



Elliptic anisotropy measurement of the $f_0(980)$ in pPb collisions and determination of its quark content by CMS

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(for the CMS Collaboration)
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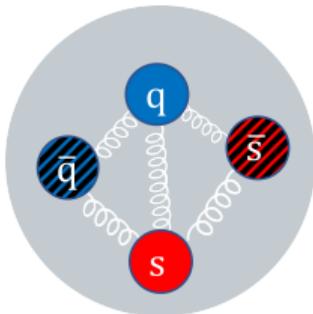
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Overview

1. Introduction and Physics Motivation
2. Data Analysis
3. v_2 Results and Systematic Uncertainties
4. Extraction of n_q for $f_0(980)$
5. Conclusion

Introduction and Physics Motivation: Exotic hadrons

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



Example of exotic hadron: tetra-quark

- ▶ $f_0(980)$: candidate exotic hadron first observed in $\pi\pi$ scattering experiments in the 1970's

S.D. Protopopescu, Phys. Rev. D 7 (1973) 1279;
B. Hyams, Nucl. Phys. B 64(1973) 134;
G. Grayer, Nucl. Phys. B 75 (1974) 189

- ▶ 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 and Physics Motivation: Elliptic Flow v_2 and NCQ scaling

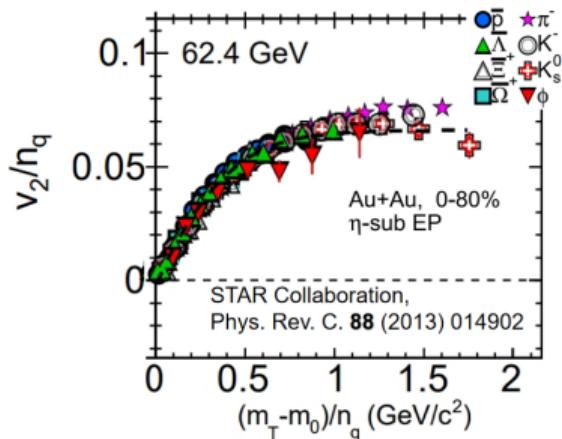
- Azimuthal anisotropy:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)], \quad (1)$$

- Approximate **number of constituent quark (NCQ) scaling** has been observed

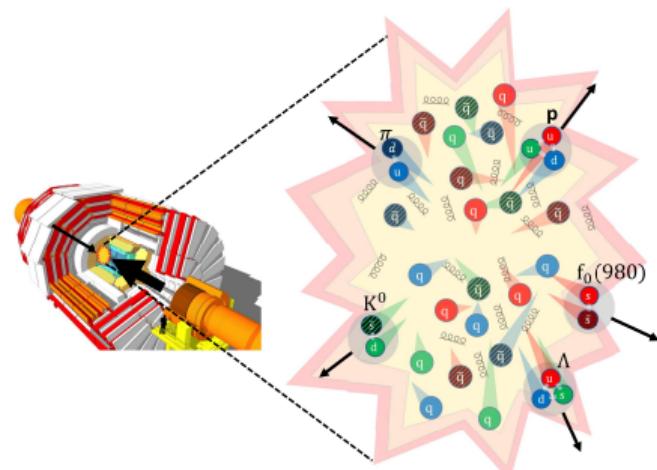
$$v_n(p_T)/n_q = v_{n,q}(p_T/n_q) \quad (2)$$

$$v_n(E_T)/n_q = v_{n,q}(E_T/n_q) \quad (3)$$



- **Coalescence** hadronization provides one possible mechanism: n_q quarks combine into a hadron with \sim equal momenta.

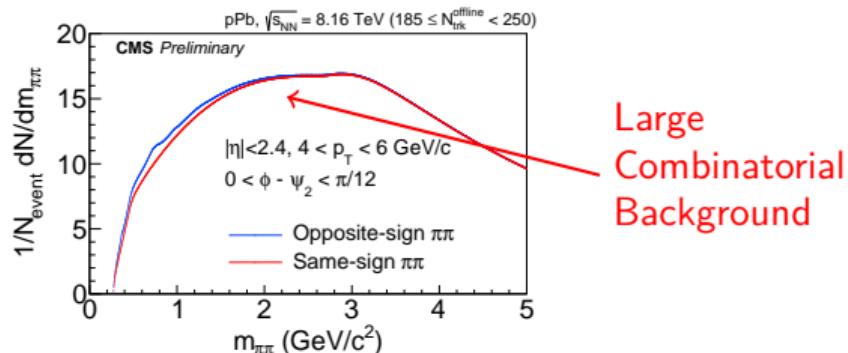
$$\frac{dN_h}{d\phi} \propto \left(\frac{dN_q}{d\phi} \right)^{n_q} \propto \\ [1 + \sum 2v_{n,q}(p_T^q) \cos(n[\phi - \psi_n])]^{n_q}$$



