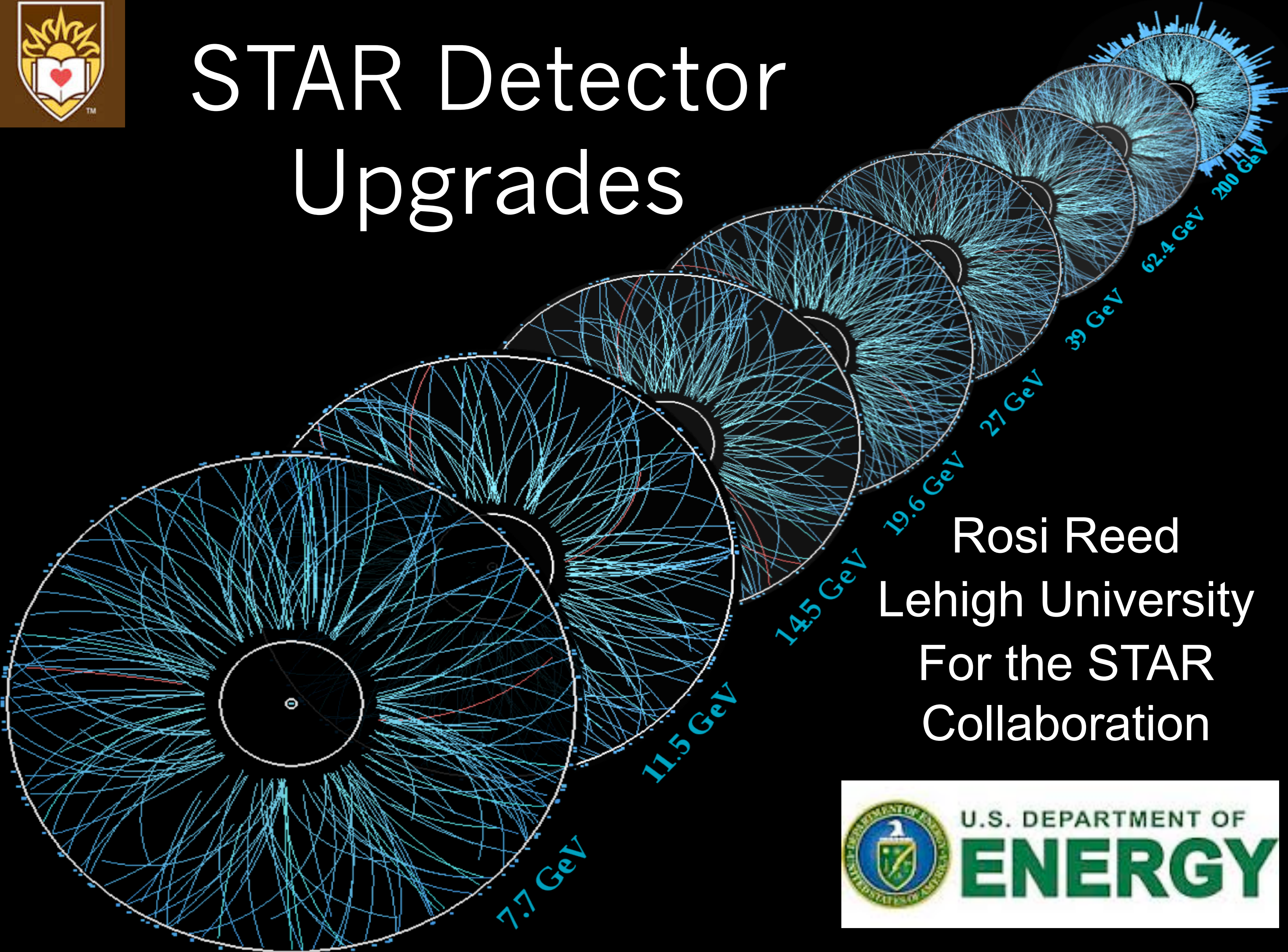
STAR Detector Upgrades



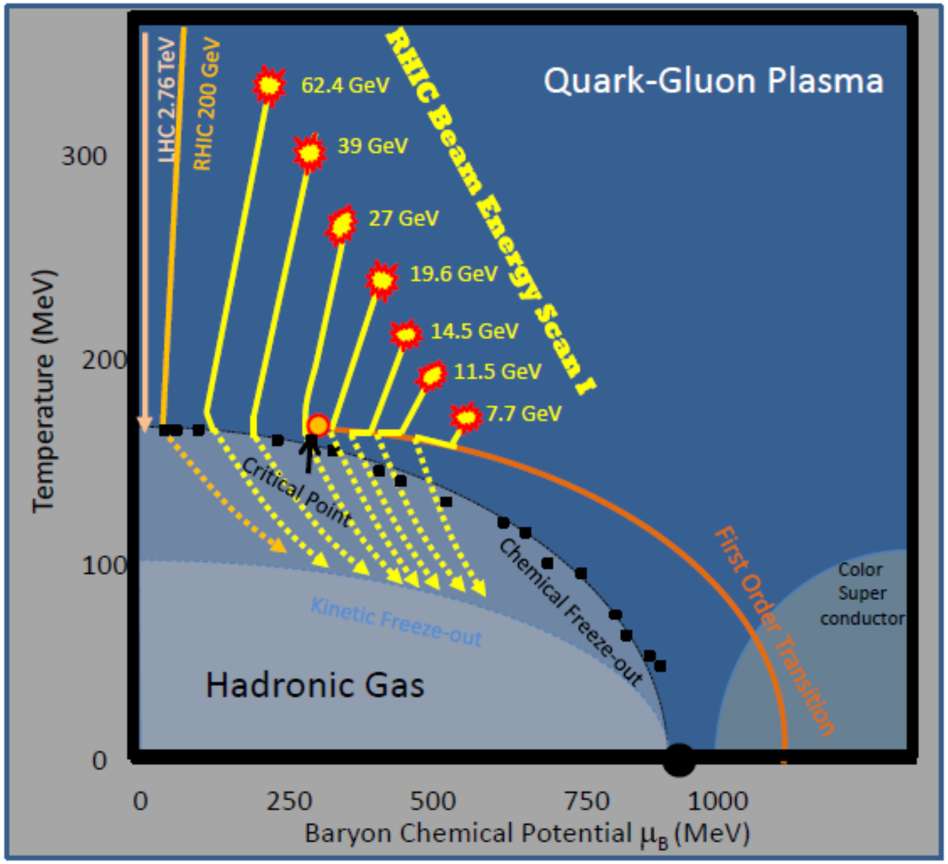
Rosi Reed
Lehigh University
For the STAR Collaboration

U.S. DEPARTMENT OF ENERGY

Outline

- Beam Energy Scan I highlights
- STAR's Beam Energy Scan II Program
- Upgrade detectors
  - **i**nner **T**ime **P**rojection **C**hamber
  - **e**ndcap **T**ime **O**f **F**light
  - **E**vent **P**lane **D**etector
- Polarized p+p/p+A/A+A program
- Upgrade detectors
  - **F**orward **C**alorimeter **S**ystem
  - **F**orward **T**racking **S**ystem

Exploring the QCD phase diagram BES-I

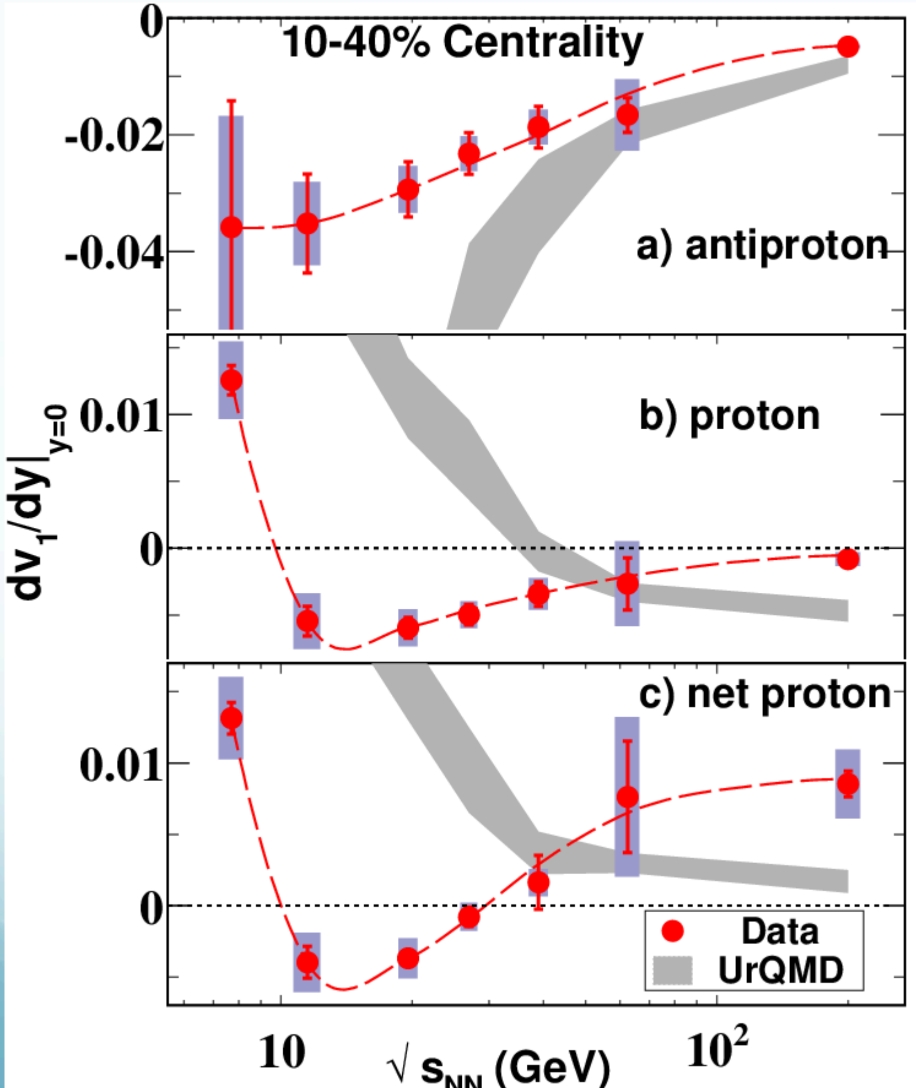


RHIC Beam Energy Scan Phase 1
Vary temperature *T* and baryon chemical potential μ_B
Carried out 2010-2014

- At low μ_B, the phase transition between QGP and hadrons is smooth cross-over
  - **Is there a 1st order transition** and a **critical point** at higher μ_B?
- At what energies is a QGP created in the lower energy collisions?
  - **Search for the turn-off of QGP signatures**

STAR BES-I

Signs of 1st order phase transition



- Directed flow (v_1)
  - Net protons: double sign change
  - Simple hydro models can predict the structure
  - Transport models such as UrQMD fail
- Softening of EOS?
- Expected in mixed phase

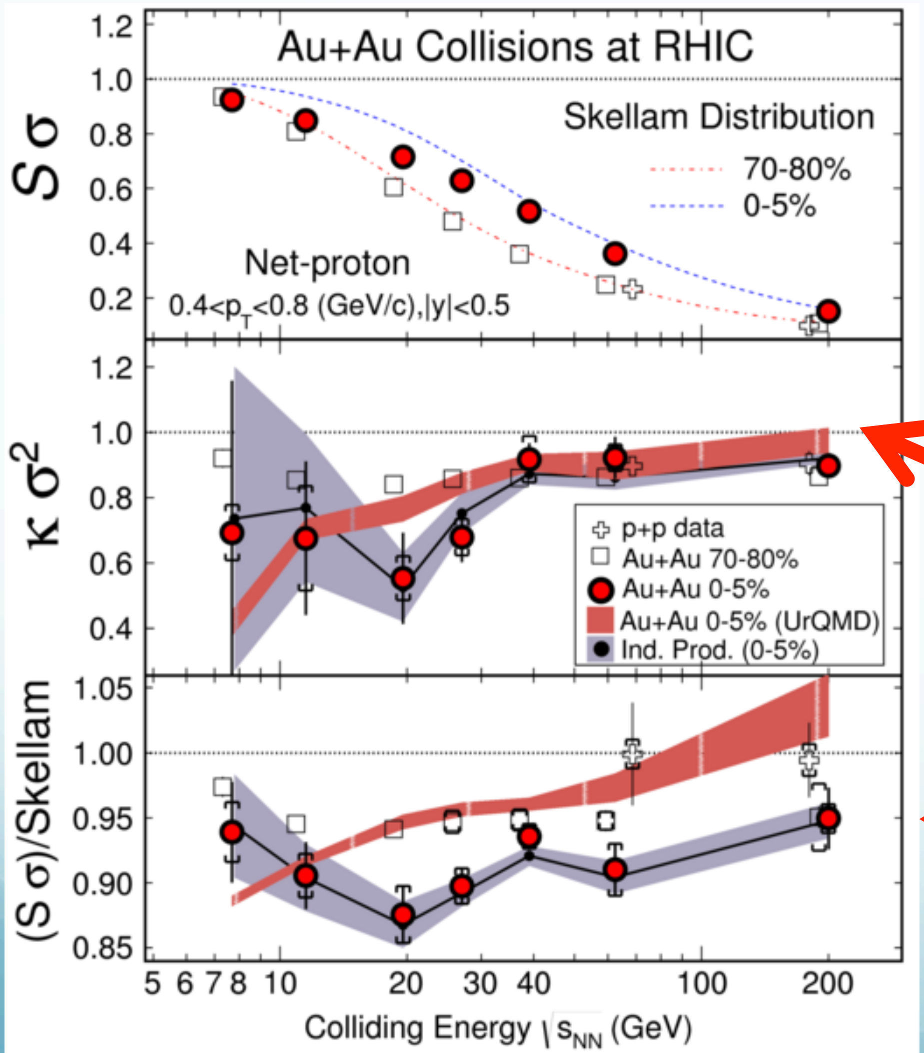
Phys. Rev. Lett. 112, 162301 (2014)

STAR BES-I

The QCD critical point

See Bill Llope's talk on Tuesday!

Phys. Rev. Lett. 112 (2014) 32302



- CP → Divergence of susceptibilities (χ) and correlation lengths (ξ)
  - Ratios of cumulants of the net-particle multiplicity distributions should diverge

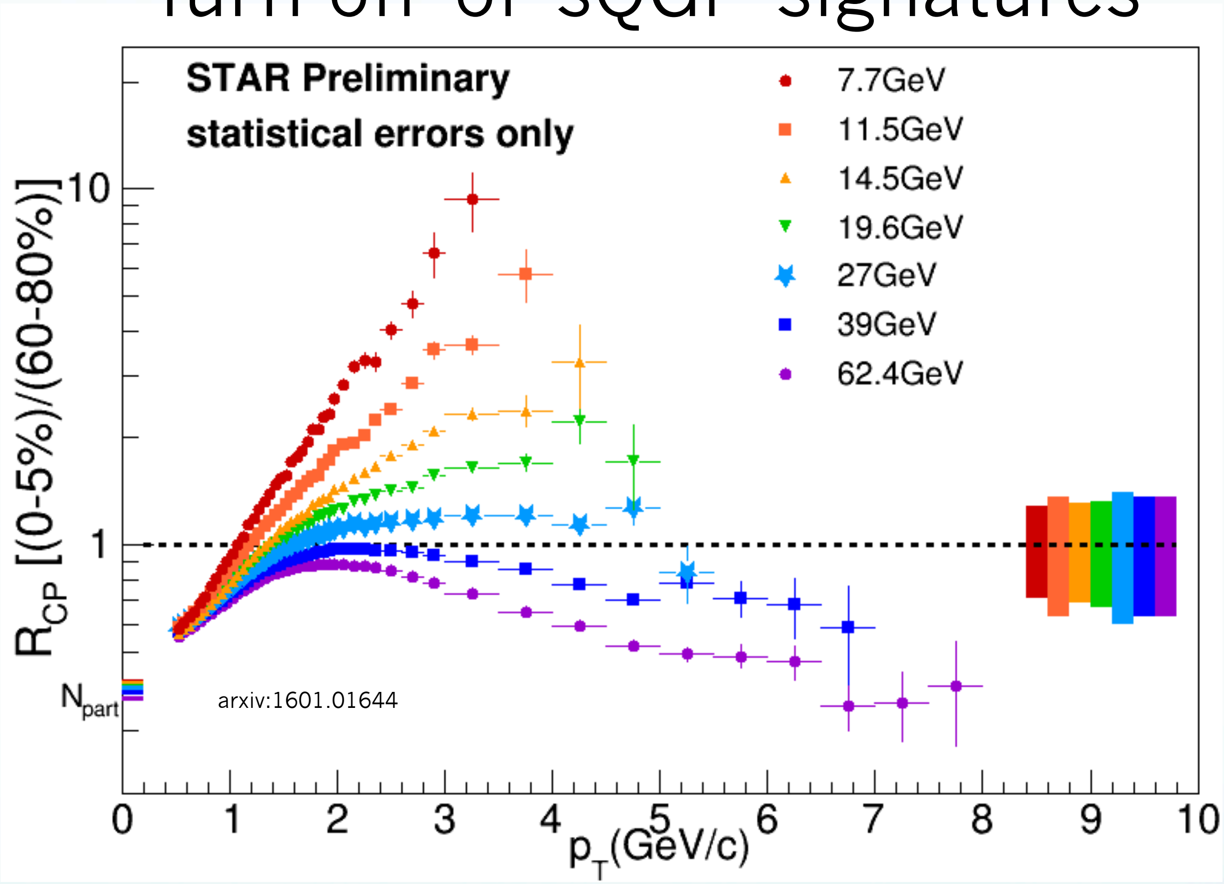
~2-3σ from Poisson

~100 MeV gap in μ_B between $\sqrt{s_{nn}}$ = 10 and 20 GeV

- Miss features that are narrow in μ_B

STAR BES-I

Turn-off of sQGP signatures



- Do we see the turn off of jet quenching?
  - Enhancement competes with suppression complicating the measure of the turn off of QGP effects at low $\sqrt{s_{NN}}$
    - 2016 d+Au Collisions will help quantify CNM effects

BES-I → BES-II

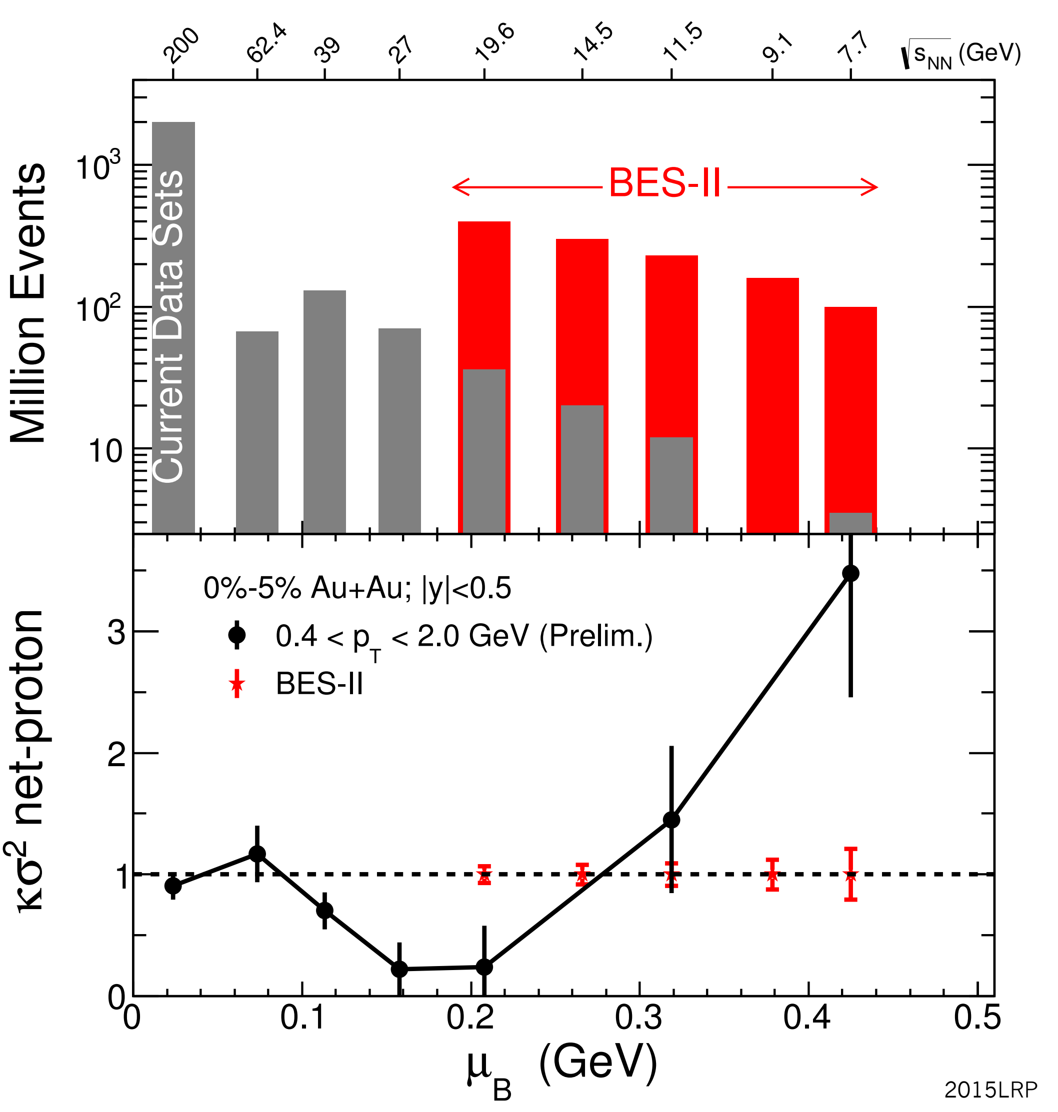
- 2015 NSAC RECOMMENDATION:
  - The **upgraded RHIC facility** provides unique capabilities that must be utilized to **explore the properties and phases of quark** and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.

    http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf
- **Trends and features** from BES-I motivate for experimental measurements with higher statistical and systematic precision
  - Requires strong and concerted theoretical response
- Detector upgrades planned for BES-II focus on **maximizing the fraction of measured particles** from each collision

The goal of BES-II is **to turn trends and features into definitive conclusions** and new understanding of the key features of QCD.

