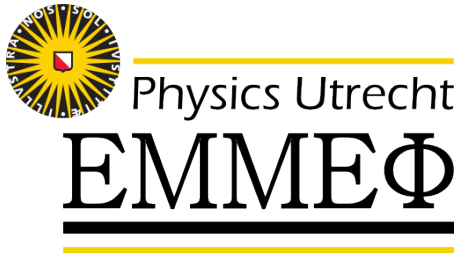
Heavy-flavour measurements from LHC and RHIC

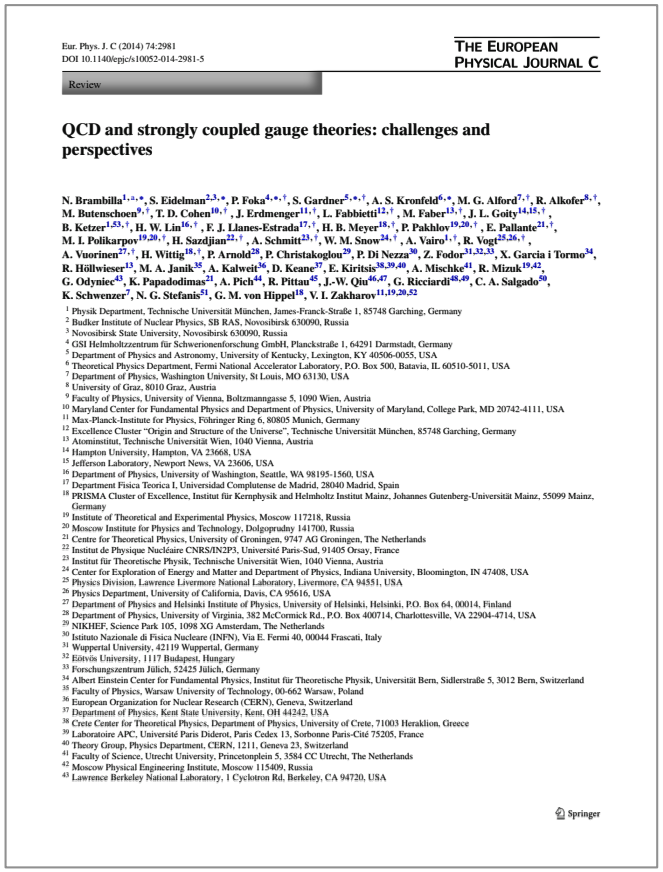


André Mischke

Utrecht University

4th International Symposium on Non-equilibrium Dynamics (NeD-2015)
Giardini Naxos (Sicily), Italy – 30 August – 5 September 2015

Recent overview papers



Eur. Phys. J. C (2014) 74:2981
DOI 10.1140/epjc/s10052-014-2981-5

THE EUROPEAN PHYSICAL JOURNAL C

Review

QCD and strongly coupled gauge theories: challenges and perspectives

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Springer

QCD and strongly coupled gauge theories: challenges and perspectives, Eur. Phys. J. C 74, 2981 (2014)

Heavy-flavour and quarkonium production in the LHC era:
from proton-proton to heavy-ion collisions

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Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions, submitted to EPJC (arXiv:1506.03981)

Outline

• Open heavy flavour (charm and beauty) allow studying the dynamical properties of hot QCD matter and degree of thermalisation

• **Probes**

- D (and B) mesons and heavy-flavour decay leptons (e and μ)

• **Collision systems**

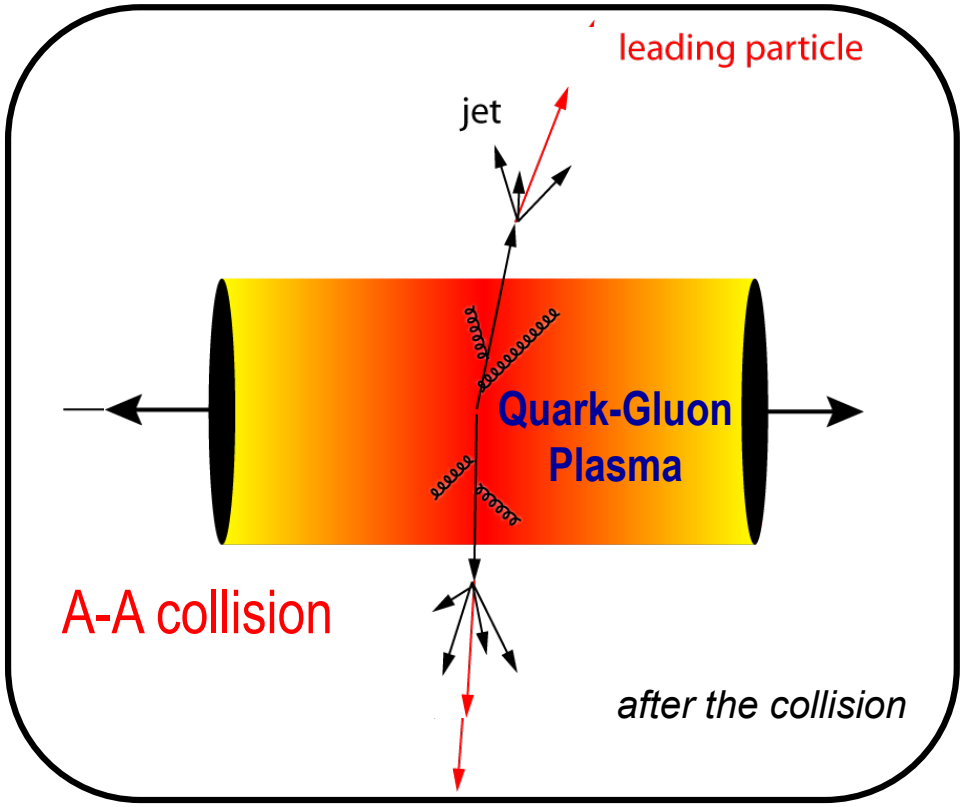
- pp: important baseline and test pQCD computations
- p-A: study cold nuclear matter effects (initial state)
- A-A: study hot QCD matter (final state); determine medium properties

• **Observables**

- R_{AA} and v_2 (versus p_T and centrality)
- Multiplicity dependence of the yield
- Angular azimuthal correlations

• **Summary**

Probing hot and dense QCD matter

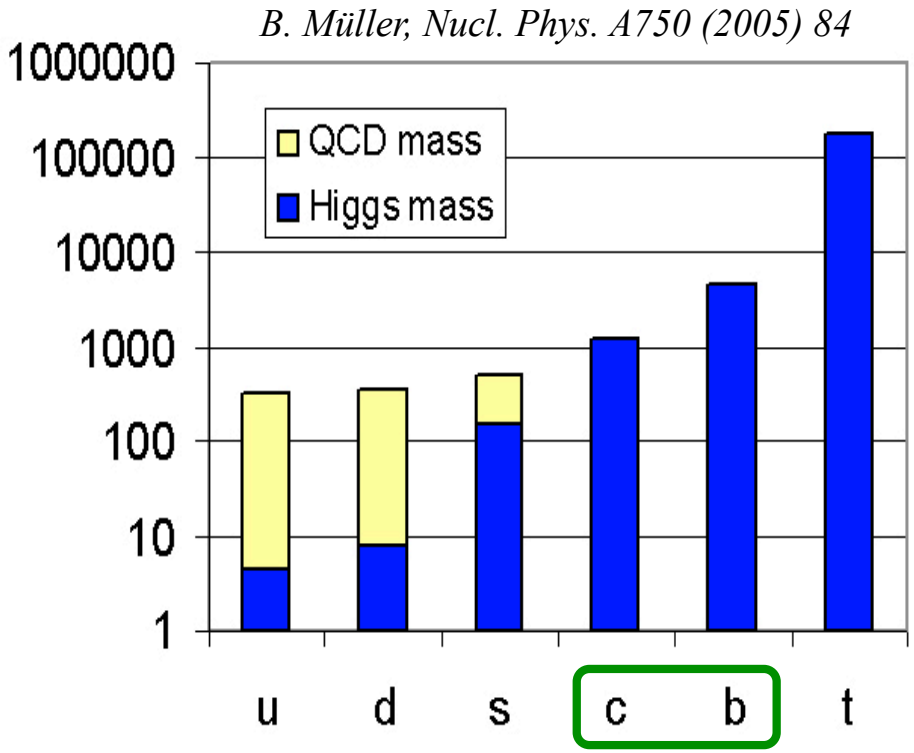


Quantify medium effects with **nuclear modification factor**

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

- "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)
  - traverse through the medium and interact strongly
  - suppression pattern provides density measurement
  - General picture: parton energy loss through medium-induced **gluon radiation** and **collisions** with medium constituents

Heavy quarks are ideal probes



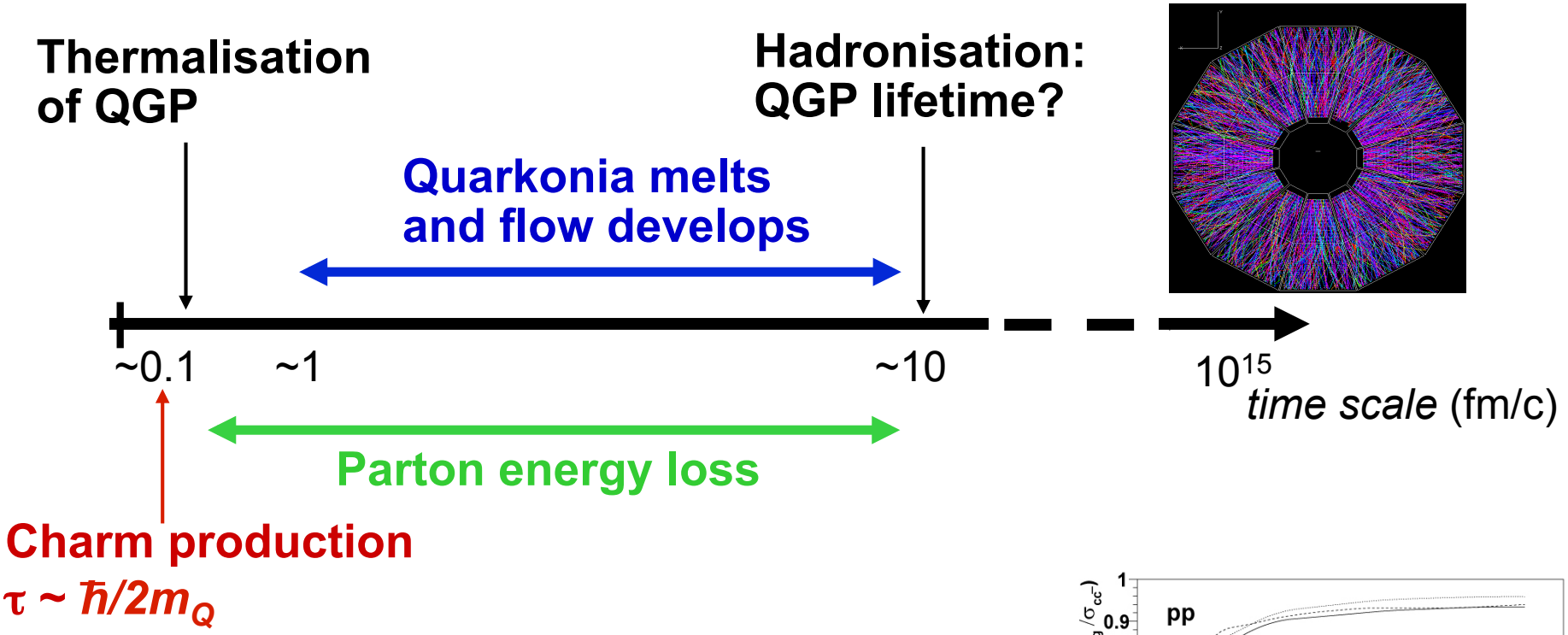
- Charm and beauty quarks are 250-450 times heavier than light quarks
- They are abundantly produced at the LHC, **predominantly in the early phase of the collisions**
- **Production rates calculable in pQCD**

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

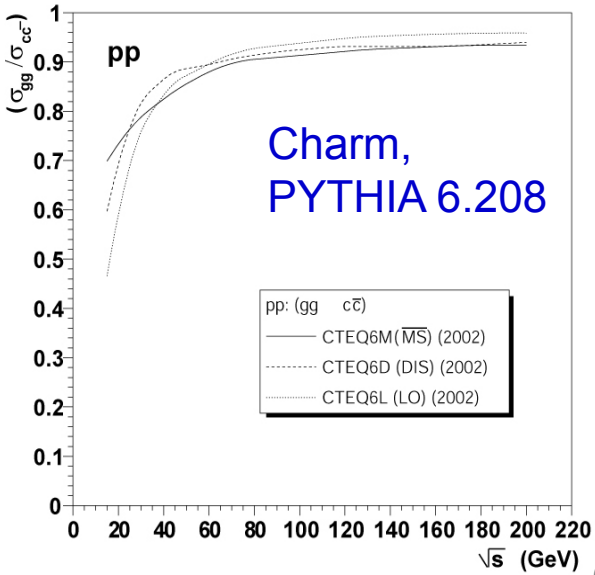
- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

- 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. C 51 (1995) 2177*
- Heavy quarks transverse through the QCD medium and interact strongly with it → **energy loss**



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 (1997) 291 ("BDMPS")

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

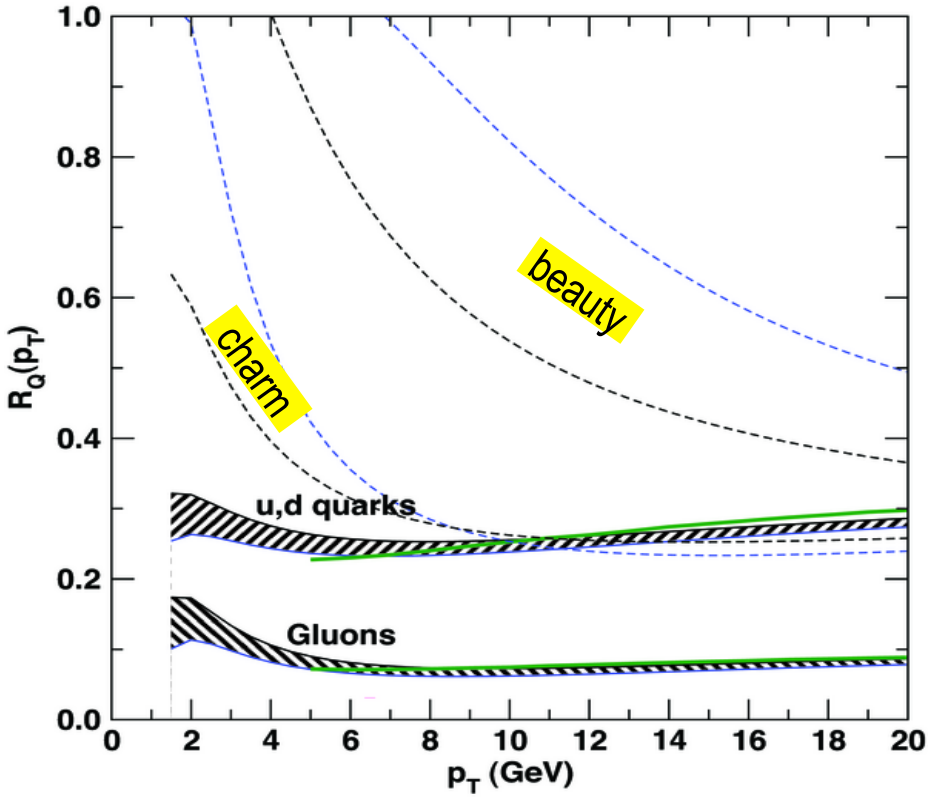
(2) Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

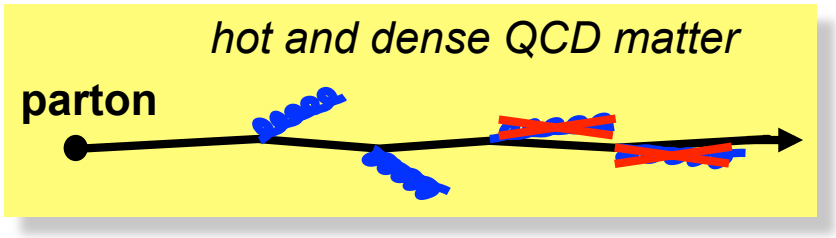
Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202

