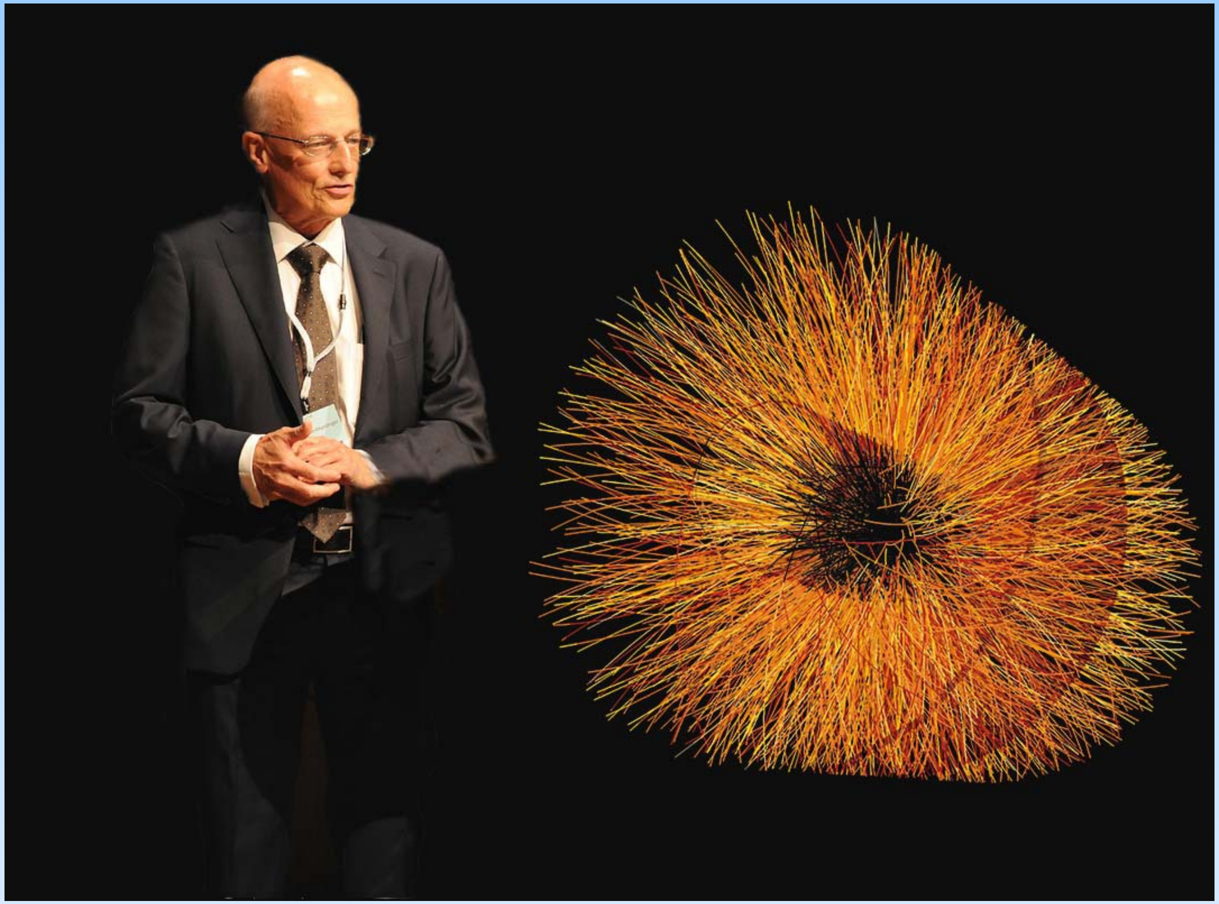


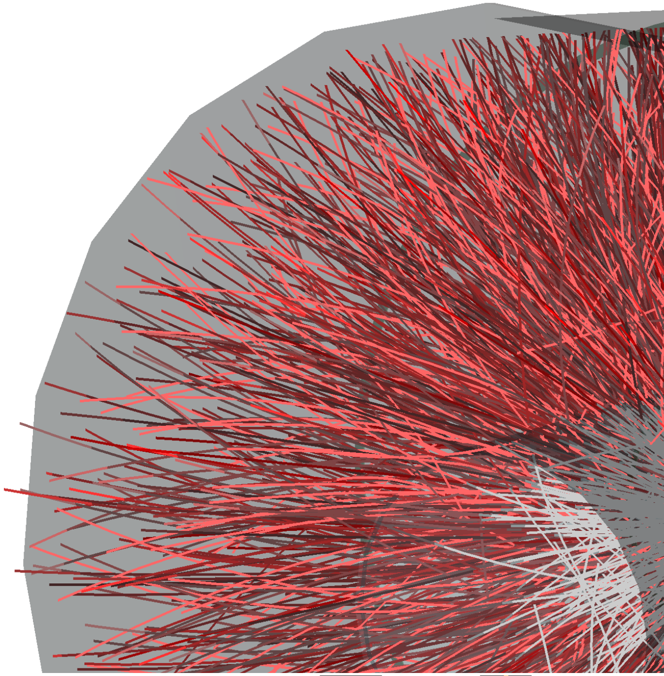
Charm and beauty in QGP physics

Silvia Masciocchi, GSI

Schloß Waldthausen, August 26, 2016

Outline

- Personal introduction: the importance of heavy flavors
- Open heavy flavors
- Charmonium
- Looking back: personal summary
- Looking ahead



My personal introduction

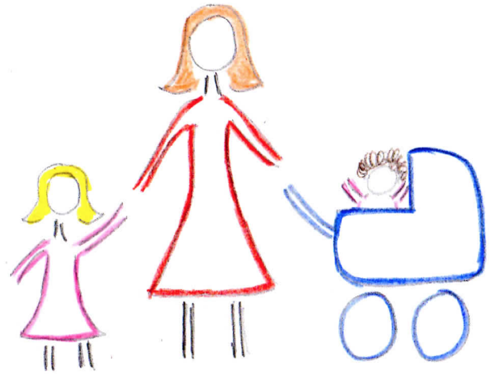
Or better:

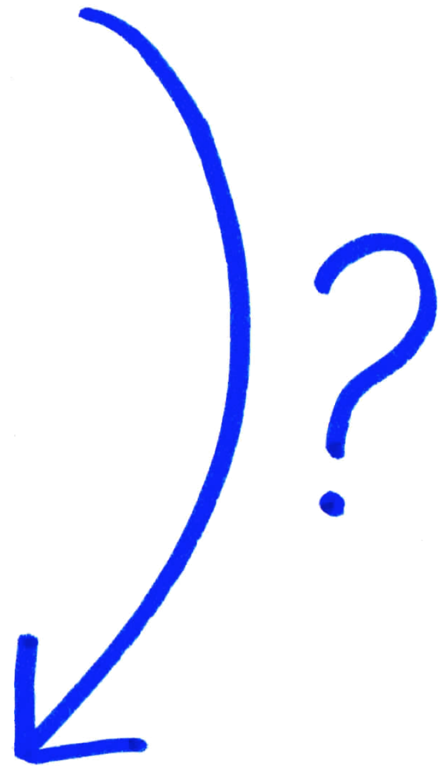
- How did Peter's and my ways crossed
- What is the importance of heavy flavors

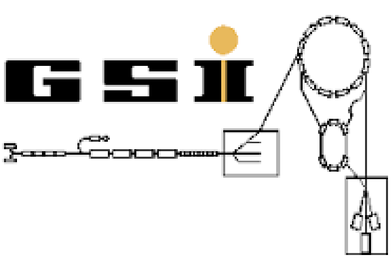
We need to go back to 2005 .....

My personal introduction

2005

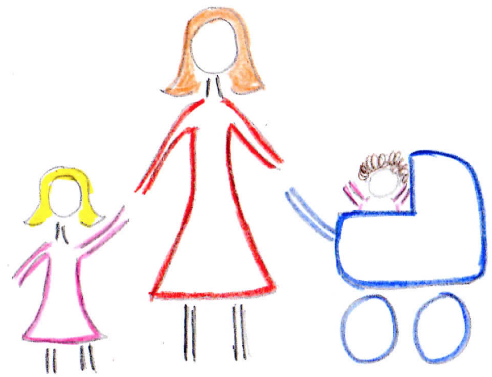


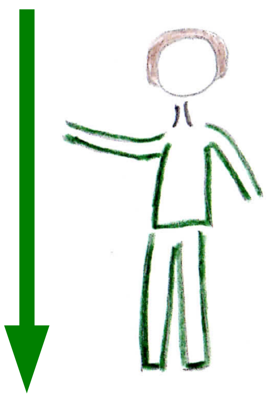


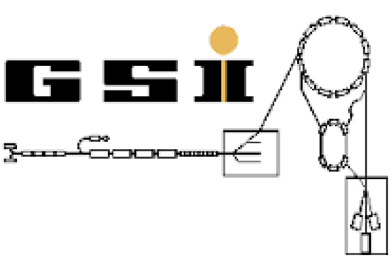


My personal introduction

2005

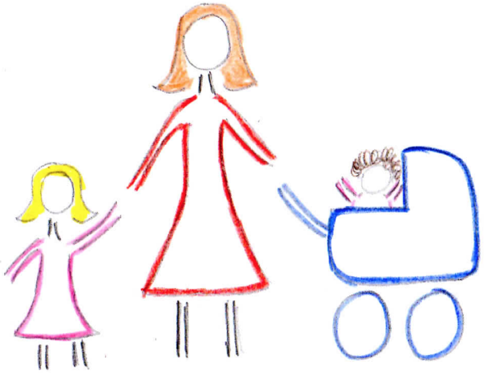


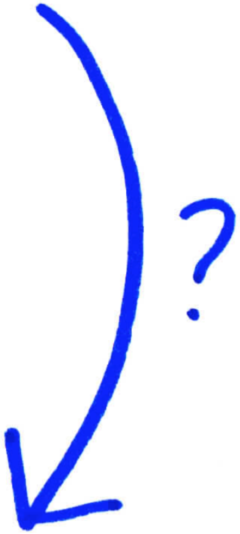


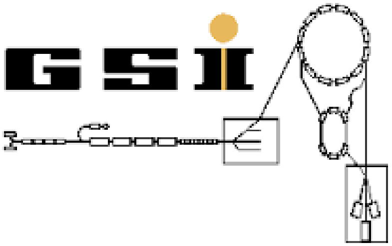


My personal introduction

2005

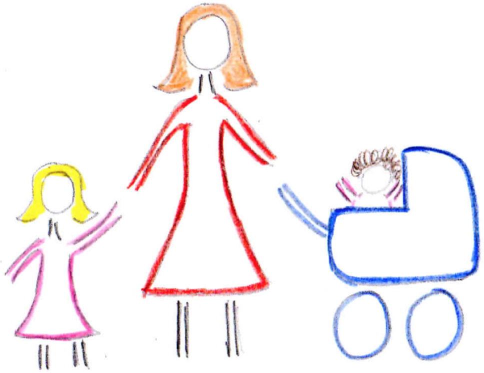




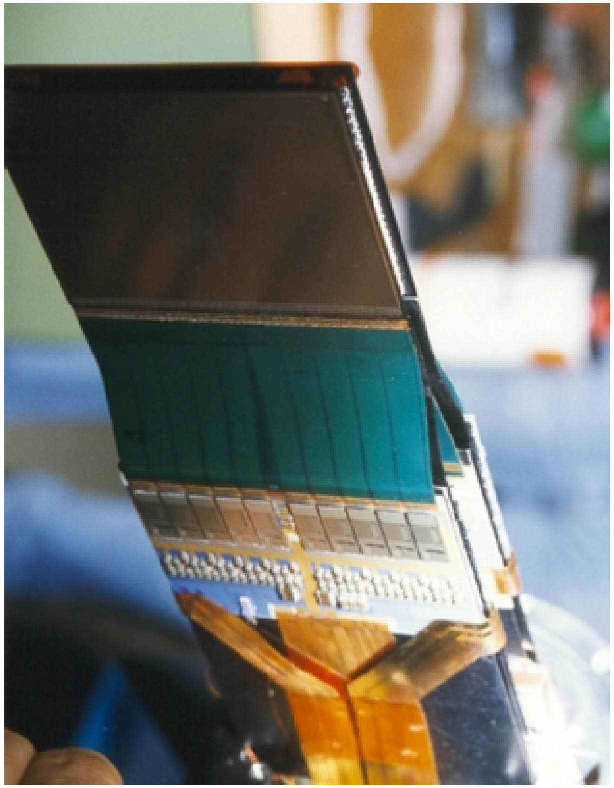


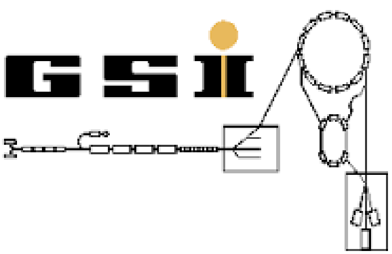
My personal introduction

2005



Silicon in the GSI detector lab

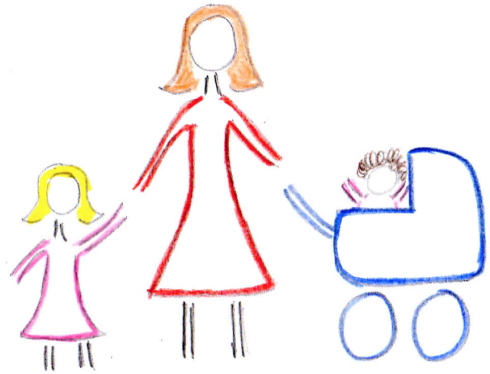




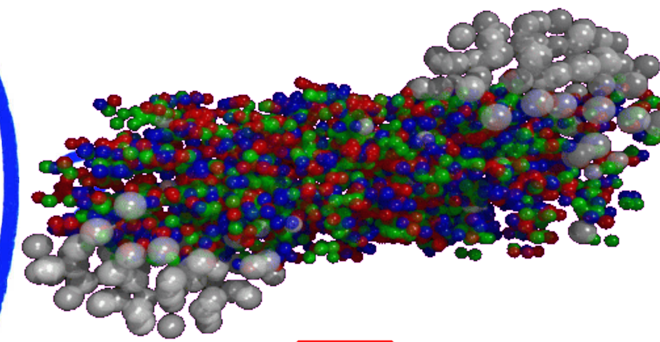
or ???

My personal introduction

2005

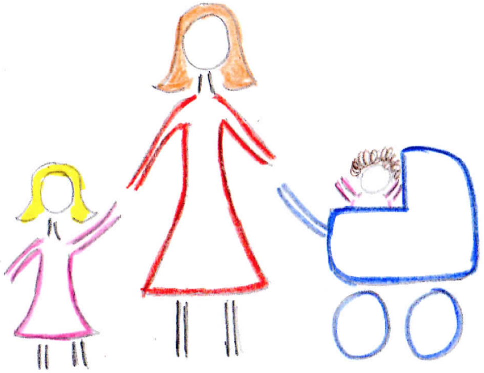


Heavy ion physics in ALICE



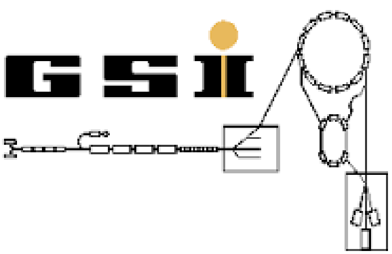
My personal introduction

2005



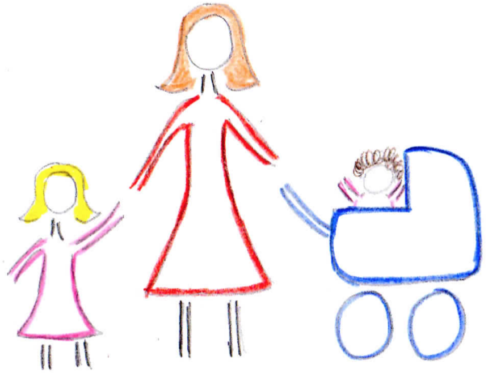
Heavy ion
physics in ALICE

… really ???



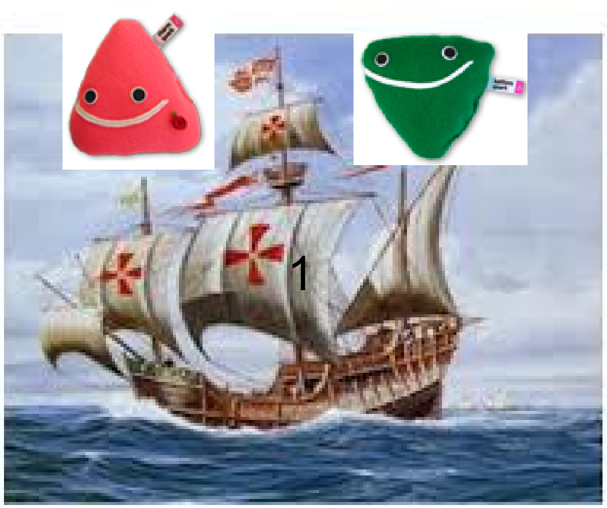
My personal introduction

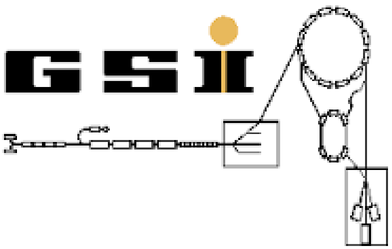
2005



Heavy ion
physics in ALICE

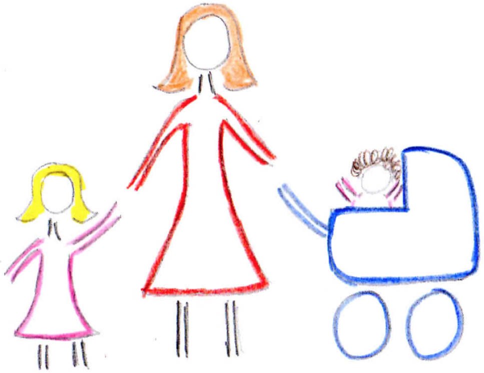
… heavy flavors in QGP,
charm and beauty!





My personal introduction

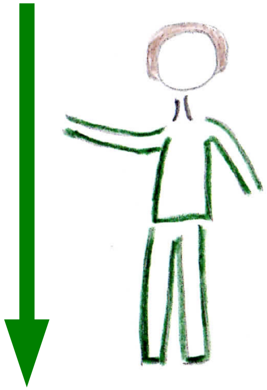
2005



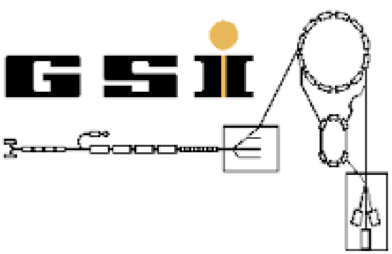
Heavy ion physics in ALICE

Heavy flavors

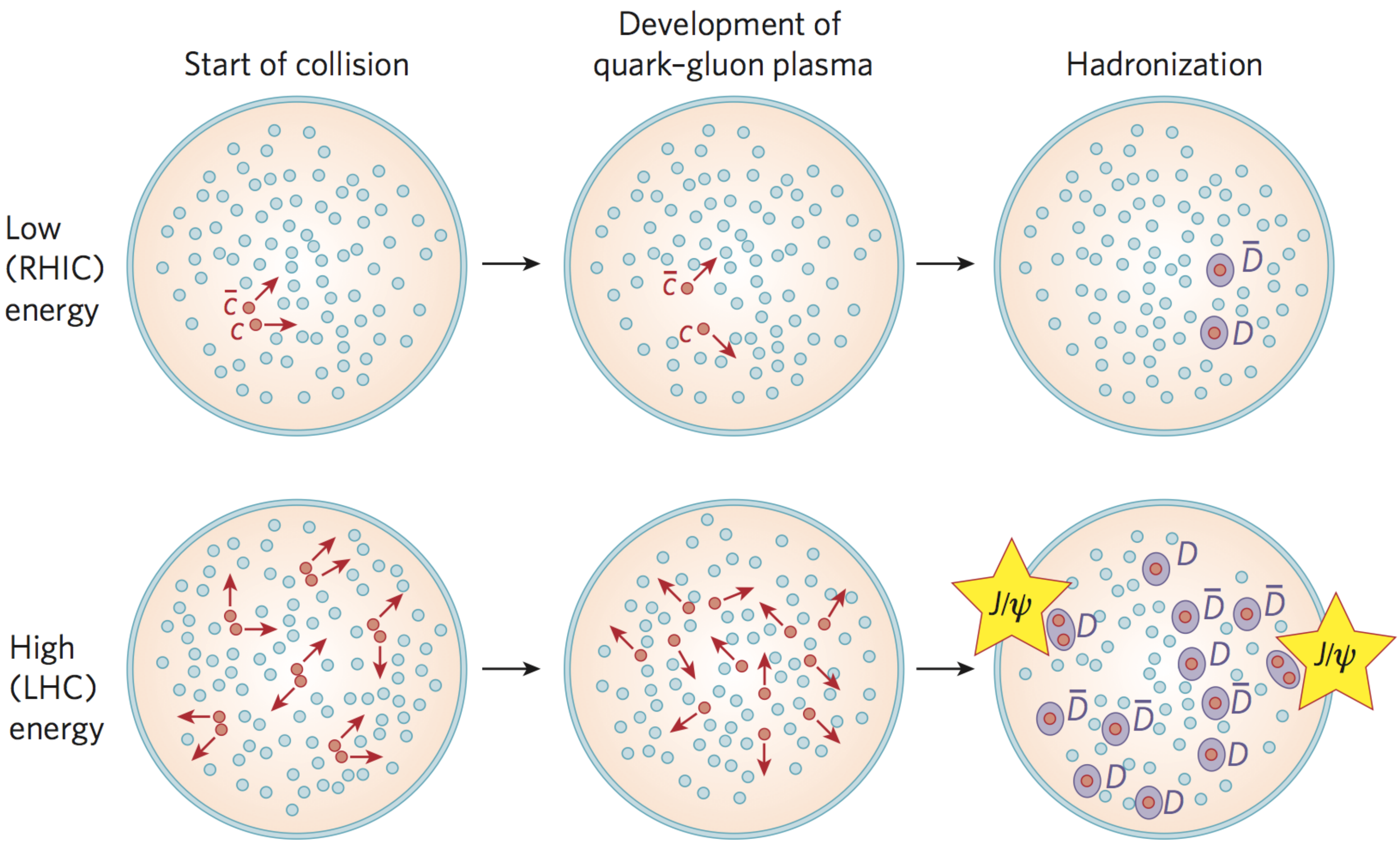
charm, beauty,
J/ψ, Λ_c, Λ_b



... rose e fiori ...



