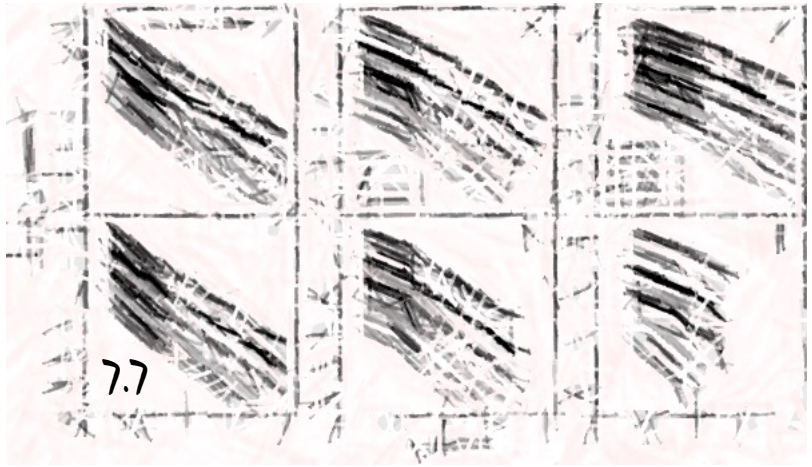
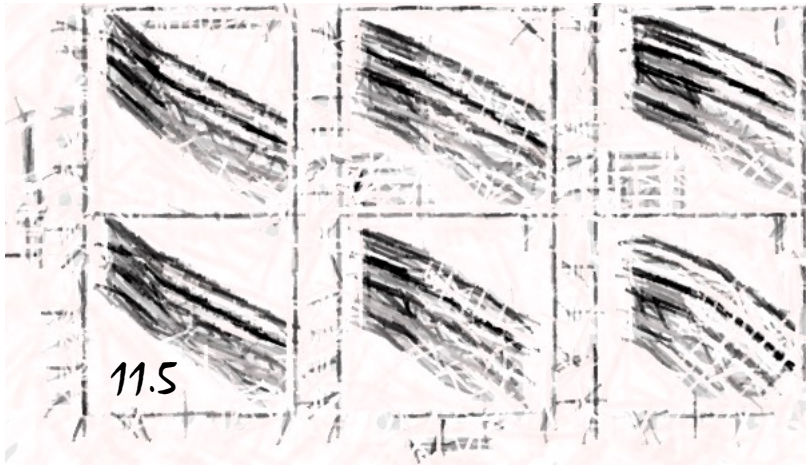
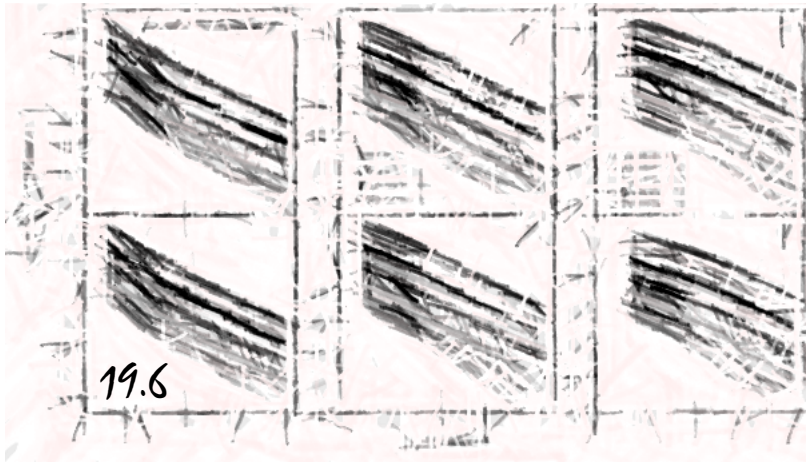


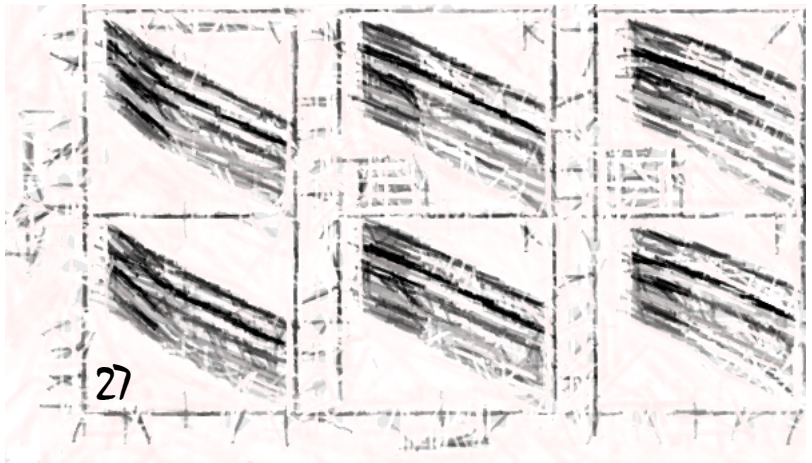


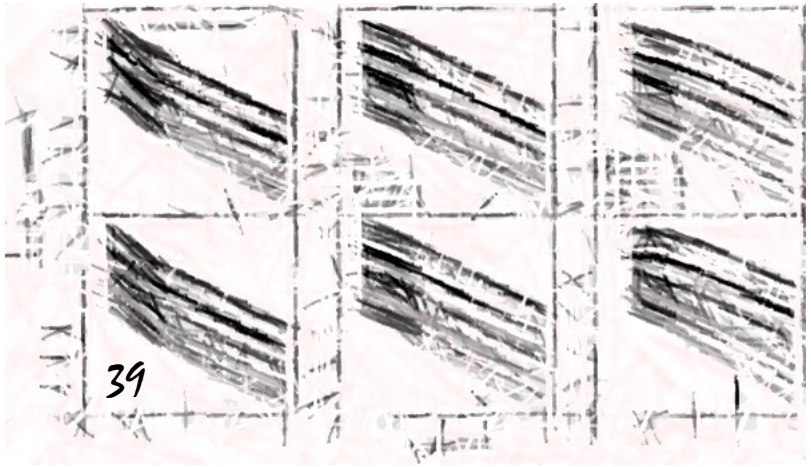
Bulk Spectra day-one physics and plans

Frank Geurts

Rice University







Office of Science
U.S. DEPARTMENT OF ENERGY

RICE

Exploring the QCD Phase Diagram

Motivation:

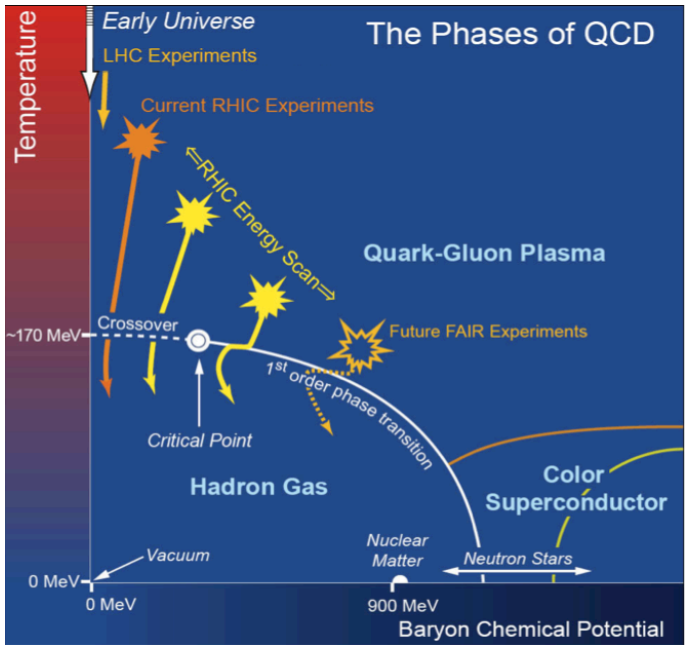
- Hadronic gas phase at low T and μ_B
- Lattice QCD calculations ⇀ expect a cross-over at high energies

➢ Study onset of QGP at high T and μ_B
  - nuclear modification (R_{CP})
  - NCQ scaling of elliptic flow

➢ Do we observe a phase transition as we lower the beam energy? What type of phase transition?
  - directed flow
  - femtoscopy

➢ Do we observe a critical point?
  - fluctuation analyses
  - dielectrons?

➢ Do we observe chiral symmetry restoration?
  - dielectrons and low-mass vector mesons



- **RHIC Beam Energy Scan (Phase I)**
  - carried out in 2010-2014
  - covered energies from $\sqrt{s_{NN}}$= 7.7 to 64 GeV
- **STAR has published 16 papers based on BES-I**
  - four papers submitted
  - five in preparation

STAR BES-I Papers

Published

1. PRC 86 (2012) 054908 – v_2 of $h^{\pm}$
2. PRL 110 (2013) 142301 - v_2 of particles vs. antiparticles, v_2 of ϕ
3. PRC 88 (2013) 014902 – PID v_2
4. PRL 112 (2014) 032302 – net-p higher moments
5. PRL 112 (2014) 162301 – v_1 of p, pbar, π
6. PRL 113 (2014) 052302 – charge separation along magn. field
7. PRL 113 (2014) 092301 – net-charge higher moments
8. PLB 750 (2015) 64 – LMR dielectron at 19.6GeV
9. PRC 92 (2015) 014904 – π HBT
10. PRC 92 (2015) 021901 – Kπ, p-π, Kp fluctuations
11. PRL 114 (2015) – charge asymmetry dependence of π v_2 and possible CMW
12. PRC 93 (2016) 014907 † – centrality dependence of PID v_2
13. PRC 93 (2016) 021903 – Ω and ϕ spectra
14. PRC 94 (2016) 024909 – charge balance functions
15. PRC 94 (2016) 034908 – v_2 of light nuclei
16. PRL 116 (2016) 112302 † – v_3 of $h^{\pm}$

Submitted

1. Energy dependence of J/ψ production (39 – 200GeV)
   arXiv: 1607.07517
2. BES global Λ polarization †
3. BES 3-particle mixed harmonic †
   arXiv: 1701.06496 and 1701.06497
4. BES bulk properties (π/K/p spectra)
   arXiv: 1701.07065

In Preparation

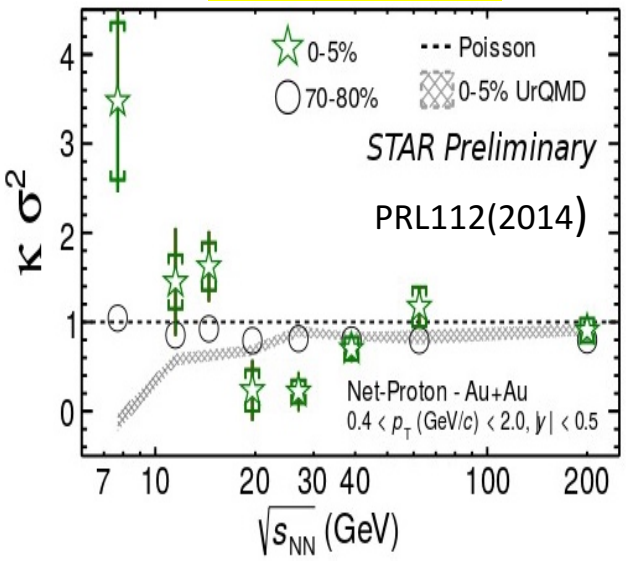
1. BES R_{CP} – in GPC ‡†
2. BES net-kaon – in GPC †
3. BES dielectron - in GPC
4. BES hypertriton lifetime – ready for GPC
5. BES strangeness – ready for GPC

