Open heavy flavor: experimental review

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STRONG-2020

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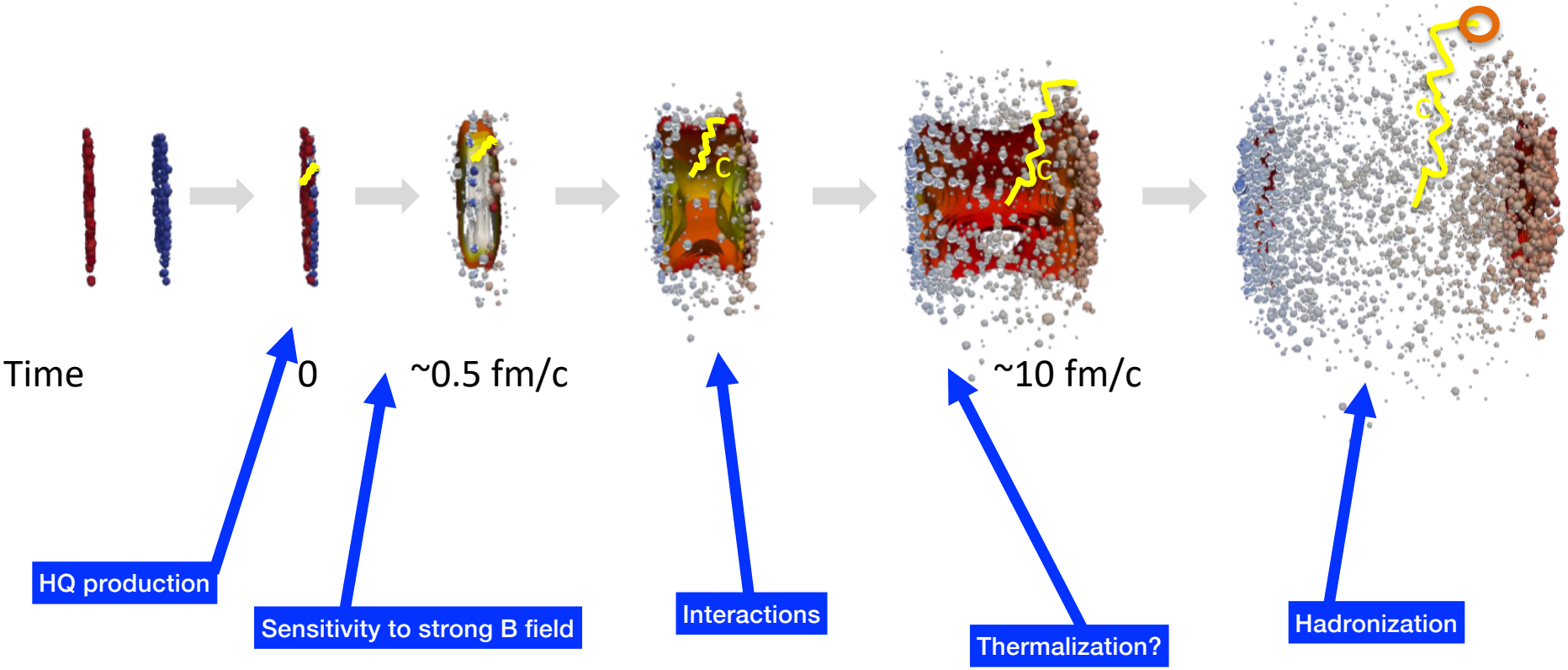
Using several slides from review by Cristina Terrevoli (SQM19), compilation plots by Jin Wang (QM2019) and Roberta Arnaldi (HP2020)

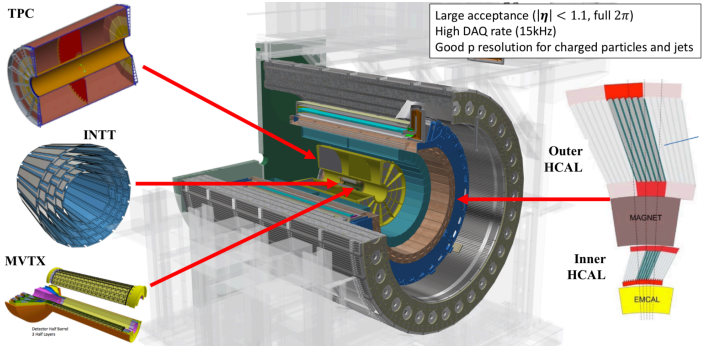
Outline: part I

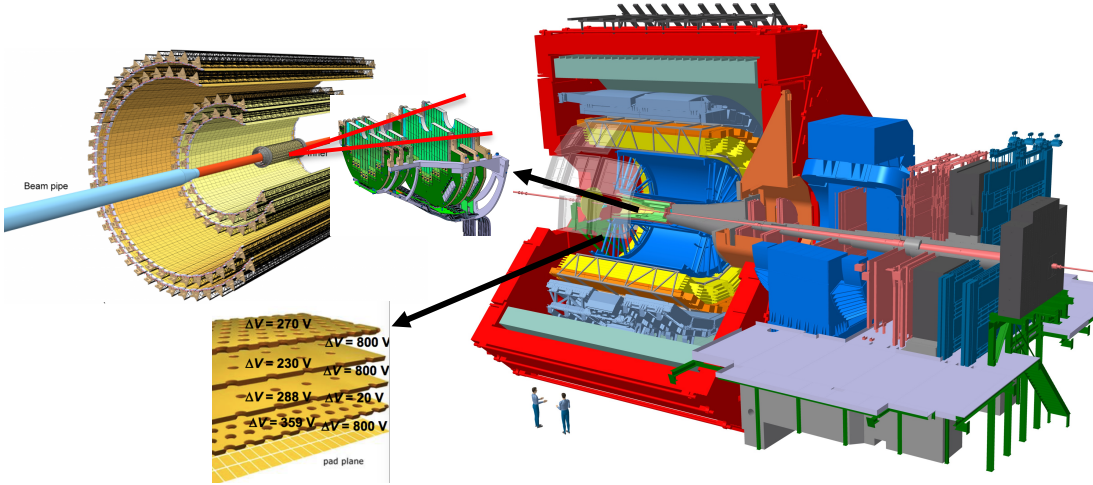
- HF measurements as probes of all stages of HICs



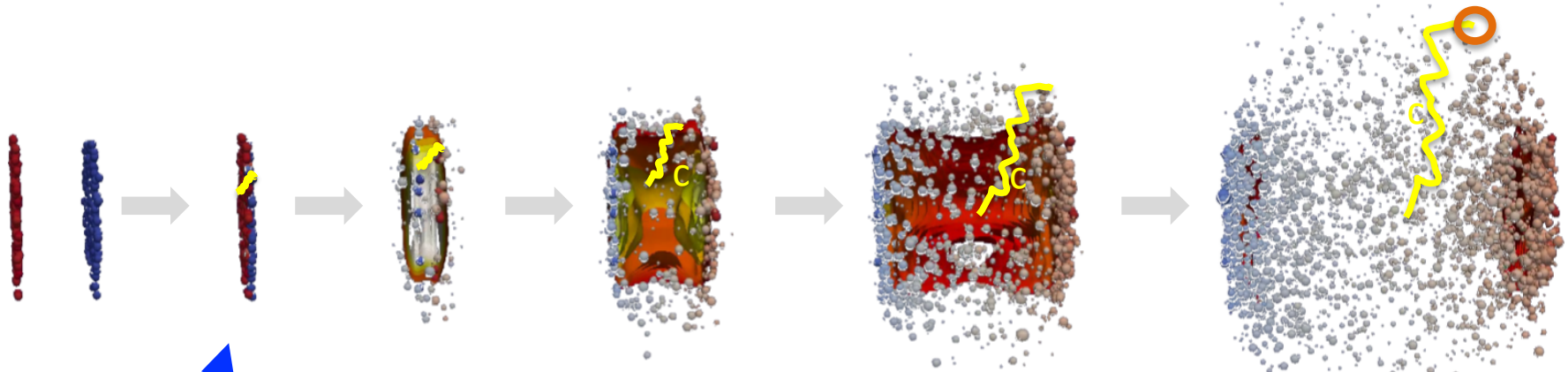
Outline: part 2 (if time left)

- HF measurements as probes of all stages of HICs
- Experimental outlook: preparing for the next 10 years





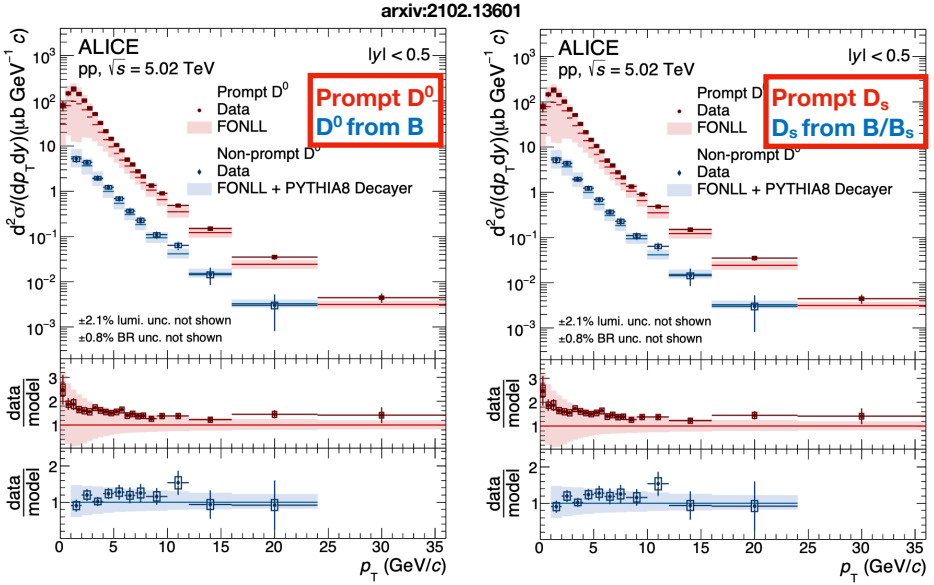
Heavy quark production in pp collisions

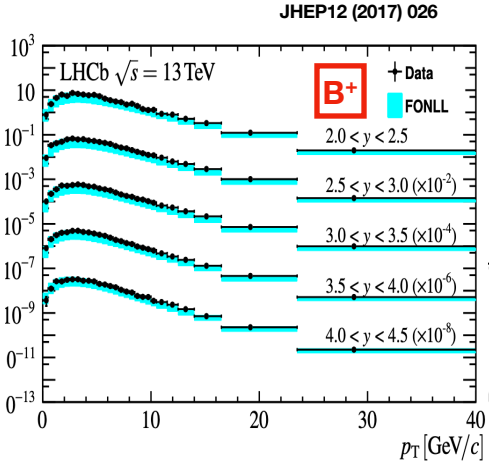


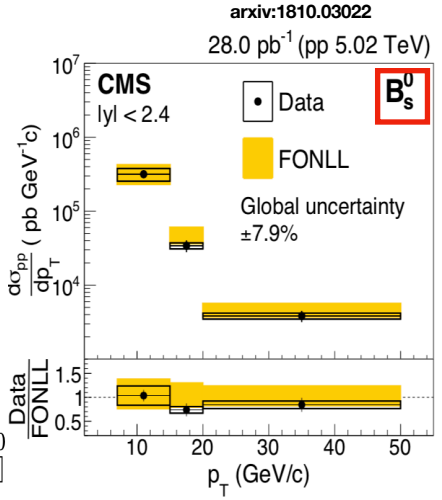
Time 0 ~0.5 fm/c ~10 fm/c

HQ production

Heavy quark production in pp collisions



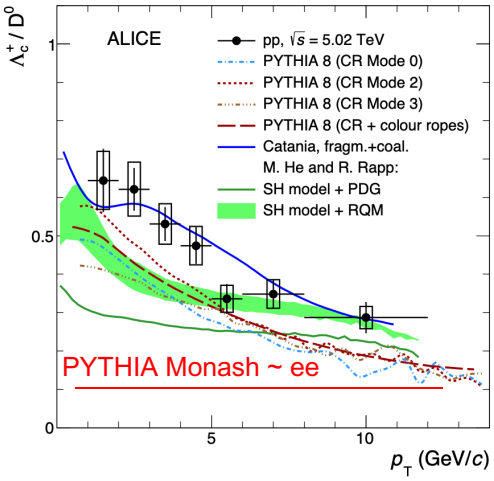


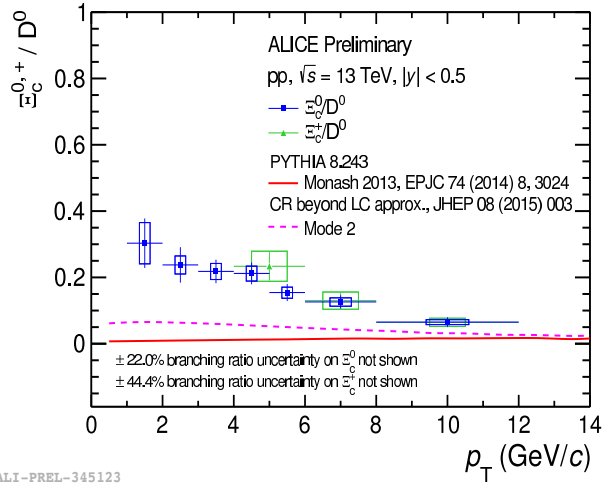


- **Measurements from 0 to ~50-100 GeV/c for both charm and beauty hadrons**
- **Systematic comparison with several pQCD calculations** with different schemes: data described within uncertainties
- **Theory uncertainties >> data uncertainties** → for AA models, use pp data uncertainties for p_T shape variations?