(Scientific) introduction



PBM and J. Stachel, Nature vol. 448 (2007) 302

Outline

Heavy flavors ...
… at the LHC, focusing on ALICE:

- Open heavy-flavor production in hadronic collisions
- Charm and beauty as probes of the QGP:
  energy loss, thermalization
- Quarkonium in the $\sqrt{s_{NN}}$ ~ TeV regime
  Probe of the phase boundary

Heavy quarks: charm and beauty

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

Charm:
m ~ 1.5 GeV/c^2

Beauty:
m ~ 5 GeV/c^2

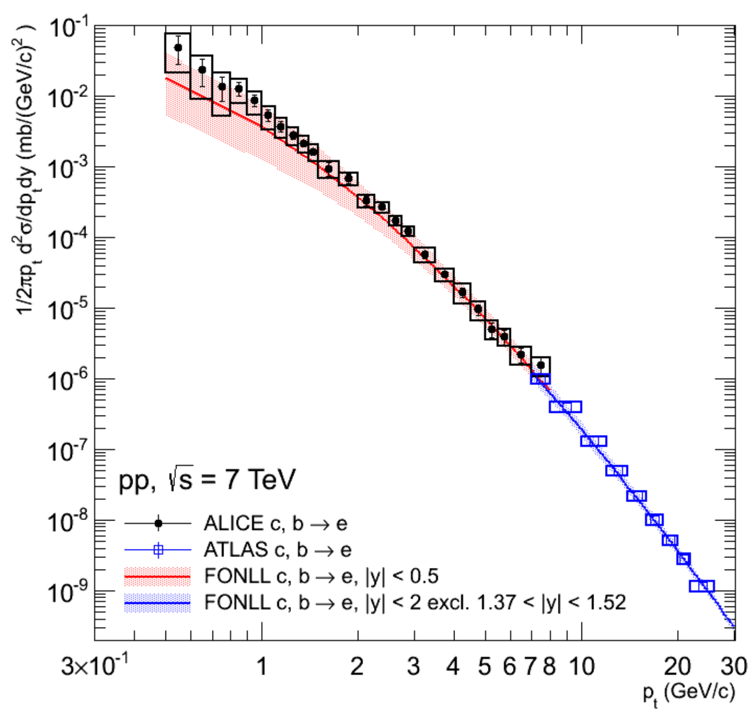
Hard probes even at low momentum

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

e.g. FONLL, GM-VFNS, ...

Theory: very large uncertainties

Proton-proton measurements have better precision → "some" input to theory ?



ALICE: Phys.Rev. D86 (2012) 112007
ATLAS: Phys.Lett. B707 (2012) 438

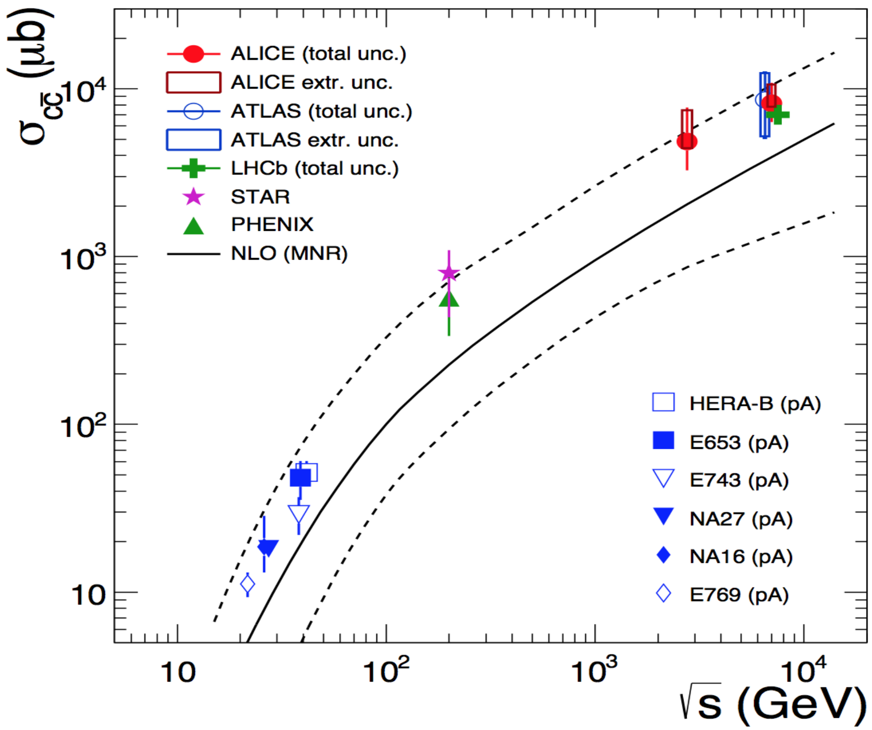
Total(*) cross section in proton-proton

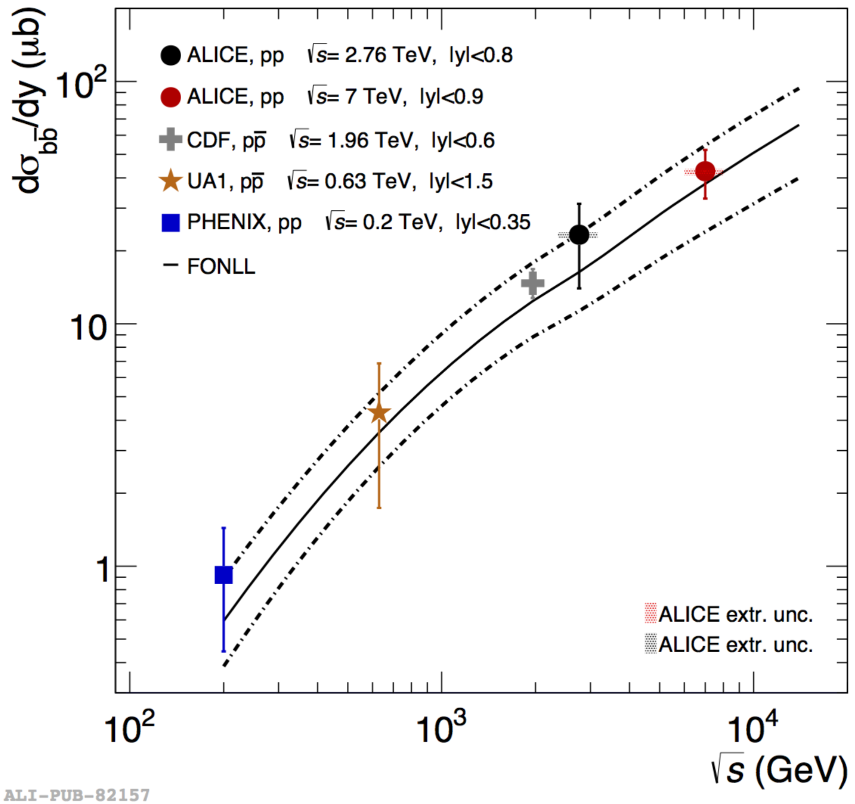
LHC energies: large production cross sections!

Charm

Beauty

arXiv:1605.07569





PLB 738 (2014) 97

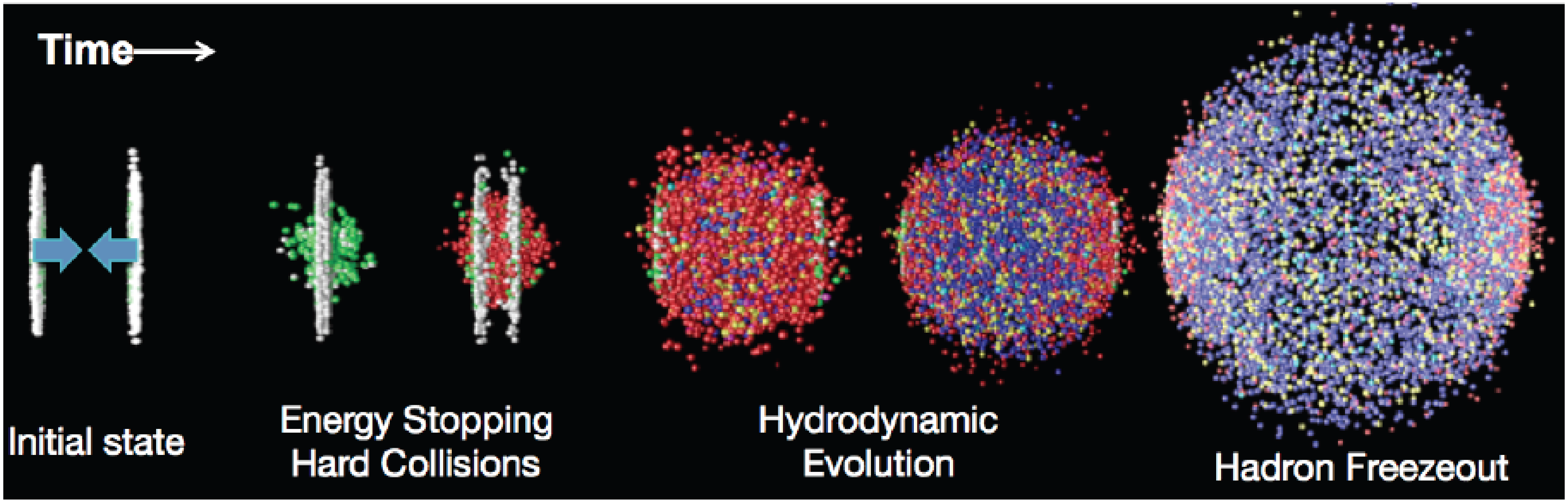
Abundant hard probe at the LHC!

(*) integrated over y and p_T

pQCD: large theoretical uncertainties

Ultra-relativistic heavy-ion collisions

Collision phases:



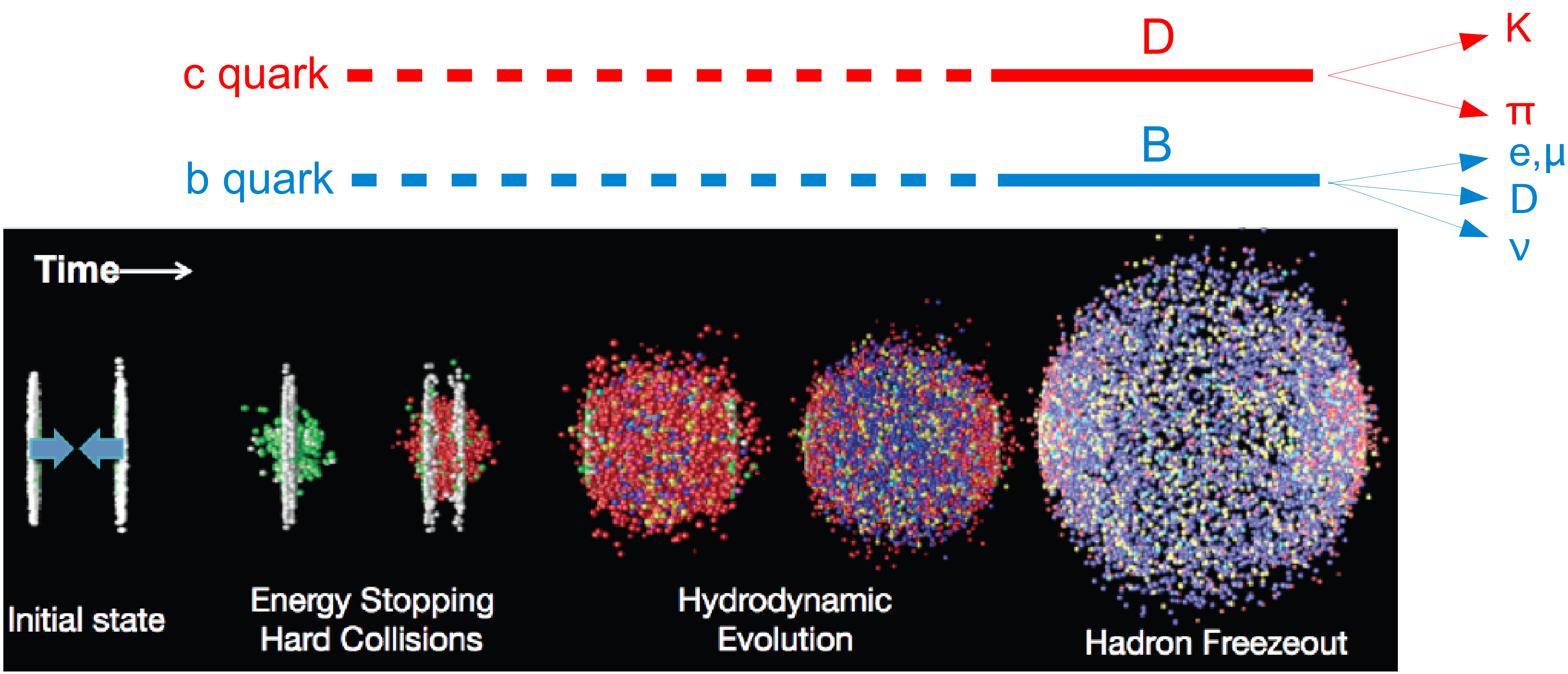
Thermalization
equilibrium is
established
(t < 1 fm/*c*)

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

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

Heavy quarks: 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:

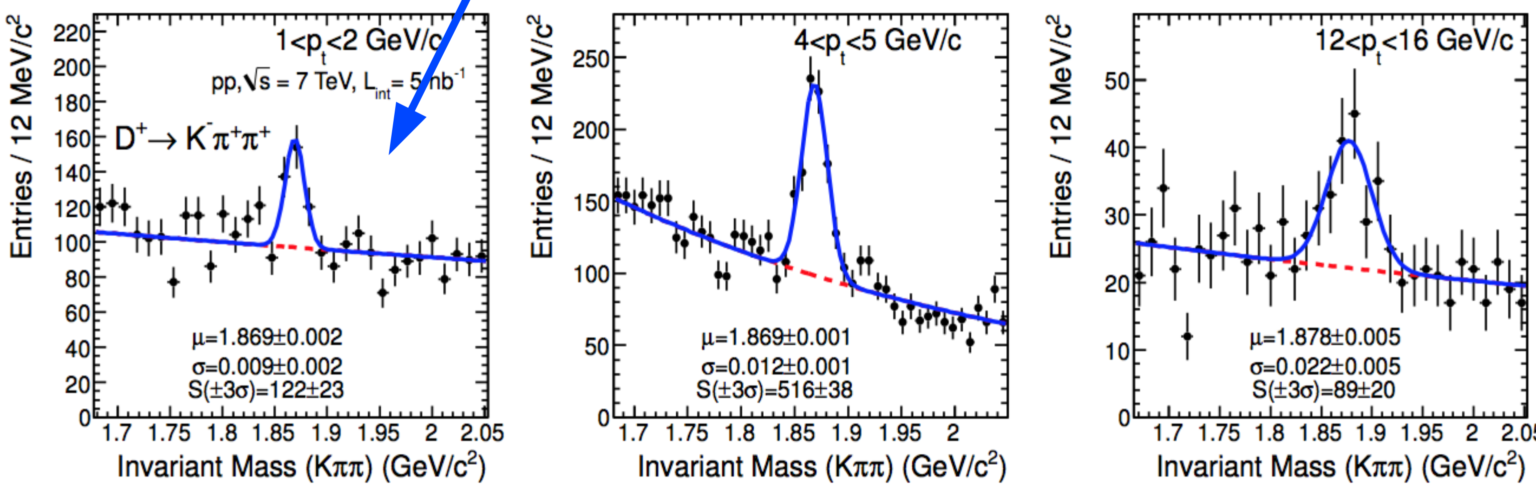
- **Energy loss in the QGP**
  How do the heavy quarks interact with the partons in the QGP?
  Via the study of their energy loss in the medium we can learn information about the strongly interacting matter transport coefficients
  - Nuclear modification factor

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

Open charm: D mesons

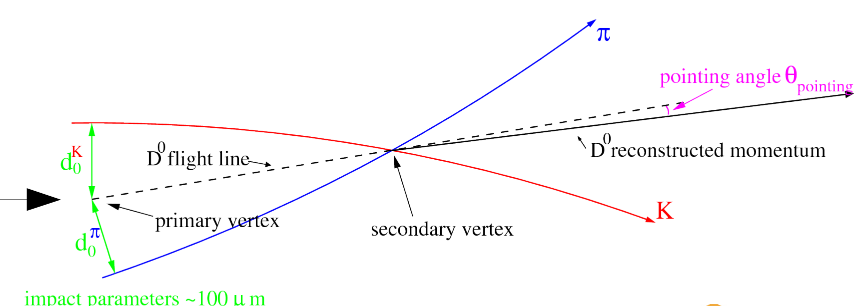
Invariant-mass reconstruction of hadronic decay channels:

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



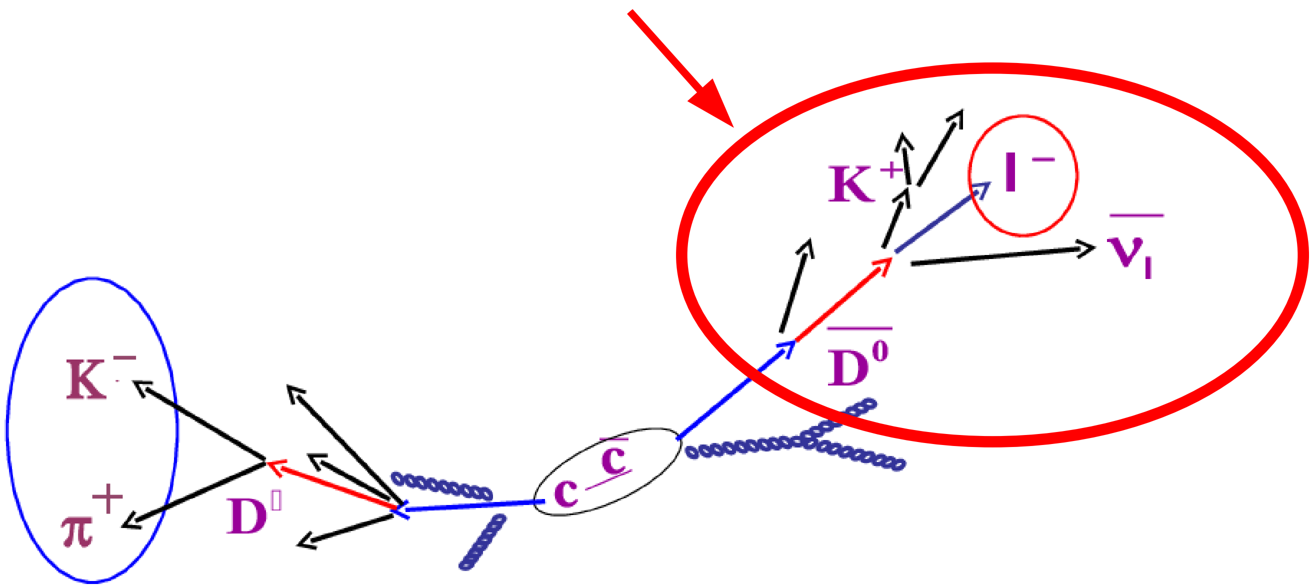
JHEP01(2012)128

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



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:

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

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

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

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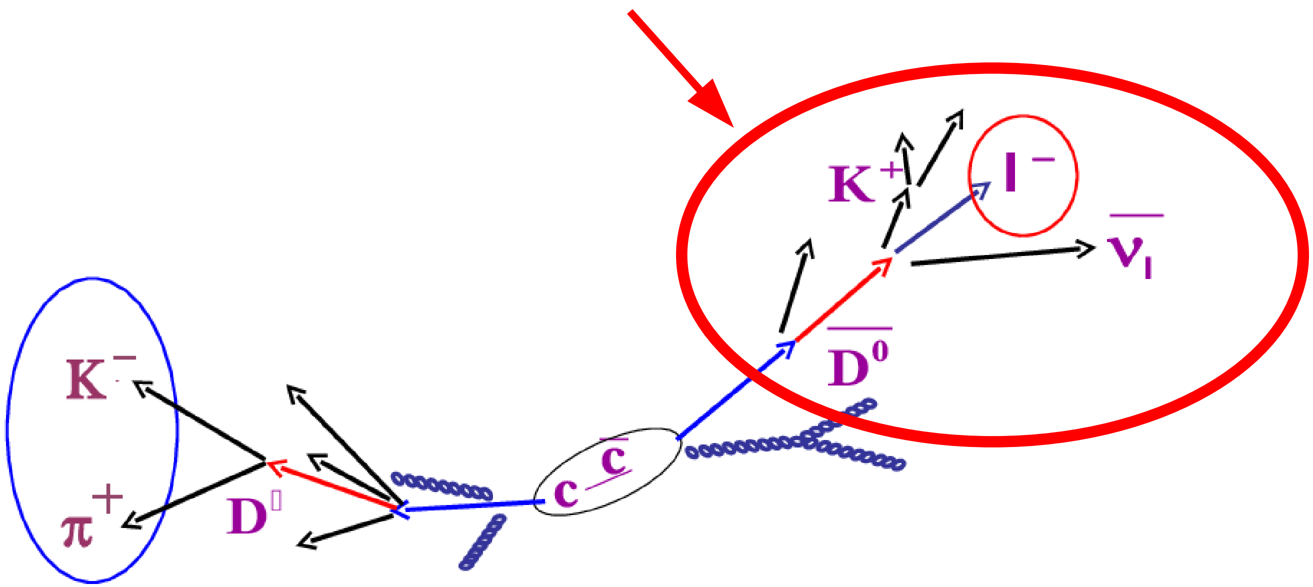

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… and with expertise in electron reconstruction, this is the (hard) way we went, at GSI ...

