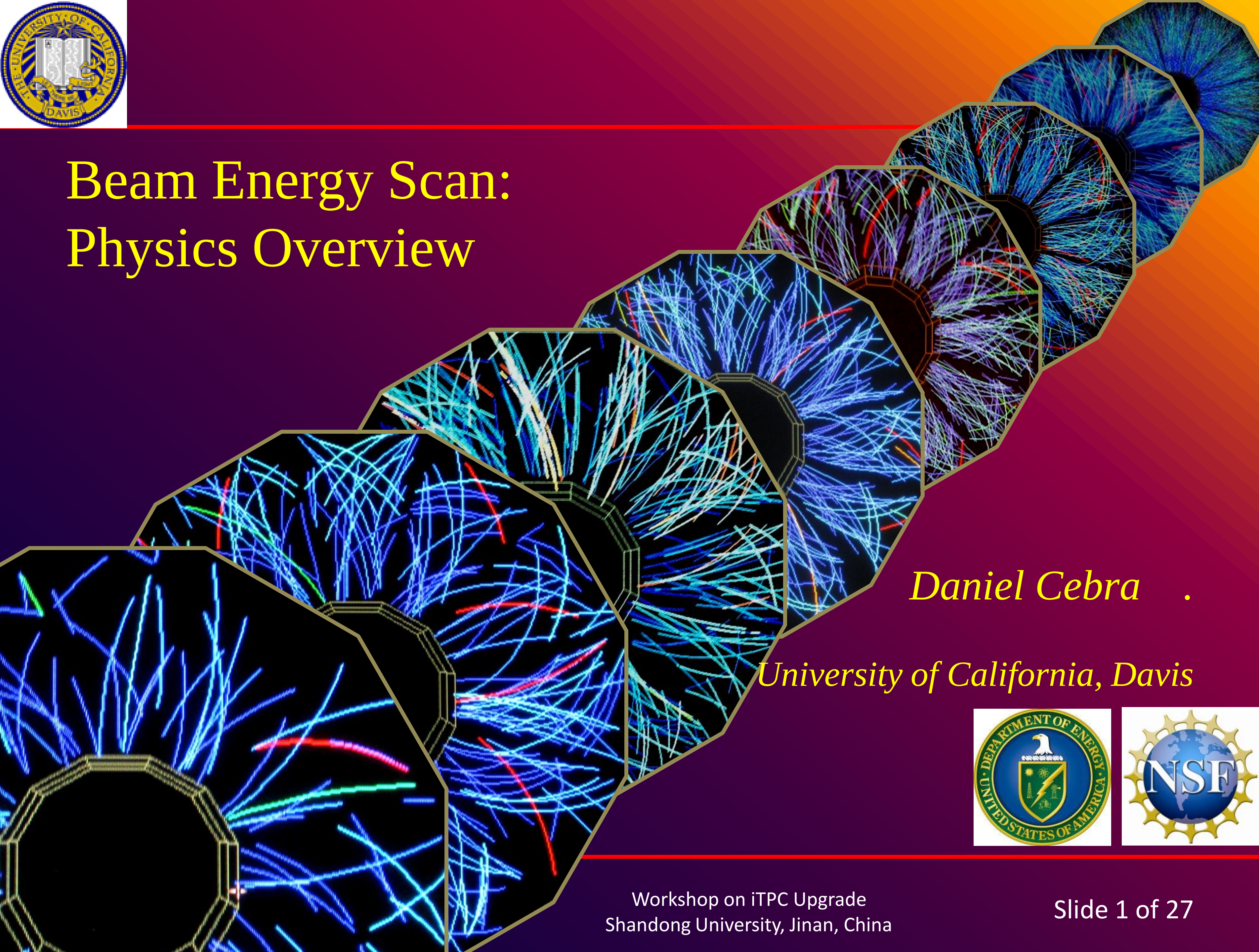
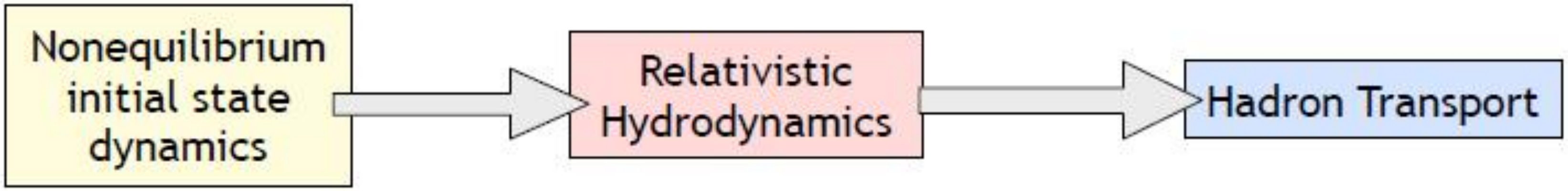
Beam Energy Scan: Physics Overview

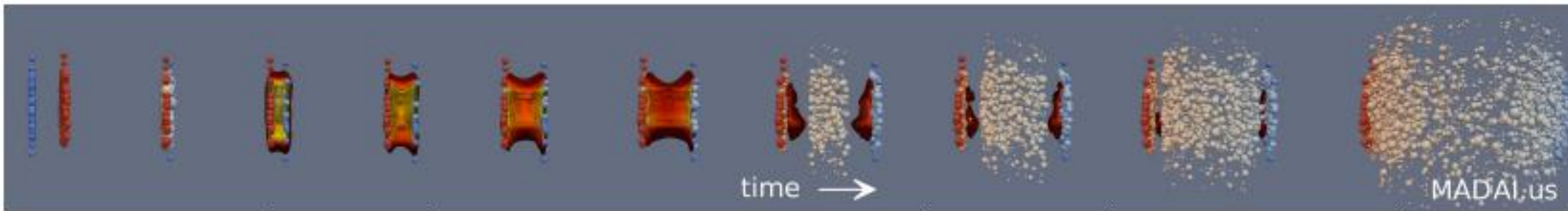


Daniel Cebra .

University of California, Davis

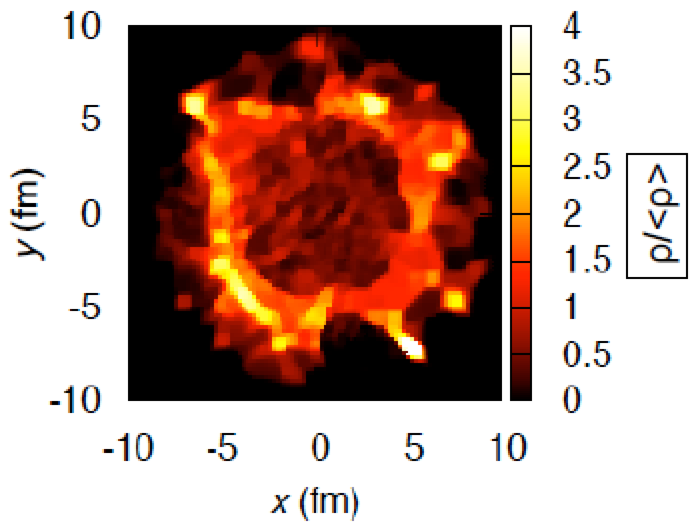
Creating Little Bangs in the Laboratory





$1x\ 10^{-23}$ s | 10×10^{-23} s | 30×10^{-23} s

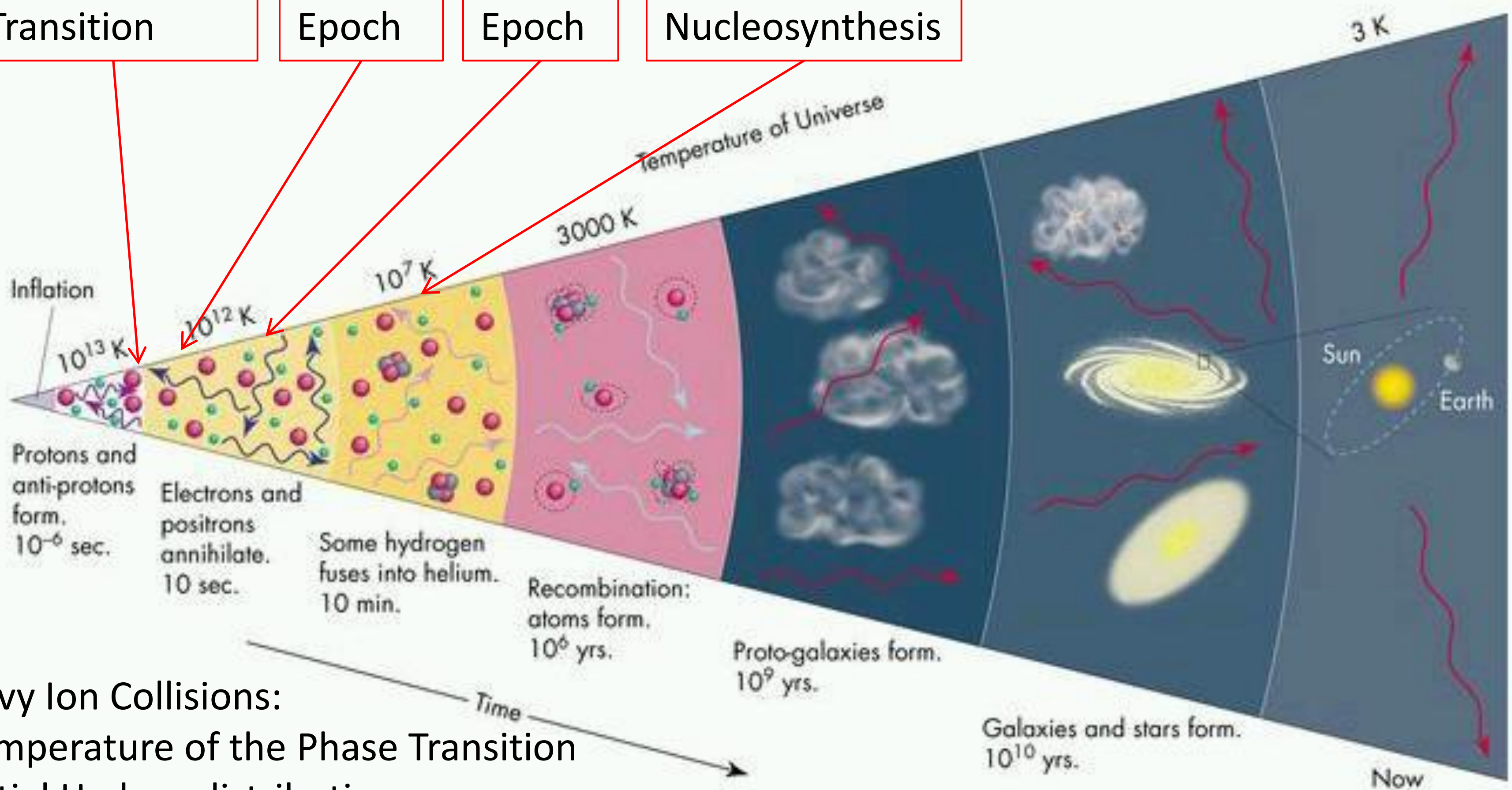
Chiral fluid dynamics



Herold, Nahrgang et al, Nucl.Phys. A925 (2014) 14-24

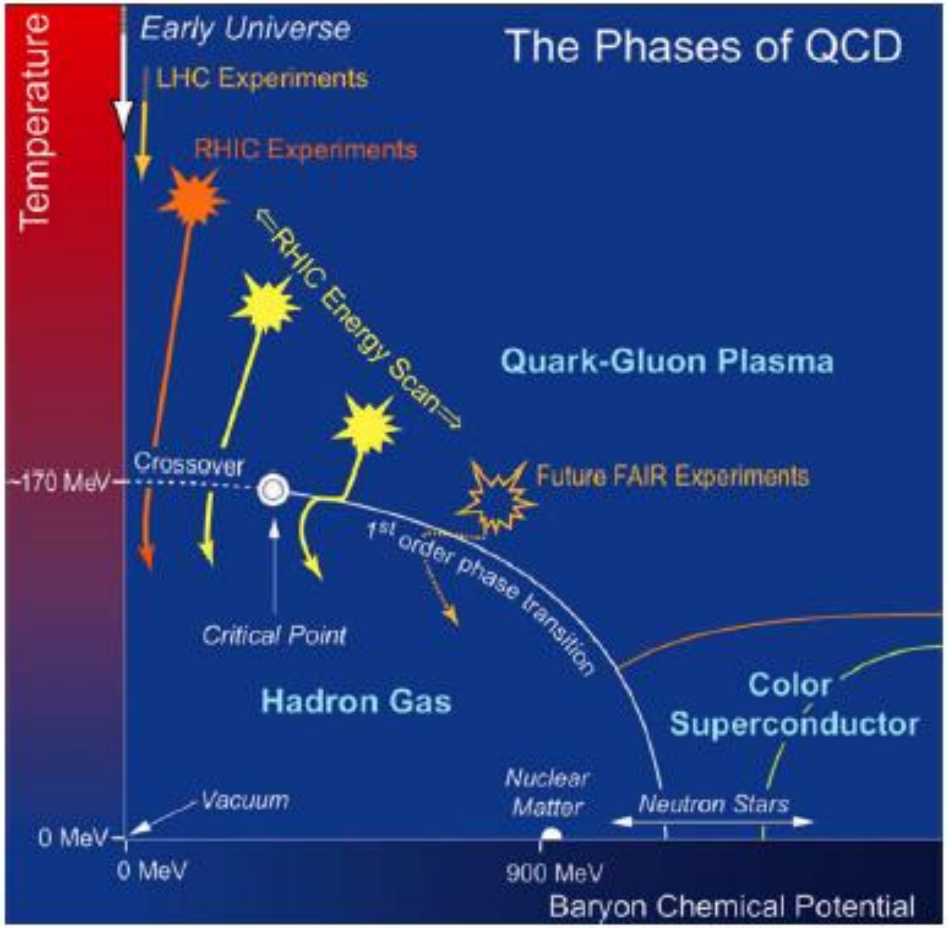
- Rapid thermalization during compression
- Local equilibrium in Quark-Gluon Plasma
- Cooling during Hubble-type expansion
- Hadronization at phase transition
- Continued cooling through elastic scattering
- Kinetic freeze-out

What do Heavy Ion Collisions Tell us about the Big Bang?



Heavy Ion Collisions:

- Temperature of the Phase Transition
- Initial Hadron distributions
- Evolution of hot hadron gas

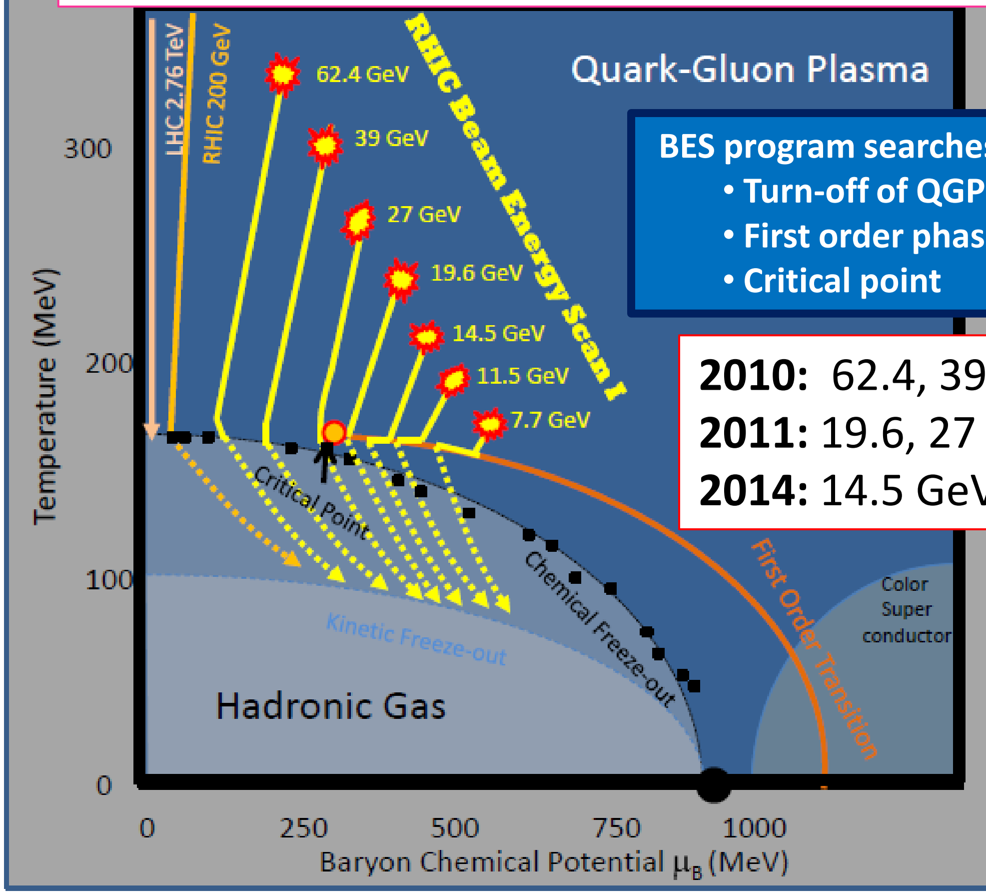


Beam Energy Scan I (2010-2011, and 2014)

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

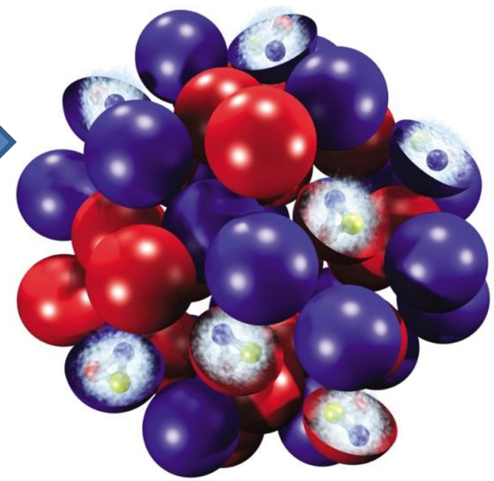


BES program searches for:
- **Turn-off of QGP signatures**
- **First order phase transition**
- **Critical point**

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

How Collision Energy Changes μ_B



- deBroglie wavelength of constituent partons is effected by the beam energy.

