Heavy Quark Hadronization in pp, pA and AA Collisions

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INT Heavy Flavor Physics Workshop, Week 3
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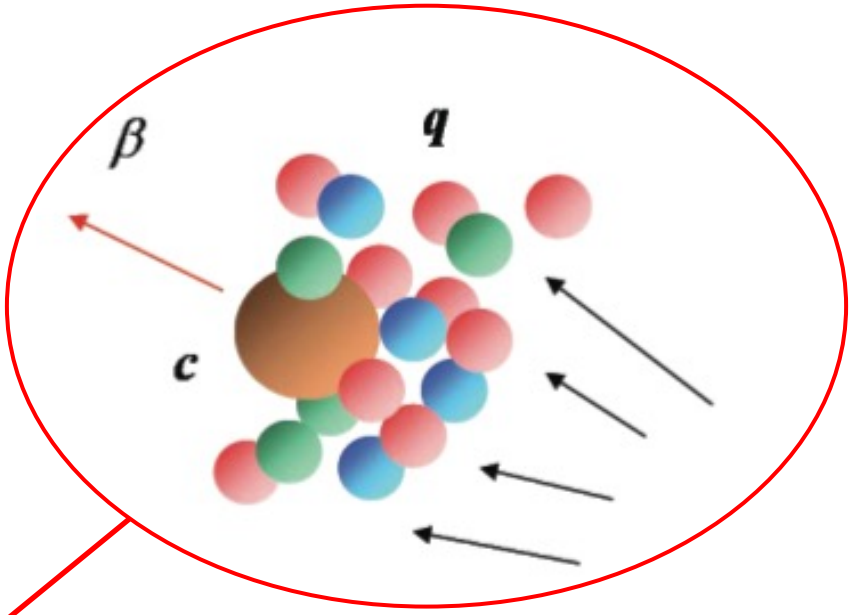
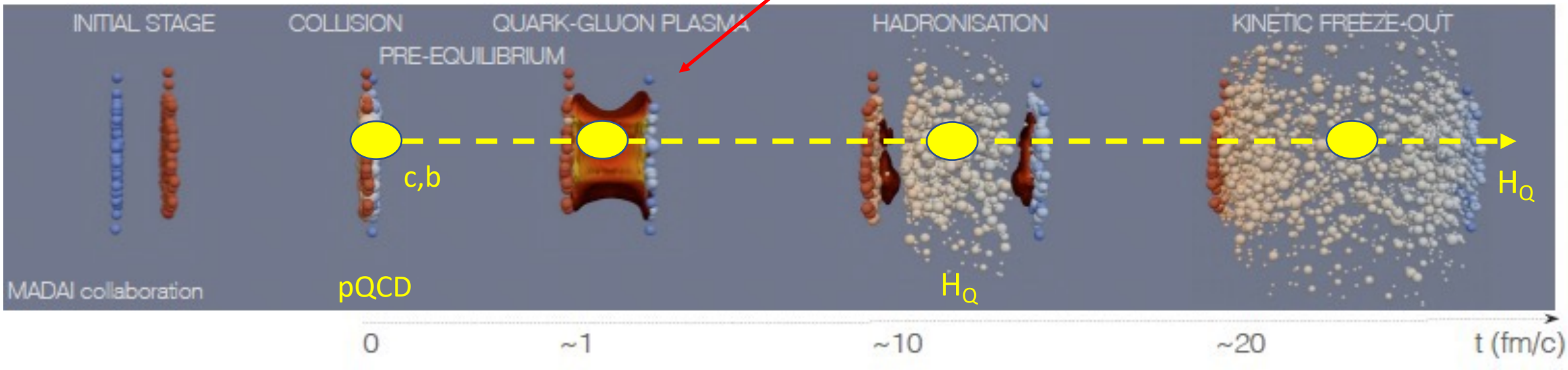
Outline

- **HQ as a probe for QGP**
- **Importance of understanding HQ hadroproduction**
  - Final state interactions, non-universality of HQ FF
- **New opportunity**
  - sPHENIX at RHIC

Heavy Quark (HQ) to Probe QGP

- **Quark diffusion in QGP: v_2**
  - ➢Flow, medium interactions
- **Quark energy loss in QGP: R_{AA}**
  - ➢Collisional vs radiative
  - ➢Mass dependence

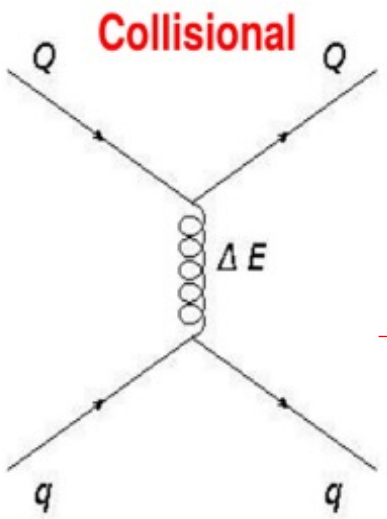


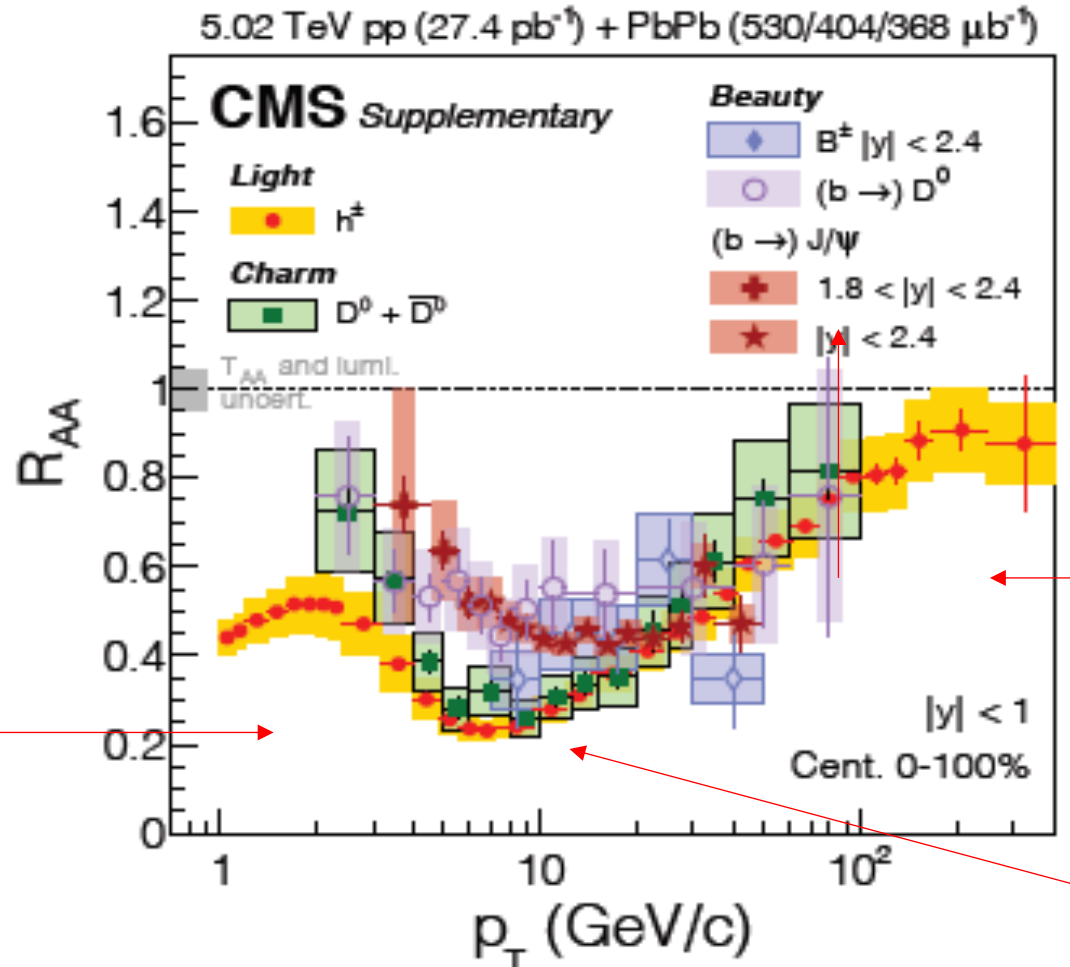


Role of Mass in Heavy Quark Energy Loss

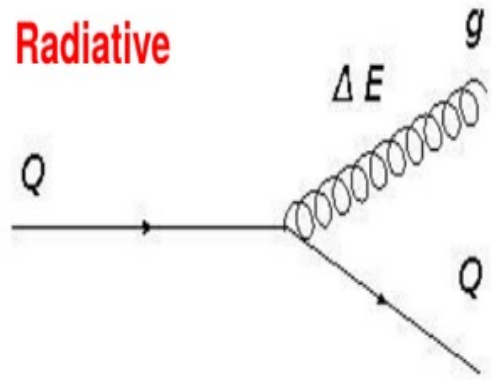
- A beautiful but over simplified picture

Low pT:
- Strong mass-dependence
- Diffusion





High pT:
- Weak mass-dependence
- Energy loss



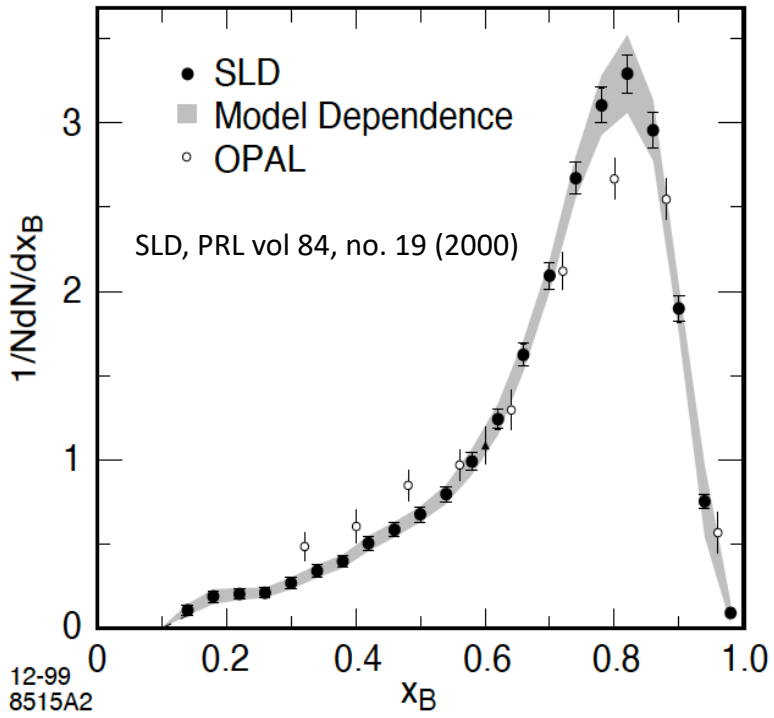
Boris's talk this week

Mass effect at intermediate pT

$$\frac{dn_g}{dx dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi x}\frac{k_T^2[1+(1-x)^2]}{[k_T^2+x^2m_q^2]^2}$$

Experimentally we measure hadrons, not quarks …
- hadronization to connect observables with QGP parameters

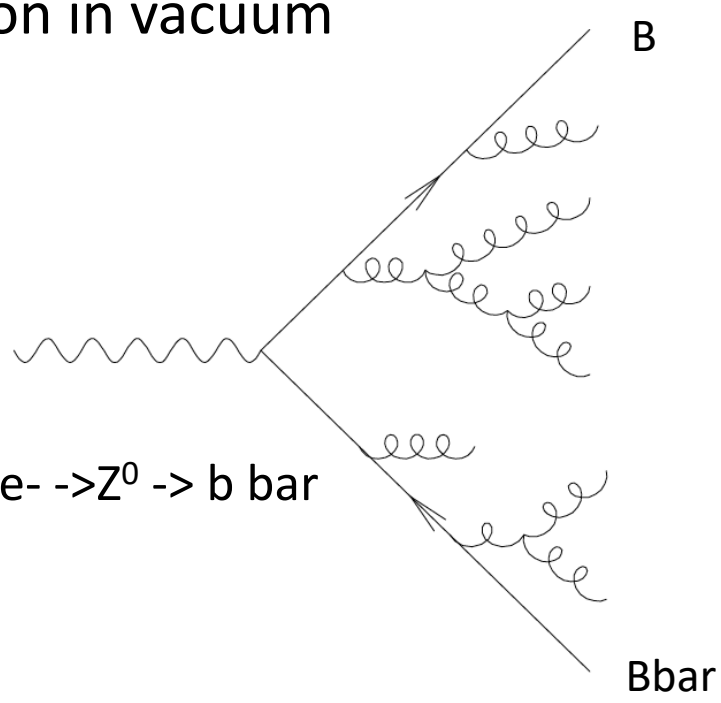
HQ FF assumed universal in all pT in most models until recently (~2018)



A good approximation at high energy e+e-/ep:

- Independent fragmentation in vacuum
- Universal FF

$$x_B = E_B / E_{\text{beam}}$$



Data: Charm Hadronization in e^+e^- and ep

Xin's talk, yesterday

- **FF seems "Universal"**

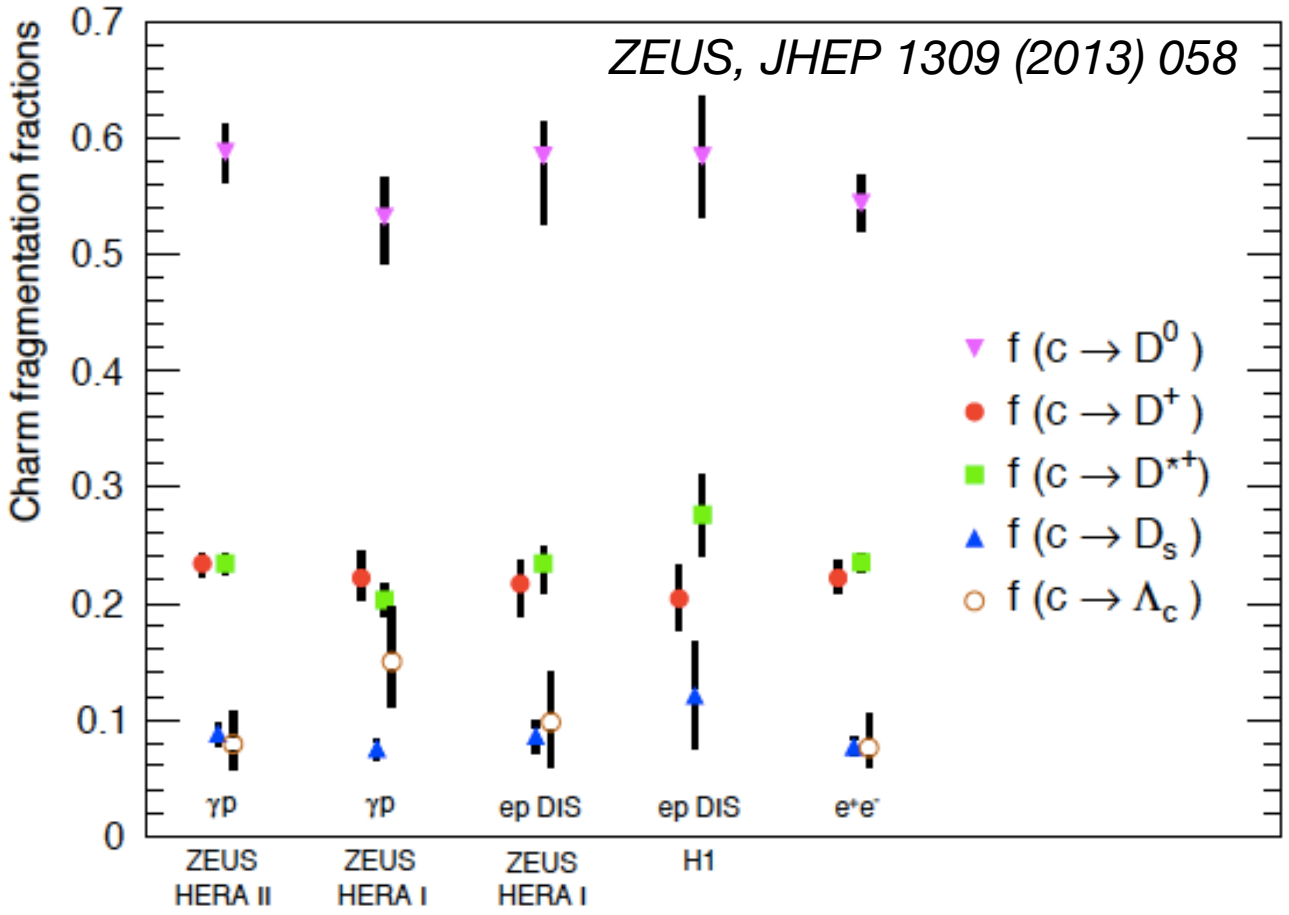
$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ + \text{c.c.}$$

