Collective flow measurements at RHIC energies

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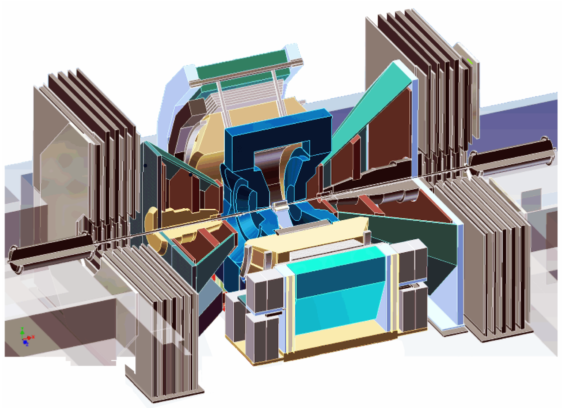
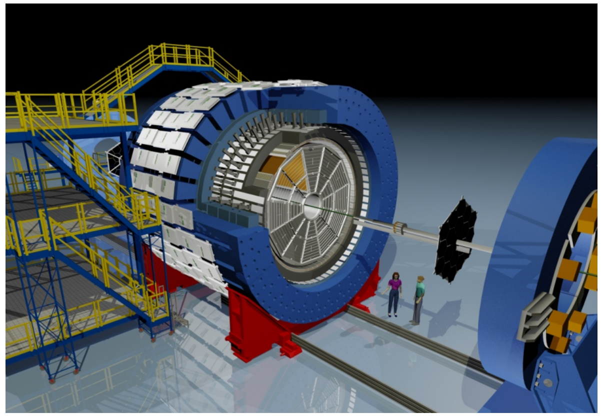
Center for Integrated Research
in Fundamental Science and Engineering (CiRfSE)

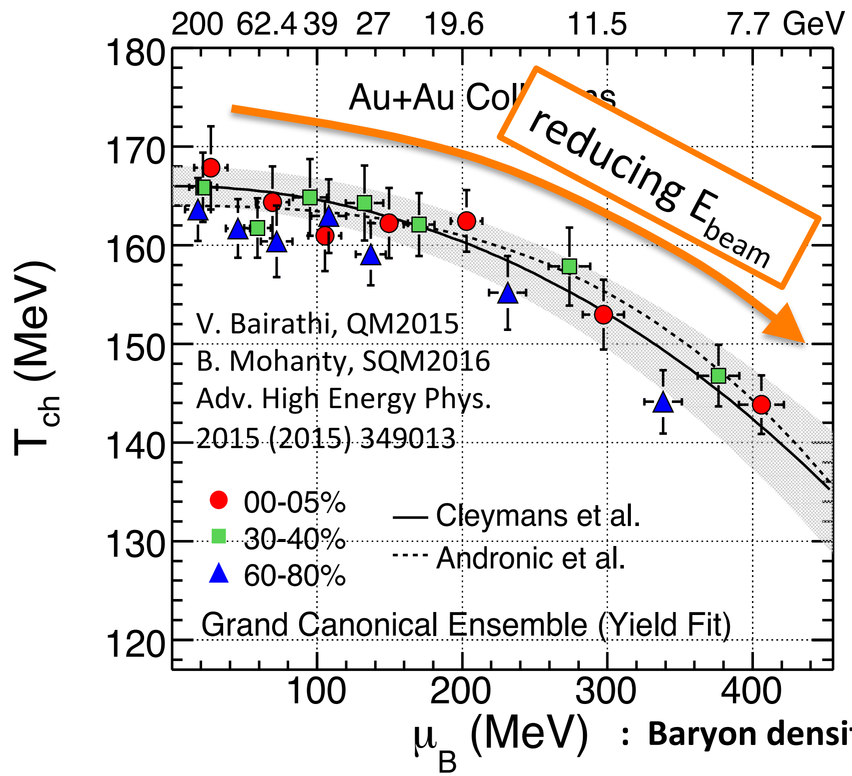




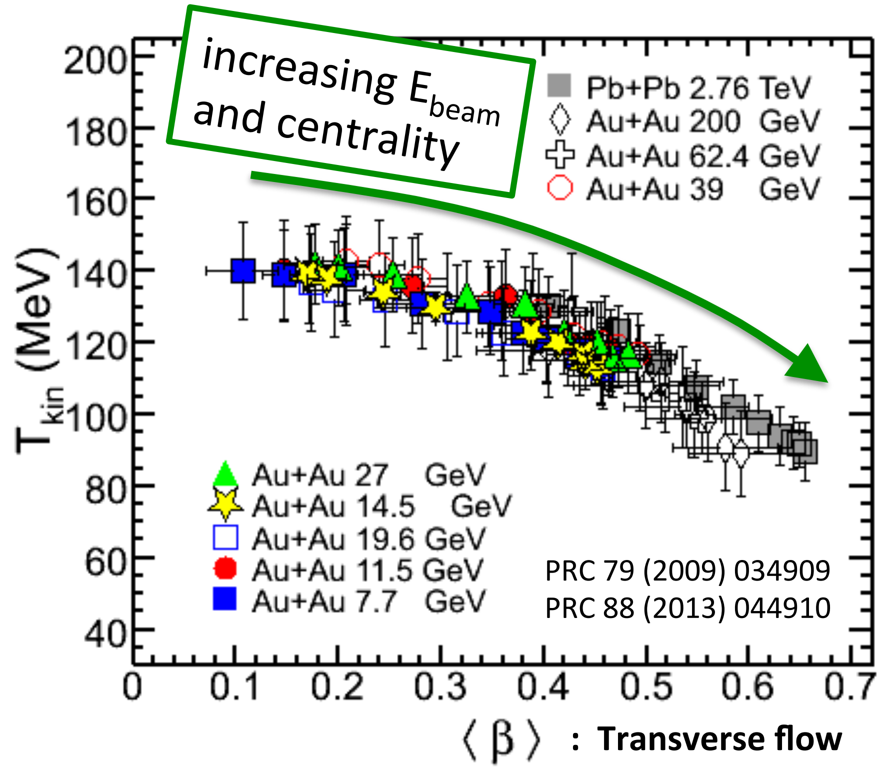
Contents

- **Radial and anisotropic flows**
- **Correlations with reaction planes**
- **Fluctuations**

Chemical and Thermal kinetic freeze-out with radial flow



: **Baryon density**



: **Transverse flow**

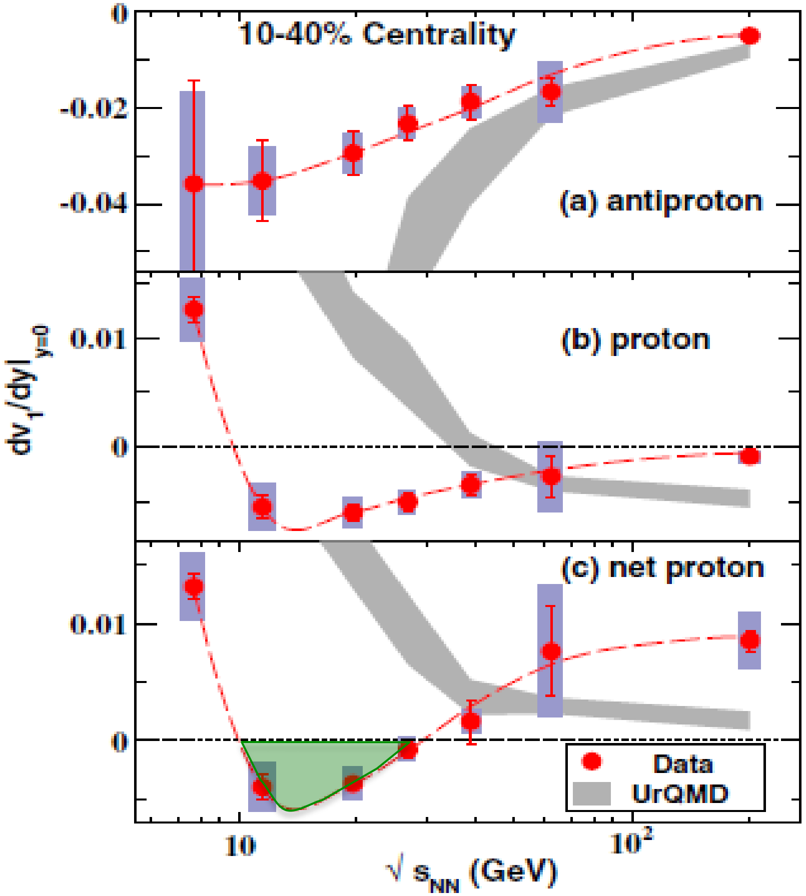
Hadron yields are fitted with chemical thermal model in order to extract (T_{ch}, μ_B) parameters.

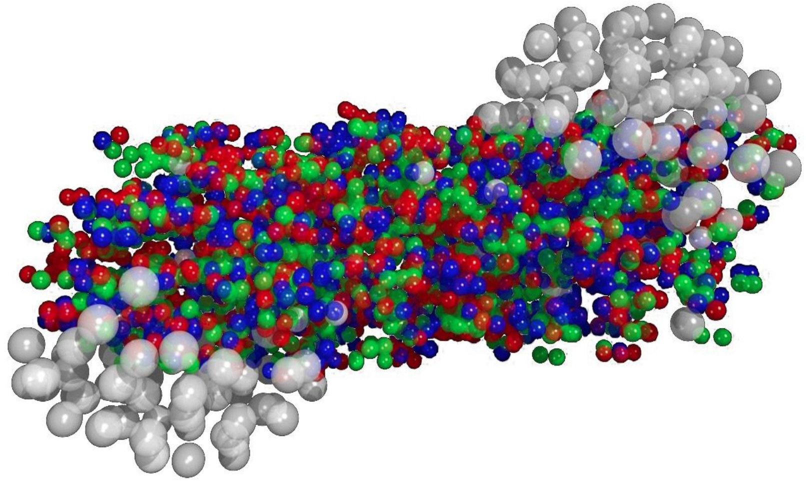
Hadron pT spectra are fitted with Blast-wave model in order to extract (T_{kin}, β_T) parameters.

Directed flow (v_1)

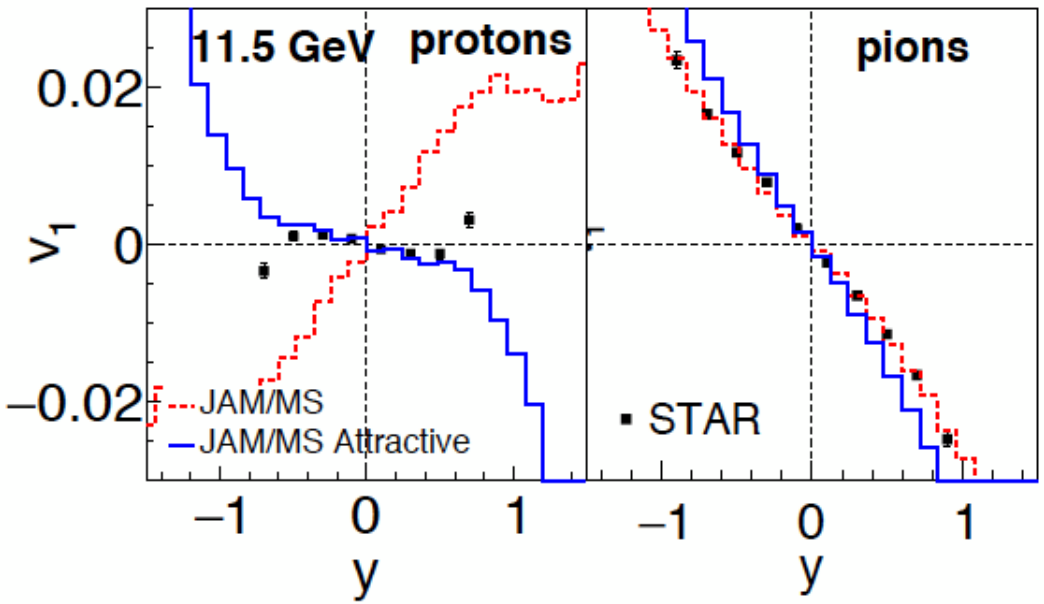
negative slope of dv_1/dy for net-proton
softening of Equation of State

