Studying hot QCD matter at the CERN-LHC with heavy quarks

Thanks to the ALICE, ATLAS and CMS Collaborations
and the LHC accelerator team

André Mischke

Universiteit Utrecht

European Research Council

Netherlands Organisation for Scientific Research

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Marseilles, France – 22-26 April 2013

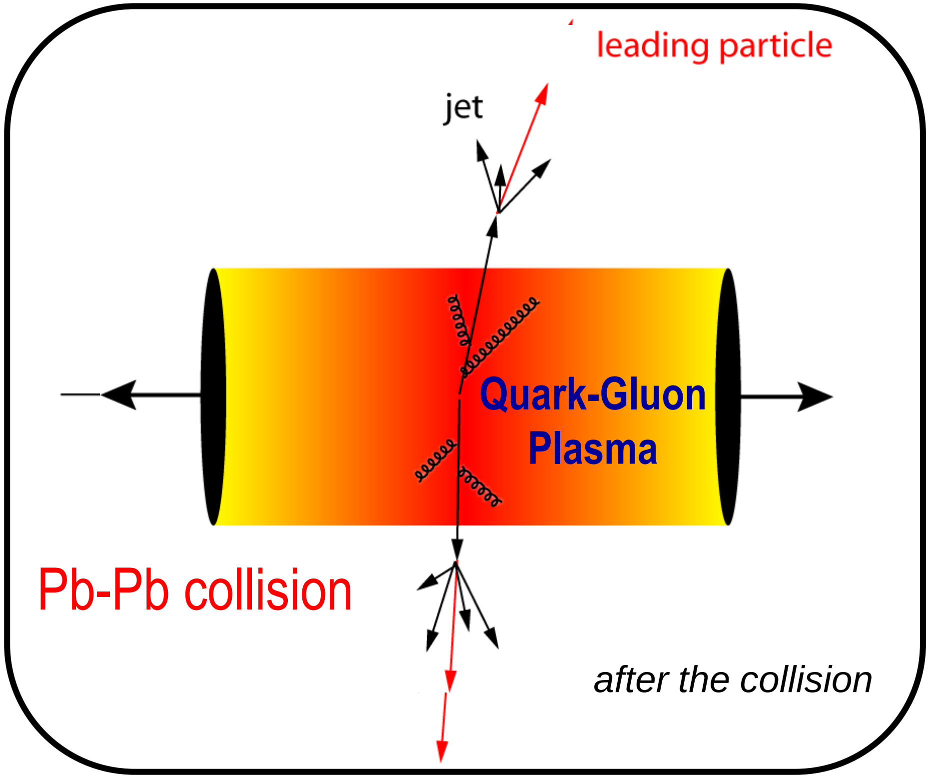
Outline

- Strongly interacting matter in extremes
- Heavy quarks (charm and beauty) and the Quark Gluon Plasma
- Measurements
  - pp interactions: important baseline; test pQCD models
  - p-Pb collisions: study cold nuclear matter effects
  - Pb-Pb collisions: study hot QCD matter; determine medium properties
- Probes
  - Open HF (prompt D mesons and HF decay leptons): **Energy loss mechanism(s) and degree of thermalization**
  - Hidden HF (J/ψ and Υ states): **Deconfinement (dissociation in hot QCD matter) and degree of thermalization**
- Summary

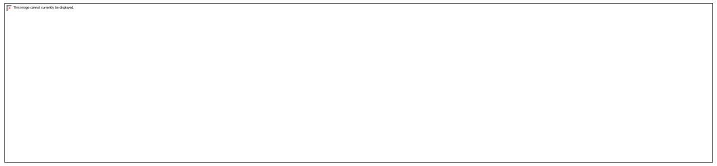
Plenary talk by Barbara Erazmus

Parallel talk by Diego Stocco

Probing hot and dense QCD matter



Quantify medium effects with
nuclear modification factor

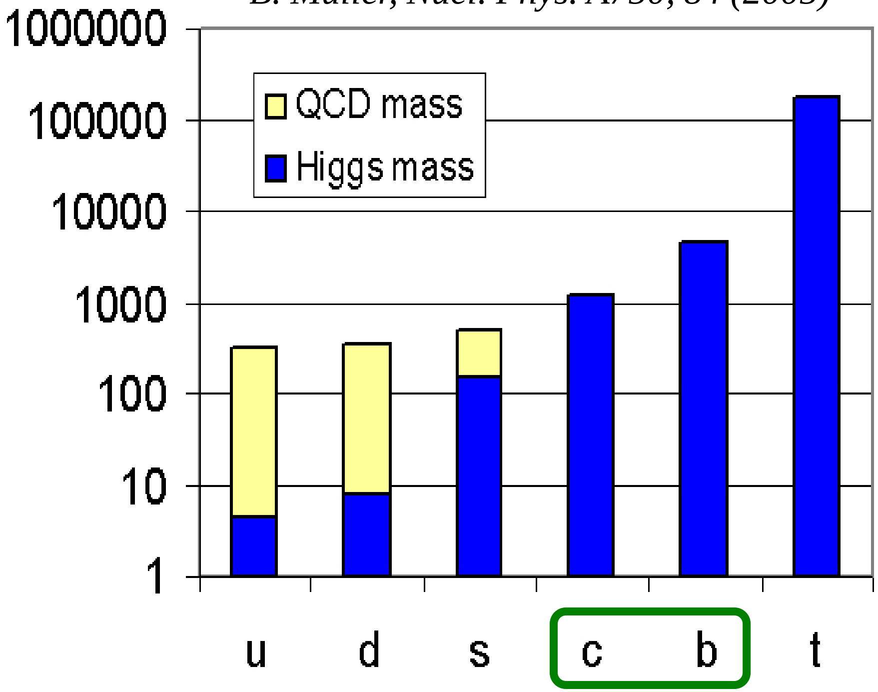


- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile

- Heavy-ion collision
  - hard processes serve as calibrated probe (pQCD)
  - traversing through the medium and interacting strongly
  - suppression provides density measurement
  - General picture: **parton energy loss through medium-induced gluon radiation and collisions with medium**

Heavy quarks are ideal probes

B. Müller, Nucl. Phys. A750, 84 (2005)



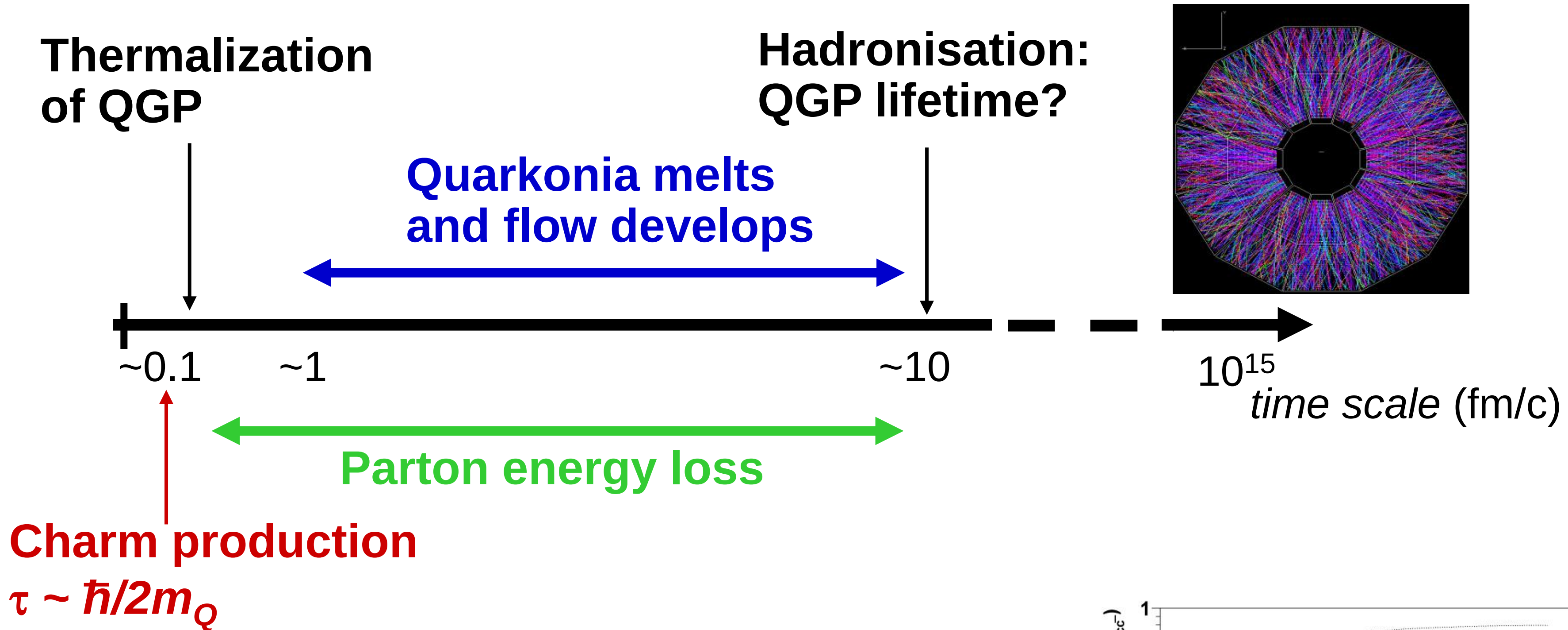
- Charm and beauty quarks are 250-450 times heavier than light quarks
- They are abundantly produced at the LHC, **predominantly in the early phase of the collisions**
- **Production rates calculable in pQCD**

- Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass

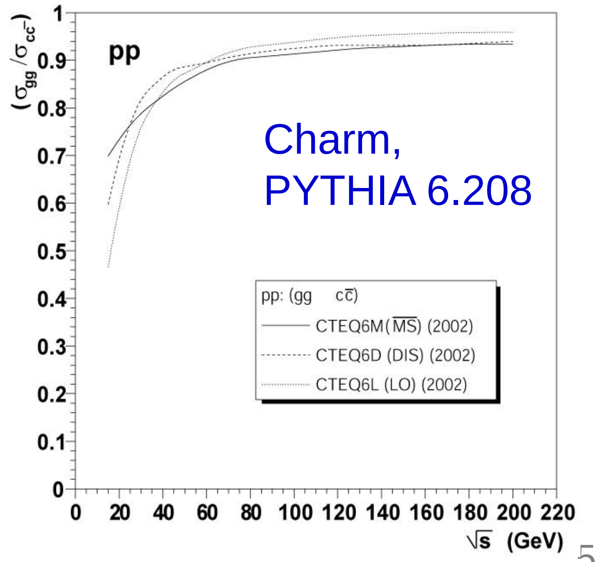
- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

- Test QCD at transition from perturbative to non-perturbative regime: charm and beauty quarks provide hard scale for QCD calculations

Time evolution of a heavy-ion collision



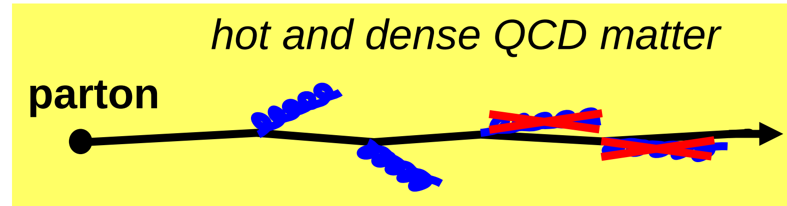
- Gluon fusion dominates → sensitivity to initial state gluon distribution *M. Gyulassy and Z. Lin, Phys. Rev. C51, 2177 (1995)*
- Heavy quarks transverse through the QCD medium and interact strongly with it → energy loss
- Due to their mass ($m_Q >> T_c, \Lambda_{QCD}$) → higher penetrating power



Energy loss of heavy quarks

(1) Radiative parton energy loss is colour charge dependent (Casimir coupling factor C_R)

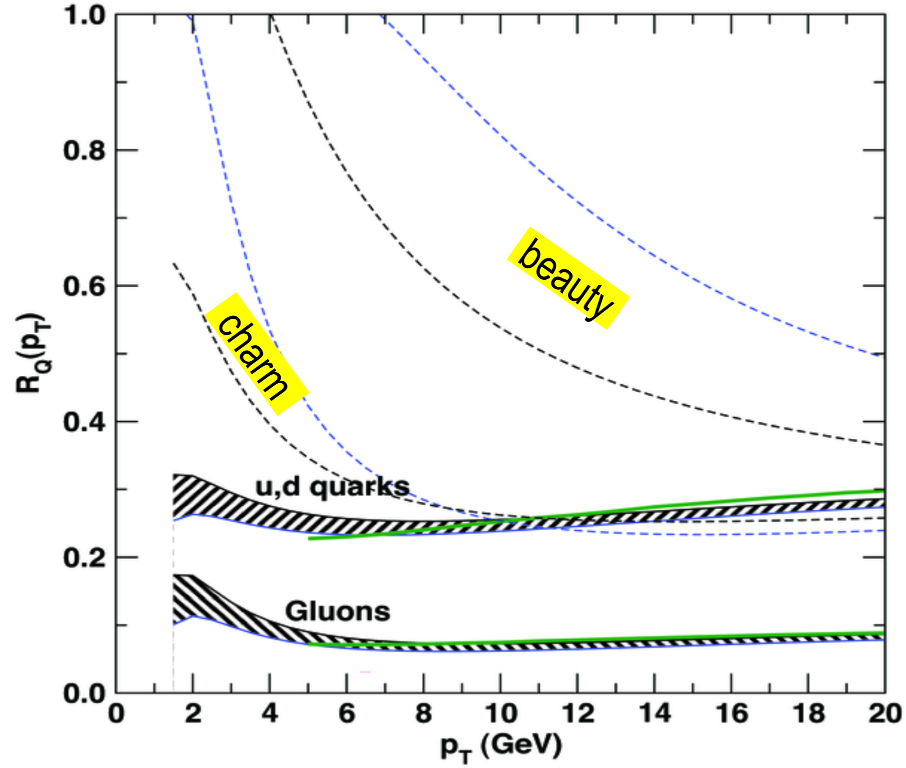
R.Baier et al., Nucl. Phys. B483, 291 (1997) ("BDMPS")



(2) Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

Y. Dokshitzer, D. Kharzeev, PLB 519, 199 (2001), hep-ph/0106202

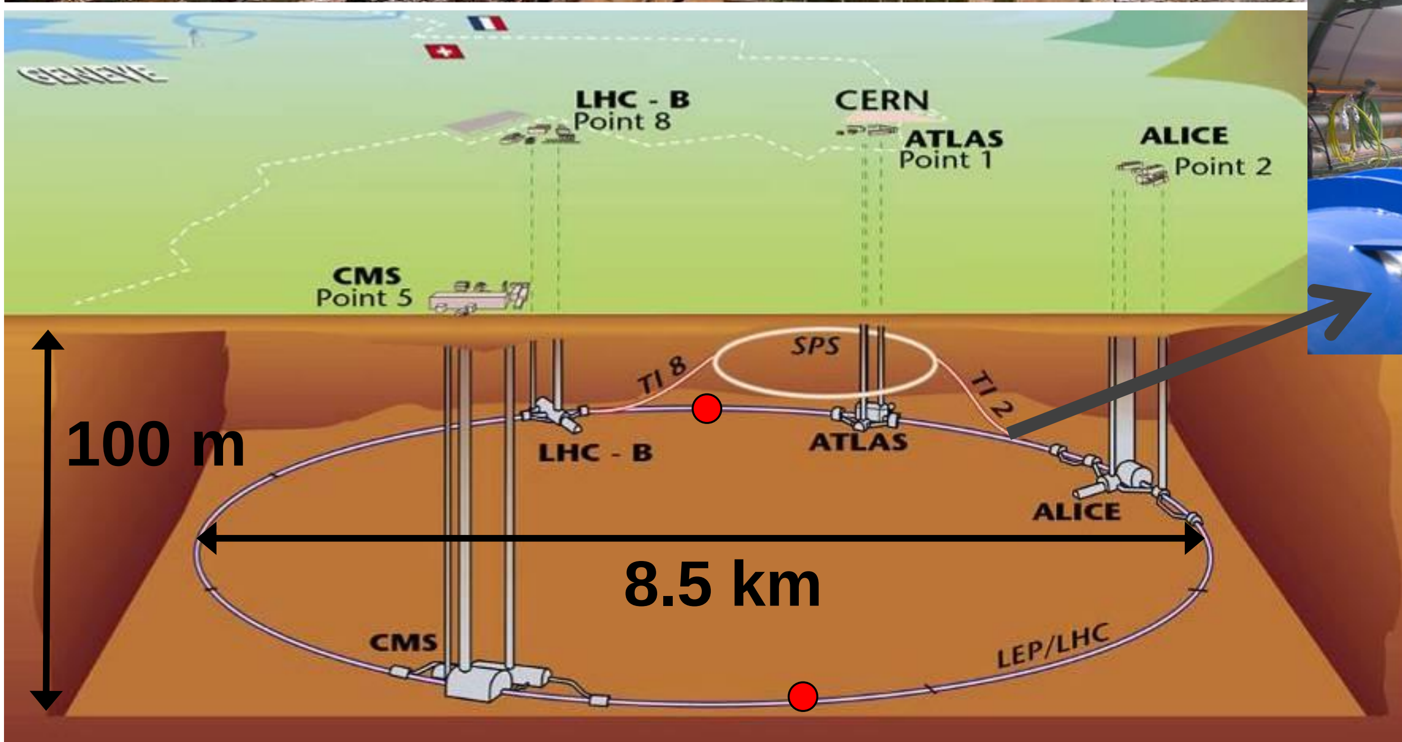
S. Wicks et al., Nucl. Phys. A784, 426 (2007)



$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

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

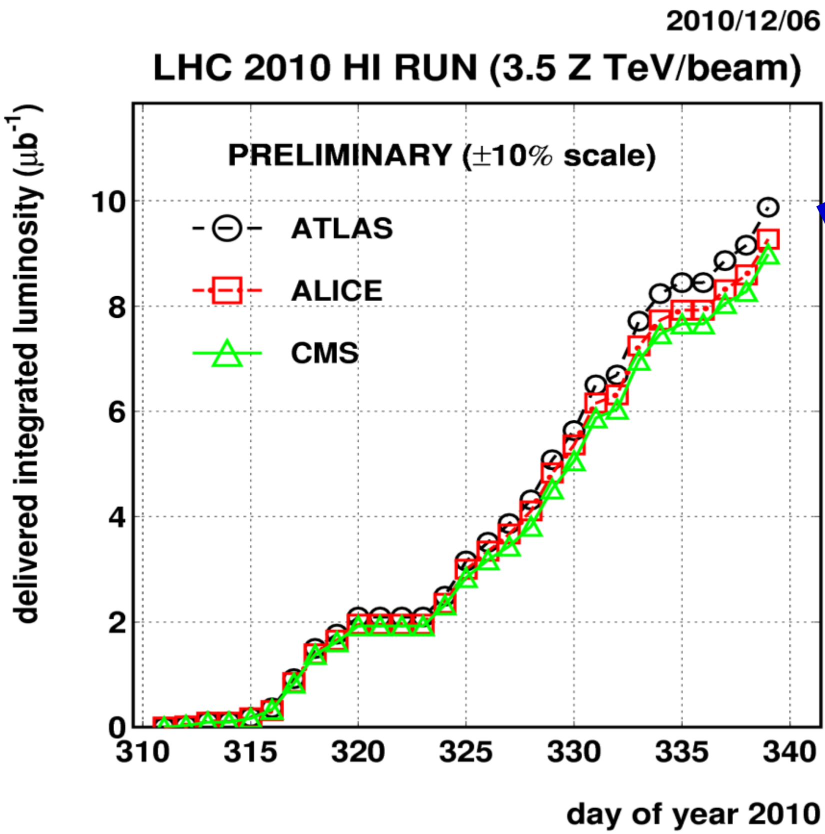
Large Hadron Collider at CERN

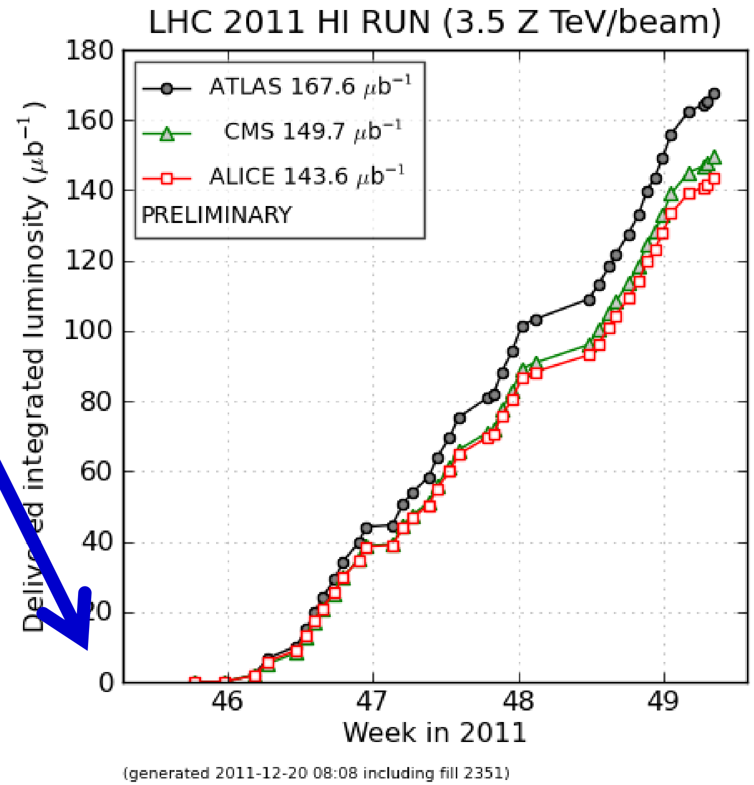


- 1232 dipole magnets
- Two counter-rotating beams
- Operation with super-fluid helium at 1.9K (~120 tons)
- 8 Tesla bending field

