OPEN HEAVY FLAVOR: EXPERIMENTAL OVERVIEW

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CHARGE FROM ORGANIZERS

- An overview and current status of open heavy flavor probes in p+p, p+A, and A+A collisions from an experimental perspective.

WHAT WE MEASURED

- Lessons learned *in the field since the last Hard Probes* conference *(n.b. October 2018)* particularly worthy of reporting.

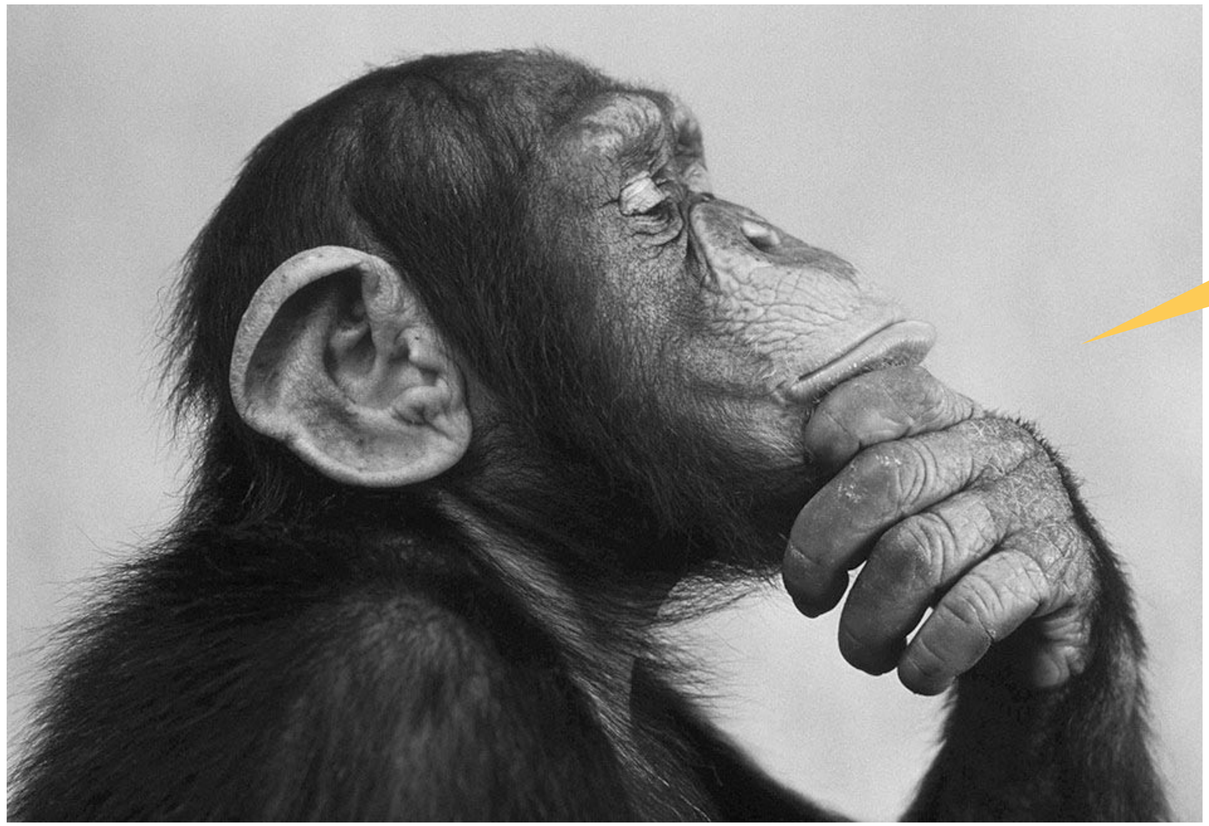
WHAT WE LEARNT

- In addition, any comments you want to share about the role of open heavy flavor in future e+A programs are welcome as well.

WHAT'S WORTH MEASURING TO LEARN SOMETHING

. . . IN 20 MINUTES

SO . . .



STRATEGY:
KEEP IT SIMPLE.

Disclaimer

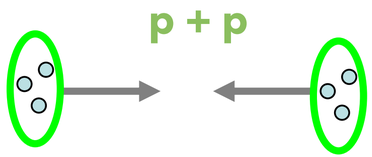
Preference to measurements (in pp & AA) …

1. in which beauty and charm are measured separately.
2. (if more than 1) results w/ the widest kinematic reach and/or highest precision.

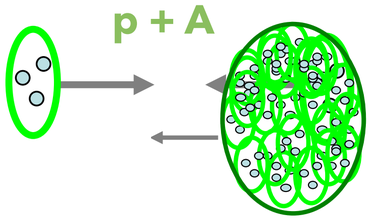
COMMON ATTITUDE TOWARDS HF: . . . OPTIMISTIC

- **“HF quarks fine/good/excellent/ideal probe to study QGP in uRHIC”**

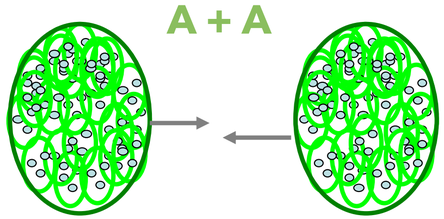
- **But this implies we understand HF (the probe)**



Have a baseline/reference system where production is understood



Nuclear/cold effects are under control

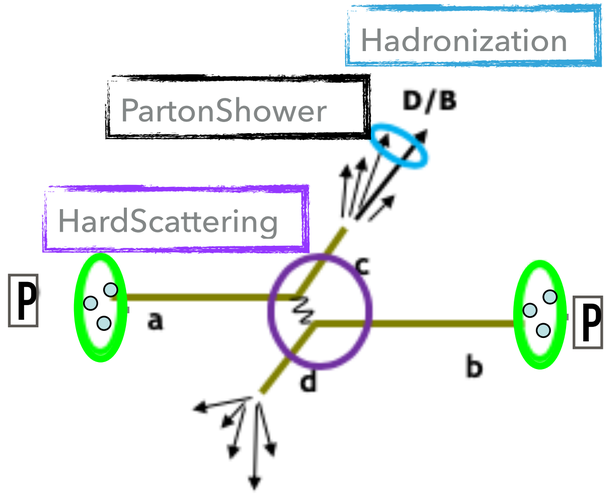


Understand the interactions/hadronization in medium

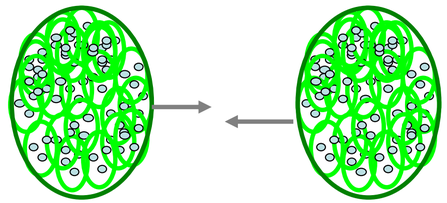
- **With LHC (open beauty & charm separated): … it’s also *complicated***

TODAY'S TALK:

- **Where we stand in our understanding of HF production in p+p?**
  - by assessing the agreement between data & models/theory (in particular PYTHIA)



- **Same exercise for A+A**
  - with an attempt of reading (in) data



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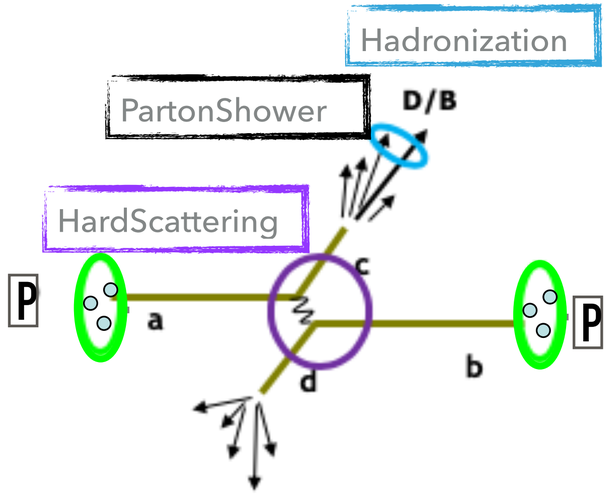
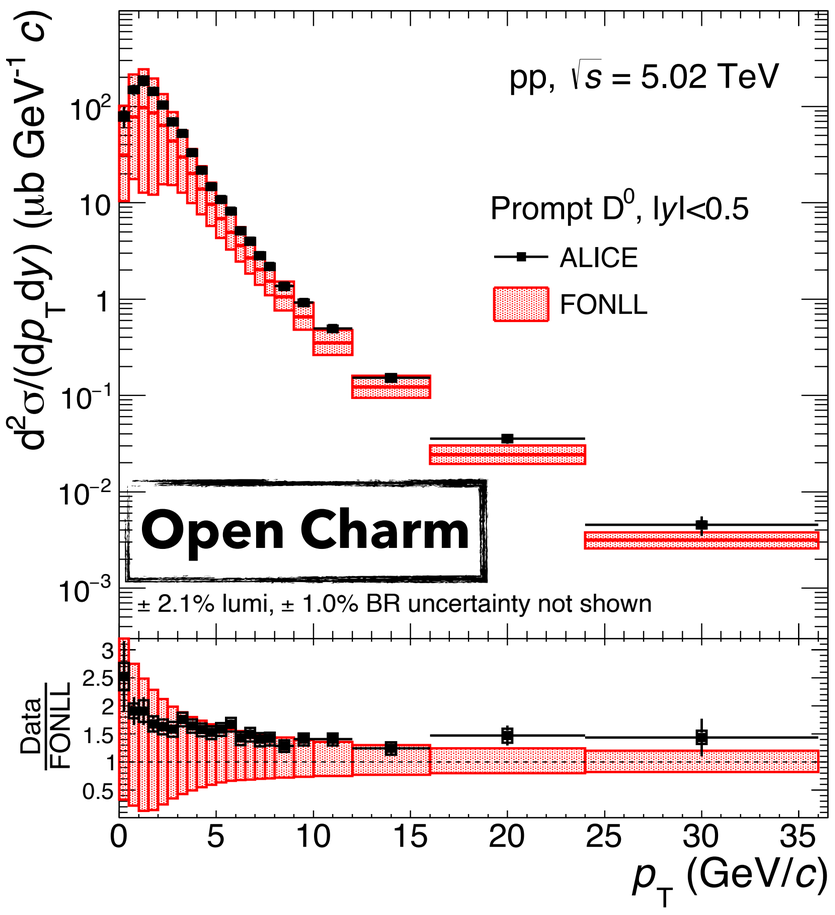


CROSS SECTION: GOOD PQCD DESCRIPTION

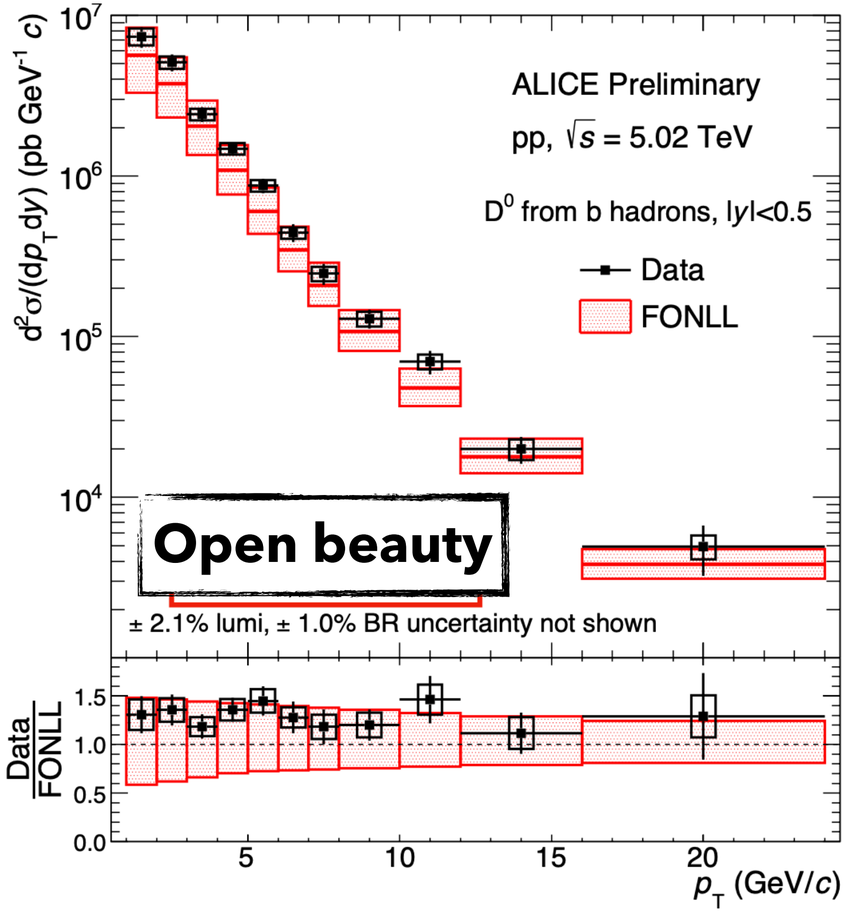
CHARM

EUR.PHYS.J. C79 (2019)



BEAUTY

ALI-PREL-319648

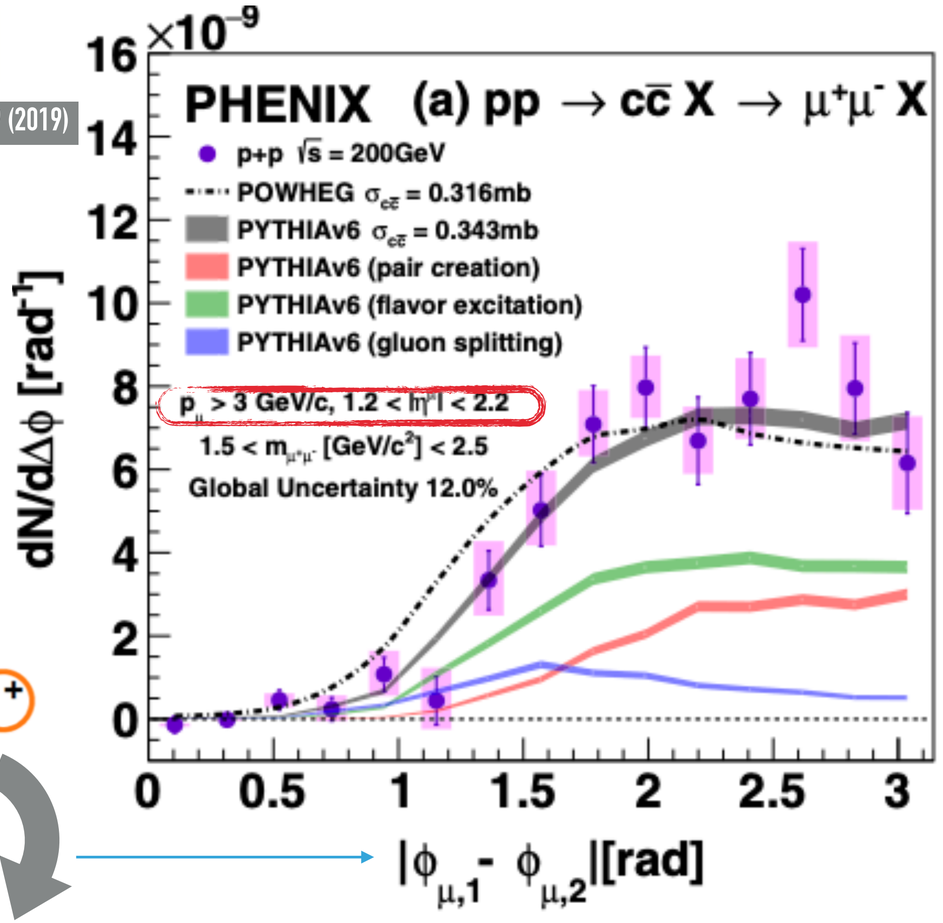


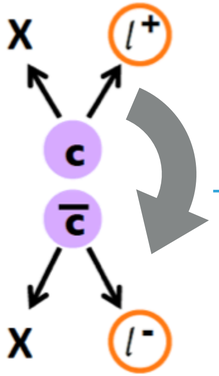
- **FONLL**
  - … data consistently @ the upper edge (and even higher at high-p_T)
  - Good news: precision data → door opened for improvements

