Exploration of the QCD Phase Diagram with Relativistic Heavy-Ion Collisions

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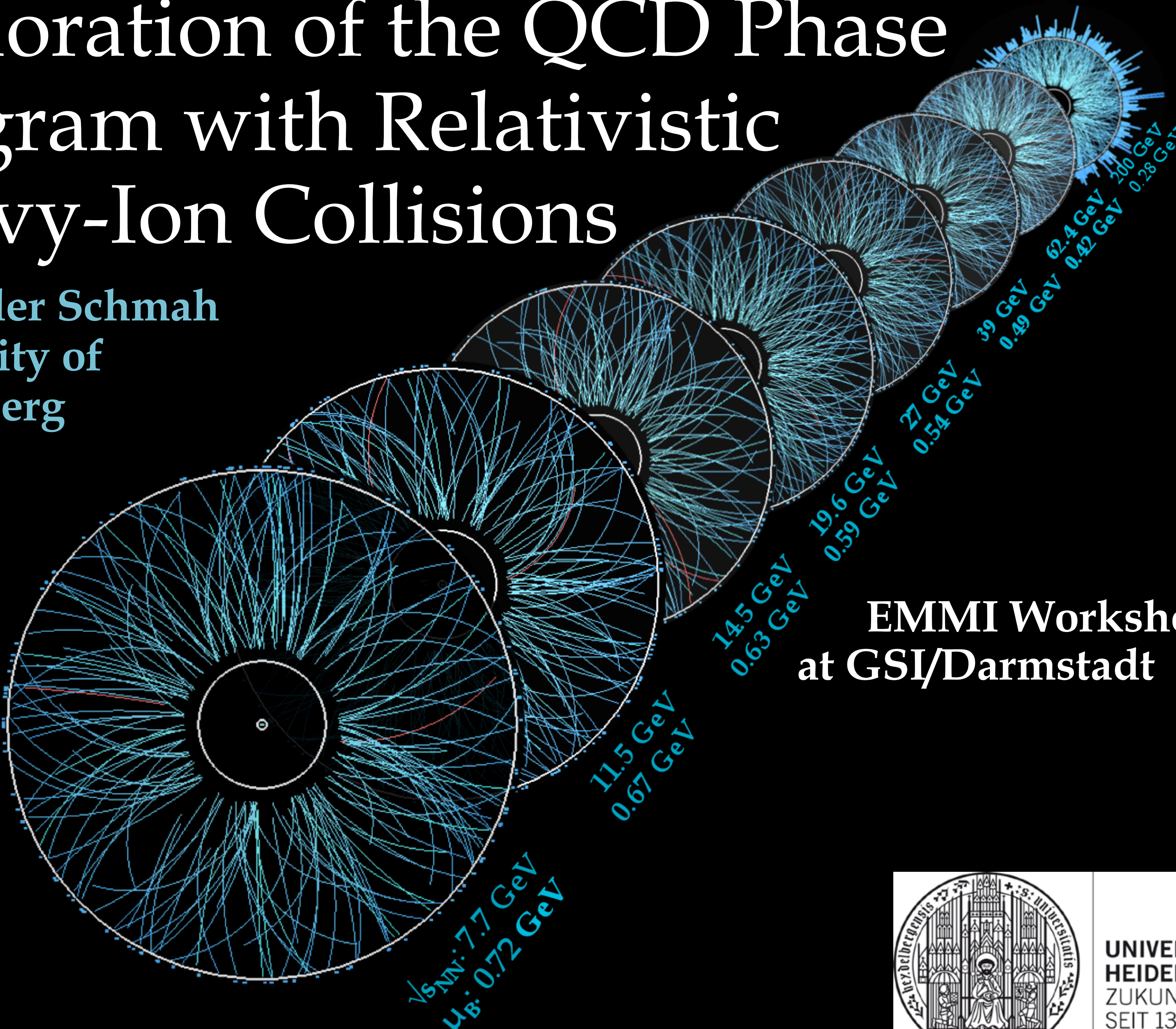
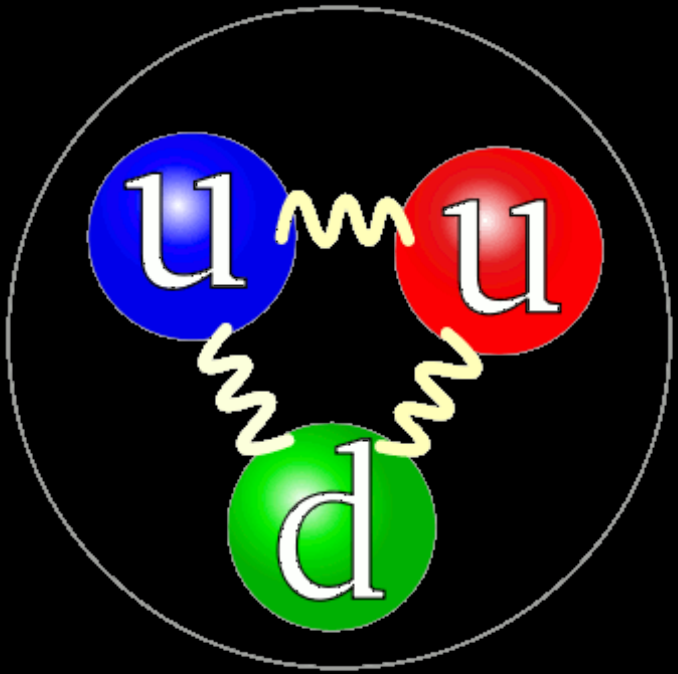


EMMI Workshop
at GSI/Darmstadt

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Outline

- The QCD phase diagram and the Beam Energy Scan at RHIC
- Elliptic flow results from BES and the 20 GeV dip
- Towards BES-II: STAR Upgrades



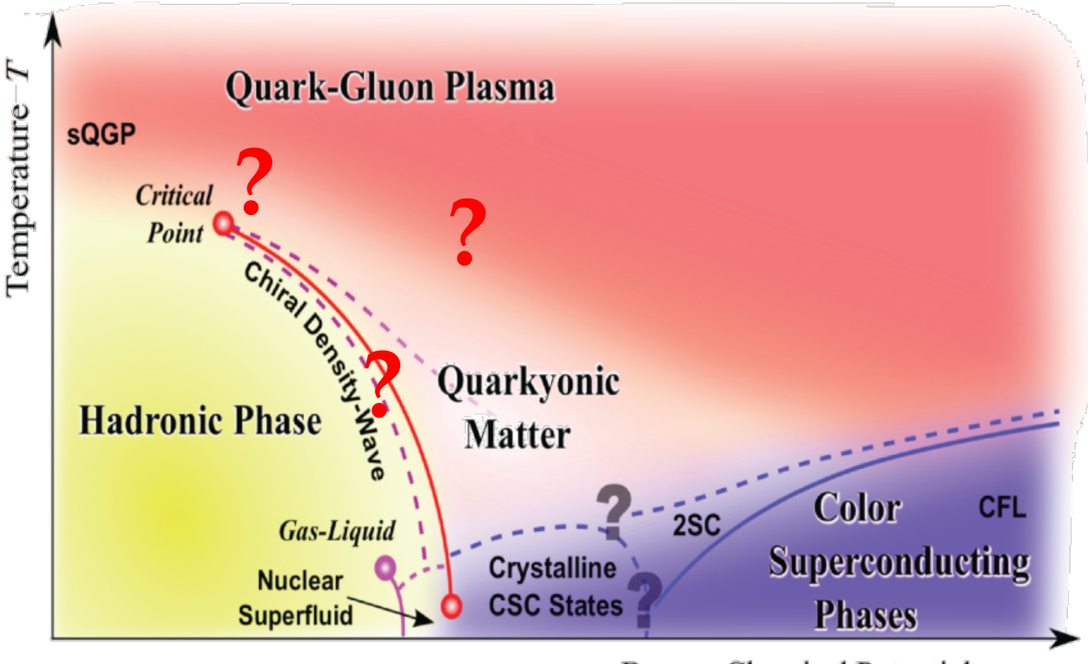
The QCD Phase Diagram

Basic motivation: Exploration of the QCD phase diagram

- Hadron gas phase at low T and/or μ_B
- We expect from QCD lattice calculations a cross over at high energies
- QGP at high T and/or μ_B
  → phase of quasi-free quarks and gluons
- (First order) phase transition?
- Critical point?

<u>Beam Energy Scan at RHIC:</u>
Vary collision energy to map T and μ_B

Rept.Prog.Phys. 74 (2011)



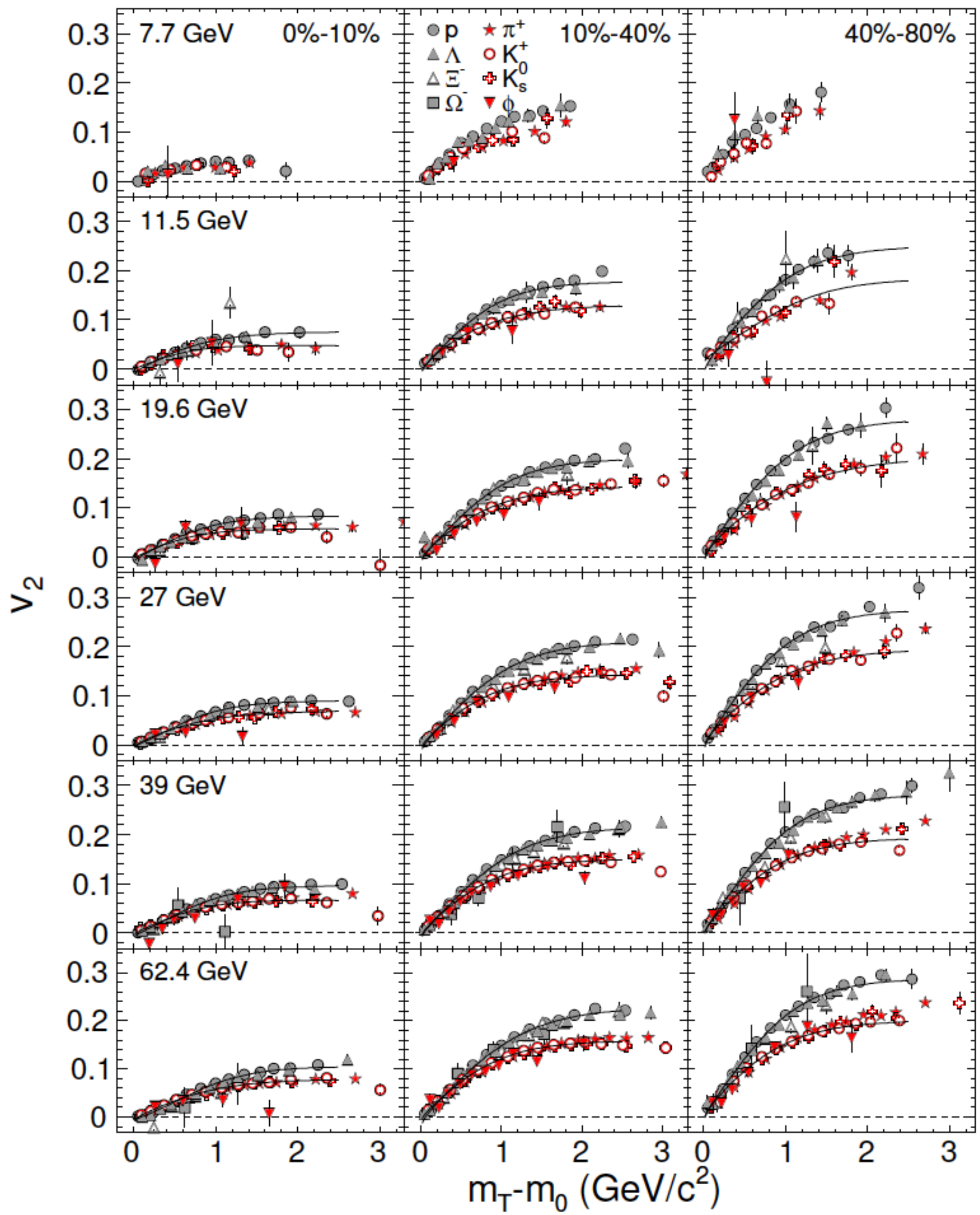
Courtesy of K. Fukushima & T. Hatsuda

? QCD critical point

? QCD phase transition

? QGP phase → properties

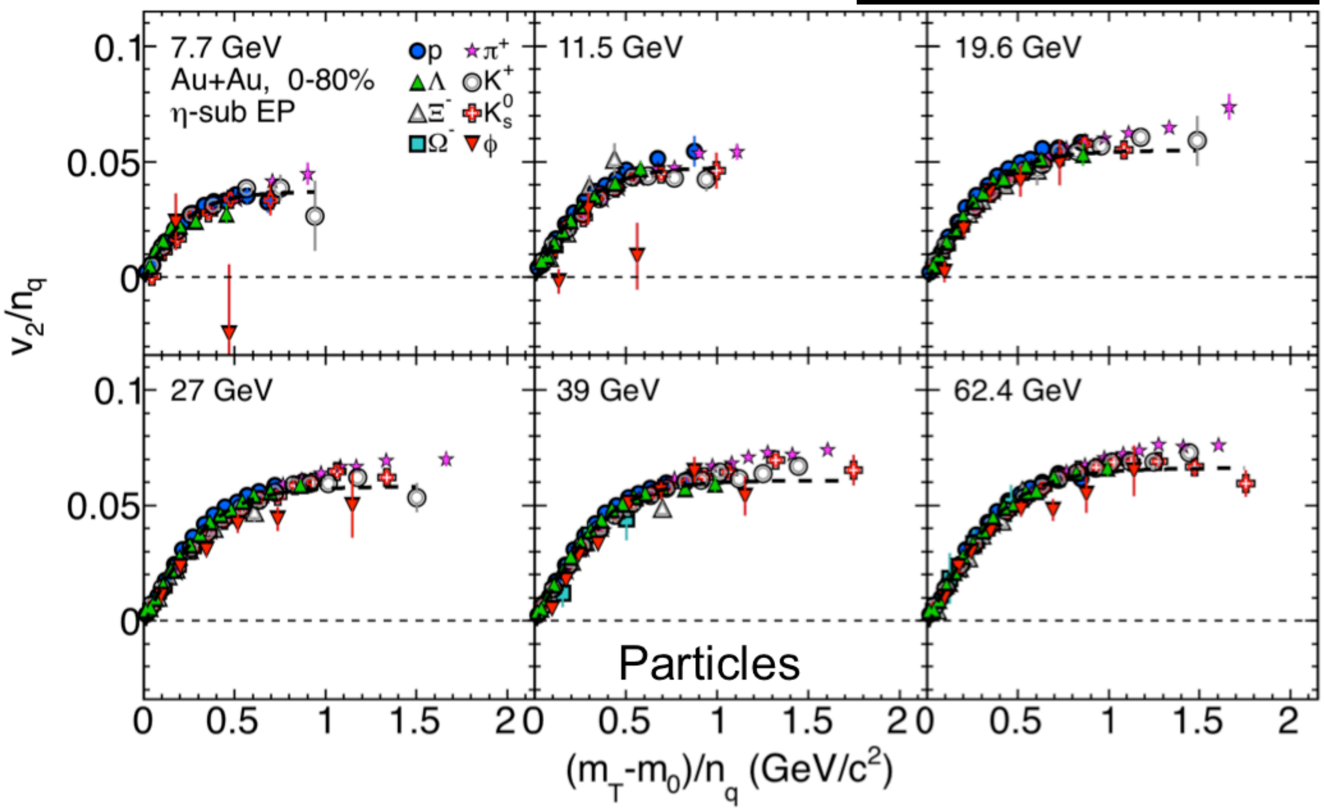
v_2 vs. m_T-m_0 for Particles



- Energy and centrality dependence of v_2 vs. m_T-m_0 for particles
- v_2 is increasing from central to peripheral
- Splitting between baryons and mesons for all energies and centralities

v_2 NCQ Scaling of Particles

Phys. Rev. C 88, 014902 (2013)

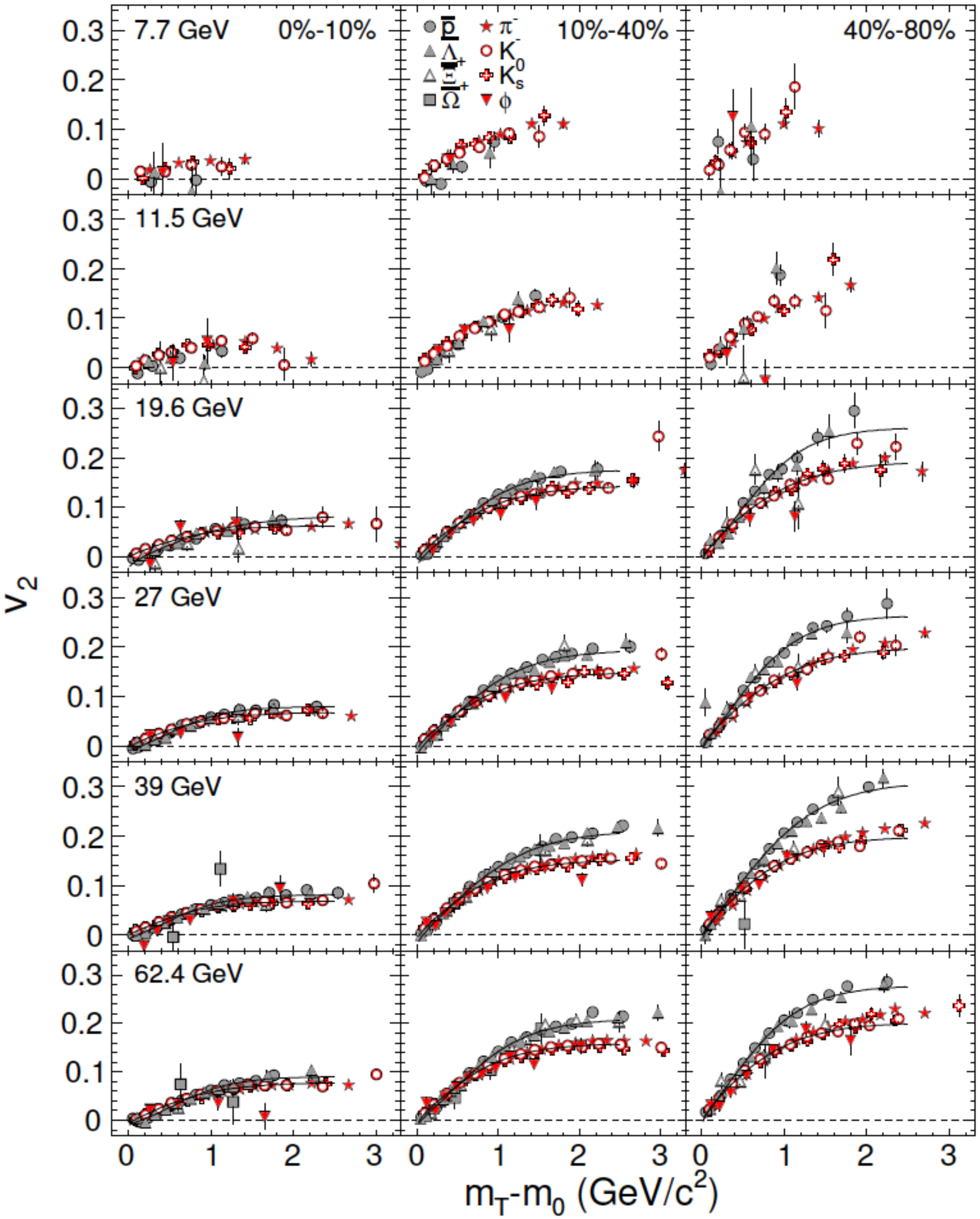


- NCQ-scaling holds for particles and anti-particles separately at all energies → Partonic degrees of freedom?

