Open heavy-flavour measurements in Pb-Pb collisions with ALICE at the LHC

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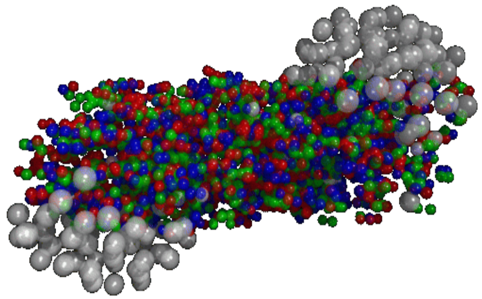
for the ALICE Collaboration

55^{th} International Winter Meeting on Nuclear Physics,
Bormio, Italy – 23-28 January 2017

Outline



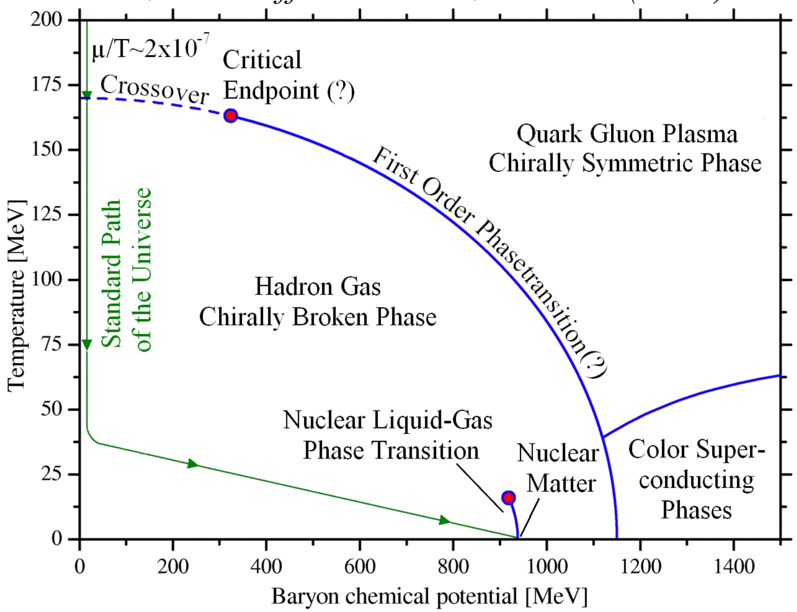
- Strongly interacting matter in extremes
- ALICE experiment
- Recent open heavy-flavour measurements
  - Probes: D mesons and heavy-flavour decay leptons (e and μ)
  - Collision systems
    - pp: test QCD and important baseline for heavy-ion measurements
    - p-Pb: study cold nuclear matter effects (initial state)
    - **Pb-Pb: study hot QCD matter (final state); determine medium properties**
  - Observables: nuclear modification factor and azimuthal anisotropy
- Conclusions

J. Norman, Wed. afternoon

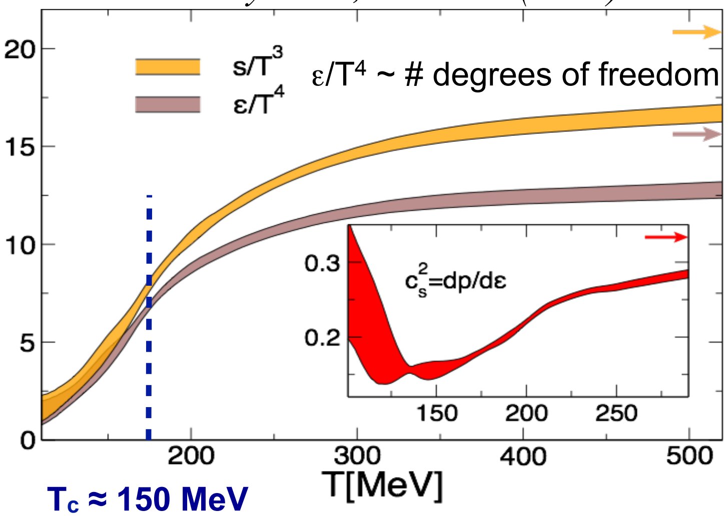
Overview talk on heavy-flavor probes
J. Stachel, Tue. morning

Matter in extremes: the QGP

T. Boeckel, J. Schaffner-Bielich, PRD 85 (2012) 103506

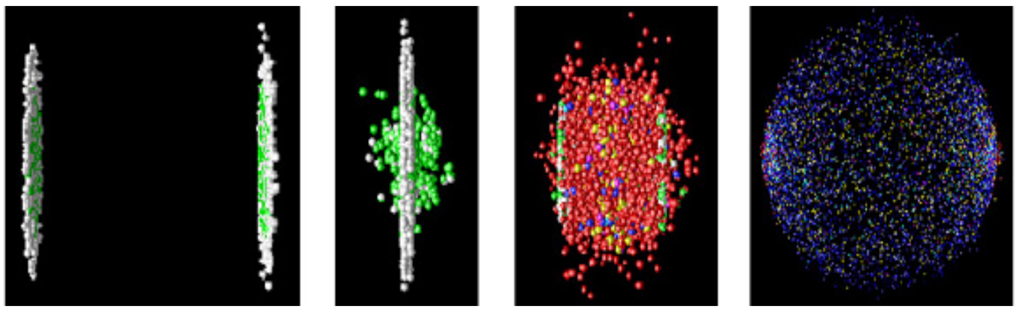


A. Borsányi et al, PLB 730 (2014) 99

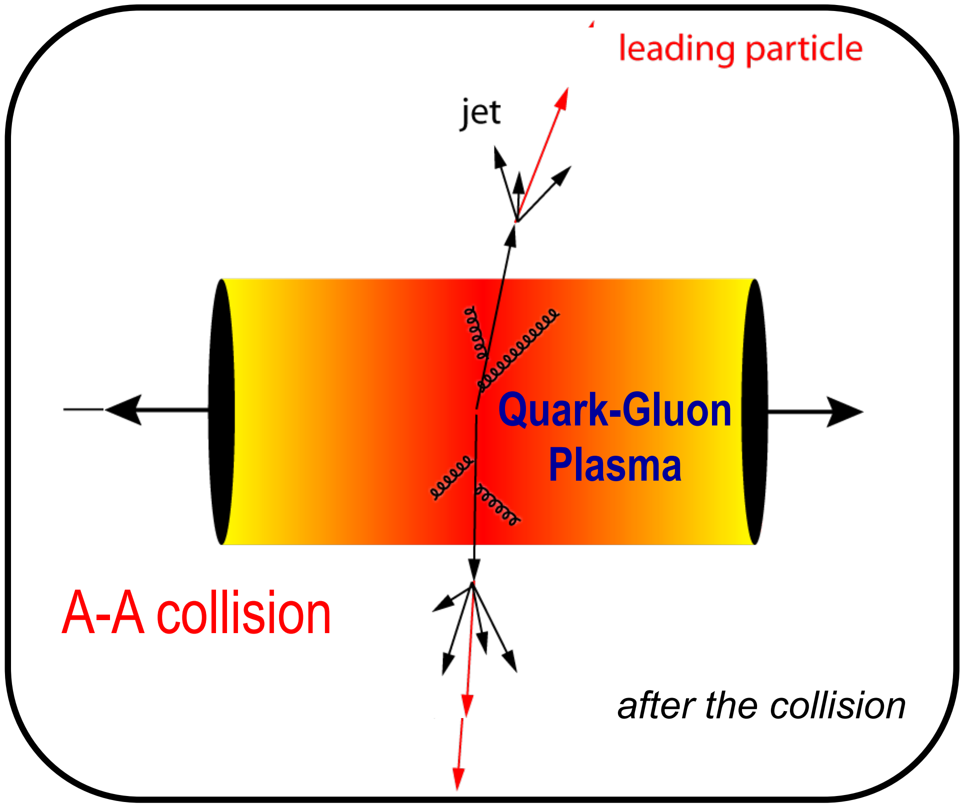


$T_c \approx$ 150 MeV

- Study strongly interacting matter under extreme conditions: high temperature and high density
- Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the quark-gluon plasma
- Experimental access via high energy heavy-ion collisions



