The Beam Energy Scans at RHIC: Results from BES-I Prospects for BES-II

Daniel Cebra

University of California, Davis

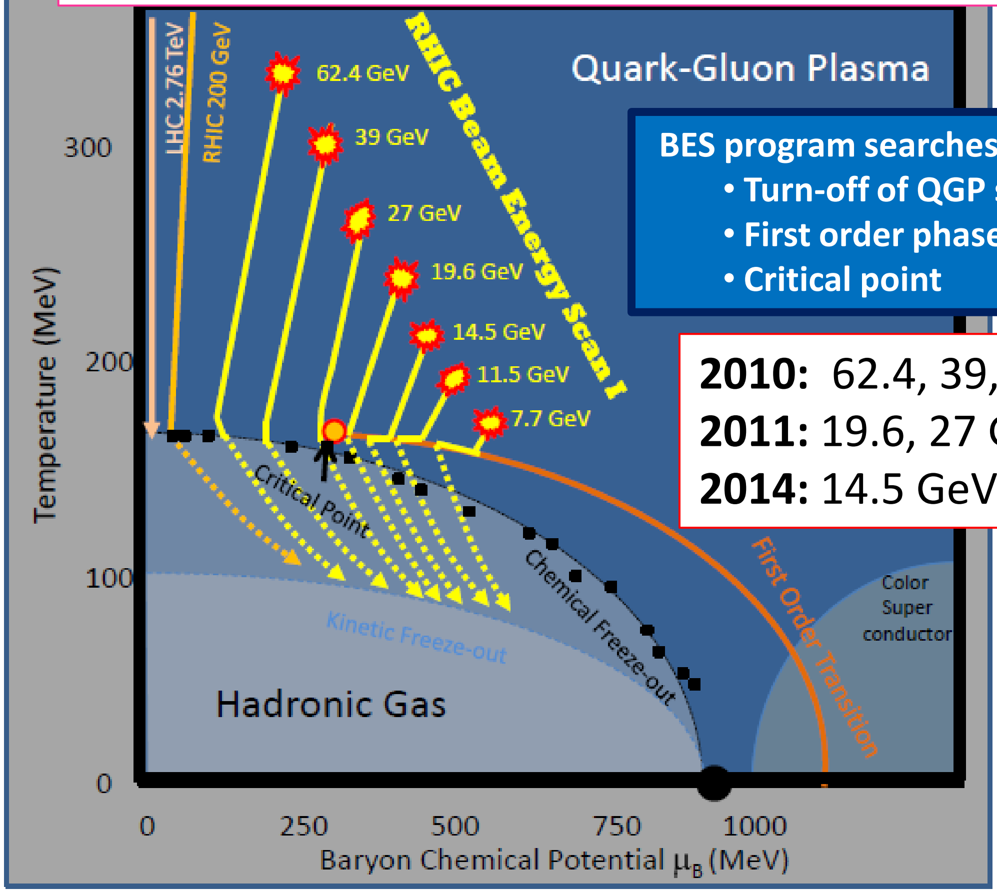
for the STAR Collaboration

34th Reimei Workshop
J-PARC, Tokai, Japan

Beam Energy Scan I (2010-2011, and 2014)

Exploring the Phase Diagram of QCD Matter

What was known prior to the RHIC Beam Energy Scan Program?
1) High Energy Heavy-ion Collisions → partonic matter
2) Highest energies → transition is a cross over
3) At increased μ_B, there might be a first-order phase transition
4) And if so, there should be a critical point



BES program searches for:
- **Turn-off of QGP signatures**
- **First order phase transition**
- **Critical point**

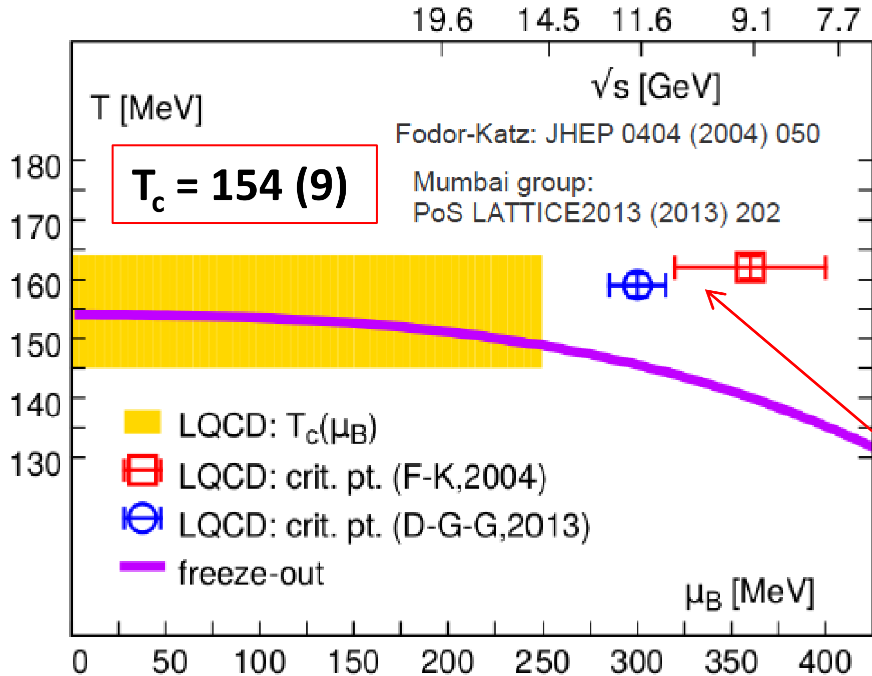
2010: 62.4, 39, 11.5, 7.7
2011: 19.6, 27 GeV
2014: 14.5 GeV

	Energy (GeV)	Chemical Potential μ_B	Pred. Temp. (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
AGS	4.7	573	114.6
AGS	4.3	602	108.8
AGS	3.8	638	100.6
AGS	3.3	686	88.9
AGS	2.7	752	70.4
SIS	2.3	799	55.8

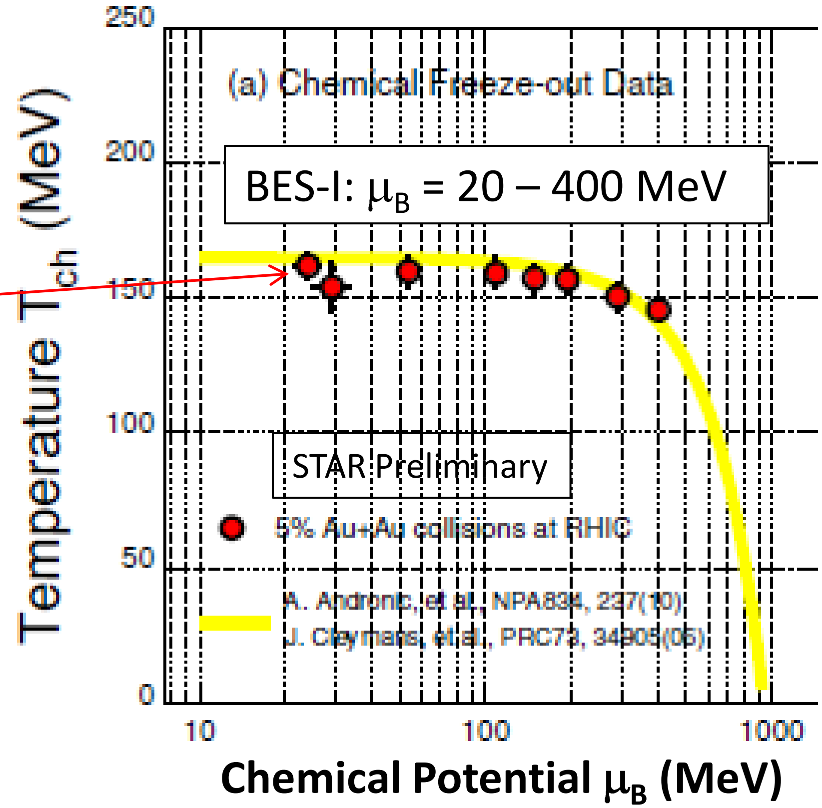
Setting the Scene

Using a statistical equilibrium model and the measured particle yields (π, K, p, Λ, Ξ, ϕ, Ω), one can estimate the location in the phase diagram.

$$N_i/V = \frac{g_i}{(2\pi)^3}\gamma_S^{S_i}\int \frac{1}{\exp\left(\frac{E_i-\mu_B B_i-\mu_S S_i}{T_{ch}}\right)\pm 1}d^3p$$



S.Mukhergee



BES-II White Paper

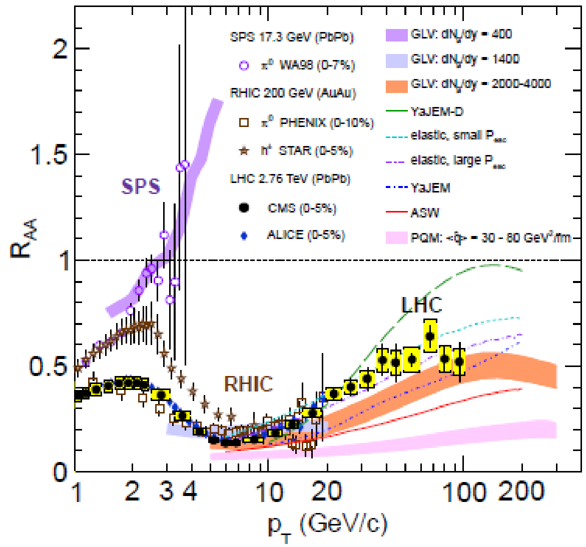
Some Lattice Gauge Theory predictions suggest that the low end of the BES-I scan one may find the critical point

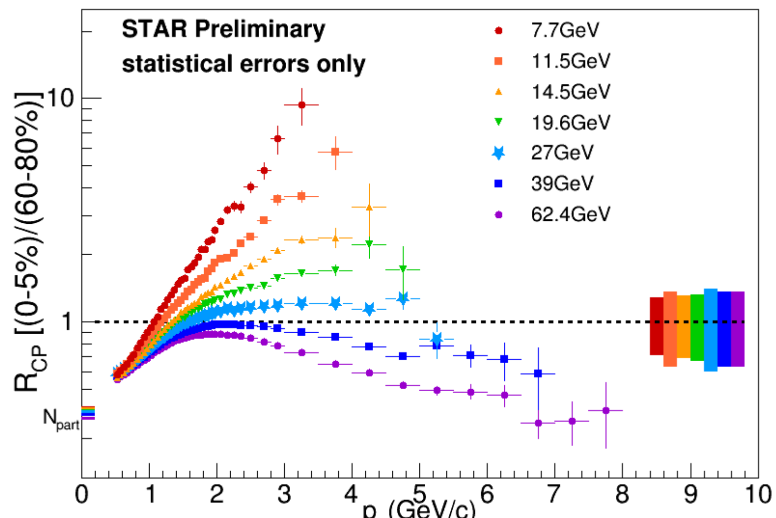
Disappearance of QGP Signatures - R_{CP}

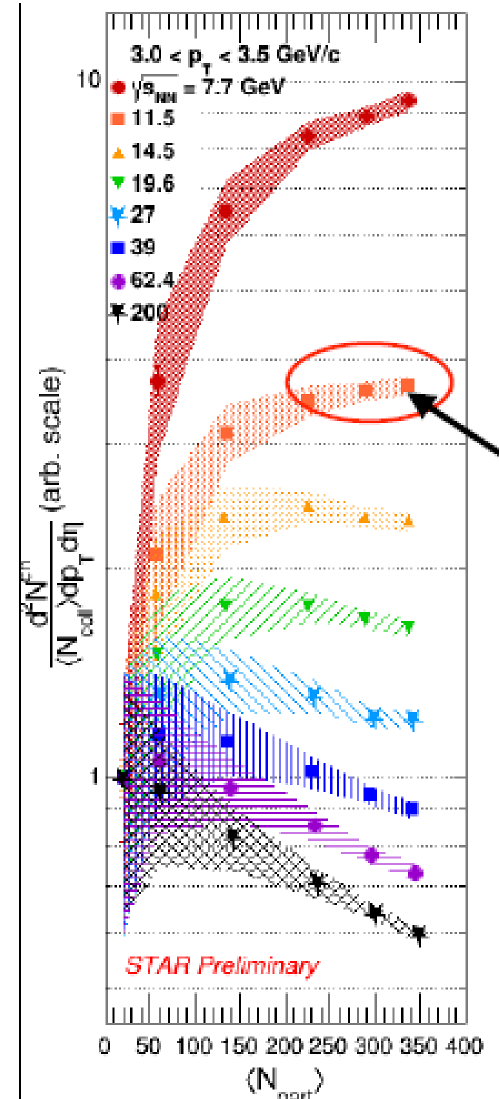
- R_{CP} for hadrons and for identified particles can provide a measure of partonic energy loss in the medium.

- Clear evidence of suppression at the higher collsions energies

- No evidence of high p_T suppression below 14.5 GeV ➔ necessary, but not suffiicient







Other QGP Signatures:

- Elliptic flow of phi meson
- Balance Functions
- v_2 of particles and anti-particles
- Chiral Magnetic effect
- Third harmonic of flow

Chiral Phase Transition

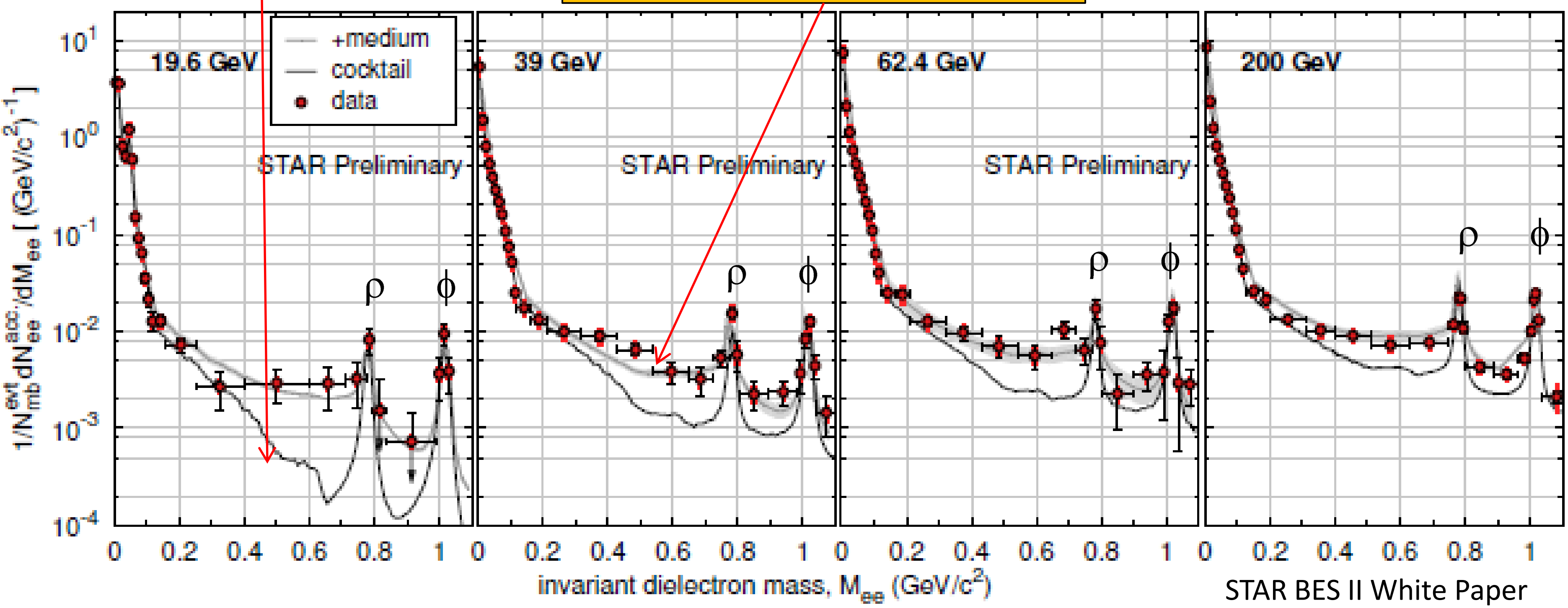
R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