60.8% 24.0% 8.0% 6.2%

Lisovyi, et. al. EPJ C 76 (2016) 397

Recent LHC and RHIC HF precision data:

- Breakdown of the "Universality of HQ FF" in hadroproduction at "low pT"



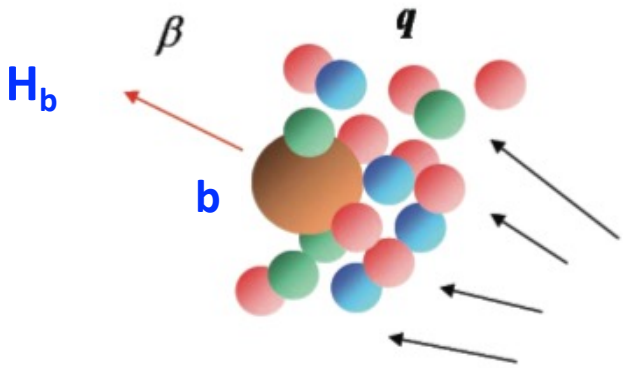
Heavy Quark Hadronization in p+p

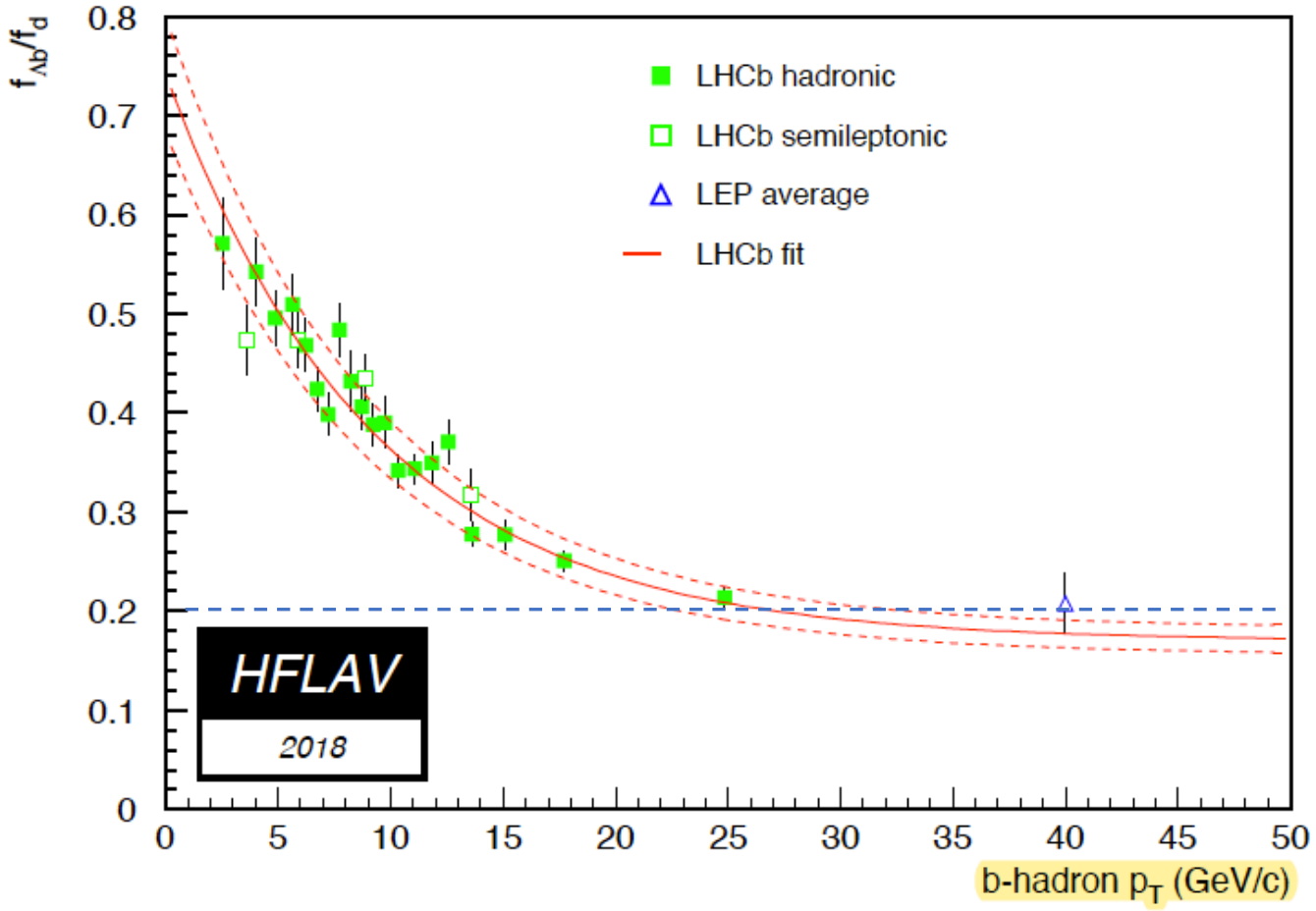
- Break down of the universality of FF at "low pT"

$\frac{f_{\Lambda_b}}{f_{B_d}}$ vs pT

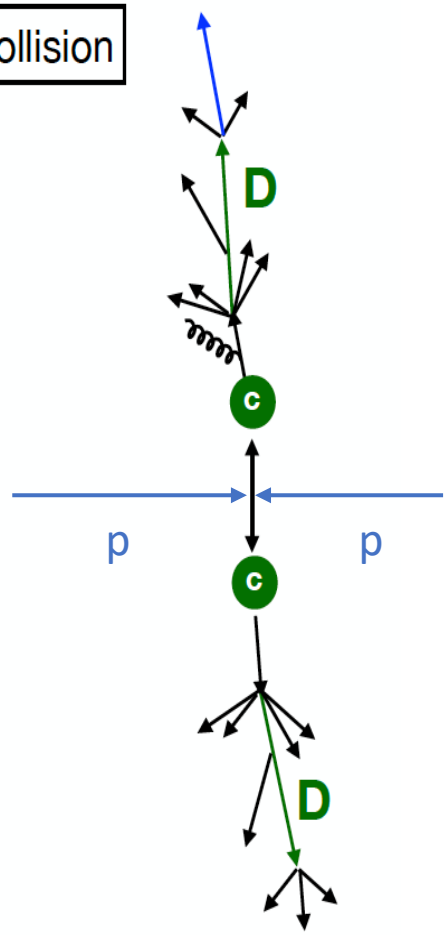
- **Final state interactions with nuclear medium modifies b-quark hadronization**

Significant at low pT ~<20 GeV (~5x M_b)





Let's Re-exam the HQ Hadroproduction …



pQCD ~Okey

1

Heavy quark pair produced in hard scattering

- pQCD, (n)PDF
- Initial state effect, energy loss, multiple-scattering etc.
  - ~small in pp
  - ~significant in AA, nPDF

What if FF not universal?

2

Open HF production

- Energy loss in the final state interaction with nuclear medium
- Coalescence in nuclear medium at low pT (what is low?)
- Expect independent fragmentation at high pT, universal FF

More complicated or simpler?

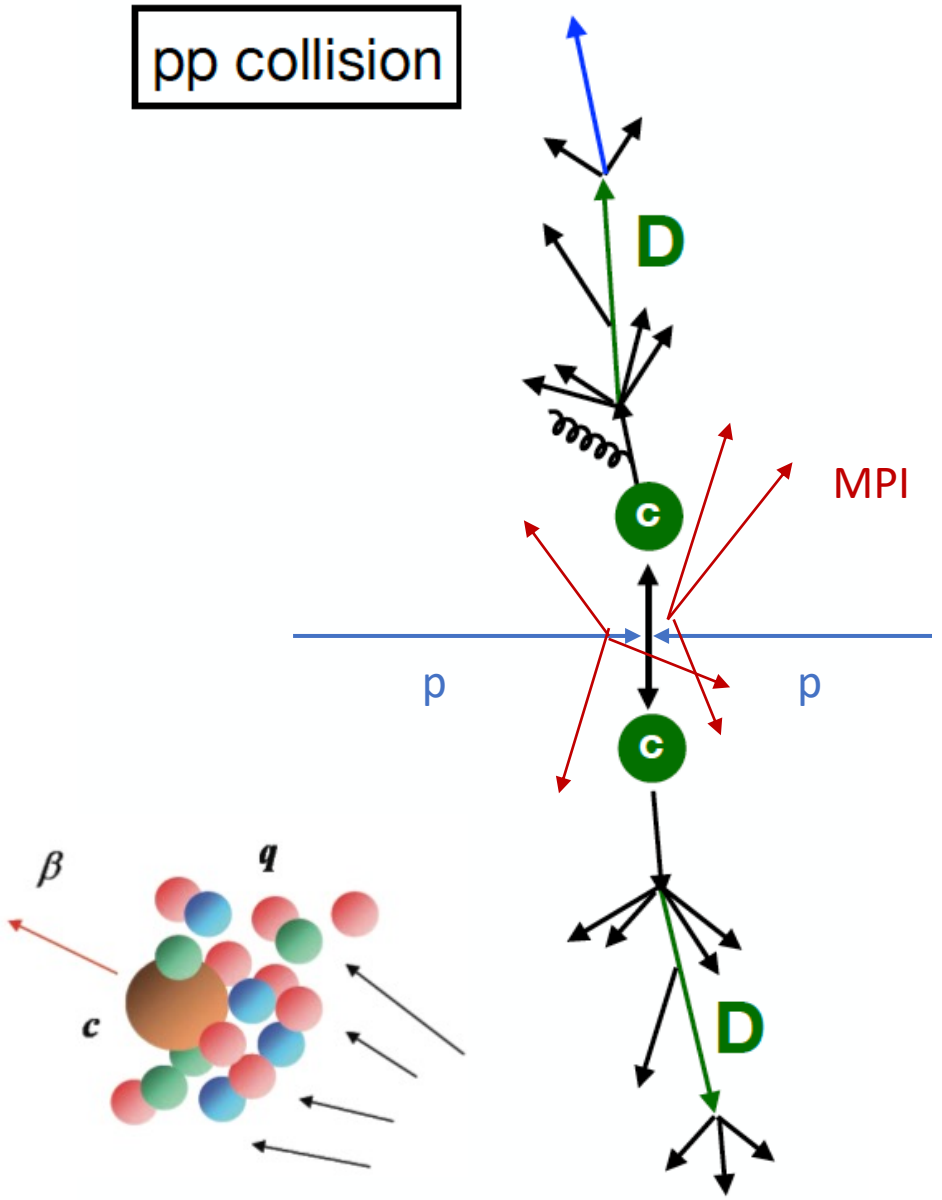
3

Heavy quarkonia

- Combination of heavy quark-antiquark pair produced in hard scatterings
  - NRQCD
  - CEM
  - Jet fragmentation

HQ Production in p+p at RHIC

- **One-pair of Q-Qbar produced from one hard-scattering**
  - ➢Double-charm possible but rare
  - ➢Multi-parton interactions important (MPI)
- **Final state interaction (FSI) matters**
  - ➢"Independent fragmentation", like in vacuum, at very high pT
  - ➢Coalescence and interactions with nuclear media important at low pT, mostly local?
    - ❑Hadronization time scale expected very short



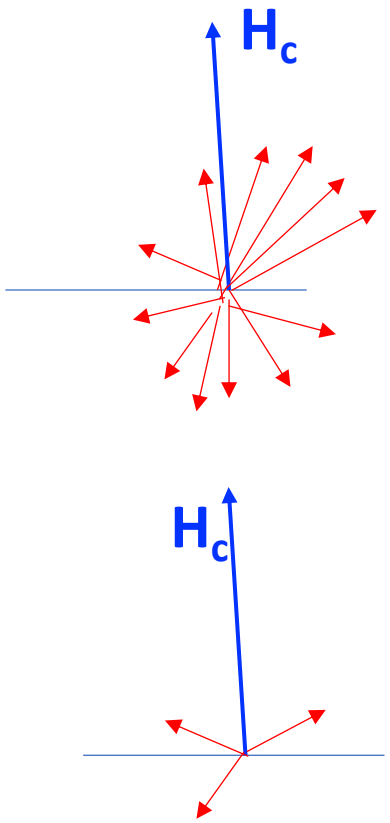
Multiplicity Dependence: Baryon/Meson Ratio in p+p

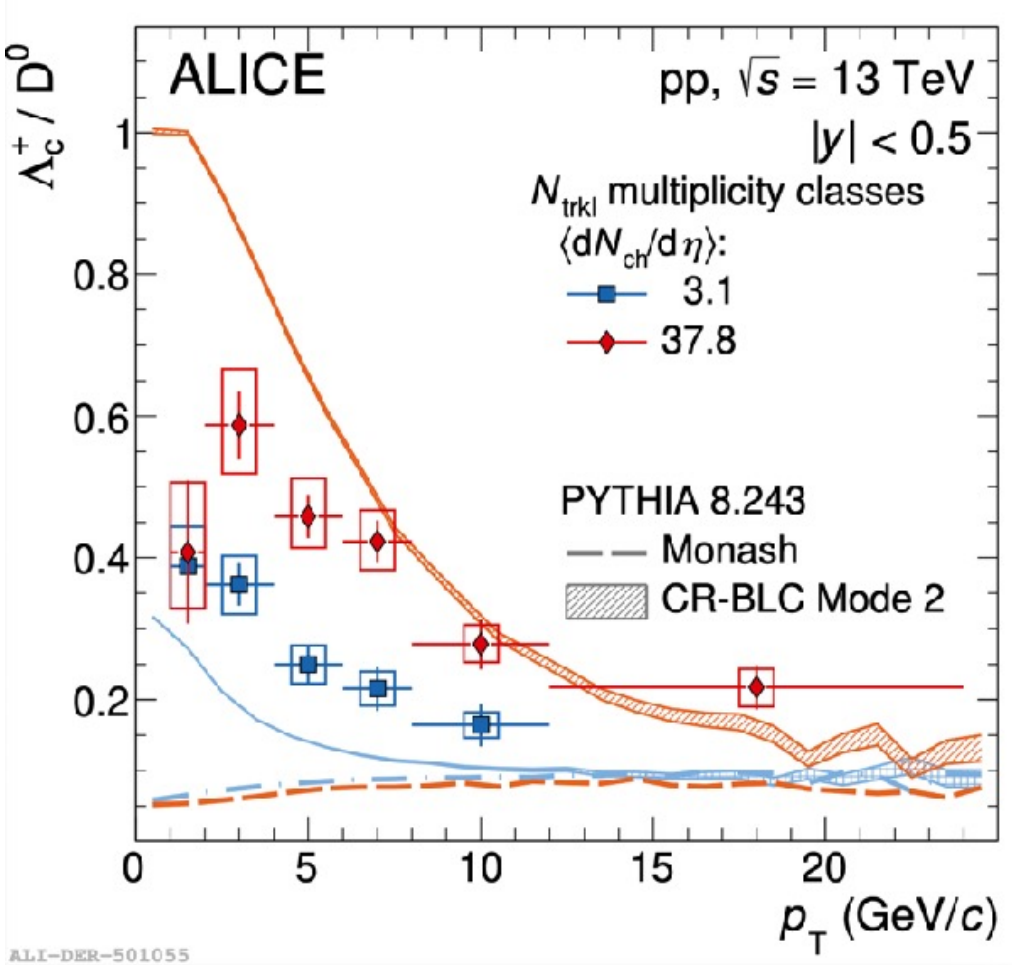
– MPI and FSI Important

- **Strong enhancement vs event multiplicity**
  - ➢ Default PYTHIA significantly underestimate data
- **With MPI and color reconnection PYTHIA agrees better with data**