SHOWER+HAD: GENERAL FEATURES OF ANGULAR DISTRIBUTIONS CAPTURED BY TH

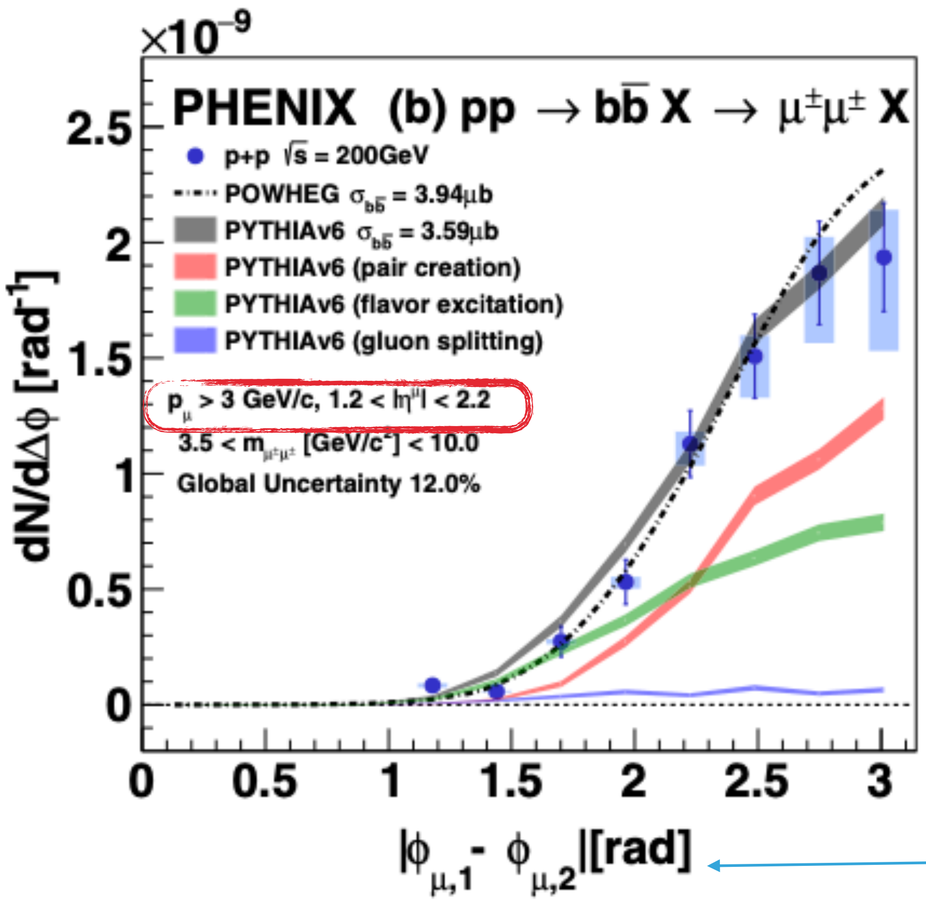
CHARM

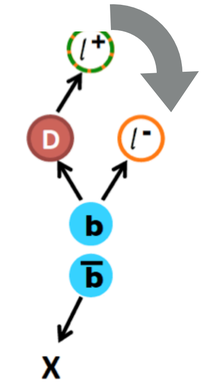
PHYS. REV. D 99 (2019)





BEAUTY





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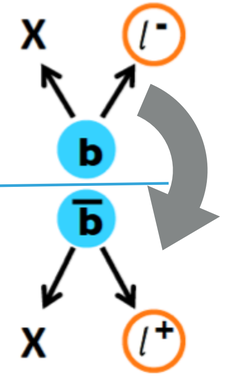


- **PYTHIA & POWHEG: details still to iron**
  - intermediate $\Delta\phi$ region the most challenging for both charm and bottom

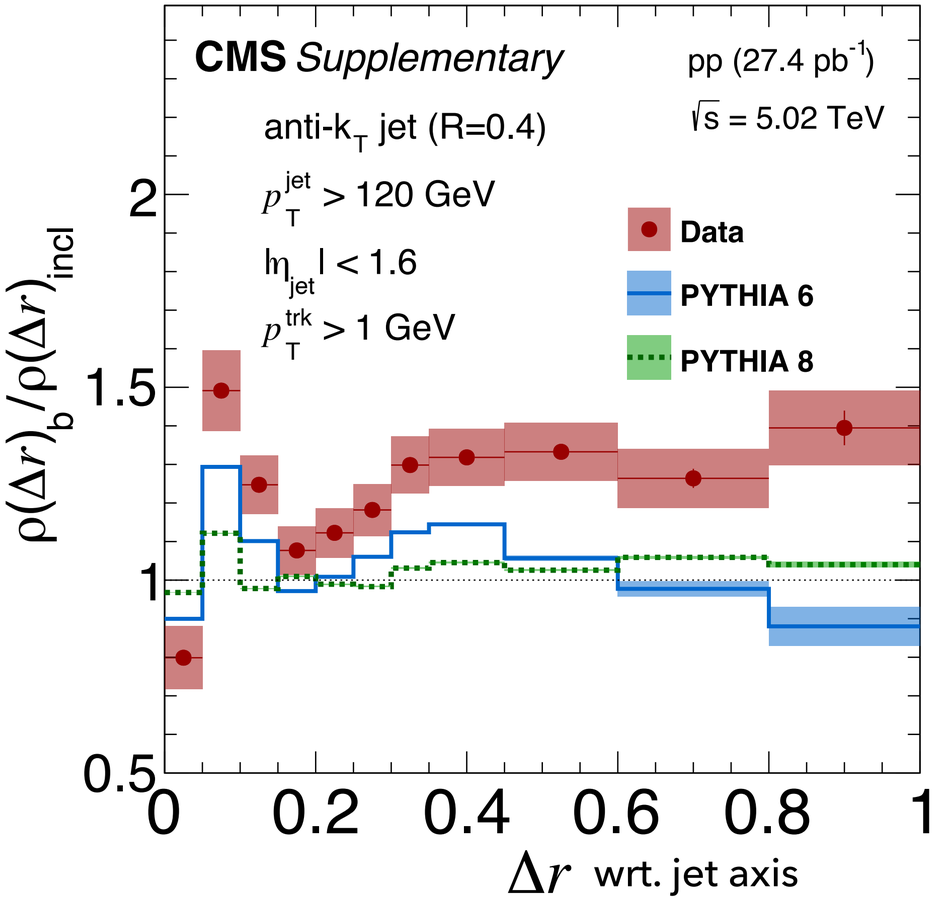
SHOWER+HAD: DIFFERENCES BETWEEN BEAUTY QUARKS AND LIGHT PARTONS

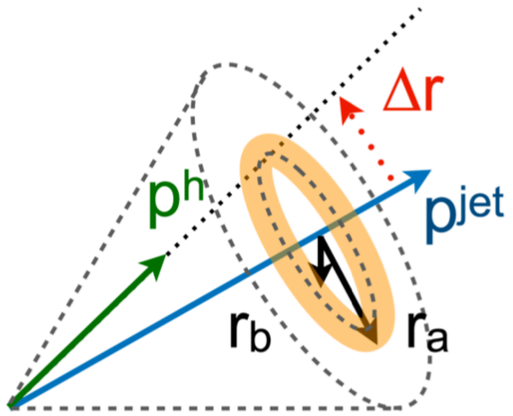
BEAUTY

ARXIV:2005.14219

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{\Sigma_{\text{jets}}\Sigma_{\text{particle}\in(\Delta r_a,\Delta r_b)} p_{\text{T}}^{\text{trk}}}{\Sigma_{\text{jets}}\Sigma_{\text{trk}} p_{\text{T}}^{\text{trk}}}$$

normalized p_T-distribution of charged hadrons as a function of angular distance from the jet axis



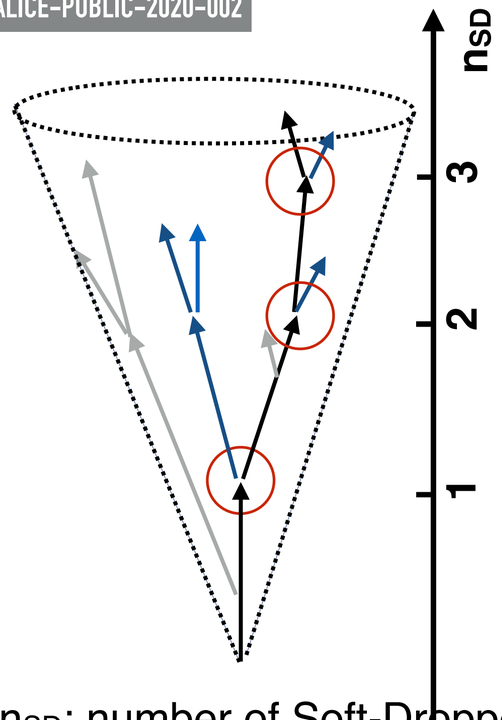


- **'Structure' of (hard) beauty jets (p_T >120GeV/c)**
  - shift of p_T further away from the jet axis in b-jets compared to light-jets
  - feature captured by PYTHIA @ low-Δr but not @ high-Δr

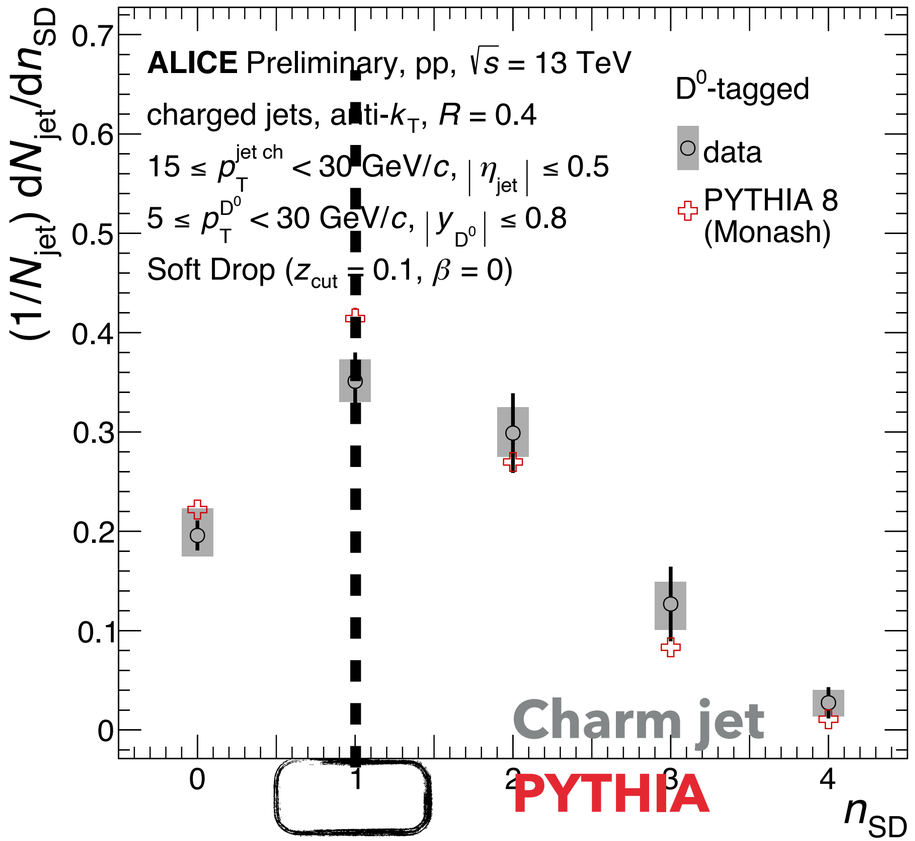
SHOWER+HAD: DIFFERENCES BETWEEN CHARM QUARKS AND LIGHT PARTONS

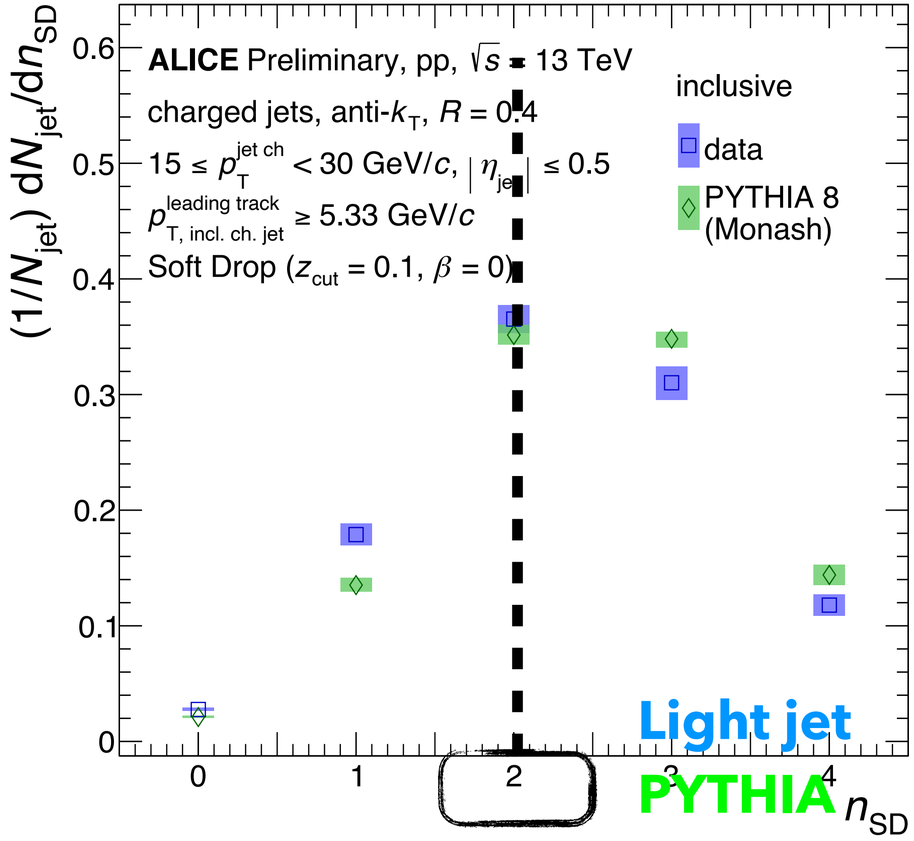
CHARM

ALICE-PUBLIC-2020-002



n_{SD}: number of Soft-Dropped splittings

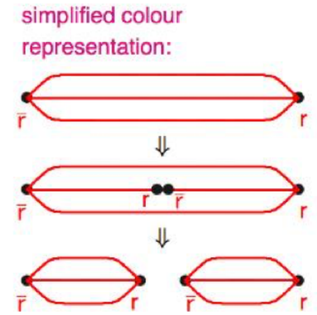




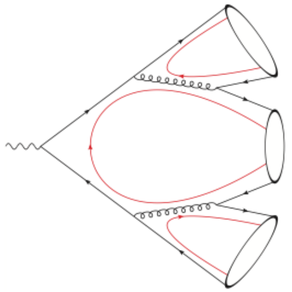
- **Substructure of (soft) charm jets (p_T 15-30GeV/c)**
  - fewer splittings than light jets → harder shower for charm vs. inclusive jets (gluon dominated)
  - a feature captured by PYTHIA

