Measurement of azimuthal anisotropy of $f_0(980)$ and D^0 in heavy ion collisions at CMS

Nihar Ranjan Saha

Indian Institute of Technology, Madras

(On behalf of CMS Collaboration, CERN)

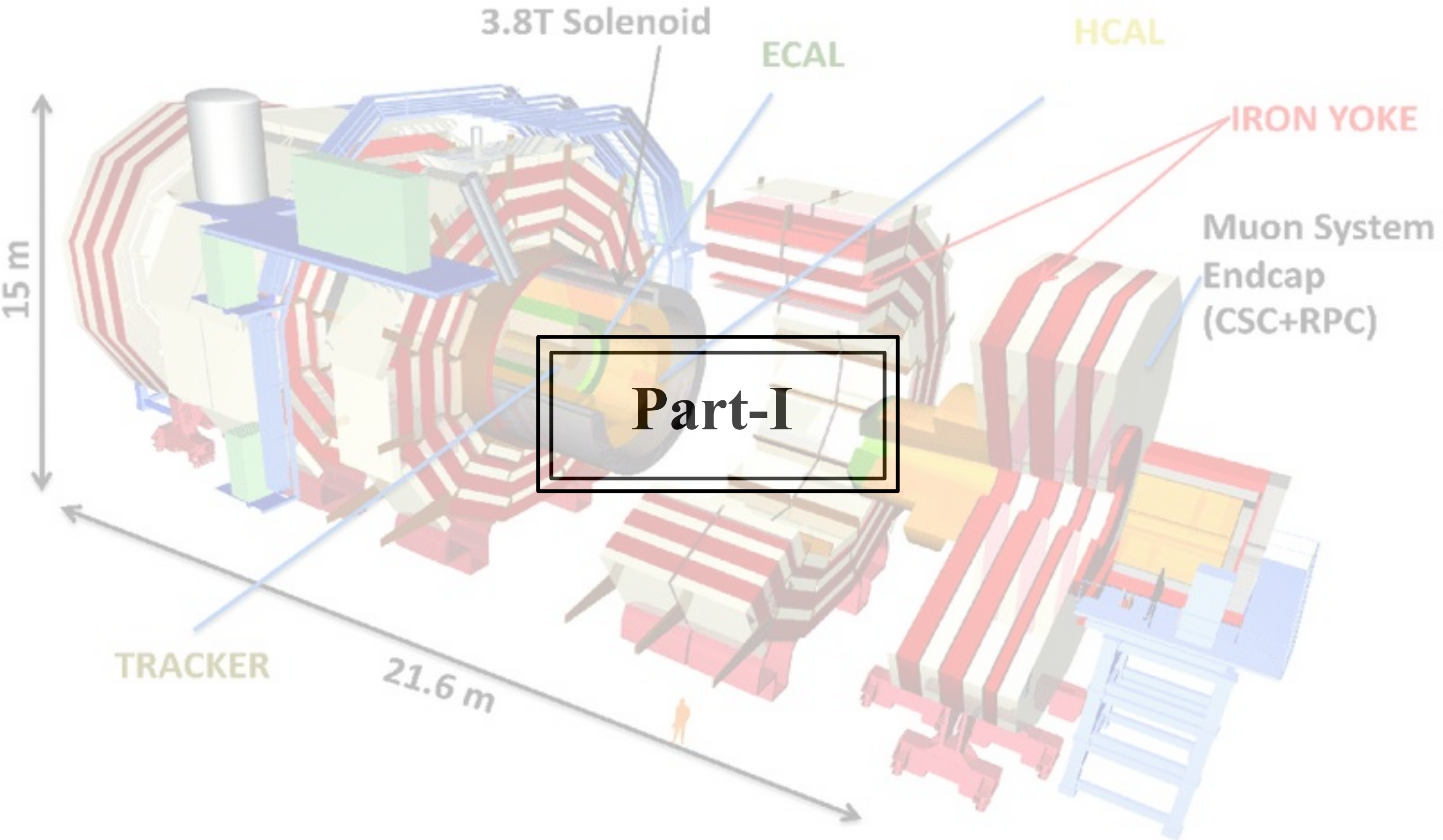

WPCF - Resonance Workshop 2023

Catania (Italy), November 6-10, 2023

Outline

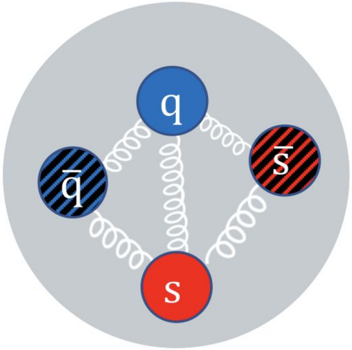
- Introduction: Exotic hadrons and azimuthal anisotropy
- Production of $f_0(980)$ and D^0
- Azimuthal anisotropy of $f_0(980)$ and D^0
- NCQ scaling of $f_0(980)$
- Results
- Summary

Part-I



3.8T Solenoid
ECAL
HCAL
IRON YOKE
Muon System
Endcap
(CSC+RPC)
15 m
TRACKER
21.6 m

Motivation: Exotic hadrons



Example of exotic hadron: tetra-quark

- **Exotic hadrons:** configurations other than the usual $q\bar{q}$ and qqq ($\bar{q}\bar{q}\bar{q}$)

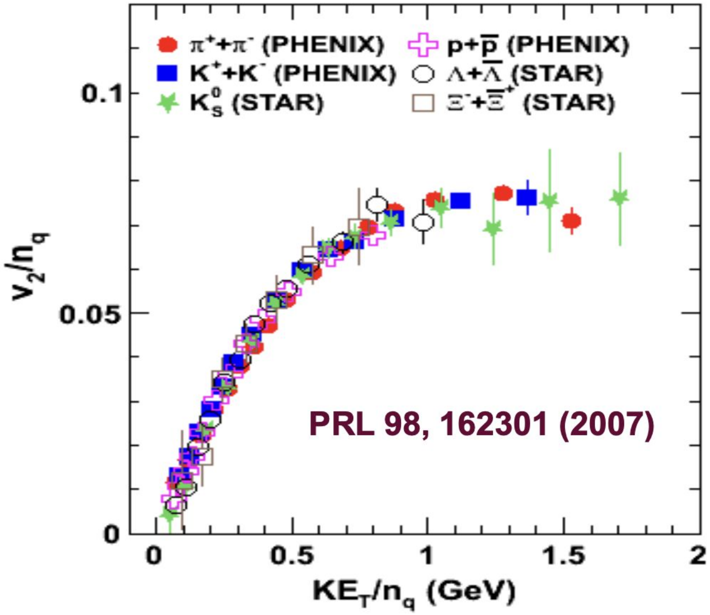
- ***f_0(980)***: candidate of exotic hadron first observed in ππ scattering experiments in the 1970's.