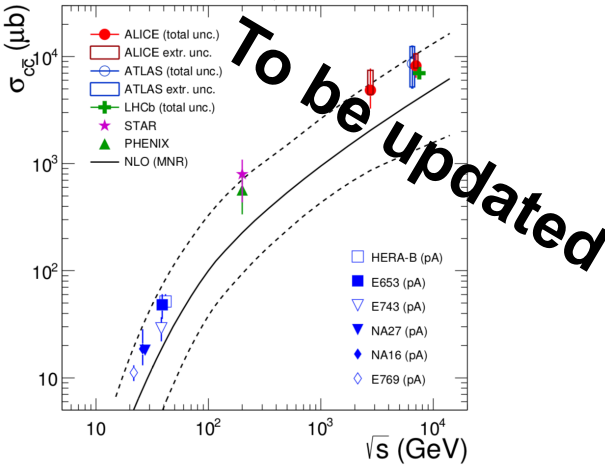
Charm baryons and total cross section

arxiv:2011.06079



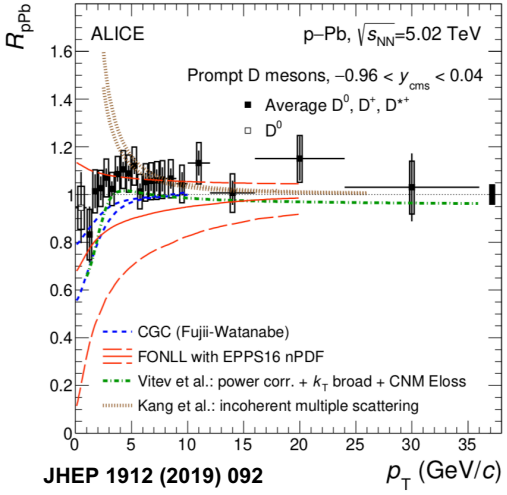


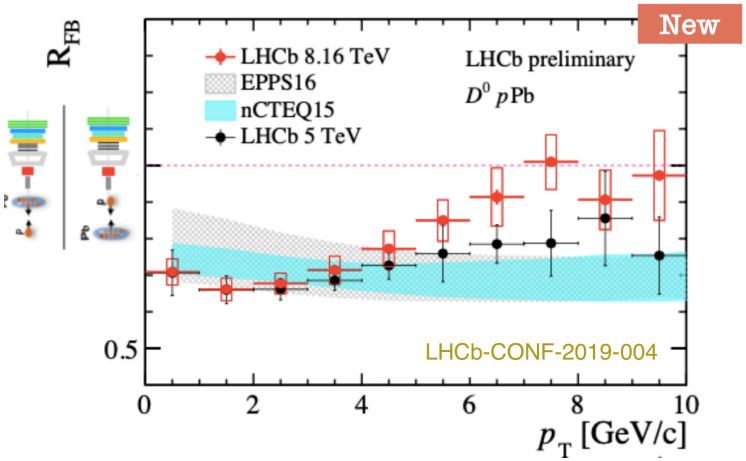
ALICE, arXiv:1605.07569

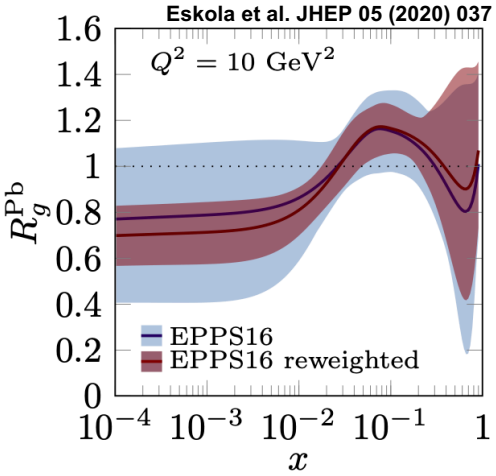


- Baryon fraction (Λ_c and Ξ_c) at low p_T much larger than predicted by string fragmentation models tuned on ee data, e.g. Λ_c/D^0 ~0.5, Ξ_c/D^0 ~0.2
- Baryon measurements crucial to understand hadronisation (discussed also later)
- Total charm cross section needs baryon measurements (Λ_c at least)
  - Expected increase with respect to extrapolations based on D mesons and ee fragmentation fractions

Initial-state effects in p-Pb (minimum-bias)

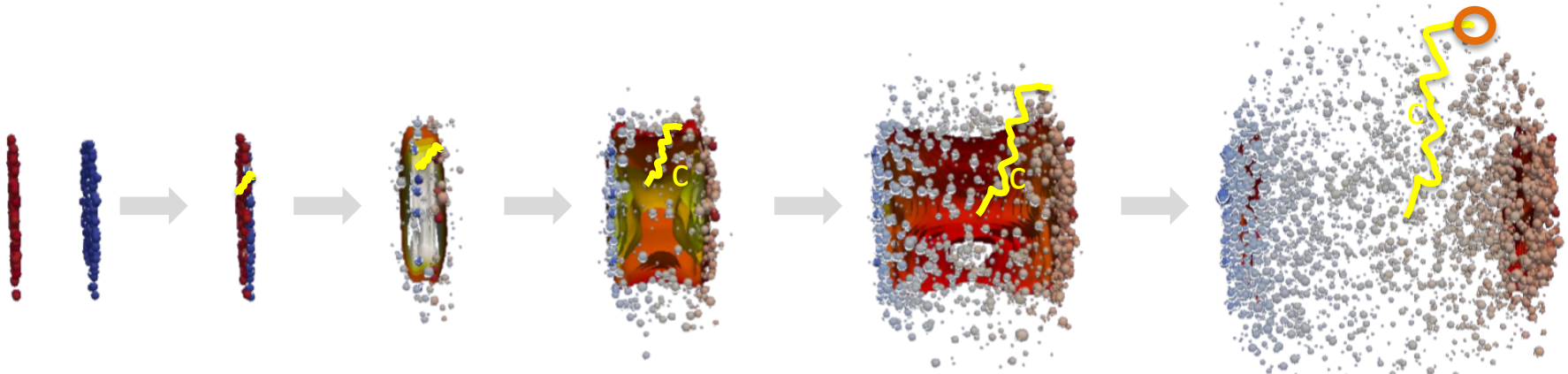






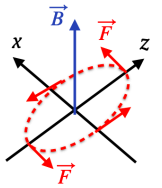
- nPDFs with shadowing describe D-meson p-Pb 5 TeV data (here shown mid-y by ALICE and forward/backward by LHCb)
  - High-p_T tension with recent forward/backward at 8 TeV by LHCb?
- Precise LHCb data potentially constrain nPDFs down to small x
  - But not final-state effects?

Heavy quarks as probes of the early e.m. field



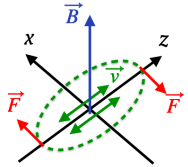
Time 0 ~0.5 fm/c ~10 fm/c

Sensitivity to strong B field



➡ Faraday effect

Electric field induced by decreasing $\vec{B}$



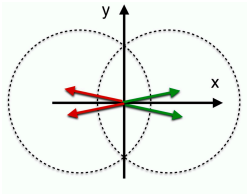
➡ Hall effect

Lorentz force induced by moving charges

$\vec{F} = q\vec{v} \times \vec{B}$

Observable

Direct flow v_1

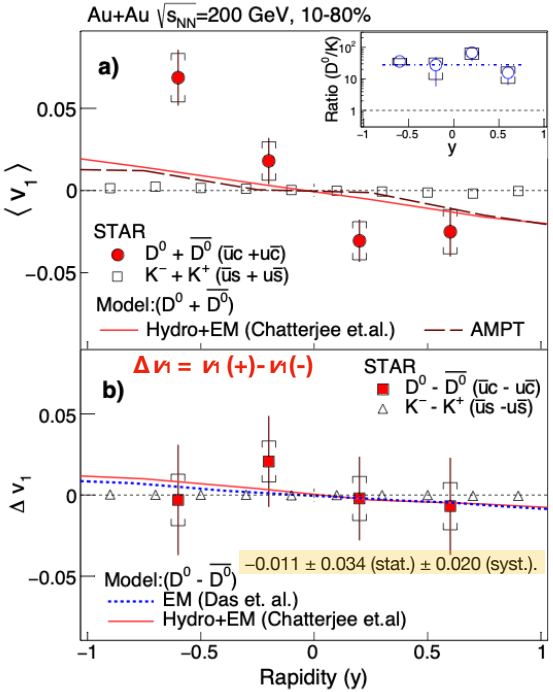


$v_1 = \langle cos(\phi_p) \rangle = \langle p_x/p_T \rangle$

v_1(D)- v_1(anti-D)

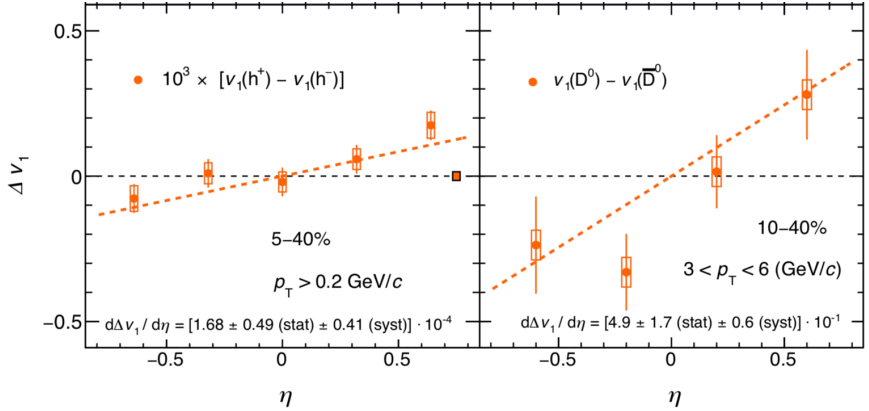
c and anti-c: opposite Lorentz force

STAR arXiv:1905.02052



LHC: larger slope w.r.t. RHIC, effect due to larger B than the induced E?