Semileptonic decays

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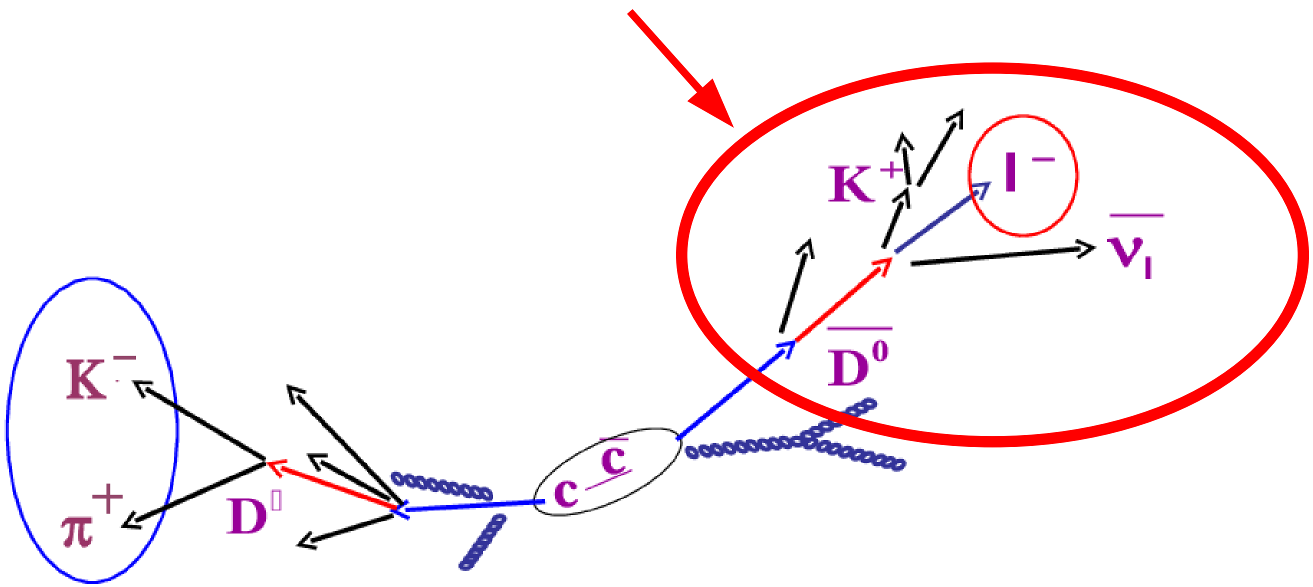

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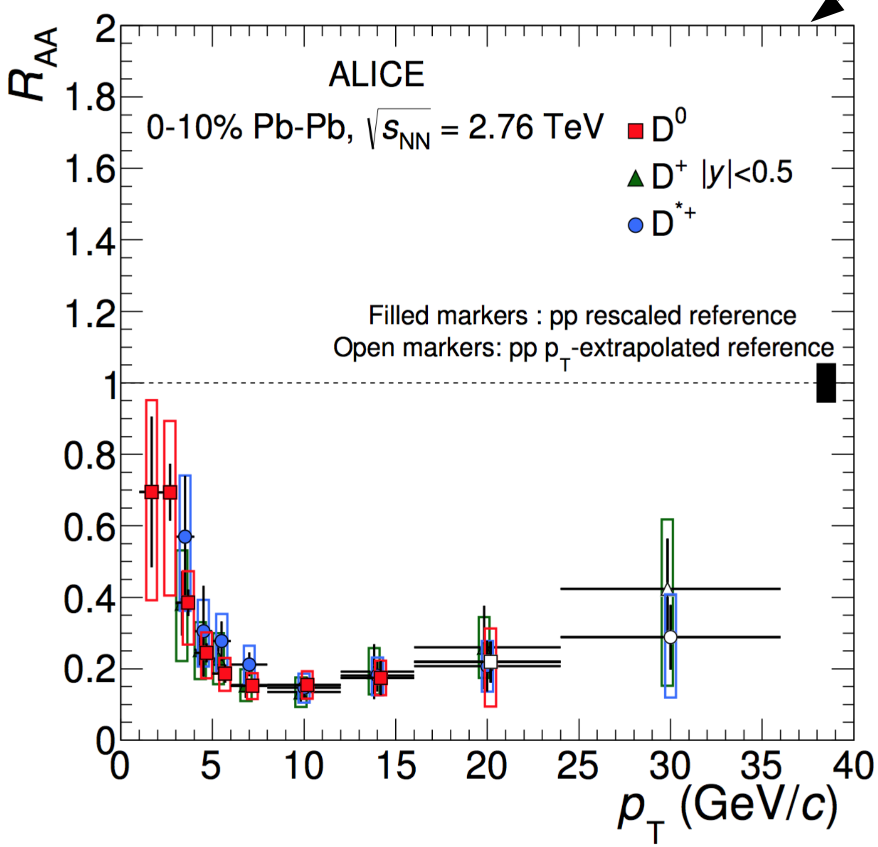
ALICE: D meson R_{AA}

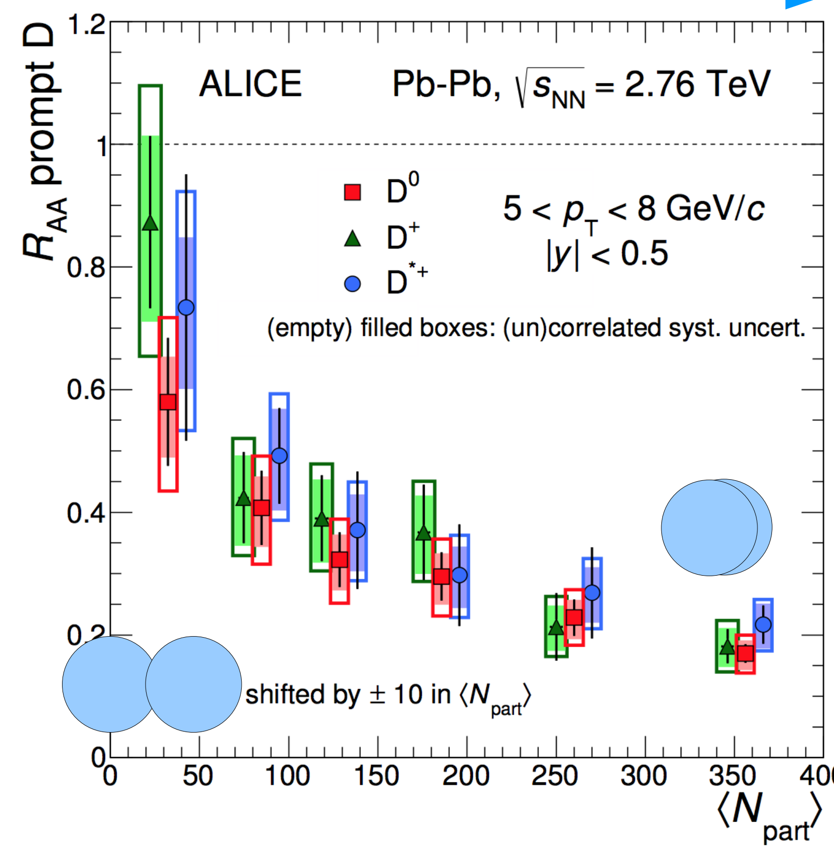
Prompt D^0, D^+, D^{*+}

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

JHEP03 (2016) 081



Energy density



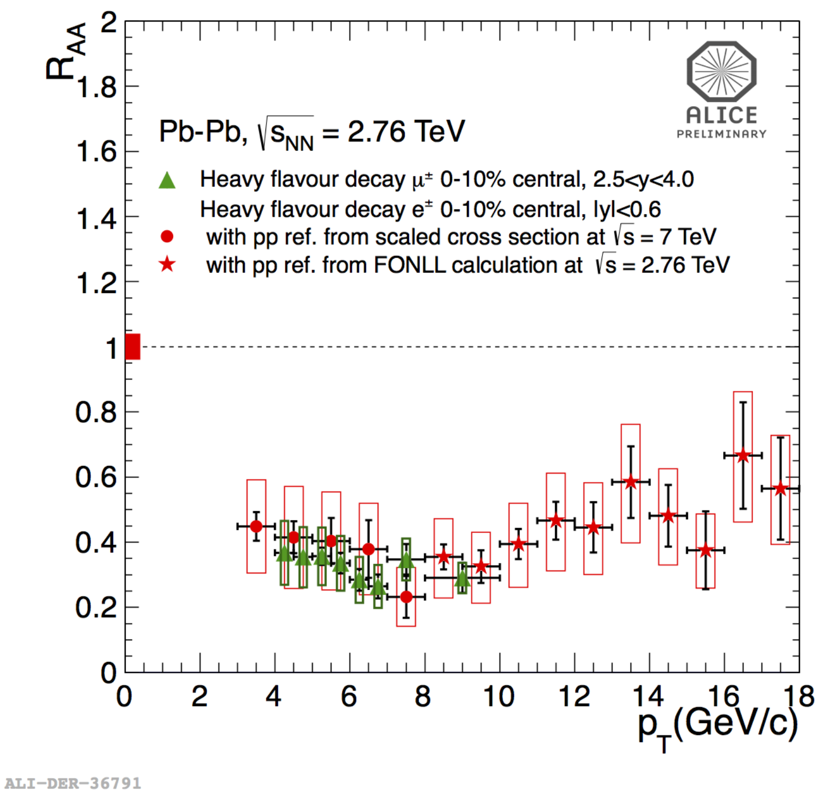
JHEP11 (2015) 205

Charm mesons exhibit strong suppression

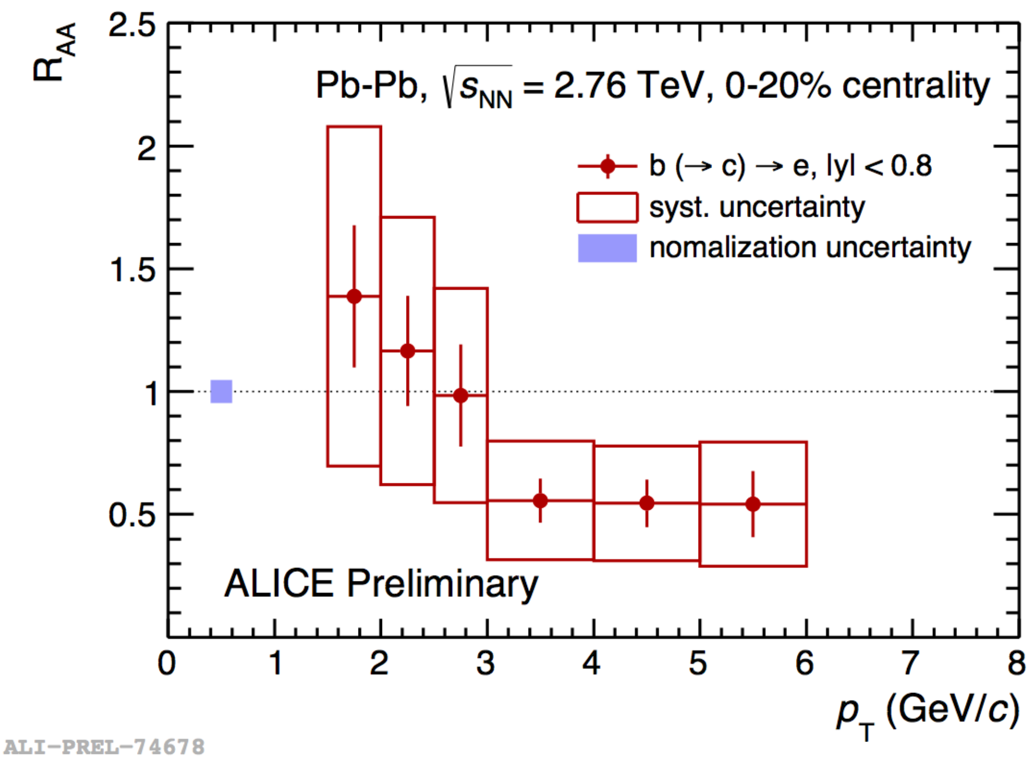
ALICE: R_{AA} of leptons from HF hadron decays