Probing hot and dense QCD matter



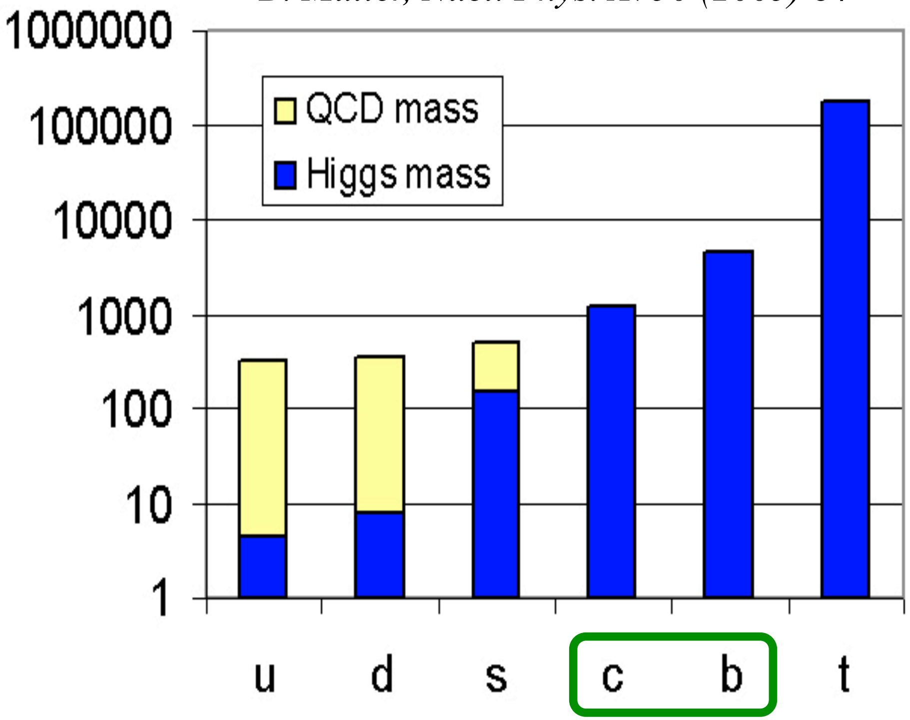
- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - modification of the transverse momentum distribution tells about density profile
- Heavy-ion collision
  - hard processes serve as calibrated probe (pQCD)
  - partons traverse through the medium and interact strongly
  - suppression provides density measurement

General picture

- parton energy loss through medium-induced gluon radiation
- collisions with medium constituents

Heavy quarks are ideal probes

B. Müller, Nucl. Phys. A750 (2005) 84



Formation time:

$\tau \sim 1/2m_Q \sim 0.1\text{fm} \ll \tau_{QGP} \sim 5\text{-}10\ \text{fm}$

- 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

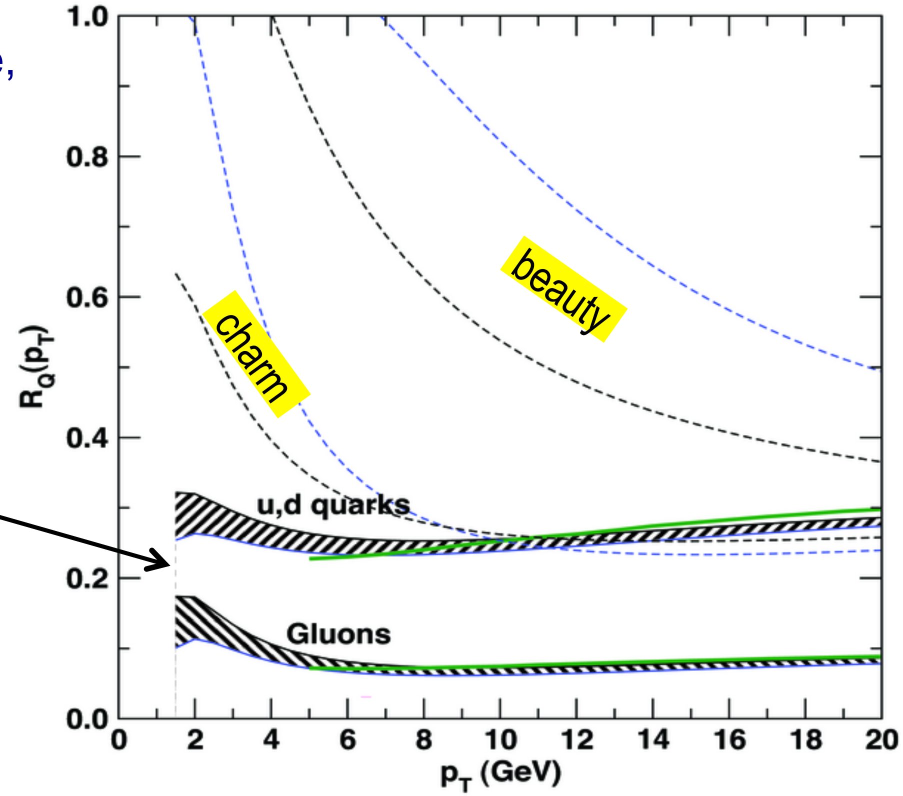
- Test QCD at transition from perturbative to non-perturbative regime: charm and beauty quarks provide hard scale for QCD calculations

Radiative parton energy loss

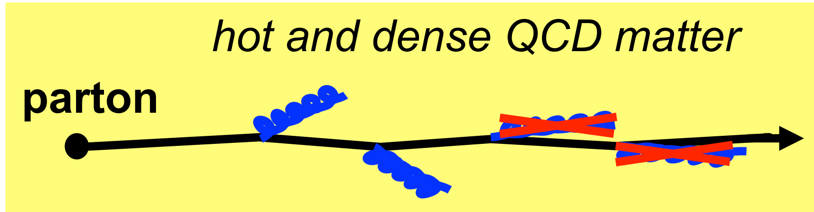
- …depends on
  - medium properties (e.g. density, temperature, mean free path)
    → transport coefficients ($\hat{q}$)
  - path length in the medium (L)
  - parton properties (colour charge and mass); traversing the medium → Casimir coupling factor (C_R):
    C_R = 4/3 for quarks and 3 for gluons
    R. Baier et al., Nucl. Phys. B483 (1997) 291 (BDMPS)

$$\langle \Delta E_{medium} \rangle \propto \alpha_S C_R \hat{q} L^2$$

S. Wicks et al., Nucl. Phys. A 784 (2007) 426



- Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)
  Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202

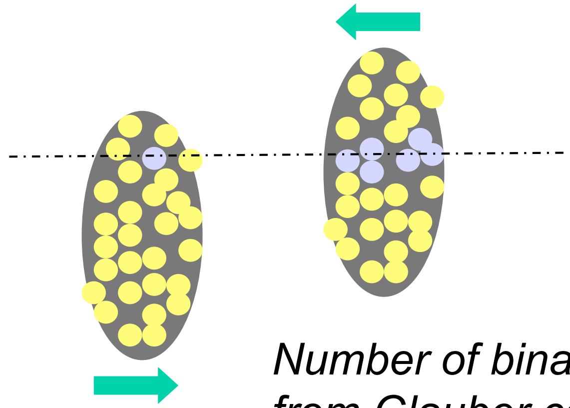


- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

mass dependence

Quantification of medium effects

Comparison of the production yield in heavy-ion collisions with the one in proton-proton collisions



Number of binary collisions from Glauber calculations

Nuclear modification factor

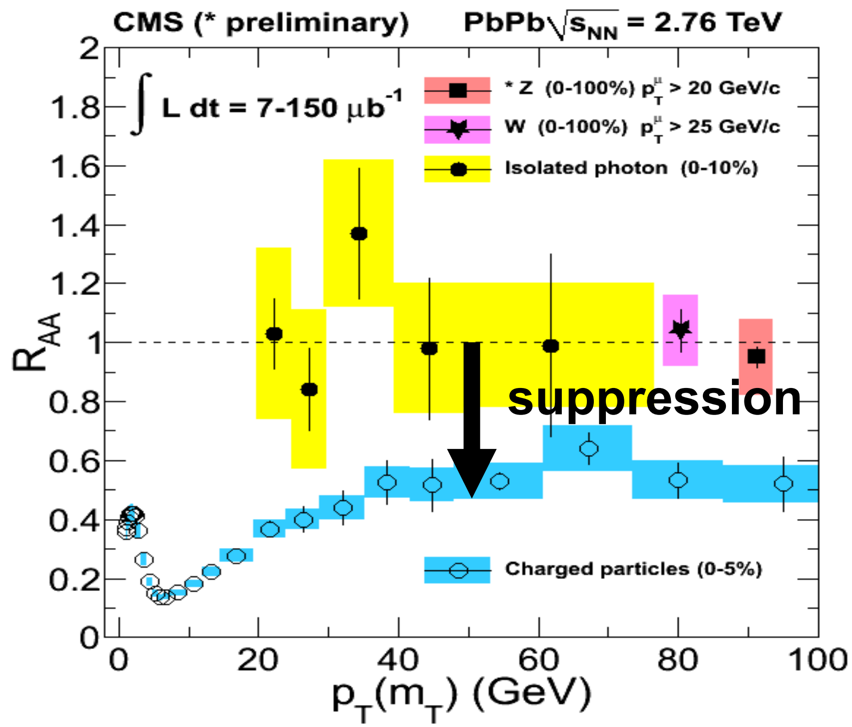
$$R_{AA}(p_T) = \frac{\mathrm{Yield}_{AA}(p_T)}{\langle N_{bin} \rangle_{AA} \, \mathrm{Yield}_{pp}(p_T)}$$

Expectation:

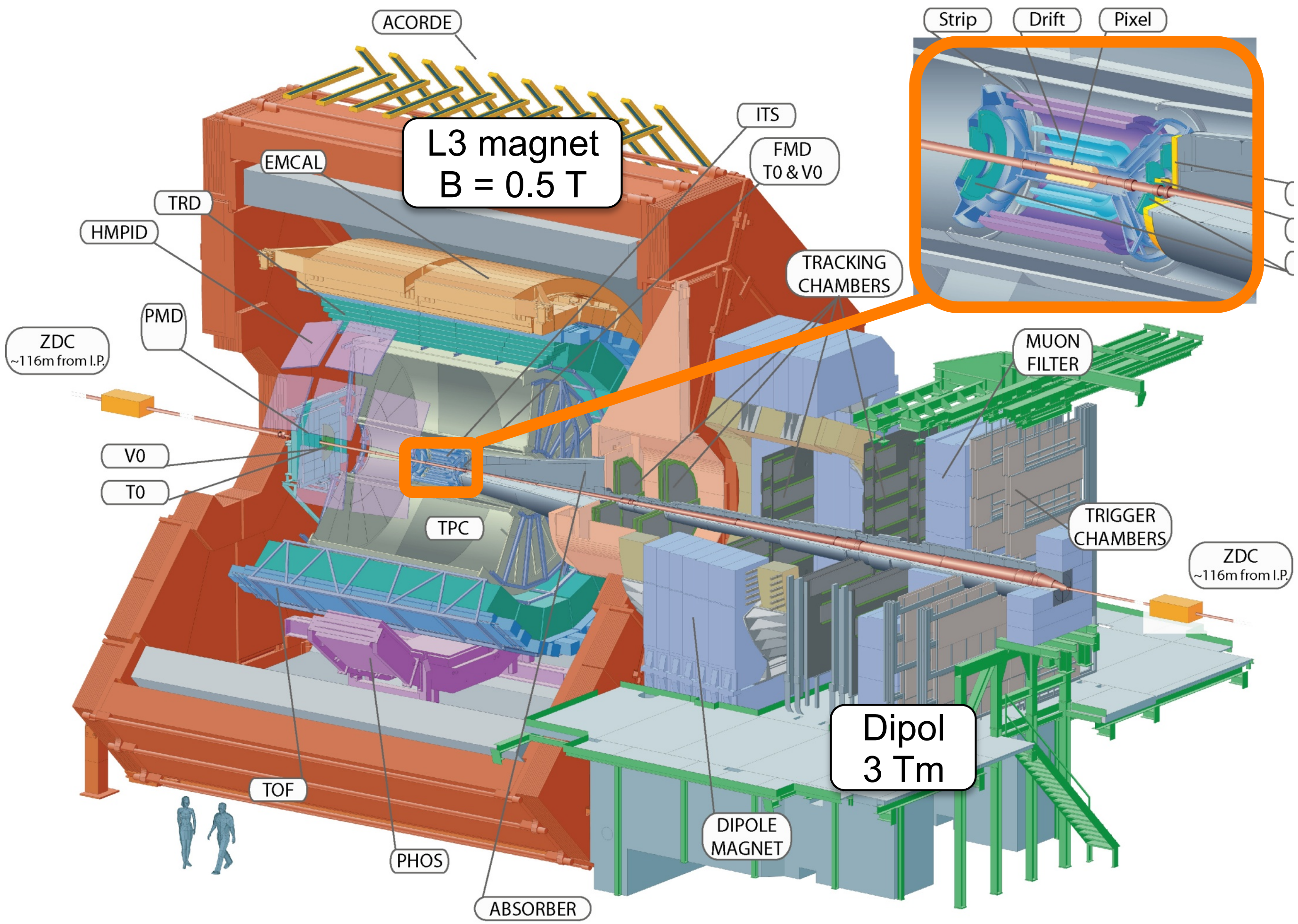
$R_{AA} = 1$ for photons

$R_{AA} < 1$ for hadrons

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



A Large Ion Collider Experiment



At the CERN
Large Hardon Collider

Sub-detector systems

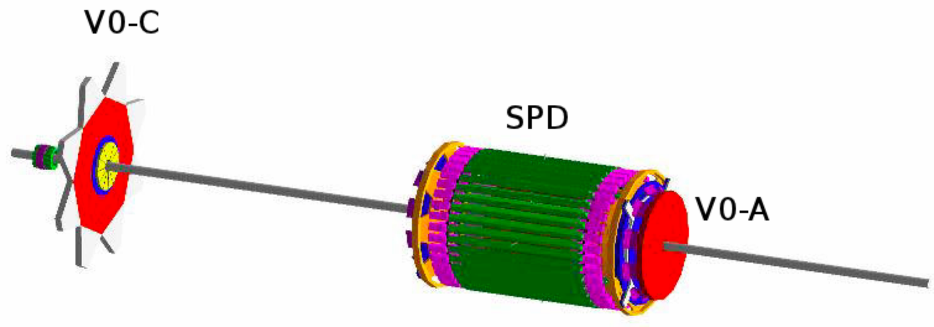
ITS, TPC, TOF, HMPID,
TRD, FMD, PMD,
T0, V0, ZDC,
EMCAL, DCAL, PHOS,
Muon arm,
DAQ, HLT (High Level Trigger)

- 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

Trigger and data samples

- Minimum bias, based on interaction trigger:
  - SPD or V0-A side or V0-C side
  - at least one charged particle in 8 η units
  - 95% efficient on σ_{inel}
- Vertex determination: SPD
- Centrality in Pb-Pb: Glauber fit to V0 signal amplitude
- Single-muon trigger (p_T > 0.5 and 4.2 GeV/c)
  - forward muon in coincidence with MB

SPD: silicon pixel detector



$\sqrt{s_{NN}}$ (TeV)	Year	Integrated luminosity
2.76	2010	10 μb^{-1}
2.76	2011	0.1 nb^{-1}
5.02	2015	202.3 μb^{-1} (muon data)

In addition (not covered in this talk):
- pp collisions at $\sqrt{s}$ = 0.9, 2.76, 7, 8 and 13 TeV
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV

Detection of open heavy-flavour particles

ALICE

1. Full reconstruction of open charmed mesons

e.g.: $D^0 \rightarrow K^- + \pi^+$ BR = 3.89%, $c\tau$ = 123 μm

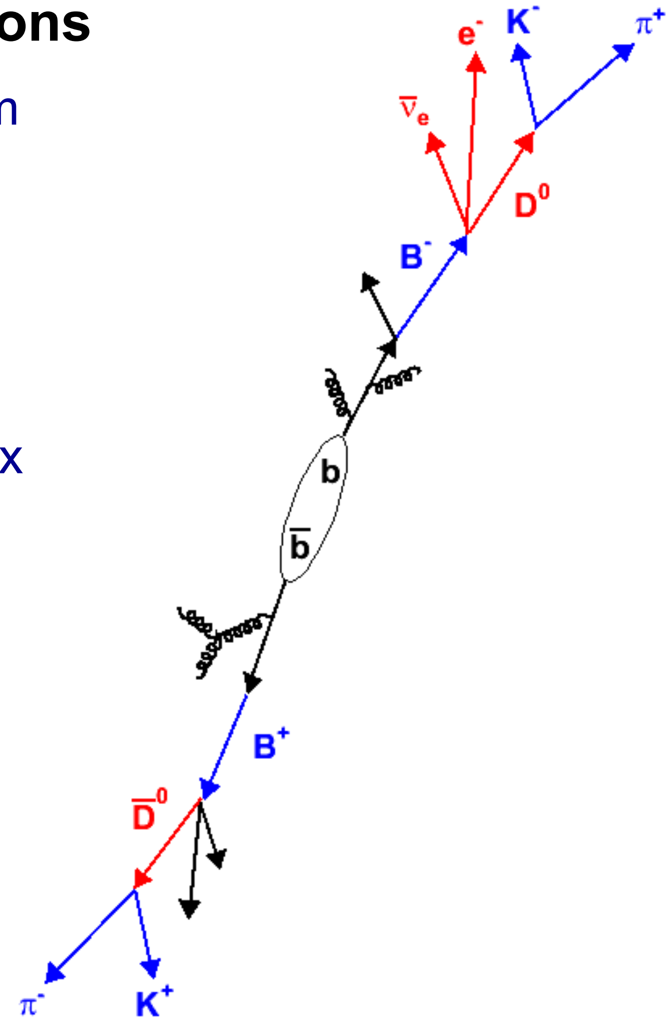
- direct clean probe: signal in invariant mass distribution
- difficulty: large combinatorial background especially in a high multiplicity environment
- techniques of background subtraction and vertex tracker needed