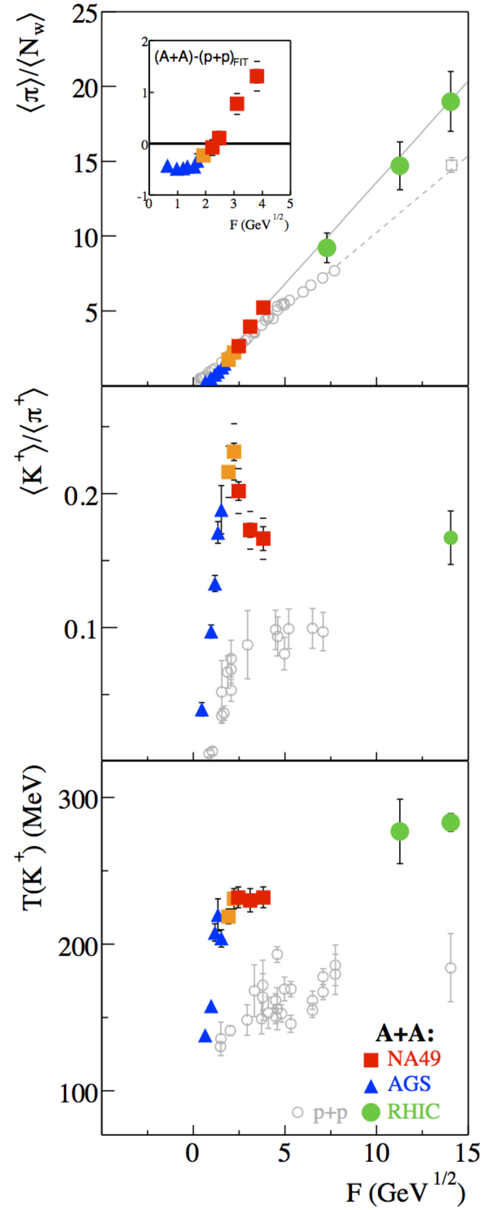
- Determines whether a parton images:
    A. The whole nucleus
    B. Individual nucleons
    C. Individual partons

At lower energy, nucleons are opaque, and the valence quarks are stopped in the fireball.
Excess quarks ➔ higher μ_B

At higher energy, nucleons are transparent, and the valence quarks are pass through and exit the fireball.
Equal quarks and anti-quarks ➔ lower μ_B

What Was Learned in the Earlier Scans?

- Summary of AGS, SPS, and early RHIC Results
- Inclusive observables → *onset of deconfinement* at 7-8 GeV.
- The observables suggest a change in the nature of the system.
- More discriminating studies were needed to understand the nature of the phase transition and to search for critical behavior.
- It is best to study regions above and below the possible onset energy.



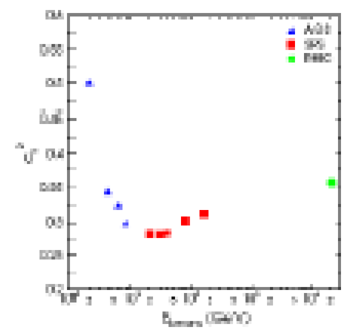
Onset of Deconfinement:
early stage hits transition line,
observed signals: kink, horn, step
Predictions SMES: APP B30 2705 (99),
Results: PR C77 024903 (08)

Kink

Horn

Step

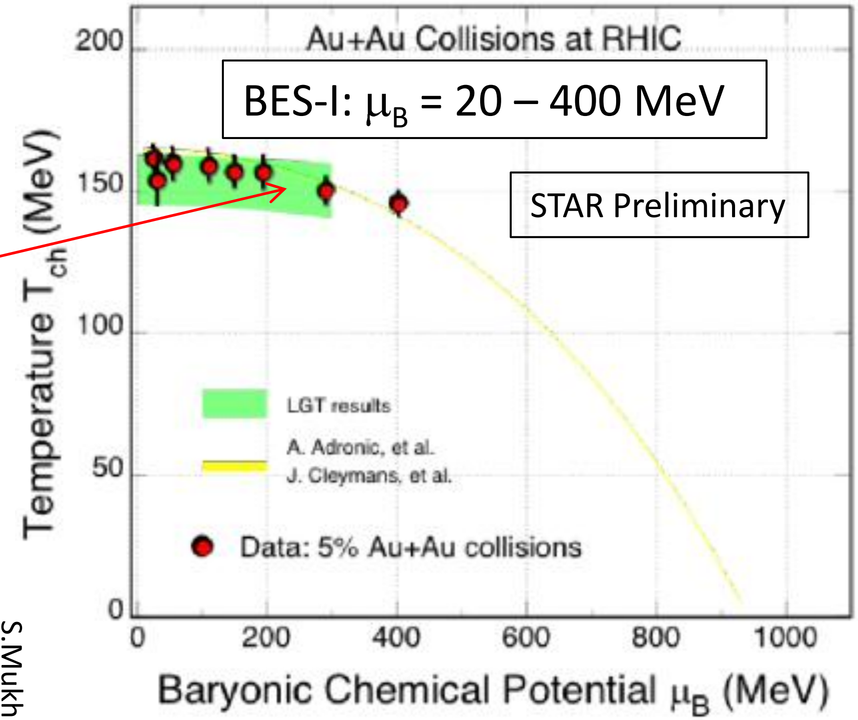
the dale
sound velocity from
width of pion rapidity spectra
nucl-th/0611001

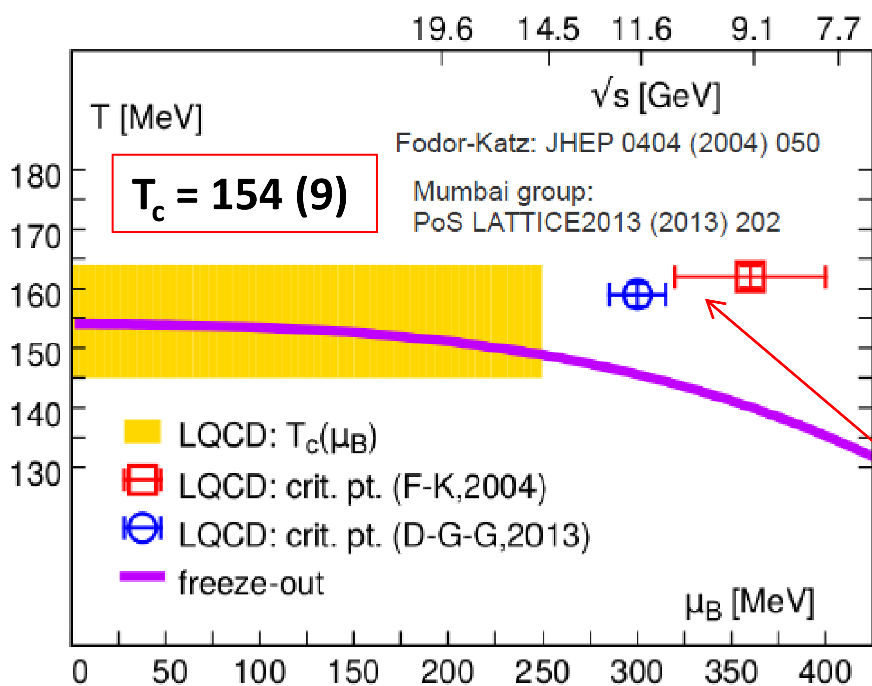


Setting the Scene

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.

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

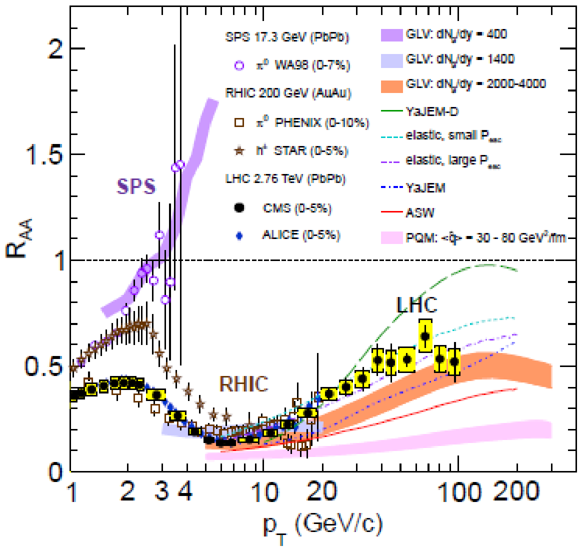


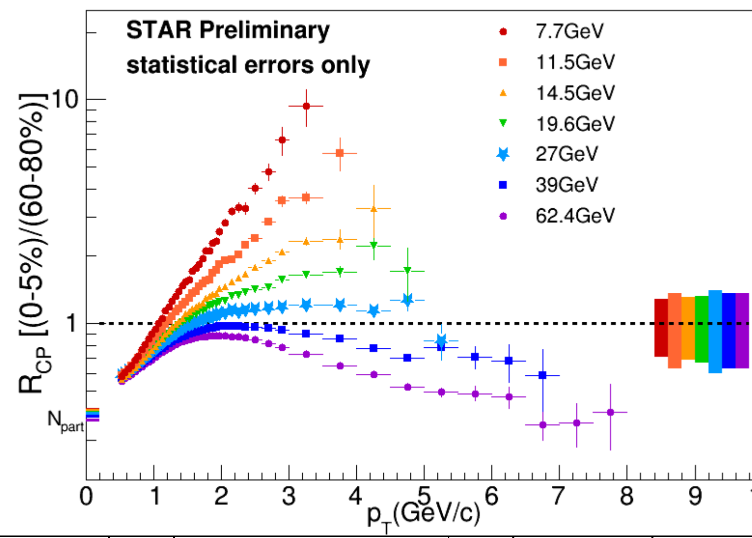


Some Lattice Gauge Theory predictions suggest that the low end of the BES-I scan one may find the critical point

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.
- Not sufficient reach to search for evidence of high p_T suppression below 19.6 GeV
- Stopped Baryons complicate inclusive R_{CP} measurements
- pQCD calculations show high p_T suppression
- Hybrid calculations describe the low p_T behavior

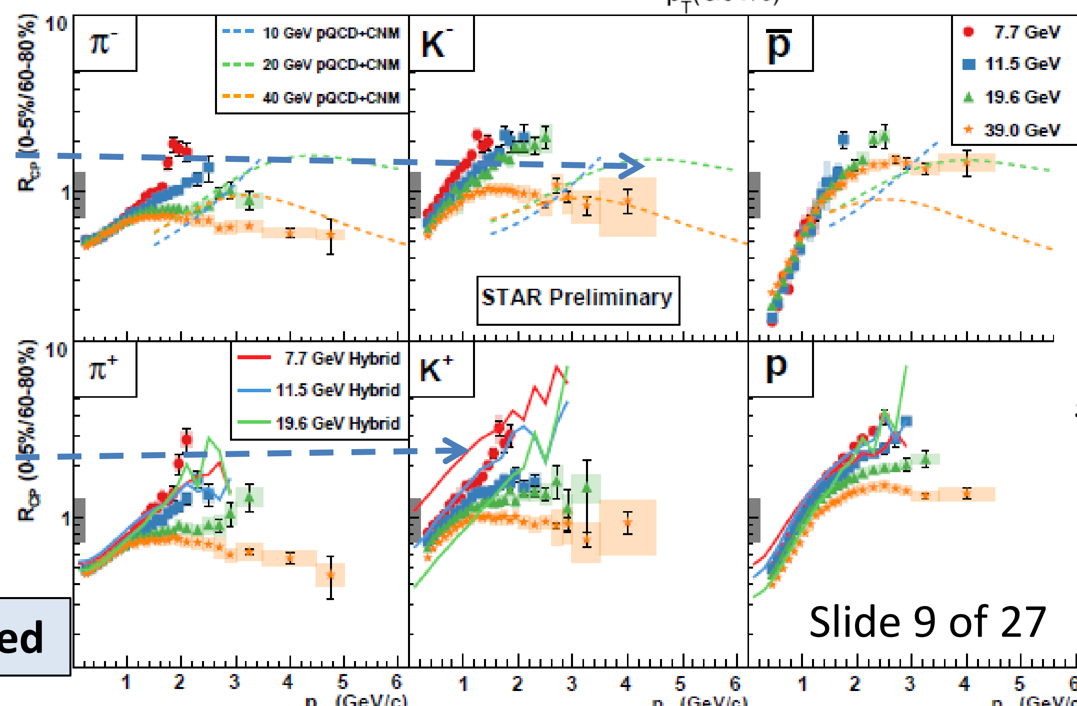




S. Horvat QM2015

pQCD calculations

Hybrid calculations



E. Sangaline QM2012

More p_T reach is needed

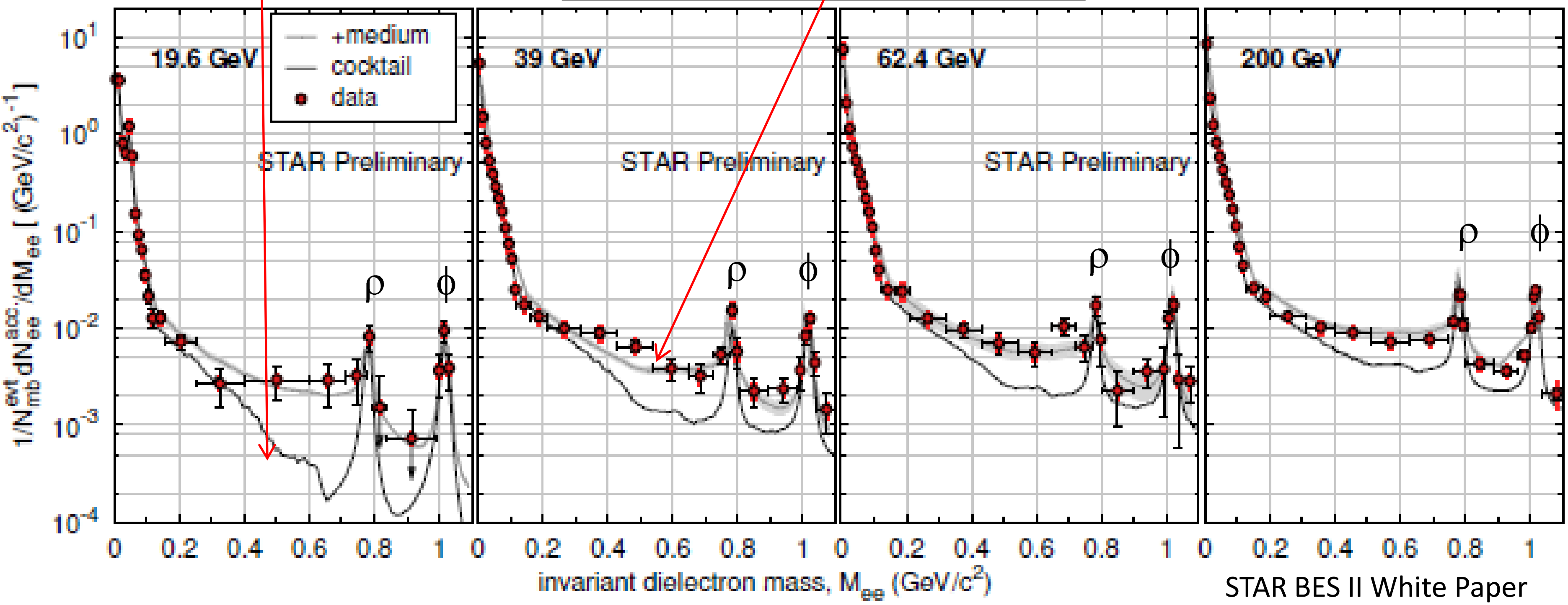
Chiral Phase Transition

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

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

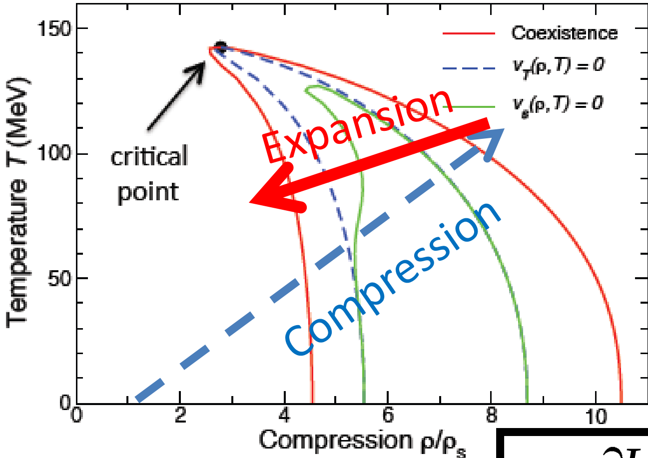
Grey lines are in medium calculations from R. Rapp which include both HG and QGP components (including medium broadened ρ meson). Model is able to match the data