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

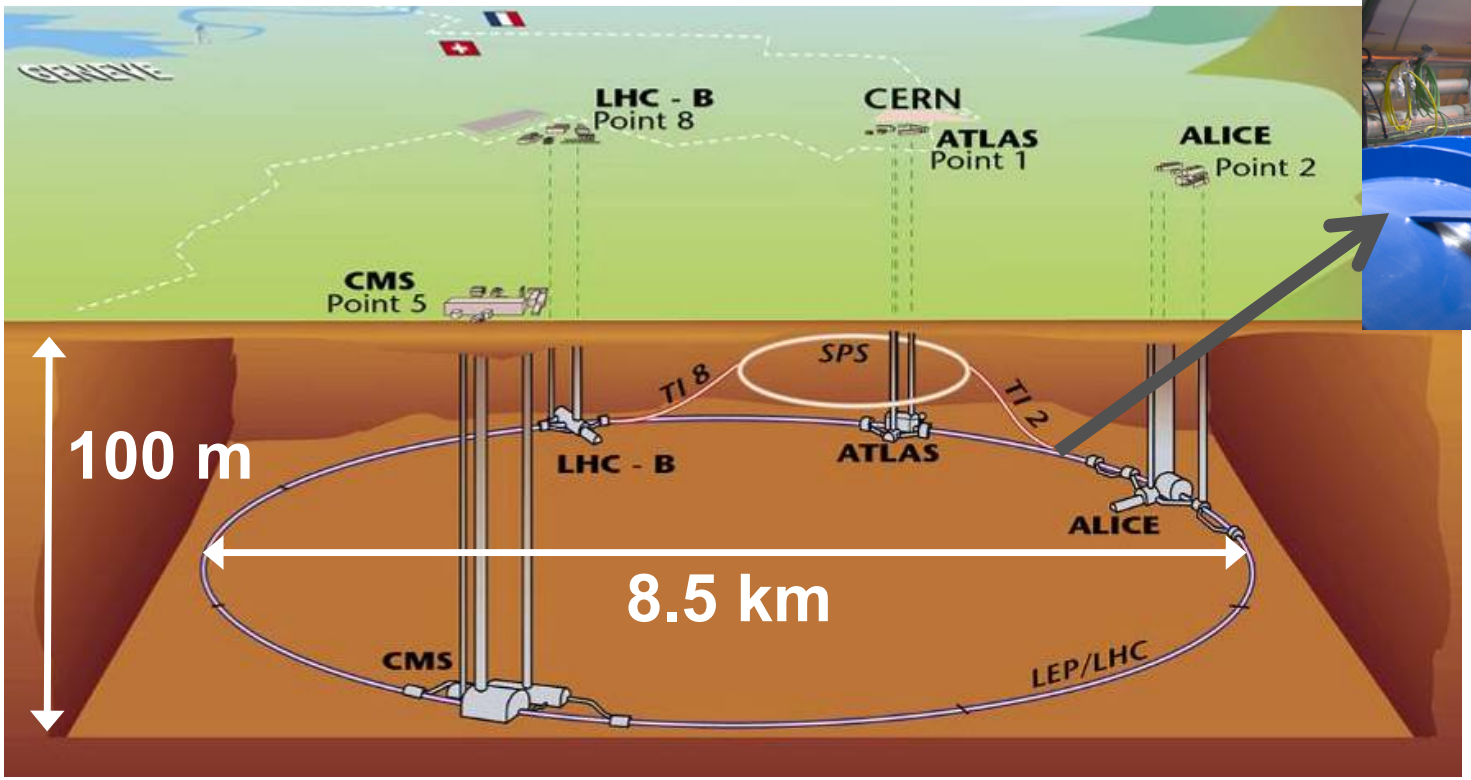
$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

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



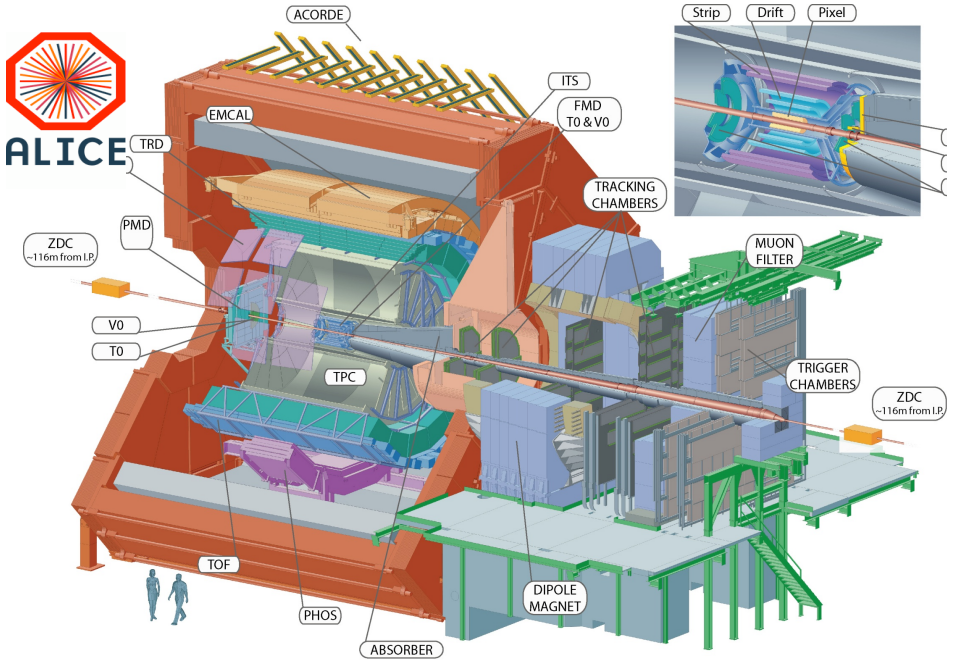


Large Hadron Collider at CERN

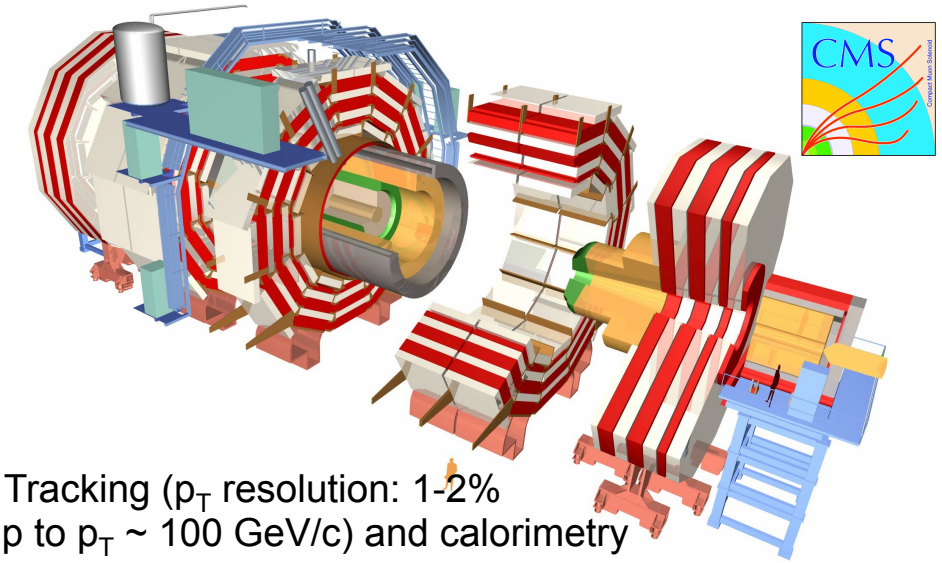


- Data taking since November 2010
- System and energies
  - Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
  - pp, $\sqrt{s}$ = 0.9, 2.36, 2.76, 7, 8 & 13 TeV
  - p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

Experiments



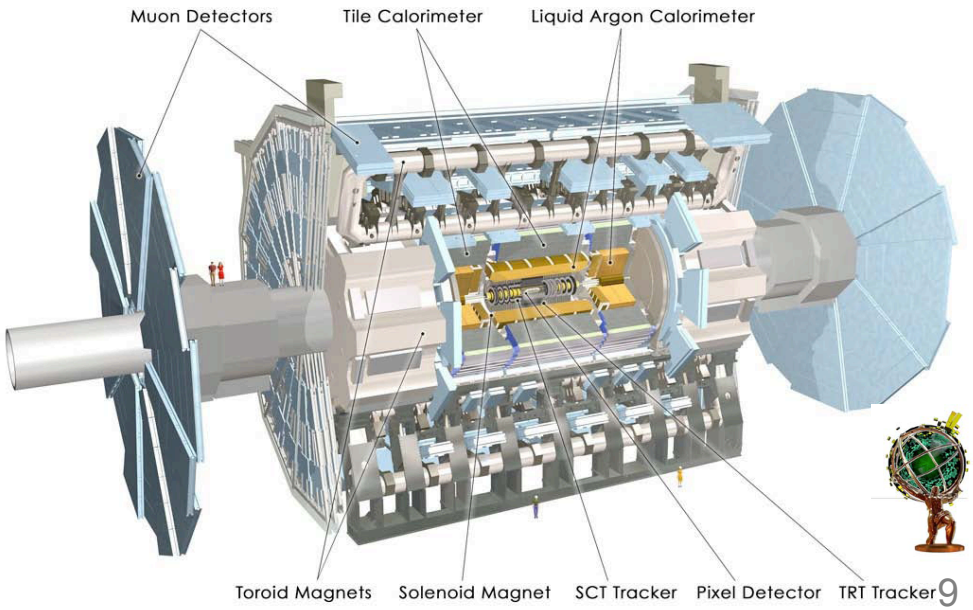
- PID over a very broad momentum range (>100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage $|\eta| < 0.9$ and $-4 < \eta < -2.5$ in forward region
- Impact parameter resolution better than 65 μm for $p_T > 1$ GeV/c



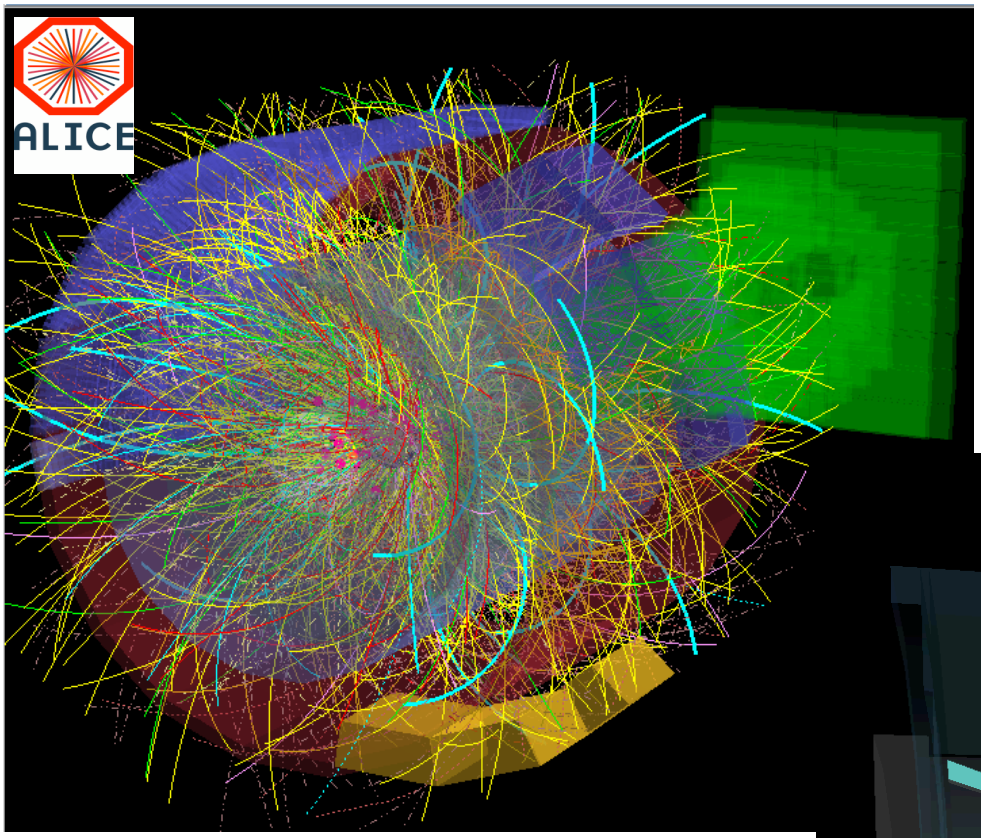
- Tracking (p_T resolution: 1-2% up to $p_T \sim 100$ GeV/c) and calorimetry
- Trigger selectivity over a large range in rapidity and full azimuth

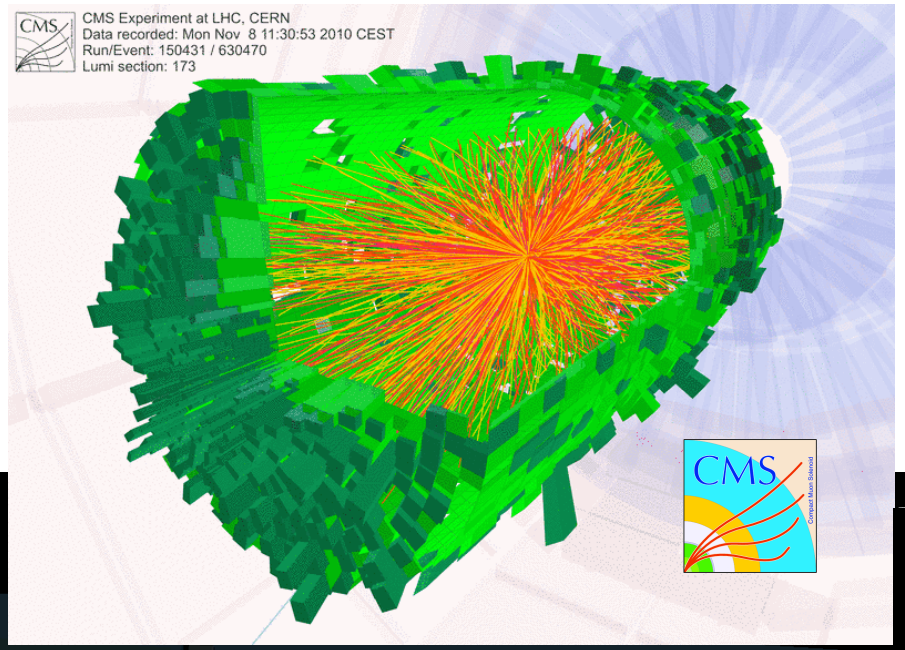
Three main subsystems with a full coverage in azimuth:

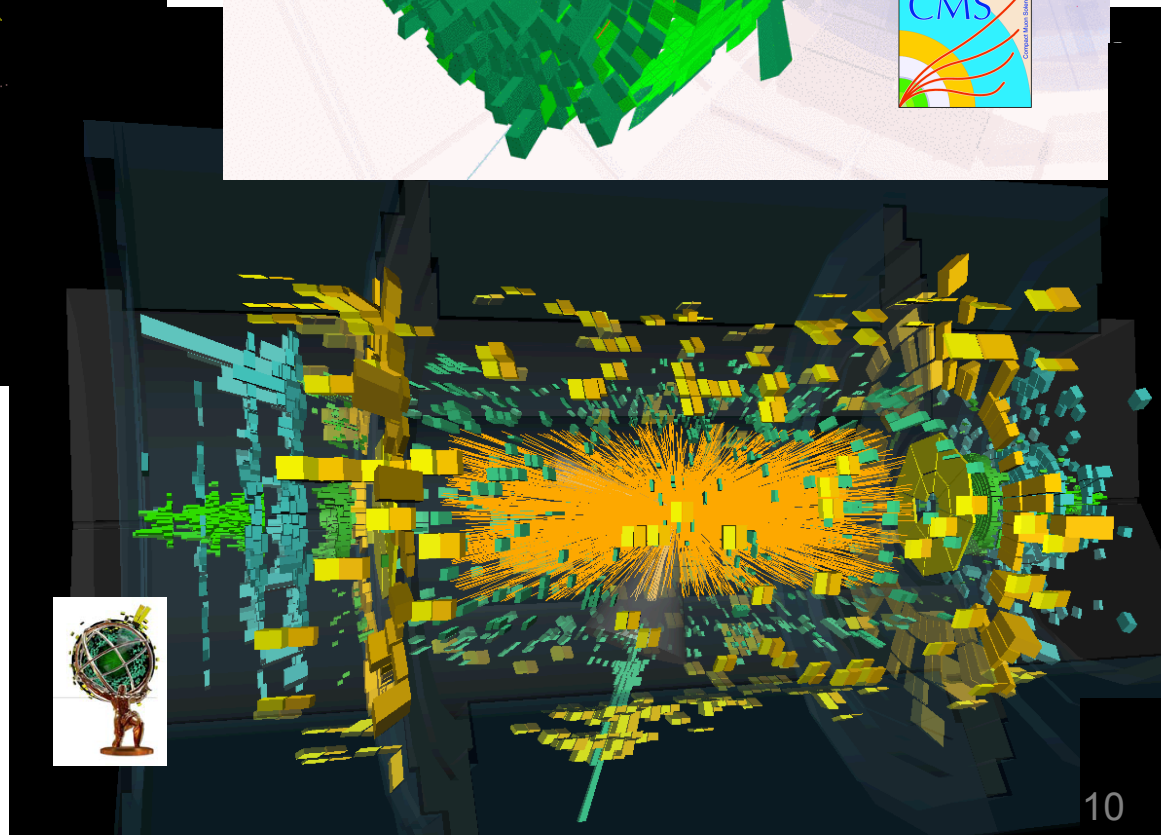
- Inner Detector: tracking $|\eta| < 2.5$
- Calorimetry $|\eta| < 4.9$
- Muon Spectrometer $|\eta| < 2.7$



