Open heavy flavour: an experimental overview

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2025/11/07

See also talks by Ralf Averbeck at QM’25 and Zebo Tang at HP’24

The 1st ALICE Experiment and Heavy-Ion Physics Workshop, November 3-9, 2025 | Fudan University, Shanghai, China

“Standard” model of heavy-ion collisions

Initial state	Hard partonic collisions	Fireball expansion	Chemical freeze-out	Kinetic freeze-out	

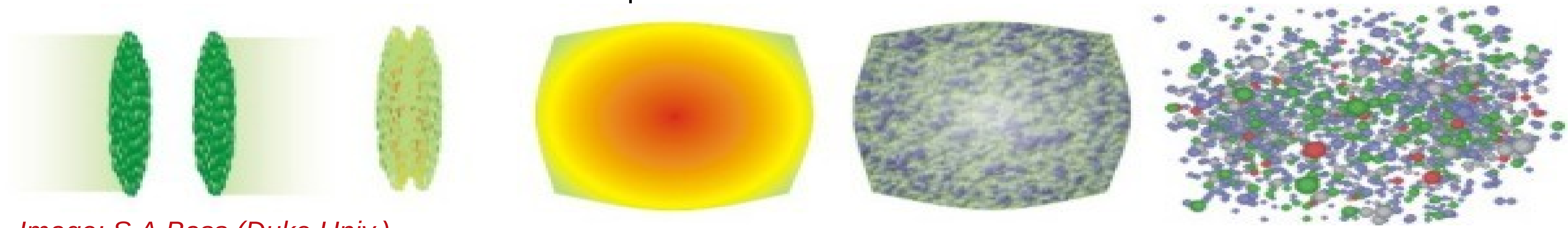


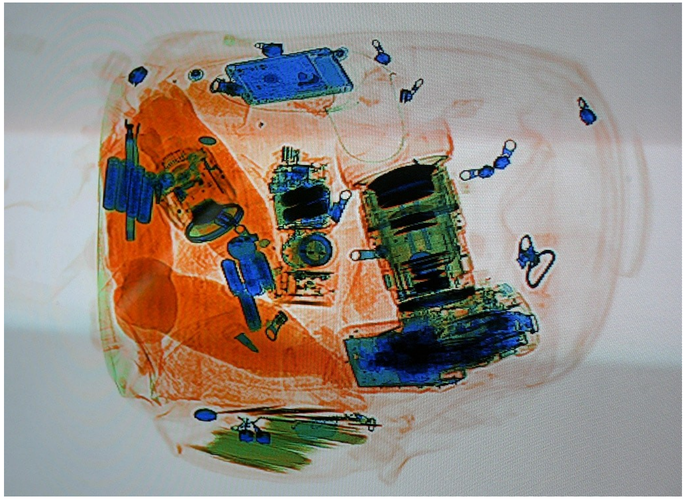
Image: S.A.Bass (Duke Univ.)

0	10^{-26}-10^{-24}	10^{-24}-10^{-23}	~10^{-23}	10^{-23}-10^{-22}	**t (s)**
0	0.01-1	1-10	~10	10-100	**(fm/c)**

- Main goal is the study of the **QGP** phase
- Experimentally we measure only the remnants of the QGP decay, so
  - All stages of a nuclear collision need to be understood simultaneously
  - Use phenomenological models to understand each collision stage

Explore the QCD medium using “hard probes”

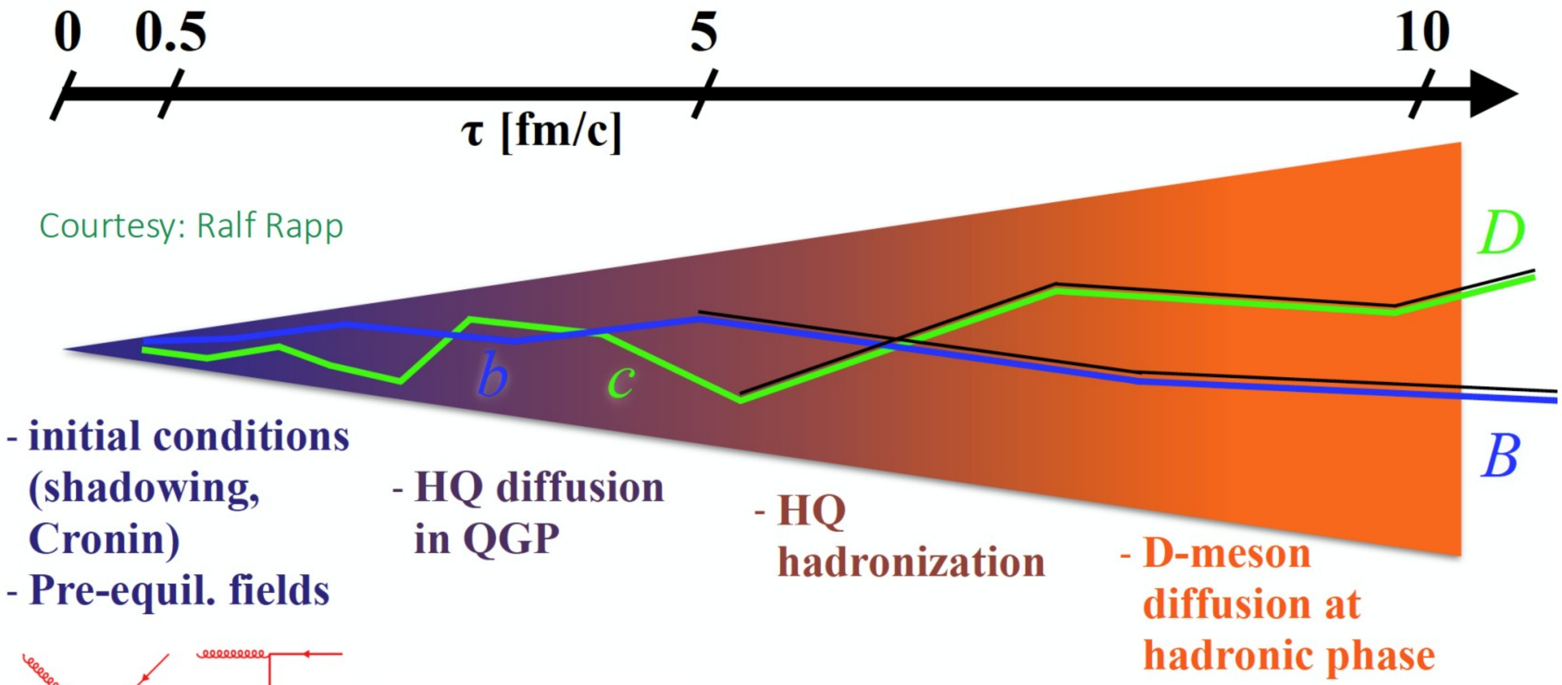
- Use calibrated probes
- Hard probes:
  - Particles created from the initial high Q^2 parton scatterings
  - Control measurement: production in vacuum
  - Information extracted from the in-medium modifications wrt vacuum



- Heavy flavour hadrons
  - $m_{c,b} >> \Lambda_{QCD}$ → initial production calculable in pQCD
  - $m_{c,b} >> T_{LHC}$ → no significant thermal production
  - $\tau_{c,b} \sim 1/(2m_{c,b}) < \tau_{QGP}$ → HQ created early
  - $\tau^{th}_{c,b} \sim m_{c,b} \sim \tau_{QGP}$ → long thermalization time

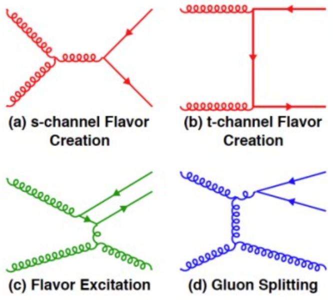
- Caveats: CNM and hadronization effects

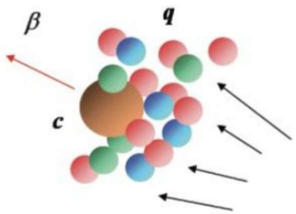
Heavy quarks and heavy-ion collisions



Number of heavy quarks is constant throughout the evolution

Probe the medium with final heavy hadrons





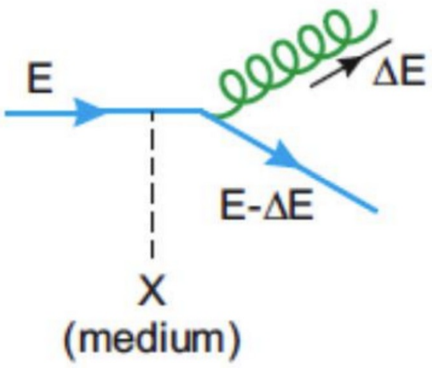
Fragmentation

+

Coalescence?

Energy loss in the QGP

Radiative energy loss
Inelastic scatterings



D.d'Enterria and B.Betz
Lect. Notes. Phys. 785 (2010) 285

- Energy lost via radiation induced by interactions with scattering centers in the hot and dense medium

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

$$\widehat{(q)} = \frac{\langle k_T^2 \rangle}{\lambda}$$

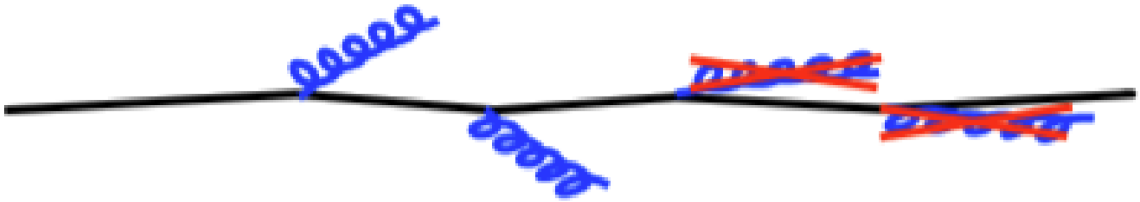
Transport coefficient of the medium (connected to the energy density of the system)

C_R Casimir coupling factor
4/3 for quark-gluon
3 for gluon-gluon

$$\langle \Delta E \rangle_g > \langle \Delta E \rangle_q$$

“Dead-cone” effect

Y.Dokshitzer, D.Kharzeev, PLB519 (2001) 199

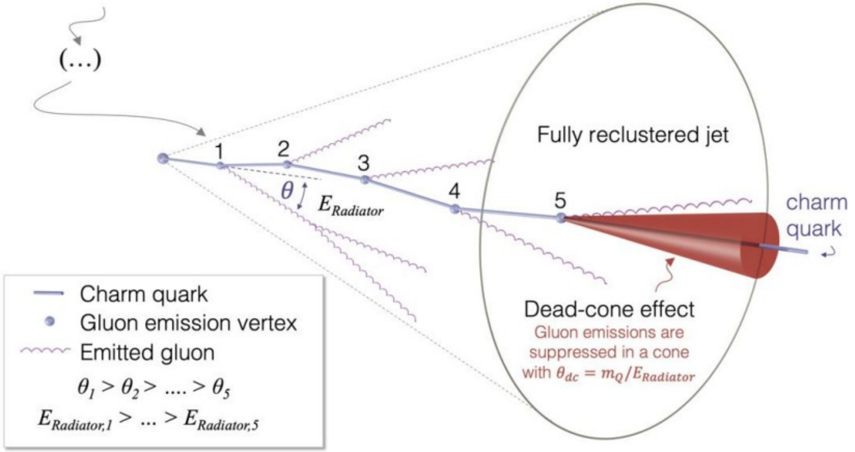


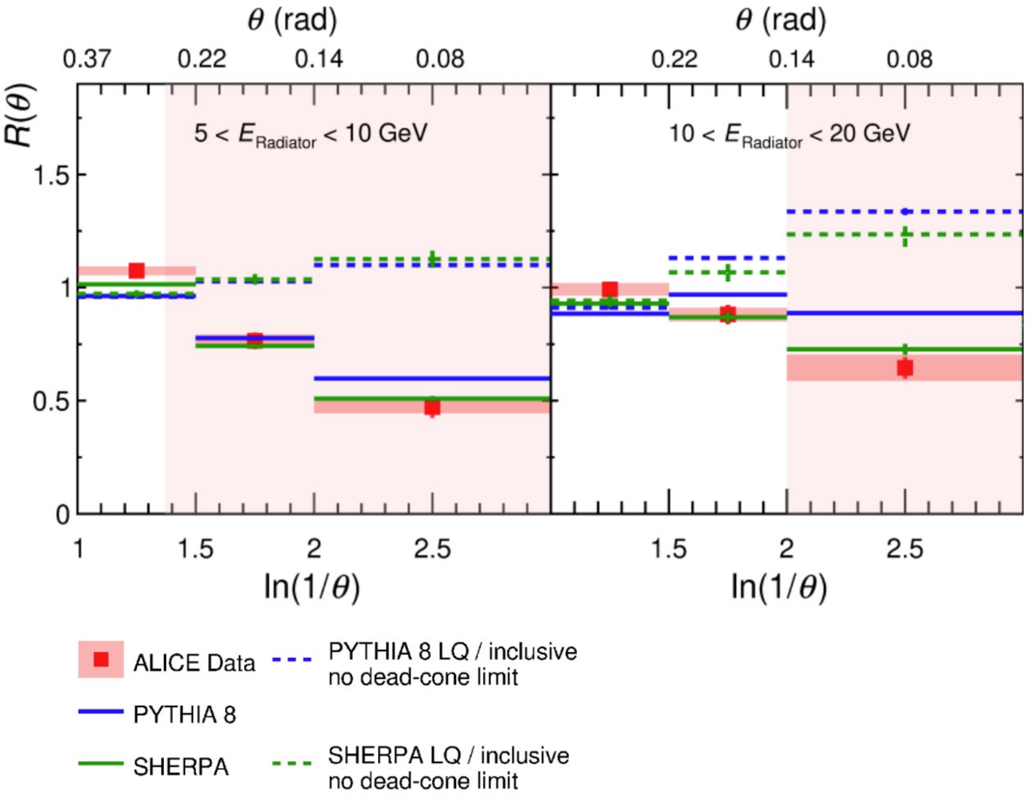
$$\langle \Delta E \rangle = \frac{\langle \Delta E \rangle_0}{(\theta^2 + \theta_0^2)} \qquad \theta_0 = \frac{1}{\gamma} = \frac{m_q}{E}$$

$$\langle \Delta E \rangle_g > \langle \Delta E \rangle_{u,d,s} > \langle \Delta E \rangle_c > \langle \Delta E \rangle_b$$