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

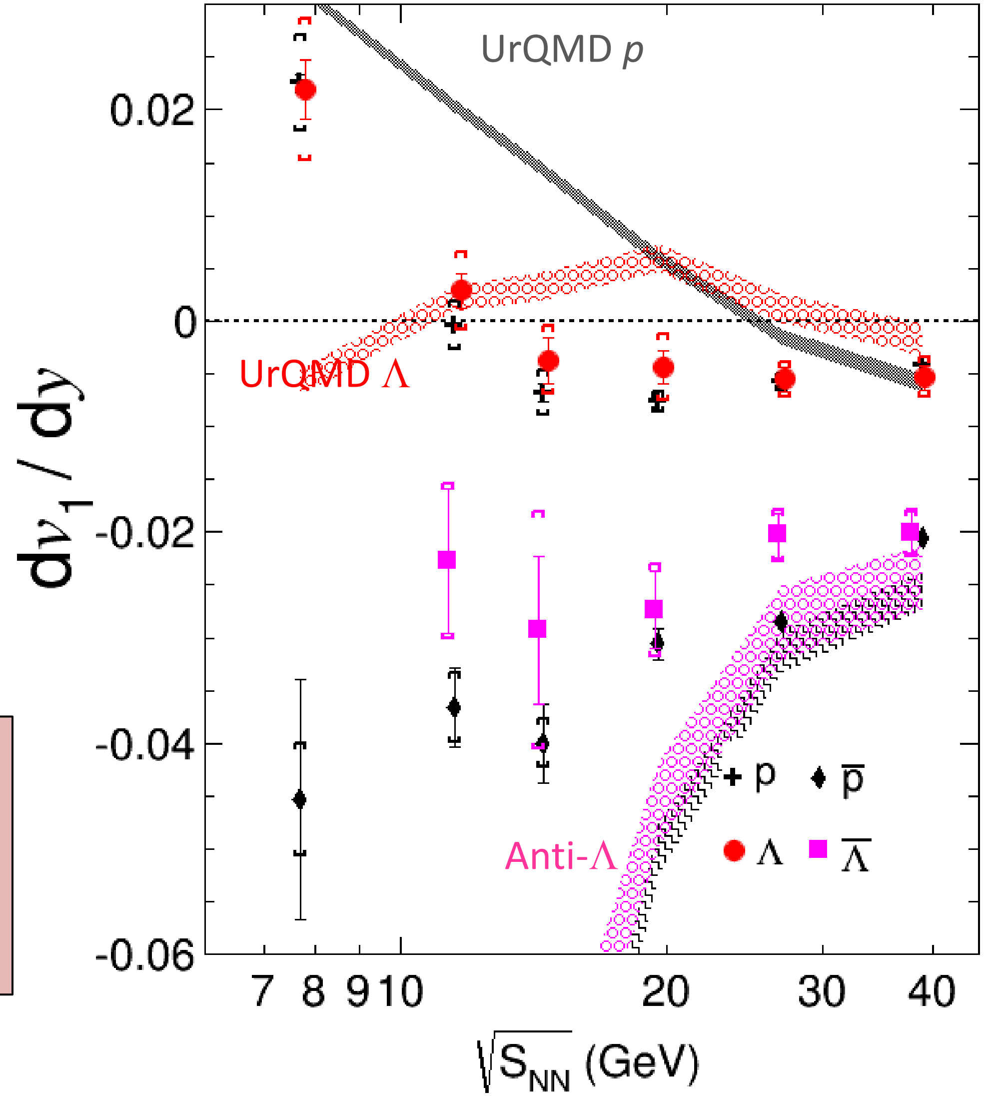


STAR BES II White Paper

Search for 1st Order Phase Transition – v_1

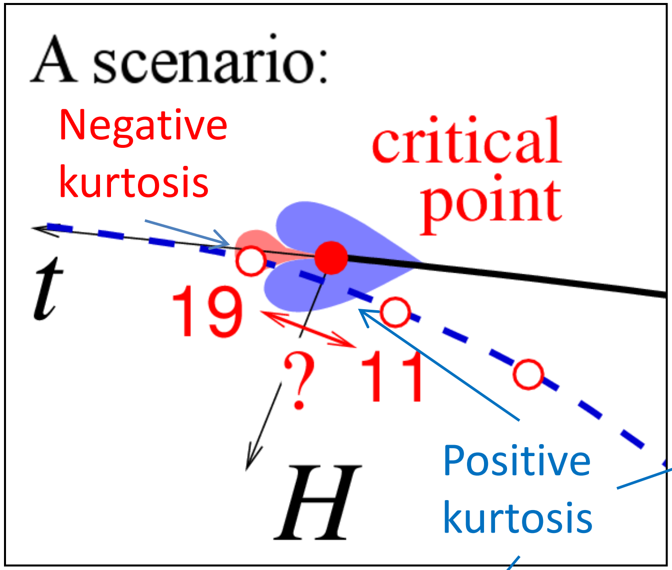


$$\mu = \frac{\partial U}{\partial N}$$

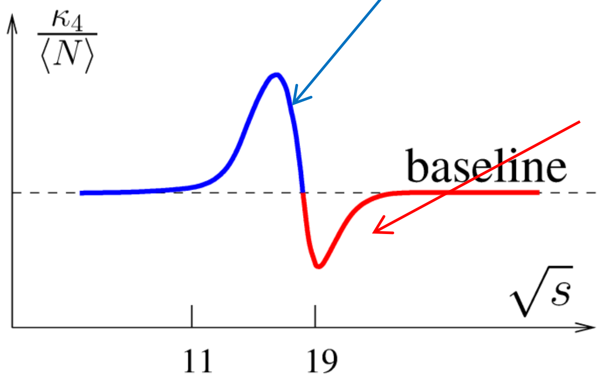


- First order phase transition is characterized by unstable coexistence region. This spinodal region will have the softest Equation of State
- v_1 is a manifestation of early pressure in the system

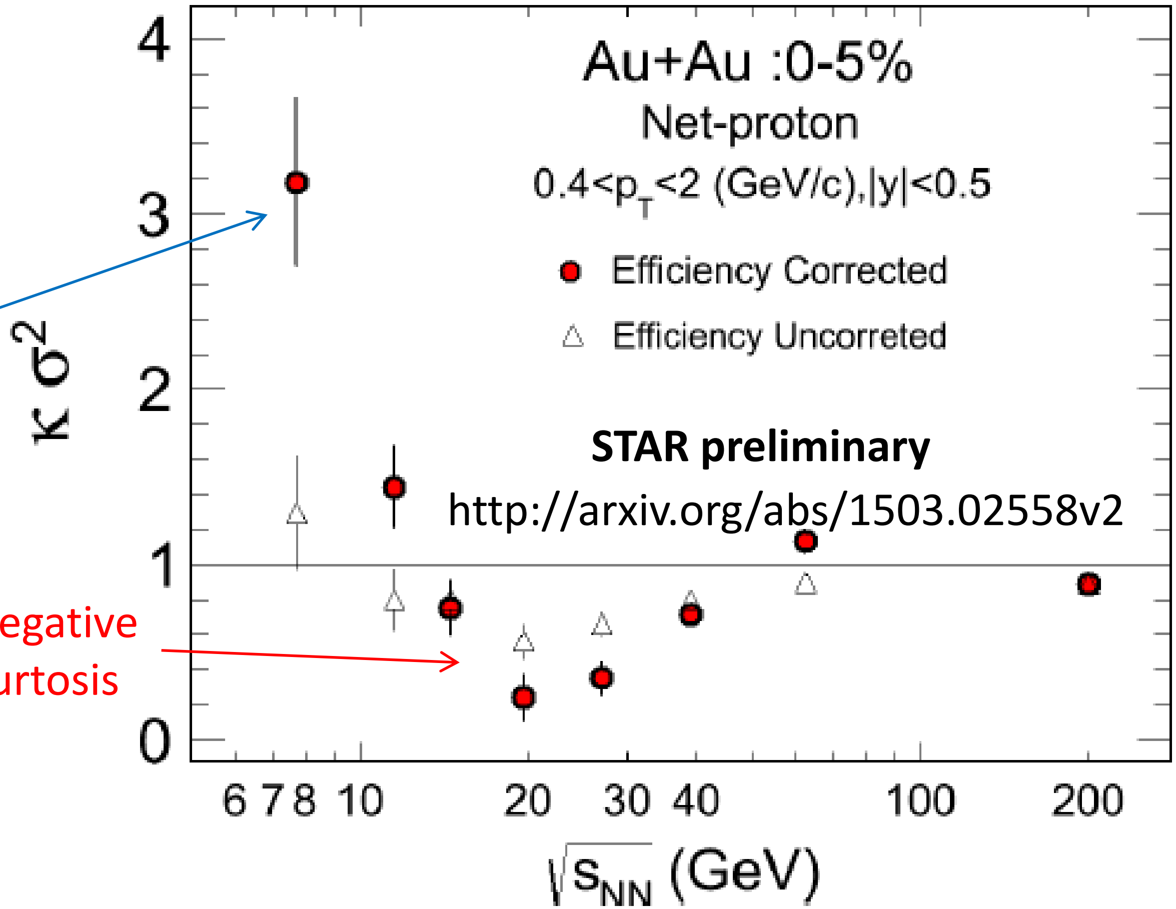
Search for the Critical Point – $\kappa\sigma^2$



M. Stephanov



STAR results show a fall and rise of the fluctuation variable



Negative kurtosis

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.

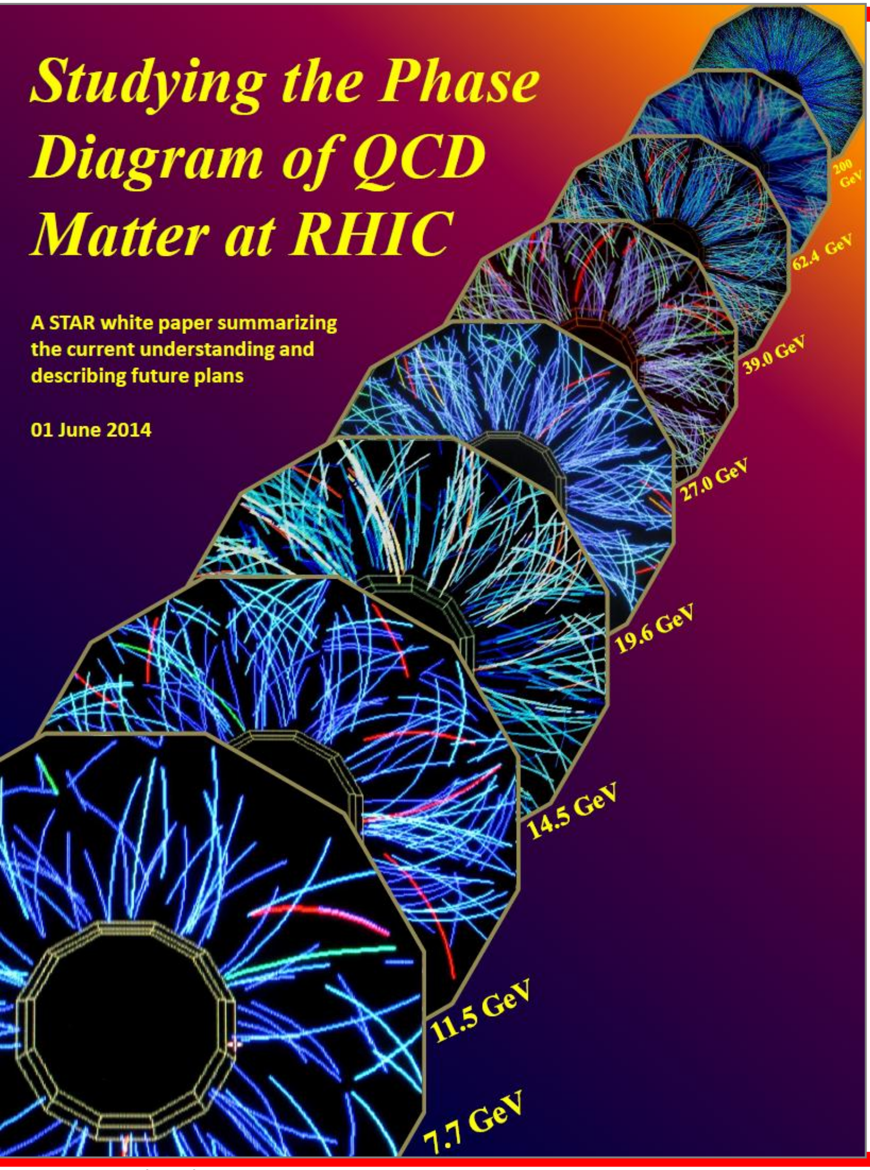
- Signatures consistent with a parton dominated regime either disappear, lose significance, or lose sufficient reach at the low energy region of the scan.

