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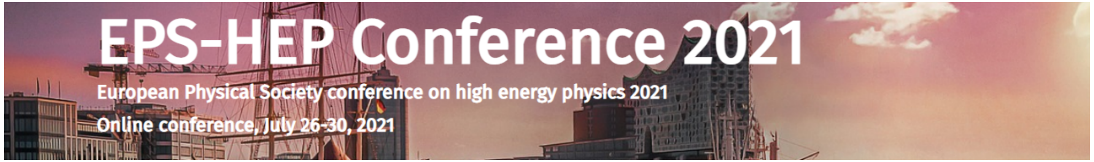
Recent results of D^0 mesons azimuthal anisotropy using the CMS detector

CESAR A. BERNARDES

IF-UFRGS, SPRACE



EPS-HEP Conference 2021

European Physical Society conference on high energy physics 2021

Online conference, July 26-30, 2021

Introduction

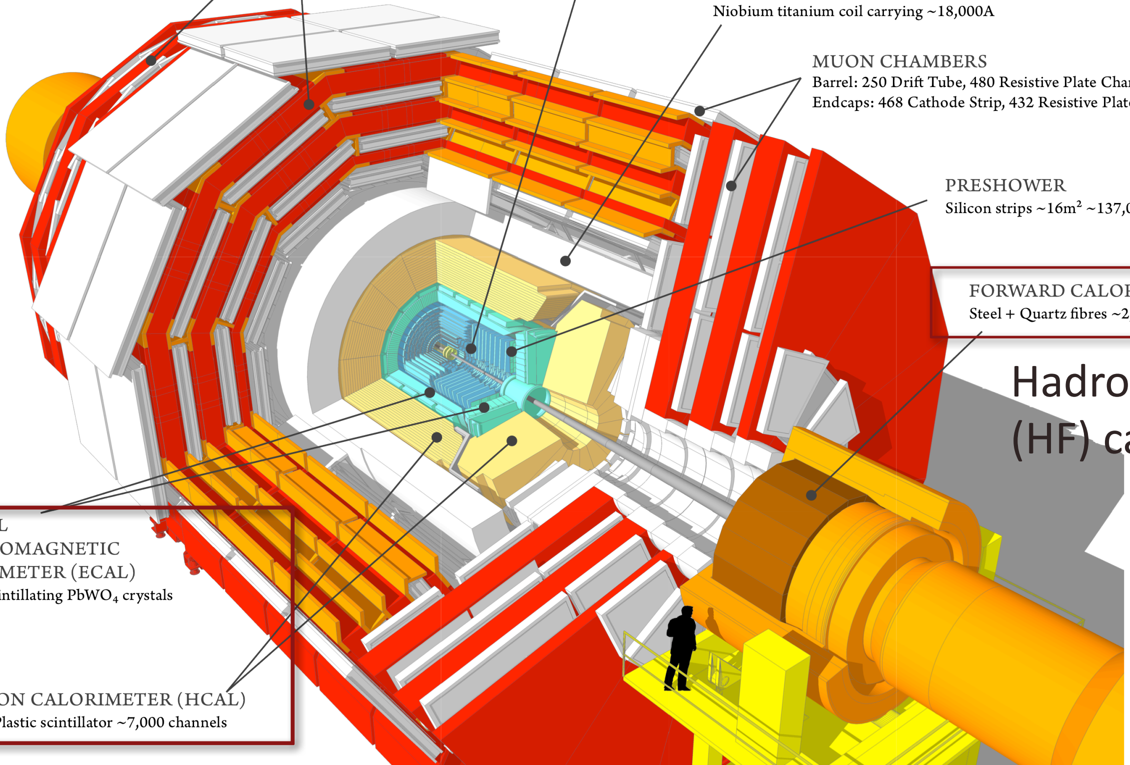
Charm quarks produced in the primordial stages of the collision (~0.1 fm/c)

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

Very good probe of initial state effects in both “Large” (PbPb) and “Small” (pp, pPb) colliding systems

- ☐ Small systems: origin of observed collective effects?
- ☐ Large systems
  - Understanding of energy loss and coalescence mechanisms
  - Electromagnetic (EM) fields effects at initial stages?
    - ○ Δv_n between positive & negative electric charges

The CMS Detector



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~9.6M channels

Tracker

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m^2 ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

Hadron Forward (HF) calorimeters

ECAL/HCAL

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Lead-lead (PbPb) Collisions

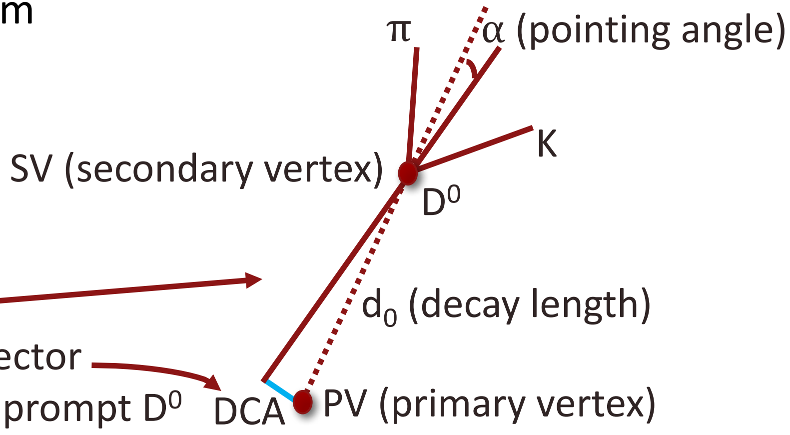
D^0 Reconstruction and Selection: 2018 Data

Minimum Bias events from PbPb collisions at 5.02 TeV

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

D^0 Reconstruction

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



DCA from detector resolution for prompt D^0

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

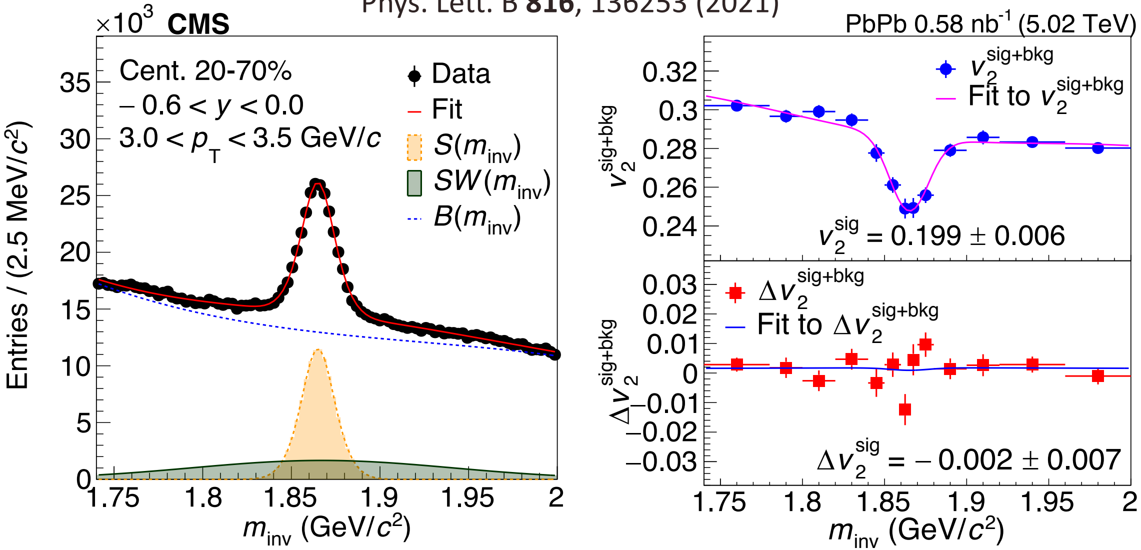
- ❑ Estimate contribution using DCA variable (nonprompt D^0 enriched region for DCA > 0.012 cm)

Signal Extraction

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

- ❑ v_n measured using Scalar Product (SP) method: correlates D^0 meson in tracker region with particles in HF

Phys. Lett. B **816**, 136253 (2021)



