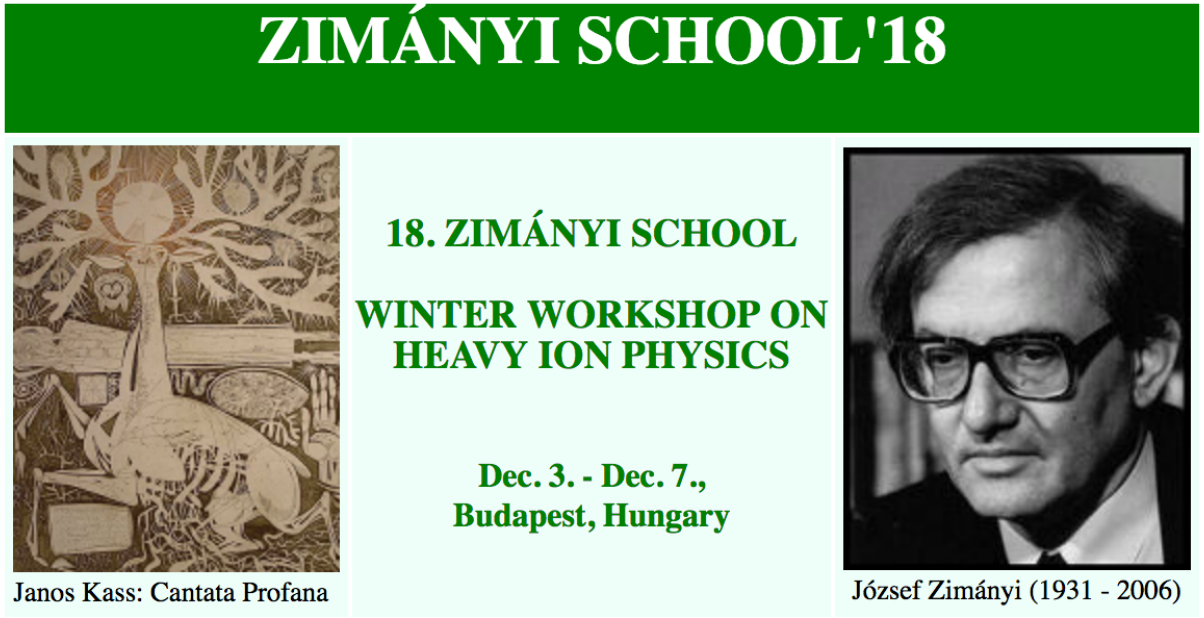
Silvia Masciocchi (GSI Darmstadt and Uni Heidelberg)

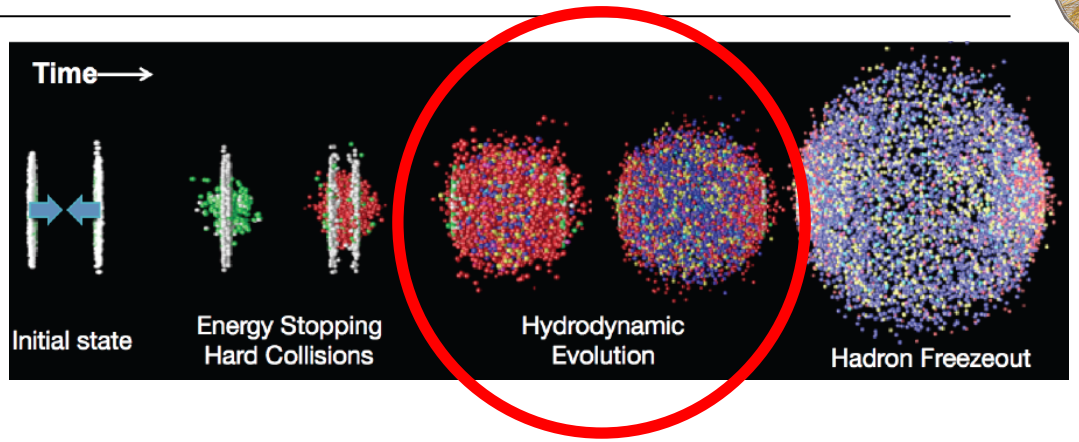
Overview
Heavy-flavor experimental results



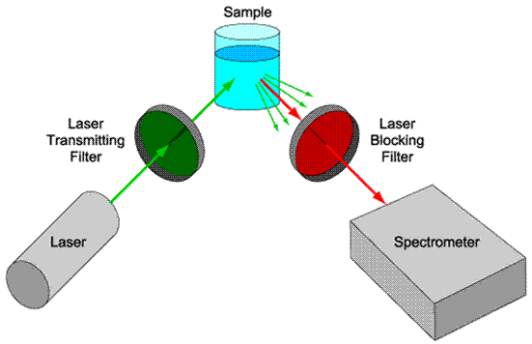
Why open heavy flavors?

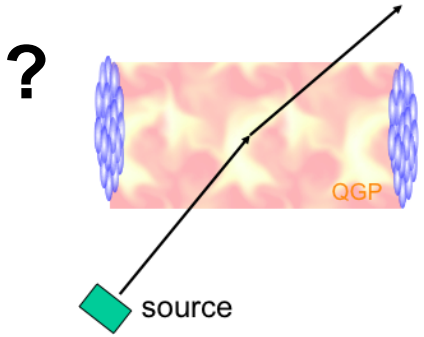
Determine characteristics of QCD matter during the quark-gluon plasma phase

$$10 \text{ fm/c} \approx 10^{-22} \text{ s}$$



Use external penetrating probes?





Courtesy of Yen-Jie Lee

Not possible!

→ Use auto-generated (hard) probes !

Why open heavy flavors?

Charm:
m ~ 1.5 GeV/c^2

Beauty:
m ~ 5 GeV/c^2

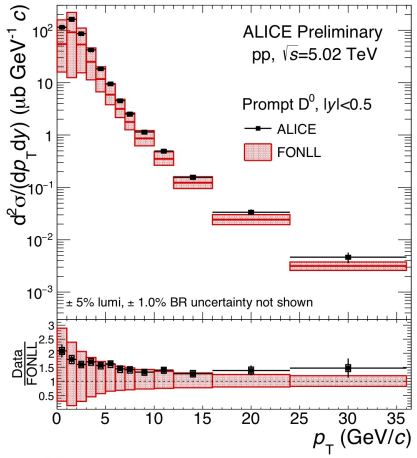
$m_{c,b} \gg \Lambda_{QCD} \rightarrow$ hard probes, even at low momentum (≠ jets)

- Large mass: can only be produced in hard scattering processes, very early in the collision history:

$$\text{charm (beauty) formation time} = \frac{\hbar}{4m_{c(b)}} \approx 0.05(0.01)\,\text{fm/c} < \text{QGP thermalization time}$$

- Production in hadronic collisions described by **perturbative QCD** approaches (FONLL, GV-VFNS, etc), affected by very large uncertainties

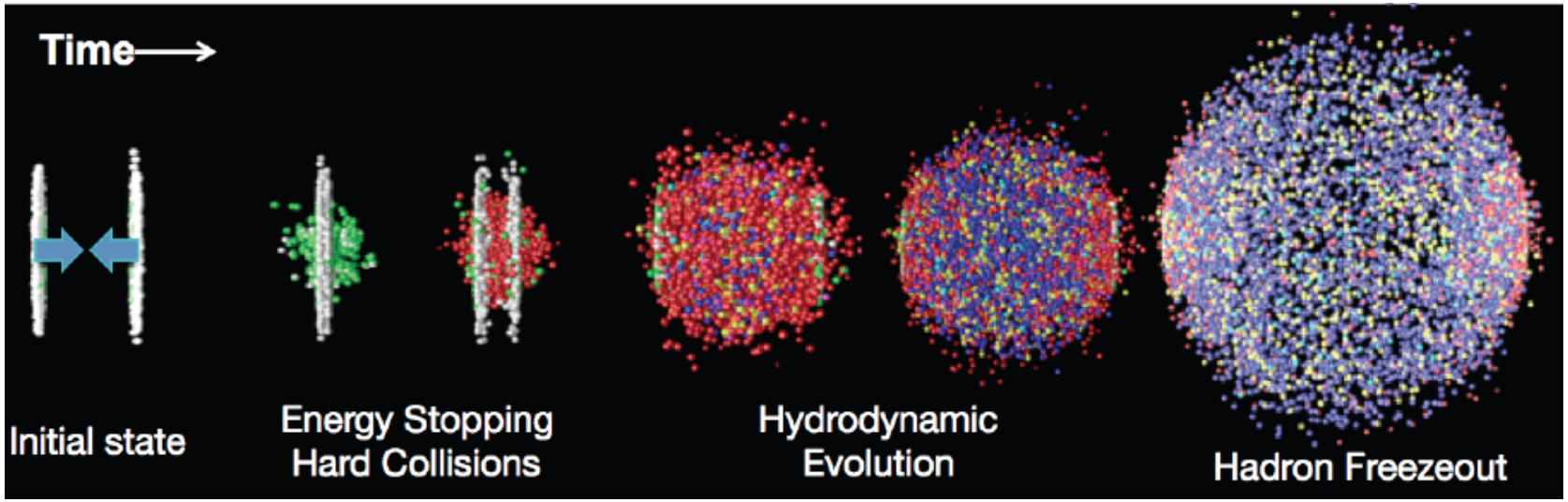
- Production in Pb-Pb or p-Pb collisions, **nuclear PDFs** must be considered (e.g. shadowing)



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

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



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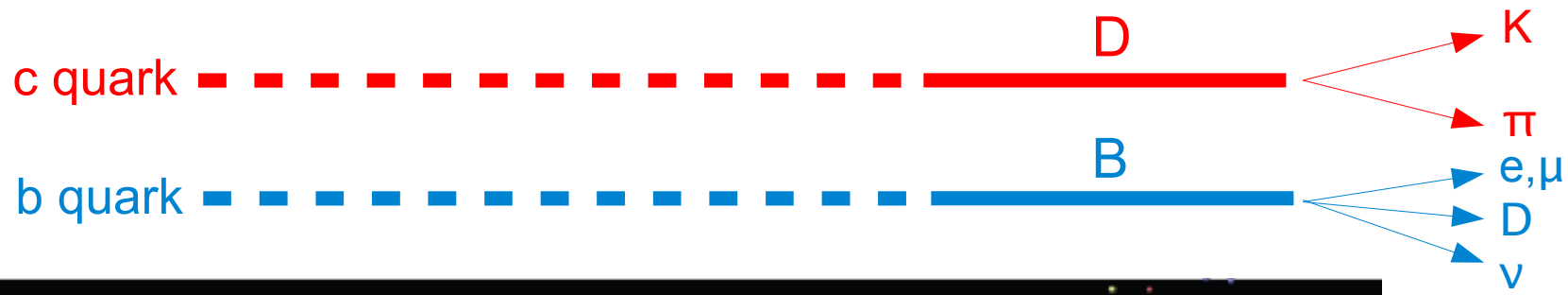
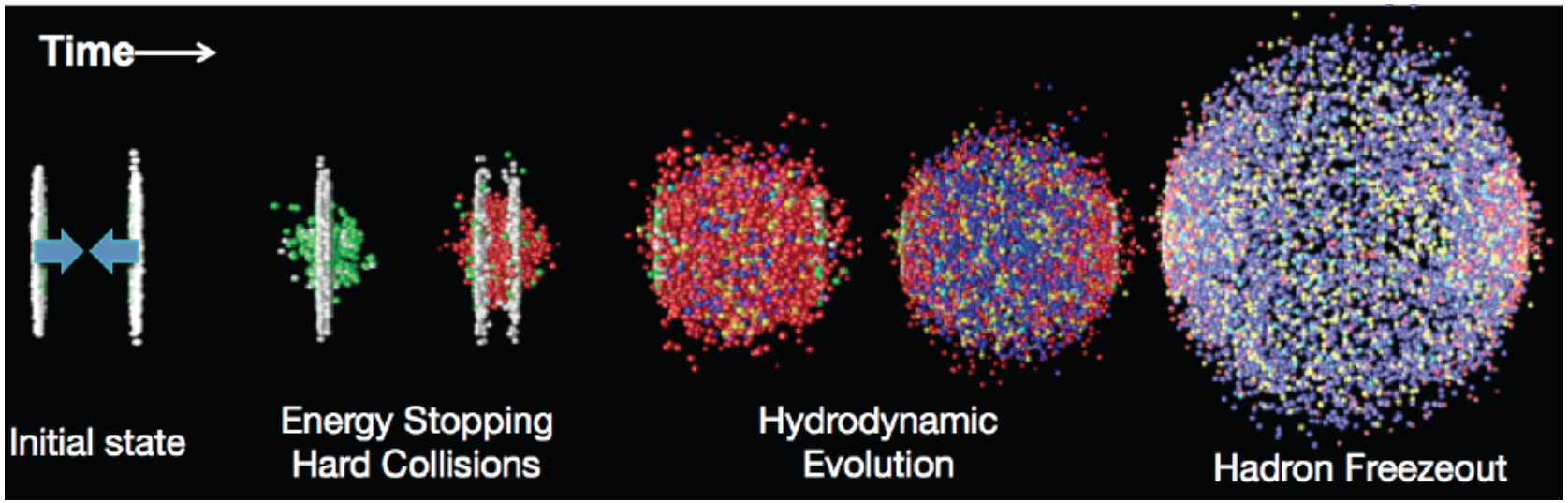
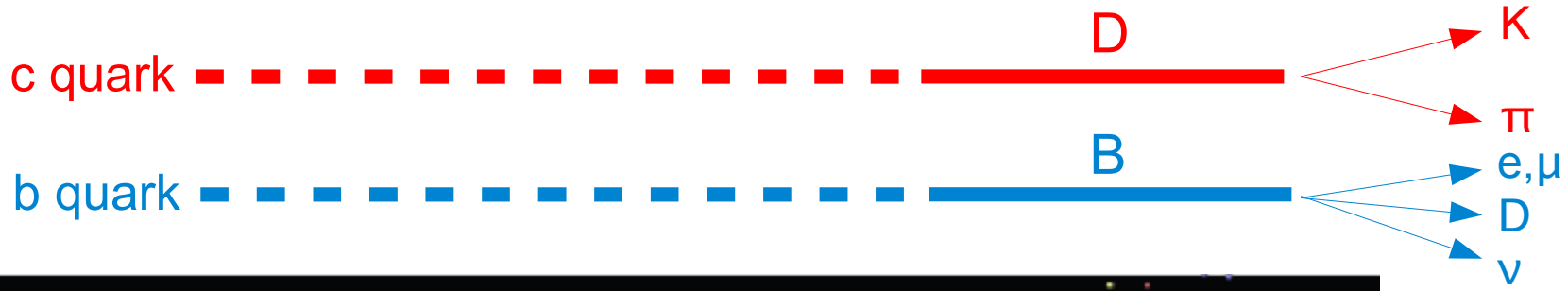