NCQ = Number of Constituent Quark

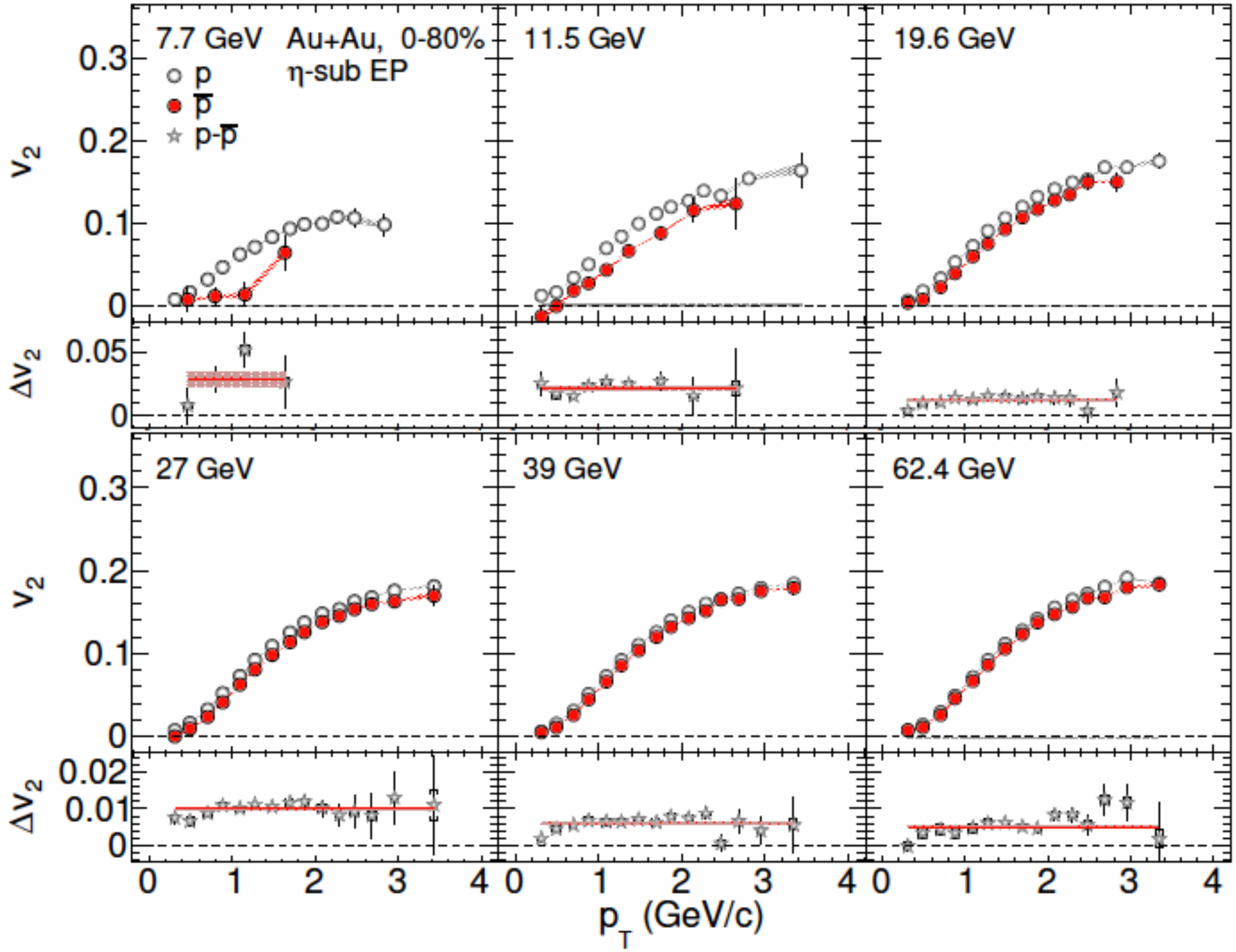
- High m_T-m_0 not measured at lower energies
- Do ϕ-mesons or multi-strange particles deviate?
- NCQ scaling should break down at even lower energies (2-5 GeV)!

v_2 vs. m_T-m_0 for anti-Particles



- Energy and centrality dependence of v_2 vs. m_T-m_0 for anti-particles
- v_2 is increasing from central to peripheral
- Splitting between baryons and mesons for all energies above 19.6 GeV and 10%-80%
- No observed splitting for 0%-10% and no splitting (or more data needed) at 7.7 and 11.5 GeV

Proton/anti-Proton Elliptic Flow



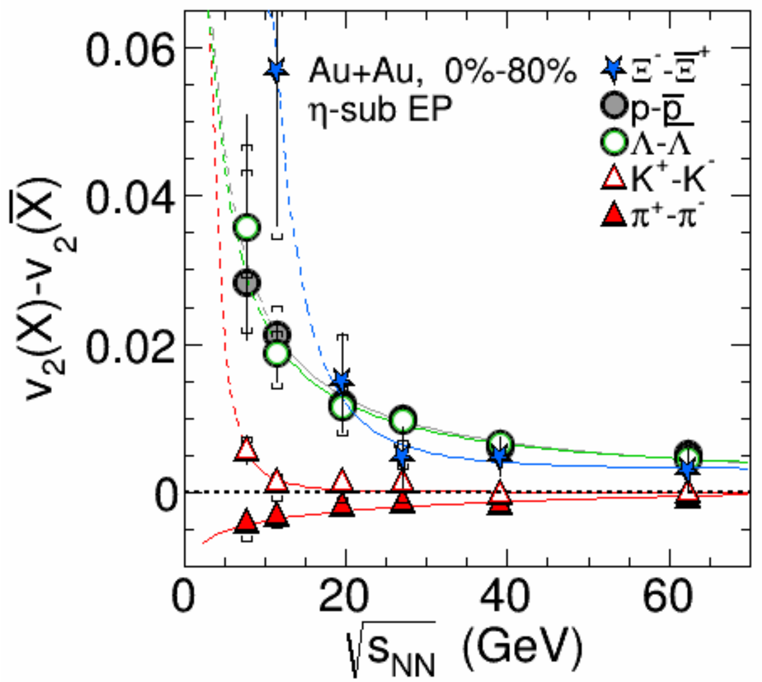
Phys. Rev. C 88, 014902 (2013)

- Difference in v_2 between particles and anti-particles was not expected

→ **Simple hydrodynamics would predict same behavior for particles and anti-particles!**

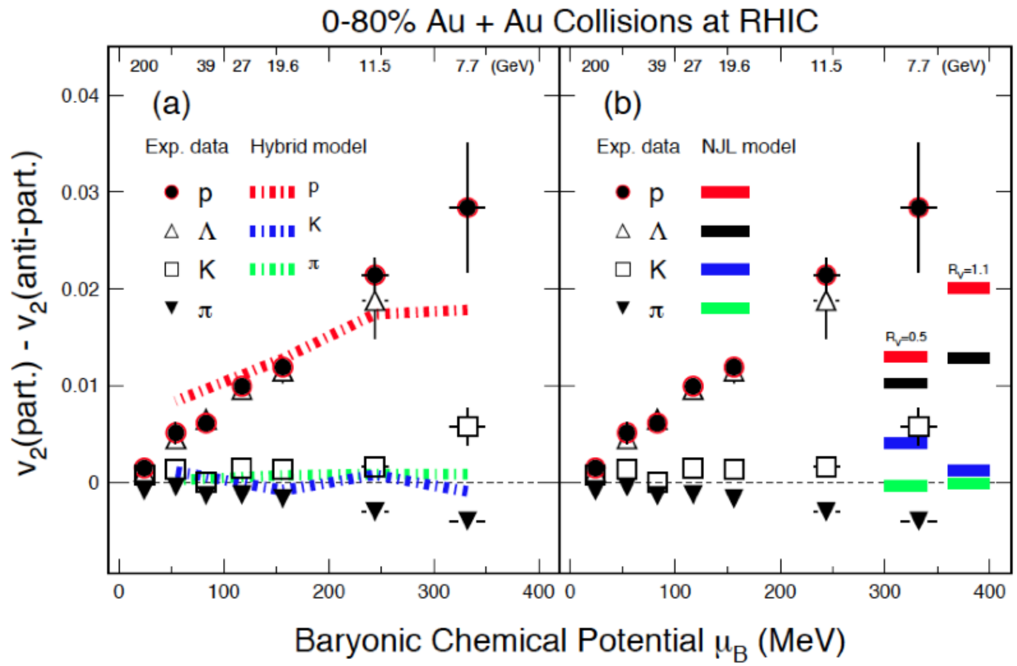
Δv_2 vs. $\sqrt{s_{NN}}$: Comparison with Theory

Phys. Rev. Lett. 110, 142301 (2013)



Hybrid: Phys. Rev. C 86, 044903 (2012)

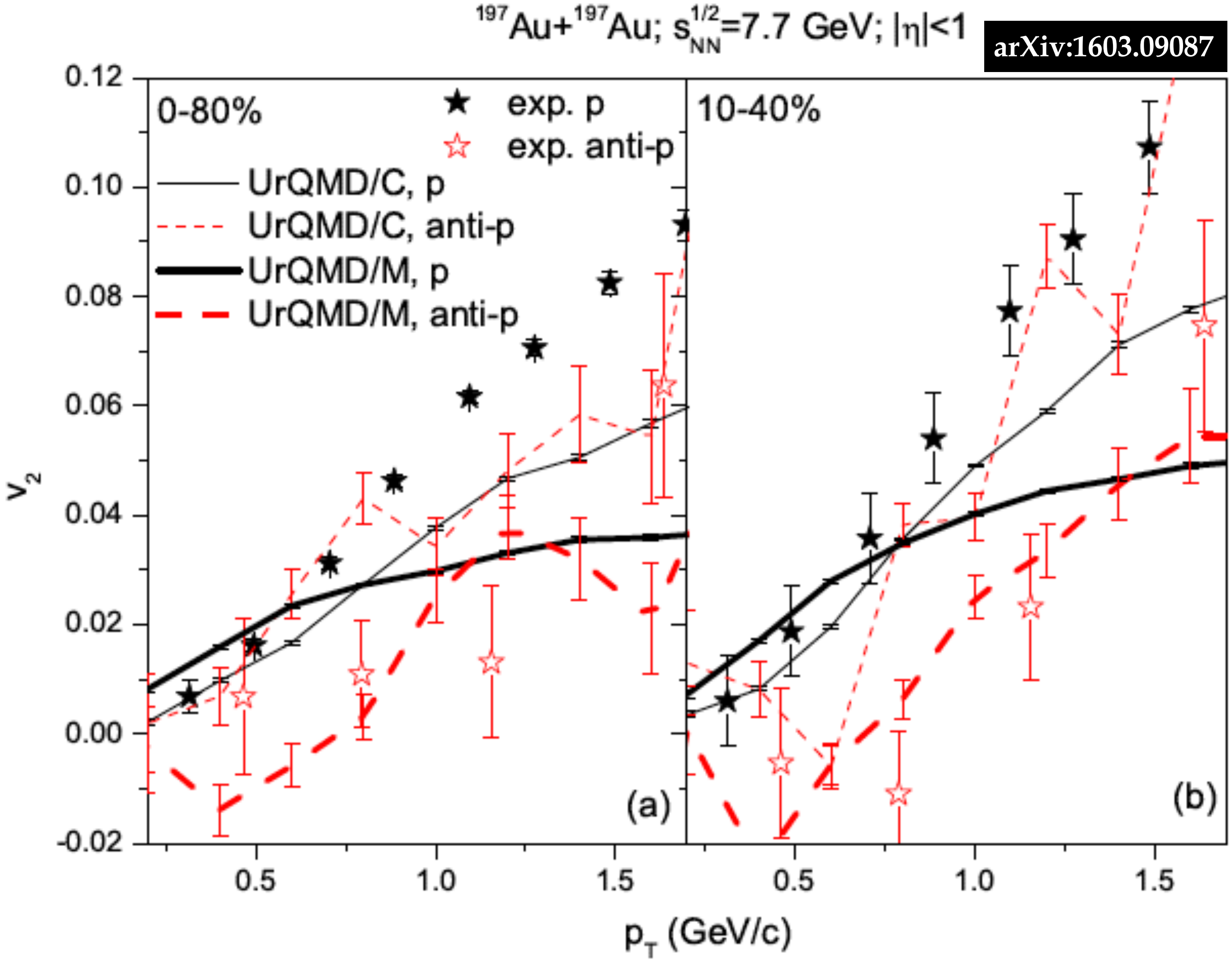
NJL: Acta Phys.Polon.Supp. 7 (2014) 1, 183



- Hydro model: Hybrid model (UrQMD + hydro) with baryon stopping
- Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive for quarks, attractive for anti-quarks

→ Very different physics in models but similar agreement with data

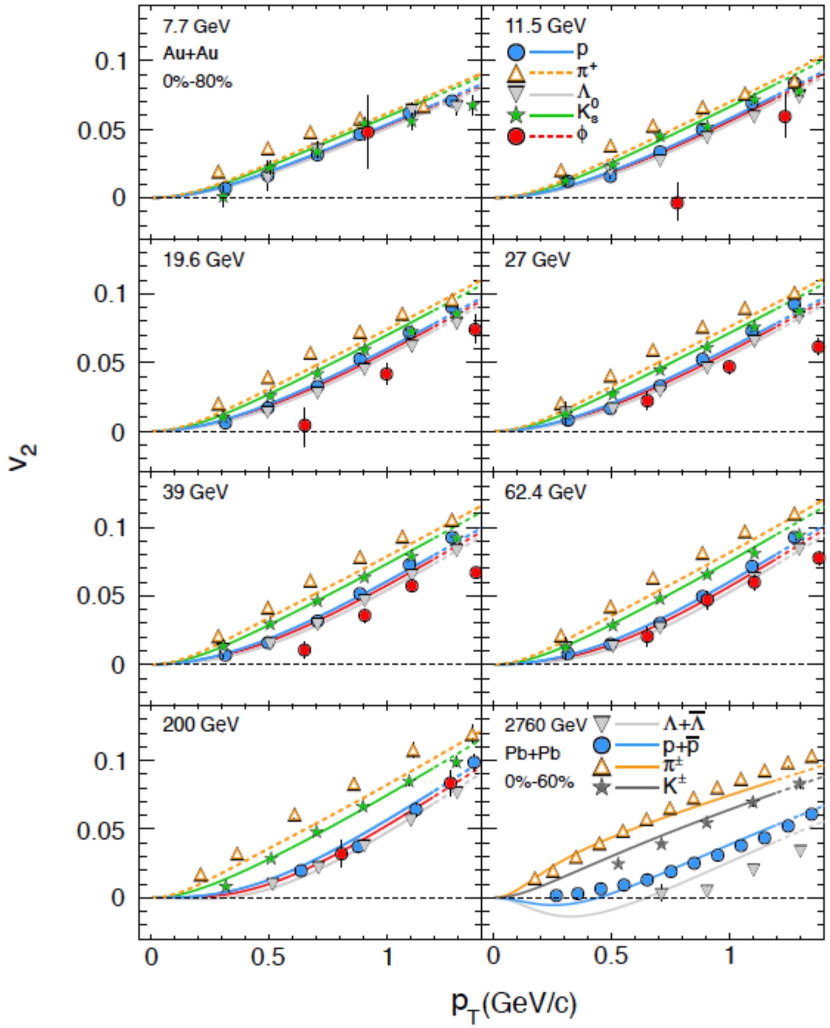
v_2 Splitting in UrQMD with Potentials



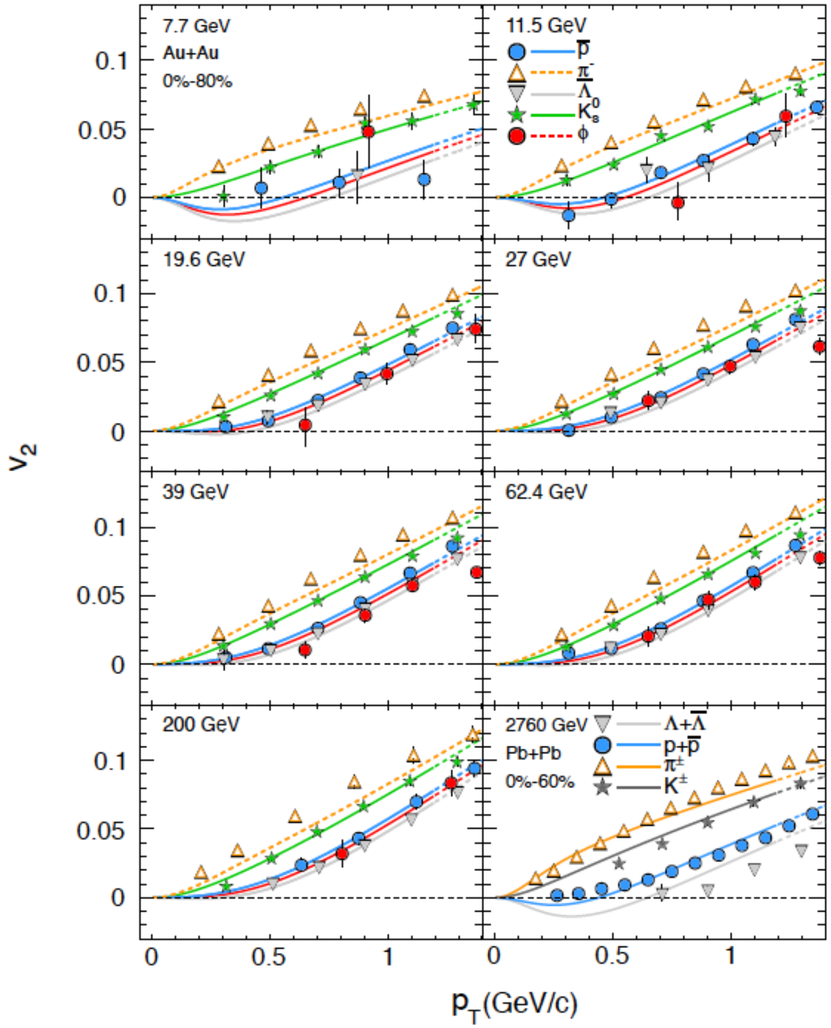
- With potentials included in UrQMD the v_2 splitting between protons and anti-protons can be reasonably well described.

Blast Wave Fits to $v_2(p_T)$

Phys. Rev. C 91, 024903 (2015)



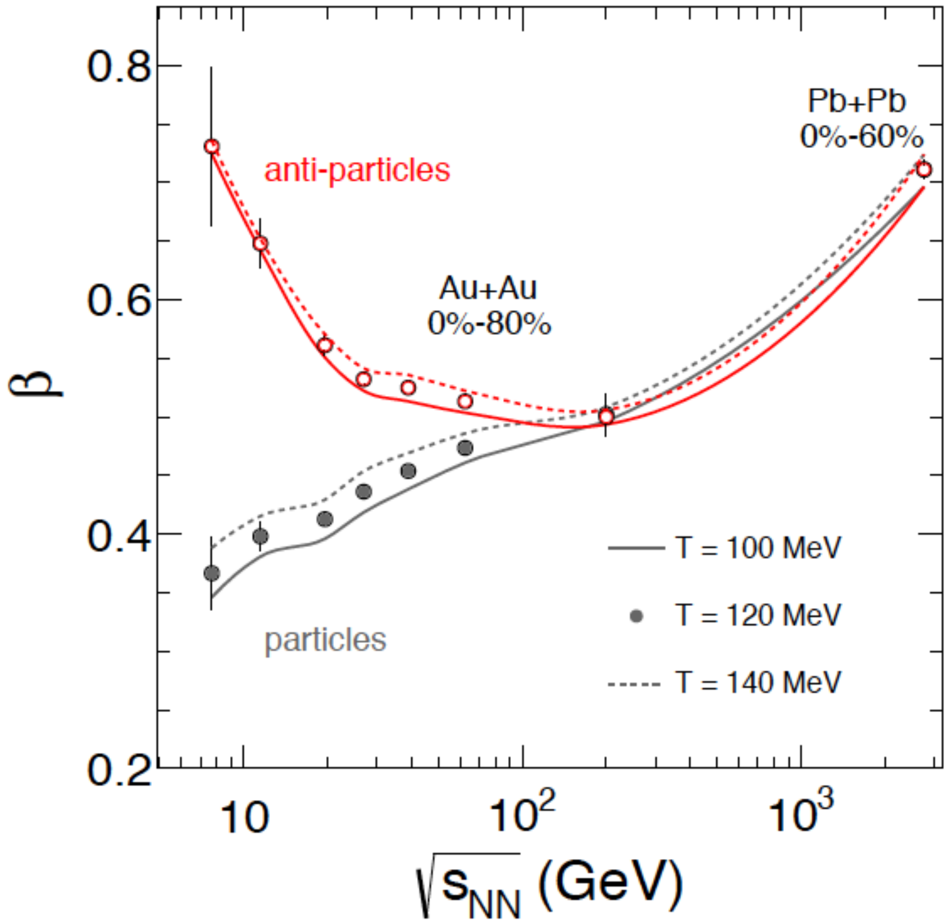
Phys. Rev. Lett. 110, 142301 (2013)
arXiv:1410.1947

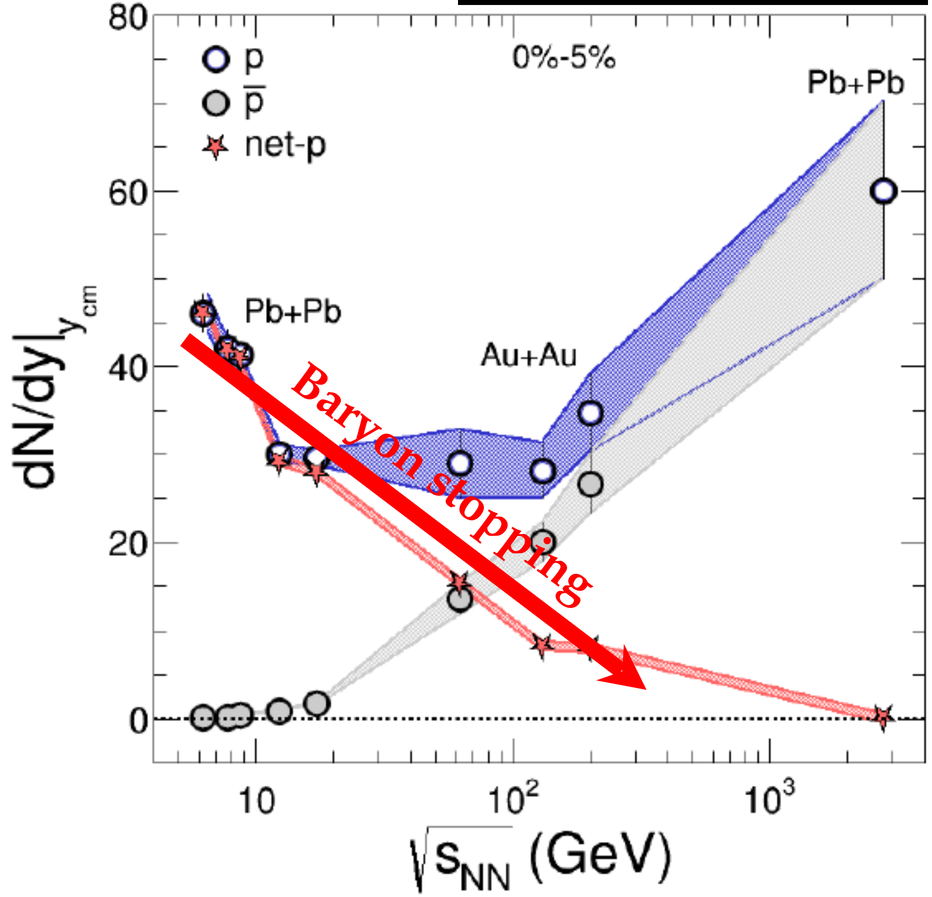


- Different mass ordering for particles and anti-particles
- Very good description of all anti-particles, φ-mesons off for particles

Radial Expansion Velocity

Phys. Rev. C 91, 024903 (2015)

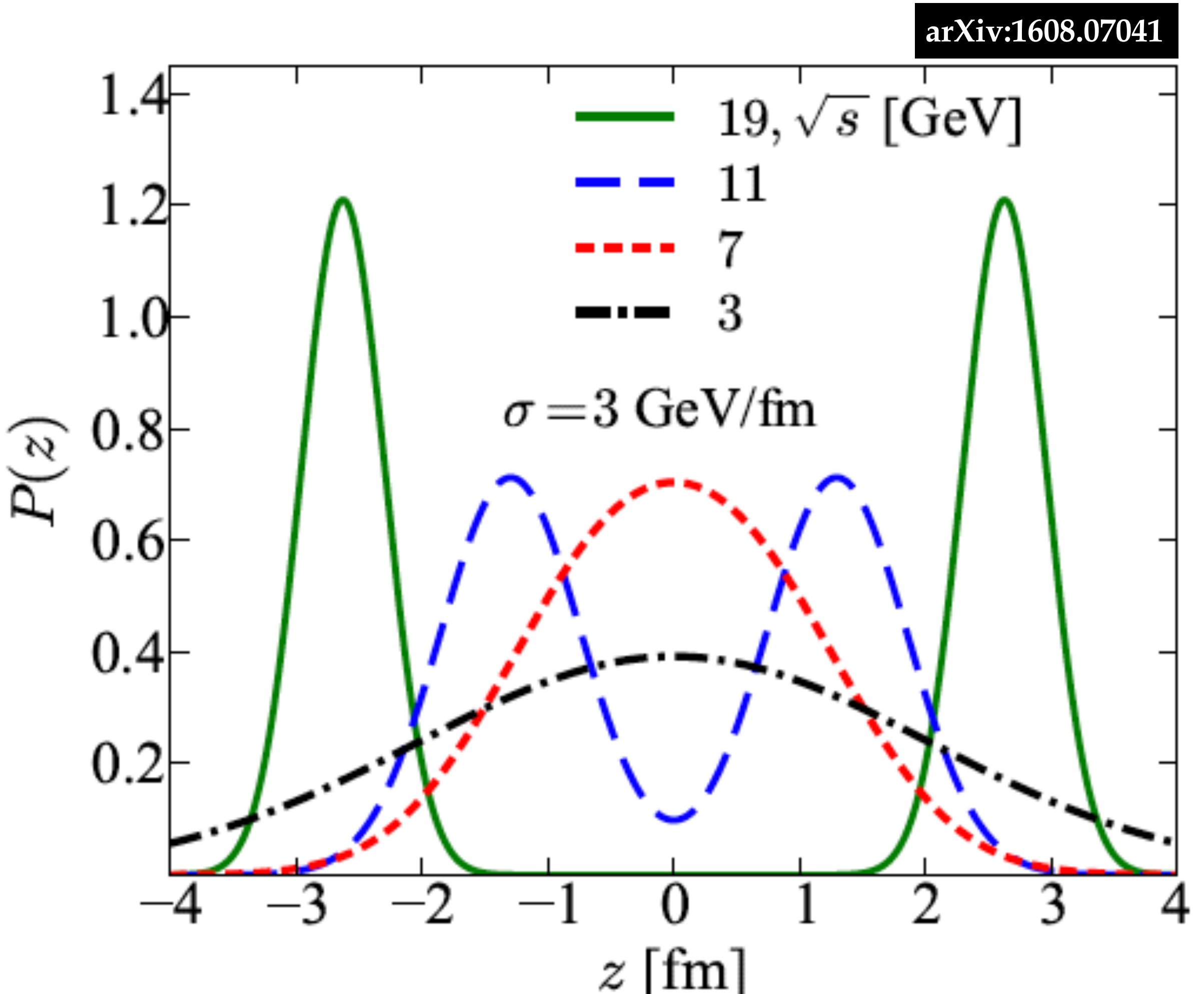




- Radial expansion velocity extracted from blast wave fits to v_2 data
- Different behavior for particles and anti-particles at lower energies
- Similarities to proton/anti-proton/net-proton curves