- Gluon radiation in vacuum (and in medium) is suppressed for small angles due to kinematical constraints
- Smaller energy loss for heavy quarks

Observation of the “Dead-cone” effect

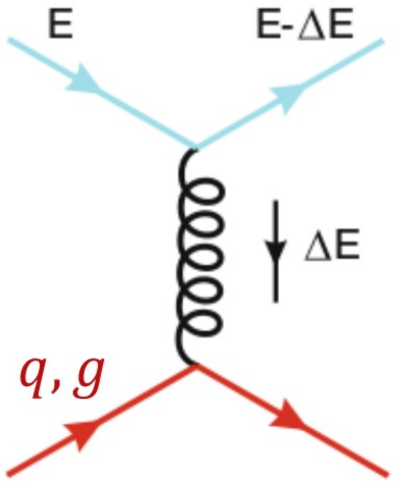


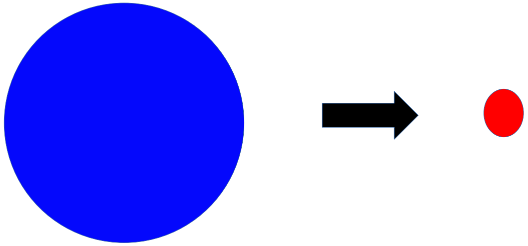


First observation of the dead-cone effect in jets containing a D-meson

ALICE, Nature 605 (2022) 440

Elastic collisions in the QGP





$$\langle \Delta E \rangle = \frac{4k}{(k+1)^2} \qquad k = \frac{M}{m} \gg 1$$

Elastic collisions in classical mechanics:

- High-energy object: lose small energy per collision
- Low-energy object: “Brownian” motion

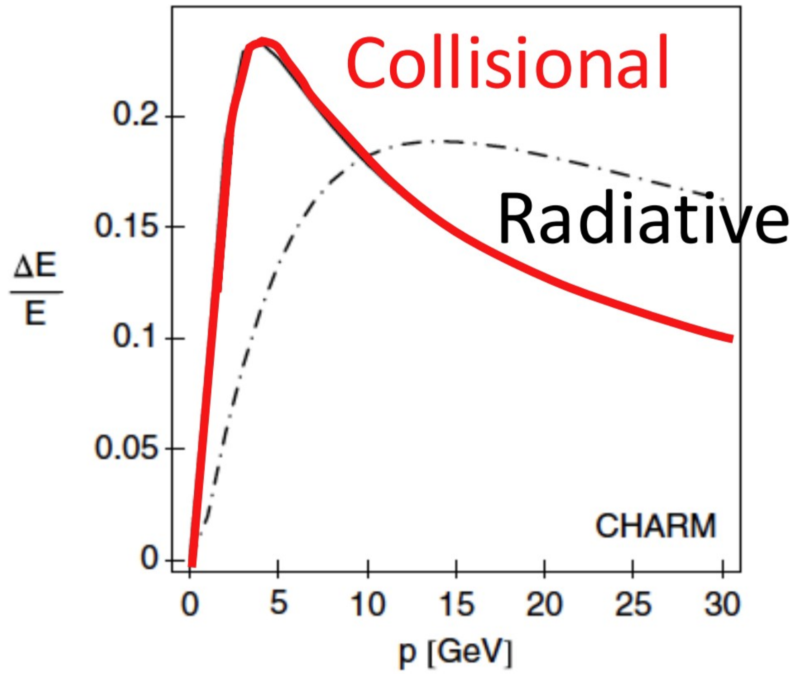
Elastic scatterings
Collisional energy “loss”

For heavy-quarks:

- Large relaxation time, comparable to the QGP lifetime (keeps memory of initial kinematics)

Inelastic vs elastic collisions in the QGP

M.Djordjevic, PRC74 (2006) 064907



Elastic collisions:

- Dominant at low-p_T
- Responsible for heavy-quark collectivity since these lead to kinetic equilibration

Inelastic collisions:

- Important at high-p_T
- Main contributor of energy loss

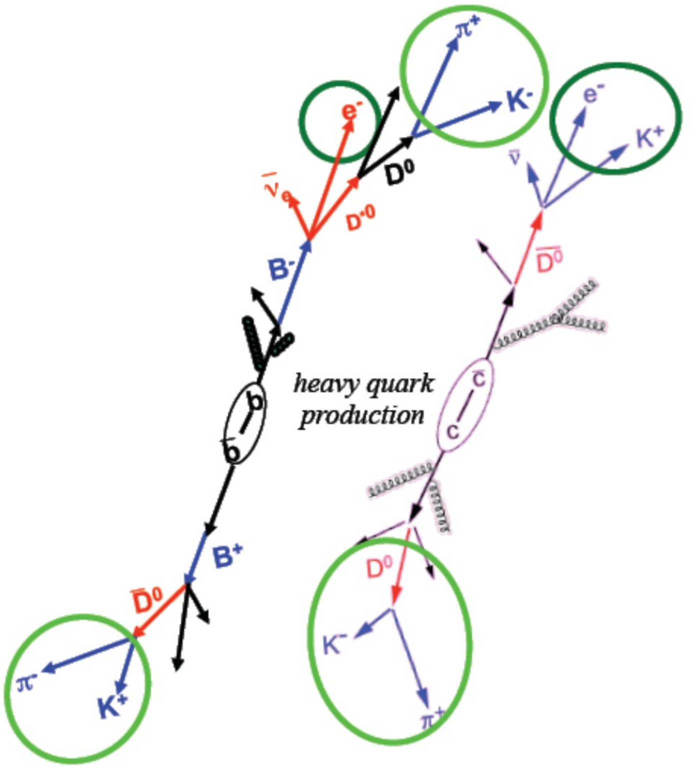
So, what are we probing with the heavy quarks ?

- Since they interact with the QGP, HQ are sensitive to
  - Bulk and microscopic properties of the medium
  - Mechanisms of the HQ interaction with medium

- Low-p_T
  - Thermalization (equilibration)
  - Diffusion coefficient
- High-p_T
  - Energy loss
  - Transport coefficient

Also, the hadronization mechanism is essential in understanding the data !

How do we measure heavy quarks ?



- Fate of the heavy quarks:
  - Production in initial hard scatterings
  - Partonic cascade within medium
  - Hadronization
  - Weak decay (~100μm for c and ~500μm for b)
- What can be measured?

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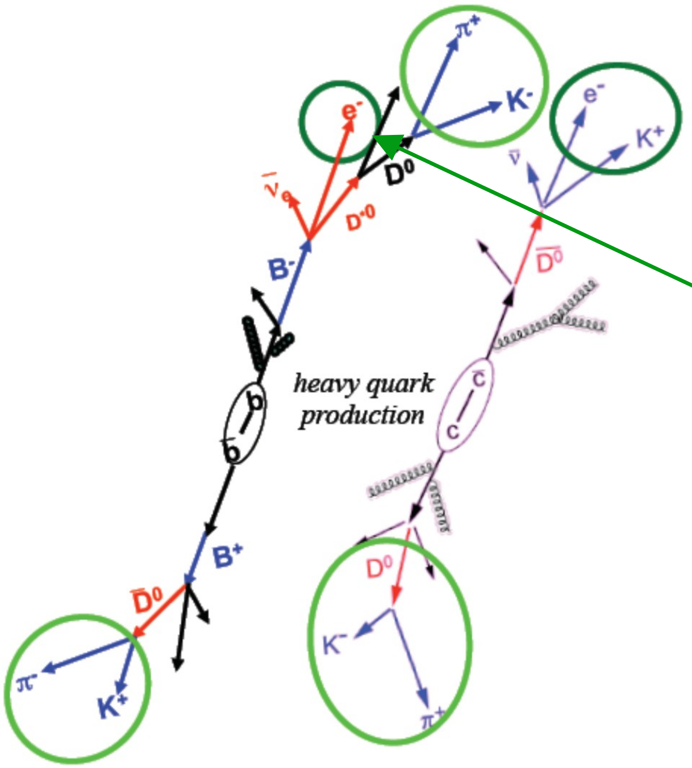

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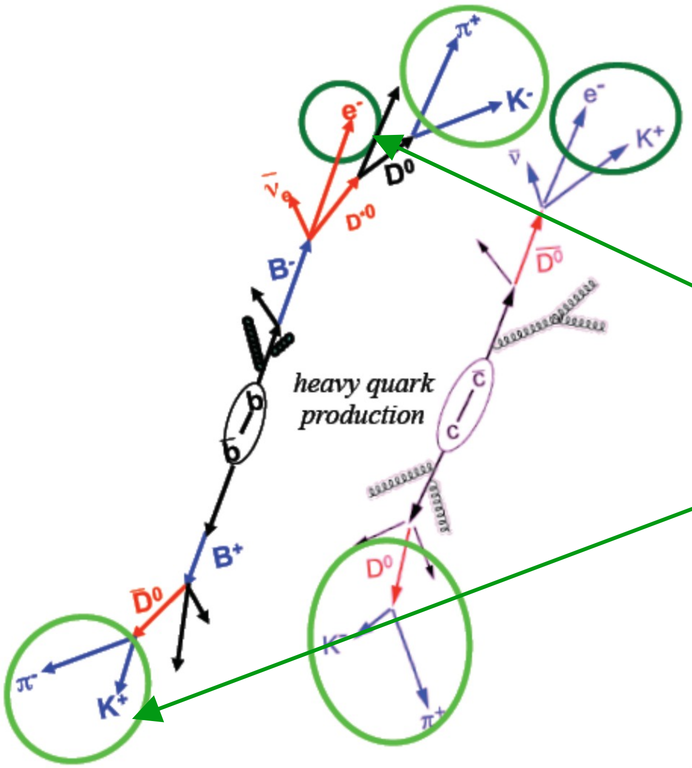

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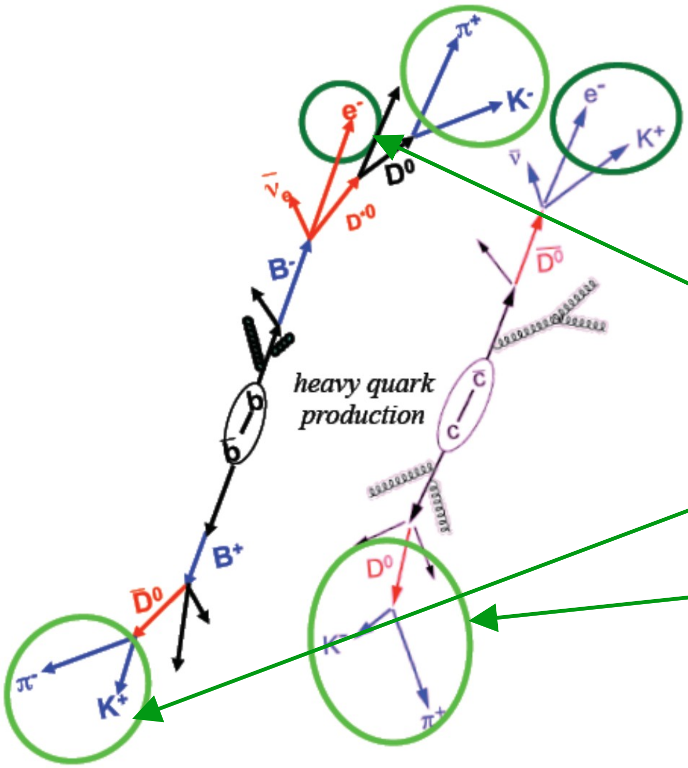

