Heavy Ion physics from SPRACE group using the CMS experiment

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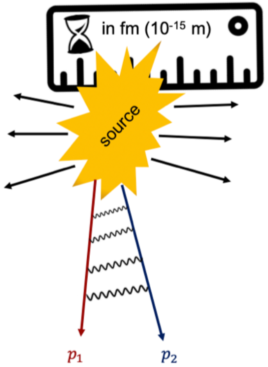
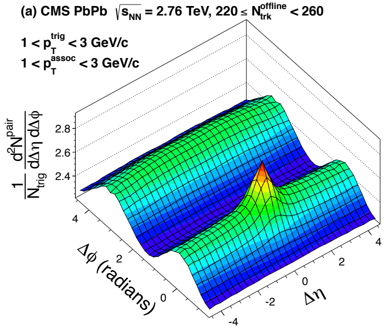
Introduction

SPRACE team participates in flow & correlation analyses in CMS

- ❑ Understanding QCD properties using pp, pPb, and PbPb collisions
- ❑ Focus in two fronts
  - Femtoscopic correlations
    - Space-time dimensions of the particle emitting source
    - Hadron-hadron final state interactions
  - Azimuthal anisotropy
    - Quark-gluon plasma (QGP) response to
      - Initial collision geometry and its fluctuations
    - Parton energy loss in the QGP
    - Hadronization mechanisms



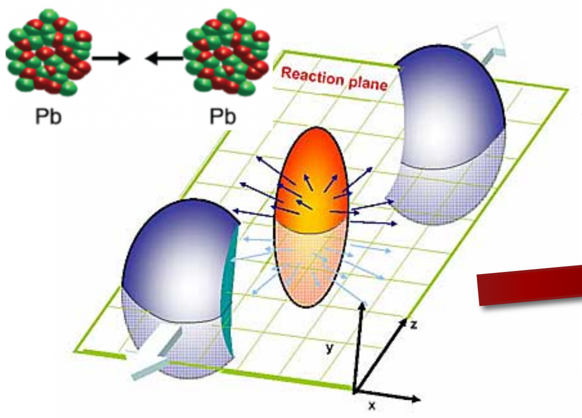


Introduction – azimuthal correlations

Recent work in analyses involving heavy-flavor quarks to probe

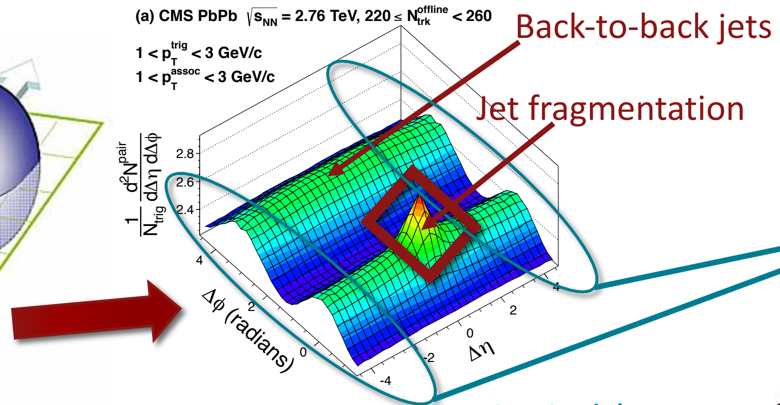
- Interactions with the QGP (energy loss), hadronization mechanisms, etc ...

In hydrodynamic models: v2 (elliptic flow) and v3 (triangular flow)

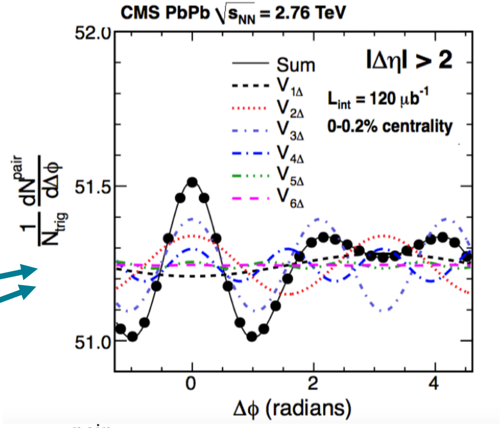


Fluctuating initial geometry + pressure

Two-particle correlations



Projecting in Δϕ the long-range correlations



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

$$V_{n\Delta} = v_n^2$$

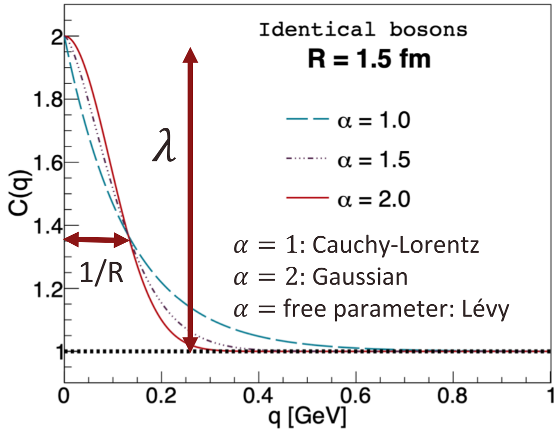
Introduction – femtoscopic correlations

Two-particle correlations at low-q

- $q^2 = q_{inv}^2 = -(p_1 - p_2)^2$

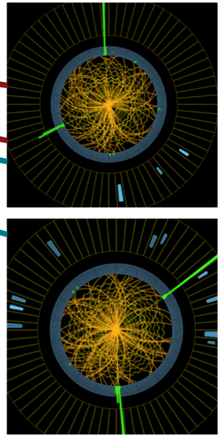
Theoretically

- Related to Fourier transform of the source shape
  - $C(q) \sim 1 \pm \lambda |F[\tilde{\rho}(q)]|^2 \rightarrow C(q) = N\left(1 \pm \lambda e^{-|qR|^{\alpha}}\right)$
  - Sensitive to final state interactions: Coulomb & strong



Experimentally

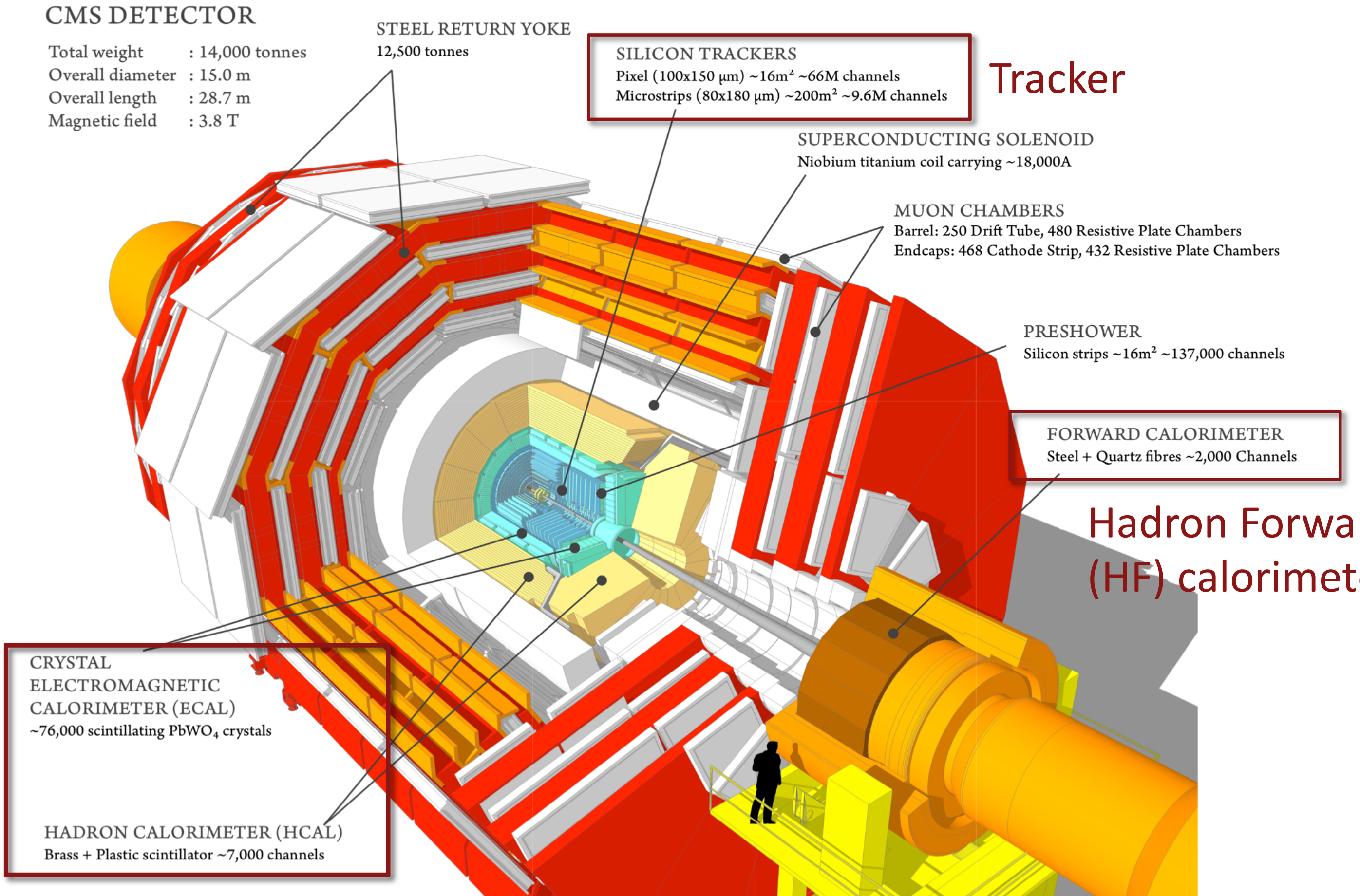
- Single-ratio (SR): $C(q) = N\frac{A(q)}{B(q)}$