- Data taking since November 2010
- Ion species and energies
  - **Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV**
  - **pp, $\sqrt{s}$ = 0.9, 2.36, 2.76, 7 and 8 TeV**
  - **p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV**

Data: integrated luminosity



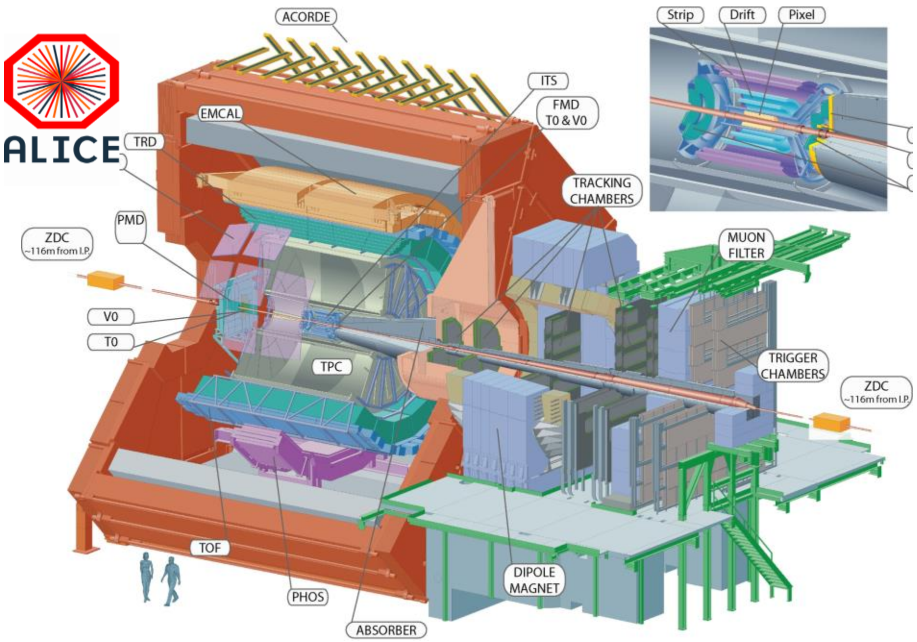


year	integrated luminosity
2010	~ 10 μb^{-1}
2011	~ 0.16 nb^{-1}

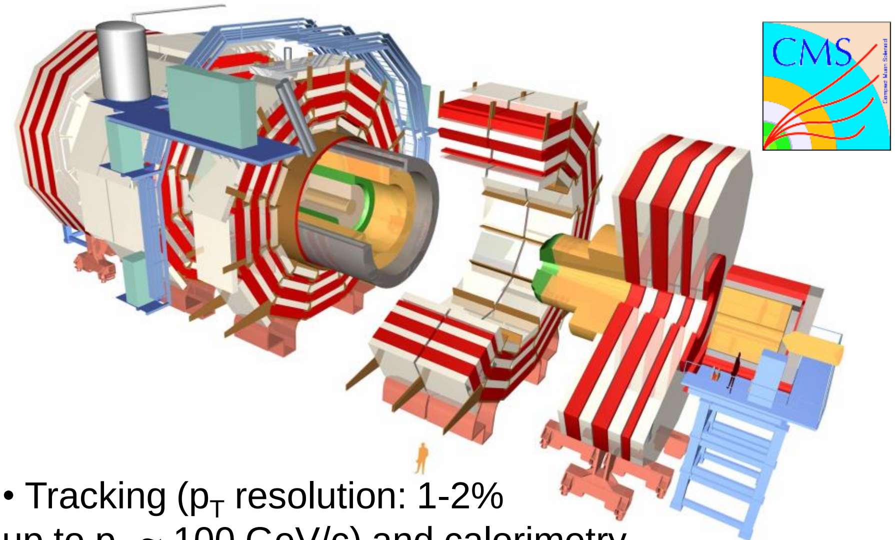
${}^{208}_{82}$Pb- ${}^{208}_{82}$Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

2010 → 2011: factor 16 improvement

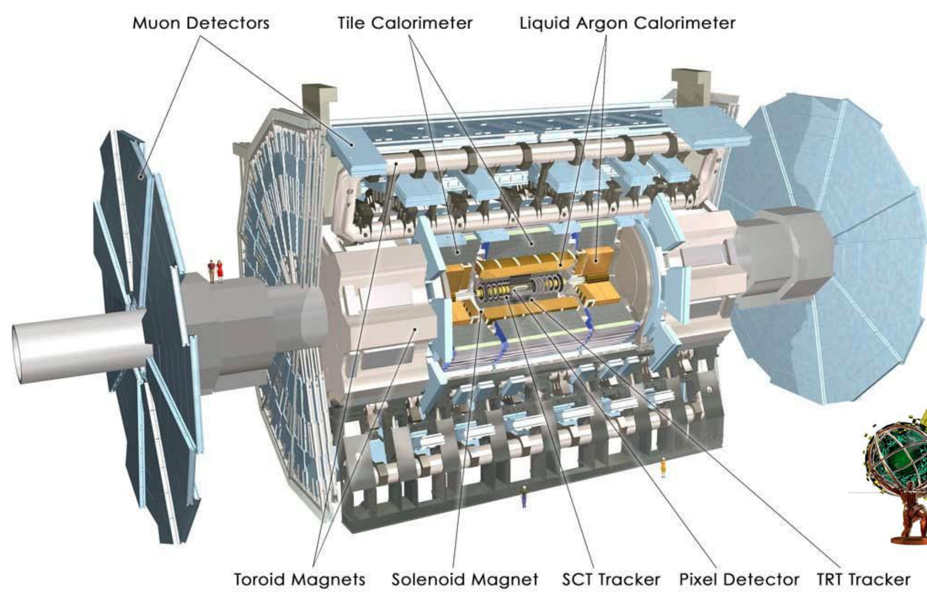
Detectors



- PID over a very broad momentum range (>100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage $|\eta| < 0.9$ and $-4 < \eta < -2.5$ in forward region
- Impact parameter resolution better than 65 μm for $p_T > 1$ GeV/c

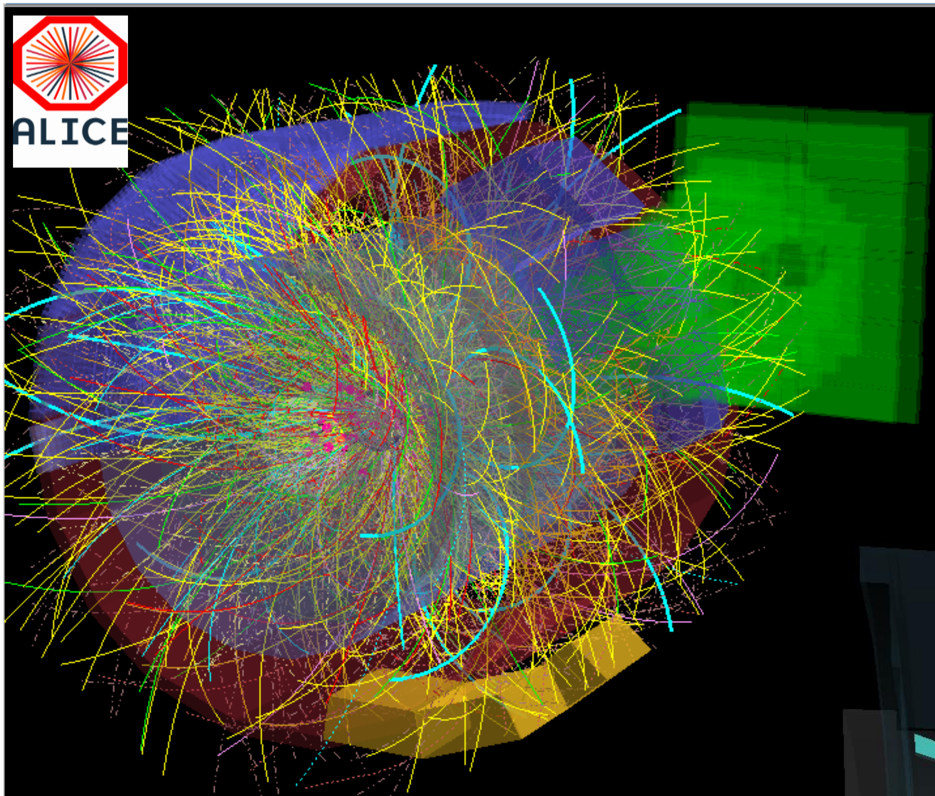


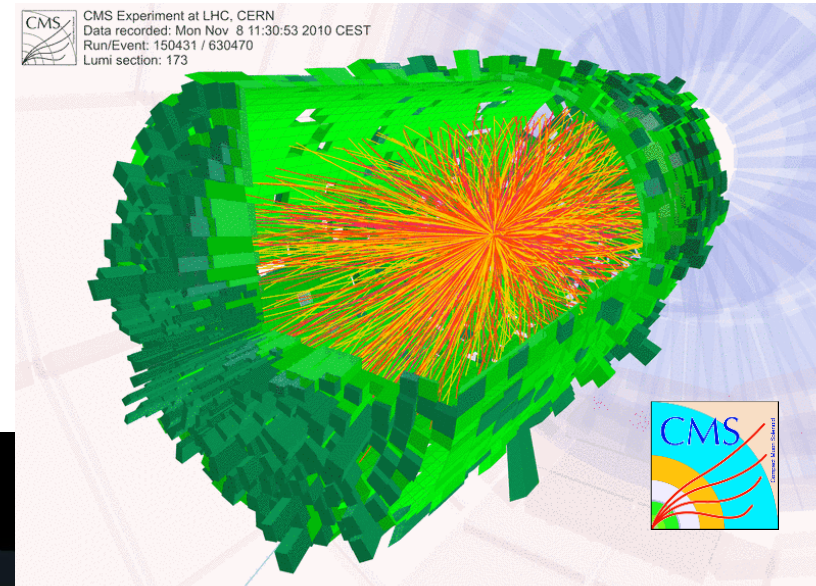
- Tracking (p_T resolution: 1-2% up to $p_T \sim 100$ GeV/c) and calorimetry
- Trigger selectivity over a large range in rapidity and full azimuth

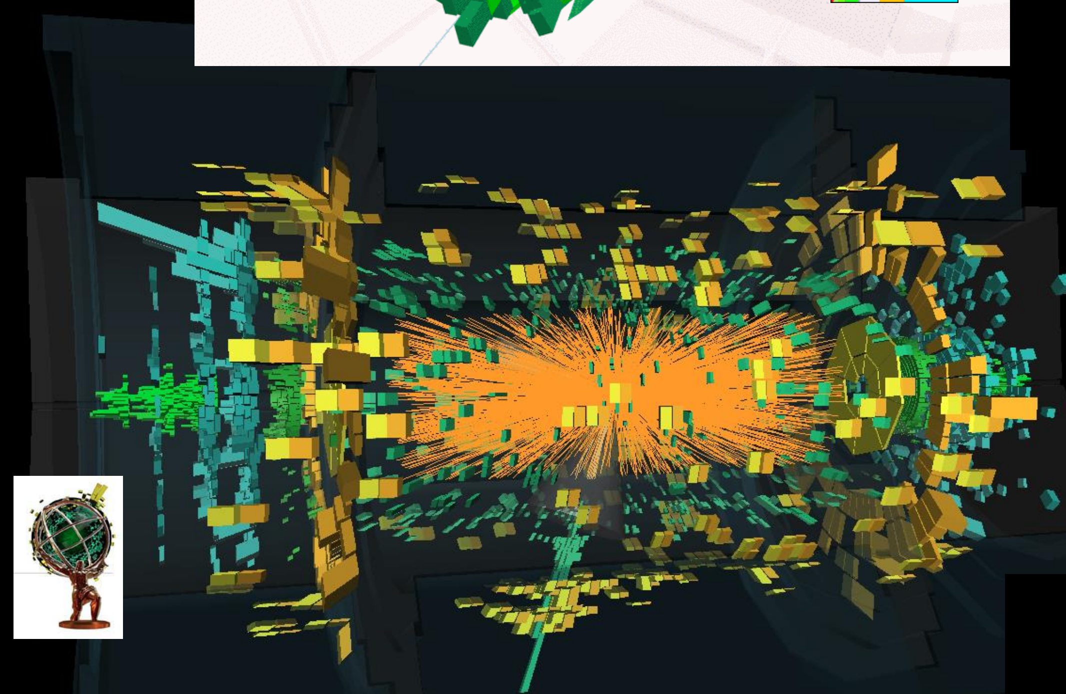


Three main subsystems with a full coverage in azimuth:
- Inner Detector: tracking $|\eta| < 2.5$
- Calorimetry $|\eta| < 4.9$
- Muon Spectrometer $|\eta| < 2.7$

Typical event displays

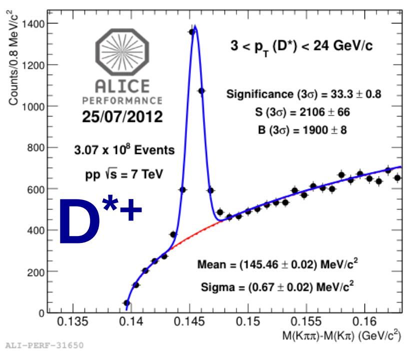


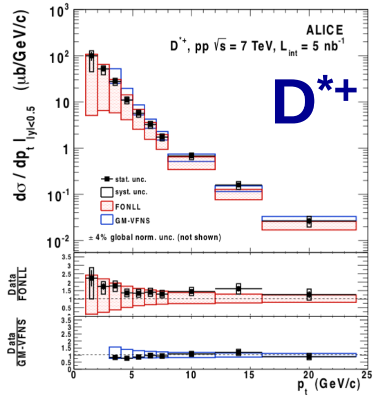


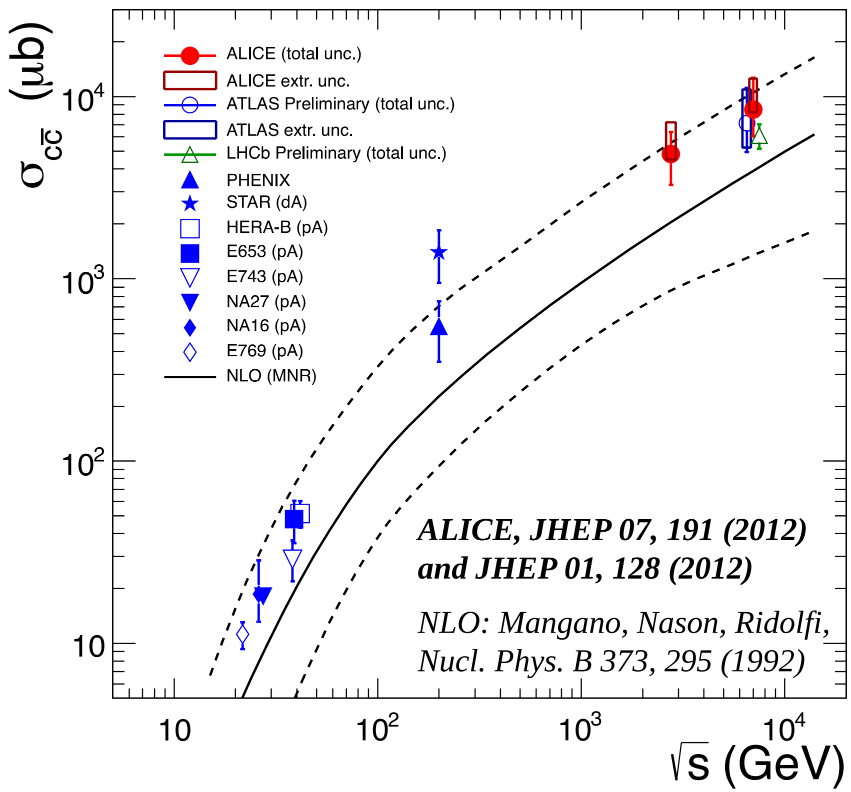


Pb-Pb at $\sqrt{s}$ = 2.76 TeV
per nucleon-nucleon pair

Total charm production cross section in pp

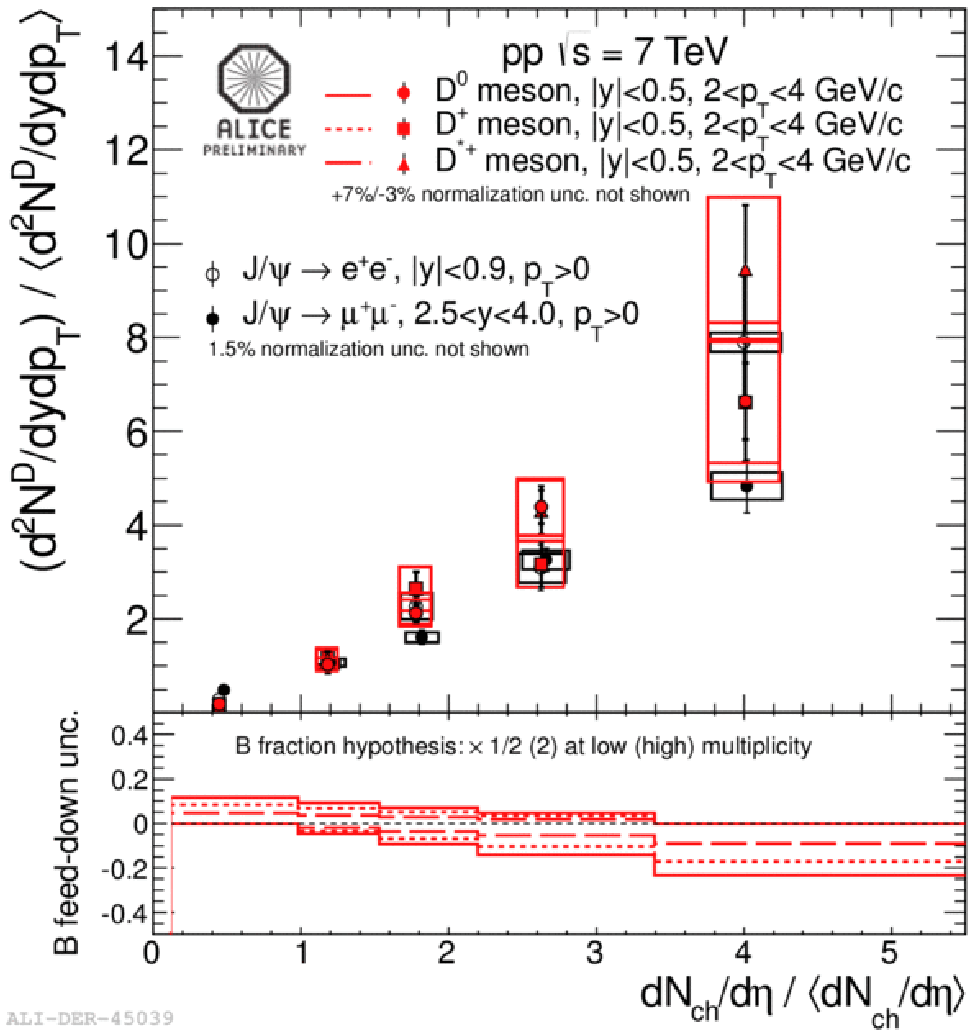






- First collider measurements at TeV scale
- Very good agreement between LHC experiments
- Consistency with NLO pQCD calculations, although at the upper limit
- Baseline for Quarkonia measurements in Pb-Pb
- Parton spectra from pQCD input for energy loss models

Multiplicity dependence of D and J/ψ yields in pp



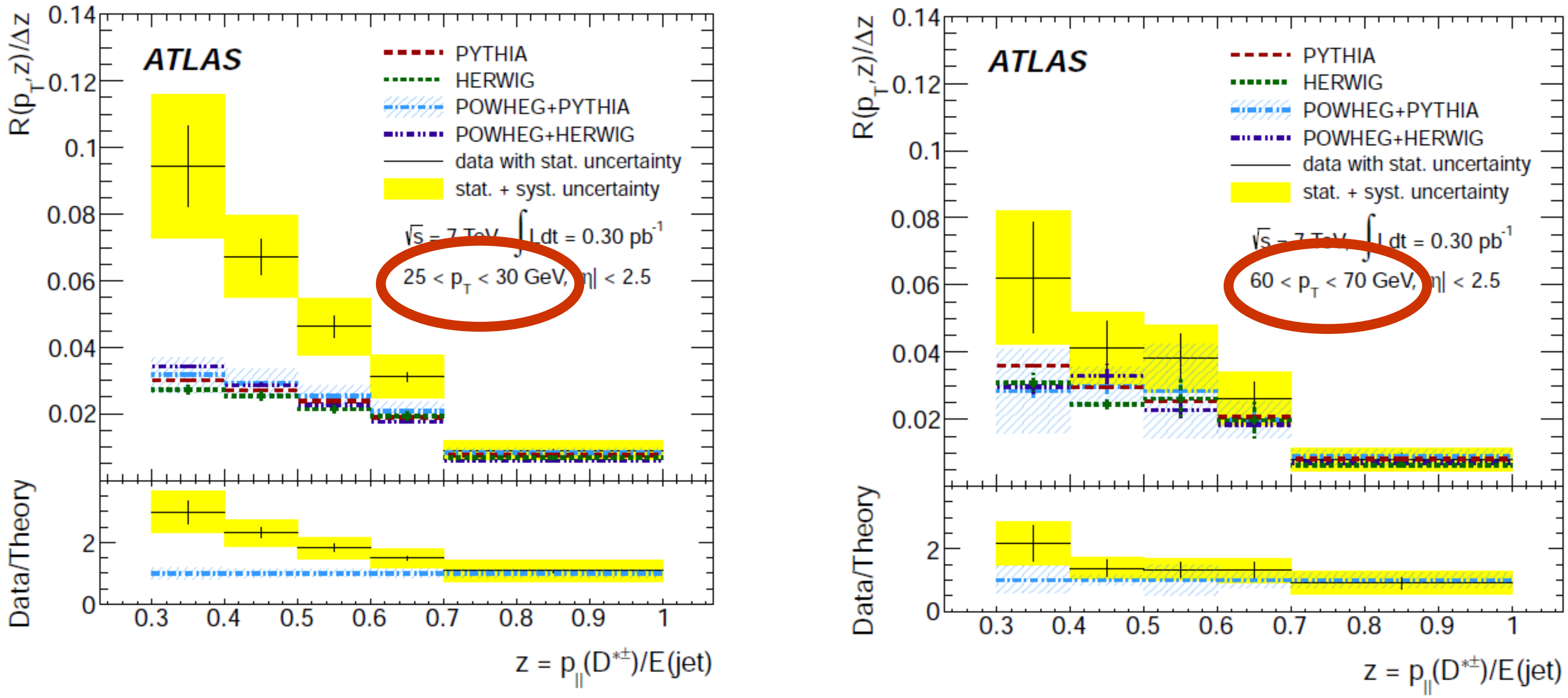
Particle multiplicity

- The ~linear increase of the yields with charged multiplicities and the similar behaviour for D and J/ψ (PLB 712, 165 (2012)) are remarkable

- Due to **multi-parton interactions**?