Phys. Rev. Lett. 112 (2014) 162301

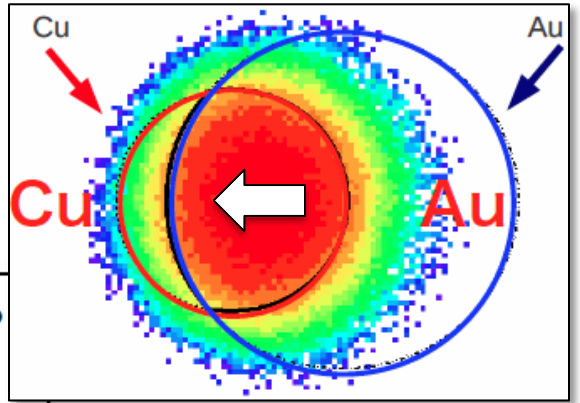


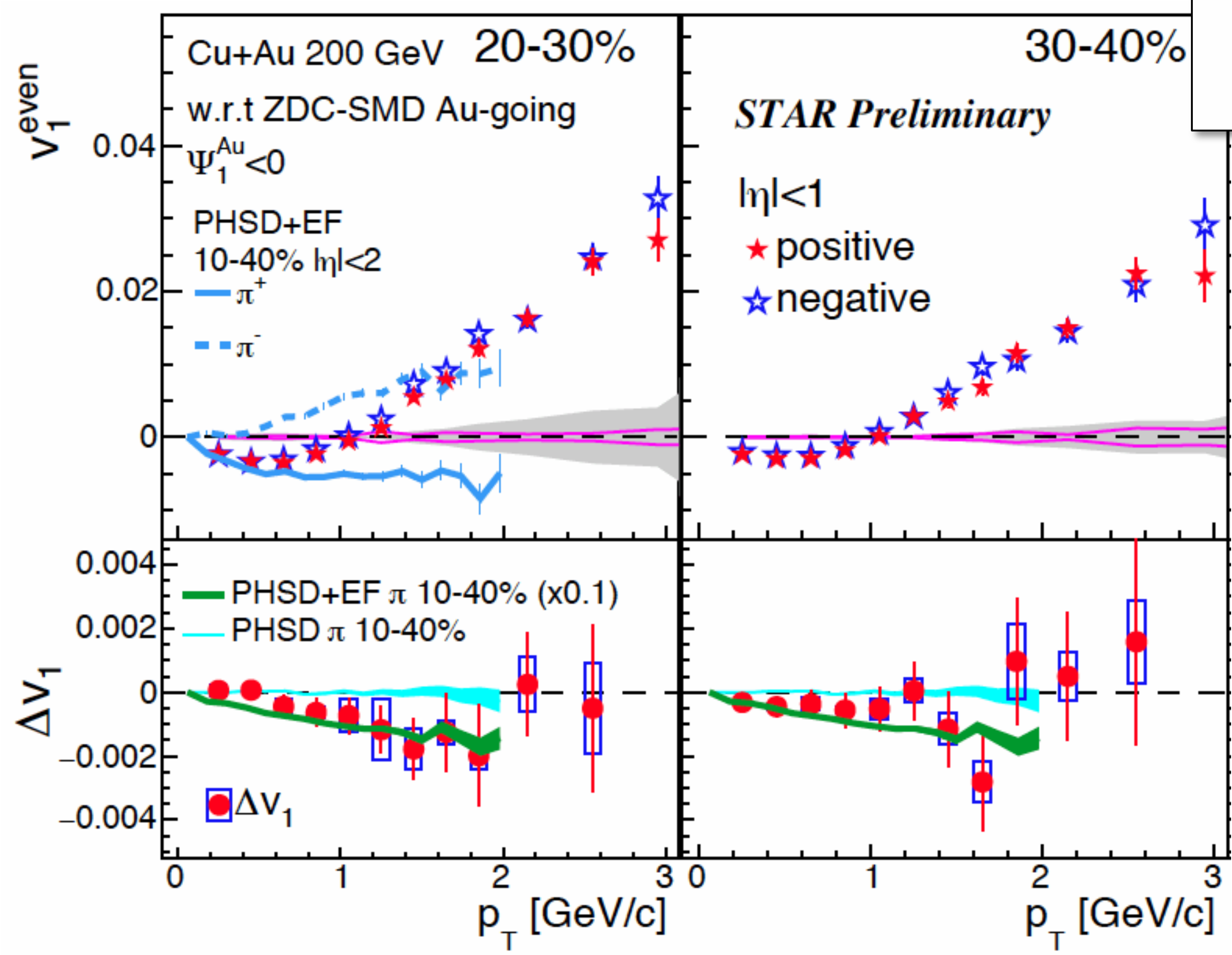


arXiv : 1601.07692



Directed flow (v_1) in Cu+Au at RHIC



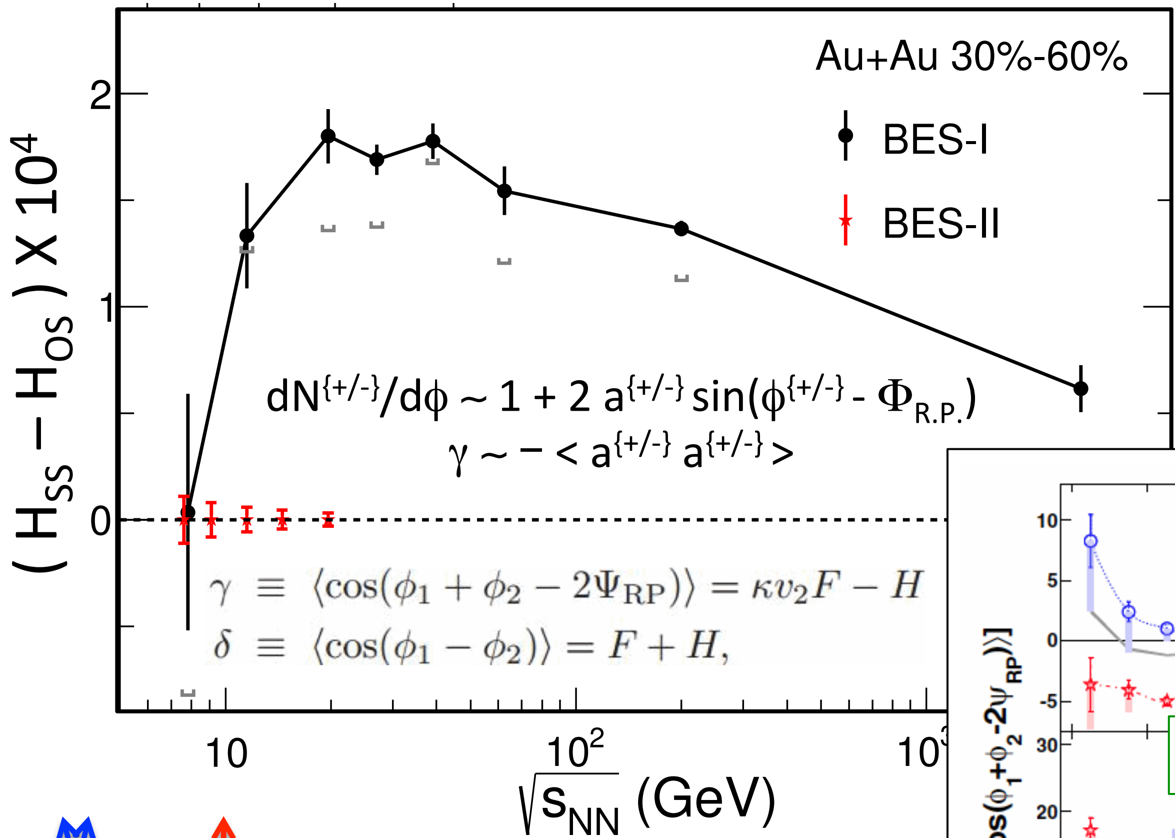


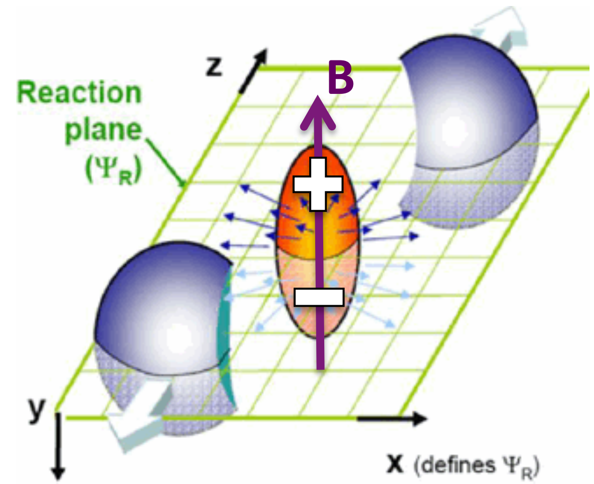
pressure gradient from asymmetric system :
Non-zero v1 at η~0

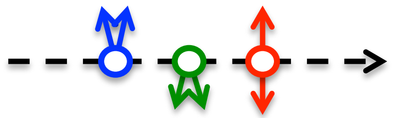
Possible E-field effect :
Charge dependent v_1
$\Delta v_1 = v_1\{h^+\} - v_1\{h^-\}$

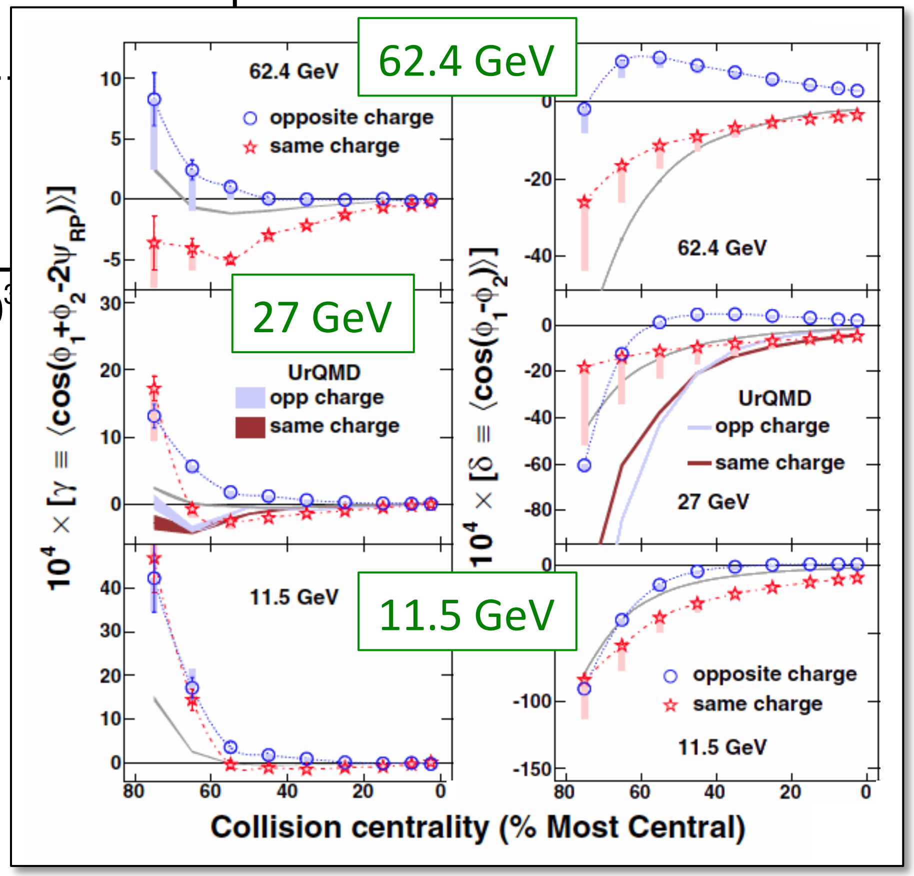
STAR, QM15
arXiv : 1608.04100

Phys. Rev. Lett. 113 (2014) 052302









Chiral magnetic effect

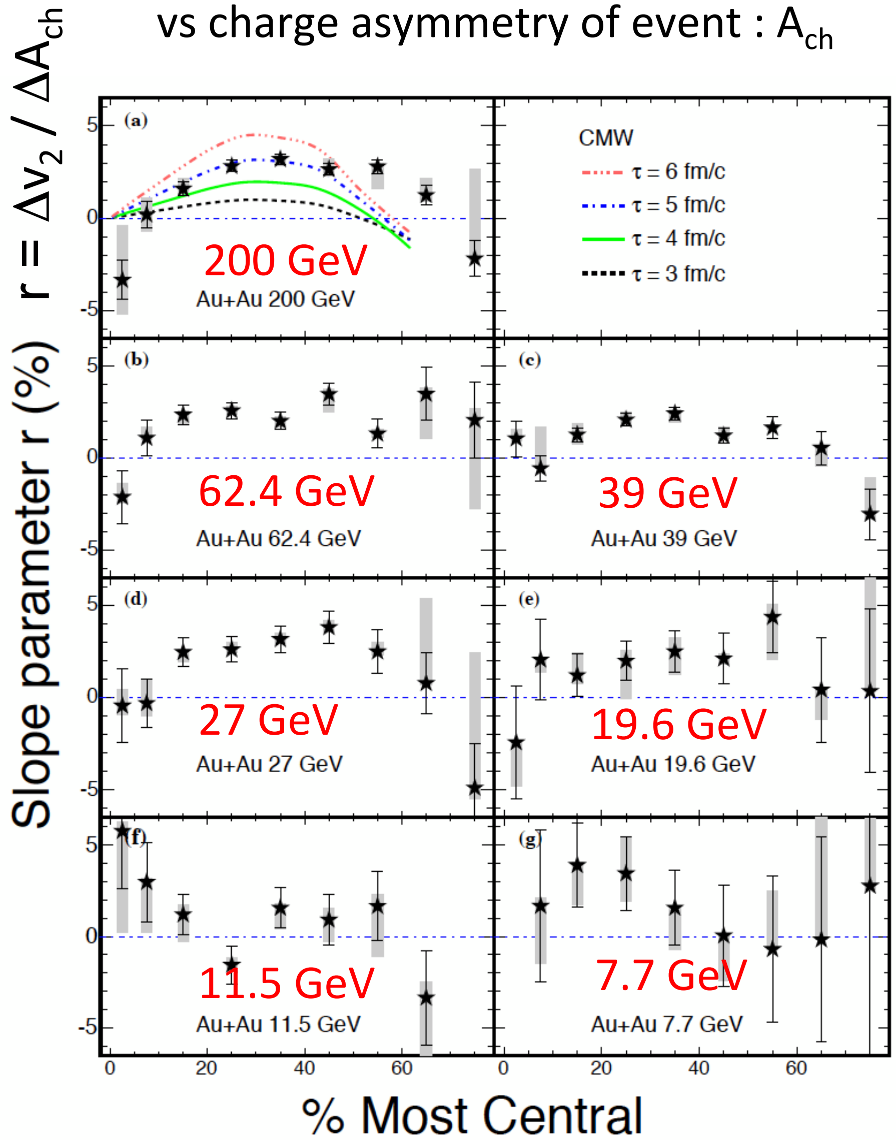
charge separation w.r.t. reaction plane

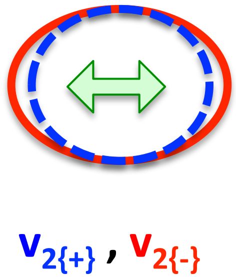
"Same-sign --- Opposite-sign" charged pair

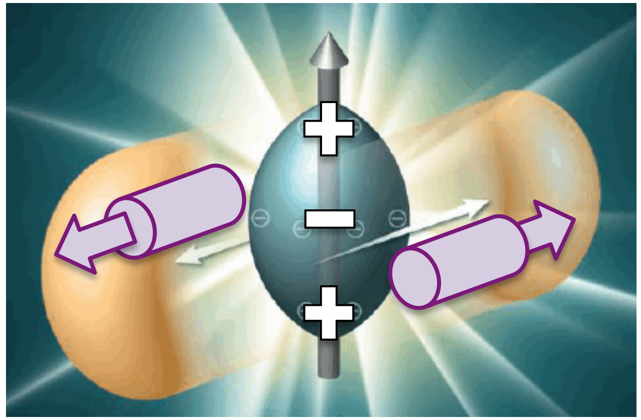
somewhat reduced by mixed event subtraction…

Chiral magnetic wave

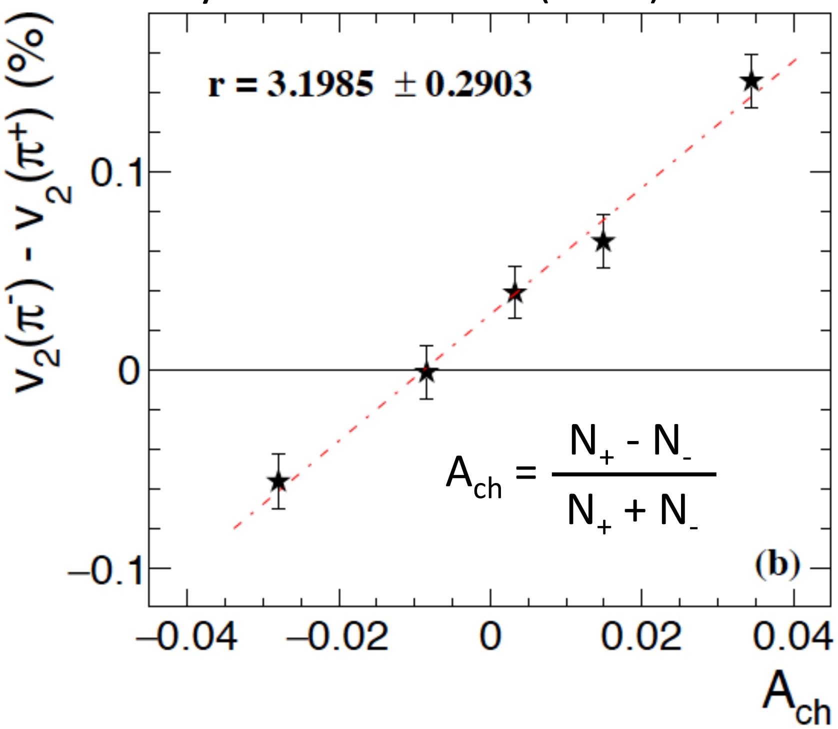
Charge dependent v_2 : $\Delta v_2 = v_2\{\pi^-\} - v_2\{\pi^+\}$
vs charge asymmetry of event : A_{ch}