$HF_{c,b} \rightarrow \mu$ 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

Mass ordering of energy loss

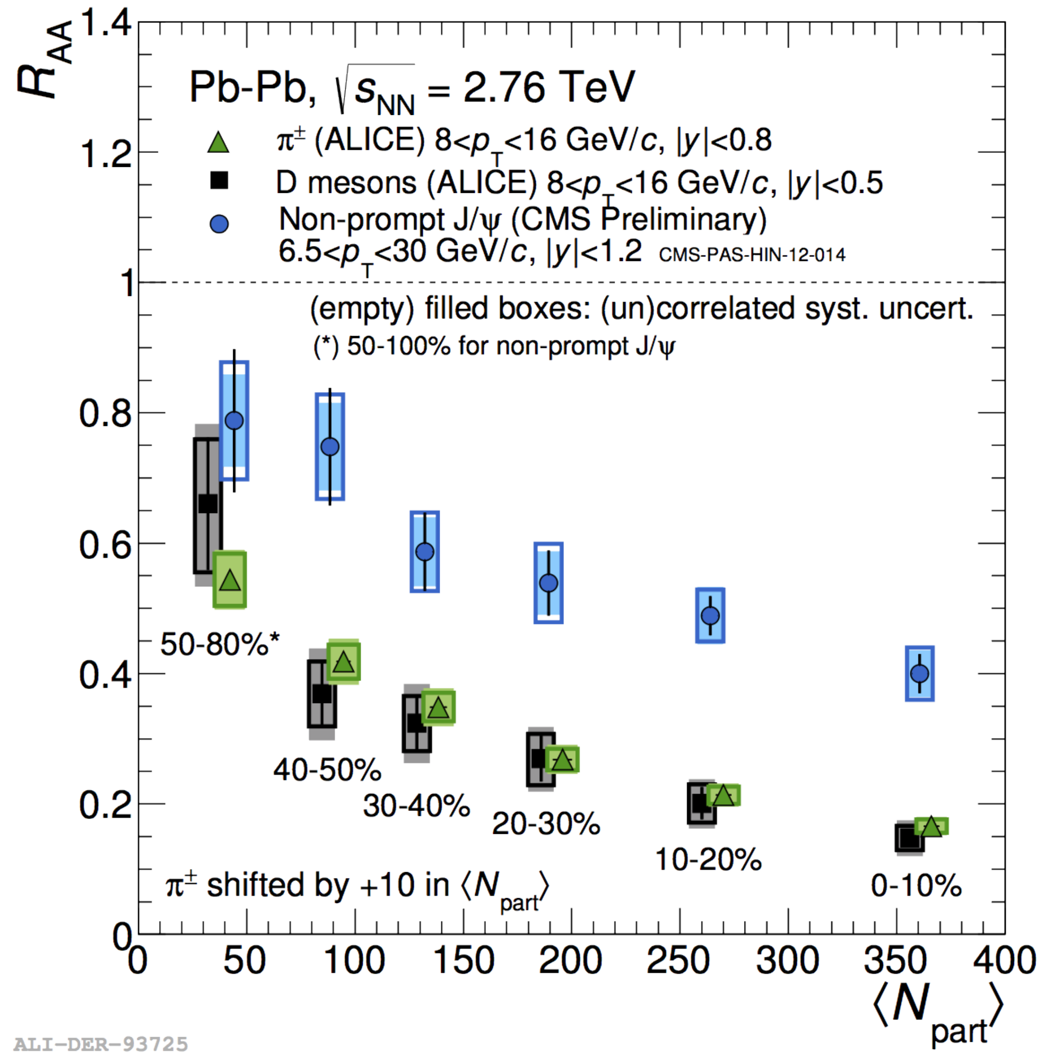
Beauty: non-prompt J/ψ

CMS-PAS-HIN-12-014

Charm: D mesons

JHEP11(2015)205

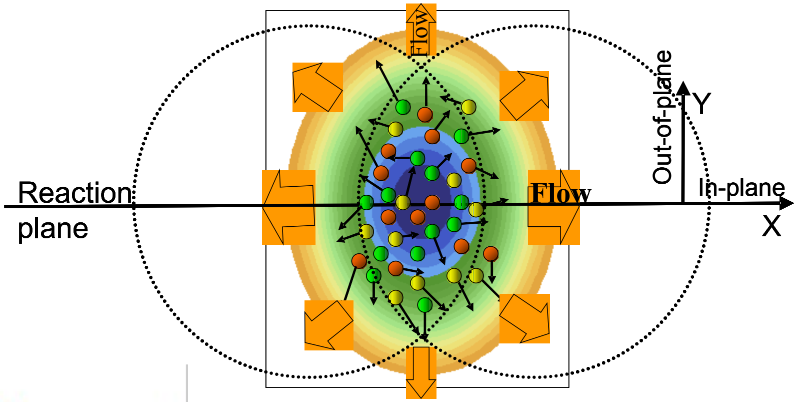
Light quarks: pions



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

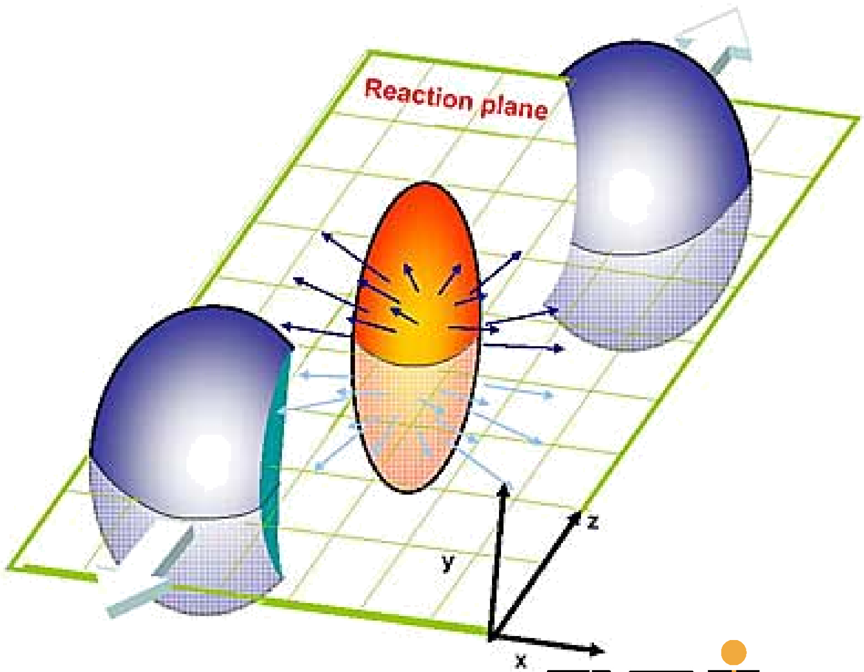
Elliptic flow: v_2

- 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

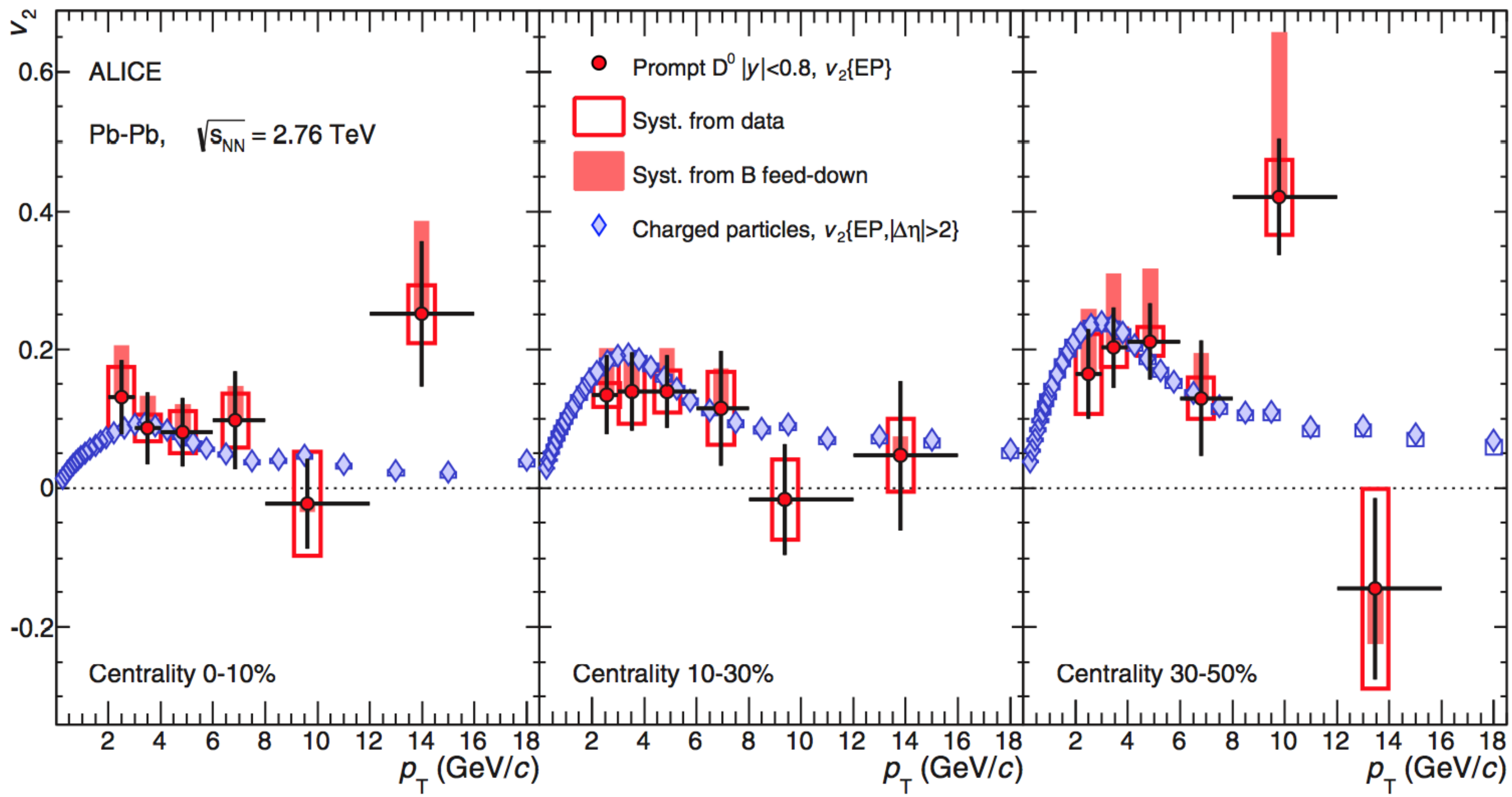


Heavy-flavor v_2 measurements

Prompt D meson v_2 compared to v_2 of charged particles

Comparable behavior!

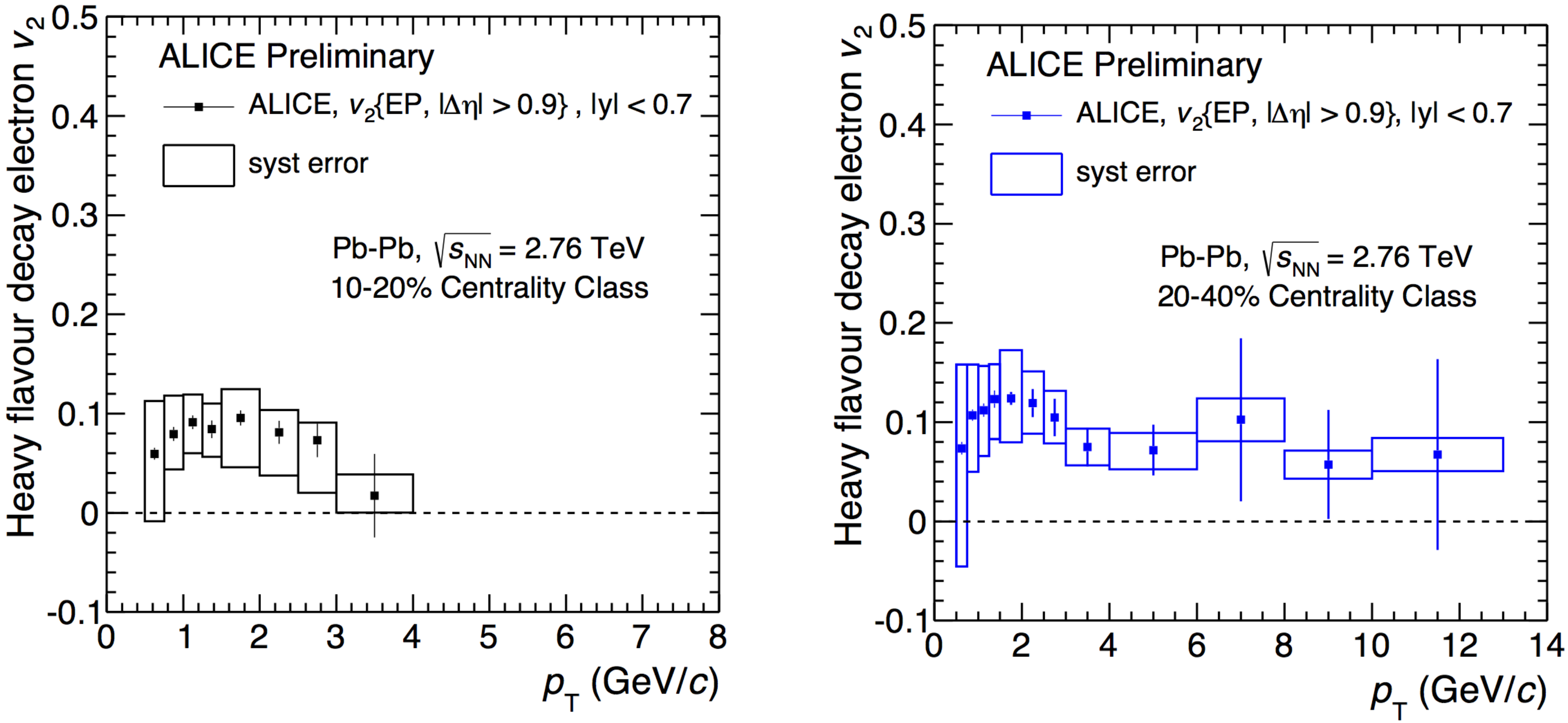
PRL 111(2013)102301
PRC90(2014)034904



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

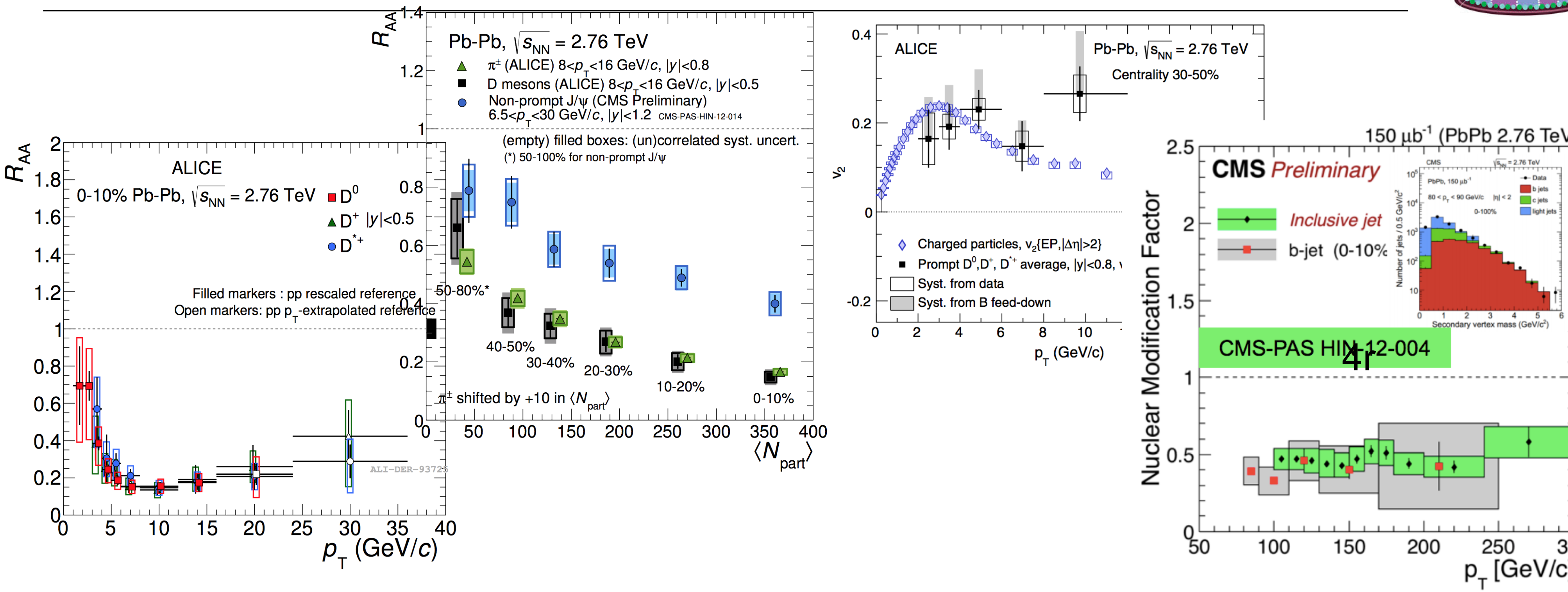
Heavy-flavor v_2 measurements

The most precise measurement is with electrons from semi-leptonic decays



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

From measurements to QCD

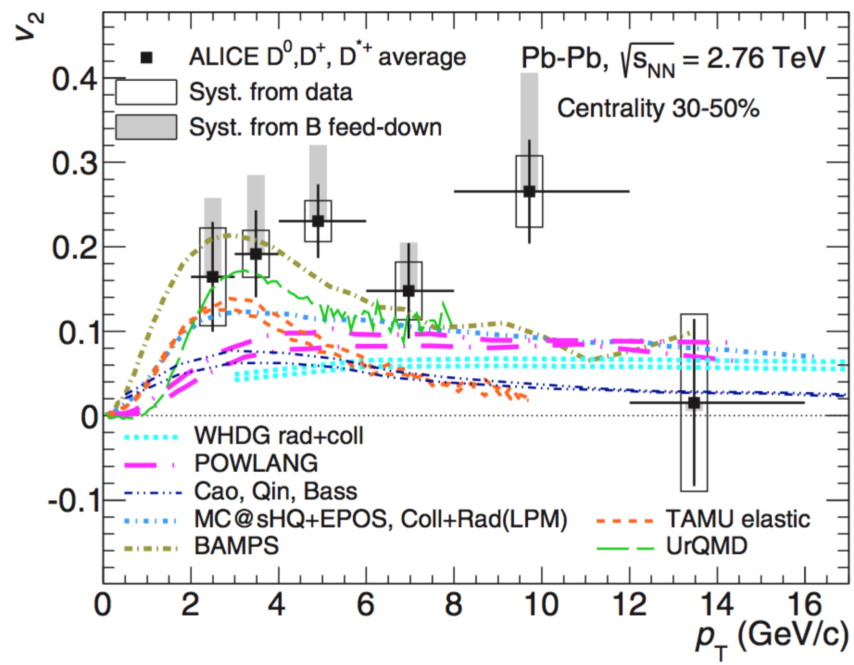


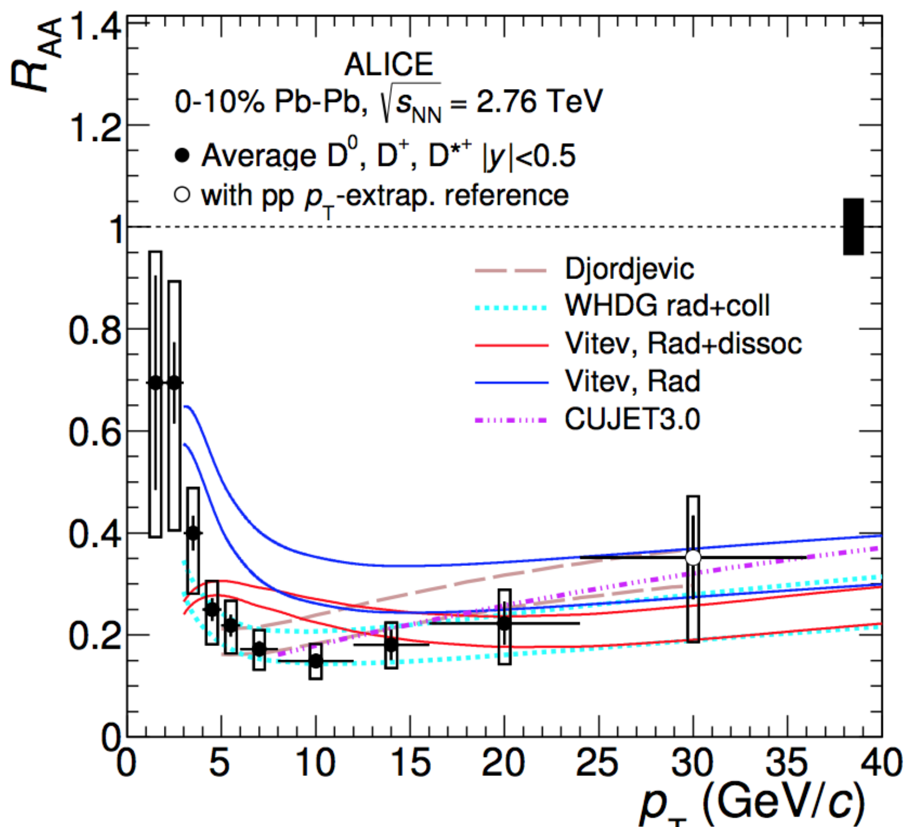
- How do charm and beauty quarks loose energy in the QGP? Elastic collisions? Radiatively?
- What are the relevant properties of the medium? Temperature and its evolution? Transport coefficients?
- How does hadronisation happen? Via fragmentation in vacuum? Or also recombination in the medium?
- What is the interplay between the low- and high-p_T regimes?

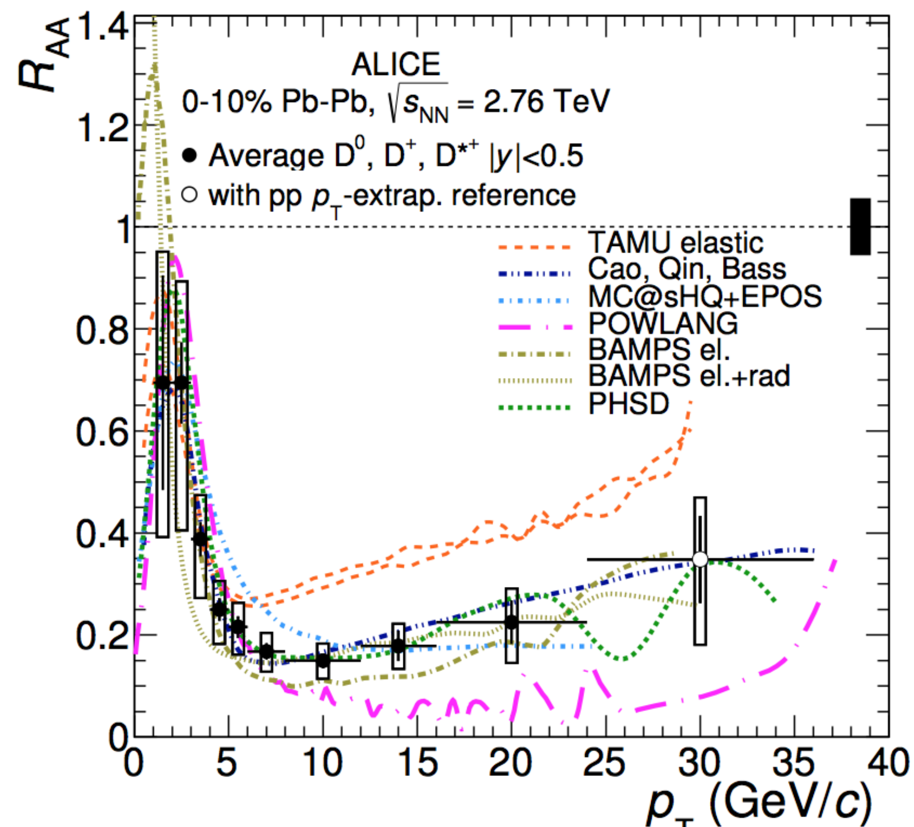
Theory models

Multitude of models attempt to describe R_{AA} and v_2

- Versus p_T
- Versus centrality
- Versus collision energy (+RHIC)







PRL 111(2013)102301
PRC90(2014)034904
JHEP03 (2016) 082

Theory models

Multitude of models attempt to describe R_{AA} and v_2

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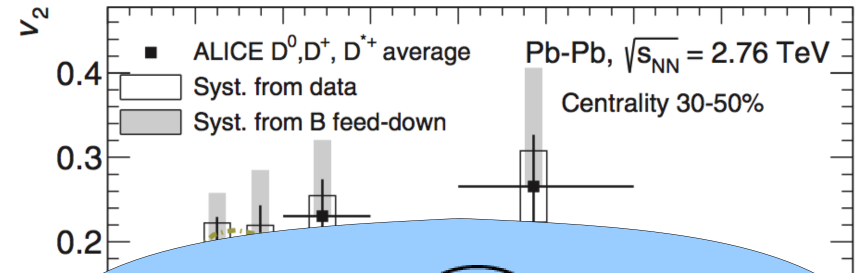
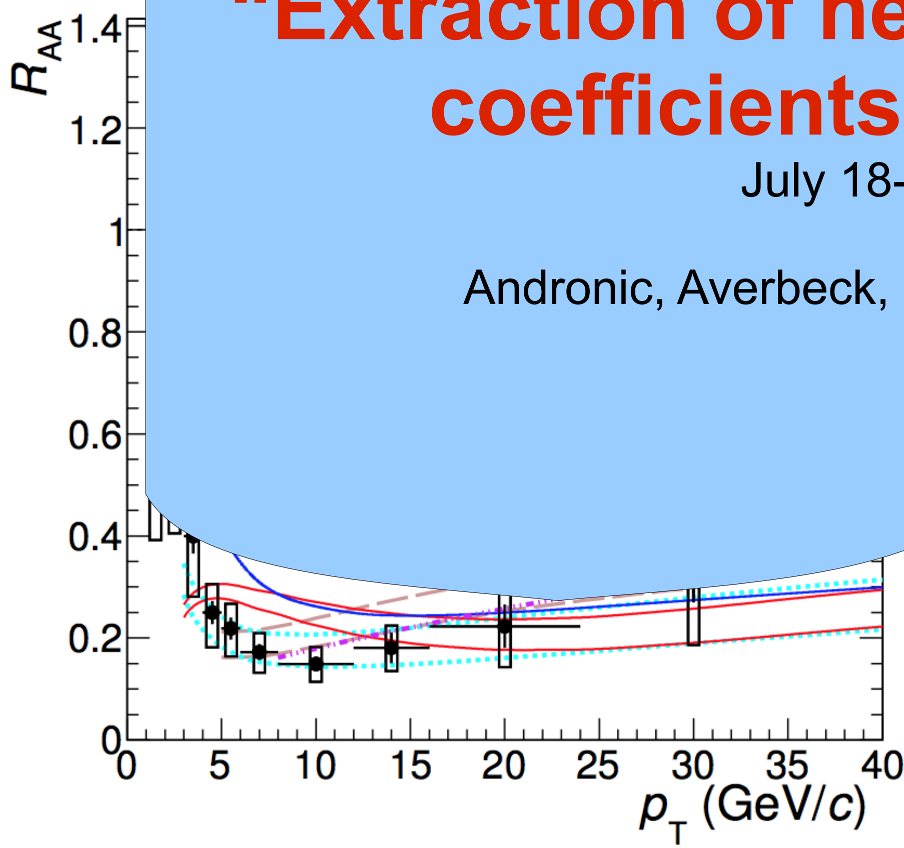