  S.D. Protopopescu, Phys. Rev. D 7 (1973) 1279
  B. Hyams, Nucl. Phys. B 64(1973) 134

- **The configuration of *f_0(980)* is still controversial:** $s\bar{s}$ meson, $s\bar{s}q\bar{q}$ tetraquark, $q\bar{q}g$ hybrid, or $K\bar{K}$ molecule.

  D.V. Bugg, Phys. Rept. 397 (2004) 257
  E. Klempt and A. Zaitsev, Phys. Rept. 454 (2007) 1
  J.R. Pelaez, Phys. Rept. 658 (2016) 1

Introduction: Elliptic Flow v_2 and NCQ scaling



$$E_T = \sqrt{p_T^2 + m_0^2} - m_0$$

- ❖ Azimuthal anisotropy: $\frac{dN}{d\phi} \propto \quad 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi - \psi\right)\right]$

- ❖ Approximate **number of constituent quark (NCQ)** scaling

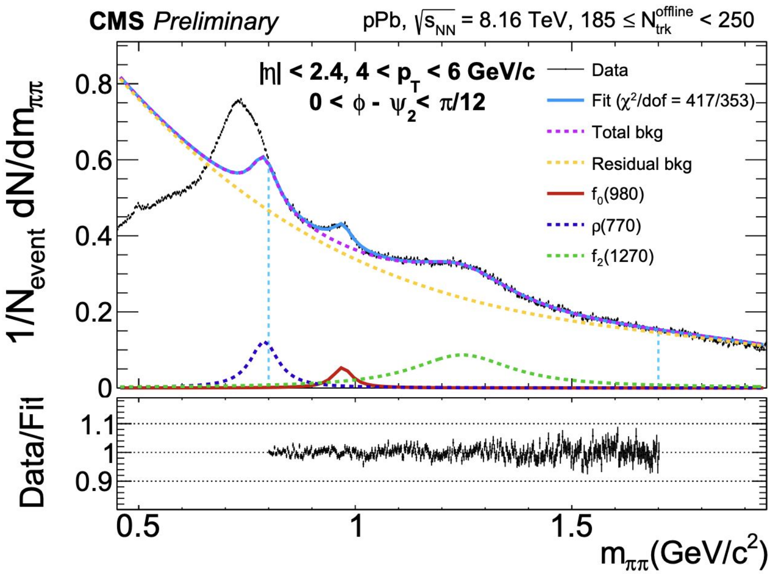
$$v_n(p_\mathrm{T})/n_\mathrm{q} = v_{n,q}(p_\mathrm{T}/n_\mathrm{q})$$
$$v_n(E_\mathrm{T})/n_\mathrm{q} = v_{n,\mathrm{q}}(E_\mathrm{T}/n_\mathrm{q})$$

- ❖ Coalescence hadronization provides one possible mechanism: n_q quarks combine into a hadron with ~ equal momenta.

$$\frac{dN_h}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^{n_q} \propto [1 + 2v_{2,q}(p_T, q)cos(2[\phi - \psi_{RP}])]^{n_q}$$
$$\propto 1 + n_q.2v_{2,q}(p_T, q)cos(2[\phi - \psi_{RP}])$$

- ❖ v_2 measurement of ***$f_0(980)$* → *n_q***

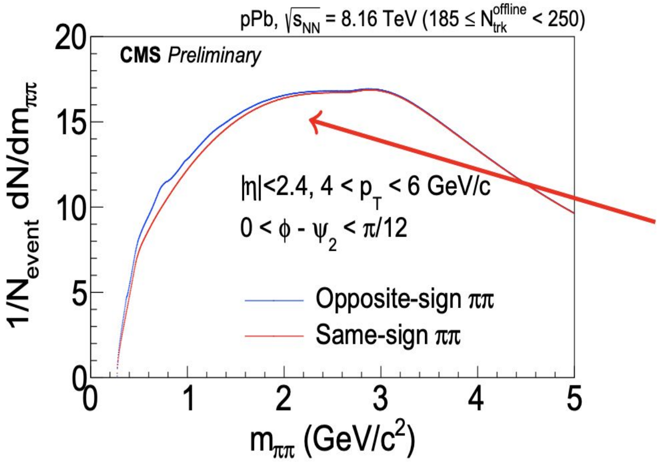
Reconstruction of $f_0(980)$



- Dataset: pPb collisions at $\sqrt{S_{NN}}$ = 8.16 TeV in high multiplicity events collected in 2016
- Dominant decay channel: $f_0(980) \rightarrow \pi^+\pi^-$
- No PID in this analysis; All charged tracks assumed to be pions.
- Mass Spectrum: opposite sign pair $\pi^+\pi^-$ subtracted by same sign pair $\pi^+\pi^+$, $\pi^-\pi^-$

