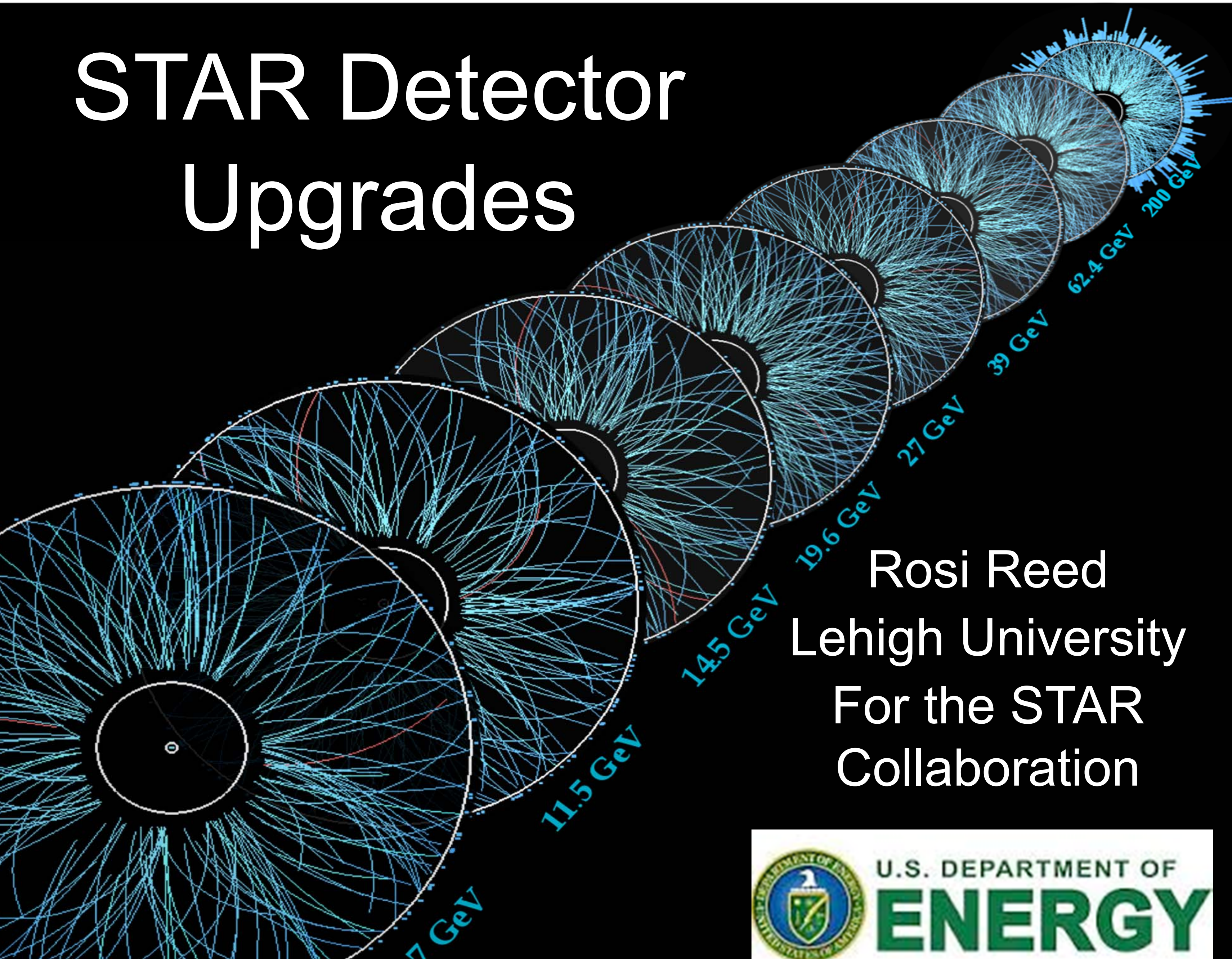
STAR Detector Upgrades



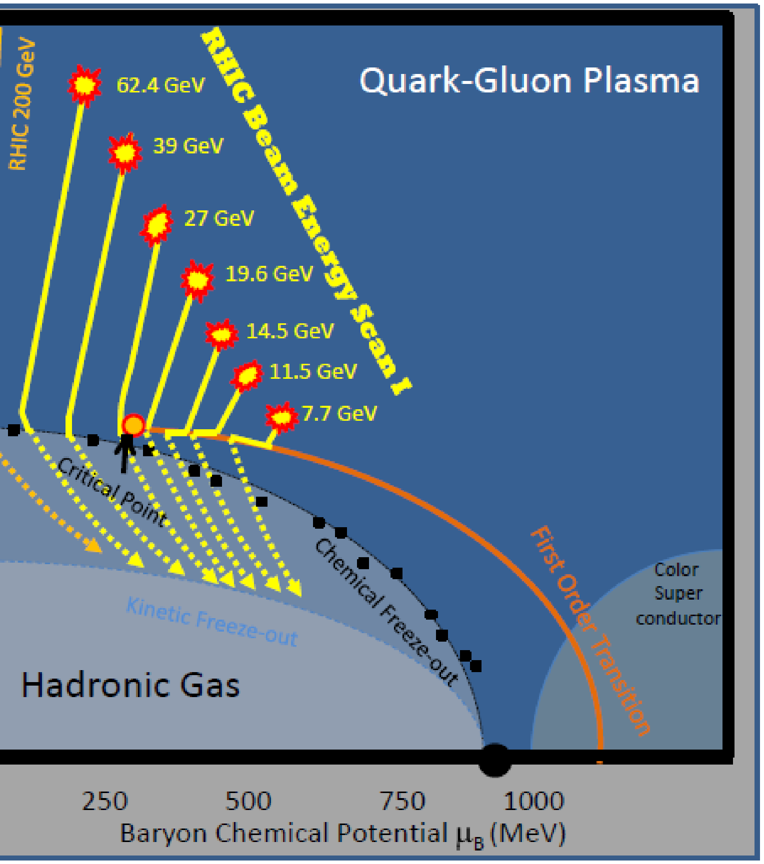
Rosi Reed
Lehigh University
For the STAR Collaboration

