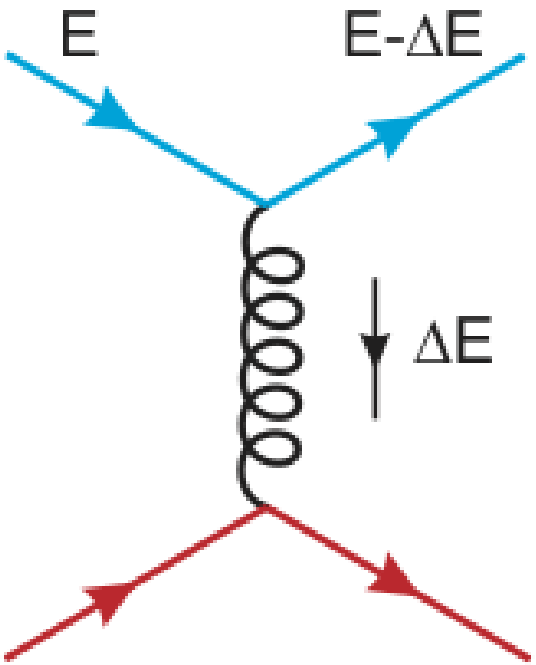
Future heavy flavor program at RHIC and LHC

(a selection; focus on AA)

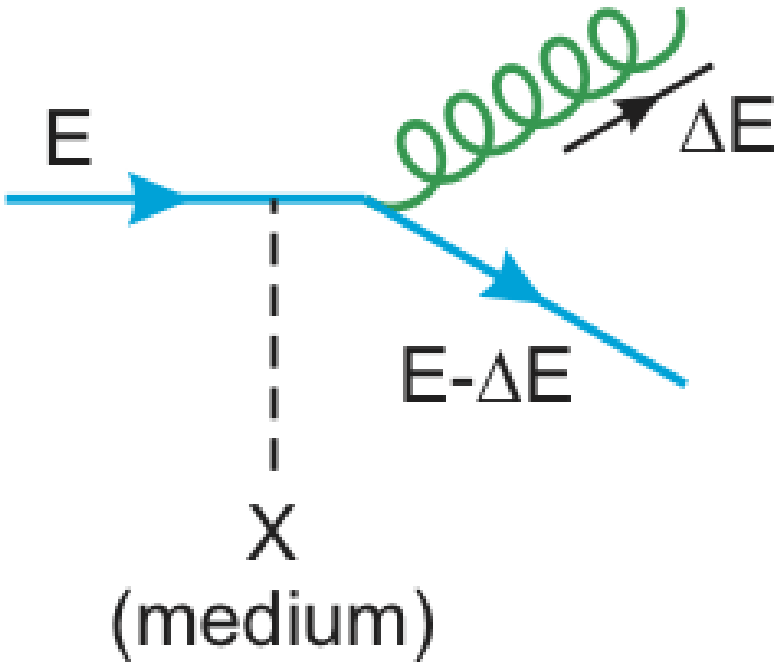
Mateusz Ploskon

E-loss: elastic/collisional and inelastic/radiative…

Longitudinal drag coef. (collisional) $\hat{e}$



p_T diffusion (radiative) $\hat{q}$



Parton type/mass dependence of energy loss - back to "early" (RHIC inspired) LHC predictions

$$\Delta E \propto \alpha_s C_R \hat{q} L^2$$

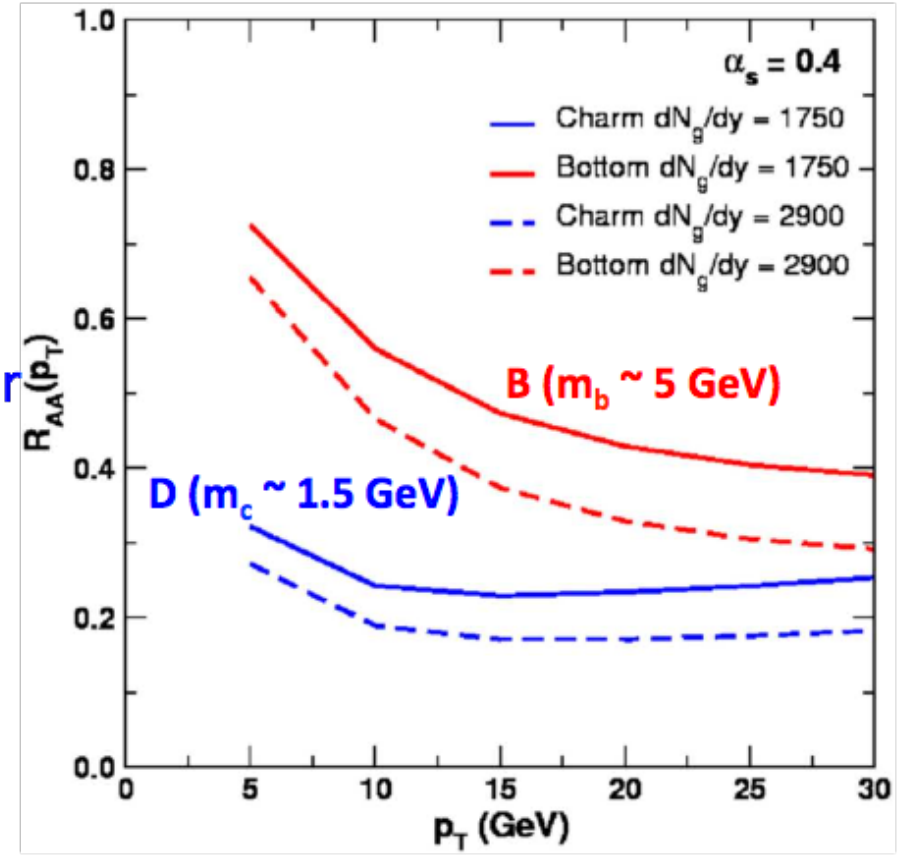
- Energy loss depends on parton:
  - Casimir factor (C_R=3 for gluons and 4/3 for quarks)
  - Mass of the quark (**dead cone** effect): radiation suppressed for angles $\theta < m/E$

$$\Delta E_{gluon} > \Delta E_{quark}$$
$$\Delta E_{light-q} > \Delta E_{heavy-q}$$

- Does it persist at low-p_T as:

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

Wicks, Gyulassy, Last Call for LHC predictions



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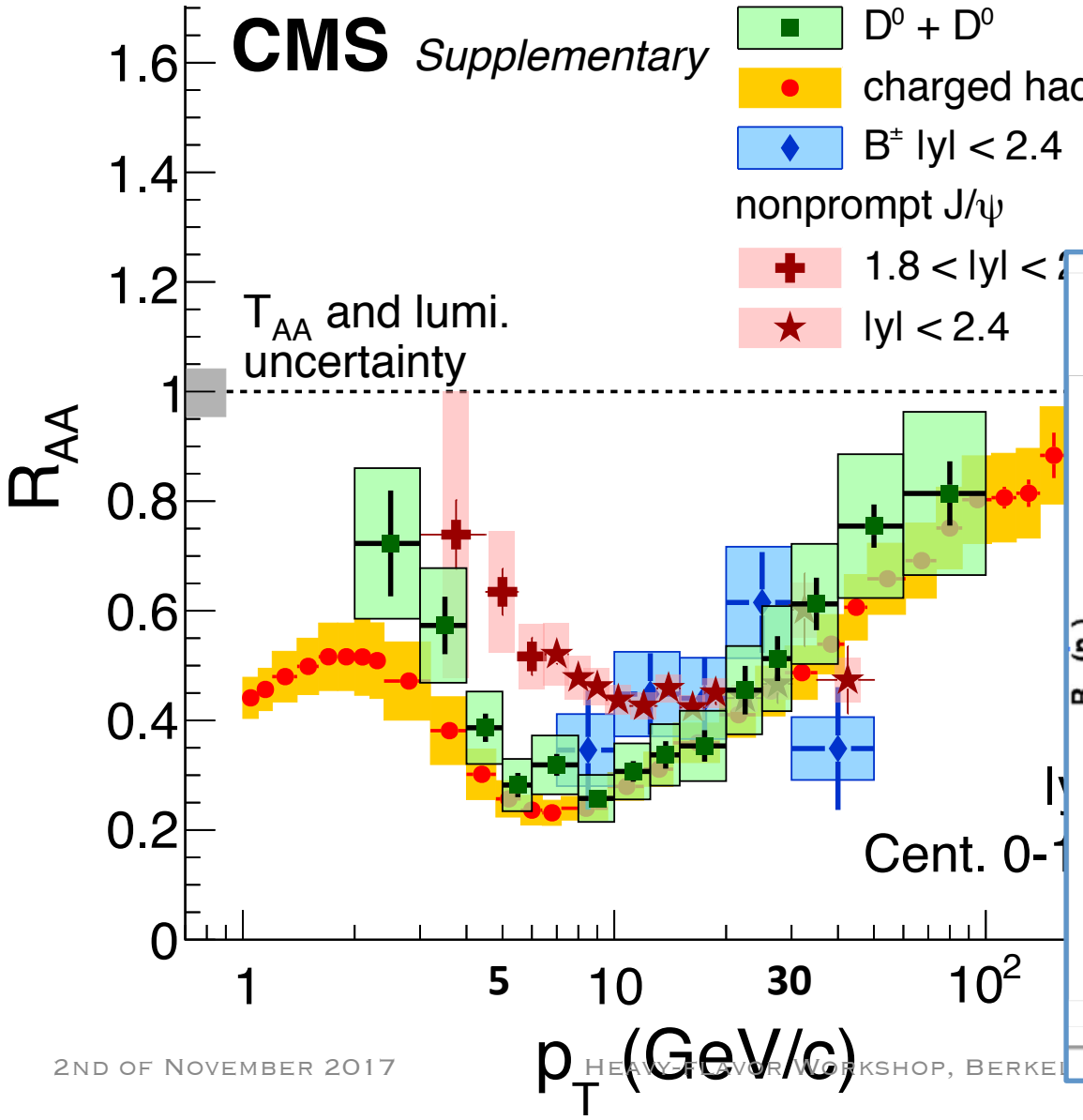
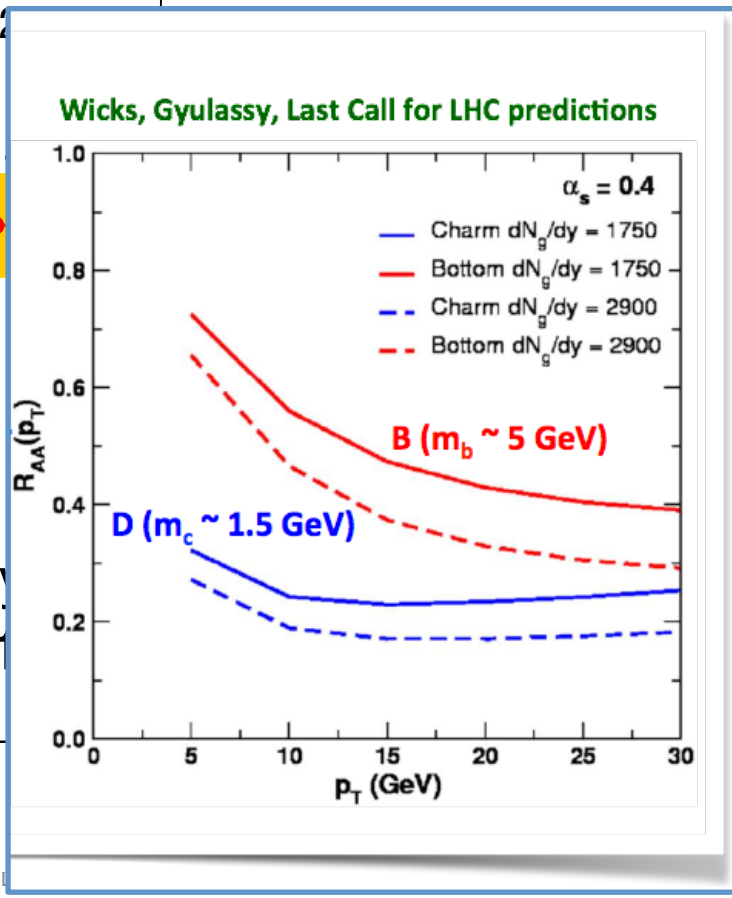


Qualitatively NOT bad!
RHIC input(!)