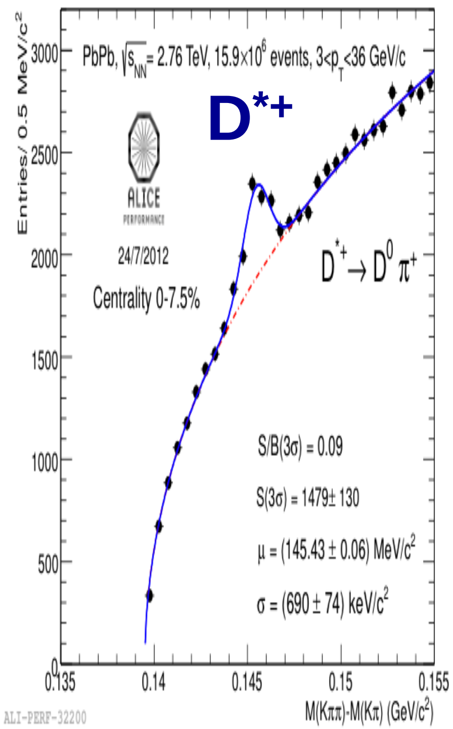
$D^{*\pm}$ production in jets in 7 TeV pp

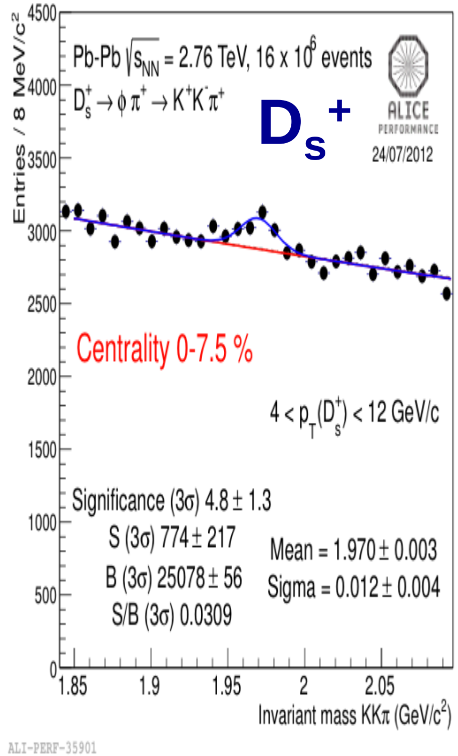
Phys. Rev. D85, 052005 (2012)

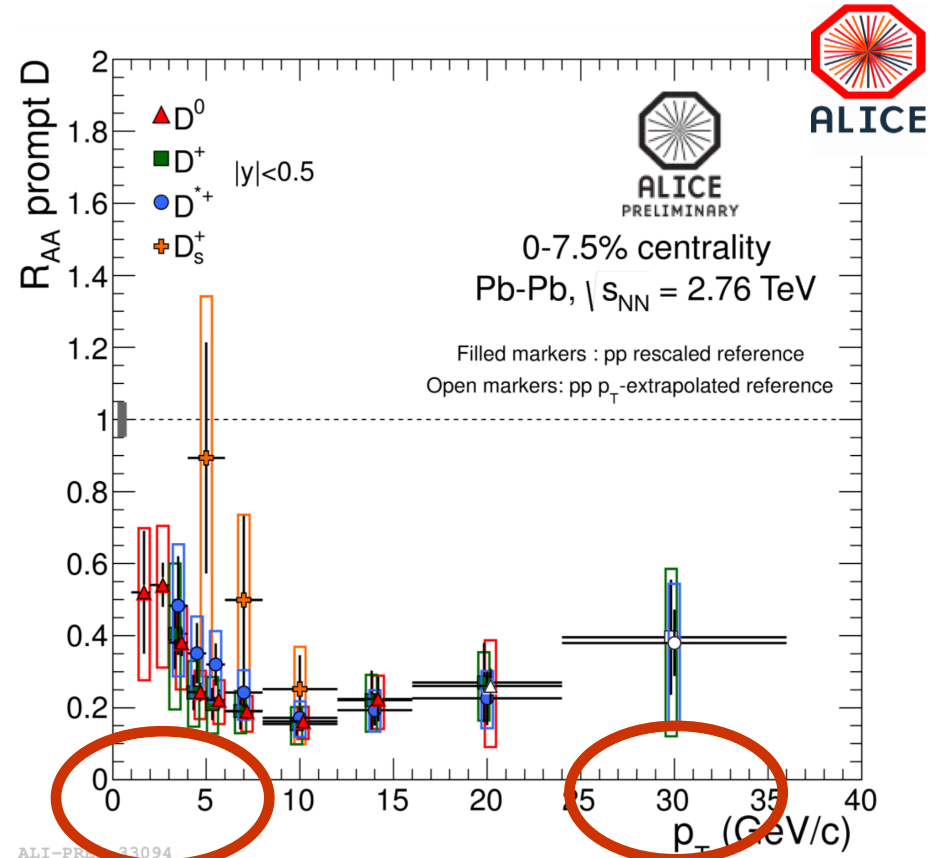


- Monte Carlo calculations fail to describe data at small z
- Strongest at low jet transverse momentum

Prompt D meson R_{AA} in Pb-Pb collisions

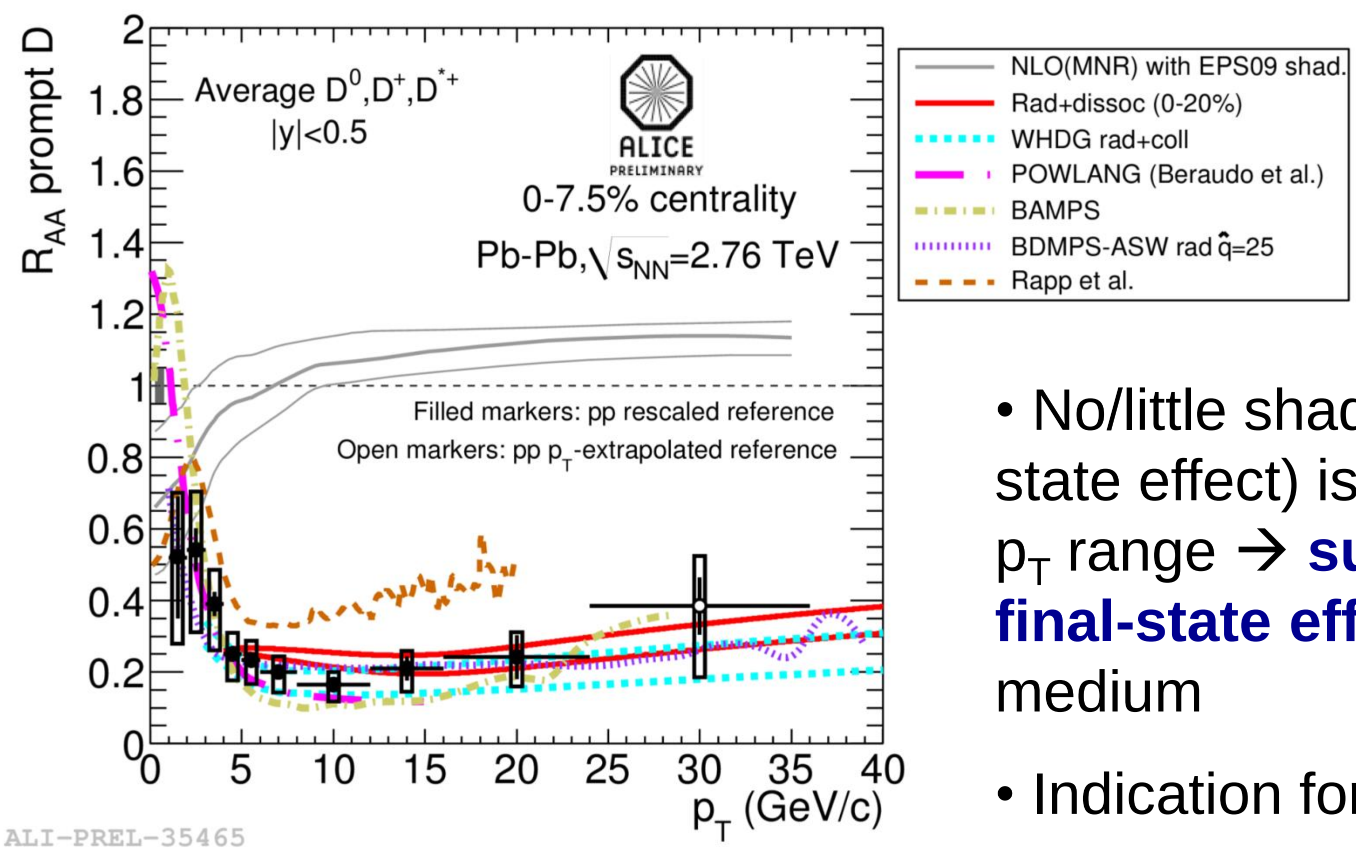






- Strong suppression (factor 4-5) above 5 GeV/c in 7.5% most central Pb-Pb, compared to binary scaling from pp
- First $D_s^+(c\bar{s})$ measurement in heavy ion collisions
- Expectation: enhancement of strange D meson yield at intermediate p_T if charm hadronizes via recombination in the medium

Comparison with model calculations

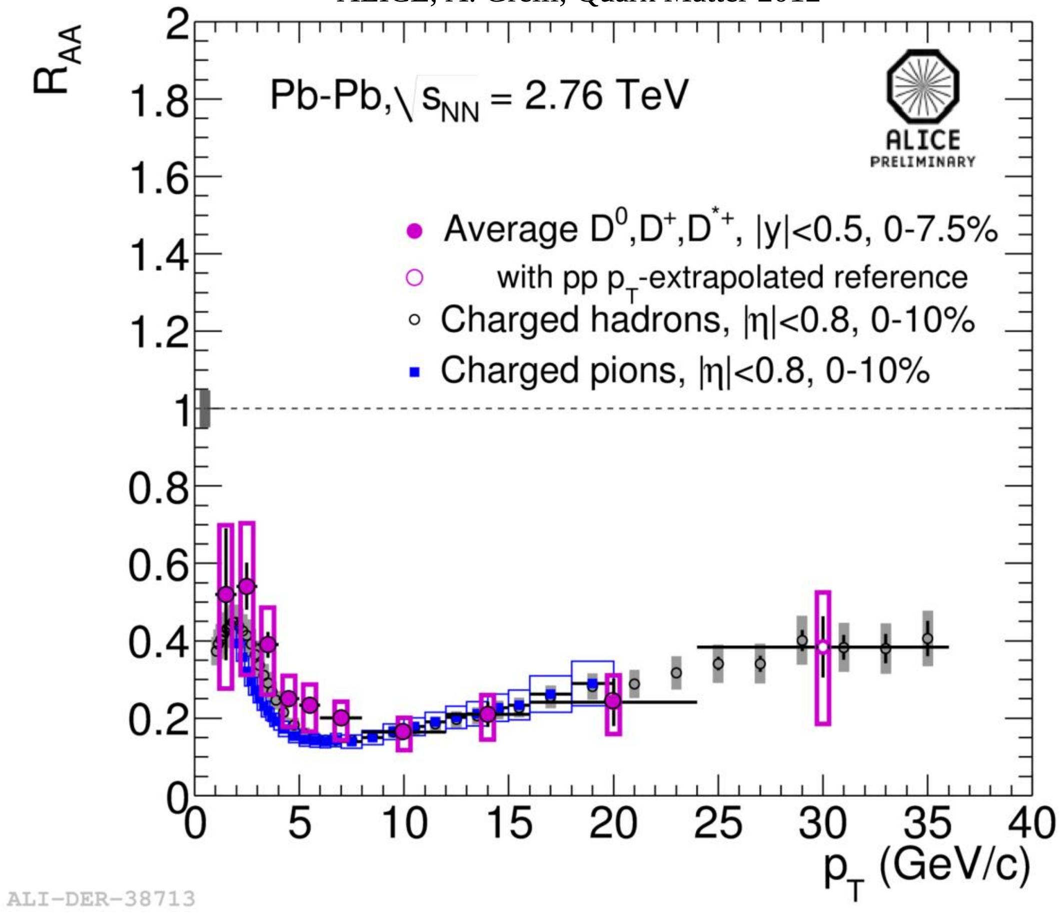


- No/little shadowing (initial-state effect) is expected in this p_T range → **suppression is a final-state effect**; due to hot medium
- Indication for rising R_{AA}?

- Rad.+dissoc.: R. Sharma, I. Vitev and B.W. Zhang, Phys. Rev. C80 (2009) 054902, Y. He, I. Vitev and B.W. Zhang, arXiv: 1105.2566 (2011)
- WHDG (coll.+rad. Eloss in anisotropic medium): W.A. Horowitz and M. Gyulassy, J. Phys. G38 (2011) 124114
- POWLANG (coll. Eloss using Langevin approach): W.M. Alberico, et al., Eur. Phyis J. C71,1666 (2011)
- BAMPS (coll. Eloss in expanding medium): O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G38 (2011) 124152
- Coll. + LPM rad. energy loss: J. Aichelin et al., Phys. Rev. C79 (2009) 044906
- BDMPS-ASW: N. Armesto, A. Dainese, C.A. Salgado and U.A. Wiedemann, Phys. Rev. D71 (2005) 054027
- Coll. Eloss via D mesons resonances excitation + Hydro evolution: M. He, R.J. Fries and R. Rapp, arXiv:1204.4442

R_{AA}: light versus heavy quark hadrons

ALICE, A. Grelli, Quark Matter 2012

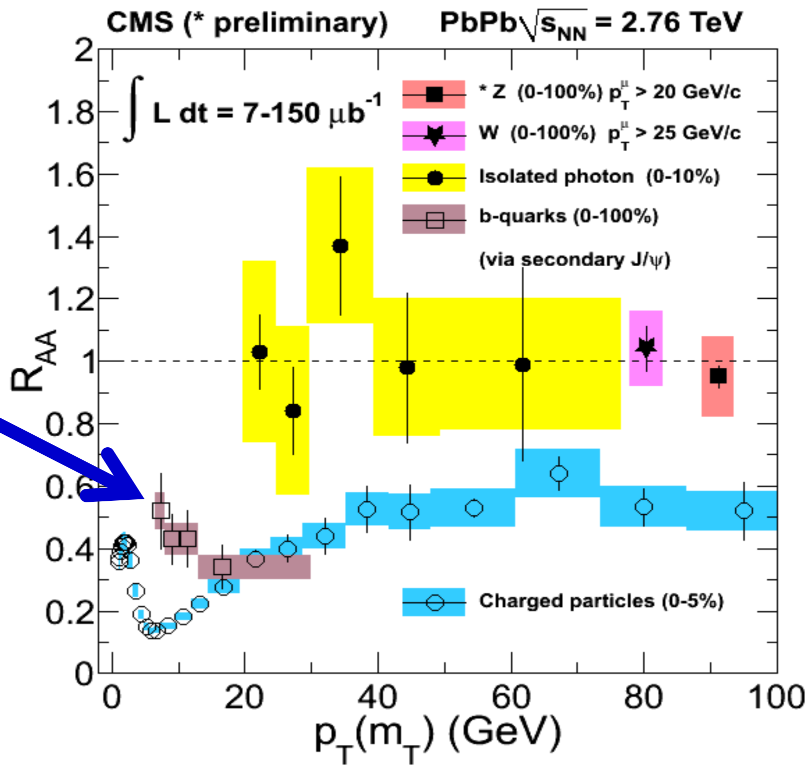


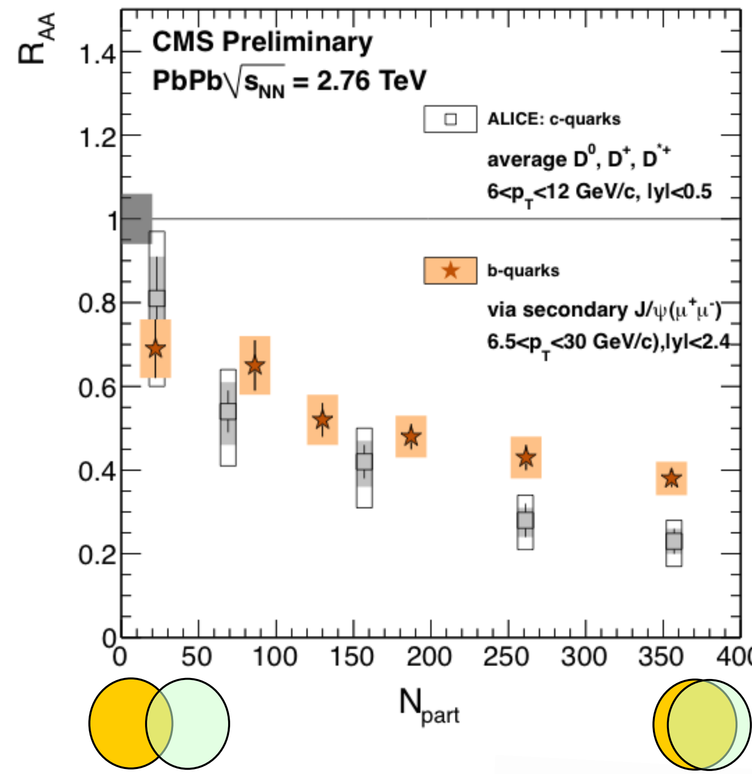
R_{AA}(D meson) > R_{AA}(pions) at low p_T ?