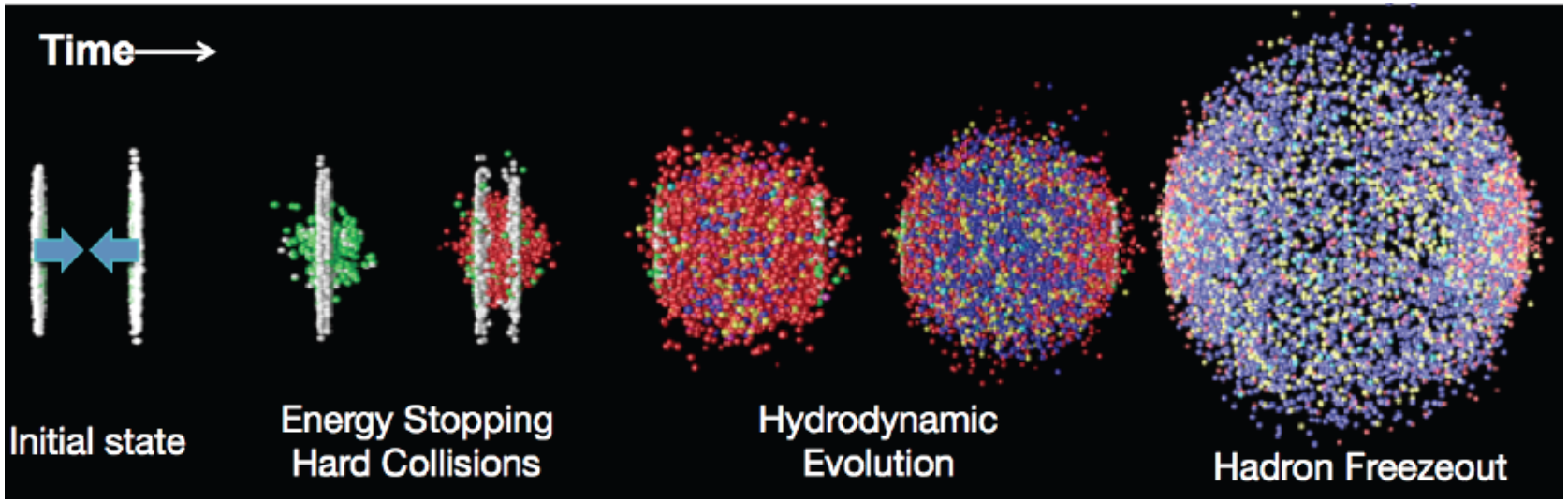


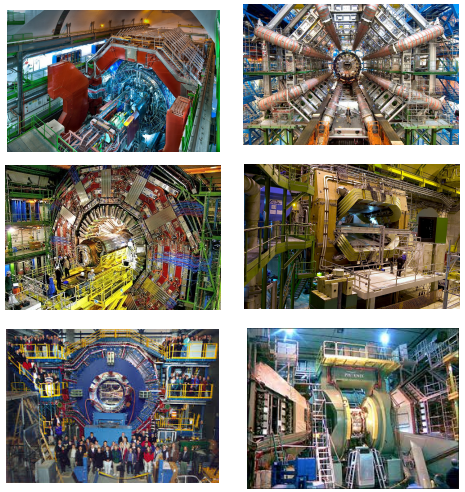
Heavy flavors experience the full evolution of the deconfined medium → QGP properties

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





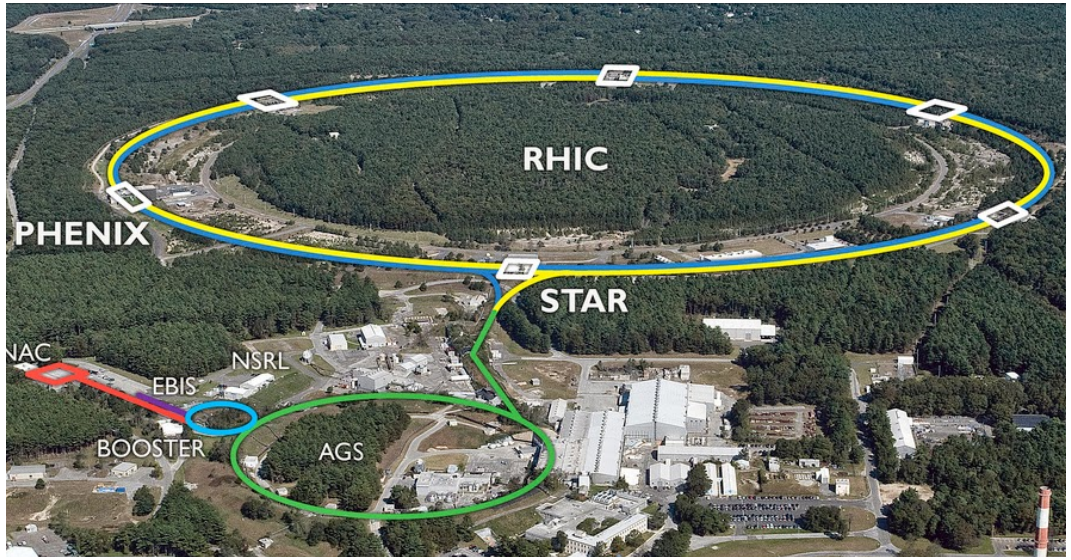


Heavy flavors experience the full evolution of the deconfined medium → QGP properties

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, 5.02 TeV , p, Pb
- ALICE, ATLAS, CMS, LHCb

Key ingredients

- High center of mass energy → large $c\bar{c}$ and $b\bar{b}$ **production cross sections**!

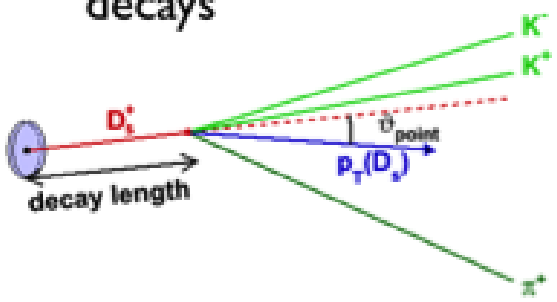
- Silicon **vertex detectors** → high spatial resolution
  → precise secondary vertex reconstruction
  Most of the times: good particle identification

- **High statistics** → better statistical precision
  → access to more probes, more exclusive decay channels, more differential measurements

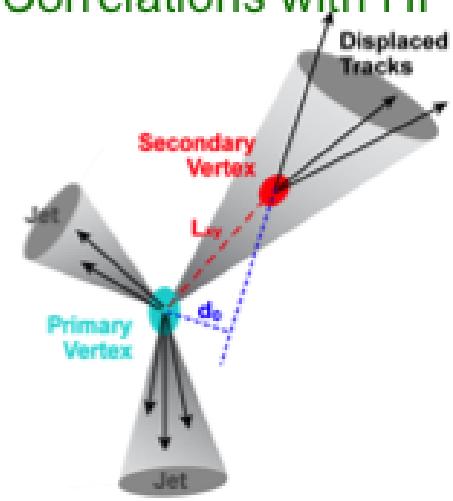
Open heavy flavor hadrons: richness of channels

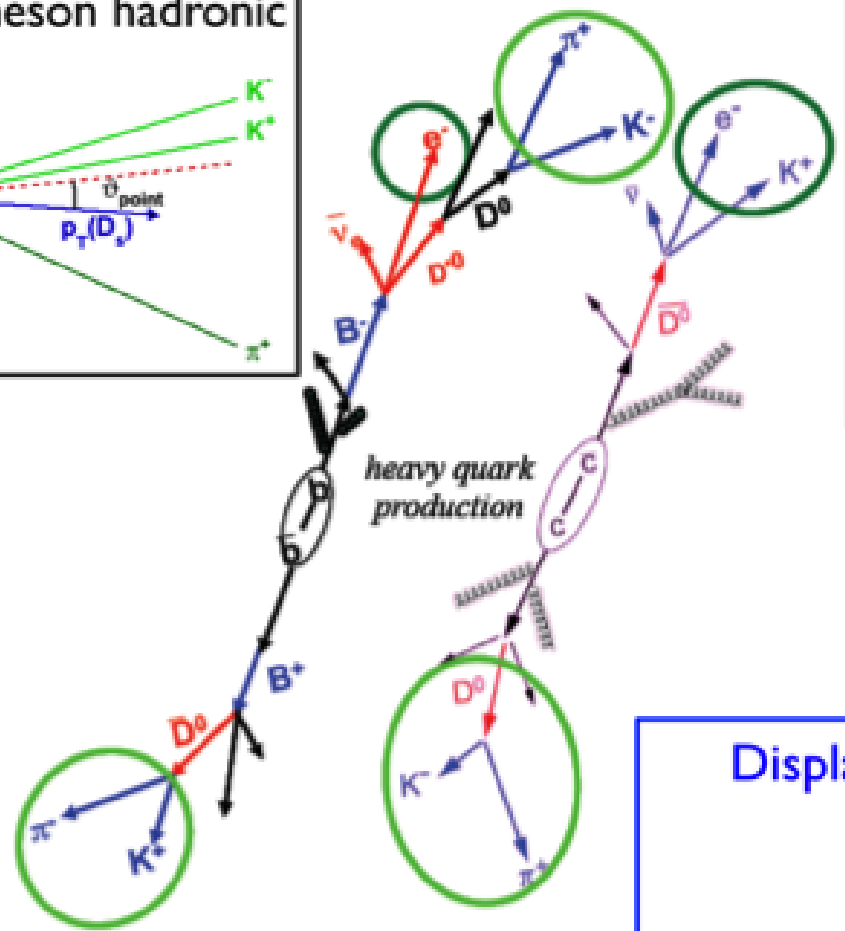
Full reconstruction of D meson hadronic decays

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

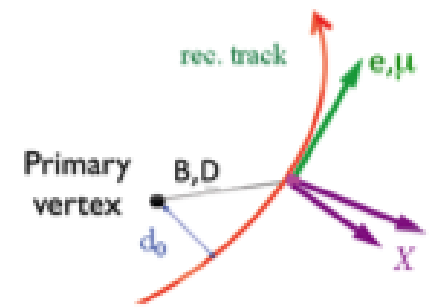


HF jets
Correlations with HF



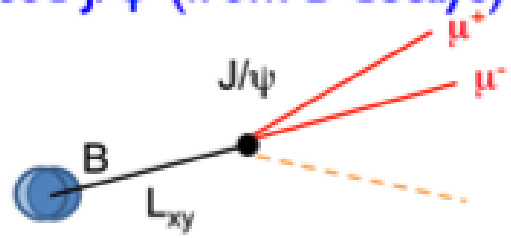


Semi-leptonic decays (c,b)



Now also exclusive B meson decays!

