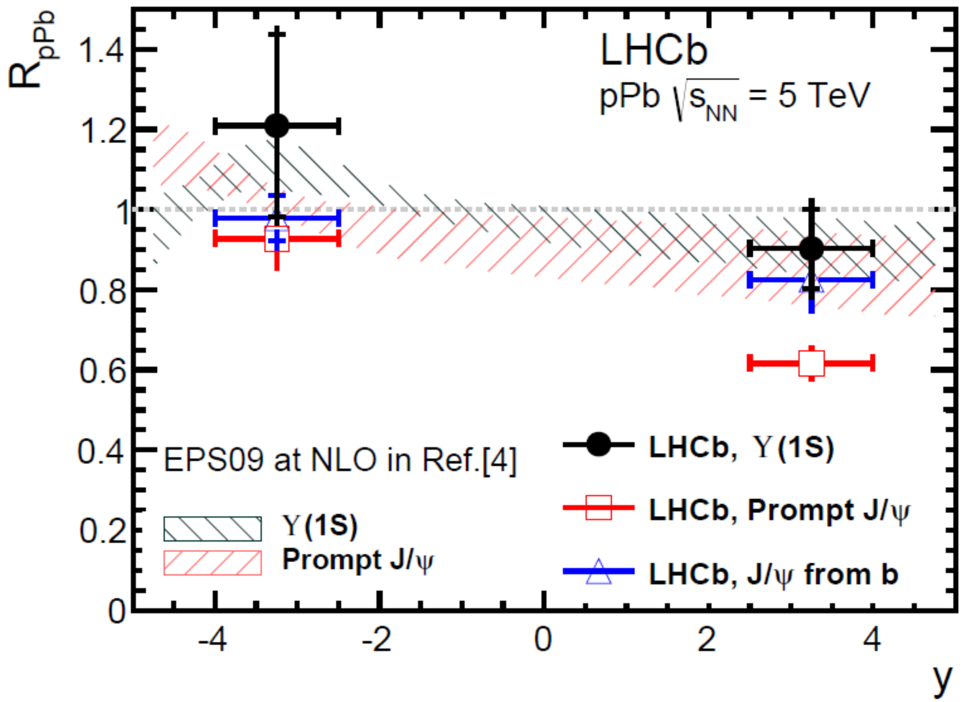
Υ production at midrapidity



Cold nuclear matter effects in Υ production

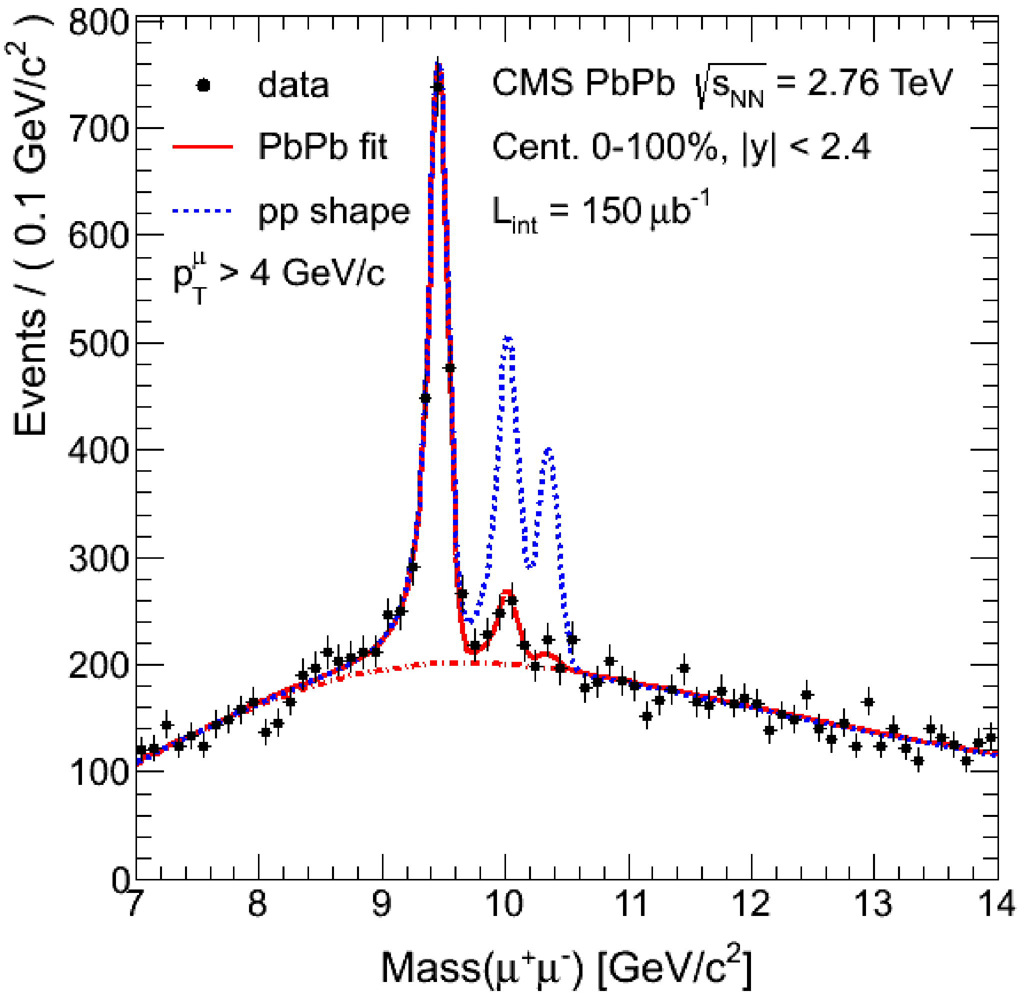
- Consistent with no suppression at backward rapidity