- ❑ 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

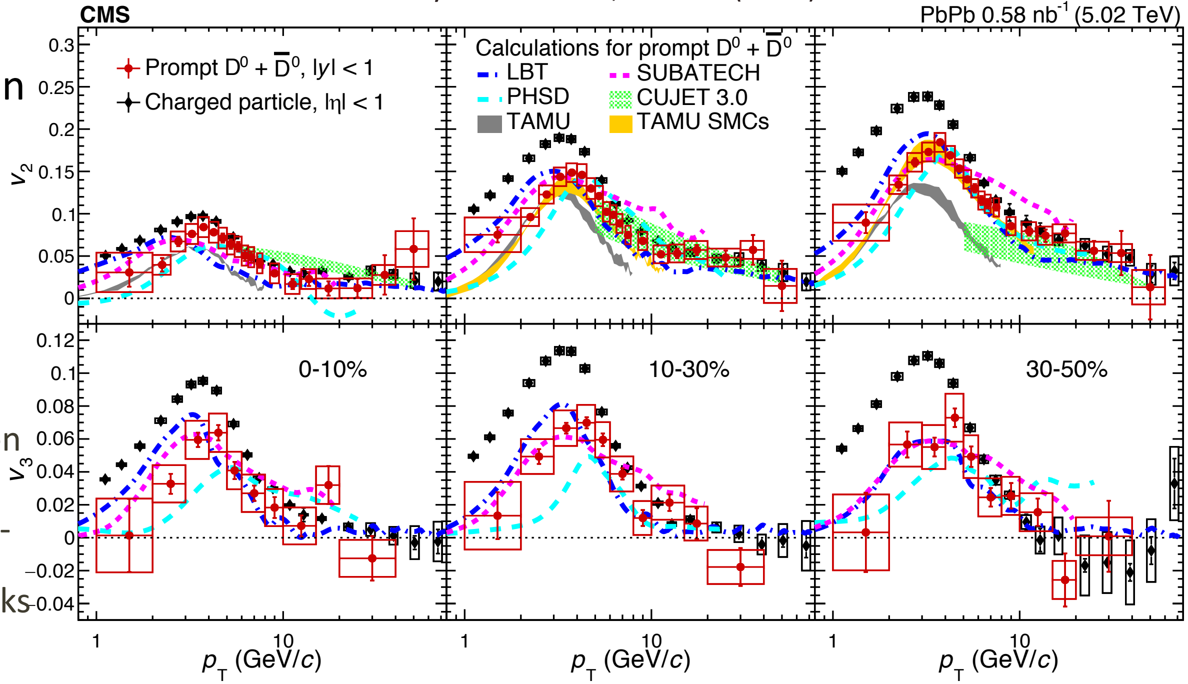
Similar trends compared to charged particles

v_2 : considerable dependence on centrality

v_3 : small dependence on centrality

Theory

- Resonable qualitative description
- TAMU
  - Added event-by-event space-momentum correlations (SMCs) between charm quarks and the high-flow partons in the QGP medium



Phys. Lett. B **816**, 136253 (2021)

$\Delta v_2(D^0 - \overline{D^0})$ 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)]

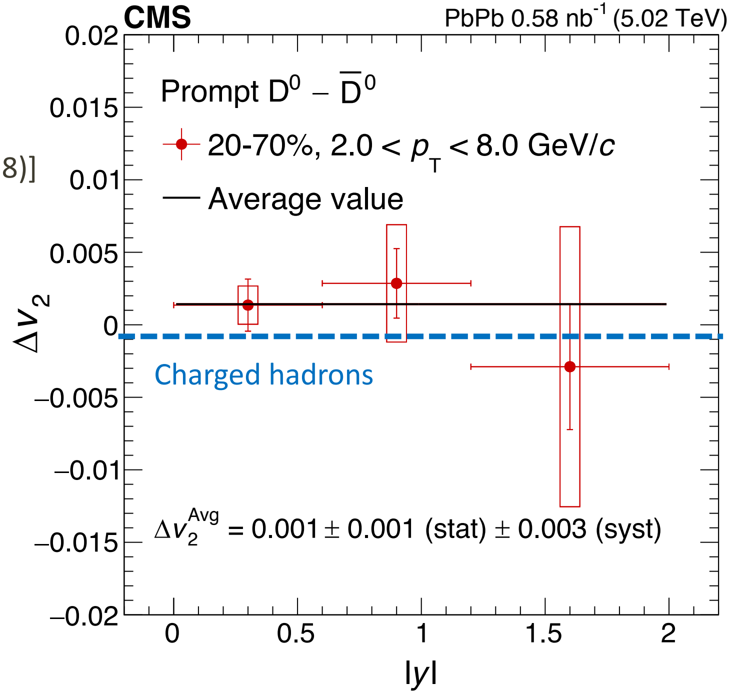
Average value extracted with a fit to data

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

Comparable to the values for charged hadrons

- ❑ Constrain medium properties: electric conductivity

Phys. Lett. B **816**, 136253 (2021)



Event-by-Event (EbyE) Flow Fluctuations

EbyE fluctuations of heavy quark flow explored experimentally

$$v_2\{2\}^2 \sim \underset{\substack{\downarrow \\ \text{flow (EP)}}}{\langle v\rangle^2} + \overset{\substack{\text{non-flow} \\ \uparrow}}{\delta} + \underset{\substack{\downarrow \\ \text{flow-fluctuations}}}{\sigma_v^2} \quad \text{(Scalar Product)}$$

$$v_2\{4\}^2 \sim \underset{\substack{\downarrow \\ \text{flow (EP)}}}{\langle v\rangle^2} - \underset{\substack{\downarrow \\ \text{flow-fluctuations}}}{\sigma_v^2} \quad \text{(4-Particle Cumulants)}$$

$$\boxed{v_2\{4\}/v_2\{2\}}$$

Considering that non-flow effects are negligible, this ratio is sensitive to flow fluctuations

- ❑ Scalar Product method use large eta gap → non-flow is suppressed

Comparison of the ratio between charm and charged particles

- ❑ Study of fluctuations from initial-state geometry and energy loss

D^0 $v_2\{4\}$ vs p_T

Overall $v_2\{4\} < v_2\{2\}$

$v_2\{4\}/v_2\{2\}$ comparison

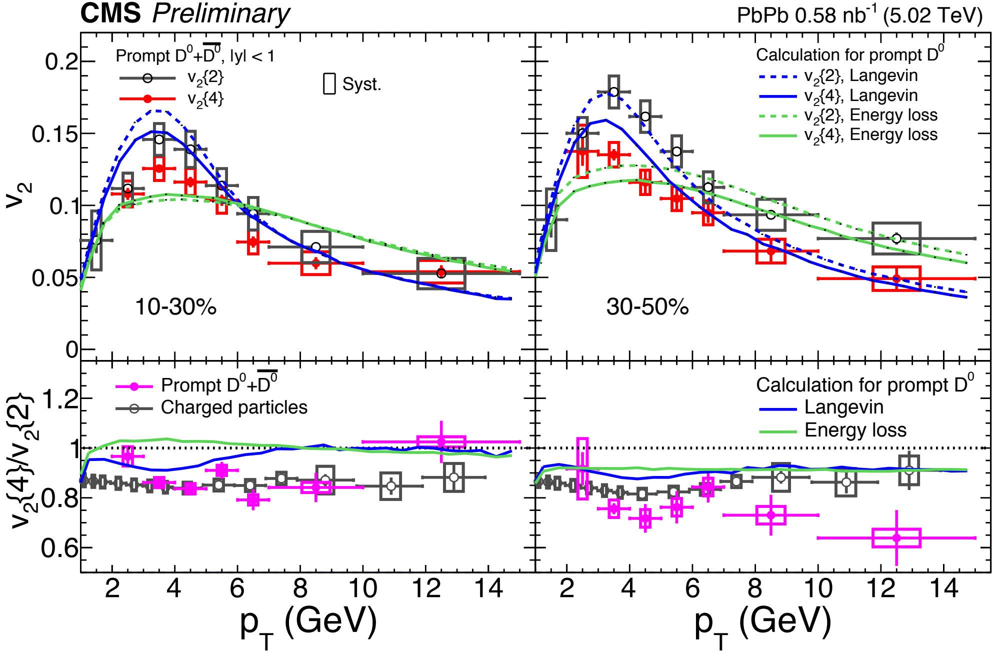
- 10-30%: consistent with charged particles
- 30-50%: hint of splitting of ratio between D^0 and charged particles at high-p_T
    - Energy loss fluctuation effects become more significant?

