Recent Measurements of D^0 Mesons Flow Using the CMS Detector

CESAR A. BERNARDES

IF-UFRGS, SPRACE

Introduction

Charm quarks produced in primordial stages of collision (~0.1 fm/c)

m_{charm} >> typical medium temperatures → experience the full evolution of any medium

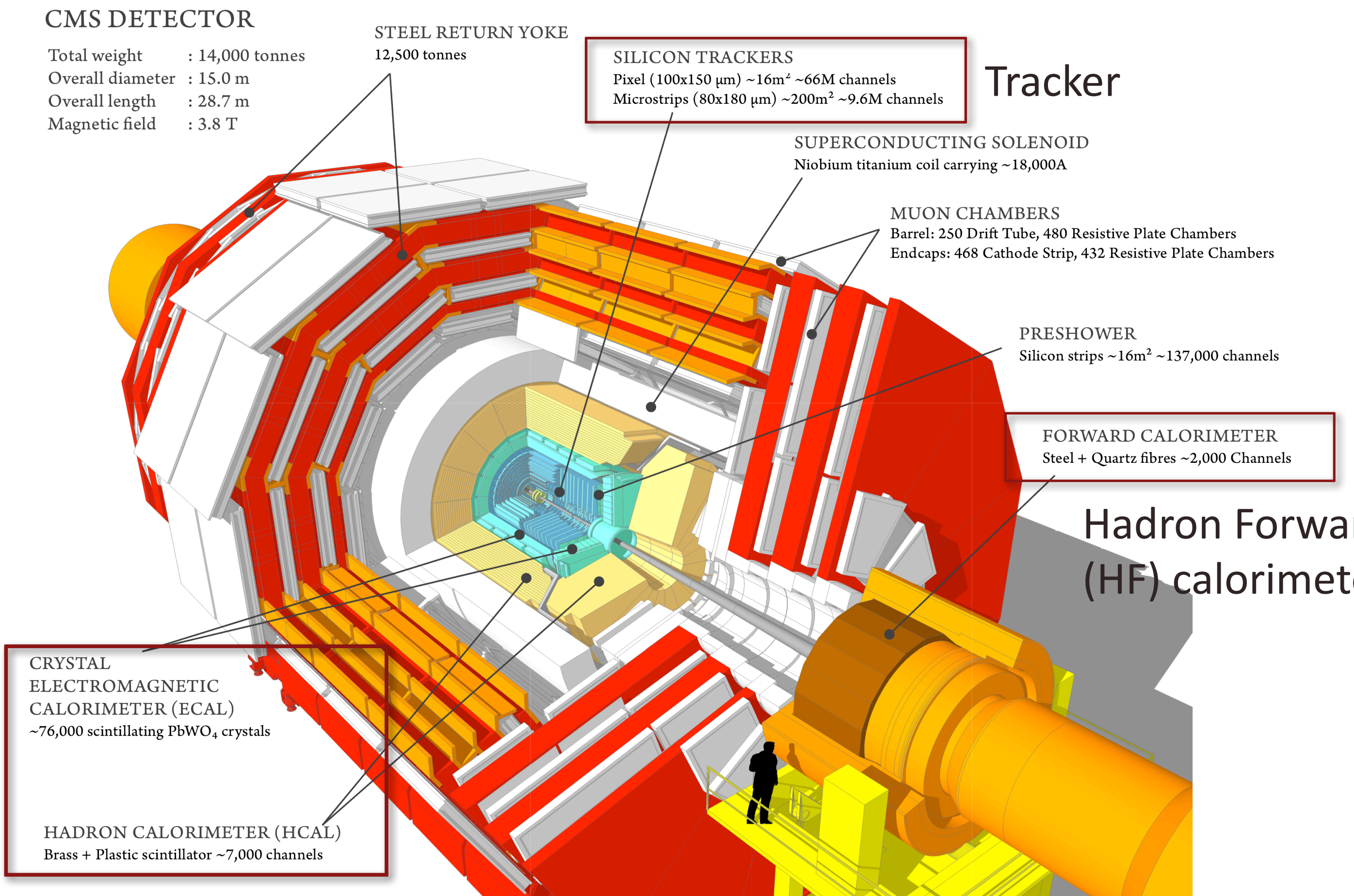
Very good probe of initial state effects in both "Large" (PbPb) and "Small" (pp, pPb) collision systems

Small systems: origin of observed collective effects?

Large systems

- Understanding of energy loss and coalescence mechanisms
- EM fields effects at initial stages?
  - Δv_n between positive & negative electric charges

The CMS Detector



Tracker

Hadron Forward (HF) calorimeters

ECAL/HCAL

Lead-lead (PbPb) Collisions

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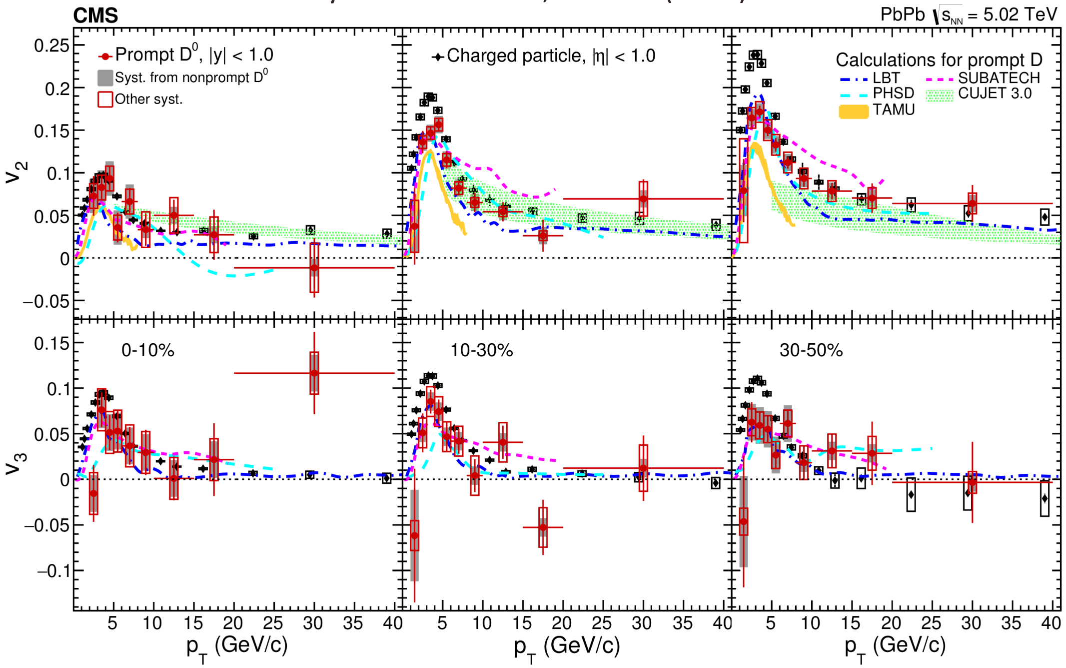
Previous Measurements by CMS: 2015 Data

Prompt D^0 v_2 and v_3: comparison with charged hadrons & theory

Phys. Rev. Lett. **120**, 202301 (2018)



- v_2 is centrality dependent
- v_3 small centrality dependence
- v_2 and v_3 similar p_T dependence as charged hadrons
- Suggests charm quarks take part of collective motion
- Measurements for $|y| < 1$, $1 < p_T < 40$ GeV

