# Experimental results on open heavy-flavour in heavy-ion collisions

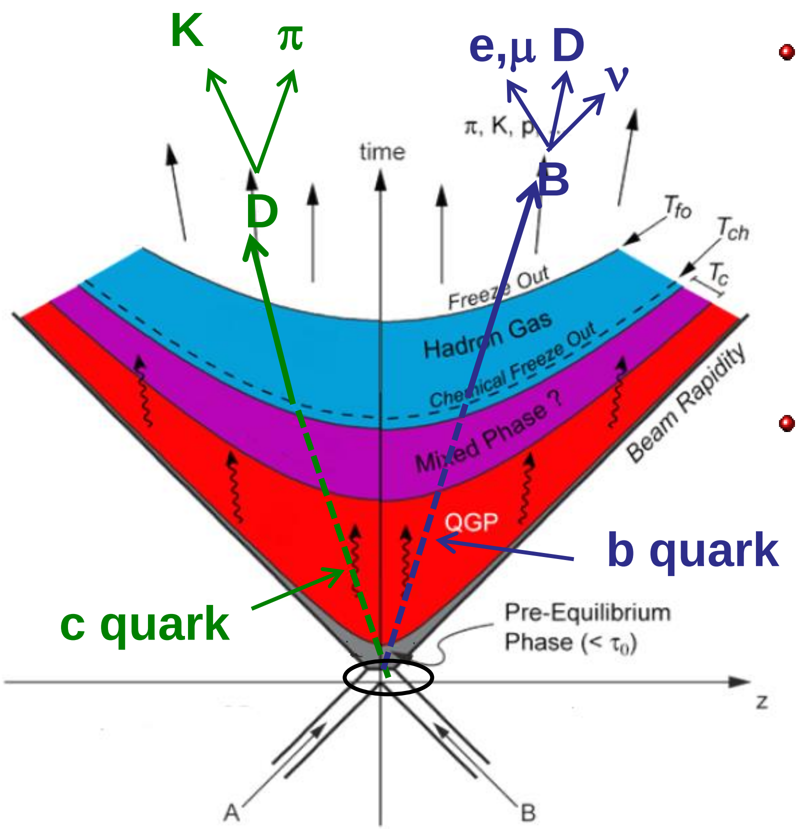
## Few outstanding open questions and how to address them

Francesco Prino

INFN – Sezione di Torino

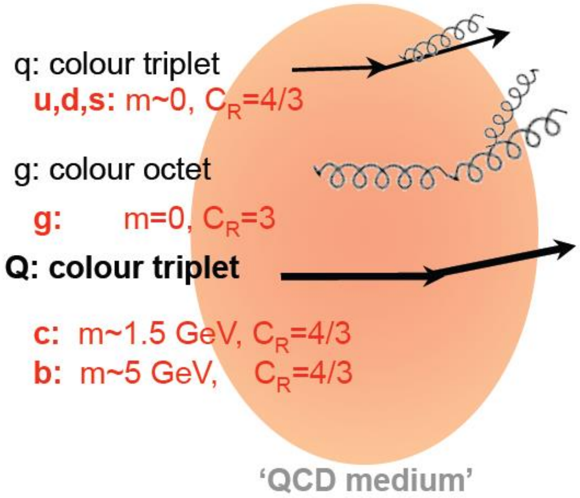

Sapore Gravis Workshop
Padova, 9-12 December 2014

# Charm and beauty quarks in heavy-ion collisions




- Produced in partonic processes with large $Q^2$ on short time scale
  - ⇨ Production in QGP expected to be negligible
  - ⇨ pQCD can be used to calculate initial cross sections
- Traverse the "full evolution" of the hot and dense medium
  - ⇨ Lose energy via elastic collisions with the medium constituents and gluon radiation
  - ⇨ Flavour conserved in the interactions with the QGP
  - ⇨ Excellent probes of the properties of the medium: transport coefficients, energy loss mechanism, collectivity, thermalization)

# Probing the medium properties

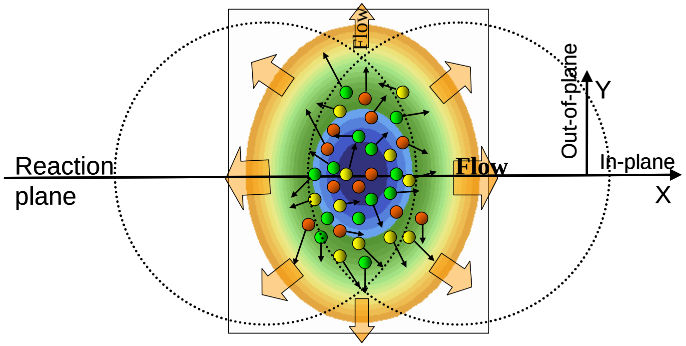



- **Hierarchy** expected due to colour-charge and quark-mass dependence of in-medium parton **energy loss**:

$$\Delta E_{gluon} > \Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$$

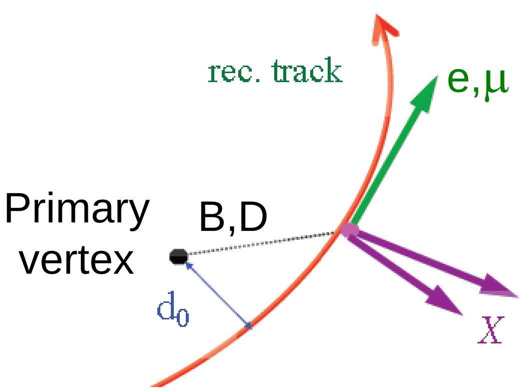
- Reflected into: $\mathbf{R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)?}$

- Interactions with the medium constituents can transfer to charm and beauty quarks the **collective flow** (radial and elliptic) of the medium
  - ⇨ Large mass: frequent interactions with large coupling needed
  - ⇨ Expectation: $\mathbf{v_2(B) < v_2(D)}$
  - ⇨ Are re-scatterings with the medium strong enough to make charm (and beauty) quarks **thermalize** in the medium?

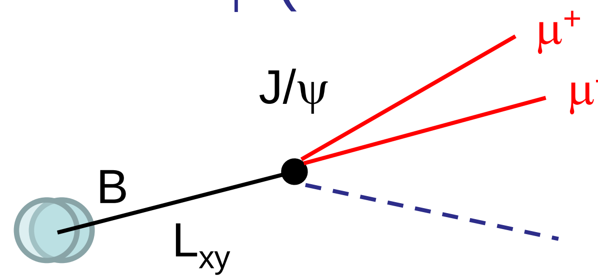


# Heavy flavour reconstruction

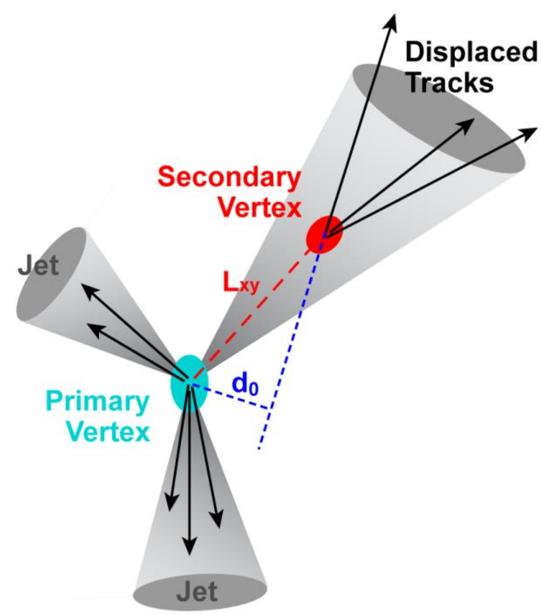
## Semi-leptonic decays (c,b)