Recent work on

- Data analysis: high charged particle multiplicity in proton-proton (pp) collisions and strange hadrons (V^0) in pPb collisions
- Phenomenology: D^0 and V^0 hadrons

The CMS Detector



Azimuthal Correlations

Promt D^0 meson flow coefficients (v_2 & v_3)

As function of p_T and centrality

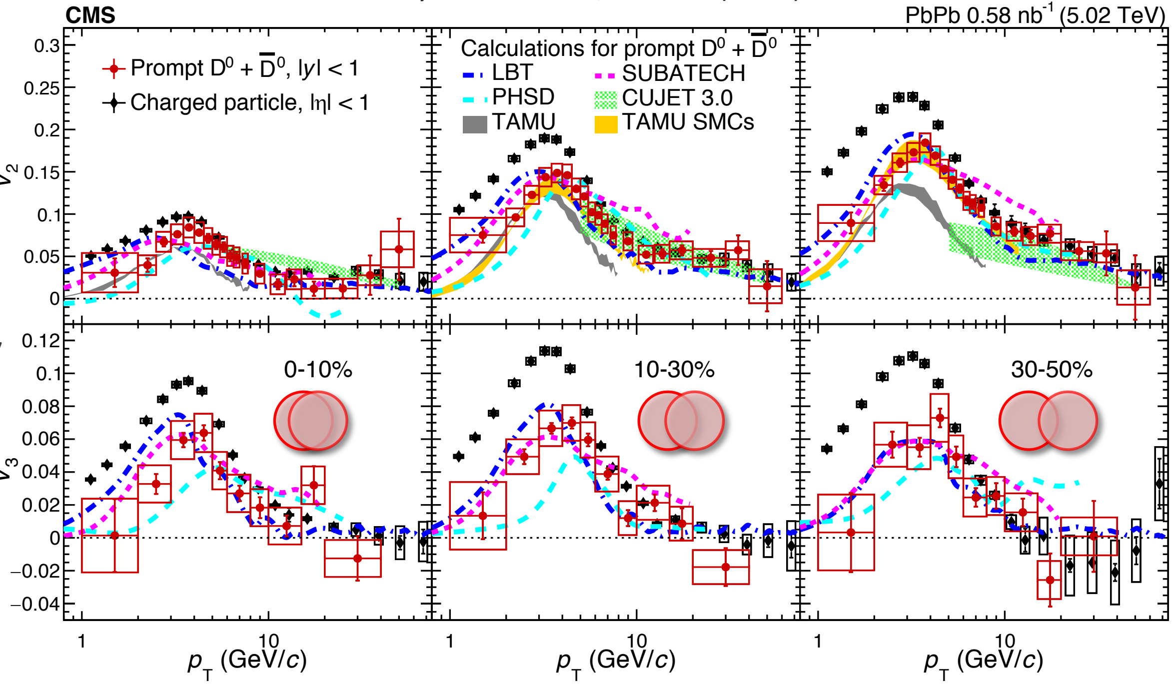
Similar trends compared to charged particles

- v_2 : considerable dependence on centrality
- v_3 : small dependence on centrality

Theory

- Resonable qualitative description

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



Charm-quark flows like lighter quarks!

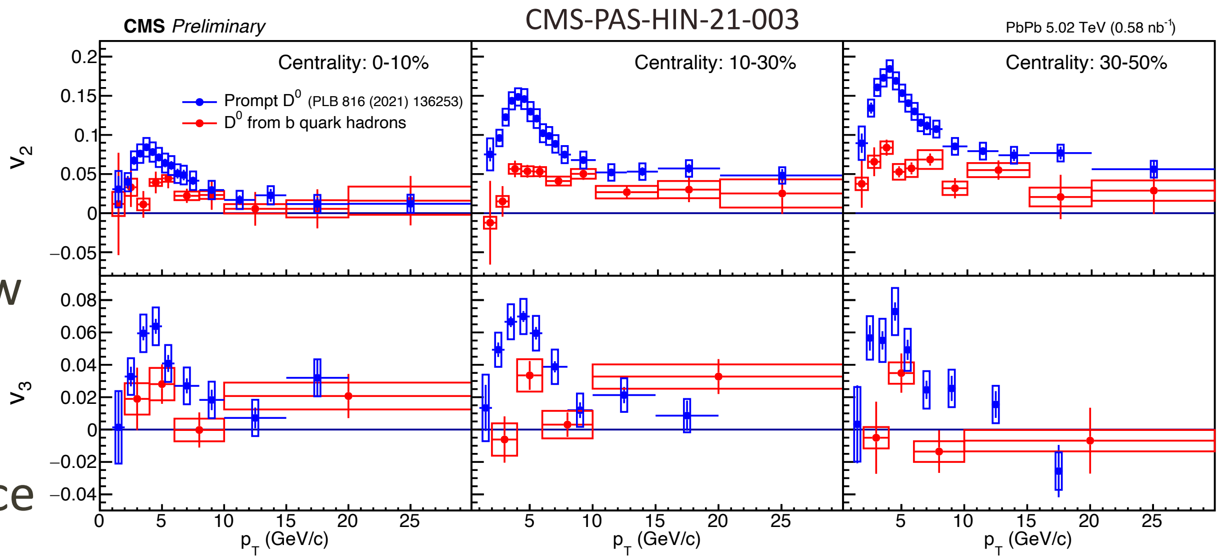
Nonpromt D^0 meson flow coefficients

B hadrons decay to D^0 mesons

Compared to prompt D^0 mesons

- ❑ Mass ordering of flow magnitudes
- ❑ Weaker p_T and centrality dependence

Observed non-zero v_3



...and also bottom-quarks!

Prompt D^0 multiparticle correlation ($v_2\{4\}$)

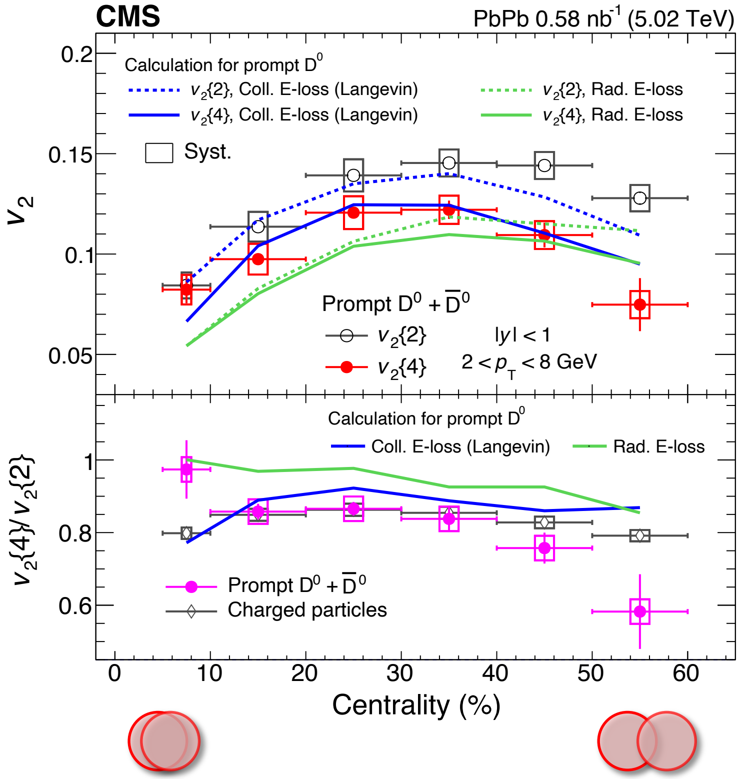
$v_2\{4\}$ increasing and then declining: explained by initial collision geometry