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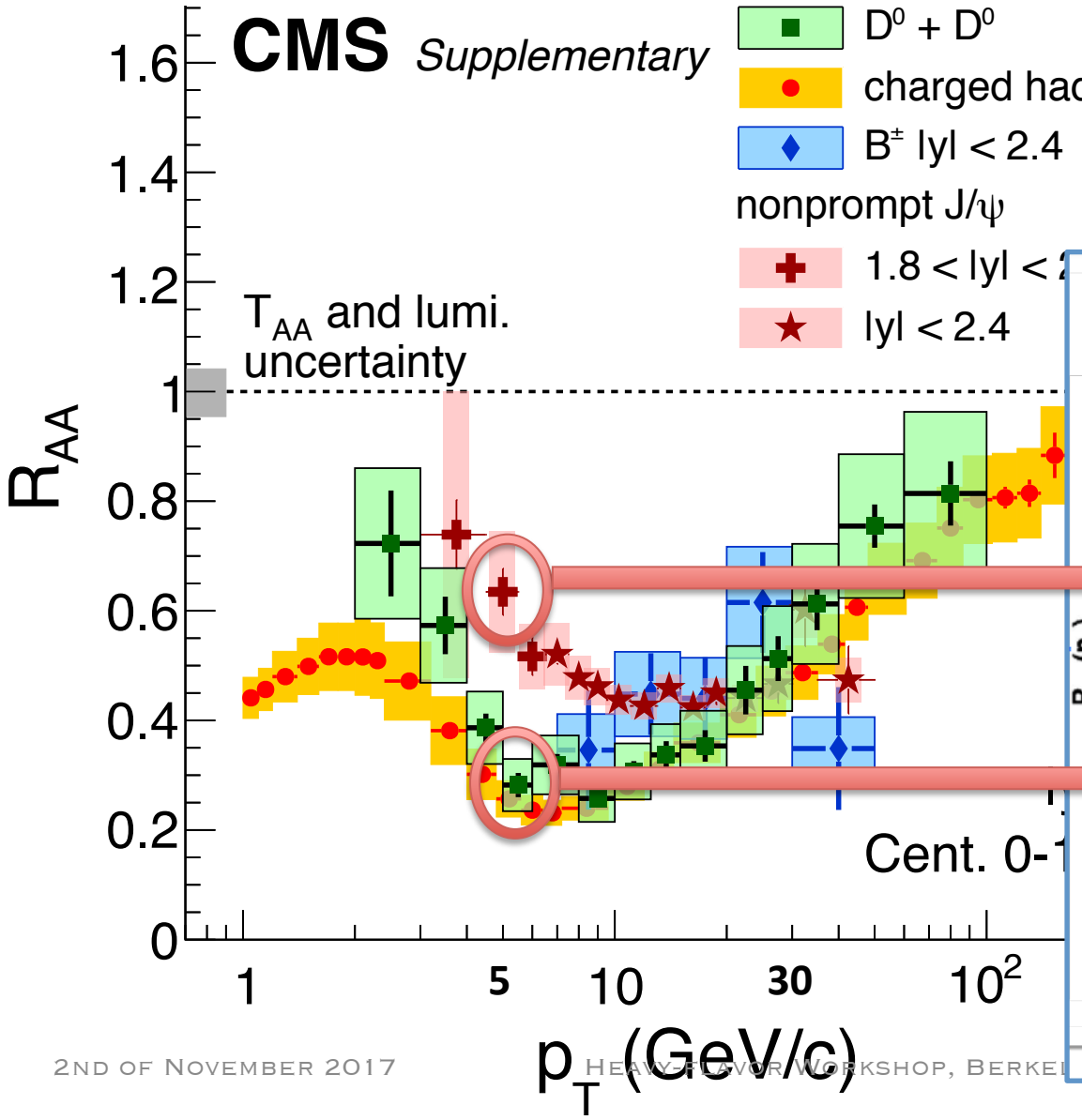

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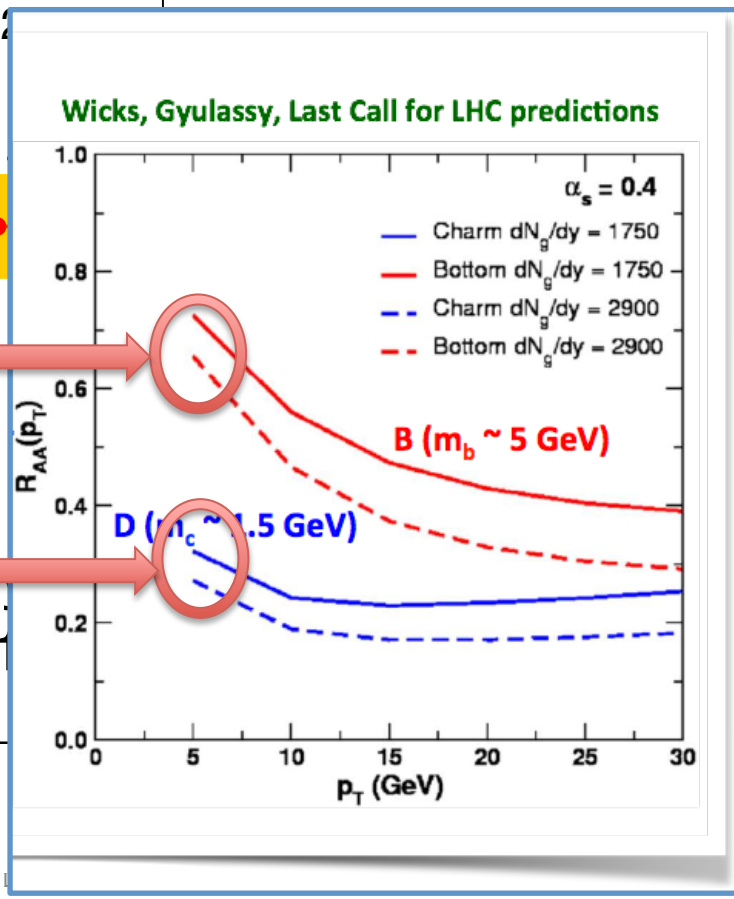

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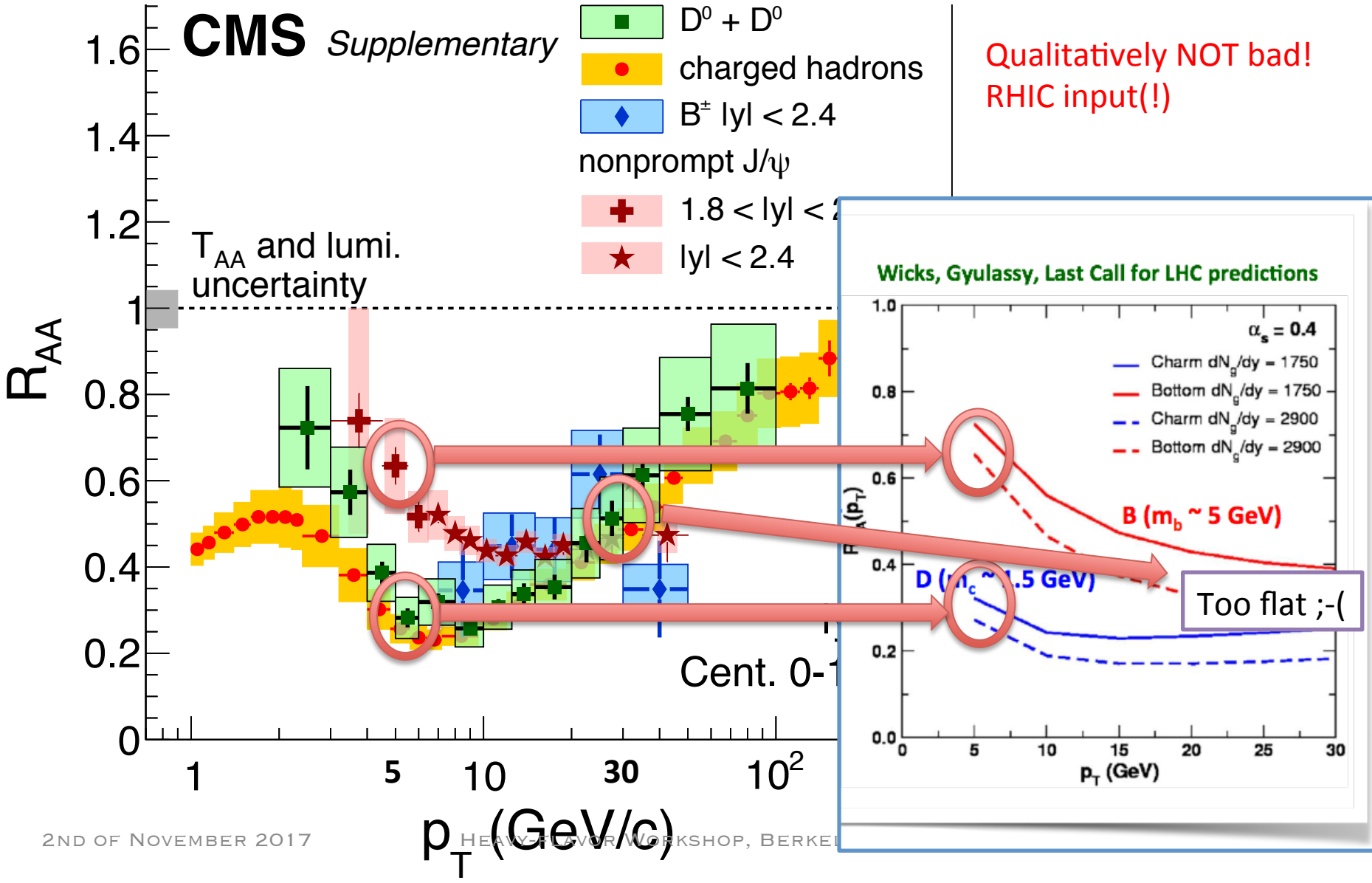
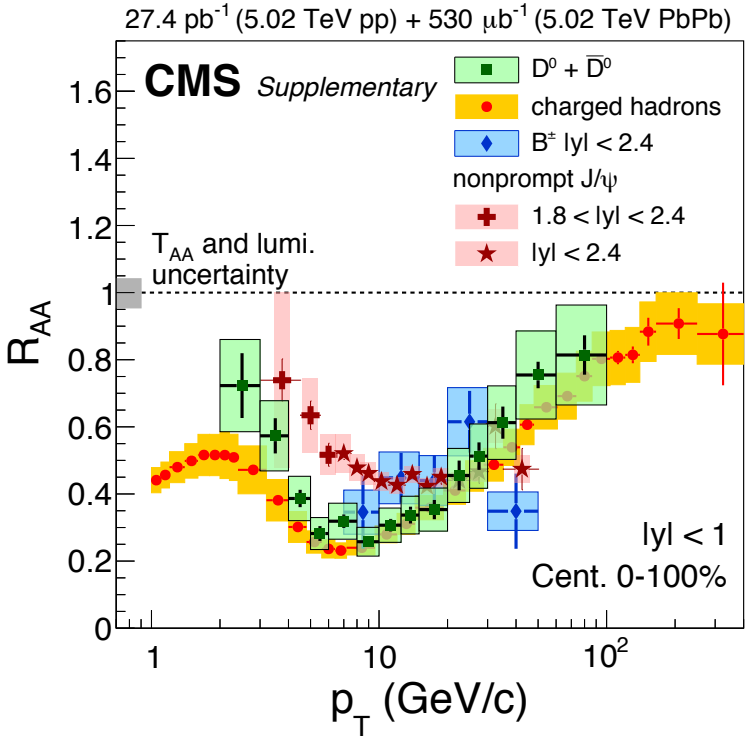
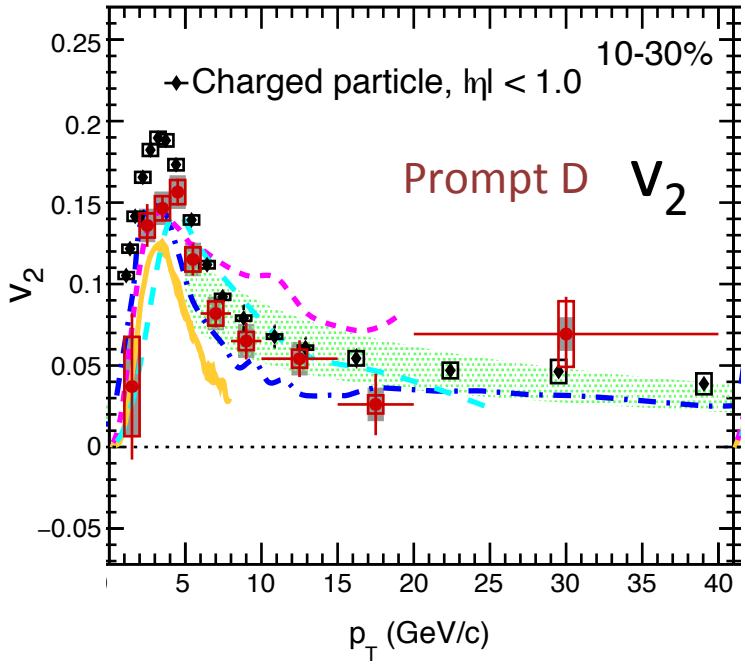


Sensitivity to medium properties (transport)? Aren't we there yet?