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

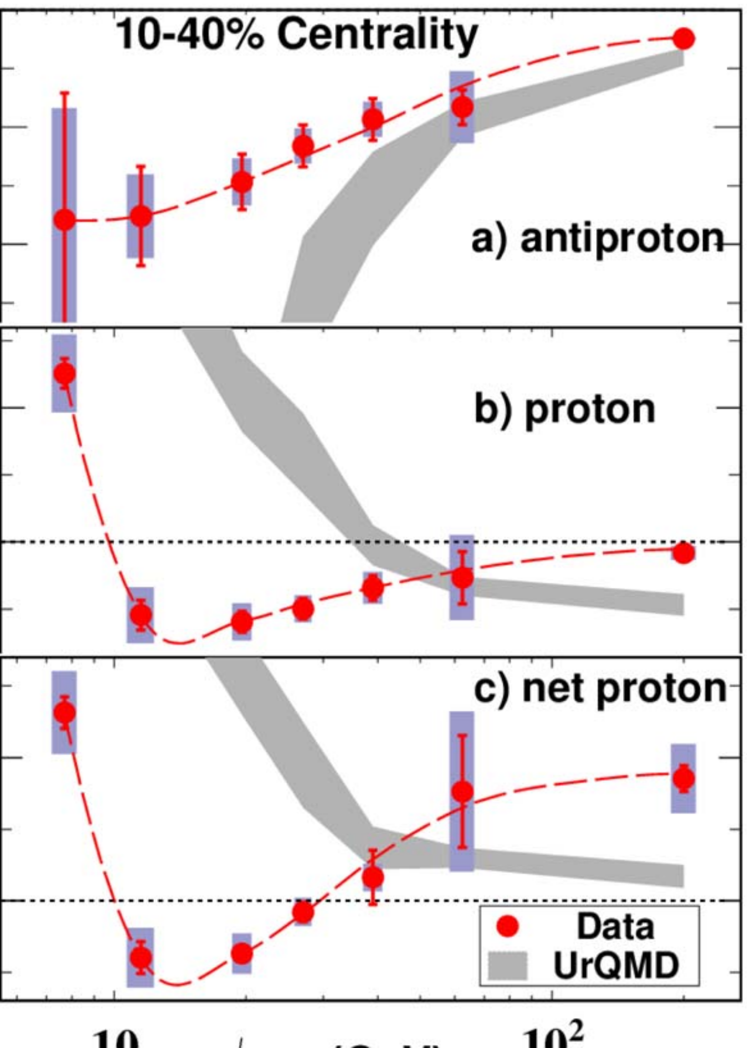


Beam Energy Scan Phase 1
emperature T and baryon chemical
ial μ_B

- 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

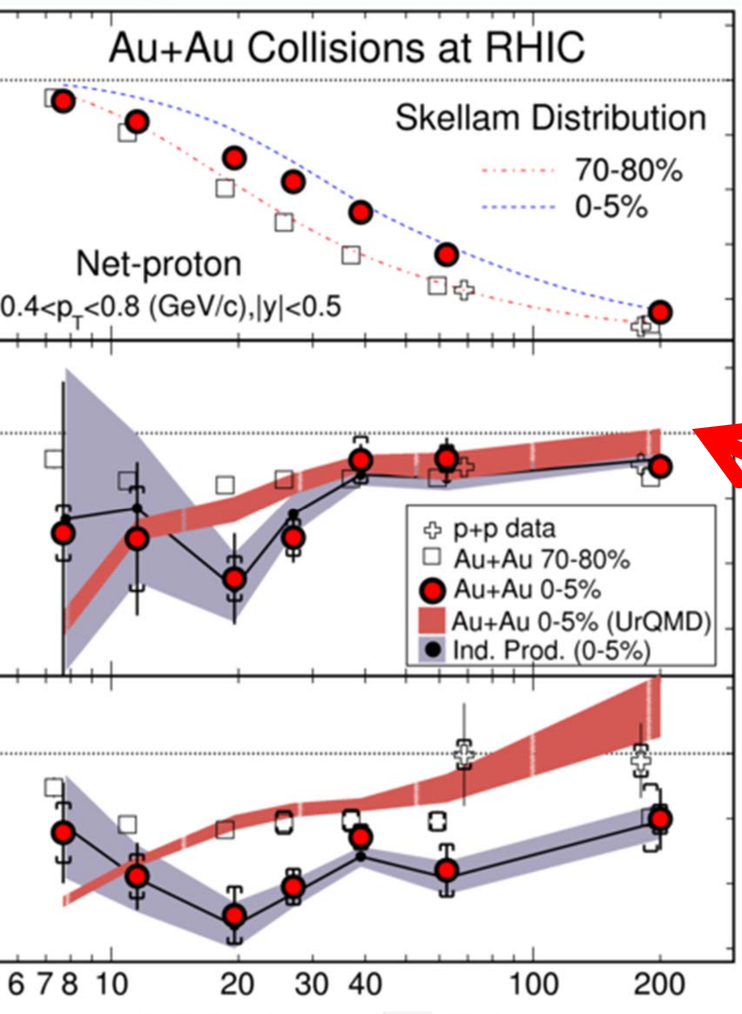
Phys. Rev. Lett. 112, 162301 (2014)

STAR BES-I

The QCD critical point

See Bill Llope's talk on Tuesday!

12 (2014) 32302



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

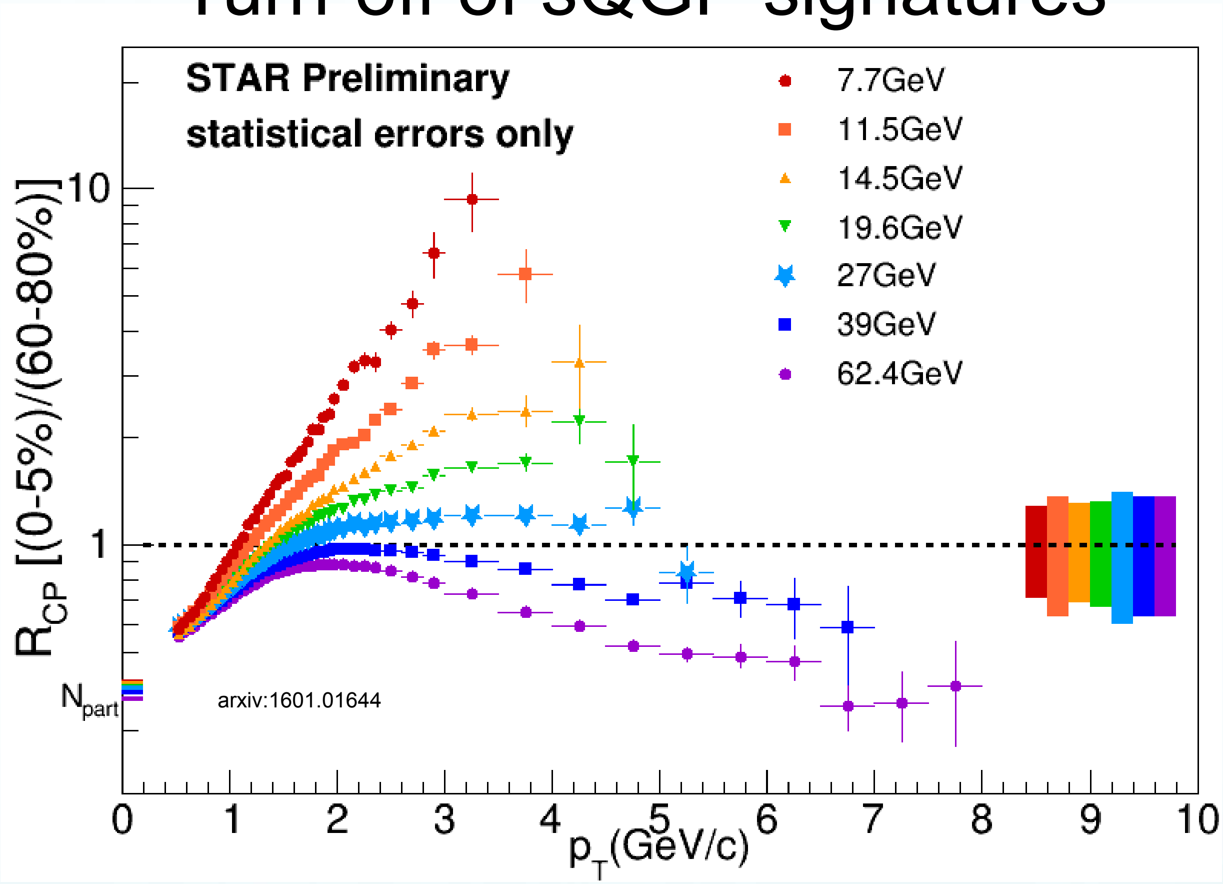
~2-3σ from Poisson

~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



we see the turn off of jet quenching?

Enhancement competes with suppression complicating the measure of the turn off of QGP effects at low $\sqrt{s_{NN}}$

BES-I → BES-II

015 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.