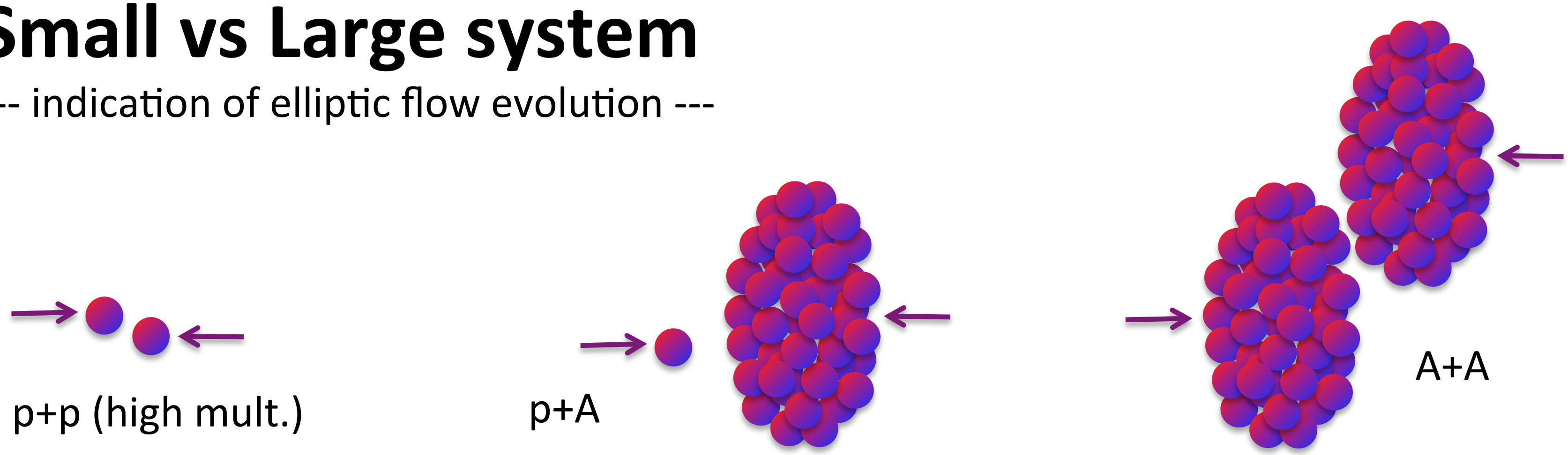


Phys. Rev. Lett. 114 (2015) 252302

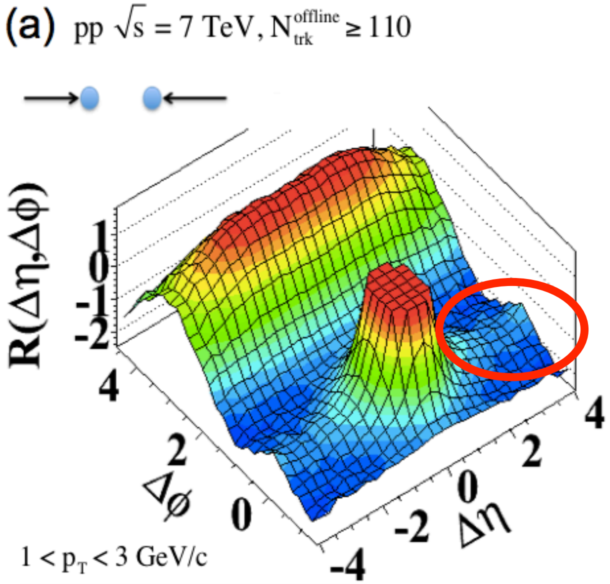


Small vs Large system

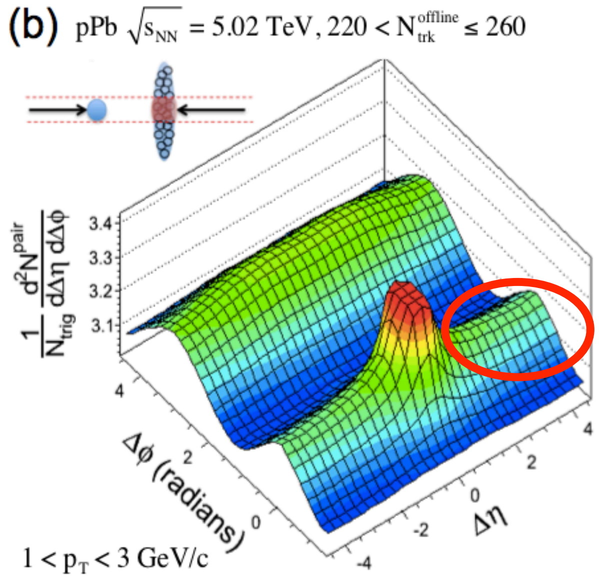
--- indication of elliptic flow evolution ---



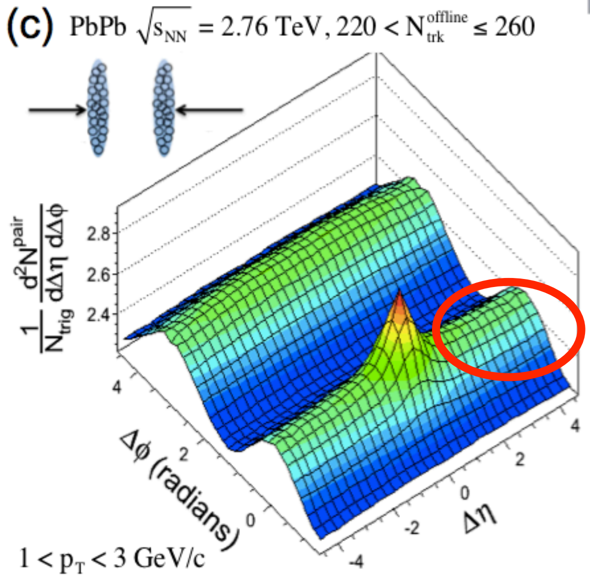
CMS, QM15



JHEP 09 (2010) 091



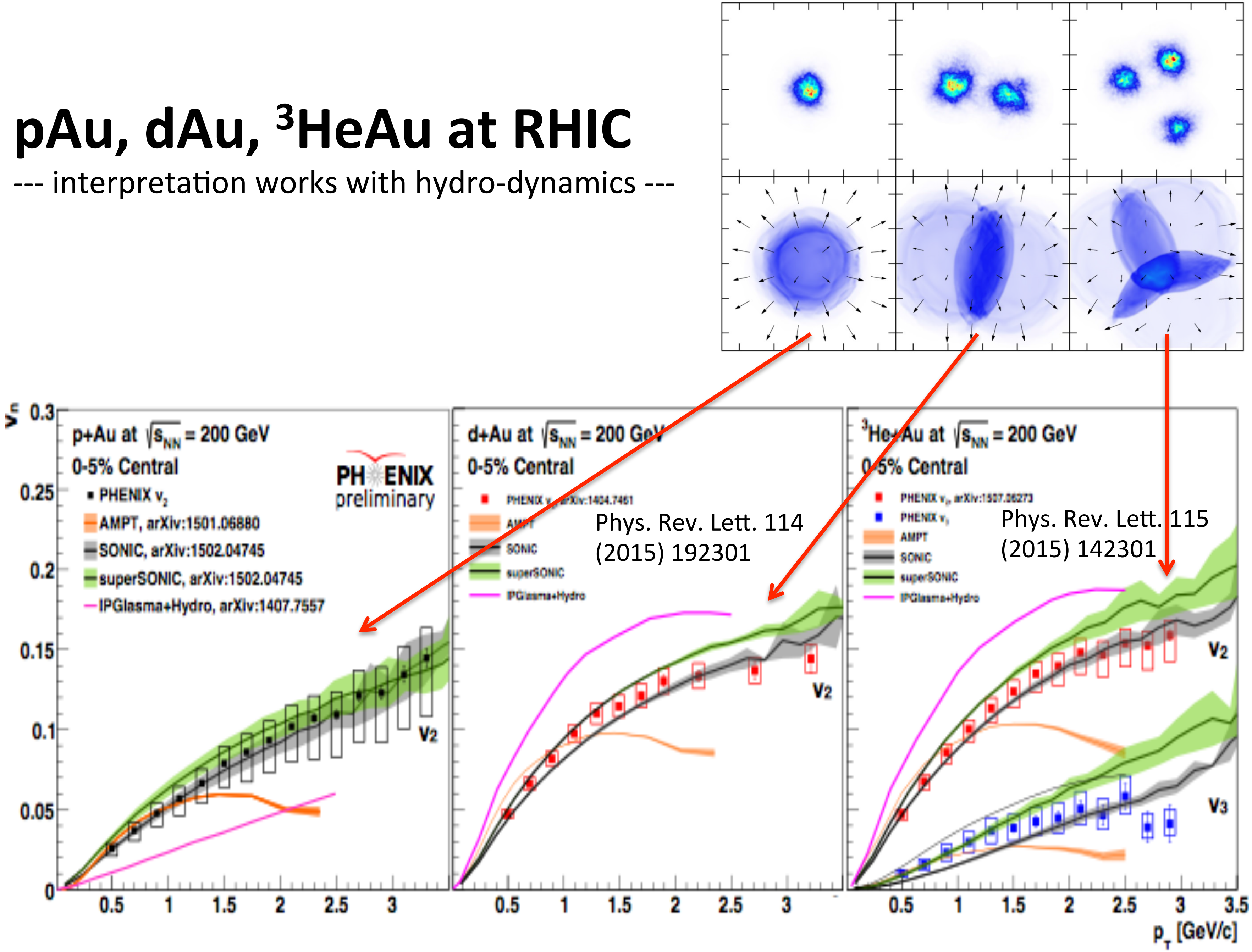
PLB 724 (2013) 213



PLB 724 (2013) 213

pAu, dAu, ^{3}HeAu at RHIC

--- interpretation works with hydro-dynamics ---

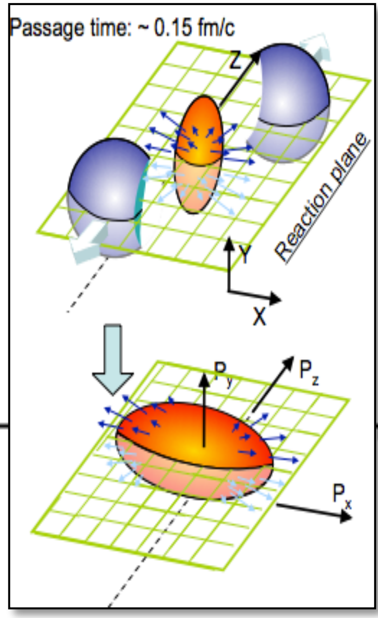


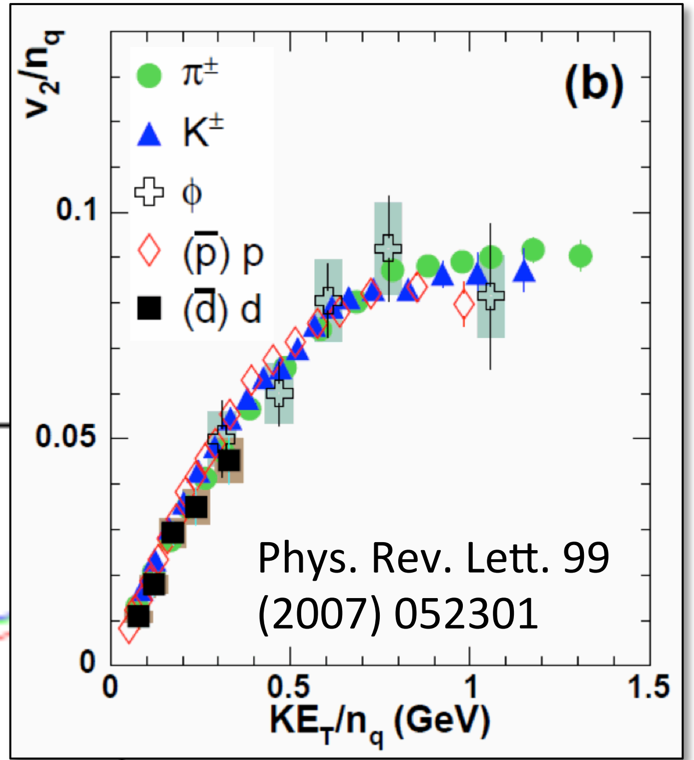
Phys. Rev. Lett. 114 (2015) 192301

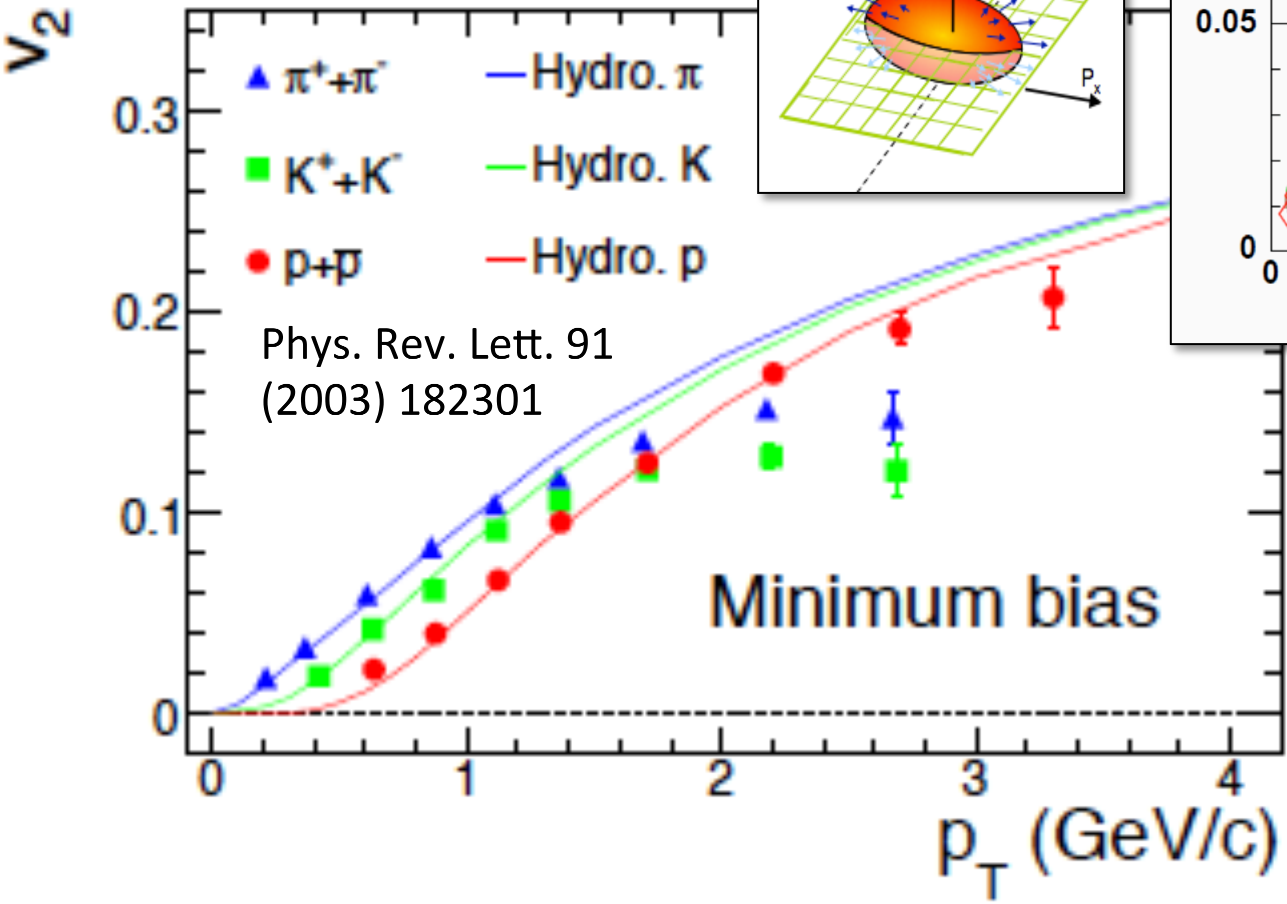
Phys. Rev. Lett. 115 (2015) 142301

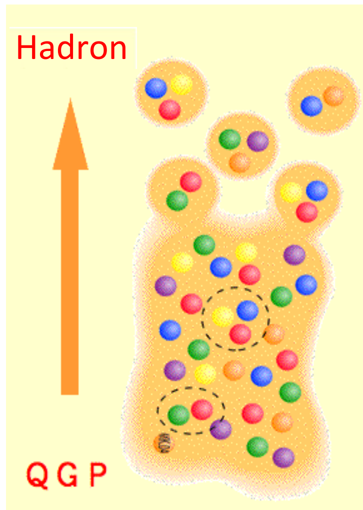
Elliptic flow

- mass dependence
  from hydro-dynamics
- number of quark scaling
  based on quark coalescence

