Critical Point and Onset of Deconfinement
7 - 11 November 2011, Wuhan, China

Probing QCD phase diagram with ϕ meson production in STAR BES program

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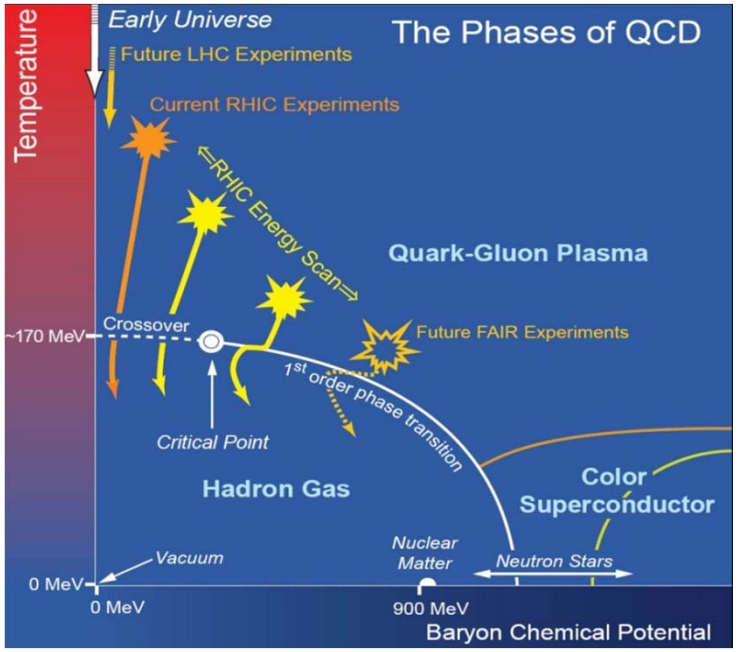
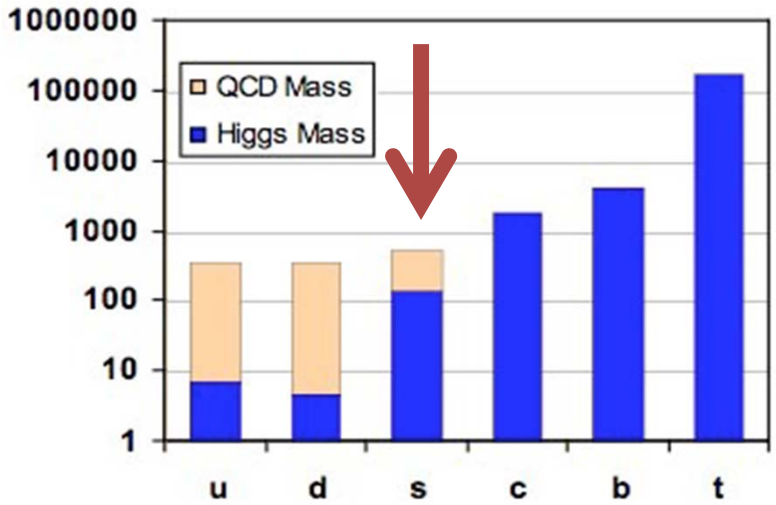
For the STAR Collaboration

- QCD phase transition and ϕ meson production
- Spectra and elliptic flow (v_2) results and discussions
- Summary and outlook

Motivation: study QCD phase diagram

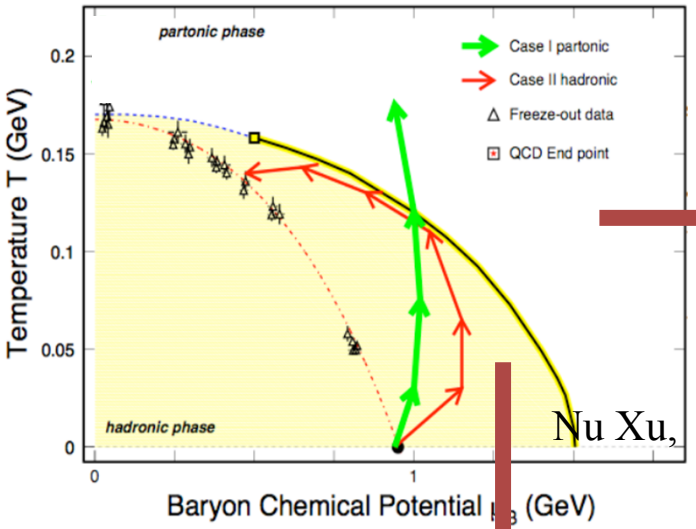




- **Beam Energy Scan at RHIC**
  Look for **onset of de-confinement, phase boundary** and critical point
  Systematic study of Au+Au collisions at 5.0, 7.7, 11.5, 19.6, 27, 39, 62.4 GeV
- Observables on de-confinement
  (1) Strangeness enhancement
  Temperature ⬆, s quark mass ⬇
  m_s(QCD) > T_c > m_s(current)
  (2) Number-of-Constituent-Quark (NCQ) scaling of elliptic flow
  partonic v.s. hadronic degree of freedom

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493; B. Müller, SQM 2011;
http://www.physik.uni-bielefeld.de/xqcd/talks/bazavov.pdf