Displaced J/ψ (from B decays)



Fundamental questions and observables

- **Parton 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 (R_{AA})

- **Thermalization?**

  Do the heavy quarks thermalize in the medium?
  To what degree do they participate to the collective motion?

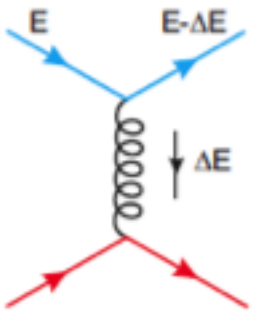
  - Elliptic flow (v_2)

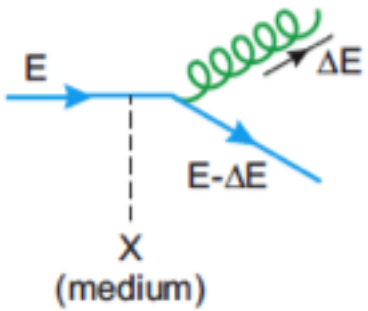
- **Hadronization mechanism**

  How does hadronization happen? Is there a modification in the QGP?

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
  - Quark mass $\Delta E_c > \Delta E_b$ → charm and beauty

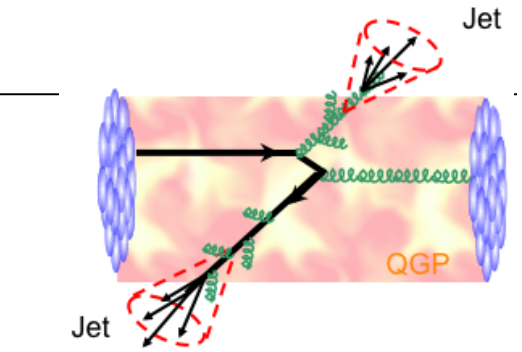
Quantifier: the **nuclear modification factor**

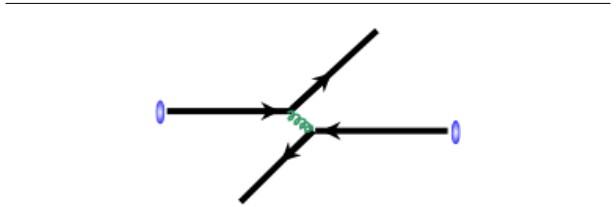
$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$

binary collisions

as function of p_T and centrality

Nuclear modification factor





Courtesy of Yen-Jie Lee

No medium effect $\rightarrow$ $R_{AA} = 1$

Medium effect $\rightarrow$ medium "slows" down particles

$\rightarrow$ $R_{AA} \neq 1$

- 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

Prompt charm: R_{AA}

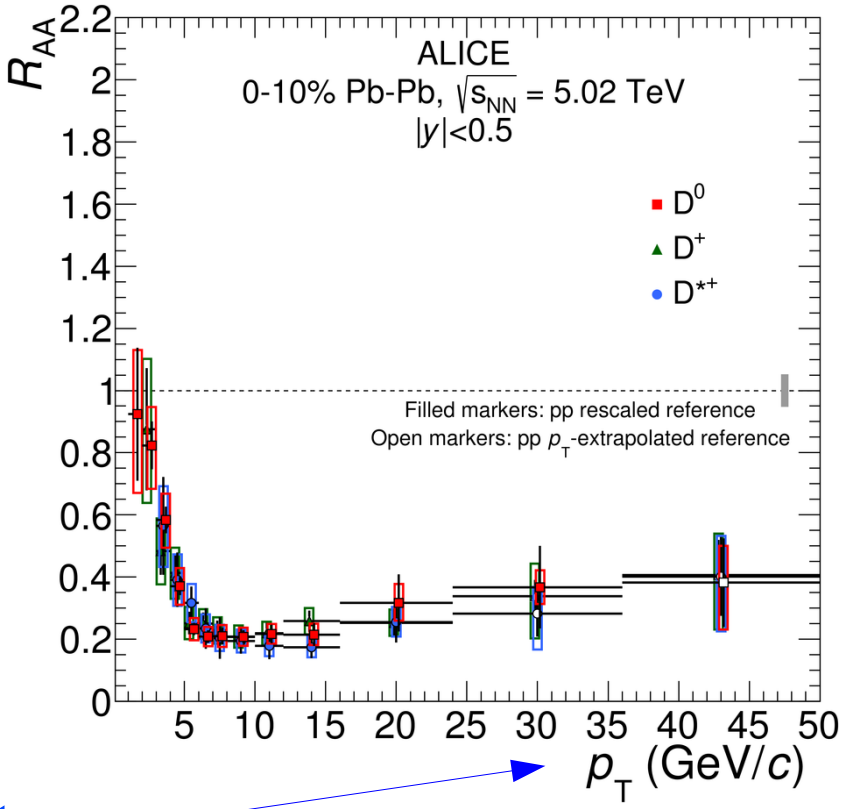
Strong suppression of charm mesons (increasing with centrality)

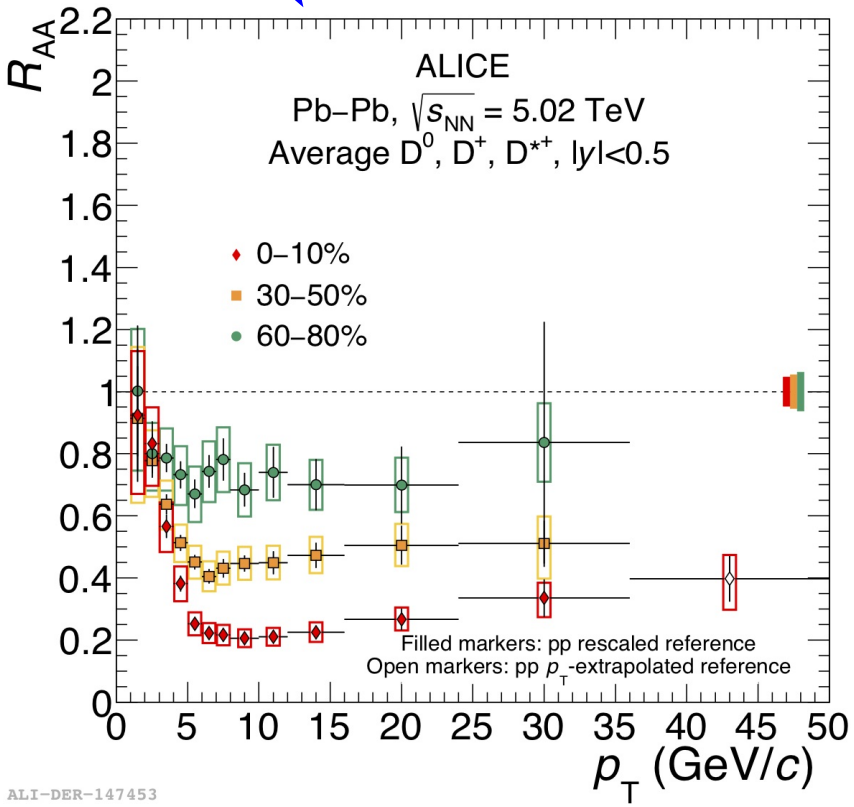
Significant energy loss of charm quark in the QGP

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

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$





Transverse momentum

arXiv: 1804.09083

Prompt charm: R_{AA} and R_{pPb}

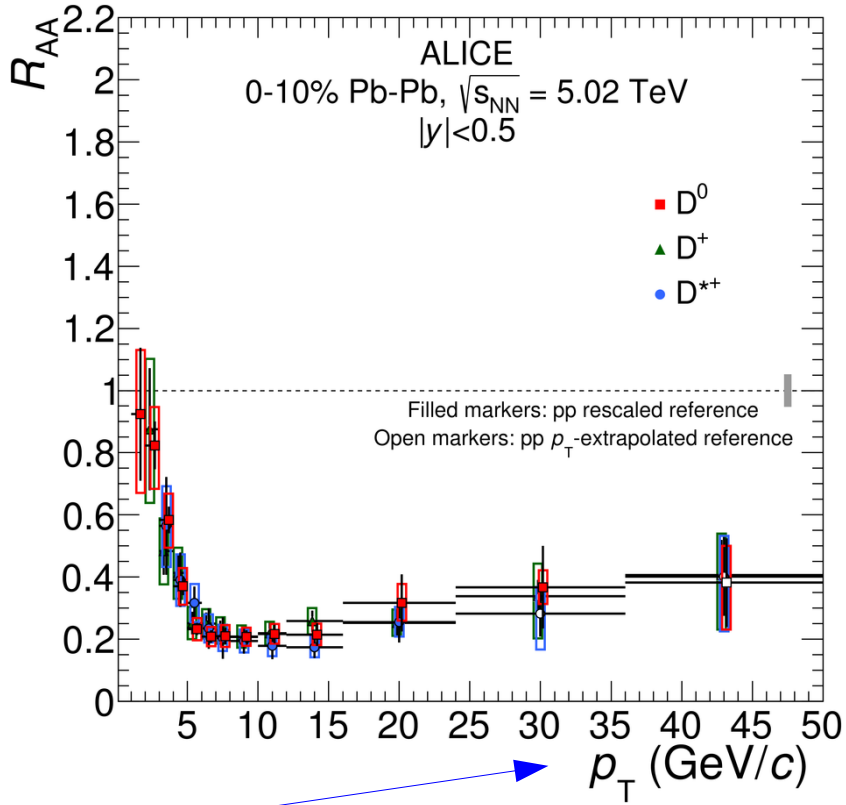
Strong suppression of charm mesons

Significant energy loss of charm quark in the QGP

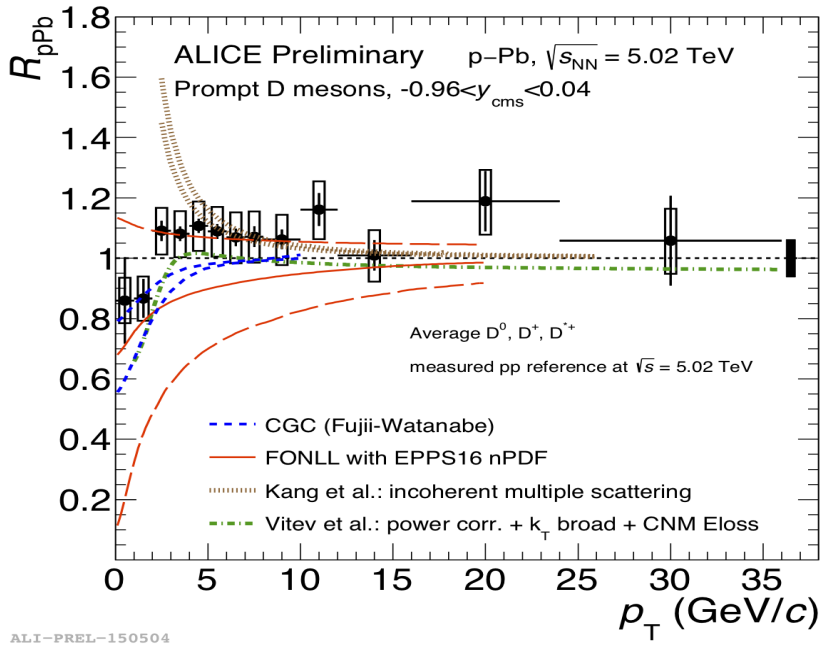
$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$



Theory models including cold nuclear matter effects only (e.g. shadowing)



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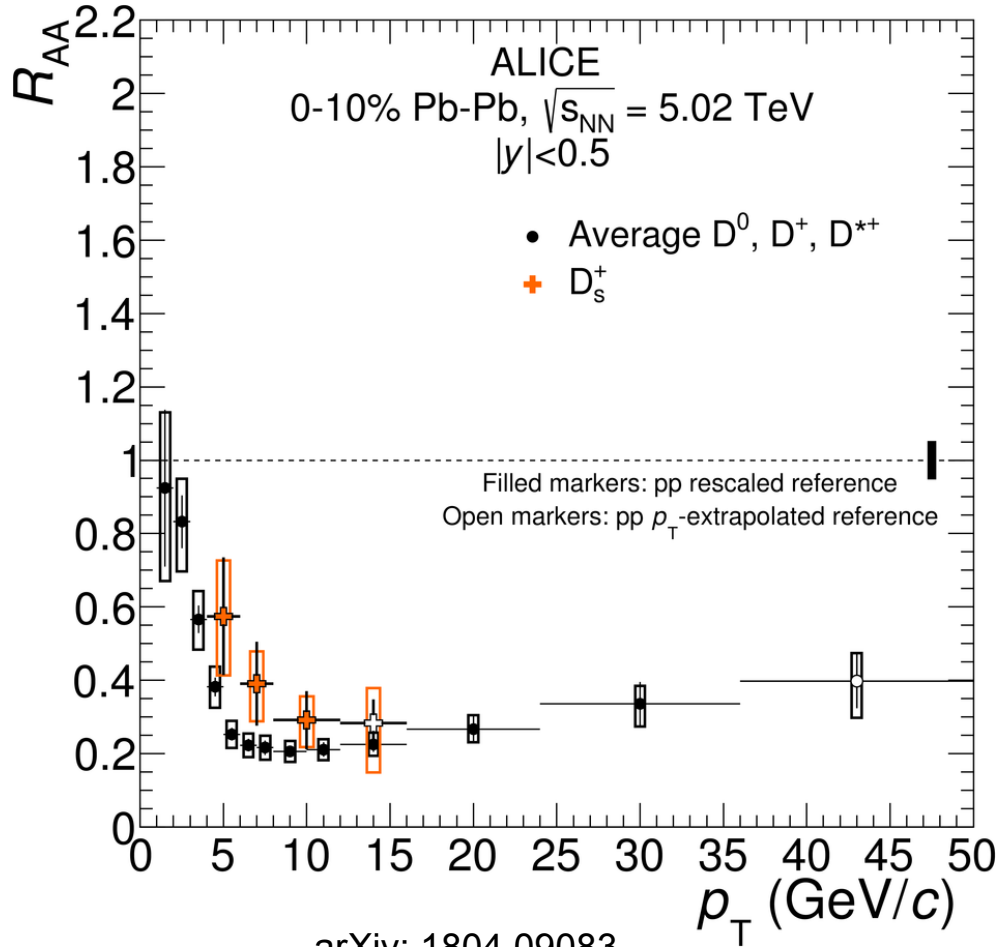
$D^{*+} \rightarrow D^0 \pi^+$

$D_s^+ \rightarrow \varphi\pi \rightarrow K^+K^- \pi^+$

Modification of hadronization in presence of a medium?
fragmentation vs recombination

Abundance of strange quarks in the medium → possible enhanced production of D_s at low p_T?