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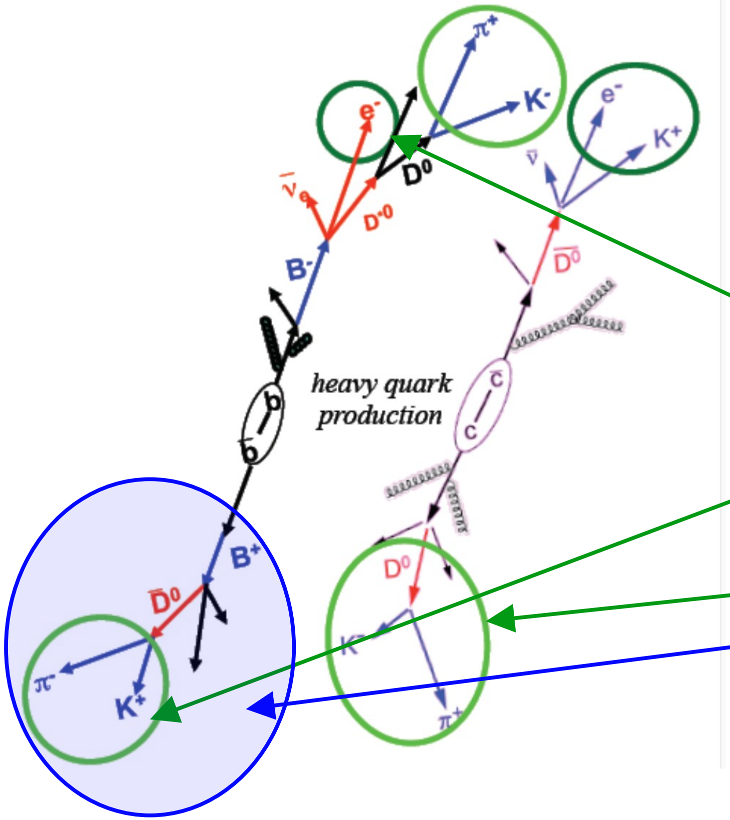

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  - **HF tagged jets**

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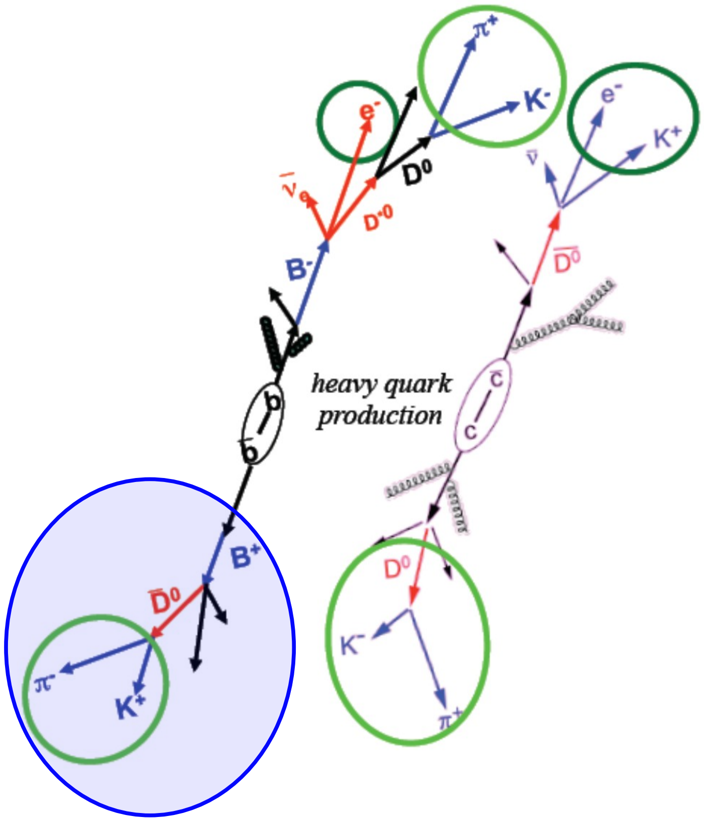

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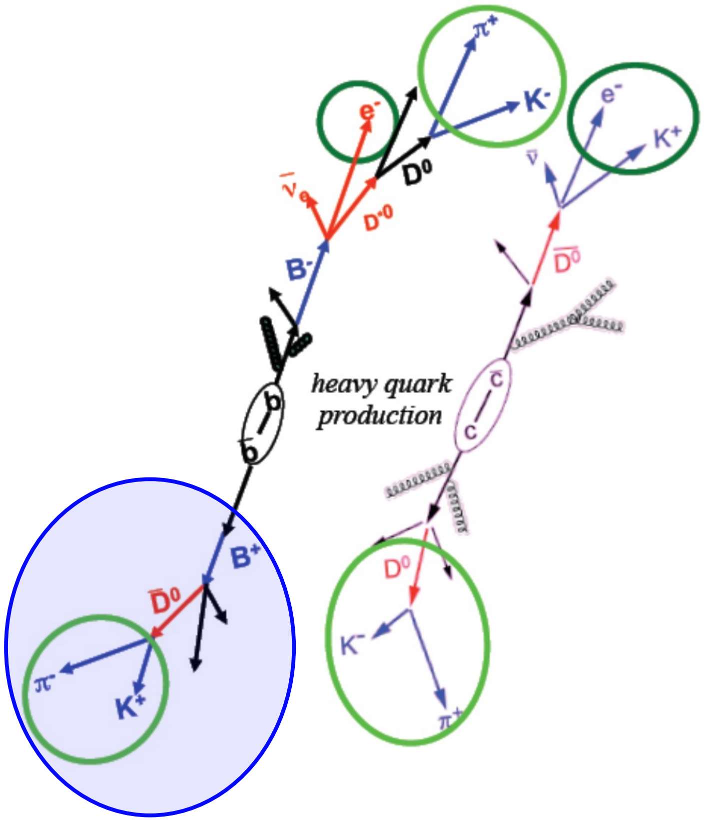
What	Pros	Cons
HFL	High efficiency, good S/B	Loose correlation to the quark kinematics
Partial hadron reco	Good correlation to the quark kinematics	Low S/B, sensitivity to hadronization effects
Full hadron reco	Very good correlation to quark kinematics	Low S/B, sensitivity to hadronization effects
HF tagged jet	Ideally, full reconstruction of quark kinematics	Requires large data samples, systematic effects

How do we measure heavy quarks ?

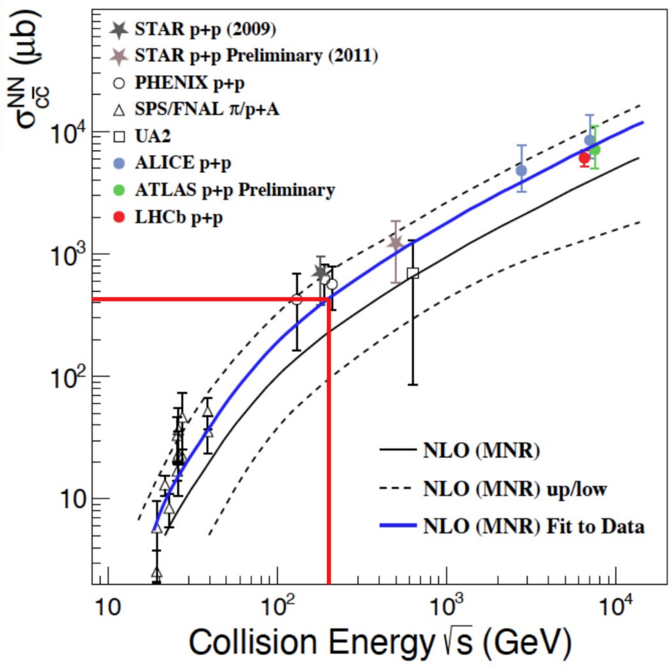


- Challenges
  - Backgrounds
    - In particular for hadronic decay channels
  - Partial vs full reconstruction
    - Connection with the kinematics of the original quark kinematics
  - Separation of charm and beauty
    - Requires very good inner trackers
  - Feed-down
    - Many decay channels, some have poorly known BRs

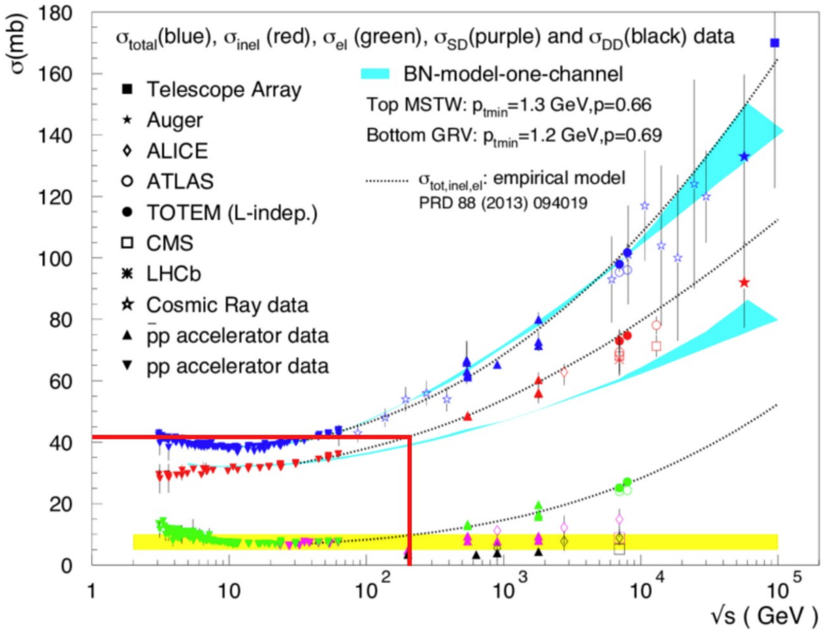
- Experimental performance requirements
  - Excellent particle ID (especially for leptons)
  - Tracking (momentum resolution)
  - Vertexing (weak decay vertex reconstruction)

How much charm is created in a collision ?

Total $c\bar{c}$ cross-section



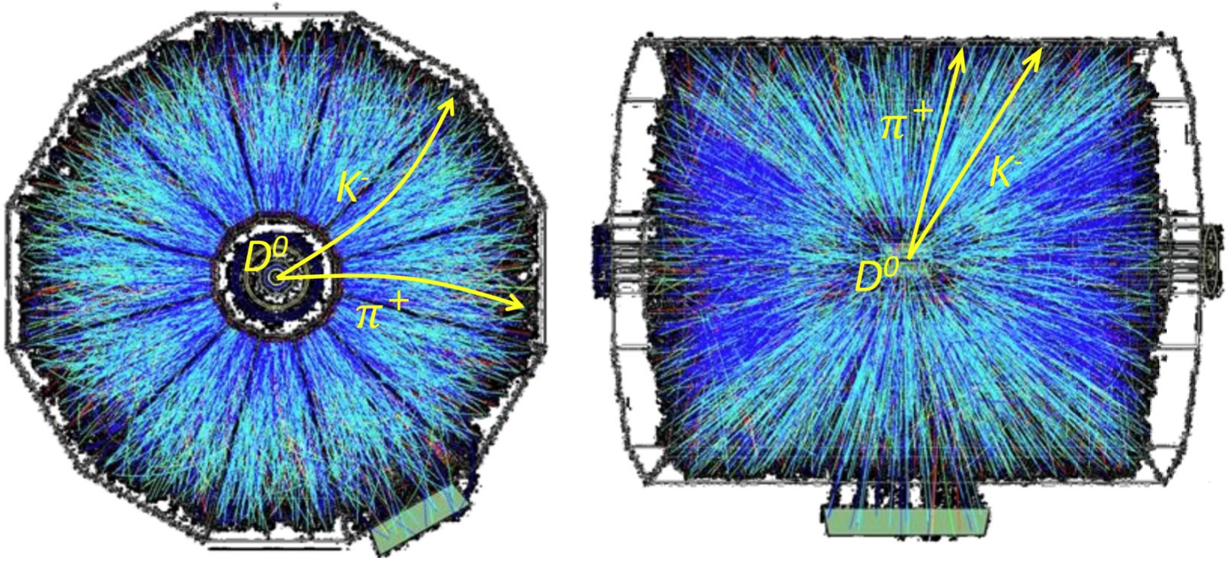
Total NN inelastic cross-section



- At RHIC: 400μb / 40mb ~ 0.01 $c\bar{c}$ pairs per min bias pp event
  - About 1 / 5 of these pairs are produced within the acceptance of STAR or ALICE
  - Using N_{coll} scalling, one gets ~ 1 $c\bar{c}$ pair per average Au+Au collision
- At LHC: one gets few tens of pairs per average Pb-Pb collision

D^0 meson reconstruction, e.g. at RHIC or LHC

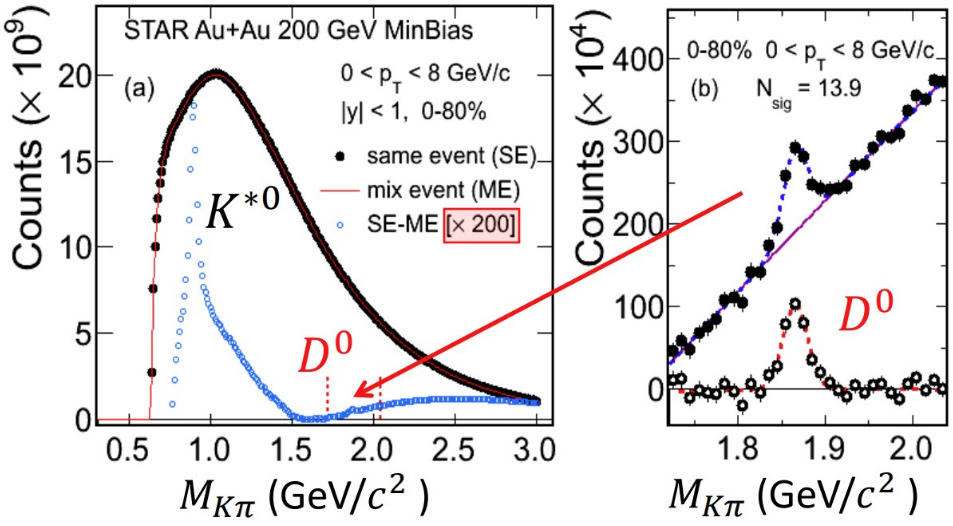
"Golden" channel:
$D^0 \rightarrow K^-\pi^+$
B.R. ~ 4%