† *includes run-14 $\sqrt{s_{NN}}$=14.5 GeV*

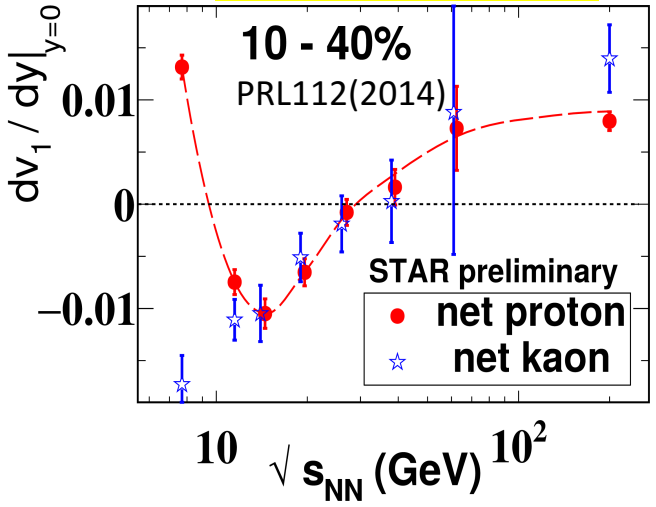
‡ *God-Parent Committee: internal STAR editorial board*

Selected Results from BES Phase-I

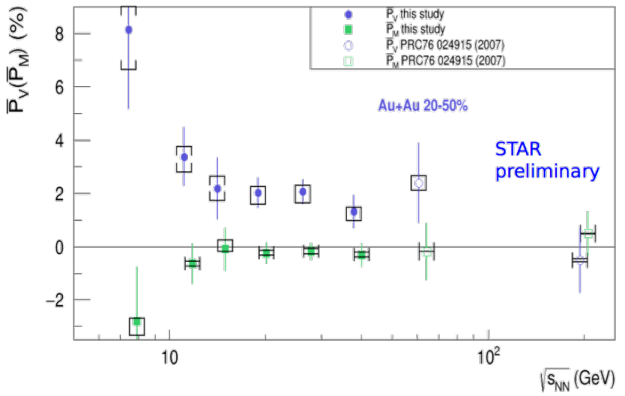
Critical Point



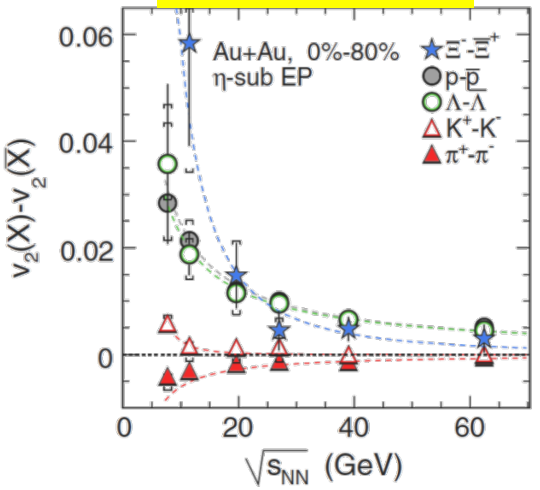
Phase Transition



Chiral Vortical Effect



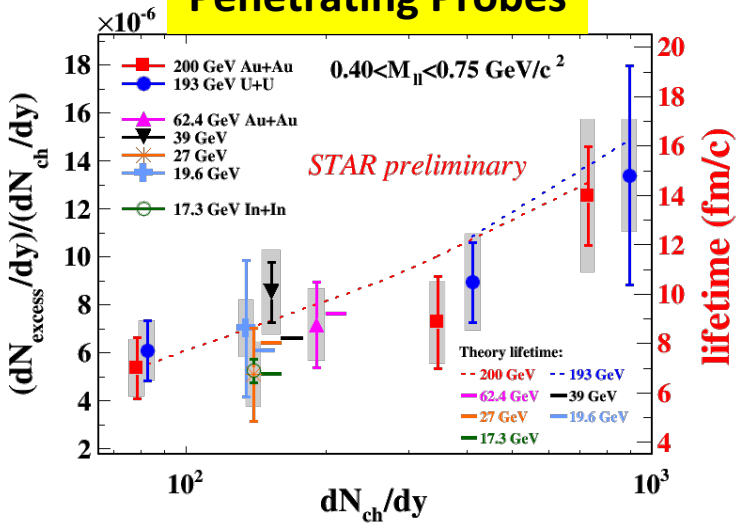
Bulk Behavior



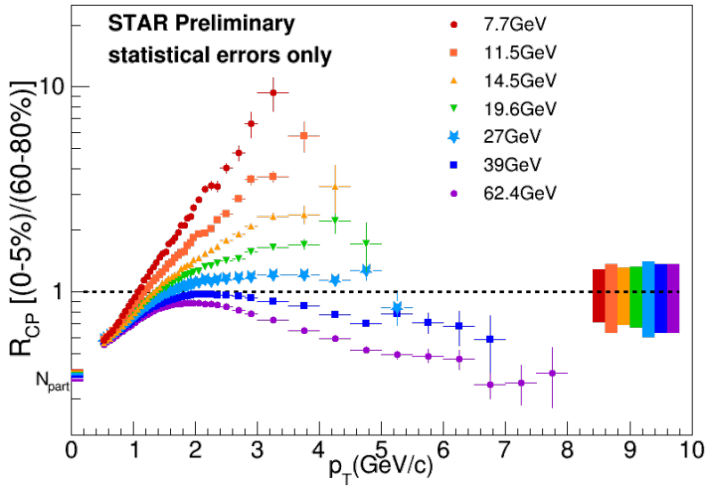
Most measurements limited by statistics and systematics

- Proposal for a BES Phase II with more statistics and new detectors

Penetrating Probes



Energy Loss



Beam Energy Scan Phase-II

Dedicated second phase of the BES program, proposed in 2014

STAR Note 598

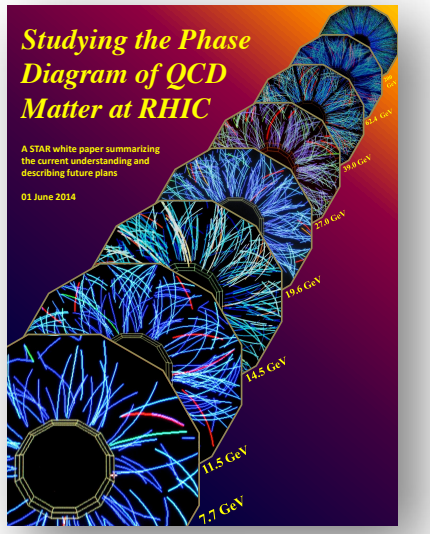


Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables.

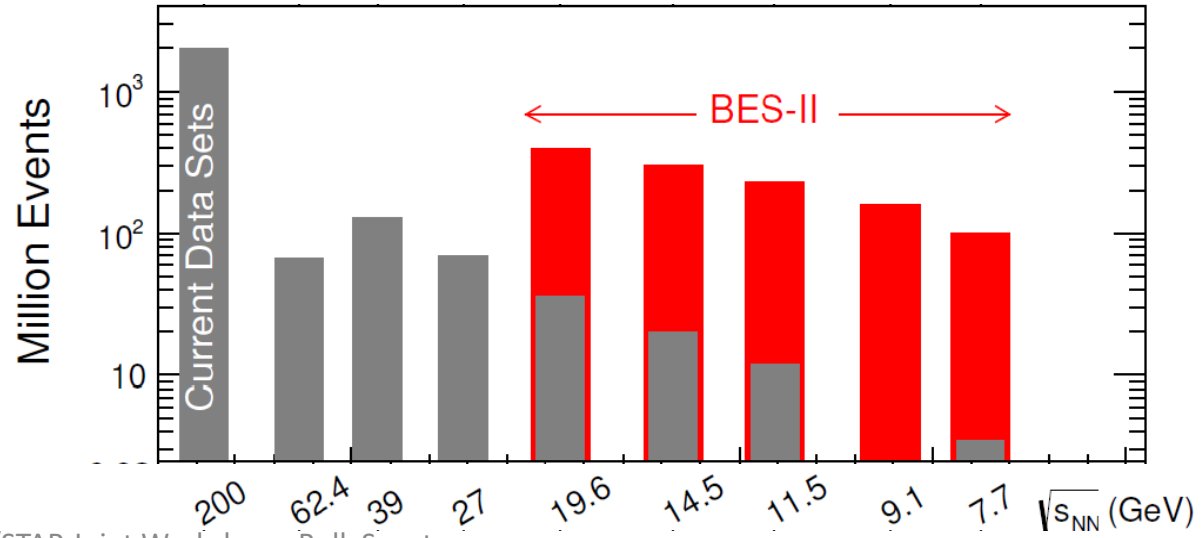
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to p_T = 5 GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	80	100	120	200	400
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**

Strong endorsement by NSAC

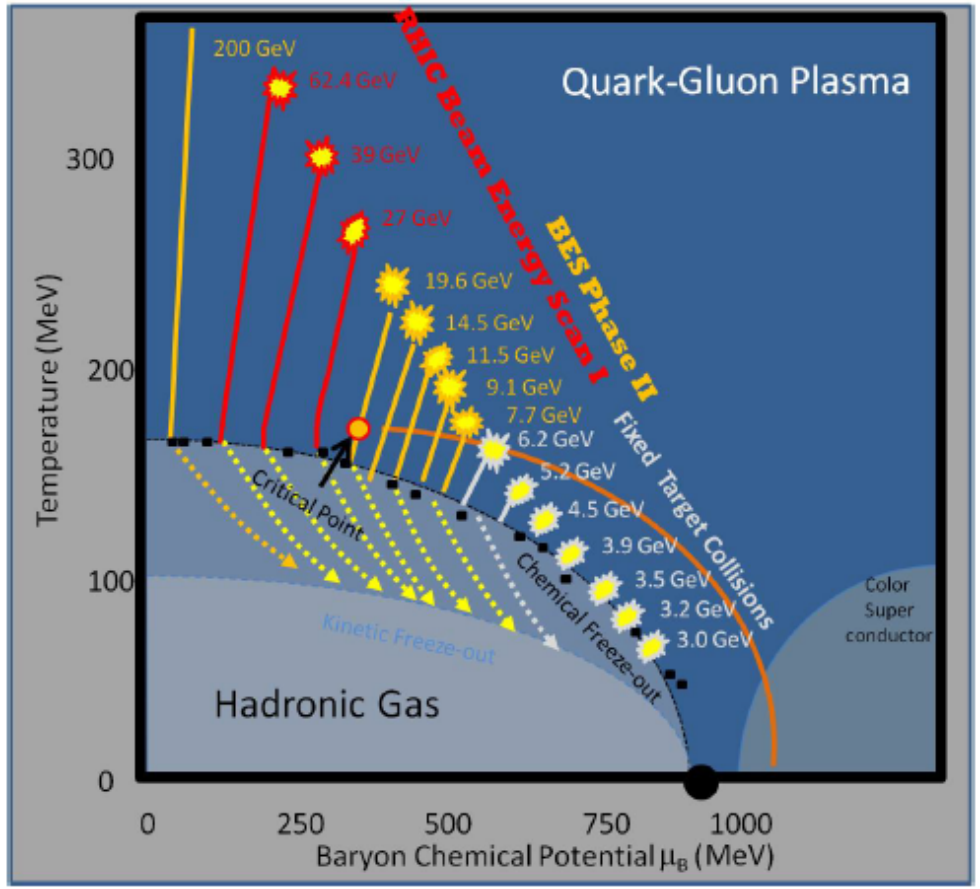
Long Range Plan 2015:

- *"Trends and features in BES-I data provide compelling motivation for […] experimental measurements with higher statistical precision from BES-II"*

http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf



BES II Fixed Target Mode



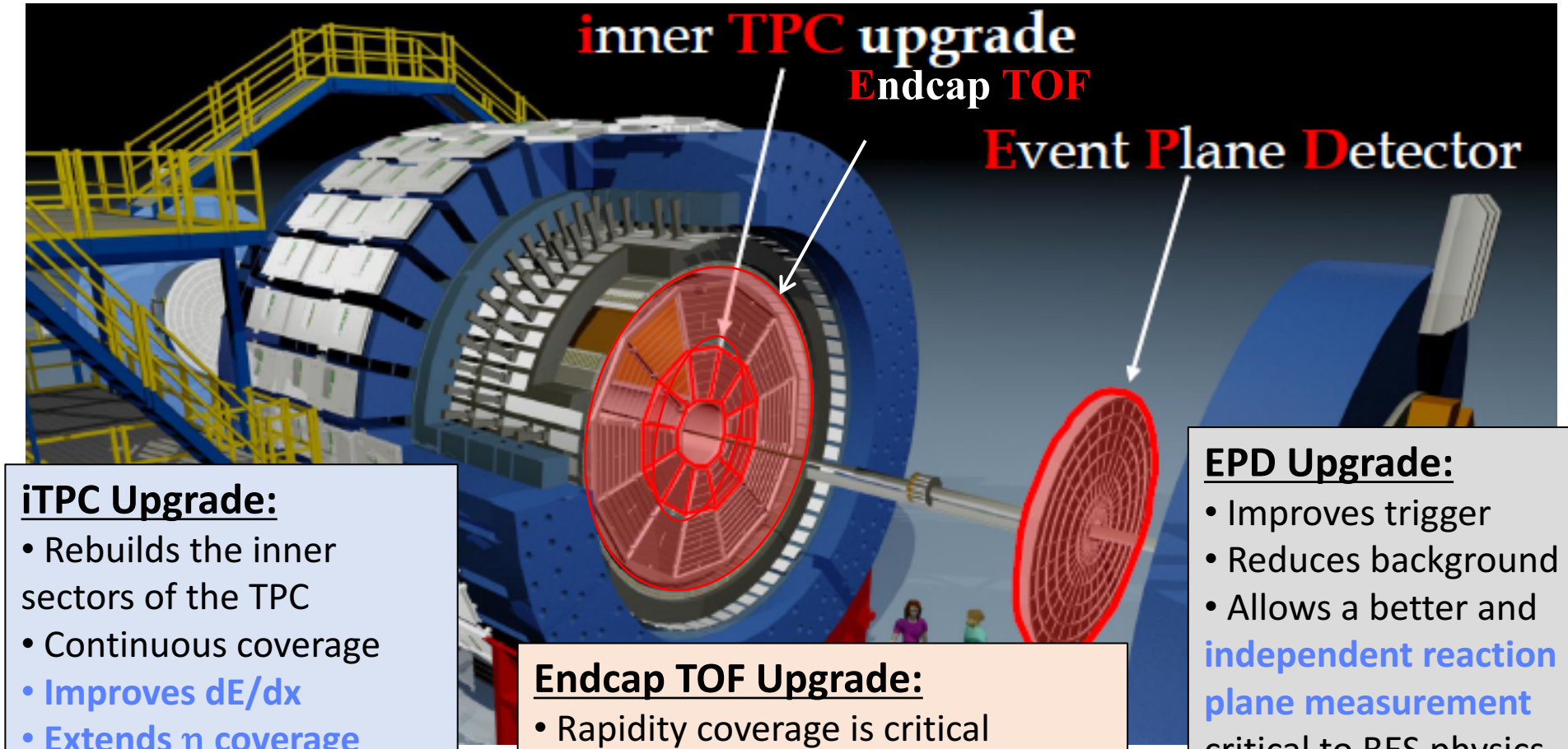
Proposal to extend CMS energy range from 7.7 down to 3 GeV

➢ increase μ_B range from 420 MeV to 720MeV

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

Expect 1-2 days dedicated beam time per energy
≈ 50M events/day

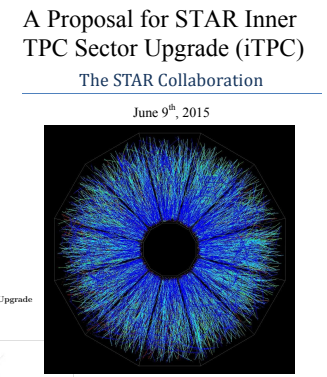
The STAR Upgrades and BES Phase II



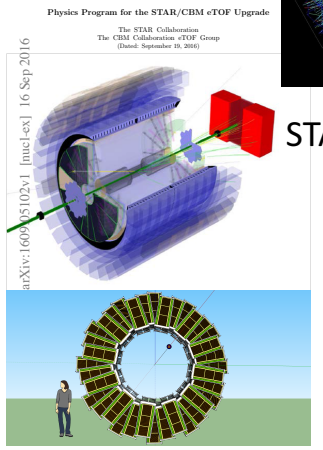
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous coverage
- **Improves dE/dx**
- **Extends η coverage from 1.0 to 1.5**
- **Lowers p_T cut-off from 125 MeV/c to 60 MeV/c**

Endcap TOF Upgrade:
- Rapidity coverage is critical
- **PID at η = 1.1 to 1.5**
- Improves the fixed target program
- Provided by CBM at FAIR