HADRONIZATION MECHANISMS AS IMPLEMENTED IN P-P IN MODELS

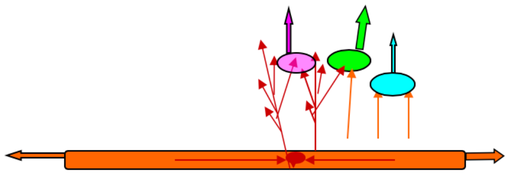
- **PYTHIA: Lund string model**
  - default: string frag.
  - +colorReconnection (CR), in which partons from MPIs interact allowing junctions



- **HERWIG: Cluster model**
  - clusters (excited hadronic states) decay into hadrons



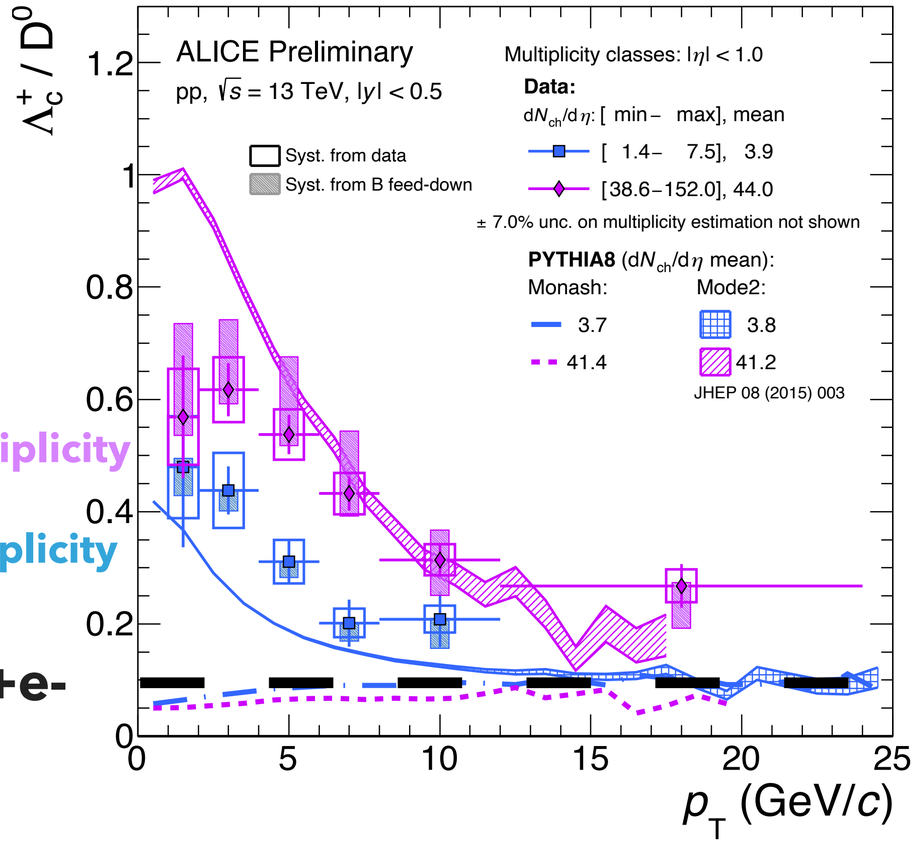
- **Recombination:** (Hwa, Yang nucl-th/0404066)
  - Note: Recombination describing pp (and pA) data DOES NOT IMPLY presence of QGP!!!



HADRONIZATION: OF CHARM AT LOW-PT NOT UNDERSTOOD

CHARM

ALI-PREL-336442



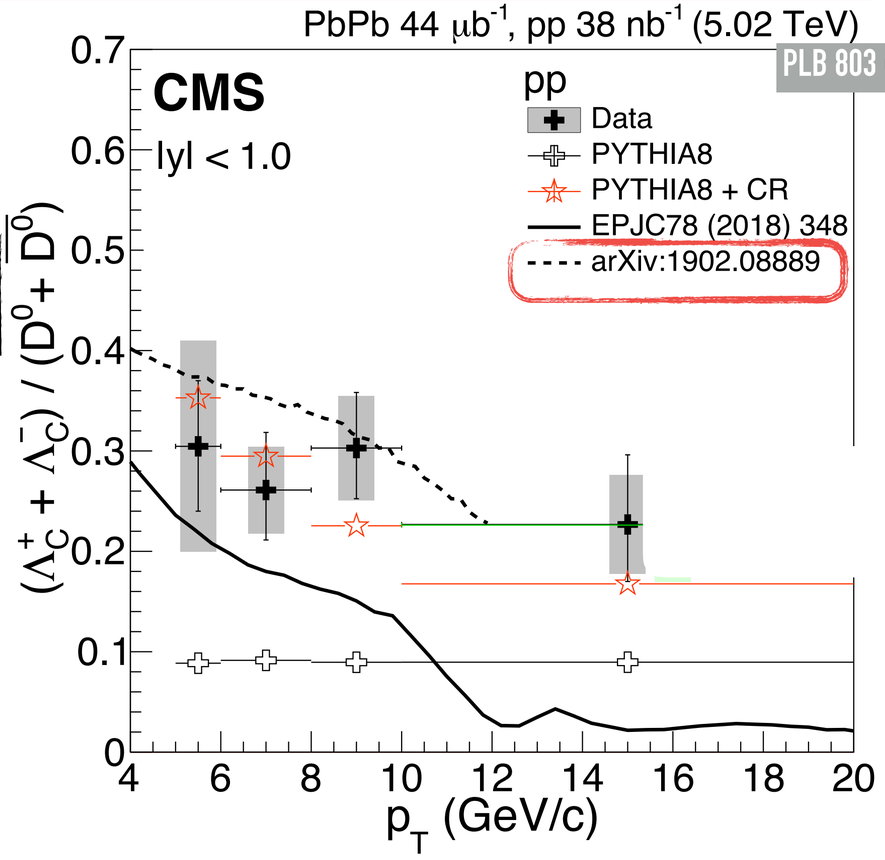
High-multiplicity

Low-multiplicity

e+e-

Λ^+_c / D^0

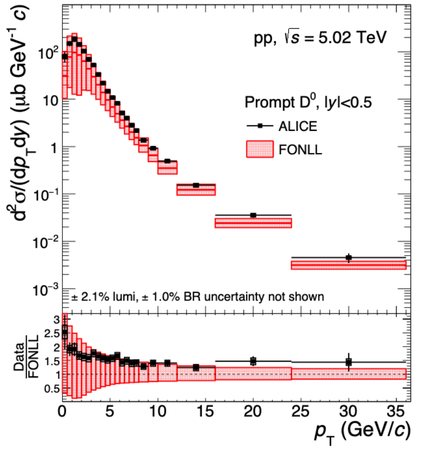
p_T<20GeV/c



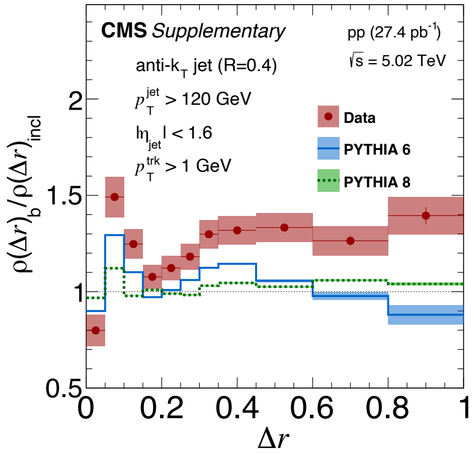
- **PYTHIA string frag.**
  - needs CR to reproduce the trend vs p_T OR multiplicity;
  - Note: hadronization not 'universal'!
    - low-p_T: not even low-multiplicity pp data is close to (e+e-)
    - high-p_T (>10-20GeV/c) : all data getting close to (e+e-)
- **Alternative mechanism**
  - statistical hadronization applied to pp + feed-down from missing charm-baryon excited states (beyond PDG).

SUMMARY: OPEN HEAVY FLAVOR IN PROTON+PROTON COLLISIONS

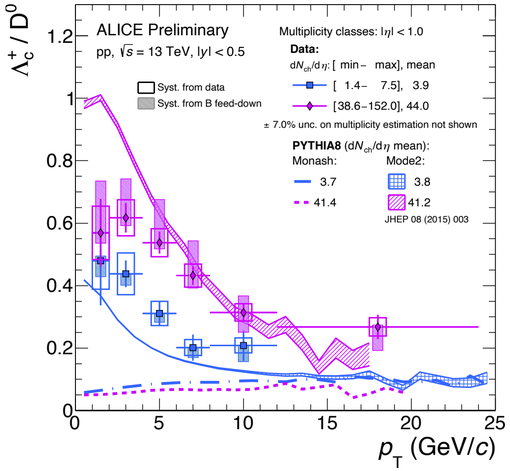
- pQCD works, but there is room and data for improvement



- More differential observables not all under control



- Hadronization: not a settled topic

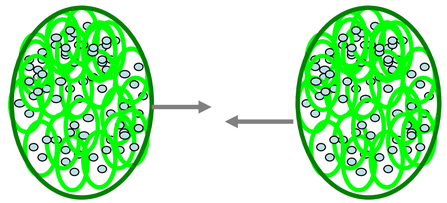


AFTER THE P+P STATUS

- Mood check: Moderately happy

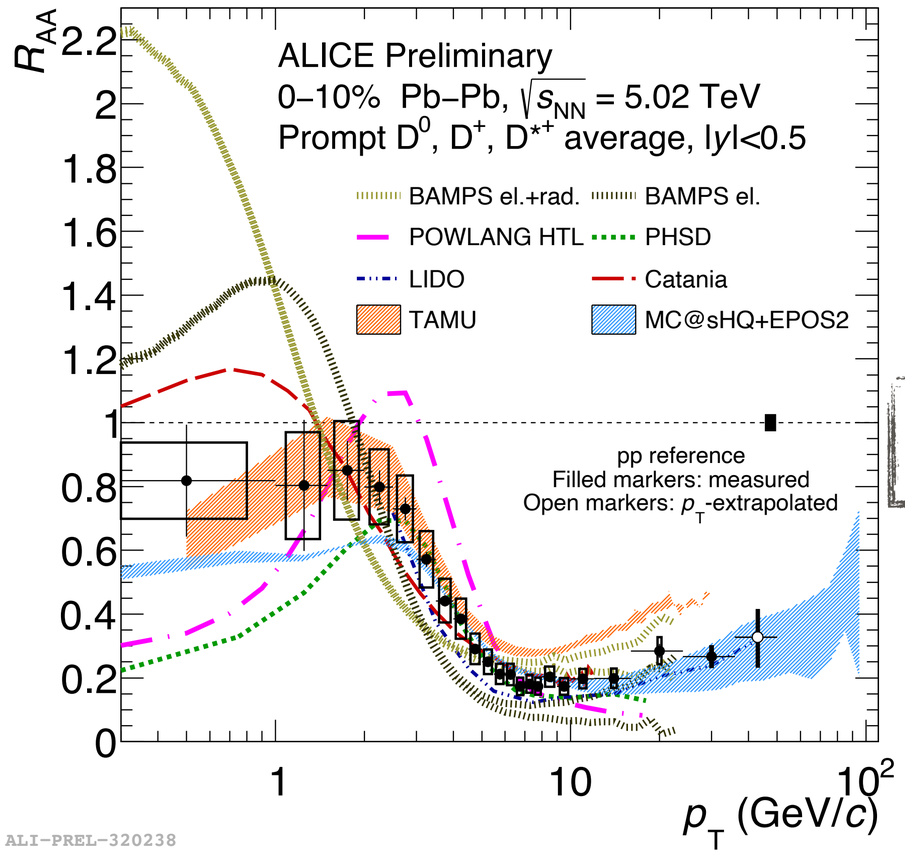
- **Where we stand in our understanding of HF production in p+p?**
  - by assessing the agreement between data & models/theory (in particular PYTHIA)