Low Mass Region:
Black lines are the Cocktail (excluding the ρ meson)

Grey lines are in medium calculations from R. Rapp which include both HG and QGP components (including medium broadened ρ meson). Model is able to match the data

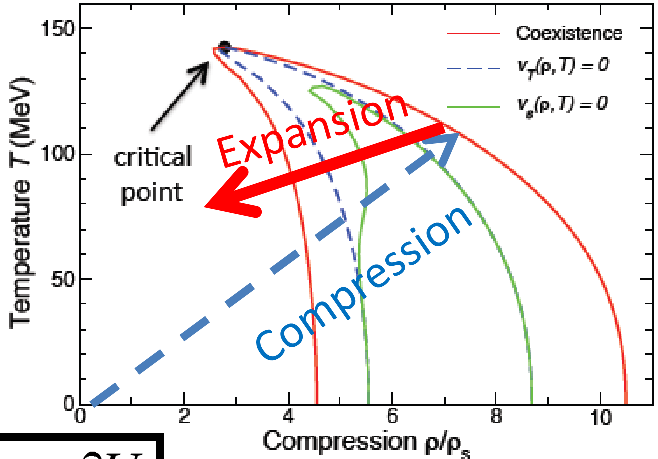
Low Mass Region:
Emission depends on T, total baryon density, and lifetime

PLB 750 (2015) 64



STAR BES II White Paper

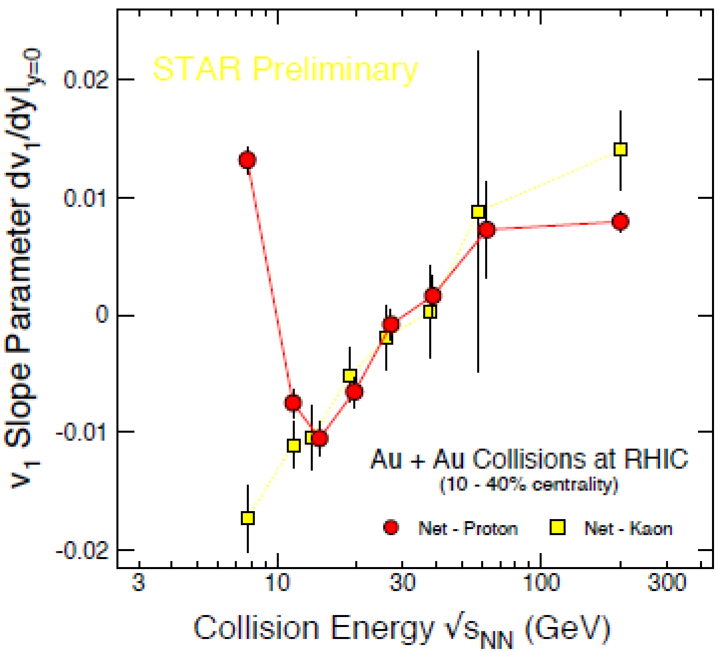
Search for 1st Order Phase Transition – v_1

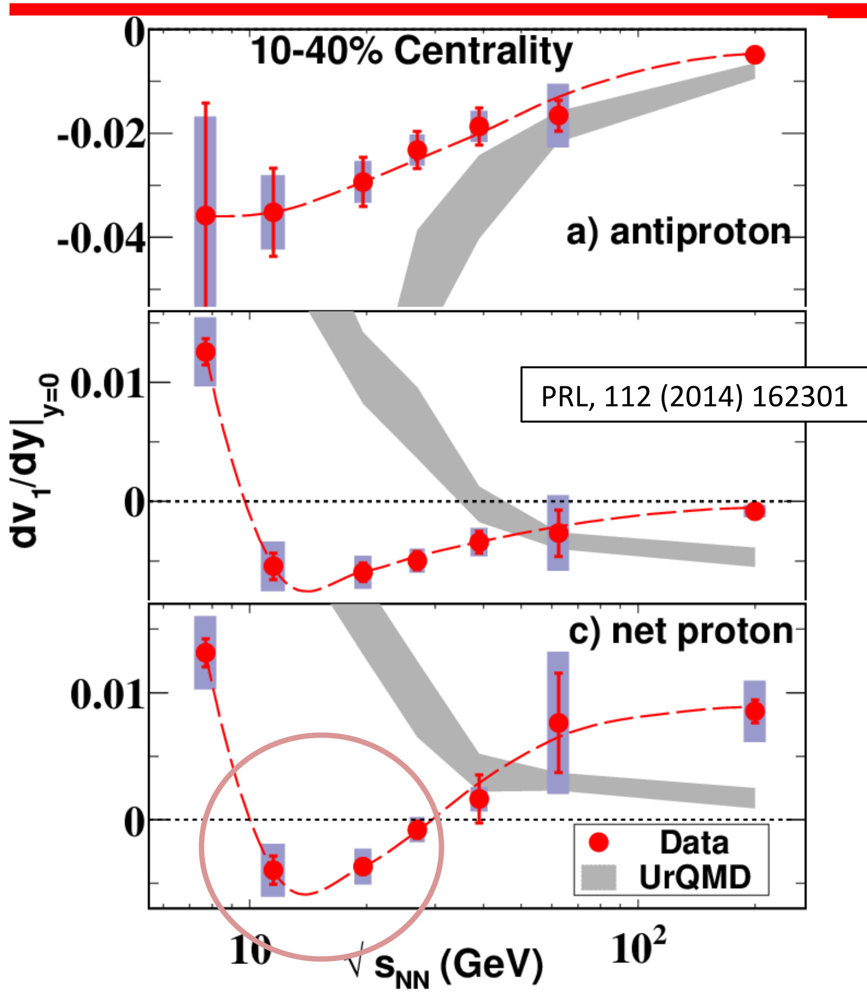


$$\mu = \frac{\partial U}{\partial N}$$

$v_T = 0$: isothermal spinodal

$v_s = 0$: isentropic spinodal



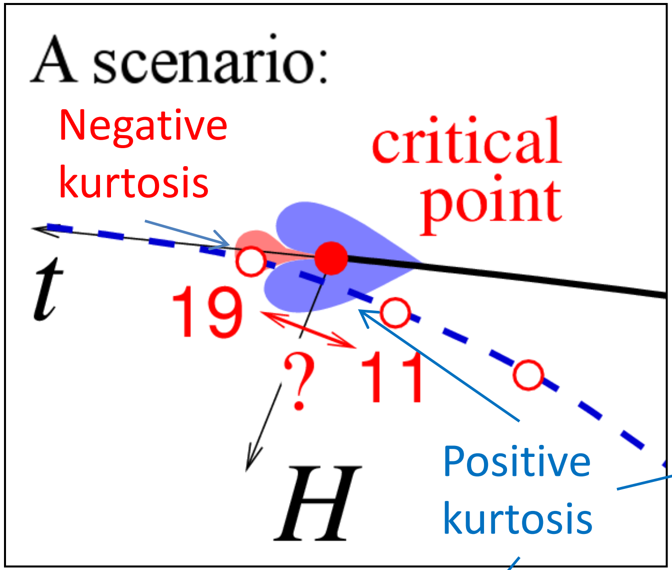


- First order phase transition is characterized by unstable coexistence region. This spinodal region will have the softest Equation of State
- v_1 is a manifestation of early pressure in the system

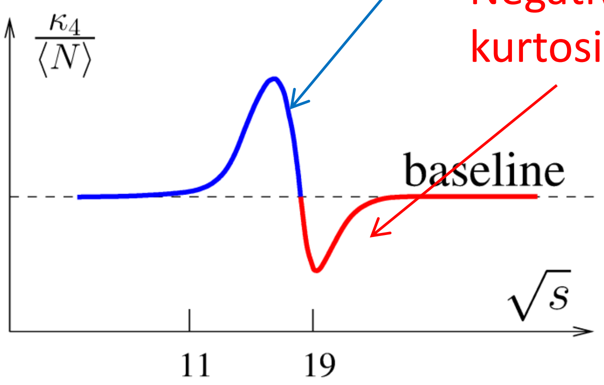
Other Signatures of Compression:

- Rapidity densities of charged particles
- HBT analyses

Search for the Critical Point – $\kappa\sigma^2$



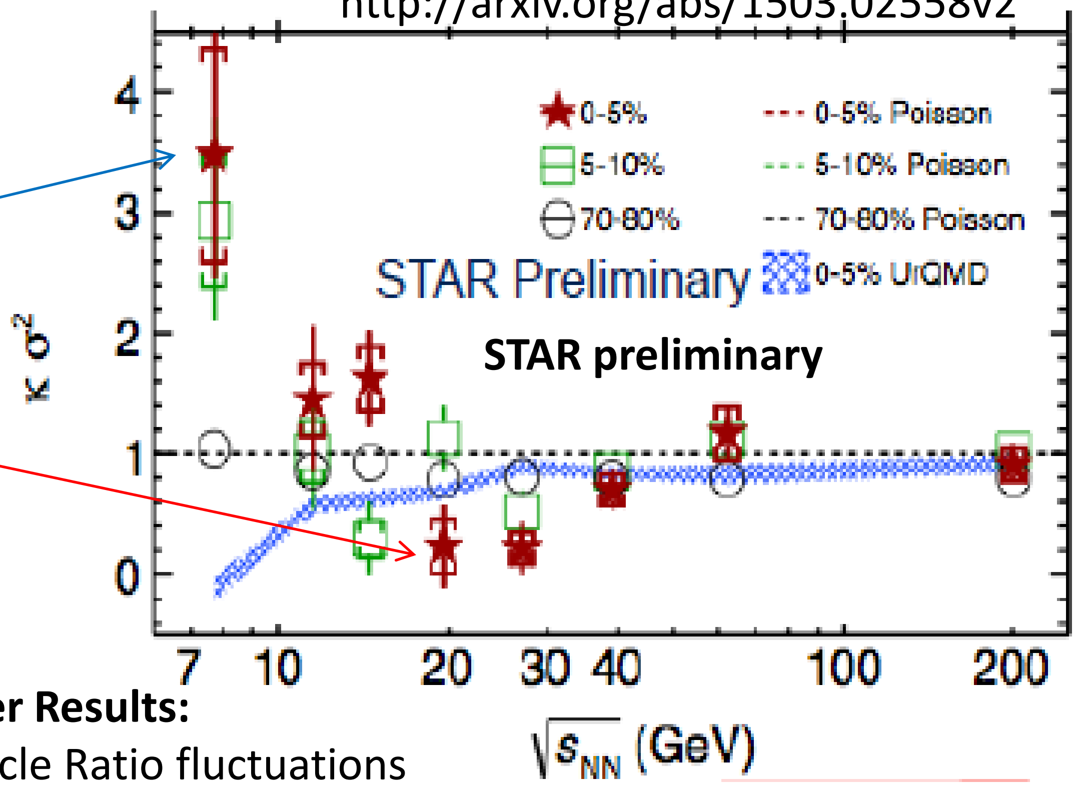
M. Stephanov



Negative kurtosis

STAR results show a fall and rise of the fluctuation variable

http://arxiv.org/abs/1503.02558v2



Other Results:

Particle Ratio fluctuations

Higher moments of pions and kaons

BES Phase I – What have We Learned

• The BES at RHIC spans a range of μ_B that could contain features of the QCD phase diagram.

• Signatures consistent with a parton dominated regime either disappear, lose significance, or lose sufficient reach at the low energy region of the scan.

• Dilepton mass spectra show a broadening consistent with models including hadron gas and quark-gluon plasma components

•There are indicators pointing towards a softening of the equation of state which can be interpreted as evidence for a first order phase transition.

• The higher moment fluctuation is sensitive to critical phenomena, but these analyses place stringent demands on the statistics.

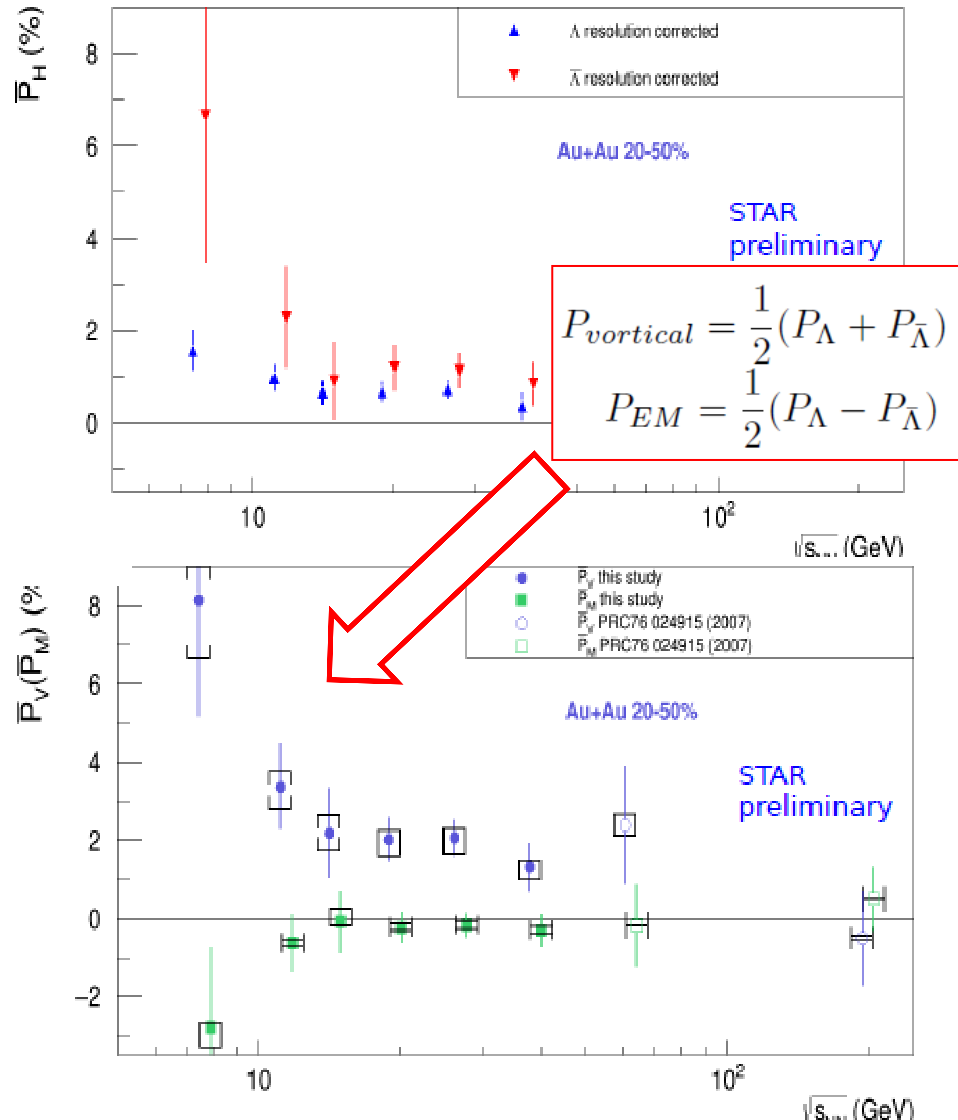
• **Open questions:** Lambda polarization and Chiral Magnetic effects

The Spinning Plasma – Lambda Polarizations

- Lambdas reveal their polarization through decay topology
- Polarization expected through “vortical alignment with the event angular momentum vector
- Polarization expected magnetic alignment with the event magnetic field
- These effects can be disentangled looking at Lambdas and anti-Lambdas