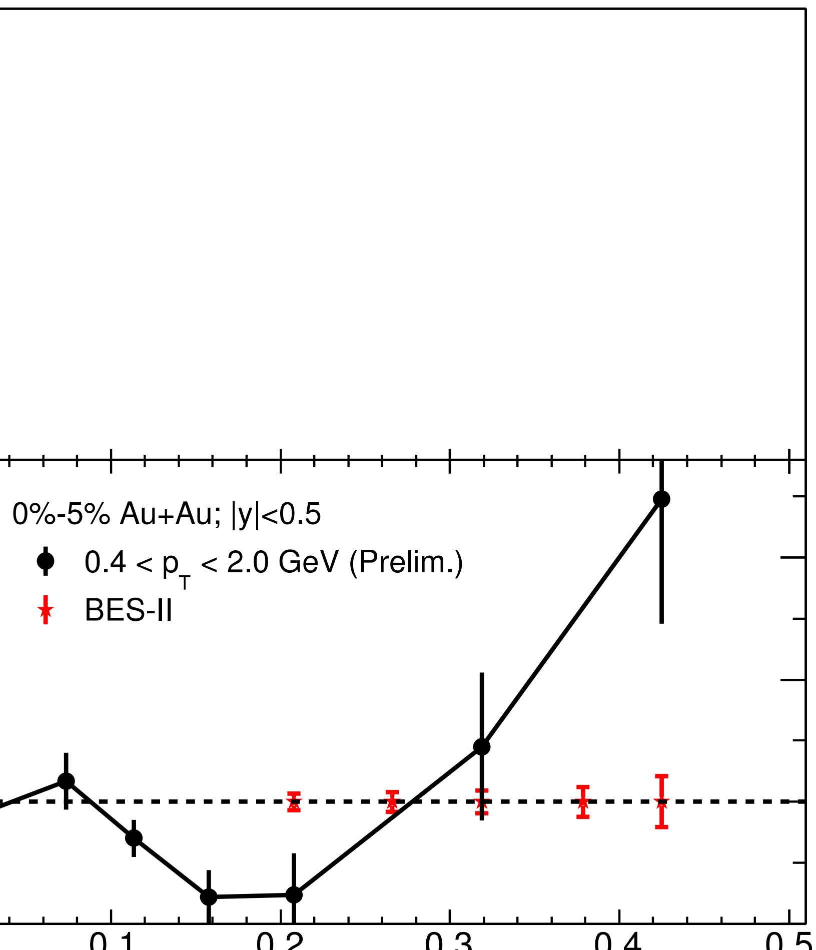
http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

rends and features from BES-I motivate for experimental neasurements with higher statistical and systematic precision

Requires strong and concerted theoretical response

etector upgrades planned for BES-II focus on **maximizing the action of measured particles** from each collision

e goal of BES-II is **to turn trends and features o definitive conclusions** and new understanding ne key features of QCD.



