Heavy-flavours as probes of the Quark-Gluon Plasma: selection of measurements by the ALICE detector at the LHC and perspectives in view of the inner tracker upgrade

Seminar at LPC, Clermont-Ferrand

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ALICE

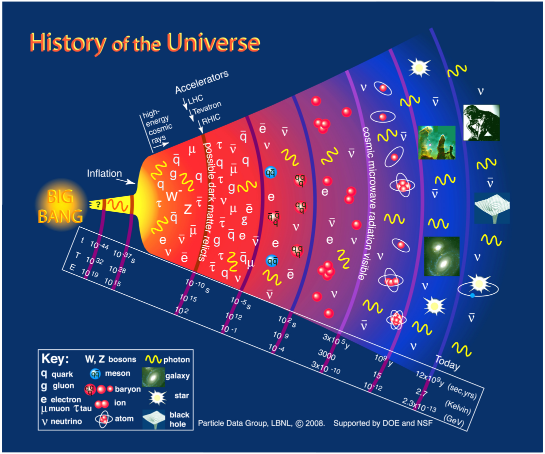
Outline

1. Introduction
   - Heavy-ion collisions
   - Heavy flavour (HF)
2. HF measurements in pp collisions
3. HF measurements Pb–Pb collisions
4. Upgrade projects
   - Inner Tracking System upgrade project
   - Physics performance
5. Conclusions & Outlook

NB: I will cover only open charm analyses on which I worked and closely related topics

From the Big Bang to the ALICE experiment

- According to the Big Bang theory, the Universe evolved from an explosion in vacuum to the present complexity.
- Initially, and till few μs after, the energy density was so large that that quarks and gluons were deconfined.
    - This "soup" of quarks and gluons is known as quark-gluon plasma (QGP)



A "little bang" in heavy-ion collisions

- The QGP is a coloured medium where the asymptotic freedom predicted by the Quantum Chromodynamics (QCD) is expected to be realized
- Nowadays the QGP could be present in the core of neutron stars. . .
- . . . or can be reproduced by colliding heavy ions at high energies
  - ⋆ In the last 20 years this is being done at the particle accelerators CERN-SPS, BNL-RHIC, and CERN-LHC with increasing beam energy
  - ⋆ At the LHC Pb beams are accelerated and collide at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$
- The deconfined constituents of a QGP are not directly observable due to the fundamental confining property of the physical QCD vacuum
- The experiments aim at finding clear and unambiguous connections between the transient QGP state and the observable final state.

Probes of the QGP

Collision evolution

- In the first scatterings among nucleons the "hardest" (high Q^2) processes occur
  - high-p_{T} quarks $\rightsquigarrow$ jets
  - and heavy quarks (charm and beauty) are formed

Pb-Pb collision at CERN-SPS energies, UrQMD transport model

Courtesy Duke Physics, http://urqmd.org/

- A few fm after the collision a phase transition to the QGP occurs
  - After a pre-equilibrium phase, the medium reaches thermal equilibrium and can be described with hydrodynamical models
- Finally hadronization occurs and the final state particles hit the detector
  - This is what we measure! We need sensitive probes which can tell about the QGP phase!

Theoretical study of the phase transition: lattice QCD

- How to describe theoretically the phase transition?
  - The theory of strong interactions, the Quantum Chromo Dynamics (QCD), can be calculated only for hard processes (perturbative QCD): the phase transition is a soft process
  - QCD calculations on a discrete space-time grid (lattice QCD) provide a reliable description of the phase transition

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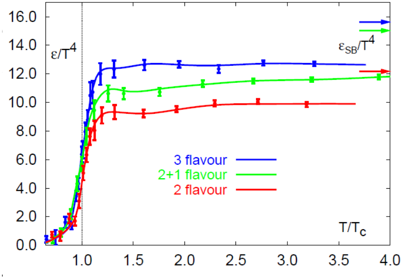
Energy density from lattice QCD



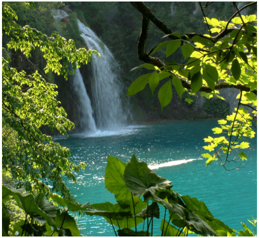
Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019

- $\epsilon/T^4 \propto n_{d.o.f}$
- Critical temperature for the phase transition estimated to $T_c \sim 175$ MeV
- Steep increase of ϵ in small ΔT: can be interpreted as the phase transition from hadronic to deconfined-quark degrees of freedom ($3 \to 37$)

Characterization of the QGP

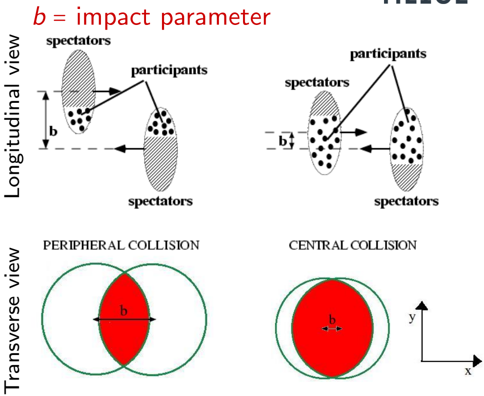
- How to investigate experimentally the QGP properties (Equation of State, viscosity, thermal equilibrium, in medium energy loss)?

- Can QGP be described by ideal hydrodynamics (perfect liquid)?
- Conditions:
  - Thermalization
  - Zero (or very small) viscosity
- What is the energy lost by particles passing through the medium? What are the mechanisms at play?
- How to investigate this experimentally?



Collision geometry (A-A)

- The collision centrality influences the number of nucleon-nucleon collisions
  - Higher density + shorter mean free path = higher probability of thermalization
  - Also:
    Higher density + shorter mean free path = more interactions with medium

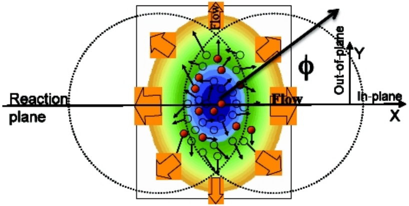


- The geometry of the overlap area is related to the centrality
- If $b \gg 0$, the coordinate space configuration is anisotropic (almond shape)

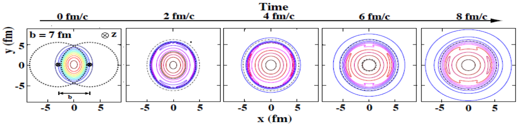
Azimuthal anisotropy and flow

- Different pressure gradients transform the initial space anisotropy into a momentum anisotropy of the produced particles ⇝ anisotropic flow
- To quantify the anisotropy a Fourier expansion can be used:

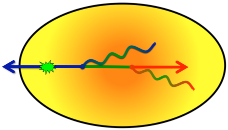
$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\phi - \Psi_{RP}) + 2v_2\cos 2(\phi - \Psi_{RP}) + \ldots\right)$$



- v_1 is expected to be negligible at central rapidity
- v_2, called elliptic flow, quantifies the initial anisotropy
- The spatial azimuthal anisotropy disappears quickly

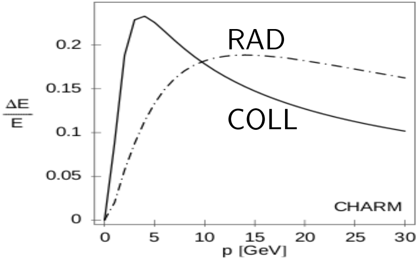


Energy loss in the medium

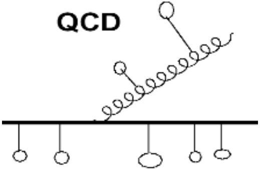


- A parton passing thought the medium interacts with its constituents losing energy

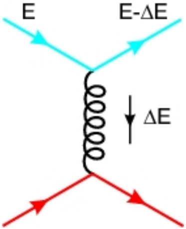
Interplay of collisional and radiative energy loss for a charm quark



Radiative en. loss



Collisional en. loss



Nuclear modification factor

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- Hypothesis: IF A-A collisions are a superposition of pp collisions
- THEN, we could scale the yields in pp collisions by the number of binary collisions to have the yields in A-A
  - The geometry is translated into the nuclear overlap function $T_{\mathrm{AA}} \propto N_{\mathrm{coll}}$

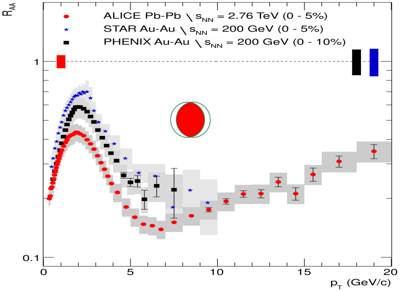
Nuclear modification factor:

$$R_{\mathrm{AA}} \equiv \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{d\sigma_{pp}/dp_{\mathrm{T}}} \begin{cases} R_{\mathrm{AA}} \neq 1 \text{ Medium effect} \\ R_{\mathrm{AA}} = 1 \text{ NO Medium effect} \end{cases} \quad (1)$$

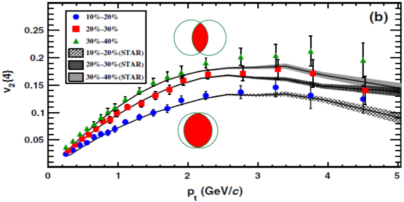
- It is a clear probe of medium effects, like energy loss
- It also includes "cold" nuclear matter effects, which can be studied in pA collisions

QGP medium at the LHC

R_{AA} of charged hadrons



Elliptic flow of charged hadrons



- Strong suppression of particle production with respect to pp collisions, in central collisions
- Large elliptic flow v_2 observed $\rightsquigarrow$ initial spatial asymmetry propagated to the final particle momenta
- Smaller v_2 in more central events
- Stronger suppression, but same differential elliptic flow as observed at RHIC

ALICE, Phys. Rev. Lett. 105 (2010), Phys. Lett. B 696 (2011)

Heavy flavour as probes of the QGP

- Heavy quarks are predominantly formed in the first hard scatterings among partons in a short time scale $t \sim 1/m_Q \sim 0.05 - 0.15\ \mathrm{fm}/c$
  - ✓ They experience the full evolution of the system
  - ✓ Their interaction with the medium tells about the medium properties

Physics scope – pp collisions

- Test perturbative QCD (pQCD) predictions for charm and beauty production
- Reference for the energy loss measurements in Pb–Pb collisions

Observables:

- D mesons have one charm quark and the decay channel in charged hadrons can be fully reconstructed
- In particular we consider:
  - $D^0 \rightarrow K^-\pi^+$ (BR 3.89%)
  - $D^{*+} \rightarrow D^0\pi^+$ strong decay (BR 67%) $\rightarrow K^-\pi^+\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$ 3 prongs, larger combinatorial bkg (BR 9.4%)
  - $D_s^+ \rightarrow K^-K^+\pi^+$ additional physics due to the strange quark (BR 5.5%)
- Measurement of the cross section

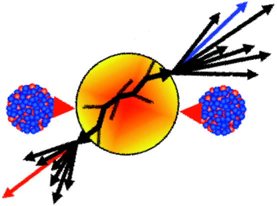
Physics scope – Pb–Pb collisions

- Energy loss in the medium: dependency on mass (dead cone effect) and colour charge (Casimir Factor)

$\theta_{\text{gluon}} > \frac{M_Q}{E_Q}$

Dokshitzer, JPG17(91)1481)

$\langle \Delta E \rangle = \alpha_s C_R \hat{q} L^2$, larger for gluons than quarks



- Medium degree of thermalization
- Path length dependence of energy loss

Observables:

- Nuclear modification factor $R_{\text{AA}} \equiv \frac{1}{\langle T_{\text{AA}} \rangle} \cdot \frac{dN_{\text{AA}}/dp_{\text{T}}}{d\sigma_{pp}/dp_{\text{T}}}$
- Elliptic flow: second Fourier coeff of the azimuthal distribution expansion $\frac{dN}{d\phi} = N_0 \left(1 + v_1 \cos(\phi - \Psi) + v_2 \cos 2(\phi - \Psi) \ldots\right)$

Predictions for R_{AA}

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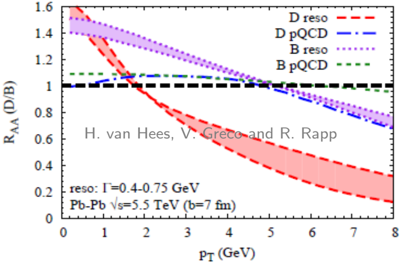
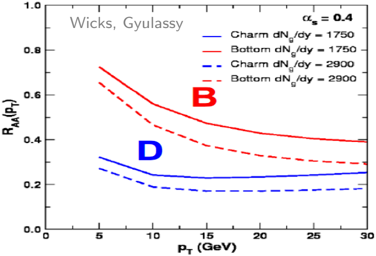
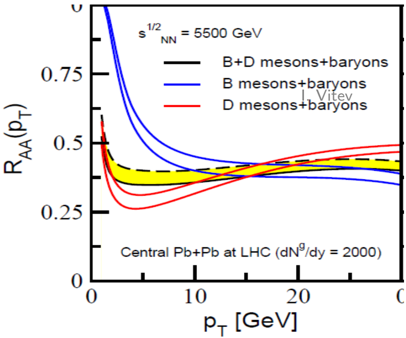
Transport model