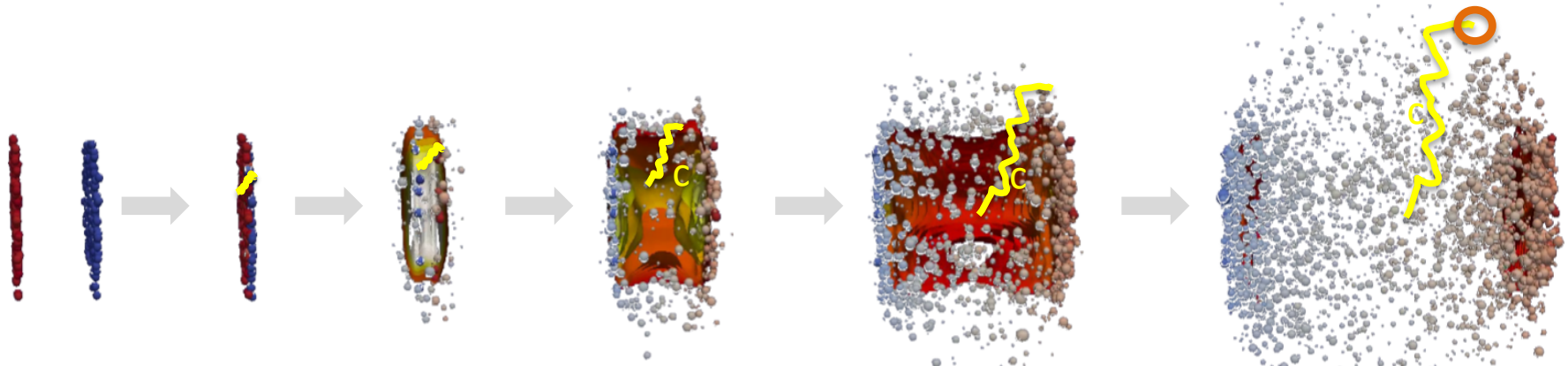
ALICE, arXiv:1910.14406



Slope ≠ 0 significance 2.7σ

3 orders of magnitude larger slopes w.r.t. **charged hadrons**

Heavy quark interactions: energy loss



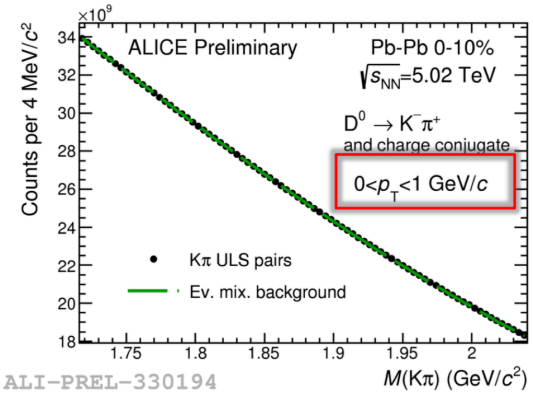
Time 0 ~0.5 fm/c ~10 fm/c

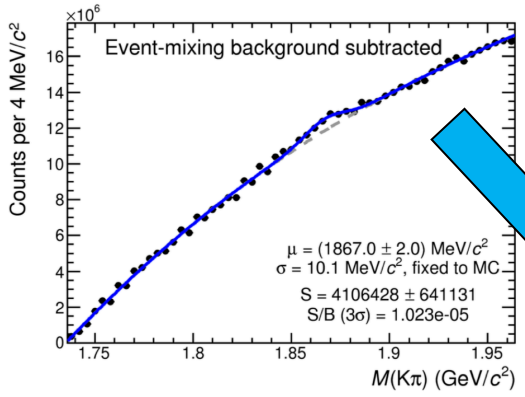
Interactions

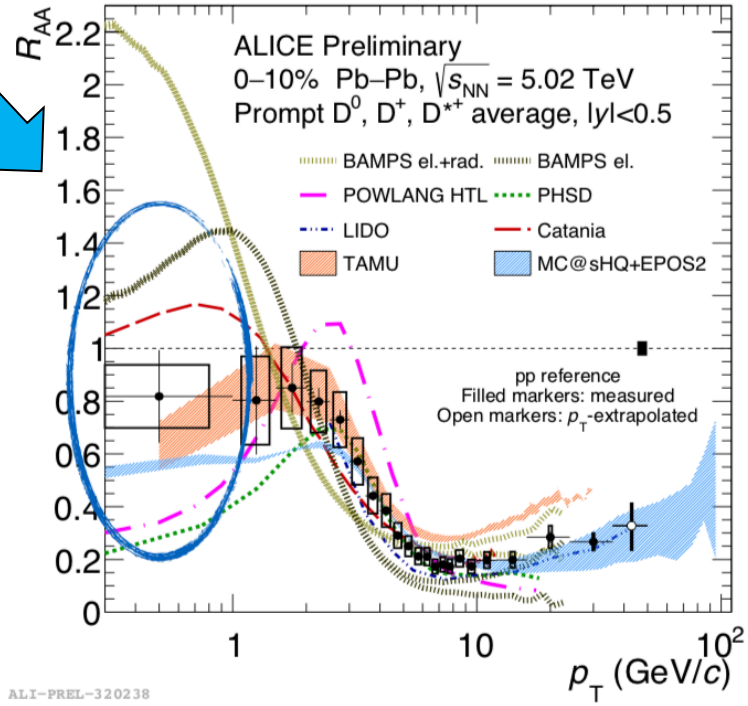
- What are the relevant energy loss mechanisms?
- Is there a flavour dependence (colour charge, mass)?
- At which p_T do radiative processes start to become dominant over collisional processes?

HF nuclear modification factors

Mass spectrum $D^0 \rightarrow K\pi$





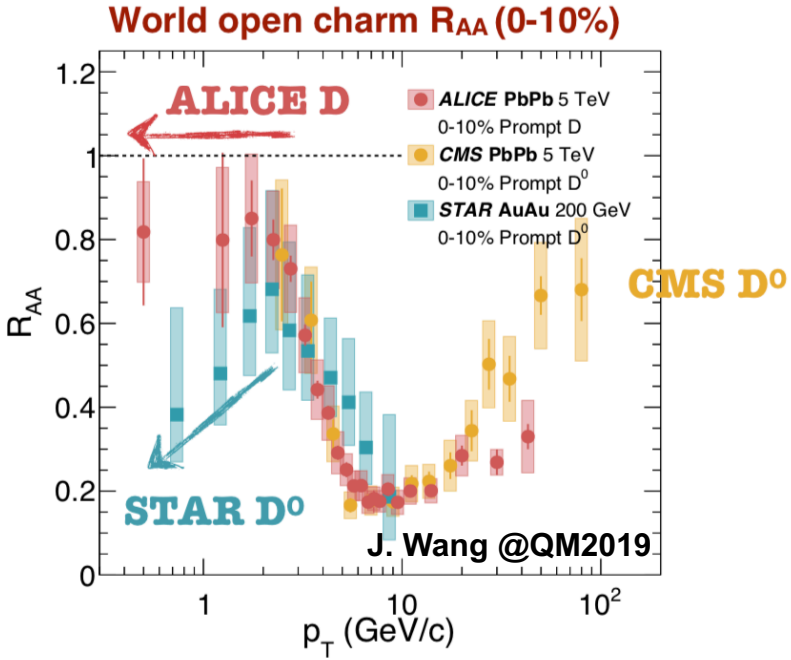


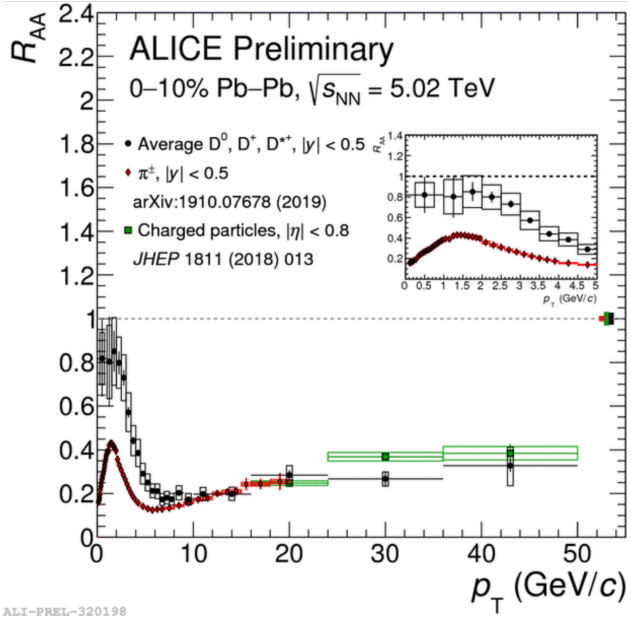
For the first time, D mesons down to p_T=0 at LHC

But huge background (S/B~10^{-5}) → limited precision

Need new-generation trackers to do better

D meson nuclear modification factor





Different trend RHIC/LHC?
Larger flow bump at RHIC?
Caused by steeper p_T distribution?

D R_{AA} > π R_{AA} for p_T<6 GeV
But difficult for now to conclude on colour charge or mass dependence, due to "confounding" factors (flow, hadroniz.)