2. 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%

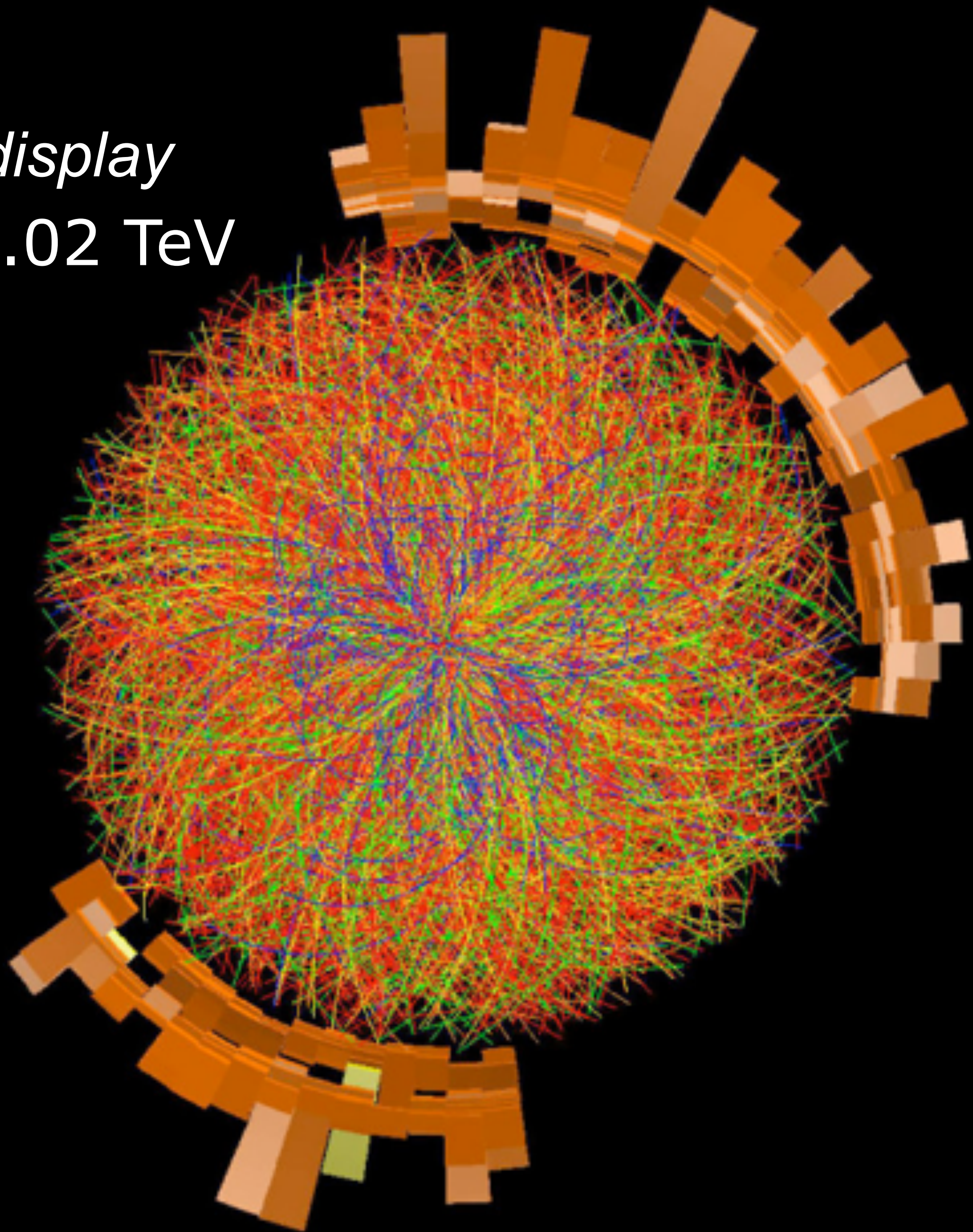
- robust electron trigger
- needs handle on photonic electron background

