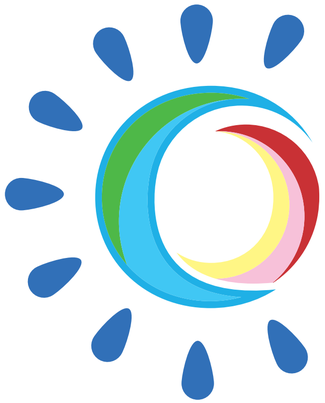
SQM2022

The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea



Recent experimental results on heavy flavor

Qipeng Hu

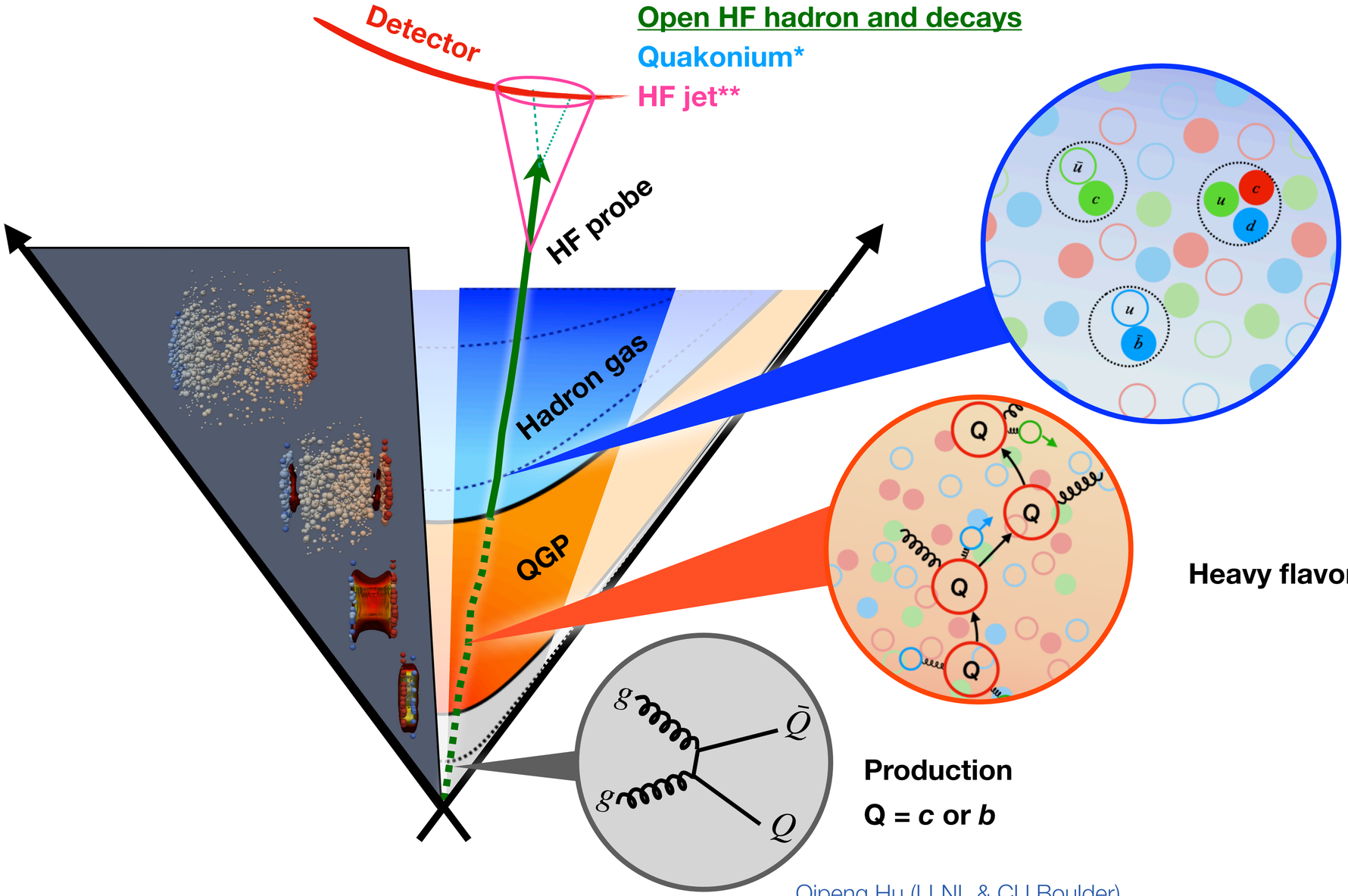
LLNL & CU Boulder

June 15, 2022

University of Colorado **Boulder**

Lawrence Livermore National Laboratory

Open heavy flavor in QGP



Open HF hadron and decays

Quakonium*

HF jet**

*Reivew of quarkonia: by Jaebeom Park

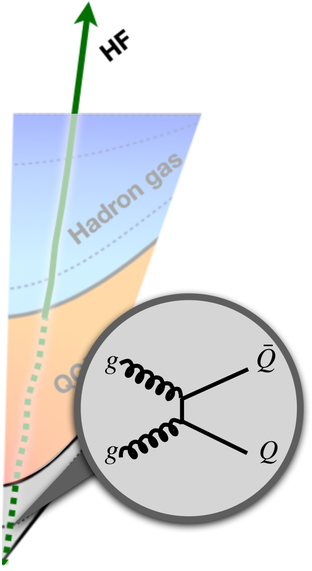
**Reivew of HF jet: by Saehanseul Oh

Heavy flavor quark hadronization

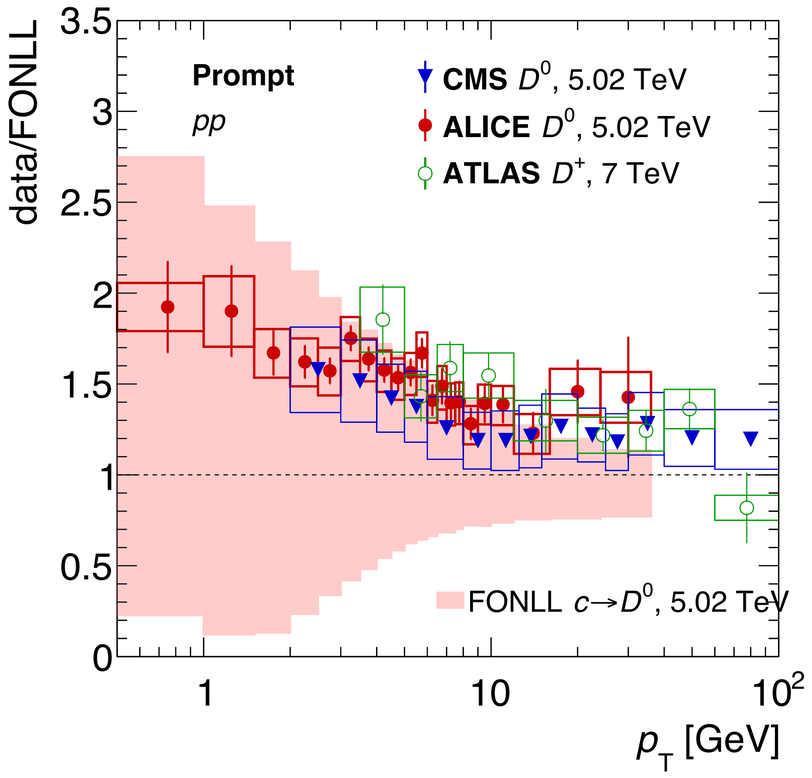
Heavy flavor quark-QGP interaction

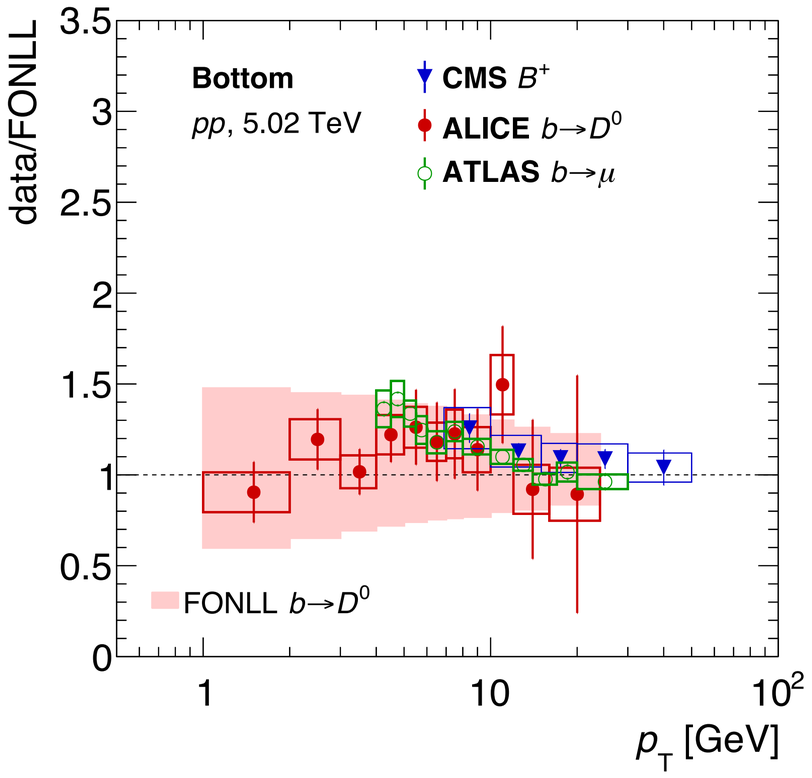
Production

Q = *c* or *b*



HF production in *pp* — cross section

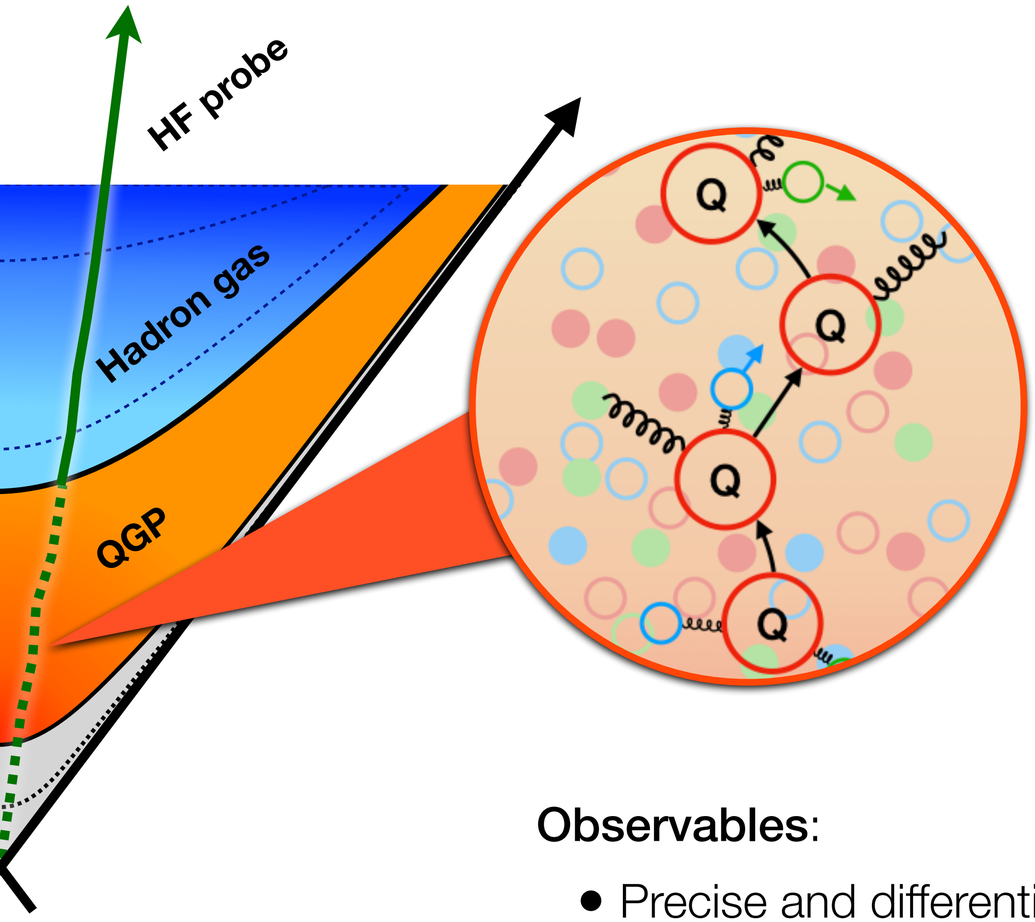




ALICE D^0: JHEP 05 (2021) 220
CMS D^0: PLB 782 (2018) 474
ATLAS D^+: NPB 907 (2016) 717
CMS B^+: PRL 119 (2017) 152301
ATLAS muon: PLB 829 (2022) 137077

- Data/FONLL of charm and bottom cross sections in *pp* collisions
- FONLL describe bottom cross section better. Charm data/FONLL ratio stays flat above 6 GeV, still good input for HF-QGP interaction

Open heavy flavor **in medium**



Open charm probes:

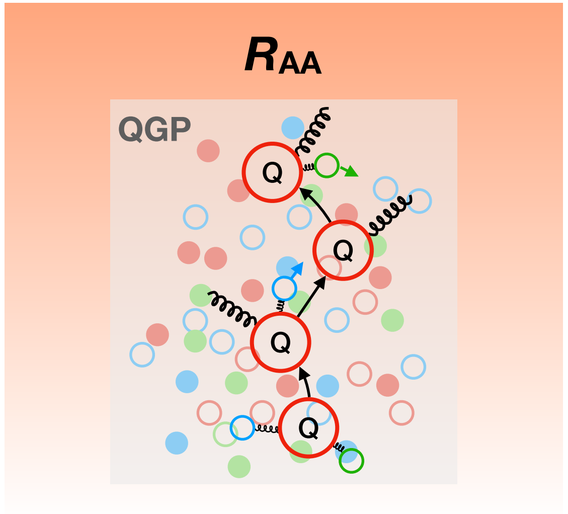
- Prompt *D* hadron
- $c \rightarrow l$

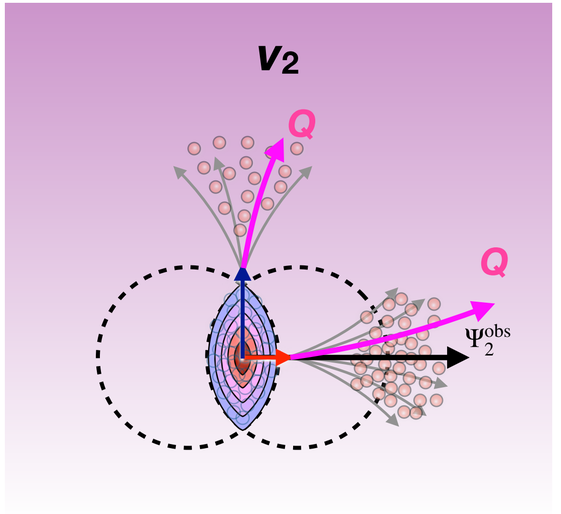
Open bottom probes:

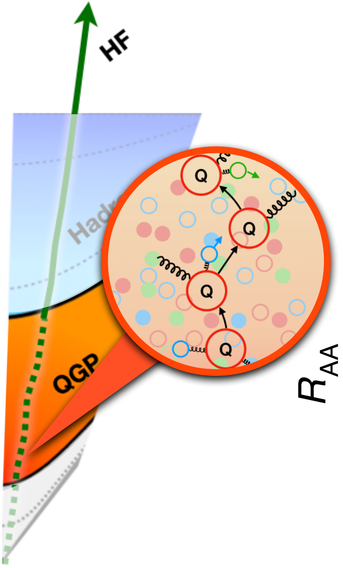
- $b \rightarrow D/\psi/l$
- Fully reconstructed *B* hadron

Observables:

- Precise and differential: R_{AA}, v_2





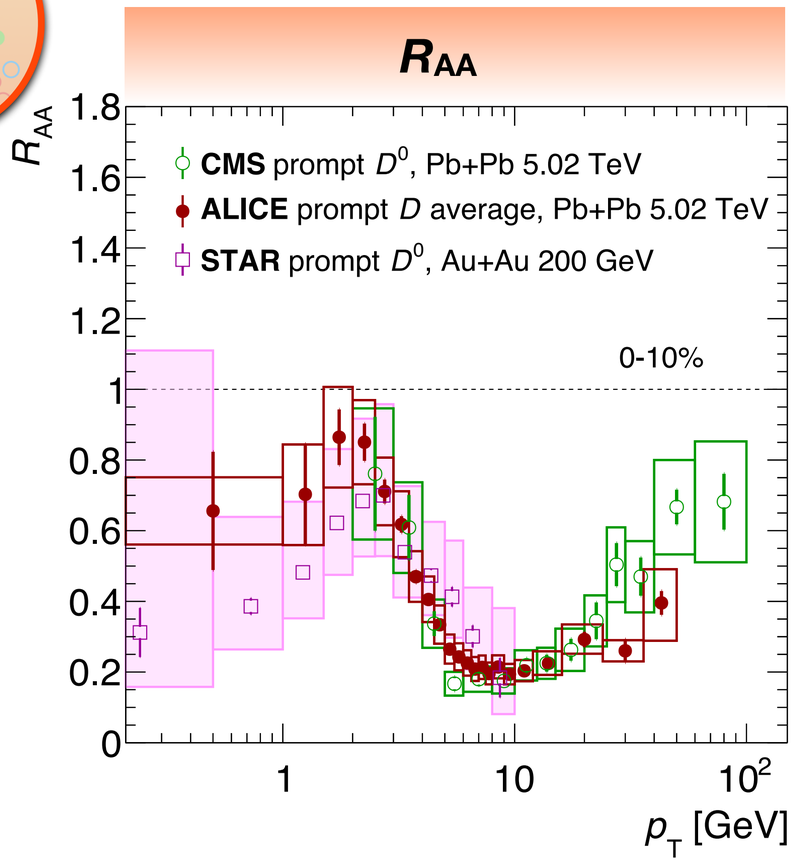


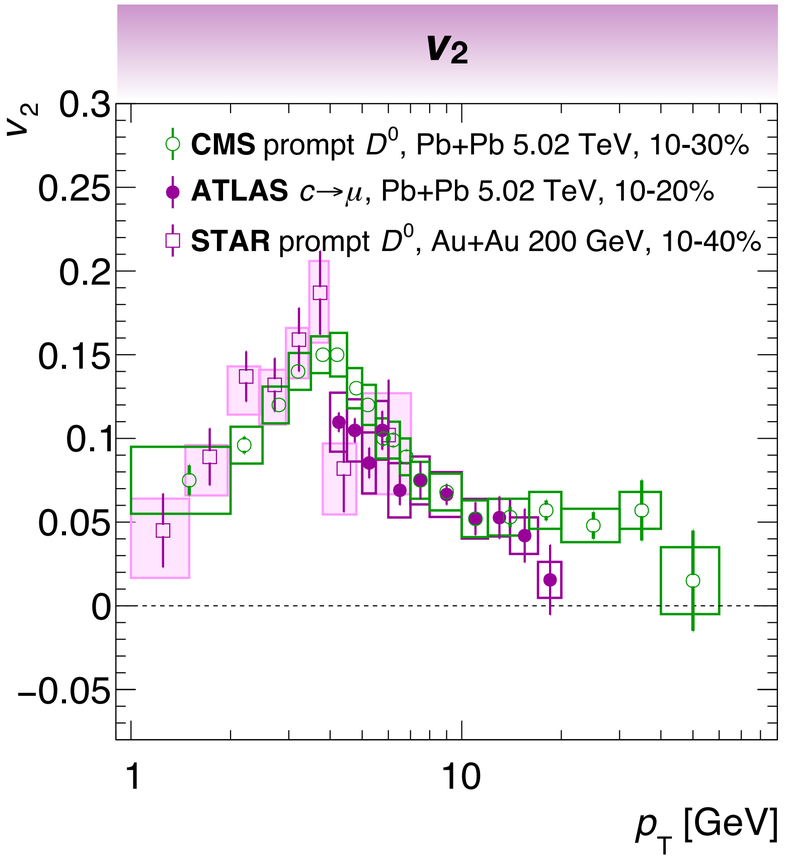
Charm-hadron in medium

ALICE talk: M. Völkl

CMS talk: M. Stojanovic

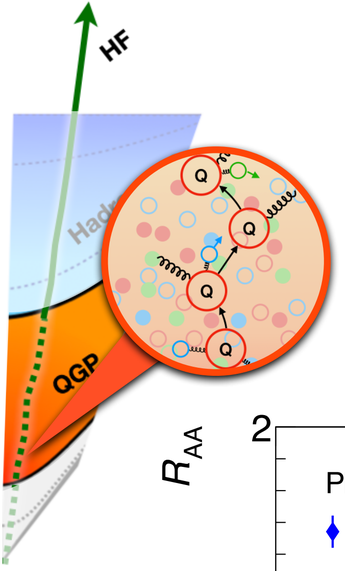
ATLAS talk: W. Zhou





ALICE R_{AA}, JHEP 01 (2022) 174
CMS R_{AA}, PLB 782 (2018) 474
STAR R_{AA} PRC 99 (2019) 034908

- Precise R_{AA} and v_2 measured down to p_T ~ 0 GeV. Open charm is stronlgy modified in a p_T dpenent way
- Perfect consistency between LHC experiments: ALICE, CMS, ATLAS
- Similarity between LHC and RHIC