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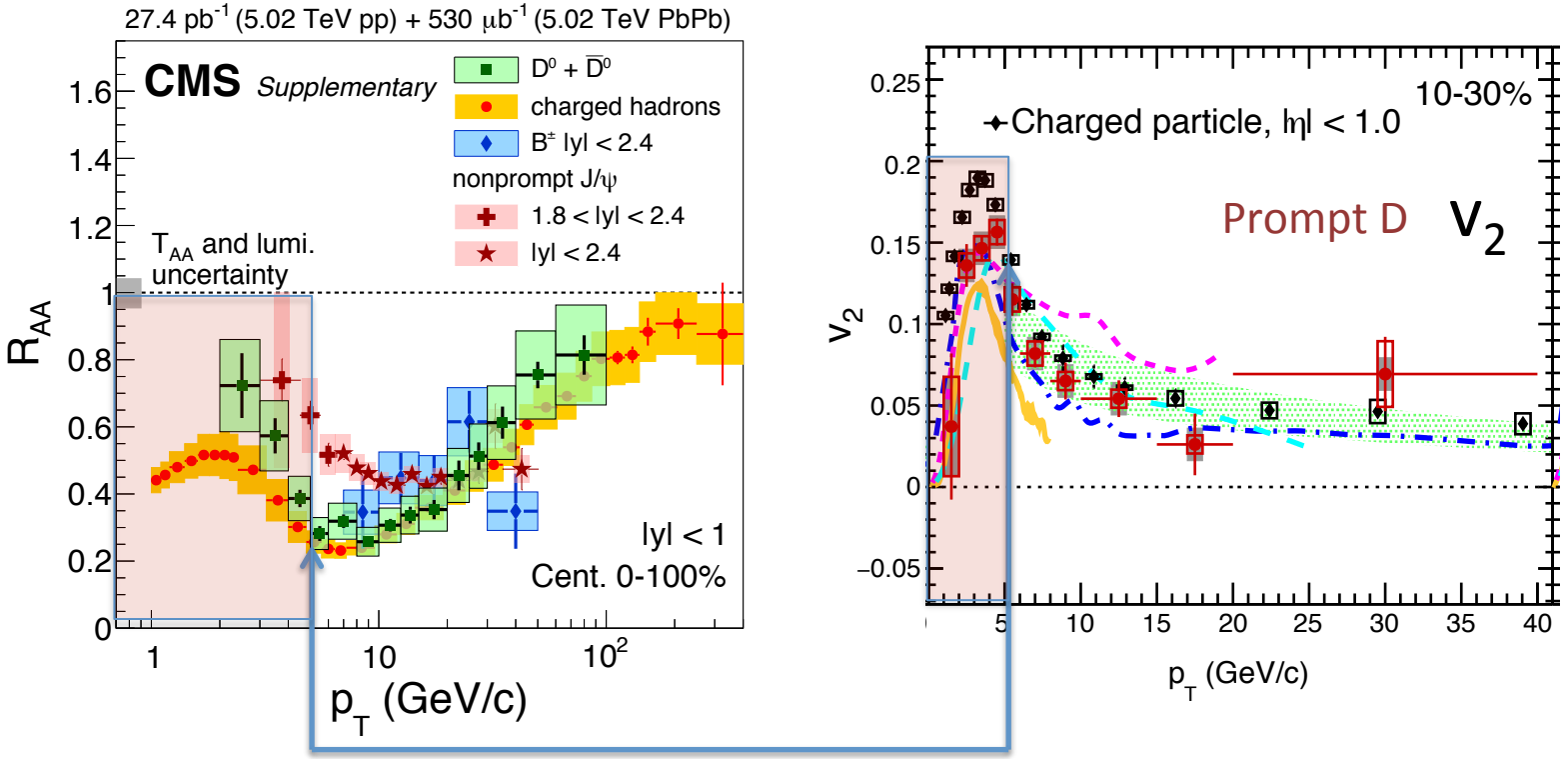

Two regions (arbitrary selection) – light vs. heavy(charm)-flavor (note p_T & mass of species)

- Lower p_T : below 5 GeV (parton energy ~ 10 GeV?) => different v_2 & different R_{AA} (coll. E-loss)
- Higher p_T : above 5 GeV (parton energy > 10 GeV) => similar R_{AA} => radiative E-loss

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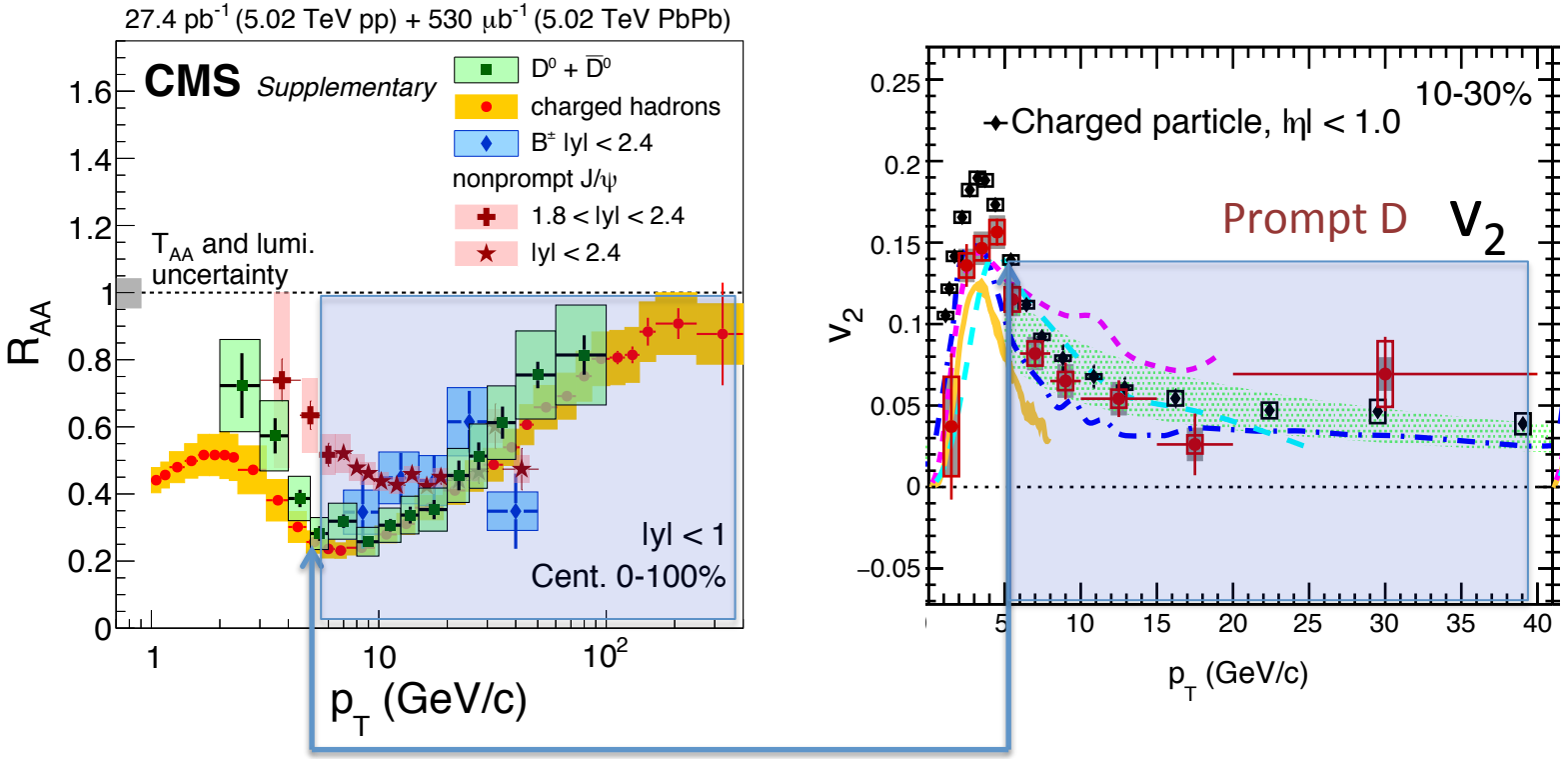

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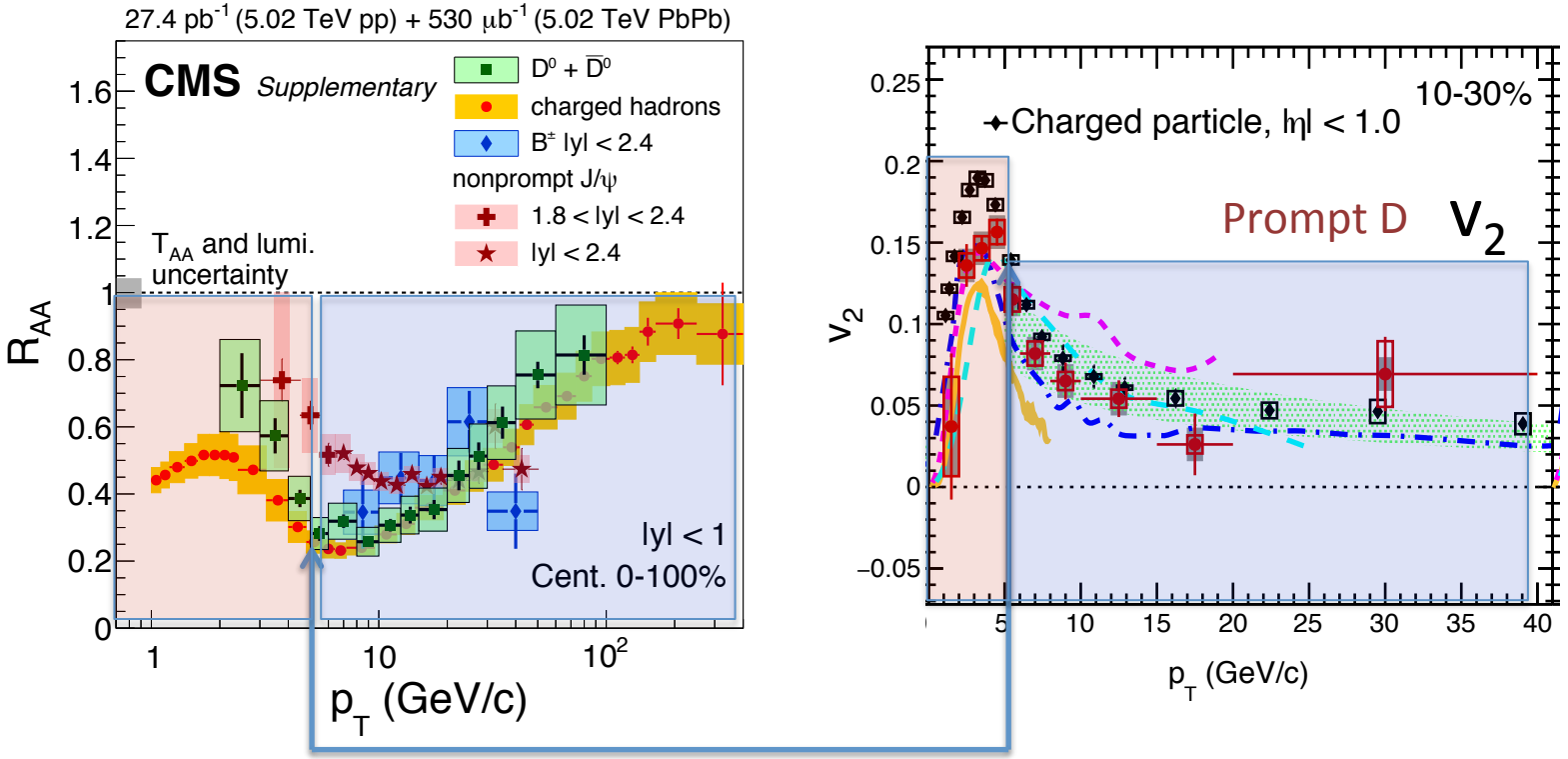

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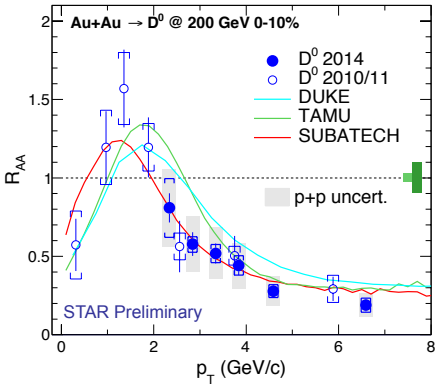
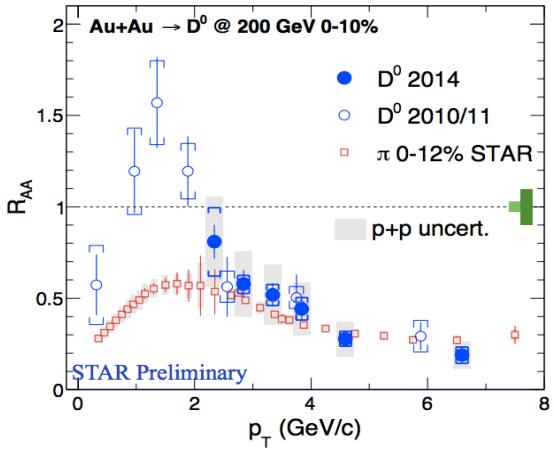
Question : radiative E-loss for light and charm the same?
(note: this is a jet/shower that looses energy not the bare quark…)

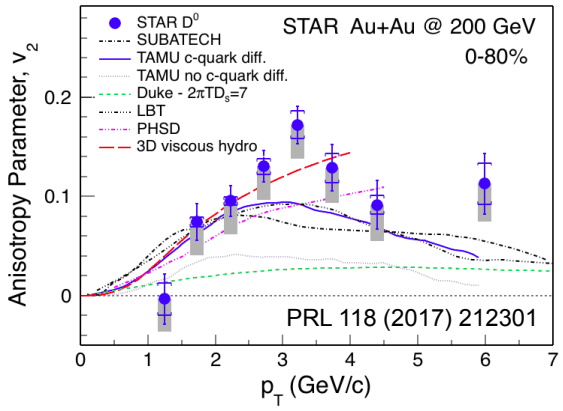


Similar TODAY at RHIC

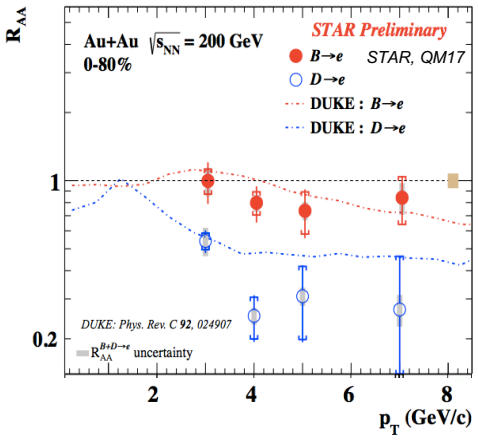
Despite vastly different centrality selections for v_2 and RAA – a similar picture to LHC:

- R_{AA} of D at high-p_T similar to light-hadrons
- D flows within the medium (similar to strange-hadrons) – mass scaling

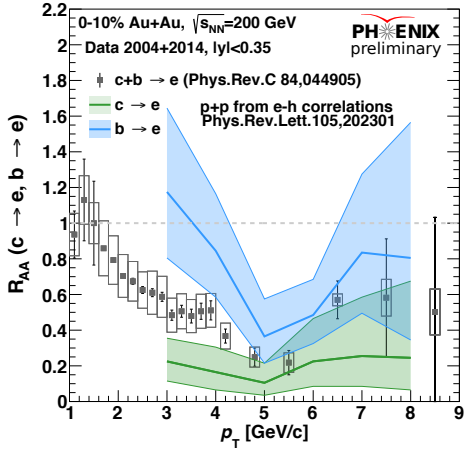




Spatial diffusion within QGP needed to describe the data



0-10% Central



Electrons from B-hadrons => beauty less suppressed than charm (low-pT < 5)

- **Needs better precision(!)**

…more measurements: non-prompt J/y; di-leptons

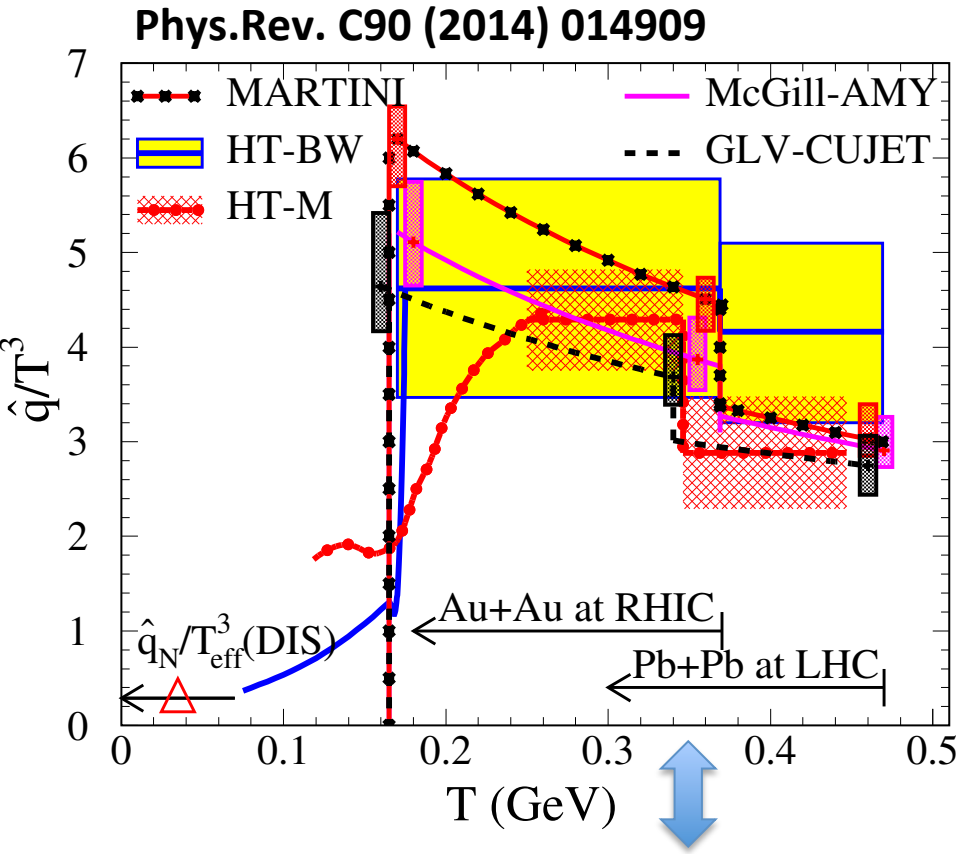
So, aren't we there yet?

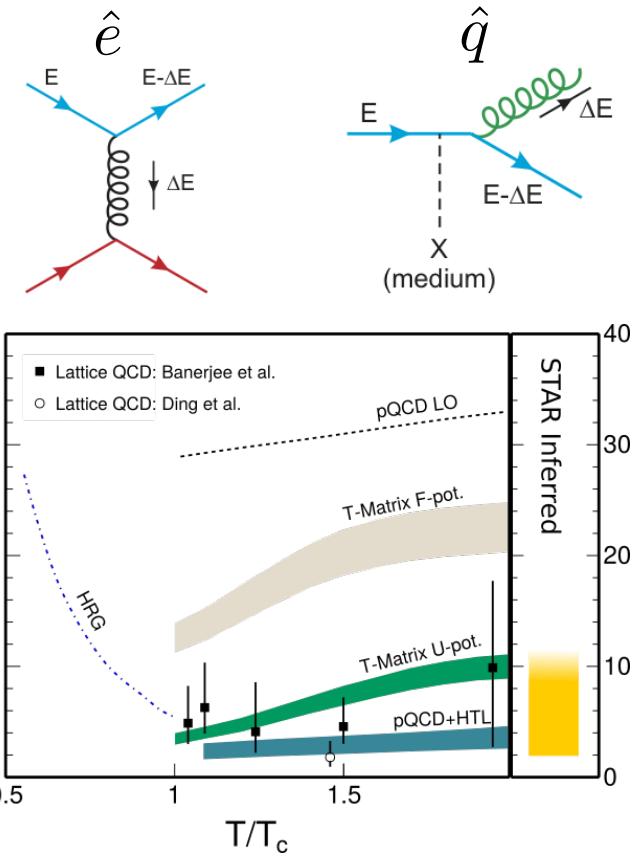
Apparently, close but not ***quite*** there yet:

- Present measurements/uncertainties (apparently) do not yet allow to "eliminate"/discriminate between models*
  - details matter; most model are within a 1-2s of exp. uncertainties – often large)
- => robust HF measurements input to **microscopic** description of QGP?
- Gluon splitting within the parton shower complicates conclusions (what energy/virtuality(?) scale is important? => what object looses energy)
- More differential measurements needed to pin down the thermalization (energy scale? – low-p_T / non-perturbative processes)
  - HF coalescence/recombination needs precision (focus on *relatively* low-momentum)
  - => still important: HF "indestructible" probe of QGP
    - => a better tool than light flavor
- Longitudinal diffusion coefficient T-dependent?
- RHIC measurements (especially beauty) stat. (and syst.) limited

Longitudinal diffusion - temperature and/or density dependence?

RHIC ⇔ LHC complementarity





- Is there an *equivalent* using **all data** for diff. coeff.?

Tech. progress / upgrades

- ALICE Upgrade – redesign of central tracking (ITS+TPC) – Run-3 – 2019+
- ATLAS & CMS in high luminosity LHC
  - ATLAS: trigger; major upgrade in LS3 (after Run-3)
  - CMS: incremental ->4 layer pixel, DAQ, trigger/HLT
- LHCb – r/o, trigger upgrade
  - take full collision rate & online event selection (software trigger) 50/fb in 5 years
- RHIC <=> sPHENIX + critical (for HF) upgrade

ALICE

- An upgrade enabling ALICE running at high-rates (benchmark: 50kHz PbPb interactions rate)
- Major focus on heavy-flavor physics (central barrel and forward muon arm)
- Continuous readout Time Projection Chamber – GEM w/ retained PID capabilities
- Forward muon tracking – 3xMAPS -> impact parameter for muons ($2.5 < \eta < 3.5$)

ITS Upgrade Design Objectives

Improve impact parameter resolution:
by a factor ~3 in rφ and ~5 in z at p_T=500MeV/c

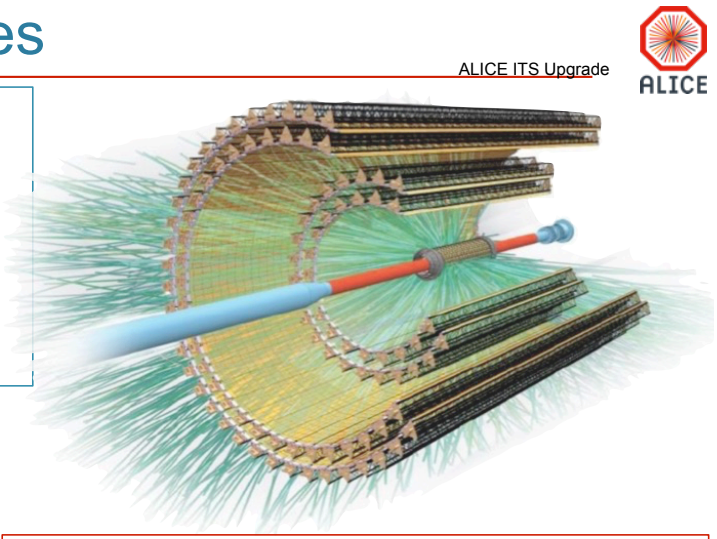
1. get closer to IP: 39mm ➔ **23mm (innermost layer)**
2. reduce material budget: ~1.14% X_0 ➔ **~0.3% X_0 (inner layers)**
3. reduce pixel size: 50x425μm² ➔ **O(30x30μm²)**
4. Spatial resolution: currently 12 μm x 100 μm (SPD) ➔5 μm x 5 μm

Improve tracking efficiency and p_T resolution at low p_T

- increase granularity: 6 layers ➔ **7 pixel layers**

Exploit LHC luminosity increase ➔Fast readout

- **readout of Pb-Pb at up to 100 kHz (presently 1kHz)** and 200kHz for pp



Withstand radiation load (10 years operation):

- TID: ~ 270 krad, NIEL: ~1.7x10¹² 1MeV n_{eq}/ cm²

Fast insertion and removal

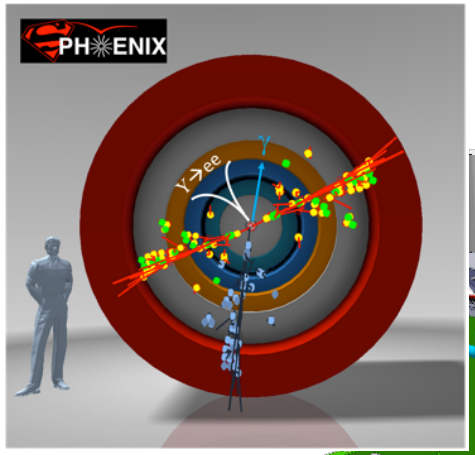
- possibility to **replace non-functioning detector staves during yearly shutdown**

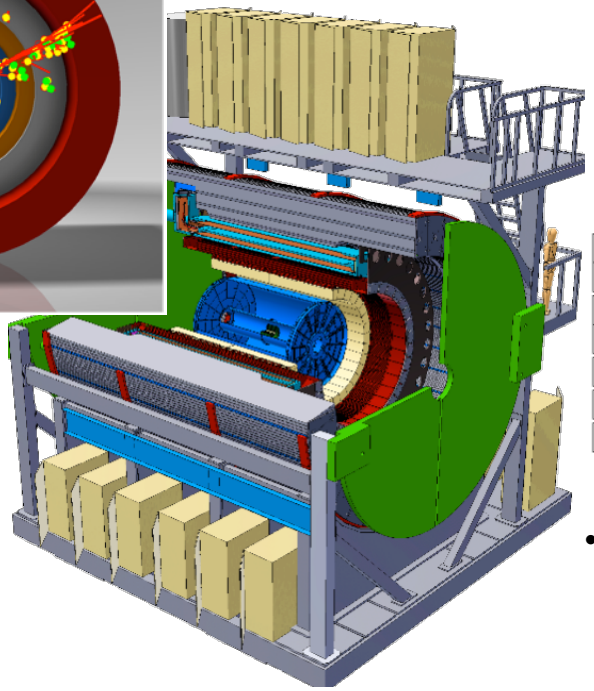
sPHENIX – new RHIC detector

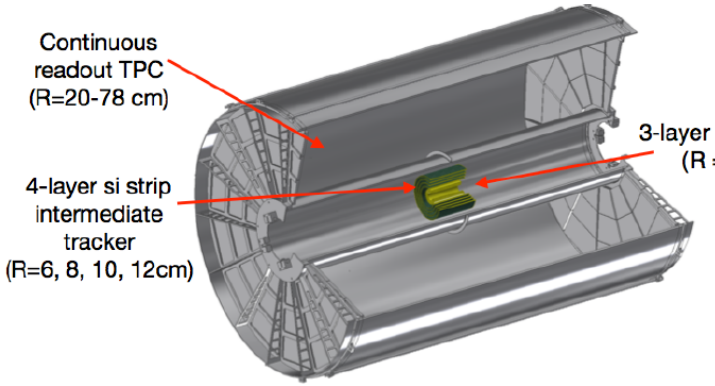
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