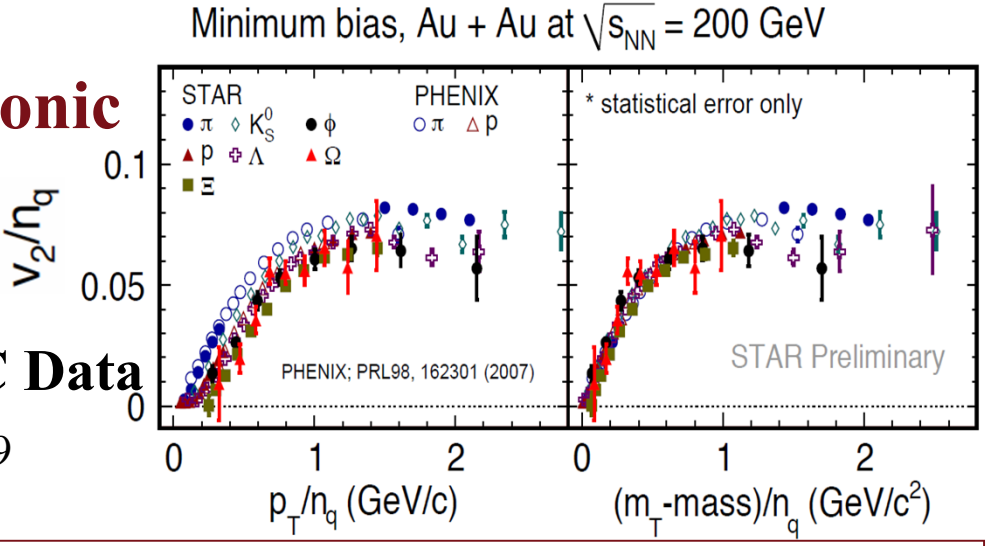
ϕ meson v_2 — A key measurement



Nu Xu, SQM2009

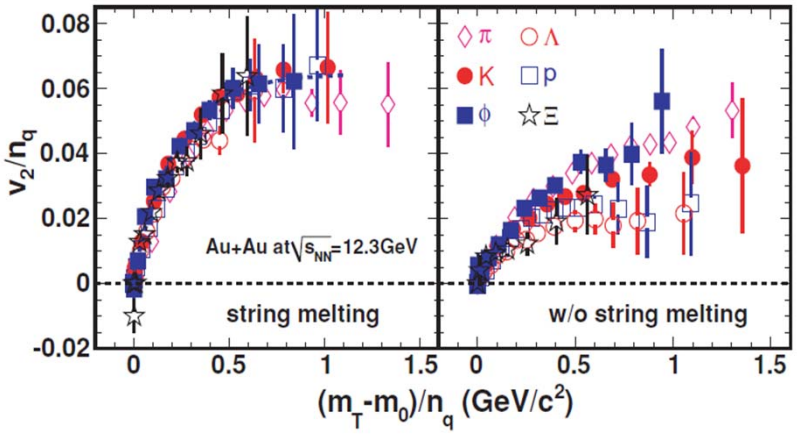
partonic

RHIC Data



hadronic

AMPT model



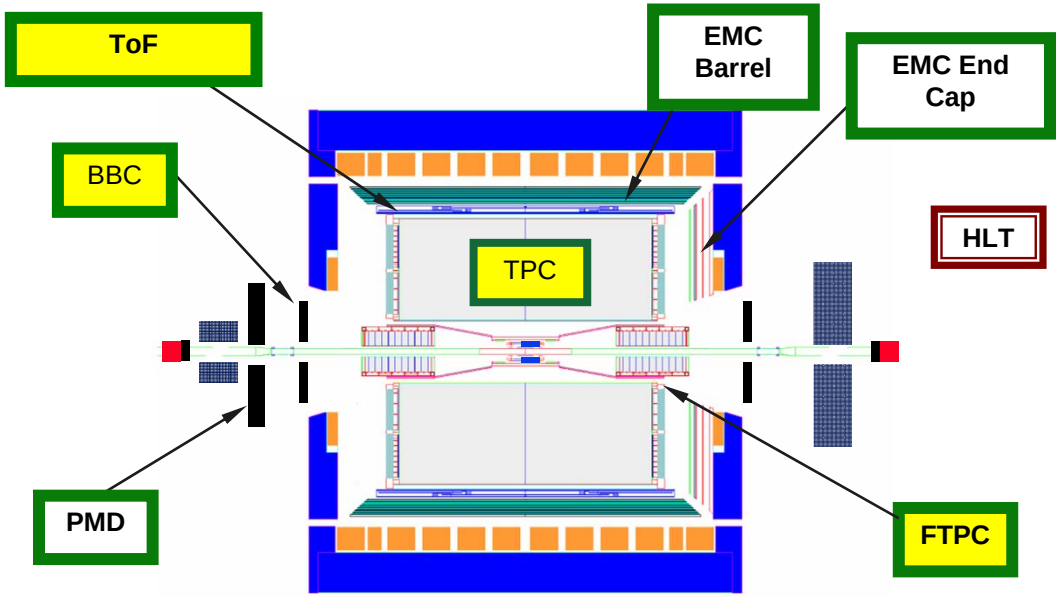
Phys. Rev. C 79, 067901 (2009); J. Phys. G 36, 064022 (2009); J. Phys. G 37, 094029 (2010)

- ✓ mass: proton ~ $\phi(s\bar{s})$ ~ Λ
- ✓ ϕ: meson, proton & Λ: baryon
- ✓ $s+\bar{s} \rightarrow \phi$ not $K^+ + K^- \rightarrow \phi$
- ✓ **small hadronic cross section**

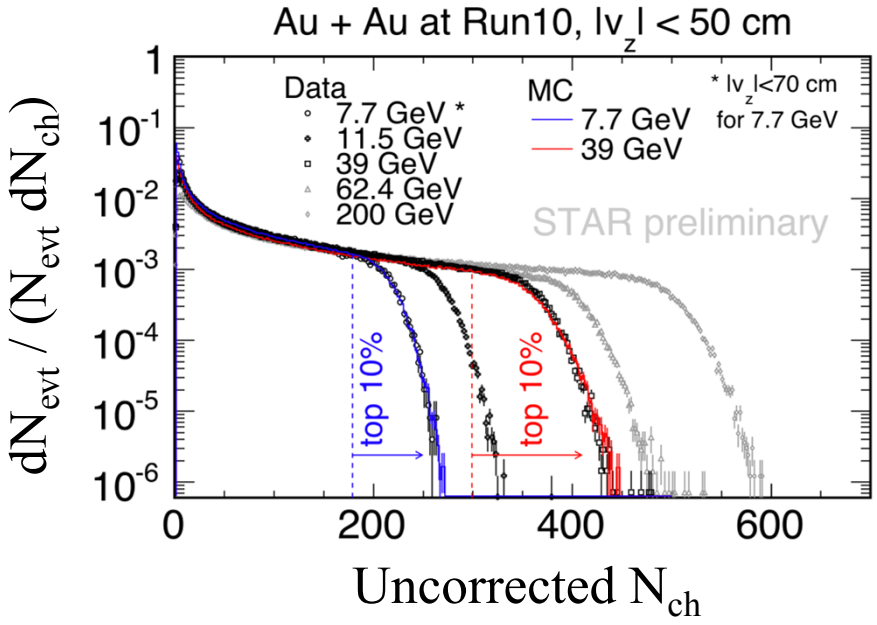
$\sigma_{\phi\text{-hadron}} << \sigma_{p\text{-}\pi,\ \pi\text{-}\pi}$

In the hadronic case, no number-of-quark scaling and the value of ϕ meson v_2 is expected to be small

Detector settings during STAR BES 2010-2011

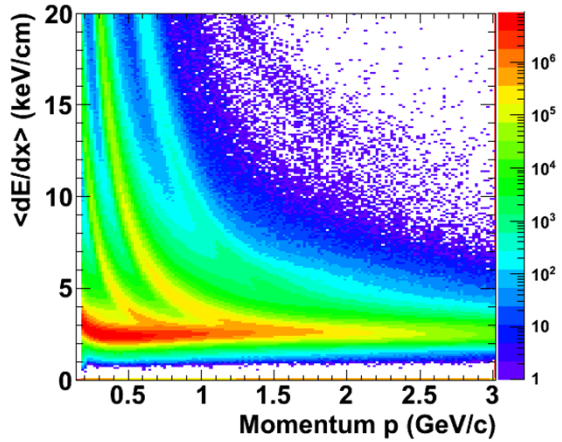


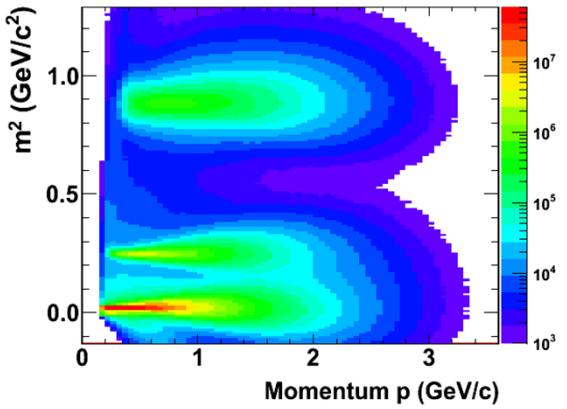
- Collisions: Au+Au
- Collisions centrality from uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$

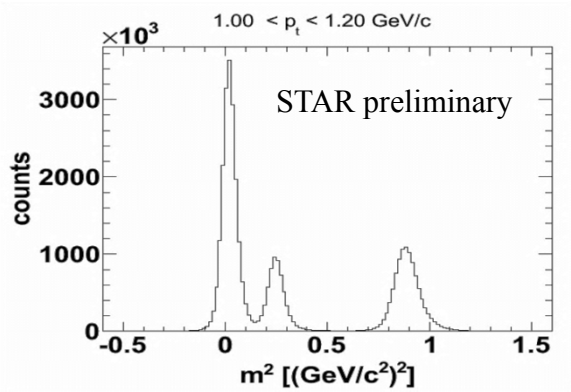


$\sqrt{s_{NN}}$ (GeV)	Good MB events in Million
5.0	
7.7	~ 4 M
11.5	~ 12 M
19.6	~ 36 M
27	~ 70 M
39	~ 130 M
62.4	~ 67 M