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$D_s^+ \rightarrow \varphi\pi \rightarrow K^+K^- \pi^+$

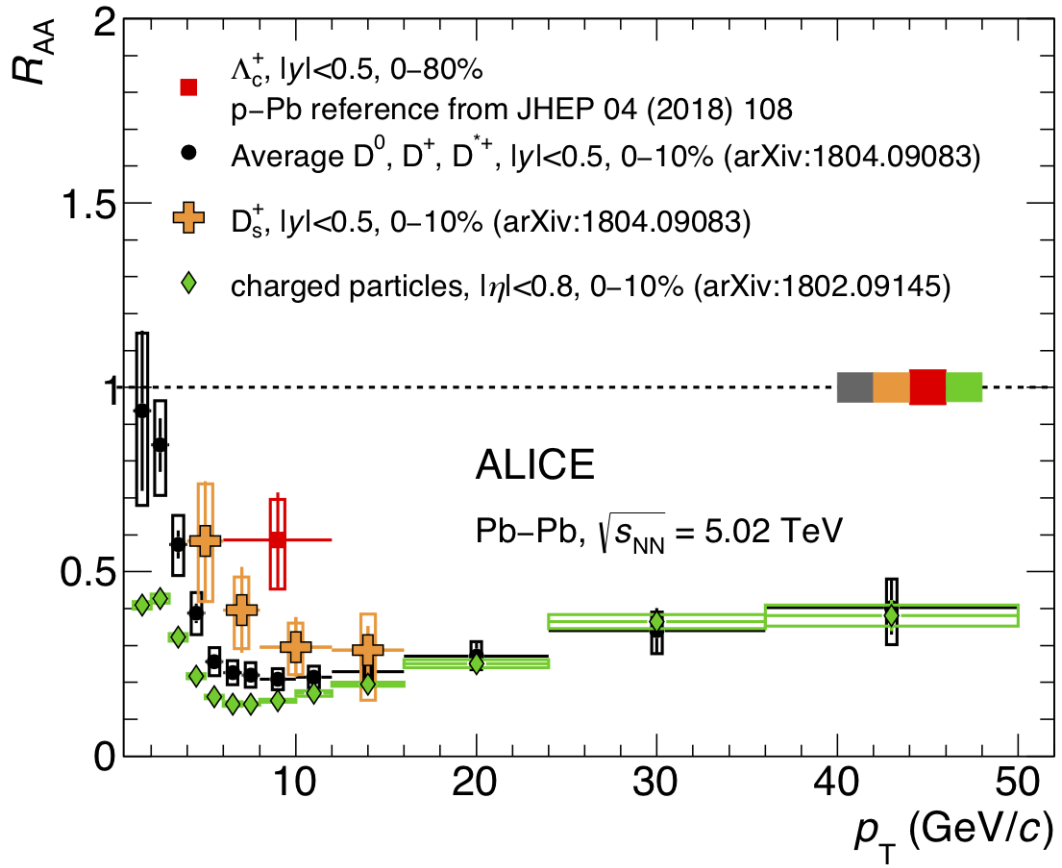
$\Lambda_c \rightarrow p\, K^0_s$

Baryon / meson ratio:

$$\left(\frac{\Lambda_c}{D^0}\right)_{PbPb} > \left(\frac{\Lambda_c}{D^0}\right)_{pp}$$

Hadronization mechanism: coalescence?

Indication of charm hadron formation in the medium

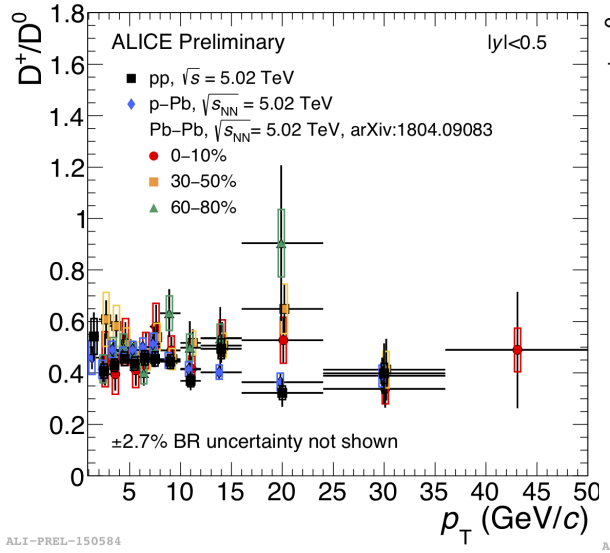


arXiv: 1804.09083, arXiv:1809.10922

Hadronization

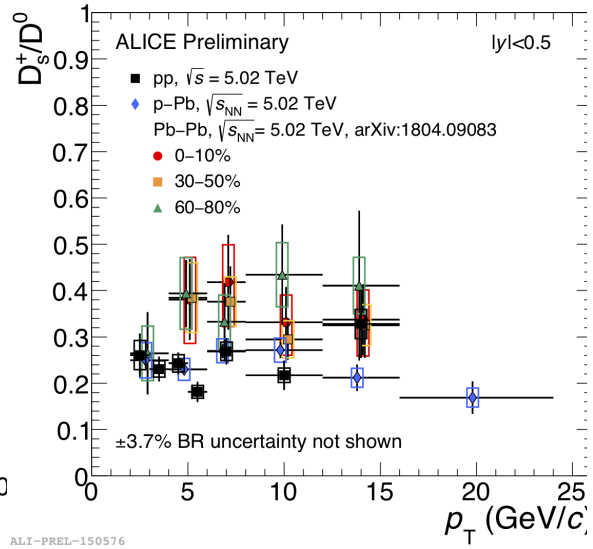
Ratio of particle spectra: proton-proton
proton-lead
lead-lead

D^+/D^0



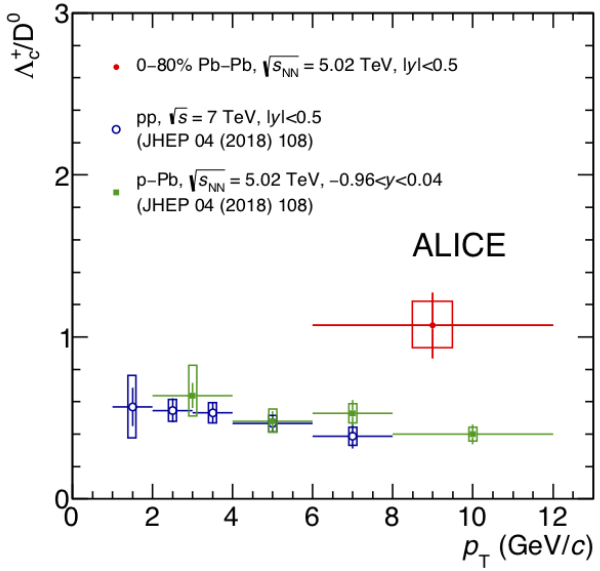
No modification for non-strange D mesons

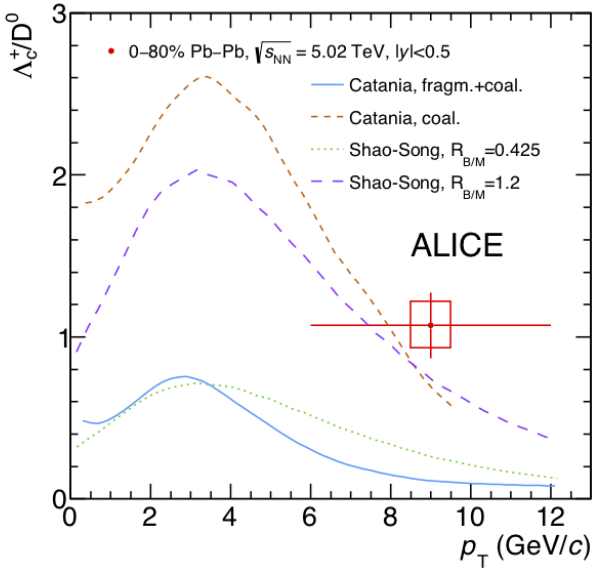
D_s/D^0



Hint of enhancement of D_s in Pb-Pb (1σ)

Λ_c/D^0





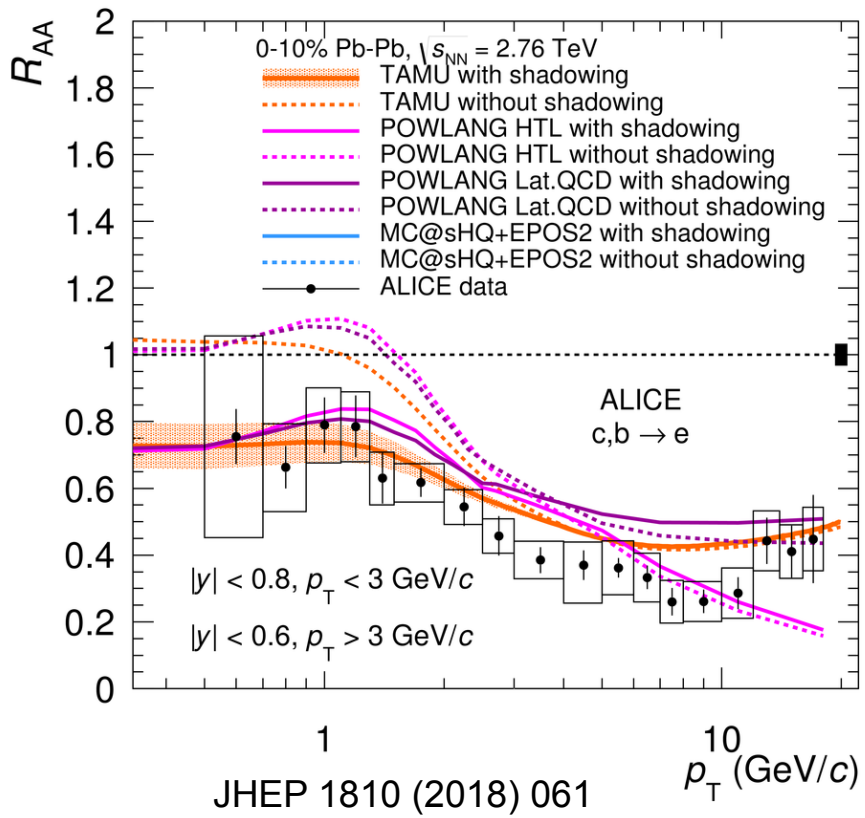
2σ higher ratio in Pb-Pb wrt pp and p-Pb