Theoretical calculations

- Resonable qualitative description

DAB-MOD [Phys. Rev. C **102**, 024906 (2020)]

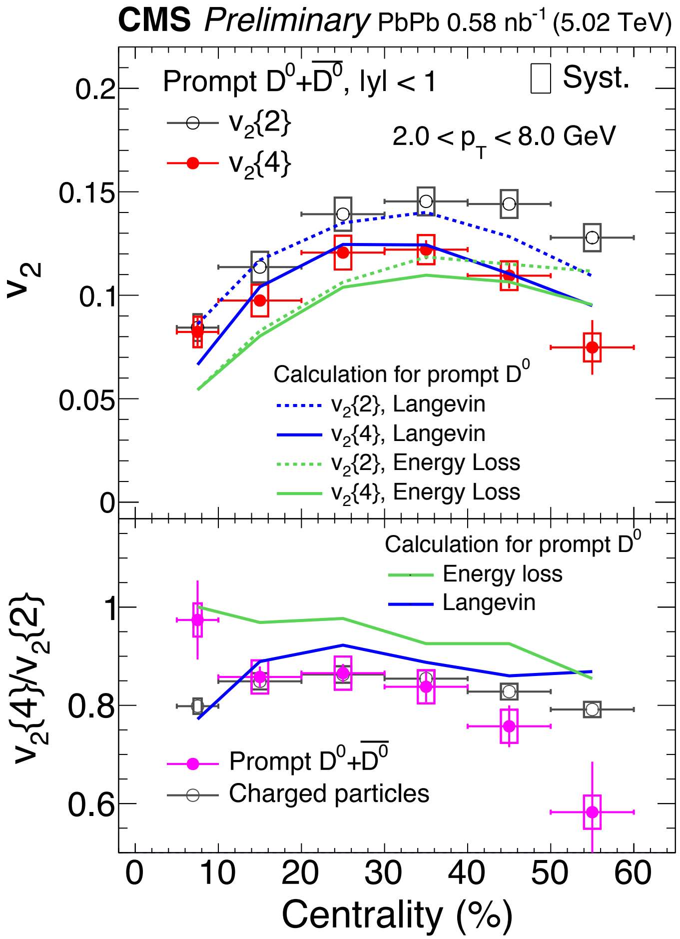
CMS-PAS-HIN-20-001



D^0 $v_2\{4\}$ vs Centrality

- $v_2\{4\}$ increasing and then declining: explained by initial collision geometry
- $v_2\{4\}/v_2\{2\}$ comparison
  - 10-40%: consistent with charged particles
  - More central and peripheral
    - Hint of splitting between D^0 and charged particles
    - Energy loss fluctuation effects more visible for D^0 mesons?
  - Theoretical calculations
    - Better description from Langevin dynamics for 10-50%
    - Larger deviation for 50-60%, but large uncertainties

CMS-PAS-HIN-20-001



DAB-MOD [Phys. Rev. C **102**, 024906 (2020)]

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

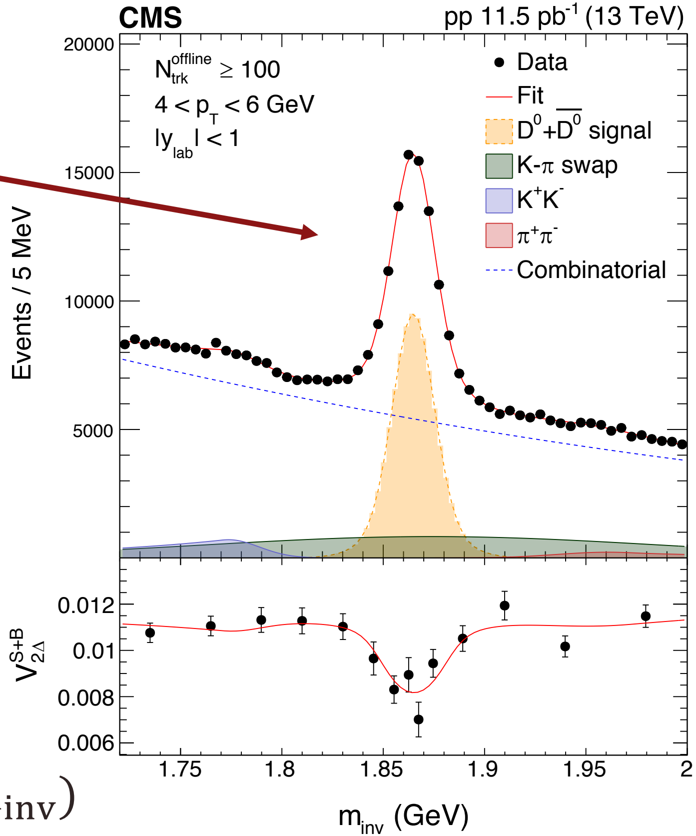
V_2 extracted from 2-particle correlations

$$\frac{1}{N_{D0}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1+\sum_{n=1}^{3} 2\underline{V_{n\Delta}}\cos(n\Delta\phi)\right]$$

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

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

Phys. Lett. B **813**, 136036 (2021)



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)

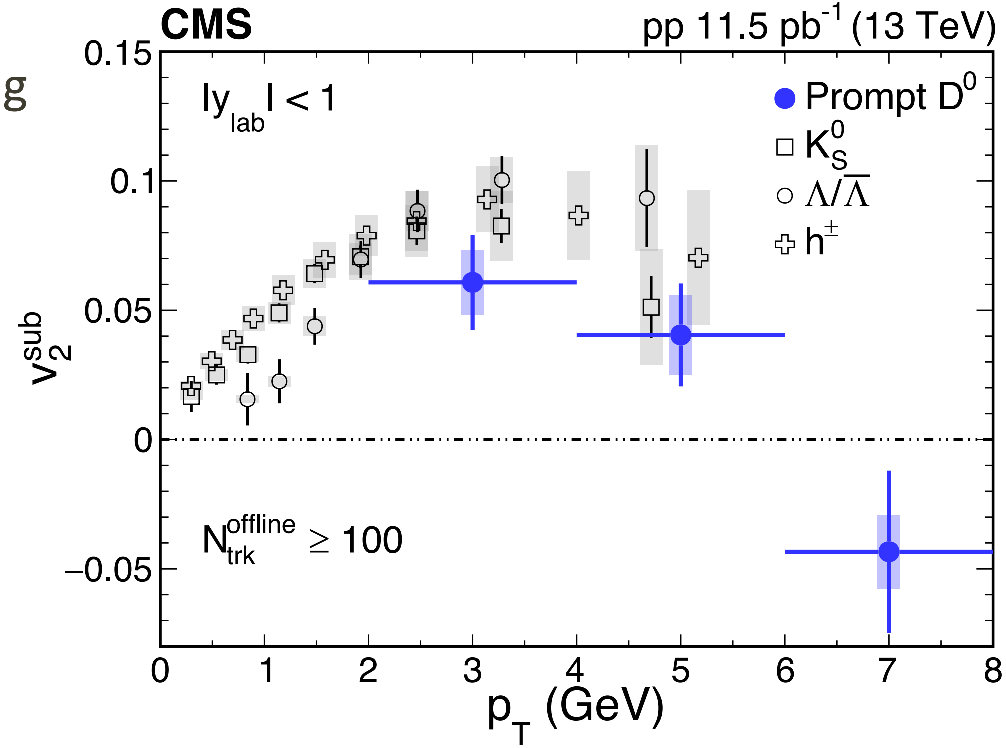
$$v_n(\mathrm{D}^0) = V_{n\Delta}(\mathrm{D}^0, \mathrm{ref}) \Big/ \sqrt{V_{n\Delta}(\mathrm{ref}, \mathrm{ref})}$$