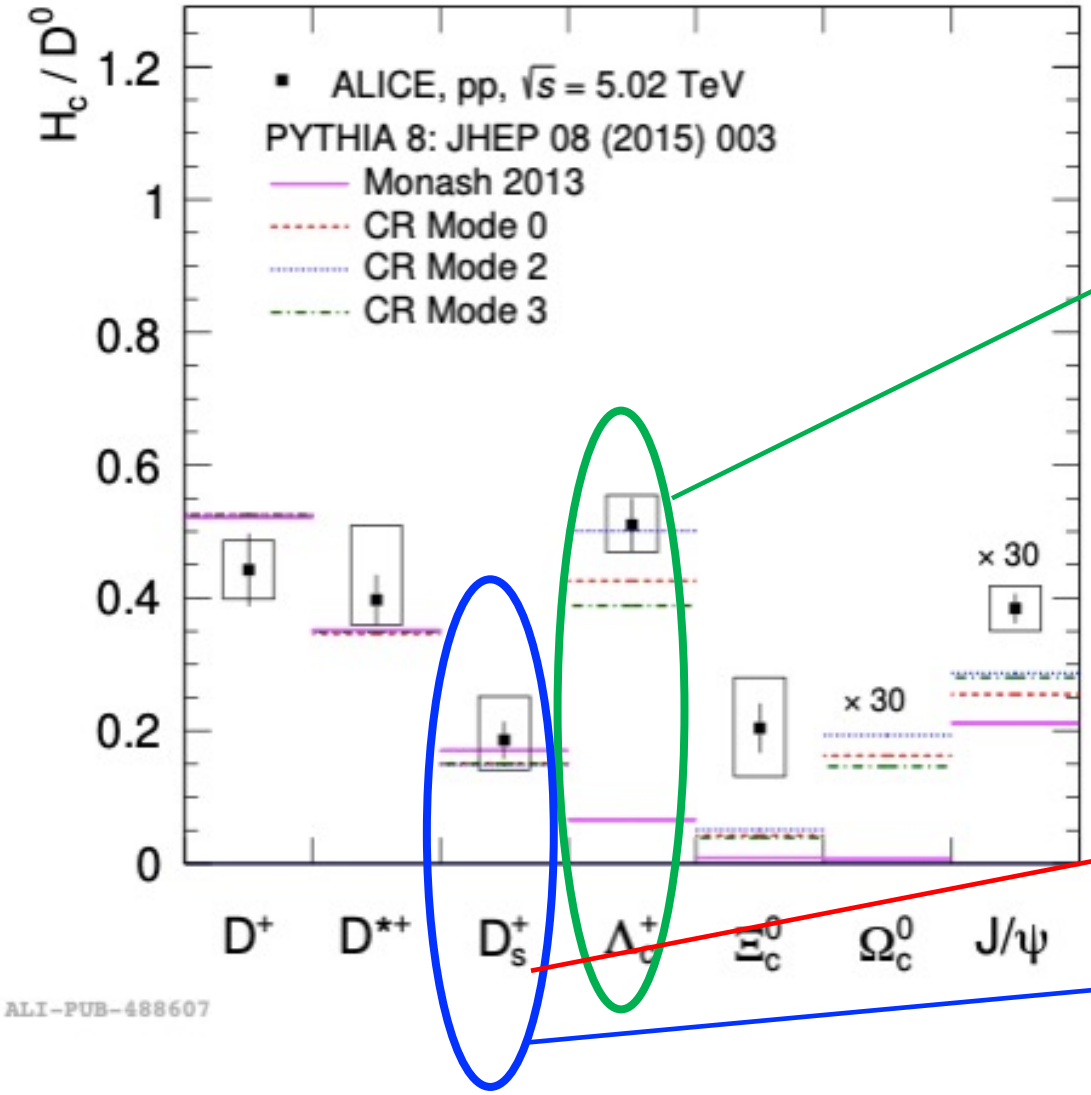
Given the small proton size, clear evidence of short hadronization time in p+p collisions, ~ 1fm

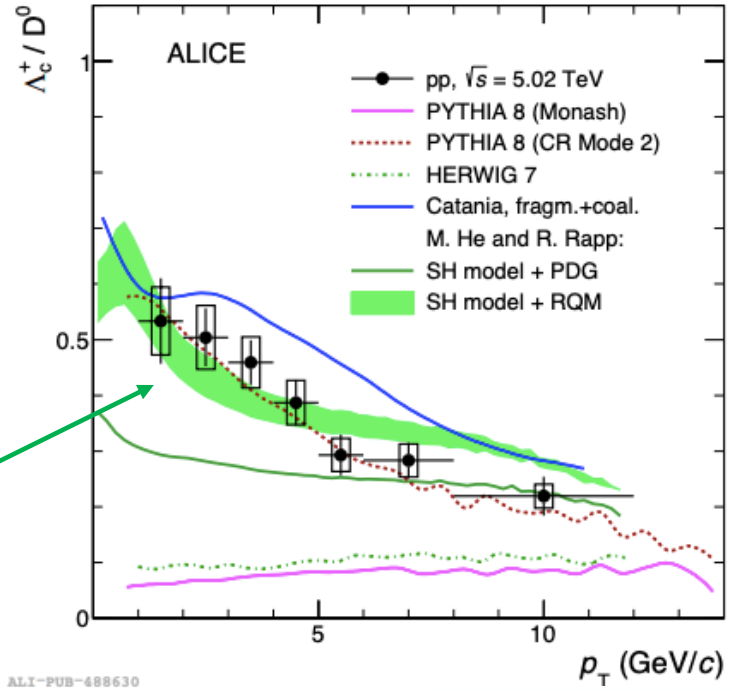
- *Strong consequence on HI data interpretation*
- *Local or long-range correlation?*





Charm Quarks: pp vs AA

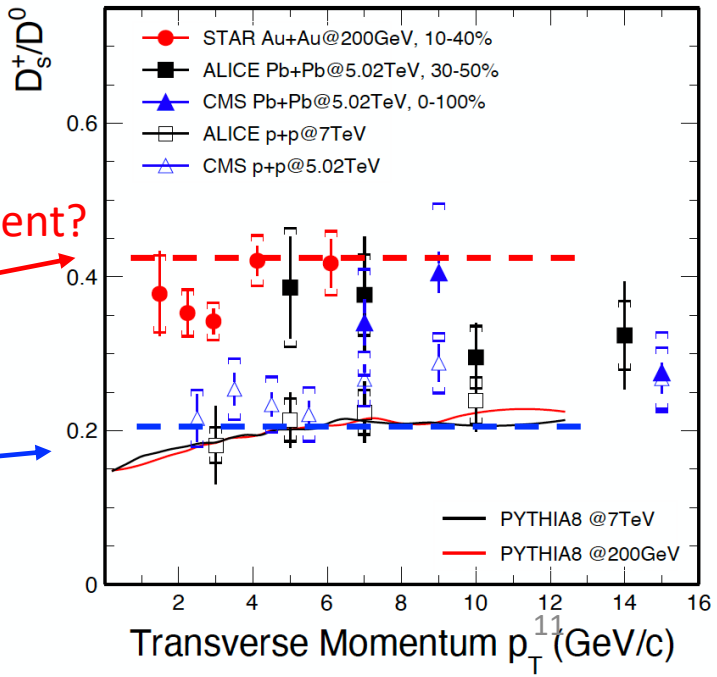




Strangeness enhancement?

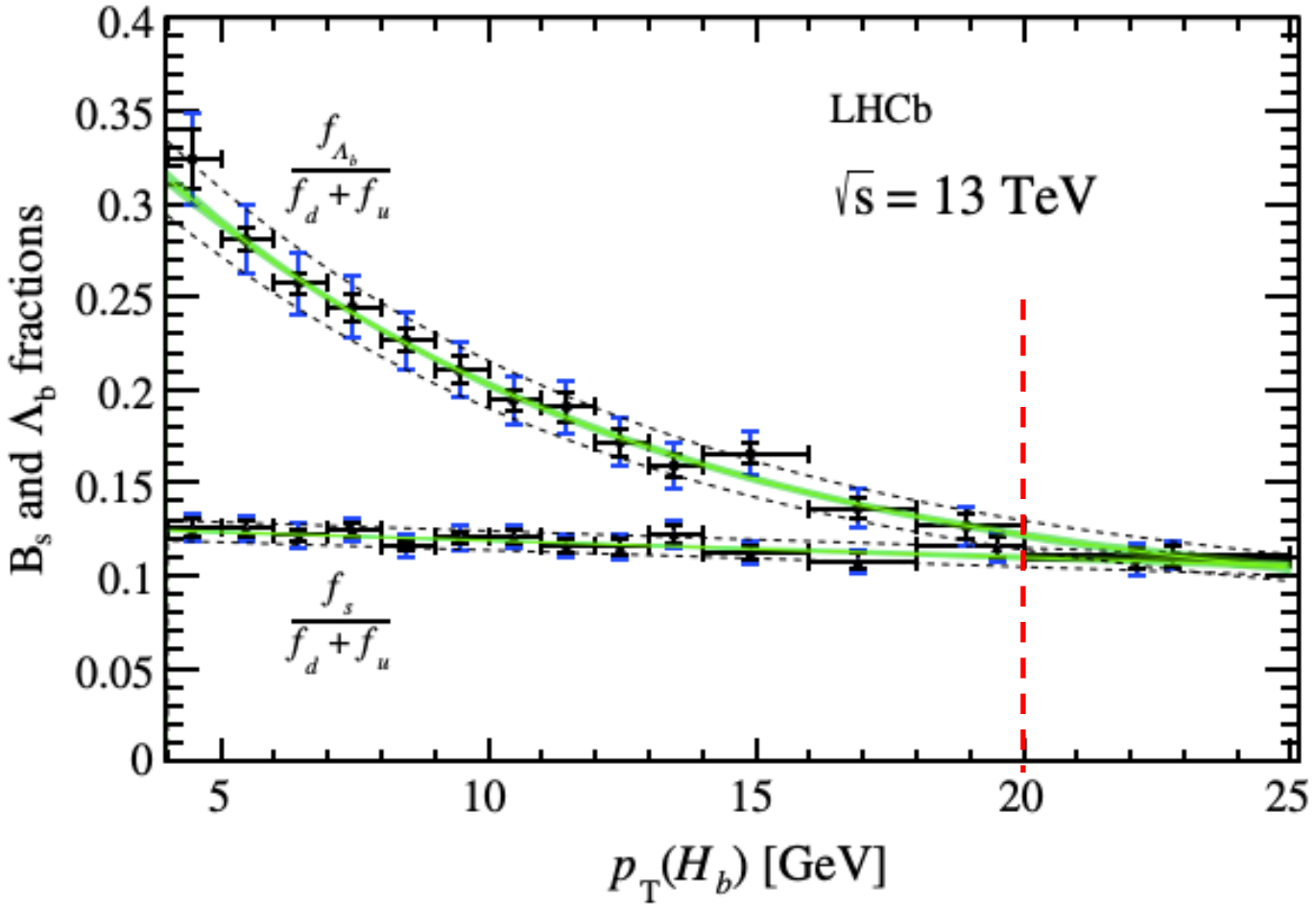
AA

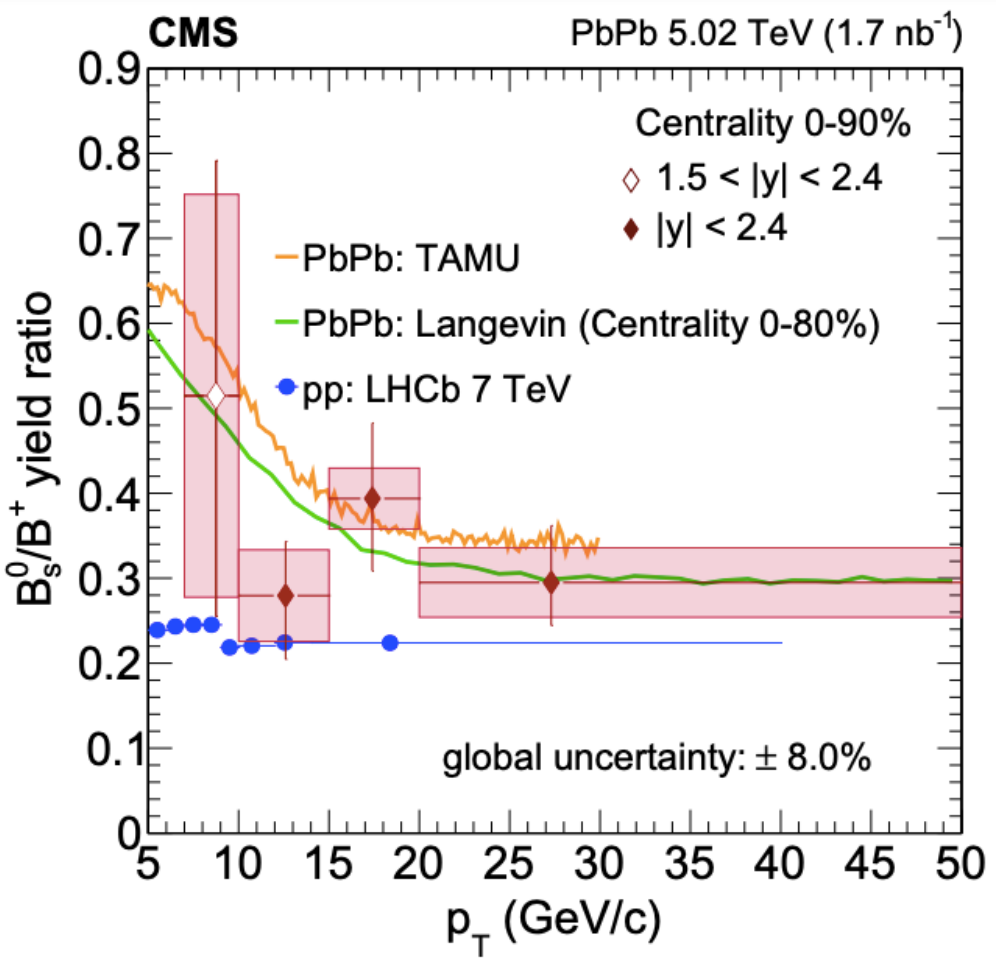
pp



Bottom Quarks: pp and AA

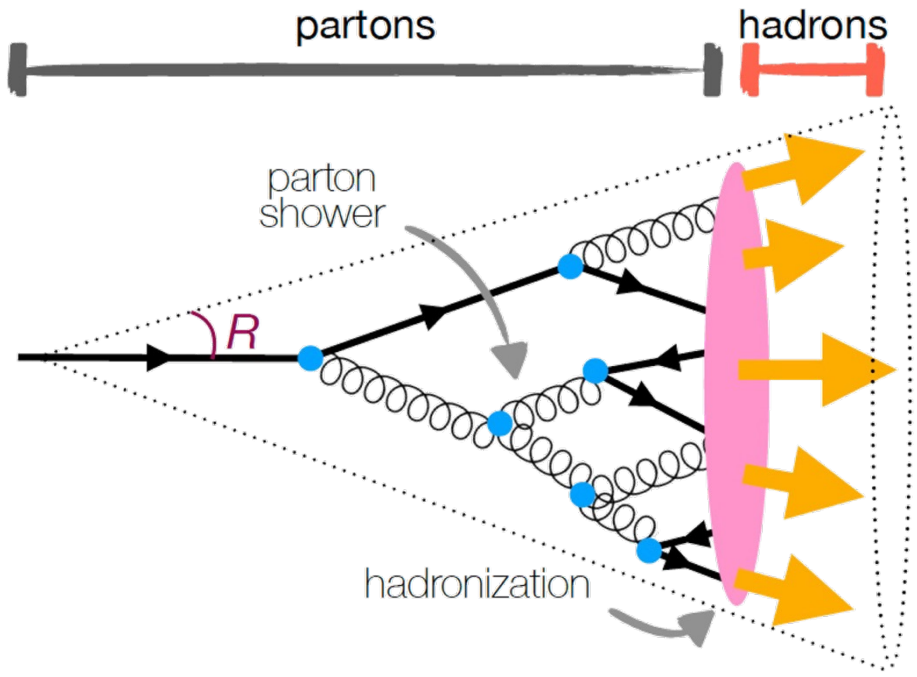
Hints of Bs enhancement in AA?