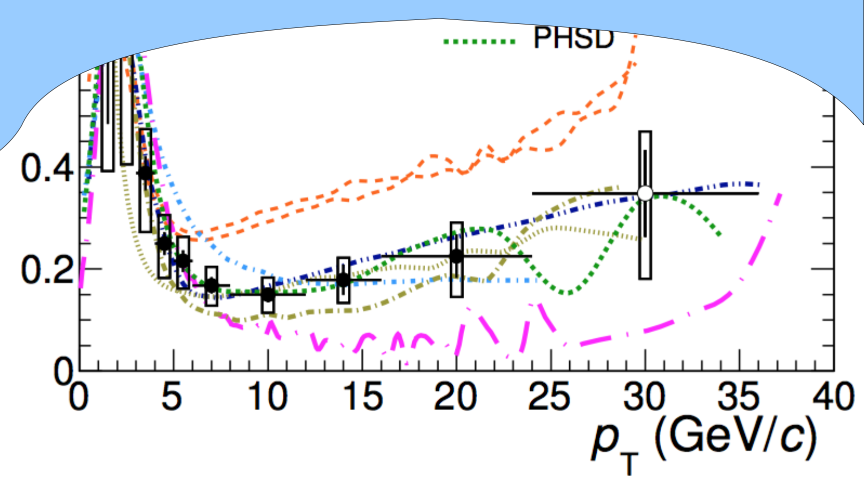
EMMI RAPID REACTION TASK FORCE

“Extraction of heavy-flavor transport coefficients in QCD matter”

July 18-22, 2016 – GSI

Andronic, Averbeck, Gossiaux, Masciocchi, Rapp



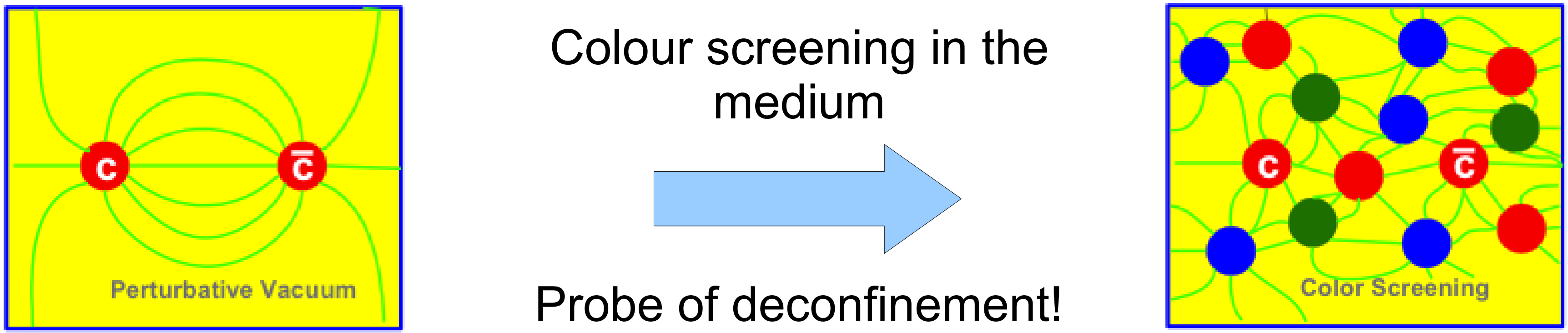


PRL 111(2013)102301
PRC90(2014)034904
JHEP03 (2016) 082

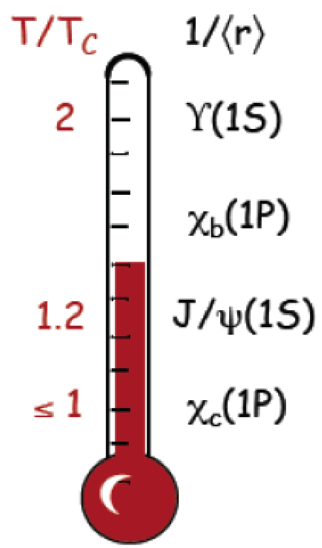
Quarkonium

$Q\bar{Q}$ states $\begin{cases} c\bar{c} & J/\psi,\ \psi',\ \chi_c \\ b\bar{b} & \Upsilon(1S),\ \Upsilon(2S),\ \Upsilon(3S),\ \chi_b \end{cases}$

Excellent probes of the medium:



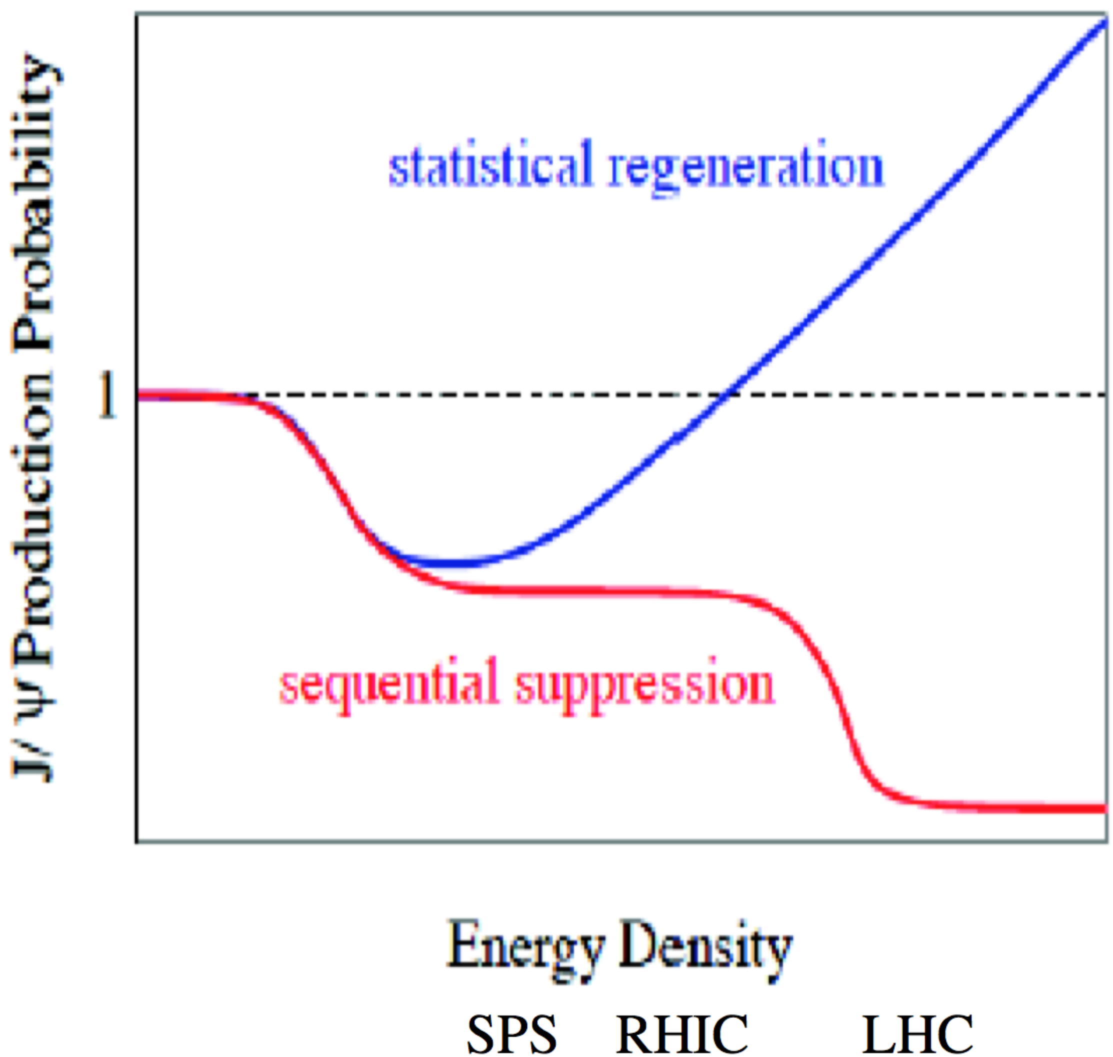
- With increasing temperature, the maximum size up to which quarkonium states are bound decreases
- The melting of the quarkonium states should follow a sequence defined by their size
- Only?



Courtesy A. Mocsy

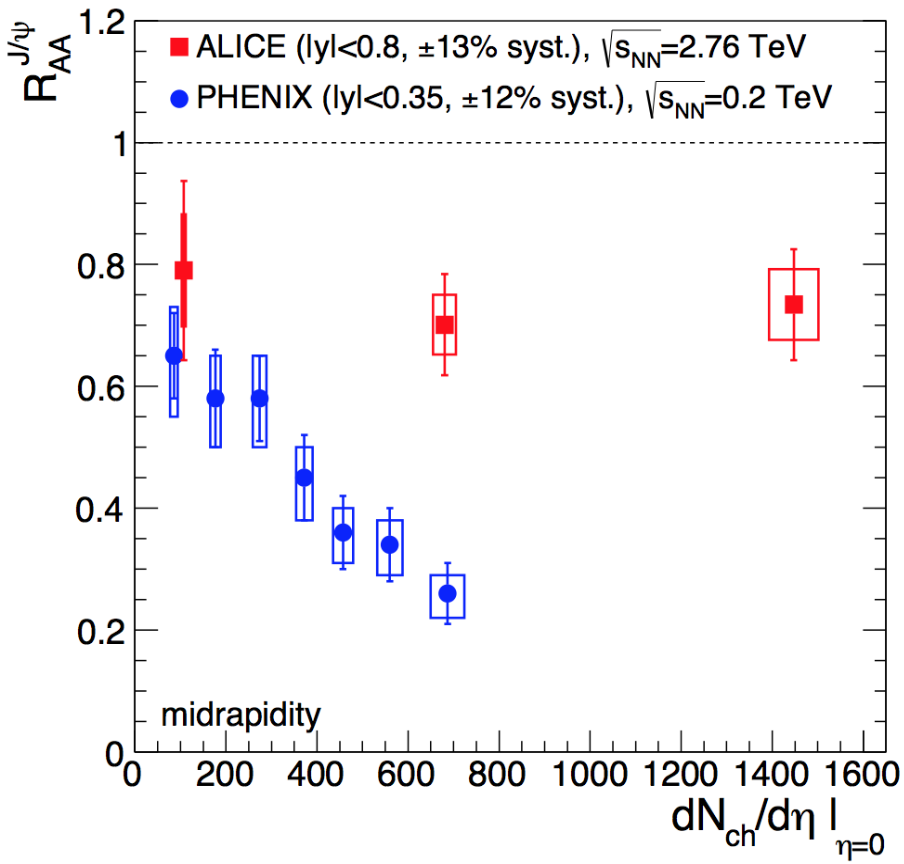
Expectations for the LHC

(Re)generation vs sequential suppression:

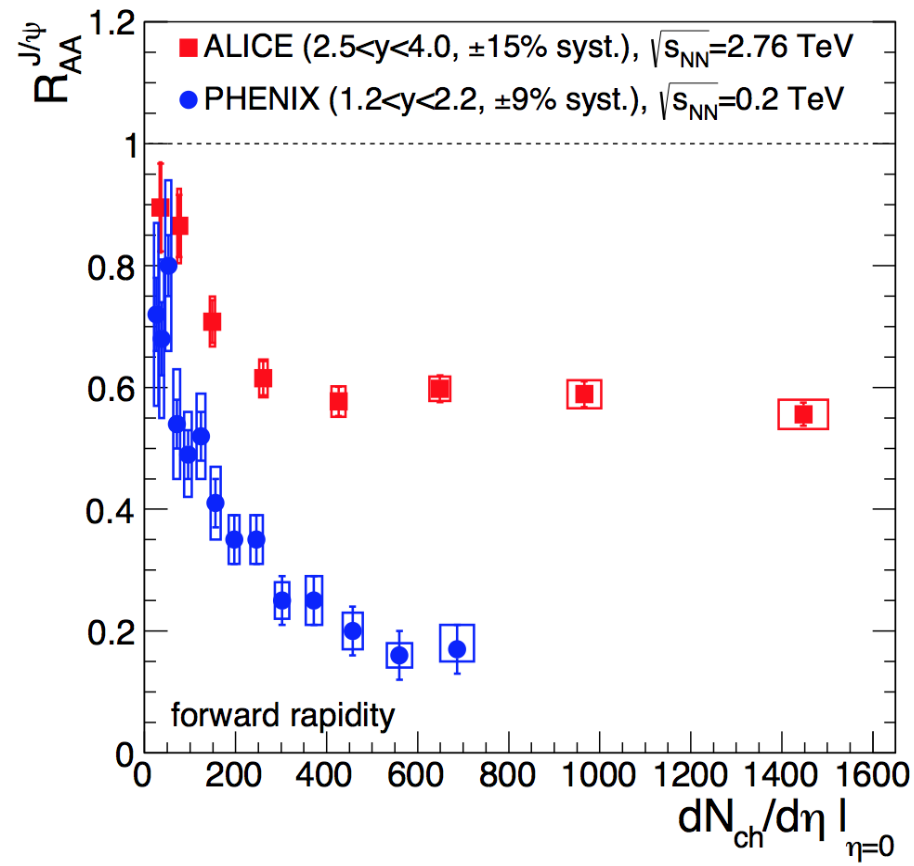


J/ψ production: results for $p_T \geq 0$

Midrapidity



Forward rapidity

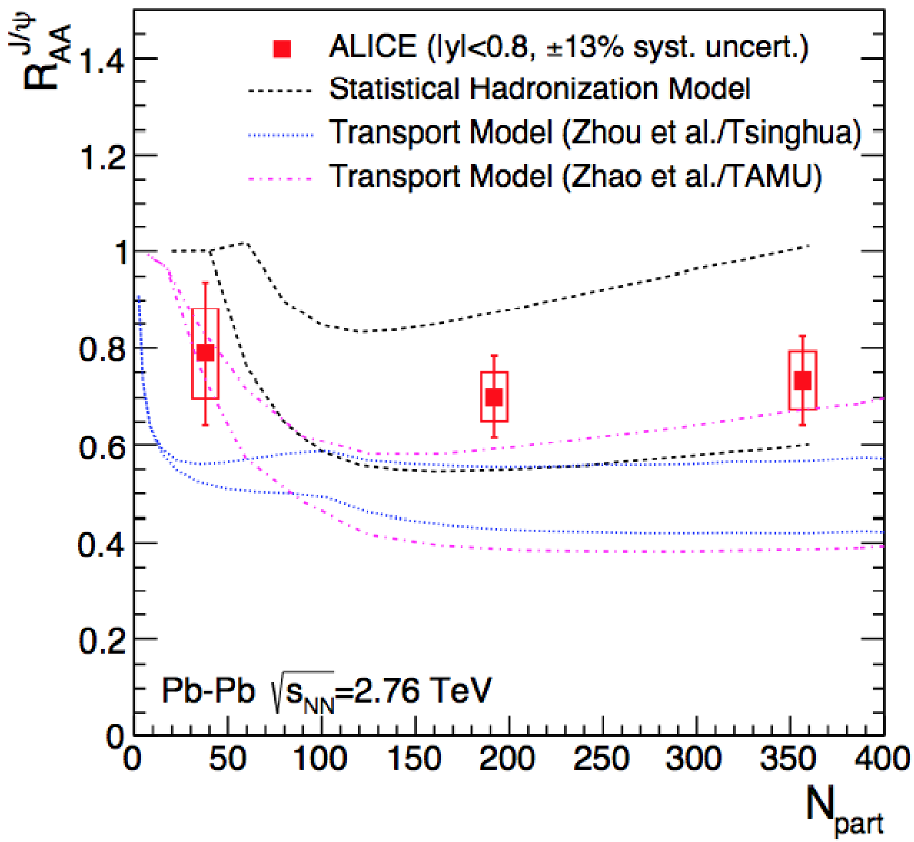


- Shown as function of energy density (proportional to dN/dη)
- ALICE compared to RHIC, PHENIX result (lower energy density)
- Higher yield at the LHC !!

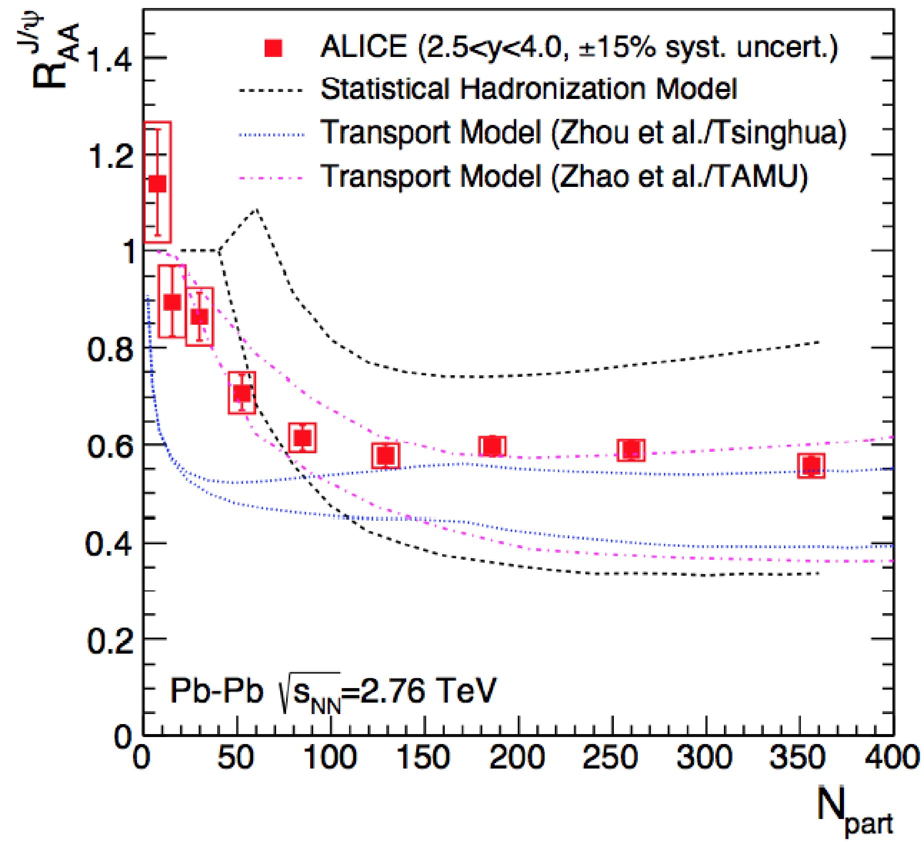
ALICE, PLB 734 (2014) 314

J/ψ: models

Midrapidity



Forward rapidity



Both model categories reproduce the data, using different charm cross section!