  → **Baryon stopping? Annihilation of anti-protons?**

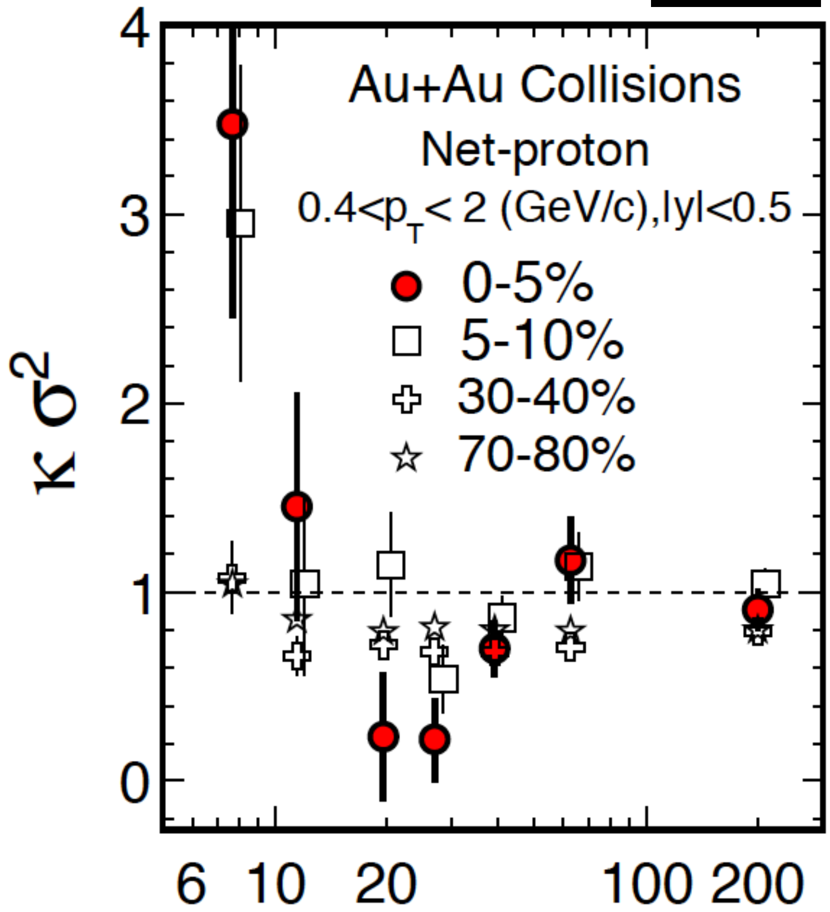
Baryon Stopping in Models



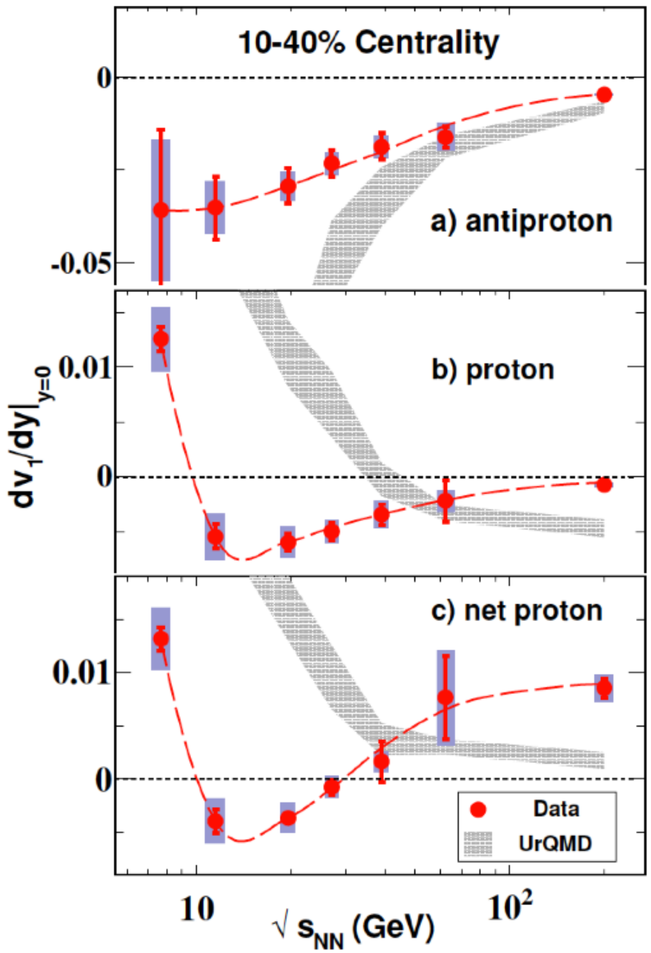
- Stopped protons are separated in configuration space at energies > 11 GeV.
- No thermalization possible in this case. Could directly affect v_2.

The "Dips" in Higher Moments and v_1

QM 2014



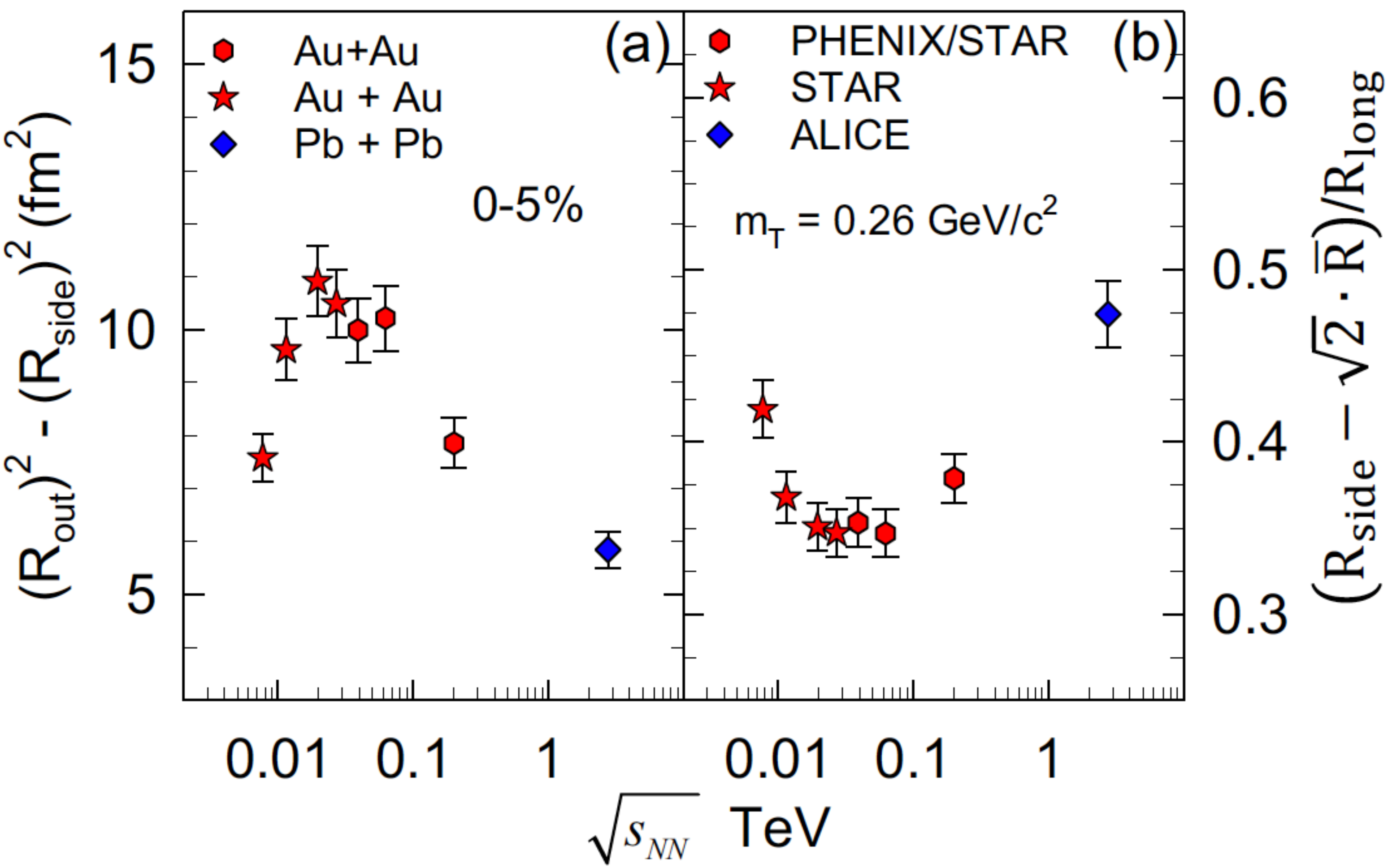
PRL, 112 (2014) 162301



- Clear non-monotonic structures observed at about 20 GeV in net-protons higher moments and dv1/dy.

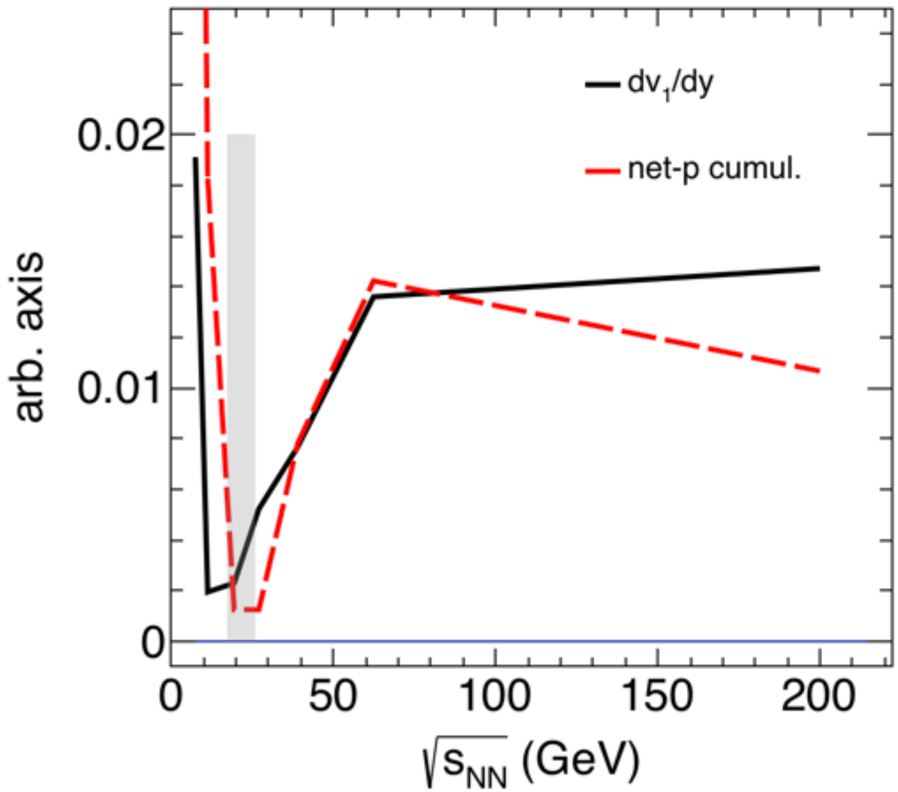
The "Dip" in HBT Radii

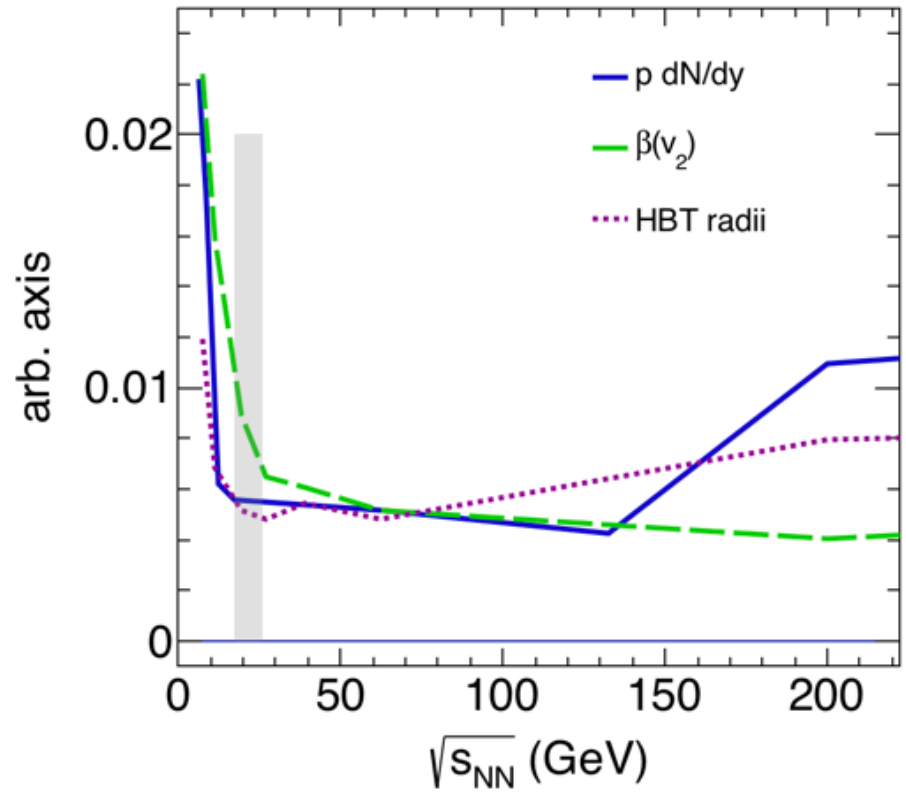
arXiv:1410.2559



- Clear non-monotonic structures observed at about 20 GeV in HBT radii.

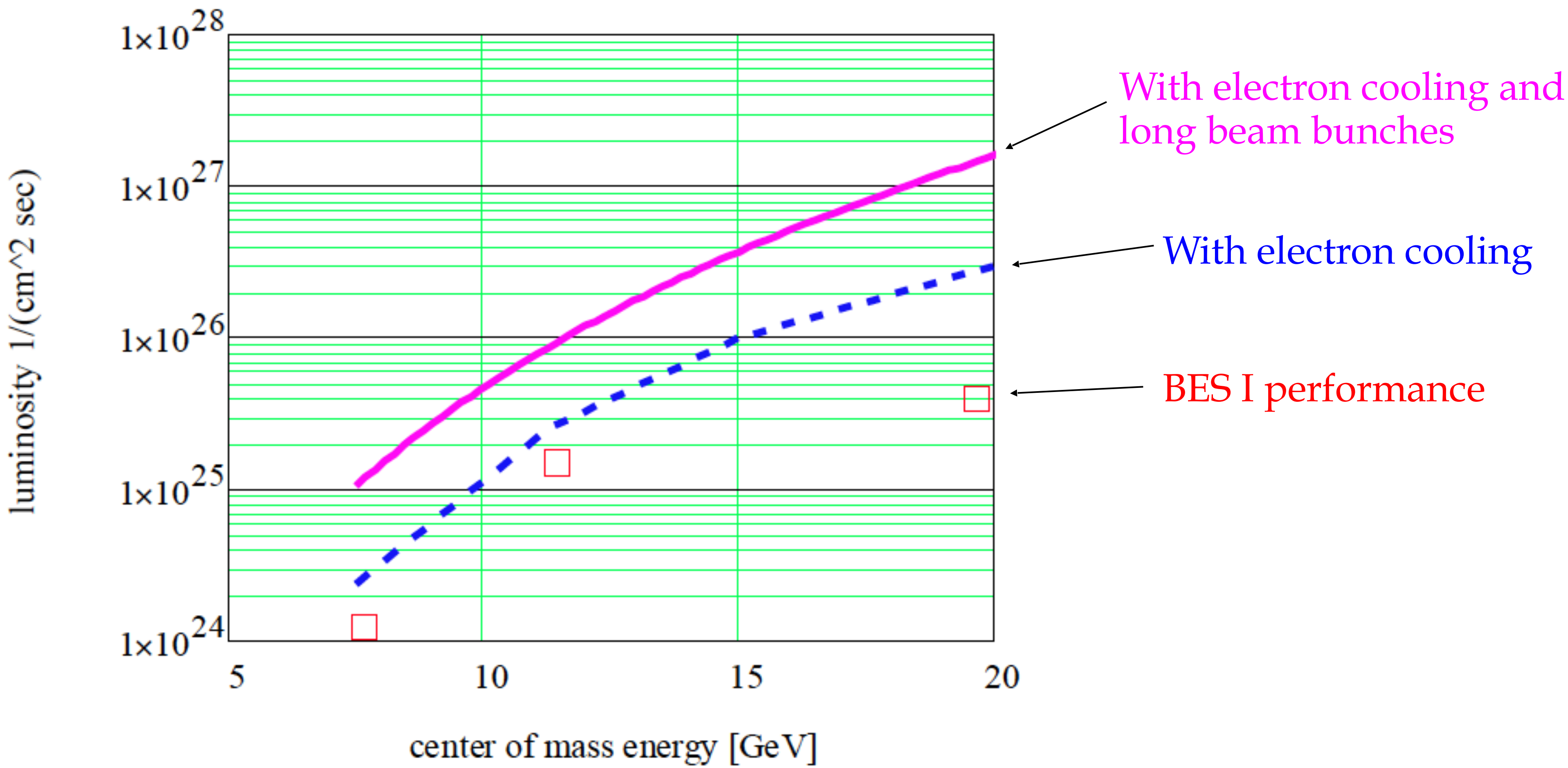
The “Dip” Compilation





- Shape comparison: “matched” via scaling + shift along y-axis.
- dv1/dy and net-proton higher moments have almost identical shape!
- Proton dN/dy, radial expansion velocity (beta) and HBT radii have almost identical shapes!
- All show the same drop from 7.7 GeV to about 20 GeV.
- The drop is clearly driven by baryon stopping/anti-proton production.

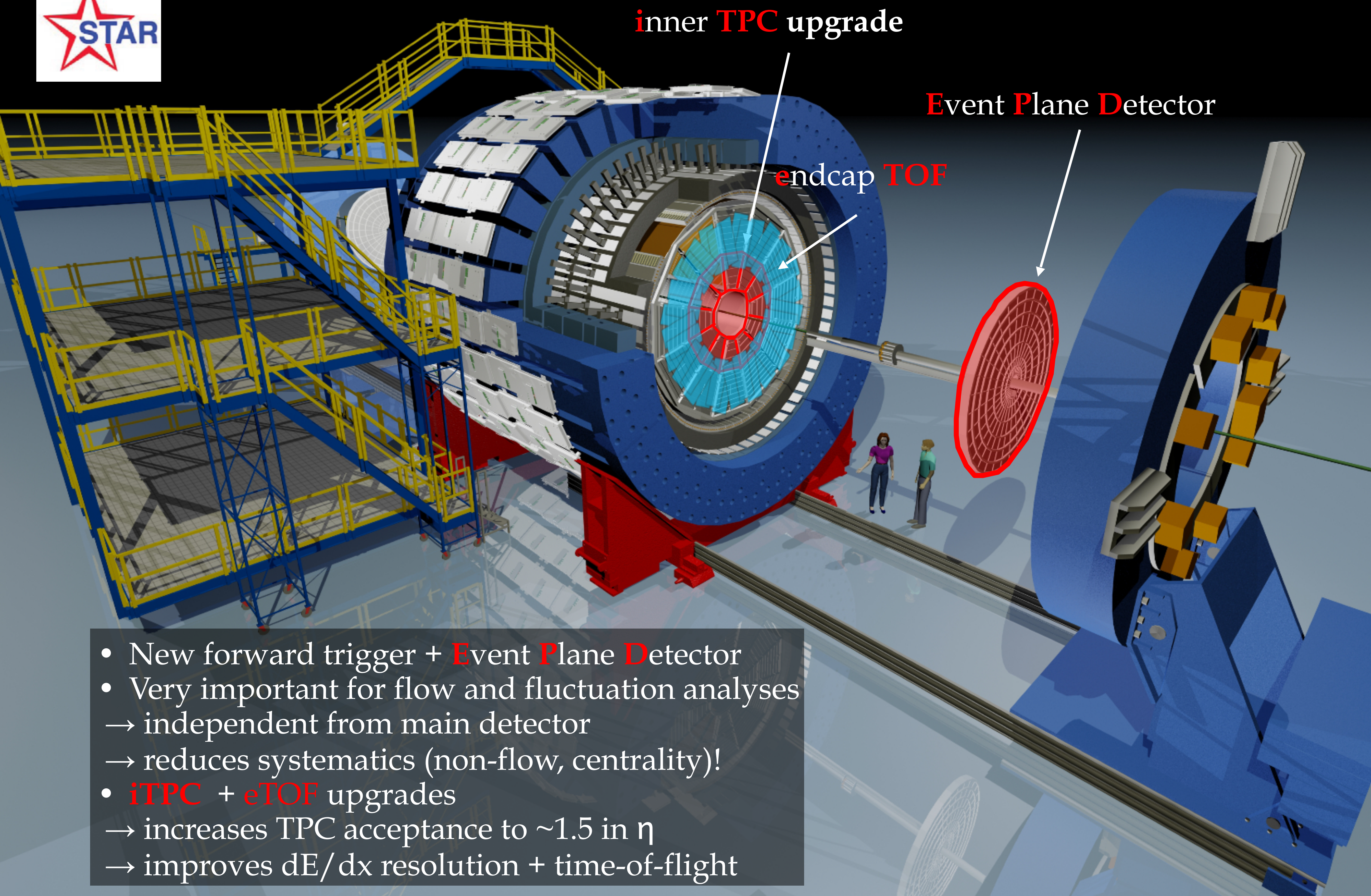
Luminosity Improvements for BES II



- Electron cooling + longer beam bunches for BES II
→ Factor 4-15 improvement in luminosity compared to BES I

- Every energy available with electron cooling!