Effects can be described by models including (only) coalescence

Charm and beauty: semi-leptonic decays

Hadrons with charm, hadrons with beauty → e (μ) + X

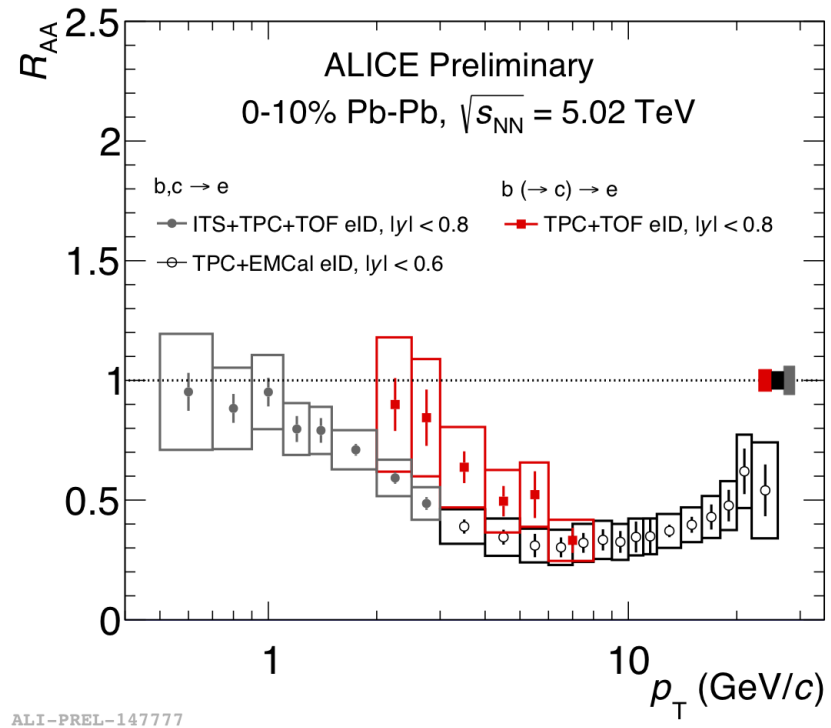
R_{AA}: Pb-Pb / pp



JHEP 1810 (2018) 061

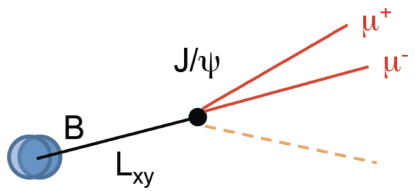
Models with and without **shadowing**

hadrons with **beauty** → e (μ) + X
5.02 TeV

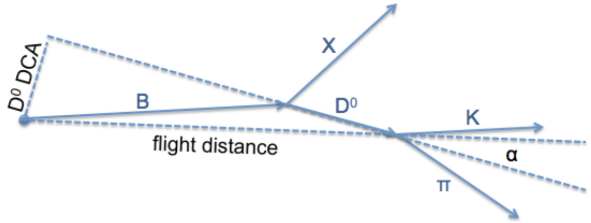


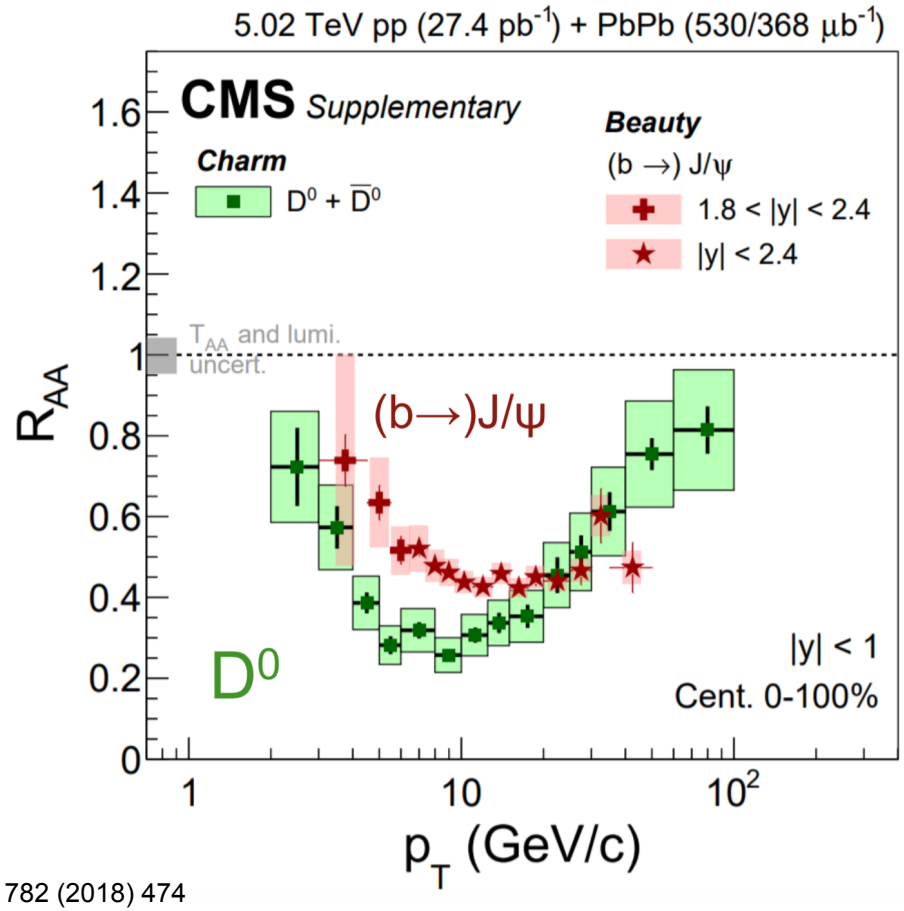
Beauty R_{AA}

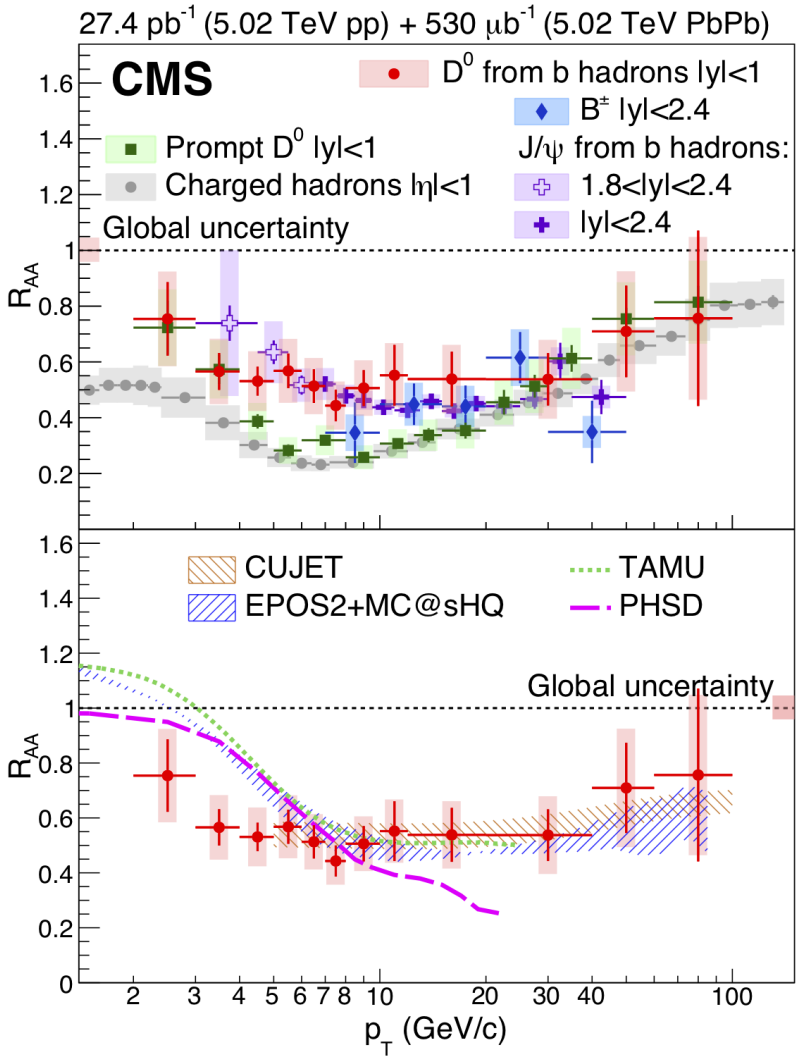
Non-prompt J/ψ



Non-prompt D^0







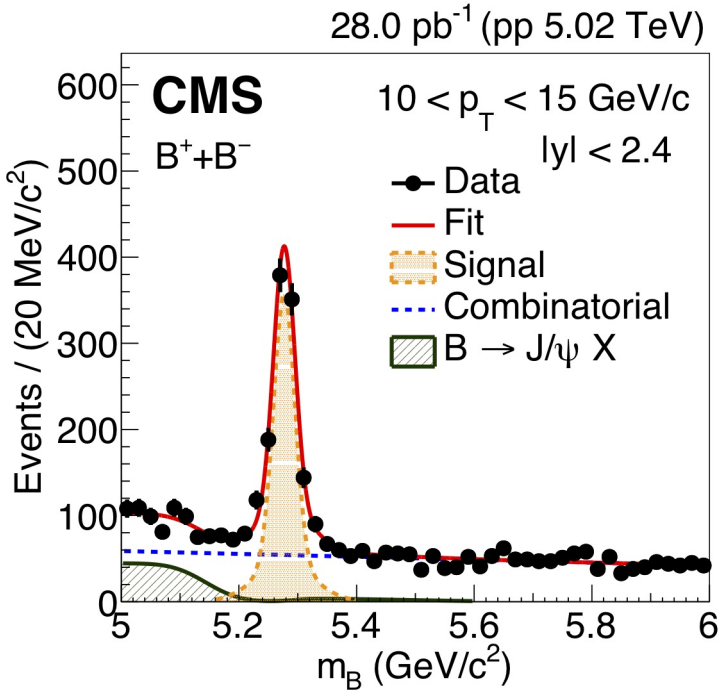
D^0 - PLB 782 (2018) 474
J/ψ - EPJC 77 (2017) 269

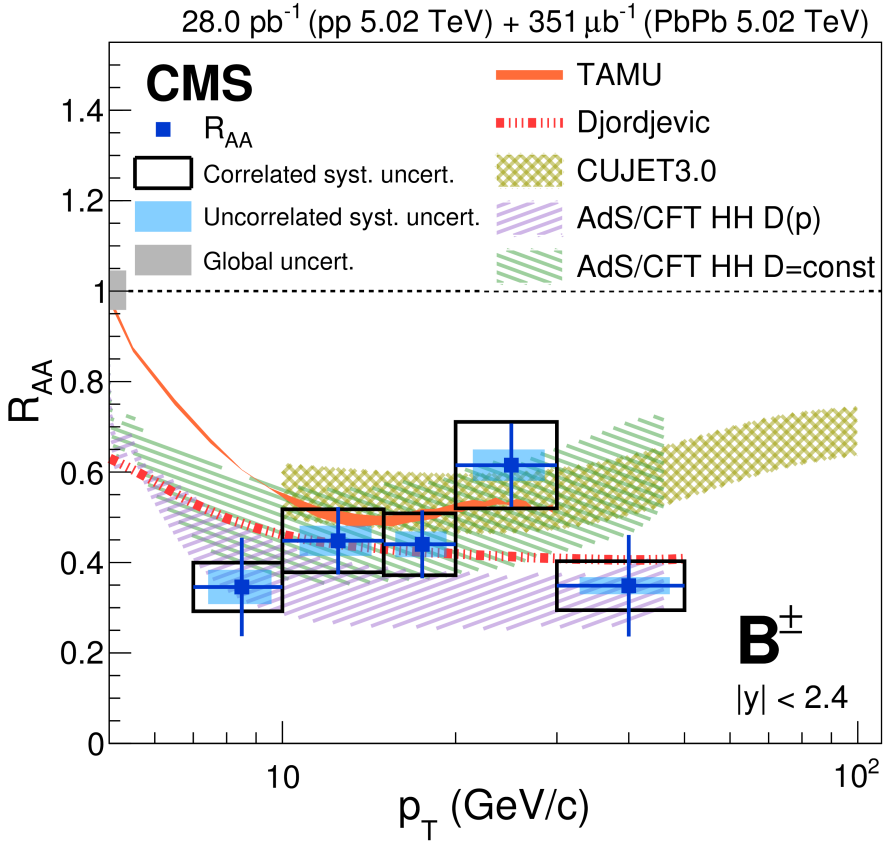
b→D^0 CMS-PAS-HIN-18-010
$B^{\pm}$ PRL 119 (2017) 152301

Beauty R_{AA}

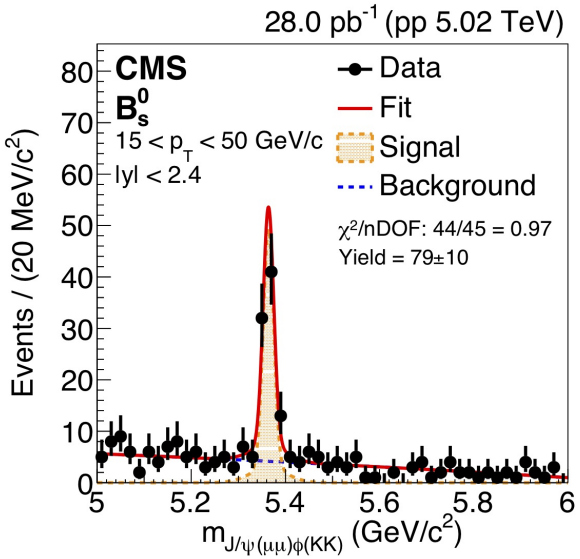
Reconstruction of exclusive decay channels

