Heavy Flavours and Quarkonia in ALICE

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for the ALICE collaboration

HELMOLTZ INTERNATIONAL SUMMER SCHOOL
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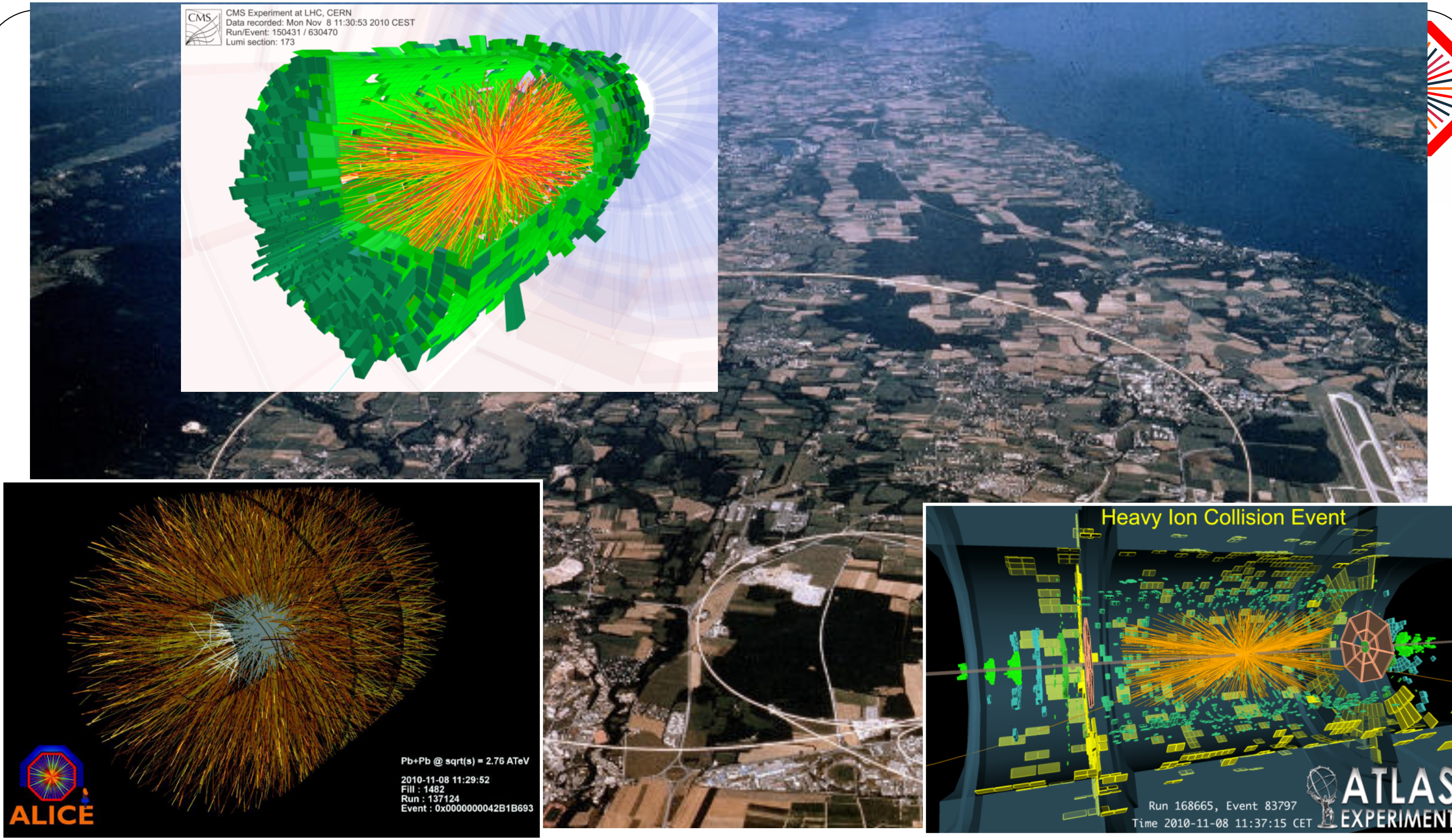
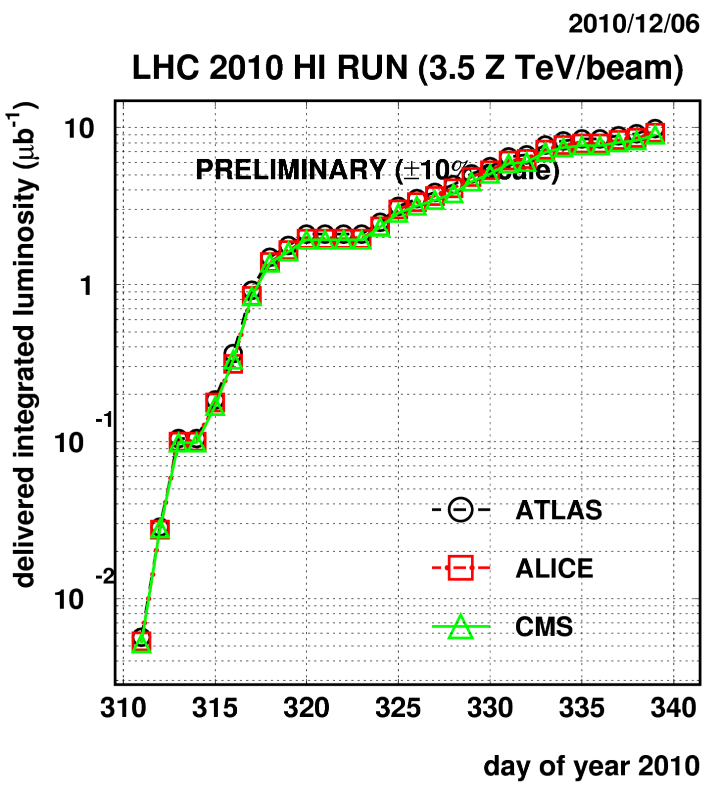
Outlook

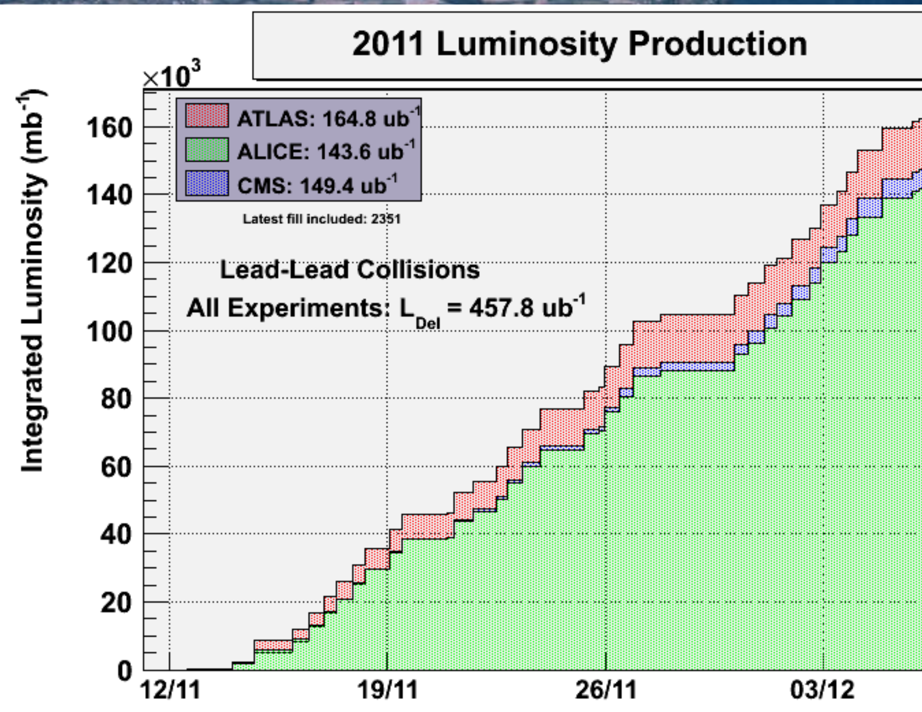
- Introduction
- Heavy Flavours in Heavy Ion Collisions
- Quarkonium in Heavy Ion Collisions
- The ALICE experiment
  - ✓ HF and Quarkonium with the ALICE experiment
- Experimental results with
  - ✓ Pb-Pb collisions
  - ✓ pPb collisions
- Conclusions



- Heavy Ion programme at the LHC started on Nov. 7th 2010 with Pb-Pb collisions at $\sqrt{S_{NN}}$=2.76 TeV
- Big jump in energy w.r.t. RHIC: 13.8× $\sqrt{S_{NN}}$
- 3 experiments: ALICE, ATLAS and CMS

Heavy Ions at the LHC

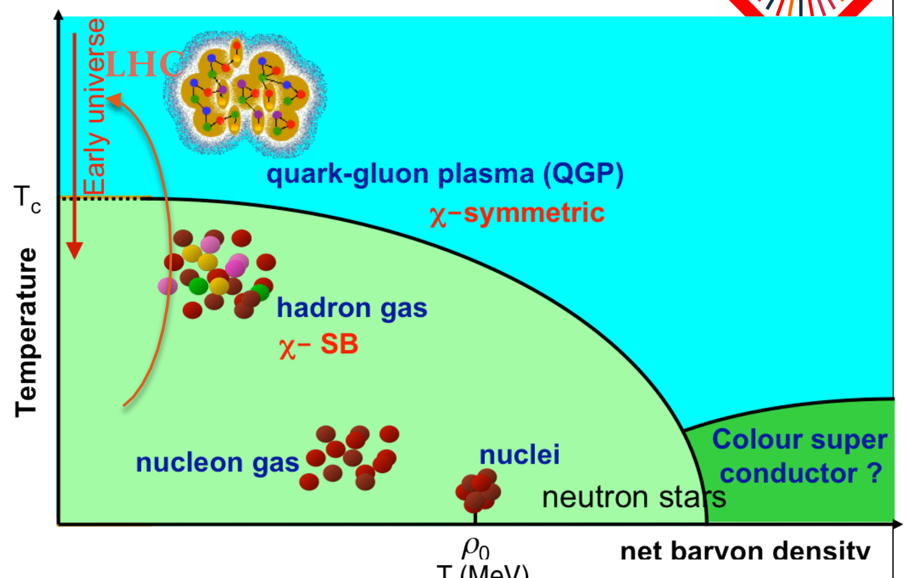


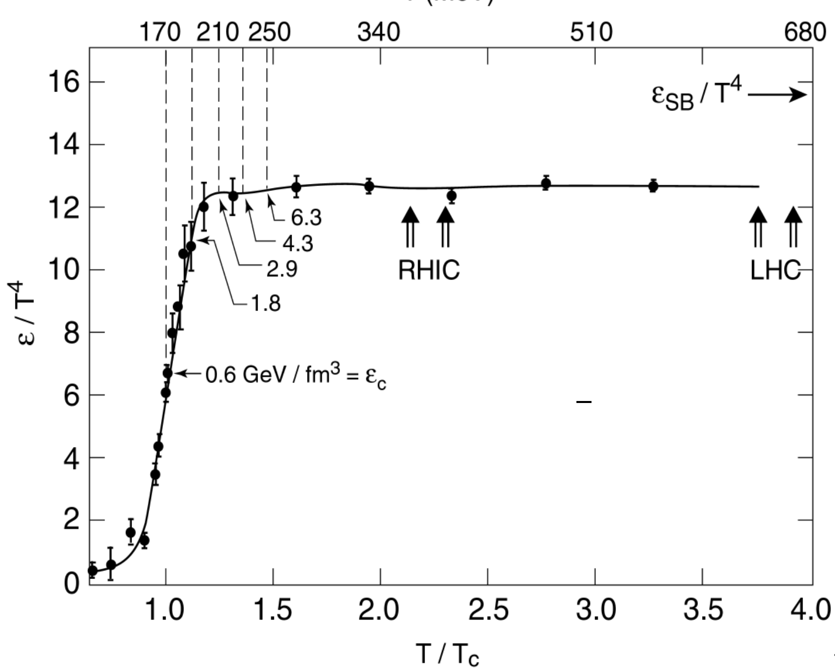


- The LHC delivered an integrated luminosity of 10 μb^{-1} in 2010 and ~150 μb^{-1} in 2011

Why Heavy Ions

- First phase diagram for nuclear matter: Cabibbo, Parisi PL B59 (1975): "We suggest … a different phase of the vacuum in which quarks are not confined"
- T.D. Lee (1975) suggested to distribute a high amount of energy over a relatively large volume
- So: collisions of nuclei at very high energy
  - ✓ Temperature of the produced "fireball" O(10^{12} K)
    - $10^5 \times$T of the centre of the Sun
    - $\approx$T of the Universe 10^{-5} s after Big Bang
- Study nuclear matter at extreme conditions of temperature and density
  - ✓ Collect evidence for a state where quarks and gluons are deconfined (Quark Gluon Plasma) and study its properties
  - ✓ Phase transition predicted by Lattice QCD calculations
    - $T_C \approx 170$ MeV $\rightarrow \varepsilon_C \approx 0.6$ GeV/fm3





Nucleus-Nucleus collision: a process

Freeze-out:

- Chemical: particle composition is fixed (no more inel. Collisions) → T_{ch} ≈170 MeV (RHIC)
- Thermal: momentum spectra are fixed (no more elastic collisions) → T_{fo}≈110÷130 MeV

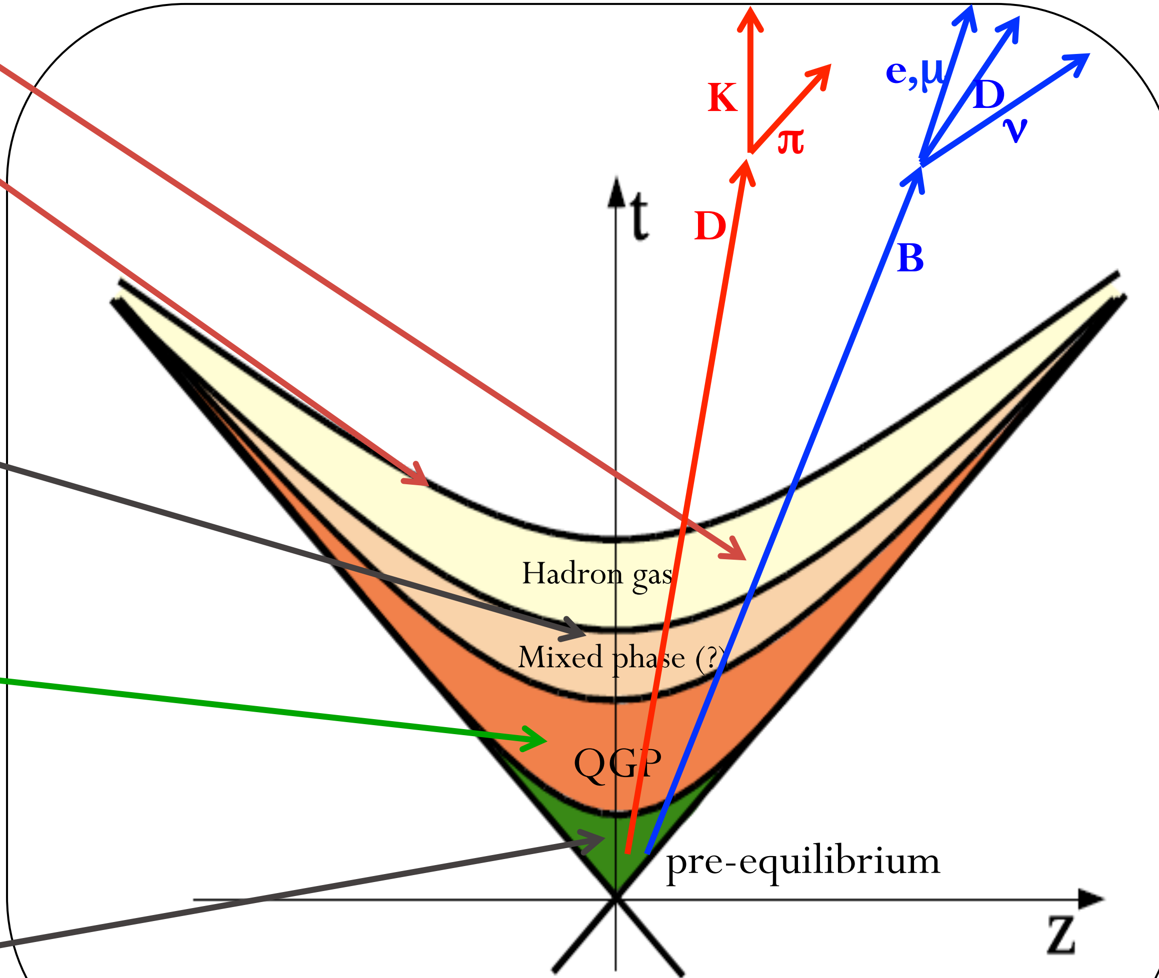
Soft processes:

- high cross section
- Decouple late - indirect signals for QGP

Photons (real and virtual): insensitive to the hadronization phase

Hard processes:

- **Charm**, Beauty, Jets
- Probe the whole evolution of the collision
- Thermalization time (RHIC) τ_{th}≅0.6 fm/c



Heavy Flavours in Heavy Ion Collisions

Charm & Beauty in HI: why?

- In Heavy Ion (HI) collisions at LHC energies, the QGP phase is expected to have a lifetime O(10 fm/c)
- Heavy Quarks are produced in the early stages of the HI collision ($\Delta t_{charm} \sim 1/m_c \sim 0.1\ fm/c$)
  - ✓ They are a natural probe of the hot medium created in HI interactions
- Naively, in HI collision the HQ p_T spectra should scale with the number of binary nucleon-nucleon collisions

$$dN_{AA}/dp_T = N_{coll} \times dN_{pp}/dp_T$$

- BUT the simple binary scaling is broken by nuclear effects:
  - ✓ Cold nuclear matter effects: Cronin effect, modifications of the PDF in the nuclei
  - ✓ Final state effects: in-medium energy loss, in-medium hadronization(?), collective phenomena (?)

Heavy Flavours: a physics programme

- A-A collisions
  - ✓ Heavy Flavours are a powerful tool to probe the high density medium via heavy quark **energy loss**, **flow**, hadronization mechanism …
- p-p collisions
  - ✓ Reference for quenching studies in AA
  - ✓ Test pQCD predictions in a **new energy regime** ($3.5\times\sqrt{s_{TEVATRON}}$)
  - ✓ Probe an unexplored region of **small Bjorken x** with charm at low p_T and/or forward rapidity
- p-A collisions
  - ✓ Address cold nuclear matter effects (Cronin enhancement, nuclear PDFs)

Charm (& Beauty): the p-p baseline

- Heavy Flavours are produced in high momentum transfer processes
  - ✓ cross sections at parton level can be computed with pQCD
  - ✓ cross sections in pp collisions can be computed assuming factorization between pQCD and non-pQCD processes
- Once the baseline is established, the deviations from the binary scaling can be ascribed to nuclear effects

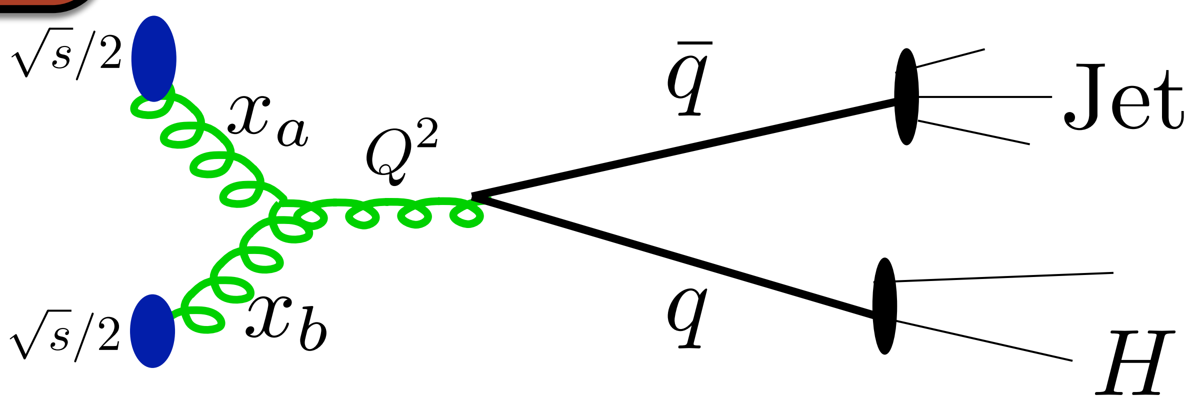
$$\sigma_{hh\to Hx} = \mathrm{PDF}\left(x_a, Q^2\right)\mathrm{PDF}\left(x_b, Q^2\right)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to H}\left(z_q, Q^2\right)$$

Cross section to produce the particle H in hadron-hadron collisions

Parton distribution functions (non perturbative)

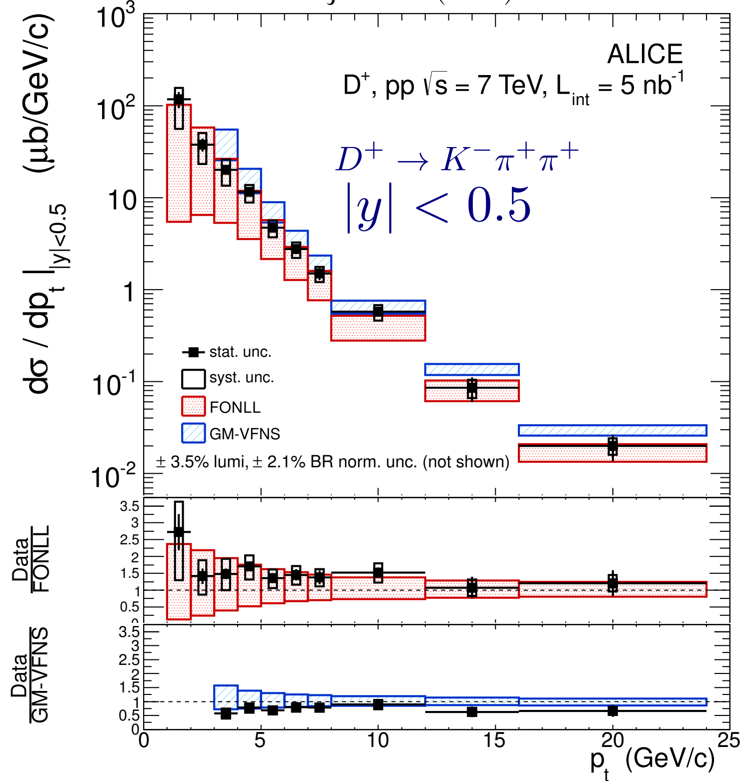
Cross section at parton level (pQCD)

Fragmentation function (non perturbative)



The baseline: HF in pp @ 7 TeV

B. Abelev et Al.JHEP 01 (2012) 128



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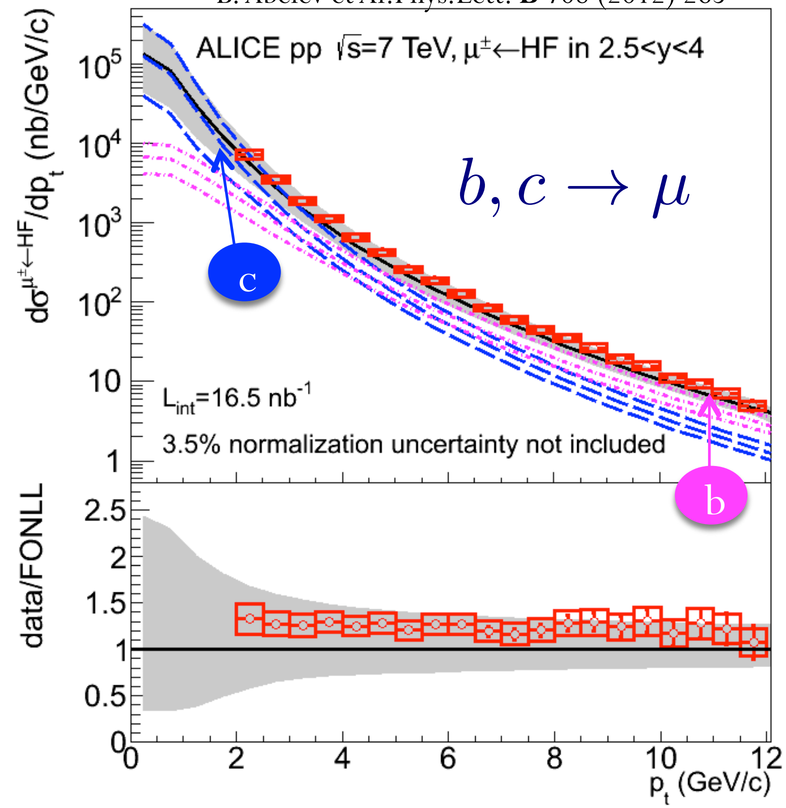
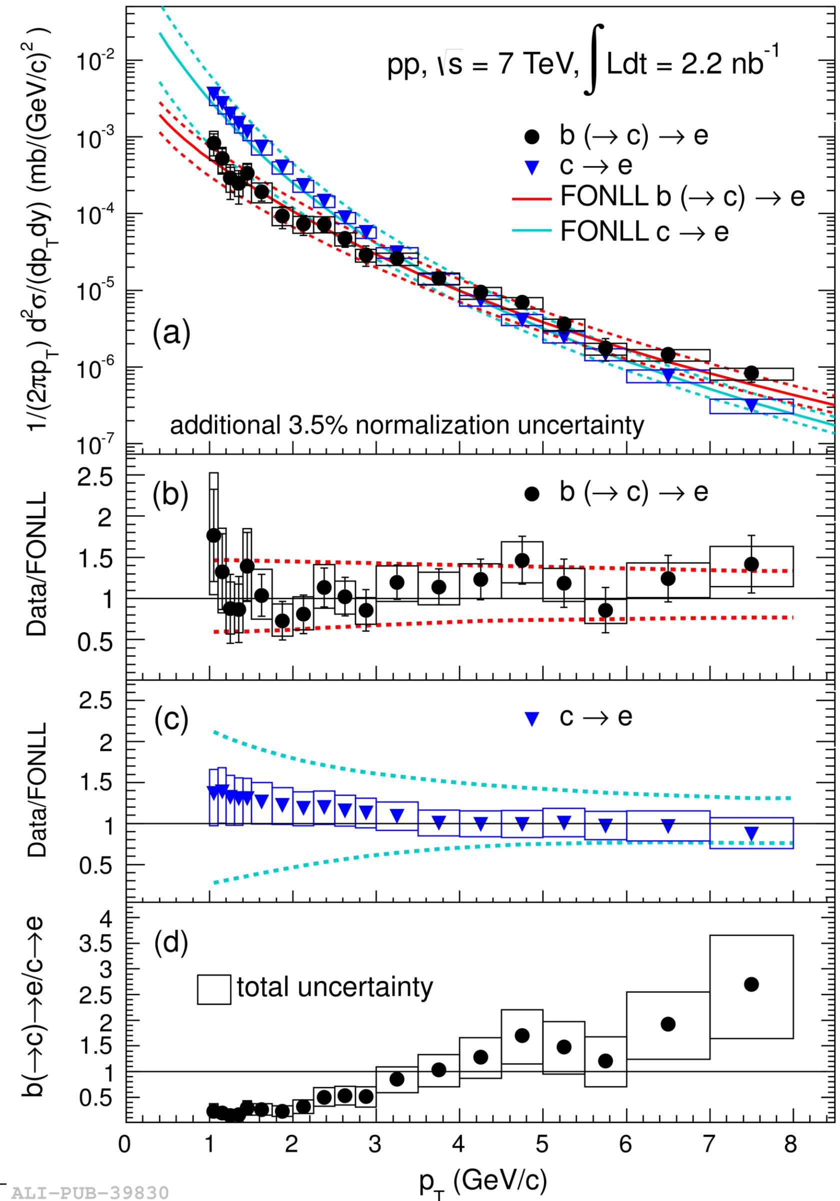


- The pp baseline is described within the errors by NLO pQCD calculations (B feed down corrected with FONLL)
- According to FONLL μ🡐b predominates for p_T>6 GeV/c (the expected μ🡐c contribution is ~40% for p_T=6 GeV/c)

The baseline: HF in pp @ 7 TeV

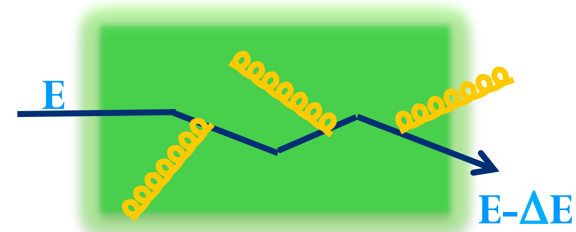
- Single electron data from HF decays are in agreement with ATLAS measurements at high p_T on a wider rapidity domain
- Electrons from beauty hadron decays were selected based on the displacement of the decay vertex from the collision vertex.
- The results (*Physics Letters B* ***721*** *(2013) 13–23*) show that also at low p_T the beauty and charm production are in agreement with the pQCD predictions



Energy loss in coloured medium

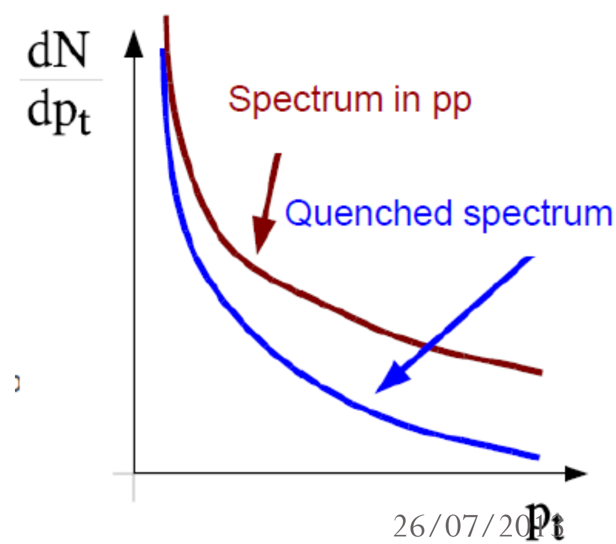
- Partons are expected to lose energy while traversing a deconfined medium via gluon radiation and elastic collisions with partonic constituents
  - ✓ see, e.g. arXiv:0902.2011[nucl-ex], Prog.Part.Nucl.Phys 66 (2011) 41-
- Basic experimental observable:

nuclear modification factor R_{AA}



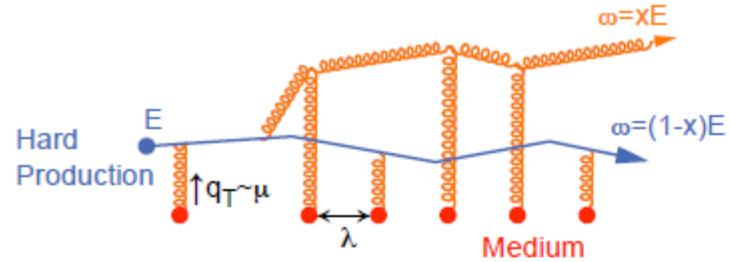
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- ✓ The reduction in the parton energy translates to a reduction in the average momentum of the produced hadron, i.e. to a reduction of the yield at high p_T wrt pp collisions → $R_{AA}<1$