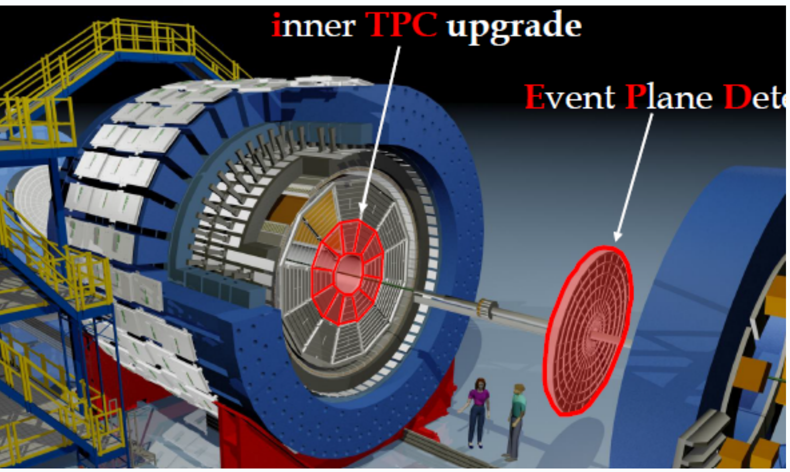
BES-II

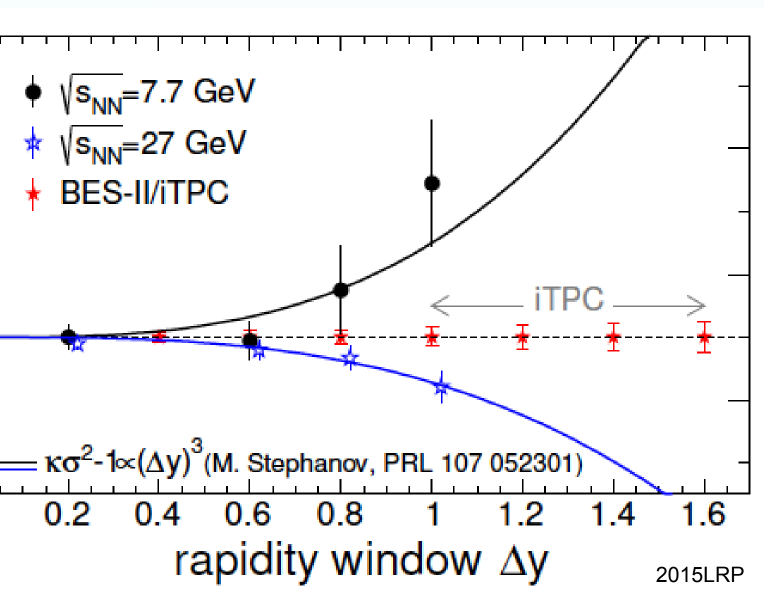
atistics

- 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

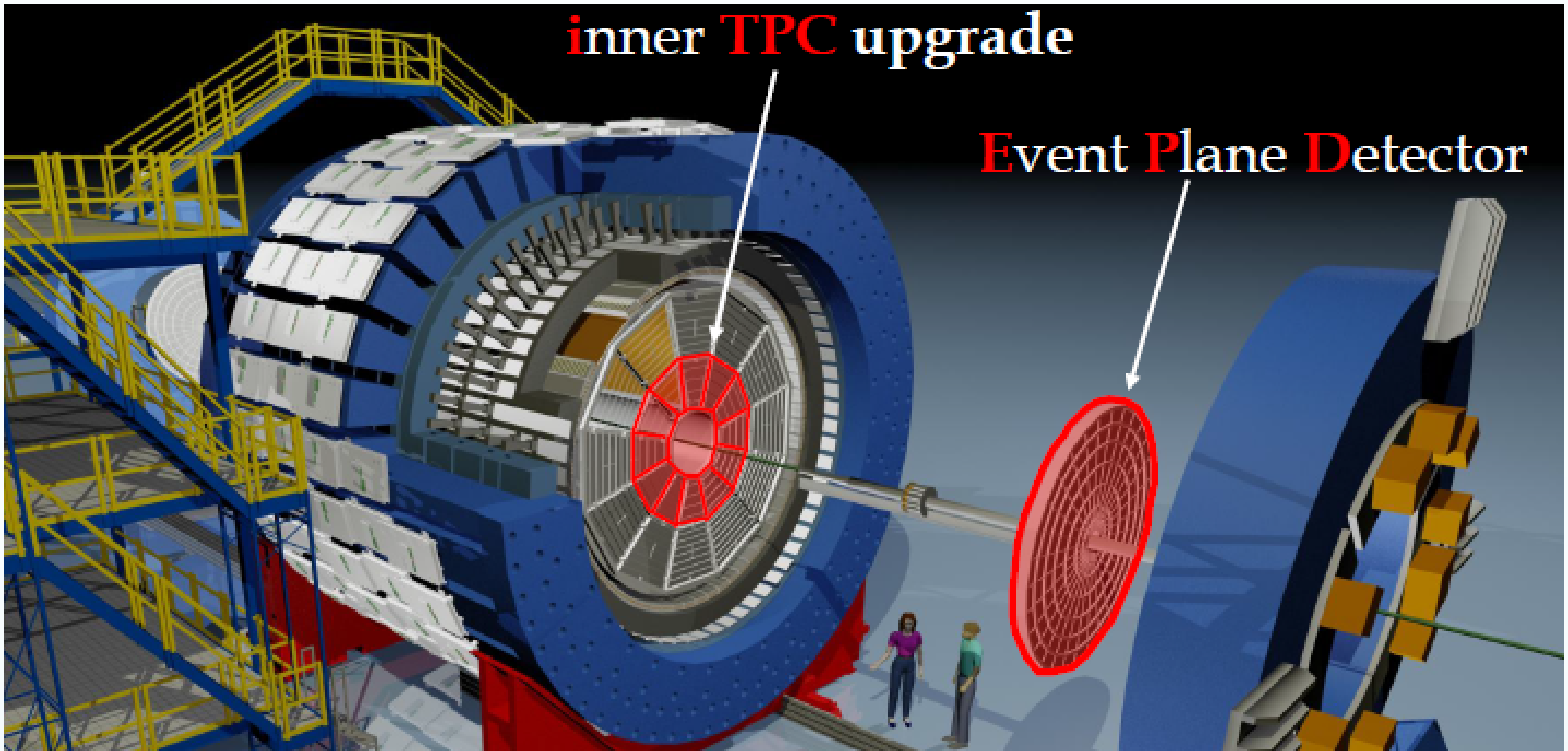
Larger Acceptance





- **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

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

roves

lomentum resolution

E/dx resolution 7.5% to 6.2%

cceptance

From |η| < ~1.0 to |η| < 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!

rent inner TPC pad row geometry is not fully instrumented

nly 20% of the inner sector path length is sampled

TPC increases the path length coverage in the inner sectors to 100%

efits many analyses, especially:

luctuations (Kurtosis)

aryon v_1 measurements

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

roves 2nd-order event-plane res, away from mid-rapidity by x2

nhancing elliptic flow measurements

or dielectron measurements it reduces hadron contamination from a dominant ource of uncertainty (20%) down by an order of magnitude

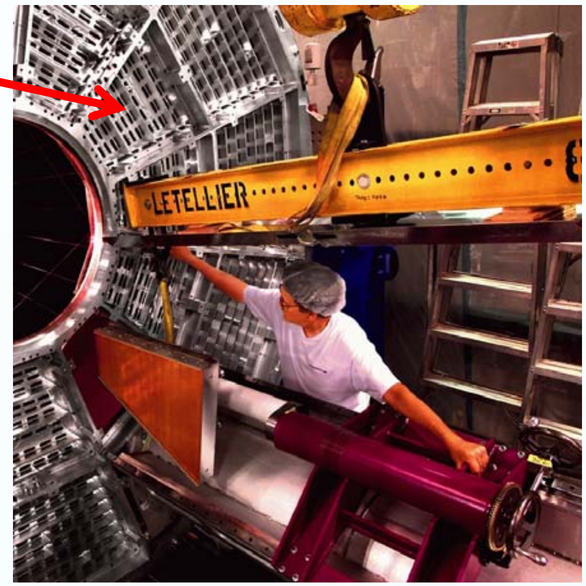
The iTPC in a nutshell

Inner sector 1/12

e upgrade increases $N_{channels}$ in
e 24 inner sectors by ~x2

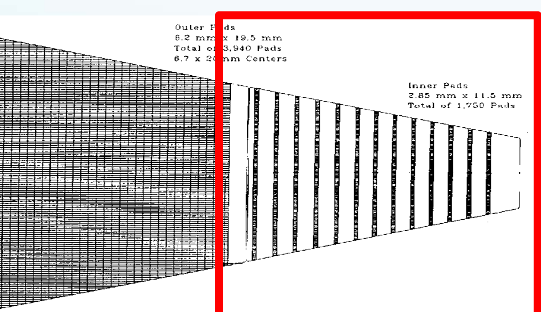
ovide complete coverage for a
ier sector

w electronics for inner sectors



plane layout for one sector

Current



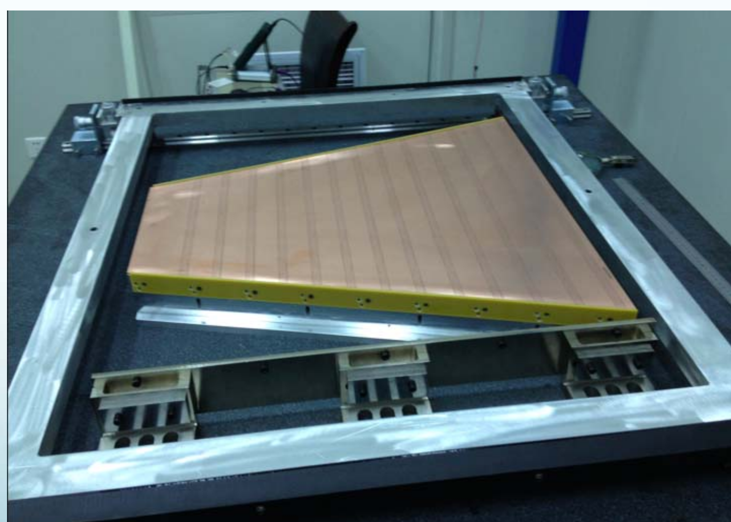
Future

iTPC sectors

otype – original layout
lane glued onto strongback

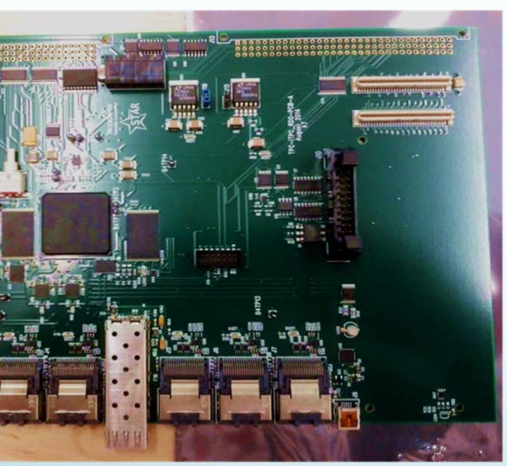
ire mounting prototype at
handong University, China

- 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

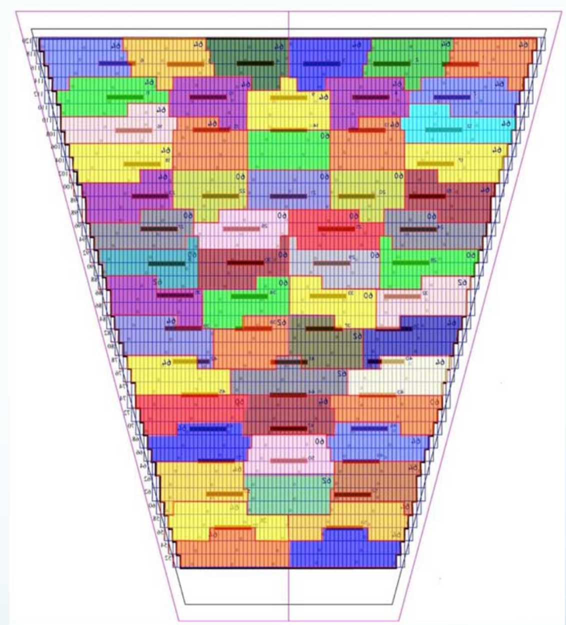
- EE based on current
E layout, but using
ICE SAMPA chip
- $N_{channels}$ per FEE
- O similar to existing
- veloped by BNL
ctronics group