- **Same exercise for A+A**
  - with an attempt of reading (in) data



WHERE WE ARE IN A+A…NOT CLEAR

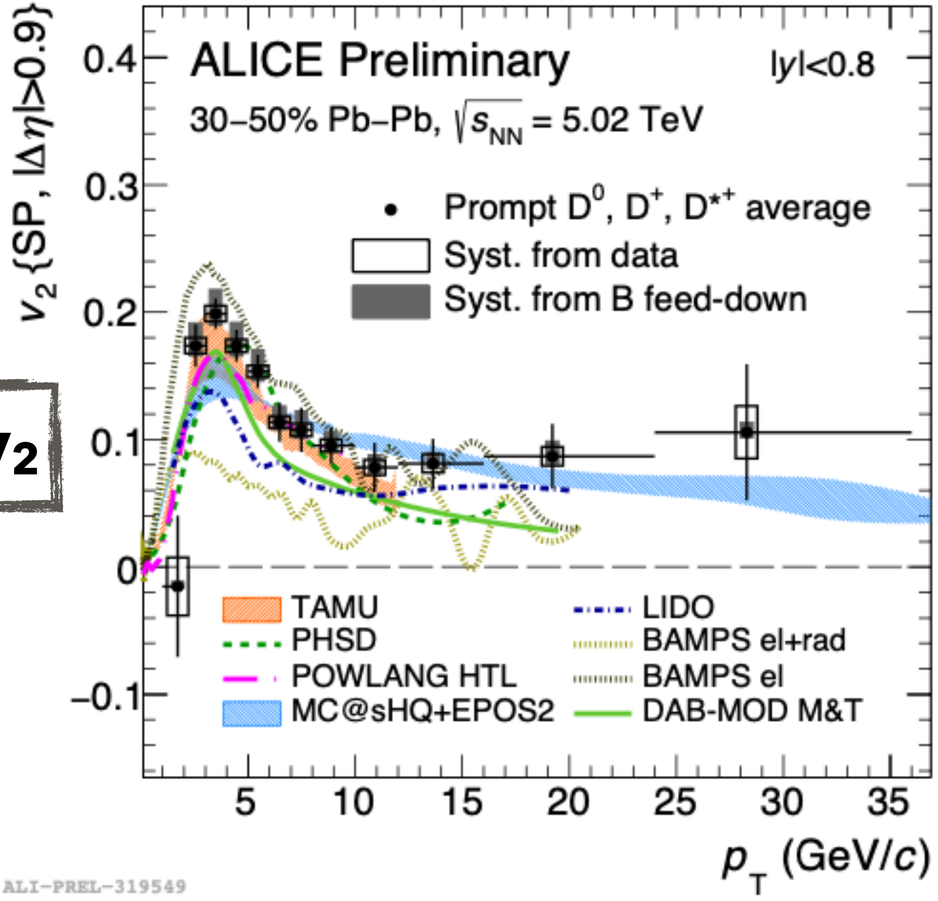
CHARM



Prompt D0

R_{AA}

v_2



- **We whether know too much or too little …**
  - models have trouble describing both R_{AA} and v_2 (as it was from ‘day one’ ;))
  - for what is worth: experimentally, can measured down to 0 pT (and up to 100GeV/c)

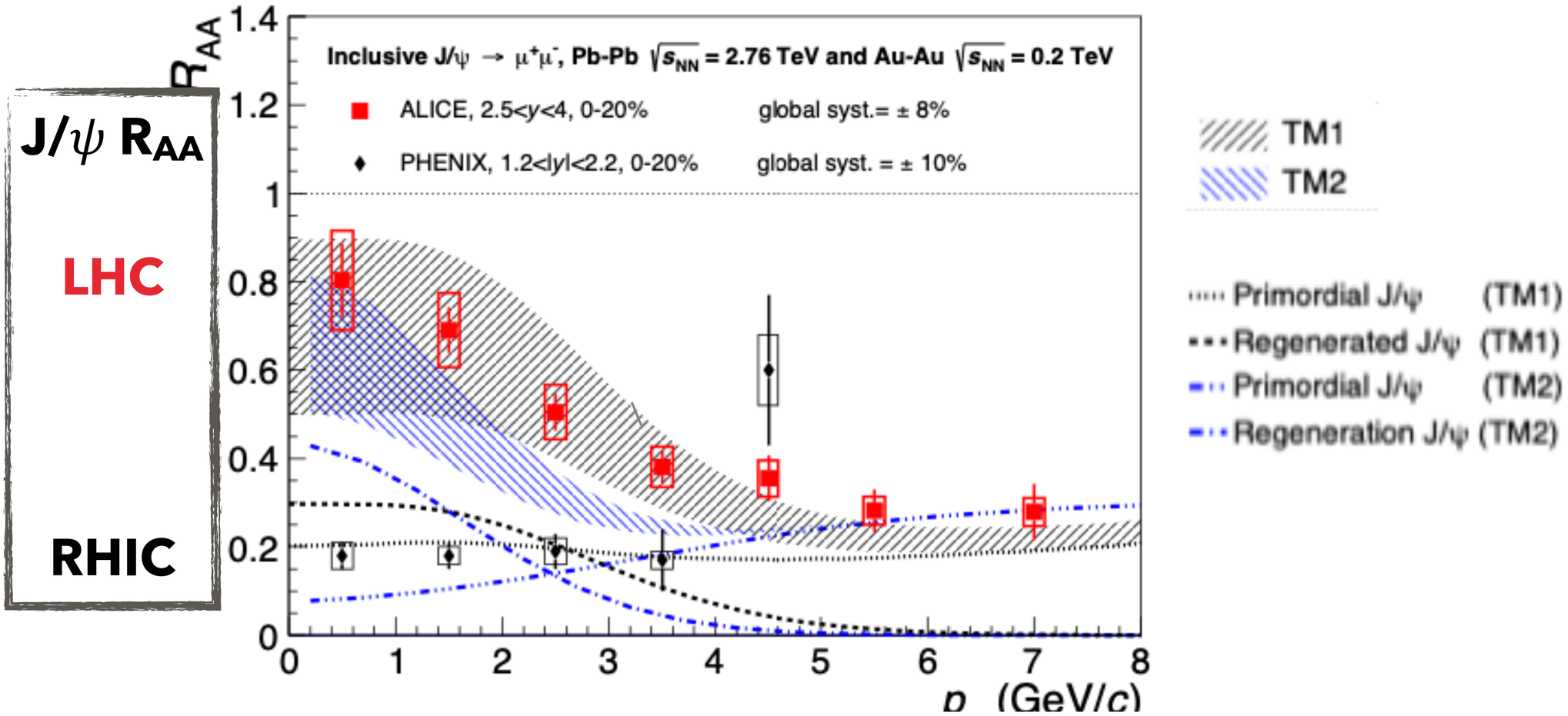
BUT WE ARE SURE WE HAVE RECOMBINATION AT WORK AT SOME LEVEL

PLB 734 (2014)

J/ψ R_{AA}

LHC

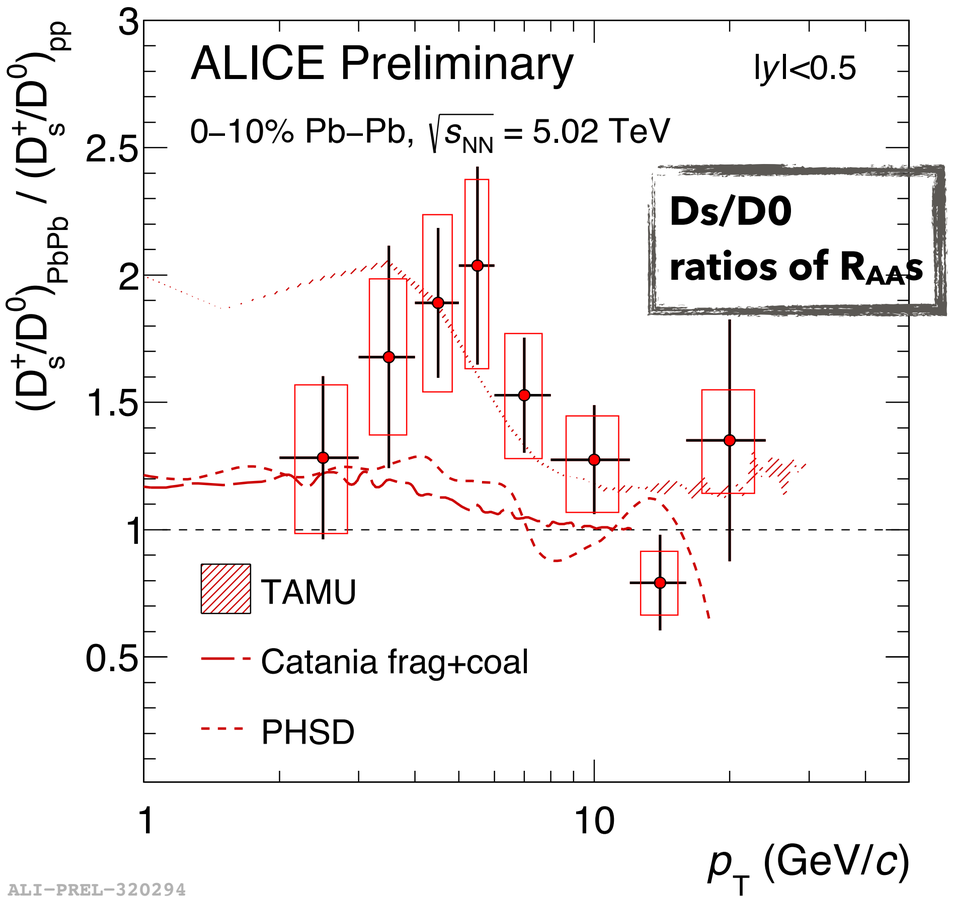
RHIC



- **Huge success for J/ψ!**
  - more charm at LHC than at RHIC

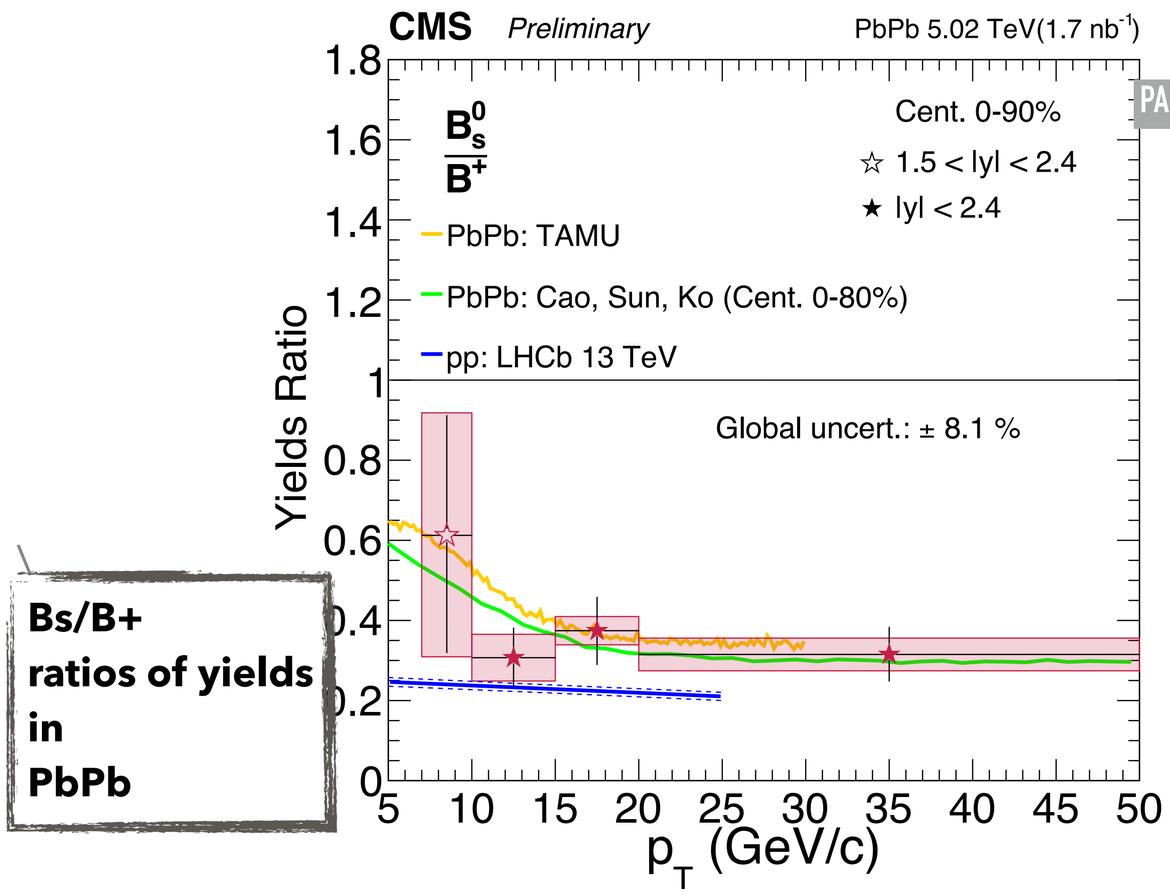
.. AND MAKES SENSE TO CONSIDER RECOMBINATION AT WORK FOR HF TOO

CHARM



BEAUTY

PAS-HIN-19-011



- … 'cose strangeness enhancement in AA (established experimentally)

- **Jury still out … and not that so simple as 'just recombination'**

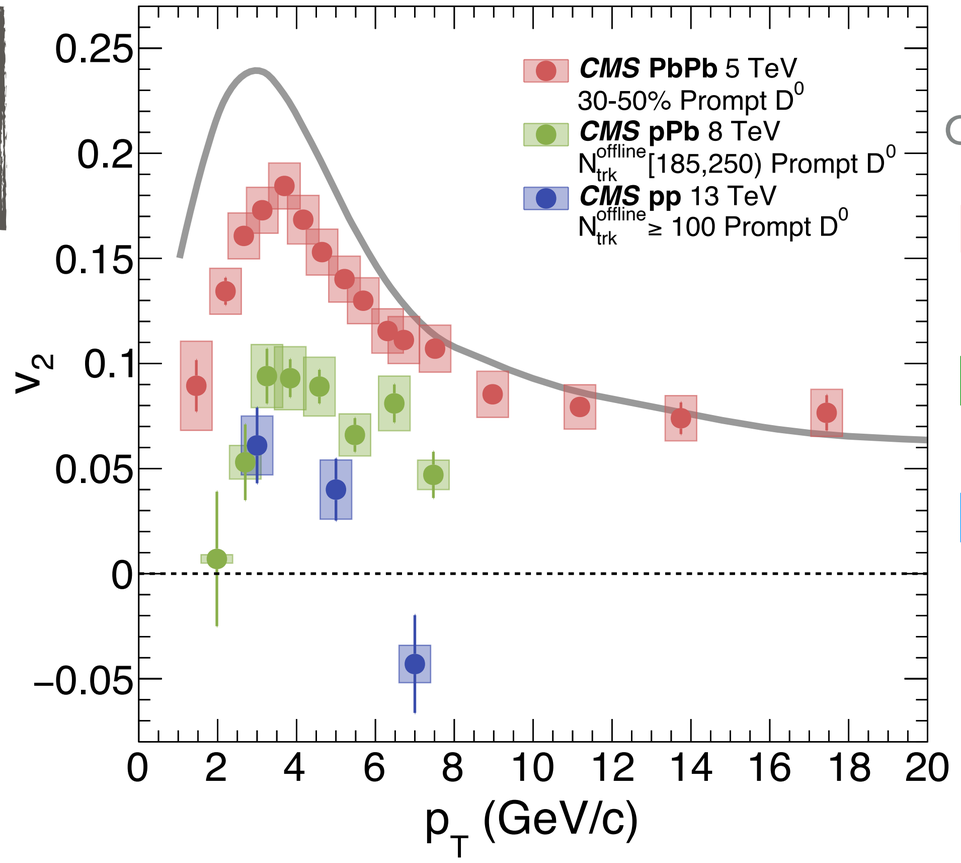
DON'T UNDERSTAND/AGREE: WHAT DOES V2!=0 FOR CHARM MEAN, IN ANY SYSTEM

CHARM

PLB 803 (2020)

