Heavy Flavor and Quarkonia Measurements from CMS

Jing Wang on behalf of the CMS Collaboration

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Brookhaven National Laboratory, Upton, NY (US)

Introduction

Heavy quarks are good probe of QGP!

- Produced mainly via initial hard scatterings (m_c, $m_b \gg T_{QGP}$)
  - ➡ Experience the whole evolution of the medium
- Production cross section calculable with pQCD (m_c, $m_b \gg \Lambda_{QCD}$)
  - ➡ Slow "hard probes"
- Brownian motion
  - ➡ Spatial diffusion coefficient D_s
- Strongly interact with the deconfined medium

$$\frac{\partial}{\partial t} f_Q(t,\vec{p}) = \frac{\partial}{\partial p_i}\left[A_i(\vec{p}) f_Q(t,\vec{p}) + \frac{\partial}{\partial p_j}\left(B_{ij}(\vec{p}) f_Q(t,\vec{p})\right)\right]$$

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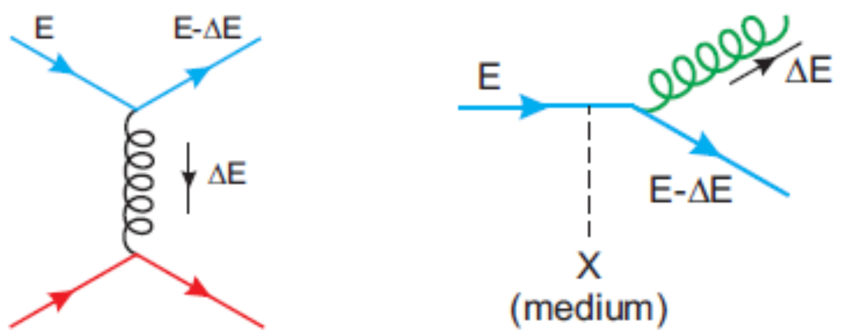
What information of QGP can we get?

- Energy loss in the medium
  - Pictures
    - ✓ pQCD: Collisional + Radiative
    - ✓ AdS/CFT: drag force
  - Depends on (pQCD)
    - ✓ color charge and quark mass (dead cone effect [1])
      - ➡ $\Delta E_l > \Delta E_c > \Delta E_b$
    - ✓ medium density and path length
- Collective flow
  - Interaction strength
  - Thermalization + Relaxation time



[1] Phys. Lett. B 519 (2001) 199

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$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}}{dp_T} \bigg/ \frac{d\sigma_{pp}}{dp_T}$$

Nuclear modification factor (R_{AA})

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos\left[n\left(\phi - \Phi_n\right)\right]$$

Azimuthal anisotropy (v_n)

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Initial Condition

Evolution Eq.

EoS (lQCD)

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Outline

Heavy-ion data collection in CMS

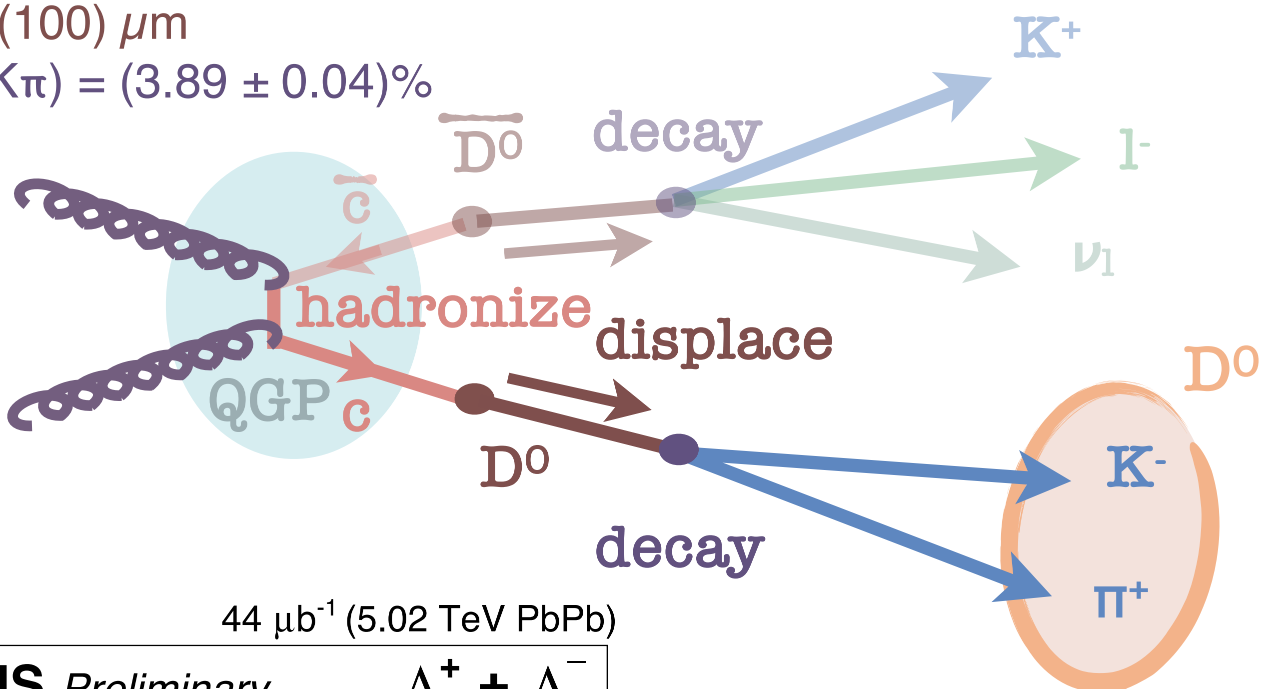
	Collision System	Energy	LHC Delivered	CMS Recorded
Run 1				
2011	Pb-Pb	2.76 TeV	184.1 μb^{-1}	174.3 μb^{-1}
2013	p-Pb	5.02 TeV	36.1 nb^{-1}	35.5 nb^{-1}
Run2				
2015	p-p	5.02 TeV	28.8 pb^{-1}	28.1 pb^{-1}
2015	Pb-Pb	5.02 TeV	0.60 nb^{-1}	0.55 nb^{-1}
2016	p-Pb	8.16 TeV	188.3 nb^{-1}	180.2 nb^{-1}
2017	Xe+Xe	5.44 TeV	6.3 μb^{-1}	6.0 μb^{-1}
2017	p-p	5.02 TeV	334.3 pb^{-1}	316.3 pb^{-1}
2018	Pb-Pb	5.02 TeV	1.80 nb^{-1}	1.71 nb^{-1}

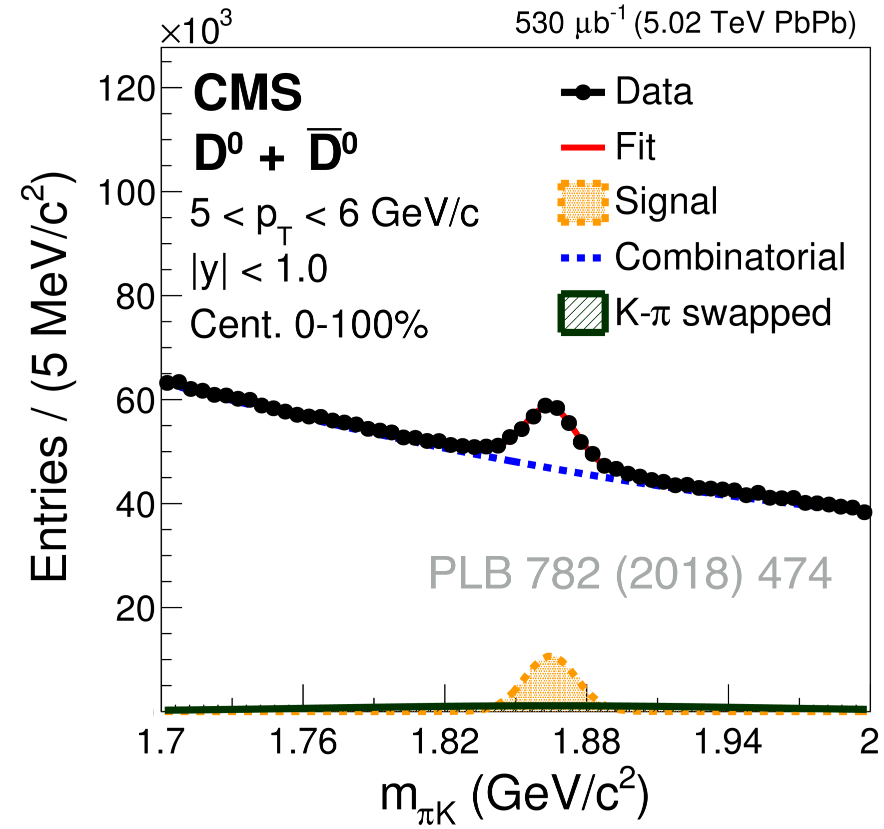
Heavy Quark Production

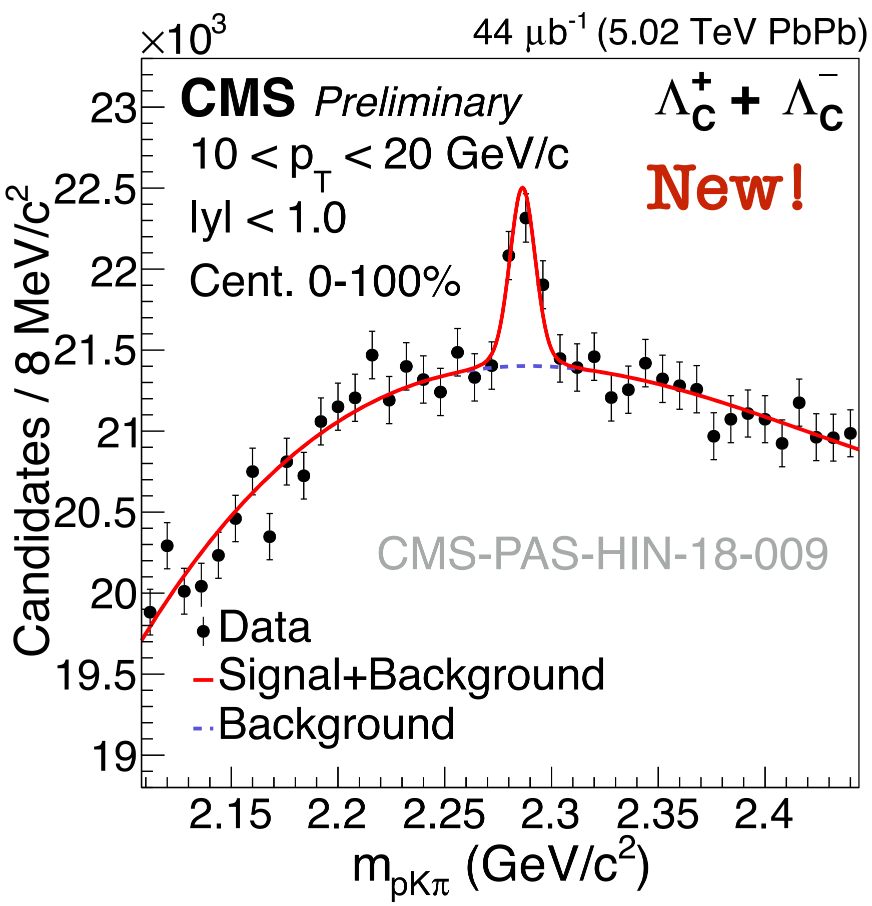
Measuring open charm in CMS

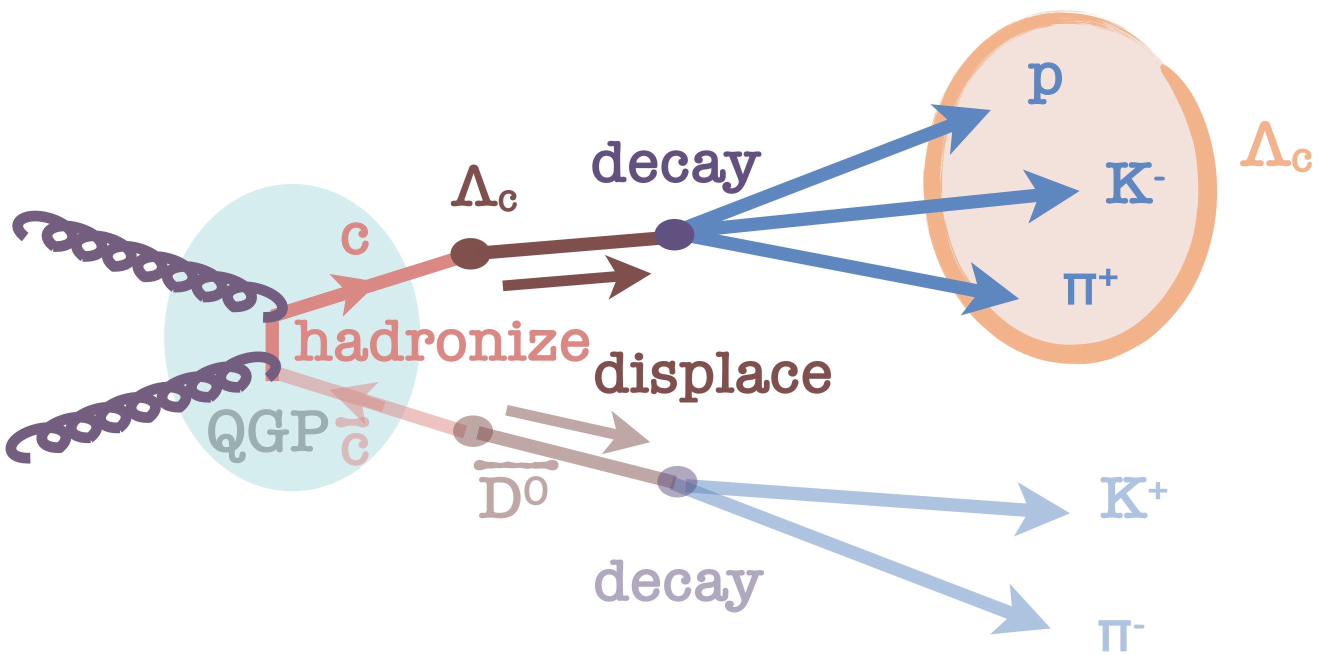
- **Fully reconstruct hadronic decays**

- $c \to D^0$: $\mathcal{O}(50\%)$
- $m(D^0) = 1864.83 \pm 0.05$ MeV/c^2
- $c\tau(D^0) = \mathcal{O}(100)$ μm
- $BR(D^0 \to K\pi) = (3.89 \pm 0.04)\%$





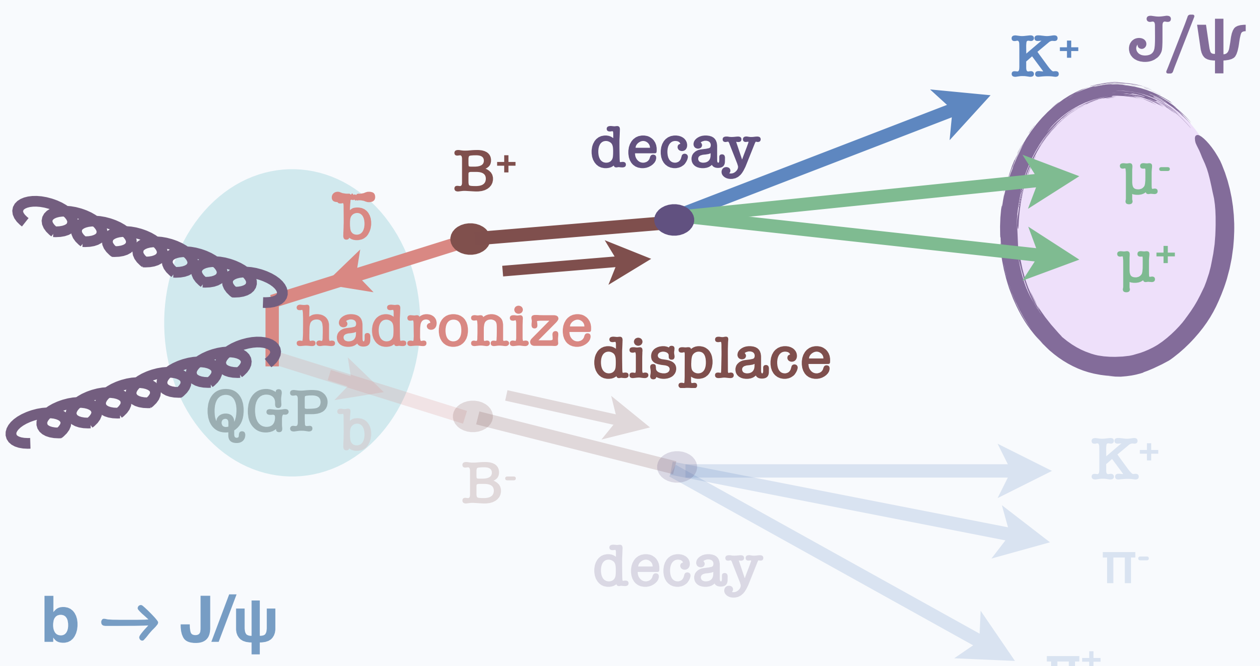




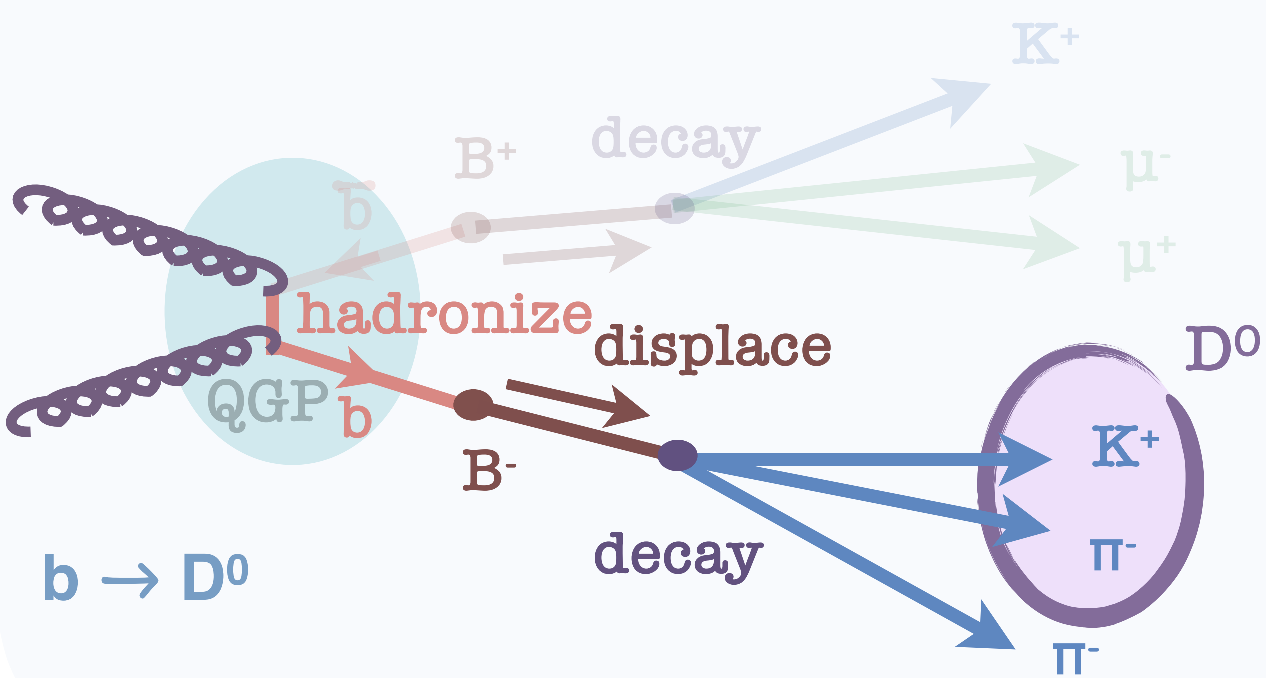
- $c \to \Lambda_c$: $\mathcal{O}(10\%)$
- $BR(\Lambda_c \to pK\pi) = (5.0 \pm 1.3)\%$
- $m(\Lambda_c) = 2284.9 \pm 0.6$ MeV/c^2
- $c\tau(\Lambda_c) = \mathcal{O}(50)$ μm

Measuring open beauty in CMS

Inclusive: reconstruct daughter resonance of b hadrons

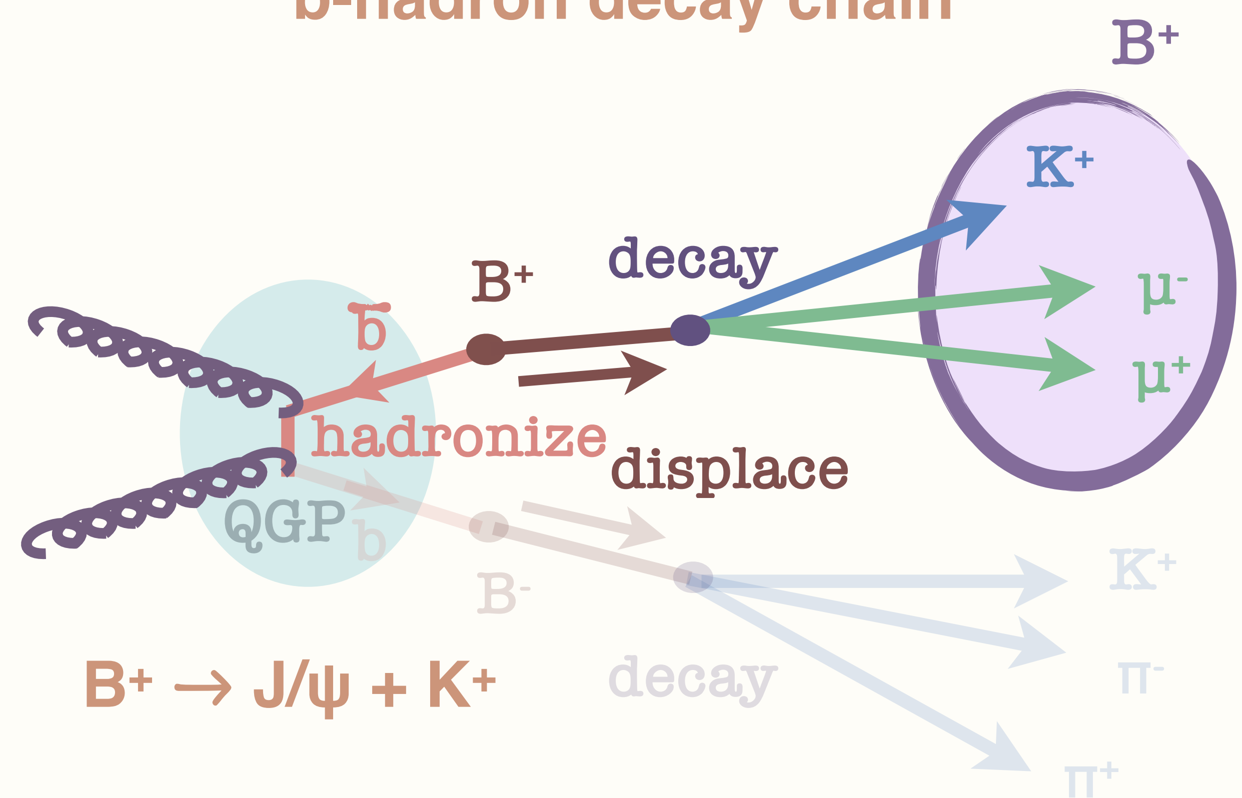


$b \rightarrow J/\psi$



$b \rightarrow D^0$

Exclusive: fully reconstruct b-hadron decay chain

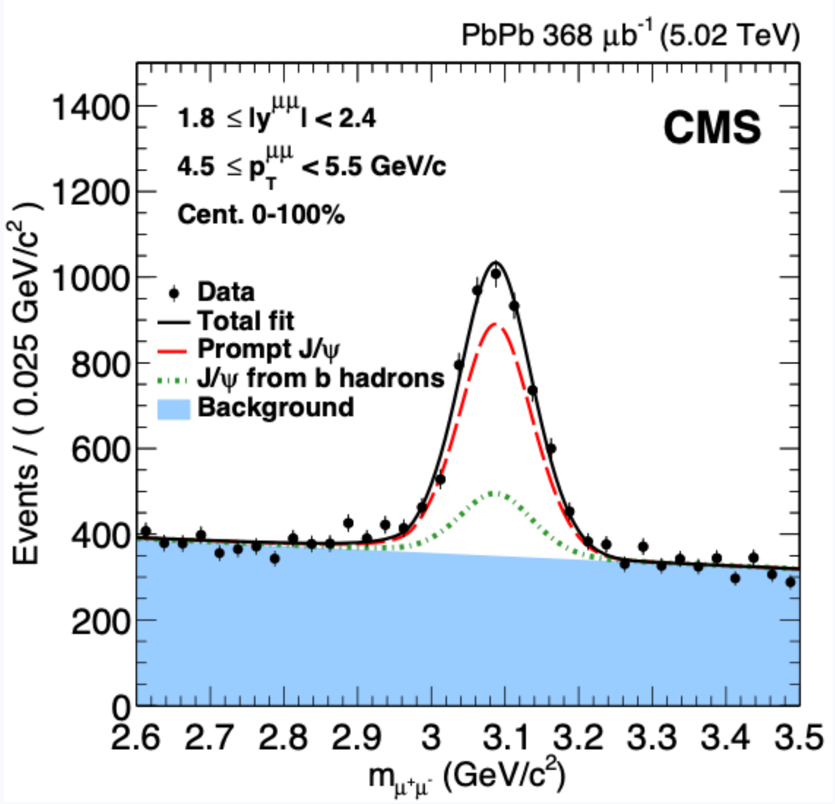


$B^+ \rightarrow J/\psi + K^+$

- $\bar{b} \rightarrow J/\psi$ + anything: ~ 1%
- $\bar{b} \rightarrow D^0$ + anything: ~ 60%
- $c\tau(B) = \mathcal{O}(500)\ \mu m$

Measuring open beauty in CMS

$b \to J/\psi$



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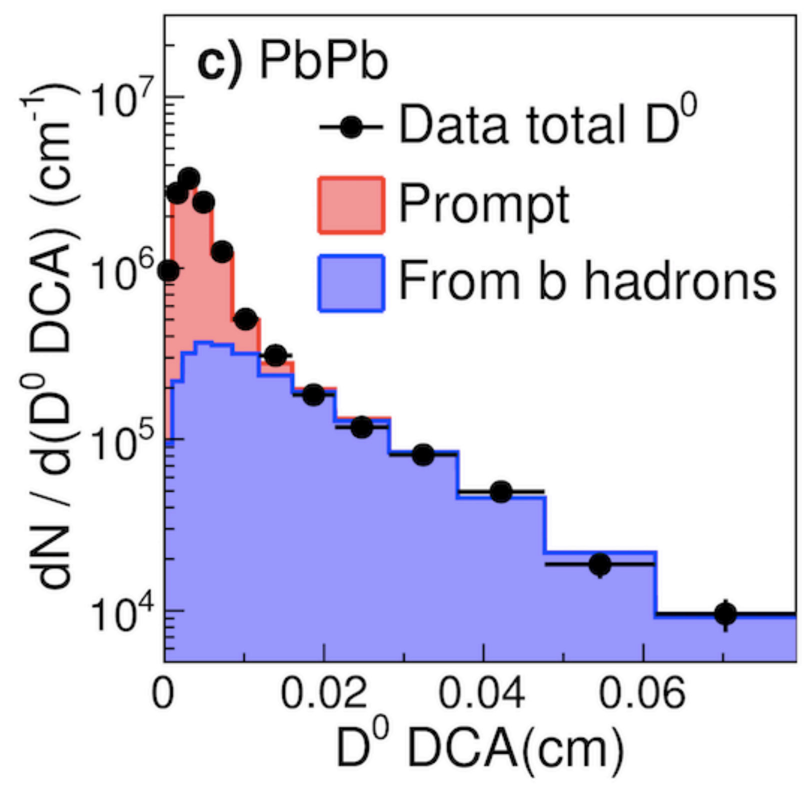

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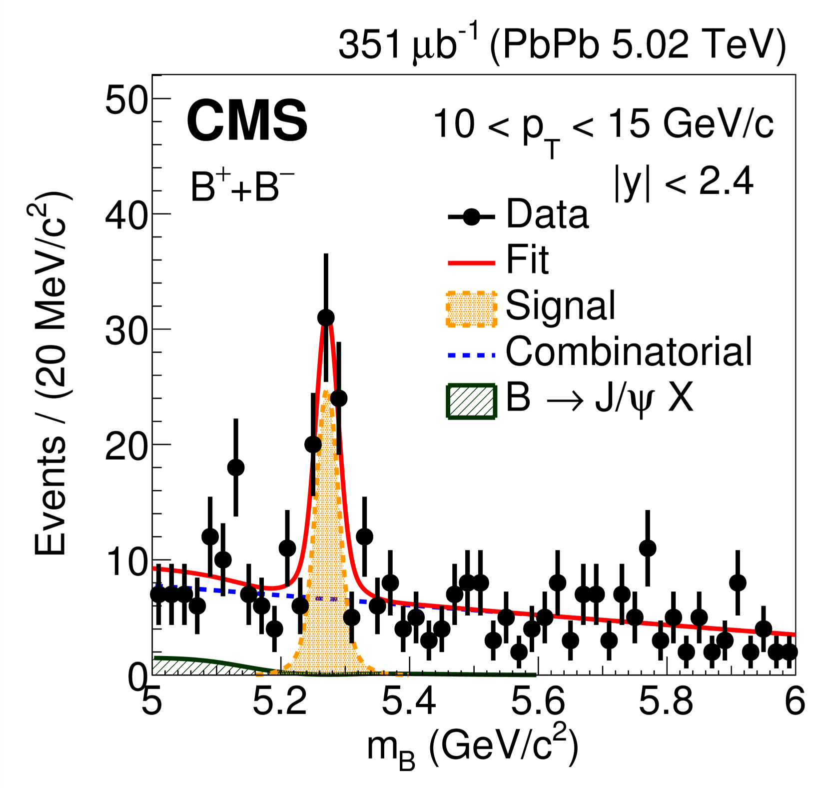
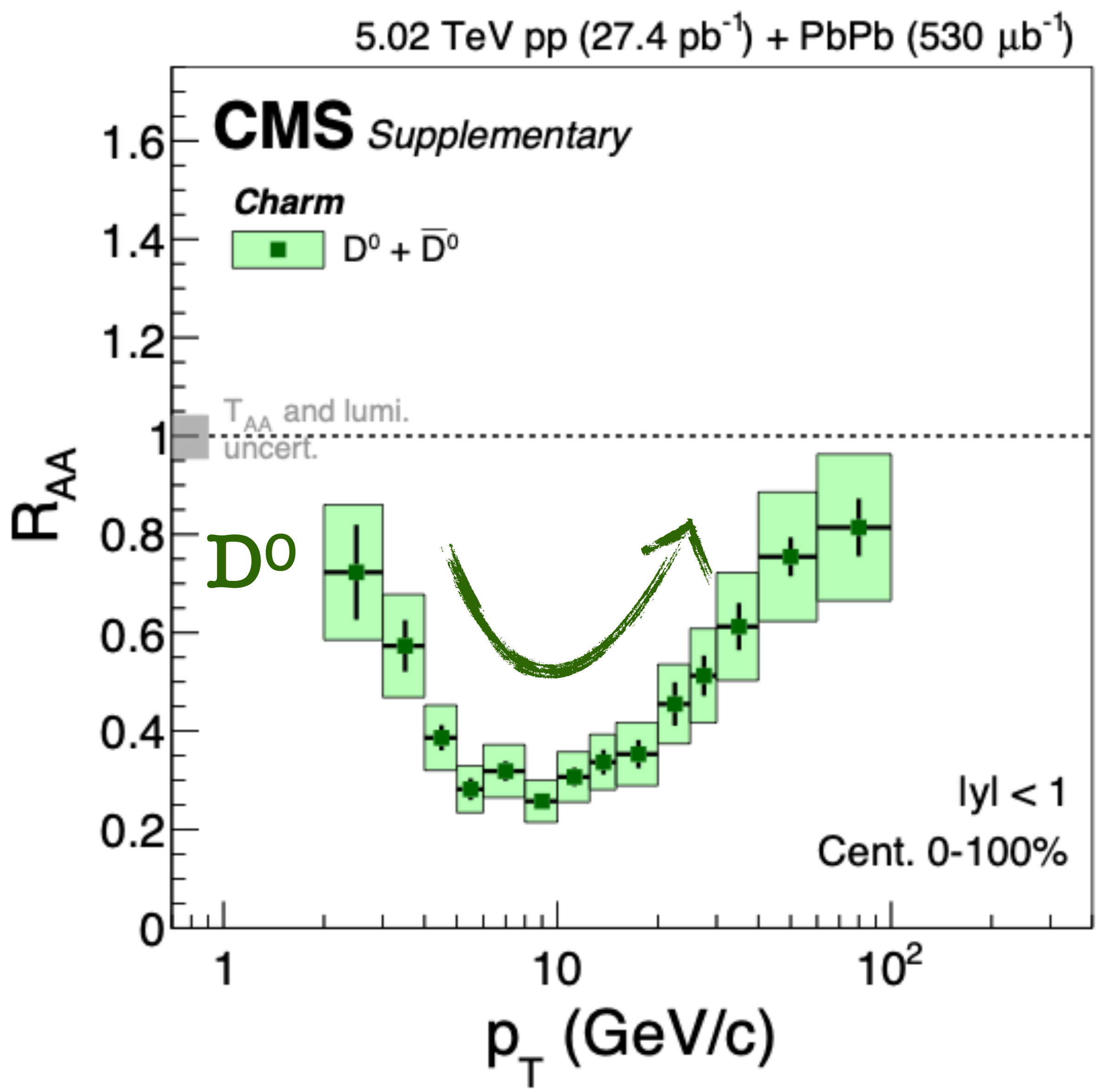


- Long decay length → Precise vertexing
- No-hadronic PID utilized
- Cut optimization via ML methods
- Advantage on μ, J/ψ reconstruction and recognization

PRL 119 (2017) 152301
arXiv:1810.11102
EPJC 78 (2018) 509

Flavor dependence of parton energy loss in PbPb

Centrality **0-100%**



Prompt D^0

- ➡ Strongest suppression at p_T 5-10 GeV/c
- ➡ No significant collision energy dependence compared with 2.76 TeV

PLB 782 (2018) 474

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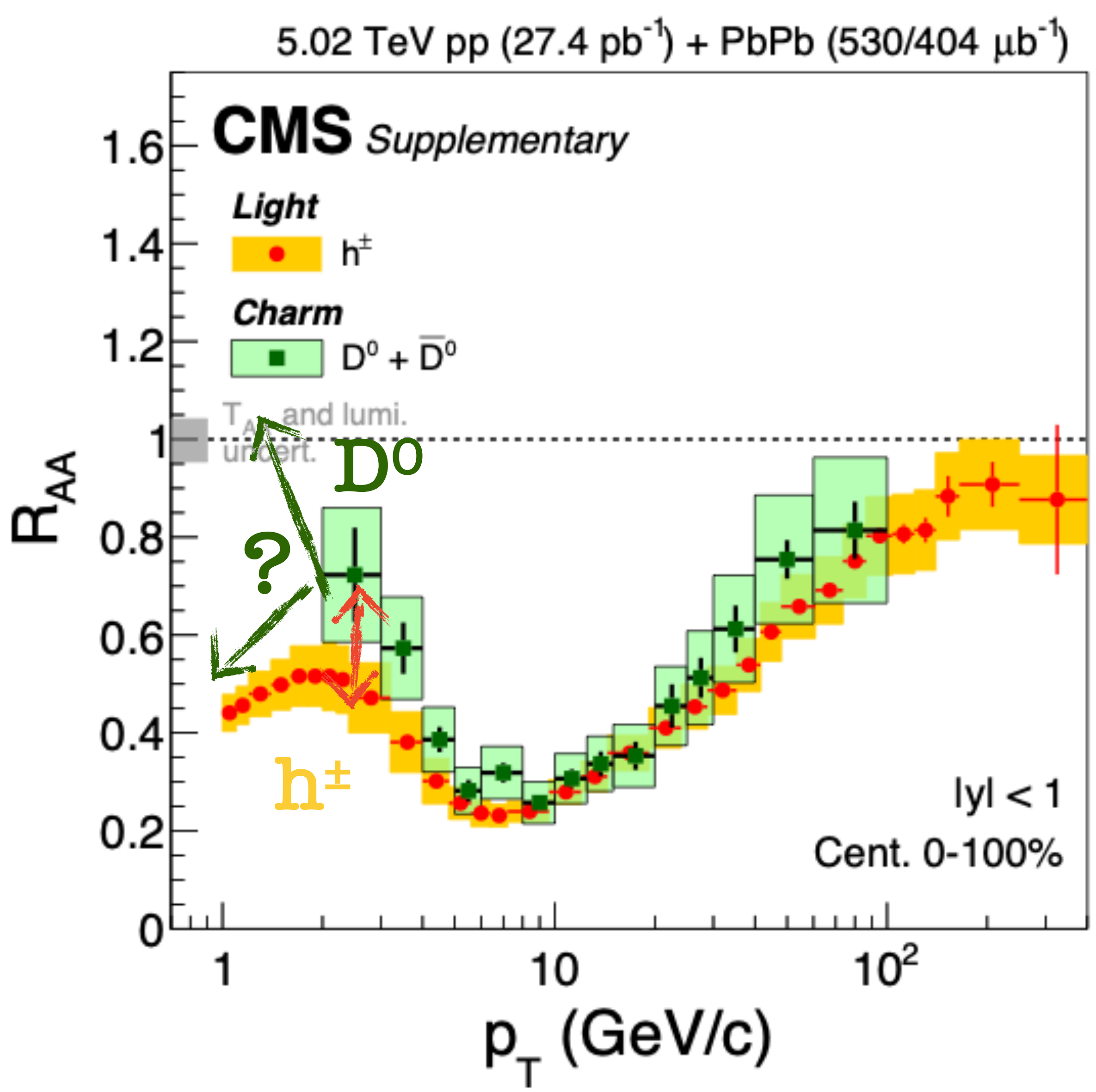

Prompt D⁰

➡ Strongest suppression at p_T 5-10 GeV/c

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Charged hadrons vs. Prompt D⁰

➡ Similar suppression in a wide kinematic range

➡ Hint of less suppression of D⁰ at low p_T

➡ Dead-cone effect? Different spectra slope? Flow peak is at lower p_T? …?