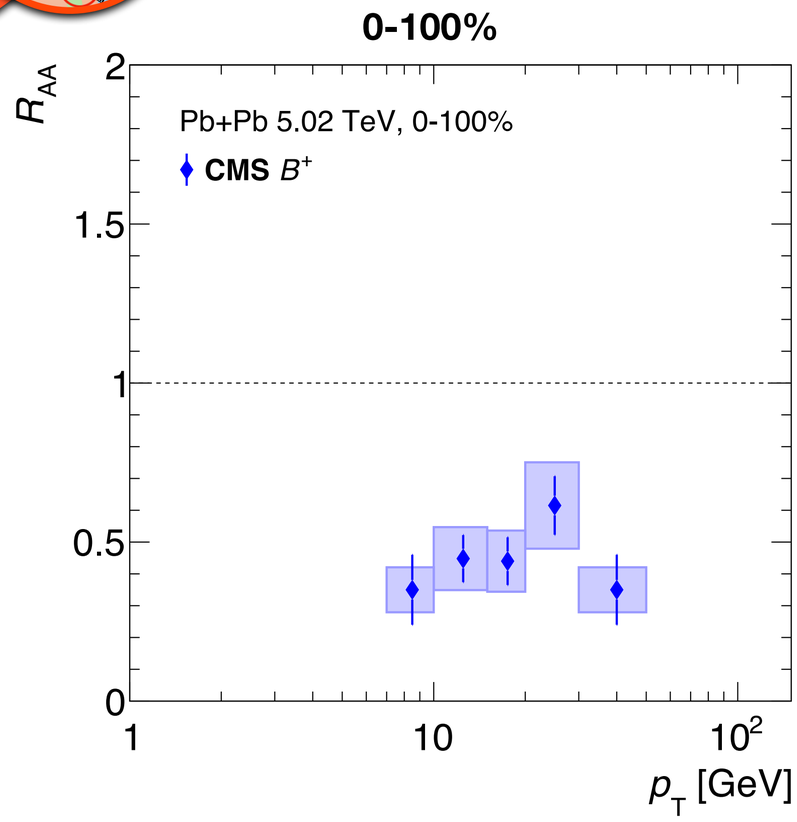
Bottom-hadron in medium — R_{AA}

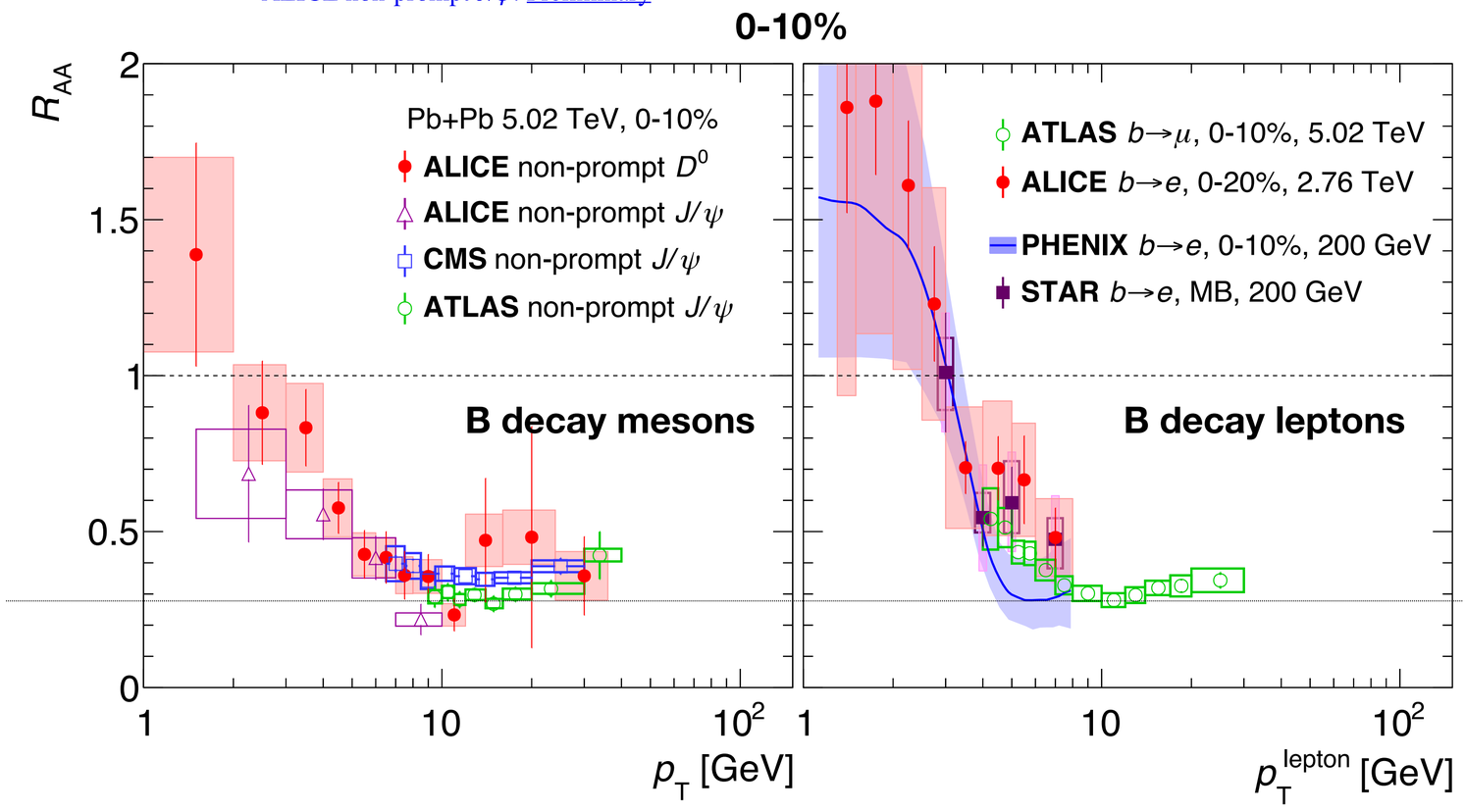
ALICE talk: S. Politanò
ATLAS talk: W. Zhou
PHENIX talk: R. Nouicer

CMS B^+: PRL 119 (2017) 152301

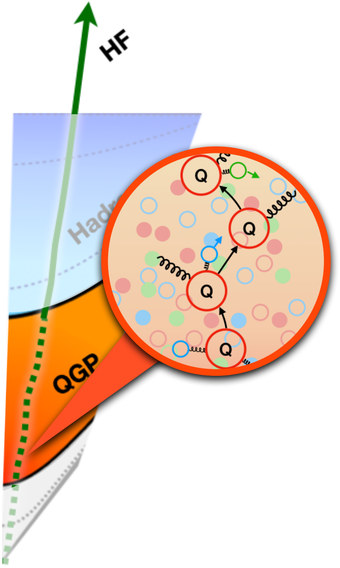
ALICE non-prompt D^0: arXiv:2202.00815
CMS non-prompt J/ψ: EPJC 78 (2018) 509
ATLAS non-prompt J/ψ: EPJC 78 (2018) 762
ALICE non-prompt J/ψ: Preliminary

ATLAS muon: PLB 829 (2022) 137077
ALICE electron: JHEP 07 (2017) 052
PHENIX electron: arXiv:2203.17058
STAR electron: arXiv:2111.14615





- B^+ R_{AA} has limited kinematic coverage and precision
- Bottom R_{AA} measured via B decays can reach much higher precision

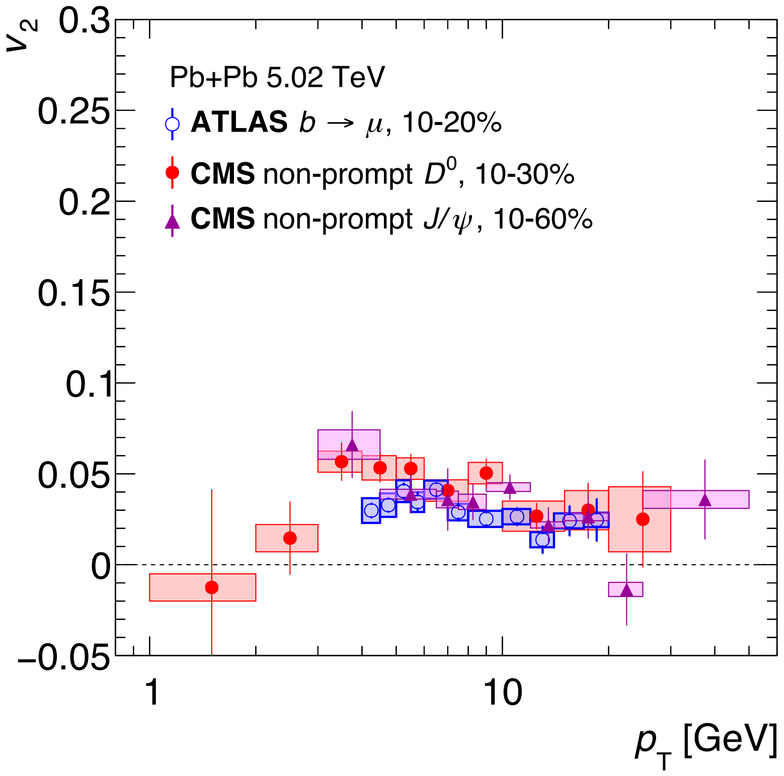


Bottom-hadron in medium — v_2

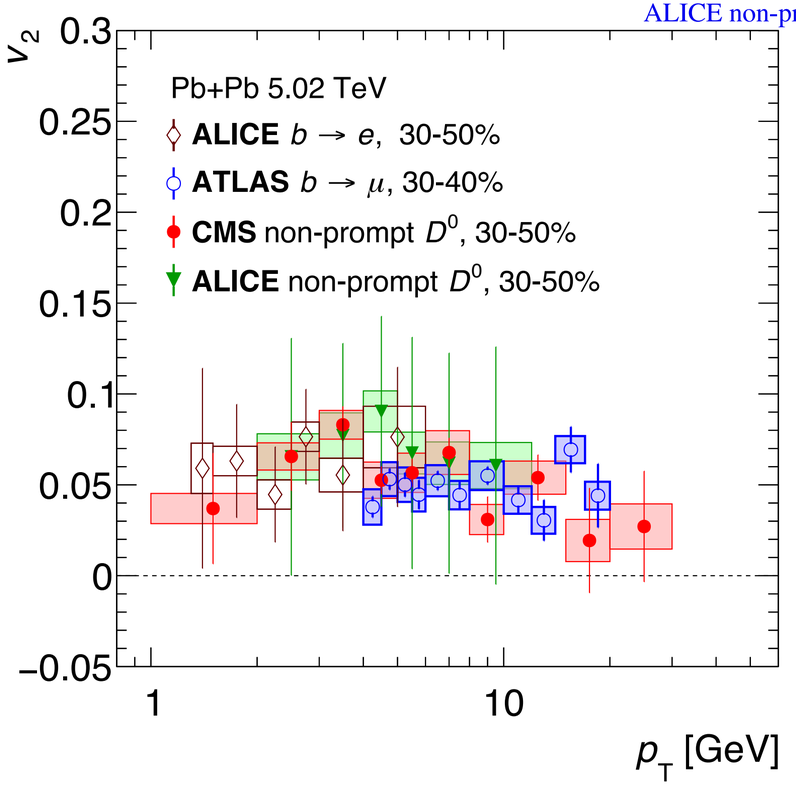
CMS talk: M. Stojanovic
ATLAS talk: W. Zhou
ALICE talk: S. Politanò

ATLAS muon: PLB 807 (2020) 135595
ALICE electron: PRL 126 (2021) 162001
CMS non-prompt J/ψ: CMS-PAS-HIN-21-008 (preliminary)
CMS non-prompt D^0: CMS-PAS-HIN-21-003 (preliminary)
ALICE non-prompt D^0: Preliminary

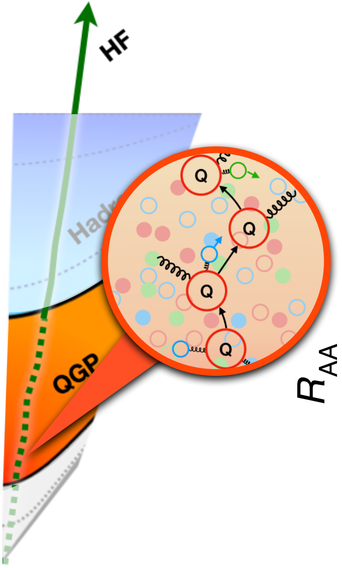
10-30%



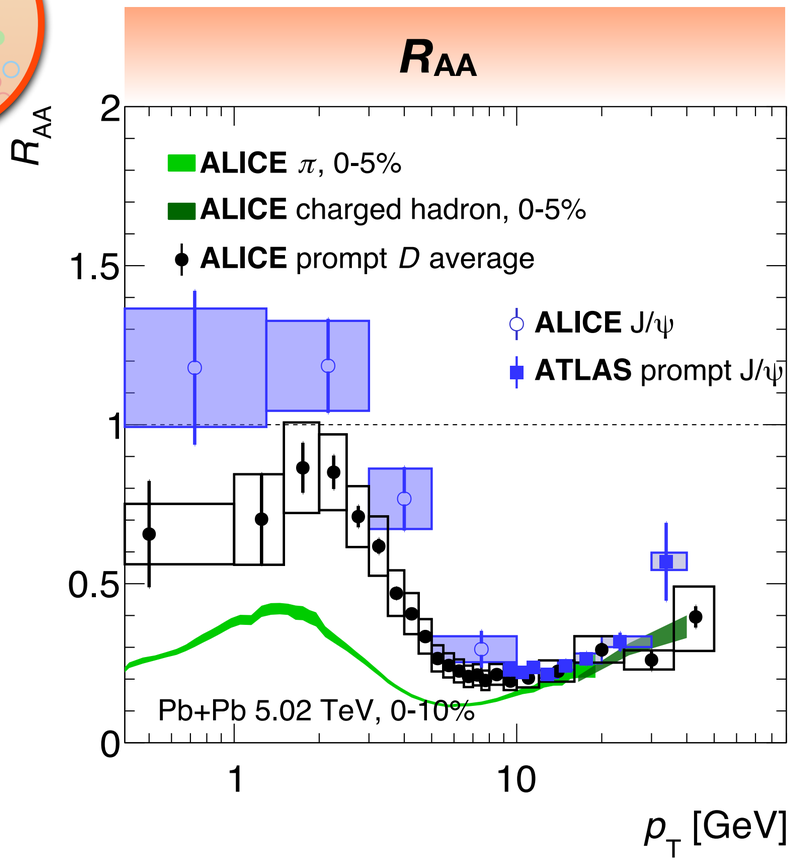
30-50%

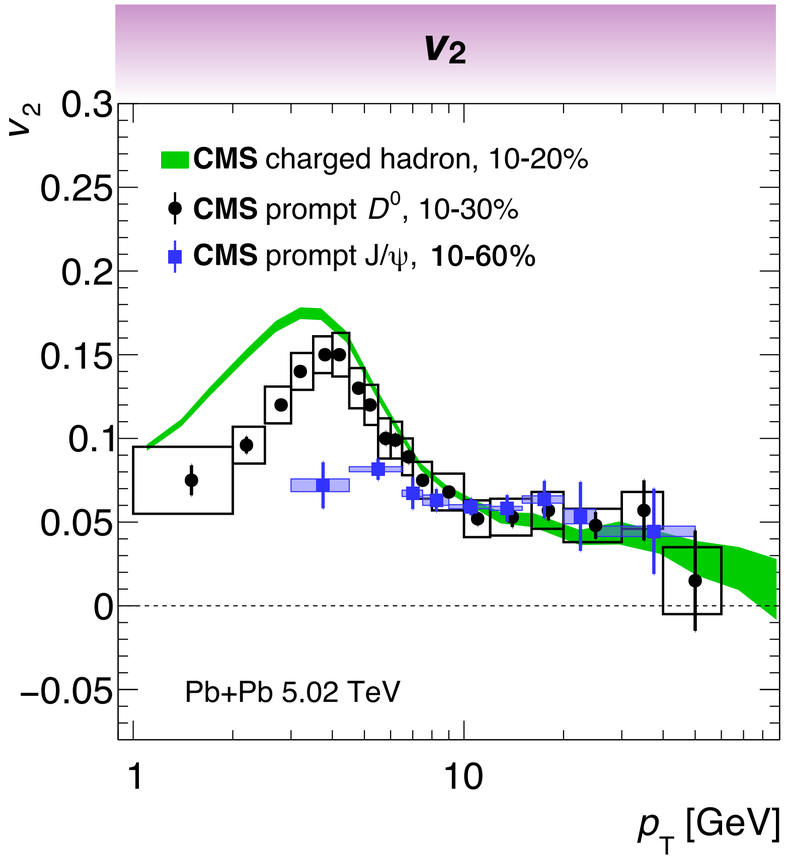


- *B* hadron v_2 measured via B decays: $b \to \mu$/e, $b \to D^0$, $b \to J/\psi$
- Consistent results from different experiements showing significant non-zero $v_2(B)$ with $p_T > 2$ GeV