## Displaced J/ψ (from B decays)




## jet b-tagging



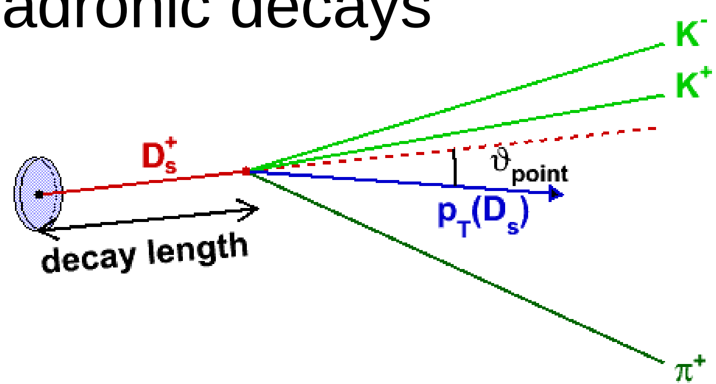

## Full reconstruction of D meson hadronic decays

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

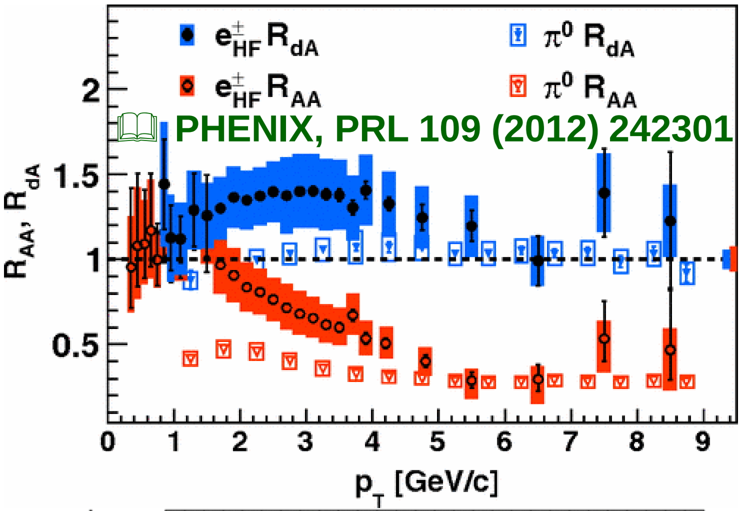
$D^+ \rightarrow K^- \pi^+ \pi^+$

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

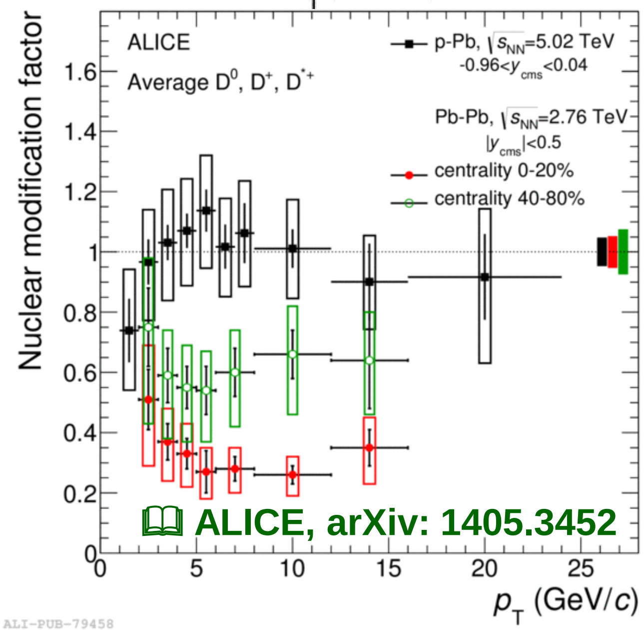
$D_s^+ \rightarrow K^- K^+ \pi^+$

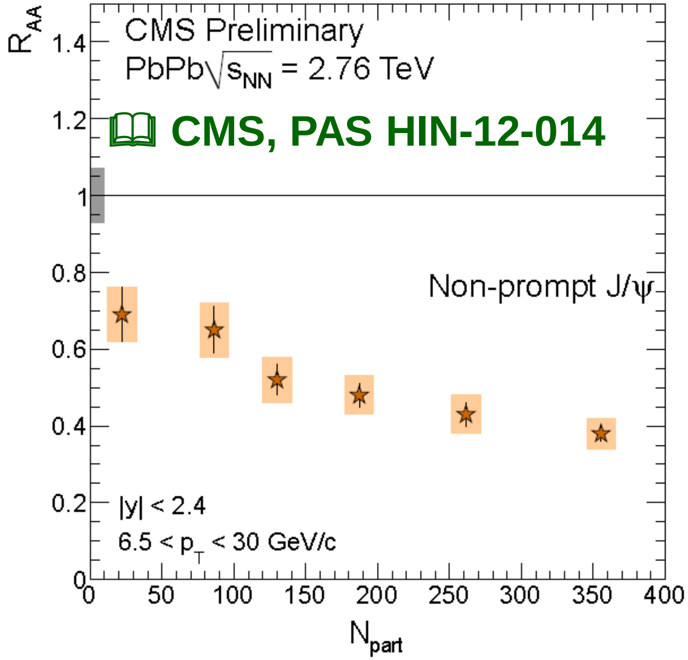


# What have we learned?
## In-medium energy loss



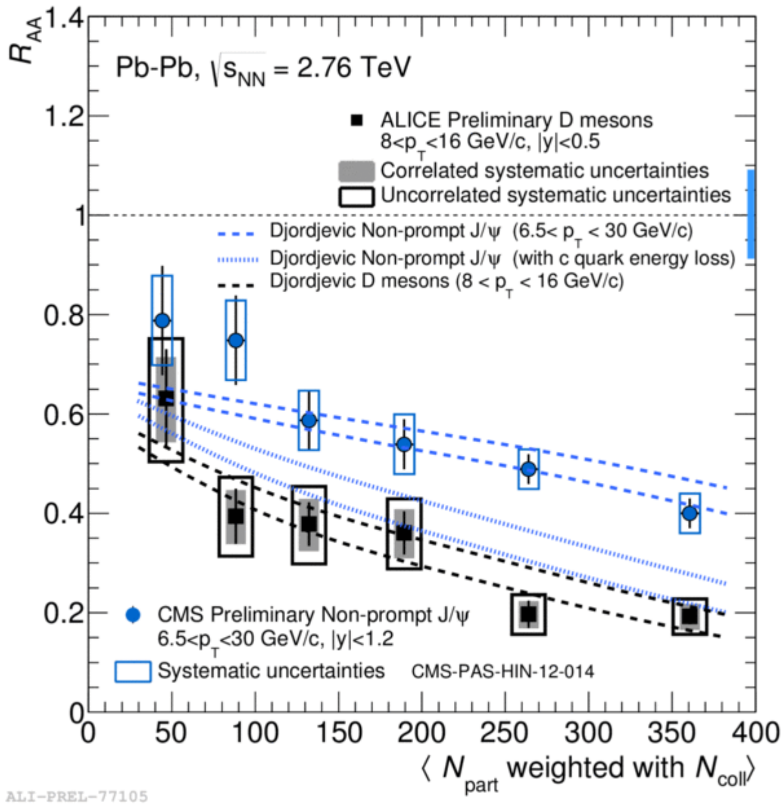

- **Strong suppression** of HF yield at **intermediate and high $p_T$**
  - ⇨ Final state effect due to in-medium energy loss (by comparing to d-Au and p-Pb)
  - ⇨ $R_{AA}$(HFE,D) ≈ $R_{AA}(\pi)$



# What have we learned?
## Beauty vs. charm $R_{AA}$

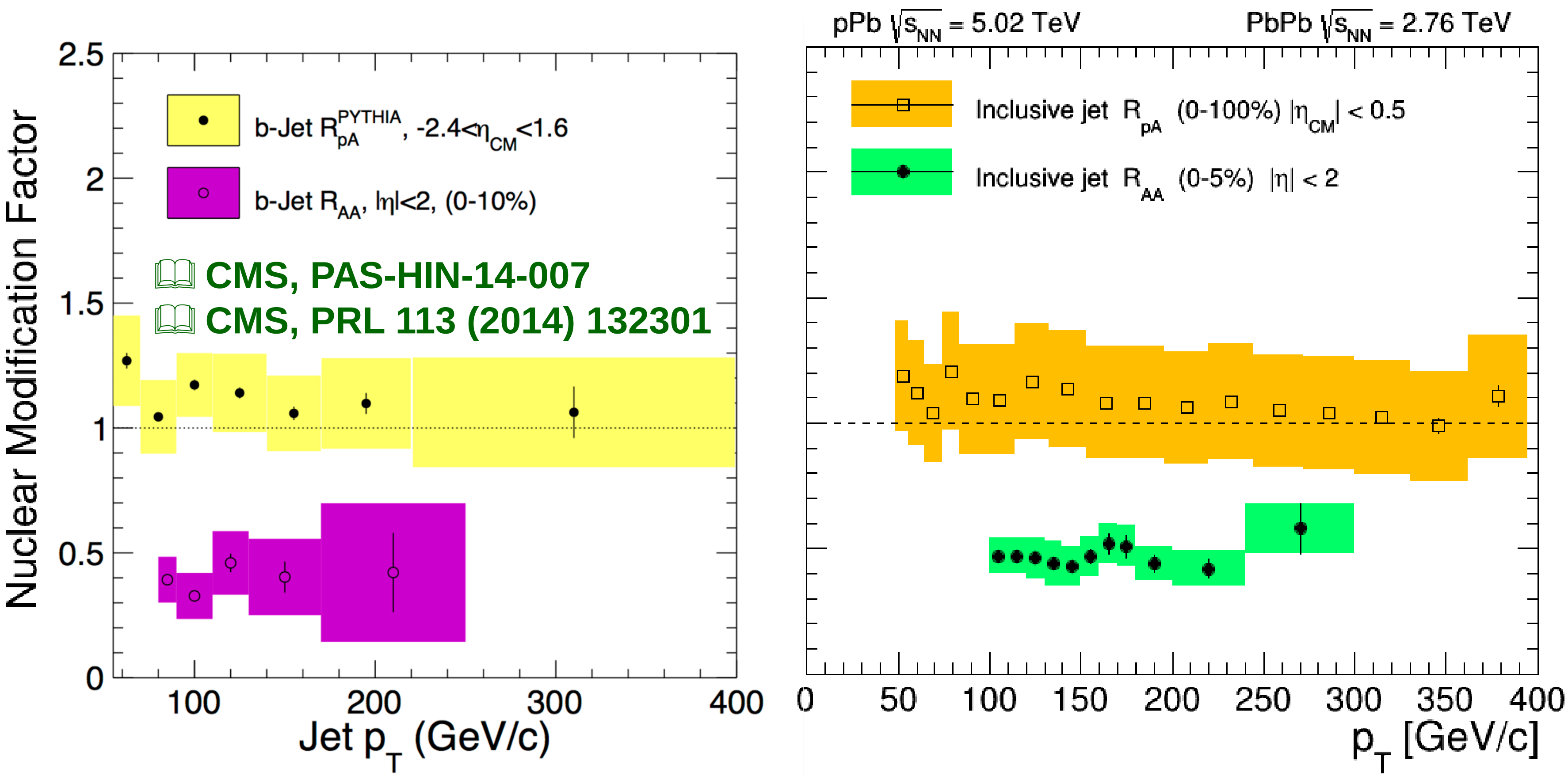
**D meson (ALICE)** and **J/ψ←B** (CMS) $R_{AA}$ vs. centrality in $p_T$ ranges tuned to have $\langle p_T(D)\rangle \approx \langle p_T(B)\rangle \approx$ 10-11 GeV/c




- Expectation from parton-mass dependent energy loss: $\Delta E_c > \Delta E_b$
- Clear indication of **$R_{AA}$(B) > $R_{AA}$(D)** for $8<p_T(D)<16$ GeV/c
  - ⇨ Also for $5<p_T<16$ GeV/c
- Described by model calculations with quark-mass dependent energy loss


📖 **Djordjevic, Djordjevic, PRL112 (2014) 042302**
📖 **MC@sHQ+EPOS: Gossiaux et al., arXiv:1409.0900**
📖 **WHDG: Horowitz et al., J Phys. G38 (2011) 124114**

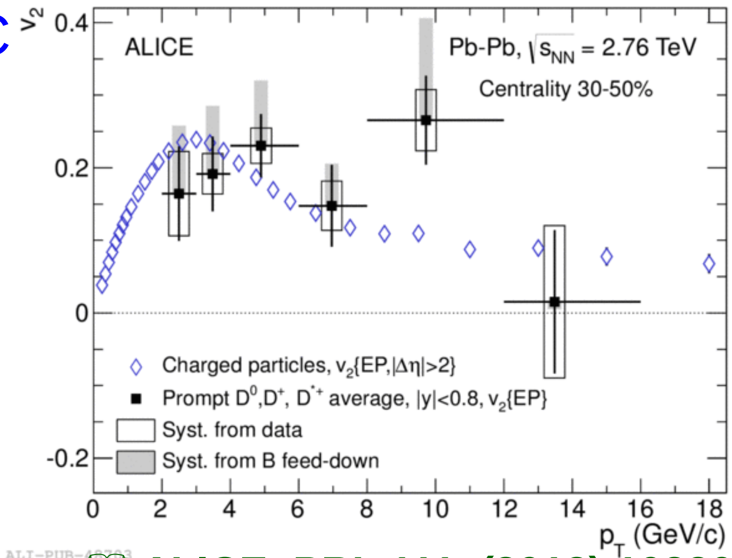
# What have we learned?
## Beauty jets at high $p_T$



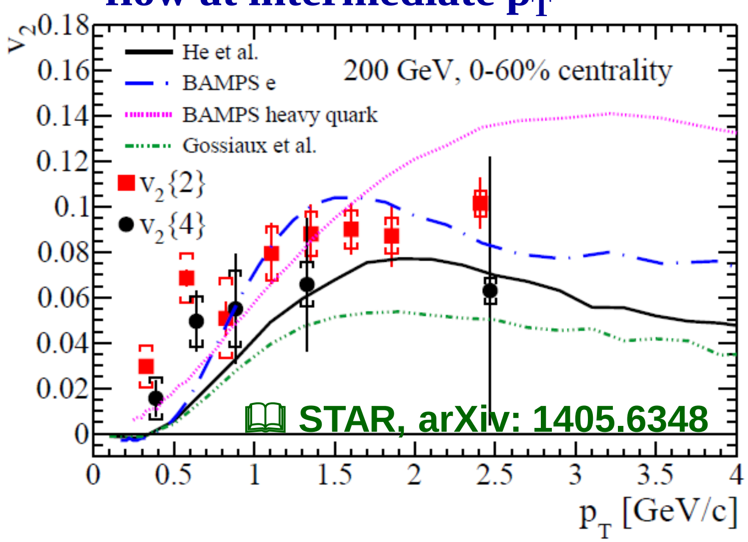

- $R_{AA}$ of b-jets found to be consistent with that of inclusive jets (dominated by light quarks and gluons) at high $p_T$ (>80 GeV/c)
  - ⇨ Mass effect on parton energy loss expected to be small at large $p_T$