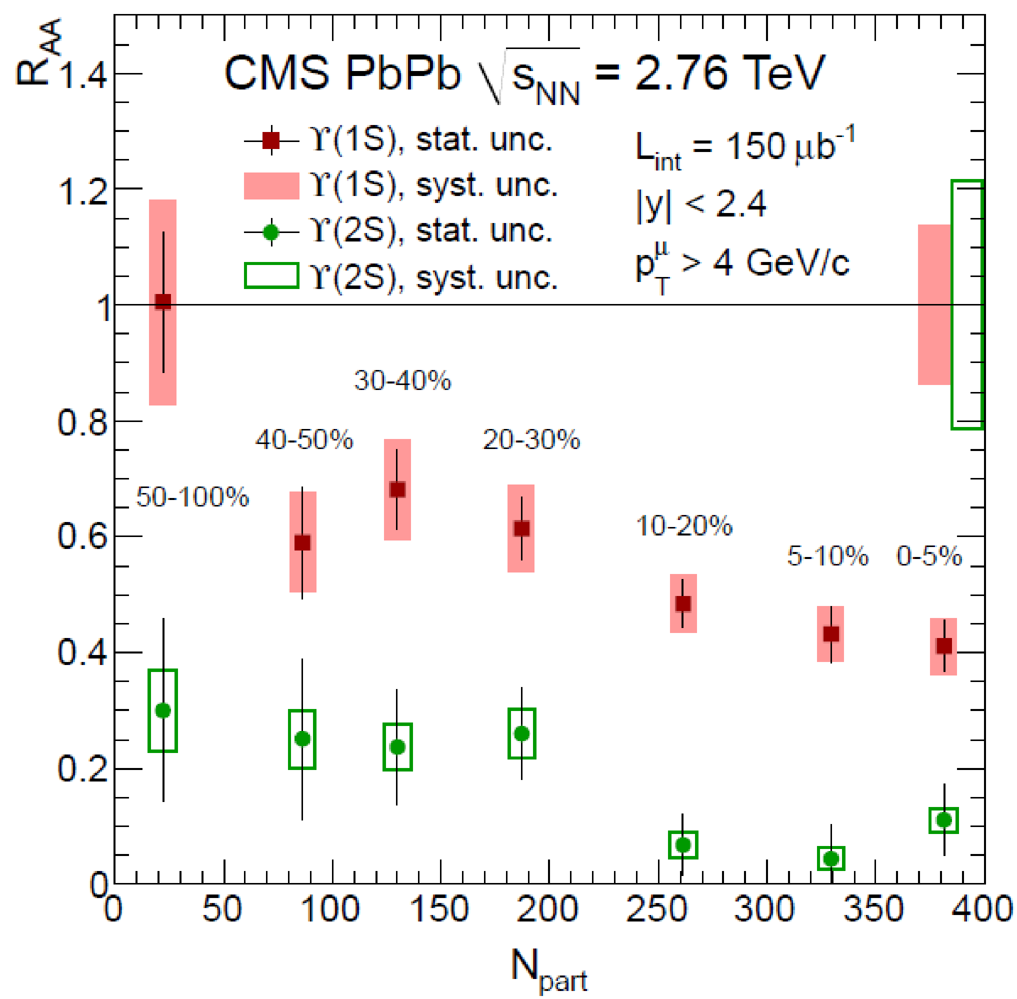




Υ R_{AA} at midrapidity

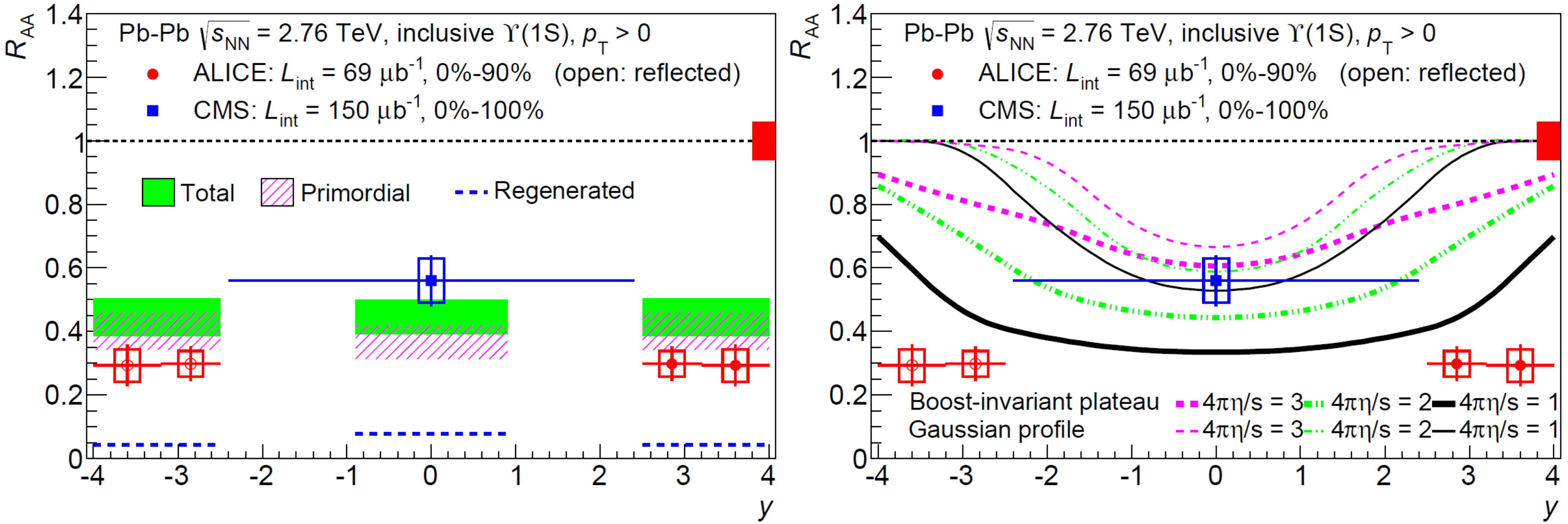
- Clear suppression of bottomonia states, stronger for central collisions
- Interpreted as almost full dissociation of Υ(2s), Υ(3s), χ_b states





Υ production at forward rapidity

- Models do not reproduce the results



Emerick et al./TAMU, EPJA 48 (2012) 72

Strickland, Bazow, NPA 879 (2012) 25

ALICE: New ITS