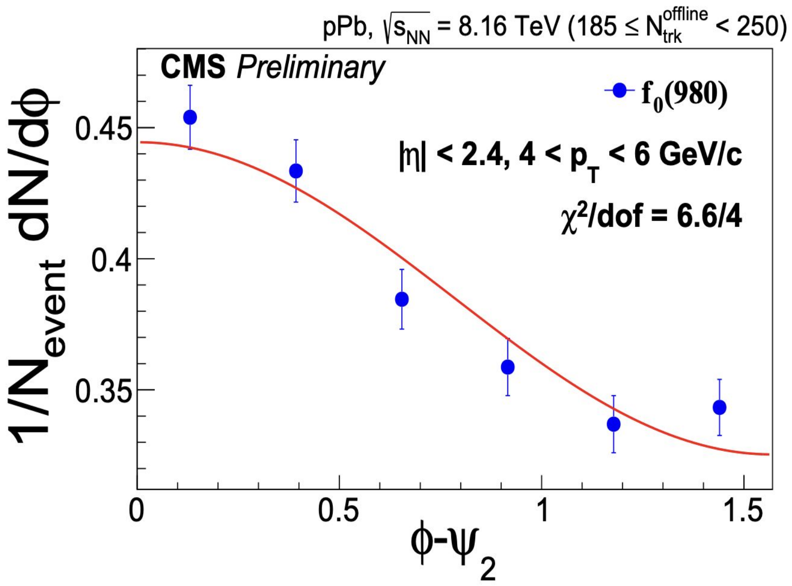
- Peak is modeled with Breit-Wigner function.
- Residual background: 3rd order polynomial.
- Fitting range: $0.8 < m_{\pi\pi} < 1.7$ GeV /c2

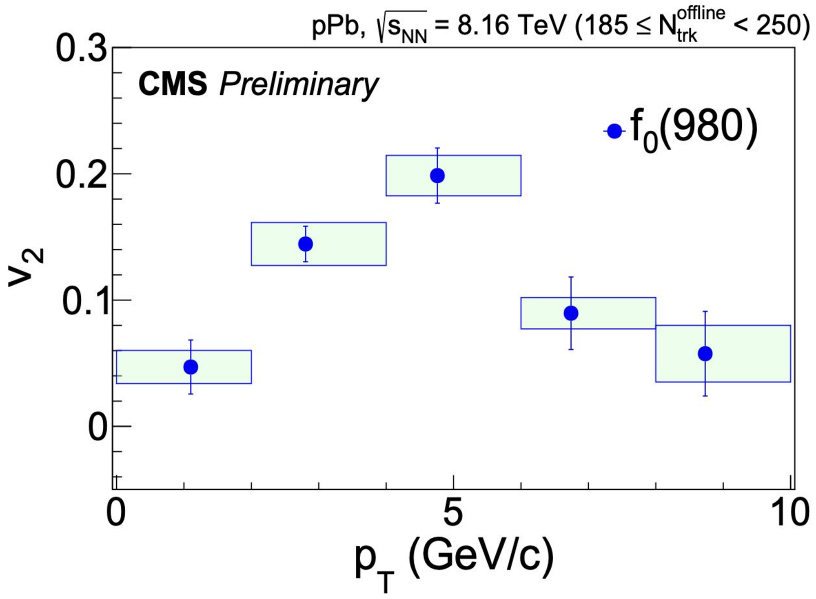
CMS-PAS-HIN-20-002



Large Combinatorial Background

v_2 Extraction of $f_0(980)$

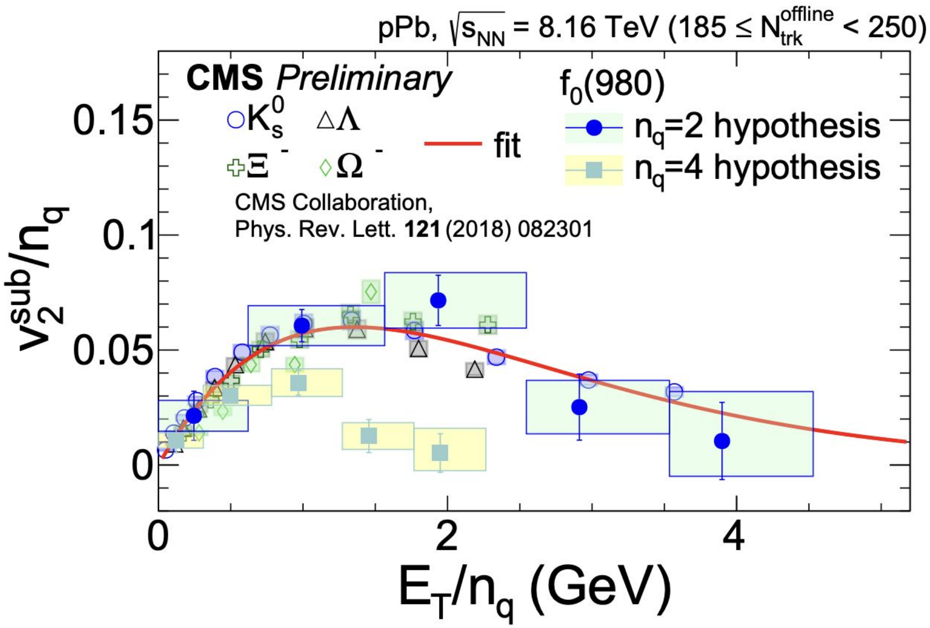




- Yield of $f_0(980)$ extracted for different $\phi - \psi_2$ ranges.
- Event-plane resolution is corrected.