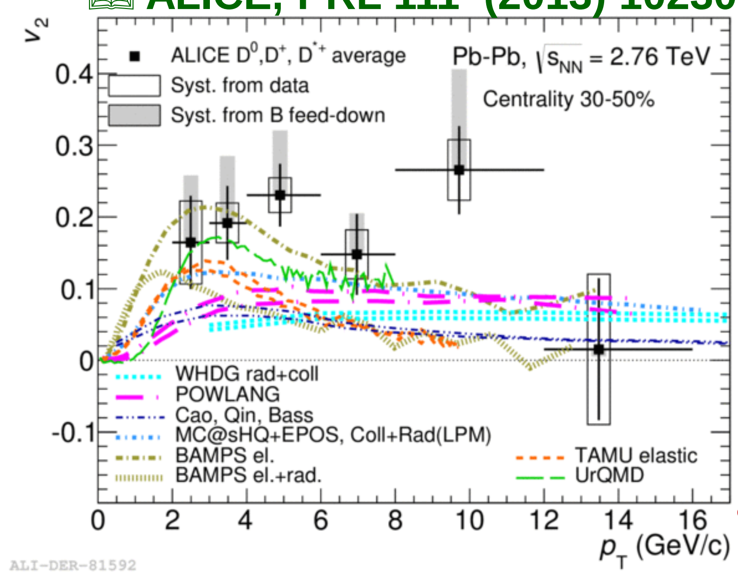
# What have we learned? Flow/collectivity

- Positive **elliptic flow** at RHIC and LHC
  - ⇨ Comparable with charged particle $v_2$
  - ⇨ Suggests that charm quarks take part in the collective expansion of the system?
- Elliptic flow at low $p_T$ also sensitive to:
  - ⇨ Interactions with medium constituents:
    - ✓ **Collisional more effective than radiative processes in building $v_2$**
  - ⇨ Hadronization mechanism:
    - ✓ **Coalescence increases radial and elliptic flow at intermediate $p_T$**

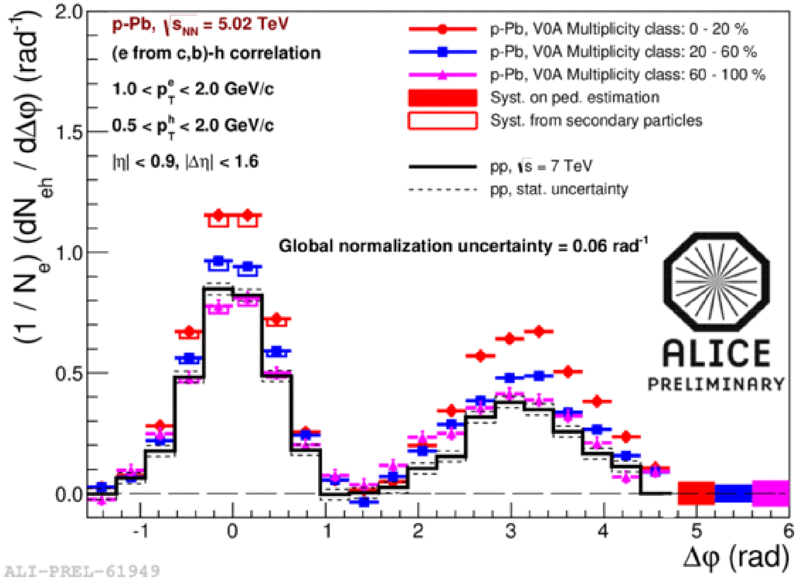


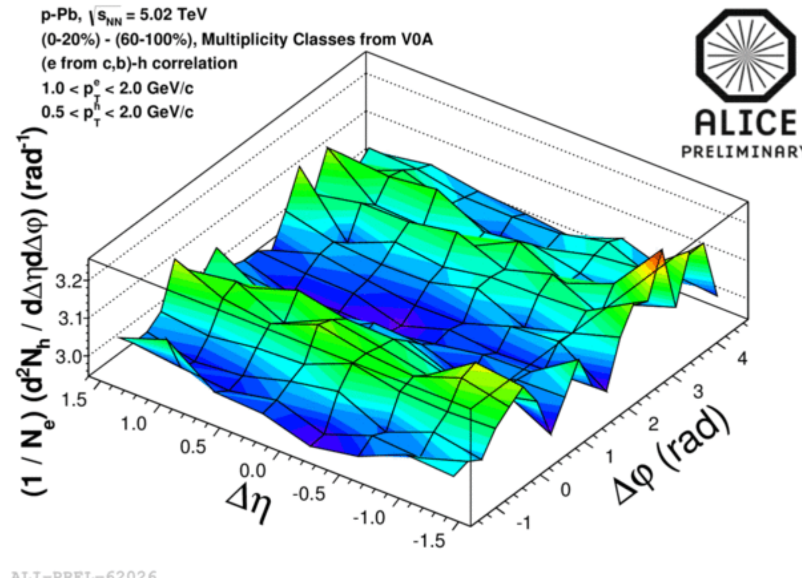

📖 ALICE, PRL 111 (2013) 102301



# What have we learned?
# Collectivity in small systems?



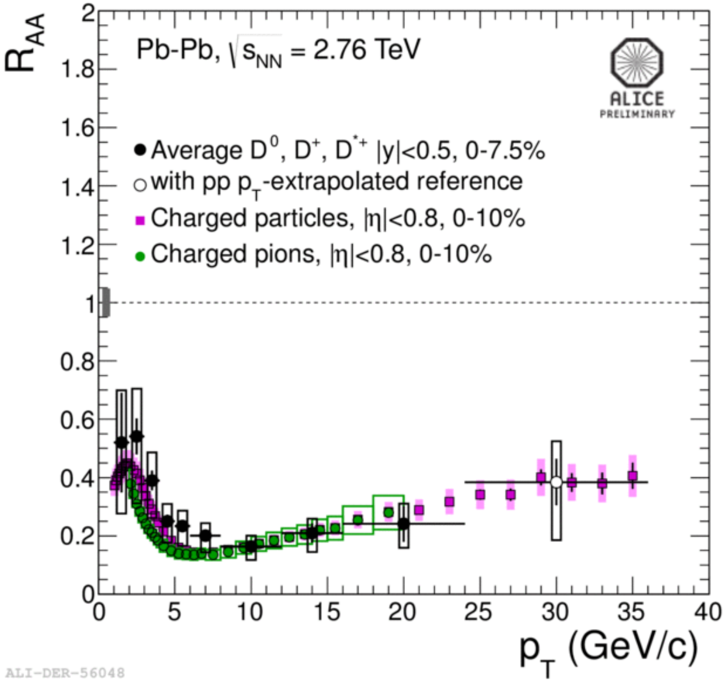




- Double-ridge structure observed in the angular correlations between HF decay electrons and charged hadrons in p-Pb collisions
  - ⇨ Similar to the one observed in the light-flavour sector (📖 **ALICE, PLB719 (2013) 29** )
  - ⇨ Suggests that the mechanism generating the double ridge is at work also for heavy flavours
    - ✓ **CGC in initial state?** 📖 **Dusling, Venugopalan, PRD87 (2013) 094034**
    - ✓ **Hydrodynamics in final state?** 📖 **Bozek, Broniowski, PLB718 (2013) 1557**
- To be considered: collective flow in small systems (📖 **Sickles, arXiv:1309.6924**) would modify the HF hadron $p_T$ spectra in addition to nuclear modification of PDFs, $k_T$-broadening, cold-nuclear-matter energy loss

# Few outstanding open questions

- **Charm** vs. **light** quark energy loss
  - Expectation **$\Delta E_c < \Delta E_{u,d,s} < \Delta E_g$** vs. observation **$R_{AA}(D) \approx R_{AA}(\pi)$**
- Charm hadrochemistry: $D_s$ and $\Lambda_c$
  - Sensitive to **hadronization mechanism** (coalescence vs. fragmentation)
- **Low-$p_T$** D-mesons: LHC vs. RHIC
  - Interplay between **radial flow, coalescence, shadowing** and **energy loss**
- Measurements at **lower collision energy**
  - $R_{AA}$>~1 measured at $\sqrt{s}$=62.4 GeV
  - Other handle to study the interplay between **radial flow, coalescence, $k_T$-broadening** and **energy loss**
- **Path length dependence** of energy loss
  - Allow to constrain the contribution of collisional and radiative processes?
- **Beauty** quark energy loss at low and intermediate $p_T$
  - Low $p_T$ (<10 GeV/c): mass effect on energy loss + radial flow?
  - Intermediate $p_T$: at which $p_T$ does $R_{AA}$(b) become compatible with $R_{AA}$(light)?
- **Elliptic flow** of charm (and beauty) hadrons
  - Is v2 of D mesons and HFE due to charm quarks participating in the **collective flow**?
  - Or is it due to hadronization via **coalescence** with light quarks from the bulk?
- Collectivity in small systems also in the HF sector?
  - Or Colour Glass Condensate?
  - Crucial to assess **cold nuclear matter effects** in the initial and final state

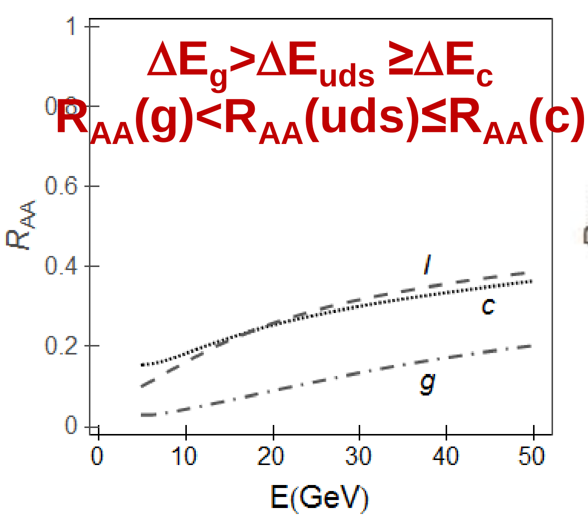
# Charm vs. light




- Similar $R_{AA}$ of D mesons and pions both at RHIC and LHC)
- Described by models including
  - ⇨ Mass and colour charge dependent E loss
  - ⇨ Different momentum spectra of charm quarks, light quarks and gluons
  - ⇨ Different fragmentation function (harder for charm than for light quarks and gluons)
    - 📖 **Djordjevic, Djordjevic, PRL112 (2014) 042302**
- Hint for $R_{AA}(D) > R_{AA}(\pi)$ for $p_T$<5 GeV/c?
  - ⇨ More data needed to study the (small) effect of c-quark mass at low $p_T$

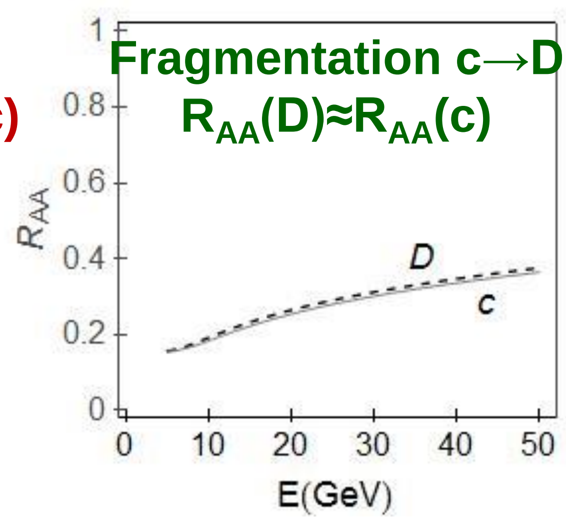
**$\Delta E_g > \Delta E_{uds} \geq \Delta E_c$**