Open charm

v_2



Curve: PbPb charged hadrons

Pb+Pb

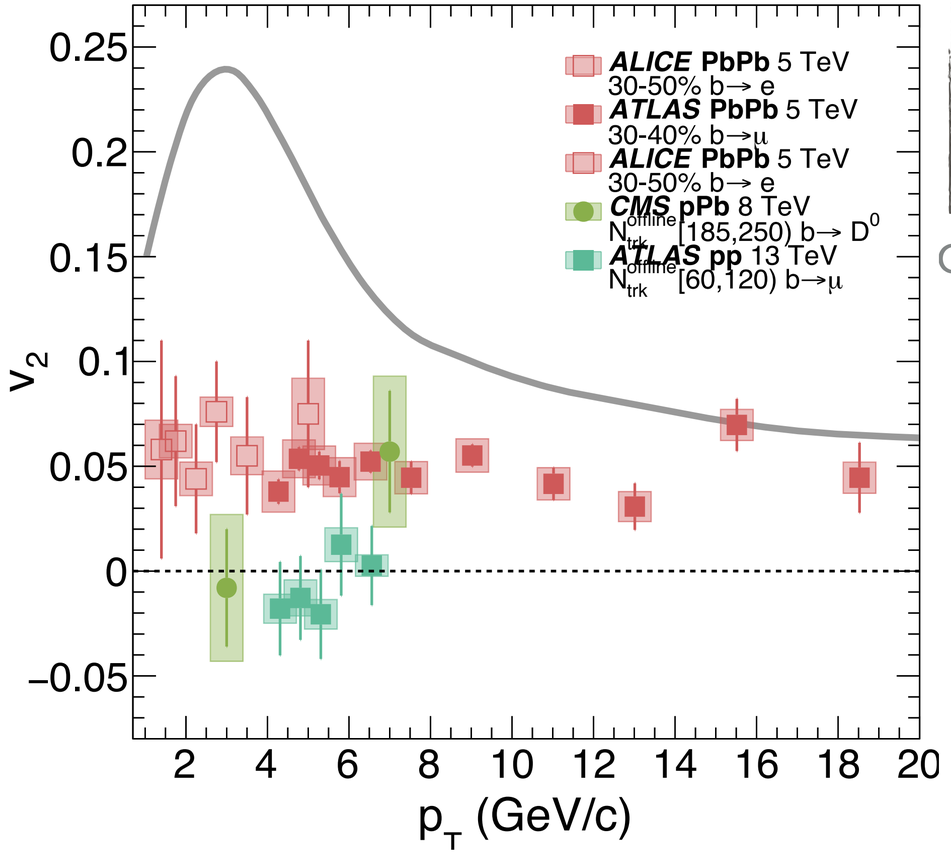
p+Pb

p+p

- **There is charm anisotropy… everywhere!**
- **Apparent ordering: v_2(PbPb)>v_2(pPb)>v_2(pp)**
  - so system size plays a role, but how?
  - options: final (QGP droplet) or initial (e.g. CGC) or …

DON'T UNDERSTAND . . . BUT AGREE IT HAPPENS AS EXPECTED . . . MOSTLY

BEAUTY



Open beauty v2

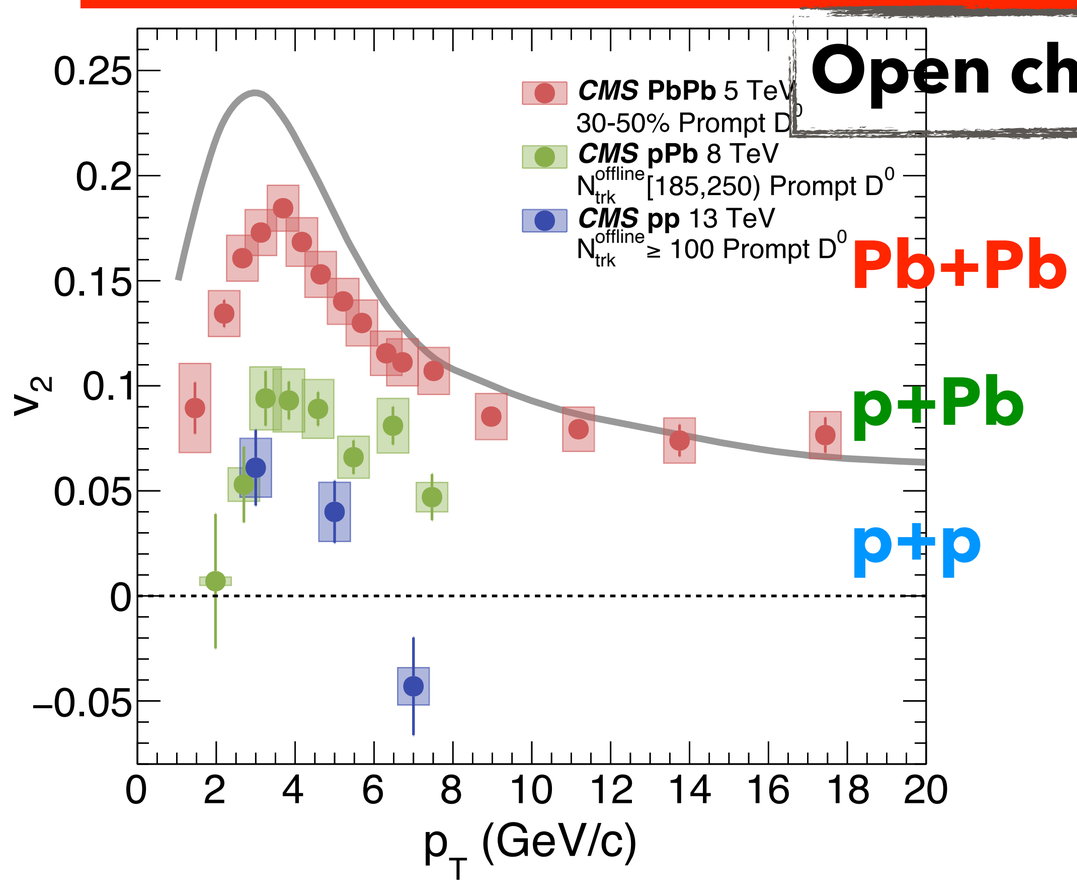
Curve: PbPb charged hadrons

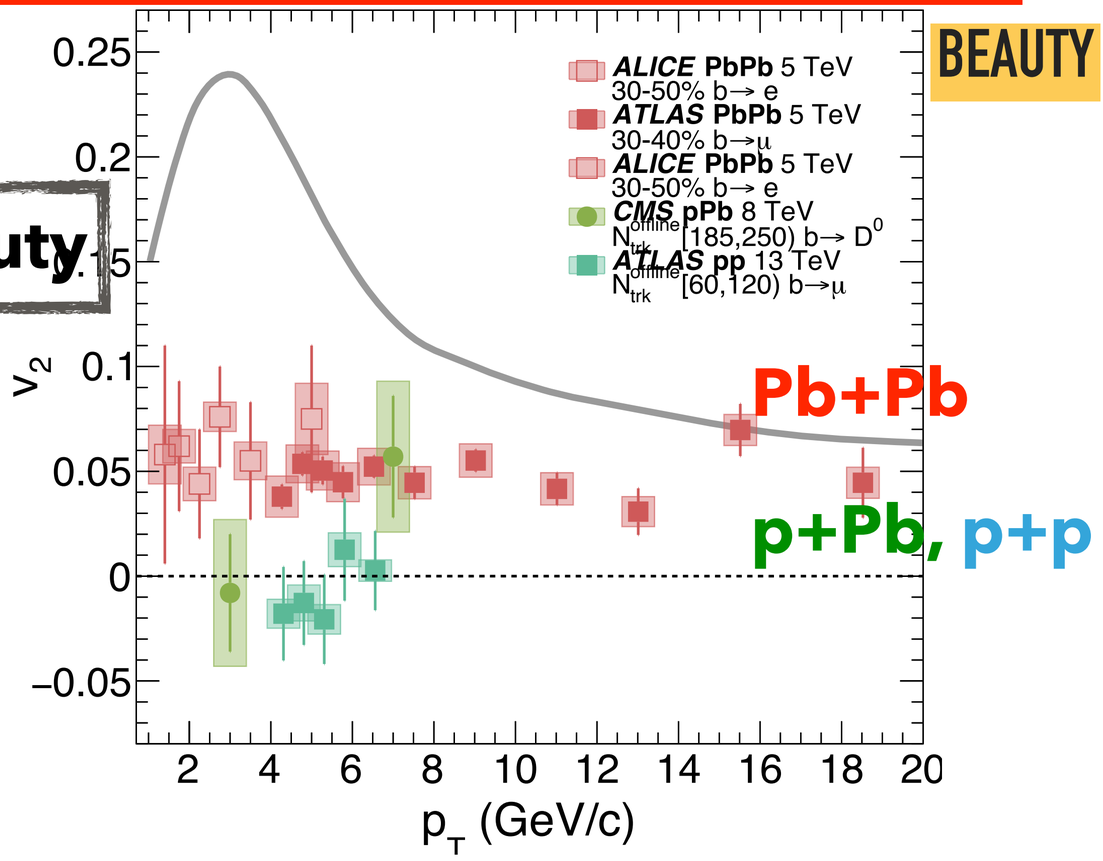
Pb+Pb

p+Pb, p+p

- **Hello 'normal'!**
  - v_2(PbPb)!=0 : a ~surprise
  - but, v_2(pPb) ~ v_2(pp) ~0

DON'T UNDERSTAND . . . BUT AGREE IT HAPPENS AS EXPECTED . . . MOSTLY





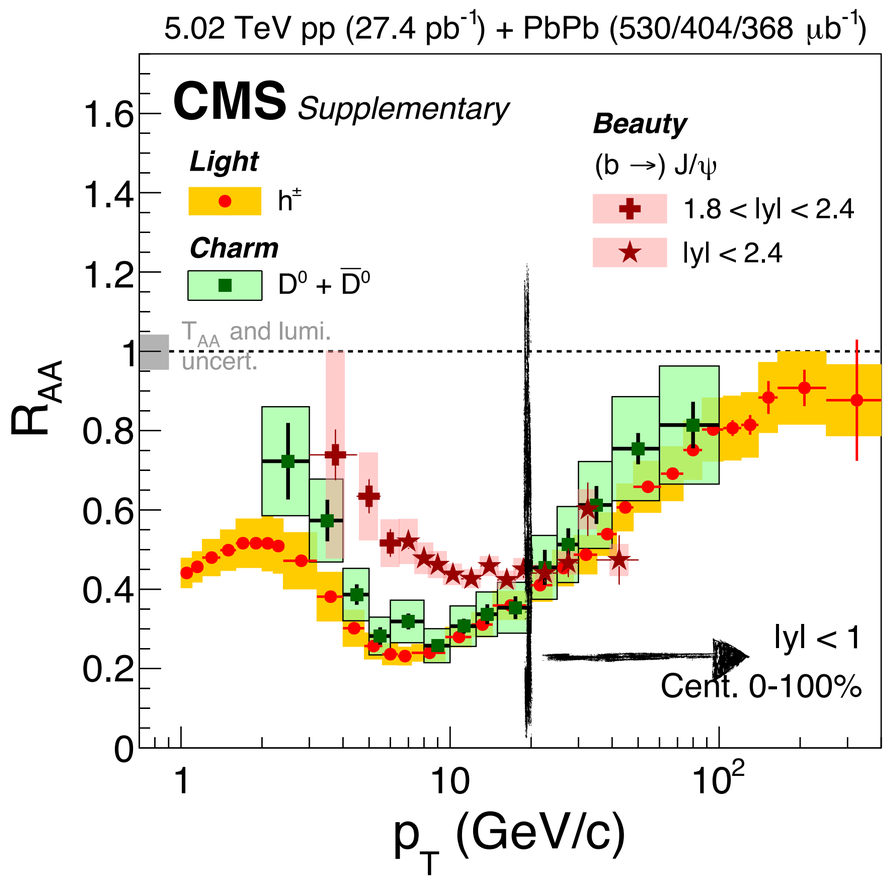
- **But what are the implications?**
  - clearly we hit some threshold, between charm and beauty phenomena
    - TBD: which limit is hit, and how/if it helps constraining the scenarios in small systems