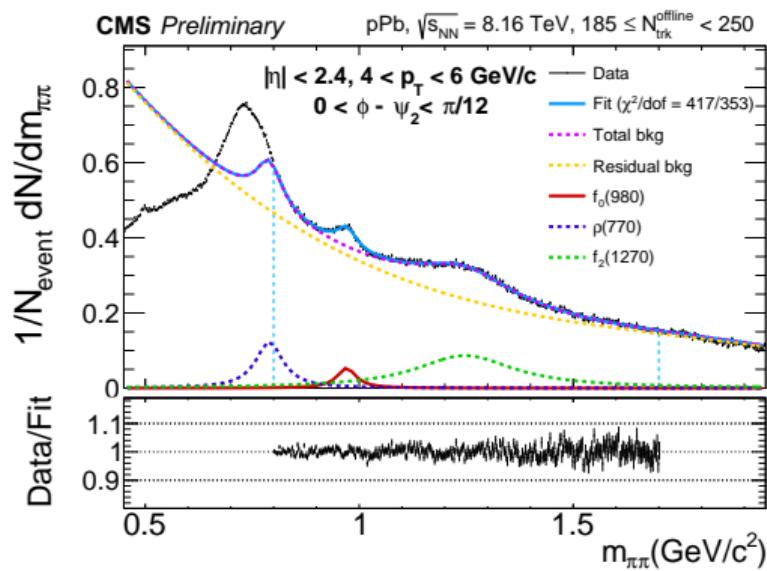
- v_2 measurement of $f_0(980) \rightarrow n_q$

Data Analysis: 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 $\pi^+ \pi^+$, $\pi^- \pi^-$

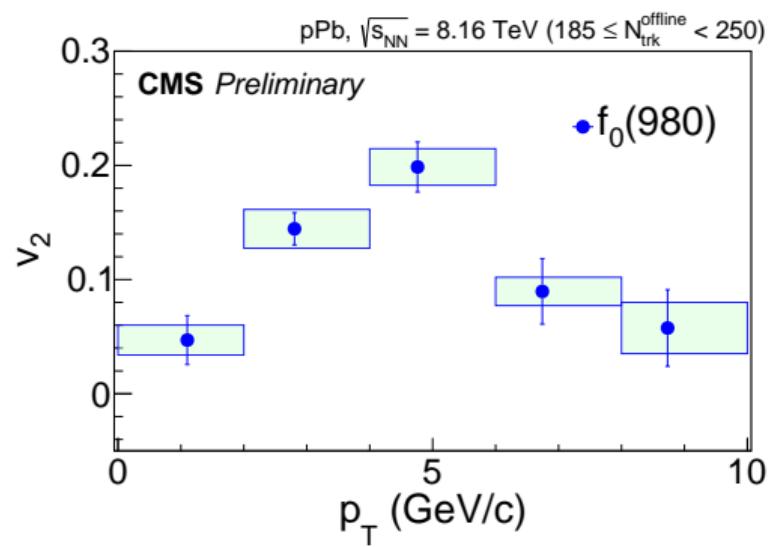
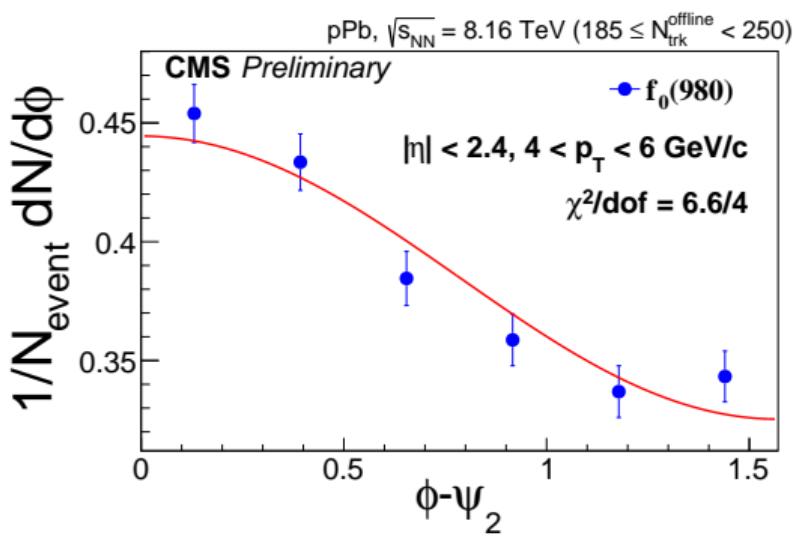