1. Improve impact parameter resolution by ×3

- Get closer to IP (position of first layer): 39 mm → 22 mm
- Reduce material budget X/X_0 / layer: ~1.14% → ~ 0.3% (for inner layers)

2. Reduce pixel size currently 50 µm x 425 µm monolithic pixels → O(20 µm x 20 µm)

3. Improve tracking efficiency and p_T resolution at low p_T

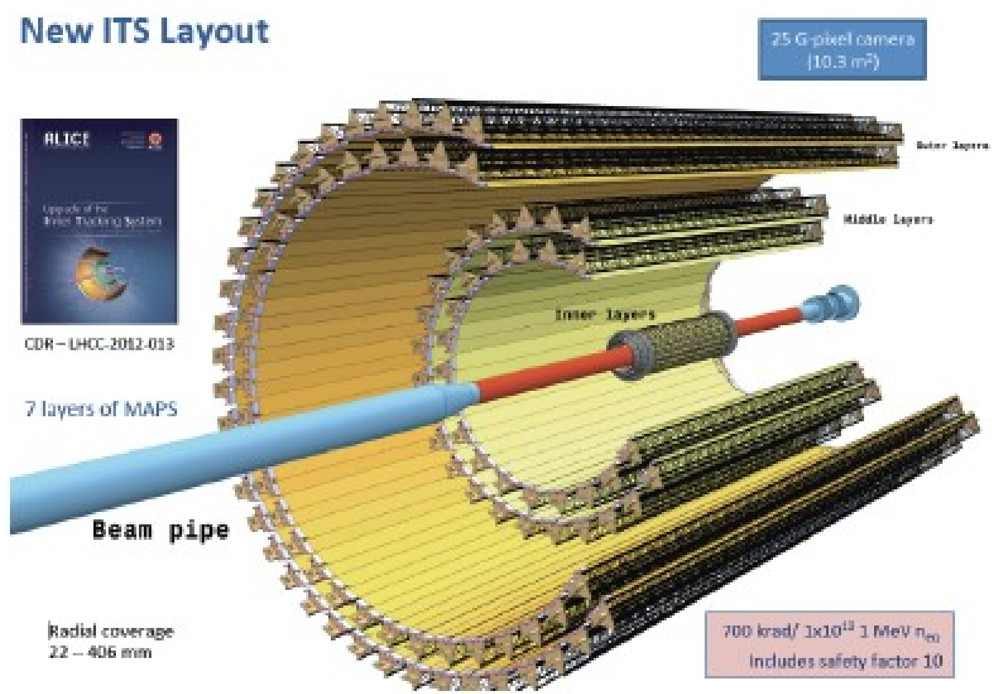
- Increase granularity: 6 layers → 7 layers, reduce pixel size