CMS-PAS-HIN-20-002

n_q extraction for $f_0(980)$



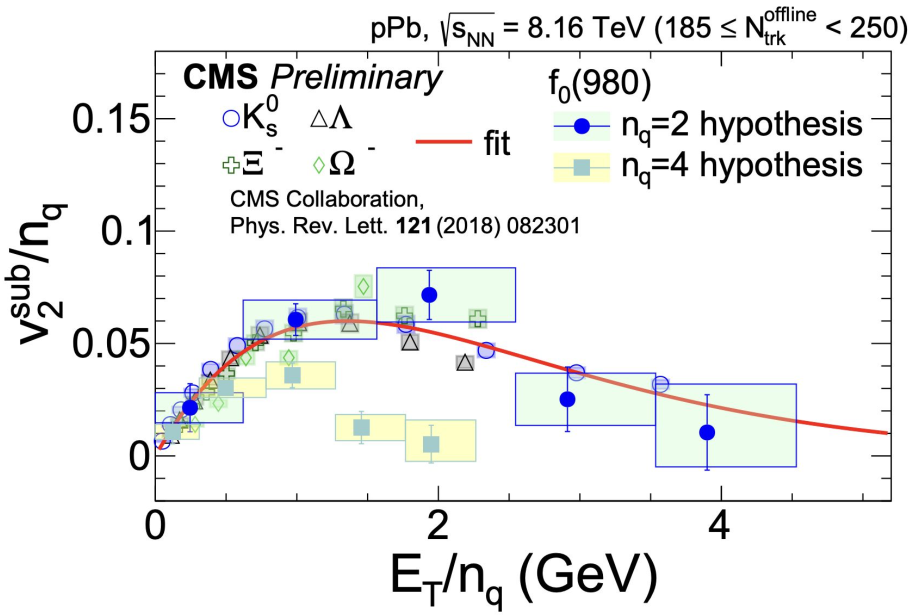
- NCQ scaling fit in E_T/n_q

$$\frac{E_T}{n_q}(p_0 + p_1\frac{E_T}{n_q})e^{-p_2\frac{E_T}{n_q}}$$

- Qualitatively consistent with $n_q = 2$ for $f_0(980)$
- Qualitatively inconsistent with $n_q = 4$ for $f_0(980)$

CMS-PAS-HIN-20-002

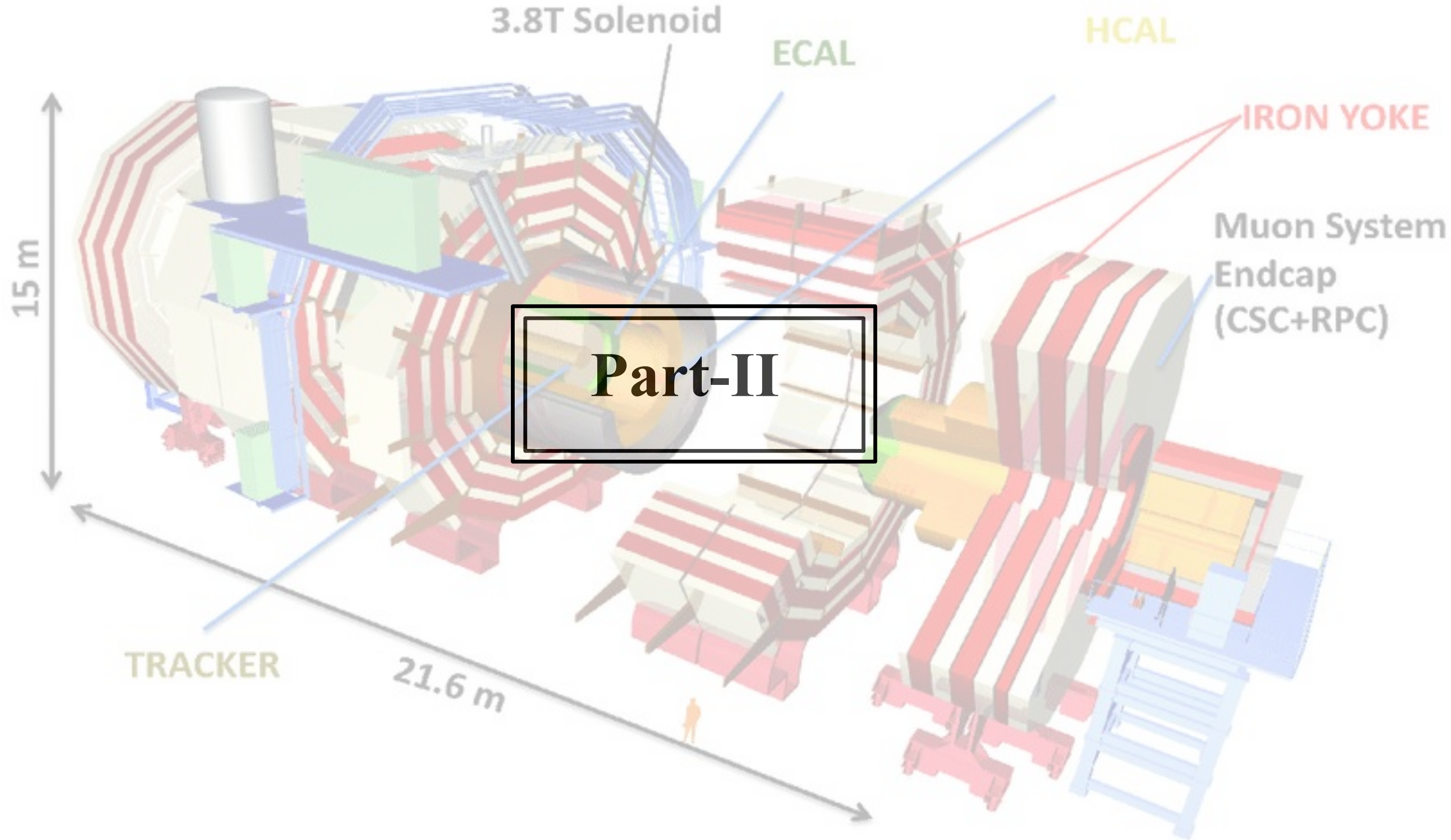
Conclusion: $f_0(980)$



- v_2 of $f_0(980)$ measured as a function of p_T up to 10 GeV/c
- Assuming NCQ scaling, n_q of $f_0(980)$ is consistent with 2
- n_q = 4 (tetra-quark state or $K\bar{K}$ molecule) excluded with 7.7σ
- n_q = 3 ($q\bar{q}g$ hybrid) excluded with 3.5σ
- CMS data favor $q\bar{q}$ normal meson state for $f_0(980)$.