➔ Two weeks of Au+Au at 27 GeV approved for 2018

➔ Goal is a definative measurement of the magnetic alignment effect



$$P_{vortical} = \frac{1}{2}(P_\Lambda + P_{\bar{\Lambda}})$$

$$P_{EM} = \frac{1}{2}(P_\Lambda - P_{\bar{\Lambda}})$$

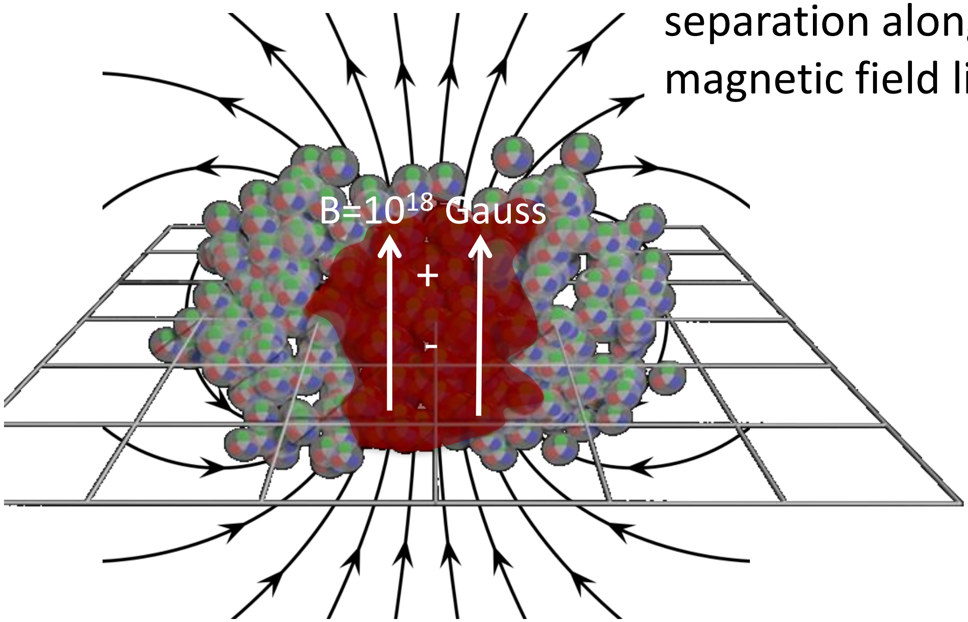
Chiral Magnetic Effect

Three Effects:

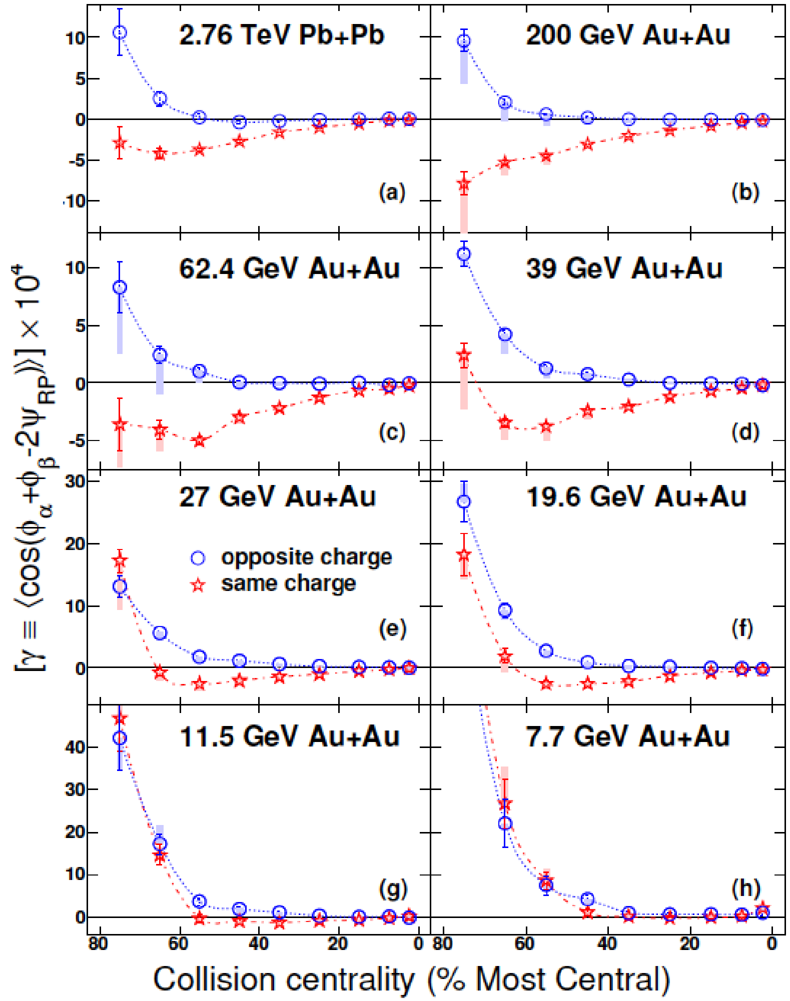
1. Chiral Magnetic Effect
2. Chiral Magnetic Wave
3. Chiral Vortical Effect

Chiral anomaly creates differences in the number of left handed and right handed quarks. Leads to charge separation along the magnetic field lines

charge separation



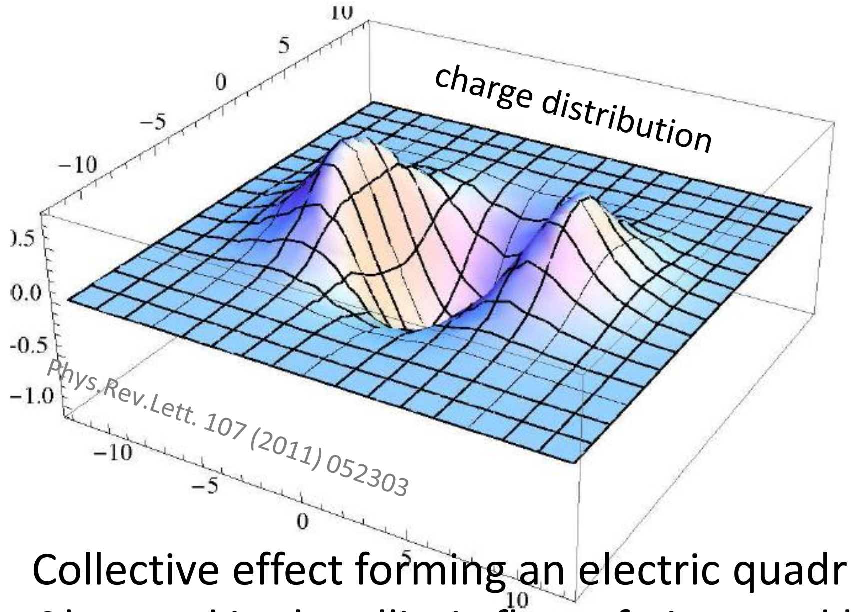
STAR, Phys. Rev. Lett. **113** (2014) 52302



Chiral Magnetic Wave

Predicted Effect

$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A \vec{B} \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V \vec{B}$$



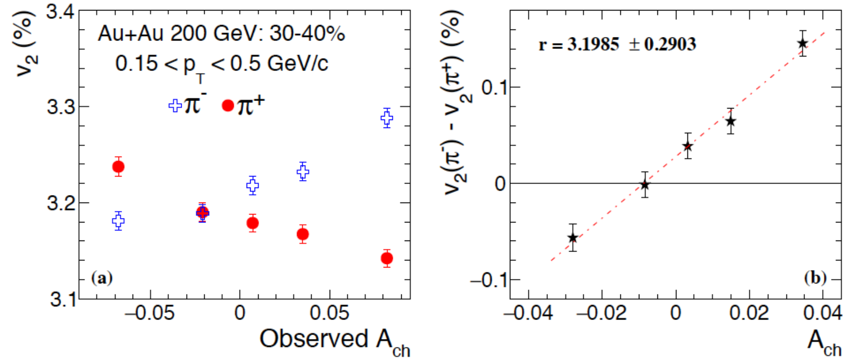
Collective effect forming an electric quadrupole
Observed in the elliptic flow of pions and kaons

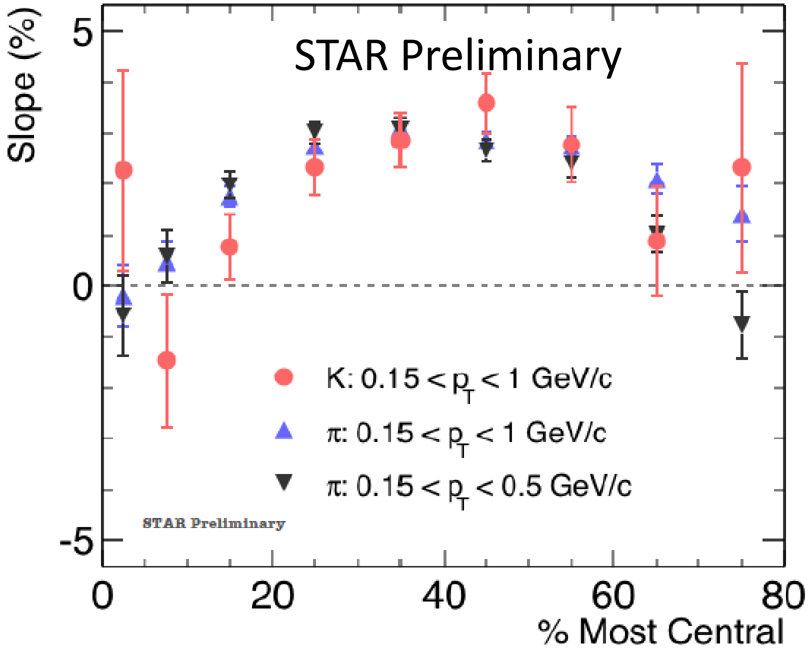
$$\Delta v_2 \equiv v_2(\pi^-) - v_2(\pi^+) = r\ A_\pm$$

$$A_\pm \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

Confirmed in Data

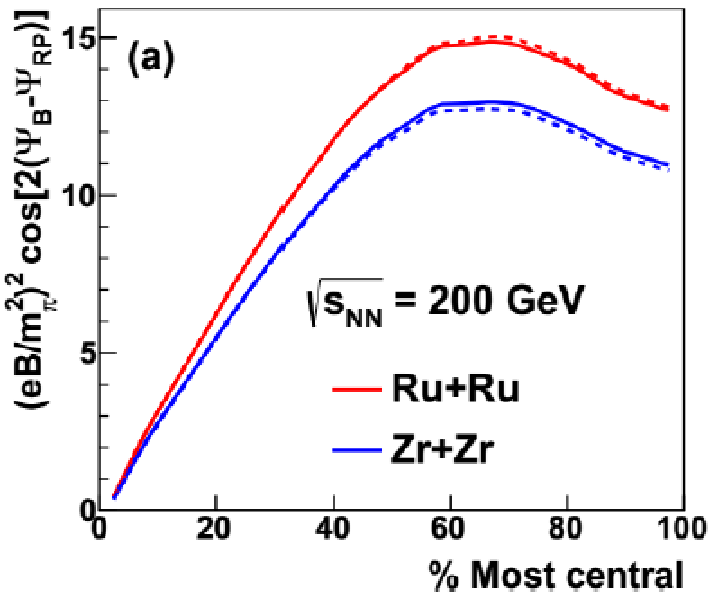
STAR, Phys. Rev. Lett. **114** (2015) 252302





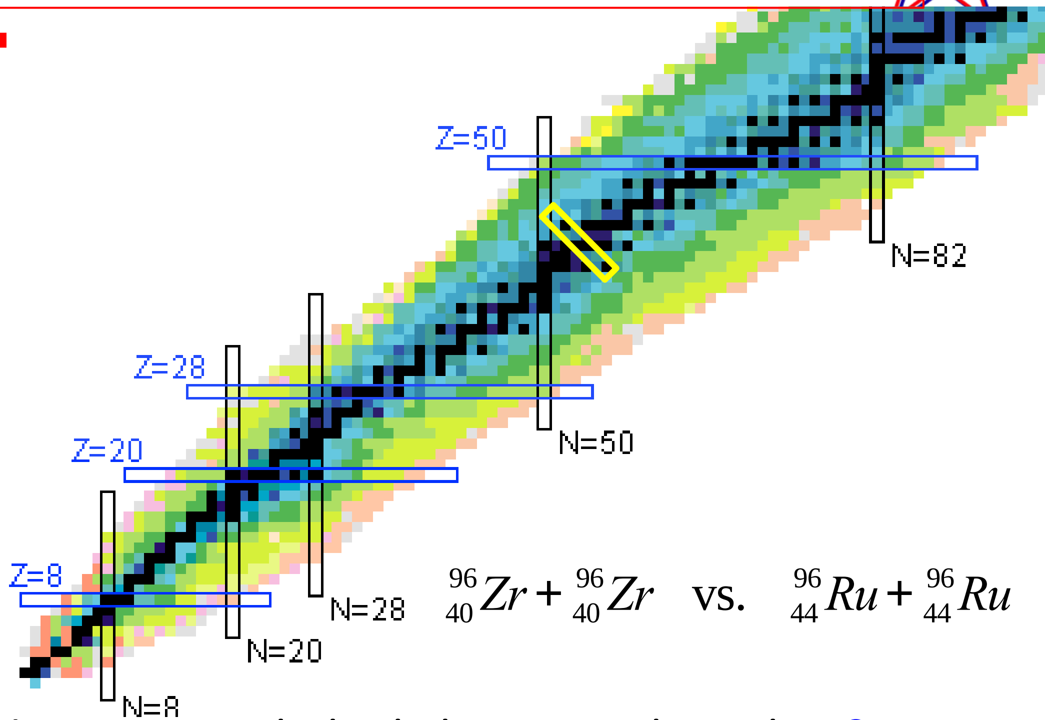
Tests of Chiral Magnet Effects with Isobar Run

Calculations: X.-G. Huang and W.-T. Deng

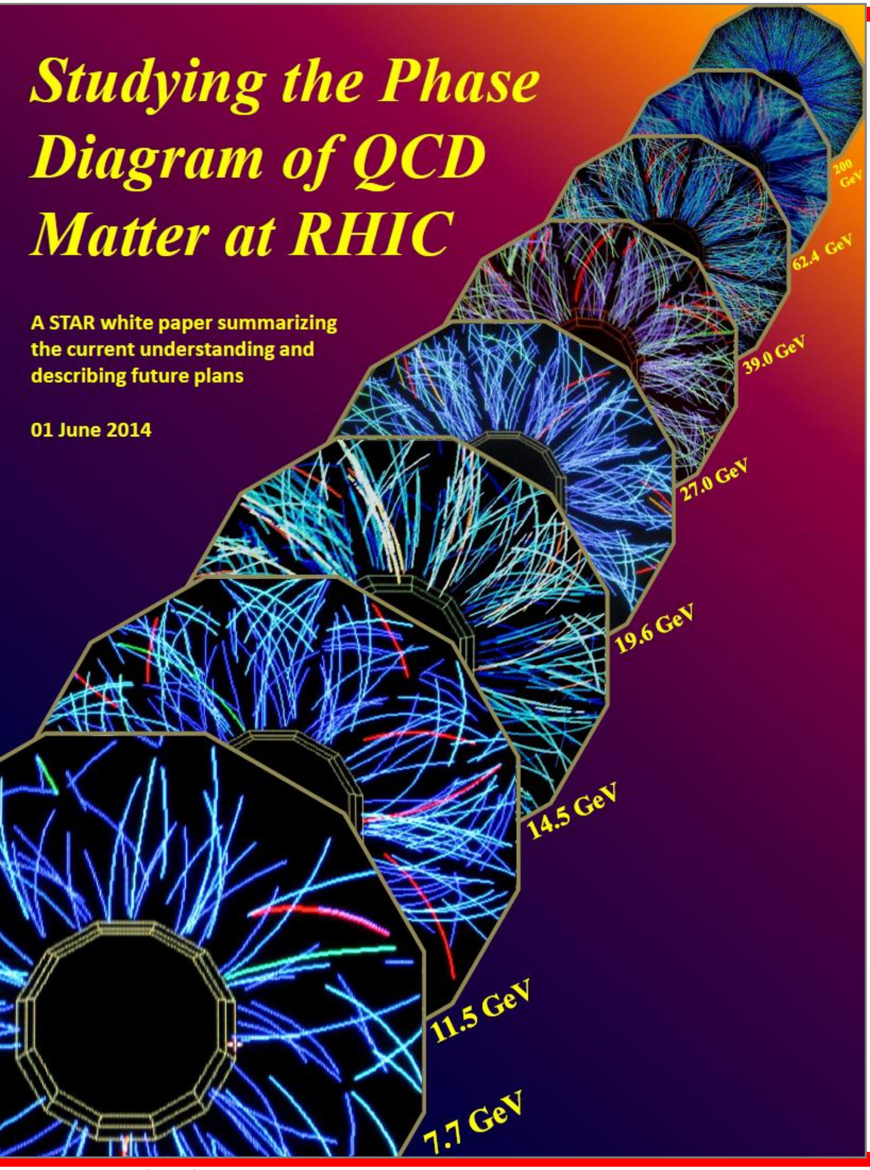


Use parameterization to convert CME calculation for Ru and Zr into expected signal

dashed:	Woods-Saxon case 1
solid:	Woods-Saxon case 2



- Large uncertainties in interpretation exist: *Current CME measurements could be entirely from background*
- There remain analyses to be done that are likely to provide some help in clarifying the relevance of CME but, *none so far have proven to be decisive*
- ➔ *seven weeks of isobars approved for 2018*