Radiative energy loss

- Gluon radiation expected to be the main mechanism of energy loss
  - ✓ The amount of energy lost is sensitive to:
    - the medium properties (density)
    - the path-length (L) of the parton in deconned matter
    - the properties of the parton probing the medium
  - ✓ Several models are available
  - ✓ e.g. in BDMPS approach:



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

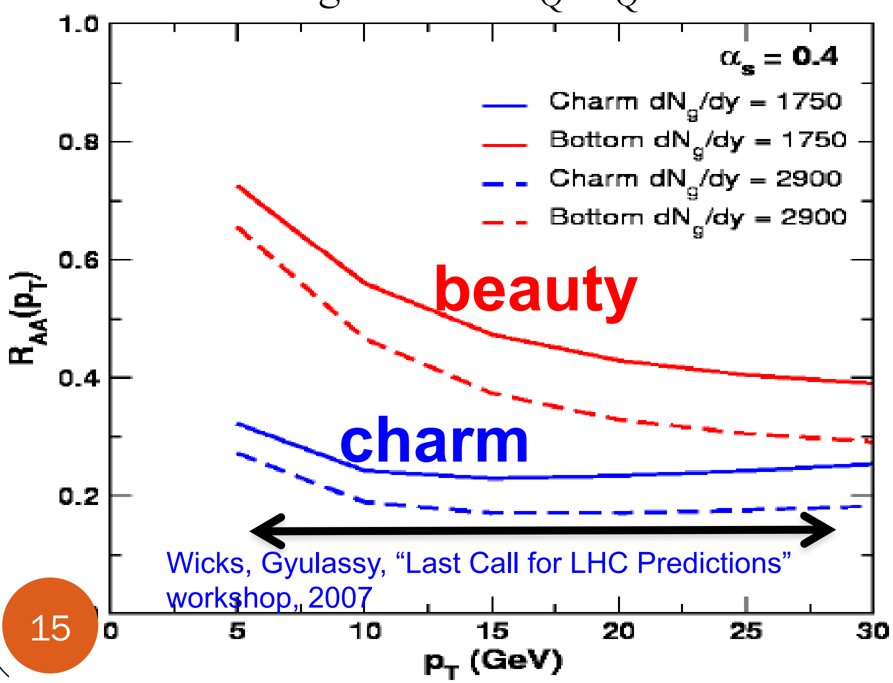
Casimir factor
→ 3 for gg interactions
→ 4/3 for qg interactions

q = transport coefficient, related to the medium characteristics and to the gluon density dN_g/dy

En. loss is proportional to L^2, taking into account the probability to emit a breemstrahlung gluon and the fact that radiated colored gluons can interact themselves with the medium

Heavy quark energy loss

- Radiative energy loss of charm and beauty quarks expected to be smaller (→ higher R_{AA}) wrt light hadrons due to:
  - ✓ Casimir factor (**color charge** dependence)
    - Cr = 3 for gg interactions, 4/3 for qg interactions
    - heavy hadrons are mainly produced from heavy quarks jet (while light hadrons are produced from gluon jets)
  - ✓ Dead cone effect (**mass dependence**)
    - Gluon radiation is suppressed for angles $\vartheta < M_Q/E_Q$



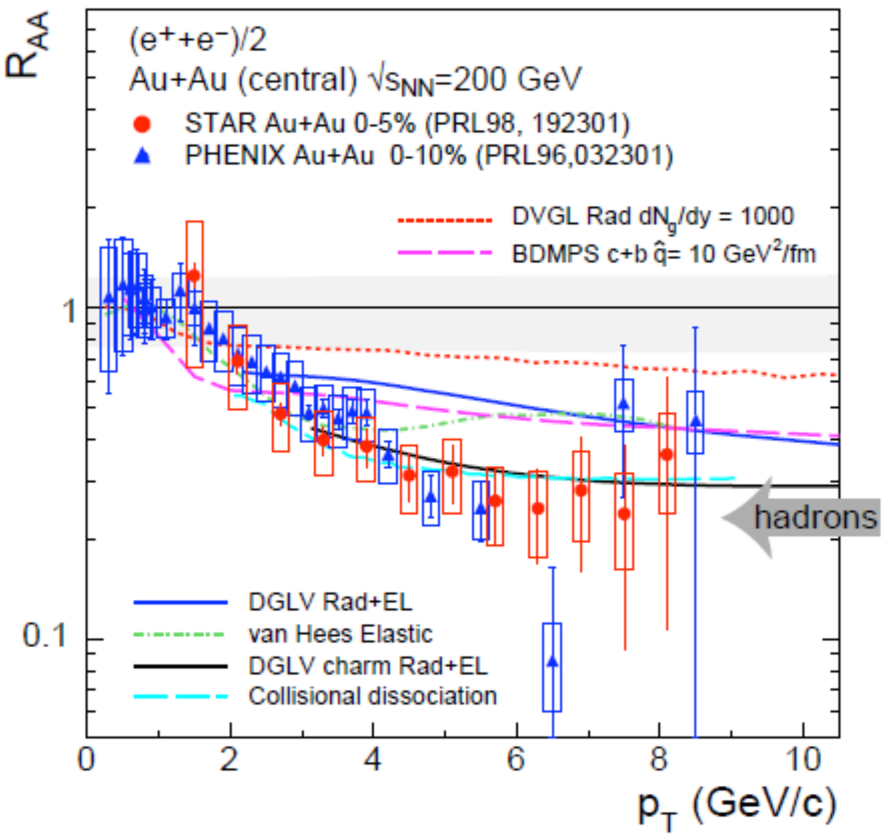
$$\Delta E_{quark} < \Delta E_{gluon}$$

$$\Delta E_{massive\ quark} < \Delta E_{light\ quark}$$

$$\Downarrow$$

$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

RHIC results: R_{AA}



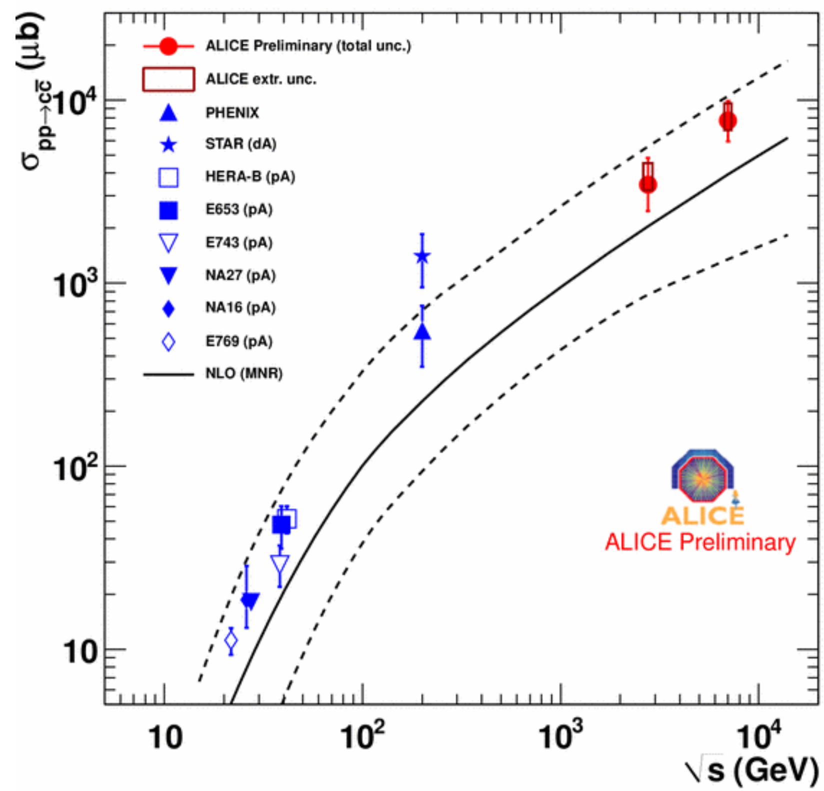
- Measurement based on non-photonic electrons
  - ✓ Start from identified electron spectra
    - STAR: dE/dx in TPC + TOF at low p_T, EMC at high p_T
    - PHENIX: combined RICH and E/p (with E from EM cal)
  - ✓ Reject non-heavy-flavour electrons, mainly "photonic"
    - Gamma conversions
    - Dalitz decay of π^0 and η
  - ✓ STAR also did exlusive reconstruction of D^0 from hadronic decays

- Non-photonic electrons show suppression similar to that of light hadrons
  - ⇨ A challenge for theory: models that work for light hadrons overestimate R_{AA} of non-photonic electrons

What can we learn at the LHC

- Higher c and b cross sections:
  - ✓ More abundant heavy flavour production
  - ✓ Better precision (reduced errors)

$$\sigma_{LHC}^{c\bar{c}} \approx 10 \cdot \sigma_{RHIC}^{c\bar{c}}$$
$$\sigma_{LHC}^{b\bar{b}} \approx 100 \cdot {}_{RHIC}^{b\bar{b}}$$

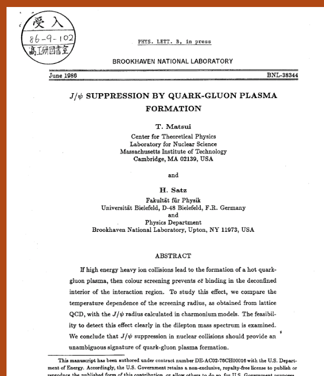


- High precision vertex detectors
  - ✓ Background removal
  - ✓ Separate c and b

Quarkonium in Heavy Ion Collisions

Quarkonium

- Quarkonium suppression is considered since a long time as one of the most striking signatures for the QGP formation in AA collisions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BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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Physics Department
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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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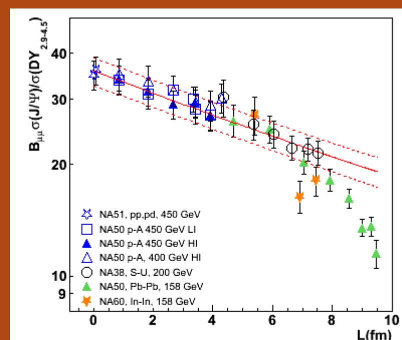
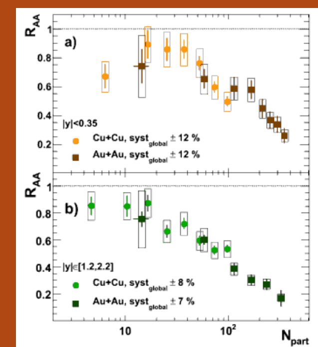
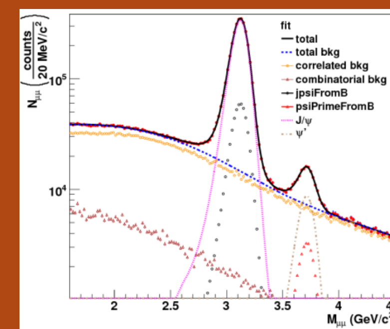
SPS



RHIC



LHC



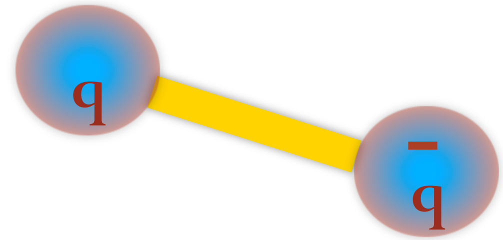
$\sqrt{s}$ — 17 GeV/c — 200 GeV/c — 2.76 TeV/c →

years — 1986 — 1990 — ~2000 — 2010 →

- …but, as for the other hard probes, in order to understand quarkonium behaviour in the hot matter (AA collisions), its interactions with the cold nuclear matter should be under control (pA/dAu collisions)

Quarkonium

- At T=0, the binding of the q and the $\bar{q}$ quarks can be expressed using the Cornell potential:



$$V(r) = -\frac{\alpha}{r} + kr$$

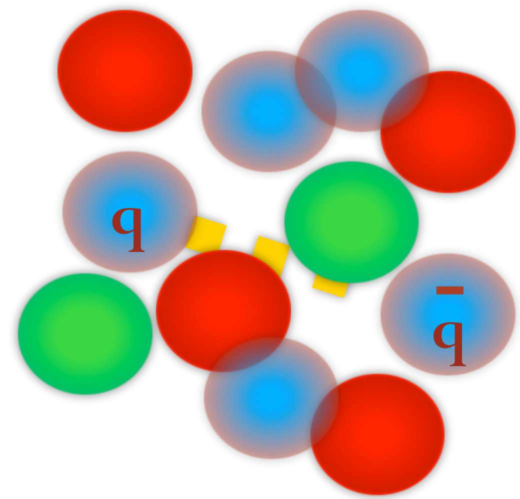
Coulombian contribution, induced by a gluon exchange between q and $\bar{q}$

Confinement term

- **What happens to a $q\bar{q}$ pair placed in the QGP?**

The QGP consists of deconfined colour charges
→ the binding of a pair is subject to the effects of colour screening

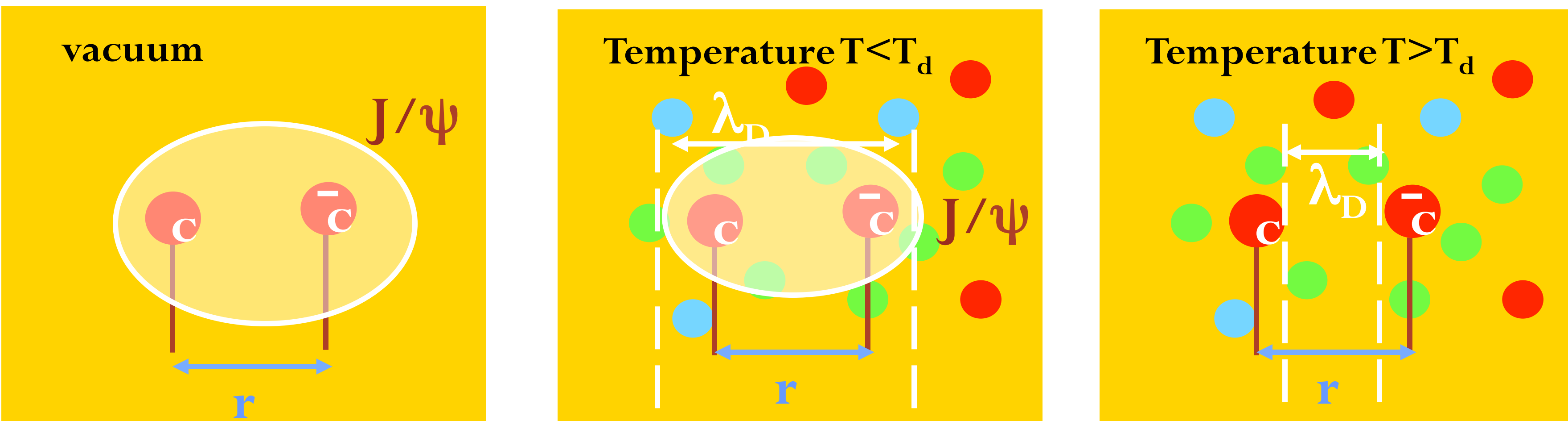
- The "confinement" contribution disappears
- The high colour density induces a screening of the coulombian term of the potential



$$V(r) = -\frac{\alpha}{r} + kr \longrightarrow V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

Debye screening

- The screening radius $\lambda_D(T)$ (i.e. the maximum distance which allows the formation of a bound $q\bar{q}$ pair) decreases with the temperature T



At a given T:

if resonance radius < $\lambda_D(T)$
→ resonance can be formed

if resonance radius > $\lambda_D(T)$
→ no resonance can be formed

Charmonium suppression

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Phys.Lett. B178 (1986) 416

This is the idea behind the suggestion (by Matsui and Satz) of the J/ψ as a signature of QGP formation (27 years ago!)

➡ Very famous paper, cited ~ 1400 times!

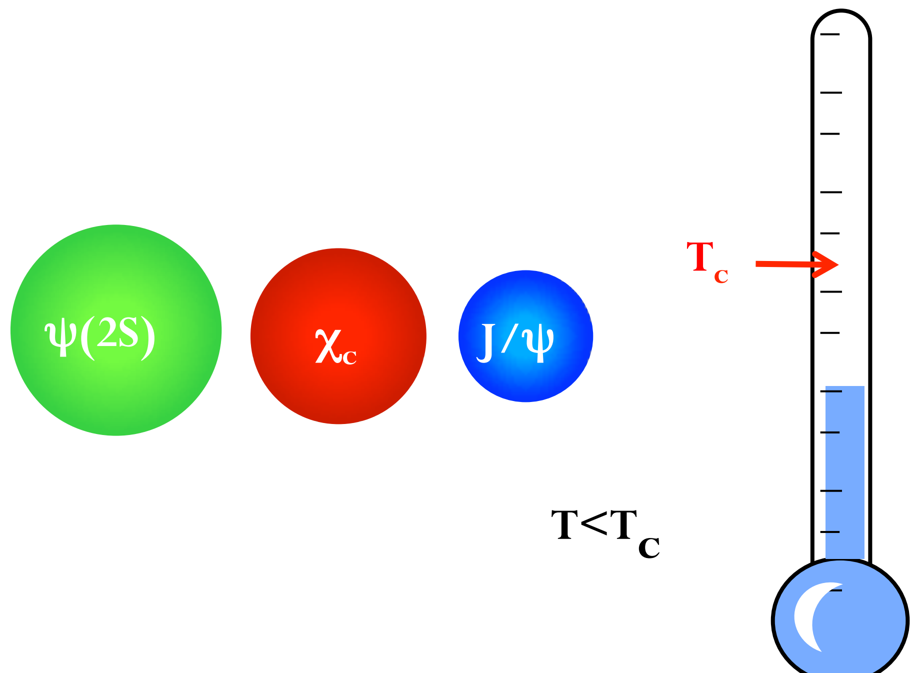
Sequential screening

- The quarkonium states can be characterized by
  - the binding energy
  - radius

state	J/ψ	χ_c	$\psi(2S)$
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_o(fm)	0.25	0.36	0.45

state	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

- More bound states have smaller size
- Debye screening condition $r_0 > \lambda_D$ will occur at different T



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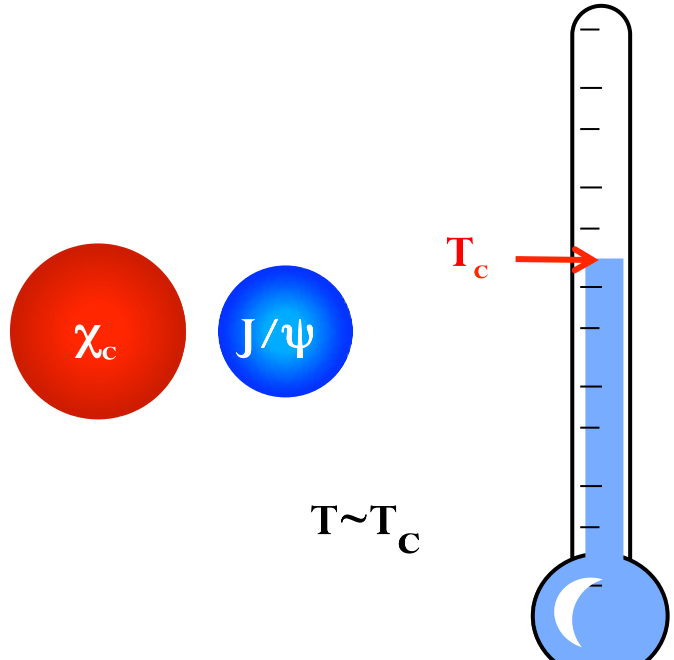

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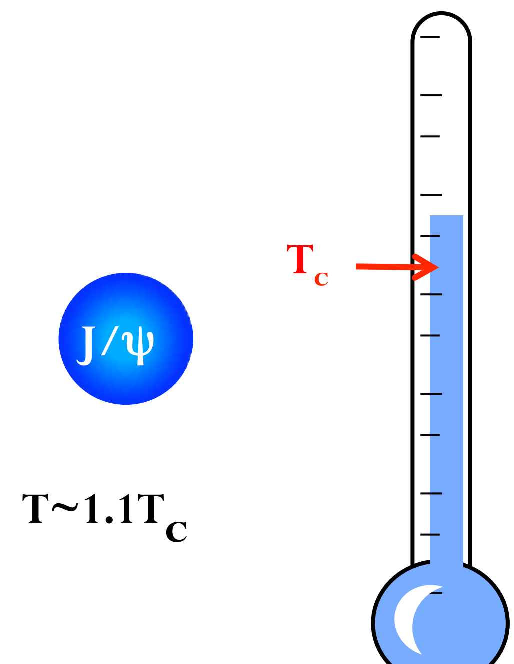

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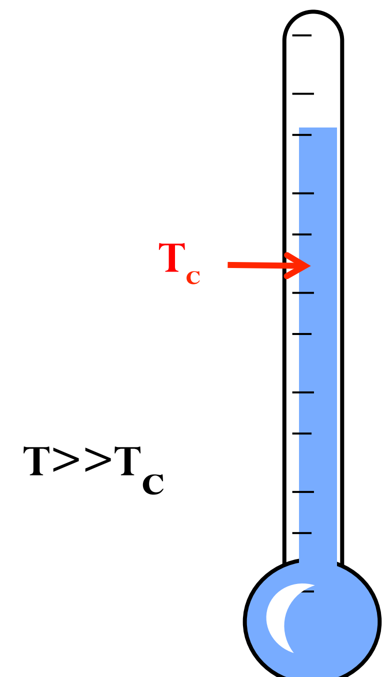


Sequential suppression of the resonances → thermometer for the temperature reached in the HI collisions

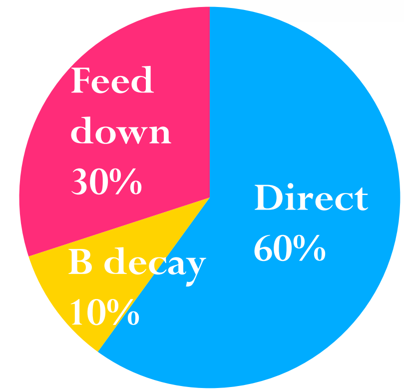
Quarkonium production and decay

J/ψ production

Quarkonium production can proceed:

- directly in the interaction of the initial partons
- via the decay of heavier hadrons (feed-down)

For J/ψ (LHC energies) the contributing mechanisms are:

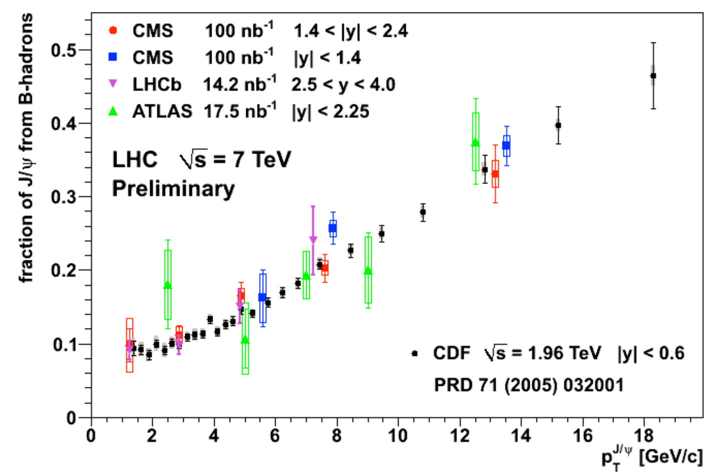


Prompt

- Direct production
- Feed-down from higher charmonium states:
  ~ 8% from ψ(2S), ~25% from χ_c

Displaced

- B decay
  contribution is p_T dependent
  ~10% at p_T~1.5GeV/c



J/ψ decay

J/ψ can be studied through its decays:

J/ψ → $\mu^+\mu^-$ **J/ψ → e^+e^-** (~6% branching ratio)

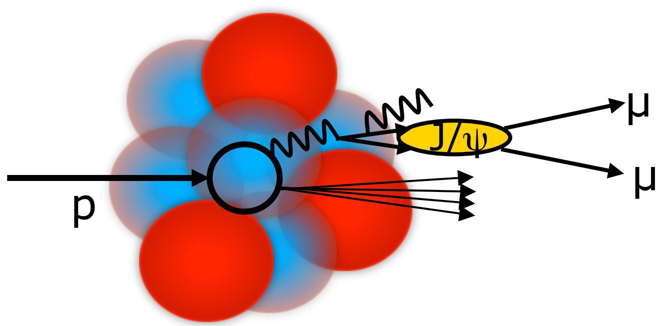
Quarkonium production in pA

- To understand quarkonium behaviour in the hot medium, it is important to know its behaviour in the cold nuclear matter.
  → this information can be achieved studying pA collisions

- allow the understanding the J/ψ behaviour in the cold nuclear medium
  → complicate issue, because of many competing mechanisms:

Initial state

shadowing,
parton energy loss,
intrinsic charm



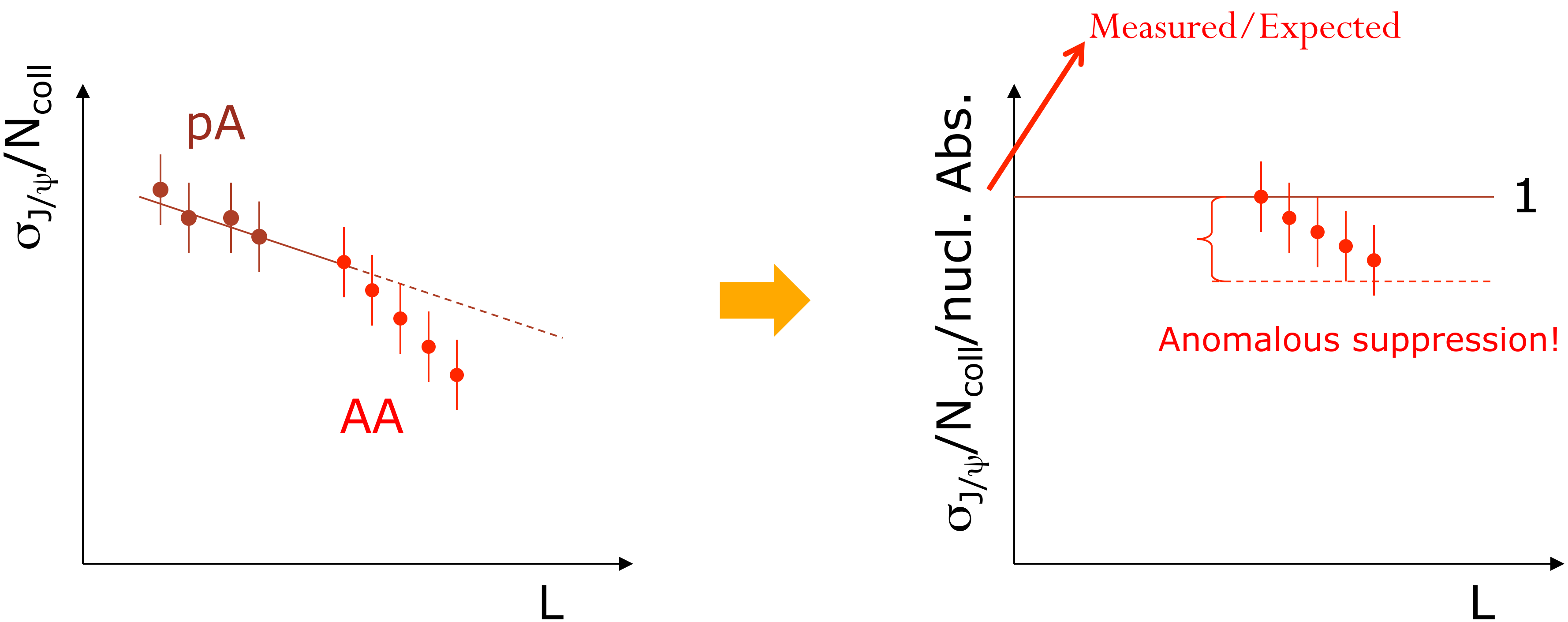
Final state

cc dissociation
in the medium,
final energy loss

- provide a reference for the study of charmonia dissociation in a hot medium

Relevance of CNM effects

- The cold nuclear matter effects present in pA collisions are of course present also in AA and can mask genuine QGP effects

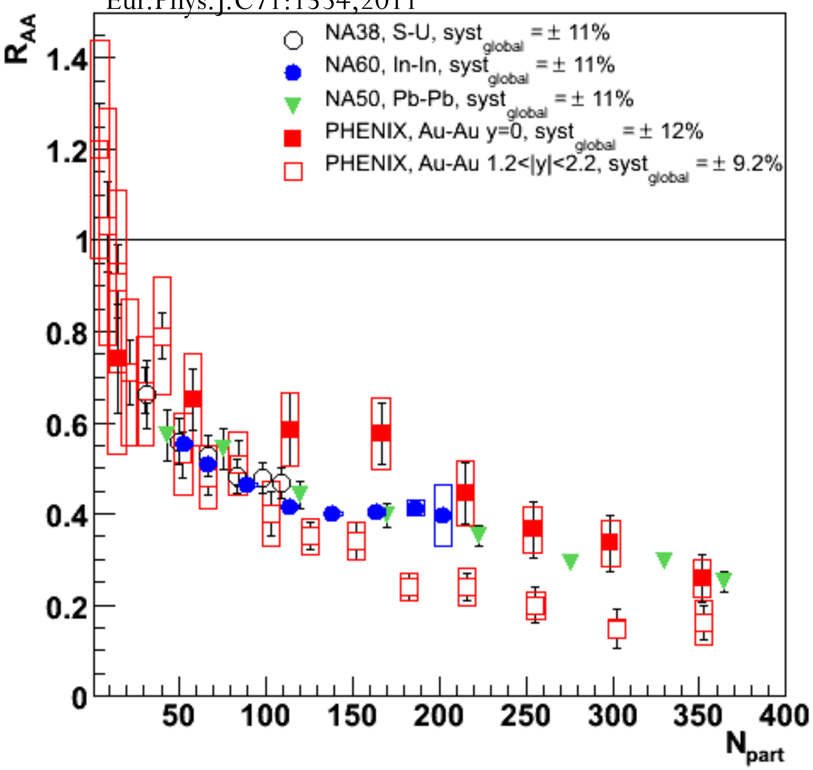


- It is very important to measure cold nuclear matter effects before any claim of an "anomalous" suppression in AA collisions
- CNM, evaluated in pA, are extrapolated to AA, in order to build a reference for the J/ψ behaviour in hadronic matter

Expectations at the LHC

- Charmonium production deeply investigated at
  - SPS (NA50, NA60) $\sqrt{s_{NN}}$ = 17 GeV
  - RHIC (PHENIX,STAR) $\sqrt{s_{NN}}$ = 200 GeV

Eur.Phys.J.C71:1534,2011

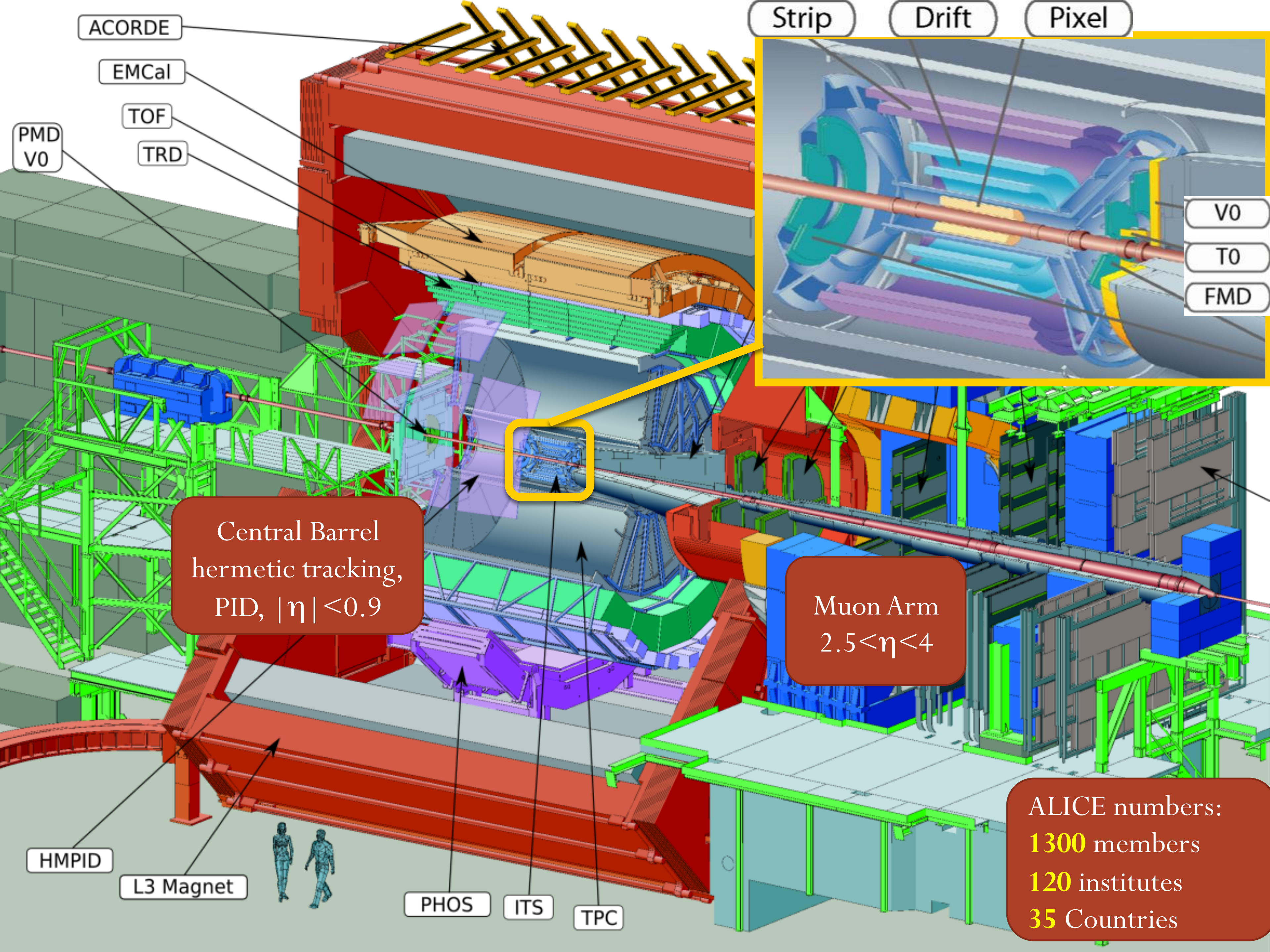


- Observation of J/ψ suppression
- Puzzles from SPS and RHIC
  - RHIC: stronger suppression at forward rapidities
  - SPS vs. RHIC: similar R_{AA} pattern versus centrality
- Hint for (re)combination at RHIC?