JHEP 04 (2017) 039
PLB 782 (2018) 474

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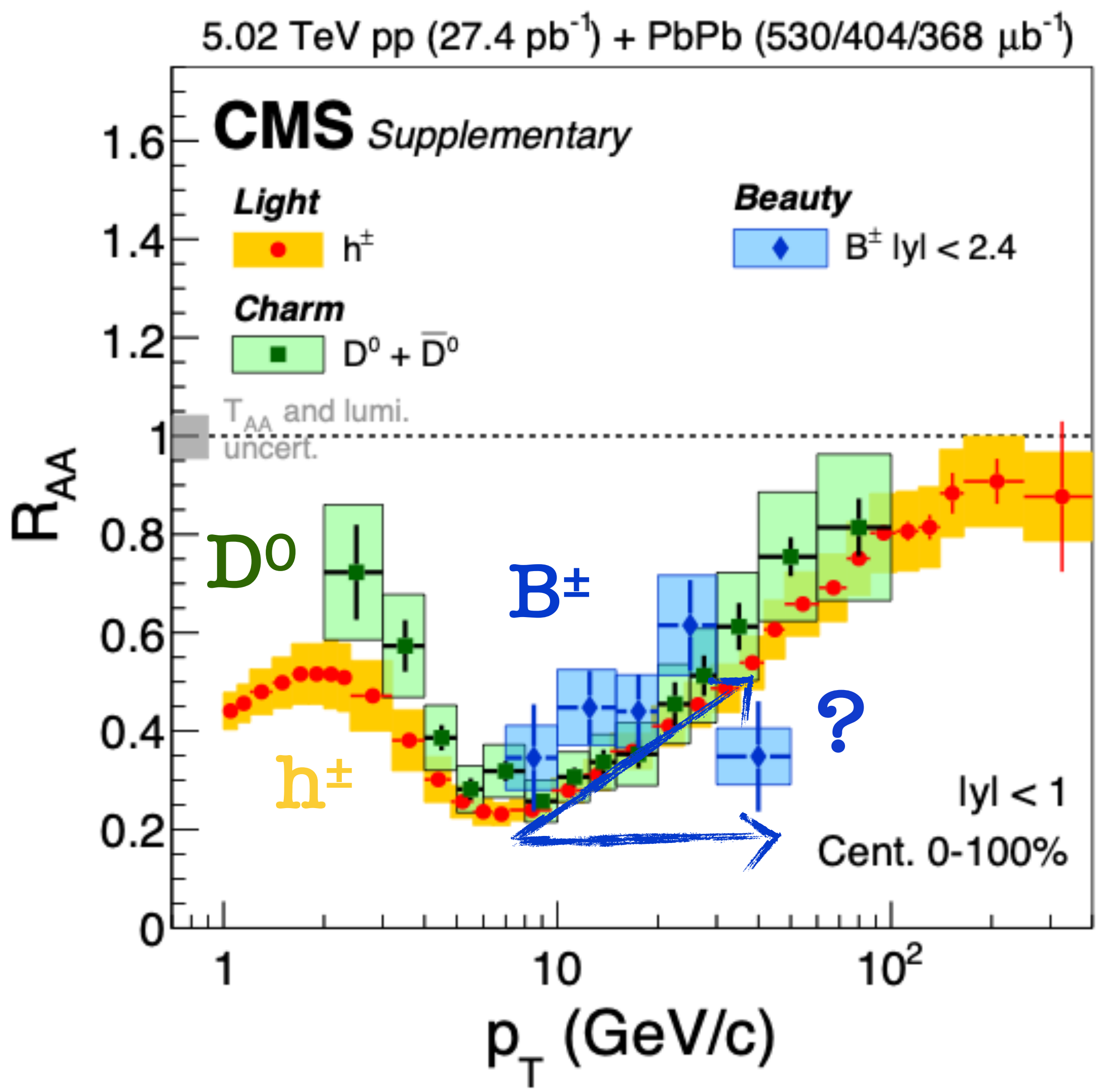

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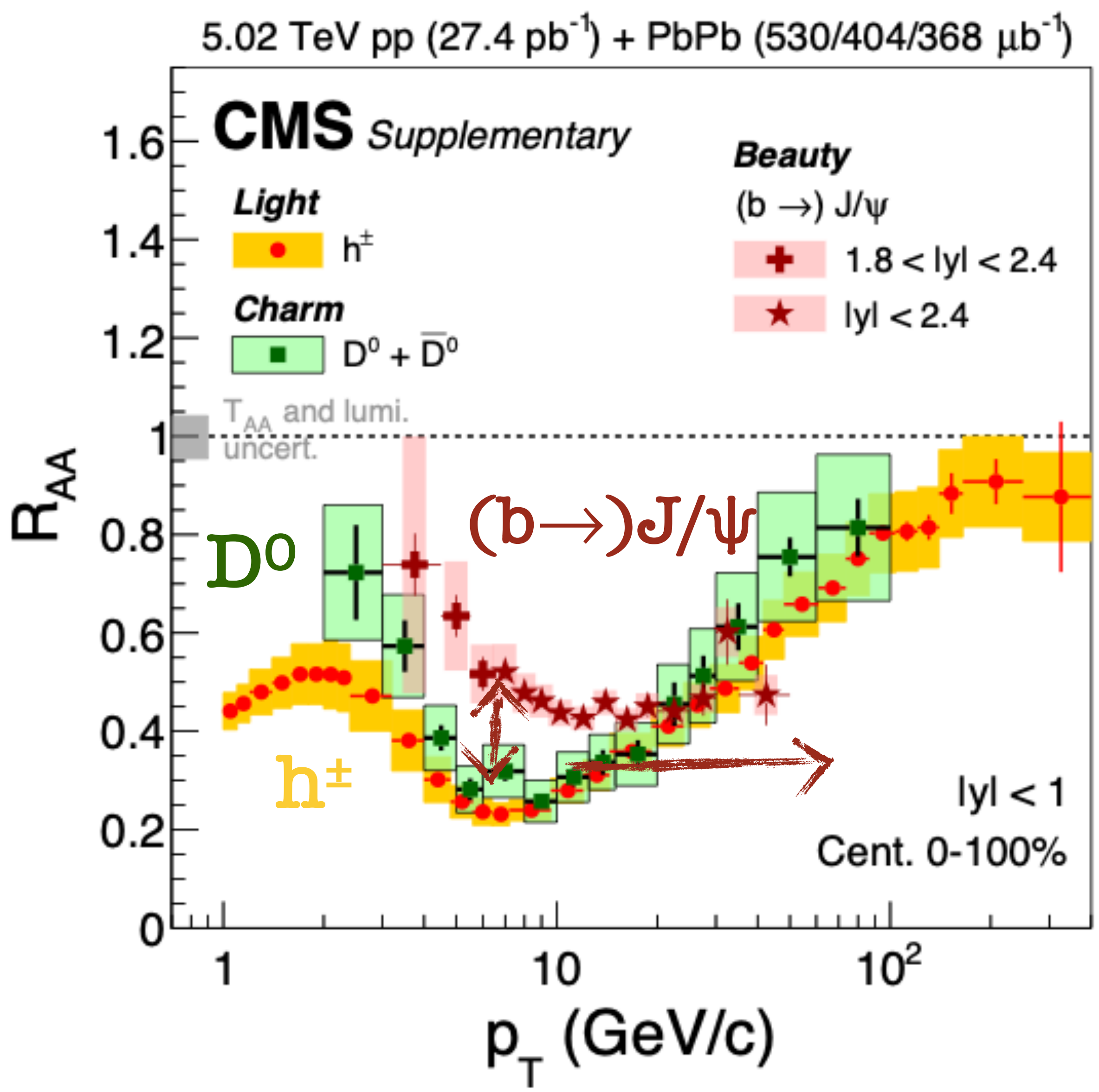

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Non-prompt J/ψ
- ➡ Flavor hierarchy of R_{AA} at low p_T
- ➡ Flat Non-prompt J/ψ R_{AA} at high p_T

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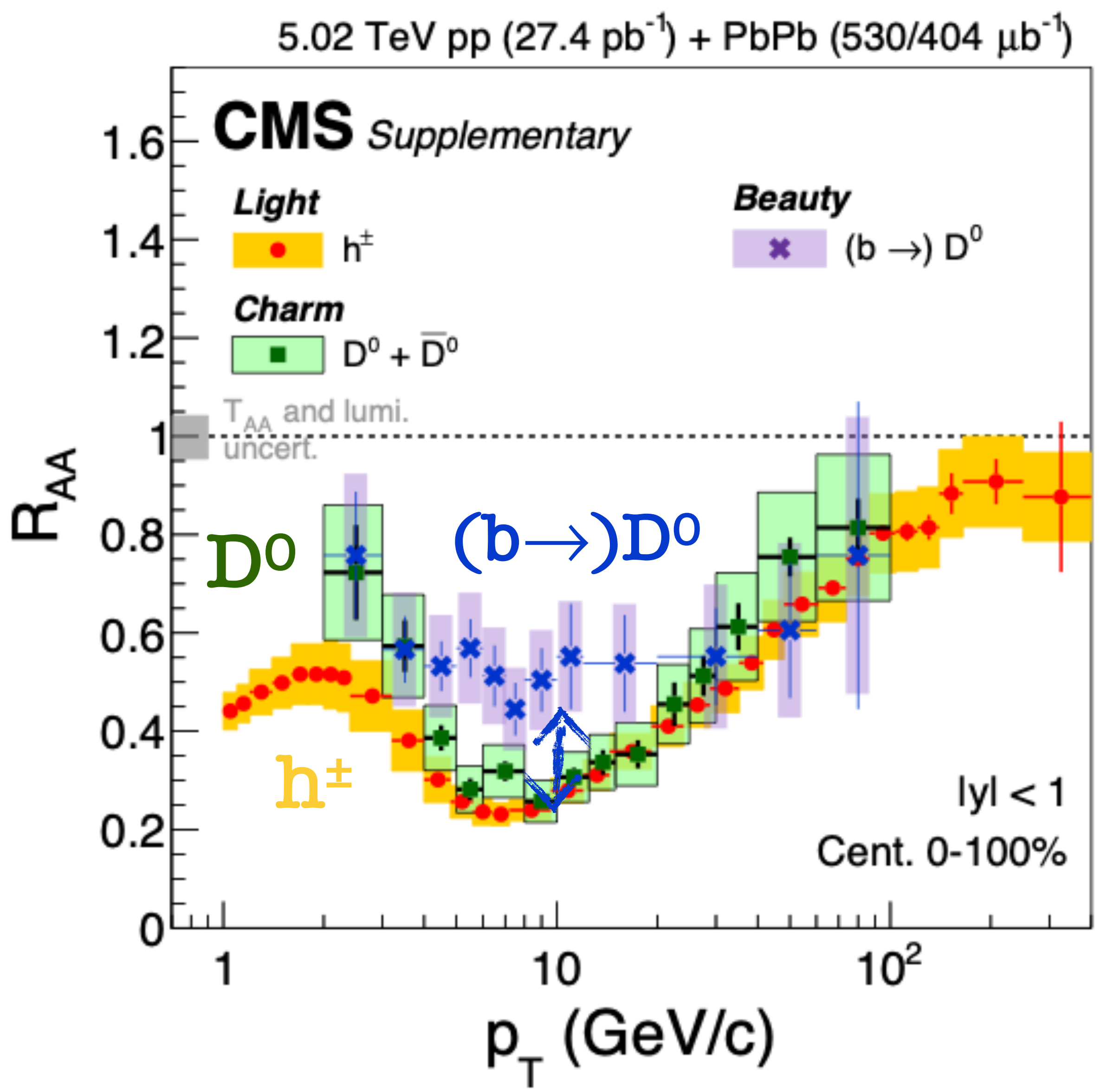

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arXiv:1810.11102
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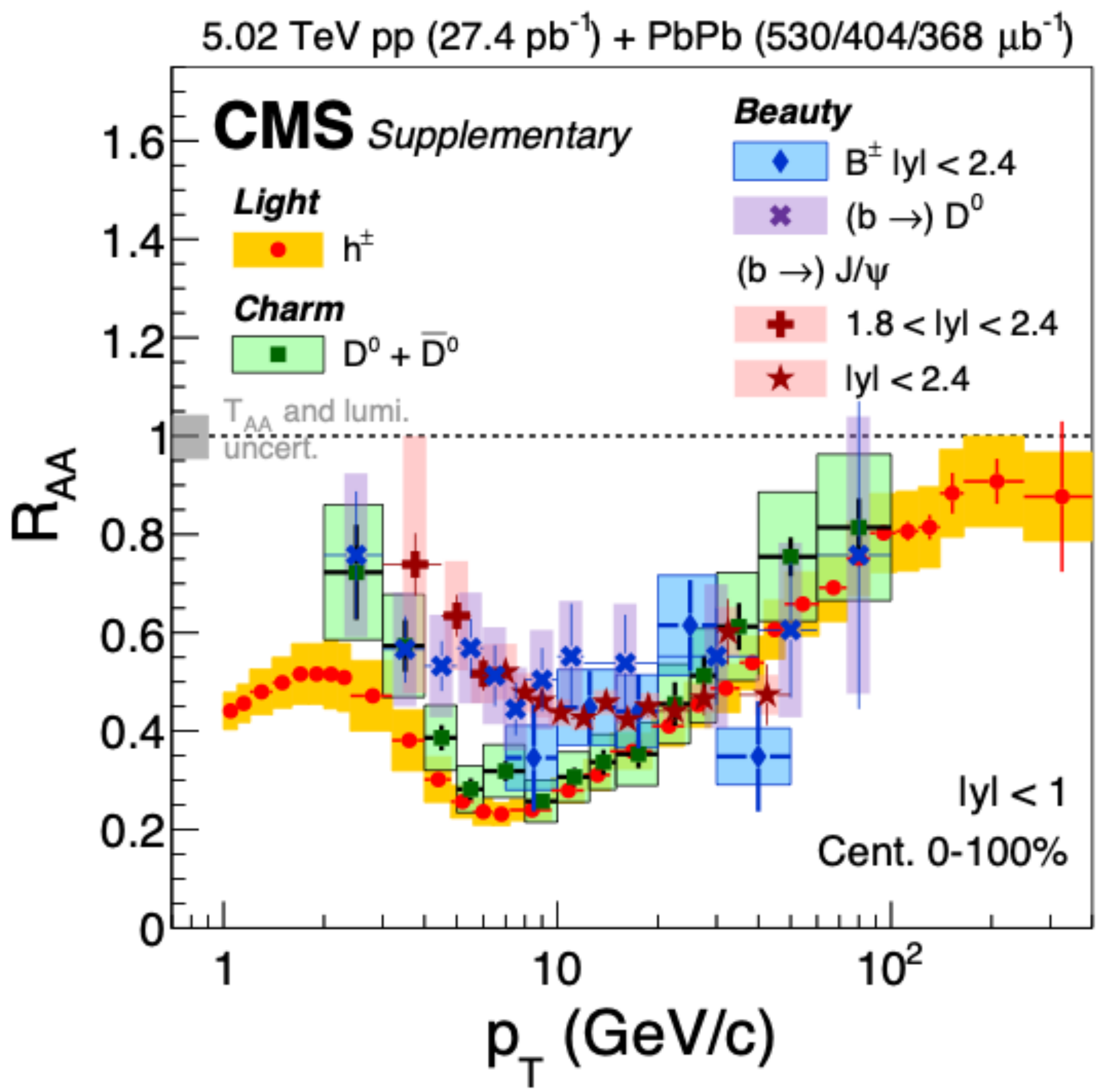

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Unprecedented information about parton mass dependence of energy loss from CMS!

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- Flavor hierarchy of R_{AA} at low p_T
- Flat Non-prompt J/ψ R_{AA} at high p_T

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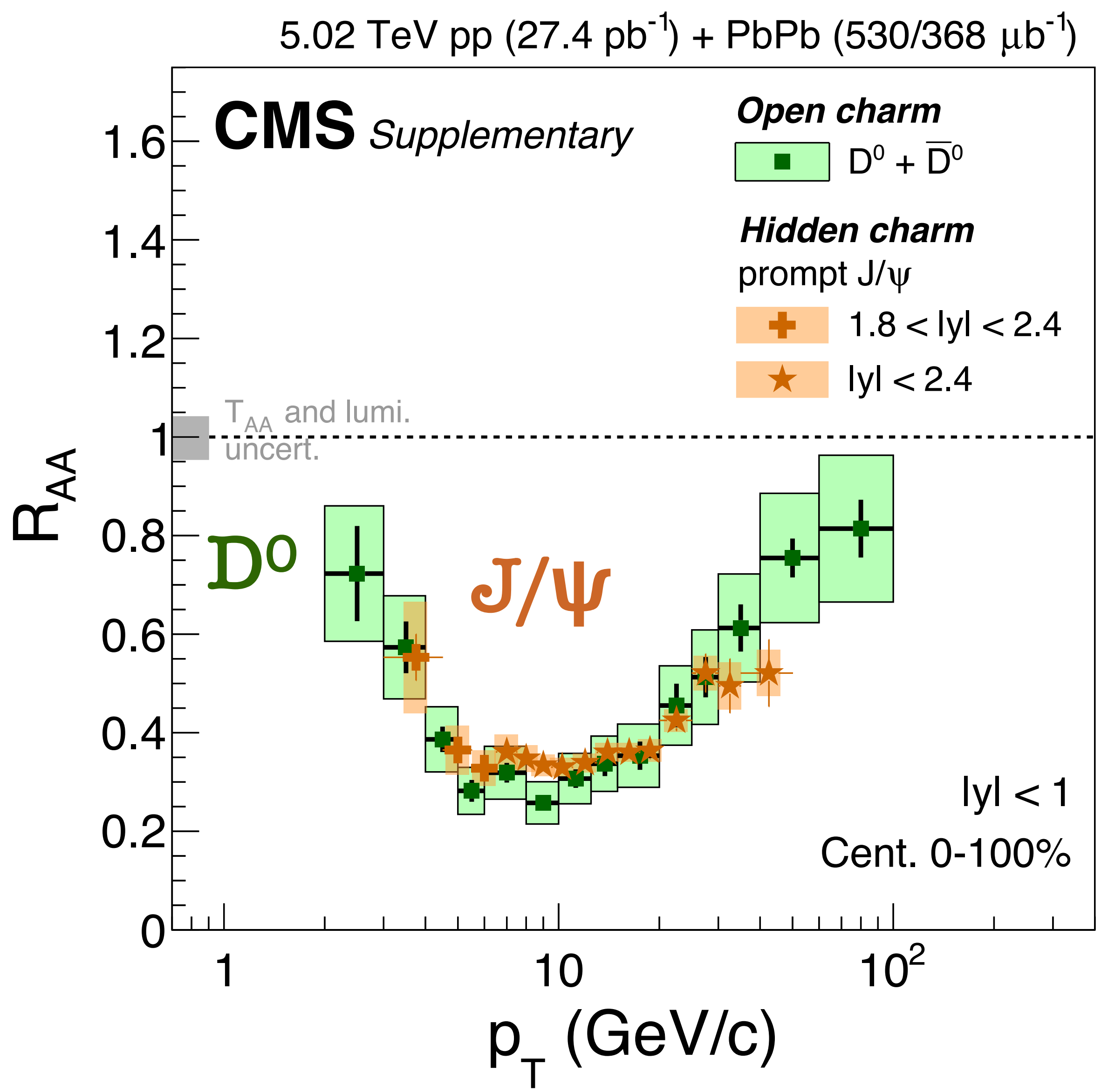

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B^+ **From Open heading to Hidden!**

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Non-prompt D^0

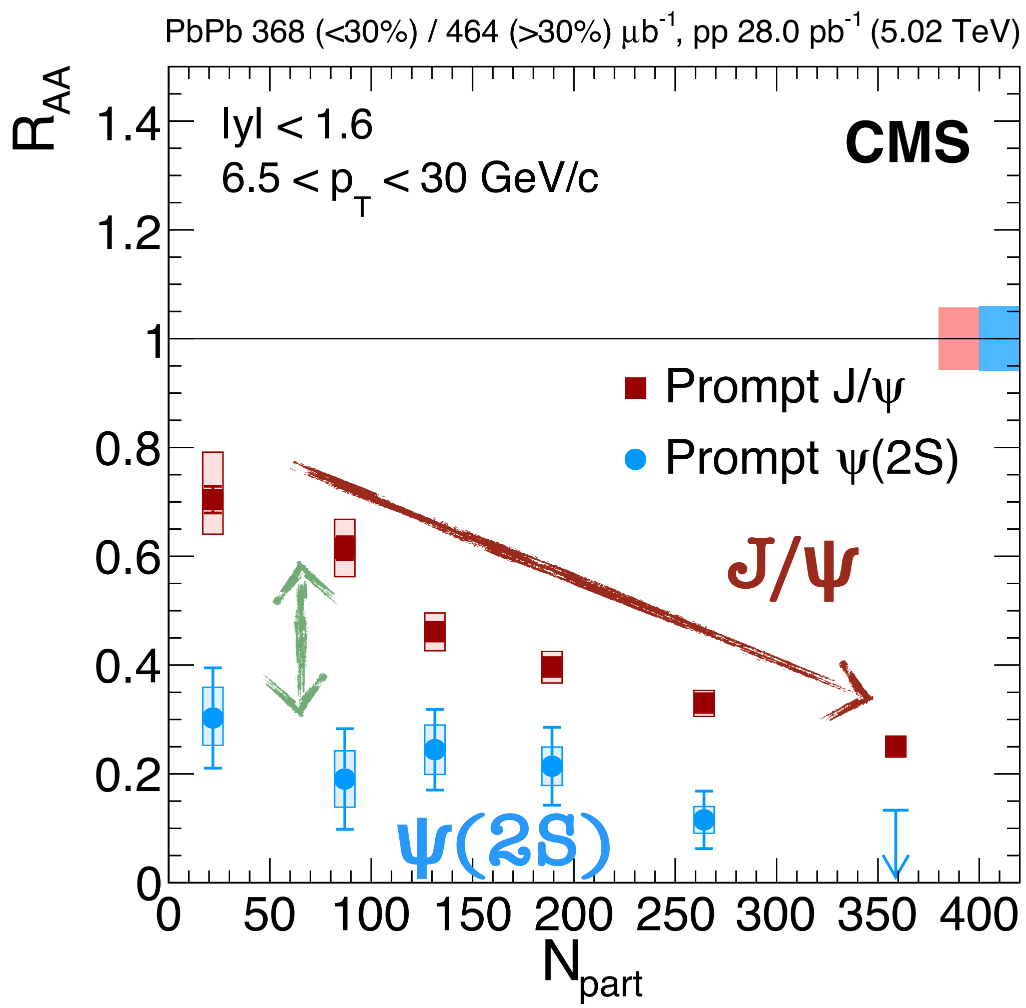
- ➡ Larger R_{AA} of non-prompt D^0 than prompt D^0 in intermediate p_T

Prompt J/ψ

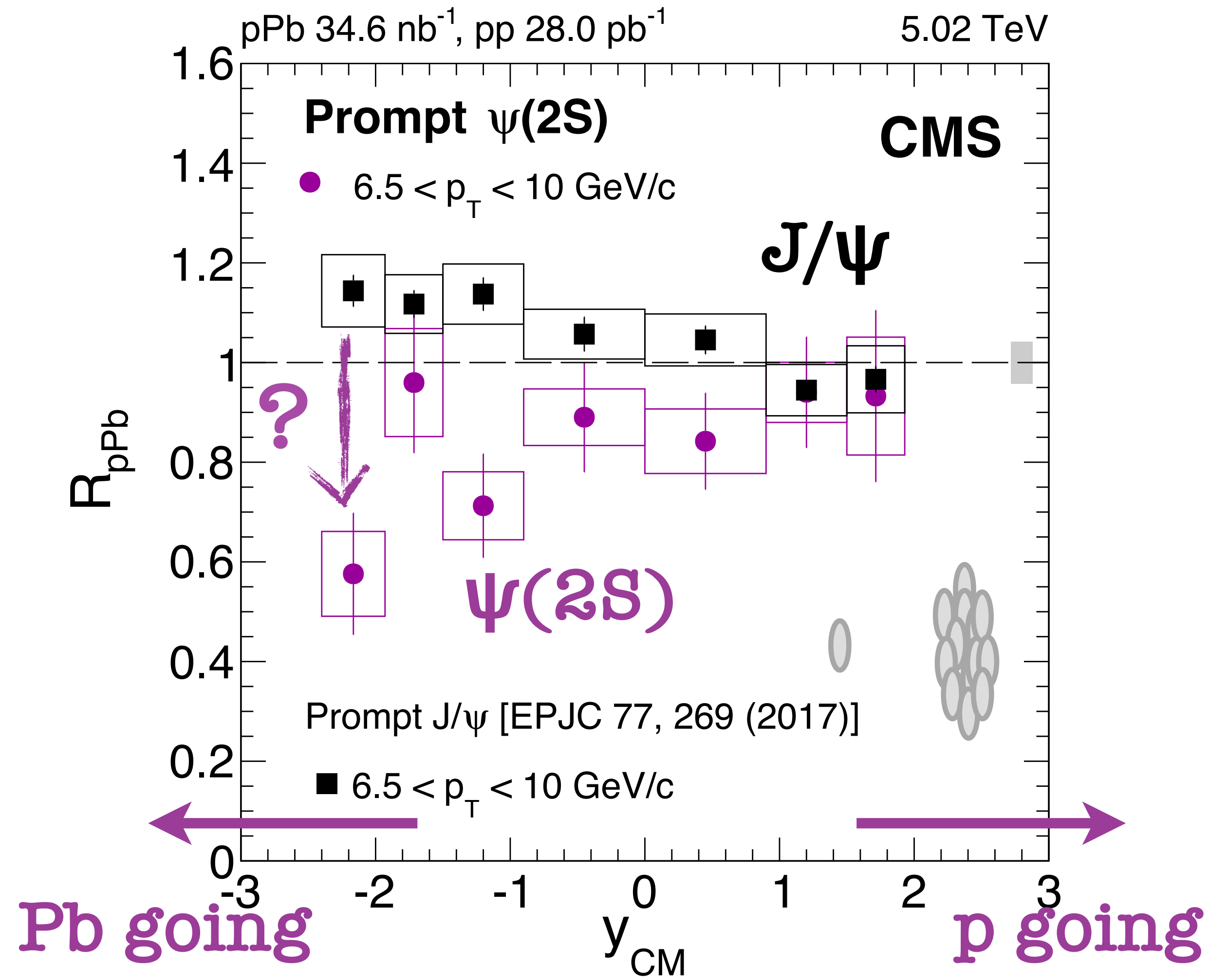
- ➡ Prompt J/ψ suffers strong suppression
- ➡ Consistent over a wide kinematic range
- ➡ Energy loss play most important role in this p_T range?

Charmonia Production in PbPb and pPb

PbPb



pPb



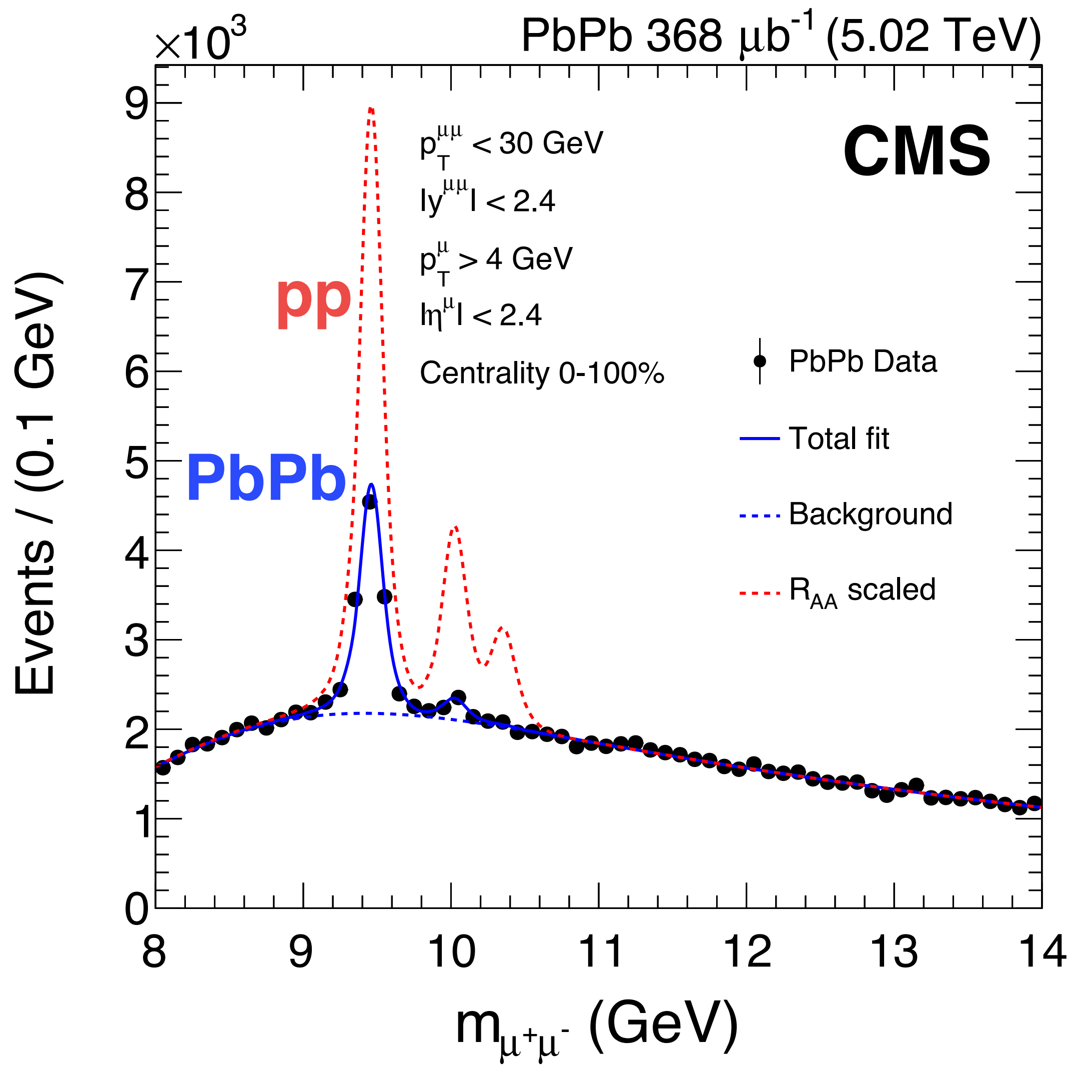
- Strong suppression for J/ψ and ψ(2S) in PbPb
- Increasing suppression towards central events
- Larger suppression for ψ(2S) than J/ψ

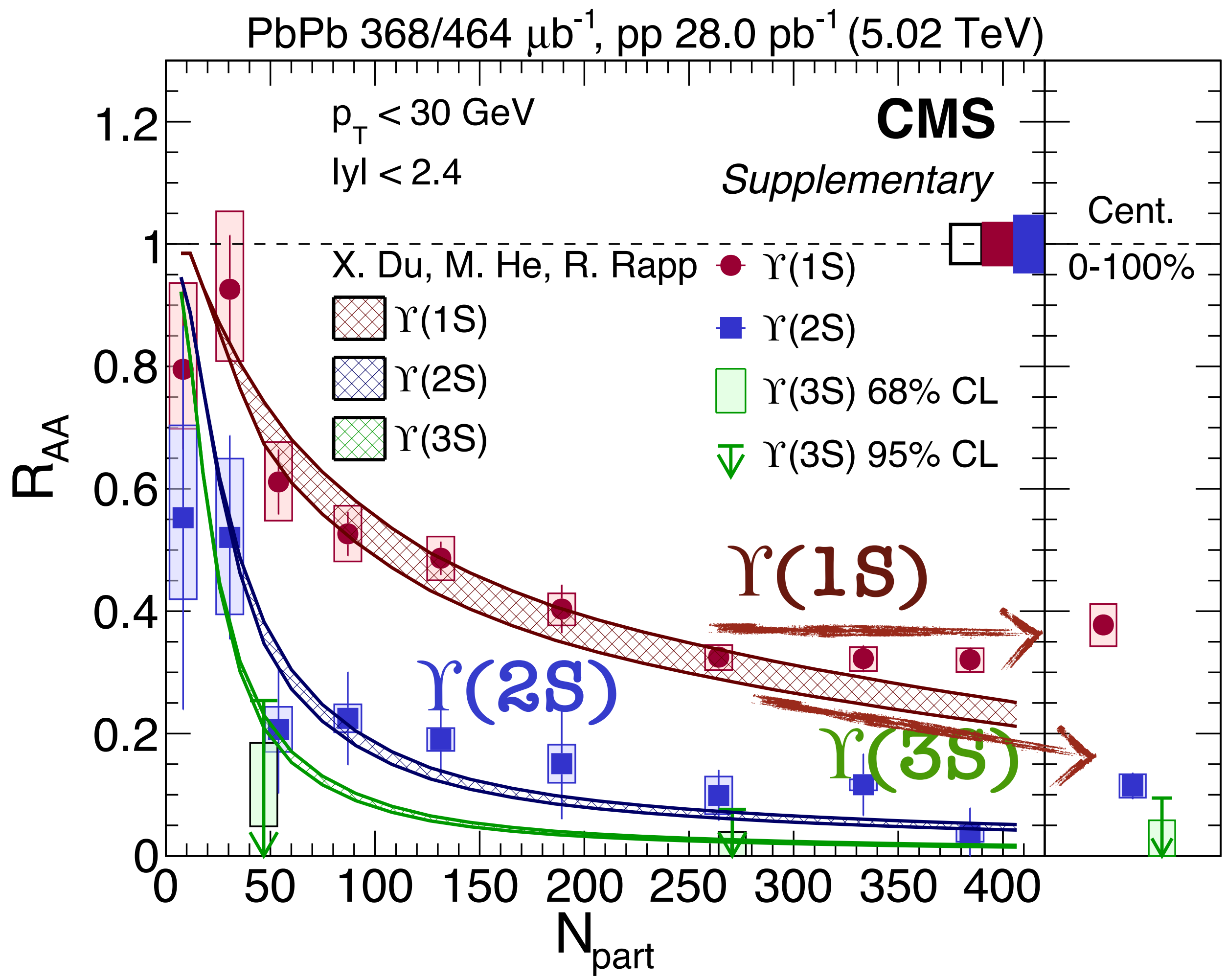
- Suppression of ψ(2S) in pPb
- Expect same modification of J/ψ and ψ(2S) from nPDF and coherent energy loss
- Indication of final state effects from comoving medium?

EPJC 78 (2018) 509

PLB 790 (2019) 509

Bottomonia Sequential Suppression in PbPb





- No sign of ϒ(3S) in the high statistic PbPb data
- Agree with models with melting + **with** or without ϒ regenerations
- Deviation between data and theory at most central events?

PLB 790 (2019) 270

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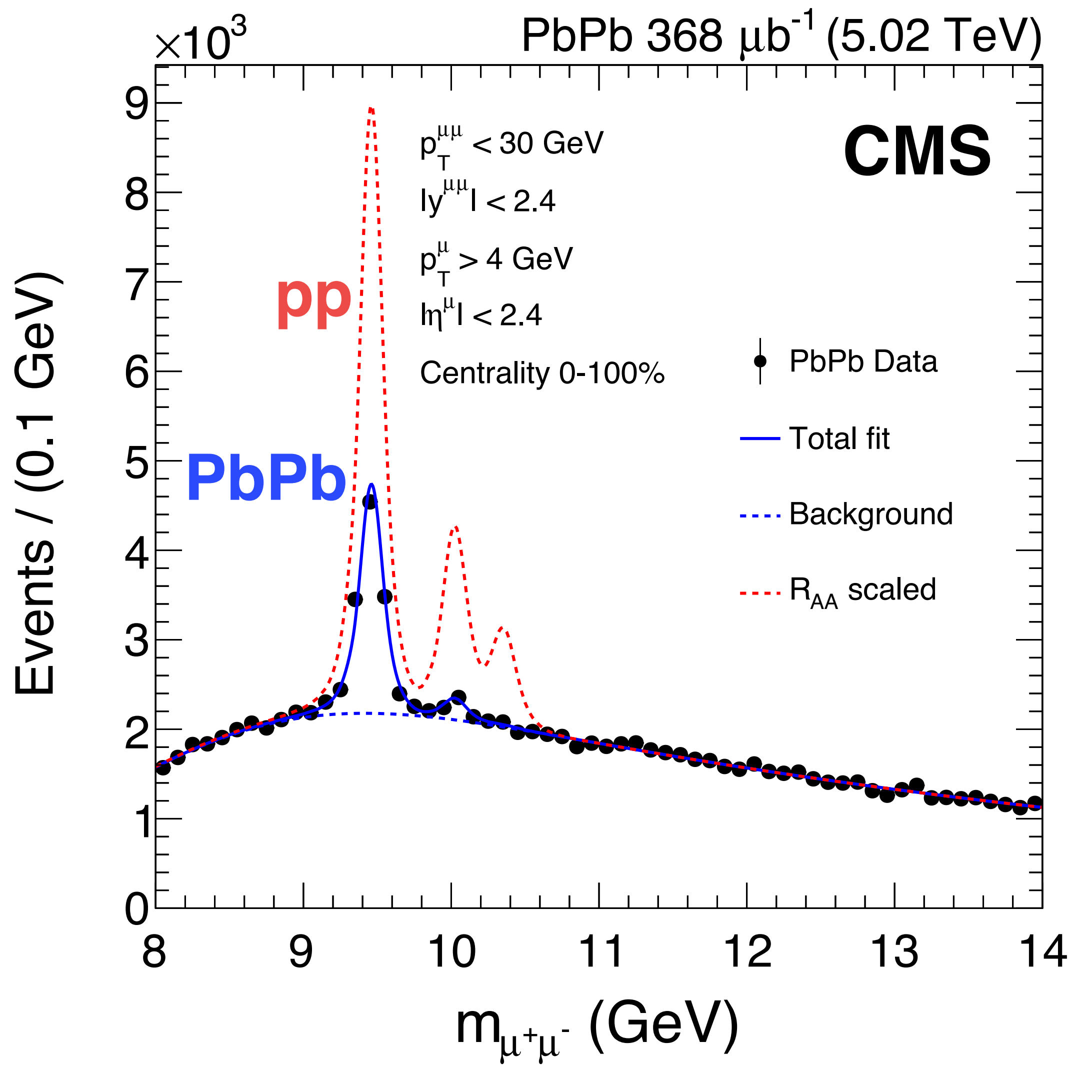

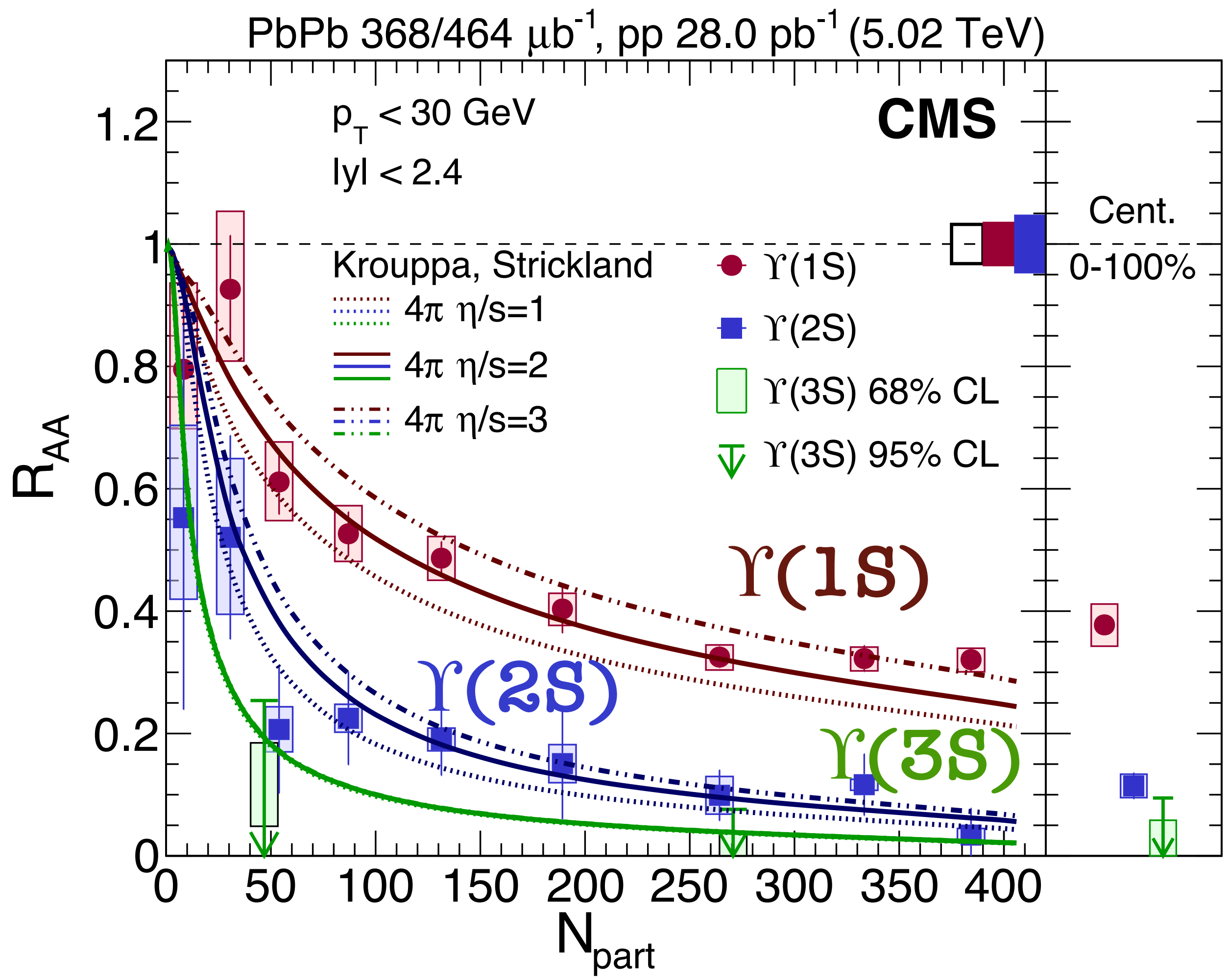

- No sign of ϒ(3S) in the high statistic PbPb data
- Agree with models with melting + with or **without** ϒ regenerations
- At most central and most peripheral events, larger η/s agrees better
  - ➡ Effect of bias from peripheral event selection?
  - ➡ Good to follow this up in 2018 + Run 3 data