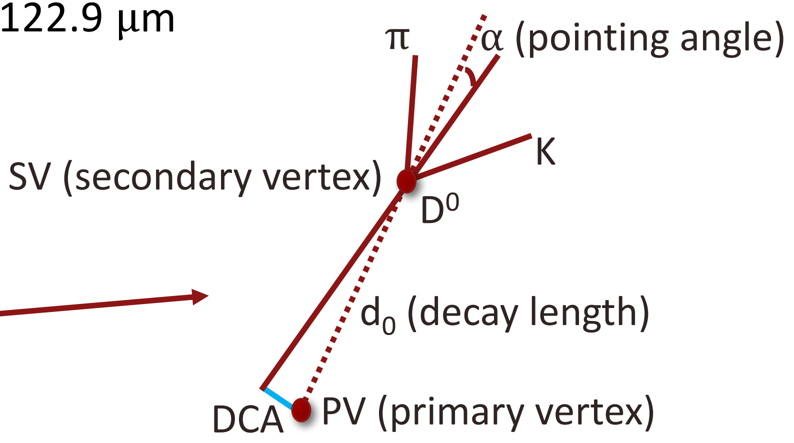
D^0 Reconstruction and Selection: 2018 Data

Minimum Bias events from PbPb collisions at 5.02 TeV

$D^0(\bar{u}c) \rightarrow K\pi$, BR = 3.88 $\pm$ 0.05 %, $c\tau(D^0)$ = 122.9 μm

D^0 Reconstruction

- Pairing oppositely charged tracks (no PID)
- Secondary vertex reconstruction



Prompt D^0 candidate selection

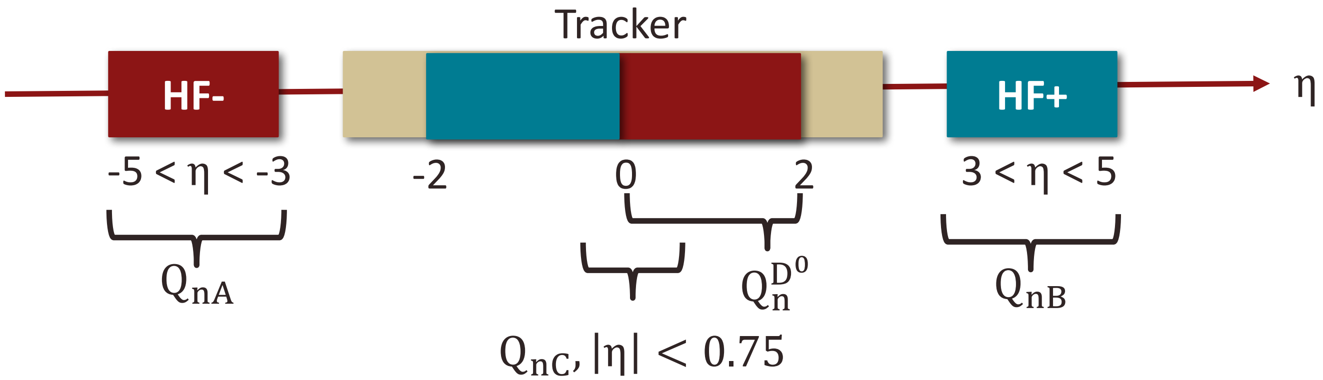
- MVA Boosted Decision Tree (BDT)
  - D^0 variables
    - $d_0/\sigma(d_0)$, α, SV probability
  - Tracks ($K\pi$)
    - Distance of closest approach significance, error on p_T, number of hits

Nonprompt D^0 (from B hadron decay) contamination (as systematic uncertainty)

- Estimate contribution using DCA variable (nonprompt D^0 enriched region for DCA > 0.012 cm)

Flow Measurement: Scalar Product Method

$v_2, v_3, \Delta v_2(D^0 - \overline{D^0})$ as functions of centrality, rapidity and p_T



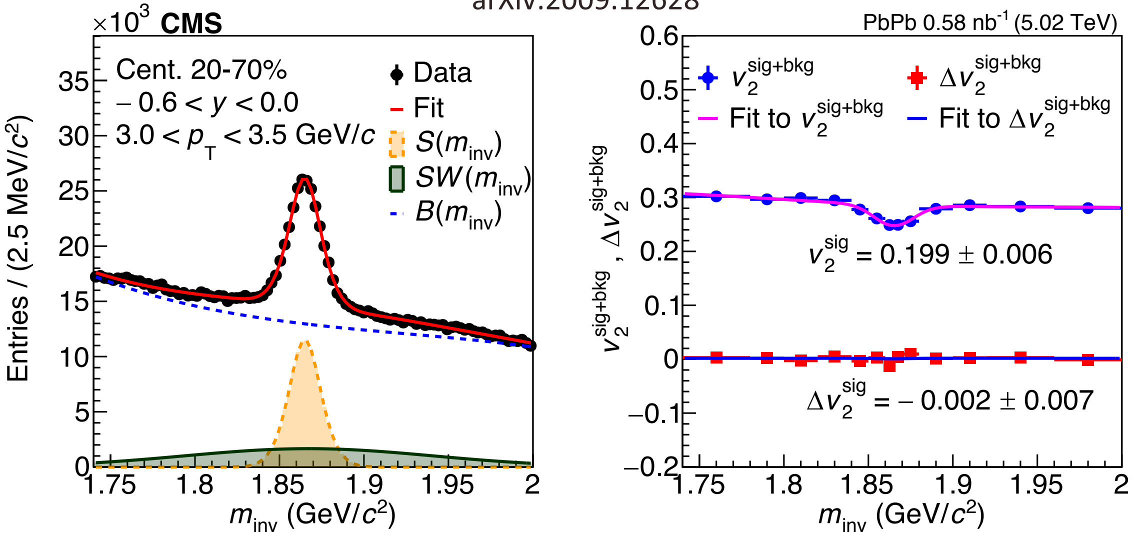
- $Q_n = \sum_j w_j e^{in\phi_j}$ (w_j = tower E_T for HF, w_j = track p_T for tracker, w_j = 1 for $D^0, \overline{D^0}$)

- $v_n\{SP\} = \dfrac{\left\langle Q_n^{D^0/\overline{D^0}} Q_{nA}^* \right\rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$ $\qquad \Delta v_n\{SP\} = \dfrac{\left\langle Q_n^{D^0} Q_{nA}^* \right\rangle - \left\langle Q_n^{\overline{D^0}} Q_{nA}^* \right\rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$ Average over all events

Signal Extraction: Simultaneous Fit on Mass

Simultaneous fit on mass distribution and v_n (Δv_n) versus mass

arXiv:2009.12628



- Mass fit: background (3rd order polynomial), signal (double Gaussian), swap (single Gaussian)
- v_n background (linear function), Δv_n (background is canceled)

Flow Coefficients (v_2 & v_3) as Functions of p_T

Mid-rapidity Region (|y|<1)

Smaller uncertainties compared to 2015 data

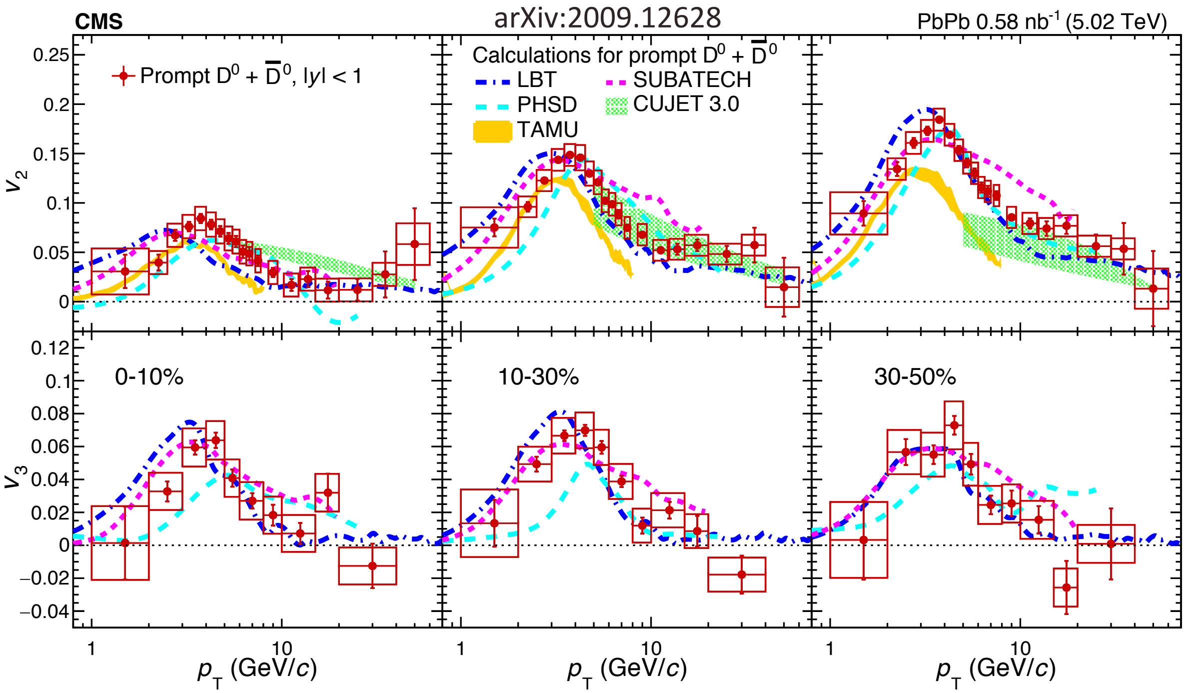
- ❑ Better constraint on theoretical models