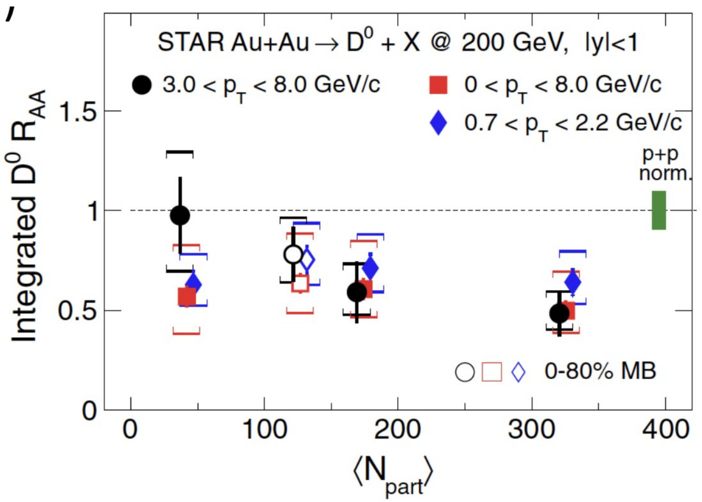


How its done:

- Pair all kaon and pion candidates in the same event
  - Leads to huge combinatorial bakground, i.e. thousands of combinatorial pairs per event

D^0 meson reconstruction





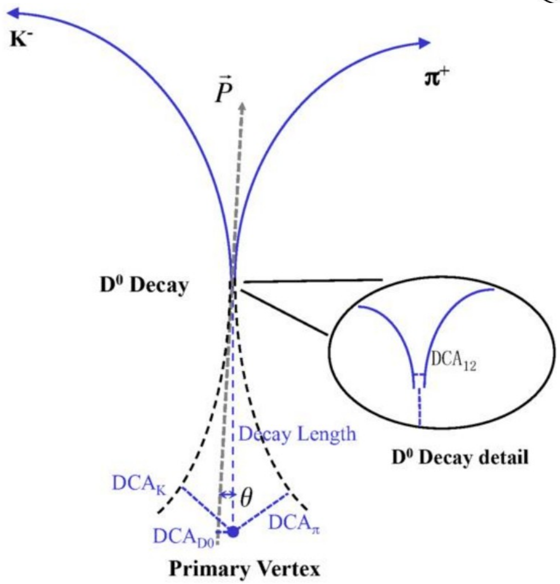
STAR, PRL113 (2014) 142301

How its done:

- Pair all kaon and pion candidates in the same event
  - Leads to huge combinatorial bakground, i.e. thousands of combinatorial pairs per event, **but it can be done!**
    - Needs good particle identification (mainly kaon) and event mixing technique
    - Comes with large syst uncertainties

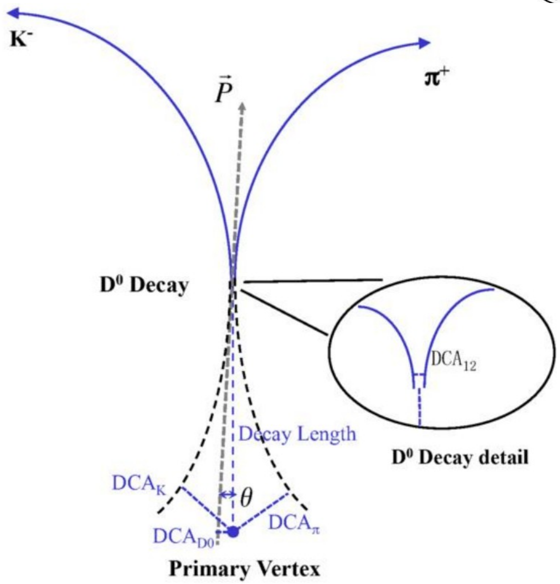
Vertexing

- Exploit the long proper lifetime of HF hadrons
  - Charm: ~100 μm
  - Beauty: ~500 μm
- State-of-the art detectors can reach resolutions of O(10μm)

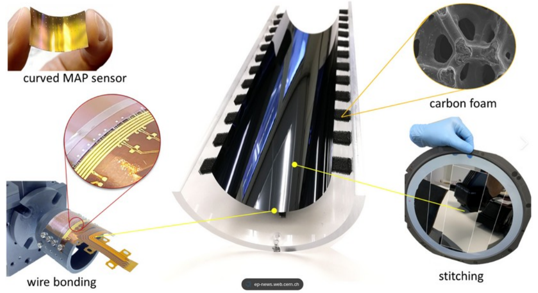


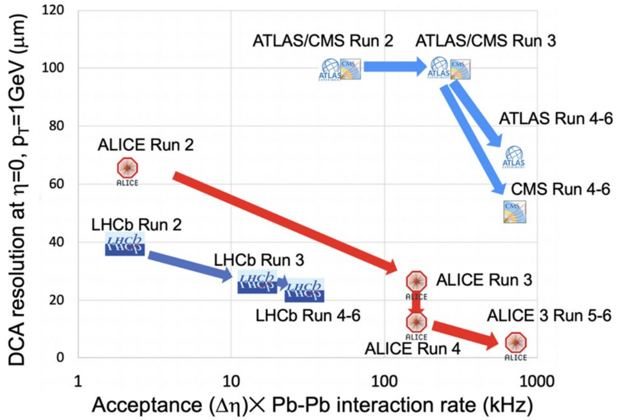
Vertexing

- Exploit the long proper lifetime of HF hadrons
  - Charm: ~100 μm
  - Beauty: ~500 μm
- State-of-the art detectors can reach resolutions of O(10μm)
- Main characteristics of such detectors:
  - Very fine spatial segmentation (e.g. CMOS pixel detectors) → **precise spatial measurements**
  - Very close to the interaction point → **as small as possible extrapolation to the secondary vertex**
  - Very low material budget → **minimize secondary interactions in the detector and additional bkg**



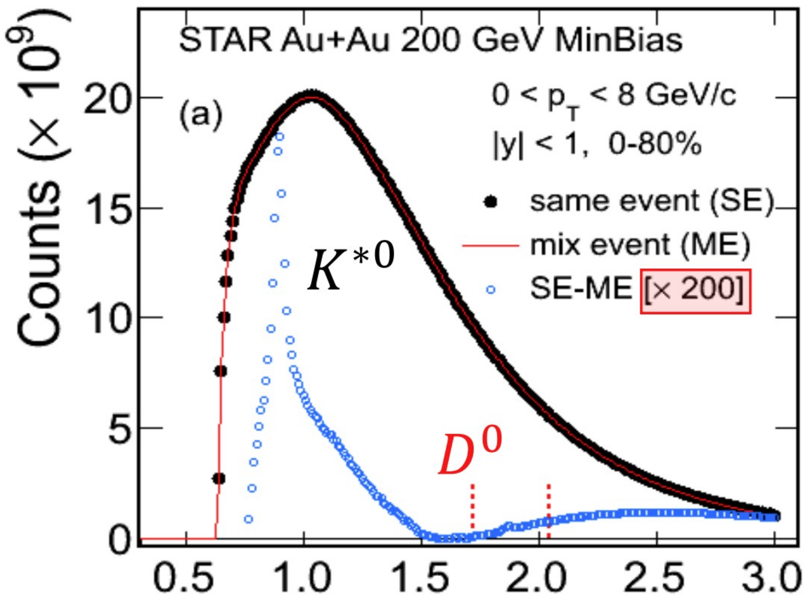
ALICE ITS3





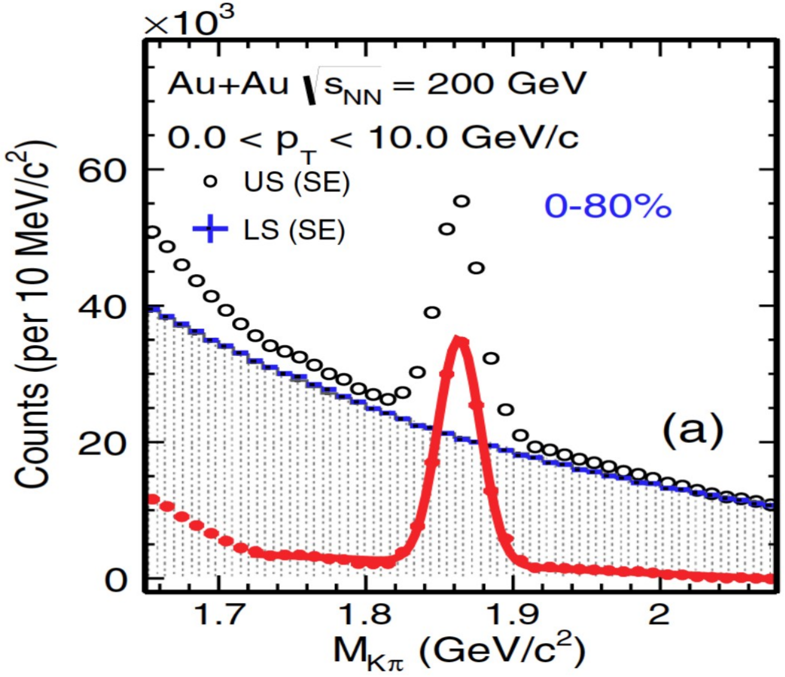
D^0 signal with vertexing selection

(Without vertexing)



STAR, PRL113 (2014) 142301

(With vertexing)

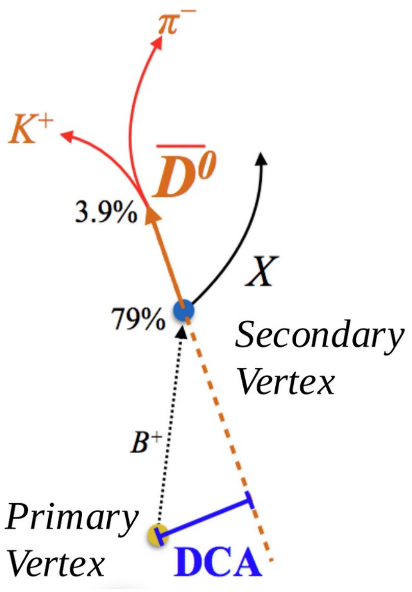


STAR, PRC99 (2019) 034908

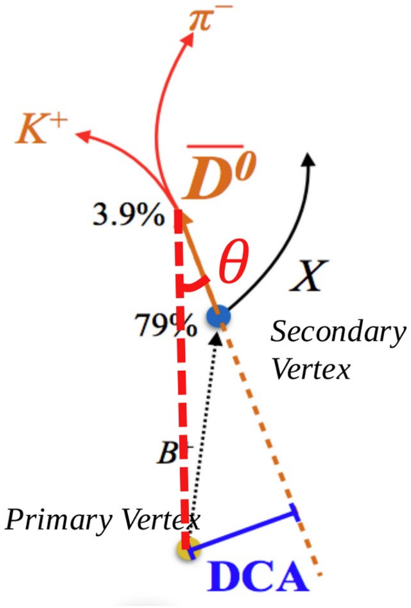
S/B improvement of O(10^4) !!!