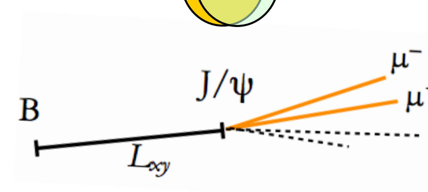
→ More data needed for final conclusion

Beauty R_{AA} via non-prompt J/ψ

CMS, Z boson: CMS PAS HIN-12-008



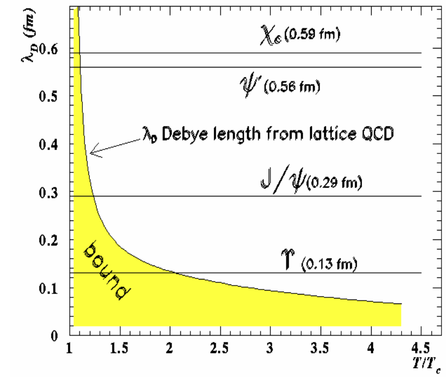




- Non-prompt J/ψ in the most central collision (0-10%) is suppressed by a factor of 2.5
- CMS non-prompt J/ψ consistent with ALICE single μ R_{AA} (not shown)
- R_{AA}(charm) < R_{AA}(beauty)

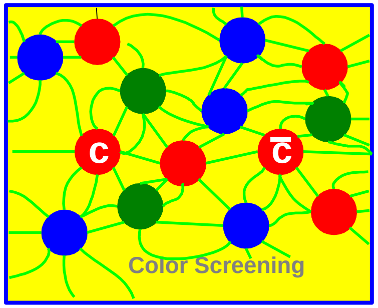
Quarkonia production in hot QCD matter

- Colour screening length λ_D in the deconfined medium decreases with temperature



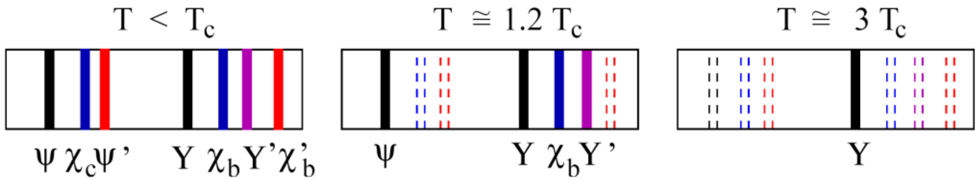
- Quarkonia "melt" when their binding distance becomes bigger than screening length → yields suppressed (one of the first QGP signatures)

T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416



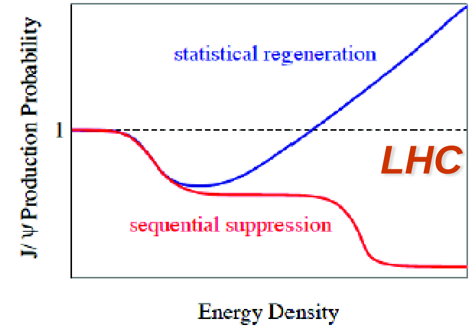
- Screening at different temperature for different states (binding energy) → sequential suppression of the quarkonium states → QCD thermometer

S. Digal, P. Petreczky and H. Satz, Phys. Rev. D 64 (2001) 0940150

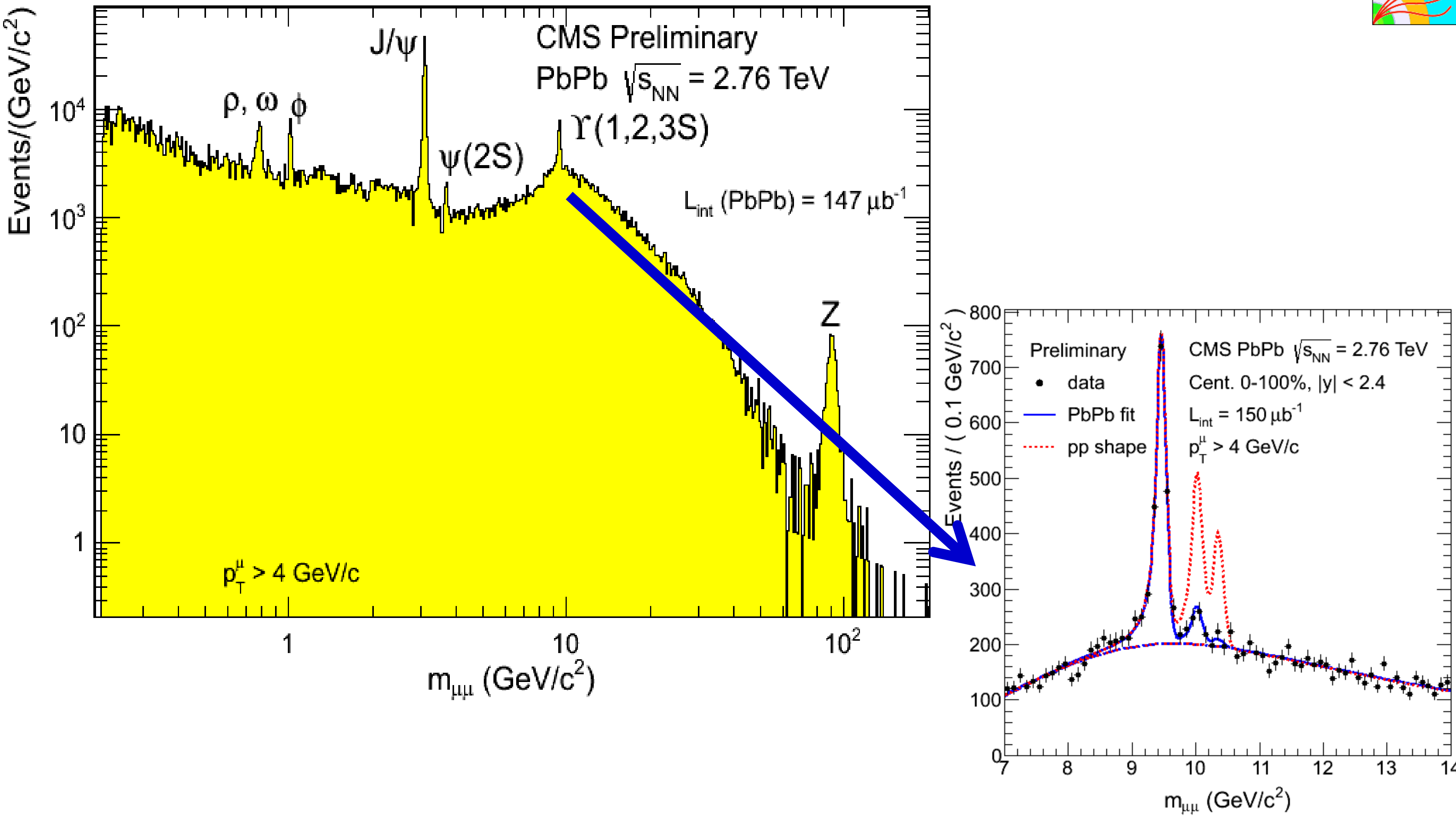


- Enhancement via (re-)generation of quarkonium states due to large heavy quark multiplicity

A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Phys. Lett. B 571(2003) 36

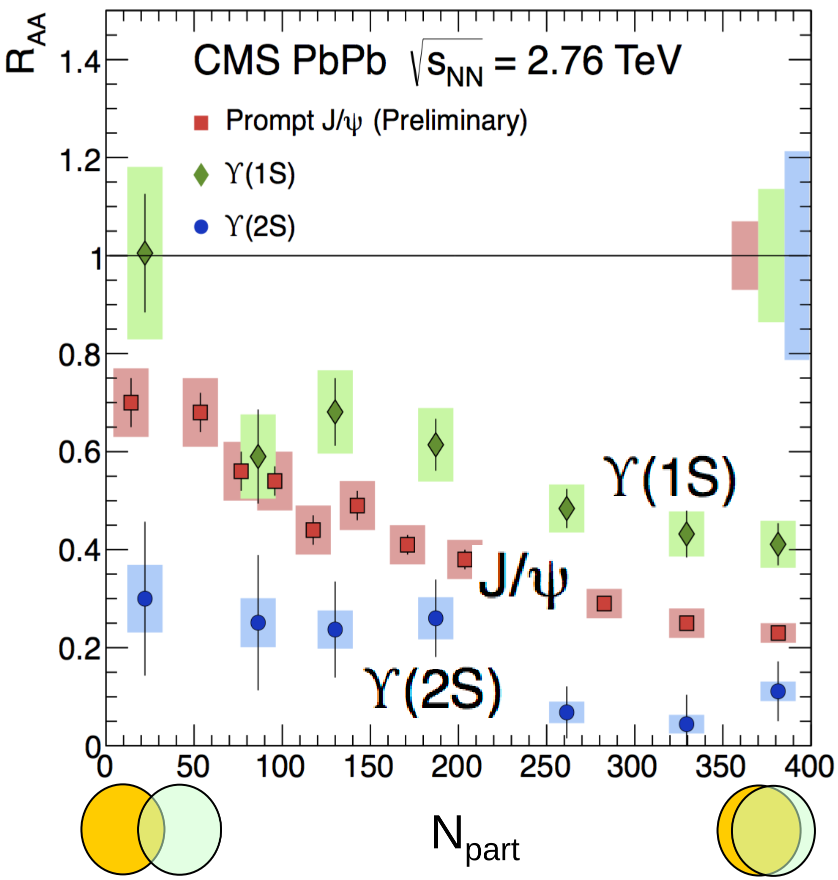


Di-muon invariant mass distribution in Pb-Pb

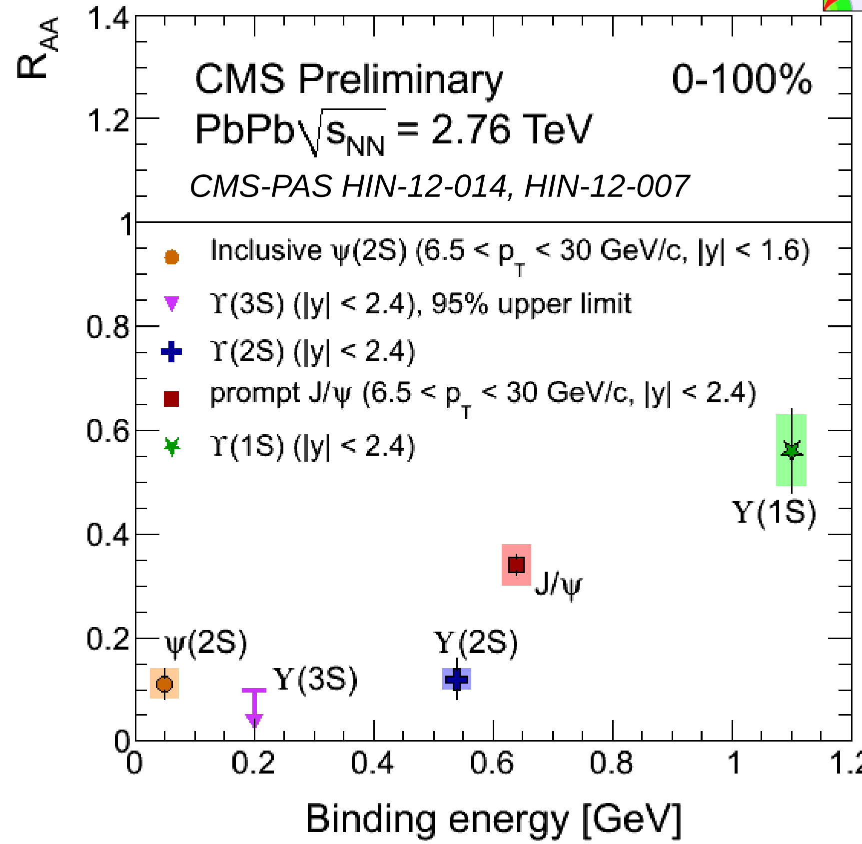


R_{AA} of Quarkonia states in Pb-Pb

Phys. Rev. Lett. 109, 222301 (2012))



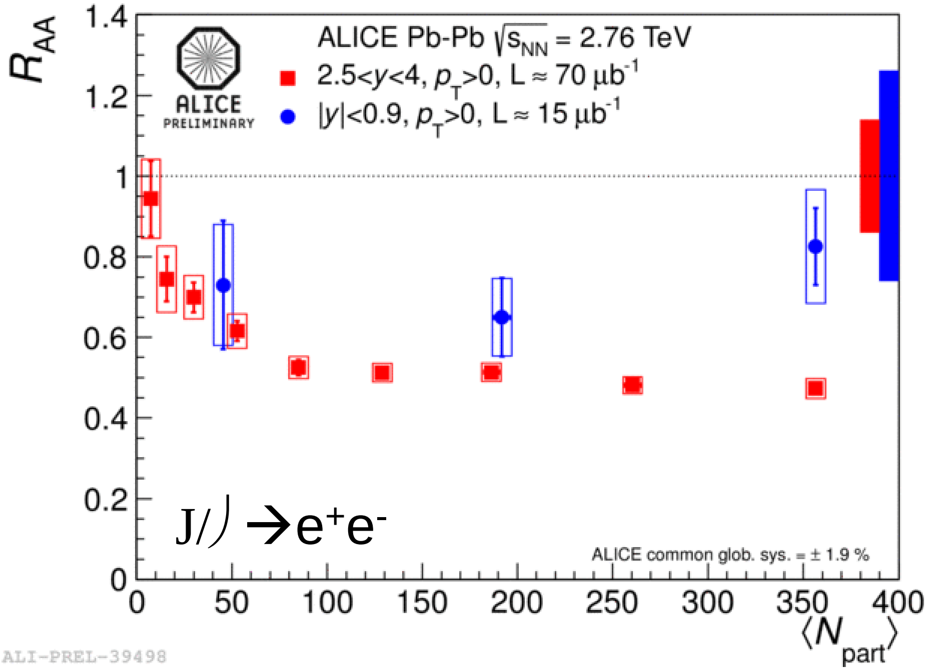
Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)

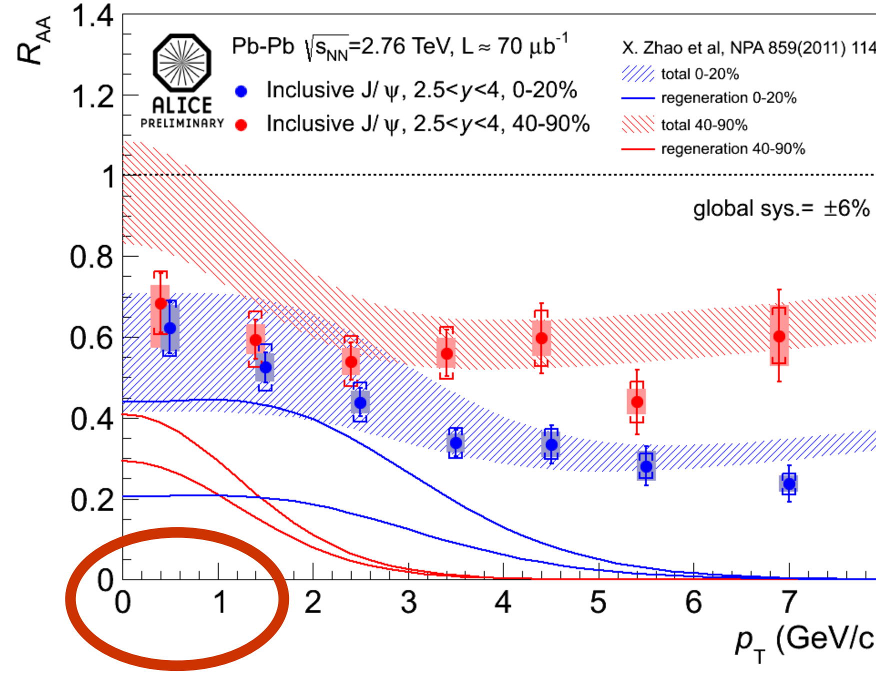


Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

R_{AA} of inclusive J/ψ





Hint for enhanced J/ψ production from forward to mid-rapidity

- Enhanced production at low p_T
- Comparison with transport model calculations: sizeable QGP regeneration component needed

Summary

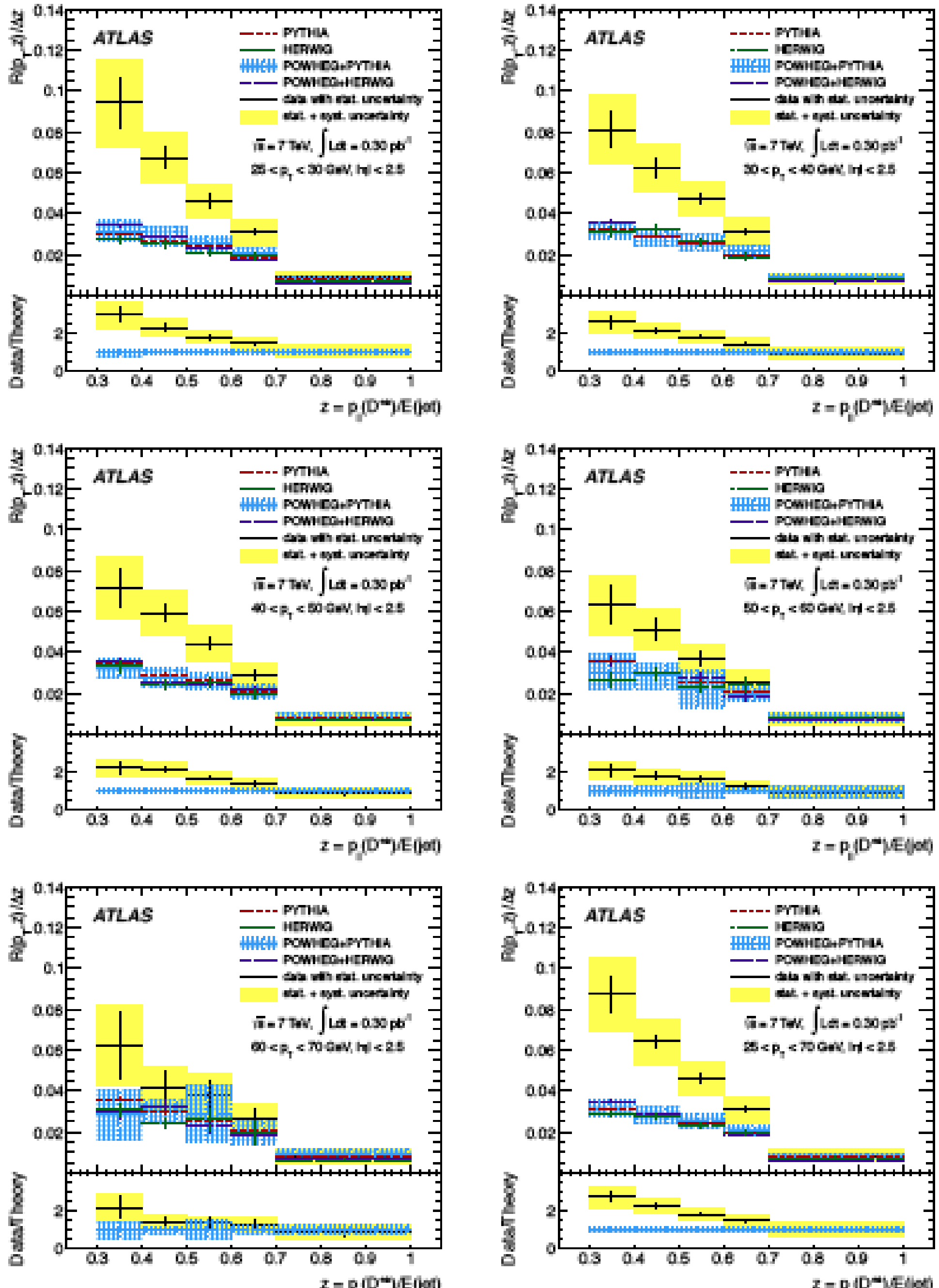
- Heavy quarks
  - particularly good probes to study the properties of hot quark matter; especially its transport properties (e.g. drag diffusion coefficient)
  - abundantly produced at LHC energies → allow precision measurements
- Lots of new data from Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- ALICE: R_{AA} of prompt D mesons, single electrons and muons
  - strong suppression at high p_T observed in most central collisions
  → more insight on energy loss mechanism(s)
- CMS: b-quark quenching via $B \rightarrow J/\psi$

→ $R_{AA}(\pi) \sim R_{AA}$(D, single leptons) $\leq R_{AA}(B \rightarrow J/\psi)$

- Quarkonia data
  - observation of sequential melting of Y family
  - sizeable regeneration needed to describe J/ψ data
- Many more exciting results with
  - 2013 p-Pb data: important baseline measurement of cold nuclear matter effects (Cronin effect, nuclear shadowing, gluon saturation)
  - 2015 5.5 TeV Pb-Pb run

Thank you

Backup


ATLAS
PYTHIA
HERWIG
POWHEG+PYTHIA
POWHEG+HERWIG
data with stat. uncertainty
stat. + syst. uncertainty
√s = 7 TeV, ∫Ldt = 0.30 pb⁻¹
25 < p_T < 30 GeV, |η| < 2.5
30 < p_T < 40 GeV, |η| < 2.5
40 < p_T < 50 GeV, |η| < 2.5
50 < p_T < 60 GeV, |η| < 2.5
60 < p_T < 70 GeV, |η| < 2.5
25 < p_T < 70 GeV, |η| < 2.5
R(p_T, z) / Δz
Data/Theory
z = p_∥(D*±)/E(jet)

Cold nuclear matter effects: p-Pb

- Important baseline measurement of **cold nuclear matter effects** (Cronin effect, nuclear shadowing, gluon saturation)
- p-Pb run at $\sqrt{s_{NN}}$ = 5.02 TeV in February 2013

~130M minimum bias events (30 nb^{-1})