No final theoretical explanation

- Decisive inputs expected from LHC results, having access to:
  - higher energy
  - larger $c\bar{c}$ multiplicity
  - other quarkonium states (bottomonium)

The ALICE experiment



ACORDE
EMCal
TOF
TRD
PMD
V0
Strip
Drift
Pixel
V0
T0
FMD
Central Barrel
hermetic tracking,
PID, |η|<0.9
Muon Arm
2.5<η<4
HMPID
L3 Magnet
PHOS
ITS
TPC
ALICE numbers:
1300 members
120 institutes
35 Countries

ALICE mission

- Detector designed primarily for Heavy Ion collisions
  - ✓ Multipurpose: able to address most of the soft and hard probes related to HI physics
  - ✓ Excellent vertexing, tracking and PID capabilities
  - ✓ low material budget at mid-rapidity → well suited to identify low p_T particles
  - ✓ Design $dN_{ch}/dy > 6000$
- Also ATLAS and CMS have a Heavy Ion programme
  - ✓ complementary rapidity and p_T coverage
- In the following I shall concentrate on Heavy Flavour measurements and on quarkonia (mostly trhough their $\mu^+\mu^-$ decay channel)

Heavy flavour hadrons

- Lower mass heavy flavour hadrons decay weakly:
  - ✓ Lifetimes ≈ 0.5-2 ps
  - ✓ cτ ≈ 100-500 μm
  - ✓ Decay vertices of open heavy flavour hadrons displaced by hundreds of microns from the interaction (primary) vertex

Hadron	Mass (MeV)	cτ (μm)
$D^+(c\bar{d})$	1869	312
$D^0(c\bar{u})$	1865	123
$D_s^+(c\bar{s})$	1968	147
$\Lambda_c^+(udc)$	2285	60
$\Xi_c^+(usc)$	2466	132
$\Xi_c^0(dsc)$	2472	34
$\Omega_c^0(ssc)$	2698	21

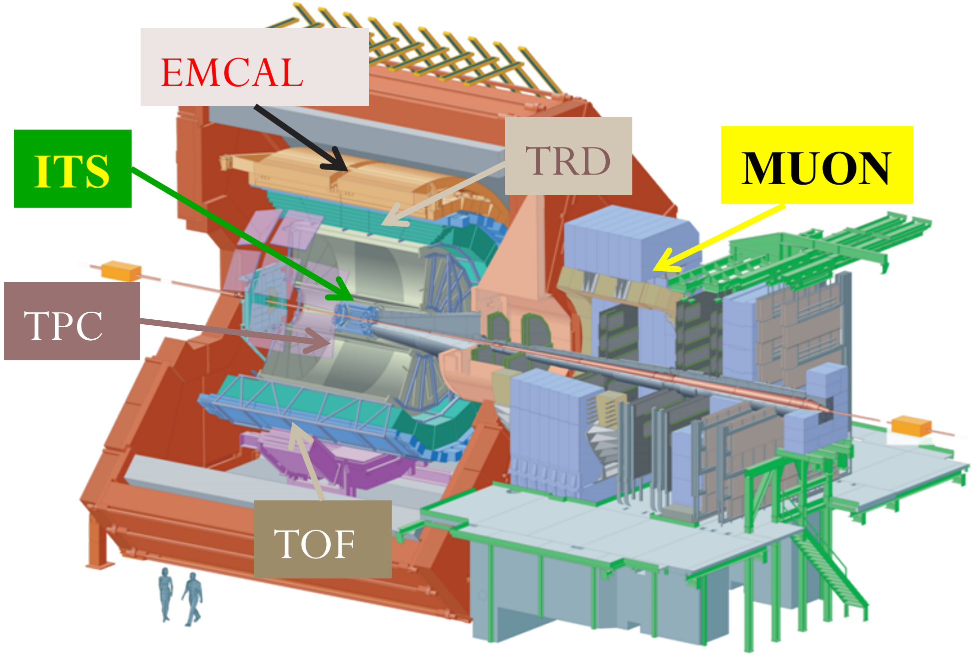
Hadron	Mass (MeV)	cτ (μm)
$B^+(u\bar{b})$	5279	501
$B^0(d\bar{b})$	5279	460
$B_s^0(s\bar{b})$	5370	438
$B_c^0(c\bar{b})$	≈ 6400	$100-200$
$\Lambda_b^0(udb)$	5624	368

Decay modes

- Large semi-leptonic branching ratio, tipically 10%
  - ✓ ~10% of heavy flavour hadrons gives $e^{\pm}$ in final state (and ~10% $\mu^{\pm}$)
- Charm hadrons have large branching ratios to kaons
  - ✓ e.g. $D^0 \to K^- + X$ BR~55%
  - ✓ Golden channels for exclusive reconstruction

Meson	*Final state*	*# charged bodies*	*Branching Ratio*
D^0	$\to K^-\pi^+$	2	3.87%
	$\to K^-\pi^+\pi^+\pi^-$	4	8.07%
D^+	$\to K^-\pi^+\pi^+$ (non-resonant or via $K^*(892)^0\pi^+$)	3	9.13%
D^{*+}	$\to D^0\pi^+ \to K^-\pi^+\pi^+$	3	67.7% * 3.87%
D_s^+	$\to K^+K^-\pi^+$ (via the resonant channel $\phi\pi^+$)	3	2.28%
Λ_c^+	$\to pK^-\pi^+$ (non-resonant or via Δ^{++}, $\Lambda(1520)$ $K^*(892)^0$)	3	5.0%

Heavy flavours with ALICE

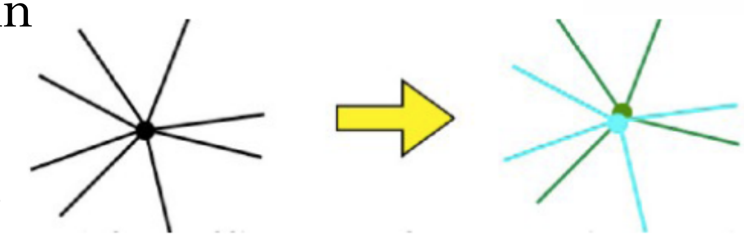


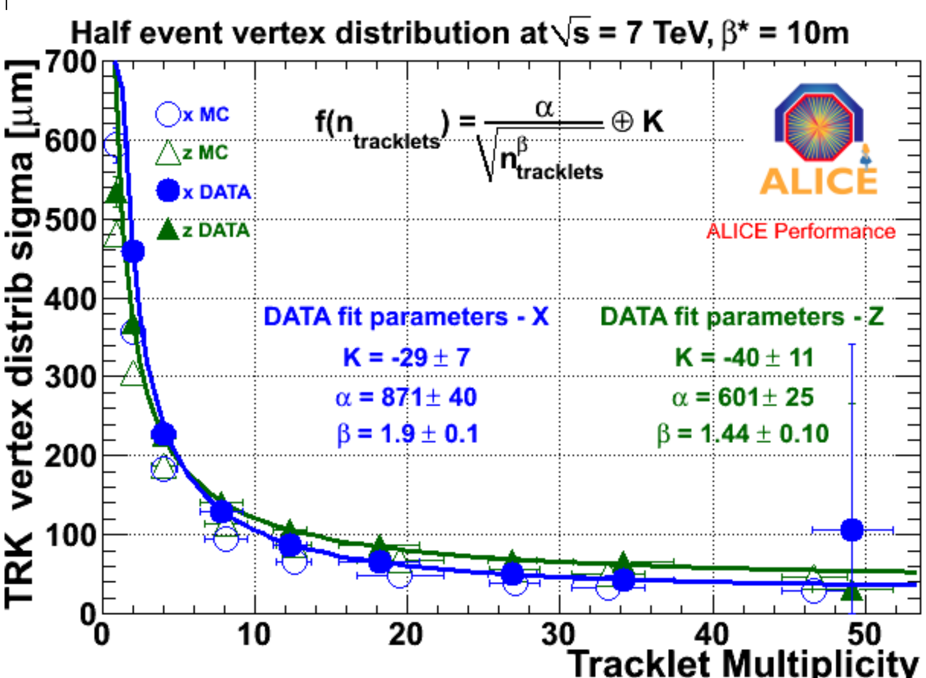
ITS: vertexing + tracking
TPC: tracking + PID (π, K, e)
TOF: PID (π, K, p)
TRD: PID (π, e)
EMCAL: PID (e)
MUON: μ tracking + PID

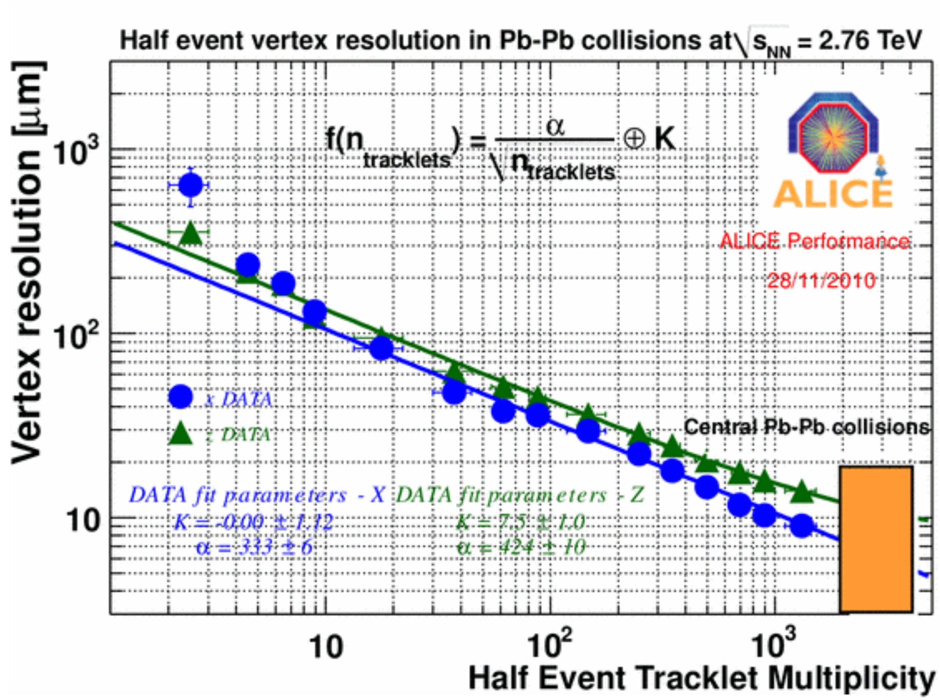
- Open charm from hadronic decays at central rapidity
  - $D^0 \to K^-\pi^+$
  - $D^+ \to K^-\pi^+\pi^+$
  - $D^{*+} \to D^0\pi^+$
  - $D^0 \to K^-\pi^+\pi^+\pi^-$
  - $D_s \to K^-K^+\pi^+$
  - $\Lambda_c^+ \to pK^-\pi^+$
- Open charm and open beauty from semileptonic decays
  - D, B $\rightarrow$ $e^\pm$ + X (central rapidity)
  - D, B $\rightarrow$ $\mu^\pm$ + X (forward rapidity)
- Open beauty from non-prompt J/ψ at central rapidity
  - $B \rightarrow J/\Psi \rightarrow e^+e^-$
  - $B \rightarrow e^\pm + X$

Tools: primary vertex reconstruction

- 3D reconstruction with tracks reconstructed in the barrel with full error-matrix treatment
- Estimate resolution on data using half events
  - ✓ Split tracks in 2 sub-samples and build residuals between reconstructed coordinates from the 2 half-events



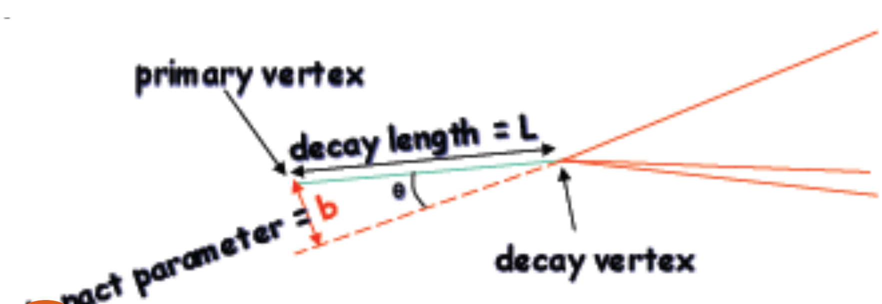


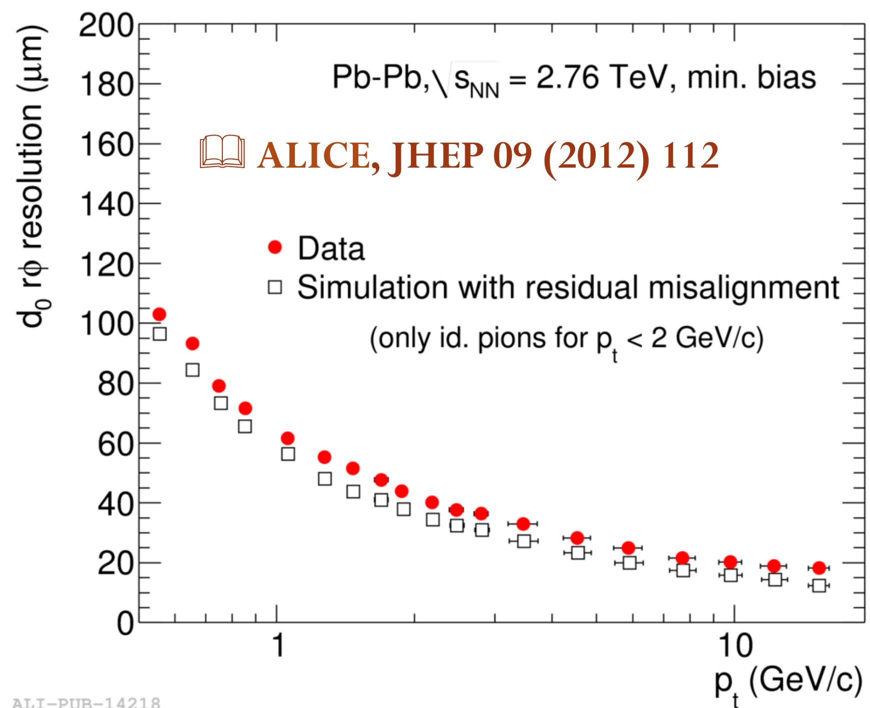


- Important for: impact parameter resolution; separation of secondary vertices; determination of the pointing angle

How to: displaced tracks

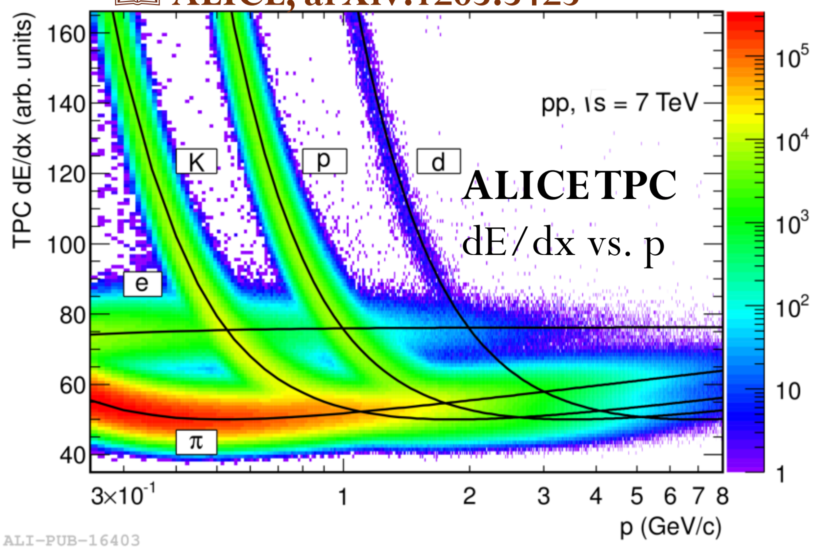
- Lower mass heavy flavour hadrons decay weakly:
  - ✓ Lifetimes: ≈0.5-1 ps for D and ≈1.5 ps for B
  - ✓ $c\tau$: ≈100-300 μm for D and ≈ 500 μm for B
- Possibility to detect decay vertices/displaced tracks
  - ✓ Tracking precision plays a crucial role
- Track impact parameter: distance of closest approach of a track to the interaction vertex

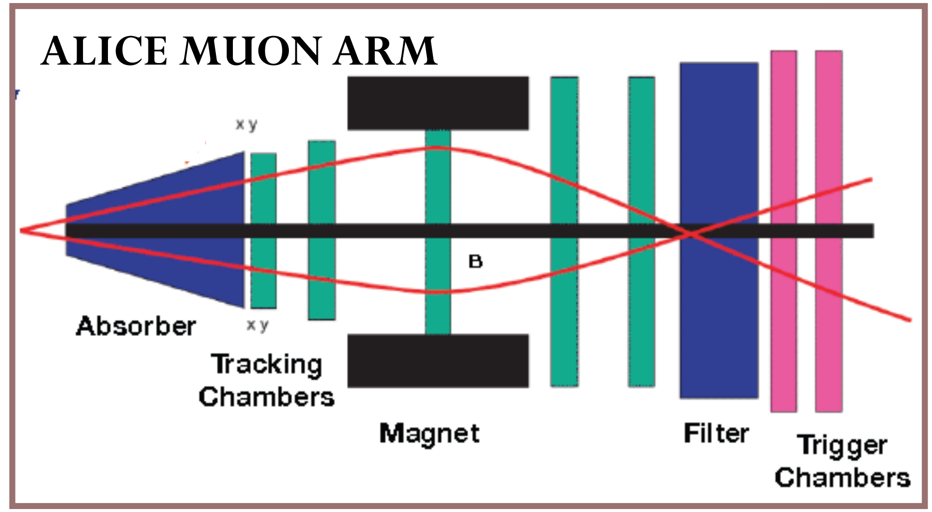


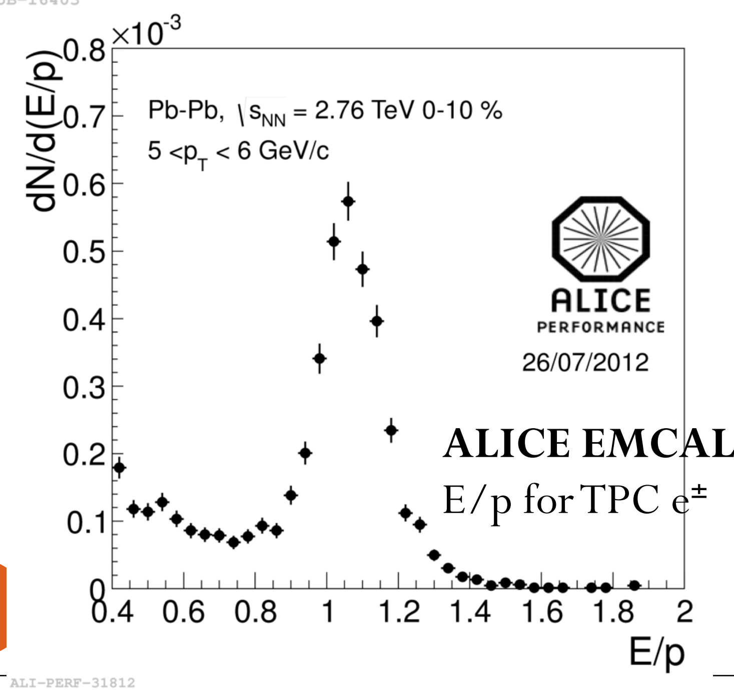


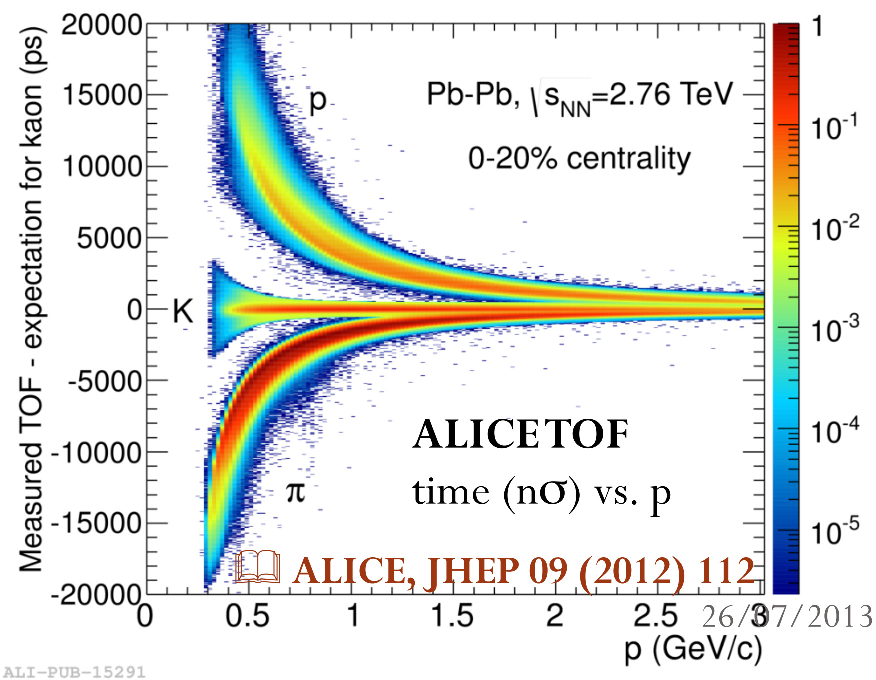
How to: particle identification

📖 ALICE, arXiv:1205.5423





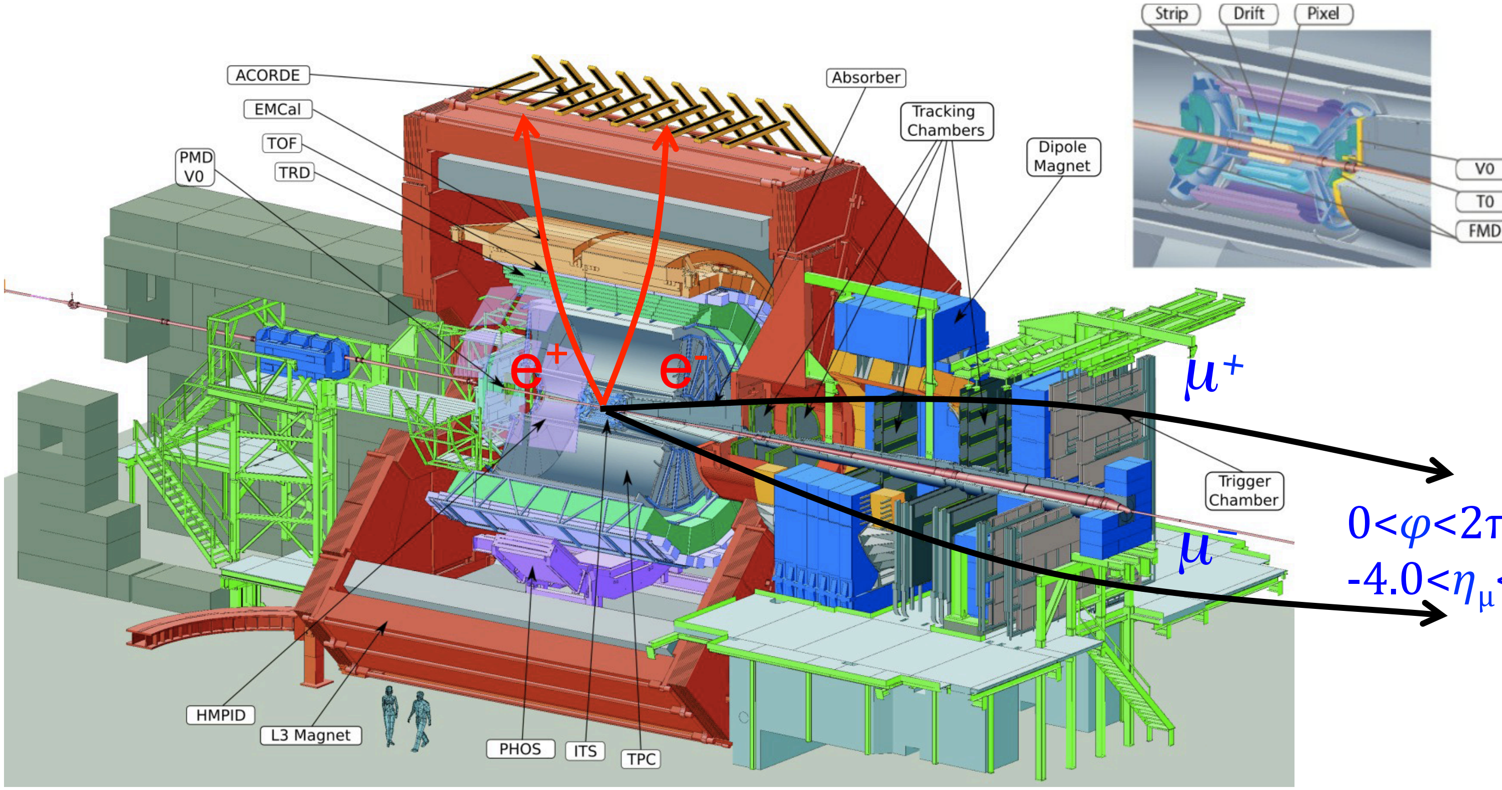




📖 ALICE, JHEP 09 (2012) 112

Quarkonia with ALICE

$0<\varphi<2\pi$
$|\eta_e| < 0.9$

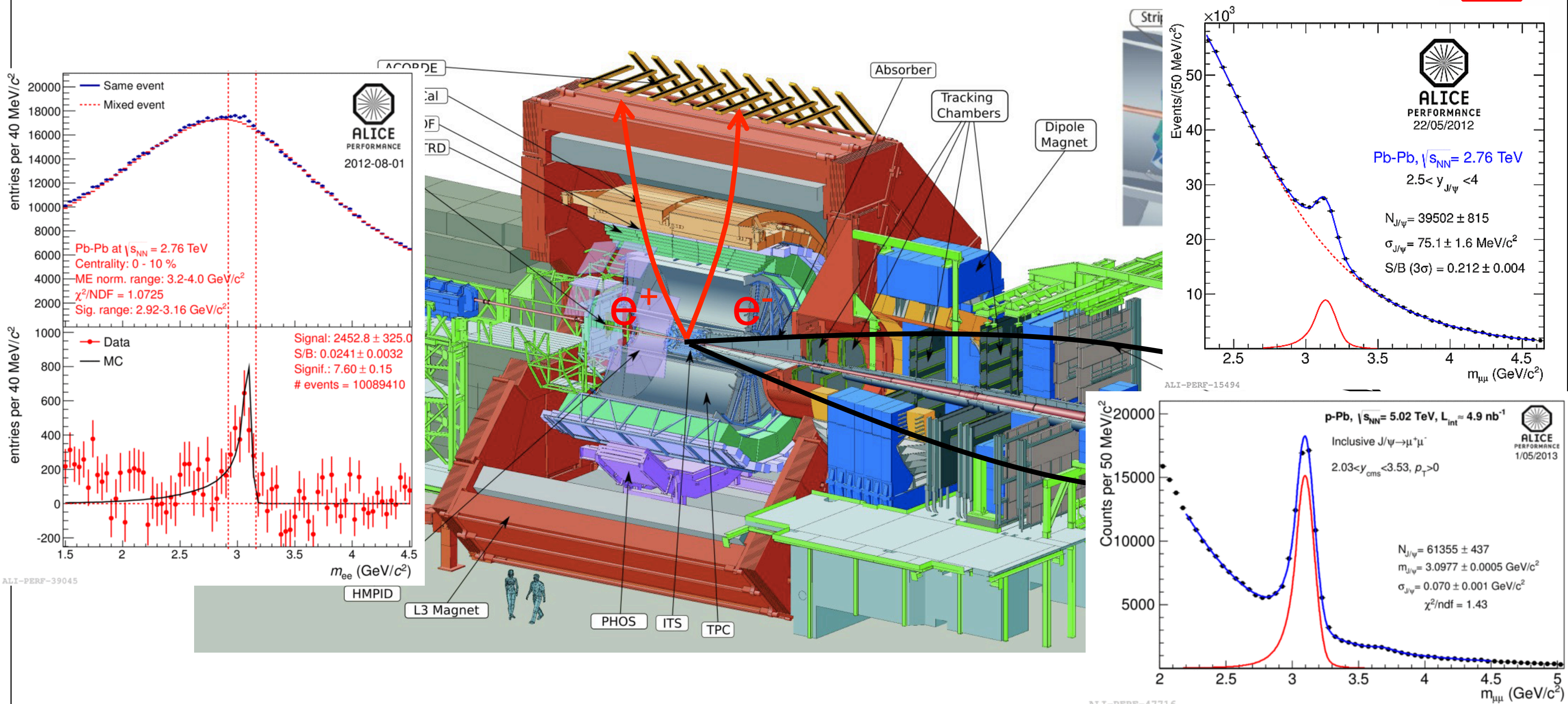


$0<\varphi<2\pi$
$-4.0<\eta_\mu<-2.5$

- measured in two ways in ALICE:
  - ✓ in the central barrel in the e^+e^- channel ($|y|<0.9$)
  - ✓ in the forward spectrometer in the $\mu^+\mu^-$ channel ($2.5<y<4$)

down to $p_T = 0$ in both channels

Quarkonia with ALICE



- measured in two ways in ALICE:
  - ✓ in the central barrel in the e^+e^- channel ($|y|<0.9$)
  - ✓ in the forward spectrometer in the $\mu^+\mu^-$ channel ($2.5<y<4$)

down to p_T =0 in both channels

Nuclear modification factor

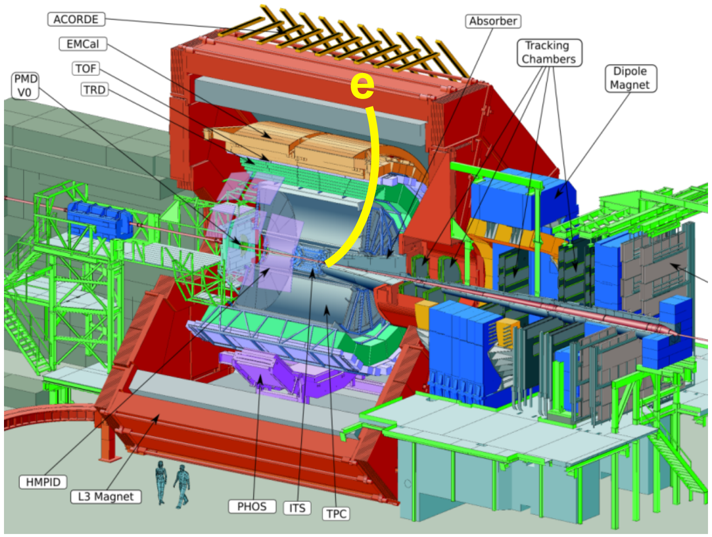
- The nuclear effects on HF production will be presented in terms of the nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