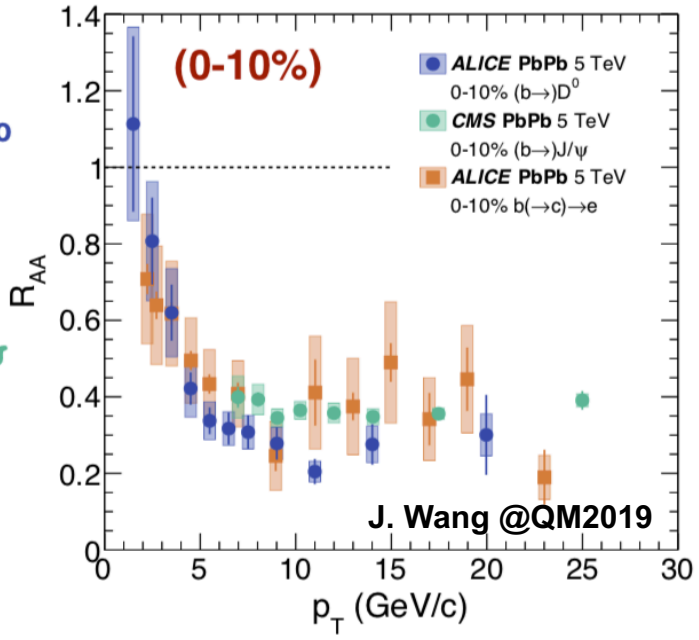
Beauty nuclear modification factor

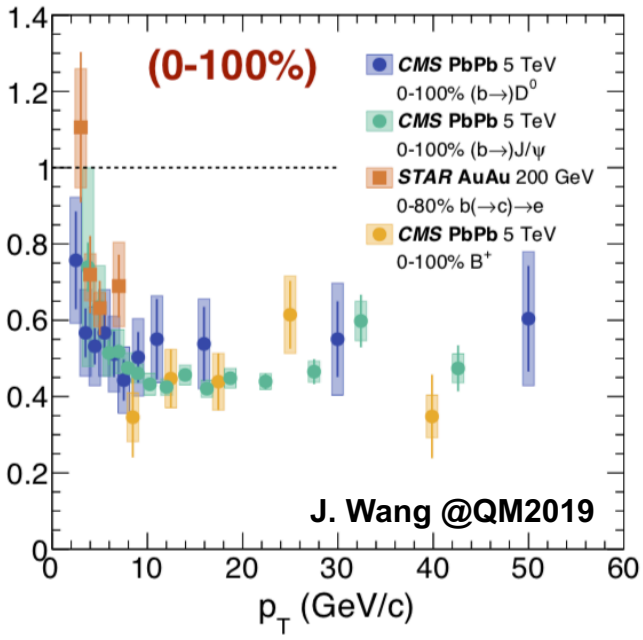
World open beauty R_{AA}

ALICE b→D⁰

ALICE b→e

CMS b→J/ψ





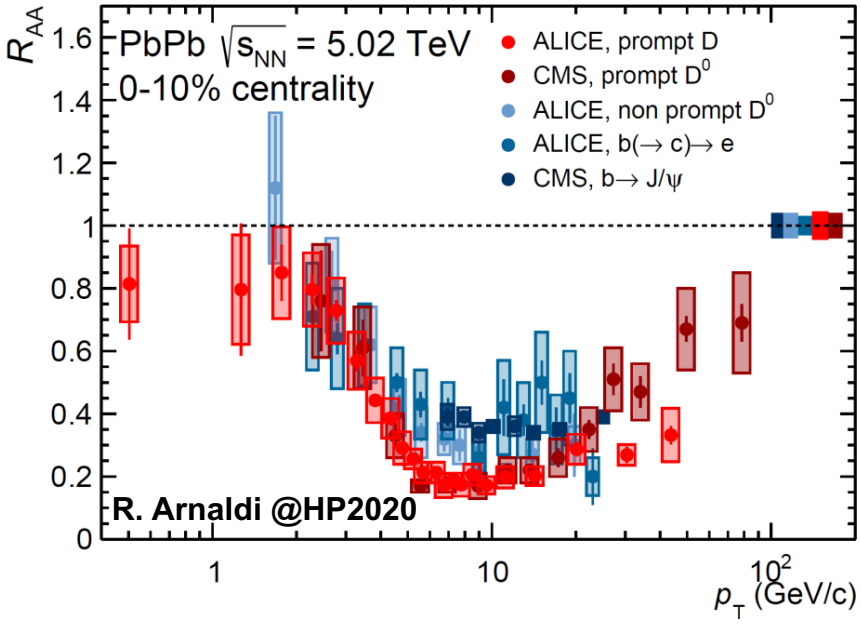
CMS b→D⁰

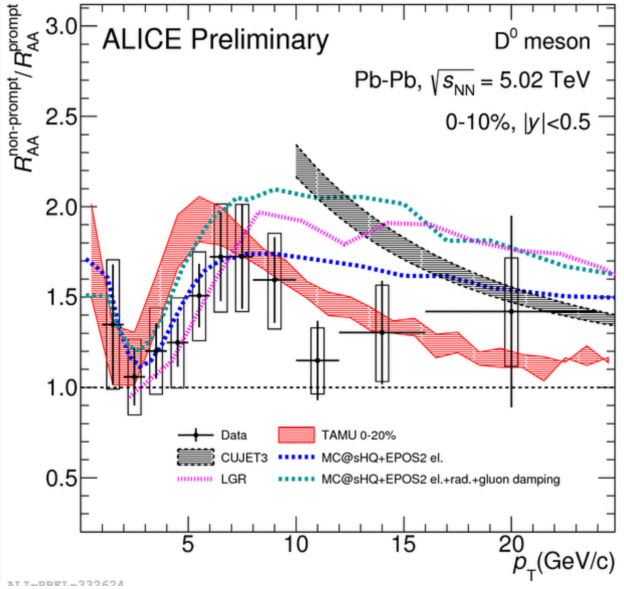
STAR b→e

CMS b→J/ψ

CMS B⁺

Beauty vs charm R_{AA}



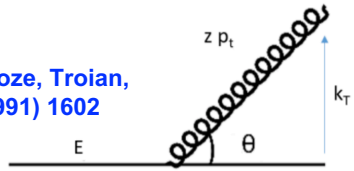


- Beauty R_{AA} > Charm R_{AA} at p_T~10 GeV → Larger energy loss for c than for b quarks?
- Qualitatively described by models (smaller elastic coupling + dead cone for gluon radiation)

Meanwhile: dead cone 'seen' in D-jets in pp

- Reduction of gluon radiation from heavy quarks at small angles

Dokshitzer, Khoze, Troian, J.Phys.G 17 (1991) 1602

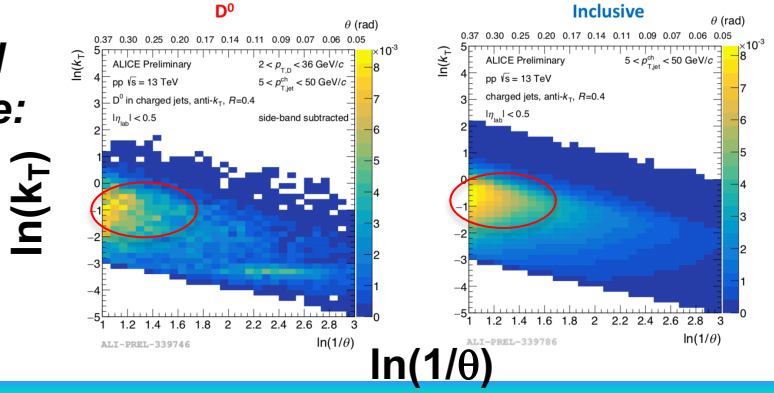


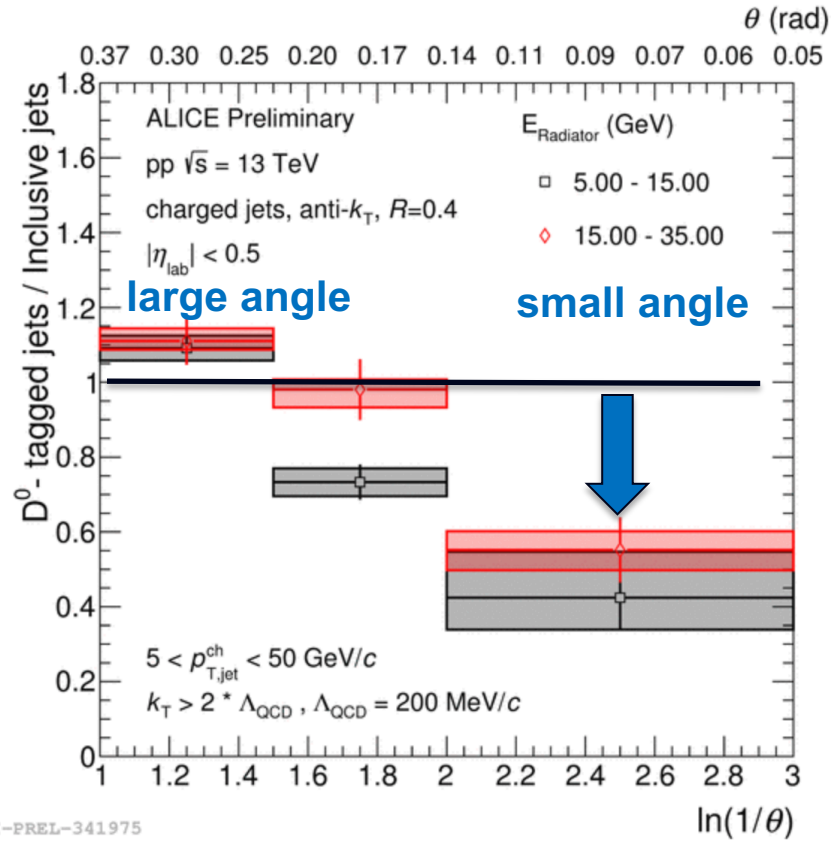
Suppression of emissions from a radiator (quark) within

$$\theta < \frac{m_q}{E_q}$$

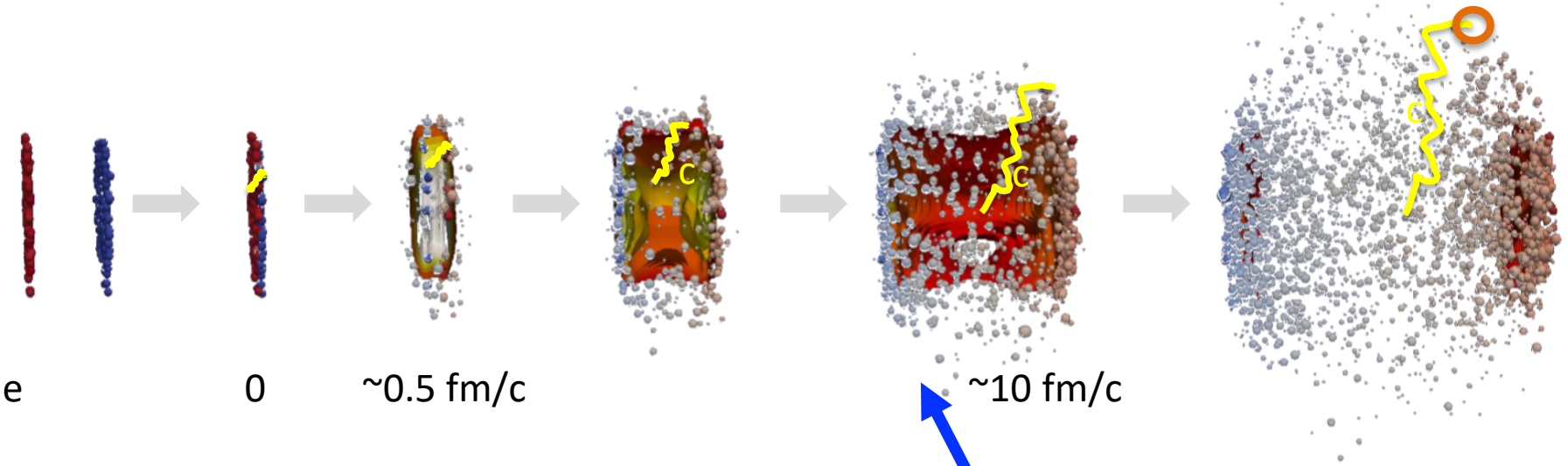
- First direct observation using jet iterative declustering and **Lund plane** analysis of jets that contain a soft D^0 meson

Lund plane:





Heavy quark interactions: thermalization?

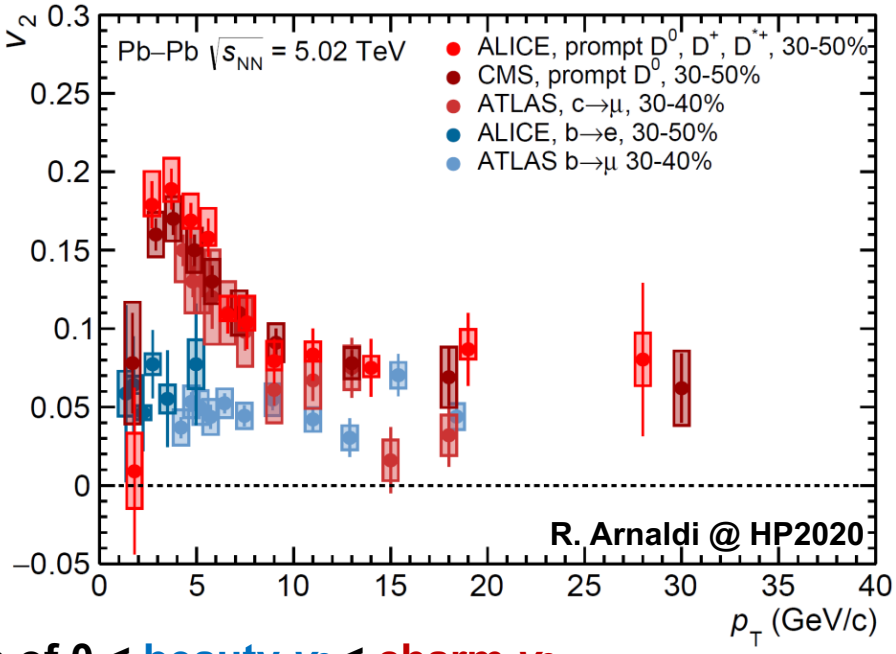


Time 0 ~0.5 fm/c ~10 fm/c

Thermalization?

- Which is the degree of thermalization of HQs in the medium?
- Do charm/beauty flow?