First publications

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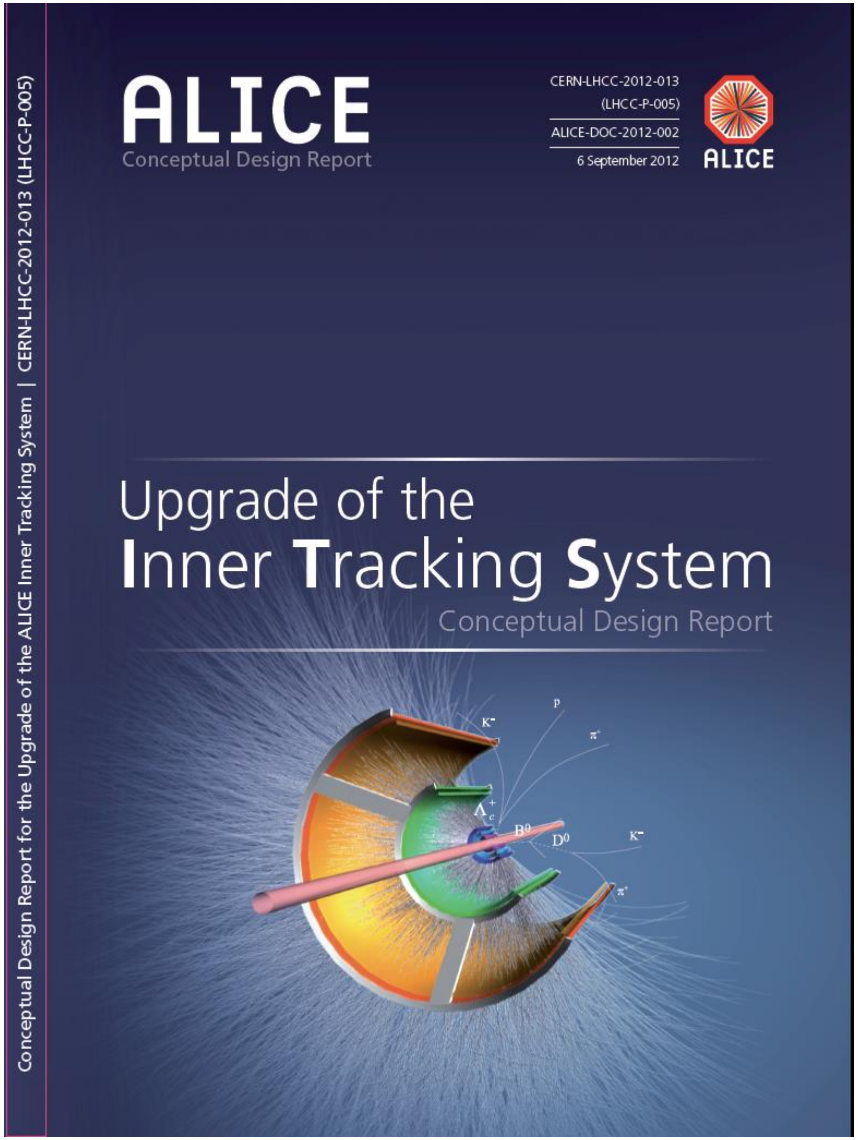
…

Upgrade of the ALICE Inner Tracker



- New Inner Tracking System based on 7 silicon layers
- Factor □3 improvement in impact parameter resolution
- Low material budget
  ($X/X_0 \leq 0.3\%$ for first 3 inner silicon layers possible)

Detection of open heavy-flavor particles

Full reconstruction of open charmed mesons

$D^0 \rightarrow K^- + \pi^+$ (BR = 3.89%), $c\tau$ = 123 μm

→ direct clean probe: signal in invariant mass distribution

→ difficulty: large combinatorial background especially in a high multiplicity environment

→ mixed-event subtraction and/or vertex tracker needed

Semi-leptonic decay of D and B mesons

$c \rightarrow$ lepton + X (BR = 9.6%)

$D^0 \rightarrow e^+ + X$ (BR = 6.87%)

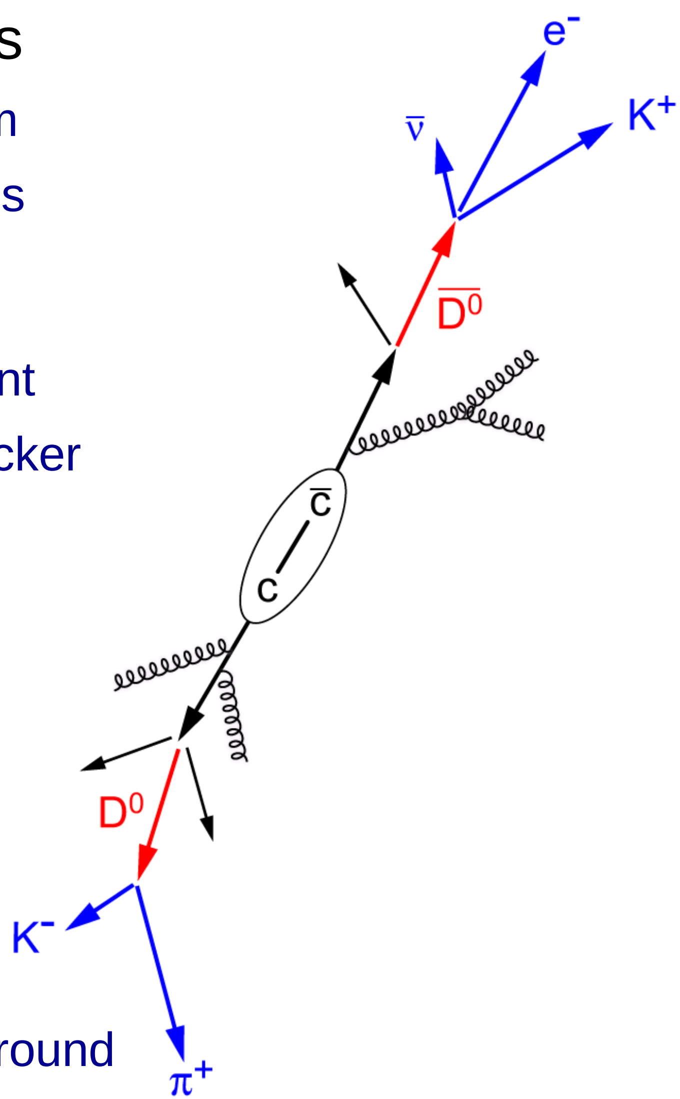
$D^0 \rightarrow \mu^+ + X$ (BR = 6.5%)

$b \rightarrow$ lepton + X (BR = 10.9%)

→ robust electron trigger

→ needs handle on photonic electron background

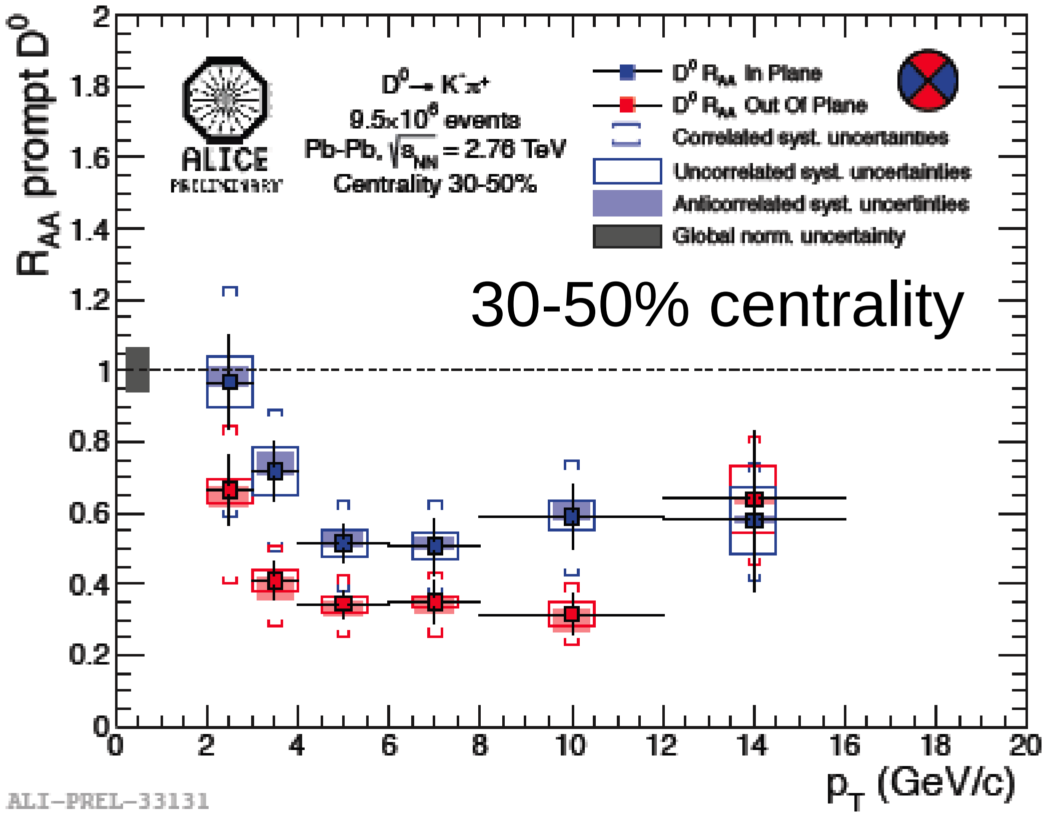
Beauty via non-prompt J/ψ

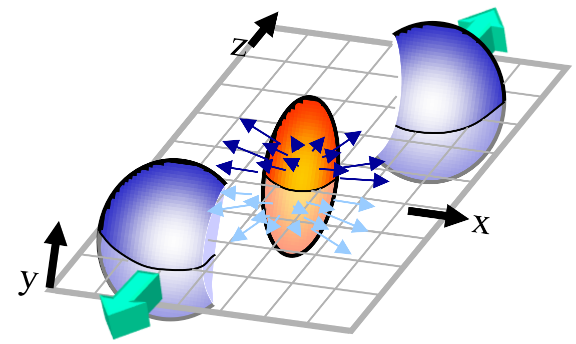


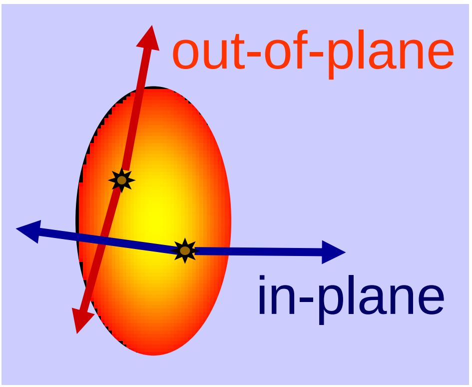
Tentative LHC schedule

2010/11:	long run with pp collisions at 7 TeV 1 month of Pb-Pb collisions each year
2012:	long run with pp at 8 TeV
2012/13:	p-Pb control measurement
2013/14:	machine consolidation and training
2014:	pp and Pb-Pb at full energy
2017/18:	long shutdown, luminosity and detector upgrades
2019:	pp and Pb-Pb at high luminosity

Prompt D^0 meson R_{AA} versus event plane

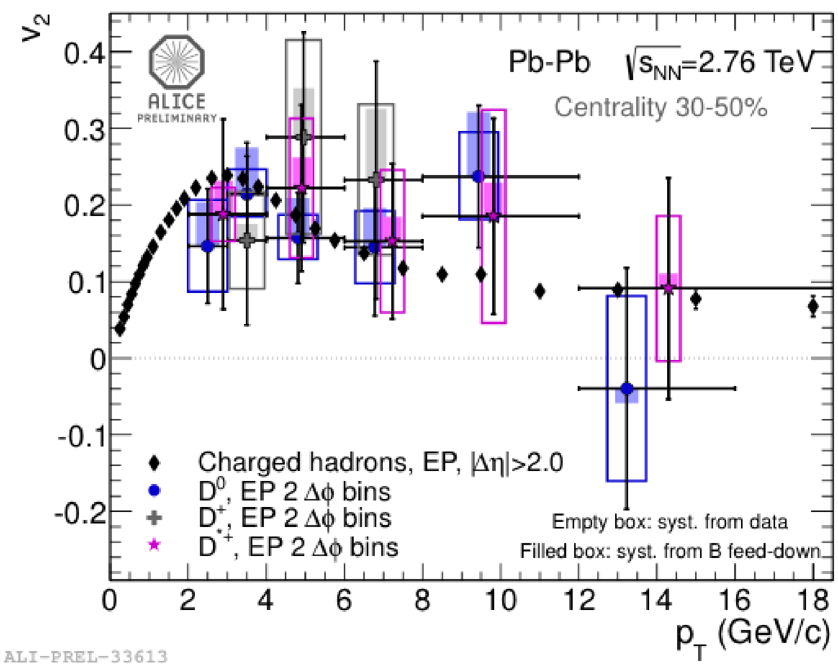


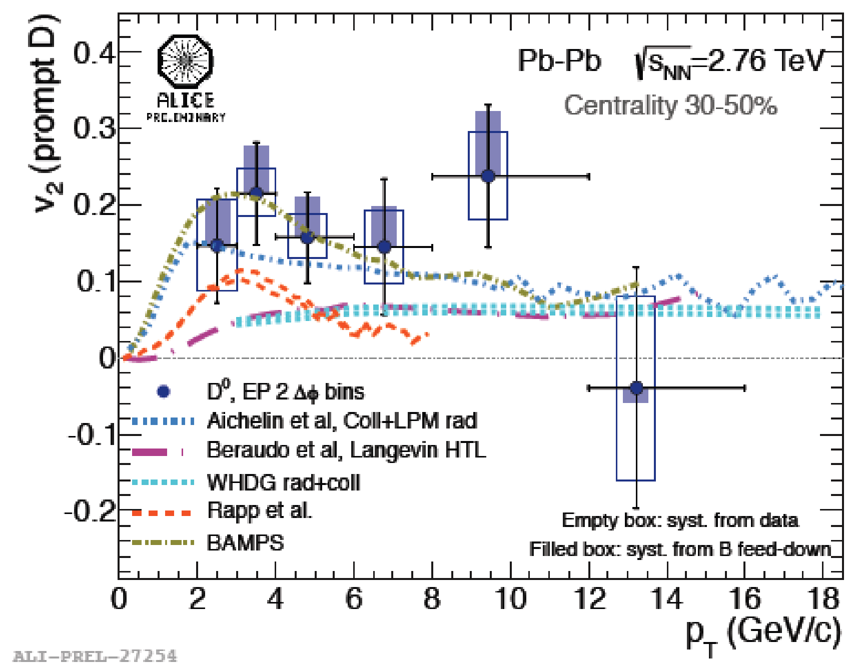




More suppression at high p_T out-of-plane with respect to in-plane due to different path length

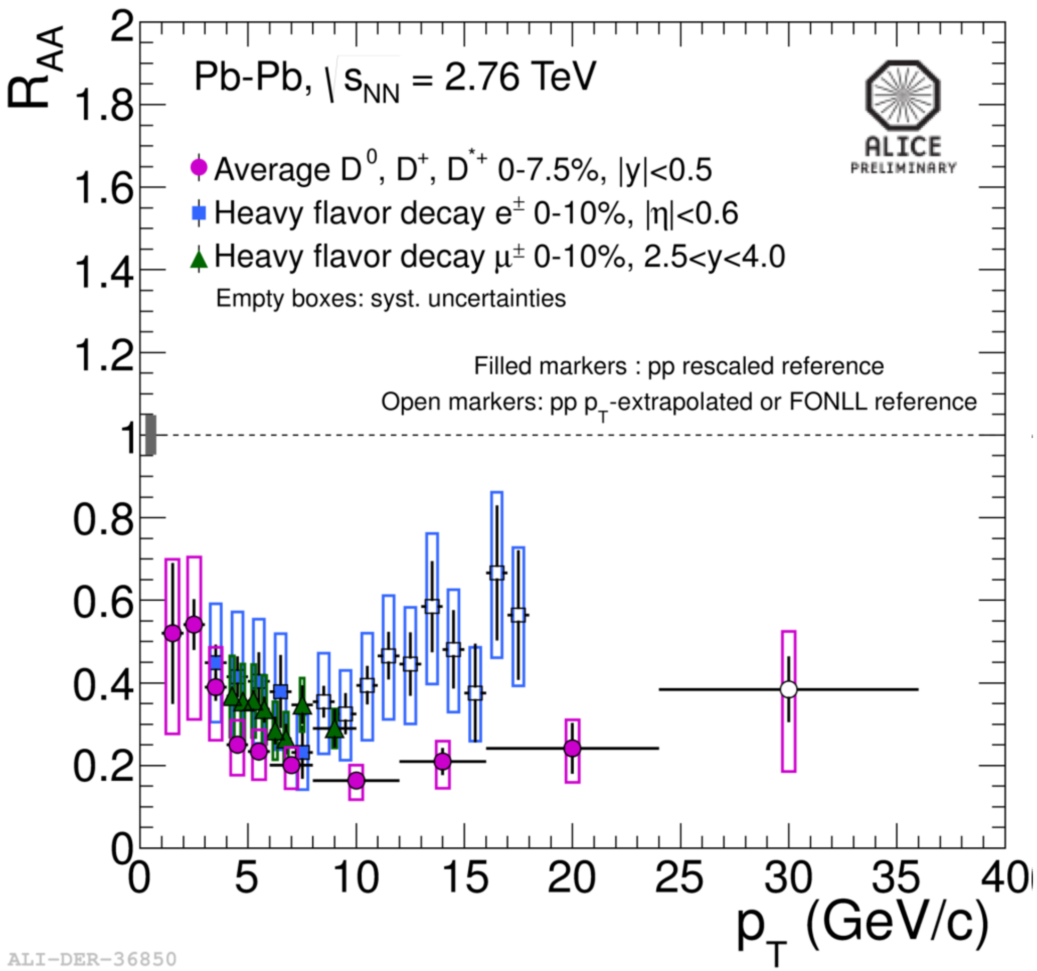
Azimuthal anisotropy of prompt open charm





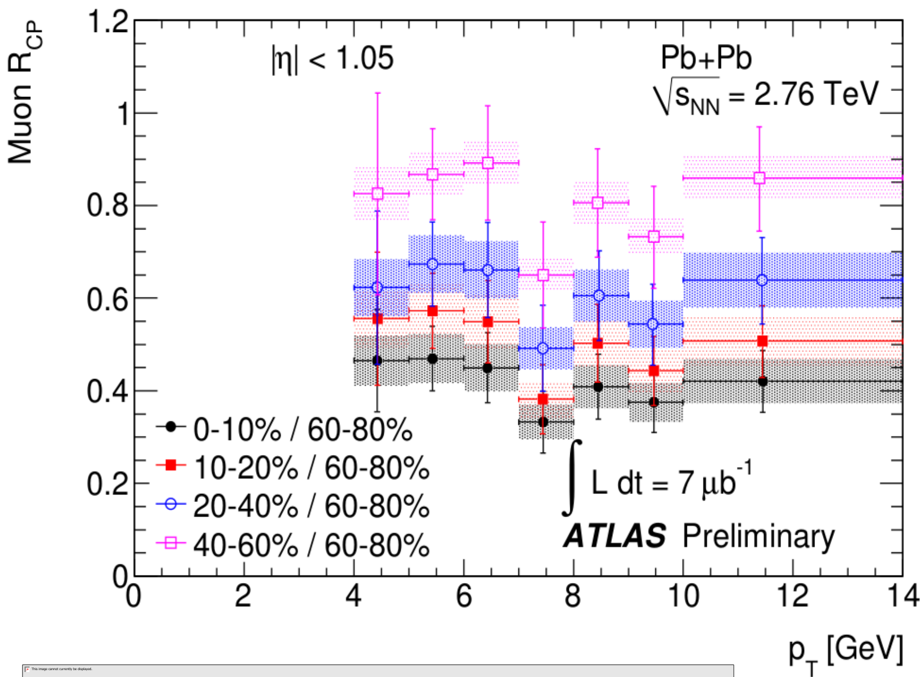
- Pressure gradient generates collective flow → anisotropy in momentum space; Fourier decomposition $\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)]$
- Indication (3σ) for non-zero charm elliptic flow at low p_T
- **Models needs to simultaneously describe v_2 and R_{AA}**; stringent constraint, gets tougher with more precision/data

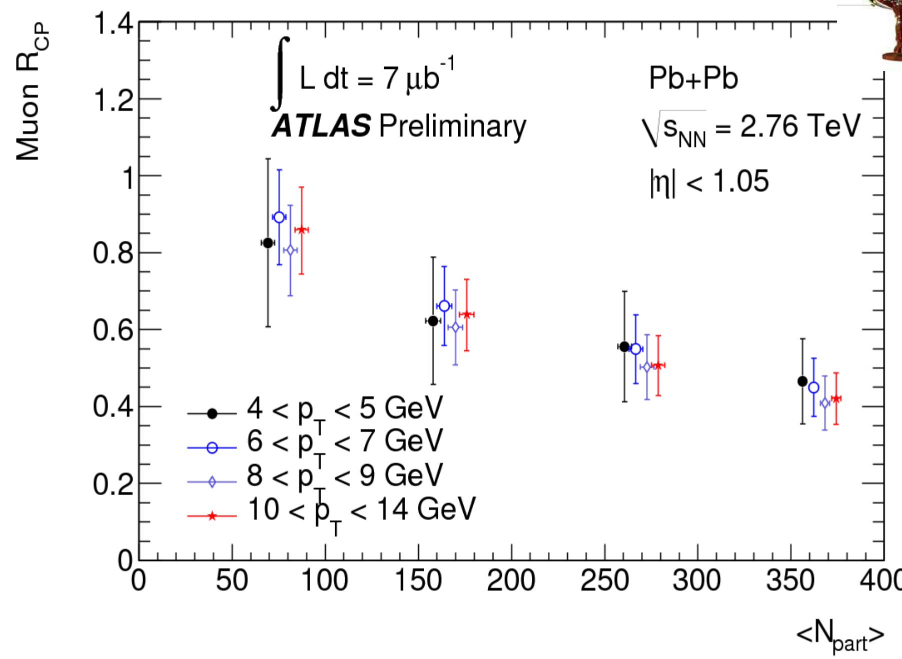
Single muons at forward rapidity



- Strong suppression of high-p_T muons from heavy flavour decays
- No significant dependence on p_T in 4 < p_T < 10 GeV/c
- Similar to single electron and D meson R_{AA} at central rapidity
- R_{AA}(single e) > R_{AA}(D) at p_T > 8 GeV/c due to beauty contribution