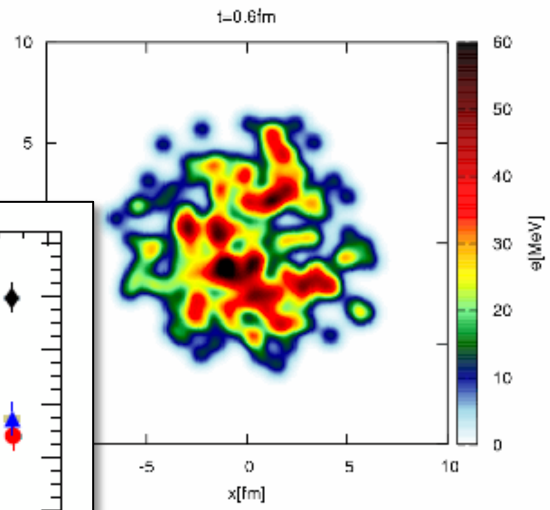


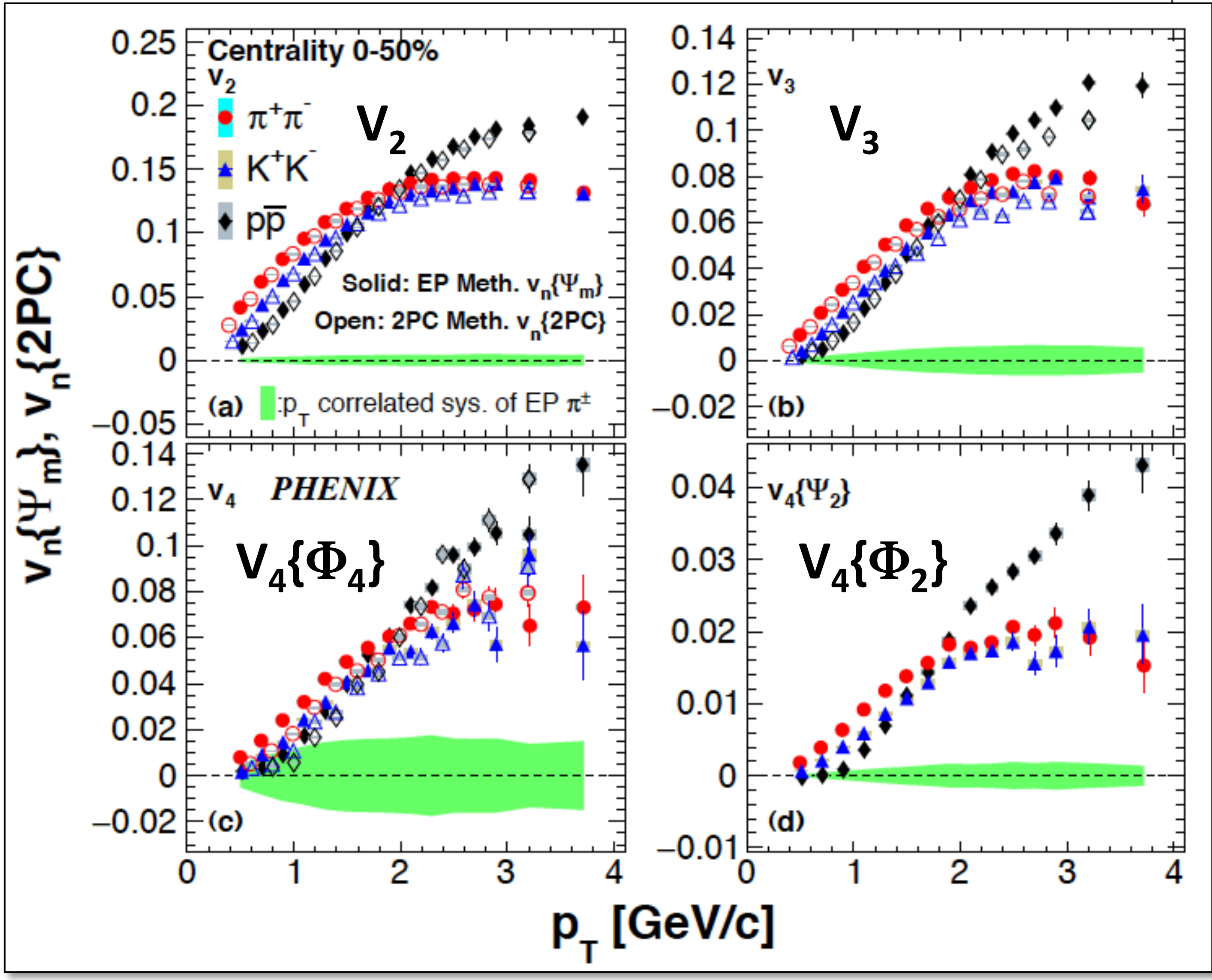






Higher order event anisotropy

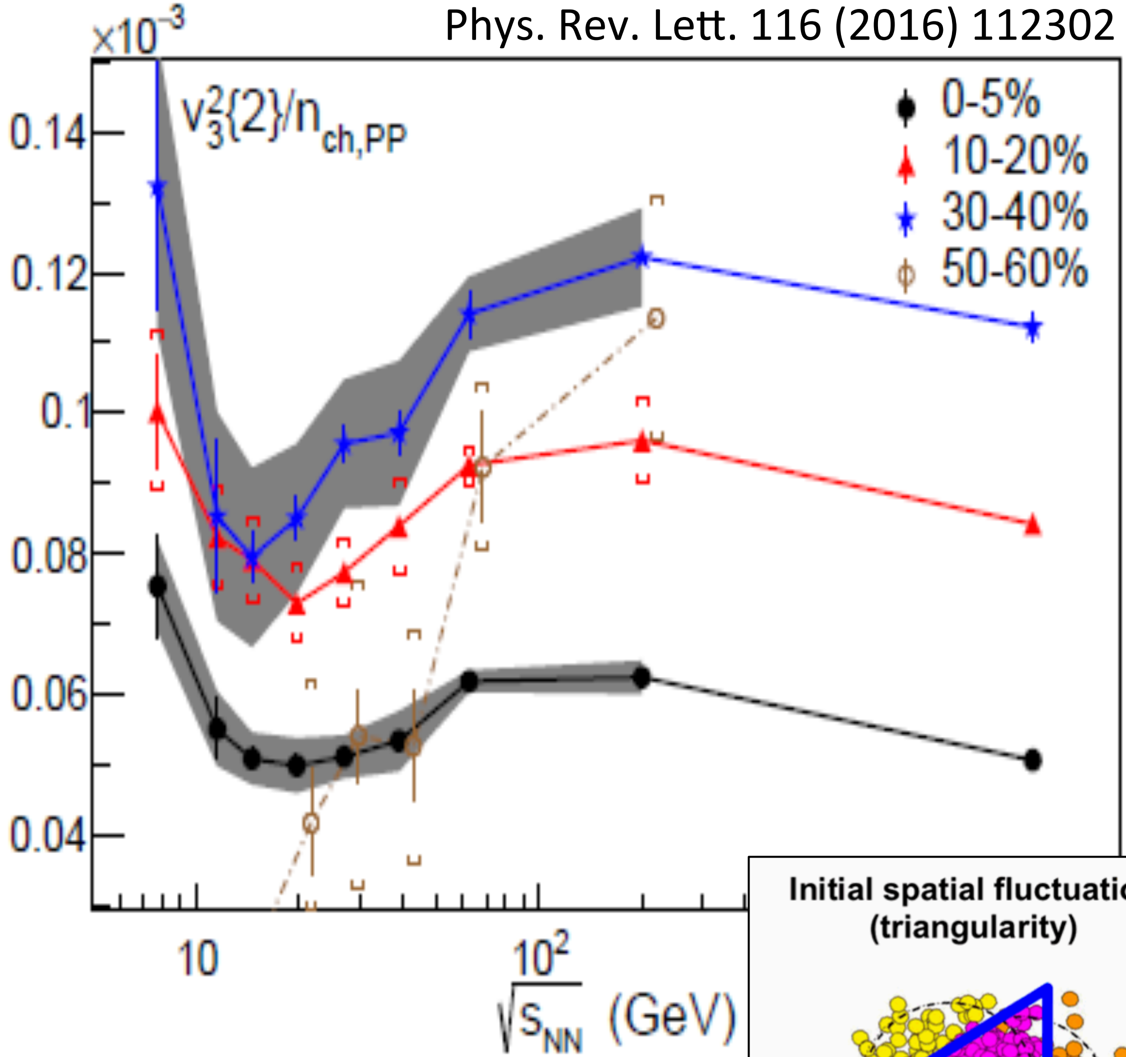




Collective expansion originated from fluctuating initial density distribution

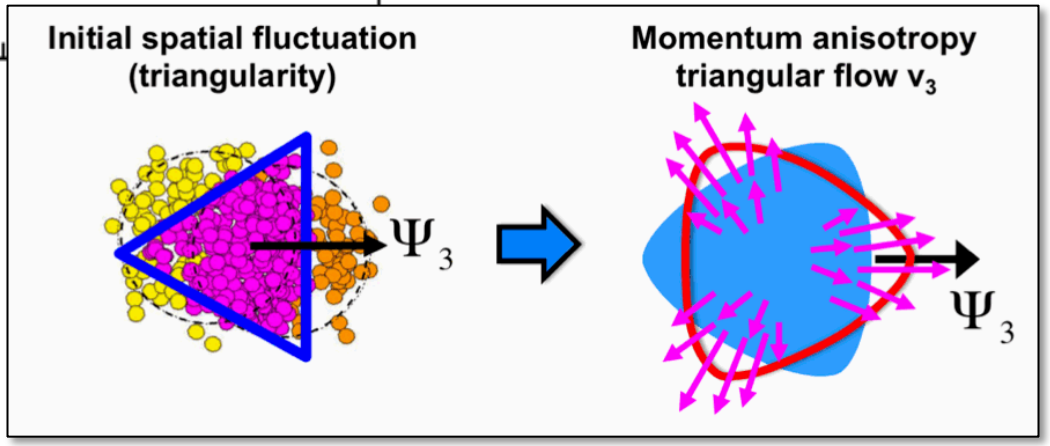
Mass dependence and meson/baryon separation

Phys. Rev. C 93 (2016) 051902R

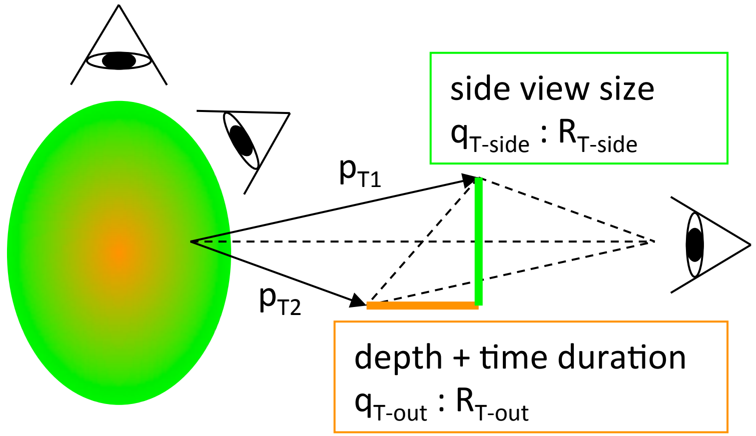


3rd order event anisotropy (v_3)

--- Triangular expansion ---
normalized by
system energy density :
$n_{ch,PP} = (dN_{ch}/d\eta) / (N_{part}/2)$

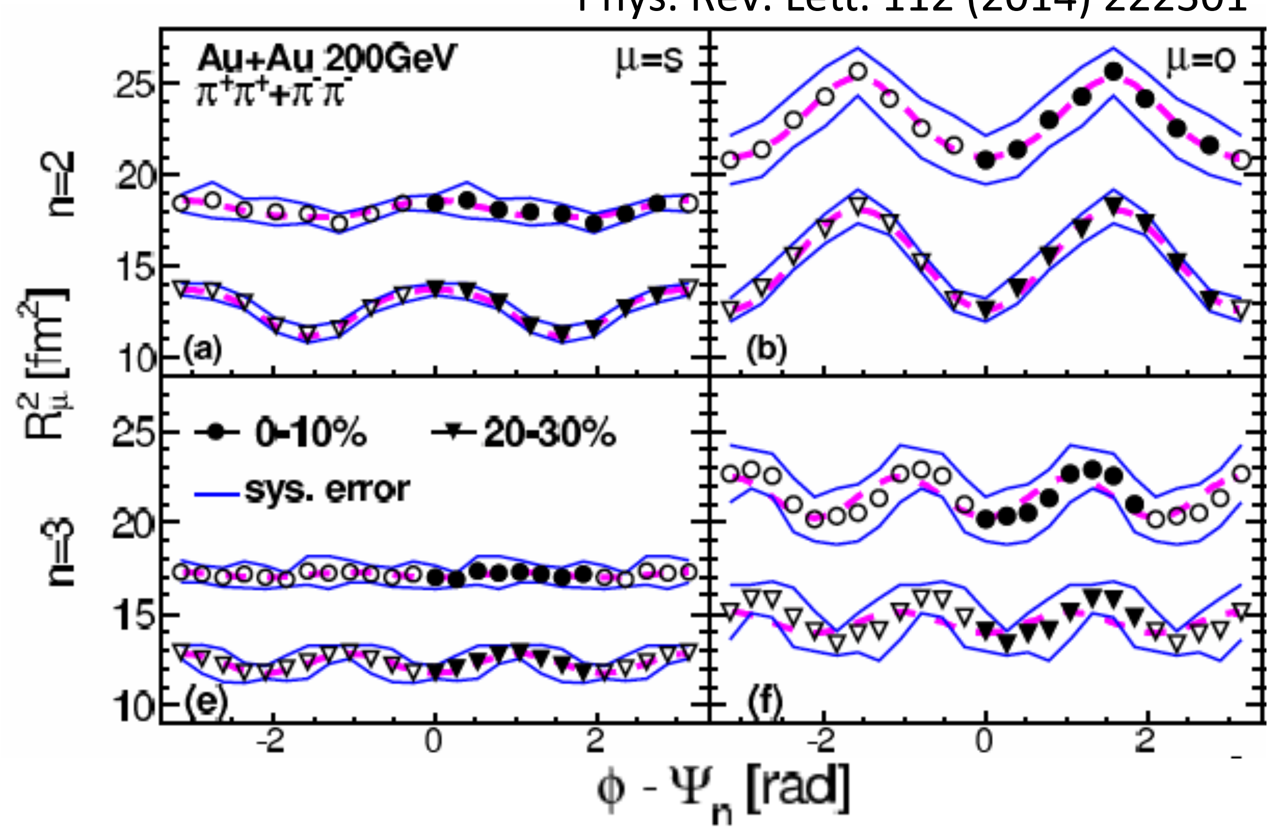


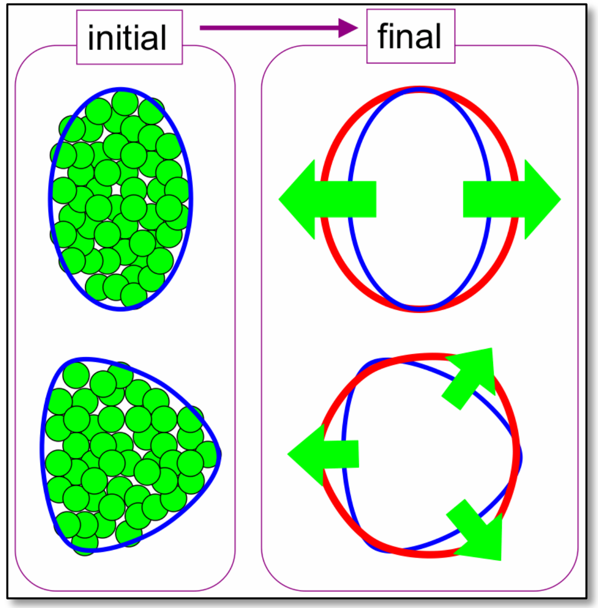
Anisotropic shape after the expansion



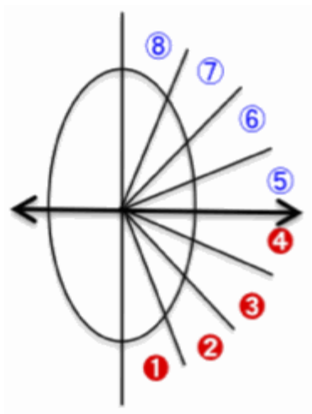
Elliptic and Triangular shape at freeze-out remained (2nd) or reversed (3rd)