Prompt D^0 v_2 slightly below strange particles

- Similarly to pPb

v_2 compatible with zero at high-p_T

Phys. Lett. B **813**, 136036 (2021)

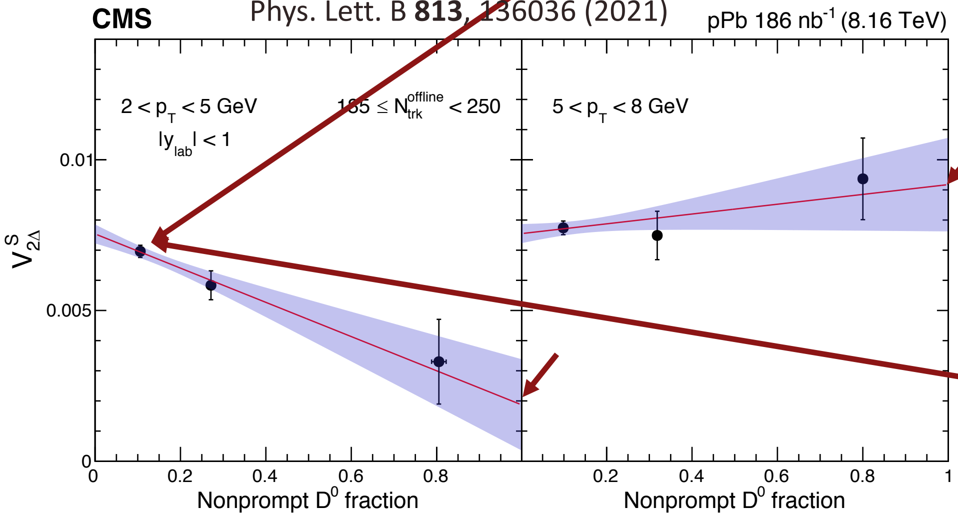


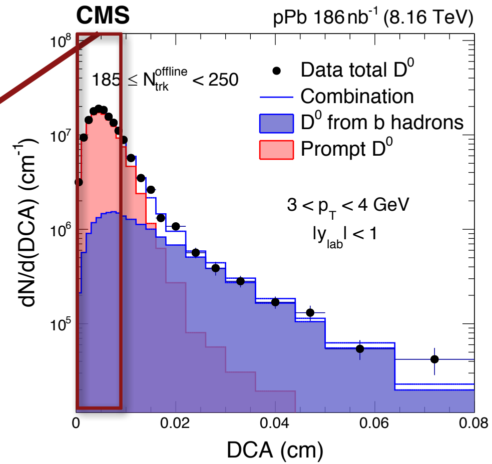
NP D^0: V_2 Signal Extraction

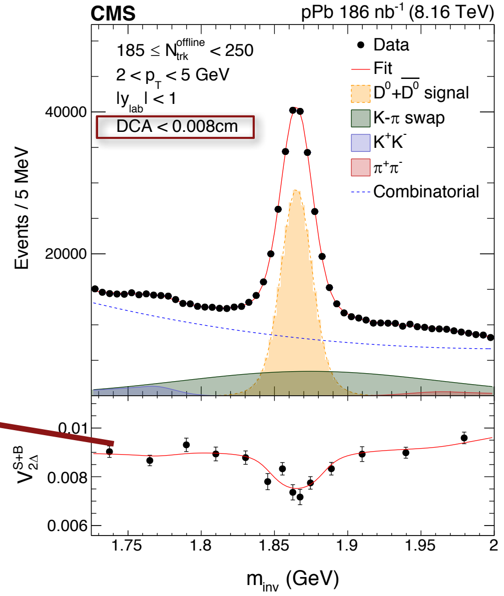
Measure $V_{2\Delta}^{S}$ for each DCA region (different nonprompt fractions)

Linear fit

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


Phys. Lett. B **813**, 136036 (2021)





Nonprompt D^0 Meson v_2

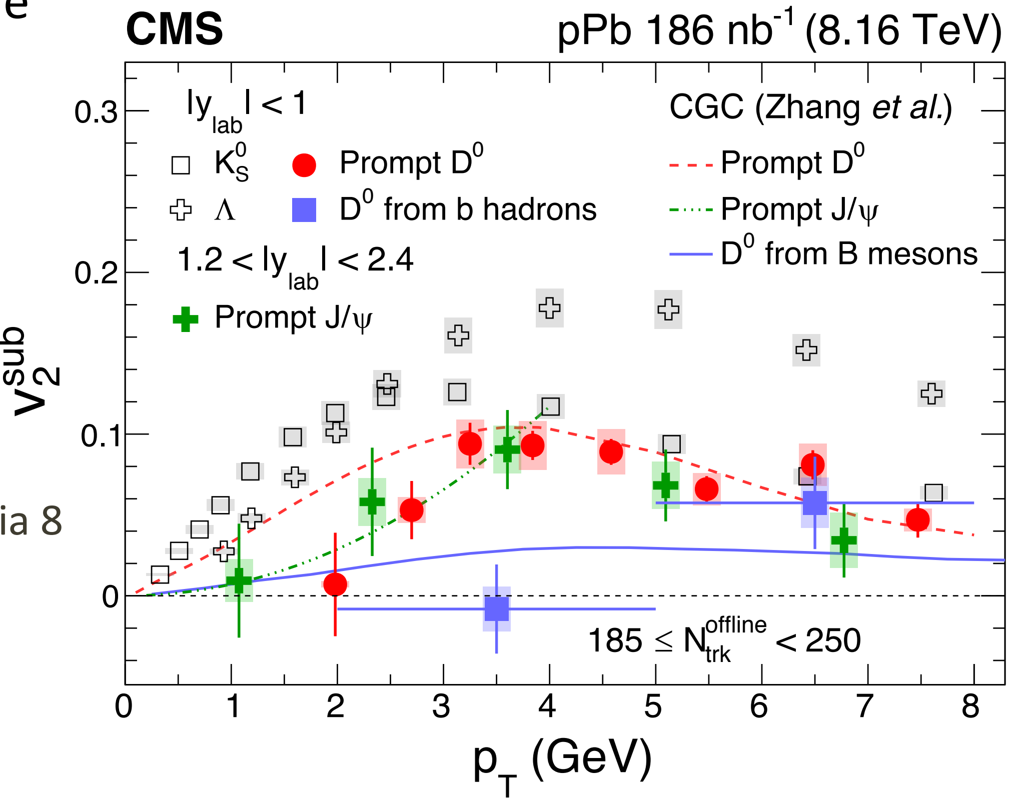
Subtract non-flow effects and divide by reference particles V_n

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

Phys. Lett. B **813**, 136036 (2021)



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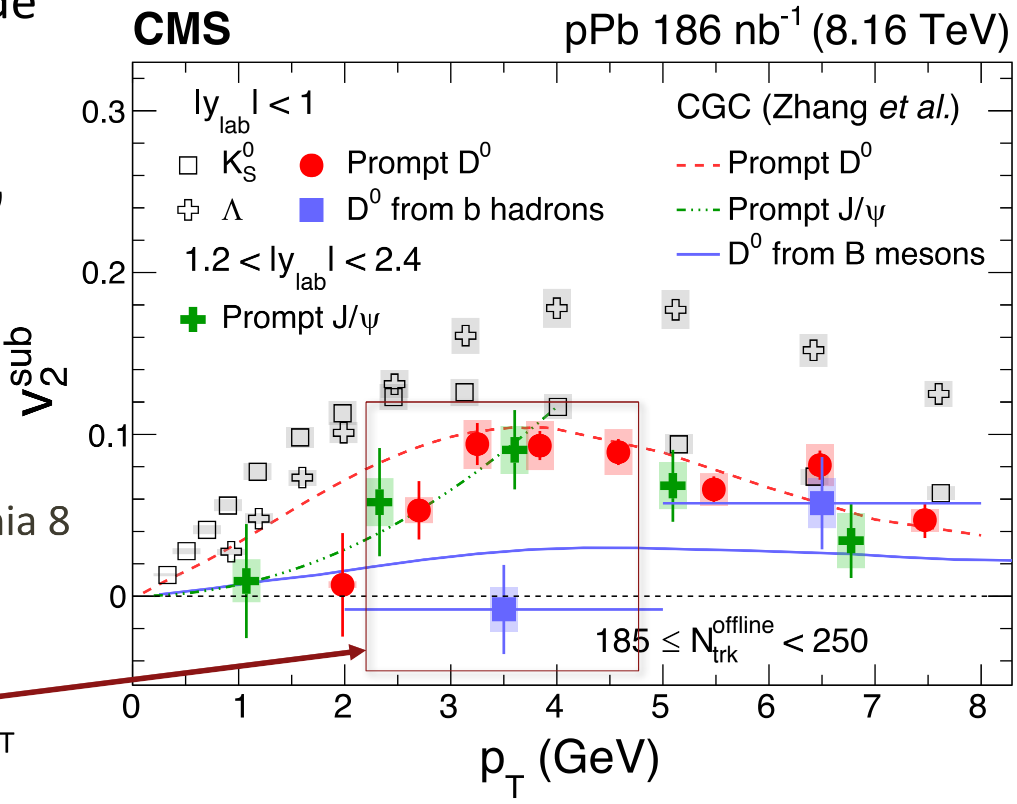
- ❑ Feed-down effects & decays by pythia 8