3. Beauty via non-prompt J/ψ and hadronic decays



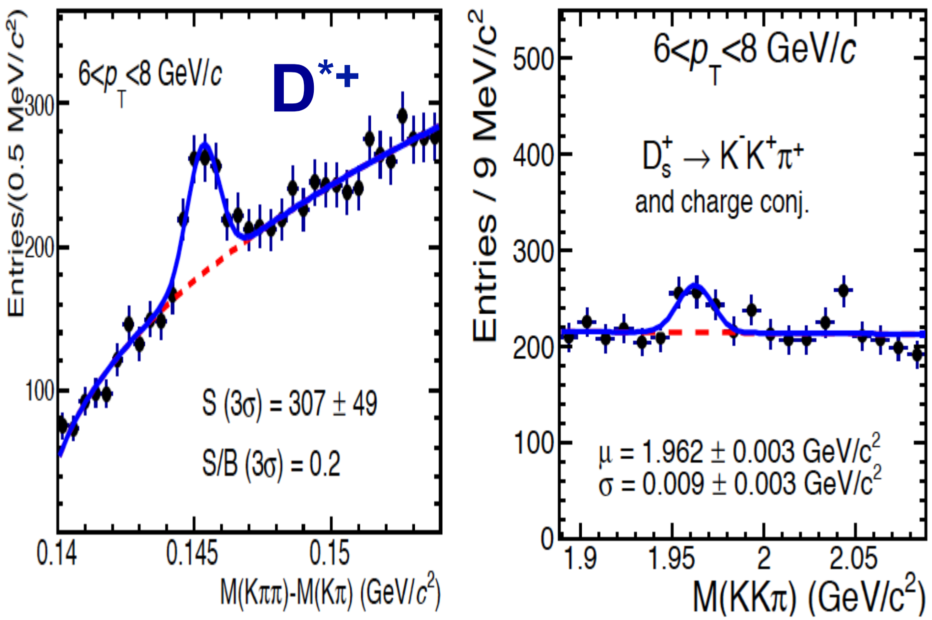
Typical event display

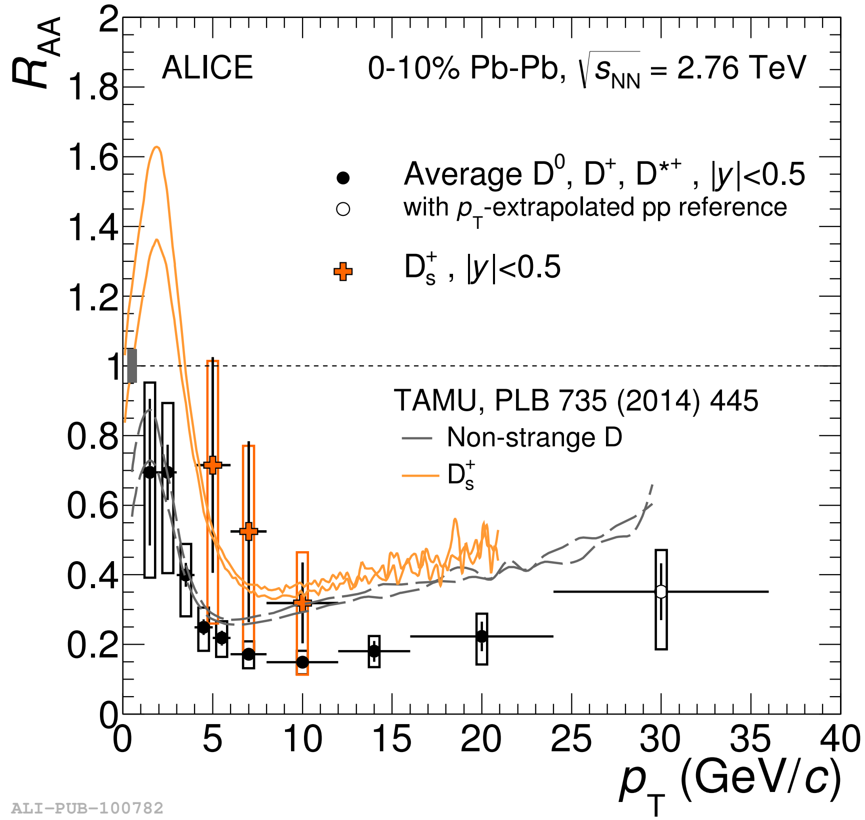
Pb-Pb at $\sqrt{s_{NN}}$ 5.02 TeV



Prompt D-meson R_{AA} in 2.76 TeV Pb-Pb

ALICE, JHEP 03 (2016) 081 and JHEP 03 (2016) 082

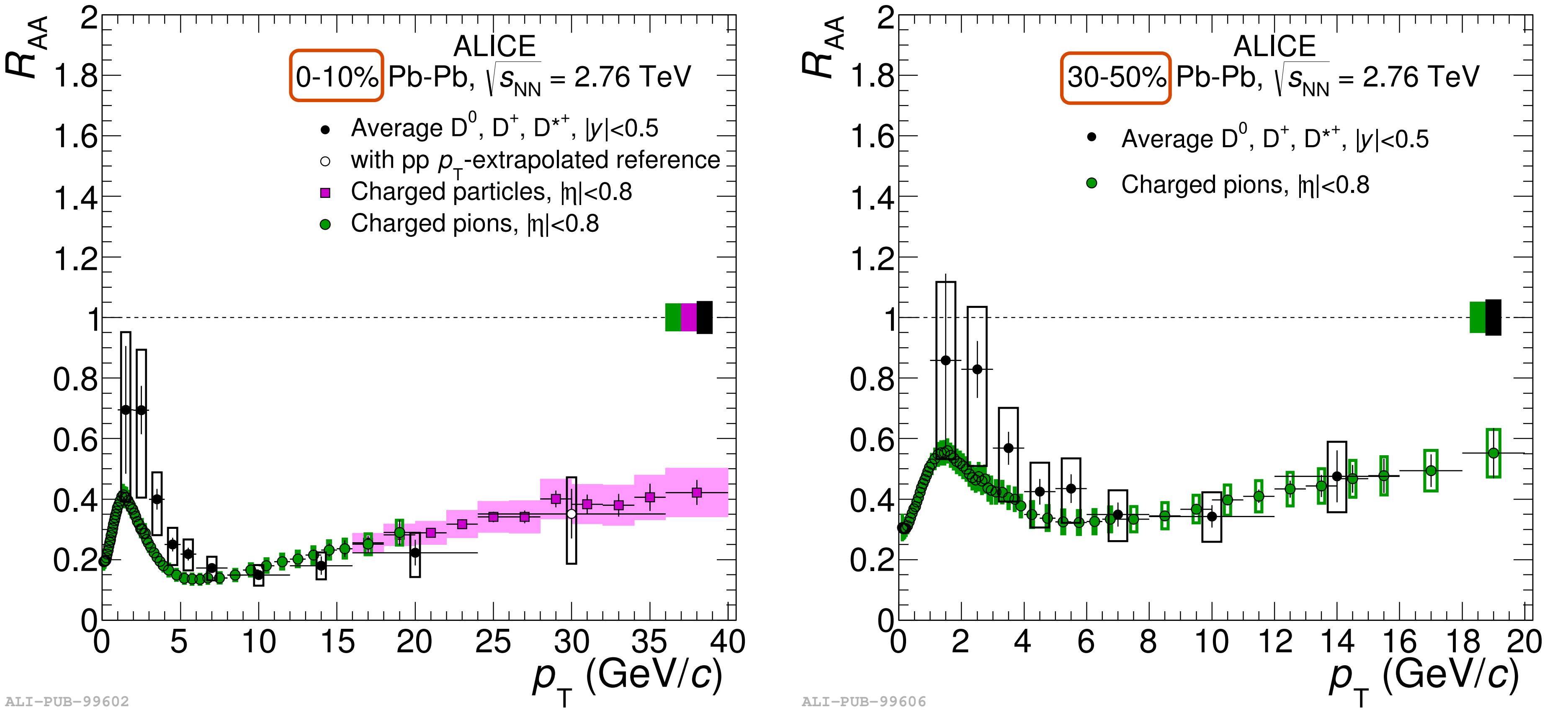




- Above 5 GeV/c strong suppression (factor 4-5) of D-meson yield in central Pb-Pb collisions, compared to binary scaling from pp collisions
- First $D_s^+(c\bar{s})$ measurement in heavy-ion collisions
- Expectation: enhancement of strange D-meson yield at intermediate p_T if charm hadronises via recombination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

R_{AA}: light versus heavy-quark hadrons

JHEP 1603 (2016) 081

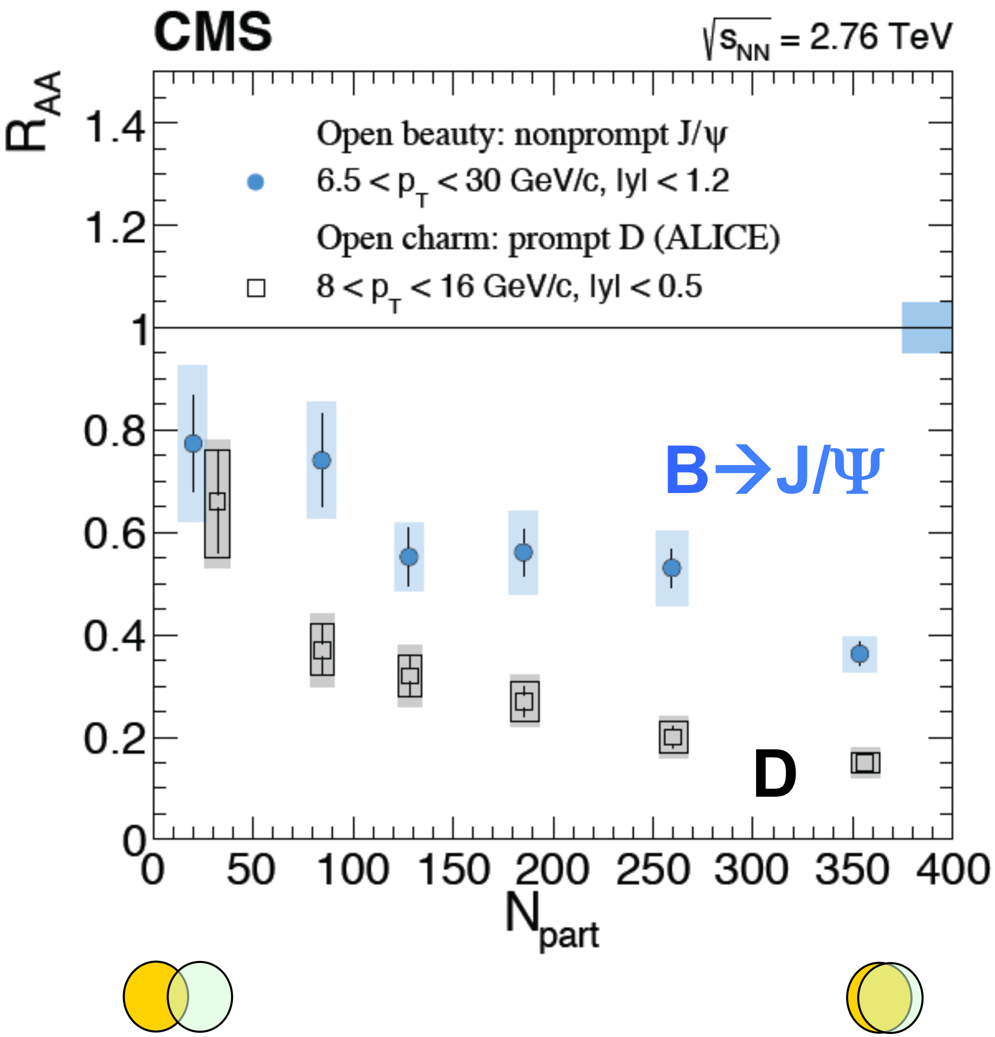


- Slight enhancement of D at low p_T for 10% most central collisions
- Indication for rising R_{AA}

Theoretical interpretation:
M.Djordjevic, PRL 112, 042302 (2014)

Prompt D and B-meson R_{AA} in 2.76 TeV Pb-Pb

ALICE, JHEP 11 (2015) 205
CMS, sub. to Eur. Phys. J. C (arXiv:1610.00613)

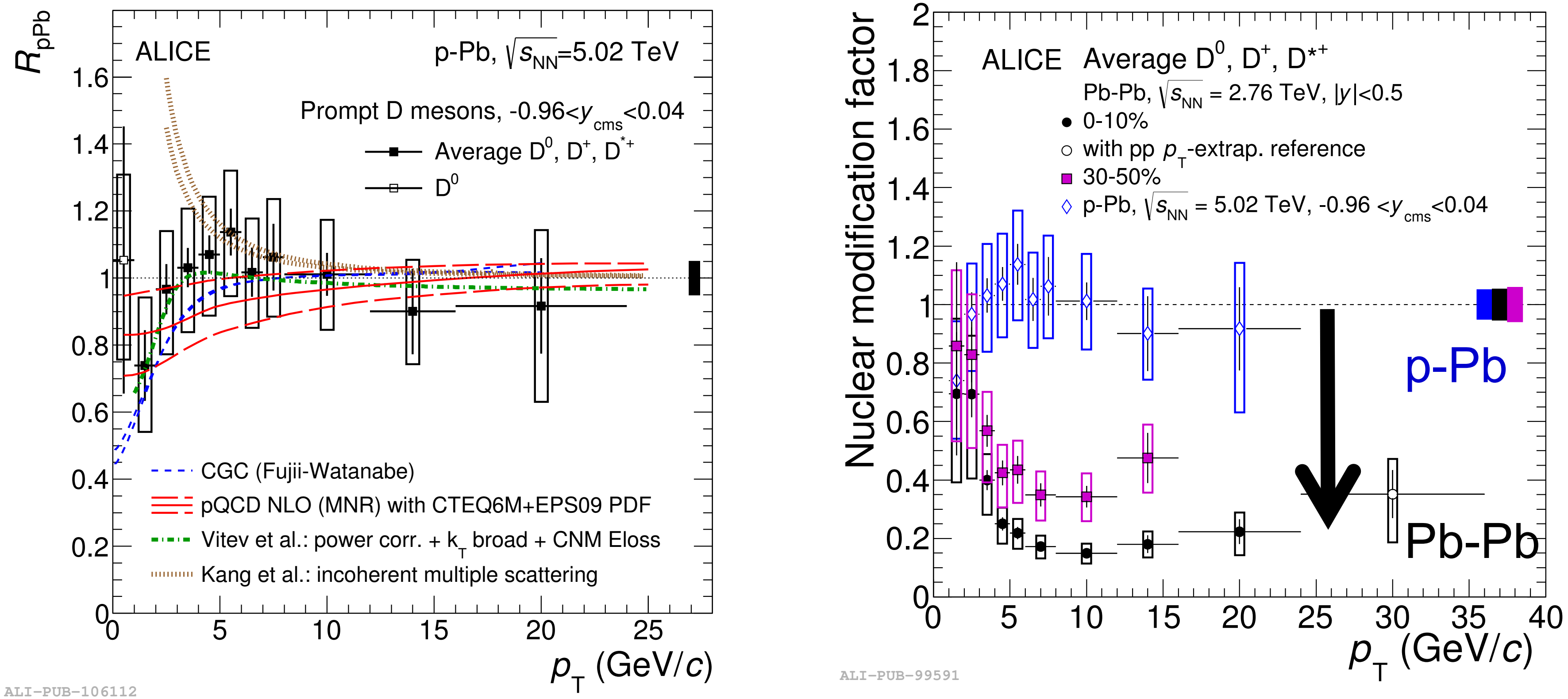


- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson $\langle p_T \rangle$ ~10 GeV/c
- Described by theoretical model calculations including quark-mass dependent energy loss ($R_{AA}^D < R_{AA}^B$) in the studied p_T range