Typical event displays

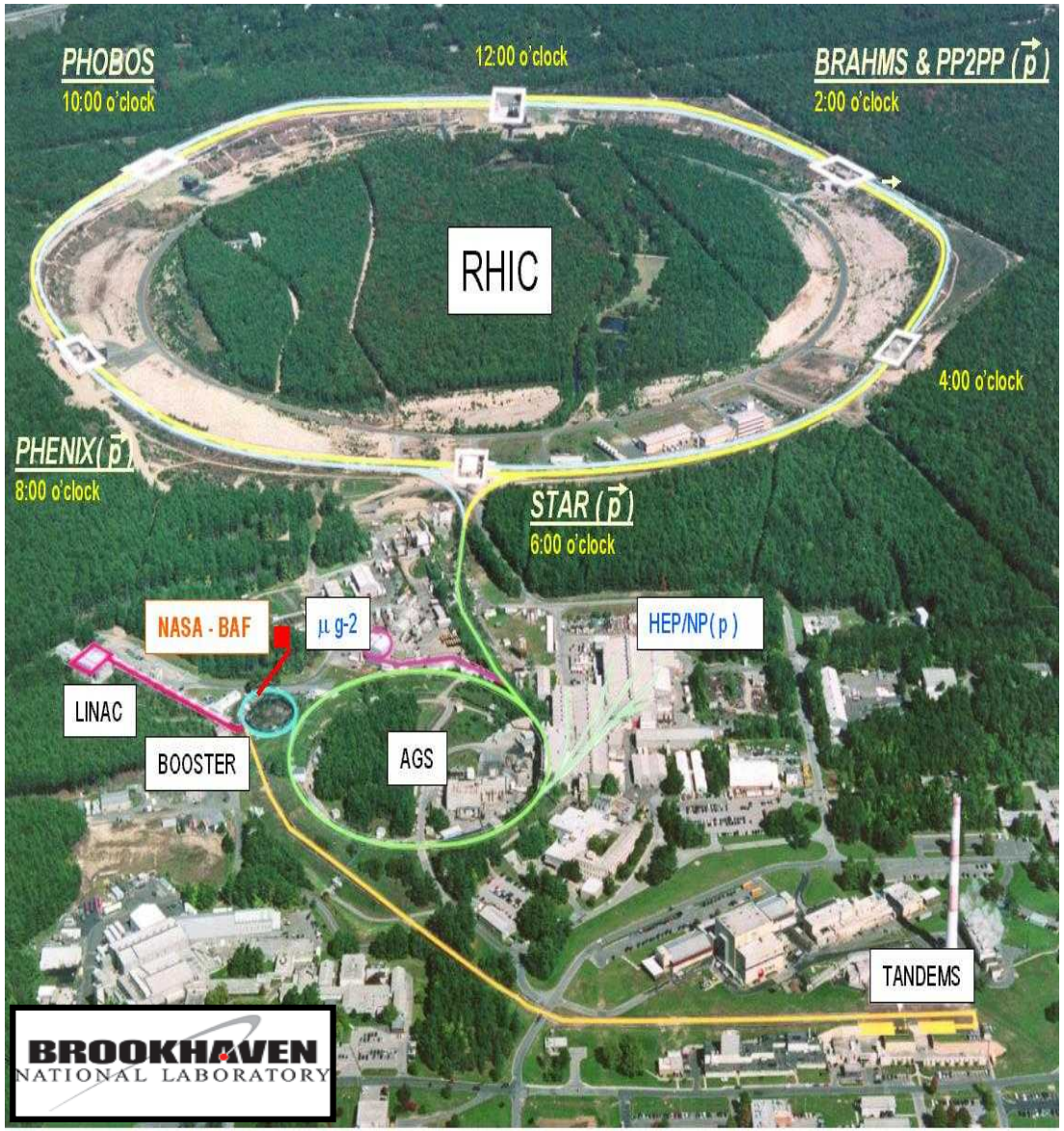






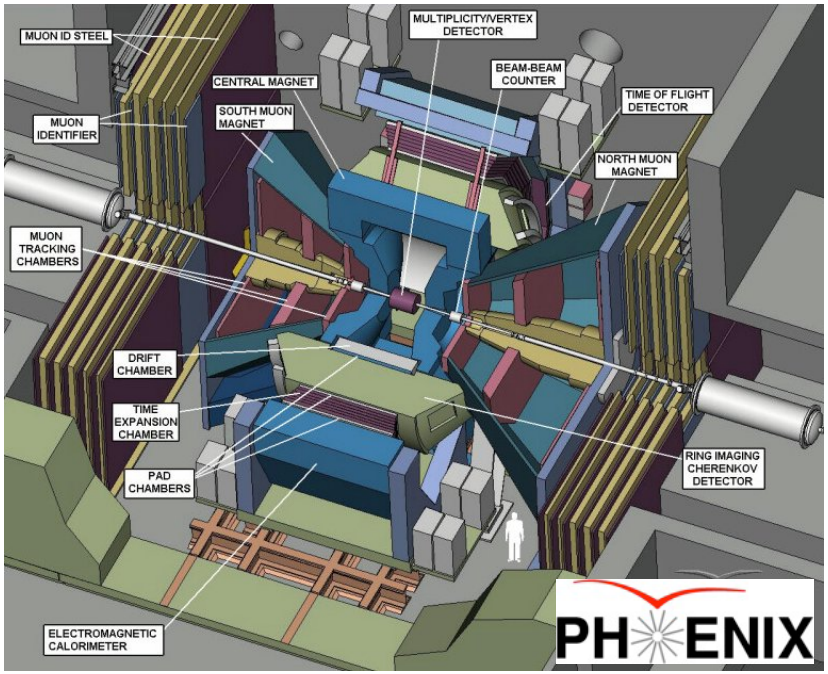
Pb-Pb at $\sqrt{s}$ = 2.76 TeV
per nucleon-nucleon pair

RHIC accelerator at BNL

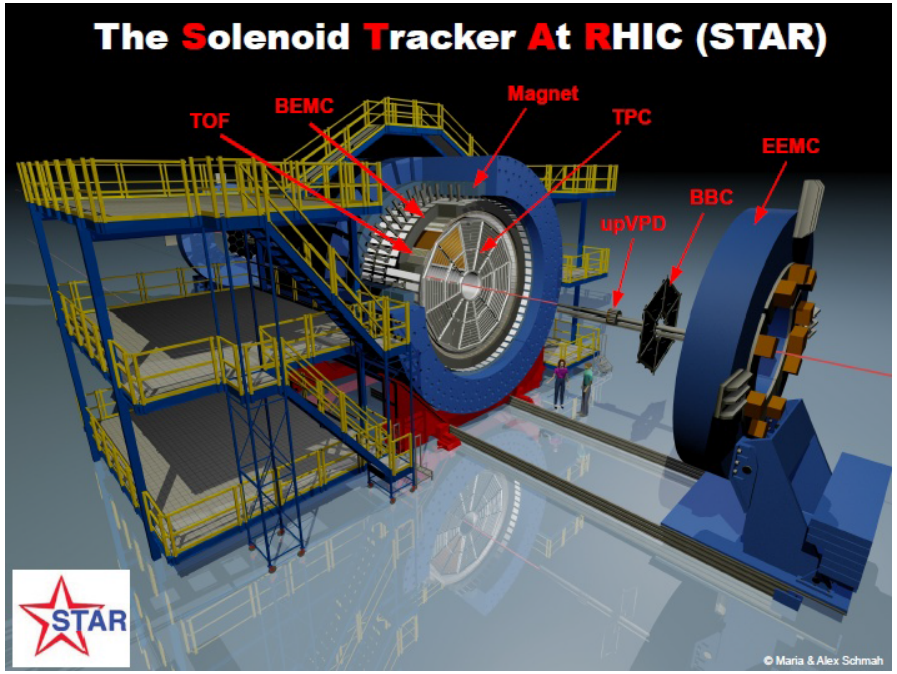


- Relativistic Heavy Ion Collider at Brookhaven National Laboratory
- Two concentric superconducting magnet rings, 3.8 km circumference
- Counter-rotating ion beams
- First collisions in June 2000
- Ion species and energies
  - Au+Au, U+U, $\sqrt{s_{NN}}$ = 7.7-200 GeV
  - Cu+Cu, Cu+Au, $\sqrt{s_{NN}}$ = 200 GeV
  - d+Au, ^{3}He+Au, $\sqrt{s_{NN}}$ = 200 GeV
  - polarized p+p, $\sqrt{s}$ = 200, 500 GeV

Experiments at RHIC



- Designed for leptonic measurements
- DC, PC, TEC, RICH, EMC and Muon tracking - low radiation length
- Open heavy flavors
  - muons (Muon arms at forward rapidities)
  - electrons
- Quarkonia states



- Large acceptance magnetic spectrometer
- High resolution TPC, ToF, CTB and EMC
- Open heavy flavors
  - hadronic reconstruction of D mesons: TPC+ToF
  - muon identification with TPC+ToF
  - electrons with EMCal
- Quarkonia states using special triggers

Detection of open heavy-flavour particles

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
- mixed-event subtraction and/or vertex tracker needed

$f(c \rightarrow D^0) = 0.565 \pm 0.032$
$f(c \rightarrow D^+) = 0.246 \pm 0.020$
$f(c \rightarrow D^{*+}) = 0.224 \pm 0.028$
$f(c \rightarrow D_s^+) = 0.080 \pm 0.017$

2. Semi-leptonic decay of D and B mesons

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

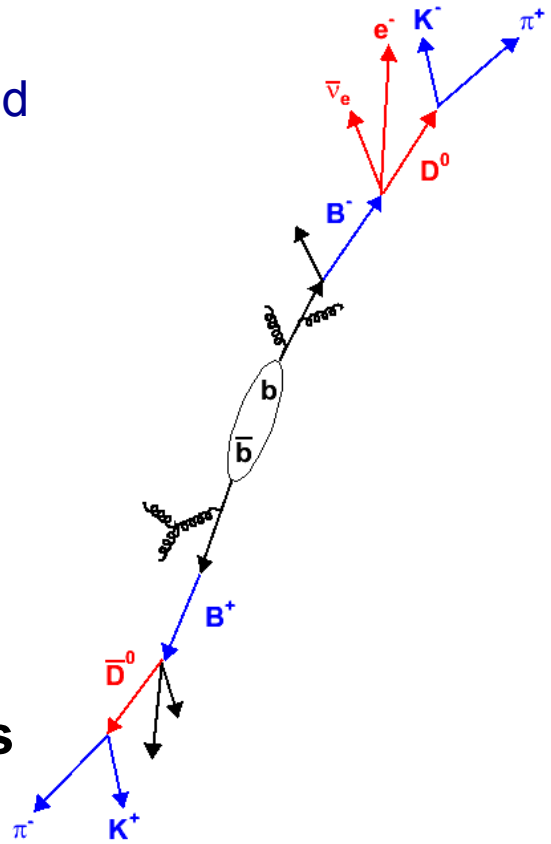
$D^0 \rightarrow e^+ + X$ BR = 6.87%

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

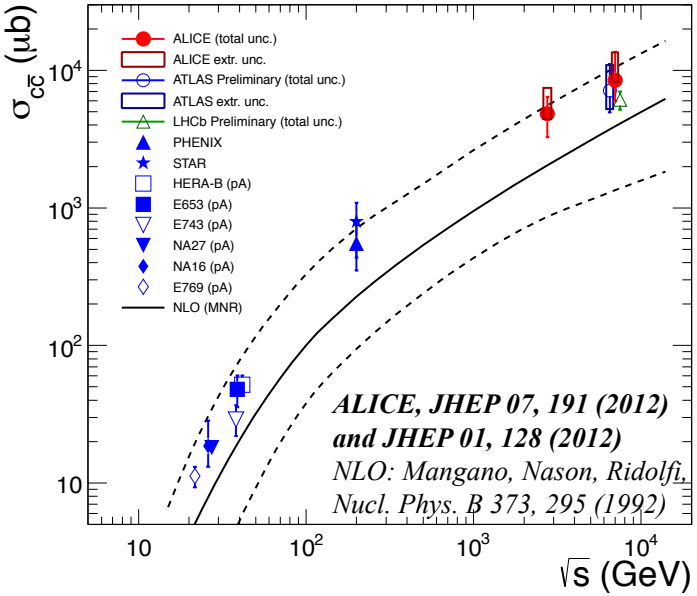
$b \rightarrow$ lepton + X BR = 10.9%

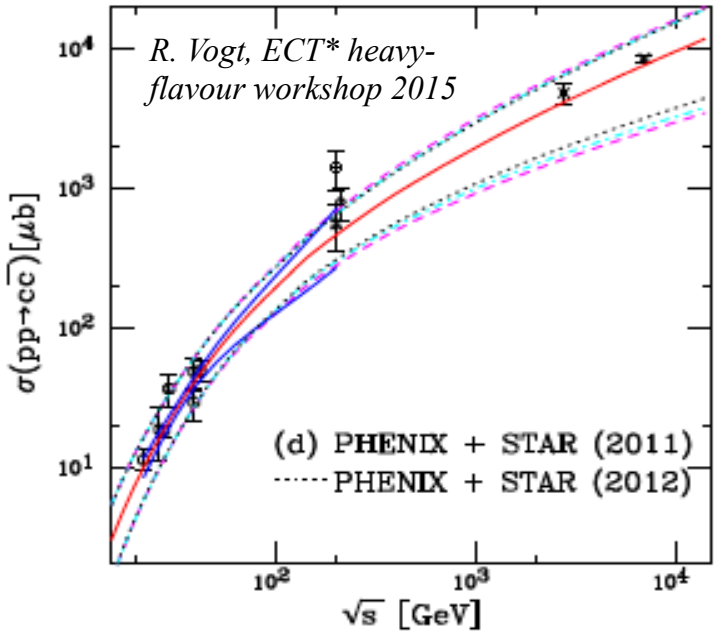
- robust electron trigger
- needs handle on photonic electron background

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



Total charm production cross section in pp





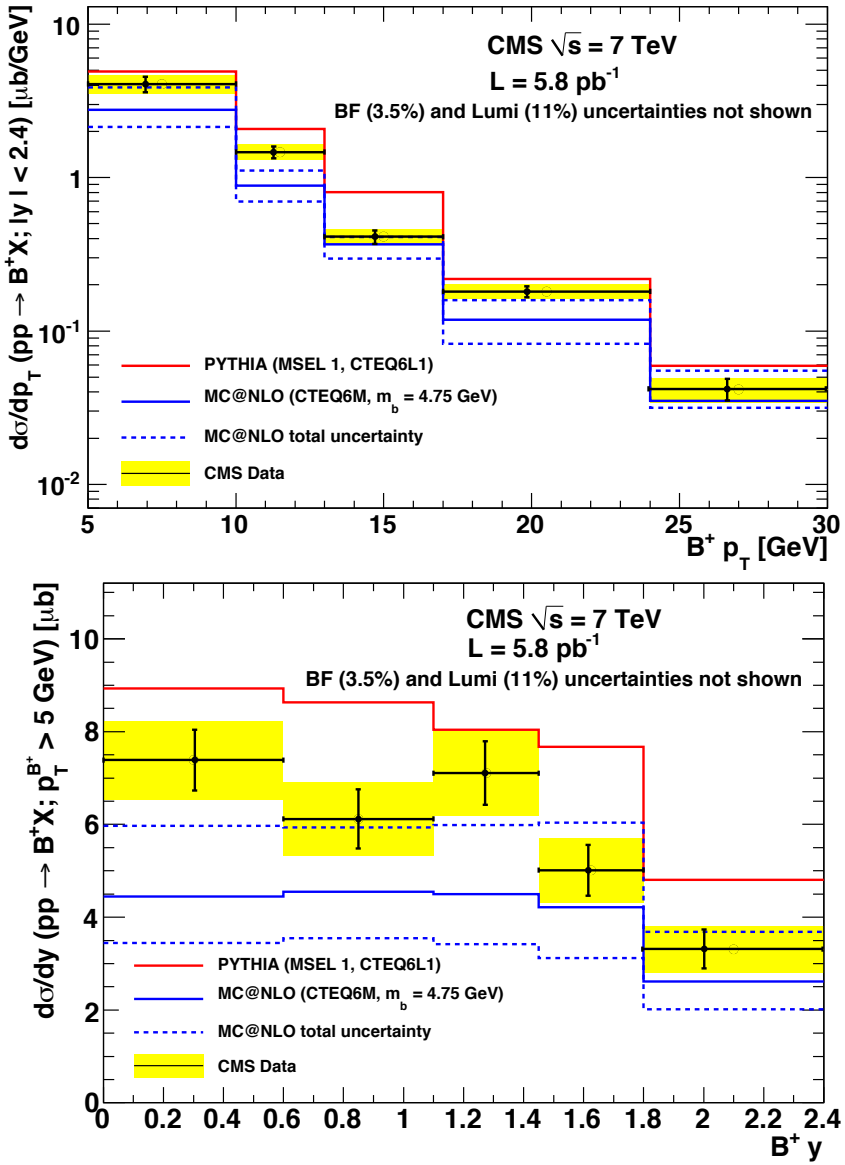
JHEP 1207 (2012) 191

- Very good agreement between LHC experiments
- Consistency with NLO pQCD calculations, although at the upper limit; progress recently
- Run-2 data will provide further constrains