CMS-PAS-HIN-20-002

Part-II


3.8T Solenoid
ECAL
HCAL
IRON YOKE
Muon System
Endcap
(CSC+RPC)
15 m
TRACKER
21.6 m

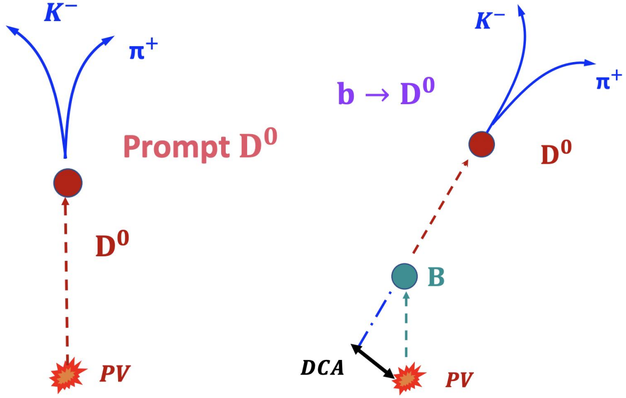
Motivation: D^0 study

Why D^0 mesons?

- ~40% of all prompt charm hadrons are D^0 meson **(Prompt D^0)**
- ~70% of all b hadrons decay to D^0 mesons **(Non Prompt D^0)**
- Best avenue for charm quark properties.

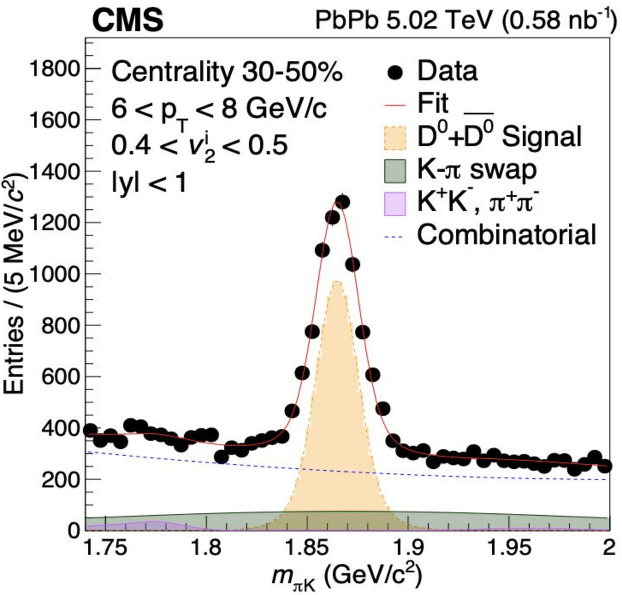
Reconstruction

- CMS PbPb $\sqrt{S_{NN}}$ = 5.02 TeV data
- Inclusive D^0 reconstruction.
- No particle identification: All opposite charge track pairs combinations.
- **B**oosted **D**ecision **T**ree for background rejection.

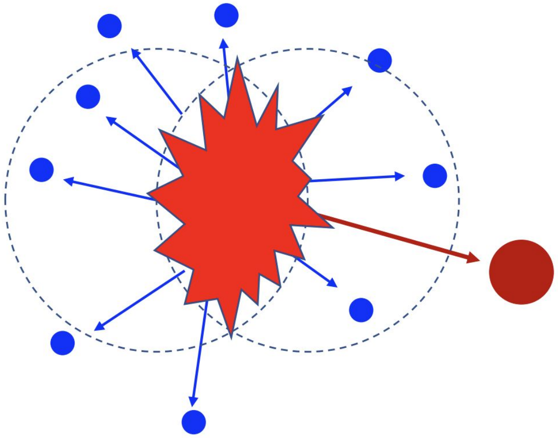


Inclusive D^0 Yield

- Signal mass spectrum: double gaussian
- Swap component: gaussian
- K^+K^- & $\pi^+\pi^-$: Crystal ball functions
- Combinatorial: polynomial 3rd order