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

- 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%

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

arXiv:2112.12236



Femtoscopic Correlations

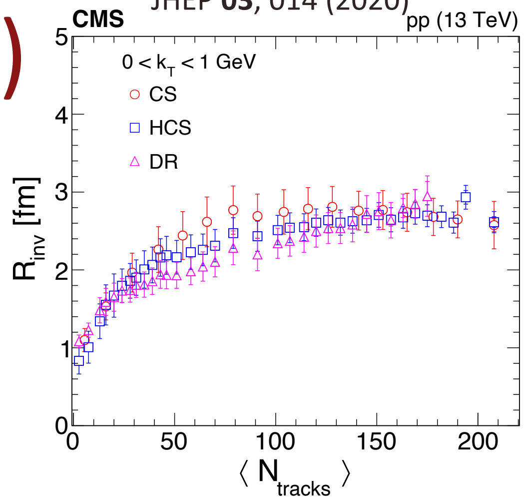
Studies on pp collisions (13 TeV)

Two-particle correlations: charged hadrons

Three different methods to measure particle emitting source parameters

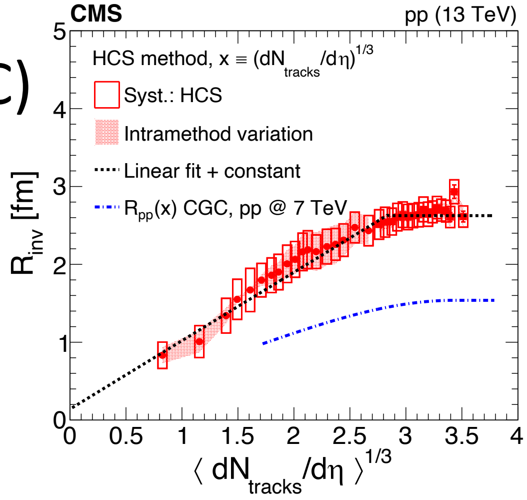
- Source size (R_{inv}) increases with number of tracks
  - But seems to saturate at higher multiplicities

JHEP **03**, 014 (2020)



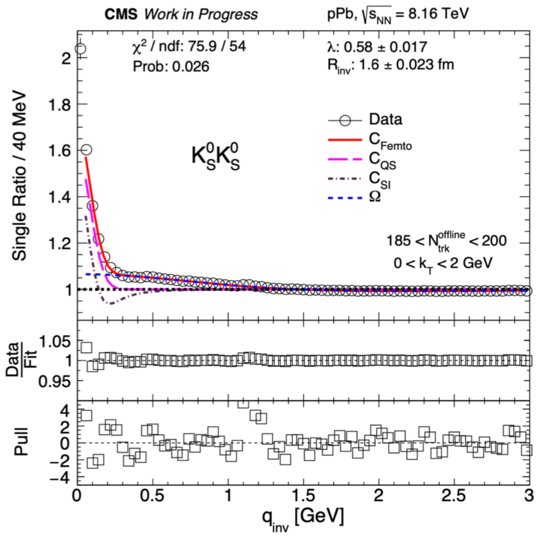
Comparison with Color Glass Condensate (CGC)

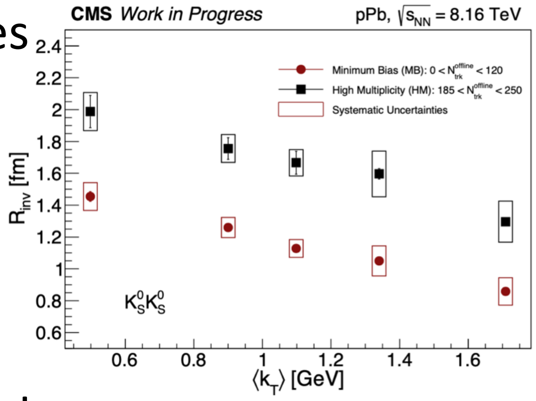
- Similar shape, but large difference in magnitude (no system expansion)
  - L. MacLerran et al. NPA **916**, 210 (2013)
  - A. Bzdak et al. PRC **87**, 064906 (2013)

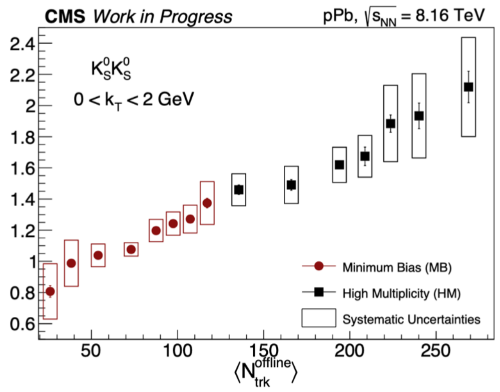


pPb collisions ($K_s^0 K_s^0$)

- Quantum statistics
  - Identical Kaons (bosons)
- Strong interactions
  - From $a_0(980)$ and $f_0(980)$ resonances
- Background
  - From jets and other sources
- Result interpretation
  - $R_{inv} \searrow$ with k_T
    - System expansion
  - $R_{inv} \nearrow$ with multiplicity
    - More particles produced, larger system



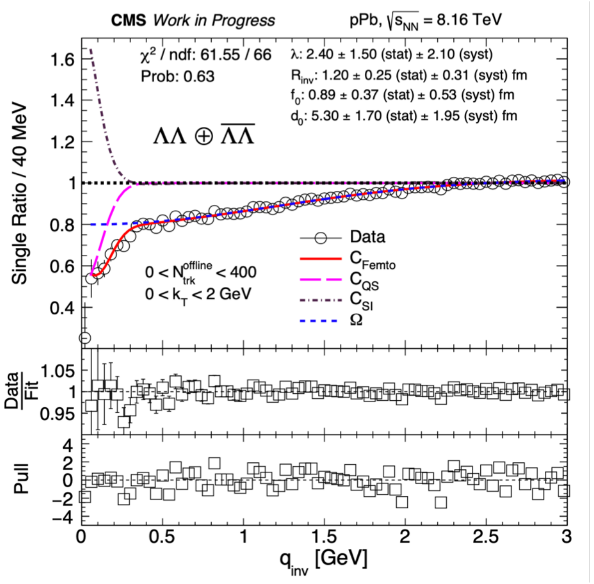


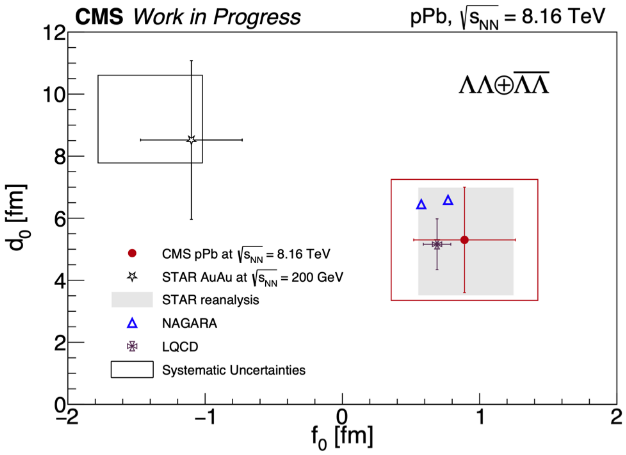


Dener's Ph. D. thesis: https://repositorio.unesp.br/handle/11449/217847

pPb collisions ($\Lambda\Lambda\oplus\overline{\Lambda\Lambda}$)

- Quantum statistics
  - Identical fermions
- Strong interactions
  - Effective range expansion
    - f_0: scattering length
    - d_0: effective range
- Background
  - From jets and other sources
- Positive f_0 indicates a positive correlation





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Femtoscopic studies of D^0 mesons correlations

- Two-particle correlation function (C(k)) vs. pair relative momentum (k)

$$C(k_1,k_2) = \frac{P(k_1,k_2)}{P(k_1)P(k_2)} \rightarrow C(k) = \int d\mathbf{r}\; S(\mathbf{r})|\Psi(\mathbf{k},\mathbf{r})|^2$$