Particle identification and v_2 analysis





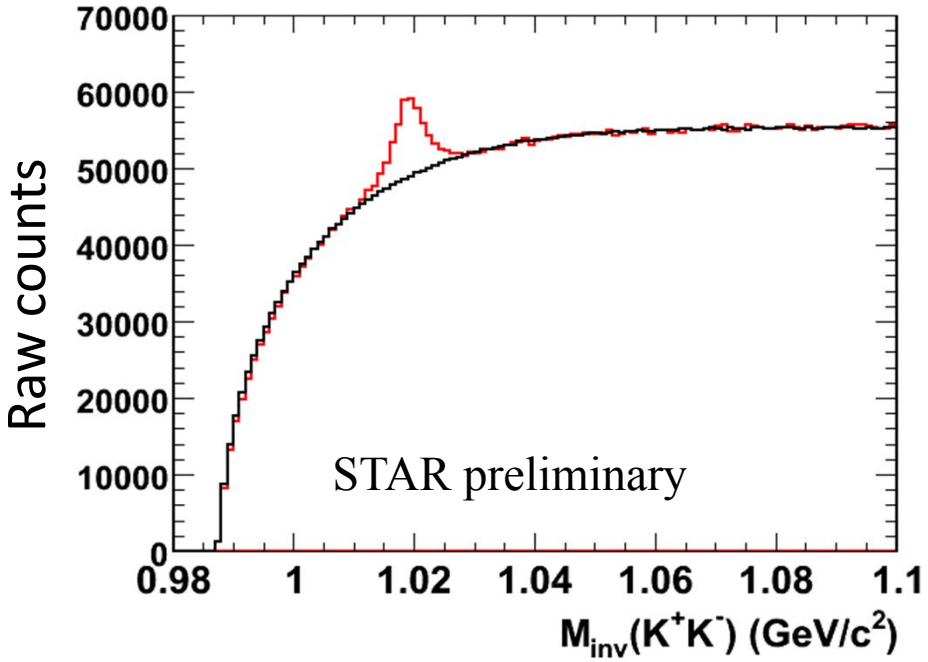


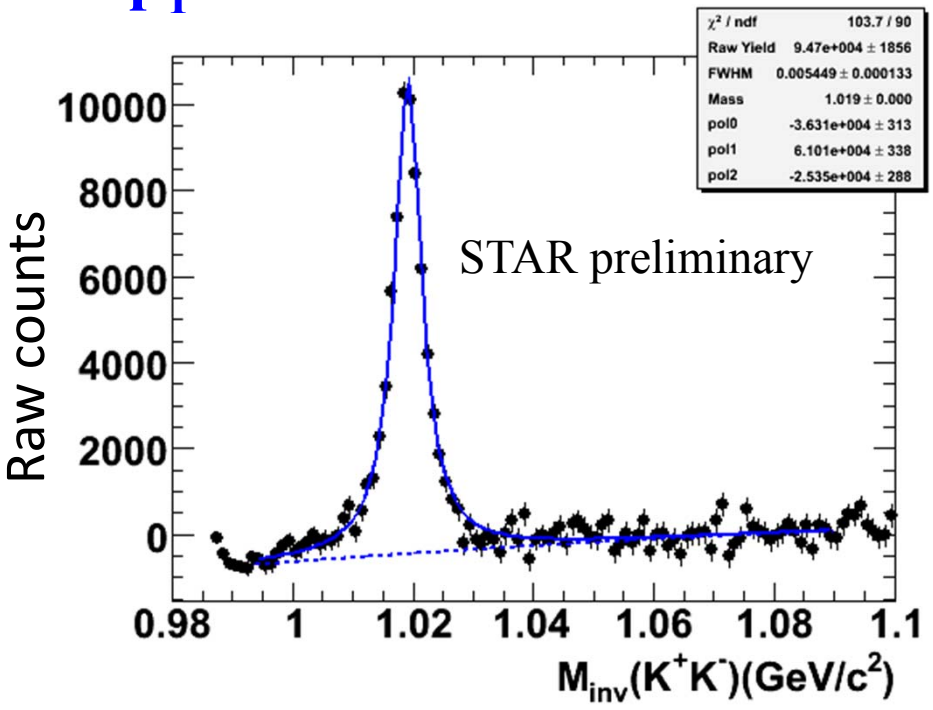
- **Time projection chamber (TPC)**
  full azimuth, $|\eta| < 1$
  dE/dx v.s. momentum
- **Barrel Time-Of-Flight (TOF)**
  full azimuth, $|\eta| < 1$
  Particle flight time
  Clean separation of K, π up to $p_T = 1.6$ GeV/c
- $v_2 = < cos2(\varphi - \psi_2)/Res >$
- **TPC η-sub event plane for v_2 analysis**
  Non-flow effect reduced

η-sub event plane method: STAR, Phys. Rev. C **77,** 054901 (2008)

$\phi \rightarrow K^+ + K^-$ reconstruction

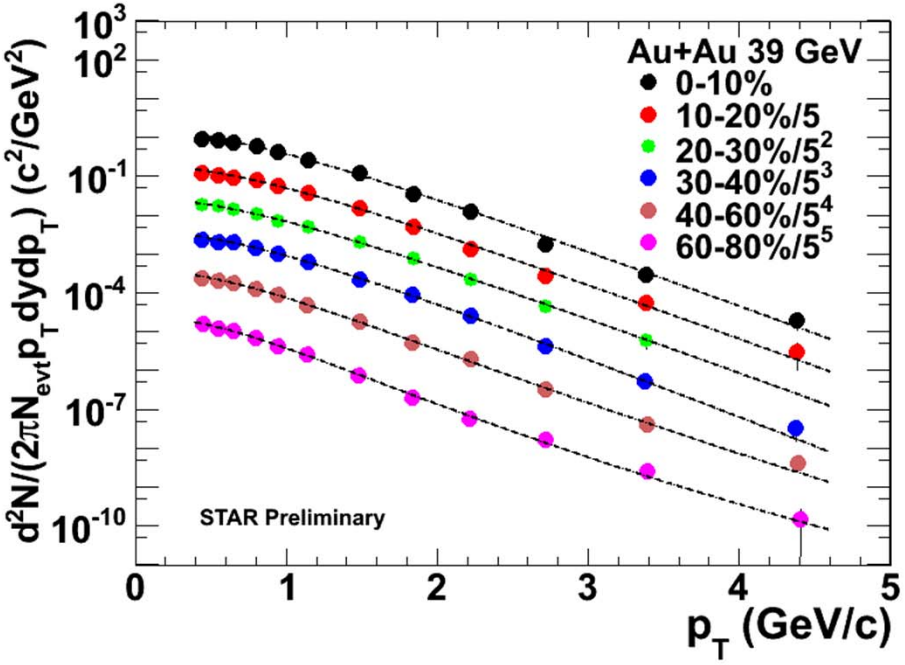
Au+Au 7.7 GeV $0.3<p_T<1.2$ GeV/c



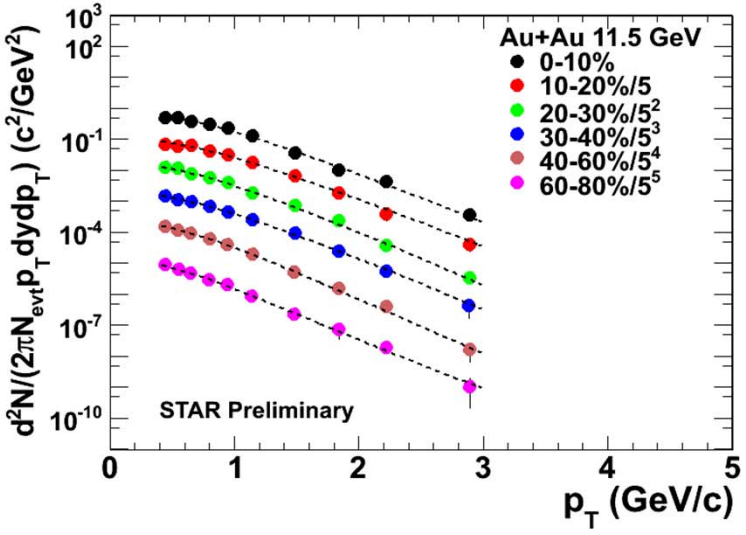


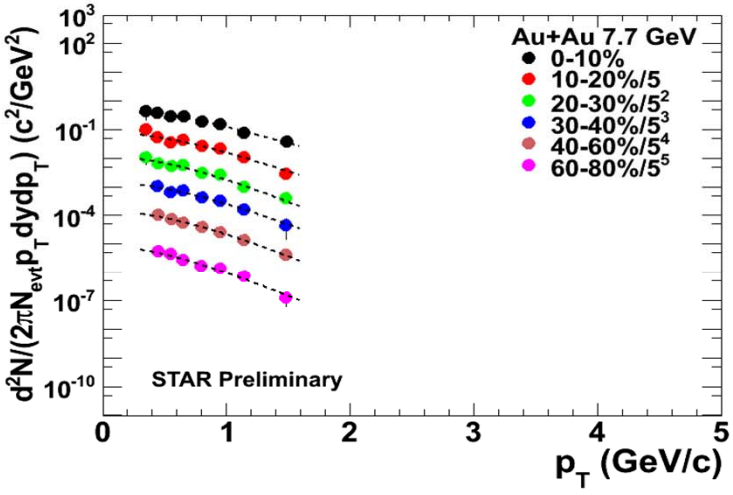
- TPC particle identification (PID) is used for spectra analysis, TPC+TOF PID is used for v_2 analysis
- **Signal/Background of ϕ resonance significantly improved with additional TOF PID**