Main focus on light flavor jets…

Context for heavy-flavor at RHIC:
additional vertex detector for jet and b-tagging







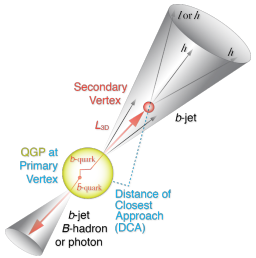
Handle interaction rates of about 200kHz in AuAu and 13MHz in pp (run trigger at 15kHz)

** Snapshot of a schedule…*

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
2022	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
2023	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
2023	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
2024	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
2025	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
2026	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

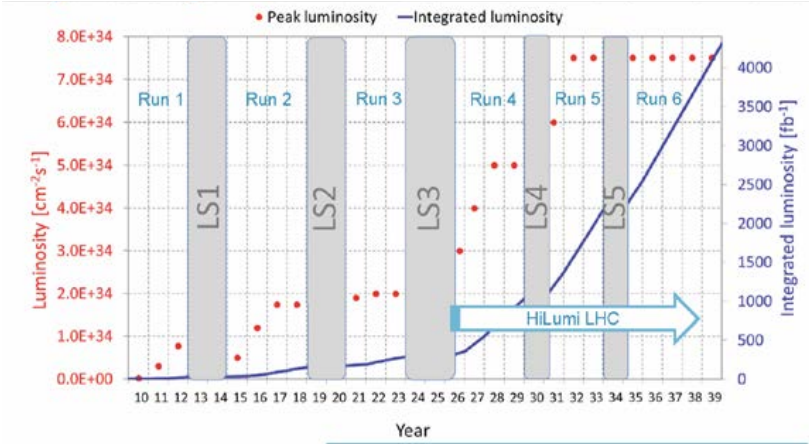
- Precision 2nd vertexing for B-tagging:
  - Tracking resolution better than 30um @pT=1GeV
  - High multiplicity HI collisions
  - Low multiplicity but high rate p+p collisions
  - High efficiency and high purity

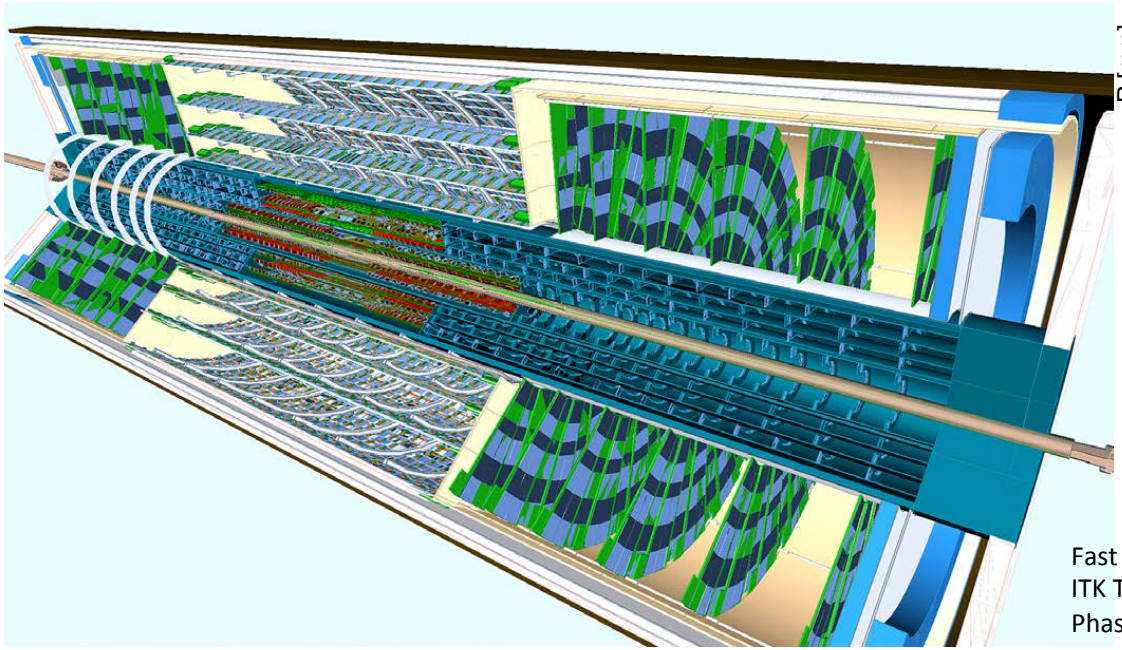
B hadrons/pT<15GeV: *O*(1M)
b-jets/pT>15GeV: *O*(100K)

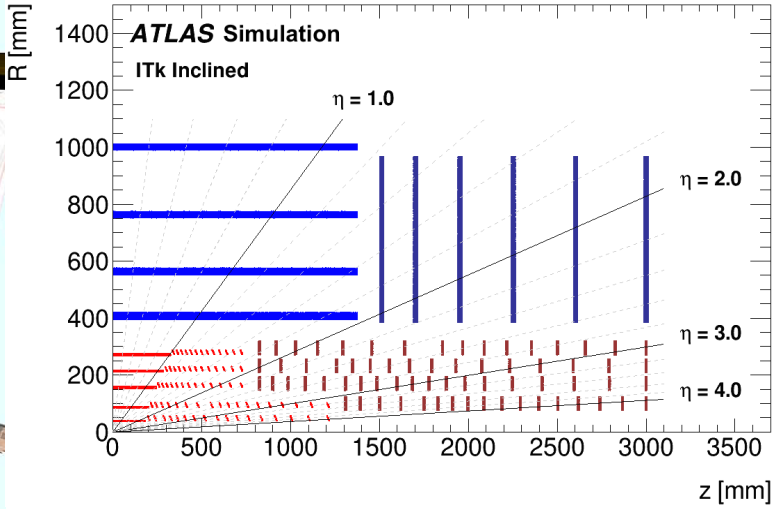


ATLAS

- Phase-1 upgrade (2019-2020)
  - Fast Tracker (software level track trigger)
    - => improved triggering strategy
  - High momentum HF hadrons in Run-3 (on par with CMS)
- Phase-2 upgrade (2024-2026) => HL-LHC
  - New inner tracking detector (ITk)
  - Pseudrapidity coverage of up to +/-4.0 units (muons)
  - Improved tracking resolution (reduction of systematic uncertainties)







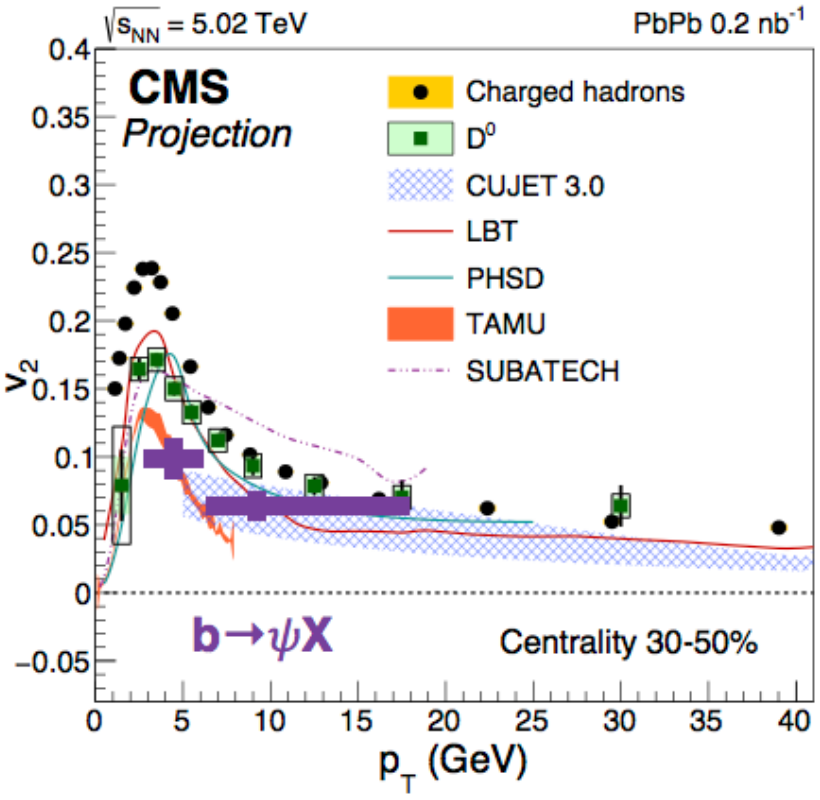
Fast tracker TDR: https://cds.cern.ch/record/1552953?ln=en
ITK TDR: https://cds.cern.ch/record/2257755/files/ATLAS-TDR-025.pdf
Phase2 LoI: https://cds.cern.ch/record/1502664/files/LHCC-I-023.pdf

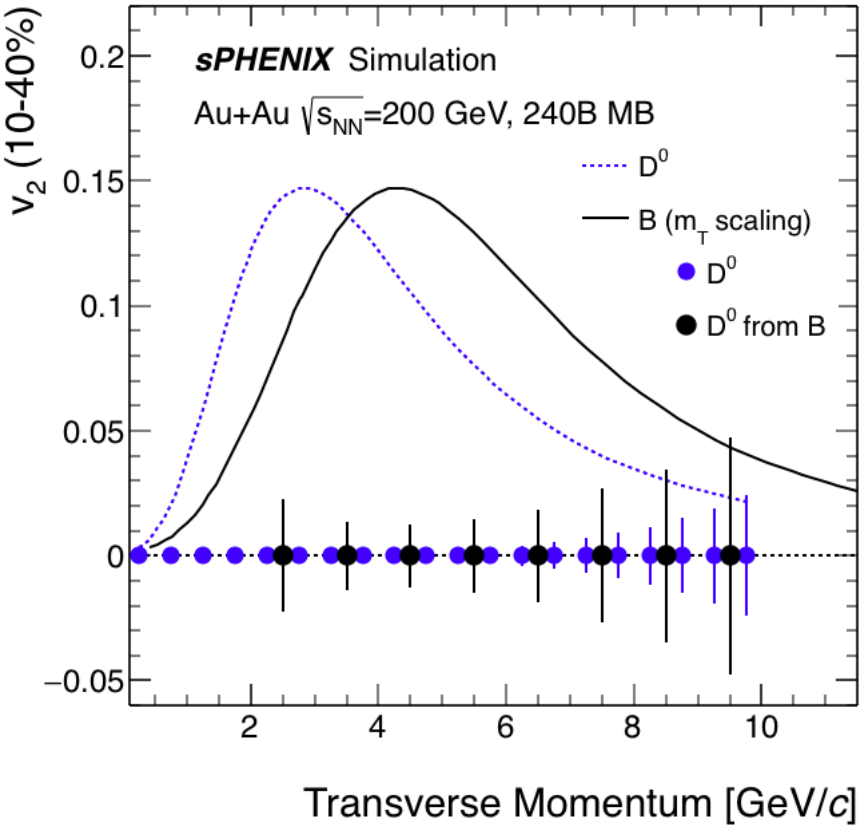
Short- & Long-term - Data

- Present AA data:
  - RHIC: finalizing STAR analyses with HFT
  - LHC: mid-Run-2 (x2+ 2018) ALICE, ATLAS, CMS, LHCb
- New AA data:
  - RHIC: > 2022 sPHENIX
  - LHC: >LS2 (10+/nb) ALICE, ATLAS, CMS, LHCb* (non central collisions only?)
- Time to reconsider [big] picture questions?
  - What is really missing? (All "present" will be improved)
  - What observables accessible vs. which are *good*?
  - Some *usual suspects* … new to be identified…

TOWARDS FUTURE MEASUREMENTS…

Eliptic flow





LHC Run-3: High precision v_2 (and v_3) for charm; good statistics for v_2 of beauty

RHIC: precise v_2^D; access to flow of beauty with ~15% (or better) uncertainty

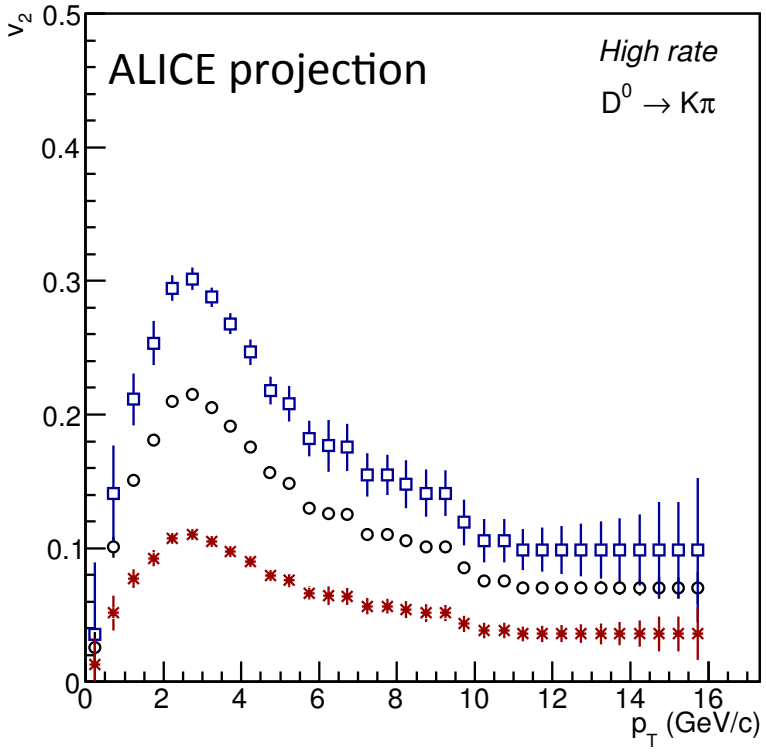
Thermalization of HF?
Novel approaches – high stat. required