Beam Energy Scan II (2019-2020)

Select the most important energy range
➔ 5 to 20 GeV

Improve significance
➔Long runs, higher luminosity

Refine the signals
➔ Detector improvements

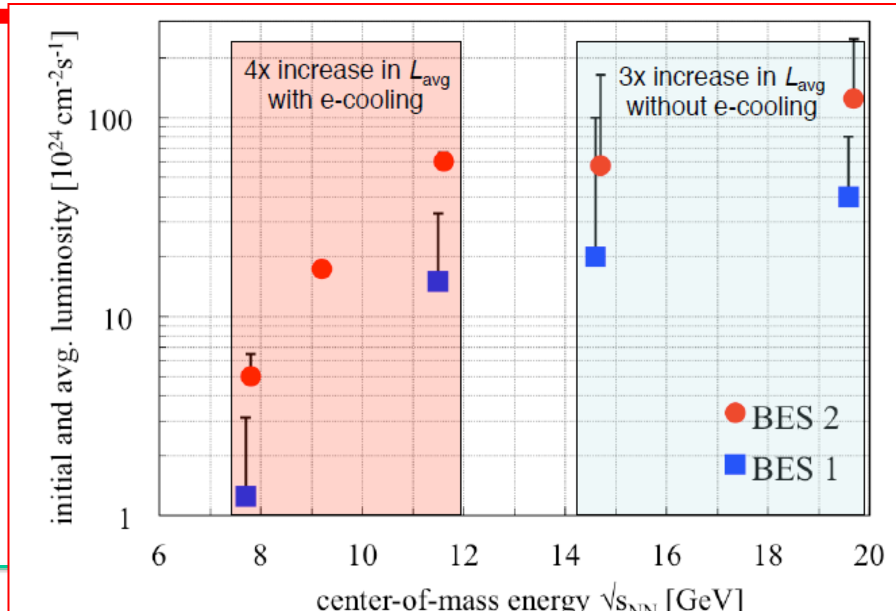
Comparison of Facilities

Facilty	RHIC BESII	SPS	NICA	SIS-100	J-PARC HI
Exp.:	**STAR** +FXT	**NA61**	**MPD** + FXT	**CBM**	**JHITS**
Start:	**2019-20**	**2009**	**2020** 2017	**2022**	**2025**
Energy: $\sqrt{s_{NN}}$ (GeV)	**7.7– 19.6** 3.0-7.7	**4.9-17.3**	**2.7 - 11** 2.0-3.5	**2.7-8.2**	**2.0-6.2**
Rate: At 8 GeV	**100 HZ** 2000 Hz	**100 HZ**	**<10 kHz**	**<10 MHZ**	**100 MHZ**
Physics:	**CP&OD**	**CP&OD**	**OD&DHM**	**OD&DHM**	**OD&DHM**
	Collider Fixed Target	Fixed Target Lighter ion collisions	Collider Fixed Target	Fixed Target	Fixed Target

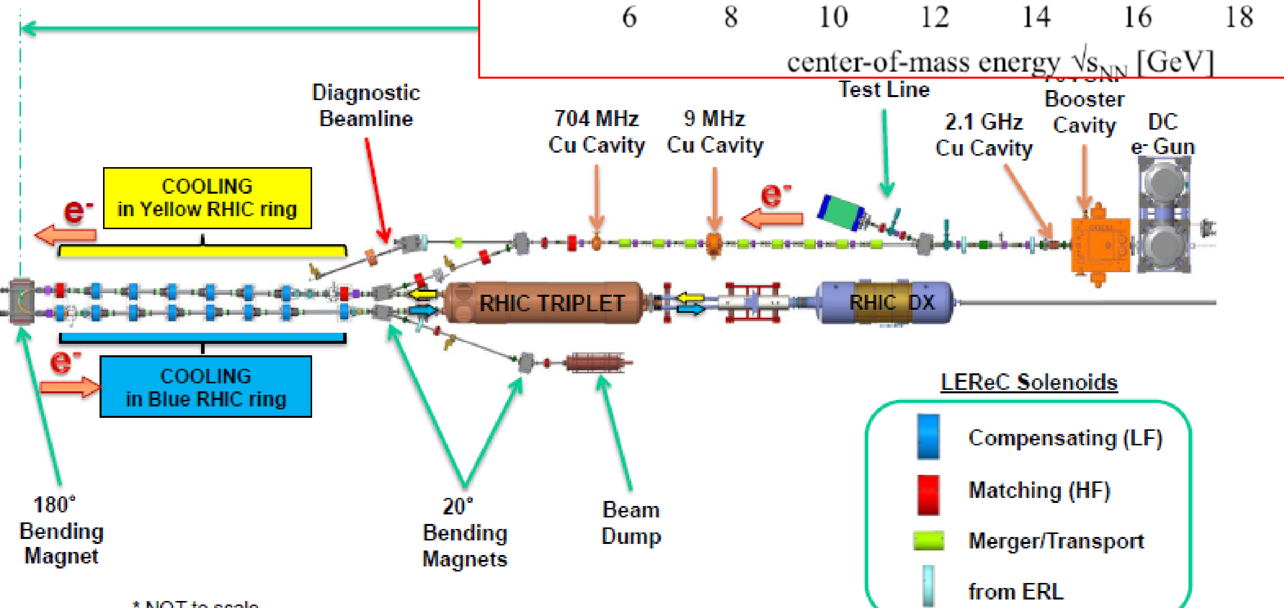
CP = Critical Point
OD = Onset of Deconfinement
DHM = Dense Hadronic Matter

Low Energy Electron Cooling at RHIC

Improve luminosity for low energy beams with electron cooling



- Start with 14.5 and 19,6 3X improvement
- Following year, 7.7, 9.1, and 11.5. 4X improvement with eCooling
- Run 24 weeks



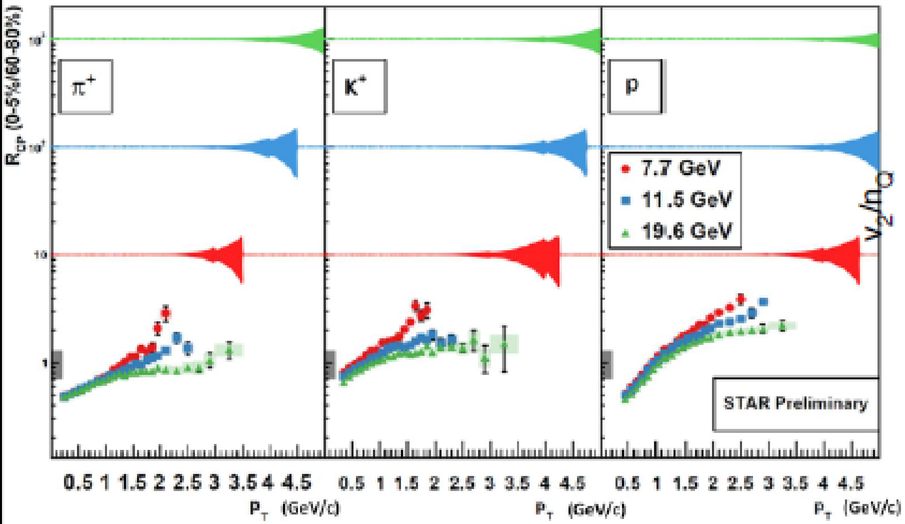
BES Phase II Proposal

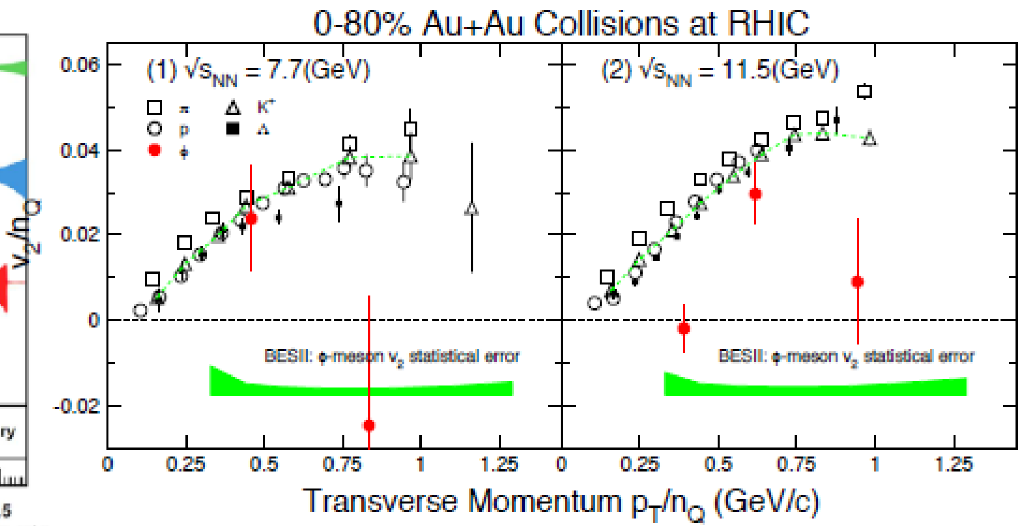
BES Phase II is planned for two 24 cryo-week runs in 2019 and 2020

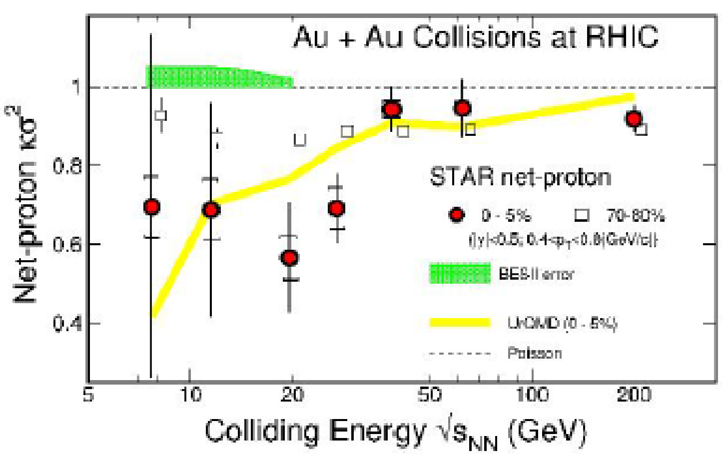
$\sqrt{S_{NN}}$ (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25		1.7	2.4	4.5
BES I $\mathcal{L}$ ($1\times10^{25}/cm^2sec$)	0.13		1.5	2.1	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	3	3
Beam Time (weeks)	**12**	**9.5**	**5.0**	**5.5**	**4.5**

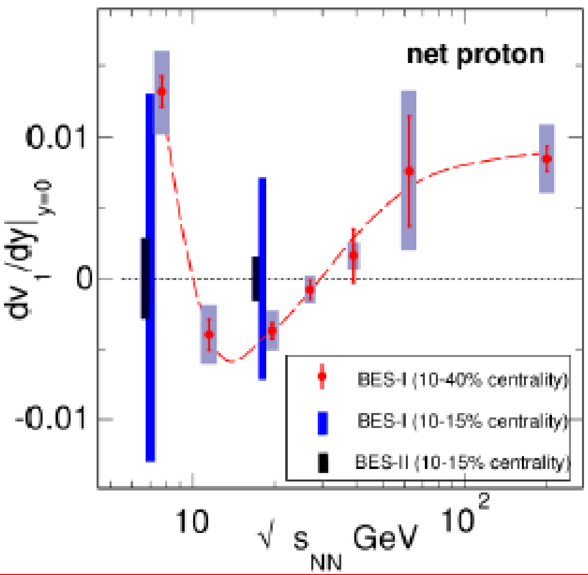
Revised estimates

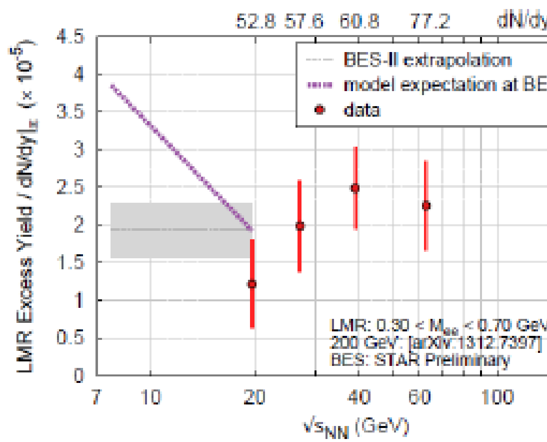
Reduction in Errors with Improved Statistics