Charm vs. light / quarkonium





ALICE D R_{AA}: JHEP 01 (2022) 174
ALICE charged hadron R_{AA}: JHEP 11 (2018) 013
ALICE pion R_{AA}: PRC 101 (2020) 044907
ALICE J/ψ R_{AA}: PLB 805 (2020) 135434
ATLAS J/ψ R_{AA}: EPJC 78 (2018) 762

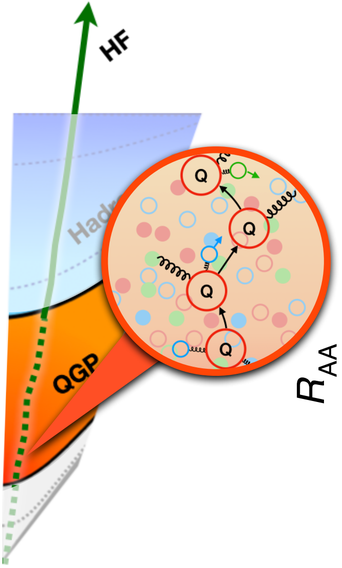
CMS D v_2: PLB 816 (2021) 136253
CMS charged hadron v_2: PLB 776 (2017) 195
CMS J/ψ v_2: CMS-PAS-HIN-21-008

Low p_T (p_T < 10 GeV):

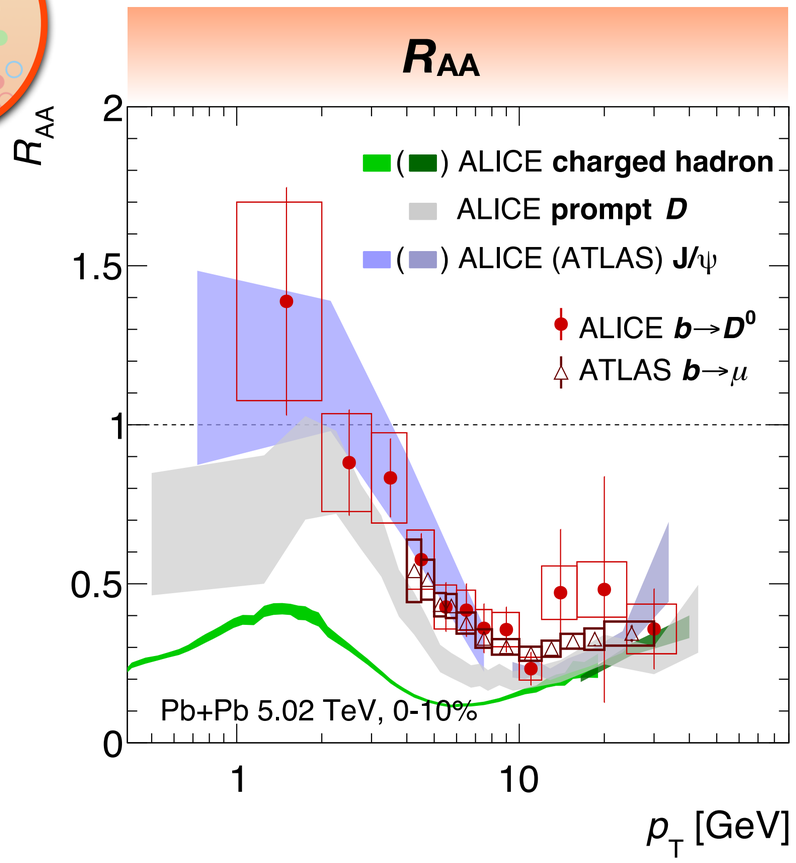
- R_{AA} : charged particle < prompt D < prompt J/ψ
- v_2: charged particle > prompt D > prompt J/ψ

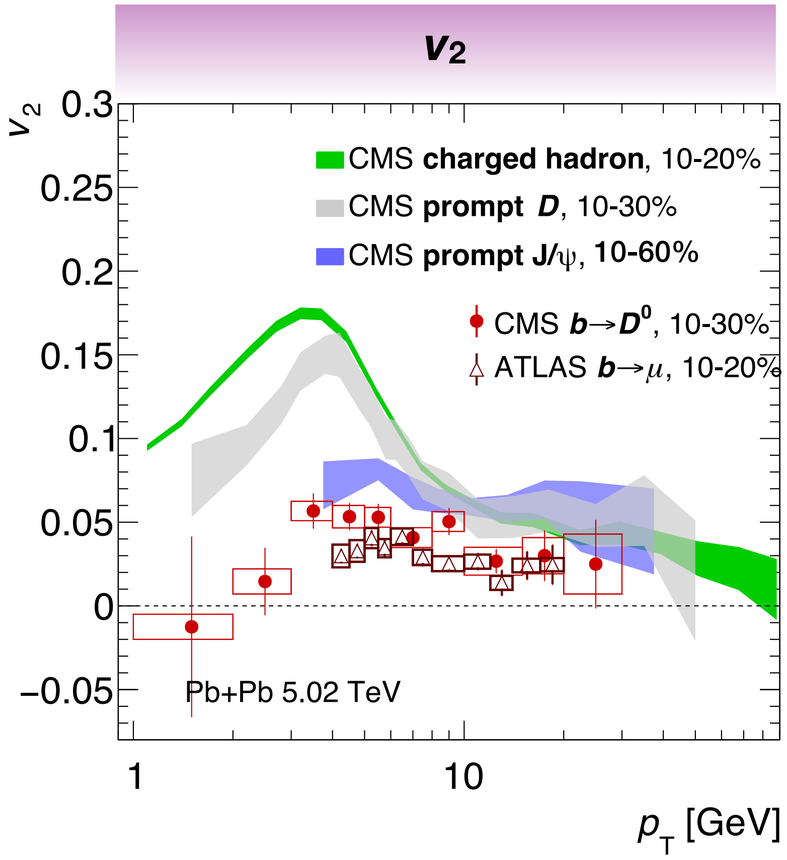
High p_T (p_T > 10 GeV):

- R_{AA} : charged particle ~ prompt D ~ prompt J/ψ
- v_2: charged particle ~ prompt D ~ prompt J/ψ



Bottom vs. charm / quarkonium / light





ALICE D R_{AA}: JHEP 01 (2022) 174
ALICE charged hadron R_{AA}: JHEP 11 (2018) 013
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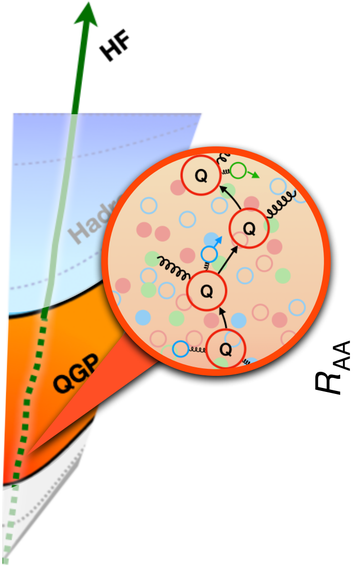
CMS J/ψ v_2: CMS-PAS-HIN-21-008

ATLAS muon: PLB 807 (2020) 135595
ALICE non-prompt D^0 R_{AA}: arXiv:2202.00815
CMS non-prompt D^0 v_2: CMS-PAS-HIN-21-003

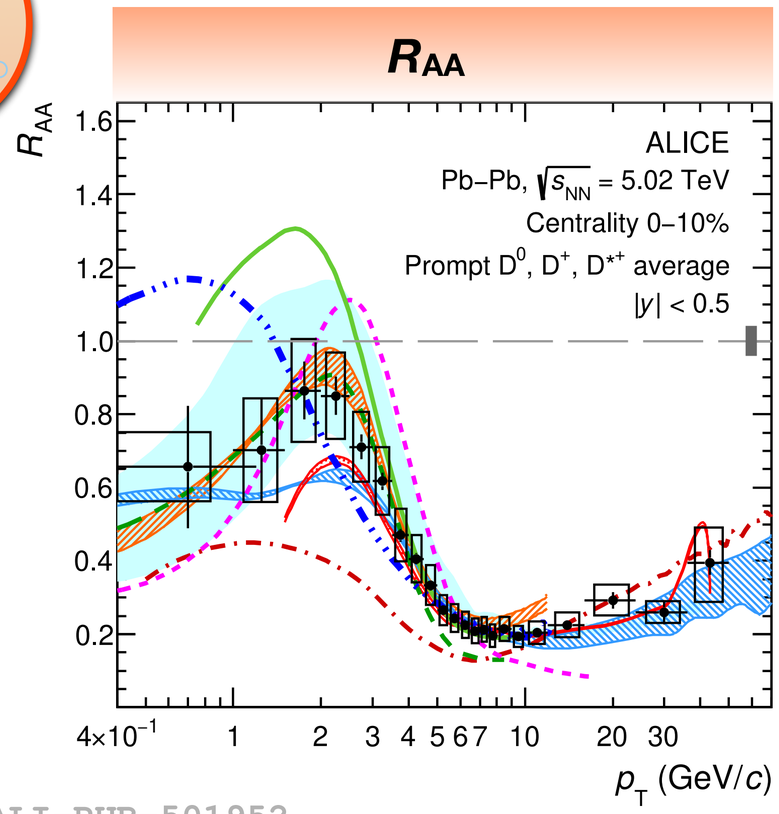
- R_{AA} (B decay) > R_{AA} (D), slightly higher than the universal trend at high p_T
- v_2 (B decay) < v_2 (anything else)

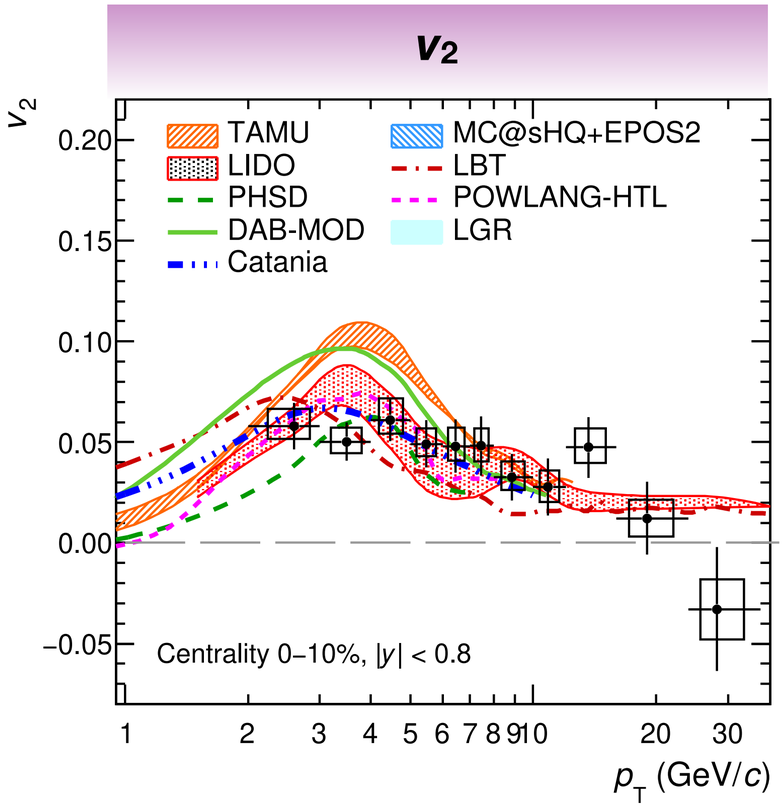


Charm-hadron — model comparison

ALICE talk: M. Völkl

JHEP 01 (2022) 174





ALI-PUB-501952

Model ingredients:

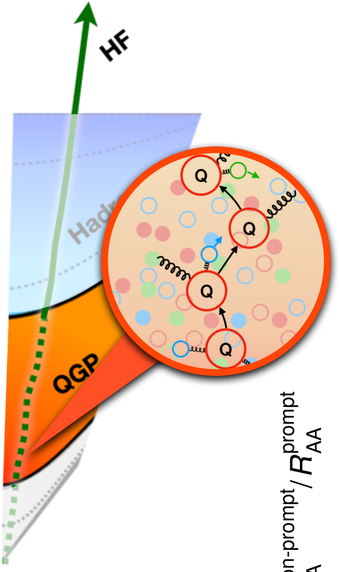
- nPDF
- Hydro medium
- Coll. and Rad. scatterings (weakly coupled approach)
- Coalescence hadronization

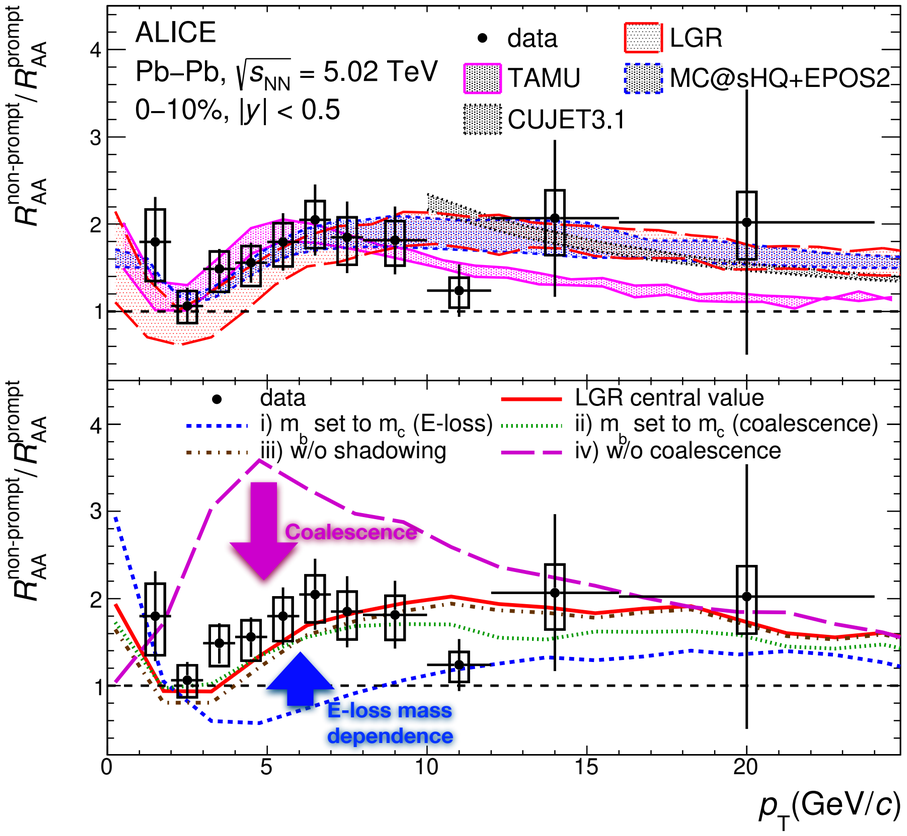
- Open charm experiences the entire QGP evolution; models also contain each stage of charm evolution
- Most models describe data over wide kinematic and centrality ranges

Bottom vs. charm in QGP — model comparison

ALICE talk: S. Politanò

ALICE prompt D^0, JHEP 01 (2022) 174
ALICE non-prompt D^0: arXiv:2202.00815





ALI-PUB-501659

- *B* hadron experience weaker interaction with QGP compared to *D* meson baseline
- LGR model demonstrate strong effects due to mass-dependent QGP interaction and coalescence
- Double ratios have uncertainties at high p_T where precise non-prompt J/ψ and lepton measurements are available