- Peak is modeled with Breit-Wigner function
- Residual background: 3rd order polynomial
- Fitting range: $0.8 < m_{\pi\pi} < 1.7$ GeV/c^2



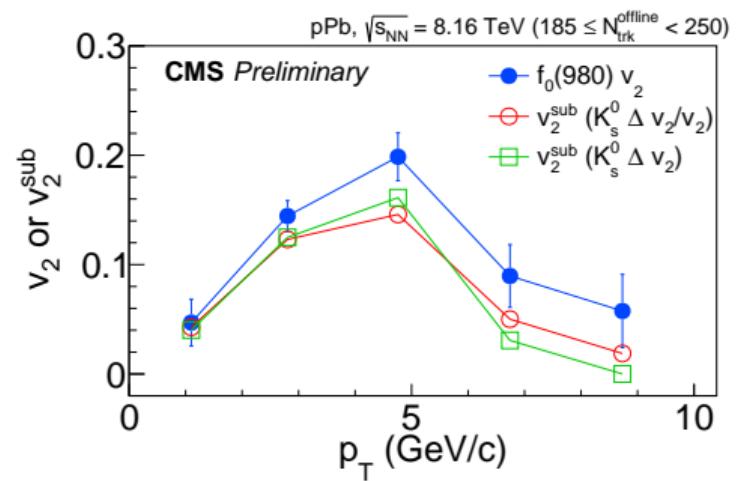
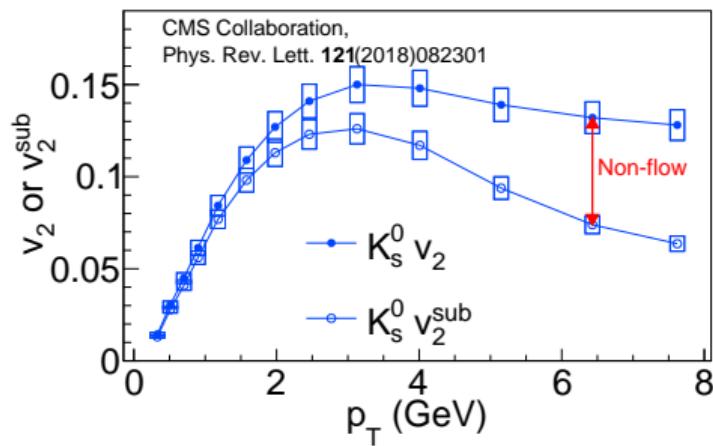
Data Analysis: v_2 Extraction

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

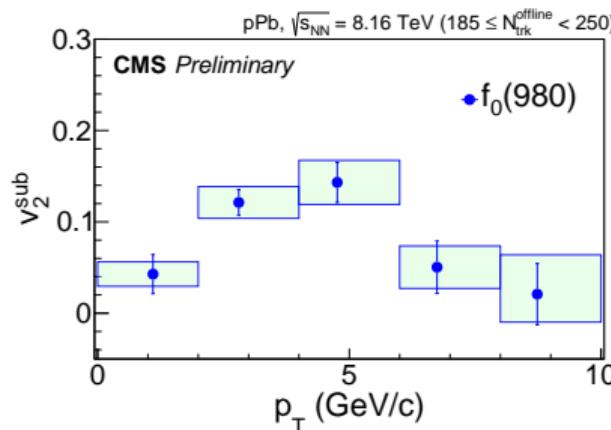


Non-flow subtraction

- ▶ Use published nonflow data of K_s^0 from low-multiplicity subtraction [10.1103/PhysRevLett.121.082301]
- ▶ Assume relative nonflow/flow to be as same as that of K_s^0 . Use absolute nonflow as a systematic. (infeasible to do $f_0(980)$ low-multiplicity subtraction)



