NCQ scaling of f_0(980) elliptic flow in 200 GeV Au+Au collisions by STAR and its constituent quark content

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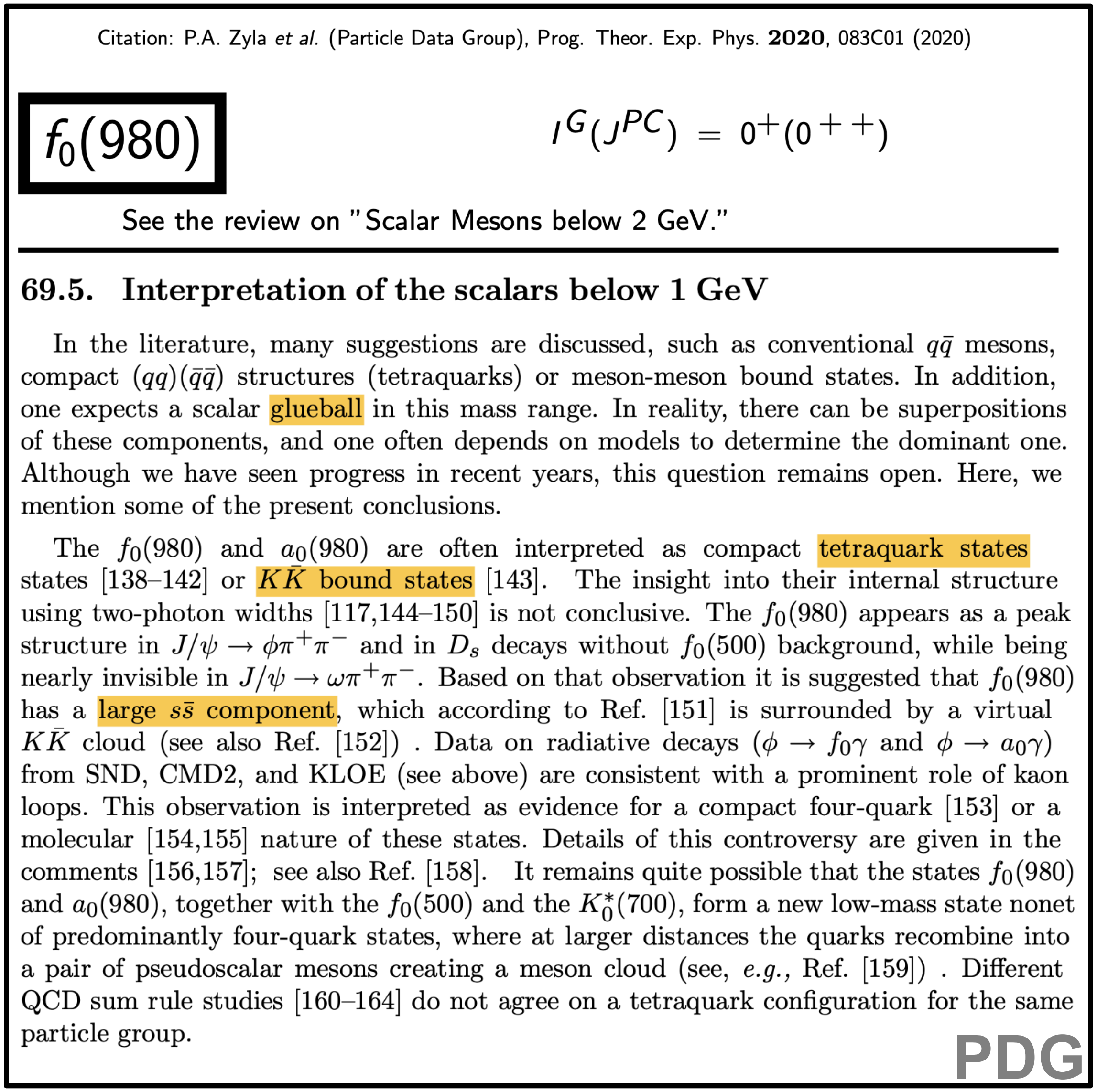
Motivation



Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$f_0(980)$ $I^G(J^{PC}) = 0^+(0^{++})$

See the review on "Scalar Mesons below 2 GeV."

69.5. Interpretation of the scalars below 1 GeV

In the literature, many suggestions are discussed, such as conventional $q\bar{q}$ mesons, compact $(qq)(\bar{q}\bar{q})$ structures (tetraquarks) or meson-meson bound states. In addition, one expects a scalar glueball in this mass range. In reality, there can be superpositions of these components, and one often depends on models to determine the dominant one. Although we have seen progress in recent years, this question remains open. Here, we mention some of the present conclusions.

The $f_0(980)$ and $a_0(980)$ are often interpreted as compact tetraquark states states [138–142] or $K\bar{K}$ bound states [143]. The insight into their internal structure using two-photon widths [117,144–150] is not conclusive. The $f_0(980)$ appears as a peak structure in $J/\psi \to \phi\pi^+\pi^-$ and in D_s decays without $f_0(500)$ background, while being nearly invisible in $J/\psi \to \omega\pi^+\pi^-$. Based on that observation it is suggested that $f_0(980)$ has a large $s\bar{s}$ component, which according to Ref. [151] is surrounded by a virtual $K\bar{K}$ cloud (see also Ref. [152]) . Data on radiative decays ($\phi \to f_0\gamma$ and $\phi \to a_0\gamma$) from SND, CMD2, and KLOE (see above) are consistent with a prominent role of kaon loops. This observation is interpreted as evidence for a compact four-quark [153] or a molecular [154,155] nature of these states. Details of this controversy are given in the comments [156,157]; see also Ref. [158]. It remains quite possible that the states $f_0(980)$ and $a_0(980)$, together with the $f_0(500)$ and the $K_0^*(700)$, form a new low-mass state nonet of predominantly four-quark states, where at larger distances the quarks recombine into a pair of pseudoscalar mesons creating a meson cloud (see, *e.g.*, Ref. [159]) . Different QCD sum rule studies [160–164] do not agree on a tetraquark configuration for the same particle group.