Spectra from $\phi \rightarrow K^+ + K^-$ decay channel



Statistical error only

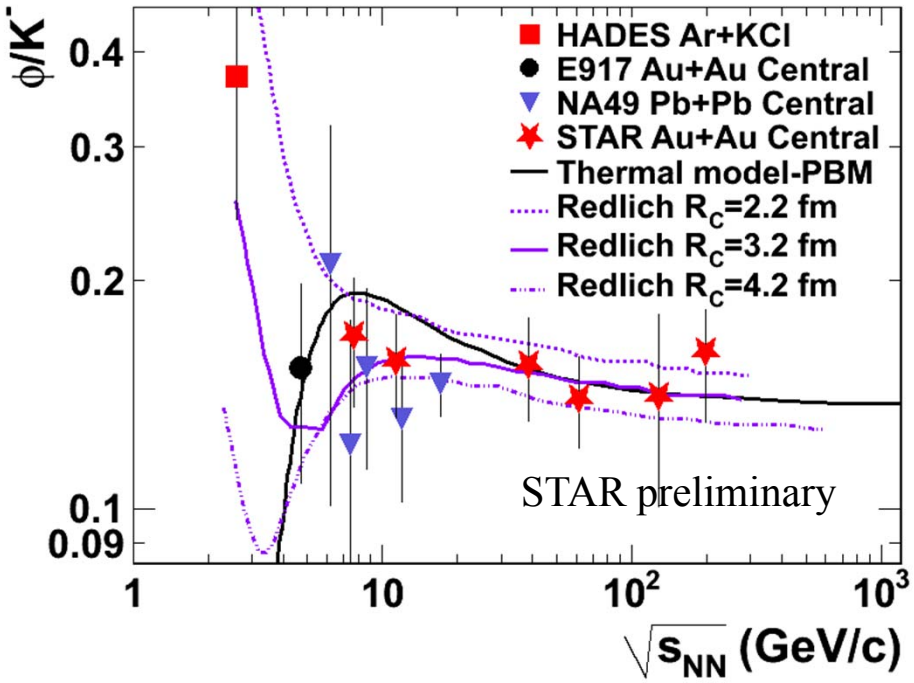


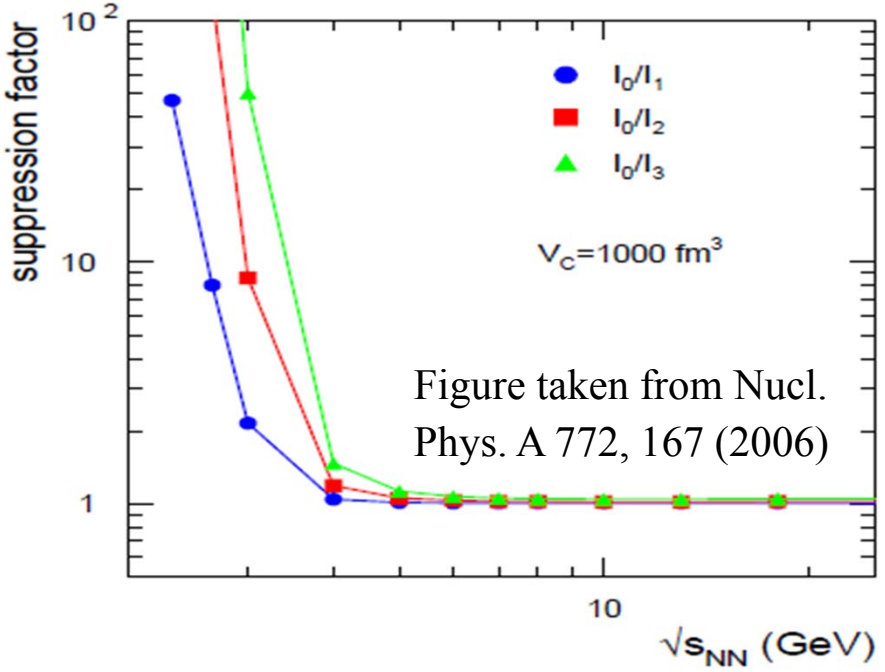


- **ϕ meson transverse momentum distribution can be well described by a Levy function**

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = dN/dy \frac{(n-1)(n-2)}{2\pi nT(nT+m(n-2))}\left(1+\frac{\sqrt{p_T^2+m^2}-m}{nT}\right)^{-n}$$

ϕ/K^- ratio



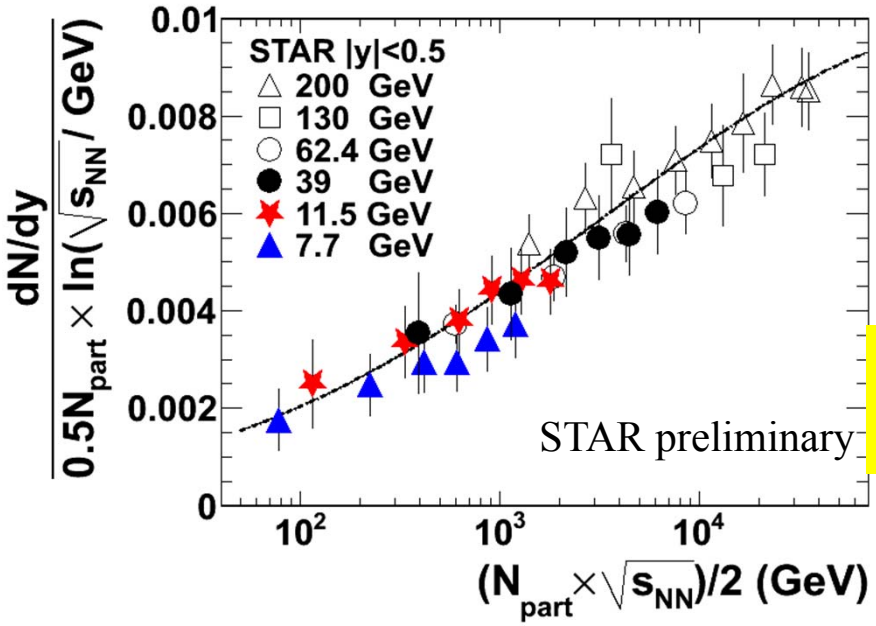


HADES: Phys. Rev. C 80, 025209 (2009) E917: Phys. Rev. C 69, 054901 (2004)
NA49: Phys. Rev. C 78, 044907 (2008) STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009)
Thermal model-PBM: Nucl. Phys. A 772, 167 (2006)
Redlich model: Phys. Lett. B 603, 146 (2004)

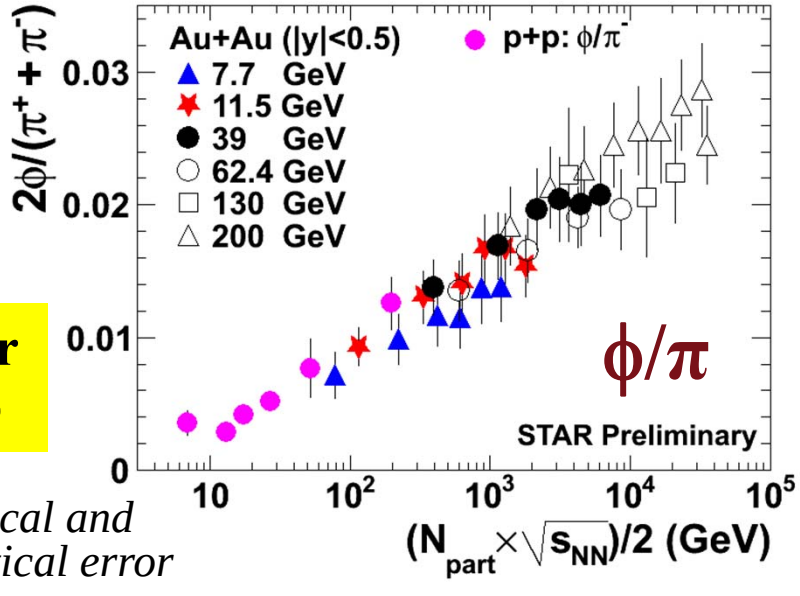
Statistical + systematical error

- **ϕ/K^- ratio is sensitive to strangeness production mechanism**
- PBM model: canonical suppression, canonical volume V_C = 1000 fm^3
- Redlich model: strangeness correlation radius R_C: 2.2 ─ 4.2 fm
- More precise measurements at BES energies 5-10 GeV might be helpful