Introduction: D^0 anisotropy

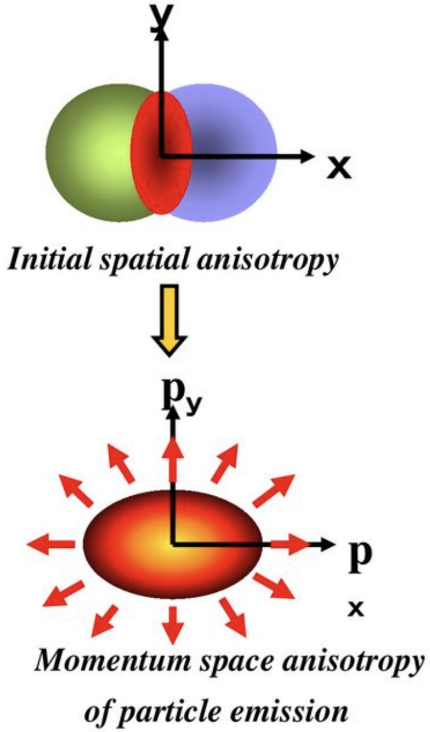


- **Anisotropy coefficient,** v_n

$$v_n = < 2cos\, n(\phi - \psi_n) >$$

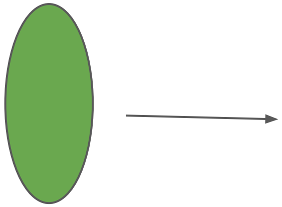
$\phi \rightarrow$ D^0 azimuthal angle

$\psi_n \rightarrow$ Symmetry plane

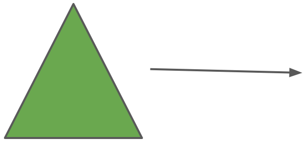


We can probe:
- Diffusion
- Path dependent parton energy loss
- Hadronization

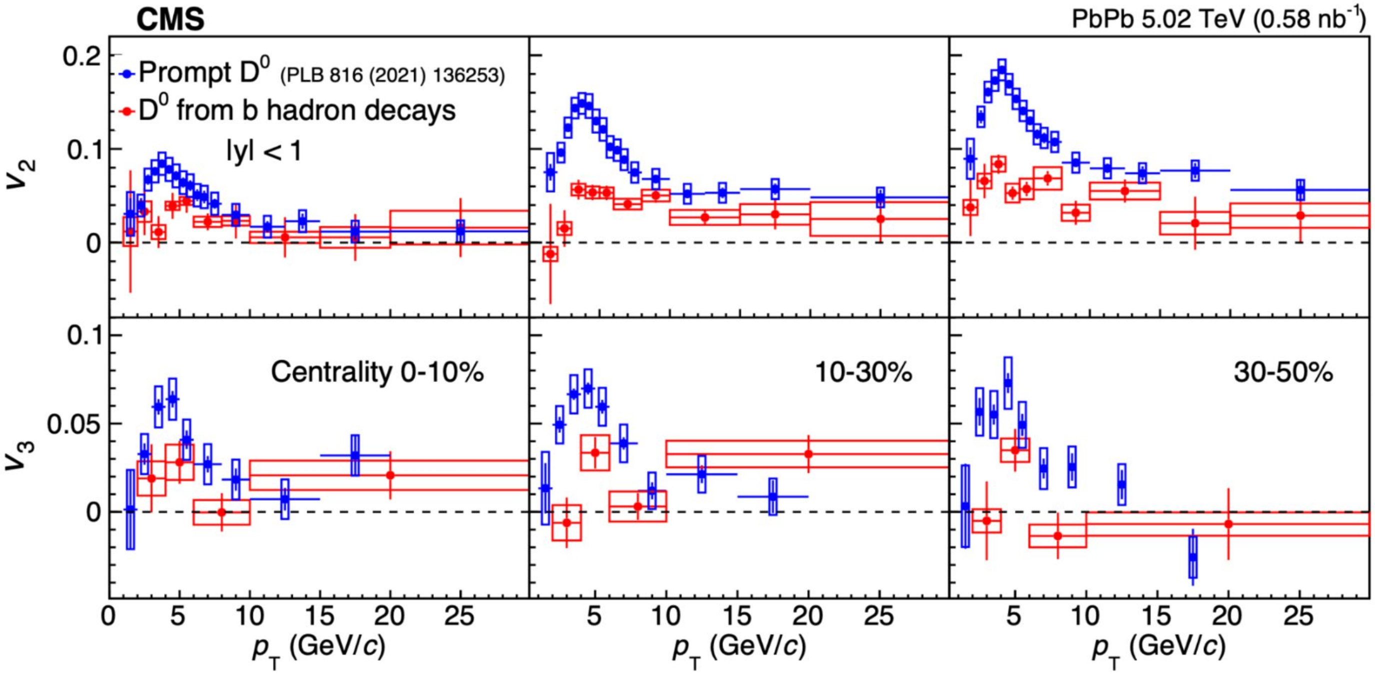
Results: D^0 anisotropy



Elliptic Flow



Triangular flow



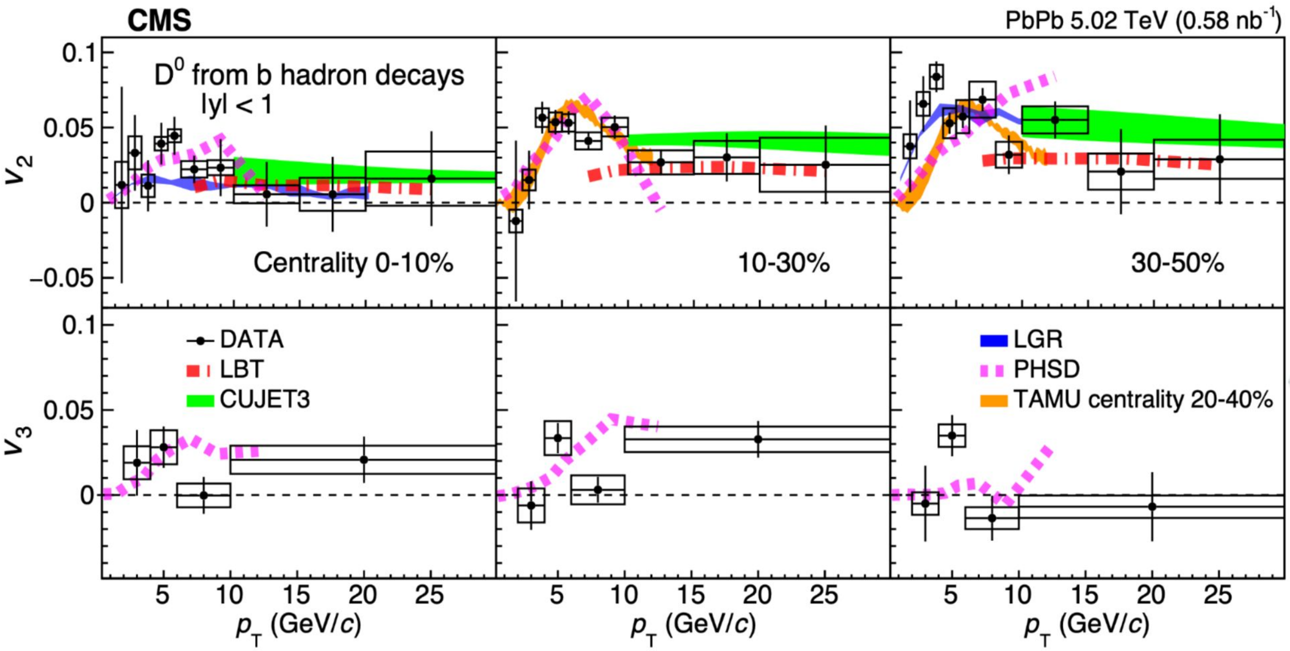
arXiv:2212.01636
submitted to PLB

First measurement of $b \rightarrow D^0$ anisotropy in PbPb collisions

- ❖ Mass ordering of flow magnitudes.
- ❖ Weak p_T and centrality dependence.
- ❖ Indication of nonzero v_3