v_2^{sub} results and systematic uncertainties



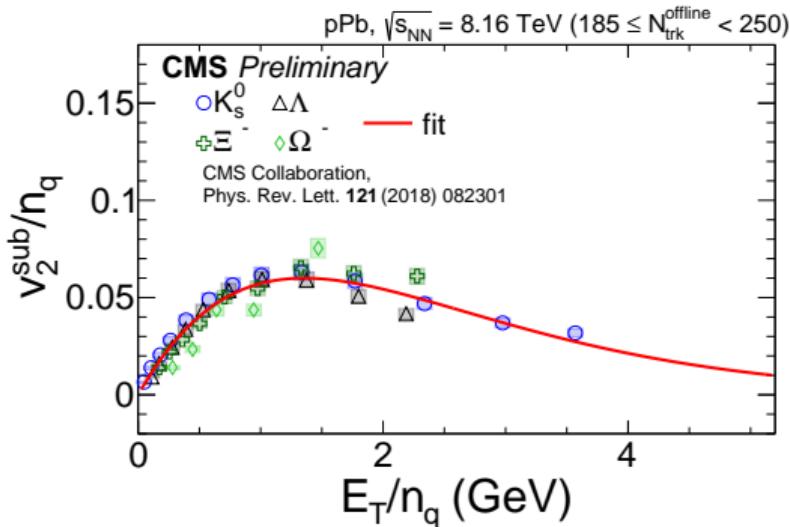
► Systematic uncertainties of $f_0(980) v_2$

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

► Systematic uncertainties of $f_0(980) n_q$

Source	n_q uncertainty
Statistical	0.16
$f_0(980) v_2$ systematics	0.12
Non-flow effects on v_2^{sub}	0.10
NCQ-scaling fit parameters	0.05
NCQ-scaling functional form	0.04
NCQ-scaling using p_T/n_q	0.04

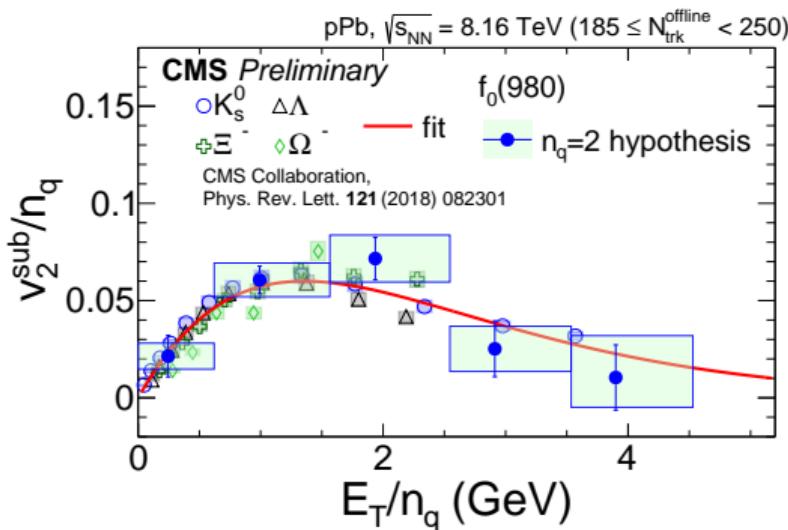
n_q extraction for $f_0(980)$



► NCQ scaling fit in $\frac{E_T}{n_q}$:

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

n_q extraction for $f_0(980)$

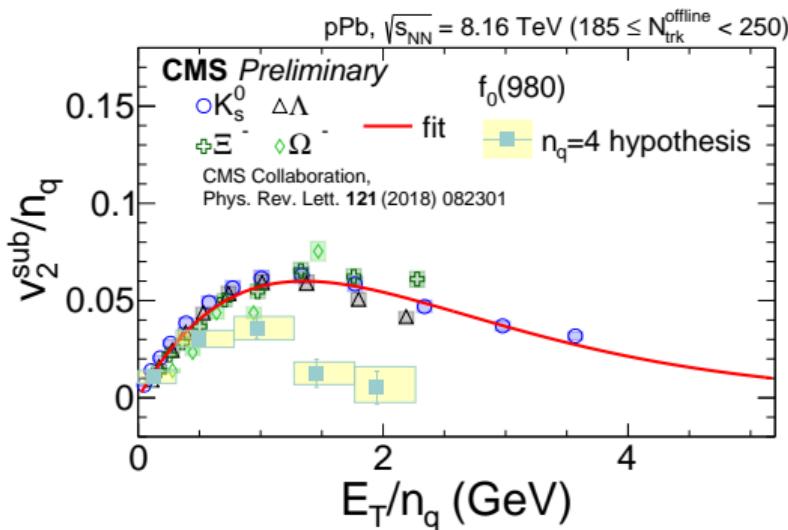


- ▶ NCQ scaling fit in $\frac{E_T}{n_q}$:

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

- ▶ Qualitatively consistent with $n_q = 2$ for $f_0(980)$.

n_q extraction for $f_0(980)$



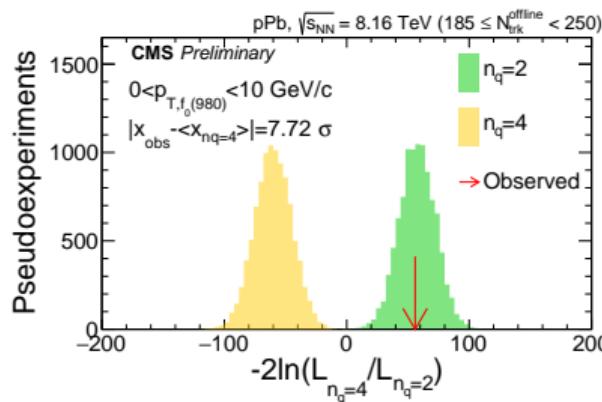
- ▶ NCQ scaling fit in E_T/n_q :

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

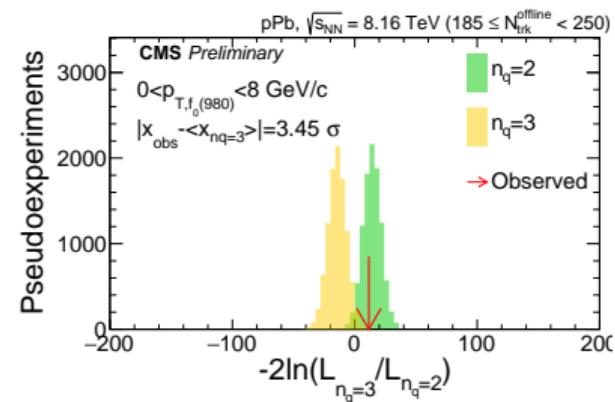
- ▶ Qualitatively inconsistent with $n_q = 4$ for $f_0(980)$.

Significance to exclude $n_q = 4$ and $n_q = 3$ hypothesis

- ▶ $\chi^2 = (\vec{y} - \vec{f})^T (C_y + C_f)^{-1} (\vec{y} - \vec{f})$, with uncertainty covariance matrix.
- ▶ Measured $f_0(980)$ data log-likelihood ratio $-2 \ln(L_{n_q=4}/L_{n_q=2})$, i.e. χ^2 difference
- ▶ Pseudo-experiment assuming $n_q = 4$ (yellow peak):
 - v_2^{sub} from NCQ-scaling curve $\times 4$; Smearing with uncertainty.
 - Same calculation of log-likelihood ratio as data → yellow peak → get significance
- ▶ Pseudo-experiment assuming $n_q = 2$ (green peak)