Feed-down contributions

- Open HF hadrons have feed-down contributions
- **For beauty:** rather complicated decay chains, with BR that have large uncertainties
- **For charm:** *Inclusive = Prompt + Non-Prompt*
  - Prompt:
    - Decay products of higher mass states, typically difficult to separate on a per candidate basis
    - Depending on the type of measurement, this feed-down can be (or not) ignored
  - Non-prompt:
    - Decay products of beauty hadrons, can be separated using vertexing
    - Good proxy for b-quarks

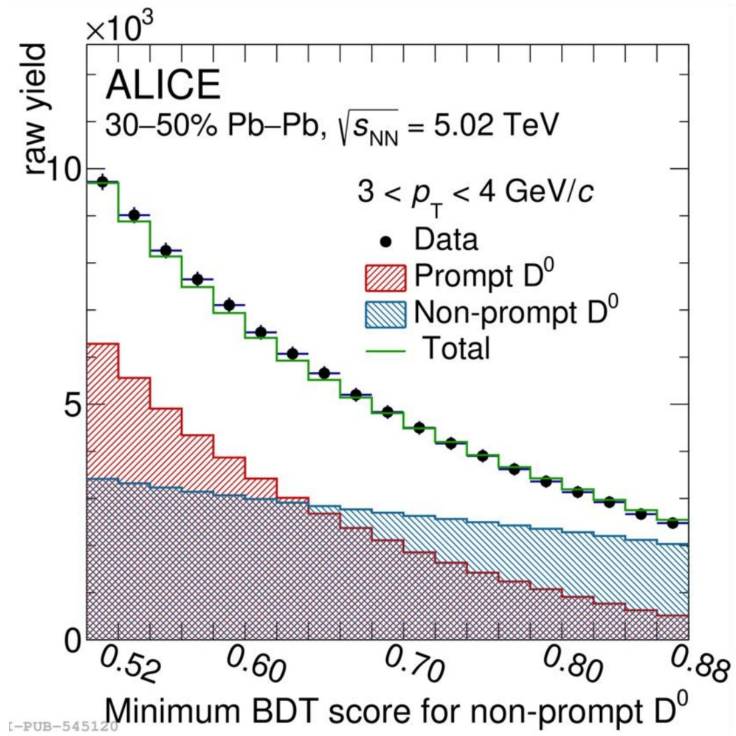


Prompt and non-prompt separation



Main discriminative quantities:

- Distance between secondary and primary vertices
- D-meson DCA to the primary vertex
- D-meson daughters DCA
- Pointing angle between secondary vertex vector and D-meson momentum

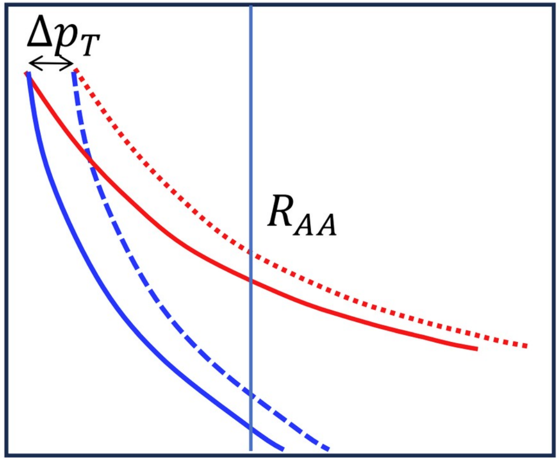


ALICE, EPJC83 (2023) 1123

- Non-prompt yields can be obtained using the secondary vertexing capabilities
- Very good application of machine learning techniques

Nuclear modification factor

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{Y_{AA}}{Y_{pp}}$$

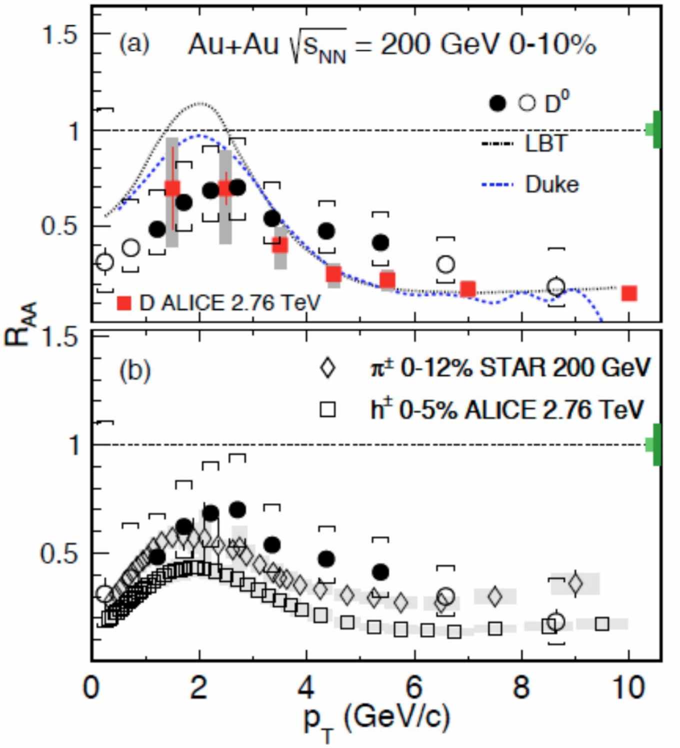


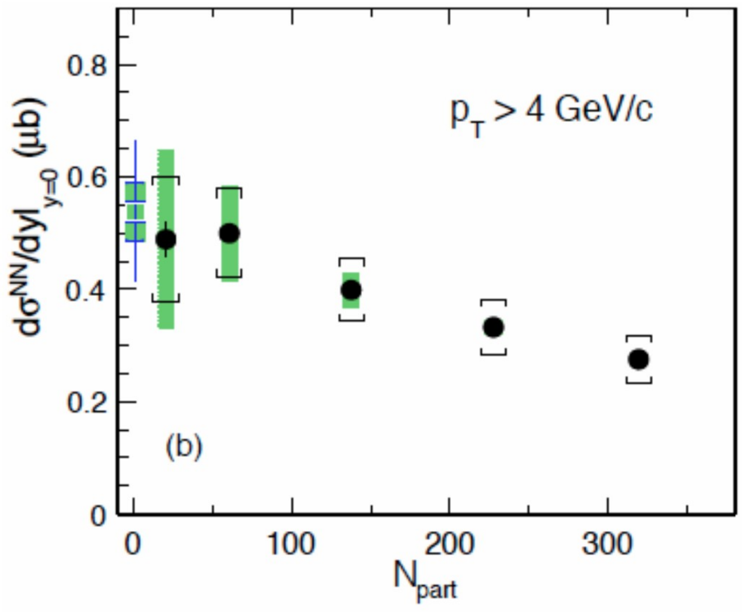
- Nuclear modification factor R_{AA} used to quantify the effect of the nuclear medium on heavy-flavour quarks

- Caveats:
  - Energy loss effects induce a shift on p_T, however its impact on the R_{AA} depends on the shape of the vacuum spectrum and on Δp_T
  - Hadronization effects, e.g. enhancement of strange D mesons, obscure the interpretation of the R_{AA}
  - One needs very detailed theory/pheno models to interpret the data

D^0 nuclear suppression at RHIC

STAR, PRC99 (2019) 034908

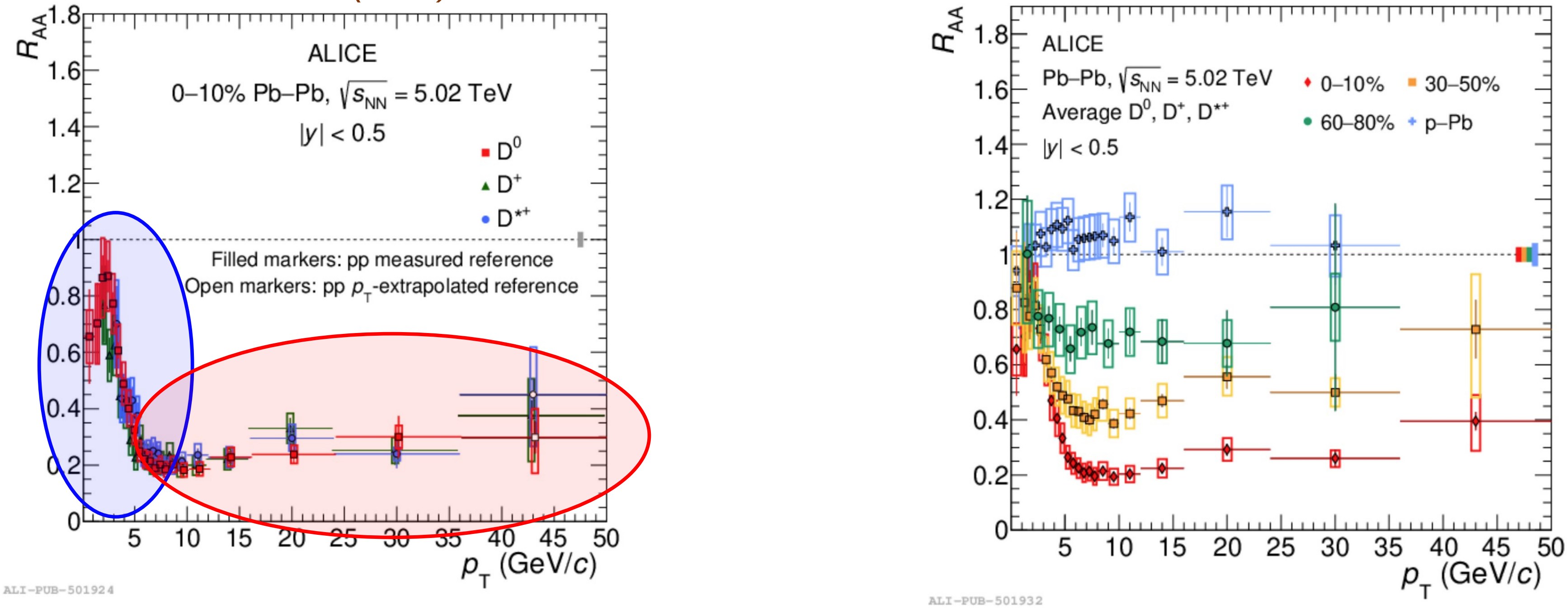




- Significant suppression of D^0 yield at high p_T in Au+Au collisions
- Stronger suppression towards central collisions
- Reasonably well described by models

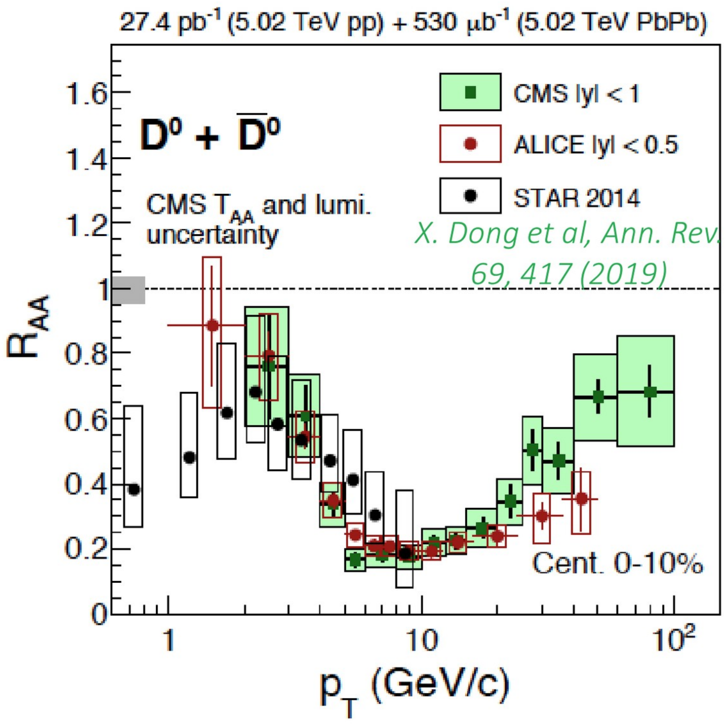
D-mesons suppression at the LHC

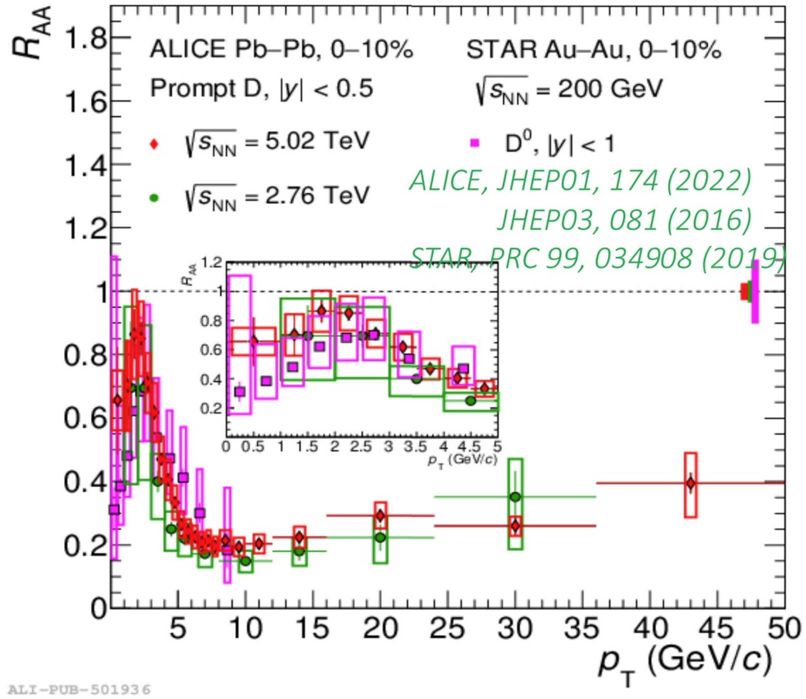
ALICE, JHEP01 (2022) 174



- Very similar suppression pattern for the most abundant D mesons: D^0, D^+ and D^{*+}
- Low-p_T: charm-quark conservation
- High-p_T: strong suppression (compatible with energy loss)
- Strong centrality dependence
- Compatible to unity in p-Pb collisions