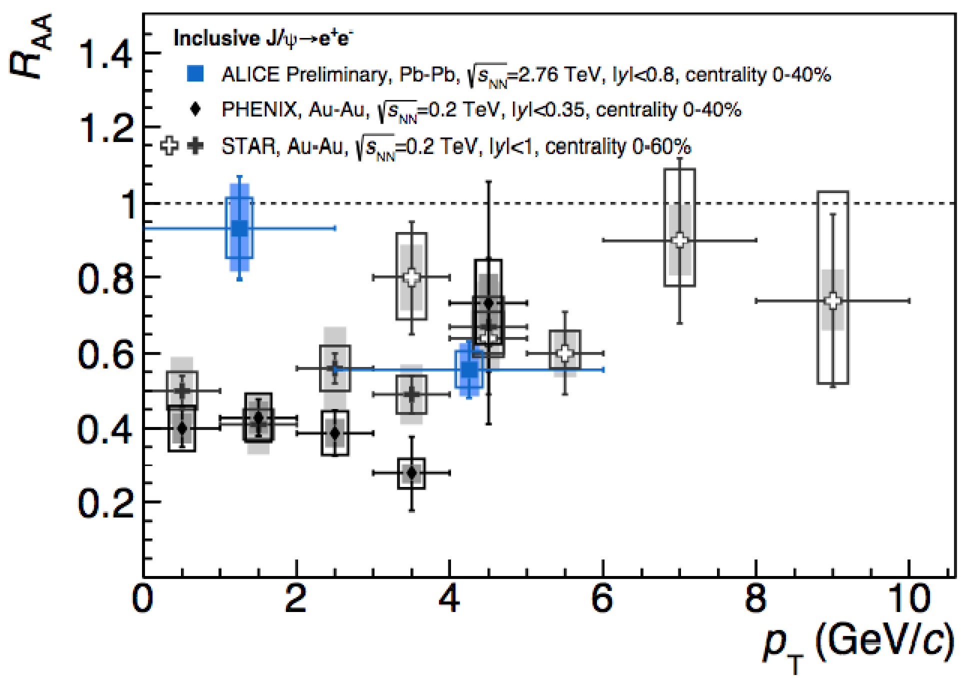
$d\sigma_{cc}/dy$ at midrapidity: statistical hadronization: 0.3-0.4 mb

transport: 0.5-0.75 mb (TAMU)

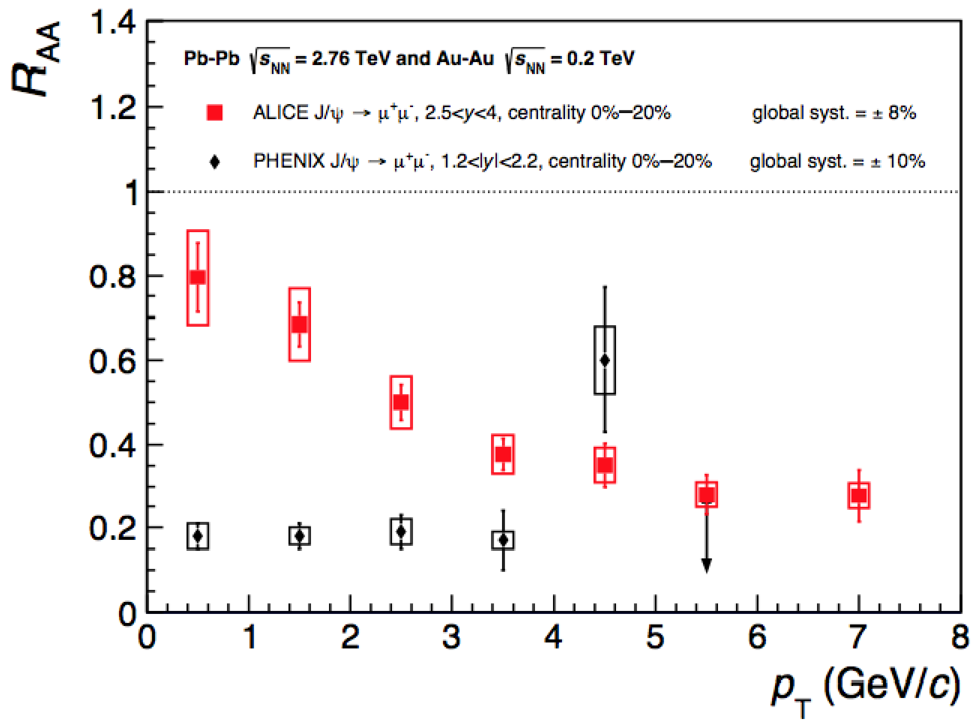
0.65-0.8 mb (Tsinghua)

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

Looking back

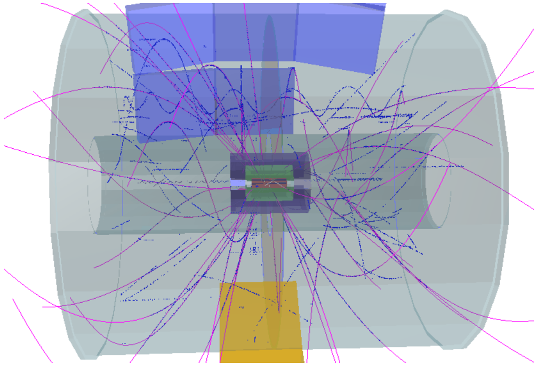
- Shared passion for heavy flavors paved my happy way into the physics of QCD at extreme conditions
- Heavy flavors are excellent probes of strongly-interacting matter produced in heavy-ion collisions
- Quarkonia possible probes of deconfinement
- Exciting results with heavy flavors from the LHC data!
  J/ψ behavior one of the most interesting results!!

More looking back

- Our GSI group

2014, first group Heraeus retreat, Kleinwalsertal

- Unforgettable times like the absolute first ALICE data (December 6, 2009): data to GSI, local reconstruction



and the first Pb-Pb ALICE data

More looking back

2009: Kletterwald in Darmstadt … and soon later: some more difficult times at GSI ...

More looking back

2009: Kletterwald in Darmstadt … and soon later: difficult times at GSI ...

Me, learning management at GSI …

More looking back

2009: Kletterwald in Darmstadt … and soon later: some more difficult times at GSI ...

Me, learning management at GSI …

… behaving as a teenager from time to time

and more

2009: Kletterwald in Darmstadt …

EMMI

and more

2009: Kletterwald in Darmstadt …

XXIV
QUARK
MATTER
DARMSTADT
2014

EMMI

and more

2009: Kletterwald in Darmstadt …

XXIV QUARK MATTER DARMSTADT 2014

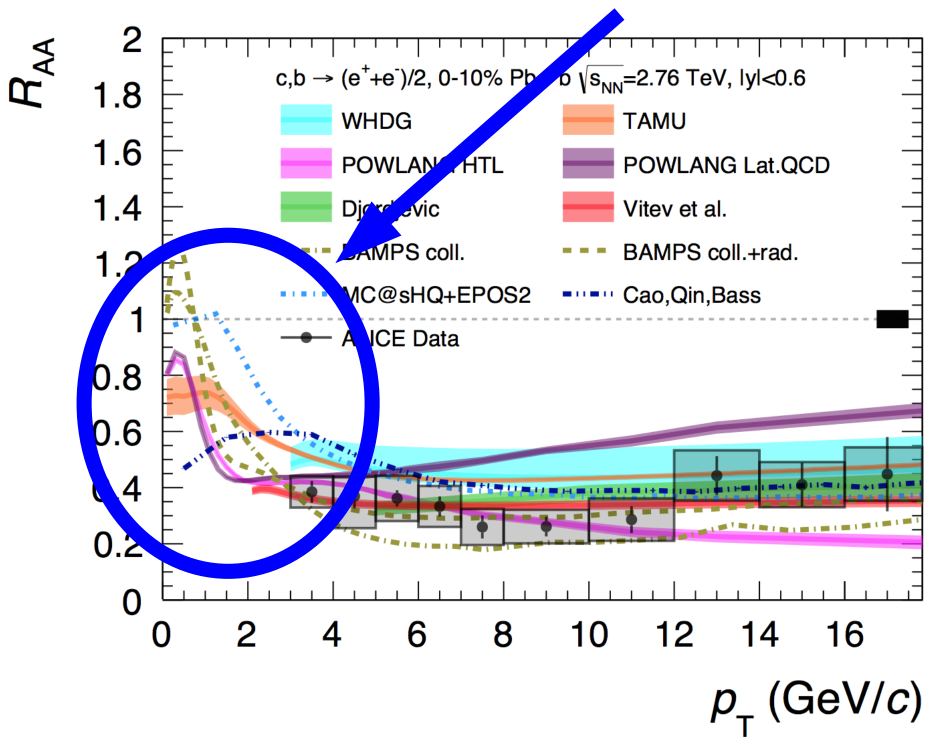
EMMI

ISOQUANT

SFB1225

Now and next

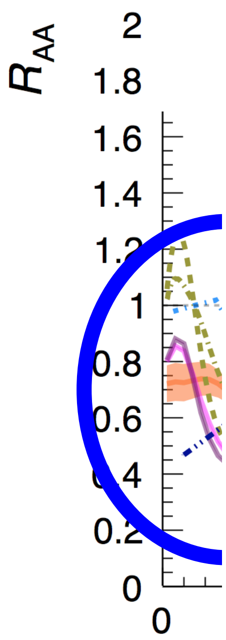
Heavy flavor R_{AA} at low p_T



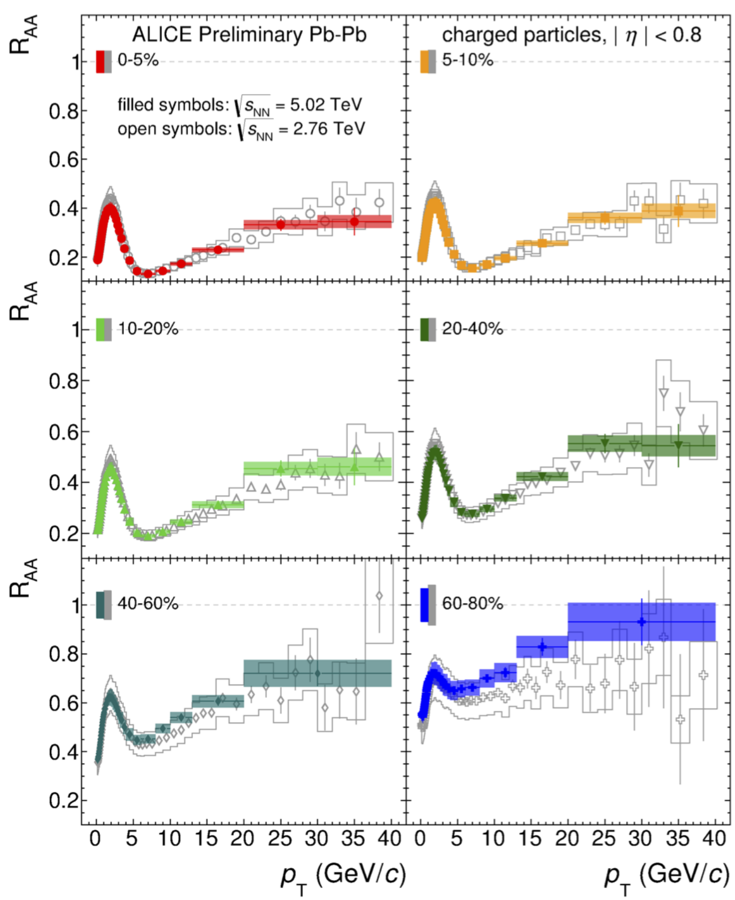
Now and next

Heavy flavor R_{AA} at low p_T

Run 2 ALICE Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV



Charged particle R_{AA}

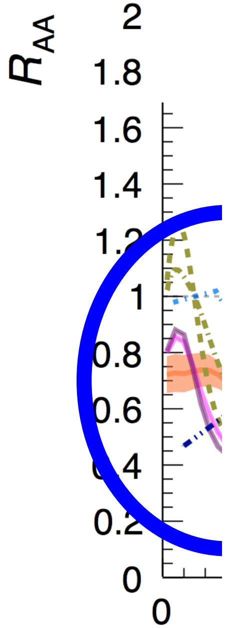


ALI-PREL-107300

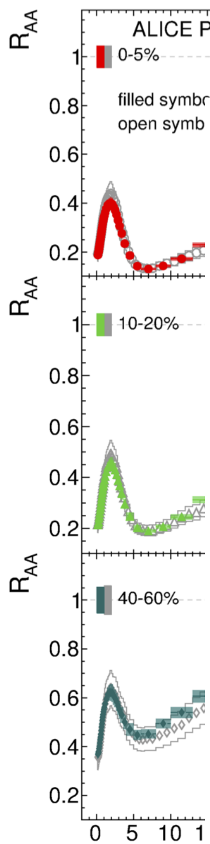
Now and next

Heavy flavor R_{AA} at low p_T

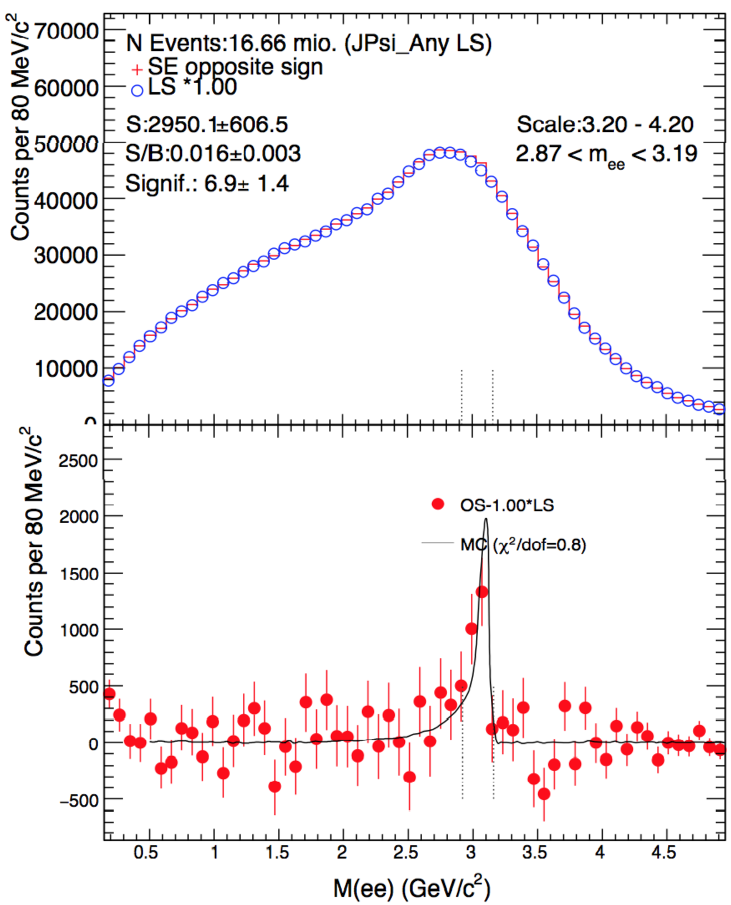
Run 2 ALICE Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV



Charged particle R_{AA}



First $J/\psi \rightarrow e^+e^-$ signals



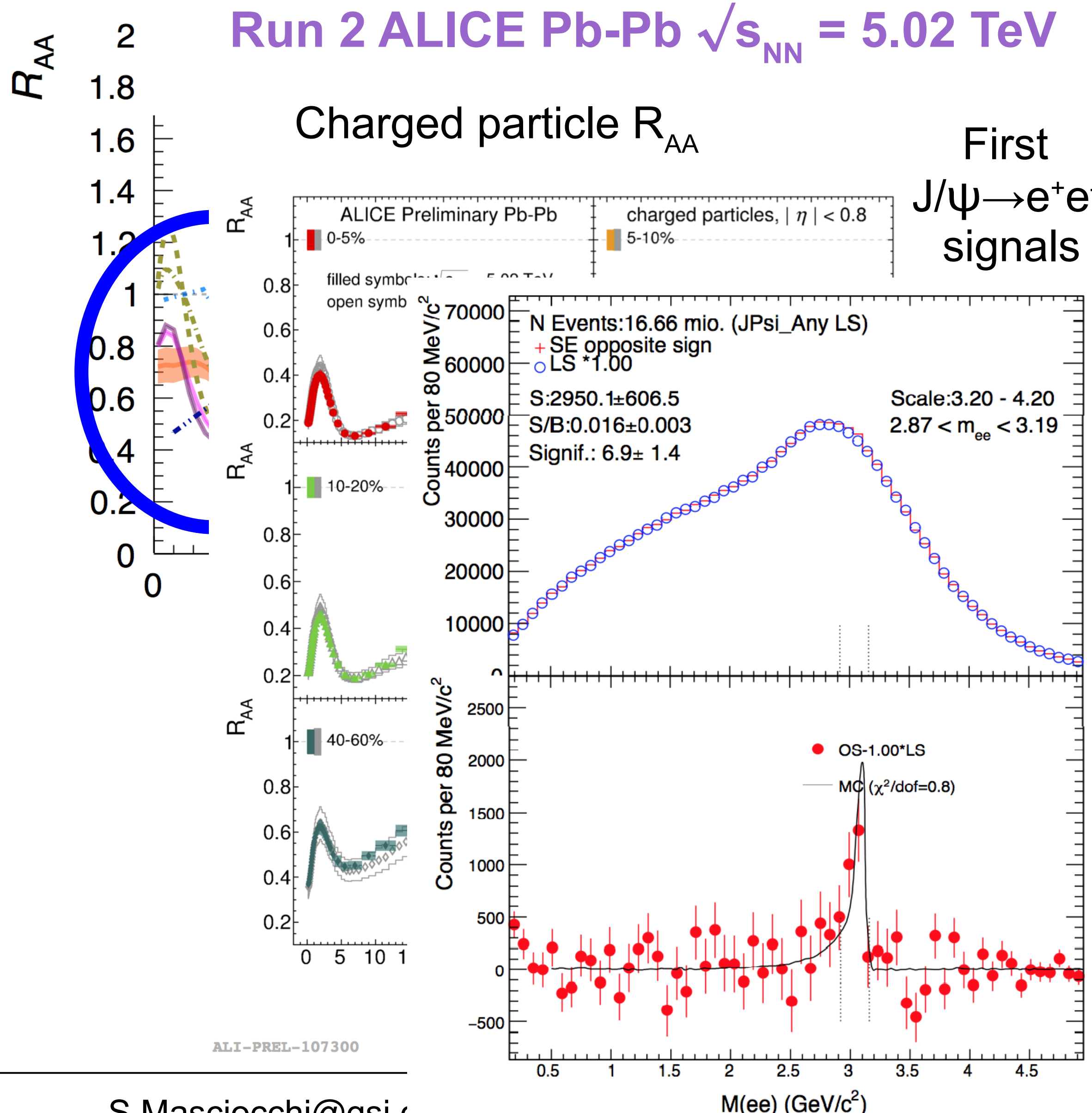
Now and next

Heavy flavor R_{AA} at low p_T

Run 2 ALICE Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Charged particle R_{AA}