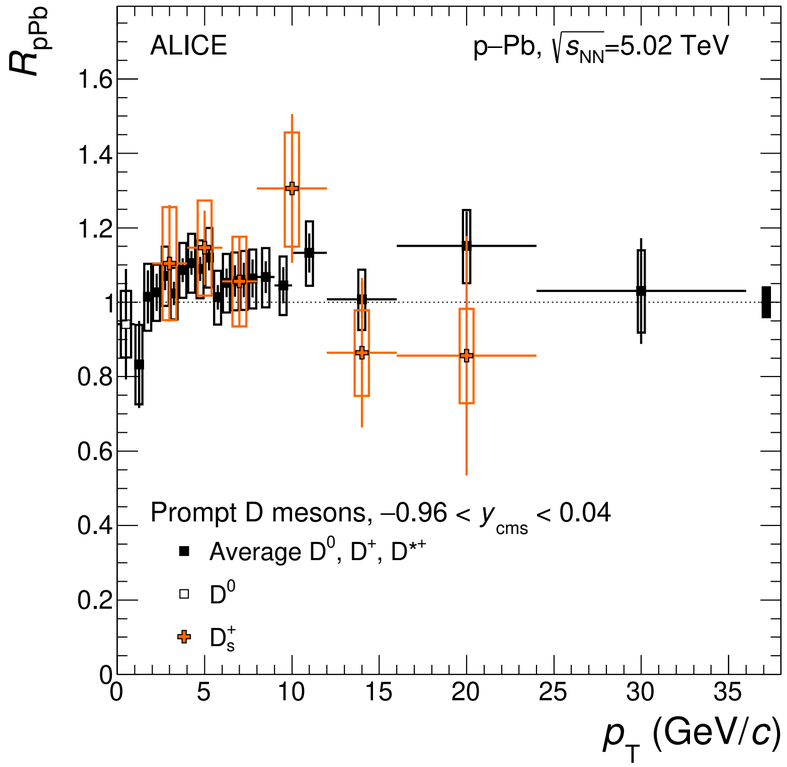
Open heavy flavor in small systems

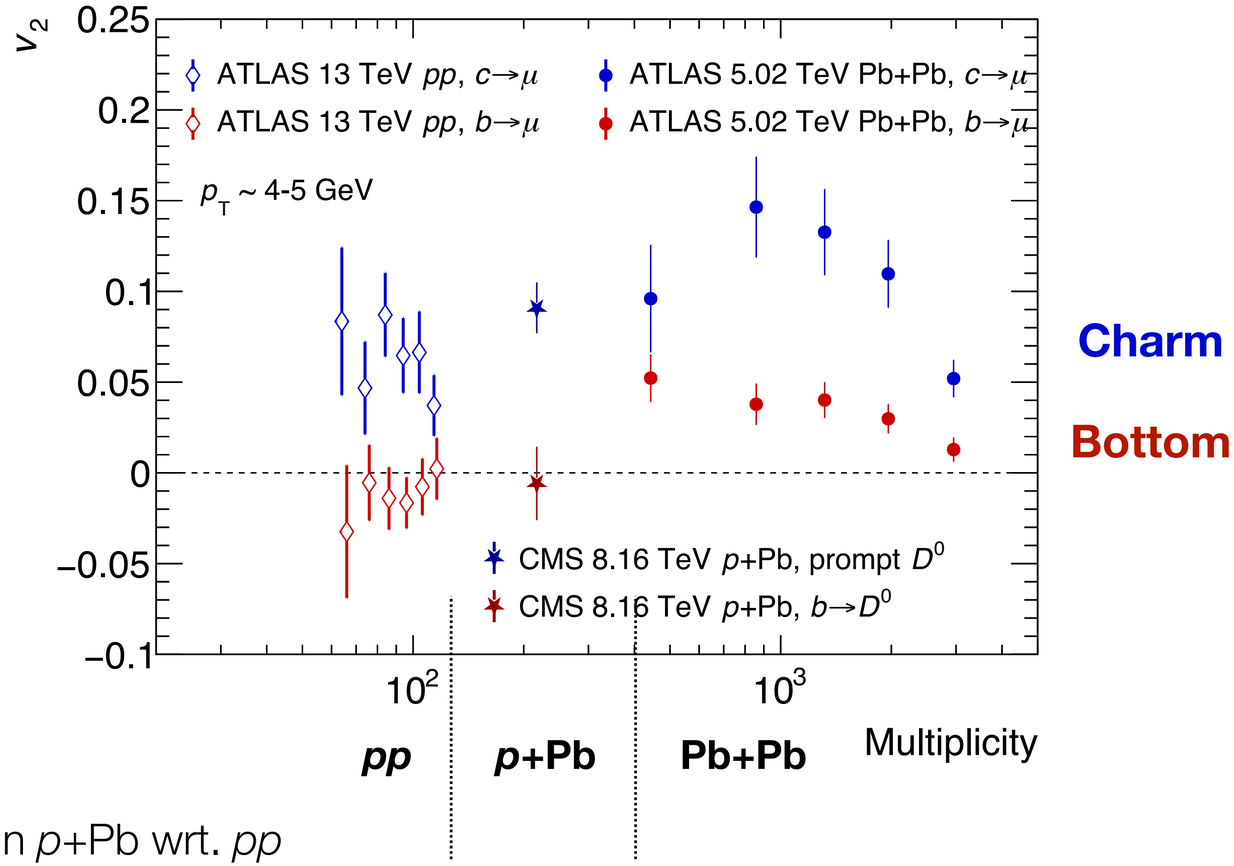
CMS talk: S. Chandra

ATLAS talk: W. Zhou

ALICE p+Pb D: JHEP 2019 (2019) 92

ATLAS Pb+Pb muon: PLB 807 (2020) 135595
ATLAS pp muon: PRL 124 (2020) 082301
CMS p+Pb prompt D^0: PRL 121 (2018) 082301
CMS p+Pb non-promt D^0: PLB 813 (2021) 136036



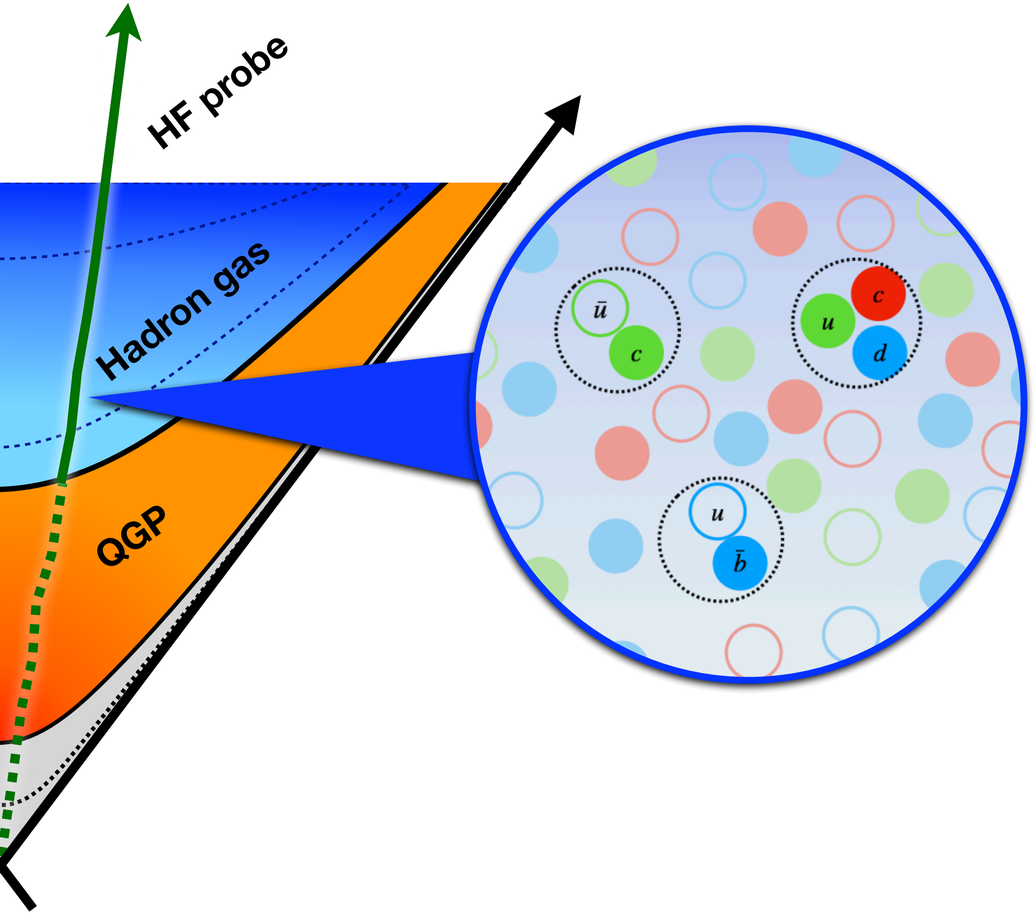


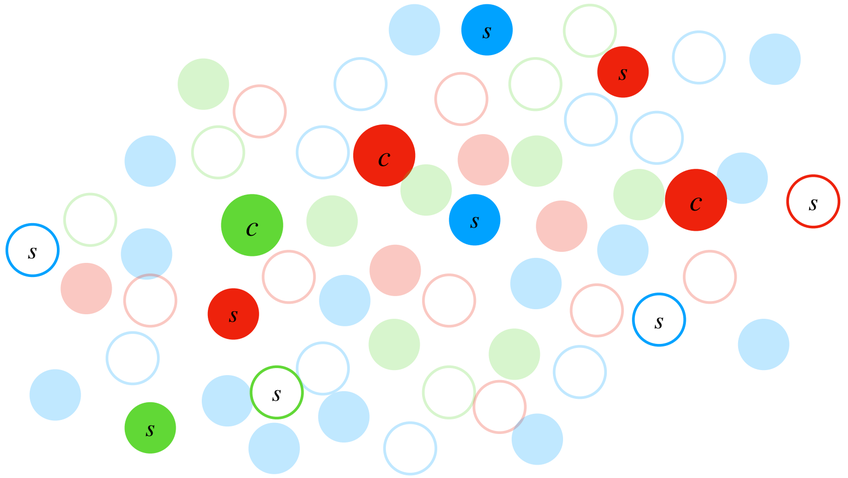
Charm

Bottom

- Prompt *D* meson show no spectra modification in *p*+Pb wrt. *pp*
- Open charm $v_2 > 0$ in both *pp* and *p*+Pb
- Open bottom $v_2 \sim 0$ in both *pp* and *p*+Pb

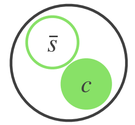
Open heavy flavor **hadronization**



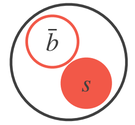


Relative production heavy flavor hadrons with additional s/c wrt heavy flavor harons:

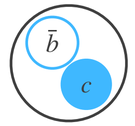
Charmed, strange hadron D_s^+



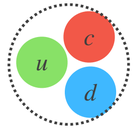
Bottom, strange hadron B_s^0



Bottom, charmed hadron B_c^+



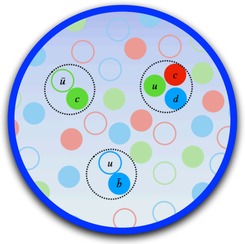
Charmed baryon Λ_c^+

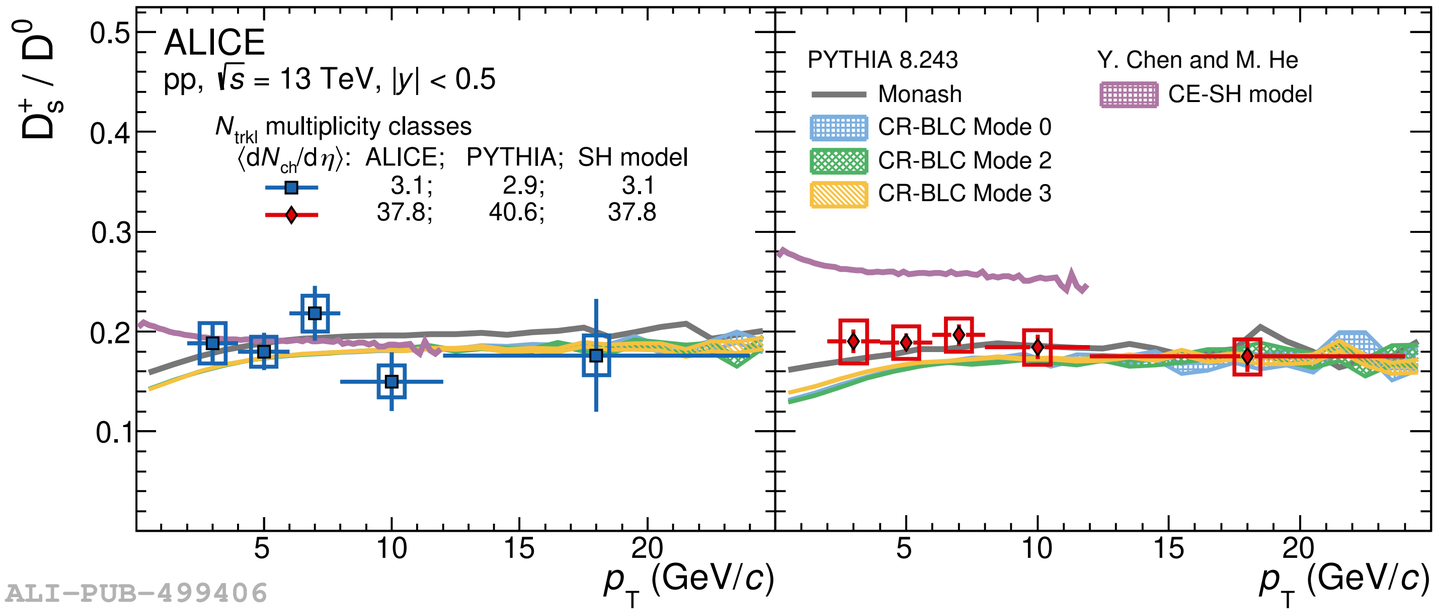


D_s^+/D^0 and B_s^0/B^0 in pp

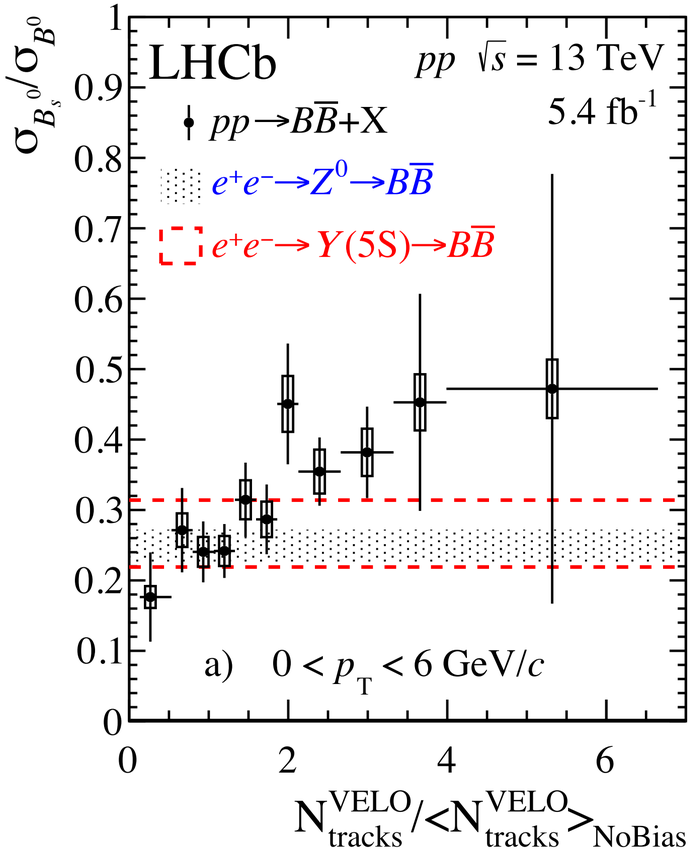
LHCb talk: C. Gu

ALICE Ds: PLB 829 (2022) 137065
LHCb Bs: arXiv:2204.13042



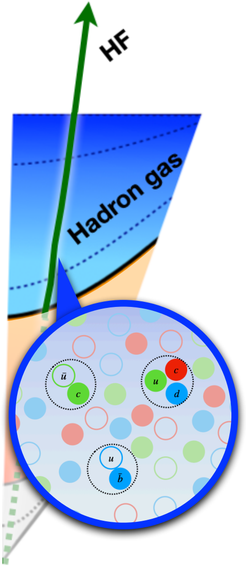


Low multi. ⟶ **High multi.**



Low multi. ⟶ **High multi.**

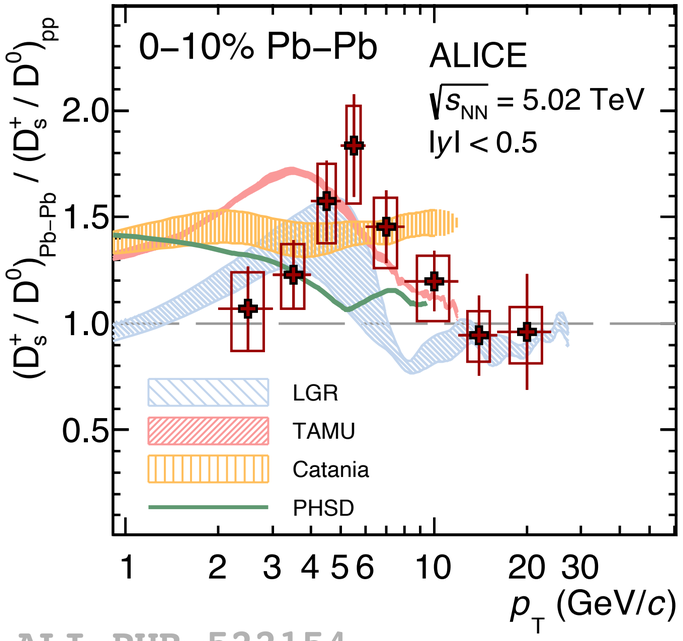
- D_s^+/D^0 in pp No significant p_T or multiplicity dependence, can be well described by PYTHIA Monash/CR
- B_s^0/B^0 is enhanced in high multiplicity pp events with full tracking multiplicity



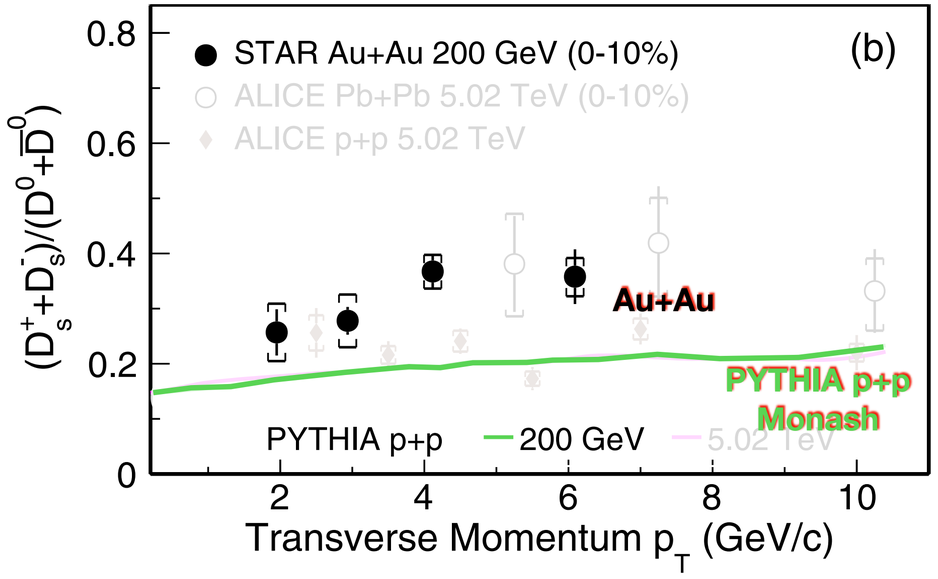
D_s^+/D^0 in A-A

ALICE talk: M. Völkl

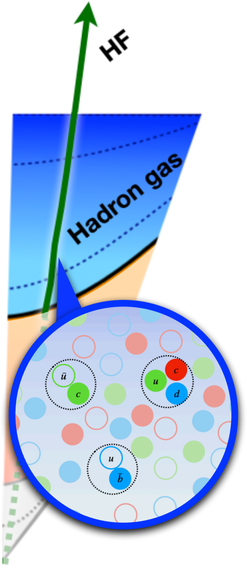
STAR: PRL 127 (2021) 092301
ALICE: PLB 827 (2022) 136986



ALI-PUB-522154



- D_s^+ is significantly enhanced compared to D^0 in Pb+Pb at LHC and RHIC
- Qualitively captured by different models with coalesce