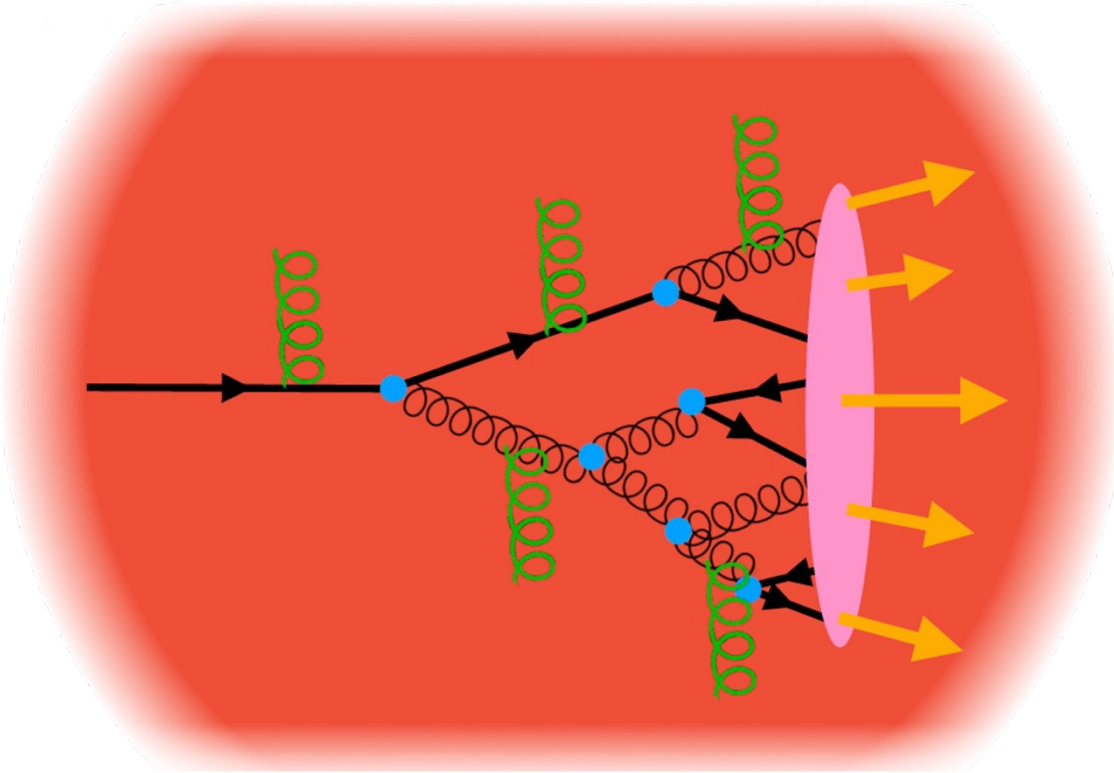


HQ Hadronization at “high pT” in pp and AA - mostly follows pQCD

pp



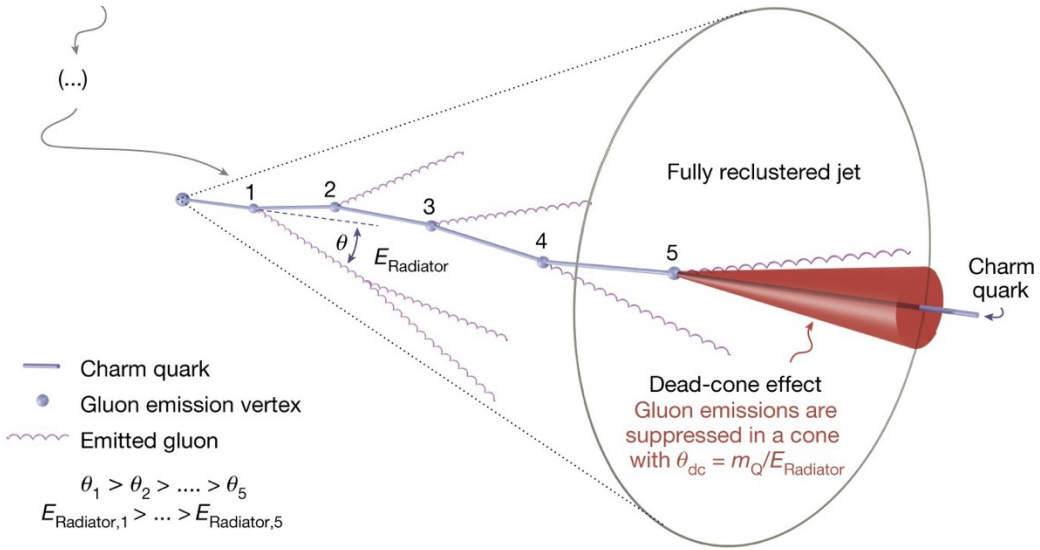
AA

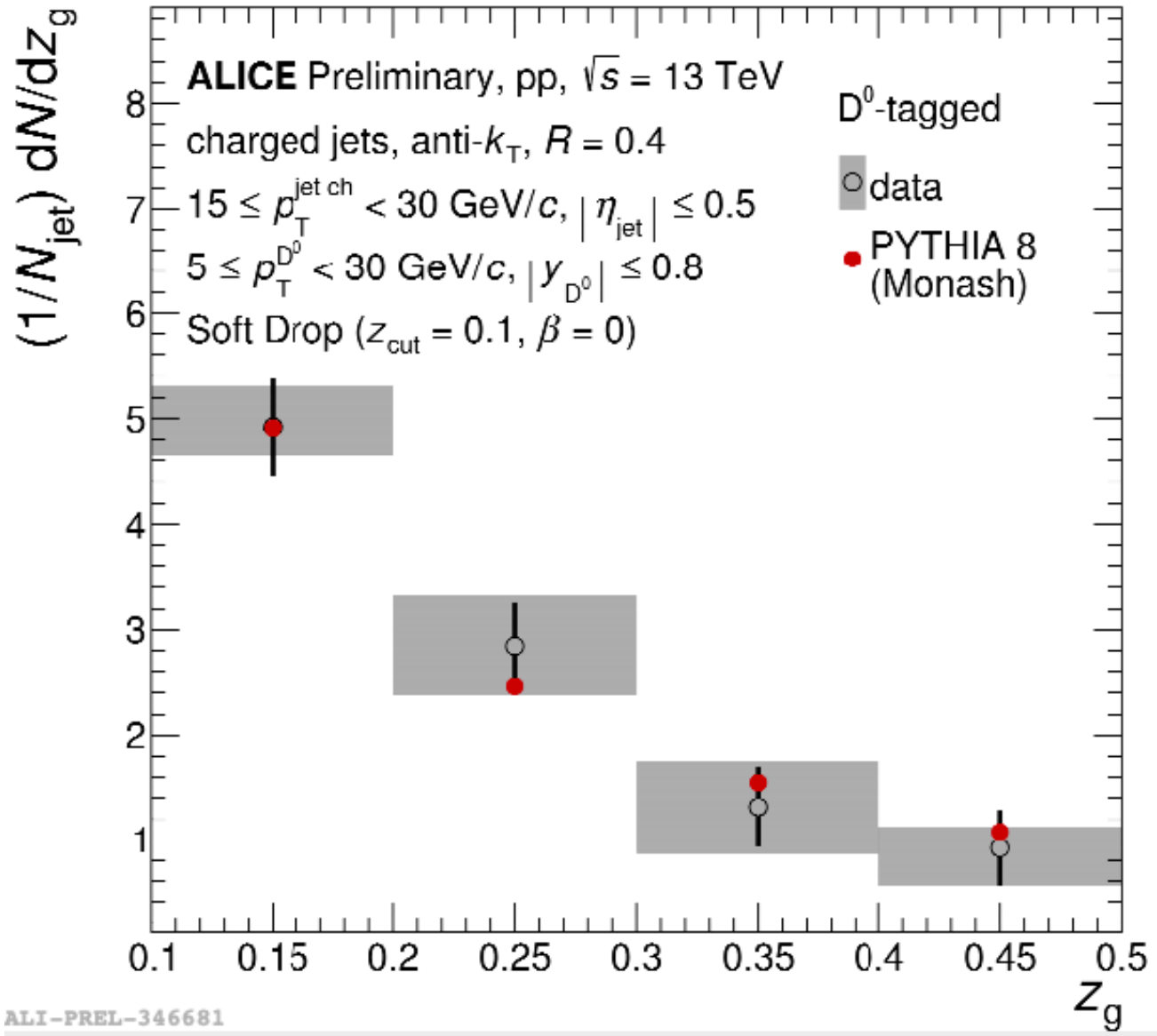


D^0-Jets in pp

- jet substructure

$$Z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

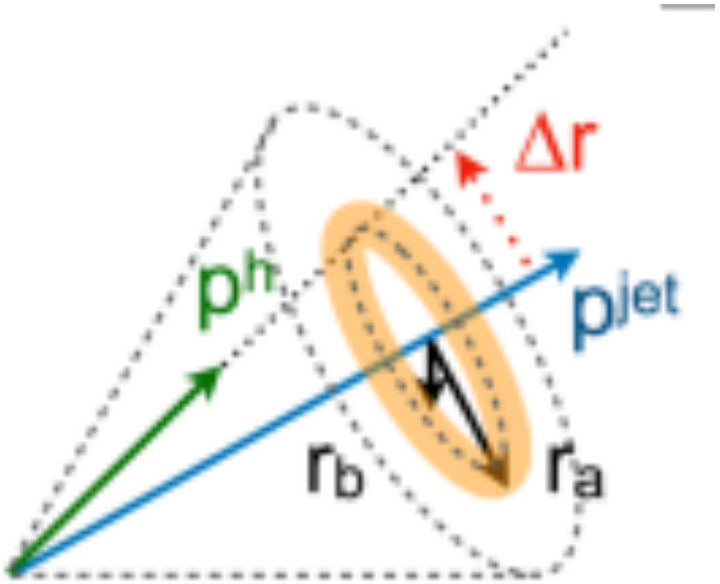


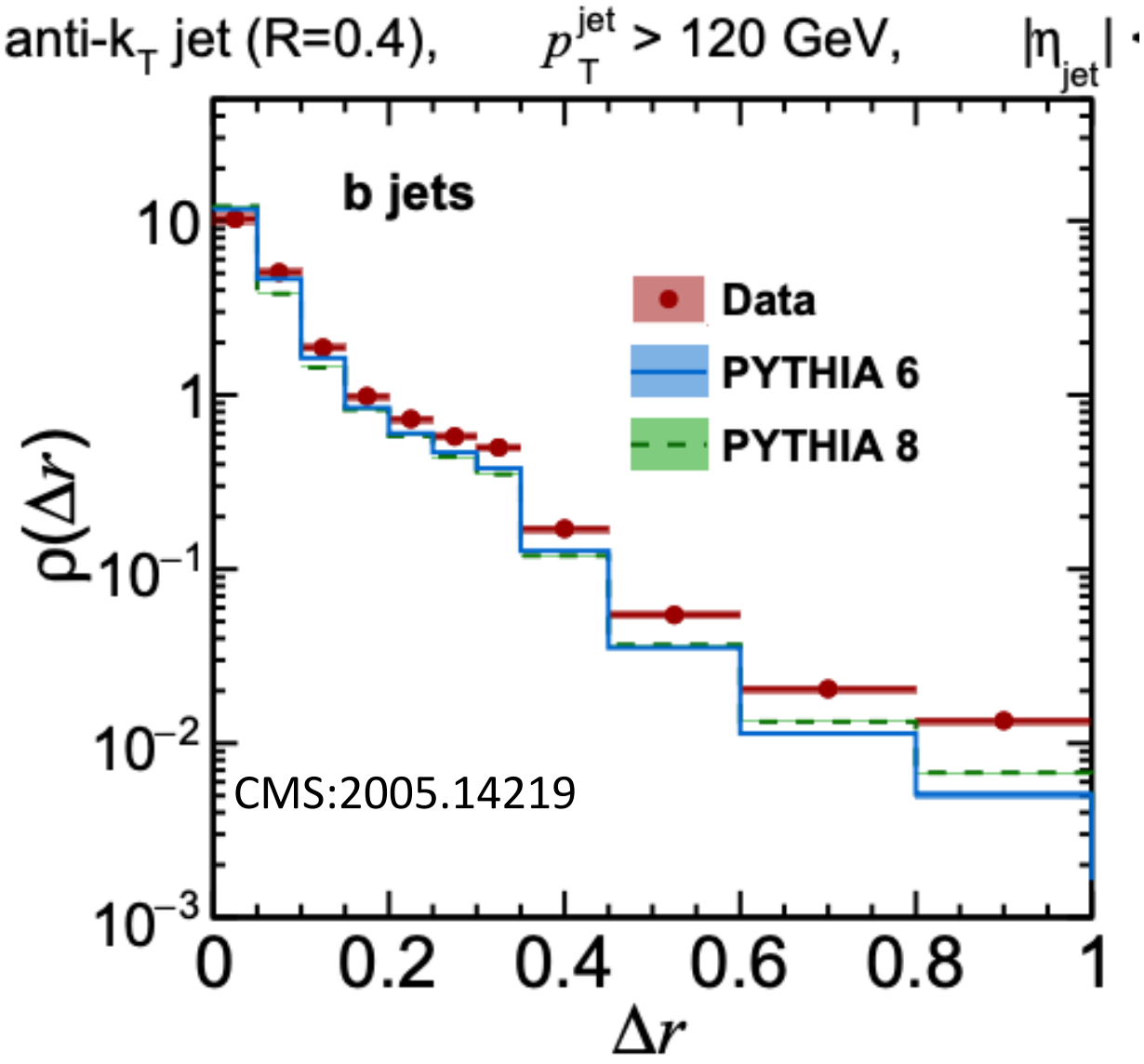


b-Jets in pp

- jet substructure

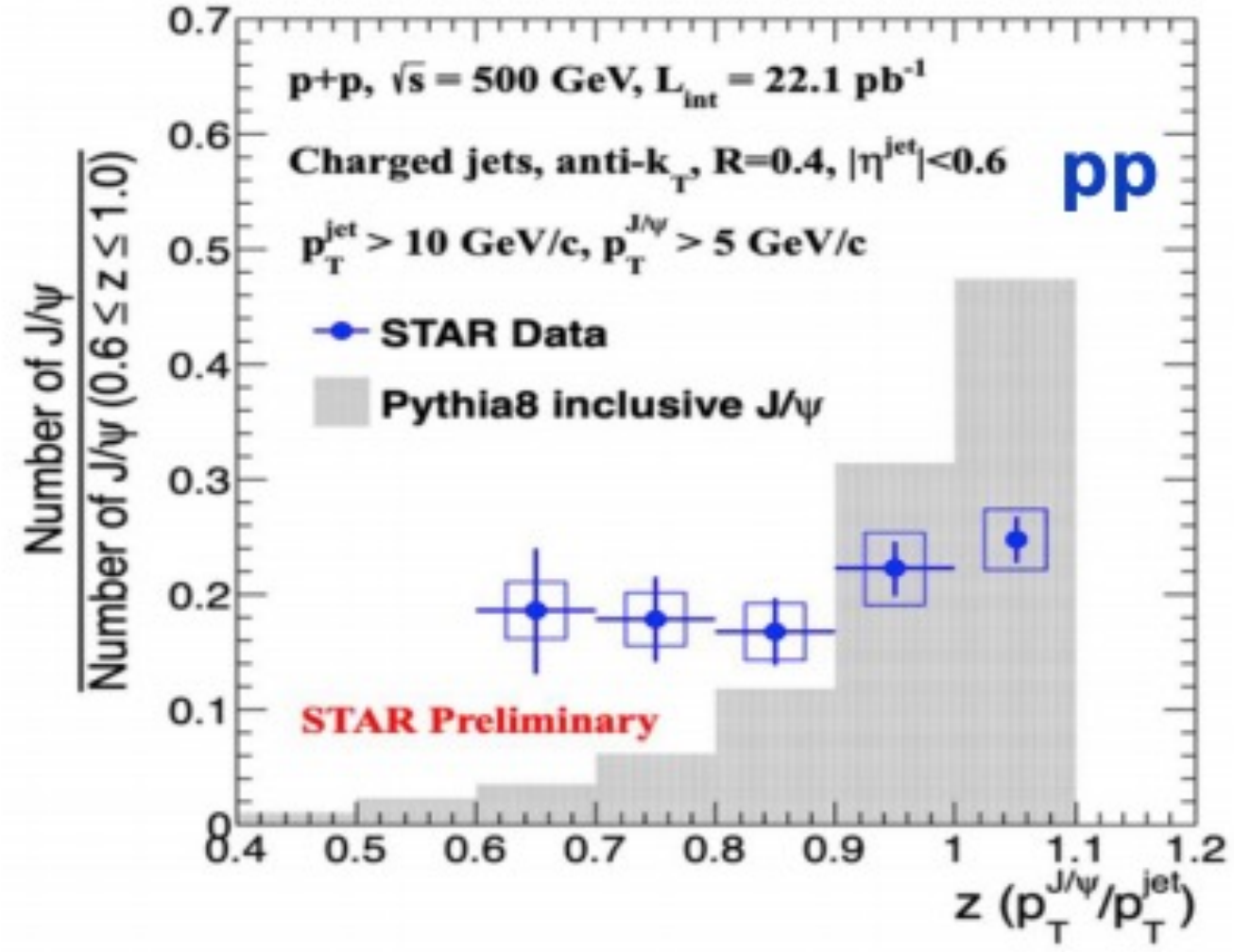
- Deviation at large radius





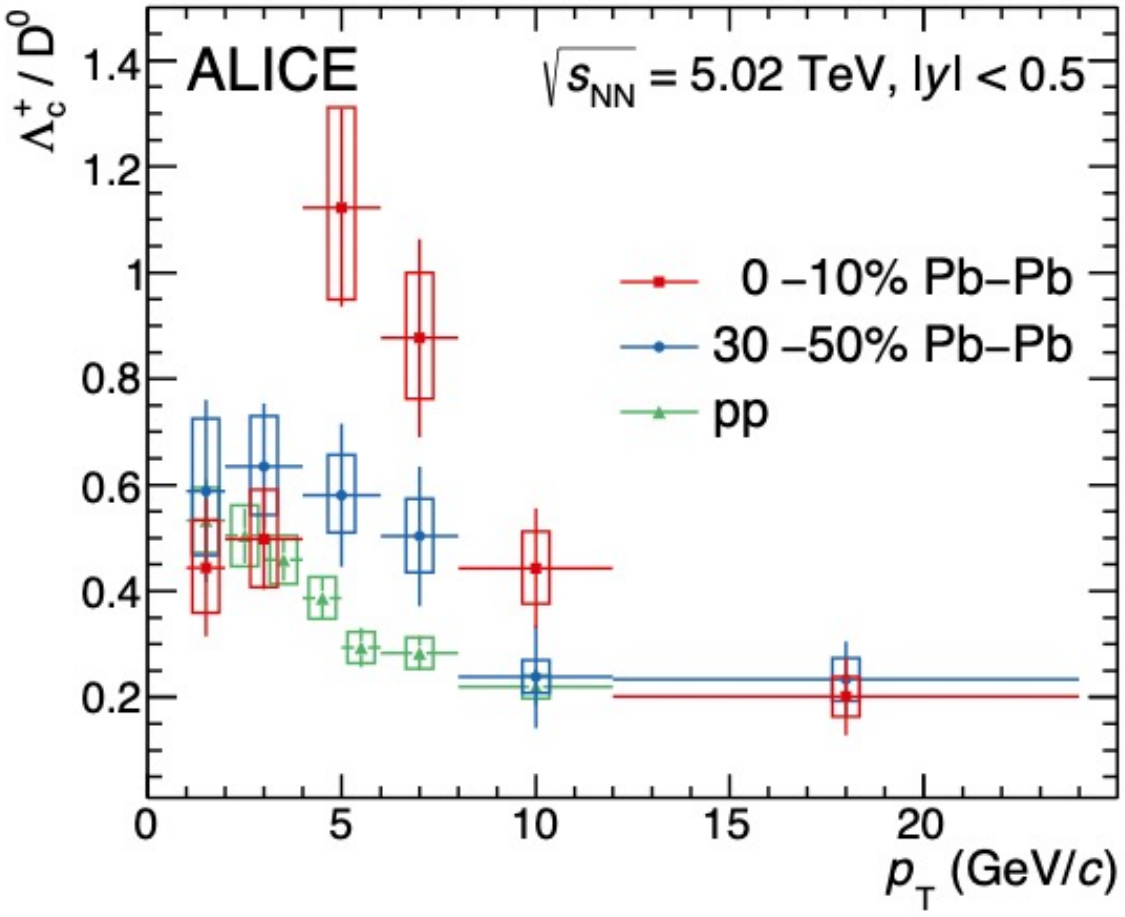
J/Psi-Jets in pp
- flat distribution?

- **Quite different from expectation**
- **J/Psi production mechanisms**
  - CEM
  - NRQCD
  - Jet fragmentation
  - …



HF in AA Collisions – more complicated !

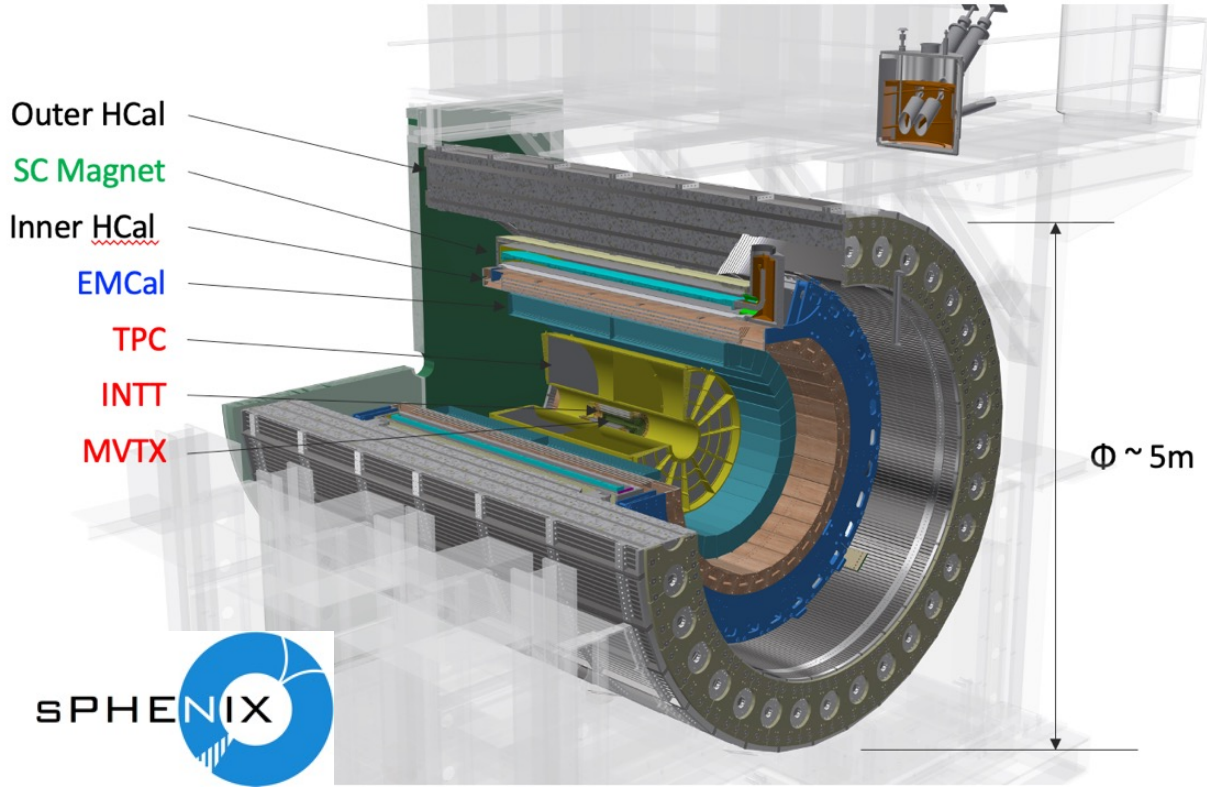
- **Charm-quark pair yield: pQCD**