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

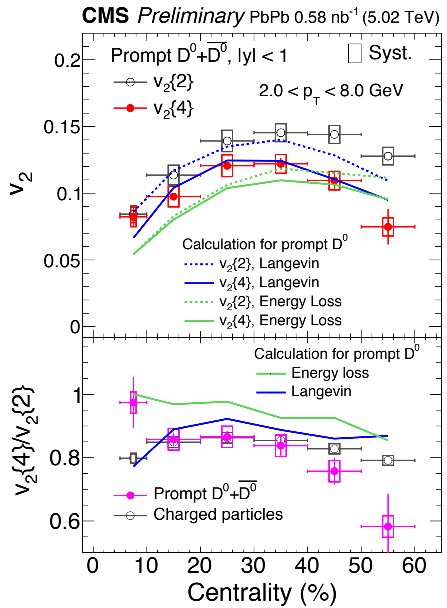
Phys. Lett. B **813**, 136036 (2021)



Summary

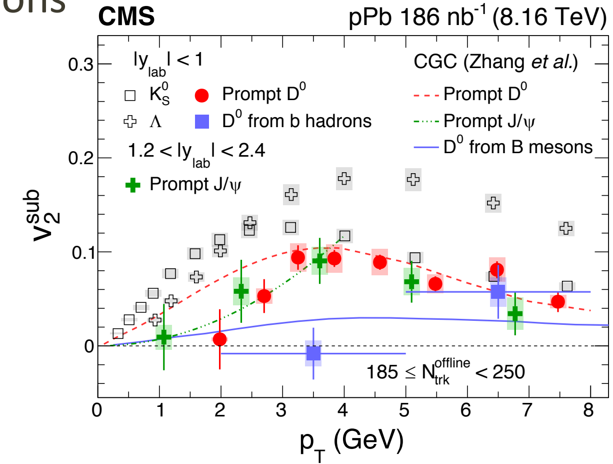
PbPb collisions

- ❑ D^0 mesons v_2 and v_3 from 2-particle correlations
  - Higher p_T coverage and finer bins in both p_T and centrality
  - Measurement of $\Delta v_2\left(D^0 - \overline{D^0}\right)$
    - ○ Information can constrain medium electric conductivity
- ❑ D^0 mesons v_2 from four-particle cumulants
  - Energy loss fluctuation effects more visible for D^0 mesons compared to charged particles?



pp and pPb collisions

- ❑ Non-zero v_2 values for prompt D^0 in pp collisions
- ❑ Indication of hierarchy between c- and b- quarks
- ❑ Resonable description of D^0 mesons flow by CGC models



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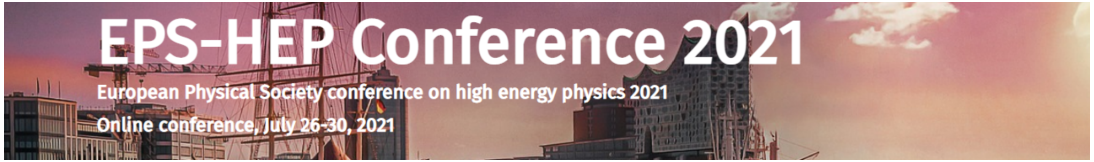
Thank You!



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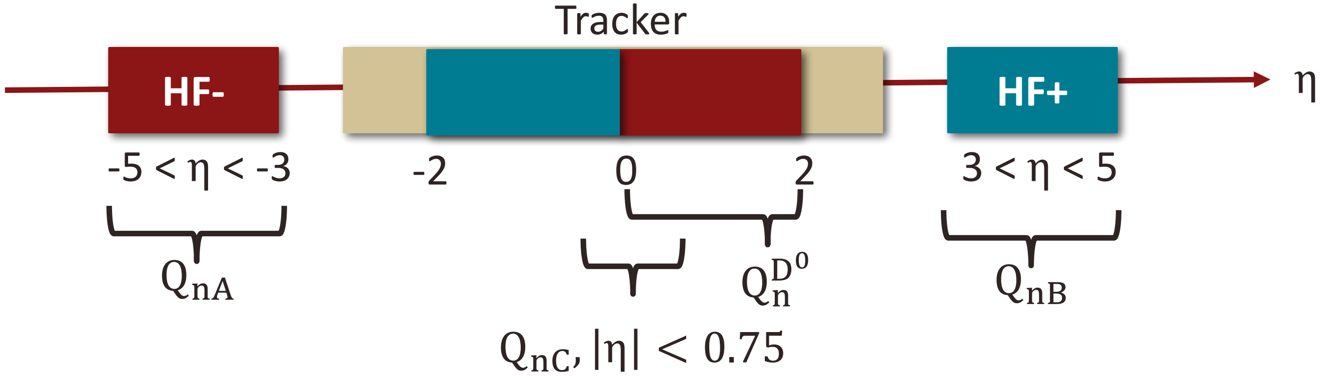
BACKUP

2018 PbPb Data

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

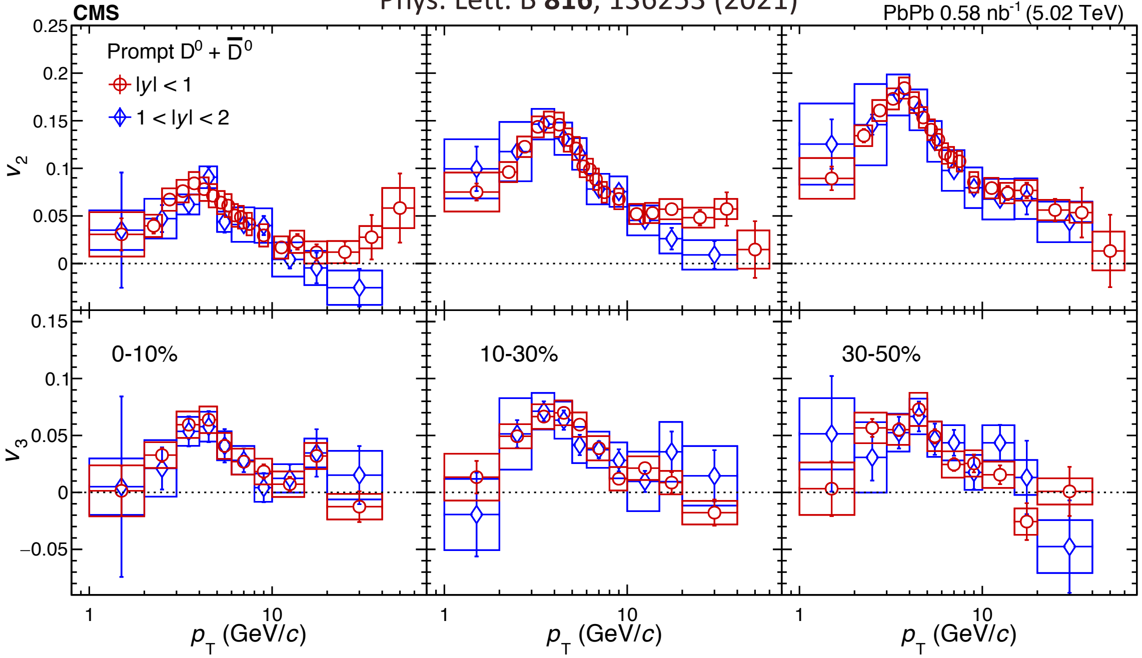


- ☐ $Q_n = \sum_j w_j e^{in\phi_j}$ (w_j = tower E_T for HF, w_j = track p_T for tracker, w_j = 1 for $D^0, \overline{D^0}$)
- ☐ $v_n\{SP\} = \dfrac{\left\langle Q_n^{D^0/\overline{D^0}} Q_{nA}^* \right\rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$ $\Delta v_n\{SP\} = \dfrac{\left\langle Q_n^{D^0} Q_{nA}^* \right\rangle - \left\langle Q_n^{\overline{D^0}} Q_{nA}^* \right\rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$ Average over all events