New Detectors for BES-II



- New forward trigger + Event Plane Detector
- Very important for flow and fluctuation analyses

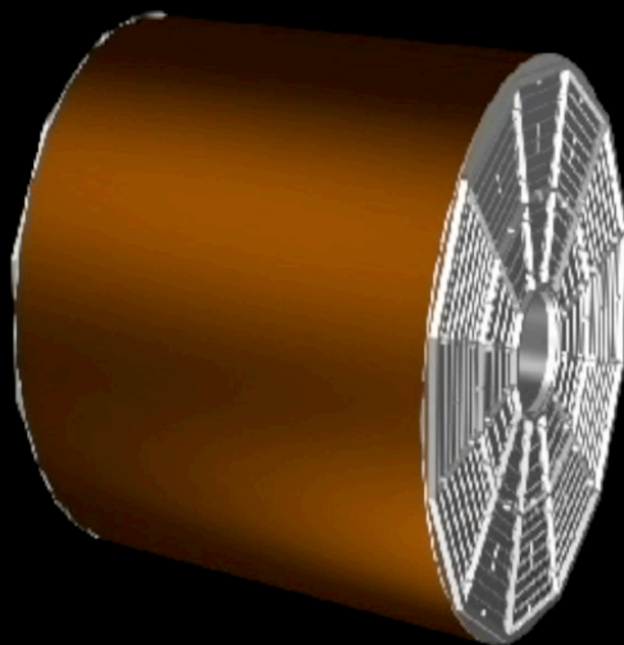
→ independent from main detector

→ reduces systematics (non-flow, centrality)!

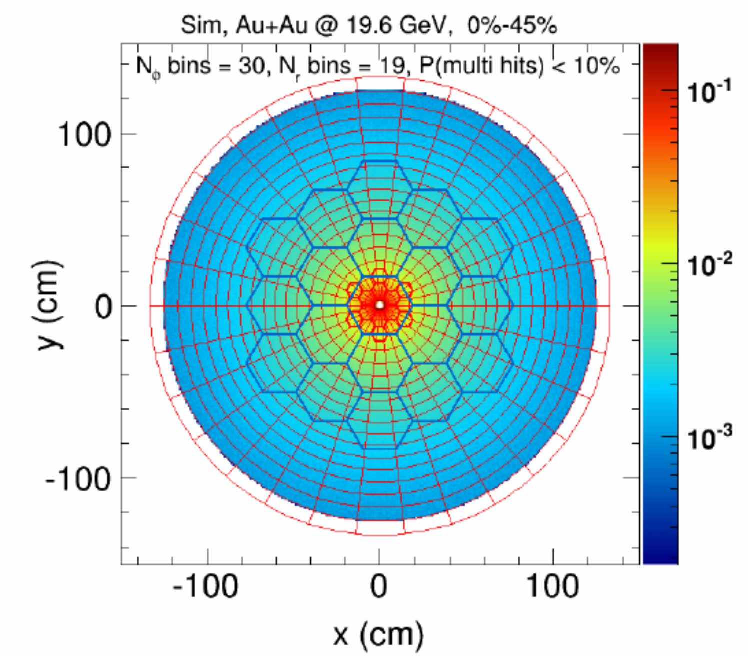
- iTPC + eTOF upgrades

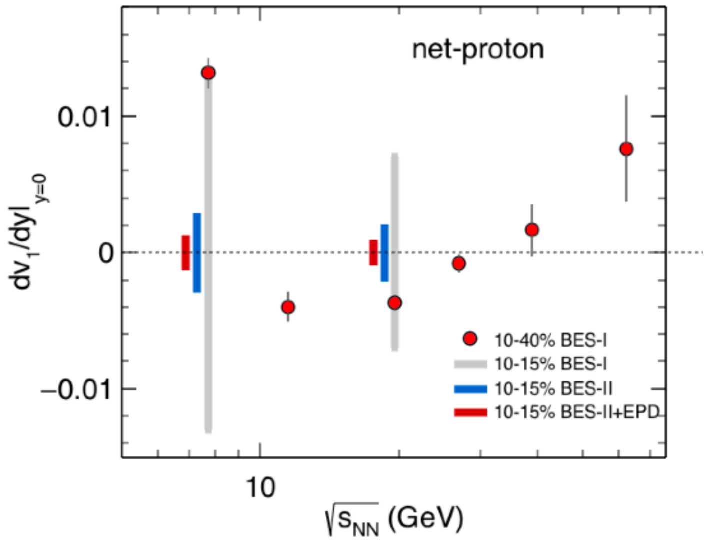
→ increases TPC acceptance to ~1.5 in η

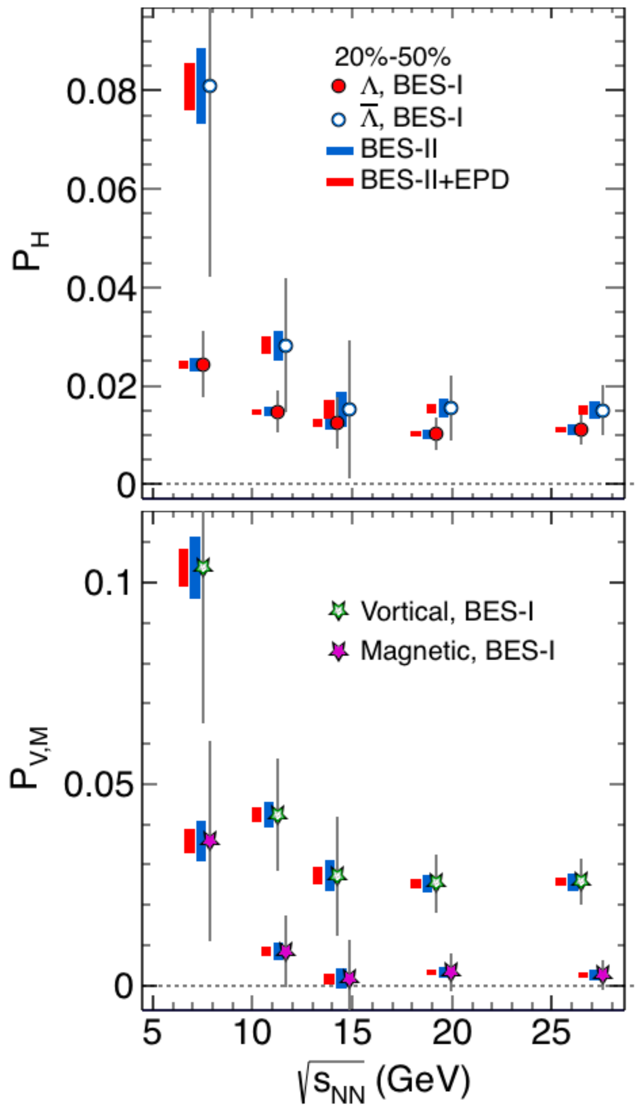
→ improves dE/dx resolution + time-of-flight



Event Plane Detector



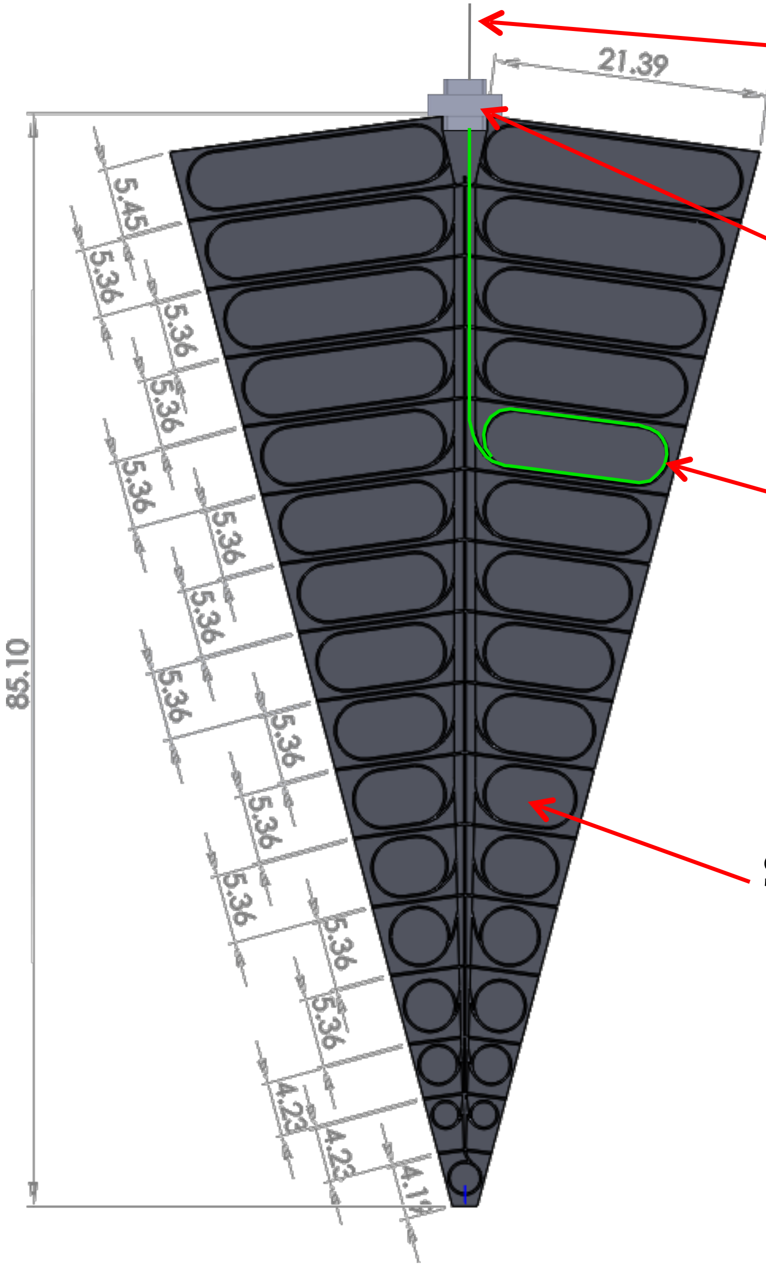




- Much higher granularity compared to previous detector
- Improvements for statistical precision but also for systematics

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666

EPD Super-Sector Design



Clear fibers (Kuraray s-type multi-cladded, 1.15 mm)

Embedded 32-channel fiber-to-fiber connector

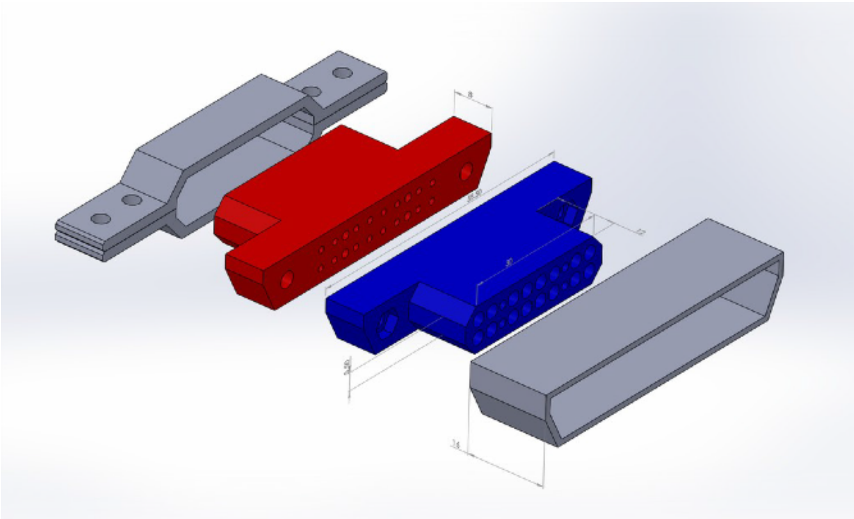
Embedded WLS fibers (triple layer, Kuraray s-type multi-cladded, 1 mm)

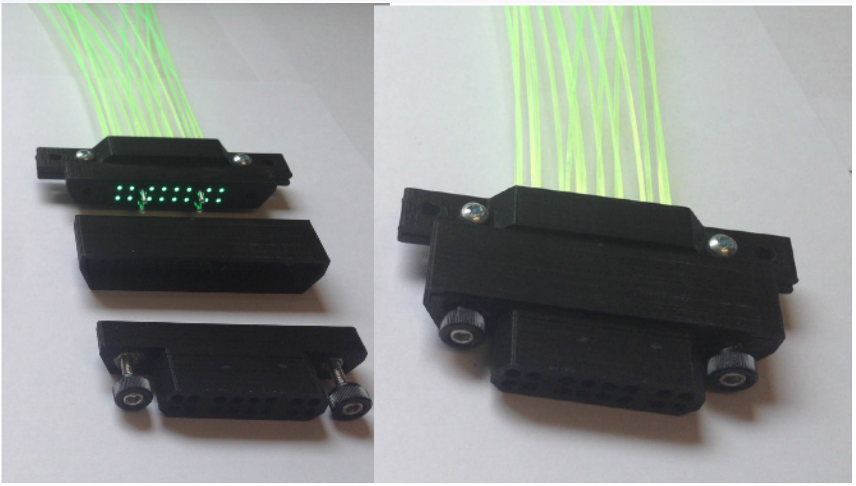
Scintillator (EJ-200)

- Each supersector has 31 channels, 16 in radial direction
- Two azimuthal segments (sectors)
- Sigma-groves for WLS fibers, triple layer
- Smallest bending radius ~1 cm!

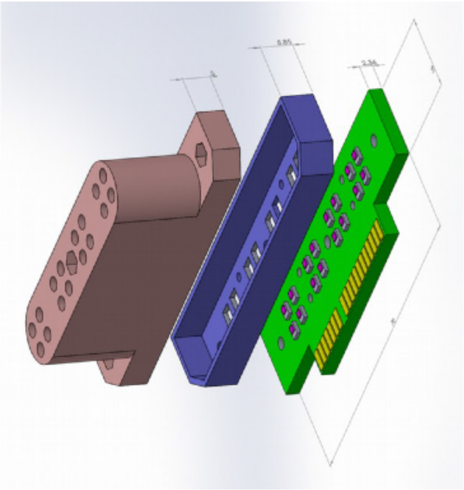
EPD Fiber Connectors

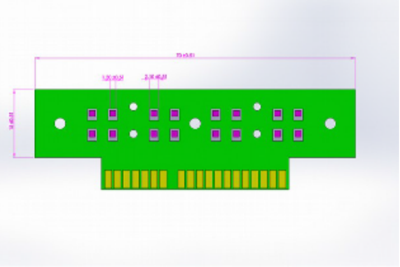
16 channel fiber-to-fiber connector

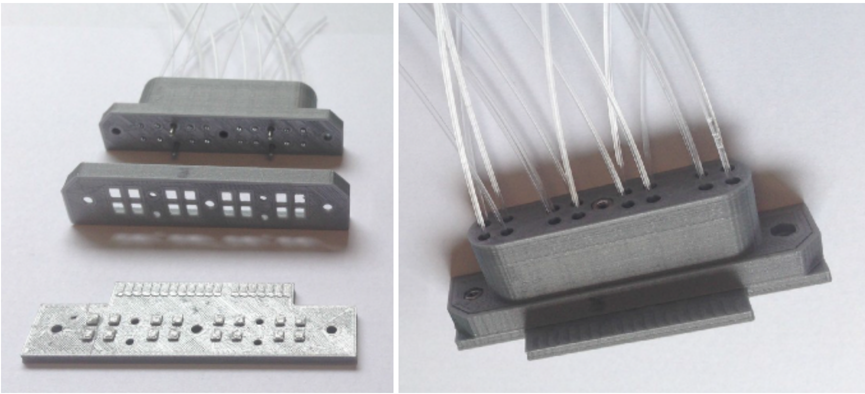




16 channel fiber-to-SiPM connector







- Computer aided design + 3D printed

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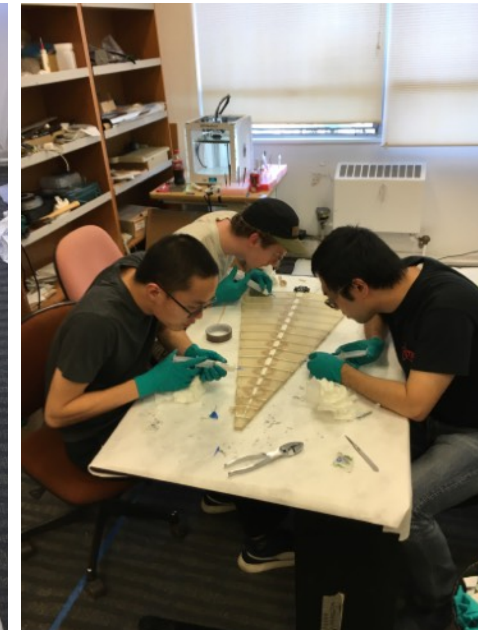
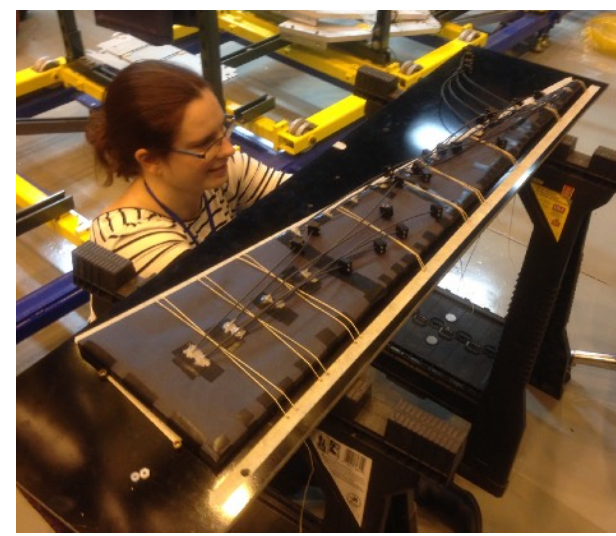
Event Plane Detector Construction

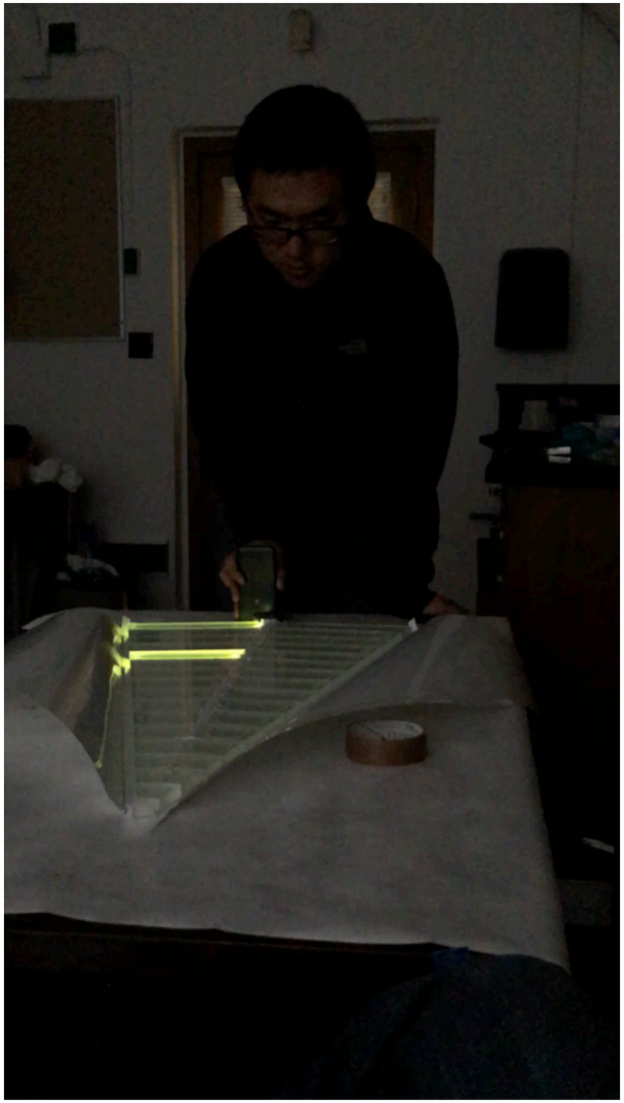


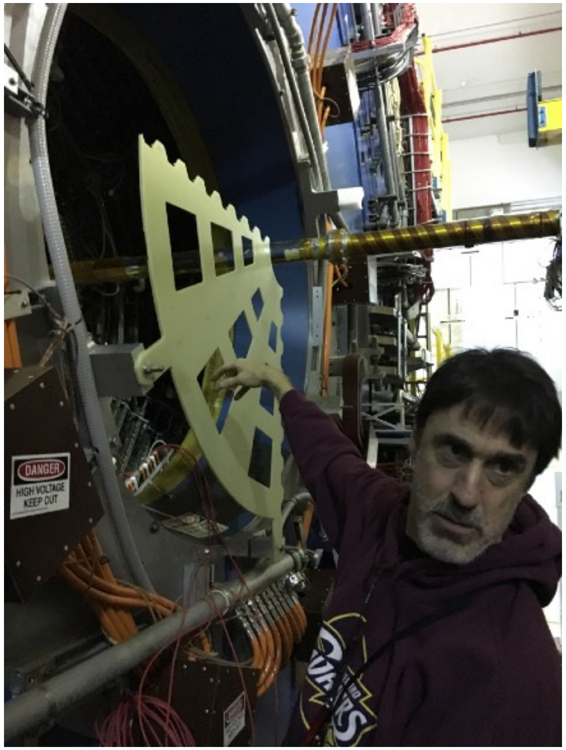



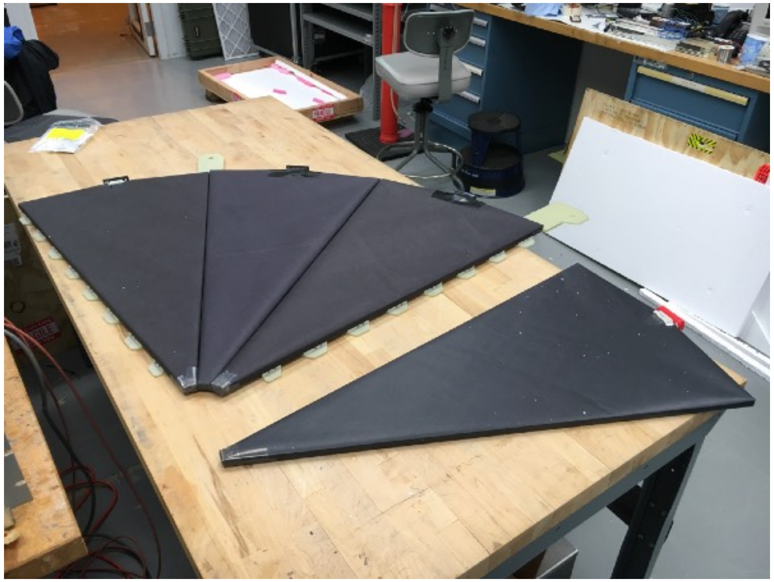



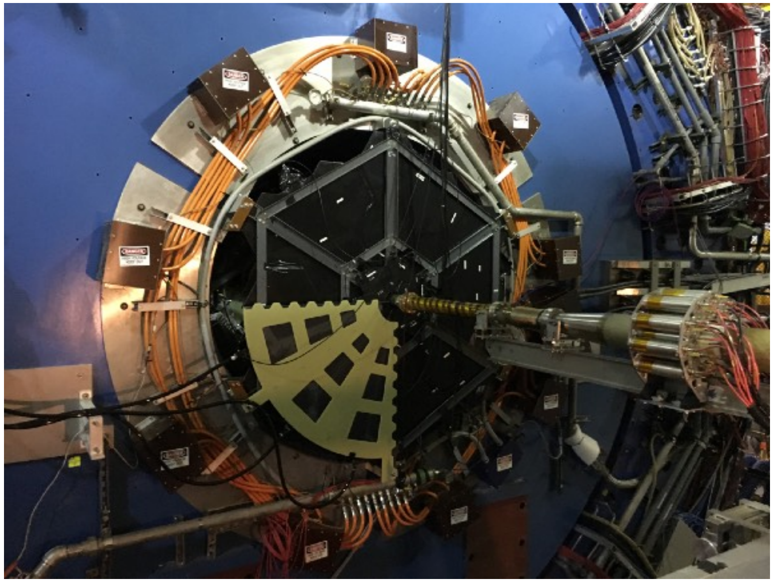
- Full R&D and main detector design done at LBNL
- Full production at Lehigh and OSU