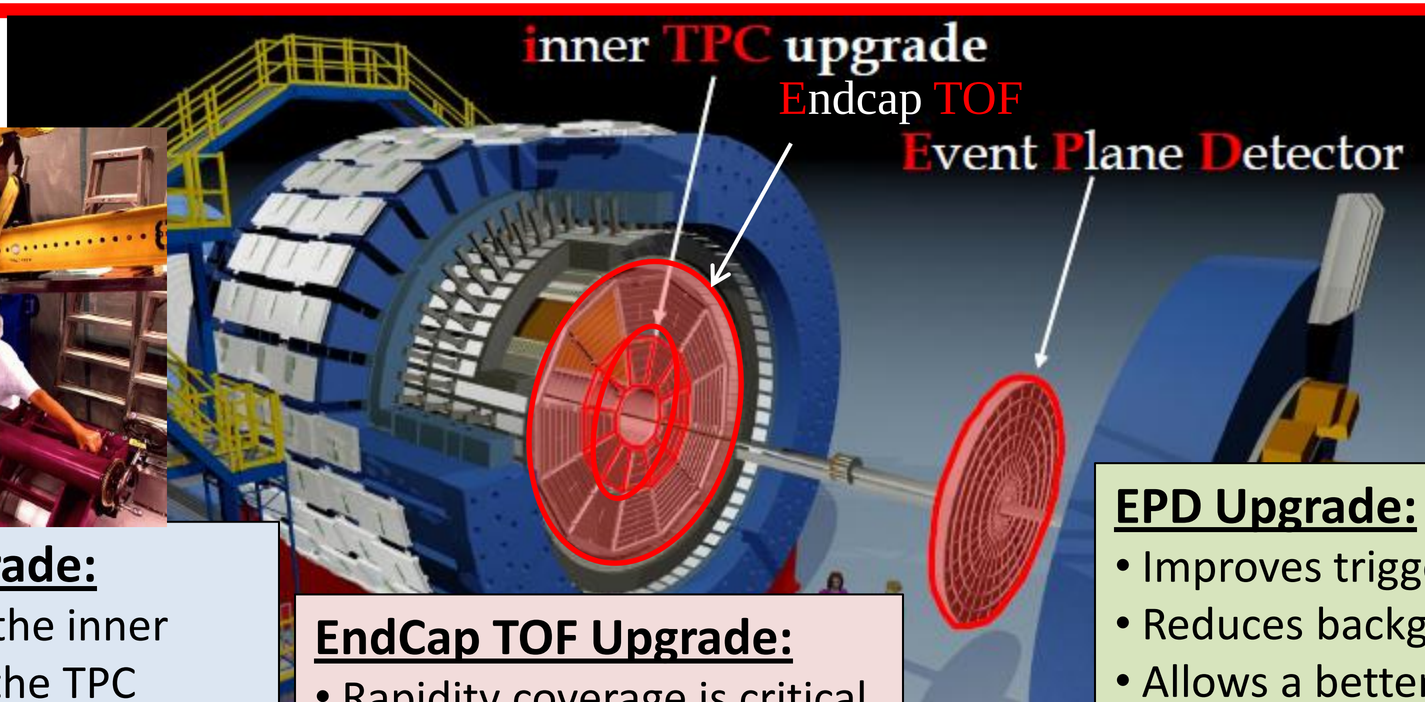






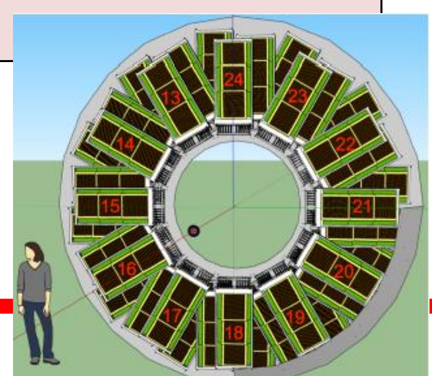


The STAR Upgrades and BES Phase II



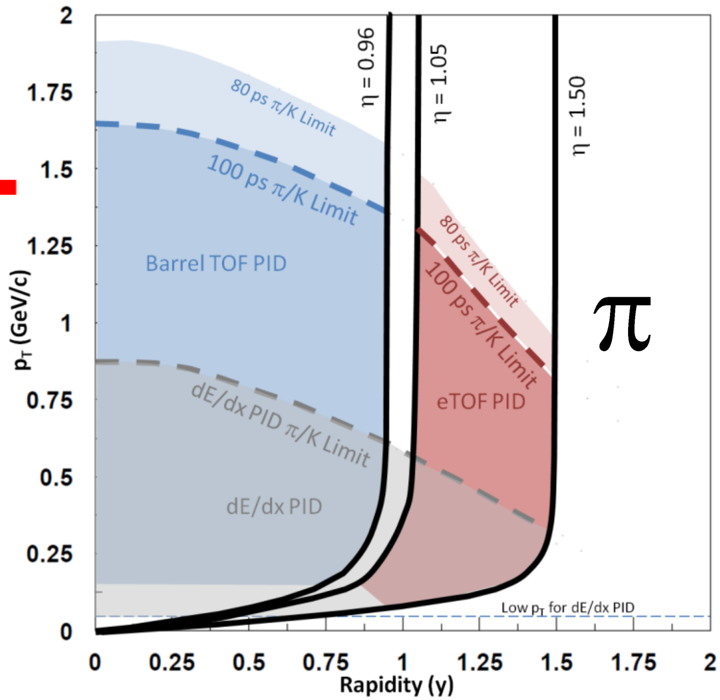
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

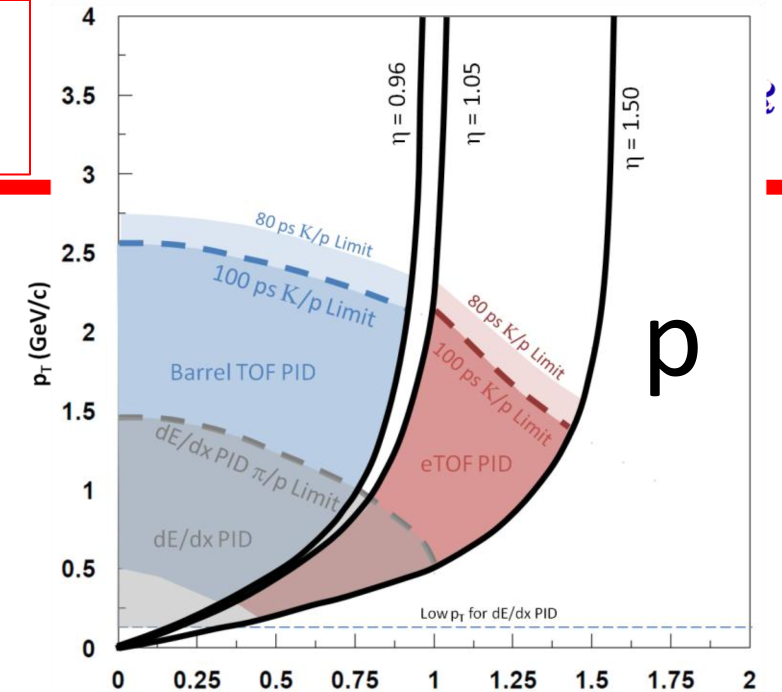
EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program



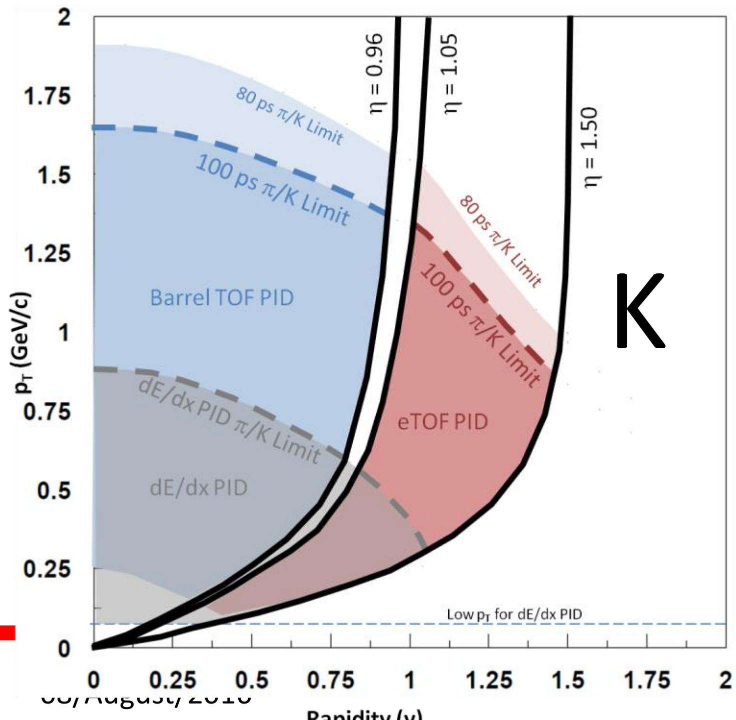
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

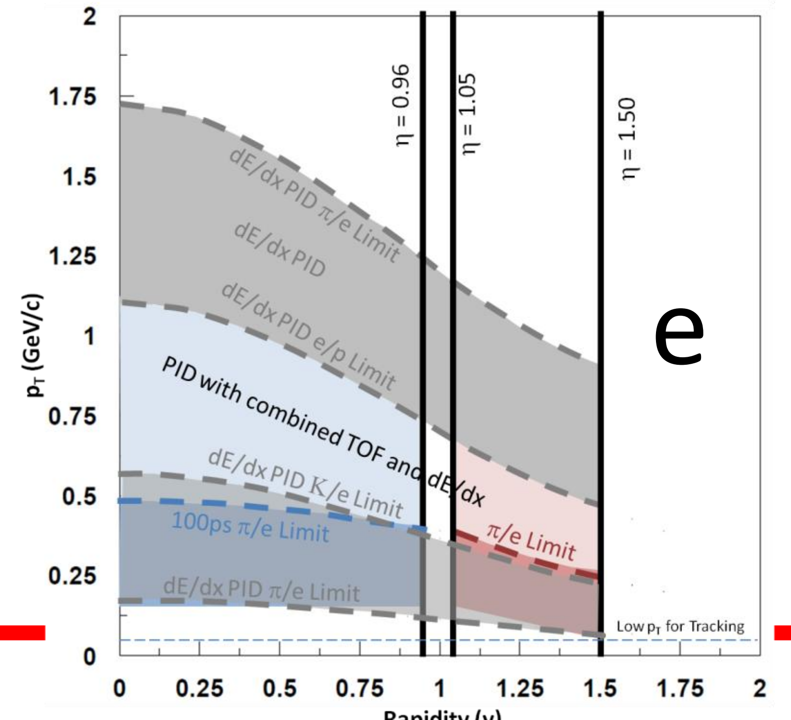
Acceptance Improvements



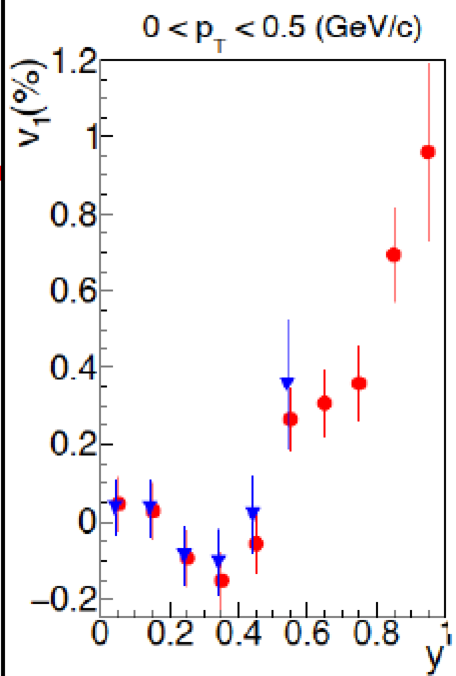


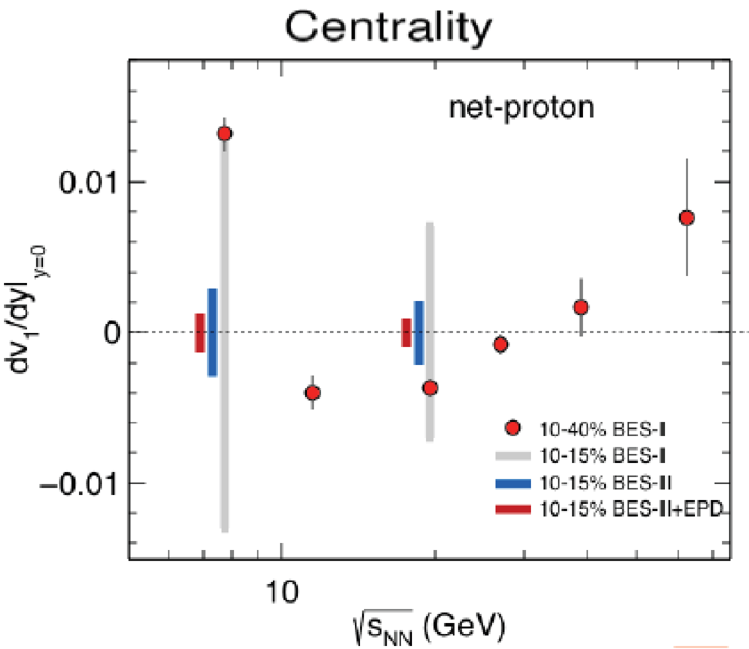
- Extends rapidity coverage ➔ allows a change in μ_B
- Improves yields of protons ➔ better kurtosis
- Improves coverage for electrons ➔ better di-electron studies