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

Phys. Lett. B **816**, 136253 (2021)



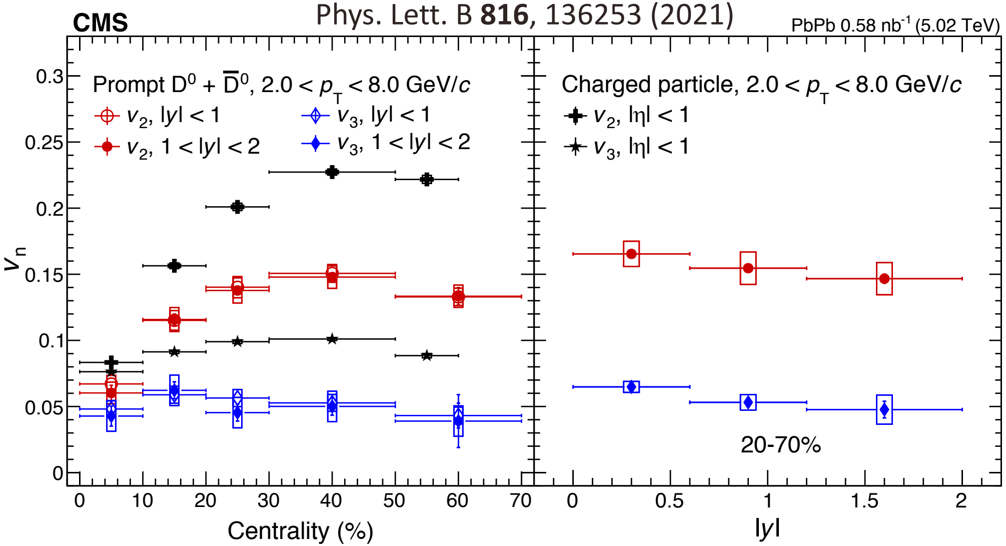
v_2 & v_3 as Function of Centrality and Rapidity

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



Phys. Lett. B **816**, 136253 (2021)

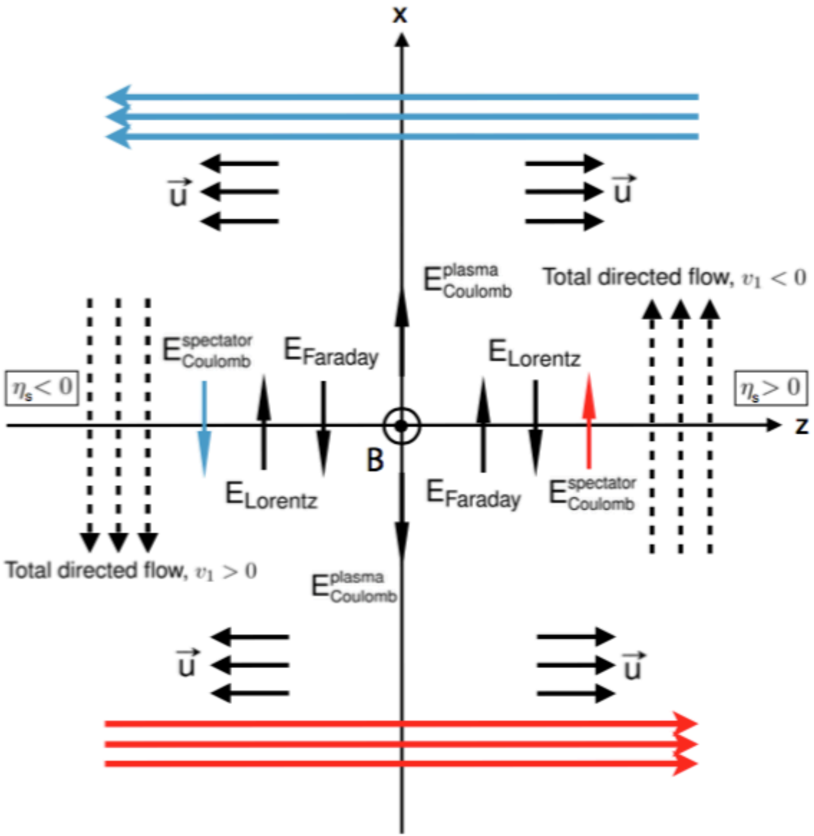
EM Fields in HI Collisions

Electromagnetic Fields in PbPb Collisions

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

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



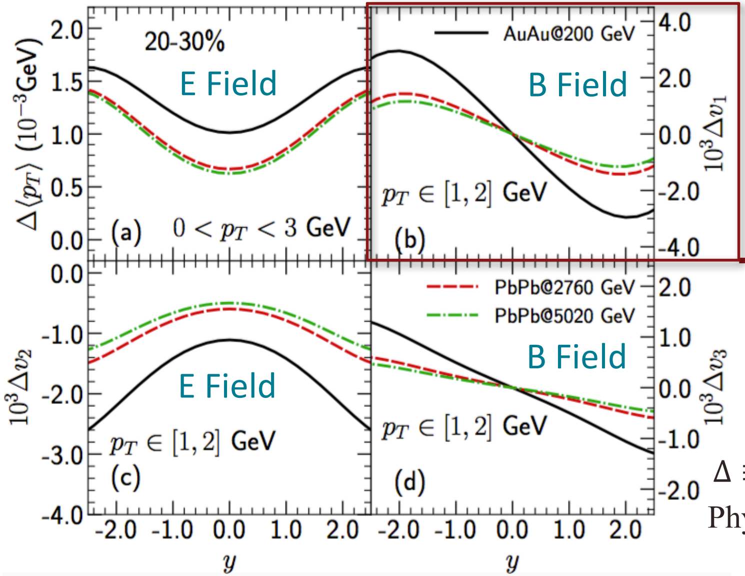
Effect on Δv_1 of $D^0(\bar{u}c)$ Mesons