Theoretical interpretation:
M.Djordjevic, Phys. Lett.B 737 (2014) 298)

D mesons: initial-state effects

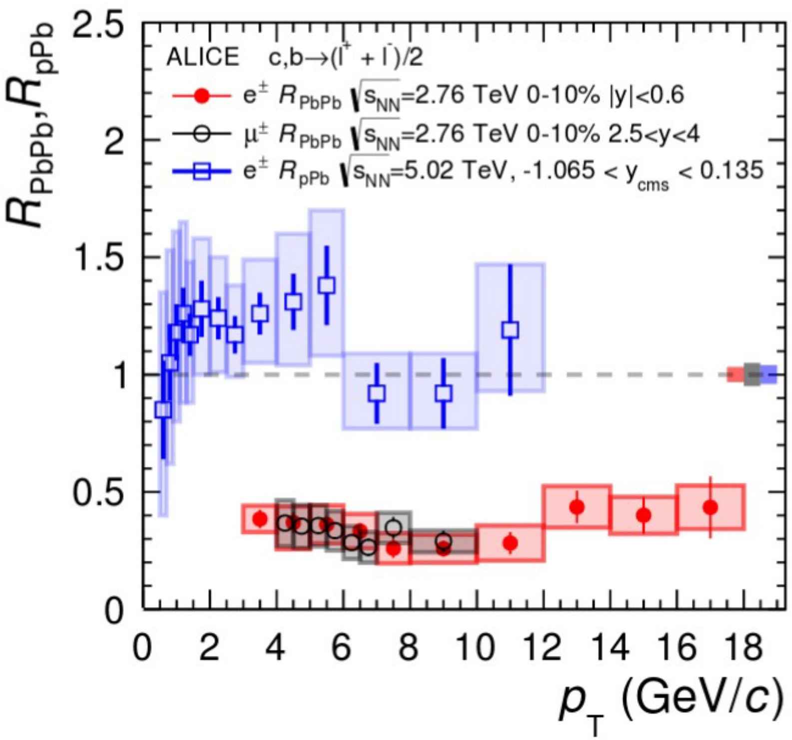
Phys. Rev. C 94, 054908 (2016) and Phys. Rev. Lett. 113 (2014) 232301

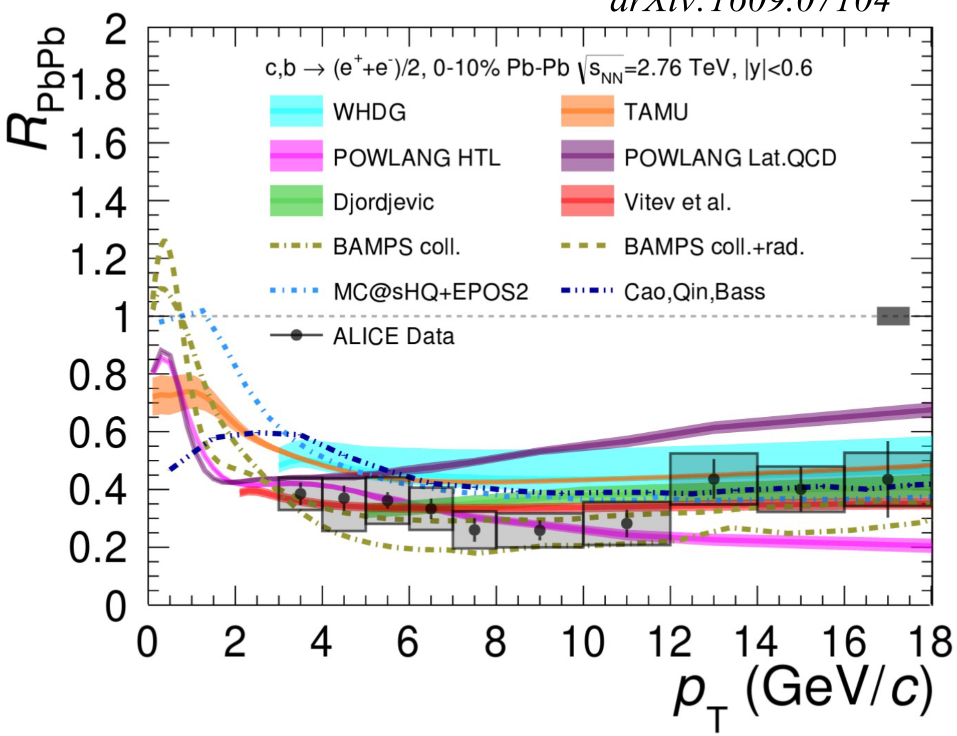


- Important baseline measurement of **cold nuclear matter effects** (e.g., Cronin effect, nuclear shadowing, gluon saturation)
- D-meson R_{pA} shows consistency with unity and predictions from shadowing and CGC model predictions
- **High-p_T suppression of particle yield in Pb-Pb is a final-state effect**

Single electron R_{AA} at 2.76 TeV

arXiv:1609.07104





- Strong suppression of single electron yield up to 18 GeV/*c* observed in 10% most central Pb-Pb collisions, unlike in p-Pb

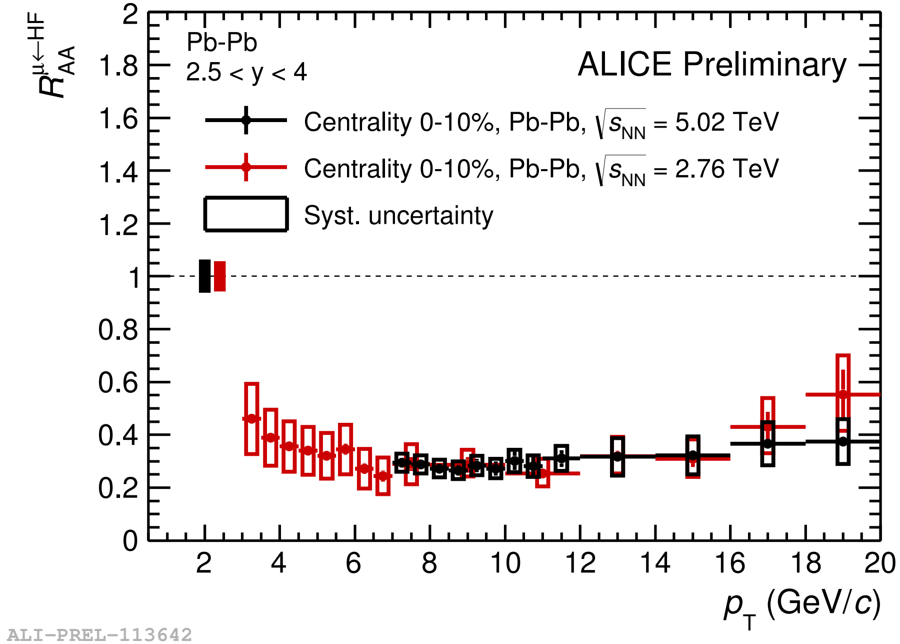
→ Substantial energy loss of heavy quarks in the medium

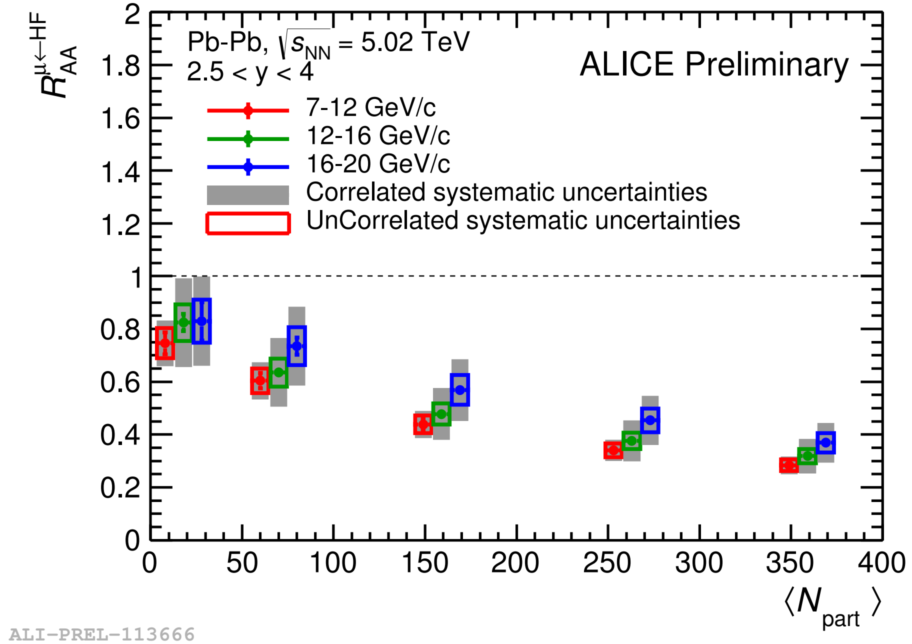
- Constrain theoretical models (with D-meson R_{AA} and v_2)