BES-I → BES-II

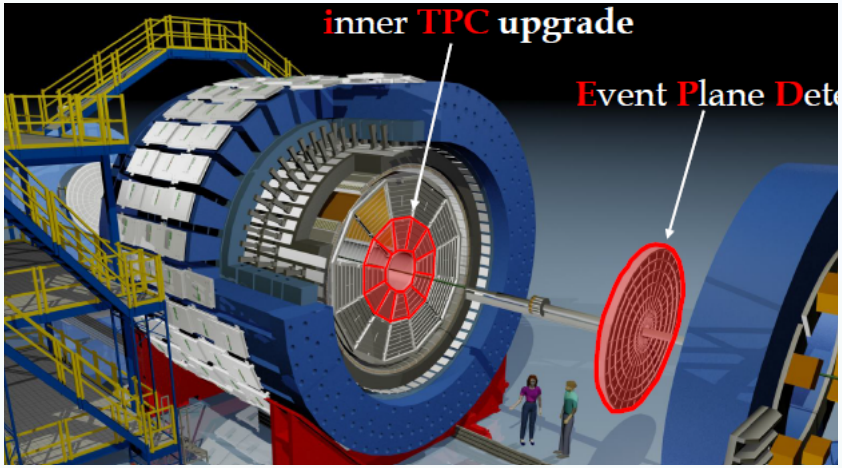
More Statistics

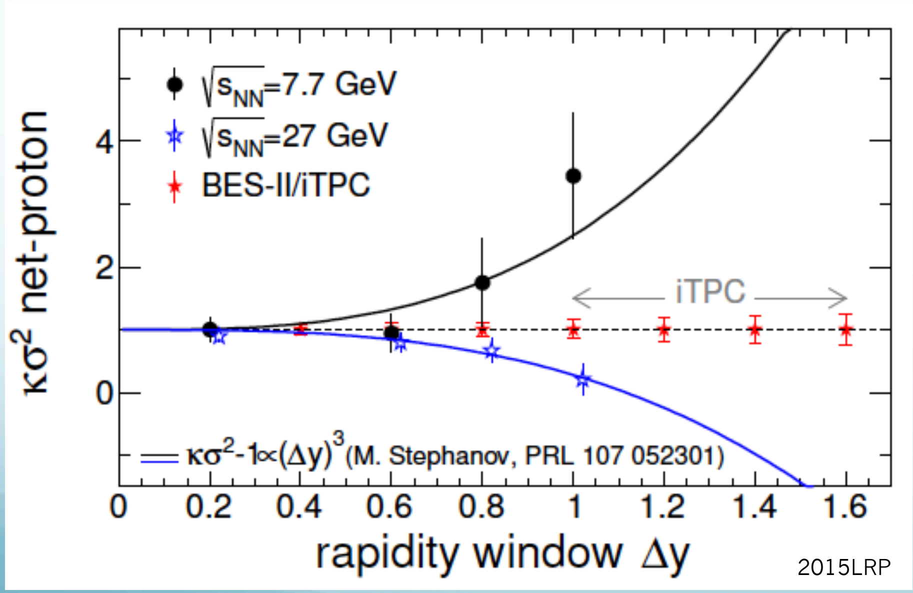


- BES-I exploratory scan was carried out to shed light on these questions
  - Tantalizing hints of a CP with $8 < \sqrt{S_{NN}} < 20$ GeV
  - How can we capitalize on these results?
- **More data**
  - **Electron cooling**
    - RHIC Luminosity upgrade
    - Needed for lower energies
  - Many results statistics limited

BES-I → BES-II

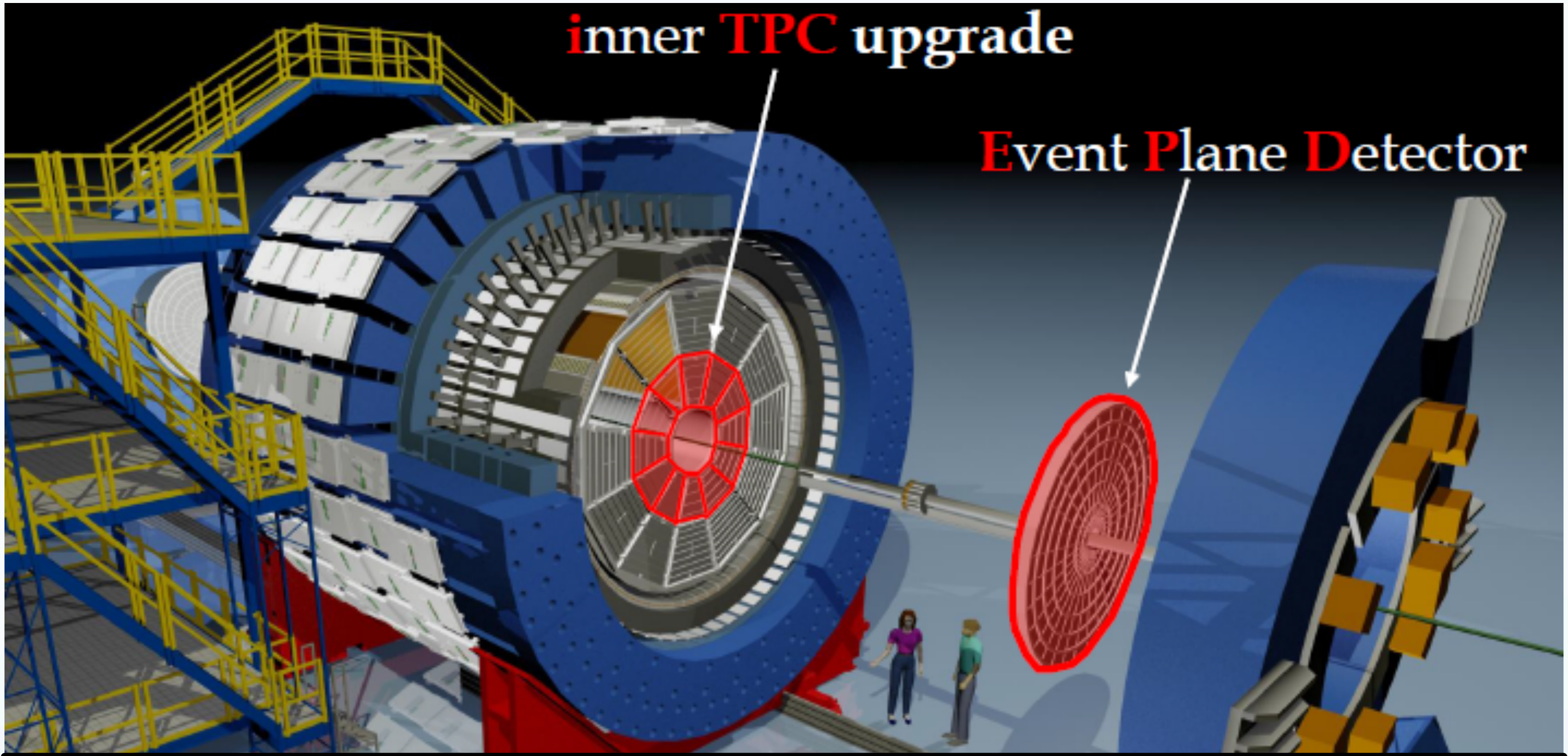
Larger Acceptance





- **Better coverage**
  - Detector upgrades increase the acceptance at high η
  - iTPC
  - eTOF
  - EPD
- Expanding in η
  - Allows better quantification of the fluctuations → ensures measurement is sensitive to the QGP physics
  - Varying μ_B either by |y| or $\sqrt{s_{NN}}$

iTPC



TPC	➡	iTPC
Sparse pads	➡	cover full area;
	➡	better *dE/dx*;
$-1 < \eta < 1$	➡	$-1.5 < \eta < 1.5$;
p_T >125 MeV/*c*	➡	p_T >60 MeV/*c*.

iTPC

- Improves
  - Momentum resolution
  - dE/dx resolution 7.5% to 6.2%
  - Acceptance
    - From $|\eta| < \sim 1.0$ to $|\eta| < 1.5$, from P_T>125 MeV/c to P_T>60 MeV/c
    - **iTPC upgrade extends the rapidity coverage by 50%**

iTPC project has been approved!

- Current inner TPC pad row geometry is not fully instrumented
  - Only 20% of the inner sector path length is sampled
  - **iTPC increases the path length coverage in the inner sectors to 100%**
- Benefits many analyses, especially:
  - Fluctuations (Kurtosis)
  - Baryon v_1 measurements

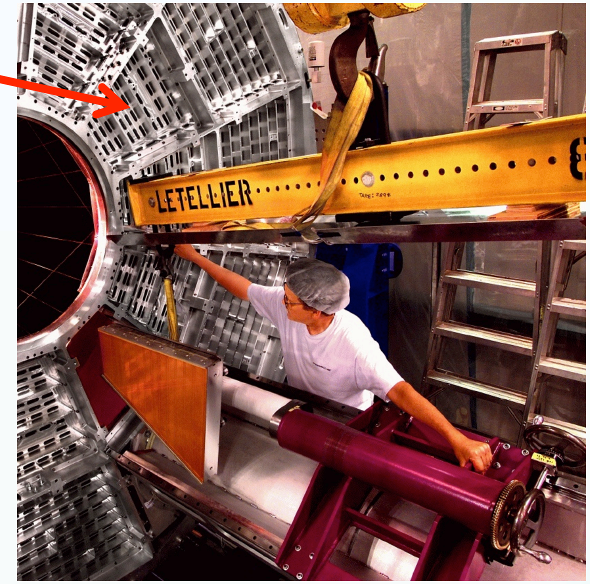
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0644

- **Improves 2nd-order event-plane res, away from mid-rapidity by x2**
  - Enhancing elliptic flow measurements
  - For dielectron measurements it reduces hadron contamination from a dominant source of uncertainty (20%) down by an order of magnitude
    - Much less than the expected statistical uncertainty (10%).

The iTPC in a nutshell

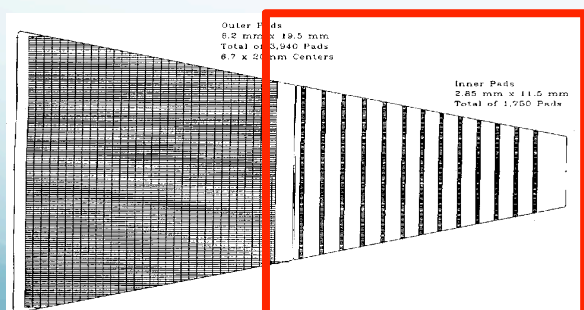
Inner sector 1/12

- The upgrade increases $N_{channels}$ in the 24 inner sectors by ~x2
- Provide complete coverage for a inner sector
- New electronics for inner sectors



Pad plane layout for one sector

Current

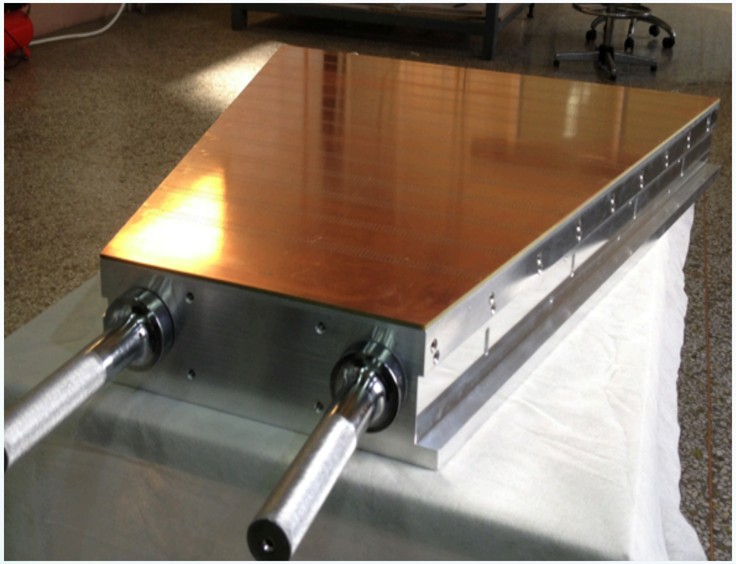


Outer Inner

Future

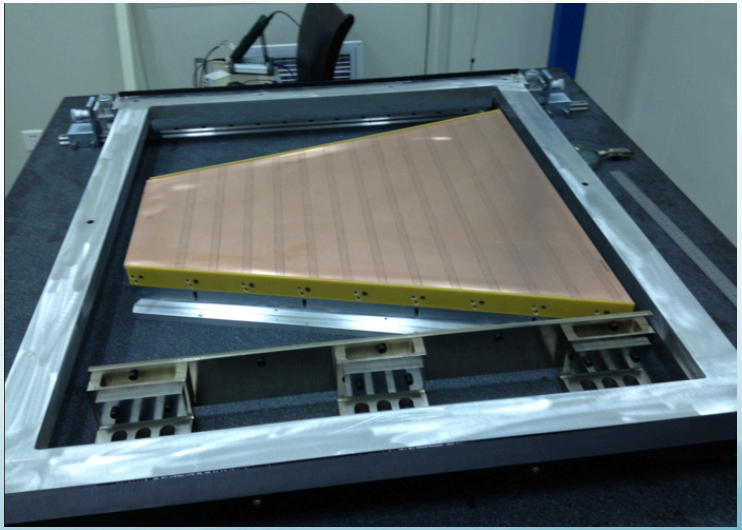
iTPC sectors

Prototype – original layout
Padplane glued onto strongback



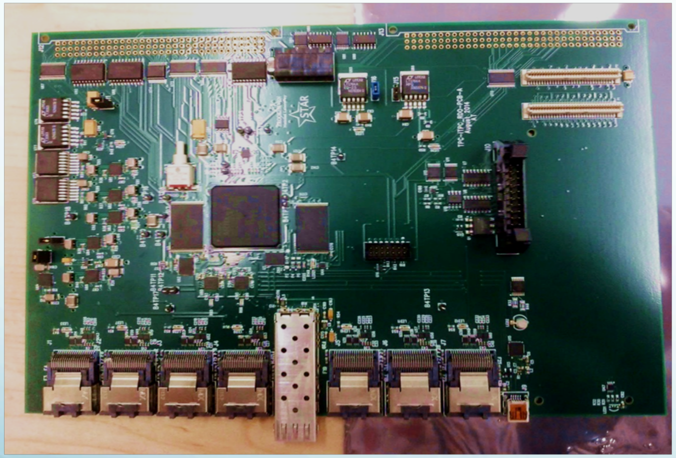
Wire mounting prototype at Shandong University, China

- Only modification is slot position
- Pure construction project, little or no engineering design left
- Improves electrostatics between inner and outer sector
- Ready for construction

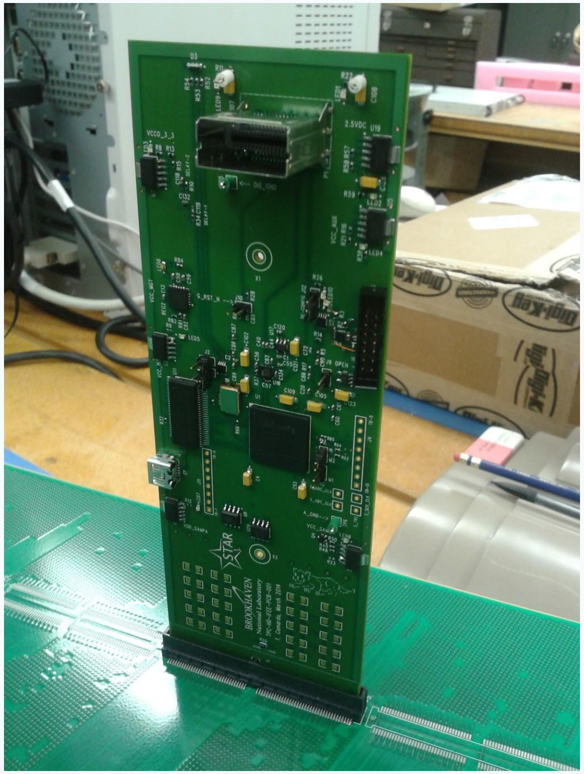


iTPC Electronics

- iFEE based on current FEE layout, but using ALICE SAMPA chip
- 2x $N_{channels}$ per FEE
- RDO similar to existing
- Developed by BNL electronics group

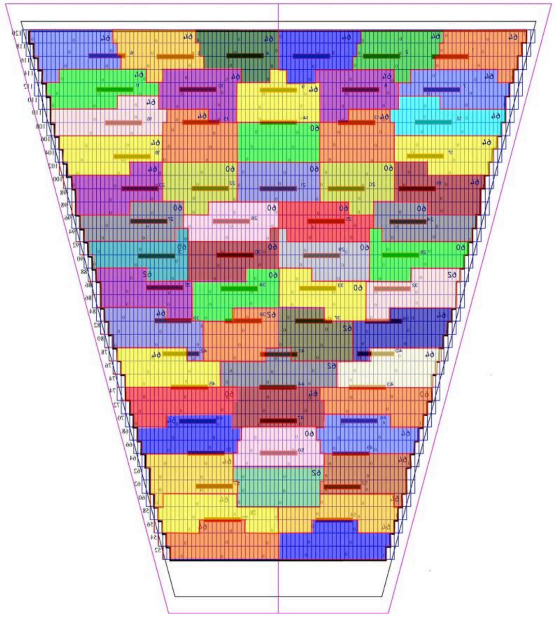


RDO prototype



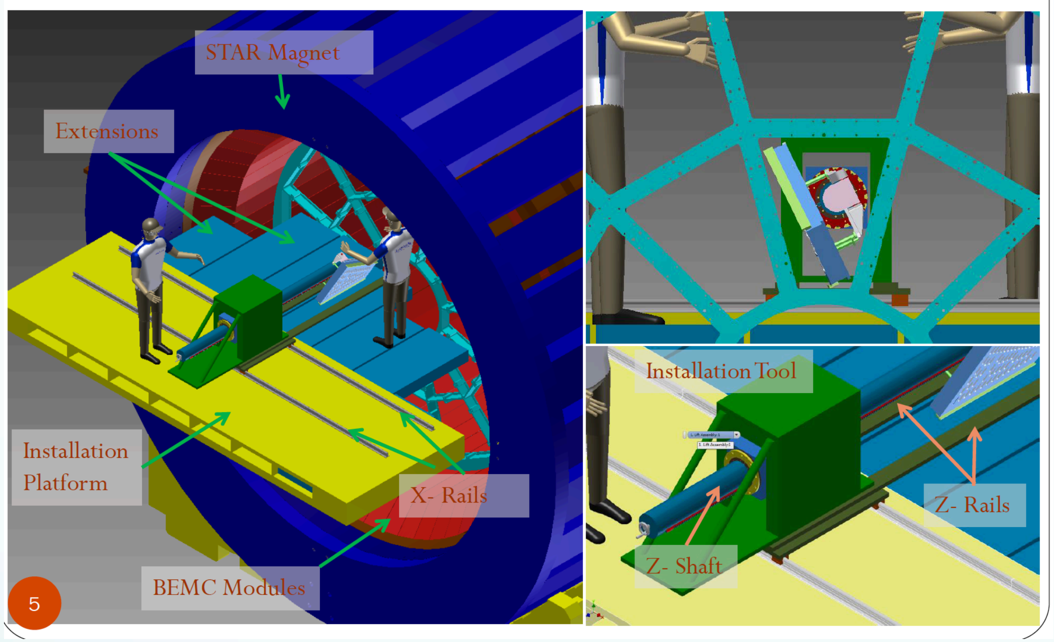
Pre-prototye iFEE electronic card shown plugged into the padplane

Fully instrumented TPC connections to FEE

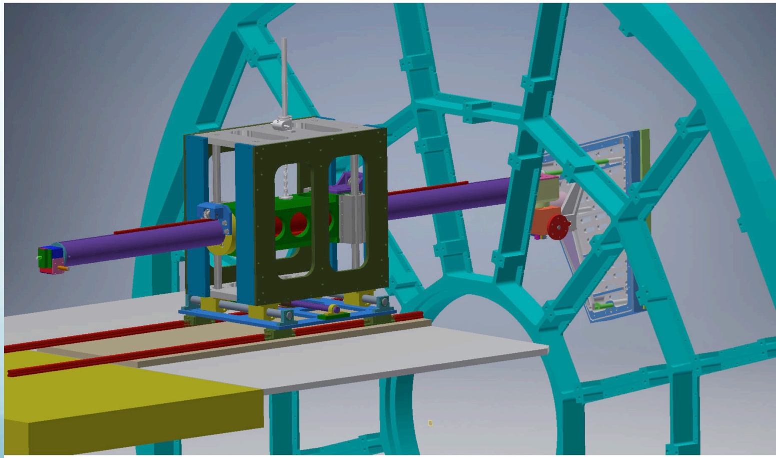


iTPC Insertion Tooling

Cartesian Installation Tool Design



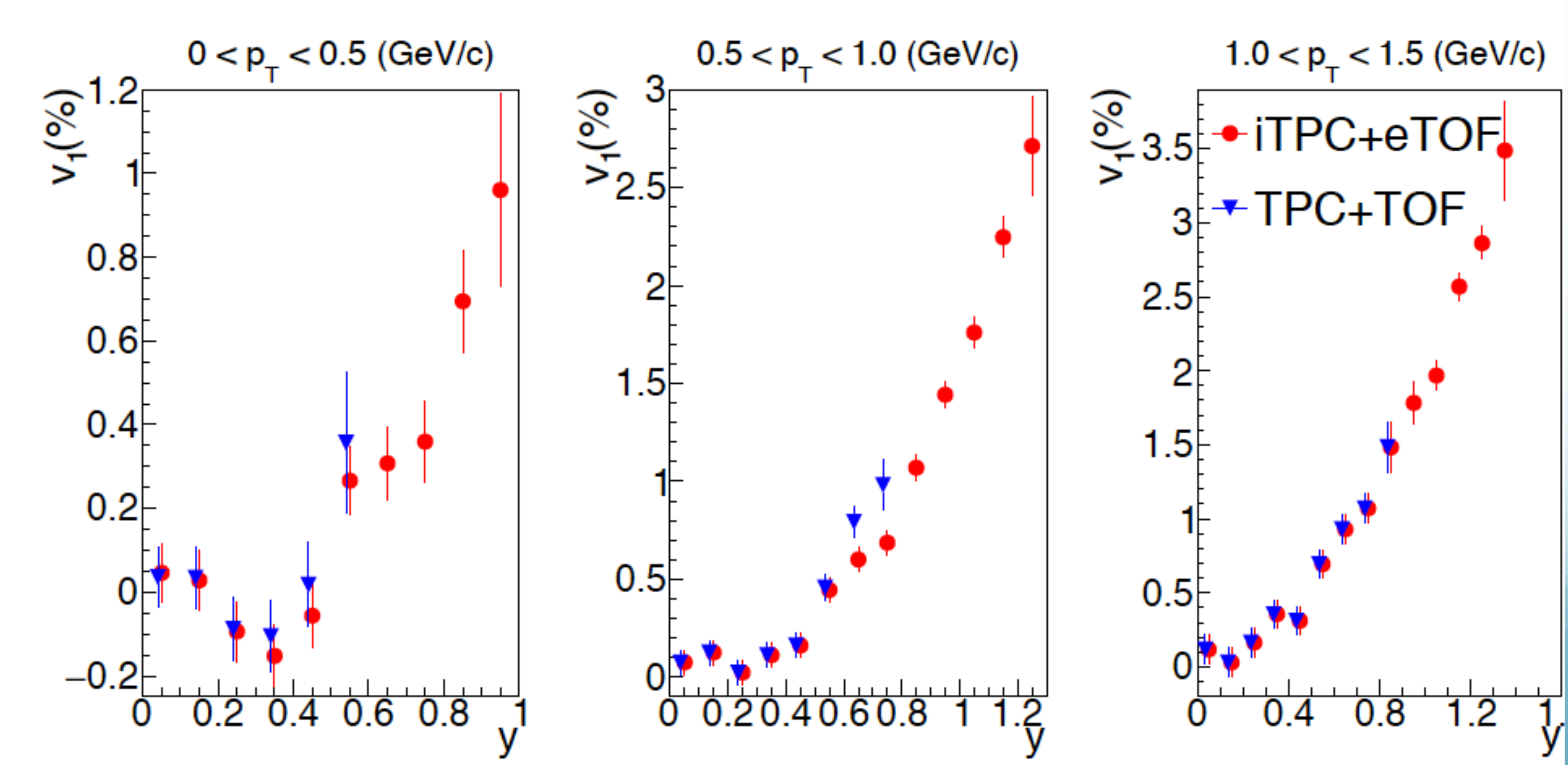
Insertion tooling needed for installation and for replacement of two outer bad sectors