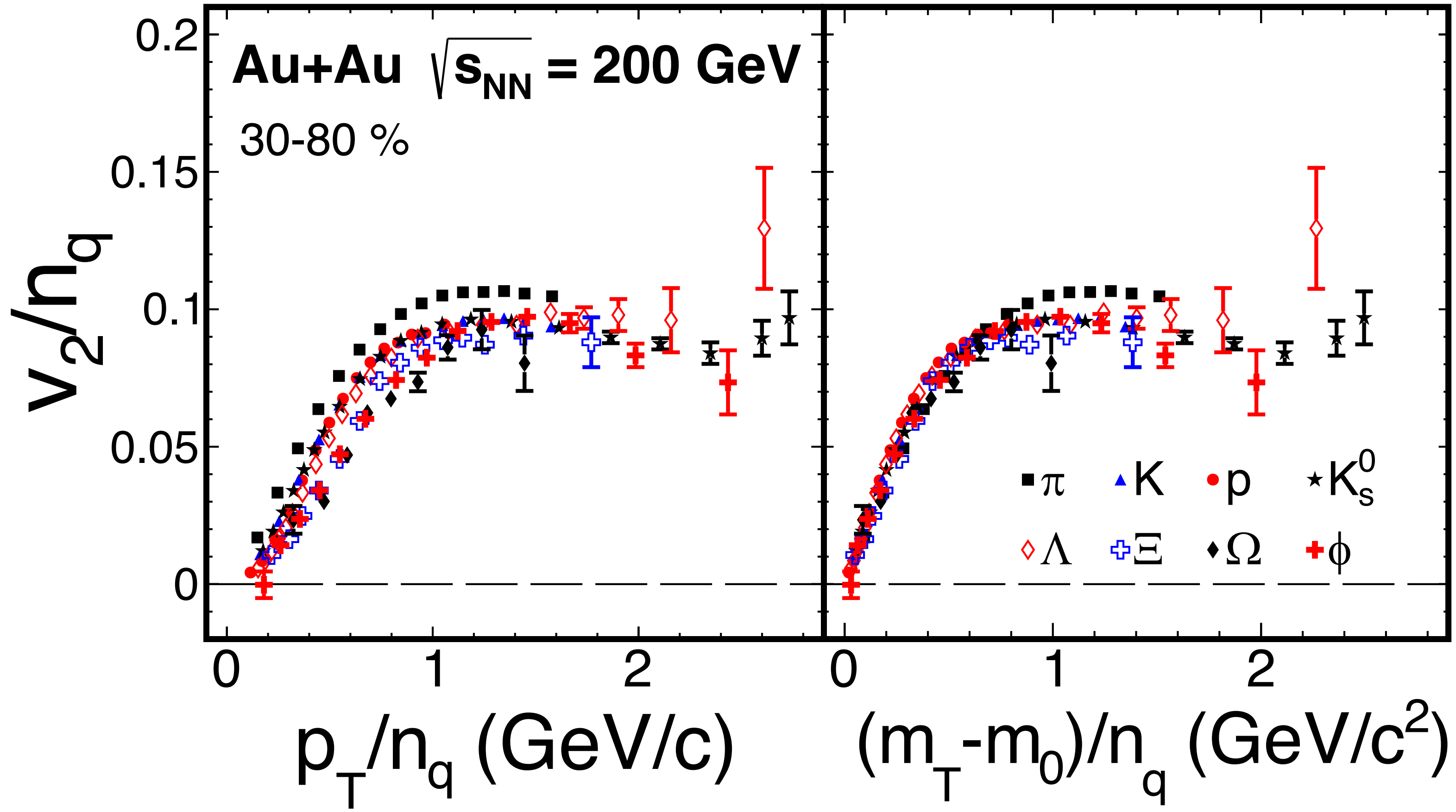
PDG

V. Baru *et al*, Phys. Lett. B 586 (2004) 53
J. Weinstein, N. Isgur, Phys. Rev. D 27, 588 (1983)
J. Weinstein, N. Isgur, Phys. Rev. D 41, 2236 (1990)
F. Kleefeld, *et al,* Phys. Rev. D 66, 034007 (2002)
N. N. Achasov *et al,* Phys. Rev. D 103, 014010 (2021)

In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle, due to large decay widths, decay channels, etc.

Motivation

D. Molnar and S. A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003).
PHENIX, Phys. Rev. Lett. 91, 182301 (2003)
STAR, Phys. Rev. Lett. 92, 052302 (2004), Phys. Rev. Lett. 116, 062301 (2016)

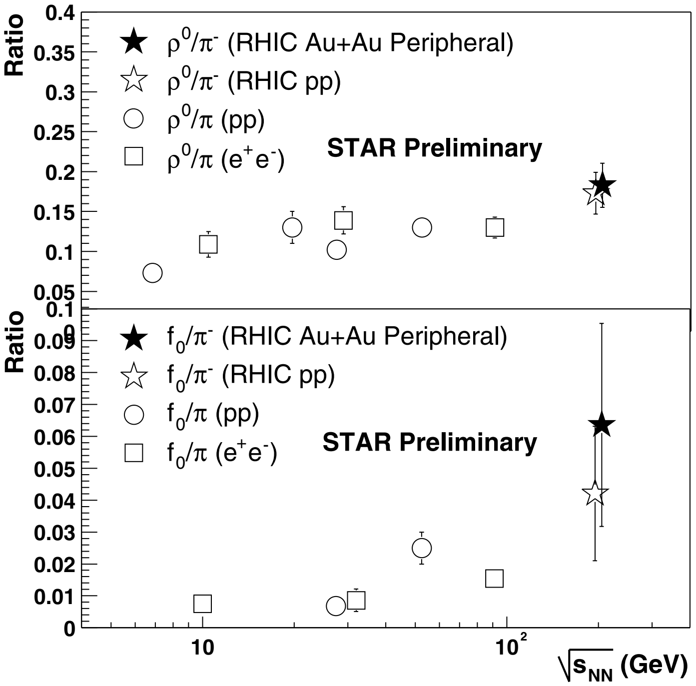


A Gu, T Edmonds, J Zhao, and F Wang, Phys. Rev. C.101.024908 (2020)

- ➢ RHIC, the number-of-constituent-quark (NCQ) scaling well explains data
- ➢ Use the v_2 NCQ scaling to test the quark content of $f_0(980)$