$B^{\pm} \rightarrow J/\psi\ K^{\pm} \rightarrow \mu^{+}\mu^{-}K^{\pm}$



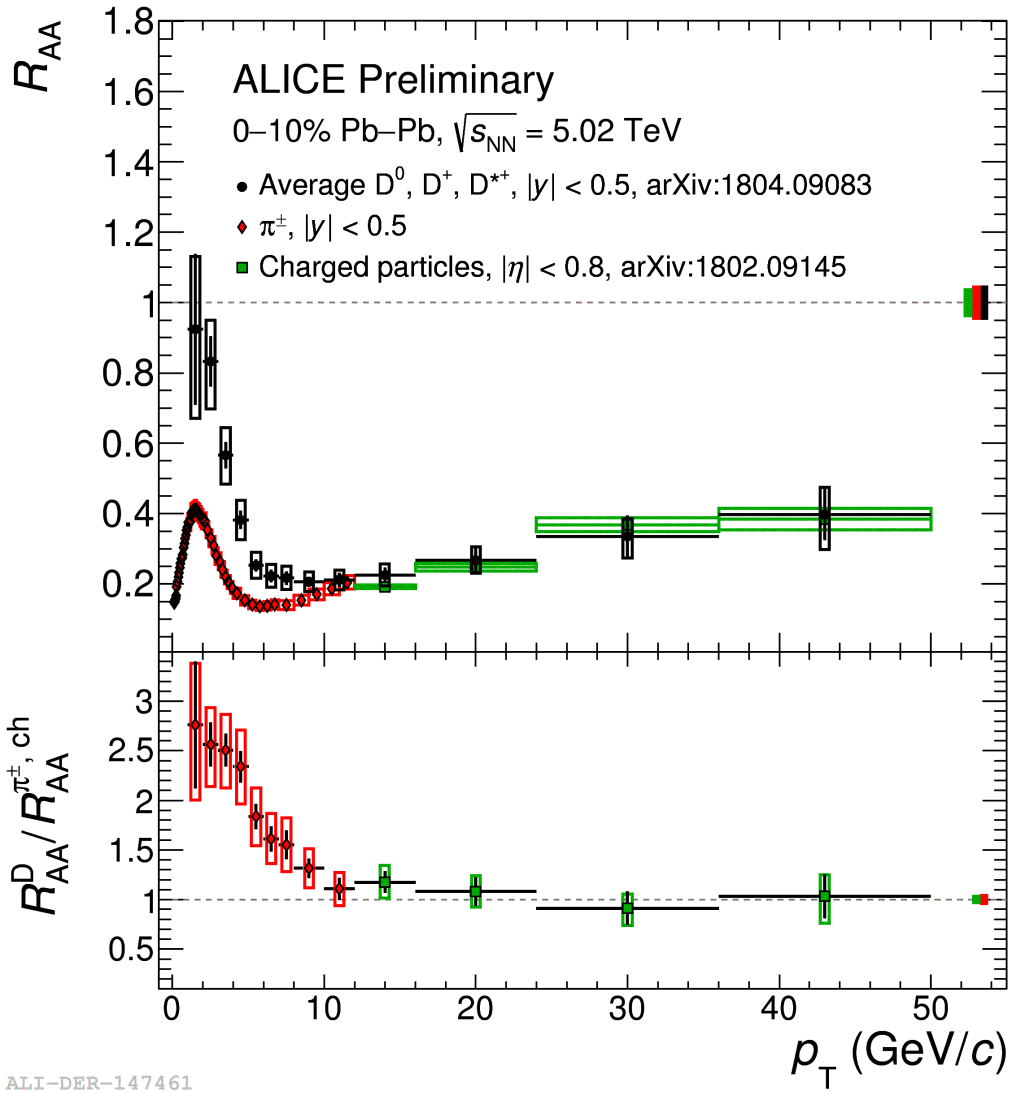


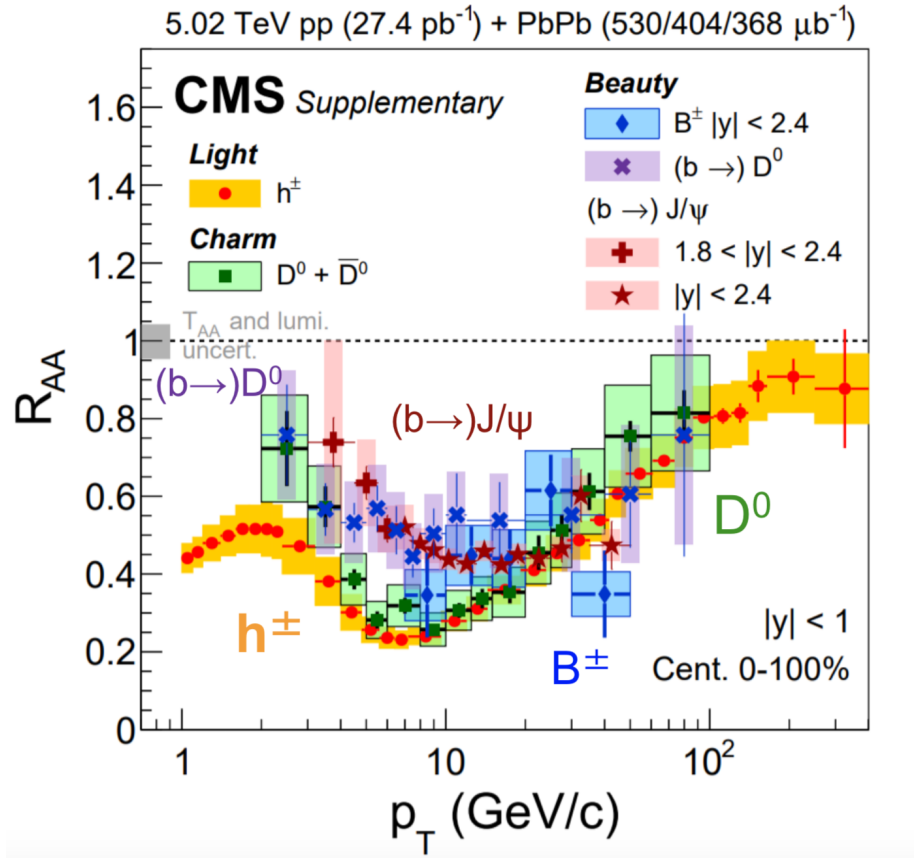
$B_S^0 \rightarrow J/\psi\ \varphi \rightarrow \mu^{+}\mu^{-}K^{+}K^{-}$



$B^{\pm}$ PRL 119 (2017) 152301

Compilation of light, charm and beauty hadrons R_{AA}



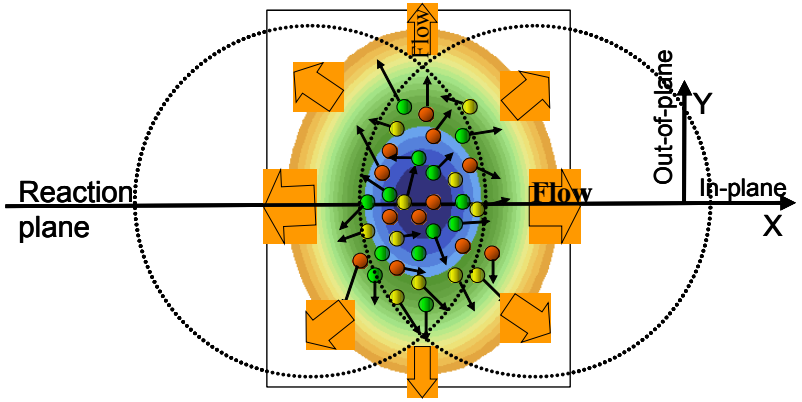


- Ordering with parton mass ...
- ... as long as the hadron $p_T \leq$ mass

Further precision will increase significance

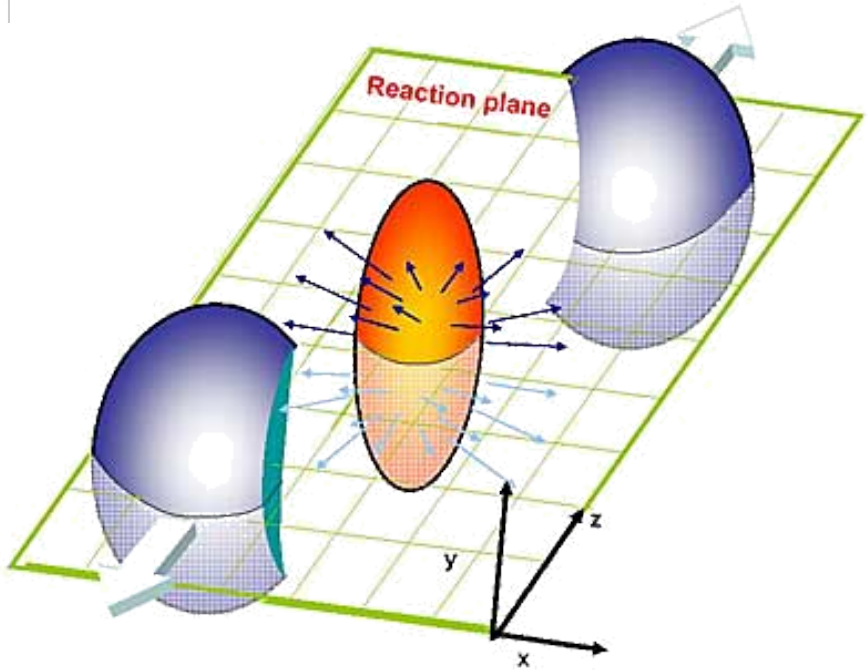
Elliptic flow: v_2

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



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

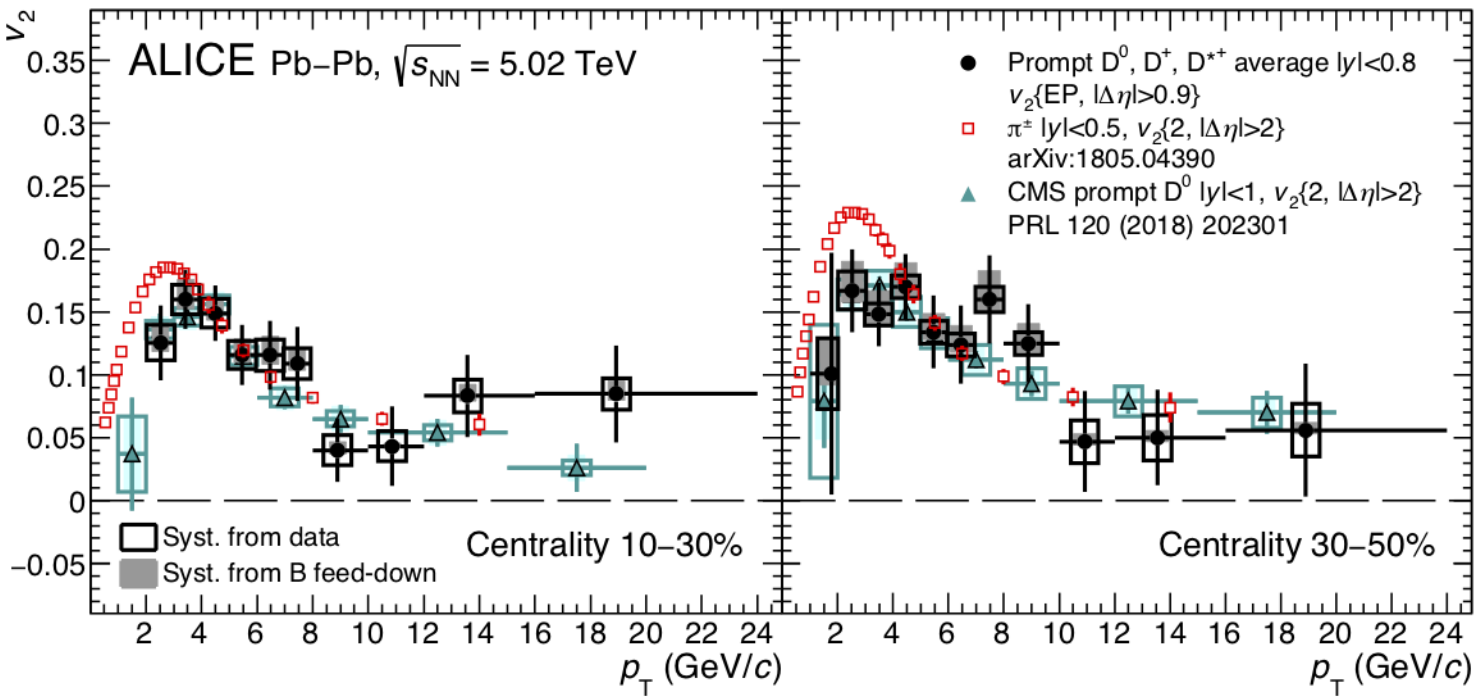
- Degree of participation of charm to the collective motion of the medium: $v_2 > 0$ at low p_T
- Path length dependence of energy loss: at high p_T