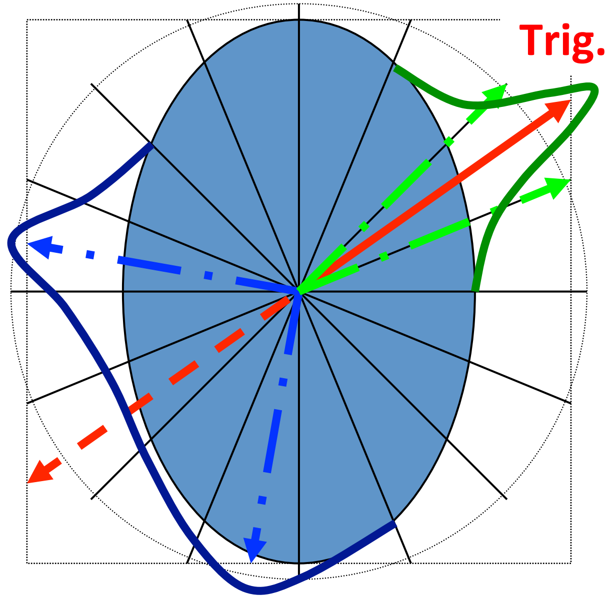
Phys. Rev. Lett. 112 (2014) 222301

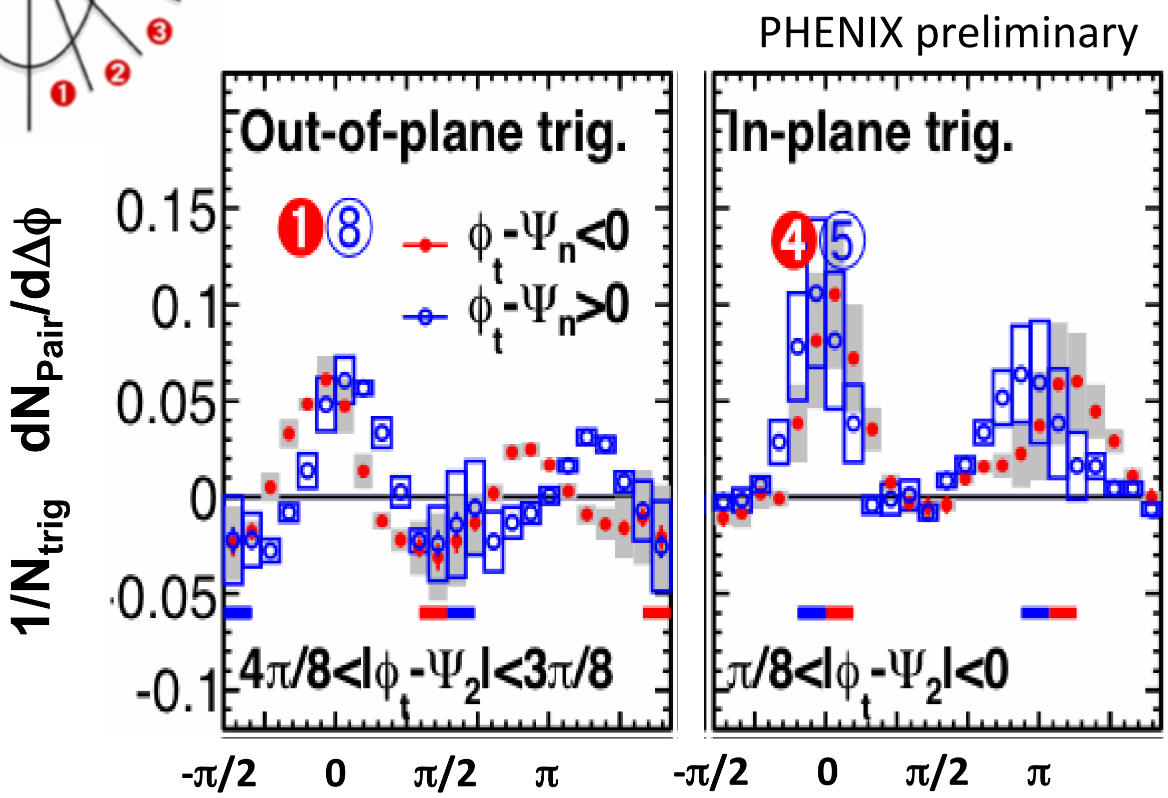




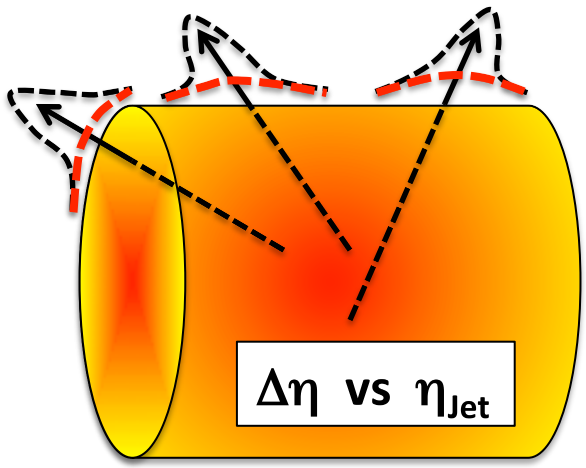
Shape and/or flow relation to the jet modification