Open charm and open beauty v_2

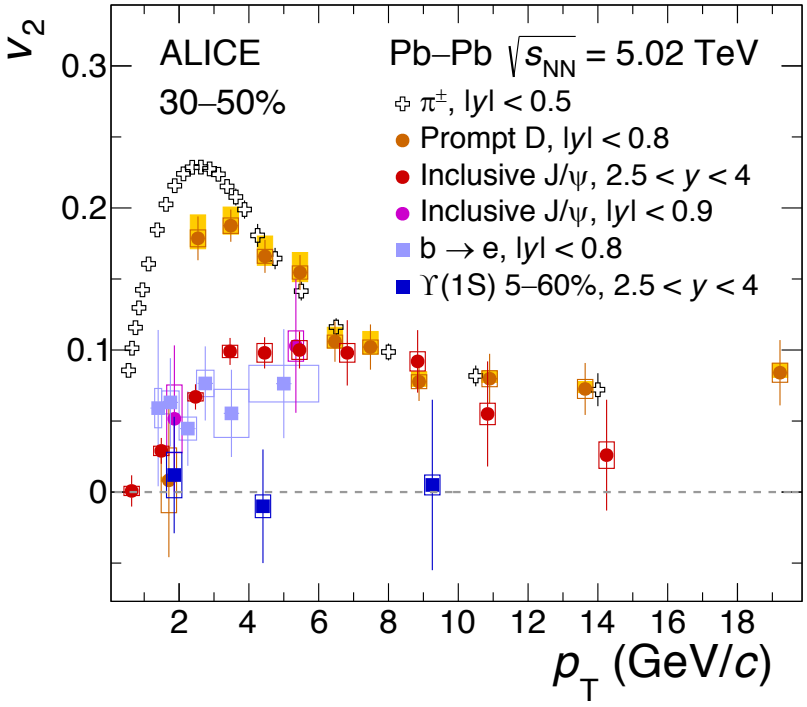


arXiv:2005.11131
arXiv:2009.12628
arXiv:2003.03565
arXiv:2005.11130

- **Low p_T: indication of 0 < beauty v_2 < charm v_2**
  - **significant uncertainties + decay kinematics shifts shapes to lower p_T**
  - **Larger mass → longer relaxation time → smaller thermalization for beauty?**
- **High p_T: 0 < beauty v_2 ~ charm v_2**
  - **Positive v_2 from path-length dependence of energy loss?**

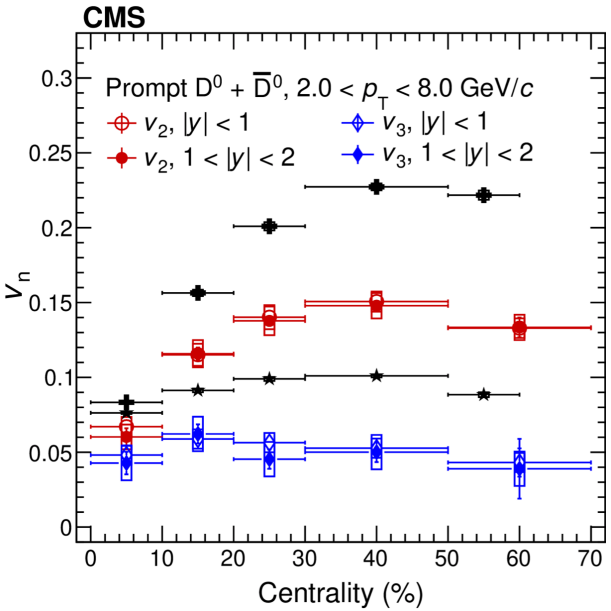
Open and hidden HF v_2

- At intermediate p_T, **J/ψ < D < pions**
  - → consistent with contribution of recombination
- No indication of **Υ(1S)** flow
  - ➢ Consistent with large Y mass and small $b\bar{b}$ recombination



π: JHEP1809(2018)006 **b→e: arXiv:2005.11130**
D: arXiv:2005.11131 **Υ(1S): PRL123(2019)192301**
J/ψ: arXiv:2005.14518

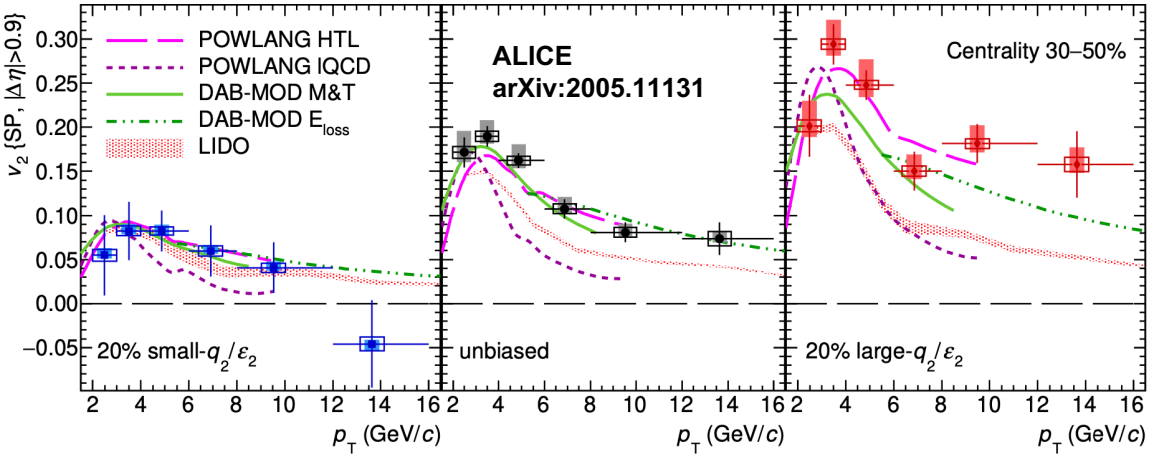
New directions in HF flow: higher harmonics (v_3) and HF-bulk flow correlation



v_2(charm) < v_2(h)

v_3(charm) < v_3(h)

v_2 in classes of events selected in 30-50% with different bulk flow

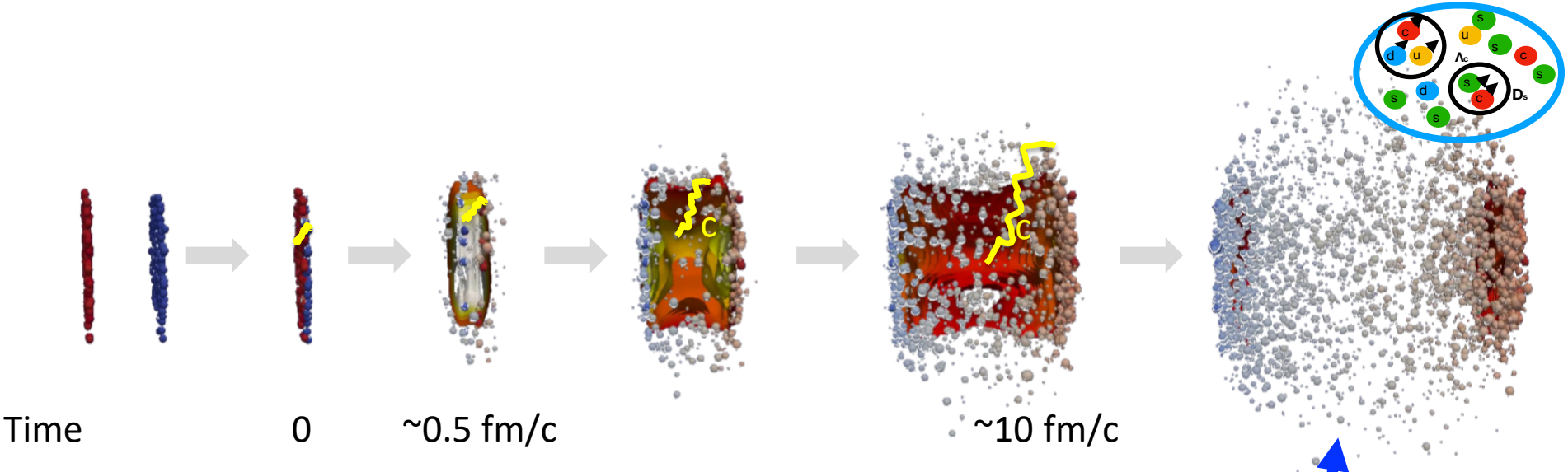


'reduced flow vector' q_2 also related to initial-state eccentricity of the collision

20% largest q_2: v_2 increased

20% smallest q_2: v_2 reduced

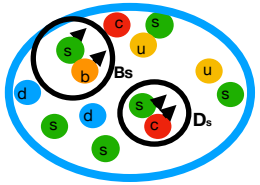
HF hadronization (from large to small systems)

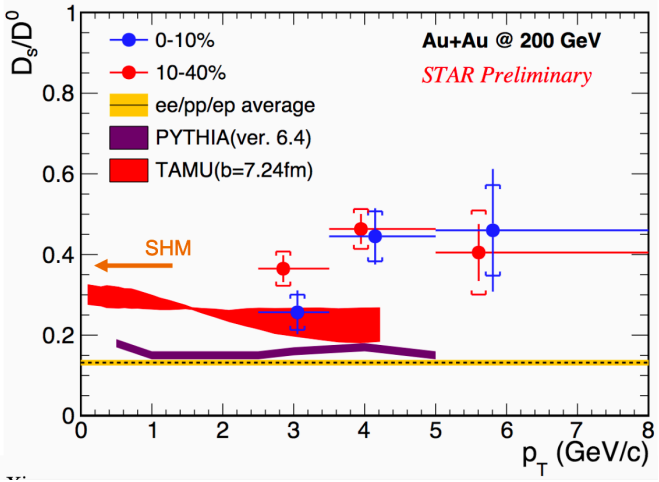


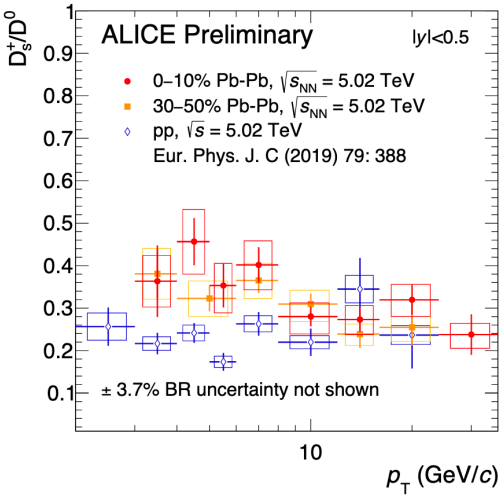
What are the hadronization mechanisms:
fragmentation in vacuum?
recombination with light quarks?

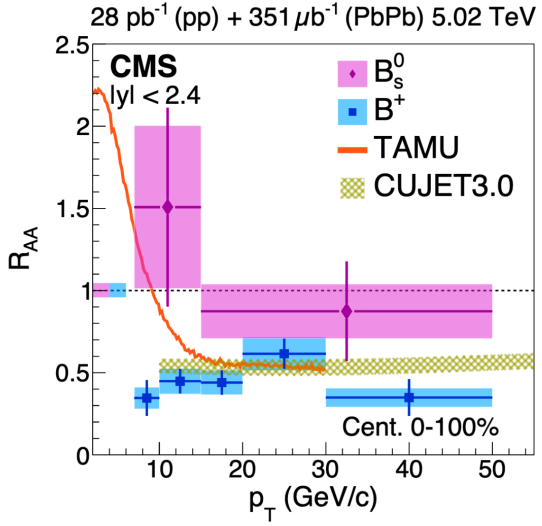
- Recombination:
→ Baryon/Meson increase
- + Strangeness-rich QGP
→ Strange/non-Strange increase

Strange-HF mesons







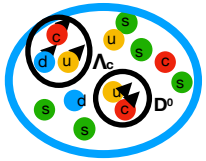


D_s/D^0 in Au-Au by STAR and in Pb-Pb by ALICE

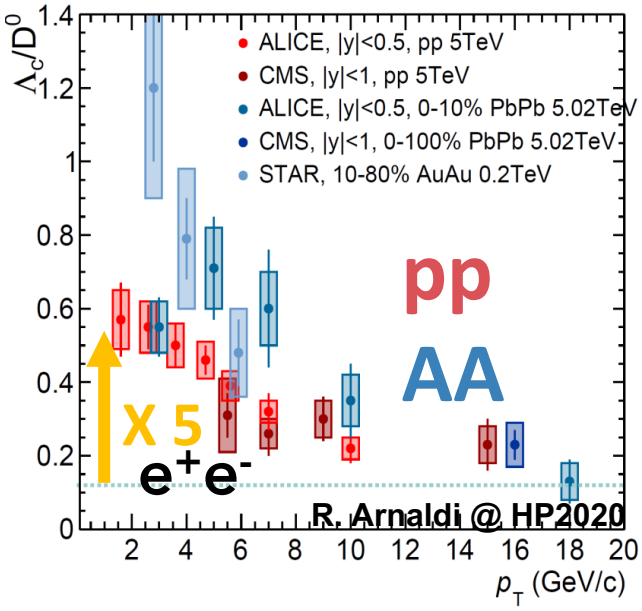
- **Compatible results at low-intermediate p_T: D_s/D^0~ 0.4**
- **No evident centrality dependence**
- **Hint of increase w.r.t pp measurements**