First $J/\psi \rightarrow e^+e^-$ signals

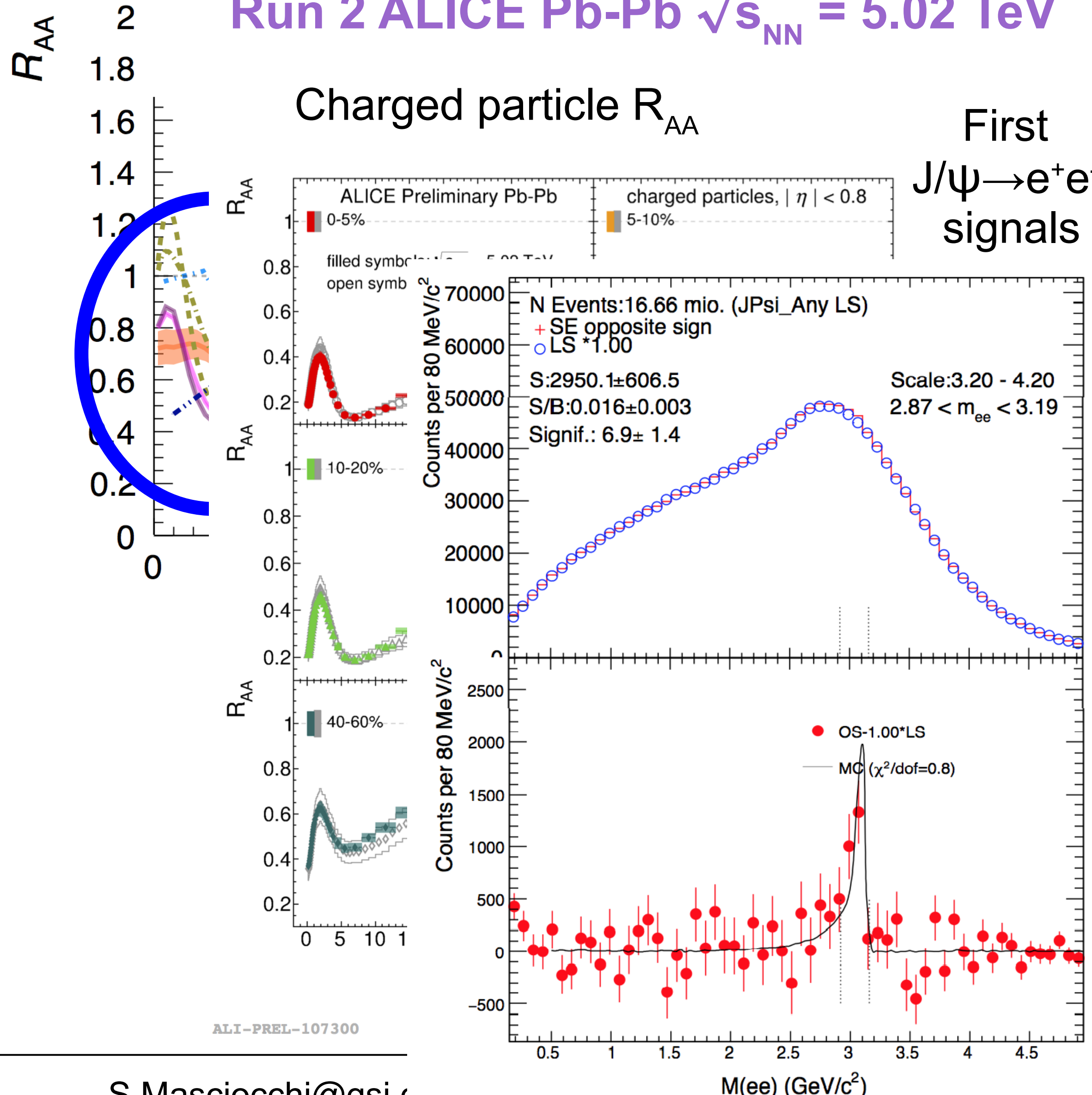


TPC upgrade with GEM chambers at GSI det lab

Now and next

Heavy flavor R_{AA} at low p_T

Run 2 ALICE Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV



TPC upgrade with GEM chambers at GSI det lab

A lot of physics to explore

ALICE

ISOQUANT SFB1225

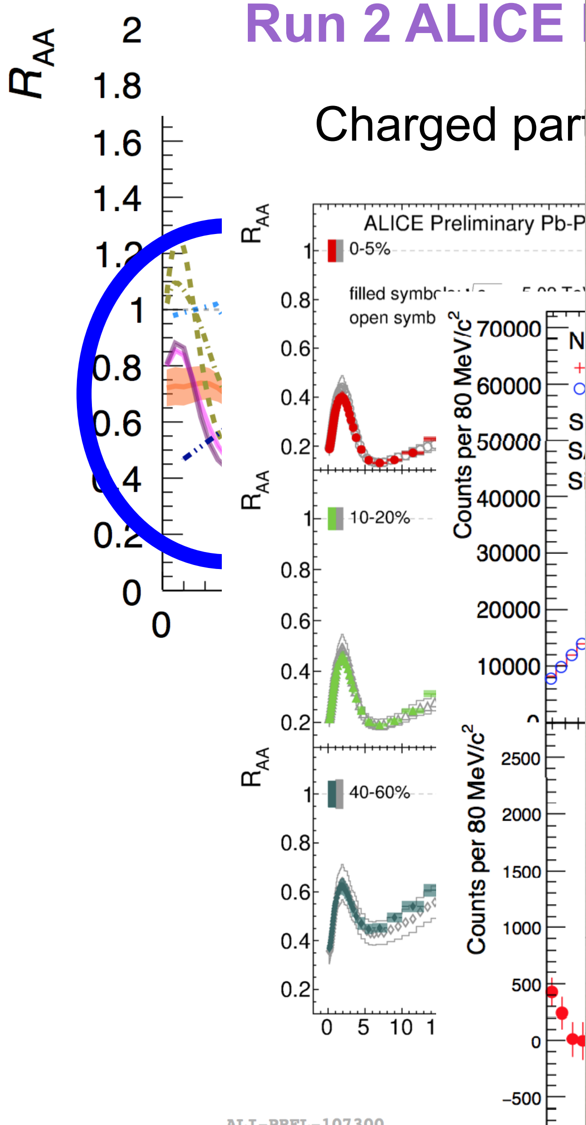
GSI

Now and next

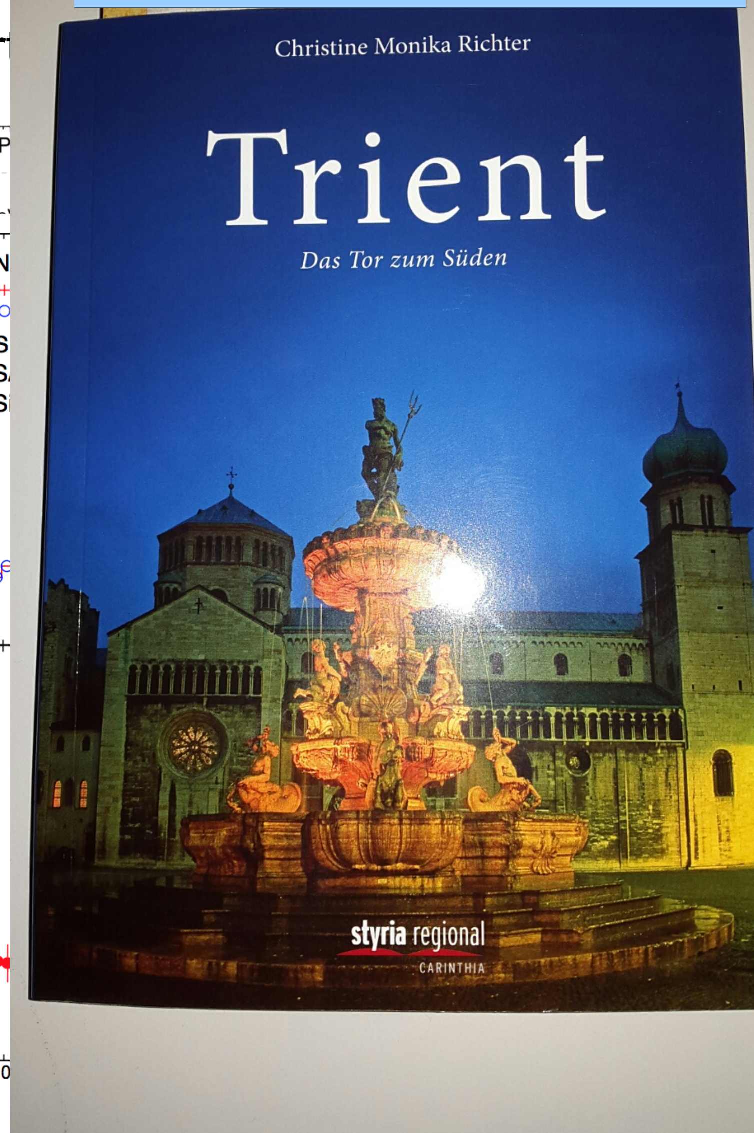
Heavy flavor R_{AA} at lo

Run 2 ALICE

Charged par



Una grappa morbida e' assicurata … ma oltre?



TPC upgrade with GEM chambers at GSI det lab

lot of physics to explore

Looking ahead

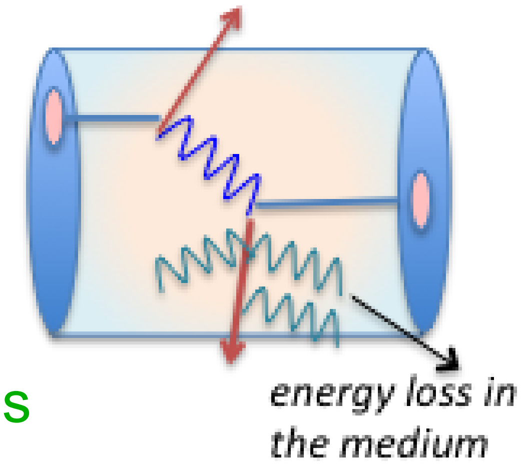
Happy birthday Peter

With the wishes for a lot of fun with physics,
and upgrades,
and much charm and beauty in life

Spares

In-medium parton energy loss

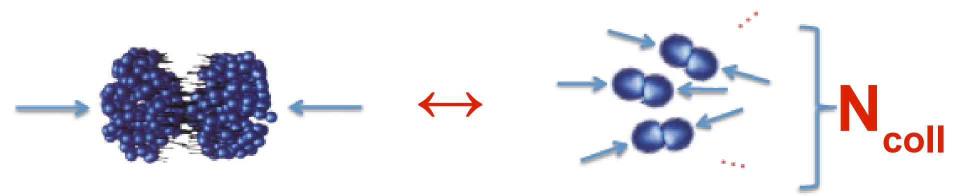
- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium constituents



- 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

Quantifier: the **nuclear modification factor**

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



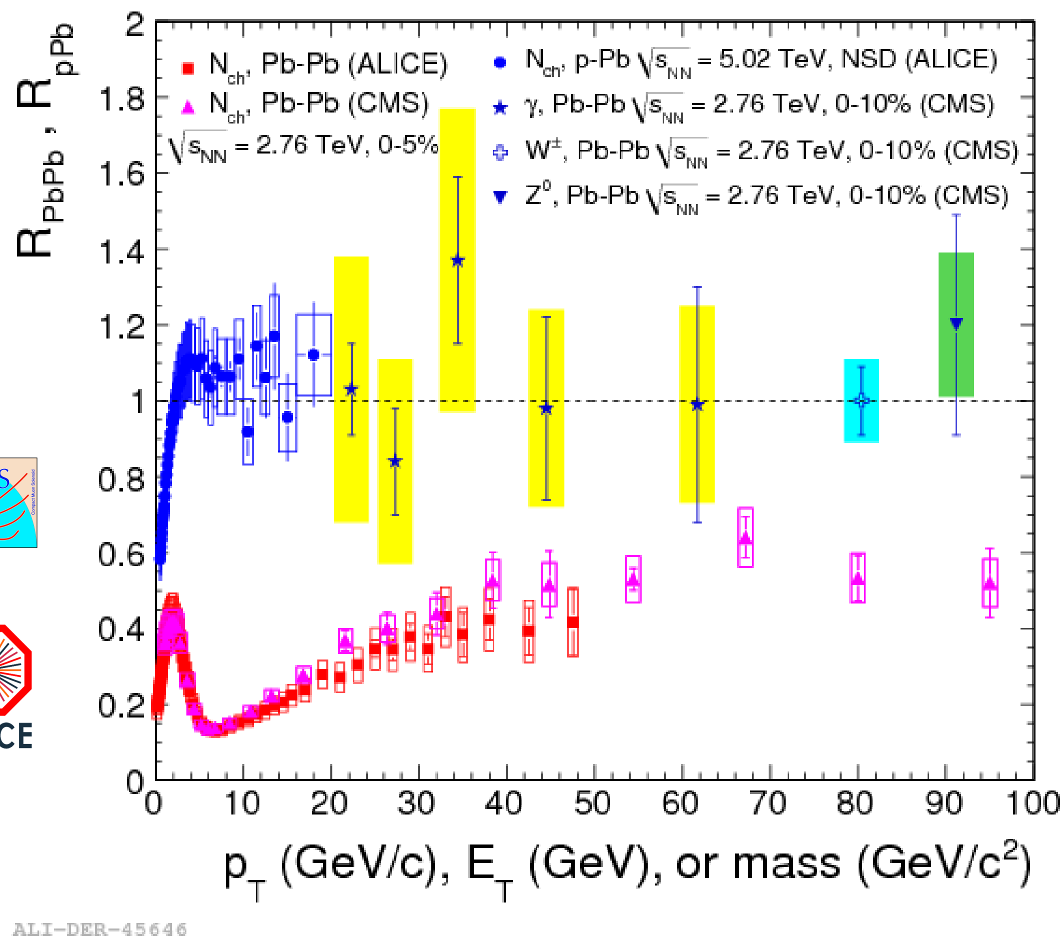
as function of p_T and centrality

binary collisions

Nuclear modification factor

No medium effect → $R_{AA} \approx 1$

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



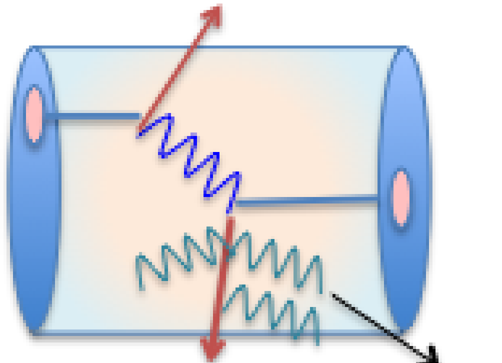
- No modification for vector bosons: γ $W^{\pm}$ Z^0
- Strong suppression for charged hadrons, still significant at 100 GeV/c !
- Look at charm and beauty

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": $\pi \geq D > B$

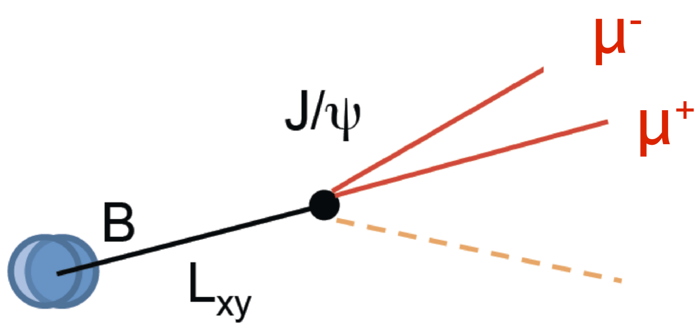
$$R_{AA}^{\pi} \leq R_{AA}^{D} < R_{AA}^{B}$$

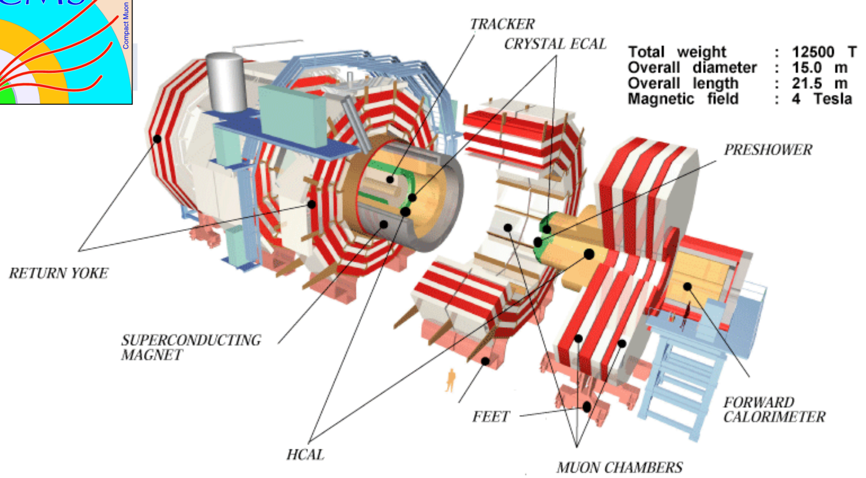
references in spares

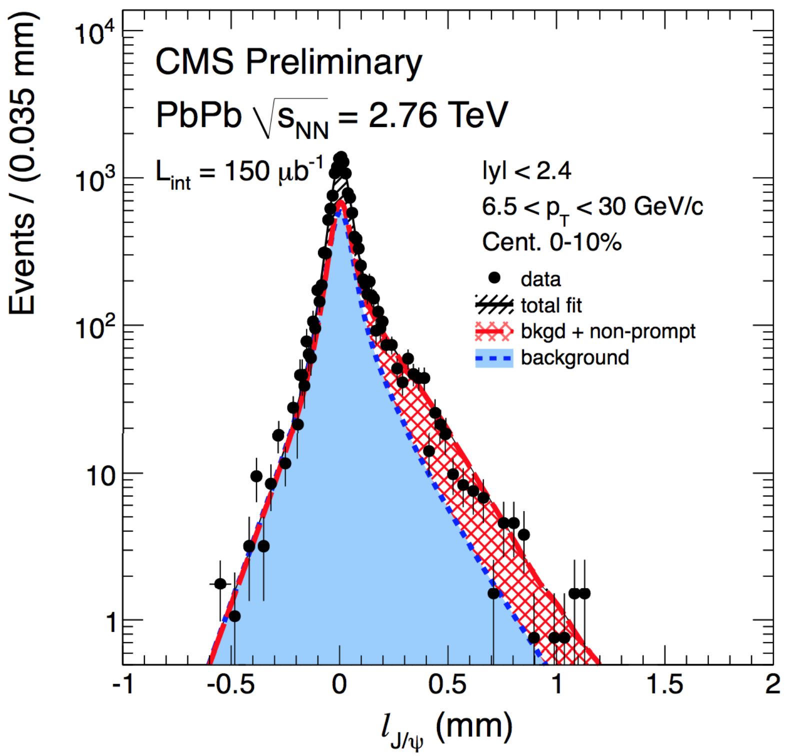
consider that other effects contribute, like different production kinematics and fragmentation of light and heavy quarks

Beauty via non-prompt J/ψ

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





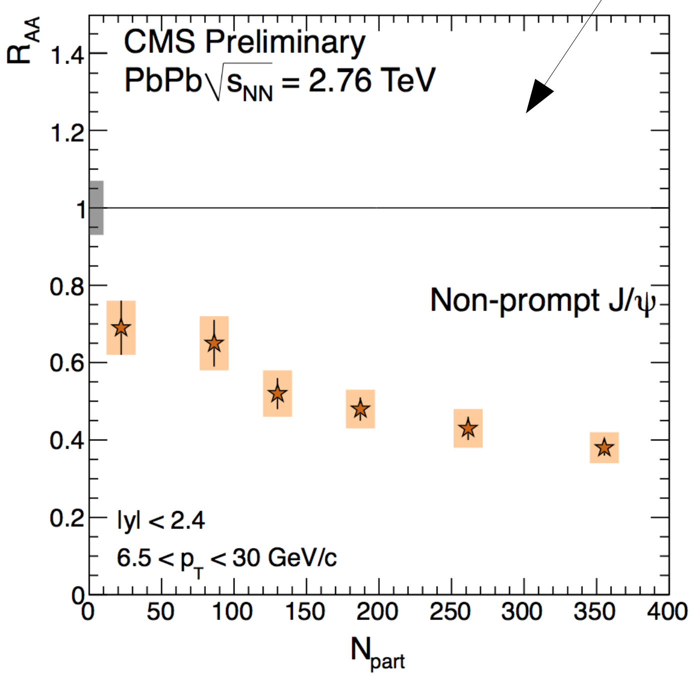


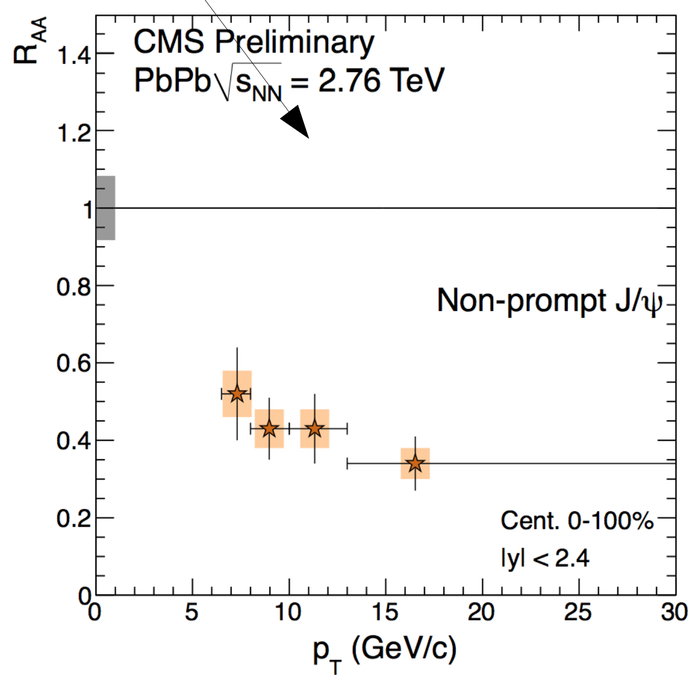
CMS PAS HIN-12-014

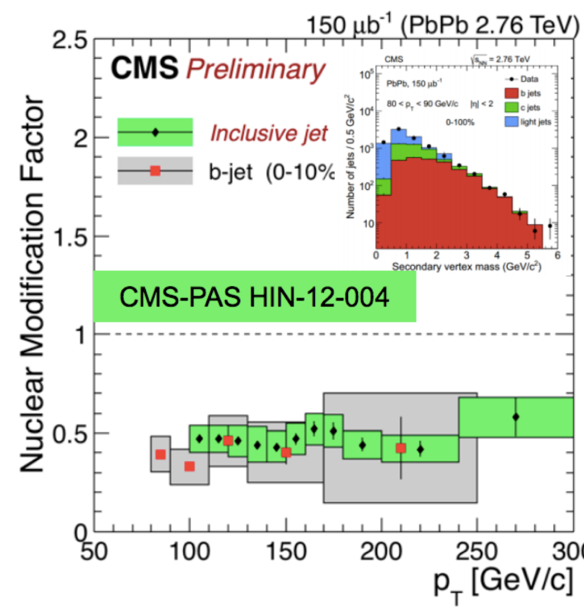
Beauty: B → J/ψ X and b-jets

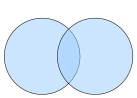
Nuclear modification factor as function of centrality and p_T

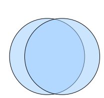
Beauty jets











of J/ψ !