→ Extraction of heavy-quark transport coefficients

Single muon R_{AA} at 2.76 and 5.02 TeV

Phys. Rev. Lett. 109 (2012) 112301

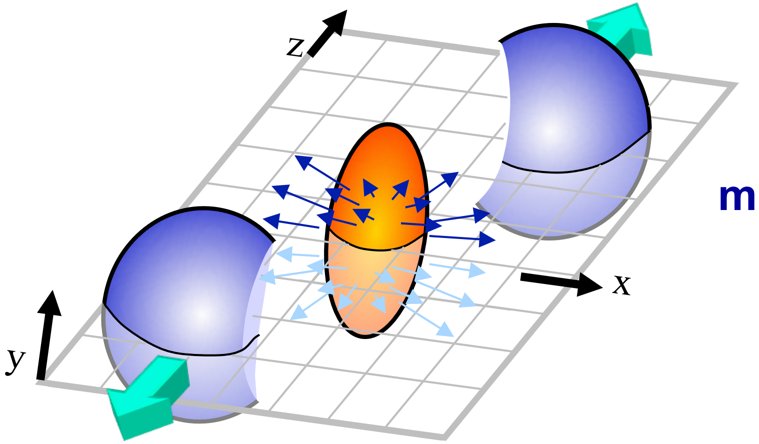




- Strong suppression in 10% most central collisions reaching a factor ~3 in $7 < p_T < 12$ GeV/c
- R_{AA} at 5.02 TeV consistent with that at 2.76 TeV in the overlap p_T region
- Suppression increases with increasing centrality

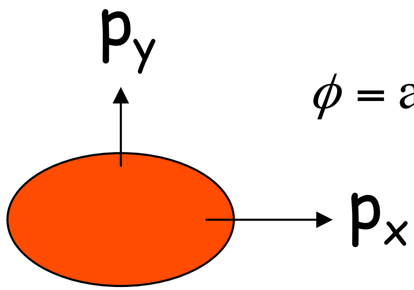
Azimuthal anisotropy (elliptic flow)

Do heavy quarks thermalise in the medium?



coordinate space:
initial anisotropy

pressure and multiple collisions



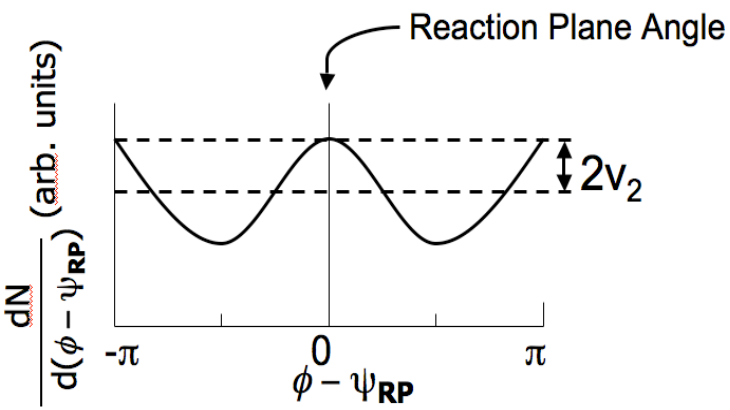
$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

momentum space:
final anisotropy

- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective expansion of the medium → anisotropy in momentum space
- Fourier decomposition:

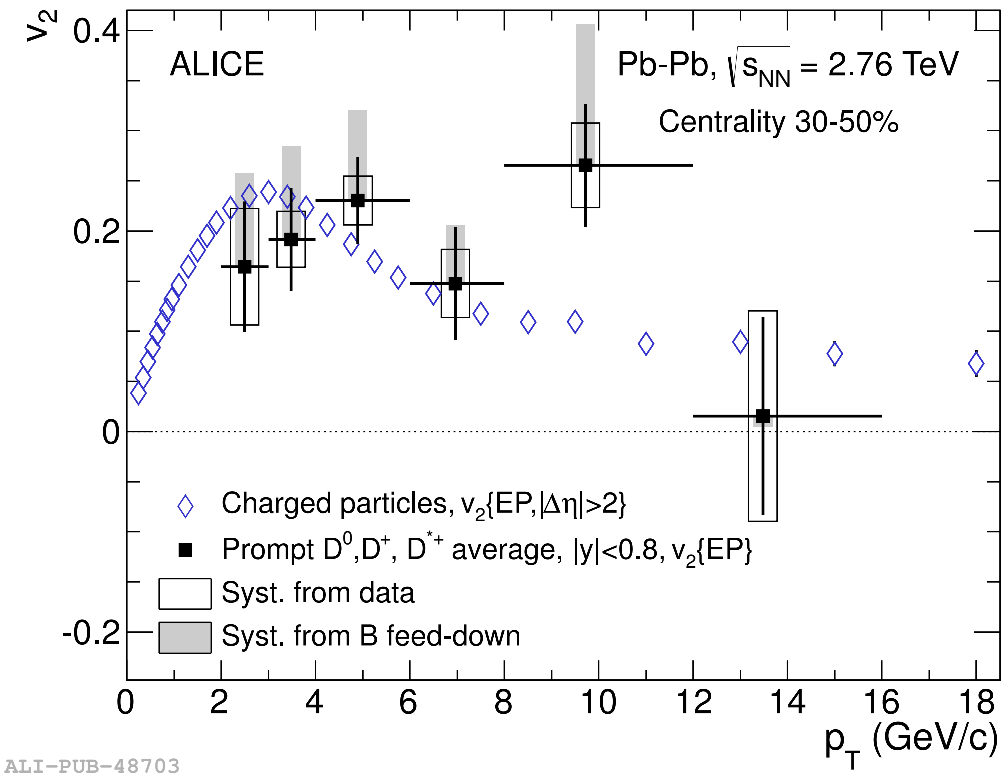
$$\frac{\mathrm{d}N}{\mathrm{d}(\varphi - \psi_n)} \propto 1 + 2\sum_{n=1} v_n \cos(n[\varphi - \psi_n])$$

$$\textit{where } v_n = \langle \cos(n[\varphi - \psi_n]) \rangle$$



Azimuthal anisotropy of prompt D mesons

Phys. Rev. Lett. 111 (2013) 102301



- Due to the large mass, long thermalisation process is expected for heavy quarks

→ less influenced by collective expansion

- Indication (3-5σ confidence level) for non-zero charm elliptic flow in the p_T range 2-6 GeV/c

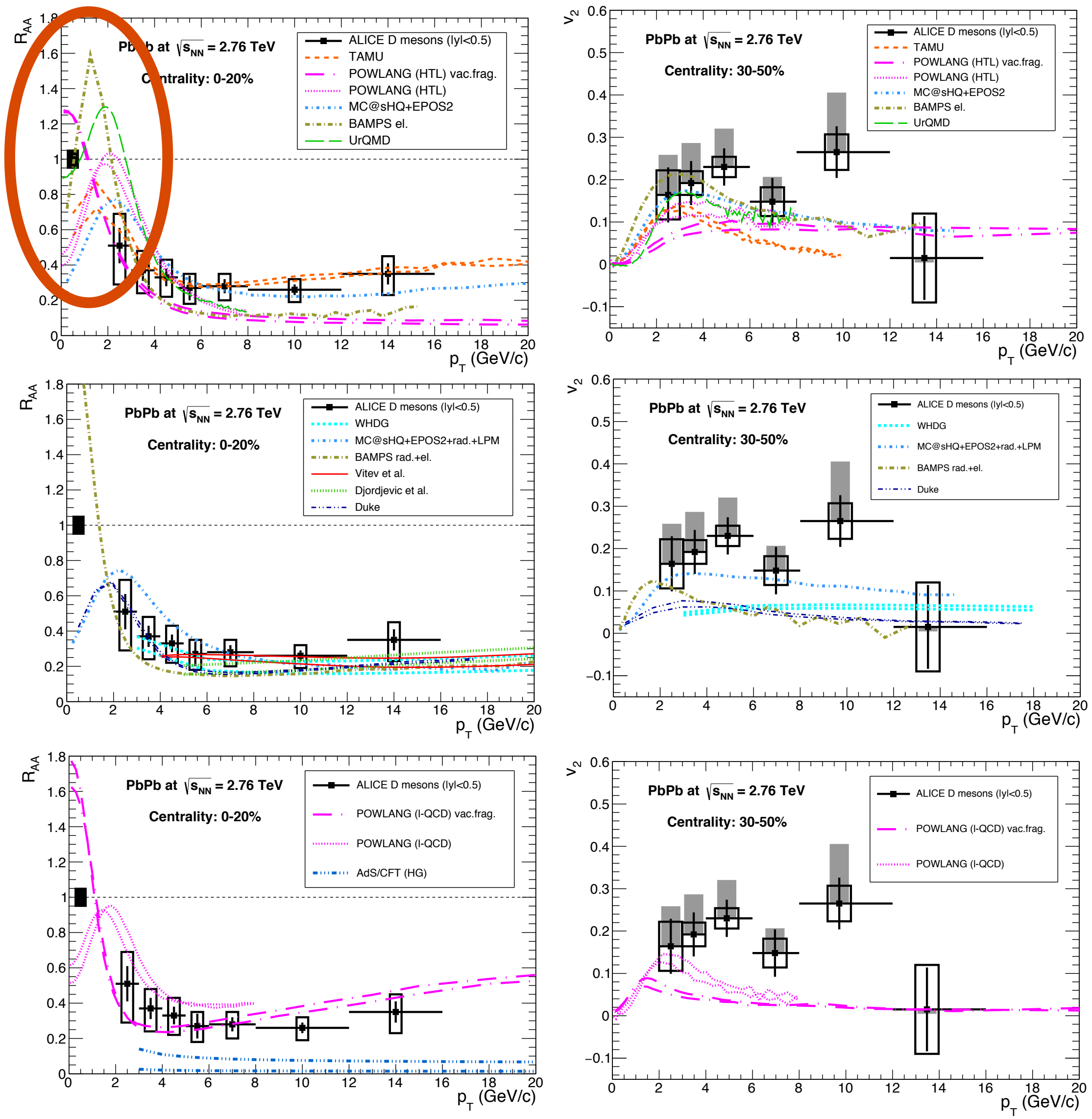
→ Significant interaction of charm quarks with the medium