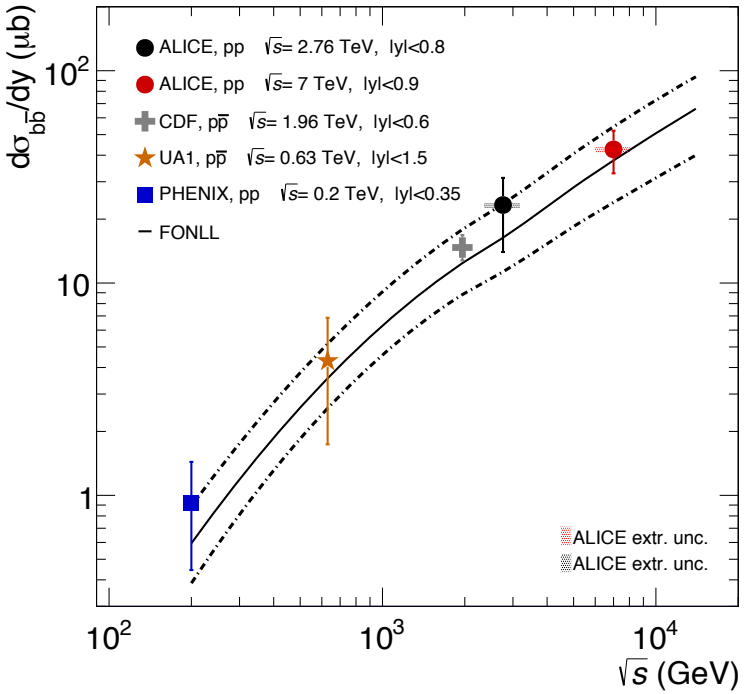
→ Parton spectra from pQCD input for energy loss models; baseline for measurements in Pb-Pb

Open-beauty production at the LHC

Phys. Rev. Lett. 106 (2011) 112001

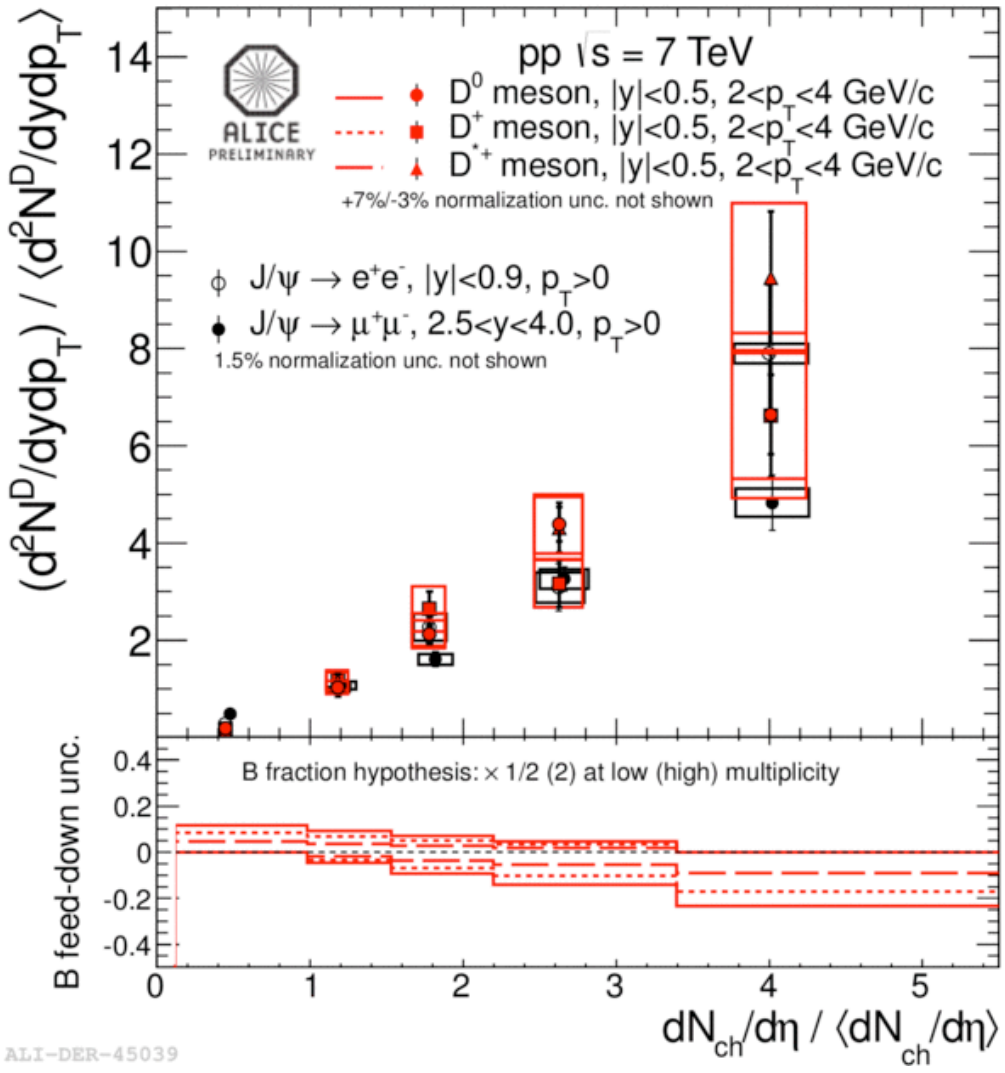


Phys. Lett. B 721 (2013) 13 and 738 (2014) 97



Relatively good description with NLO pQCD calculations

D and J/ψ yields vs. multiplicity in pp

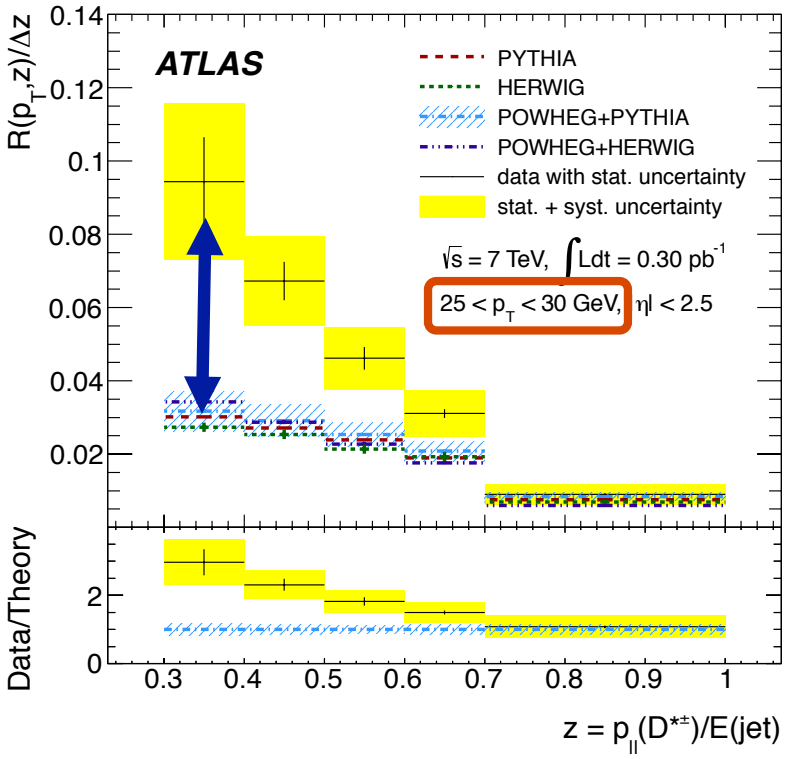


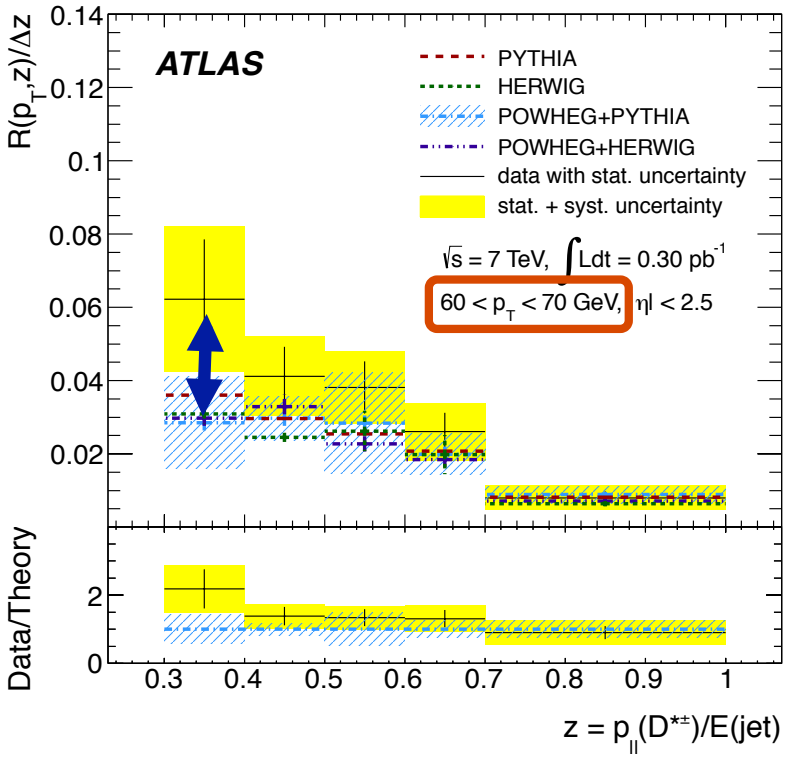
Particle multiplicity

- Linear increase of D-meson yield with charged multiplicities
- Similar behaviour for D mesons and J/ψ
  (Phys. Lett. B 712 (2012) 165)
- No p_T dependence
- Due to multi-parton interactions?

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

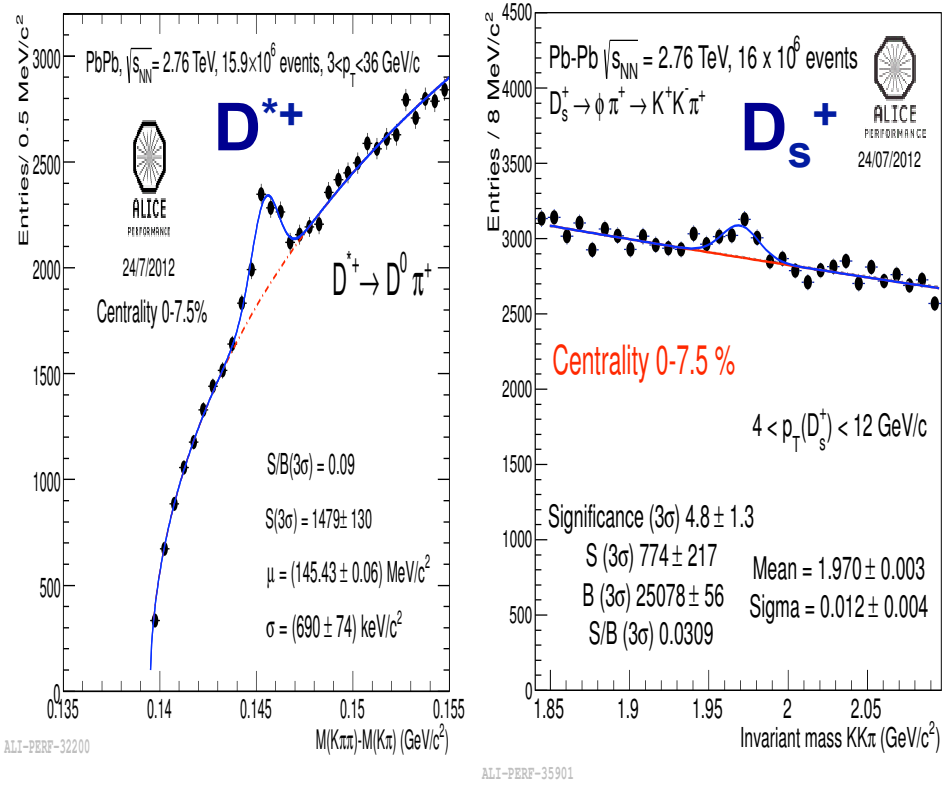
Phys. Rev. D 85 (2012) 052005

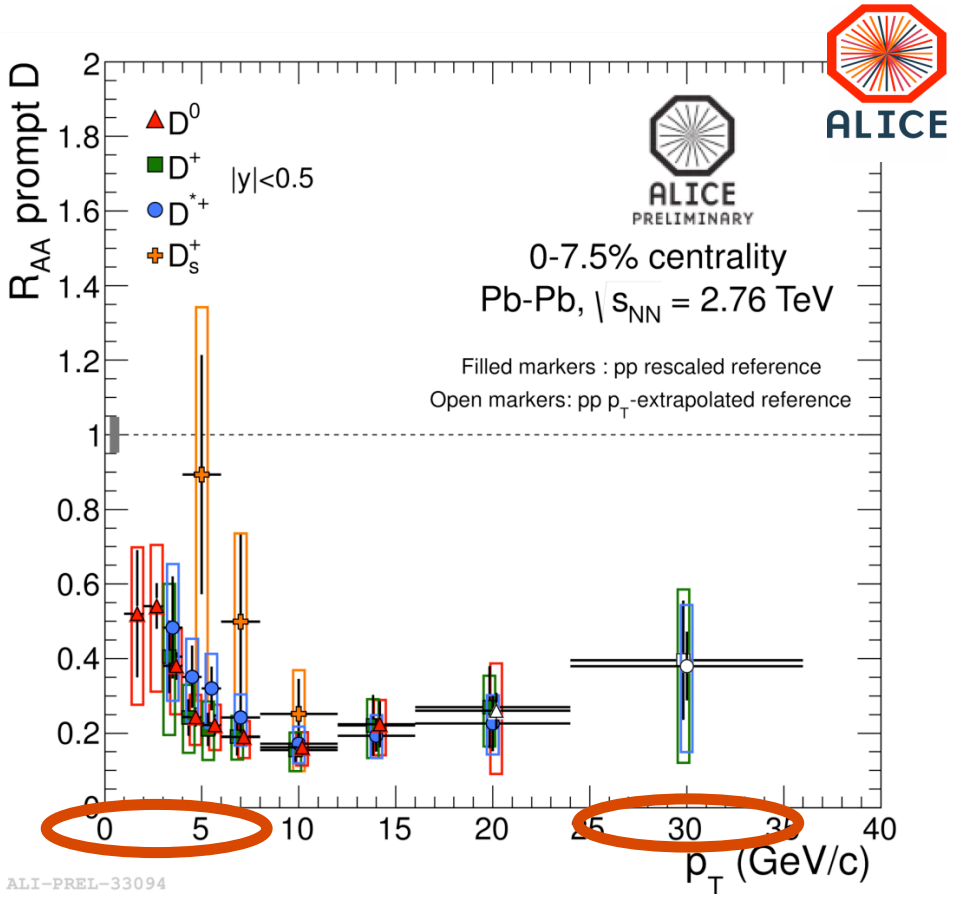




- MC calculations fail to describe data at small z; strongest at low jet transverse momentum
- Indication that jet fragmentation into D^{*+} not well modeled in current MC generators

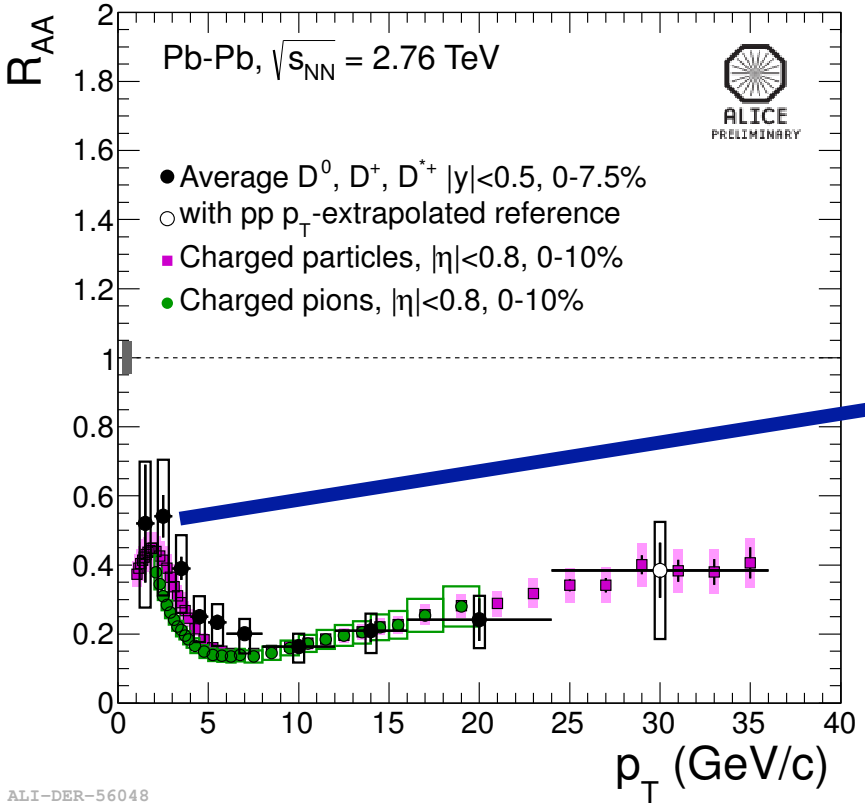
Prompt D meson R_{AA} in Pb-Pb collisions