Event Plane Detector: Testing and Installation



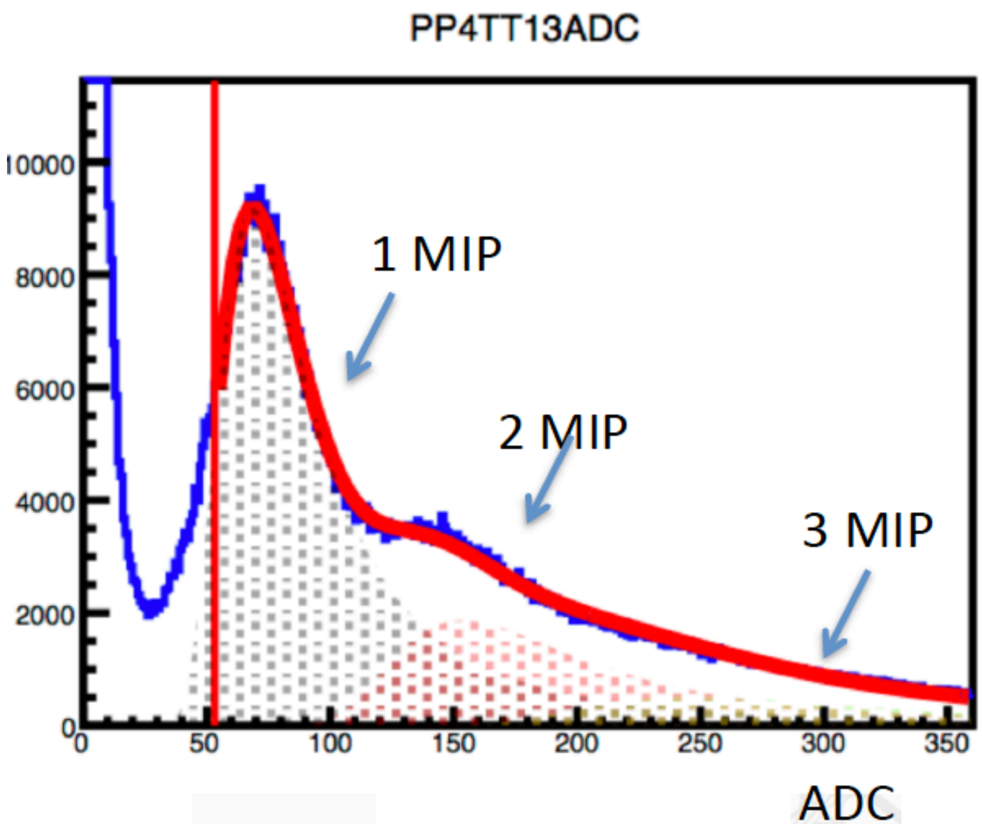


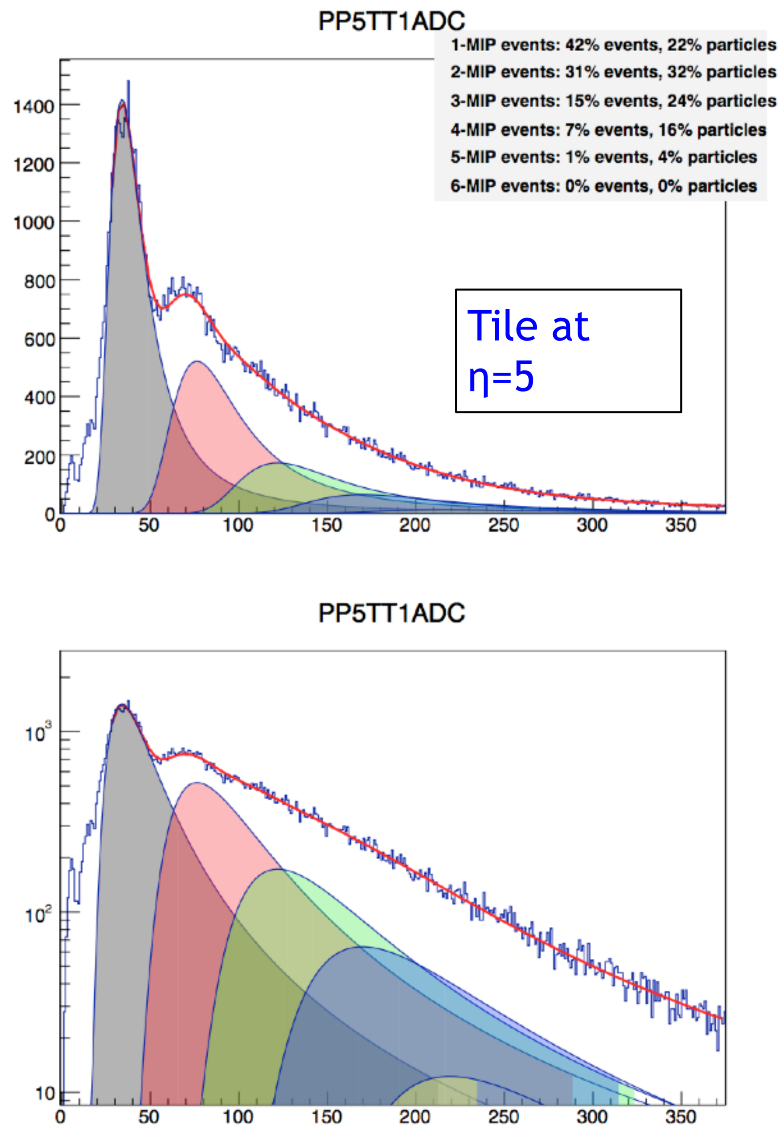




- Installed in STAR for 2017 run
- First physics!

Event Plane Detector: Signals

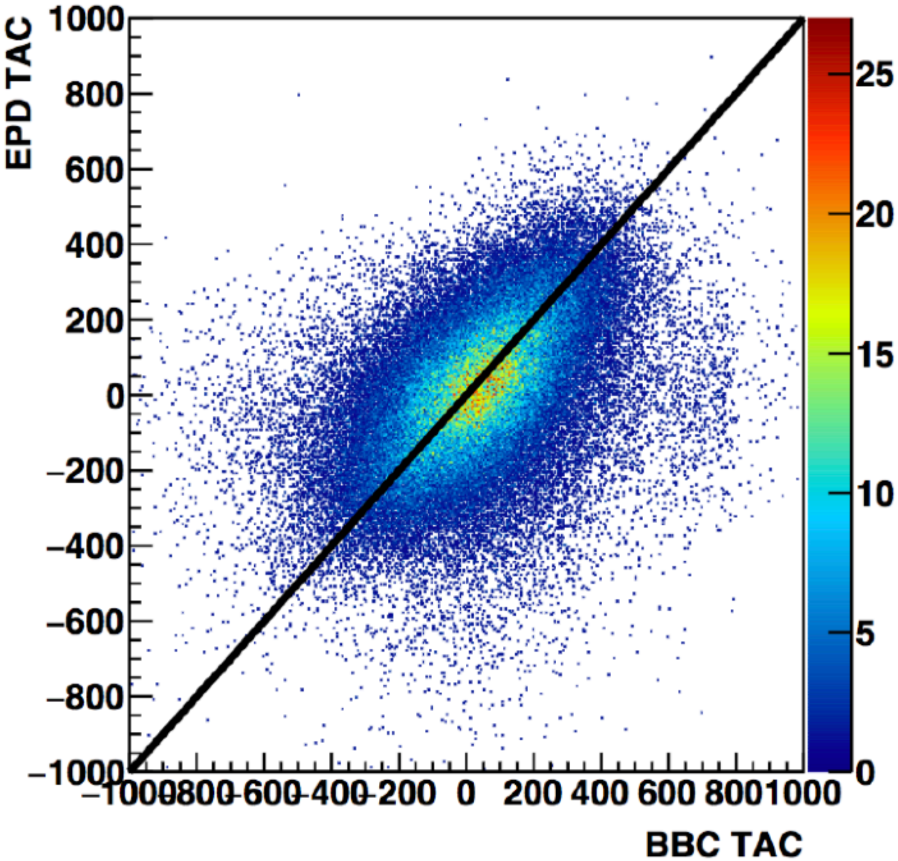




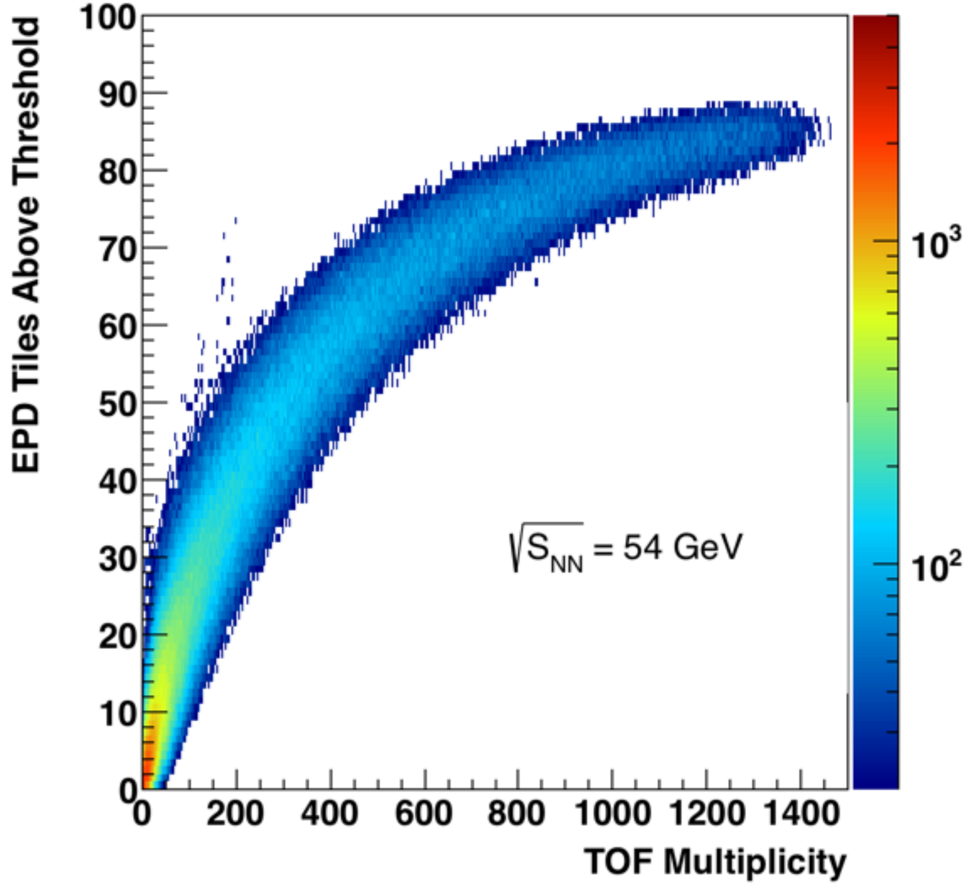
- 1 vs. 2 MIP resolution!
- Good understanding of ADC spectra → in agreement with PHOBOS data expectations

Event Plane Detector: Correlations

BBC Correlation



TOF Correlation



- Good correlation with TOF and BBC detectors

Event Plane Detector: Installation

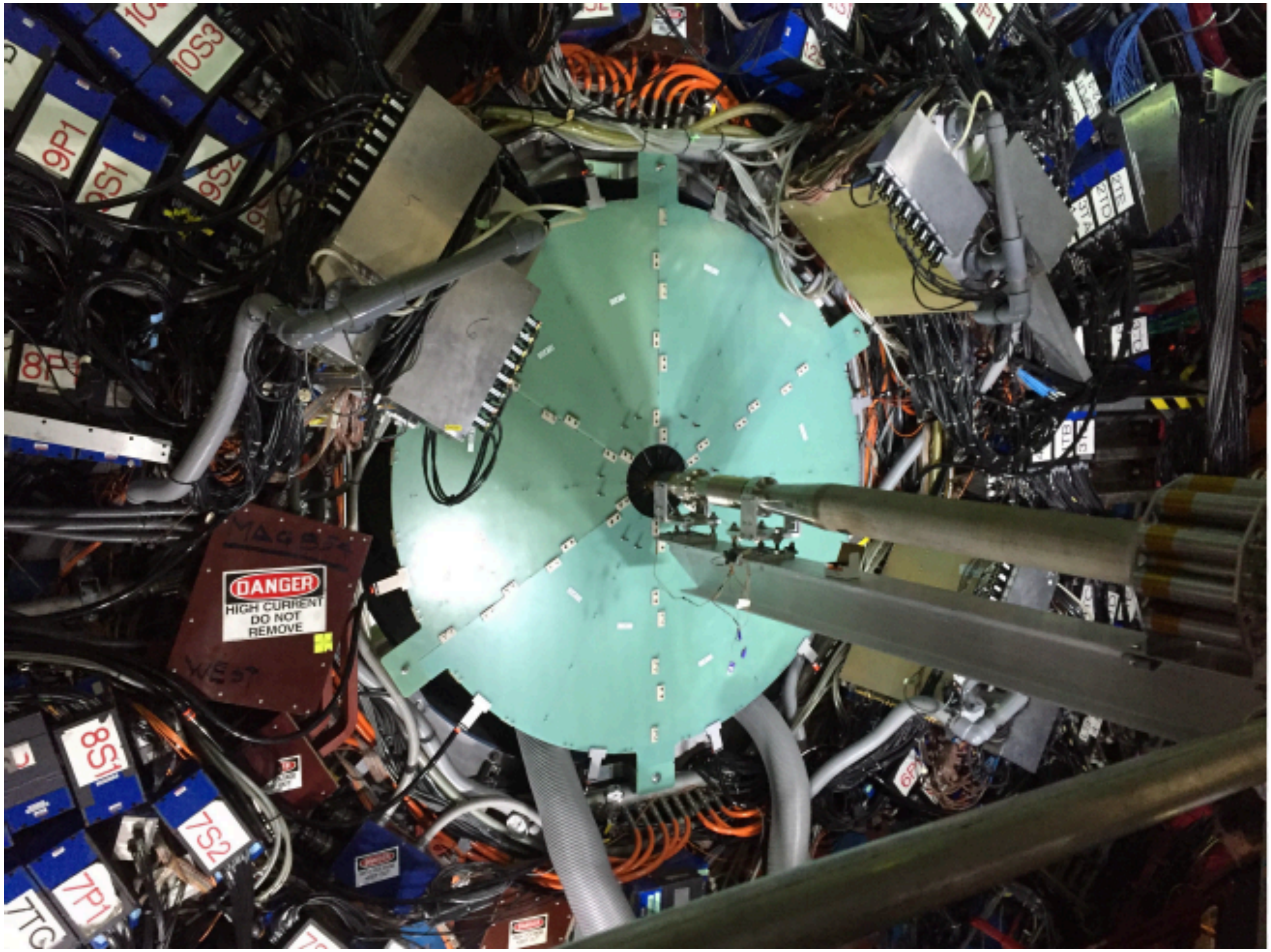
Bill

Bob

Raul

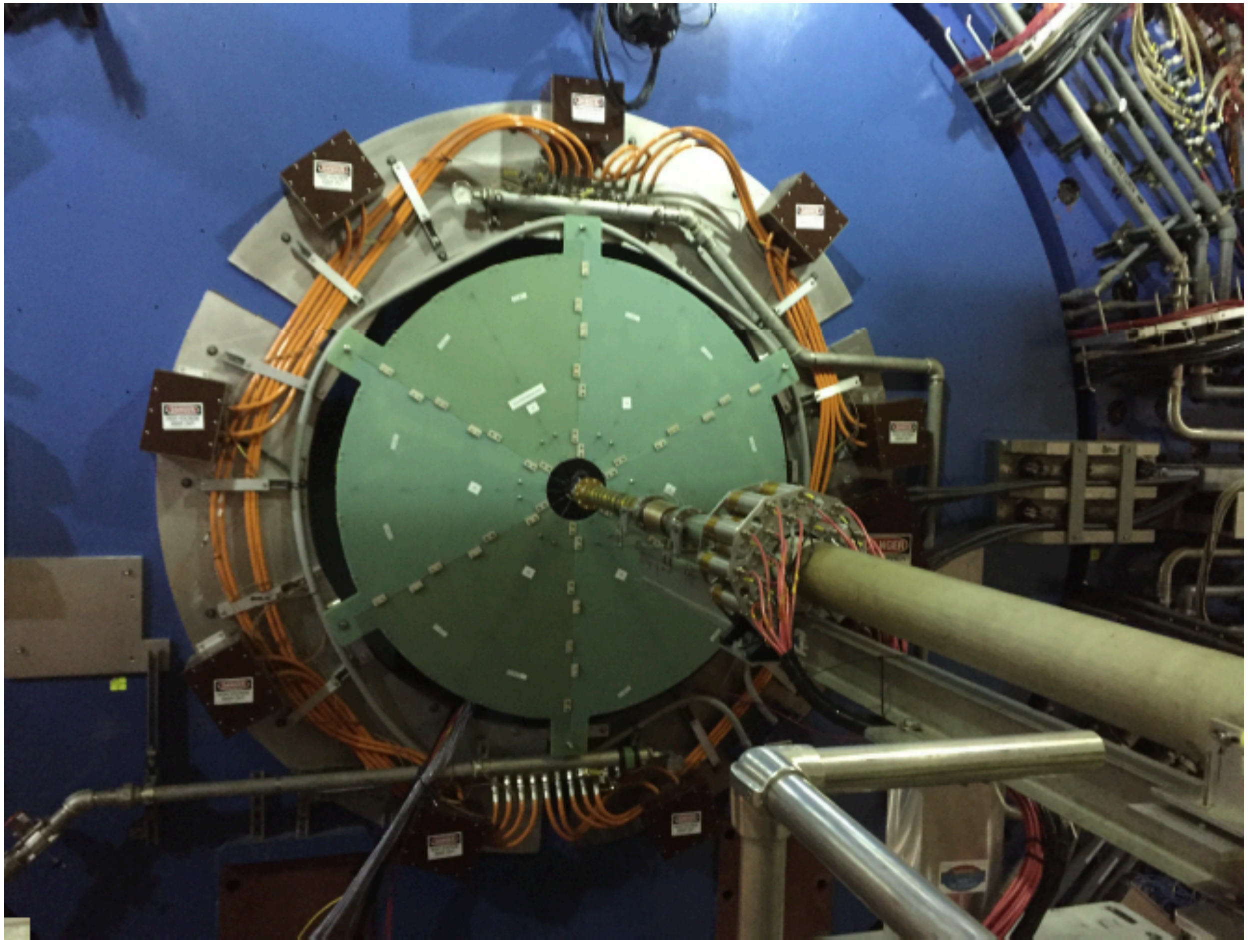
• Two supersectors with attached clear fiber bundles.

Event Plane Detector: West



- Full EPD installation on West side of STAR.

Event Plane Detector: East



- Full EPD installation on East side of STAR.

Conclusions

- We need to focus on baryon stopping effects!

- The Event Plane Detector is the first BES-II upgrade detector being fully operational. First data with full detector will be taken in the upcoming days.

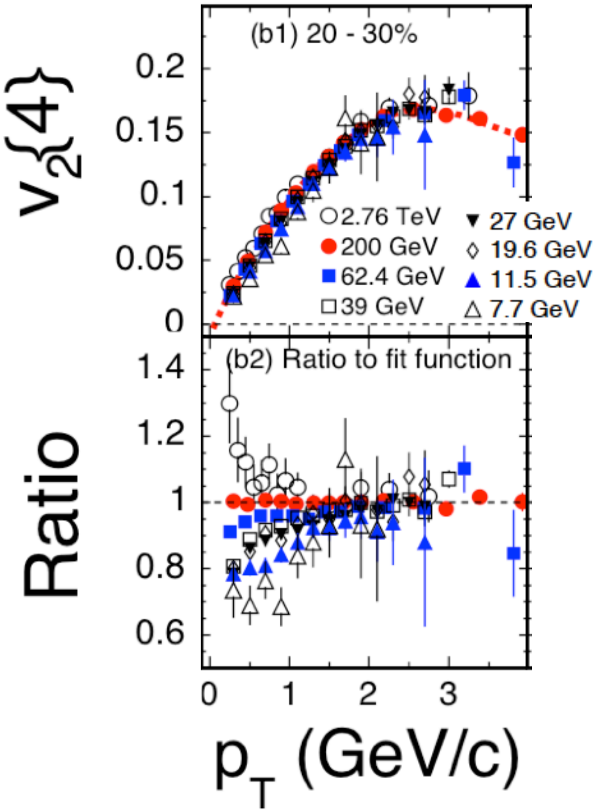
Thank you Helmut!