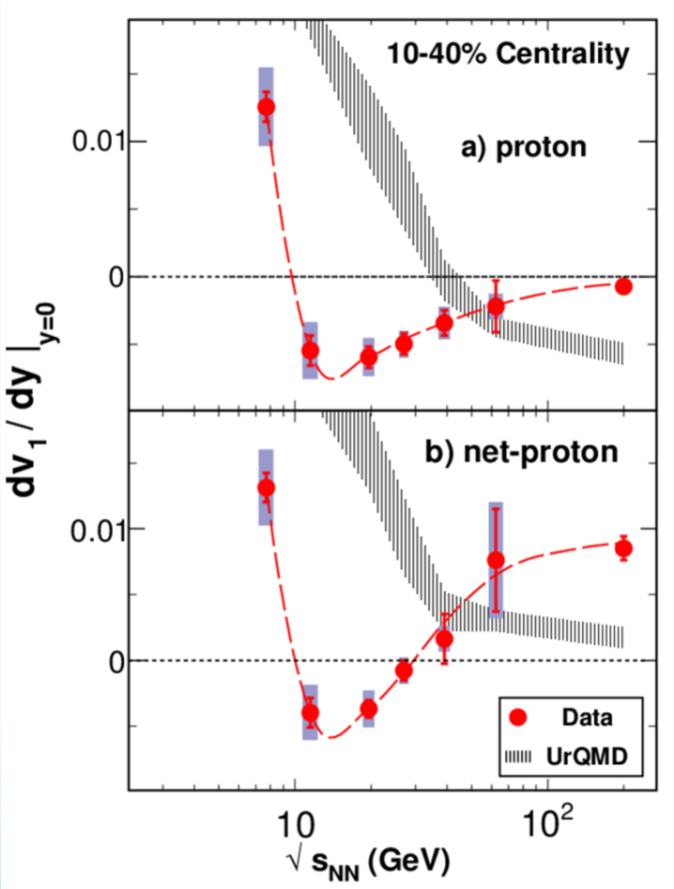
Designed by Rahul Sharma, Ralph Brown and much input from LBL, CERN

Direct Flow Improvements

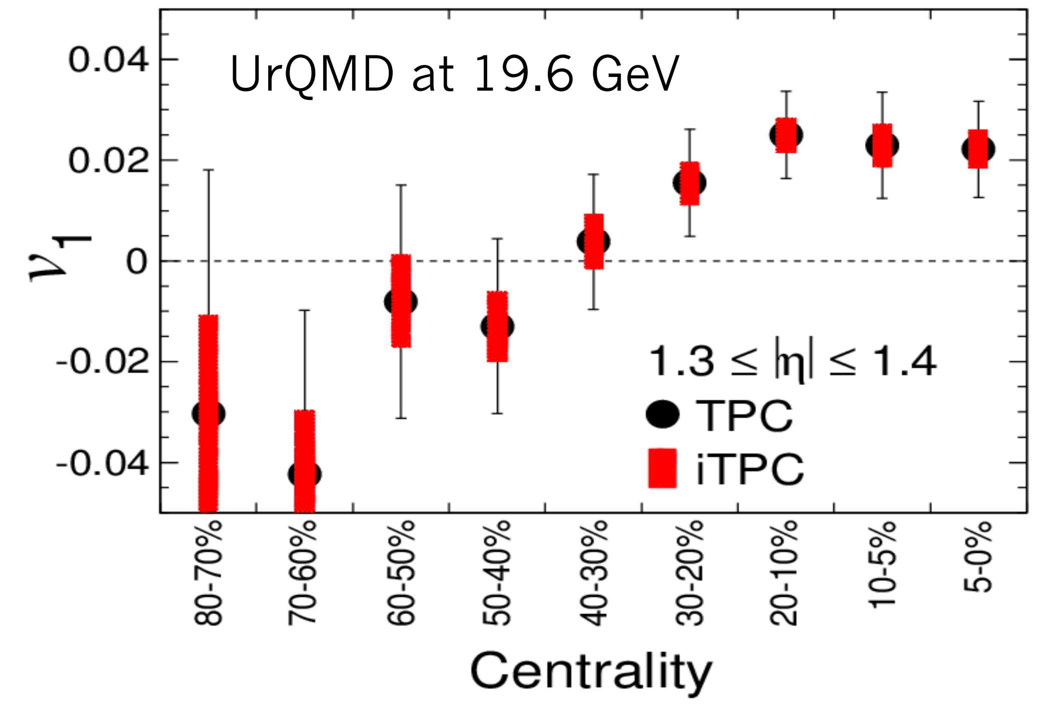
- Proton directed flow as a function of rapidity for minimum-bias Au + Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV
  - Based on UrQMD
- Simulated $v_1(y)$ compared between the acceptance of the STAR TPC with the existing TOF barrel and the upgraded acceptance after addition of the iTPC and the eTOF



iTPC → BES II directed flow

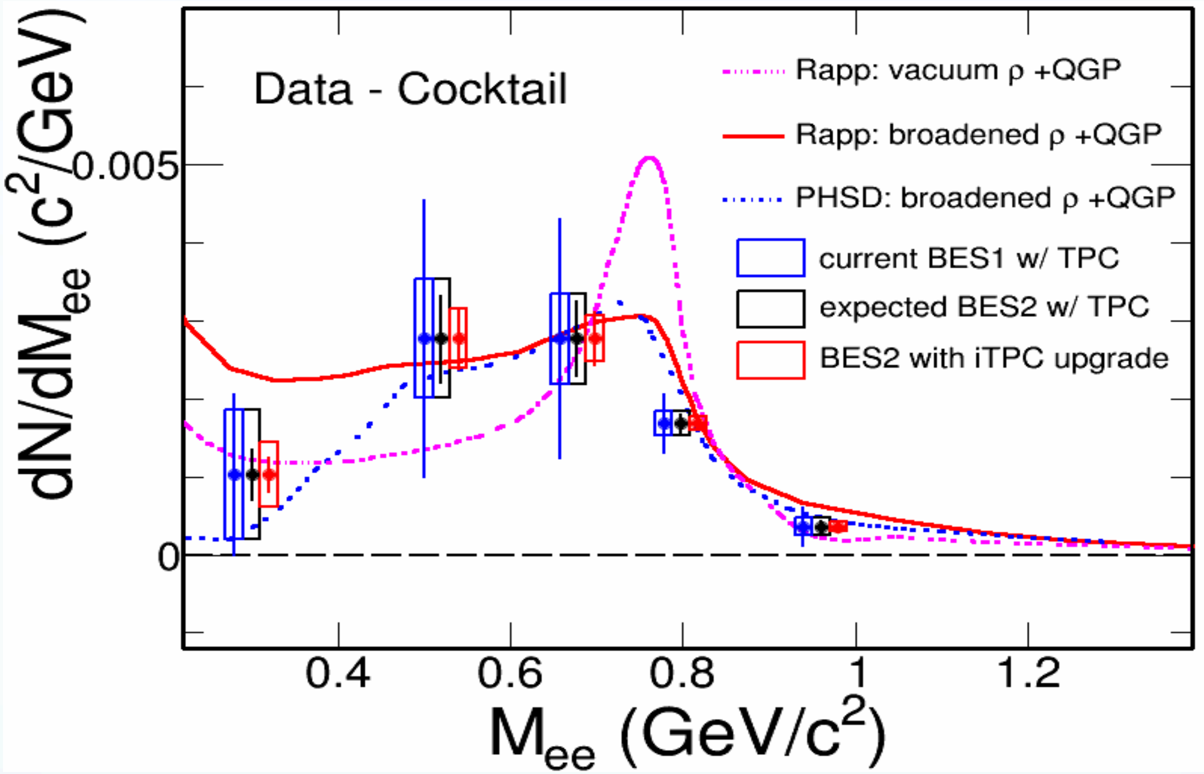


Directed flow for protons and net-protons BES-I PRL 112,162301 (2014)



- The Forward v_1 measurement as a function of centrality
  - Shows improvements due to iTPC coverage

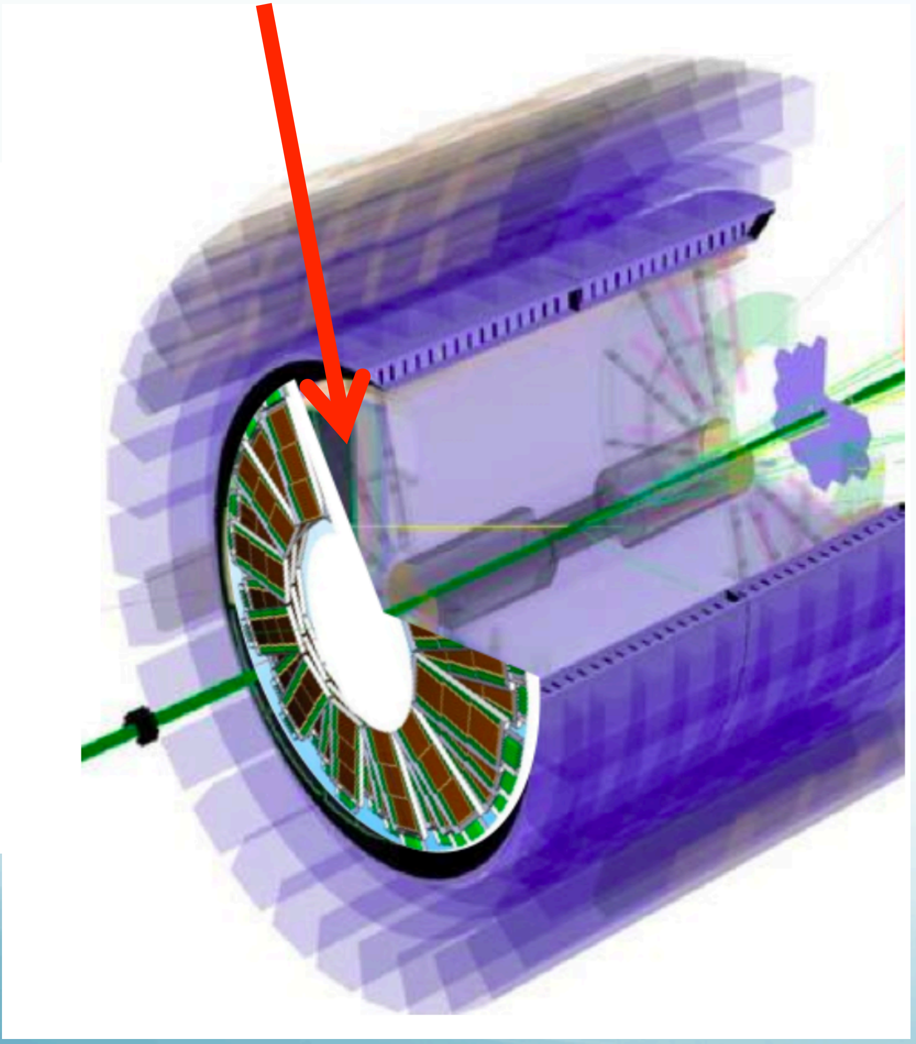
Di-electron measurements in BES-II



- Improved dE/dx will reduce the dominant systematic error
- Distinguish between models with different ρ-meson broadening
- Study effect of total baryon density on Low-Mass Region (LMR) excess

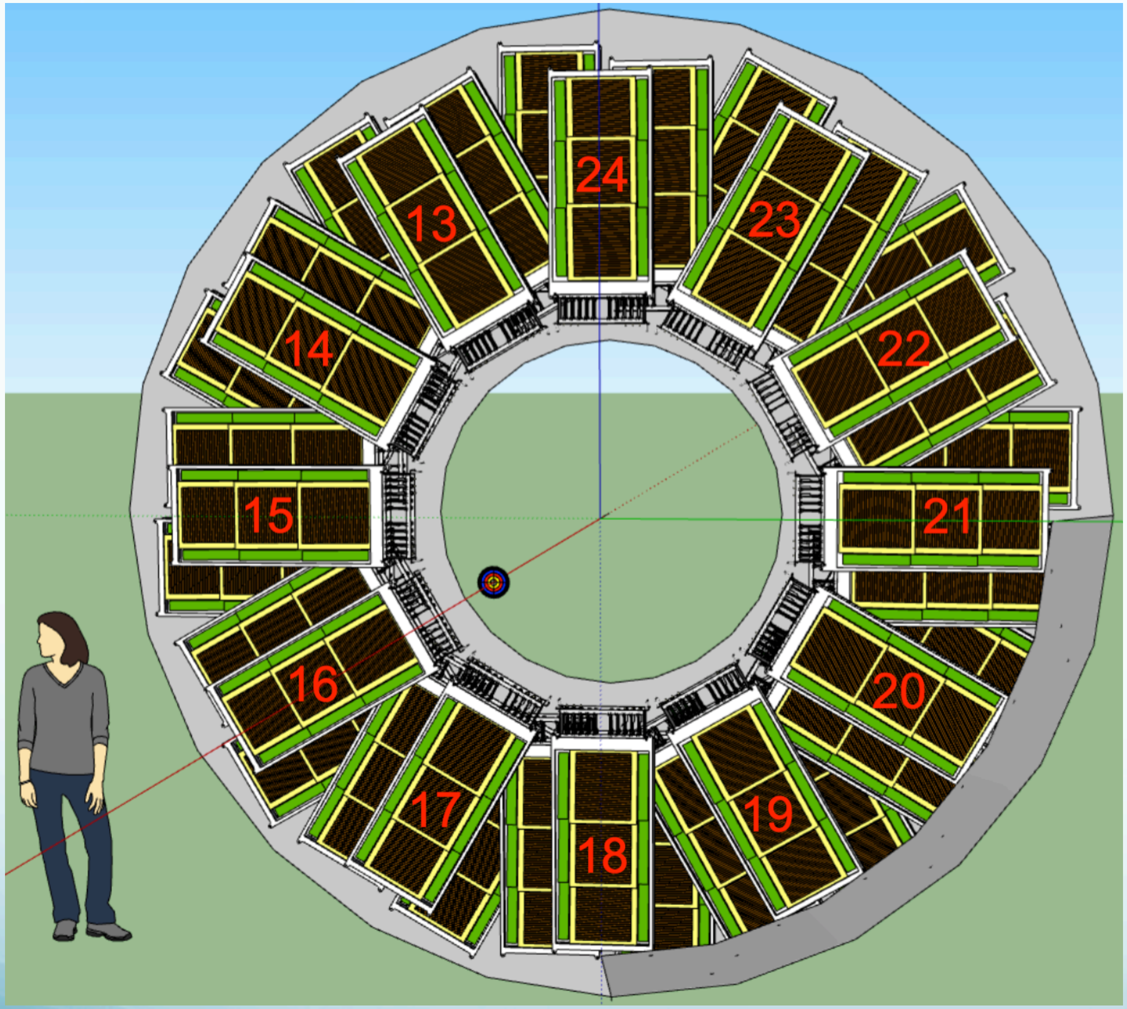
eTOF

endcap **T**ime **O**f **F**light



- Compressed Baryonic Matter Experiment (CBM) institutions proposed installing CBM TOF modules inside east pole-tip
- Acceptance
  - $-1.6 < \eta < -1.1$
- Provides STAR with an endcap TOF for BES-II
- Provides CBM a large-scale integration test of the CBM TOF system

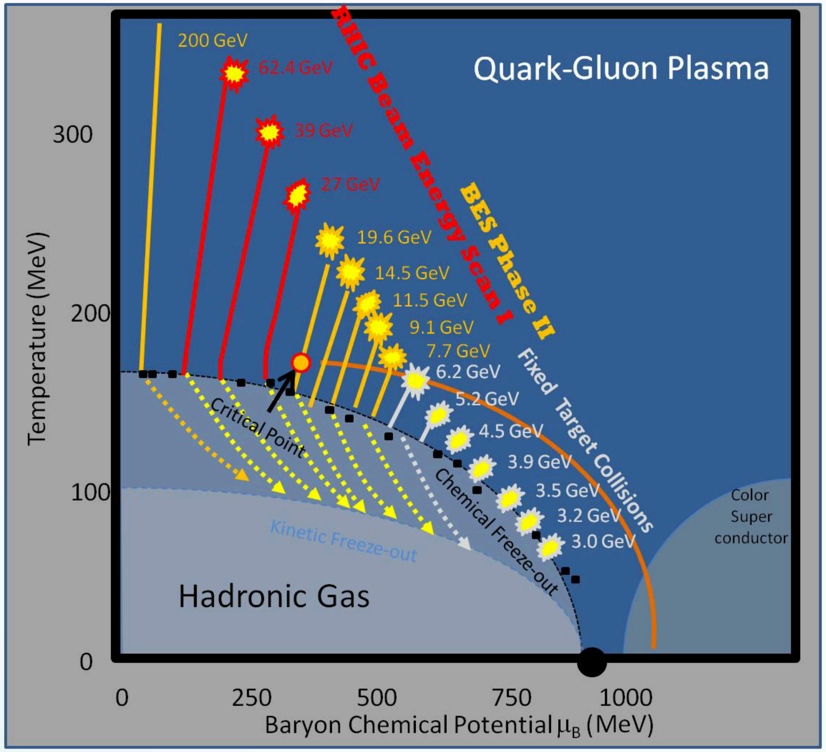
eTOF

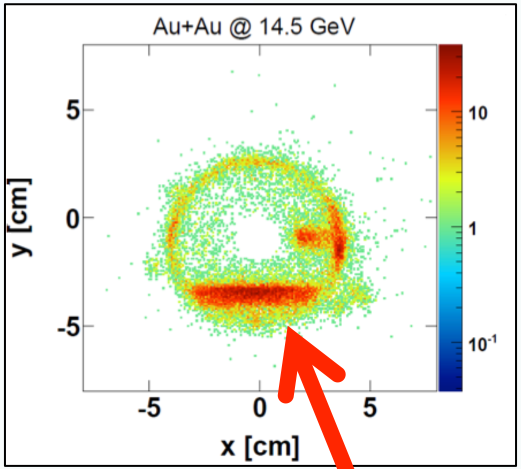


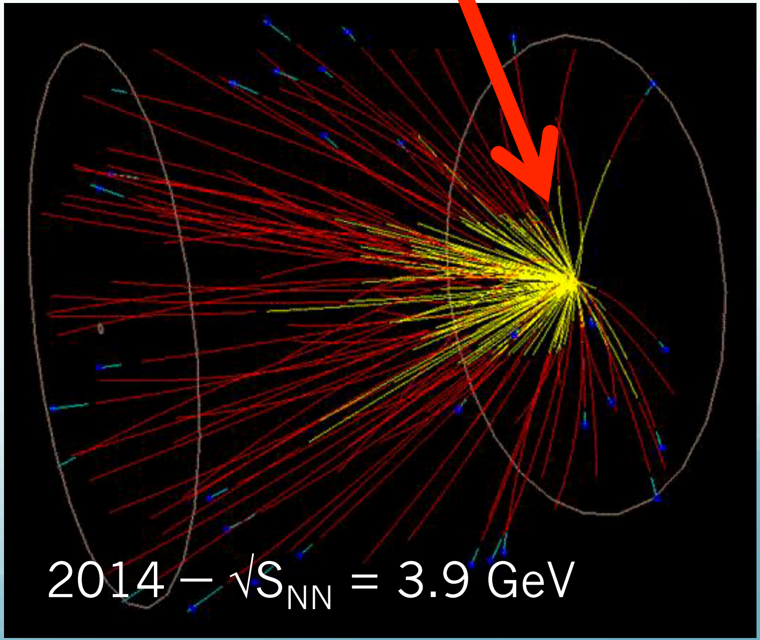
- Allows for PID in the η range provided by the iTPC upgrade
- eTOF needed for PID at forward rapidities
  - Efficiency dE/dx drops rapidly due to p_Z boost
  - Key for the fixed target program

BES-I → BES-II
New energies

See Kathryn Meehan's talk on Tuesday!