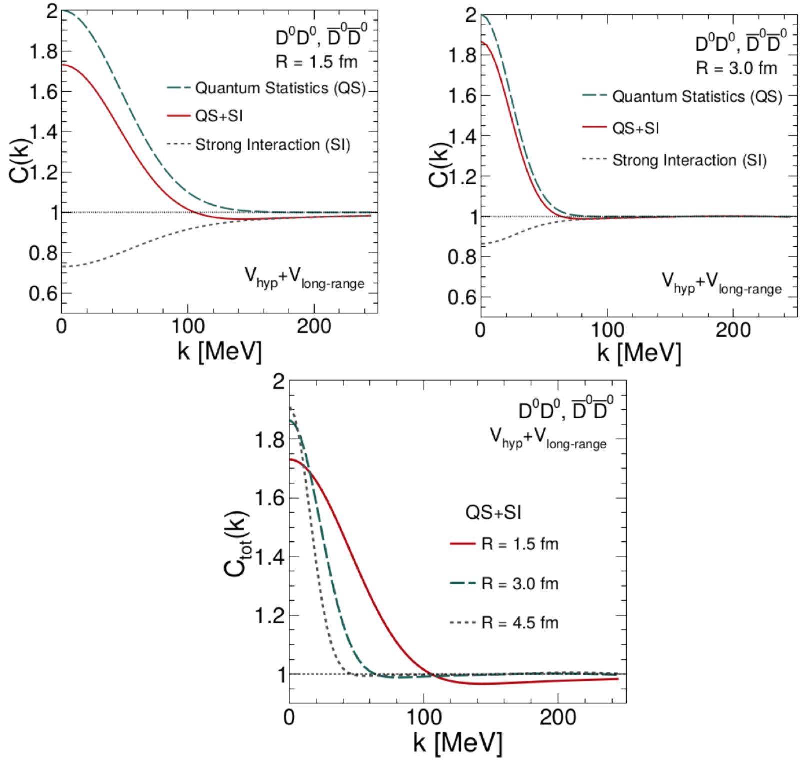
  - **Quantum Statistics (QS)**
  - Final-state interactions
    - Coulomb interaction
    - **Strong interaction (SI)**

- For the case of two identical spin zero mesons

$$C(k) = 1 + \underbrace{e^{-4k^2R^2}}_{\text{QS}} + \underbrace{8\pi \int_0^{\infty} dr\; r^2 S(r)\left[|\psi_0(k,r)|^2 - j_0^2(kr)\right]}_{\text{SI}}$$

- Scattered wave function $\Psi_0(k,r)$ and C(k) → numerically from
  - Lippmann-Schwinger equation for non-local potential

https://scipost.org/submissions/2110.15455v1/



More visible effect of the strong interaction for lower value of R

Isabela's M. Sc. dissertation: https://repositorio.unesp.br/handle/11449/215132

Summary

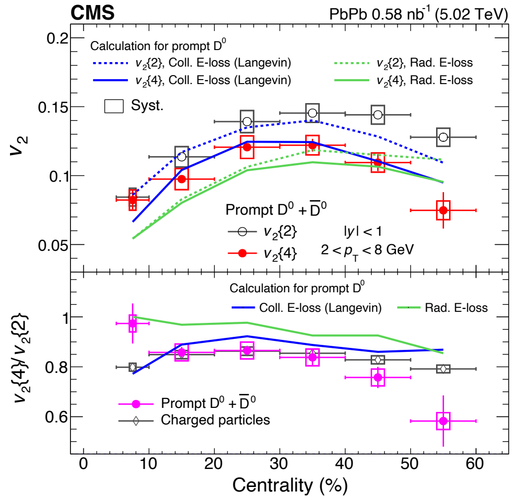
SPRACE team participates in flow & correlations analyses in the CMS collaboration

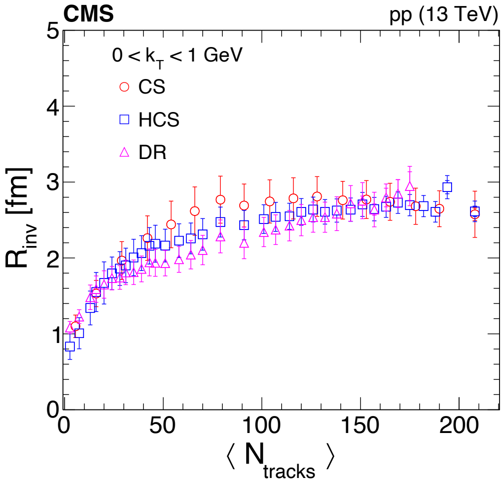
Studies on the QCD properties by using

- ❑ Femtoscopic & azimuthal correlations

Recent contributions to

- ❑ Azimuthal anisotropy with D^0 mesons
- ❑ Femtoscopic correlations with
  - Charged particles, V^0 hadrons, and D^0 mesons





Plans

Finish ongoing analyses and publish the results

- ❑ $v_2\{4\}$ with D^0 mesons: on arXiv (submitted to PRL)
- ❑ $v_n\{2\}$ of $B \rightarrow D^0$: just released preliminary results (Quark Matter 2022)
- ❑ Femtoscopy with V^0 hadrons: in approval process in the CMS collaboration

New studies

- ❑ Femtoscopic correlations
  - Involving heavier hadrons (composed by c/b-quarks)
  - Other colliding systems & more dimensions
  - Phenomenology: final state interaction → development of treatment based on effective field theory
- ❑ Azimuthal correlations
  - Two-particle and multiparticle v_n using heavy-flavor (Run3 data)
    - Including searches for strong magnetic fields created in PbPb collisions

Thank You!

THIS MATERIAL IS BASED UPON WORK SUPPORTED BY THE SÃO PAULO RESEARCH FOUNDATION (FAPESP) GRANTS NO. 2018/01398-1 AND NO. 2013/01907-0. ANY OPINIONS, FINDINGS, AND CONCLUSIONS OR RECOMMENDATIONS EXPRESSED IN THIS MATERIAL ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF FAPESP.

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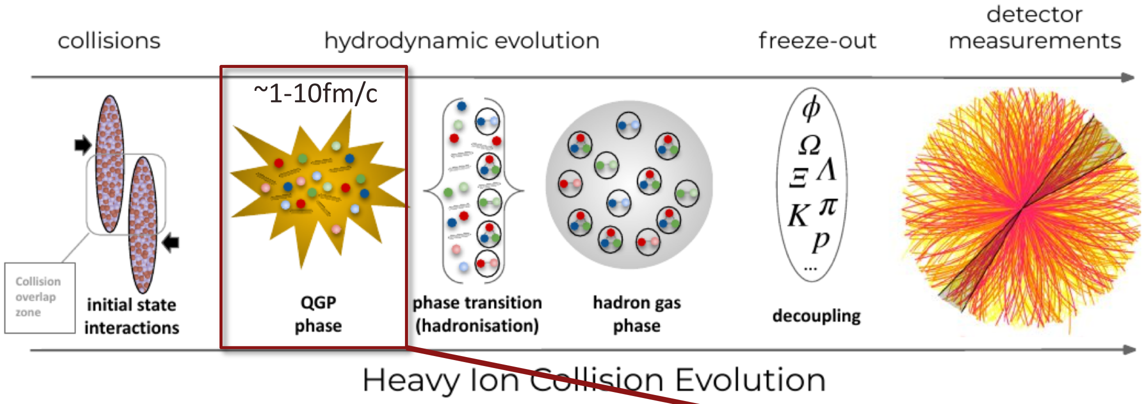
BACKUP

Introduction – why study heavy-flavor (HF)?

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



$M_{HF\ quarks}$ >> typical medium temperatures

- Experience the full evolution of the medium

Langevin drag and diffusion modeling

- HF quarks flow with the medium
- Energy-loss by scatterings with medium constituents

Phys.Rev.C 90 (2014) 2, 024911

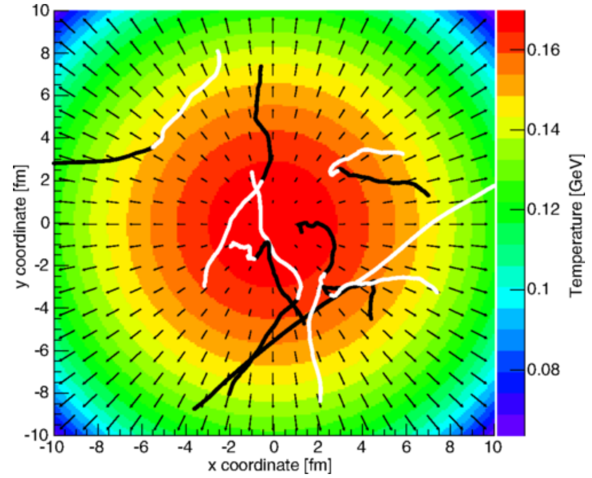


Illustration of few $c\bar{c}$ pair trajectories in the expanding medium after 10 fm/c

Introduction – why study heavy-flavor?