**$R_{AA}(g) < R_{AA}(uds) \leq R_{AA}(c)$**



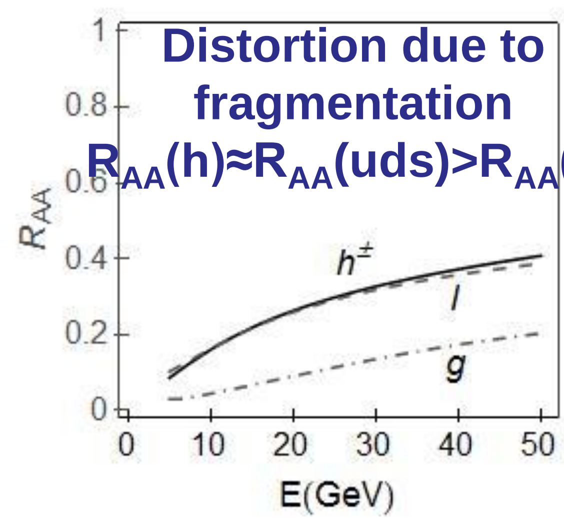

**Fragmentation c→D**

**$R_{AA}(D) \approx R_{AA}(c)$**

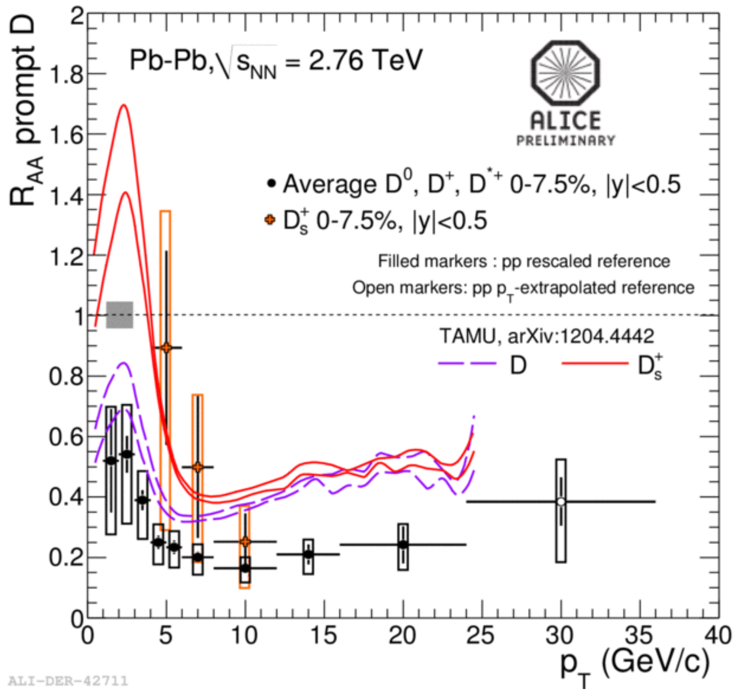


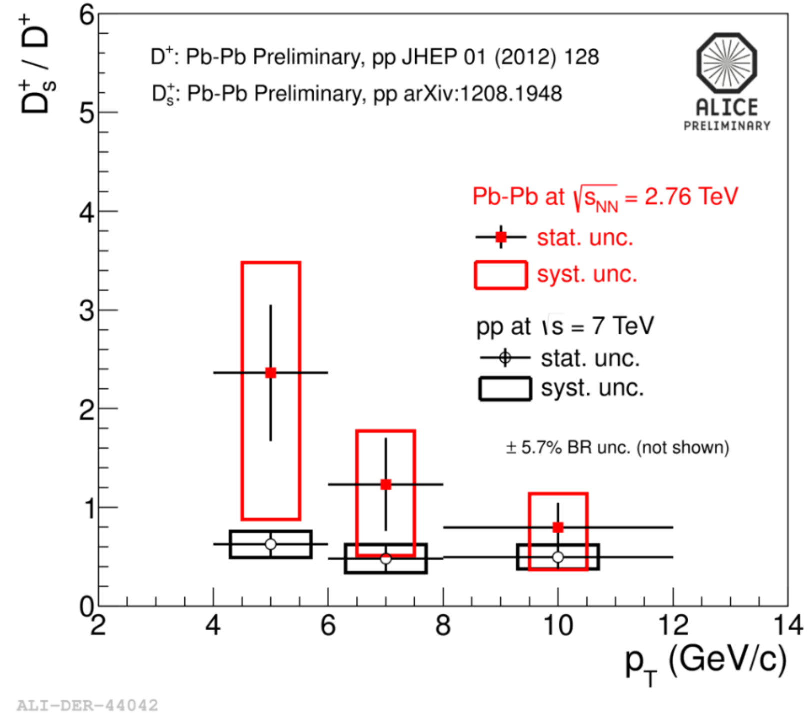

**Distortion due to fragmentation**

**$R_{AA}(h) \approx R_{AA}(uds) > R_{AA}(g)$**



# The strange frontier



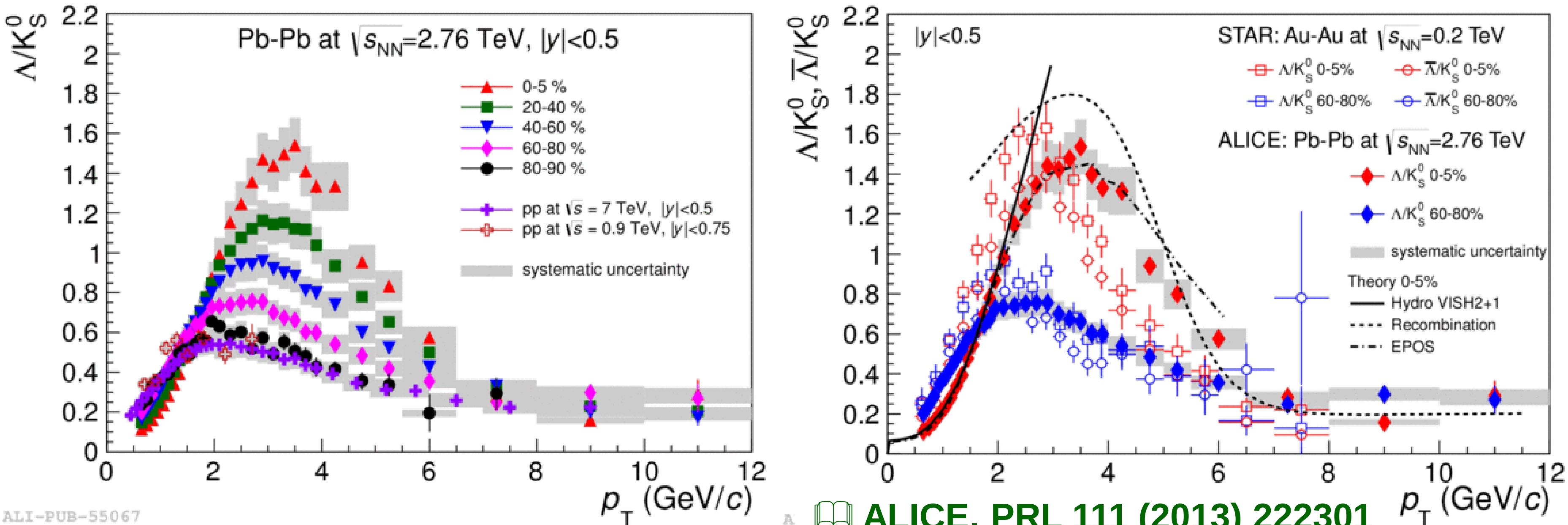




- $D_s^+$ results in Pb-Pb at low $p_T$ (<6 GeV/c) might hint at an increased ratio $D_s$/non-strange D in Pb-Pb collisions at √s=2.76 TeV
- More statistics needed to conclude on the predicted enhancement of the strange/non-strange D meson yield at low/intermediate $p_T$ if charm hadronizes via **recombination** in the medium
- Important also for the interpretation of **$R_{AA}$(D) vs. $R_{AA}$(π)**

📖 **Kuznetsova, Rafelski, EPJ C 51 (2007) 113**

📖 **He, Fries, Rapp, PRL 110 (2013) 112301**

# The baryon frontier

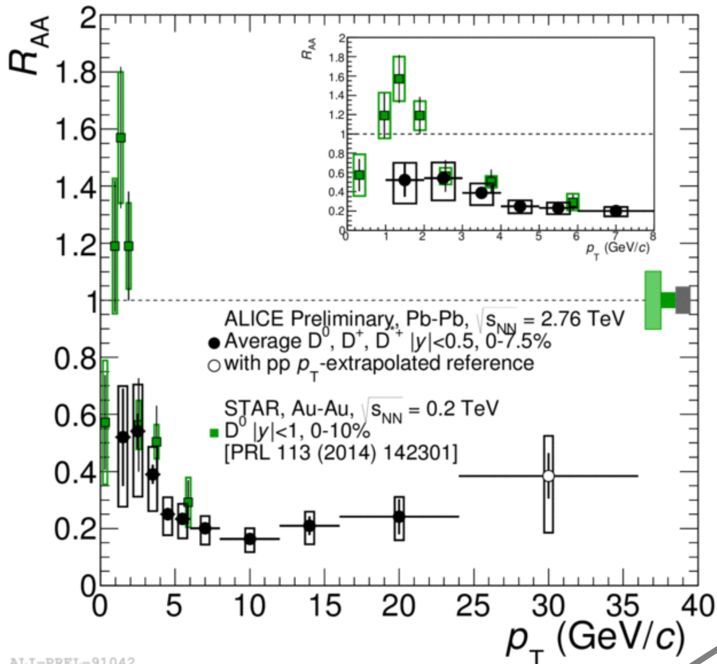



**ALICE, PRL 111 (2013) 222301**
**STAR, PRL 108 (2012) 072301**

- Enhancement of baryon/meson ratios at intermediate $p_T$ for light flavour hadrons in central A-A collisions at RHIC and LHC
  - ⇨ Described by hadronization via parton-recobination and radial flow
- At high $p_T$ the baryon/meson ratio is consistent with pp results
  - ⇨ Dominated by hard processes and hadronization via fragmentation
- Is baryon/meson enhanced also in the HF sector?
  - ⇨ With larger data samples $\Lambda_c$ could become accessible at the LHC
- Important also for the interpretation of **$R_{AA}$(D) vs. $R_{AA}(\pi)$**

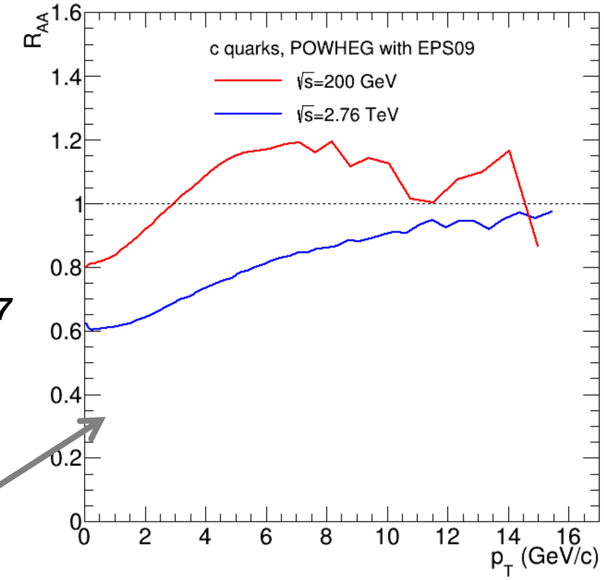
# The low-$p_T$ frontier

- Bump in D meson $R_{AA}$ at $\sqrt{s}$=200 GeV
  - ⇨ Due to charm quark radial flow/coalescence