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

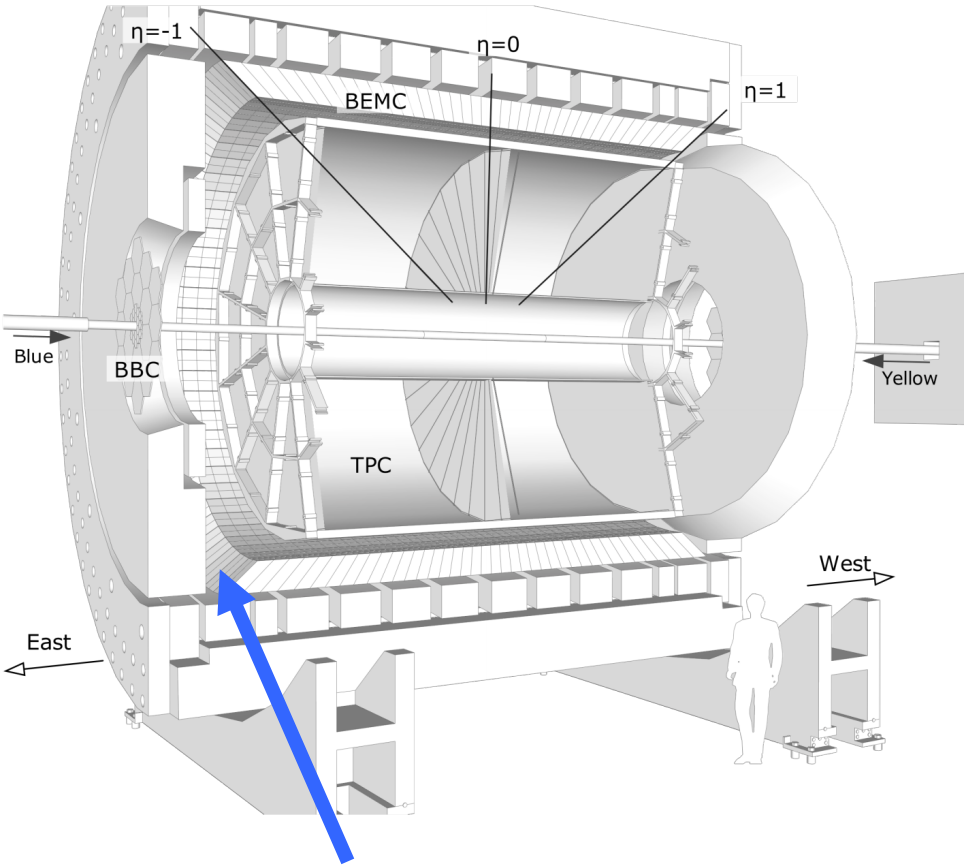


STAR Note 619

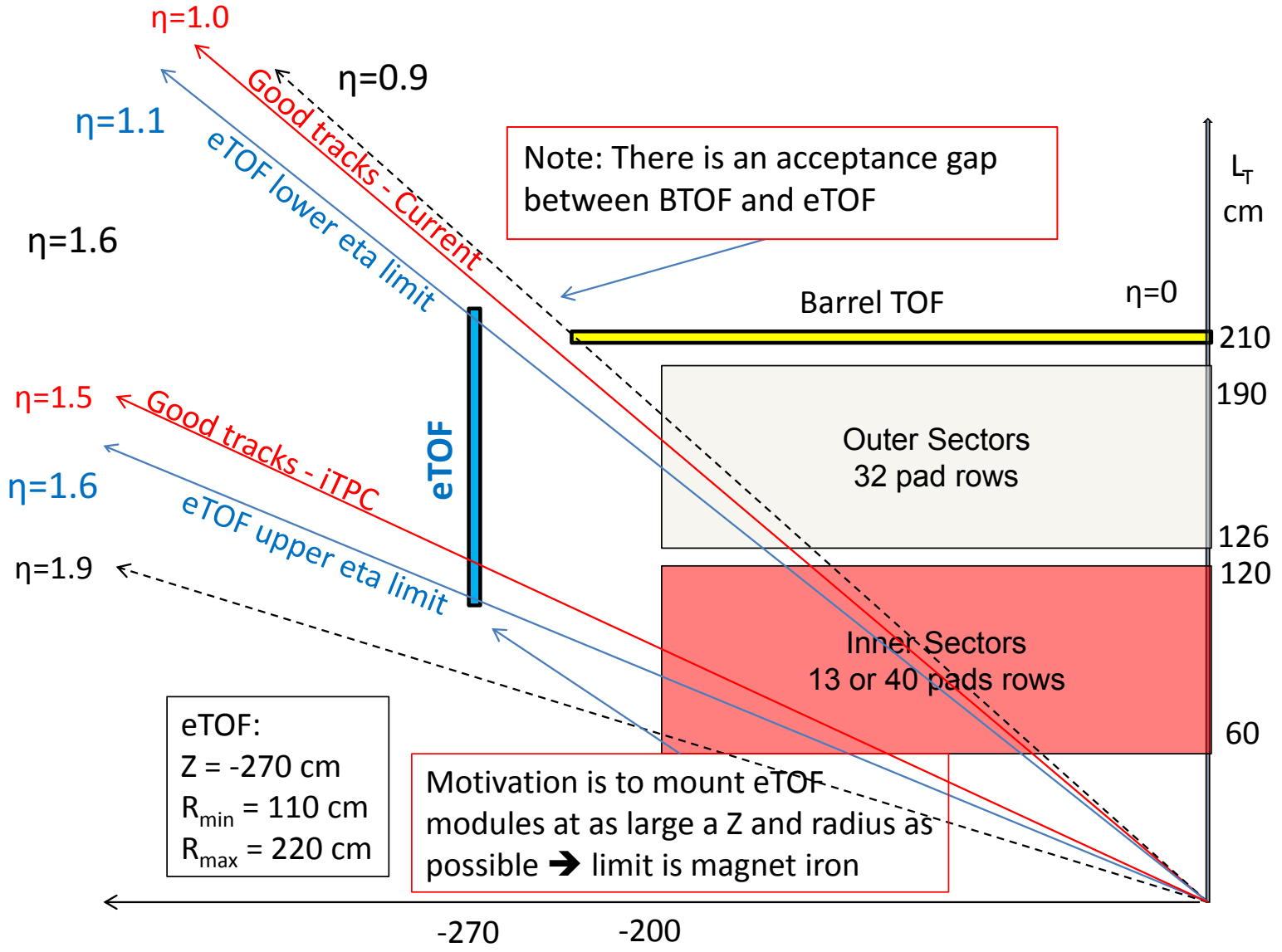


arXiv:1609.05102v1

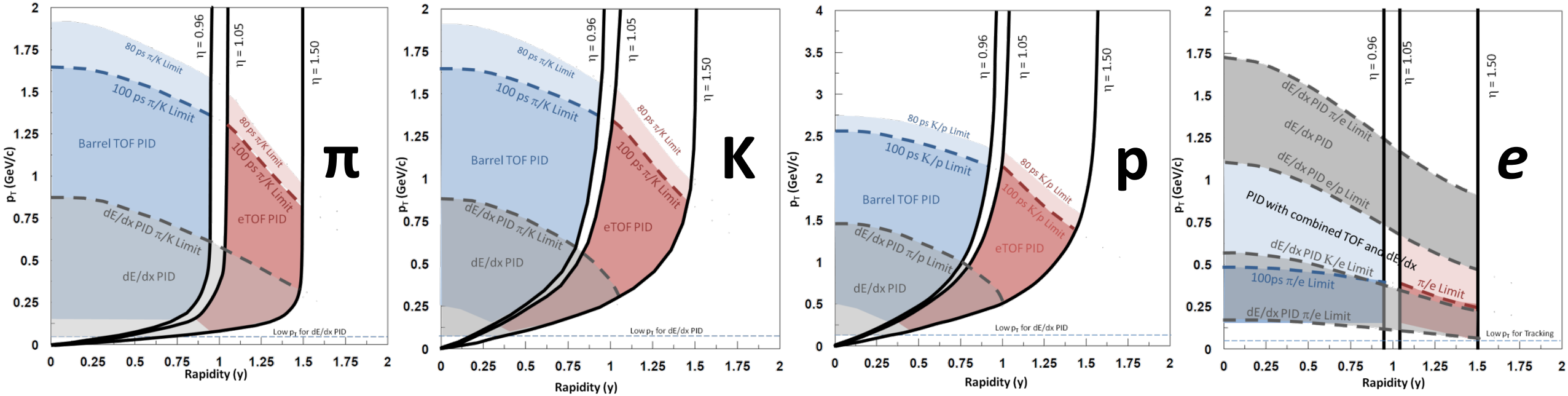
iTPC + eTOF : Acceptance Considerations



space for
endcap TOF modules



iTPC + eTOF : PID in Collider Mode



- Lower p_T limit – from track length of the TPC (multiple scattering);
  - for BTOF lower p_T limit from minimal track rigidity
- High p_T limit – from the TOF time resolution (σ_{TOF} = 100 and 80 ps ranges)

BES-II : Identified Particle v_2

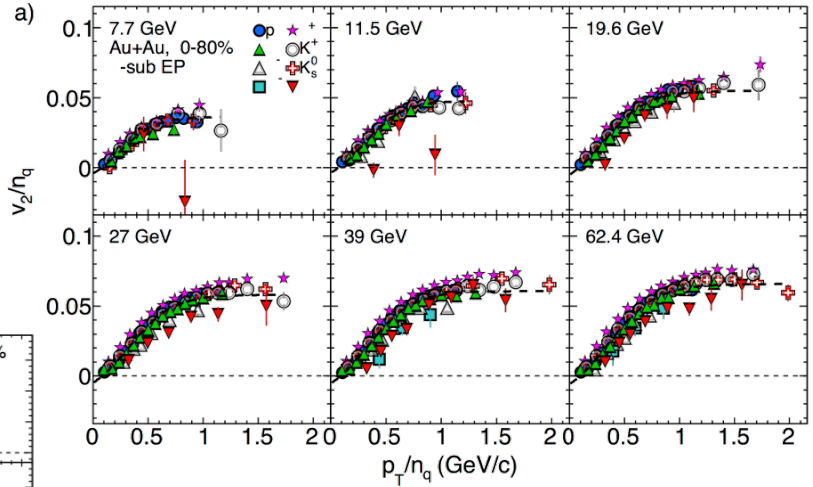
- BES-I: clear indications of baryon-meson splitting at higher energies for $\sqrt{s_{NN}} \geq 19.6$GeV
- NCQ scaling seen for higher energies
  - scaling indication of partonic behavior
    - ➢ ϕ meson may not follow trends below 19.6GeV

➢ Need more statistics:

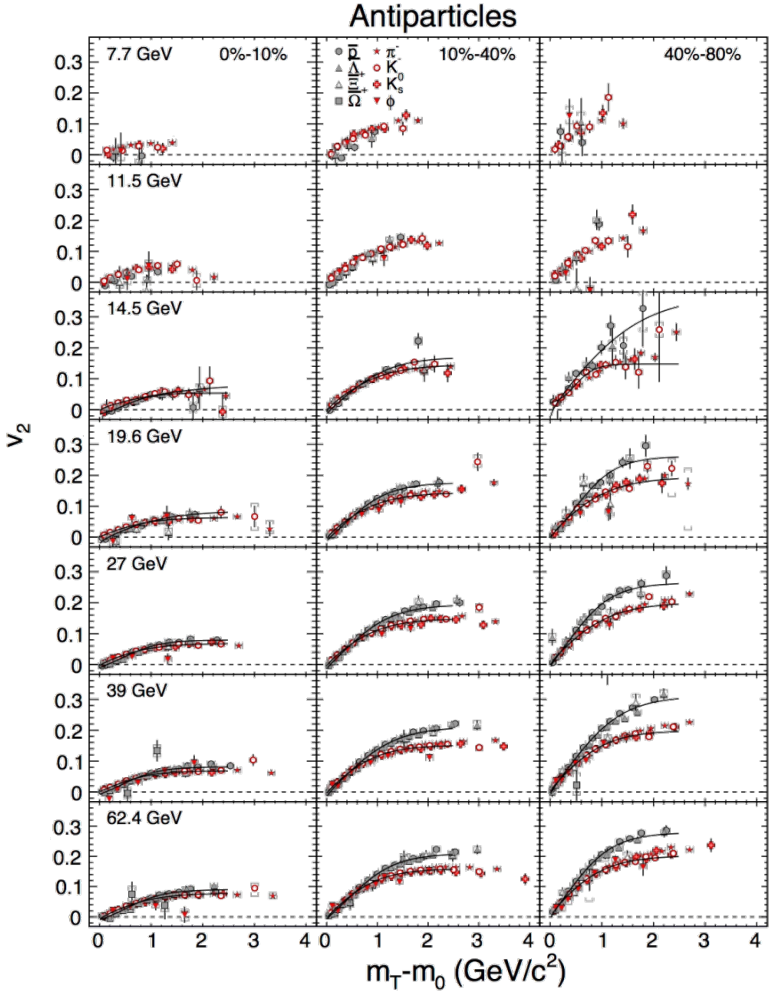
- for energies below $\sqrt{s_{NN}} \leq 11.5$GeV limited by statistics
- improve statistics for ϕ meson at 7.7 and 11.5GeV

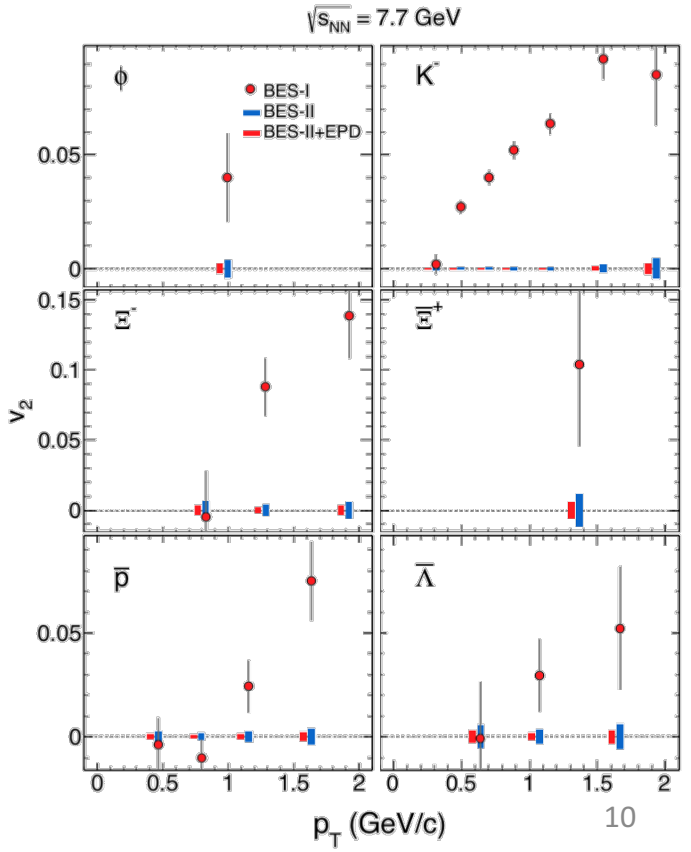
➢ iTPC/EPD: improve EP resolution

STAR, PRC 88 (2013) 014902



STAR, PRC 93 (2016) 014907





EPD Construction Proposal

BES-II : Directed Flow Measurements

- Directed flow expected to be sensitive to early evolution of collision
  - models with explicit 1st order phase transition predict dip of v_1 slope with double-sign change
  - net-protons proxy for transported protons
- BES-I: Minimum in net-proton v_1 slope
  - interplay between baryon stopping and soft EOS