- Improved measurement with Run-2 data

Comparison with model calculations: D mesons

R_{AA} (0-20%) v_2 (30-50%)

Eur. Phys. J. C 76 (2016) 107



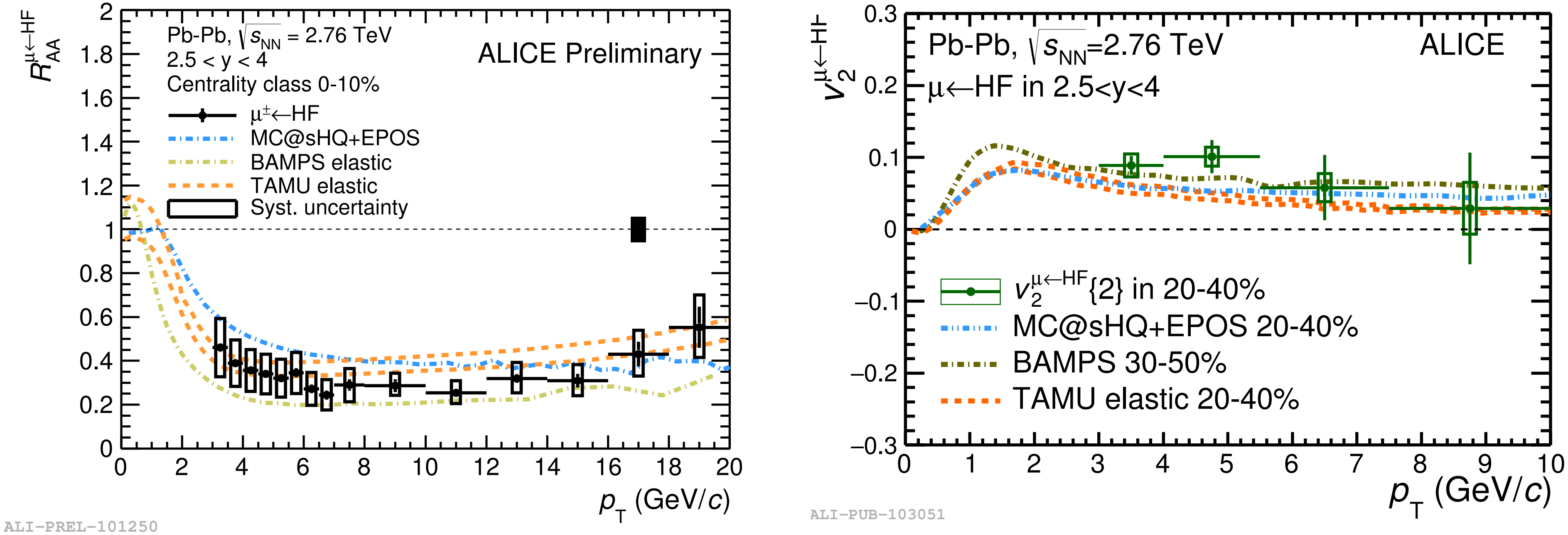
Collisional energy loss only

Collisional and radiative energy loss

No final conclusion possible at the moment → more precision data needed

Comparison with model calculations: single muons

Phys. Lett. B753 (2016) 41

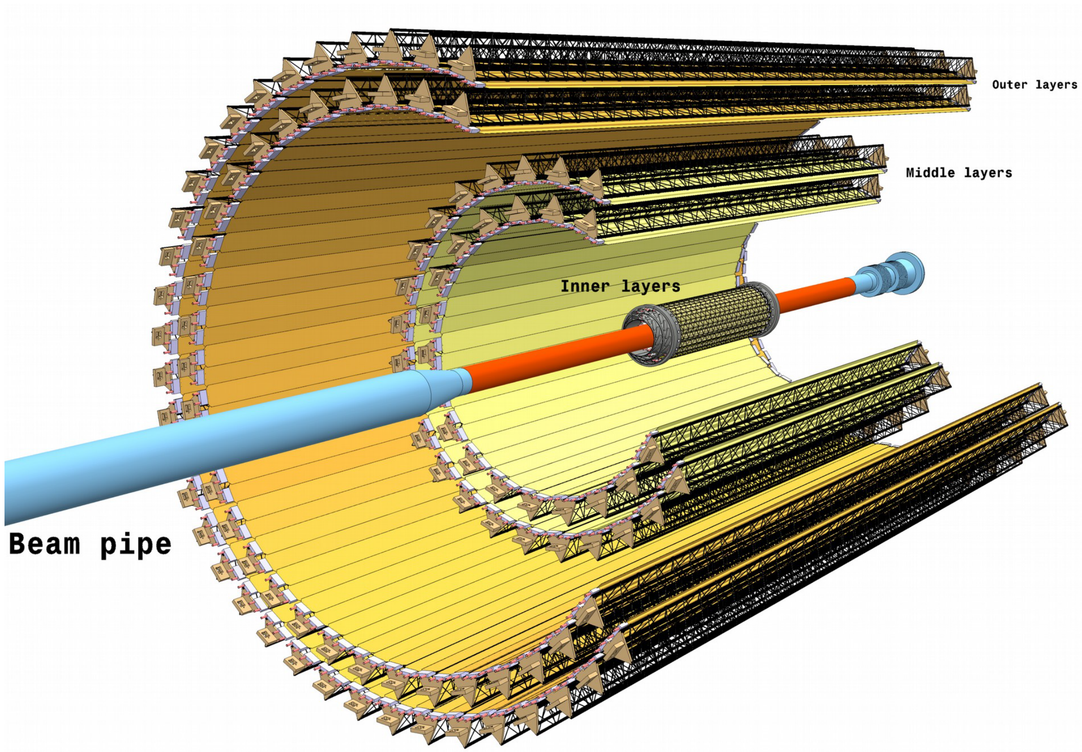


- Simultaneous description of R_{AA} in central collisions and v_2 in semi-central collisions is challenging
- R_{AA} and v_2 measurements provide constraints on energy-loss models

Summary

- LHC ideal for studying the properties of hot dense QCD matter
  - large volume, long lifetime, high production rates for rare probes
- Heavy quarks are particularly good probes to study **transport properties** (e.g. drag and diffusion coefficient) and **degree of thermalisation**
  - R_{AA} and v_2 of prompt D mesons and single leptons (run-2 muons)
    - strong suppression of the yield at high p_T (>6 GeV/c) observed in central collisions → more insight on energy-loss mechanisms
    - non-zero elliptic flow → suggest strong re-interactions within the medium
  - Quark-mass dependence: $R_{AA}(\pi) \sim R_{AA}$(D, single leptons) < $R_{AA}(B \rightarrow J/\psi)$
  - Precision measurements in extended p_T ranges needed to further constraint theoretical model calculations
- Many more exciting results ahead of us
  - Run-2 Pb-Pb data at $\sqrt{s_{NN}}$ = 5.02 TeV and after upgrades in 2019/20
  - p-Pb data taking at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV in 2016

Upgrade of the ALICE Inner Tracker



12.5 G-pixel camera (~10 m²)

Also upgrade of the Muon Forward Tracker at forward rapidity

- 7-layer barrel geometry based on CMOS pixel sensors
- Factor ~3 improvement in impact parameter resolution
- η coverage: $|\eta| \leq 1.22$
- Low material budget; goal
  - $X/X_0 \leq 0.3\%$ for first 3 inner silicon layers
  - X/X_0 ~1% for for outer barrel
- Installation in 2019/2020
- Design requirements: event readout rate
  - Pb-Pb: 100 kHz
  - pp: >400 kHz