4. Fast readout

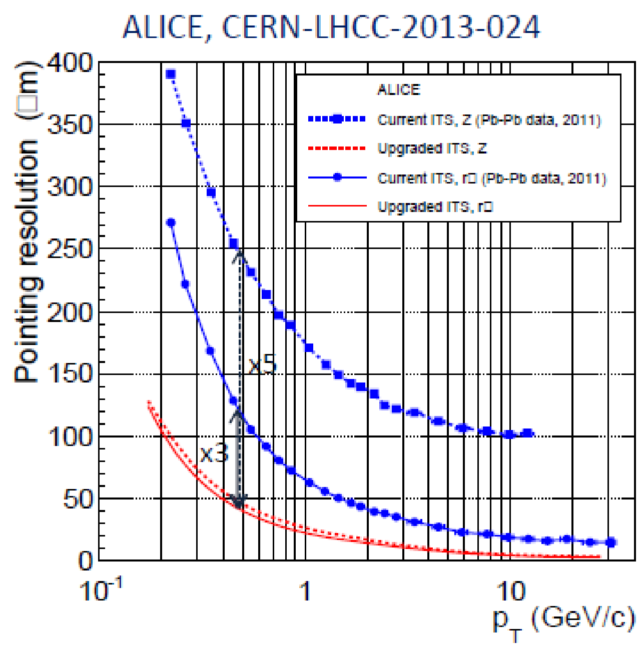
- readout of PbPb interactions at > 50 kHz and pp interactions at ~ 1 MHz

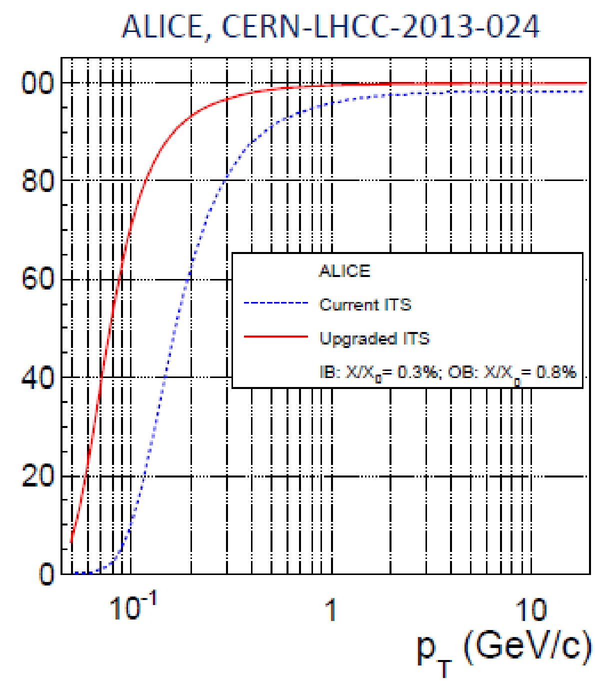
5. Fast insertion/removal for yearly maintenance