➢BES-II: improve statistics

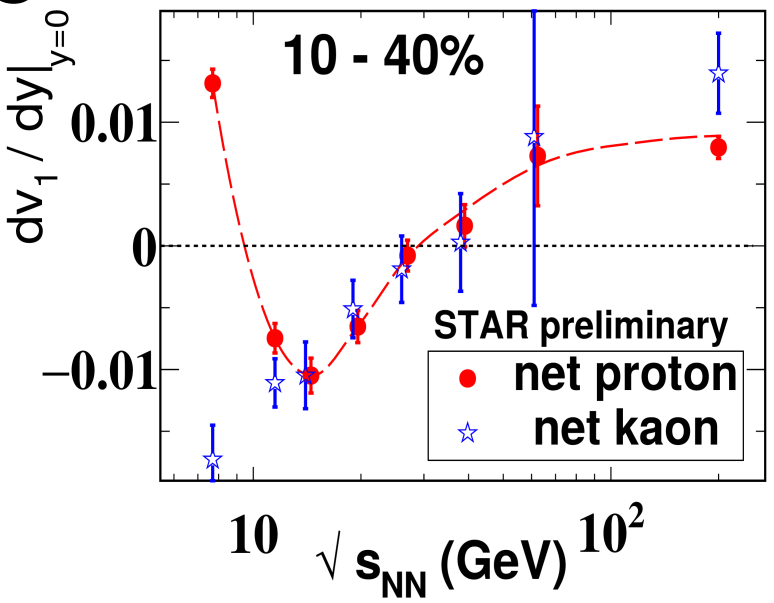
➢BES-II: improved event-plane resolution from EPD

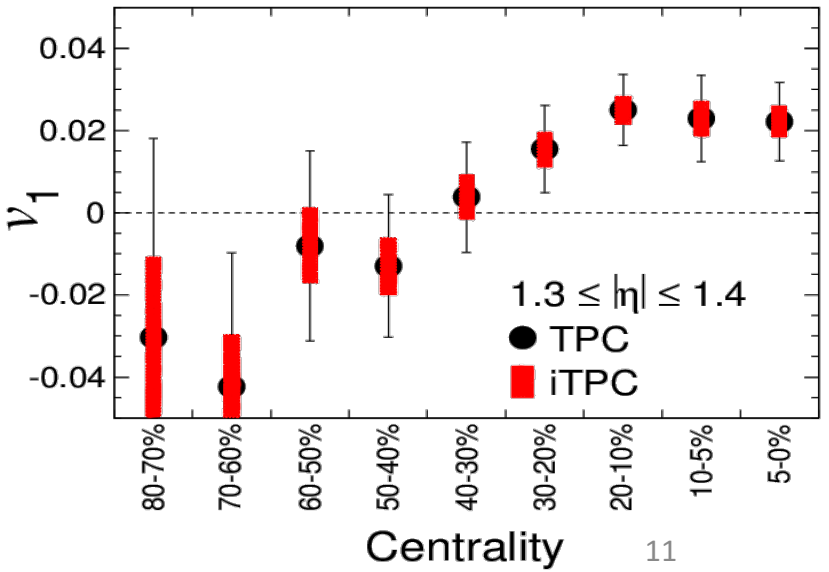
- include Λ baryons

- Forward v_1 measurements as a function of centrality

➢BES-II: improvements due to extended iTPC coverage

STAR, PRL 112 (2014) 032302





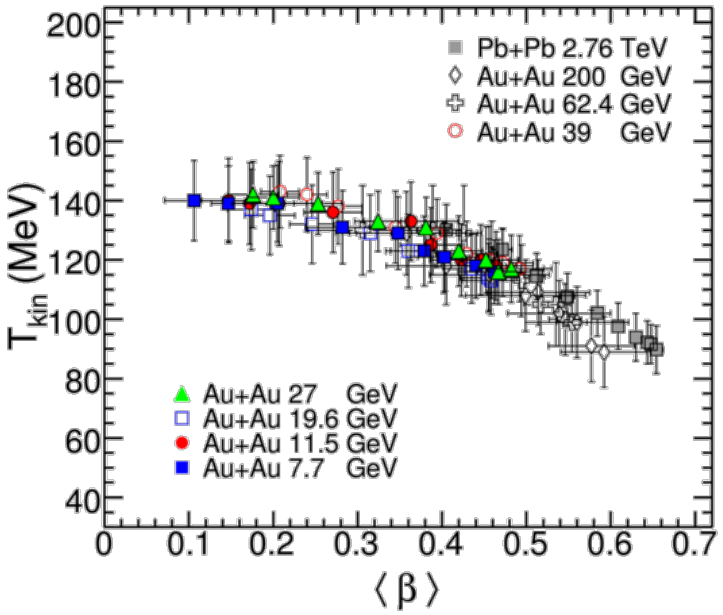
BES-I : Bulk Spectra and Freeze-out Parameters

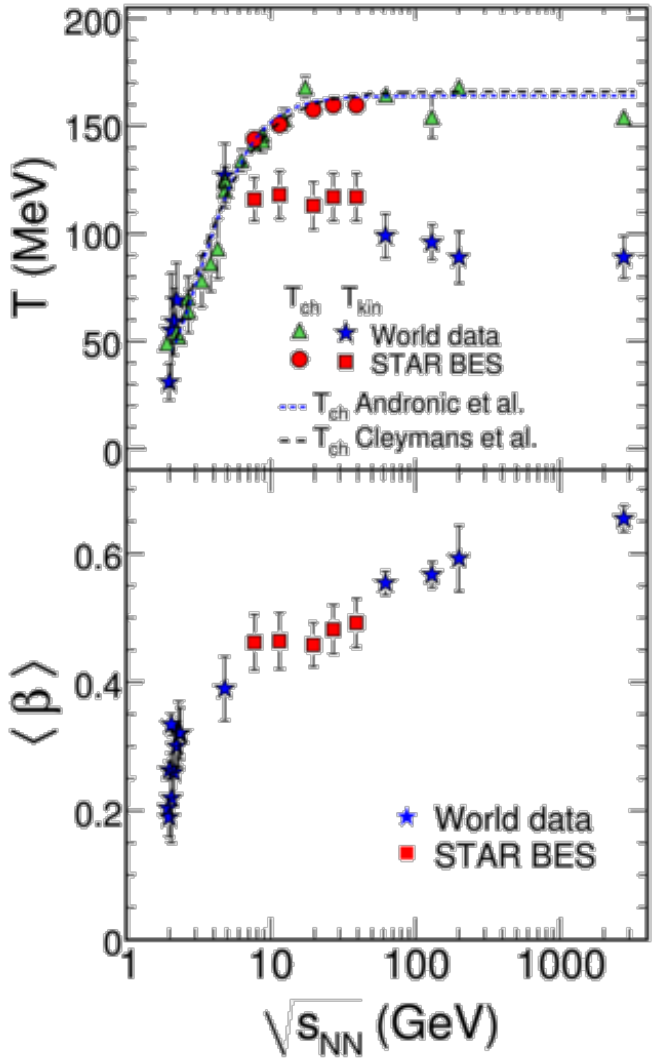
arXiv:1701.07065

- Statistical-thermal models in combination with measured particle yields allow the extraction of chemical (T_{chem}, μ_B) and kinetic (T_{kin}, β) freeze-out parameters.

➢ T_{kin} and T_{chem} are comparable for $\sqrt{s_{NN}} \leq 7$ GeV

- Stronger collectivity at higher beam energies
- Central collisions show lower T_{kin} and higher β





BES-II : Bulk Spectra and Freeze-out Parameters

➢iTPC : Lowering the lower p_T cut-off from 125 to 60 MeV/c

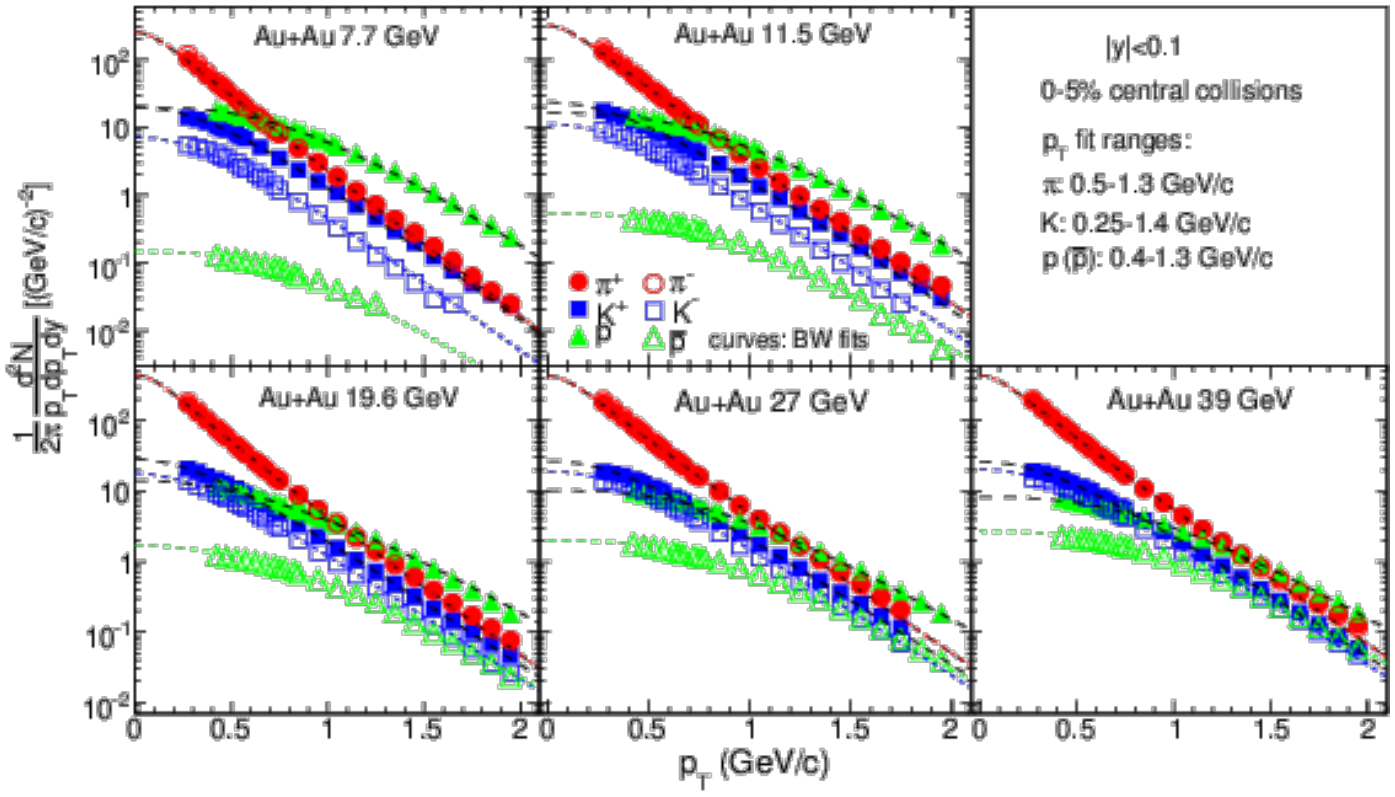
- Reduce the magnitude of extrapolation by ~2x