- ❖ Method: Scalar Product
- ❖ DCA is used to estimate non-prompt fraction

Results: Model comparison



High pT

CUJET3 CPC 43 4 (2019) 044101

LBT PRC 94 (2016) 014909

Low pT

PHSD: PRC 92 (2015) 014910

TAMU PLB 735 (2014) 445

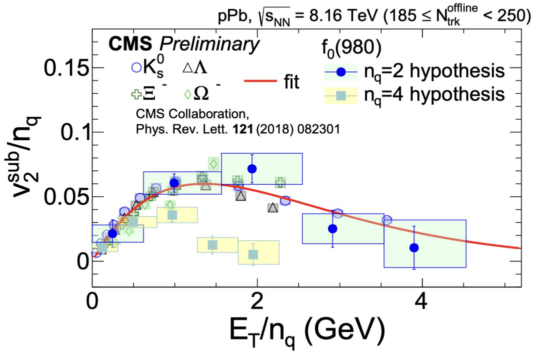
LGR EPJ C 80 7 (2020) 671

- Qualitatively good agreement between theory and data
- No model can describe whole p_T range

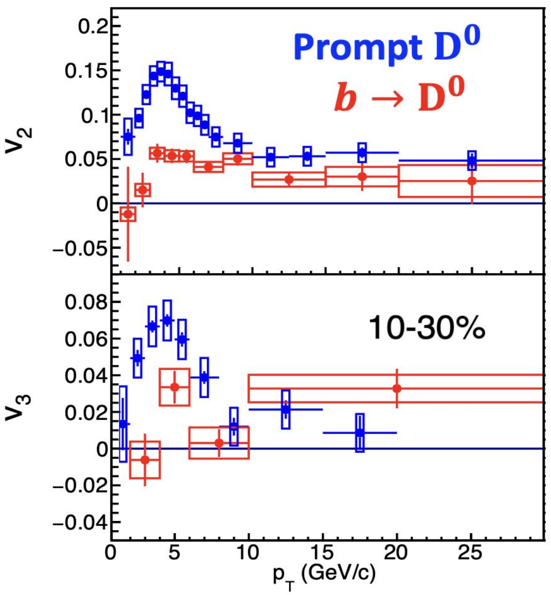
arXiv:2212.01636
submitted to PLB

Summary

- ❖ v_2 of *f_0(980)* measured as a function of p_T up to 10 GeV/c
- ❖ CMS pPb data favor 2 quark state (normal meson) for *f_0(980)* over 4 quark state.
- ❖ Strong p_T and centrality dependence of azimuthal anisotropy of Prompt D^0 mesons.
- ❖ First measurement of b→D^0 azimuthal anisotropy in PbPb collisions at CMS.
- ❖ CMS PbPb data indicates non-zero Elliptic flow (v_2) as well as triangular flow (v_3) of Non-prompt D^0 mesons.



CMS-PAS-HIN-20-002

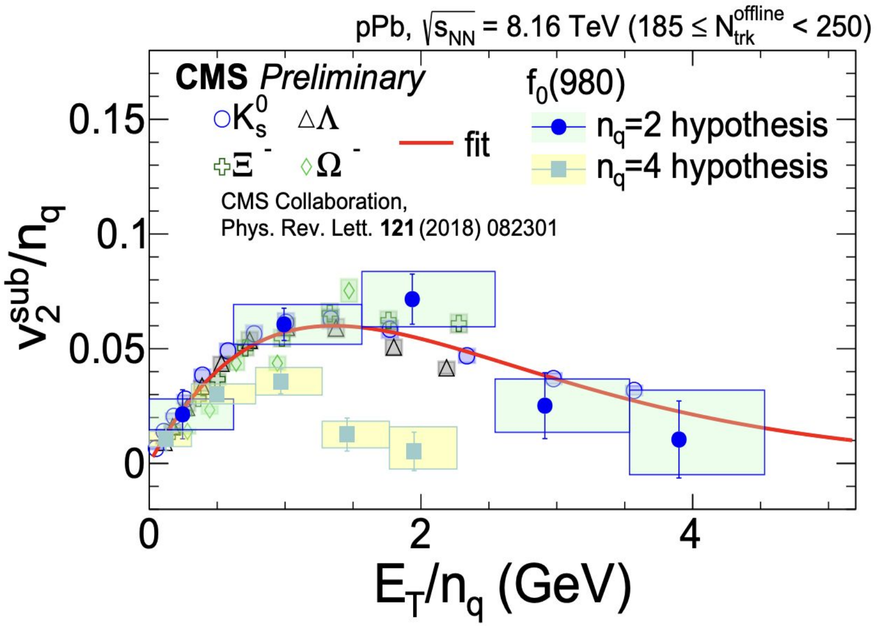


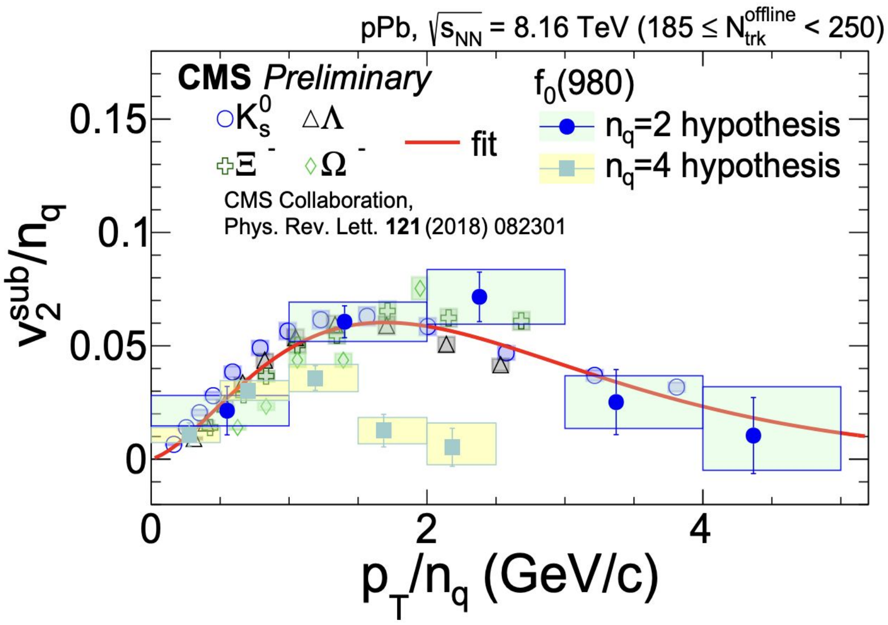
arXiv:2212.01636
submitted to PLB

Thank you!