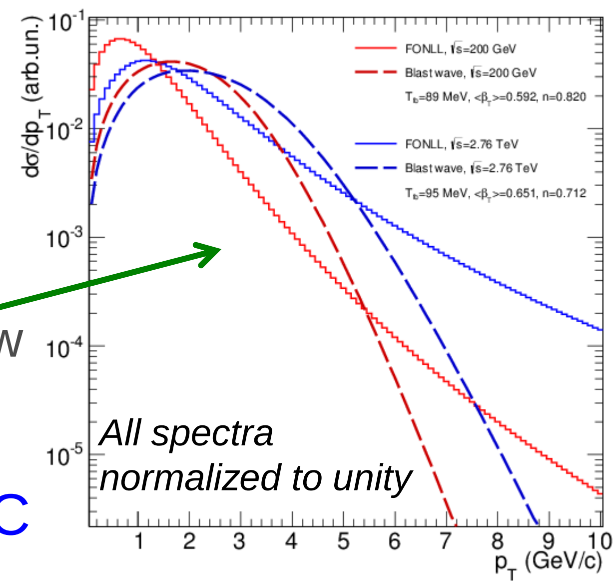



***N*$_{events}$*(STAR)=2.4·10*$^8$**

***N*$_{events}$*(ALICE)=1.6·10*$^7$**

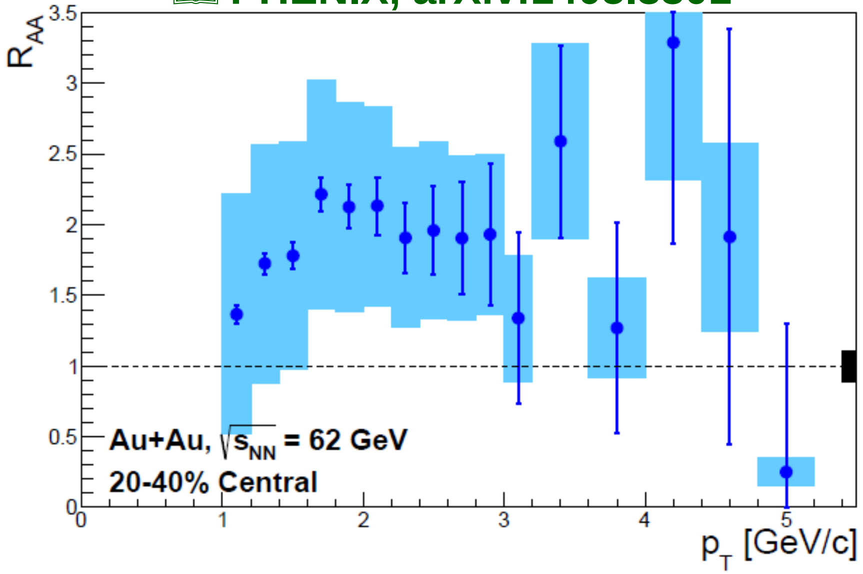



- At LHC energy:
  - ⇨ More shadowing, different effect of the radial flow on $R_{AA}$ (less steep spectrum in pp)
  - ⇨ Some models (e.g. TAMU) describe both results
- Need more precise measurements at the LHC down to $p_T$=0
  - ⇨ More statistics + pp reference at same energy

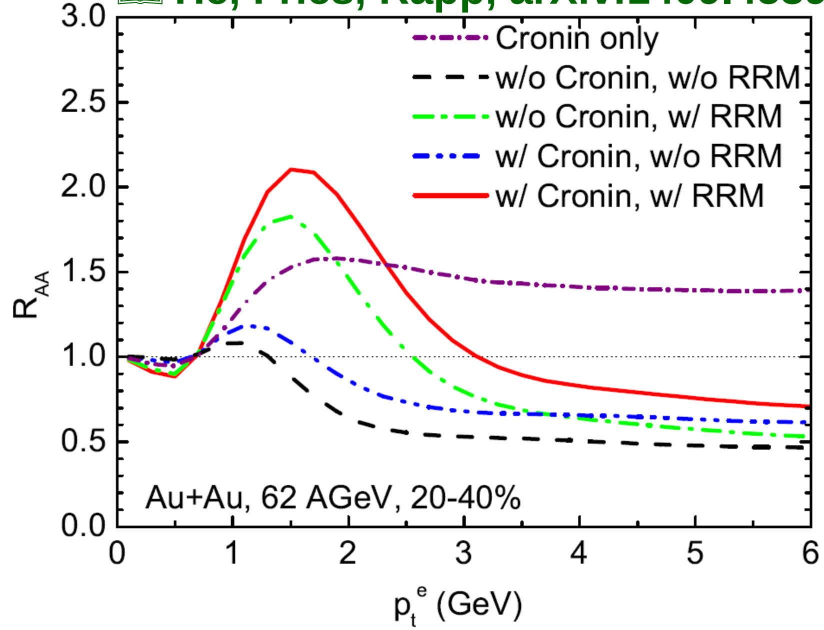


# The low-energy frontier

📖 PHENIX, arXiv:1405.3301



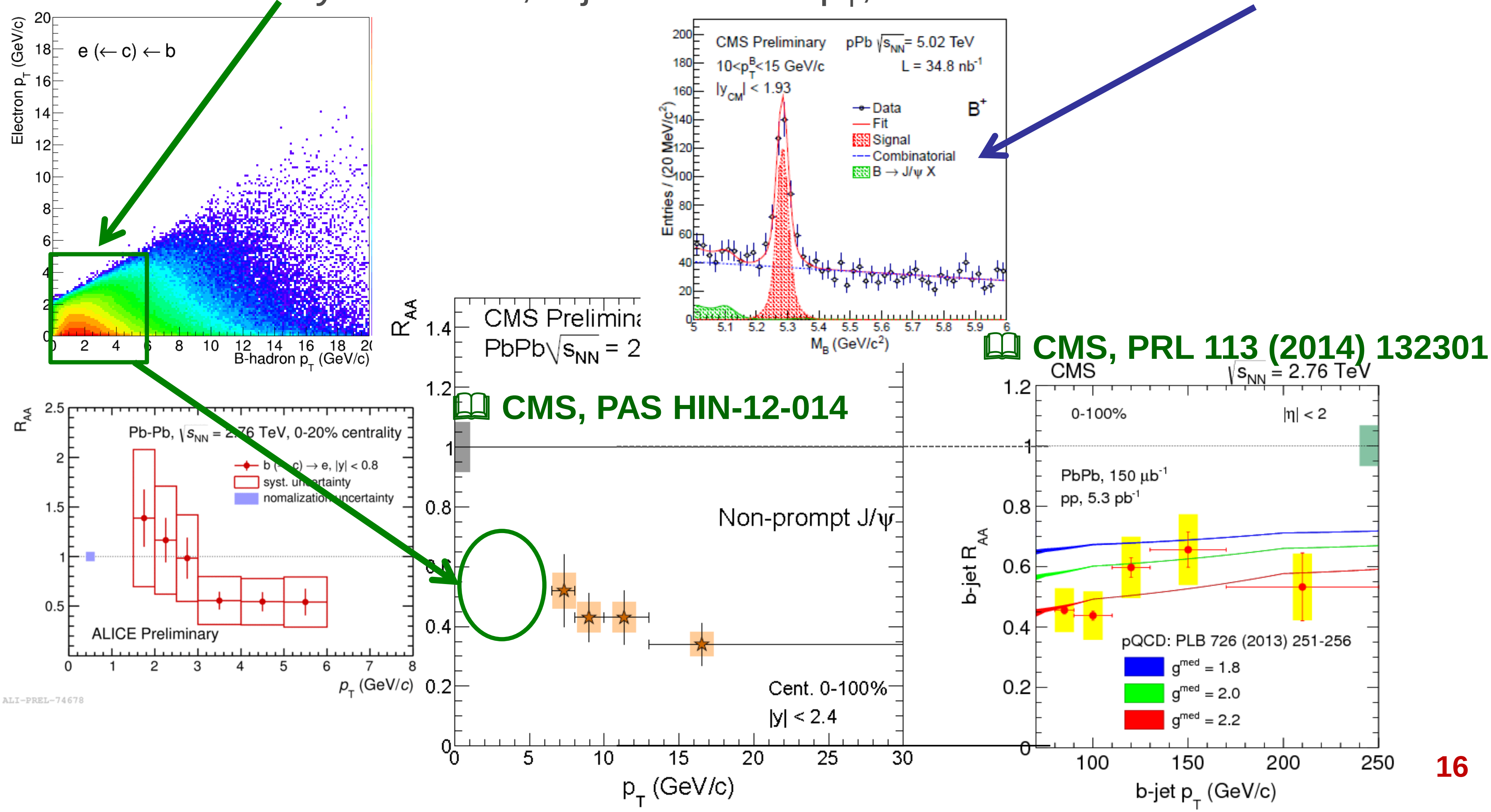

📖 He, Fries, Rapp, arXiv:1409.4539



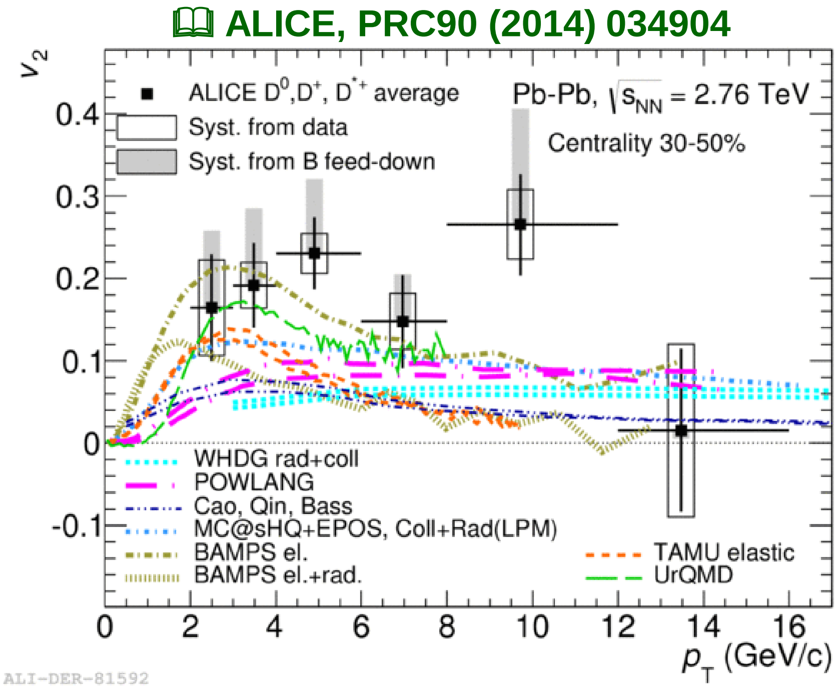

- Yield of HF decay electrons at $\sqrt{s}$=62.4 GeV **enhanced** with respect to binary scaled pp collisions
  - ⇨ Large uncertainties, pp reference from ISR experiments
- Described by TAMU model as an **interplay** between different effects:
  - ⇨ **$k_T$-broadening**, **radial flow**, **coalescence** and in-medium **energy loss**
- Important to: improve precision, pp reference from same experiment, separate c and b

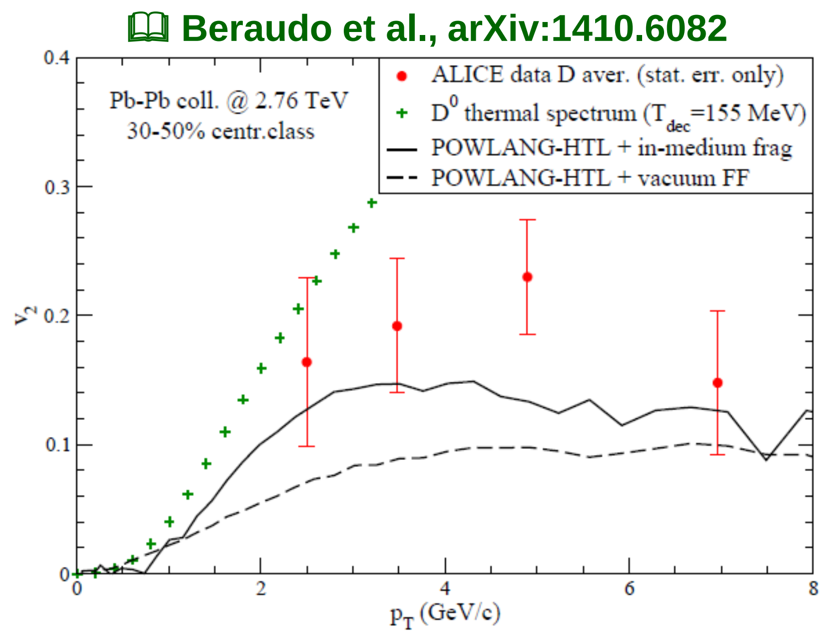
# The beauty frontier

- Low $p_T$ region (<6 GeV/c) and intermediate $p_T$ (20-80 GeV/c) to be explored
  - ⇨ HF decay electrons, b-jets at lower $p_T$, full reconstruction of B mesons?