RHIC previous measurements

P. Fachini (STAR Collaboration) J. Phys. G: 30 (2004) 565



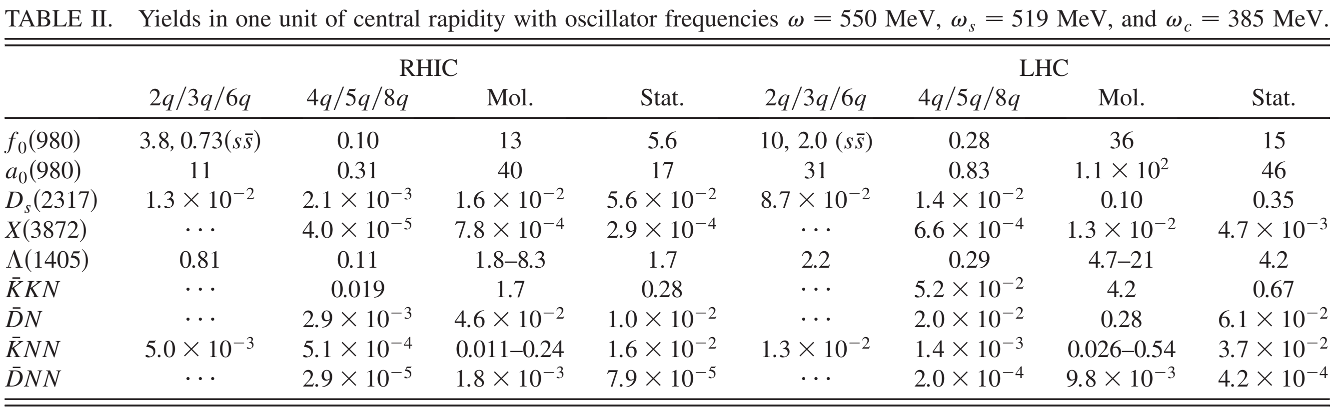


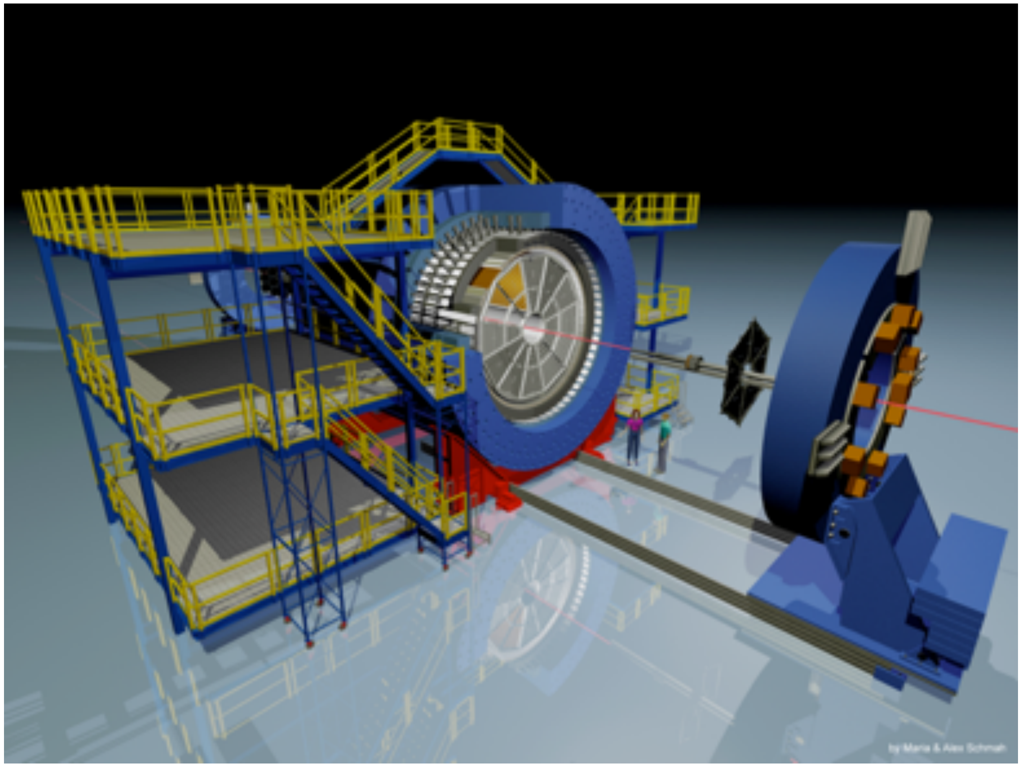
TABLE II. Yields in one unit of central rapidity with oscillator frequencies $\omega = 550$ MeV, $\omega_s = 519$ MeV, and $\omega_c = 385$ MeV.

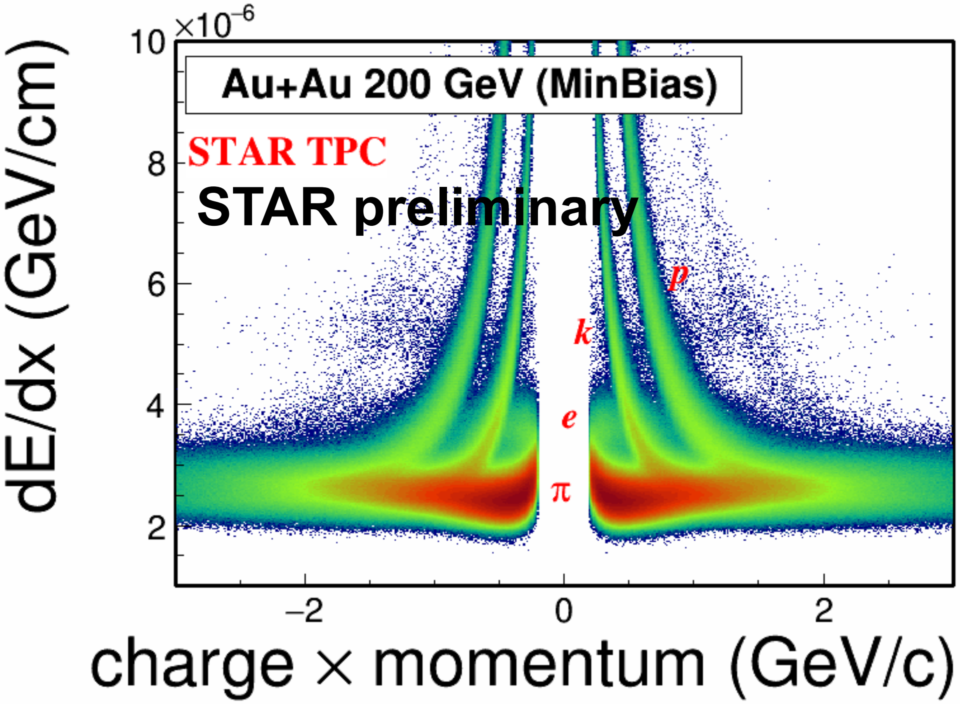
	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
$f_0(980)$	3.8, 0.73($s\bar{s}$)	0.10	13	5.6	10, 2.0 ($s\bar{s}$)	0.28	36	15
$a_0(980)$	11	0.31	40	17	31	0.83	1.1×10^2	46
$D_s(2317)$	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
$X(3872)$	⋯	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	⋯	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$\Lambda(1405)$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
$\bar{K}KN$	⋯	0.019	1.7	0.28	⋯	5.2×10^{-2}	4.2	0.67
$\bar{D}N$	⋯	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	⋯	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{K}NN$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026–0.54	3.7×10^{-2}
$\bar{D}NN$	⋯	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	⋯	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}

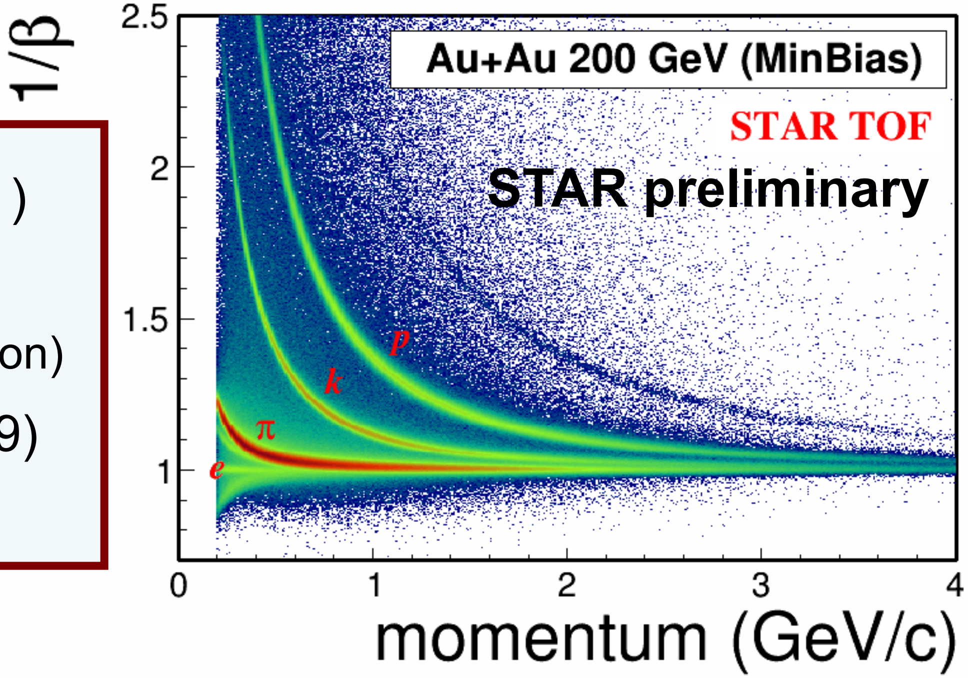
Sungtae Cho *et al.* (ExHIC Collaboration), Phys. Rev. Lett. 106:212001, (2011)

"Using the statistical model prediction for the yield of ρ=42 leads to f_0(980)~8. Comparing this number to the numbers predicted for f_0(980) in Table II, we find the data consistent with the KK picture. Therefore. Despite the quoted experimental error of around 50%, the STAR data can be taken as evidence that the f_0(980) has a substantial KK component, and a pure tetraquark configuration can be ruled out for its structure."