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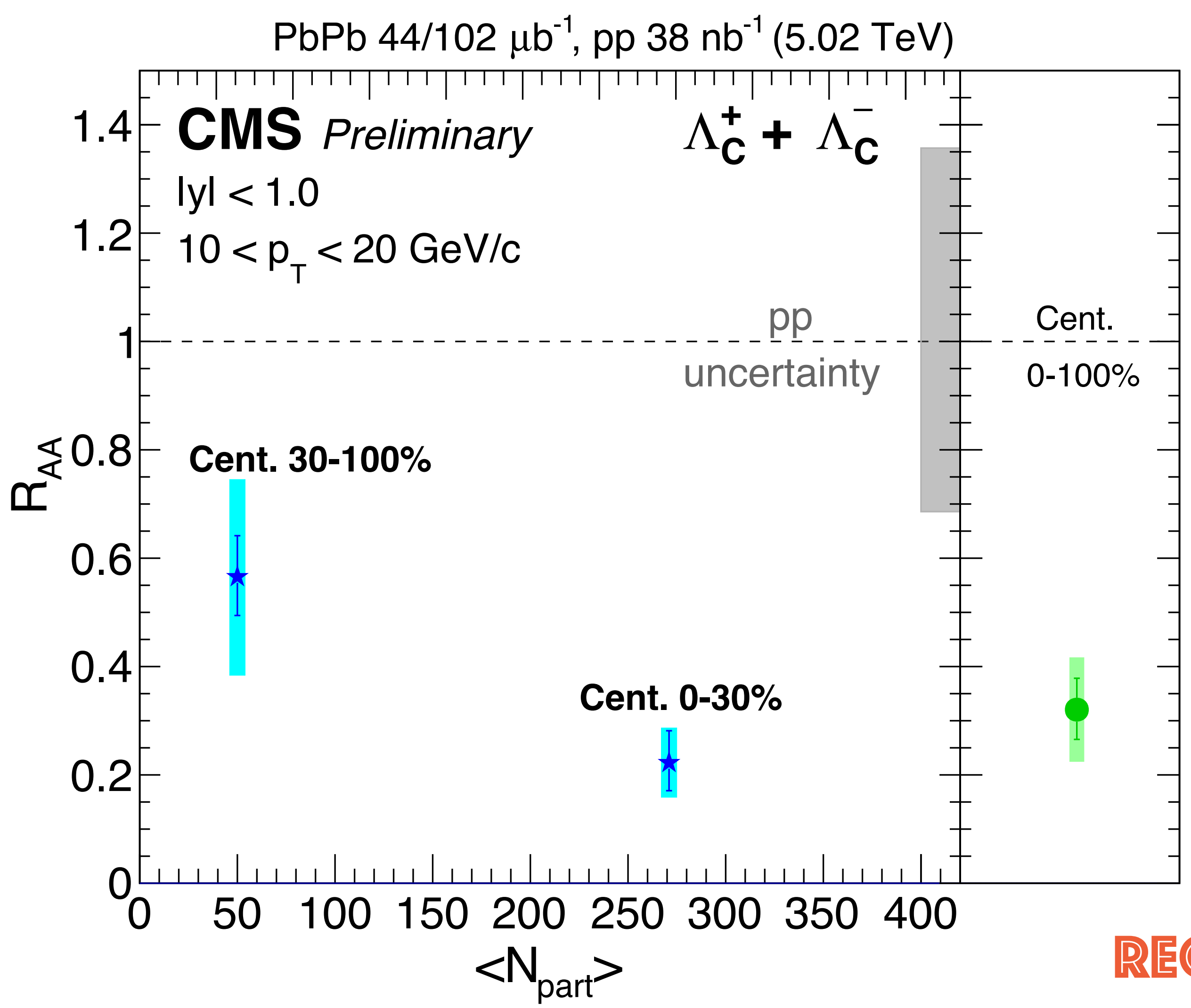
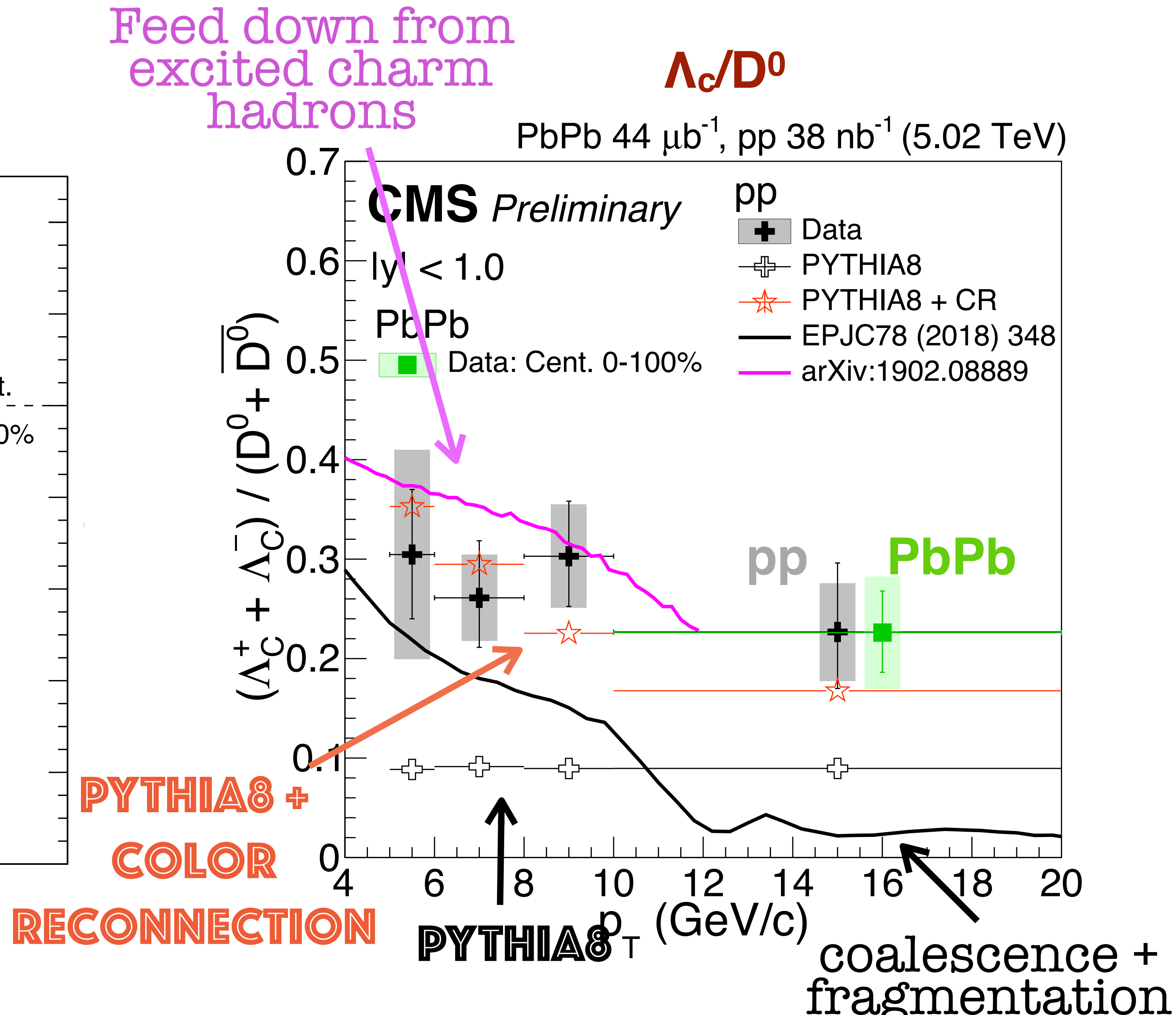
Charm hadronization - Λ_c in PbPb

New since last HP!



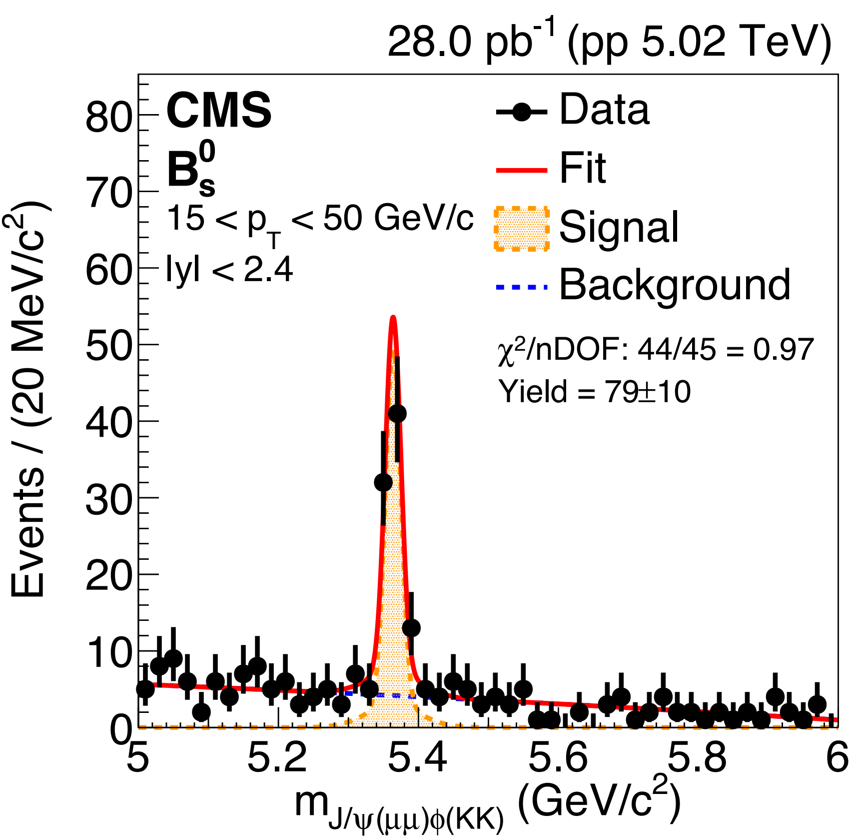


- Stronger suppression of Λ_c in central PbPb events
- pp Λ_c to D^0 ratio is ~3x higher than PYTHIA8
- Agreement with PYTHIA8 + color reconnection mechanism
- Is there p_T dependence? ➔ extend to higher p_T
- Similar ratio of Λ_c to D^0 in $10 < p_T < 20$ GeV/c in pp and PbPb

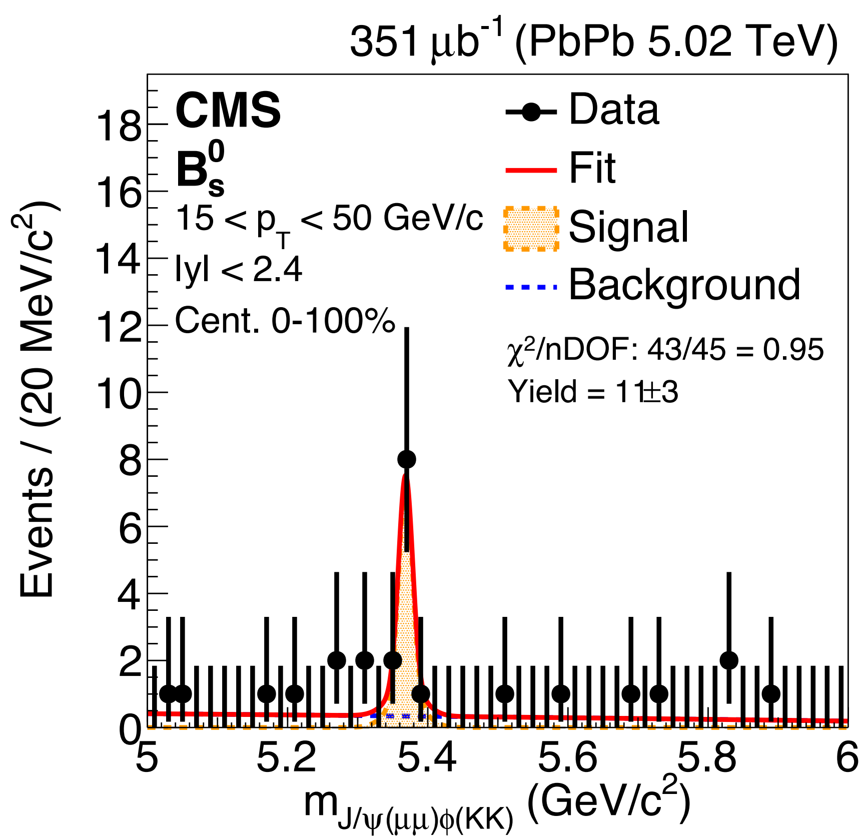
HIN-PAS-HIN-18-009

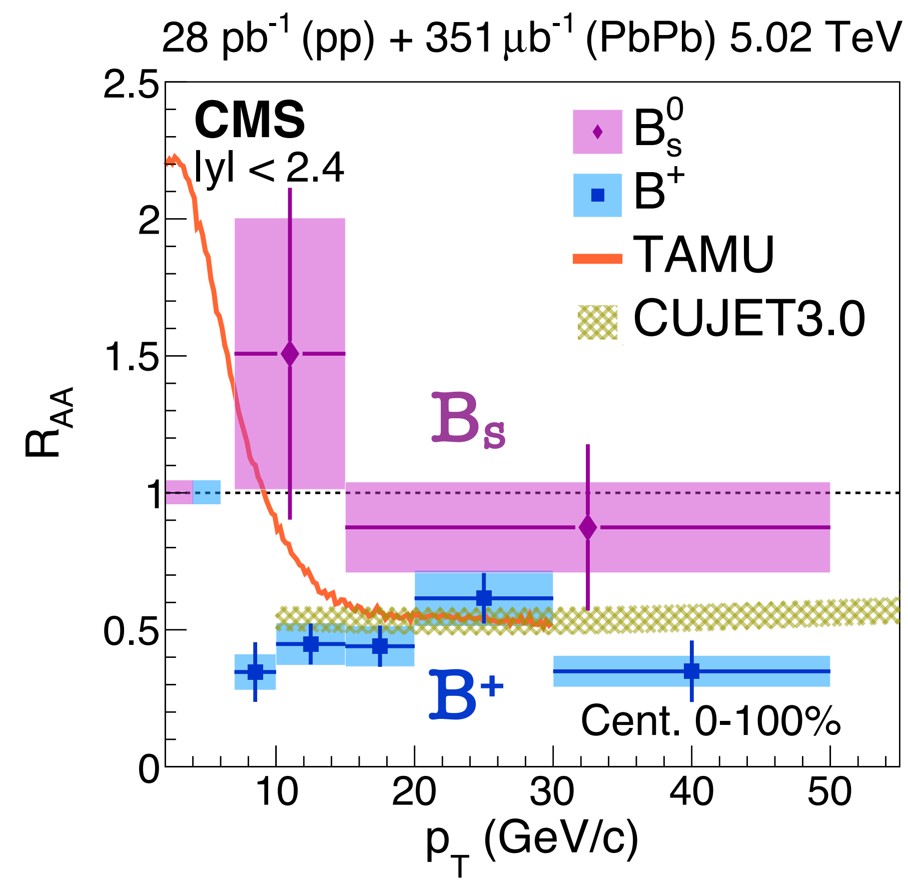
Beauty hadronization - B_s in PbPb

pp



PbPb



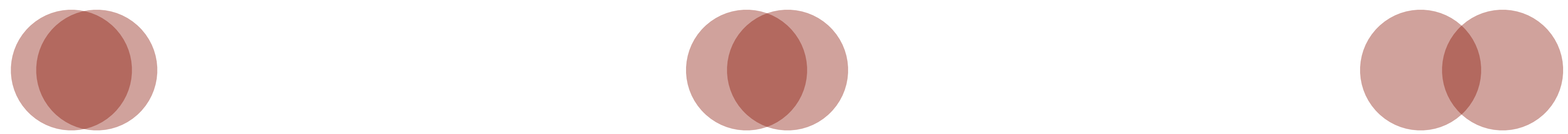


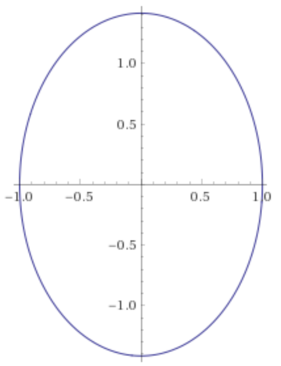
- First measurement on combination of beauty and strange in HI collisions!
- Hint of higher R_{AA} of B_s compared with non-strange B meson
- Substantial statistical and systematic uncertainty
- Good first try! → CMS's capability to perform fully reconstructed B_s measurement
- 4-5x more statistics in 2018 data taking

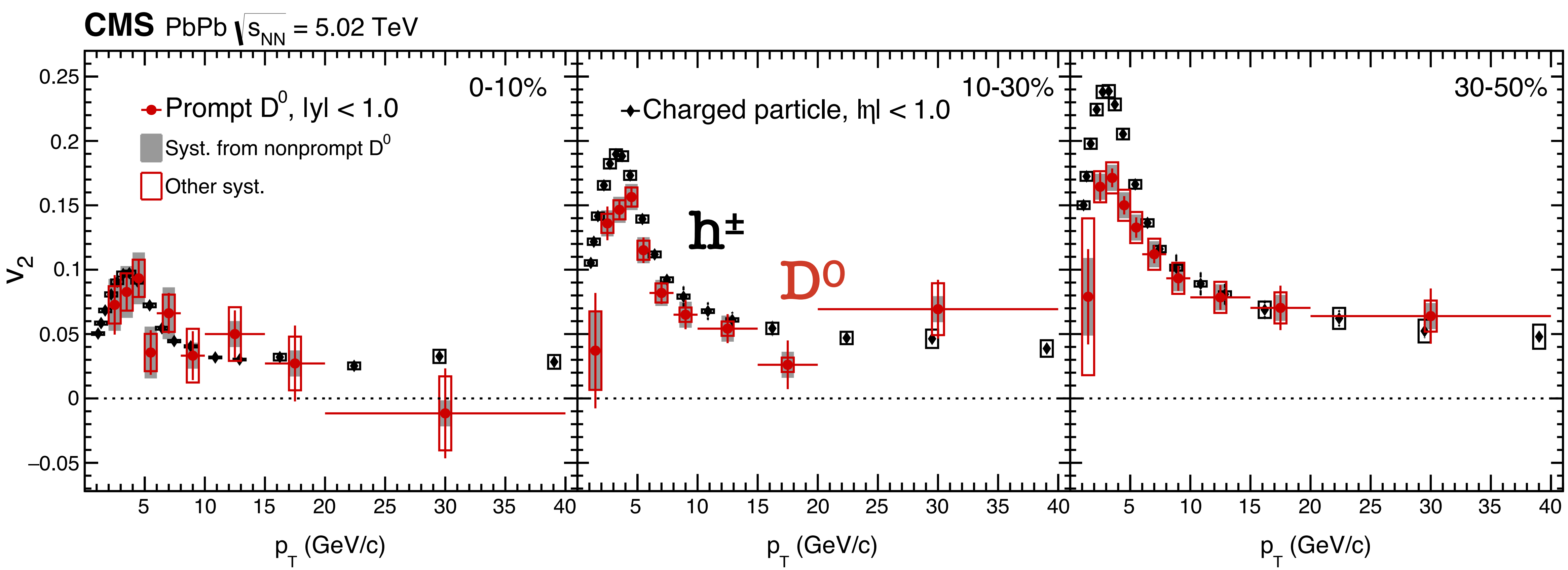
arXiv:1810.03022

Heavy Quark Azimuthal Anisotropy

Prompt D^0 v_2 in PbPb







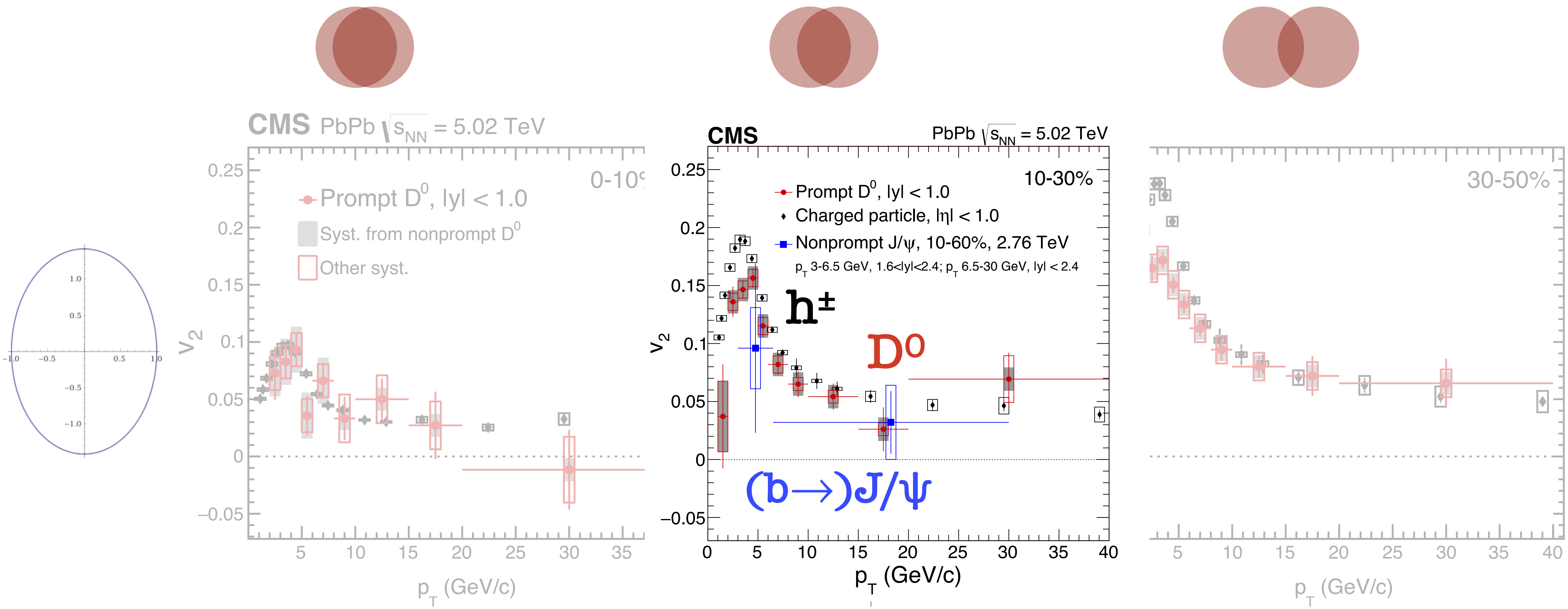
- Positive prompt D^0 v_2 in studied p_T range
  - ➡ **Low p_T: charm quarks take part in the collective motion**
  - ➡ **High p_T: indicates path length dependence of energy loss**
- **Peaks around p_T at 3 GeV/c**
- Increase at peripheral events as expected
- What about very peripheral events?

- **Low p_T: v_2 (prompt D^0) < v_2 (charged particles)**
  - ➡ Difference in most central events is smaller
- **High p_T: v_2 (prompt D^0) ≈ v_2 (charged particles)**
  - ➡ consistent with ΔE (charm) ≈ ΔE (light quark) at high p_T observed in R_{AA}
- Similar p_T dependence

PLB 776 (2017) 195

PRL 120 (2018) 202301

Prompt D^0 + Nonprompt J/ψ v_2 in PbPb



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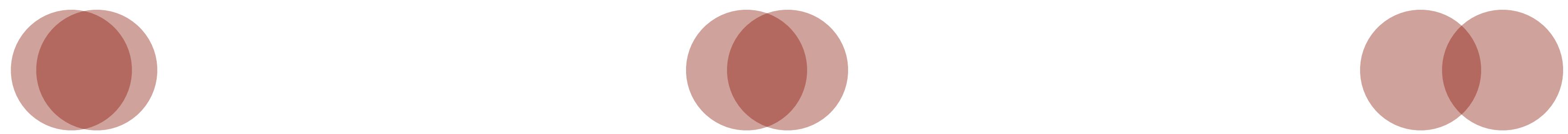
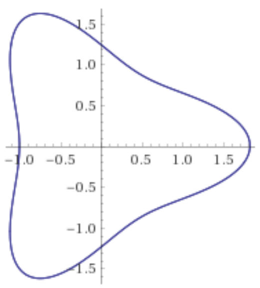
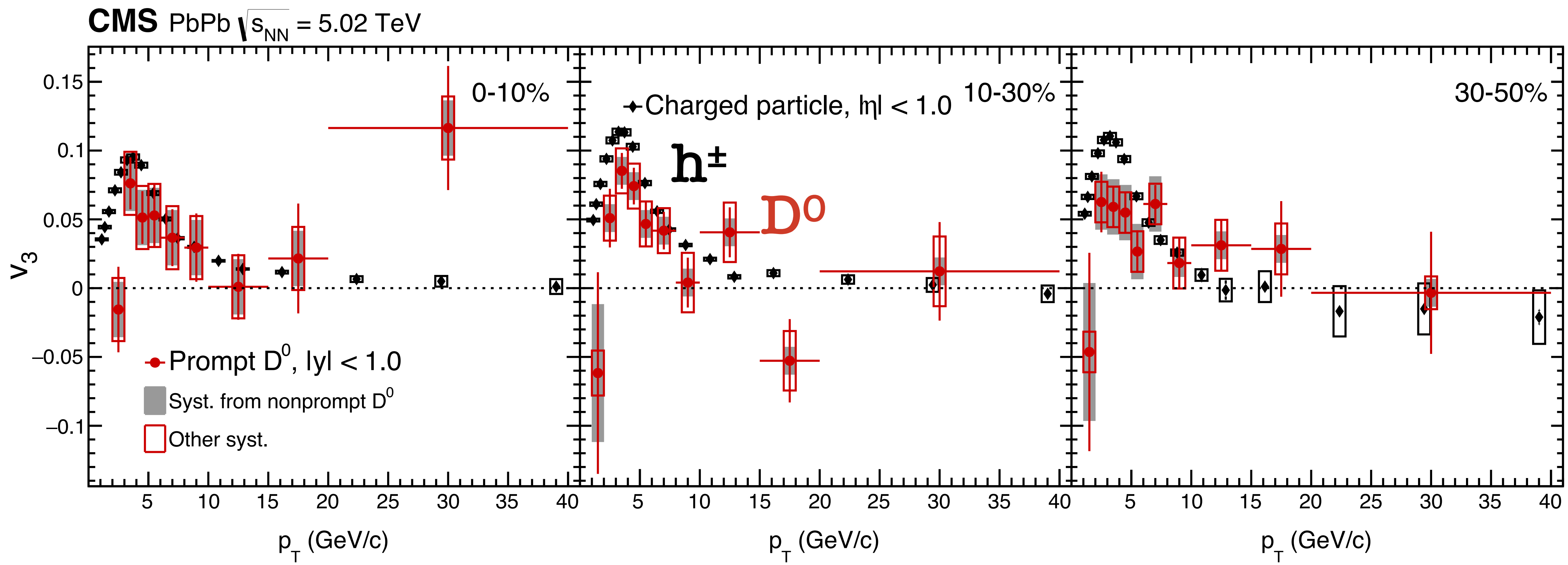
  - ➡ consistent with ΔE (charm) ≈ ΔE (light quark) at high p_T observed in R_{AA}
- Similar p_T dependence
- Positive v_2 (nonprompt J/ψ)
- Low p_T: v_2 (nonprompt J/ψ) < v_2 (prompt D^0)?

EPJC 77 (2017) 252
PLB 776 (2017) 195
PRL 120 (2018) 202301

Prompt D^0 v_3 in PbPb







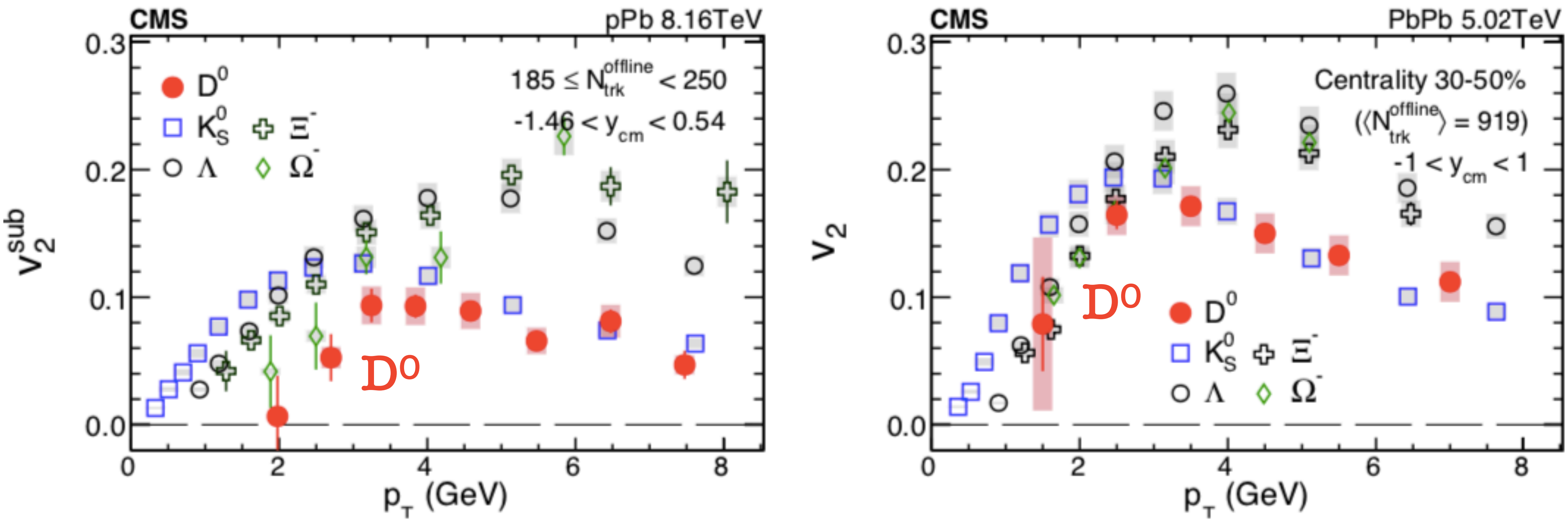
- First measurements of D^0 v_3
  - ➡ Low p_T: v_3 (prompt D^0) > 0
  - ➡ High p_T: v_3 (prompt D^0) ≈ 0
- Peaks around 3 GeV/c
- Little centrality dependence
- **Charm can see the collision geometry!**
  - ➡ Initial fluctuations

- Low p_T: v_3 (prompt D^0) < v_3 (charged particles)
  - ➡ but very similar
- High p_T: v_3 (prompt D^0) ≈ v_3 (charged particles)
- Similar p_T dependence
- Both have little centrality dependence

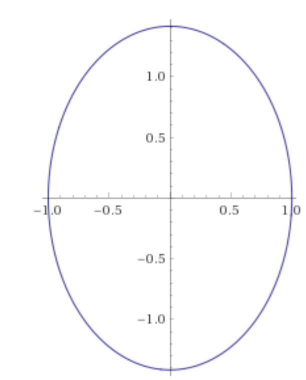
PLB 776 (2017) 195
PRL 120 (2018) 202301

D^0 v_2 in high-multiplicity pPb

pPb **PbPb**

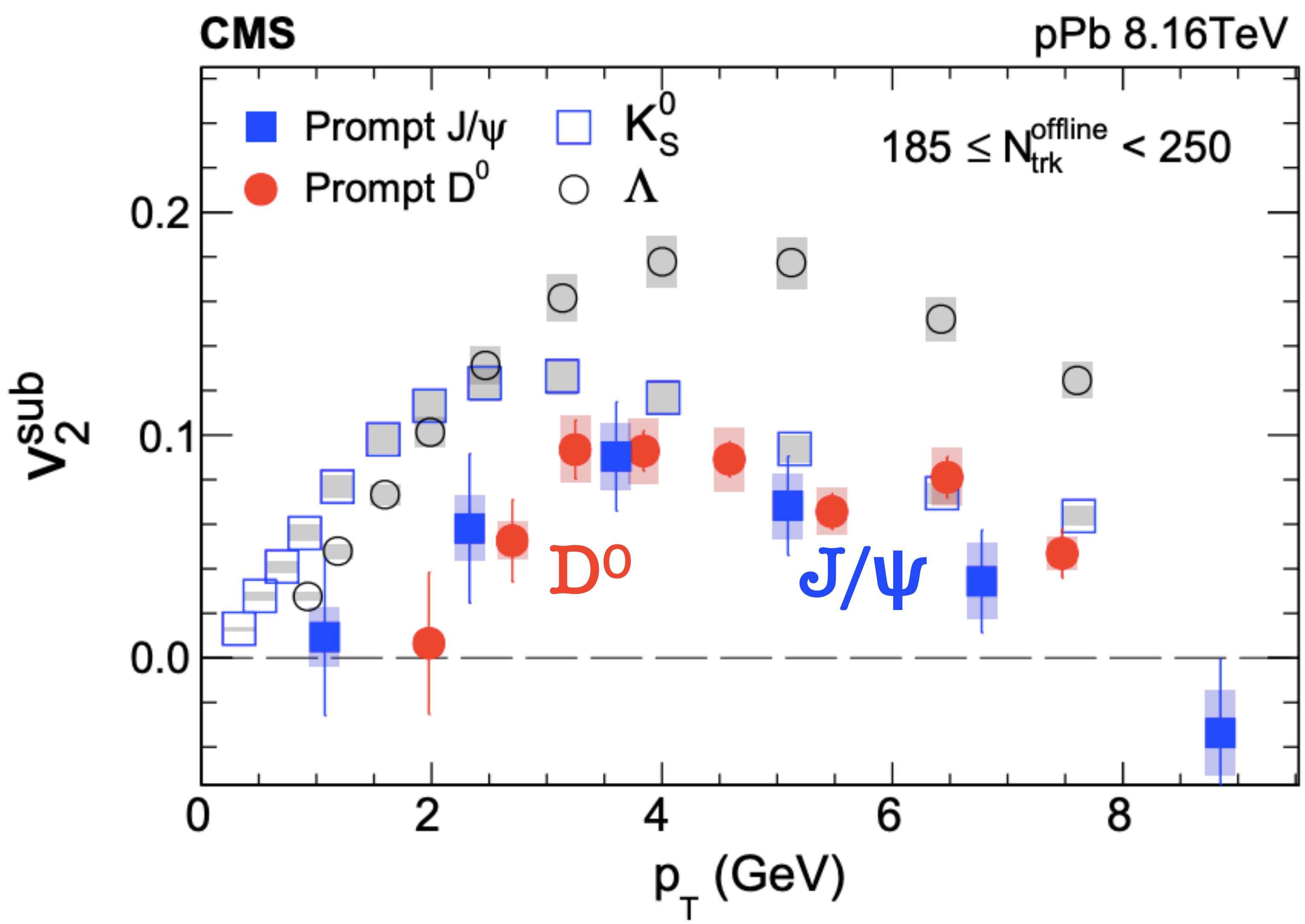


- Significantly positive prompt D^0 v_2 observed in high-multiplicity pPb collisions
  - ➡ origin of large v_2 of D^0 in pPb?
- D^0 v_2 (pPb) < D^0 v_2 (PbPb) at given p_T
- D^0 v_2 smaller than that of strange hadrons
- Is it possible that v_2 comes from the u quark?

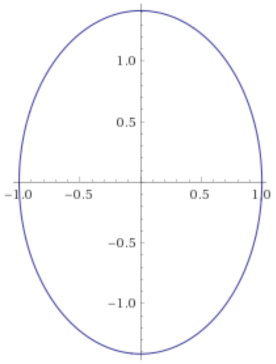


PRL 121 (2018) 082301

J/ψ v_2 in high-multiplicity pPb



- v_2 (prompt D^0) ≈ v_2 (prompt J/ψ)
- Significantly positive prompt J/ψ v_2 observed in high-multiplicity pPb collisions
  - ➡ Direct evidence of collectivity of charm
  - ➡ D^0 v_2 is not coming only from u

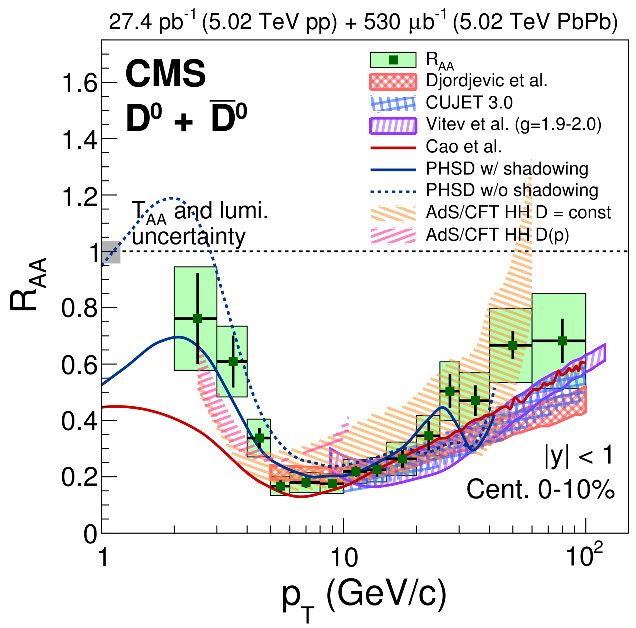


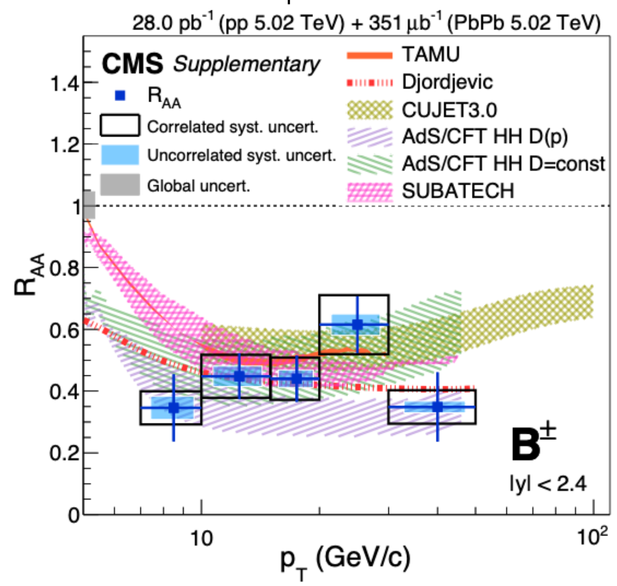
PLB 791 (2019) 172

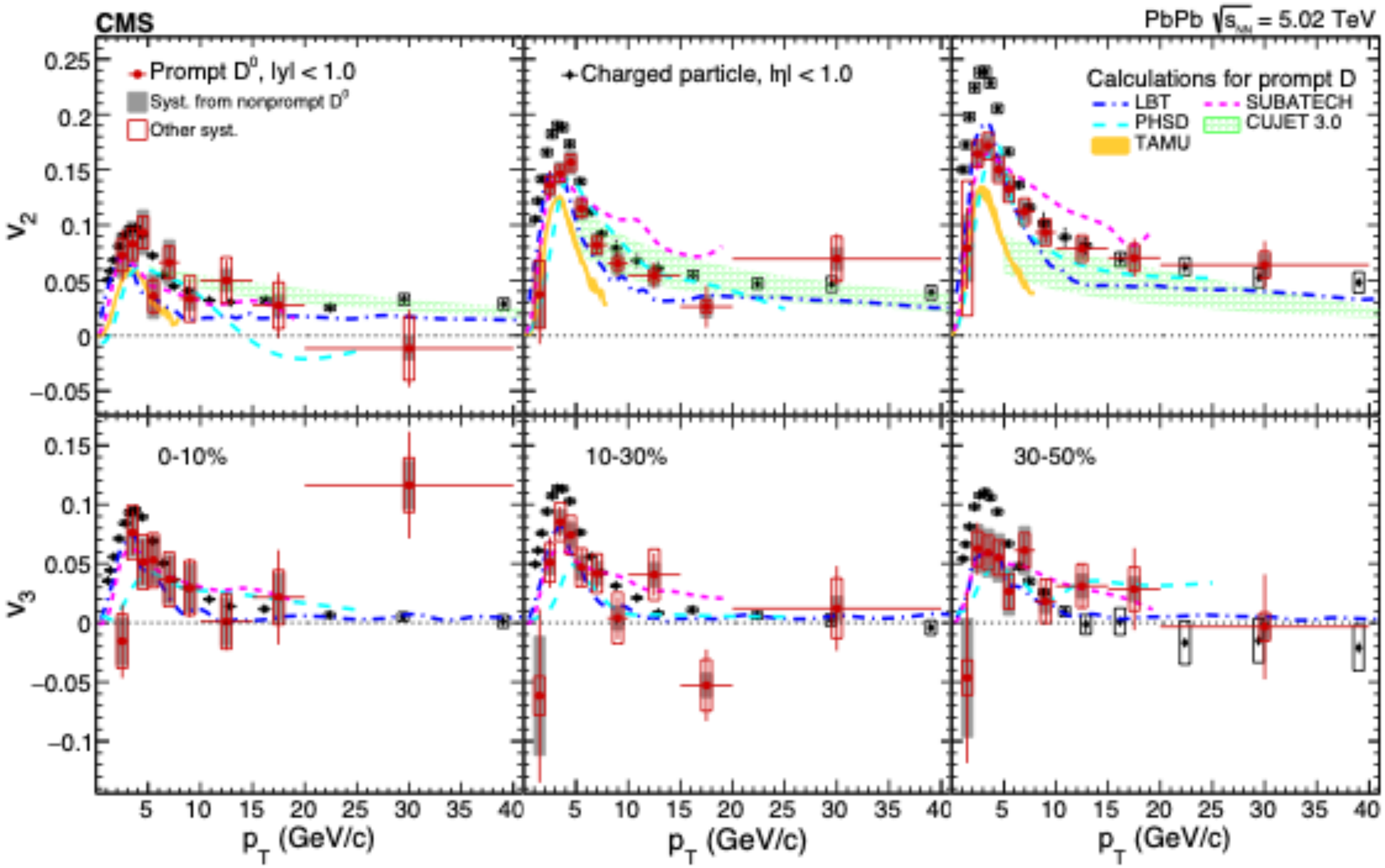
Model Market

Model	Ref.	Trans. Impl.	Bulk Evolution	Initial Condition	Coll. E loss	Rad. E loss	Group
UrQMD Hybrid	[67]	LV	3+1D ideal hydro	Smeared UrQMD string/energy density	✓		**Transport Models**
TAMU	[140]	LV	2+1D ideal hydro	Smooth initial condition	✓		
SUBATECH Nantes MC@sHQ EPOS2	[141]	BM	EPOS2 3+1D ideal hydro	Fluctuating initial condition	✓	✓	
Catania	[142]	BM	HQ interact with bulk massive quasi-particles, T-dependence of α_S is tuned to match the lQCD EoS	-	✓		
LBL-Duke Cao et al.	[135] [136]	LV	VISHNU 2+1D viscous hydro	Event-by-event fluctuating initial conditions	✓	✓	
POWLANG Torino	[143]	LV	ECHO-QGP 3+1D viscous hydro	Event-by-event fluctuating initial conditions	✓	✓	
PHSD	[137] [138]	BM	HQ interact with off-shell light quasi-particles whose masses and widths are determined to match lQCD EoS	-	✓		
Djordjevic	[129]	DGLV: variant of GLV approach including gluon radiation from multiple scattering up to 1st order in opacity			✓	✓	**Jet Models**
Vitev et al.	[133] [134]	Soft Collinear Effective Theory with Glauber Gluons including quark masses ($\mathrm{SCET_G}$)				✓	
CUJET3.0	[130] [131] [132]	DGLV + VISHNU 2+1D viscous hydro			✓	✓	
AdS/CFT	[139]	Model based on the anti-de Sitter/conformal field theory					**String Models**