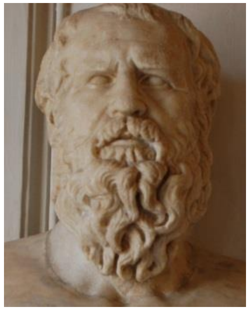


# Collectivity and thermalization



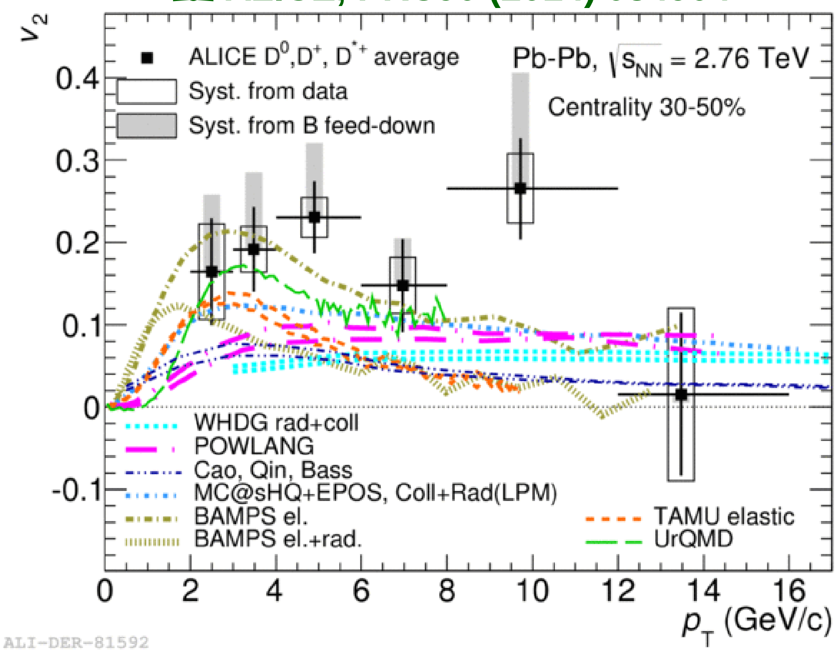




- Positive HF $v_2$ observed at RHIC and LHC at low $p_T$:
  - ⇨ Due to charm quarks participating in the collective flow?
  - ⇨ Or due to coalescence with a light quark from the bulk?
- More statistics at LHC energy could allow to:
  - ⇨ Constrain energy loss (collisional/radiative) and hadronization (coalescence/fragmentation) mechanisms
  - ⇨ First measurement of beauty $v_2$
  - ⇨ Παντα ρει? (Ηραχλειτος, ~500 b.C.)

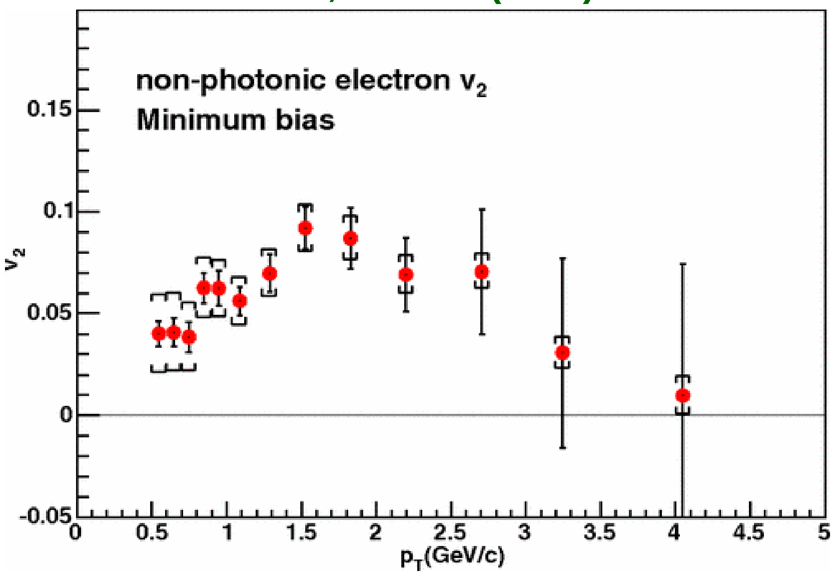


# Elliptic flow at high $p_T$

ALICE, PRC90 (2014) 034904

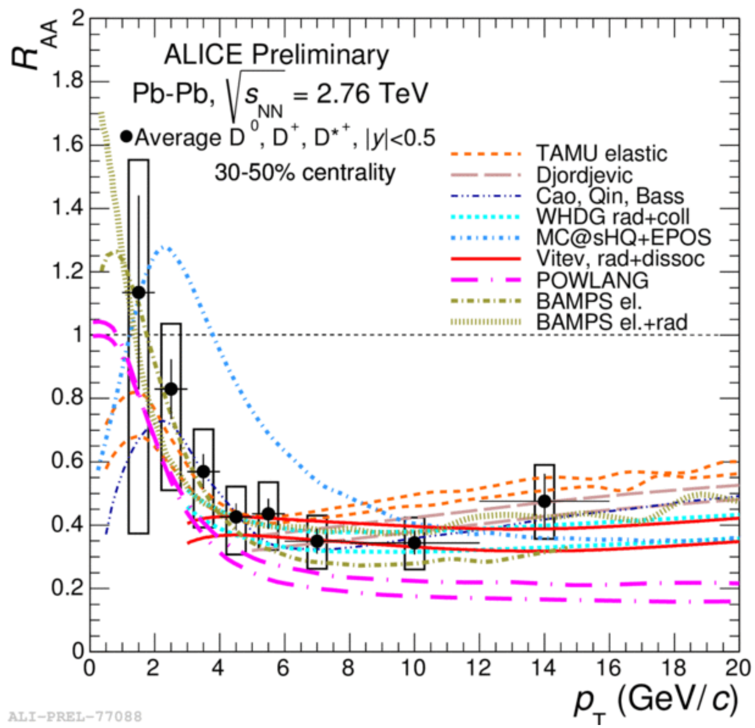


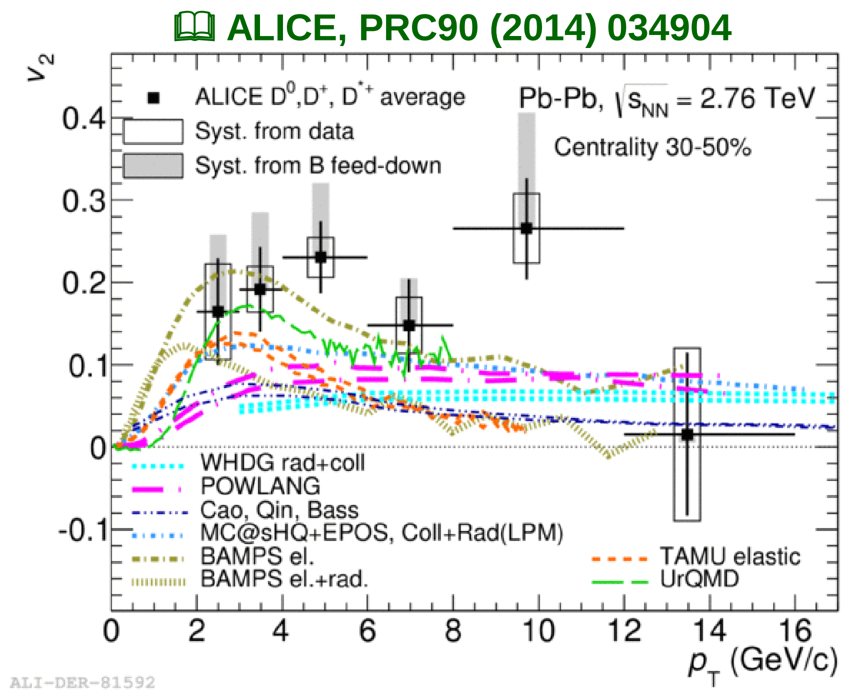

PHENIX, PRC 84 (2011) 044905




- Current $v_2$ measurements at high $p_T$ not yet conclusive
  - ⇨ Positive $v_2$ at high $p_T$ due to in-medium energy loss
  - ⇨ Sensitive to path length dependence of parton in-medium energy loss
    - ✓ ***Different dependence of the partonic energy loss on the in-medium path length expected for collisional and radiative processes (linear vs. ~ quadratic)***
- More statistics needed to constrain HF energy loss models exploiting also high-$p_T$ $v_2$