  - ➢Same per nucleon pair
- **Enhancement in AA at low pT**
  - ➢FSI important, centrality
  - ➢Models with fragmentation and coalescence agree with data better



More precision data needed to better understand HQ hadronization

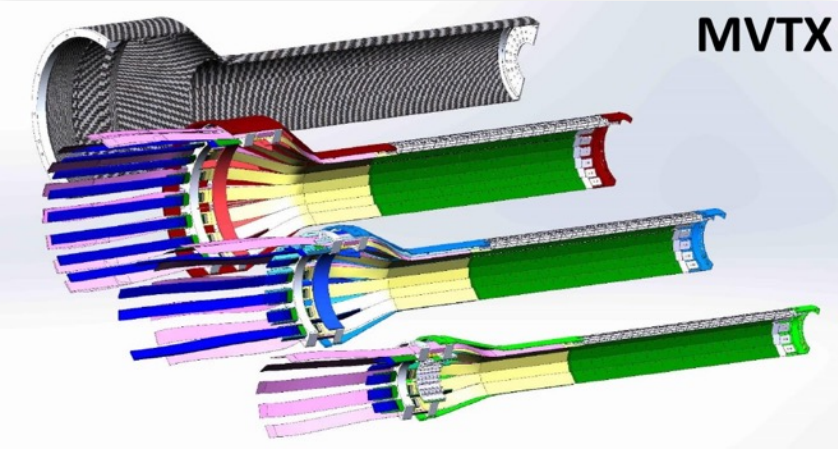
New Opportunity at RHIC
- sPHENIX: 2023-2025

- **Open HF jet in AuAu**
  - ➢ Beauty jets
  - ➢ Charm jets
  - ➢ J/Psi jets
- **Open HF hadrons**
- **Quarkonia**
  - ➢ Charm – many <c-cbar> in central AuAu
    - ❖ J/Psi : strong coalescence
  - ➢ Beauty – single <b-bbar> in central AuAu
    - ❖ Upsilon: no coalescence



Open HF Tagging with MVTX

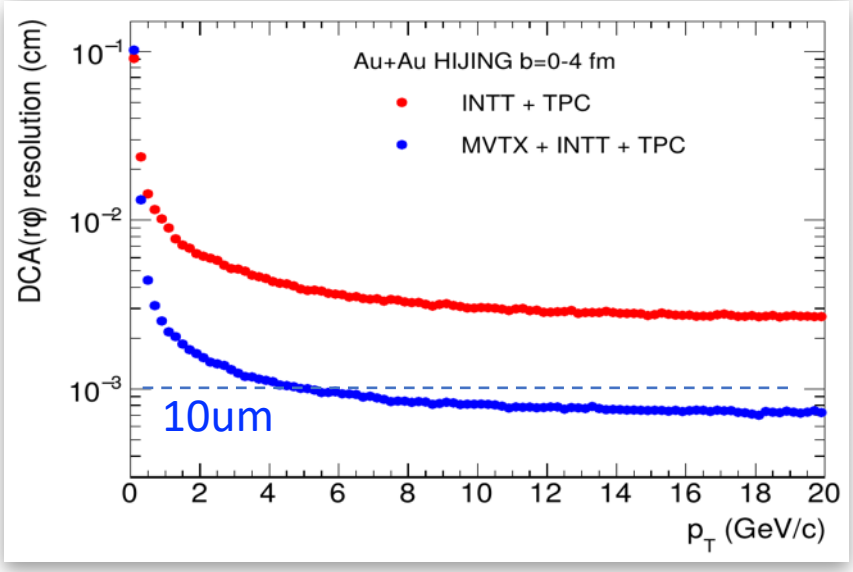
- Monolithic-active-pixel-sensor based VerTeX detector

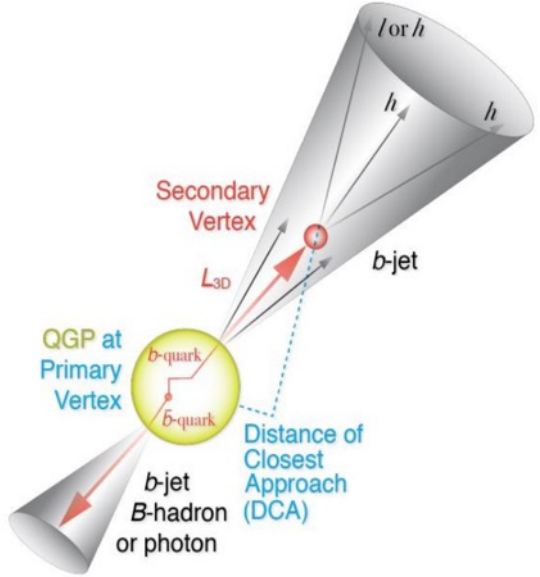


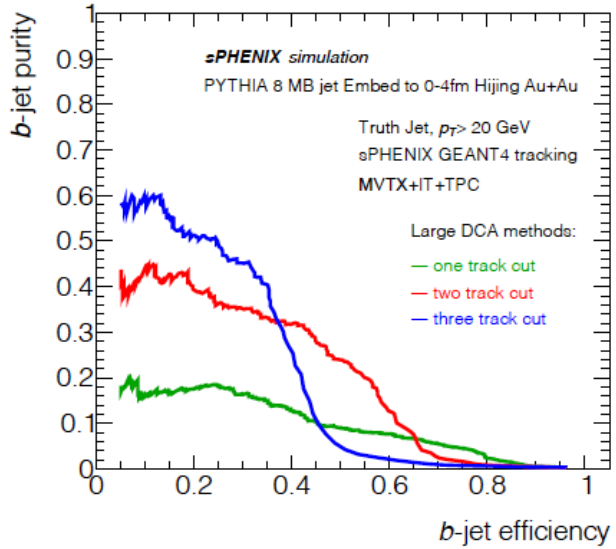
MVTX key parameters: (ALPIDE)