Compare with theory - R_{AA} and v_2, v_3





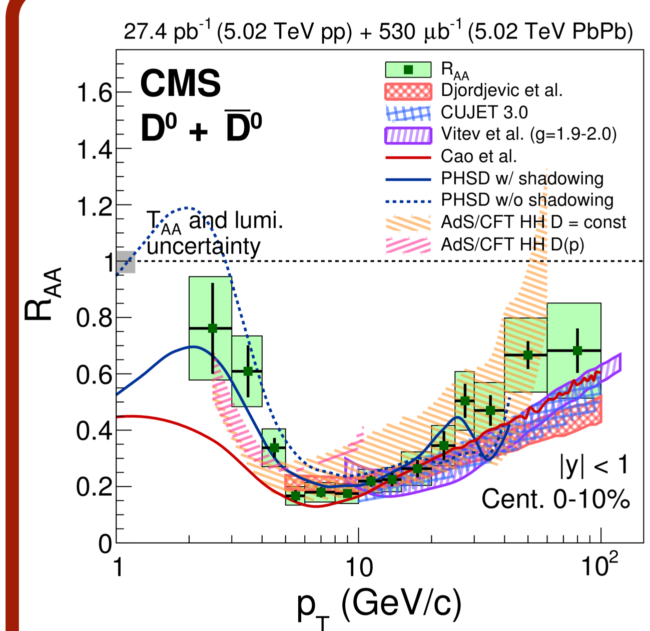


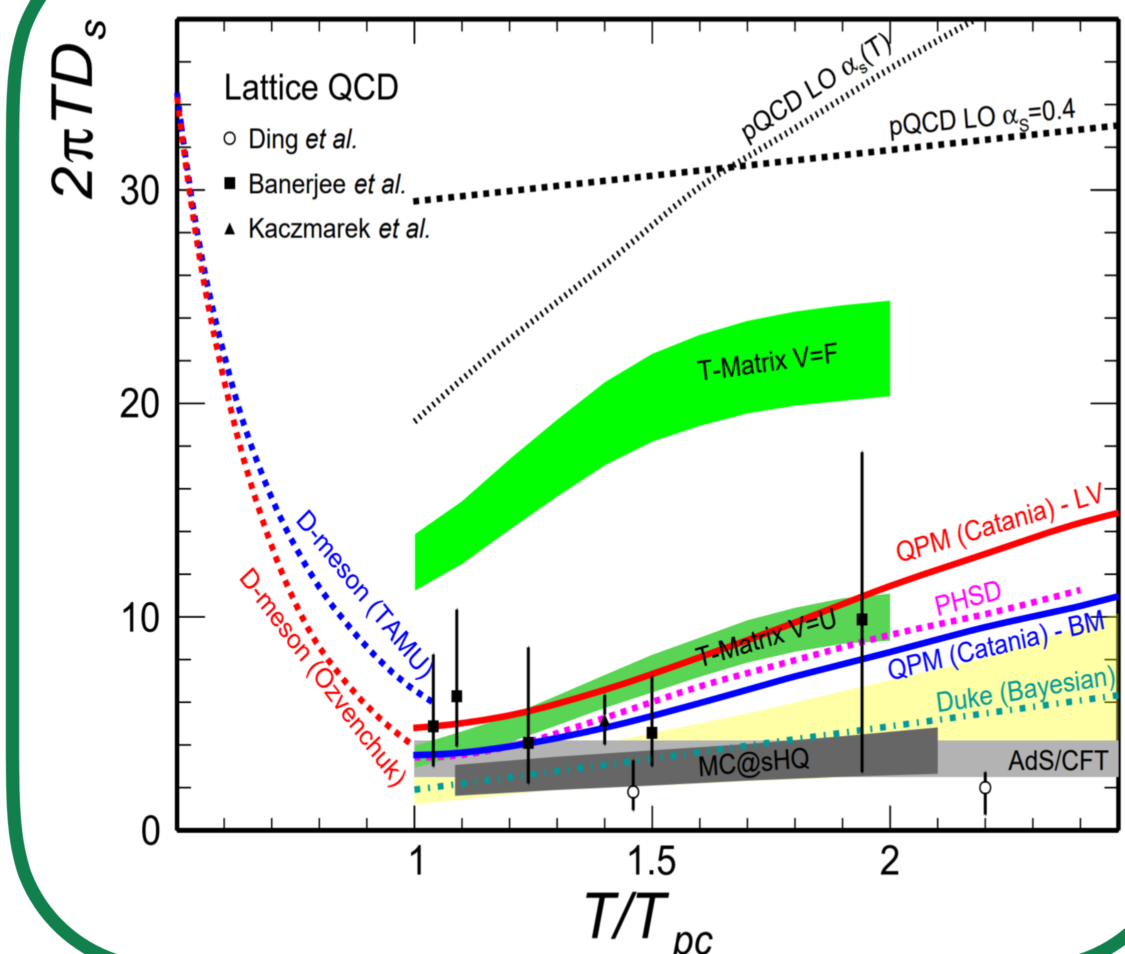
- Most models can roughly predict the shape
- Strong constraints by simultaneously predicting R_{AA} and v_n

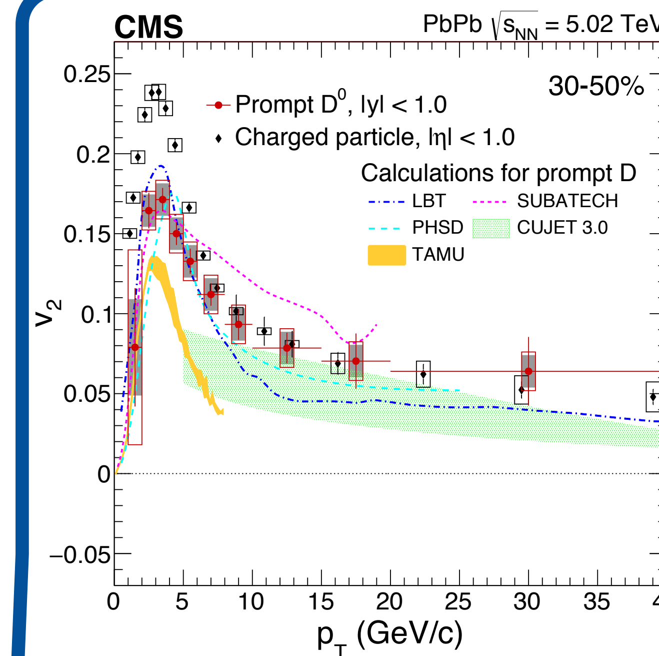
arXiv:1703.00822
PRC 92 (2015) 024918
JHEP 02 (2016) 169
PRD 91 (2015) 085019
PRD 93 (2016) 074030
PRC 93 (2016) 034906

PRC 94 (2016) 014909
PRC 91 (2015) 014904
PRC 93 (2016) 034906
JHEP 02 (2016) 169
PLB 735 (2014) 445

Constrain theory - D_s



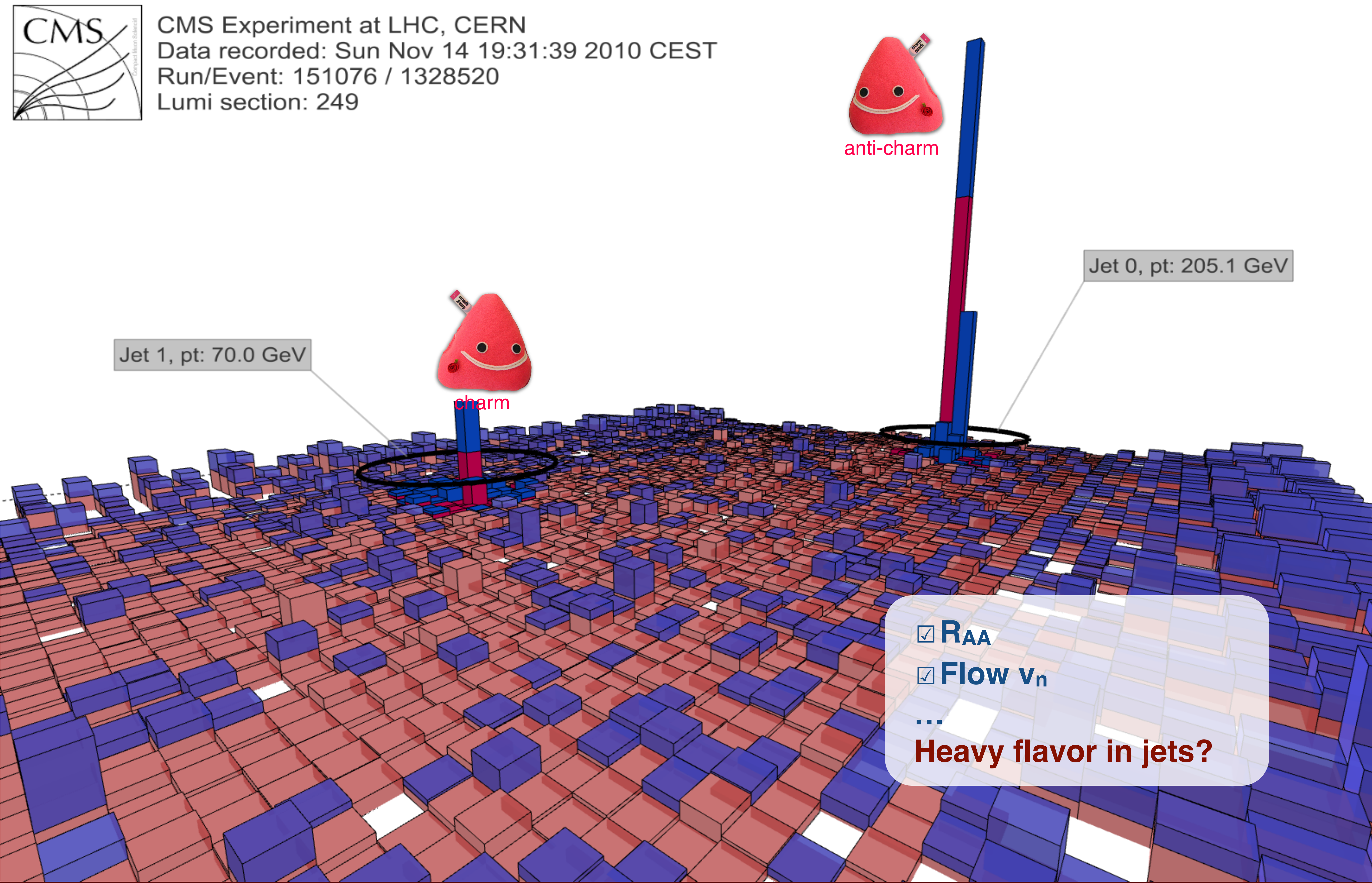




- The spatial diffusion coefficient D_s can be extracted/constrained
- Not consistent with LO pQCD calculations
- Close to quenched lattice QCD and AdS/CFT calculations
- **What do we do now - Any better observables?**

Prog. Part. Nucl. Phys. 104:97 (2019)

Other observables?



- ☑ R_{AA}
- ☑ Flow v_n

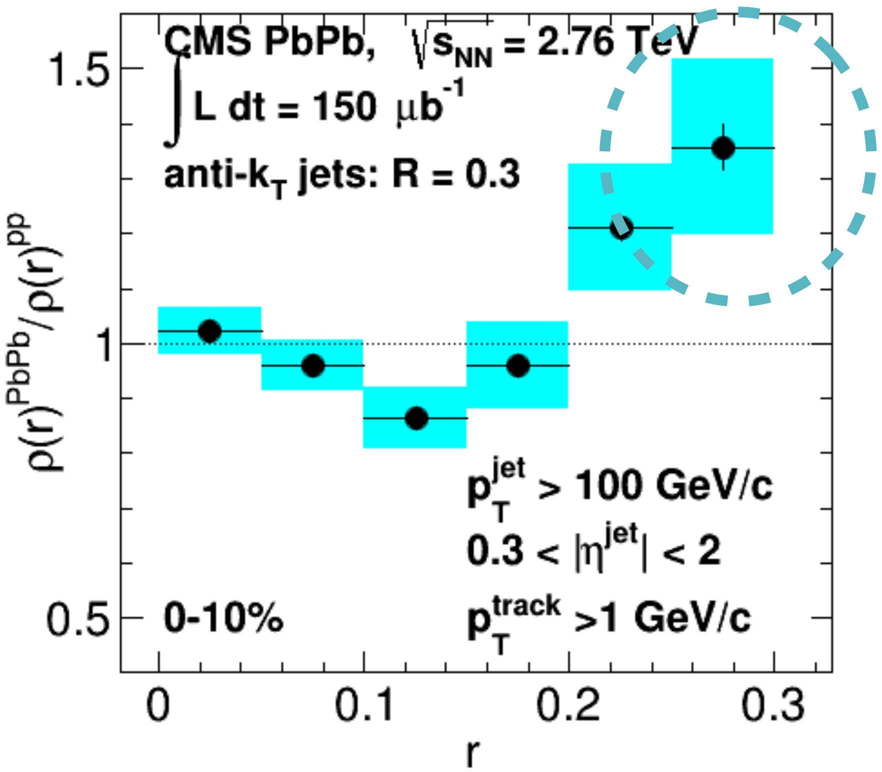
…

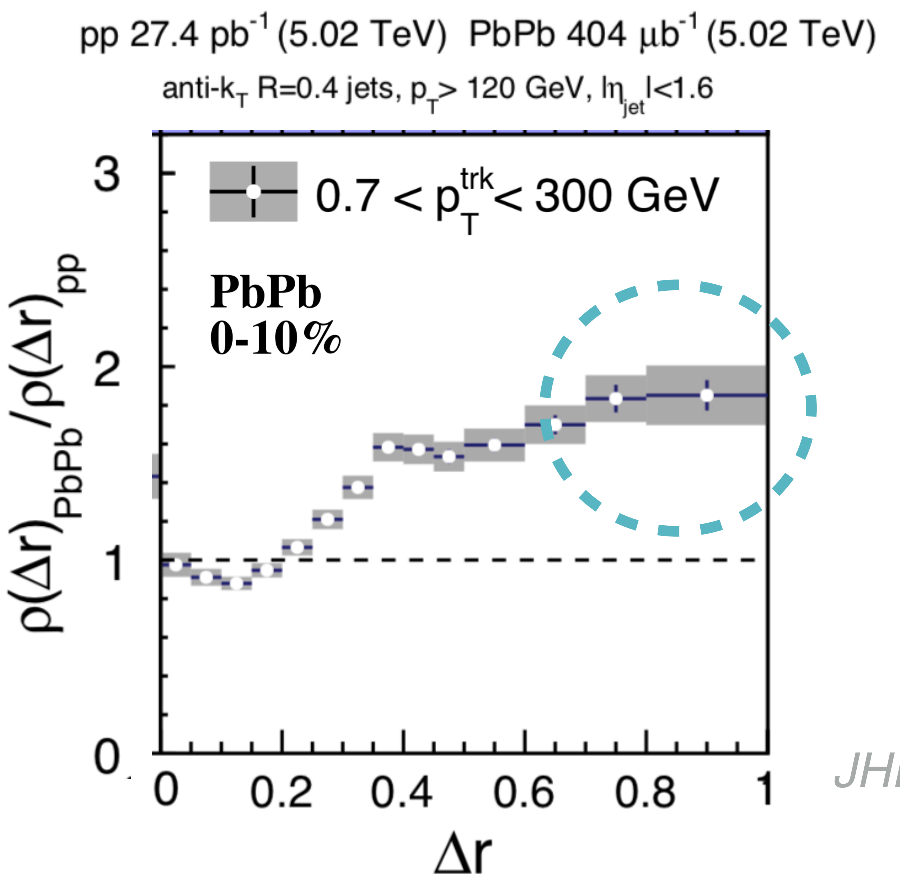
Heavy flavor in jets?

Heavy Quarks in Jets

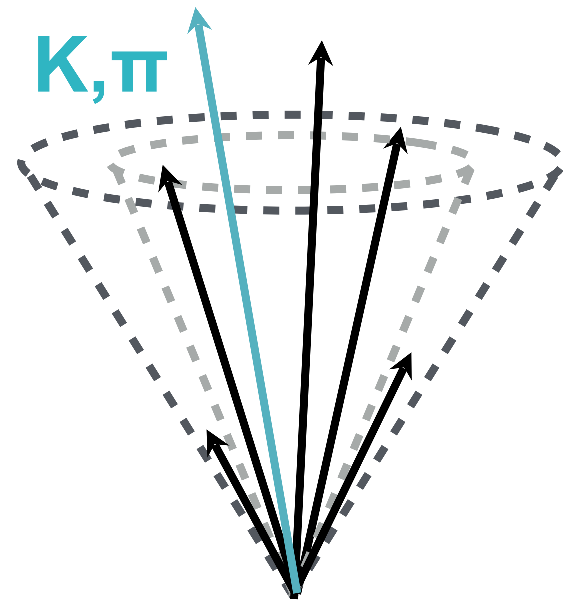
Heavy Quarks in Jets

Phys. Lett. B 730 (2014) 243





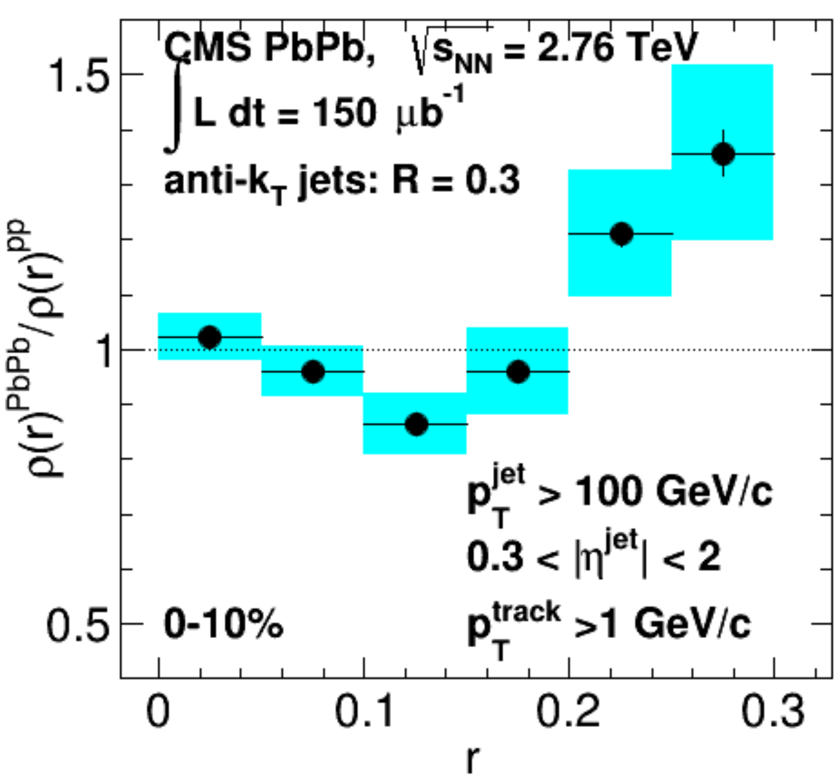
JHEP 05 (2018) 006

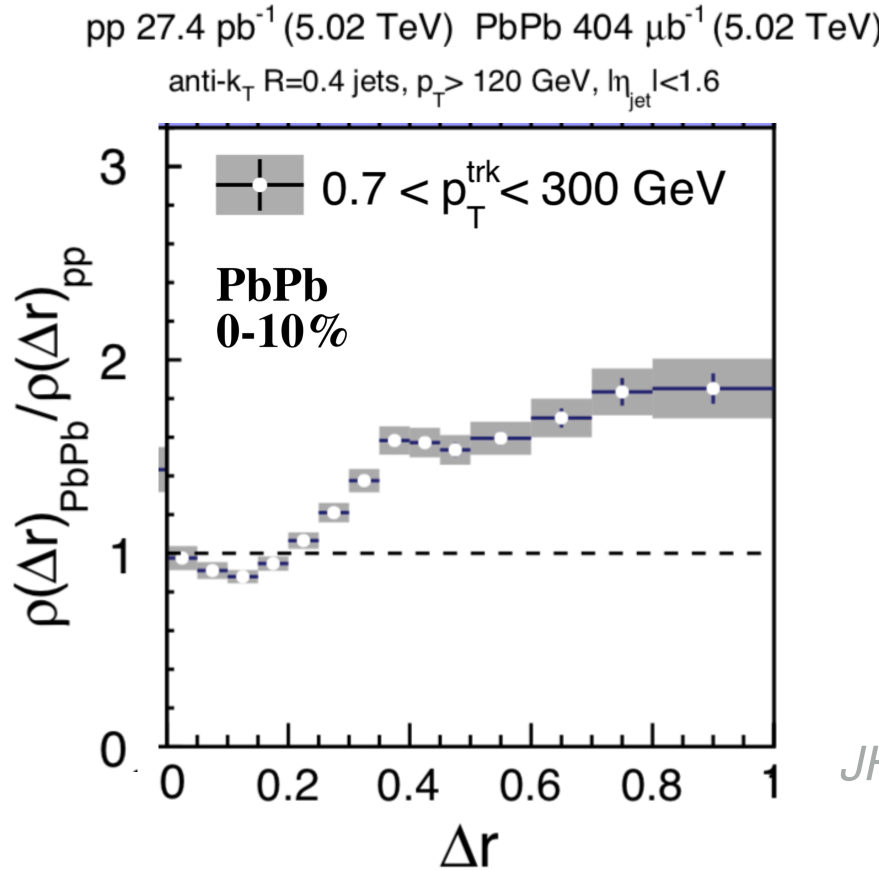


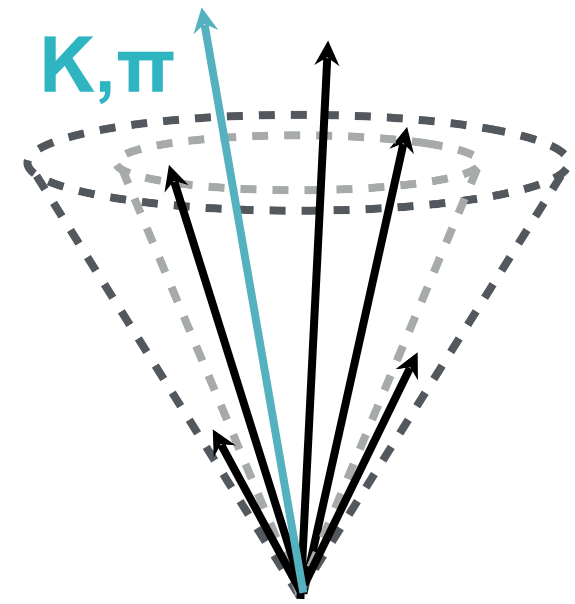
- **Enhancement of low p_T light hadrons at large angles about jets**
  - ➡ Light hadron jet shape analysis
- **How to explain**
  - ➡ medium-induced gluon radiation?
  - ➡ medium response?
  - ➡ multiple scatterings?
  - ➡ ……

Heavy Quarks in Jets

Phys. Lett. B 730 (2014) 243

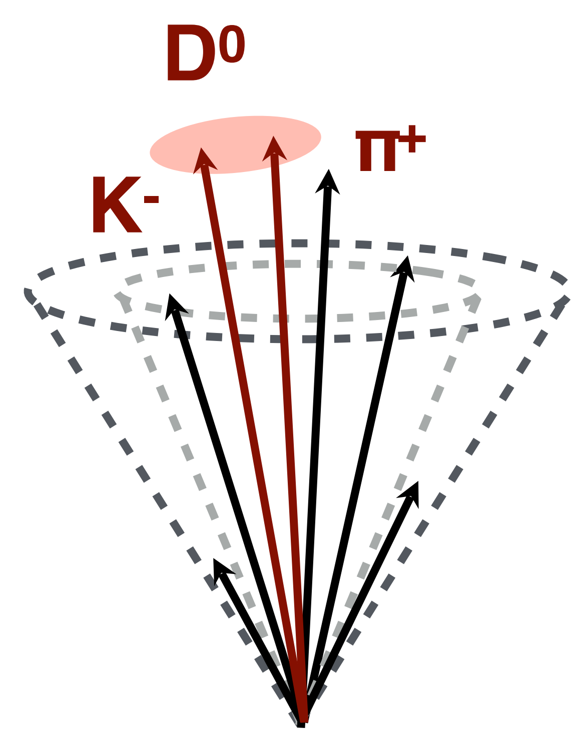






JHEP 05 (2018) 006

- Enhancement of low p_T light hadrons at large angles about jets
  - ➡ Light hadron jet shape analysis
- How to explain
  - ➡ medium-induced gluon radiation?
  - ➡ medium response? $m_c \gg T_{QGP}$
  - ➡ multiple scatterings?
  - ➡ ……
- **Vary mass of the associated hadrons**
  - ➡ **Heavy flavor!**



More …

pp

Charmonia production mechanism

- Isolation
- Polarization

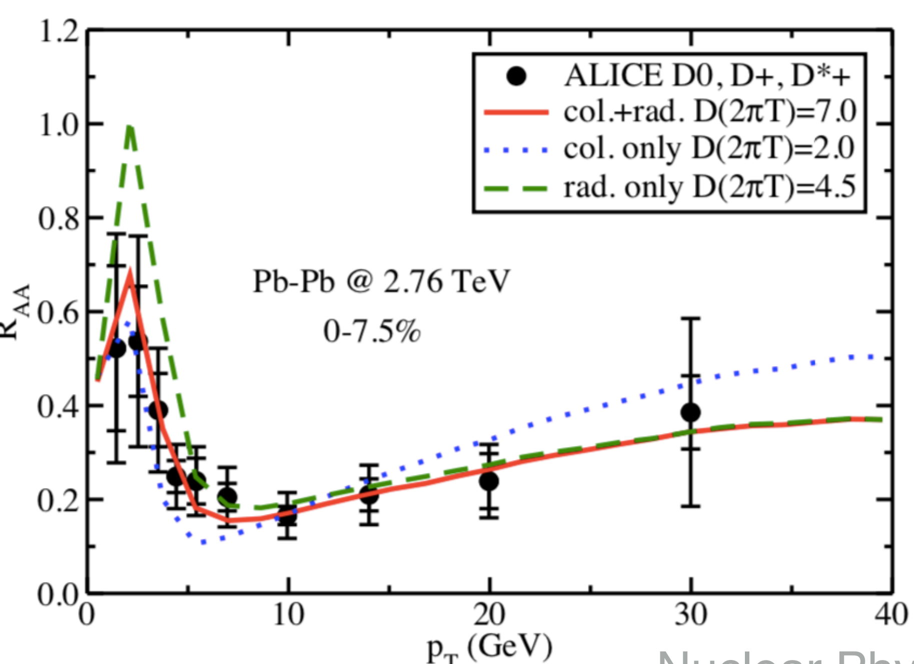
Production mechanism of charm and D^0

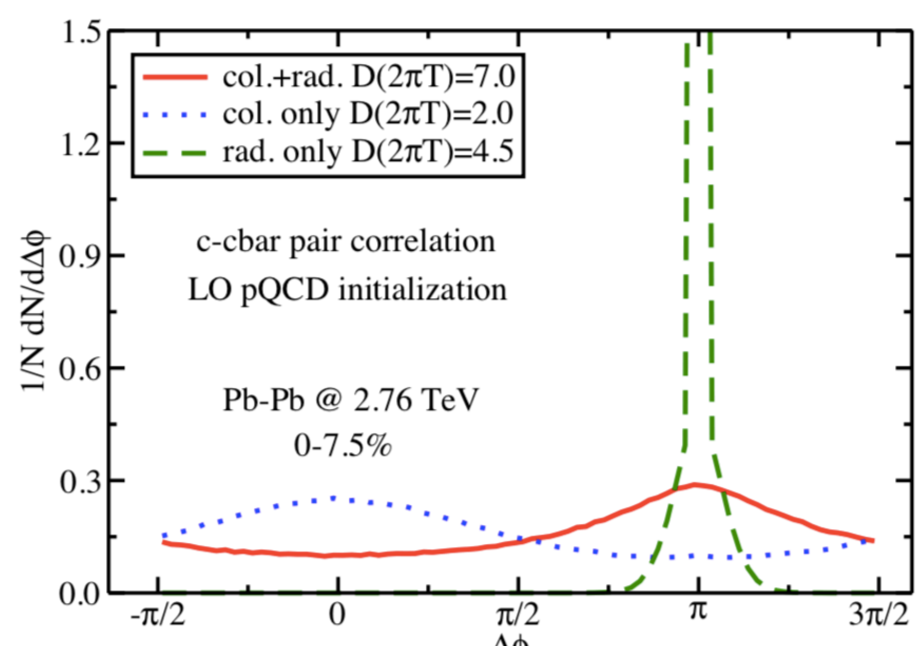
- The role of gluon splitting
- Recombination in the medium

PbPb

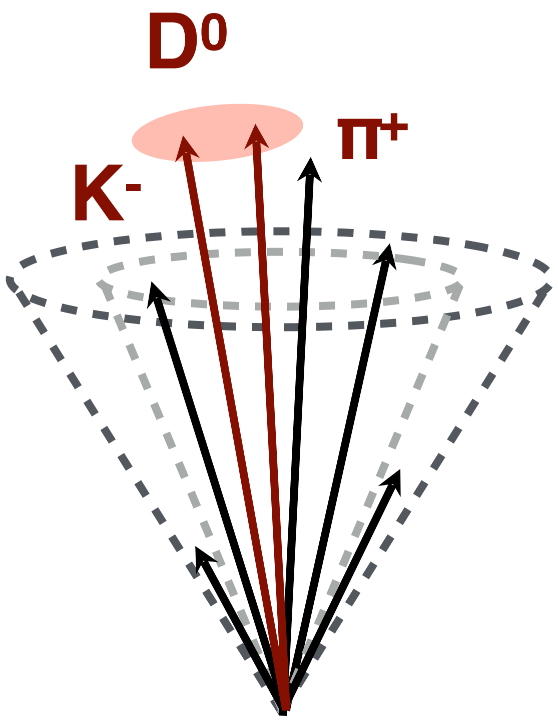
Heavy quark behavior and interactions in the medium

- Complementary to inclusive measurements
- Correlation: more sensitive observable to HQ diffusion coefficients + models



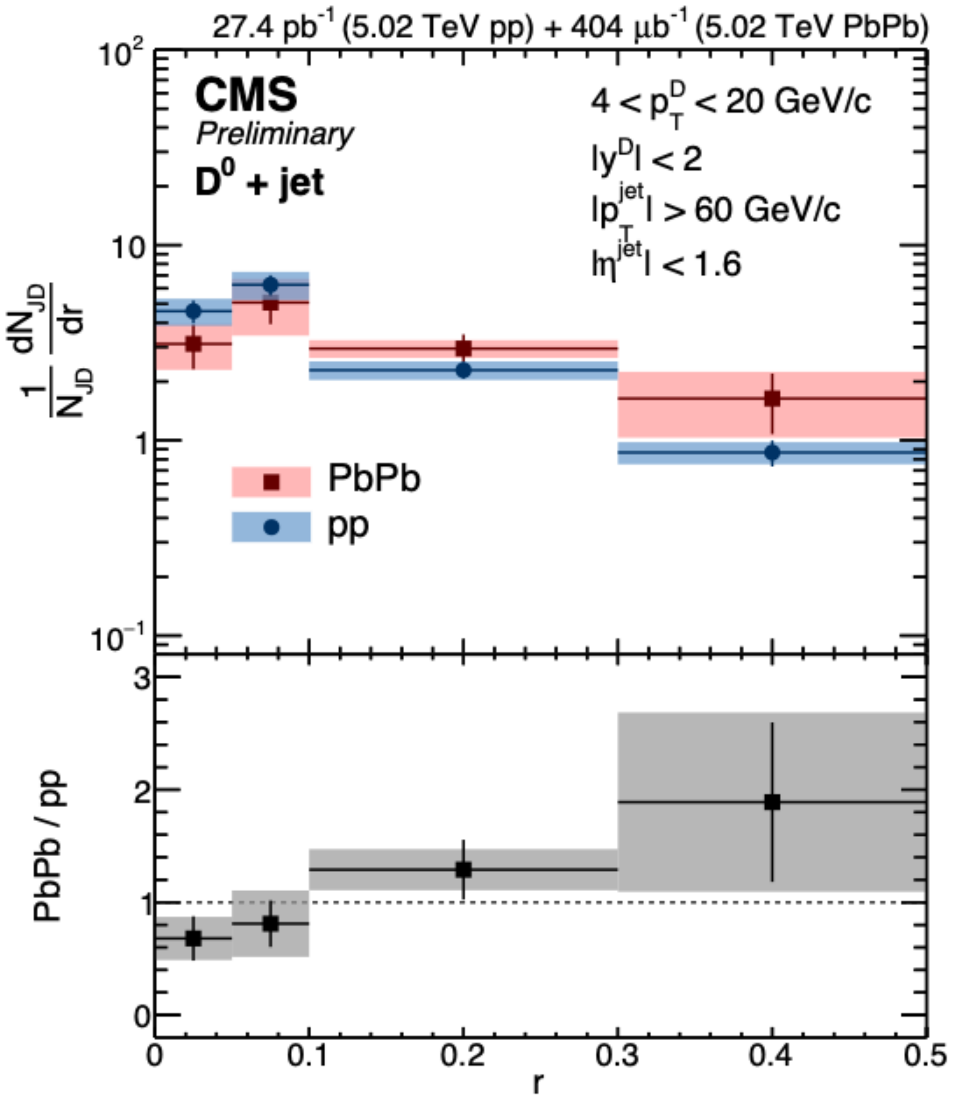


Nuclear Physics A 00 (2018) 1–4

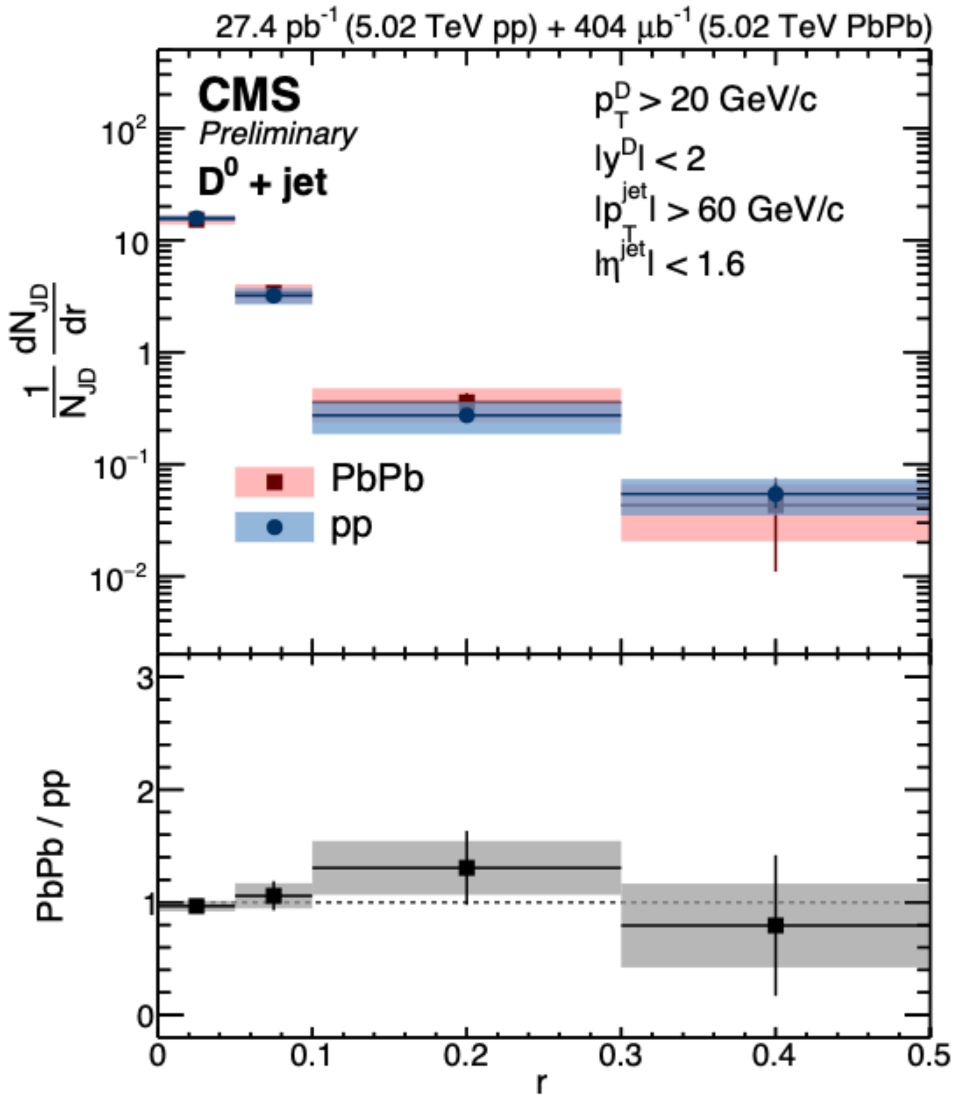


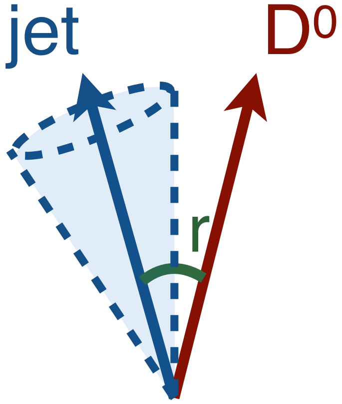
Radial profile of D^0 in jets in PbPb

Low D p_T: $4 < p_T^D < 20$ GeV/c



High D p_T: $p_T^D > 20$ GeV/c





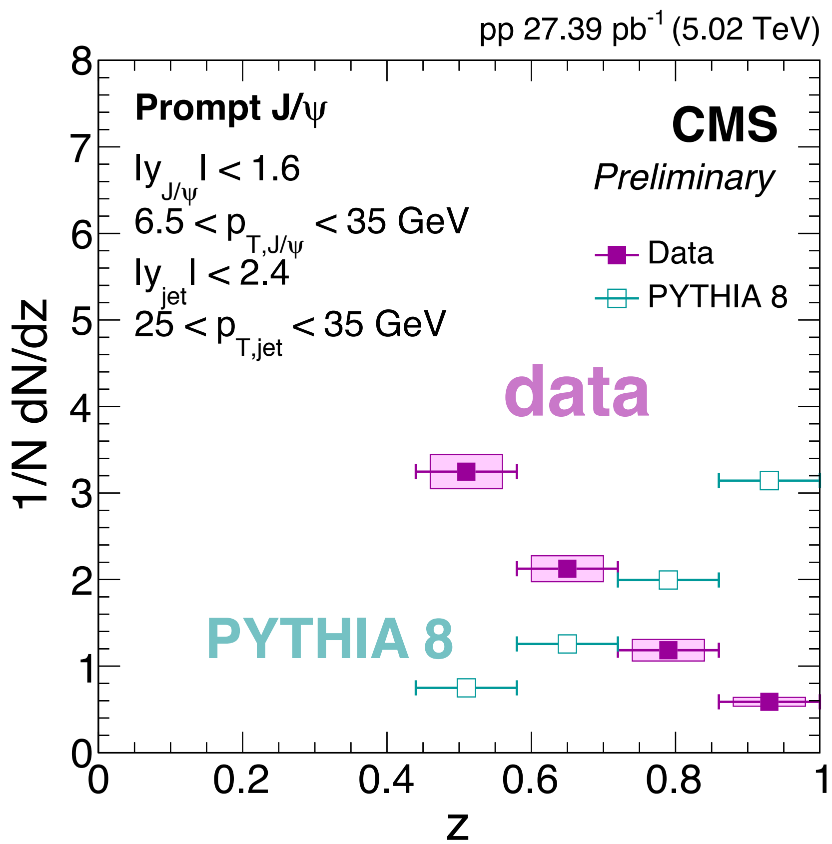
- The ratio of PbPb over pp:
- Low D p_T: increases as a function of r
  - ➡ Hint that D^0 are further from jet axis in PbPb than pp
- High D p_T: consistent with unity