v_2 : considerable dependence on centrality

v_3 : small dependence on centrality

Theory

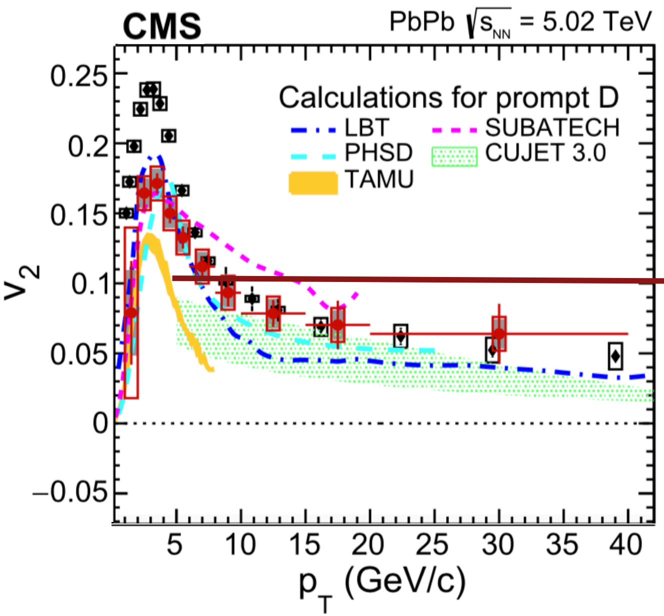
- ❑ Resonable qualitative description
- ❑ Further tunning needed for better quantitative description



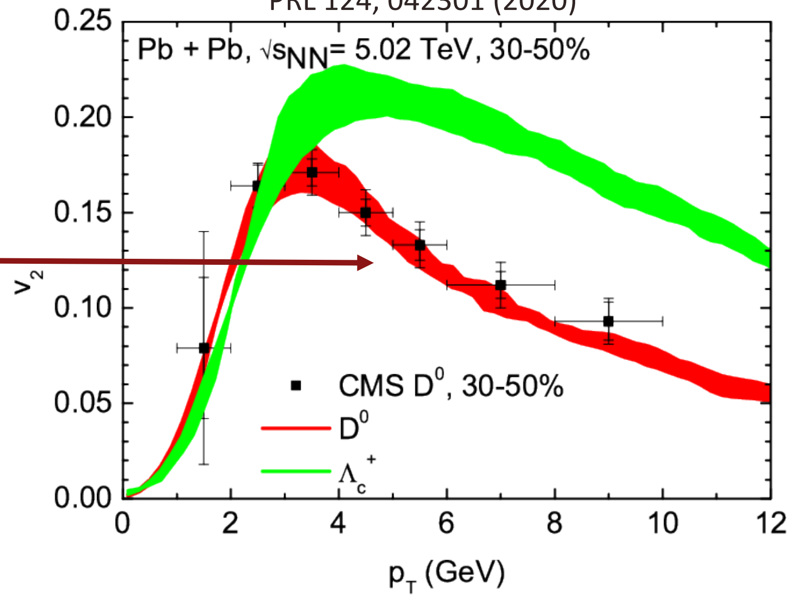
New Theoretical Developments

Improvements in TAMU model

- Add event-by-event space-momentum correlations (SMCs) between charm quarks and the high-flow partons in the QGP medium



PRL 124, 042301 (2020)



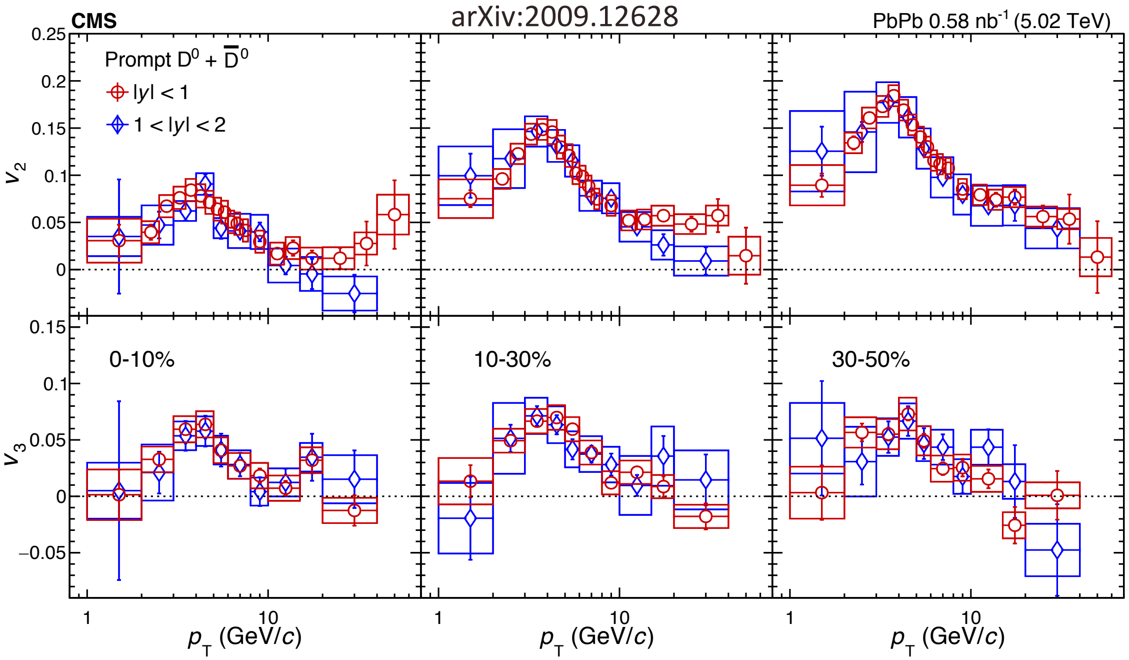
v_2 & v_3 as Functions of p_T (|y|<1 vs 1<|y|<2)

First time: forward region (1<|y|<2)