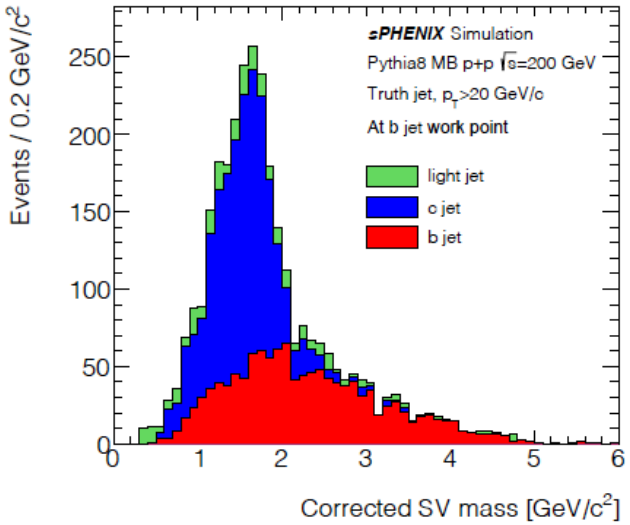
- pixel size: **27um x 29 um**
- ultra-thin stave: **0.35%X_0**
- Integration time: **~5us**

- Multi-tracks w/ large DCA
- 2nd vertex mass
- Exclusive hadron reconstruction





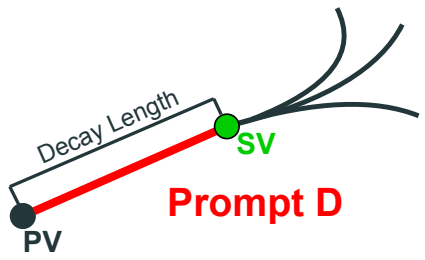


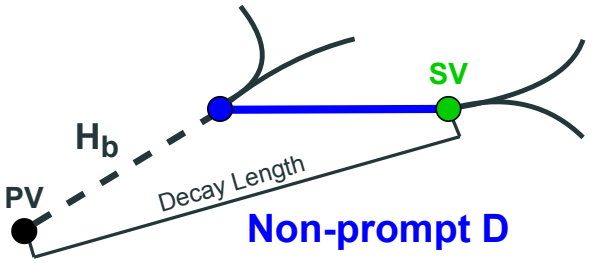


Work in Progress: from Full Monte Carlo Simulations

PYTHIA 8 p+p with full detector GEANT sim + reco

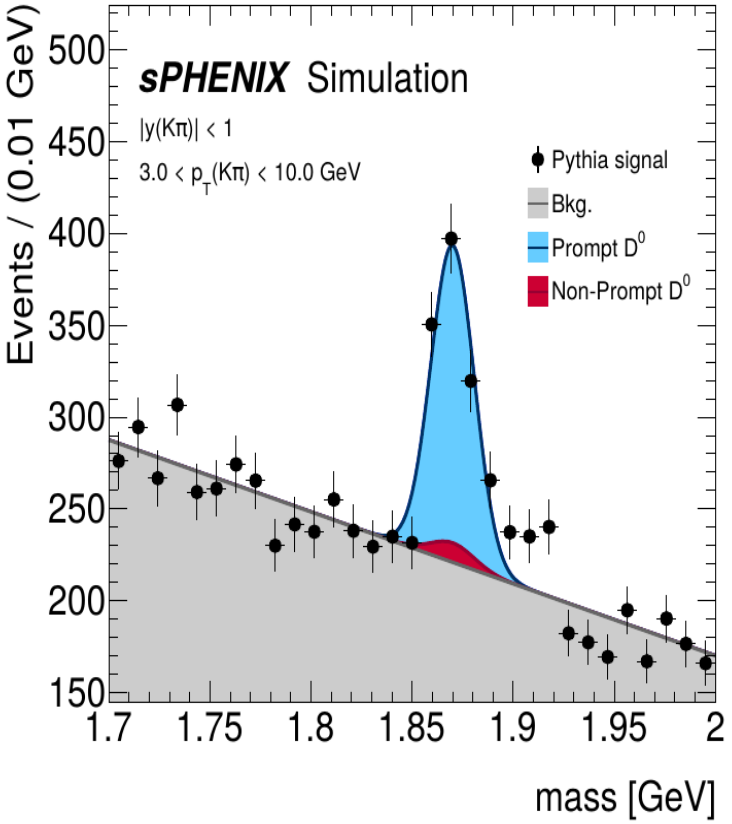
$$p + p \rightarrow D^0 + X \rightarrow (K^-\pi^+) + X$$

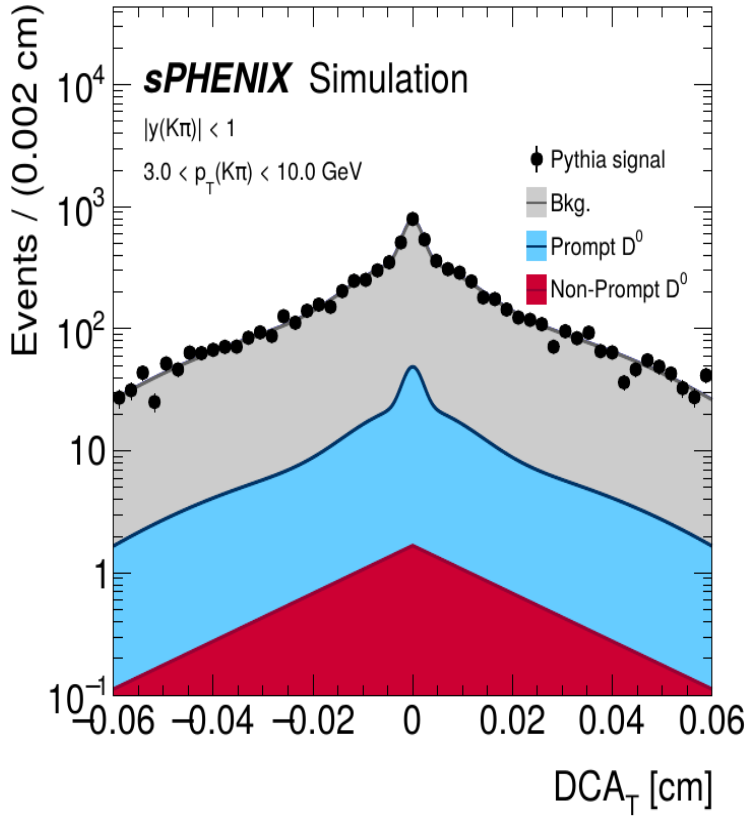




$$p + p \rightarrow H_b + X \rightarrow (D^0 + X') + X$$

KFParticle package implemented for exclusive HF hadron reconstruction



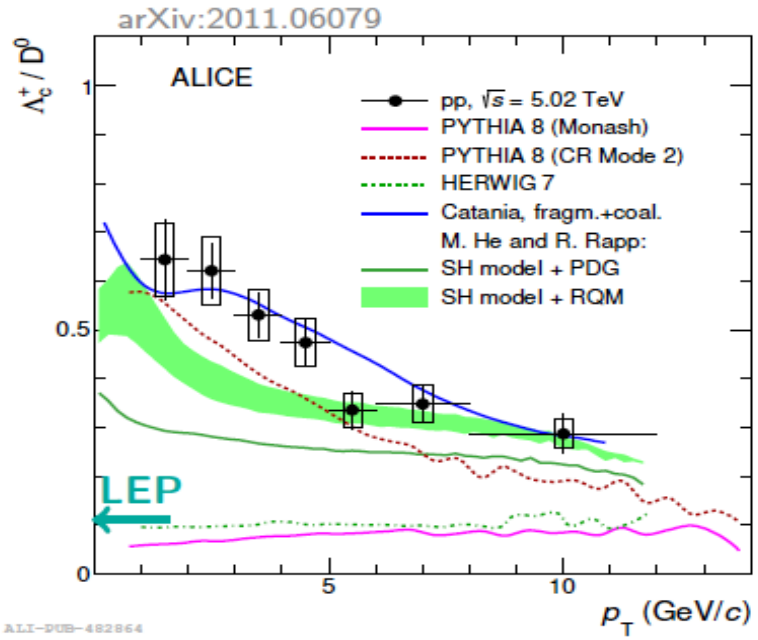


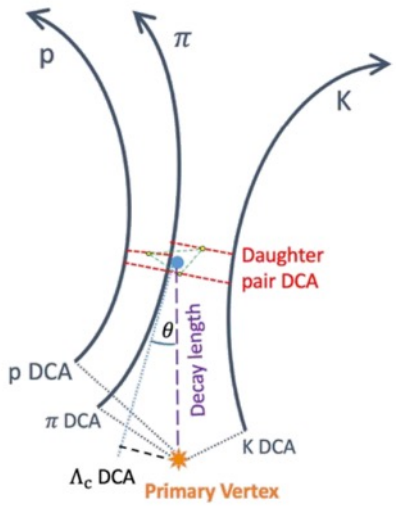
From Quark to Hadron in QGP

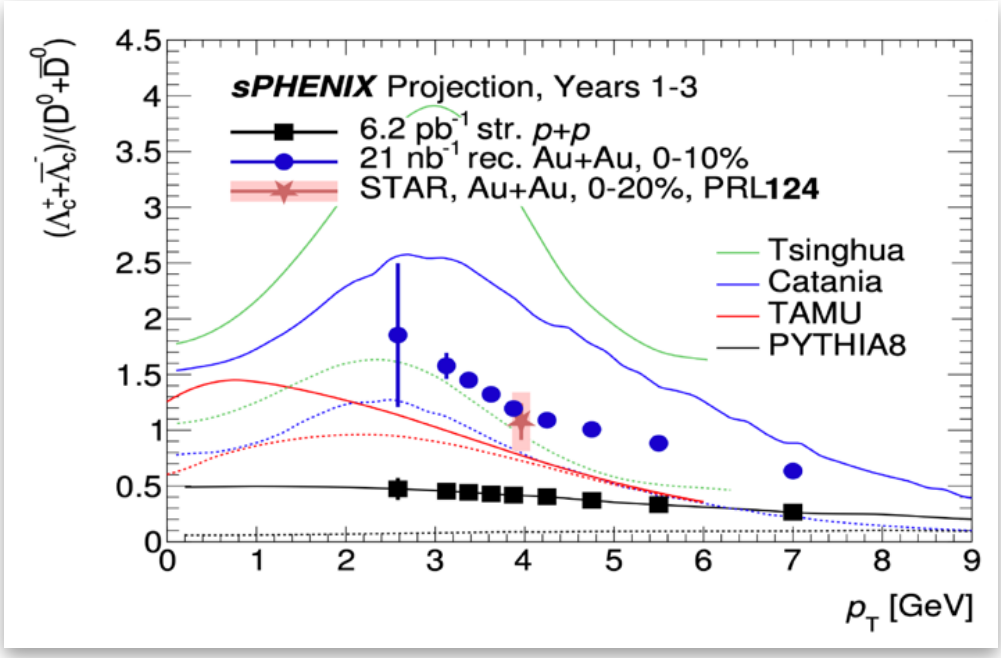
- Critical to understand the hadronization process

- **Hadron production strongly affected by the QCD environment**
  - Non-perturbative process important at low pT, coalescence etc.
  - Strong multiplicity dependence observed in p+p, pA and AA … @RHIC and LHC
  - Study the breakdown of pQCD factorization at low pT …
- **High precision measurements of HF meson and baryons in sPHENIX**

Clear pT dependence observed: e+e- vs pp



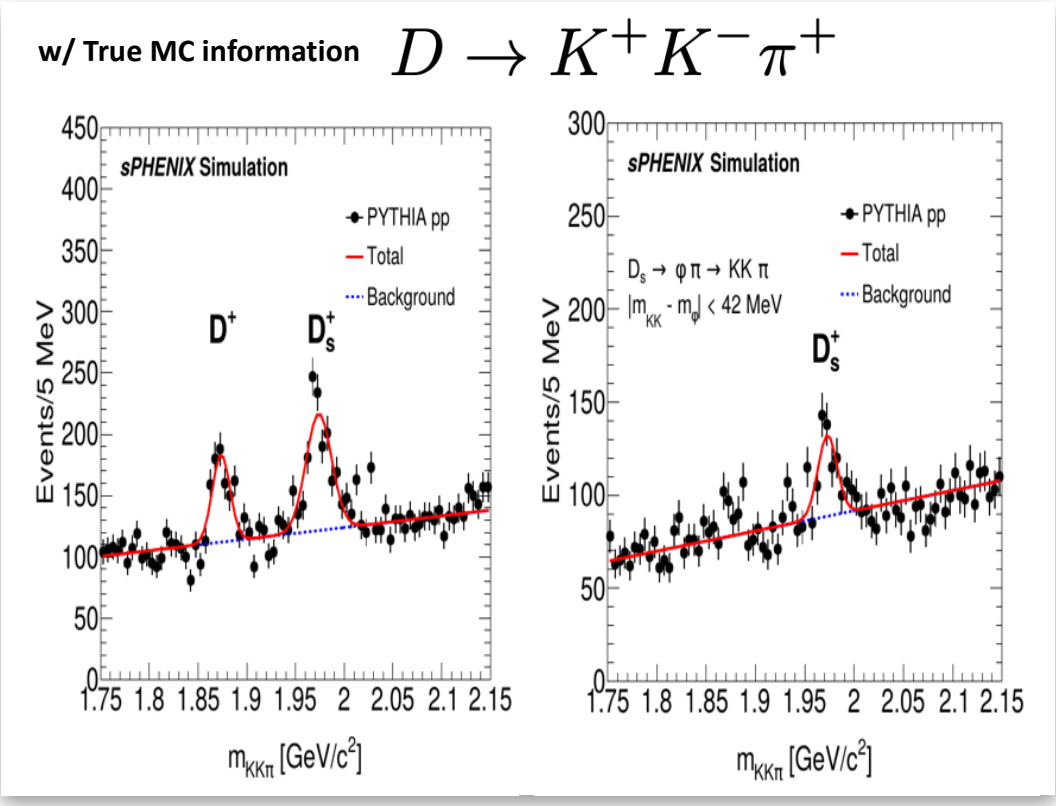




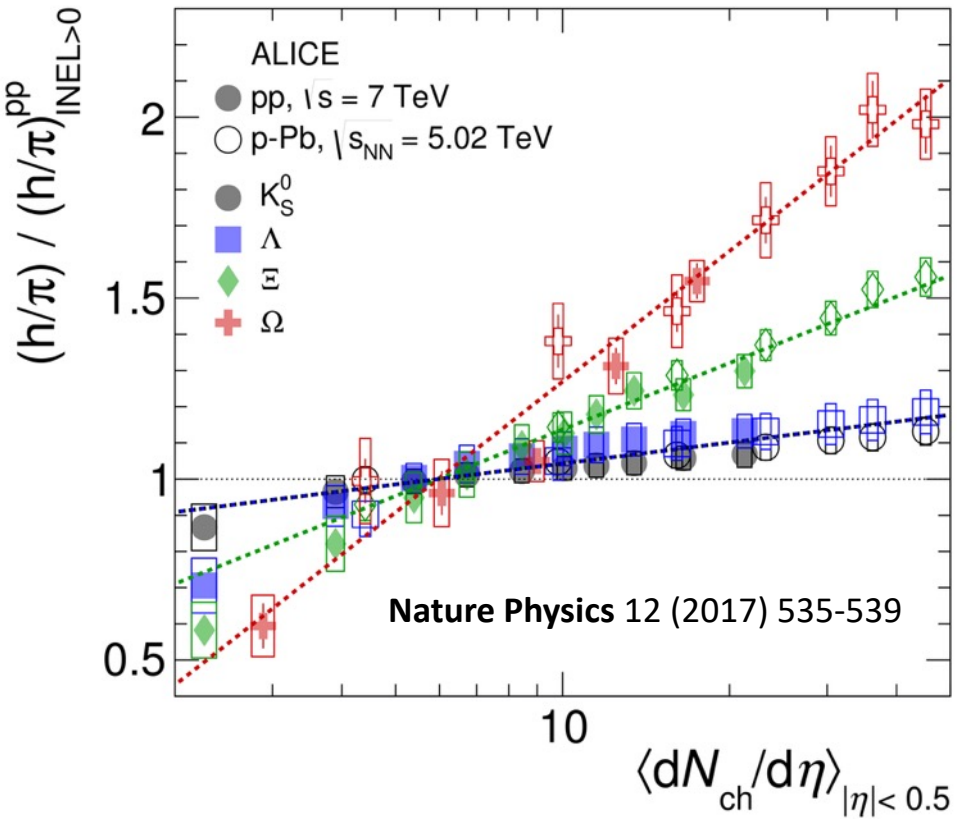
From Quarks to Hadrons (Cont.)