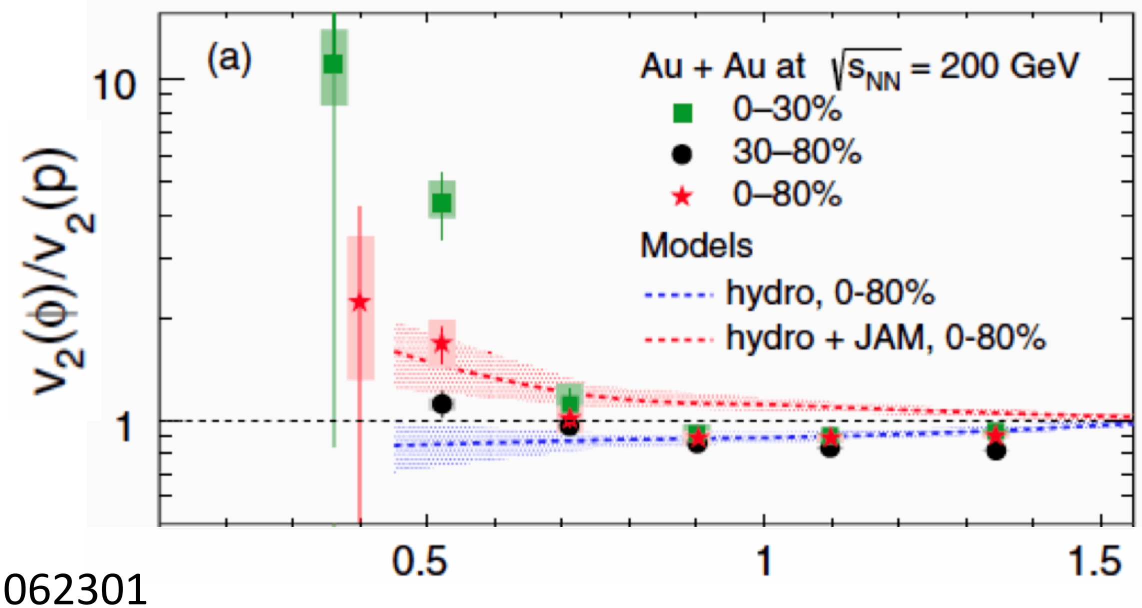


$\Delta\phi = \phi_{Asso.} - \phi_{Trig.}$

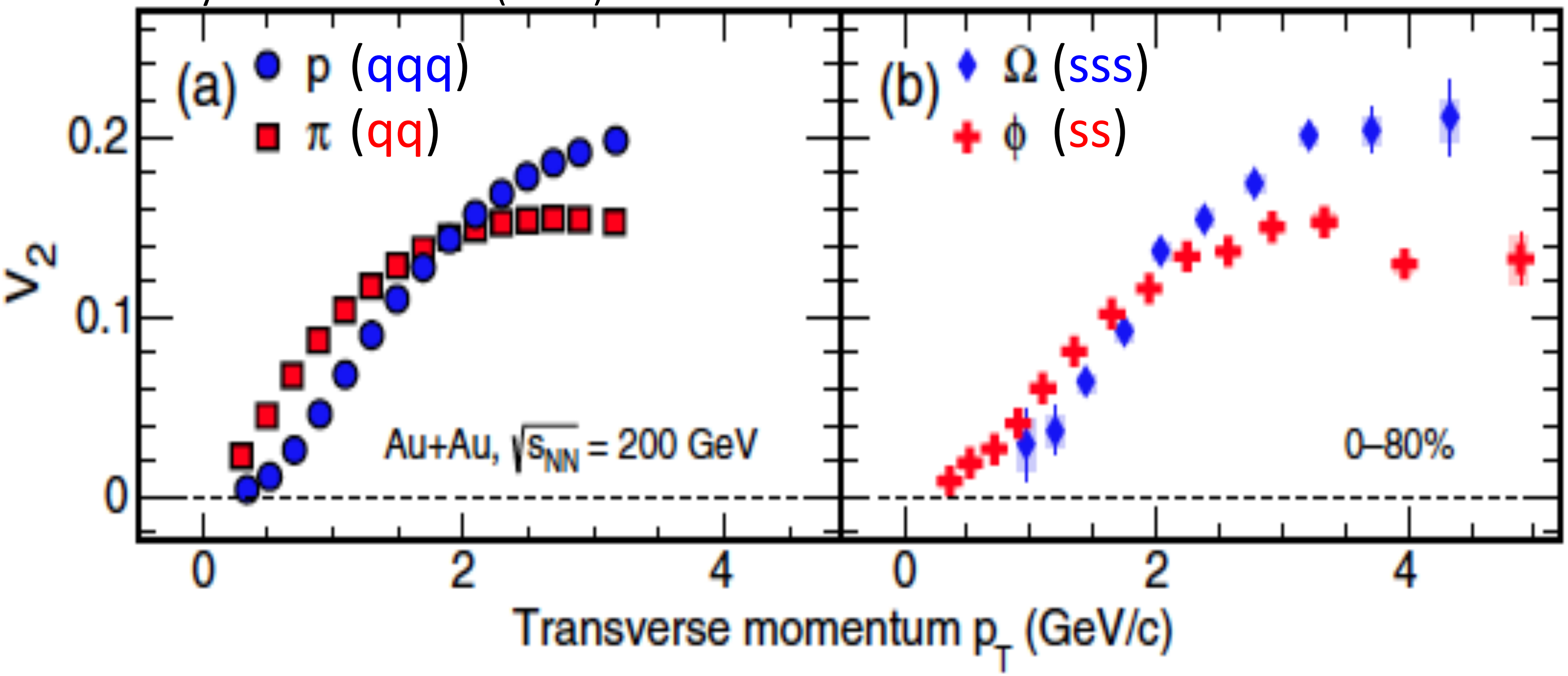


N_{CQ} and hydro scaling of v_2

--- partonic & hadronic effects ---



Phys. Rev. Lett. 116 (2016) 062301

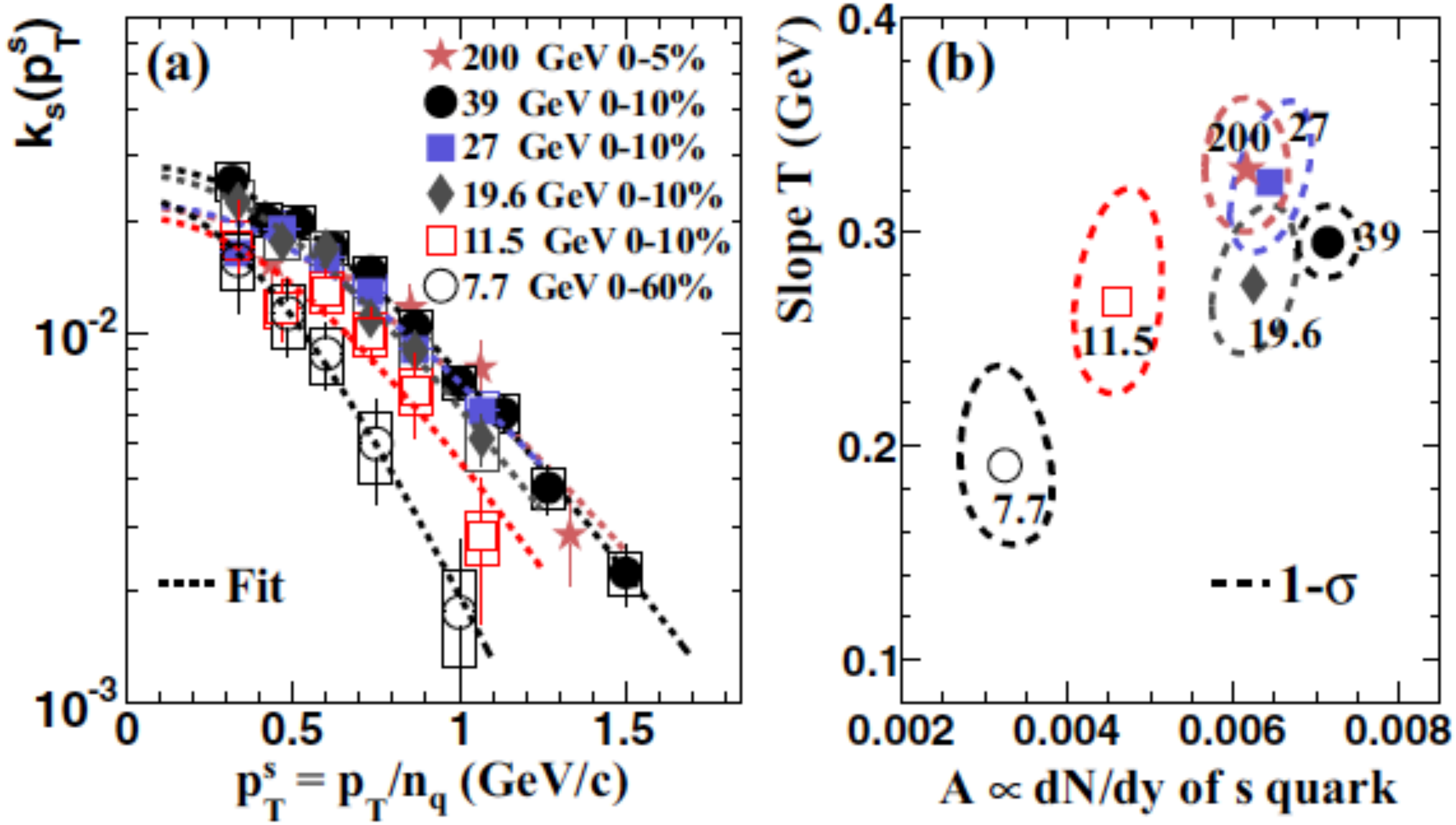


Extraction of quark p_T distribution

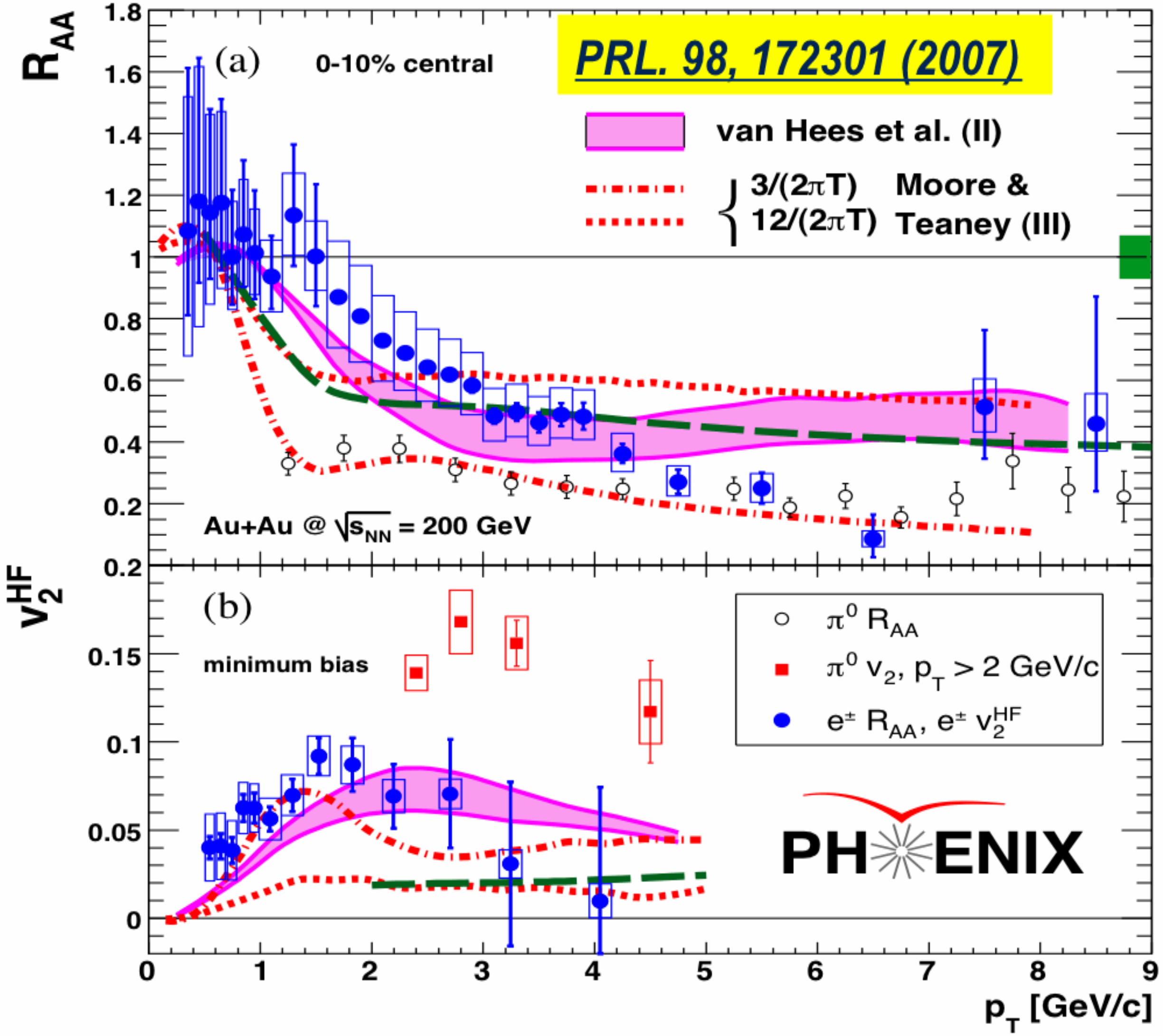
--- based on quark coalescence ---

$k_s = N(\Omega)/N(\phi)$ = N(sss)/N(ss)

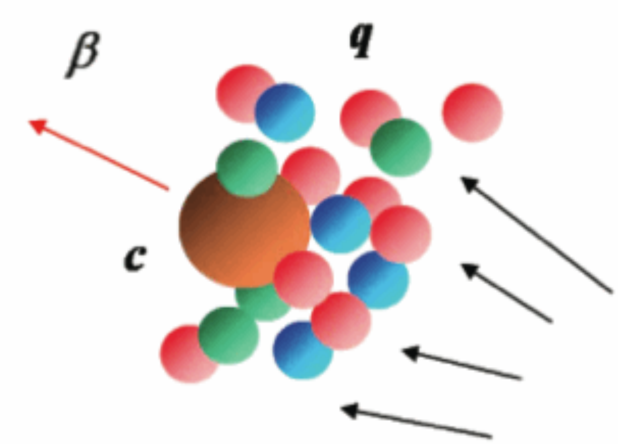
Phys. Rev. C 93 (2016) 021903R



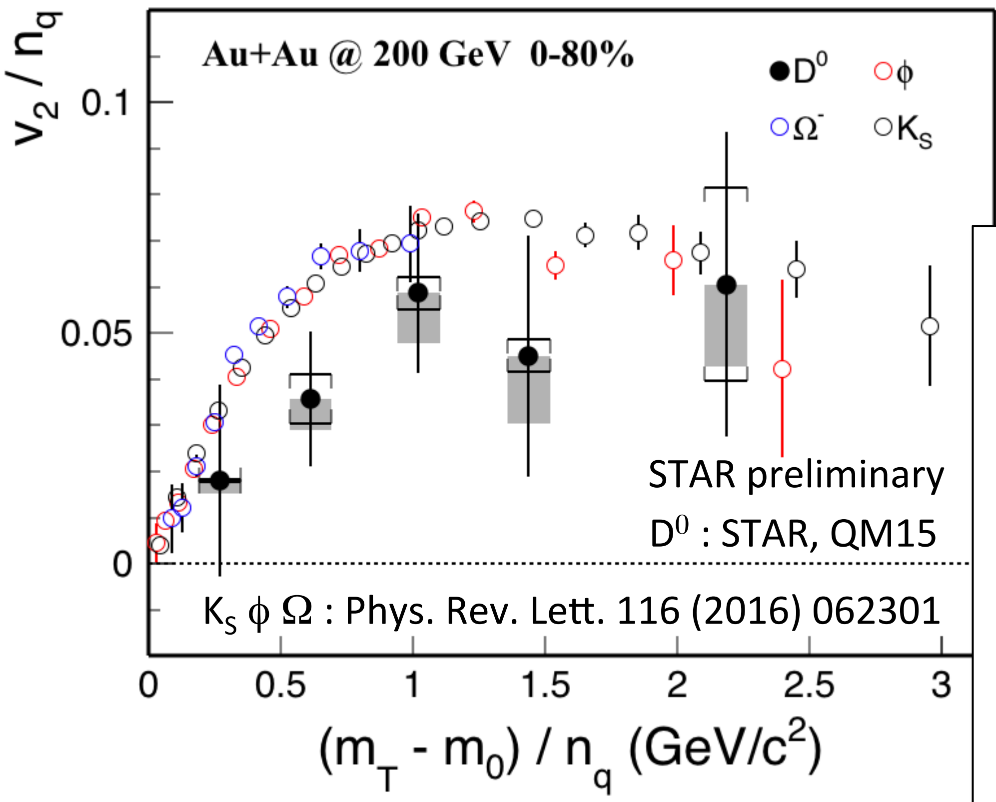
Suppression and flow of heavy quark



Strong suppression and sizable flow of heavy quarks via single inclusive electron measurements

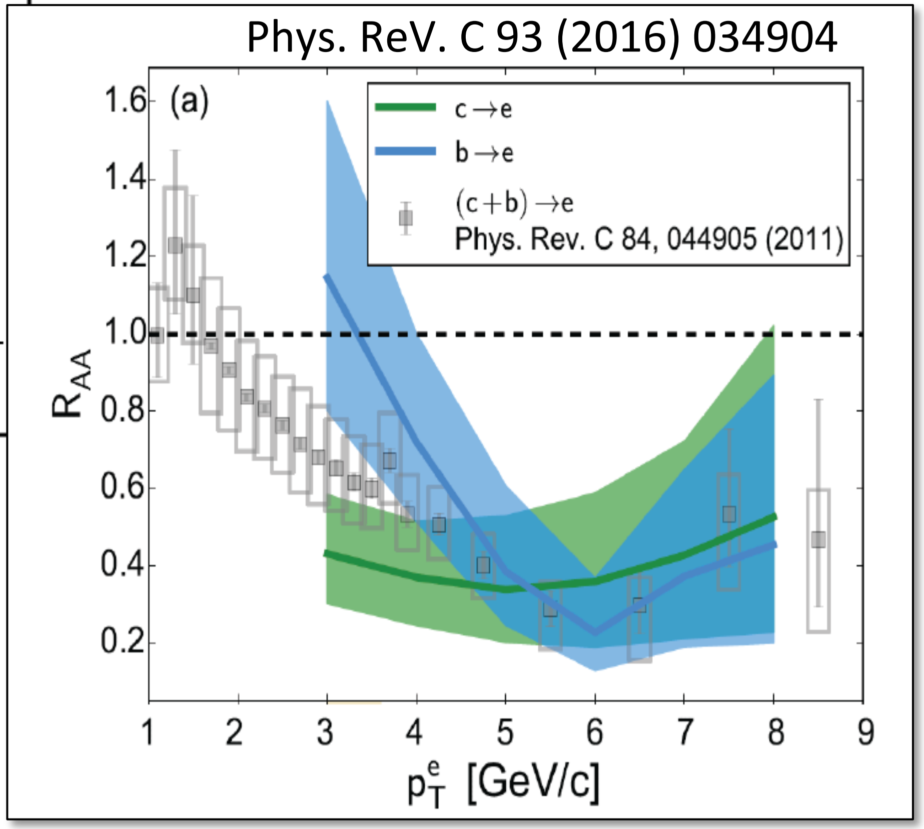


Identification/separation of heavy quarks

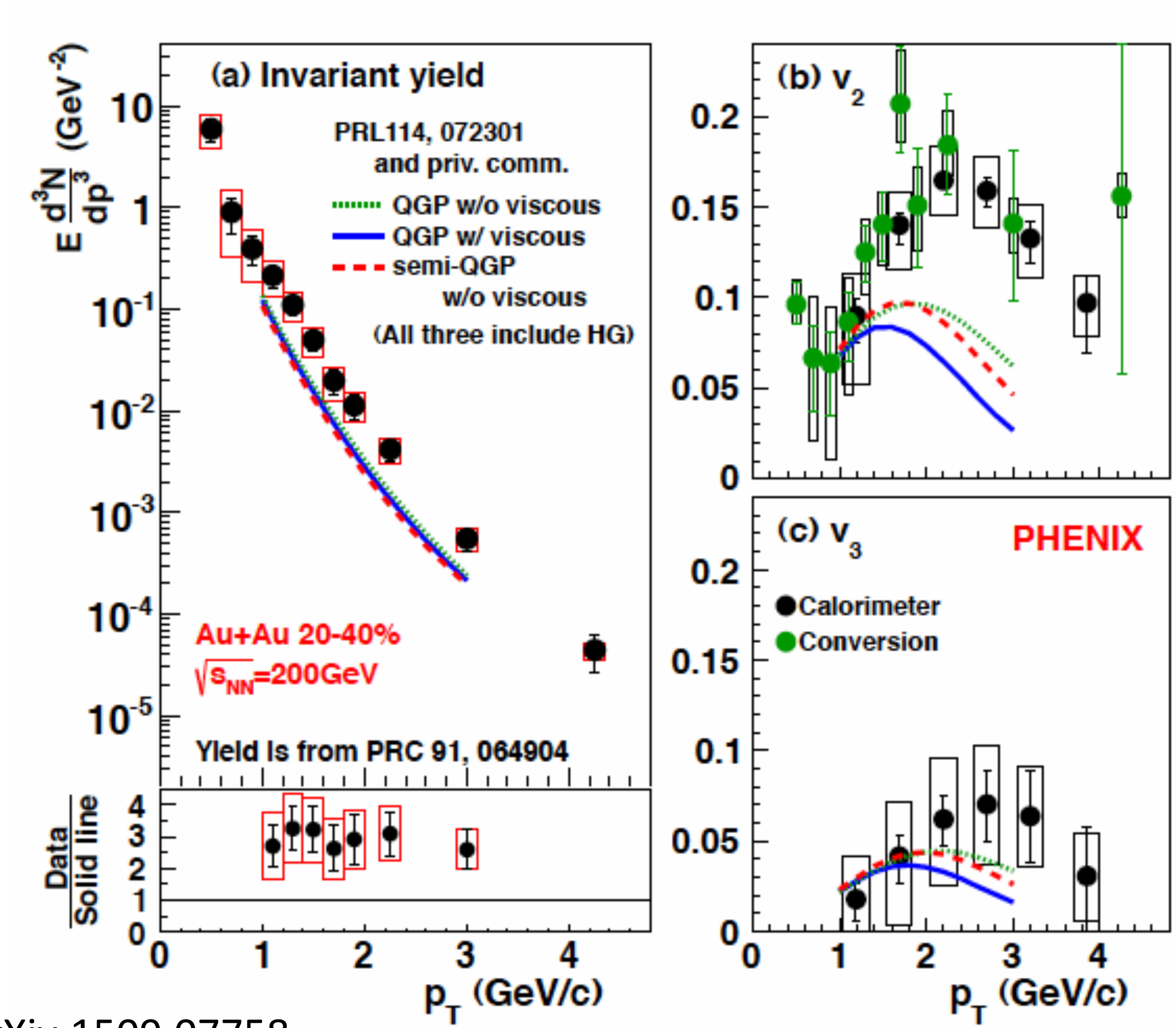


Improvement with
Heavy-Flavor Tracker (HFT)
upgrade at STAR

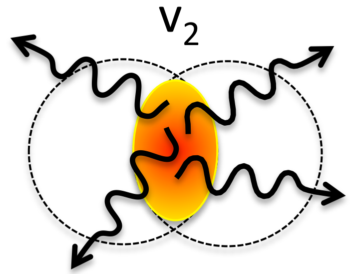
Improvement with
Silicon Vertex Detector (VTX)
upgrade at PHENIX