ATLAS: Single muon R_{CP}

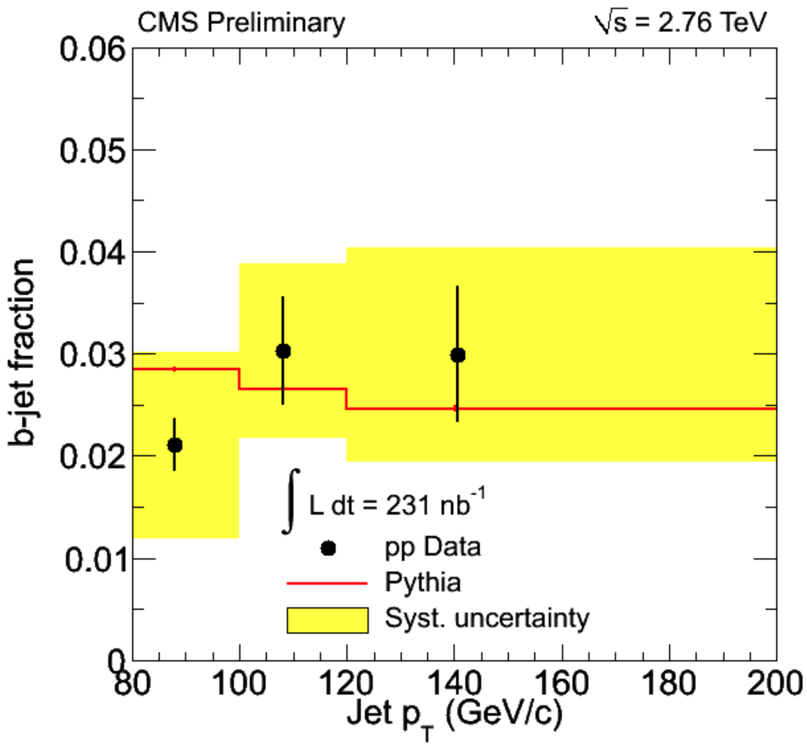


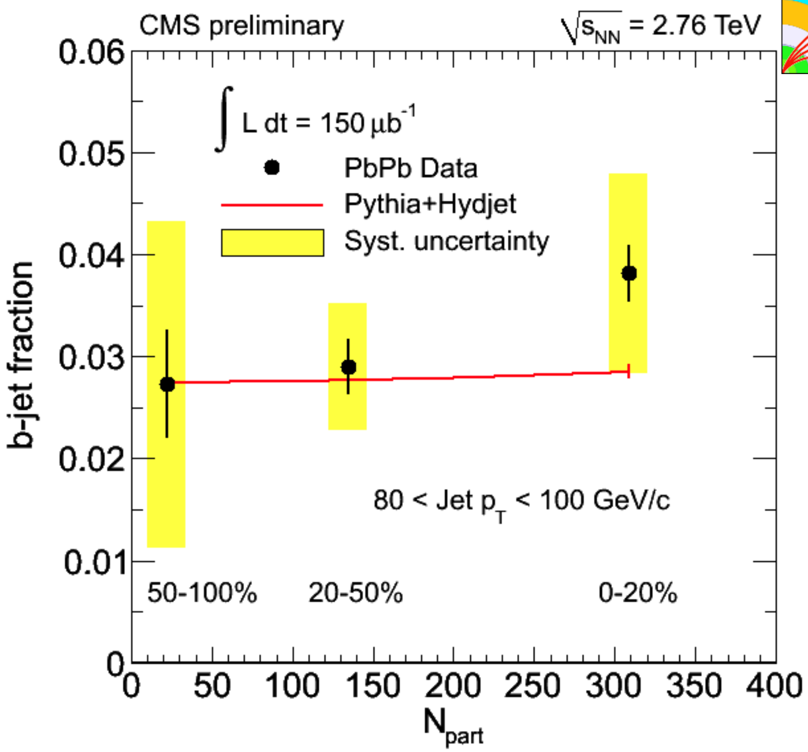


- A factor of 2 suppression 0-10%/60-80%, independent of p_T
- Indications for weaker suppression than for charged hadrons and as compared to RHIC electron results

b-tagged jets

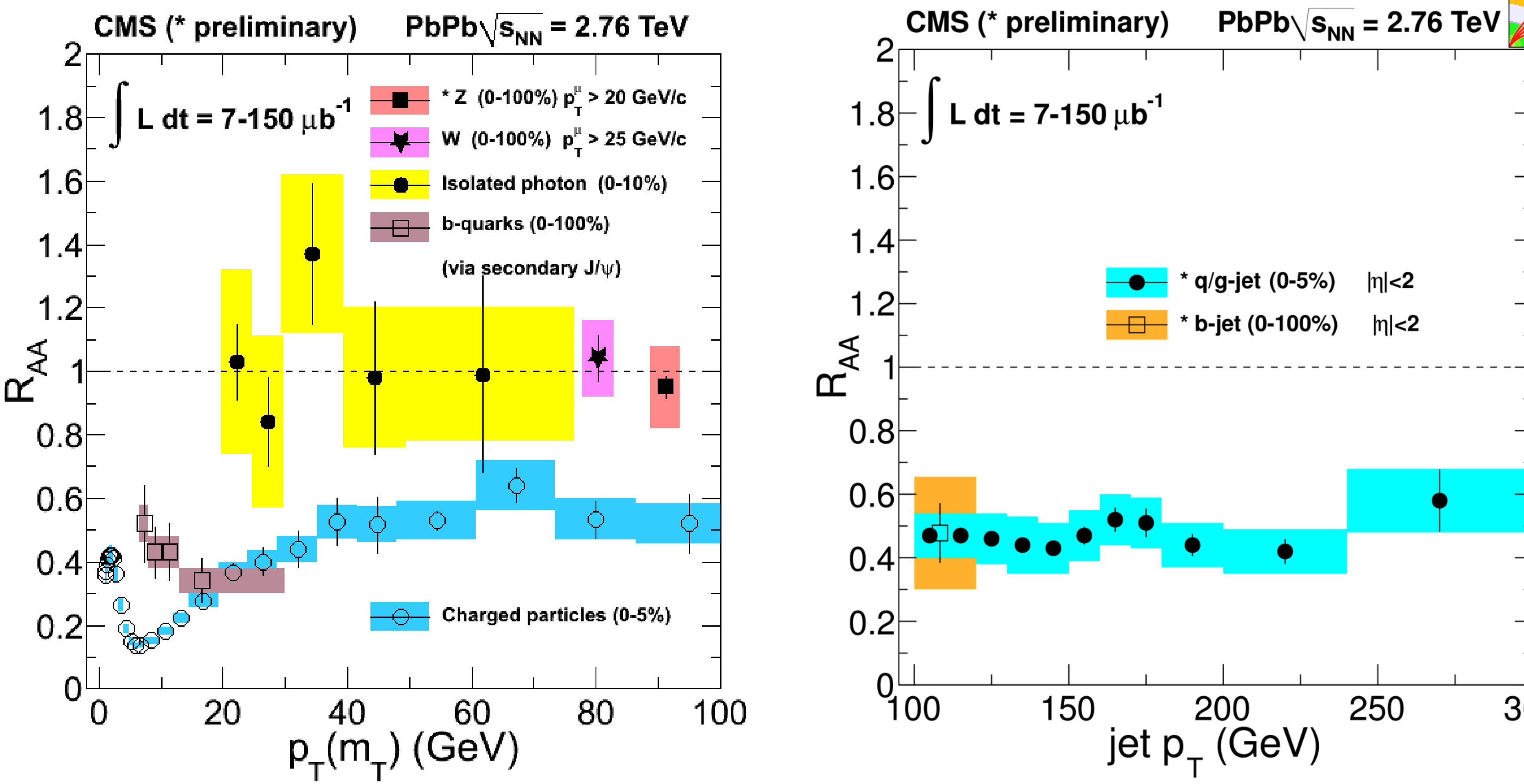
CMS-PAS HIN-12-003





- Jets from b-quark fragmentation are identified for the first time in heavy ion collisions
  - Jets are tagged by their secondary vertices
  - b-quark contribution is extracted using template fits to their secondary vertex mass distributions

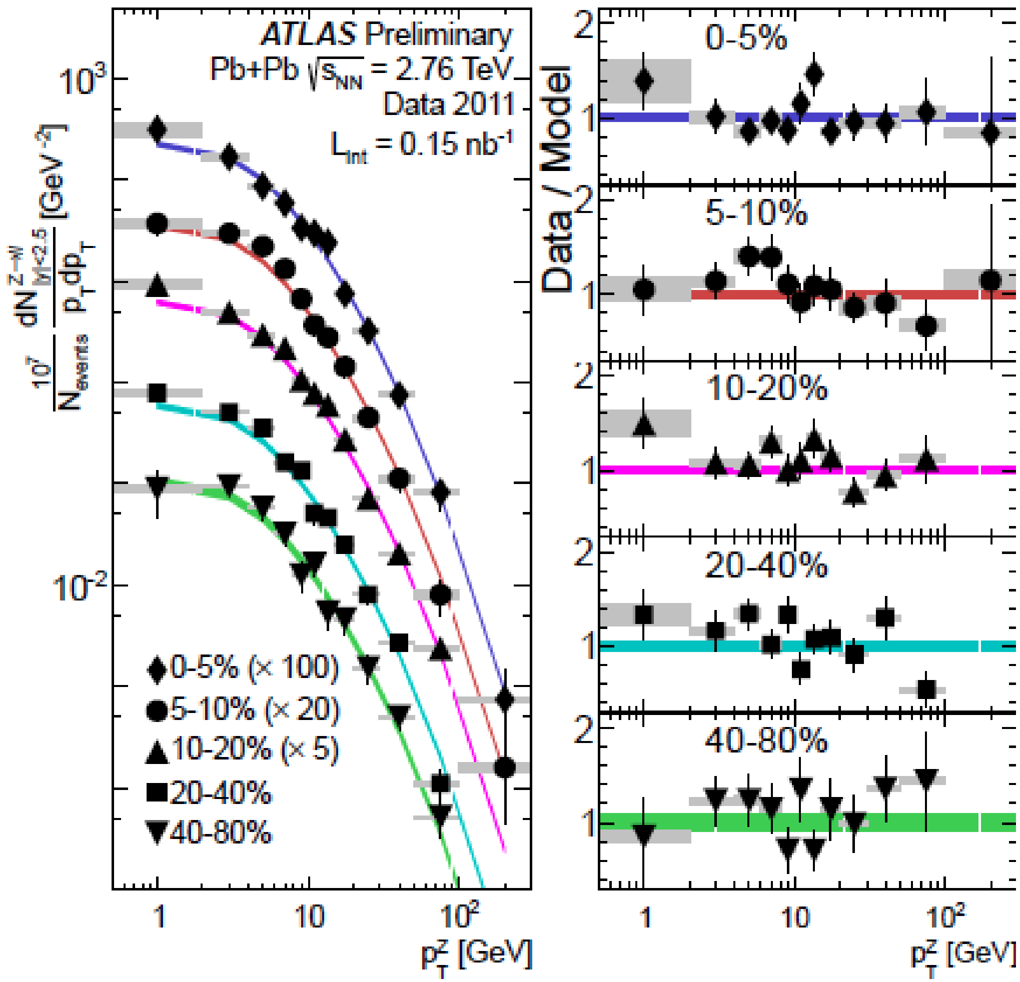
Inclusive and b-jets



Distinct b-quark suppression pattern at low p_T

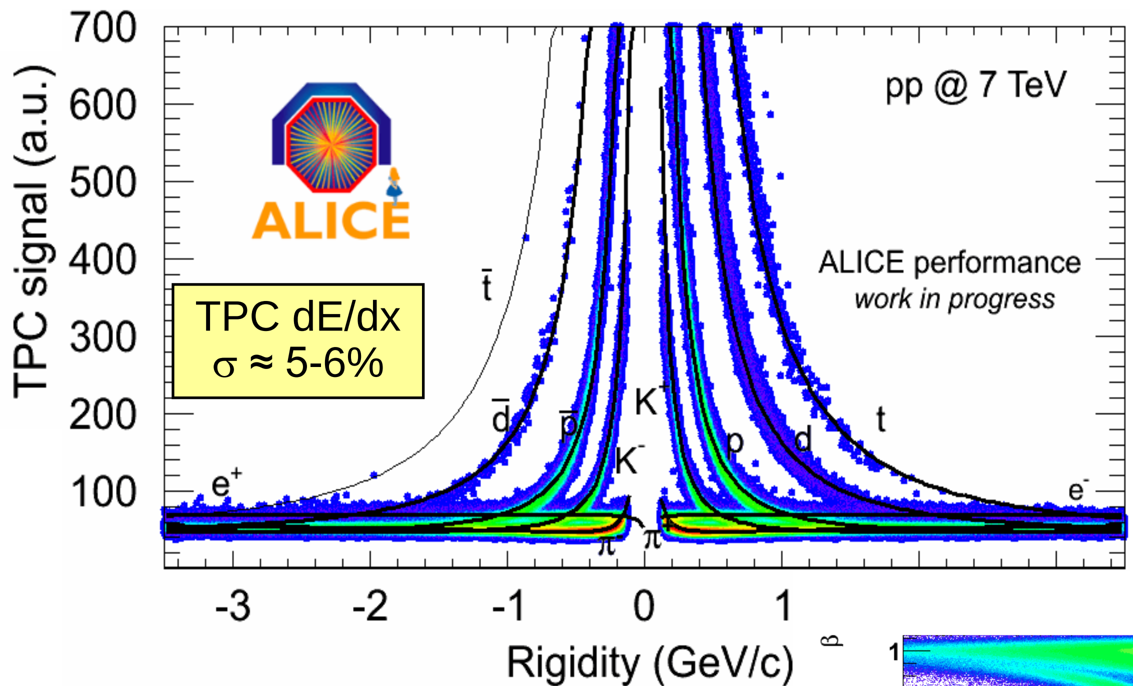
First observation of b-jet suppression at high p_T

Centrality dependence of Z boson p_T spectra

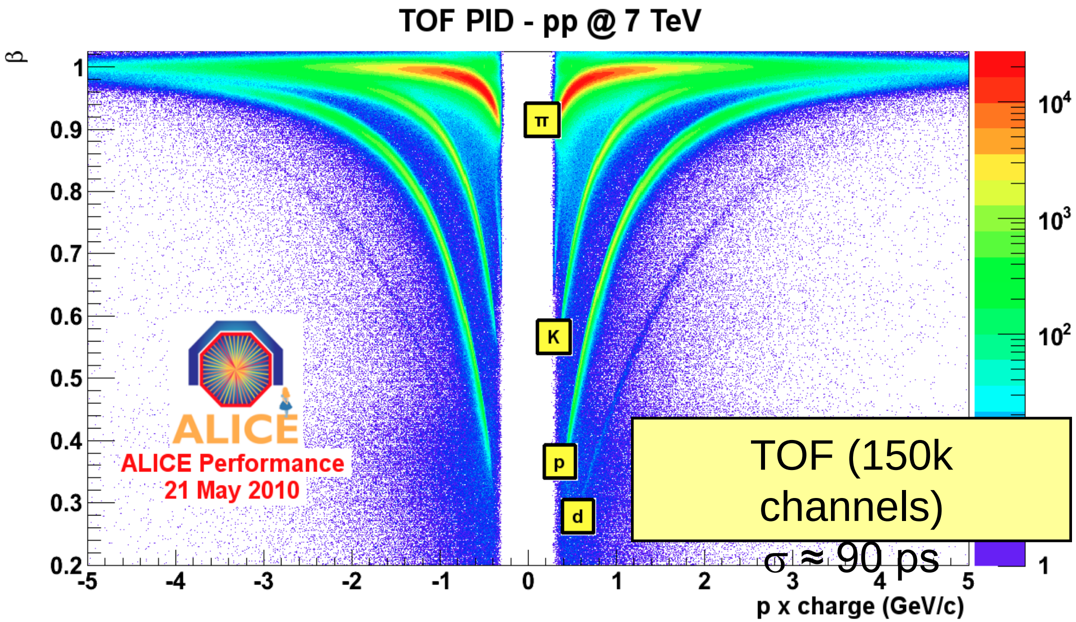


- $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$
- p_T and y (not shown) distributions consistent with Pythia simulations for pp with NNLO cross section times $\langle T_{AA} \rangle$
- Yields consistent with N_{coll} scaling

Particle Identification



Specific ionisation energy loss; PID based on comparison with Bethe-Bloch curves



PID based on comparison of time of flight with particle mass hypothesis

Explore energy loss mechanisms in more detail

MC simulations

$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \frac{\omega \frac{dI}{d\omega}\Big|_{LIGHT}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

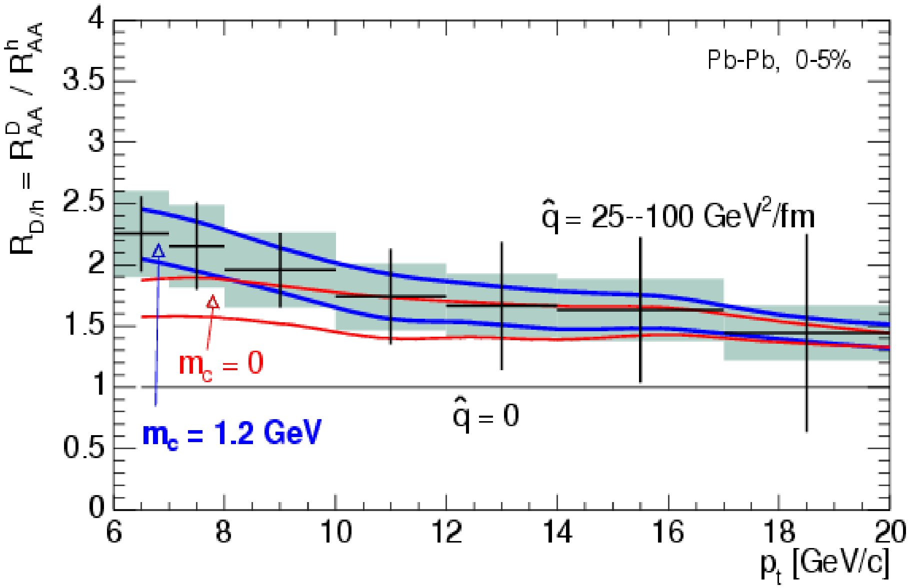
Colour charge dependence

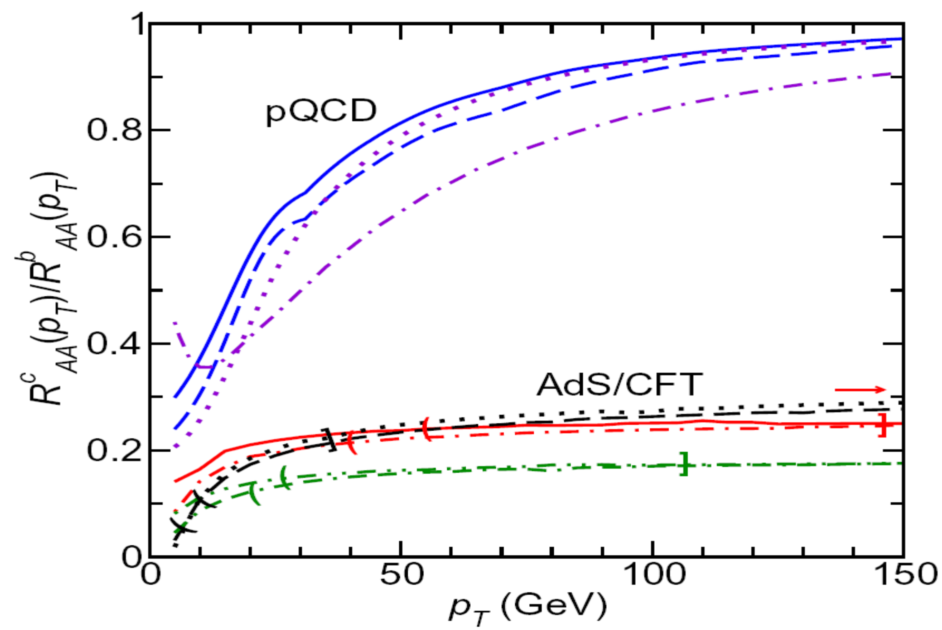
Mass dependence (dead cone effect)

$$R_{D/h}(p_t) = R_{AA}^{D}(p_t)/R_{AA}^{h}(p_t)$$

C_R is 4/3 for quarks and 3 for gluons

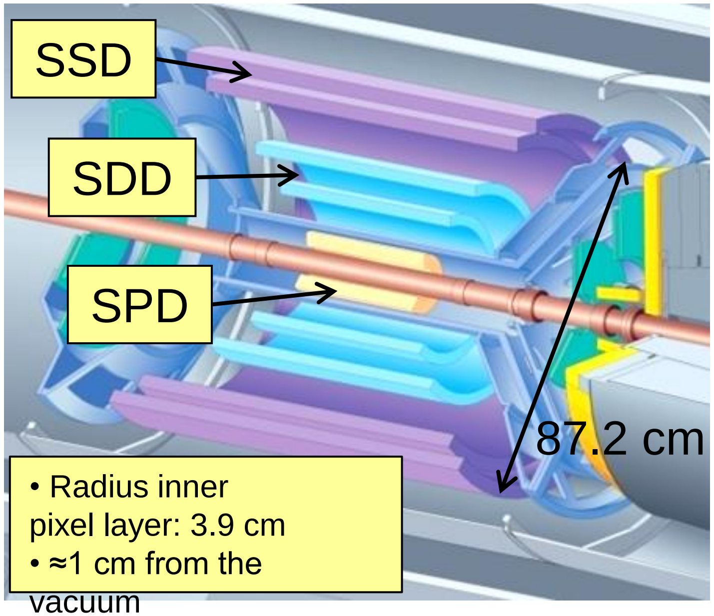
$$R_{B/D}(p_t) = R_{AA}^{e\,\mathrm{from}\,B}(p_t)/R_{AA}^{e\,\mathrm{from}\,D}(p_t)$$