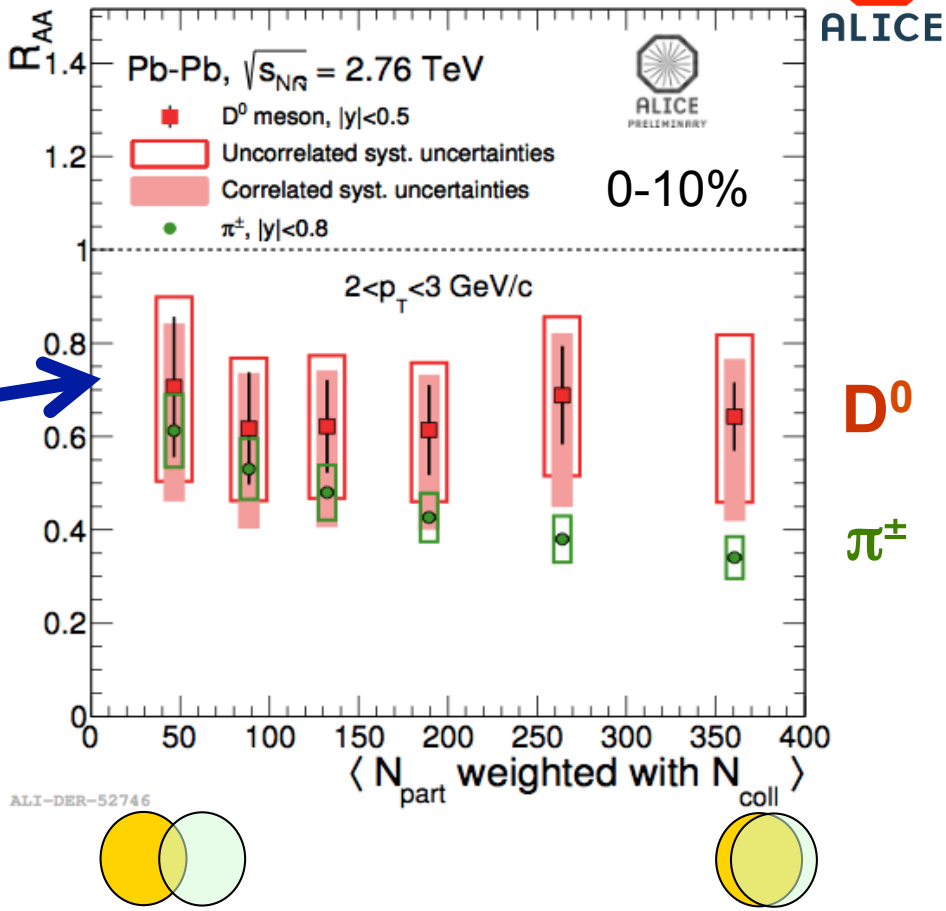




- First $D_s^+(c\bar{s})$ measurement in heavy ion collisions
- Expectation: enhancement of strange D meson yield at intermediate p_T if charm hadronises via recombination in the medium
- Strong suppression (factor 4-5) above 5 GeV/c in most central Pb-Pb, compared to binary scaling from pp

R_{AA}: light versus heavy-quark hadrons





ALICE

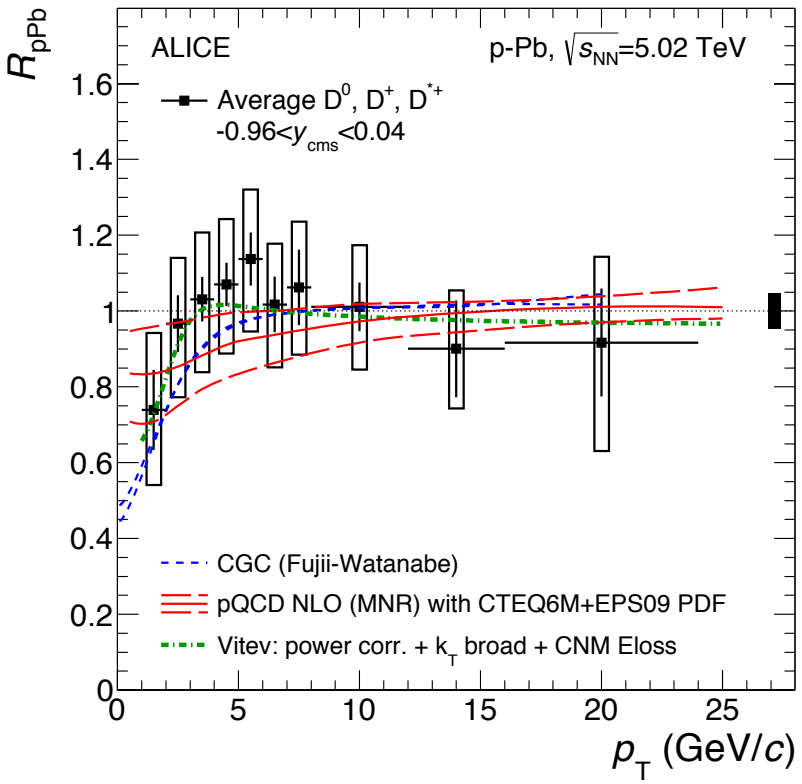
D^0

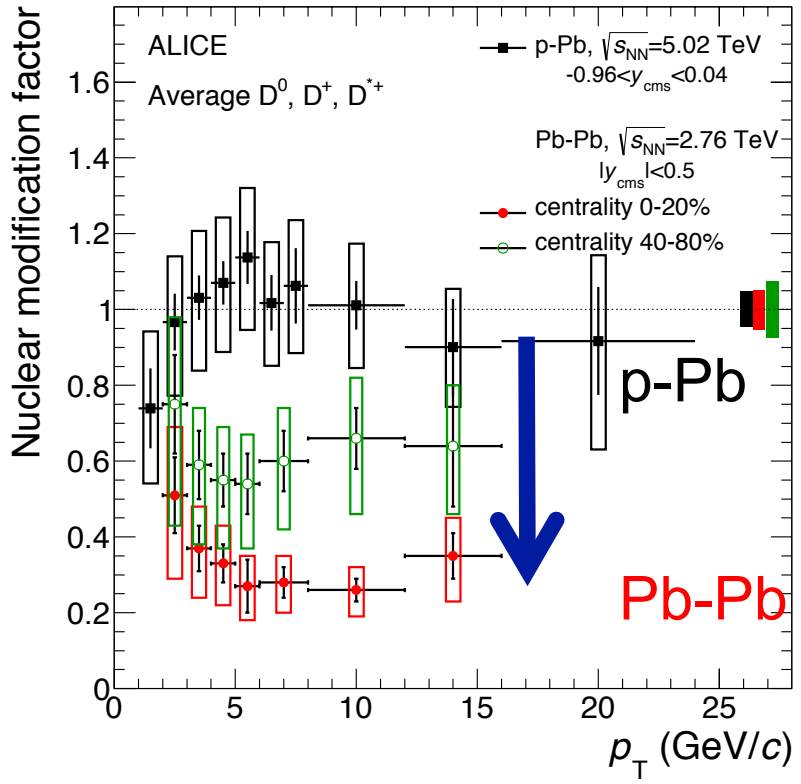
$\pi^{\pm}$

- $R_{AA}^{D} > R_{AA}^{pions}$ at low p_T?
  More data needed for final conclusion
- Indication for rising R_{AA}?

p-Pb: measurement of initial state effects

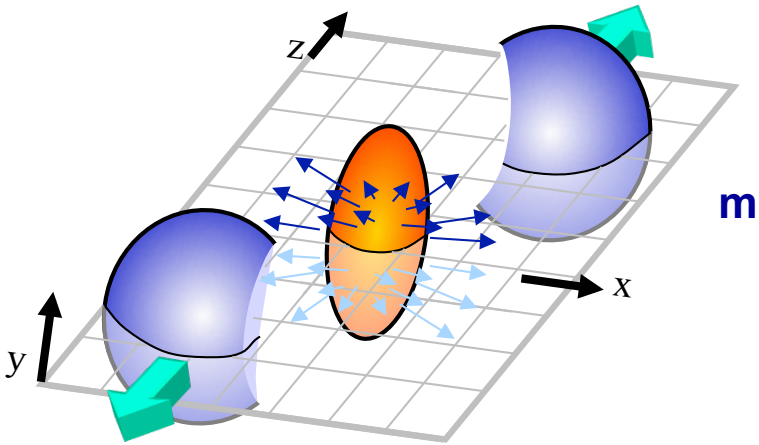
Phys. Rev. Lett. 113 (2014) 232301



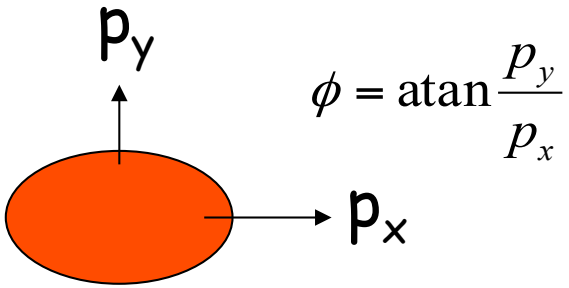


- Important baseline measurement of **cold nuclear matter effects** (e.g., Cronin effect, nuclear shadowing, gluon saturation)
- D R_{pA} shows consistency with unity and predictions from shadowing and CGC model predictions
- **High-p_T suppression of particle yield in Pb-Pb is a final state effect**

Azimuthal anisotropy



pressure and multiple collisions



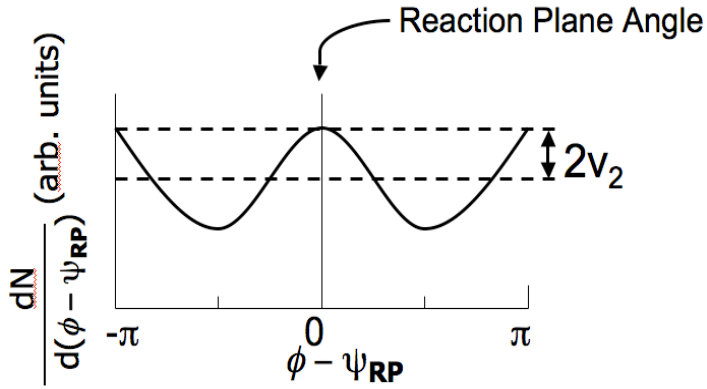
coordinate space: initial anisotropy

momentum space: final anisotropy

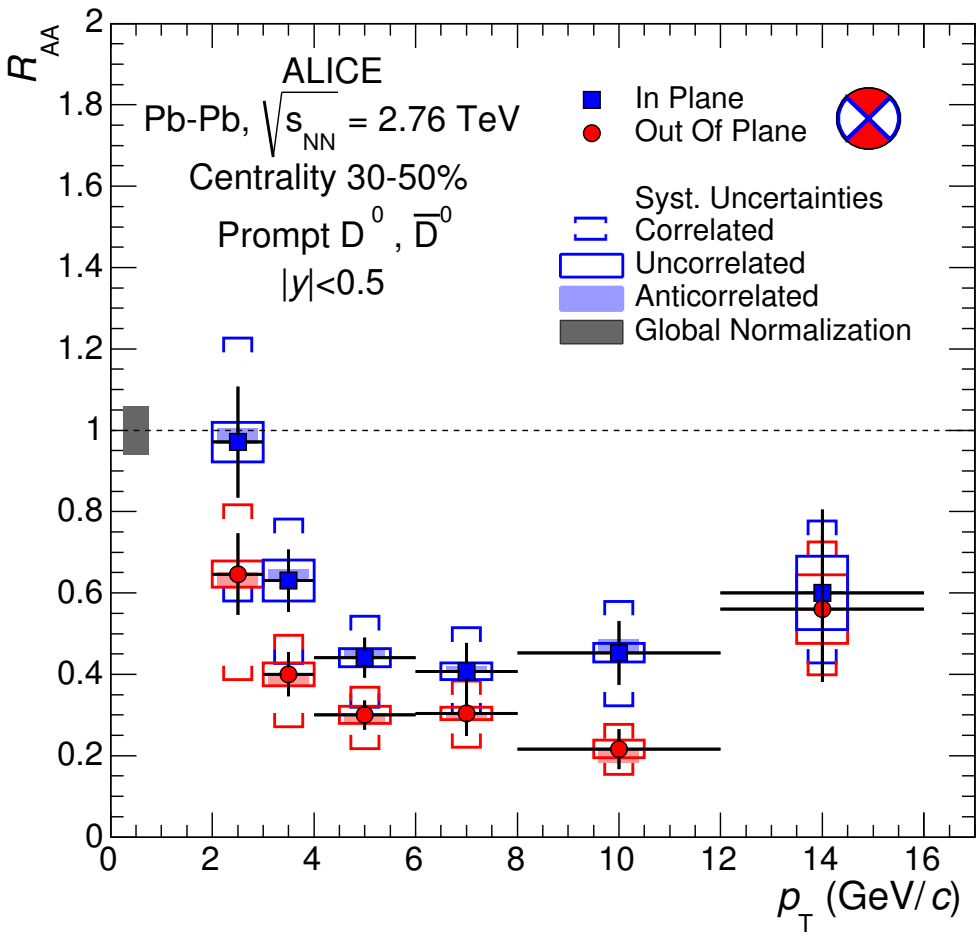
- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective flow → anisotropy in momentum space
- Fourier decomposition:

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

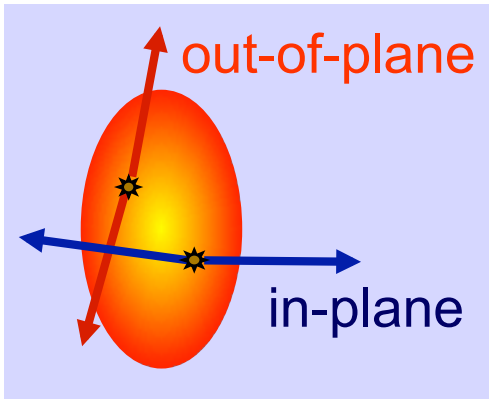
$$v_n = \left\langle \cos(n[\varphi-\psi_n]) \right\rangle$$



Prompt D^0 R_{AA} versus event plane



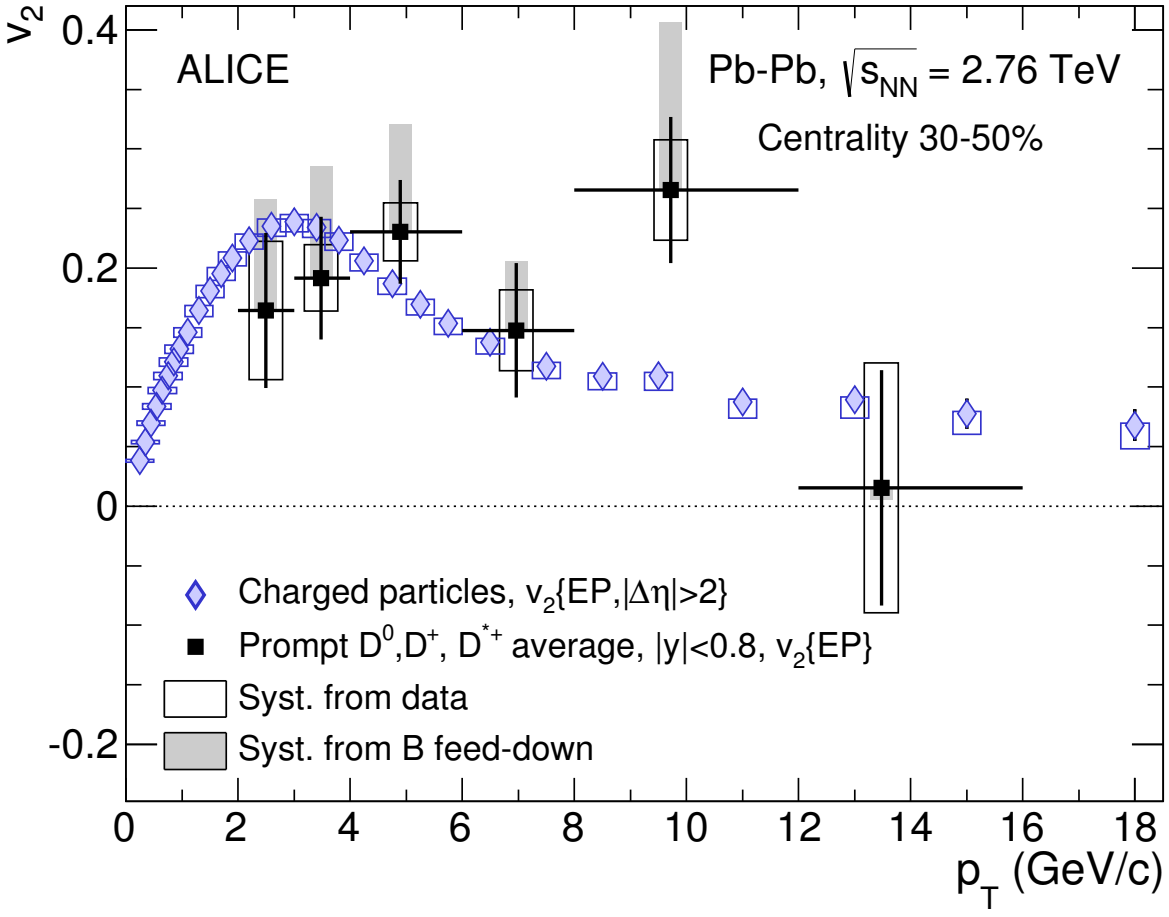
Phys. Rev. C 90 (2014) 034904,
Phys. Rev. Lett. 111 (2013) 102301