Radiative energy loss



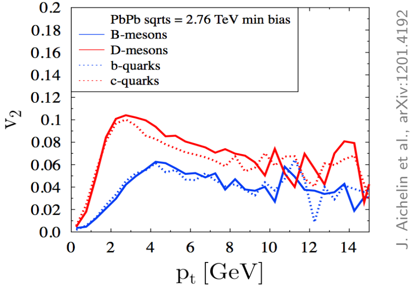
Mesons dissociation in the medium

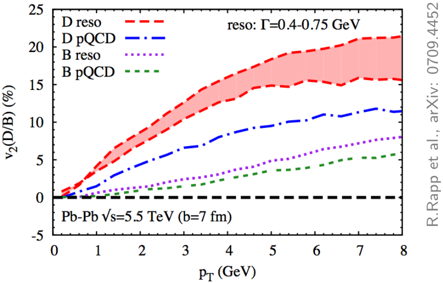


Last call for LHC predictions Workshop

- The hierarchy $R_{\mathrm{AA}}^{\mathrm{light}} < R_{\mathrm{AA}}^{\mathrm{charm}} < R_{\mathrm{AA}}^{\mathrm{beauty}}$ is expected (see previous slide)

Predictions for v_2



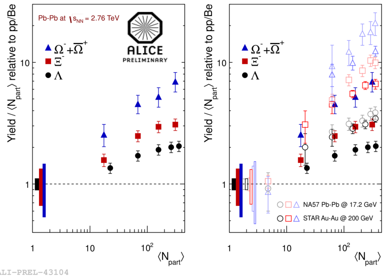


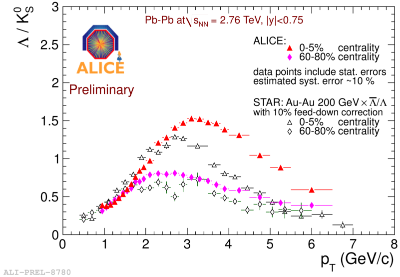
- Collisional and radiative energy loss
- QGP hydrodynamical expansion

- Effective model for heavy-light quark scattering via D and B resonances

Baryon/Meson and strangeness enhancement

- Restoration of chiral symmetry $\rightsquigarrow$ mass of the strange quark expected to be $m_s \sim 150$ MeV $\sim$ T$_c$
- Expected copious production of $s\bar{s}$ quarks, mostly from gluon-gluon fusion, with stronger effect for multi-strange hadron production Rafelski: Phys. Rep. 88 (1982) 331
- In the intermediate p_T range, where hadronization via coalescence is dominant, baryon yield is enhanced





Quark Matter 2011

Charmed mesons with strangeness and baryons

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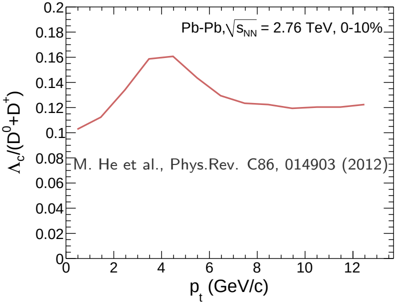
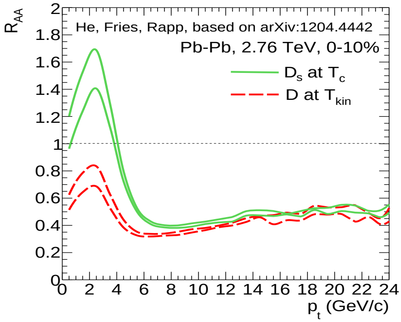
Prediction $\Lambda_c/(\mathrm{D}^0 + \mathrm{D}^+)$



Prediction $R_{\mathrm{AA}}(\mathrm{D_s})$

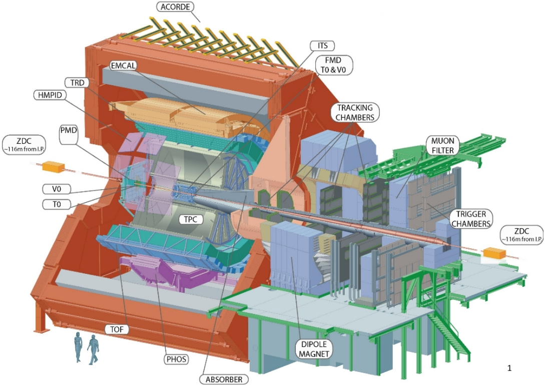


- Prediction with charm-quark transport in the QGP and hadronization via coalescence
- Need to measure Λ_c from $p_T \approx 2$ GeV/c

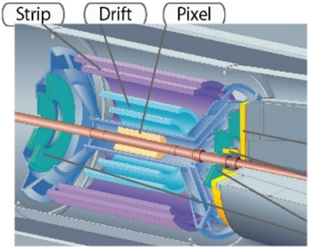
- If coalescence is dominant for charm hadronization, the $\mathrm{D_s}$ production is expected to be enhanced at low p_T

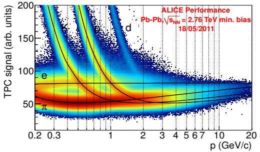
ALICE Experiment

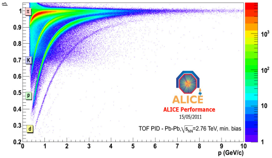
A Large Ion Collider Experiment (ALICE)



- ITS for vertexing and low-p_{T} tracking (and PID, not used for HF)
- TPC main tracker, PID
- TOF PID



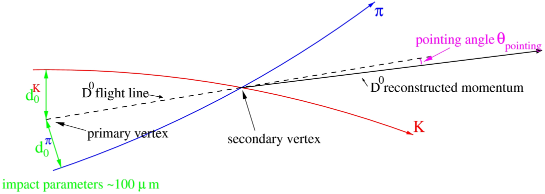




Open charm measurements pp collisions

D meson reconstruction in ALICE

$D^0 \rightarrow K^- \pi^+$ decay topology



- Topological selection and particle identification

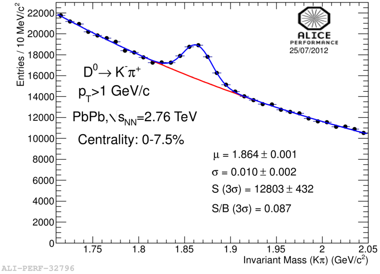
Cross section:

$$\left.\frac{d\sigma^{\mathrm{D}}}{dp_{\mathrm{T}}}\right|_{y<|0.5|} = \frac{1}{2}\frac{1}{\Delta y \Delta p_{\mathrm{T}}}\frac{f_{\mathrm{prompt}}(p_{\mathrm{T}}) \cdot N^D\big|_{y<y_{fid(p_{\mathrm{T}})}}}{(Acc \times \epsilon)_{\mathrm{prompt}}(p_{\mathrm{T}}) \cdot \mathrm{BR} \cdot L_{\mathrm{int}}} \quad (2)$$