CMS PAS HIN-12-014

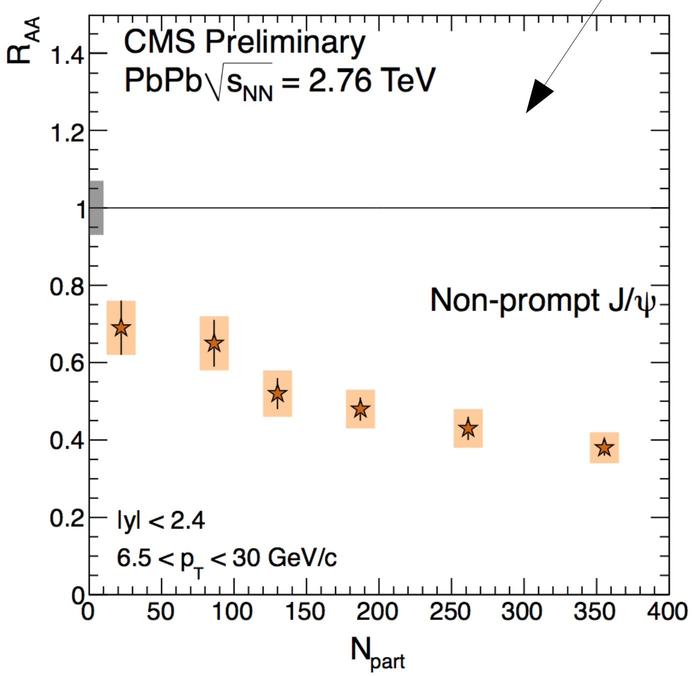
Strong suppression of beauty

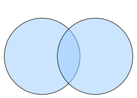
Beauty: B → J/ψ X

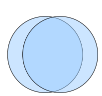
Nuclear modification factor as function of centrality and p_T

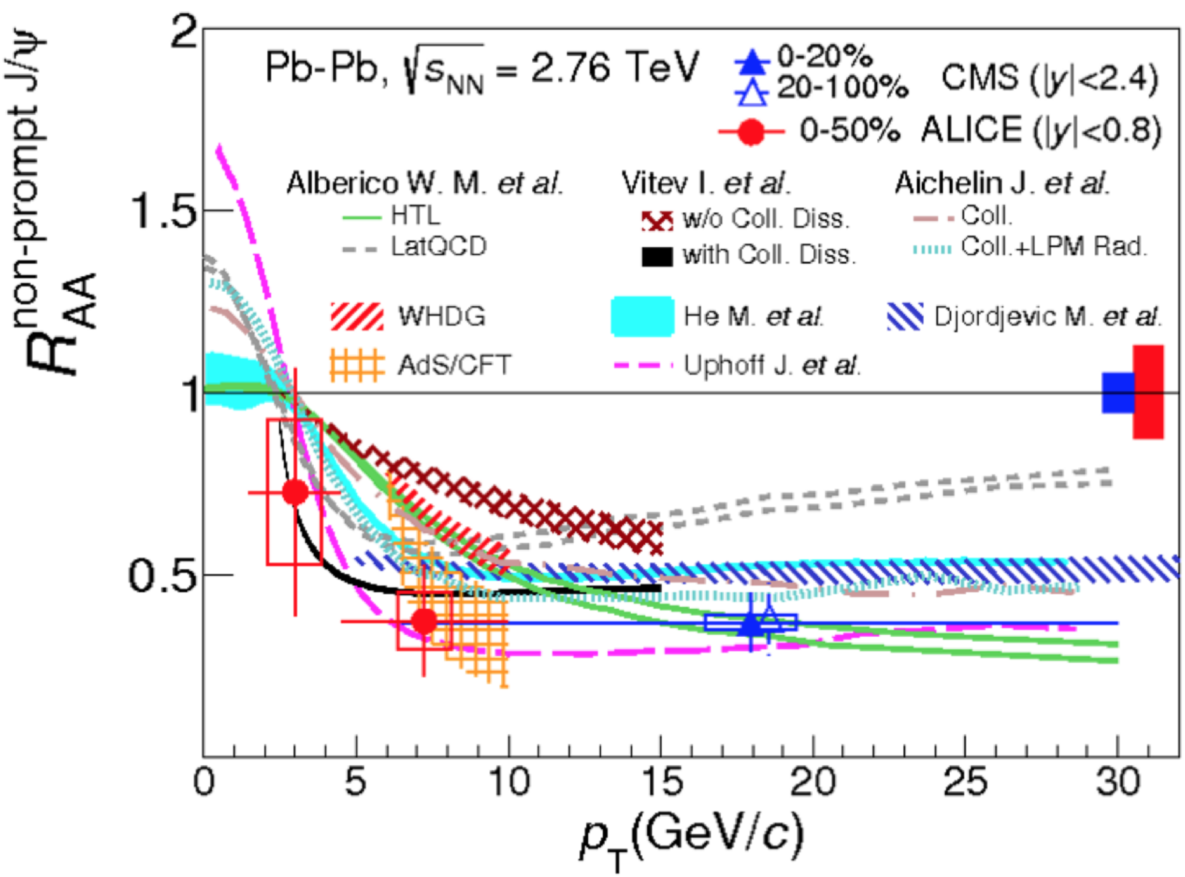
ALICE starts to reach lower p_T!

JHEP 1507 (2015) 051









CMS PAS HIN-12-014

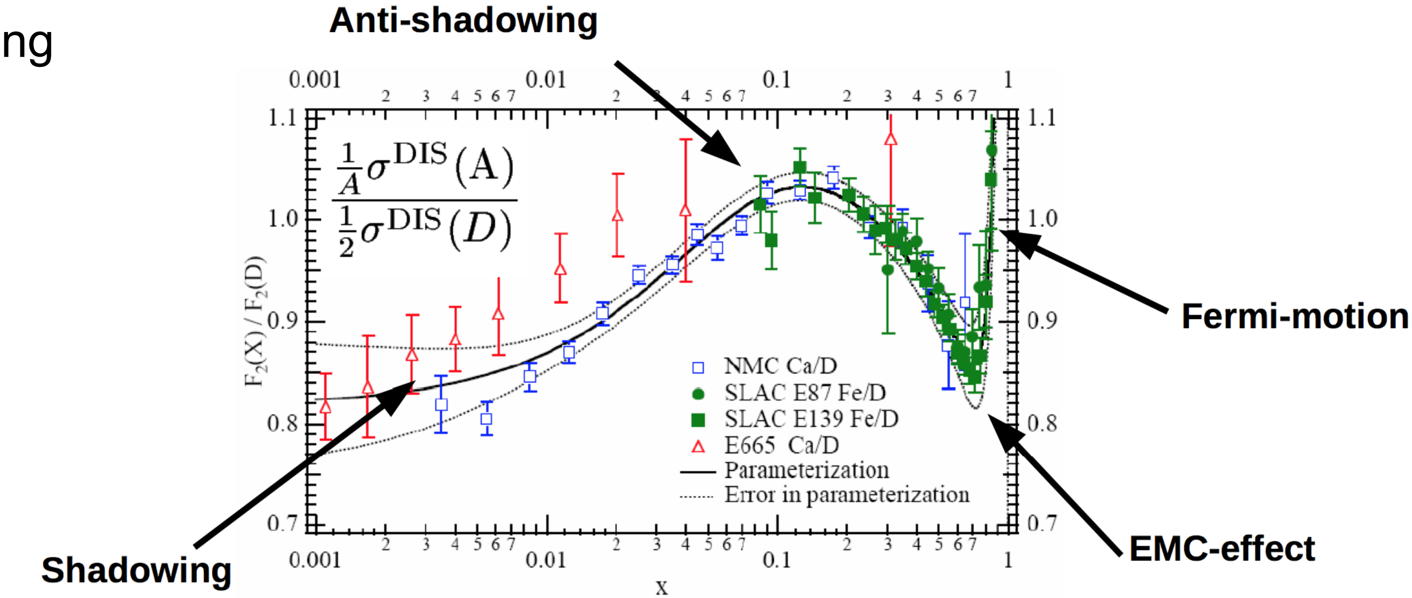
Strong suppression of beauty

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 ...



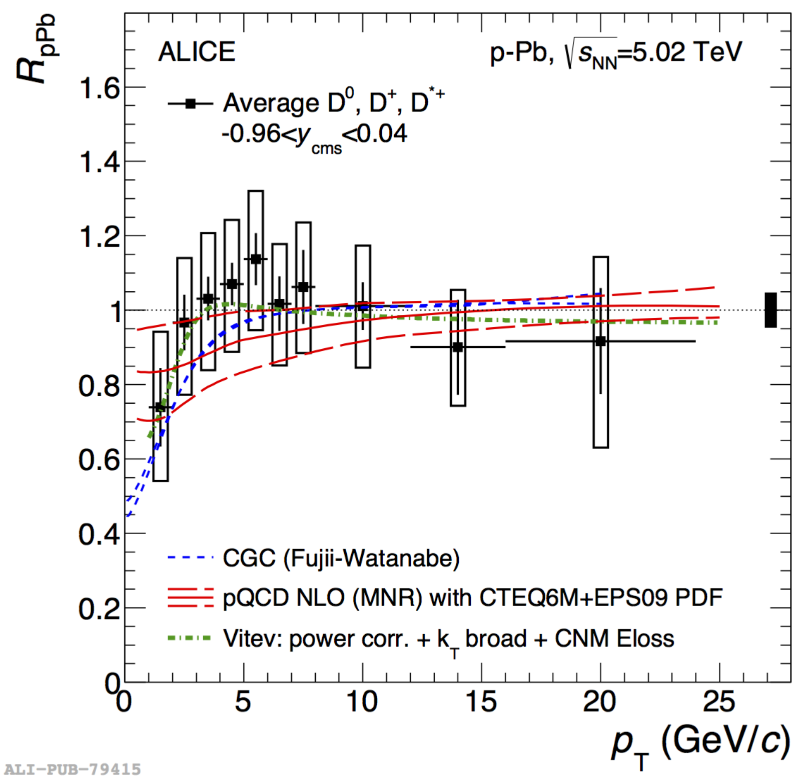
EPS90 Eskola, Paukkunen, Salgado

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

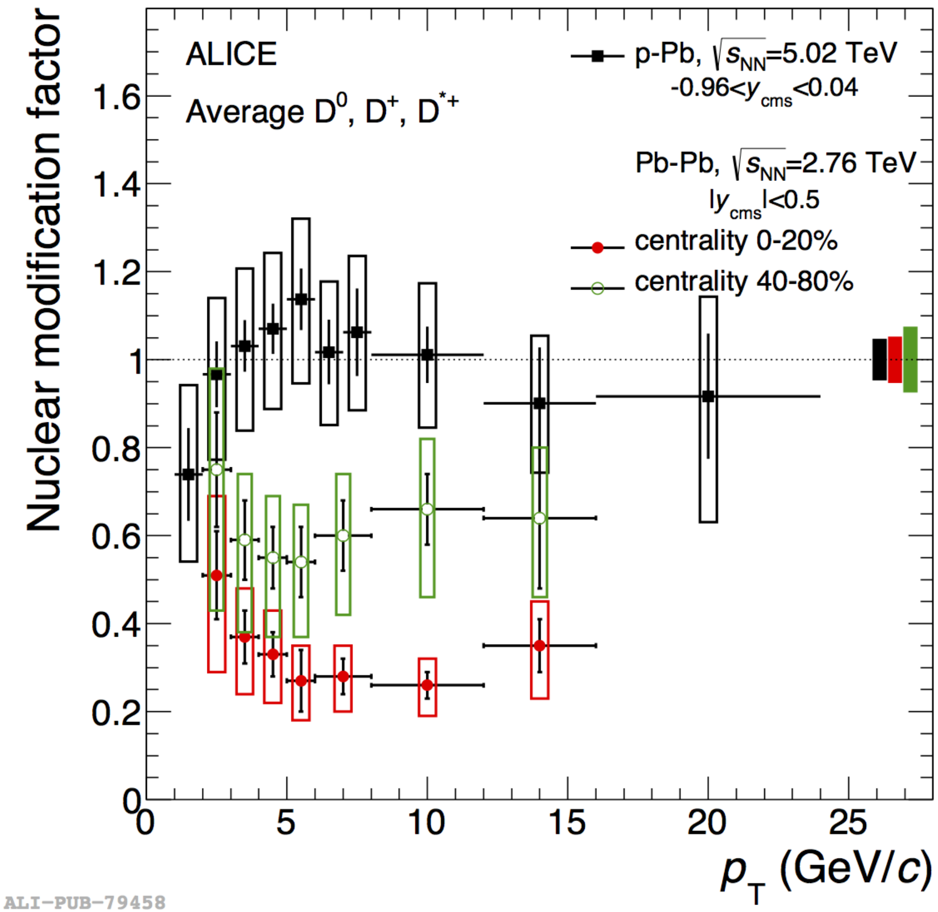
ALICE: D meson R_{pPb}

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

PRL 113 (2014) 232301

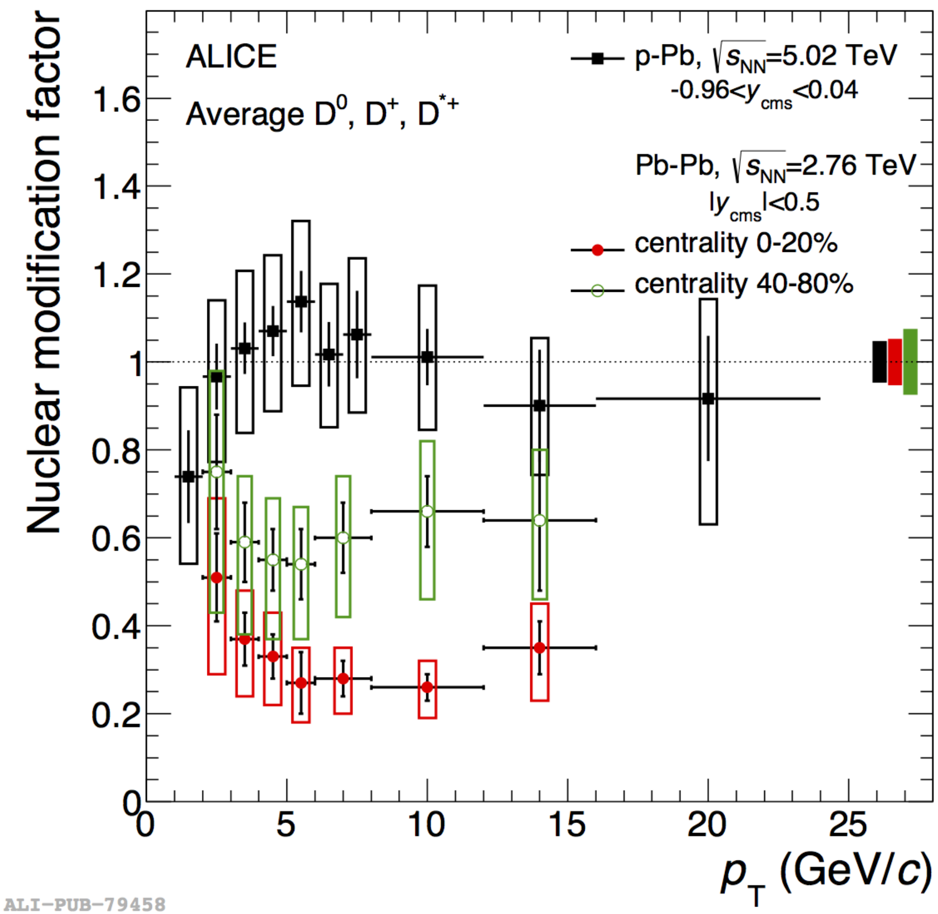


Compared to R_{AA}:



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

ALICE: D meson R_{AA} and R_{pA}



PRL 113 (2014) 232301

Comparison of R_{AA} (0-20% and 40-80%) with R_{pA} allow us to conclude:

Suppression (p_T > 3 GeV/c) is a final state effect

Interaction of charm quarks with the medium

As a matter of fact ...

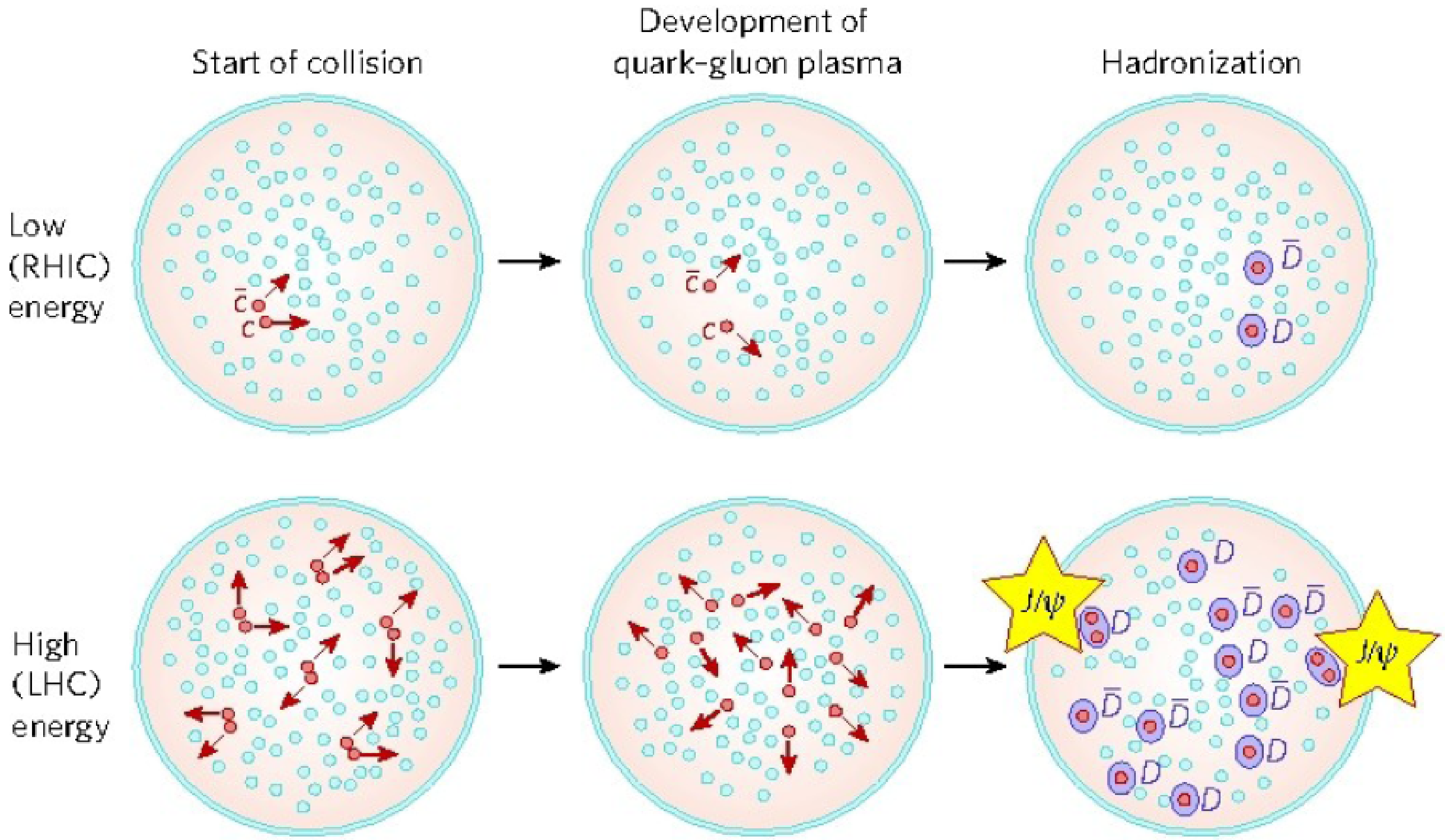
- Heavy-quark **energy loss**: collisional AND radiative, only collisional
- **Medium description**: hydrodynamic expansion, or Glauber model nuclear overlap without radial expansion
- Initial **heavy-quark production** in hard scatterings: pQCD (FONLL) or PYTHIA
- **Hadronisation**

  High p_T: fragmentation in vacuum

  Low p_T: some models include some recombination with light quarks from the medium
- Some models also include rescattering in the late **hadronic phase**
- Some include **shadowing** (nPDF, EPS09)

J/ψ production: mechanism?

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



Coming up

- **RHIC**: both STAR and PHENIX have new microvertex detectors
  → 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