AFTER SOME A+A RESULTS

- Mood check: getting ugly …

HAVE SOME FUN!
OPEN CHARM VS OPEN BEAUTY

NEED TO UNDERSTAND THE MEANING OF THE FEATURES OBSERVED

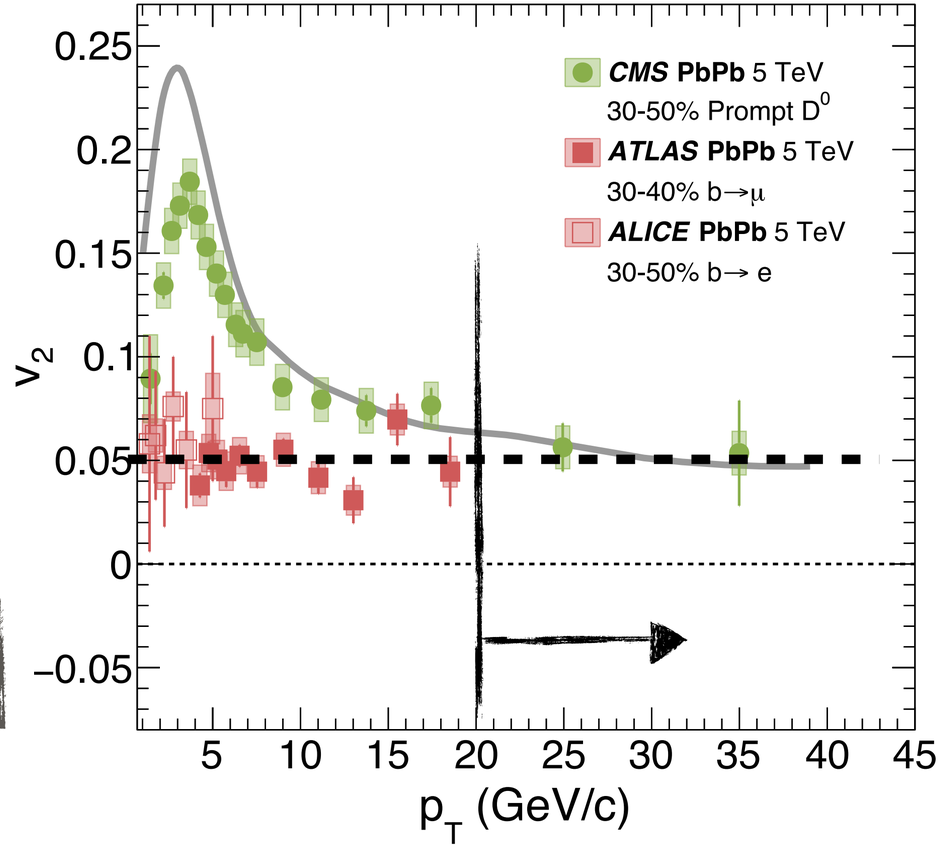


Open charm

Open beauty

R_{AA}

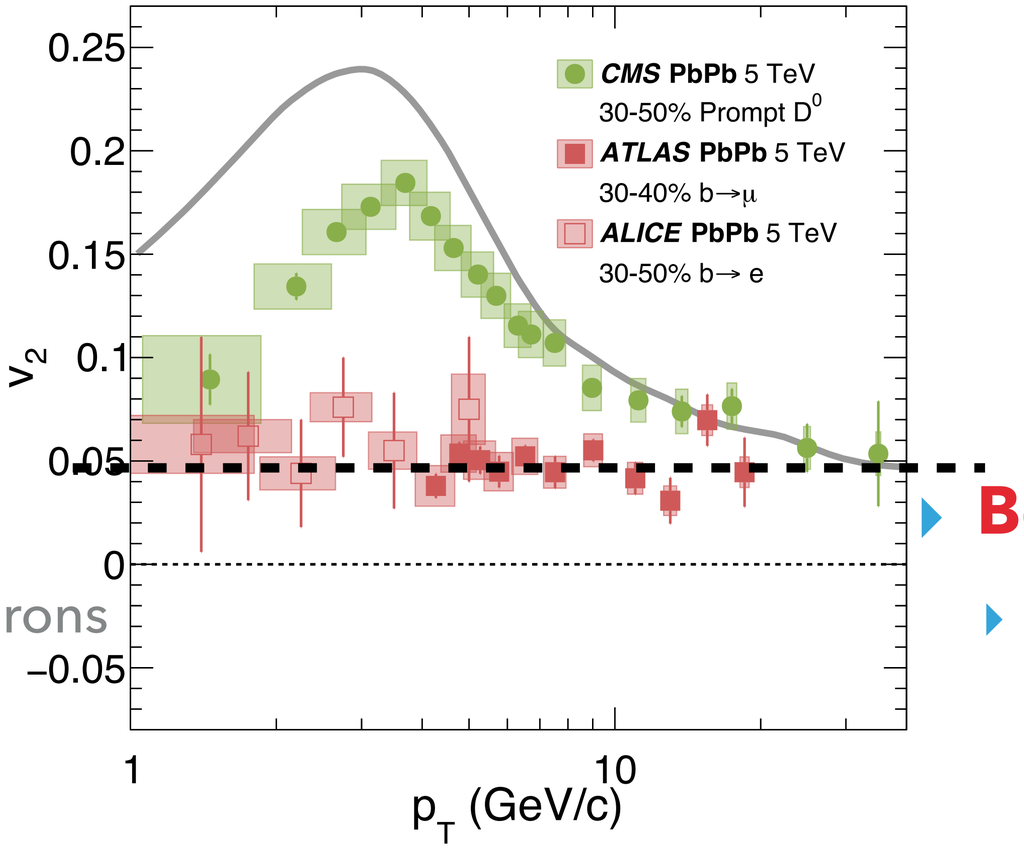
v_2



- **Something is happening around ~20GeV/c**
  - mass/flavor differences washed out
  - is data telling us we are hitting another .. 'threshold'?

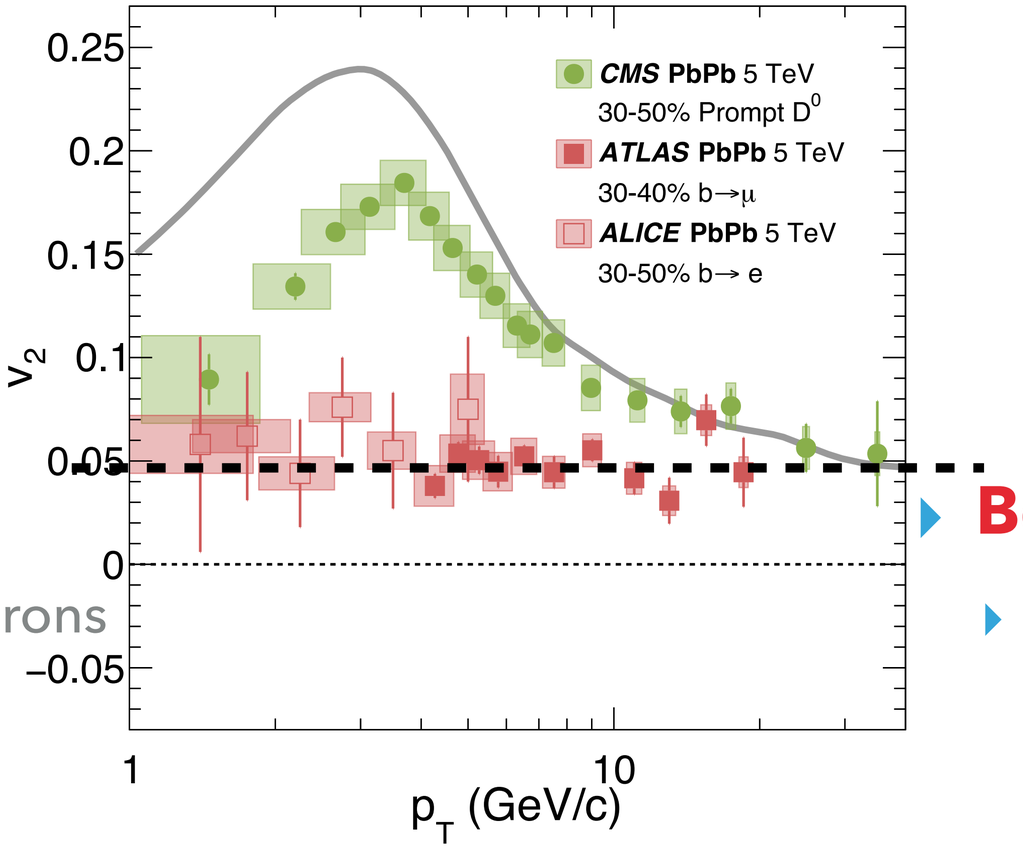
WHAT IS DATA EGGING US TOWARD?

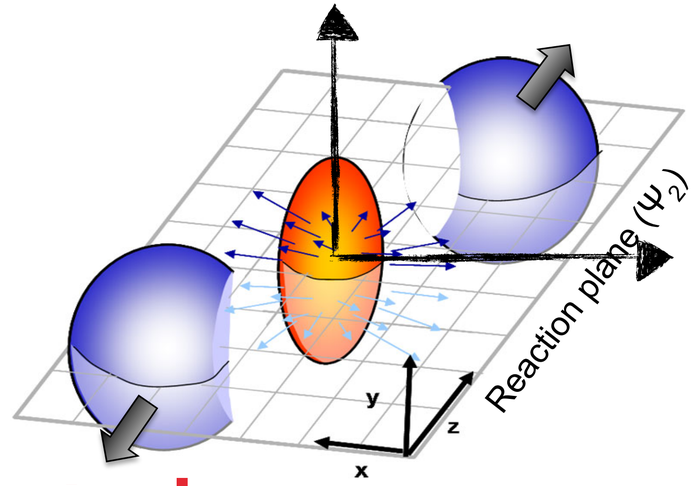
v_2



- **Charm shape**
  - following the charged hadrons
- **Beauty shape**
  - **conspicuously flat**

WHAT IS DATA EGGING US TOWARD?





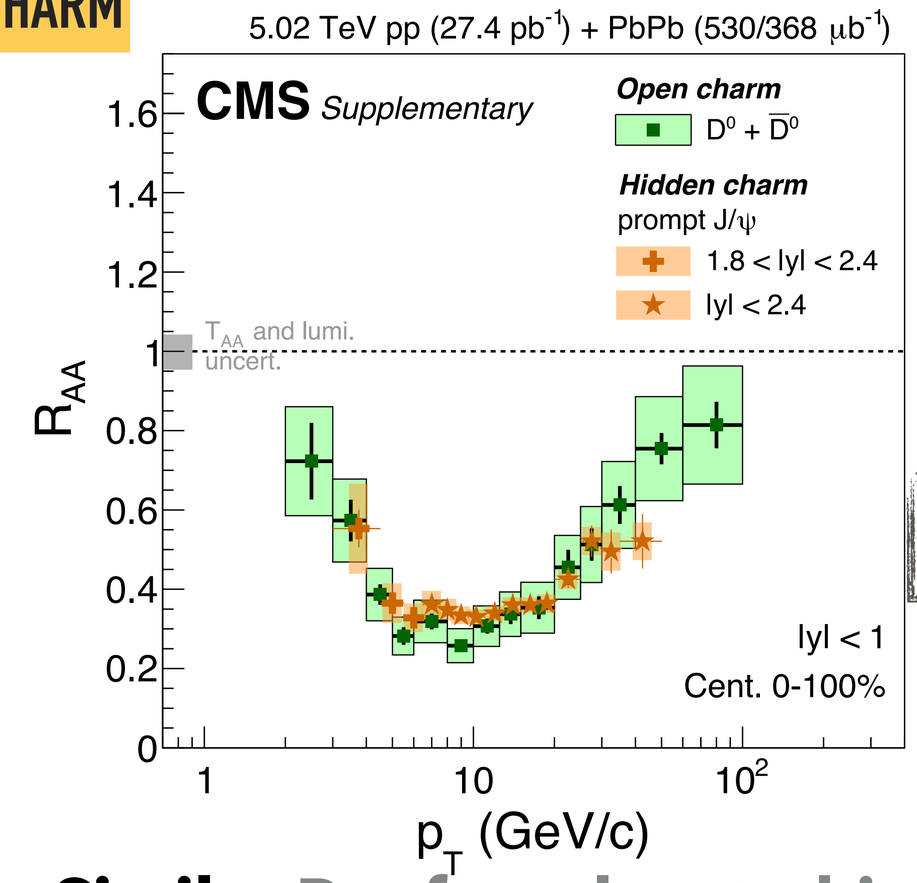
- **Charm shape**
  - following the charged hadrons
- **Beauty shape**
  - **conspicuously flat**

- **Found a reference for size of path-length dependent energy loss?**
  - anything (?) beside this would produce a ‘bump ‘at low-p_T …
    - yes, need more precise data, yes, the decay chain can flatten-out a peak.
    - BUT, whatever ‘peaky’-making additional effect, it looks like it’s.. tiny

HAVE SOME MORE FUN!
OPEN VS HIDEN HEAVY FLAVOR

WHAT ELSE IS DATA TELLING US?

CHARM



OPEN CHARM

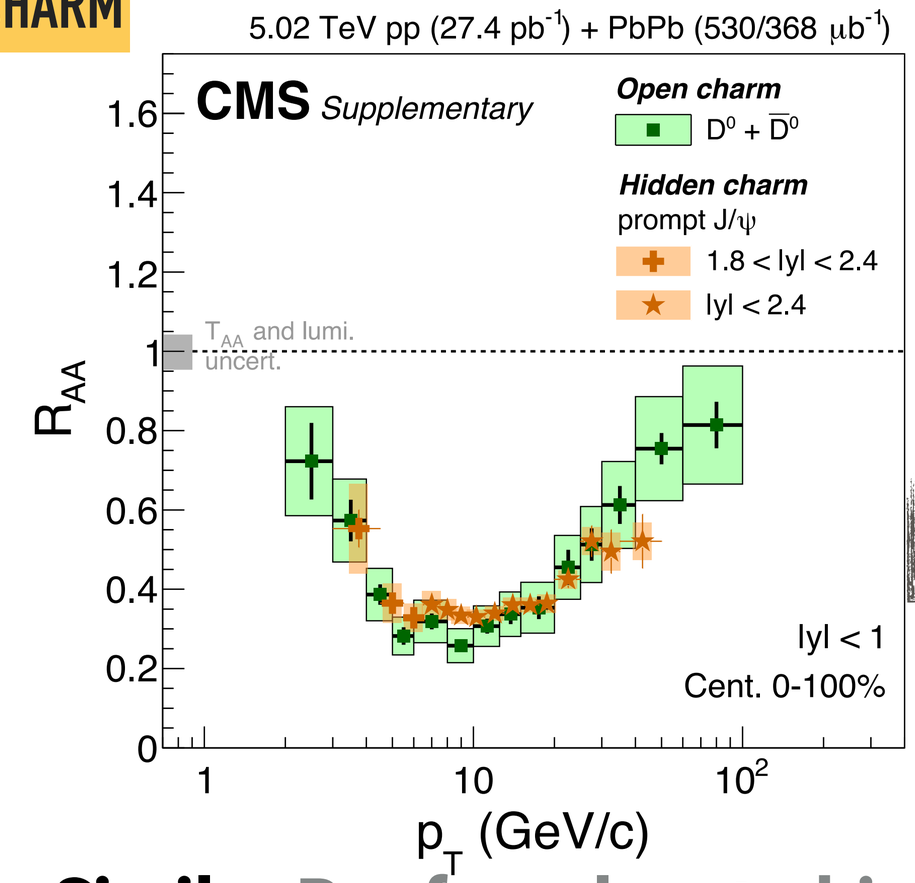
HIDDEN CHARM

R_{AA}

- **Similar R_{AA} from low to high-p_T!**

WHAT ELSE IS DATA TELLING US?