Overall similar behavior

- Small deviation at high-p_T
- Similar features as in charged hadrons

Important information for 3D hydrodynamic medium description



v_2 & v_3 as Function of Centrality and Rapidity

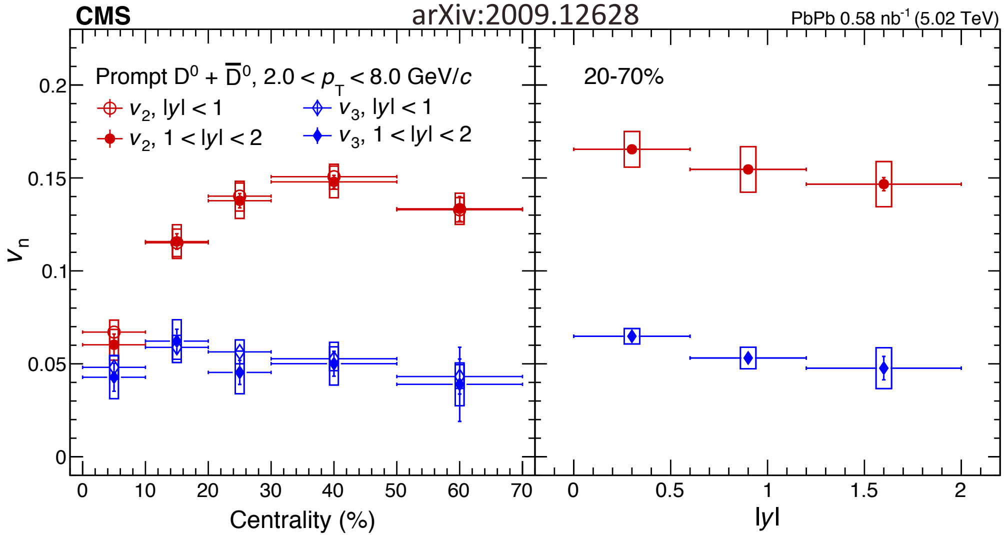
Centrality bins

- Mid-rapidity & forward region: similar trends
- Clear dependence of v_2 as function of centrality
- v_3 is almost constant with centrality
- v_n trends understood in terms of collision geometry

Rapidity bins

- Weak dependence observed
- Slight tendency to lower values at larger rapidities

arXiv:2009.12628

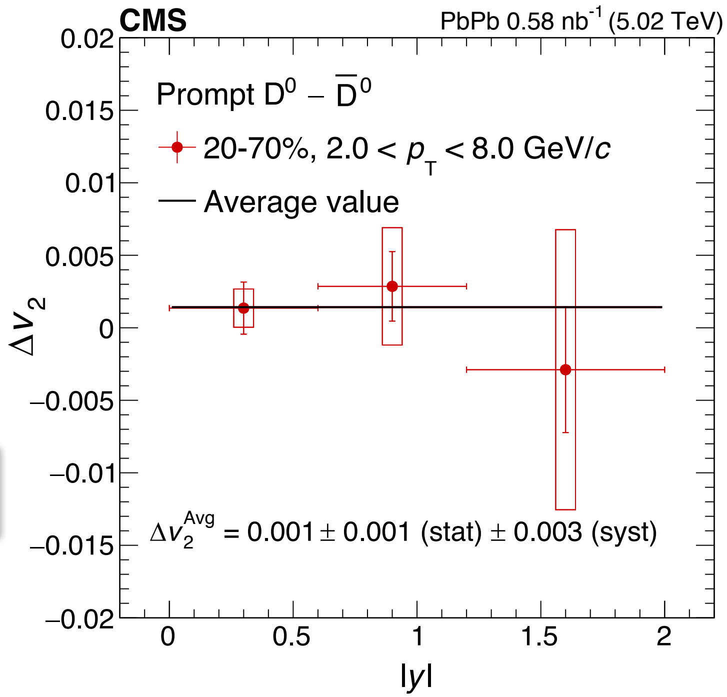


$\Delta v_2(D^0 - \overline{D^0})$ as Function of Rapidity

Electric field can generate non-zero Δv_2

- Currently, no theoretical predictions for D^0 mesons
  - Predictions for charged hadrons at LHC energies: $|\Delta v_2| \sim 0.001$ [Phys. Rev. C **98**, 055201 (2018)]
  - Expected bigger values for D^0 [Phys. Rev. C **98**, 055201 (2018)]

arXiv:2009.12628



Average value extracted with a fit to data

- $\Delta v_2^{\text{Fit}} = 0.001 \pm 0.001\ (\text{stat}) \pm 0.003\ (\text{syst})$

Comparable to the values for charged hadrons

- Constrain medium properties: electric conductivity

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Proton-proton (pp) & proton-lead (pPb) Collisions

V_2 Signal Extraction

D^0 mesons selected using BDT

- Similar to PbPb

Also considers $D^0 \rightarrow KK, \pi\pi$

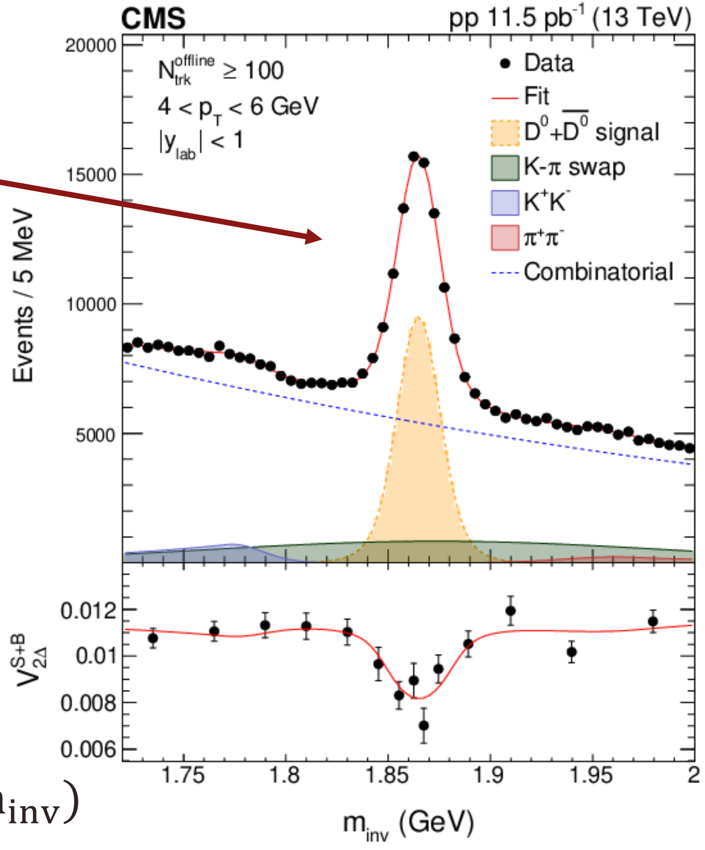
V_2 extracted from 2-particle correlations

$$\frac{1}{N_{D^0}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1 + \sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

Signal fraction $[\alpha(m_{inv})]$ from mass fit

$$V_{2\Delta}^{S+B}(m_{inv}) = \alpha(m_{inv})V_{2\Delta}^{S} + [1-\alpha(m_{inv})]V_{2\Delta}^{B}(m_{inv})$$