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

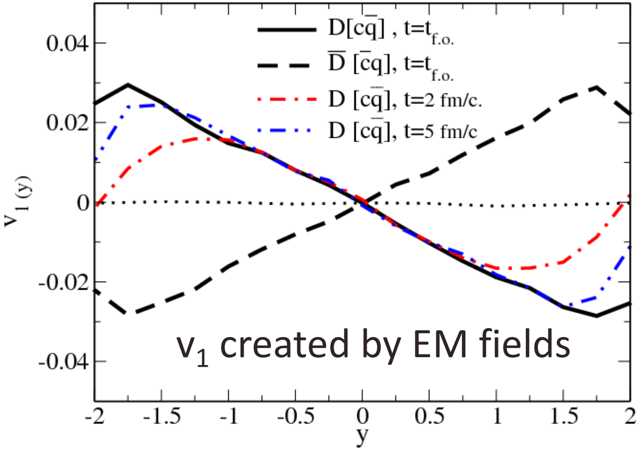


$\Delta \equiv (\pi^+ - \pi^-)$

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

Larger effect on D^0 mesons

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

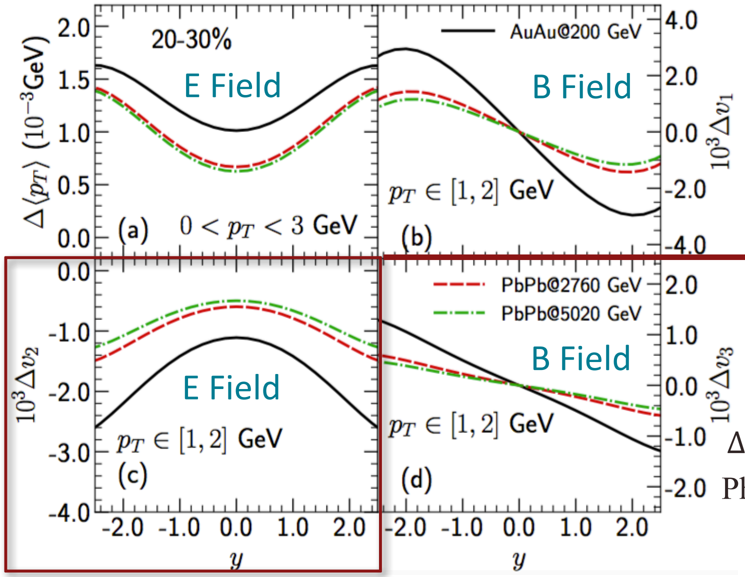


v_1 created by EM fields

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!!!

4-particle Cumulant Method

Four-particle Cumulants (I)

Differential flow: PRC 83, 044913(2011)

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle \quad (2)$$

$$v_n'\{4\}(D^0) = -\frac{d_n\{4\}(D^0)}{(-c_n\{4\})^{3/4}} \quad (1)$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 * \langle\langle 2 \rangle\rangle^2 \quad (3)$$

$d_n\{4\}$: fourth-order differential cumulant.

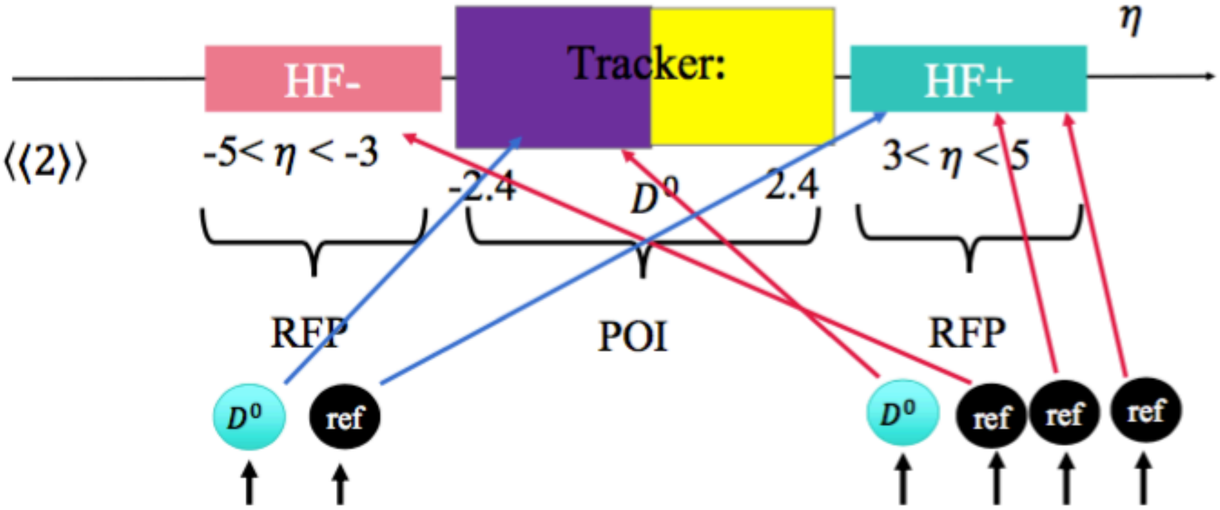
$c_n\{4\}$: four-particle cumulant → reference flow.

Four-particle Cumulants (II)

Liuyao Zhang, IS2021

$d_n\{4\}$:

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \, \langle\langle 2 \rangle\rangle$$



$$\langle 2' \rangle = \left\langle e^{in(\psi_1 - \phi_2)} \right\rangle$$

$$\langle 4' \rangle = \left\langle e^{in(\psi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle$$

$$\downarrow$$

definition:

$$Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$$

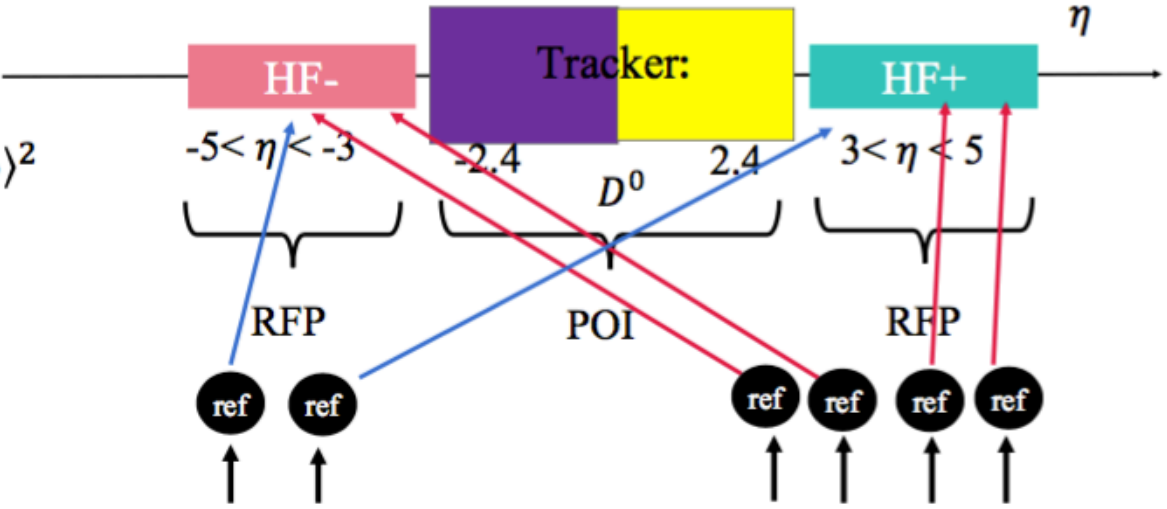
$$\langle 4' \rangle = \frac{Re[\, Q_n^{D^0} Q_n^{HF-} (Q_n^{HF+})^* (Q_n^{HF+})^*] - Q_n^{D^0} Q_n^{HF-} (Q_{2n}^{HF+})^*]}{M^{HF-} M^{HF+} (M^{HF+} - 1)} \quad \text{if: } D^0(\text{eta}<0) \quad (4)$$

Note: weight $M^{HF-} = \sum (E_T)_i$ from HF- , $M^{HF+} = \sum (E_T)_i$ from HF+

Four-particle Cumulants (III)

$c_n\{4\}$:

$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2 * \langle\langle 2\rangle\rangle^2$$



$$\langle 2\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle \qquad \langle 4\rangle = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle$$