	Low pT Yield w/o iTPC	Low pT Yield with iTPC
pion	35%	18%
kaon	17%	8%
proton	13%	5%

- Reduce uncertainty on final yields

	Yield Error w/o iTPC	Yield Error with iTPC
pion	9%	5%
kaon	7%	4%
proton	14%	6%

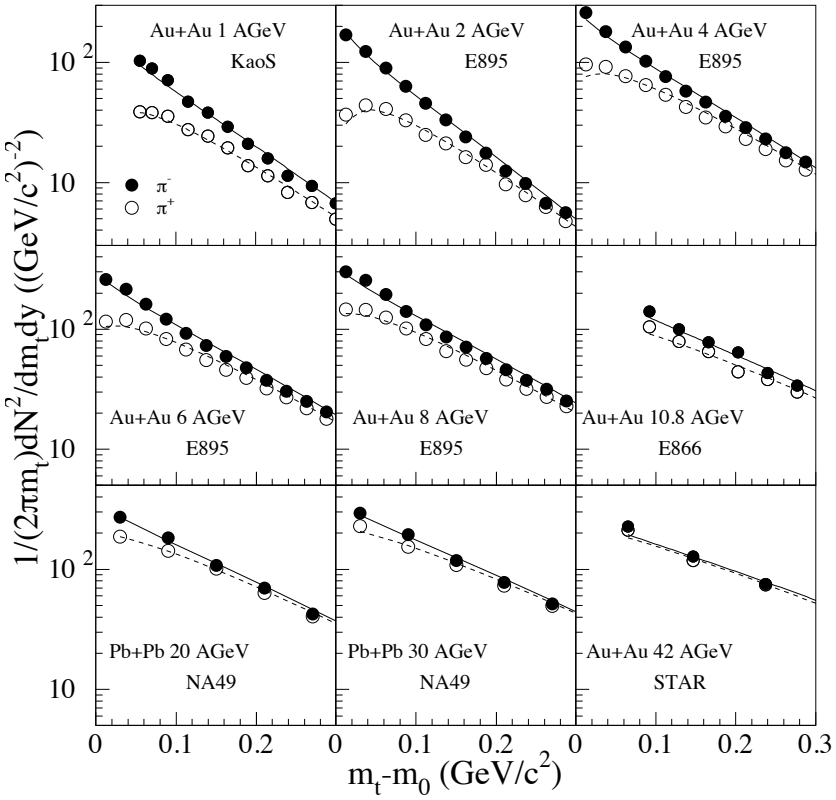
arXiv:1701.07065



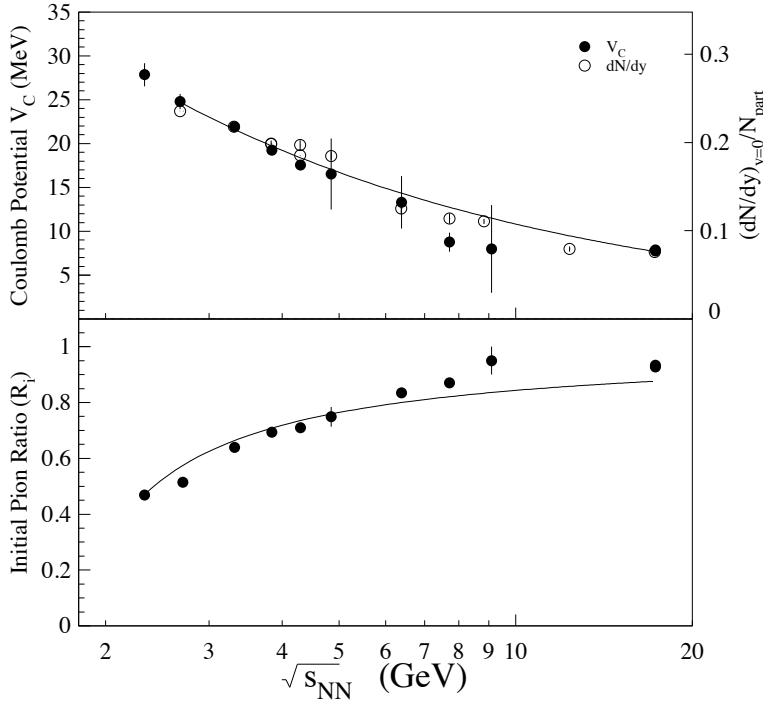
BES-II : π^-/π^+ Ratios

Lowering p_T cut-off to 60 MeV/c :

- Allow for study of Coulomb potential of the source
  - ➢relates to baryon stopping
    - … protons bring (net) positive charge to interaction region
- Measure Coulomb enhancement for of π^-/π^+ ratios for p_T<100MeV/c



D. Cebra, *et al.* arXiv: 1408.1369



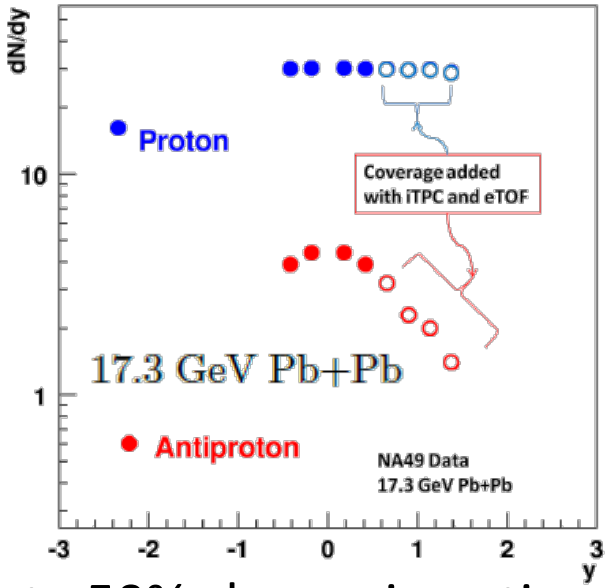
➢Decrease of V_C indicative of expansion of source or reduction in baryon stopping

BES-II : Bulk Spectra and Rapidity Dependence

iTPC allows measurements that extend to larger rapidities

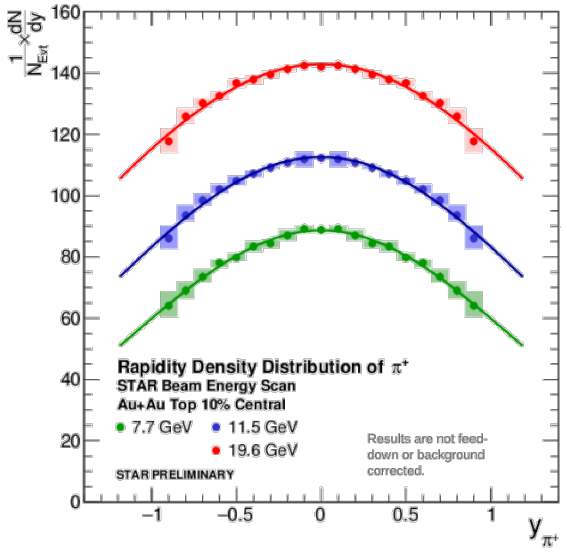
- proton rapidity to y=1.6 (70% of yield at 19.6 GeV)
- RHIC will run longer bunches ⟹ displaced vertices out to y=2.3 (90% of yield at 19.6 GeV)

STAR, arXiv:1609.05102



➢STAR :: from a mid-rapidity to a 4π detector

Expect to improve constraints on thermodynamics



- At NA49: from y = 0 to 1.2:
  - no change in proton yields, but ~50% change in anti-protons
  - indicator for changes in μ_B
  - factor of 2 in dN/dy ⟹ $\Delta\mu_B \approx 50$MeV

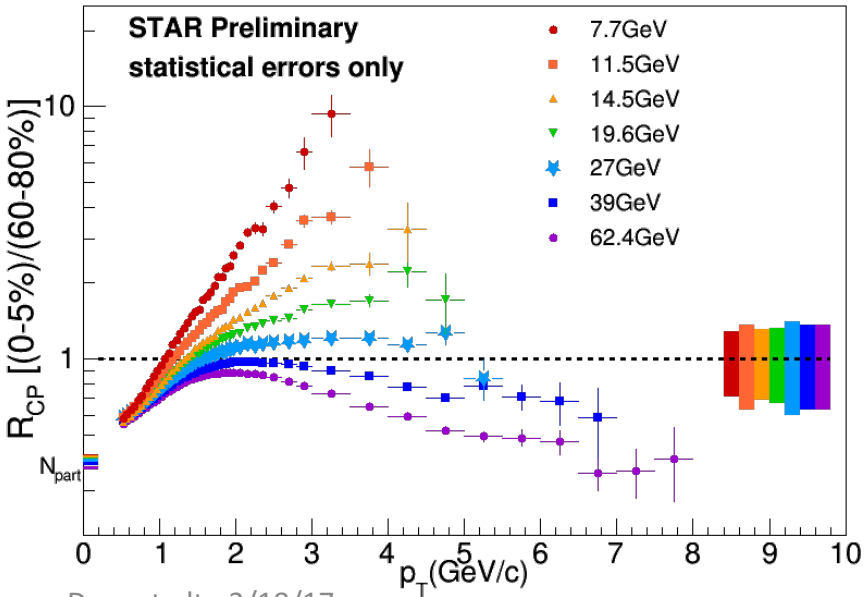
➢Further include rapidity dependence in the collider physics progra