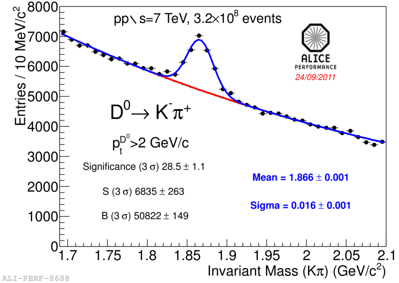
D meson signal extraction in ALICE

- Invariant mass analysis
- Signal extraction via a fit to the invariant mass distribution

Central Pb-Pb collisions

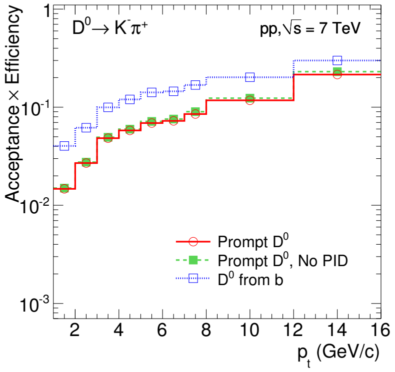


pp collisions

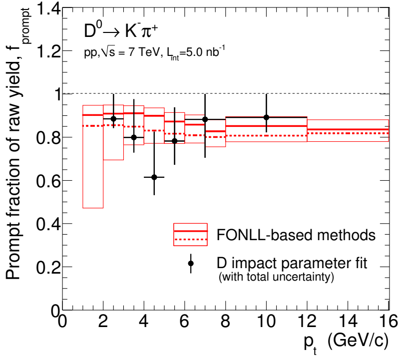


Efficiency and B feed-down corrections

Efficiency from MC (D^0)



Fraction of prompt D^0

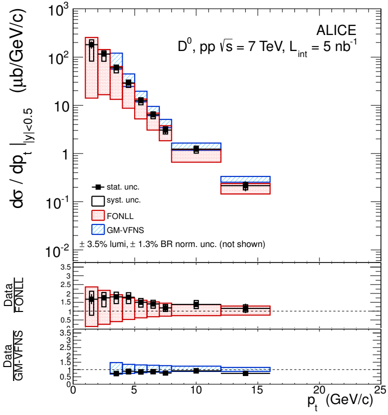


JHEP 01 (2012) 128

- FONLL-based methods, used for the measurement
  - FONLL b cross section and charm/beauty efficiencies used
- Cross check with data-driven method exploiting the different impact parameter shape of prompt and secondary

D meson cross section measurements

D^0 cross section at 7 TeV

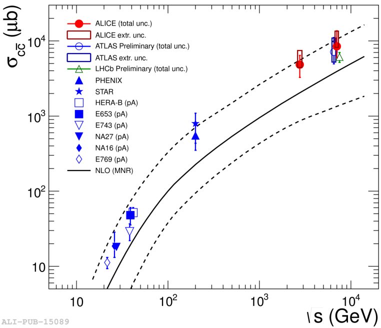


JHEP 01 (2012) 128, Phys. Lett. B 718 (2012) 279294

JHEP 1207 (2012) 191

- Also D^+, D^{+*}, D_s cross section measured
- . . . and at 2.76 TeV

Total charm cross section vs $\sqrt{s}$



Others HF measurements

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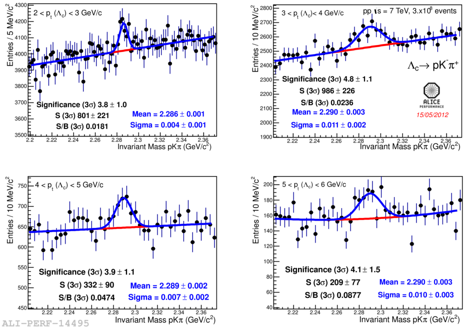
Λ_c baryons

- Heavy use of PID (Time Projection Chamber and Time-of-Flight used) to reduce the background
- $c\tau \sim 60\ \mu$m, small impact parameter, topological selections are not very effective with the current setup

- Λ_c measurement in Pb–Pb interesting for: baryon/meson ratio, R_{AA}, v_2
- Signal not significantly visible so far in Pb–Pb collisions
- A better impact parameter resolution and large statistics needed!

$\Lambda_c \to \mathrm{pK}\pi$ signals in $2 < p_{\mathrm{T}} < 6$ GeV/c – pp collisions

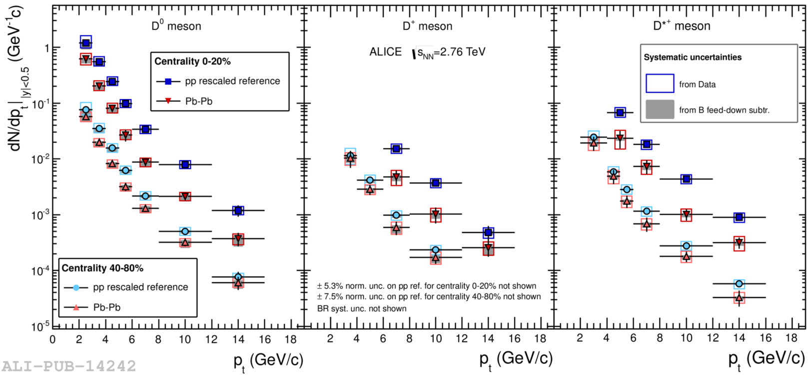


ALI-PERF-14495

Open charm measurements Pb–Pb collisions

D mesons suppression in Pb-Pb collisions

- Same signal extraction strategy in Pb–Pb collisions but with in general tighter cuts
- 7 TeV cross section scaled to 2.76 TeV used as reference for the R_{AA}