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

- Origin of observed collective effects in small systems
- Understand energy loss and coalescence mechanisms
- Electromagnetic field effects at initial stages of collisions
  - Δv_n between positive & negative electric charges

Phys.Rev.C 90 (2014) 2, 024911

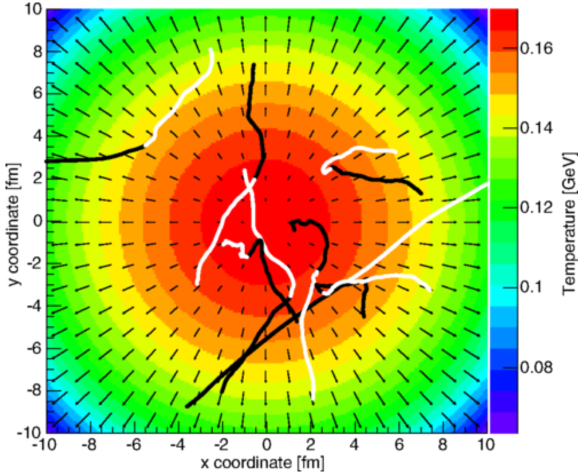


Illustration of few $c\bar{c}$ pair trajectories in the expanding medium after $10\mathrm{fm}/c$

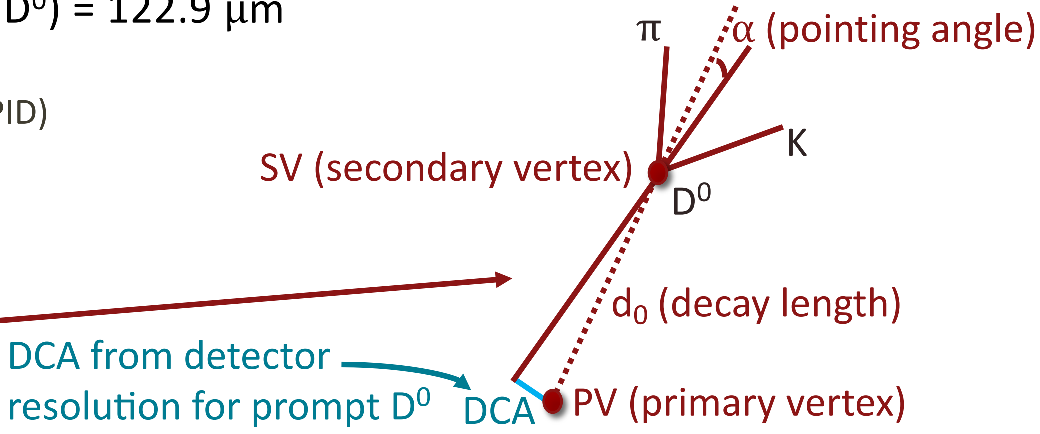
D^0 Reconstruction and Selection: 2018 Data

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

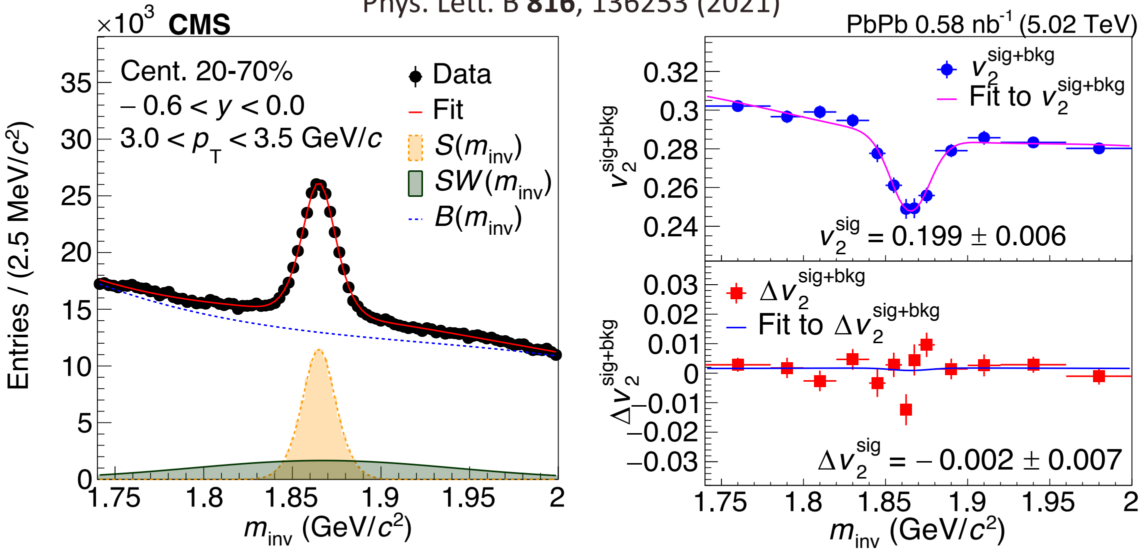
- Estimate contribution using DCA variable (nonprompt D^0 enriched region for DCA > 0.012 cm)

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

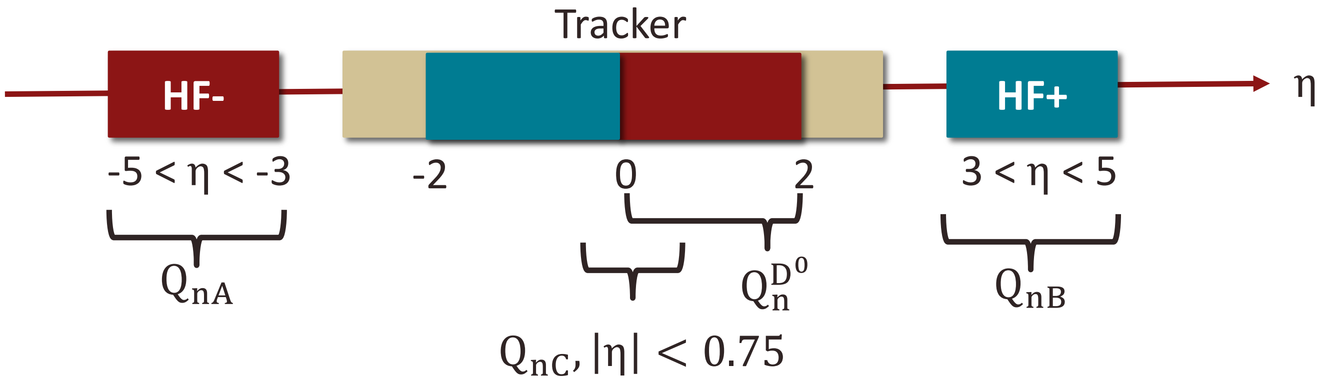
Phys. Lett. B **816**, 136253 (2021)



- ❑ Mass fit: background (3rd order polynomial), signal (double Gaussian), swap $K \leftrightarrow \pi$ (single Gaussian)
- ❑ v_n background (linear function), Δv_n (background is canceled)

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

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

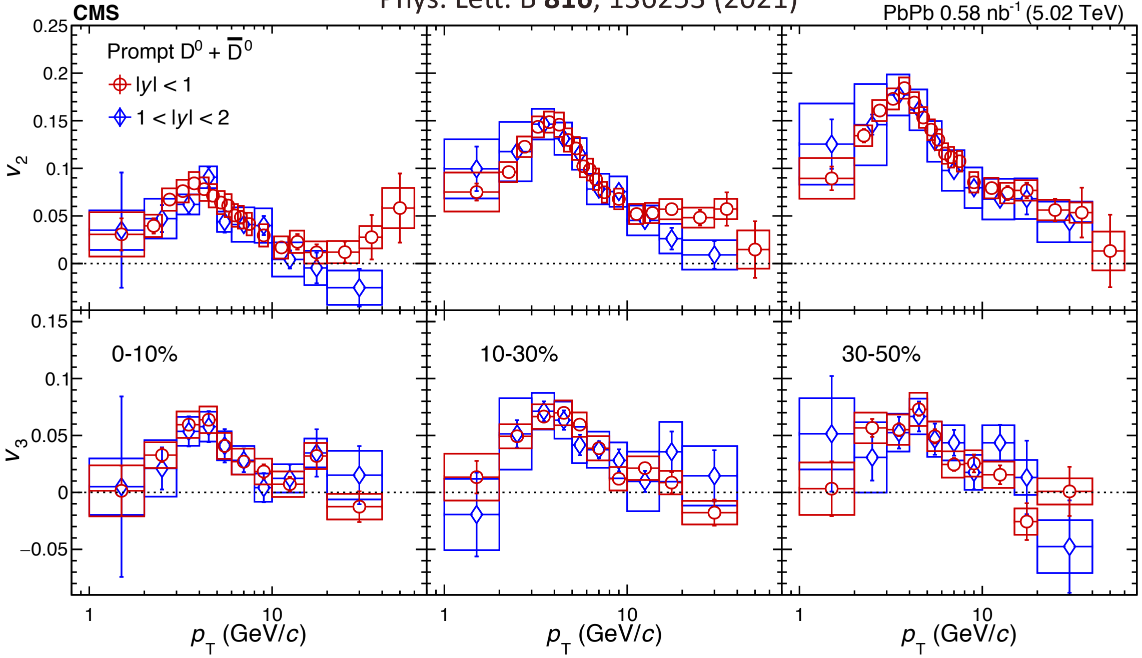
First time: forward region (1<|y|<2)