- dileptons, directed flow, elliptic flow, fluctuations, …

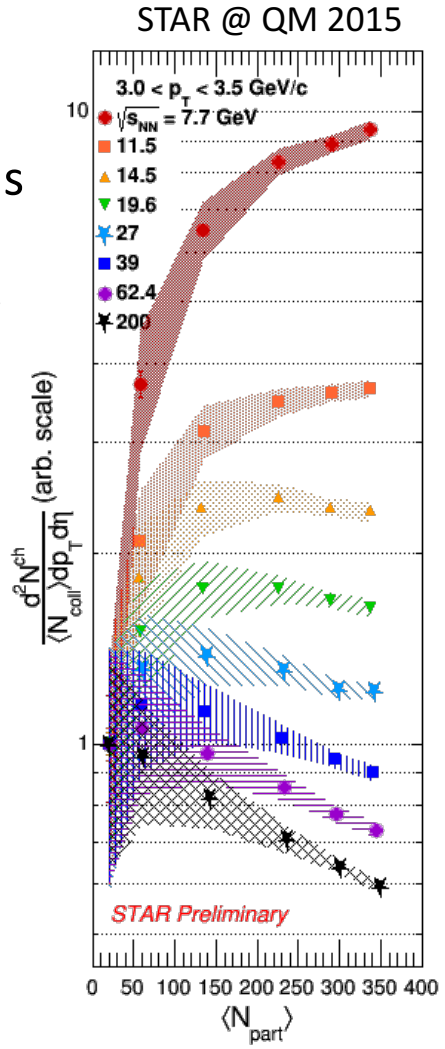
BES-I : Nuclear Modification

- LHC/RHIC@200GeV high-p_T suppression
- BES-1: disappearance of high-p_T suppression
  - enhancement and suppression mechanisms compete
  - evident suppression at high beam energies
  - no evidence below 14.5GeV

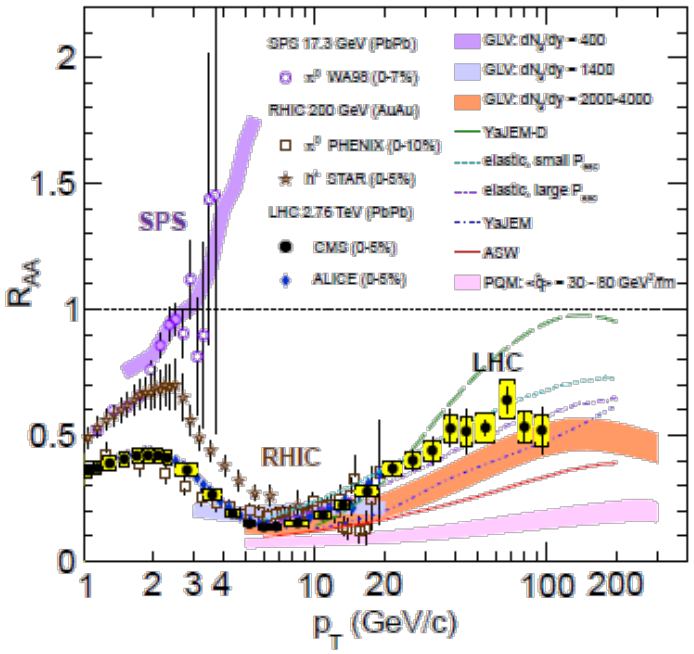
STAR @ QM 2015



STAR @ QM 2015



CMS, EPJ C72 (2012) 1945



Investigate competing enhancement and suppression as a function of centrality

$$\Upsilon(N_{part}) = \left(\frac{d^2N}{N_{coll} dp_T d\eta}\right)_{high-p_T\ bin}$$

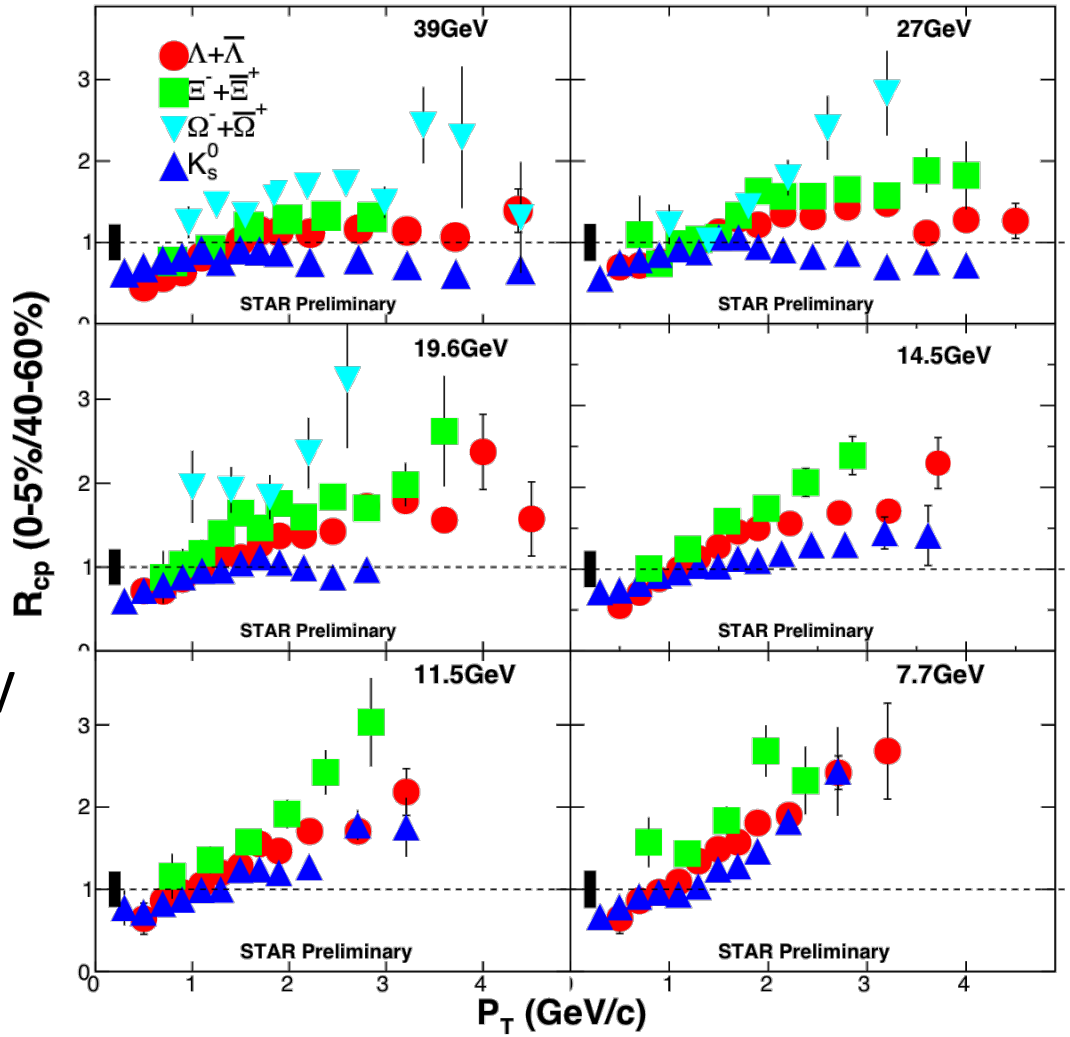
Observe that most central data for $\sqrt{s_{NN}} \geq 14.5$GeV turnover $\Rightarrow$ suppression

200 GeV decreases monotonically
7.7 and 11.5 GeV increase monotonically

BES-I : Strangeness R_{CP}

- K_s^0 R_{CP} increases with decreasing beam energies
  - ➢ Effect from partonic energy loss less important at lower $\sqrt{s_{NN}}$
    - CNM effects take over at collisions energies
- R_{CP} differences between particles less pronounced at small collisions energies
  - $\sqrt{s_{NN}}$ = 7.7, 11.5GeV compared to $\sqrt{s_{NN}} \geq$ 19.6GeV
  - ➢ indicative of different properties of system when going to lower energies

STAR @ SQM 2016

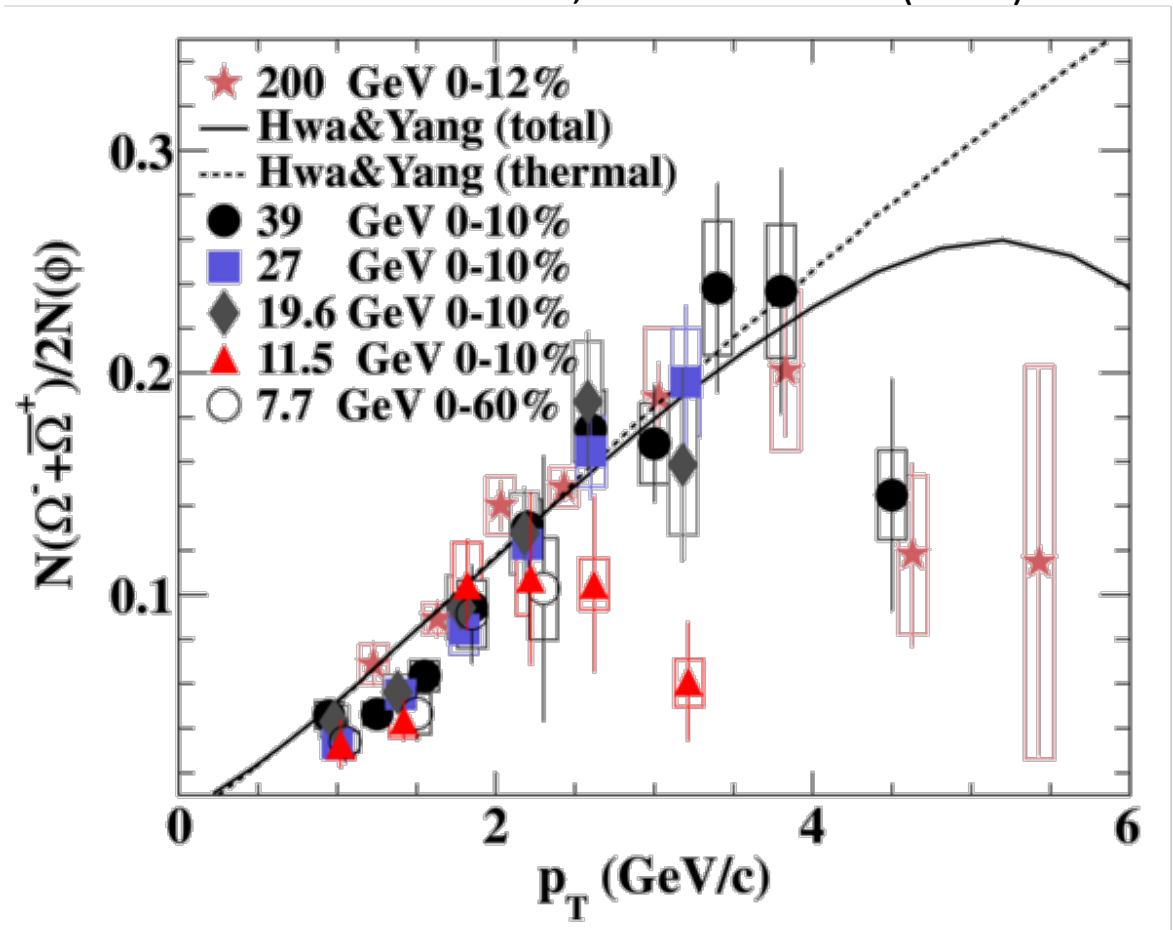


BES Strangeness : Ω and ϕ Production

- Coalescence and recombination models
  for 200GeV:
  - Ω up to p_T = 6GeV/c dominated by thermal quark recombination
  - recombination for ϕ up to 4GeV/c
  - expect straightline of $N(\Omega + \overline{\Omega})/2N(\phi)$ *vs* p_T with deviations ~4GeV/c
- BES measurements
  - ratios for 19.6 – 39 GeV follow 200GeV
  - at $\sqrt{s_{NN}}$ = 11.5GeV turn down at p_T = 2GeV/c
  - Ω and ϕ have small hadronic cross sections
    - ➢ early turn-down originates from partonic phase?