arXiv:2009.07065



Prompt D^0 v_2 in pp@13 TeV

After non-flow subtraction

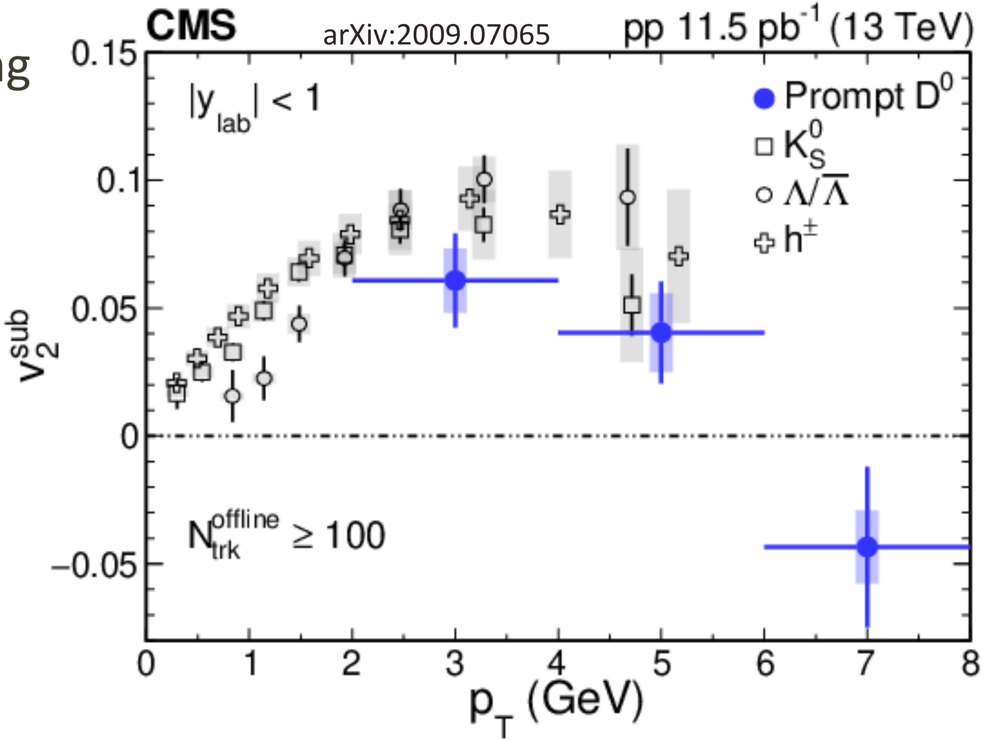
- Single particle v_2 from $V^S_{2\Delta}$ using charged particles as reference ($0.3 < p_T < 3.0$ GeV/c)

$$v_n(\mathrm{D}^0) = V_{n\Delta}(\mathrm{D}^0, \mathrm{ref}) \Big/ \sqrt{V_{n\Delta}(\mathrm{ref}, \mathrm{ref})}$$

Prompt D^0 v_2 slightly below strange particles

- Similarly to pPb

v_2 compatible with zero at high-p_T



Multiplicity Dependence

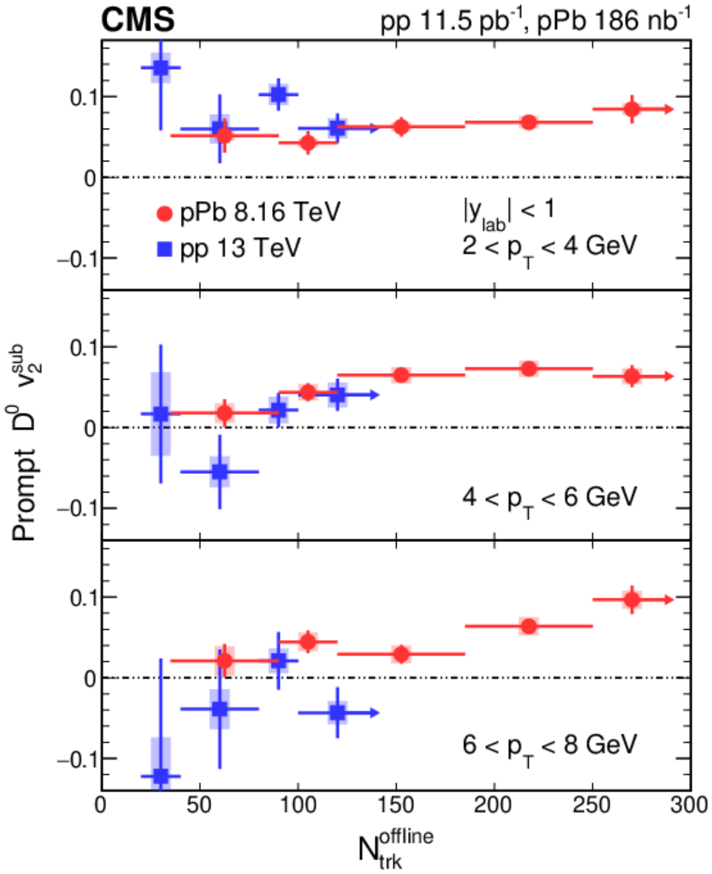
First time: D^0 v_2 as function of N_{trk} in pp and pPb collisions

Within uncertainties, no clear trends for v_2 Vs N_{trk} in pp

Compatible results of pp and pPb for multiplicities around 100

Significant non-zero v_2 values down to multiplicity equal to 50 in pPb

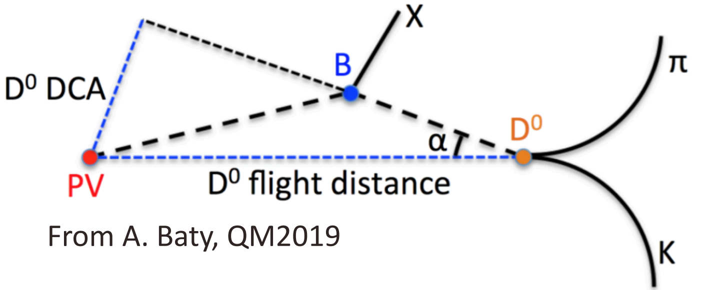
arXiv:2009.07065



Nonprompt (NP) D^0 mesons in pPb collisions

Nonprompt D^0 mesons mostly from B hadrons decay

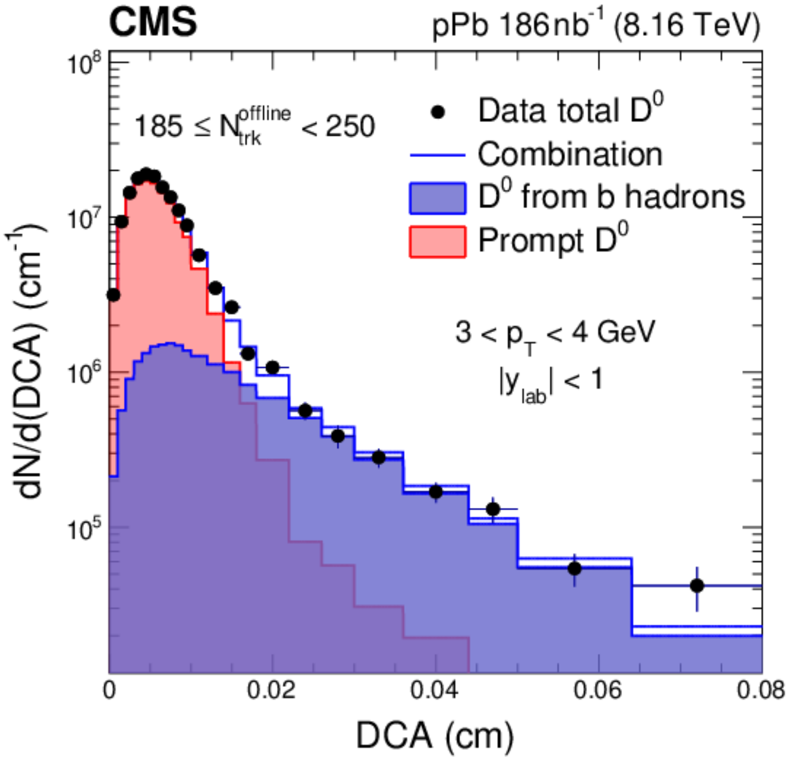
- Distinguish prompt vs nonprompt D^0 mesons by using DCA variable