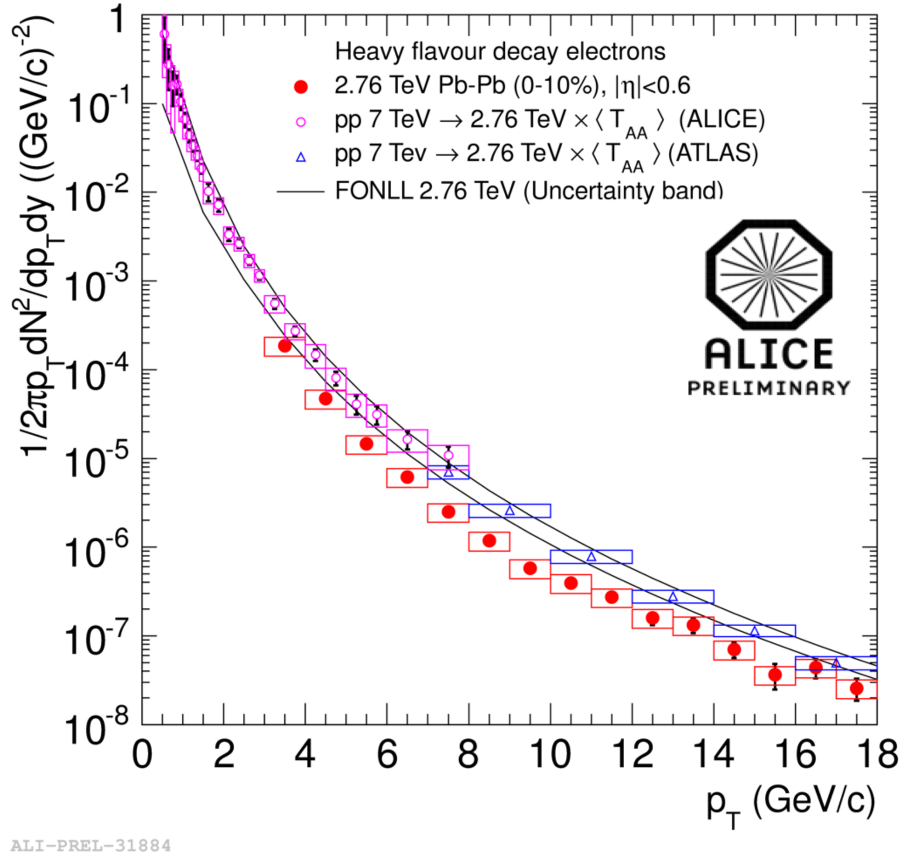
where $<T_{AA}>$ is the average overlap function for the selected centrality class and it is proportional to $<N_{coll}>$

- Inclusive b+c measurements:
  - ✓ Heavy Flavour decay electrons
  - ✓ Heavy Flavour Decay Muons
- Exclusive measurements:
  - ✓ Hadronic Open Charm: study of D mesons through their 2-3 body hadronic decay channels at midrapidity

Heavy flavour decay electrons

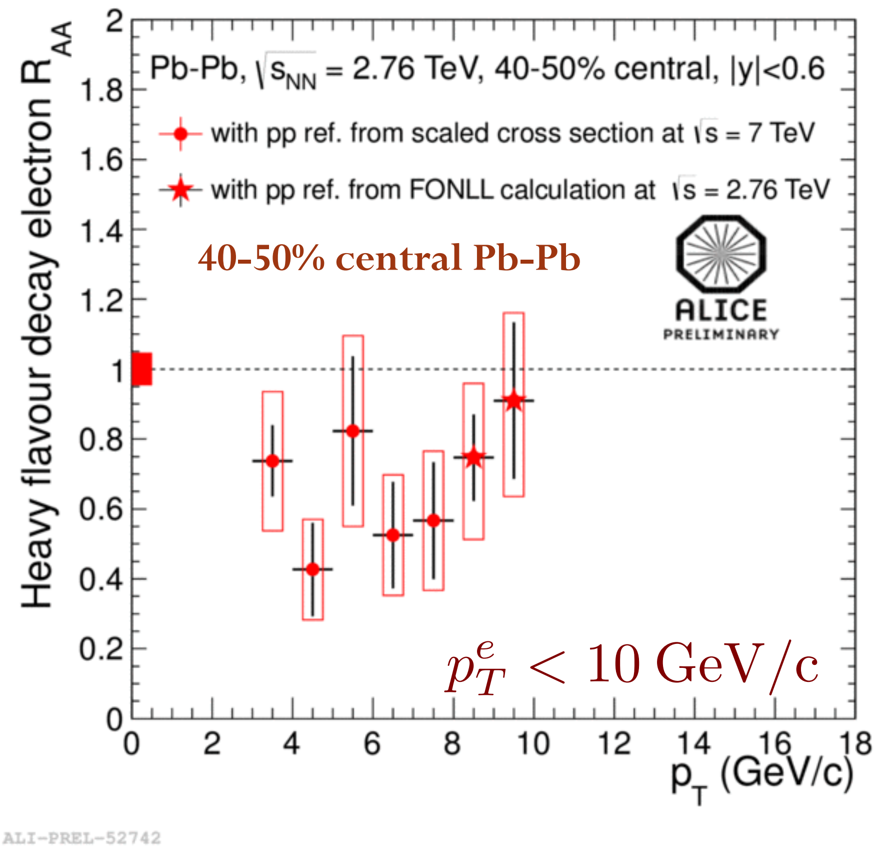


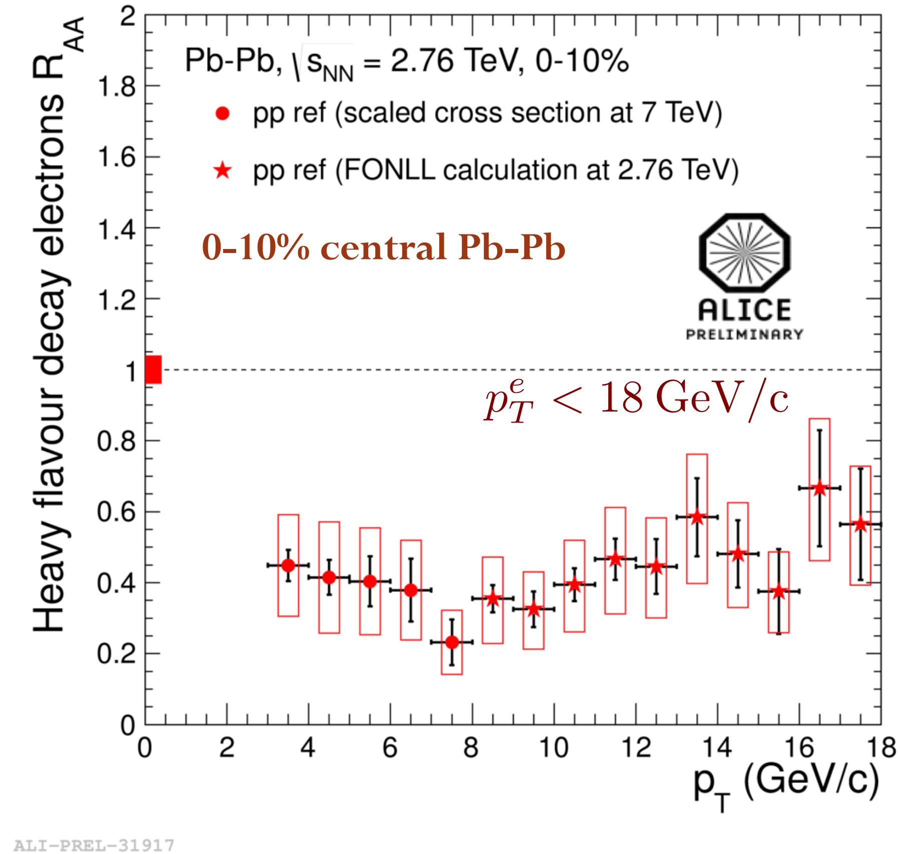
- Inclusive electron spectrum with two different PID analyses: TPC+TOF+TRD and TPC+EMCAL
- Subtract background electrons
  - ✓ Electron pair invariant mass method
  - ✓ Cocktail method
- Inclusive – background → c+b
- pp reference:
  - ✓ 7 TeV pp data scaled to 2.76 TeV for p_T<8 GeV/c
  - ✓ FONLL for p_T>8 GeV/c



- Background sources:
  - ✓ Photon conversions
  - ✓ Dalitz decays of neutral mesons
  - ✓ Quarkonia decays

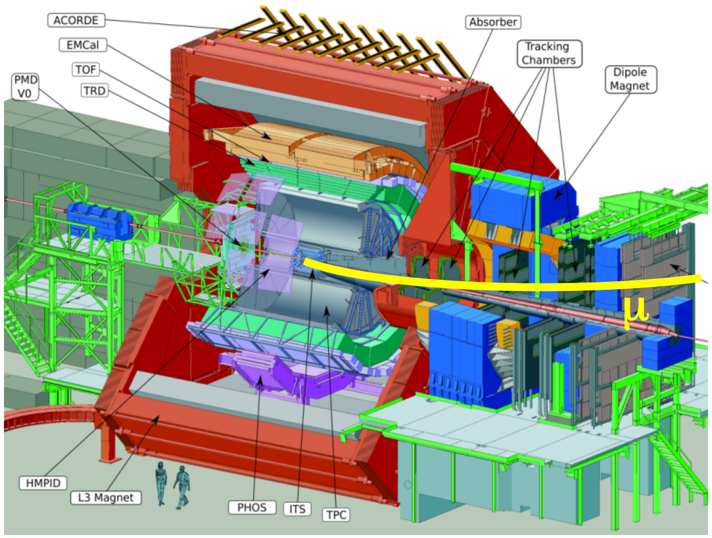
Heavy flavour decay electrons

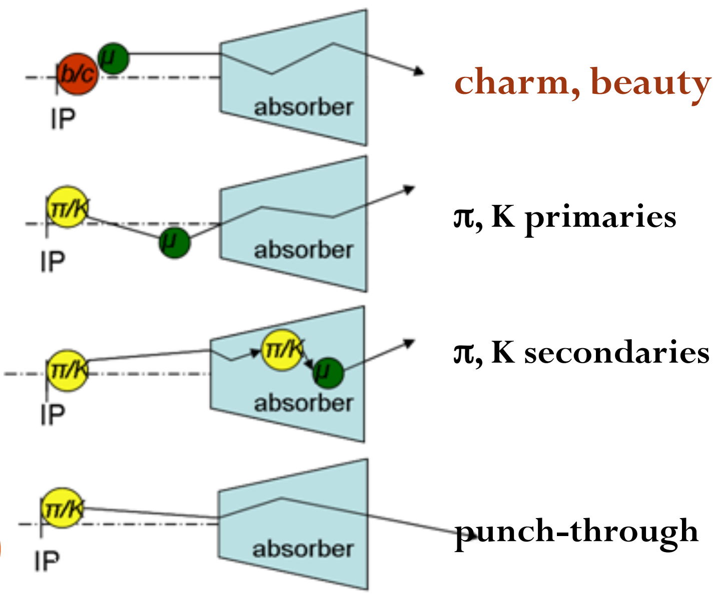




- Clear suppression (R_{AA}~0.4) of central HF electrons
- Reduced suppression for semi-central Pb-Pb collisions (R_{AA}~0.6)

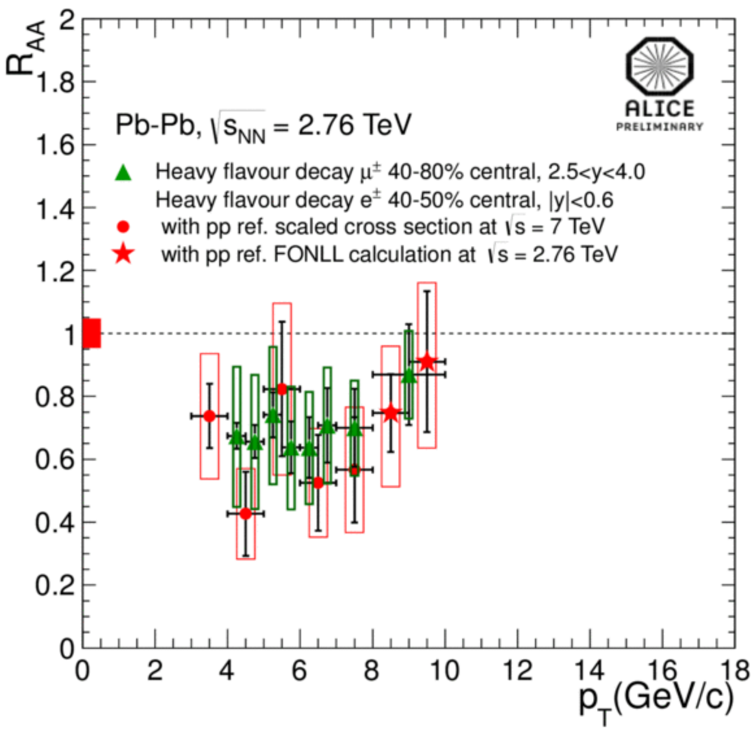
Heavy flavour decay muons at forward rapidity



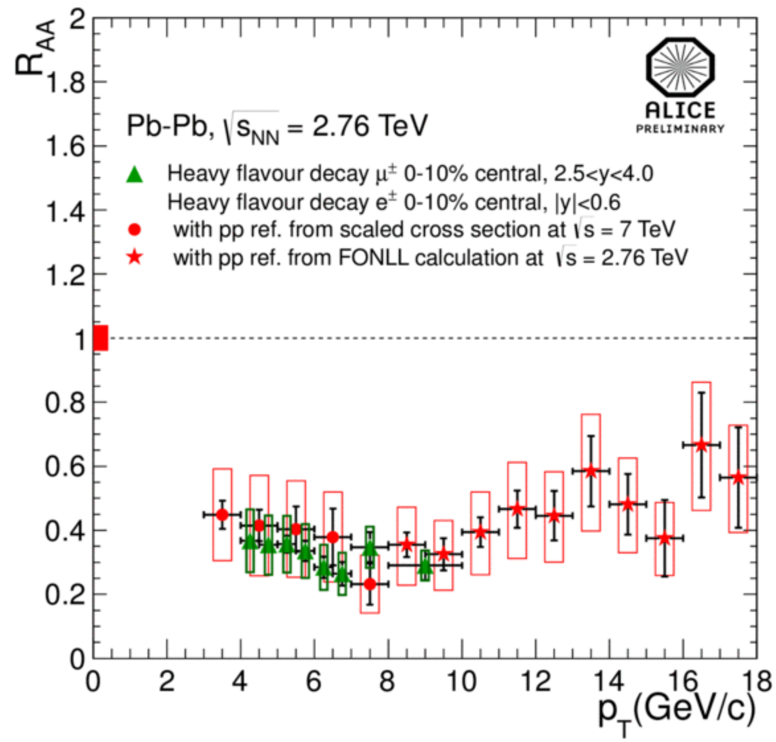


- Single muons at forward rapidity ($-4<\eta<-2.5$)
  - ✓ Punch-through hadrons rejected by requiring match with trigger chambers
  - ✓ Residual beam induced background and fake tracks are removed using the correlation between the momentum and the DCA with the interaction point
  - ✓ Subtract background μ from π/K decay
    - Extrapolated from mid-rapidity measurement with an hypothesis on the rapidity dependence of R_{AA}
- pp reference measured at 2.76 TeV

Heavy flavour decay muons at forward rapidity



ALI-DER-53851

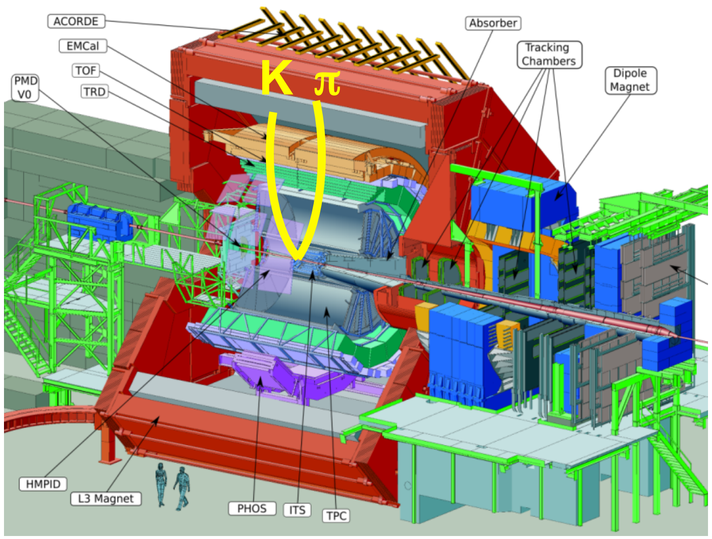


ALI-DER-36791

- The suppression pattern for HF muons at forward rapidity (2.5<y<4) is compatible with electron results at central rapidity

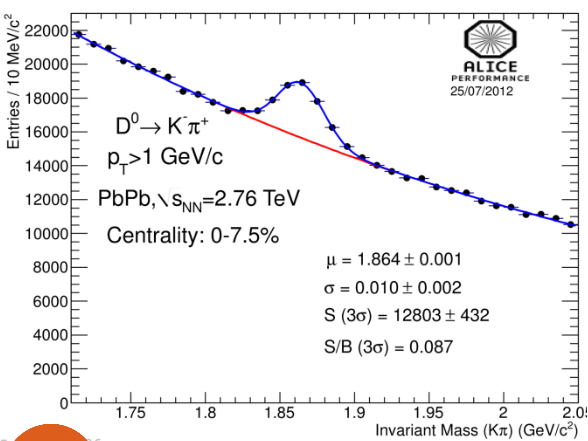
📖 HF muons: ALICE, PRL 109 (2012) 112301

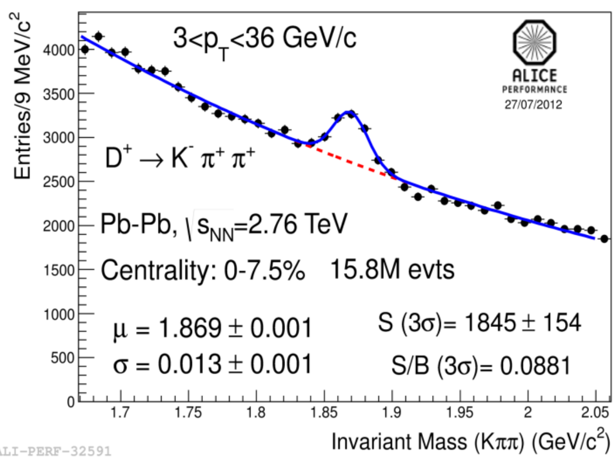
D mesons

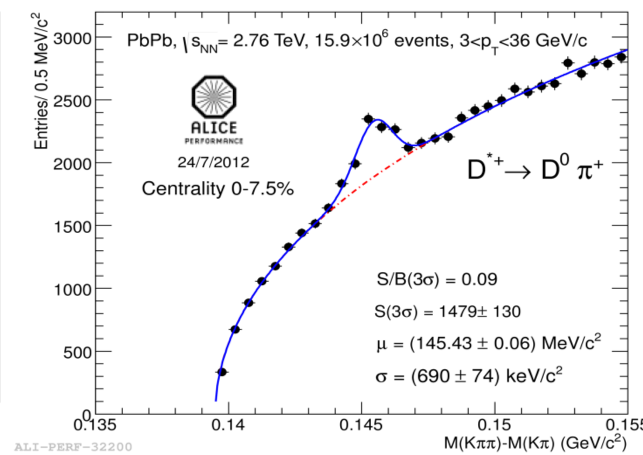


- Analysis strategy
  - ✓ Invariant mass analysis of fully reconstructed decay topologies displaced from the primary vertex
- Feed down from B (10-15 % after cuts) subtracted using pQCD (FONLL) predictions
  - ✓ Plus in PbPb hypothesis on R_{AA} of D from B

$D^0 \rightarrow K^-\pi^+$ | $D^+ \rightarrow K^-\pi^+\pi^+$ | $D^{*+} \rightarrow D^0\pi^+$

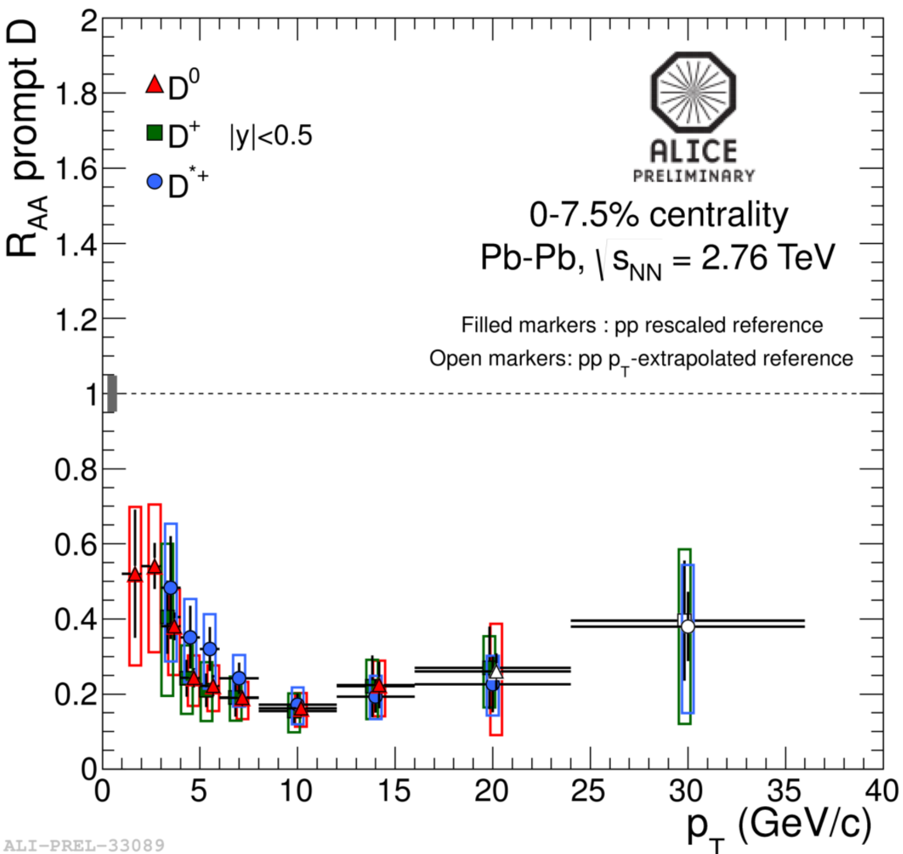






D meson R_{AA}

- pp reference from measured D^0, D^+ and D* p_T-differential cross sections at 7 TeV scaled to 2.76 TeV with FONLL
  - ✓ Extrapolated assuming FONLL p_T shape to highest p_T bins not measured in pp

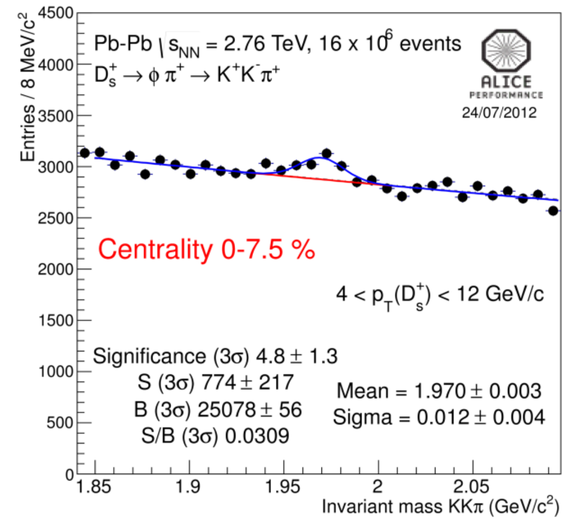


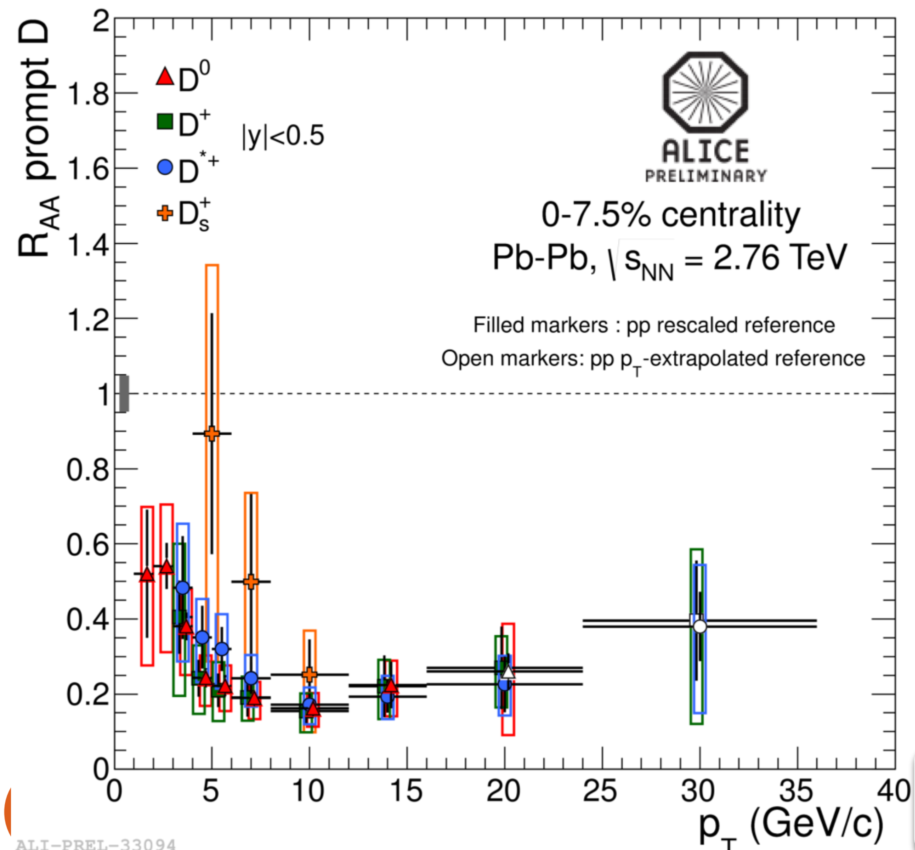
- D^0, D^+ and D^{*+} R_{AA} agree within uncertainties

Strong suppression of prompt D mesons in central collisions
→ up to a factor of 5 for $p_T \approx 10$ GeV/c

Charm + strange: D_s^+

- First measurement of D_s^+ in AA collisions
- Expectation: enhancement of the strange/non-strange D meson yield at intermediate p_T if charm hadronizes via recombination in the medium