- possibility to replace non functioning modules during yearly shutdown



ALICE ITS upgrade: expected performances

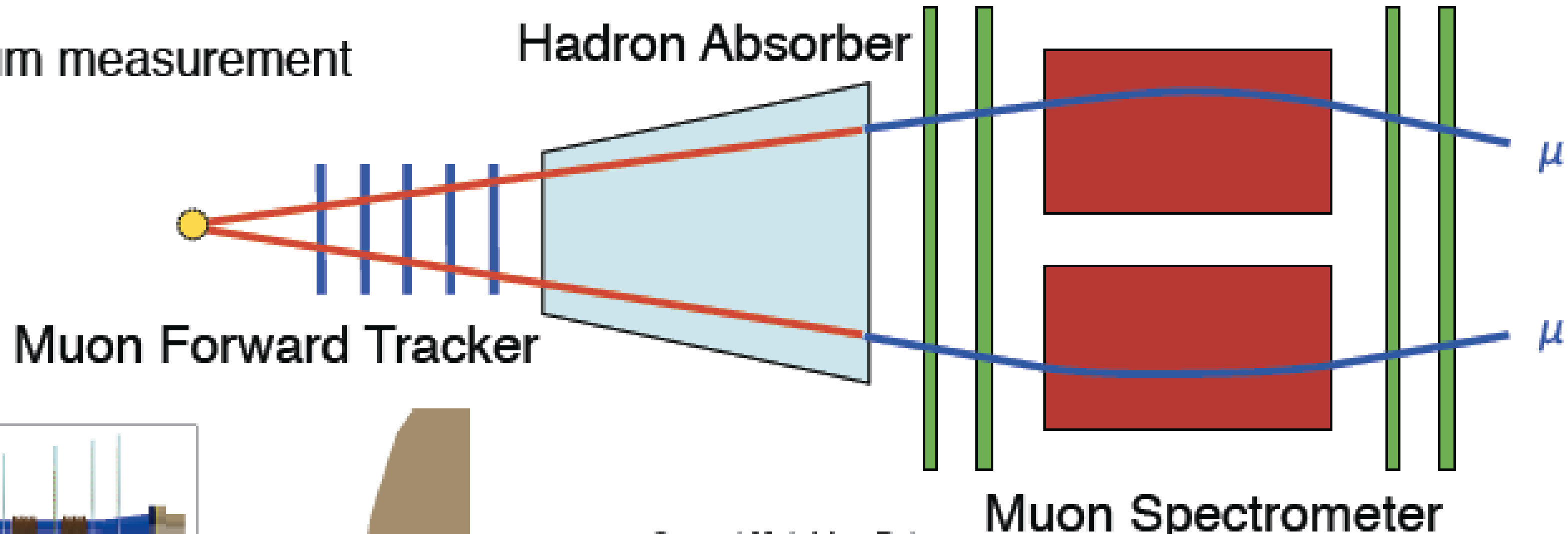


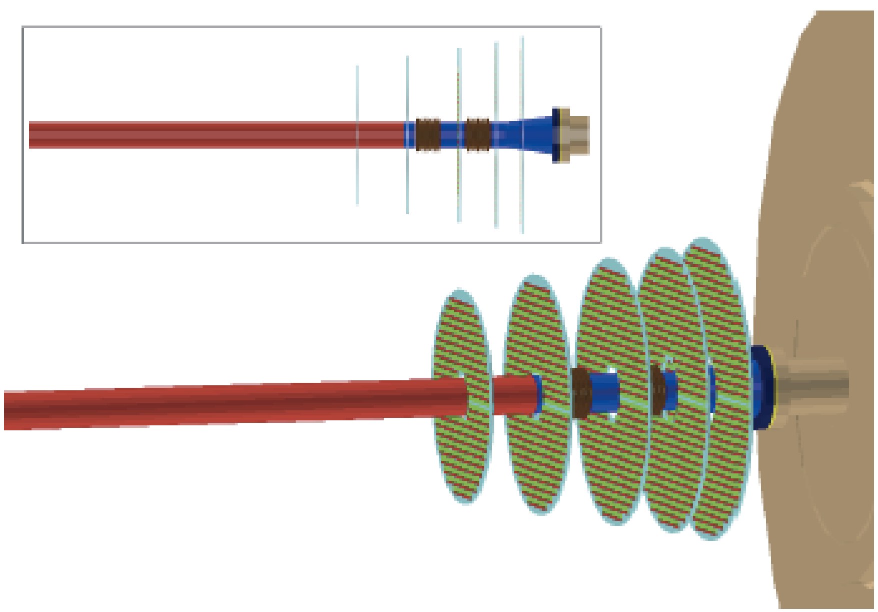


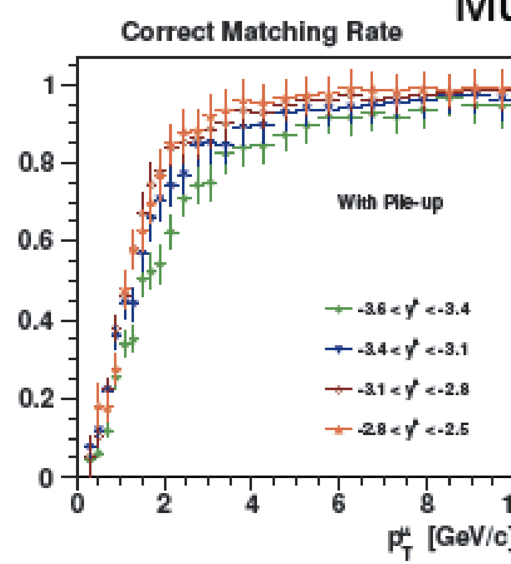
Observable	Current, $0.1\,\mathrm{nb}^{-1}$		Upgrade, $10\,\mathrm{nb}^{-1}$	
	$p_{\mathrm{T}}^{\min}$ (GeV/c)	statistical uncertainty	$p_{\mathrm{T}}^{\min}$ (GeV/c)	statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
$\mathrm{D_s}$ meson R_{AA}	4	15 %	< 2	3 %
D meson from B R_{AA}	3	30 %	2	1 %
J/ψ from B R_{AA}	1.5	15 % (p_{T}-int.)	1	5 %
B^+ yield	not accessible		3	10 %
Λ_c R_{AA}	not accessible		2	15 %
Λ_c/D^0 ratio	not accessible		2	15 %
Λ_b yield	not accessible		7	20 %
D meson v_2 ($v_2 = 0.2$)	1	10 %	0	0.2 %