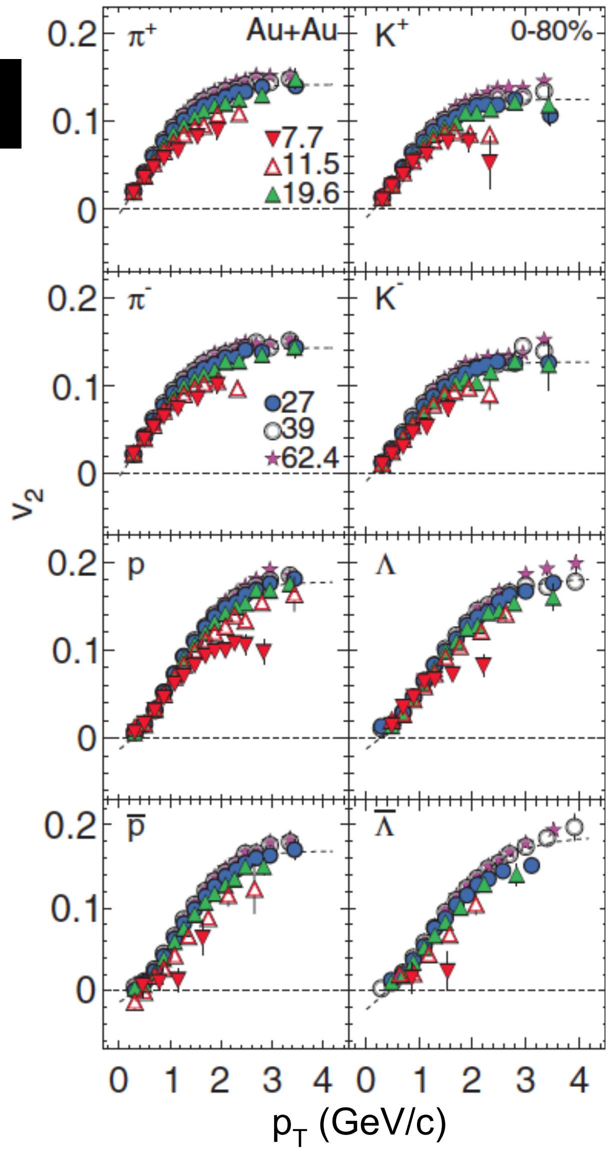
San Francisco 24.11.2013


Thanks!

Energy Dependence of Elliptic Flow (v_2)

STAR: Phys.Rev. C86, 054908 (2012)
ALICE: Phys. Rev. Lett. 105, 252302 (2010)





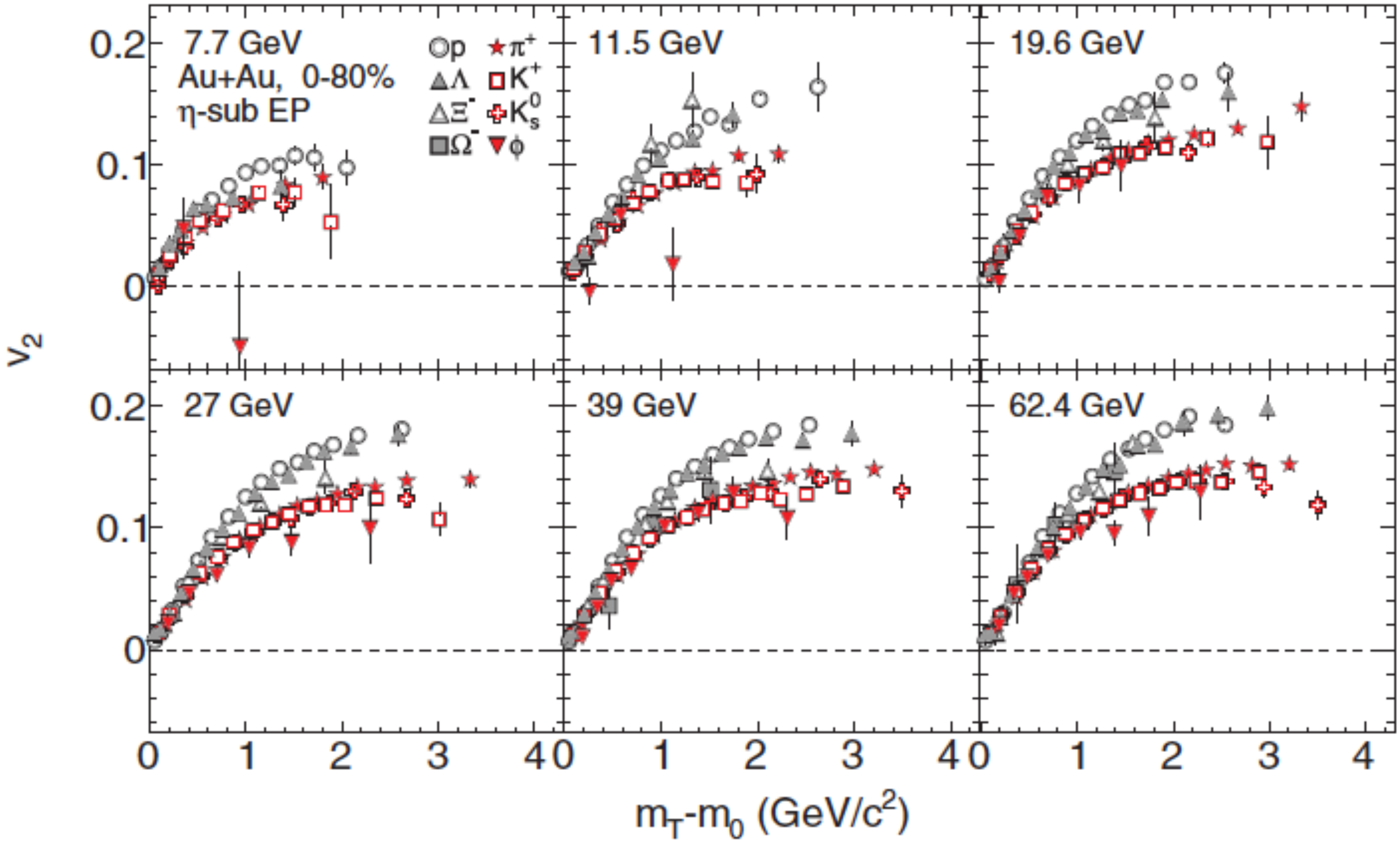
Phys. Rev. C 88, 014902 (2013)

- Large (similar) collectivity at all energies?

- But particle composition changes with energy!
  → v_2 increases for every particle
- What about rare particles at low energies?
- Conclusions for hydro, η/s?

Energy dependence of v_2 Splitting

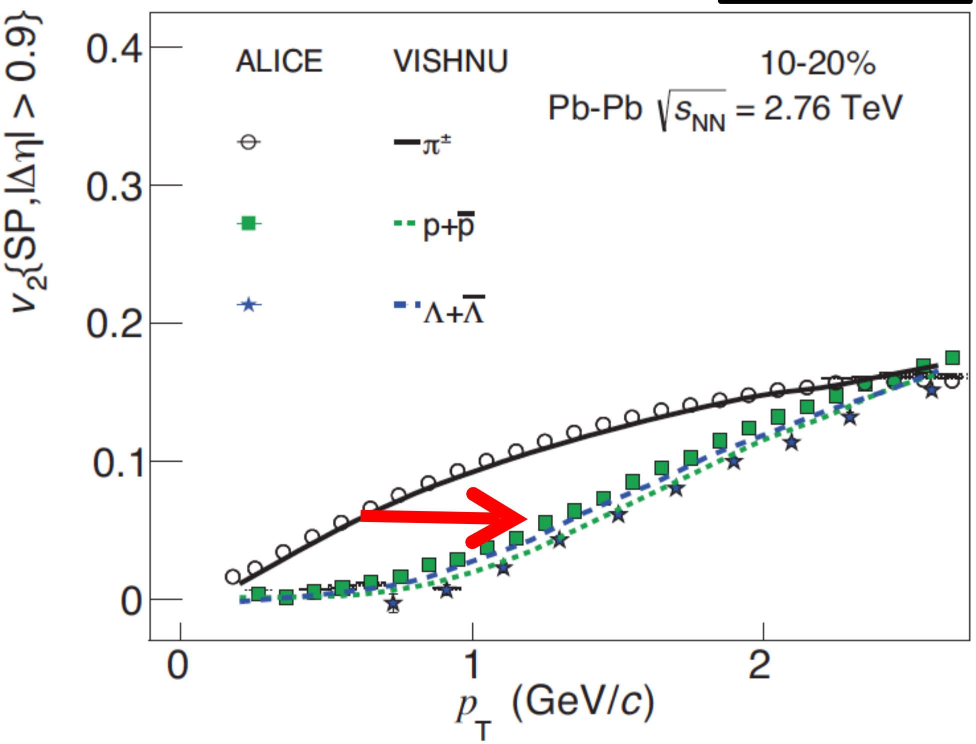
Phys. Rev. C 88, 014902 (2013)



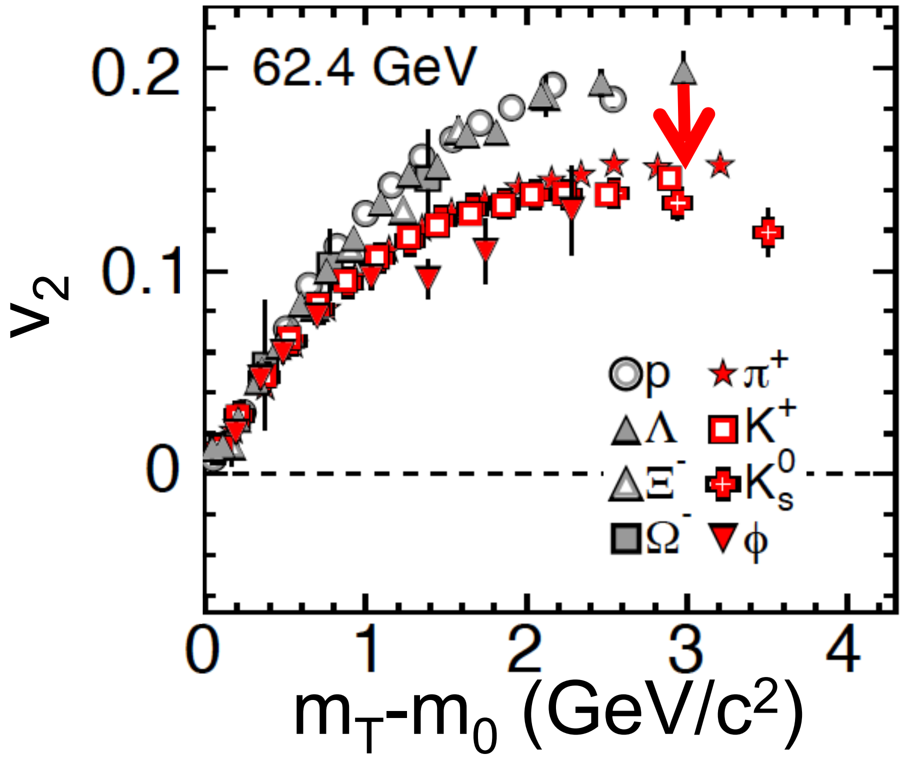
- Very similar trend for all energies!
  → no clear signature for a change of the phase
  → QGP at $\sqrt{s_{NN}}$ = 7.7 GeV?

Elliptic Flow

arXiv:1405.4632

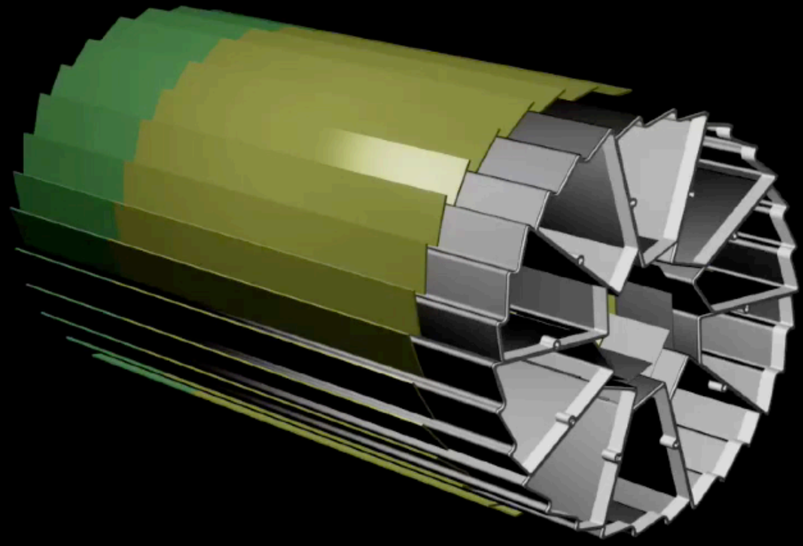


Phys. Rev. C 88, 014902 (2013)



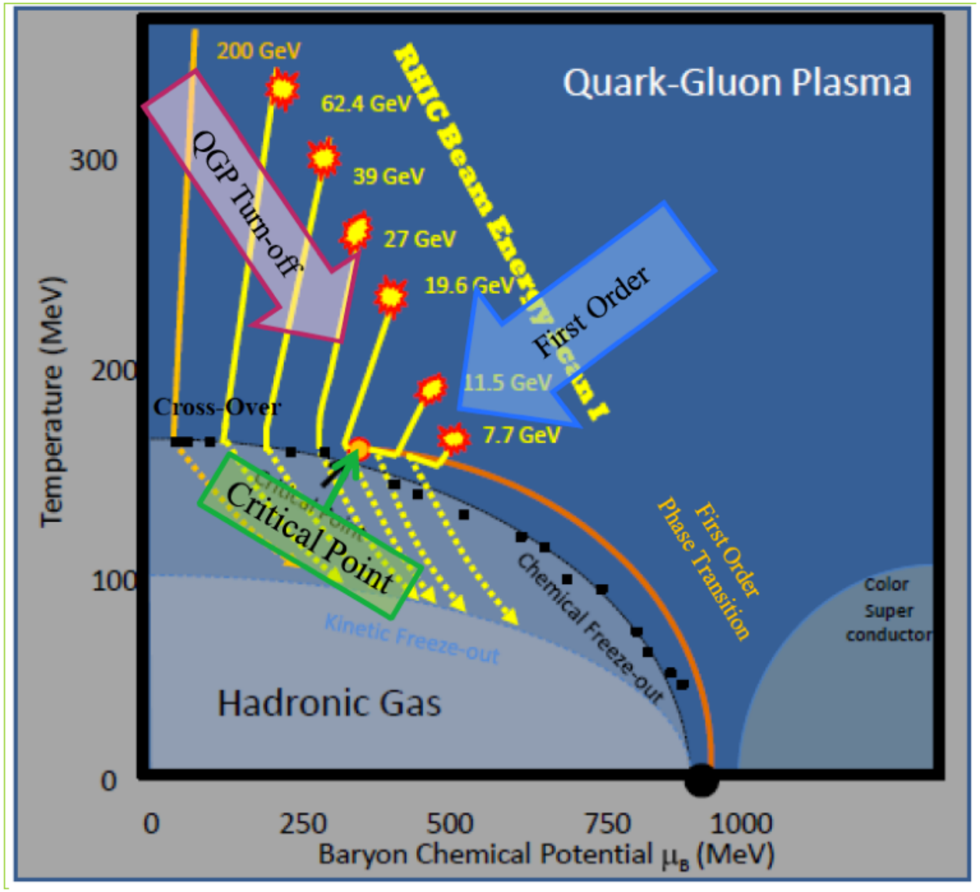
- **Mass ordering** of v_2 at low p_T, very good description with viscous **hydrodynamics**
  → very small shear viscosity
  → strongly interacting system
  → perfect liquid

- **Baryon-meson** splitting at large transverse kinetic energies (m_T-m_0)
  → indicative for partonic degrees of freedom (QGP)
  → does it disappear at lower energies (hadronic phase)?



The Beam Energy Scan Program at RHIC

D. Cebra



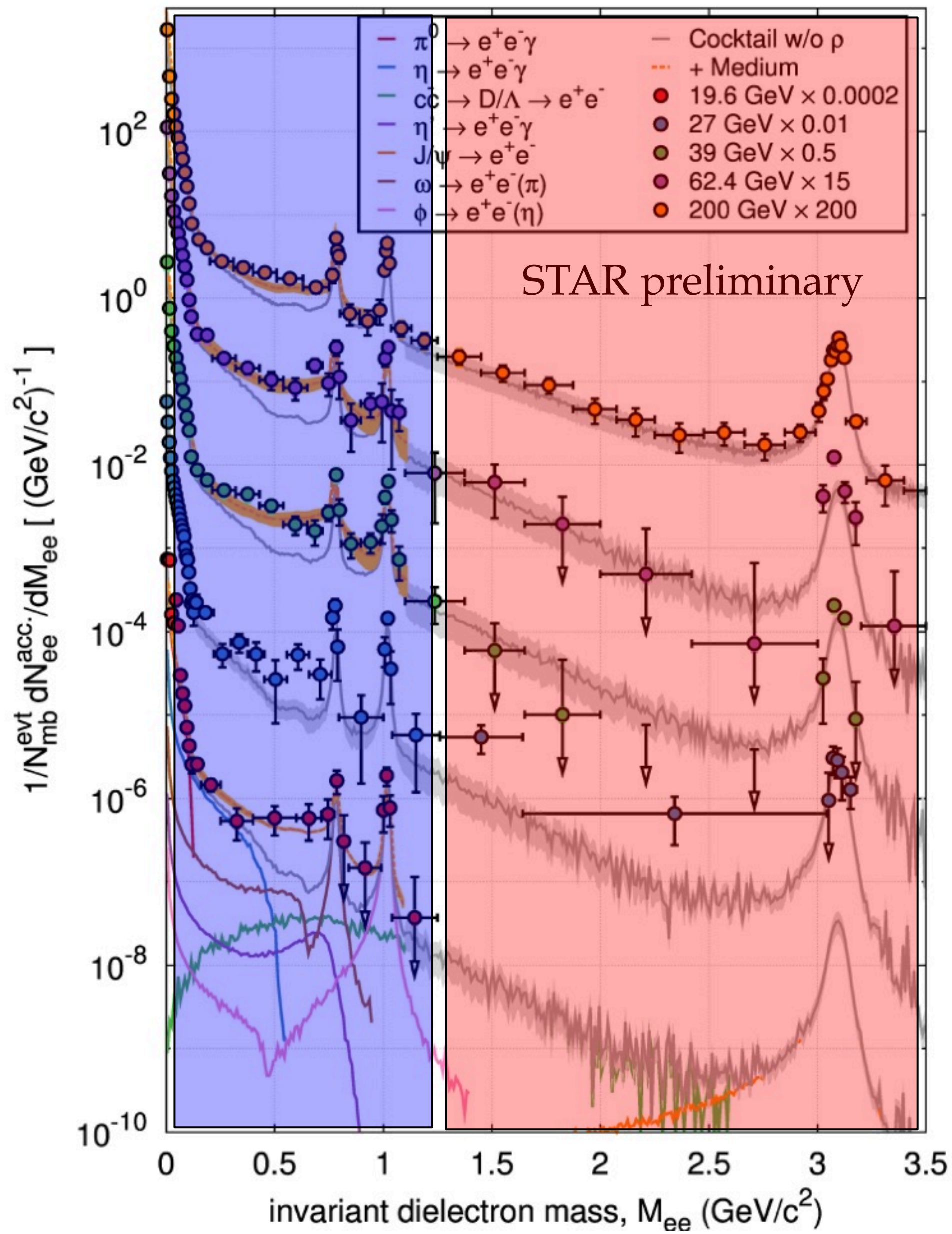
- **Energy scan to experimentally vary T and μ_B:**

→ Started in 2010 at RHIC, 7 different energies for the collision system Au+Au

→ Reaction fireball changes T and μ_B during expansion/cooling phase

→ Find signatures for phase transition and QCD critical point

Rare Probes: Di-Electron Spectra



Good probes of created matter
→ No strong interaction!

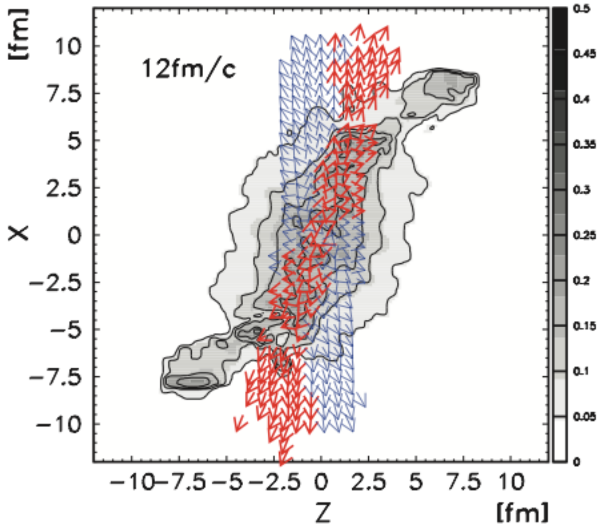
- Fair agreement of di-lepton data and cocktail over the whole mass range for all energies
- The scenario of a broadened rho spectral function can consistently describe the LMR excess yield from $\sqrt{s_{NN}}$=19.6 up to 200 GeV

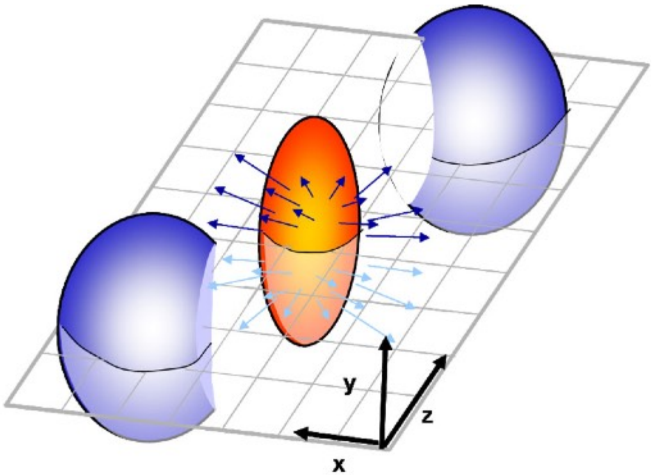
- Charm cross sections not known at lower energies
- Chiral symmetry restoration?
- What about QGP radiation?
  → We need **MUCH** more statistics at the lowest energies!