$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$

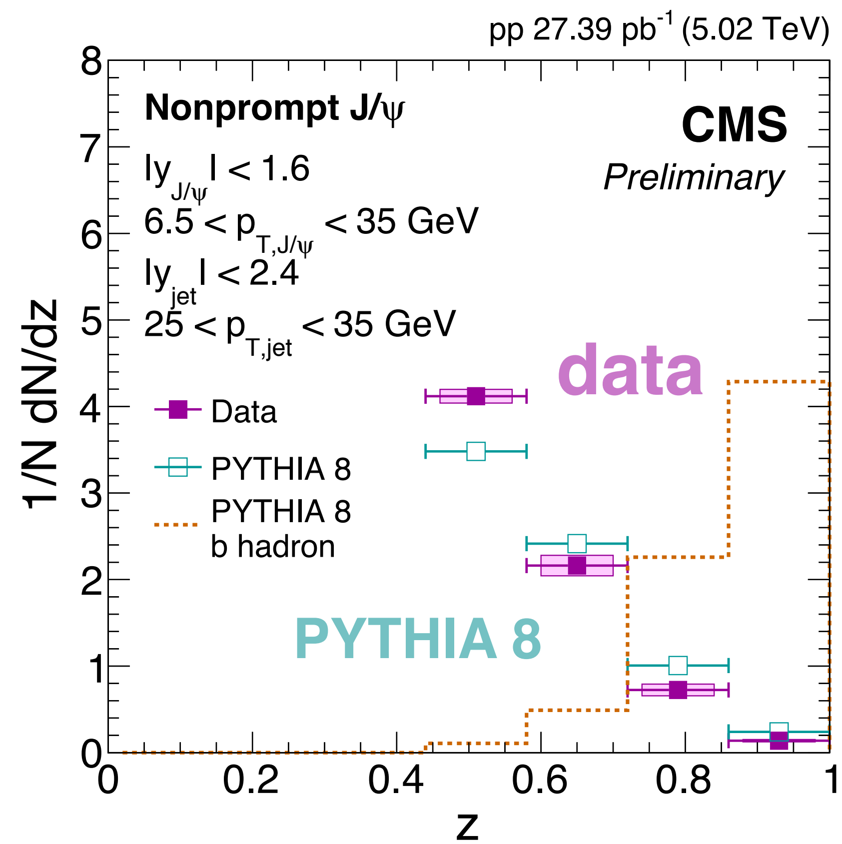
CMS-PAS-HIN-18-007

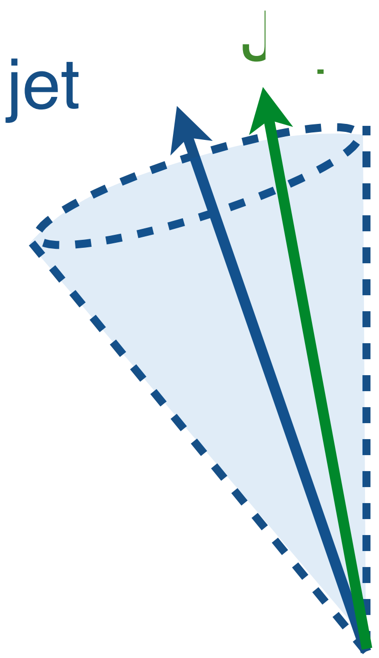
J/ψ fragmentation function in pp

prompt J/ψ



non-prompt J/ψ





- Prompt J/ψ not described by PYTHIA 8
  ➡ PYTHIA 8 too much harder
- Nonprompt J/ψ similar between PYTHIA 8 and data
- Similar results with LHCb in different kinematics

$$z \equiv \frac{p_{T,J/\psi}}{p_{T,jet}}$$

CMS-PAS-HIN-18-012

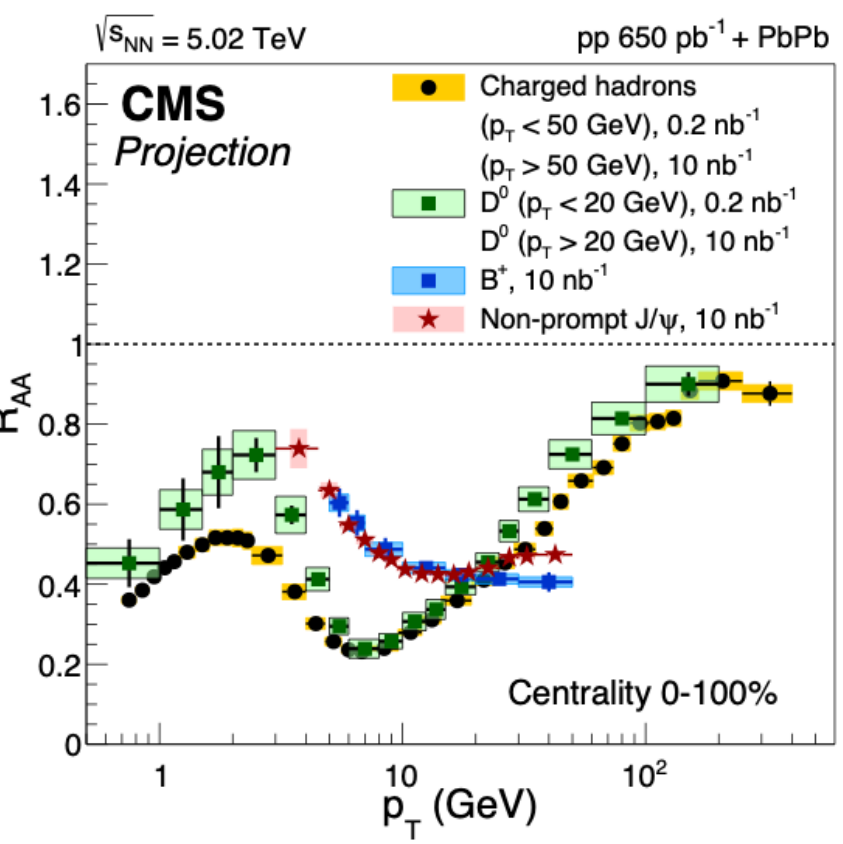
What to expect from CMS in HL-HLC era? (1/2)

High-Luminosity LHC!

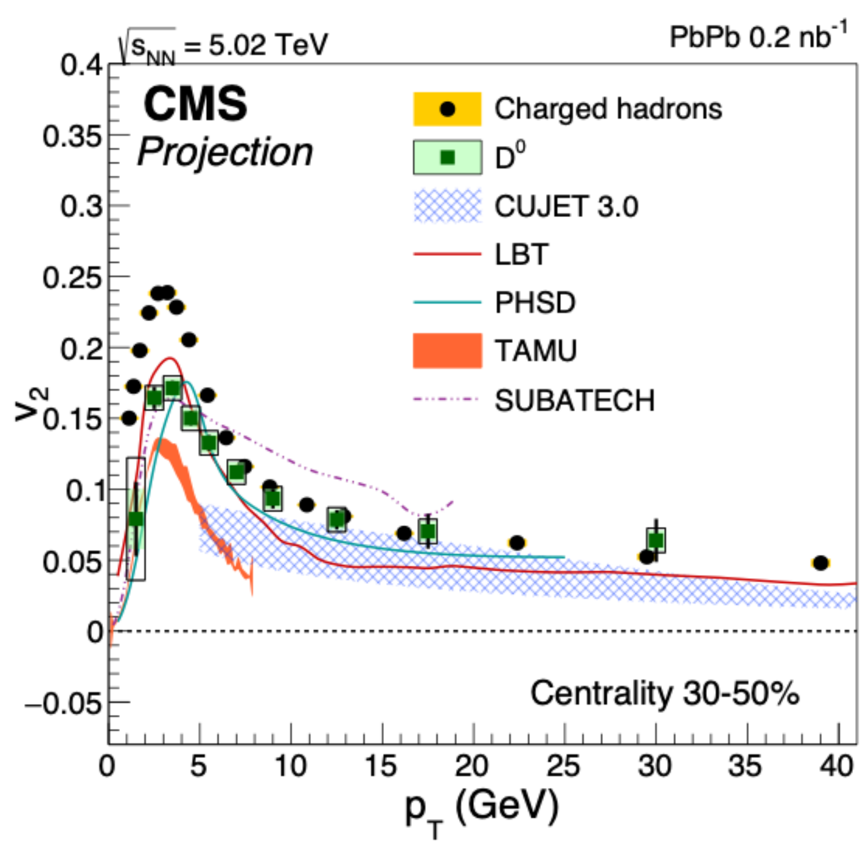
CMS Upgrade in Run 3/4 benefiting heavy flavor studies

- Higher luminosity ~10 nb^{-1} PbPb data
- Upgrade inner tracker to cover a large acceptance up to $|\eta| < 4$
- Improve L1 and DAQ rate
  - ➡ more sophisticated triggers
  - ➡ recording a larger number of minimum-bias triggered events
- Propose MIP Timing Detector with a good time resolution ➔ PID

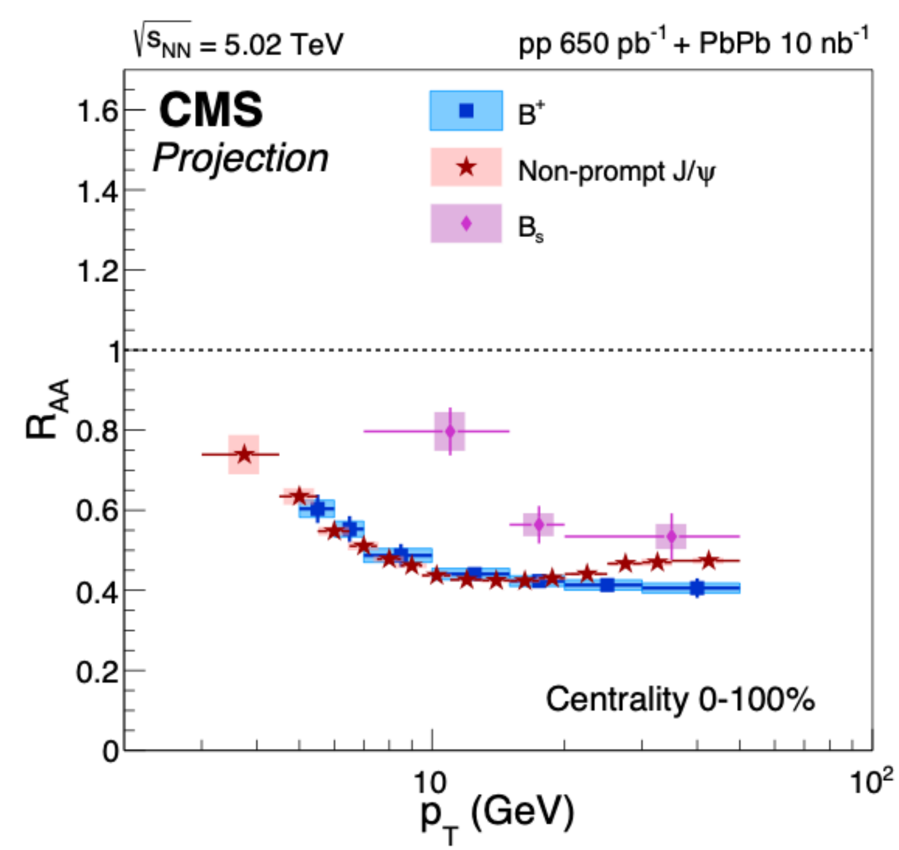
R_{AA}



v_2

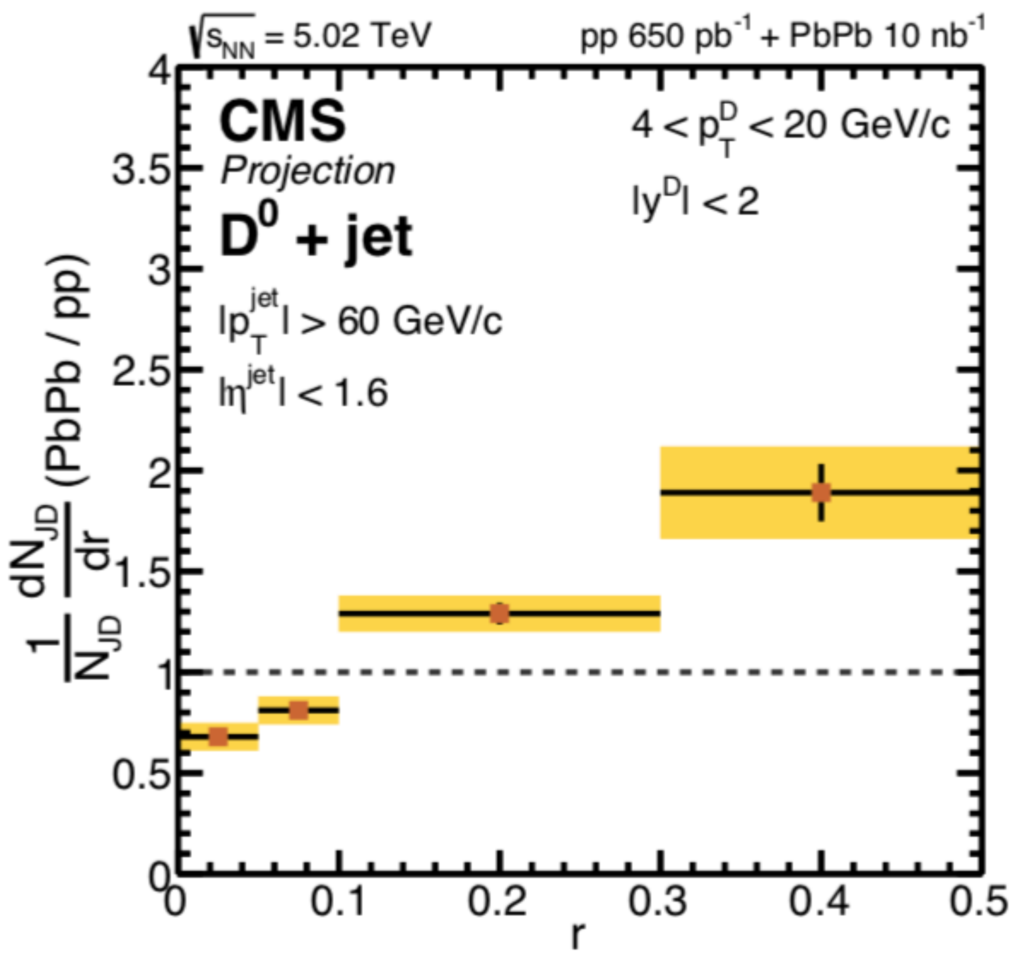


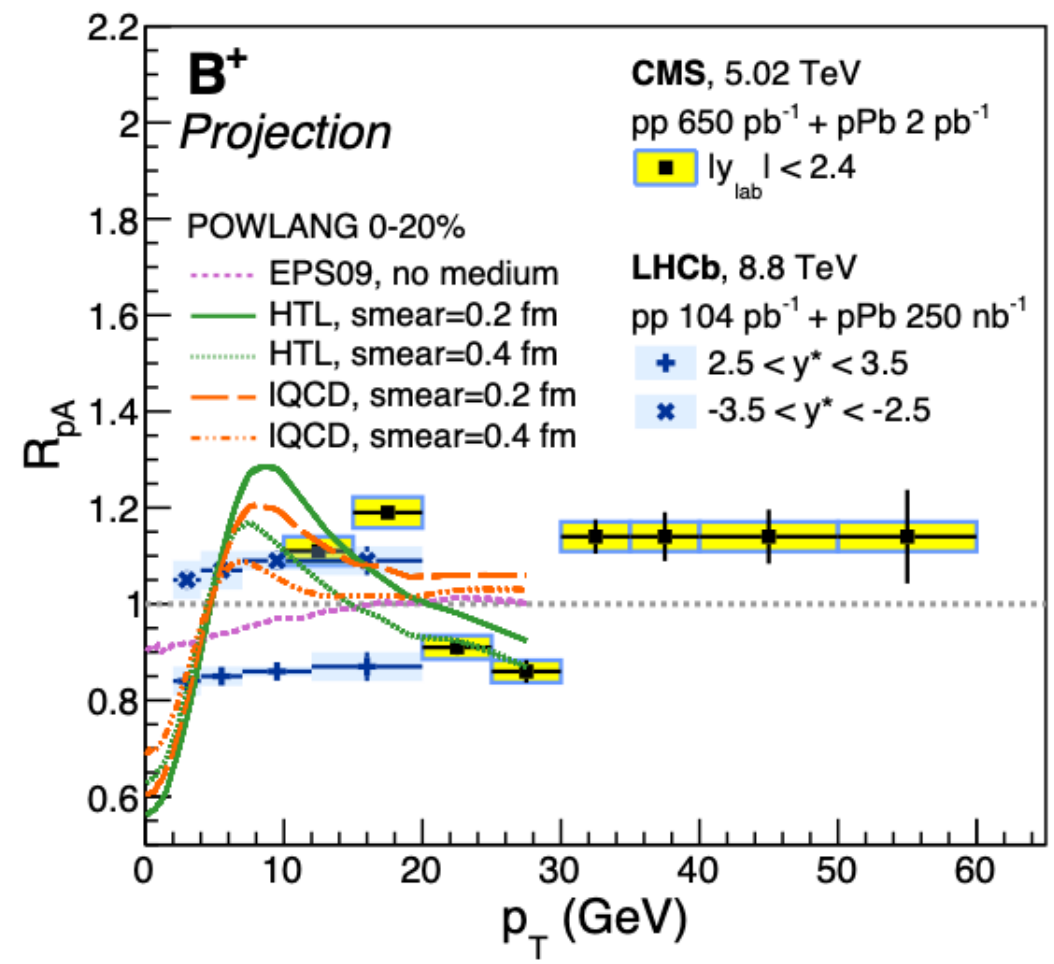
Hadronization



arXiv:1812.06772

High-Luminosity LHC!





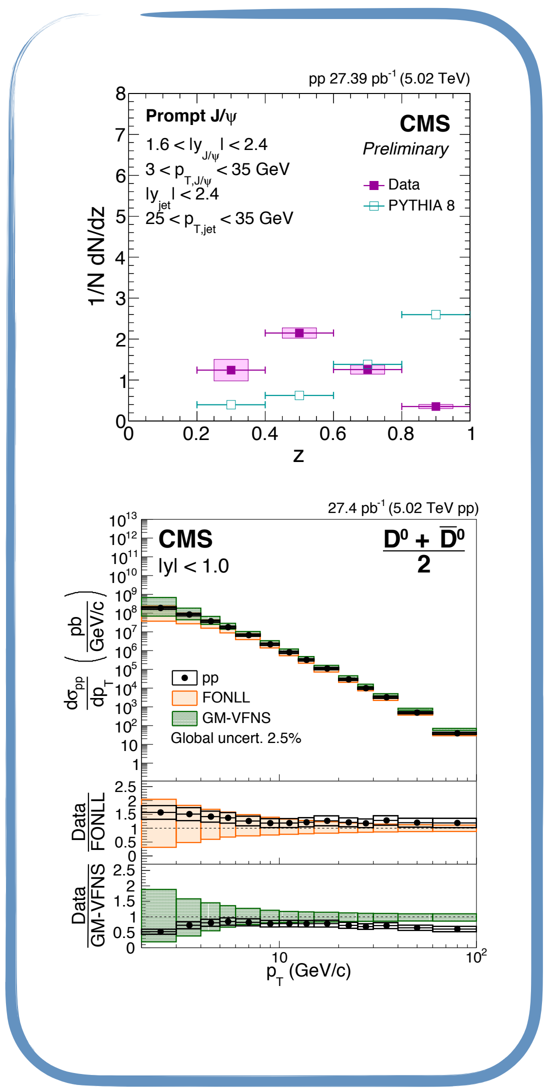
- High-precision HF correlation measurements
- Strong constraints on CNM effects

arXiv:1812.06772

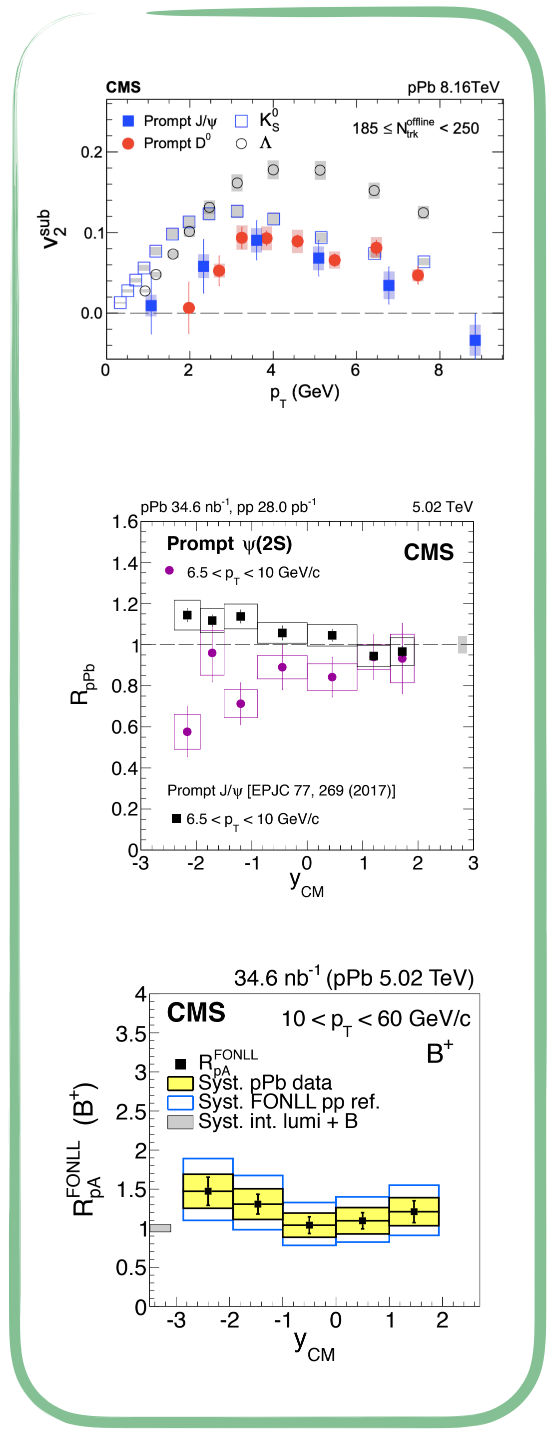
Summary

Great achievements from CMS on heavy flavor measurements in various system and observables!

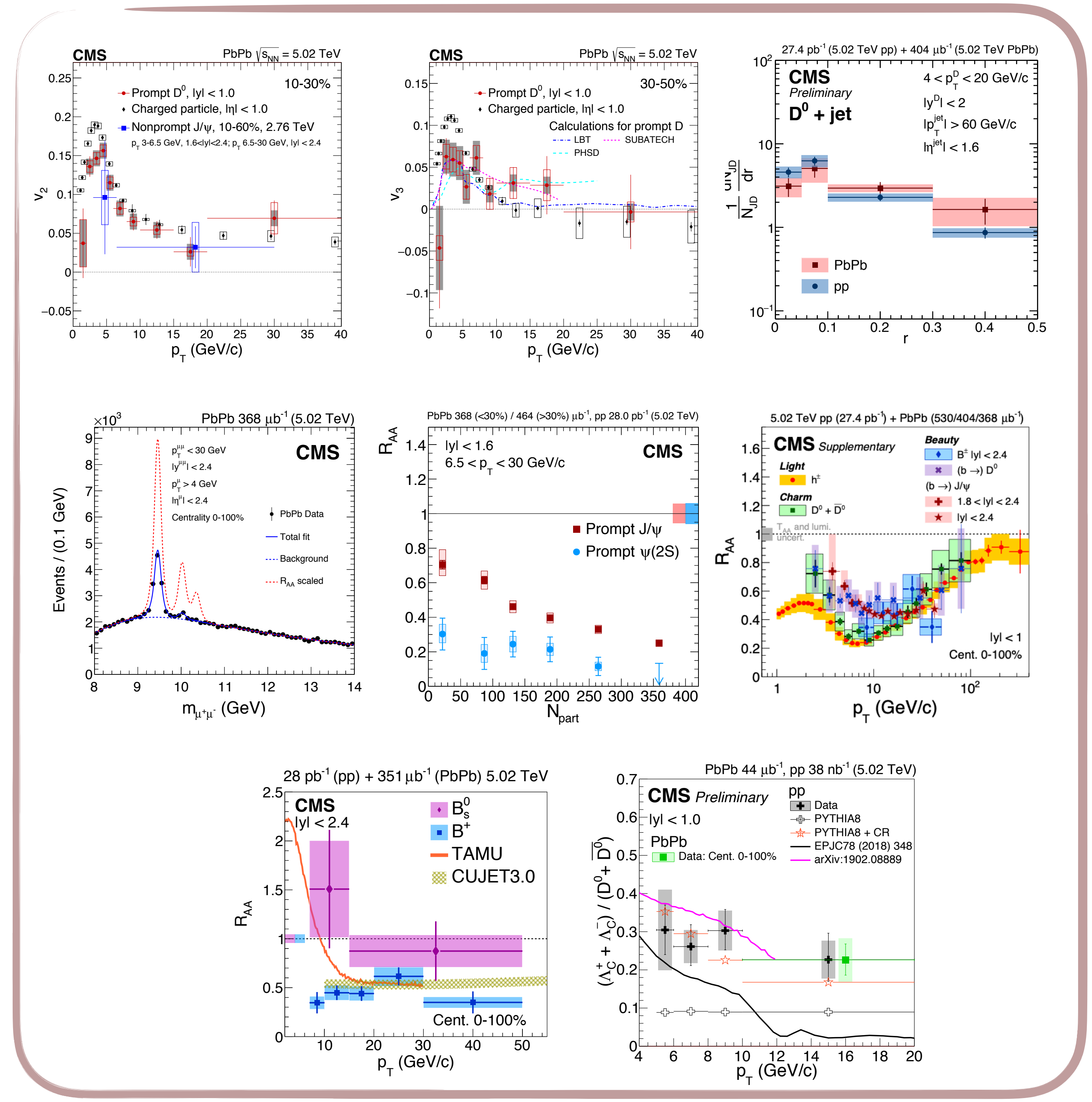
pp



pPb



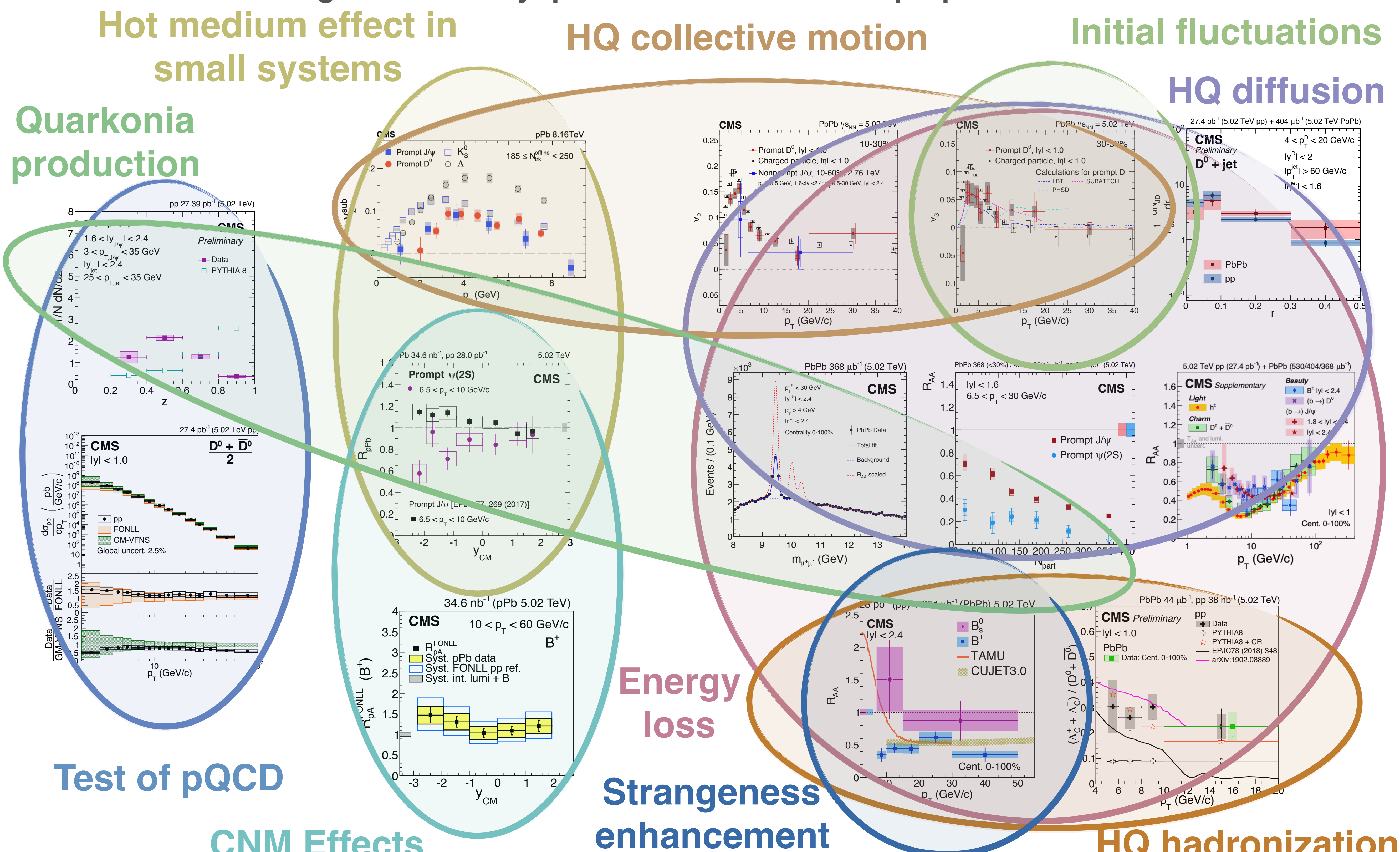
PbPb



The MIT RHIG's work was supported by US DOE-NP

Summary

Great insights into heavy quark behavior and QGP properties from CMS!

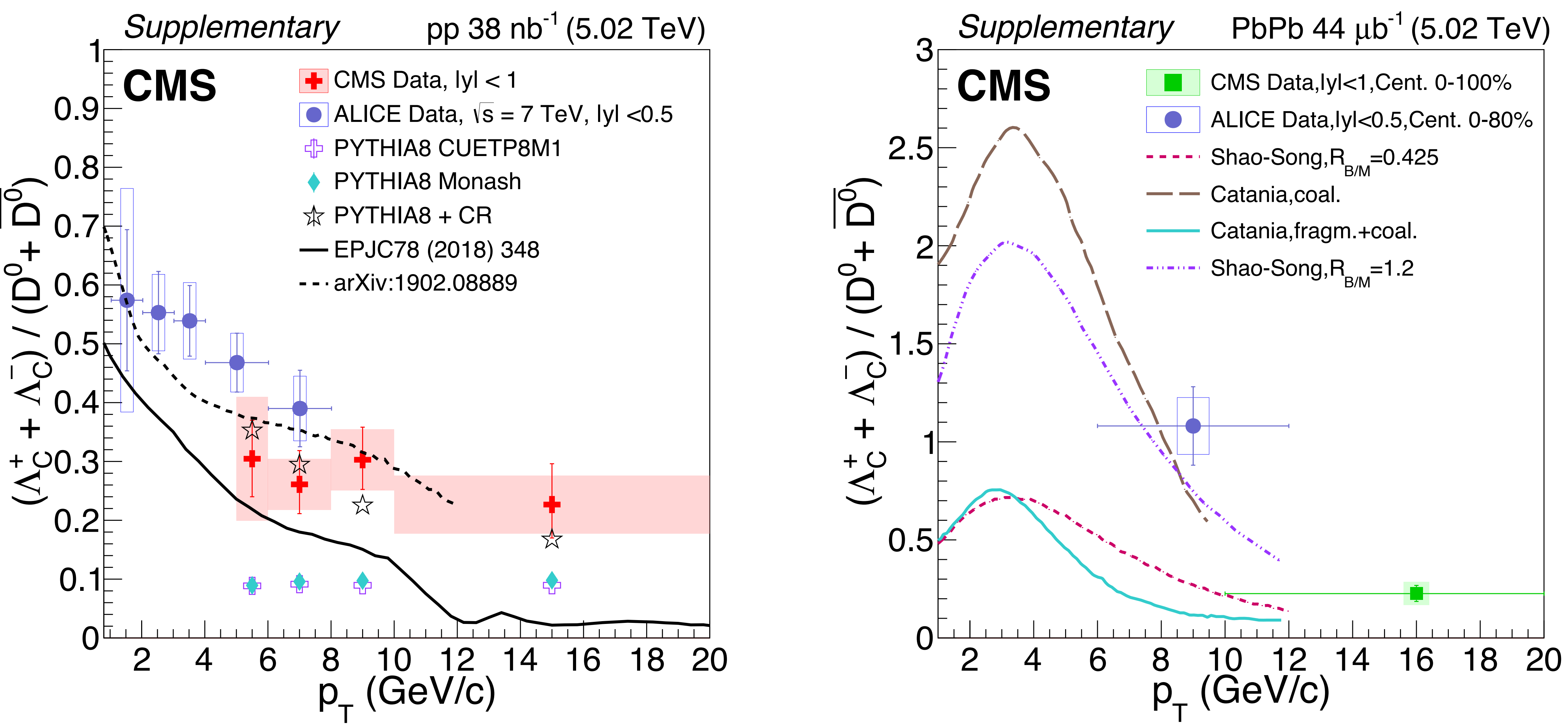


The MIT RHIG's work was supported by US DOE-NP

Back up

Thanks for your attention!