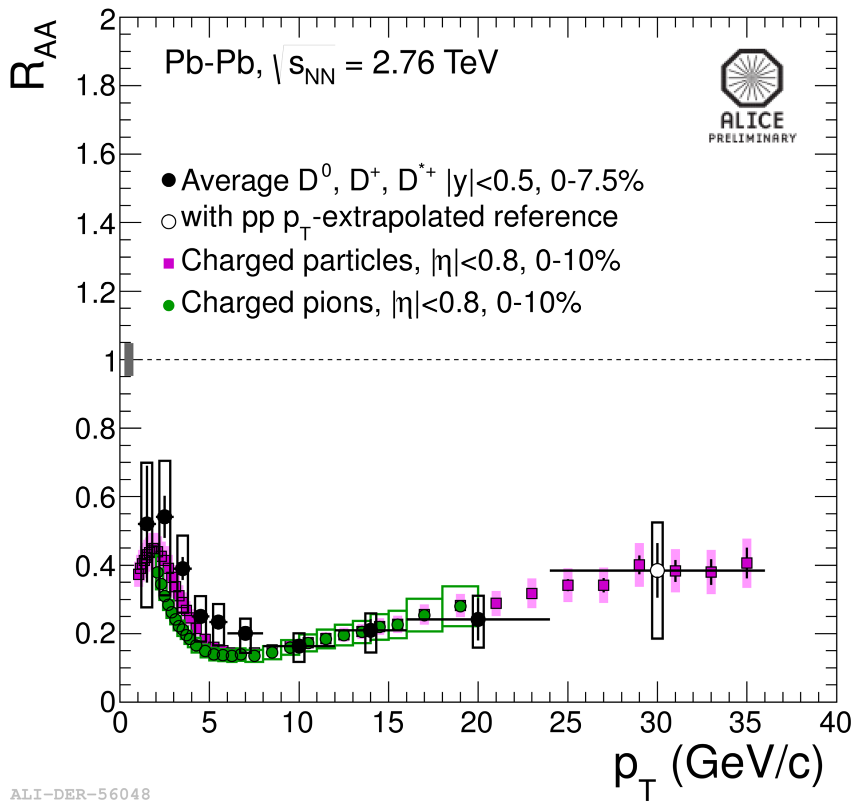


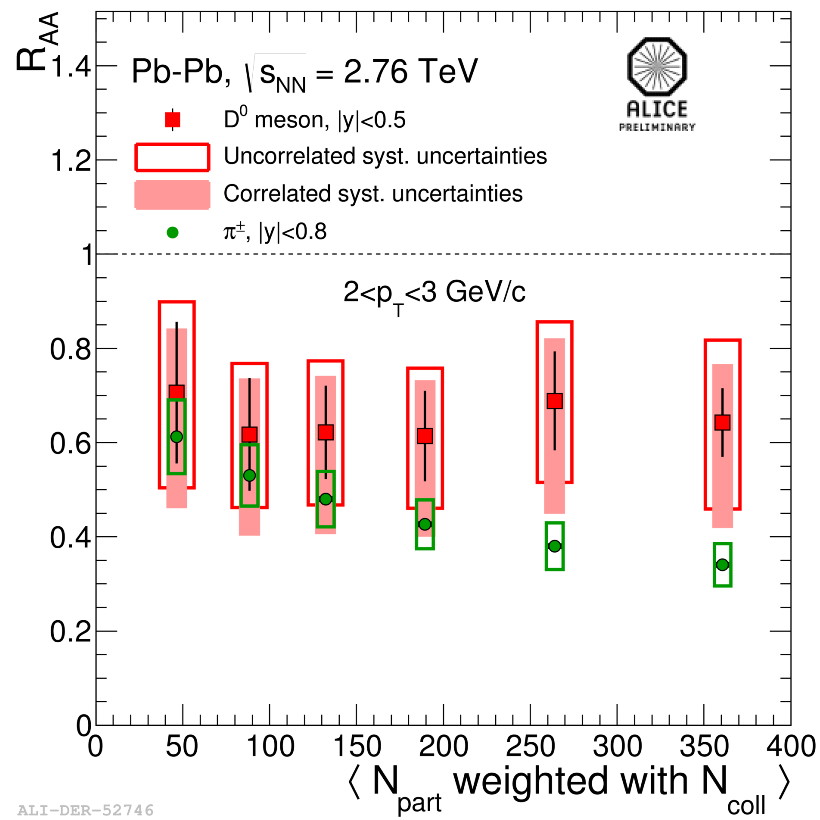


- Strong D_s^+ suppression (similar as D^0, D^+ and D^{*+}) for 8< p_T <12 GeV/C
- R_{AA} seems to increase (=less suppression) at low p_T
  - ✓ Current data do not allow a conclusive comparison to other D mesons within uncertainties

📖 Kuznetsova, Rafelski, EPJ C 51 (2007) 113
📖 He, Fries, Rapp, Phys. Rev. Lett. 110 (2013) 112301

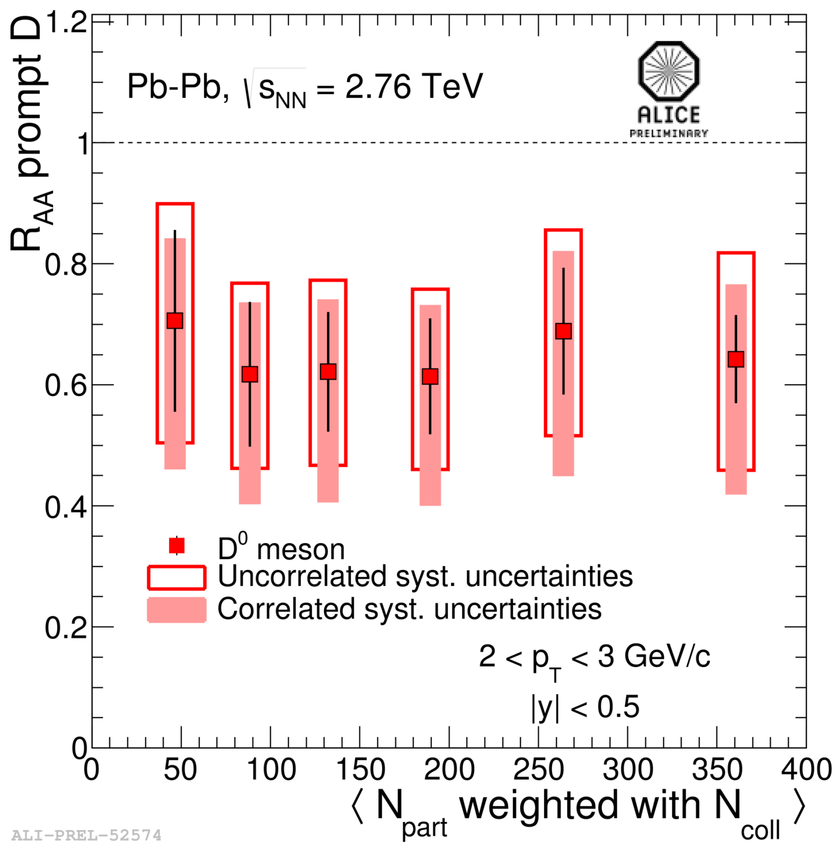
R_{AA} of D mesons vs R_{AA} of light hadrons

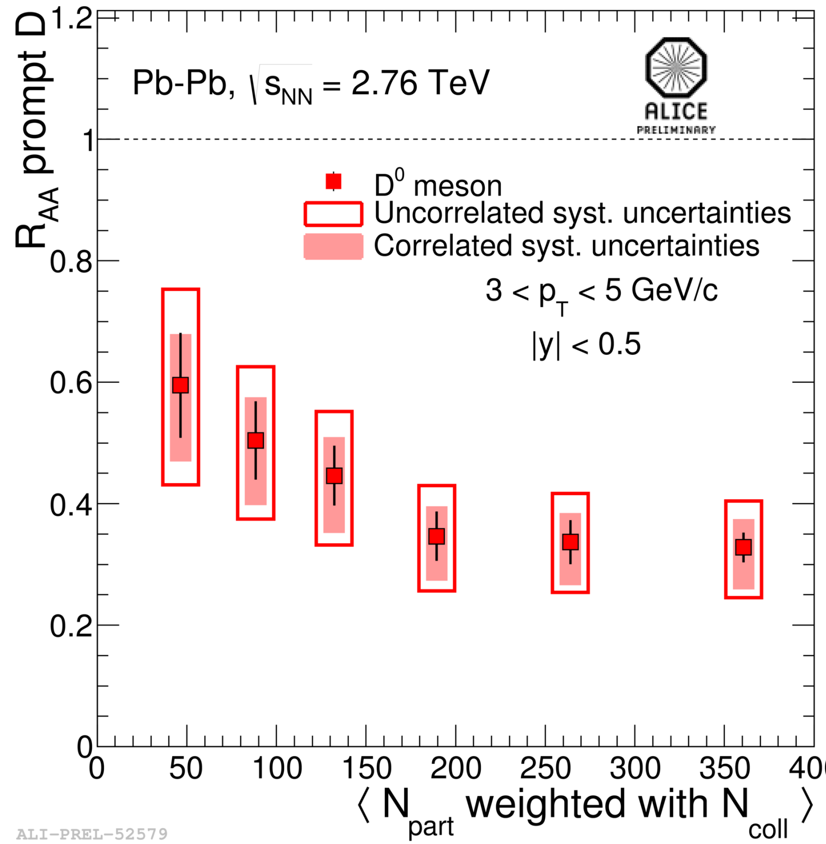




- Similar trend vs. p_T for D, charged particles and $\pi^{\pm}$
  - ✓ Maybe a hint of $R_{AA}^{D} > R_{AA}^{\pi}$ at low p_T
- More statistics needed to draw conclusions on the expected difference between D and π suppression: $R_{AA}(D)>R_{AA}(\pi)$ from mass hierarchy and colour charge dependence of energy loss

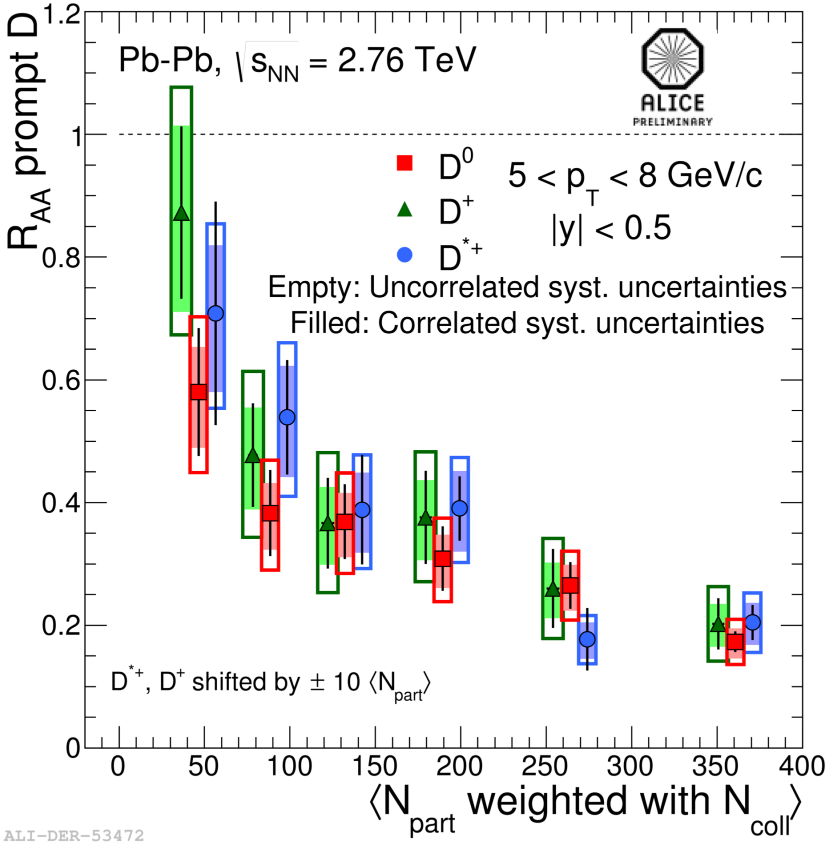
R_{AA} vs centrality

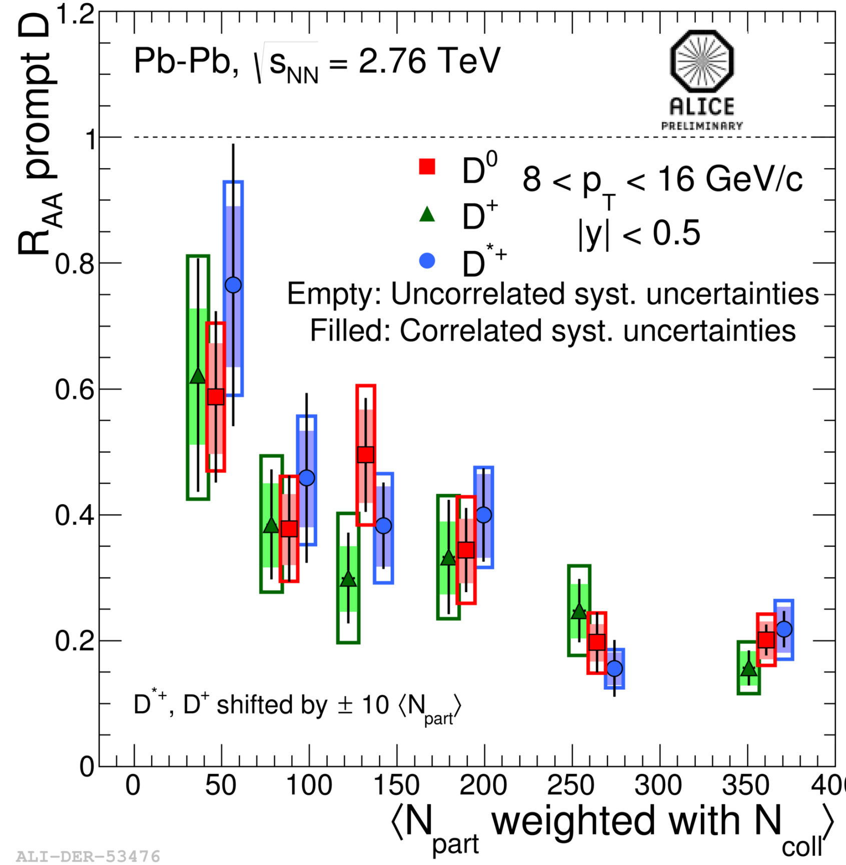




- Different suppression trend of D^0 mesons vs N_{part} in 2-3 and 3-5 GeV/c p_T classes
- Systematic errors:
  - ✓ correlated in centrality classes: normalization, pp reference cross section
  - ✓ uncorrelated: B feed-down might depend on centrality at low p_T

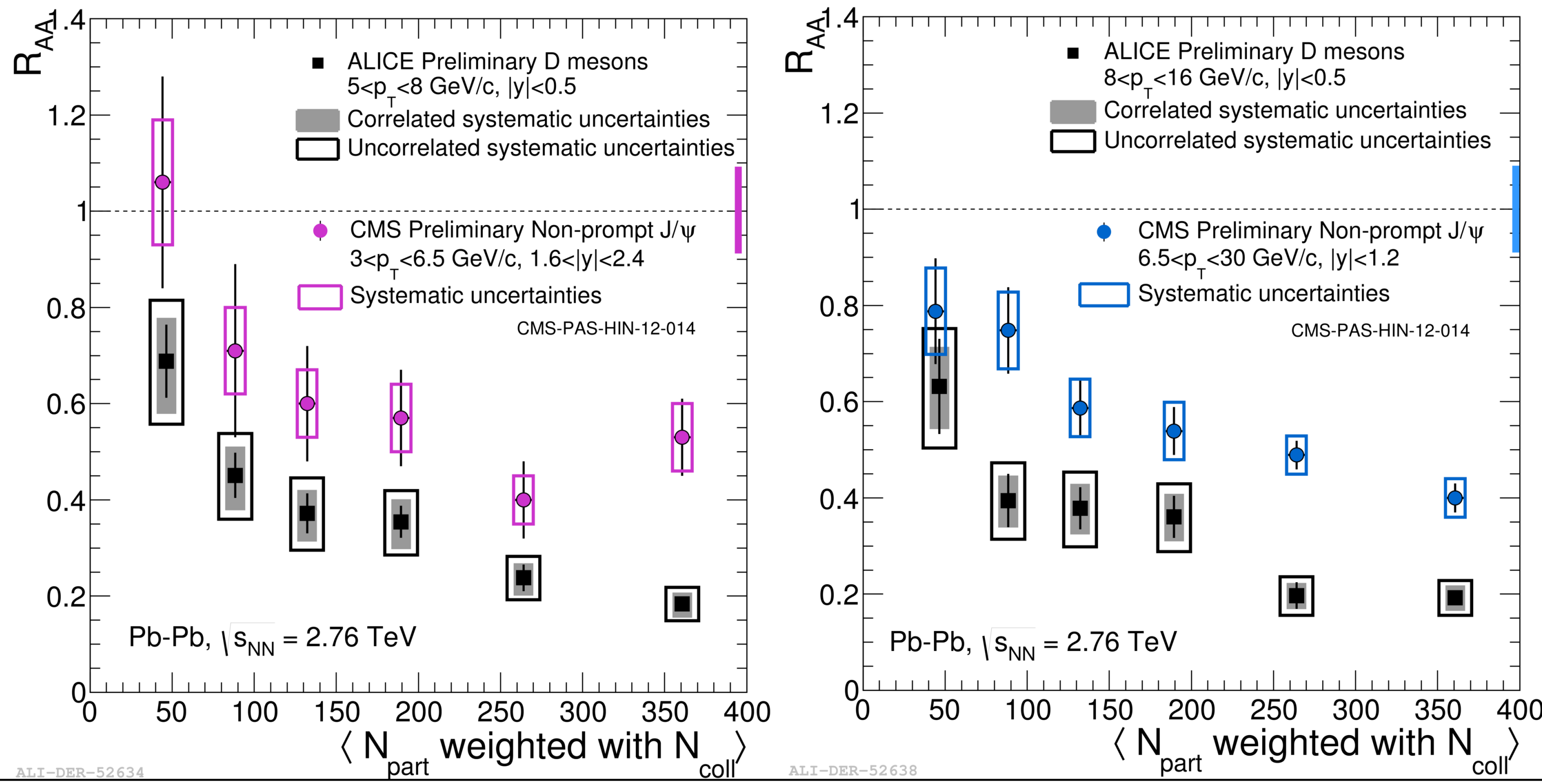
R_{AA} vs centrality





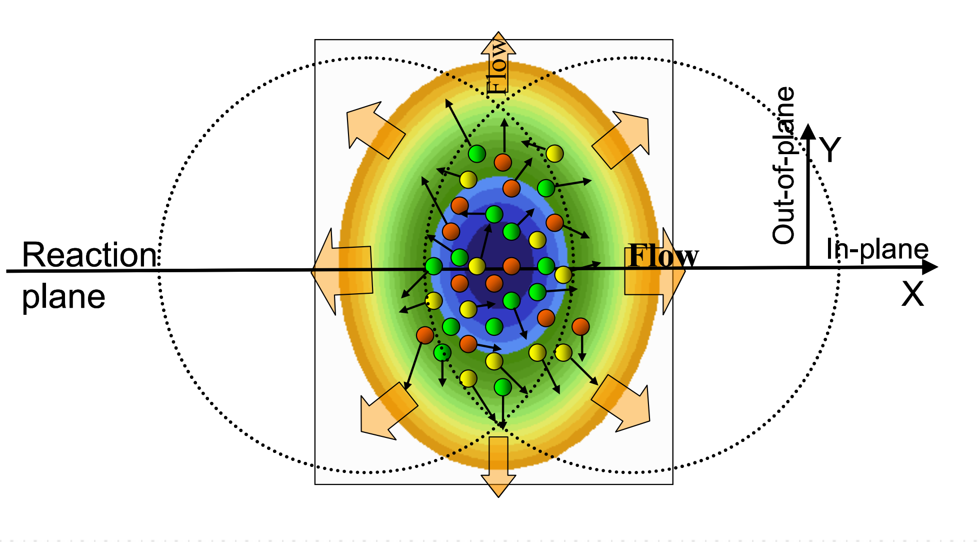
- Suppression of D mesons increases with centrality in 5-8 and 8-16 GeV/c p_T classes

Comparison with non-prompt J/ψ



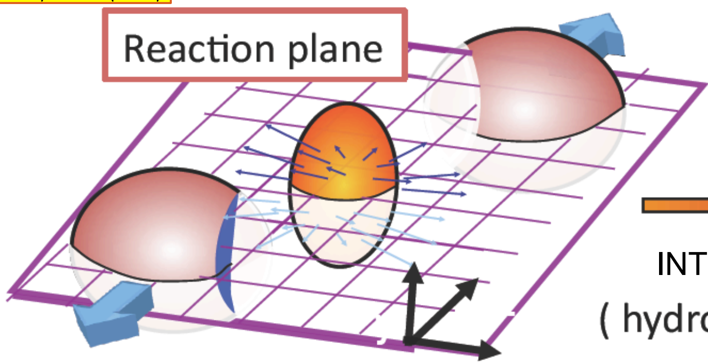
- p_T ranges chosen to have similar kinematics for D and B mesons, parents of non prompt J/ψ, though with different y ranges
  - ✓ $<p_T>^D \sim 10.5$ GeV/c
  - ✓ $<p_T>^B \sim 11.5$ GeV/c
- Indication of a smaller energy loss for beauty w.r.t. charm

Azimuthal anisotropy



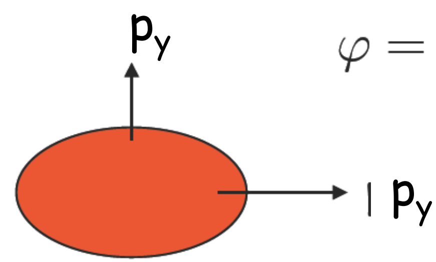
Anisotropic transverse flow

$$\epsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



INTERACTIONS

(hydrodynamics?)



$$\varphi = \arctan \frac{p_y}{px}$$

"elliptic" flow

$$v_2 = \frac{\langle p_y^2 \rangle - \langle p_x^2 \rangle}{\langle p_y^2 \rangle + \langle p_x^2 \rangle}$$

Initial spatial asymmetry → Final momentum asymmetry → Azimuthal distribution

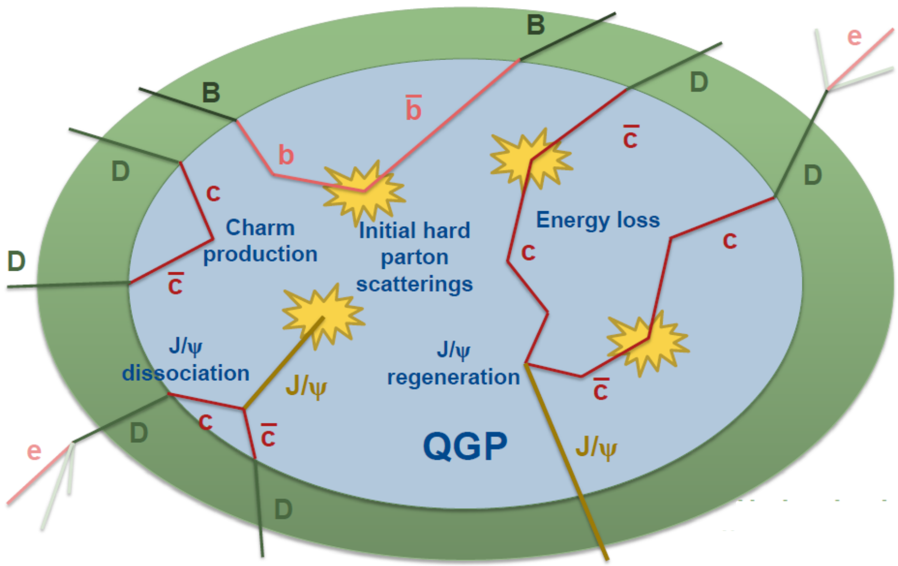
$$\frac{dN}{d(\varphi - \psi_{RP})} \propto 1 + 2\sum_{n=1} v_n \cos(n[\varphi - \psi_{RP}])$$

$$v_n = \langle \cos(n[\varphi - \psi_{RP}]) \rangle$$

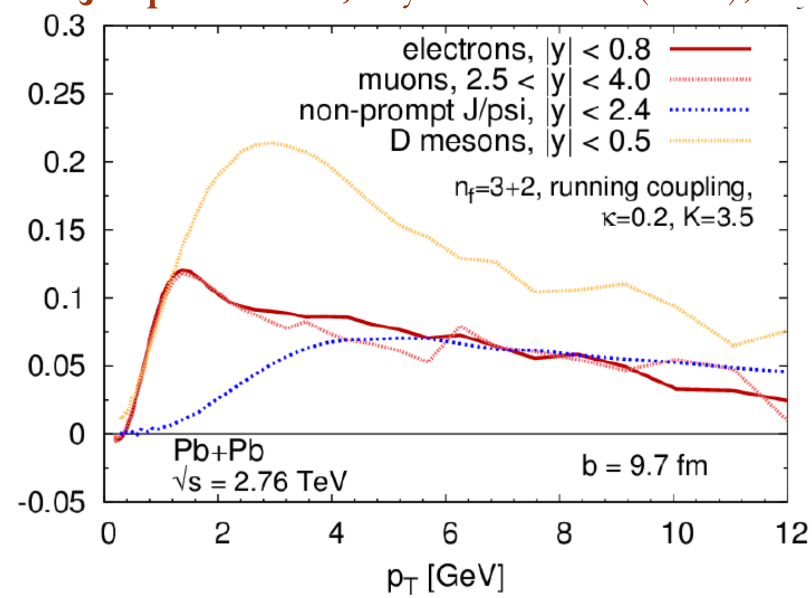
- Fourier decomposition of azimuthal distributions w.r.t. the initial state spatial plane of symmetry
- Observables: Fourier coefficients
- Azimuthal asymmetry is expressed by the second Fourier coefficient v_2 (elliptic flow)

Heavy flavour v_2

- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
  - ✓ $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium
  - ✓ Transported through the full system evolution



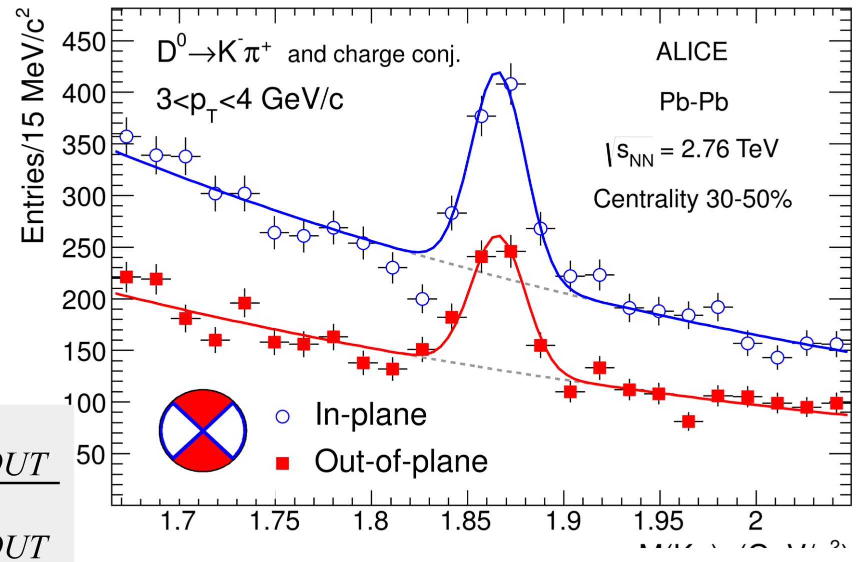
📖 **J. Uphoff et al.,** Phys. Lett. B **717** (2012), 430

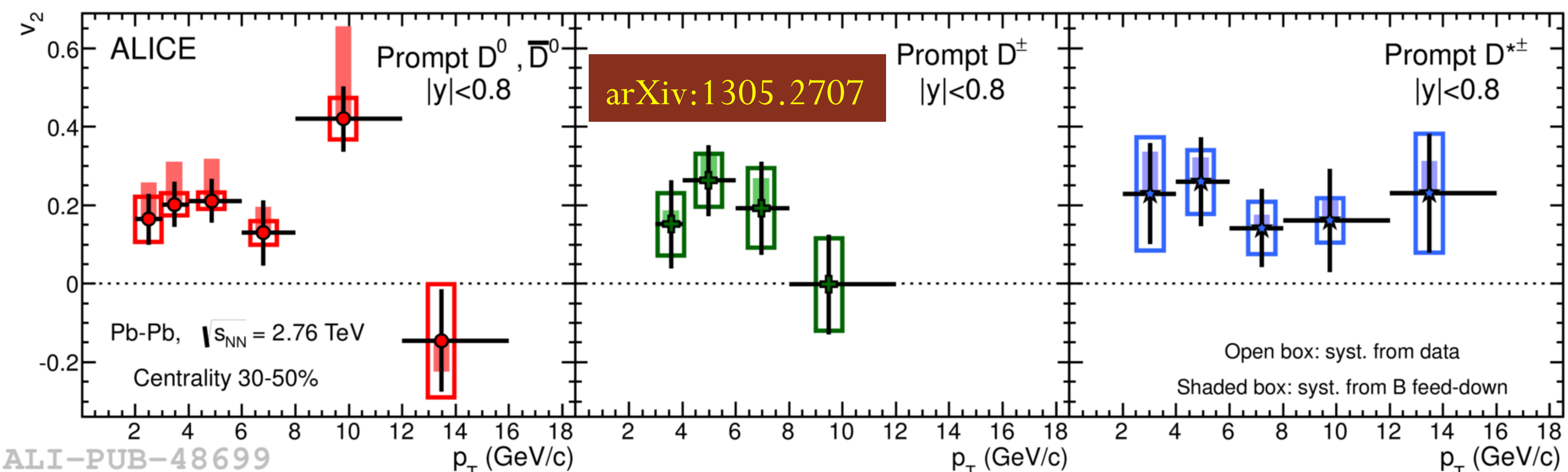


v_2 for D mesons

- First direct measurement of D anisotropy in heavy-ion collisions
- Yield extracted from invariant mass spectra of Kπ candidates in 2 bins of azimuthal angle relative to the event plane