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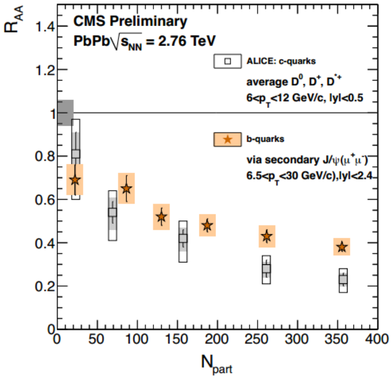
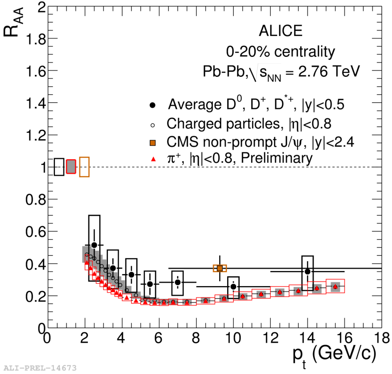
R_{AA} and suppression hierarchy

D and B R_{AA}



arXiv:1203.2160, arXiv:1205.6443, arXiv:1201.5069

D and hadrons R_{AA}



JHEP09(2012)112

- Large suppression of D mesons observed
- A hint of the expected hierarchy $R_{AA}^{\mathrm{light}} < R_{AA}^{\mathrm{charm}} < R_{AA}^{\mathrm{beauty}}$ is visible

Azimuthal anisotropy, elliptic flow

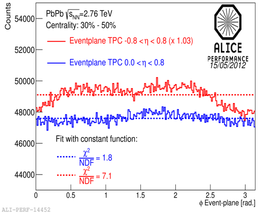
- From the R_{AA} measurement we see a large suppression of charm quark in the medium
- Does the charm quark thermalize in the medium?
  - Does it interact enough?
  - In other words, does it flow?

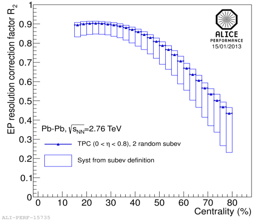
Strategy of the measurement

- The signal selection is performed as in the other analyses
- Different methods used for the v_2 measurement
  - Event plane (EP): need to correct for EP resolution and non uniformity of detector, no subtraction of non-flow, but less statistic demanding, large errors to be sensitive to non-flow
  - Scalar product (SP): same physics as EP method but no EP to be measured
  - Two-particle cumulants (QC{2}): automatically correct for detector anisotropies, no need of event plane, still non-flow effects and more statistic demanding
  - Multi-particle cumulants could not be used because of the small statistics

Event Plane method

TPC event plane

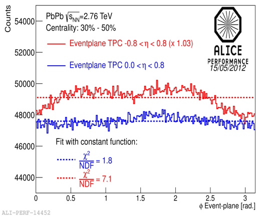


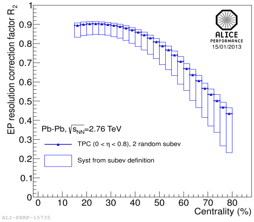


$$\frac{dN}{d\phi} = N_0 \left(1 + v_2 \cos 2 \left(\phi - \Psi_2\right)\right) \qquad (3)$$

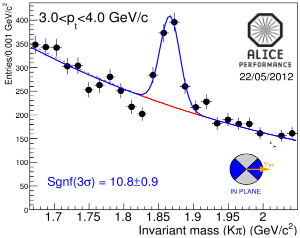
Event Plane method

TPC event plane





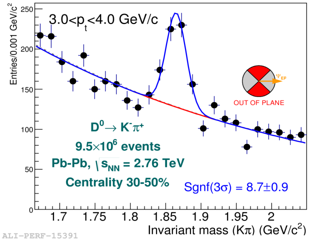
D^0 inv mass



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}} \qquad (3)$$

R_2 correction factor for finite EP resolution with 2 sub-events method

Poskanzer, Voloshin, Phys.Rev. C58 (1998) 1671



The Scalar Product method

ALICE

Scalar Product definition

$$v_2 = \frac{\left\langle u \cdot \frac{Q}{M} \right\rangle}{\sqrt{\left\langle \frac{Q_a}{M_a} \cdot \frac{Q_b}{M_b} \right\rangle}} \quad (4)$$

C. Adler et al., Phys.Rev. C66, 034904 (2002)

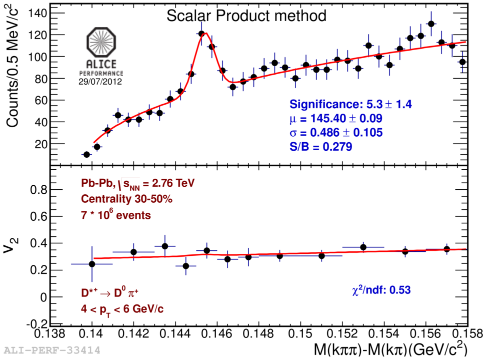
- $Q = \sum_{j=1}^{M_{\rm RP}} \exp^{i2\phi_j}$,
  - ϕ_j azimuth of j-th Reference Particle (RP)
- $M_{\rm RP}$ multiplicity
- $u = \exp^{i2\phi}$
  - ϕ azimuth of D meson (Particle Of Interest, POI)
- a, b indicate two sub-events

- With a $\Delta\eta$ between POI and RF, non-flow correlations are reduced (not included in this analysis)

Strategy of the measurement with the Scalar Product

- Simultaneous fit of yield and v_2 vs. mass

D^{*+} double fit in $4 < p_T < 6$ GeV/c



▷ $v_2(m) = \frac{S}{S+B}(m)v_2^S + \frac{B}{S+B}(m)v_2^B(m)$

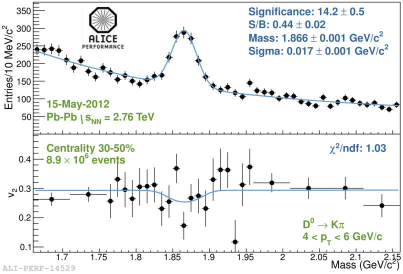
▷ $v_2^B(m)$ linear function

Q-cumulant (QC) method

- n-particle correlators are proportional to different Fourier harmonics v_n
- Correlators can be calculated using cumulants in term of moments of the flow vector $Q_n = \sum_i^M \exp^{in\phi_i}$
- The 2nd order cumulant, $c_n\{2\}$, is the average over all events of the 2-particle correlator $\langle 2 \rangle \dashrightarrow \langle\langle 2 \rangle\rangle$
- Different order cumulants provide independent estimates for the same harmonic v_n
- With the current D meson statistics only 2-particle cumulants are accessible
  - $v_2\{2\} = \sqrt{c_2\{2\}}$

A. Bilandzic,R. Snellings and S. Valoshin, Phys. Rev. C83, 044913 (2011)

Strategy of the measurement with the QC{2}



- The procedure is the same as described before
- Signal selection with topological selection and PID
- Simultaneous fit of the invariant mass spectrum and the v_2 vs mass, measured with QC{2}