Λ_c vs. ALICE

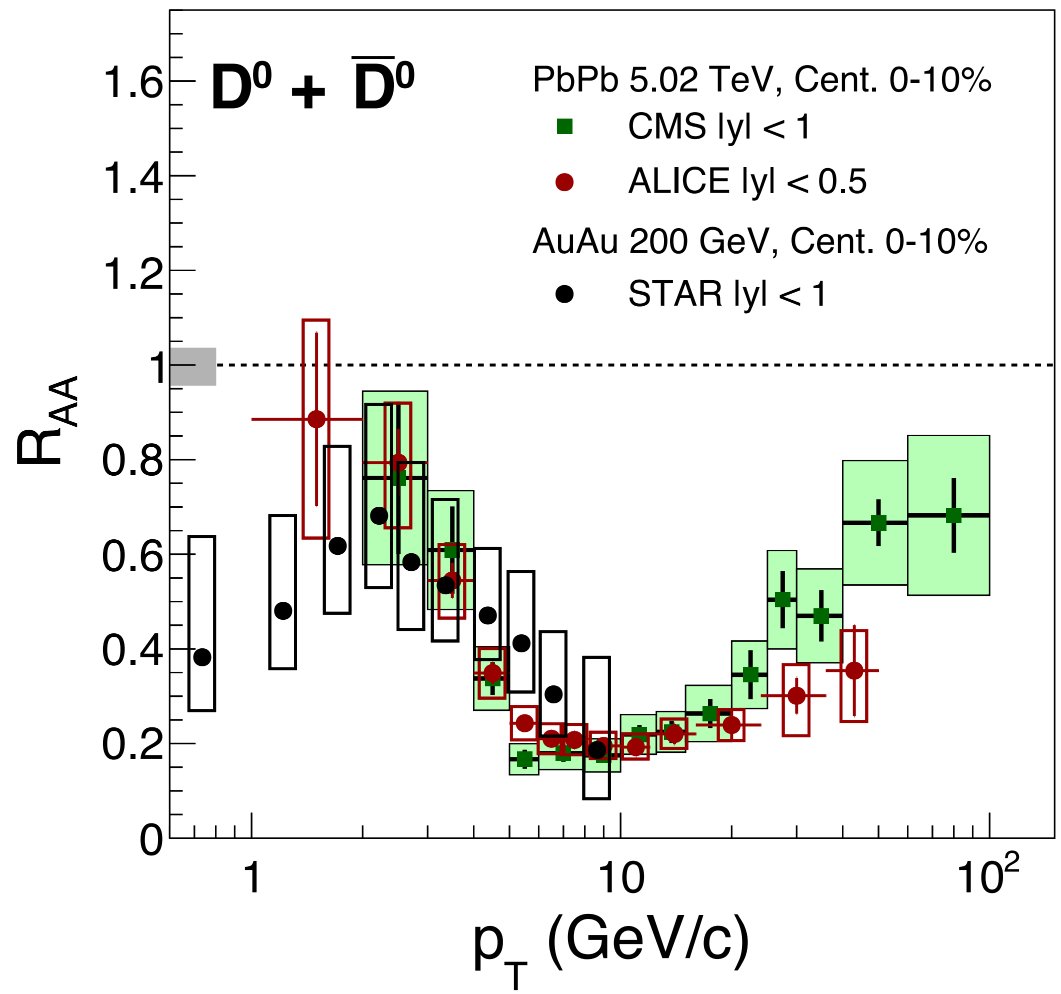


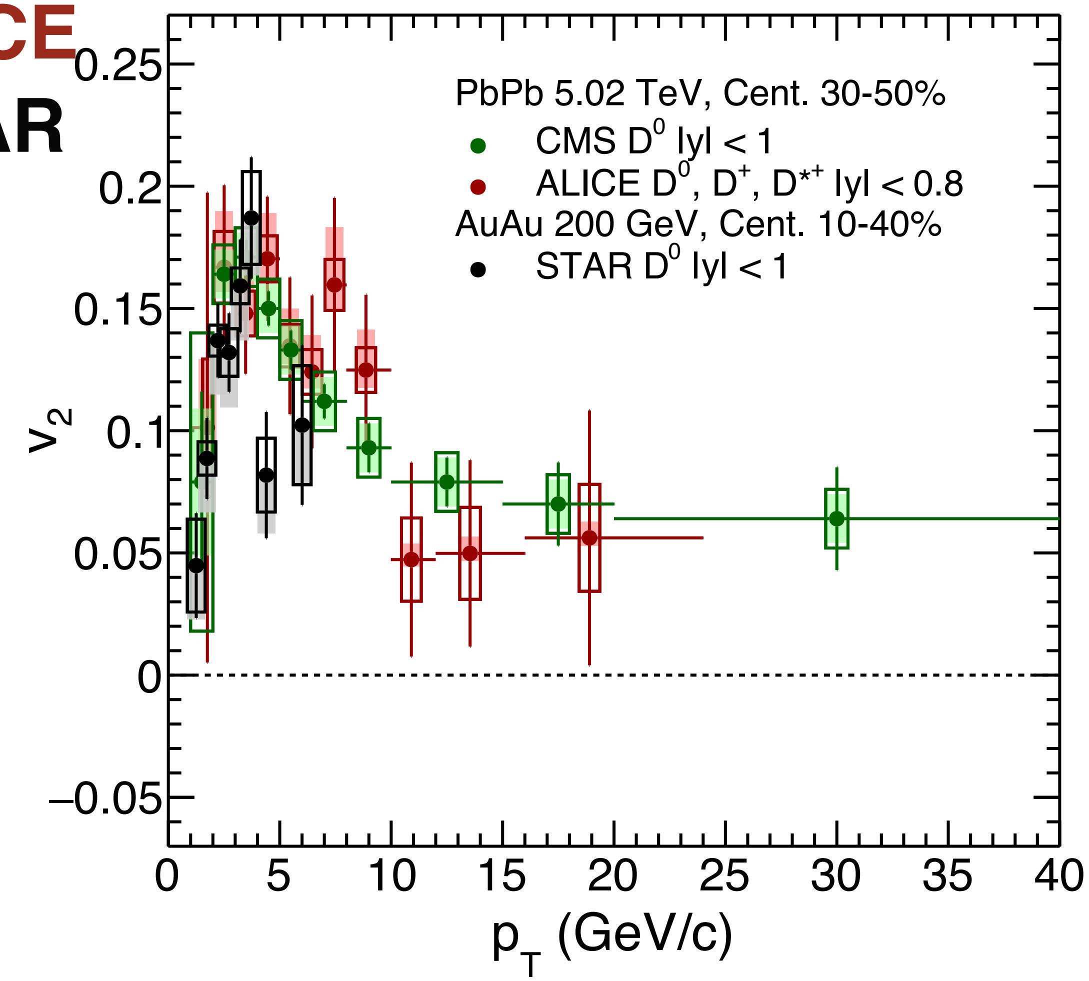
Different Collision Systems

R_{AA}

CMS
ALICE
STAR

v_2



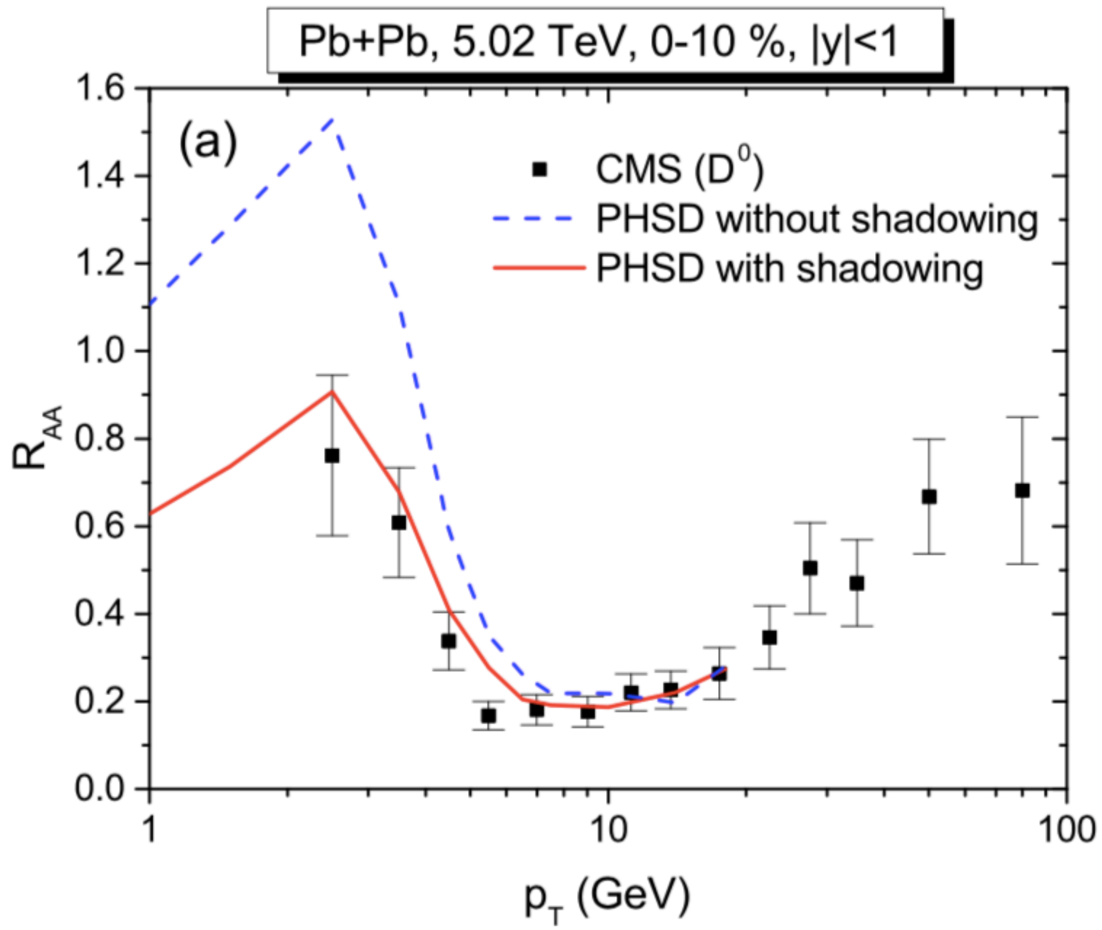


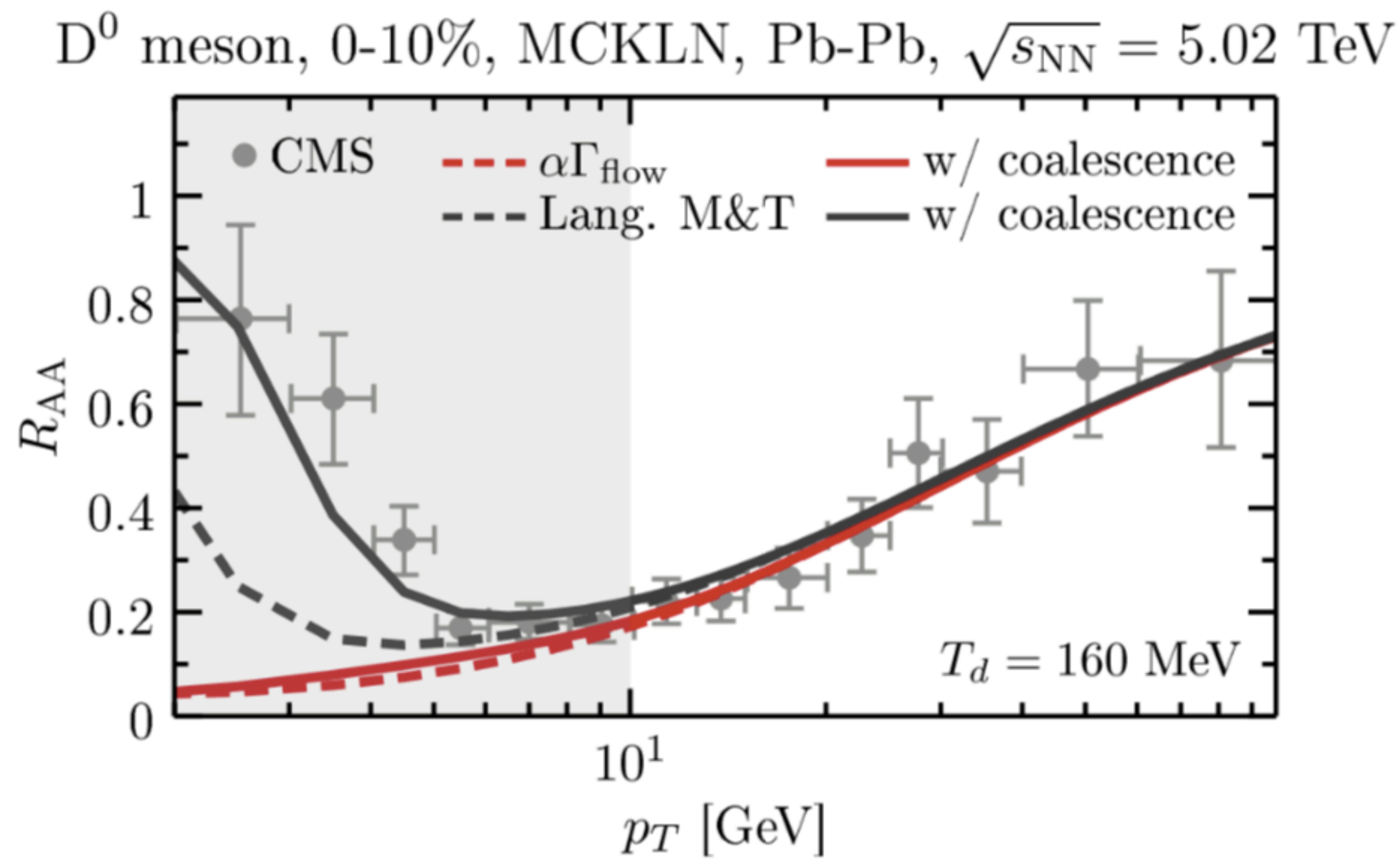
- **CMS** cross-check with **ALICE** measurements
- No Significant difference between **PbPb@5 TeV** vs. **AuAu@200 GeV** within large uncertainties
- CMS did a good job :)

PRC 99 (2019) 034908
JHEP 10 (2018) 174
PLB 782 (2018) 474

PRL 118 (2017) 212301
PRL 120 (2018) 102301
PRL 120 (2018) 202301

R_{AA} vs. Theoretical Predictions





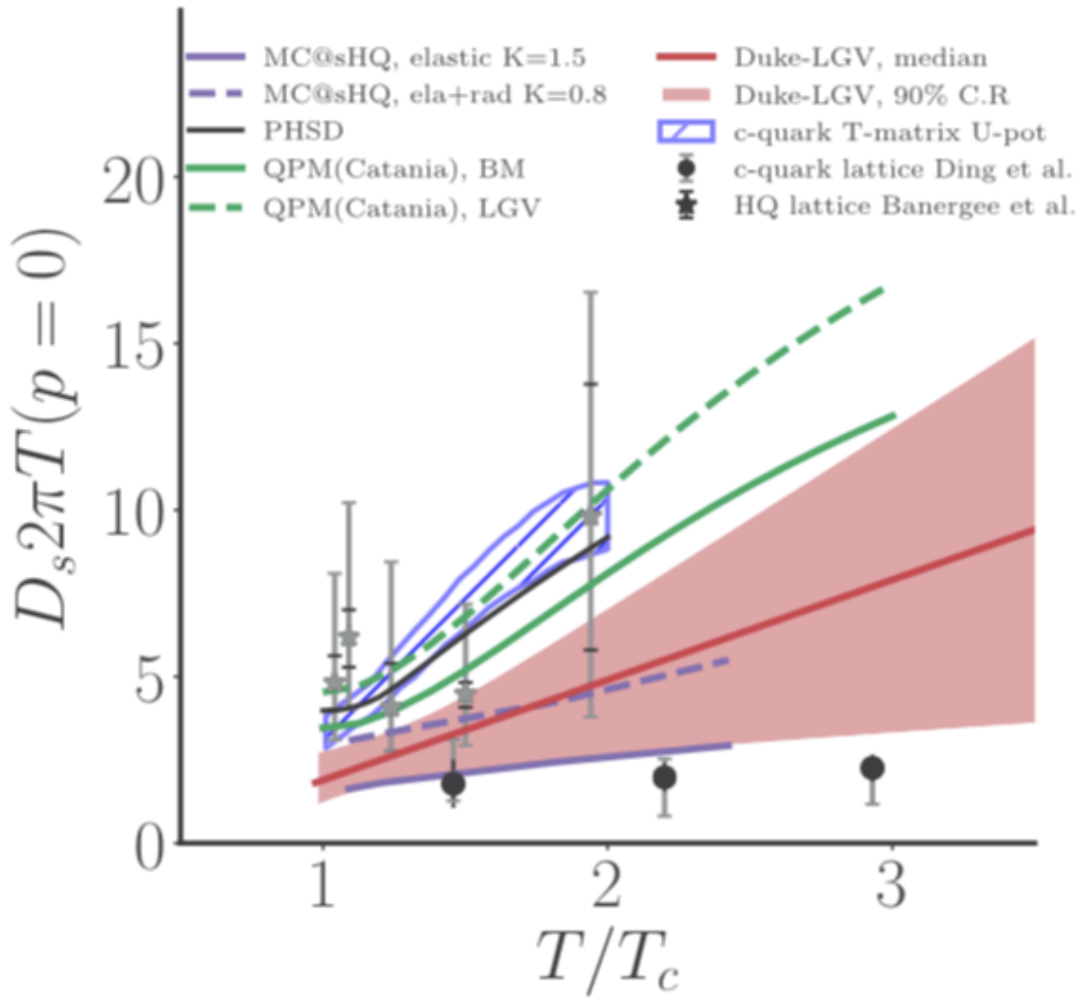
- Shadowing plays an important role at low p_T
- Coalescence hadronization significantly enhances D^0 production at low p_T

Phys. Rev. C 97 (2018) 064907

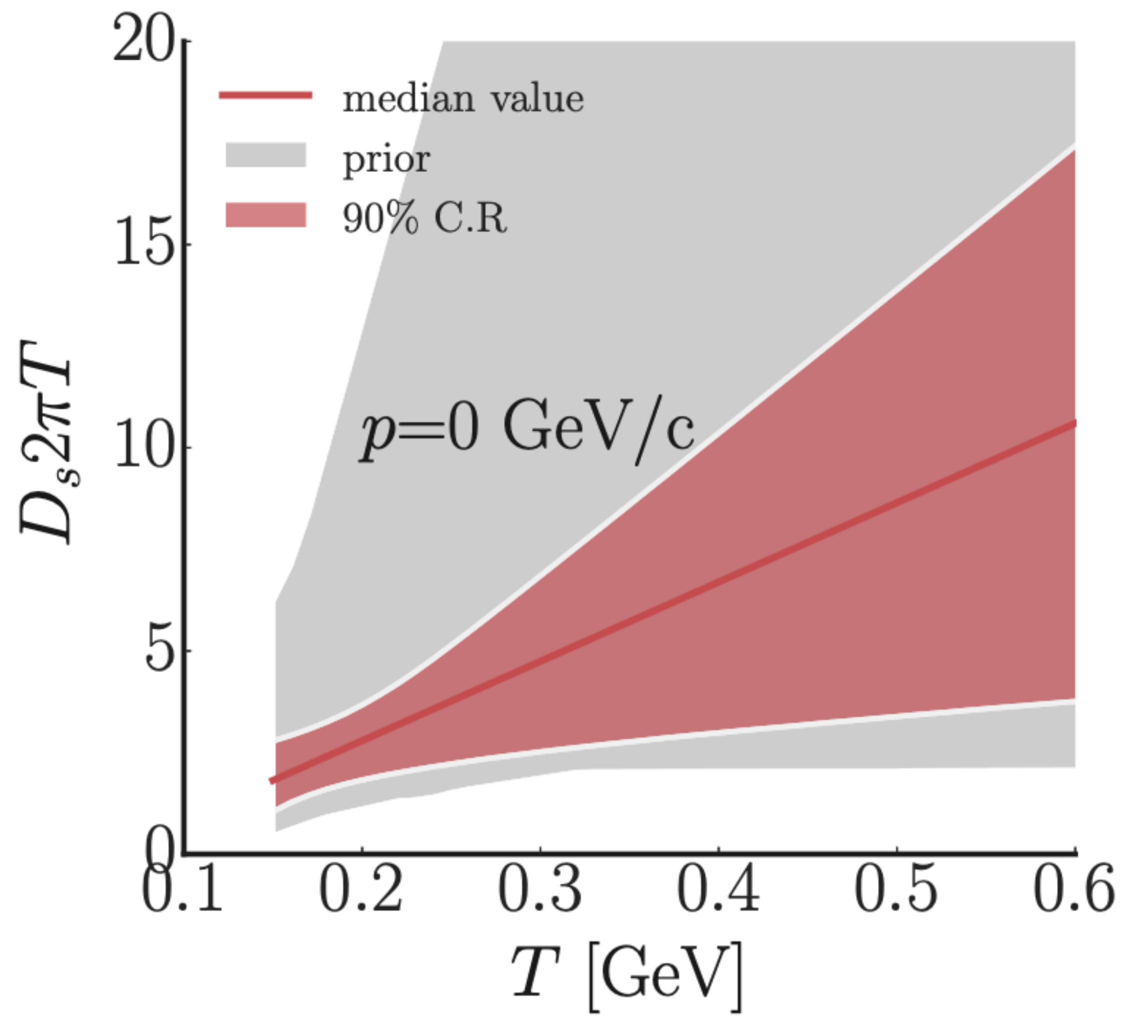
arXiv:1812.08009

Spatial diffusion coefficient D_s extraction

Different models



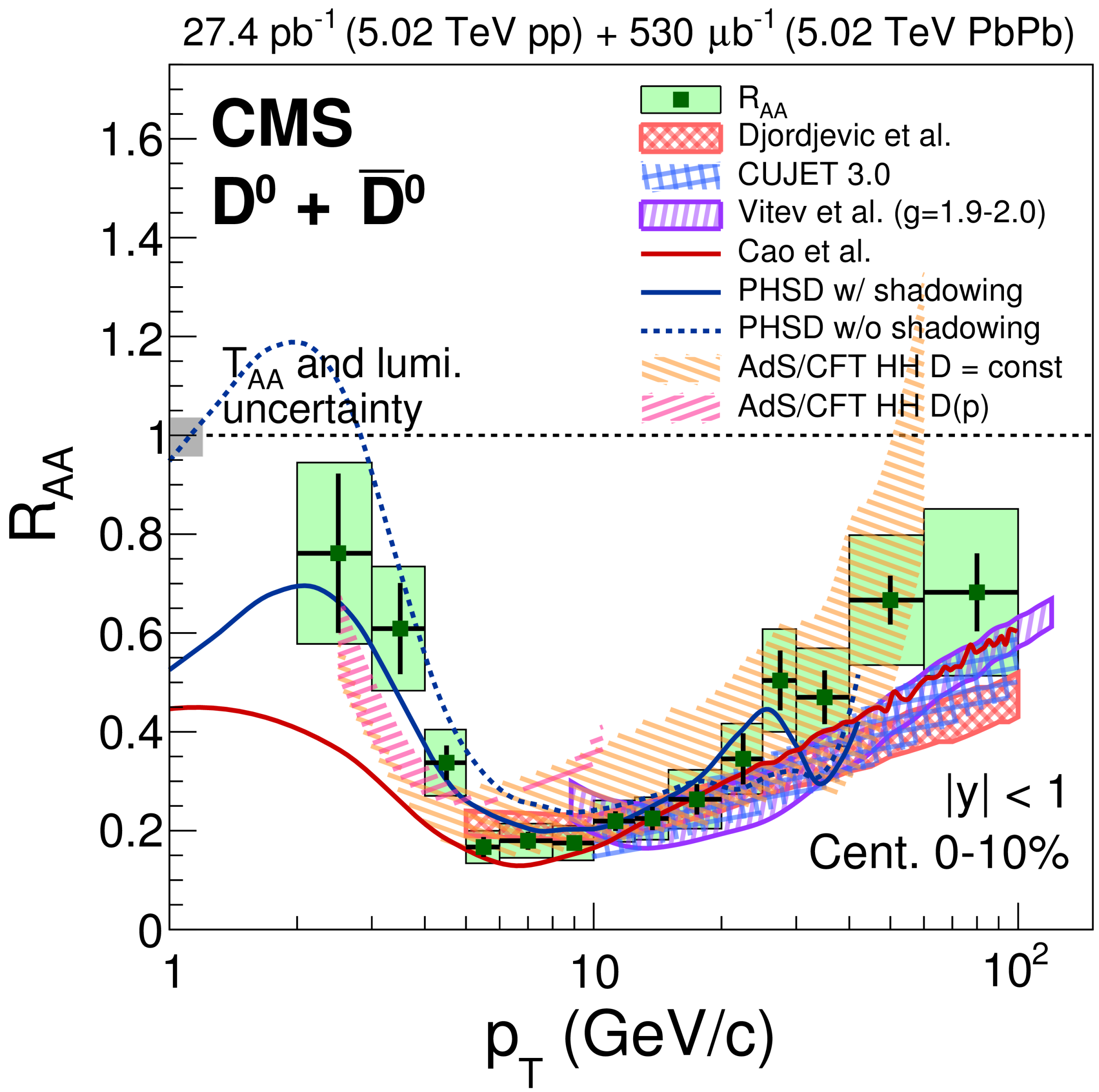
w/ and w/o latest experimental constraints

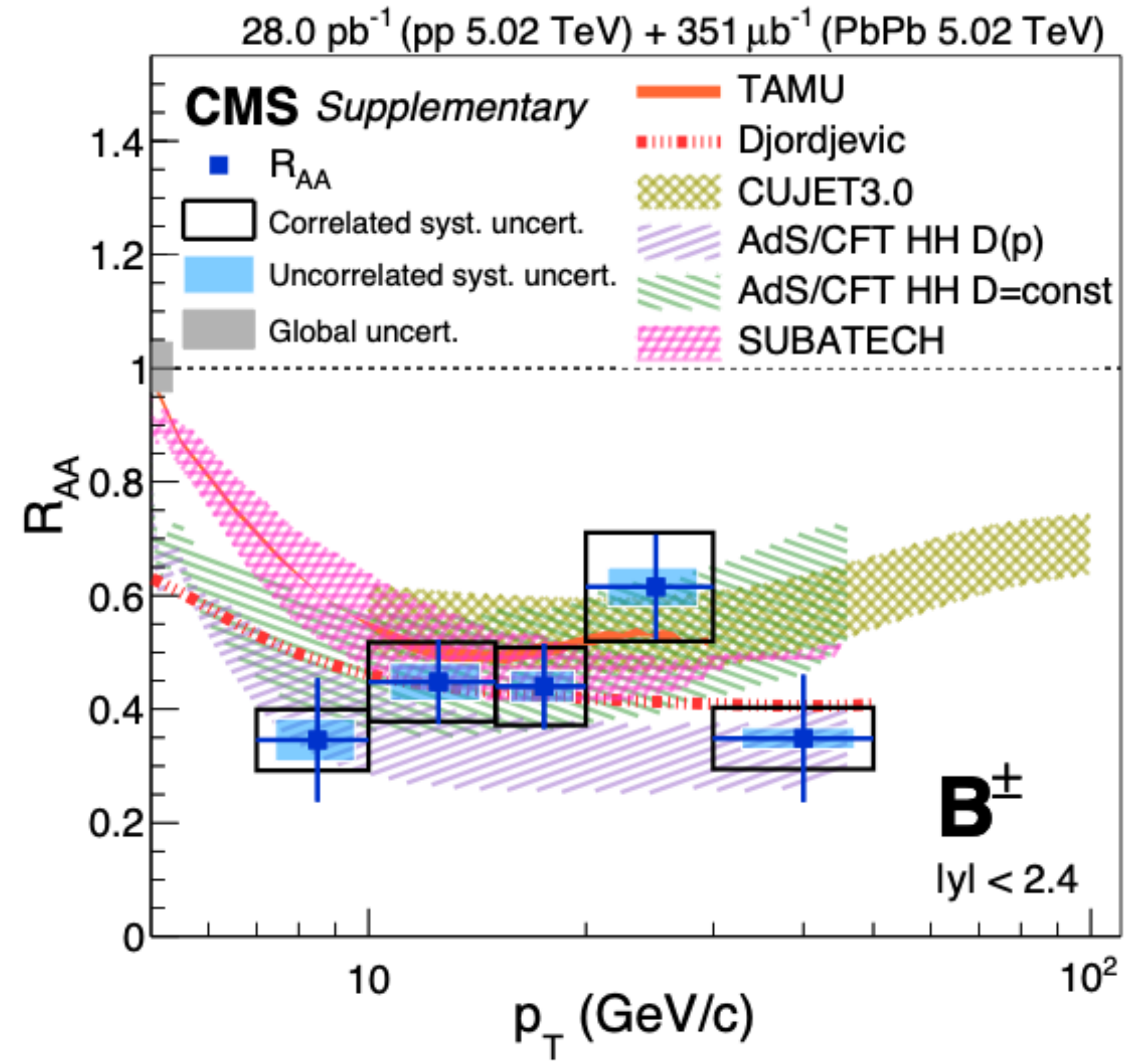


- Constrained by the input of D meson R_{AA} and v_2 from CMS, ALICE, STAR
- $D_s\, 2\pi T(p=0, T_c) = 1 — 7$ at $T \sim T_c$
- Significant constraint from experimental measurements

PRC 97 (2018) 014907

Theoretical Predictions - R_{AA}





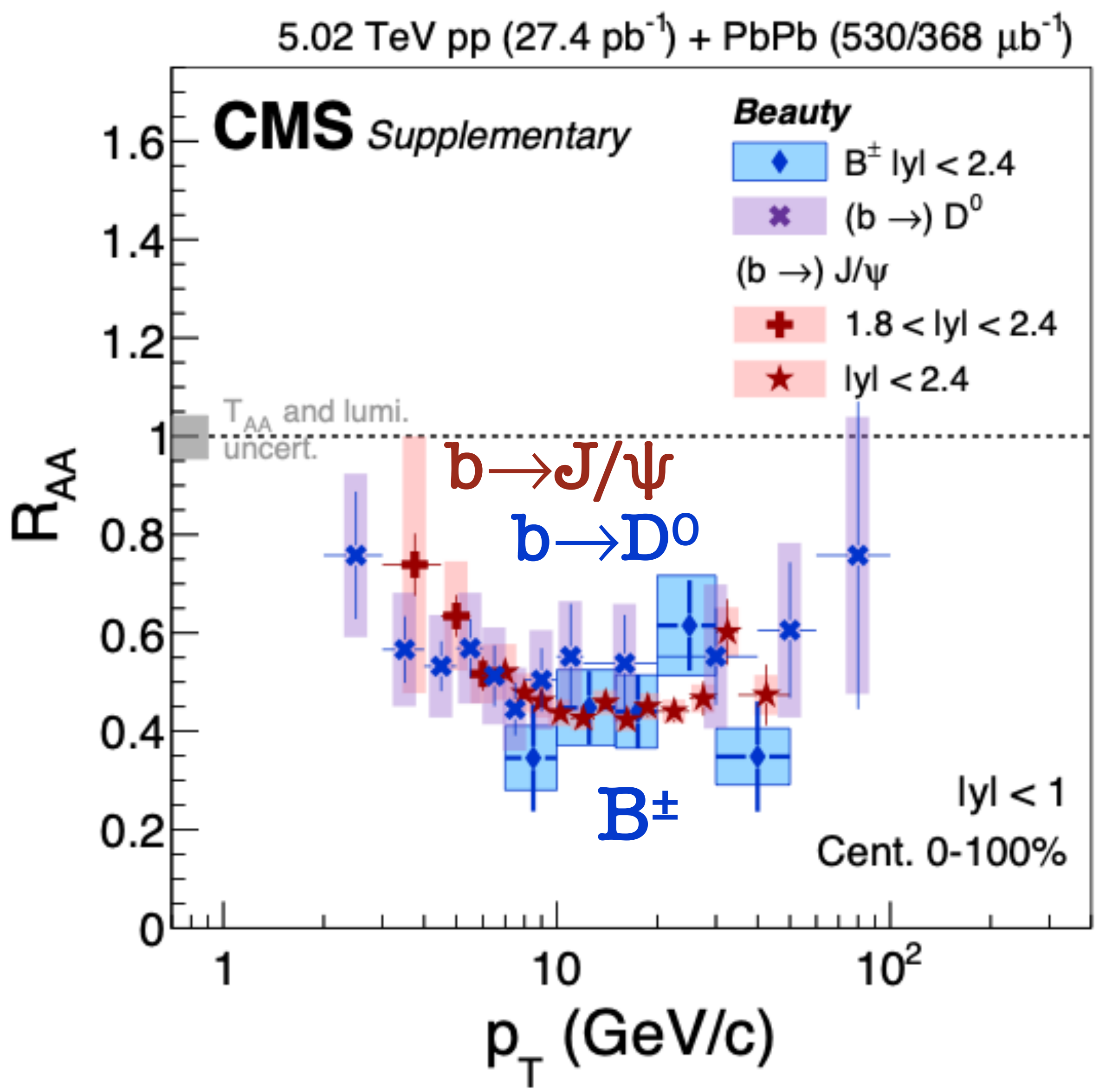
- Most models can predict the shape
- Theoretical calculation is below data at high p_T
- R_{AA} is sensitive to evolution models at low p_T
- Jet models only works at high p_T

arXiv:1703.00822
Phys. Rev. C 92 (2015) 024918
JHEP 02 (2016) 169
Phys. Rev. D 91 (2015) 085019
Phys. Rev. D 93 (2016) 074030
Phys. Rev. C 93 (2016) 034906

PLB 782 (2018) 474

Flavor dependence of parton energy loss

Centrality **0-100%**



Prompt D^0

- ➡ Strongest suppression at p_T 5-10 GeV/c
- ➡ No significant collision energy dependence compared with 2.76 TeV

Charged hadrons vs. Prompt D^0

- ➡ Similar suppression in a wide kinematic range
- ➡ Hint of less suppression of D^0 at low p_T?

B^+ vs. Prompt D^0

- ➡ No significant meson flavor dependence of R_{AA} at high p_T with the current accuracy

Non-prompt J/ψ vs. Prompt D^0

- ➡ Hint of flavor hierarchy of R_{AA} at low p_T
- ➡ Flat Non-prompt J/ψ R_{AA} at high p_T

Non-prompt D^0 vs. Prompt D^0

- ➡ Stronger suppression for Prompt D^0 in intermediate p_T

Non-prompt J/ψ vs. Non-prompt D^0 vs. B^+

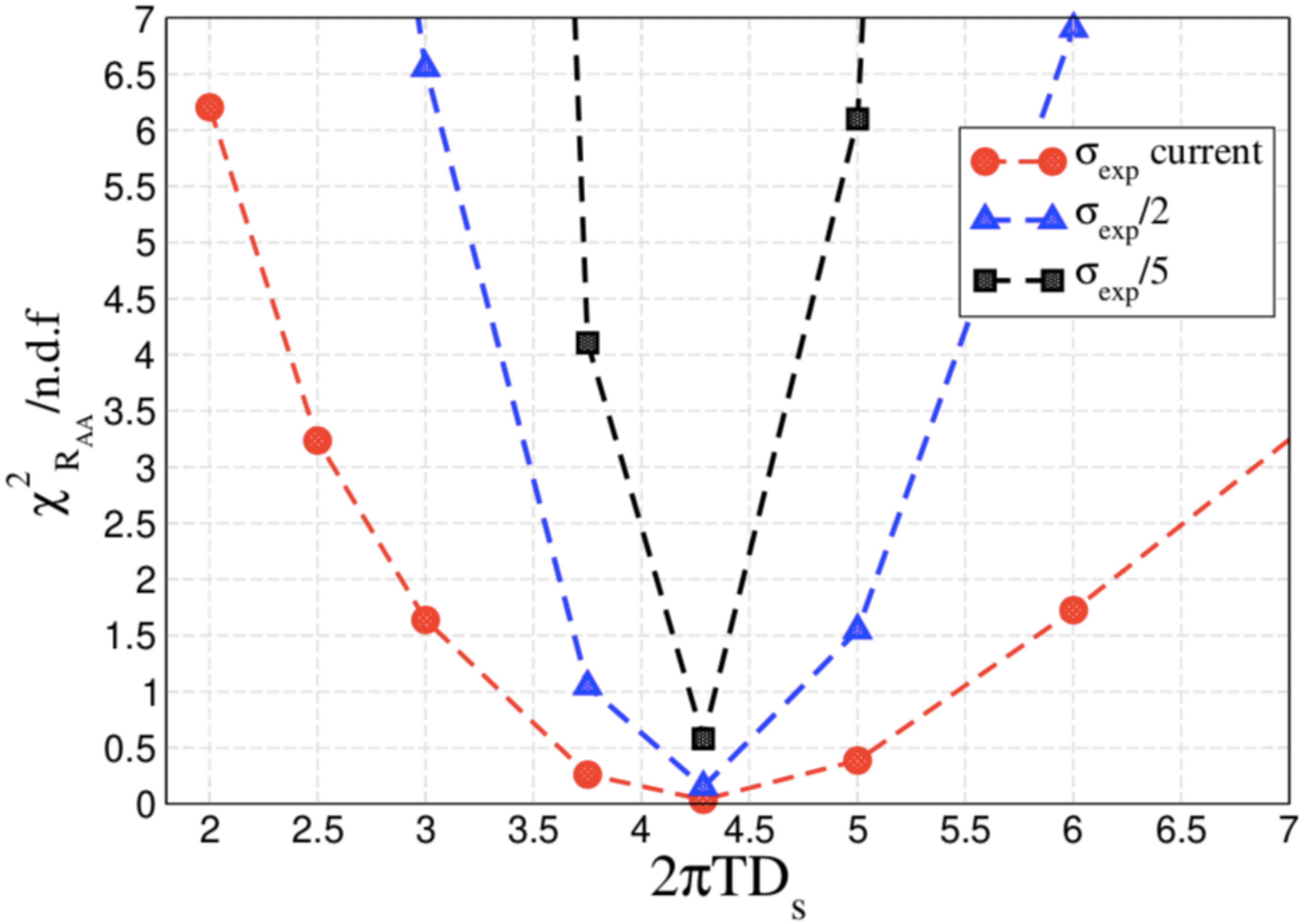
- ➡ Consistent at 10-20 GeV/c
- ➡ B→D analysis is on-going to reach lower p_T

arXiv:1810.11102
EPJC 78 (2018) 509
PRL 119 (2017) 15230

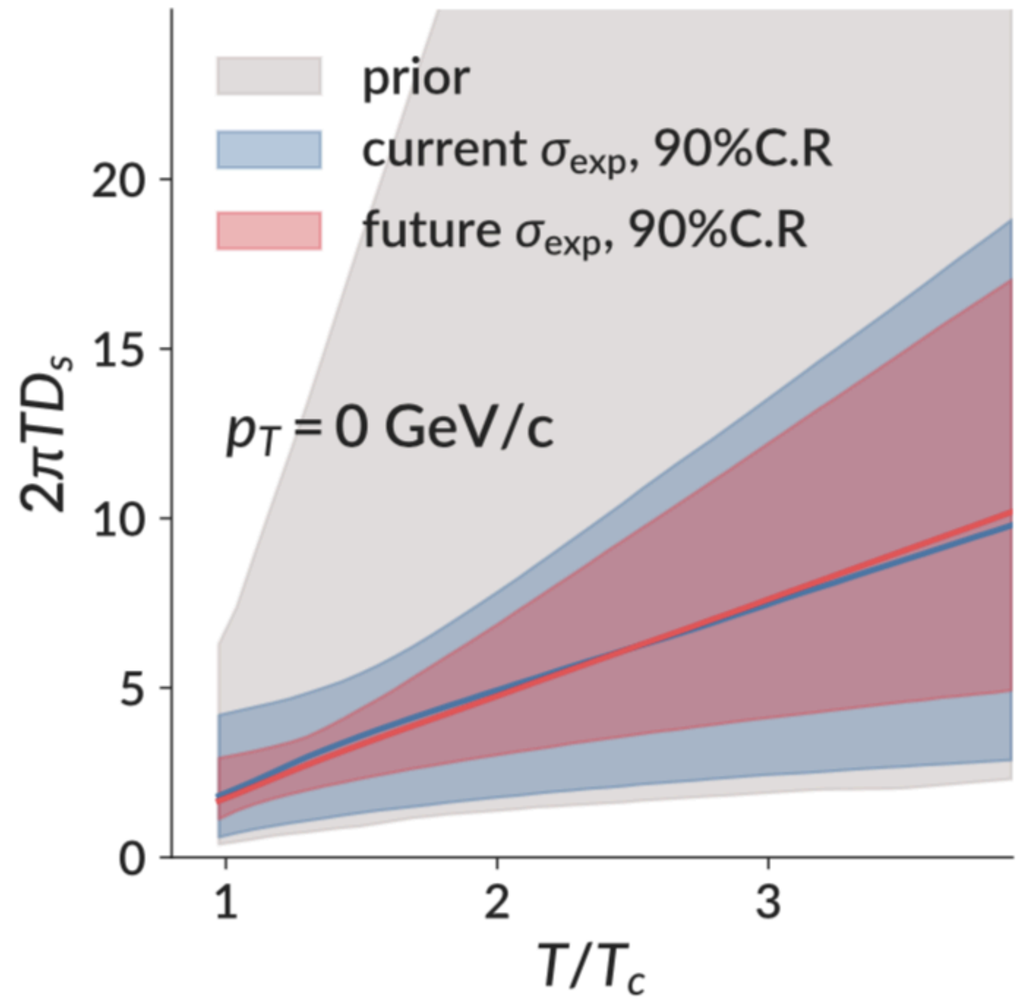
What can we expect by the HL-HLC era? (3/4)

High-Luminosity LHC!

Catania group



Duke group

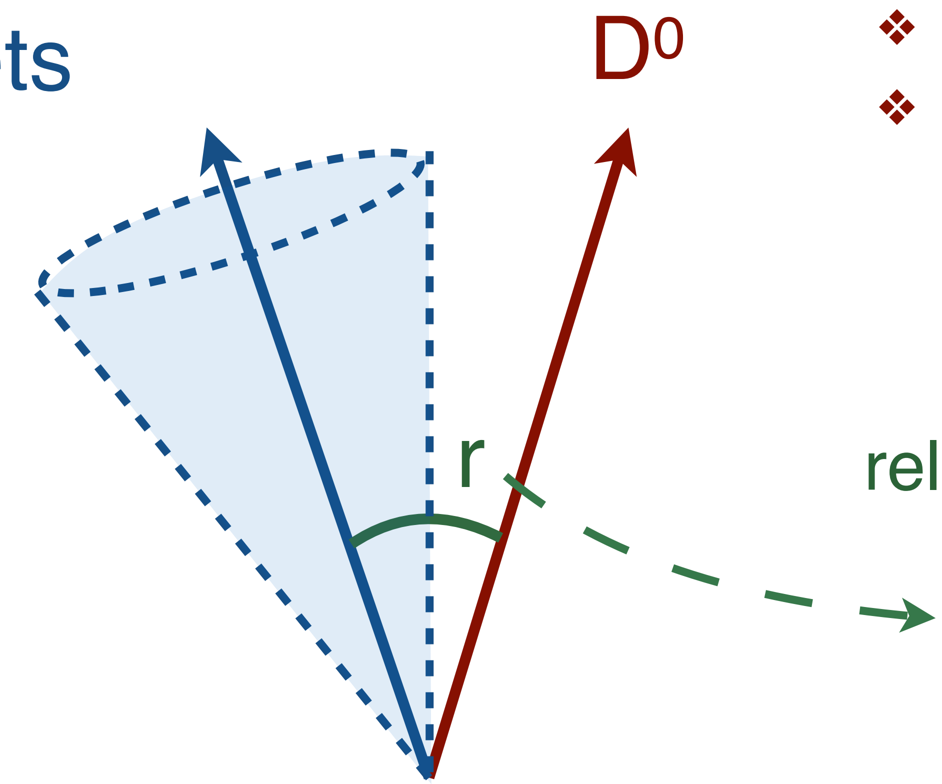


- Stronger constraints on the diffusion coefficients

arXiv:1812.06772

Dataset + Observables

- Jet-triggered events in pp and PbPb collisions
  - ➡ MinimumBias events are used for background subtraction
  - ➡ Cross-checked with D-triggered events



- ❖ Particle flow jets
- ❖ anti-k_T, R = 0.3
- ❖ $p_T^{jet} > 60$ GeV/c
- ❖ $|\eta^{jet}| < 1.6$

- ❖ $|y^D| < 2$
- ❖ Two p_T bins
  - ➡ $4 < p_T^D < 20$ GeV
  - ➡ $p_T^D > 20$ GeV

relative η,Φ between D^0 and jets

$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$

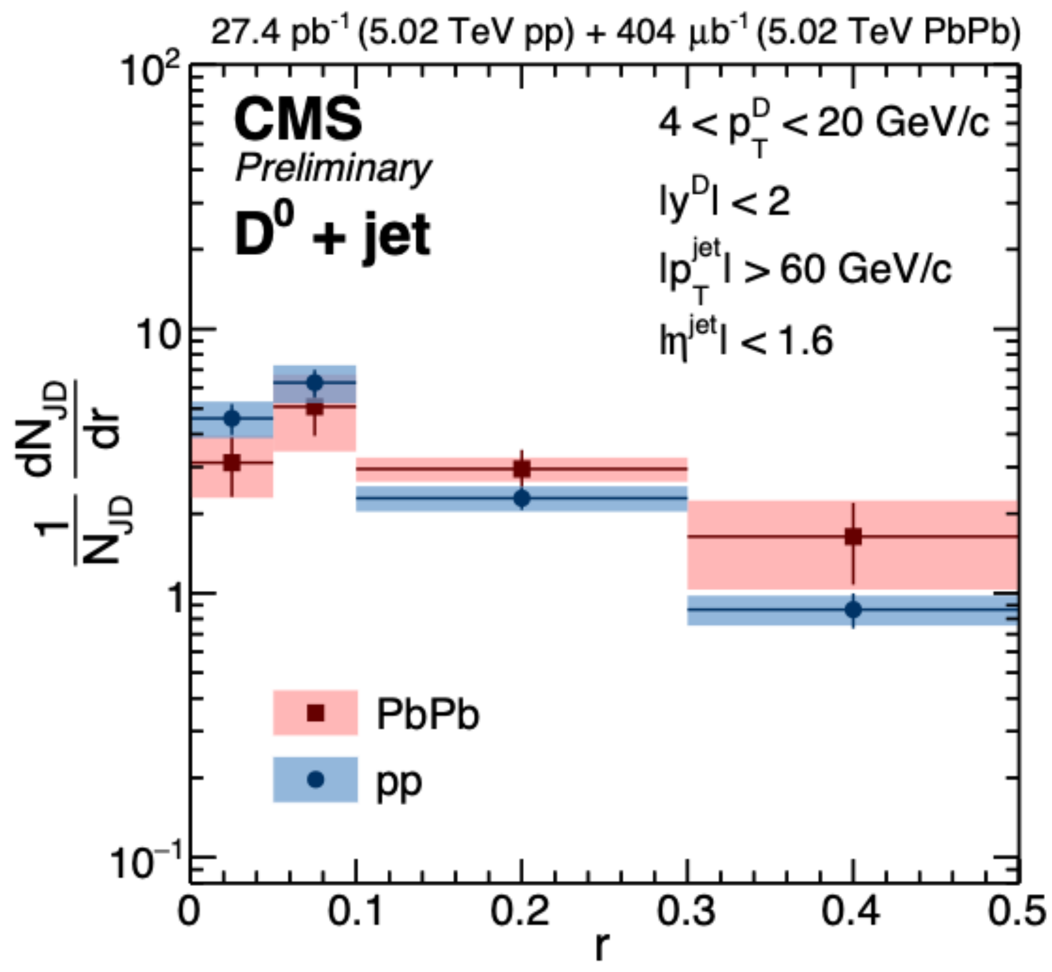
- Radial distribution of D^0 with respective to the jet axis:

$$\frac{1}{N_{JD}} \frac{dN_{JD}}{dr}$$

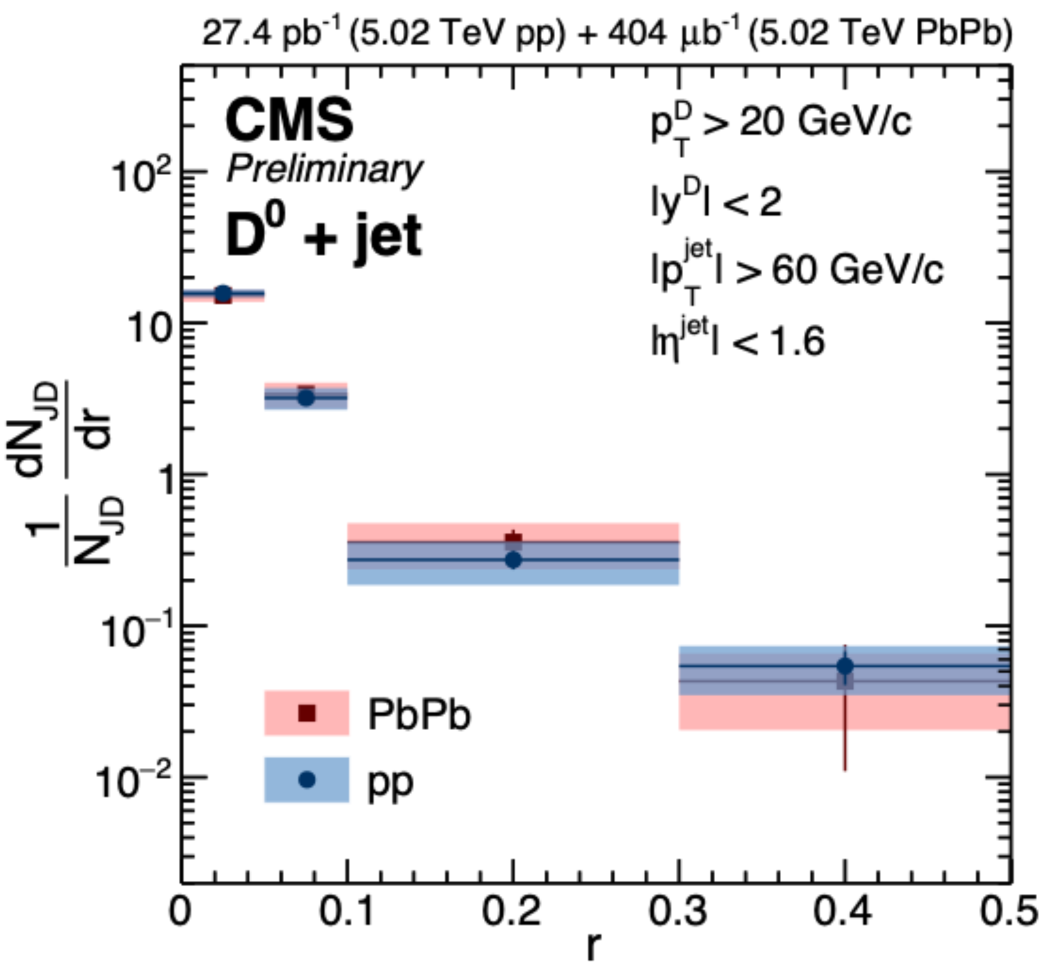
- The final distribution is normalized to unity in $r < 0.3$
- No p_T weight as light-hadron jet shape analysis