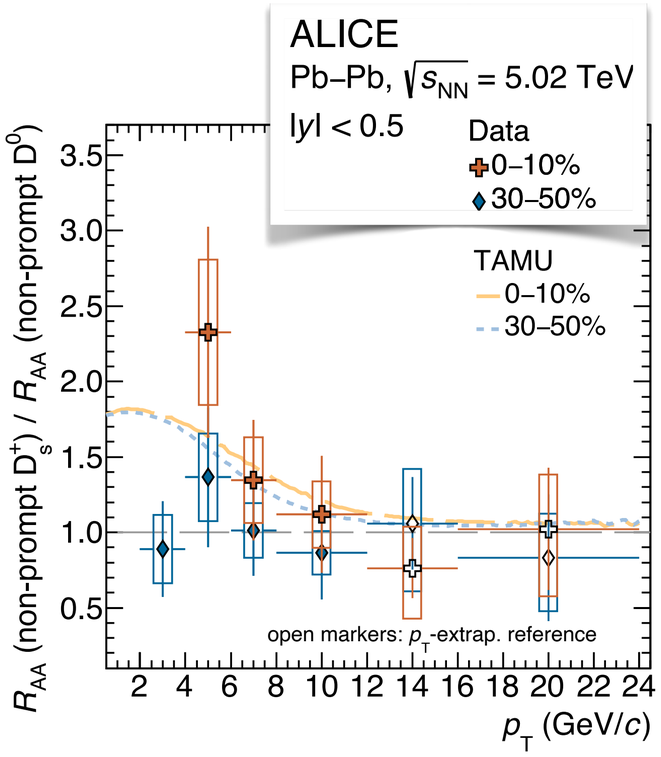


B_s^0/B^+ in Pb+Pb

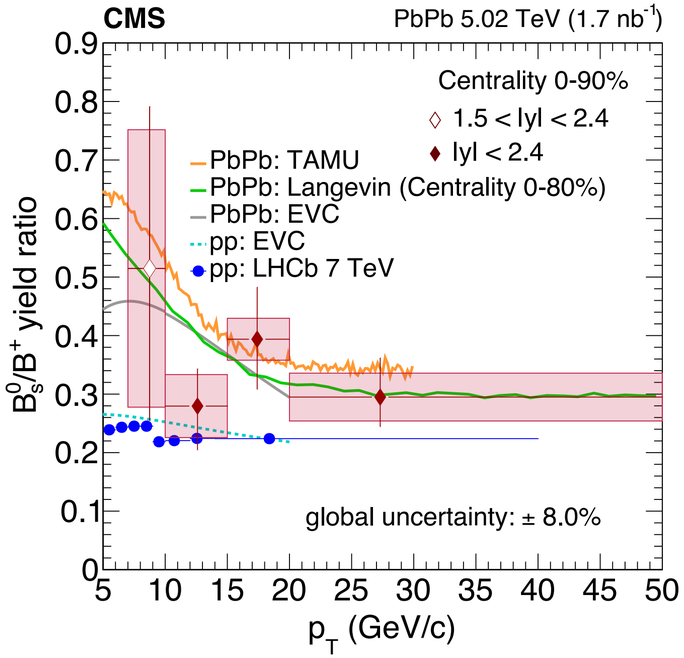
CMS talk: F. Damas

ALICE talk: S. Politanò

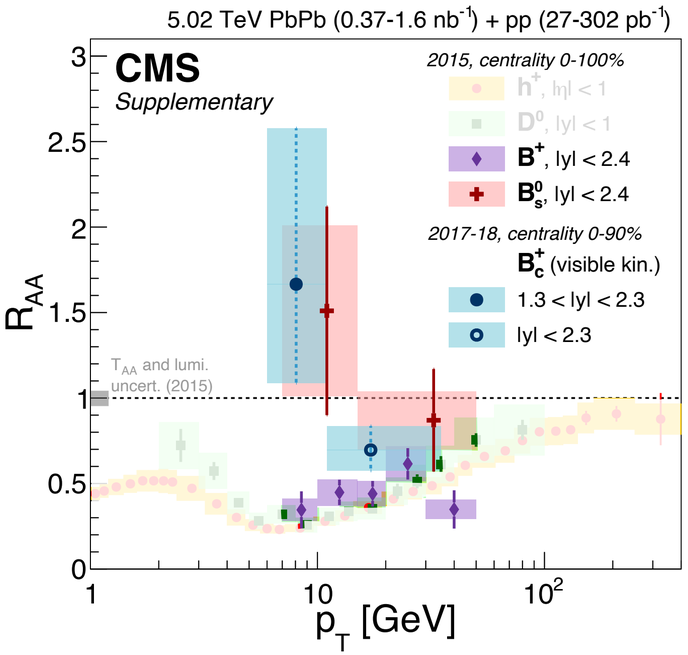
CMS: PLB 829 (2022) 137062
ALICE: arXiv:2204.10386
CMS: arXiv:2201.02659



R_{AA} ratio of $b \to D_S^+$ / $b \to D^0$

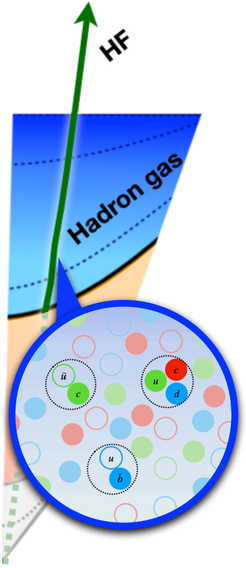


Yield ratio of B_s^0/B^+



$R_{AA}(B_c^+)$ vs. $R_{AA}(B_s^0)$ vs. $R_{AA}(B^+)$

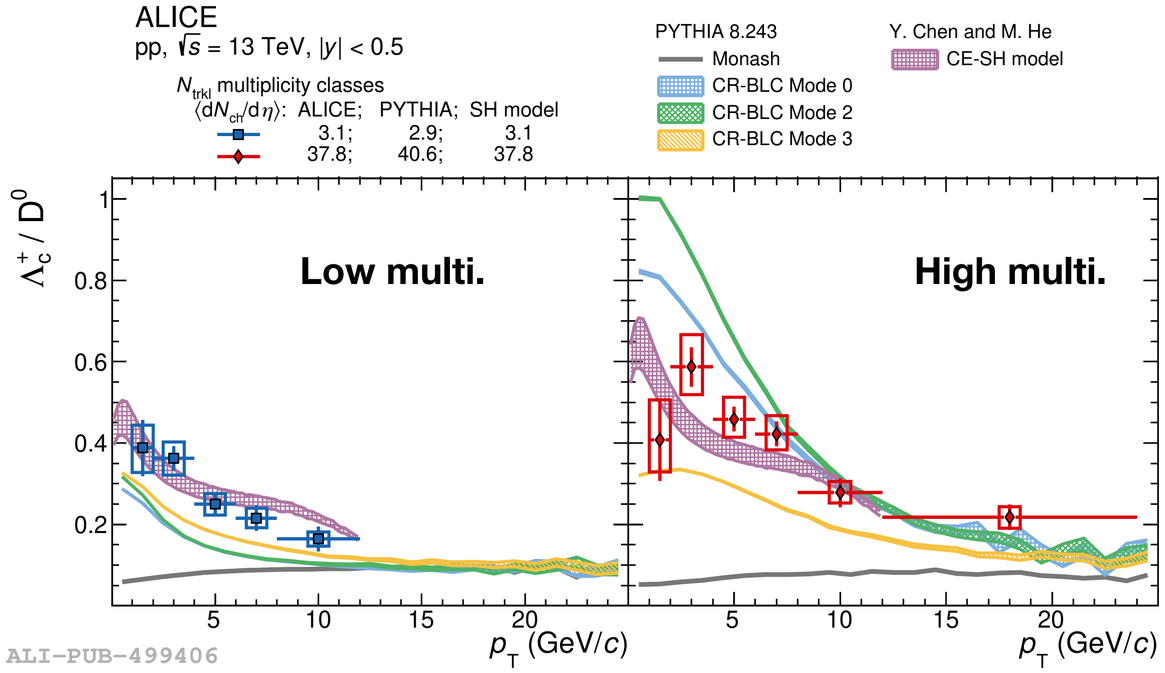
- Hint of B_s^0 enhancement wrt. B^+ in (central) Pb+Pb collisions at low p_T, described by model predictions
- First B_c^+ measurements in Pb+Pb, $R_{AA}(B_c^+) \sim R_{AA}(B_s^0) > R_{AA}(B^+)$

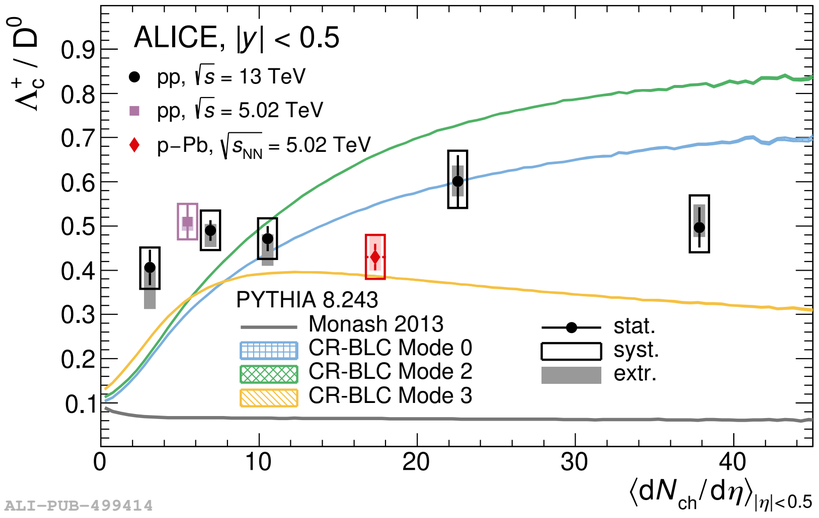


Λ_c^+/D^0 in *pp*

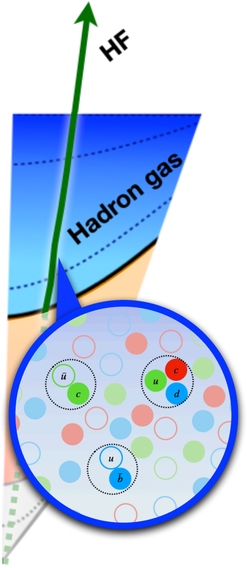
ALICE talk: J. Seo

arXiv:2112.08156





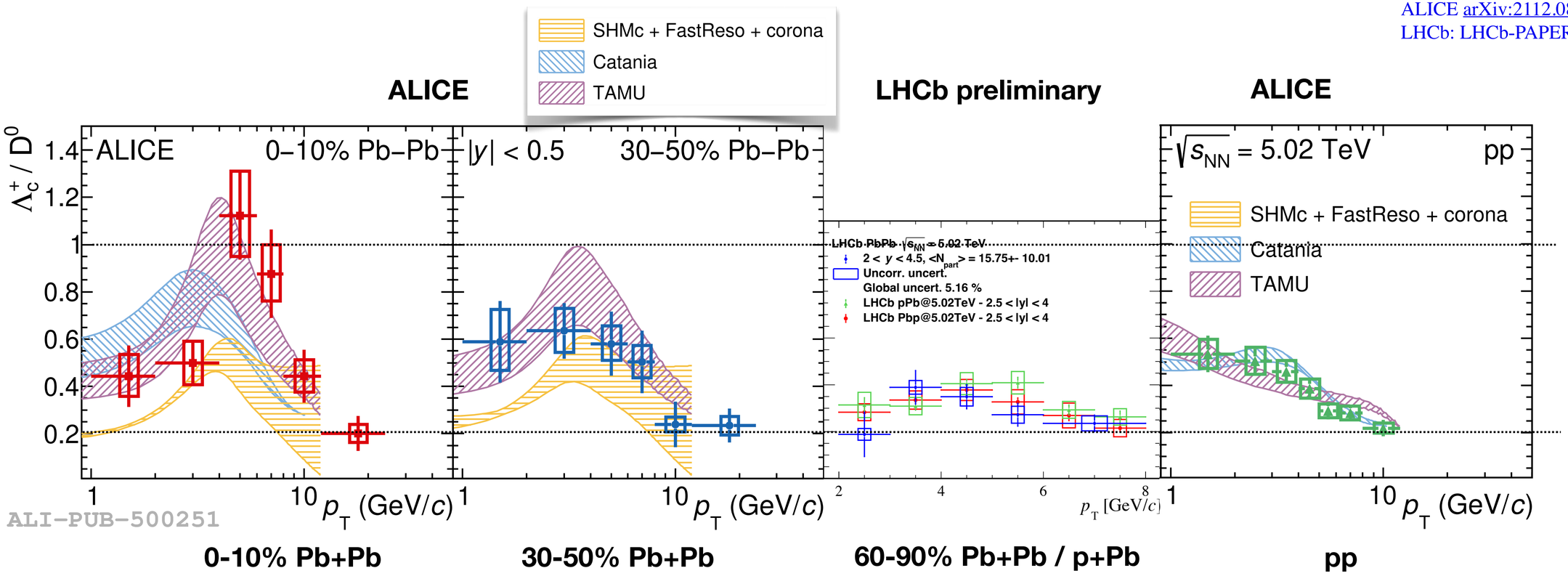
- p_T- and multiplicity-dependent Λ_c^+/D^0 enhancement in *pp* collisions, significantly different from Pythia Monash
- Pythia with CR can qualitatively describe p_T dependence but not the multiplicity dependence
- SH model can quantitatively describe the results



Λ_c^+/D^0 in A-A

ALICE talk: M. Völkl

ALICE arXiv:2112.08156
LHCb: LHCb-PAPER-2021-046

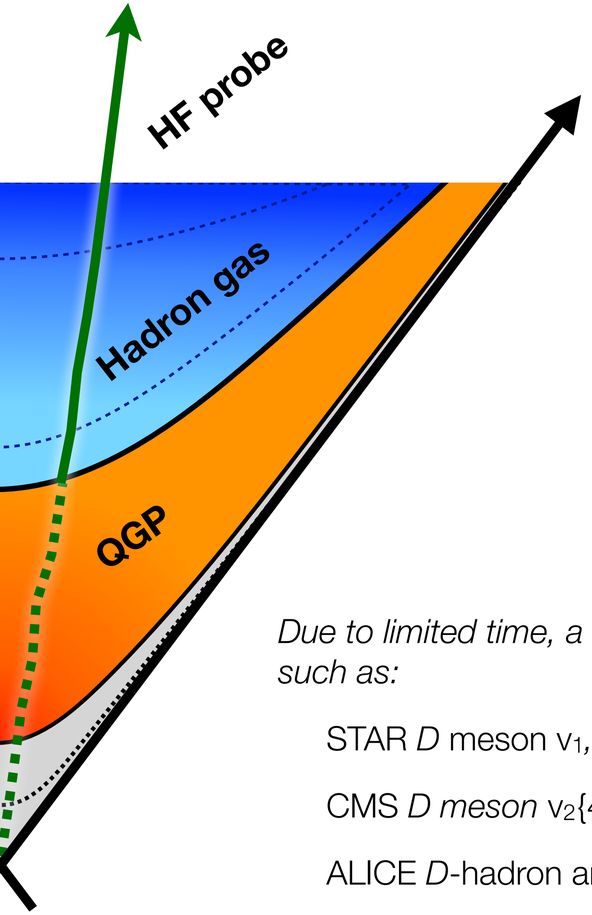


0-10% Pb+Pb | **30-50% Pb+Pb** | **60-90% Pb+Pb / p+Pb** | **pp**

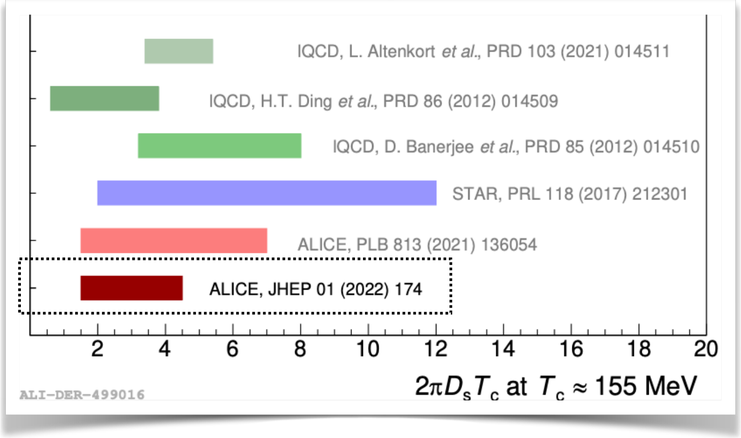
- Λ_c^+/D^0 show increasing trend with increasing <N_{part}> at low $4 < p_T < 6$ GeV
- Similar Λ_c^+/D^0 at high p_T in *pp*, *p*+Pb and Pb+Pb

Summary

ALICE talk: M. Völkl



- Thanks to tremendous experimental efforts, charm and bottom hadron R_{AA} / v_2 measurements are pushed to unprecedented kinematic coverage and precision
- Systematic data-model comparisons lead to improved modeling and tightener estimation of medium property
- Measurements of D_s^+/D^0, Λ_c^+/D^0, B_s^0/B^+, B_c^+/B^+ provide valuable insight into hadronization heavy flavor quark in Pb+Pb and high multiplicity *pp*



Due to limited time, a lot of interesting results cannot be covered in my talk, such as:

STAR *D* meson v_1,

CMS *D meson* $v_2\{4\}/v_2\{2\}$, D meson v_3

ALICE *D*-hadron angular correlation

ATLAS HF muon pair correlation, muon v_3

LHCb HF probes in *p*+Pb

….