Scaling behavior of ϕ meson yields and ϕ/π ratio



New for CPOD

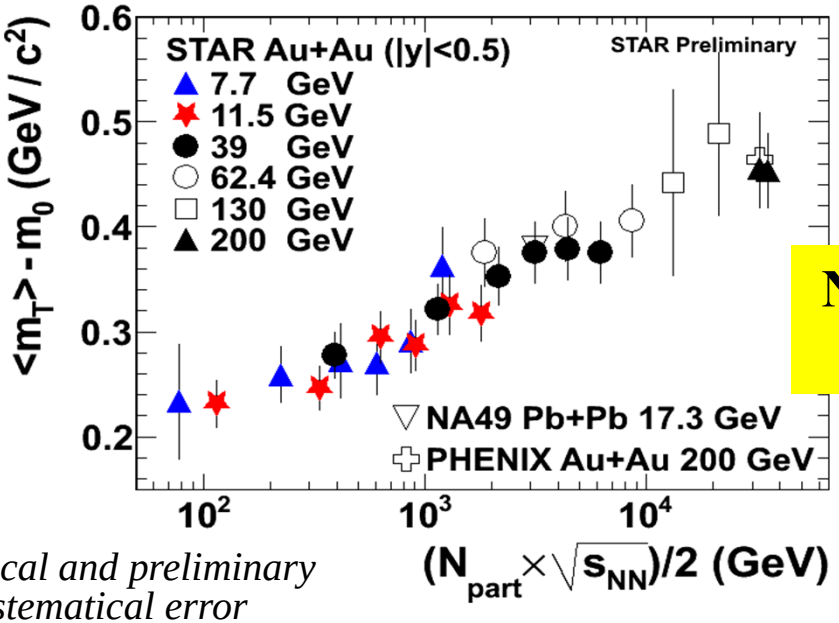


Statistical and systematical error

STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009). ϕ data in pp are from Phys. Lett. B 491, 59 (2000), Phys. Rev. C 63, 024004 (2001), Phys. Lett. B 468, 7 (1999); ibid. 59, 88 (1975); ibid. 110, 326 (1982); Nucl. Phys. 186, 205 (1981); Z. Phys. C 9, 293 (1981). π data: STAR, L. Kumar, QM2011; Phys. Rev. C 79, 034909 (2009).

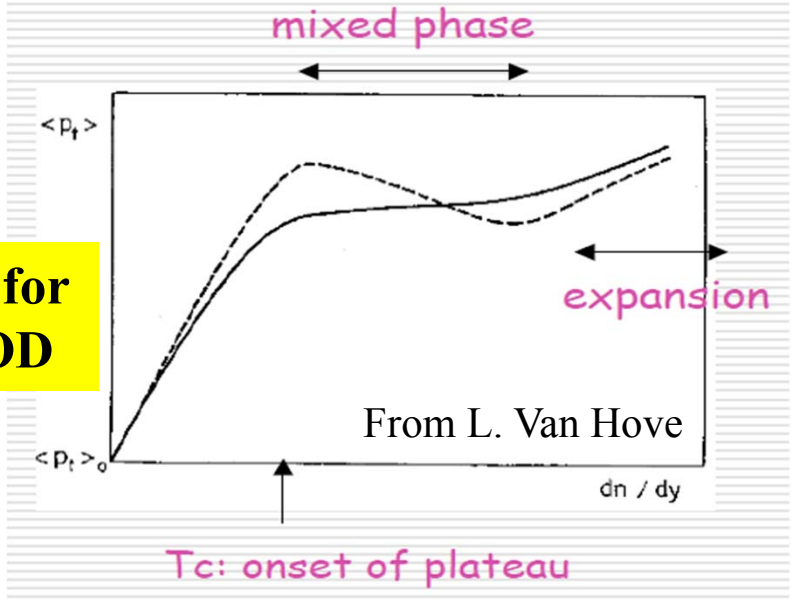
- dN/dy per participant pair scaled by $ln\sqrt{s_{NN}}$ v.s. ~ total collision energy
- **A common curve for above energies and collision centralities**
- ϕ/π ratio v.s. ~ total collision energy has the similar scaling
  p+p data fall in the same trend!
- Increase of ϕ/π ratio with ~ total collision energy, **strangeness enhancement**

ϕ meson $\langle m_T \rangle - m_0$



Statistical and preliminary systematical error

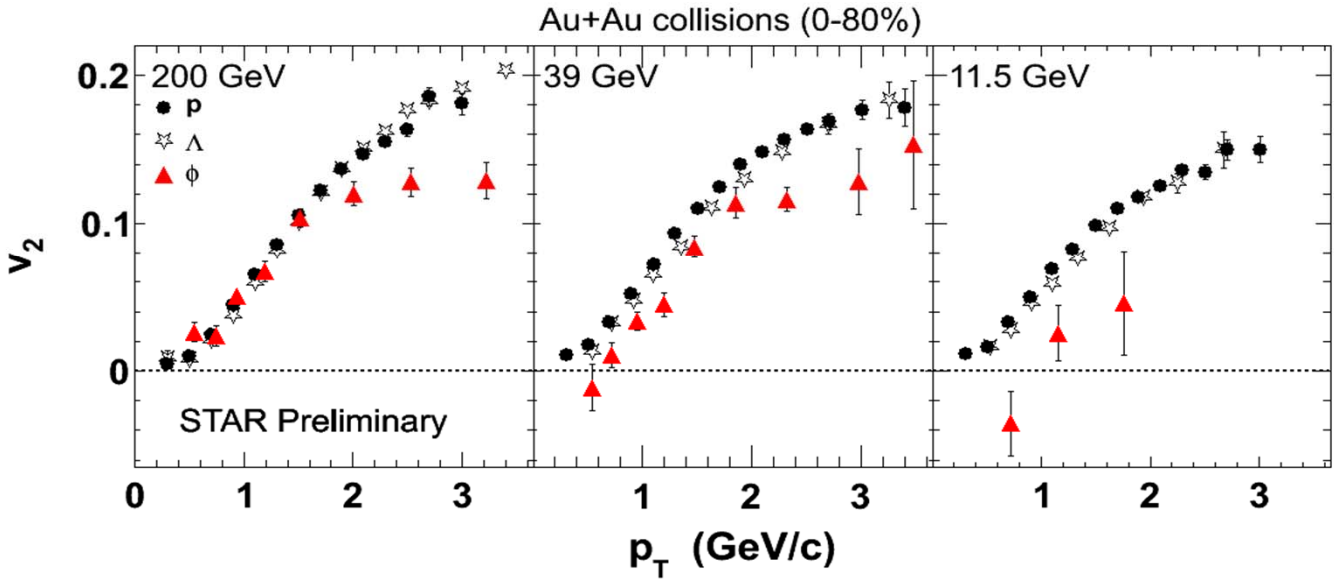
New for CPOD

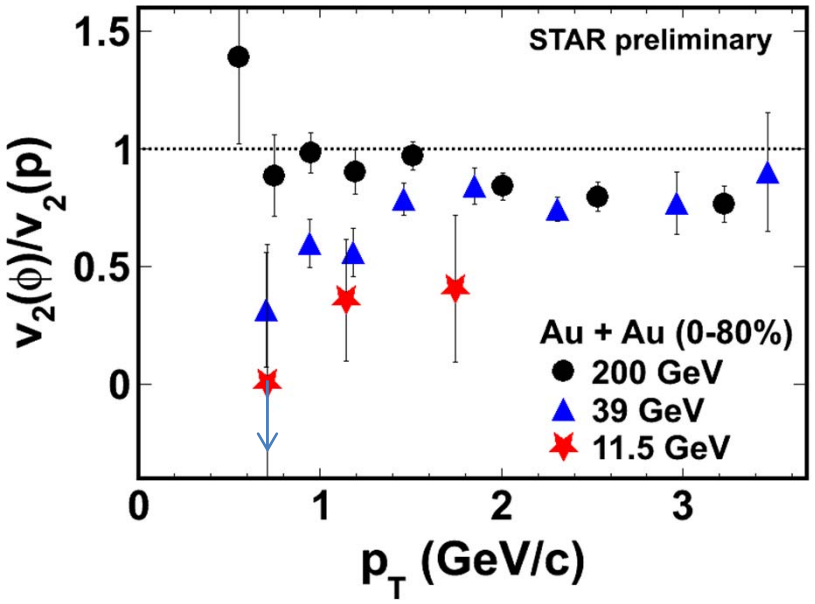


- $\langle m_T \rangle - m_0$ is sensitive to transeverse expansion of the system
- Mixed phase: constant T and p, plateau structure is expected
- ϕ meson $\langle m_T \rangle - m_0$ v.s. ~ total collision energy
- **A common curve for above energies and collision centralities**
- ϕ meson $\langle m_T \rangle - m_0$ show a roughly increasing trend, more data are helpful to see if plateau exists

STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009); PHENIX: Phys. Rev. C 72, 014903 (2005);
NA49: Phys. Rev. C 78, 044907 (2008); L. Van Hove, Phys. Lett. B 118, 138 (1982); R. Sahoo et al., arXiv: 1007.4335v1

ϕ meson v_2 v.s. p_T

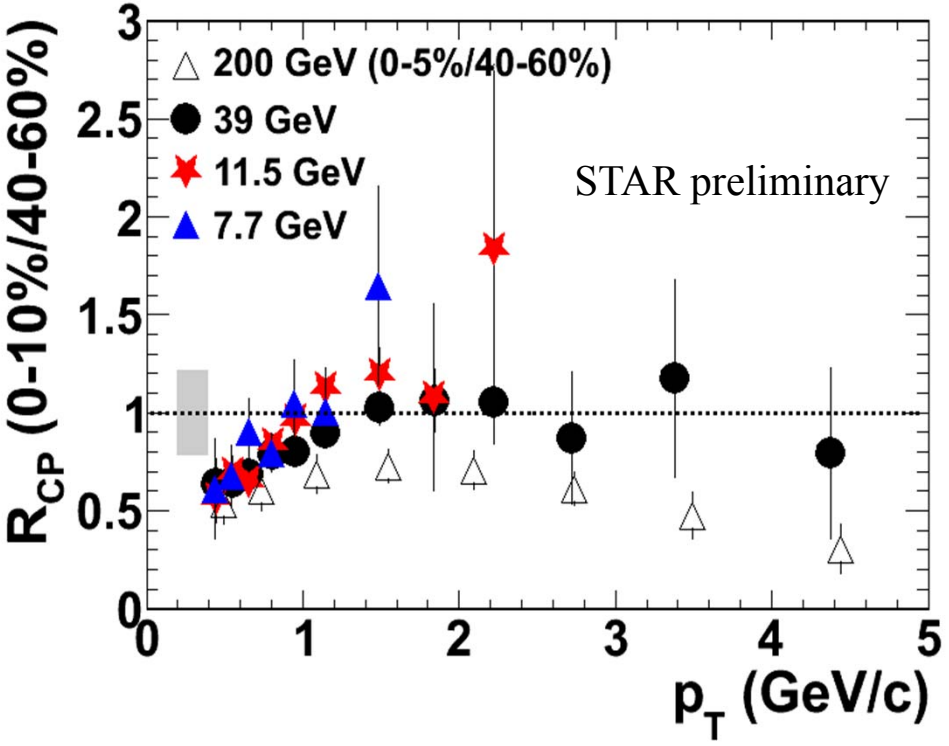


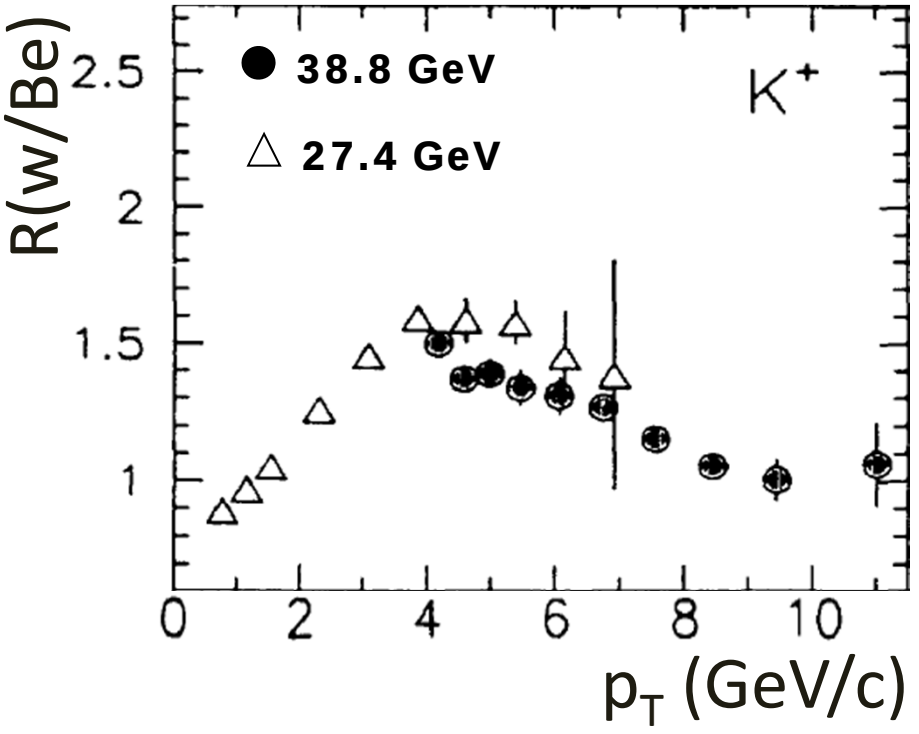


- Mass: proton ~ ϕ ~ Λ
- At low p_T, $v_2(\phi)/v_2(p)$ decreases with decreasing beam energies
  → **strange quark collectivity becomes weaker relative to light quarks**

200 GeV: TPC full event plane; 11.5 and 39 GeV, TPC η-sub event plane; statistical error only

ϕ meson nuclear modification factor (R_{CP})





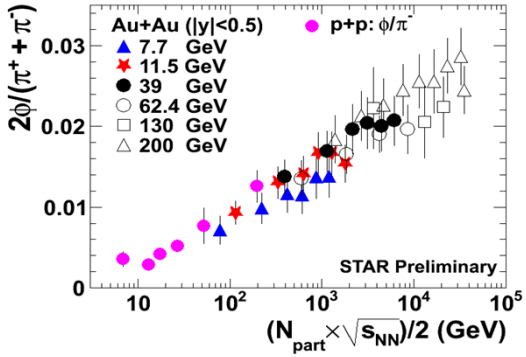
P. B Straub et al., Phys. Rev. Lett. 68, 452 (1992)

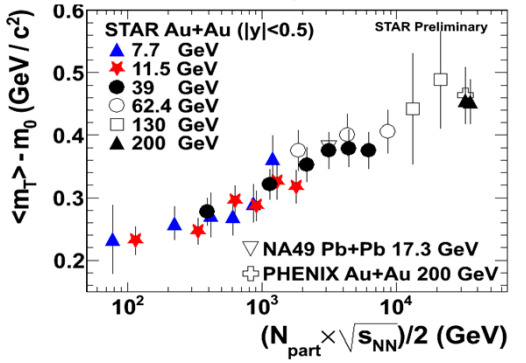
Grey band: normalization error on number of binary collisions Points: statistical error

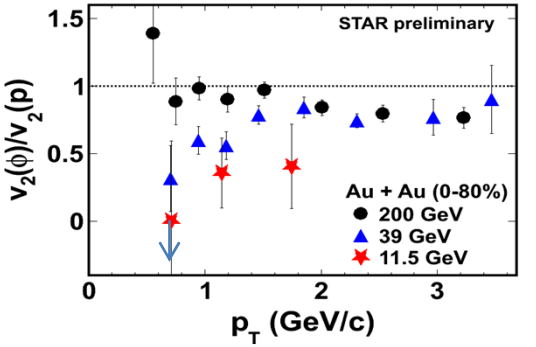
- **R_{CP}(0-10%/40-60%) consistent with unity for p_T > 1 GeV/c at 39 GeV, no suppression**
- Interplay between Cronin effect (p_T broadening due to multiple scatterings) and parton energy loss?

