2015 European Nuclear Physics Conference

European Physical Society — university of groningen — kvi - center for advanced radiation technology

Groningen | 31 August - 4 September 2015 | www.EuNCP2015.org

Heavy flavour production and suppression in ultra-relativistic heavy-ion collisions

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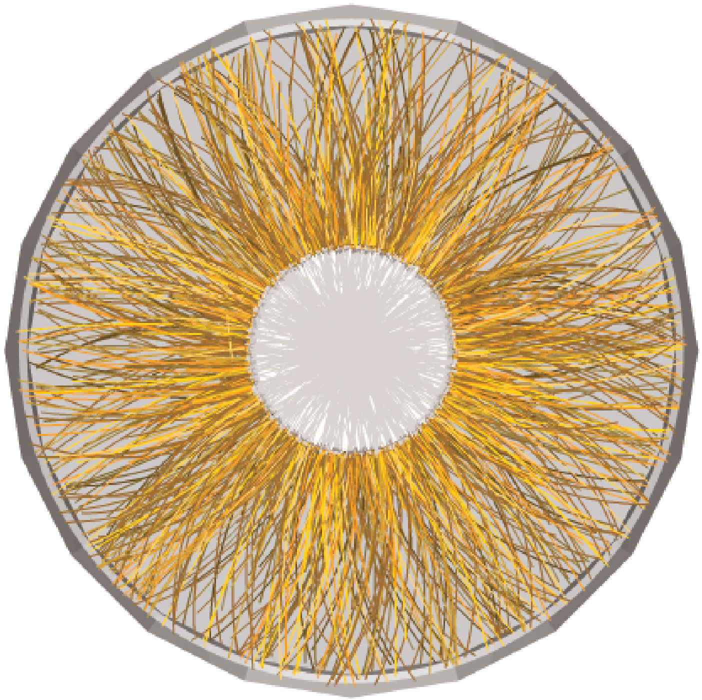
EuNPC, Groningen, September 1, 2015

Outline

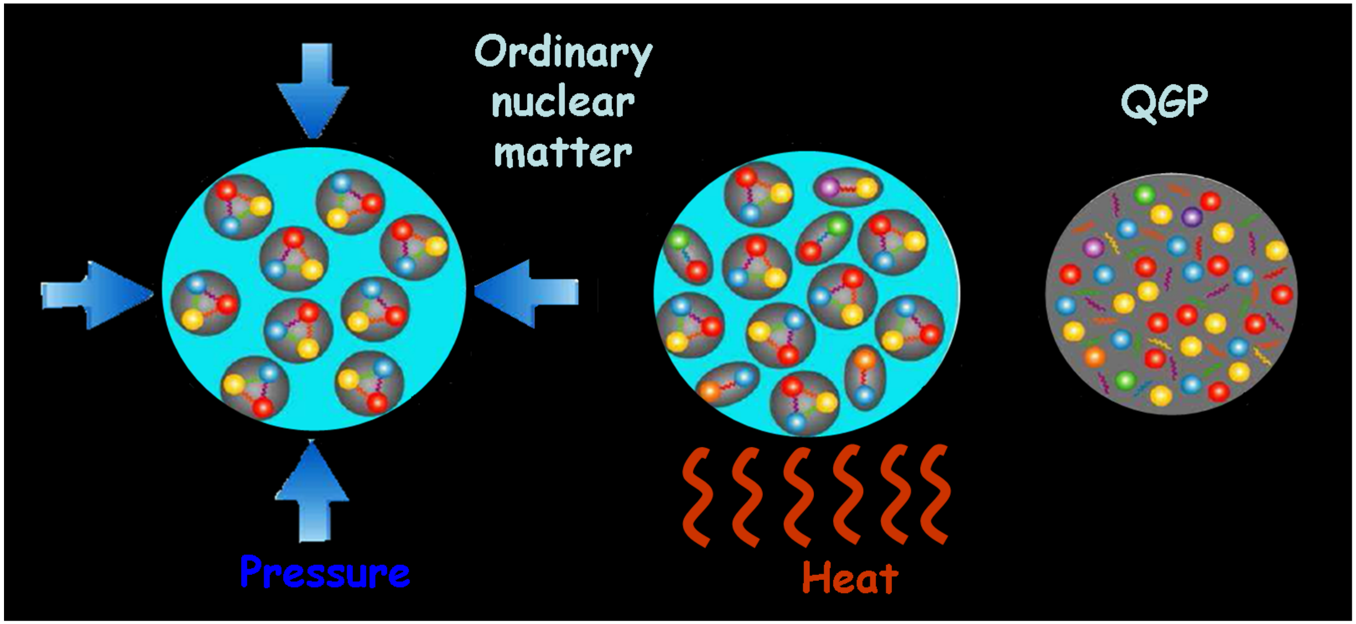
- Quark-gluon plasma
- Heavy-ion collisions

- Heavy flavours
- Experimental results
- Summary and outlook



Many results not included here, apologies!

Quark-gluon plasma (QGP)

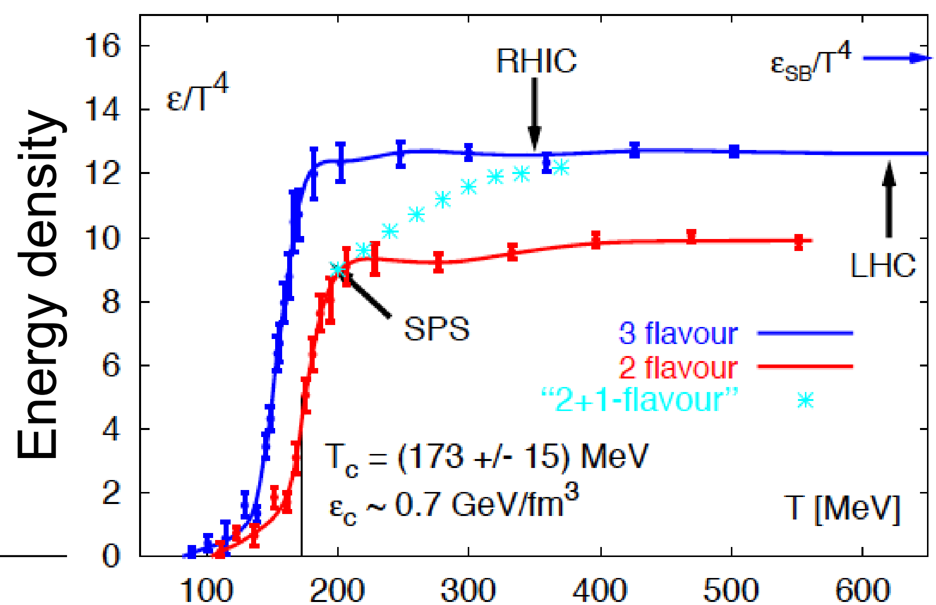


Deconfined quarks and gluons

Cabibbo, Parisi PLB 59, 67 (1975); Collins, Perry PRL 34, 1353 (1975)

Predicted by lattice QCD

hep-lat/0106019



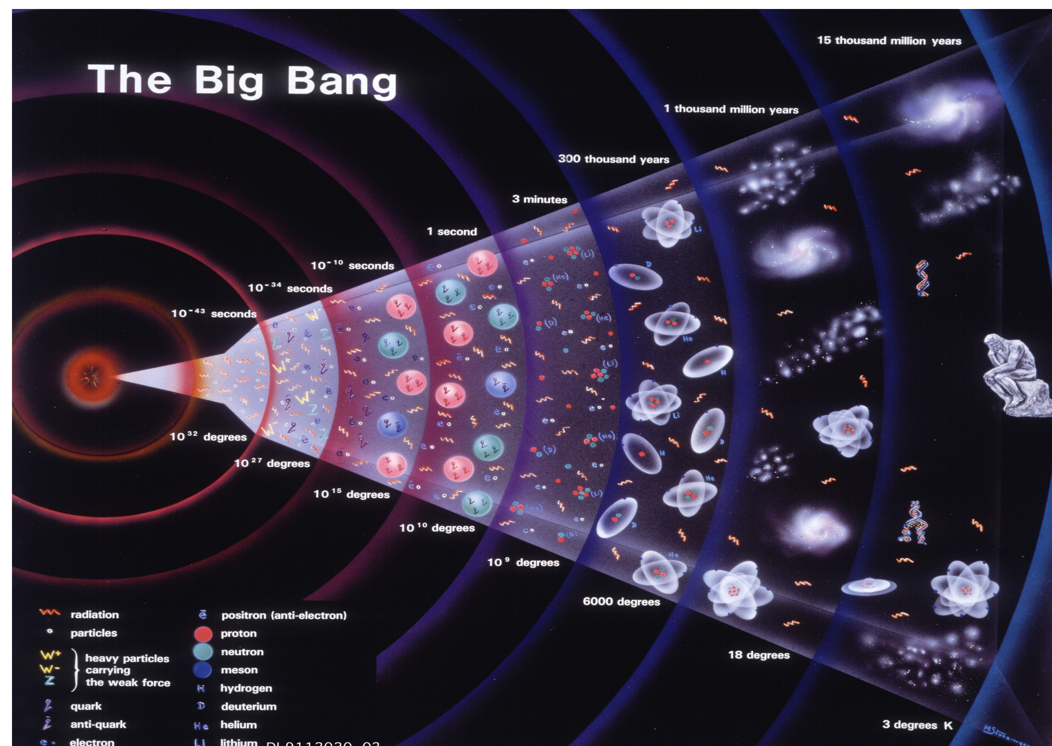
Partonic number of degrees of freedom

Dense and hot nuclear matter: why?

Status of matter in:

- Neutron stars and core-collapse supernovae

- First instants of our universe 10^{-6} seconds



Dense and hot nuclear matter: why?

Determine fundamental properties of

QCD matter at extreme conditions:

high pressure and/or temperature,
gluons and quarks de-confined,
chiral symmetry restored

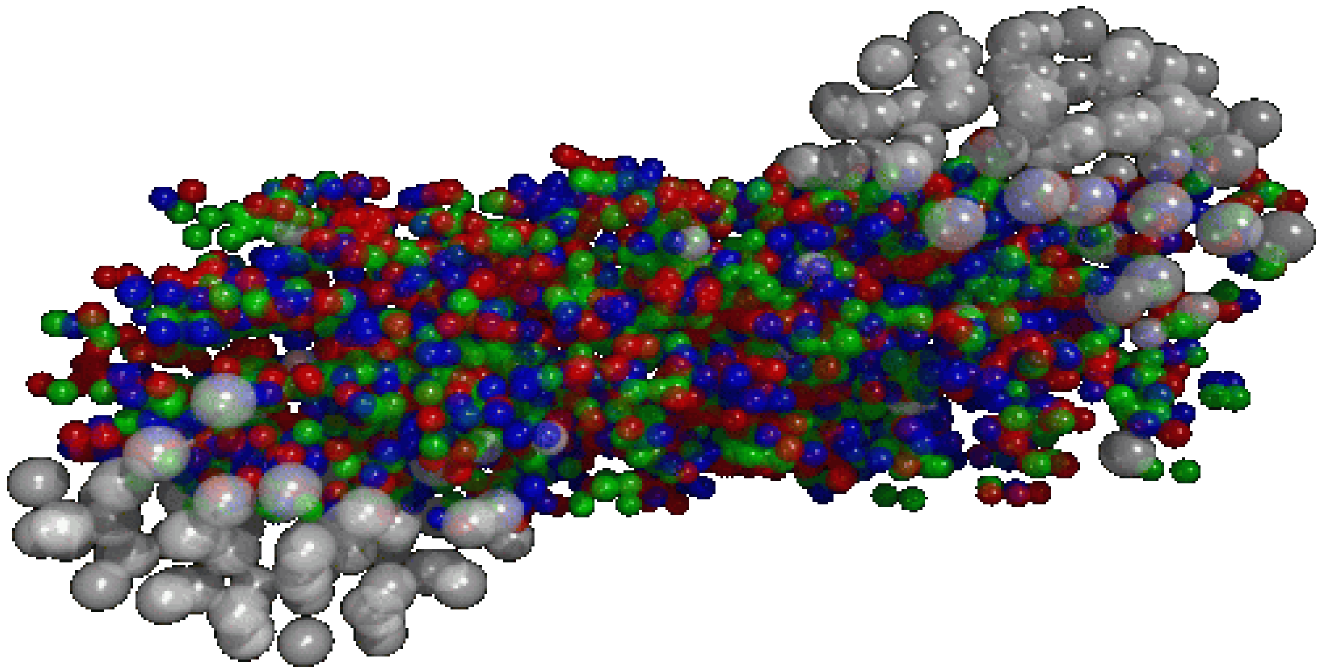
Describe matter thermodynamic properties and transport properties:

- Bulk viscosity
- Shear viscosity η
- Shear viscosity to entropy ratio η/s
- Heat conductivity
- Drag and diffusion coefficient (heavy quarks)

QGP in the laboratory: HIC

Produced in the collisions of **heavy nuclei** at **high energies**

Since ~1975



A

A

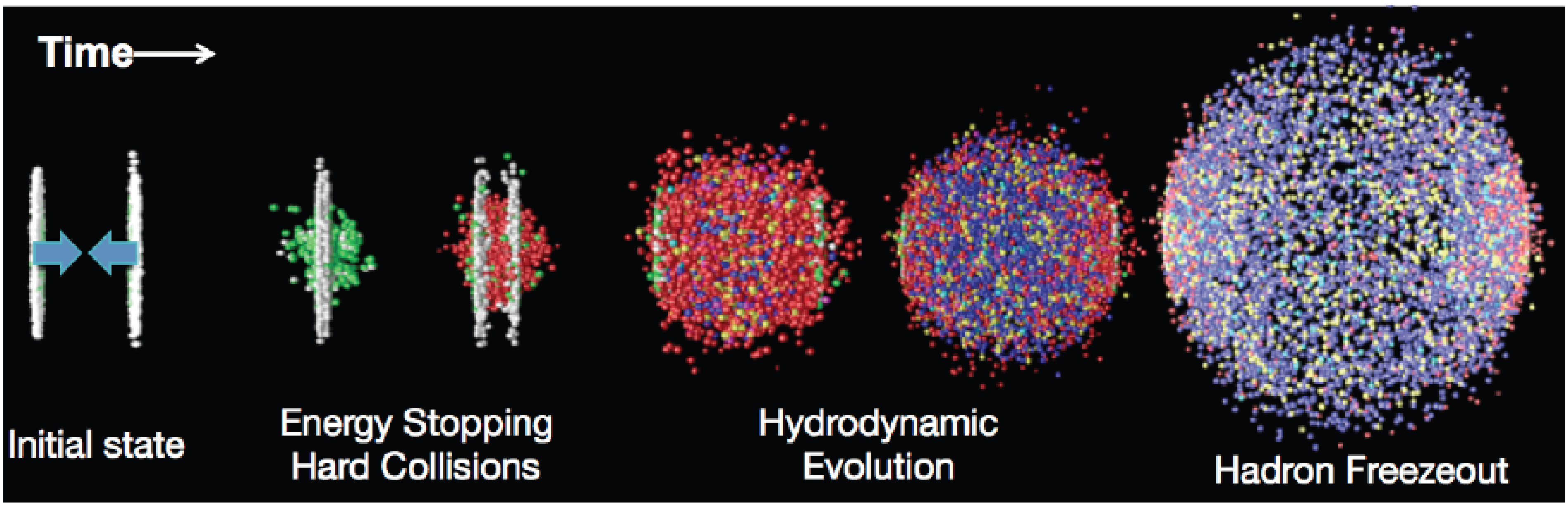
(Au, Pb ...)

$\sqrt{s_{NN}}$ from few GeV at Bevalac, AGS, SPS, GSI
up to 200 GeV at RHIC
up to 2.76 TeV at LHC

UrQMD

Ultra-relativistic heavy-ion collisions

Collision phases:



Thermalization
equilibrium is
established
(t < 1 fm/*c*)

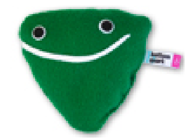
Expansion and cooling:
(t < 10-15 fm/*c*)

Chemical freeze-out
(particle yields)
Kinetic freeze-out
(particle spectra)

Heavy quarks: charm and beauty

Pictures from http://www.particlezoo.net/

Charm:
m ~ 1.5 GeV/c^2

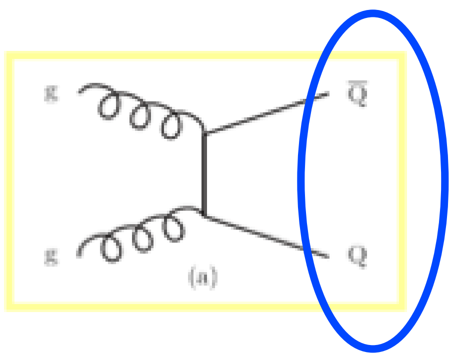


Beauty:
m ~ 5 GeV/c^2

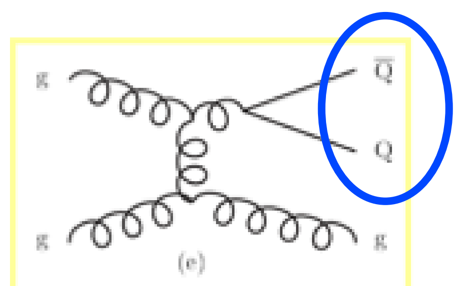
Hard probes even at low momentum

Large mass → **perturbative QCD approaches used!**

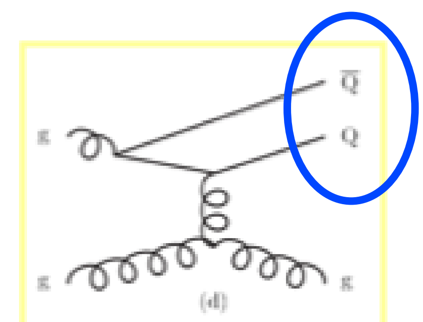
Dominant production diagrams: gluon-gluon fusion, hard scattering



Pair production
(LO)



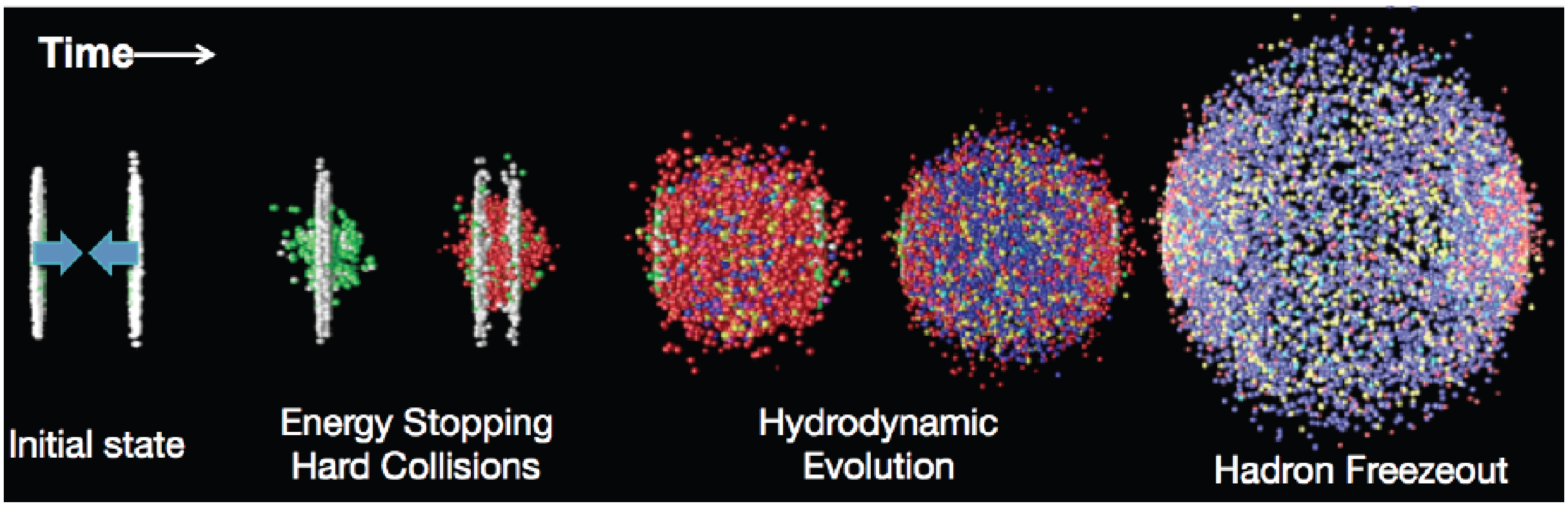
Gluon splitting
(NLO)



Flavor excitation
(NLO)

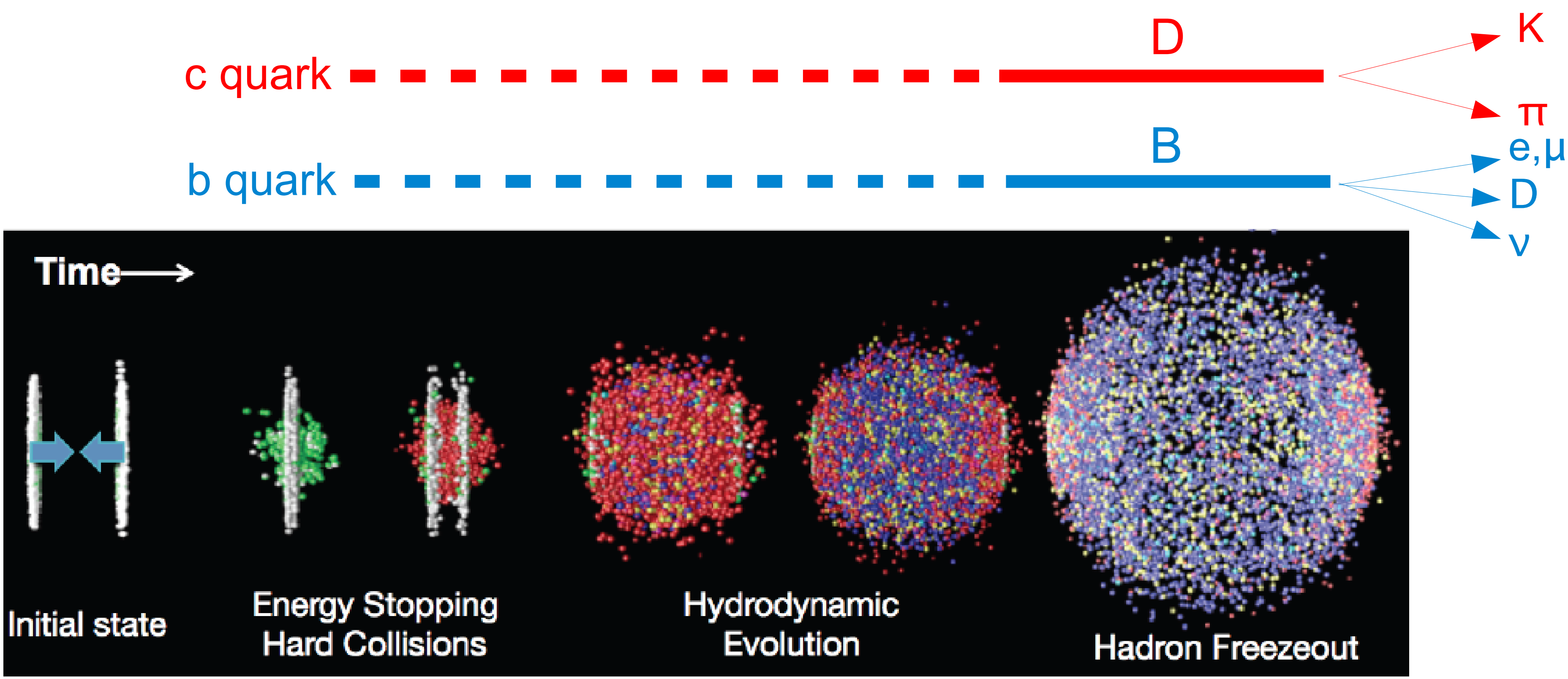
Heavy quarks and heavy-ion collisions

- Heavy quarks are produced in initial hard scattering processes, before the thermalized QPG phase
- Flavor is conserved by the strong interaction