$\mathrm{D_s}$ meson v_2 ($v_2 = 0.2$)	not accessible		< 2	8 %
D from B v_2 ($v_2 = 0.05$)	not accessible		2	8 %
J/ψ from B v_2 ($v_2 = 0.05$)	not accessible		1	60 %
Λ_c v_2 ($v_2 = 0.15$)	not accessible		3	20 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$)	not accessible			10 %
Low-mass spectral function	not accessible		0.3	20 %
Hypernuclei				
${}^{3}_{\Lambda}\mathrm{H}$ yield	2	18 %	2	1.7 %

ALICE: MFT Upgrade

- Match tracks in MFT and Muon spectrometer
  - improve pointing accuracy in vertex region
- No B-field in MFT region
  - no momentum measurement







Matching inefficient for $p_T(\mu) < 1$ GeV/c

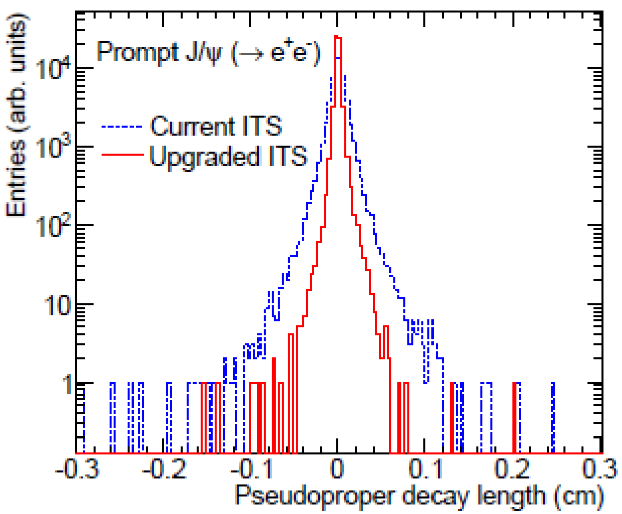
Heavy ions at the LHC

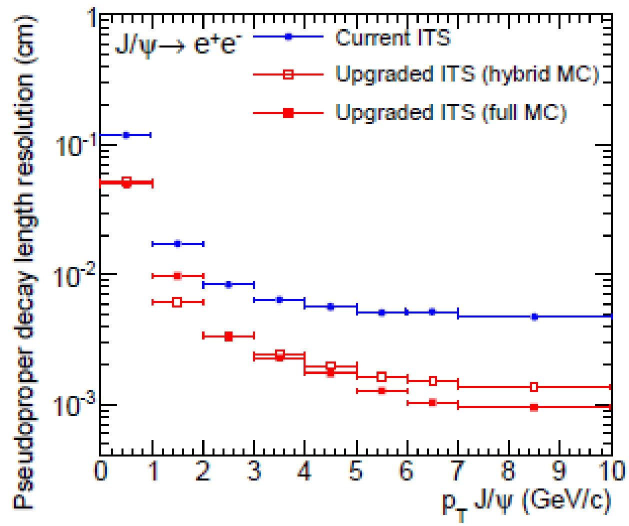
RUN 1:

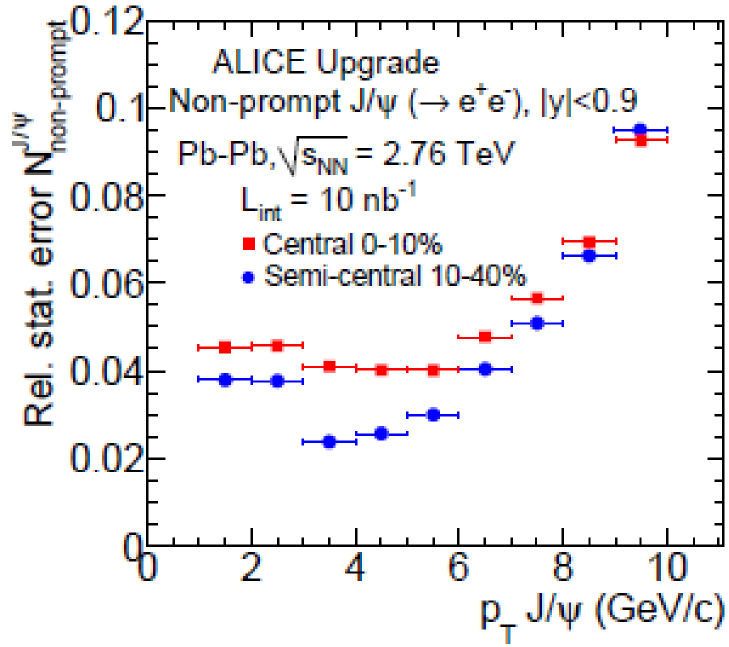
year	system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
2010	**Pb-Pb**	**2.76**	**~ 10 μb^{-1}**
2011	pp	2.76	~ 250 nb^{-1}
2011	**Pb-Pb**	**2.76**	**~ 150 μb^{-1}**
2013	p-Pb	5.02	~ 30 nb^{-1}
2013	pp	2.76	~ 5 pb^{-1}

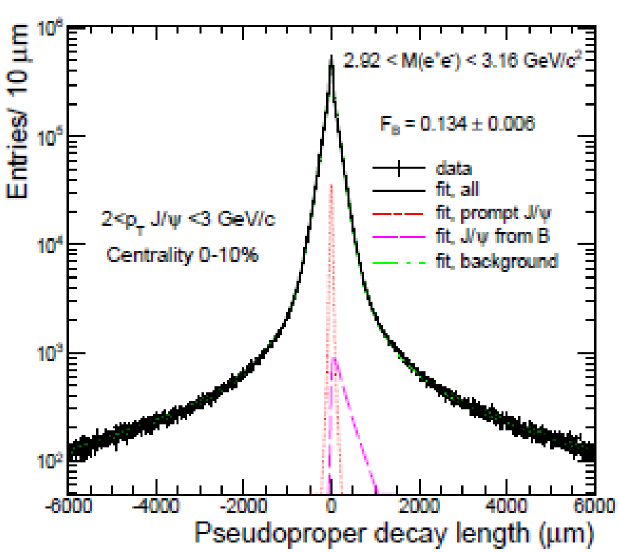
- Run 2:
  - Pb-Pb: 1 nb^{-1} at sqrt(s)=5.1 TeV
  - p-Pb
  - pp reference at the same energy as Pb-Pb
- Run 3-4:
  - Experiment request: L_{INT}> 10 nb^{-1} in Pb-Pb
  - High luminosity p-Pb, pp reference at 5.5 TeV, possibly light ions