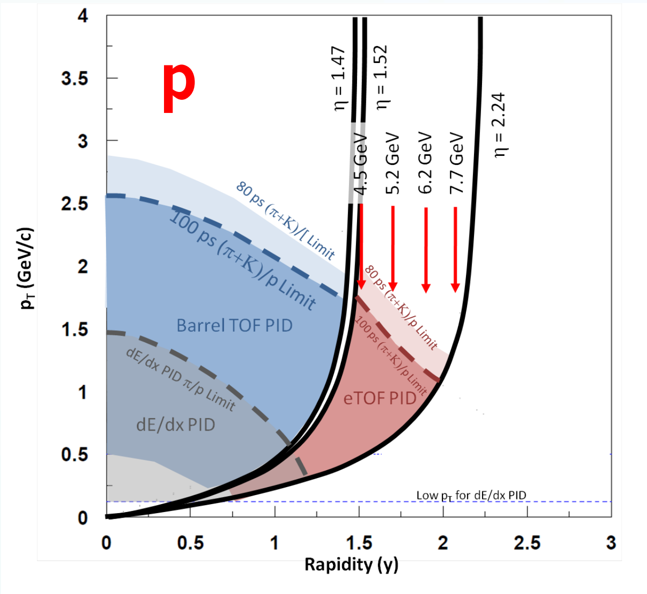




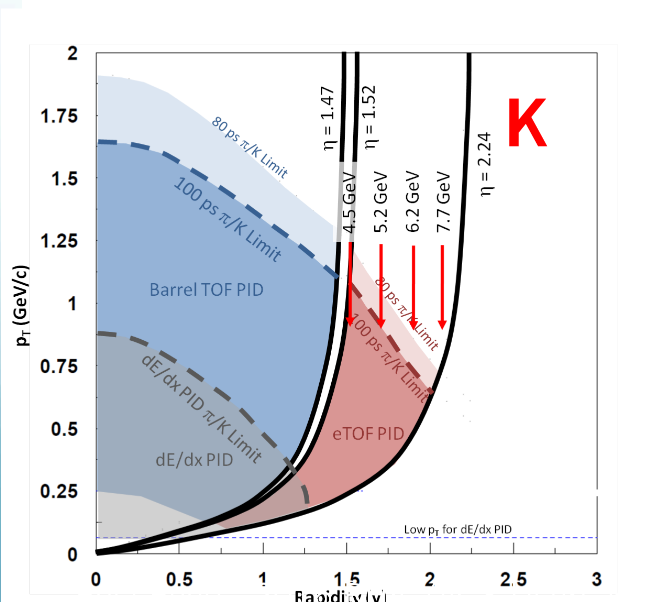


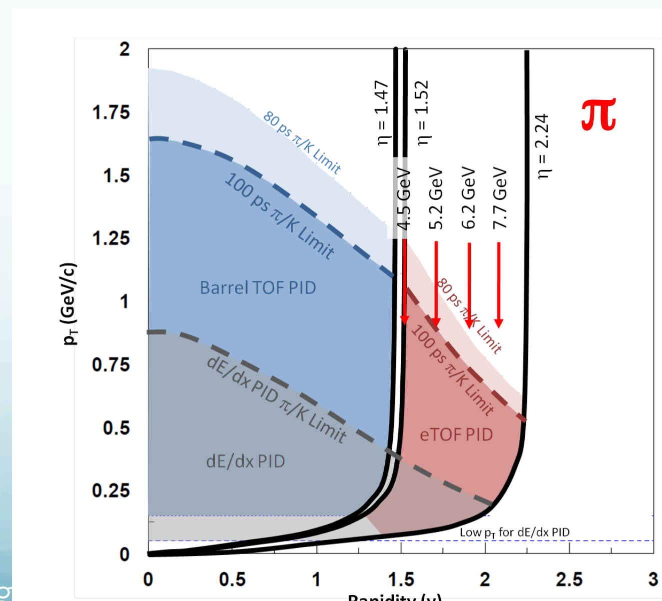
- Target inserted into beam pipe
  - Z = 210 cm
- Test run done parasitically
  - No interference w/collider mode data
- More efficient →small dedicated runs

$y - p_T$ Map Fixed Target

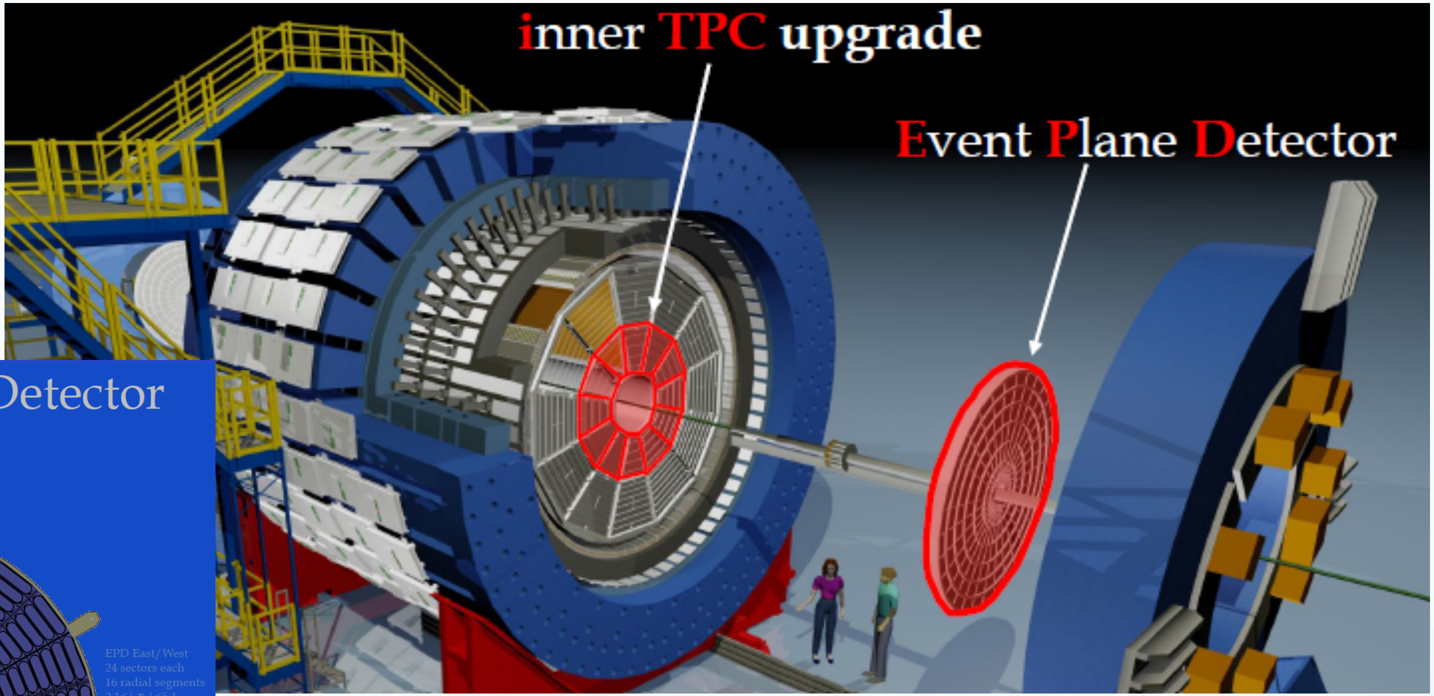


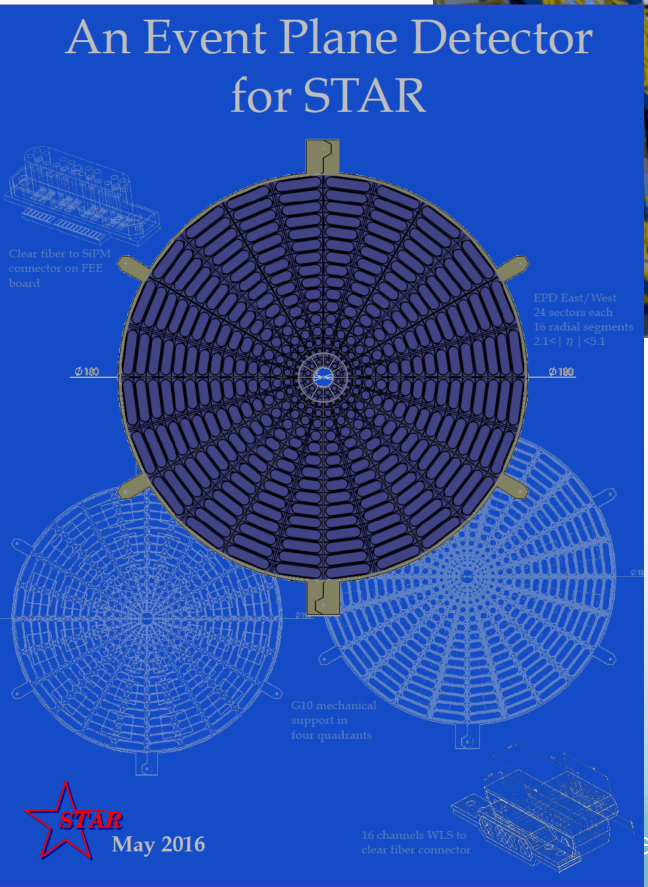
- NA49 → onset of deconfinement = $\sqrt{S_{NN}}$ = 7.7GeV Phys. Rev. C77, 024903 (2008),
  - < 7.7 GeV not possible in collider mode
- Using just the iTPC upgrade → energy range from 3 to 4.5 GeV
- eTOF upgrade allows $\sqrt{S_{NN}}$ = 3-7.7 GeV





EPD

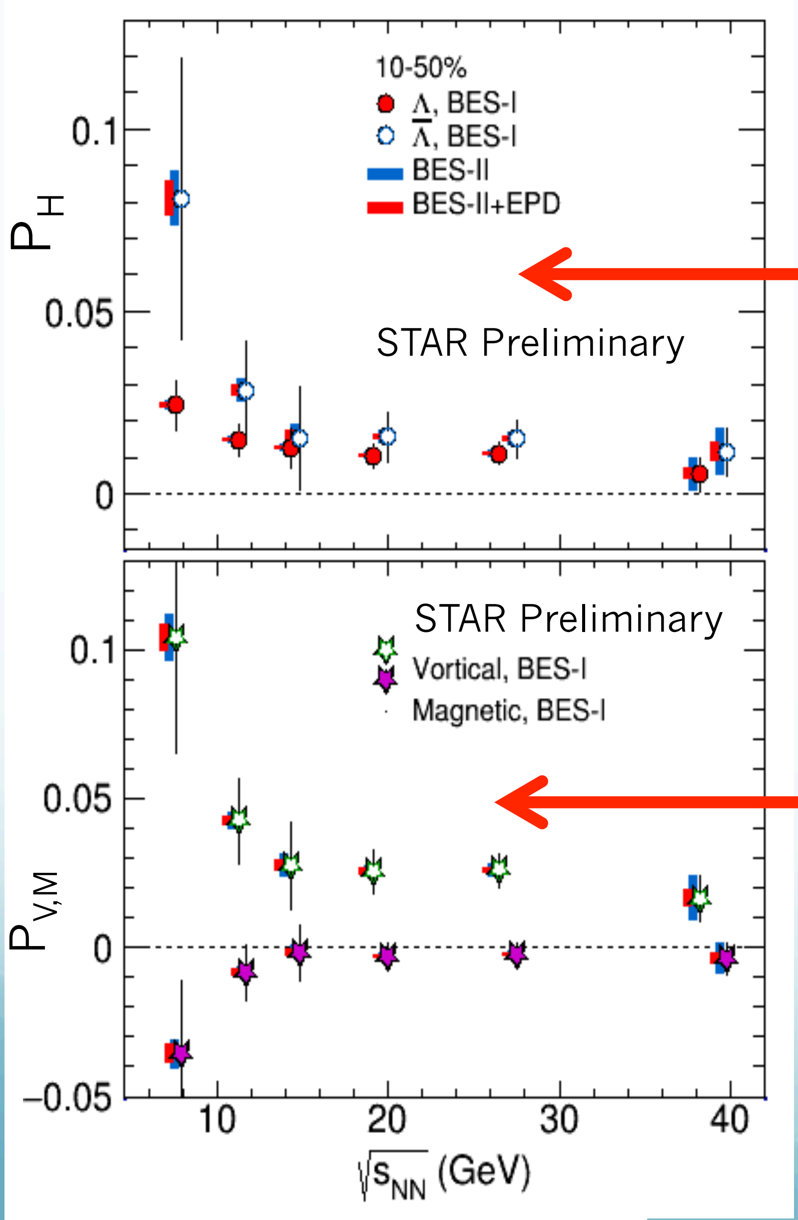




$2.1 < |\eta| < 5.1$

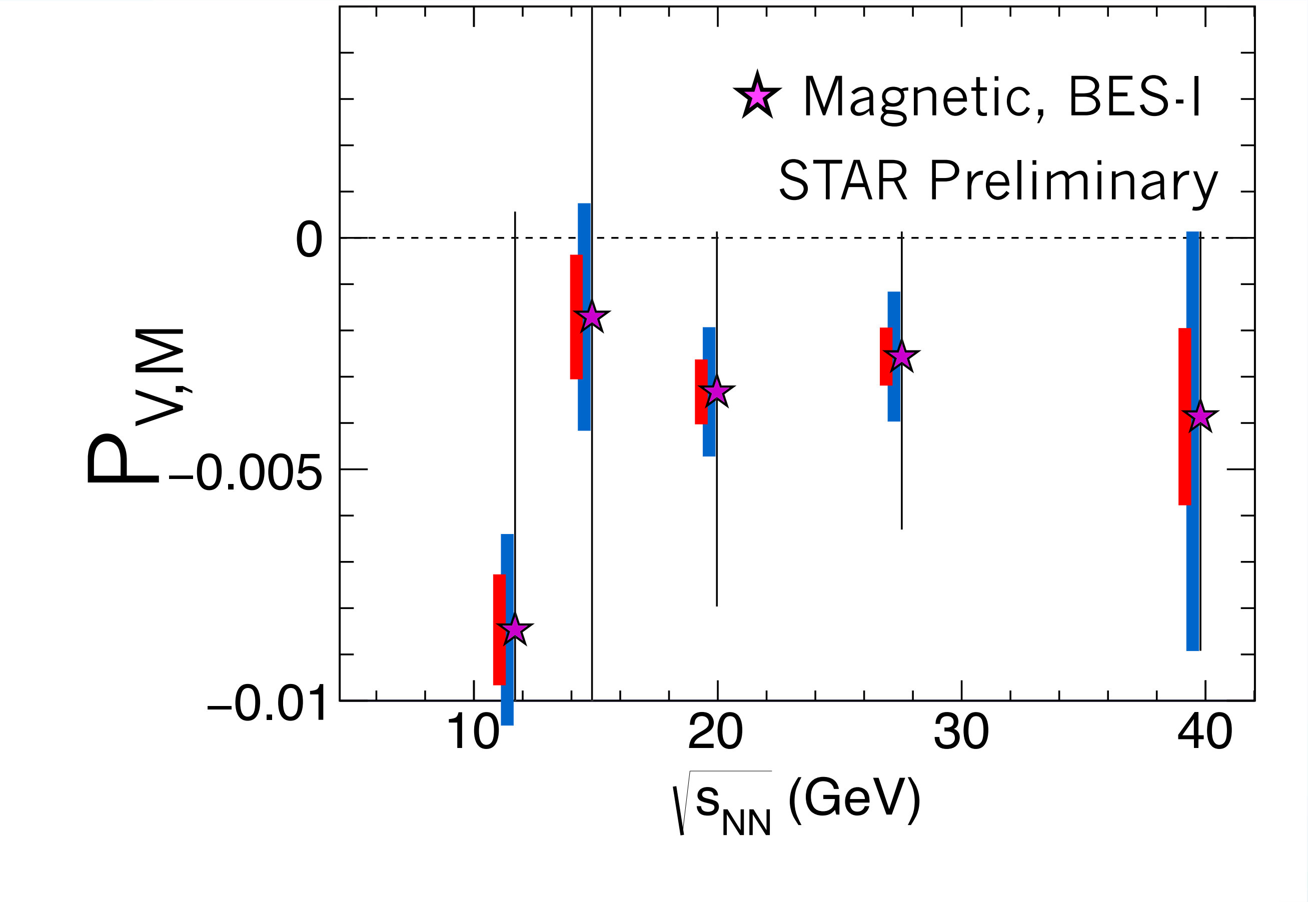
- Greatly improved Event Plane info (especially 1st-order EP)
- Determine Centrality outside mid-rapidity
- Better trigger & background reduction

EPD Improvements



- **BES-II**
- **BES-II + EPD**
- The **average polarization** of $\bar{\Lambda}$ and Λ from 20-50% central collisions
  - No feed-down effects → Stat uncertainty only
- The **vortical and magnetic contributions** to Λ and $\bar{\Lambda}$ emitted directly from the hot zone created in a heavy ion collision
  - Statistical errors only
  - Scale of P_V has an uncertainty of +60% and -5% due to uncertainty in the amount of feed-down

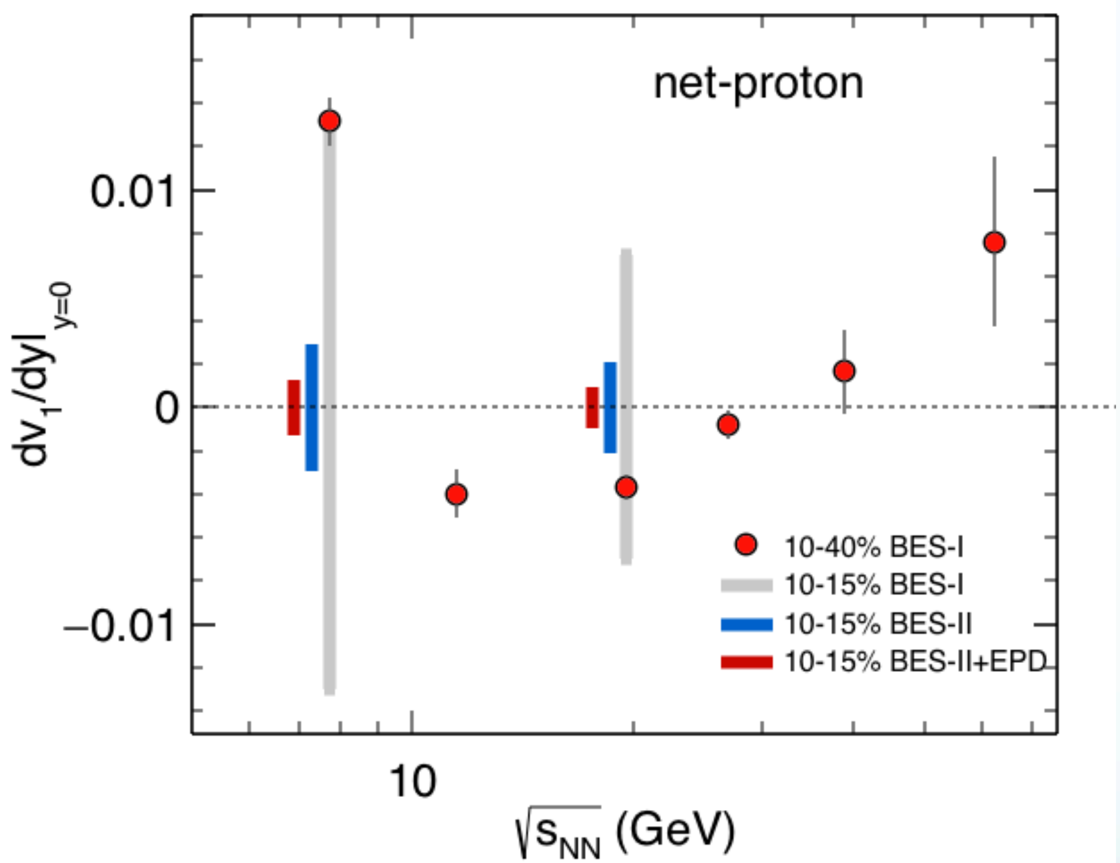
EPD Improvements



Zooming we can see that the current results are not significant for $\sqrt{s_{NN}} \geq 27$ GeV

- Increase in statistics and EPD allow for a ~3σ effect
- Gives an independent measure of B, key for CME/CVE verification

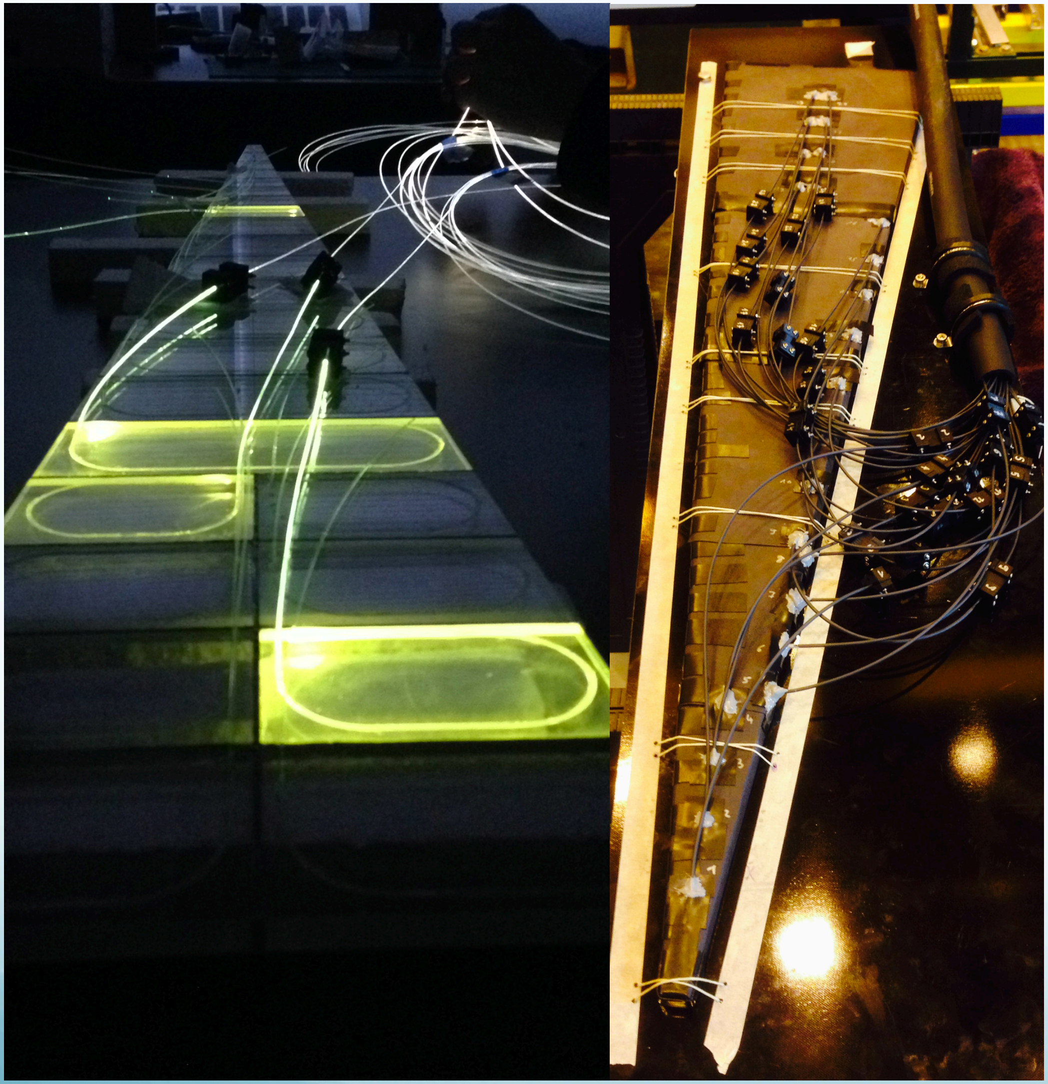
EPD Improvements



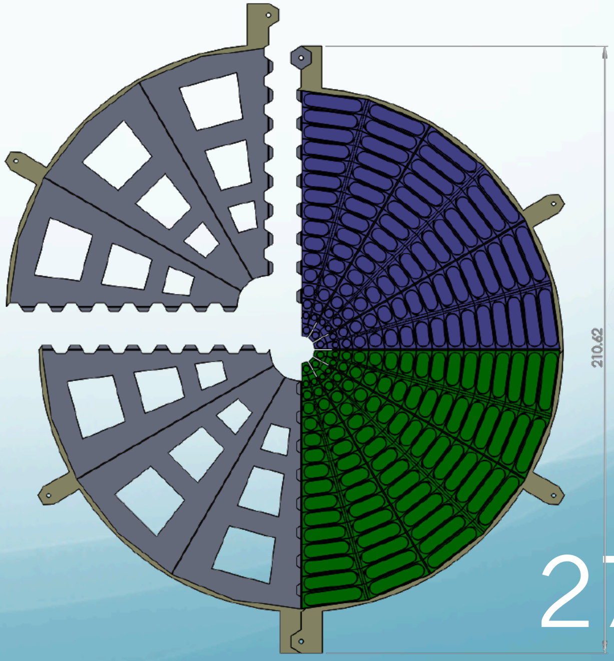
- Net proton v_1 versus $\sqrt{s_{NN}}$ at mid-rapidity
  - BES I data from 10-40%
- The grey bars indicate what the error bars would have been with a narrow centrality

BES-I Data ●
BES-II
BES-II + EPD

EPD Prototype and Design



- 1 sector prototype successfully deployed in run 16
- EPD internal STAR review complete
- 1/8th EPD installation run 17 for Detector Commissioning