Heavy quarks: probes of the QGP

- Heavy quarks produced in initial hard scattering processes, before the thermalized QPG phase
- Flavor is conserved by the strong interaction



Heavy flavors experience the full evolution of the deconfined medium
→ QGP properties

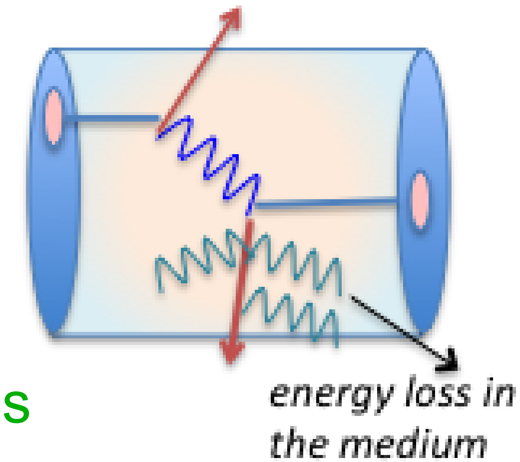
Heavy flavors, probes of the QGP

Two fundamental questions and observables:

- **Energy loss in the QGP**
  How do the heavy quarks interact with the partons in the QGP? Via the study of their energy loss in the medium we can learn information about the strongly interacting matter transport coefficients
  - Nuclear modification factor

- **Thermalization?**
  Do the heavy quarks thermalize in the medium? To what degree do they participate to the collective motion?
  - Elliptic flow

In-medium parton energy loss



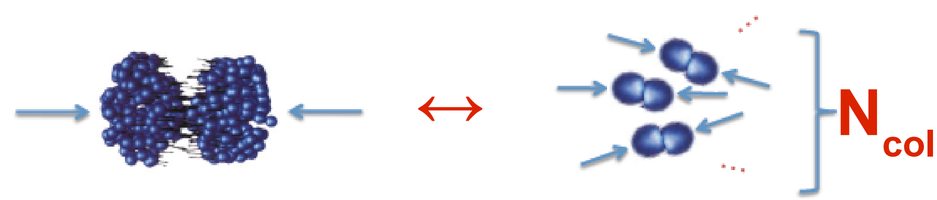
- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium constituents

- Depends on:
  - Colour charge $\Delta E_{gluon} > \Delta E_{q}$ $\rightarrow$ heavy to light hadrons
  - Parton mass $\Delta E_{c} > \Delta E_{b}$ $\rightarrow$ charm and beauty

Compare

Quantifier: the **nuclear modification factor**

$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$



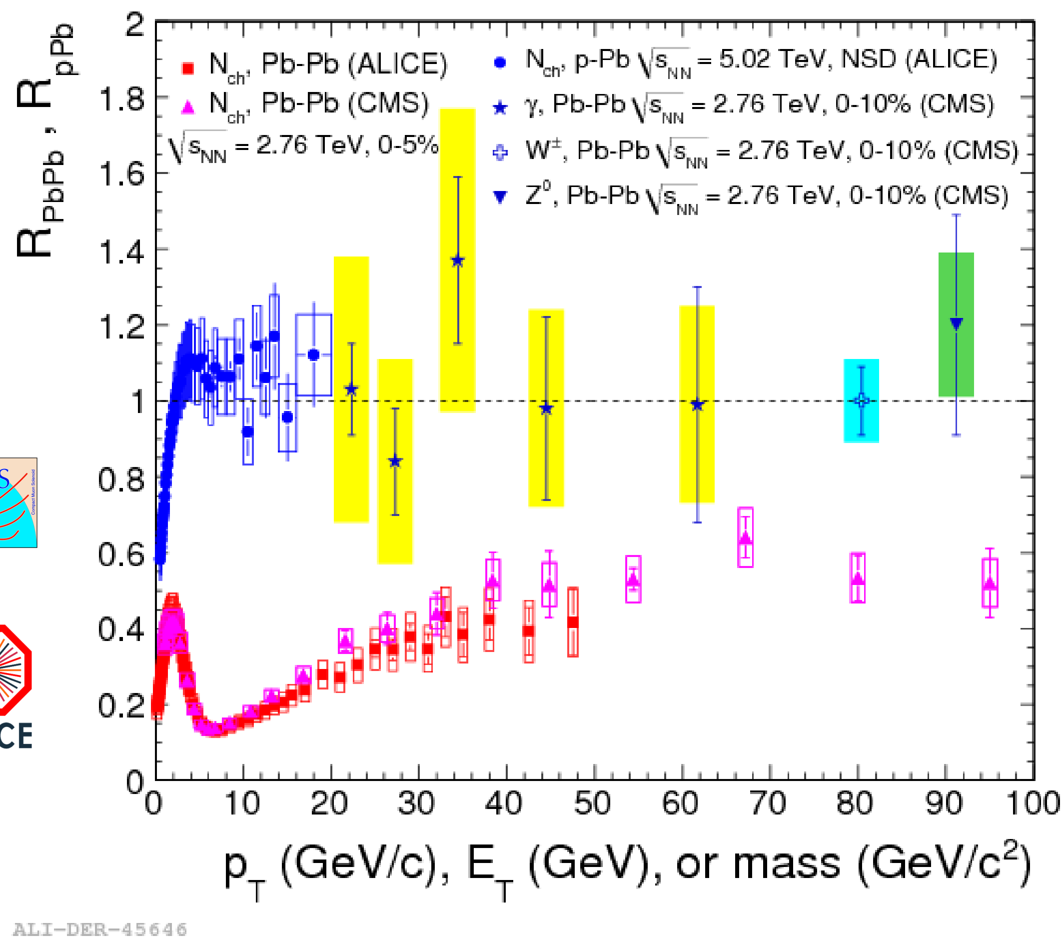
as function of p_T and centrality

binary collisions

Nuclear modification factor

No medium effect → $R_{AA} \approx 1$

Medium effect → medium "slows" down particles → $R_{AA} < 1$



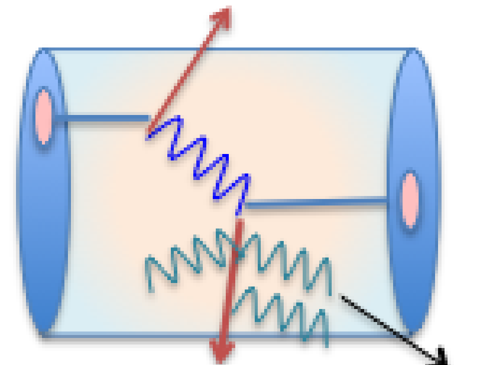
- No modification for vector bosons: γ $W^{\pm}$ Z^0
- Strong suppression for charged hadrons, still significant at 100 GeV/c !
- Look at charm and beauty

ALICE: (Pb-Pb) PLB720 (2013) 52, (p-Pb) PRL 110, 082302 (2013)

CMS: (W) PLB 715 (2012) 66; (Z) PRL 106, 212301 (2011); (γ) PLB 710 (2012) 256; (charged) EPJC (2012) 72:1945

Nuclear modification factor

- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium constituents



- Depends on: Compare
  - Colour charge $\Delta E_{gluon} > \Delta E_{q}$ → heavy to light hadrons
  - Parton mass $\Delta E_{c} > \Delta E_{b}$ → charm and beauty

- Considering all effects together: the predicted energy loss was

$$\Delta E_{gluon} \geq \Delta E_{q \approx c} > \Delta E_{b}$$

- Thinking of the spectra modification (R_{AA}), we could expect:

“suppression”: $\pi \geq D > B$

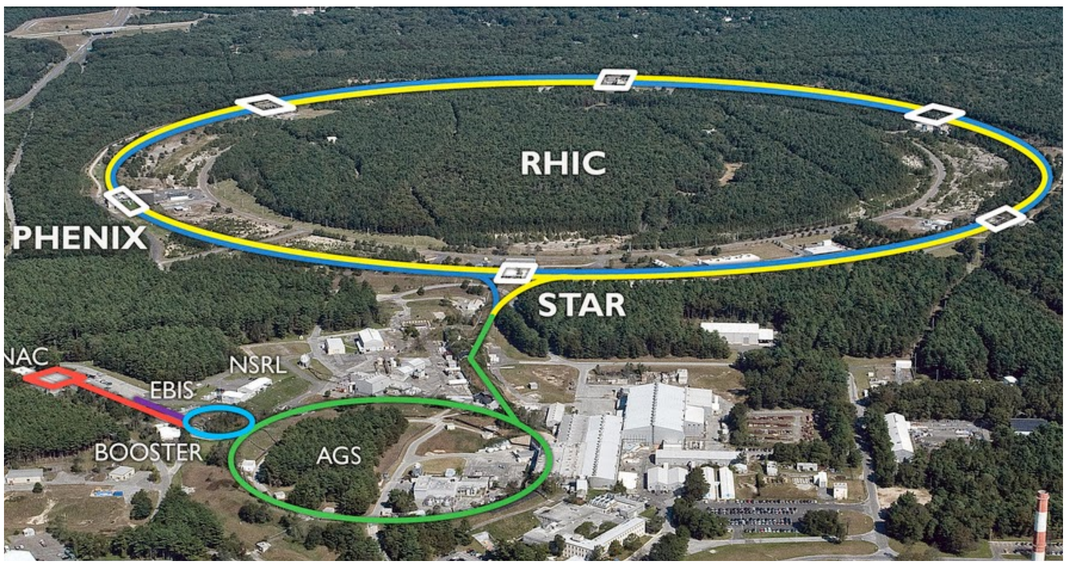
$$R_{AA}^{\pi} \leq R_{AA}^{D} < R_{AA}^{B}$$

consider that other effects contribute, like different production kinematics and fragmentation of light and heavy quarks

references in spares

Experimental program

RHIC
Brookhaven National Laboratory



- Au-Au $\sqrt{s_{NN}}$ = 200 GeV

  p, d, ^{3}He, Cu, U. Beam Energy Scan (BES): 7.7 … 200 GeV
- PHENIX, STAR

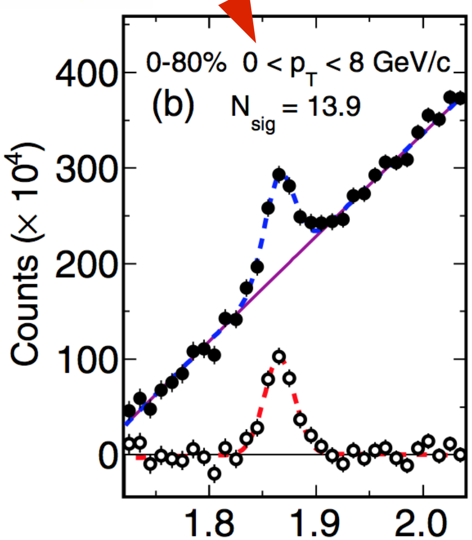
LHC
CERN

- Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV , p, Pb
- ALICE, ATLAS, CMS, LHCb (p-Pb only)

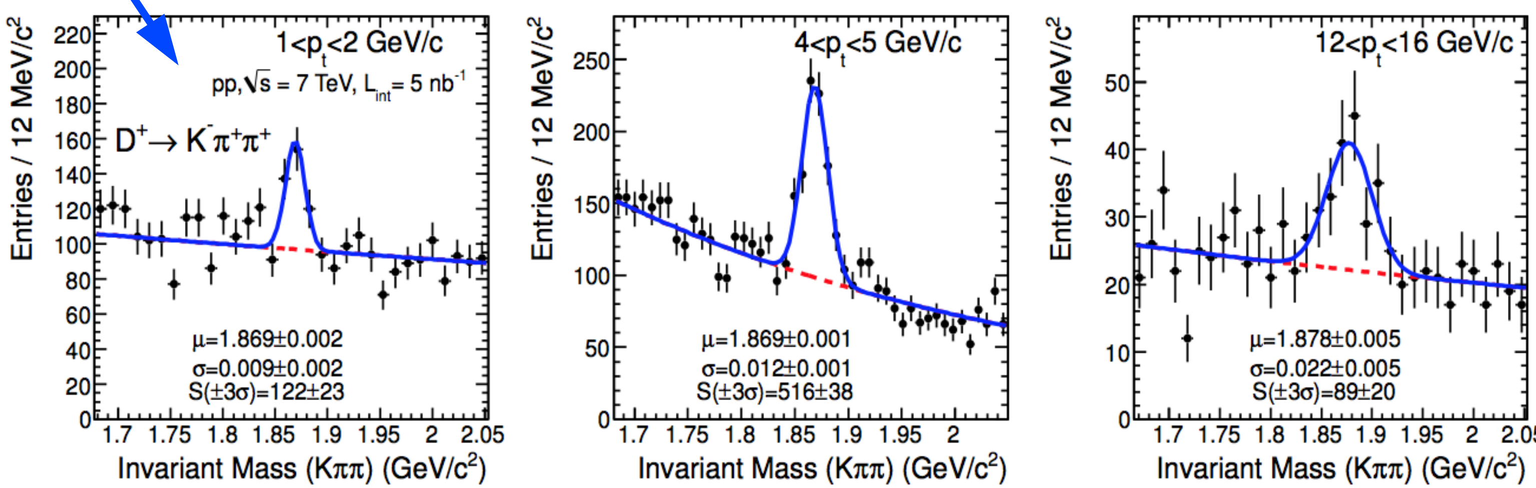
Open charm: D mesons

Invariant-mass reconstruction of hadronic decay channels:

$D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$, $D_s^+ \rightarrow \varphi\pi \rightarrow K^+K^-\pi^+$



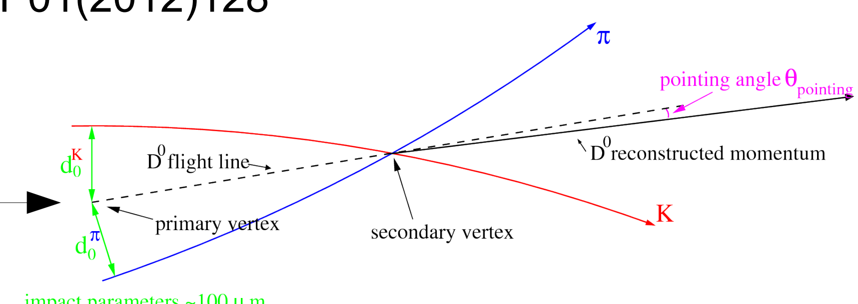
PRL 113, 142301 (2014)



JHEP01(2012)128

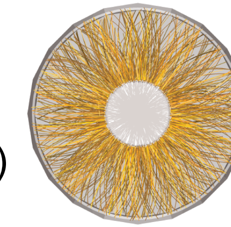
- Particle identification: TPC, TOF
- Topological selection, precise vertexing

(not for STAR results shown here)

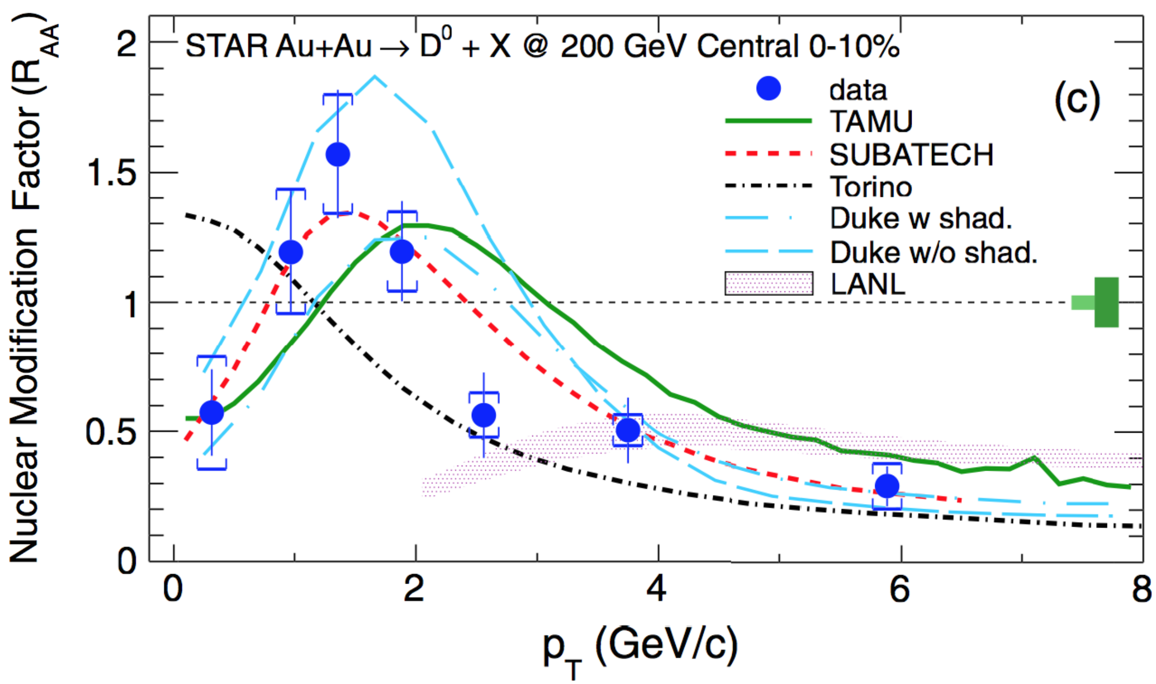


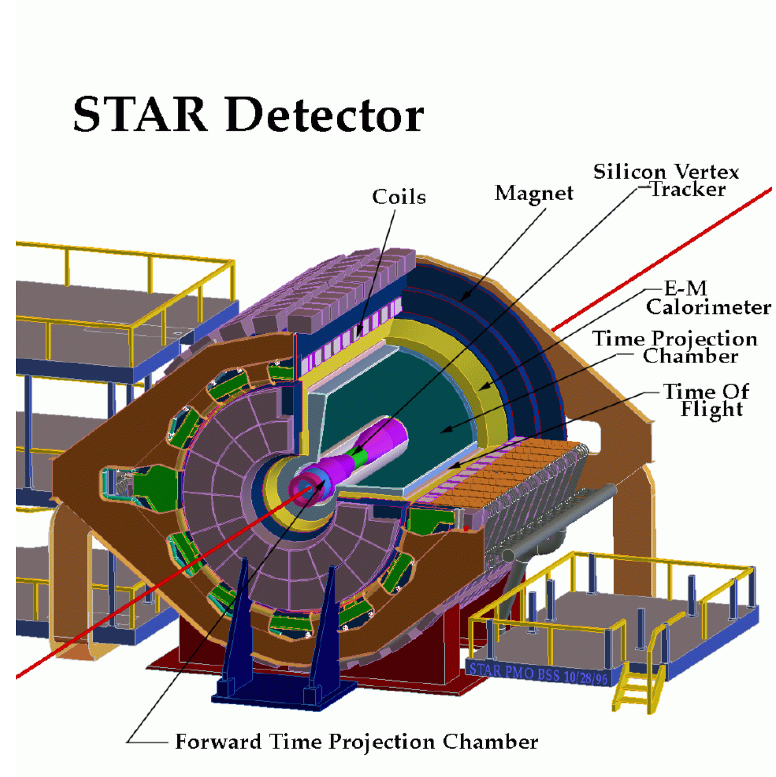
at RHIC: $D^0 \rightarrow K\,\pi$

PRL 113, 142301 (2014)



Nuclear modification factor R_{AA}





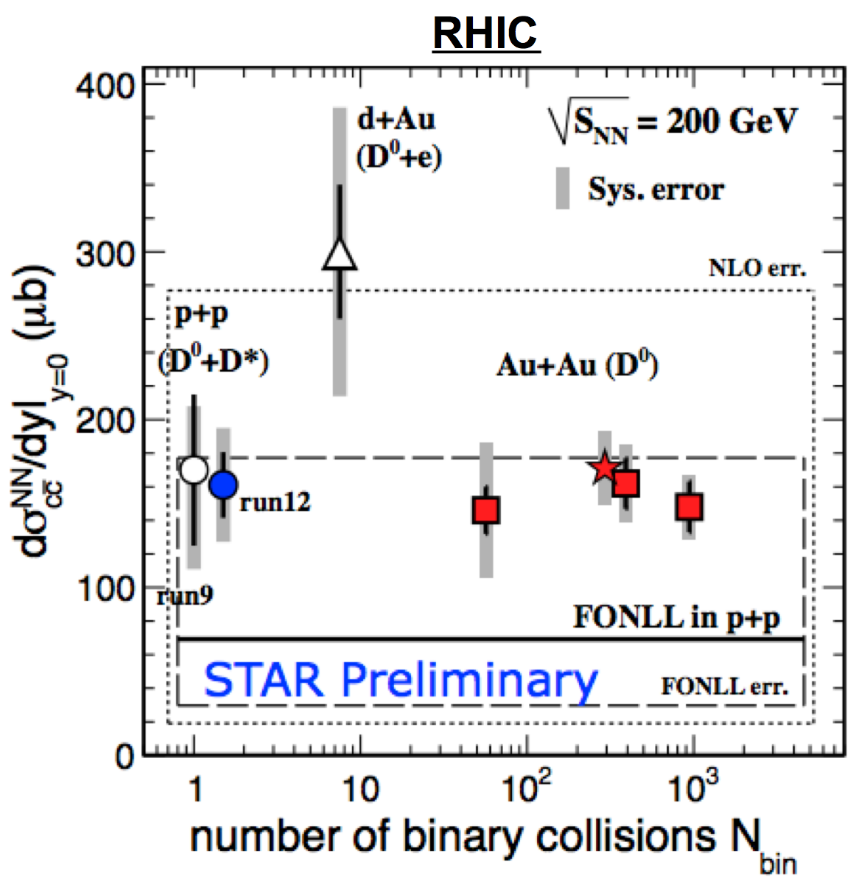
- Significant suppression above 3 GeV/c
- Enhancement in the intermediate p_T region (0.7-2.2 GeV/c)
- Described by models including strong charm-medium interactions and hadronization by coalescence

Running with Heavy Flavor Tracker (HFT) since 2014 !!!!