Hint of $R_{AA}(B_s) > R_{AA}(B)$

arxiv:1810.03022



Charm baryons vs mesons

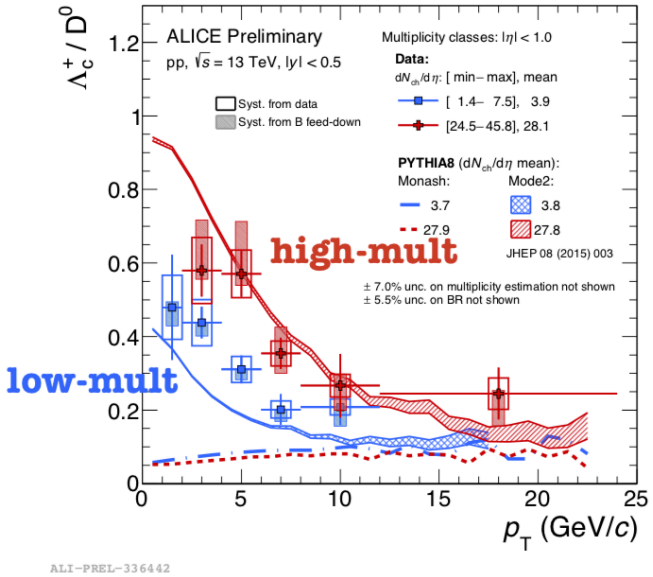


ALICE pp arxiv:2011.06079
ALICE Pb-Pb Preliminary
CMS, arXiv:1906.03322
STAR, arXiv:1910.1462

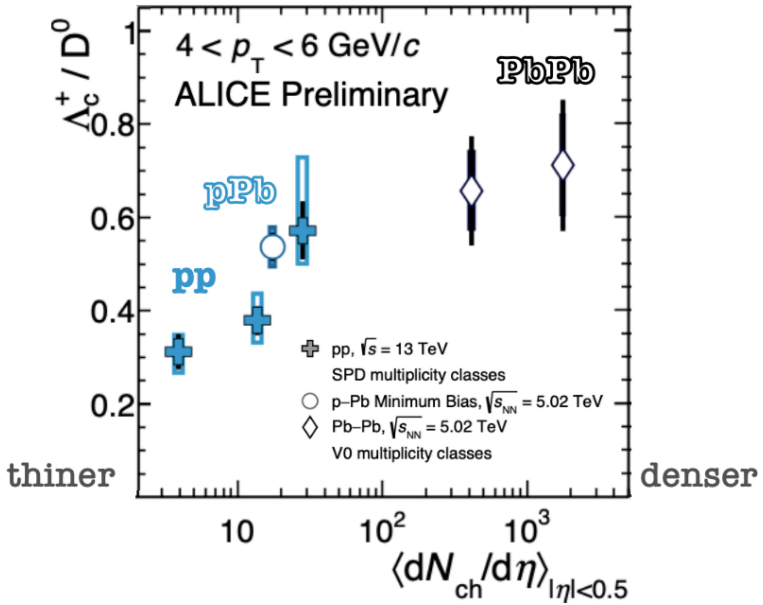
- ALICE and CMS compatible in pp and Pb-Pb (but different p_T and centrality ranges)
- No clear diffrence between Pb-Pb and pp

STAR: higher value for Λ_c/D^0 ~1 in Au-Au at low p_T (3-6 GeV/c), but no pp measurement

Charm baryons vs mesons: focus on pp



- Effect in pp is larger at larger event multiplicity
- Qualitatively described in PYTHIA8 with color reconnection



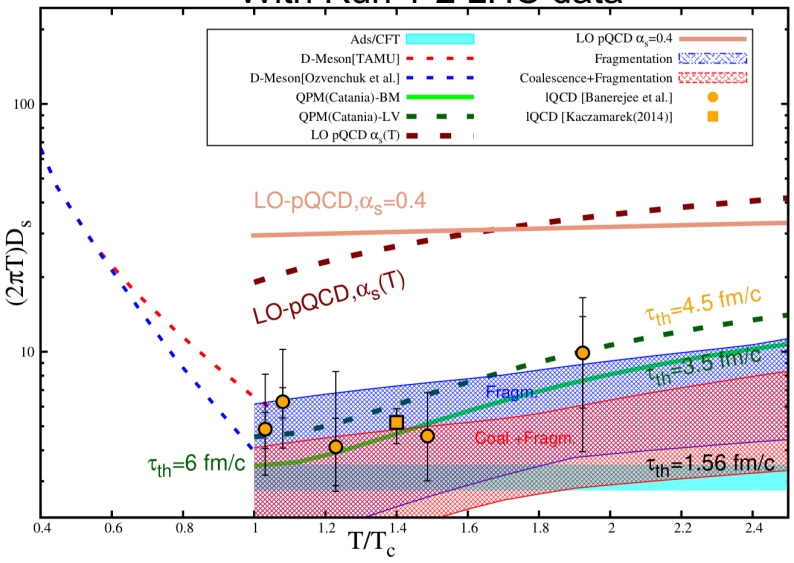
- Smooth trend from pp to Pb-Pb?
- Is the enhancement saturating already in pp at high multiplicity?
- Does it connect to e+e- (~0.1) at low pp multiplicity?

Need more data and better detectors

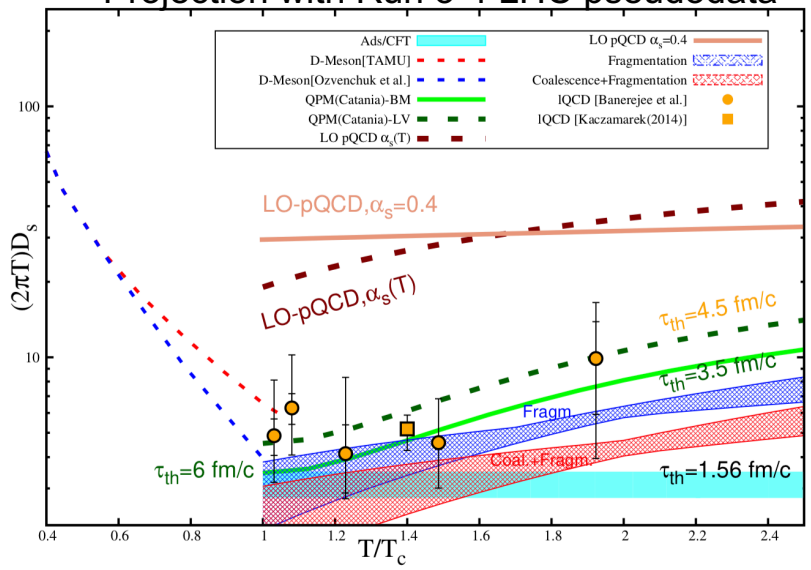
Understanding HF hadronisation

- Not only interesting per se, but also pre-requisite to extract HQ transport parameters of the QGP
- Interesting exercise (S. Plumari et al.) shown in HL-LHC Yellow Report

With Run 1-2 LHC data



Projection with Run 3-4 LHC pseudodata



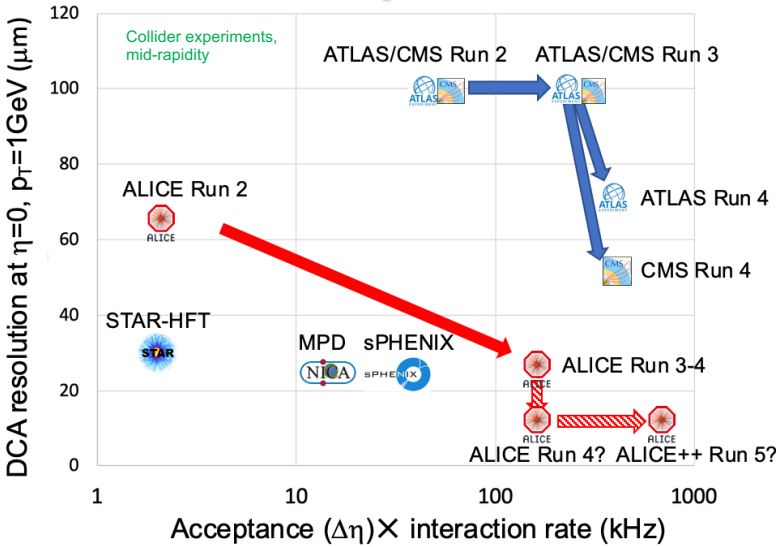
arXiv:1812.06772

Experimental outlook

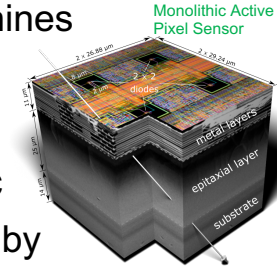
HF frontier: mainly pushed by detector technology

- Main frontiers to enhance physics reach:
  - **rate capabilities & acceptance**
  - **tracking precision**

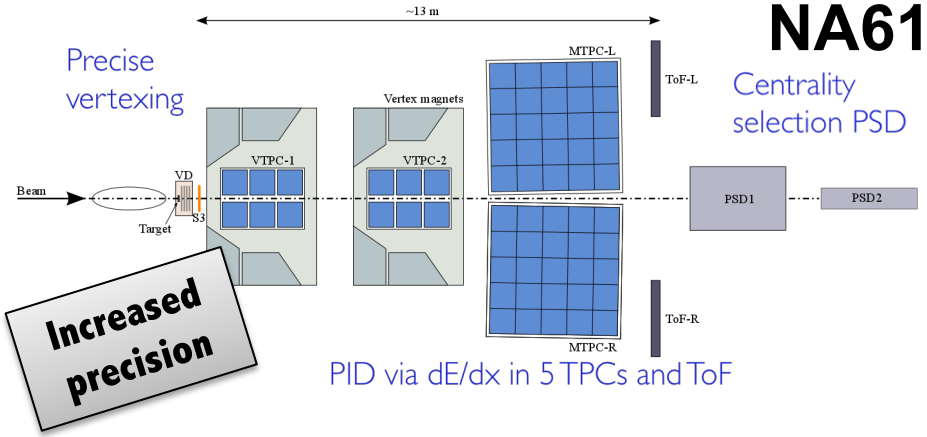
→ high precision, reduce backgrounds, access to rarer probes (e.g. HF-correlations, HF-jet hadrochemistry, higher harmonics, (multi-)HF baryons…)

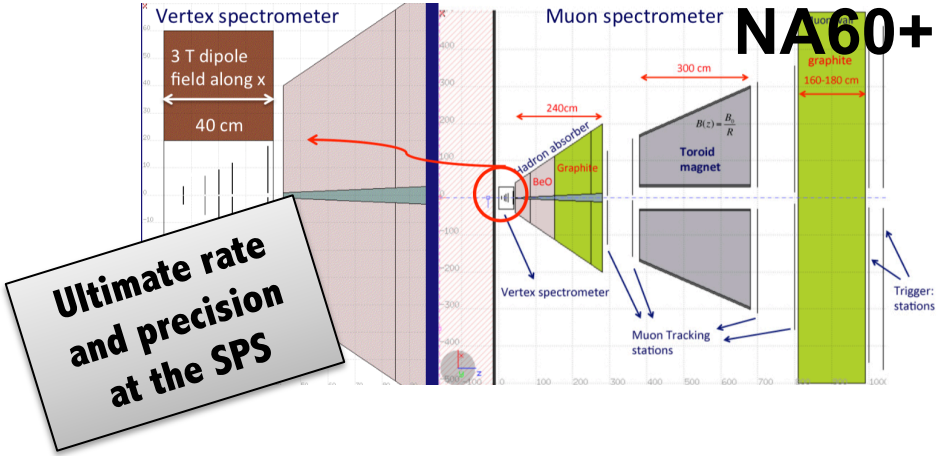


- x10-100 in “statistics” at RHIC and LHC
  - Increased interaction rate at both machines
  - Faster readout and larger acceptance
- Monolithic pixel trackers bring DCA resolution to 20-30 μm at p_T=1 GeV/c
  - Pioneered by STAR; key development by ALICE, will be adopted also by sPHENIX, CBM, MPD, NA61, NA60+