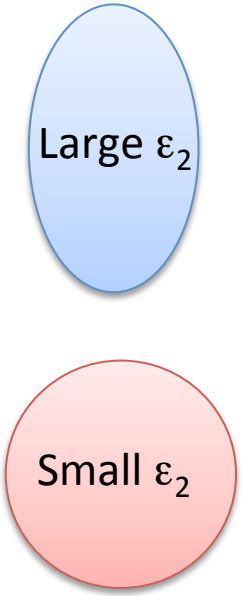
"Event shape engineering" – event selection technique – separate events with large and small v_2 – q-vector selection (proportional to the event eccentricity ε)

Goal: study the sensitivity of the charm to the collective motion of the bulk

$\Rightarrow$ the **degree** of thermalization

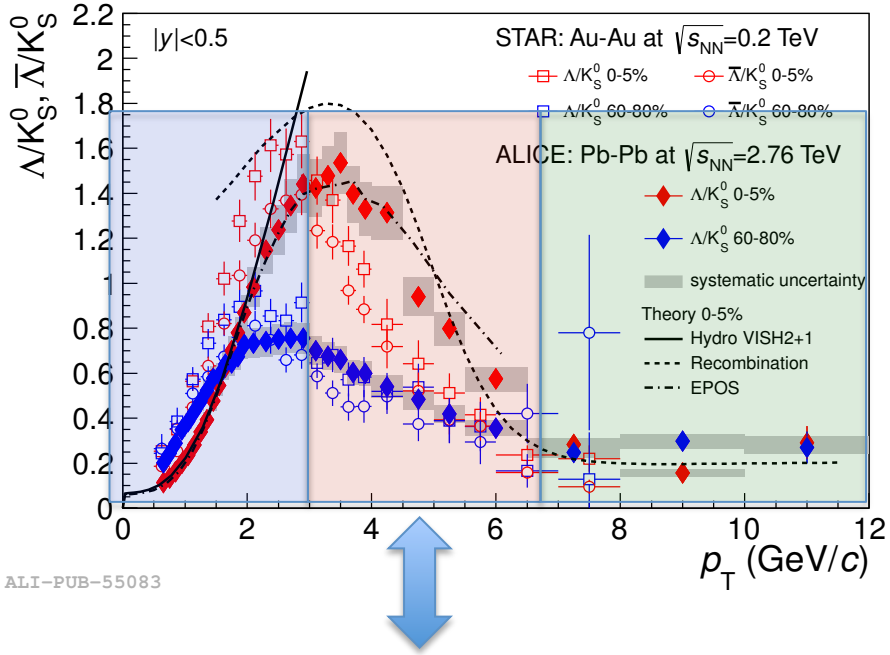
For thermal D^0: v_2 must increase linearly with $\langle\varepsilon_2\rangle$ - similar to the light flavor hadrons

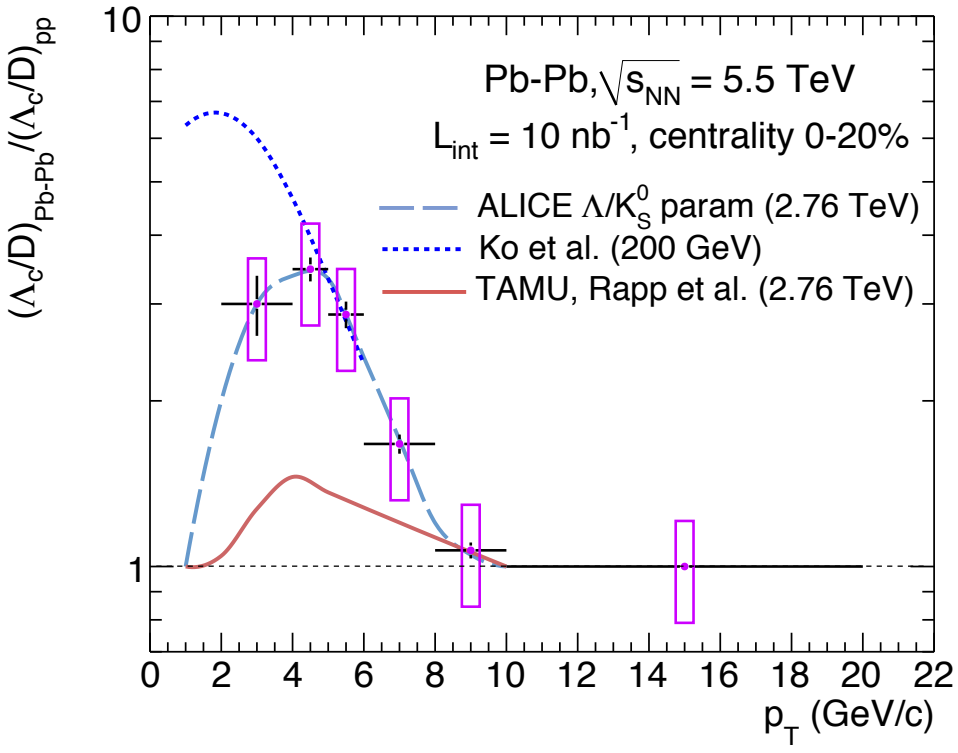




(Radial) Flow & coalescence/recombination

Test with charmed baryon / meson ratio



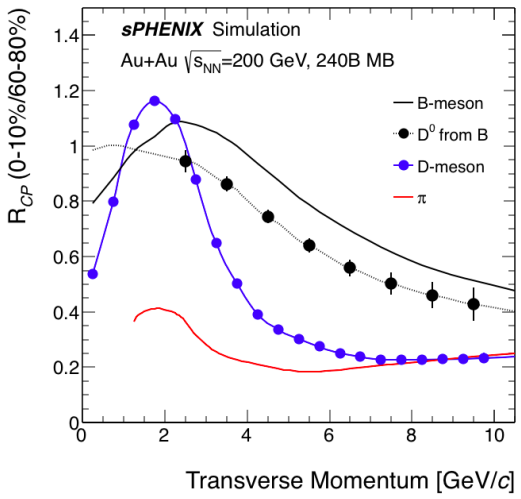


Analogue baryon/meson – light sector

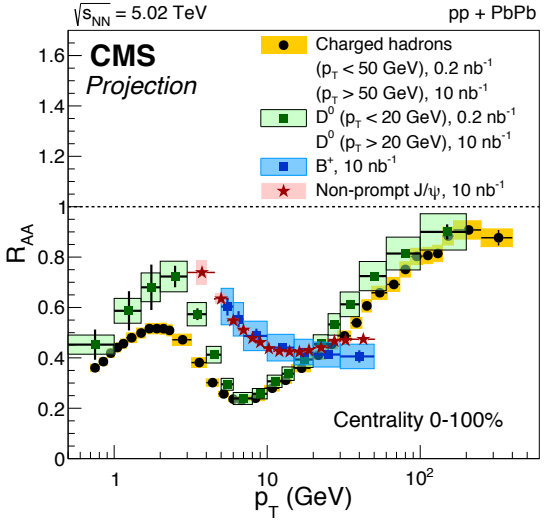
- Low-p_T hydrodynamics/flow
- Intermediate – recombination/coalescence
- High-pT – dominated by hard jet fragmentation

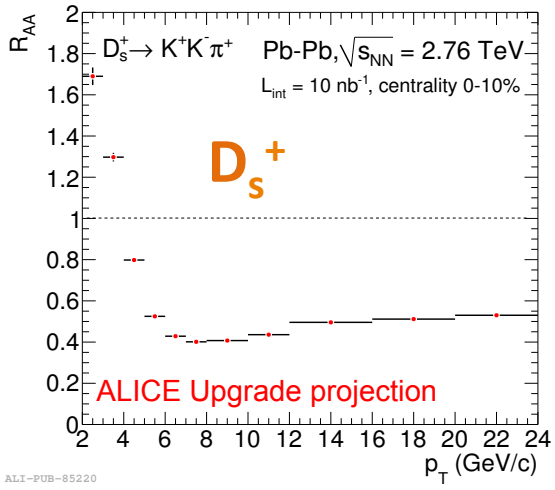
Nuclear modification factor

RHIC



LHC (examples)





CMS http://cds.cern.ch/record/2291105?ln=en
ALICE https://cds.cern.ch/record/1625842

Key measurements:

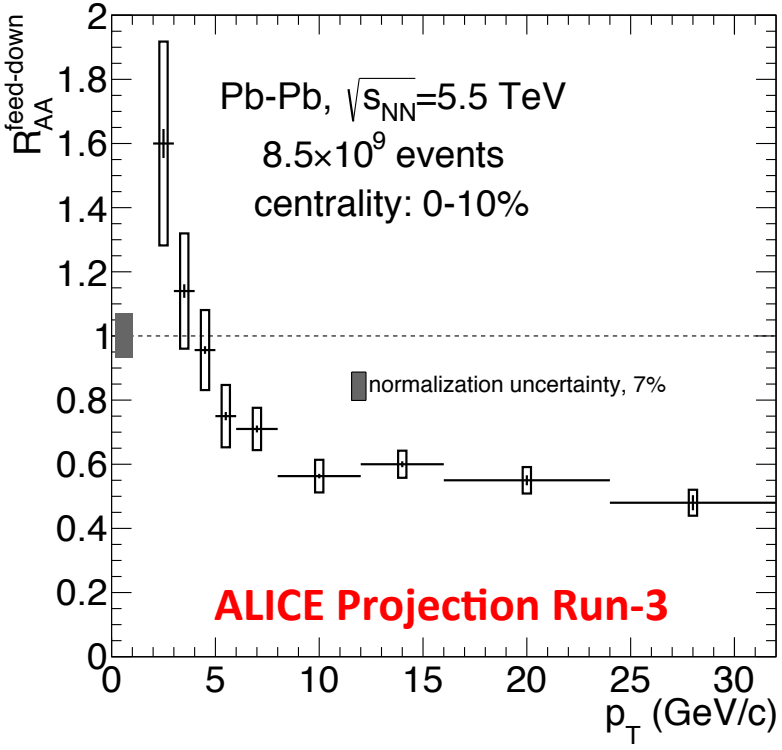
- Focus on the lower part of p_T range
- Precision for HF vs. light parton energy loss
- High statistics measurements of D_s – coalescence in heavy-flavor sector
- Precision beauty vs. charm suppression (p_T>5 GeV/c)
- Quantitative progress: compare and contrast RHIC and LHC
  - In particular: very different regimes for gluon splitting… (not present at RHIC)

Charm and beauty energy loss prompt vs. non-prompt D-meson

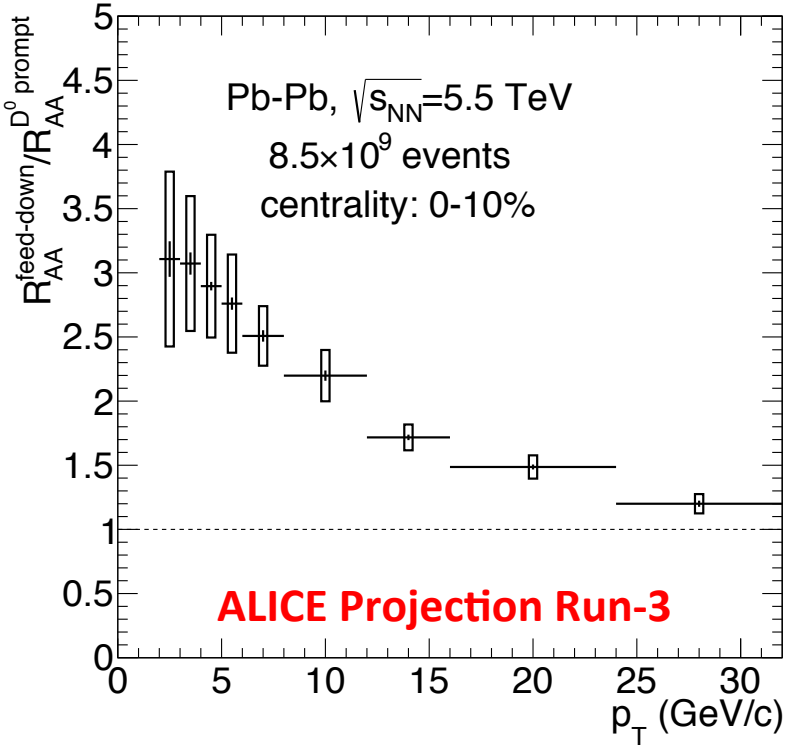
Additional handles on systematic uncertainties of the measurements & mass dependence of energy loss – ALICE: Beauty via non-prompt D^0 -> $K\pi$