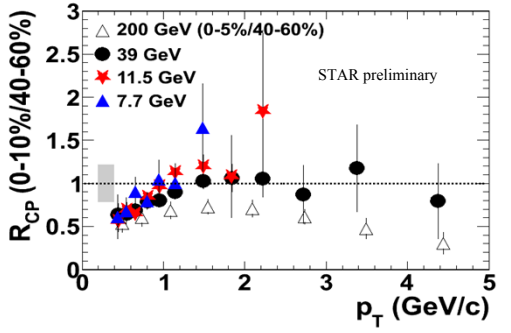
Summary and outlook

- STAR preliminary ϕ meson spectra and v_2 results in $\sqrt{s_{NN}}$ = 7.7, 11.5 and 39 GeV Au+Au collisions have been presented
- Scaling behavior of ϕ meson production in different collision energies and centralities
  With increasing total collision energies:
  ϕ yields enhancement relative to π meson
  ϕ meson $<m_T> - m_0$ show a increasing trend
- $v_2(\phi)/v_2(p)$ decreases with decreasing beam energies at low p_T → **strange quark collectivity becomes weaker relative to light quarks**
- ϕ meson R_{CP}(0-10%/40-60%) consistent with unity at **39 GeV, no suppression**
- Outlook: 19.6, 27 and 62.4 GeV data under analysis





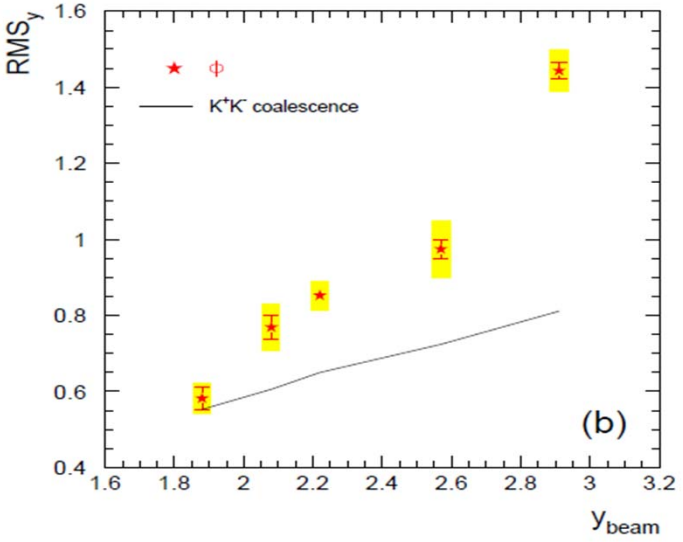




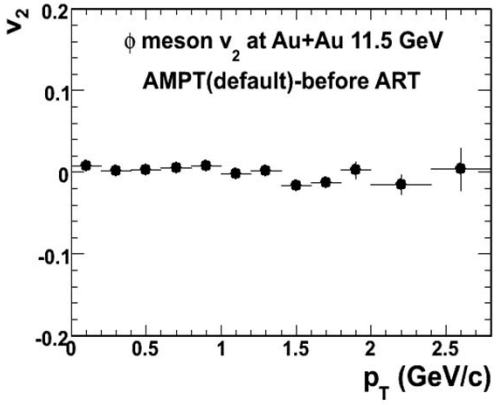
Backup

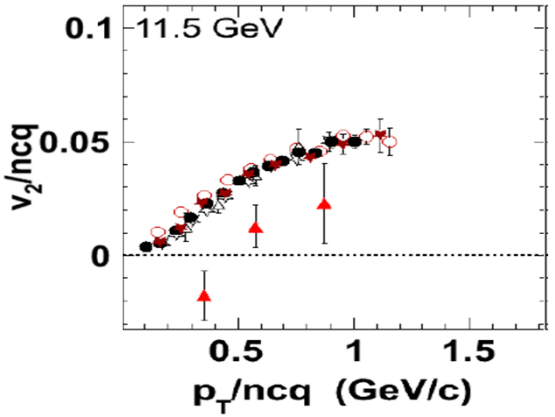
Why $\phi(s\bar{s})$ is special?

- K^+K^- is not the main production channel in our interested region
- ϕ meson $v_2 \sim 0$, if only from string fragmentation
- ϕ meson has small hadronic cross section. $\sigma(\phi N) \sim 10$ mb
- **Small ϕ v_2 at hadronic phase**
- **ϕ meson v_2 indicates strange quark collectivity becomes weaker with decreasing beam energy**



$\sigma_{\rho N} \sim 3\ \sigma_{\phi N}$
$\sigma_{\pi N} \sim 2.6\ \sigma_{\phi N}$
$\sigma_{KN} \sim 2.1\ \sigma_{\phi N}$
$\sigma_{\Lambda N} \sim 3.5\ \sigma_{\phi N}$
$\sigma_{NN} \sim 4\ \sigma_{\phi N}$