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$

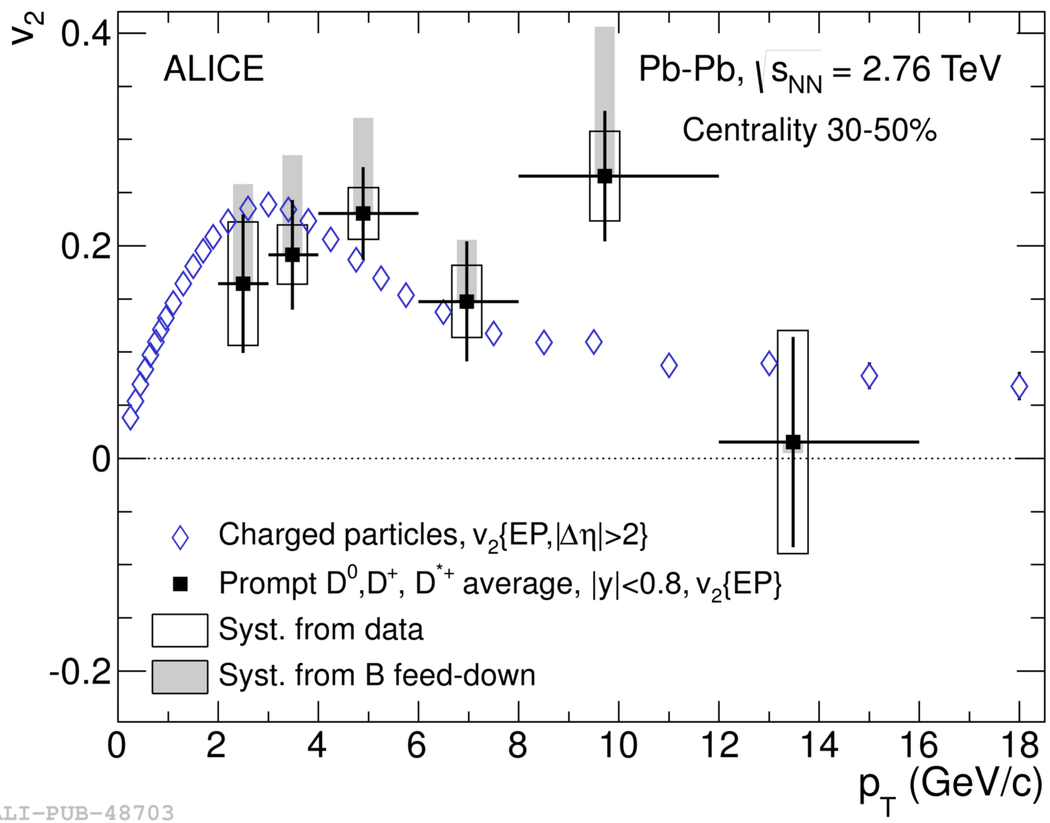




arXiv:1305.2707

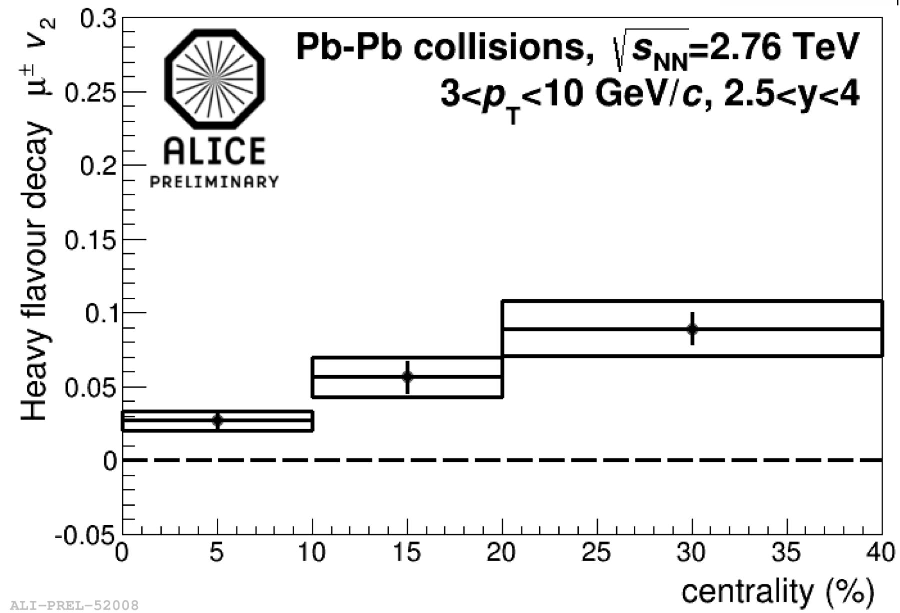
v_2 for D mesons

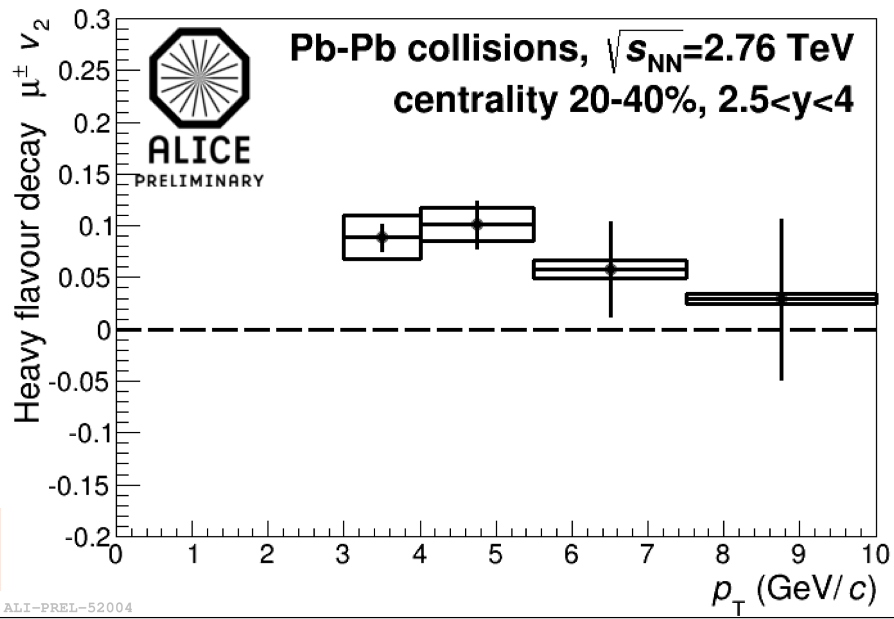
- v2 consistent for D^0,D^+ and D^{*+}
- $v_2>0$ at low p_T
  - ✓ ~5σ effect for $2<p_T<6$ GeV/c
- D meson v_2 comparable to that of charged particles
  - ✓ hint for collective motion of charm quarks at low p_T

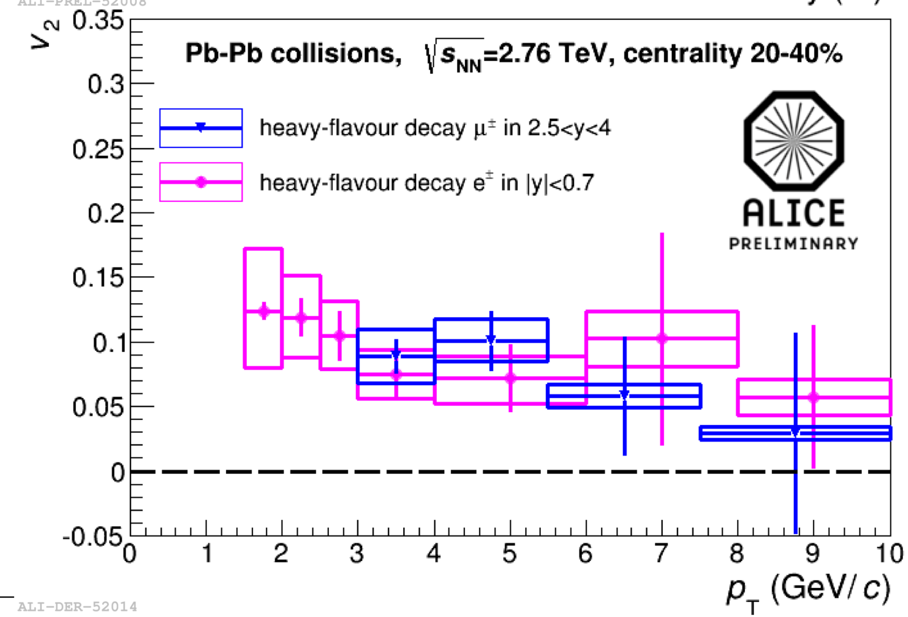


v_2 for HF decay leptons (e/μ)

- Elliptic flow of muons from HF decays measured in 2.5<y<4
- Positive v_2 (3σ) observed for centrality class 20-40%
- similar results for heavy flavour decay electrons at mid rapidity







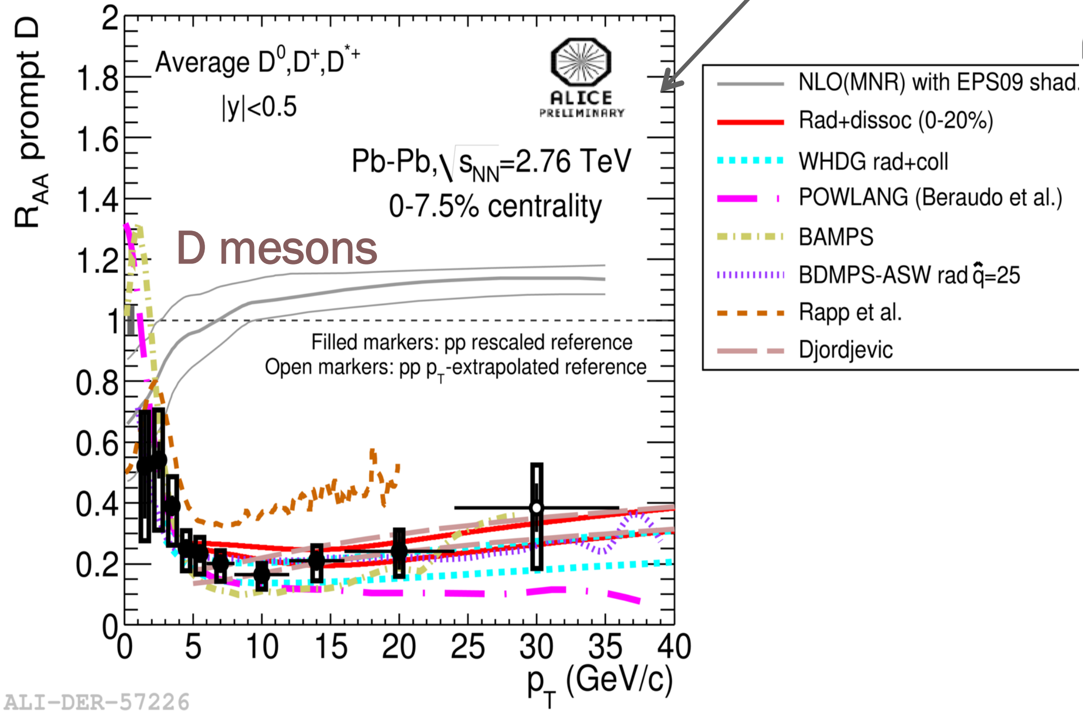
Data and models

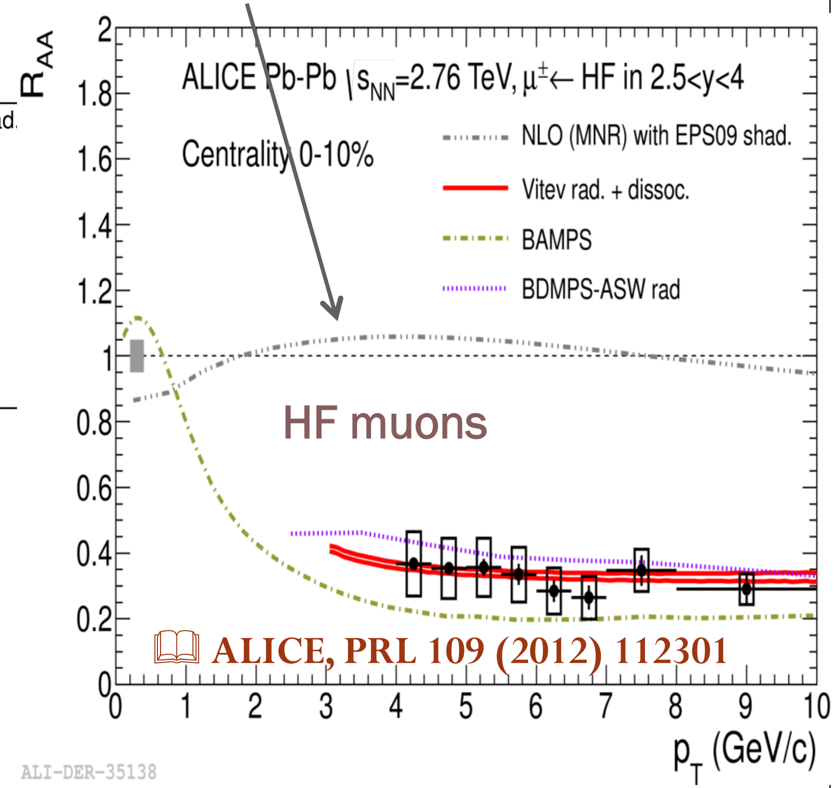
Model references

- **BDMPS-ASW:** N.Armesto, A.Dainese, C. A.Salgado and U. A. Wiedemann Phys. Rev D**71** (2005) 054027;
- **Radiative en. loss+in medium dissociation:** R.Sharma , I.Vitev and B.W.Zhang Phys. Rev. C**80** (2009) 054902; Y. He , I.Vitev and B.W. Zhang Physics Letters B **713** (2012) 224;
- **POWLANG:** W.M.Alberico, A.Beraudo, A.De Pace, A.Molinari, M.Monteno, M.Nardi, and F. Prino Eur. Phy.s J. C**71** (2011) 1666
- **UrQMD:** T. Lang, H. van Hees, J. Steinheimer and M.Bleicher arXiv: 1211.6912, J. Phys. Conf. Ser. 426, 012032 (2013)
- **WHDG:** W.A.Horowitz and M.Gyulassy J. Phys. G **38** (2011) 124114
- **BAMPS:** O.Fochler, J.Uphoff, Z.Xu and C.Greiner J. Phys. G **38** (2011) 124152, J.Uphoff, O.Fochler, Z.Xu and C.Greiner Phys. Lett. B **717** (2012), 430
- **TAMU:** M. He, R.J. Fries and R.Rapp Phys. Rev. C 86, 014903 (2012)
- **Coll+Landau-Pomeranchuk-Migdal effect** P. B. Gossiaux, R. Bierkandt and J. Aichelin, Phys. Rev. C79 (2009) 044906; P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. G37 (2010) 094019
- **Djordjevic:** M.Djordjevic and M.Djordjevic arXiv:1307.4098

Comparison with models: R_{AA}

Little shadowing at high p_T
→ suppression is a hot matter effect
→ need pPb data to quantify initial state effect

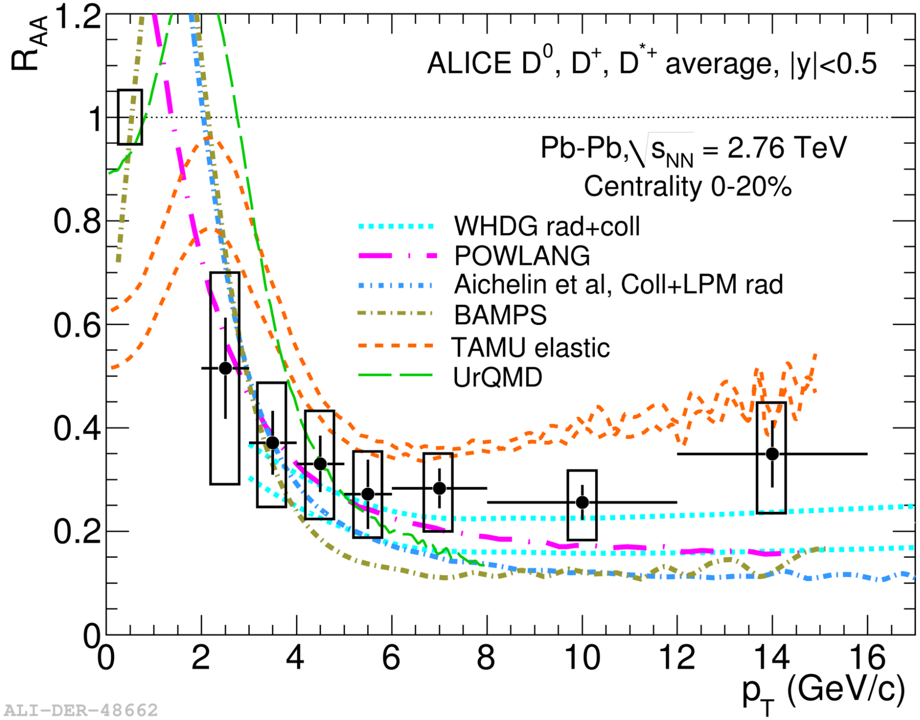




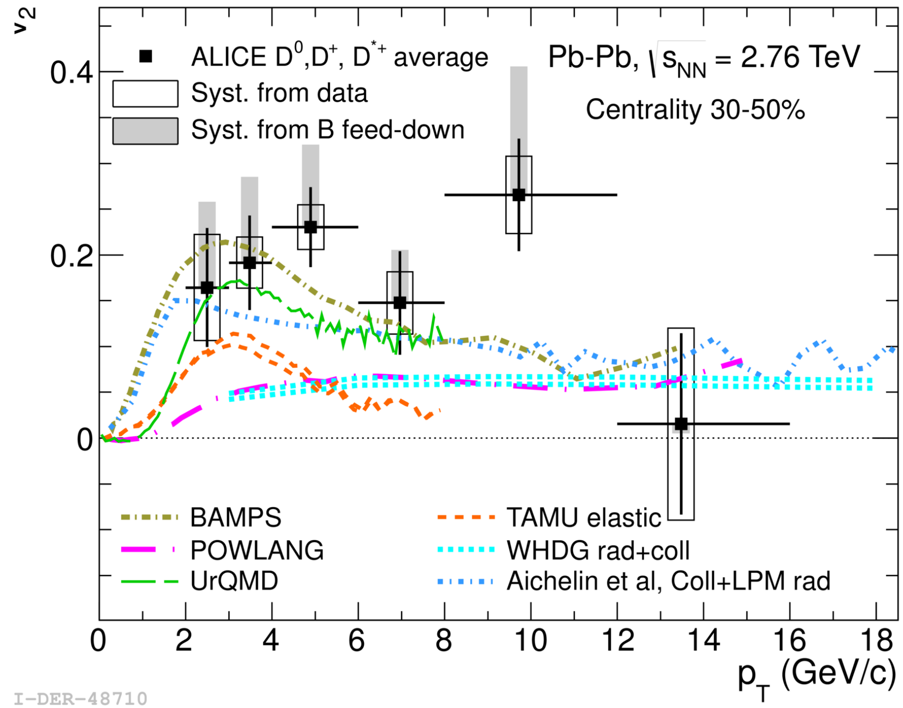
- Models of in-medium parton energy loss can describe reasonably well heavy flavour decay muons at forward rapidity and D mesons at midrapidity

R_{AA} and v_2 for D mesons

JHEP 1209 (2012) 112

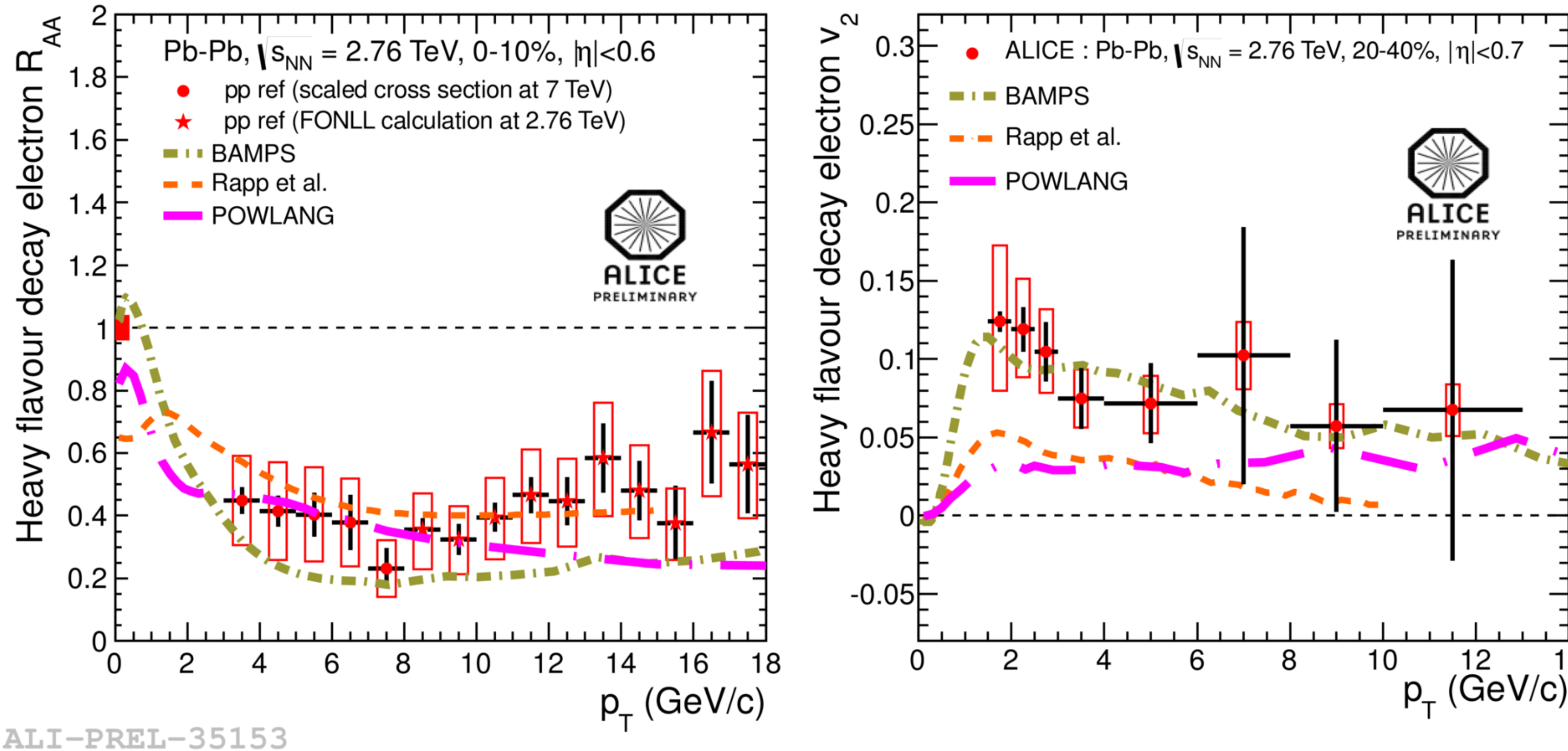


arXiv:1305.2707



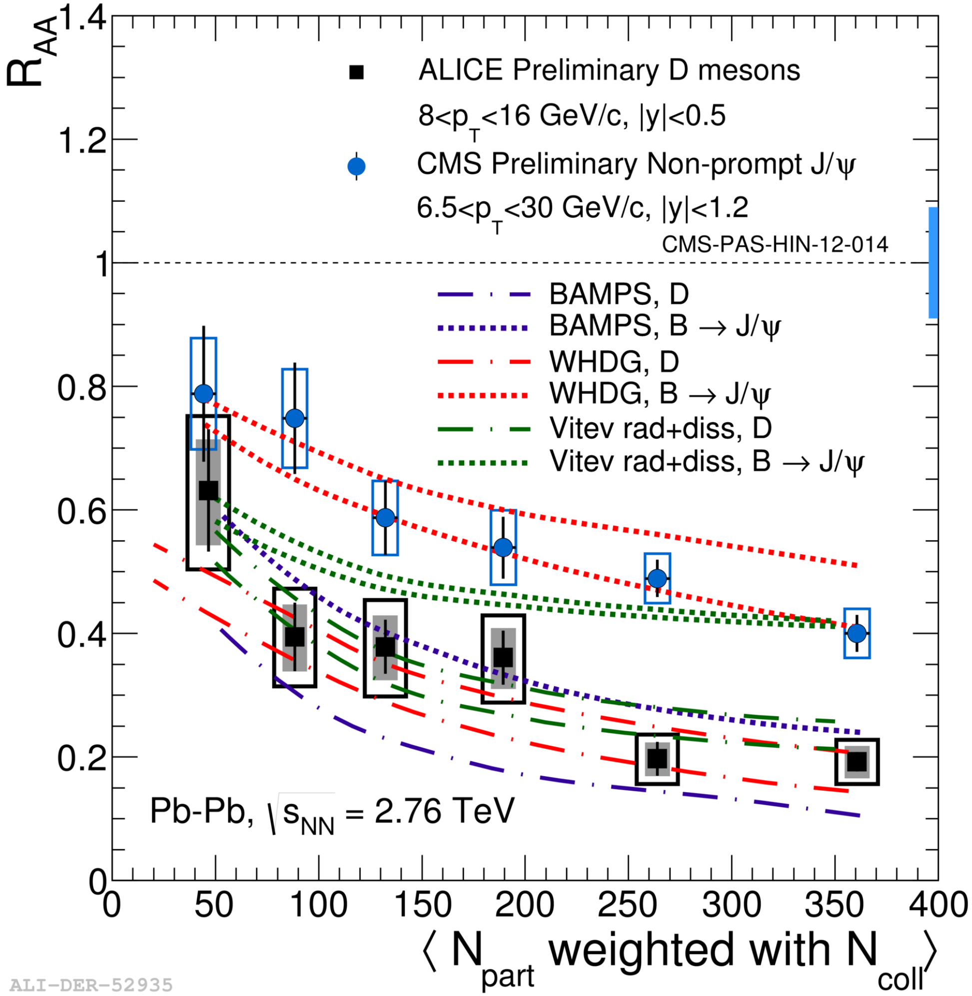
- Challenge: successful models should provide a simultaneous description of D meson R_{AA} and v_2
- Data: a reduction of uncertainties (both statistical and systematic) is needed

R_{AA} and v_2 for Heavy Flavour electrons



- Challenge: successful models should provide a simultaneous description of HF electrons R_{AA} and v_2
- Data: a reduction of uncertainties (both statistical and systematic) is needed

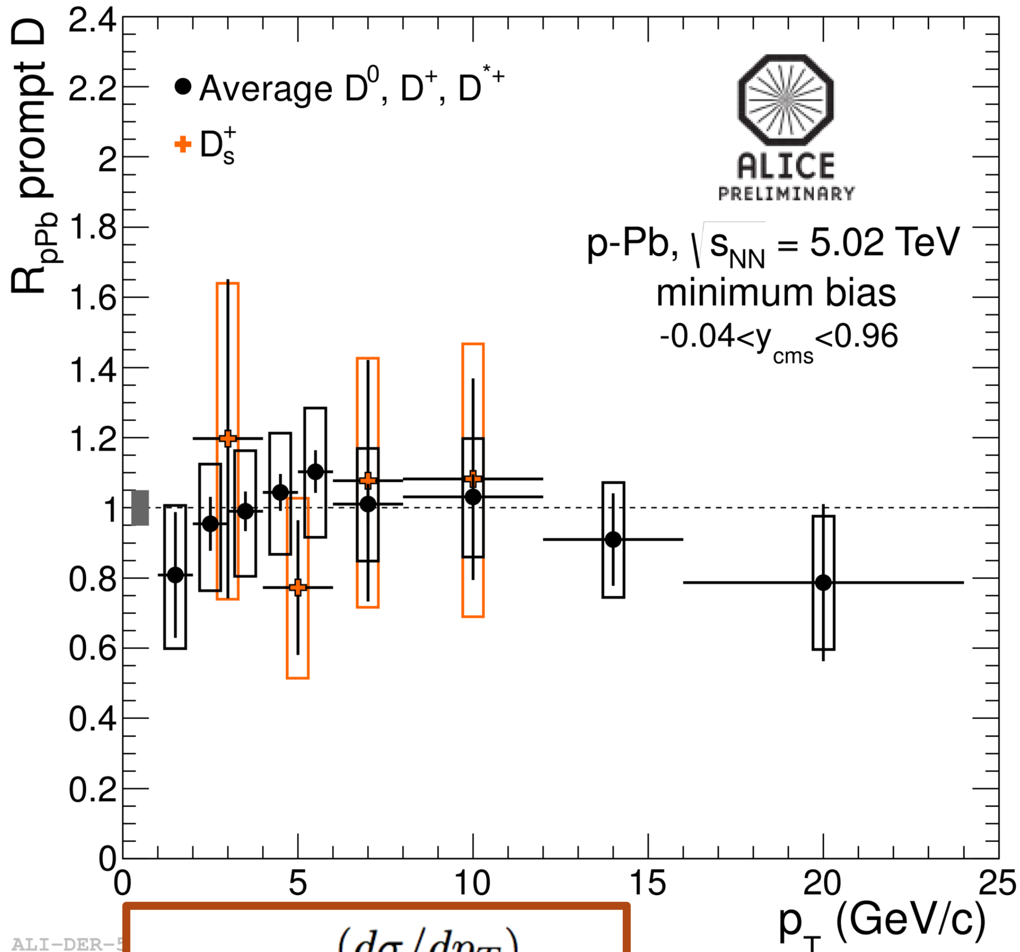
Comparison with models: centrality dependence



- Testing the mass hierarchy of energy loss: $R_{AA}(c)>R_{AA}(b)$ expected
- p_T ranges chosen to have similar kinematics for D and B mesons measured via J/ψ, though with different y ranges
  - ✓ $\langle p_T\rangle^D \sim 10.5$ GeV/c
  - ✓ $\langle p_T\rangle^B \sim 11.5$ GeV/c
- Indication of a smaller energy loss for beauty w.r.t. charm
- WHDG model: agreement with both D and non prompt J/ψ

p-Pb: cold nuclear matter effects

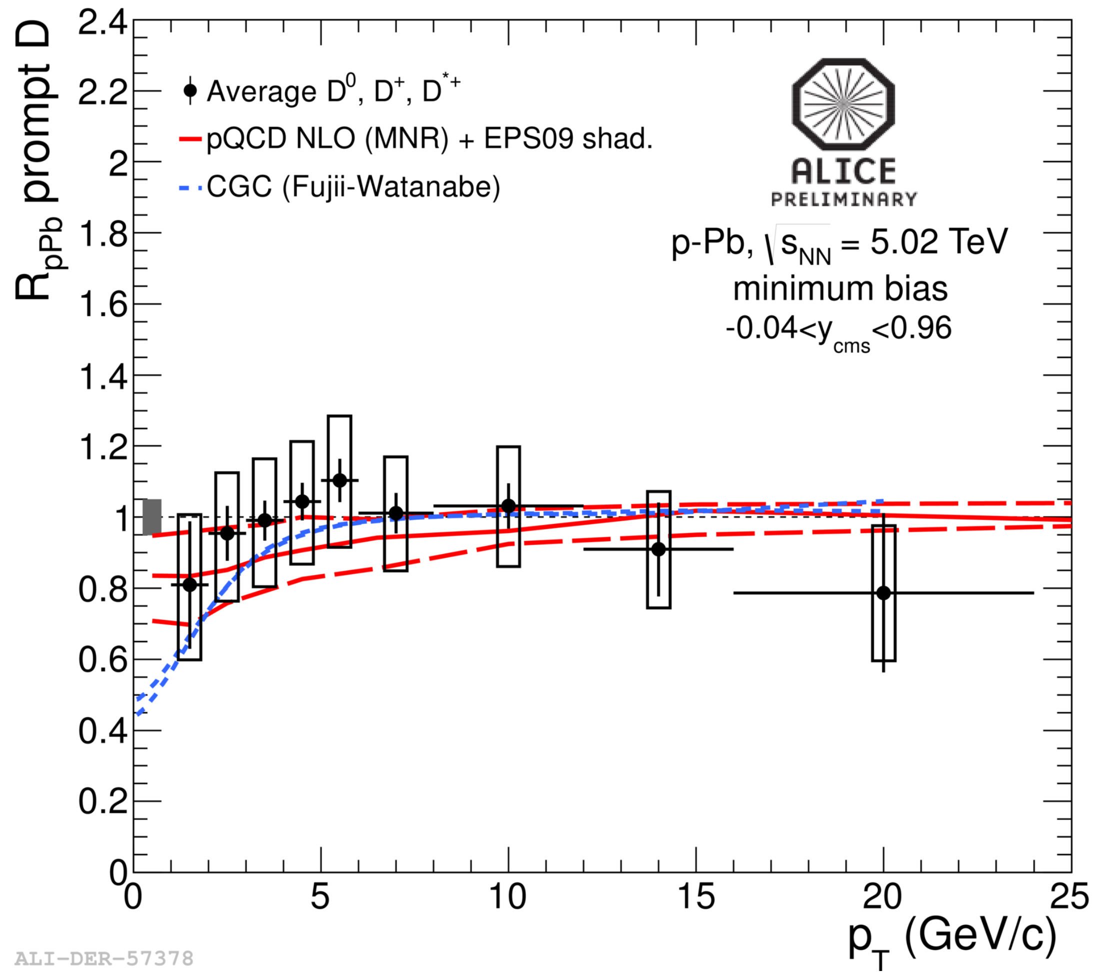
- R_{PbPb} → evidence for a strong medium effects in nuclear collisions for prompt D mesons
- R_{pPb} → assessment of cold nuclear matter effects
- pPb data collected in February 2013
- R_{pPb} for D^0, D^+, D^{*+} and D_S → compatible with unity within uncertainties



$$R_{pPb} = \frac{(d\sigma/dp_T)_{pPb}}{A \times (d\sigma/dp_T)_{pp}}$$

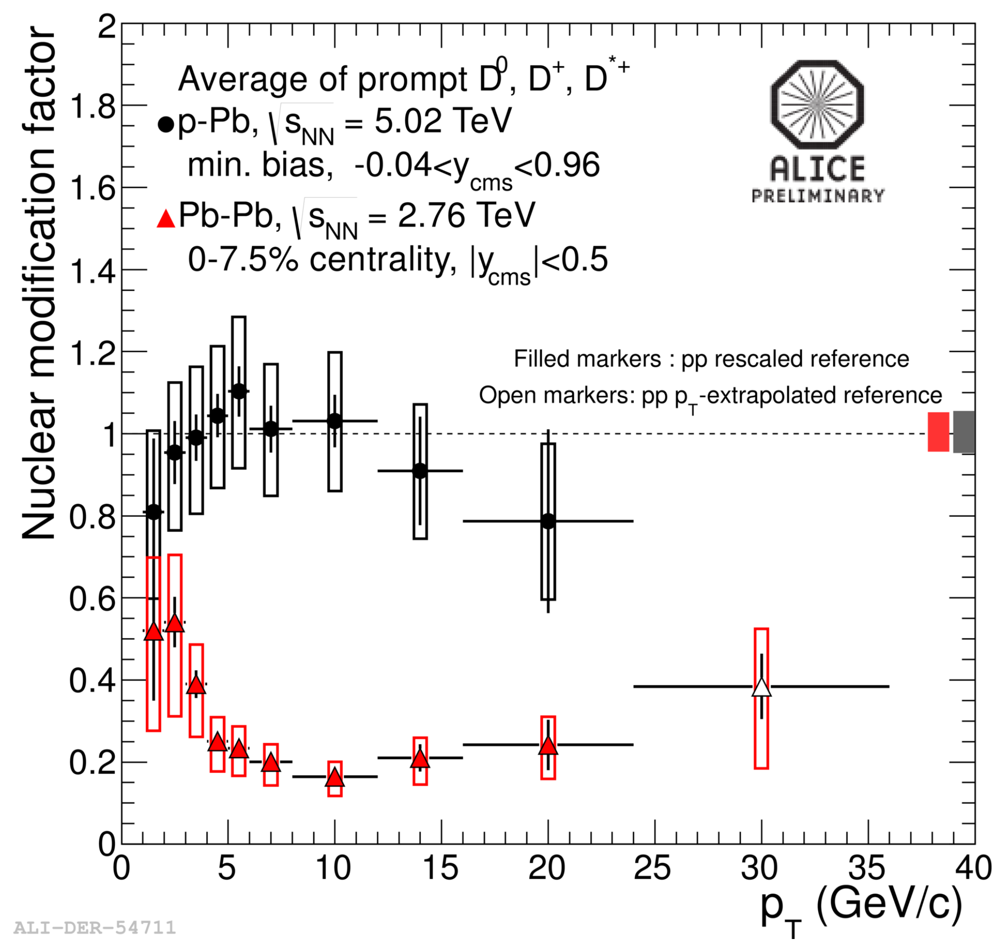
RpPb: comparison with predictions

- Average R_{pPb} compared with predictions from pQCD (MNR) including shadowing (EPS09):
  - ✓ M.Mangano, P.Nason and G.Ridolfi, Nucl. Phys. B373 (1992) 295
  - ✓ K.J.Eskola, H.Paukkunen and C.A. salgado JHEP 0904 (2009) 065
- and to calculations done in the framework of the CGC approach
- Data consistent with predictions within statistical and systematic uncertaities