- More exclusive HF hadrons – $D^{+/-}$, Ds, Bs yields etc.
- Event multiplicity dependence

w/ True MC information $D \rightarrow K^+K^-\pi^+$

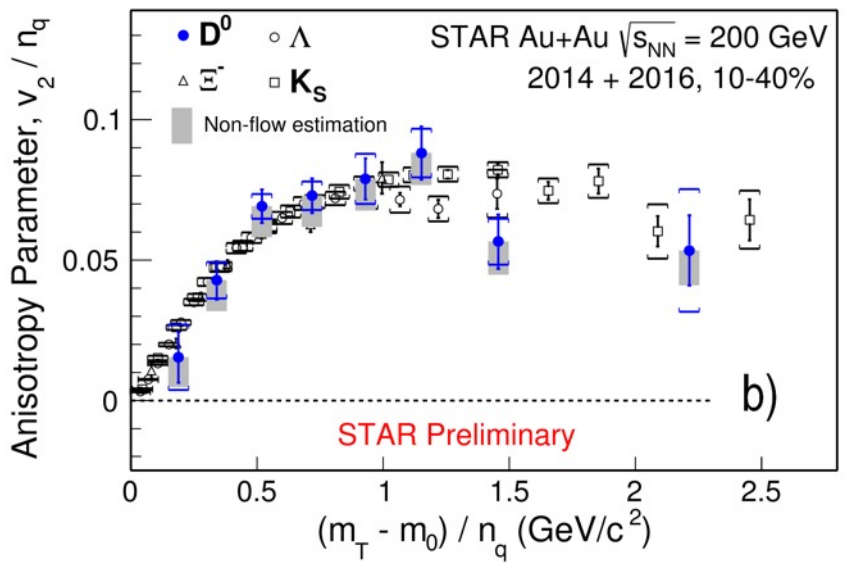


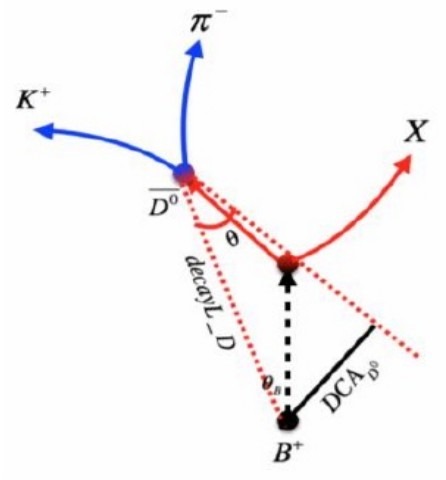
Strangeness enhancement in high multiplicity pp



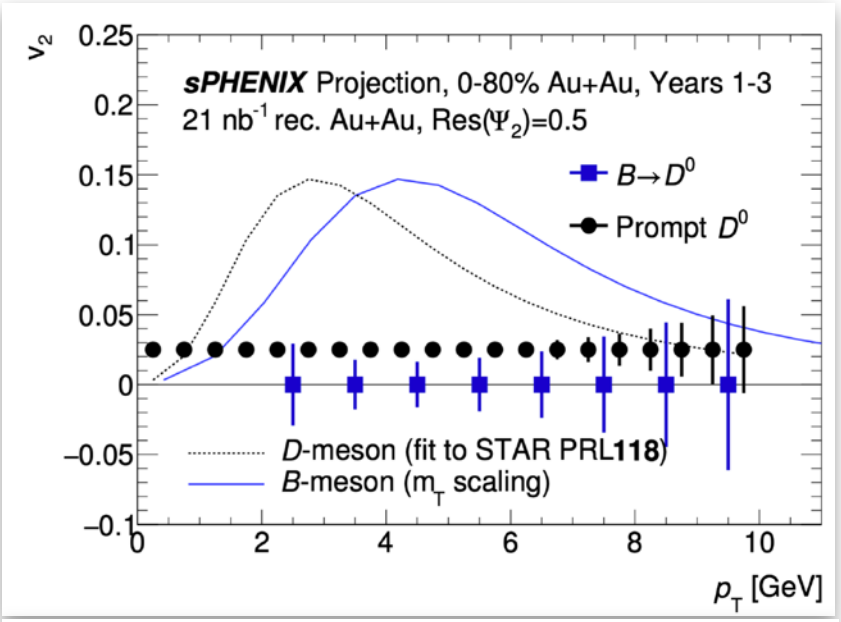
Precision “Flow” Measurements of B-hadron and b-Jets

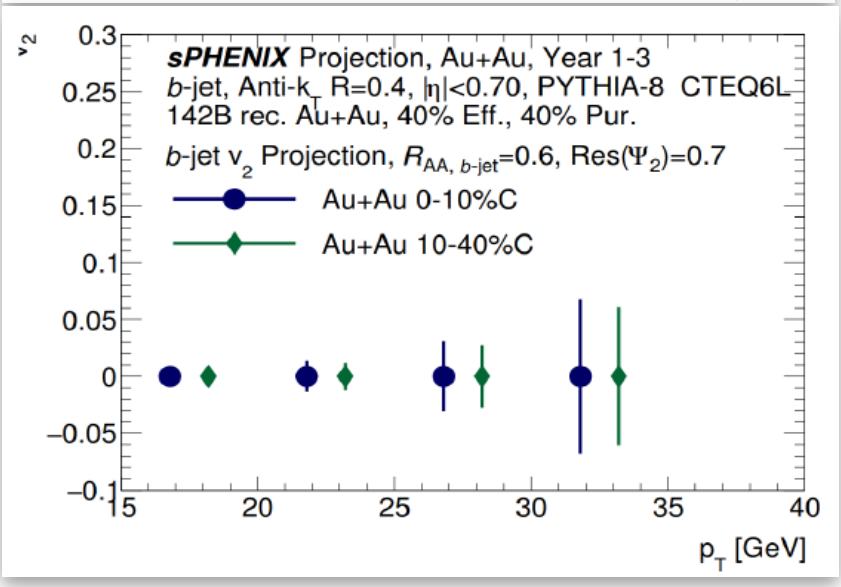
STAR: D^0 v2 m_T scaling observed





$B \rightarrow \overline{D^0} + X$ (B.R. 60%)





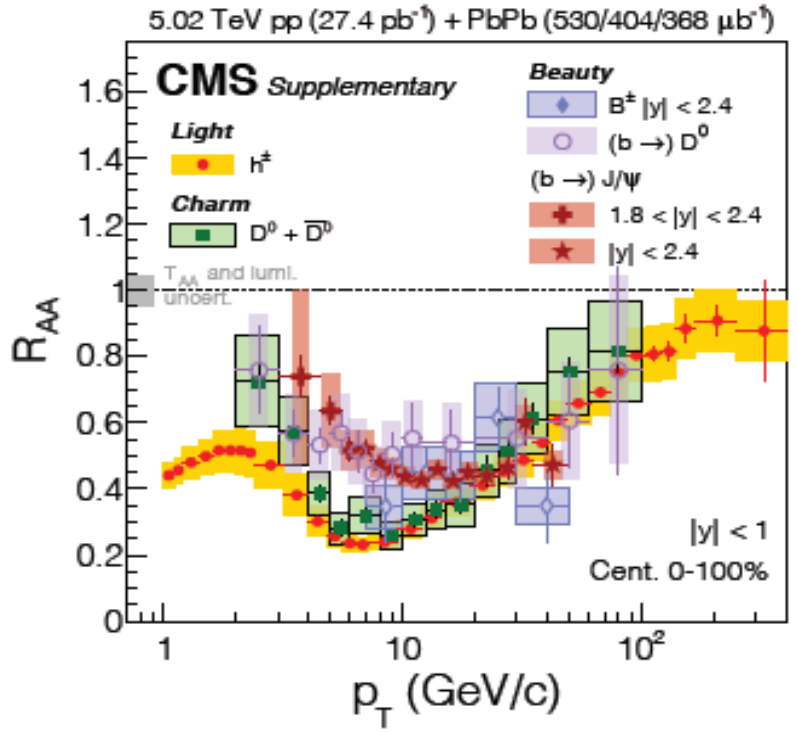
Many factors affect the HF hadron production:

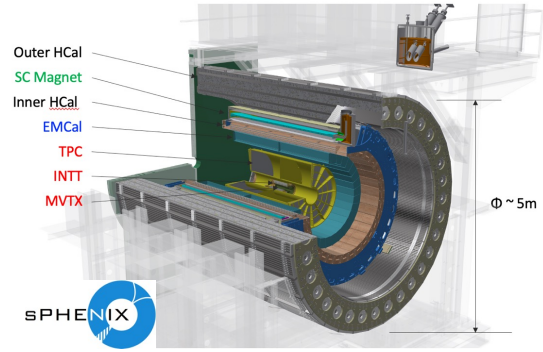
- Heavy quark energy loss in QGP
- Heavy b-quark diffusion in QGP
- Heavy quark hadronization in QGP

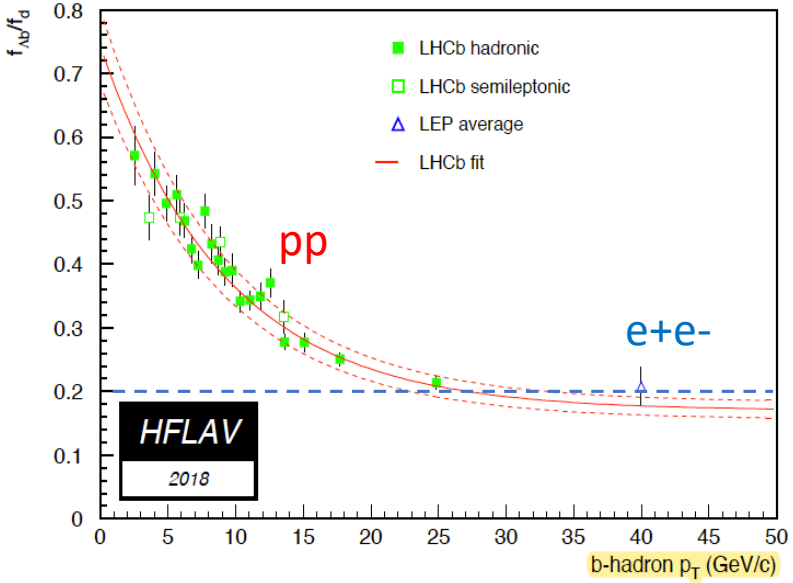
b-jet flow, pQCD:
- Energy loss induced v2?

Summary and Outlook

- **HQ are excellent probes for QGP study**
  - ➢ mass-dependent, energy loss, flow
  - ➢ strong coupling with QGP
- **Critical to understand the HF hadroproduction mechanisms**
  - ➢ Breakdown of FF universality at pT ~<20GeV, but also most interesting region to study
  - ➢ FSI and coalescence important even in pp and pA
    - ❖ Multiplicity dependence requires further study
- **HF jets are important to isolate non-perturbative effects from QGP**
  - ➢ Energy loss
- **New! sPHENIX online early 2023**
  - ➢ Very rich HF physics program
  - ➢ Complementary to LHC