at RHIC: charm cross section

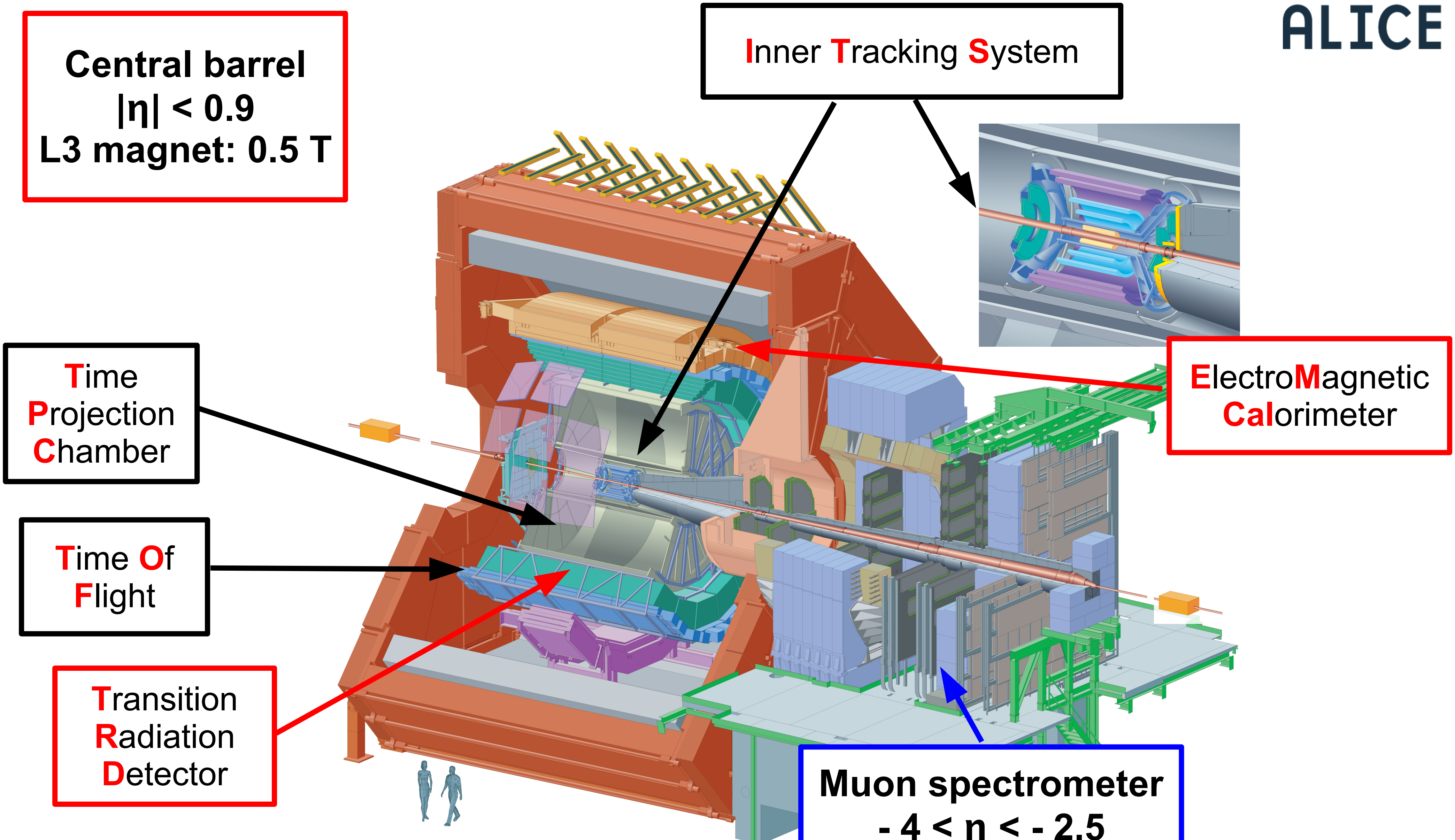
Charm production cross section scales with the number of binary collisions:

(measurement down to p_T ~ 0 GeV/c needed)



Consistent with charm quarks originating predominantly from initial hard scattering at RHIC

ALICE at the LHC



ALICE at the LHC

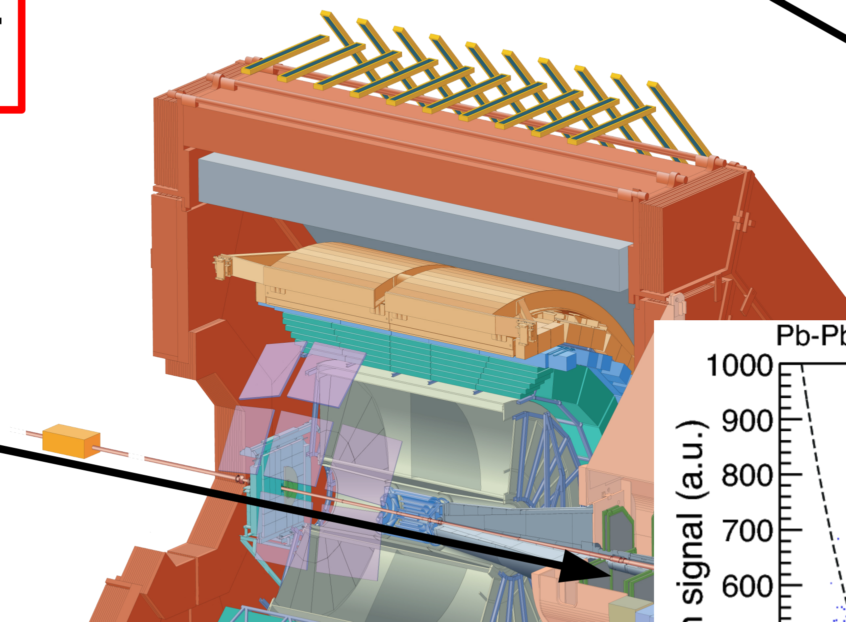
Central barrel
$|\eta| < 0.9$
L3 magnet: 0.5 T

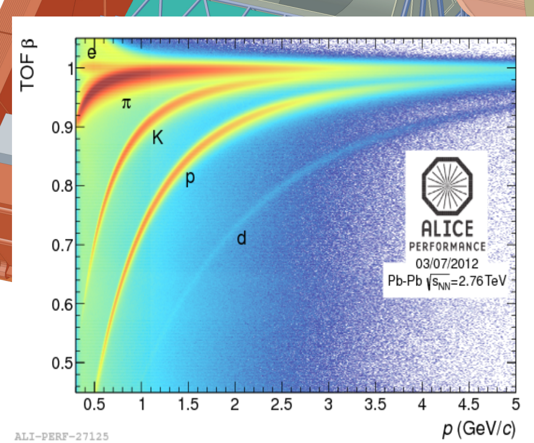
Inner Tracking System

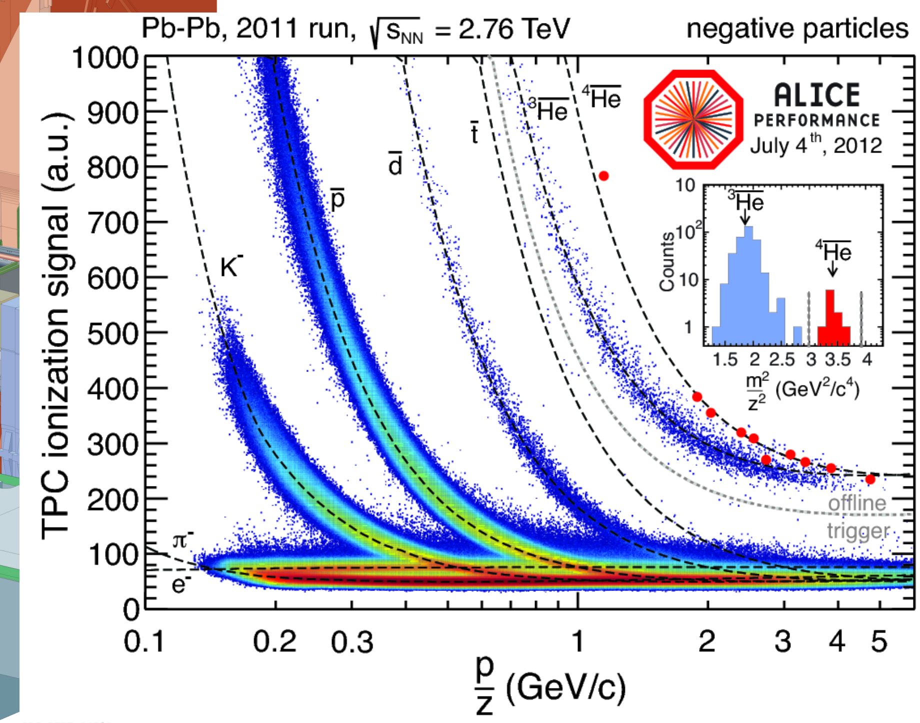
High resolution track and vertex reconstruction (tens of microns)

Time Projection Chamber

Time Of Flight



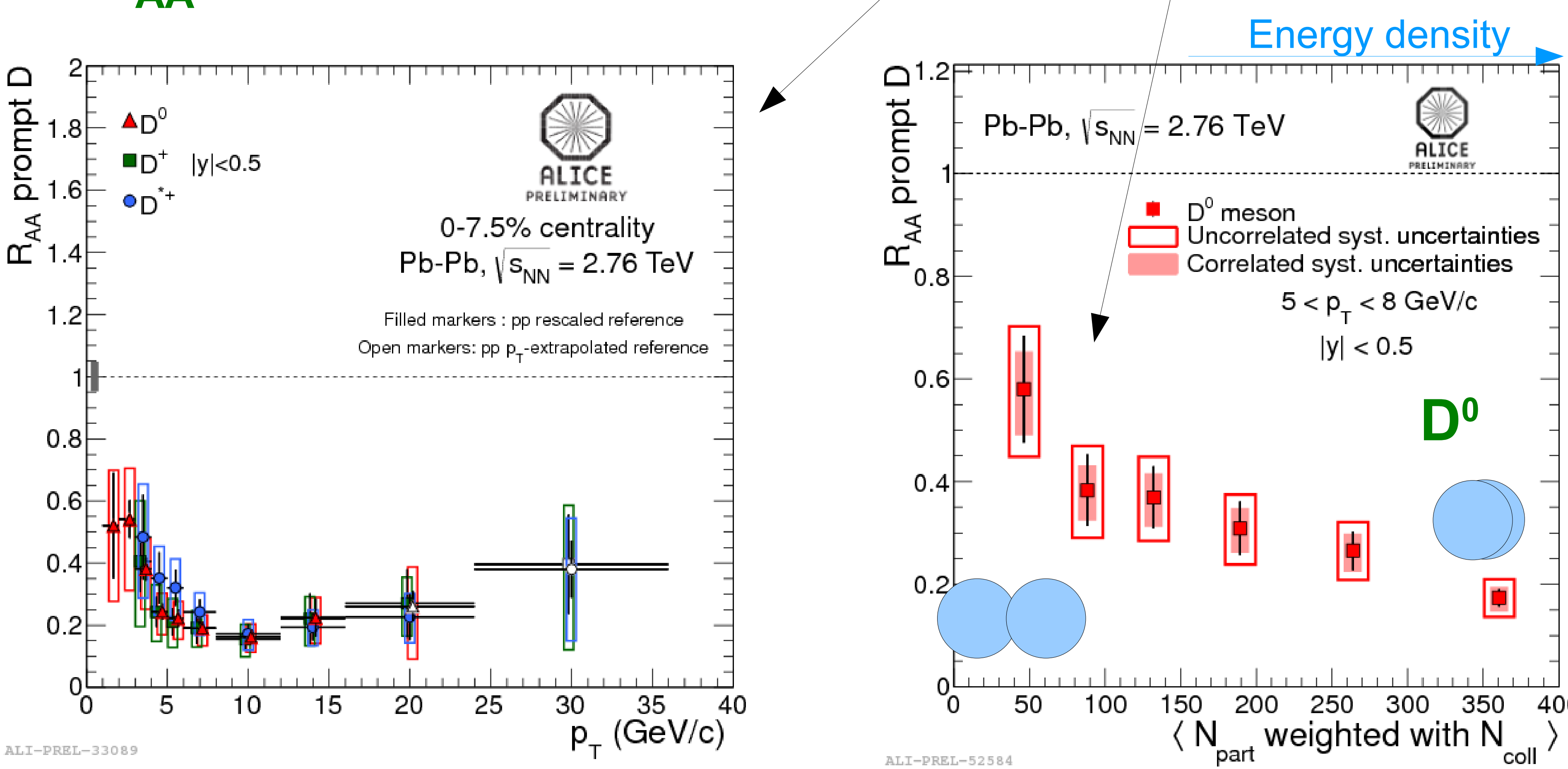




ALICE: D meson R_{AA}

Prompt D^0, D^+, D^{*+}

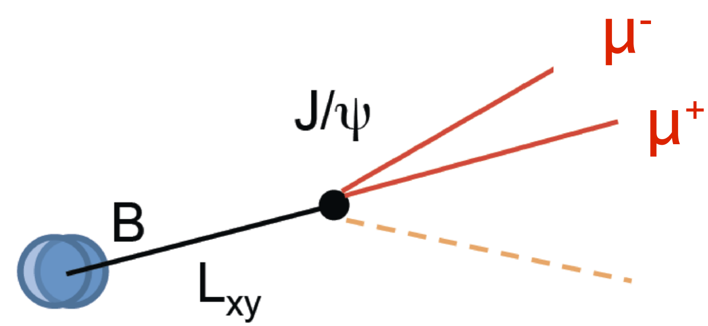
R_{AA} Nuclear modification factor vs p_T and collision centrality

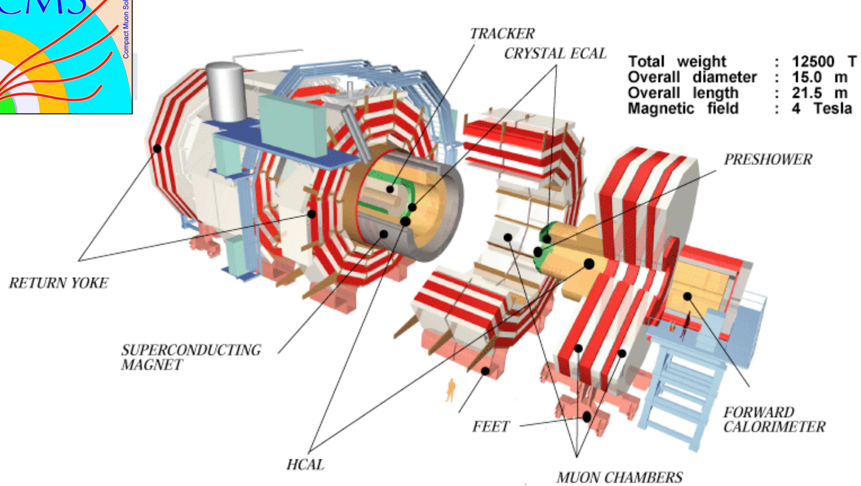


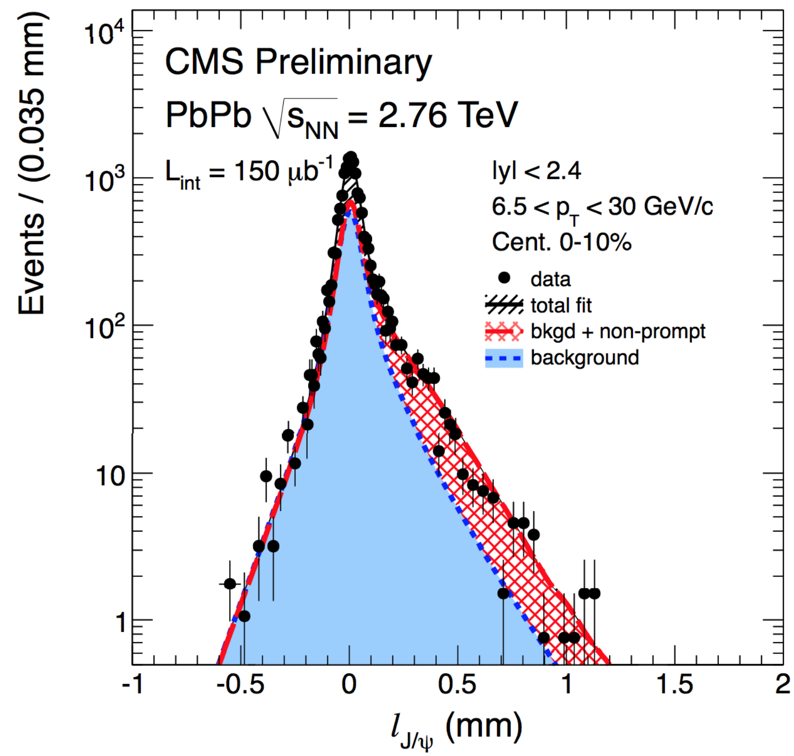
Charm mesons exhibit strong suppression

Beauty via non-prompt J/ψ

- Detect J/ψ decay vertices detached from the primary interaction
- Measure the pseudo-proper decay length





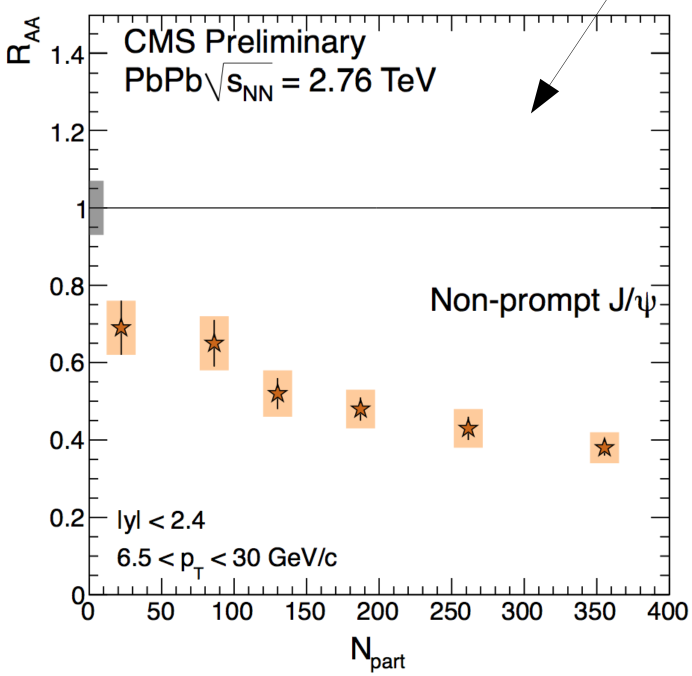


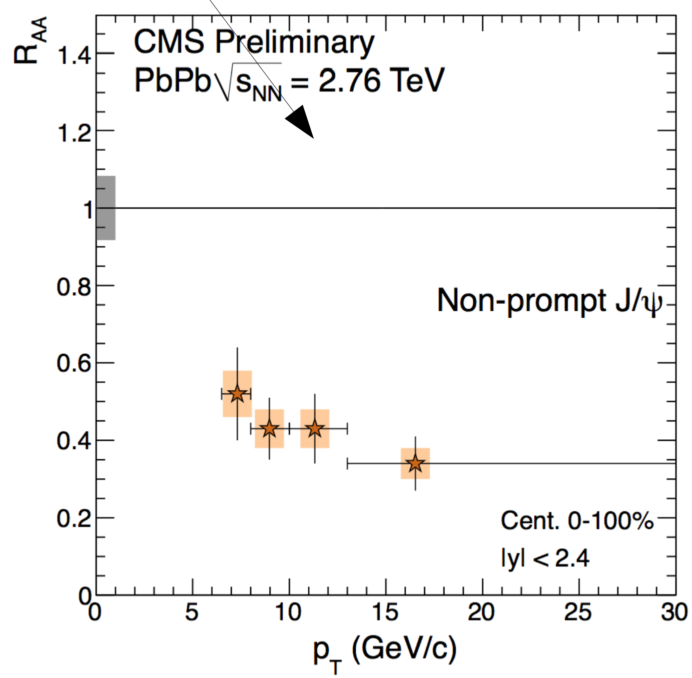
CMS PAS HIN-12-014

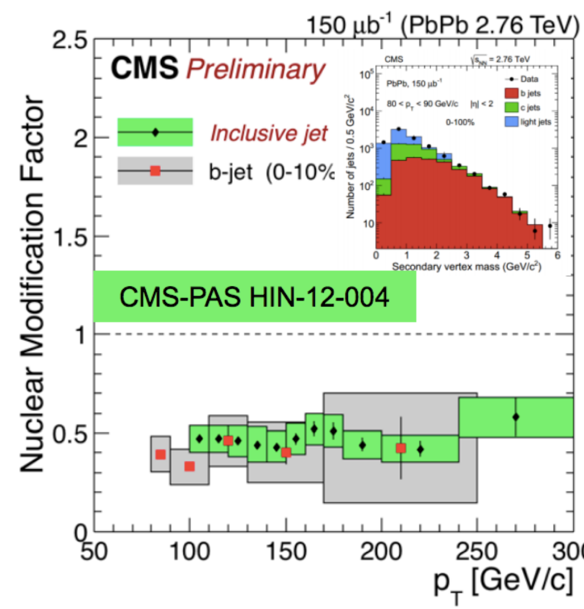
Beauty: B → J/ψ X and b-jets

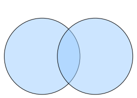
Nuclear modification factor as function of centrality and p_T

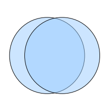
Beauty jets











of J/ψ !

CMS PAS HIN-12-014

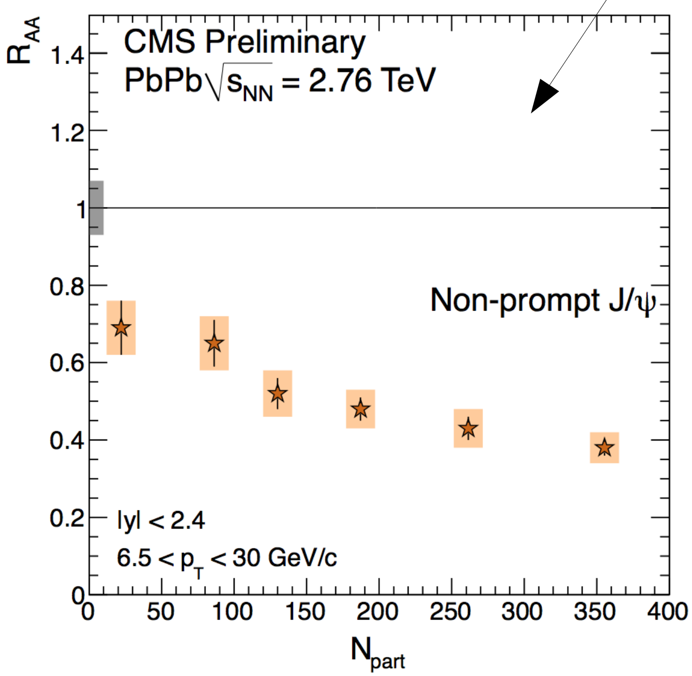
Strong suppression of beauty

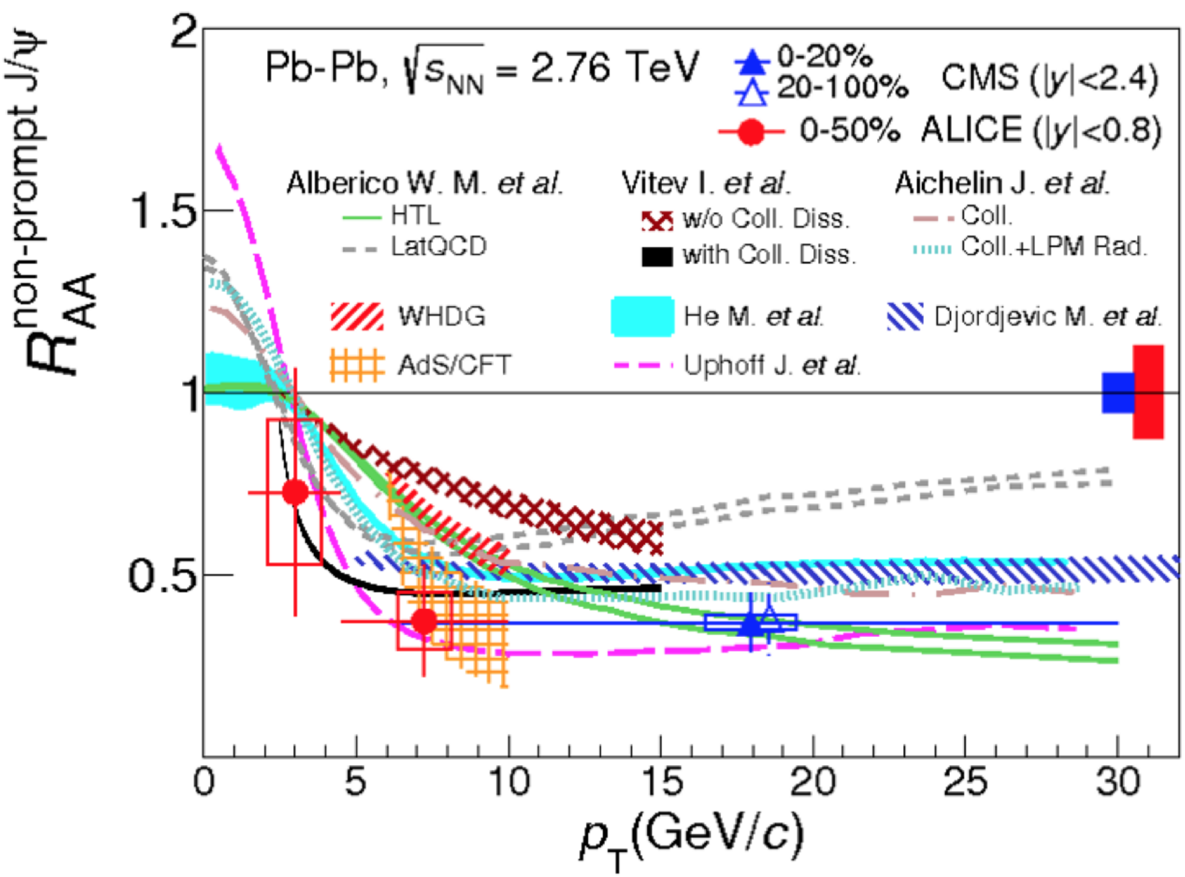
Beauty: B → J/ψ X

Nuclear modification factor as function of centrality and p_T

ALICE starts to reach lower p_T!