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

Azimuthal anisotropy of prompt D mesons

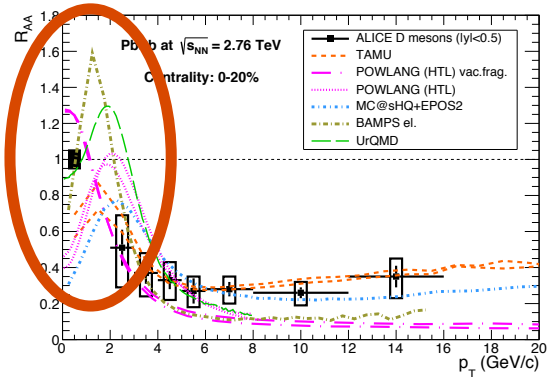
Phys. Rev. Lett. 111 (2013) 102301

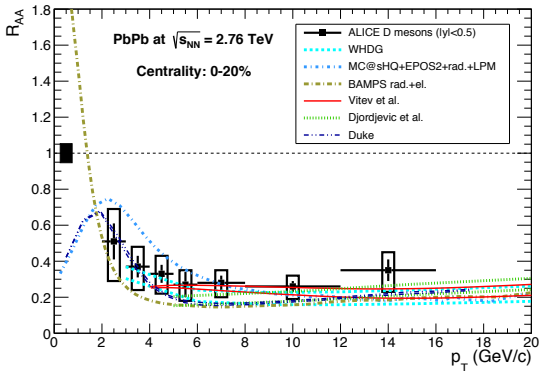


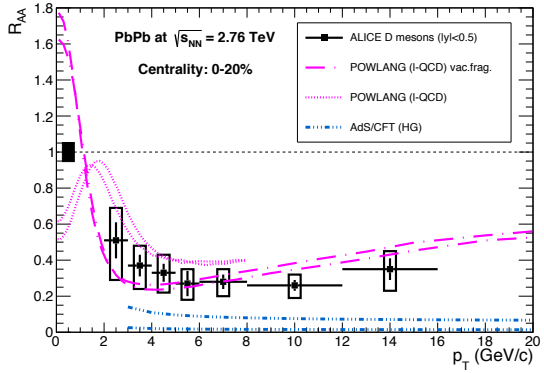
Indication (3-5σ confidence level) for non-zero charm elliptic flow in the p_T range 2-6 GeV/c

Comparison with model calculations: LHC

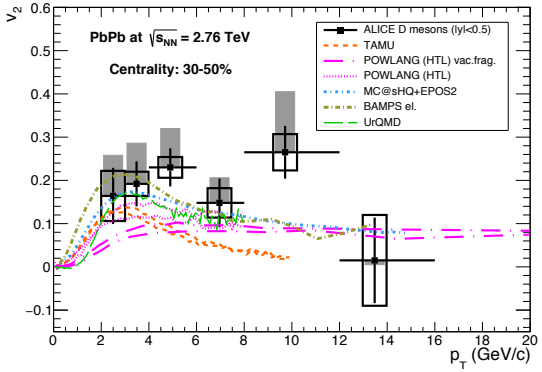
R_{AA} (0-20%)

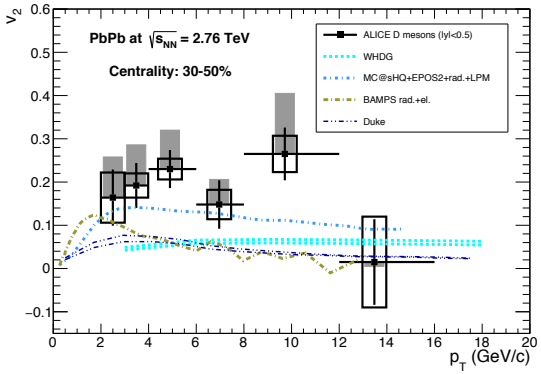


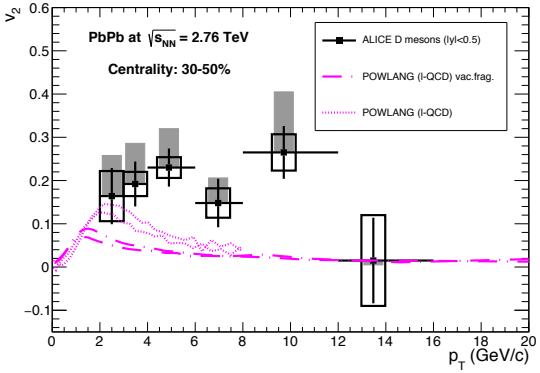




v_2 (30-50%)







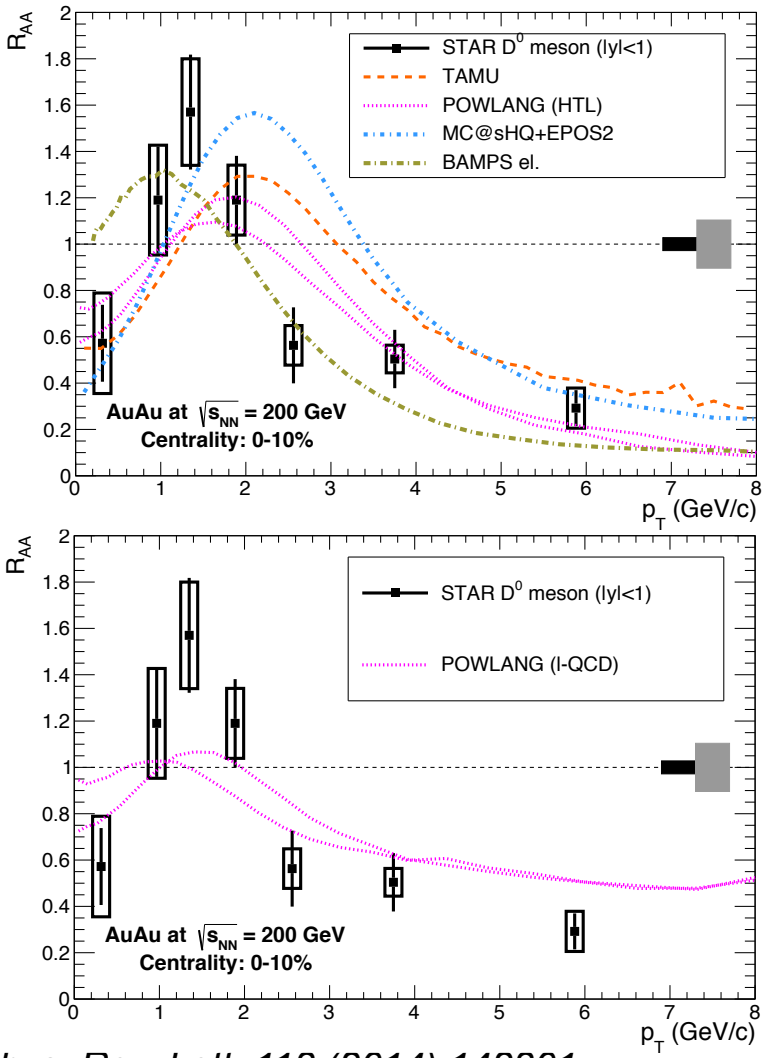
Collisional Eloss only

Collisional and radiative Eloss

arXiv:1506.03981

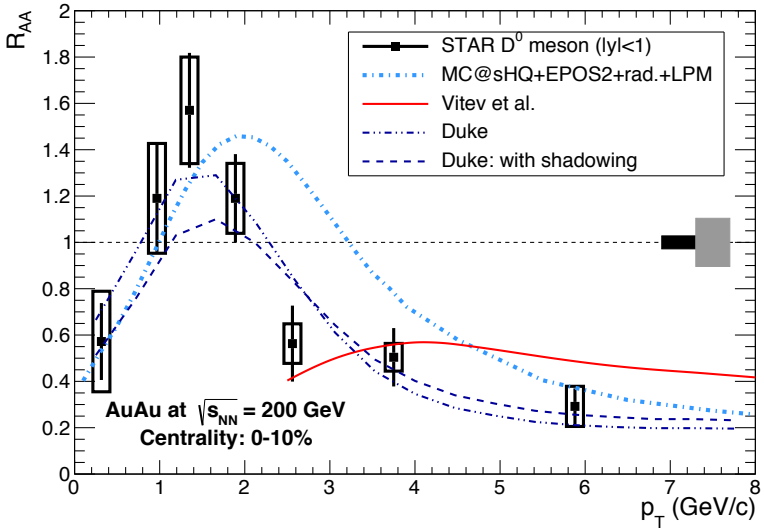
Comparison with model calculations: RHIC

Collisional Eloss only



Phys. Rev. Lett. 113 (2014) 142301
and arXiv:1506.03981

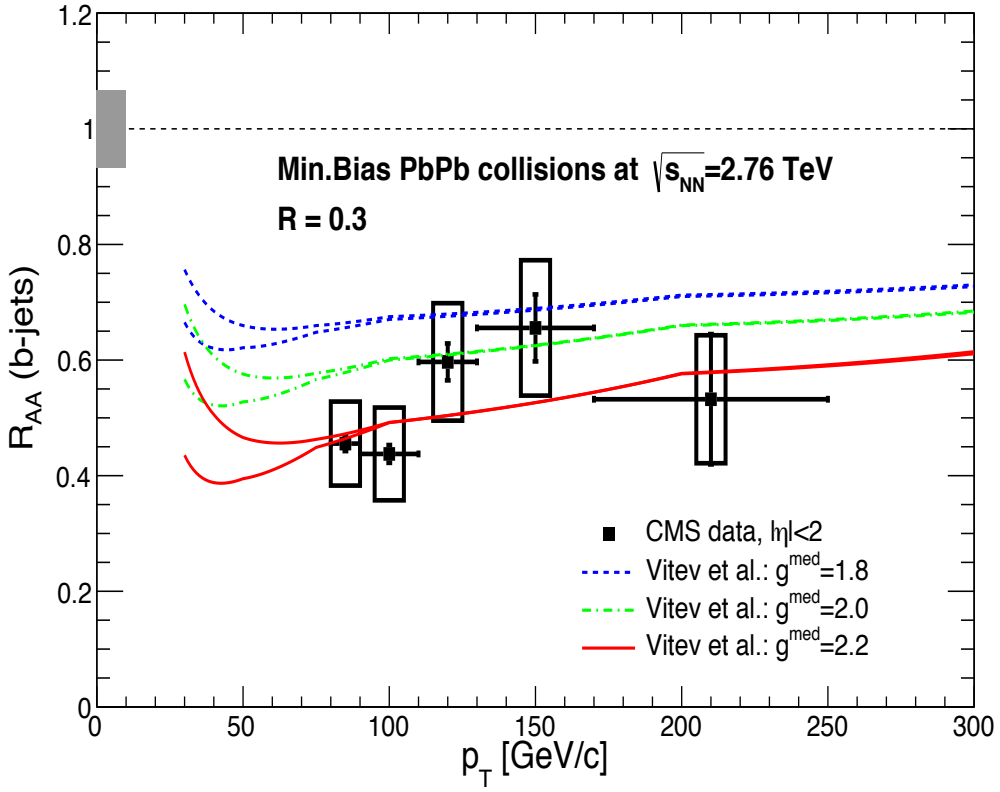
Collisional and radiative Eloss

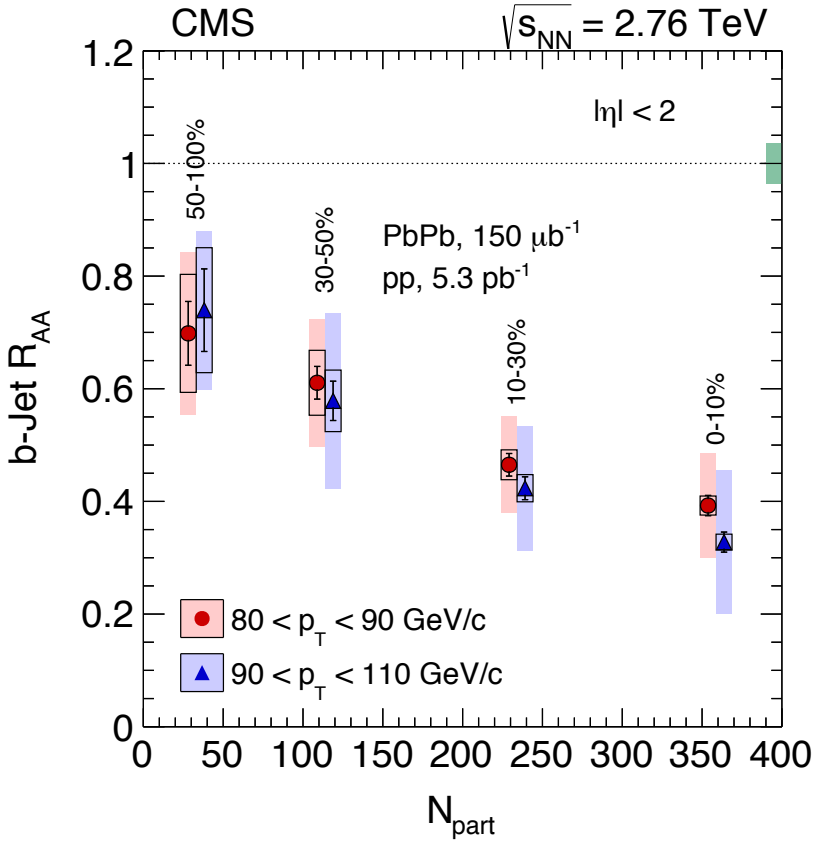


- Maximum at 1.5 GeV/c: effect of radial flow on light and charm quarks (TAMU: also flow in hadronic phase)
- Same trend in 193 GeV U+U collisions

R_{AA} of b-tagged jets in Pb-Pb

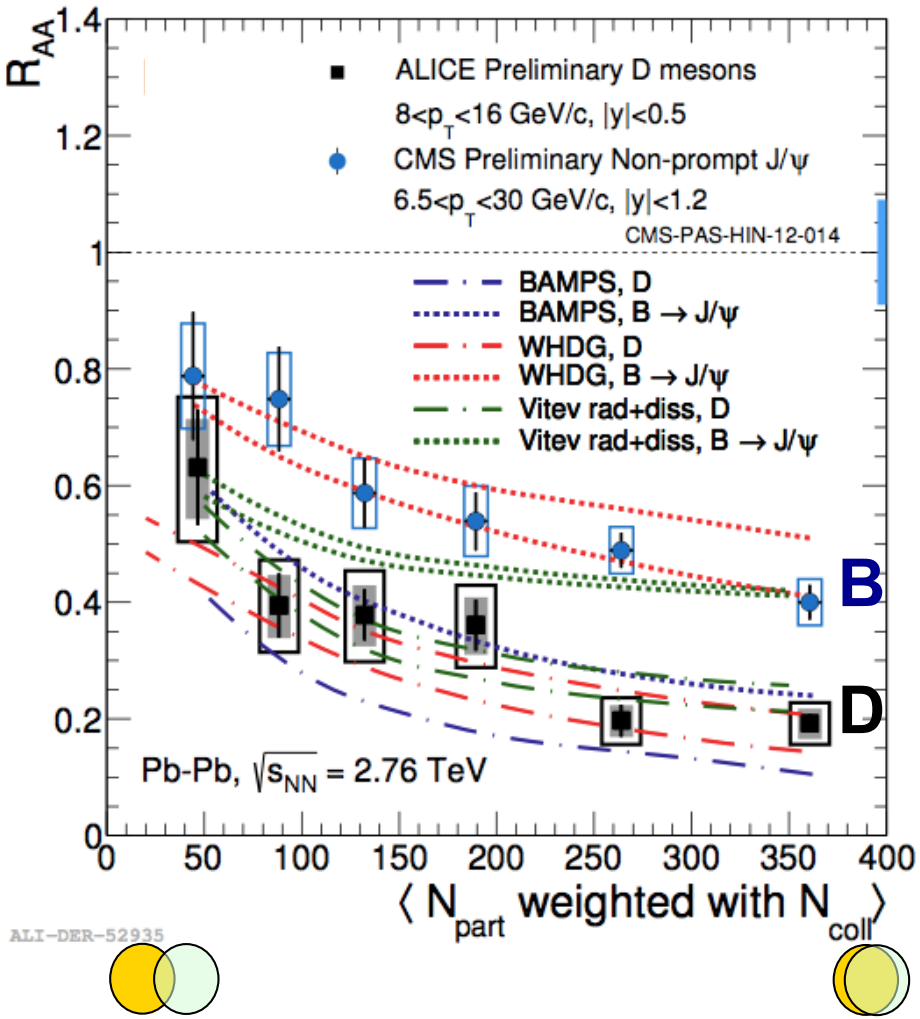
Phys. Rev. Lett. 113 (2014) 132301



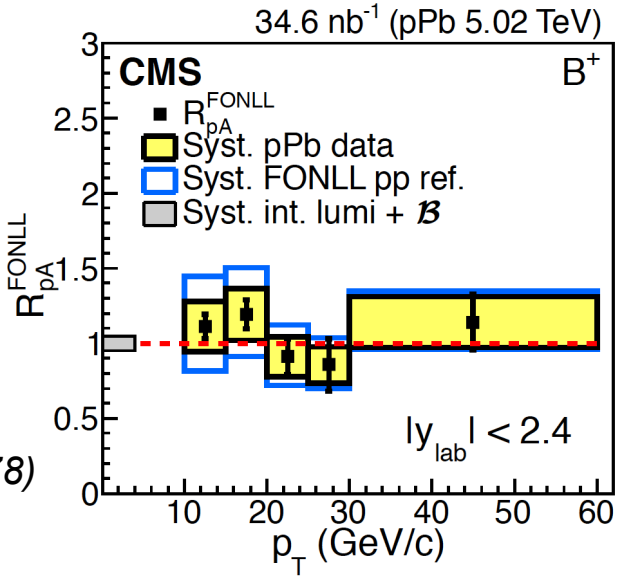


Future precision measurement should allow to constrain quark–medium coupling parameter g^{med}