From A. Baty, QM2019

- Template fits using Monte Carlo simulations to extract nonprompt D^0 fractions

arXiv:2009.07065

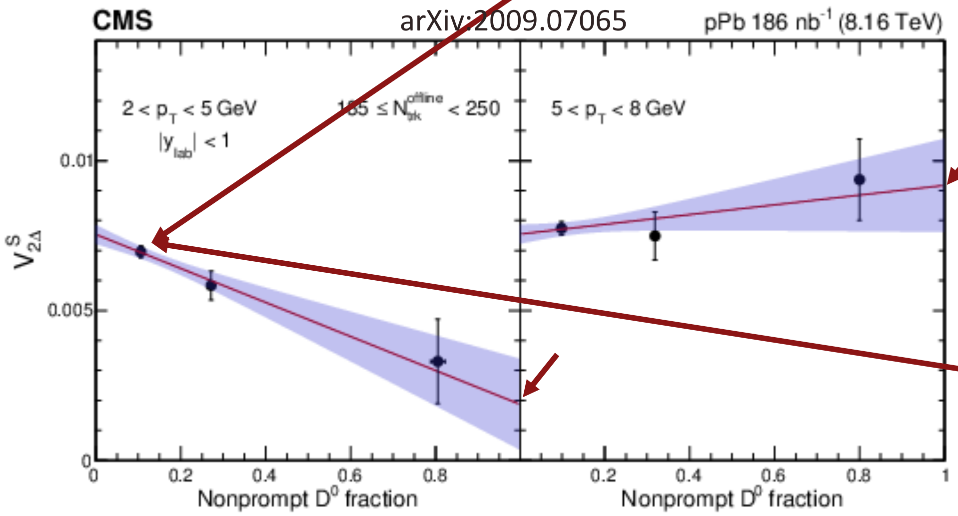


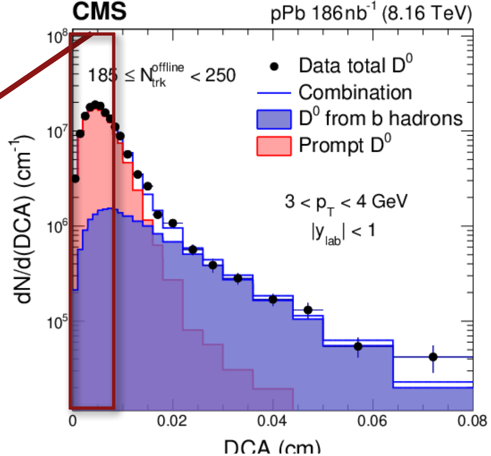
NP D^0: V_2 signal extraction

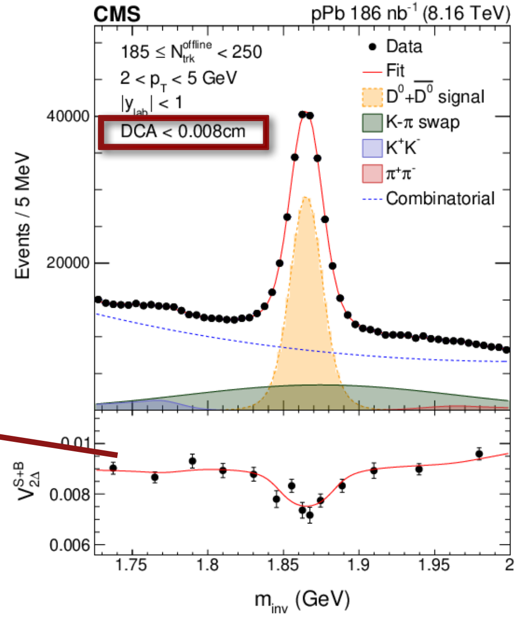
Measure $V_{2\Delta}^{S}$ for each DCA region
(different nonprompt fractions)

Linear fit

- Nonprompt D^0 V_2 is the extrapolation to “fraction=1”