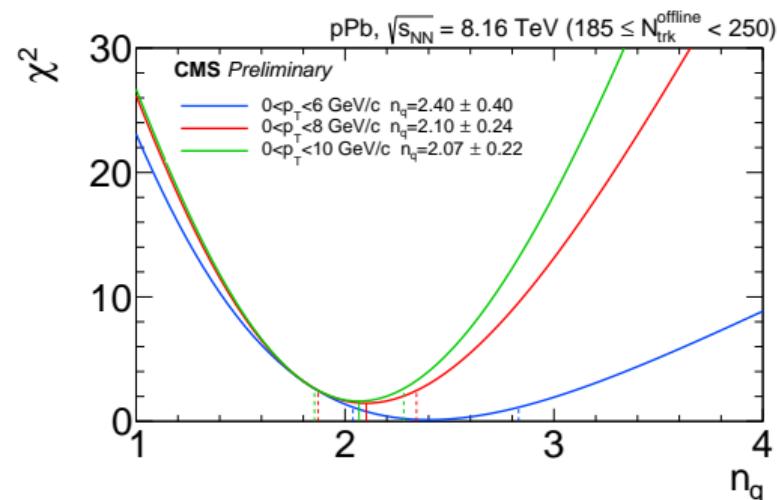
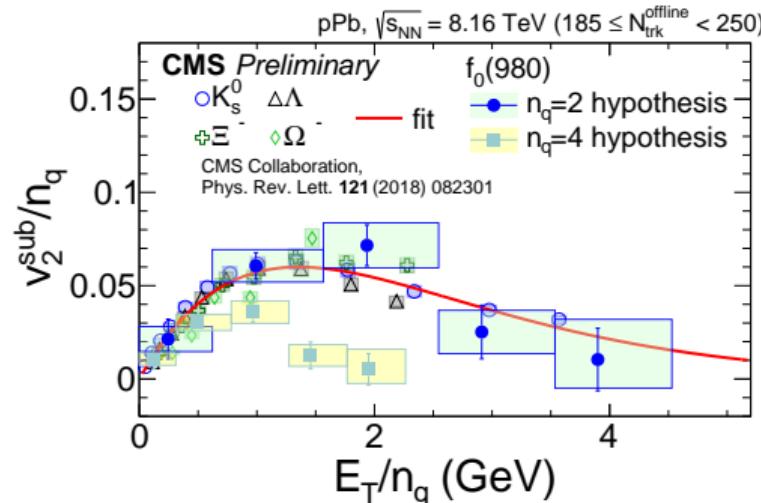
NCQ scaling measured up to $p_T/n_q \approx 3 \text{ GeV}/c$,
so use $p_T < 10 \text{ GeV}/c$ for $n_q = 4$ case



NCQ scaling measured up to $p_T/n_q \approx 3 \text{ GeV}/c$,
so use $p_T < 8 \text{ GeV}/c$ for $n_q = 3$ case

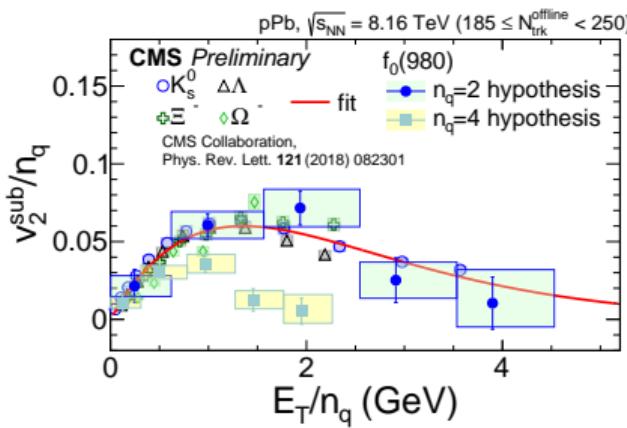
χ^2 scan to extract n_q

- $\chi^2 = (\vec{y} - \vec{f})^T (C_y + C_f)^{-1} (\vec{y} - \vec{f})$, with uncertainty covariance matrix.



- NCQ scaling is measured up to $p_T/n_q \sim 3$ GeV/ c , so we use $f_0(980)$ data within $p_T < 6$ GeV/ c . Extracted $n_q = 2.4 \pm 0.4$.
- Assuming NCQ scaling holds beyond $p_T/n_q \sim 3$ GeV/ c , then $n_q = 2.10 \pm 0.24$ (2.07 ± 0.22) using data from $p_T < 8$ (10) GeV/ c .