Radial profile of D^0 in jets (1/3)

Low D p_T: $4 < p_T^D < 20$ GeV/c



High D p_T: $p_T^D > 20$ GeV/c

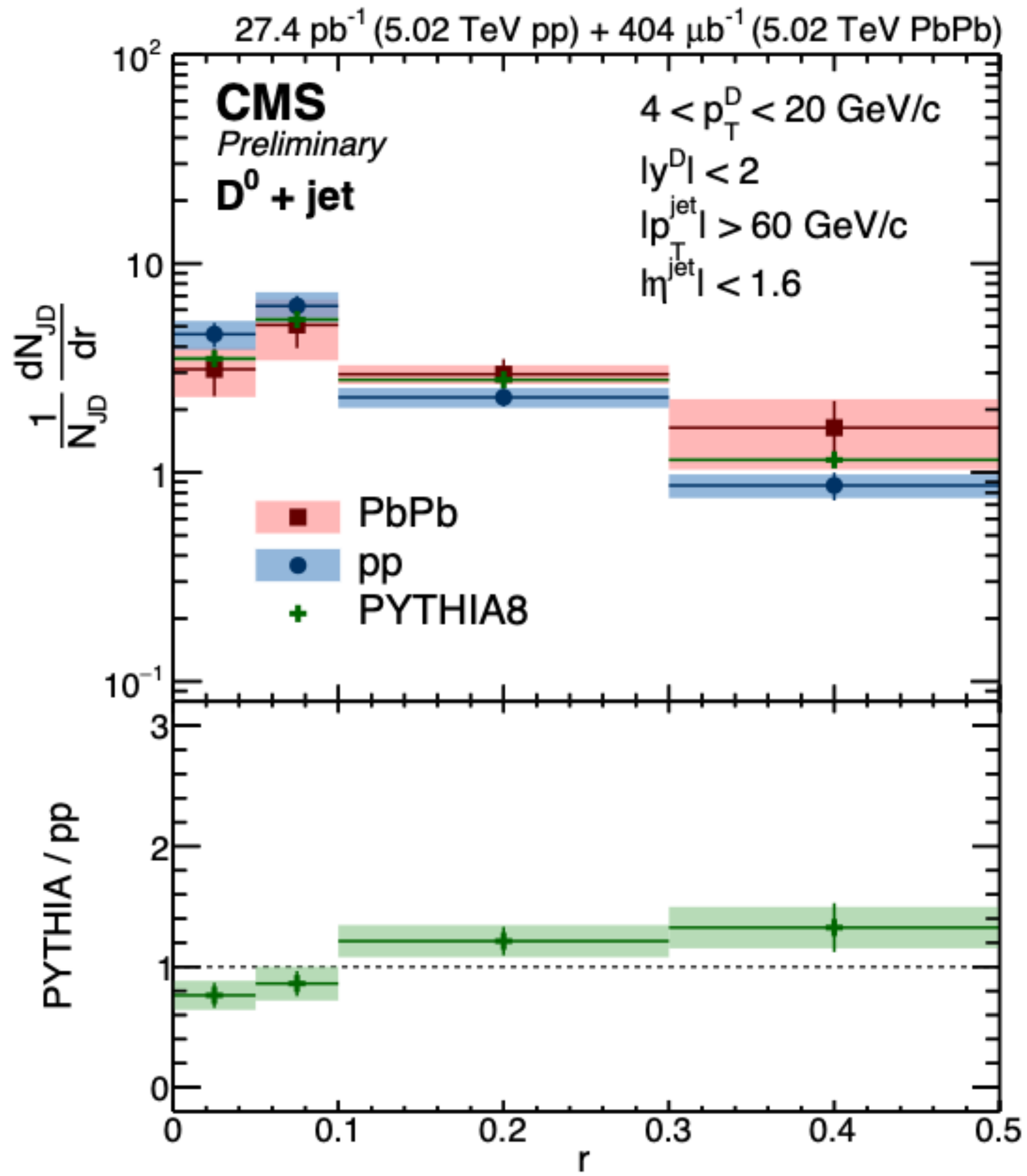


- Low D p_T: reach maximum at $0.05 < r < 0.1$
- High D p_T: fall rapidly as a function of r

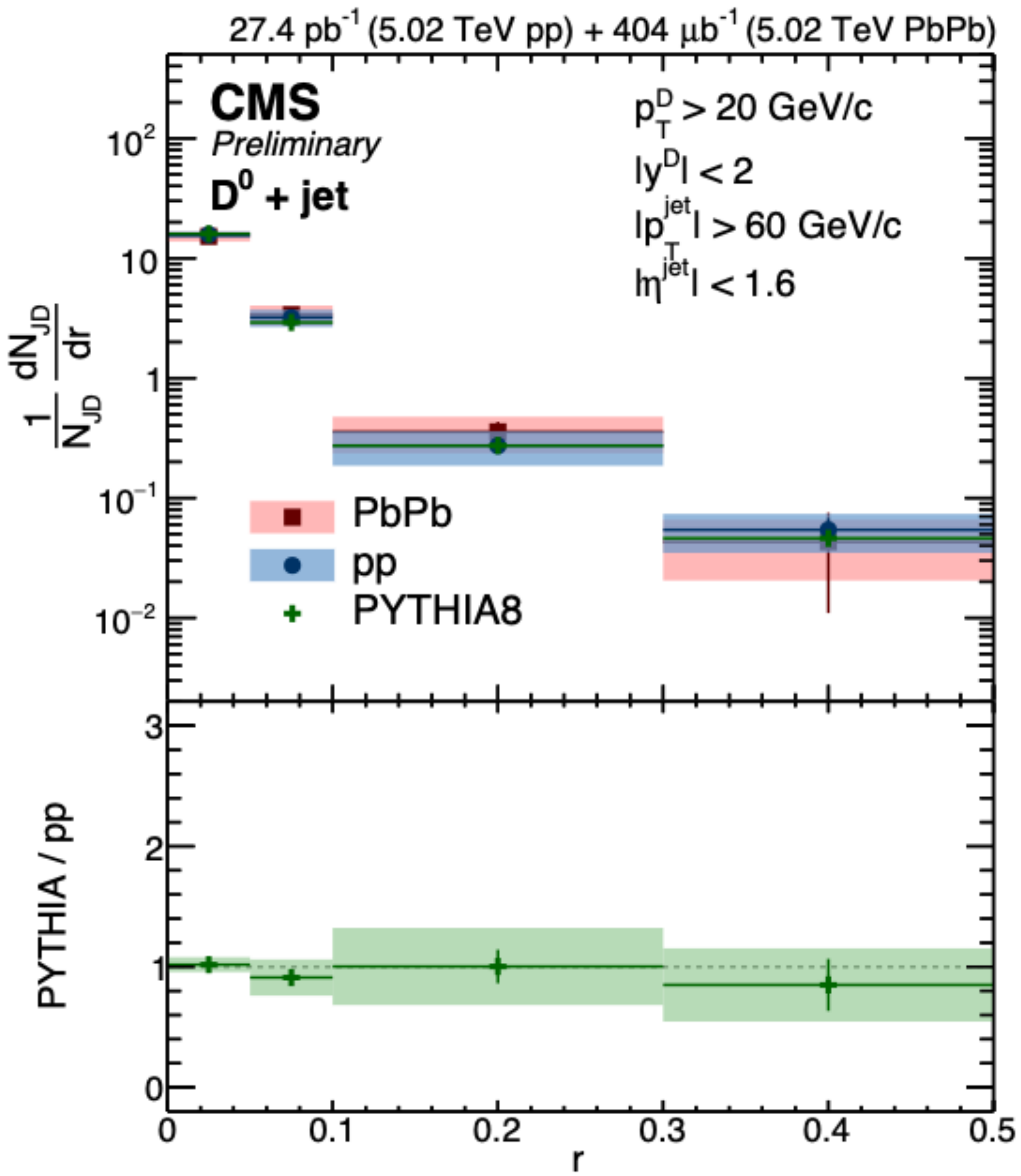
CMS-PAS-HIN-18-007

Radial profile of D^0 in jets (2/3)

Low D p_T: $4 < p_T^D < 20$ GeV/c



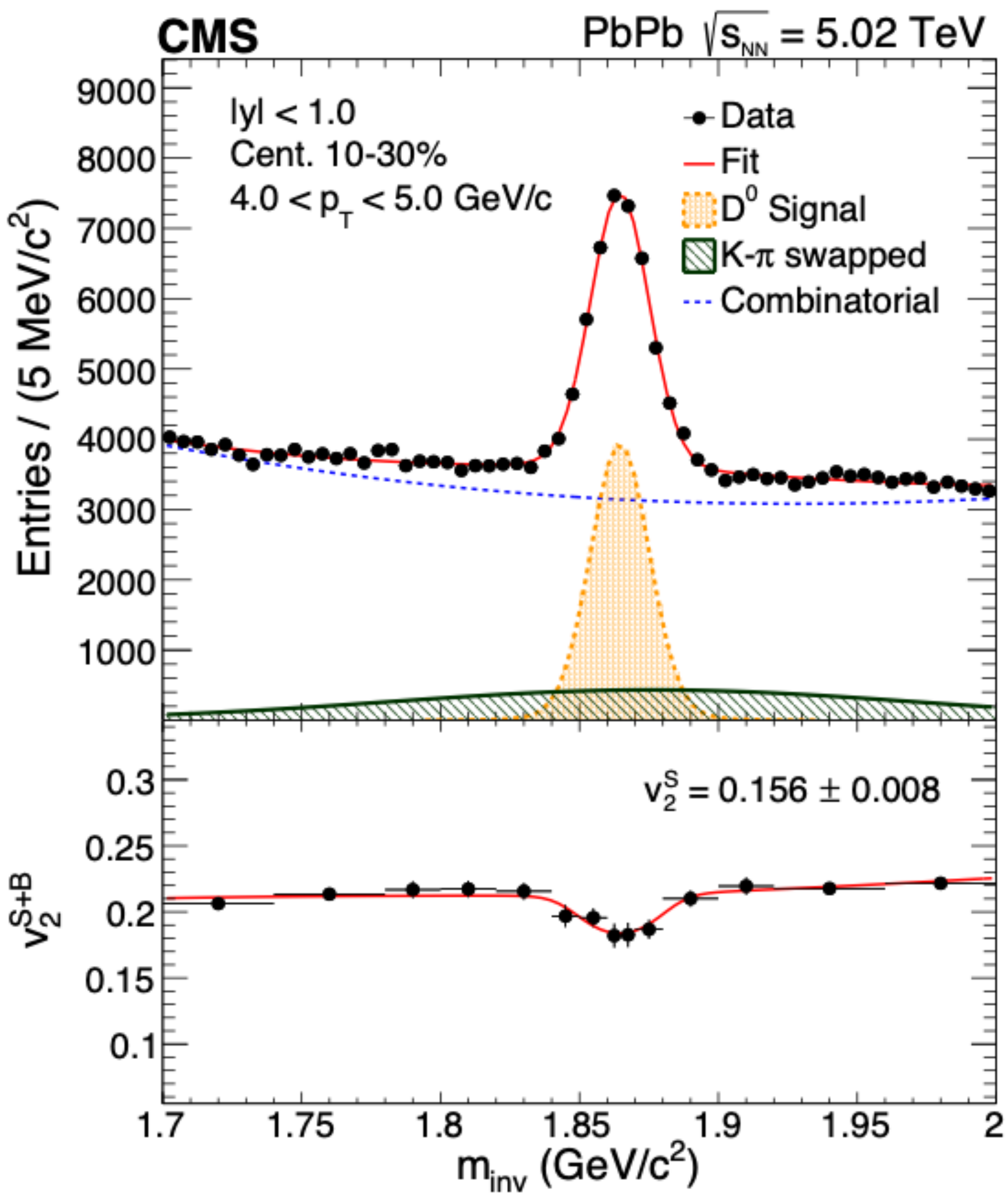
High D p_T: $p_T^D > 20$ GeV/c



- Predictions from PYTHIA8
  - ➡ Low D p_T: produce a wider radial profile than measurements
  - ➡ High D p_T: agree with measurements

CMS-PAS-HIN-18-007

Extraction of D^0 v_n



arXiv: 1708.03497

- Simultaneous fit on invariant mass distribution and v_n vs mass

$$\boxed{v_n^{S+B}}(m_{\rm inv}) = \boxed{\alpha}(m_{\rm inv}) v_n^S + [1 - \alpha(m_{\rm inv})] \boxed{v_n^B}(m_{\rm inv}),$$

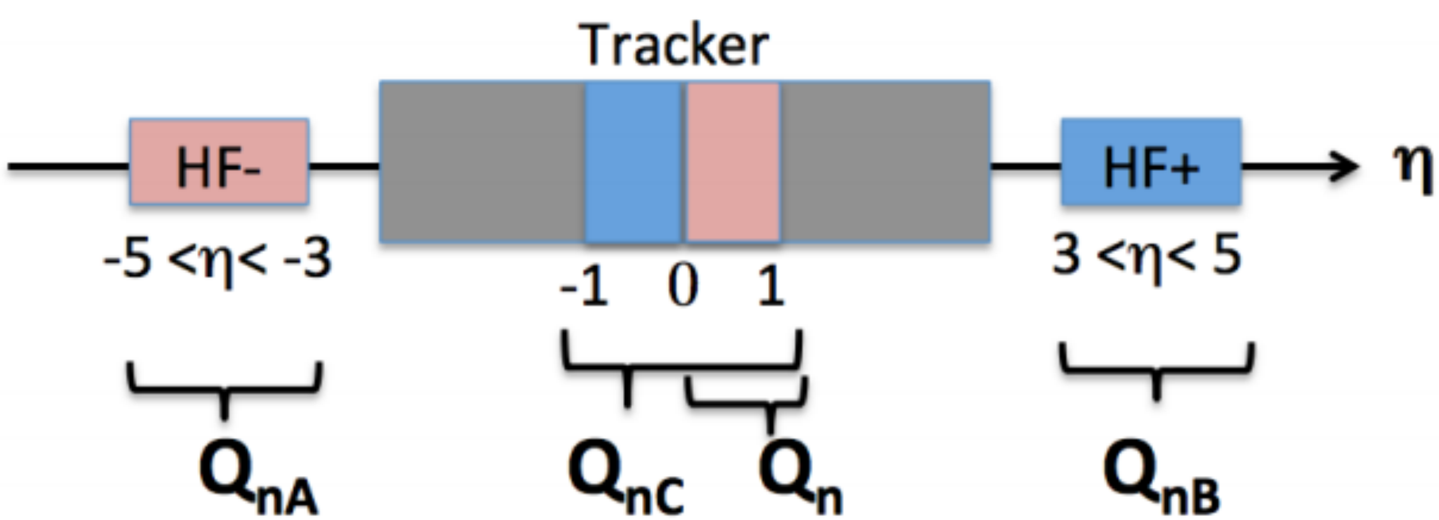
- v_n^S: v_n of signal D^0
  - ➡ fit parameter
- other terms:
  - ➡ $v_n^{S+B}(m_{inv})$: v_n of all D^0 candidates
  - ➡ $v_n^B(m_{inv})$: v_n of combinatorial background, modeled by a linear function
  - ➡ $\alpha(m_{inv})$: signal fraction from invariant mass spectra fit

Scalar Product Method

- v_n coefficient can be expressed in terms of Q-vectors as

$$v_n\{\mathrm{SP}\} = \frac{\left\langle Q_{n,\mathrm{D}^0} Q^*_{nA} \right\rangle}{\sqrt{\frac{\left\langle Q_{nA} Q^*_{nB} \right\rangle \left\langle Q_{nA} Q^*_{nC} \right\rangle}{\left\langle Q_{nB} Q^*_{nC} \right\rangle}}}, \qquad Q_n = \sum_{k=1}^{M} \omega_k e^{in\phi_k}$$

Scaling factor from 3 sub events



	A	B	C
sub evts	HF-	HF+	Tracker
M	towers	towers	tracks
ω_k	E_T	E_T	p_T

What can we expect by the HL-HLC era?

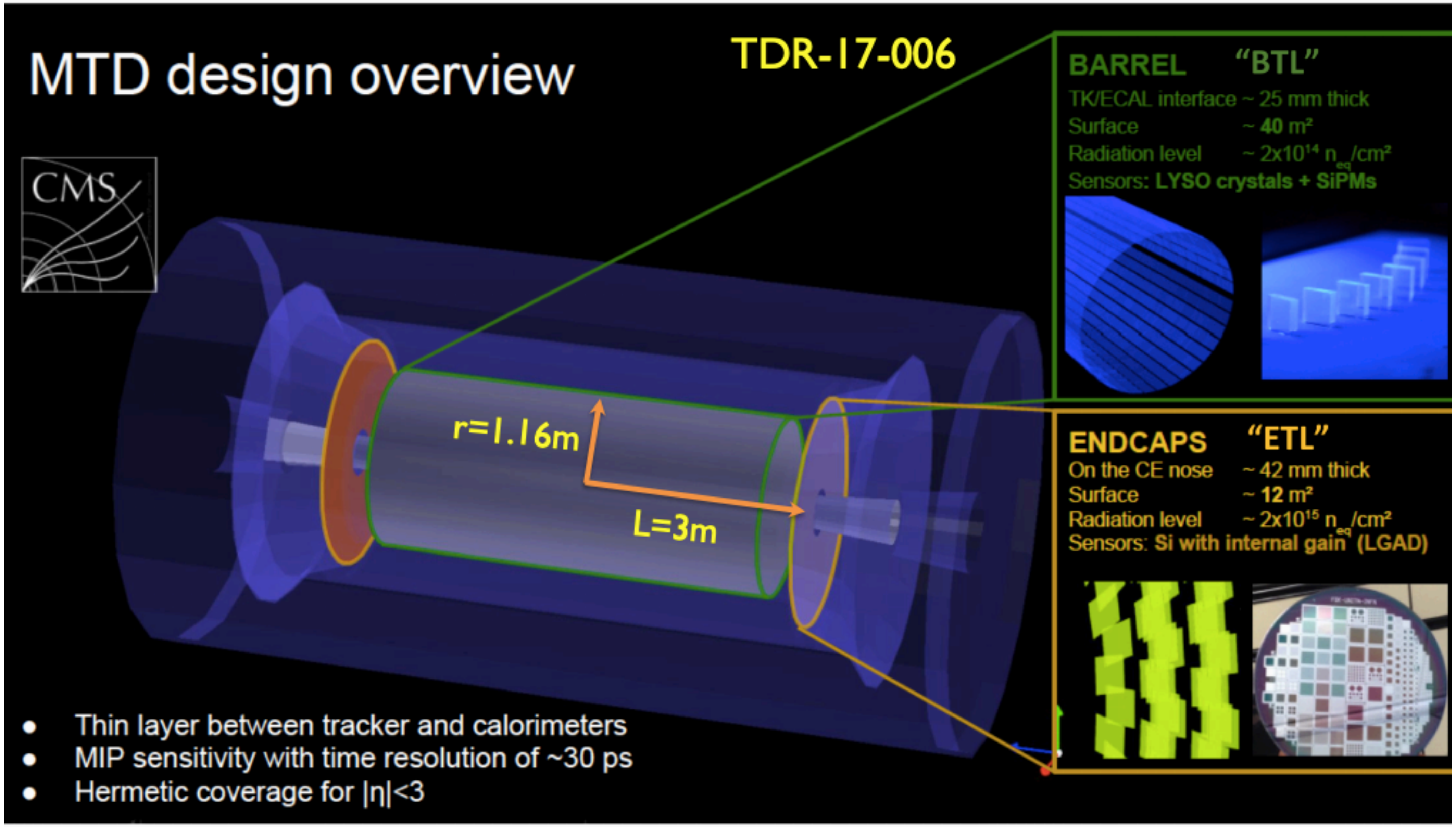
LHC and CMS schedule

LS-2	Run-3	LS-3	HL-LHC (run-4)
CMS Phase I	PbPb: 6-7/nb	CMS Phase II • Tracker $\lvert\eta\rvert<4$ • L1: 750kHz • DAQ: 60 GB/s …	PbPb: 6-7/nb
2019-2020	2021-2023	2024-2025	2026-2029
ALICE upgrade • ITS • TPC readout (50kHz)			

arXiv:1812.06772

What can we expect by the HL-HLC era?

A Mip Timing Detector at CMS



Design constraints:
- Timing resolution of 30ps
- Radiation tolerance to 4/ab
- Cost effective design over large area
- Manageable data volume and power
- Marginal impact on rest of CMS
- Integration fits within schedule

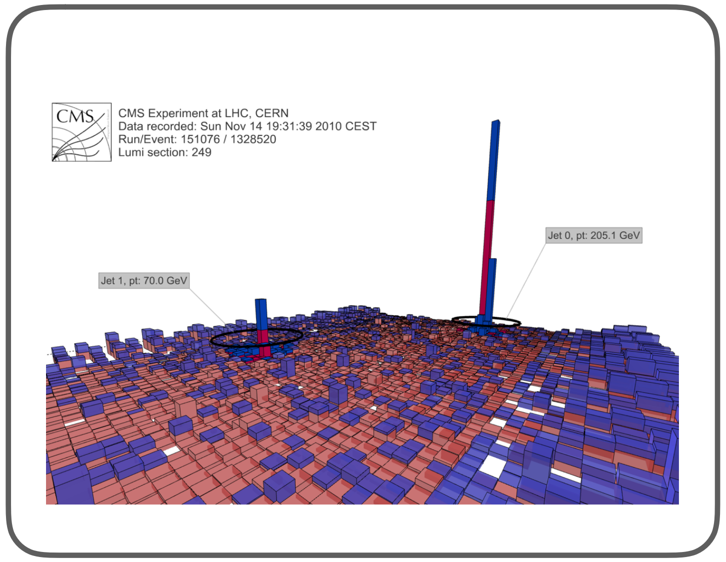
C. Neu, US CMS collaboration meeting, 2018 5

D^0 Trigger in CMS (1/2)

Hardware Level-1 Trigger

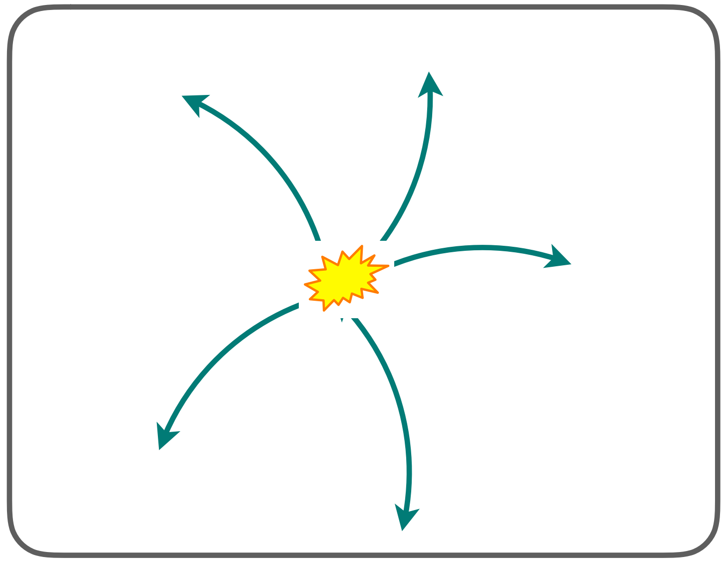
Software High-Level Trigger

L1 high-p_T jet triggers selection



- Level-1 (L1) jet algorithm with online background subtraction

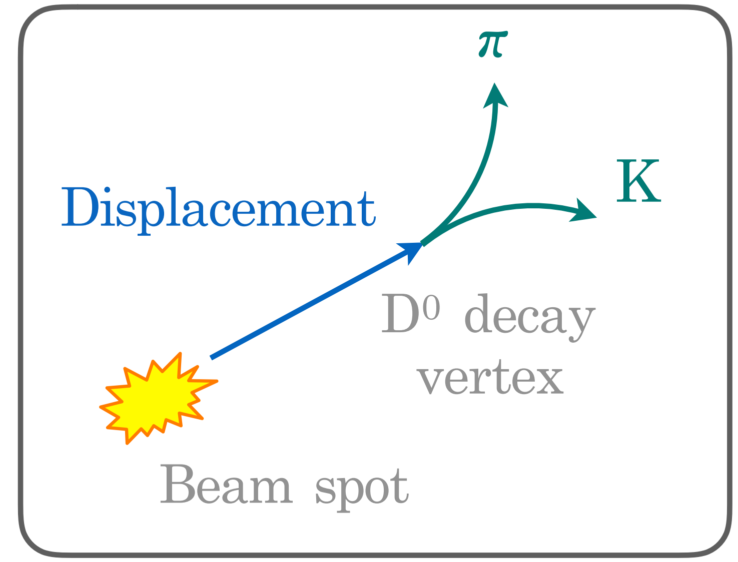
Track selection in software triggers



Track quality and p_T cut applied:

- p_T > 2 GeV for pp
- p_T > 8 GeV for PbPb

D^0 selection

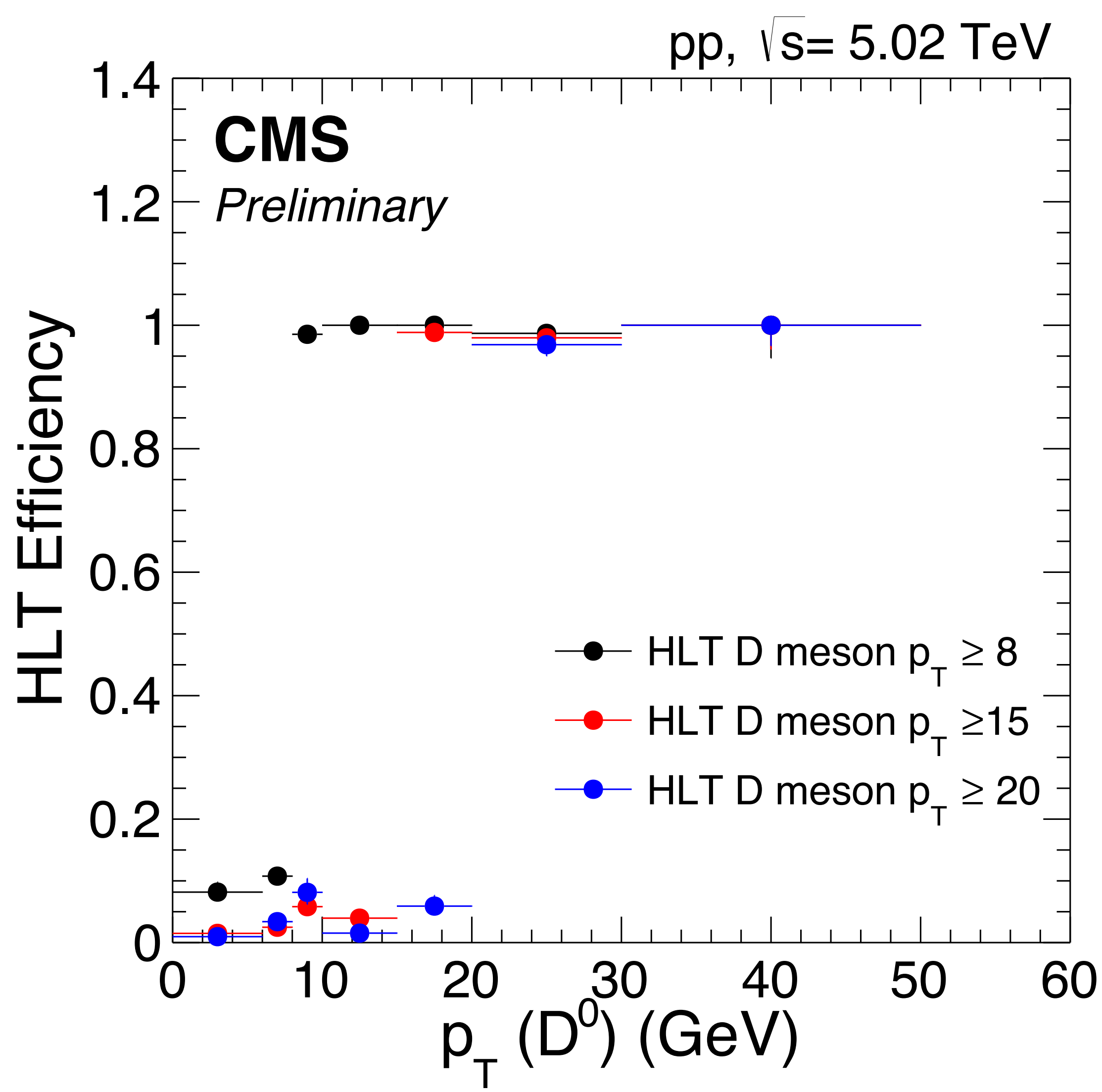


- D^0 online reconstruction
- Loose selection based on D^0 vertex displacement

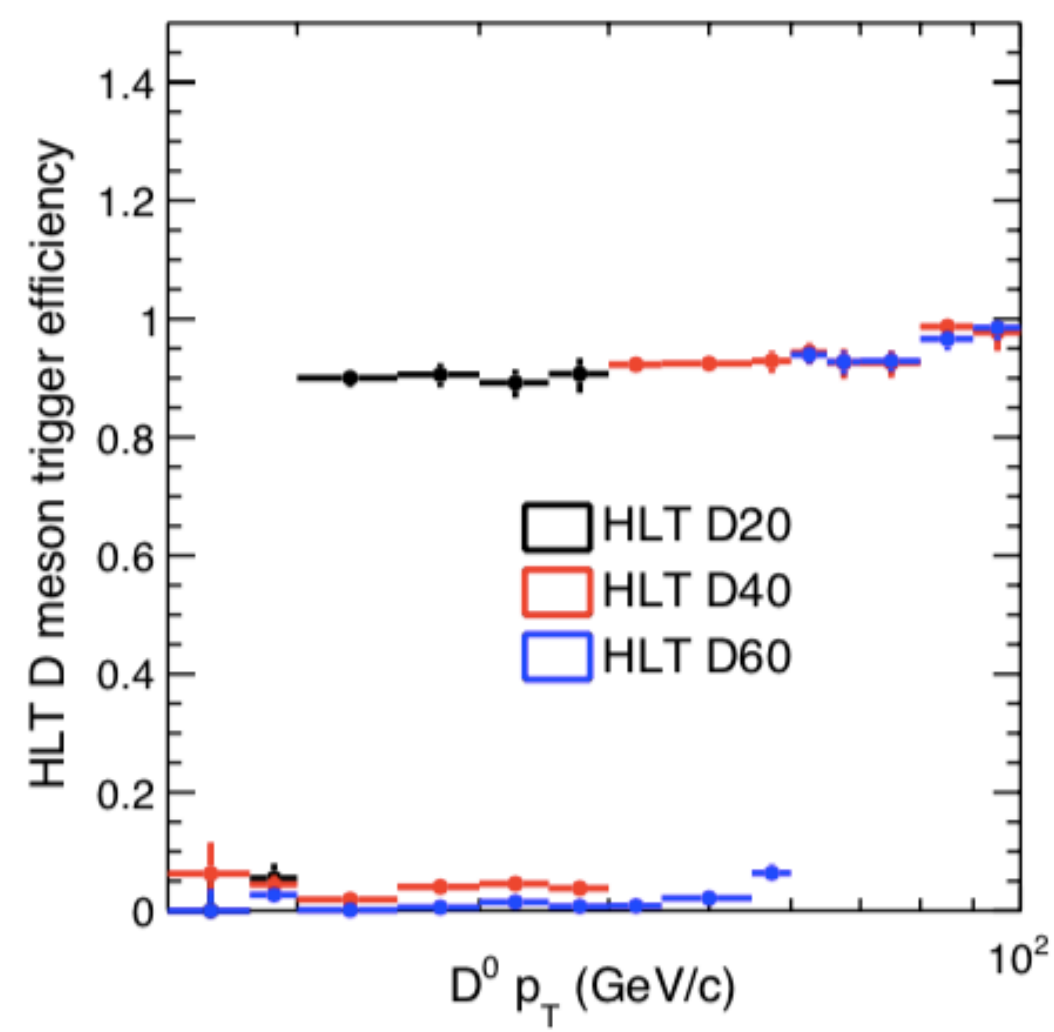
- Dedicated triggers for high-p_T D^0 in CMS

D^0 Trigger in CMS (2/2)

pp

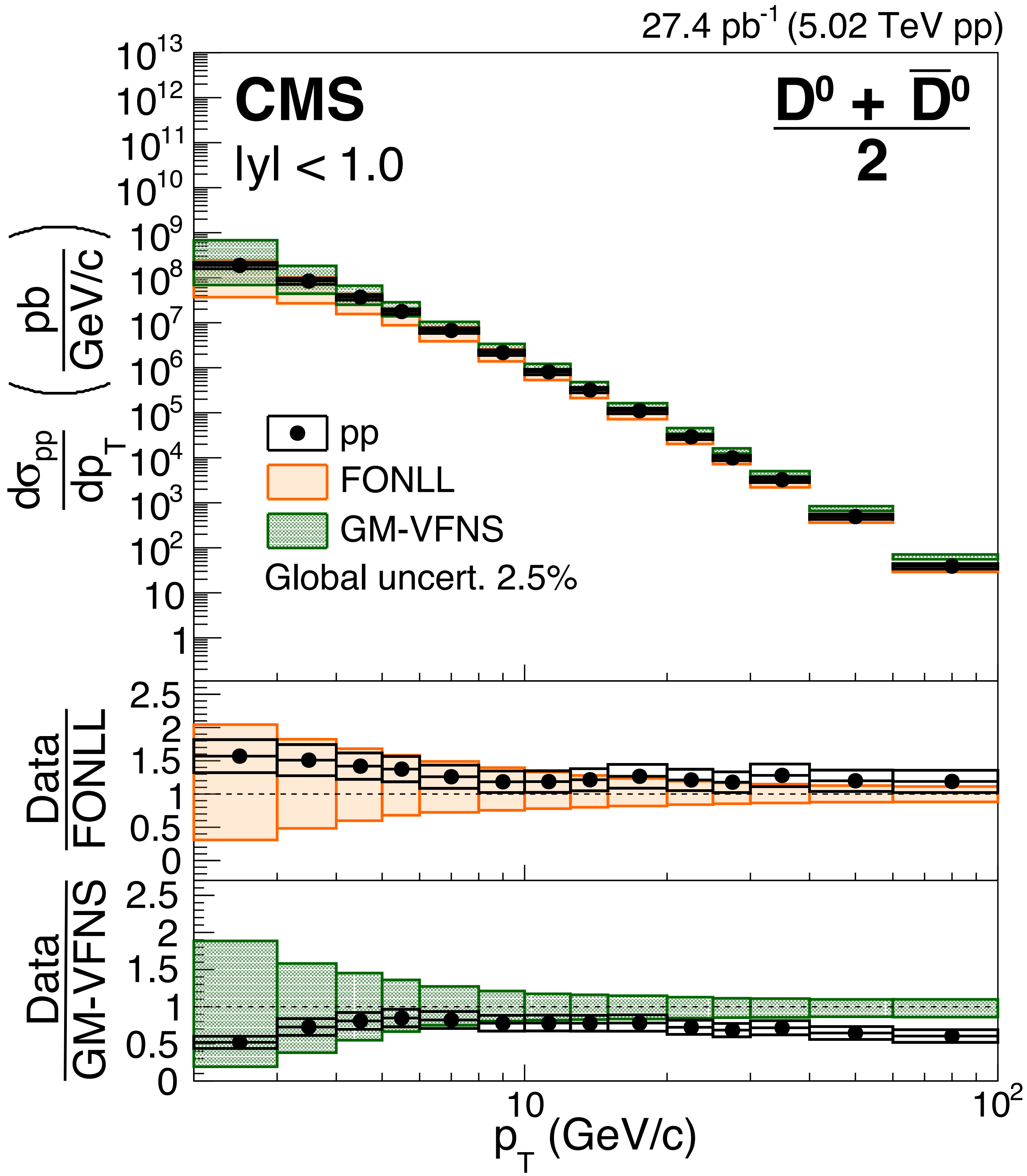


PbPb



- Dedicated triggers for high-p_T D^0 in CMS
- Almost fully efficient (> 98%) for pp, > 90% for PbPb
- MB events for p_T < 20 GeV/c, D^0 trigger for p_T > 20 GeV/c