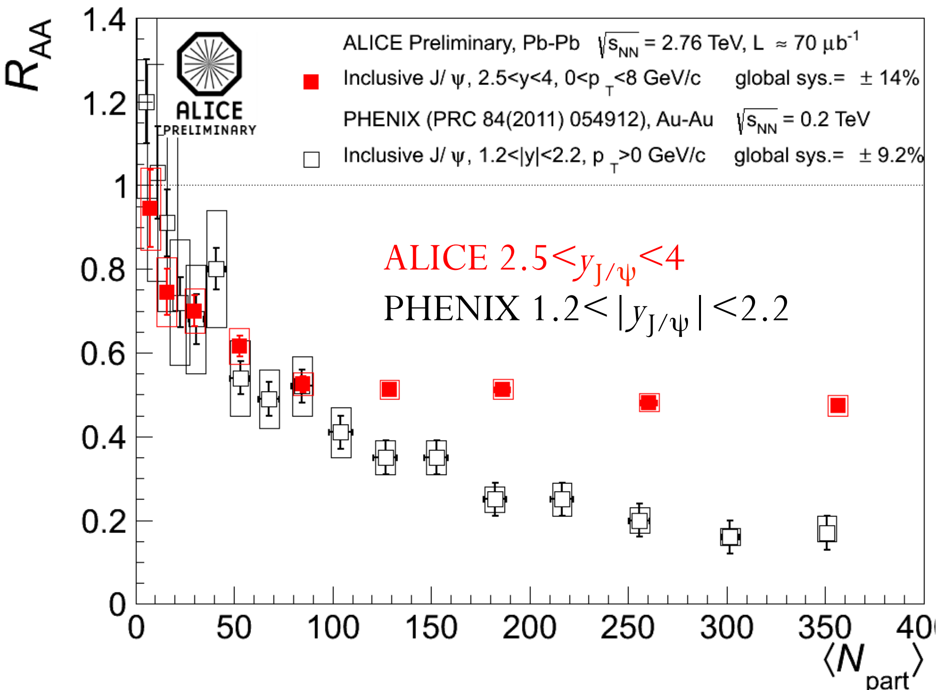
Comparison with R_{PbPb}

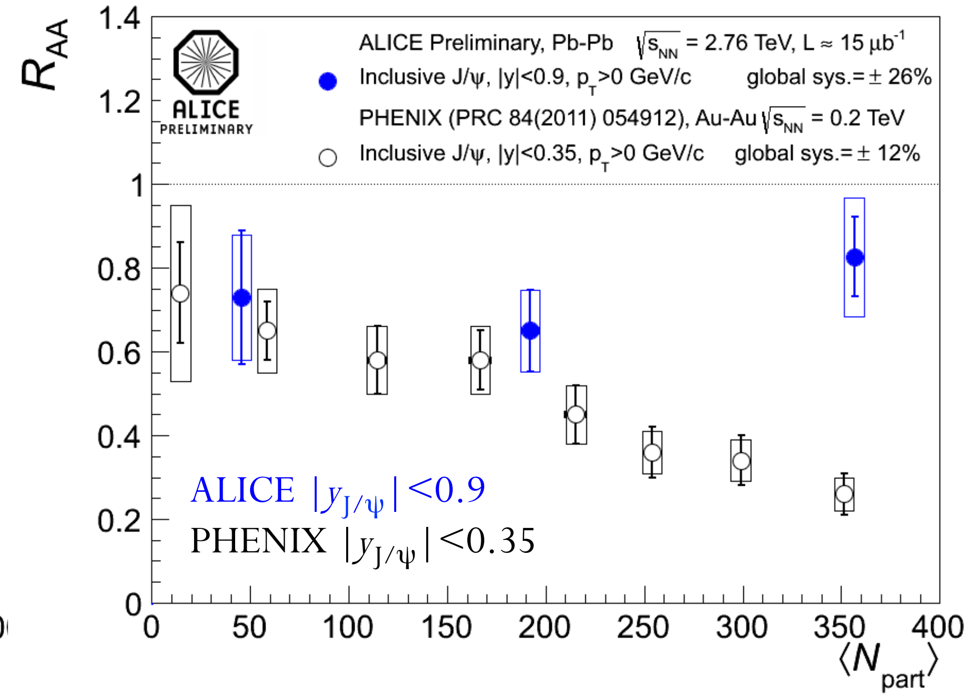
- The observed suppression in nucleus-nucleus collisions is a final state effect



Quarkonia in ALICE

J/ψ R_{AA} as a function of centrality

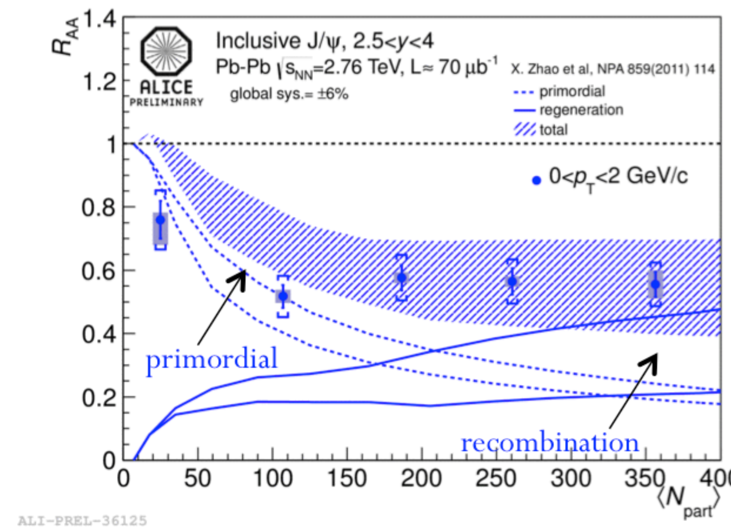


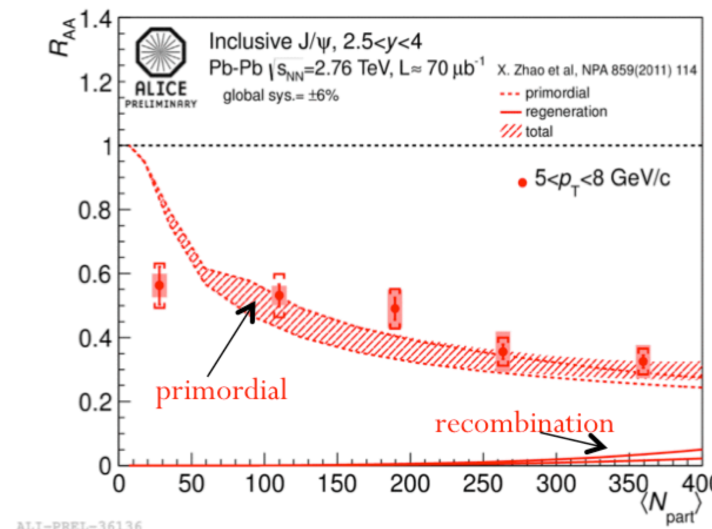


- From RHIC ($\sqrt{s_{NN}}$=0.2 TeV) to LHC ($\sqrt{s_{NN}}$=2.76 TeV):
  - ✓ ALICE: clear J/ψ suppression with no centrality dependence for N_{part}>100
  - ✓ ALICE: stronger suppression at forward rapidity for central events
  - ✓ PHENIX: Strong centrality dependence
  - ✓ PHENIX: stronger suppression w.r.t. ALICE for central event
- Data qualitatively consistent with a significant role of recombination at LHC energies

J/ψ R_{AA} vs centrality in p_T bins

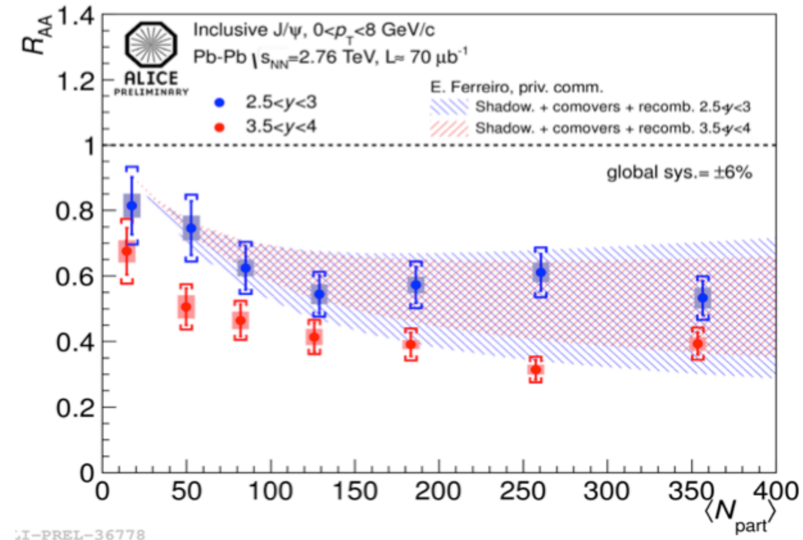
- J/ψ production via (re)combination should be more important at low transverse momentum
- Stronger suppression at high p_T
- Expectation from model:
  - ✓ ~50% of low p_T J/ψ are produced via (re)combination
  - ✓ recombination negligible at high p_T
  - ✓ data are in fair agreement with the expectation for N_{part}>100

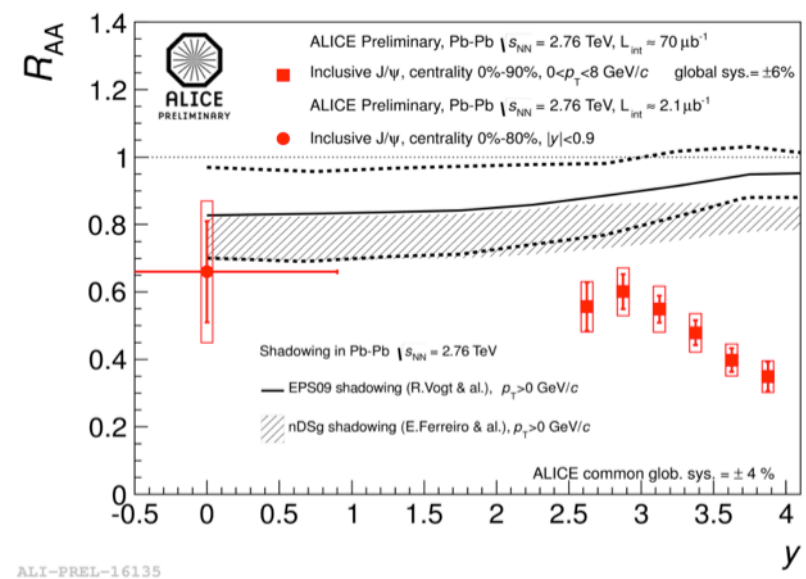




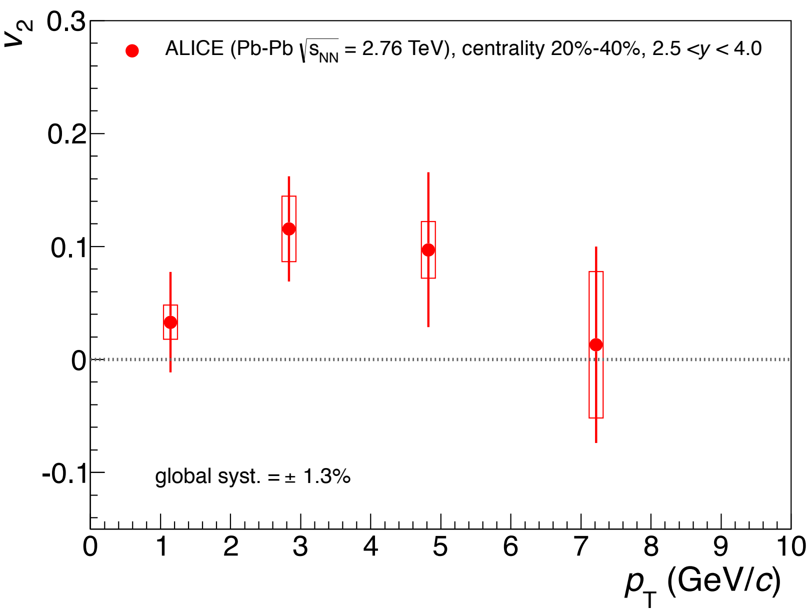
J/ψ R_{AA}: rapidity dependence

- J/ψ R_{AA} decreases by 40% from y=2.5 to y=4
- Comover+regeneration model shows a weaker rapidity dependence
- Suppression beyond the current shadowing estimates
- Important to quantify cold nuclear matter effects in pPb collisions

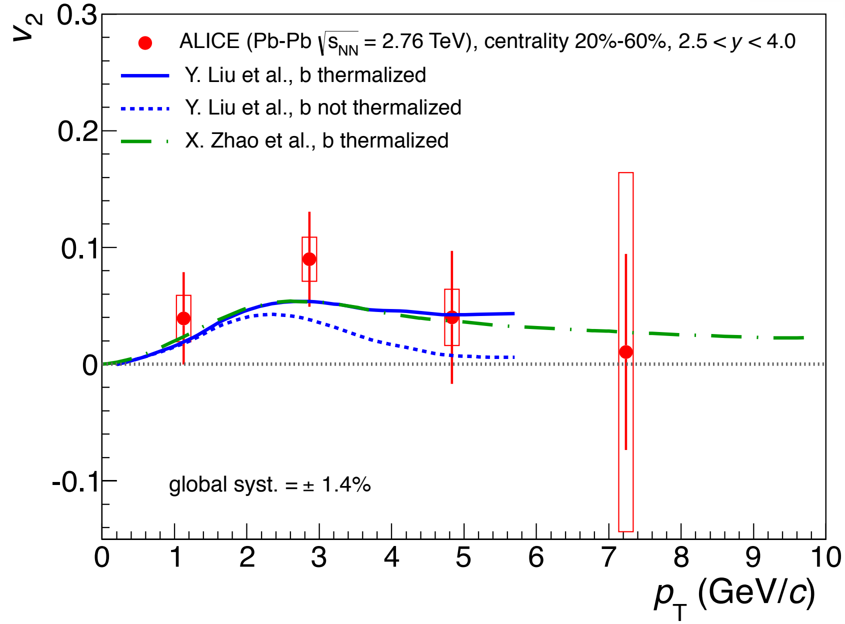




J/ψ elliptic flow



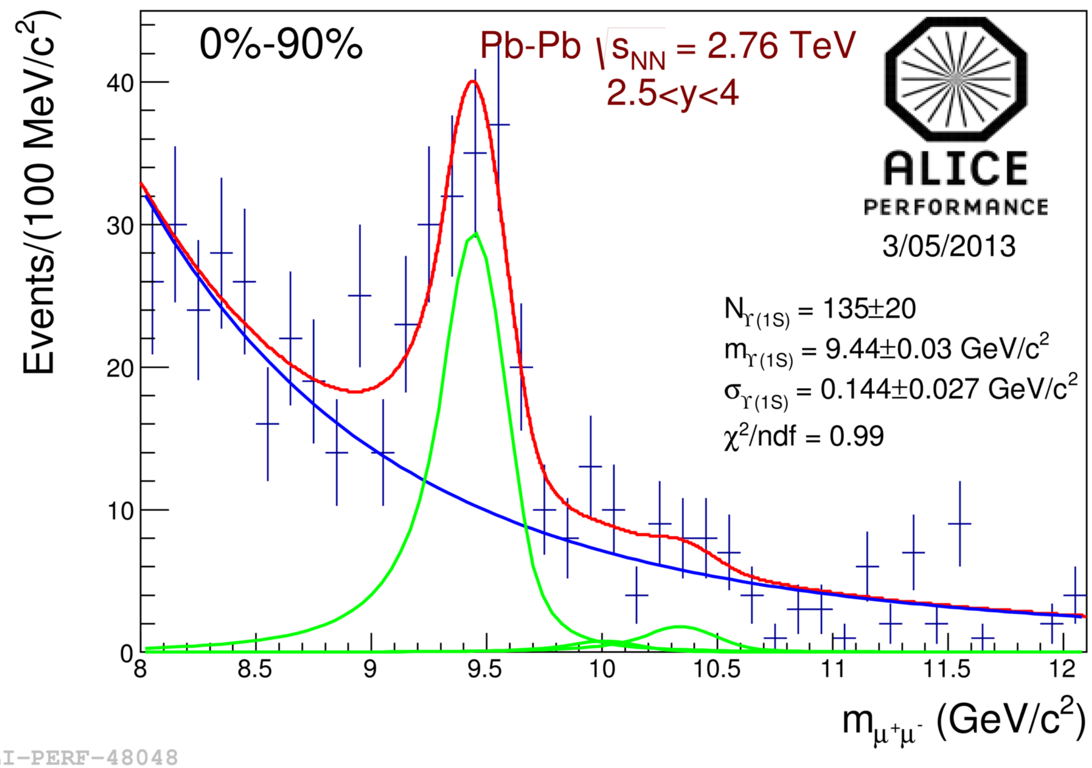
arXiv:1303.5880



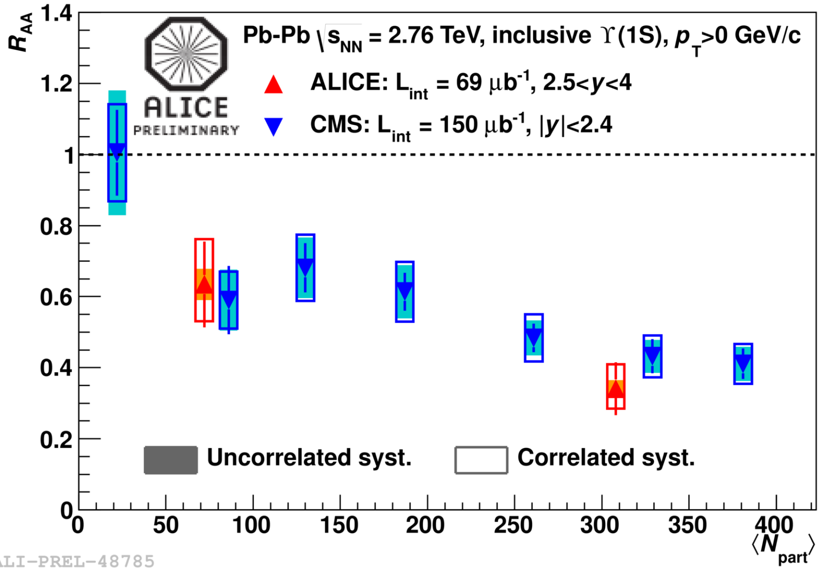
- The contribution of J/ψ from (re)combination should imply a significant elliptic flow at the LHC
- Data are suggestive for a non zero flow in ALICE (significance up to 3σ), while it was v_2~0 at RHIC
- Qualitative agreement with transport models including regeneration

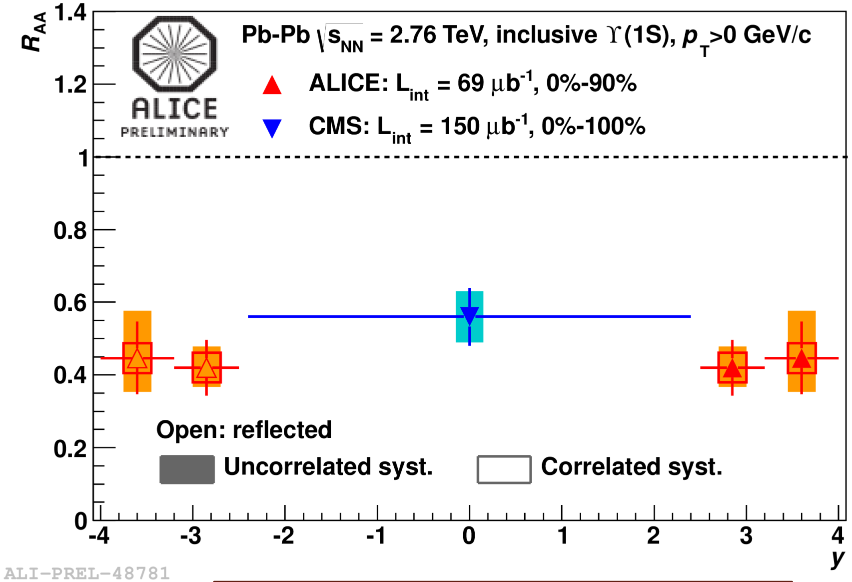
Bottomonium: the Υ family

- LHC is the place to study bottomonium in heavy ion collisions
- Features:
  - ✓ no B hadron feed-down
  - ✓ gluon shadowing effect are smaller
  - ✓ recombination plays a minor or negligible role
- Excellent data from CMS



Υ(1s) R_{AA}



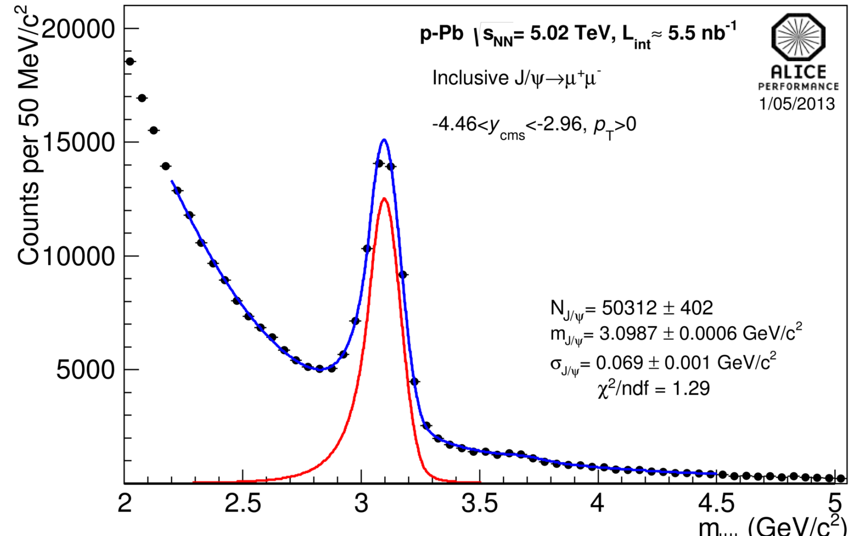


CMS PRL 109, 222301 (2012)

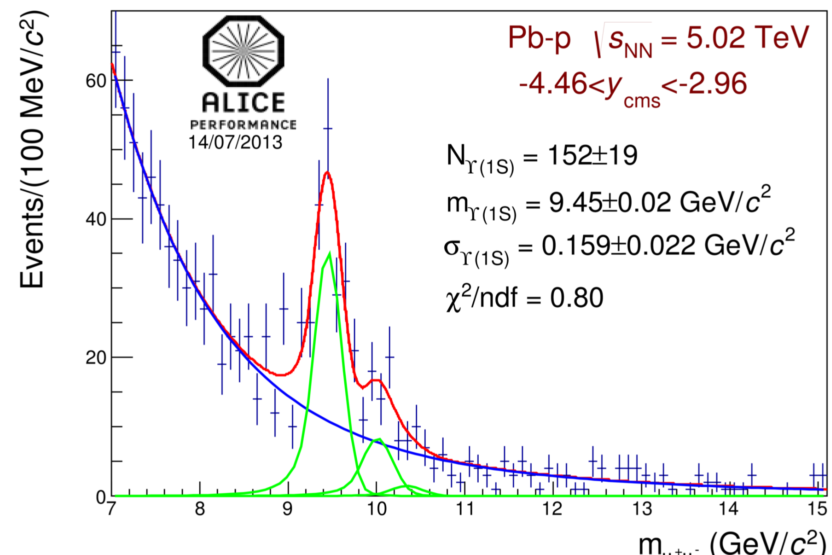
- Relevant suppression increasing with centrality
- Factor 2.5 for central collisions
- Reference pp cross section at 2.76 TeV from an interpolation procedure
- No evidence of rapidity dependence
- Observed R_{AA} significantly due to higher states suppression: in pp ~50% of Υ(1s) are not prompt

p-Pb collisions

- First results from p-Pb data at $\sqrt{s_{NN}}=5.02$ TeV
- Data sample in the dimuon channel for the present results:
  - ✓ p-Pb ($2.03<y_{CMS}<3.53$) – $L_{int}\sim5\ nb^{-1}$
  - ✓ Pb-p ($-4.46<y_{CMS}<-2.96$) – $L_{int}\sim6\ nb^{-1}$
- Goals:
  - ✓ study Cold Nuclear Matter effects on J/ψ
  - ✓ give a reference for PbPb collisions



ALI-PERF-47720



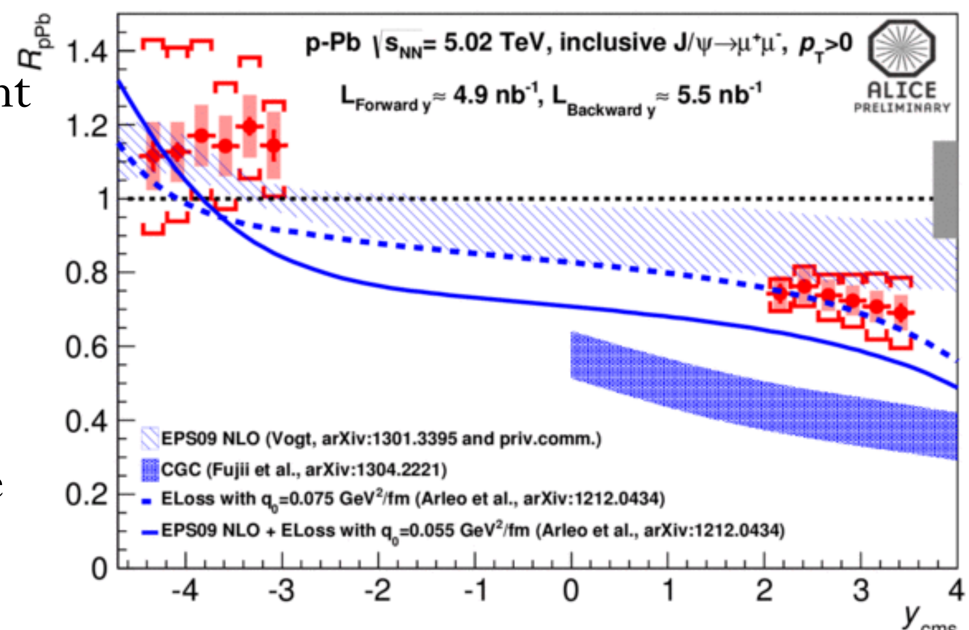
ALI-PERF-51309

Nuclear modification factor R_{pA}

- R_{pA} decreases towards forward rapidity
- Uncertainty dominated by the pp reference (based on data interpolation):
  - ✓ ~25% (18%) at backward (forward) rapidity
- Boxes → uncorrelated ; Brackets →largely correlated; grey box at 1 → fully correlated

$$R_{pPb}^{Q\bar{Q}} = \frac{Y_{pPb}^{Q\bar{Q}}}{\langle T_{pPb} \rangle \sigma_{pp}^{Q\bar{Q}}}$$

- Theoretical expectations: fair agreement within the uncertainties with:
  - ✓ shadowing EPS09 NLO calculations (R.Vogt)
  - ✓ models including parton energy loss contributions (Arleo et Al)
- CGC description is not favoured by the data