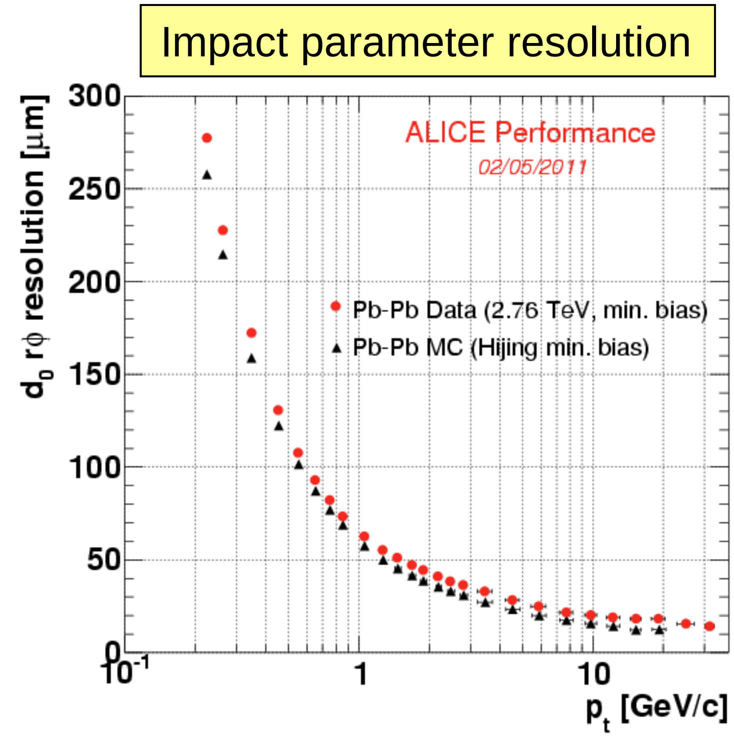




$R^c{}_{AA}/R^b{}_{AA}$ ratio different for pQCD and AdS/CFT

Open heavy-flavour reconstruction





Inner Tracking System (ITS)

6 layers of silicon detectors

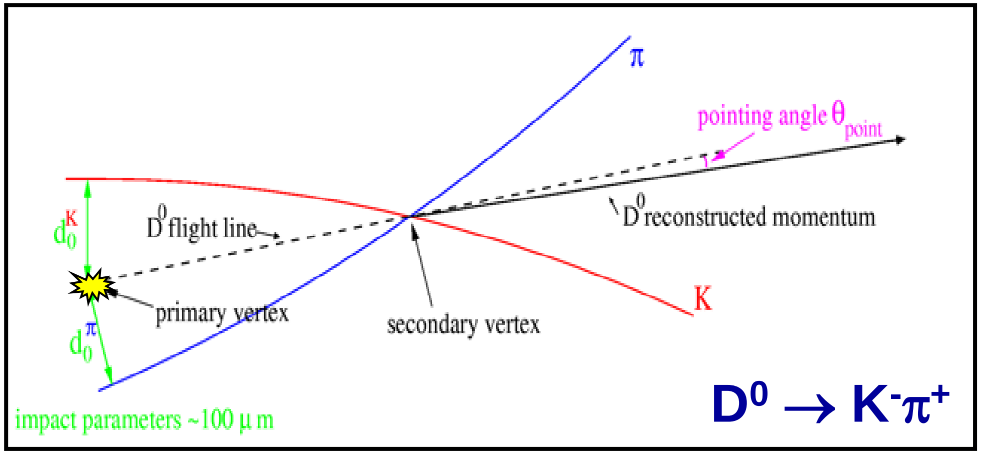
- aligned using cosmics and first pp data
- current resolution for pixels: 14 μm (nominal ≈11 μm)
- X/X_0 = 7.7% for radial tracks

• Capabilities to measure open charm down to p_T=0 in pp and p-Pb (1 GeV/c in Pb-Pb)

• High precision tracking, better than 65 μm for p_T > 1 GeV/c

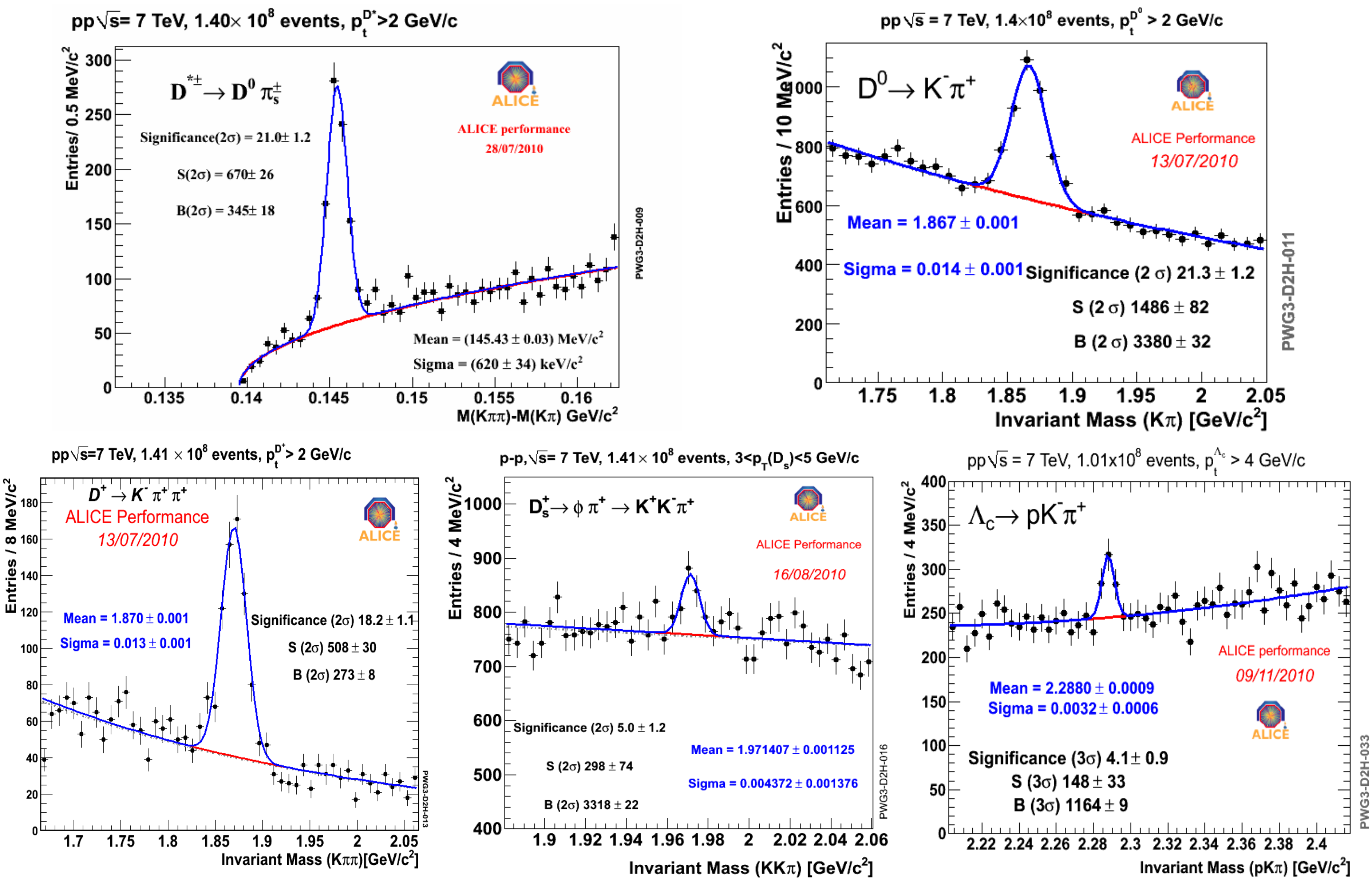
Reconstruction of D mesons

$D^0 \to K^-\pi^+$	BR: 3.89%
$D^0 \to K^-\pi^+\pi^+\pi^-$	BR: 8.09%
$D^{*+} \to D^0(\to K\pi)\pi^+_s$	BR: 67.7%
$D^+ \to K^-\pi^+\pi^+$	BR: 9.22%
$D_s^+ \to K^+K^-\pi^+$	BR: 5.5%
$\Lambda_c^+ \to pK^-\pi^+$	BR: 5.%



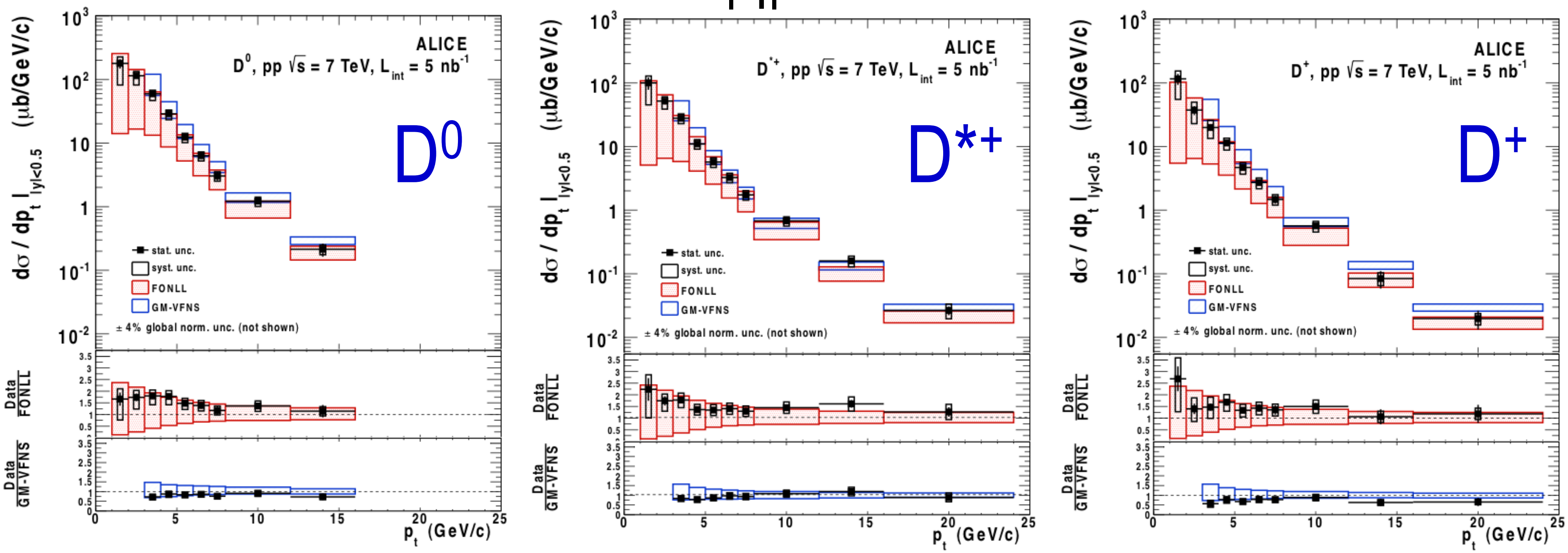
- Analysis based on decay topology and invariant mass technique
- Essential selection cuts
  - impact parameter
  - distance of closest approach
  - pointing angle
- High precision tracking (ITS+TPC)
- K and π identification (TPC+TOF) → reducing background at low p_T

Open charm signals in 7 TeV pp collisions



D meson cross sections in 7 TeV pp

$|\eta| < 0.5$

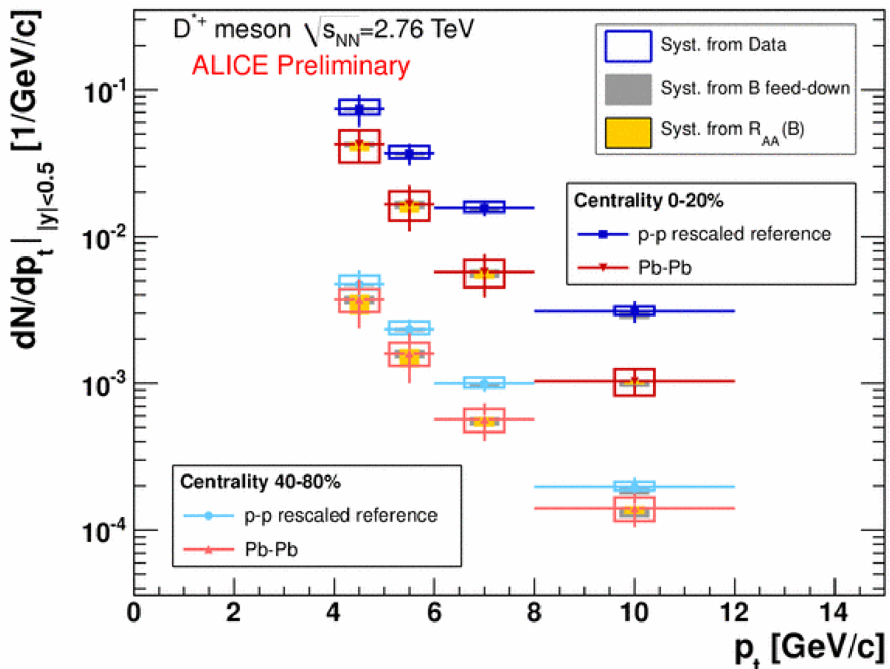


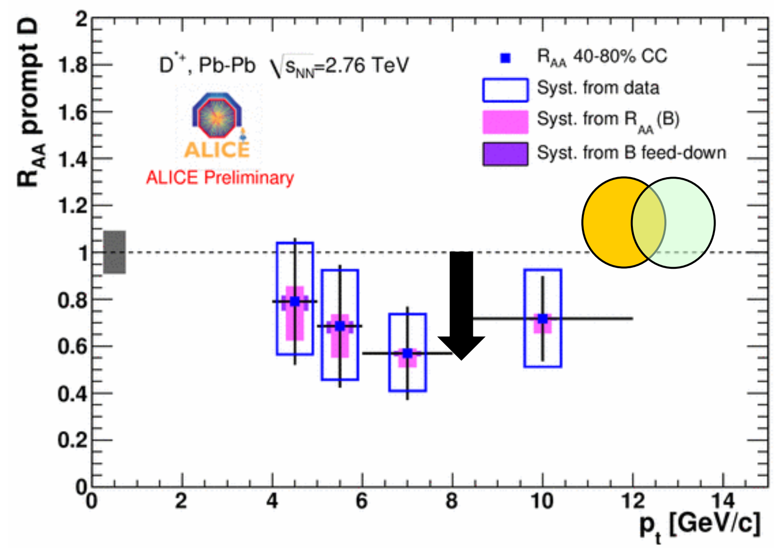
Paper accepted by JHEP, arXiv:1111.1553

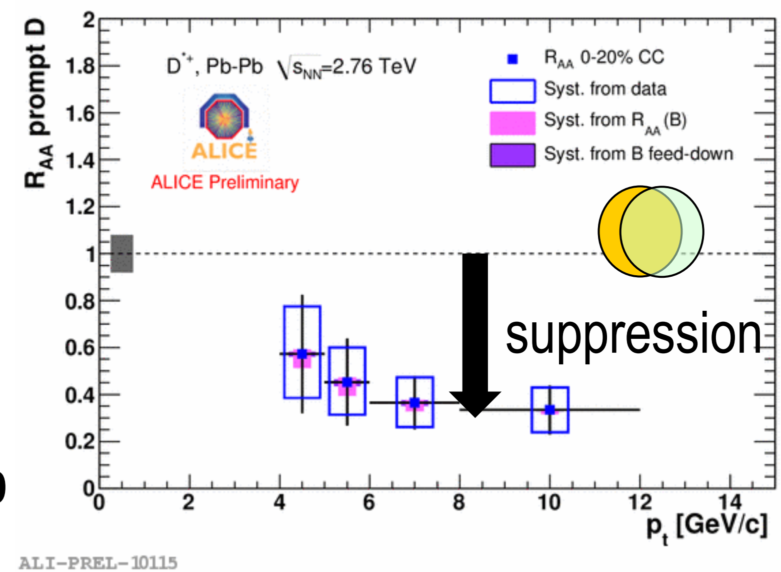
- p_T range: 1-24 GeV/c with 5 nb^{-1}
- Data well described within uncertainties by NLO pQCD calculations: - **FONLL**, M. Cacciari *et al.*, JHEP 0103 (2001) 006

  - **GM-VFNS**, B.A. Kniehl *et al.*, PRL 96 (2006) 012001

p_T spectra and R_{AA} for prompt D*+

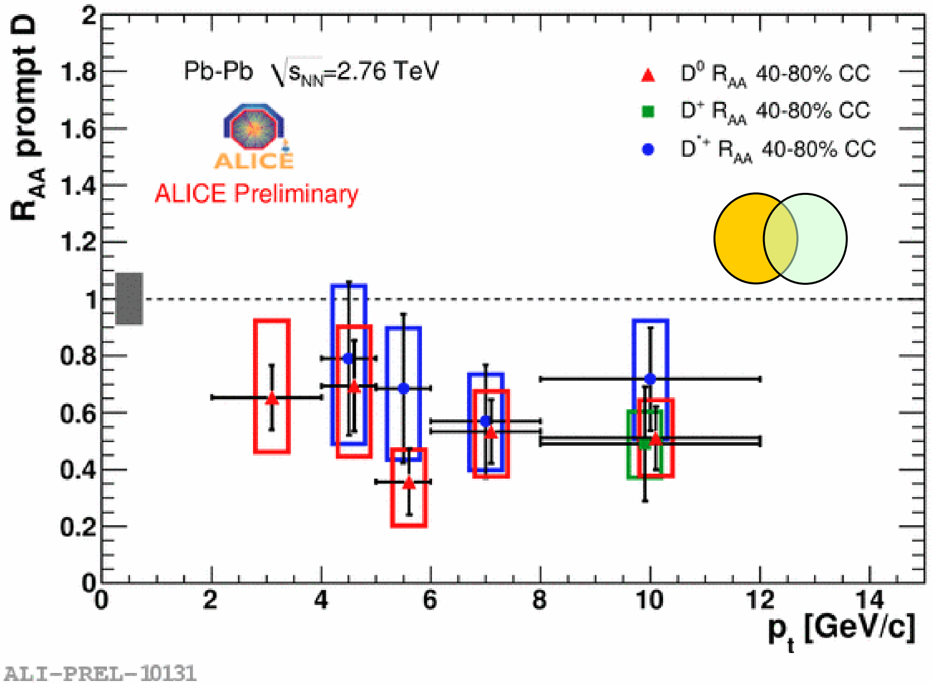


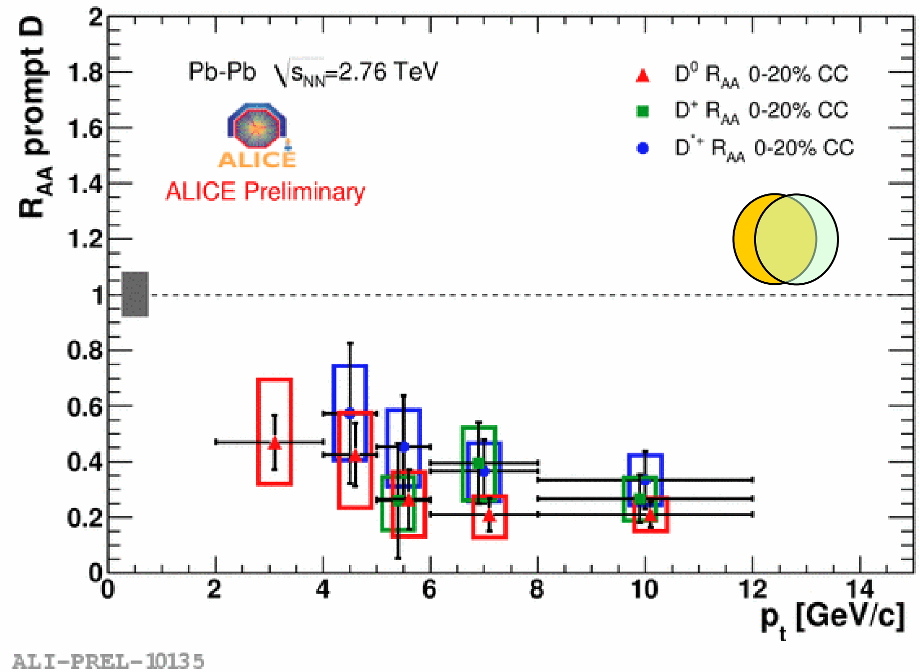




- Strong suppression observed in central (0-20%) Pb-Pb
- Less suppression in 40-80% Pb-Pb