Conclusion



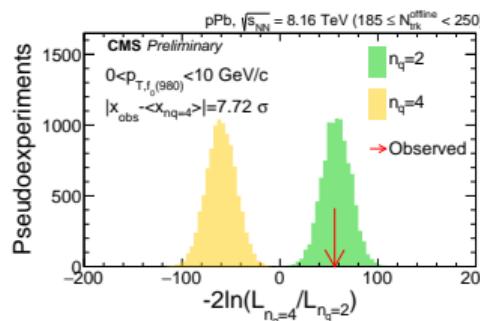
- ▶ v_2 of $f_0(980)$ measured as a function of p_T up to 10 GeV/c
- ▶ Assuming NCQ scaling, n_q of $f_0(980)$ is consistent with 2.
- ▶ $n_q = 4$ (tetra-quark state or $K\bar{K}$ molecule) excluded with 7.7σ .
- ▶ $n_q = 3$ ($q\bar{q}g$ hybrid) excluded with 3.5σ .
- ▶ Our data favor $s\bar{s}$ normal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

Back-up: Eventplane Reconstruction

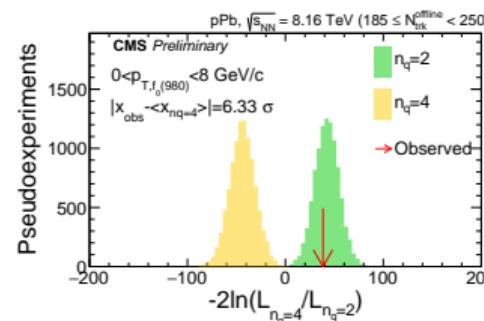
- ▶ Event Plane: $\psi_n = \frac{1}{n} \text{atan}2 \left(\sum_i w_i \sin(n\phi_i), \sum_i w_i \cos(n\phi_i) \right)$,
 i^{th} -tower of forward hadron calorimeter (HF) ($3 < |\eta| < 5$); ϕ_i azimuthal angle, w_i transverse energy in each tower as weight
- ▶ Event Plane Recentering and Flattening
 - Recentering:
 $\psi_n = \frac{1}{n} \text{atan}2 \left(\sum_i w_i \sin(n\phi_i) - \langle \sum_i w_i \sin(n\phi_i) \rangle, \sum_i w_i \cos(n\phi_i) - \langle \sum_i w_i \sin(n\phi_i) \rangle \right)$,
⟨⟩ indicates the average over all events in the same centrality class and vertex locations
 - Flattening:
$$\psi_n' = \psi_n' \left(1 + \sum_{j=1}^{j_{max}} \frac{2}{jn} (-\langle \sin(jn\psi_n') \rangle \cos(jn\psi_n') + \langle \cos(jn\psi_n') \rangle \sin(jn\psi_n')) \right)$$
- ▶ HF calorimeter in the Pb-going direction for better resolution ($3 < \eta < 5$ for pPb beam,
 $-5 < \eta < -3$ for Pbp beam)

Pseudo-experiments to exclude $n_q = 4$ hypothesis

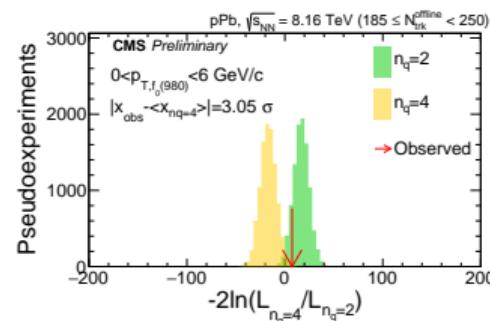
- **Observed:** $-2 \ln(L_{n_q=4}/L_{n_q=2})$: log-likelihood ratio , (χ^2 difference)
- Pseudo-experimental data:
 - $f_0(980) v_2^{\text{sub}}$ from NCQ-scaling curve for a given n_q hypothesis; Smearing with uncertainty.
 - Distribution (yellow peak) fit by a Gaussian
 - Significance extracted from the observed (red)