- 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



Beam Energy Scan II (2019-2020)

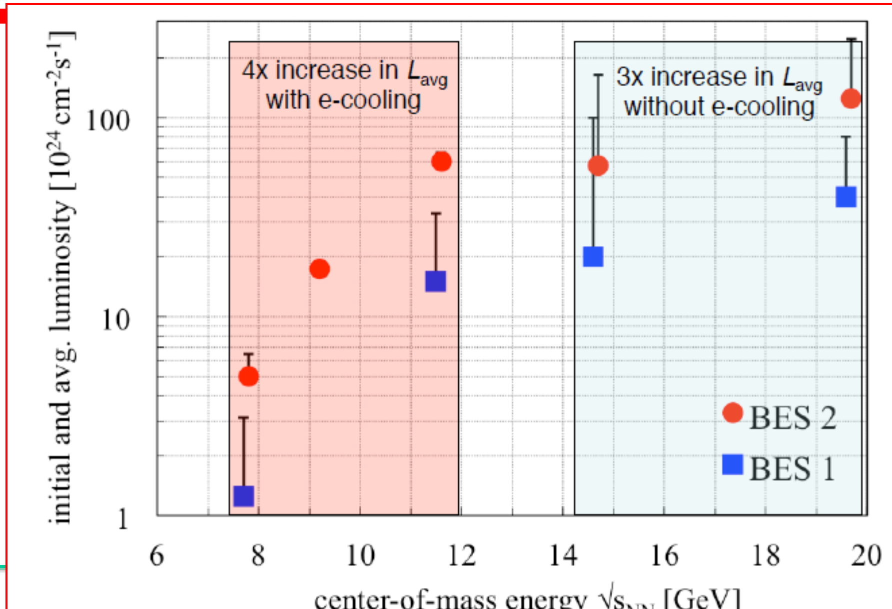
Select the most important energy range
➔ 5 to 20 GeV

Improve significance
➔Long runs, higher luminosity

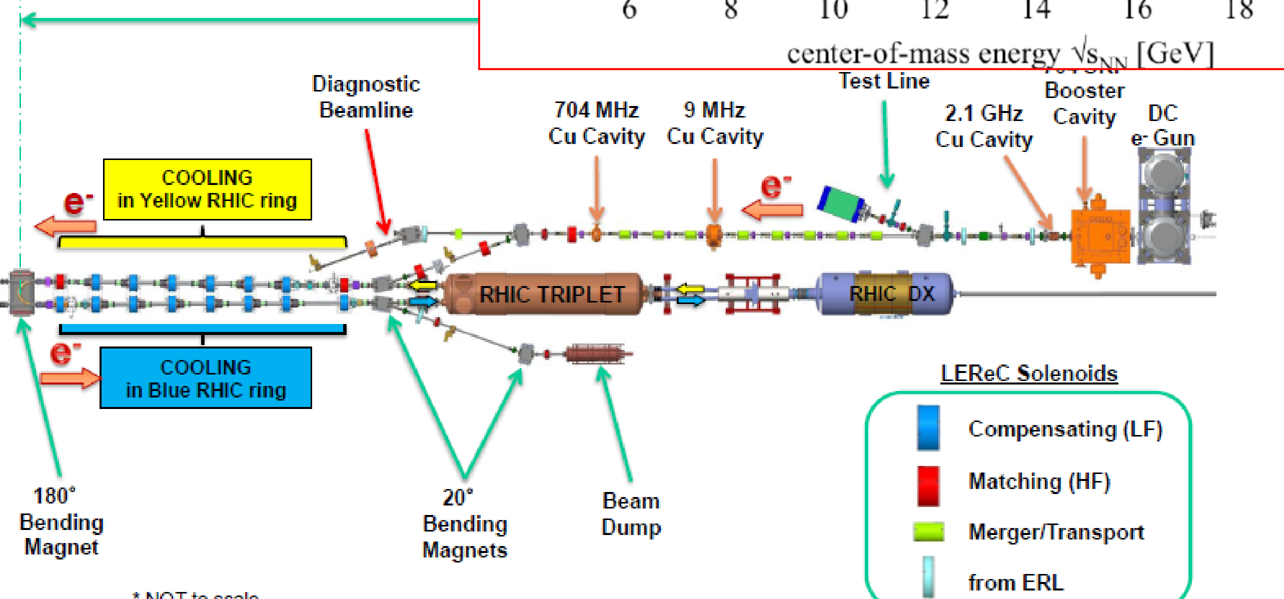
Refine the signals
➔ Detector improvements

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



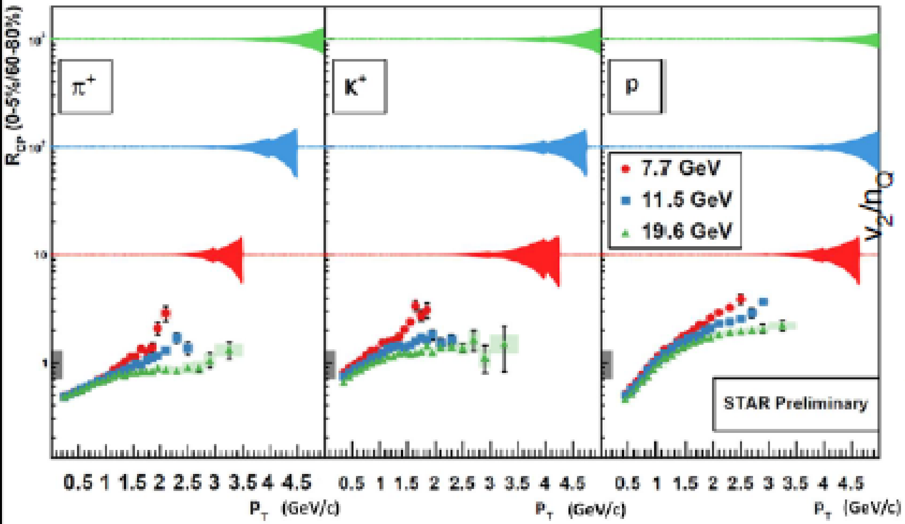
BES Phase II Proposal

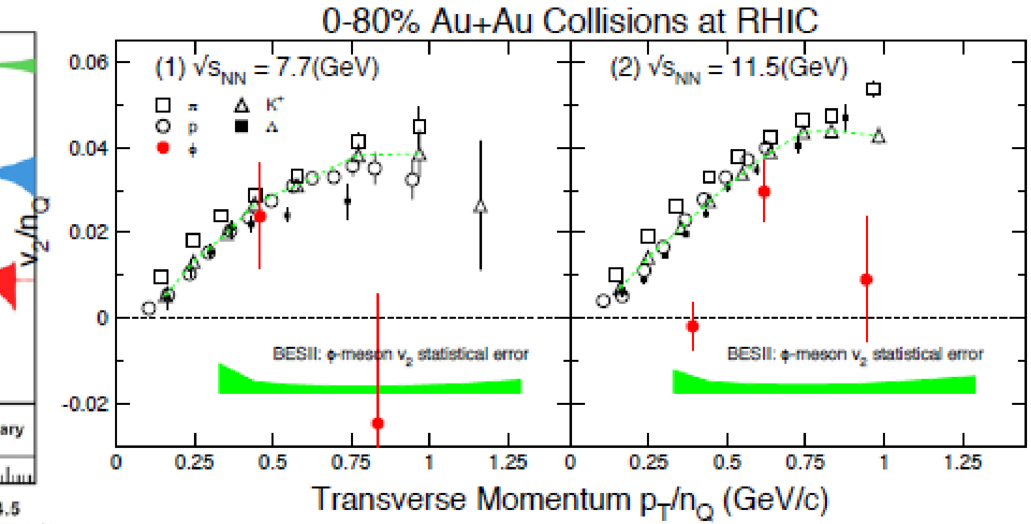
BES Phase II is planned for two 24 cryo-week runs in 2019 and 2020

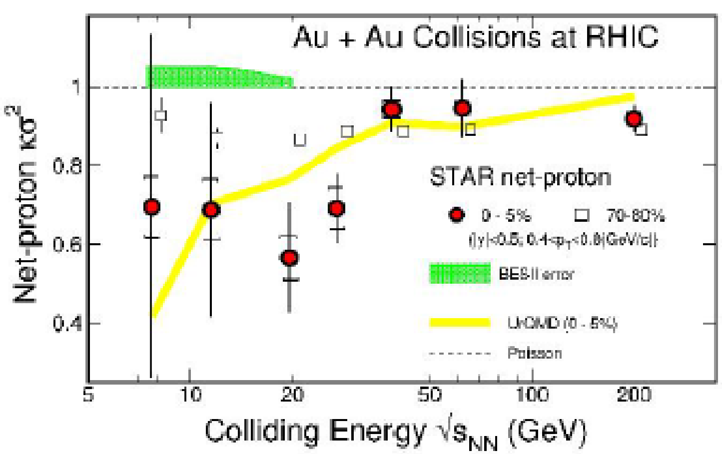
	2020			2019	
$\sqrt{S_{NN}}$ (GeV)	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25		1.7	2.4	4.5
BES I $\mathcal{L}$ ($1\times10^{25}/cm^2sec$)	0.13		1.5	2.1	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	3	3
Beam Time (weeks)	**12**	**9.5**	**5.0**	**5.5**	**4.5**
	With electron cooling			Without cooling	

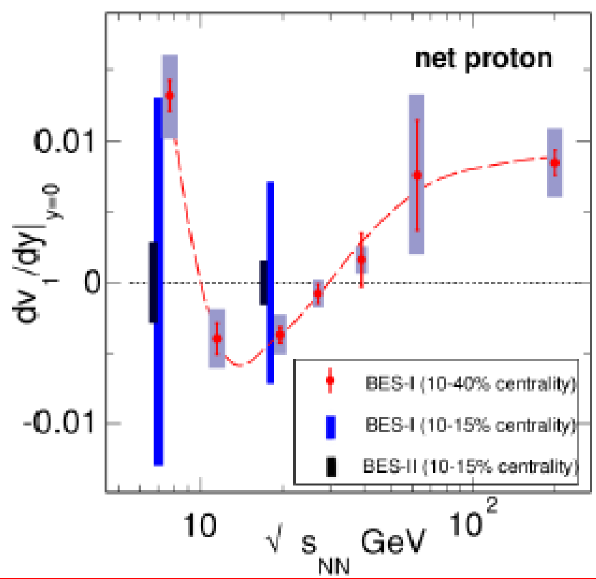
Revised estimates

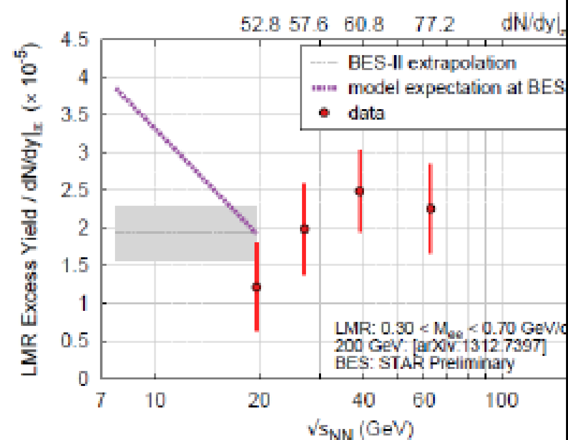
Reduction in Errors with Improved Statistics



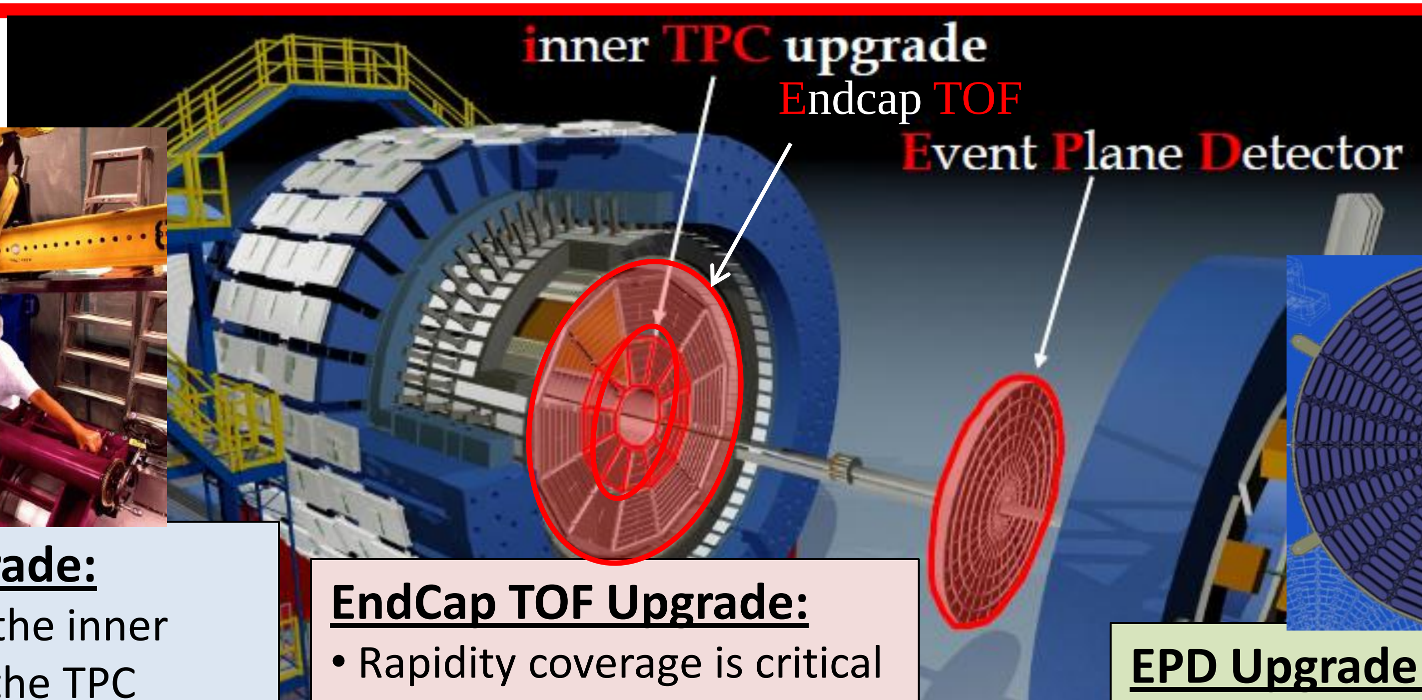






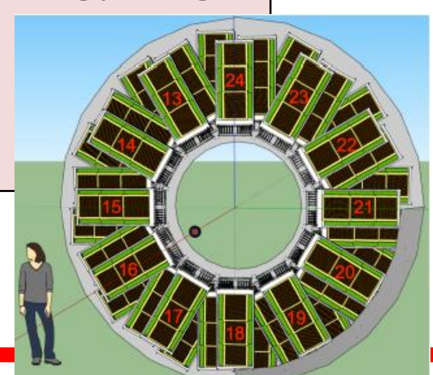


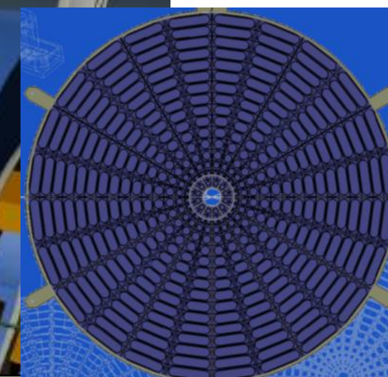
The STAR Upgrades and the FXT program



iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage to 1.5 (2.2 for FXT)
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c
- Ready in 2019

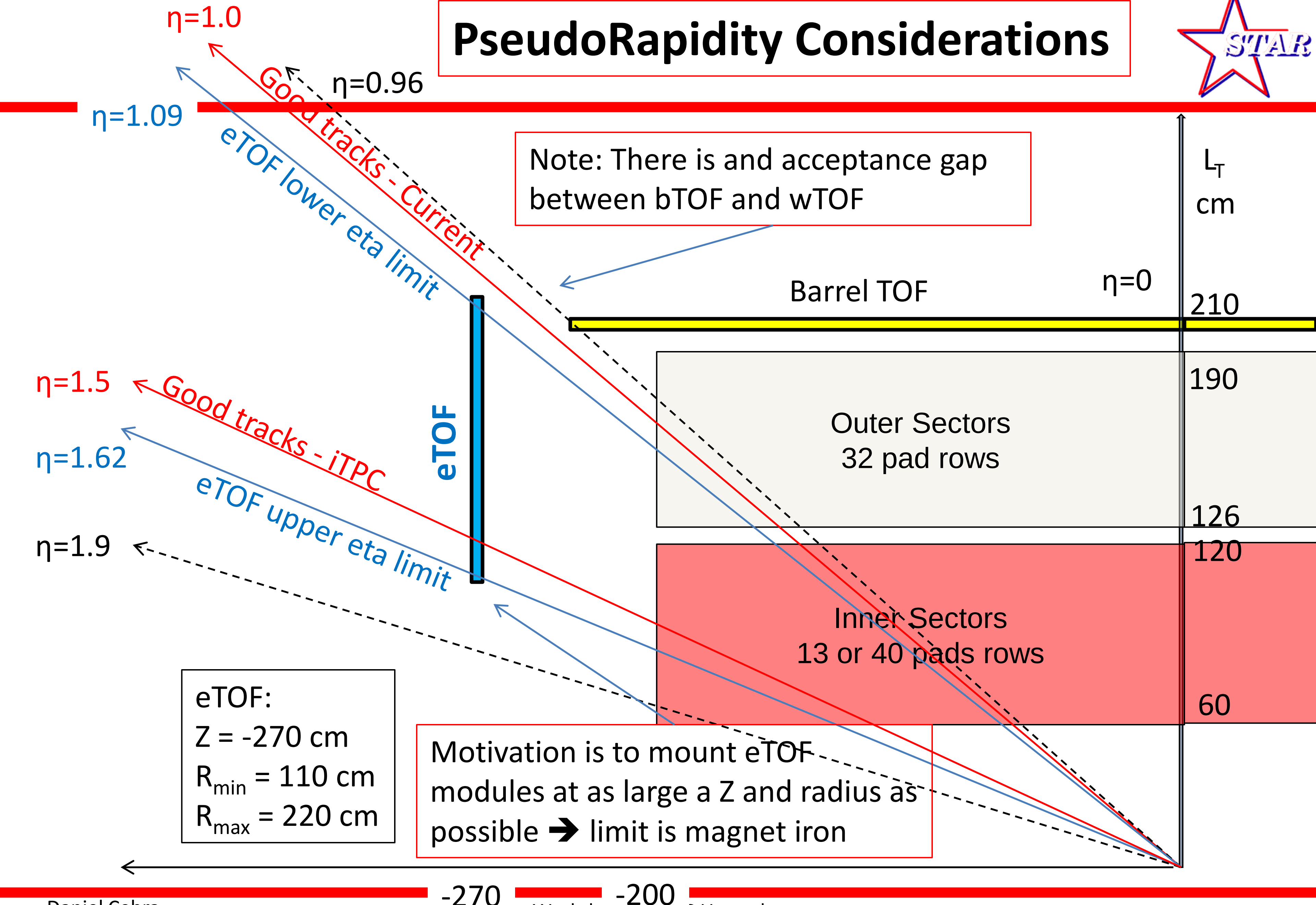
EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity
- Allows higher energy range of FXT program
- CBM/FAIR
- Ready 2019





EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics
- Ready 2018

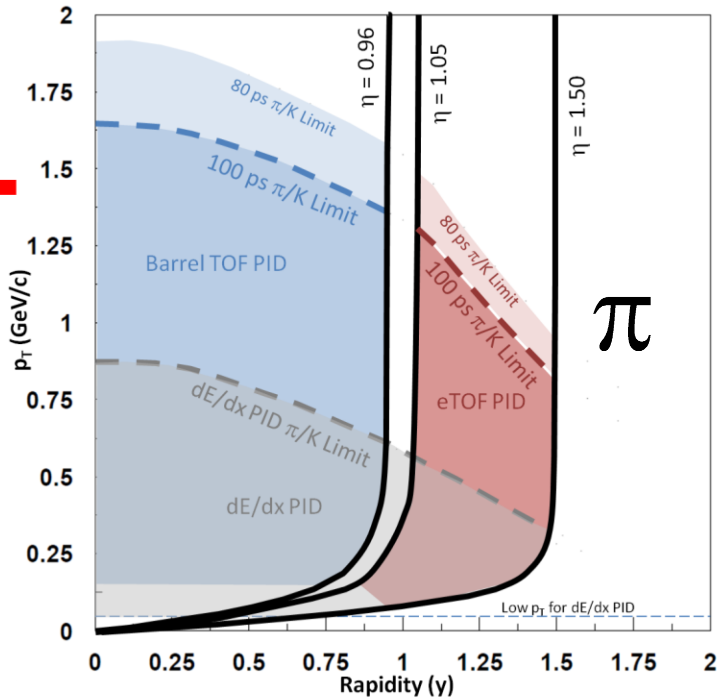
PseudoRapidity Considerations

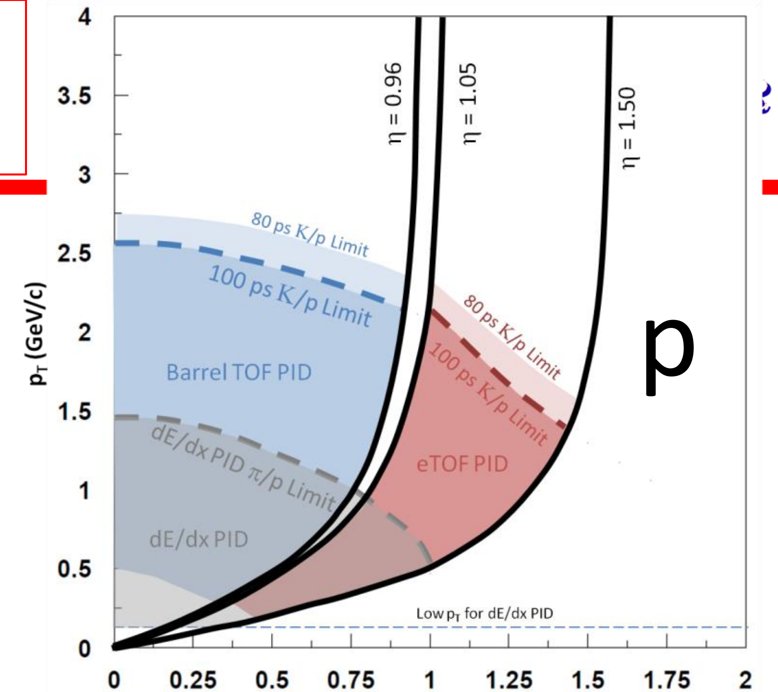


eTOF:
Z = -270 cm
R_{min} = 110 cm
R_{max} = 220 cm

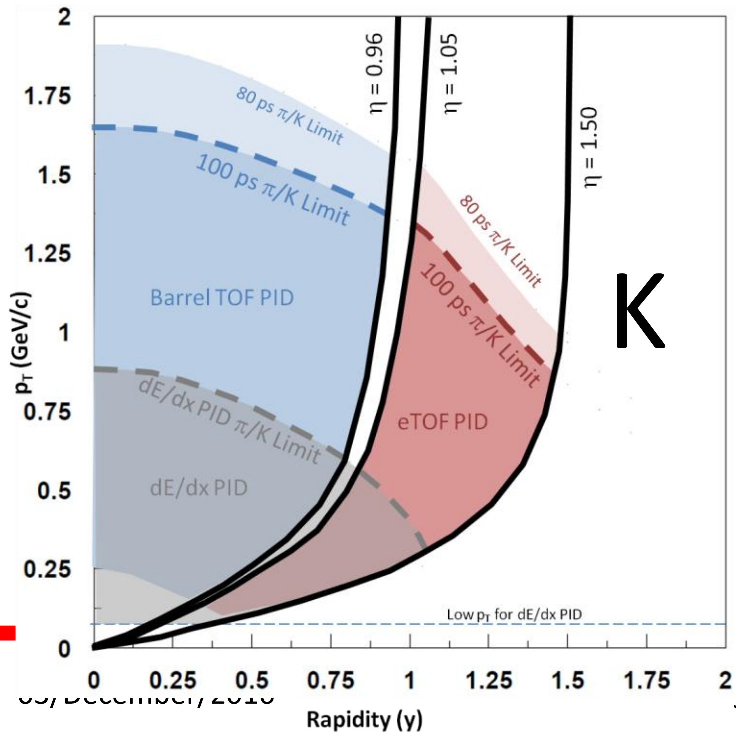
Motivation is to mount eTOF modules at as large a Z and radius as possible ➔ limit is magnet iron

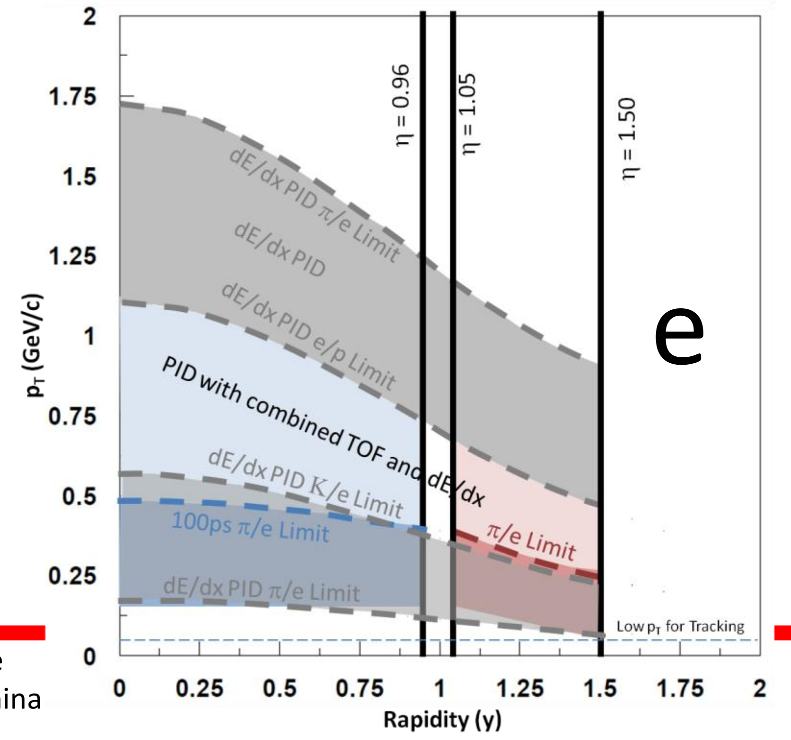
Acceptance Improvements



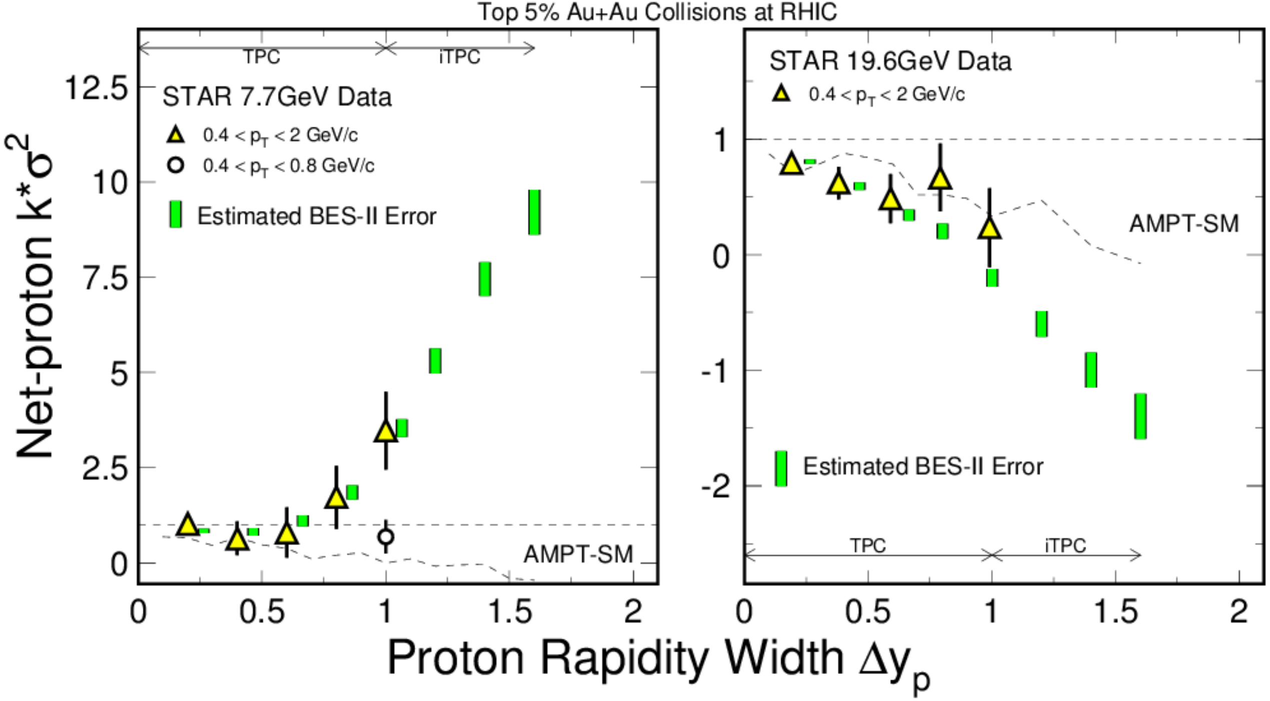


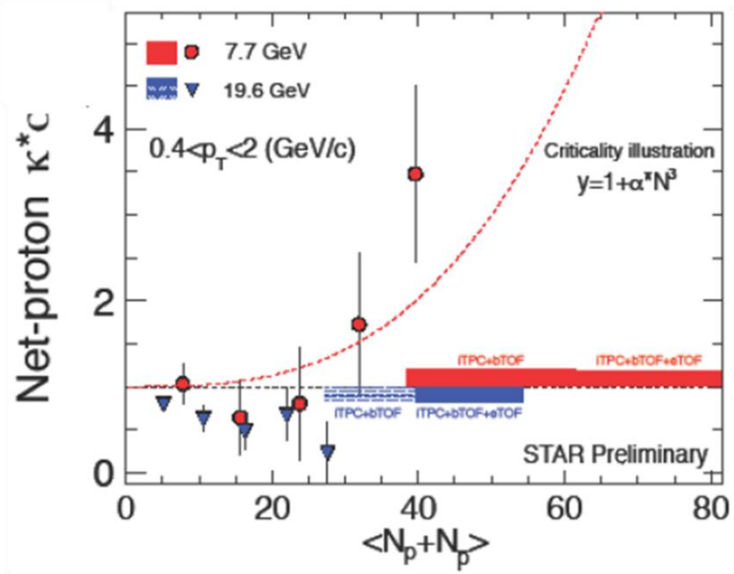
- Extends rapidity coverage ➔ allows a change in μ_B
- Improves yields of protons ➔ better kurtosis
- Improves coverage for electrons ➔ better di-electron studies