NA61/SHINE (2022), NA60+ (>2025?) @ SPS

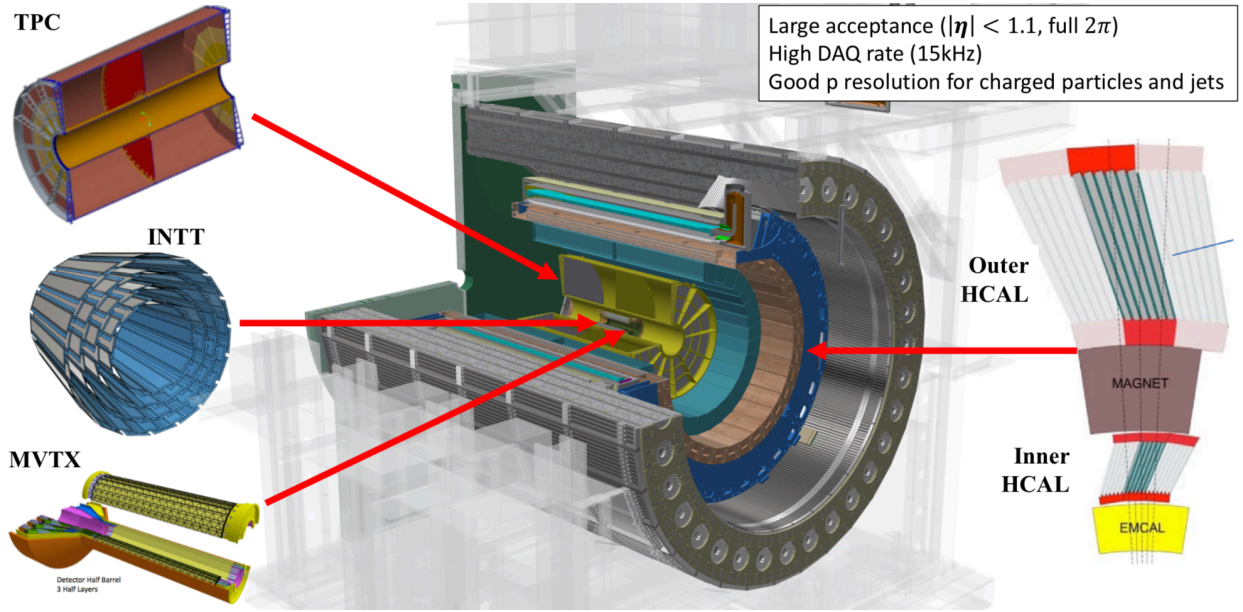




- Ongoing upgrade: pixel tracker, TPC readout at 1 kHz
- Pb-Pb at $\sqrt{s_{NN}}$ = 5 and 17 GeV in 2022-24
- Main goals: **open charm cross section with ~10% precision**, critical fluctuations with higher precision

- Proposal for a high-rate dimuon spectrometer with a silicon pixel tracker
  - EoI submitted to SPSC, LoI in prep.
- 10 MHz Pb-Pb at $\sqrt{s_{NN}}$ = 5-17 GeV
- Main goals: caloric curve with thermal dimuons, characterize χ-symmetry restoration, **charmonia and open charm (~1% precision)**

sPHENIX @ RHIC (2023)



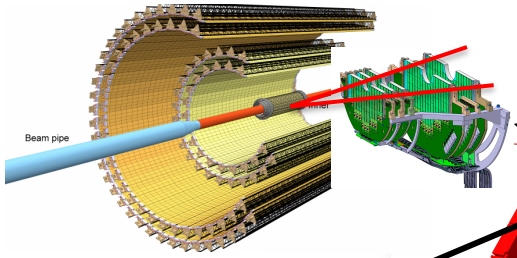
Ultimate performance for jets and HQs at RHIC

- Got CD2/3: construction can start
- Compact and hermetic design
- Continuous readout at 15 kHz
  - ~100B Au-Au events per year

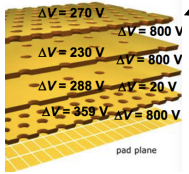
- Focus on:
  - Fully reconstructed jets, with HCAL
  - Bottomonium states
  - HF mesons and baryons, with MAPS

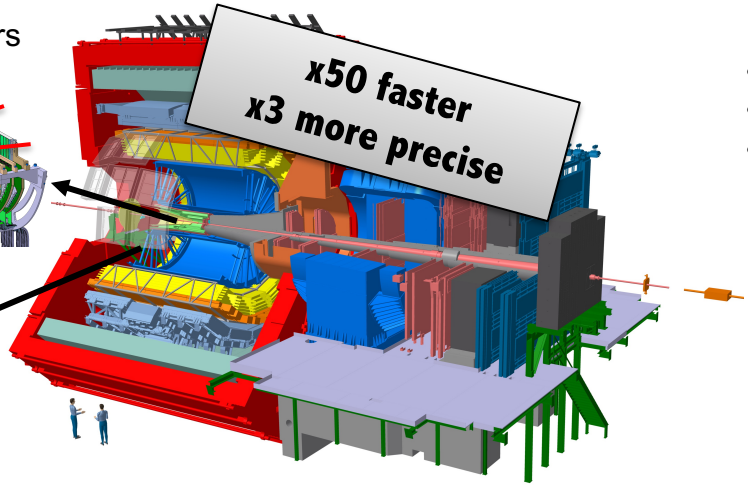
ALICE in Run 3 (2021) and ideas for Run 4 (2028)

All-pixel central and fwd trackers



GEM-based TPC readout



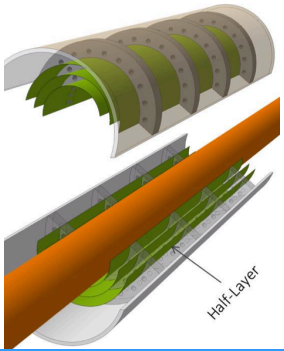


… and more:
- Fast Interaction Trigger
- New Online-Offline system
- Readout upgrade of several detectors

- x3 better tracking precision
- Continuous readout at 50 kHz

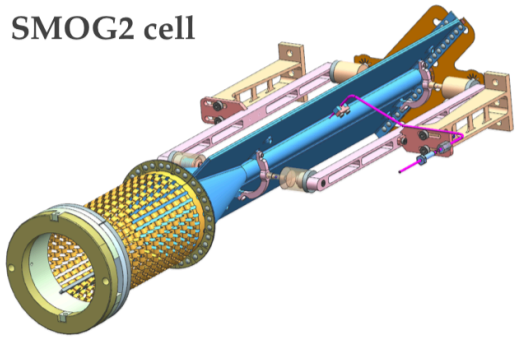
→ ~100B Pb-Pb in Runs 3+4

- Upgrade proposal for LS3 (2026): replace **inner barrel** with a **truly-cylindrical ultralight** one: x3 less material
  - e.g. improves by a factor 4 the precision for the Λ_c
  - More HF studies ongoing: Λ_b, B_s, search for "super-nuclei"

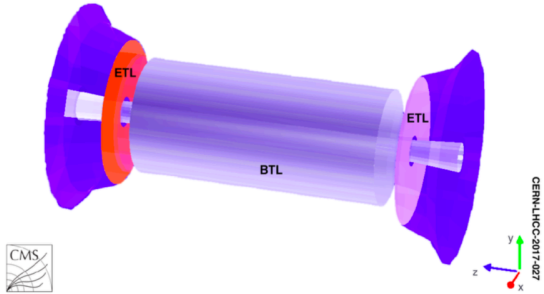


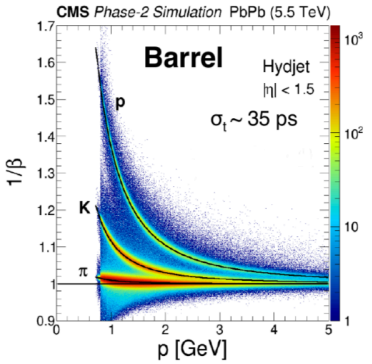
LHCb (2021), ATLAS and CMS (2026) Upgrades

- LHCb: ongoing LS2 upgrade:
  - Tracker with higher granularity
    → **Pb-Pb 30-100%**
  - New **storage cell for fixed-target collisions** at up to x100 higher rates (p … Ne … Xe)

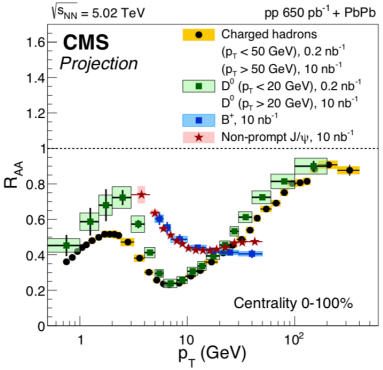


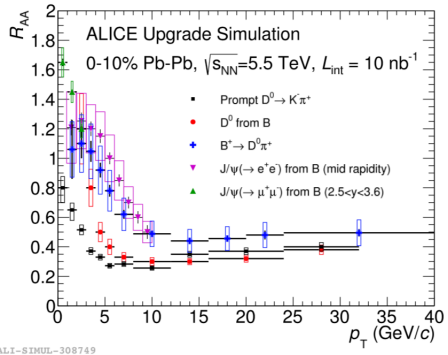
- ATLAS and CMS: major Phase-2 upgrades for HL-LHC
  - Extension of tracker acceptance to $|\eta|<4$
  - Precise timing detectors for pile-up rejection → t.o.f. PID
    - ATLAS $2.5 < |\eta| < 5$
    - CMS $|\eta| < 4$

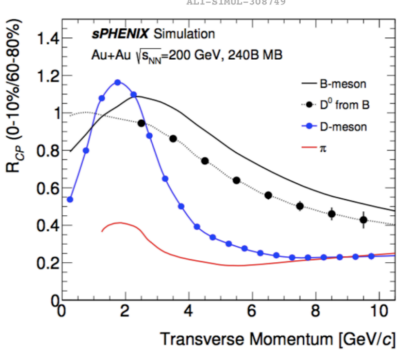




HF performance outlook: energy loss and transport





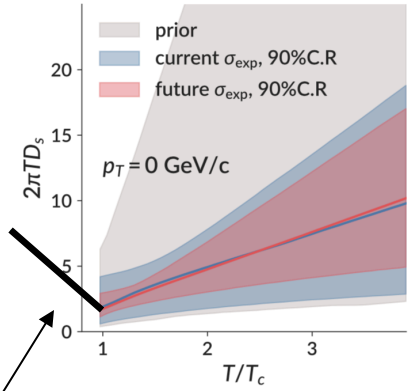


D and B at LHC and RHIC

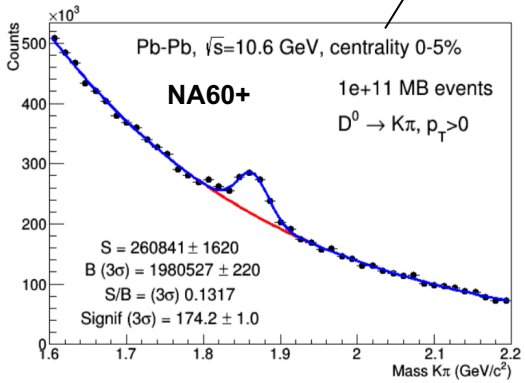
→ **Heavy quark diffusion coefficients** $2\pi TD_S(T)$

- e.g. Bayesian analysis with modified Langevin (Bass et al.)