➢ Need further study below 19.6GeV
- increase statistics
- improve systematics

STAR, PRC 93 021903 (2016)



Strangeness Baryon-to-Meson Ratio : $\overline{\Lambda}/K_S^0$

- Enhancement of $\overline{\Lambda}/K_S^0$ ratios at intermediate p_T
  - ➢ due to parton recombination and collectivity
- Separation of central (0-5% ●) and peripheral (40-60% □)

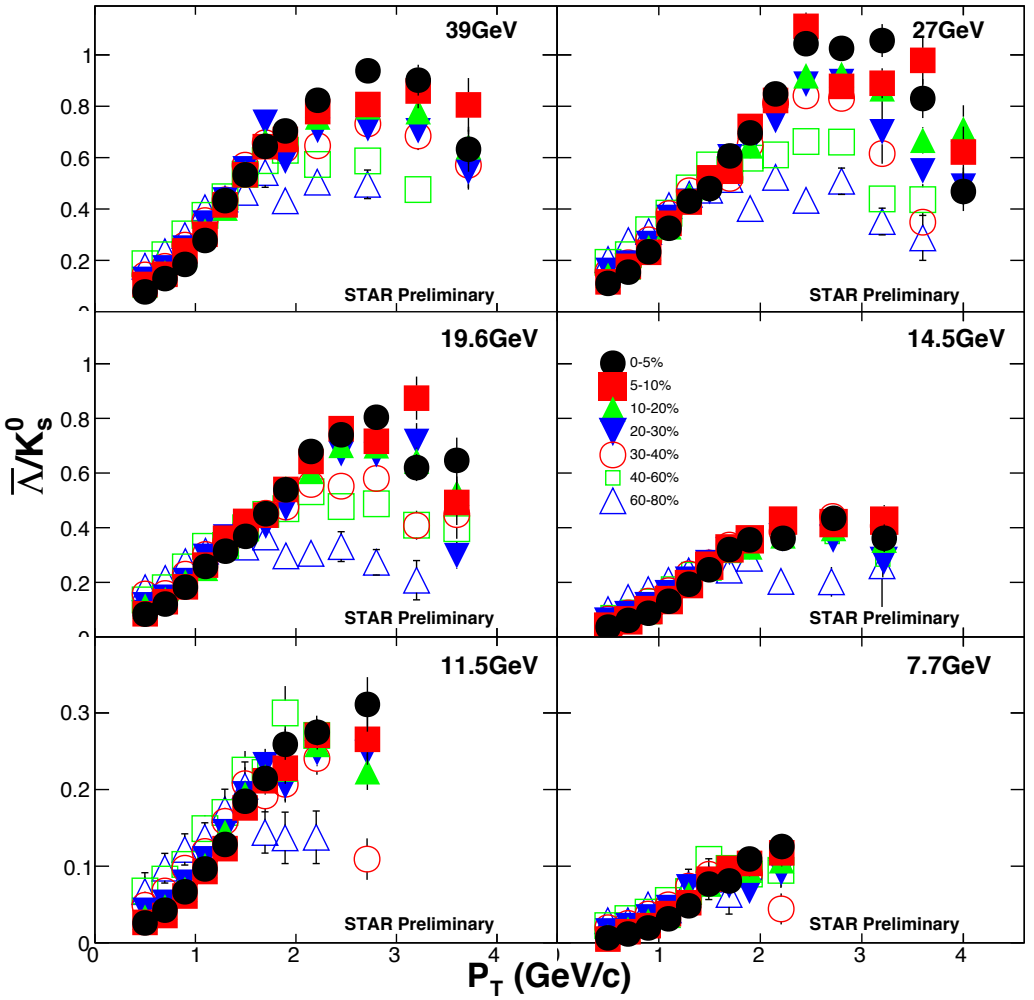
➢ less obvious for $\sqrt{s_{NN}} \leq 14.5$GeV

- less baryon enhancement

$\Longrightarrow$ possible change of medium properties

➢ Need more statistics at lower collision energies

STAR @ SQM 2016



“… (issues and improvements)”

the second part of the title

Some thoughts on …

Time to publication

	2012	2013	2014	2015	2016	2017
published	1	2	4	4	5 (1)	-
submitted	1	3	5	5	3	3
GPC	3	7	3	5(1)	6(5)	

(run-14)

BES-I : 2010/2011 (+2014)

- First GPCs within a year. Great!
  - ✓ Detector calibration and production QA
- Increased complexity ⟹ more time before GPC is formed
  - complex/new algorithms; may need more QA
  - realistic detector simulations for corrections, incl. efficiency calculations (embedding)
  - ➢ but, also danger of attrition in analysis team
- Resource competition: BES involves many (small) data sets
  - ➢ but, embedding in principle still needed for each running condition

BES-II : 2019/2020

How to speed-up time-to-publication?

- can we improve production turn-around?
  - e.g. calibrations procedures familiar – involve HLT?
  - ➢ new detectors: iTPC, EPD, and ETOF - reconstruction/calibration readiness
- picoDST distribution across institutes?

➢ Identify early analysis teams

- encourage multiple independent teams
- test-drive reconstruction+analysis chains
- set up PWG structures for QA cross-check and combination
- encourage early paper drafts

✓ continue active internal tracking of GPCs (from GPC to journal)

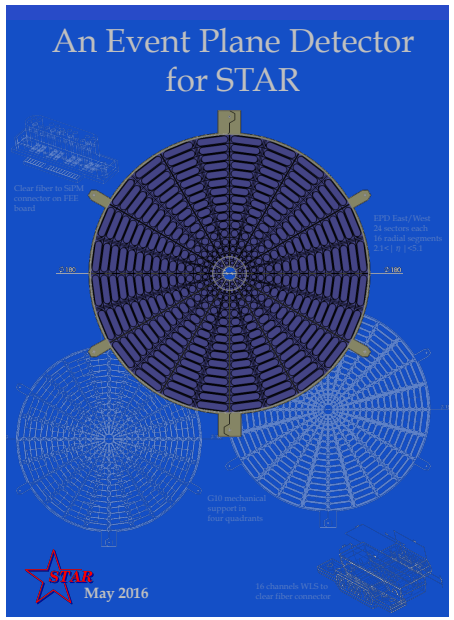
Short Summary …

- BES-II Proposal calls for more statistics and new detectors
  - iTPC, EPD, and ETOF detector upgrades are all well underway
  - several day-one bulk-spectra topics are getting in the starting blocks
    - significant improvements in uncertainties
    - enable new measurements

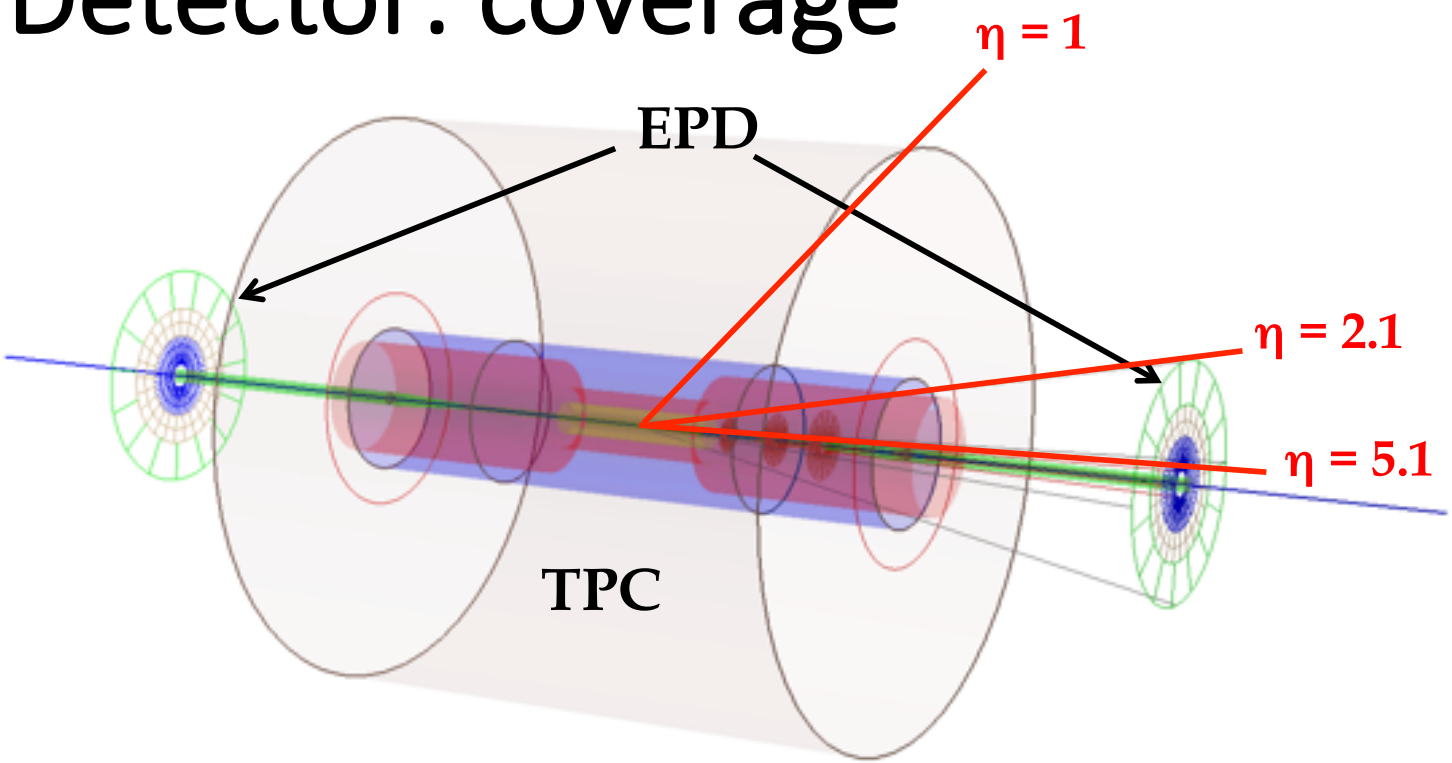
- Encourage multiple, independent analysis teams
  - important internal QA checks between teams
  - prepare (skeleton) paper drafts early on

Backup

Event Plane Detector: coverage



https://drupal.star.bnl.gov/STAR/system/files/EPD_Construction_Proposal.pdf



- Large eta coverage 2.1< |η|< 5.1 compared to TPC (|η|<1.0),
- Installed at z position +/- 375 cm
- High η (radial, 16) and azimuthal (24) segmentation
- Good timing resolution (~ 1 ns)

→ Adds mid-rapidity independent event plane and centrality determination. Also used as trigger detector for BES-II.

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Alex Schmah
at SQM2016