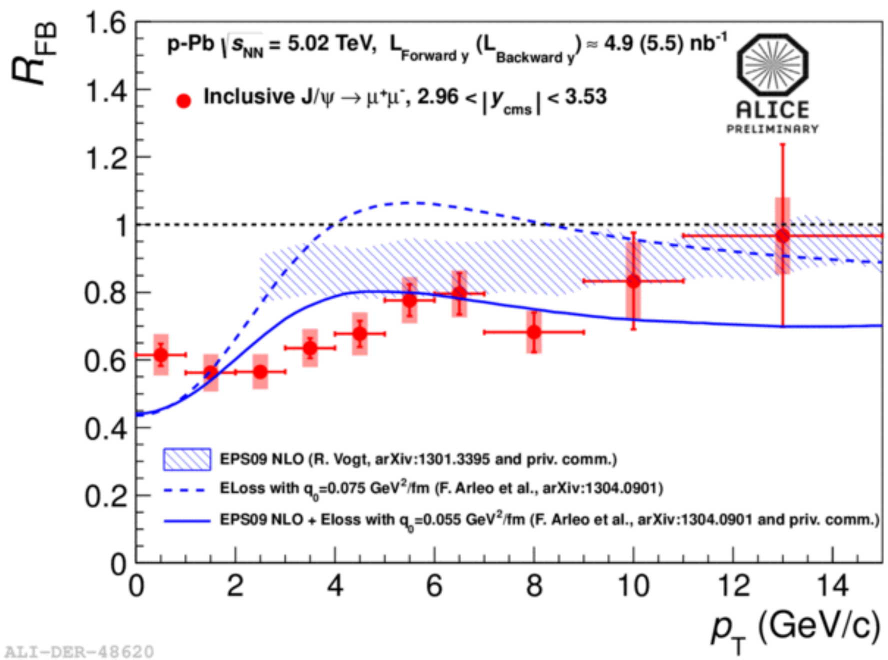


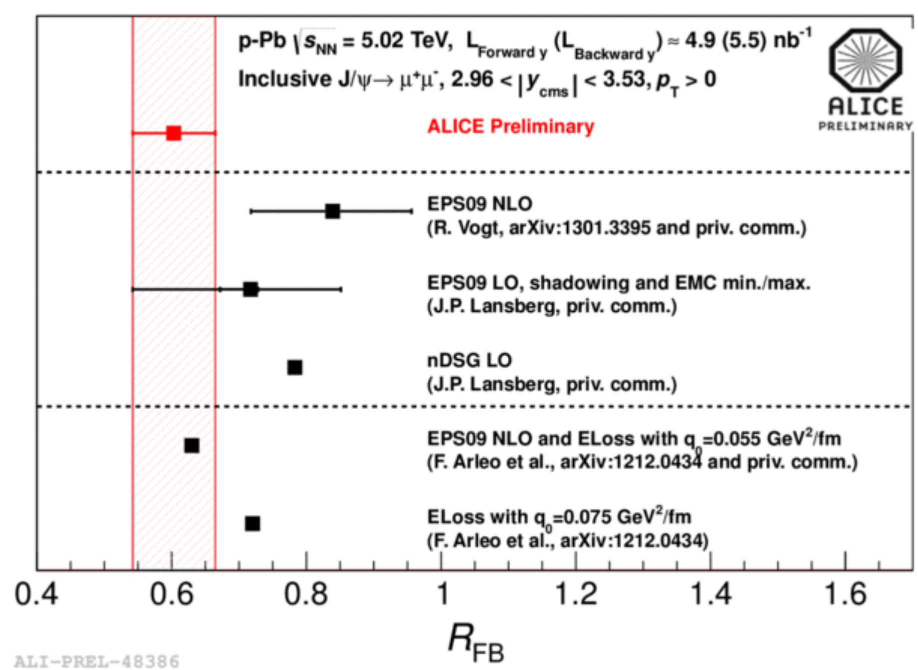
ALI-DER-48480

Ratio forward/backward yields: R_{FB}

- R_{FB} free from uncertainties on the pp reference
- R_{FB} vs p_T: stronger forward to backward suppression at low p_T
- R_{FB} does not depend on y in the restricted rapidity range $2.96 < |y_{CMS}| < 3.53$
- Pure shadowing overestimates slightly the data
- Better agreement with for models including energy loss

$$R_{FB} = \frac{Y_{Q\bar{Q}}^{Forward}}{Y_{Q\bar{Q}}^{Backward}}$$





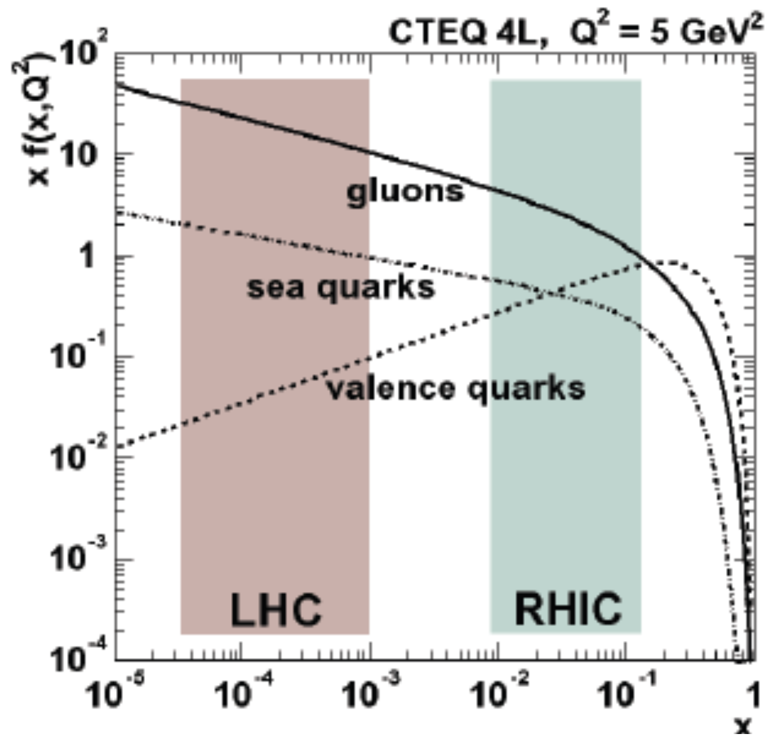
Conclusions

- **Heavy Flavours:**
  - ✓ pp data are described by perturbative QCD → HF are a calibrated probe
  - ✓ Pb-Pb data:
    - there is a clear suppression, with hints of a stroger suppression for charm than for beauty.
    - no strong conclusions can be drawn from the R_{AA} comparison of D mesons and pions at low p_T, given the large uncertainties and that different mechanisms are at work in the two cases (soft production and radial flow for pions)
  - ✓ pPb data:
    - results consistent with pQCD + shadowing: the observed suppression in Pb-Pb collisions is a hot nuclear matter effect
- **Quarkonium:**
  - ✓ J/ψ production studied vs. p_T and rapidity. The observed v_2 and R_{AA} vs centrality indicate that the J/ψ production occurs also through recombination, especially at low p_T
  - ✓ Υ : a relevant suppression has been observed also for the bottomonium. The suppression is stronger for central events. The combined results from CMS and ALICE indicate that there is not a dependence on y within the present uncertainties
  - ✓ pPb: the R_{FB} and R_{AA} ratios for J/ψ is in fair agreement with models including shadowing and/or a coherent energy loss of the partons in cold nuclear matter

Backup

Parton Distribution Functions

- PDFs: probability of finding a parton with a fraction x of the proton momentum, in a hard scattering with momentum transfer (virtuality) Q^2
  - PDFs are obtained by means of a global fit to experimental data, for one or more physical processes which can be calculated using pQCD, such as deep inelastic scattering and the Drell-Yan process
  - PDFs depends on the Q^2 value
  - The Q^2 evolution can be calculated in pQCD, using the DGLAP equations

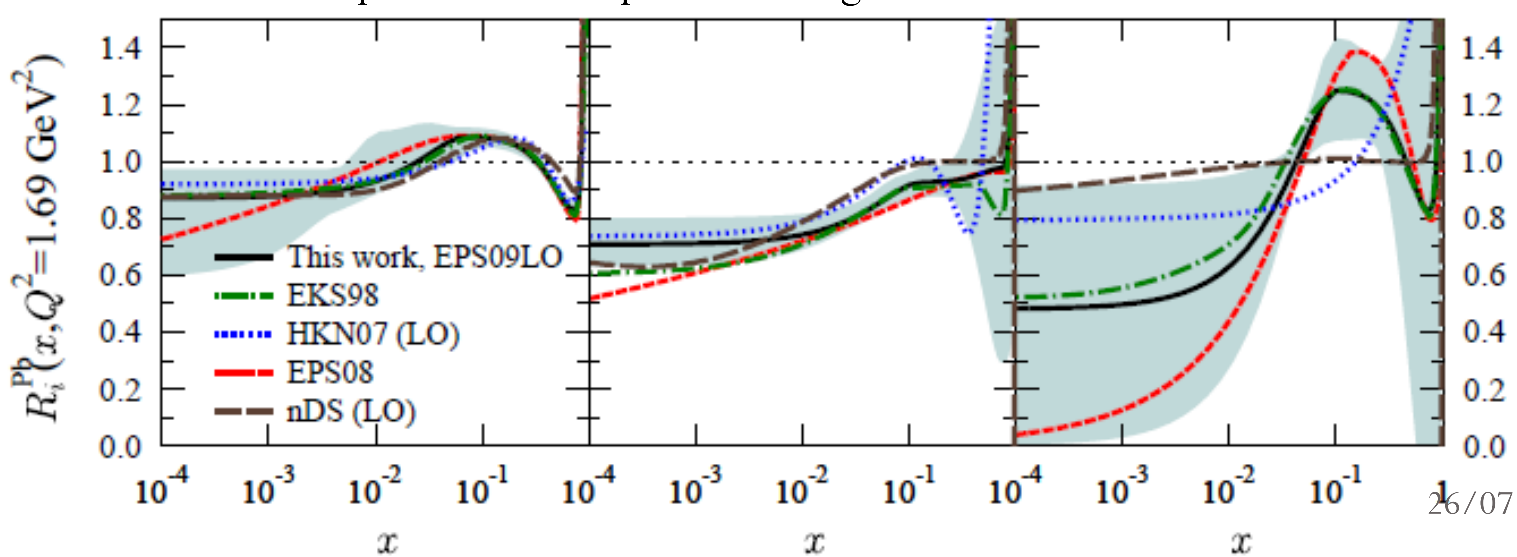


PDF in nuclei

- Parton distributions in nuclei are modified with respect to those in a free nucleon
  - ✓ First observed by EMC experiment in 1983
- Nuclear modification depends on:
  - ✓ Fraction x of the hadron momentum carried by the parton
  - ✓ Momentum scale Q^2
  - ✓ Mass number of the nucleus

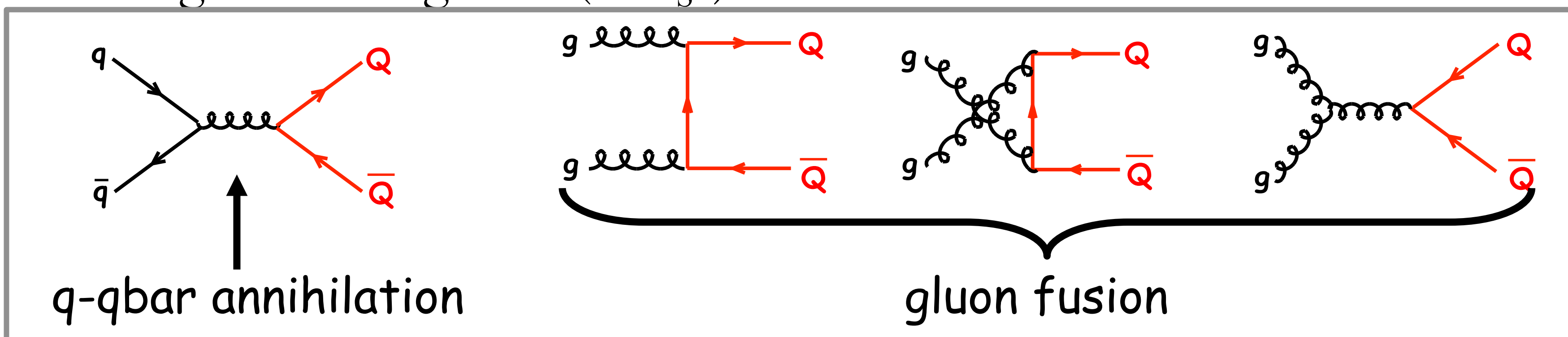
$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

- Different parameterizations are available to convert free nucleon distributions into the nuclear one

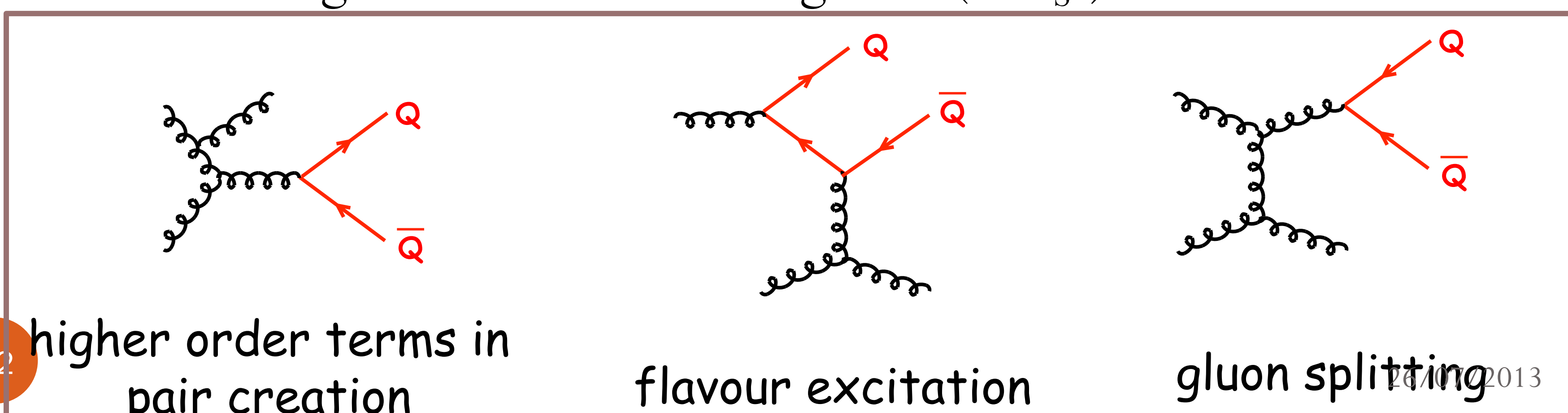


Partonic cross section

- Perturbative expansion in powers of α_S
  - ✓ State of the art: FONLL = Fixed Order calculation (at NLO) + resummation of next to leading logs
- Leading order diagrams ($\propto \alpha_S^2$)

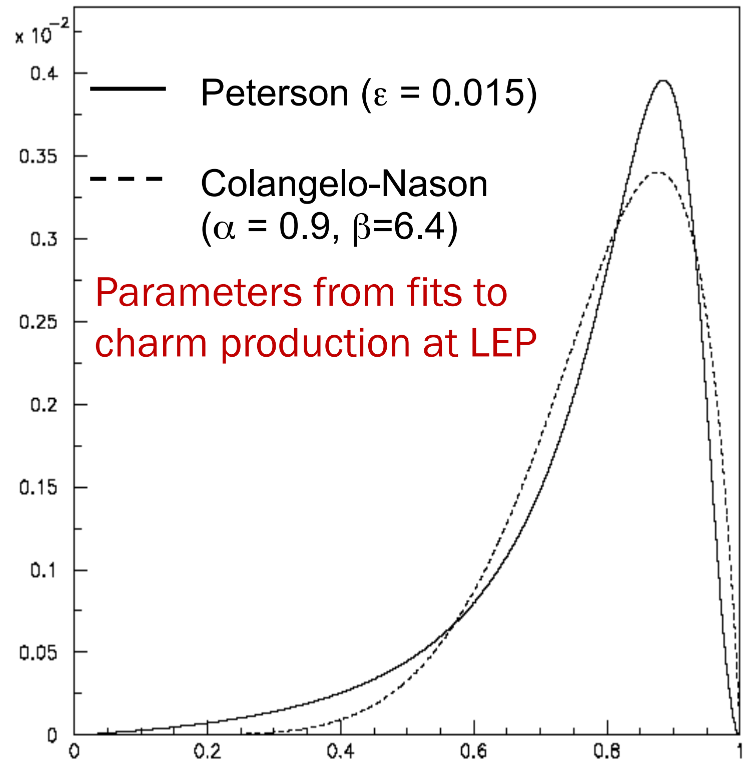


- Next to leading order additional diagrams ($\propto \alpha_S^3$)



Fragmentation function

- Fragmentation function $D_{q\rightarrow H}(z,Q^2)$ gives the probability that a quark q produces an hadron H carrying a fraction z of the quark momentum ($p_H = zp_q$)
  - ✓ Usually extracted from e^+e^- data and used in other collision systems
- In case of heavy quark fragmentation, the D/B meson takes a large fraction z of the quark momentum
  - Fragmentation function shows a peak for z close to 1 (-> hard fragmentation function)
  - Example of parameterizations:



Peterson

$$D_{D/c}(z) \propto \frac{1}{z[1-1/z-\varepsilon/(1-z)]^2}$$

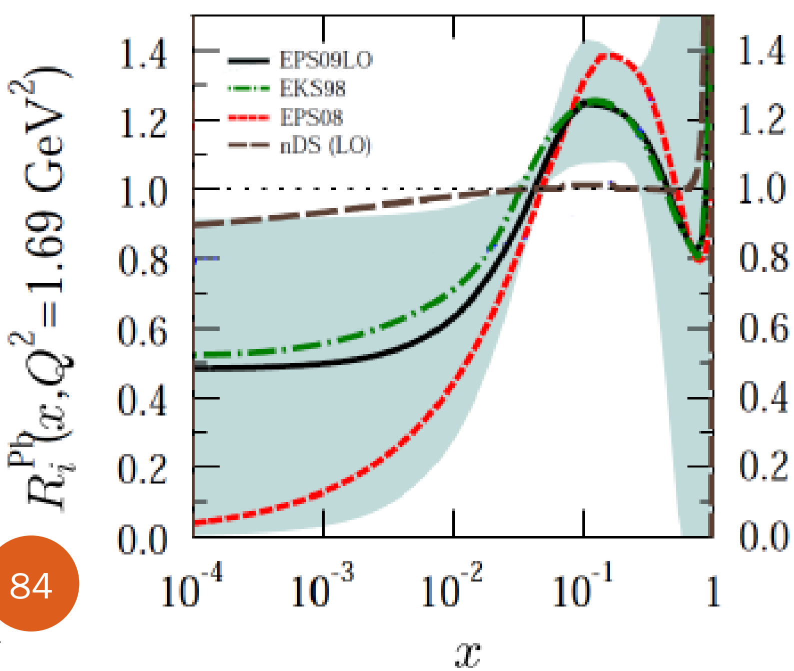
Colangelo-Nason

$$D_{D/c}(z) \propto (1-z)^{\alpha} z^{\beta}$$

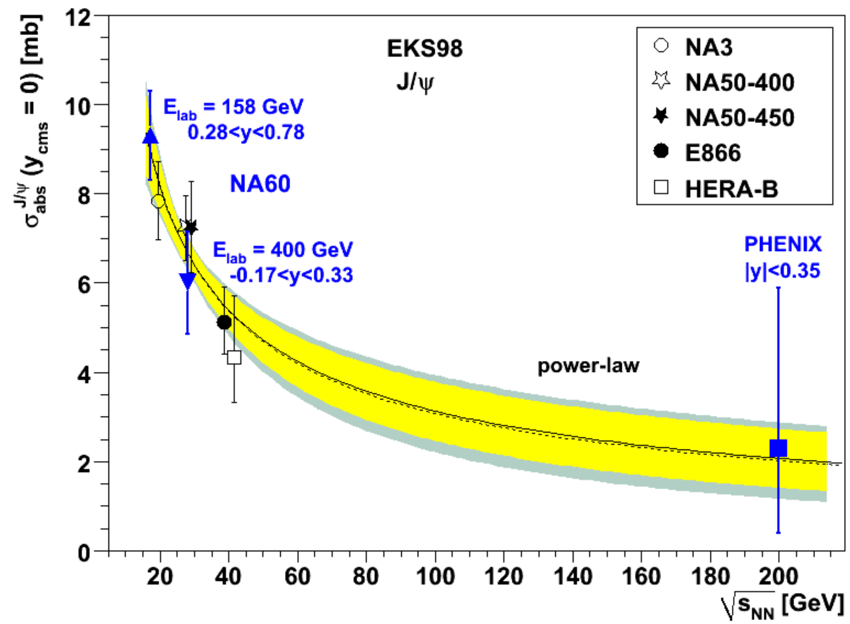
Nuclear effects

- Interpretation of results not easy
  → many competing effects affect J/ψ production/propagation in nuclei
    - anti-shadowing (with large uncertainties on gluon densities!)
    - final state absorption…
  → need to disentangle the different contributions

Size of shadowing effects may be large → to be taken into account comparing results at different √s

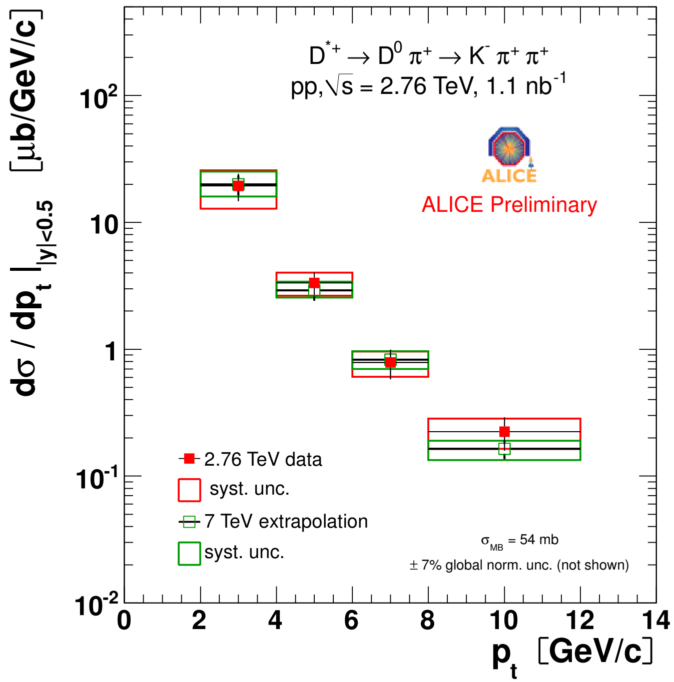


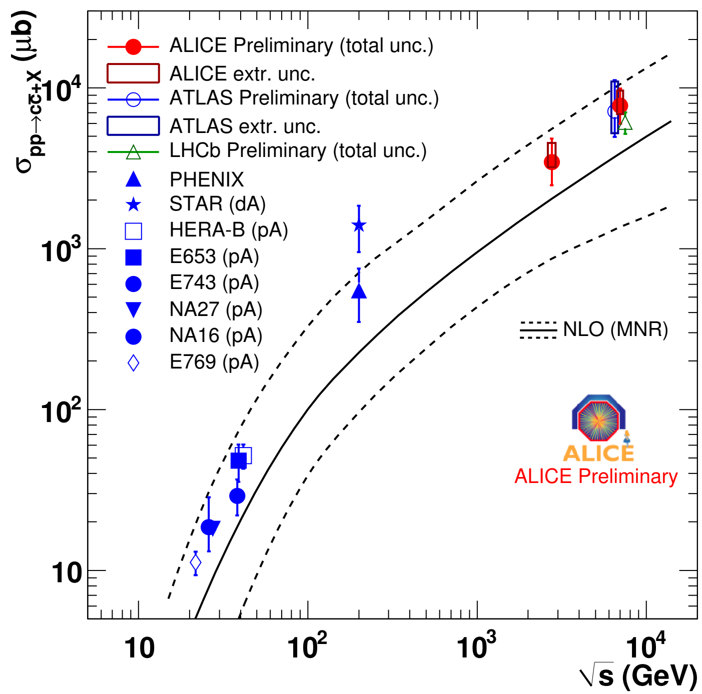
- Clear tendency towards stronger absorption at low √s



C. Lourenco, R. Vogt and H. Woehri, JHEP 0902:014,2009
F. Arleo and Vi-Nham Tram Eur. Phys. J. C55:449-461,2008, arXiv:0907.0043

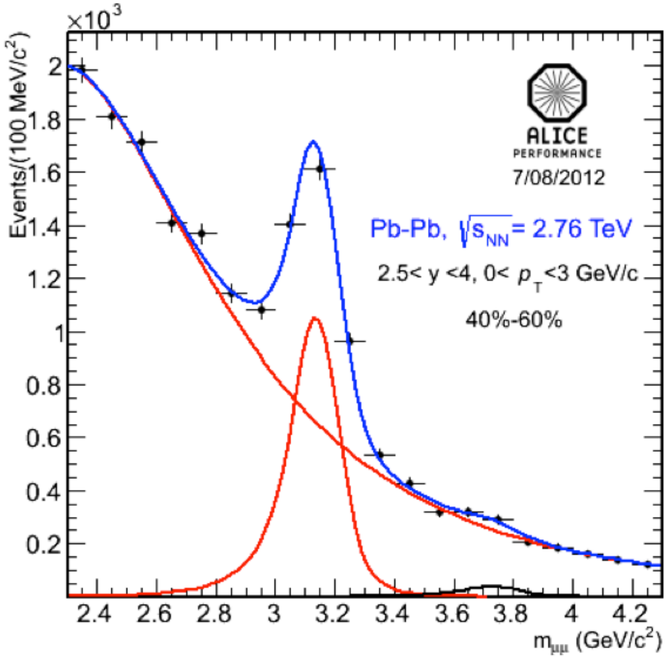
Extrapolation to √s=2.76 TeV and total charm σ

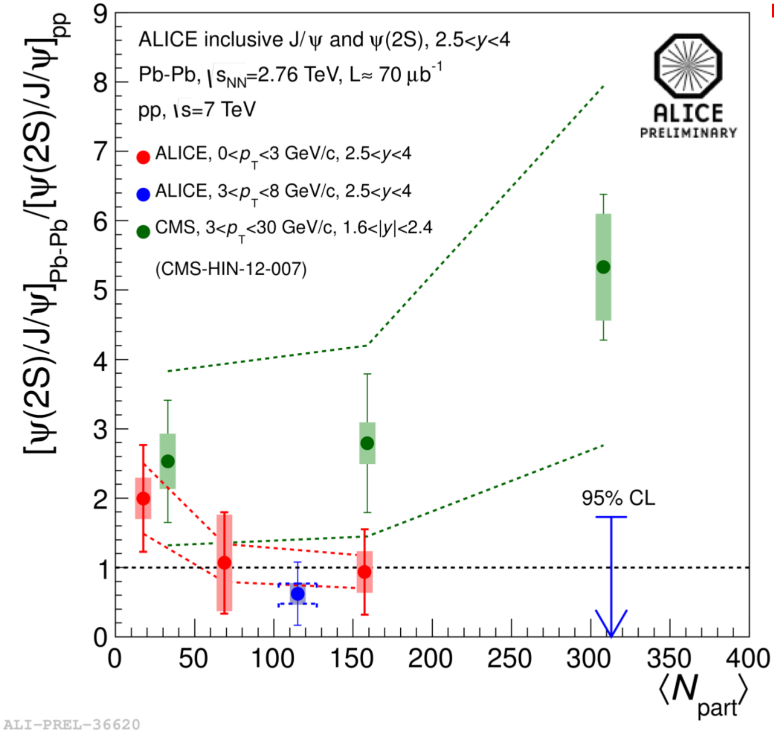




- Three days of data taking @2.76 TeV (1.1 nb^{-1})→ same energy as PbPb
- 7 TeV data have been scaled to 2.76 using FONLL 2.76/7 factor (R.Averbeck et Al., arXiv:1107.3243)
  - ✓ Scaling uncertainty: from 25% at low p_T to 10% at high p_T
  - ✓ Checked with ALICE @2.76 TeV and CDF data at 1.96 TeV
- Total charm cross section (extrapolated to p_T=0 and full rapidity) is in good agreement with ATLAS and LHCb measurements

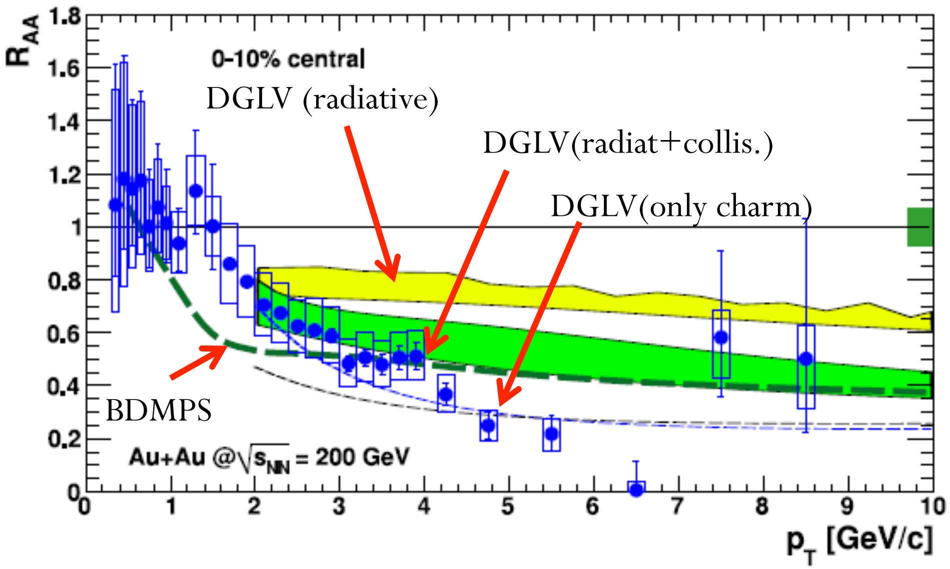
ψ(2s) vs J/ψ

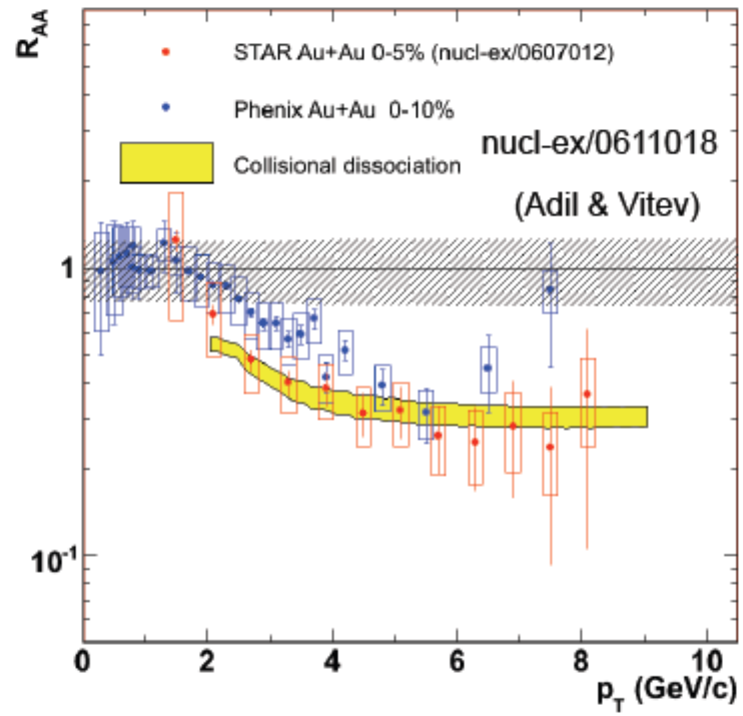




- ψ(2s) is much less bound than J/ψ
- At the SPS ψ(2s)/(J/ψ) suppression increased with centrality
- CMS data are suggestive for a relative enhancement of ψ(2s) vs J/ψ
- ALICE excludes a large enhancement
- No firm conclusion can be drawn due to the large uncertainties. Main systematics from signal extraction and MC input for acceptance calculation
- More precise measurement expected with the ALICE upgrade

R_{AA} at RHIC: interpretations





- Collisional energy loss to be taken into account?
- Energy loss models sensitive to the B/D admixture
  - ✓ Important to establish b and c contributions, since their energy loss should be different

- Collisional dissociation of D/B mesons formed in the medium early after hard scattering?