Special thanks to A. Dainese, S. Lim, X. Dong, J. Nagle, P. Onyisi, M. Rybar for suggestions and discussions

SQM2022 experimental open HF hadron parallel talks

Charm production: constraint to transport models and charm diffusion coefficient with ALICE

Martin Andreas Volkl

Constraining hadronization processes with charm baryons in pp and p-Pb collisions with ALICE

Jinjoo Seo

Beauty production in heavy-ion collisions with ALICE at the LHC

Stefano Politano

ALICE determines the scattering parameters of *D* mesons with light-flavor hadrons

Emma Chizzali

ALICE

Measurement of non-prompt and prompt D^0 azimuthal anisotropy in Pb-Pb collisions at 5.02 TeV

Milan Stojanovic

New insights on heavy flavor dynamics and hadronization from small to large collision systems from Λ_c^+ production with CMS

Soumik Chandra

Studies of heavy flavor dynamics using B^+, B_s^0 and B_c mesons with CMS

Florian Damas

CMS

Multiplicity-dependent production of heavy mesons with strangeness in small systems at LHCb

Chenxi Gu

PHENIX Probing QCD Matter Through Heavy Flavor and Quarkonium at RHIC

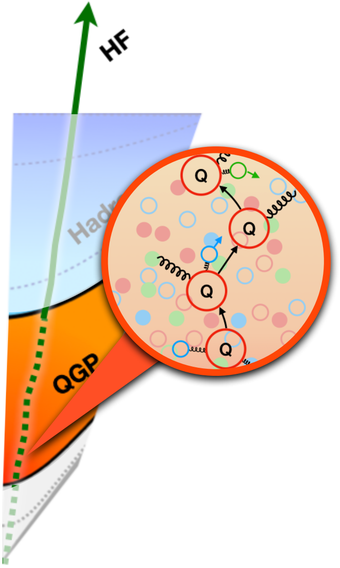
Rachid Nouicer

Heavy flavor and hard probes of the Quark Gluon Plasma with ATLAS

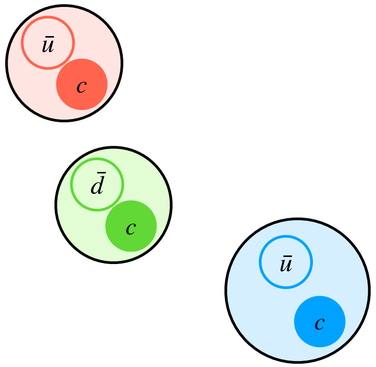
Wenkai Zou

LHCb/PHENIX/ATLAS

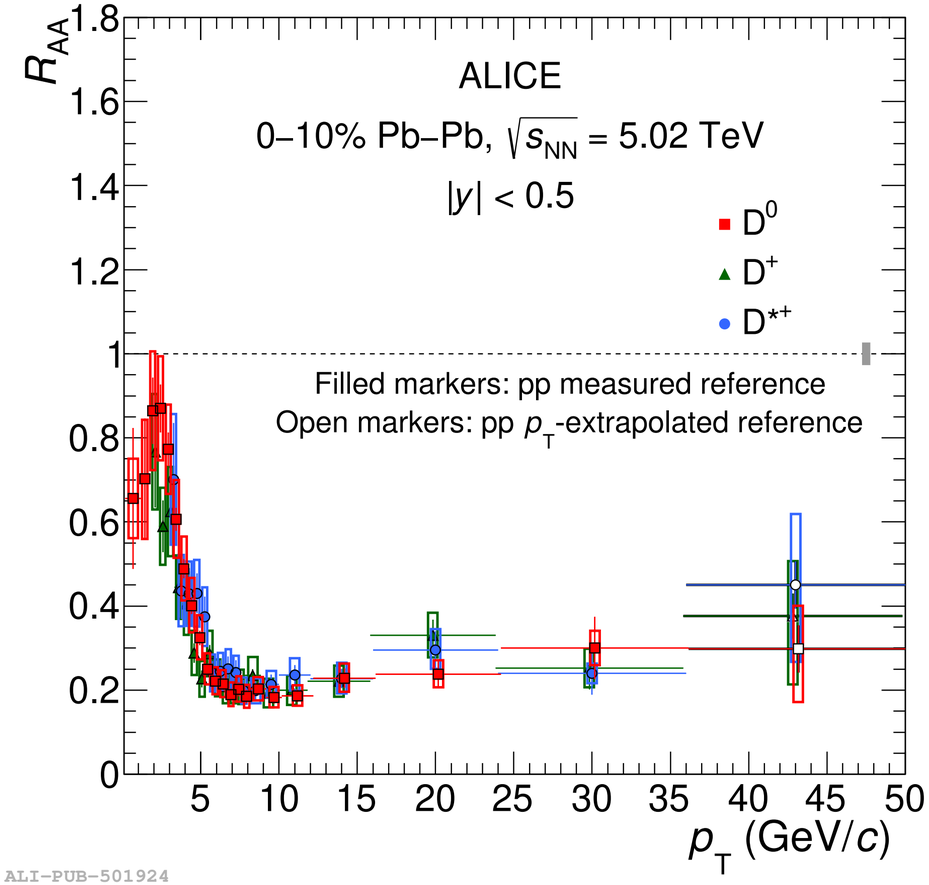
Backup Slides

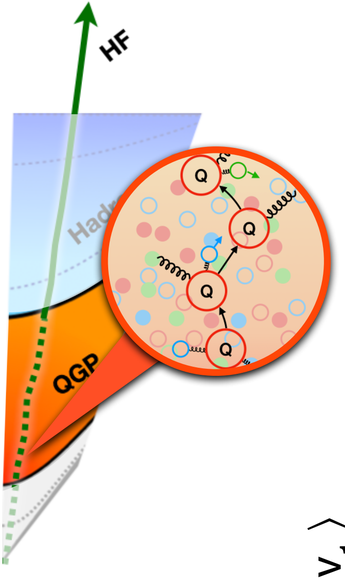


Charm-hadron in medium — D0, D+ and D*+

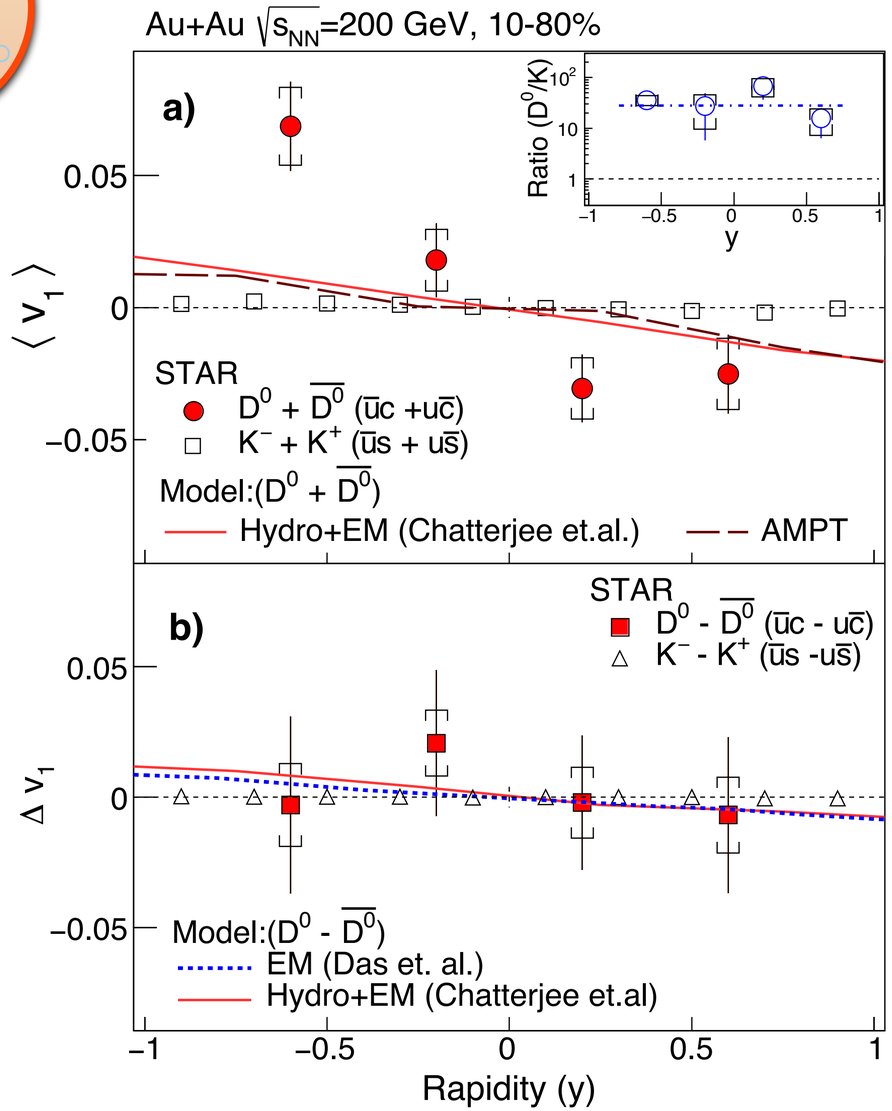


JHEP 01 (2022) 174



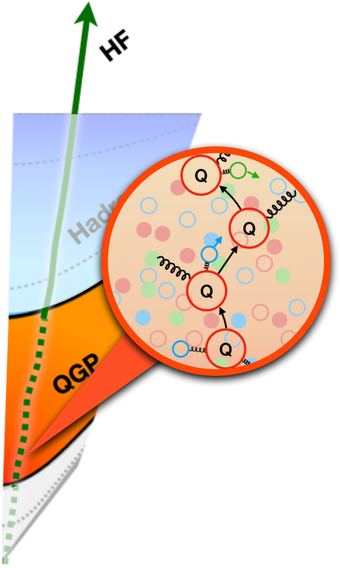


Charm-hadron in medium — v_1



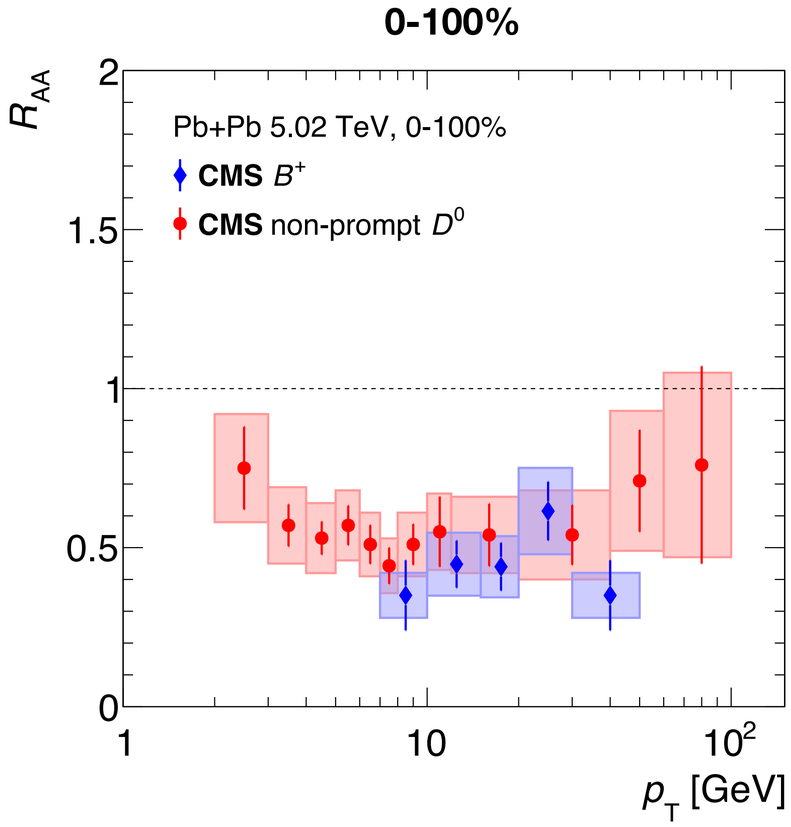
PRL 123 (2019) 162301

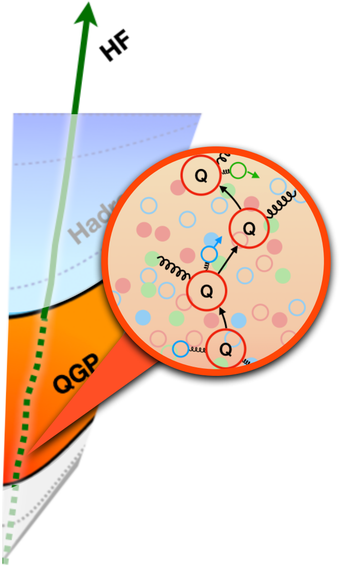
- $v_1(D^0)$ 25 times larger than $v_1(K)$
- Negative $v_1(D^0)$ slope qualitatively described by hydro with an initially tilted QGP source and AMPT
- $v_1(D^0)$ has better sensitivity to the T-dependence diffusion coefficient. Δv_1 between D^0 and $\bar{D}^0$ offers a unique access to the initial B-field.



Bottom-hadron in medium — B hadron vs. B decay

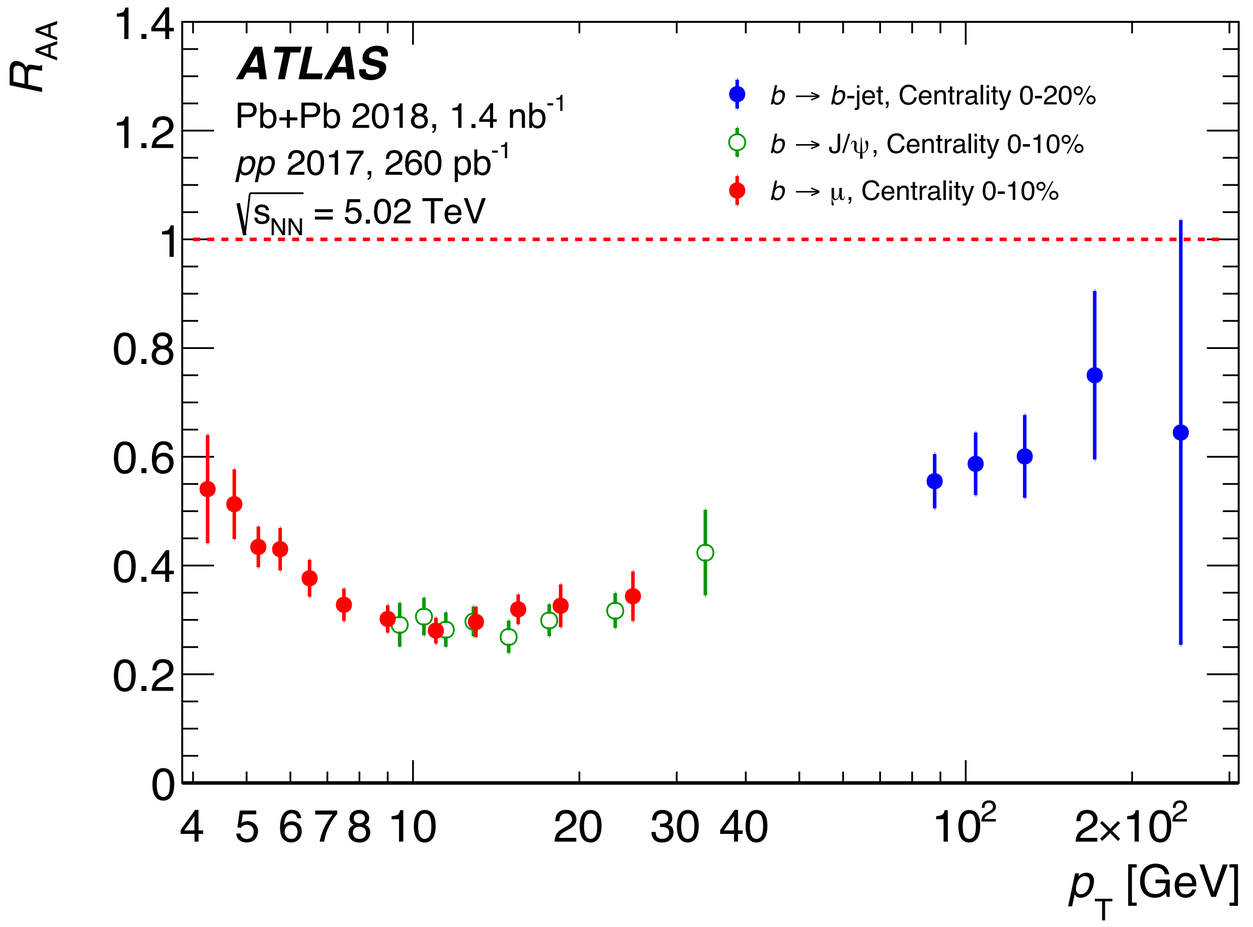
CMS B^+: PRL 119 (2017) 152301
CMS non-prompt D: PRL 123 (2019) 022001