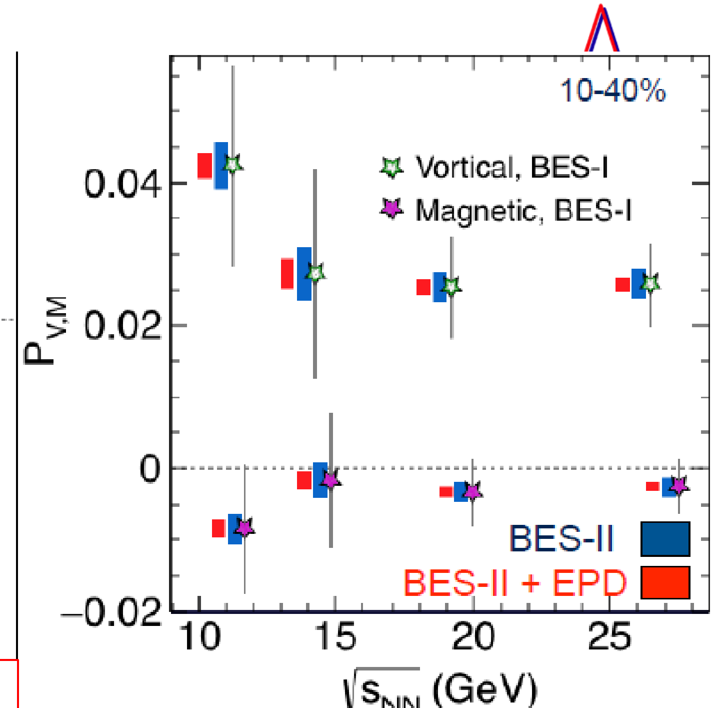


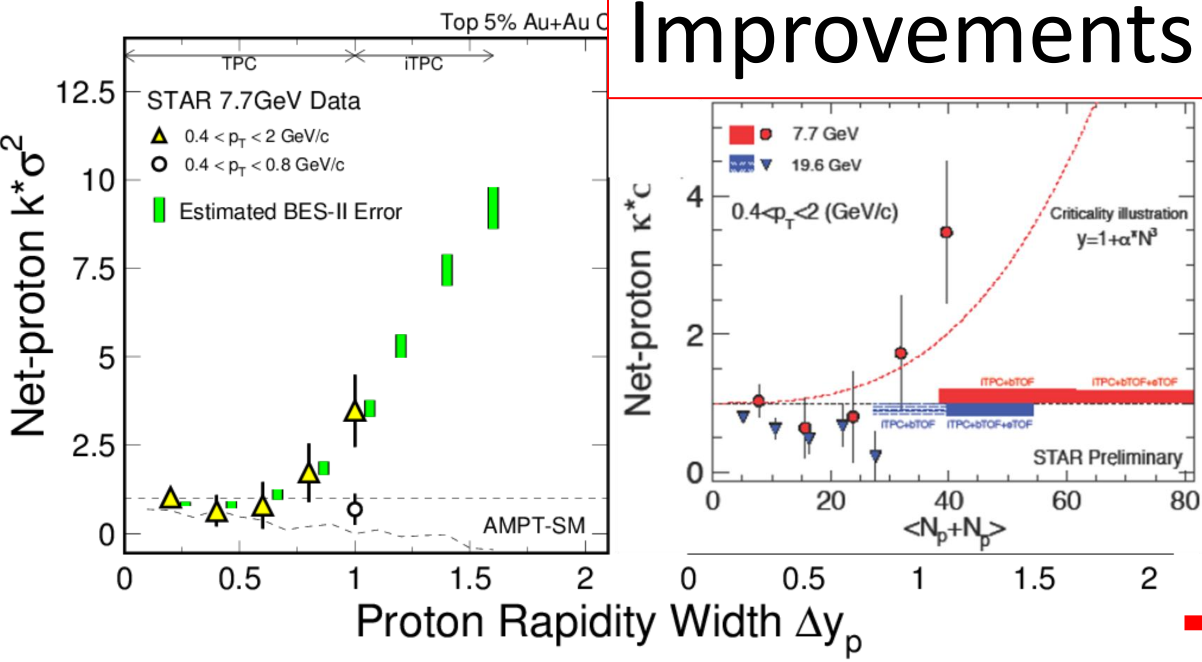


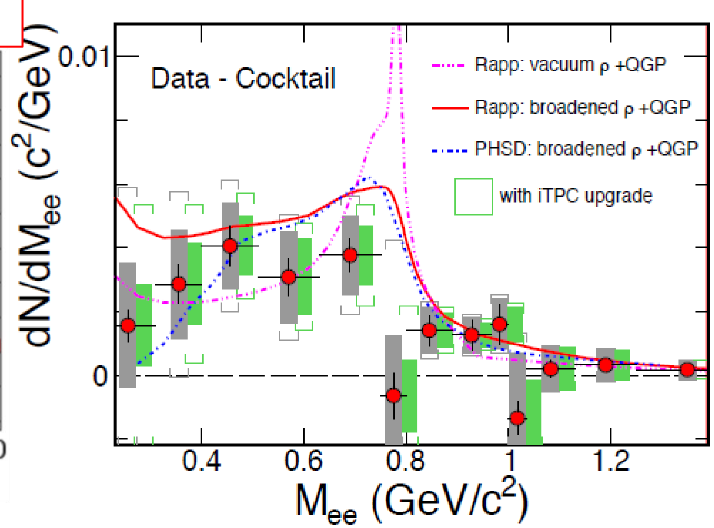
Improvements







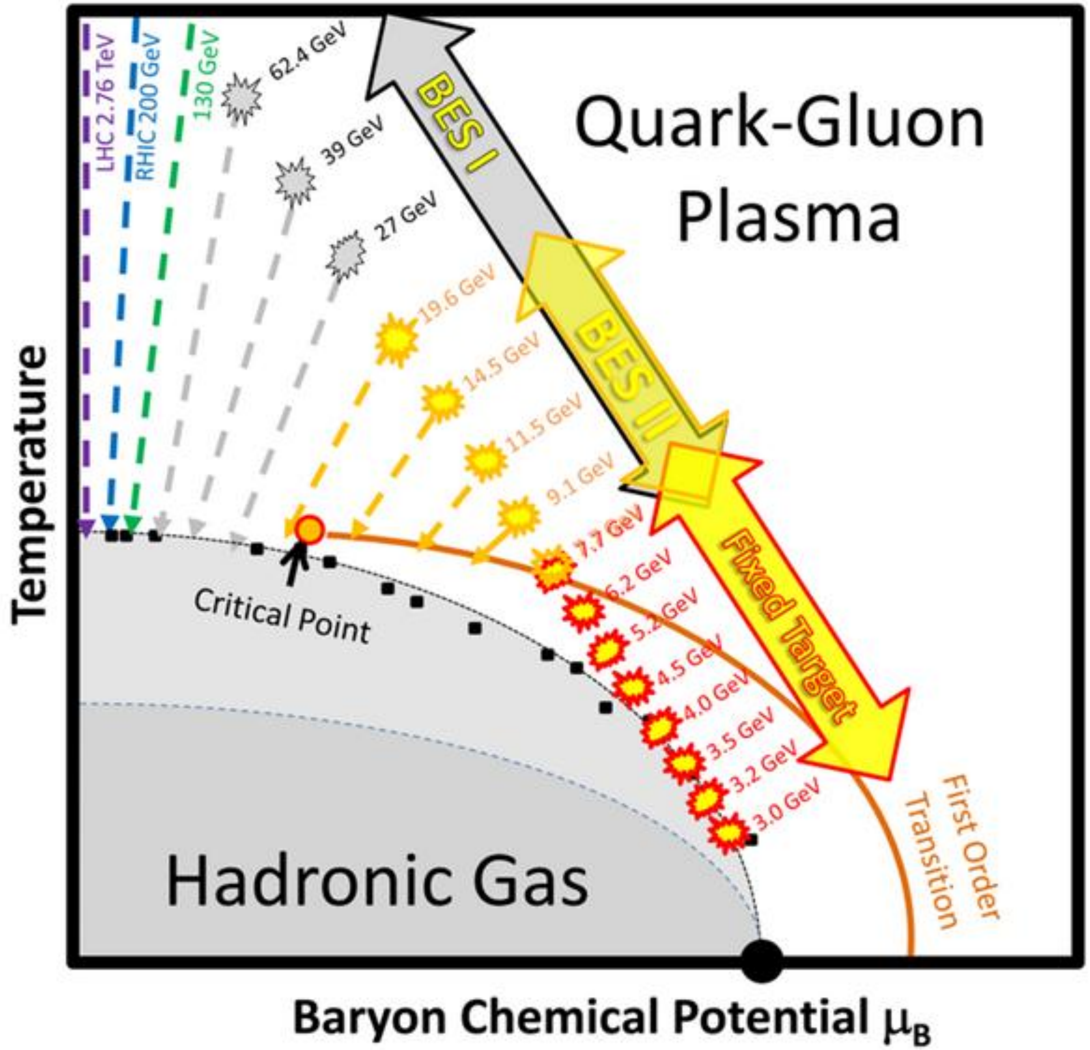




Fixed-Target Program 3.0 to 7.7 GeV

The Fixed-Target Program will extend the reach of the RHIC BES to higher μ_B.

Goals:
1) Search for evidence of the first entrance into the mixed phase
2) Control measurements for BES collider program searches for Onset of Deconfinement
3) Control measurements for Critical Point searches



Target Design 2014 and 2015

Target design:

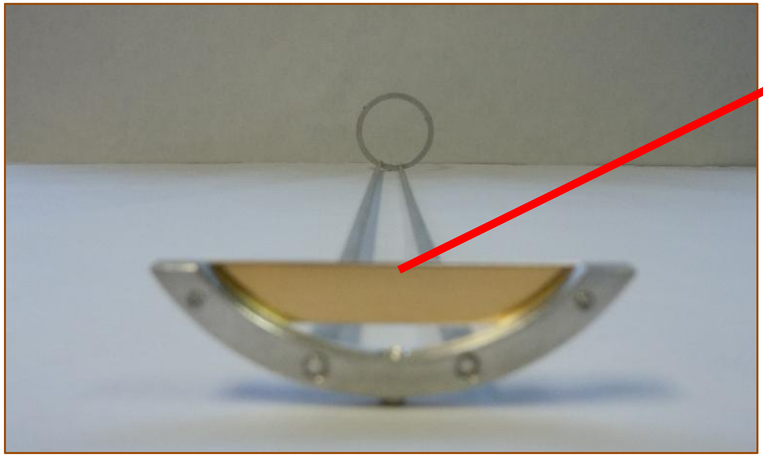
- Gold foil
- 1 mm Thick (4%)
- 1 cm High
- 210 cm from IR

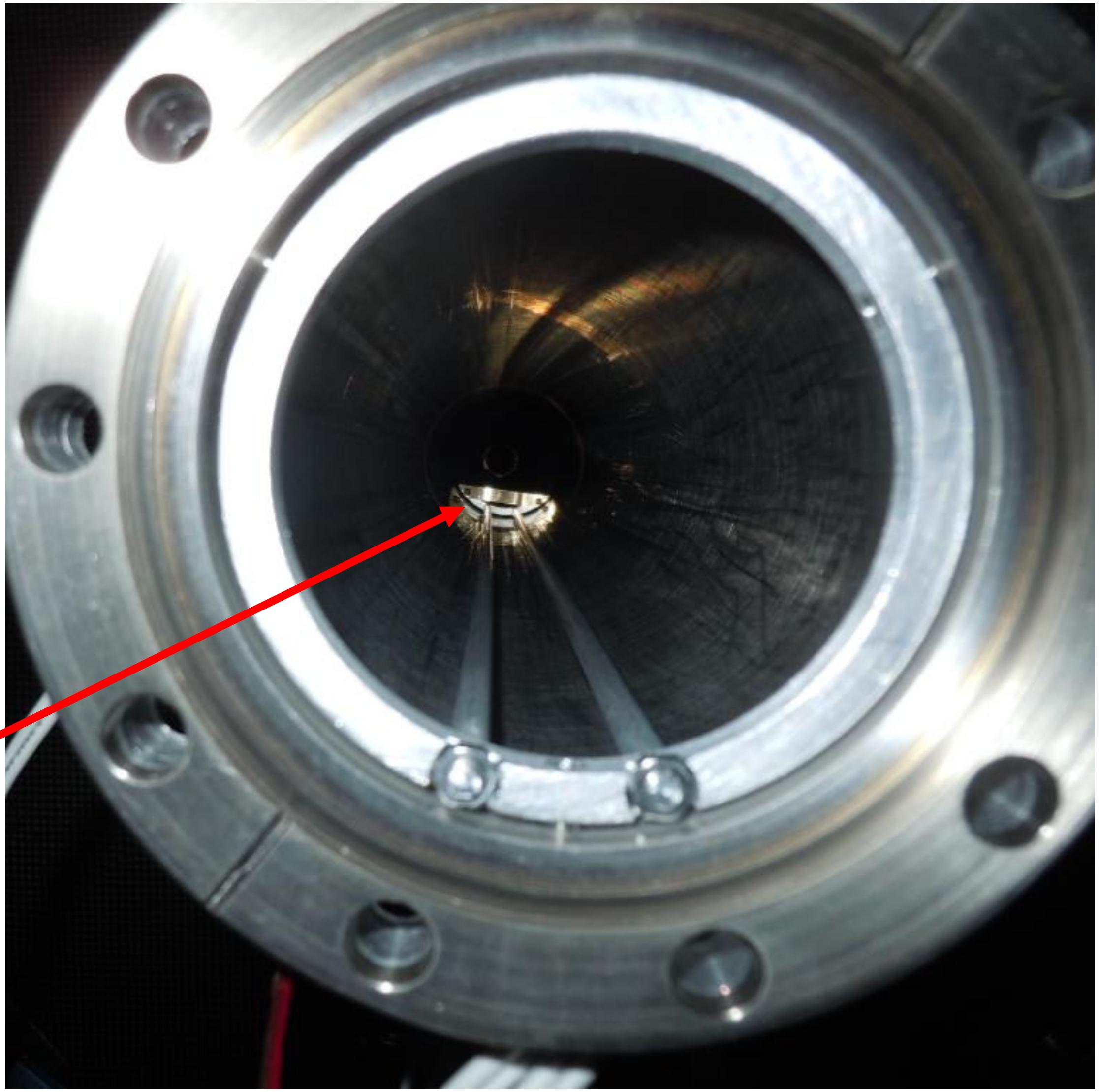
2014 Parasitic tests (two weeks):

- ~5000 central Au+Au events

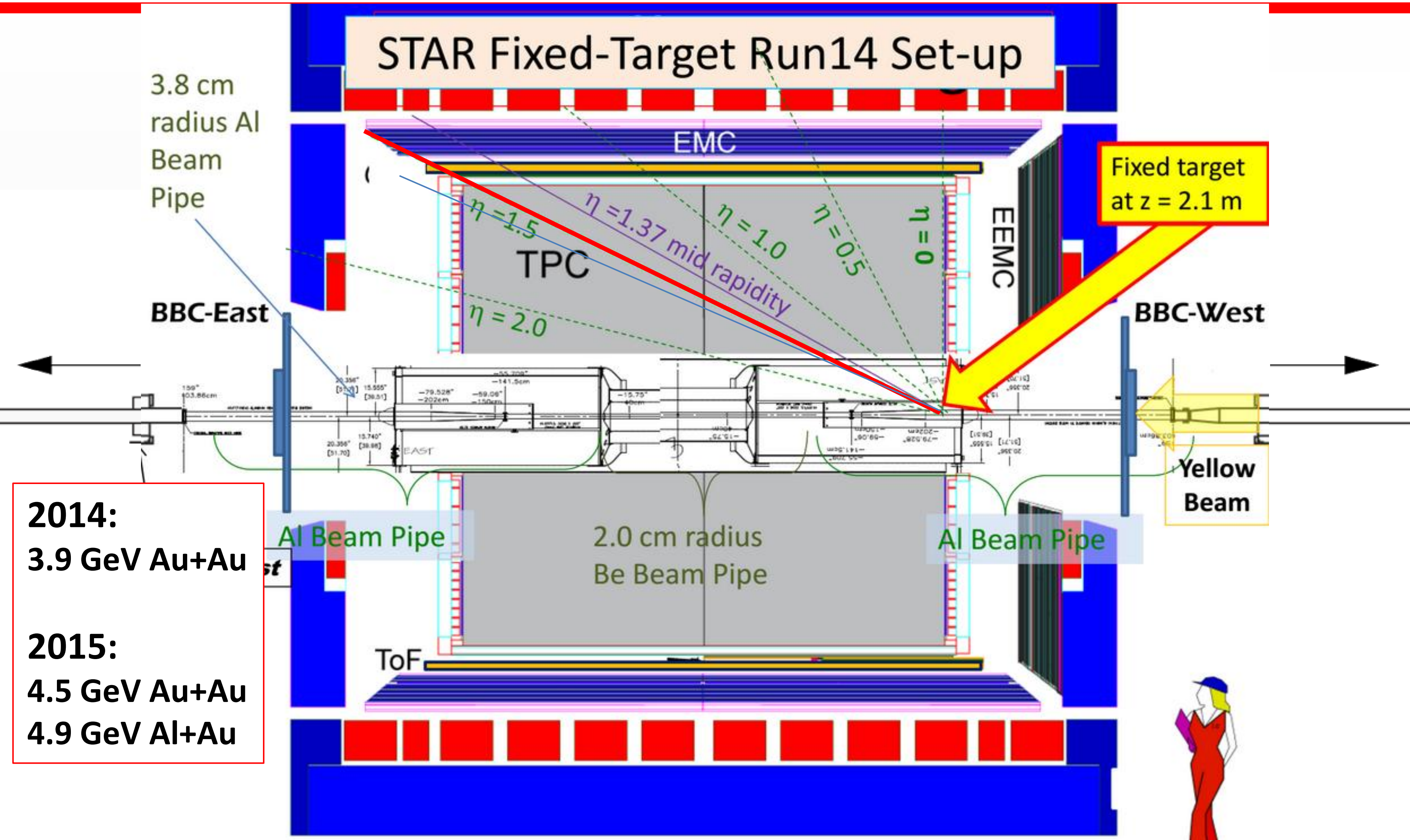
2015 Direct beam tests (few hours):