Results - Prompt D^0 Production in pp

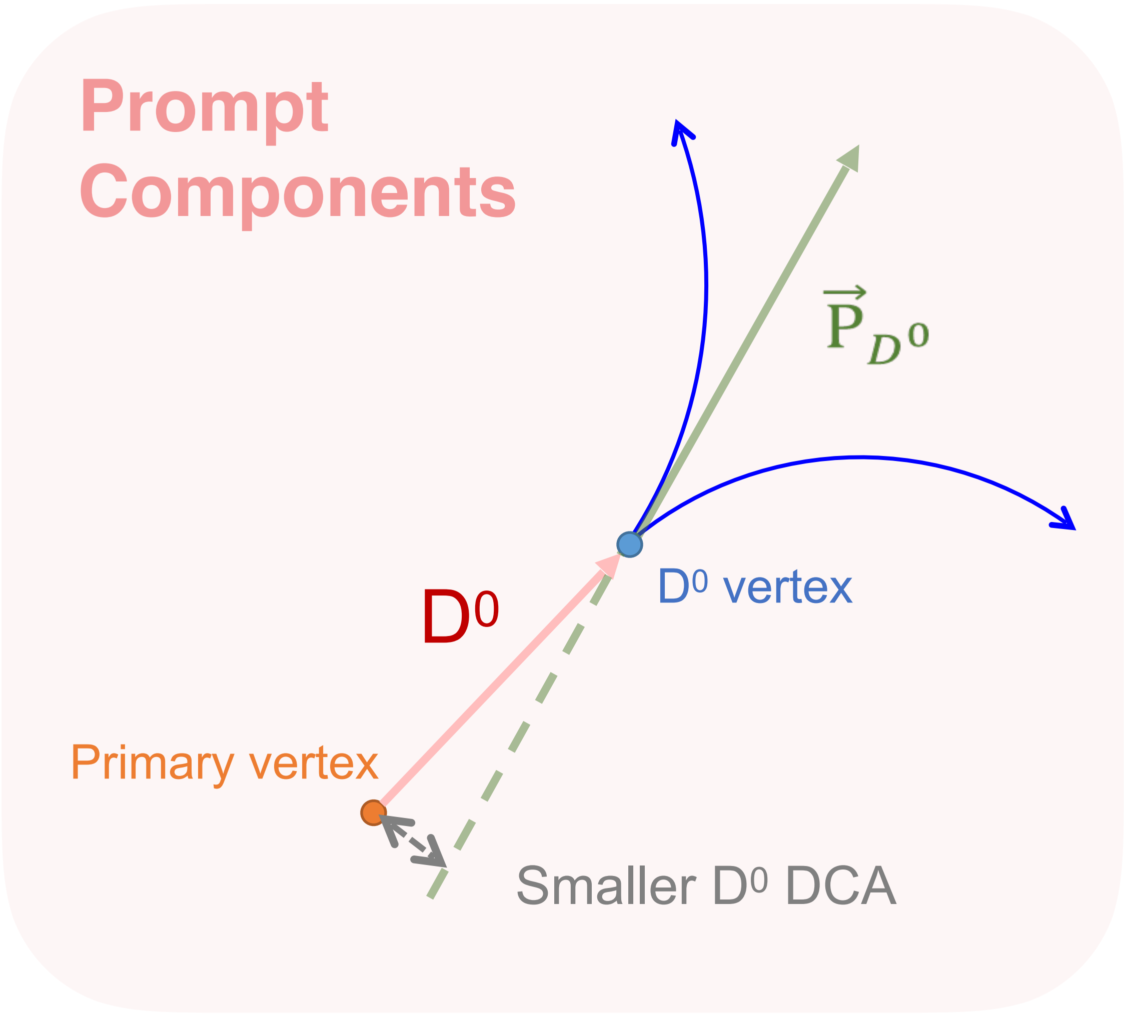


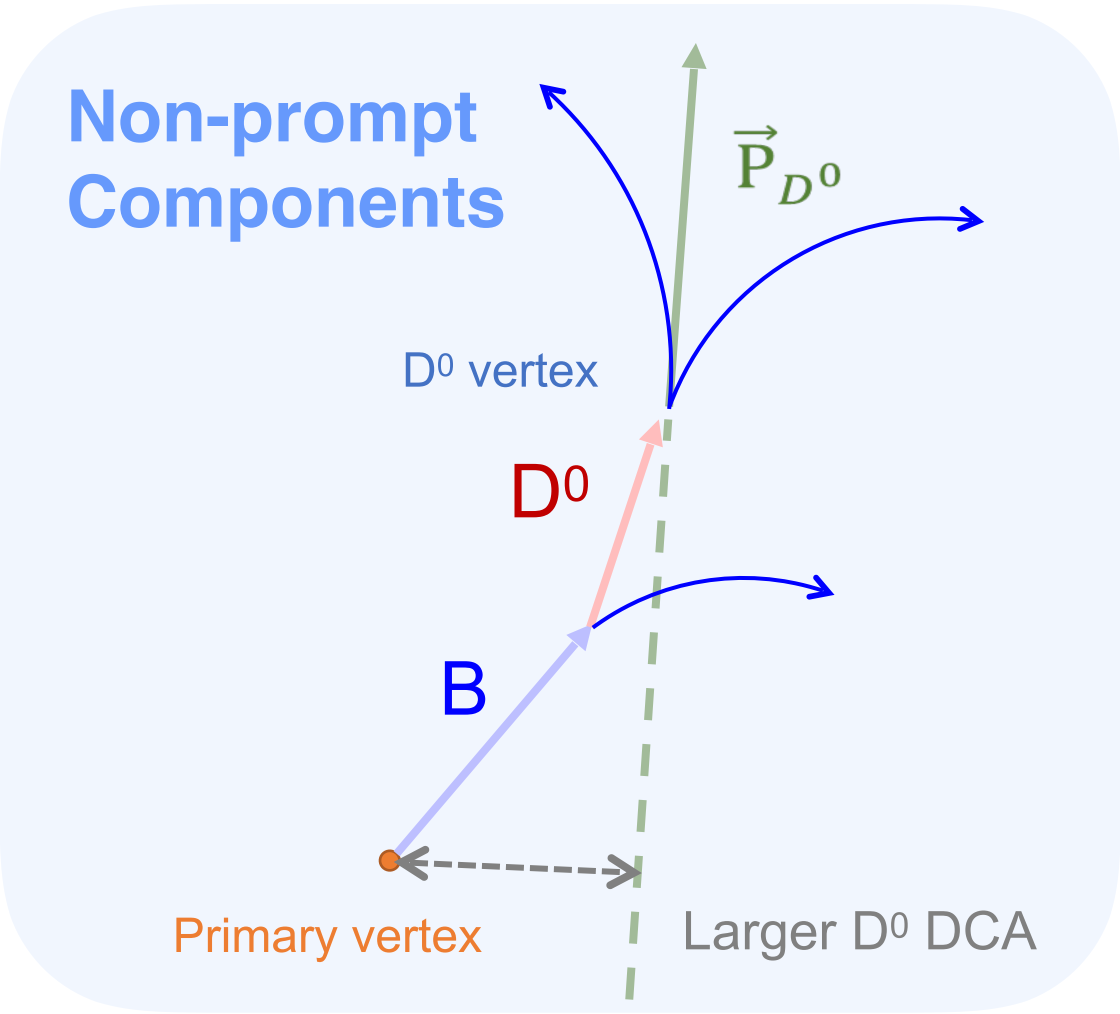
- Wide kinematic range: 2-100 GeV/c
  - ➡ First measurement of D^0 up to very high p_T 100 GeV/c
- Test on pQCD calculations
  - ➡ Consistent with the upper bound of FONLL (Fixed Order calculations with Next-to-Leading-Log resummation)
  - ➡ Consistent with the lower bound of GM-VFNS (General-Mass Variable Flavour Number Scheme)
- Reference to study hot medium effect

JHEP 05 (1998) 007
Eur. Phys. J. C 72 (2012) 2082
PLB 782 (2018) 474

b-hadron Feed-down Subtraction

- Inclusive D^0:
  - ✔ Prompt D^0: D^0 mesons coming from c-quark fragmentation
  - ✗ Non-prompt D^0: D^0 mesons from b-hadron decays
- Extract prompt fraction with data (new method!)
- Different Distance of Closest Approach *(DCA)* between prompt and non-prompt D^0





b-hadron Feed-down Subtraction

- Inclusive D^0:
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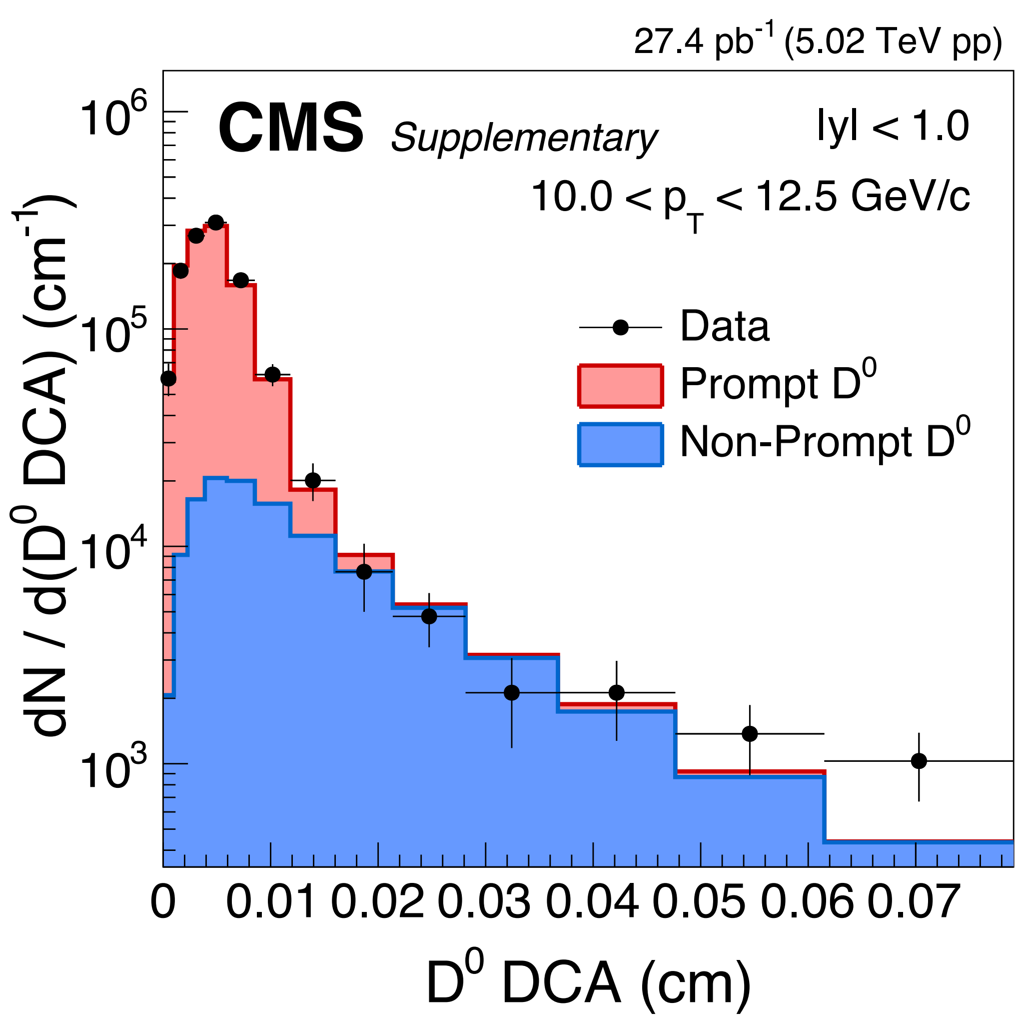
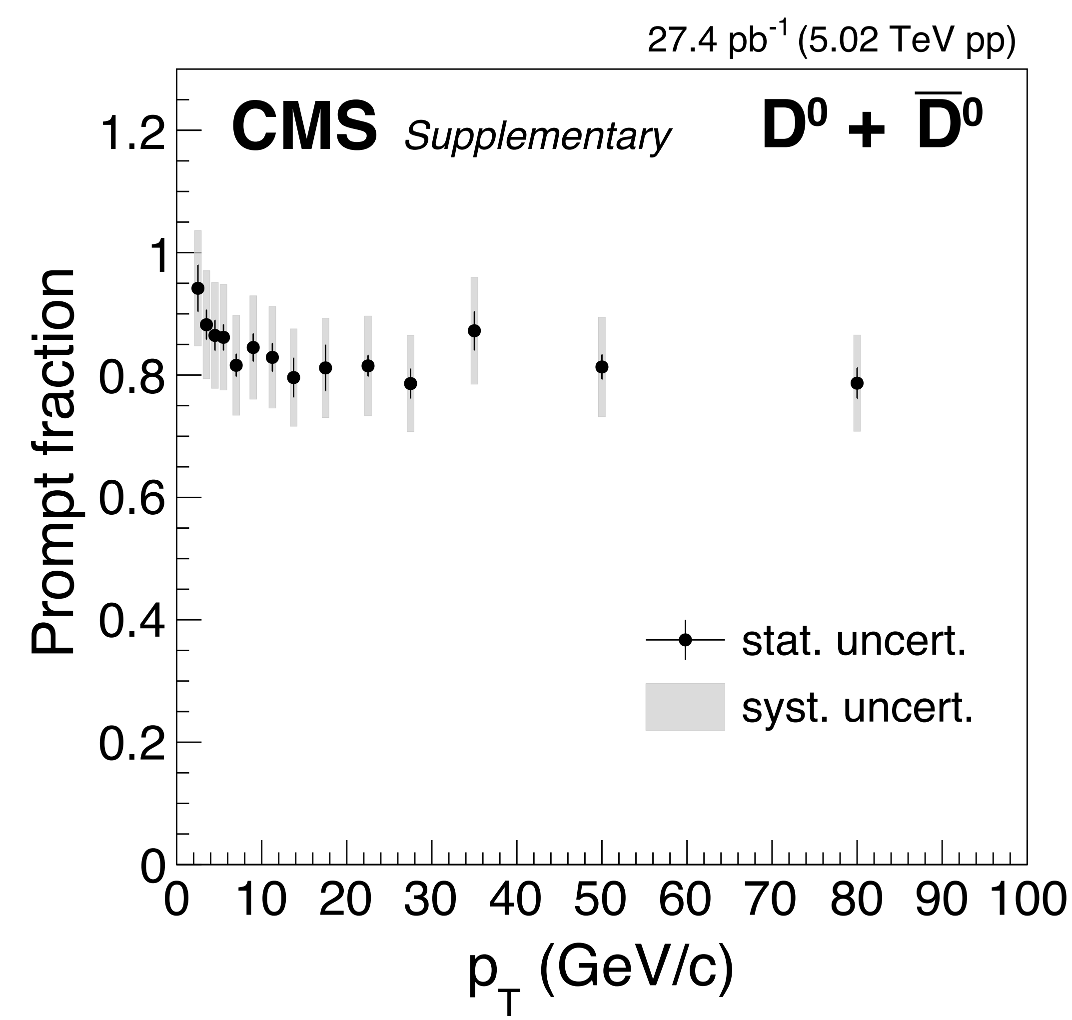
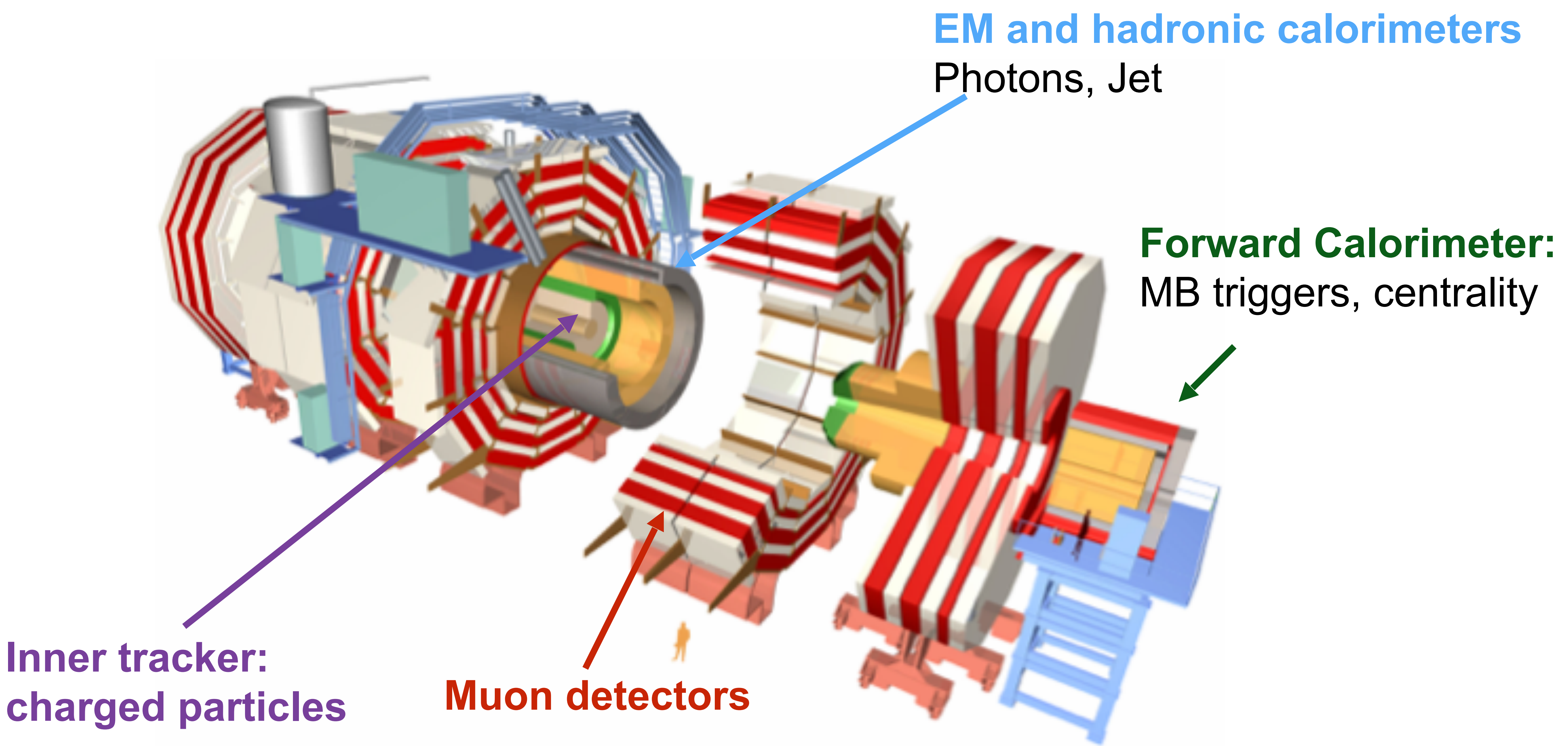
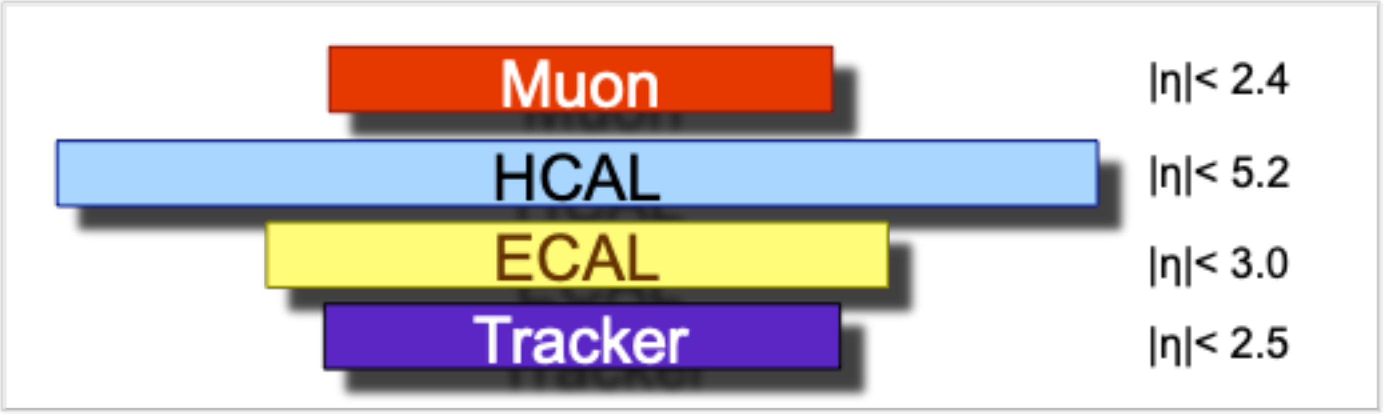
  - ✗ Non-prompt D^0: D^0 mesons from b-hadron decays
- Extract prompt fraction with data (new method!)
- Different Distance of Closest Approach *(DCA)* between prompt and non-prompt D^0
- Fit DCA distributions of signal D^0 from data with the DCA templates from simulations





CMS detector





Systematics of fprompt for v_n analysis

- Systematic uncertainties from non-prompt D^0 are evaluated in a data driven method based on:
  - v_n of D^0 with all analysis cut and w/o b_0 cut
  - Fractions of prompt D^0 with all analysis cut and w/o b_0 cut

All analysis cut: $v_{n,1}^{sig} = f_{p,1}\, v_n^{p} + (1\text{-}f_{p,1})\, v_n^{np}$

Without b_0 cut: $v_{n,2}^{sig} = f_{p,2}\, v_n^{p} + (1\text{-}f_{p,2})\, v_n^{np}$

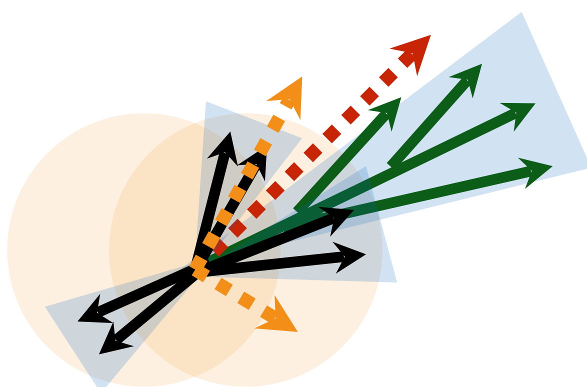
$$\Rightarrow \boxed{v_n^{p} = v_{n,1}^{sig} + \frac{1-f_{p,1}}{f_{p,1}-f_{p,2}}\left(v_{n,1}^{sig} - v_{n,2}^{sig}\right)}$$

D^0 v_n with all analysis cuts as central value

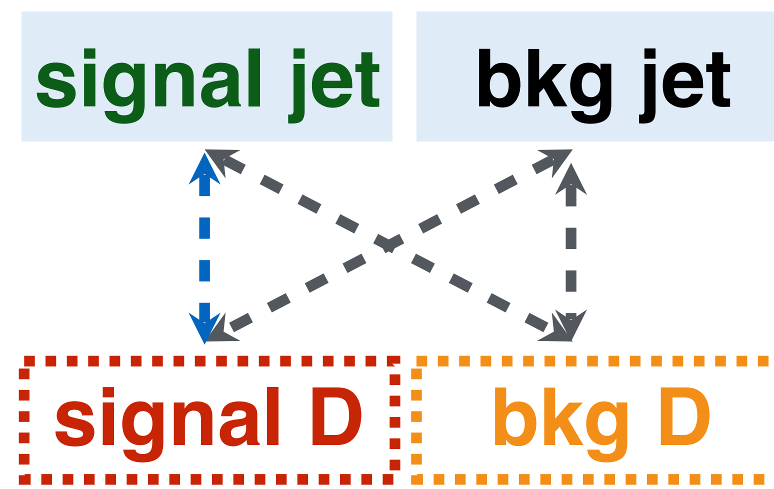
As systematics from non-prompt D^0

Event mixing technique

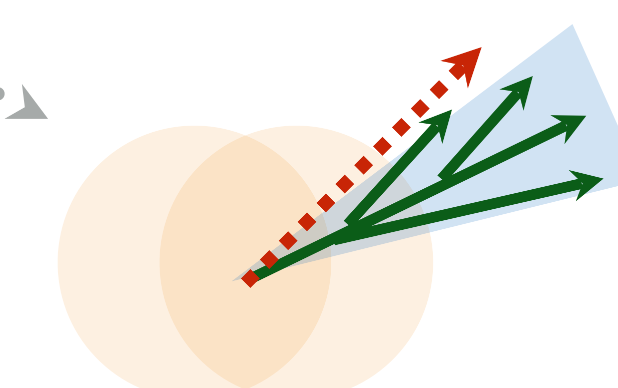
- **Signal**: jets and D^0 mesons from the same hard scattering
- **Background**: fake jets, jets and D^0 mesons in underlying events, …



before subtraction

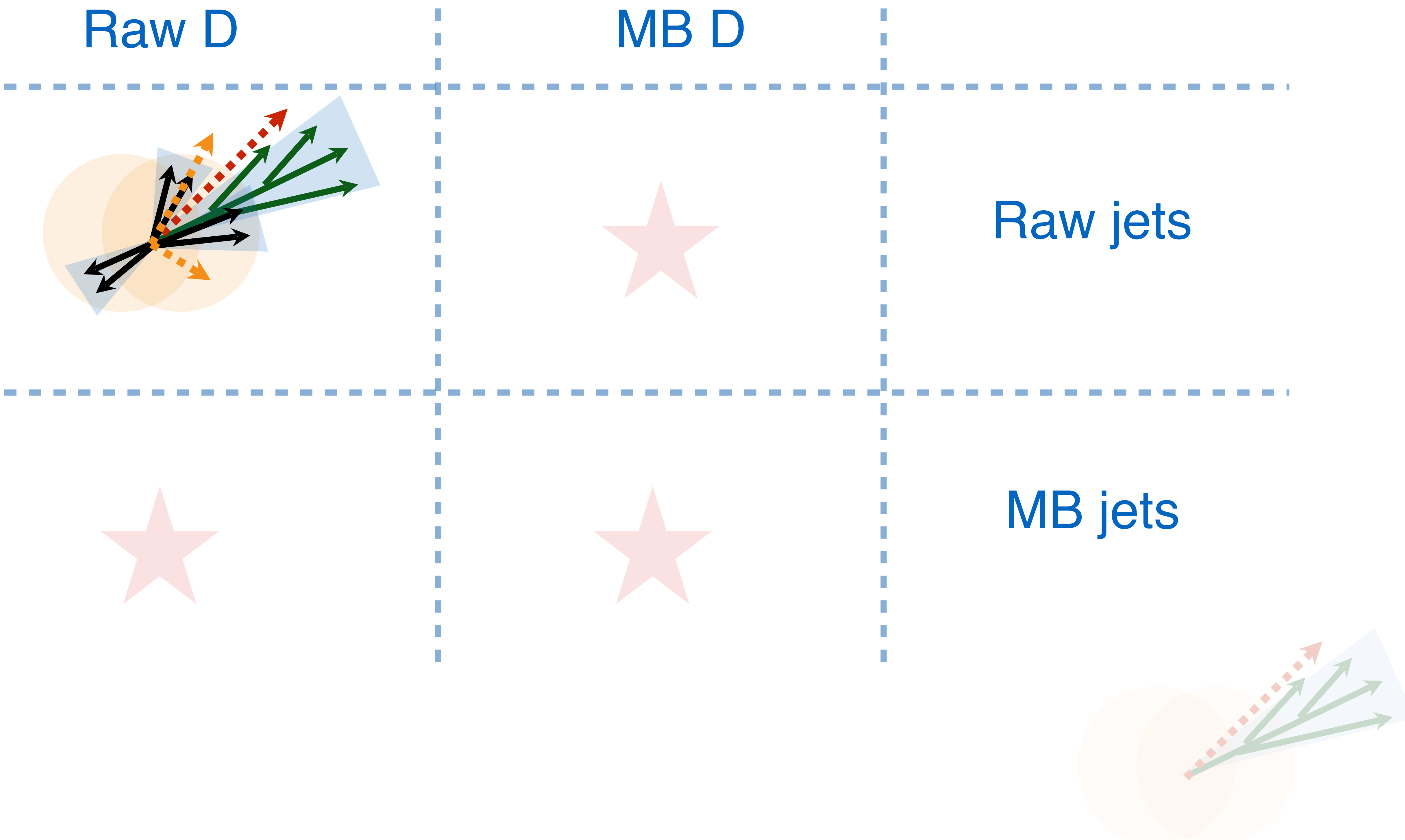


pure signal



Event mixing technique

- Correlate D^0 mesons and jets in **triggered events (raw)** and **MB events (bkg)**



Event mixing technique

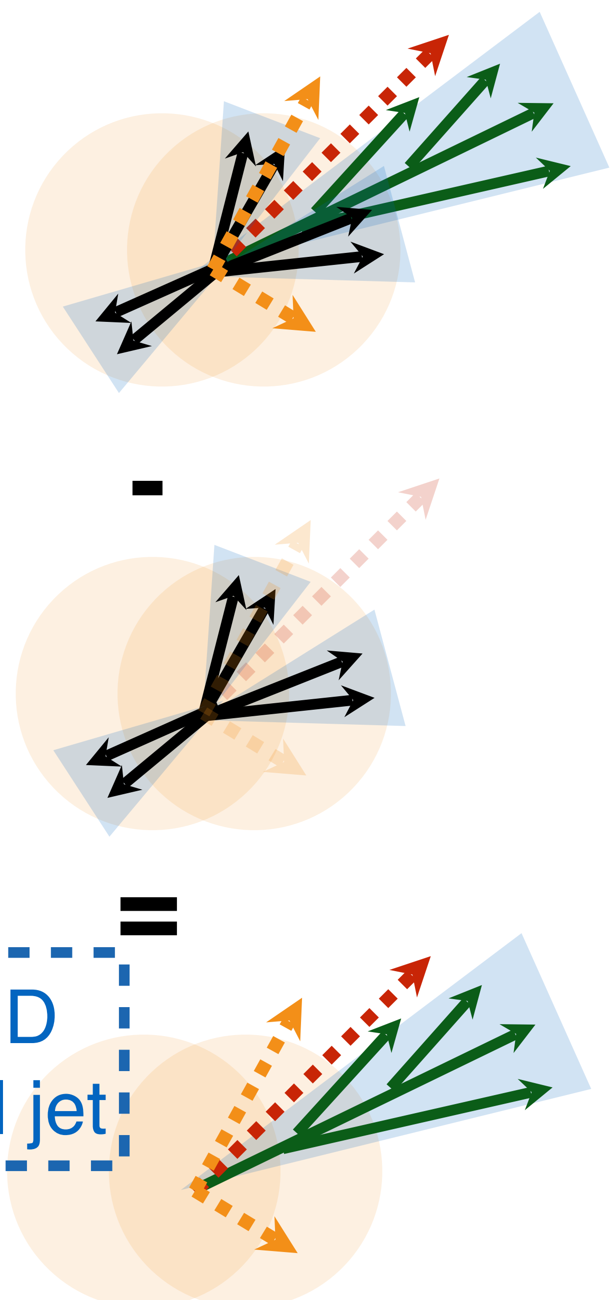
- Correlate D^0 mesons and jets in **triggered events (raw)** and **MB events (bkg)**

Raw D

MB D

Raw jets

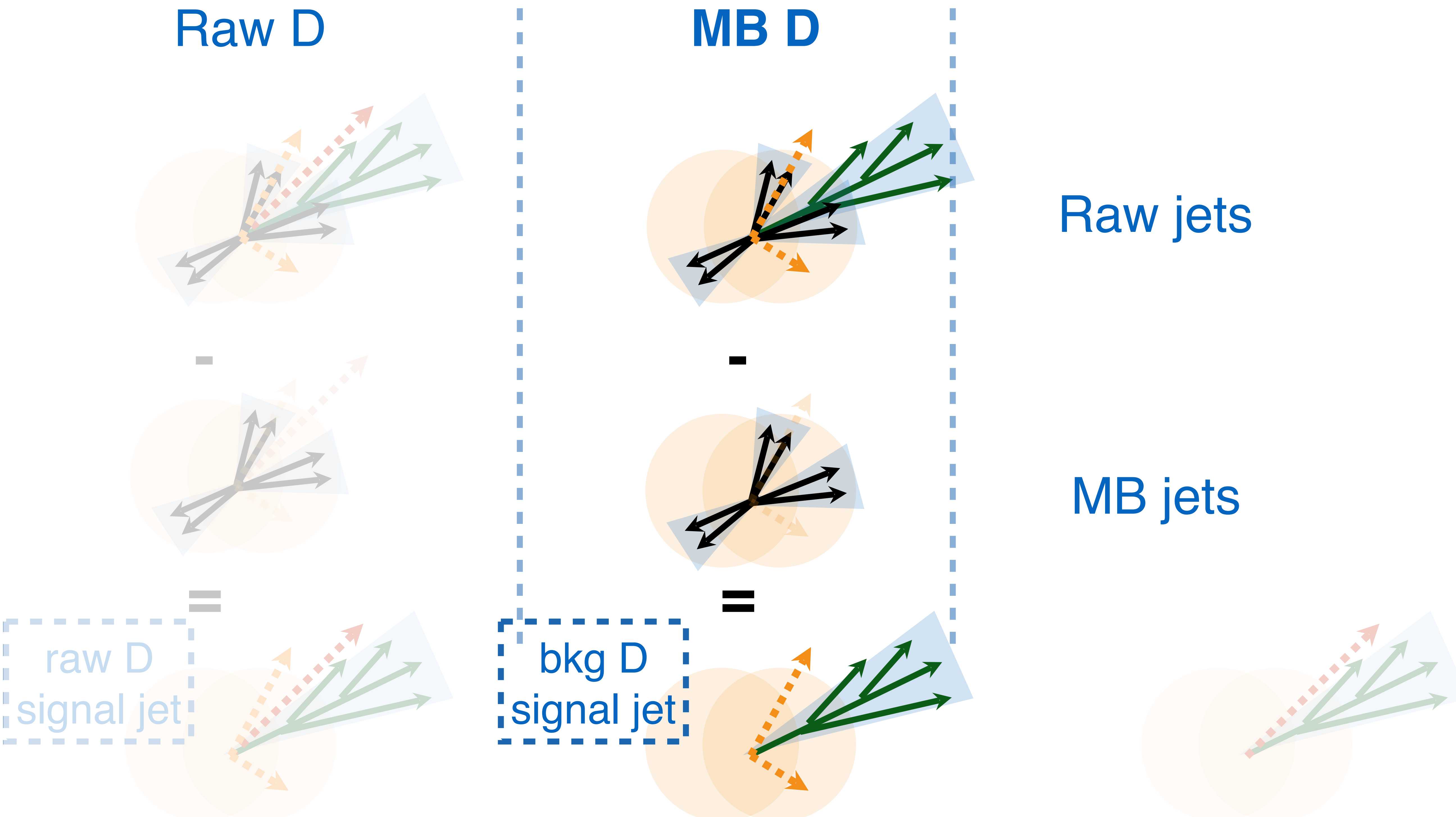
MB jets



raw D
signal jet

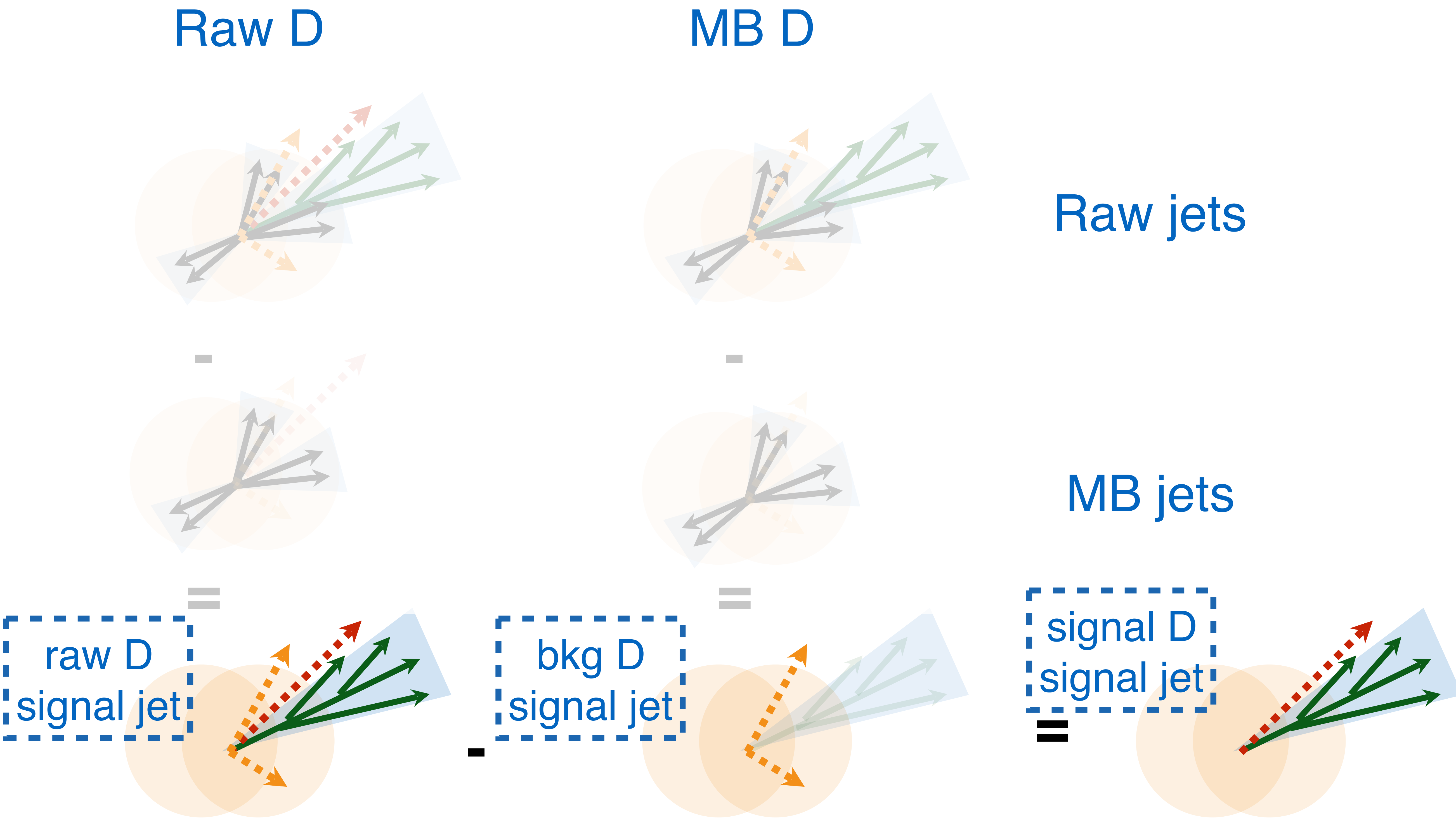
Event mixing technique

- Correlate D⁰ mesons and jets in **triggered events (raw)** and **MB events (bkg)**



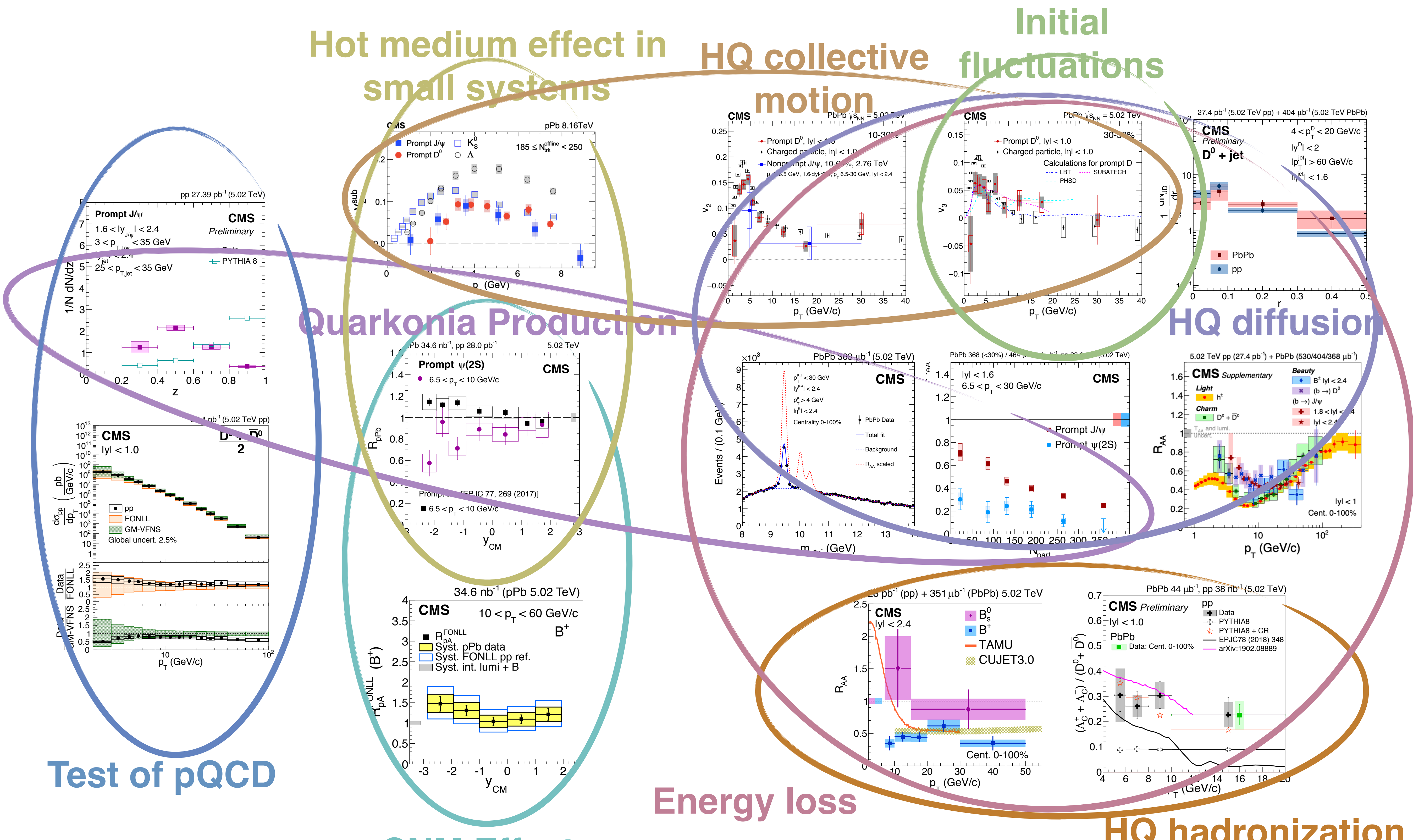
Event mixing technique

- Correlate D^0 mesons and jets in **triggered events (raw)** and **MB events (bkg)**



Summary

Great insights into heavy quark behavior and QGP properties from CMS!



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