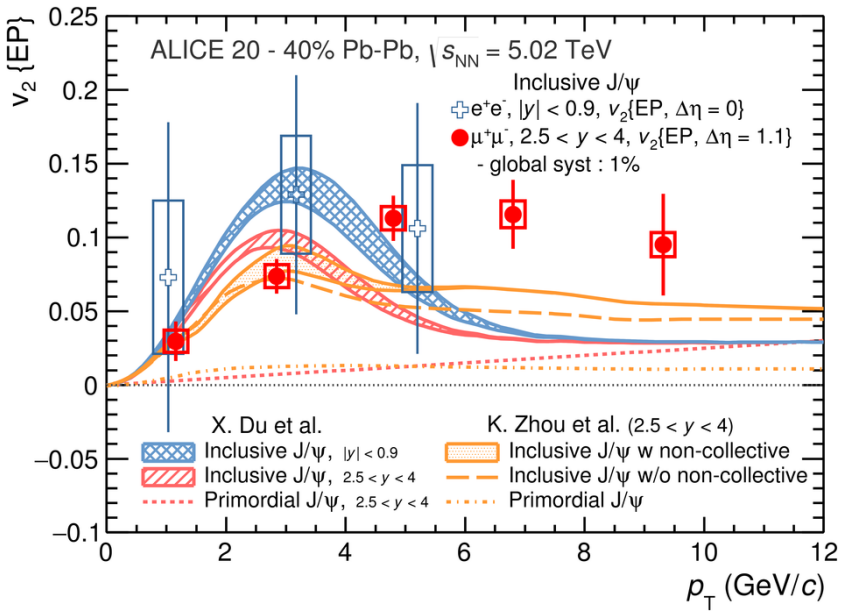
Prompt D^0 mesons v_2

Inclusive J/ψ v_2

CMS: PRL 120 (2018) 102301
ALICE: arXiv:1809.09371



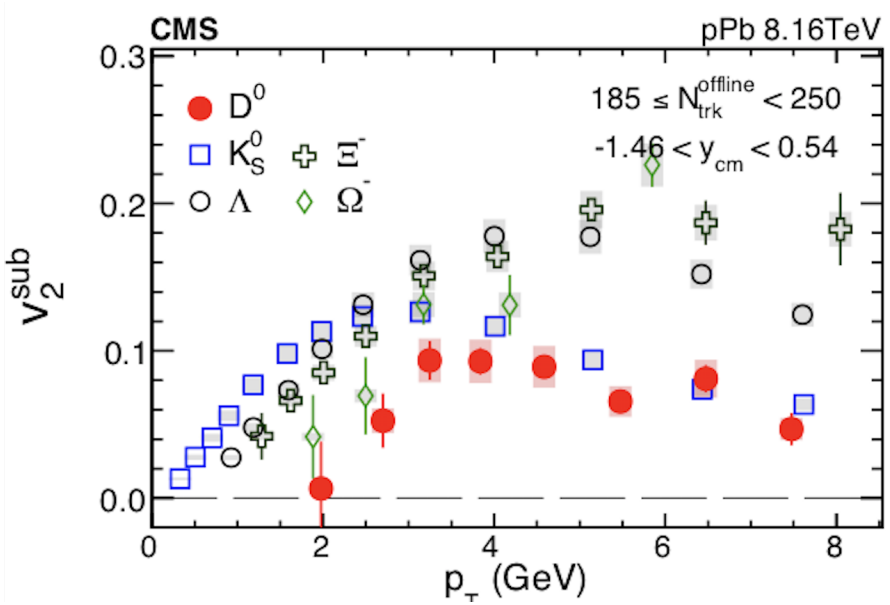
ALICE: PRL 119 (2017) 242301

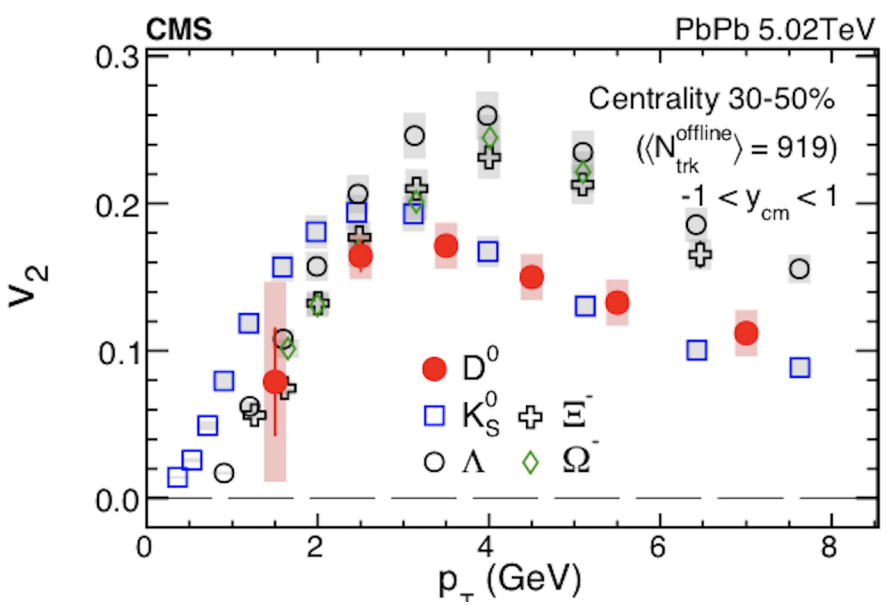


Charm quarks participate to the collective expansion of the medium
Degree of thermalization?

Prompt D^0 mesons v_2 in pPb and in PbPb

CMS: PRL 121 (2018) 082301

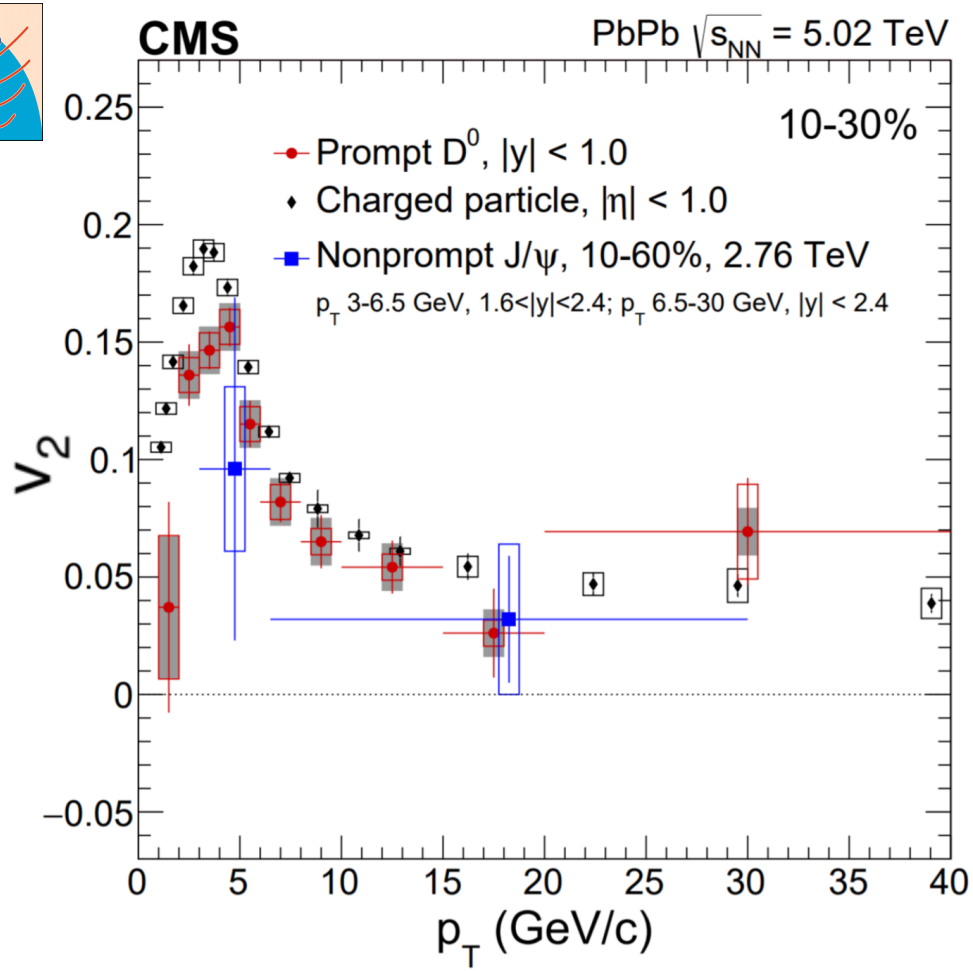


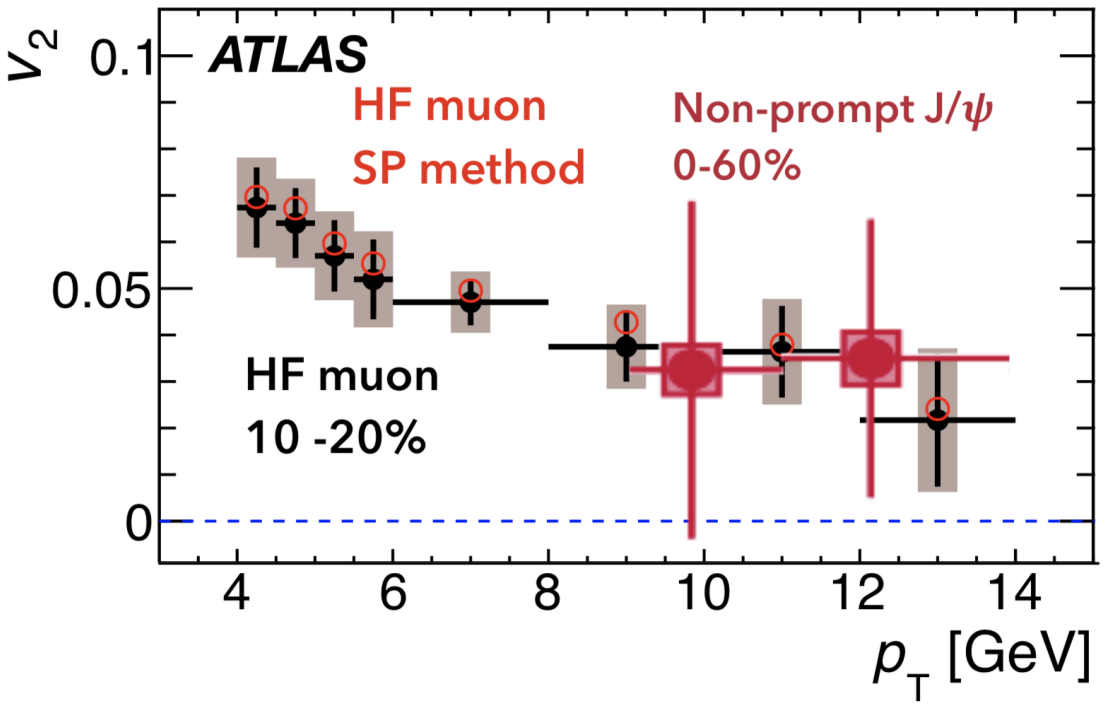


PbPb: D^0 mesons have
- Similar v_2 wrt hadrons with strangeness
- Same meson/baryon mass ordering