prototype

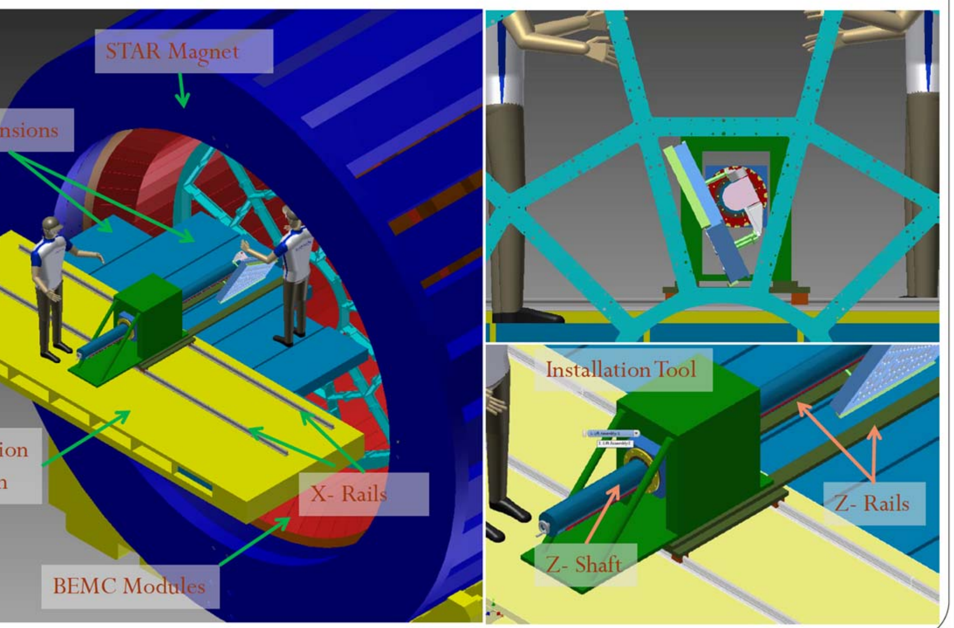
Pre-prototye iFEE electronic card shown plugged into the padplane

Fully instrumented TPC connections to FEE



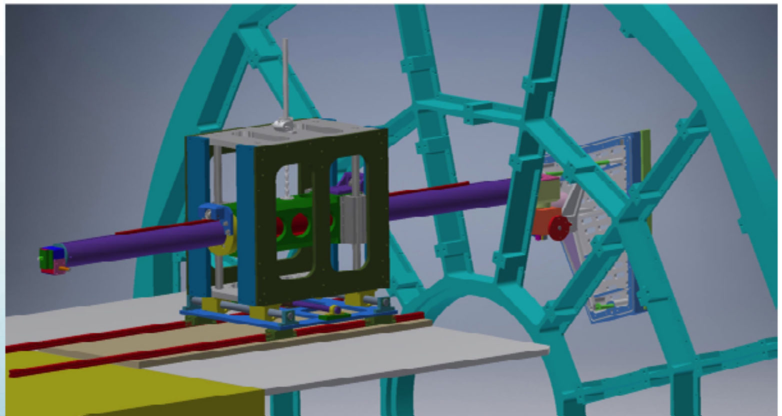
iTPC Insertion Tooling

artesian Installation Tool Design



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

signed by Rahul Sharma, Ralph
own and much input from LBL,
RN

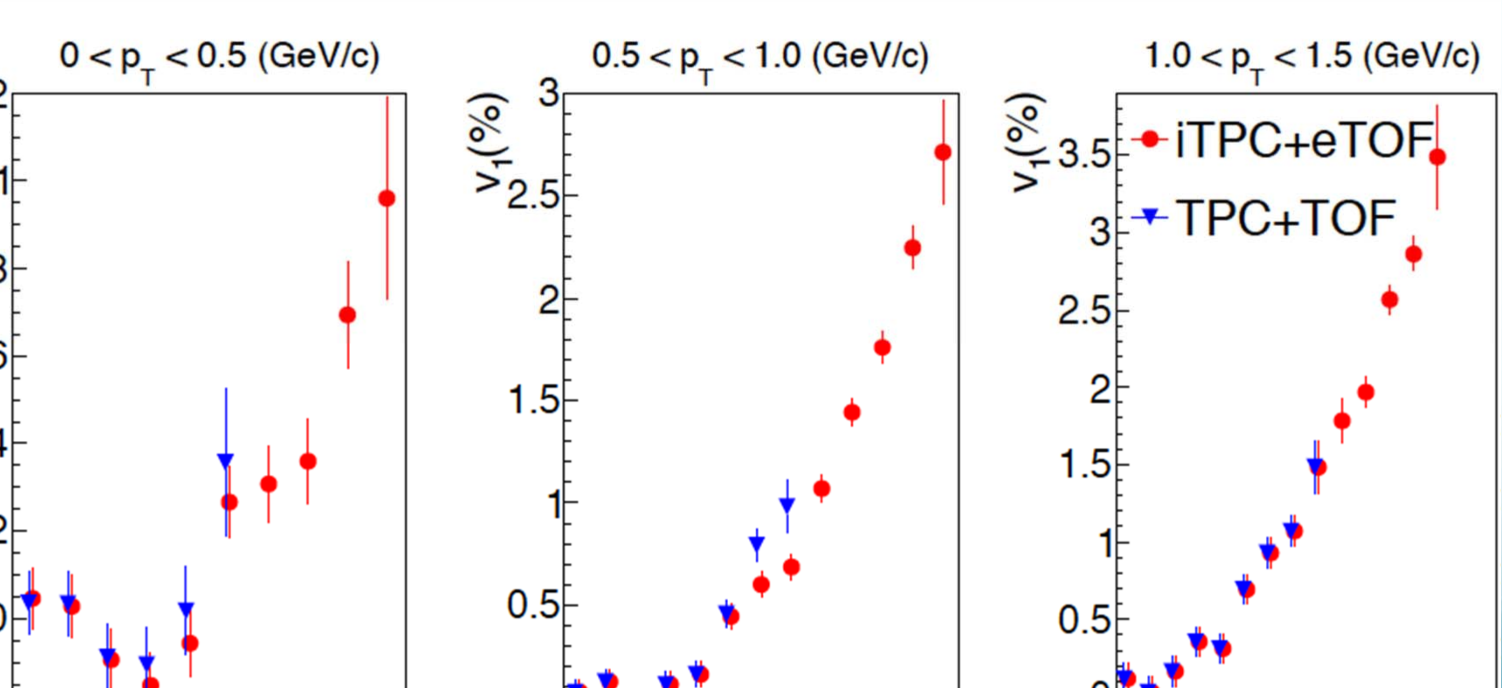


Direct Flow Improvements

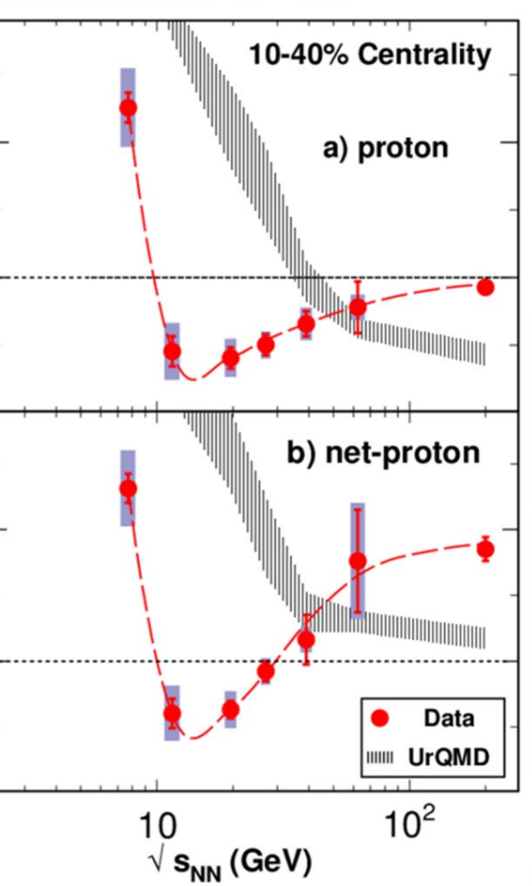
roton directed flow as a function of rapidity for minimum-bias Au Au collisions at $\sqrt{s_{NN}}$ = 19.6 GeV