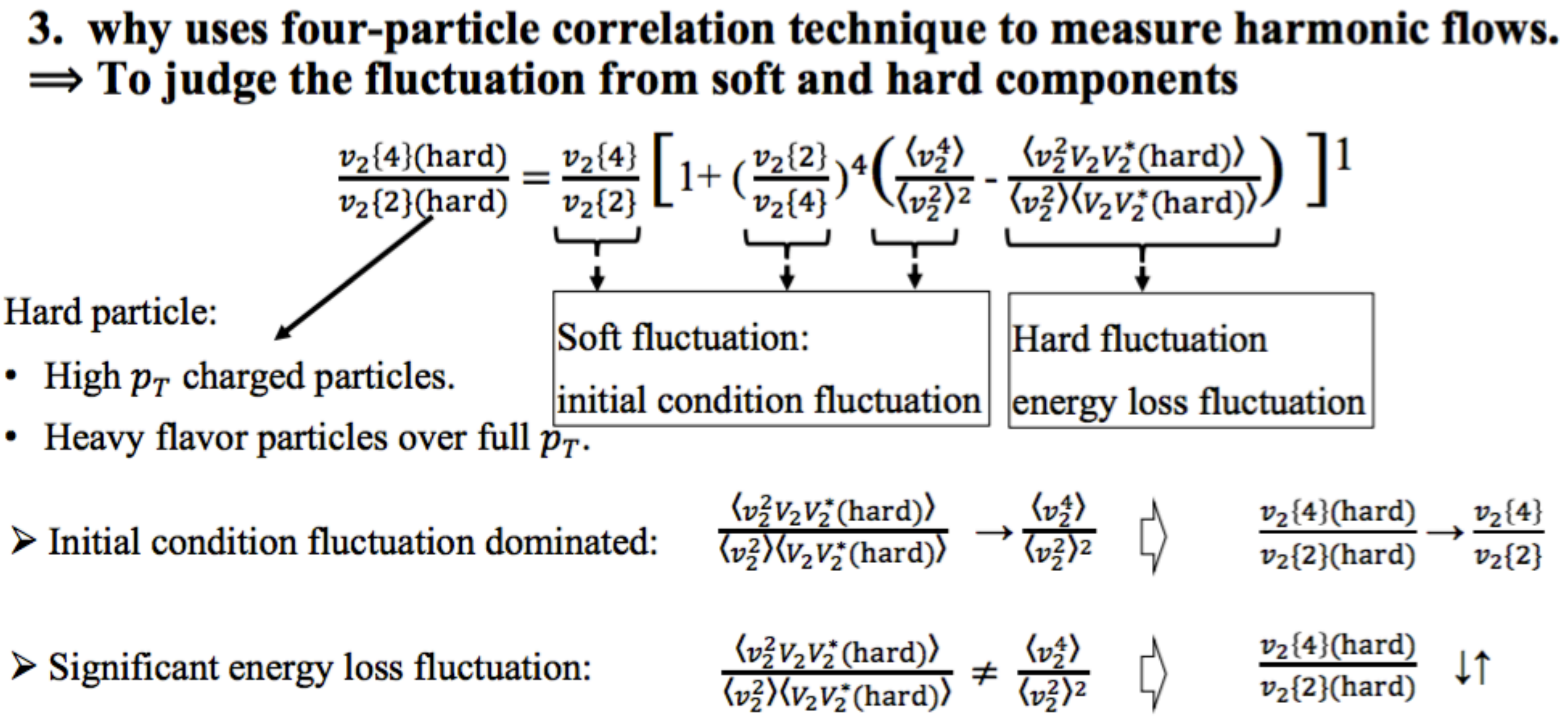
↓

$$\langle 4\rangle = \frac{Re[\,Q_n^{HF-}Q_n^{HF-}(Q_n^{HF+})^*(Q_n^{HF+})^*\,]+Re[\,Q_{2n}^{HF-}(Q_{2n}^{HF+})^*\,]-Re[\,Q_{2n}^{HF-}(Q_n^{HF+})^*(Q_n^{HF+})^* + Q_n^{HF-}Q_n^{HF-}(Q_{2n}^{HF+})^*]}{M^{HF-} * (M^{HF-}-1) * M^{HF+}\,(M^{HF+}-1)} \quad (5)$$

Note: weight $M^{HF-} = \sum(E_T)_i$ from HF- , $M^{HF+} = \sum(E_T)_i$ from HF+

Motivation to Use the Ratio

Liuyao Zhang, IS2021



3. why uses four-particle correlation technique to measure harmonic flows.

⟹ To judge the fluctuation from soft and hard components

$$\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} = \frac{v_2\{4\}}{v_2\{2\}} \left[1 + \left(\frac{v_2\{2\}}{v_2\{4\}}\right)^4 \left(\frac{\langle v_2^4 \rangle}{\langle v_2^2 \rangle^2} - \frac{\langle v_2^2 V_2 V_2^*(\text{hard}) \rangle}{\langle v_2^2 \rangle \langle V_2 V_2^*(\text{hard}) \rangle} \right) \right]^1$$

Hard particle:

- High p_T charged particles.
- Heavy flavor particles over full p_T.

Soft fluctuation:

initial condition fluctuation

Hard fluctuation

energy loss fluctuation

➢ Initial condition fluctuation dominated: $\frac{\langle v_2^2 V_2 V_2^*(\text{hard}) \rangle}{\langle v_2^2 \rangle \langle V_2 V_2^*(\text{hard}) \rangle} \rightarrow \frac{\langle v_2^4 \rangle}{\langle v_2^2 \rangle^2}$ ⇨ $\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} \rightarrow \frac{v_2\{4\}}{v_2\{2\}}$

➢ Significant energy loss fluctuation: $\frac{\langle v_2^2 V_2 V_2^*(\text{hard}) \rangle}{\langle v_2^2 \rangle \langle V_2 V_2^*(\text{hard}) \rangle} \neq \frac{\langle v_2^4 \rangle}{\langle v_2^2 \rangle^2}$ ⇨ $\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})}$ ↓↑

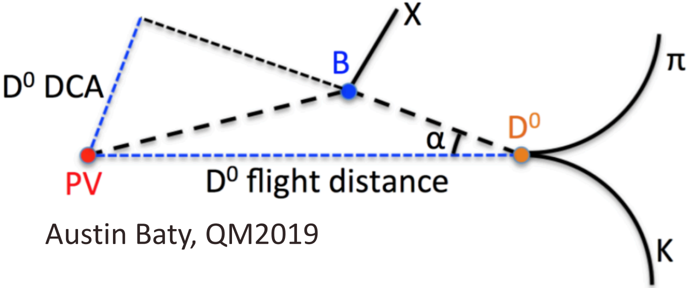
1. arXiv:1906.10768v2

Small Systems

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



Austin Baty, QM2019

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

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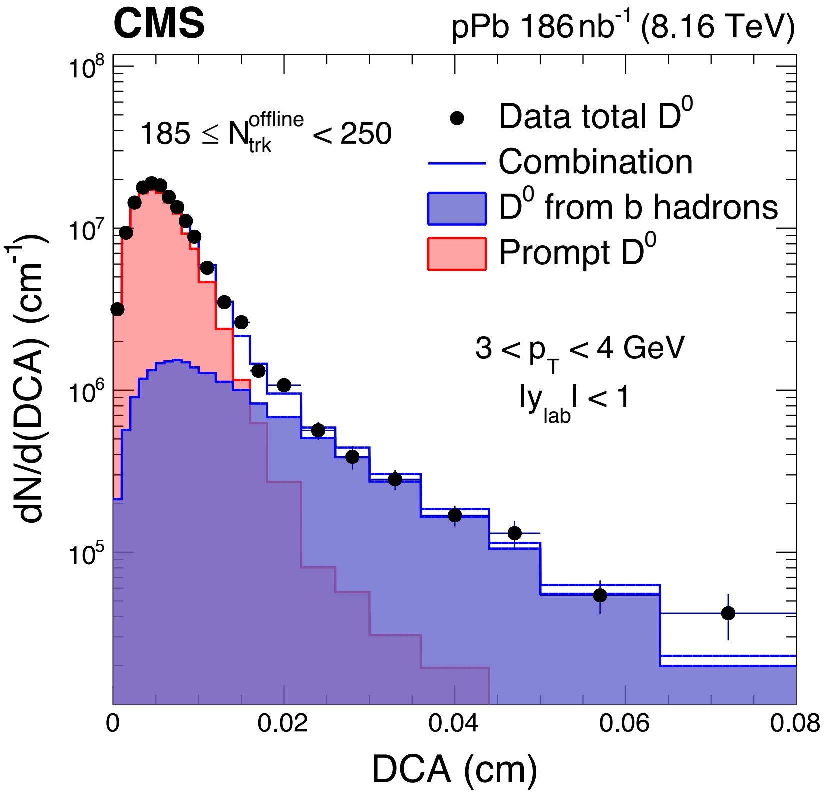

Non-flow subtraction: jets contribution

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

total number of pairs per D^0 candidate

Jet yield

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

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

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

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