pPb: D^0 mesons have
- Lower v_2 wrt PbPb
- Similar mass ordering

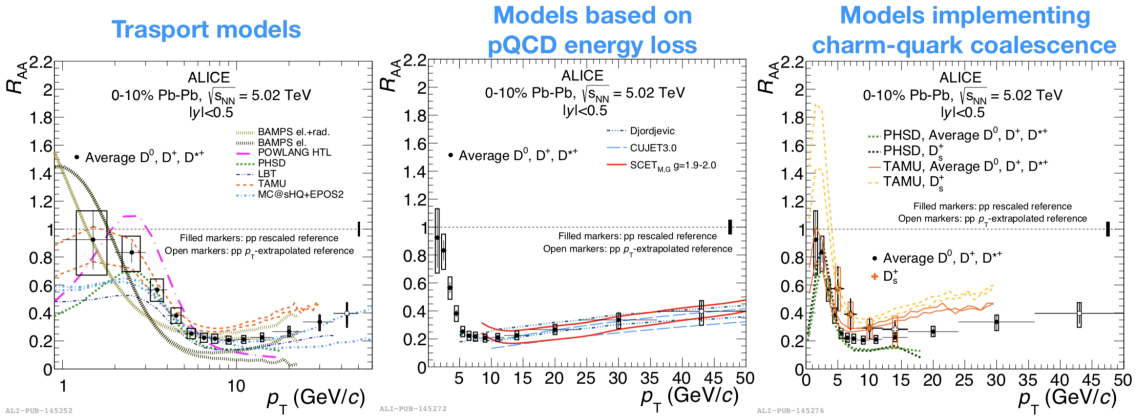
First steps towards beauty v_2



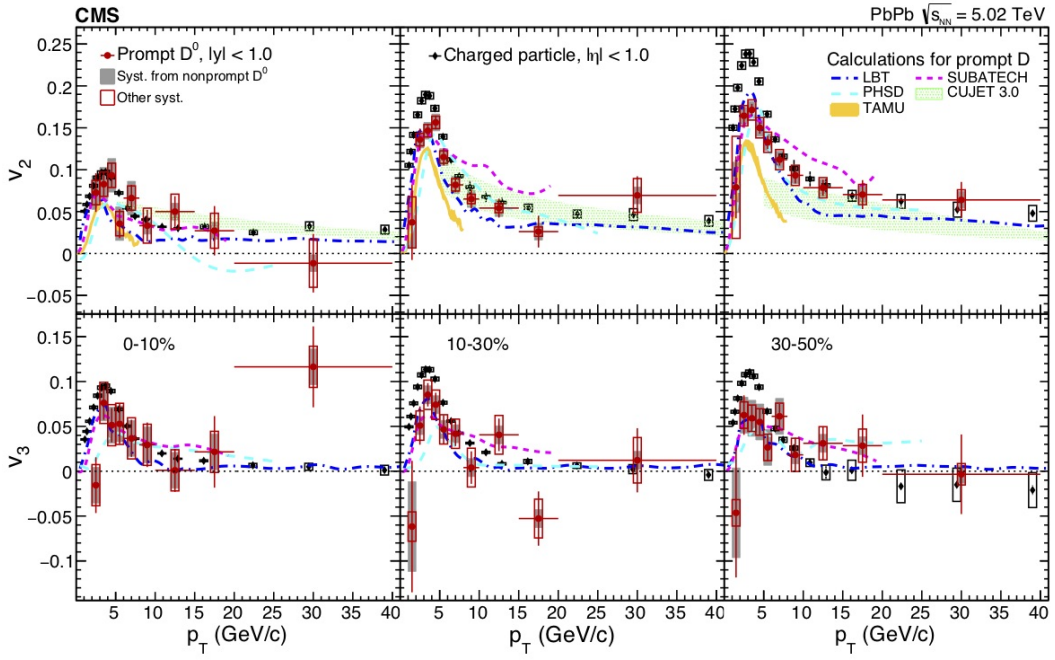


Much more statistics needed !

Data and theory models



arXiv:1804.09083

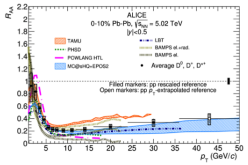


- Simultaneous description of R_{AA} and v_2 starts to constrain models

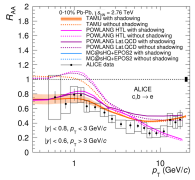
- Ongoing effort to extract transport properties from data/model comparison
  Rapid reaction task force, July 2016 "Extraction of heavy-flavor transport coefficients in QCD matter" Nucl.Phys. A979 (2018) 21-86

Summary and outlook

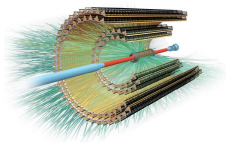
- Heavy quarks: excellent probes of hot QCD matter



- Great progress in the last years on the experimental side, thanks to very precise detectors and high data statistics



- Ongoing systematic work with theory, towards the determination of fundamental transport properties of the QGP



- Rapidly moving towards a high precision era:
  - LHC Run 2 (stopped yesterday morning!)
  - Detector upgrades and then LHC Run 3 and 4

Summary and outlook

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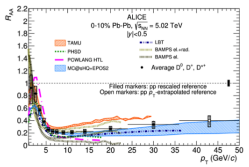

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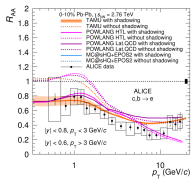

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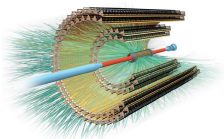

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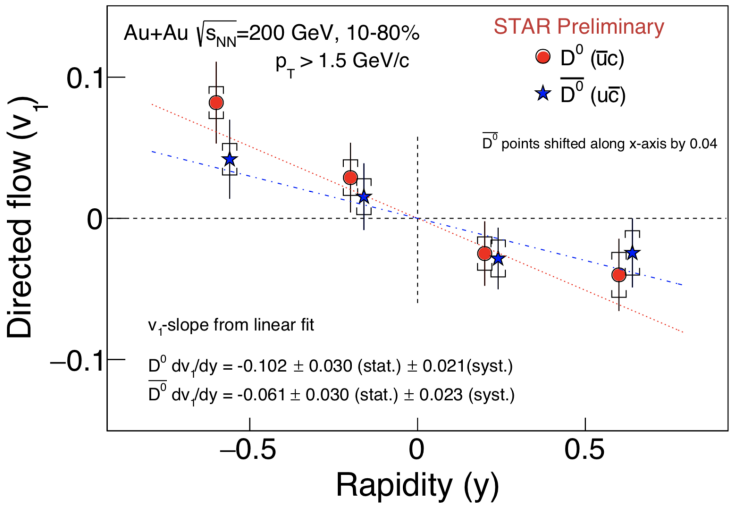
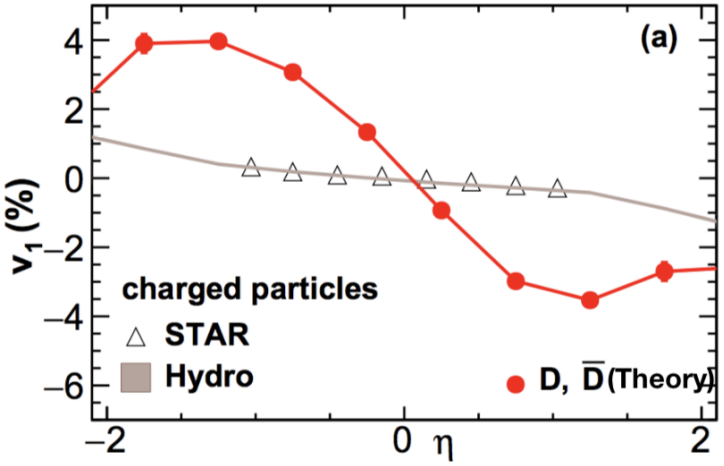
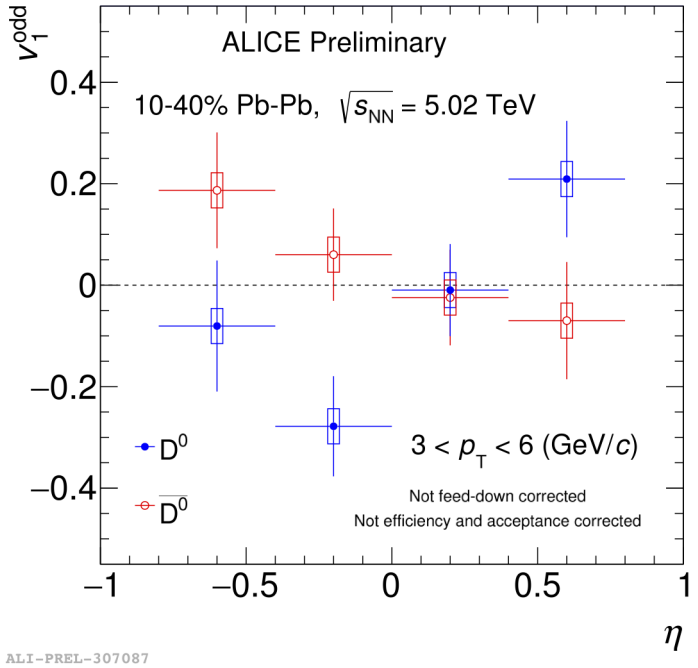
SPARES

D^0 directed flow





Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)



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)

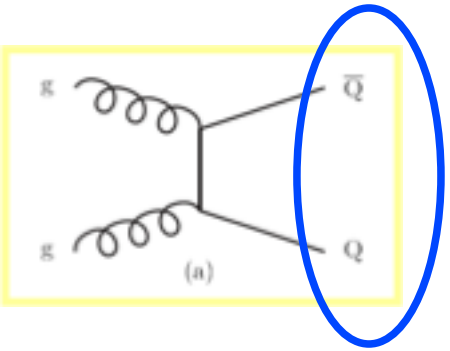
Heavy quarks: charm and beauty

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

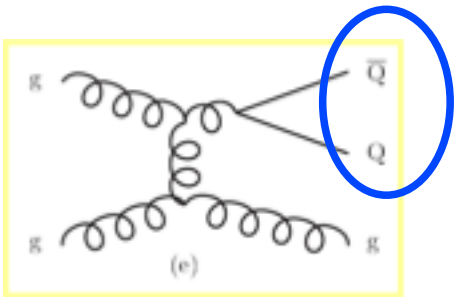
Charm:
m ~ 1.5 GeV/c^2

Beauty:
m ~ 5 GeV/c^2

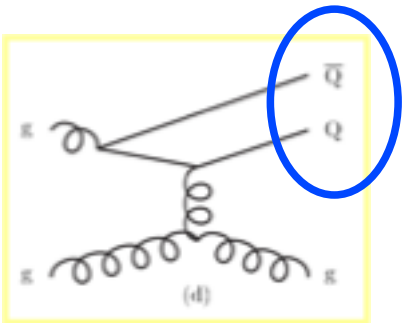
Dominant production diagrams: gluon-gluon fusion, hard scattering



Pair production
(LO)

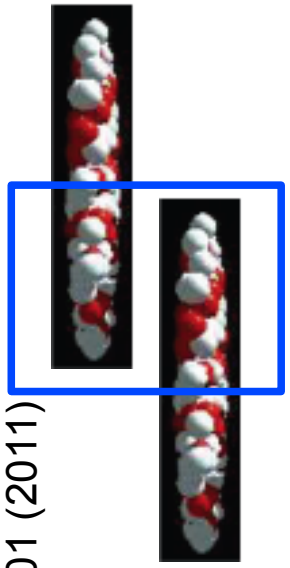


Gluon splitting
(NLO)



Flavor excitation
(NLO)

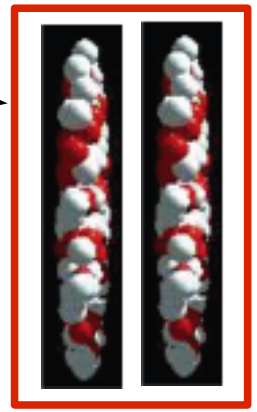
Geometry of a Pb-Pb collision



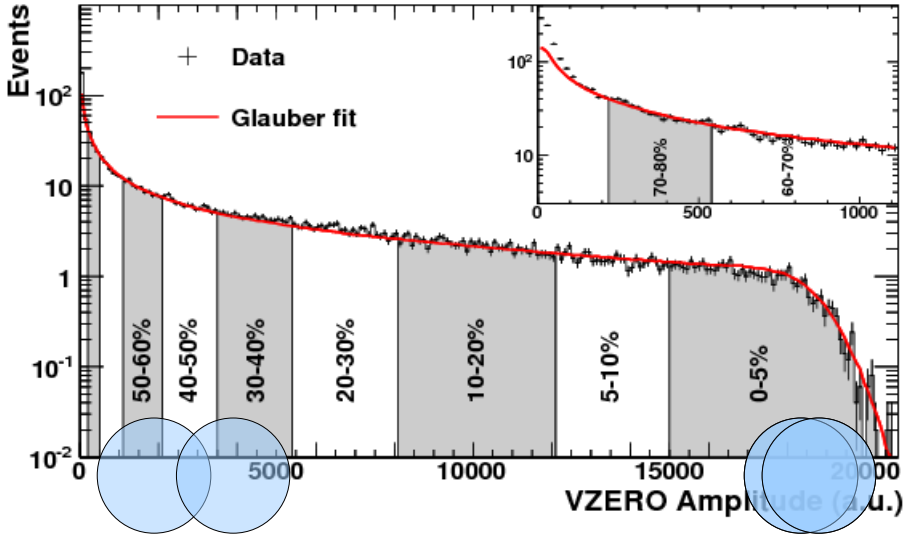
Phys. Rev. Lett. 106, 032301 (2011)
arXiv:1301.4361

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



peripheral

central

Centrality: percentile of total hadronic cross section