$2\pi TD_S$ in hadronic matter ($T<T_c$) with NA60+ at SPS?

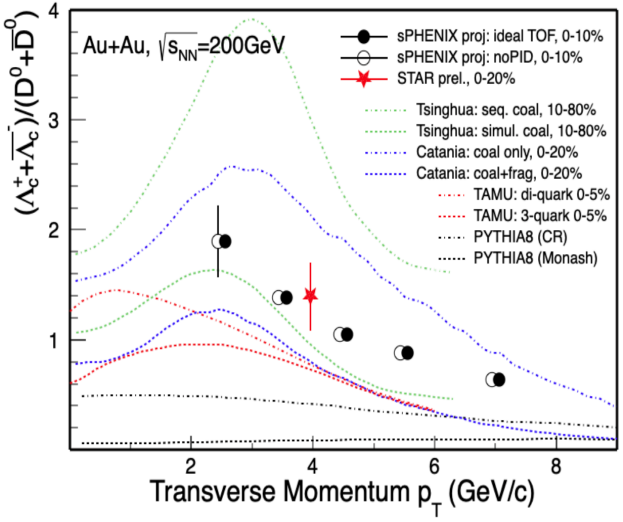


arXiv:1812.06772

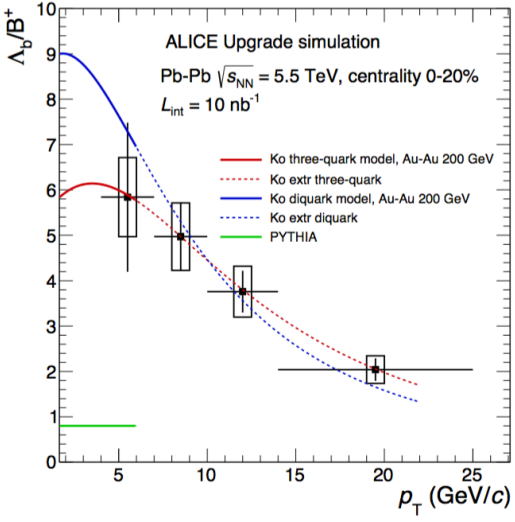


HF performance outlook: hadronisation of HQs

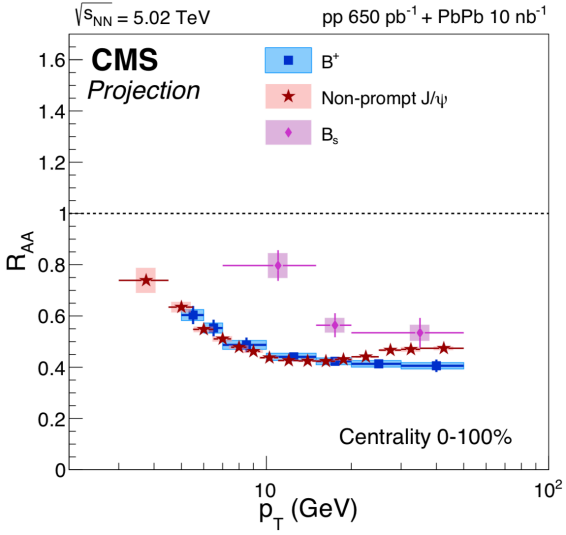
sPHENIX Λ_c / D



ALICE Λ_b / B



CMS B and B_s

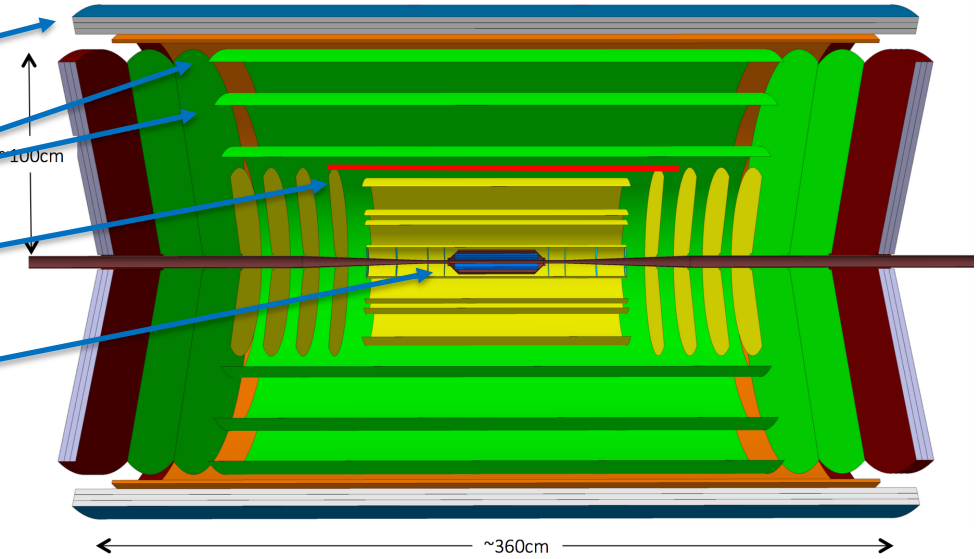


Some examples, many more studies available and ongoing

”Si-only” HI experiment for LHC Run 5 (>2031?)

- Fast, ultra-thin detector with precise tracking and timing
  - Exploit higher NN lumi with intermediate-A nuclei (e.g. Kr)
  - Ultimate performance for (multi-)HF, thermal radiation and soft hadrons (<50 MeV)

- All-pixel tracking and PID detector $|\eta|<4$
- Pre-shower layers with W+pixels for ID high-*p* electrons
- Timing layers σ~25 ps for t.o.f. ID of hadrons and low-*p* electrons
- Insertable converter layer for photon detection
- Innermost layers inside the beam pipe



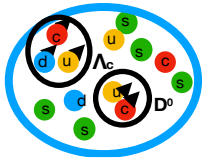
arxiv:1902.01211

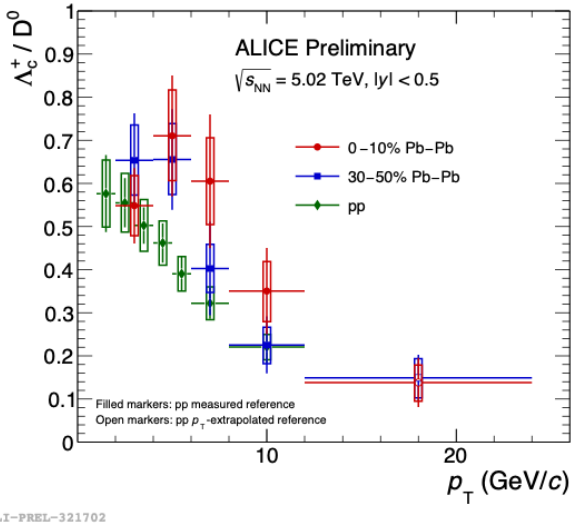
Looking forward to HF transport properties extracted from present and future measurements !

Have an interesting and productive workshop !

EXTRA SLIDES

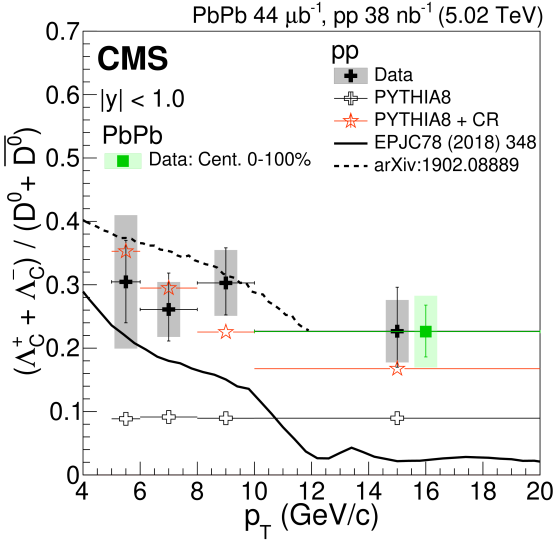
Charm baryons vs mesons





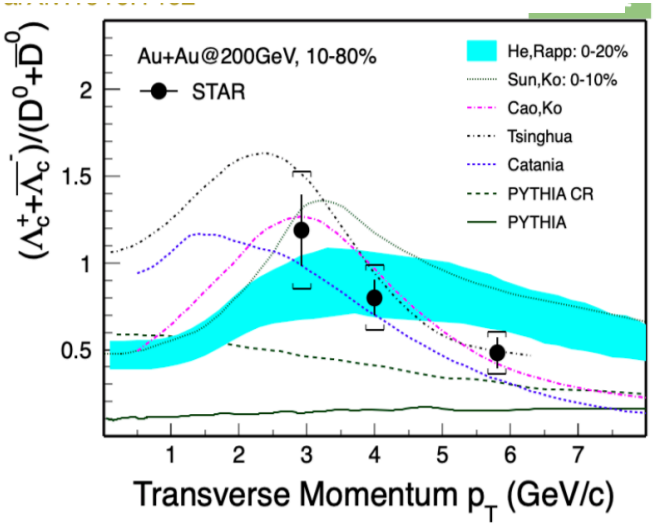
ALICE: hint of larger Λ_c/D^0 in Pb-Pb w.r.t. to pp for 4 <p_T< 6 GeV/c

arXiv:1906.03322



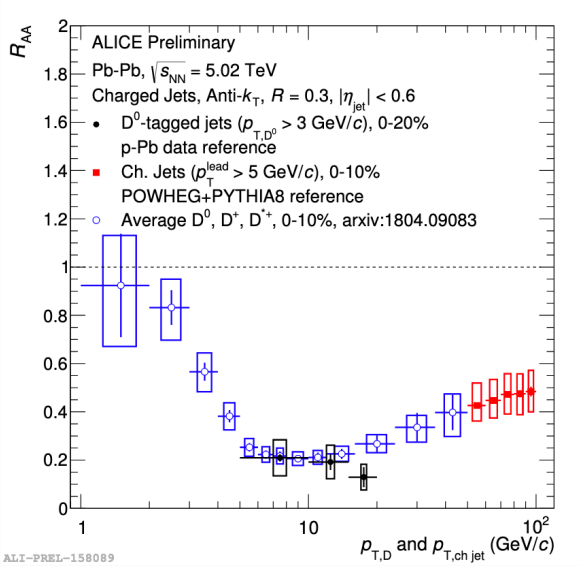
CMS: similar Λ_c/D^0 in Pb-Pb and pp at high p_T

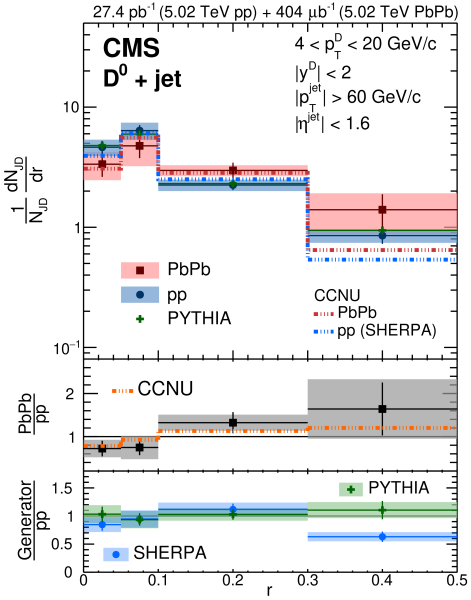
arXiv:1910.1462



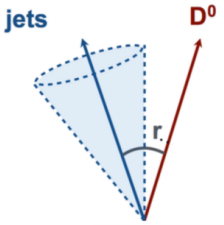
STAR shows higher value for Λ_c/D^0 ~1 in Au-Au at low p_T (3-6 GeV/c), but no pp comparison

D-jets also studied in Pb-Pb





arXiv:1911.01461



- **D-meson tagged jets *R*AA** consistent with **D-meson *R*AA**
- Hint of larger suppression for **low *p*T D-jets** than **high *p*T charged jets**

- Broader radial distribution of D meson with respect to the jet axis in Pb-Pb?