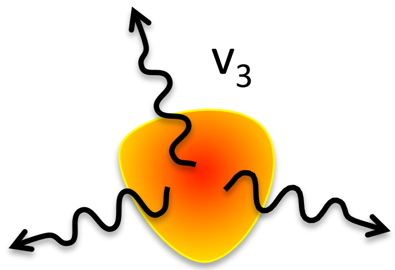


Thermal photon yield and flow



arXiv:1509.07758

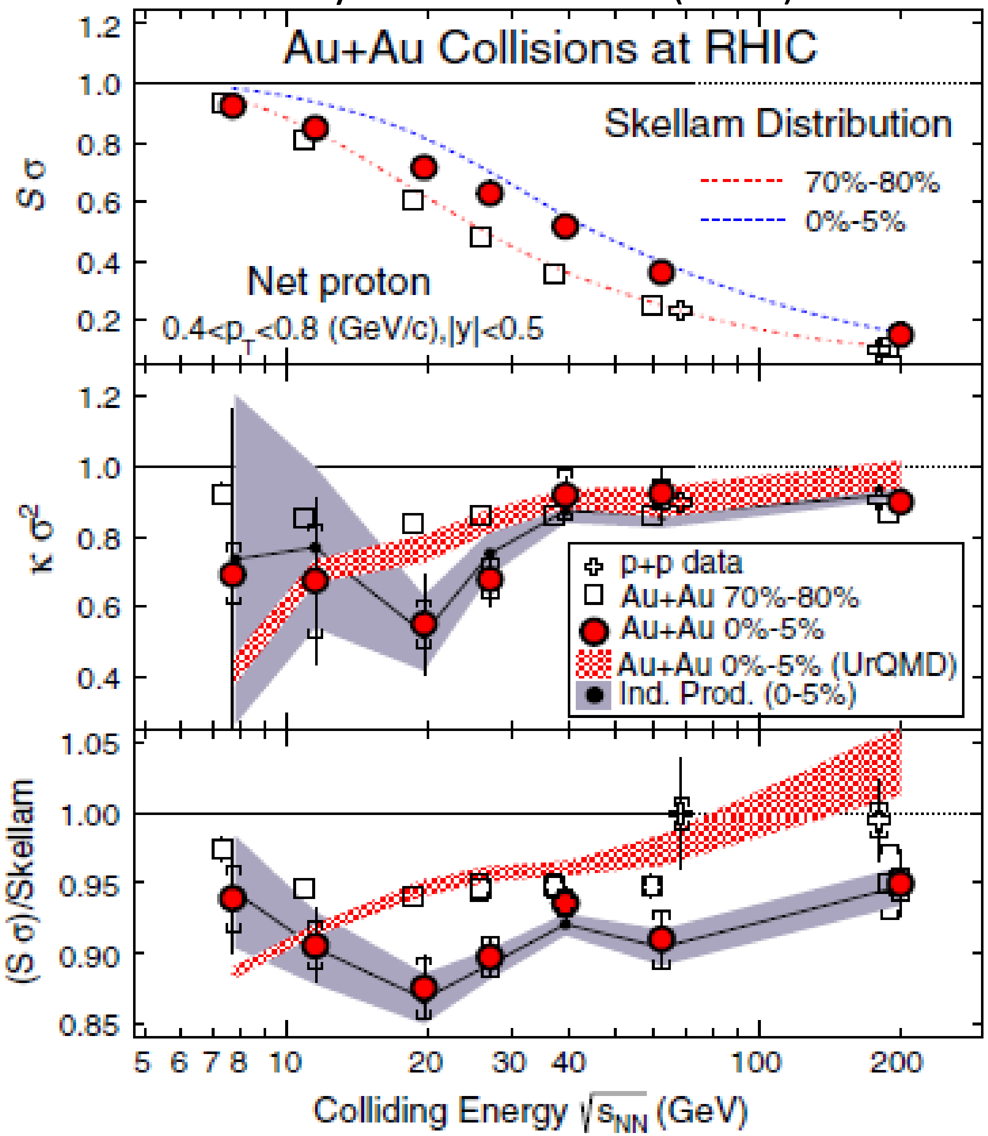




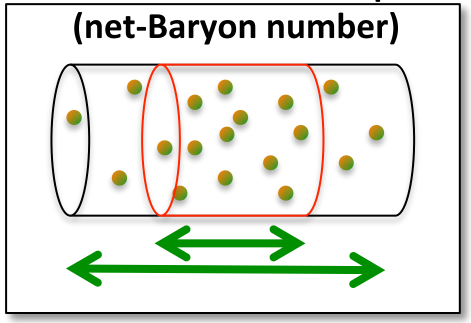
- Large photon yield from early stage
- Large photon flow from later stage
- New data from STAR at arXiv:1607.01447 with somewhat smaller yield
- Bremsstrahlung with B-field…

Net-proton distribution

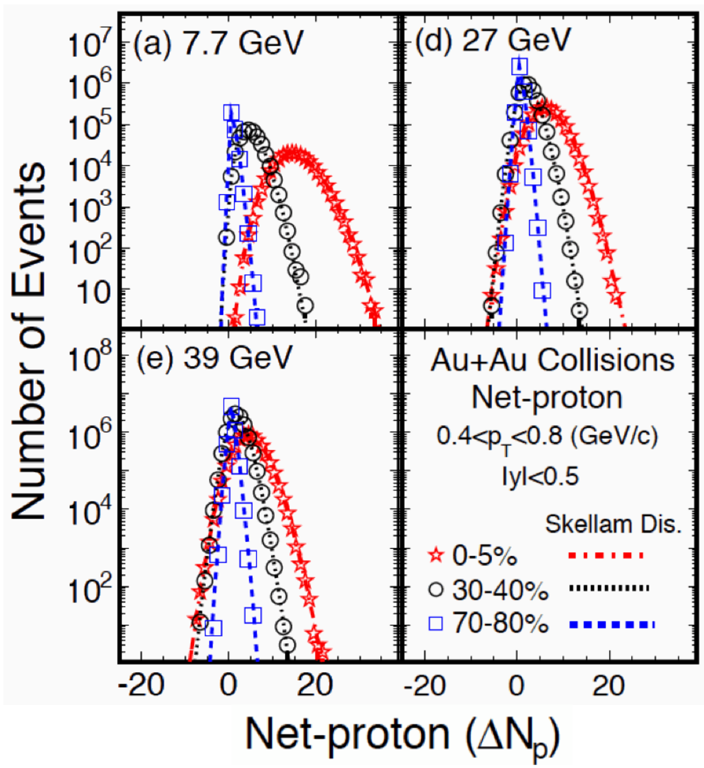
Phys. Rev. Lett. 112 (2014) 032302

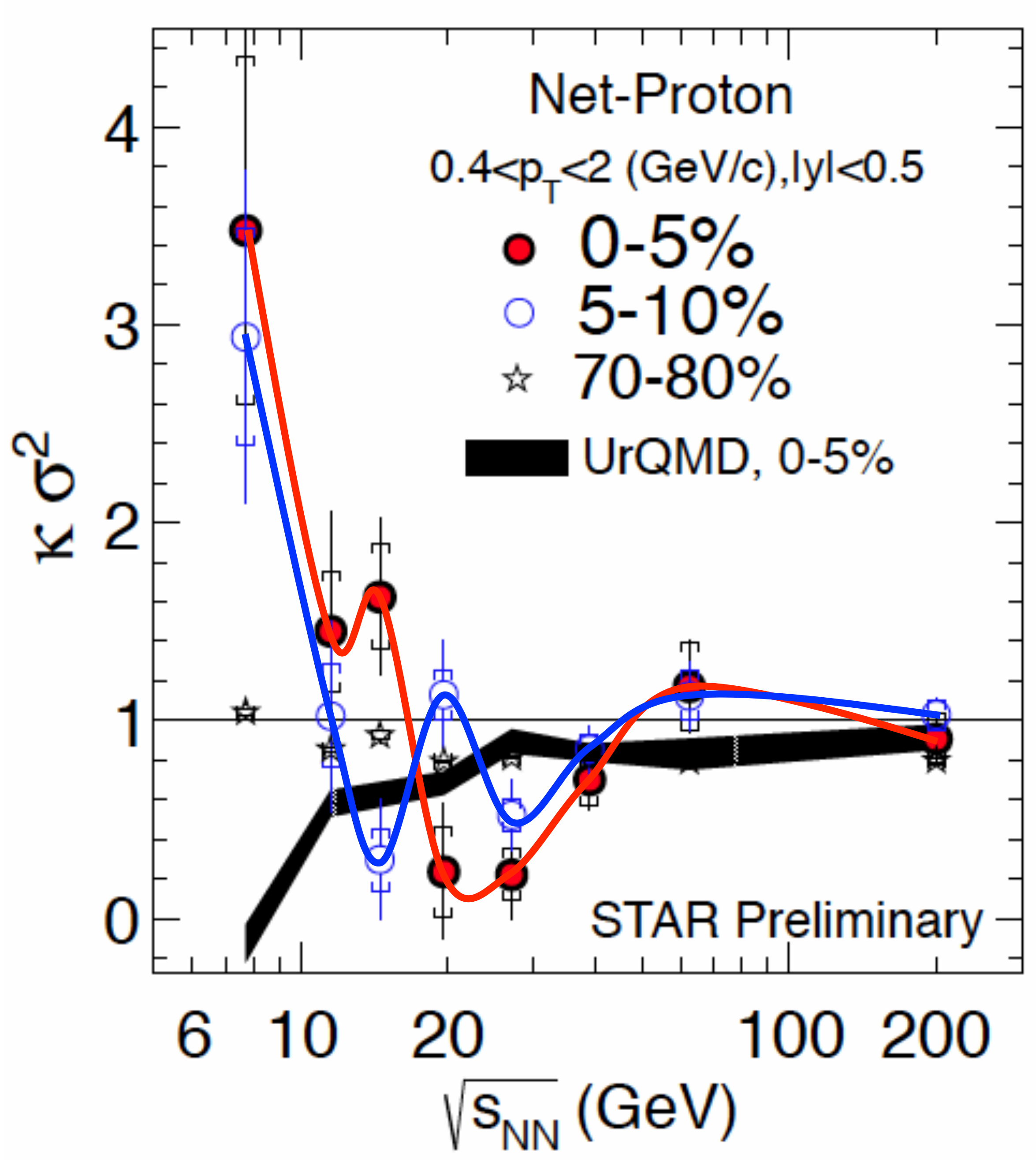


Fluctuation of conserved quantity (net-Baryon number)

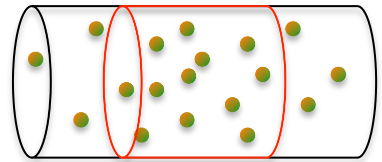


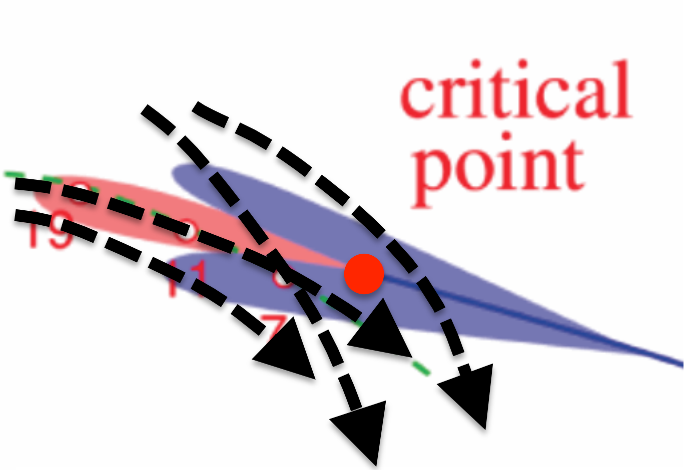
Change of correlation length at phase boundary close to the critical point




Net-Proton
0.4<p$_T$<2 (GeV/c),|y|<0.5
0-5%
5-10%
70-80%
UrQMD, 0-5%
STAR Preliminary
$\kappa\,\sigma^2$
$\sqrt{s_{NN}}$ (GeV)
0
1
2
3
4
6
10
20
100
200