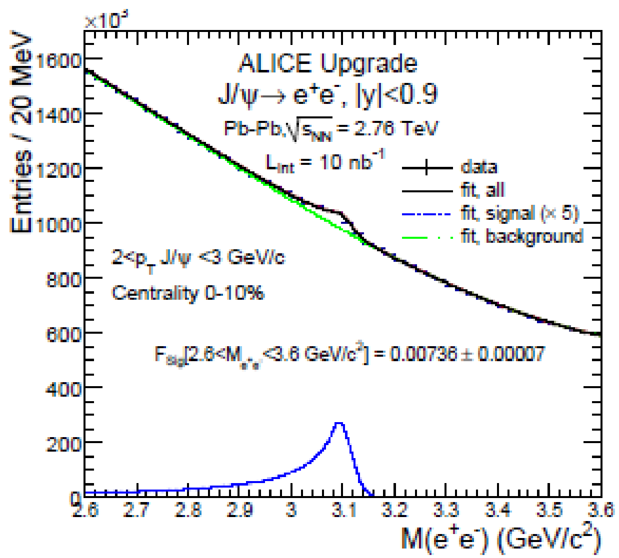
ALICE upgrade: J/ψ from B

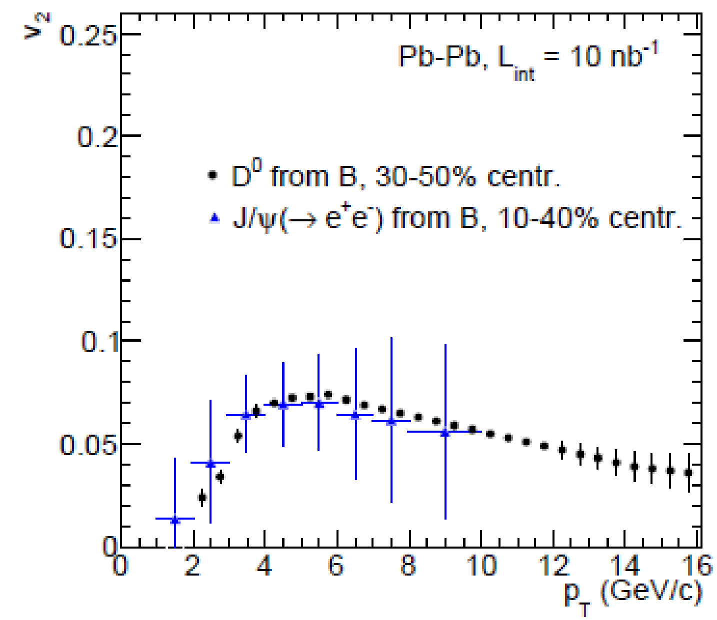




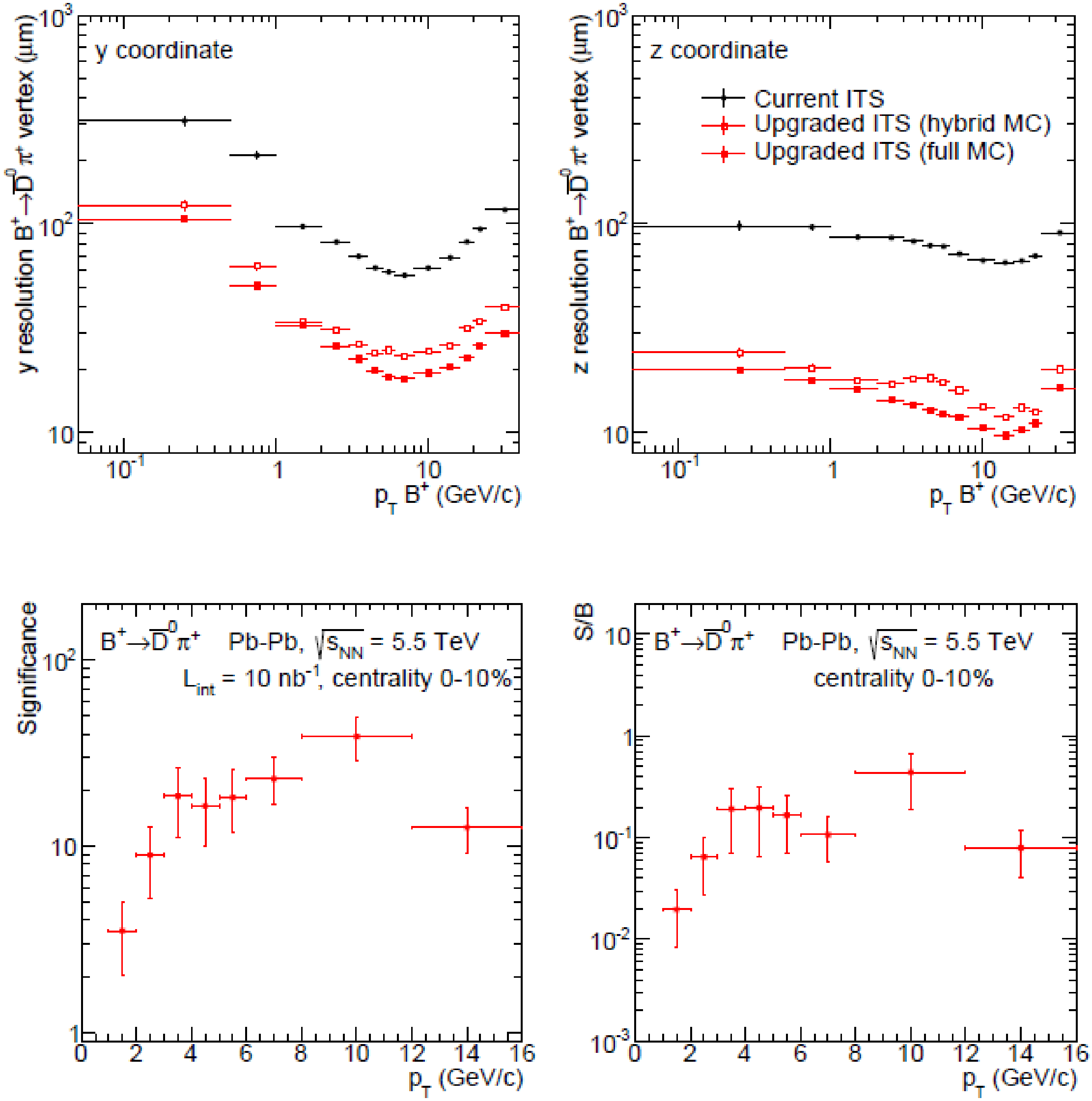








ALICE upgrade: full B reconstruction



$$c\tau = 492\,\mu m$$

ALICE ITS upgrade: Λ_b