R_{AA} of D and B mesons

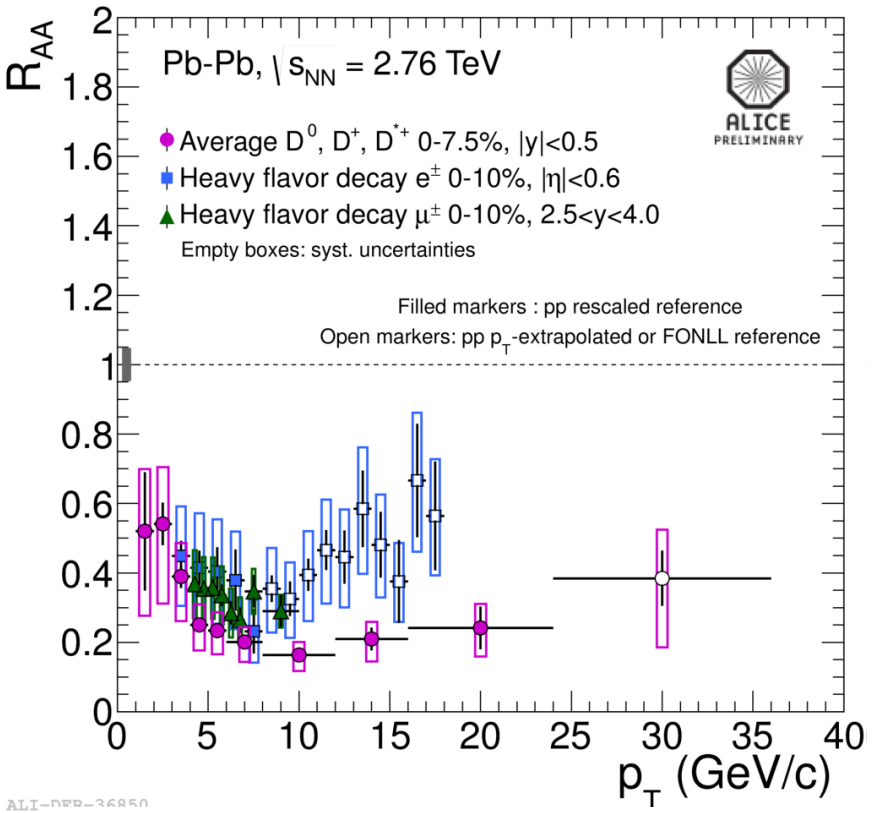


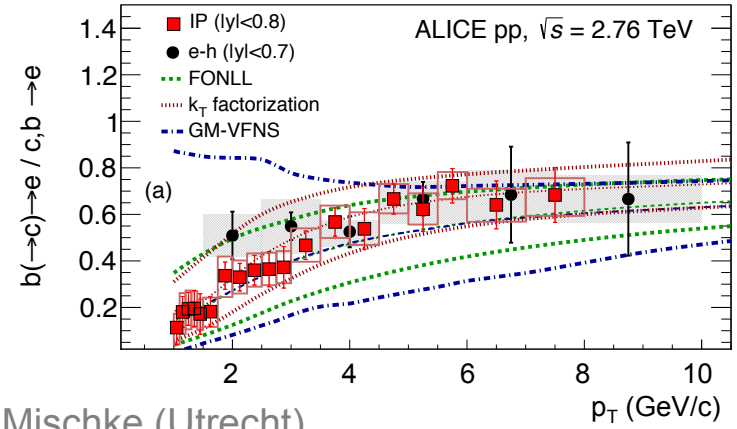
- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson $<p_T>$ ~10 GeV/c
- First indication of quark mass dependence of the parton energy loss: $R_{AA}^{D} < R_{AA}^{B}$



Open beauty in p-Pb,
submitted to PRL (arXiv:1508.06678)

Heavy-flavour decay muons and electrons



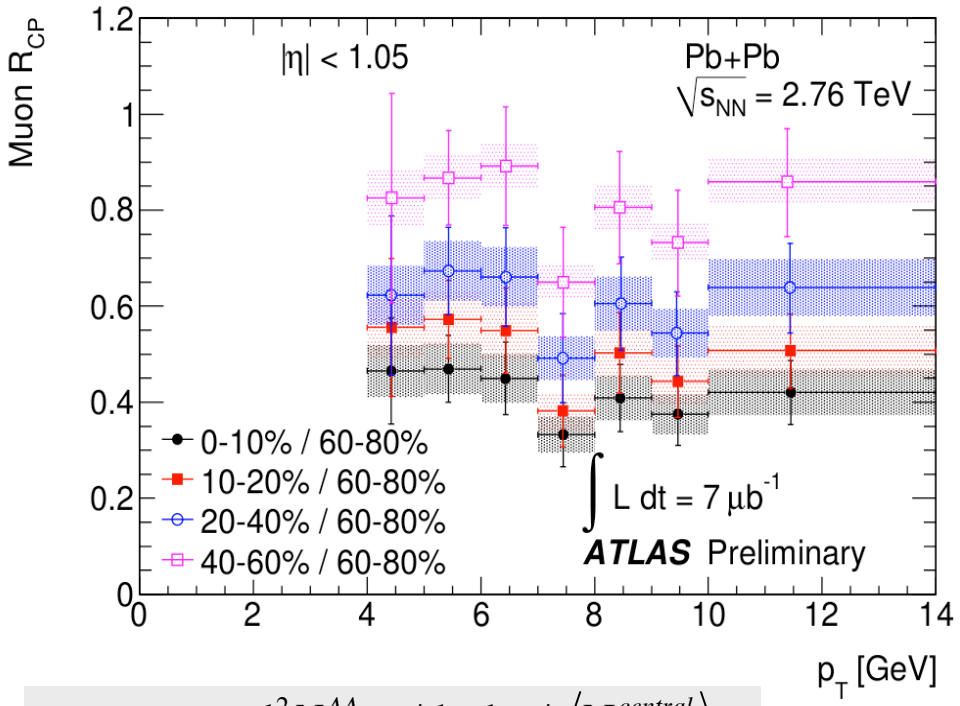


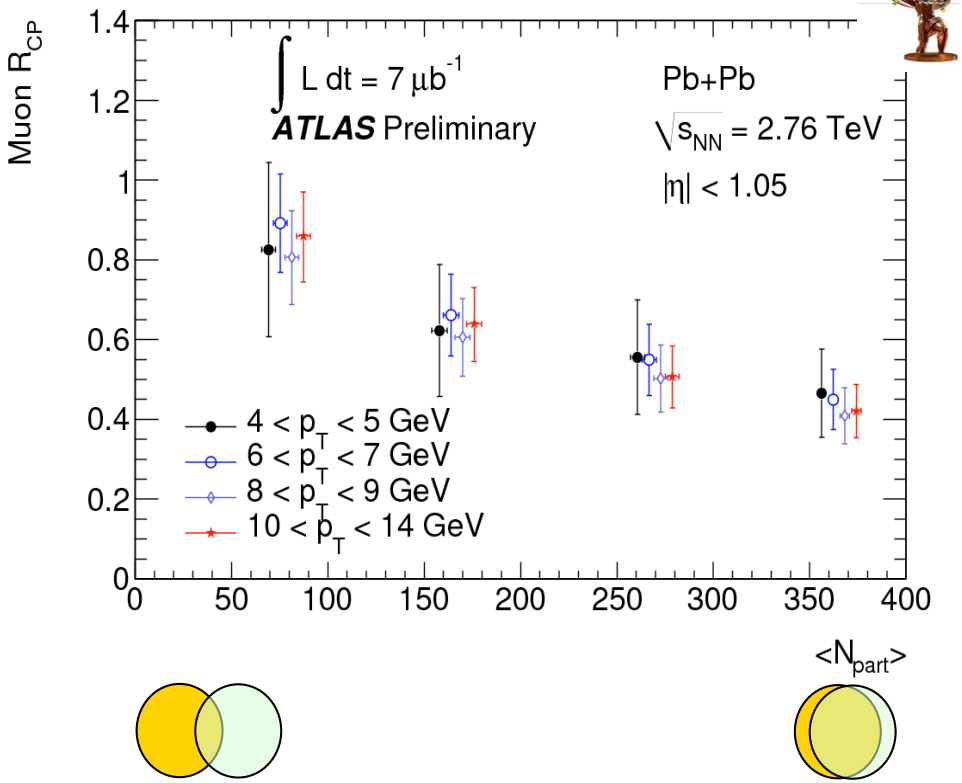
- Strong suppression of high-p_T muon yield from heavy-flavour decays
- No significant dependence on p_T in 4-10 GeV/c range
- Similar to single electron and D R_{AA} at central rapidity
- $R_{AA}^{\text{single e}} > R_{AA}^{D}$ at $p_T > 8$ GeV/c due to beauty contribution

Relative beauty contribution to single electron yield from electron-hadron azimuthal correlations

Phys. Lett. B 738 (2014) 97

ATLAS: R_{CP} of heavy-flavour decay muons



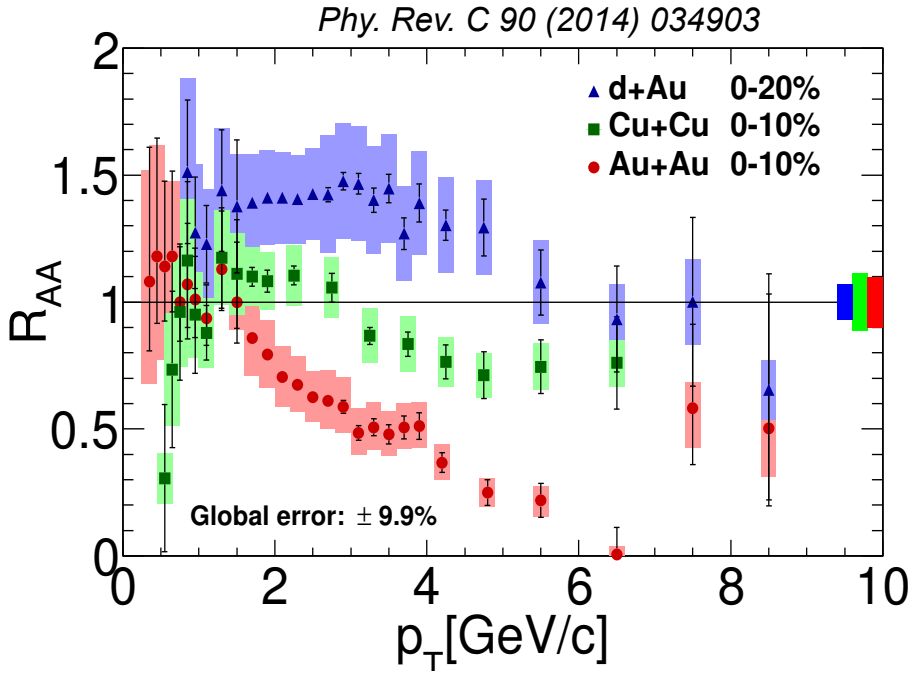


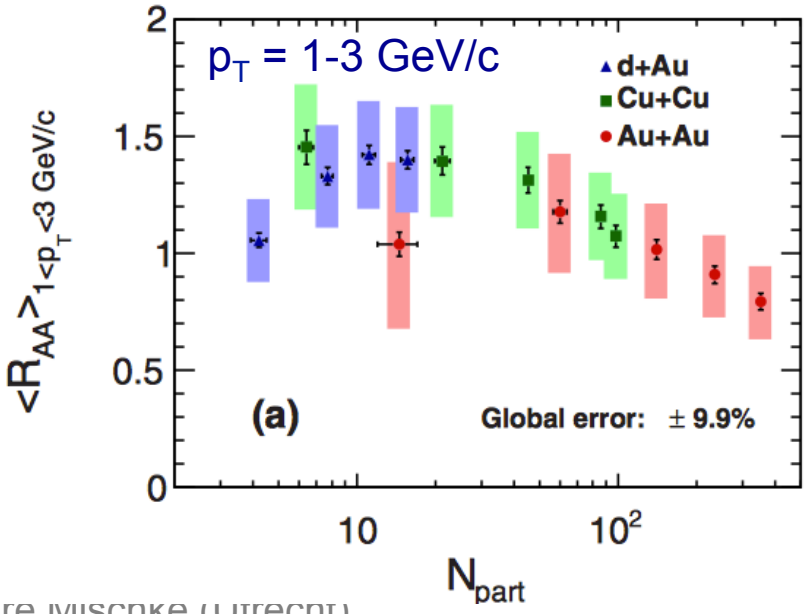
$$R_{CP}(p_t) = \frac{d^2N^{AA}_{central}/d\eta dp_t \,/\, \left\langle N^{central}_{coll} \right\rangle}{d^2N^{AA}_{peripheral}/d\eta dp_t \,/\, \left\langle N^{peripheral}_{coll} \right\rangle}$$

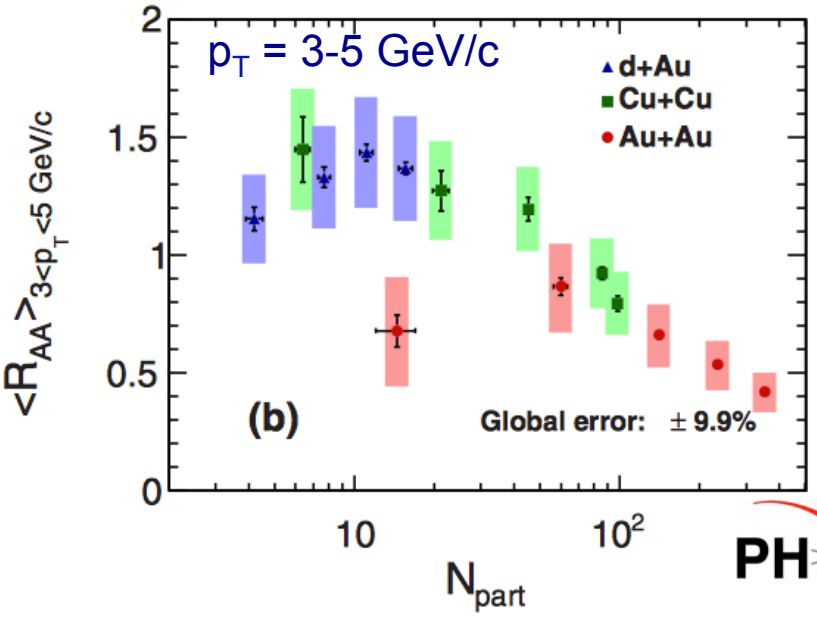
- A factor of 2 suppression 0-10%/60-80%, independent of p_T
- Indications for weaker suppression than for charged hadrons and as compared to RHIC electron results

R_{AA} of heavy-flavour decay electrons at RHIC

- d+Au, Cu+Cu and Au+Au
- Smooth evolution of R_{AA} with N_{part} and p_T for all systems
- Enhancement for N_{part} ~ 5-50
- Suppression for N_{part} > 100