# Data vs. Theory

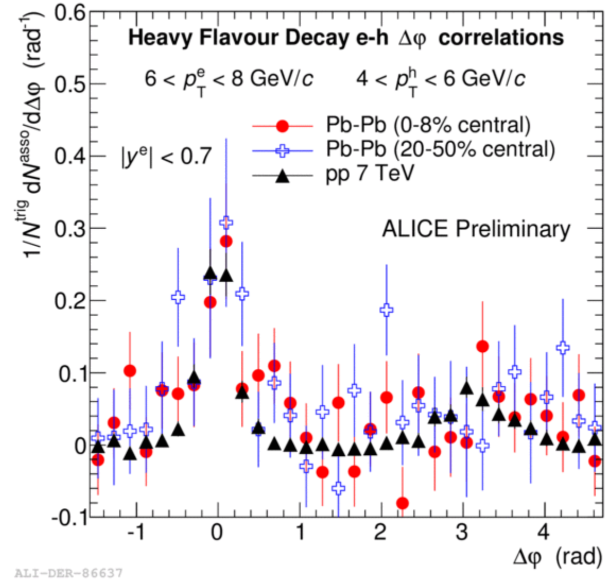


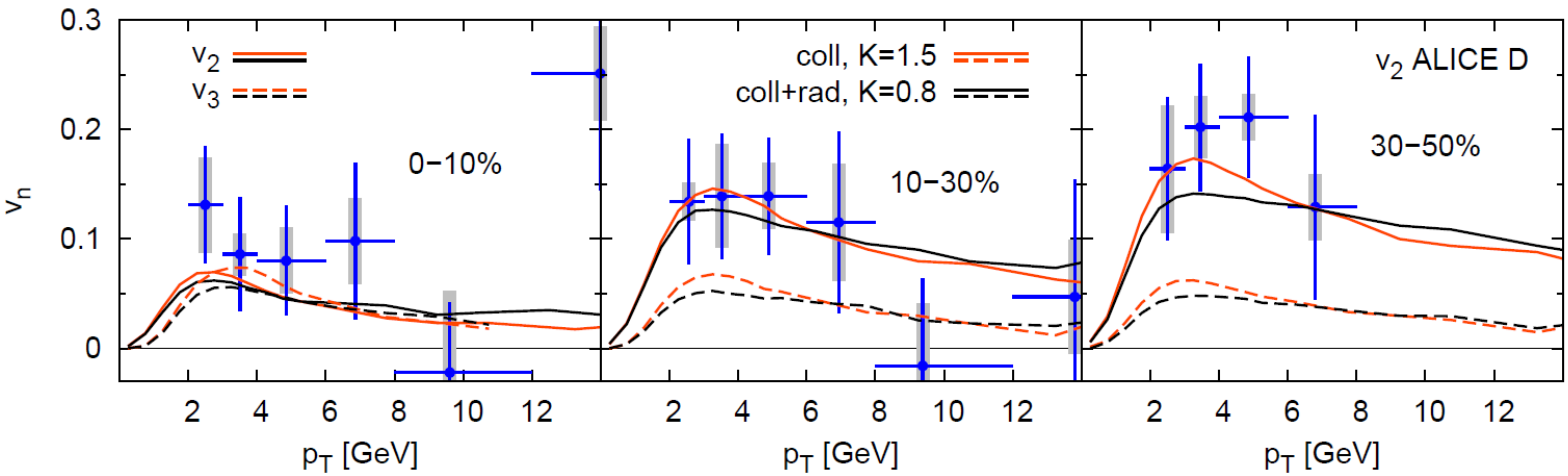




- Simultaneous description of HF decay electron $R_{AA}$ and $v_2$ is challenging for theoretical models
- Data can start to constrain energy loss models
  - E.g.: models that include collisional energy loss in an expanding medium + coalescence better reproduce the measured $v_2$
- Next steps: more systematic comparisons data vs. theory + new observables

# New observables (with larger data samples)

- More differential measurements to better constrain model calculations
- Examples:
  - **Angular correlations** (D-hadron, electron-hadron, electron electron) in Pb-Pb and $\mathbf{I_{AA}}$
  - **Higher-order flow harmonics** ($v_3$)
    - ✓ **Triangular flow more enhanced than elliptic flow in a purely collisional scenario with respect to the collisional+radiative case**
    - ✓ **Higher-order Fourier coefficients more sensitive incomplete coupling of heavy quarks to the medium**
    - 📖 **Nahrgang et al., arXiv:1410.5396**



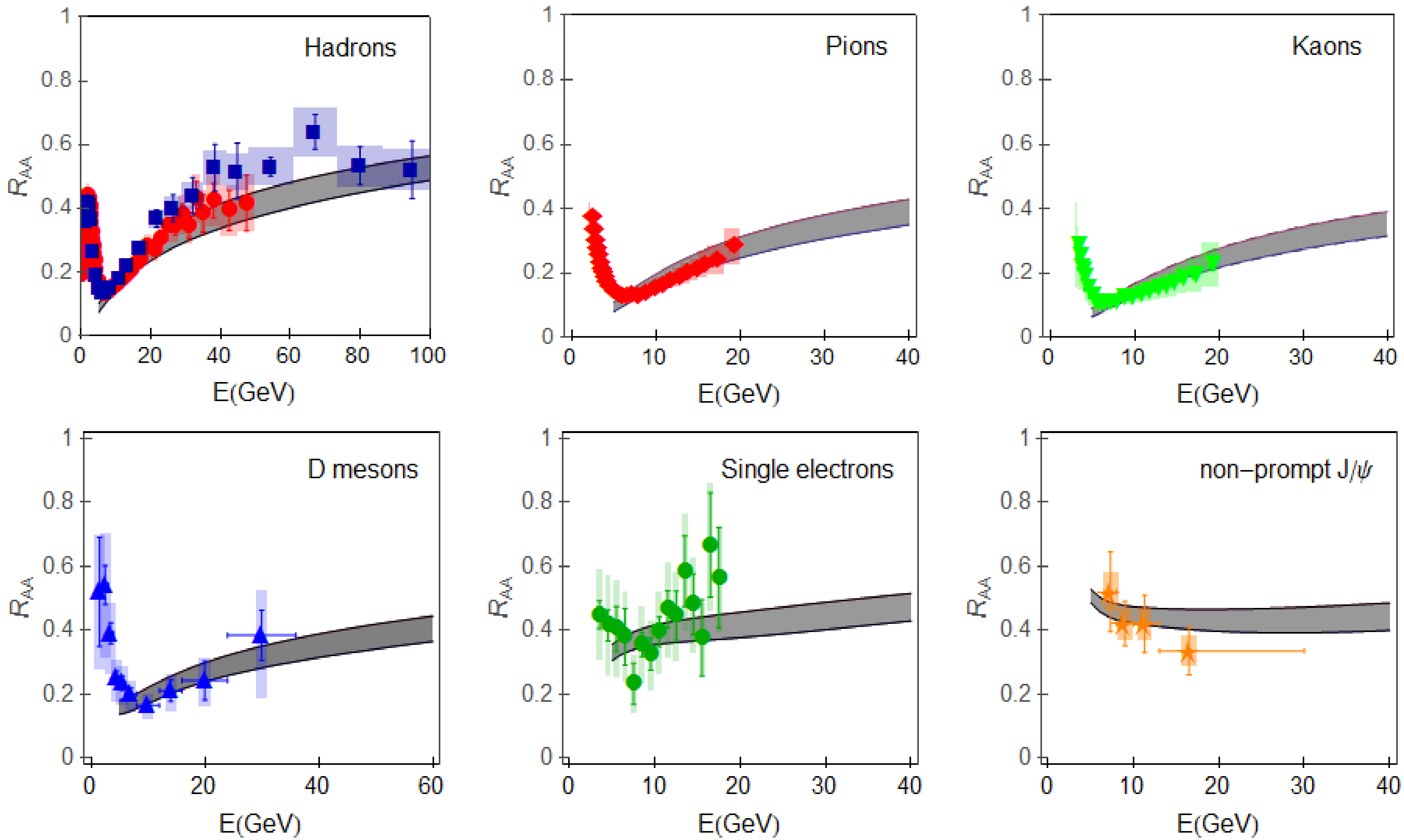
# Few outstanding open questions

- **Colour charge** and **quark mass** dependence of energy loss
  - Expectation $\Delta E_c < \Delta E_{u,d,s} < \Delta E_g$ vs. observation $R_{AA}(D) \approx R_{AA}(\pi)$
  - Extend $p_T$ range of **beauty** $R_{AA}$ measurements
- Energy loss mechanism: **collisional** vs. **radiative**
  - Path length dependence of energy loss (via $v_2$ at high $p_T$)
  - Constrained also by elliptic flow at low $p_T$?
- Hadronization mechanism: **coalescence** vs. **fragmentation**
  - Measure $D_s$ with reduced uncertainties and $\Lambda_c$
  - Constrained also by more precise $R_{AA}$ and $v_2$ measurements **at low** $p_T$
- Crucial to assess **cold nuclear matter effects** in the initial and final state
- Interplay between **radial flow, coalescence, shadowing**, $k_T$**-broadening** and **energy loss** in the measured $R_{AA}$
  - D mesons at the LHC down to $p_T=0$ and with reduced uncertainties
  - More precise measurements at **lower collision energy**
  - **More differential** measurements: e.g. **correlations** and $I_{AA}$
- **Collectivity** and thermalization
  - More precise charm $v_2$ and $R_{AA}$ measurements at low $p_T$
  - **Beauty** $v_2$ and **higher harmonics** accessible with more statistics at the LHC

- To address these questions and eventually access the QGP **transport coefficients** we need a systematic comparison of **data** vs. **theory**