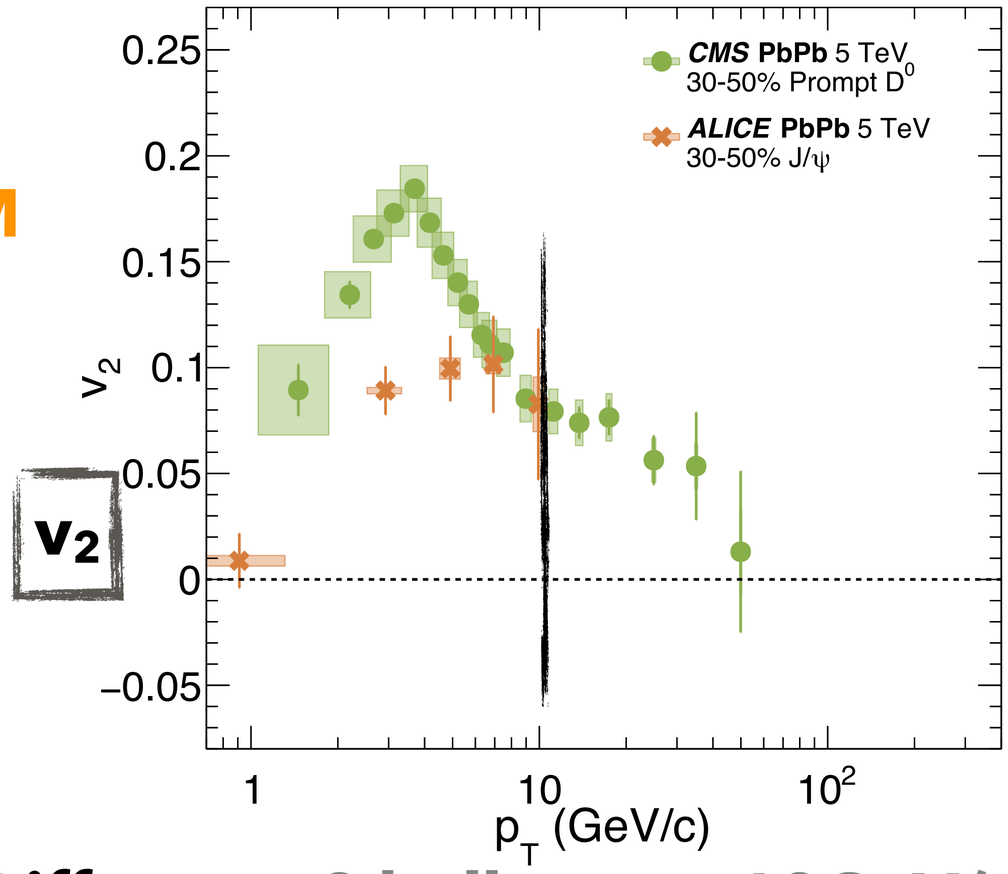
CHARM



OPEN CHARM

HIDDEN CHARM

R_{AA}



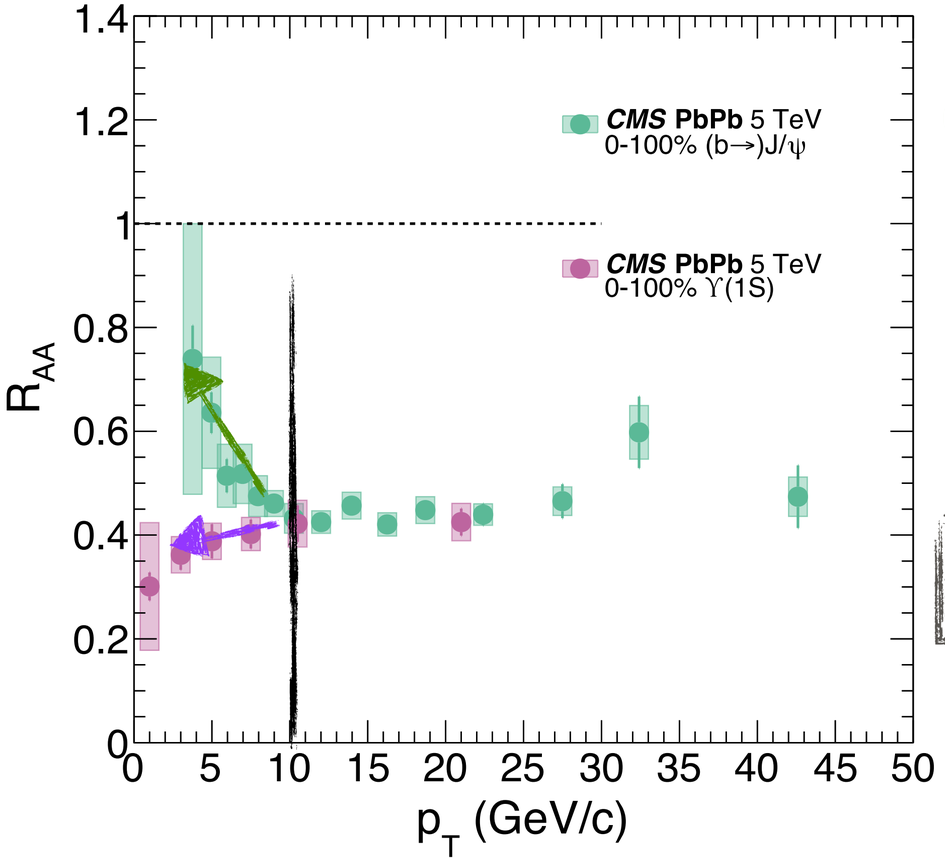
v_2

- **Similar R_{AA} from low to high-p_T!**
- **Different v2 bellow p_T~10GeV/c**

- **Another 'threshold' of sorts, @~10GeV between open and hidden charm ?**
  - Chance?

WHAT ELSE IS DATA TELLING US?

BEAUTY



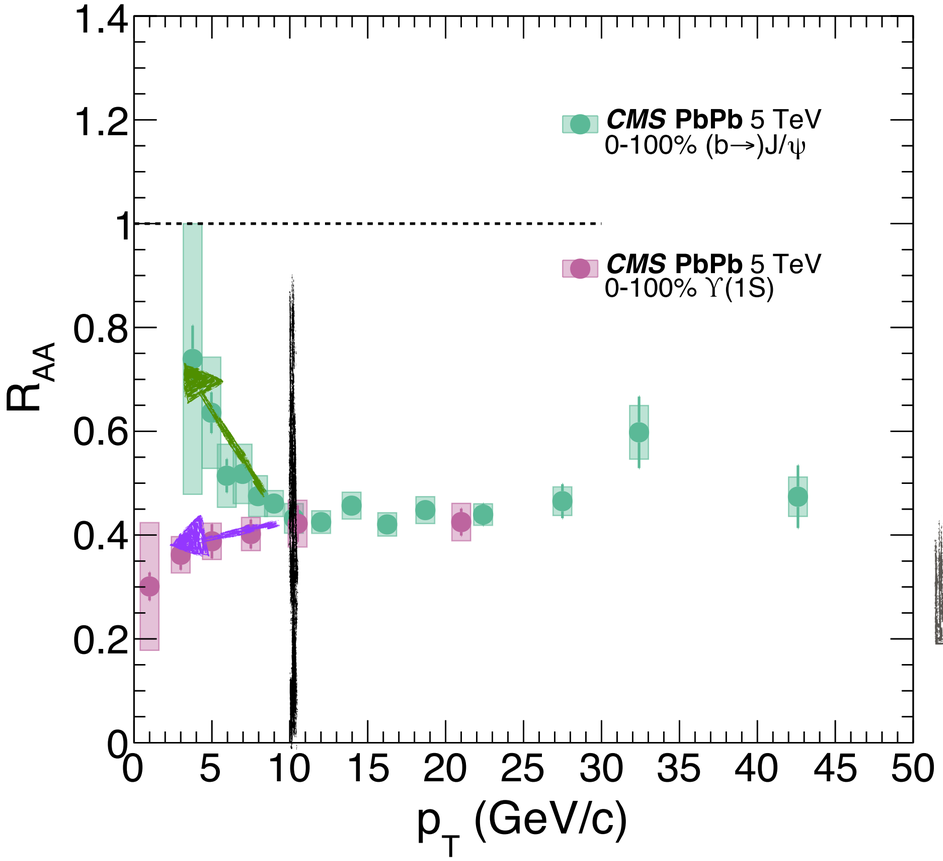
OPEN BEAUTY

HIDDEN BEAUTY

R_{AA}

- Similar R_{AA} for p_T > ~10GeV/c

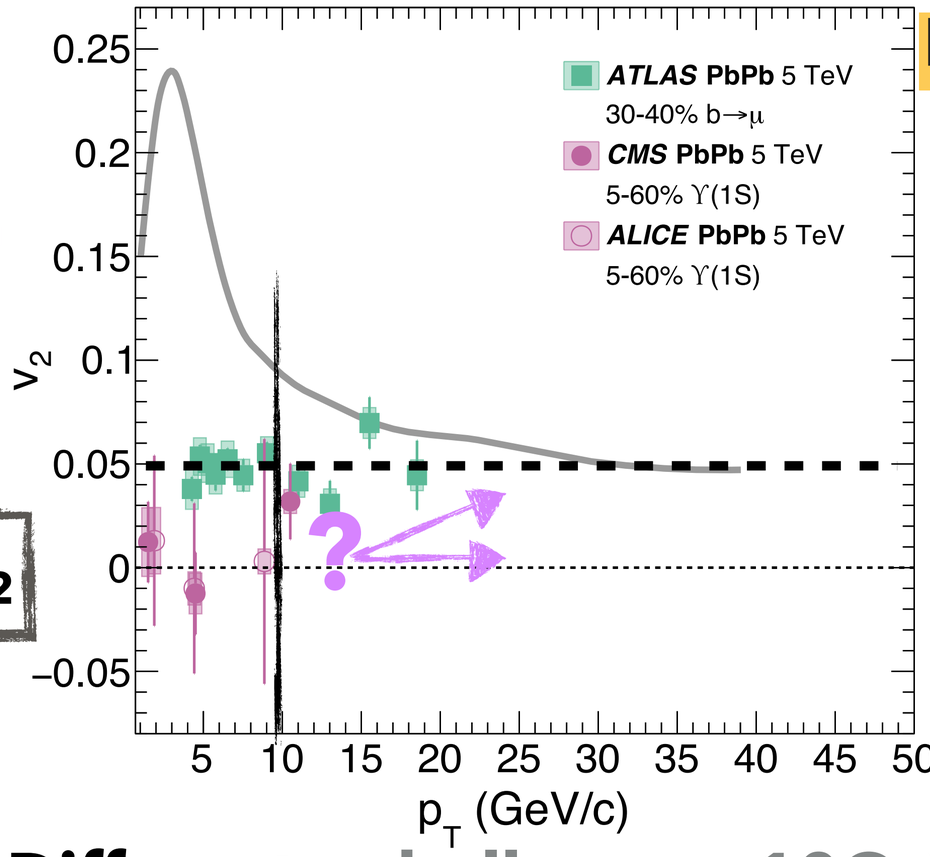
WHAT ELSE IS DATA TELLING US?



OPEN BEAUTY

HIDDEN BEAUTY

R_{AA}



v_2

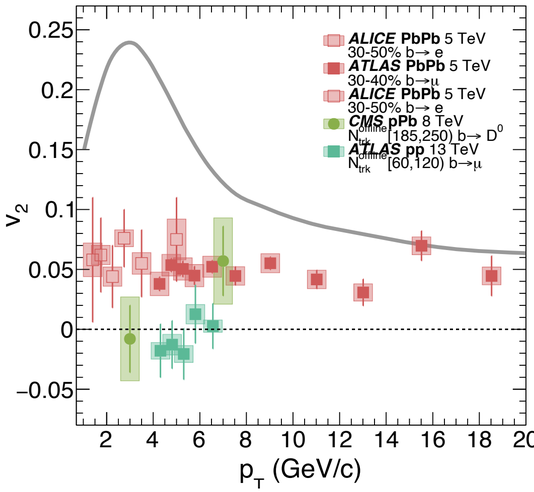
BEAUTY

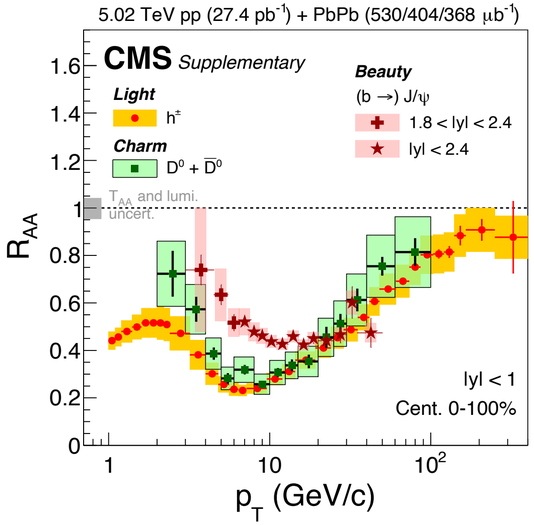
- **Similar R_{AA} for p_T > 10GeV/c!**
- **Different v_2 bellow p_T~10GeV/c**
  - 1000$ question: does Υ(1S) v2 goes up at higher pT??!

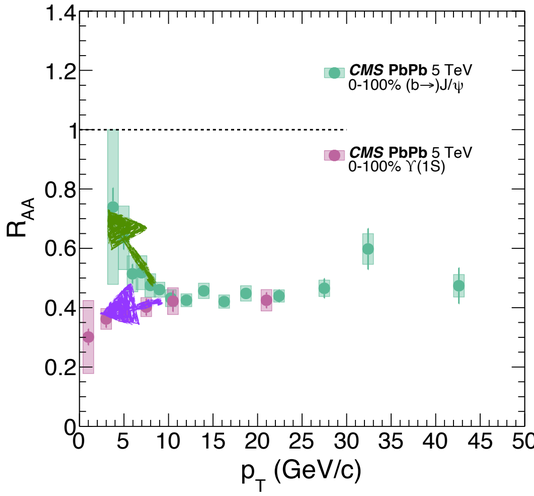
- **~10GeV seems some sort of threshold also for open and hidden beauty**

SUMMARY: OPEN HEAVY FLAVOR IN A+A COLLISIONS

- **Data seems to unravel some ‘thresholds’, between**
  - charm & beauty when going from A+A to p+p
  - (beauty, light+charm), and (charm, light)
  - open and hidden HF, in some form, at low-p_T