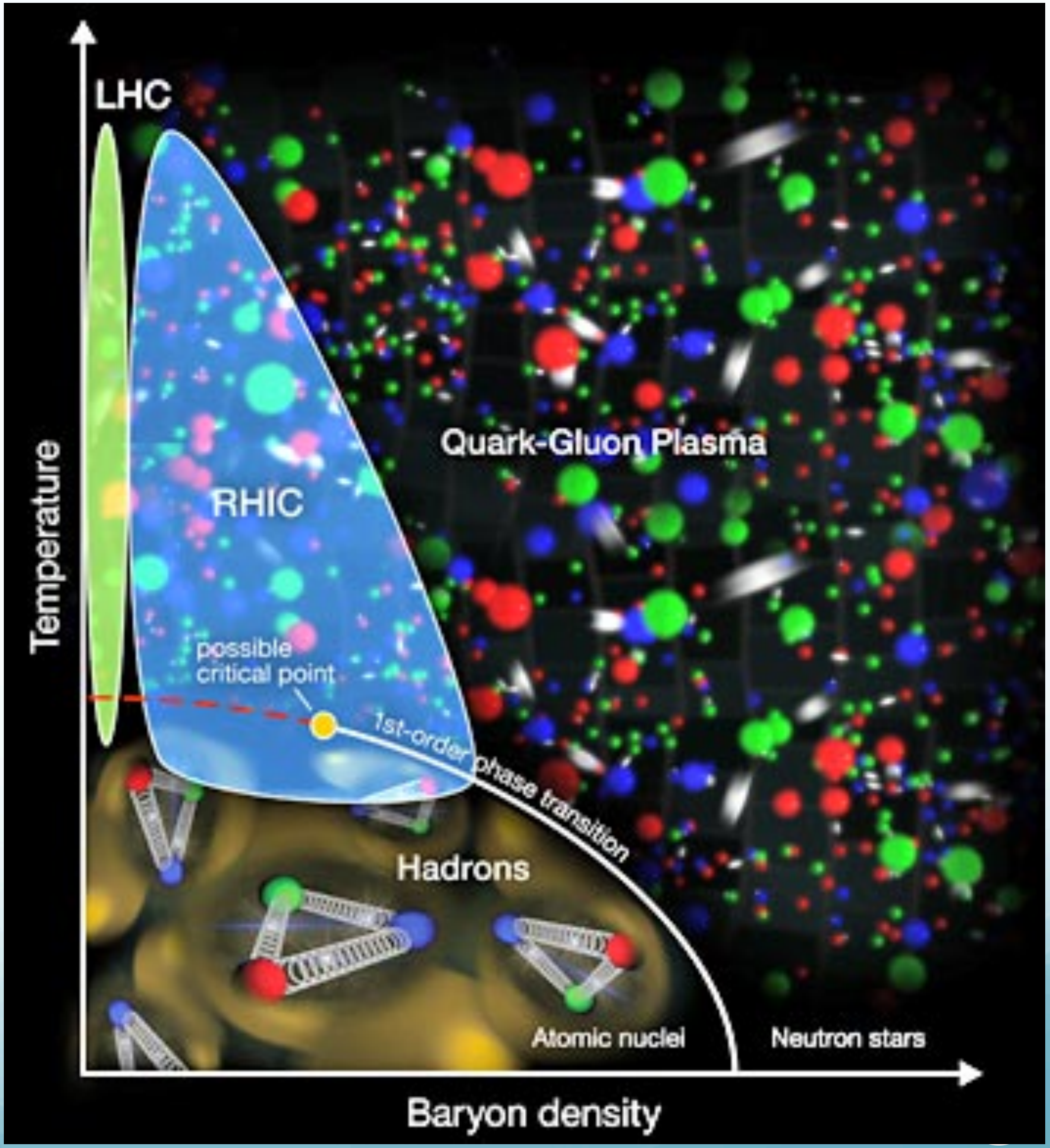


From 7.7 GeV →510 GeV

RHIC is an amazingly versatile machine

7.7 GeV (and below!) to study QCD phase diagram →

510 GeV polarized protons to study the spin structure of the proton



R_{pA} in Drell Yan + Direct Photon

- Fundamental questions
  - What is the A dependence of nuclear PDFs
    - R_{pA} in Drell-Yan channels
  - What are the signals for gluon saturation? What is the A dependence?
    - Diffraction
    - Di-hadron
    - Hadron+jet or γ+jet
  - What is the origin of the large single spin asymmetries at high x and η?
    - Only possible with polarized pp collisions
- See the RHIC Cold QCD Plan at: Arxiv: 1602.03922

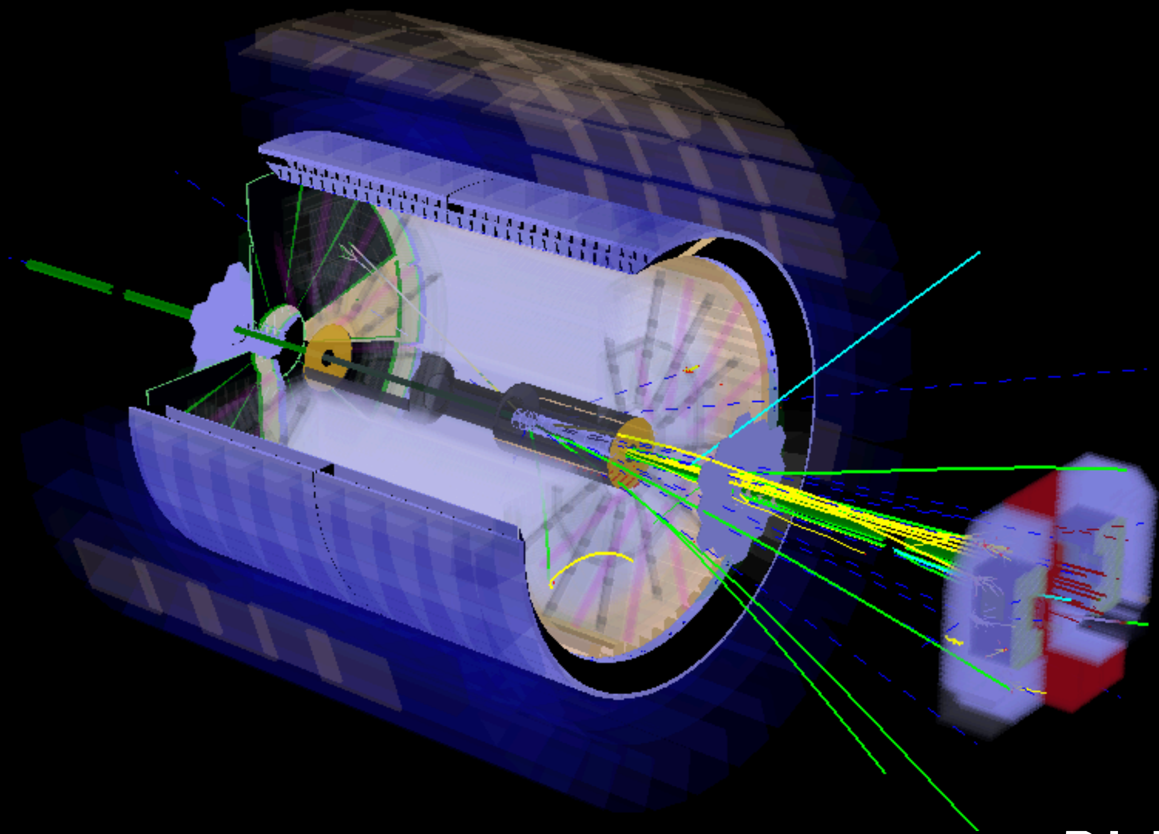
See Elke-Caroline Aschenauer's talk later today!

FCS and FTS

- Proposed FCS+FTS provide access to very small x
  - Facilitates investigations into the dynamics and nonlinear evolution effects in the regime of high gluon-density.

Forward
Calorimeter
System

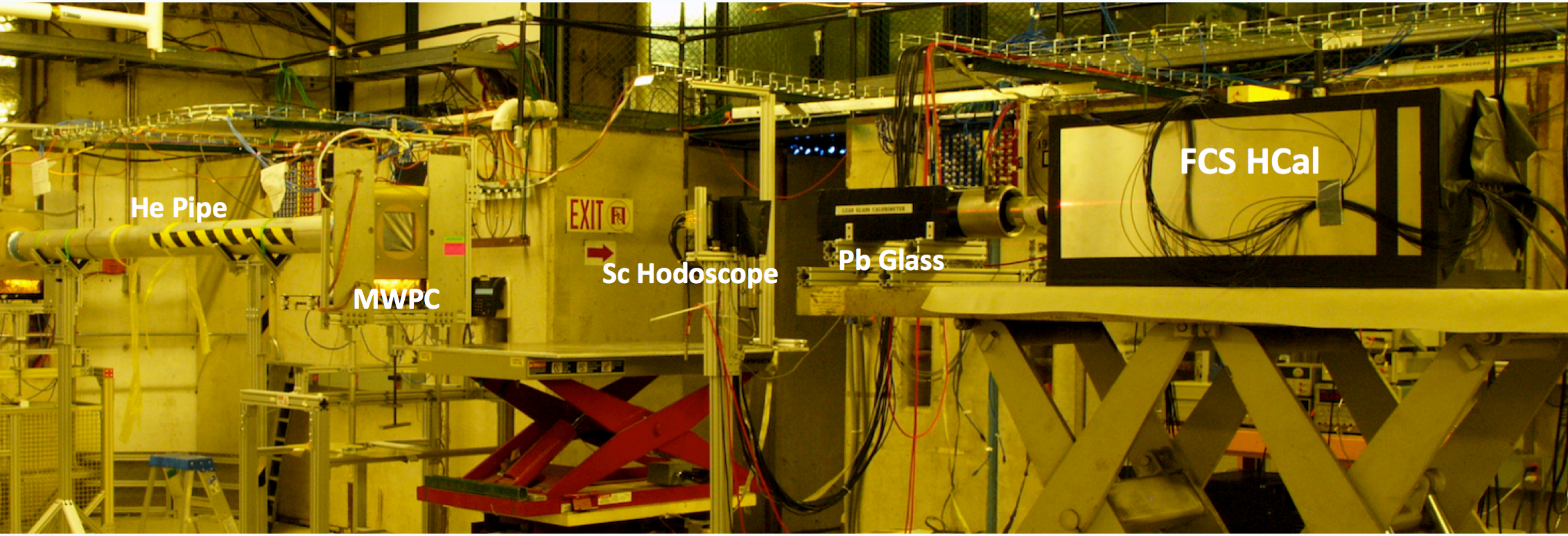
Forward
Tracking
System



Forward Calorimeter System (FCS)

- Uses the refurbished PHENIX sampling ECal
  - **EM resolution ~8%/√E**
- Hadronic calorimeter is a sandwich Pb scintillator plate sampling type
  - **Hadronic resolution ~70%/√E**
  - HCAL reuses QT based FMS readout system
    - ~30% of the FMS electronics
    - The rest of FMS used for the EMCal section
- Uses the existing Forward Preshower Detector installed in 2015
  - $2.5 < \eta < 4$

FCS – 2014 Beam test at FNAL

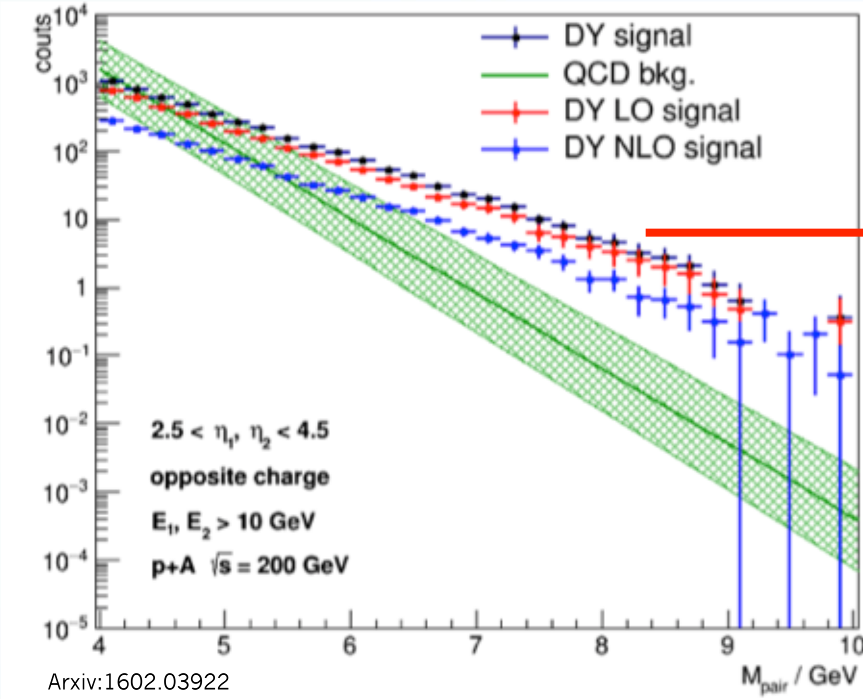


- Tested the response to hadrons, electrons and muons
  - $3 < E < 32$ GeV
  - Successful test results from 2012
- Ideally reconstructed $E = E_{EMCal} + E_{HCal}$
- **With E dependent weighting of E_{EMCal} energy measured e/h ratio ~0.95**
  - Constant above 10 GeV.

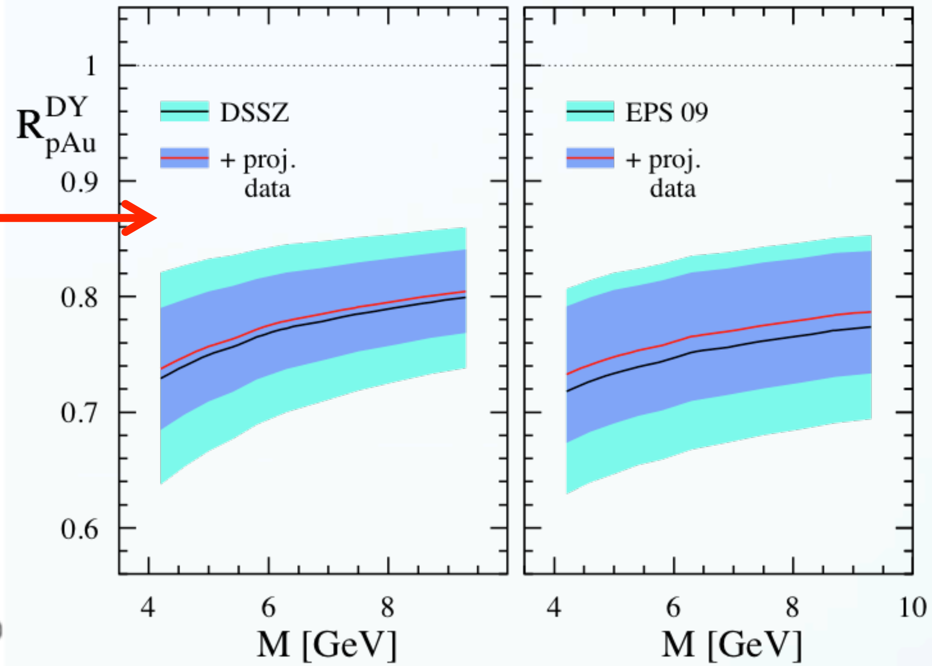
Forward Tracking System (FTS)

- Forward transverse spin asymmetry measurements for p+p and p+A **requires distinguishing h^+/h^- for p < 80 GeV/c**
- Forward Drell-Yan measurements require excellent eID/ γID to suppress hadron background
  - **Improves eID** by comparing charged p to E from FCS
- Saturation signals with γ+jet
  - **Improves γID** by vetoing hits from charged particles
- Use single-sided double-metal Silicon Ministrip sensors
  - Builds on the successful experience from the STAR IST detector (part of HFT)
- Low material budget in detector acceptance

A dependence of nuclear PDFs



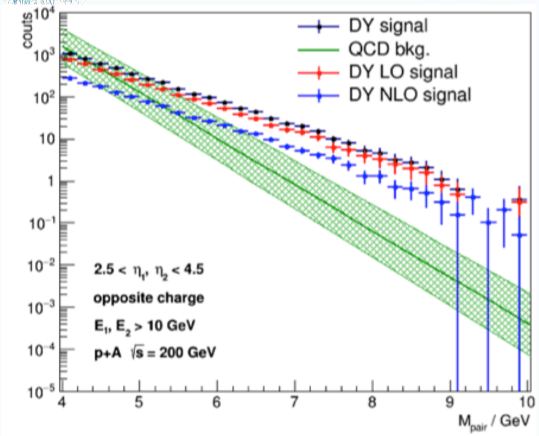
Arxiv:1602.03922

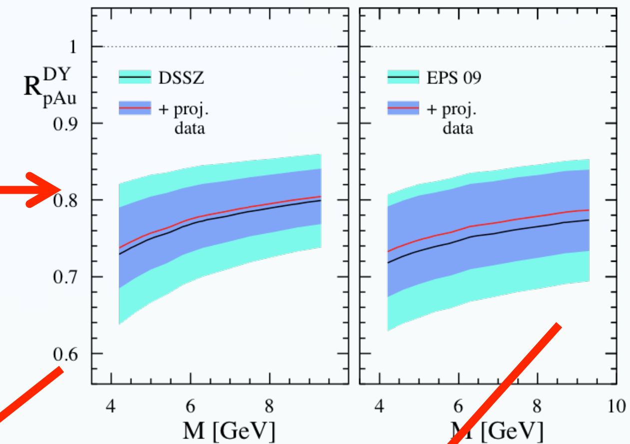


DY measurement: challenge is to suppress hadronic background while maintaining high electron efficiency

The impact of the DY R_{pA} data for the anticipated statistics for a future p+Au run compared current DSSZ/EPS-09 uncertainties

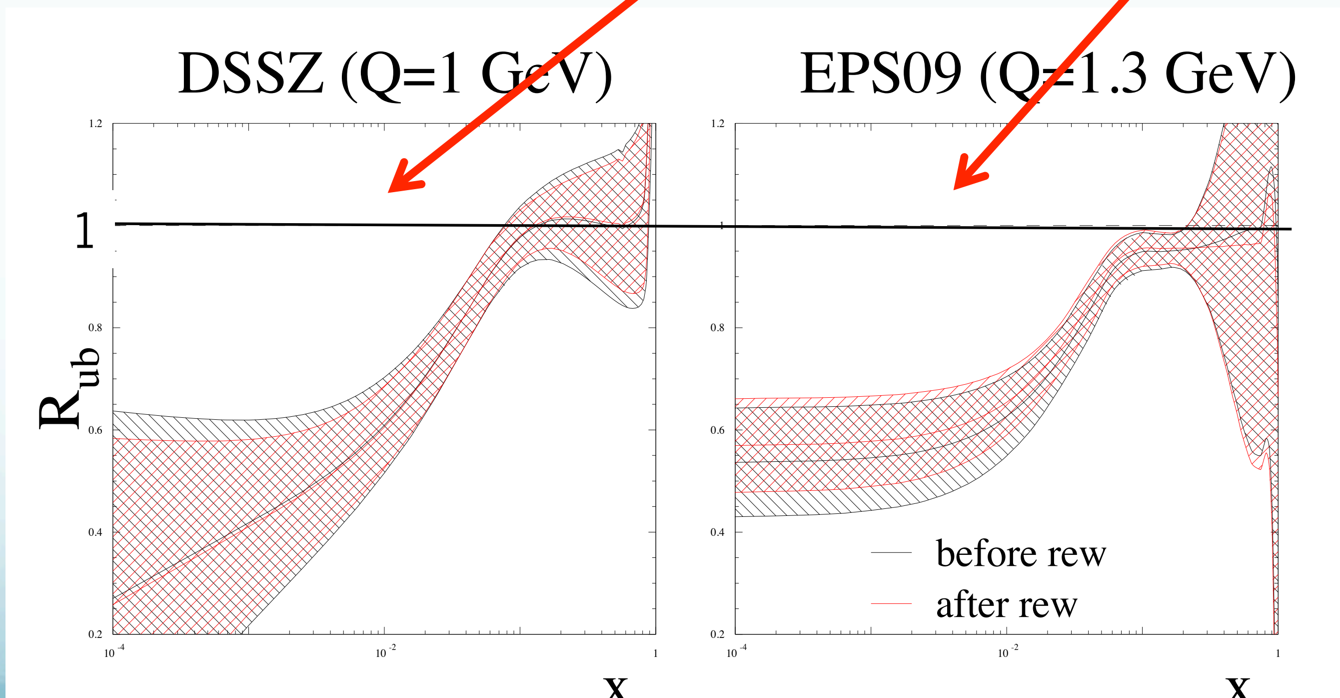
A dependence of nuclear PDFs





$R_{ub} = 1$ indicates nuclear PDF is not modified

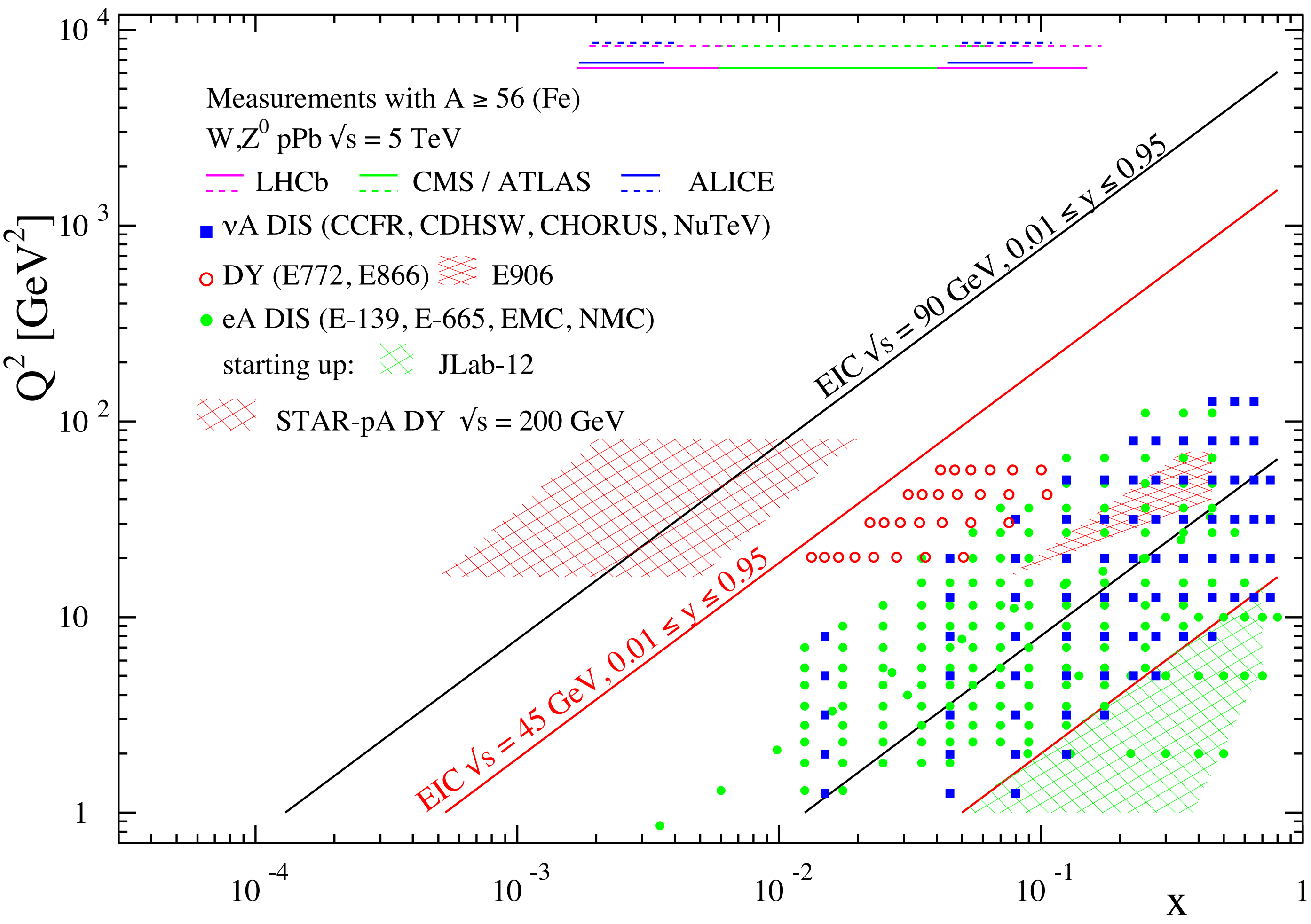
- ub → ubar
- Other PDFs at: Arxiv. 1602.03922