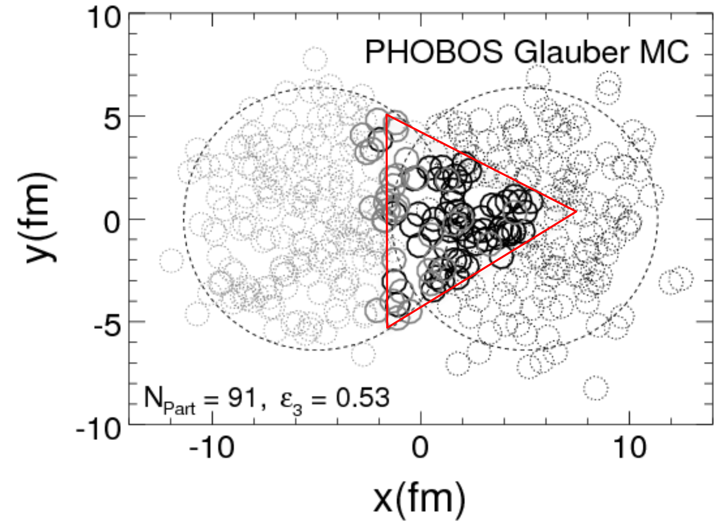
R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

Ralf Rapp → yesterday
Xangbu Xu → next talk

Flow: v_1, v_2, v_3







Directed flow (**v_1**)
- Sensitive to EoS

Elliptic flow (**v_2**)
- Sensitive to initial spacial anisotropy

Triangular flow (**v_3**)
- Sensitive to initial state fluctuations

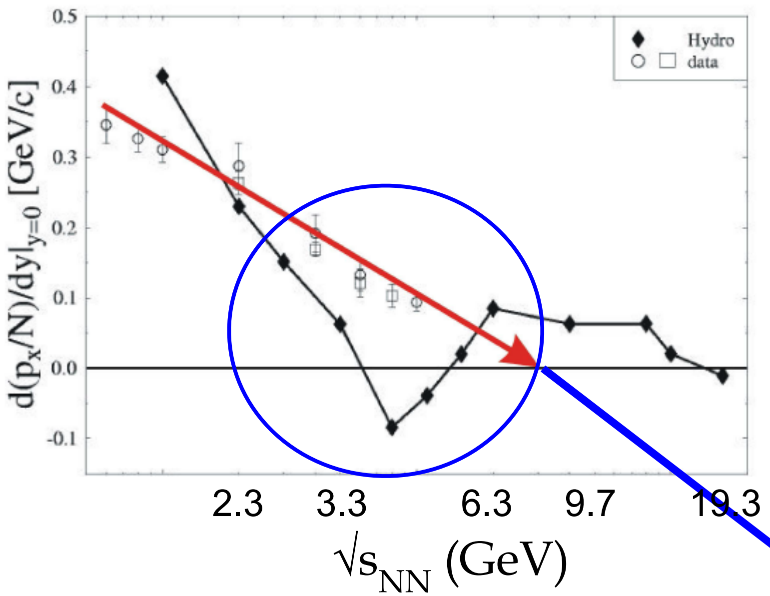
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2 v_n \cos\left[n(\phi-\Psi_R)\right]\right)$$

- It is important to understand ALL harmonics!

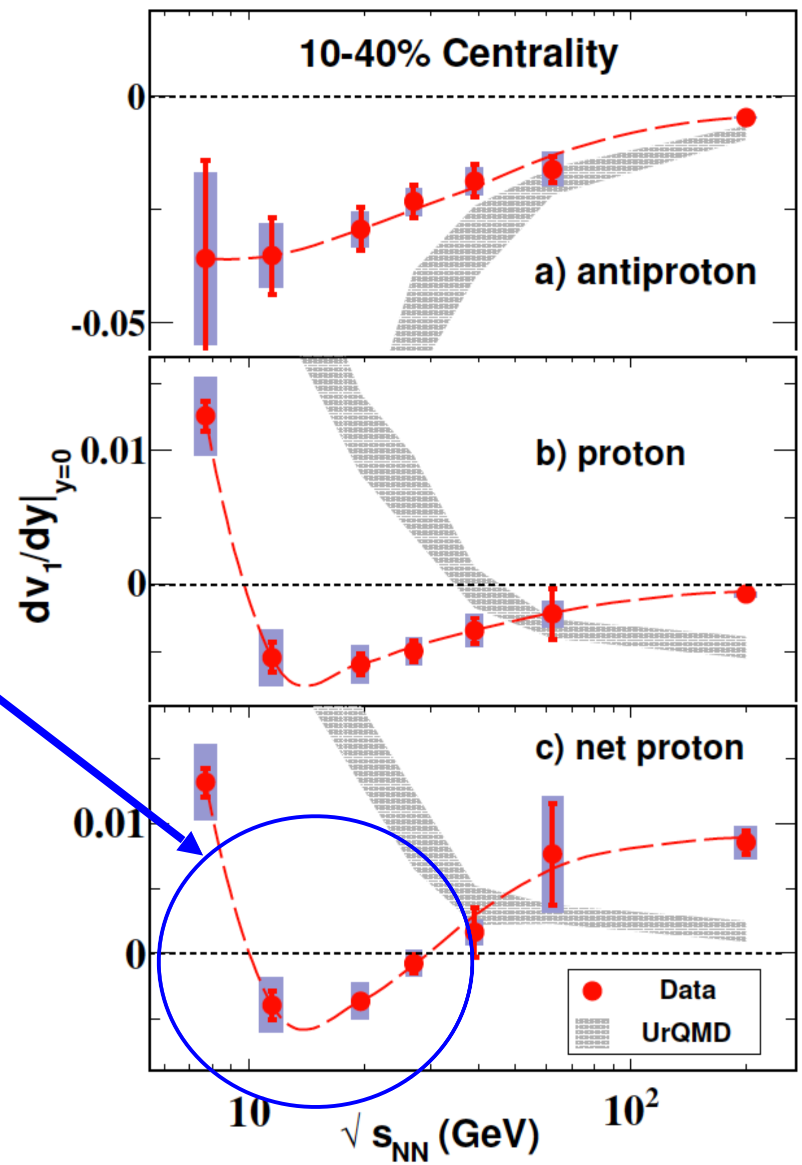
Directed Flow (v_1)

The hunt for the first order phase transition

H. Stoecker, Nucl. Phys. A 750 (2005)



PRL, 112 (2014) 162301



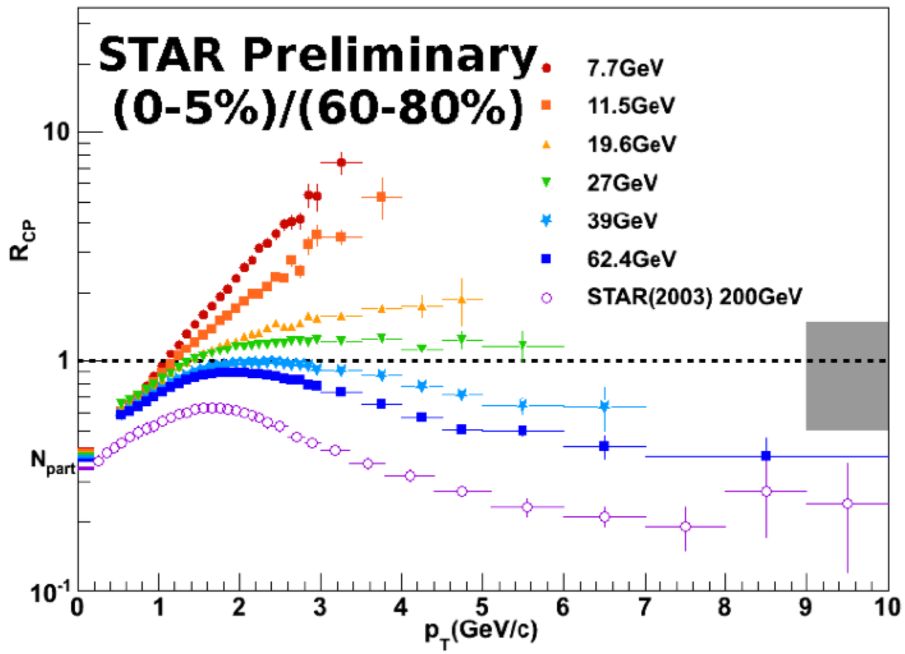
- Dip in net-proton dv_1/dy reproduces theory prediction
  → Softest point of EoS?

- Rising and falling trends of protons and anti-protons qualitatively reproduced by UrQMD
- Dip at different position than model
  → trend correlated to baryon stopping?

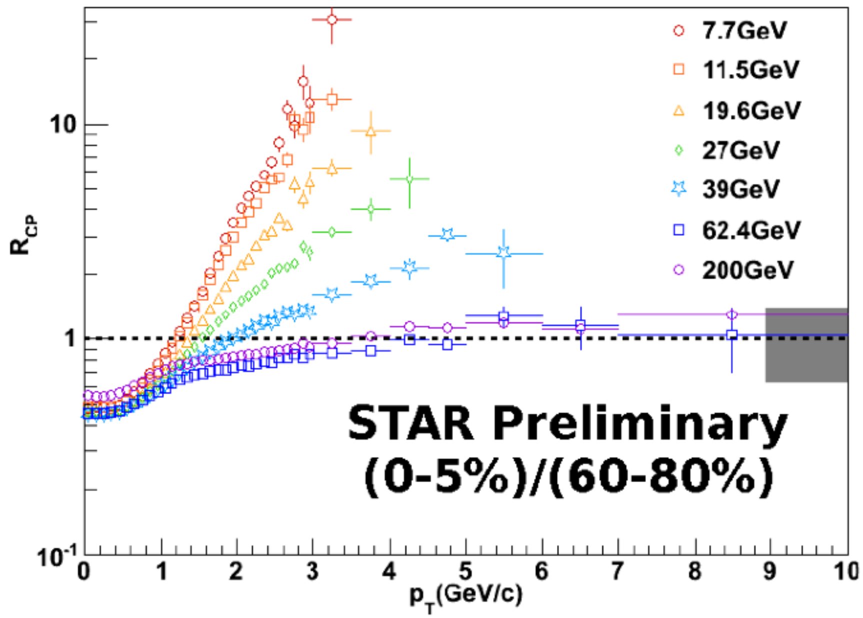
Rare Probes: High p_T R_{CP}

RCP: "Normalized p_T spectra ratio Central to Peripheral"

Data



Hijing



QM 2014 poster

- R_{CP} suppression at high pT for $\sqrt{s_{NN}}$ >= 39 GeV
  → signature for partonic energy loss
- R_{CP} is increasing to lower energies
  → change of energy loss?

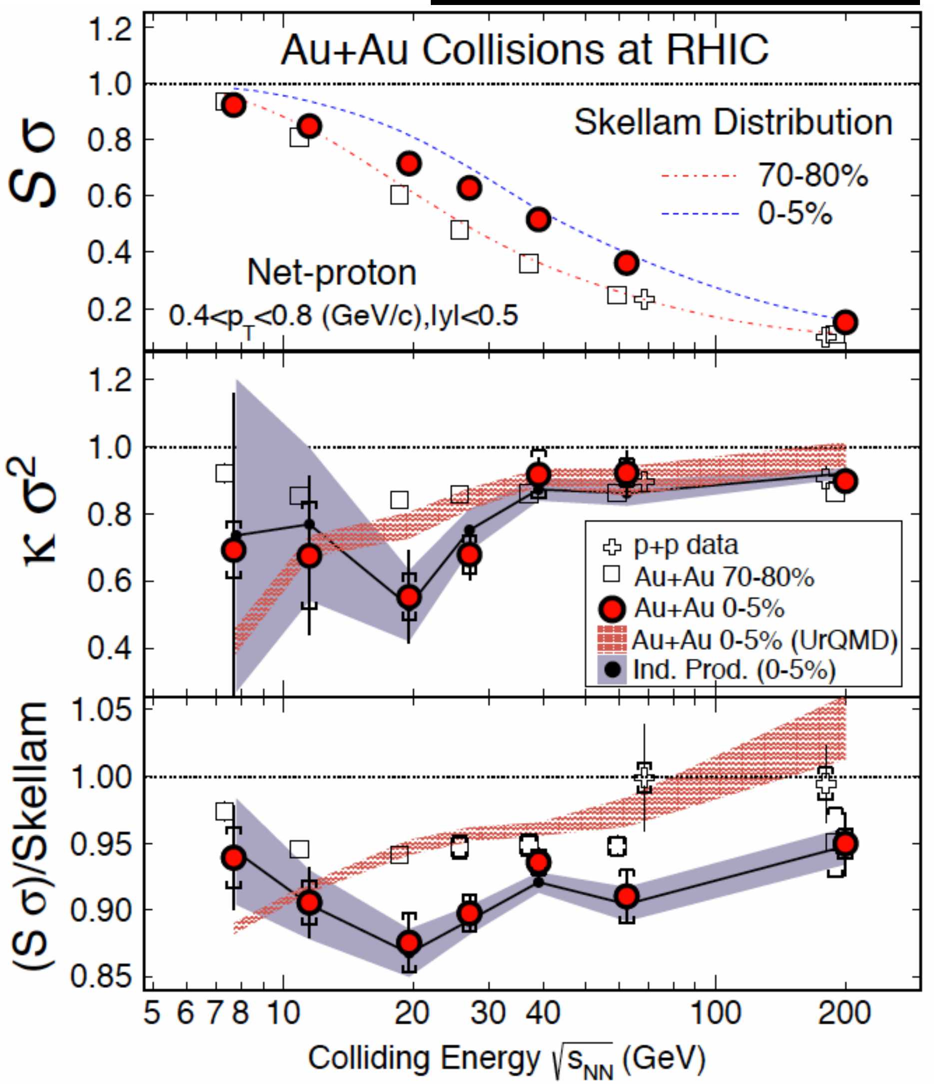
- Radial flow is changing a lot over the BES energy range
- Hijing calculation with Cronin effect but without partonic energy loss shows similar trends
- High p_T particles not measured at lower energies

Higher Moments of Net-Protons

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

The hunt for the QCD critical point

Phys. Rev. Lett. 112 (2014) 32302



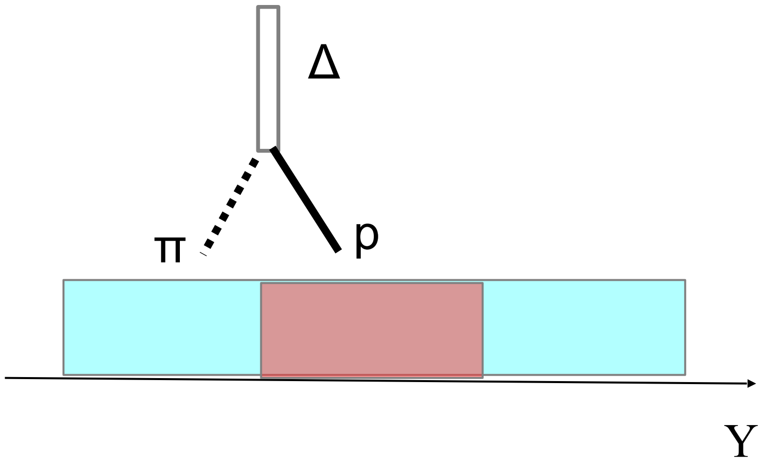
- Net-protons as proxy for net-baryons (conserved quantity)
- Non-monothonic behavior → hint for CP
- Hints of a structure around 19.6 GeV

- UrQMD model shows similar trends as data and similar magnitude at 0-5%
- More statistics and better control of systematic is needed to make a conclusion
- Additional energies needed
  → 14.5 GeV already taken by STAR/PHENIX
- …

Rare Probes: Higher order Moments

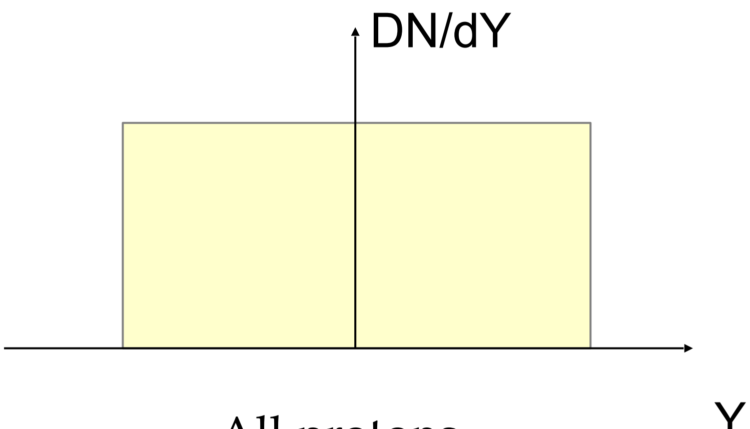
Higher order moments more sensitive to tails
àBetter observable for critical point measurement
à Much more statistics needed

Graphics: Volker Koch

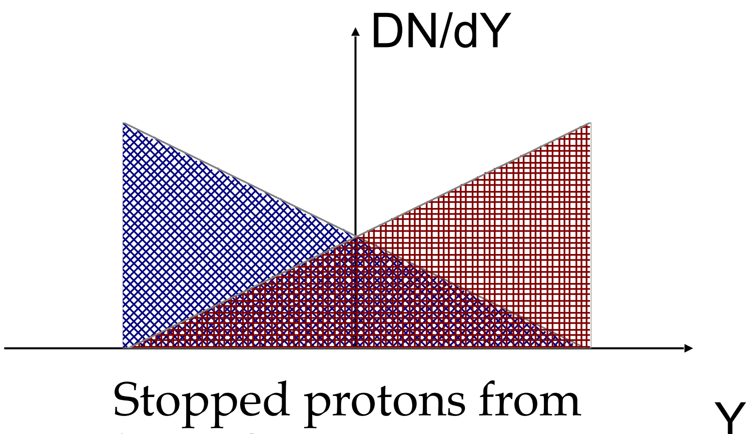


Autocorrelations:
àCentrality detector needed independent in acceptance from main detector!

Baryon stopping:
àFluctuations might bias critical point measurement

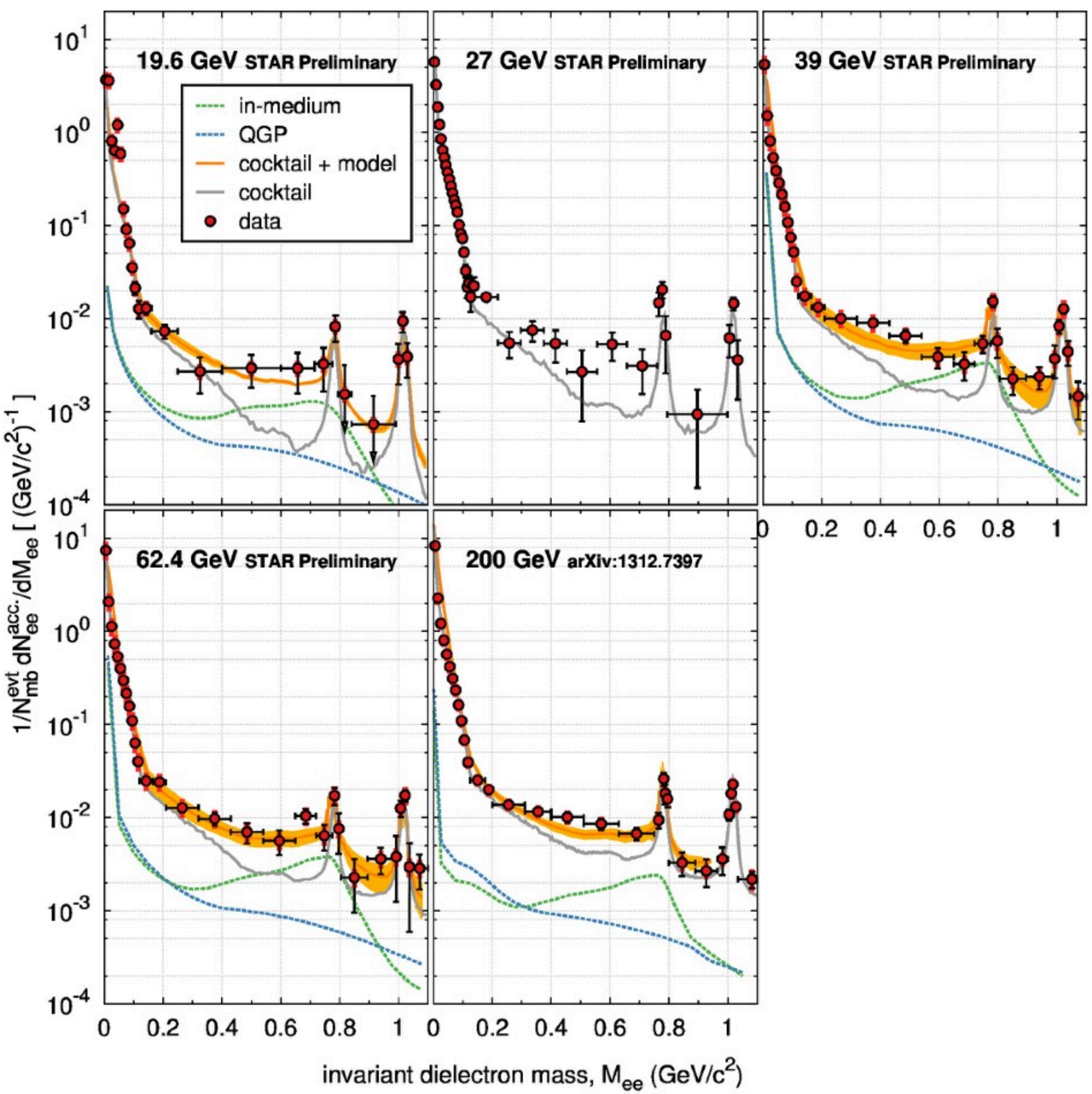


All protons



Stopped protons from beam/target

Di-Electron Spectra: Low Mass Region



R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

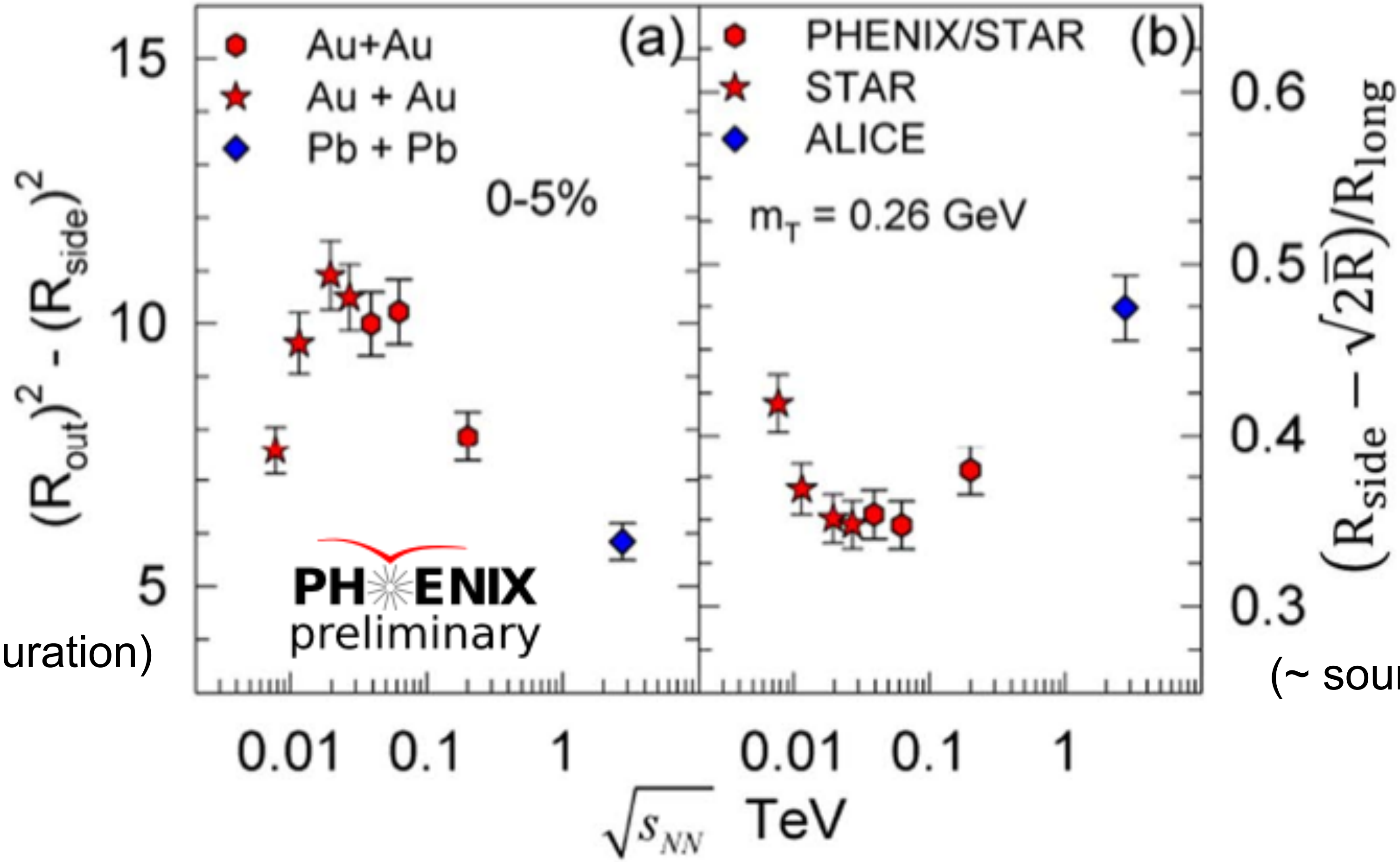
- The scenario of a broadened rho spectral function can consistently describe the LMR excess yield from $\sqrt{s_{NN}}$=19.6 up to 200 GeV

- What about the p_T dependence of model/data? (first results shown)
- Systematic errors for model?
- Chiral symmetry restoration?