Nonprompt D^0 meson v_2

Subtract non-flow effects

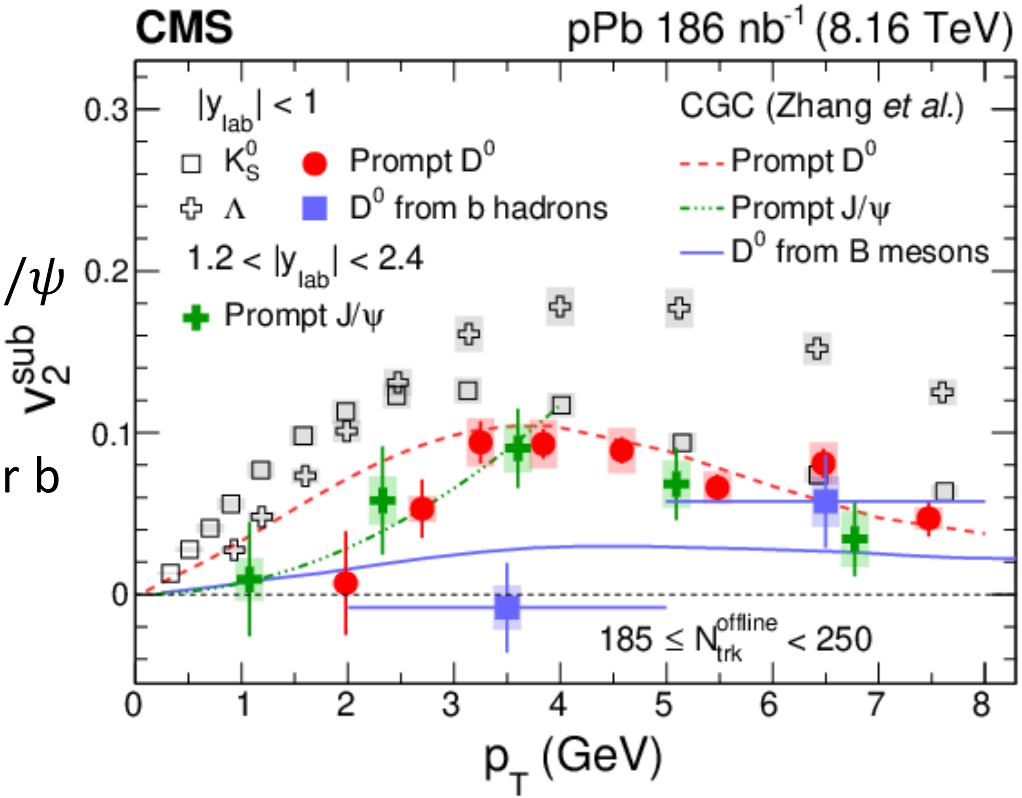
Divide by ref. particles V_n

Prompt D^0 v_2 comparable with J/ψ

Comparison with Color Glass Condensate (CGC) models for b hadrons

- Feed-down effects & decays by pythia 8

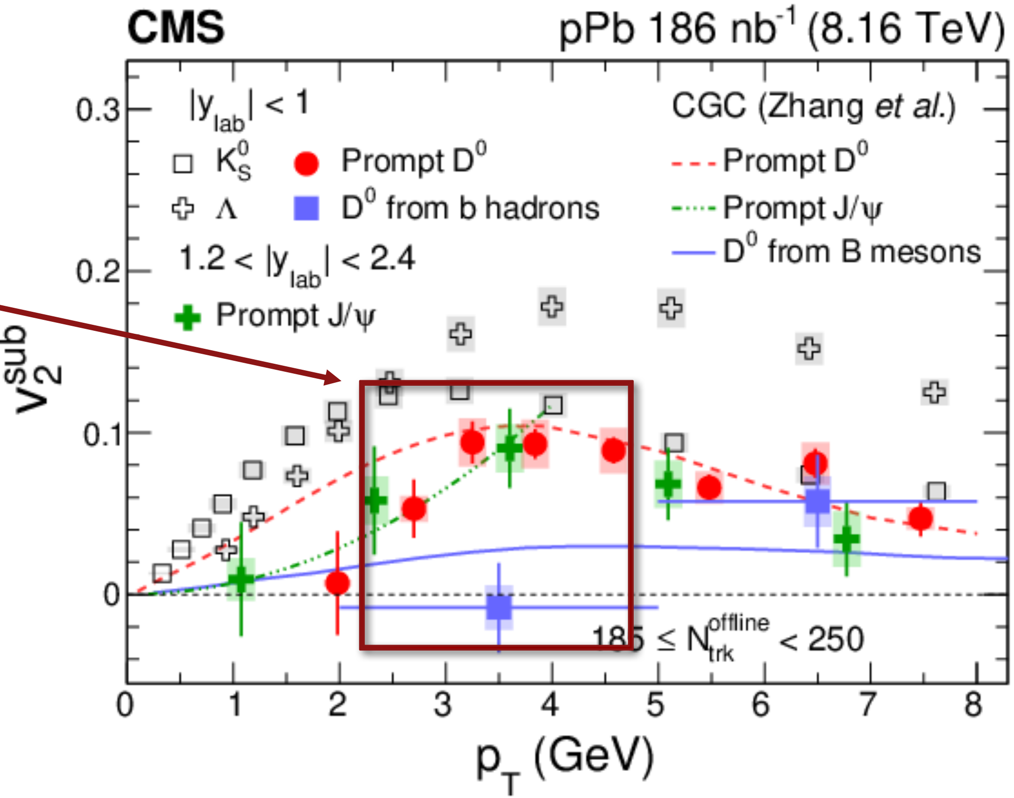
arXiv:2009.07065



Nonprompt D^0 meson v_2

Indication of flavor hierarchy between charm and bottom quarks at low-p_T

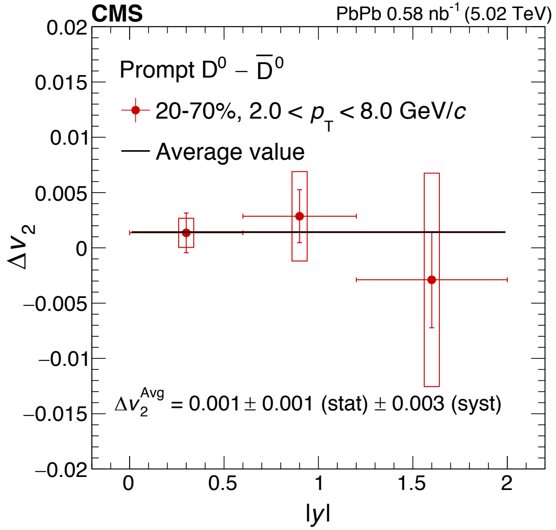
arXiv:2009.07065



Summary

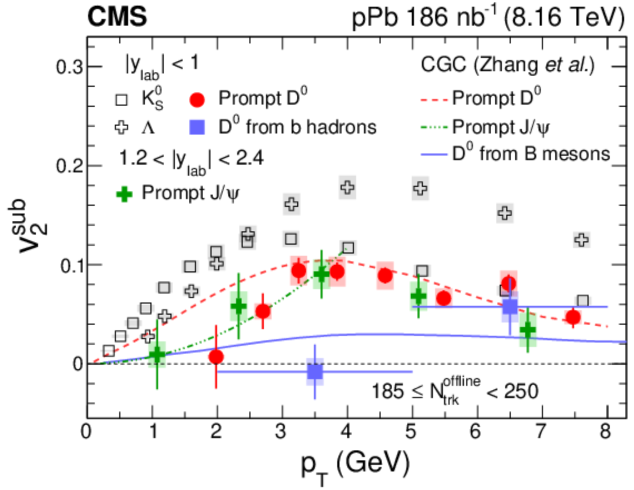
PbPb collisions

- ❑ Higher p_T coverage and finer bins in both p_T and centrality
- ❑ Rapidity dependence of v_2 and v_3
  - 1<|y|<2 range measured for the first time
- ❑ First measurement of $\Delta v_2(D^0 - \overline{D^0})$
  - Average: $\Delta v_2^{Fit} = 0.001 \pm 0.001\ (stat) \pm 0.003\ (syst)$
  - Information can constrain medium electric conductivity



pp and pPb collisions

- ❑ Non-zero v_2 values for prompt D^0 in pp collisions
- ❑ Multiplicity dependence studies in pp and pPb
- ❑ Indication of hierarchy between c- and b- quarks
- ❑ Comparison with CGC models



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Thank You!

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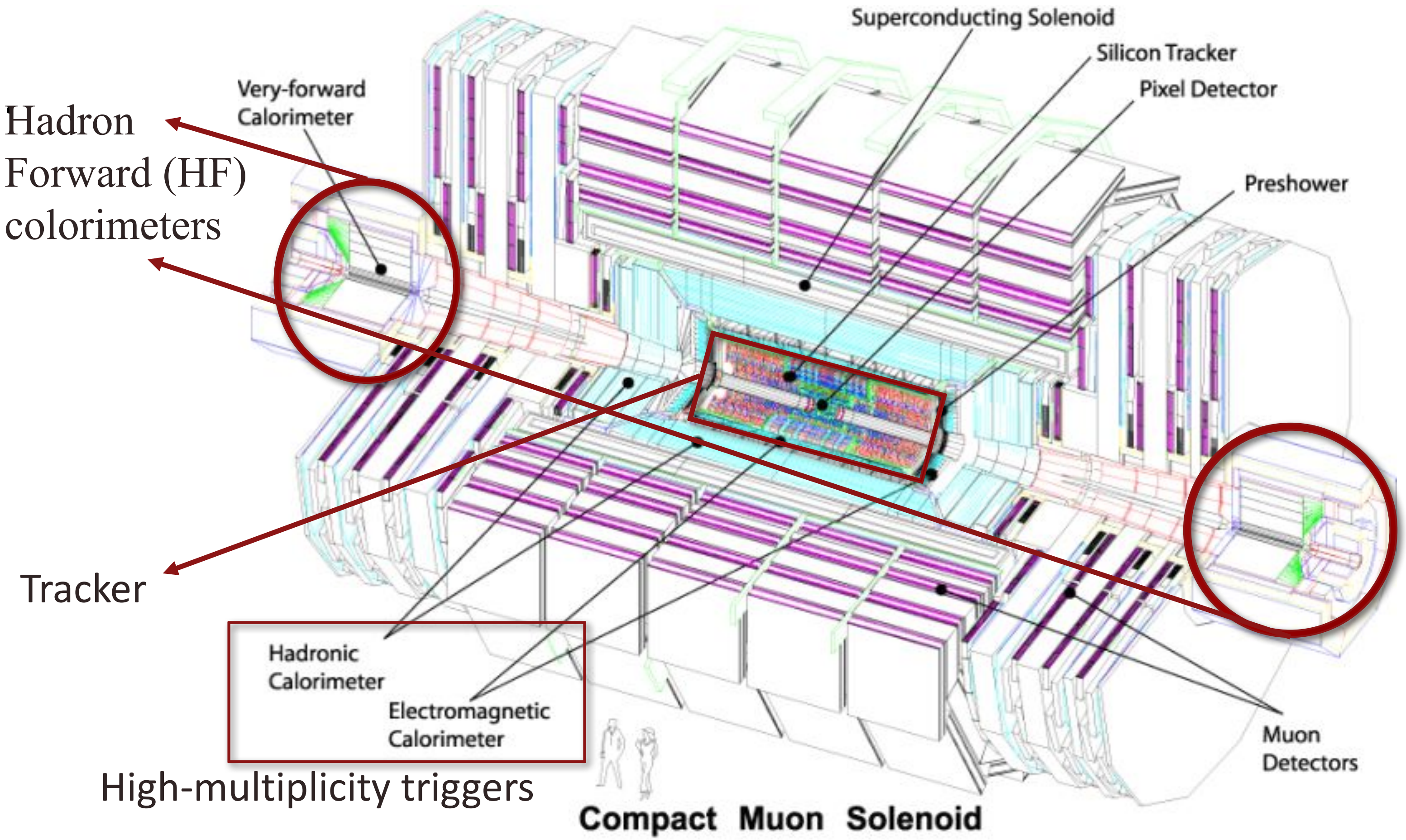
BACKUP