Arxiv:1602.03922

Kinematic Coverage in x–Q^2

Past, Present, and Future Experiments Capabilities

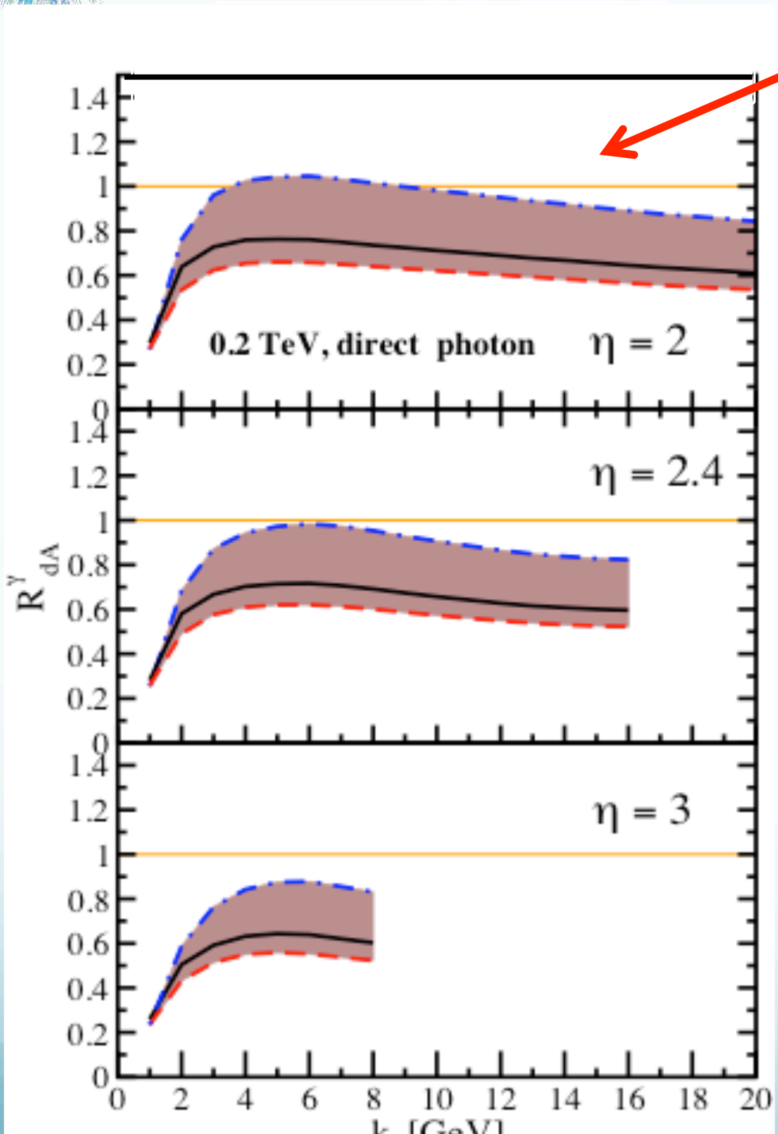


Arxiv:1602.03922

LHC experiments cover the same x-range as DY at forward h at RHIC → higher Q^2

- Nuclear modifications already significantly reduced
- At intermediate Q^2, DY at RHIC will extend the low-x reach by nearly one decade compared to EIC

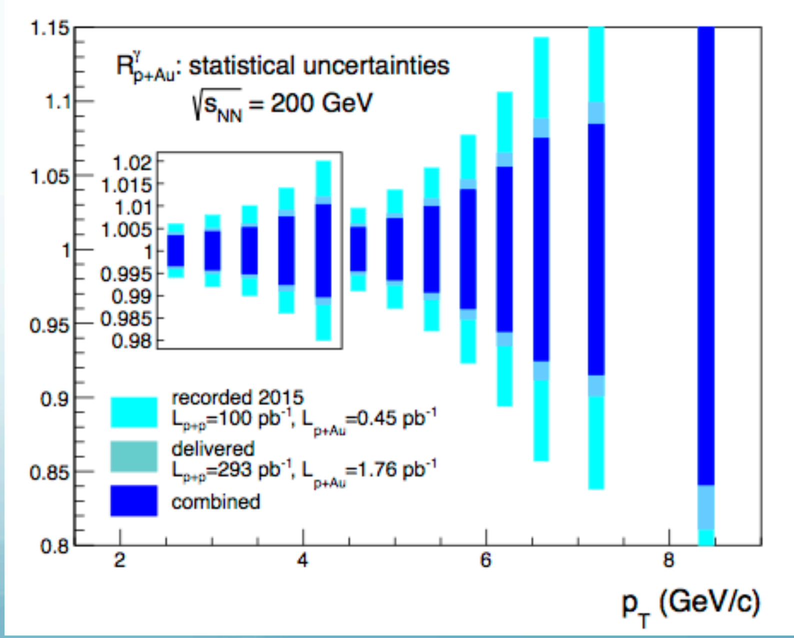
Gluon Saturation



Arxiv:1602.03922

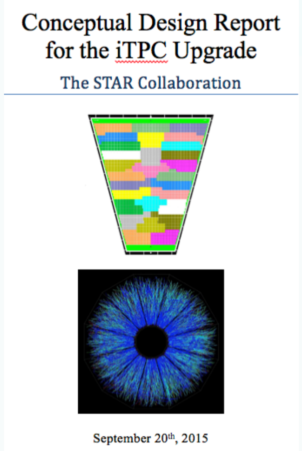
$A: Q_{0A}^2$ [GeV^2], $p: Q_{0p}^2$ [GeV^2]
A: 0.67, p: 0.168
A: 0.50, p: 0.168
A: 0.60, p: 0.20

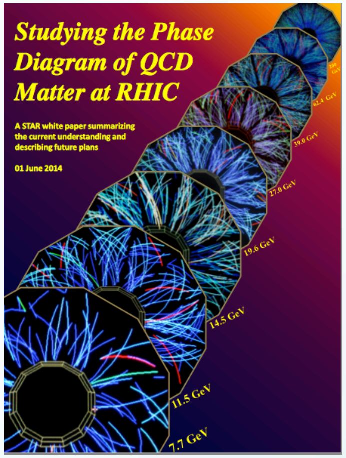
- Measurements so far in p(d)+A collisions have strongly interacting initial+ final states
  - Complicates theoretical treatment
- Remove final state strong interaction by using γ and DY electrons

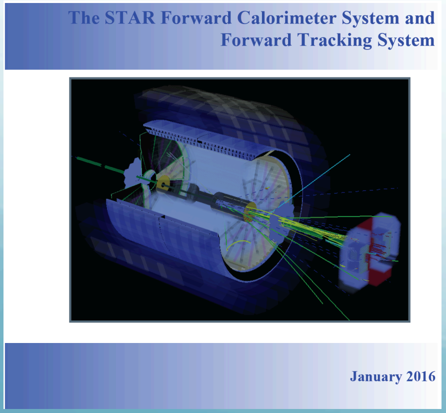


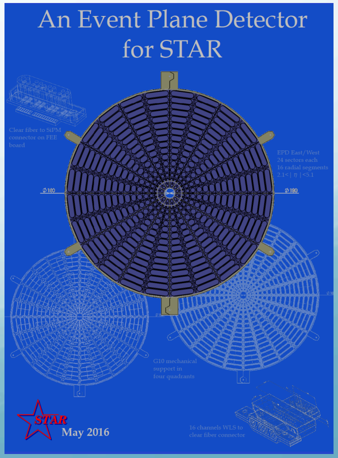
Summary

- FCS and FTS will allow reach to low x to probe the fundamental structure of nucleons in new kinematic regimes
- iTPC, EPD, eTOF enable superior BES-II program
  - Increase acceptance
  - Increase statistics
  - Decrease systemic uncertainties





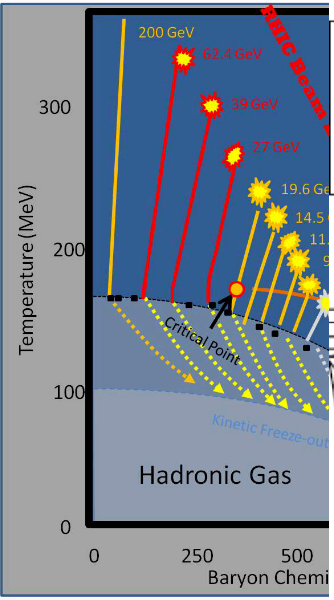


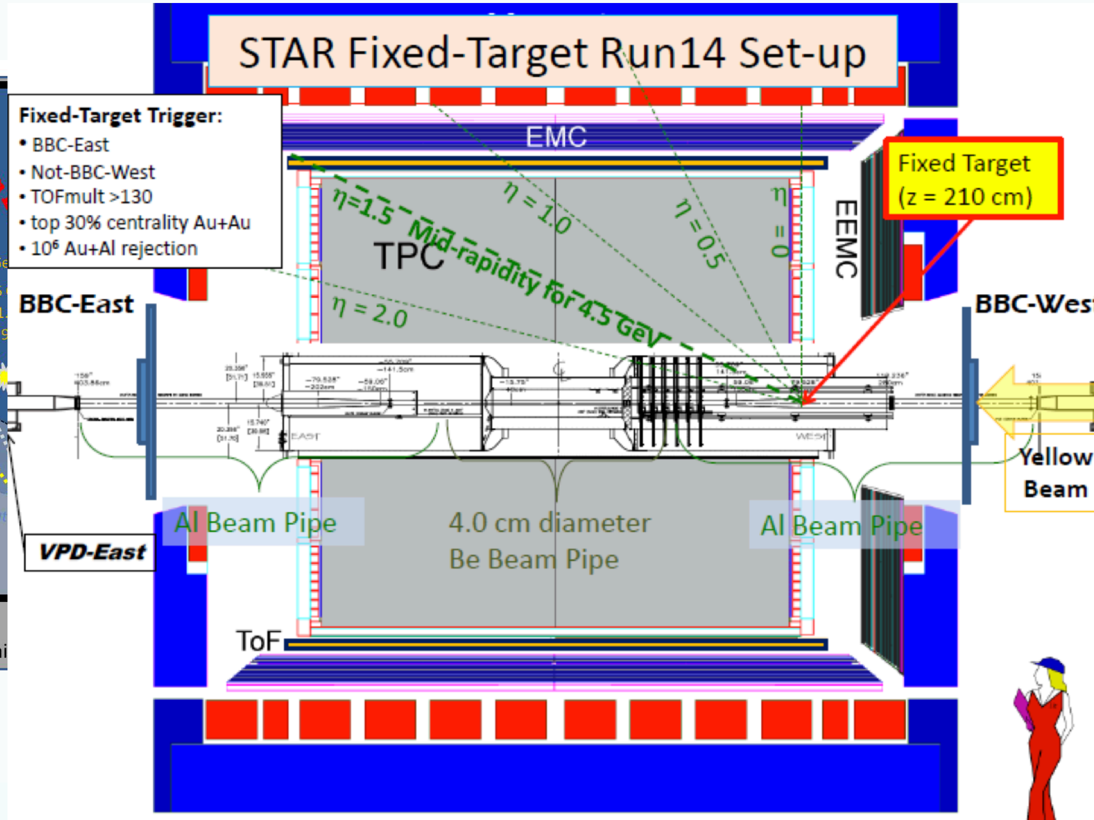


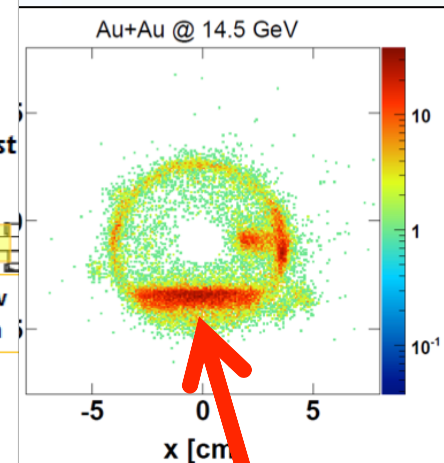
Back up

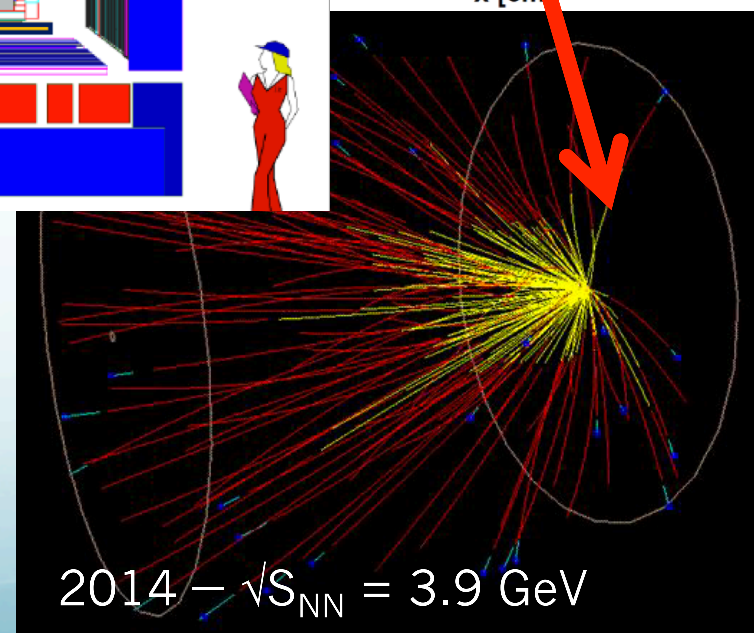
BES-I → BES-II

See Kathryn Meehan's talk on Tuesday!



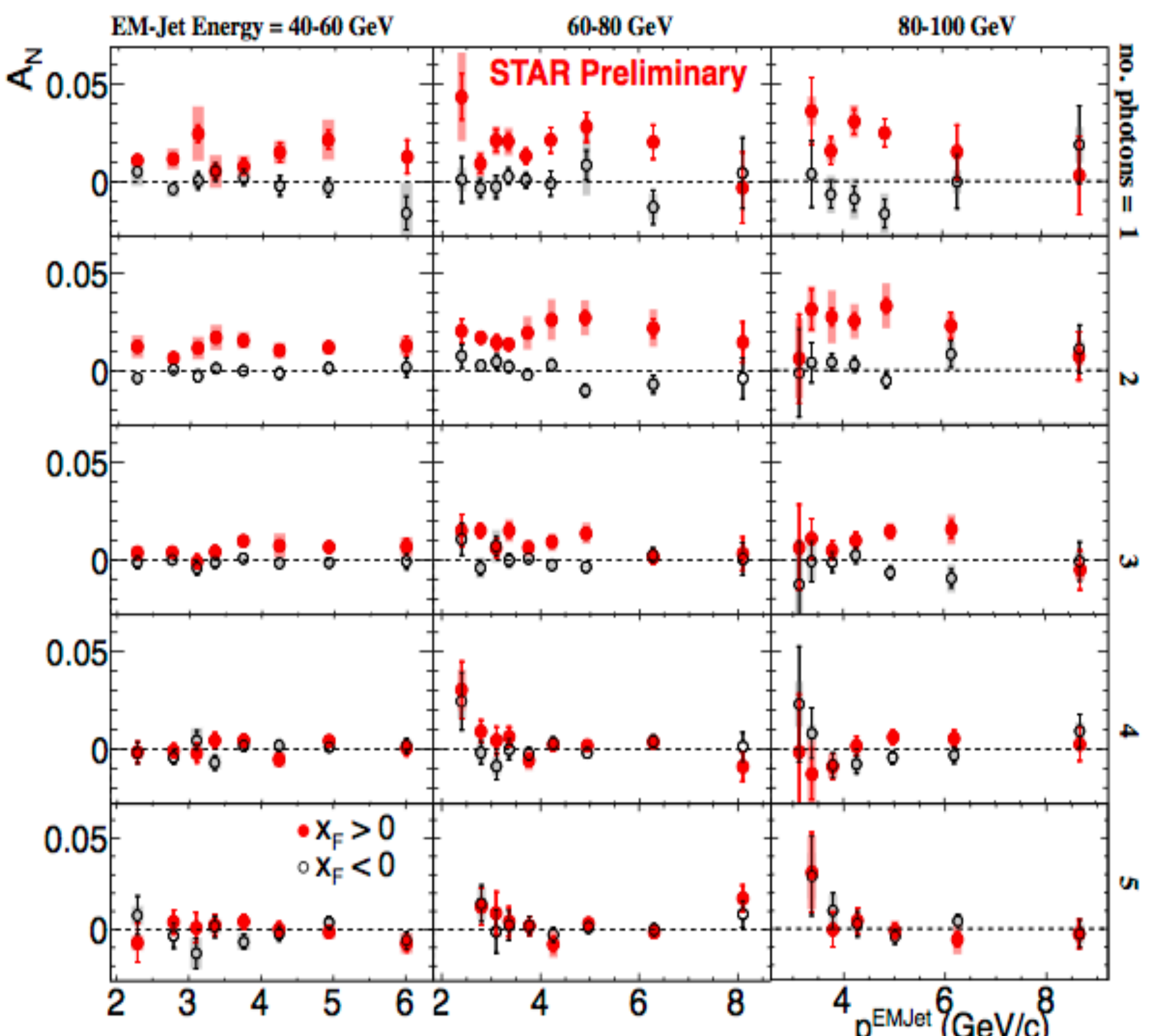






- Target inserted into beam pipe
- Test run done parasitically
  - No interference w/collider mode data
  - More efficient →small dedicated runs

Single Spin Asymmetries



Arxiv:1602.03922

What are the subprocesses driving the large A_N at high x_F and η?

FTS allows π^+/π^-

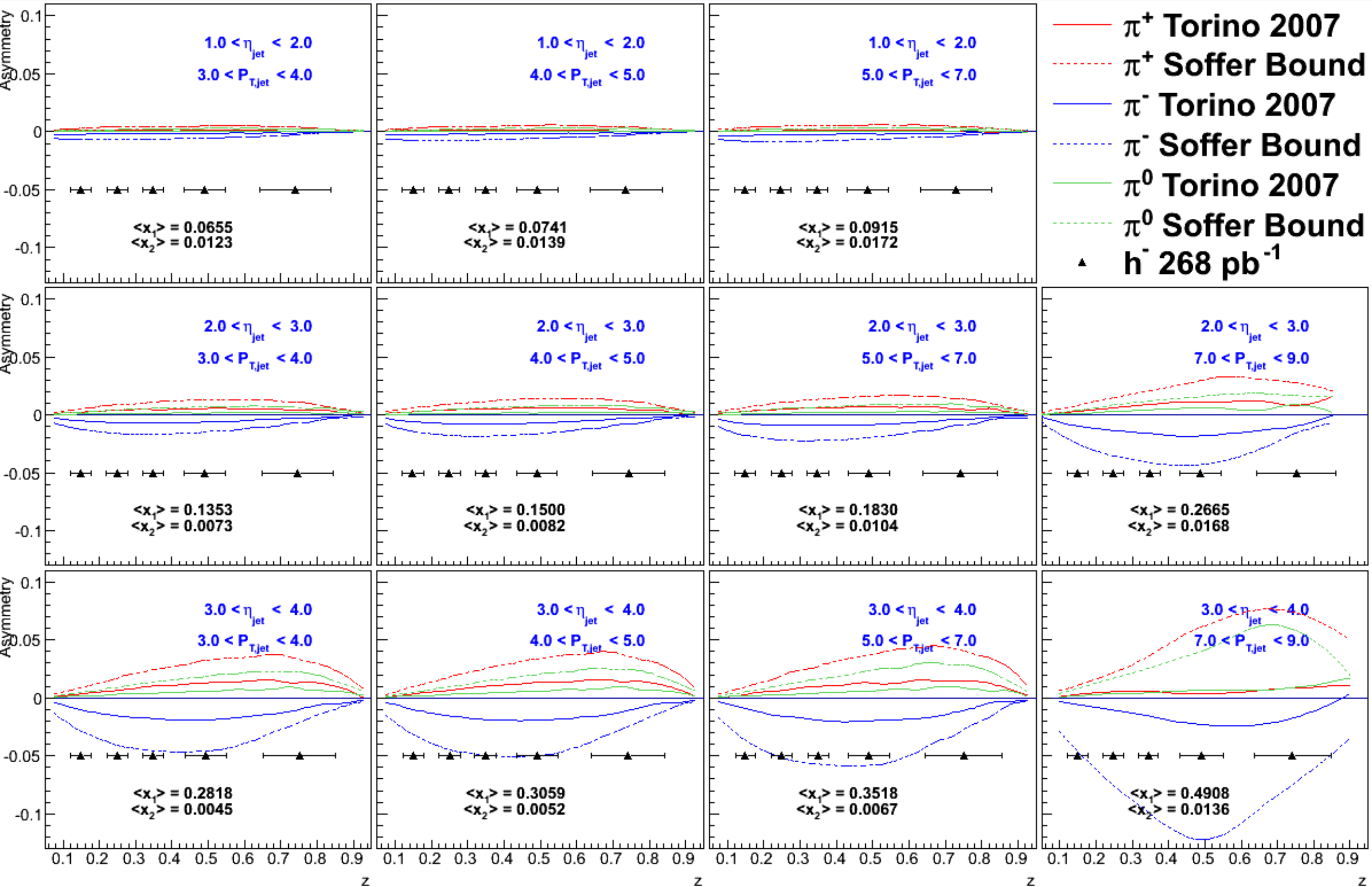
Calorimeters only allow π^0

Want to explore η (can already measure mid-η)

Results show the process is not 2-2

- Diffraction?