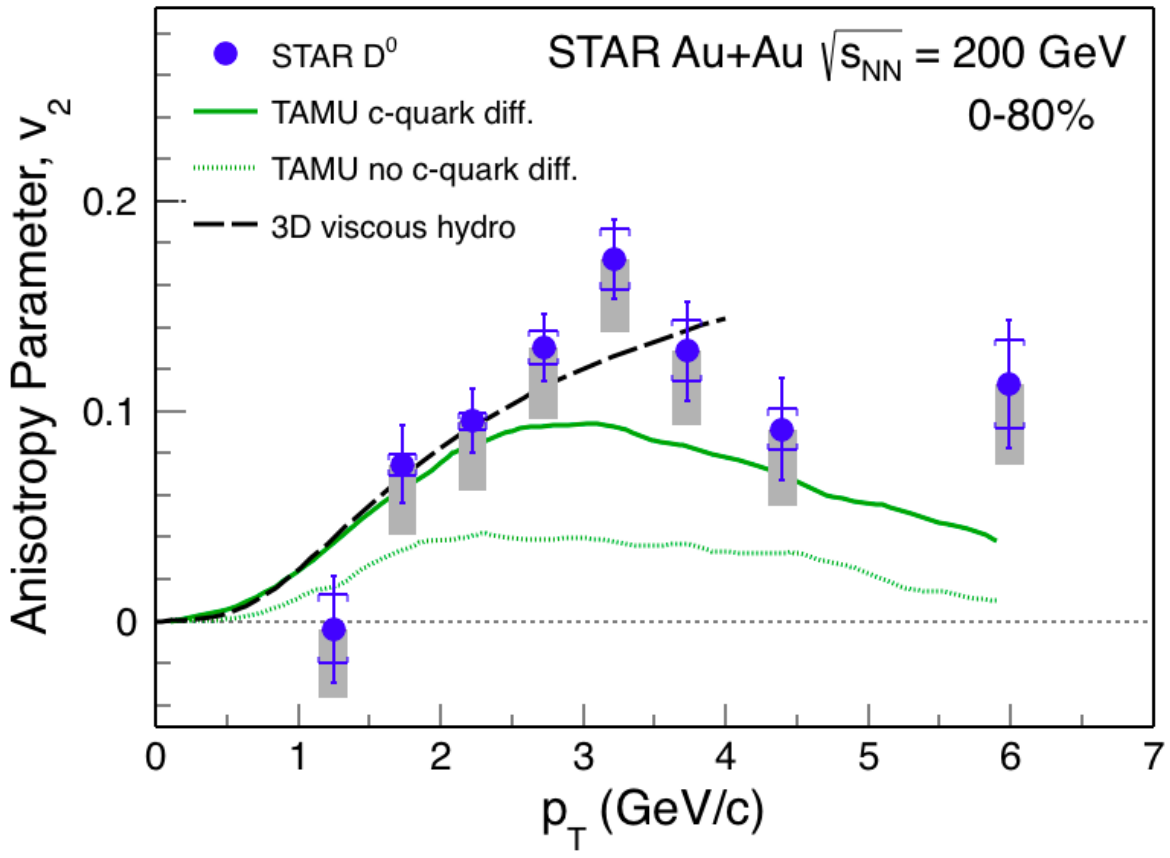


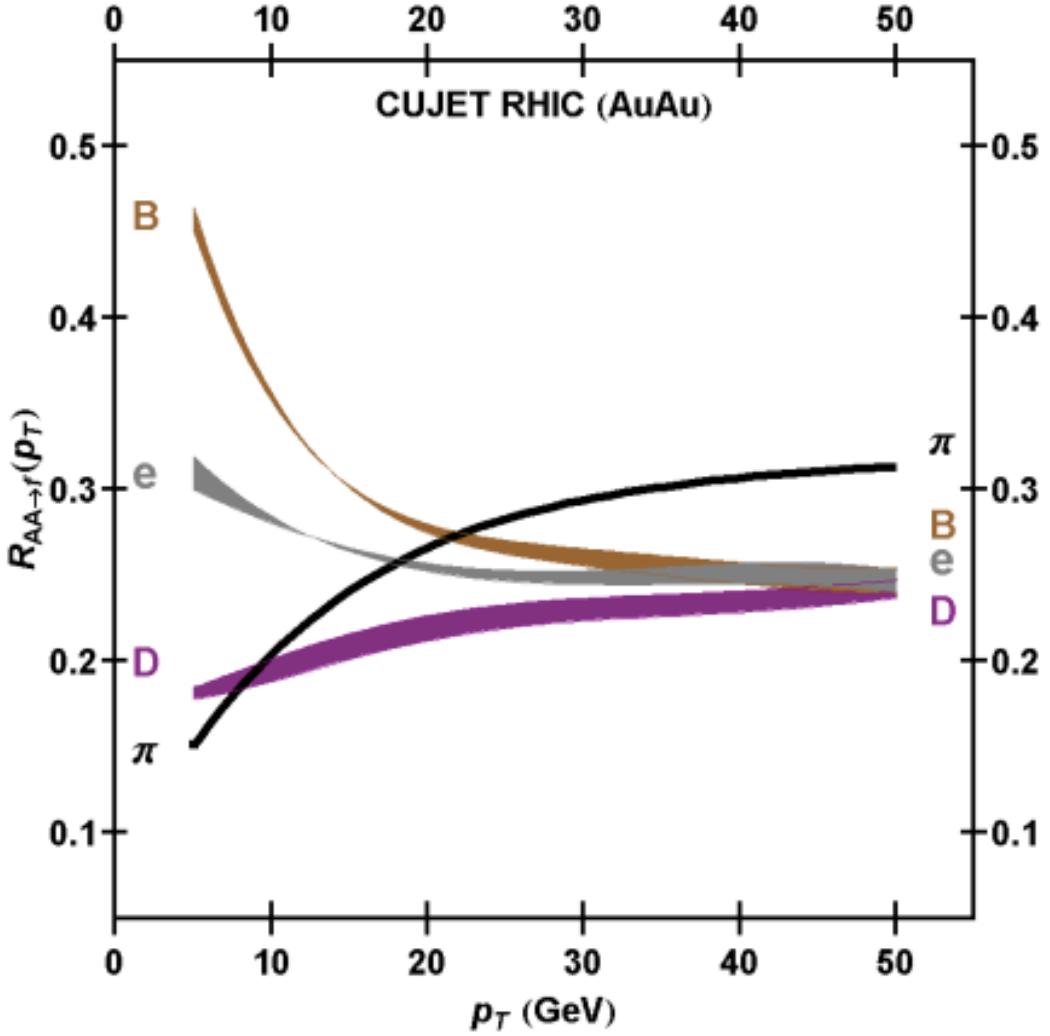




Backup

HQ Flow and Energy Loss





HQ Diffusion in QGP

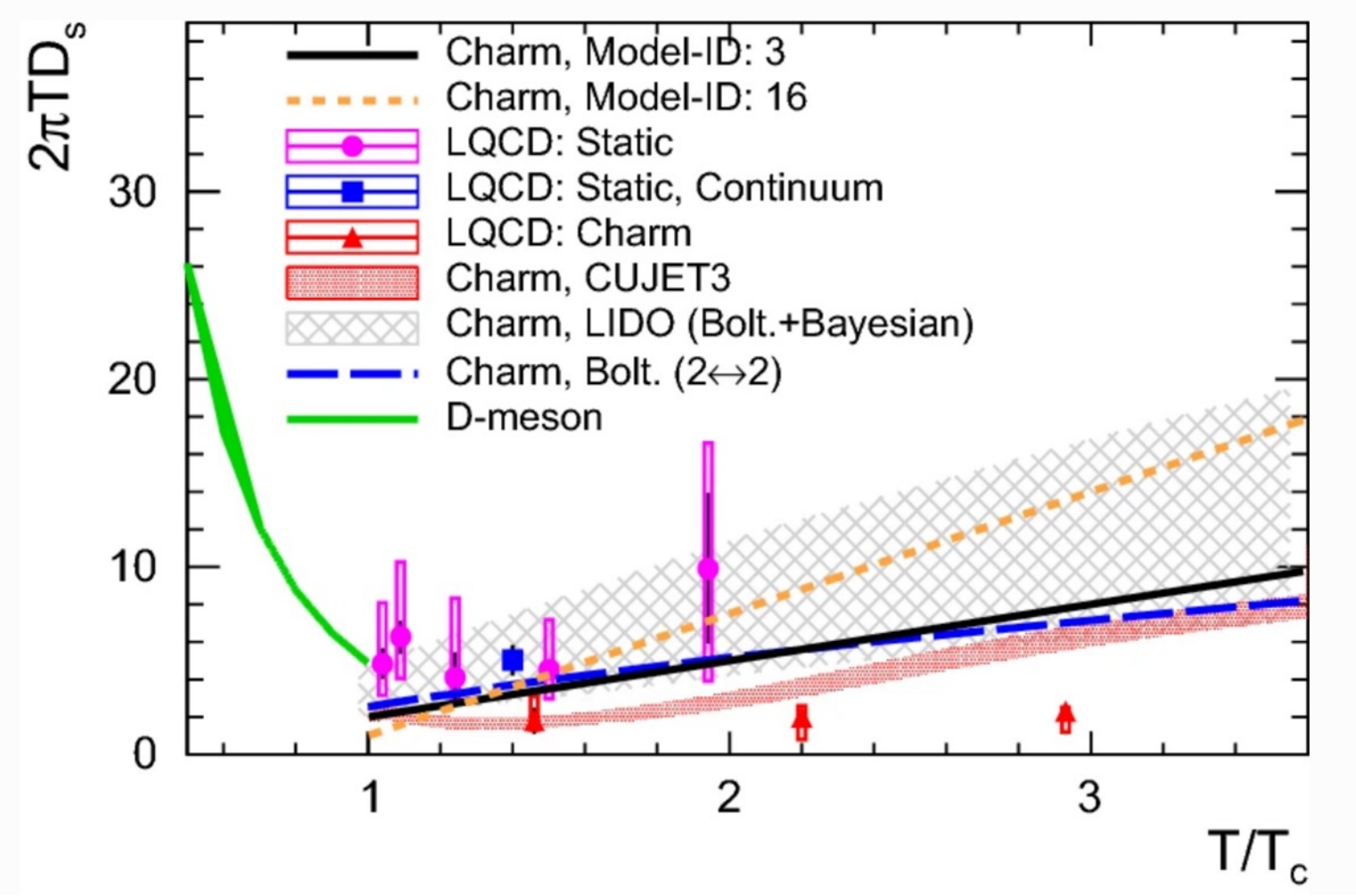
- Model calculations

Classical Brownian motion:

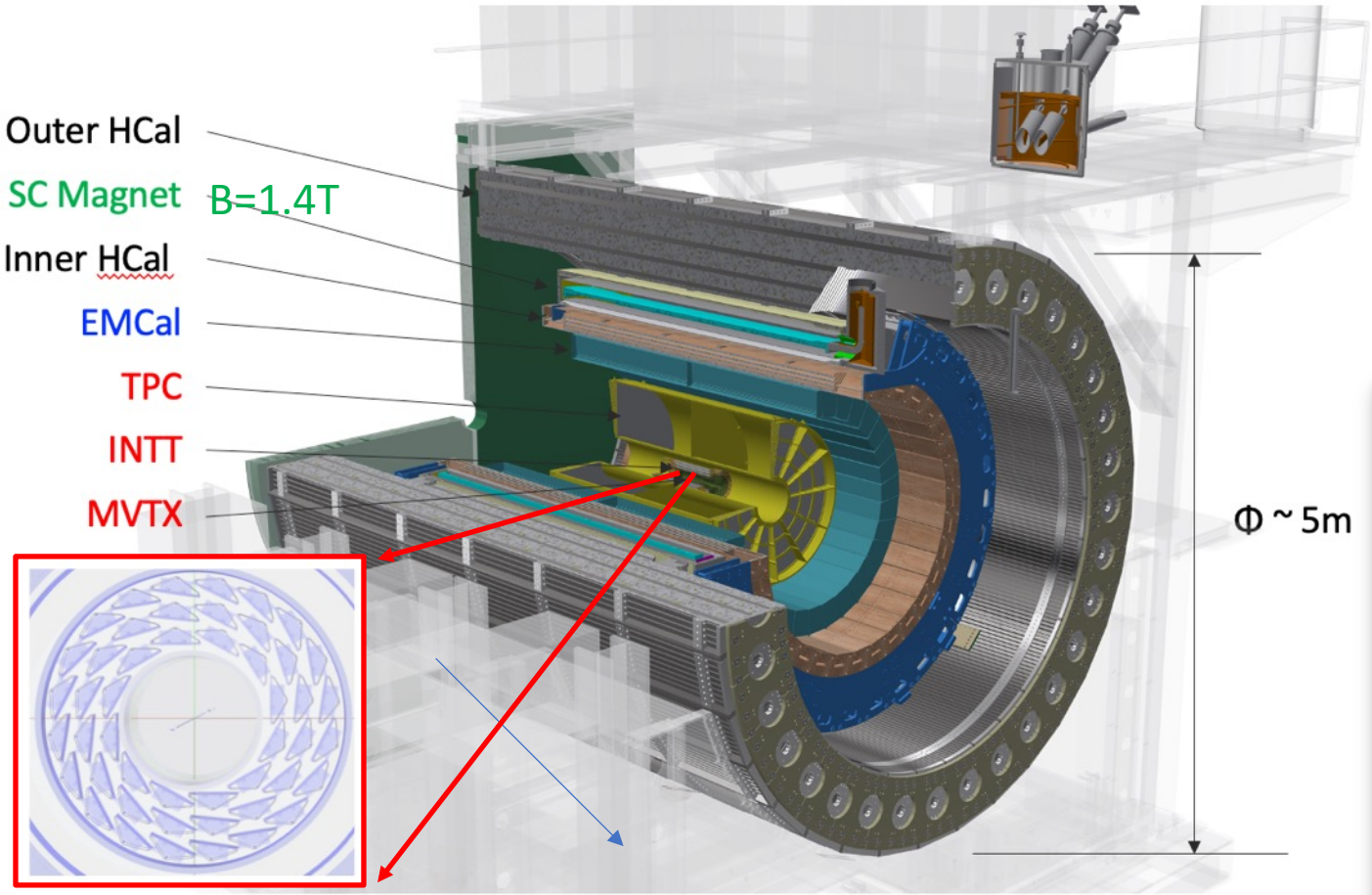
$$\sigma_x^2 = 2Dt$$

$$D \propto \frac{k_B T}{\eta}$$

Shuang Li and Jinfeng Liao, Eur. Phys. J. C (2020) 80: 671



The sPHENIX Experiment



MVTX beam view
R = 2.5 – 4.0 cm

Key capabilities:

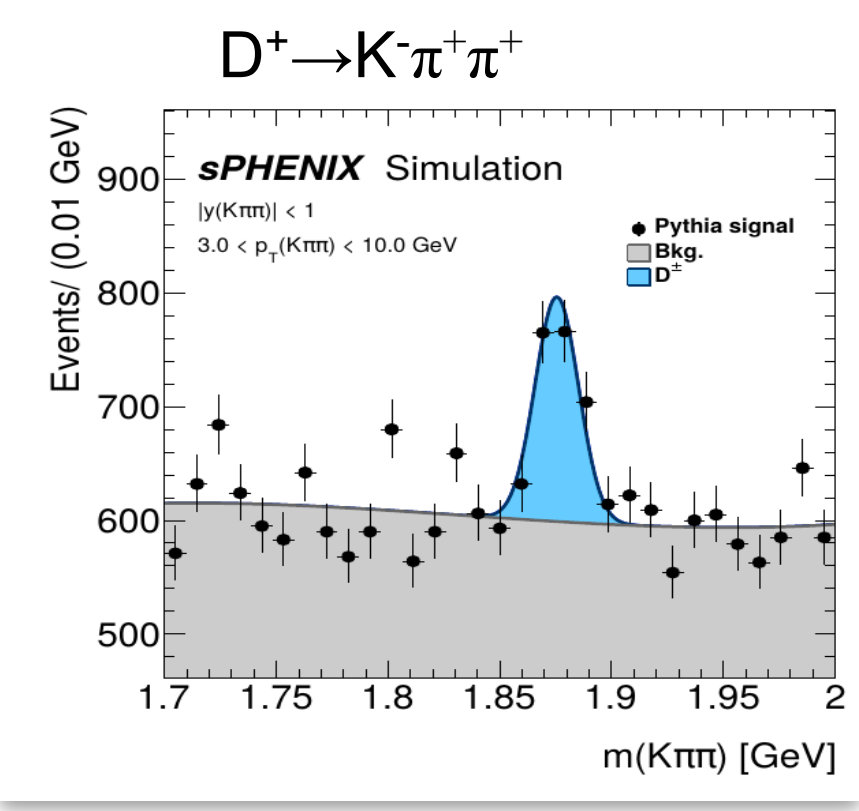
- Full azimuth, |eta| < 1.1
- High trigger rate ~15kHz, collect all central AuAu
- EMCal: high pT direct photons
- Inner and outer HCals: jets
- Precision tracking: HF and more
  - 0.2 < pT < 40 GeV

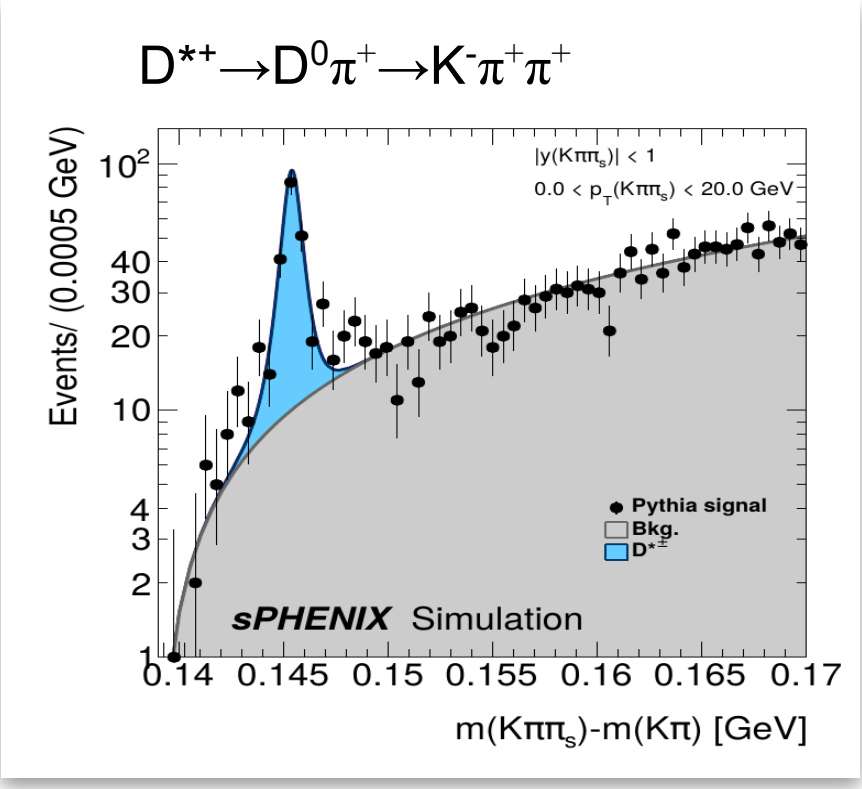
  Trigger-less streaming readout, p+p and pAu

sPHENIX Run Plan

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Work in Progress





For D*, pT ~> 1.5GeV, with soft pion pT > 0.2GeV

A Puzzle or Not
– No event multiplicity dependence?

- Similar values for pT integrated ratios
  - Low pT dominant,
  - Coalescence and breakup
  - Missing anything?

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