Additional opportunity for measurements in reconstructed low-p_T jets

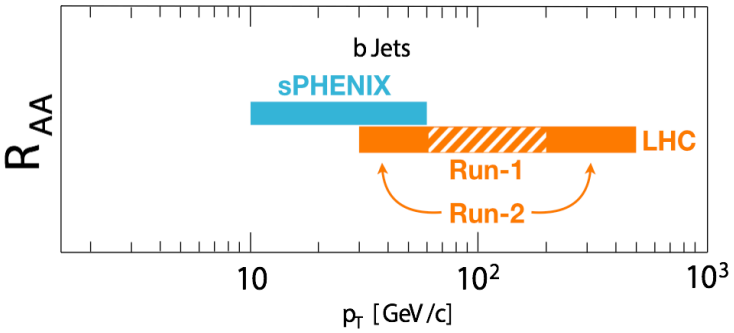
R_{AA} of feed-down D's

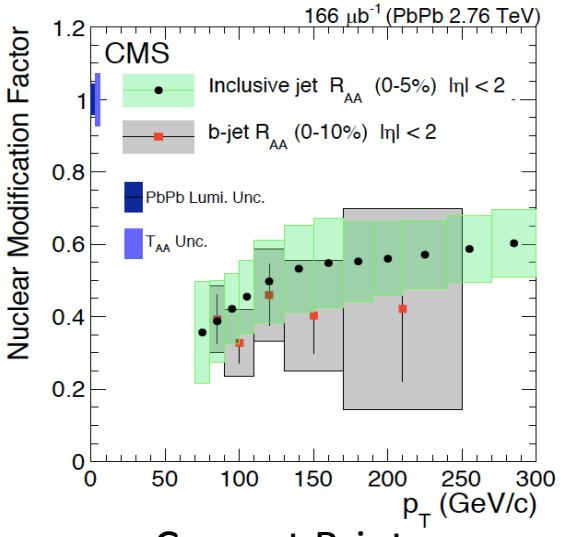


Double ratio: R_{AA} of b / R_{AA} of c

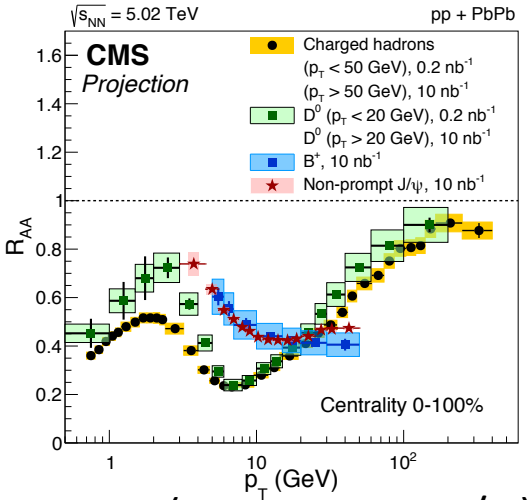


Heavy-flavor – jets – b-jet example

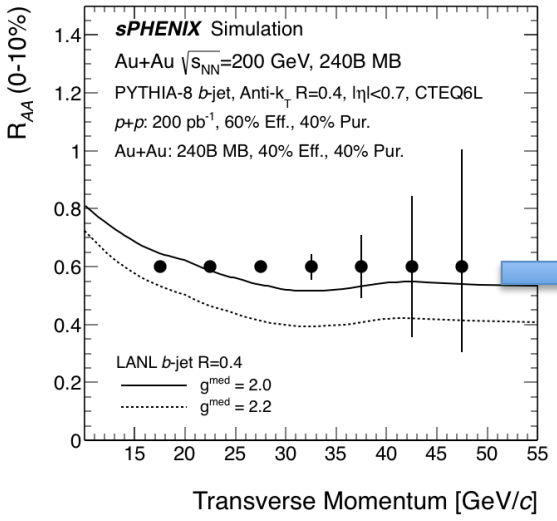




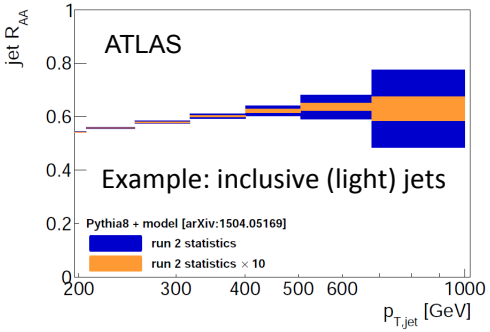
Current B-jet



Future B (+non-prompt J/ψ)



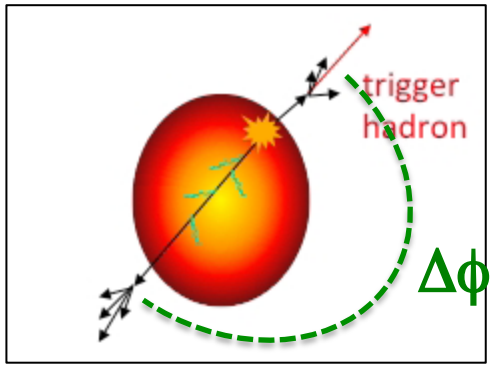
Much needed, strong improvement in precision is expected but also…



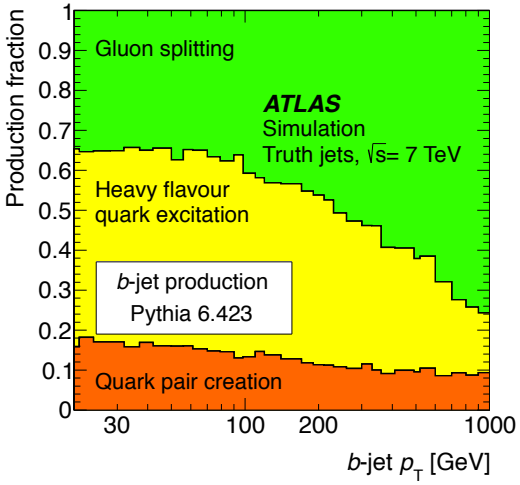
@ LHC: Reach to low-p_T - 20-30 GeV? (ALICE, ATLAS, CMS)
@ RHIC: New capabilities - reach to high-p_T with sPHENIX

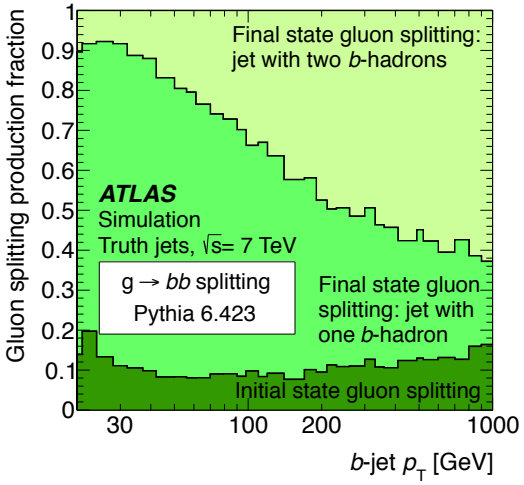
Correlations (a la two-particle)

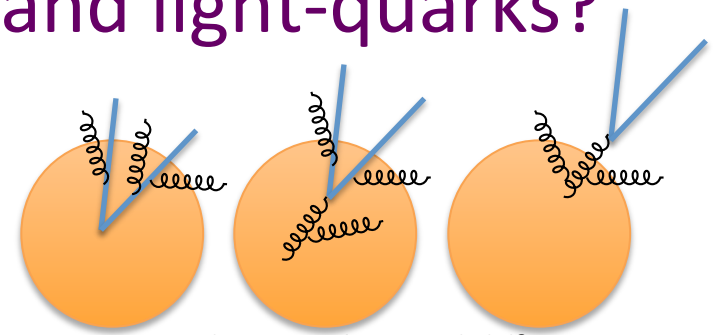
- *Comments on LHC…*
- HF-hadron – precision in LHC Run-3
  - D hadron-jet correlations in general
- HF-HF and photon-HF
  - feasible but precision questionable – order(s) of magnitude penalty in statistical uncertainties (depends on experimental acceptance and kinematics) => Run-4?
  - Certainly good for disentangling gluon splitting from flavor creation but unclear if required for discrimination between energy-loss models



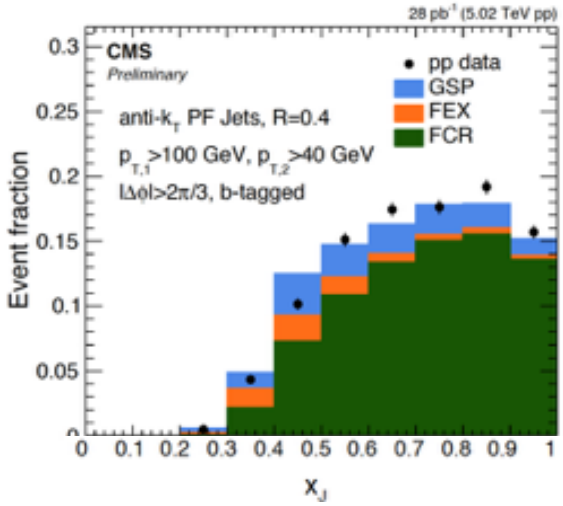
Pair creation vs. gluon splitting…
Relation to similar R_{AA} for heavy and light-quarks?



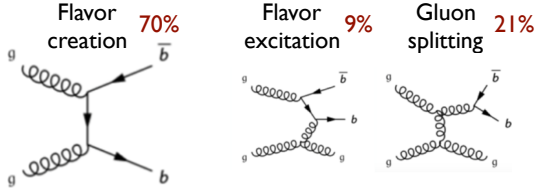


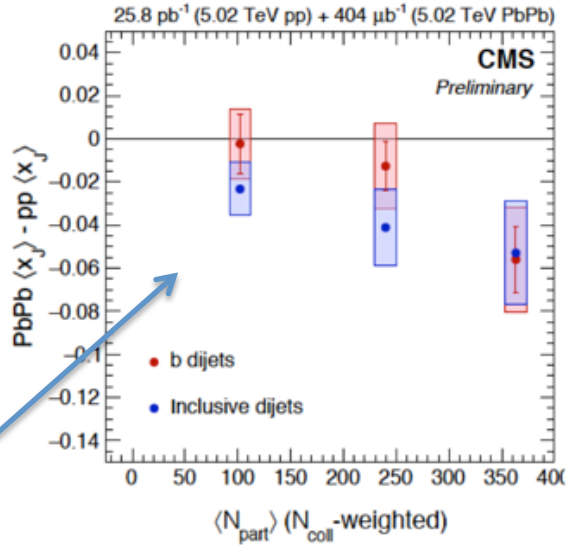


HFQ in medium − e-loss and different times of gluon split ⇔ sensitivity to the e-loss of the parent gluon (?)



New: using b di-jet suppress contributions from gluon splitting





Di-jets: still high-p_T beauty R_{AA} similar to light-flavor

Outlook – need of a measurement: low-pT correlations

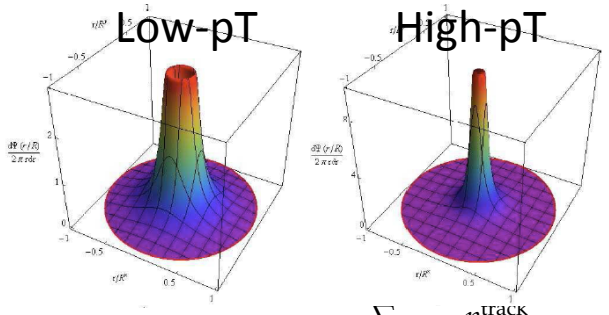
New direction(?): combine jet and v_2 of low-z HF *inside* jets - Event engineering with ε_2?

Jet shapes & substructure

- Intensive development for inclusive (light flavor jets)
  - Potential use in AA collisions for flavor-discrimination
- HF: Low and moderate p_T jets are of interest
  - Explore complete fragmentation kinematics (low- & high-z fragments) & ρ(r)
- Sub-jets: tool(s) to study splitting(s) within the parton shower
  - access to selection of "early" and "late" splitting?
  - possibly a qualitatively new area for HF measurements

Jet shapes

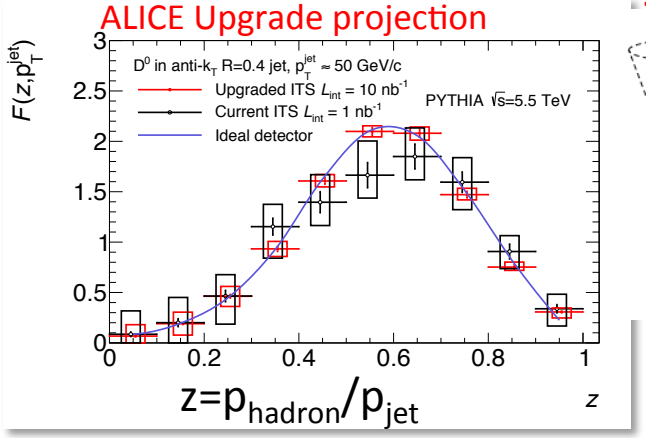
Low-pT High-pT



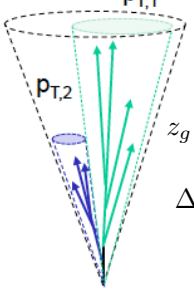
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks}\in[r_a,r_b)} p_{\text{T}}^{\text{track}}}{p_{\text{T}}^{\text{jet}}}$$

$$r = \sqrt{(\eta_{\text{track}}-\eta_{\text{jet}})^2+(\phi_{\text{track}}-\phi_{\text{jet}})^2} \leq 0.3$$

ALICE Upgrade projection



Sub-jets

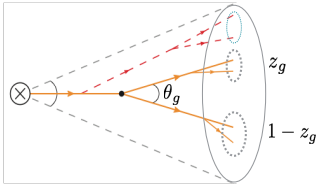


a) "Soft drop" algorithms
- Remove large angle soft radiation
- Select 1st branching in angular ordering (vacuum)