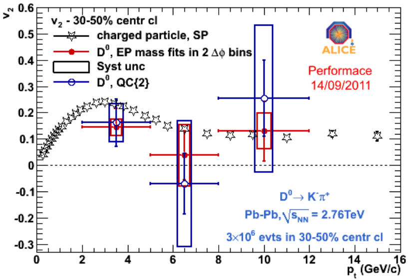
Effect of feed-down from B decays

$$v_2^{\mathrm{all}} = f_{\mathrm{prompt}} v_2^{\mathrm{prompt}} + (1 - f_{\mathrm{prompt}}) v_2^{\mathrm{feed\text{-}down}} \quad (5)$$

- Models predict $v_2^{\mathrm{feed\text{-}down}} < v_2^{\mathrm{prompt}}$
  - We consider the range $0 < v_2^{\mathrm{feed\text{-}down}} < v_2^{\mathrm{prompt}}$
  - v_2^{all} is calculated in the extreme hypothesis $v_2^{\mathrm{feed\text{-}down}} = v_2^{\mathrm{prompt}}$
  - The lower limit of the systematics is set at $v_2^{\mathrm{feed\text{-}down}} = 0$, giving $v_2^{all} = \frac{v_2^{\mathrm{prompt}}}{f_{\mathrm{prompt}}}$
- f_{prompt} is estimated with FONLL as for the R_{AA} and cross-section measurements Cacciari et al. JHEP 9805 (1998) 007
  - $0.7 < f_{\mathrm{prompt}} < 0.95$

D mesons elliptic flow measurement

2010 data...



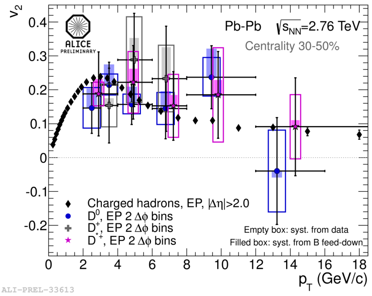
D^0 EP and QC{2}

Acta Phys. Pol. B Proc. Suppl. 5, 2 (2012) pp.335-342

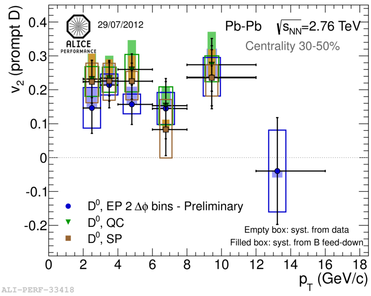
Number of events: 3.4×10^6 in 30-50%

D mesons elliptic flow measurement

2011 data!



Different mesons

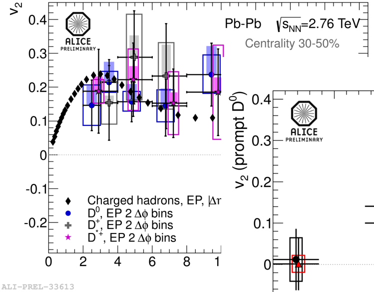


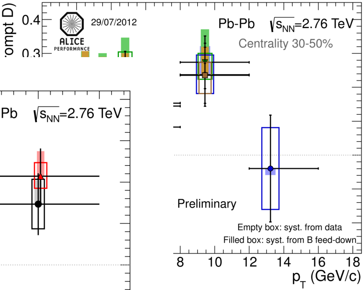
Different methods

Number of events: 9.5×10^6 in 30-50%, 7.1×10^6 in 15-30%, 16×10^6 in 0-7.5%

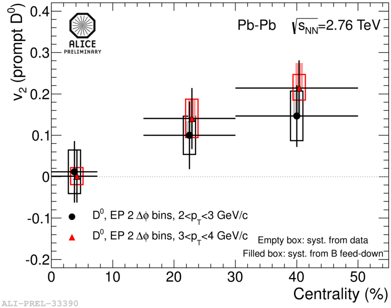
D mesons elliptic flow measurement

2011 data!





Different ... nt methods

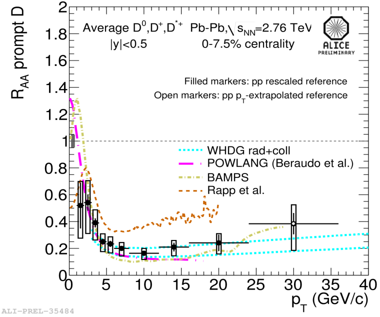


Number of events: ... 5-30%, 16×10^6 in 0-7.5%

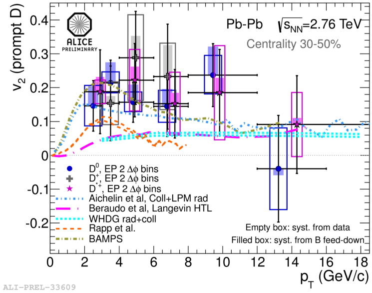
Different centralities

Comparison with models

R_{AA}



v_2



- WHDG collisional and LPM radiative, no hydro
- Beraudo et al. Langevin eq.
- Rapp et al. D and B treated as resonances in the medium

- BAMPS collisional energy loss in expanding medium
- Aichelin et al. coll and rad en loss, with a running α_s

Reference models R_{AA} and v_2

- BAMPS collisional energy loss in expanding medium (Uphoff et al. axXiv:1112.1559)
- Aichelin et al. collisional and radiative energy loss. Based on pQCD with a running coupling constant (Aichelin et al. Phys. Rev. C79 (2009) 044906)
- WHDG collisional and LPM radiative $\rightsquigarrow$ suppression of gluon emission spectrum (W. A. Horowitz et al. J. Phys. G38, 124064 (2011))
- Beraudo et al. Langevin equation (W. M. Alberico et al. Eur. Phyis J. C 71, 1666 (2011))
- Rapp et al. Hydrodynamical evolution, D and B treated as resonances in the medium (M. He,R.J.Fries and R. Rapp, arXiv:1204.4442[nucl-th])

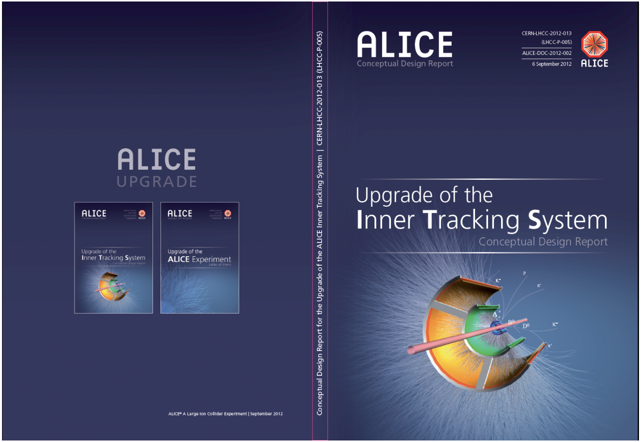
A project for the future: the ALICE Upgrade

ALICE upgrade

Why?