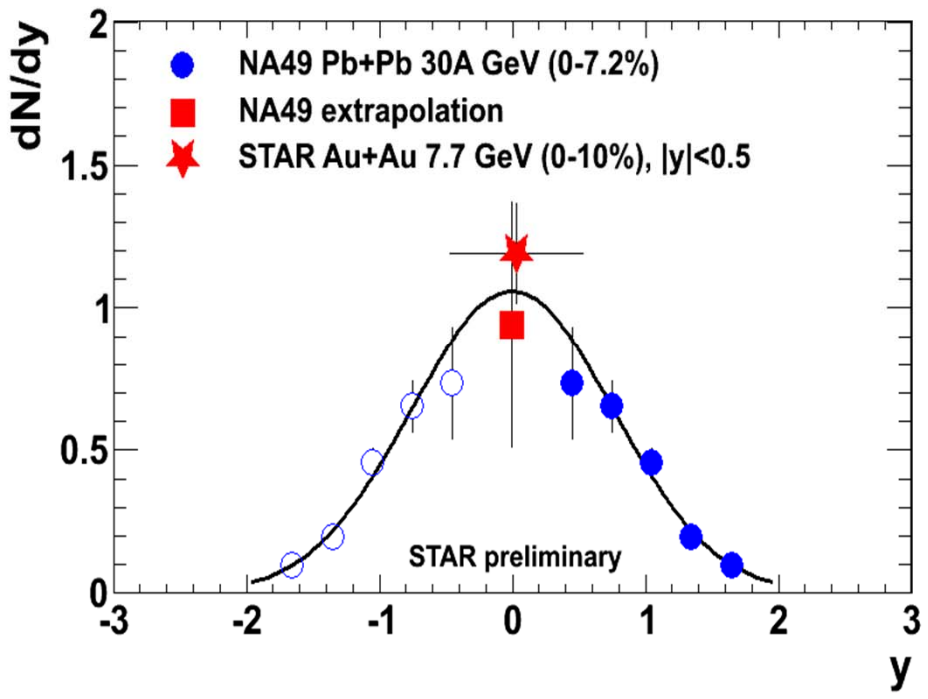


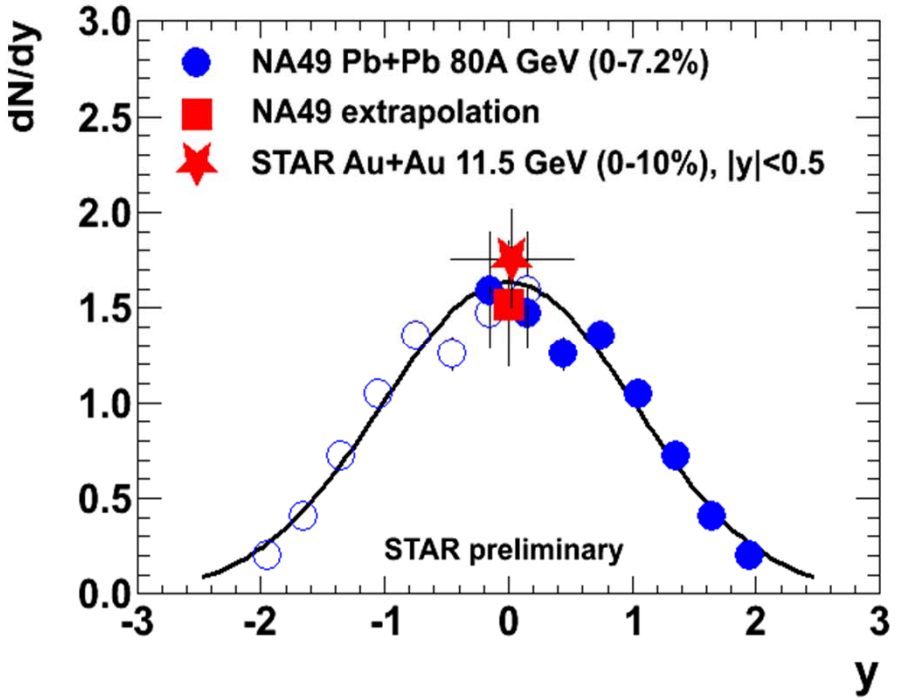


$\sqrt{s}$ (GeV) 6.3 → 17.3

B. Mohanty and N. Xu, J. Phys. G 36 (2009) 064022
NA49, Phys. Rev. C 78 (2008) 044907

ϕ meson yields comparison

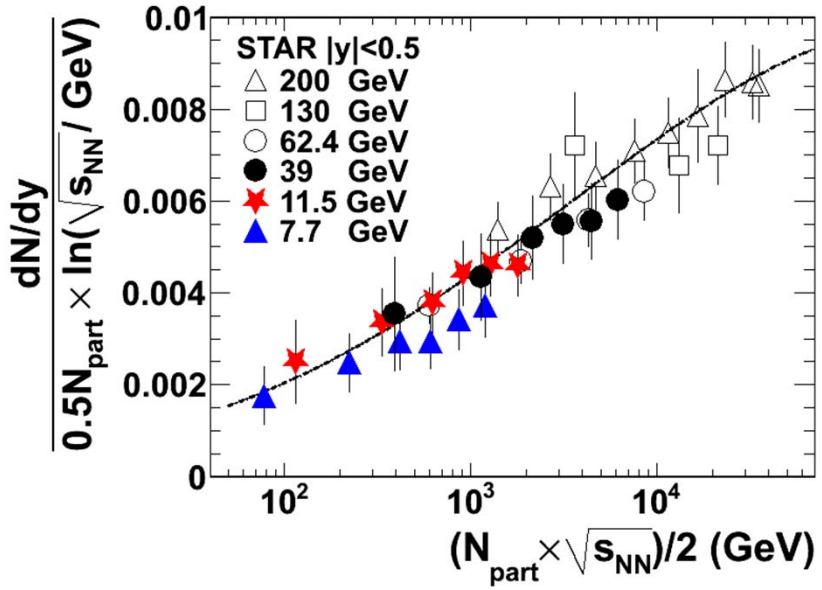




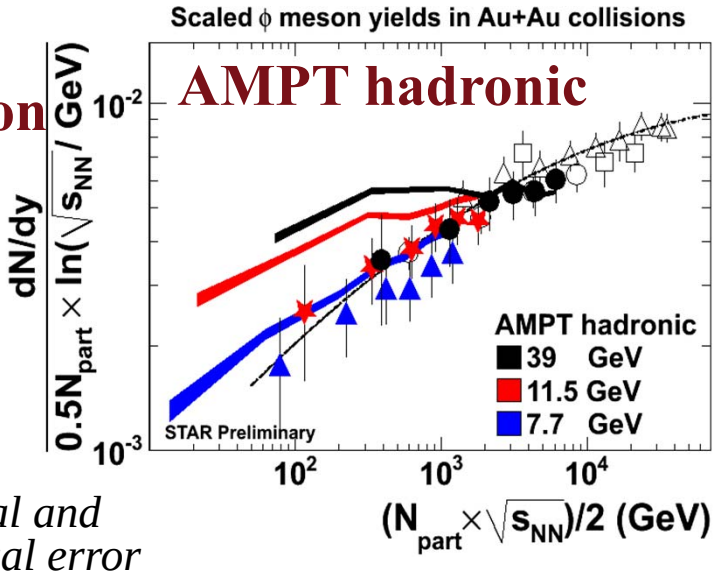
- NA49: 30A GeV ~ $\sqrt{s_{NN}}$ = 7.6 GeV, 80A GeV ~ $\sqrt{s_{NN}}$ = 12.3 GeV
- Consistent within error bars: statistical + systematical error

NA49, Phys. Rev. C 78, 044907 (2008)

Scaling behavior of ϕ meson yields

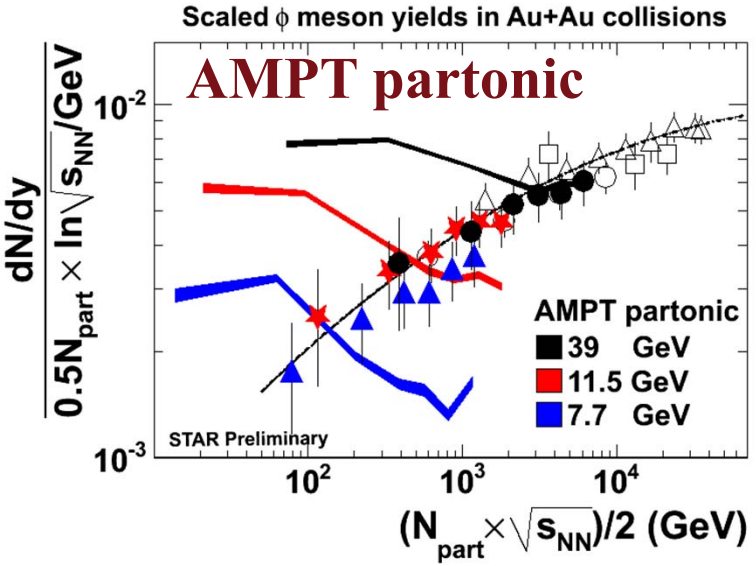


Model comparison



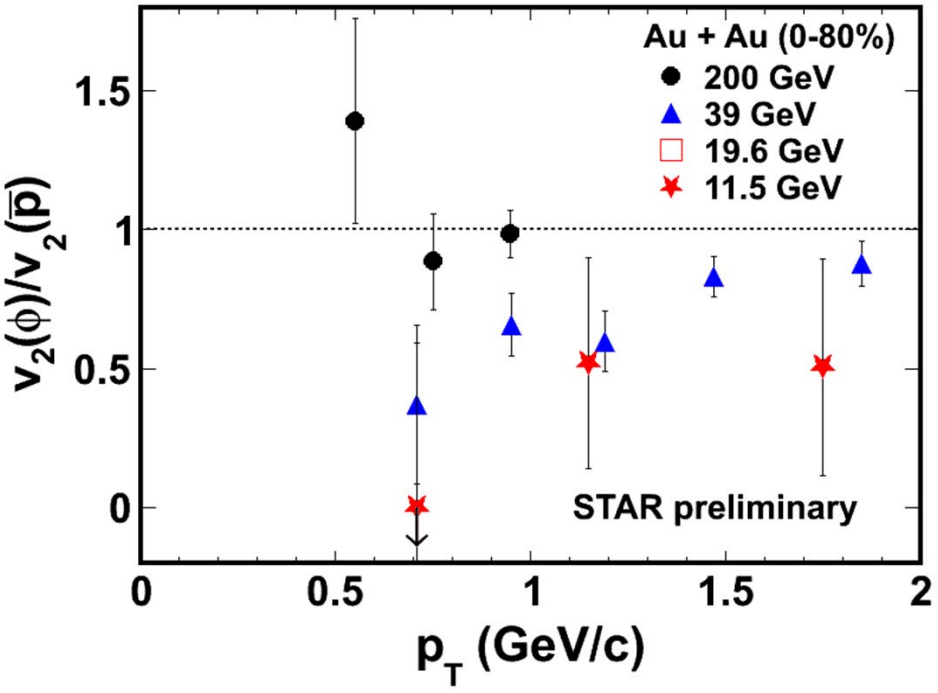
Statistical and systematical error

STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009).



- dN/dy per participant pair scaled by $ln\sqrt{s_{NN}}$ v.s. ~ total collision energy
- **A common curve for above energies and collision centralities**
- Rapid increase in $0.5N_{part} \times \sqrt{s_{NN}} < 2000$
- AMPT model with hadronic interactions approximately reproduces the 7.7 GeV data
- AMPT model with partonic interactions reproduces data at 39 GeV mid-central to central collisions

$v_2(\phi) / v_2(\bar{p})$



200 GeV: TPC full event plane; 11.5 and 39 GeV, TPC η-sub event plane; statistical error only