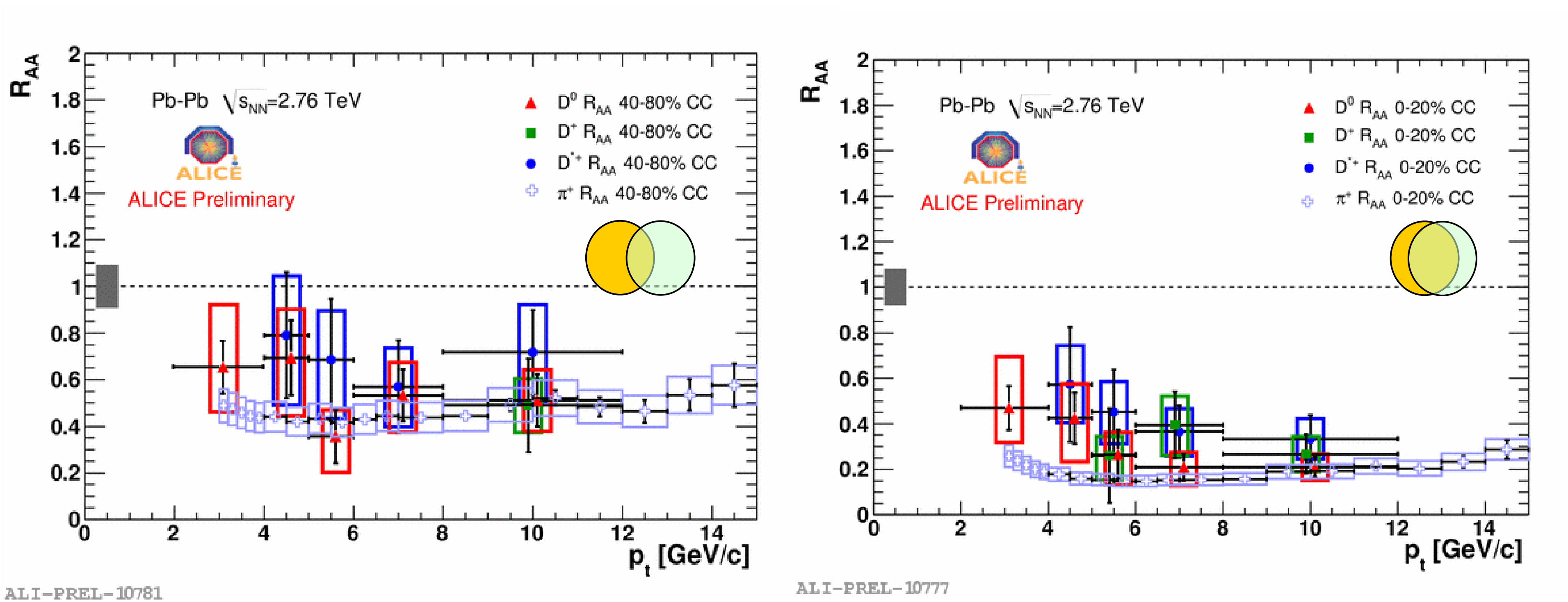
Comparison of D meson R_{AA}





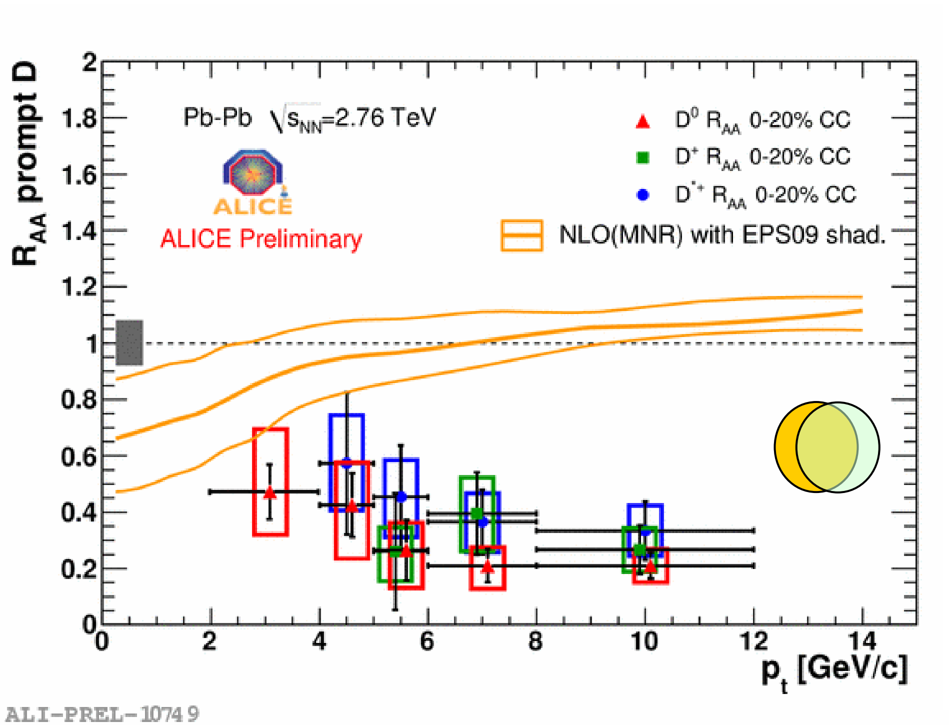
- **First Prompt Open Charm R_{AA} in heavy-ion collisions**
- Results of different D mesons in agreement within stat. error
- Large suppression for charm (factor 4-5) above 5 GeV/c in central (0-20%) Pb-Pb collisions

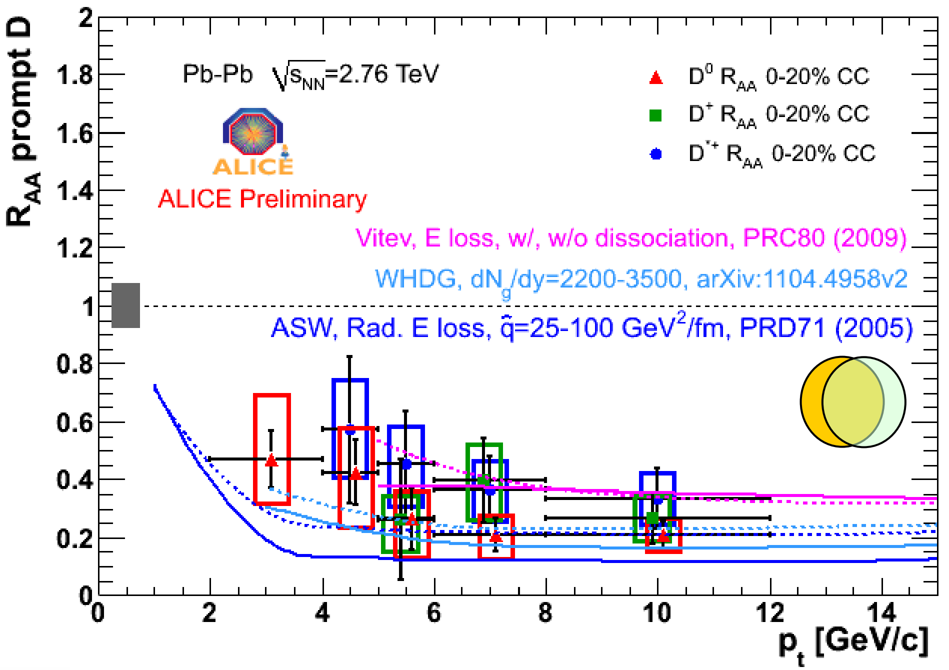
Comparison with charged pion R_{AA}



- D meson R_{AA} compatible, within errors, with charged pions for p_T > 5 GeV/c
- Possible hints that R_{AA} (D) > $R_{AA}(\pi)$ at lower p_T; more data needed for final conclusion

Comparison with model calculations

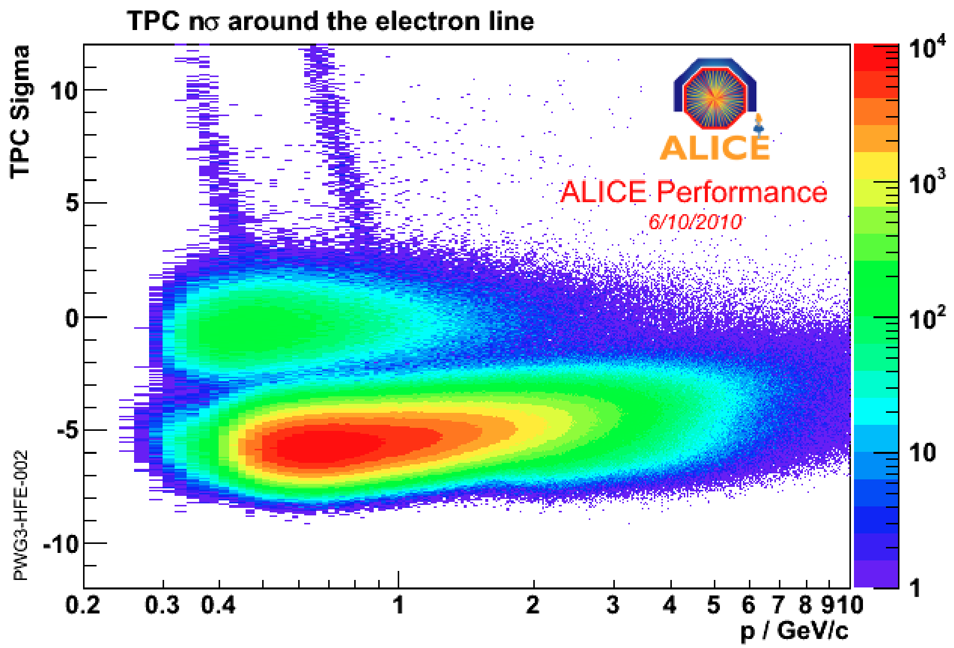


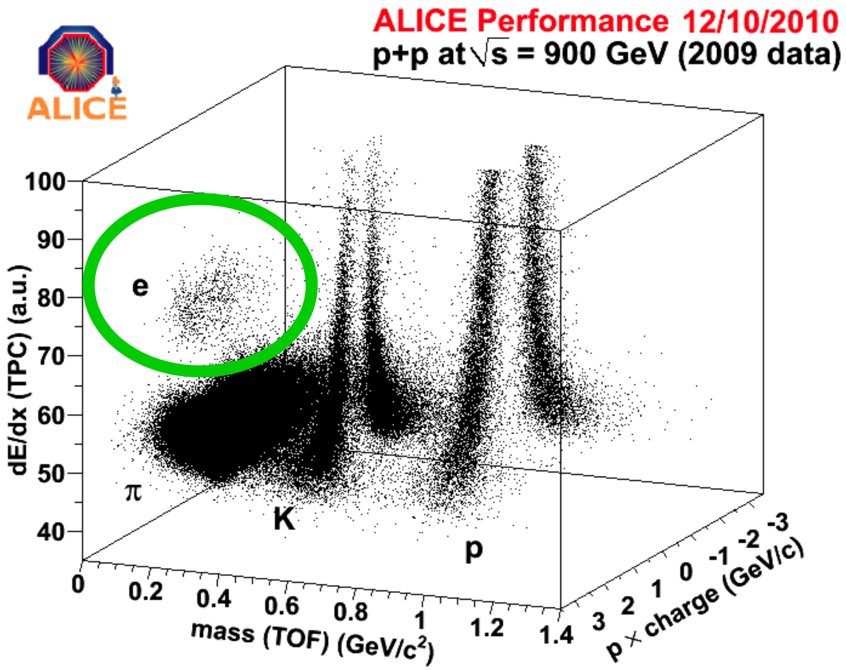


- No/little shadowing is expected in this p_T range → suppression is a final state effect; due to hot medium

- Next: extend p_T range; study centrality dependence

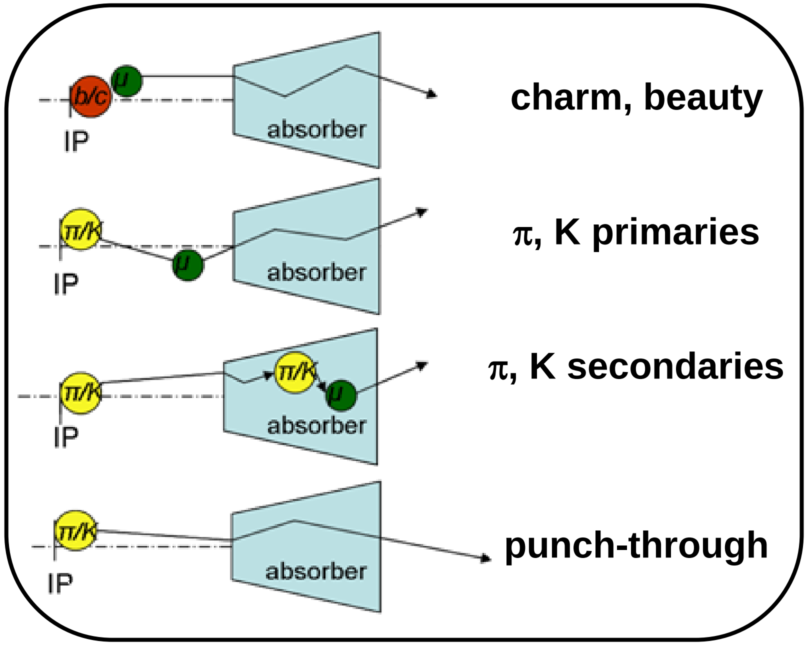
Single electrons at mid-rapidity

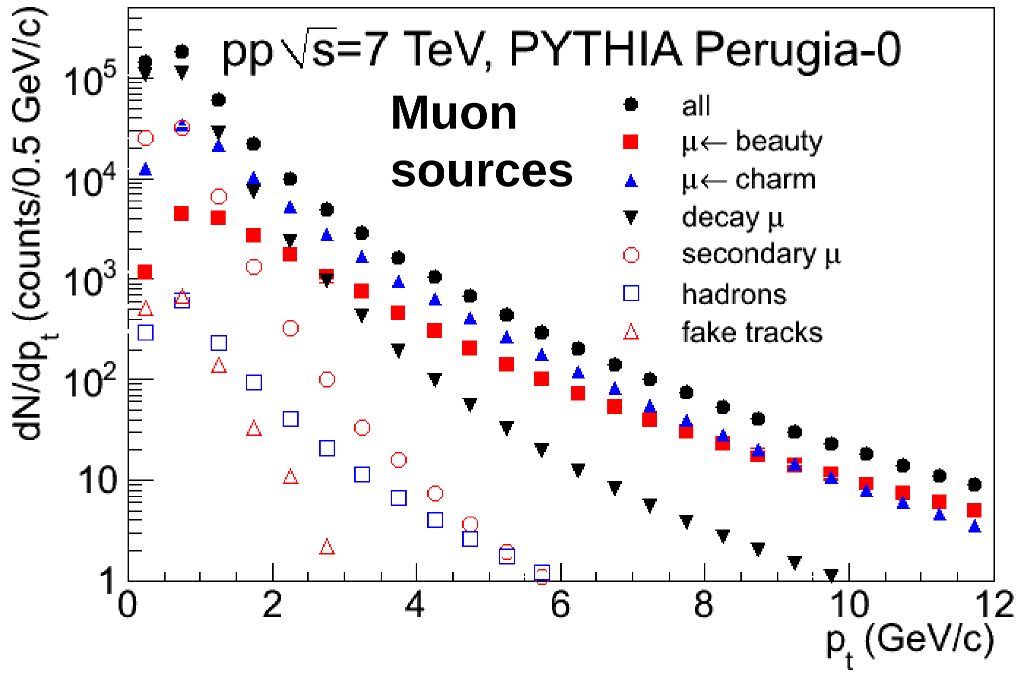




- High quality tracks in TPC and ITS
  - hit in innermost pixel layer to reduce © conversions
- Electron identification using TPC and TOF
  - TOF to reject Kaons (<1.5 GeV/c) and protons (<3 GeV/c)
  - TPC: asymmetric cut around the electron Bethe-Bloch curve
- Background is subtracted using the cocktail method

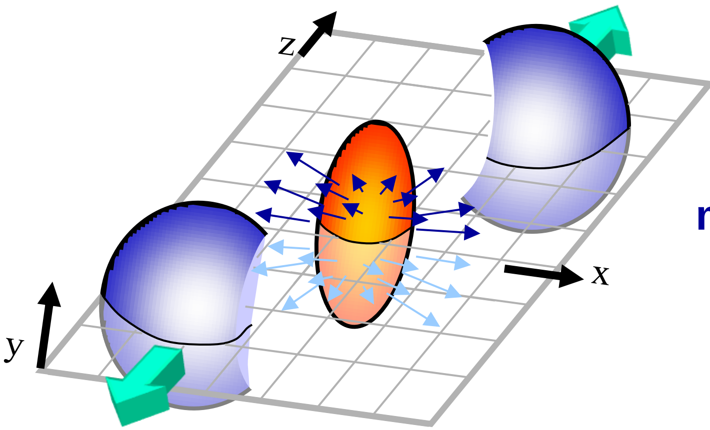
Single muons: analysis procedure



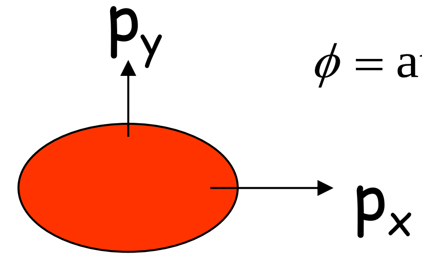


- Remove hadrons and low-p_T muons (secondary π, K) by requiring muon tracking-trigger
- Remove **decay muons** (primary π, K) by subtracting MC dN/dp_T normalized to data at low p_T (< 2 GeV/c)
- Remaining contribution are muons from charm and beauty
- Corrections on acceptance x efficiency (~80% for p_T > 2 GeV/c)

Azimuthal anisotropy: Elliptic flow



pressure and multiple collisions

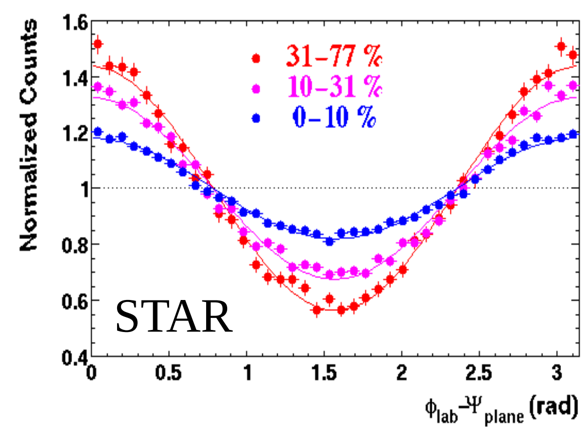


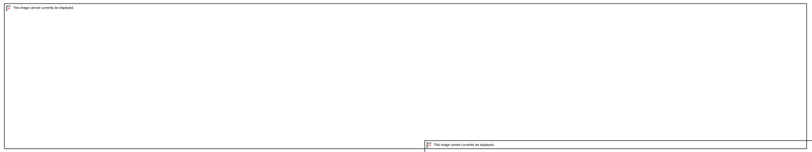
$$\phi = \operatorname{atan}\frac{p_y}{p_x}$$

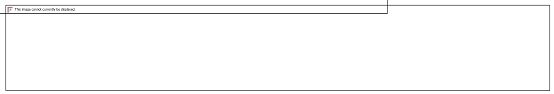
coordinate space: initial anisotropy

momentum space: final anisotropy

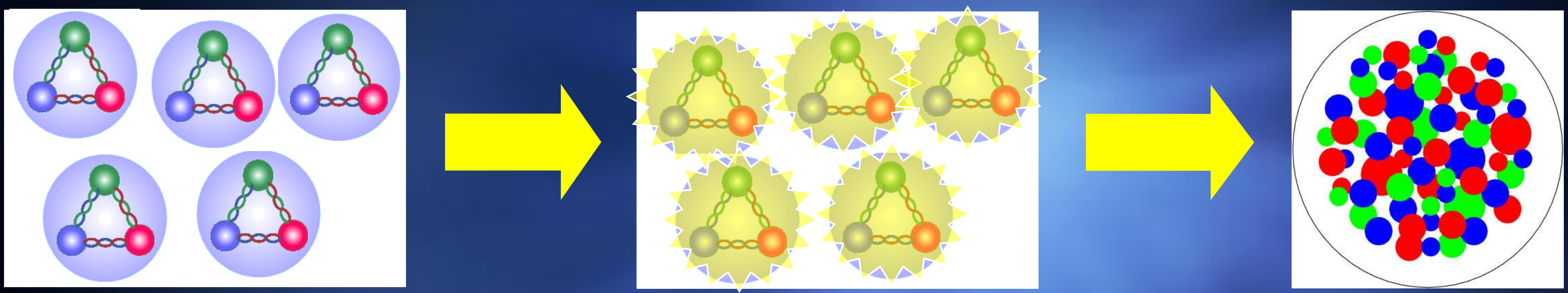
- Multiple interactions lead to thermalisation $\rightarrow$ hydrodynamic behavior of the system
- Pressure gradient generates collective flow $\rightarrow$ anisotropy in momentum space
- Fourier decomposition:







The Quark-Gluon Plasma (QGP)



Heat and pressure

Phase transition to QGP
T ≈ 10^{12} K ≈ 10^5x sun's core

- Novel state of matter: quarks and gluons are liberated (deconfinement)
- Evolution of the early universe
- Produce and study QGP in the laboratory
  - sufficient large reaction volume
  - high density and temperature
- Collisions of heavy atomic nuclei (lead or gold)