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)



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

Electric field created by participants → 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

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

Comparable to values for charged hadrons

- ❑ Constrain medium properties: electric conductivity

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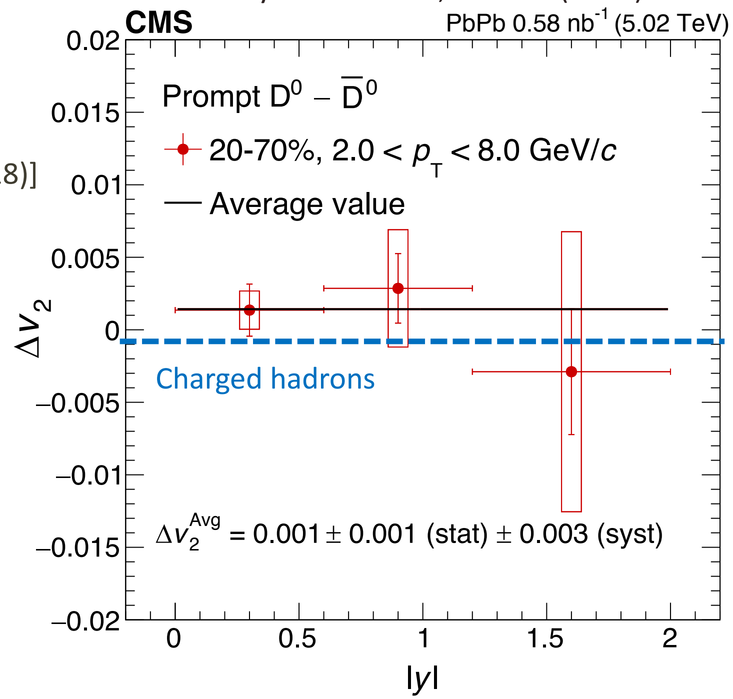


v_2 & v_3 as Function of Centrality and Rapidity

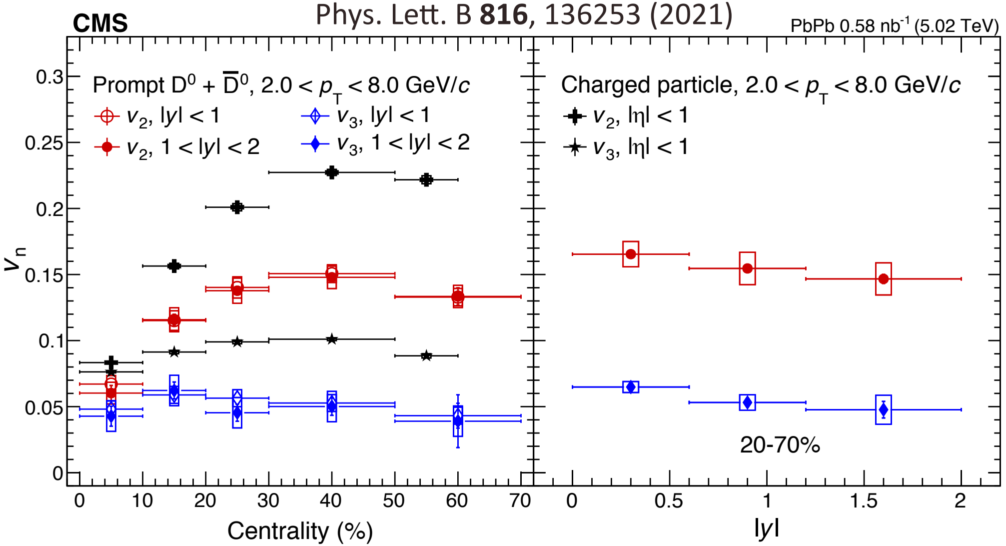
Centrality bins

- 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)



Event-by-Event (EbyE) Flow Fluctuations

EbyE fluctuations of heavy quark flow explored experimentally

$$v_2\{2\}^2 \sim \langle v \rangle^2 + \delta + \sigma_v^2$$ (Scalar Product)

- $\langle v \rangle^2$: flow (EP)
- δ: non-flow
- σ_v^2: flow-fluctuations

$$v_2\{4\}^2 \sim \langle v \rangle^2 - \sigma_v^2$$ (4-Particle Cumulants)

- $\langle v \rangle^2$: flow (EP)
- σ_v^2: flow-fluctuations

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

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 in 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

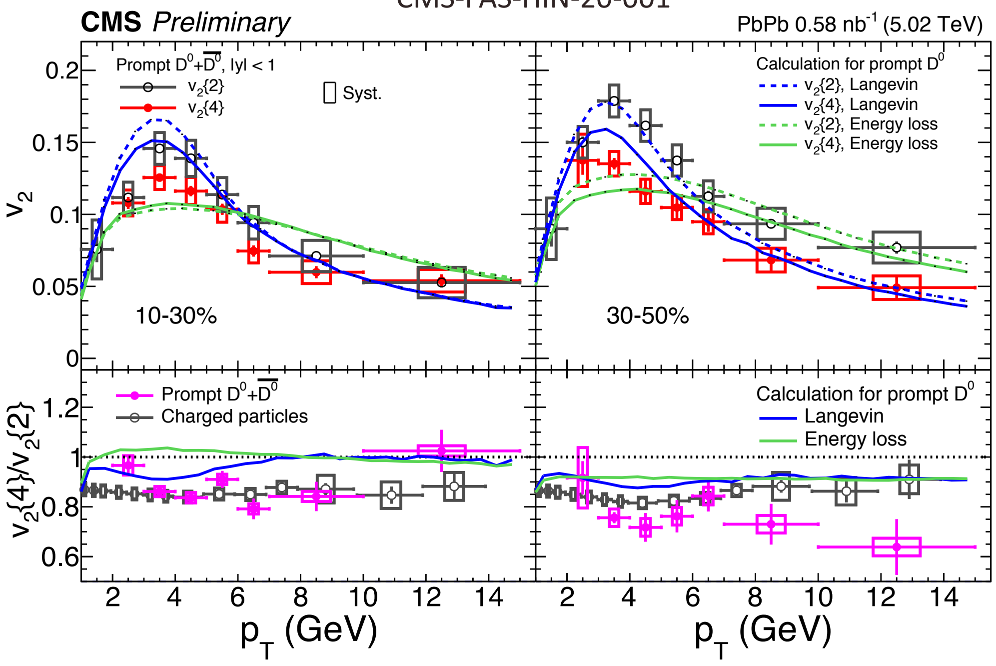
- 10-30%: consistent with charged particles
- 30-50%: hint of splitting of ratio between D^0 and charged particles at high-p_T
  - Energy loss fluctuation effects become more significant?