Based on UrQMD

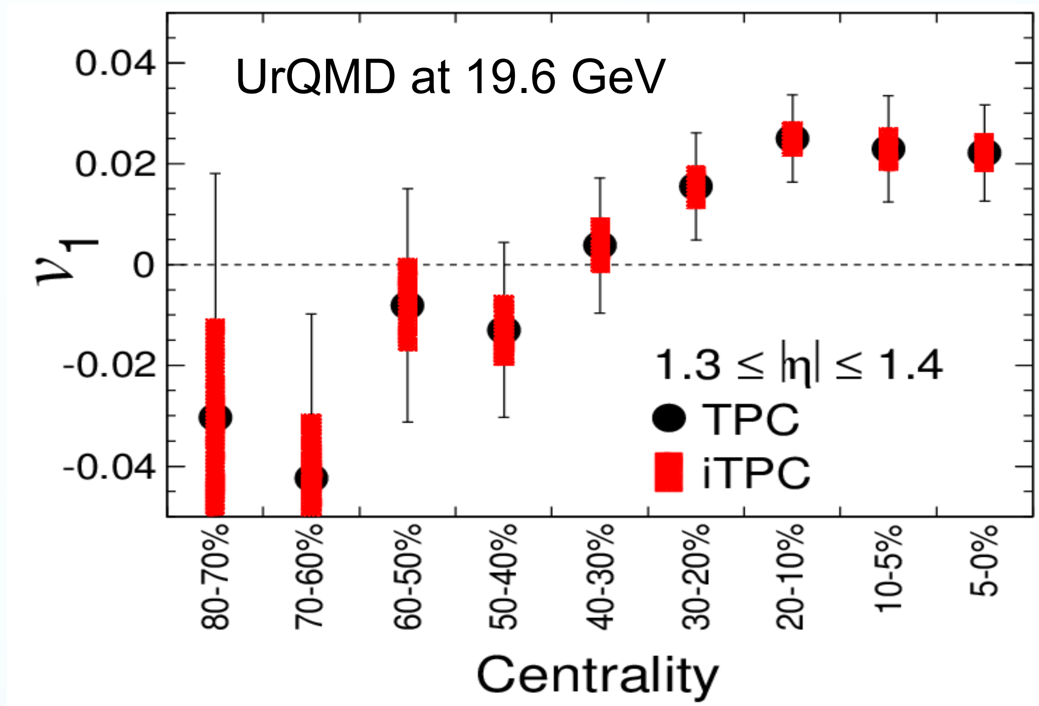
imulated $v_1(y)$ compared between the acceptance of the STAR PC with the existing TOF barrel and the upgraded acceptance fter addition of the iTPC and the eTOF



iTPC → BES II directed flow

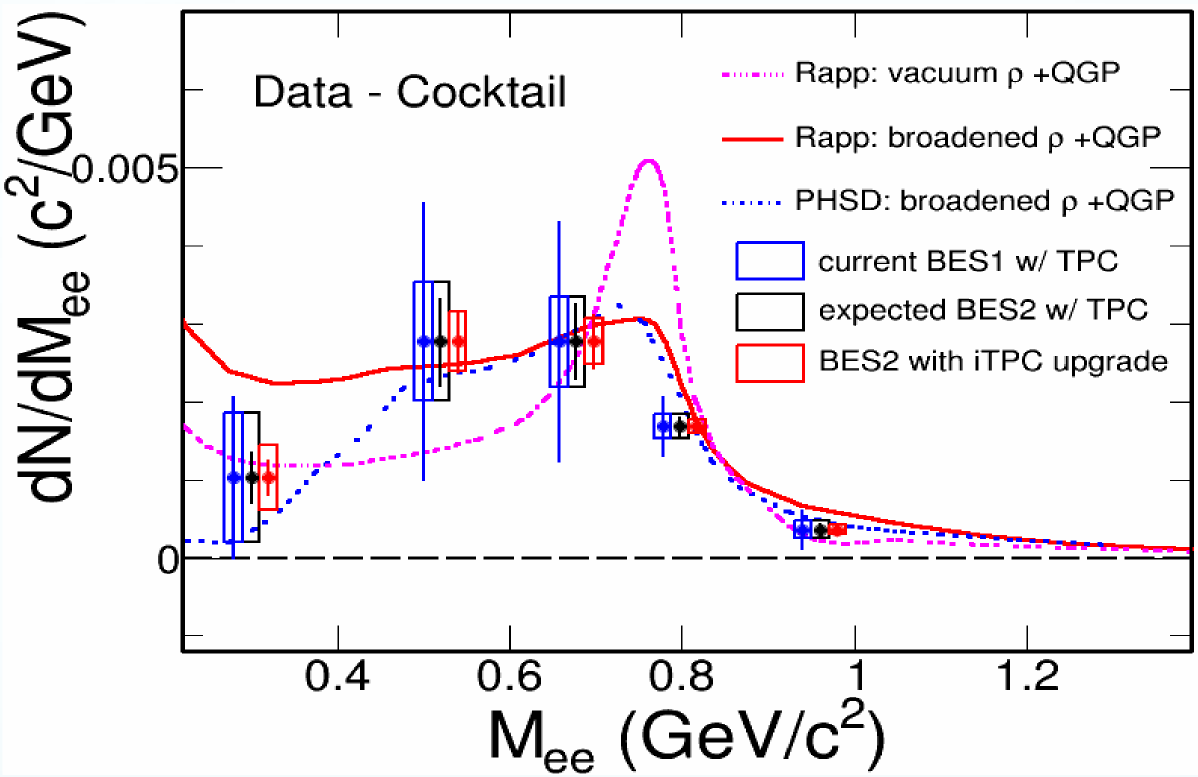


ected flow for protons
net-protons BES-I
L 112,162301 (2014)