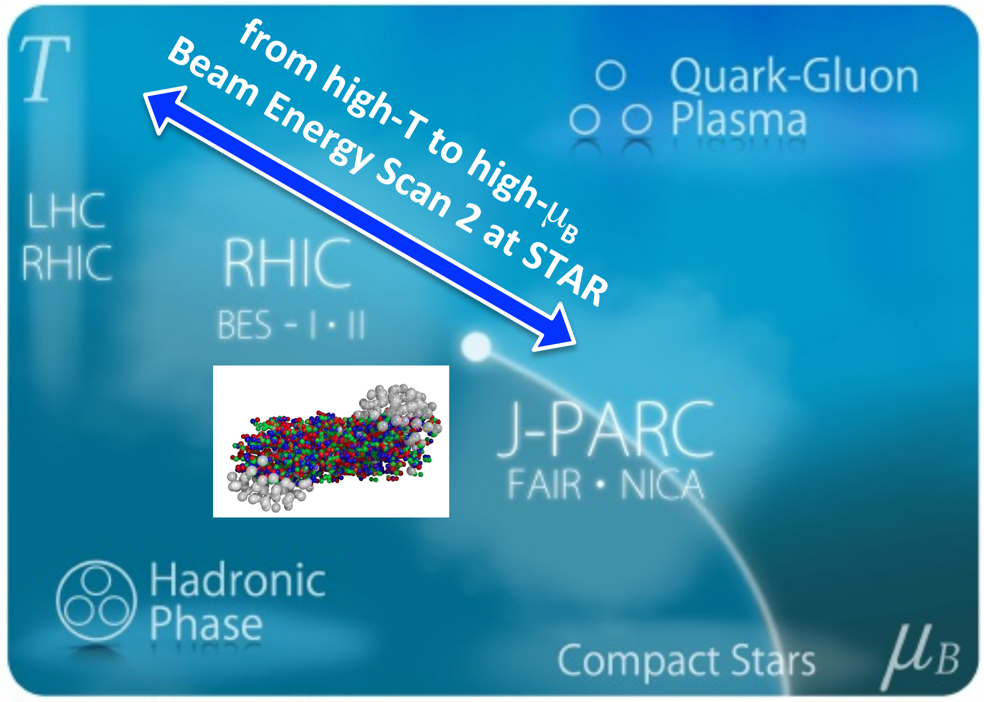
STAR, QM15



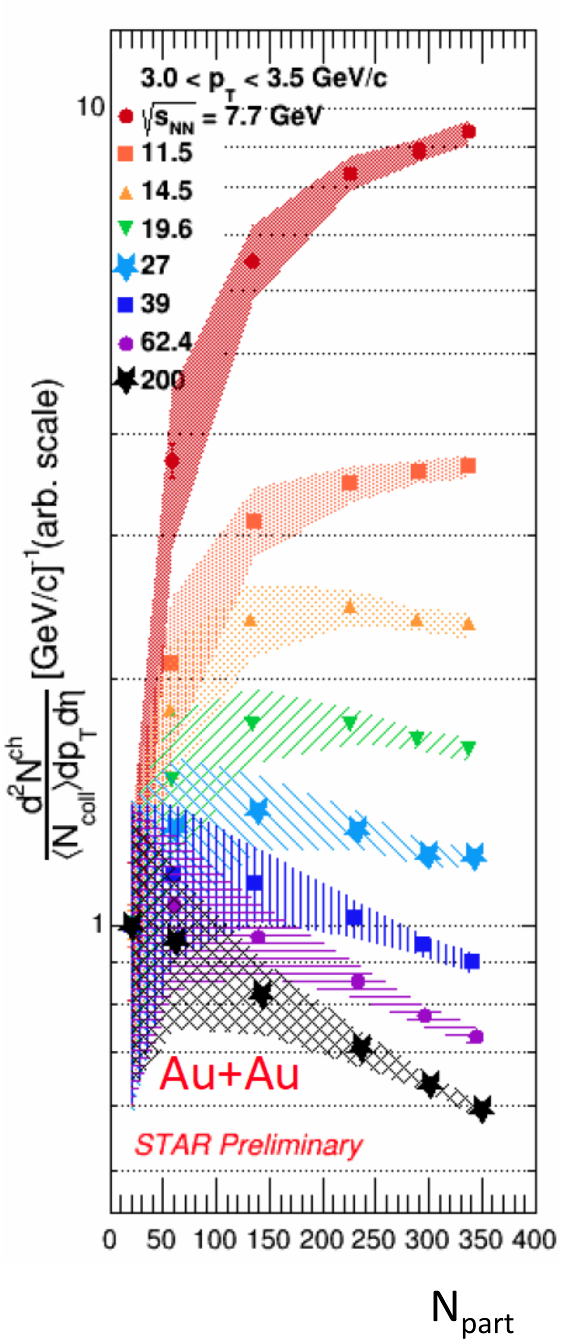

critical point

Summary

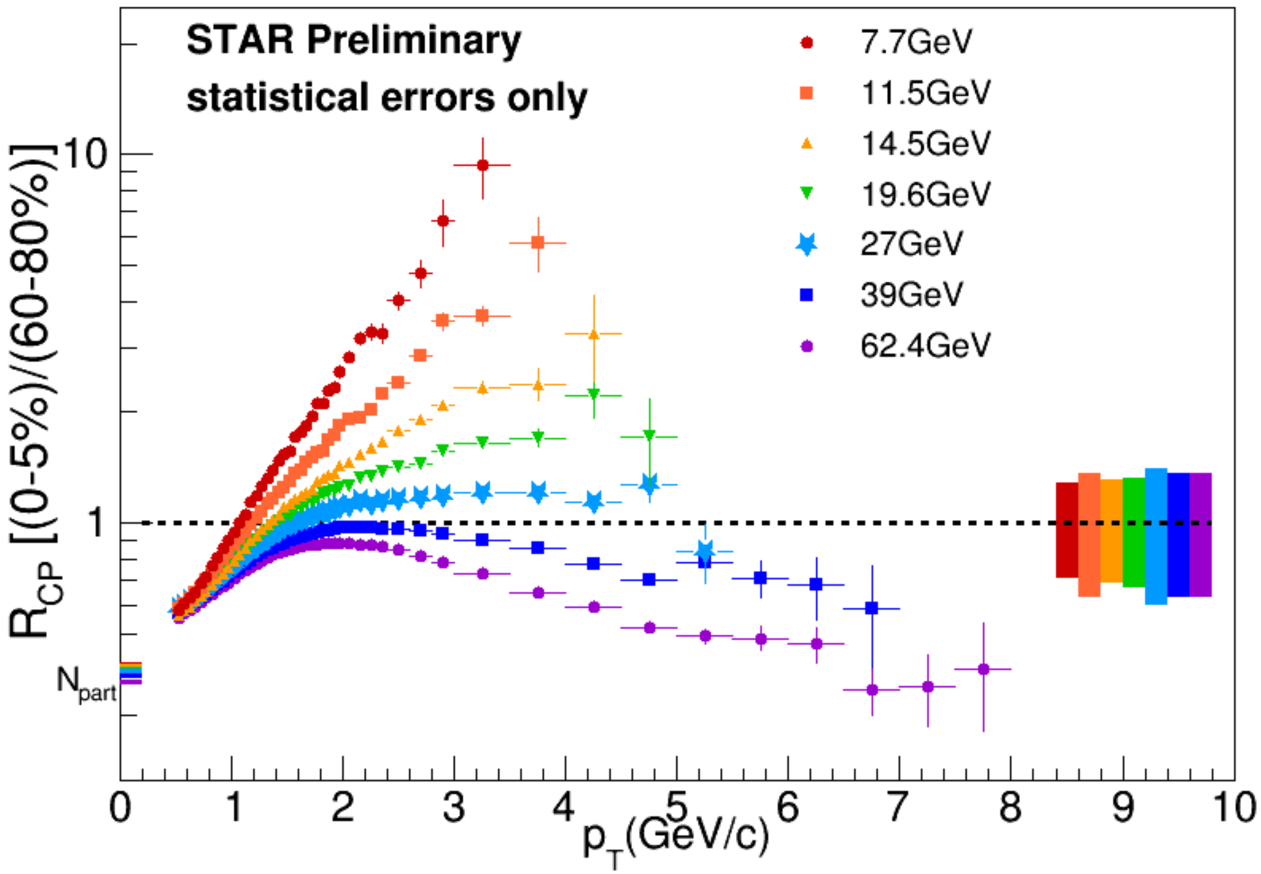
- **Radial and anisotropic flows**
- **Correlations with reaction planes**
- **Fluctuations**



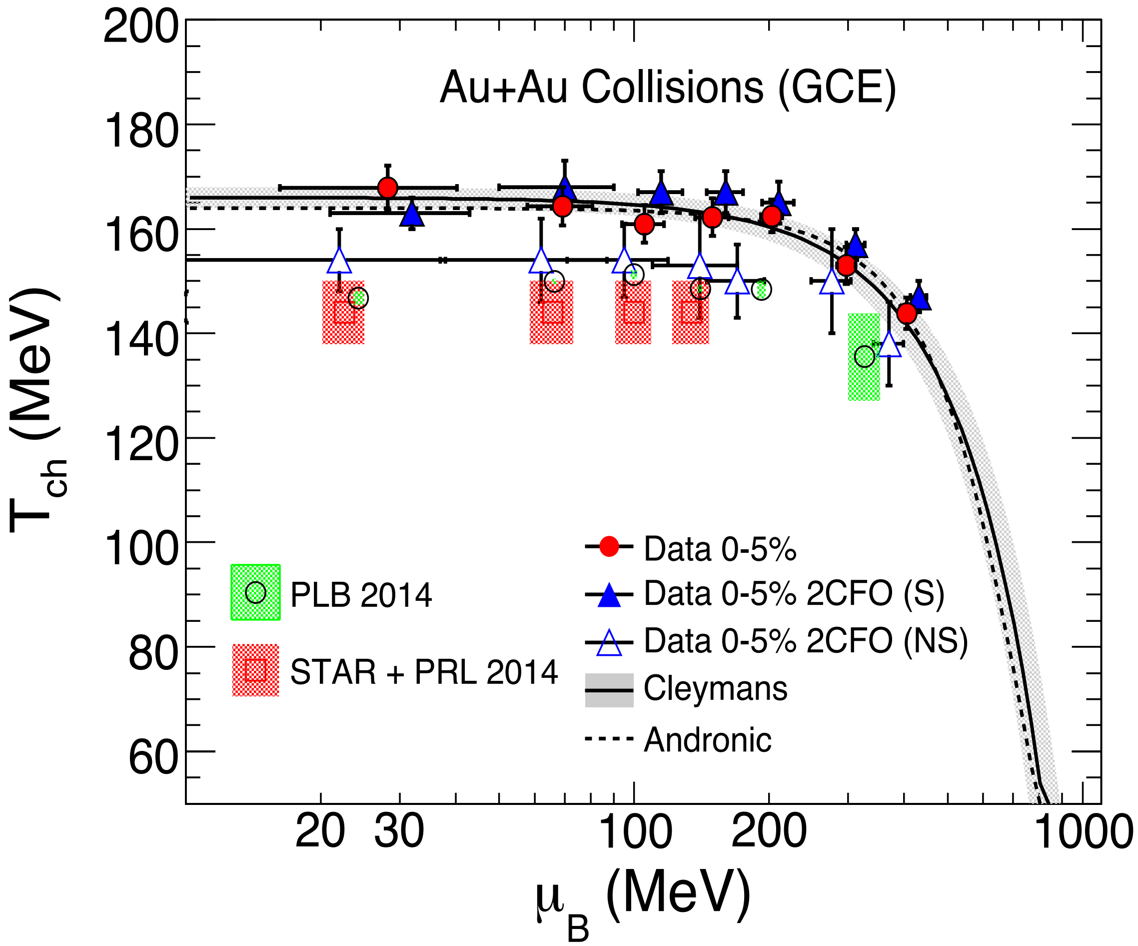
M. Kitazawa,
H. Sako, et. al.
(J-PARC-HI LOI)



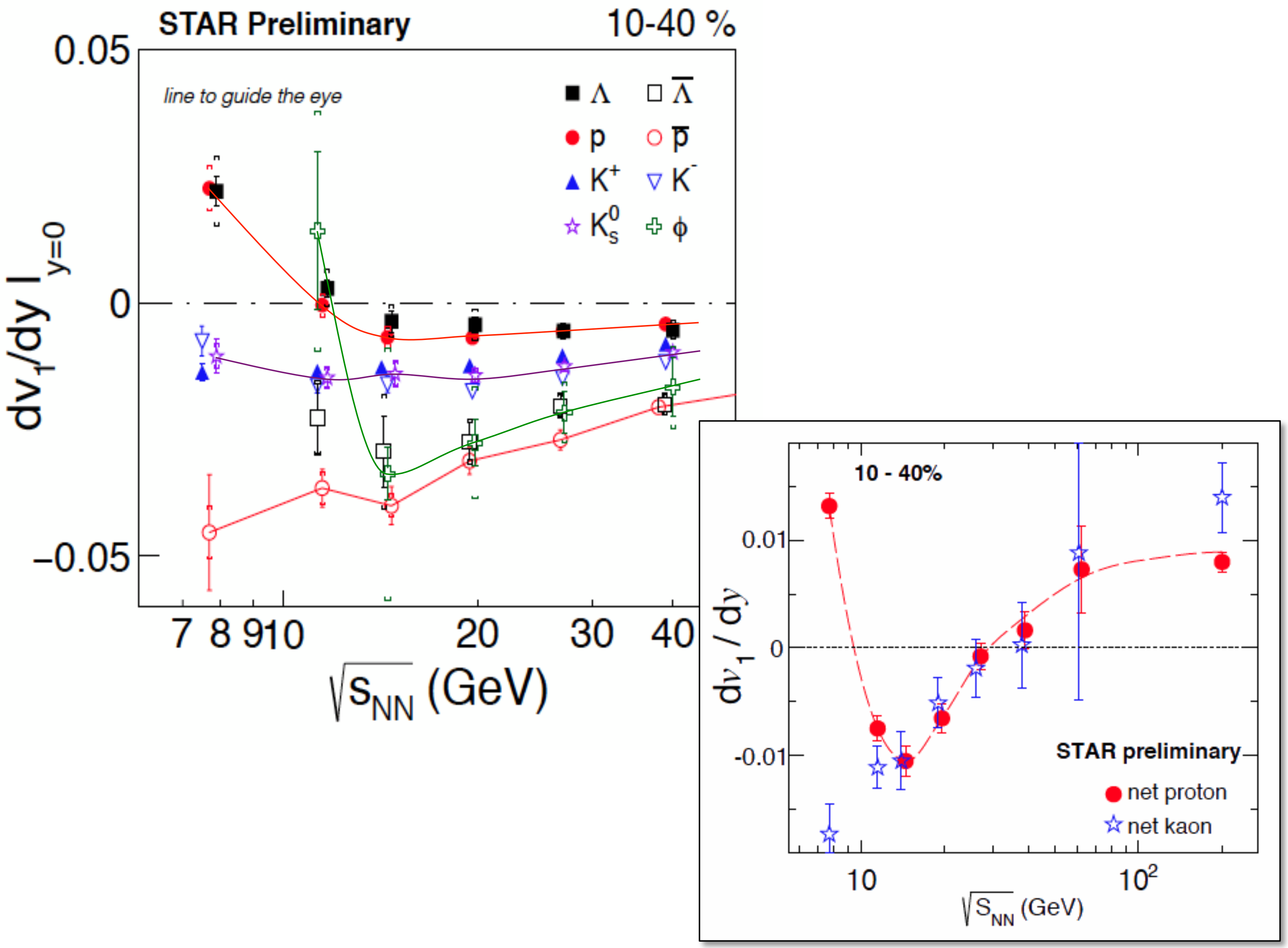
3.0 < p_T < 3.5 GeV/c
√s_NN = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
Au+Au
STAR Preliminary
d²N^ch / ⟨N_coll⟩dp_T dη [GeV/c]⁻¹(arb. scale)
0 50 100 150 200 250 300 350 400
N_part

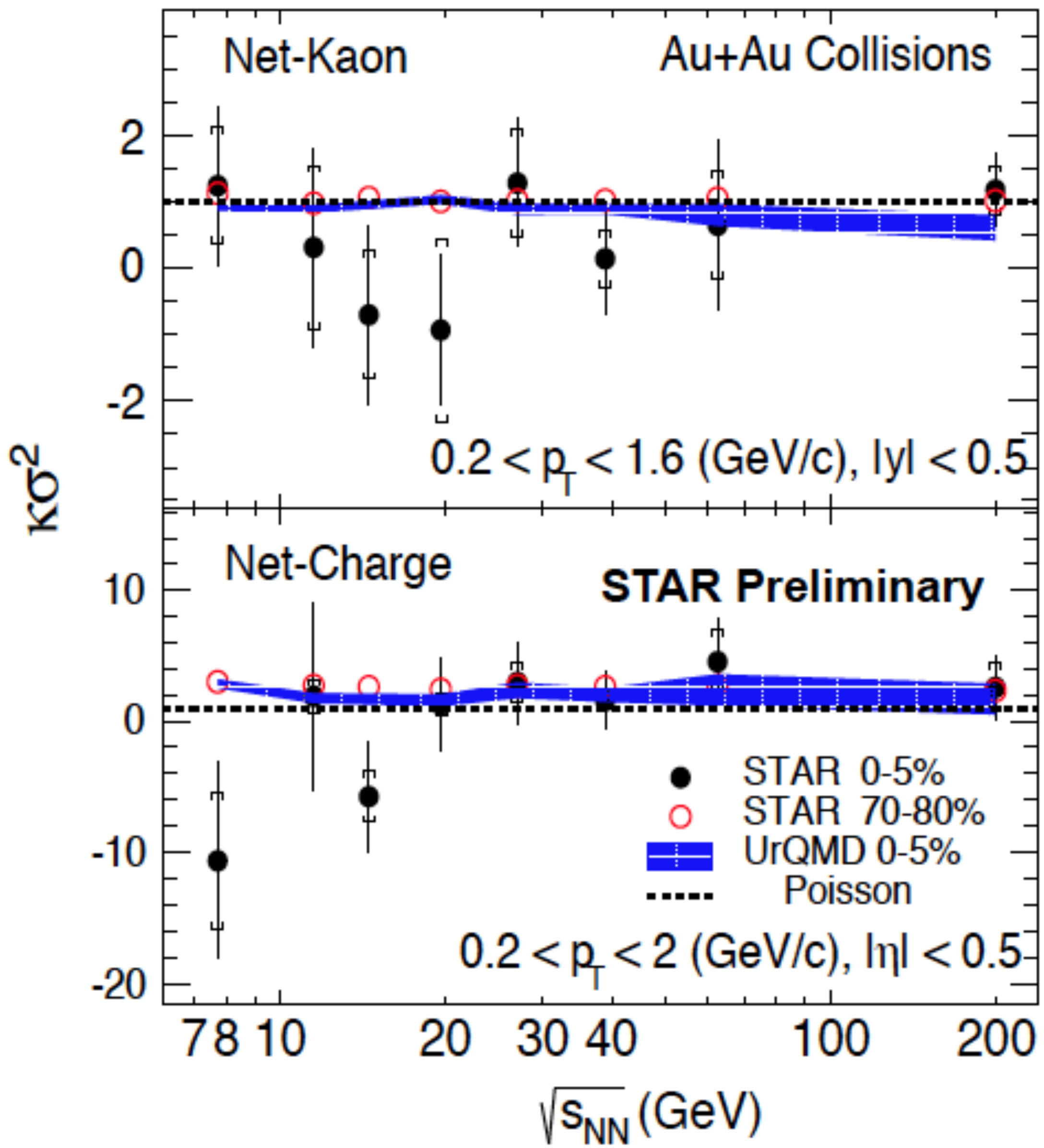


STAR Preliminary
statistical errors only
7.7GeV
11.5GeV
14.5GeV
19.6GeV
27GeV
39GeV
62.4GeV
R_CP [(0-5%)/(60-80%)]
N_part
p_T (GeV/c)



Au+Au Collisions (GCE)
200
180
160
140
120
100
80
60
20
30
100
200
1000
T_{ch} (MeV)
μ_B (MeV)
PLB 2014
STAR + PRL 2014
Data 0-5%
Data 0-5% 2CFO (S)
Data 0-5% 2CFO (NS)
Cleymans
Andronic


STAR Preliminary
10-40 %
line to guide the eye
Λ
p
$\bar{p}$
K^+
K^-
K^0_s
ϕ
$dv_1/dy|_{y=0}$
0.05
0
−0.05
7 8 910 20 30 40
$\sqrt{s_{NN}}$ (GeV)
10 - 40%
STAR preliminary
net proton
net kaon
dv_1/dy
0.01
0
-0.01
10
10^2
$\sqrt{S_{NN}}$ (GeV)



Net-Kaon
Au+Au Collisions
0.2 < p_T < 1.6 (GeV/c), |y| < 0.5
Net-Charge
STAR Preliminary
STAR 0-5%
STAR 70-80%
UrQMD 0-5%
Poisson
0.2 < p_T < 2 (GeV/c), |η| < 0.5
$\kappa\sigma^2$
$\sqrt{s_{NN}}$ (GeV)