JHEP 1507 (2015) 051





CMS PAS HIN-12-014

Strong suppression of beauty

Mass ordering of energy loss

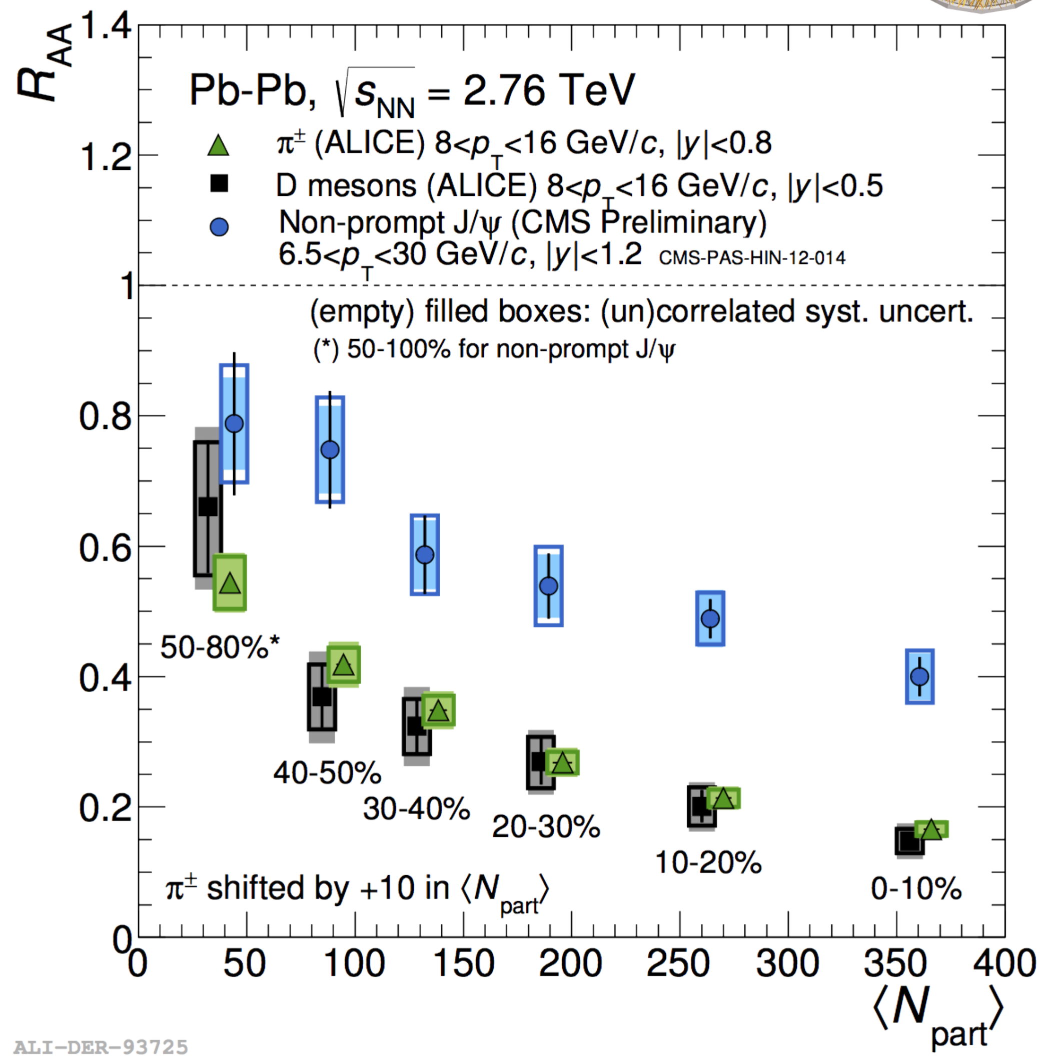
Beauty: non-prompt J/ψ

CMS-PAS-HIN-12-014

Charm: D mesons

arXiv: 1506:06604

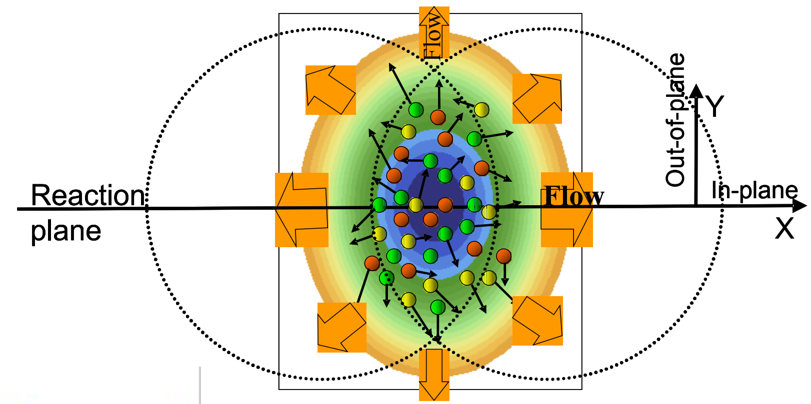
Light quarks: pions



No significant difference between D mesons and π's
Indication of mass ordering for charm and beauty

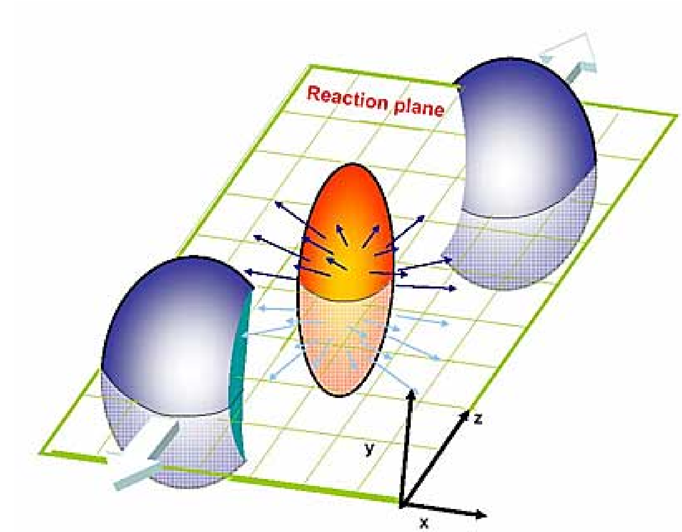
Elliptic flow: v_2

- Initial spatial asymmetry in semi-central collisions → azimuthal anisotropy of final hadrons



$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

- Degree of participation of charm to the collective motion of the medium: $v_2 > 0$ at low p_T
- Path length dependence of energy loss: at high p_T

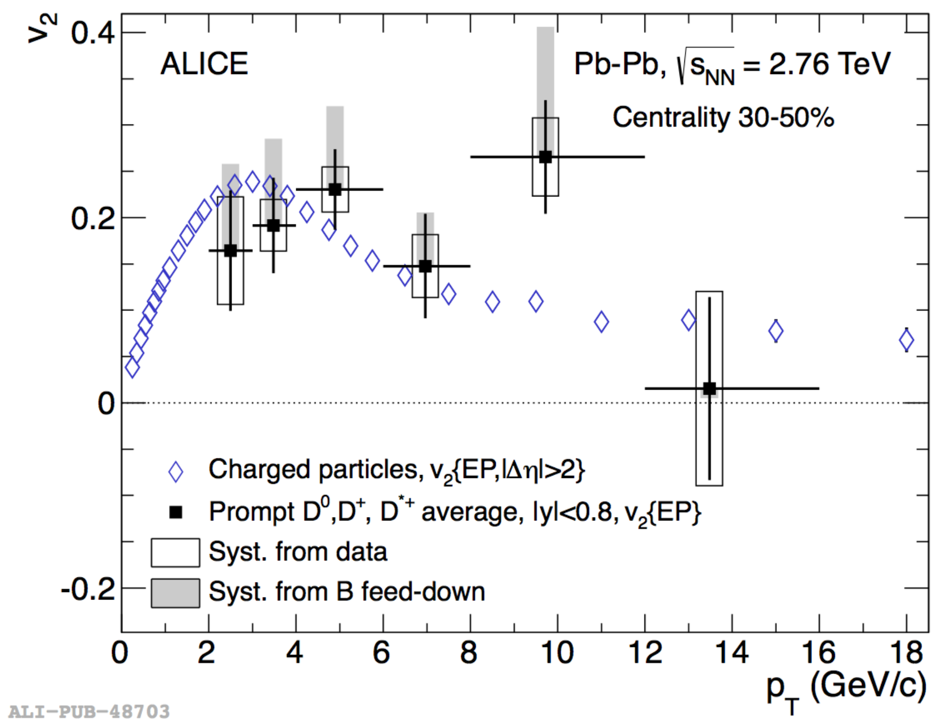


Heavy-flavor v_2 measurements

Prompt D meson v_2

compared to v_2 of charged particles

Comparable behavior!



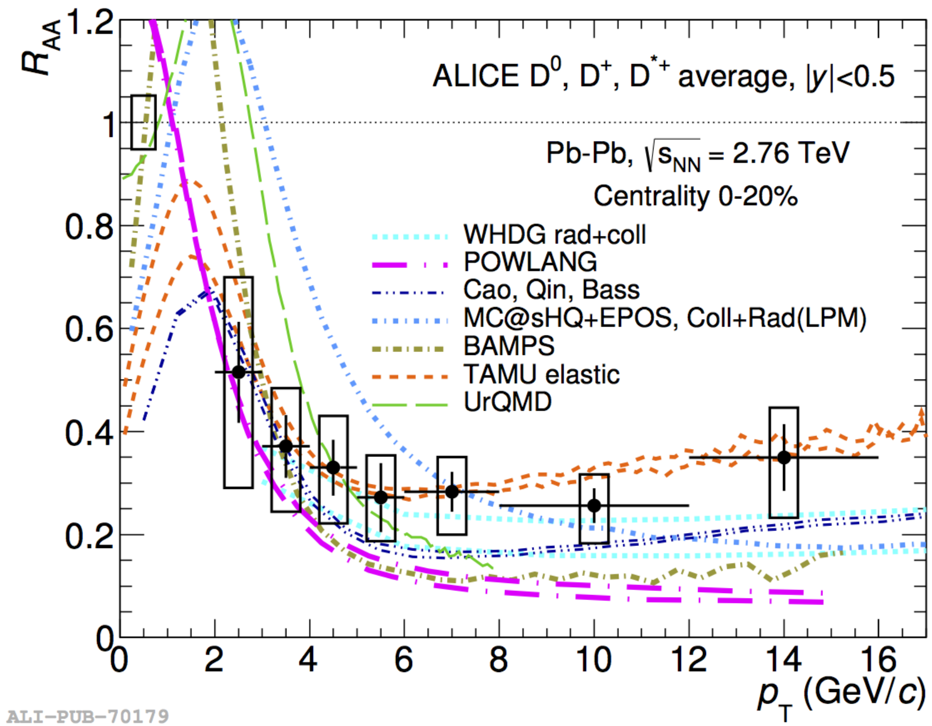
PRL 111(2013)102301
PRC90(2014)034904

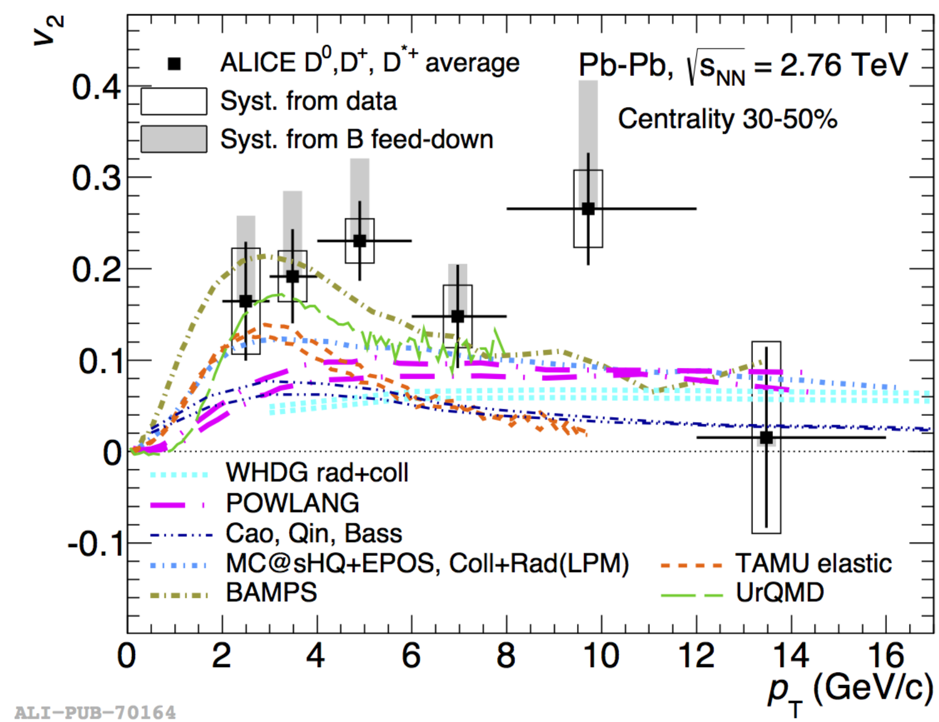
Non-zero v_2 coefficient at low p_T:
hint for participation of charm to the collective motion

Data and theory

(*) references in spares

Theoretical model to translate the measured observables to fundamental properties of the QGP: transport coefficients





PRC90(2014)034904

Simultaneous description of R_{AA} and v_2 challenging!

Data start to be precise enough to constrain energy loss models

I have omitted (see backup!)

- Measurements with inclusive leptons from **semi-leptonic decays** of heavy-flavour hadrons
  - FIRST evidence of heavy-flavour hadron suppression! PHENIX
    Recent results from ALICE ATLAS

- Discussion of cold nuclear matter effects (incoming nuclear-PDFs, gluon saturation/shadowing, k_T broadening, CNM energy loss ...).
  Measurements show that **heavy flavour suppression is a QGP, final state effect**

- **Beauty jet** measurements by CMS
  insights into parton shower in the QGP
  Study heavy-flavour fragmentation (ALICE potential for charm in jets)

Summary

- **Heavy quark energy loss**

  $R_{AA}(\pi) \approx R_{AA}$ (e, μ ← HQ) $\approx R_{AA}$ (D) < R_{AA} (J/ψ ← B)$^{\text{high pT}}$

  described by model calculations based on pQCD, with collisional and radiative energy loss

- **Charm flow**

  R_{AA} of D^0 at RHIC → hint of charm flow + coalescence

  $v_2(D) \sim v_2(h)$ at LHC → charm flow

  More precise data needed!

- **Extraction of transport coefficients?**

  Unify different theory models (initial conditions, medium evolution, coherent description of R_{AA} and v_2, etc)

Coming up

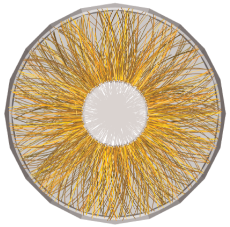
- **RHIC**: both STAR and PHENIX have new microvertex detectors
  $\rightarrow$ new results very soon

- **LHC:**
  - Run 2 on-going: Pb-Pb run at $\sqrt{s_{NN}}$ = 5.1 TeV, high statistics
  - Run 3 from 2020 with upgraded detectors

	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	STAR HFT PHENIX (F)VTX Precision charm			Spin		BES-II		STAR HFT+ sPHENIX Open bottom	
LHC		Run 2 (x10 statistics)					ALICE ITS upgrade CMS/ATLAS upgrades Run 3 (x100 statistics)		

Courtesy of X. Dong, Hard Probes 2015

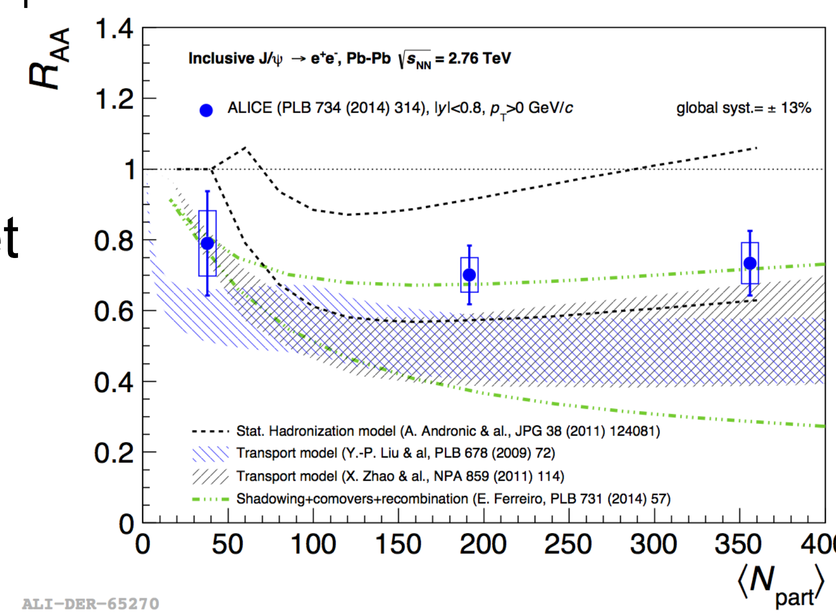
Outlook



High precision experimental data:

- Extend measurements to low p_T and high p_T
- Essential to determine $\sigma_{c\bar{c}}$ in AA collisions

Discriminate models which interpret J/ψ suppression at the LHC



- Extend beauty measurements
  - p_T range, uncertainties, new methods

Coherent extraction of QGP transport coefficients and properties

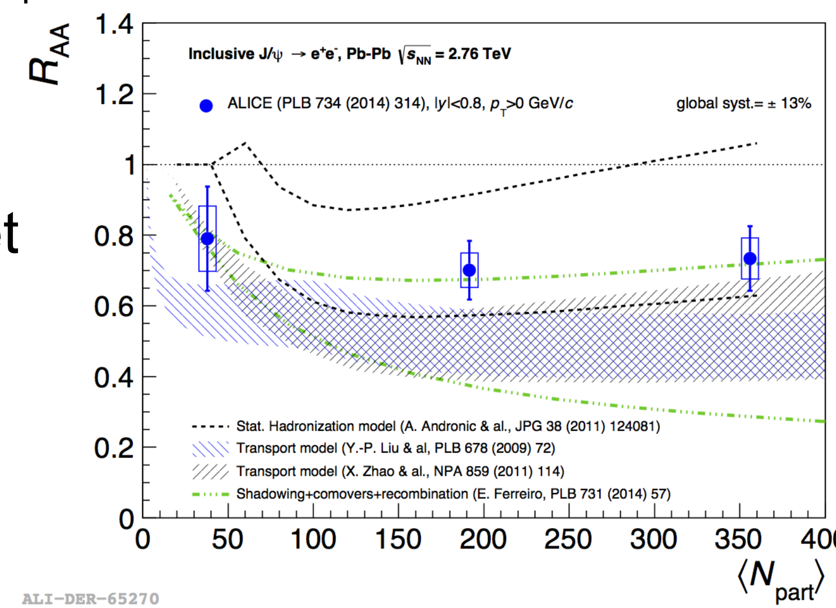
- Important work on the theoretical side
- Initial conditions

Outlook

High precision experimental data:

- Extend measurements to low p_T and high p_T
- Essential to determine $\sigma_{c\bar{c}}$ in AA collisions

Discriminate models which interpret J/ψ suppression at the LHC



- Extend beauty measurements
  - p_T range, uncertainties, new methods

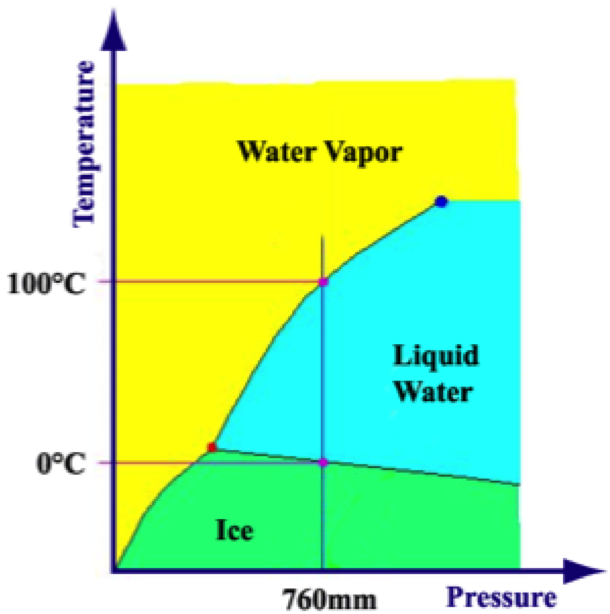
Coherent extraction of QGP transport coefficients and properties

- Important work on the theoretical side
- Initial conditions

Spares

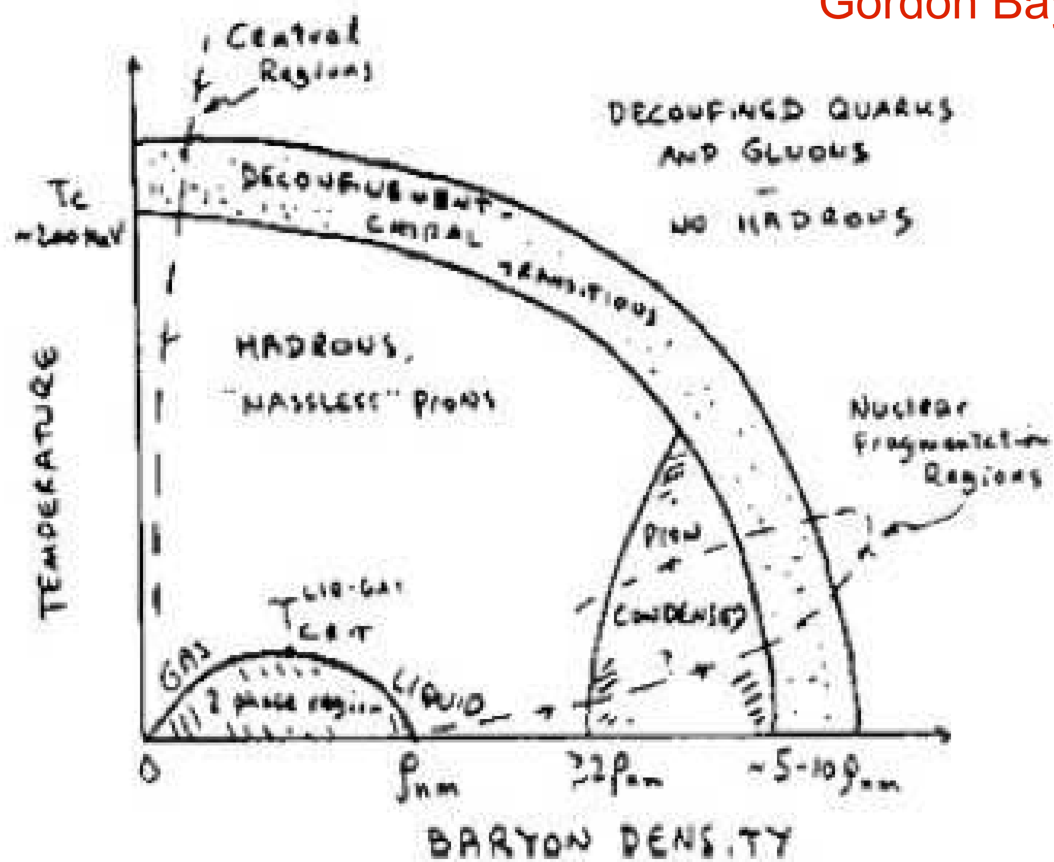
QCD phase diagram

In analogy to QED, phase diagram for strongly interacting matter:



Gordon Baym, 1983

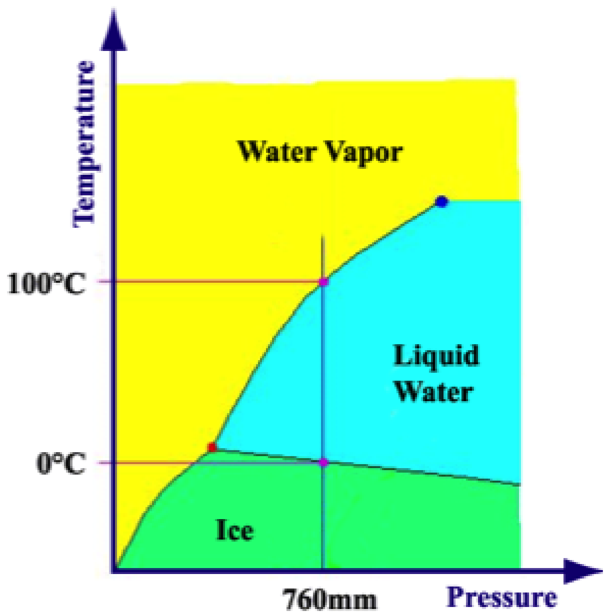
TEMPERATURE

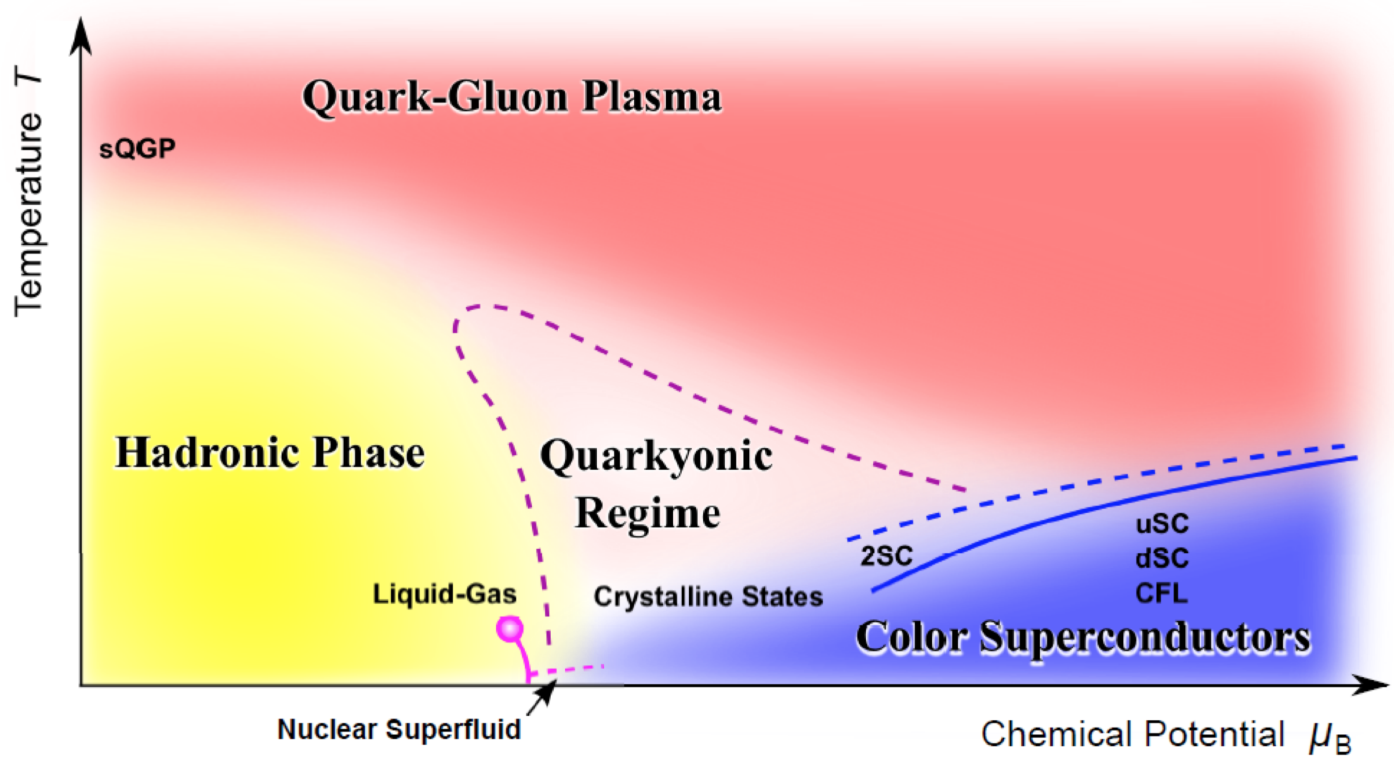


BARYON DENSITY

QCD phase diagram

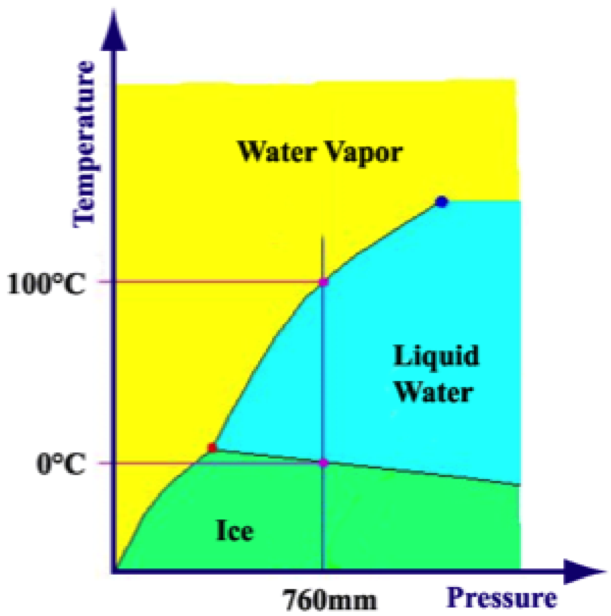
In analogy to QED, phase diagram for strongly interacting matter:

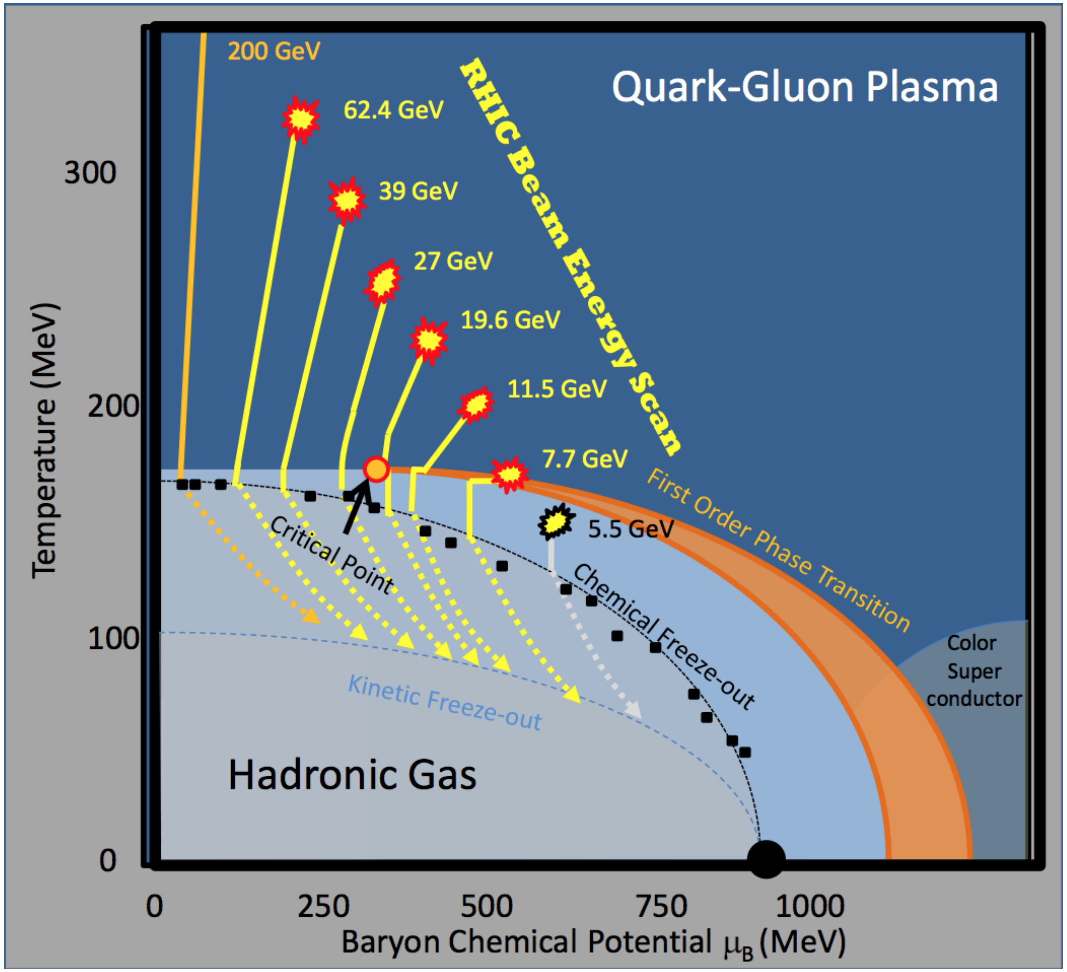




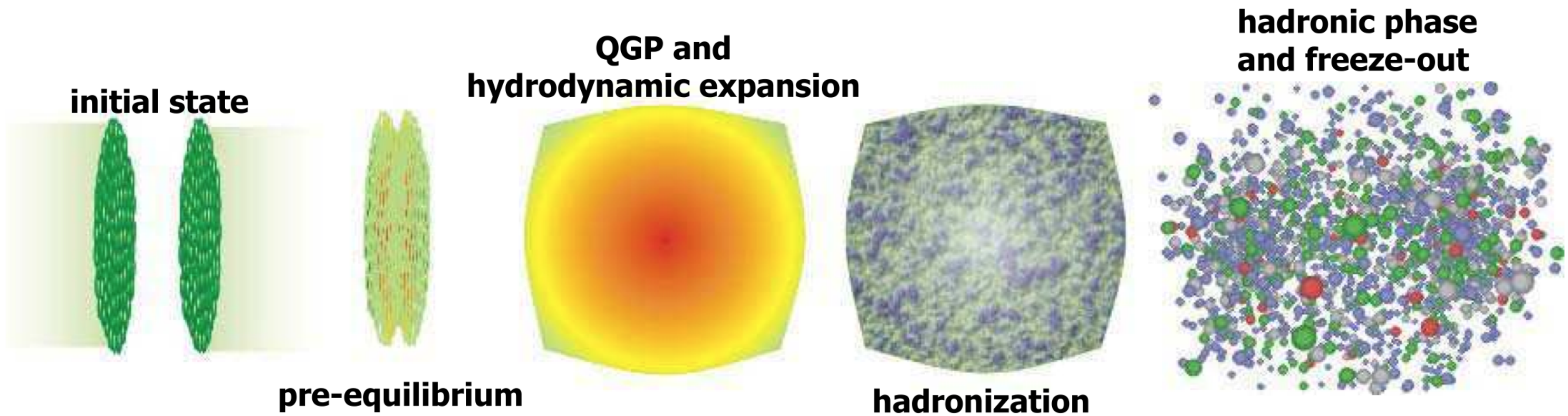
QCD phase diagram

In analogy to QED, phase diagram for strongly interacting matter:





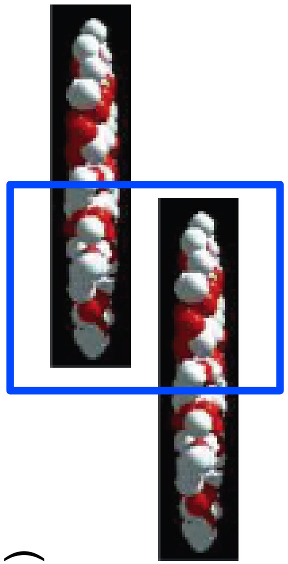
Ultra-relativistic heavy-ion collisions



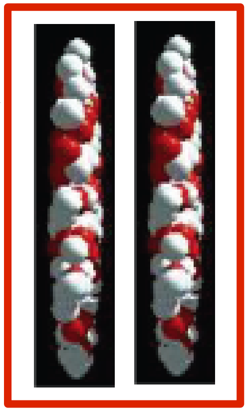
1. Initial collision, pre-equilibrium
2. Thermalization: equilibrium is established ($t \leq 1$ fm/c)
3. Expansion and cooling ($t < 10 – 15$ fm/c)
4. Hadronization (quarks and gluons form hadrons)
5. Chemical freeze-out: inelastic collisions cease, yields are defined
6. Kinetic freeze-out: elastic collisions cease, spectra are frozen (a few fm/c later)

Measurements can only be performed at stages 5 and 6. From those, we want to deduce information on phases 1, 2, and 3

Geometry of a Pb-Pb collision

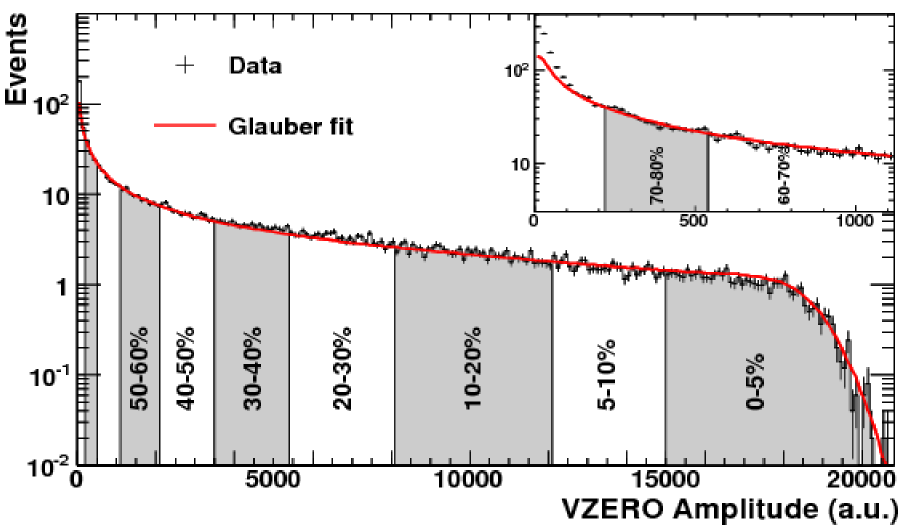


Central collisions → high number of **participants**
→ high multiplicity
Peripheral collisions → low number of **participants**
→ low multiplicity



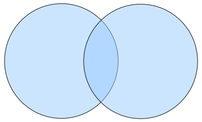
E.g. measure by VZERO scintillators +
reproduced by Glauber model fit

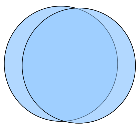
Phys. Rev. Lett. 106, 032301 (2011)
arXiv:1301.4361



Centrality: percentile of total hadronic cross section

peripheral





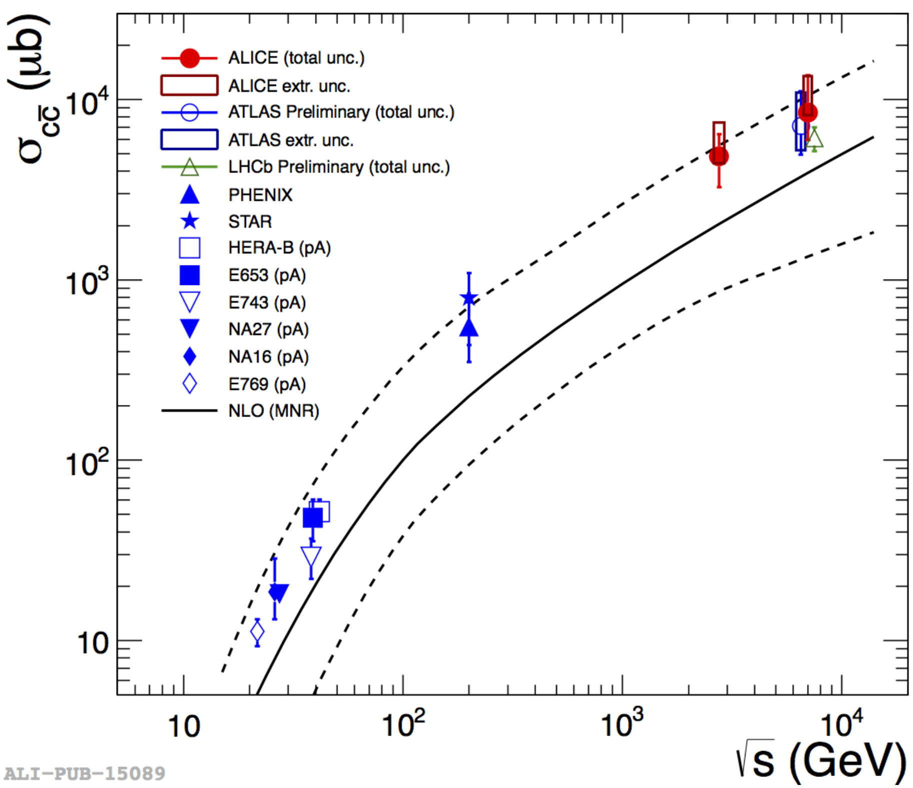
central

Total(*) cross section in pp: 2.76 and 7 TeV

LHC energies: large production cross sections!

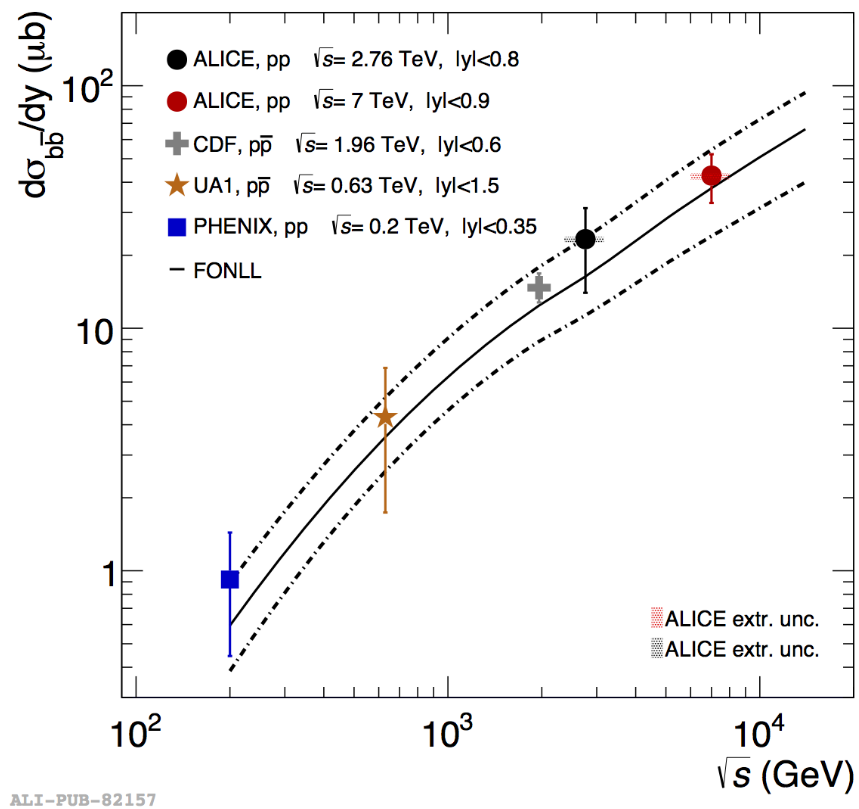
Charm

JHEP 1207 (2012) 191



Beauty

PLB 738 (2014) 97



Abundant hard probe at the LHC!