$0 < p_T < 10 \text{ GeV}/c$



$0 < p_T < 8 \text{ GeV}/c$



$0 < p_T < 6 \text{ GeV}/c$

Systematic Uncertainties

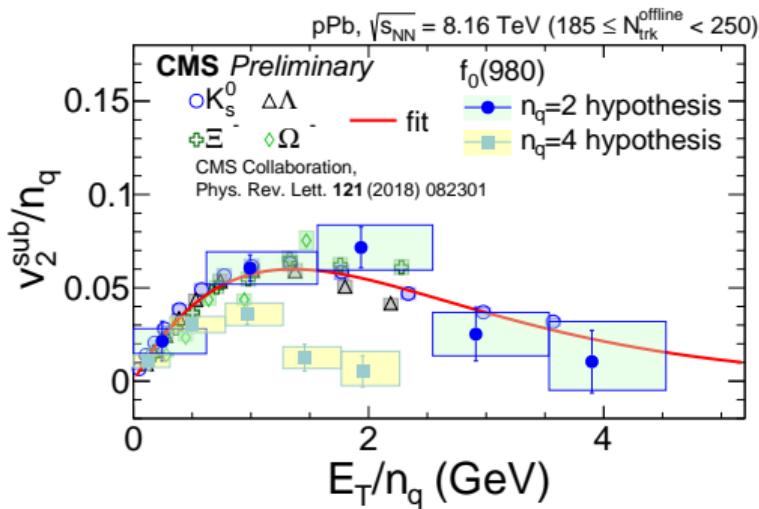
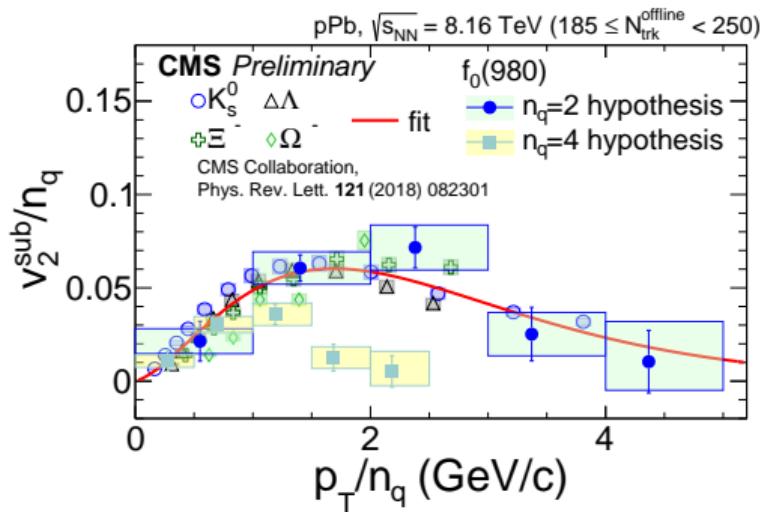
- ▶ Systematic uncertainties of $f_0(980) v_2$
 - Mix-Event Correction
 - Applying mixevent $H_{OS,mixEvent}/H_{SS,mixEvent}$ on $H_{SS,singleEvent}$
 - Track Selection
 - loose and tight track selections
 - Track Efficiency
 - track efficiency correction decreased and increased by 2.4%
 - Event-plane Resolution
 - Error propagation of uncertainties in event-plane resolution
 - Signal Form
 - Breit-Wigner and relativistic Breit-Wigner
 - Residual Background Form
 - 2nd, 3rd (defatul), 4th, 5th-order polynomial
 - Fit Range
 - Variate $0.02GeV/c^2$ on each side
 - Nonflow Subtraction
 - $K_s^0 \Delta v_2/v_2$ (default), $K_s^0 \Delta v_2$

Systematic Uncertainties

► Systematic uncertainties of $f_0(980) n_q$

- Statistical: error propagated from $f_0(980) v_2$ statistical uncertainties
- $f_0(980) v_2$ systematics: error propagated from $f_0(980) v_2$ systematic (nonflow uncertainty not included)
- Non-flow effects on v_2^{sub} : error propagated from $f_0(980) v_2$ nonflow systematic
- NCQ-scaling fit parameters: n_q uncertainty due to fit parameter uncertainties
- NCQ-scaling functional form: standard deviation of n_q with different fit function form
- NCQ-scaling using p_T/n_q : n_q difference from using v_2^{sub}/n_q vs. E_T/n_q

NCQ scaling of v_2



- ▶ NCQ scaling fit in E_T/n_q : $f(E_T/n_q) = E_T/n_q (p_0 + p_1 E_T/n_q) e^{-p_2 E_T/n_q}$.
- ▶ Qualitatively consistent with $n_q = 2$ for $f_0(980)$.