Collins

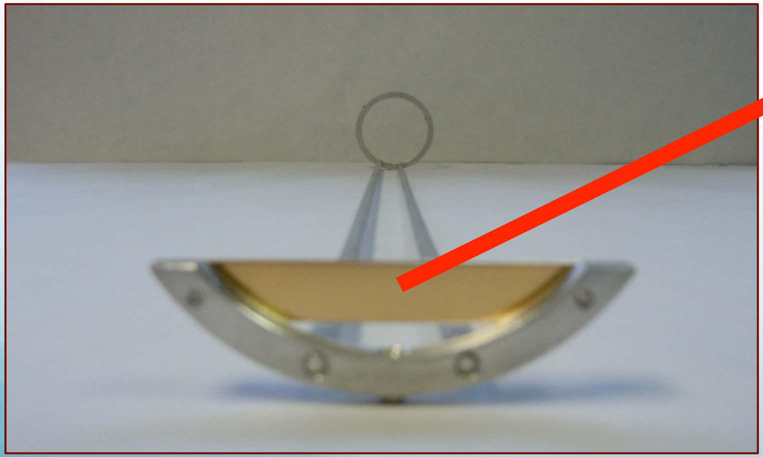


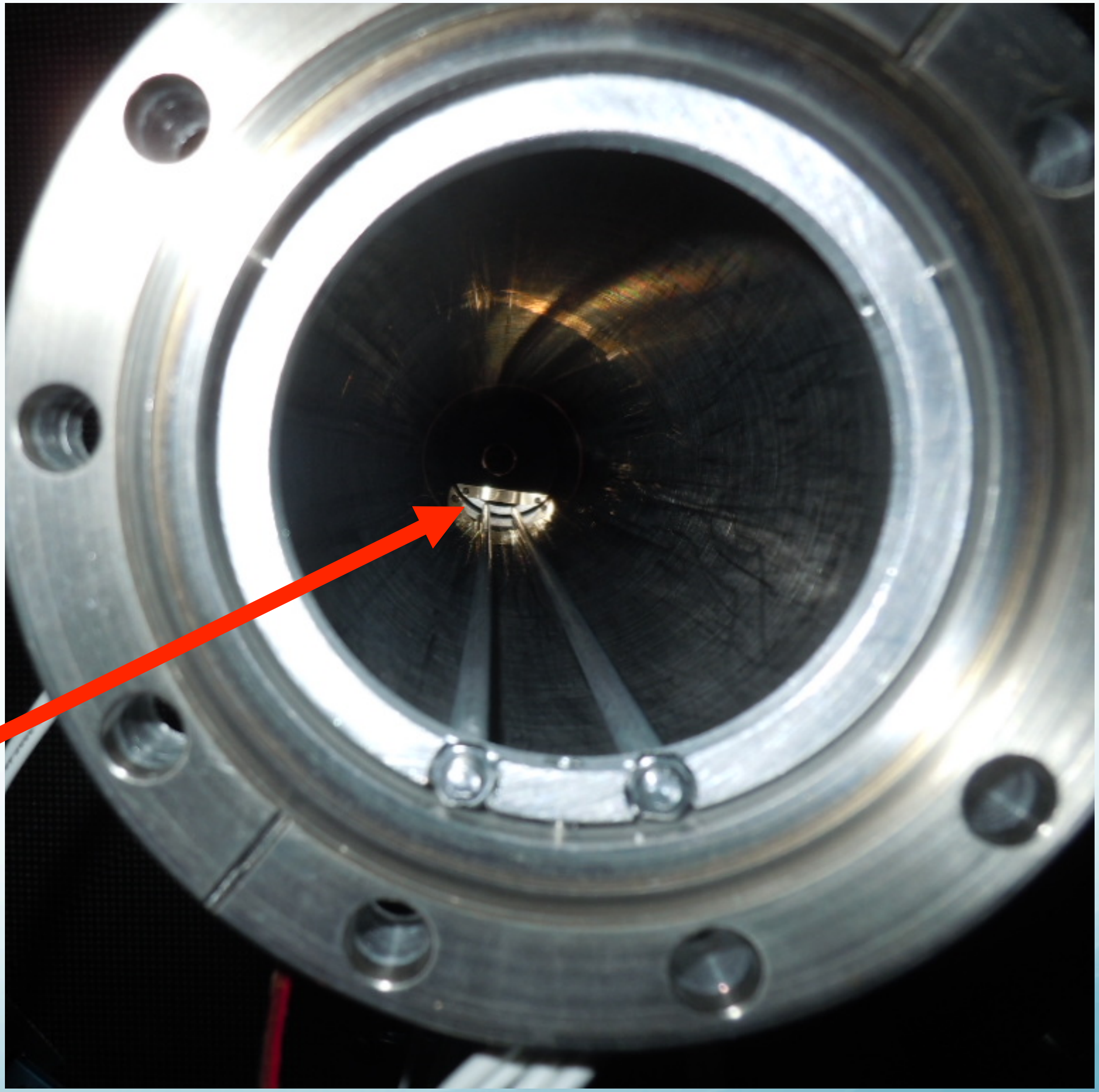
π+ Torino 2007
π+ Soffer Bound
π- Torino 2007
π- Soffer Bound
π0 Torino 2007
π0 Soffer Bound
h- 268 pb-1
Asymmetry
z
1.0 < η_jet < 2.0
3.0 < P_T,jet < 4.0
<x1> = 0.0655
<x2> = 0.0123
1.0 < η_jet < 2.0
4.0 < P_T,jet < 5.0
<x1> = 0.0741
<x2> = 0.0139
1.0 < η_jet < 2.0
5.0 < P_T,jet < 7.0
<x1> = 0.0915
<x2> = 0.0172
2.0 < η_jet < 3.0
3.0 < P_T,jet < 4.0
<x1> = 0.1353
<x2> = 0.0073
2.0 < η_jet < 3.0
4.0 < P_T,jet < 5.0
<x1> = 0.1500
<x2> = 0.0082
2.0 < η_jet < 3.0
5.0 < P_T,jet < 7.0
<x1> = 0.1830
<x2> = 0.0104
2.0 < η_jet < 3.0
7.0 < P_T,jet < 9.0
<x1> = 0.2665
<x2> = 0.0168
3.0 < η_jet < 4.0
3.0 < P_T,jet < 4.0
<x1> = 0.2818
<x2> = 0.0045
3.0 < η_jet < 4.0
4.0 < P_T,jet < 5.0
<x1> = 0.3059
<x2> = 0.0052
3.0 < η_jet < 4.0
5.0 < P_T,jet < 7.0
<x1> = 0.3518
<x2> = 0.0067
3.0 < η_jet < 4.0
7.0 < P_T,jet < 9.0
<x1> = 0.4908
<x2> = 0.0136

Target Design 2014 and 2015
remove

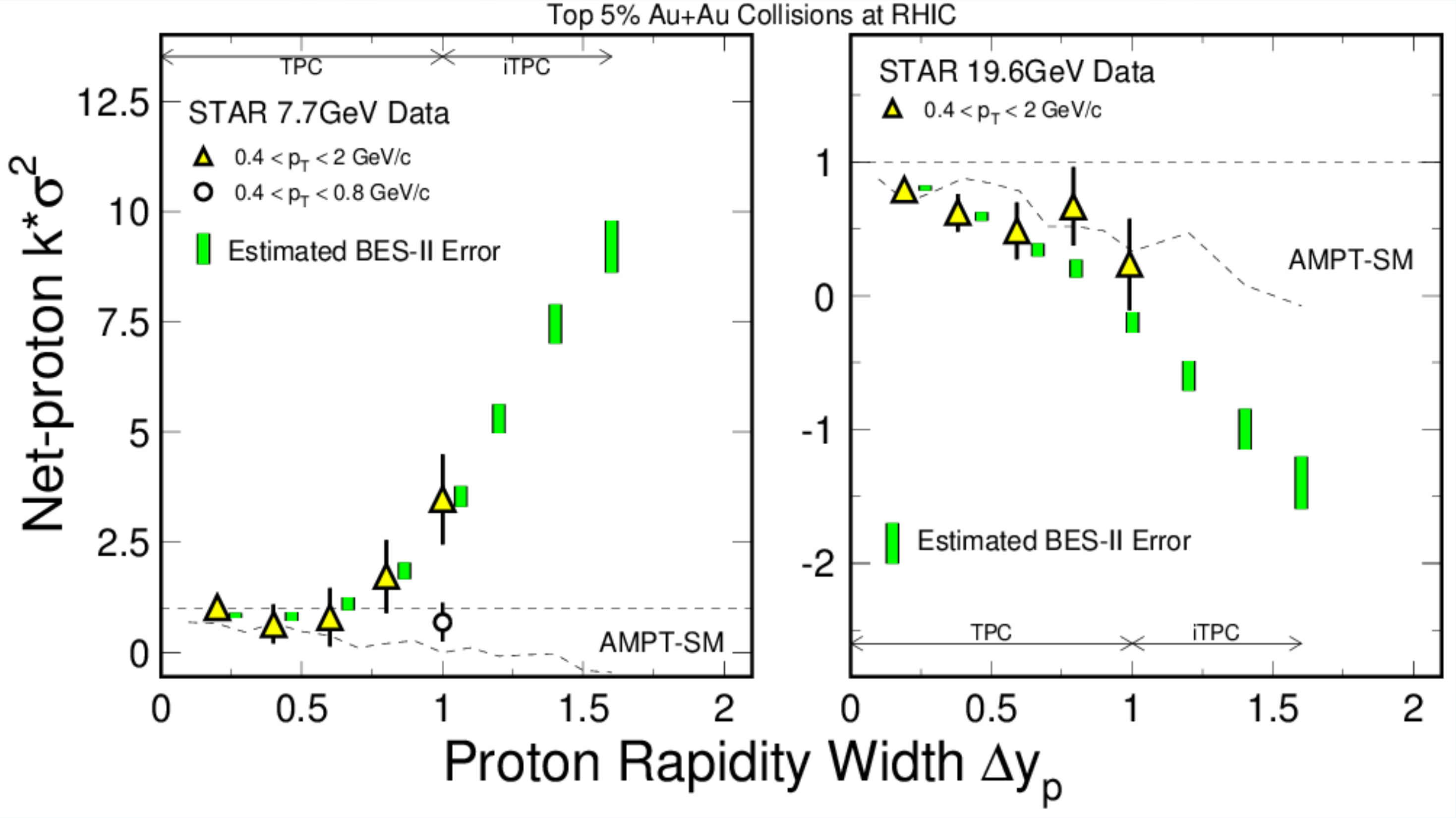
Target design:

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





Net-proton cumulants in BES-II



- BES-I has revealed a non-trivial energy dependence Rapidity length of the correlation is important
- Measure as function of Δy_p in wide range is needed to establish true nature of correlation → iTPC

Planned BES II Measures

	Collision Energies (GeV):	7.7	9.1	11.5	14.5	19.6
	Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
	Observables	Millions of Events Needed				
QGP	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
QGP	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
1st P.T.	asHBT (proton-proton)	35	40	50	65	80
C.P.	net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
EM Probes	Dileptons	100	160	230	300	400
	Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**

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.

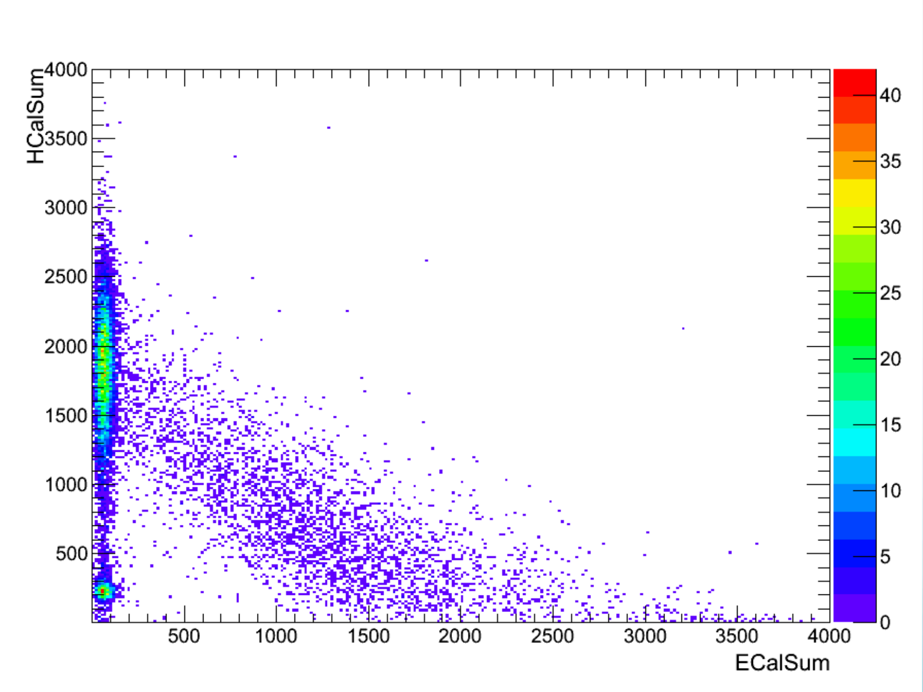
• Dilepton mass spectra show a broadening consistent with models including hadron gas and quark-gluon plasma components

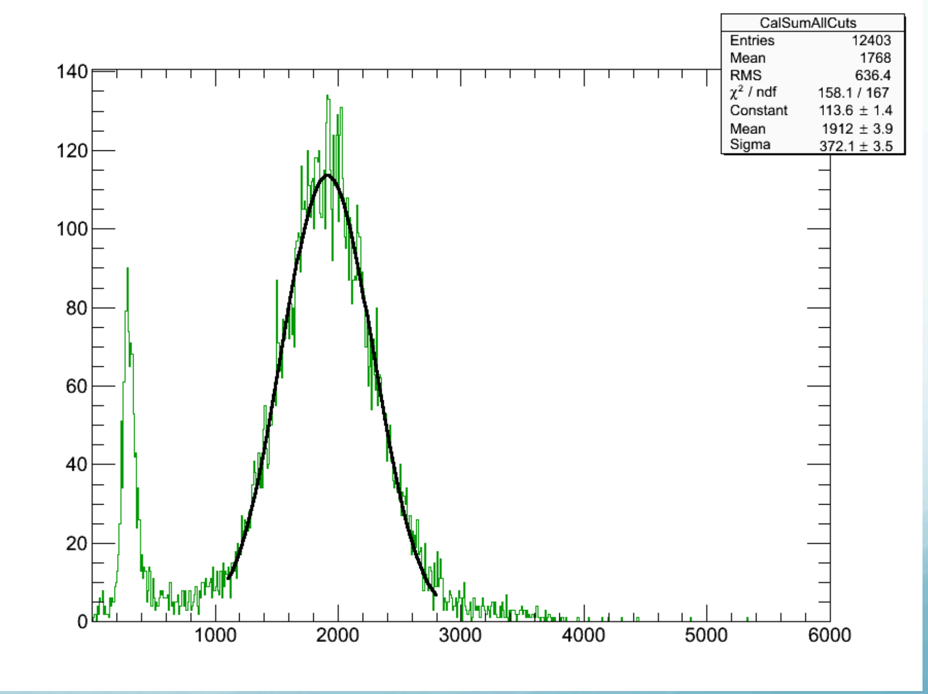
•There are indicators pointing towards a softening of the equation of state which can be interpreted as evidence for a first order phase transition.

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

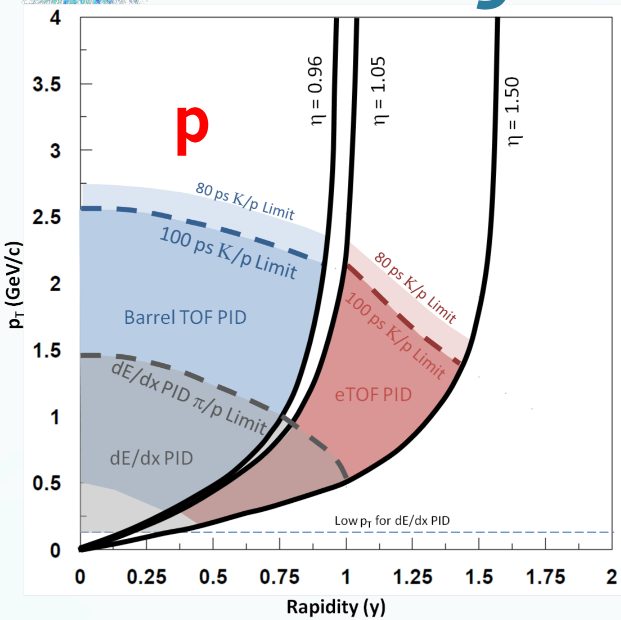
Response of the FCS prototype module to hadrons

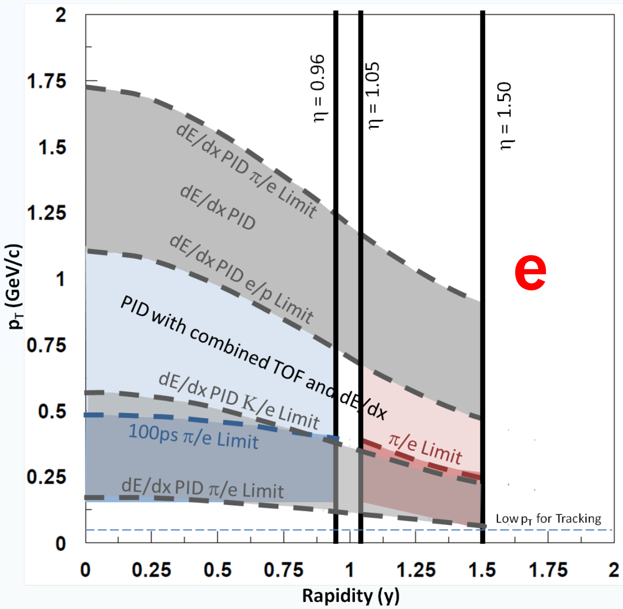
Energy deposition in HCal section (Y-axis) vs energy deposition in EMCal section (X-axis) for 12 GeV hadrons (left panel). A weighted sum of the energy deposited in EMCal and HCal section for 12 GeV hadrons (right panel).

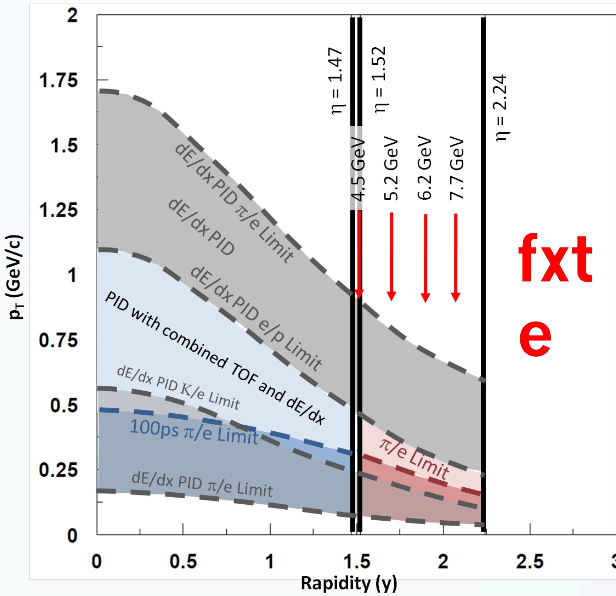


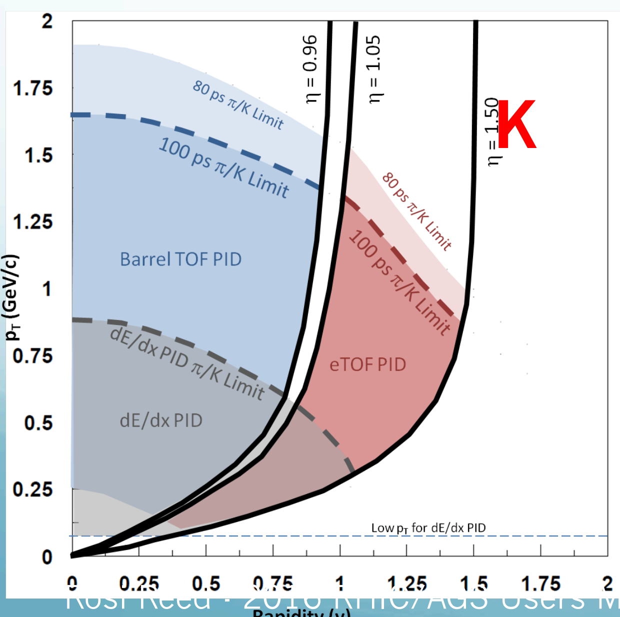


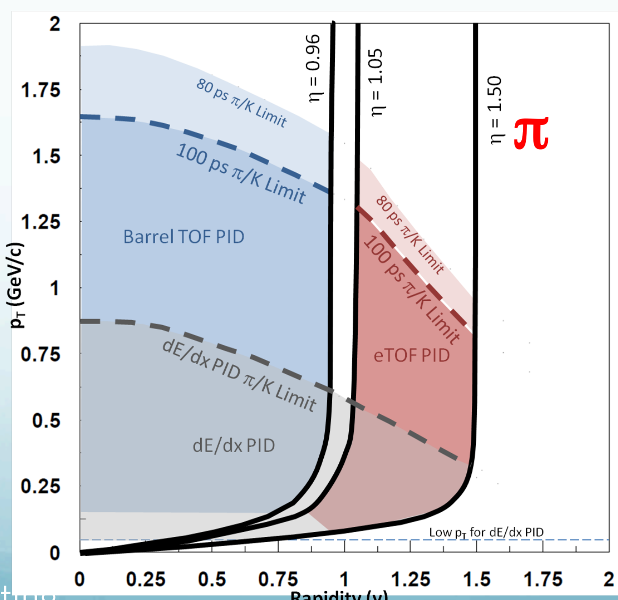
$y - p_T$ Map Colider





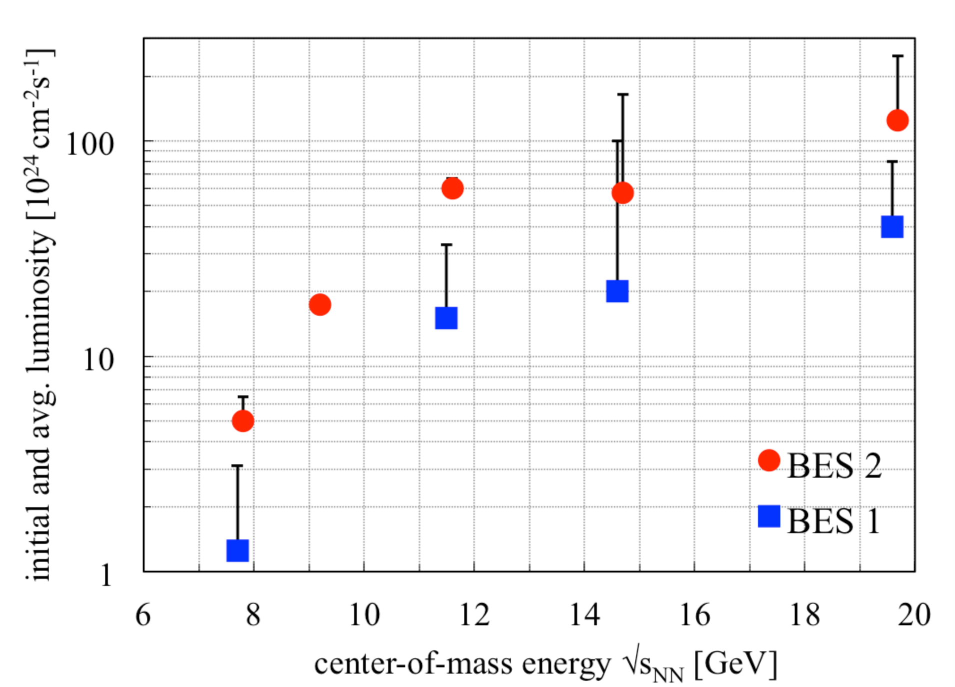




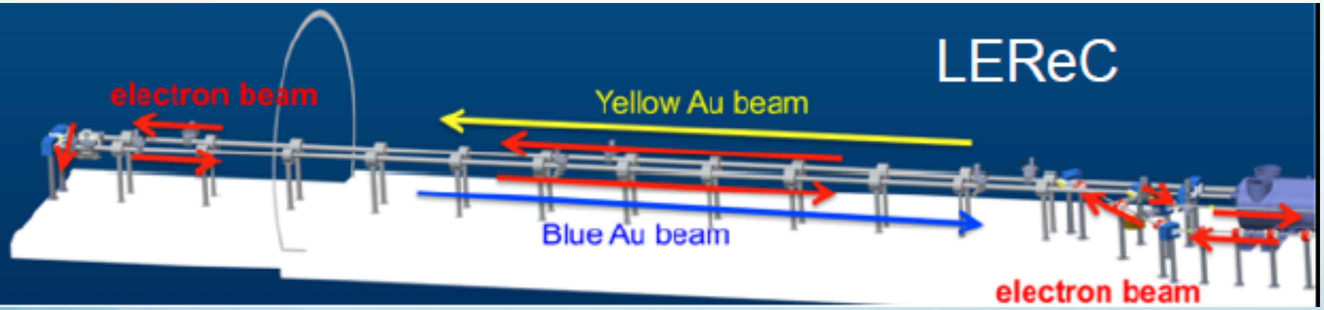


Low Energy Electron Cooling at RHIC

Improve luminosity for low energy beams with electron cooling

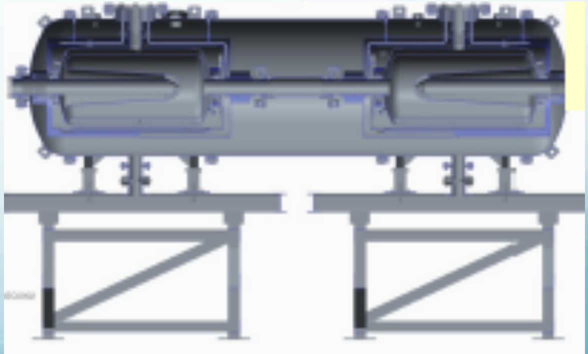


- Start with 14.5 and 19,6 3X improvement
- Following year, 7.7, 9.1, and 11.5. 4X improvement with eCooling
- Run 24 weeks