- Extend the low-p_{T} reach: essential to assess the energy loss and thermalization through HF elliptic flow
  - Tough due to large background and more difficult topological selection of signal
  - The upgrade aims at making it accessible and/or with high precision
- E.g.: More precise measurement of $R_{\mathrm{AA}}(\mathrm{D_s})$, first measurement of Λ_c in Pb–Pb collisions (baryon/meson ratio), separation of D and B elliptic flow
- . . . (Refer to LHCC-I-022 Letter of Intent)
- Exploiting the potentialities which open for Pb–Pb with the high luminosity upgrade in LHC!
  - Goal: integrate $10\ \mathrm{nb}^{-1}$ minimum bias in Pb-Pb after 2018 ($\sim 10^{11}$ collisions), 10 times the expected sample before the upgrade

References



- Conceptual Design Report CERN-LHCC-2012-13
- Letter Of Intent CERN-LHCC-2012-012

ALICE upgrade

Challenge

- Triggering is not possible at low p_{T} $\rightsquigarrow$ large combinatorial bkg
- Collect all collisions at a rate till 50 kHz in Pb–Pb ($\approx$ MHz in pp)
- Improve vertexing and tracking capabilities at low p_{T}
- Preserve ALICE unique PID capabilities

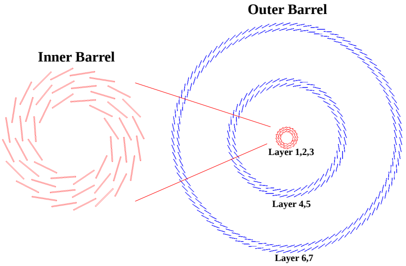
Strategy

- New Inner Tracking System (ITS)
- Upgrade of the TPC readout detectors (MWPC $\rightarrow$ GEMs for continuous readout)
- Modification of the readout electronics of other detectors
- Online data reduction to cope with the increased data amount
- New, integrated, HLT and DAQ systems

ITS upgrade project

Focus on ITS upgrade

- Impact parameter resolution: improve by a factor of 3 in $r\phi$, 5 in z
  - First detection layer closer to the interaction point (thanks to the smaller beam pipe radius)
  - Reduced material budget and pixel size



A 7 layers of pixels ($4\ \mu\mathrm{m}$ intrinsic resolution per layer)

B 3 layers of pixels and 4 layers of strips (better particle identification)

- Extreme radii: 2.2 to 43 cm $\rightsquigarrow$ current inner layer 3.9 cm

- radial position of intermediate layers optimized for standalone tracking

Technology under development

Pixels:

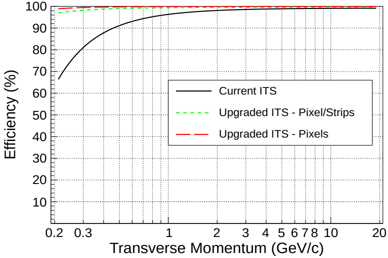
- Current ITS: hybrid technology, size $50\ \mu\mathrm{m} \times 425\ \mu\mathrm{m}$
- Under study:
  - Monolithic Active Pixel Sensors (MAPS), size $20\ \mu\mathrm{m} \times 20\ \mu\mathrm{m}$
  - Hybrid pixel technology, state of the art size $50\ \mu\mathrm{m} \times 50\ \mu\mathrm{m}$
  - Material budget: $X/X_0 = 0.3\%$ per layer (currently 1.2%)

Strips:

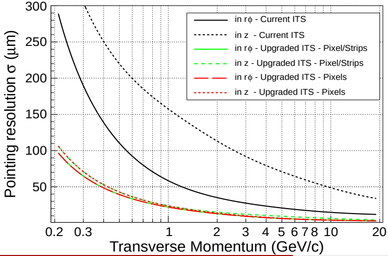
- Currently, $95\ \mu\mathrm{m} \times 2\ \mathrm{cm}$, double sided
- Under study:
  - Similar technology, reduced occupancy
  - Material budget: $X/X_0 = 0.83\%$ per strip layer (currently and 1.3%)

Performance

Tracking efficiency(ITS-TPC)



Impact parameter reso (ITS-TPC)



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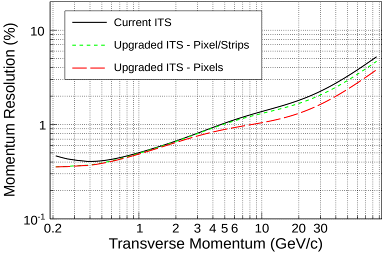
p_{T} resolution (ITS-TPC)



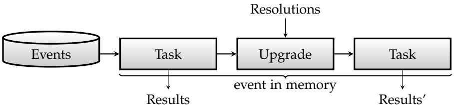
- Pixel and strip scenarios are equivalent for global tracks
  - Better p_{T} resolution for pixel only and ITS standalone scenario
- Dramatic improvement in impact parameter resolution

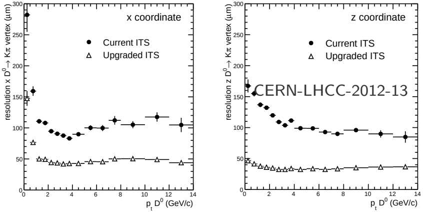
Simulation method

The *Hybrid* approach

- Based on existing MC productions including detailed geometry and response of the current ALICE setup
- The coordinates and momenta are recalculated according to the new ITS resolutions[1]
  - The scaling factors are the ratios of the upgrade/current resolutions on these variables

D^0 secondary vtx resolution (x, z)





[1] In the following consider: 7 pixel layers, thickness 0.3% X_0 per layer, intrinsic resolution $(\sigma_{r\phi}, \sigma_z) = (4, 4)$ μm

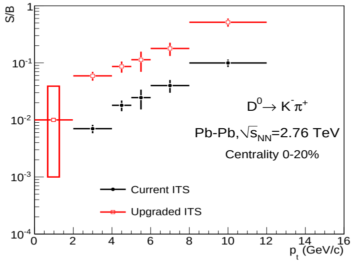
Benchmark cases considered (HF)