The STAR detector







- **Time Projection Chamber** (ϕ=0-2π, |η|<1)

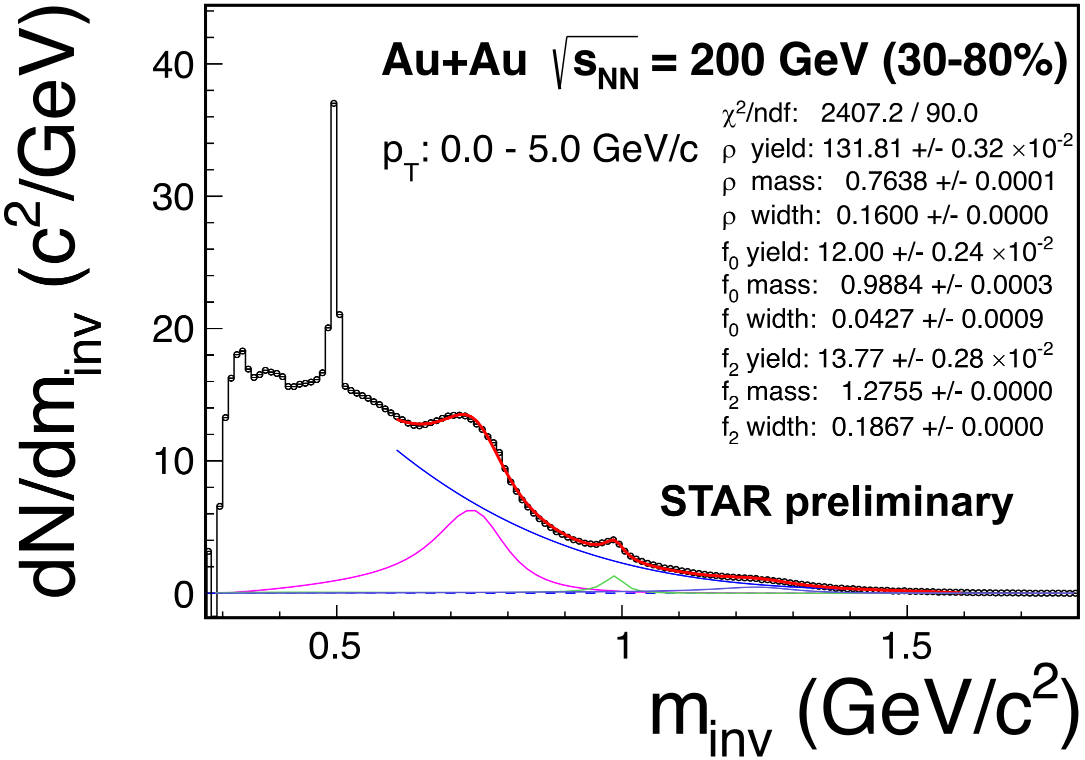
  Tracking - momentum

  Ionization energy loss - dE/dx (particle identification)

- **Time Of Flight detector** (ϕ=0-2π, |η|<0.9)

  Timing resolution <100ps - PID improvement

f_0 signal extraction



$$Relativistic\,BW\,(M_{\pi\pi}) = \frac{A M_{\pi\pi} M_0 \Gamma\,(M_{\pi\pi})}{[({M_0}^2 - {M_{\pi\pi}}^2)^2 + {M_0}^2\Gamma^2\,(M_{\pi\pi})]}$$

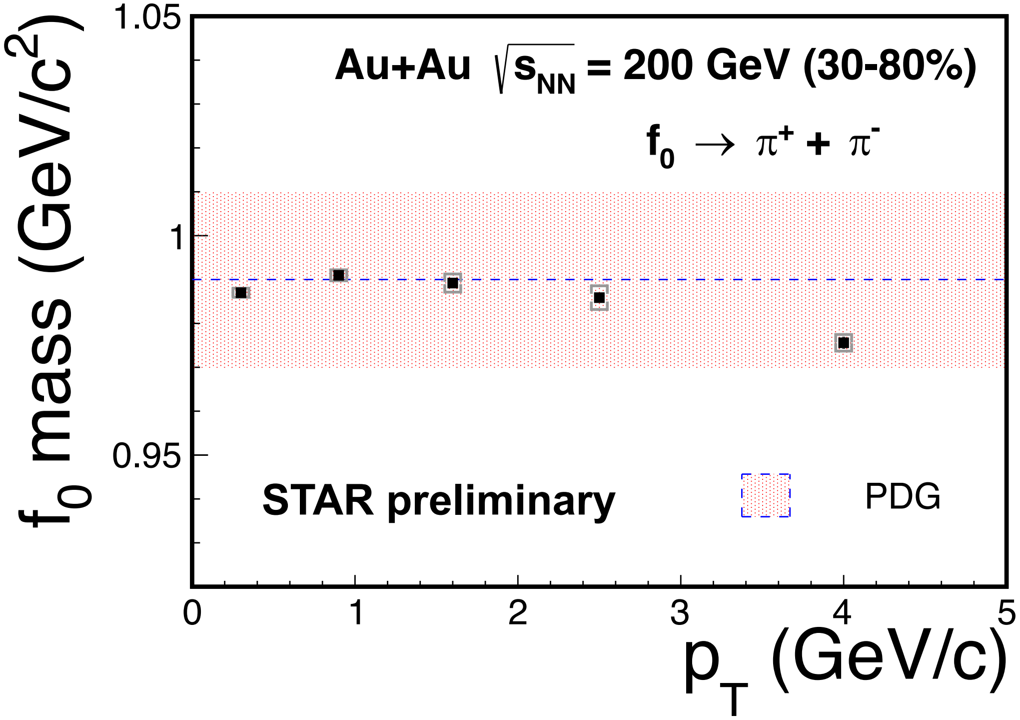
$$\Gamma\,(M_{\pi\pi}) = \left[\frac{(M_{\pi\pi}^2 - 4m_\pi^2)}{(M_0^2 - 4m_\pi^2)}\right]^{(2J+1)/2} \times \Gamma_0 \times (M_0/M_{\pi\pi})$$

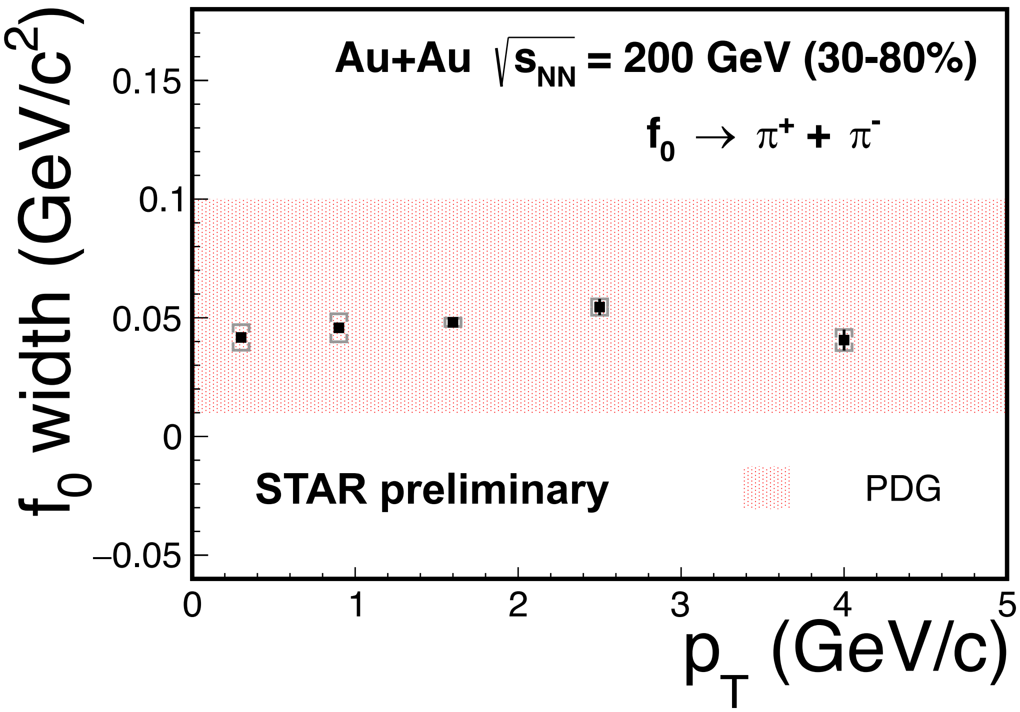
$$PS\,(M_{\pi\pi}) = \frac{M_{\pi\pi}}{\sqrt{M_{\pi\pi}^2 + p_T^2}} \times exp(-\sqrt{M_{\pi\pi}^2 + p_T^2}/T)$$