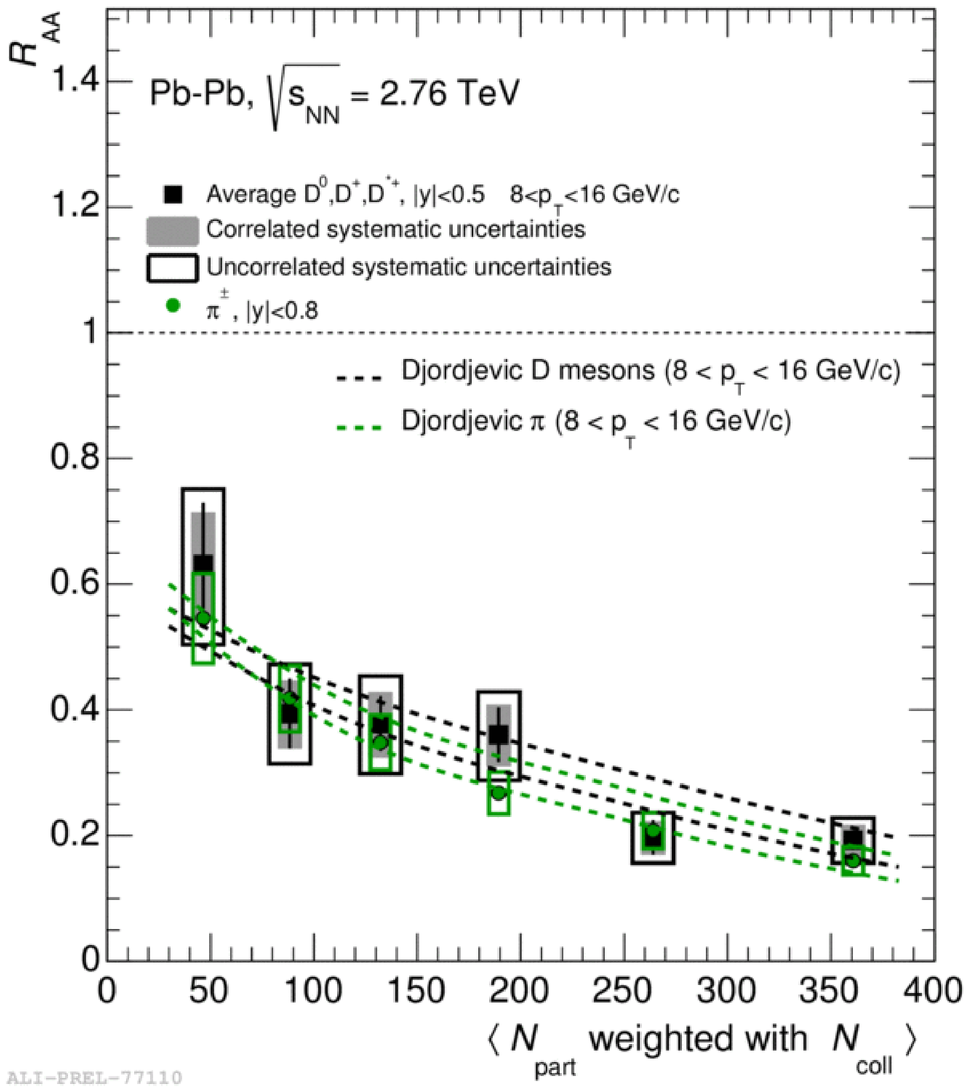
# *Backup*

# D meson and pion $R_{AA}$




📖 **Djordjevic, Djordjevic, PRL112 (2014) 042302; arXiv:1307.4098**

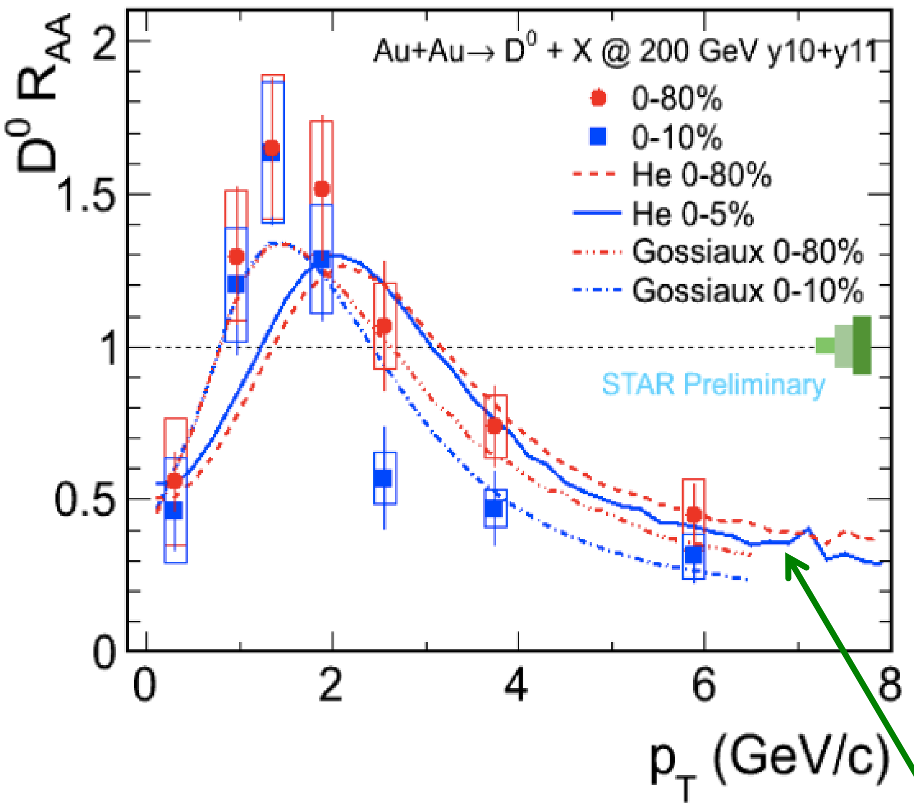
# D meson and pion $R_{AA}$

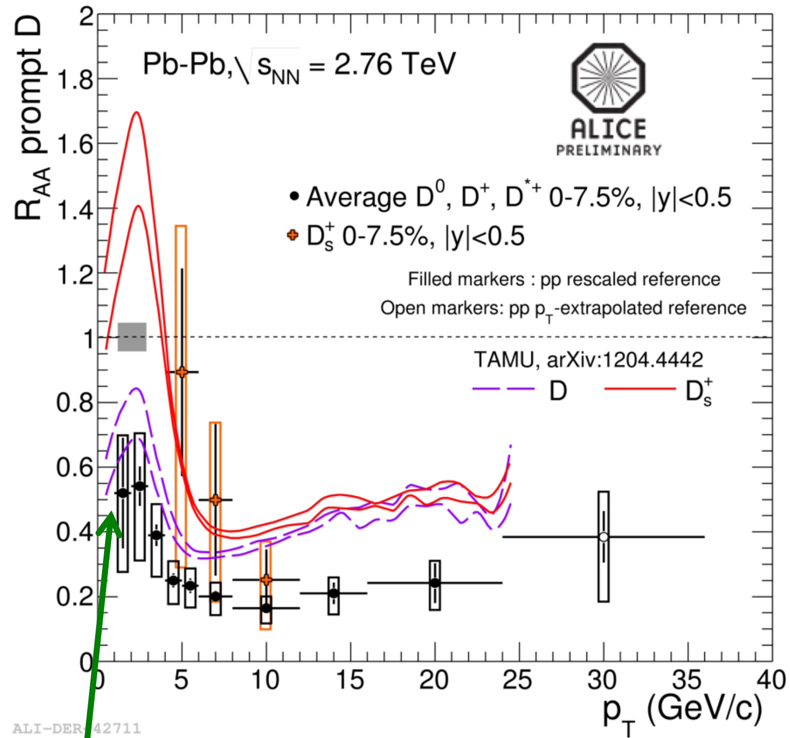



- Similar $R_{AA}$ of D mesons and pions both at RHIC and LHC)
- Described by models including
  - Mass and colour charge dependent E loss
  - Different momentum spectra of charm quarks, light quarks and gluons
  - Different fragmentation function (harder for charm than for light quarks and gluons)

**Djordjevic, Djordjevic, PRL112 (2014) 042302; arXiv:1307.4098**

# D meson $R_{AA}$: LHC vs RHIC

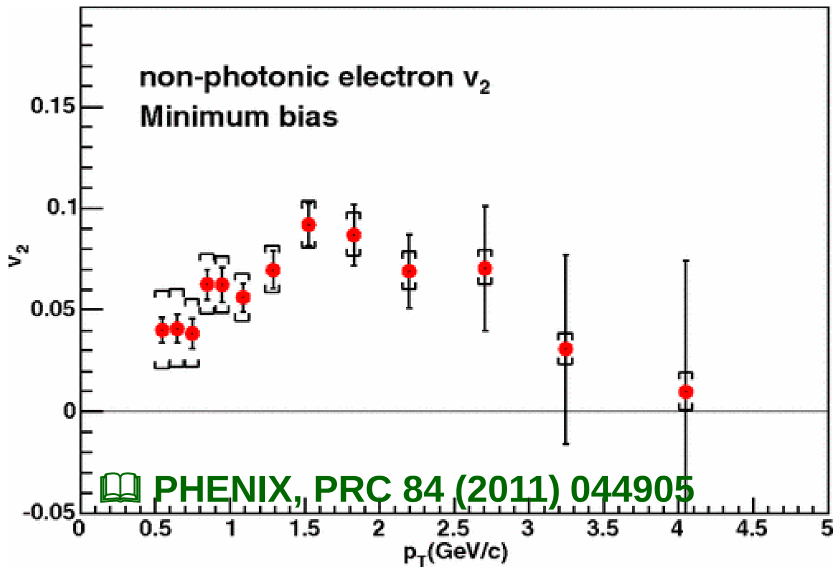


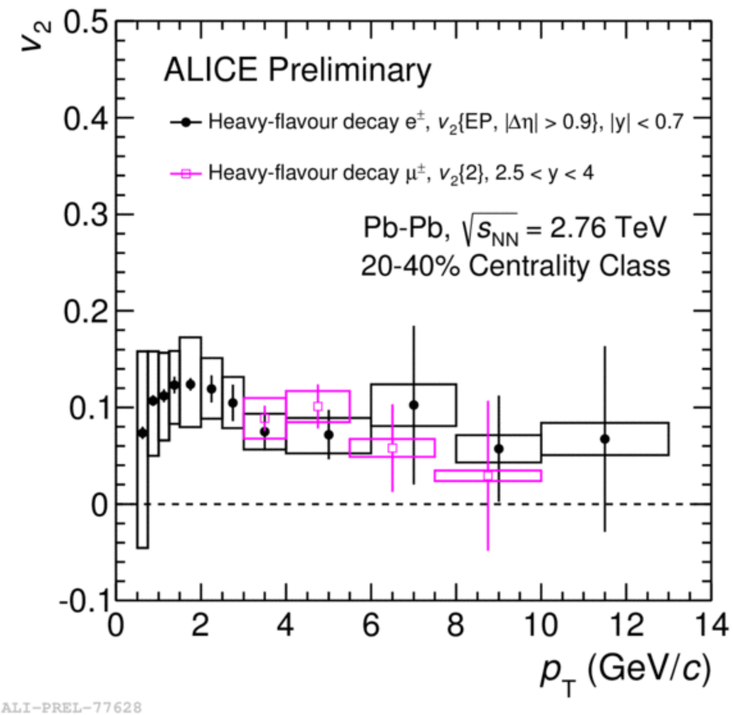




**same theoretical model**

- D meson $R_{AA}$ quite different for $1<p_T<2$ GeV/c
  - ⇨ Recombination + radial flow?
    - ✓ ***Stronger effect at RHIC because of steeper $dN/dp_T$?***
  - ⇨ Different role of shadowing at low $p_T$ at the two energies?

# HFE (and HFM) v2 at RHIC, LHC

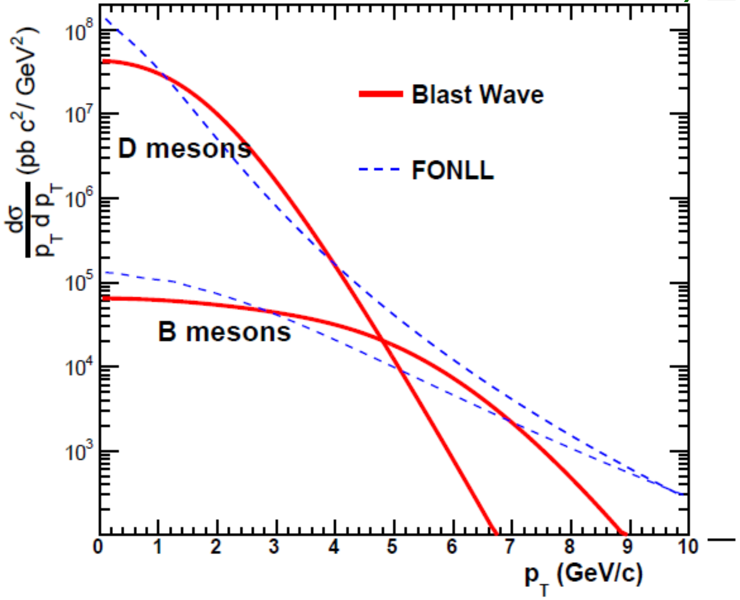


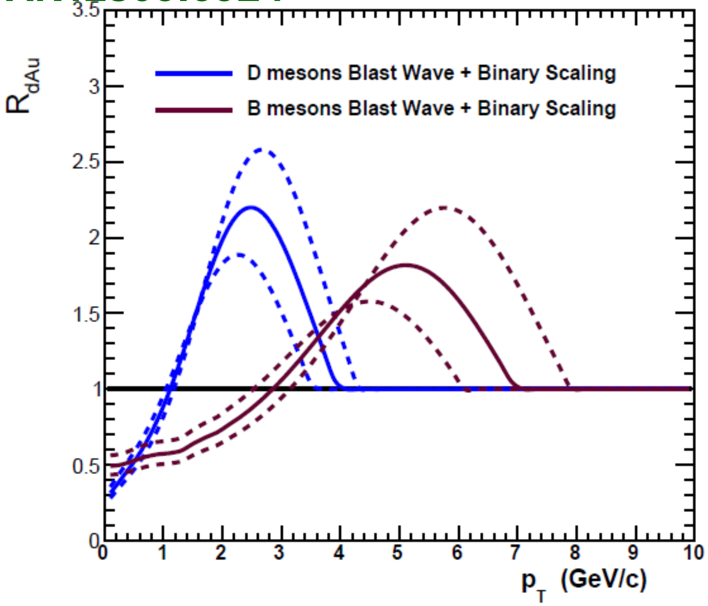




- Similar $v_2$ of HFE at midrapidity at RHIC and LHC
  - ⇨ Maybe slightly larger at the LHC, although compatible within uncertainties
- At the LHC: $v_2$ of HF decay electrons at midrapidity compatible with that of HF decay muons at forward rapidity

# Radial flow in small systems?

📖 Sickles, arXiv:1309.6924




- Radial-flow interpretation of HF data in p-Pb collisions
  - Final state effect in addition to “usual” cold-nuclear matter effects in the initial state (nPDFs - shadowing/antishadowing -, $k_T$-broadening, cold-nuclear-matter energy loss)
  - Smaller modification expected at LHC energies