The CMS Detector



High-multiplicity triggers

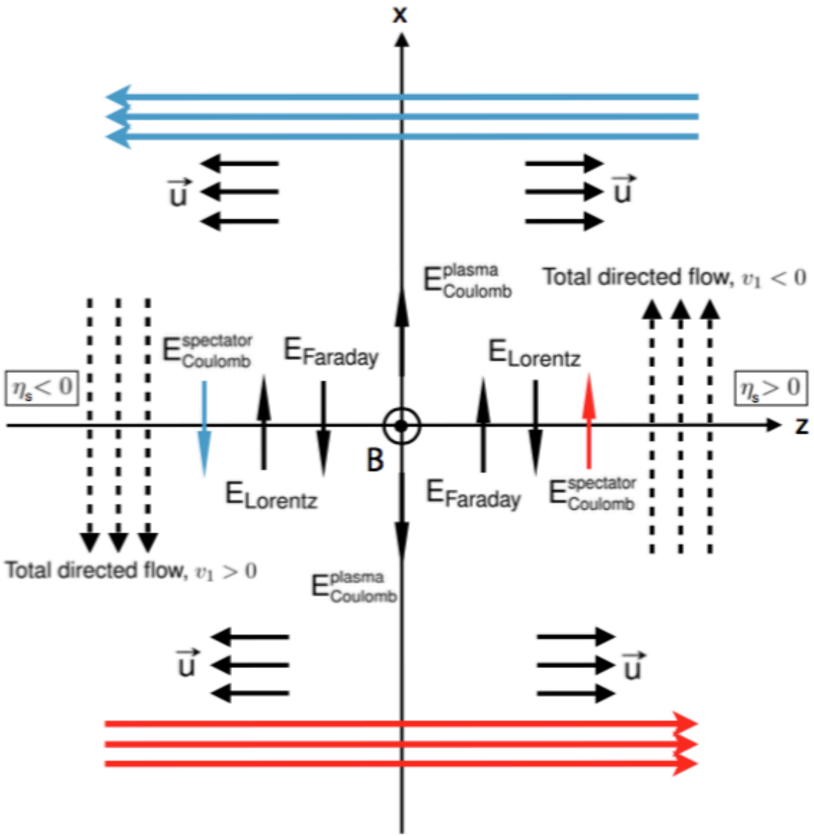
EM Fields in HI Collisions

Electromagnetic Fields in PbPb Collisions

Phys. Rev. C **98**, 055201 (2018)

Strong and short lived EM fields in PbPb collisions at LHC

- ❑ Generated by spectators and participants
- ❑ Charge-odd contributions to flow coefficients (v_n)
  - Non-zero Δv_n for opposite-charge
- ❑ Measurements constrain medium parameters
  - E.g. electric conductivity



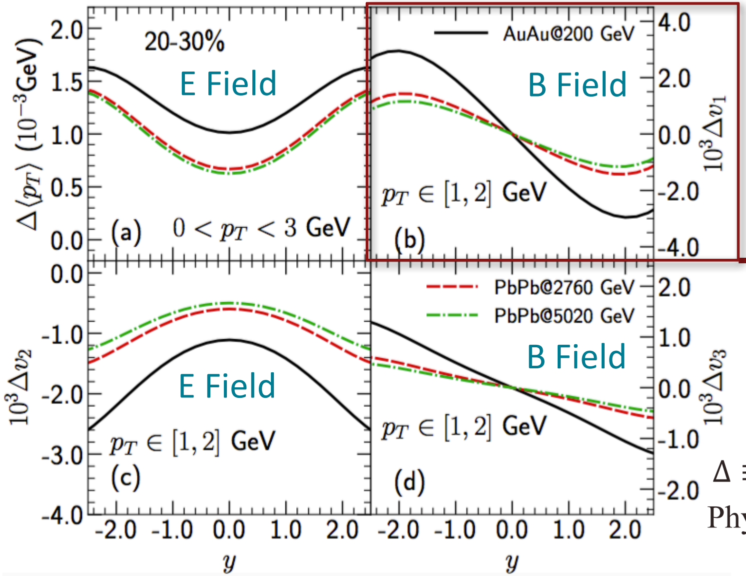
Effect on Δv_1 of $D^0(\bar{u}c)$ Mesons

Charm quarks produced in primordial stages of collision (~0.1 fm/c)

- m_{charm} >> typical medium temperatures: lower probability of annihilation

EM fields vanish very fast: peak magnitude approx. 0.1 - 0.2 fm/c

Non-zero Δv_1 mainly due to magnetic field from spectators

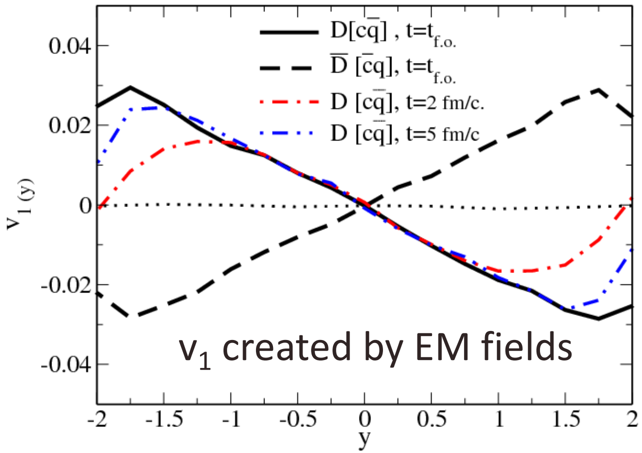


$\Delta \equiv (\pi^+ - \pi^-)$

Phys. Rev. C **98**, 055201 (2018)

Larger effect on D^0 mesons

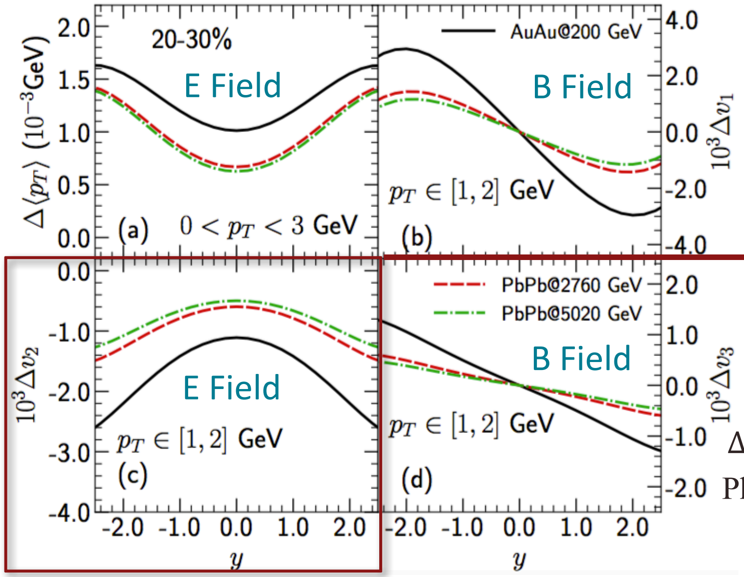
Phys. Lett. B **768**, 260 (2017)



Effect on Δv_2 of D^0 Mesons

Mostly produced by Electric field from collision participants

- Coulomb interaction



$\Delta \equiv (\pi^+ - \pi^-)$

Phys. Rev. C **98**, 055201 (2018)

Bigger effect on D^0 meson Δv_2?

Δv_2 measured for D^0 mesons!!!

Non-flow Subtraction

Subtract jets contribution

Removes residual contribution of back-to-back dijets to the measured v_2 results

total number of pairs per D^0 candidate

Jet yield

$$V_{n\Delta}^{sub} = V_{n\Delta} - V_{n\Delta}(N_{trk}^{offline} < 35) \frac{N_{assoc}(N_{trk}^{offline} < 35)}{N_{assoc}} \frac{Y_{jet}}{Y_{jet}(N_{trk}^{offline} < 35)}$$

N_{assoc} ratio

- Scale of the relative contribution from number of pairs

Jet yield ratio

- Account for increasing of jet yields in high-multiplicity region
- Little dependence on p_T over full p_T range

Jet yield := difference between integrals of the short-range ($|\Delta\eta|<1$) and long-range ($|\Delta\eta|>2$) event-normalized associated yields for each multiplicity class