STAR, Phys. Rev. Lett. 92. 092301 (2004)
STAR, Phys. Rev. C. 92, 024912 (2015)

- Combinatorial background subtraction:
  1) Same-event and mix-event are used to construct the combinatorial background
  2) Acceptance-corrected like-sign pairs are used to subtract the background
- Signal function of f_0, f_2, and ρ with: (residual background with pol. 3, blue line)
  1) Relativistic Breit-Wigner function x phase space factor (PS), with T=120 MeV
  2) Breit-Wigner

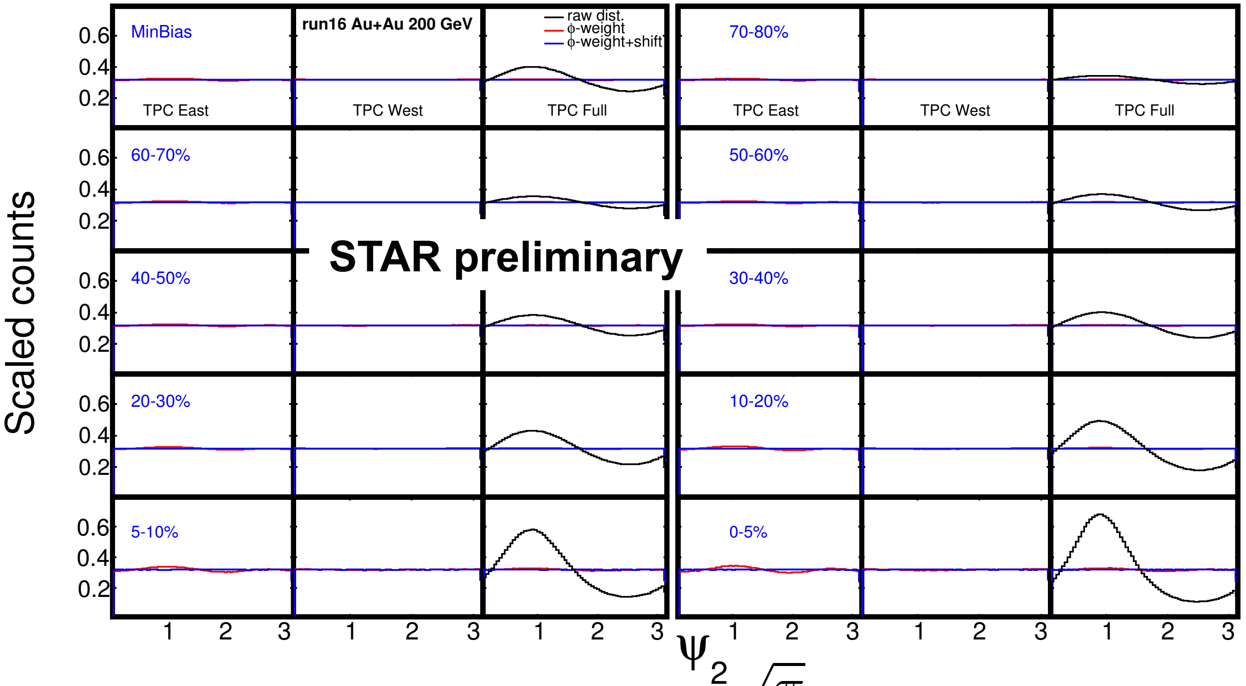
f_0 signal extraction

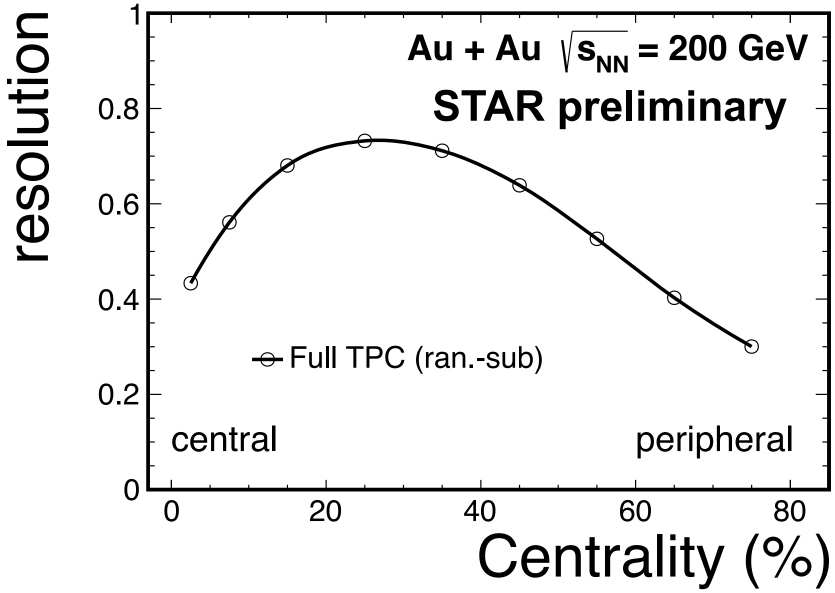




- **f_0, f_2, and ρ with:**
  1) Relativistic Breit-Wigner times phase space, with T=120 MeV
  2) Breit-Wigner
- Assuming no $\Delta\phi = \phi - \psi_2$ dependence in the mass and width, fix them according to the results above