- The $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$ is already well measured and serve as a meter of the improvement
  - R_{AA} and v_2
- Beauty production via $\mathrm{B} \rightarrow \mathrm{D}^0$ will be accessible
  - R_{AA} and v_2
- Charm baryon production via $\Lambda_c \rightarrow \mathrm{pK}^-\pi^+$
  - R_{AA} and baryon-to-meson ratio
- $\mathrm{D_s} \rightarrow \mathrm{K}^+\mathrm{K}^-\pi^+$, $\mathrm{B} \rightarrow \mathrm{D}^0 + \pi^+$, $\mathrm{B} \rightarrow \mathrm{J}/\psi(\mathrm{e}^+\mathrm{e}^-)$, $\mathrm{B} \rightarrow \mathrm{e}^+$

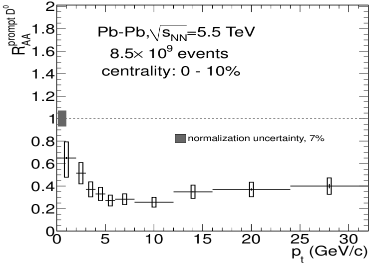
D^0 – R_{AA}

- $10\ \mathrm{nb}^{-1}$, **high rate scenario**, considered

S/B: 0-20% central events



R_{AA} : 0-10% central events



- The S/B improves by a factor of 5-10
- Signal down to $p_T = 0$

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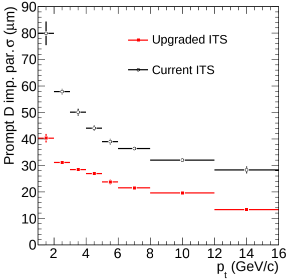
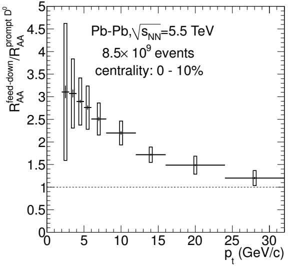
$B \to D^0$

- So far the fraction of secondary D mesons is estimated using FONLL
- Presently not enough statistics to use a data-driven method exploiting the different impact parameter distribution for prompt and secondary[2]
- High rate scenario mandatory to reach $p_T \approx 1 - 2$ GeV/c!





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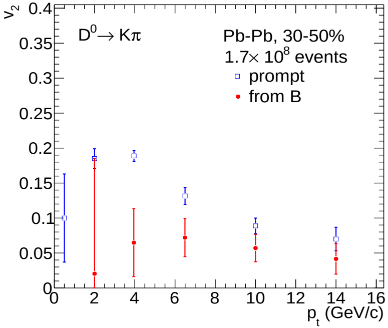
- With the upgrade the impact parameter method can be used to measure B at low p_T!

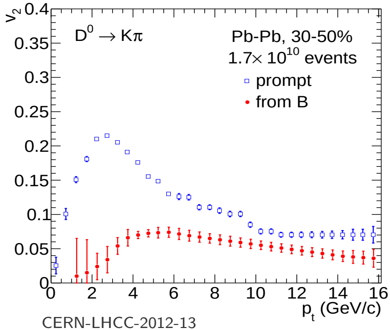
[2] CDF Collaboration, Phys. Rev. Lett. 91 24 (2003)

D^0 – Elliptic flow

Upgraded resolution



High rate scenario



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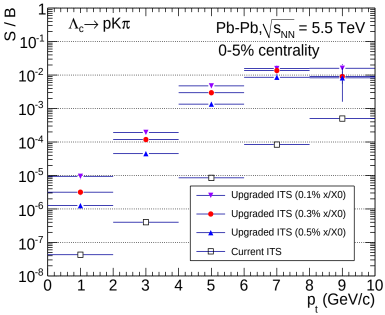
- Need high rate scenario to perform this measurement!
- v_2 values from BAMPS[3] model

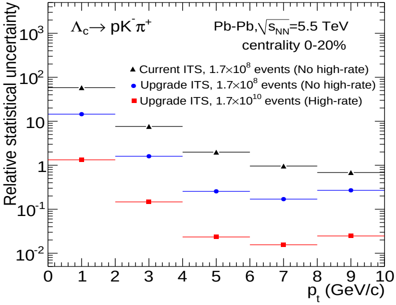
[3] J. Uphoff et al., Phys. Lett. B 717 (2012) 430

Λ_c signal extraction

S/B (0-5% Pb–Pb)



Relative statistical error (0-20% Pb–Pb)



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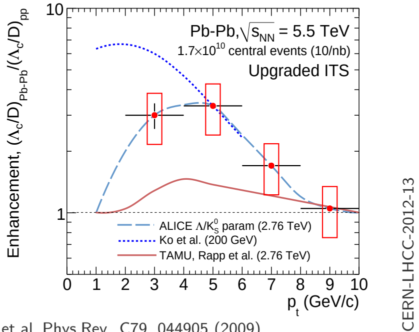
Significance $(10\ \mathrm{nb}^{-1})$ =

- 7 in $2 < p_T < 4$ GeV/c,
- 40 in $4 < p_T < 6$ GeV/c,
- 53 in $6 < p_T < 8$ GeV/c.

- With the high rate scenario the Λ_c should be measurable down to 2 GeV/c

Λ_c/D and R_{AA}

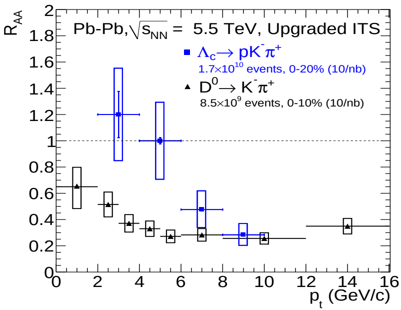
Λ_c/D enhancement in Pb–Pb



Ko et al.,Phys.Rev. C79, 044905 (2009)
Rapp et al., arXiv:1204.4442

- The precision allows for distinguishing among models
- In the picture the points have the magnitude of the measured Λ/K^0_S

$R_{AA}(\Lambda_c)$



- Limited precision at low p_T
  - Further studies are planned for improving the low p_T region

Conclusions

- The ALICE experiment studies heavy-ion and pp collisions in order to understand the hot and dense QGP properties
- Very interesting probes of the QGP are the heavy quarks, since they are produced in the first hard scattering
- pp collisions serve as a reference for Pb–Pb and to test pQCD calculations
- The charm nuclear modification factor and azimuthal anisotropy were measured in PbPb collisions
  - Large suppression and indication of non-zero elliptic flow for D mesons

Outlook

- More precise measurements are required, in particular at low-p_{T}
- Charmed baryons and separation between B and D are two important goals
- The ALICE upgrade project plan to answer these and other questions in the next years (> 2018)