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

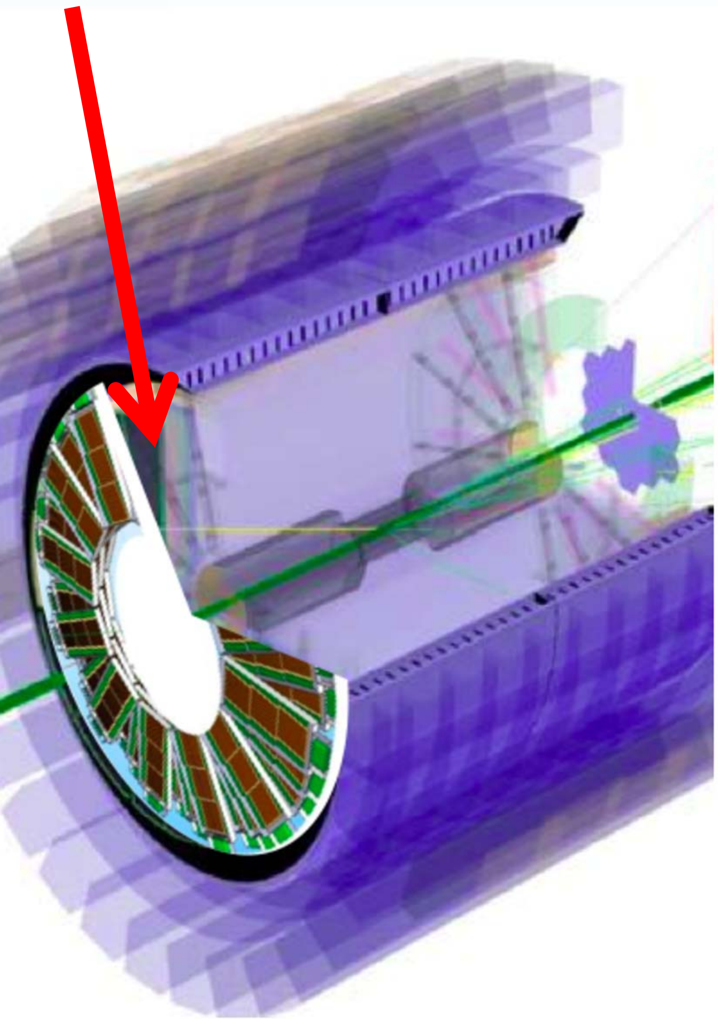
Di-electron measurements in BES-II



- nproved dE/dx will reduce the dominant systematic error
- istinguish between models with different ρ-meson broadening
- tudy effect of total baryon density on Low-Mass Region (LMR) xcess

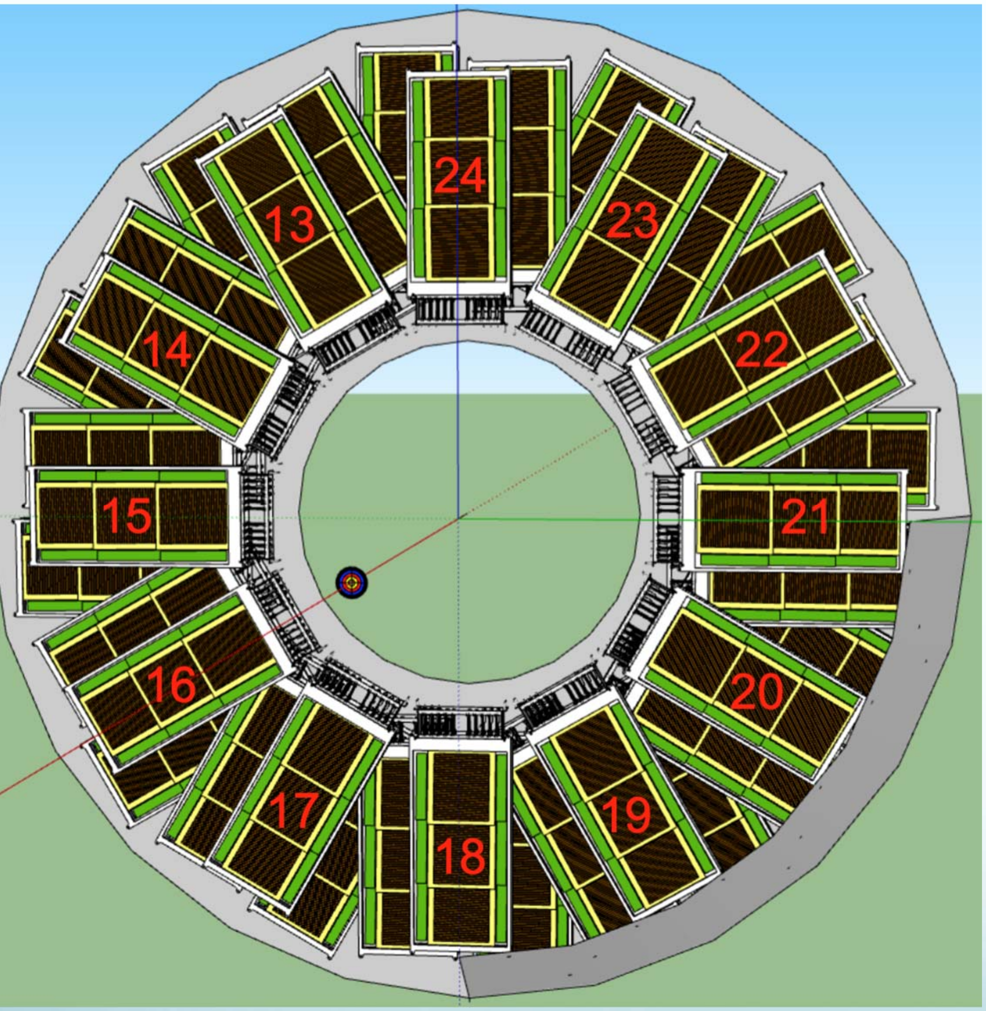
eTOF

dcap **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

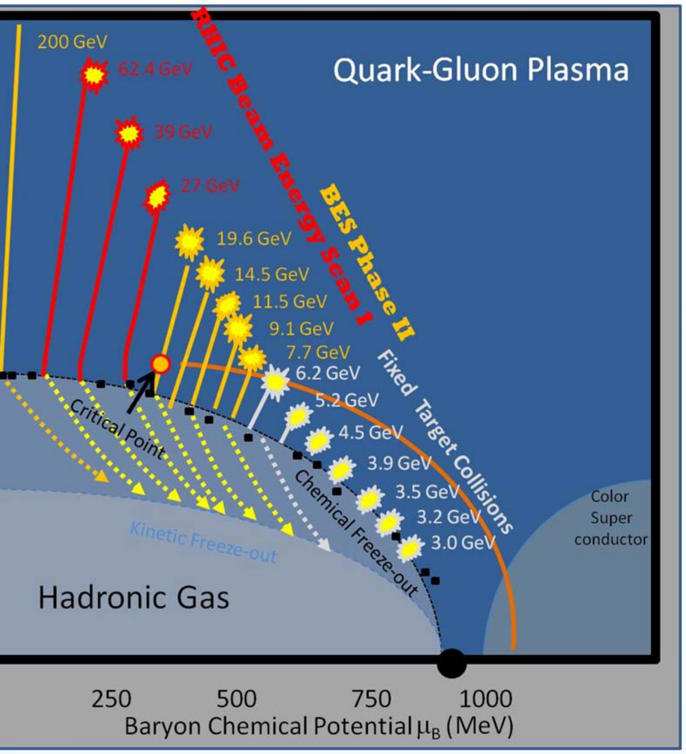


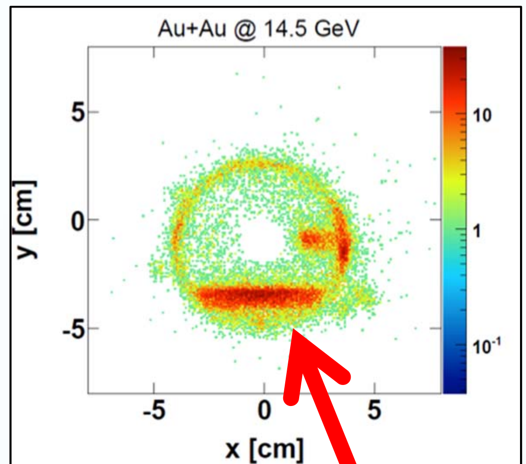
- Allows for PID in the η range provided by the iTPC upgrade
- eTOF needed for PID at forward rapidities
  - Efficiency dE/dx drops rapidly due to p_Z boost
  - Key for the fixed target program