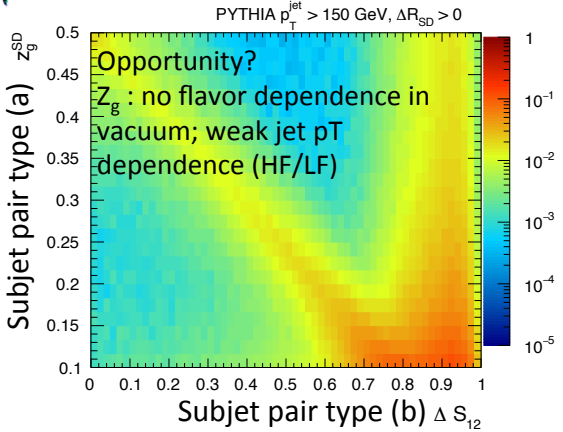
b) Re-cluster & select leading and sub-leading sub-jets

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} \text{(a)}$$

$$\Delta S_{12} = \frac{p_{T,1}-p_{T,2}}{p_T^{\text{jet}}} \text{(b)}$$



https://arxiv.org/abs/1710.07607



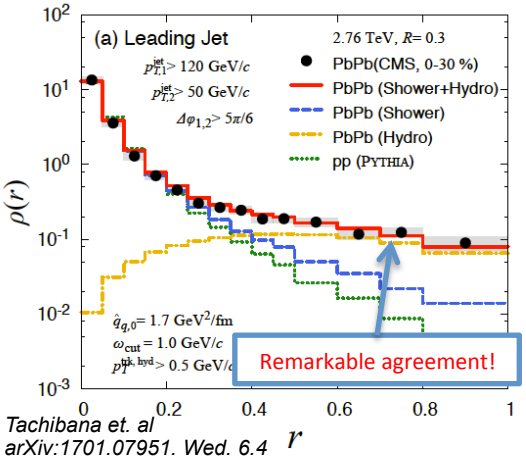
New from LF-jet studies:

Quenched parton shower + medium excitation

Quenched parton shower

Vacuum parton shower

Medium response needed to explain large angle measurements



Tachibana et. al
arXiv:1701.07951. Wed. 6.4

Goal: fully explore momentum and angular structure of jets
=> Contrast LF with HF

Present => Future

	v_n	yields	jets	correlations
charm	v_2>0; => precision: v_3? (n>2); baryon/meson; Event engineering?	R_{AA}<1 ~ light flavor => New: D_s; c-baryons	First measurement => extension to low p_T; jet structure modifications?	D-hadron, HFE, HFM correlations; HF di-jets; photon-Q? – not all accessible
beauty	as above; v_2^b smaller than v_2^c?	R_{AA}<1; b less suppressed than c => precision in p_T dependence	as above	as above
Comments on e-loss and gluon splitting (LHC)	soft split products thermalize? => contribution only to low-p_T v_n?	=> precision at low-momentum	fragmentation details => low/ moderate $z=p_T^h/p_T^Q$	desired tool to disentangle production mechanism

Recurring themes: @LHC low-pT, precision;
@RHIC: statistics (new instrumentation) enable measurements

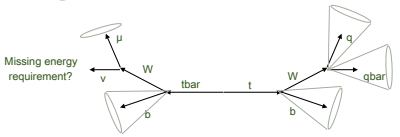
Instead of a summary – what to look forward to

- Better precision, low-pT, more species => total charm & beauty
- Light vs. heavy-Q e-loss => quantitative not qualitative question
- Gluon splitting vs. flavor creation => impact on discussion of in-medium energy loss? *what* object looses energy?
- HF fragmentation from high to low-z for medium and low-pT jets – kinematic range where significantly different
- Microscopic structure of the medium? Angular decorelation of QQbar pairs ⇔ in-medium Moliere scattering?
- Precision v_2 & v_3 for heavy-flavor ⇔ better sensitivity to initial anisotropy?; impact on transport calculations?
- Is HF flowing in small systems? (not suppressed)
- HF/LF ratios as a function of multiplicity ⇔ consistent with QGP in AA? Other physics at play?
- Consistent relation of LHC and RHIC measurements?

It seems we went a long way but still some way to go…

In case b-quark not heavy-enough…

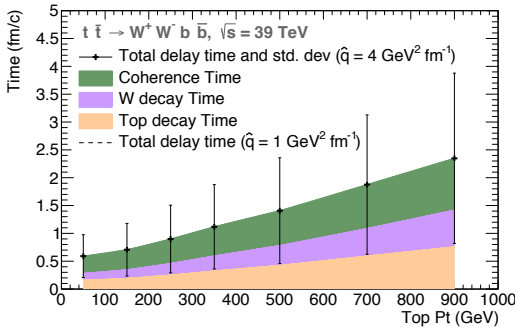
An appetizer… Heavy-ion perspective on FCC but also **high-lumi LHC**



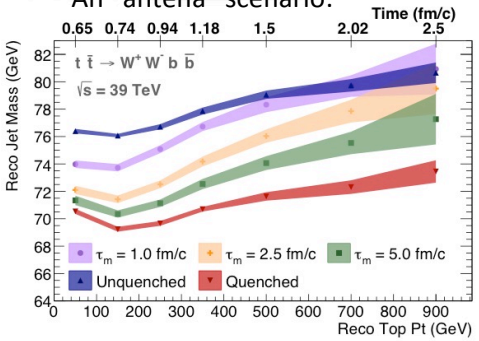
"Time" tomography of the medium with boosted tops (accessible at sLHC but also some at high-luminosity LHC)

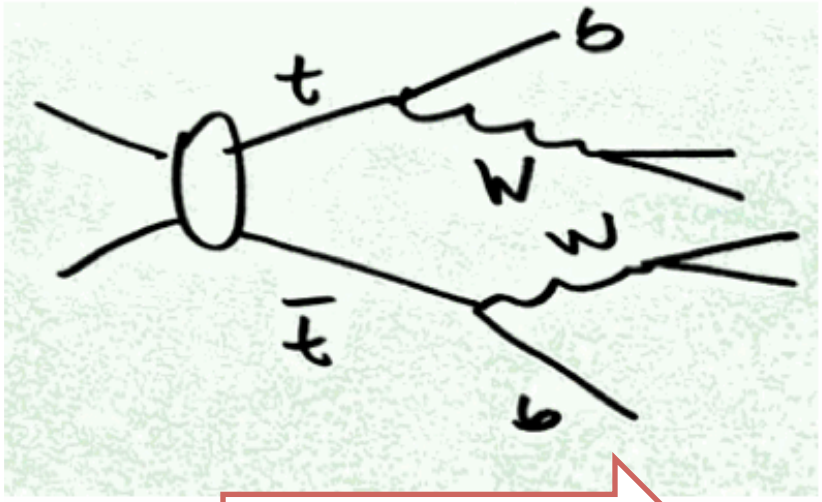
$$t\bar{t} \rightarrow b\bar{b} + \ell + 2\,jets + E_T$$

$\sigma_{ttbar \rightarrow qqbar + \mu\nu}$ ~ 10 pb (LHC) and 1 nb (FCC)



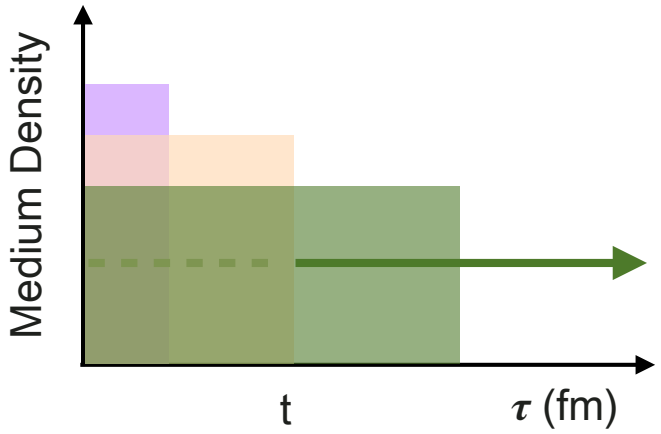
An "antena" scenario:





http://www.int.washington.edu/talks/WorkShops/int_17_1b/People/Apolinario_L/Apolinario.pdf

time



time

	Pt=1 TeV	Pt=500 GeV
ttbat produced	0 fm/c	0 fm/c
top → W+b	1 fm/c	0.5 fm/c
W decay	1.6 fm/c	0.8 fm/c
qqbar in singlet	2.3 fm/c	1.3 fm/c

L. Apolinário, G. Salam (CERN), C. A. Salgado (USC) (IST), G. Milhano (IST and CERN),

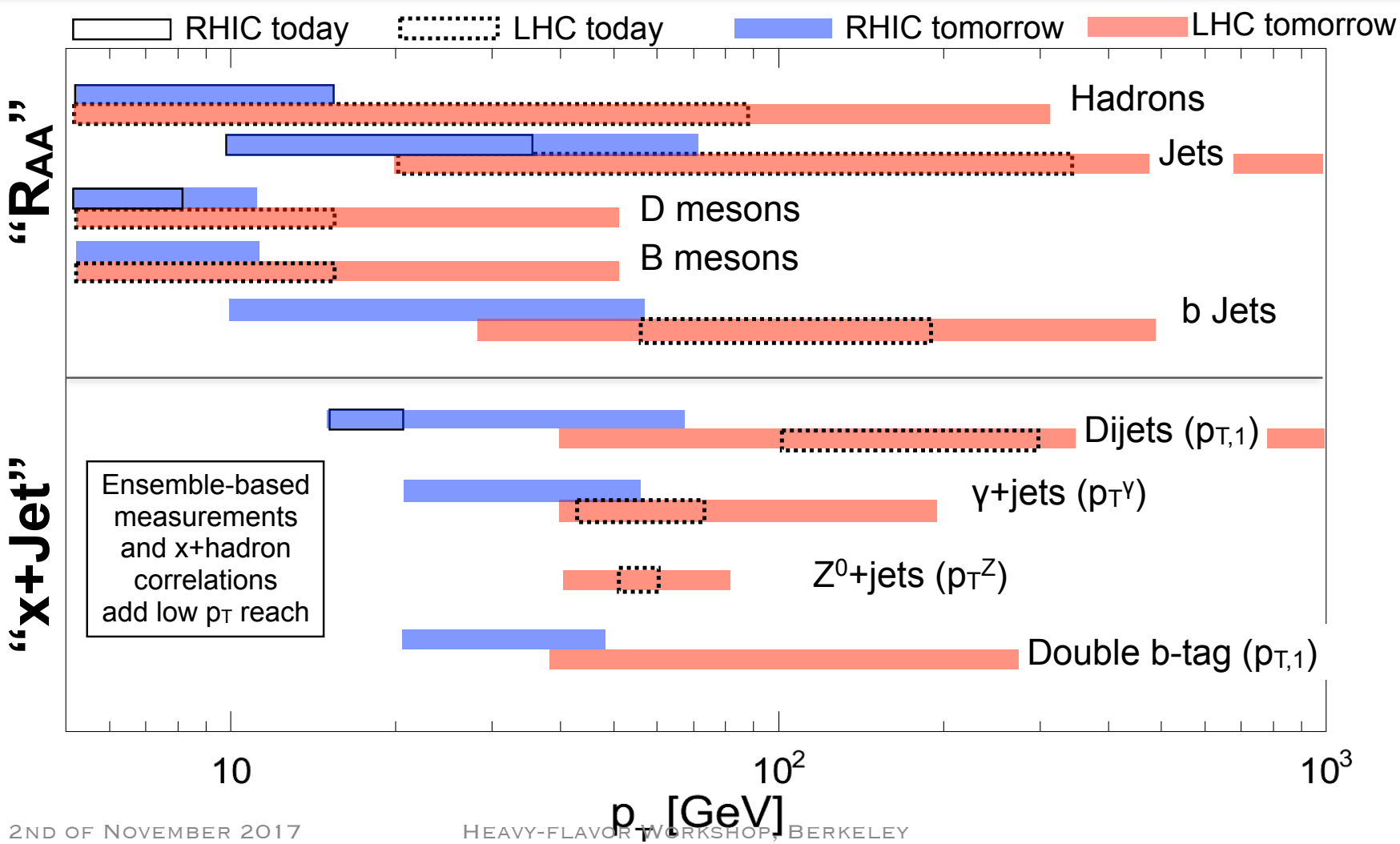
ADDITIONAL SLIDES

RHIC and LHC outlook

Figure by G. Roland

Kinematic reach: Now and tomorrow(*)

(*)*Artist's impression*



Small(er than PbPb) systems

- Next pPb run at the LHC – 2026 (?)
- Small(er) nuclei: XeXe (?)
- RHIC – no plans

Comments to the table

what we know now & what will be the experimental progress…

- V2: clear separation between elastic and inelastic e-loss?
  - V3? N>2
- Correlations: HF-hadron; HF-jet in reach; QQbar difficult
- Strong suppression
  - Hadrons, electrons, enhancement of charmed baryons in pp?
  - High-pT jets => low-pT jets in the future?
- Role of gluon splitting
  - pT spectrum? Time of the splitting?
  - Measurements?
- Small systems -> charm flows?
  - Muon-hadron v2
- Reference measurements -> pp