Theoretical calculations

- Resonable qualitative description

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

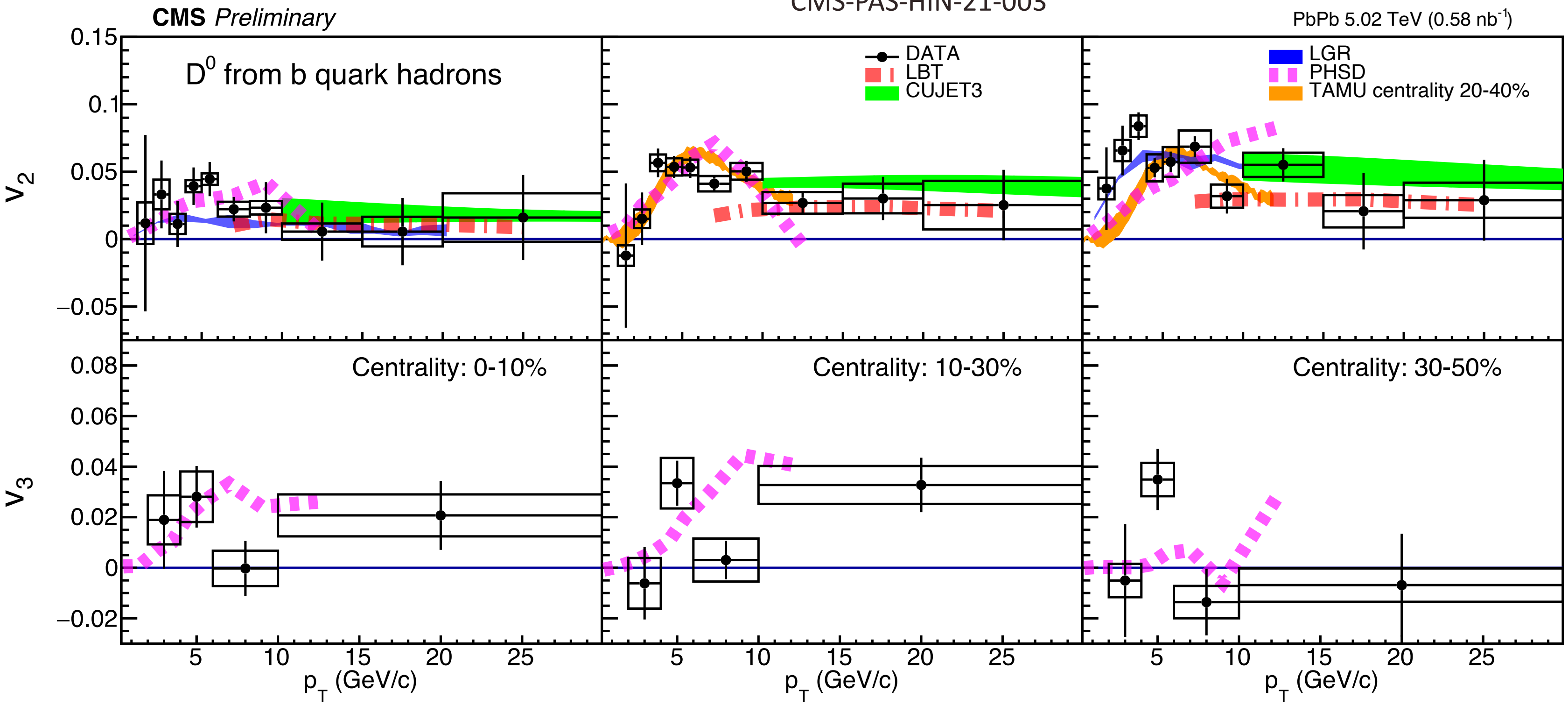
CMS-PAS-HIN-20-001



B→ D^0 Flow

Comparison with models

CMS-PAS-HIN-21-003



4-particle Cumulant Method

Four-particle Cumulants (I)

Liuyao Zhang, IS2021

Differential flow: PRC 83, 044913(2011)

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

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

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

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

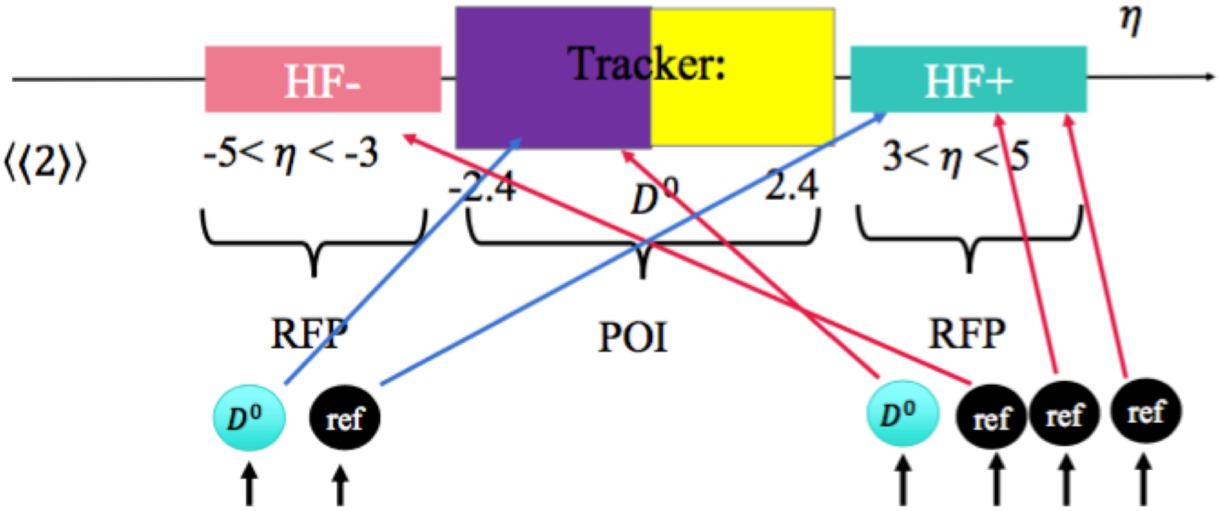
$c_n\{4\}$: four-particle cumulant $\rightarrow$ reference flow.

Four-particle Cumulants (II)

Liuyao Zhang, IS2021

$d_n\{4\}$:

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



$\langle 2' \rangle = \left\langle e^{in(\psi_1 - \phi_2)} \right\rangle$ $\quad$ $\langle 4' \rangle = \left\langle e^{in(\psi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle$

definition:

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

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

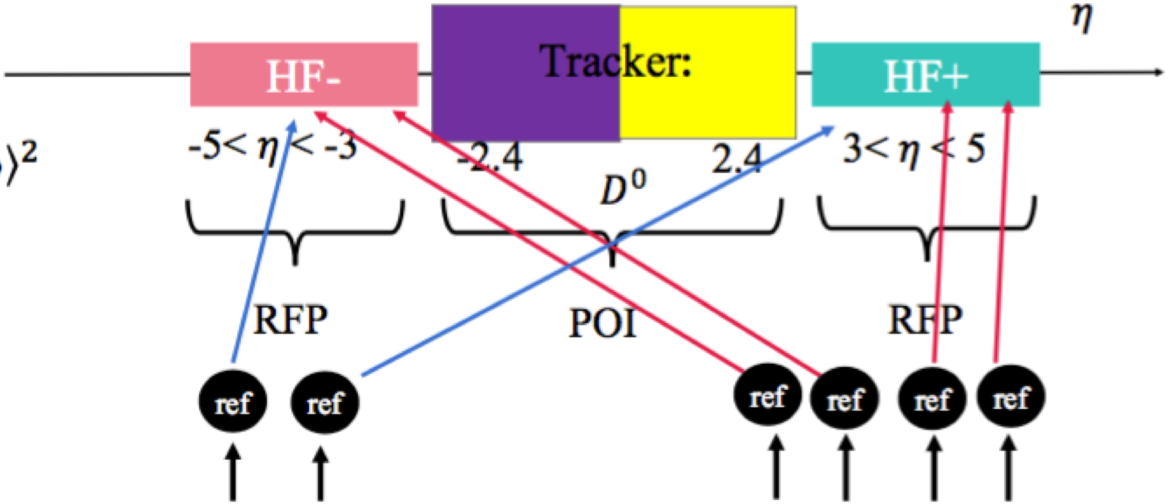
Note: weight $M^{HF-} = \sum(E_T)_i$ from HF- , $M^{HF+} = \sum(E_T)_i$ from HF+

Four-particle Cumulants (III)

Liuyao Zhang, IS2021

$c_n\{4\}$:

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



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

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

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.
$\Longrightarrow$ To judge the fluctuation from soft and hard components

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

Soft fluctuation: initial condition fluctuation

Hard fluctuation energy loss fluctuation

Hard particle:

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

➢ Initial condition fluctuation dominated: $\frac{\langle v_2^2 V_2 V_2^*(\mathrm{hard})\rangle}{\langle v_2^2\rangle\langle V_2 V_2^*(\mathrm{hard})\rangle} \to \frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2} \Rightarrow \frac{v_2\{4\}(\mathrm{hard})}{v_2\{2\}(\mathrm{hard})} \to \frac{v_2\{4\}}{v_2\{2\}}$

➢ Significant energy loss fluctuation: $\frac{\langle v_2^2 V_2 V_2^*(\mathrm{hard})\rangle}{\langle v_2^2\rangle\langle V_2 V_2^*(\mathrm{hard})\rangle} \neq \frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2} \Rightarrow \frac{v_2\{4\}(\mathrm{hard})}{v_2\{2\}(\mathrm{hard})} \downarrow\uparrow$