Event-plane reconstruction





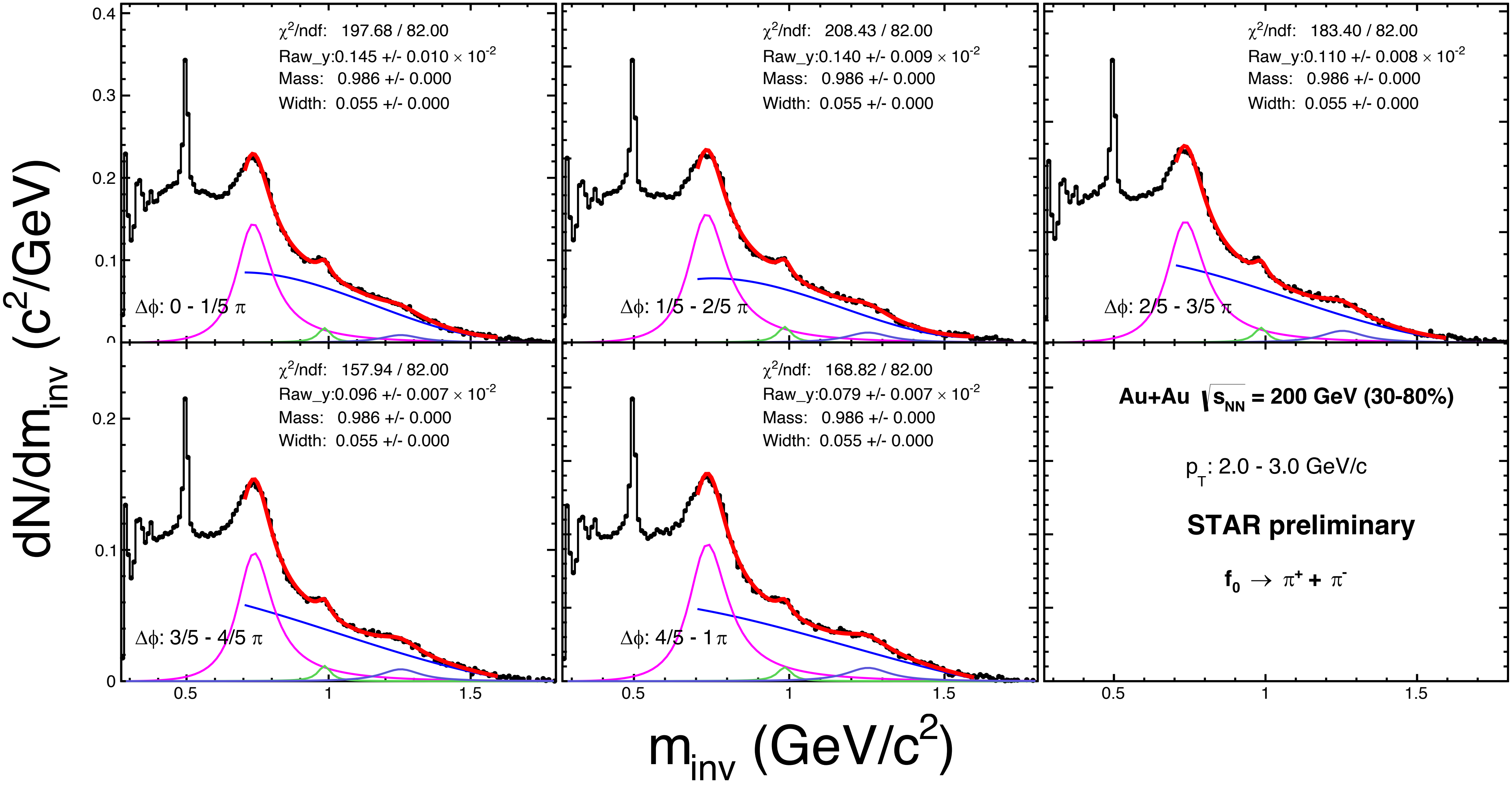
$$\langle coskm(\Psi_m - \Psi_r)\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_m exp(-\chi_m^2/4)[I_{(k-1)/2}(\chi_m^2/4) + I_{(k+1)/2}(\chi_m^2/4)]$$

A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C.58.3 (1998)

- ➢ The TPC 2nd-order event plane was reconstructed with a conventional method using charged tracks in the TPC
- ➢ ϕ-Weight + shift method are used to flatten the event-plane distribution
- ➢ modified Bessel function used to calculate the resolution
- ➢ event-plane resolution for f_0 in wide centrality bin: $R_{wide} = (\Sigma R_i \times Y_i)/(\Sigma Y_i)$

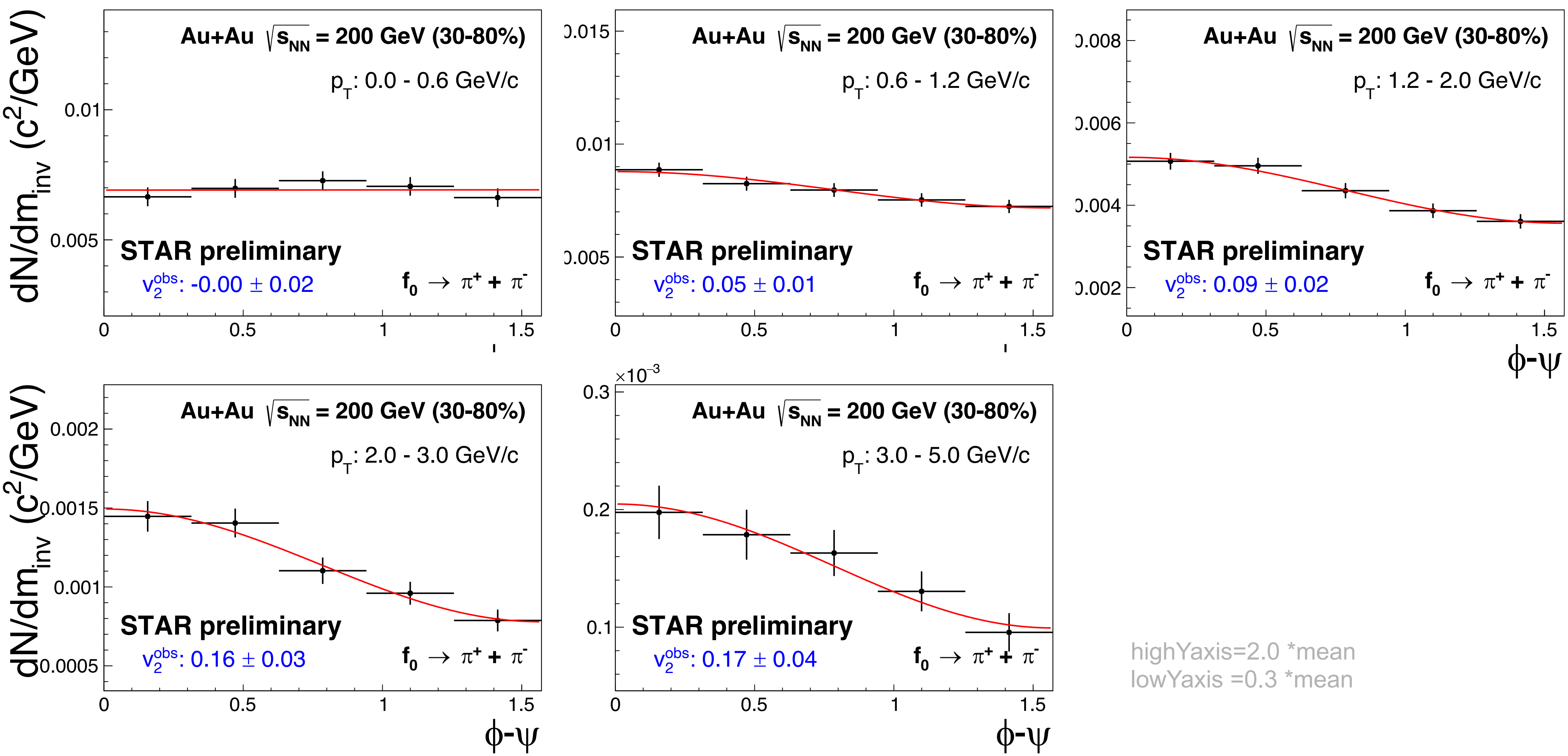
  R_i, Y_i are the resolution and f_0 yield in fine centrality bin

f_0 elliptic flow



- Event-plane method, signal in different **Δϕ**=ϕ-ψ_2 bins.