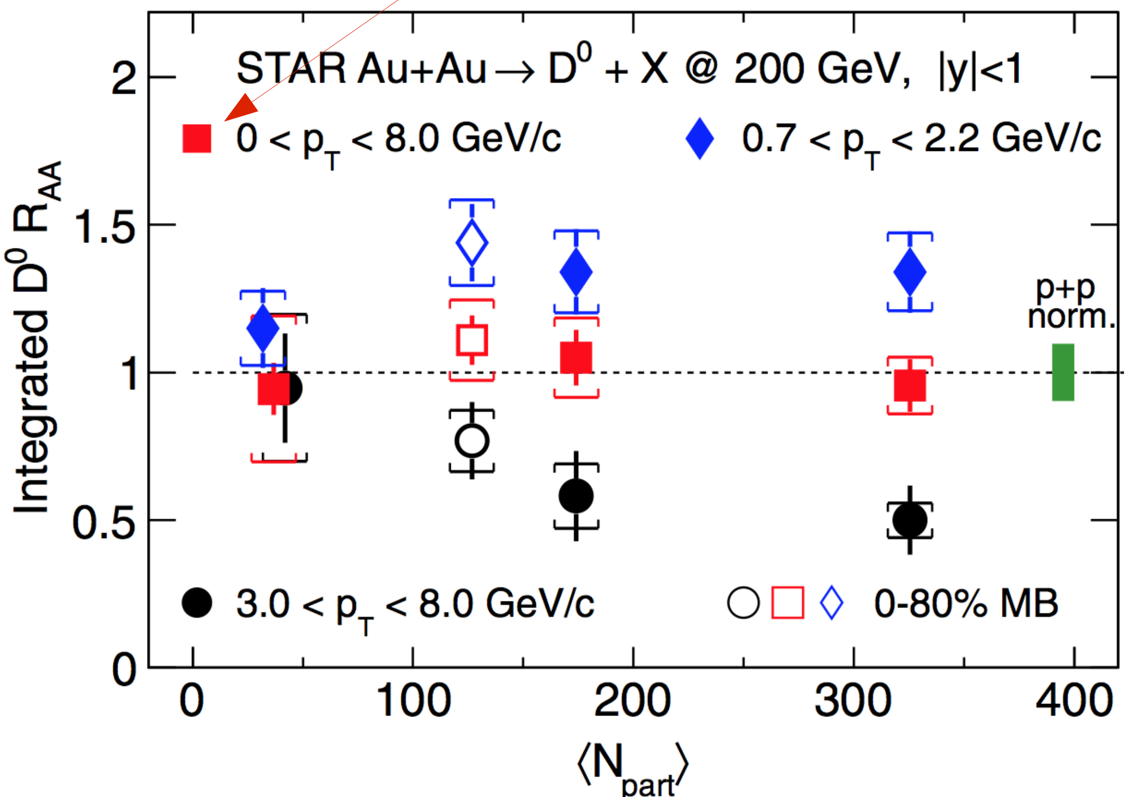
pQCD: large theoretical uncertainties

(*) integrated over y and p_T

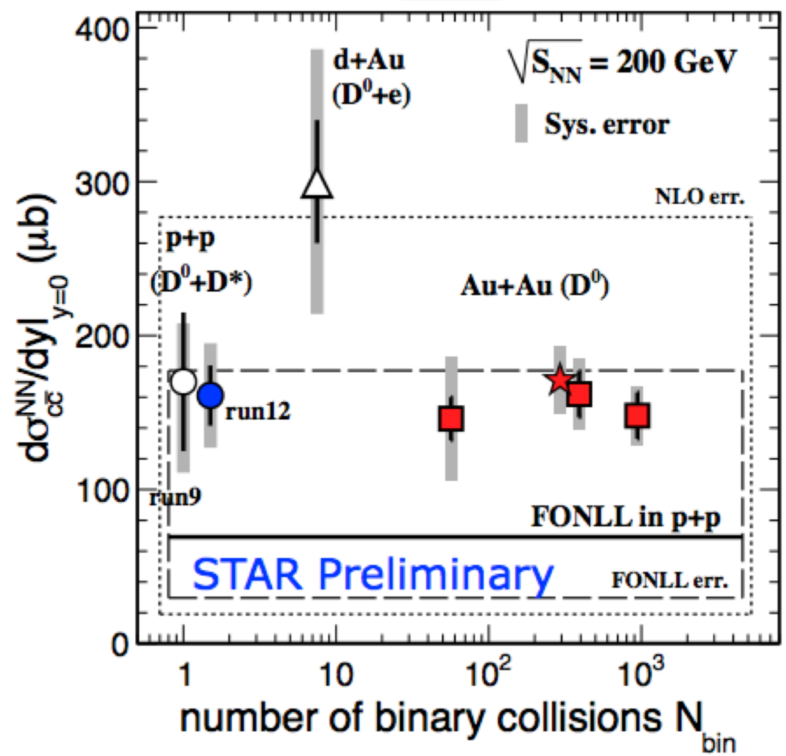
at RHIC: charm cross section

PRL 113, 142301 (2014)

Integrated D^0 R_{AA} over full p_T region:



RHIC

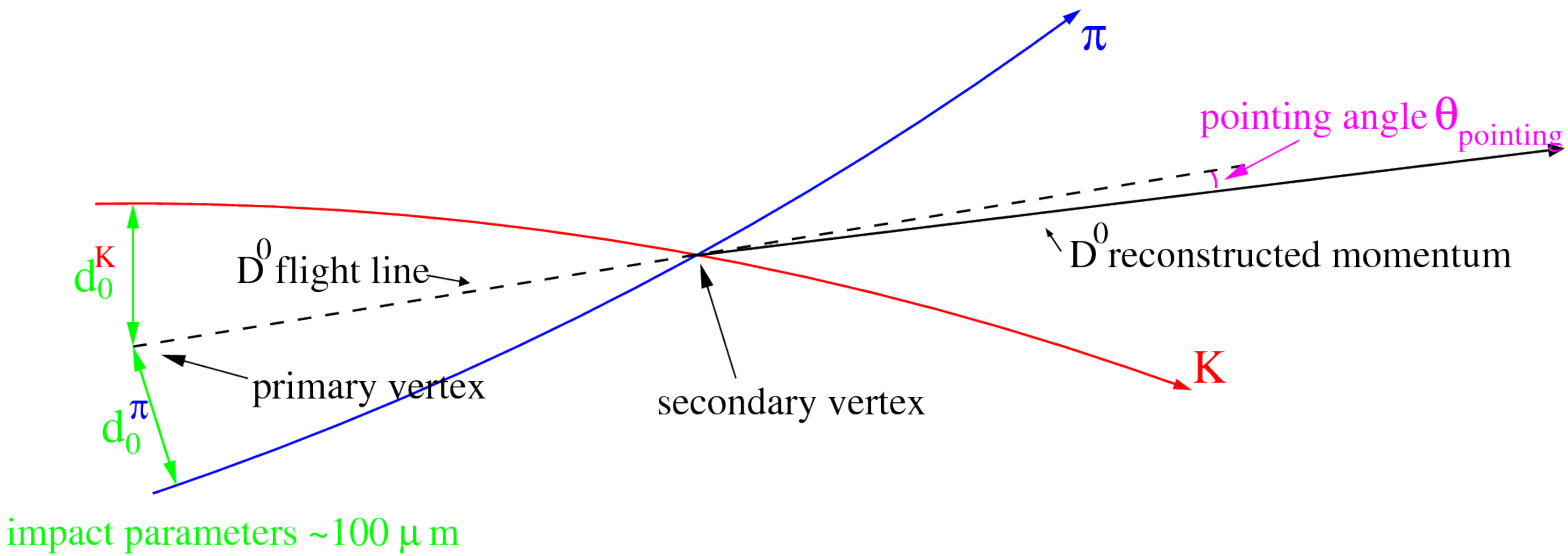


Consistent with unity:

→ charm production cross section scales with the number of binary collisions

→ consistent with charm quarks originating predominantly from initial hard scattering at RHIC

D-meson reconstruction



- Reconstruction of secondary vertices
- Particle identification
- Invariant mass analysis

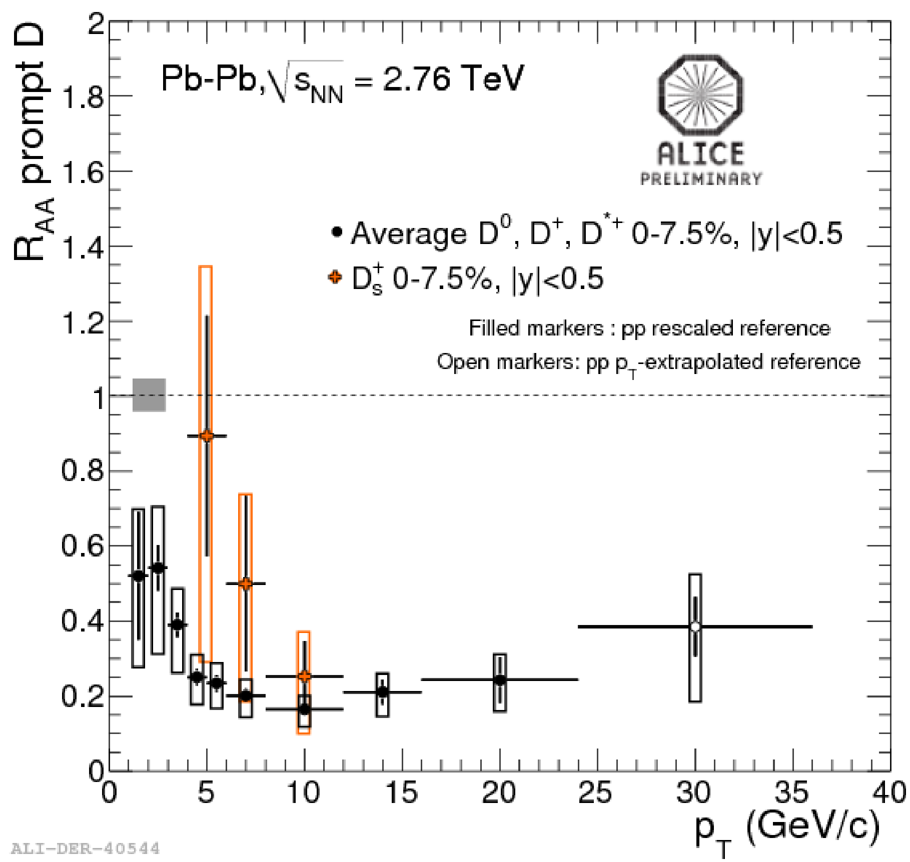
- Minimum bias data
- Mid-rapidity

Charm: D_s mesons

D^0, D^+, D^{*+} **averaged**

D_s

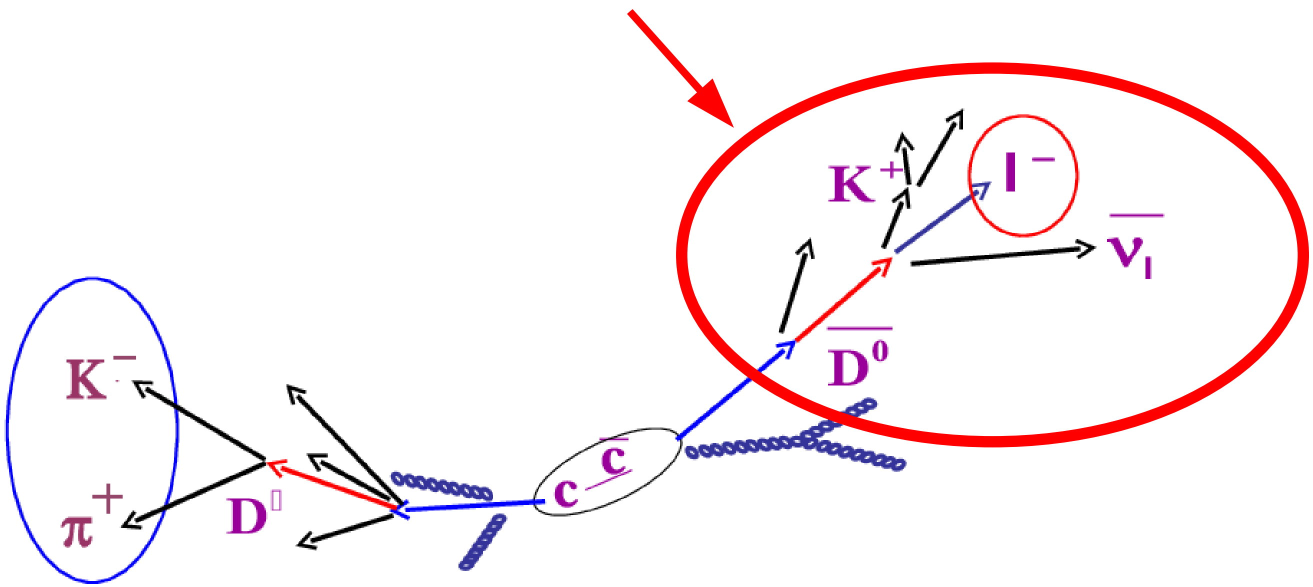
expected to be slightly different from non-strange D mesons at intermediate p_T: possible enhancement due to recombination / coalescence



Kuznetsova, Rafelski, EPJC 51(2007) 113; He et al, PRL 110(2013)112301; Andronic, PLB 659(2008)149

Semileptonic decays

Measure the $c\bar{c}$ and $b\bar{b}$ production cross sections through **semi-leptonic decays** of open charm and open beauty hadrons:



Branching Ratios:

$c \to e + X$ $\mathcal{O}$ (9.6%)

$b \to e + X$ $\mathcal{O}$ (11%)

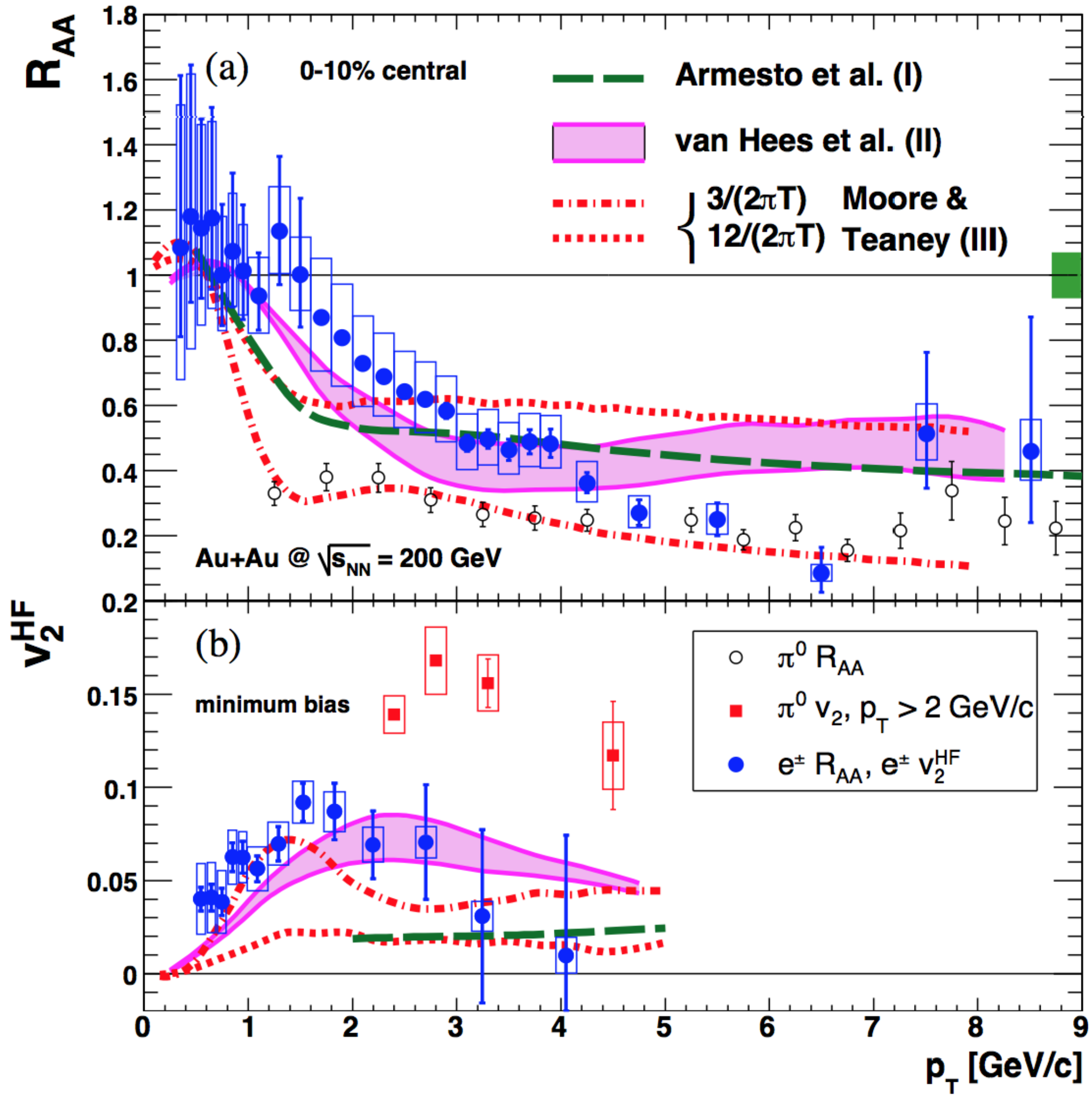
$b \to c \to e + X$ $\mathcal{O}$ (10%)

First measurement of heavy-flavor hadron suppression in HIC with this method by

PHENIX

Recent results by ATLAS and ALICE

PHENIX : semileptonic decays

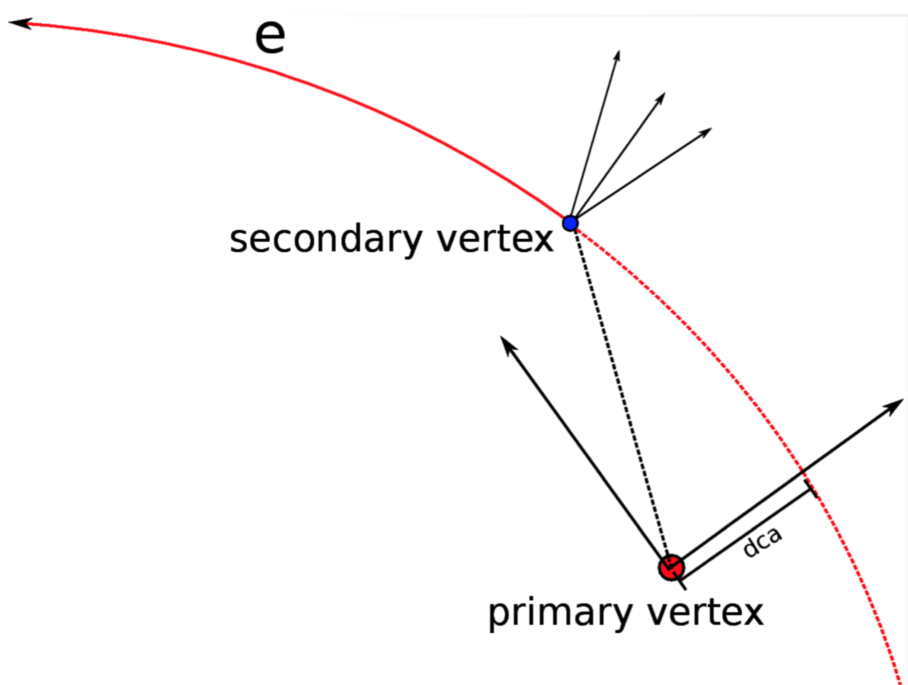


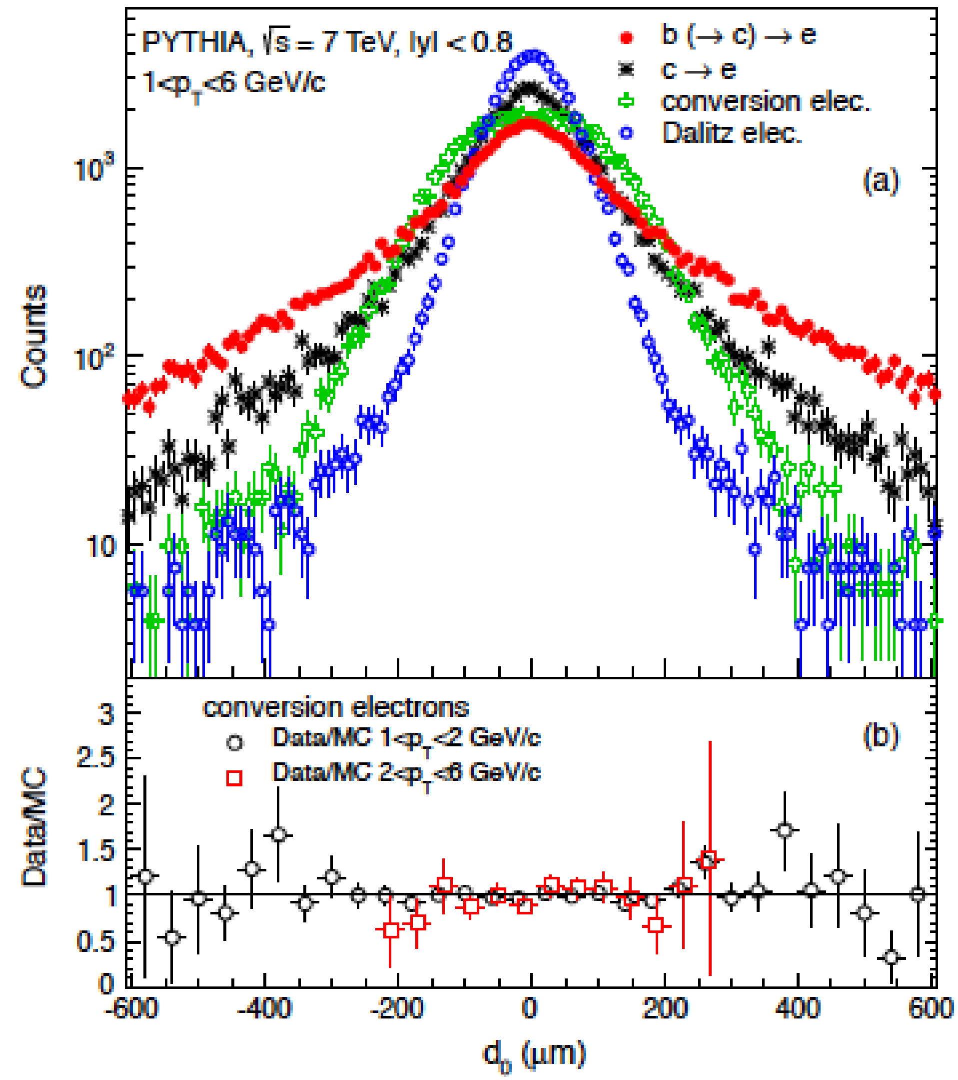
First evidence of strong suppression of leptons from heavy-flavour hadron decays, comparable to light flavours

PRL 96(2006) 032301
PRL 98(2007) 172301

Semileptonic decays: beauty

Exploit longer lifetime of beauty hadrons
→ larger **impact parameter of electrons** to the primary vertex





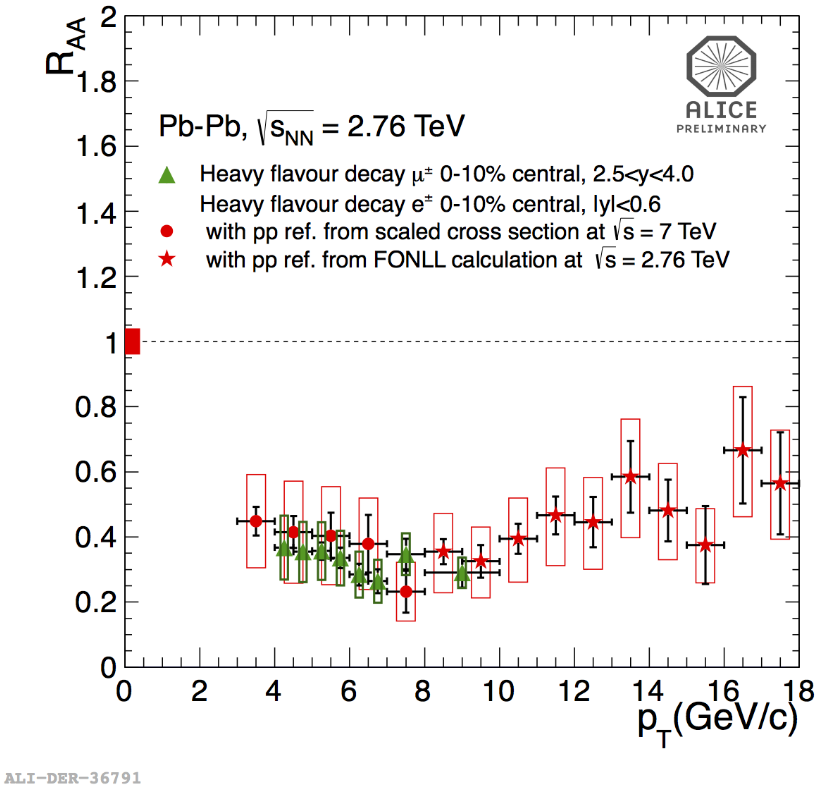
Phys.Lett. B721 (2013) 13-23

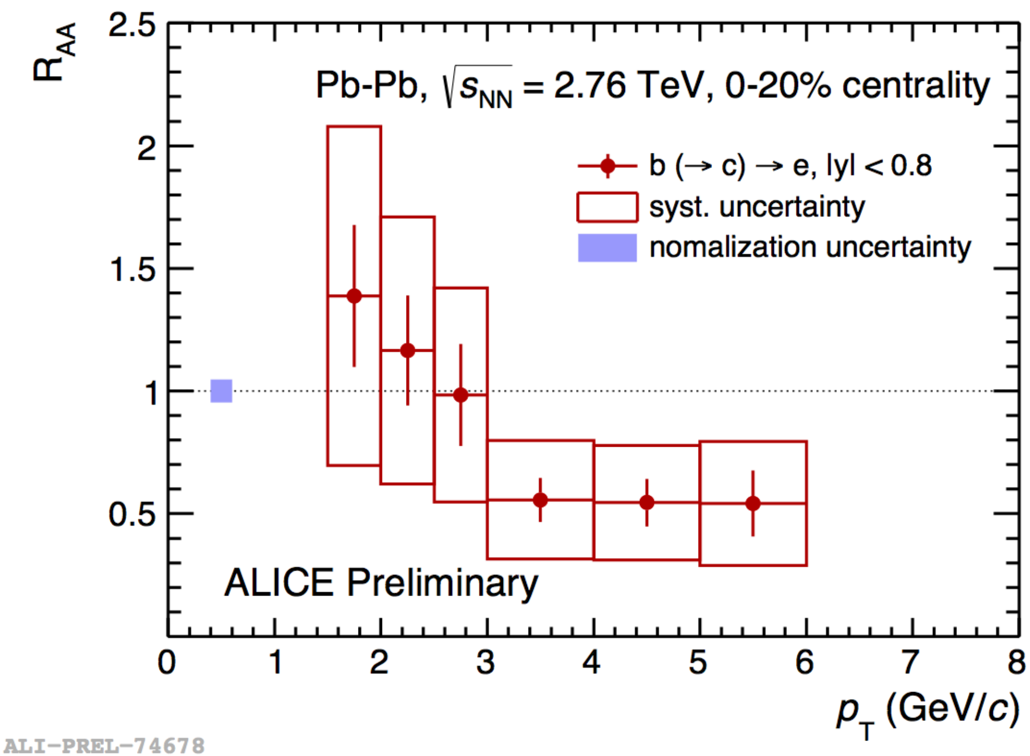
ALICE: R_{AA} of leptons from HF hadron decays