BACKUP

NCQ scaling v_2





CMS-PAS-HIN-20-002

Systematic uncertainty

Systematic uncertainties of $f_0(980)$ v_2:

- Mix-Event Correction
- Track Selection
- Event-plane Resolution
- Signal Form
- Residual Background Form
- Fit Range
- Non-flow Subtraction

Systematic uncertainties of D^0 v_2:

- Signal PDF variation
- Background PDF variation
- BDT variation
- Track quality selections
- Efficiency x Acceptance

Event plane reconstruction

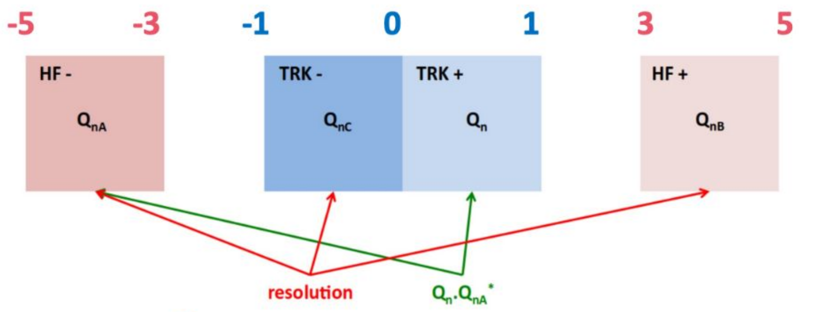
Event Plane: $\psi_n = \frac{1}{n} atan2\left(\sum_i w_i sin(n\phi_i), \sum_i w_i cos(n\phi_i)\right)$, i^{th}-tower of forward hadron calorimeter (HF) $(3 < |\eta| < 5)$; ϕ_i azimuthal angle, w_i transverse energy in each tower as weight

Event Plane Recentering and Flattening

- Recentering:
  $\psi_n = \frac{1}{n} atan2\left(\sum_i w_i sin(n\phi_i) - \left\langle \sum_i w_i sin(n\phi_i) \right\rangle, \sum_i w_i cos(n\phi_i) - \left\langle \sum_i w_i sin(n\phi_i) \right\rangle\right)$,
  $<>$ indicates the average over all events in the same centrality class and vertex locations
- Flattening:
  $\psi_n = \psi'_n \left(1 + \sum_{j=1}^{j_{max}} \frac{2}{jn} \left(- \langle sin(jn\psi'_n) \rangle cos(jn\psi'_n) + \langle cos(jn\psi'_n) \rangle sin(jn\psi'_n)\right)\right)$

HF calorimeter in the Pb-going direction for better resolution $(3 < \eta < 5$ for pPb beam, $-5 < \eta < -3$ for Pbp beam)

$b \rightarrow D^0\ v_n$ extraction



Q_n − D^0 candidate flow vector

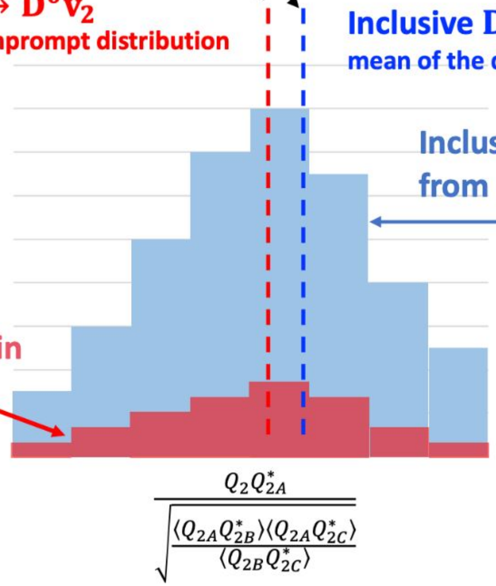
Q_{nA}, Q_{nB}, Q_{nC} − event plane vectors from subevent

$$v_n\{SP\} \equiv \frac{\langle Q_n Q_{nA}^*\rangle}{\sqrt{\frac{\langle Q_{nA}Q_{nB}^*\rangle\langle Q_{nA}Q_{nC}^*\rangle}{\langle Q_{nB}Q_{nC}^*\rangle}}}$$

mean value

$b \rightarrow D^0 v_2$
mean of the nonprompt distribution

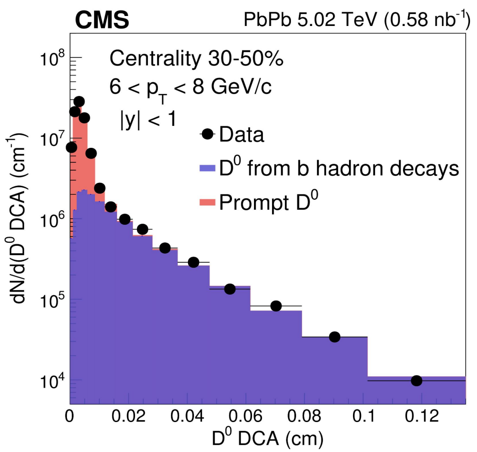
Inclusive $D^0 v_2$
mean of the distribution



Inclusive D^0 yield
from mass fit in each bin

$b \rightarrow D^0$ yield
From mass + DCA fit in each bin

$$\frac{Q_2 Q_{2A}^*}{\sqrt{\frac{\langle Q_{2A}Q_{2B}^*\rangle\langle Q_{2A}Q_{2C}^*\rangle}{\langle Q_{2B}Q_{2C}^*\rangle}}}$$



arXiv:2212.01636

submitted to PLB