- 1.3 Million central Au+Au
- 3.4 Million central Al+Au





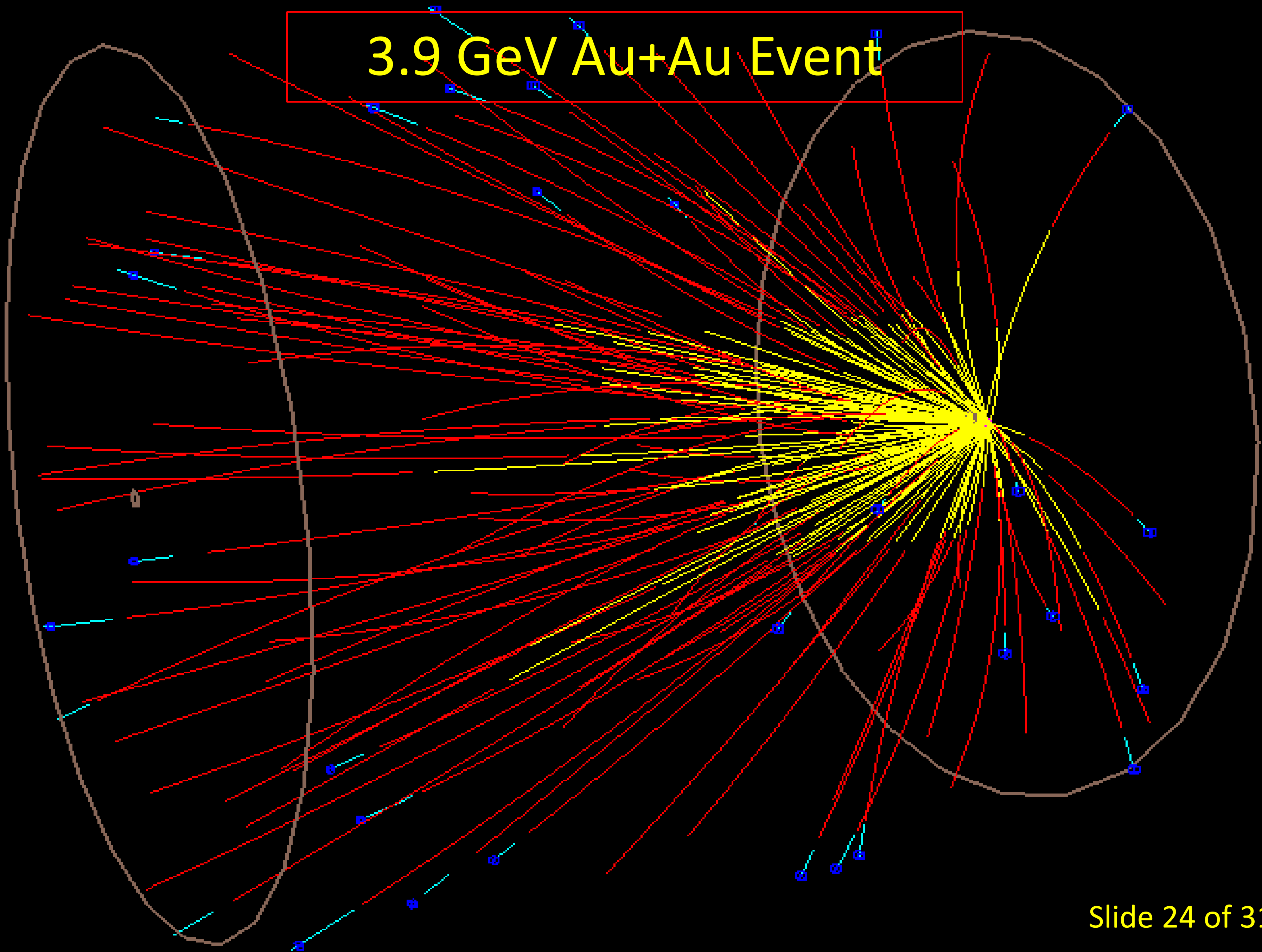
Run 14 and 15 Setup



2014:
3.9 GeV Au+Au

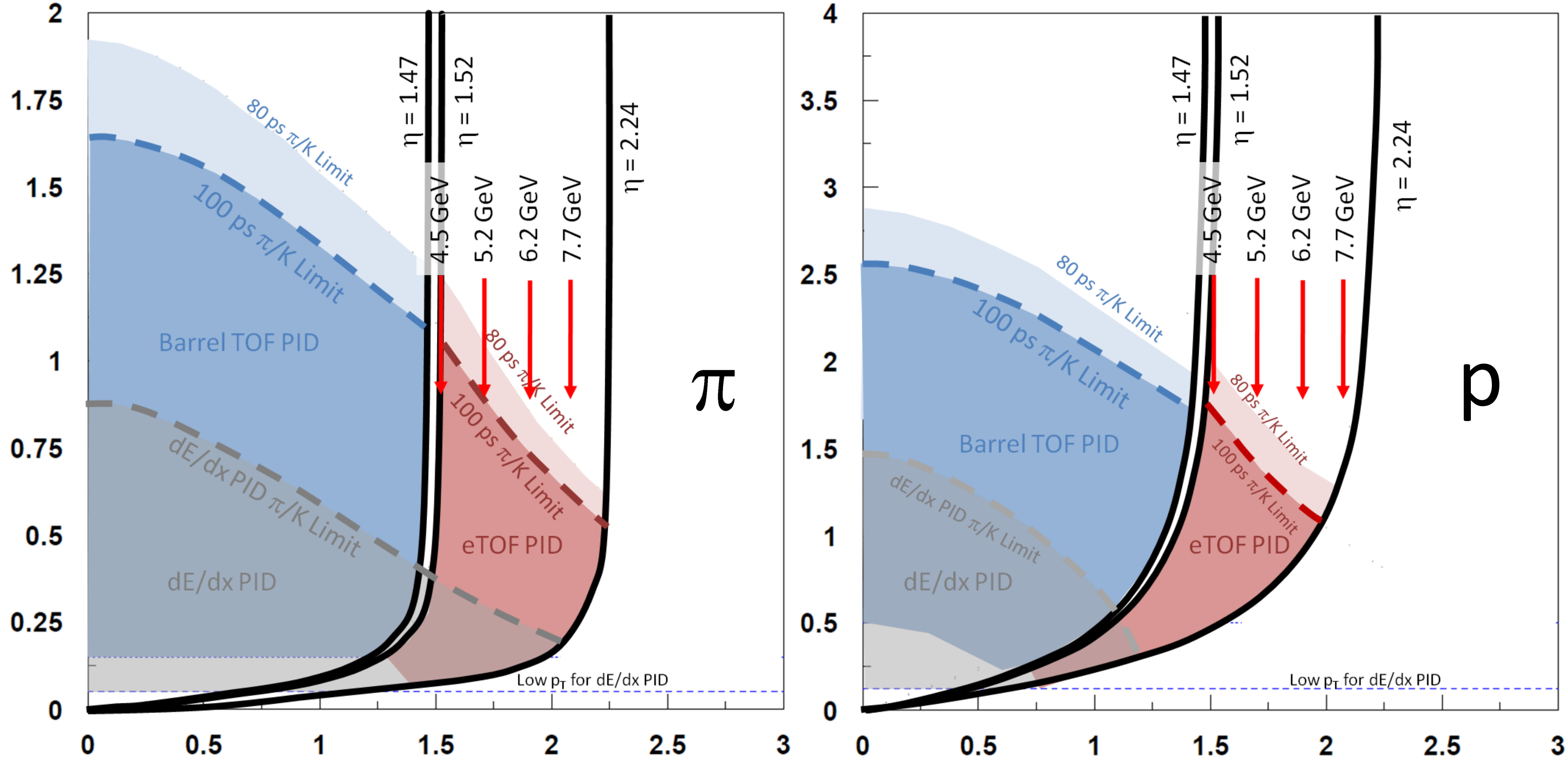
2015:
4.5 GeV Au+Au
4.9 GeV Al+Au

3.9 GeV Au+Au Event

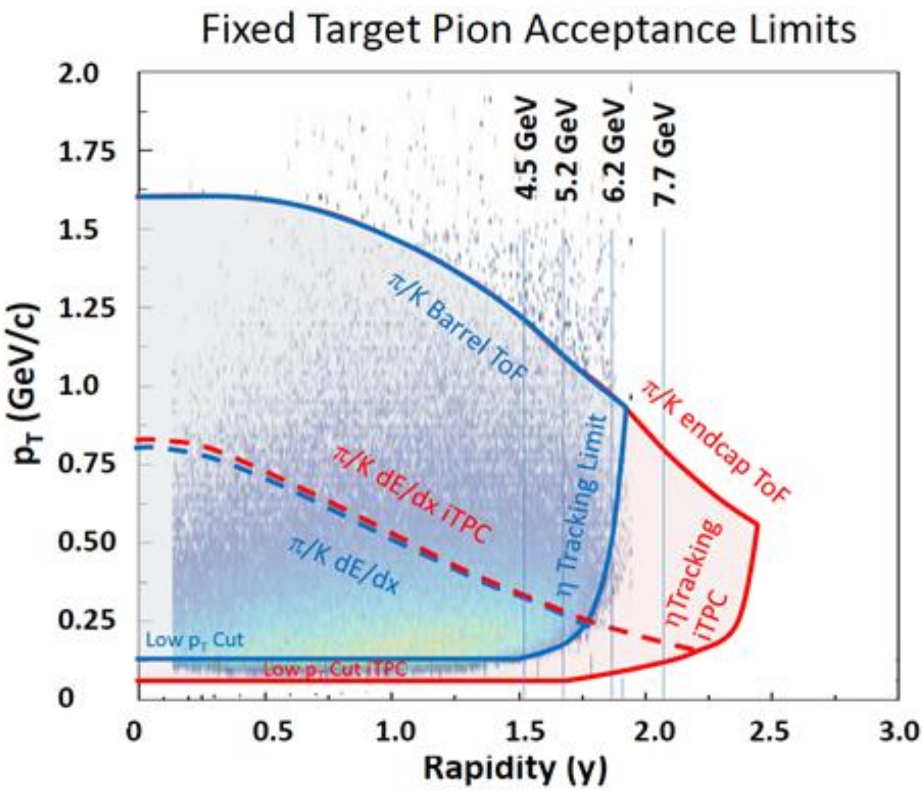


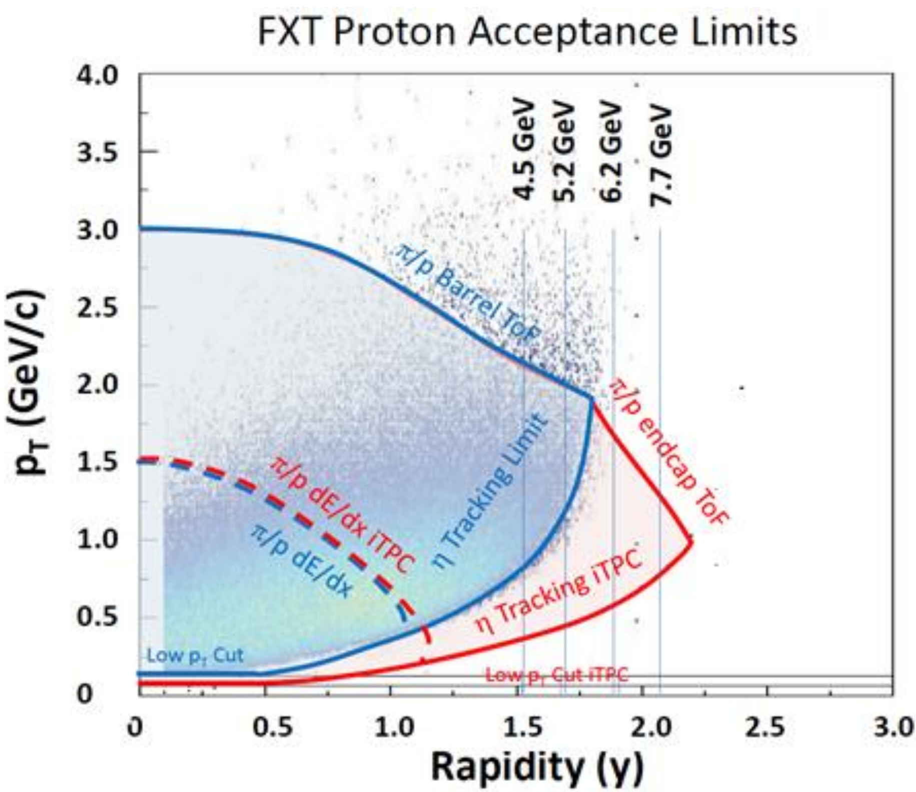
What do the iTPC and eTOF do for Fixed Target?

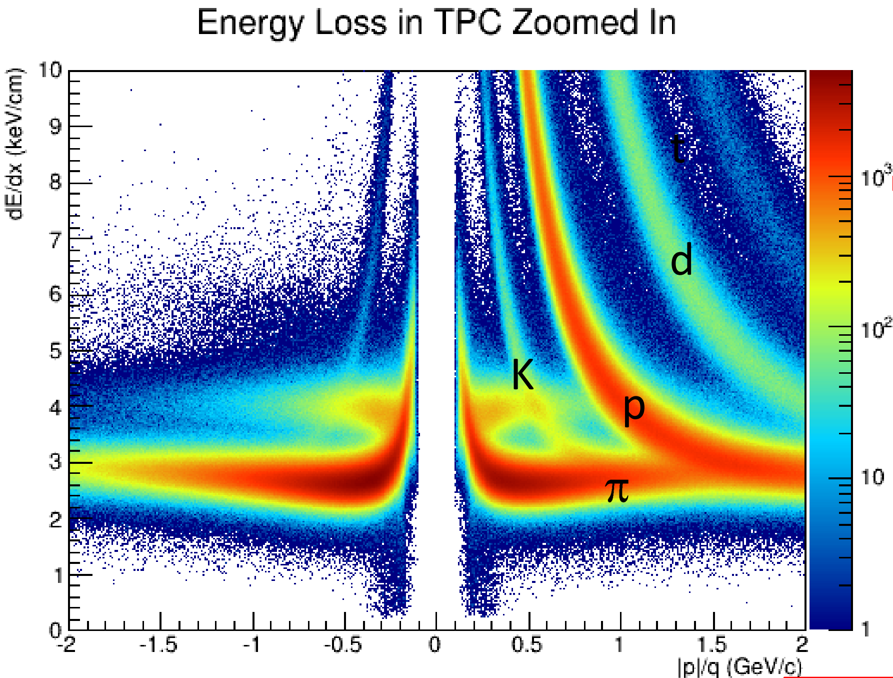
Allows the FXT program to reach 7.7 GeV!