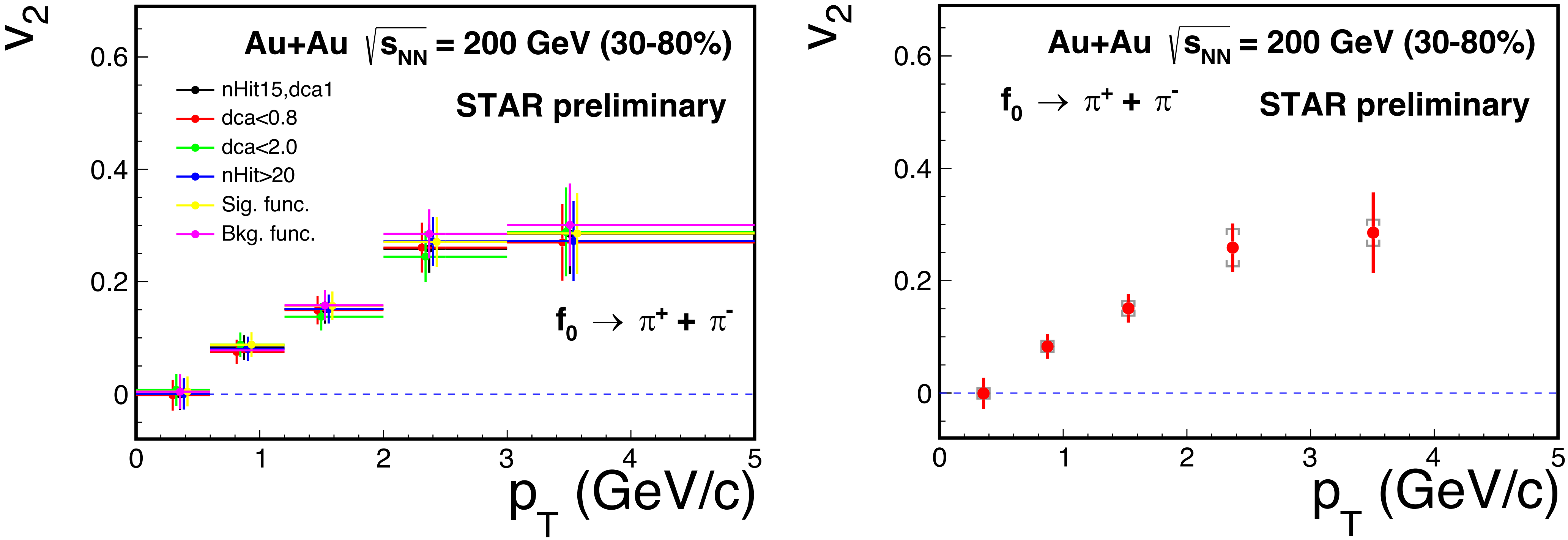
f_0 elliptic flow



highYaxis=2.0 *mean
lowYaxis =0.3 *mean

- ➢ Event-plane method, f_0 yields in different **Δϕ** bins.
- ➢ Results fit with amp*(1+2*v_2^{obs}cos(2**Δϕ**))

Systematic uncertainty



dca: distance of closest approach to the primary vertex
nHitFits: number of hits used in track fitting

- **Systematic uncertainty sources:**

dca: < 0.8cm, 2.0 (1.0)
nHitFits : >20 (15)
Signal function: Breit-Wigner (Relativistic Breit-Wigner x PS)
Background fun.: pol2 (pol3)

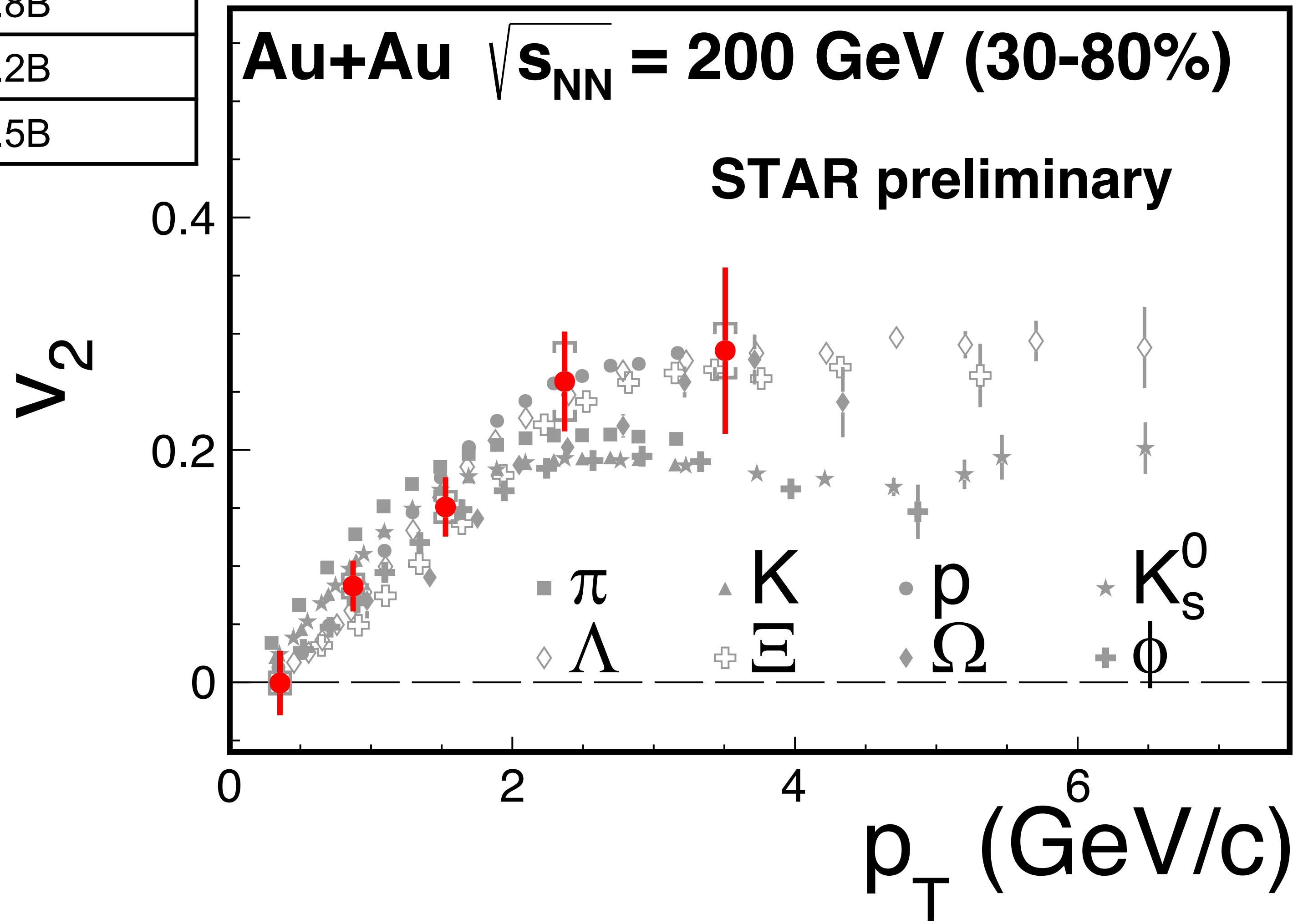
- **Total systemic uncertainty :**

RMS(σ (tracks cuts)) $\otimes$ σ(Sig) $\otimes$ σ(Bkg)