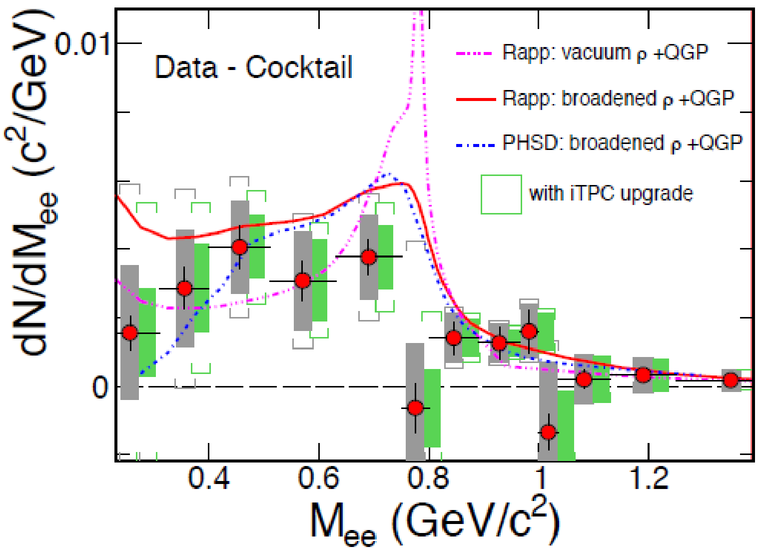




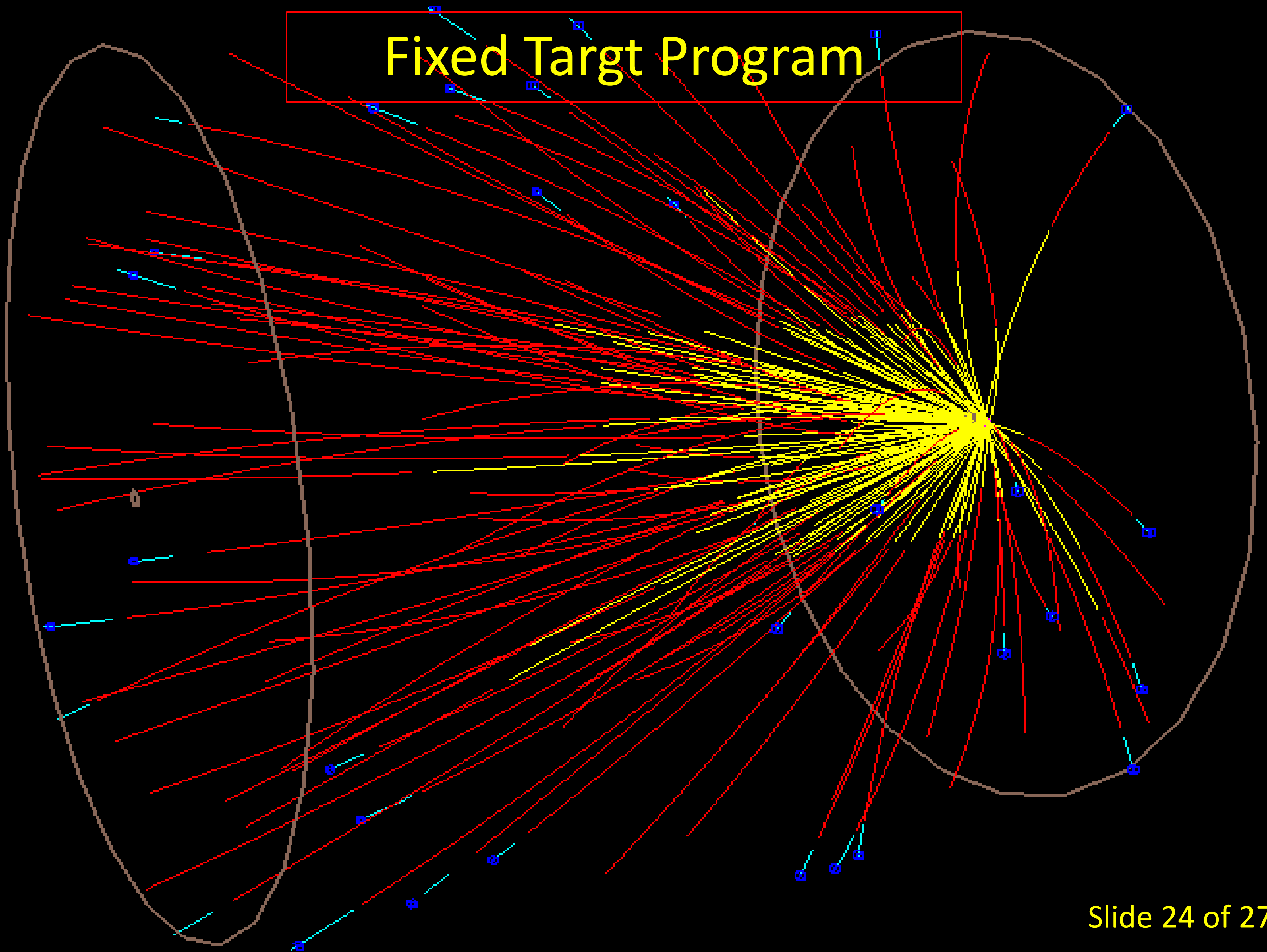
Improvements due to Upgrades







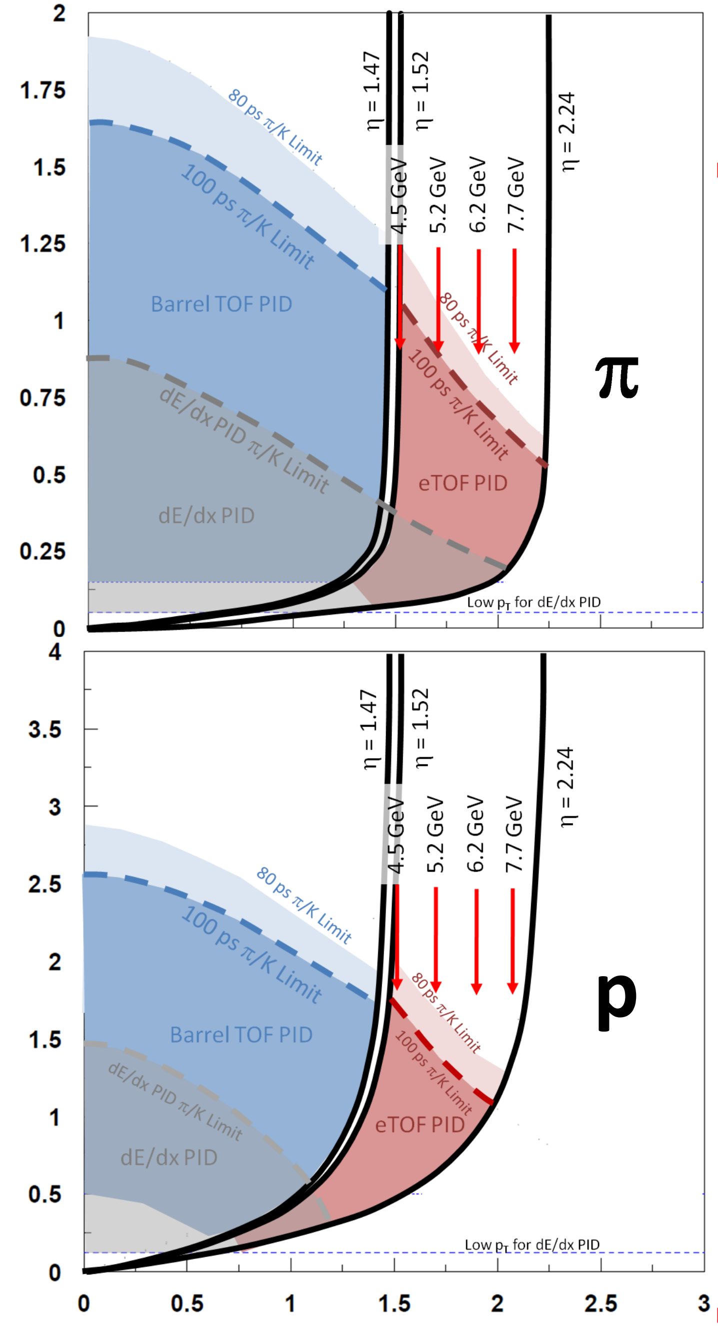
Fixed Targt Program



FXT Program

Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721
5.0	2.5	1.6	0.82	774

- Data rate is DAQ limited
- Would need 100 Million Events at each energy to make the sensitivity of BES-II
- Roughly one to two days per energy

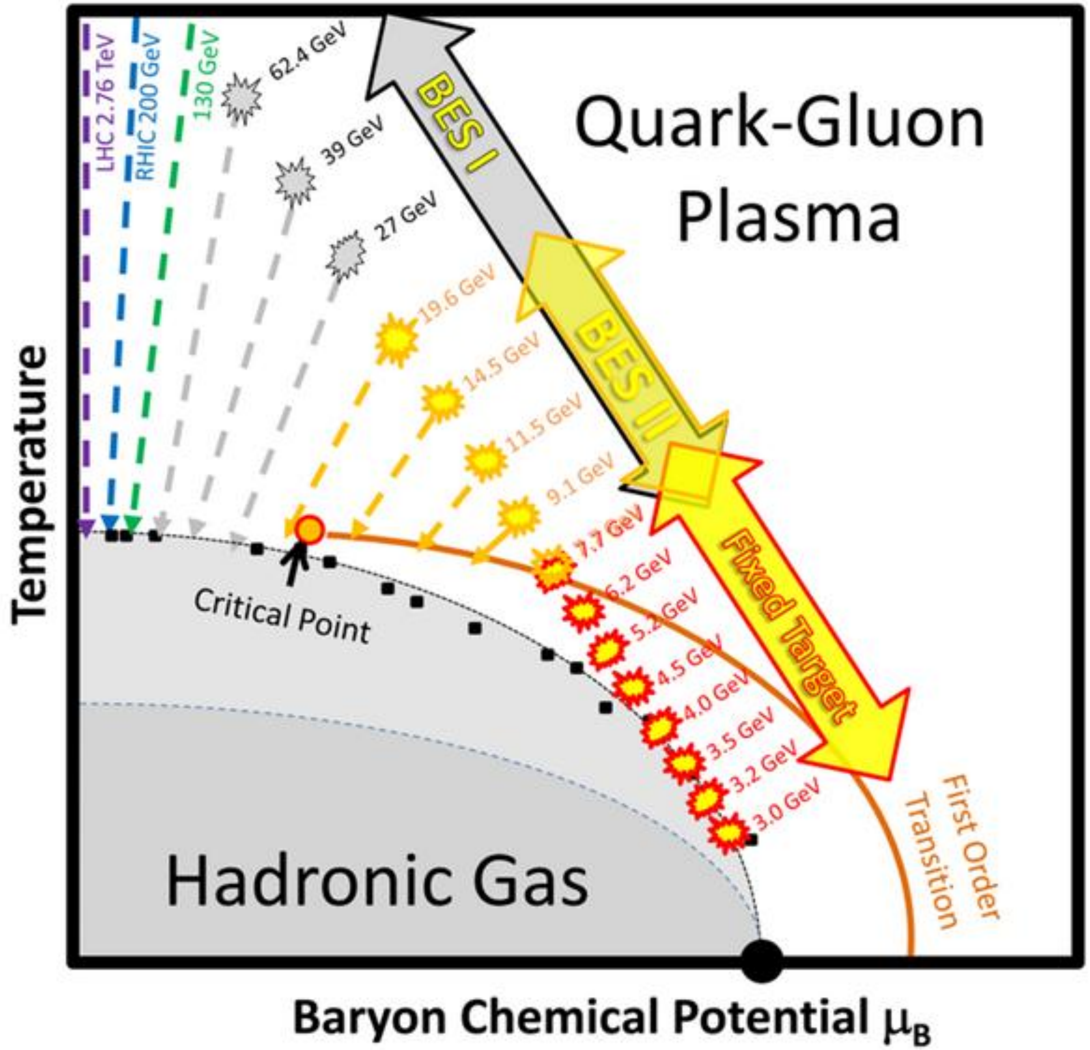


Fixed-Target Program 3.0 to 7.7 GeV

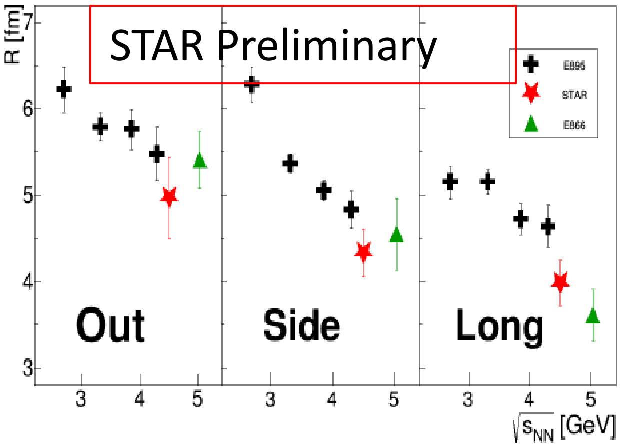
The Fixed-Target Program will extend the reach of the RHIC BES to higher μ_B.

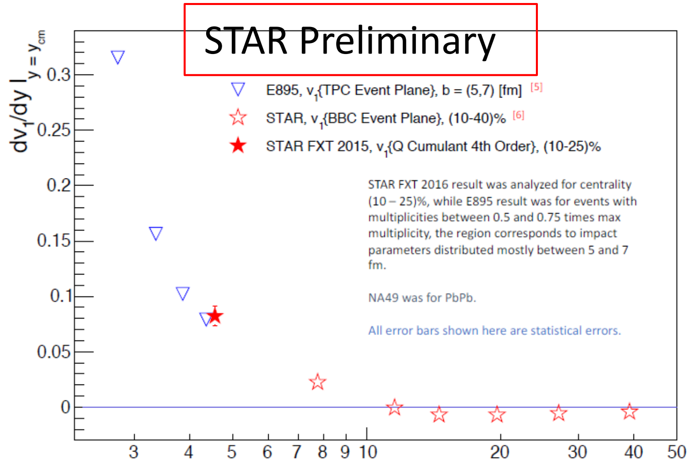
Goals:

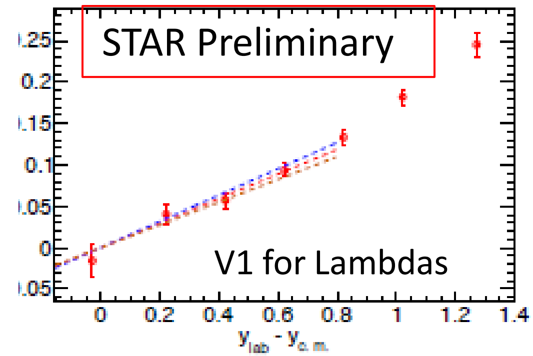
1) Search for evidence of the first entrance into the mixed phase
2) Control measurements for BES collider program searches for Onset of Deconfinement
3) Control measurements for Critical Point searches

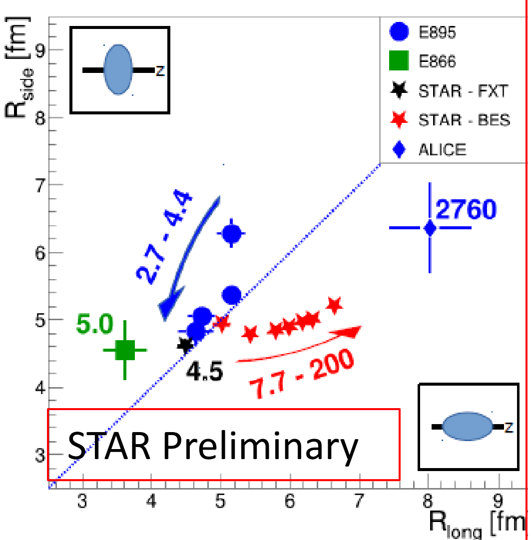


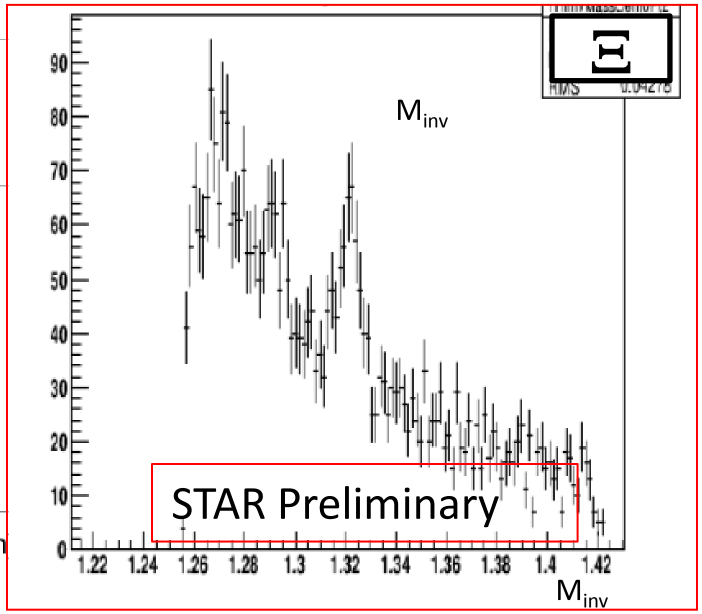
Sampling of Preliminary FXT Results

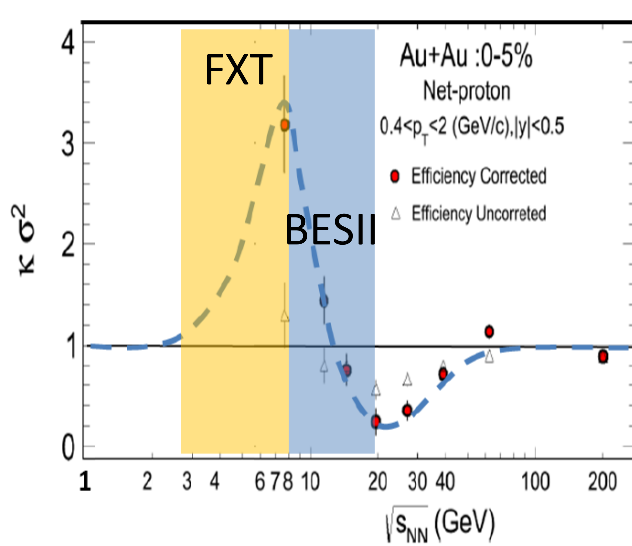






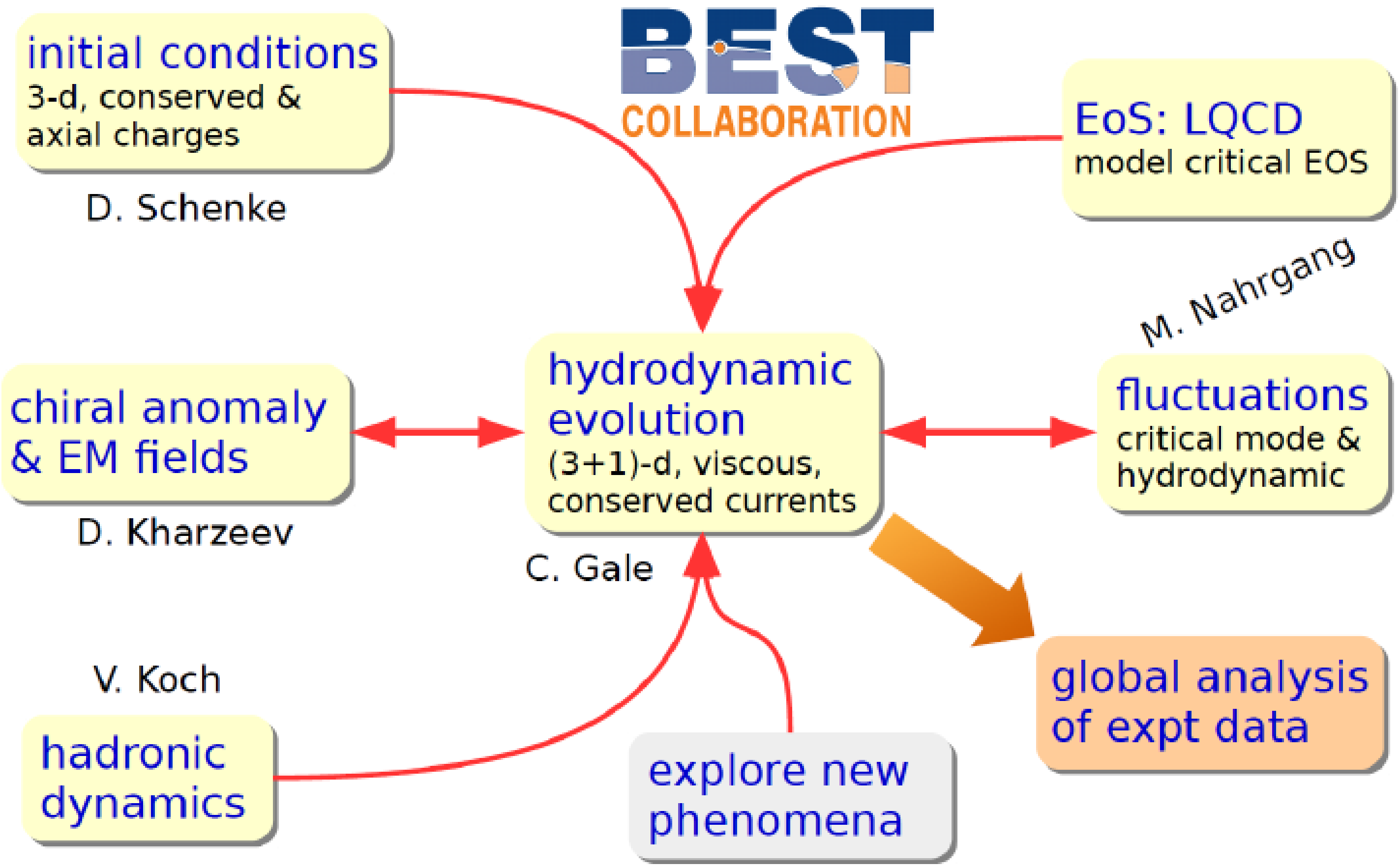






Beam Energy Scan Theory (BEST) Collaboration

"Fixed-term, multi-institution collaboration established to investigate a specific topic in nuclear physics of special interest to the community"



Conclusions

- Results from Beam Energy Scan programs at AGS, SPS, and RHIC support a model of QCD matter that has both a hadronic and partonics state.