$HF_{c,b} \rightarrow \mu$ $2.5<y<4.0$

$HF_{c,b} \rightarrow e$ $|y|<0.6$

Electron at mid rapidity:
beauty R_{AA}





Suppression of leptons from charm-hadron decays, similar at mid and at forward rapidity.
Hint for suppression of beauty-decay electrons

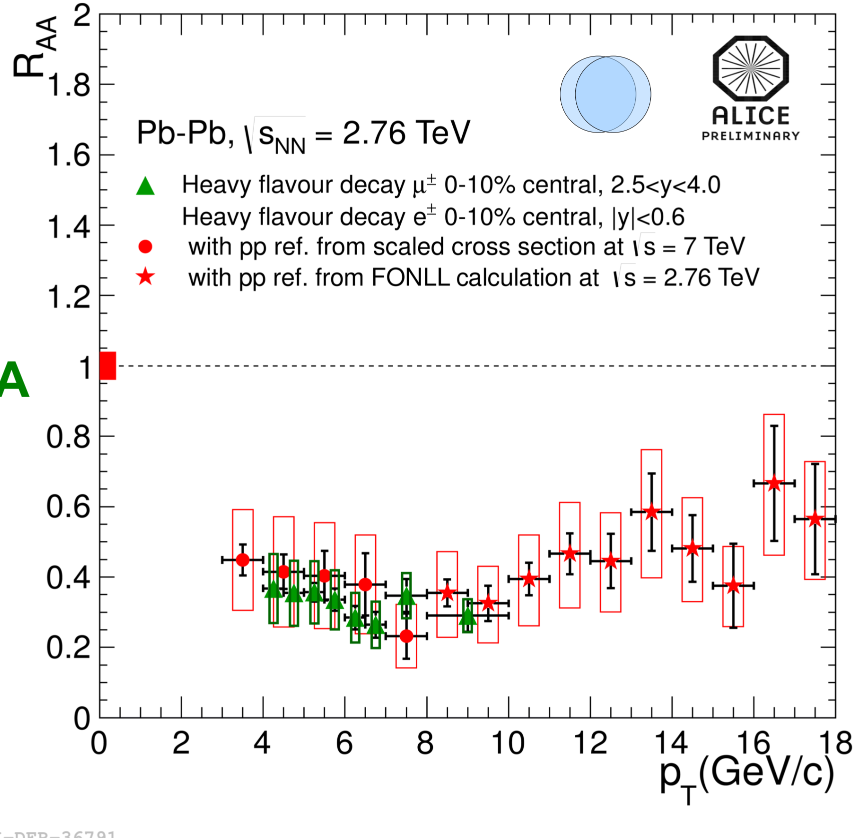
Semi-leptonic decays

c, b → lepton + X   inclusive measurements

Low p_T: background subtraction needed

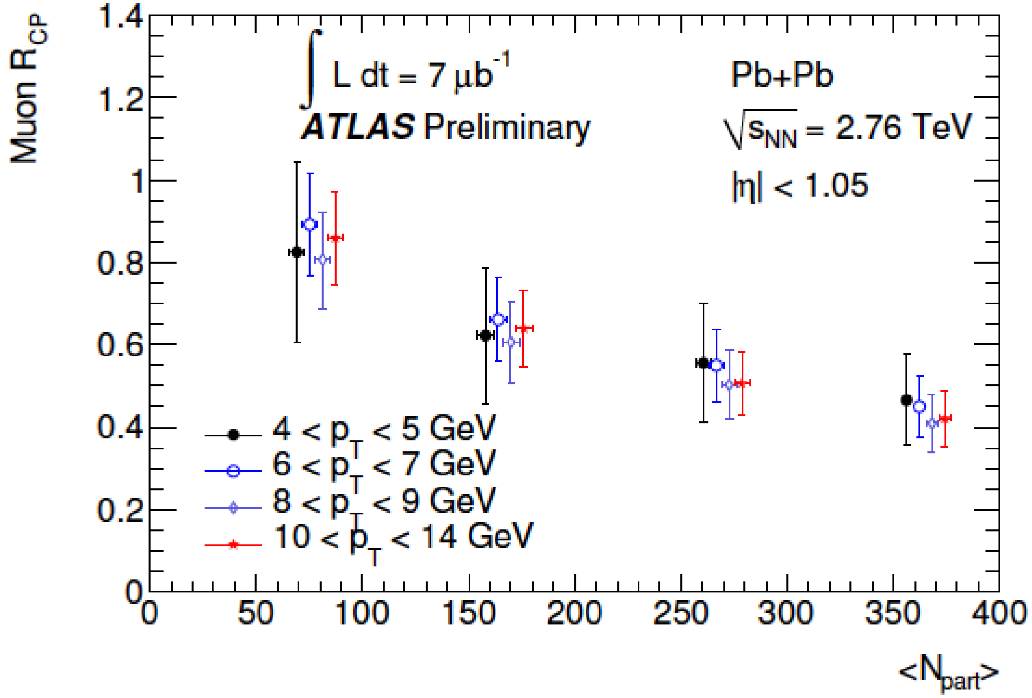
Above 4-5 GeV/c: beauty dominant

R_{AA}



R_{CP}

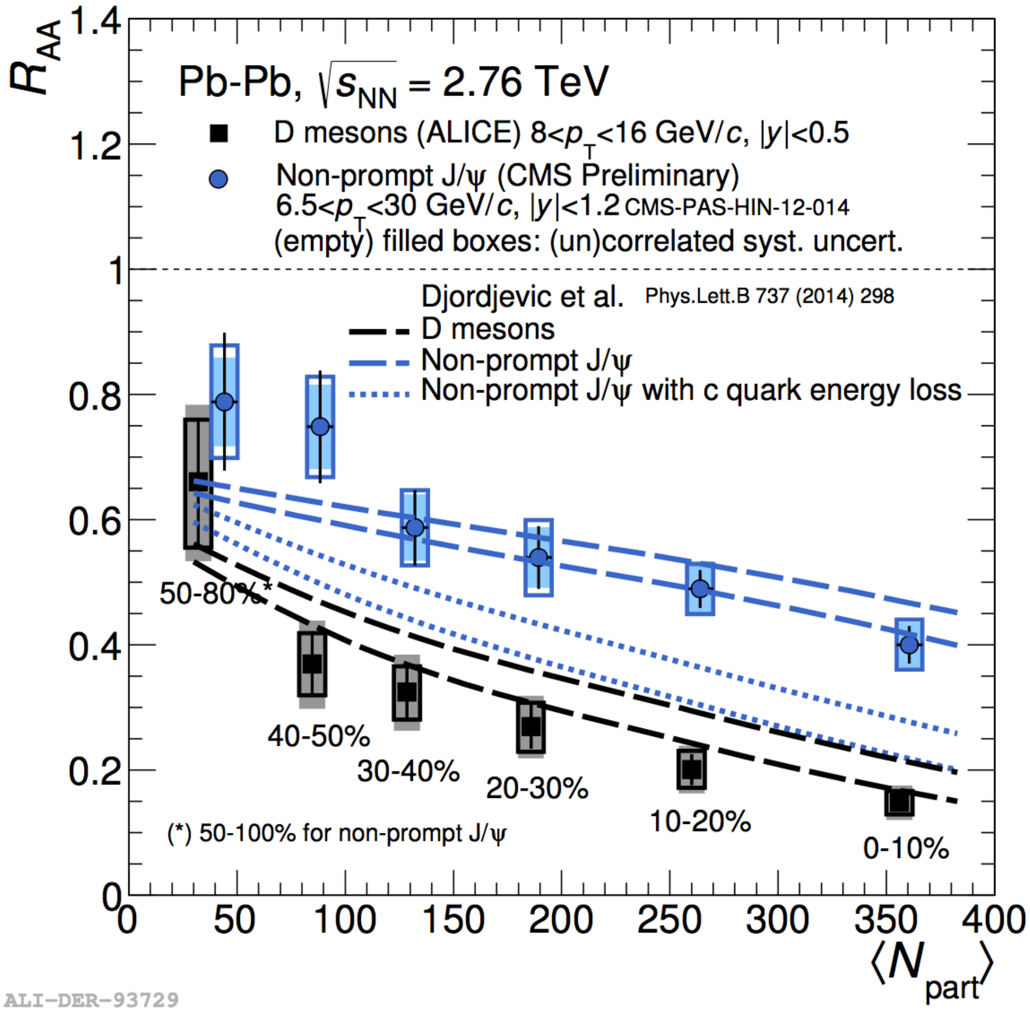
ATLAS-CONF-2012-050



Significant suppression of both charm and beauty

Mass ordering of energy loss

Charm compared to **beauty (B → J/ψ)**



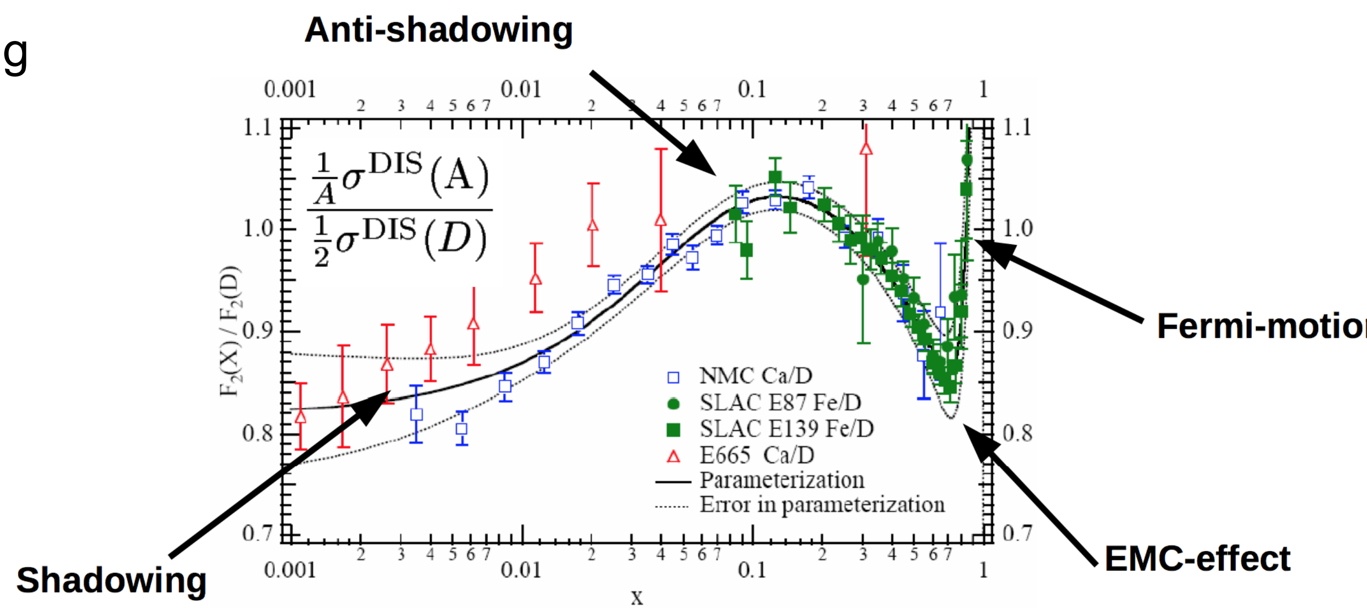
- Similar kinematic region selected
- Indication of mass ordering in central Pb-Pb collision
  $R_{AA}(D) < R_{AA}(B \rightarrow J/\psi)$
- Comparison with theoretical model based on pQCD
  Djordjevic, PL B734(2014)286

Cold-nuclear matter effects

What is the effect of having a nucleus as incoming projectile?

Modification of nuclear PDFs:

Gluon saturation/shadowing at low x, k_T-broadening, CNM energy loss ...



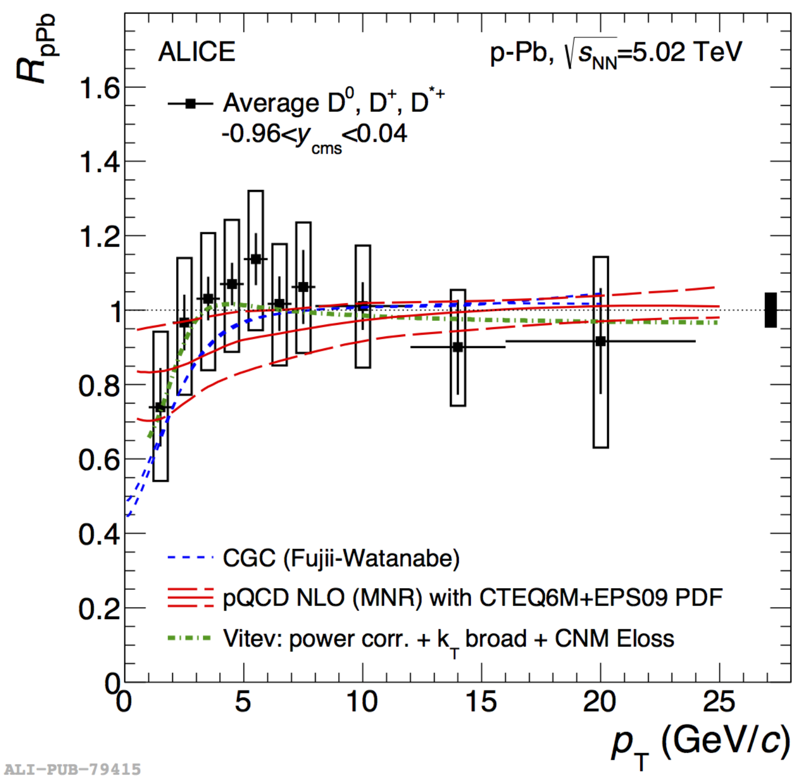
EPS90 Eskola, Paukkunen, Salgado

Investigated with p-Pb collisions to discriminate between initial-state and final-state effects ($\sqrt{s_{NN}}$ = 5.02 TeV)

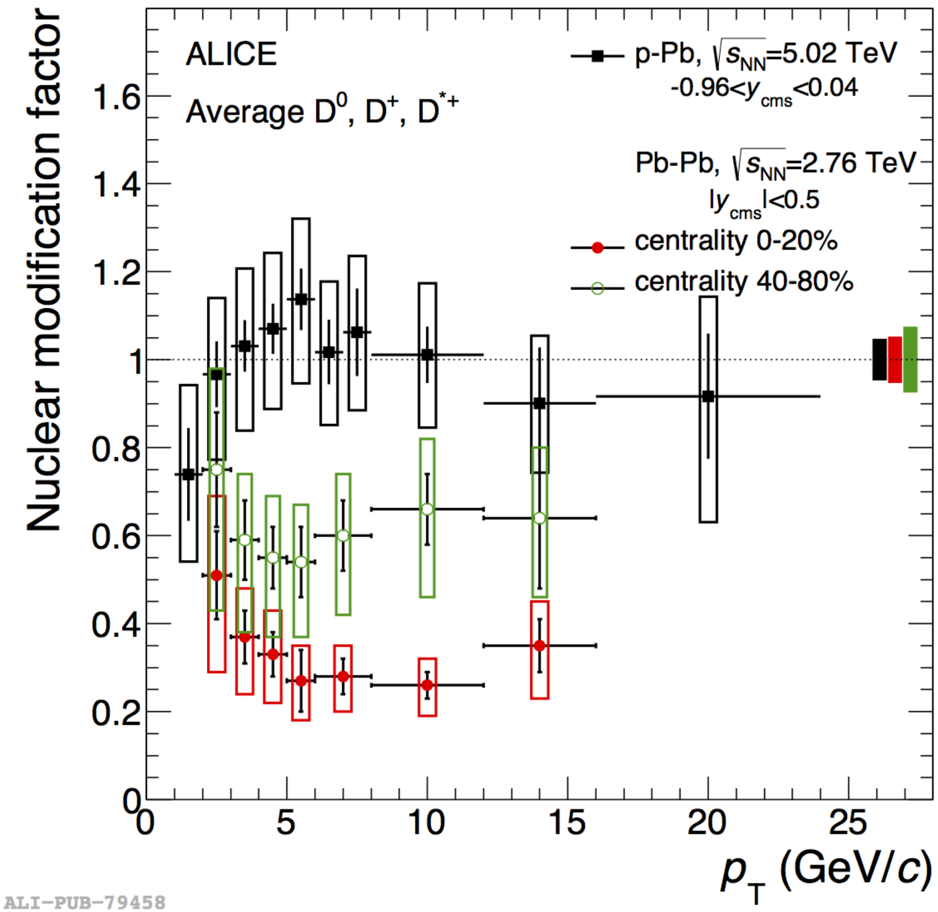
ALICE: D meson R_{pPb}

$$R_{pPb}(p_T) = \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T} \cdot \frac{1}{A}$$

PRL 113 (2014) 232301



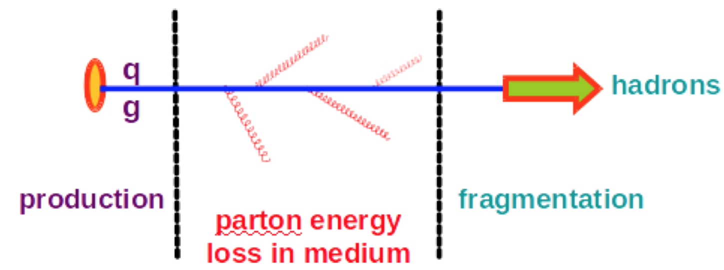
Compared to R_{AA}:



The suppression at large p_T in Pb-Pb collisions is a final-state effect

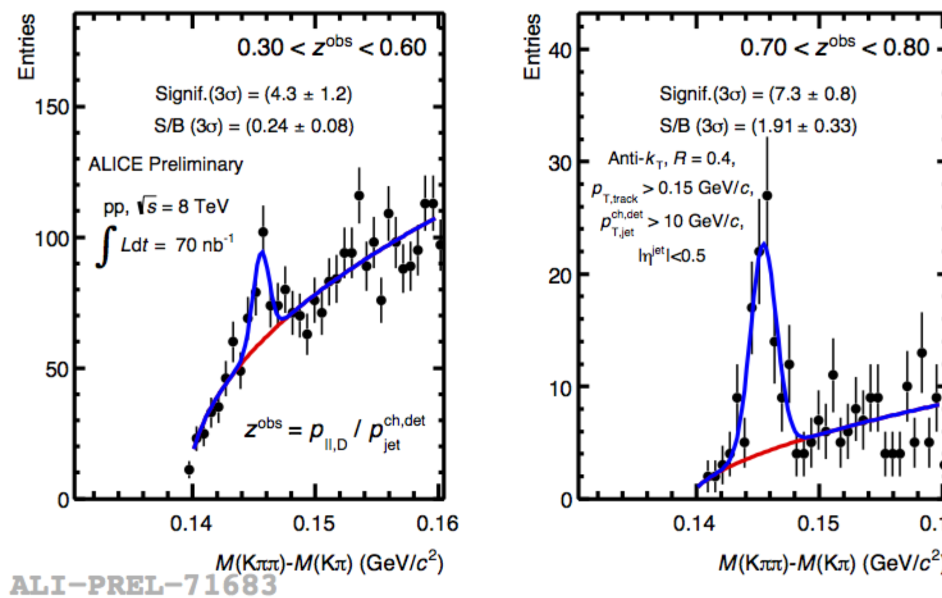
Heavy-flavor fragmentation

- Important to understand interplay between production, interaction with medium, and fragmentation



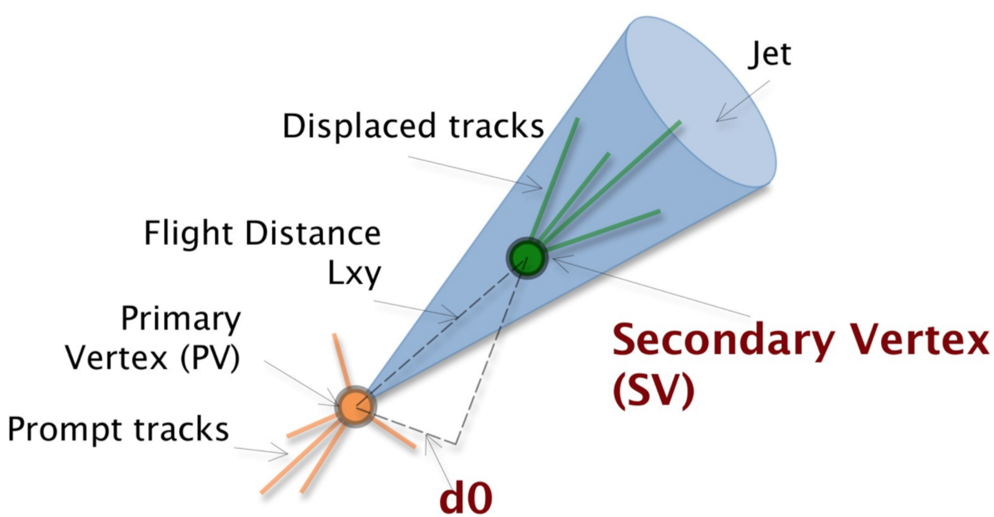
- ATLAS results on charm fragmentation in pp not described by theory at low p_T and low z PRD 85 (2012)