f_0(980) elliptic flow

Year	Minbias events
Y2011	~0.5B
Y2014	~0.8B
Y2016	~1.2B
Total	~2.5B

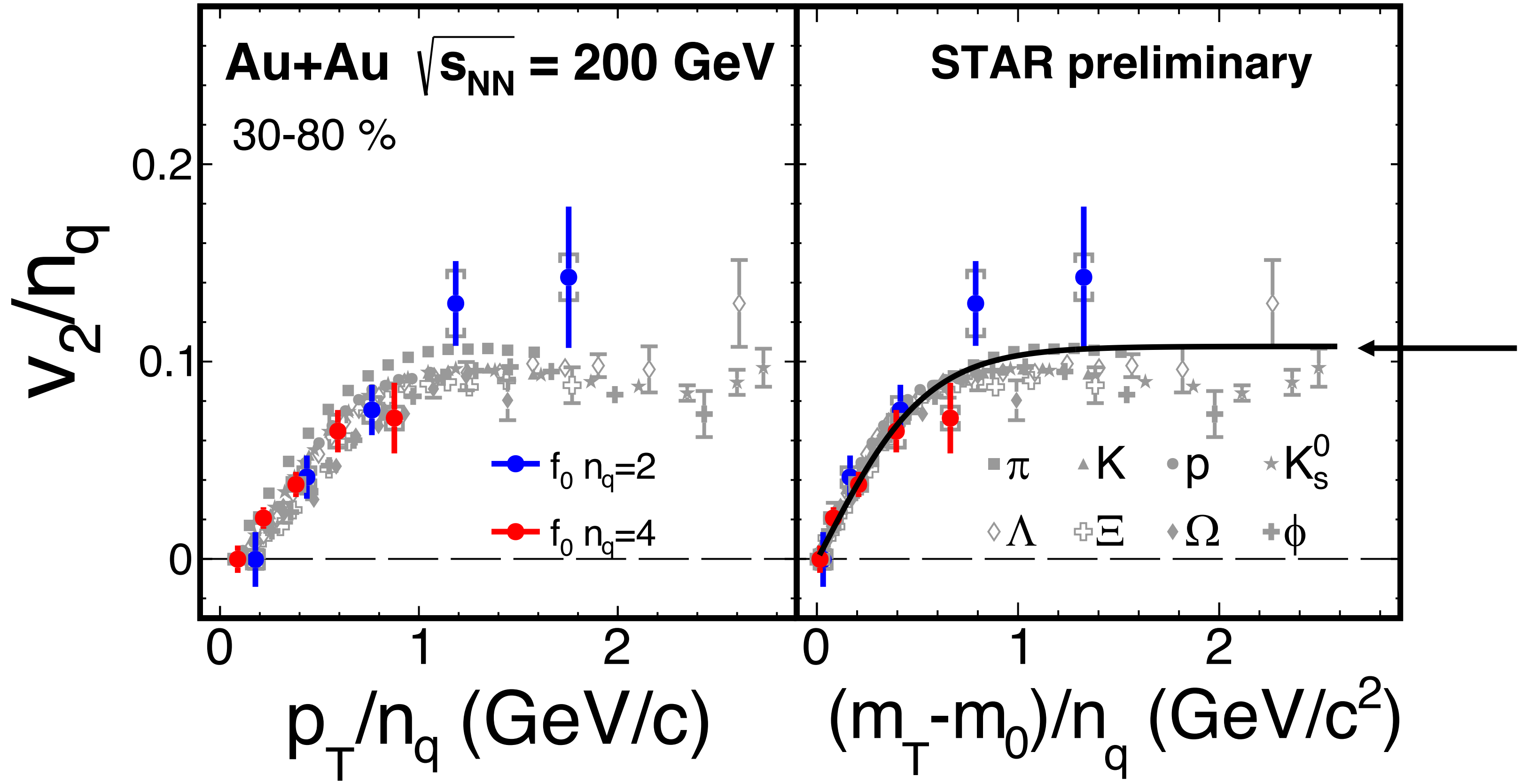
STAR, Phys. Rev. Lett. 116, 062301 (2016)



- ➢ Results are compared with other particles

NCQ scaling test

STAR, Phys. Rev. Lett. 116, 062301 (2016)



Fit to other hadrons

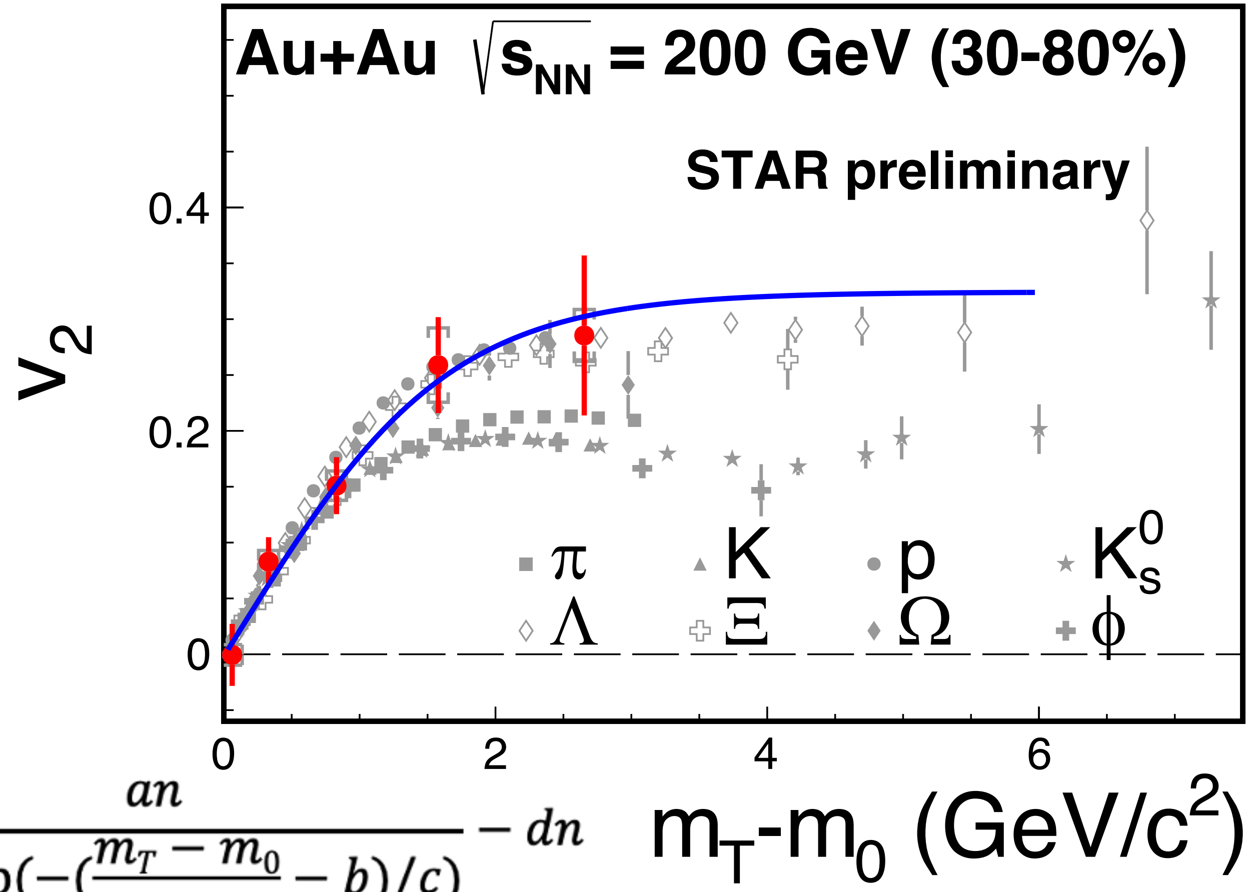
$$f_{v_2}(n) = \frac{an}{1+\exp(-(\frac{m_T-m_0}{n}-b)/c)} - dn$$

X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu. Phys. Lett. B 597 (2004) 328

- Results are compared with other particles
- NCQ scaling tests the $f_0(980)$ content

NCQ scaling test

STAR, Phys. Rev. Lett. 116, 062301 (2016)



$$f_{v_2}(n) = \frac{an}{1+\exp(-(\frac{m_T-m_0}{n}-b)/c)} - dn$$

X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu. Phys. Lett. B 597 (2004) 328

- a, b, c, d fixed according to the fit to other hadrons
- NCQ scaling test the f_0(980) quark content：
  n_q(f_0(980)) = 3.0+/-0.7+/-0.5

Summary and outlook

- Preliminary results on the f_0(980) elliptic flow
- NCQ slcaing test for the f_0(980) quark content indicates:

  $n_q(f_0(980))$ = 3.0 +/- 0.7 +/- 0.5

  tetraquark, KK, ss, or $\pi\pi$ coalescence? more data
- Indicate the heavy-ion collisions can be a useful place to examine the quark content of scalar mesons
- Study of the spectra will be followed-up, and compare with model
- Isobar data with more statistics, and ~8 more statistics at RHIC 2023-2025