1. arXiv:1906.10768v2

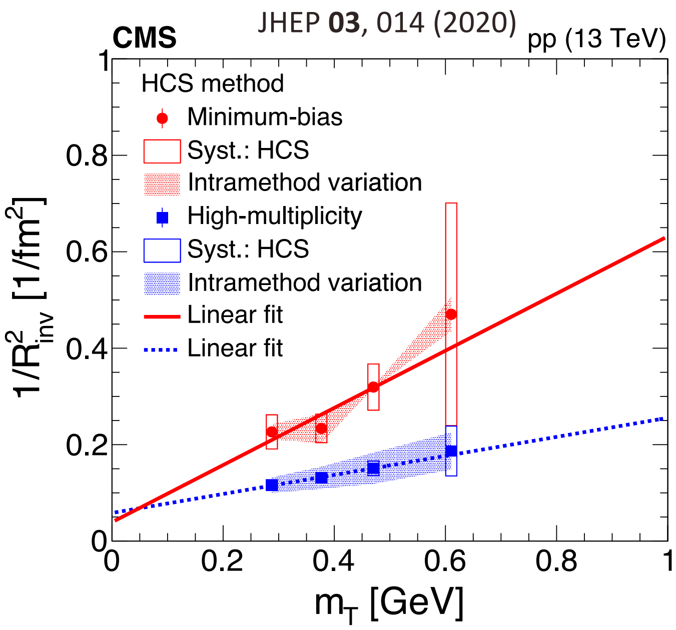
Femtoscopy

Studies on pp collisions (13 TeV) – m_T dependence

From hydrodynamics

NPA **946**, 227 (2016)

- Intercept
  - Source geometrical size (at freeze-out)
- Slope
  - Larger slope → larger flow
    - Lower multiplicities
  - Smaller slope → smaller flow
    - Higher multiplicities



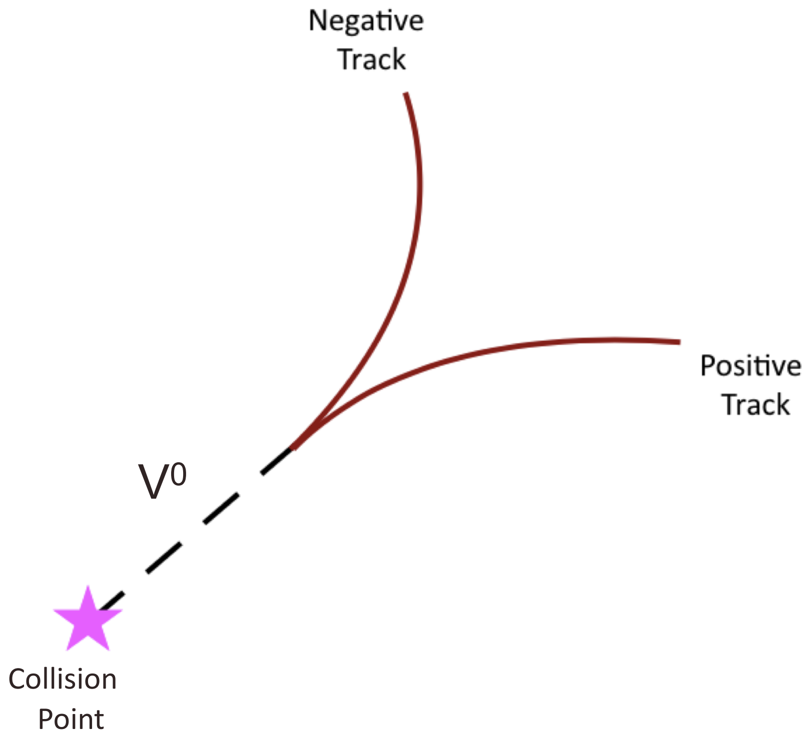
Measuring strange particles

V^0 particles:

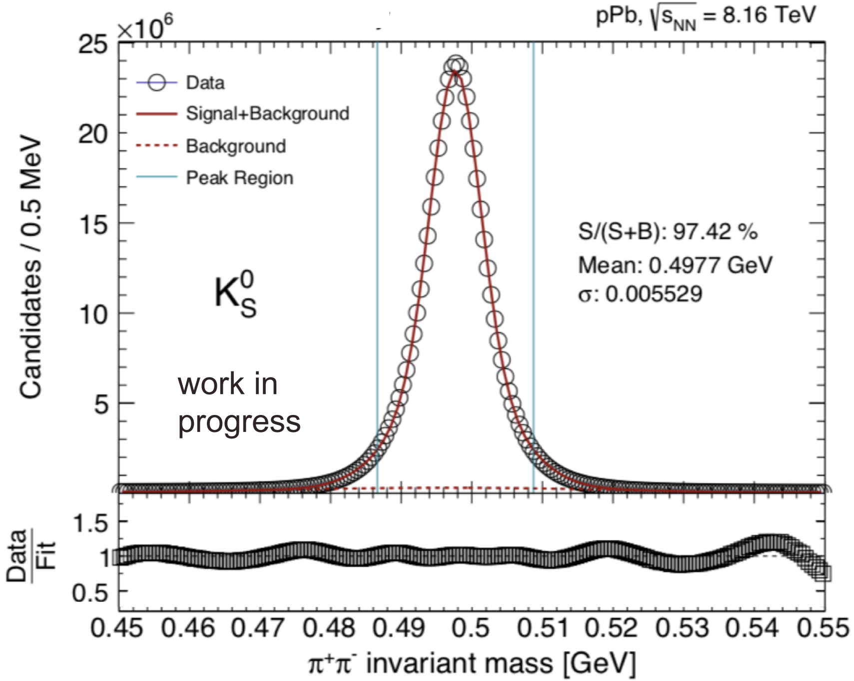
- $K^0_s \rightarrow \pi^+\pi^-$ (BR: 69.2%)
  - Mass (PDG): 0.4976 GeV
- $\Lambda/\overline{\Lambda} \rightarrow p\pi^-/\bar{p}\pi^+$ (BR: 63.9%)
  - Mass (PDG): 1.1156 GeV
  - the lower-momentum track is assumed to be the pion

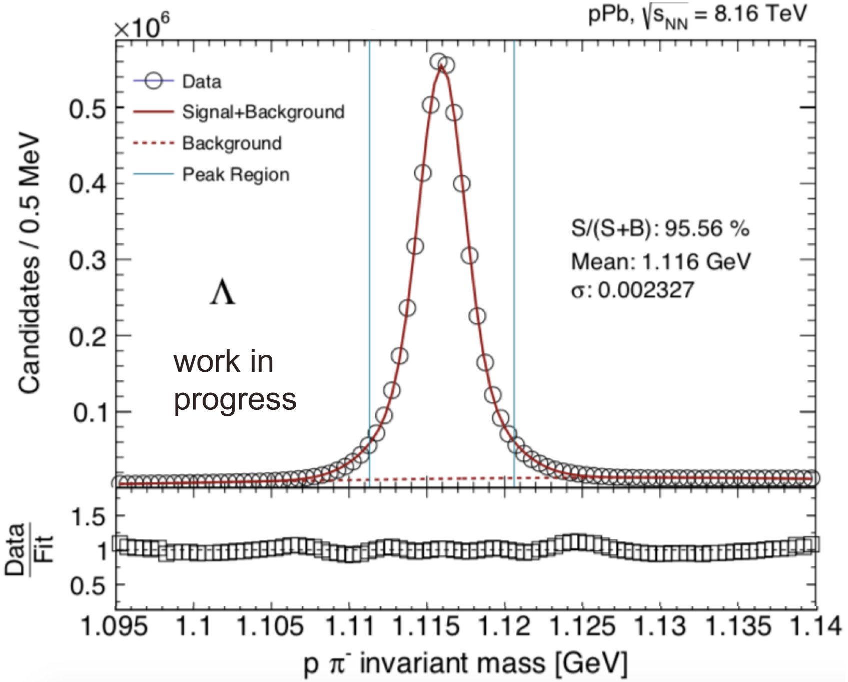
CMS does not have yet a PID detector

- Combine positive tracks and negative tracks in certain range of M_{inv}



Invariant mass





Fit: Double gaussian with same mean (signal) + 4th order polynomial (background)

Non-identical lambdas

- Strong interactions
  - ERE
- Background
  - from jets and other sources
- Result interpretation of SI
  - Non-zero imaginary part
    - annihilation process
  - Negative f_0 indicates an repulsive femtoscopic behavior