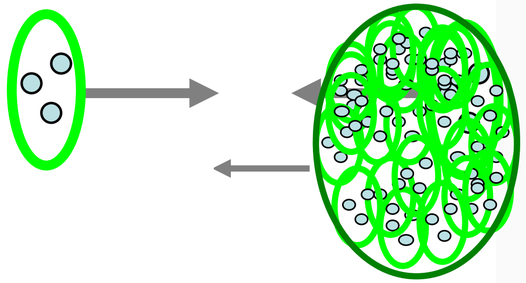


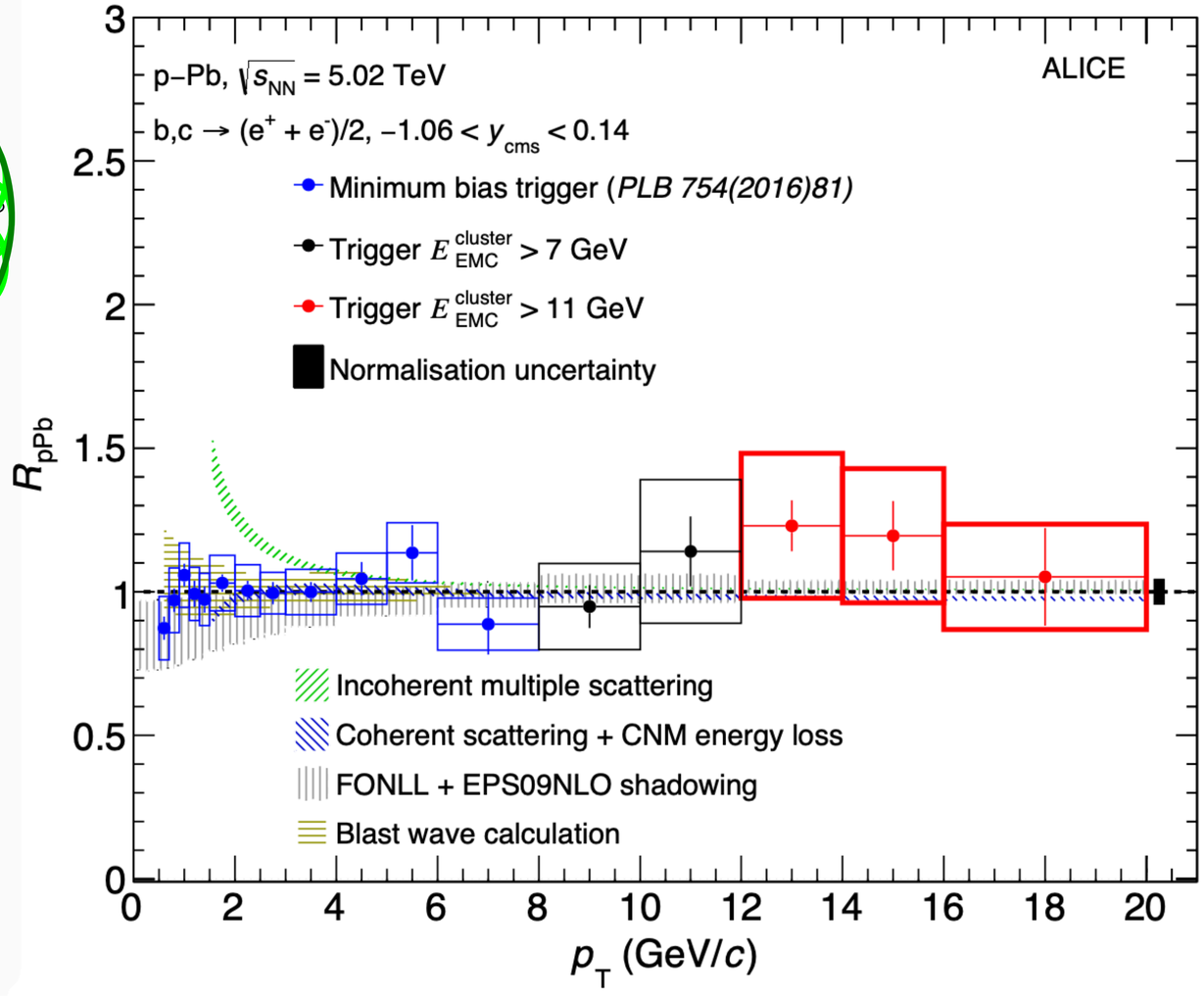
SO . . .

- **We are on a good path**
  - a plethora of new results, in pp, pA, and AA
  - many varied measurements: HF in jets, HF jets, correlations of all kinds
- **HF ‘Probe’ of uHIC?**
  - not yet, but getting there
- **Mood check: cautiously optimistic!**

AAAAND . . . I'M DONE!

SUMMARY: OPEN HEAVY FLAVOR IN PROTON+ION COLLISIONS





CHARM+BEAUTY

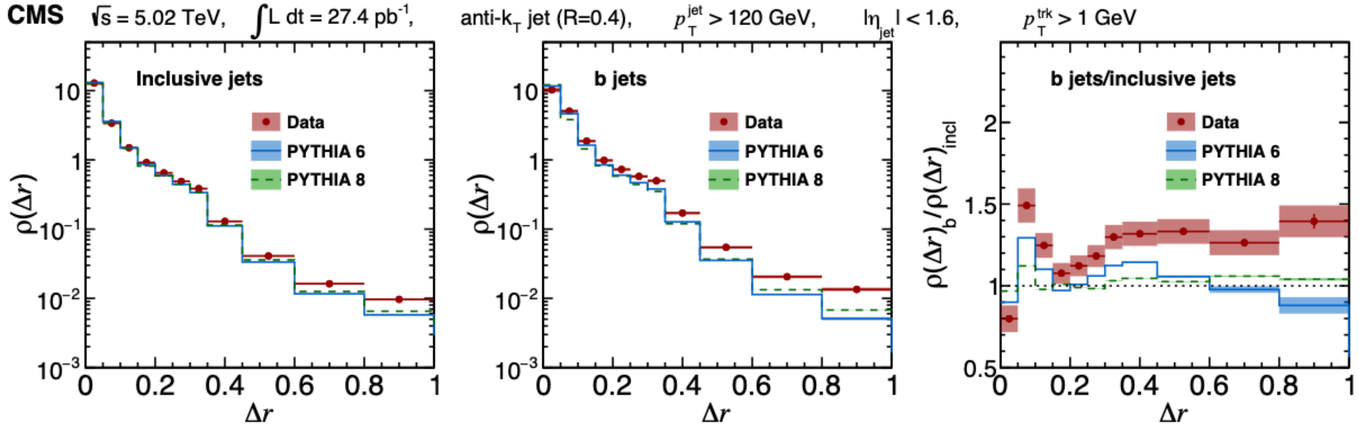


Figure 4: The jet shape distribution $\rho(\Delta r)$ of inclusive jets (left) and b jets (middle), both with $p_{\mathrm{T}} > 120\,\mathrm{GeV}$ and $p_{\mathrm{T}}^{\mathrm{trk}} > 1\,\mathrm{GeV}$ are presented as functions of Δr for data(red markers), the PYTHIA 6.426 (blue line) and the PYTHIA 8.230 (green dashed line) simulations. The right plot shows the b-to-inclusive jet shape ratio as functions of Δr for data, PYTHIA 6 (blue line) and PYTHIA 8.230 (green dashed line) simulations. The shadowed boxes represent the systematic uncertainty.

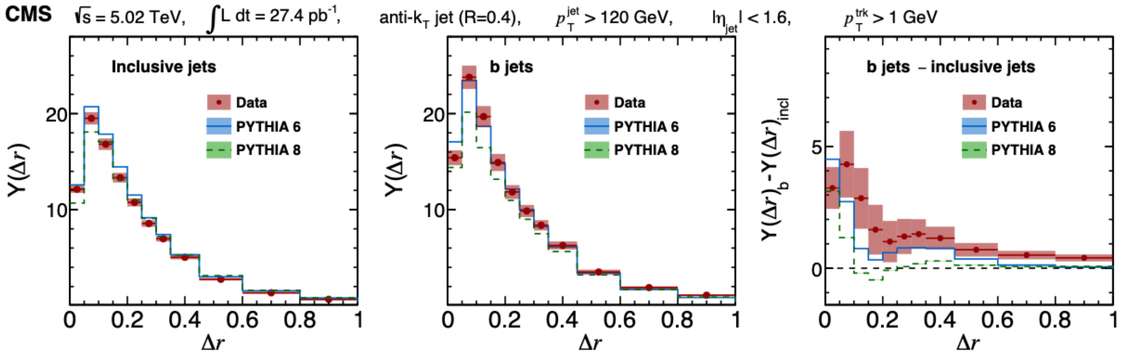
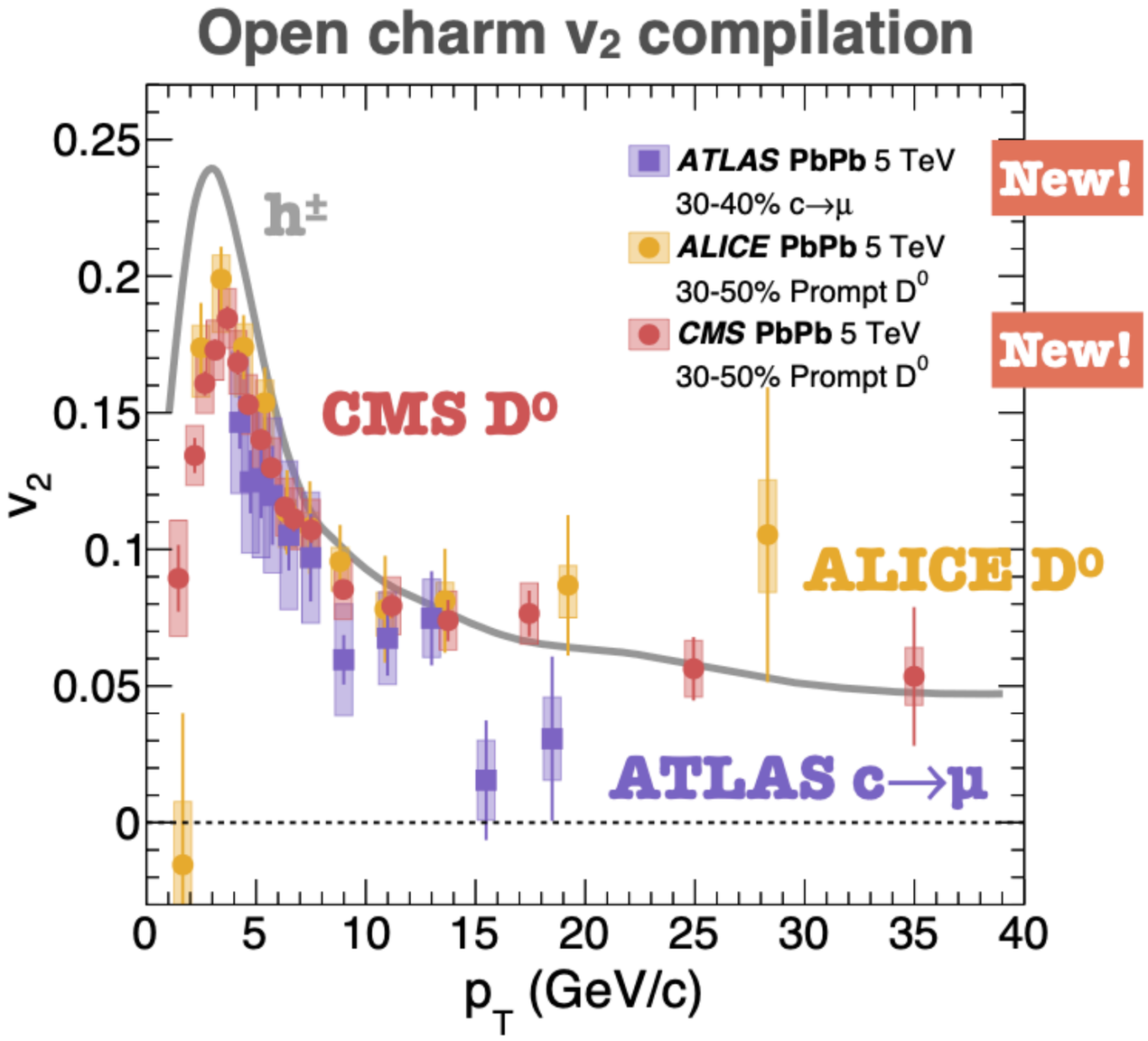
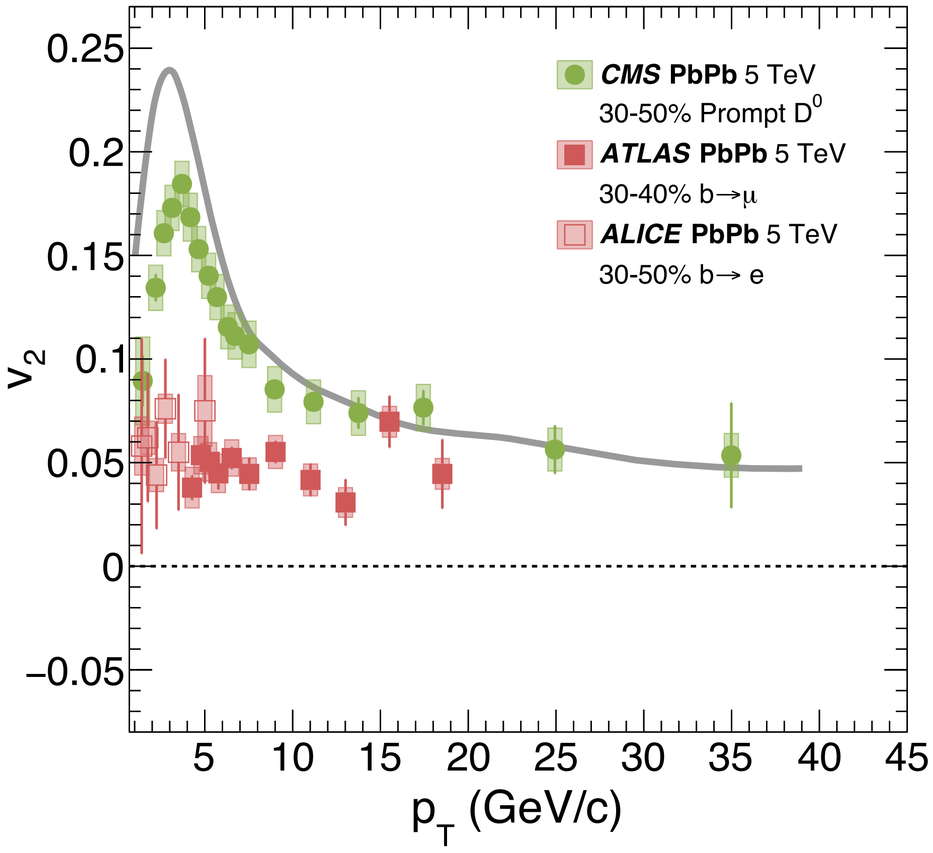


Figure 2: Charged particle yield distributions $Y(\Delta r)$ of inclusive jets (left) and b jets (middle) with $1 < p_{\mathrm{T}}^{\mathrm{trk}} < 12\,\mathrm{GeV}$ are presented as functions of Δr. Both types of jets with $p_{\mathrm{T}} > 120\,\mathrm{GeV}$ and charged particles with $1 < p_{\mathrm{T}}^{\mathrm{trk}} < 12\,\mathrm{GeV}$ are used to construct the distributions as functions of Δr for data (red), PYTHIA 6.426 (blue line) and PYTHIA 8.230 (green dashed line) simulations , respectively. The right plot shows the particle yield difference of b jets and inclusive jets as functions of Δr for pp data and PYTHIA 6.426 (blue line) and PYTHIA 8.230 (green dashed line) simulations. The shadowed boxes represent the systematic uncertainties.


Open charm v2 compilation
h±
ATLAS PbPb 5 TeV
30-40% c→μ
ALICE PbPb 5 TeV
30-50% Prompt D0
CMS PbPb 5 TeV
30-50% Prompt D0
New!
New!
CMS D0
ALICE D0
ATLAS c→μ
v2
pT (GeV/c)


CMS PbPb 5 TeV
30-50% Prompt D0
ATLAS PbPb 5 TeV
30-40% b→μ
ALICE PbPb 5 TeV
30-50% b→ e
v2
pT (GeV/c)