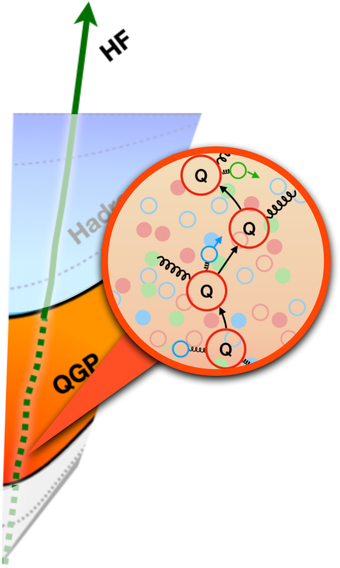




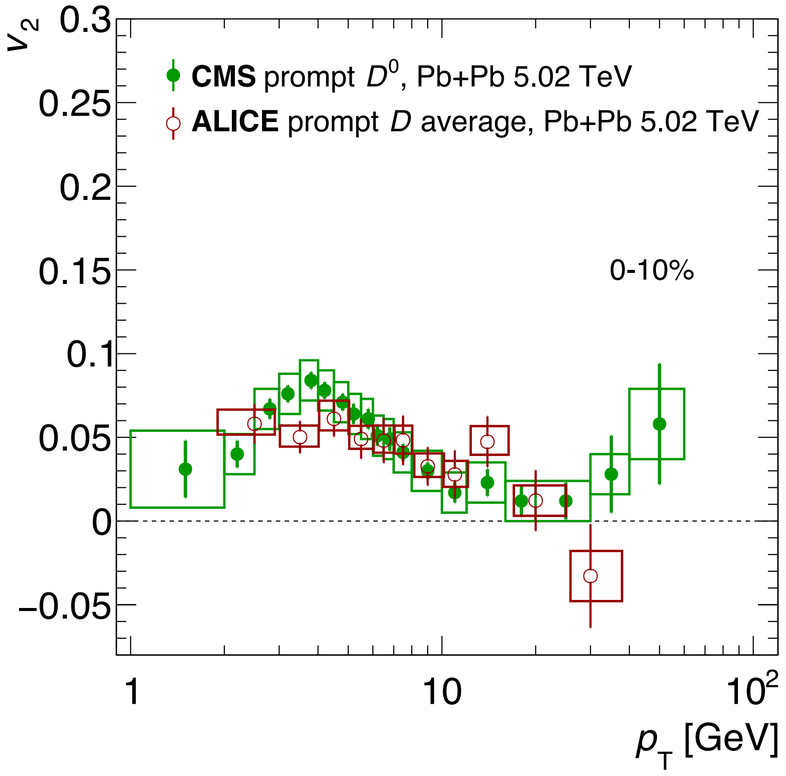
HF jets vs open bottom hadron decays

arXiv:2204.13530

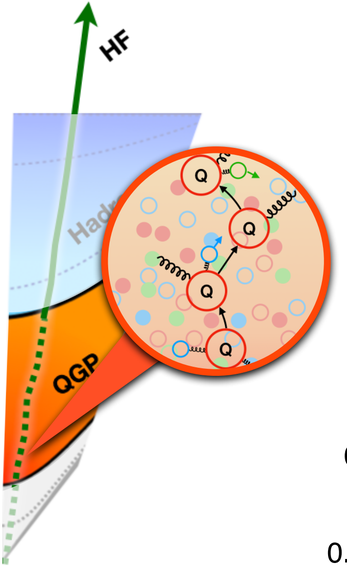




Prompt D v_2 in central collisions

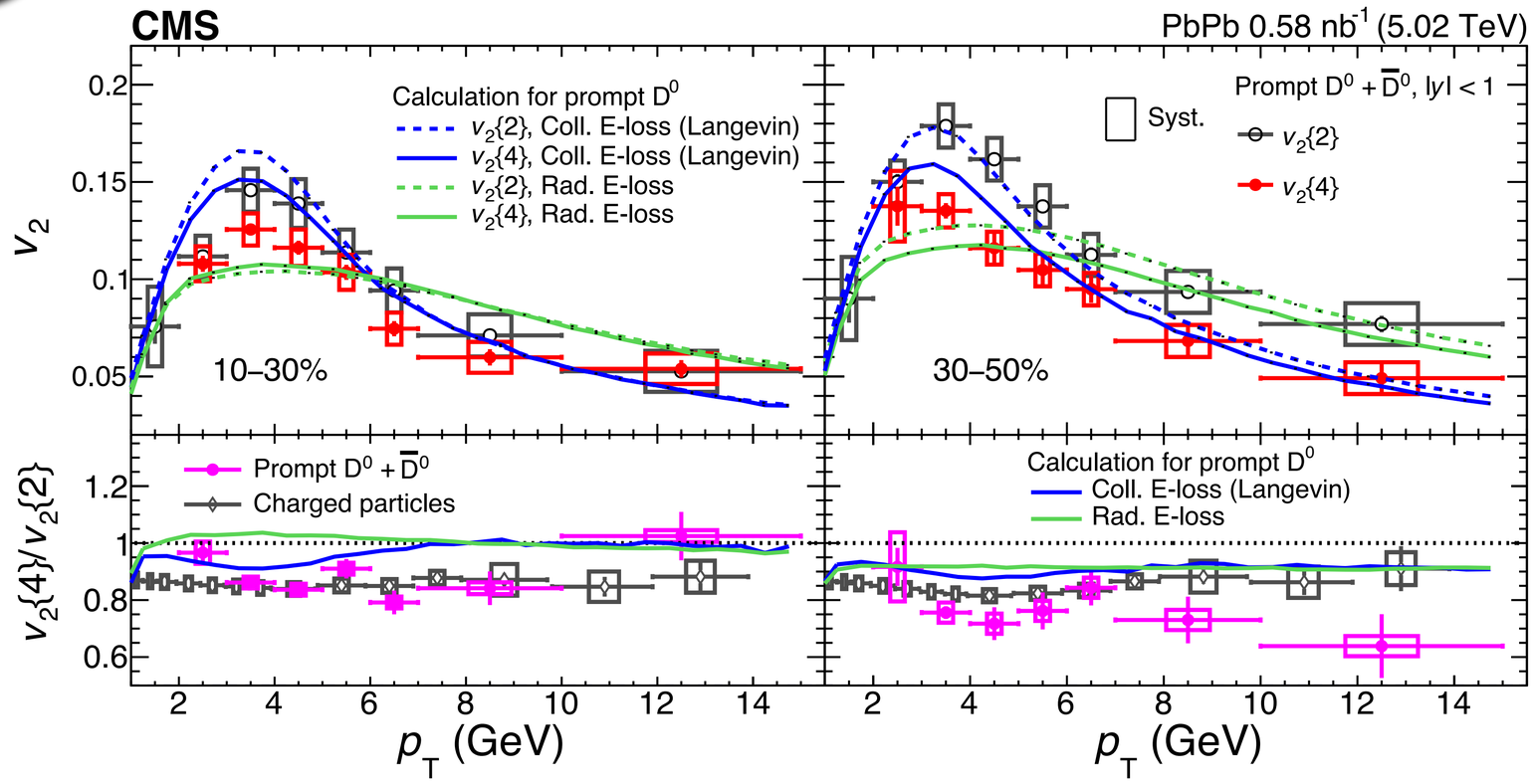


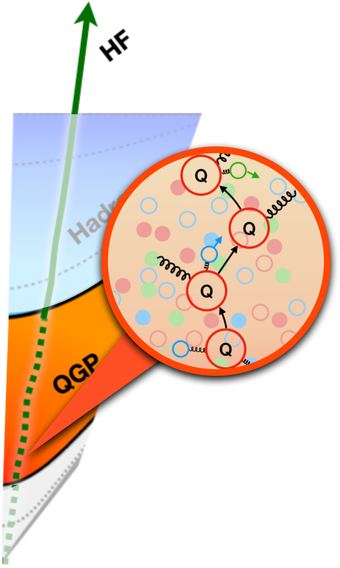
CMS: PLB 816 (2021) 136253
ALICE: PLB 813 (2021) 136054



Prompt D meson $v_2\{2\}$ vs. $v_2\{4\}$

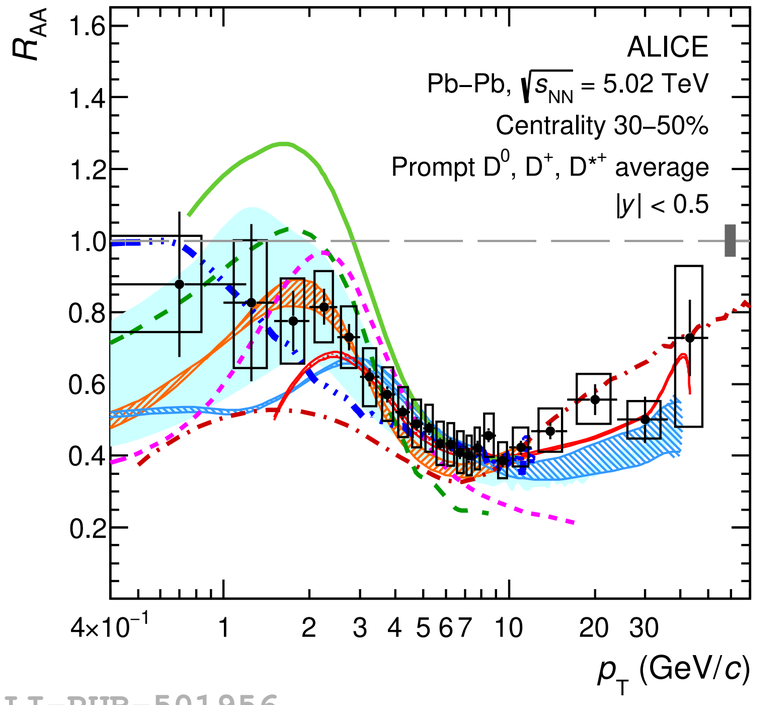
arXiv:2112.12236

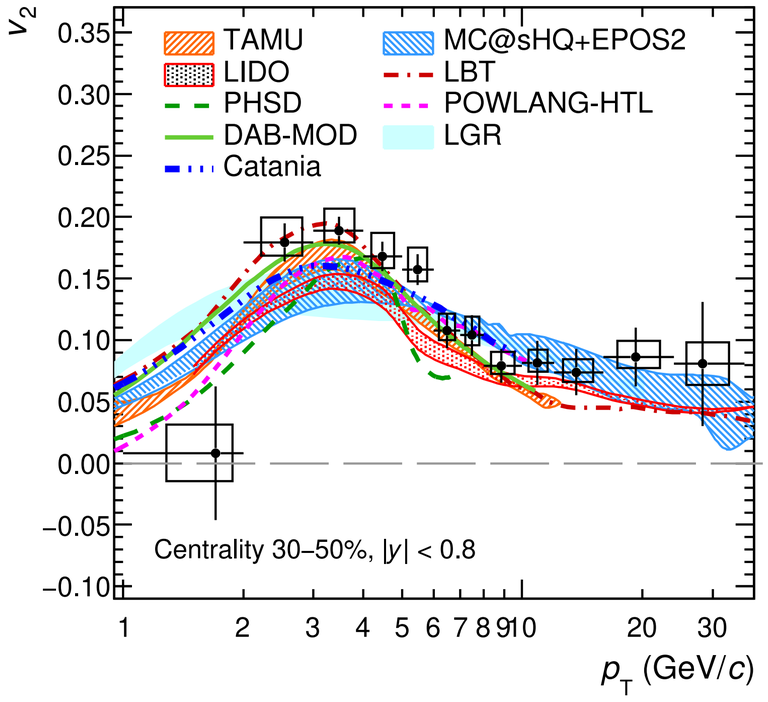




D meson measurements vs. models — 30-50%

JHEP 01 (2022) 174

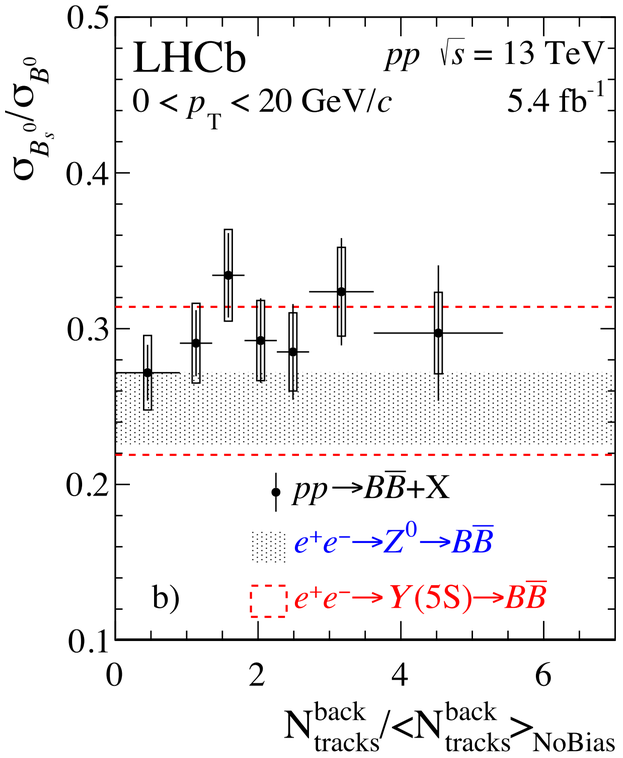




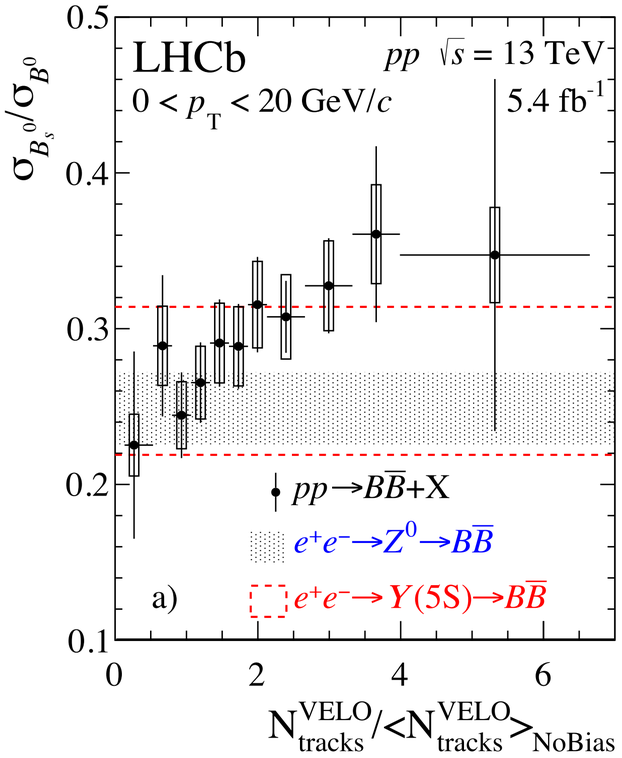
ALI-PUB-501956

B_s^0/B^0 in pp

LHCb Bs: arXiv:2204.13042

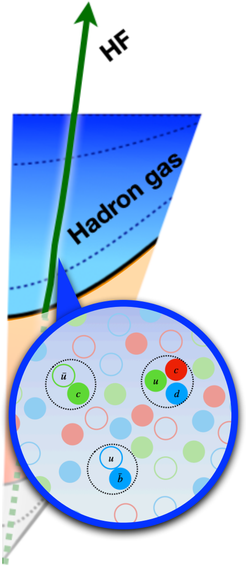


Backward VELO multiplicity



Full VELO multiplicity

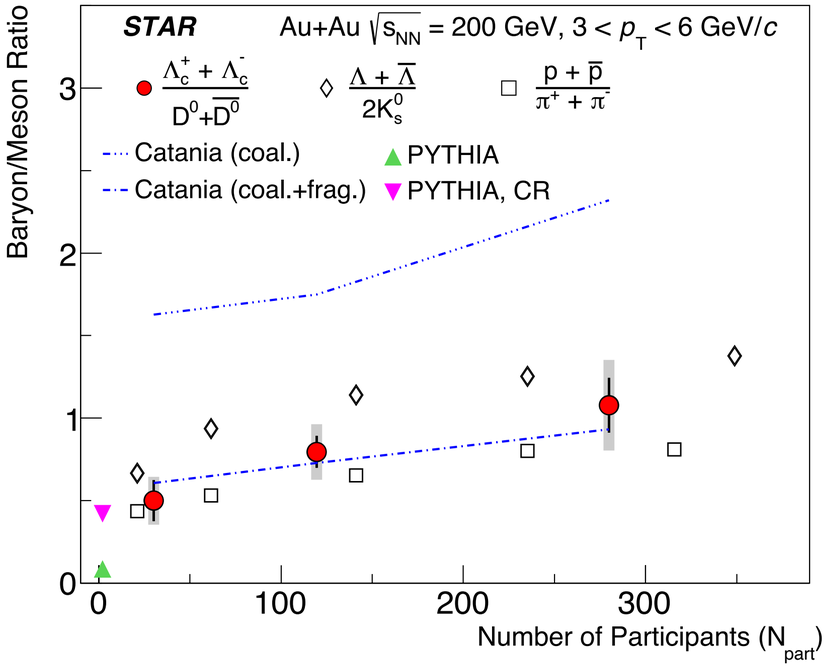
- B_s^0/B^0 is enhanced in high multiplicity pp events with full tracking multiplicity
- Being flat wrt. backwad multiplicity indicates the enhancement is due to B_s^0 local particle density

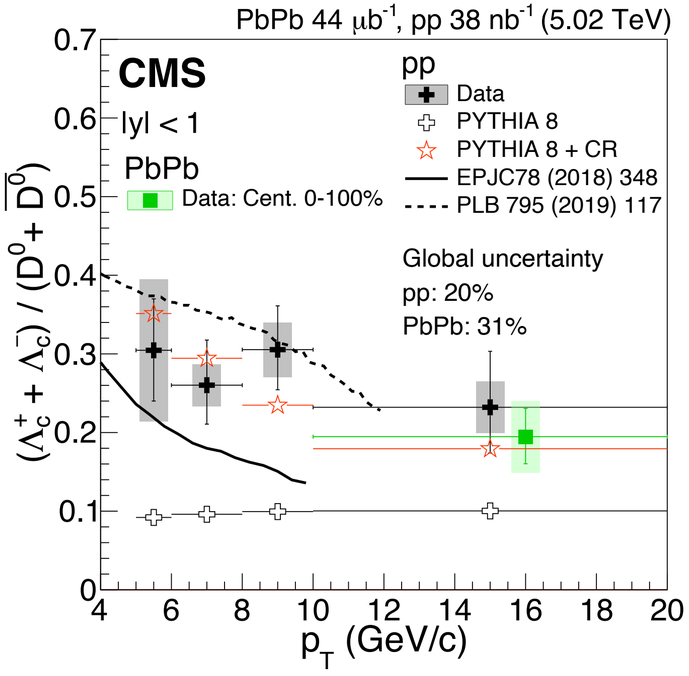


Λ_c^+/D^0 in A-A

CMS talk: S. Chandra

STAR: PRL 124 (2020) 172301
CMS: PLB 803 (2020) 135328



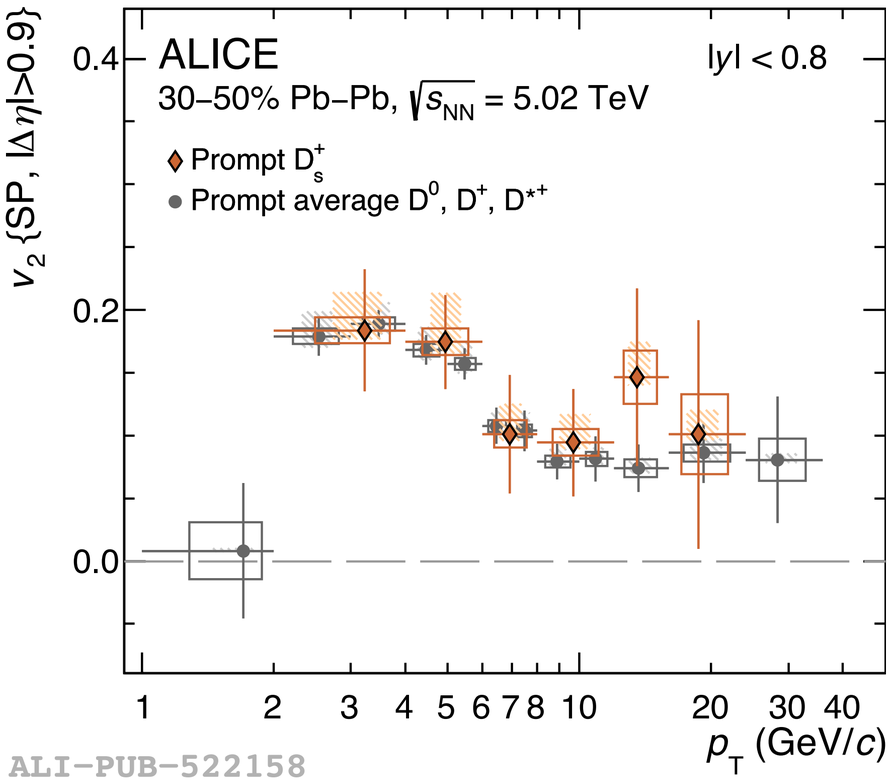


STAR and CMS results are consistent with ALICE/LHCb results:

- PYTHIA with CR can describe Λ_c^+/D^0 in pp and peripheral Pb+Pb
- Λ_c^+/D^0 stays the same at high p_T in pp and Pb+Pb