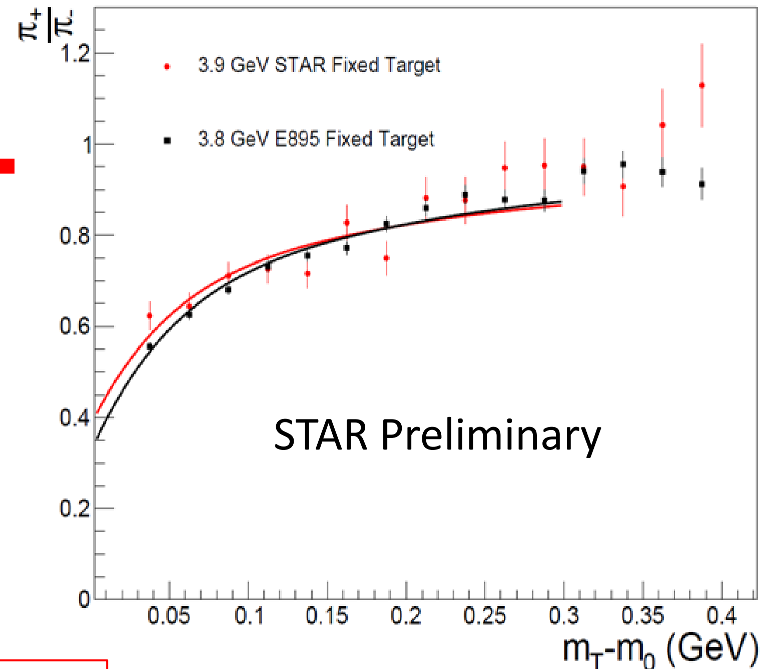
Verification of Acceptance Maps





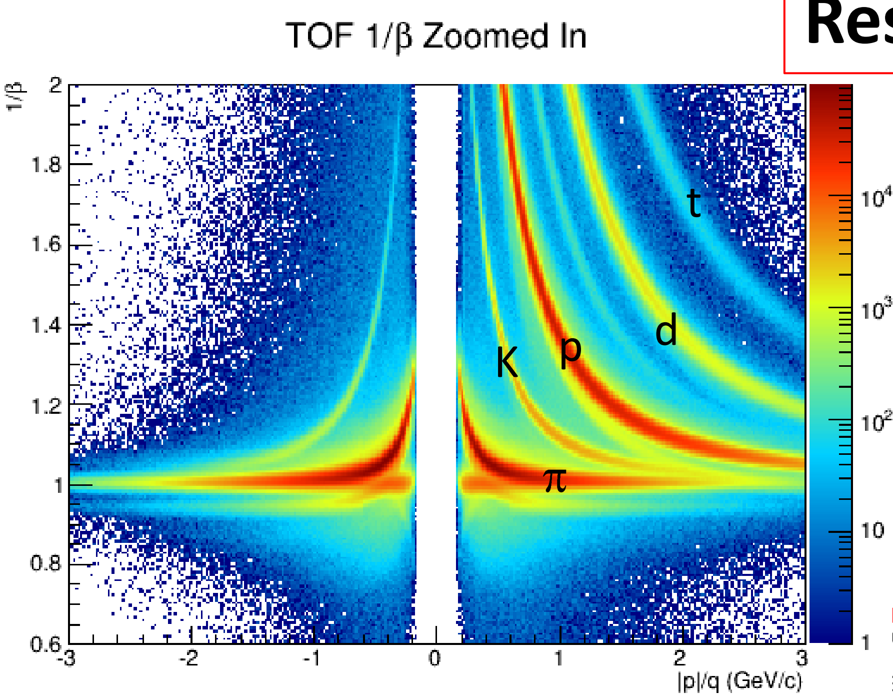


Energy Loss in TPC Zoomed In
dE/dx (keV/cm)
|p|/q (GeV/c)
K
p
π
t
d

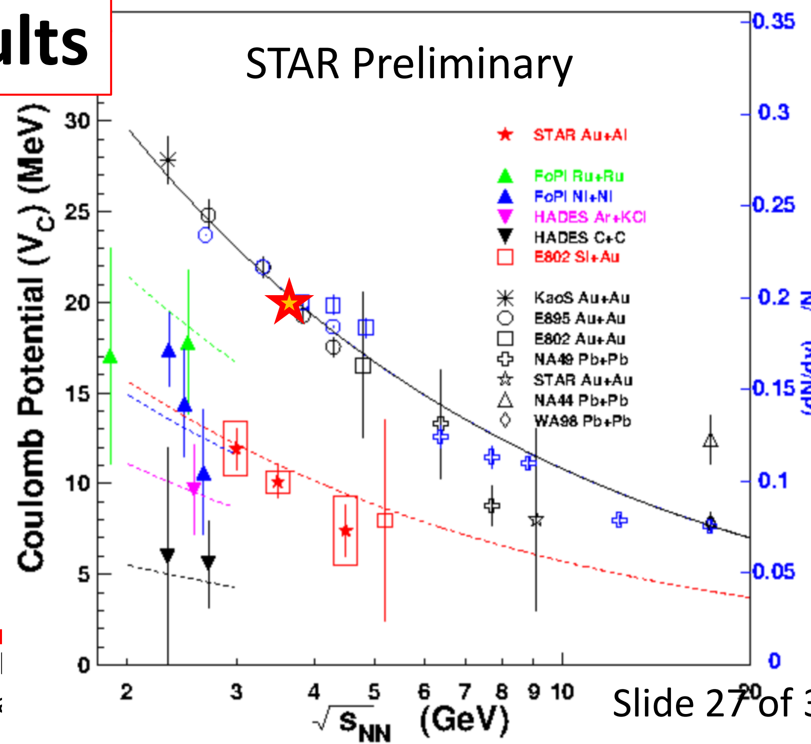


π+/π-
3.9 GeV STAR Fixed Target
3.8 GeV E895 Fixed Target
STAR Preliminary
mT-m0 (GeV)

Results

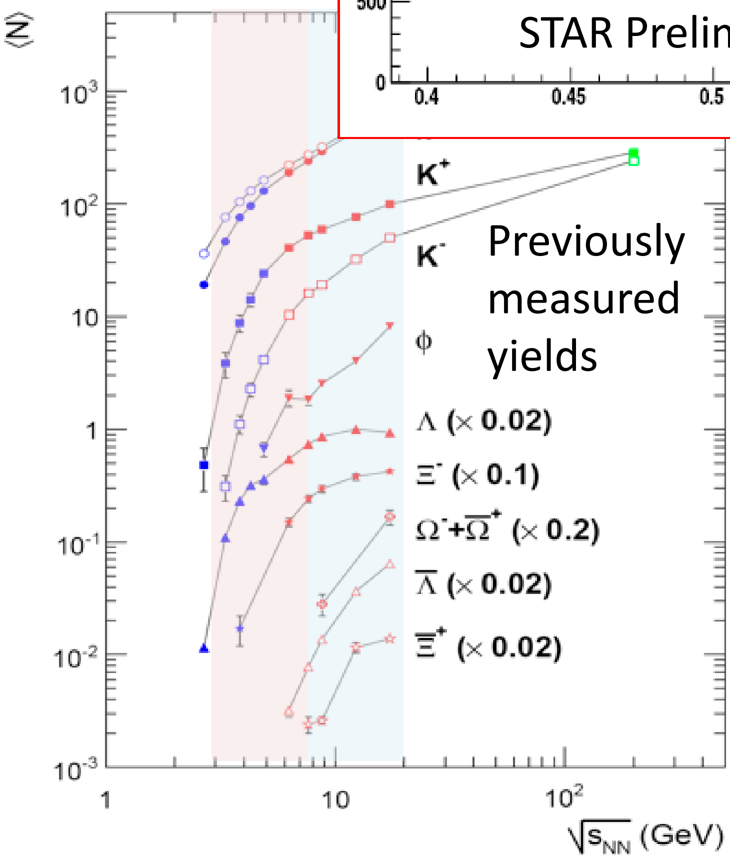


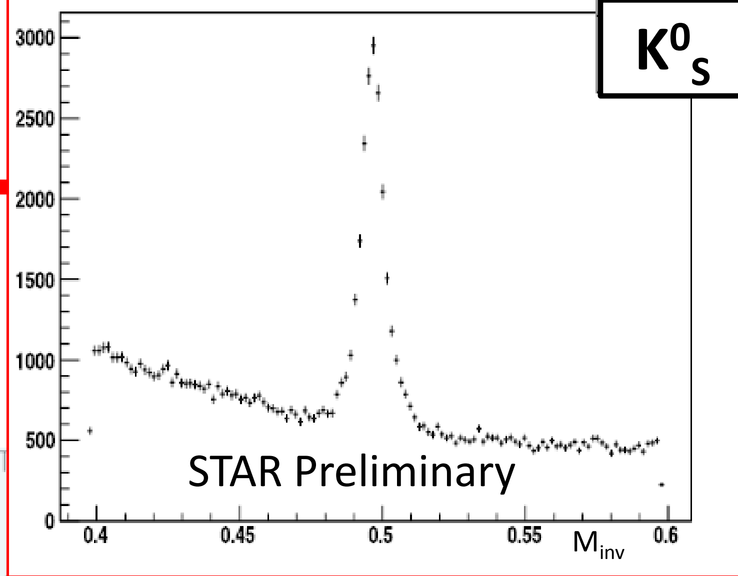
TOF 1/β Zoomed In
1/β
|p|/q (GeV/c)
K
p
π
t
d

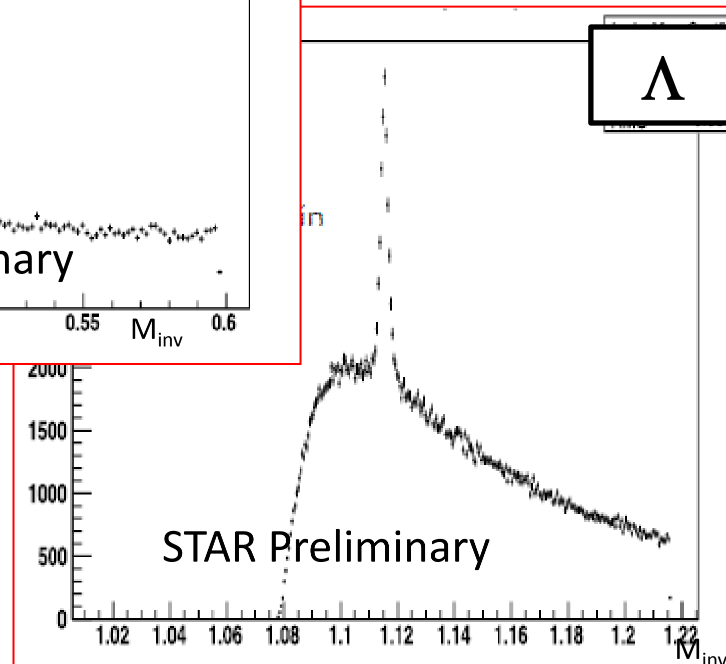


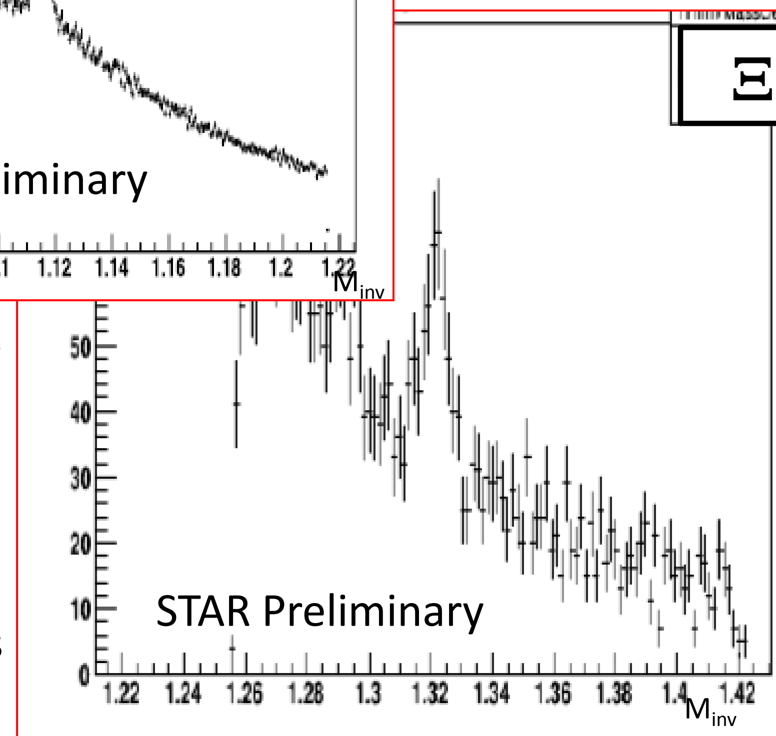
STAR Preliminary
Coulomb Potential (VC) (MeV)
(dN/dy)y=0/Npart
√sNN (GeV)
STAR Au+Al
FoPI Ru+Ru
FoPI Ni+Ni
HADES Ar+KCl
HADES C+C
E802 Si+Au
KaoS Au+Au
E895 Au+Au
E802 Au+Au
NA49 Pb+Pb
STAR Au+Au
NA44 Pb+Pb
WA98 Pb+Pb

Strange Hadrons









Other preliminary results:

- HBT
- Directed flow
- Elliptic flow
- Ratio fluctuations

Physics Goals of the FXT Program

The Onset of Deconfinement:
- High p_T suppression
- N_{CQ} scaling of Elliptic Flow
- LPV through three particle correlators (CME)
- Balance Functions
- Strangeness Enhancement

Compressibility → First Order Phase Transition
- Directed flow
- Tilt angle of the HBT source
- The Volume of the HBT source
- The width of the pion rapidity distributions (Dale)
- The zero crossing of the elliptic flow (~6 AGeV)
- Volume measures from Coulomb Potential

Criticality:
- Higher moments
- Particle Ratio Fluctuations

Chirality:
- Dilepton studies

No measurements in this energy range

Conclusions

- BES Phase I told us the regions of interest
- Collider upgrades improve luminosity
- Detector upgrades extend physics reach
- Fixed-target program will extend reach of BES program

The focused and improved studies of BES Phase II will allow us to define the energy of the onset of deconfinement and allow us to characterize the phases and transitions of QCD matter.

Chiral Vortical Effect

Chiral Magnetic Effect vs Chiral Vortical Effect

Chirality Imbalance (μ_A)

Magnetic Field (ω μ_e) Fluid Vorticity (ω μ_B)

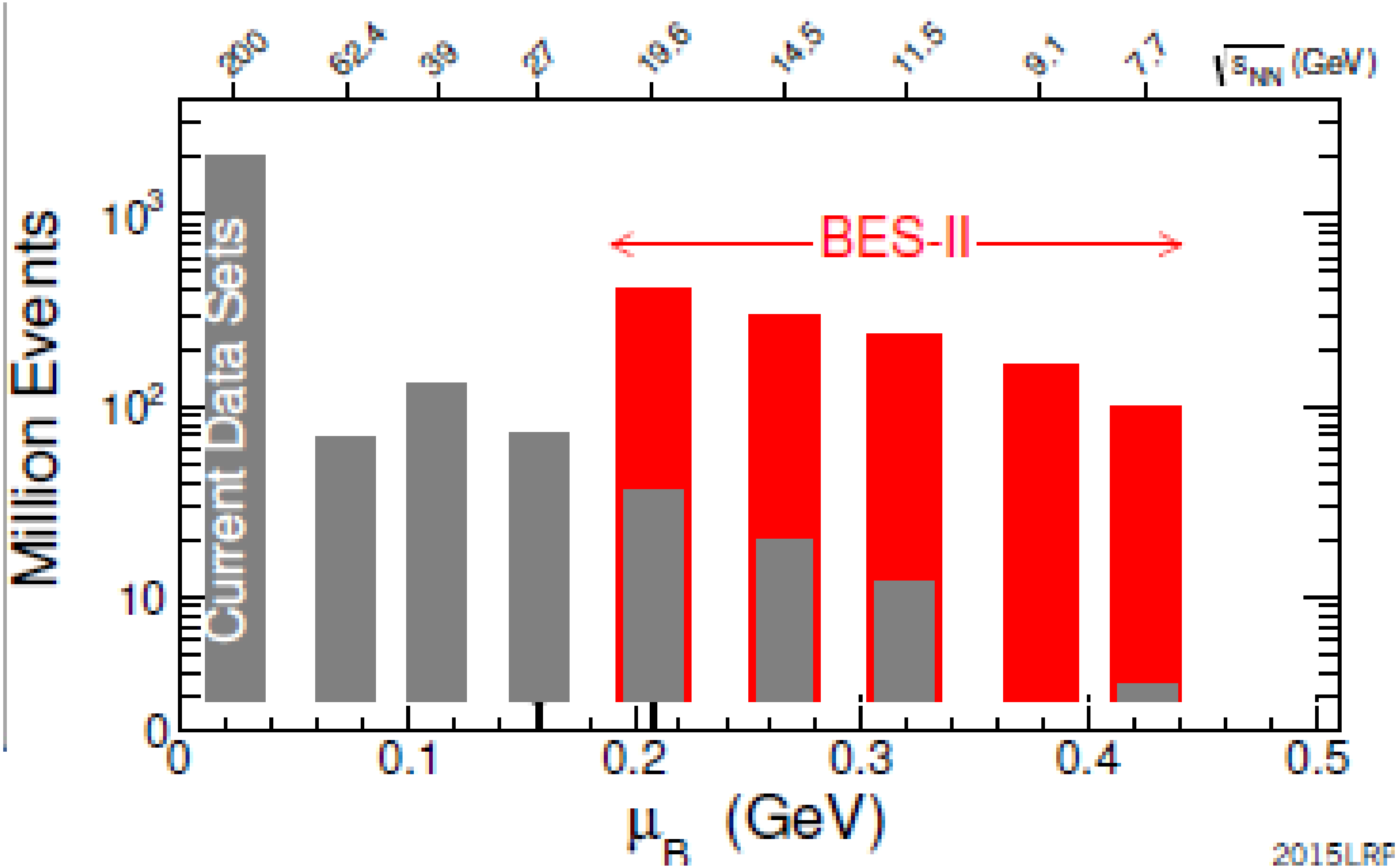
$\downarrow$ $\downarrow$

Electric Charge (j_e) Baryon Number (j_B)

D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

$$\langle \cos(\phi_{\Lambda} + \phi_{\mathrm{p}} - 2\Psi_{RP}) \rangle$$

correlate Λ–p to search for the Chiral Vortical Effect



200
62.4
39
27
19.6
14.5
11.5
9.1
7.7
$\sqrt{s_{NN}}$ (GeV)
Million Events
10^3
10^2
10
0
Current Data Sets
BES-II
0
0.1
0.2
0.3
0.4
0.5
μ_B (GeV)
2015LRP

Hypernuclei

Perfect energy range to map out the production of $^3_\Lambda H$ and $^4_\Lambda H$

Previously only measured at two energies

Dynamic range will exclude searches for doubly strange hypernuclei