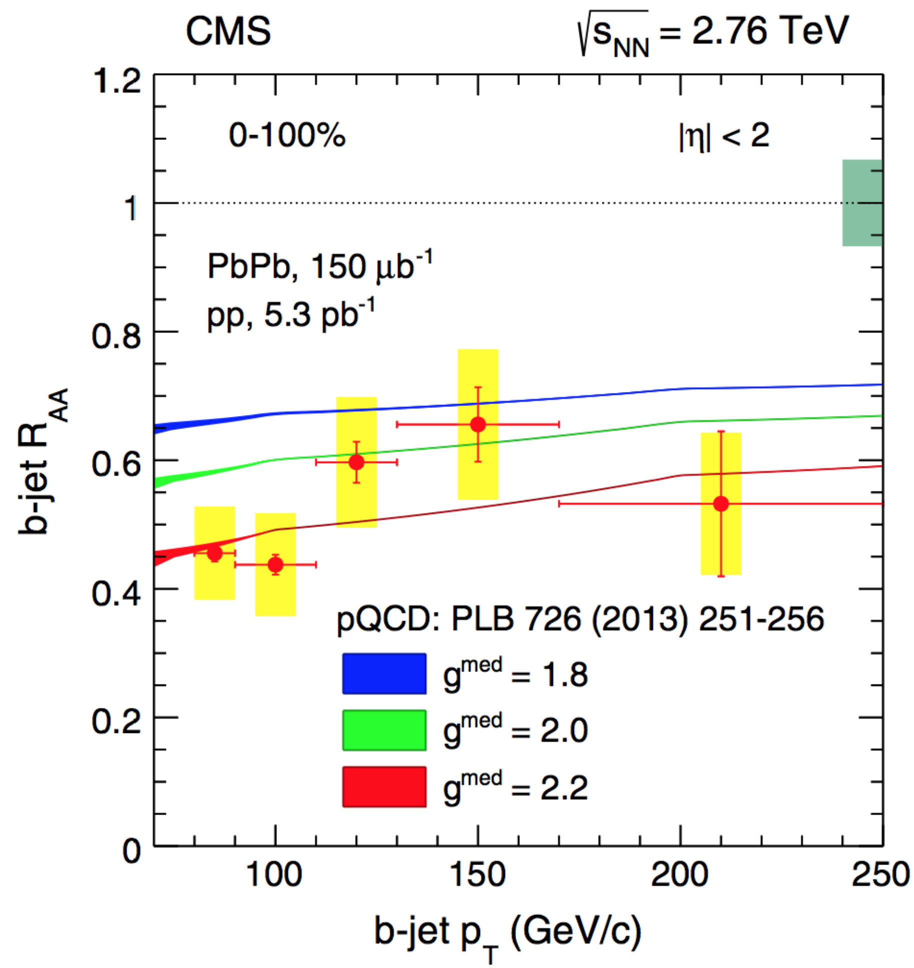
- ALICE has the best chance to address this region with low p_T coverage and particle identification
  - D^{*+} in jets
  - Important program for Run2 (statistics)



Beauty jets

- Jets tagged by their secondary vertices
- Template fits to the secondary vertex mass distribution



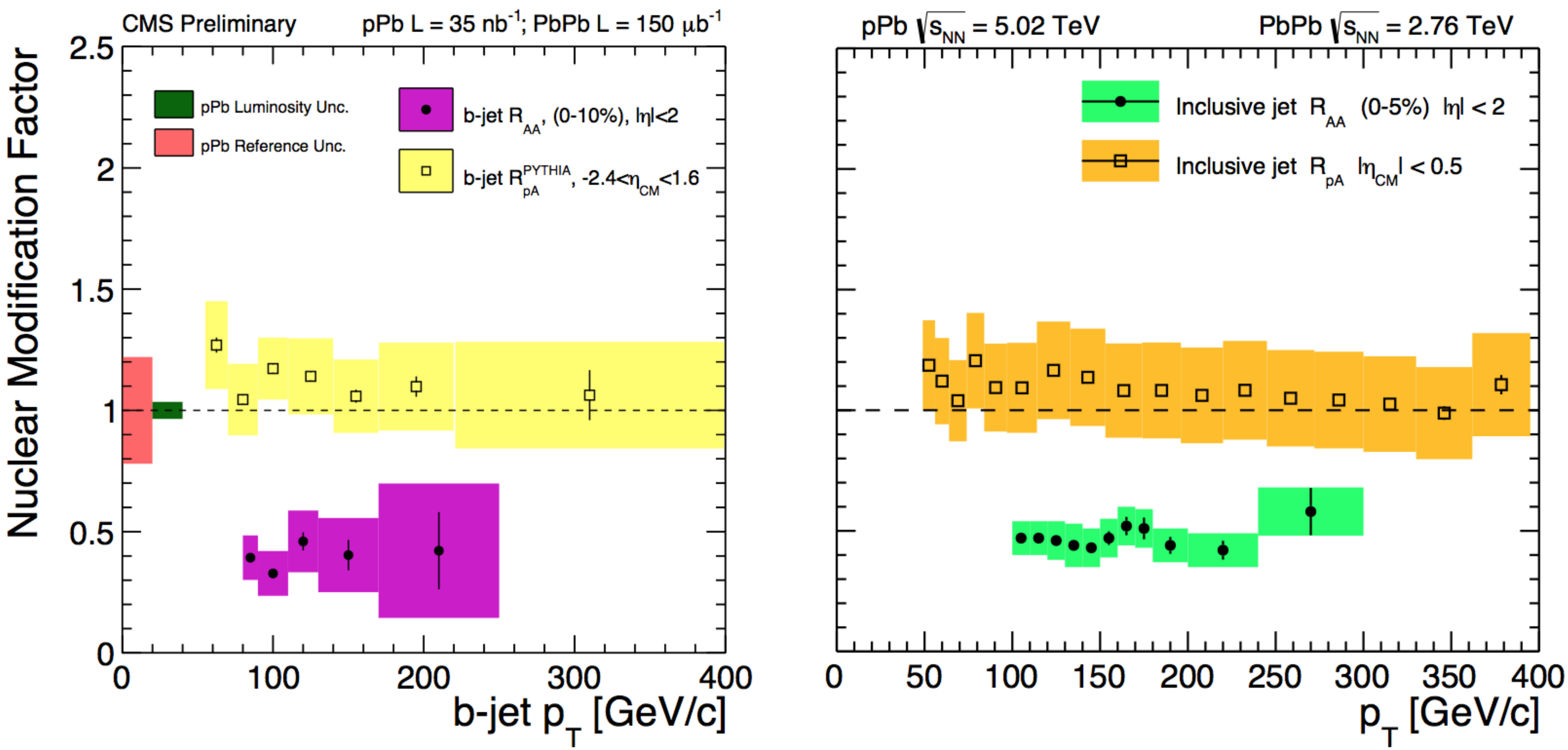


PRL 113, 132301 (2014)

Beauty and inclusive jets

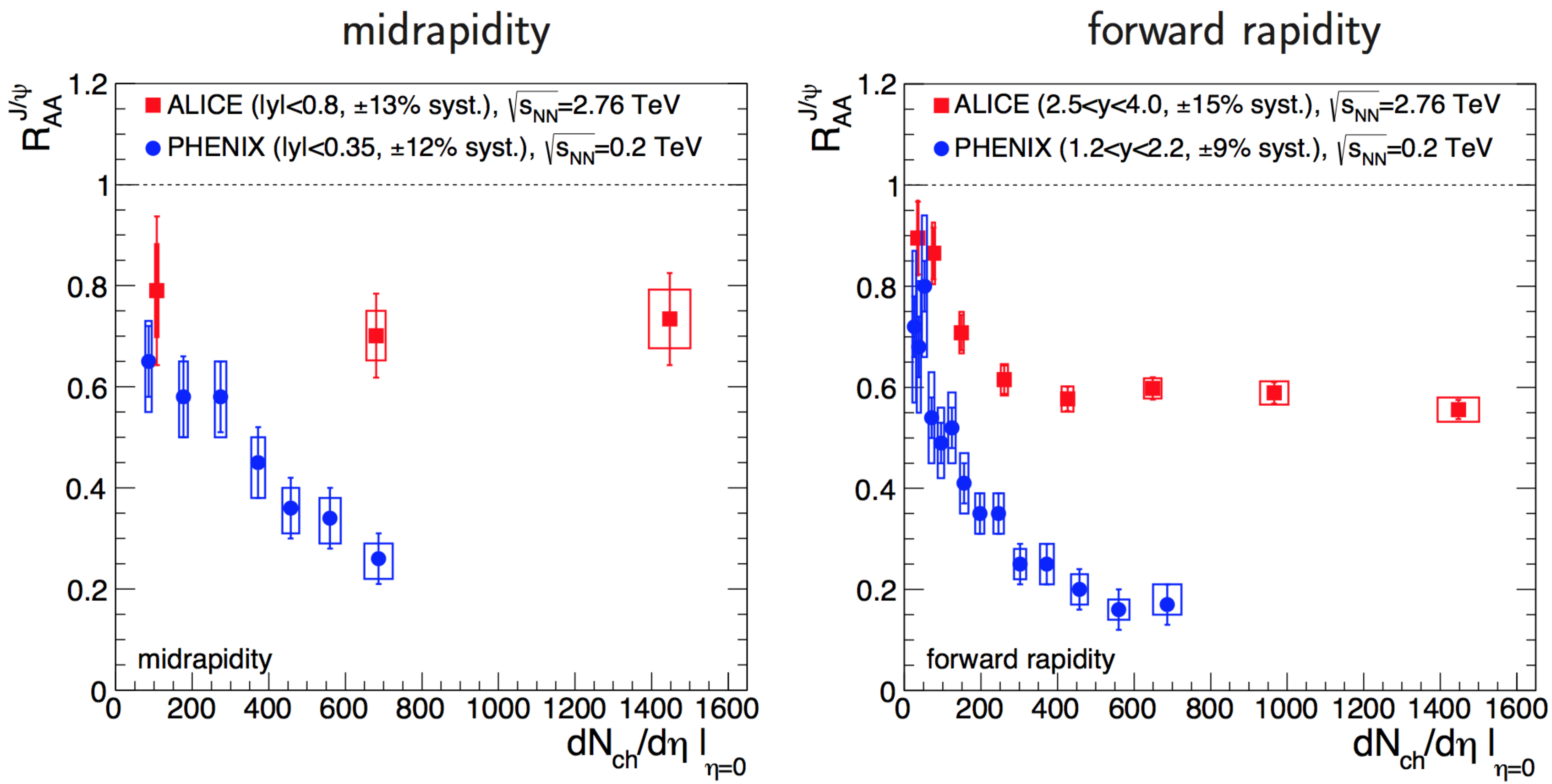
b jet: (PbPb) PRL 113, 132301 (2014)
(pA) CMS PAS HIN-14-007

Inclusive jet: (PbPb) CMS PAS HIN-12-004
(pA) CMS PAS HIN-14-001



No jet flavor dependence observed at high p_T

J/ψ production: results for $p_T \geq 0$

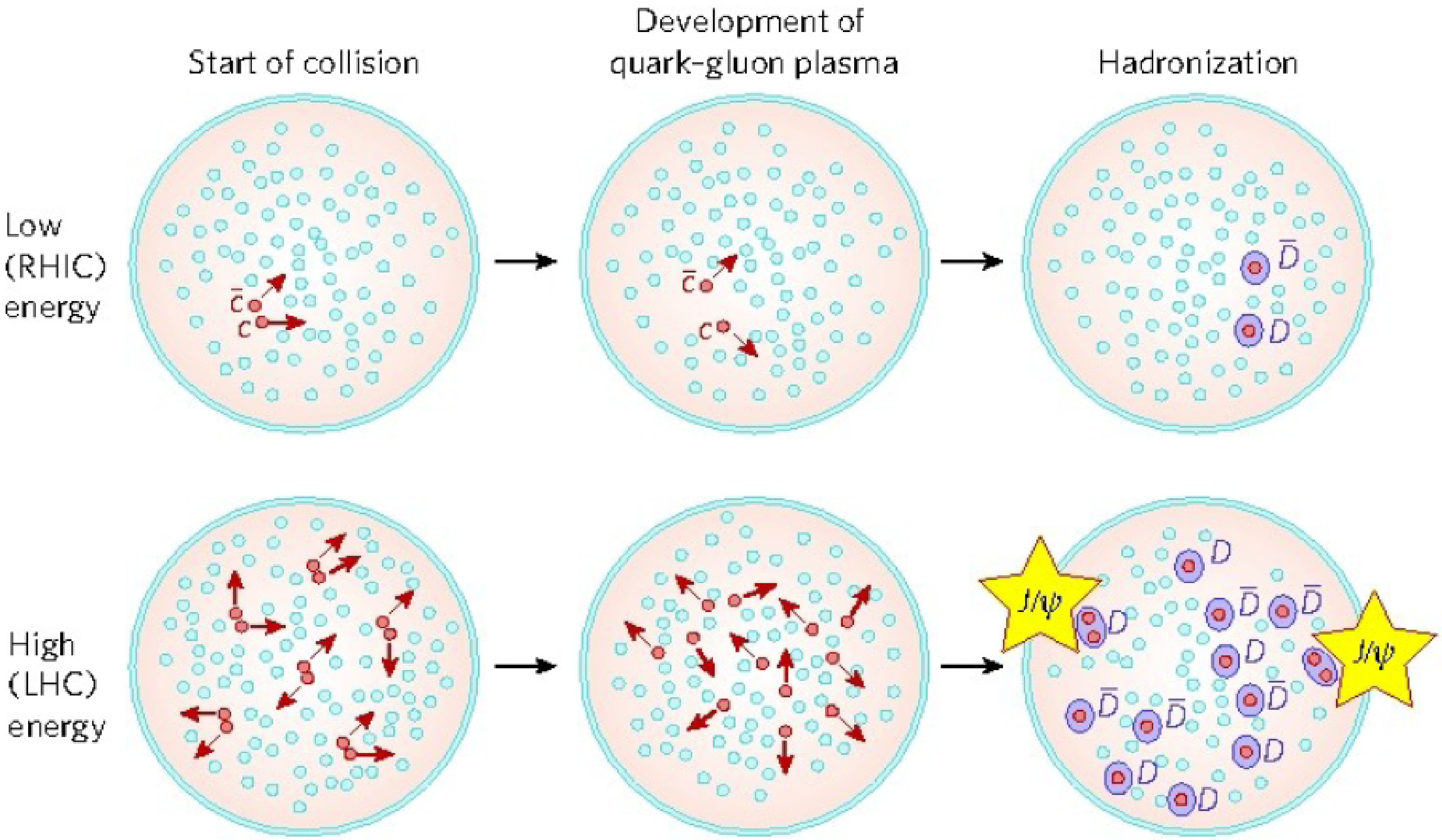


- Shown as function of energy density (proportional to dN/dη)
- ALICE compared to RHIC, PHENIX result (lower energy density)
- Higher yield at the LHC !!

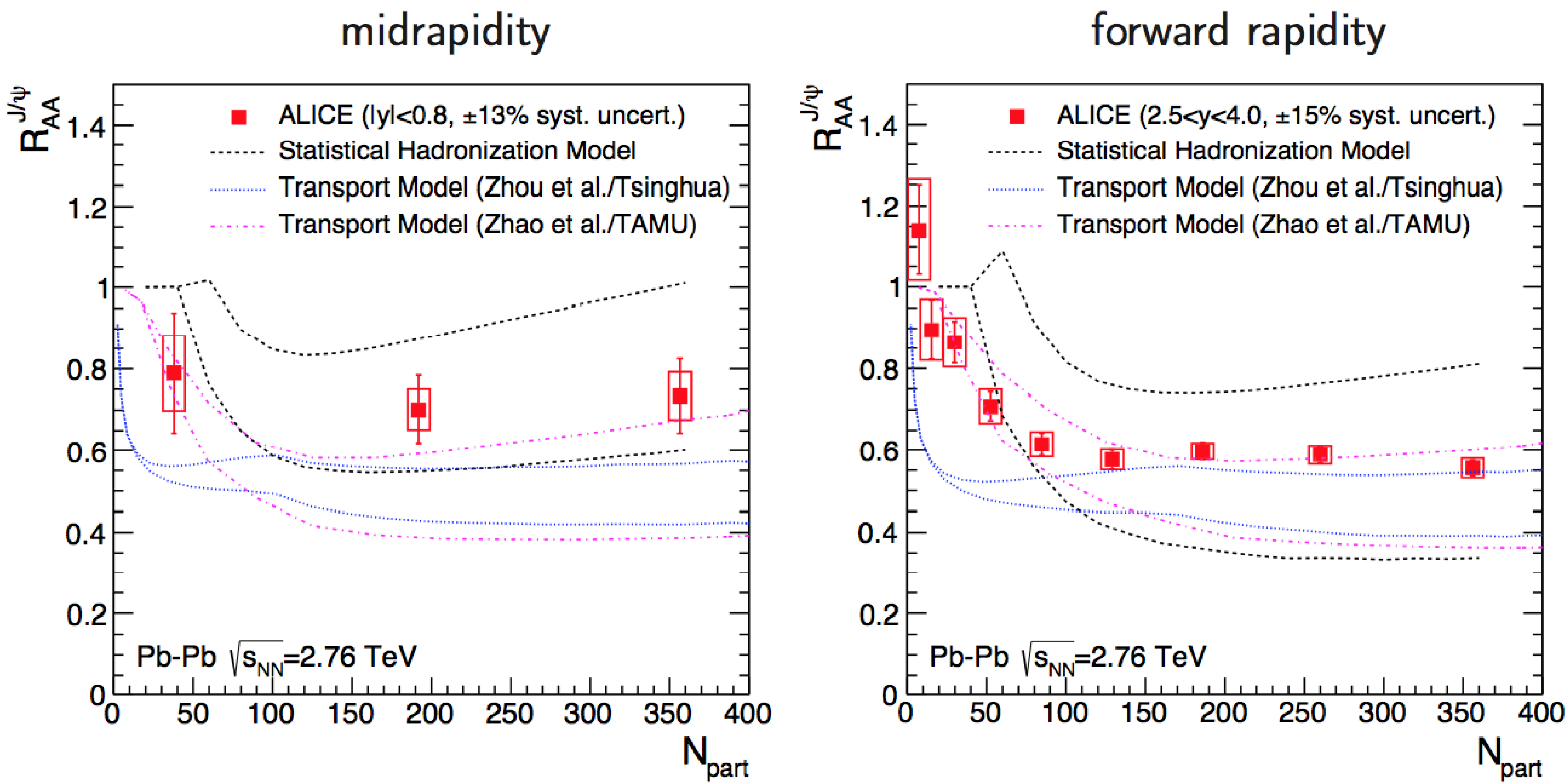
ALICE, PLB 734 (2014) 314

J/ψ production: mechanism?

can be explained by regeneration in the QGP or by statistical hadronization
→ signature of deconfinement



J/ψ: models



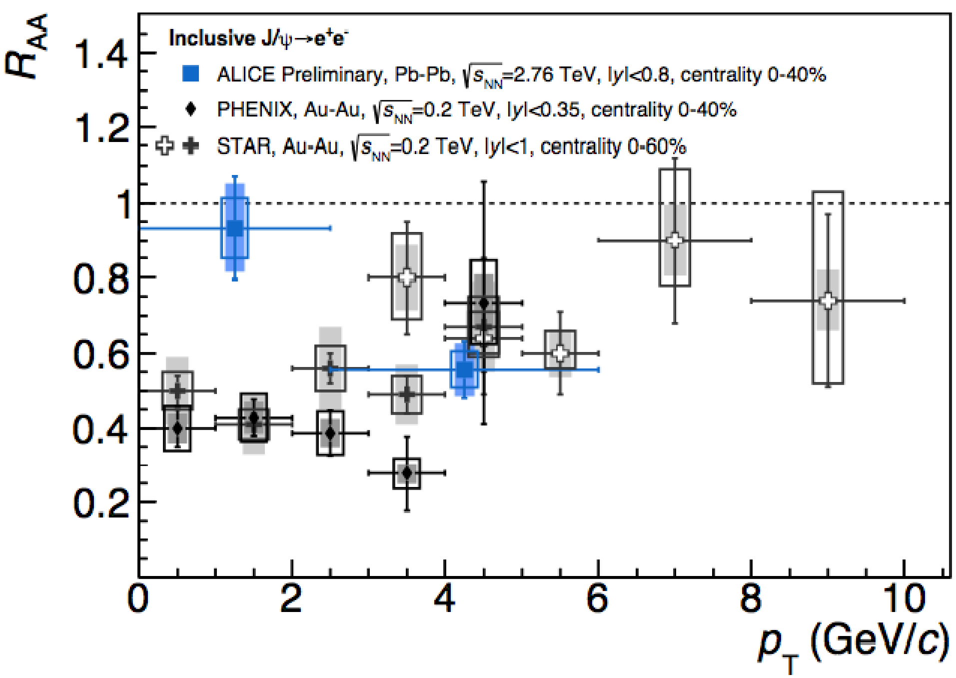
Both model categories reproduce the data ...$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ values rather different:

midrapidity: Stat. Hadr.: 0.3-0.4 mb

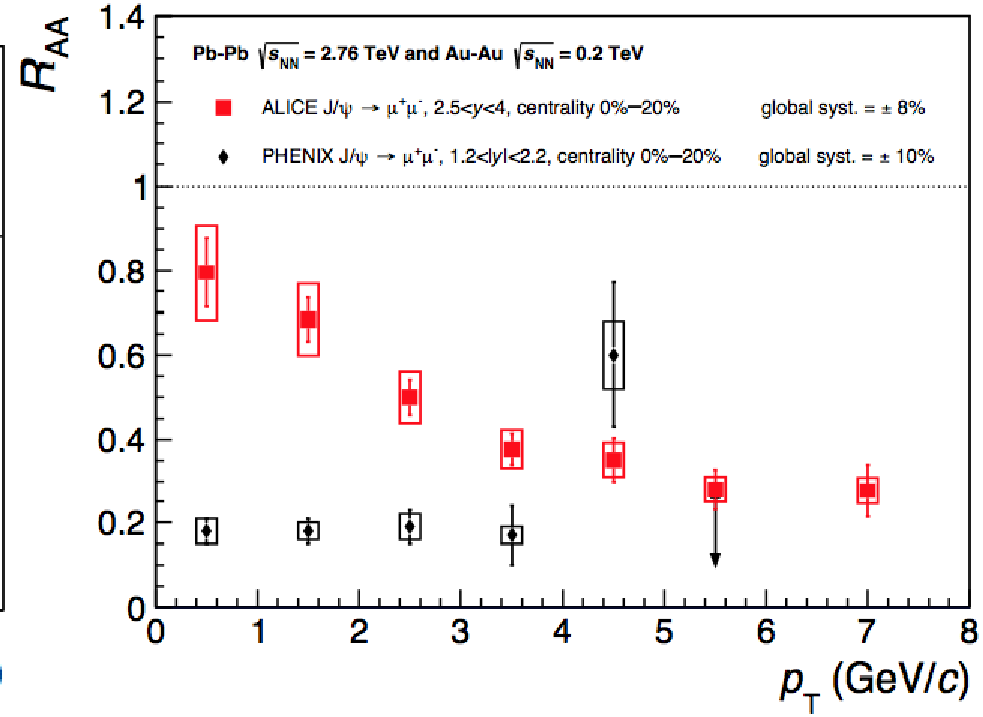
Transport: 0.5-0.75 mb (TAMU), 0.65-0.8 mb (Tsinghua)

J/ψ versus p_T

midrapidity



forward rapidity



Further support of (dominance of) a new production mechanism: (re)generation in the QGP or at chemical freeze-out

Remarks

- Heavy quarks are excellent probes of strongly-interacting matter produced in heavy-ion collisions
- Heavy quarks are interacting with the dense medium and being significantly slowed down, by collisional and radiative energy loss
- Flow measurements hint at participation of charm to the collective motion of the medium
- Important theoretical work needed now, to provide coherent description of observables and extract fundamental properties of the QGP

Theory references - Pb-Pb

- QCD-based models with in-medium radiative/collisional energy loss
  - Dokshitzer, Kharzeev, PL B519(2001)199
  - Armesto et al., PRD 69(2004)114003
  - Djorjevic et al., NP A783(2007)493

- Mass hierarchy of parton energy loss included
  - Djorjevic, PL B734(2014)286
  - Wicks et al., NP A872(2011)265

- More
  - BAMPS, JPG 38(2011)124152
  - WHDG, JPG 38(2011)124114
  - Vitev et al., PR C(2009)054902

Theory references - Pb-Pb

- Description of R_{AA} and v_2
  - TAMU elastic: PL B735(2014)445
  - Djordjevic: PL B734(2014)286
  - Cao, Qin, Bass: PR C88(2013)044907
  - WHDG rad+coll: NP A872(2011)265
  - MC@sHQ+EPOS: PR C89(2014)014905
  - Vitev, rad+dissoc: PR C80(2009)054902
  - POWLANG: JP G38(2011)124144
  - BAMPS: PL B717(2012)430