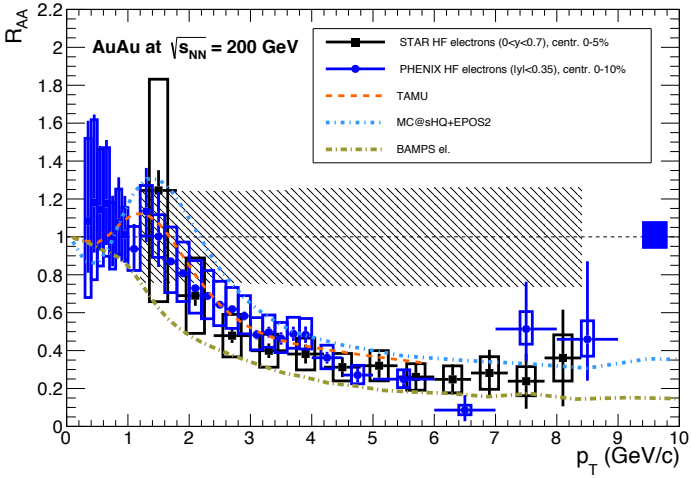


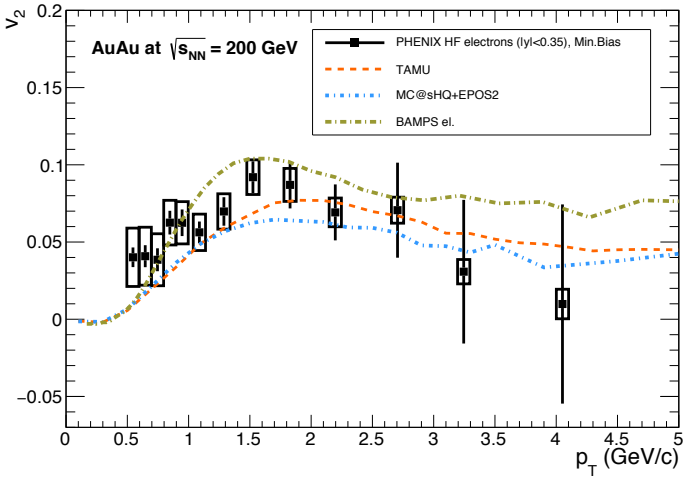




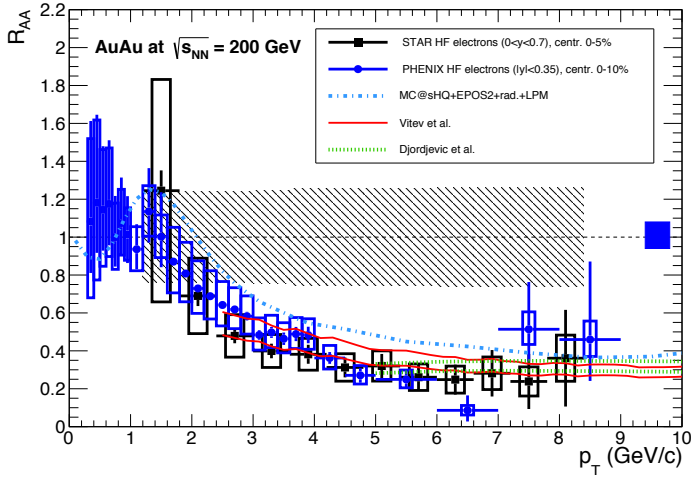
Single electron R_{AA} and v_2 at RHIC

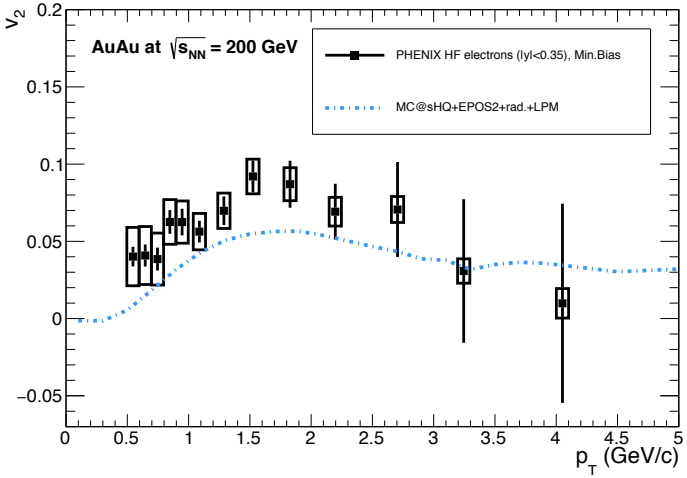
arXiv:1506.03981





Collisional Eloss only





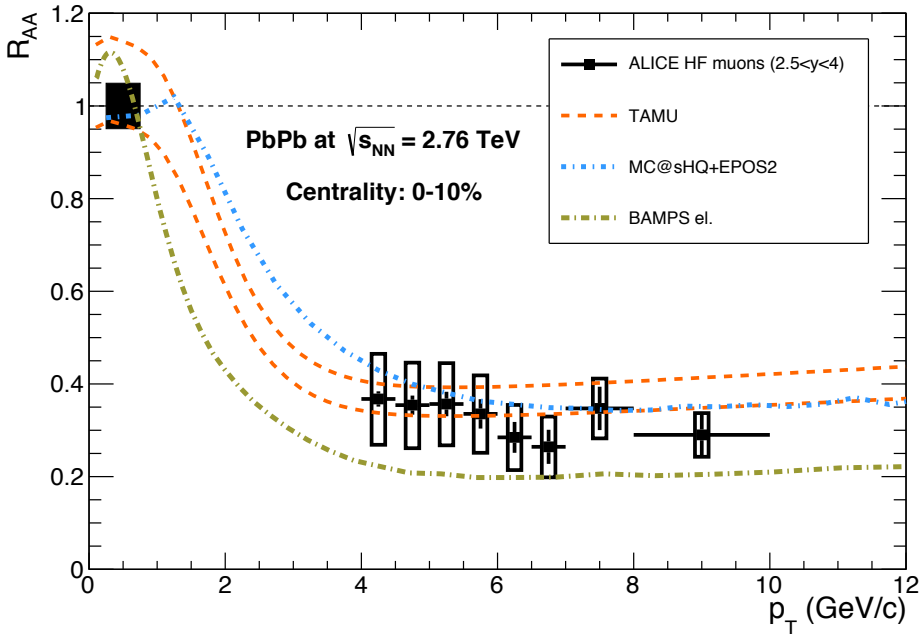
Collisional and radiative Eloss

Single muon R_{AA} at LHC

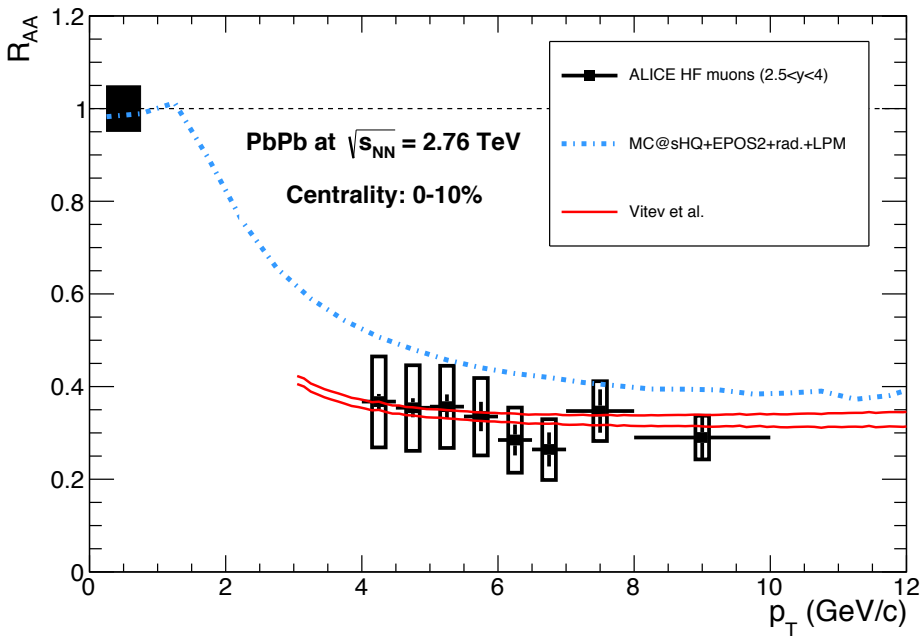
arXiv:1506.03981

ALICE

Collisional Eloss only



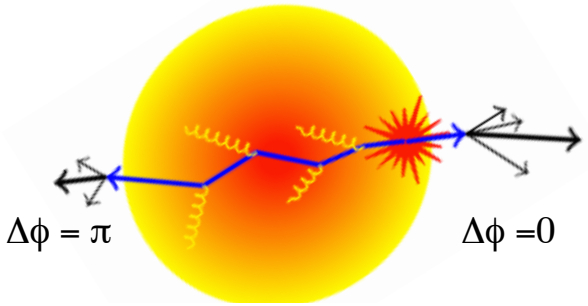
Collisional and radiative Eloss

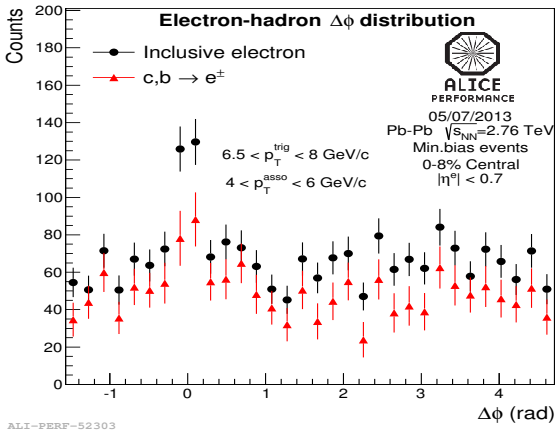


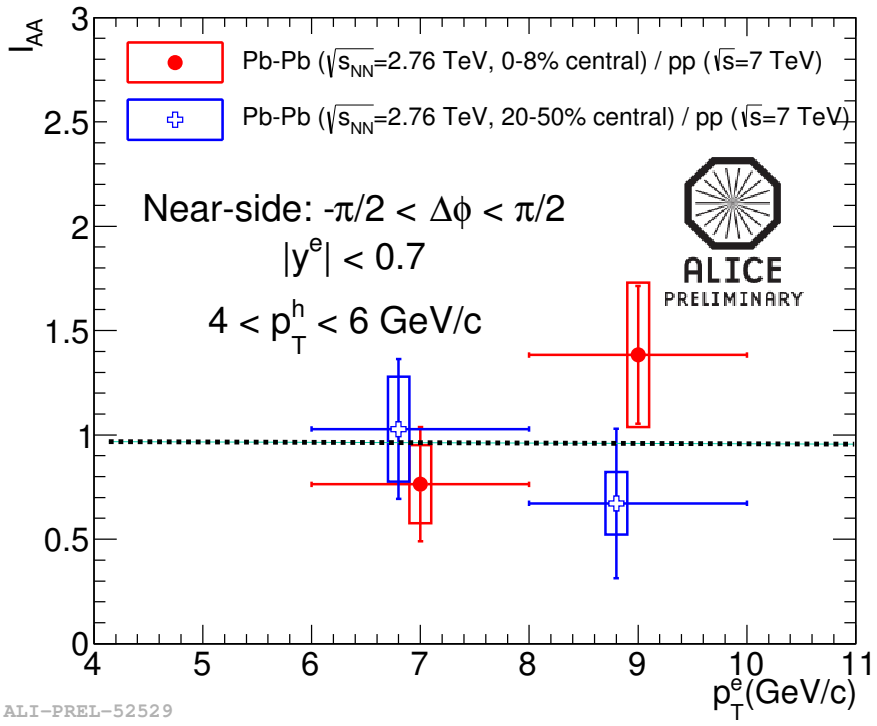
Differences between the various model predictions are less pronounced

- p_T-dependent contributions from c and b decays
- Decay kinematic shifts lepton spectra to low p_T

Heavy-quark particle correlations in Pb-Pb



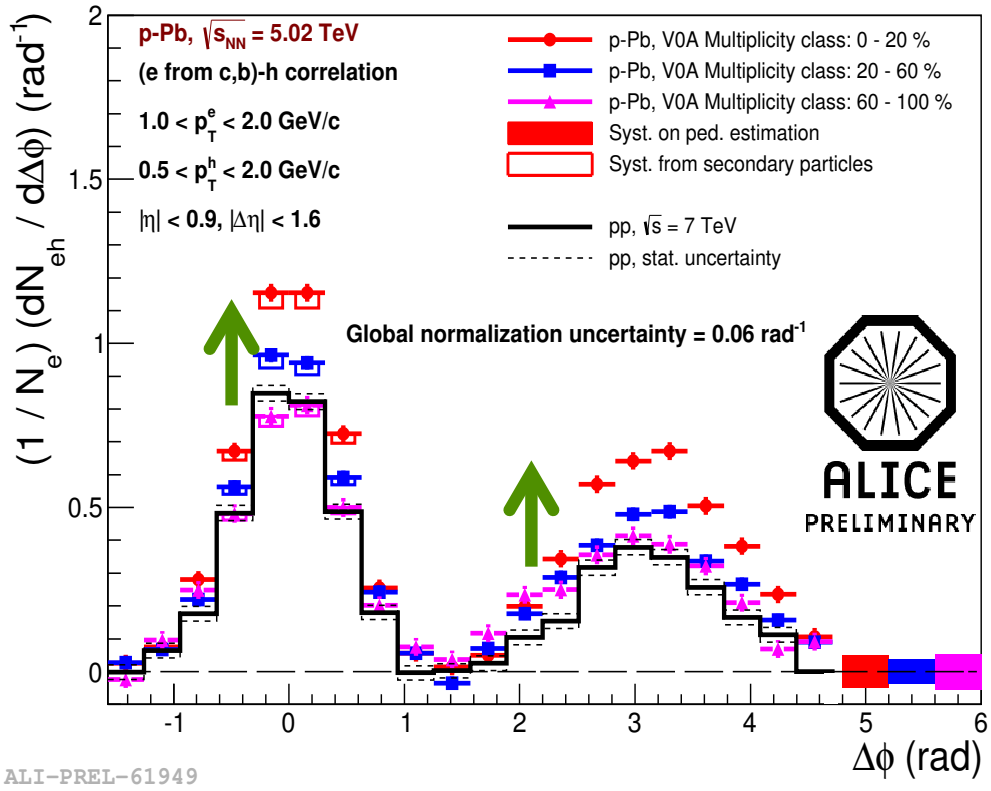




- Heavy-flavour decay electron-hadron angular correlations
  - Near side ($\Delta\phi=0$) sensitive to fragmenting jet leaving the medium
  - Away side ($\Delta\phi=\pi$) sensitive to recoiling parton that survives the traversal through the medium
- Agreement with RHIC measurement
- Full exploration with Run-2 data (5.1 TeV)

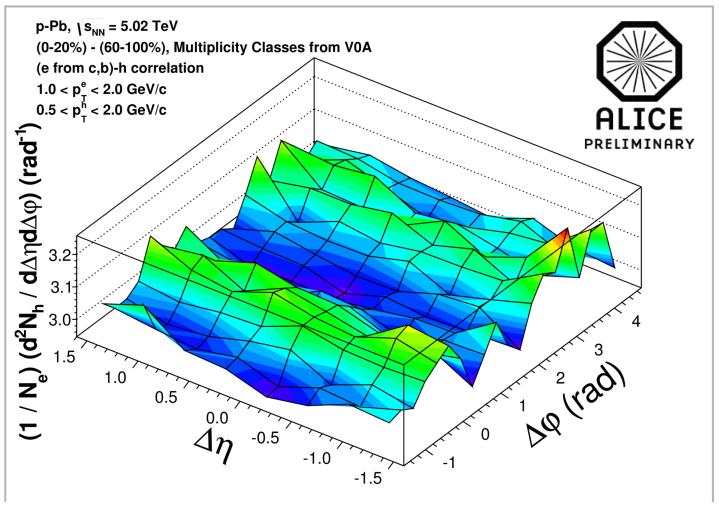
$$I_{AA} = \frac{dN^{Asso}_{Pb-Pb}/dN^{Trig}}{dN^{Asso}_{p-p}/dN^{Trig}}$$

Unexpected result: e-h correlations in p-Pb



Azimuthal angular correlation between heavy-flavour decay electrons and charged hadrons

- Most central events have higher correlation yield for low-p_T electrons
- Indication for long-range correlation in $\Delta\eta$; also seen for light flavours
- Hydrodynamics or CGC?
- Advanced model calculations needed



Difference of the correlation distribution for high and low multiplicity events

Summary

- Heavy quarks are particularly good probes to study the transport properties (drag and diffusion coefficient)
- Lots of data from RHIC and LHC programmes
- R_{AA} and v_2 of prompt D mesons and single leptons
  - strong suppression of the yield at high p_T observed in most central collisions → more insight on energy loss mechanisms
  - non-zero elliptic flow → strong re-interactions within the medium
- LHC: b-quark energy loss via B→J/ψ
  - $R_{AA}(\pi) \sim R_{AA}$(D, single leptons) < R_{AA}(B→J/ψ)
- Precision measurements in extended p_T ranges needed to further constraint model calculations (and open beauty!)
- Many more exciting results ahead of us
  - LHC: Run-2 (5.1 TeV Pb-Pb) and upgrades (2019)
  - RHIC: 200 GeV Au+Au in 2014, p+A run in 2015 and upgrades

Thank you