D_s^+ v_2 in Pb+Pb

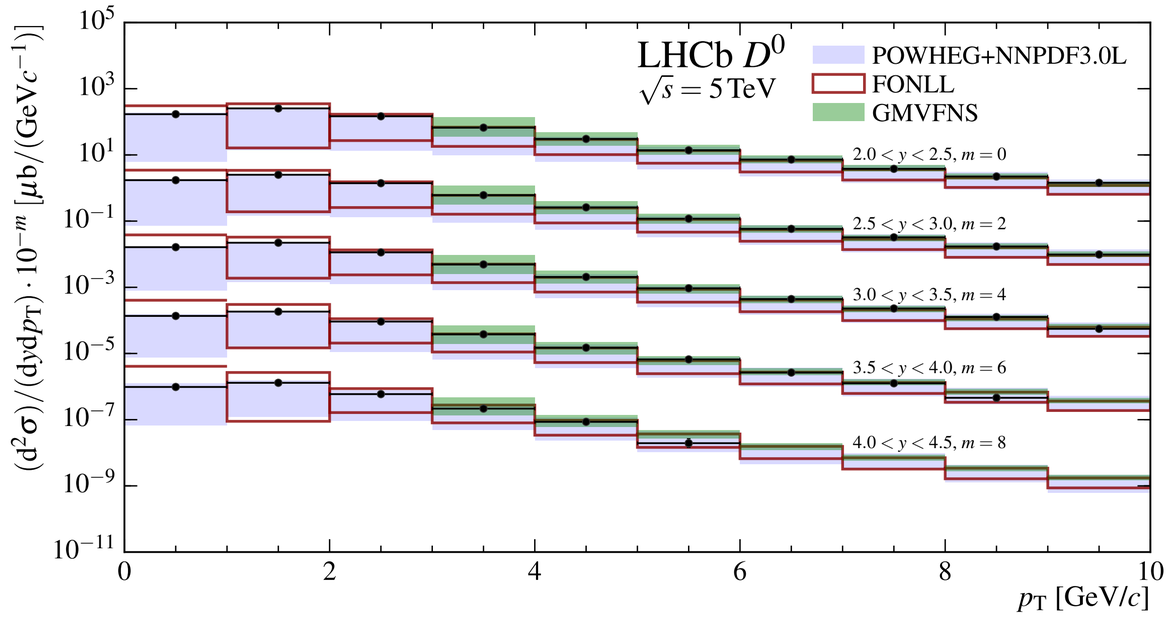
Phys. Lett. B 827 (2022) 136986

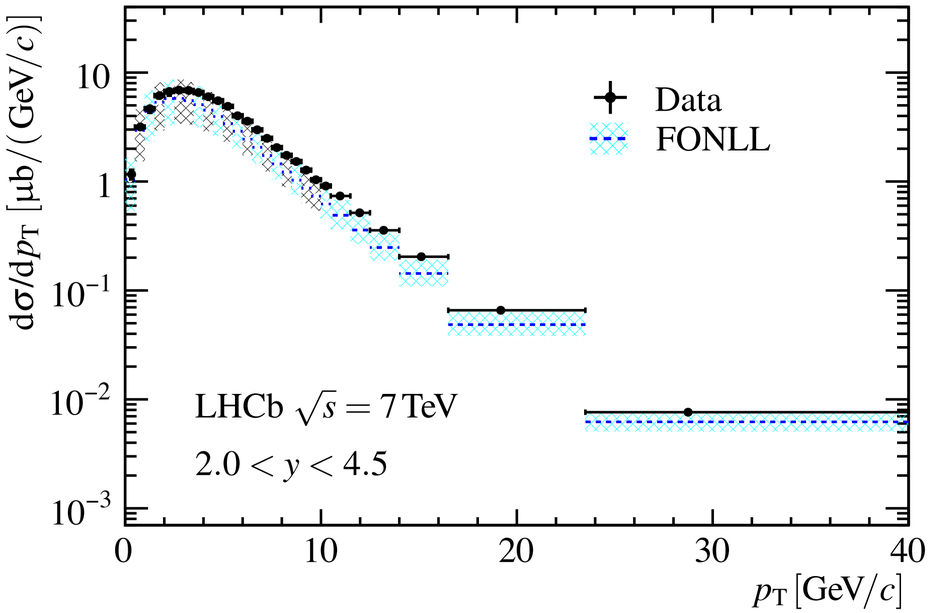


- No significant difference between D_s^+ v_2 and average prompt D meson v_2

LHCb D/B cross sections in pp

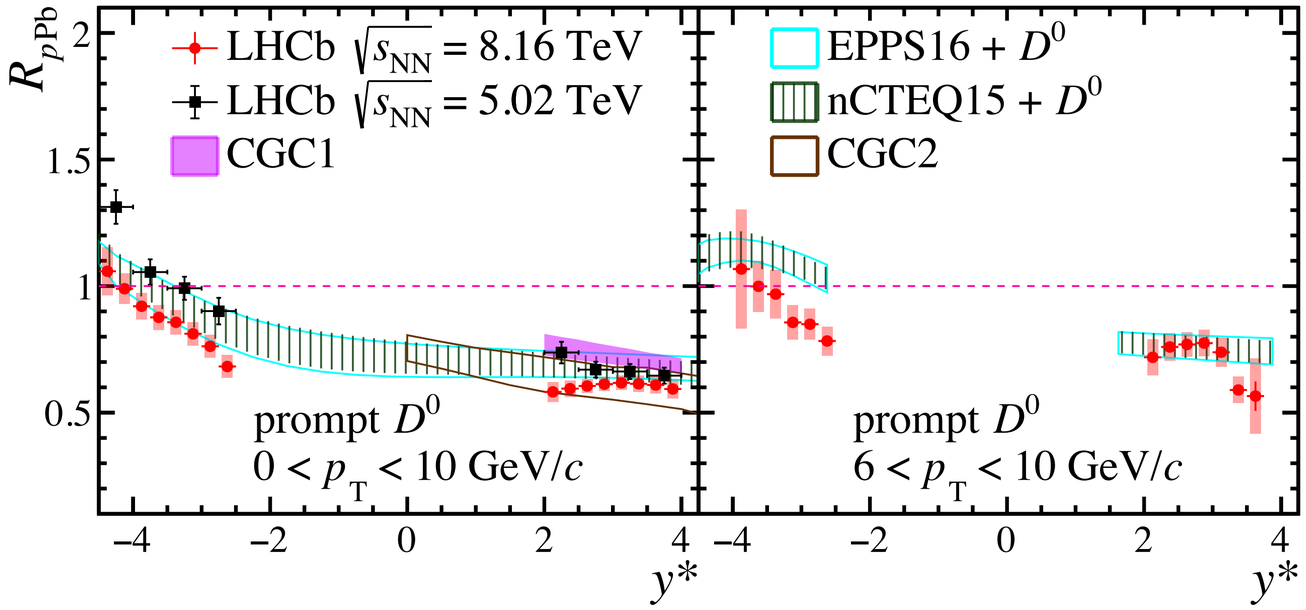
JHEP 06 (2017) 147
JHEP 12 (2017) 026



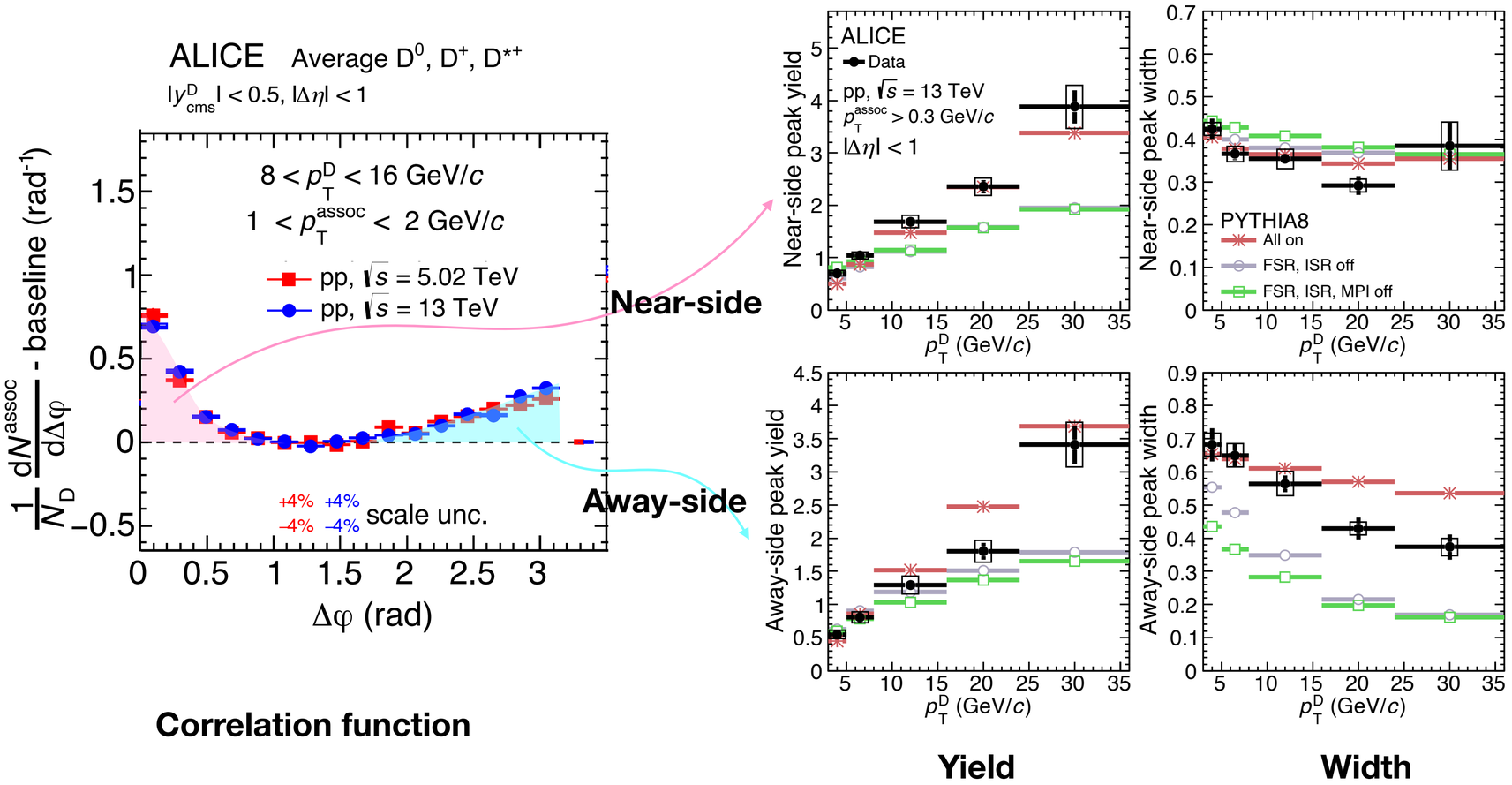


D in p+Pb

arXiv:2205.03936v2



D-charged particle correlation in *pp*

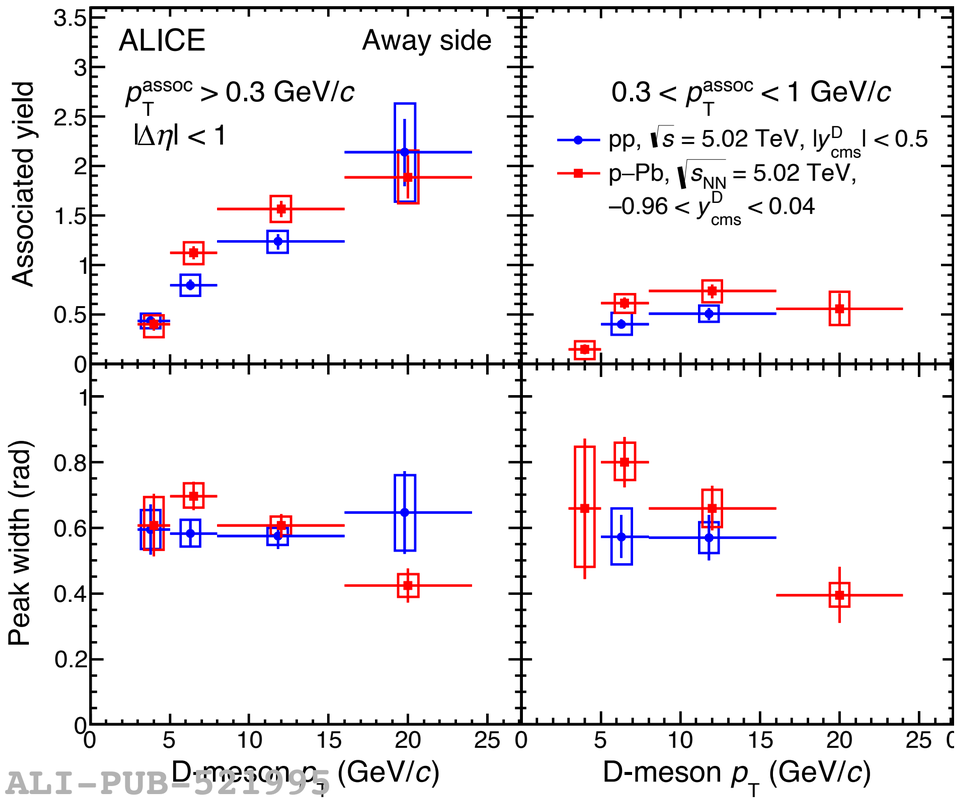


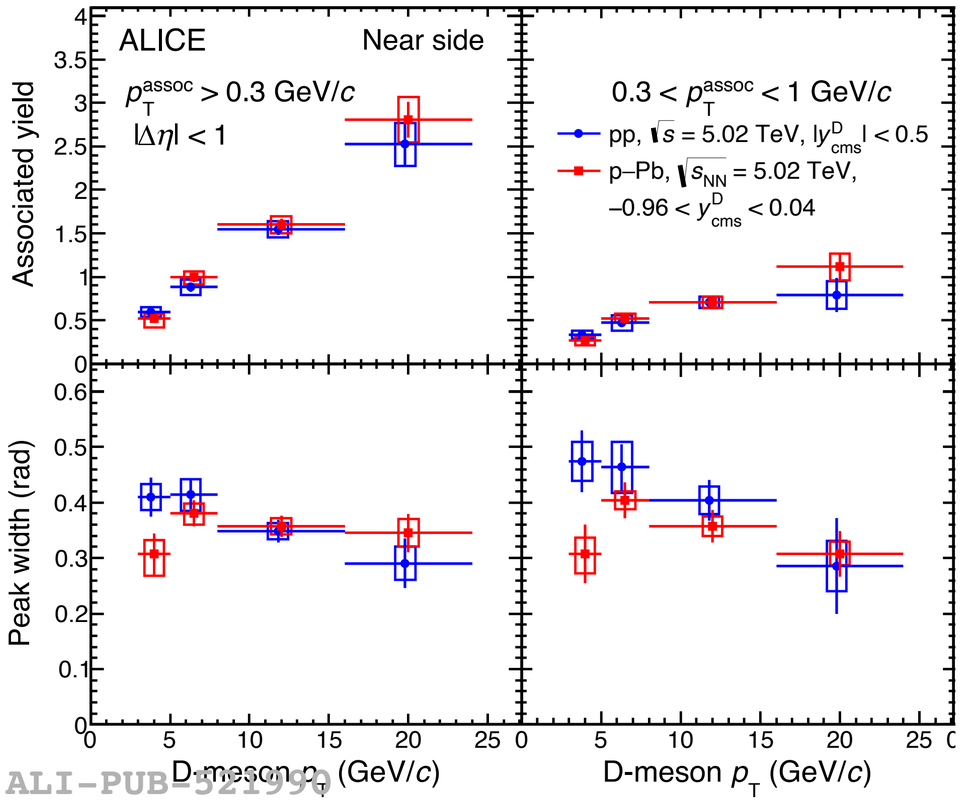
EPJC 82 (2022) 335

- PYTHIA8 with FSR, ISR and MPI can decribe well prompt *D*—charged particle correlation function

D-charged particle correlation in *pp* and *p*+Pb

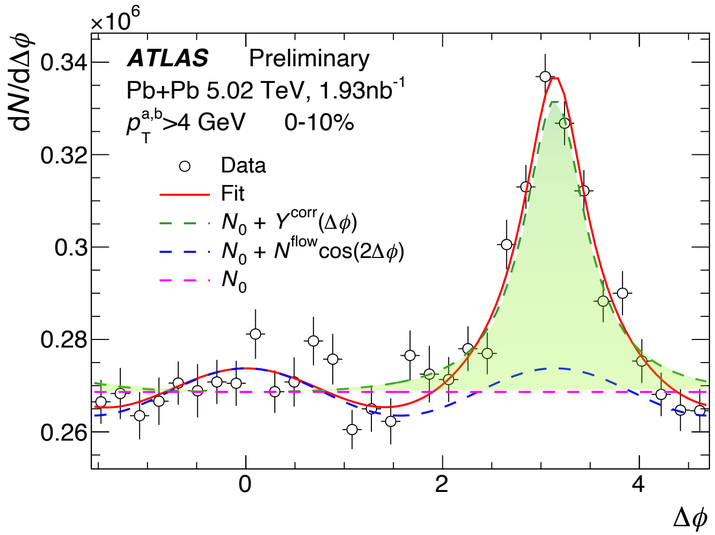
EPJC 80 (2020) 979



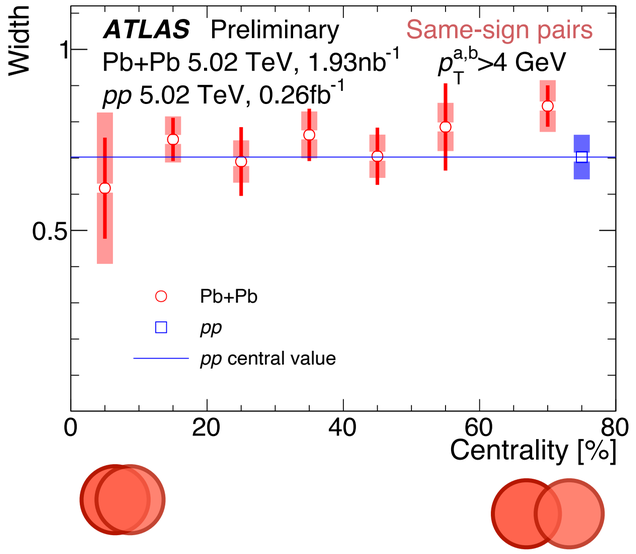


HF pair correlation in Pb+Pb

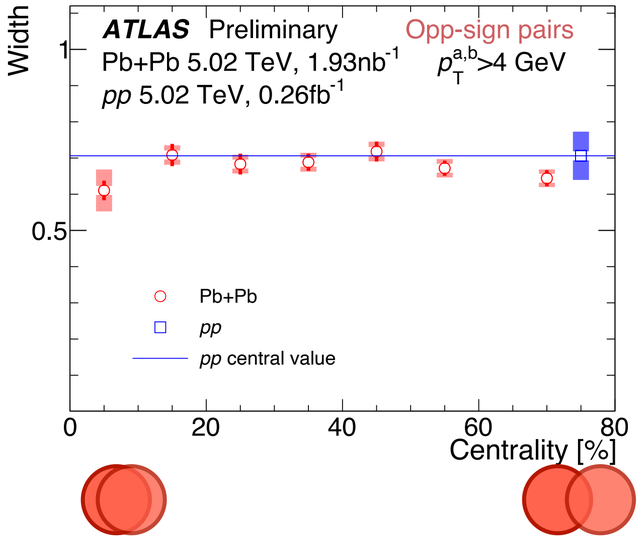
ATLAS-CONF-2022-022



Same-sign ($b\bar{b}$)



Opposite-sign ($c\bar{c} + b\bar{b}$)



- Comparable width between different centralities and between Pb+Pb and *pp*
- Centrality-independent width indicates small angular deflection