Collision energy dependence

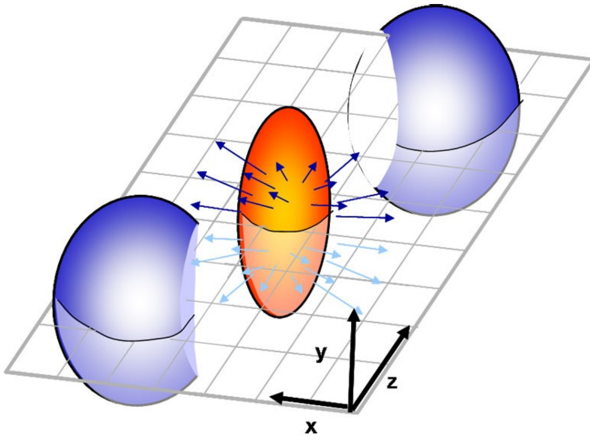


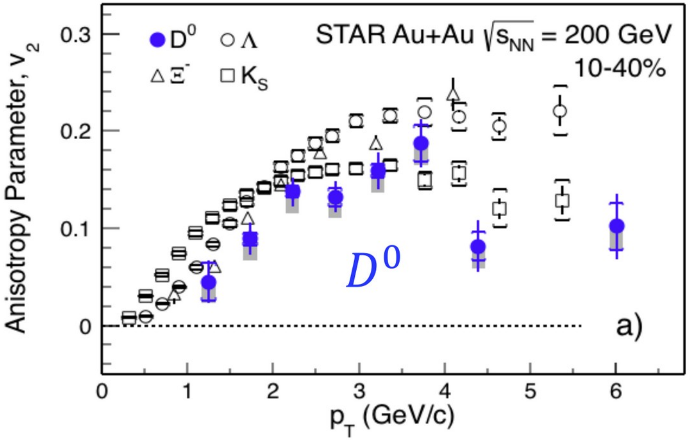


- Within experimental uncertainties, nuclear modification at RHIC and LHC are well compatible
- Combination of factors: medium properties vs p_T spectrum hardness

Azimuthal anisotropy measurements

STAR, PRL118 (2017) 212301



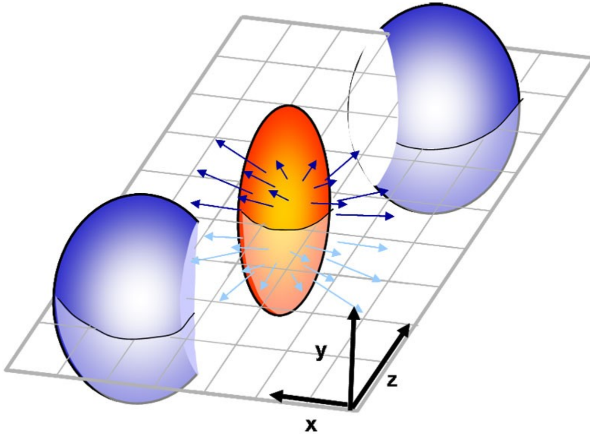


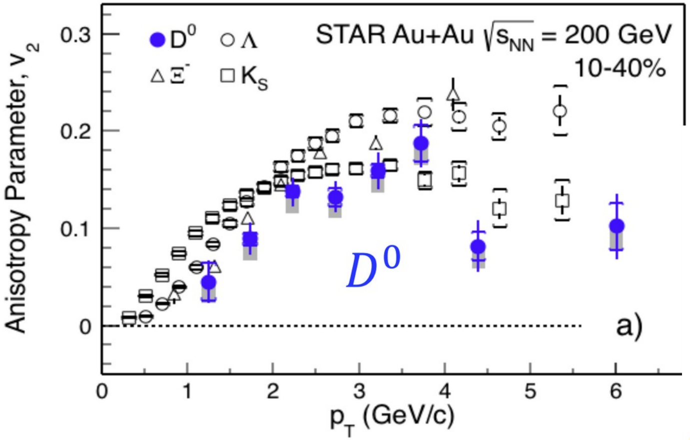
$$\frac{dN}{d\phi} \simeq 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$

- Strong elliptic flow observed at both RHIC and the LHC
- Mass ordering in the low p_T range

Azimuthal anisotropy measurements

STAR, PRL118 (2017) 212301





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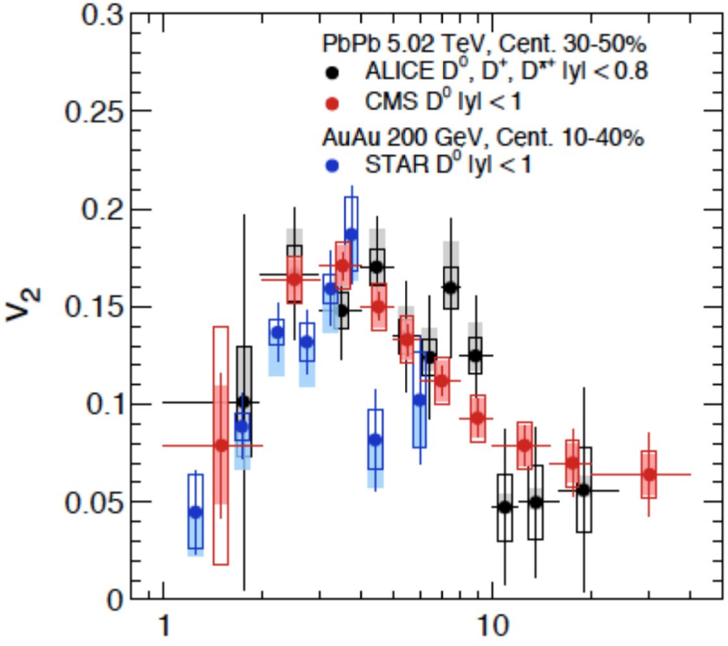
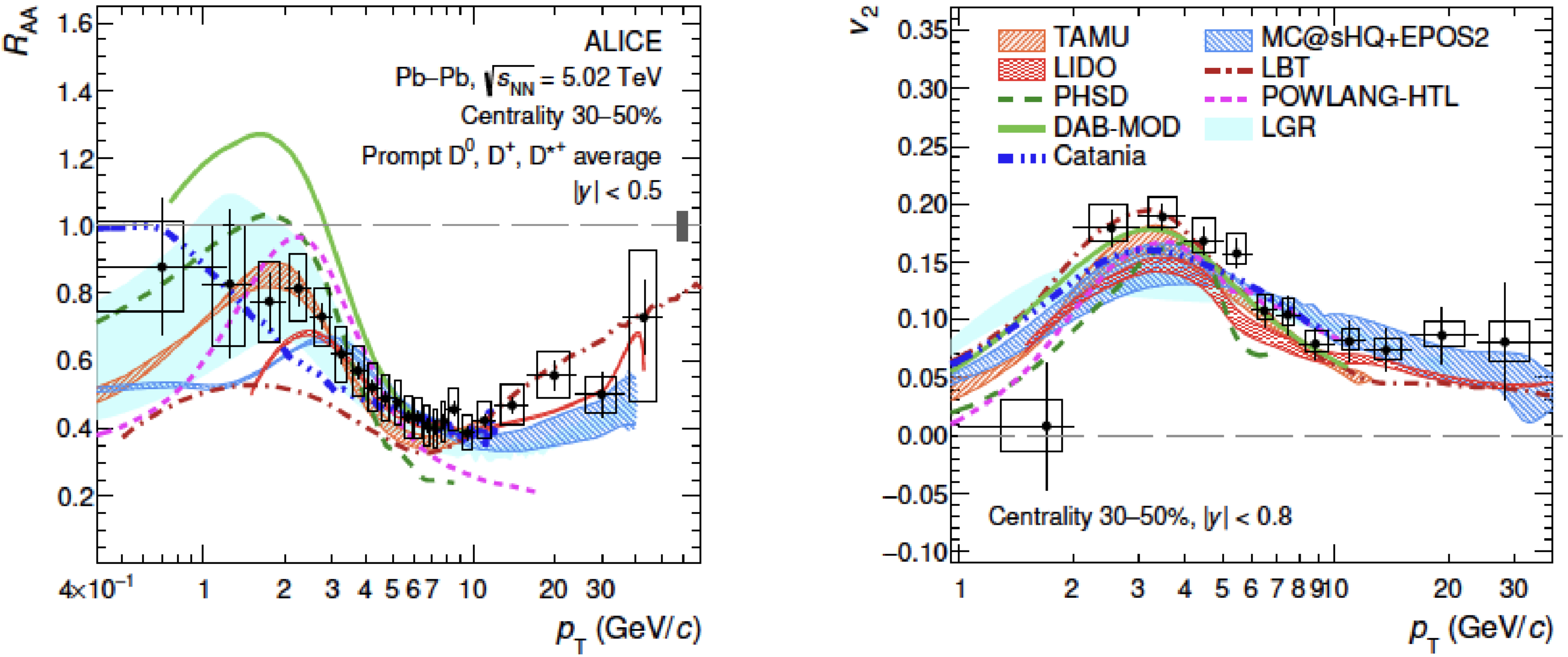


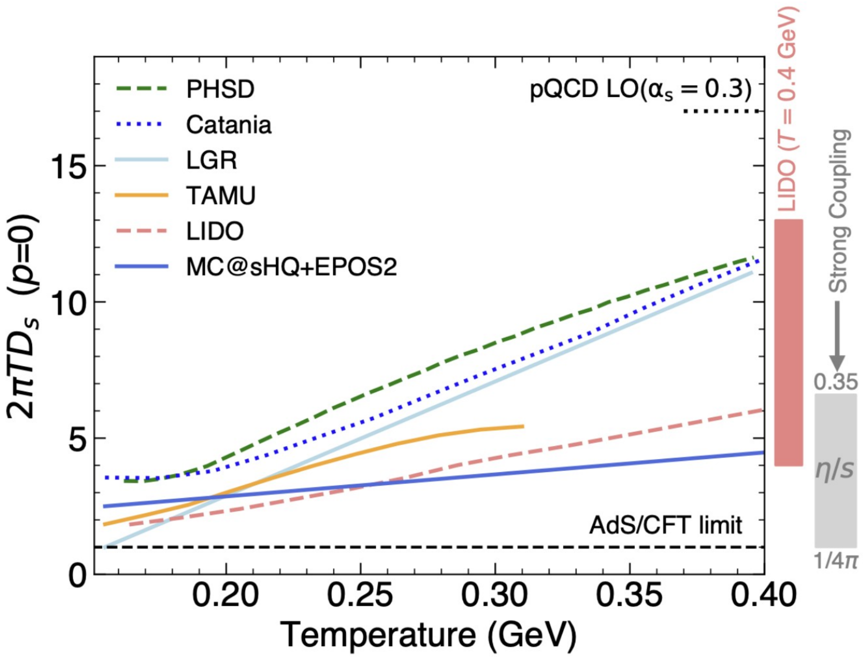
- Strong elliptic flow observed at both RHIC and the LHC
- Mass ordering in the low p_T range
- No significant energy dependence, similar as for the light particle species

Comparison to model calculations



- Overall, good qualitative description of both R_{AA} and v_2 for many different calculations, e.g. TAMU, MC@sHQ+EPOS, LIDO, LGR and Catania
  - All implement charm quark diffusion in the medium and quark coalescence at hadronization time
  - Data provides constraints for the spatial diffusion coefficient

Charm quark diffusion coefficient, D_S



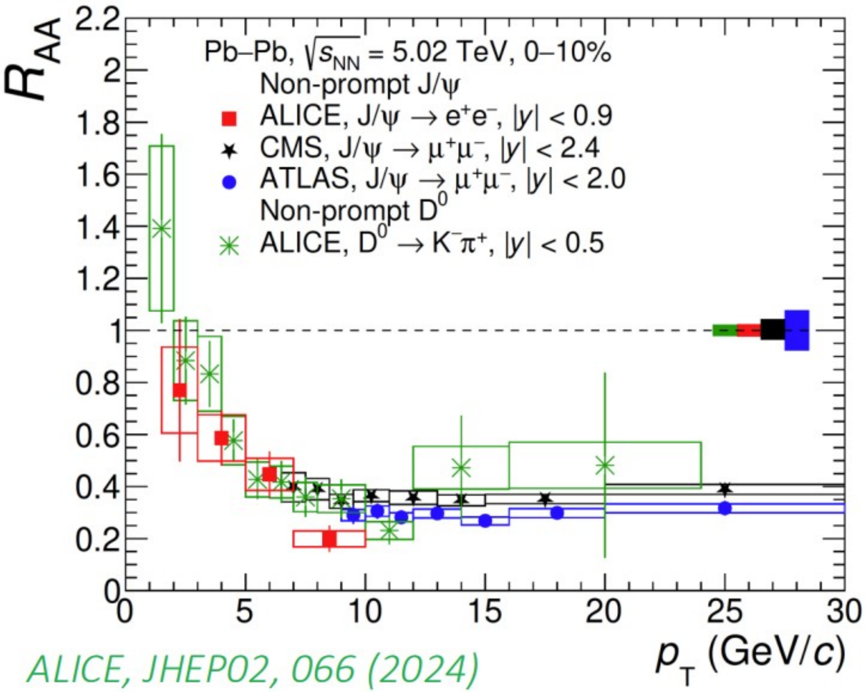
$$D_S \propto \frac{T}{m_Q \gamma}$$

$$\tau_Q = \frac{m_Q}{T} D_S$$ charm quark relaxation time

- Small D_S: fast relaxation time (more flow)
- Large D_S: slow relaxation (less flow)

- Large differences between models in extracting the temperature dependence of D_S
- Relaxation time values: $3<\tau_{relax}<9$ fm/c
  - Overall less than the QGP lifetime, but large theoretical uncertainty