- Key measurements need more data (v_2 of ϕ, dileptons)

- Detector upgrades extend coverage ➔ physics reach ($\kappa\sigma^2$)

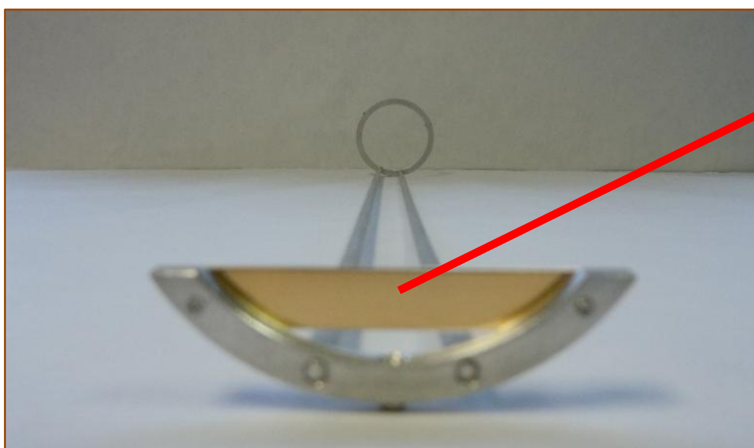
- Fixed-target program will extend energy (μ_B) reach of BES program ➔ coverage of upgrade detectors needed

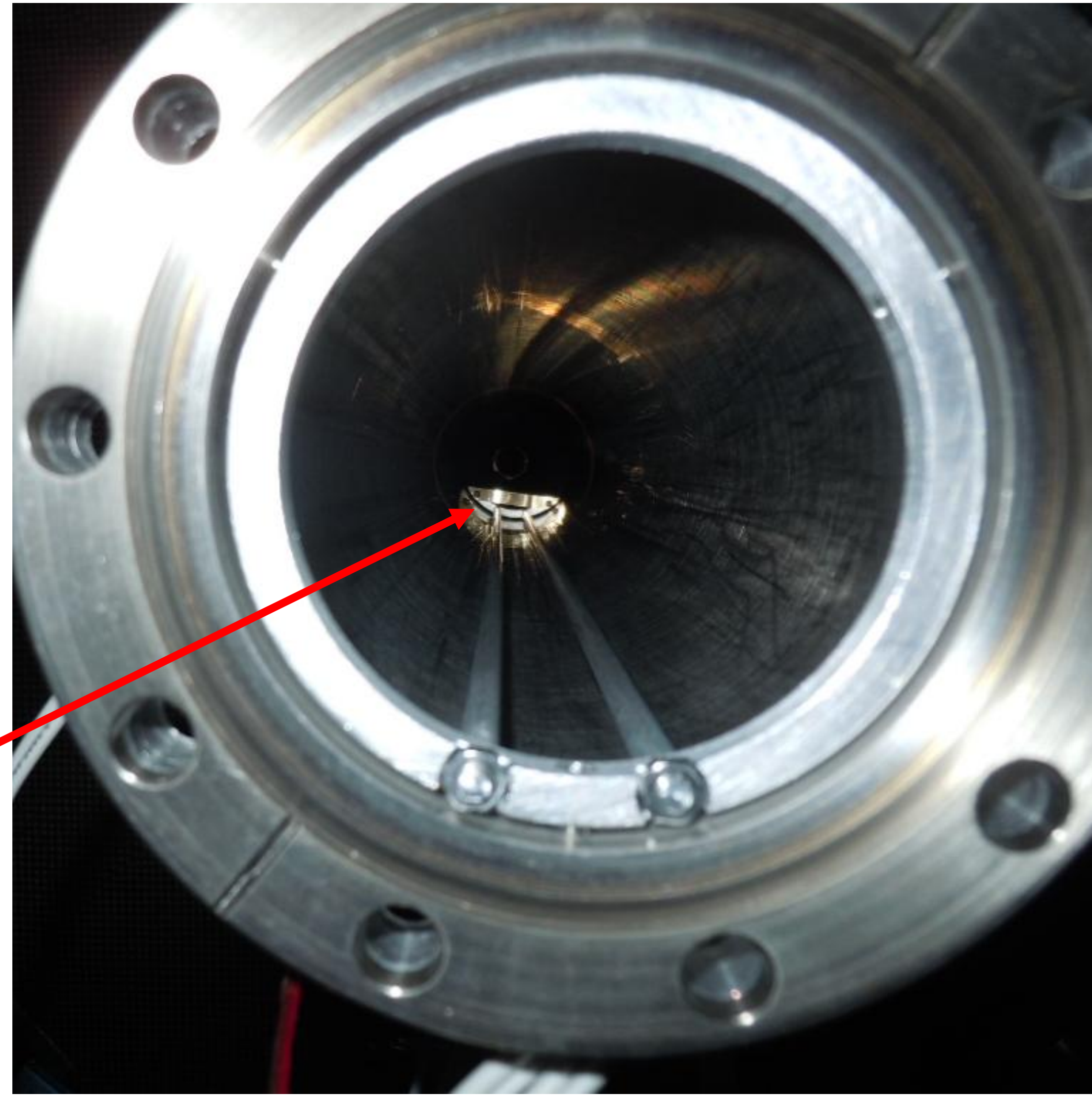
Extras

Target Design 2014 and 2015

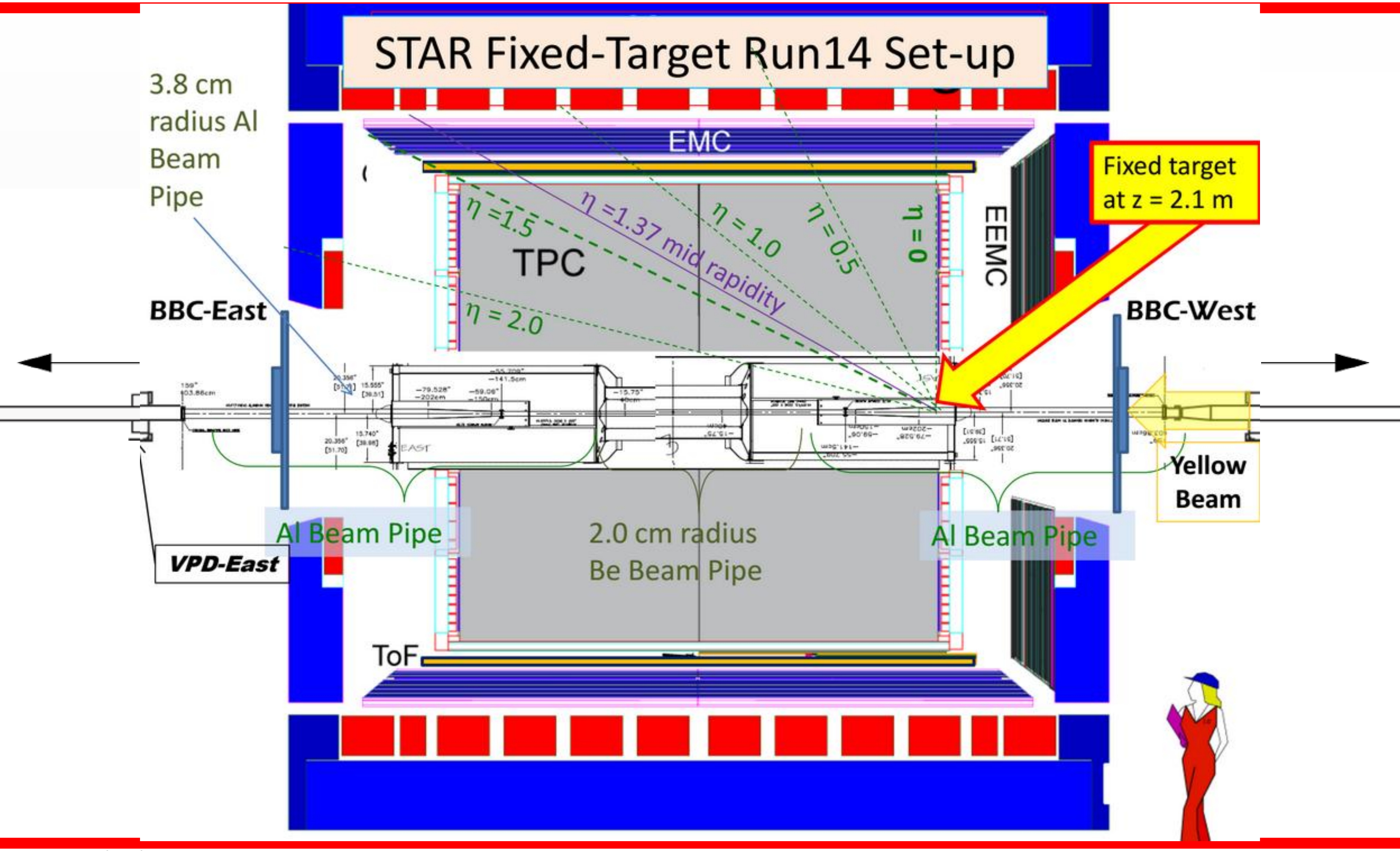
Target design:

Gold foil
1 mm Thick
~1 cm High
~4 cm Wide
210 cm from IR



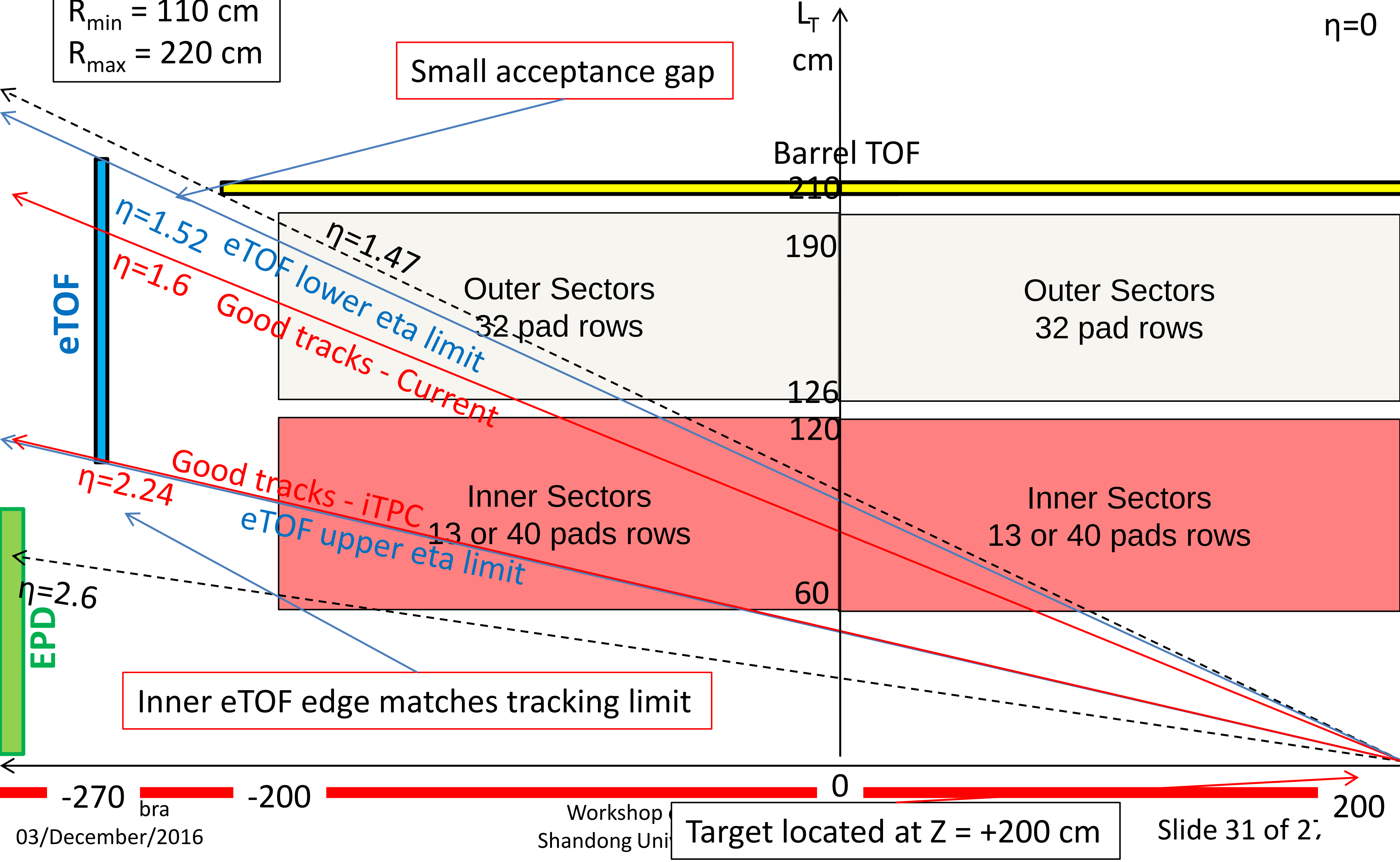


Run 14 and 15 Setup



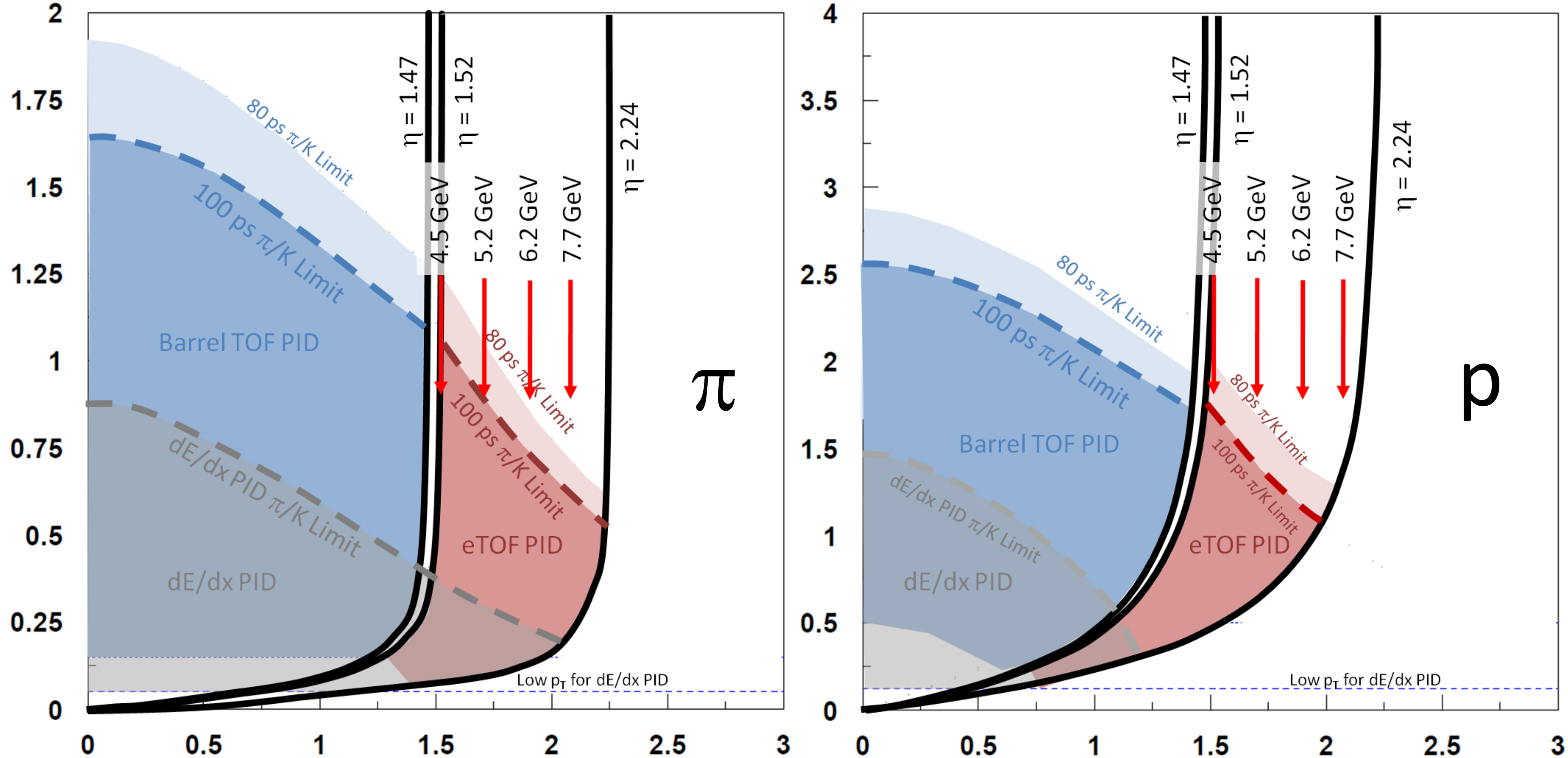
Internal Fixed Target PseudoRapidity Considerations