Emission Duration and Expansion/Lifetime

The hunt for the first order phase transition

QM 2014



(~ emission duration)

(~ sound speed)

- Non-monotonicity in $(R_{out})^2 - (R_{side})^2$
- R_{side}/R_{long} indicative of expansion/lifetime

l Softest point of EoS?
l Indication for CEP?

Requested Statistics for BES II

Table 3. Beam Energy Scan Phase-II proposal for 22 weeks of RHIC running in each of the years 2018 and 2019.

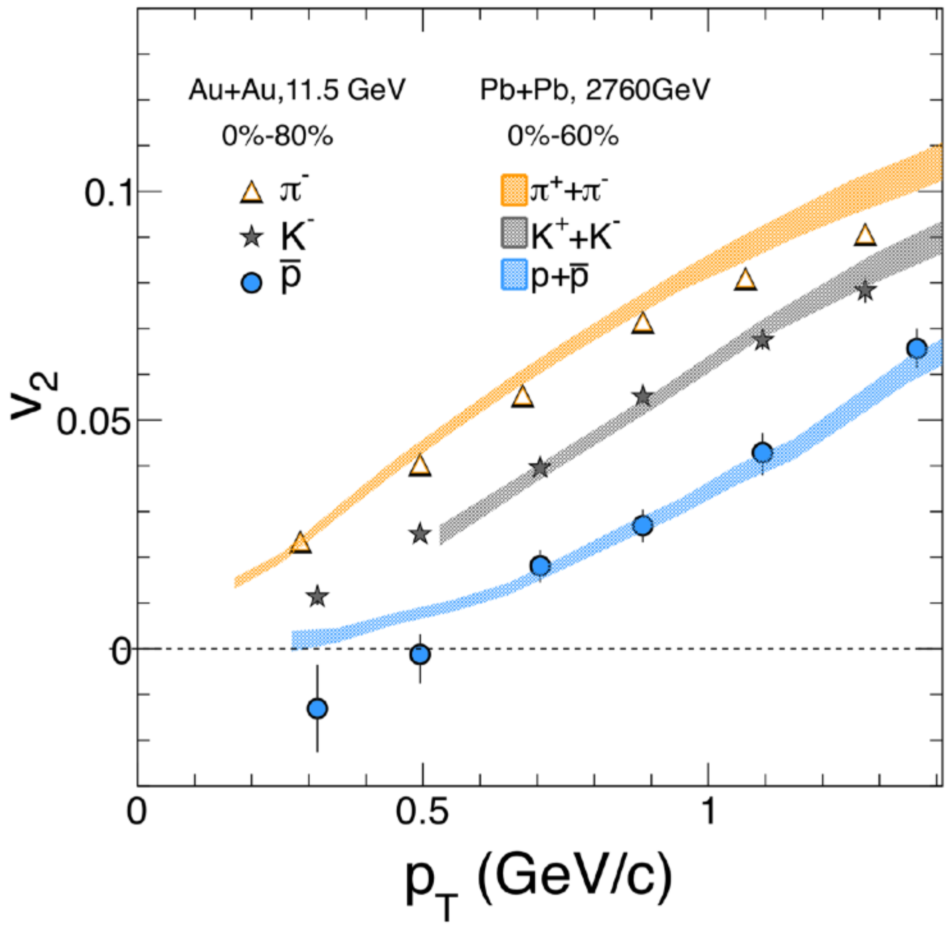
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% Central Collisions	420	370	315	260	205
BES-I (Million Events)	4	–	12	20	36
BES-I Event Rate (Million Events/Day)	0.25	0.6	1.7	2.4	4.5
BES-I Int. Luminosity (1×10^{25}/cm^2 s)	0.13	0.5	1.5	2.1	4.0
e-Cooling Luminosity Improvement Factor	4	4	4	8	15(4)
BES Phase-II (Million Events)	100	160	230	300	400
Required Beam Time (Weeks)	14	9.5	5.0	2.5	4.0+

*From STAR BES II white paper

- Factor 25 more statistics (10^8 events) at $\sqrt{s_{NN}}$ = 7.7 GeV (~ SIS300 energy)

What is going on with Flow?

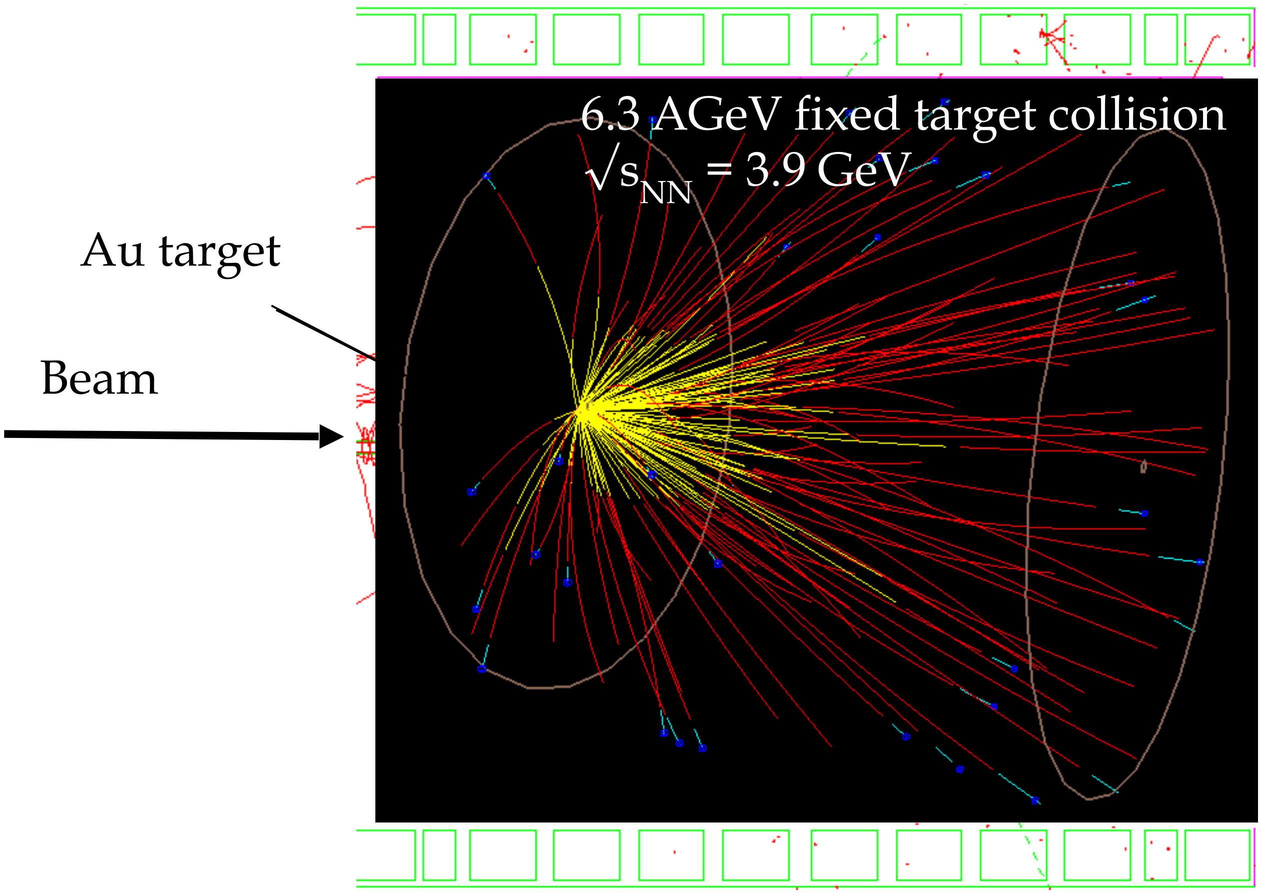
STAR: Phys. Rev. C 88, 014902 (2013)
ALICE: arXiv:1405.4632

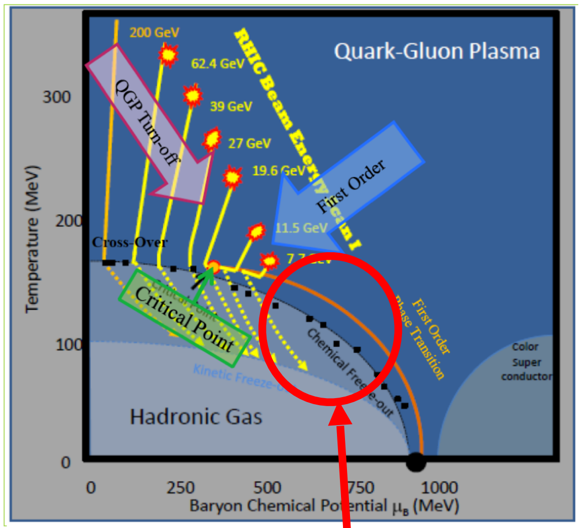


- Anti-particle v_2 at low energies (SIS100/300 regime) seems to be very similar to v_2 at LHC energies ($\sqrt{s_{NN}}$ = 2760 GeV)!
- More detailed studies at energies below $\sqrt{s_{NN}}$ = 11.5 GeV are needed

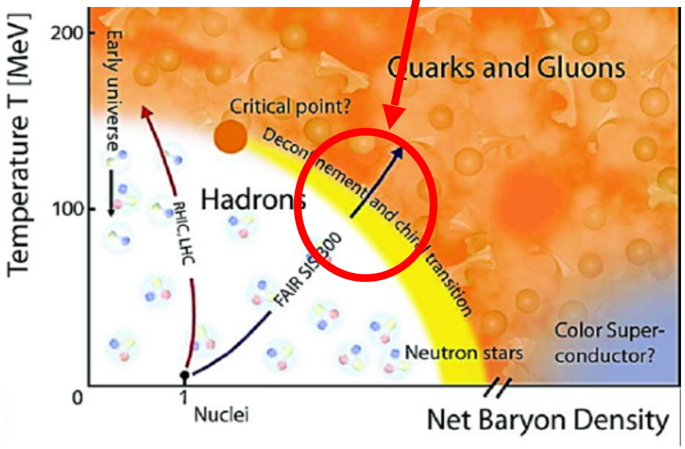
Fixed Target Program for BES II

STAR QM 2014



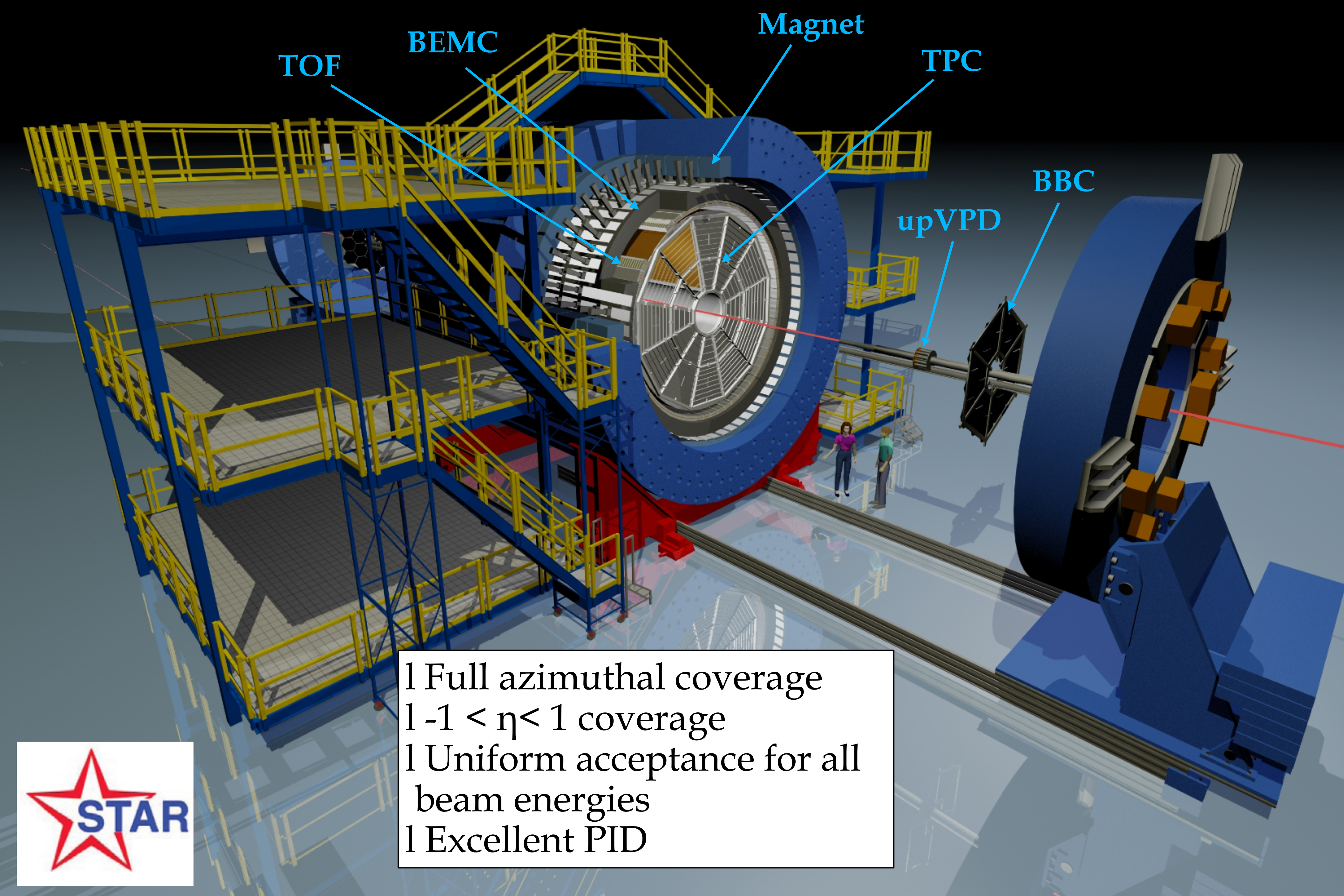


Access to low T, high μ_B



- Fixed target program extends STAR's physics reach to region of compressed baryonic matter
- Simultaneous run with collider mode (ions from the halo) **but** much lower luminosity compared to CBM!

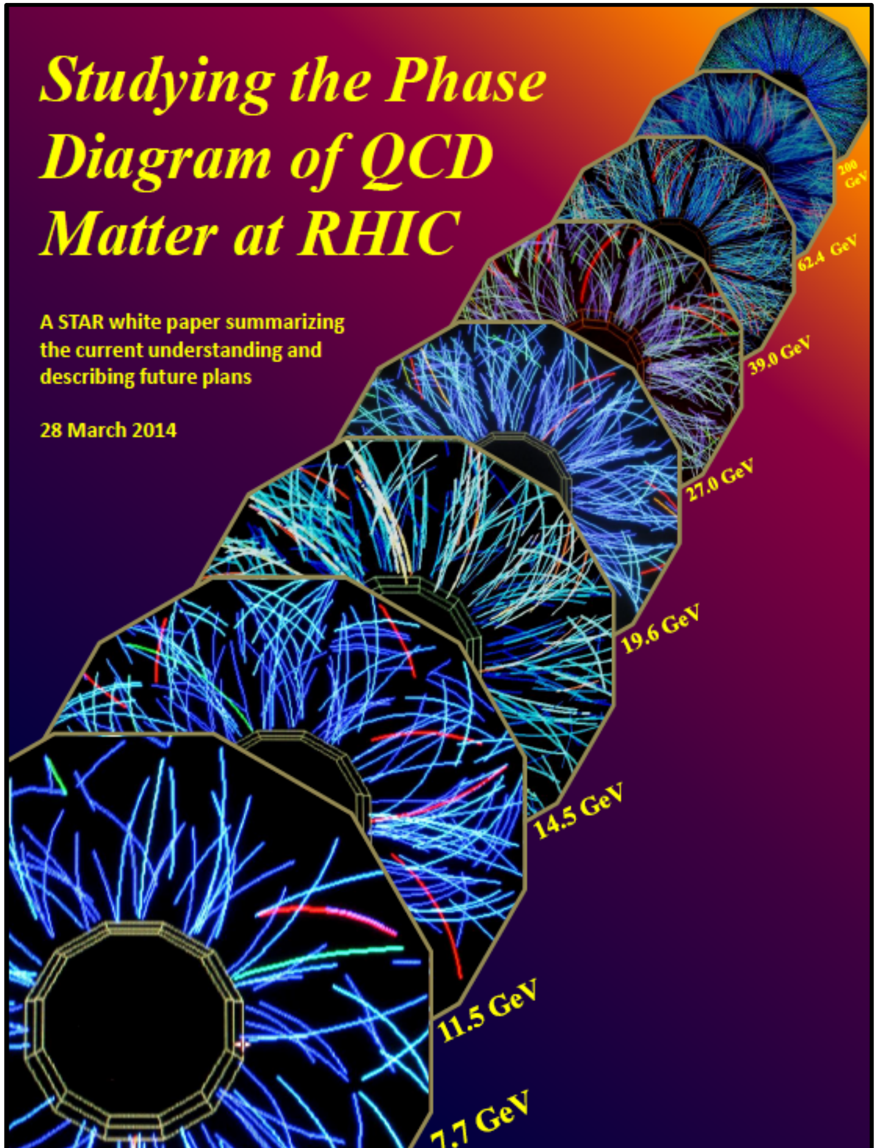
The Solenoidal Tracker At RHIC (STAR)



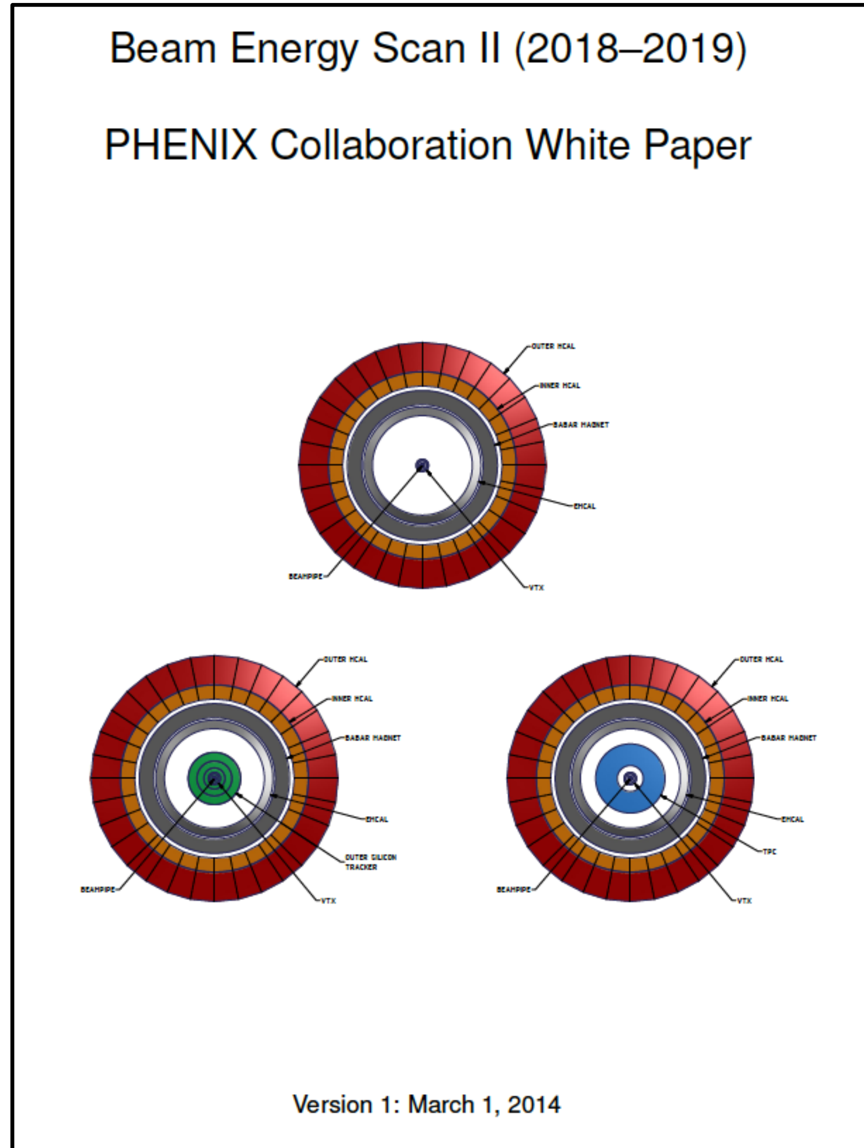
- Full azimuthal coverage
- $-1 < \eta < 1$ coverage
- Uniform acceptance for all beam energies
- Excellent PID

RHIC BES Phase II White Papers

STAR



PHENIX



BES II workshop: http://besii2014.lbl.gov/Program/bes-ii-talk-files