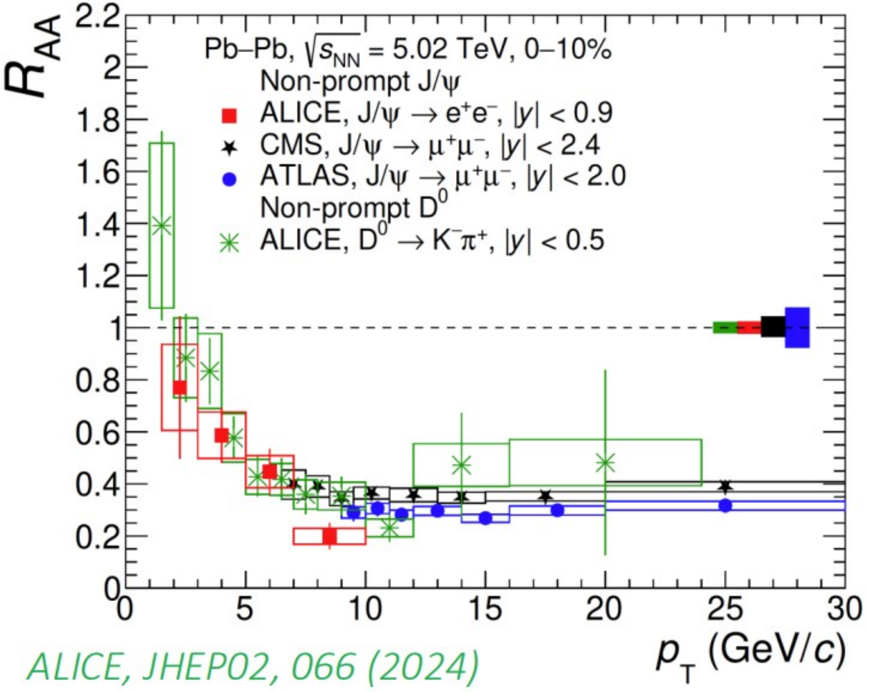
Beauty quark nuclear suppression



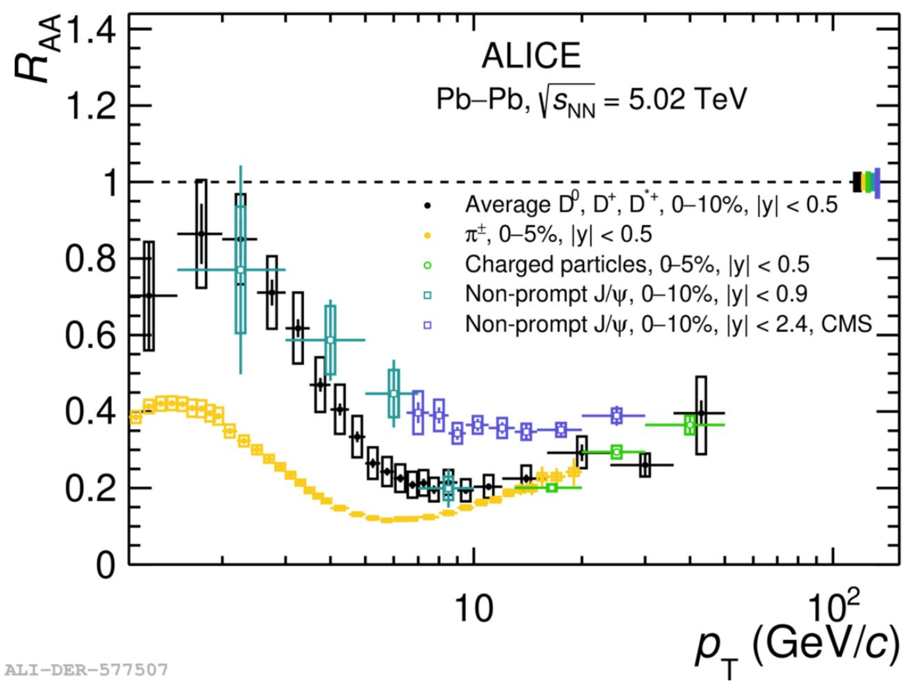
ALICE, JHEP02, 066 (2024)

- Best measured using non-prompt J/ψ and D^0
- High-p_T: strong suppression
- Low-p_T: R_{AA} goes up to nearly 1 (quark number conservation again)

Beauty quark nuclear suppression



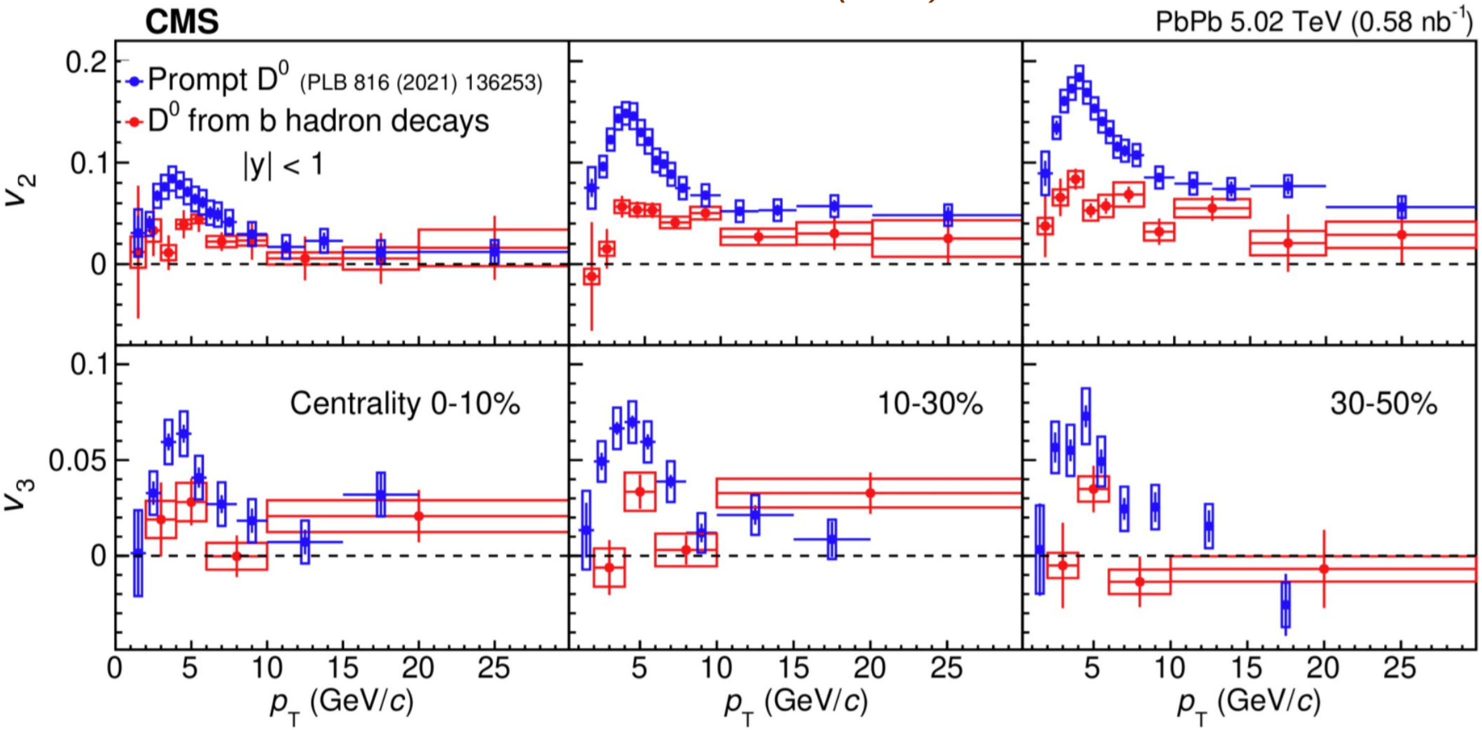
ALICE, JHEP02, 066 (2024)



- Best measured using non-prompt J/ψ and D^0
- High-p_T: strong suppression
- Low-p_T: R_{AA} goes up to nearly 1 (quark number conservation again)
- Mass hierarchy of R_{AA} up to about 10 GeV/c: $R_{AA}(B) > R_{AA}(D) > R_{AA}$ (light)
  - Remember expectations of energy loss hierarchy!!

Azimuthal anisotropy for beauty

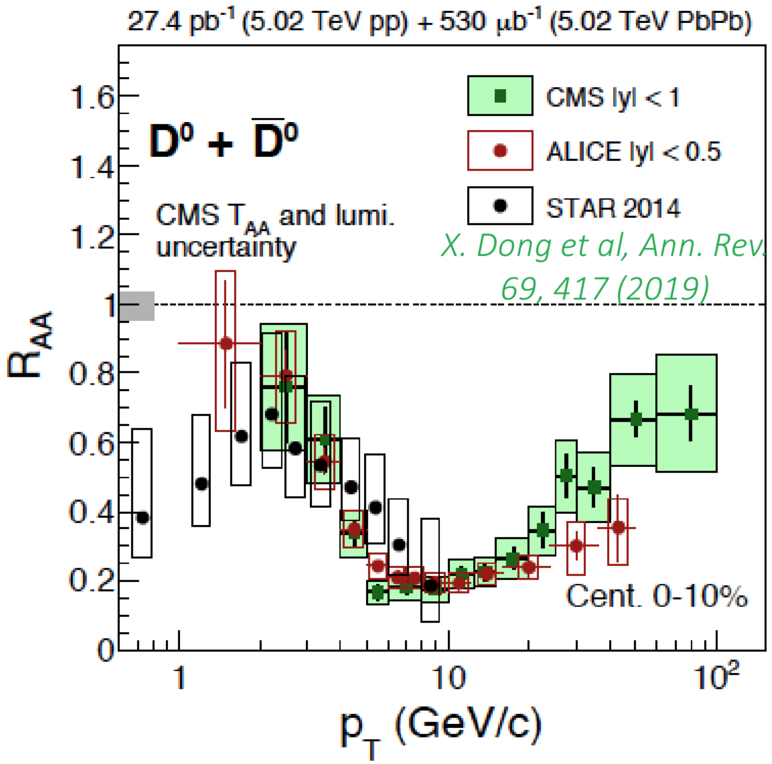
CMS, PLB850 (2024) 138389



- Flow of D mesons from B decays smaller than for prompt D, but its significant
- Partial thermalization for beauty quarks?
- Effect of hadronization (Upsilon does not seem to flow) ?

Back to charm hadrons...

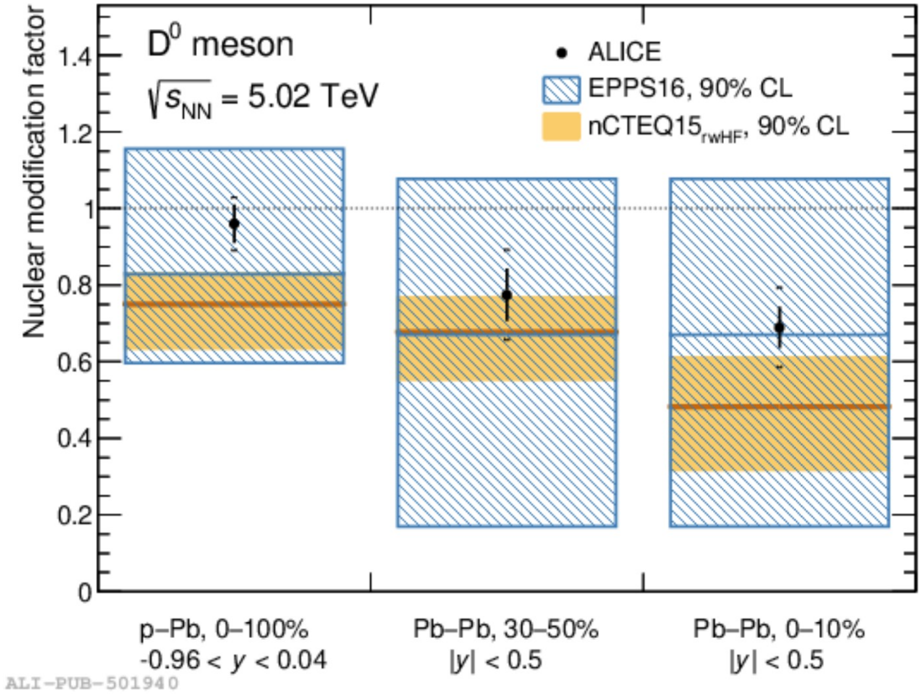
- Question: if charm quark number is conserved, why is the R_{AA} overall below 1 ?
  - Cold nuclear matter effects ?
    - Gluon shadowing / saturation
  - Hadronization effects ?
    - QGP affects the charm hadron chemistry