eTOF:
Z = -270 cm
ΔZ = 480 cm
R_{min} = 110 cm
R_{max} = 220 cm

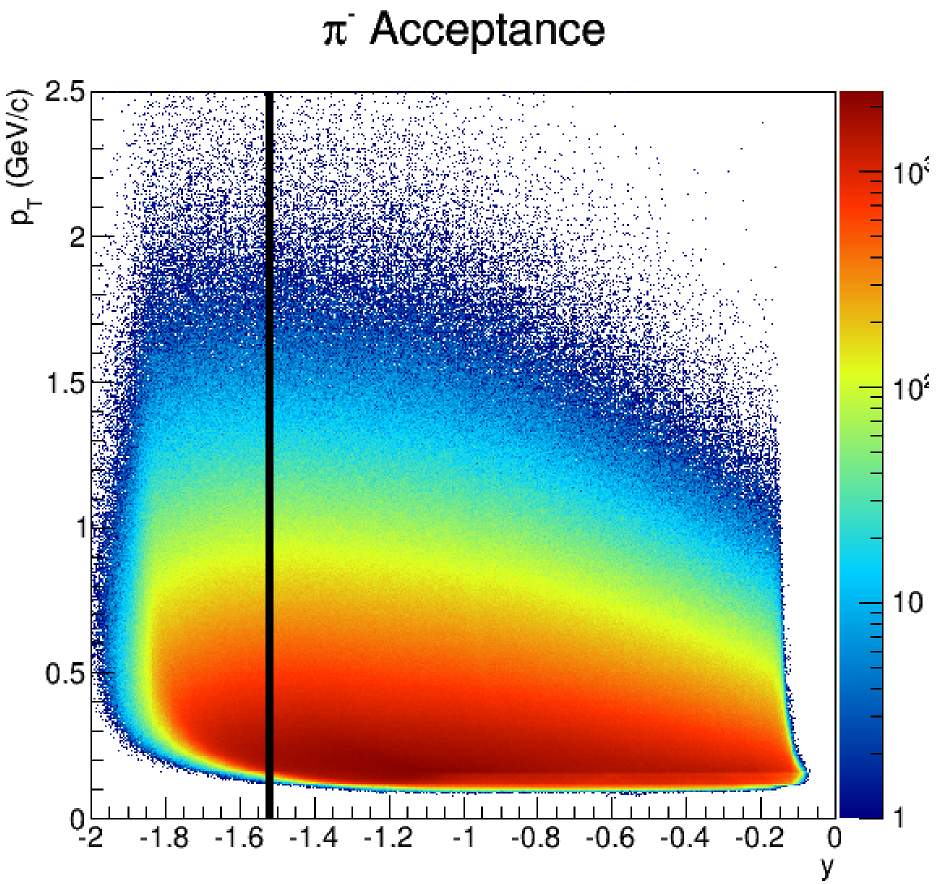


What do the iTPC and eTOF do for Fixed Target?

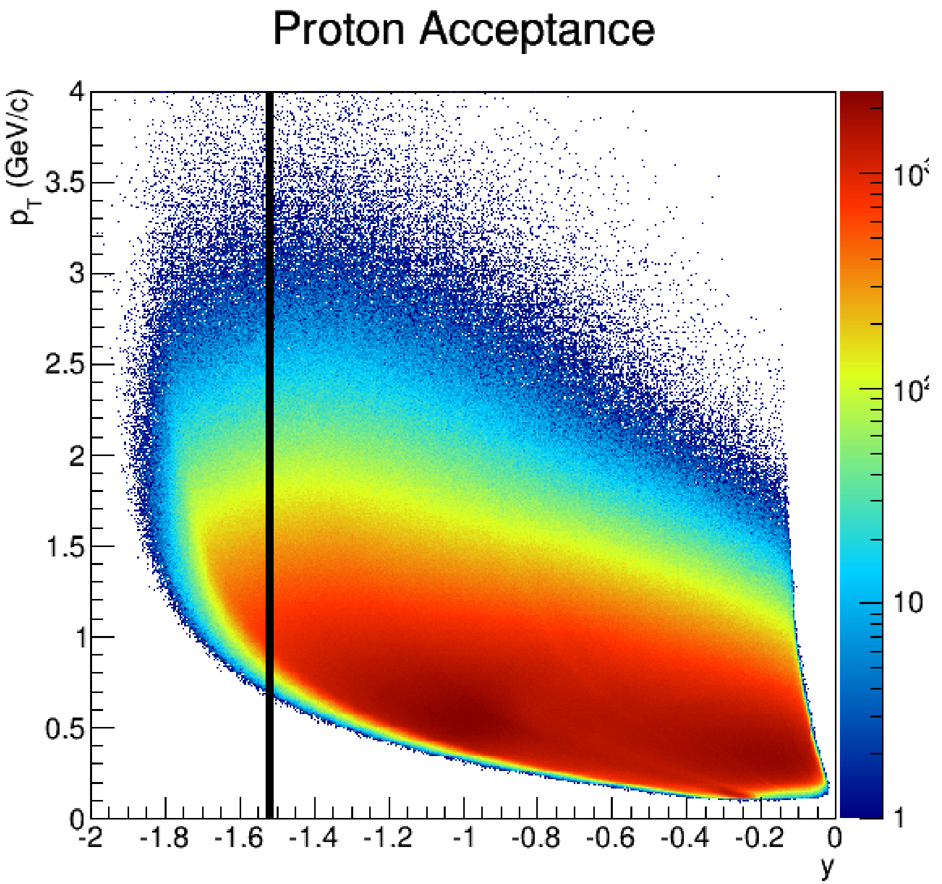
Allows the program to reach 7.7 GeV!



Acceptance



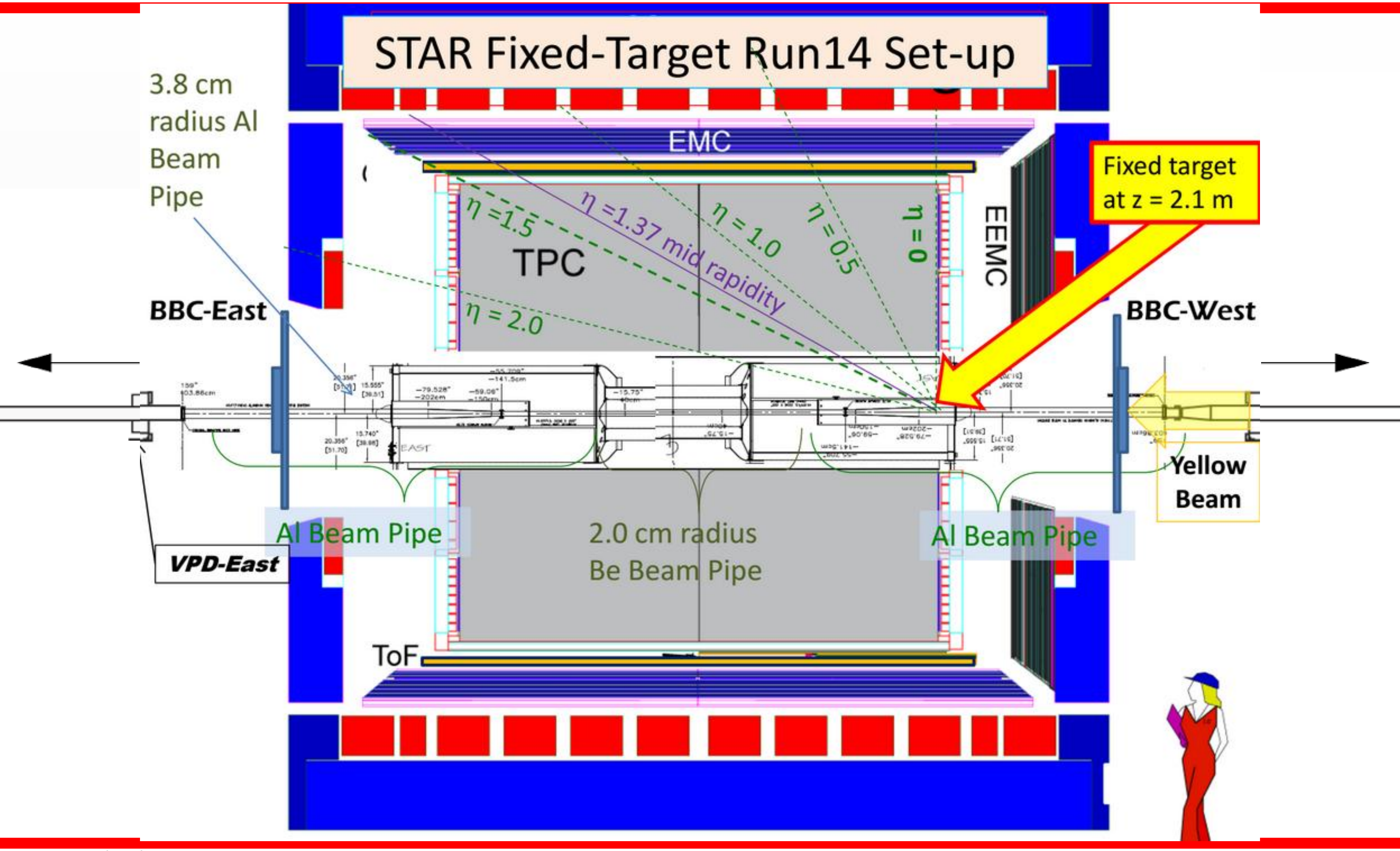
π^- Acceptance
p_T (GeV/c)
2.5
2
1.5
1
0.5
0
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
y
10
1



Proton Acceptance
p_T (GeV/c)
4
3.5
3
2.5
2
1.5
1
0.5
0
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
y
10
1

Collision Energy (GeV)	Single Beam Energy	Fixed Target Root s	Single Beam Rapidity	Center of Mass Rapidity	Chemical Potential μ_B	Events (Millions)
200	100	13.713	5.369	2.685	0.276	NA
130	65	11.083	4.938	2.469	0.325	NA
62.4	31.2	7.737	4.204	2.102	0.420	100
39	19.5	6.170	3.734	1.867	0.487	100
27	13.5	5.185	3.366	1.683	0.541	100
19.6	9.8	4.468	3.042	1.521	0.589	100
14.5	7.25	3.904	2.741	1.370	0.633	100
11.5	5.75	3.528	2.507	1.253	0.666	100
9.1	4.55	3.196	2.269	1.134	0.699	100
7.7	3.85	2.985	2.097	1.049	0.721	100
5.0	2.50	2.320	1.644	0.822	0.774	100

Run 14 and 15 Setup



Comparison of Facilities

Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2017	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	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

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 $\mathcal{L}$ (1×10^{25}/cm^{2}sec)	0.13		1.5	2.1	4.0
BES II (MEvts)	100	160	230	300	400
Improvement (X)	4	4	4	3	3
Beam Time (weeks)	**12**	**9.5**	**5.0**	**5.5**	**4.5**

Revised estimates

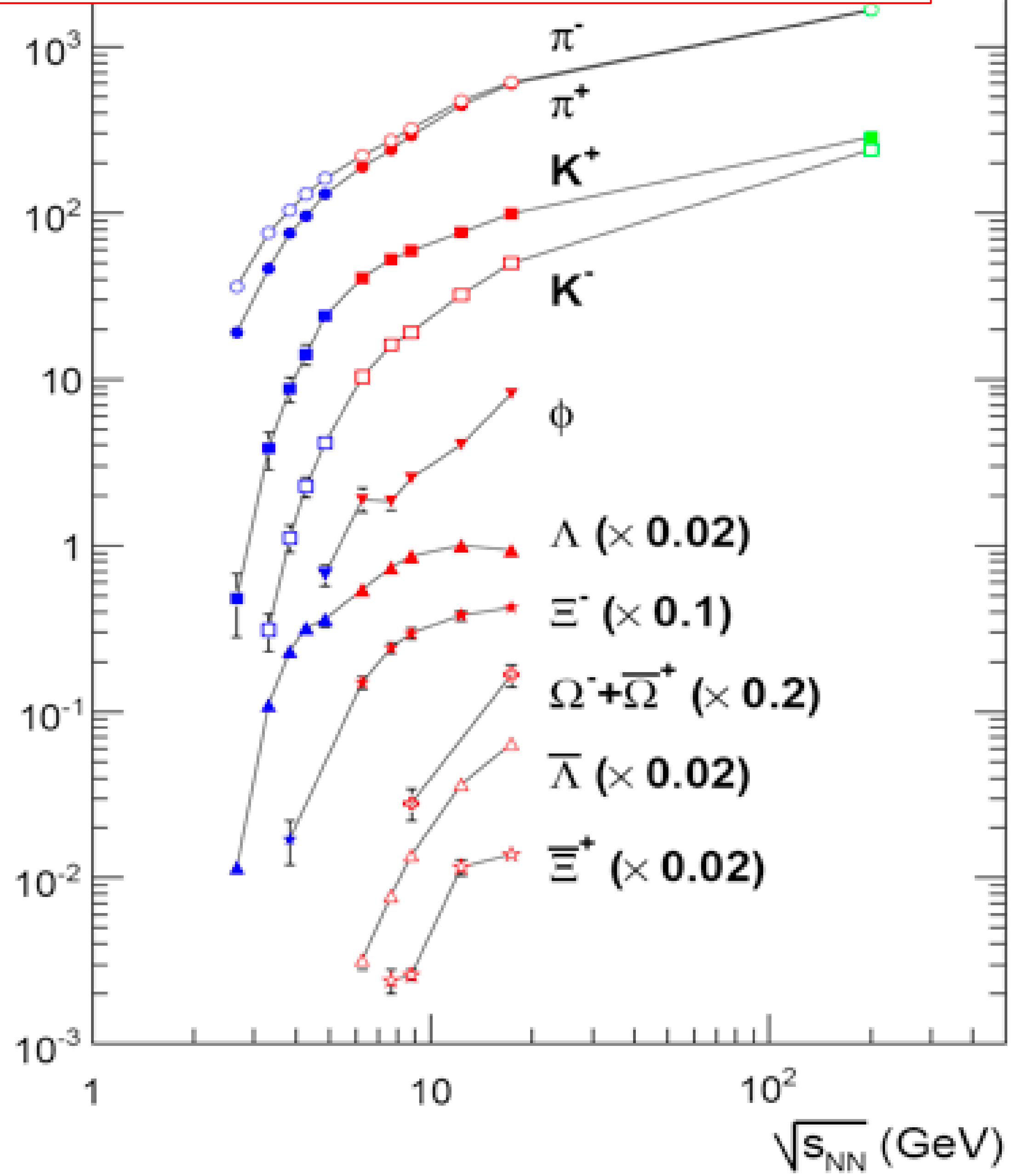
Yields of Hadrons → Mapping the Phase Boundary

Acceptance of π, K, p is good to midrapidity at all FXT energies. Acceptance for weak decay parents should be good as well.

Measurements can be extrapolated to 4π

Will be able to extend the low energy limits of measurements of most strange hadrons

4π strange hadron yields are needed for chemical equilibrium models to determine T and μ_B



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