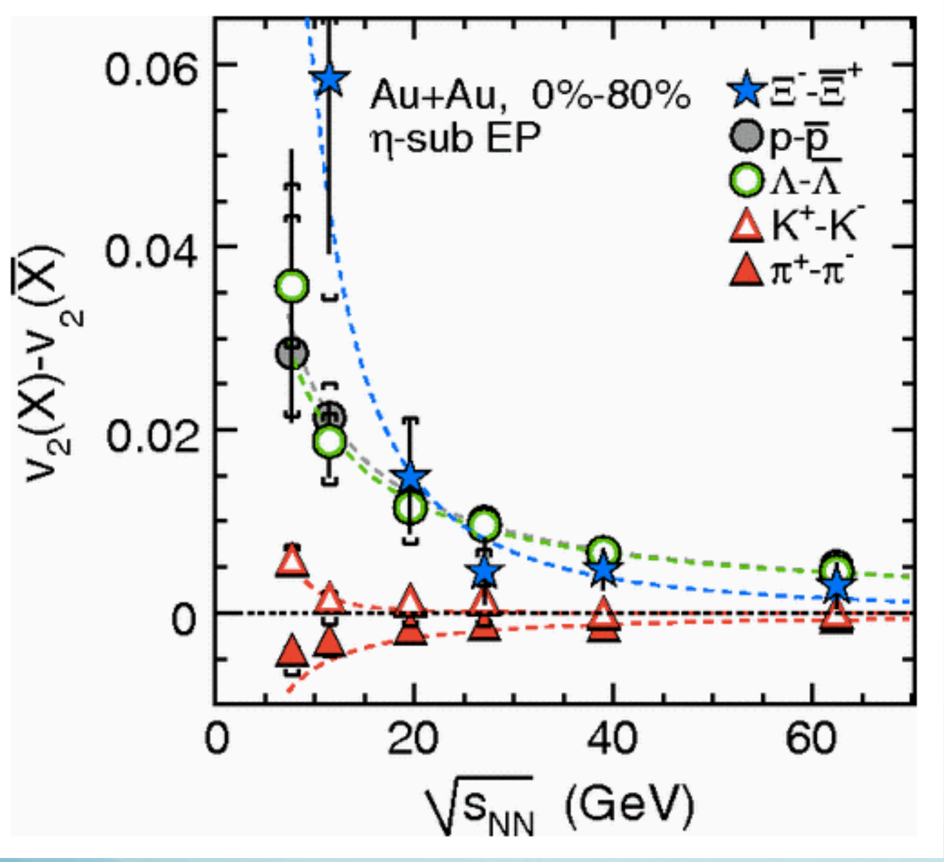
58 m from IP2

100 MHz SRF Gun



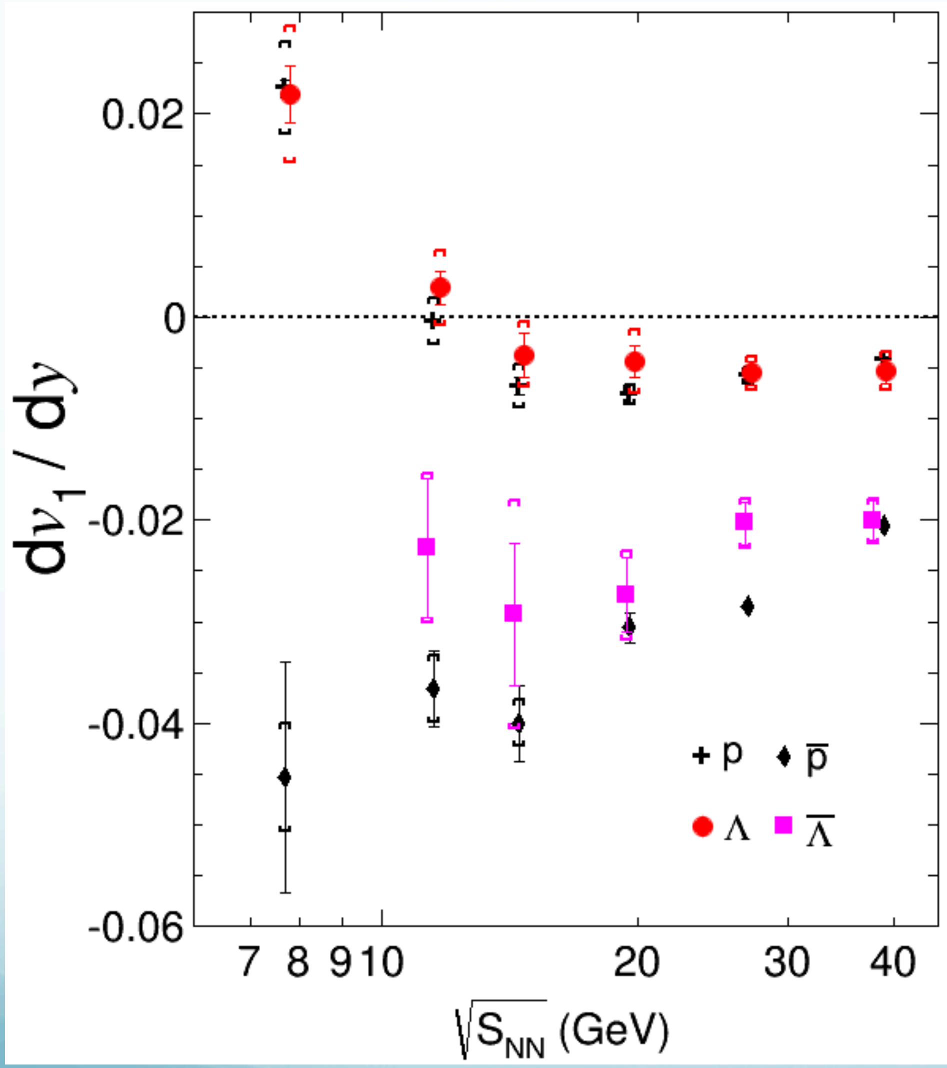
STAR BES-I
Turn-off of sQGP signatures

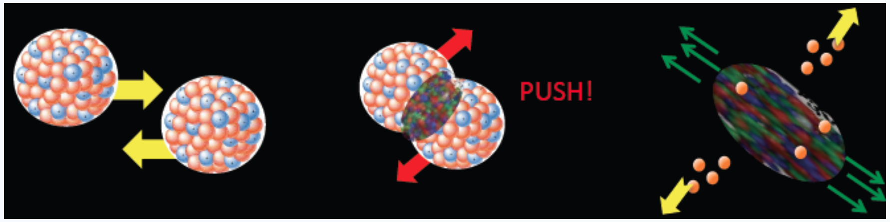
Phys.Rev.Lett. 110 (2013) 142301



- Substantial particle-antiparticle split at lower $\sqrt{s_{NN}}$
- Linear dependence on the baryon chemical potential

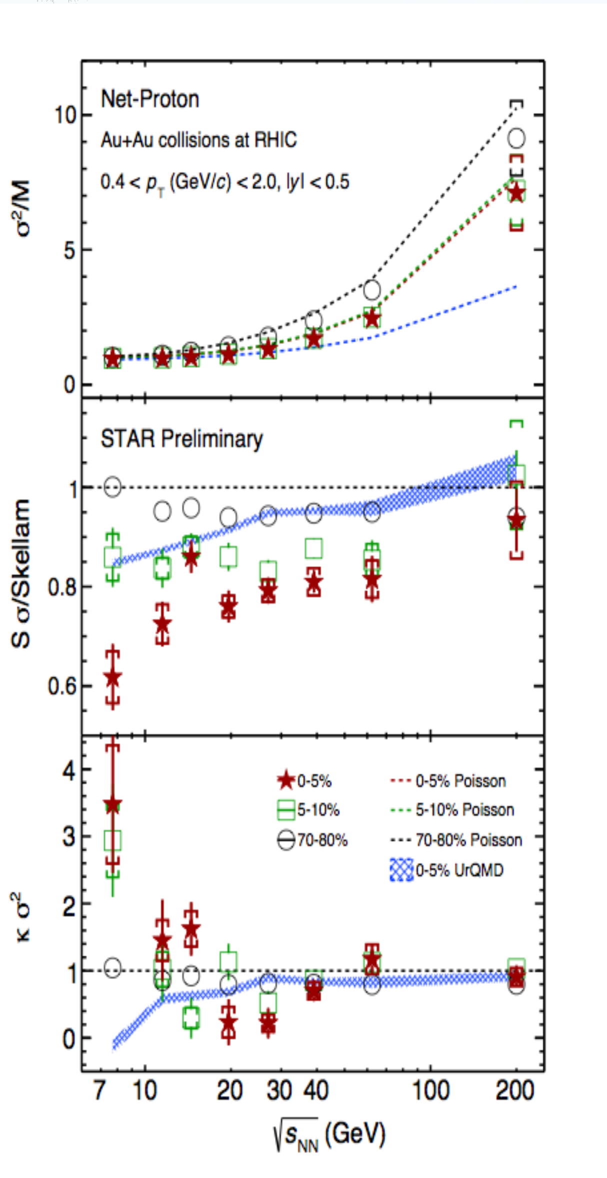
Search for Phase Transition : directed flow





- A linear fit over |y| ≤ 0.5 used to find dv1/dy for all species & energies
- The dip in dv1/dy indicates an interplay between hydro and baryon dynamics (EOS)
- Λ follows p within errors

Cumulant Ratio of Net-Proton multiplicity distributions Collision Energy Dependence

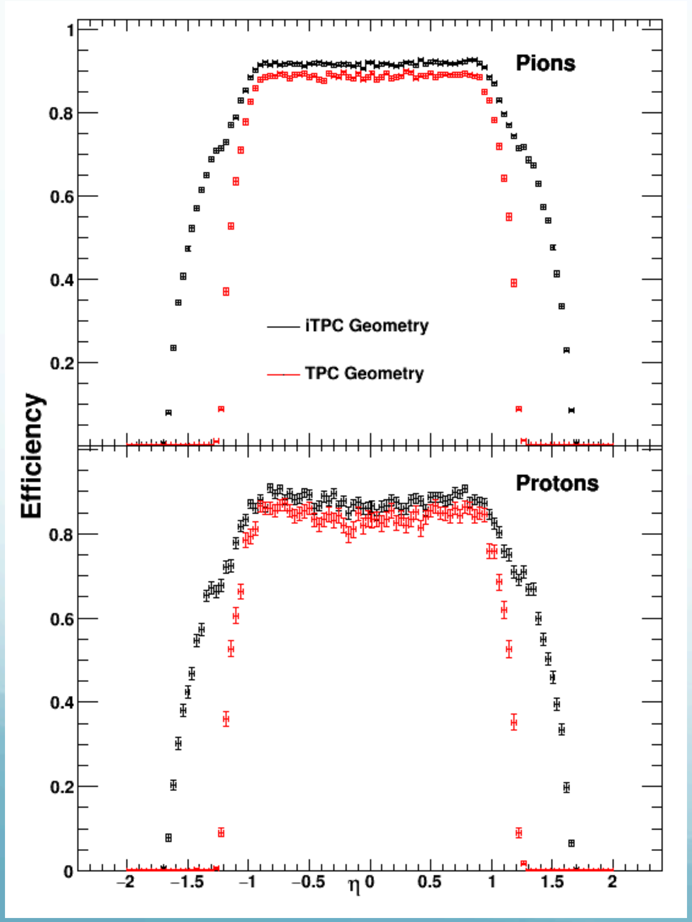


- Looking for fluctuation in S and κ
- $\sigma 2/M$ increases with increasing energy, consistent with Poisson expectation
- Non-monotonic behavior of net-proton $\kappa\,\sigma 2$ seen in top 5% central collisions
- Peripheral collisions show smooth trend
- UrQMD (no Critical Point), shows suppression at lower energies - due to baryon number conservation
- Uncertainties requires better measurements – motivation for BES II

iTPC Improved performance

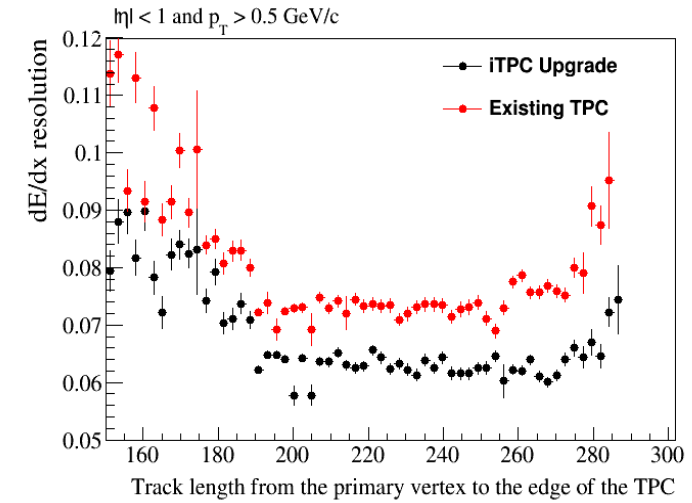
Increase rapidity coverage $|\eta| < 1$ to $|\eta| < 1.5$

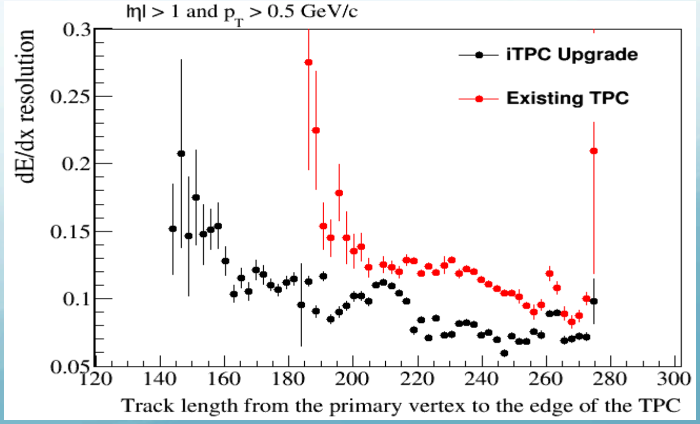
Increased efficiency for $|\eta| > 1$ both in p_T and particle specieS



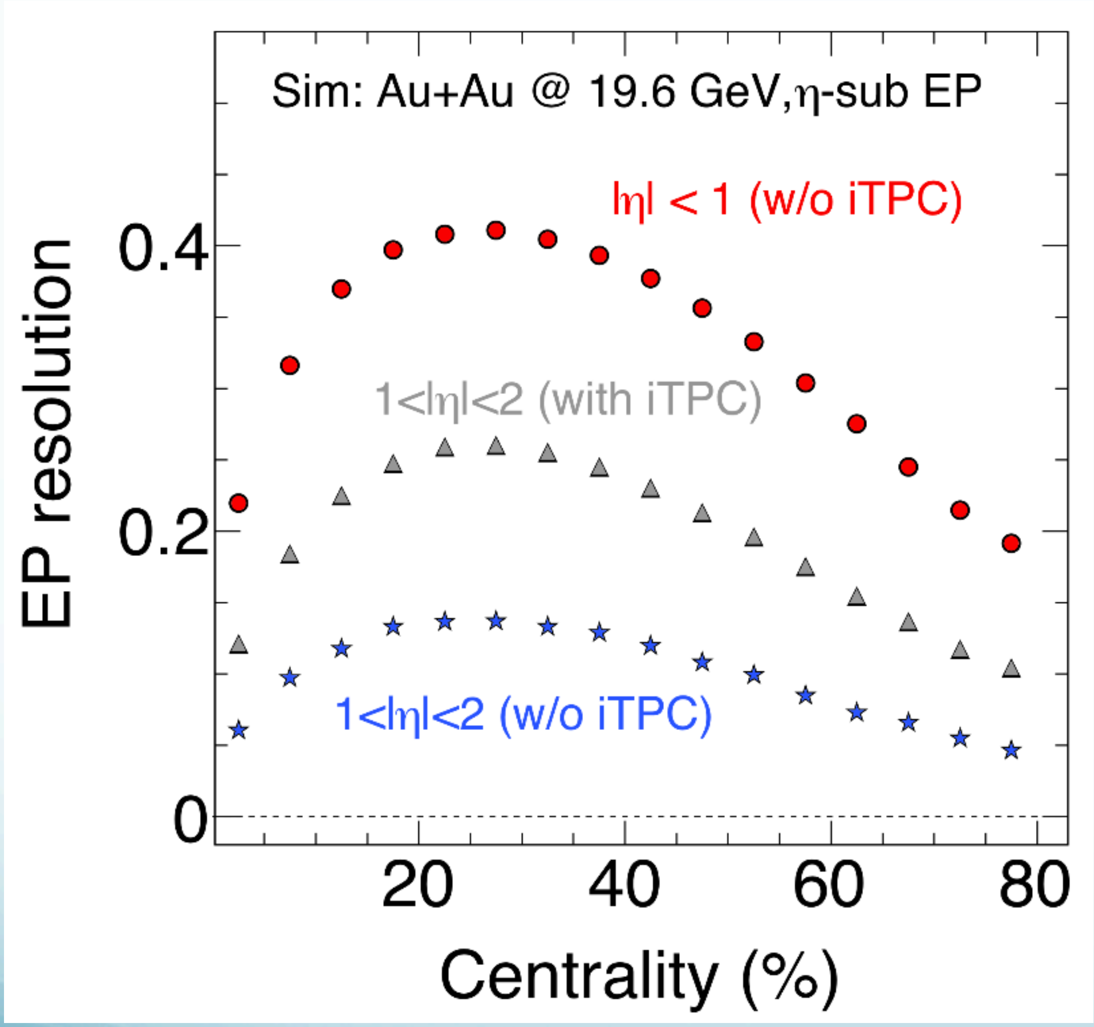
Improved dE/dx

7.5->6.2%

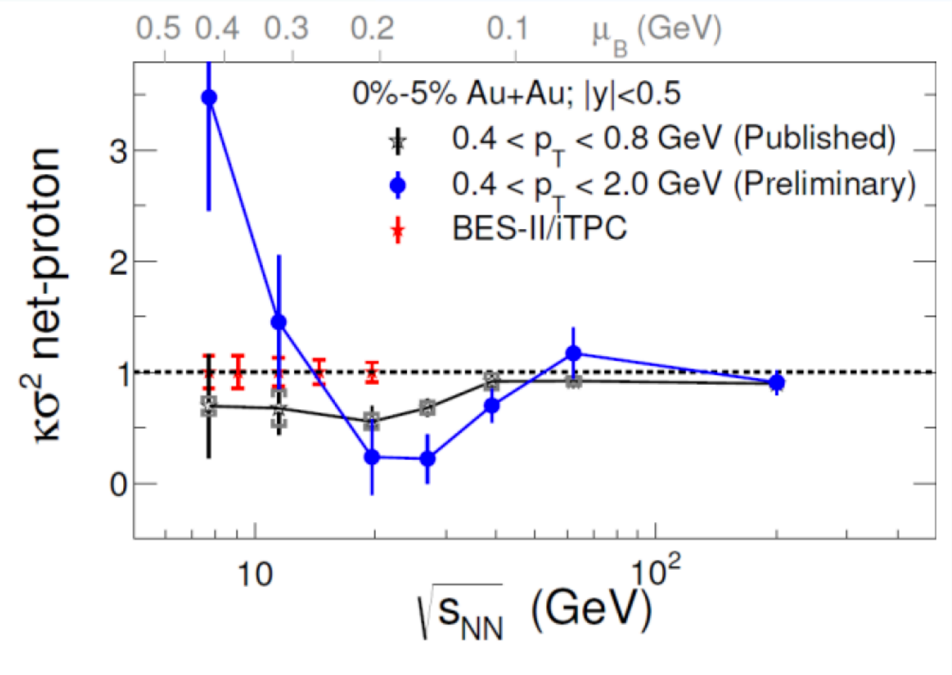


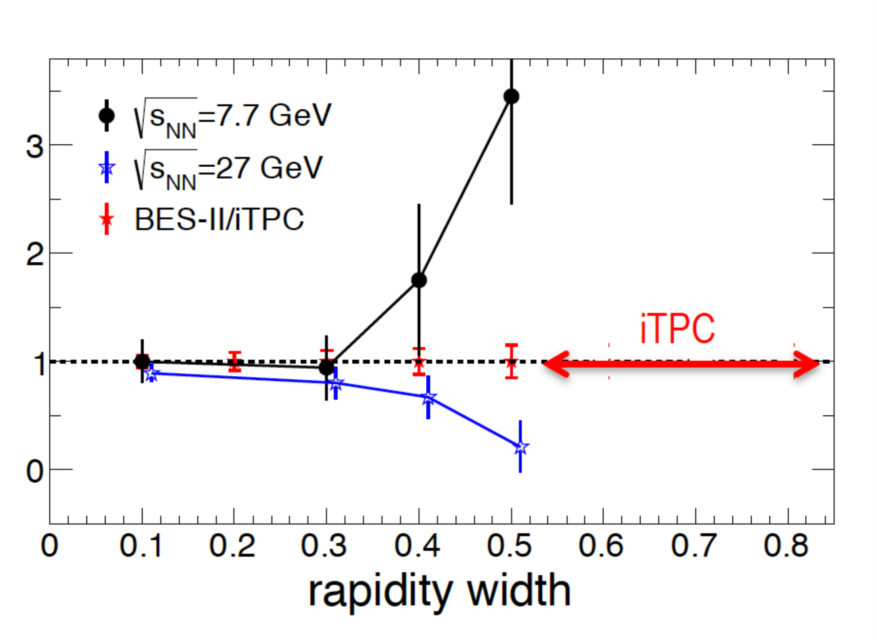


iTPC


Sim: Au+Au @ 19.6 GeV,η-sub EP
|η| < 1 (w/o iTPC)
1<|η|<2 (with iTPC)
1<|η|<2 (w/o iTPC)
EP resolution
0
0.2
0.4
20
40
60
80
Centrality (%)

iTPC


0.5 0.4 0.3 0.2 0.1 μB (GeV)
0%-5% Au+Au; |y|<0.5
0.4 < pT < 0.8 GeV (Published)
0.4 < pT < 2.0 GeV (Preliminary)
BES-II/iTPC
κσ2 net-proton
√sNN (GeV)


√sNN=7.7 GeV
√sNN=27 GeV
BES-II/iTPC
iTPC
rapidity width

BES-I White paper