X. Dong et al, Ann. Rev. 69, 417 (2019)

Cold nuclear matter effects

ALICE, PLB839 (2023) 137796

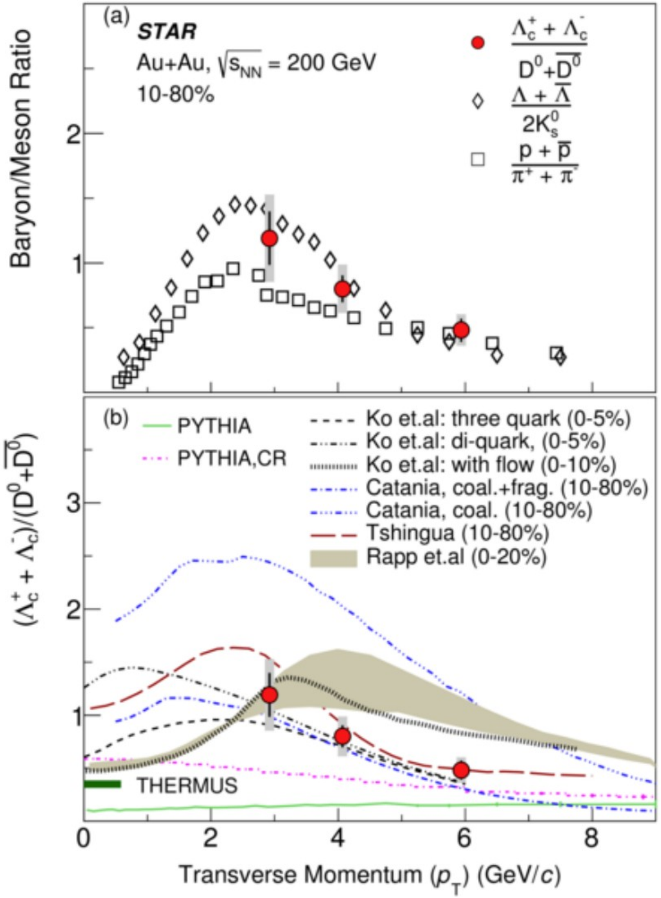


p_T-integrated D^0 meson R_{AA}

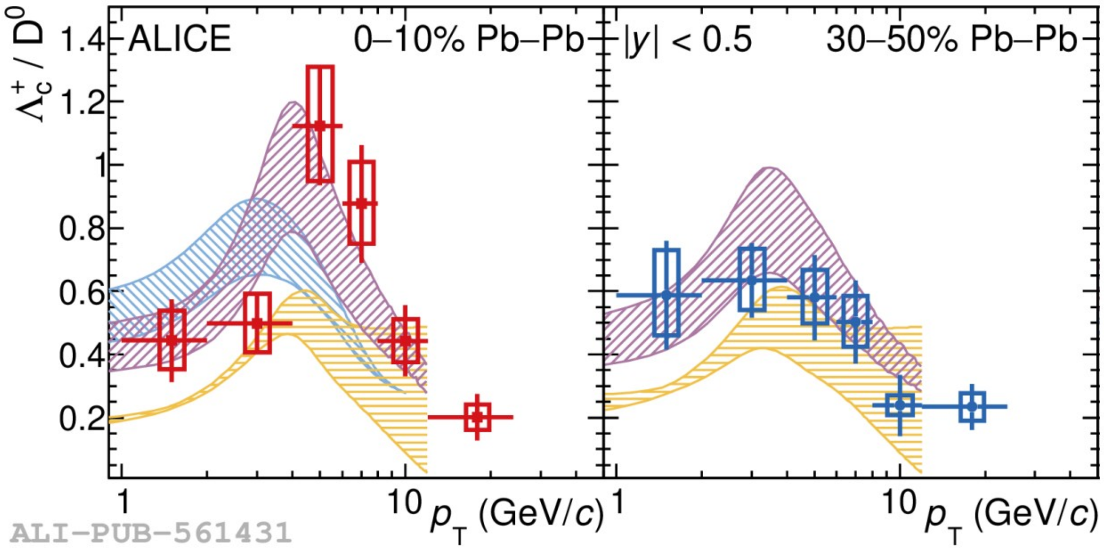
- About 30% observed suppression in central Pb-Pb
- Consistent with calculations based on nuclear gluon PDFs
  - But large uncertainties

Charmed baryon/meson ratios

STAR, PRL124 (2020) 172301



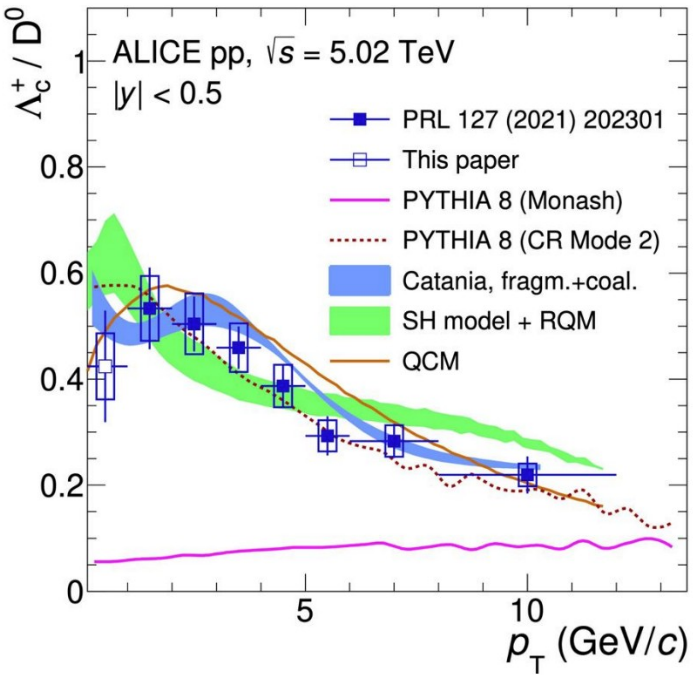
ALICE, PLB839 (2023) 137796



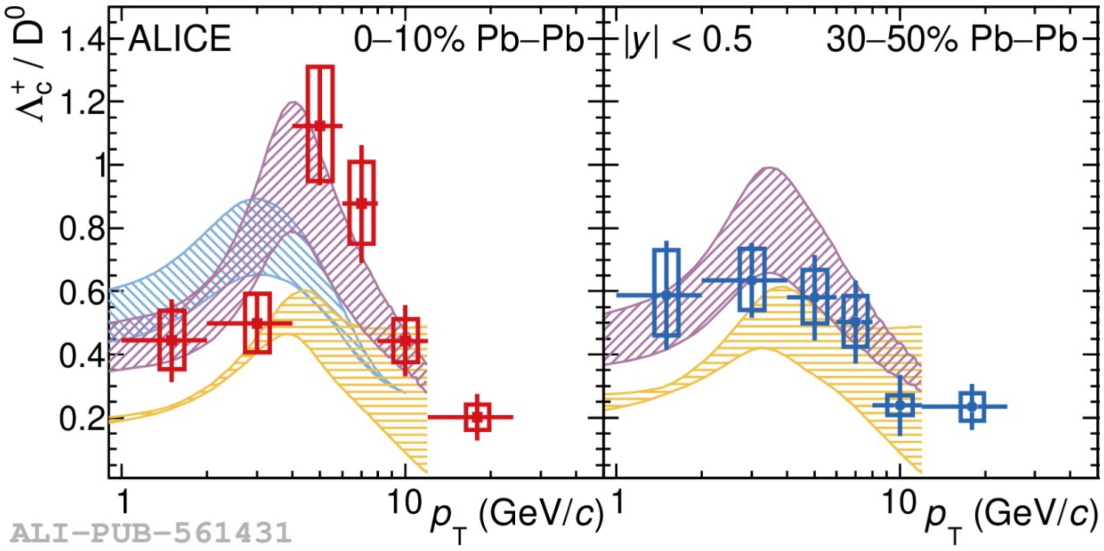
- Charmed baryon/meson ratio similar to light hadrons
- Significantly higher than usual PYTHIA
- Possibly features also centrality dependence

Charmed baryon/meson ratios

ALICE, PRC107 (2023) 064901



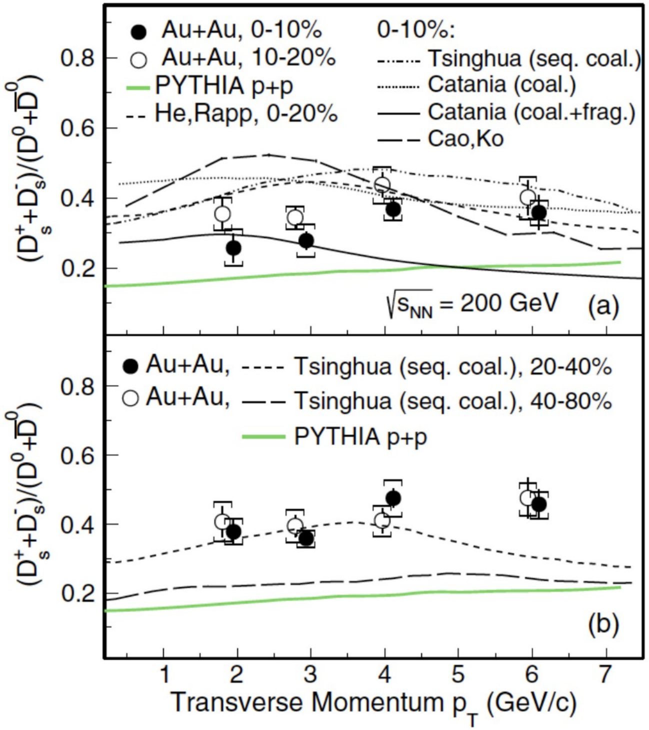
ALICE, PLB839 (2023) 137796



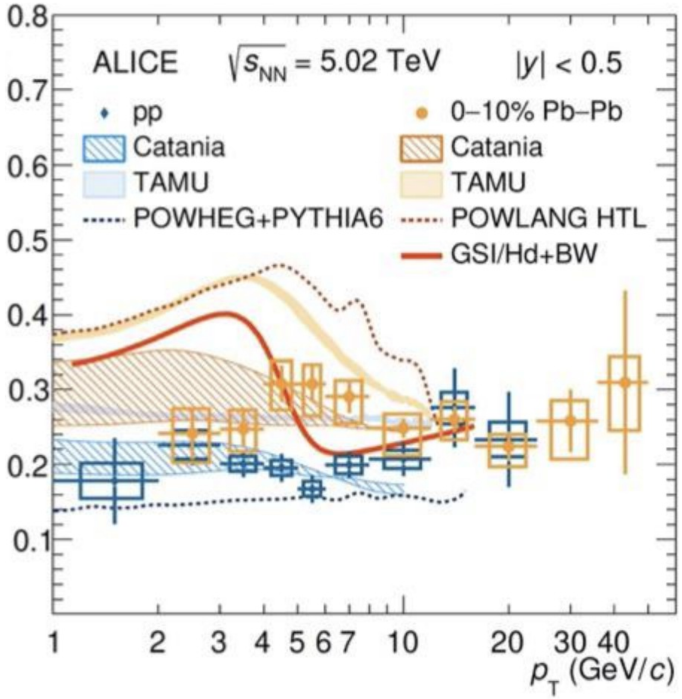
- Charmed baryon/meson ratio similar to light hadrons
- Significantly higher than usual PYTHIA
- Possibly features also centrality dependence
- Semi-central ratio in agreement with pp ratio

D_s / D^0 ratio

STAR, PRL127 (2021) 092301



ALICE, PLB827 (2022) 136986

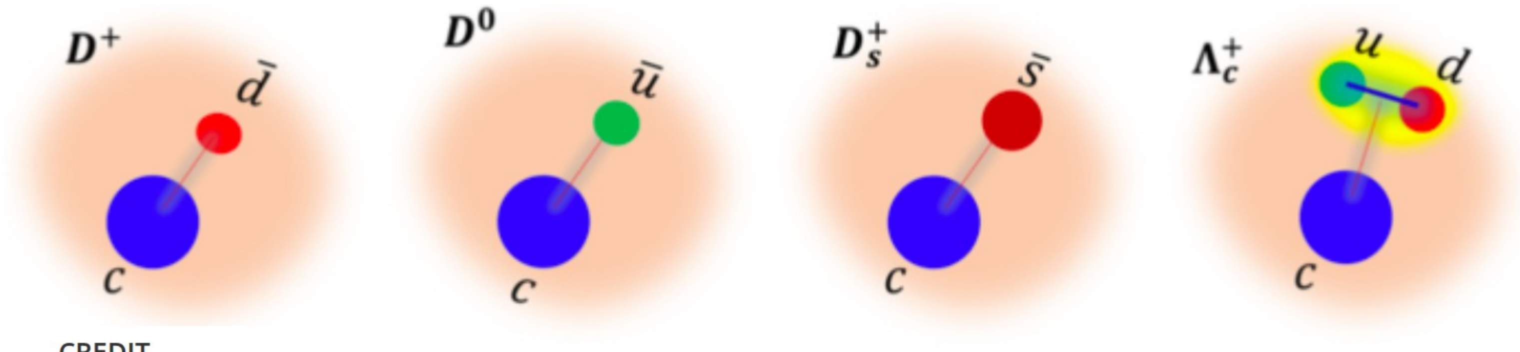


- D_s / D^0 ratio is larger in AA than in pp
  - Strangeness enhancement in the QGP + coalescence
- Together with the modifications of the baryon/meson ratio, this highlights the need for higher precision understanding of the most abundant charm hadron species

Summary

- Heavy quarks offer valuable information on the macro- and microscopic properties of the QGP
- Charm quarks
  - experience significant energy loss
  - thermalize to a very high degree within the plasma
- Additional effects such as CNM and hadronization play an important role in the interpretation of the data

Open heavy flavour hadrons



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- All hadrons containing net heavy flavour quantum number
- "Heavy" refers to charm and beauty quarks
  - $m_c \sim 1.3$ GeV/c^2
  - $m_b \sim 5$ GeV/c^2
- What can we learn from them ?
- How can they be measured ?