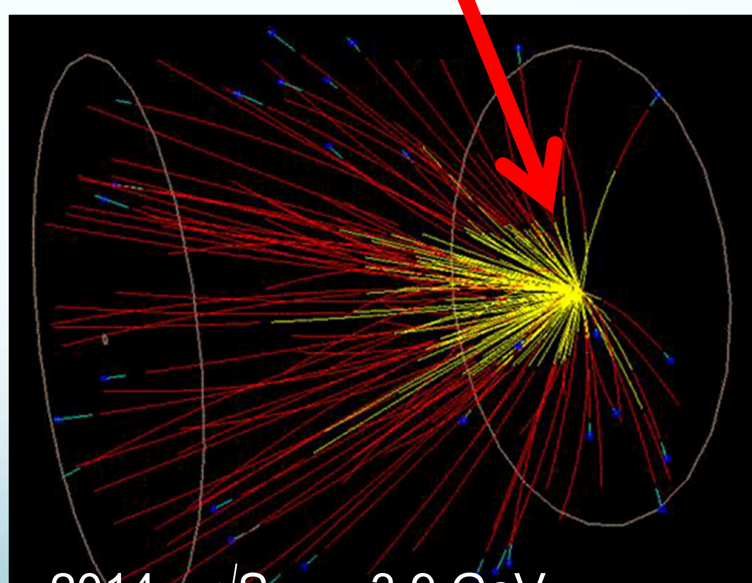
BES-I → BES-II

New energies

See Kathryn Meehan's talk on Tuesday!

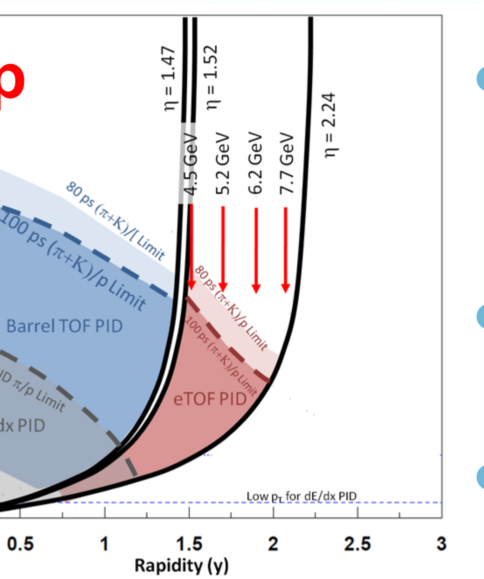




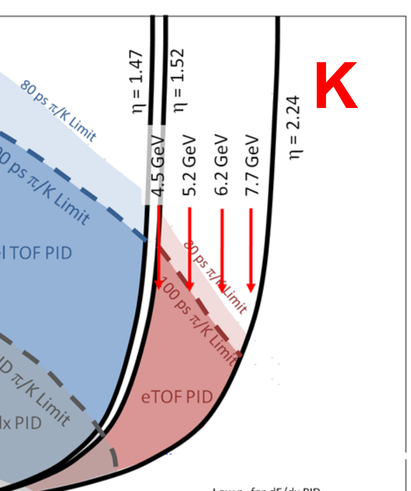


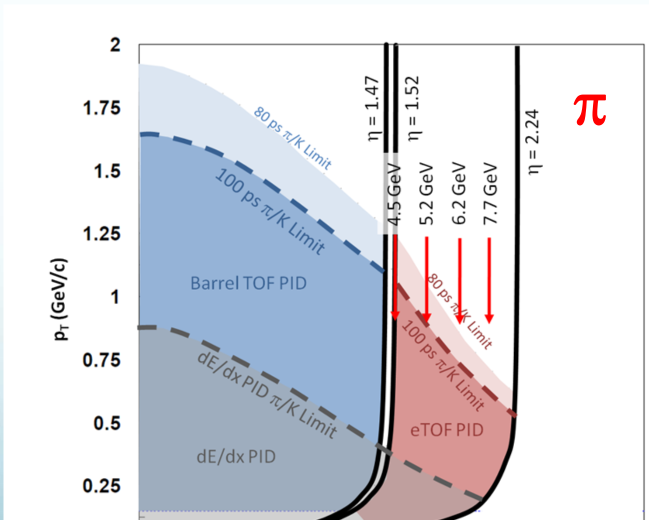
- et inserted into beam pipe
- = 210 cm
- run done parasitically
- o interference w/collider mode data
- e efficient → small dedicated runs

y – p_T Map Fixed Target

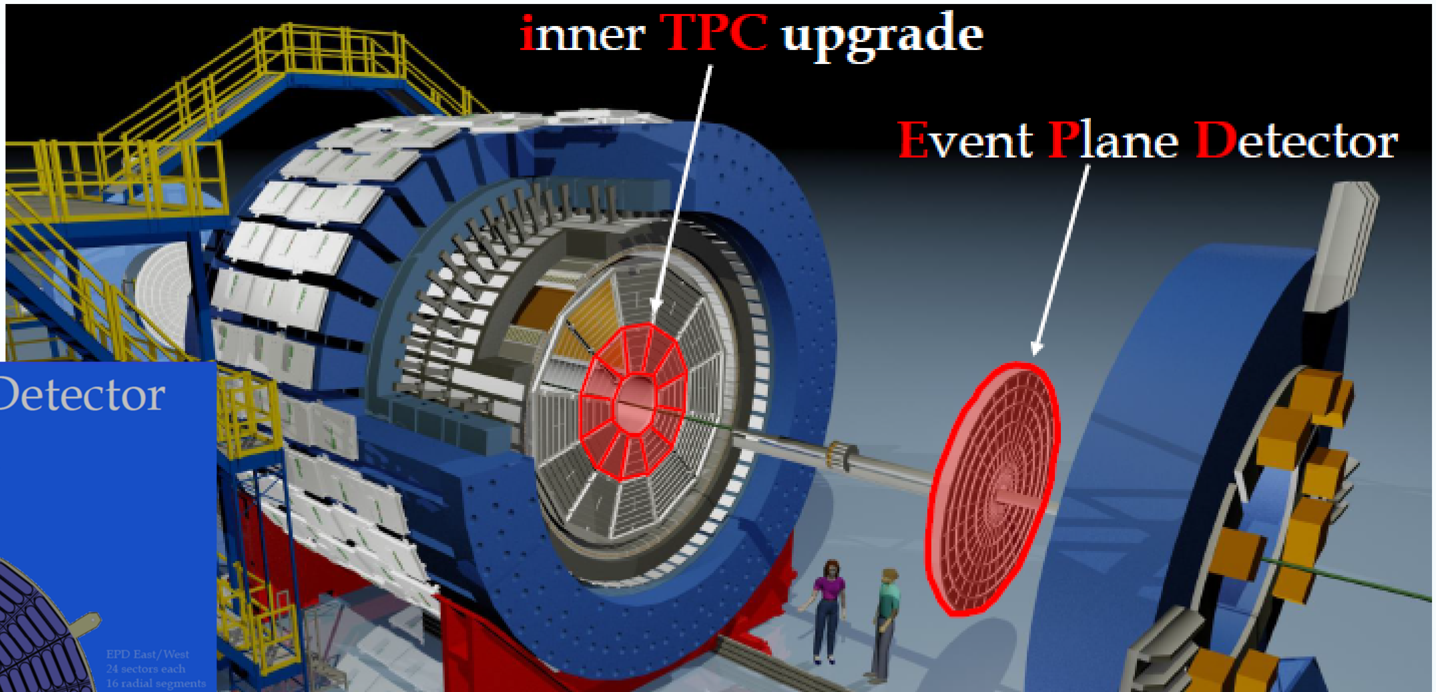


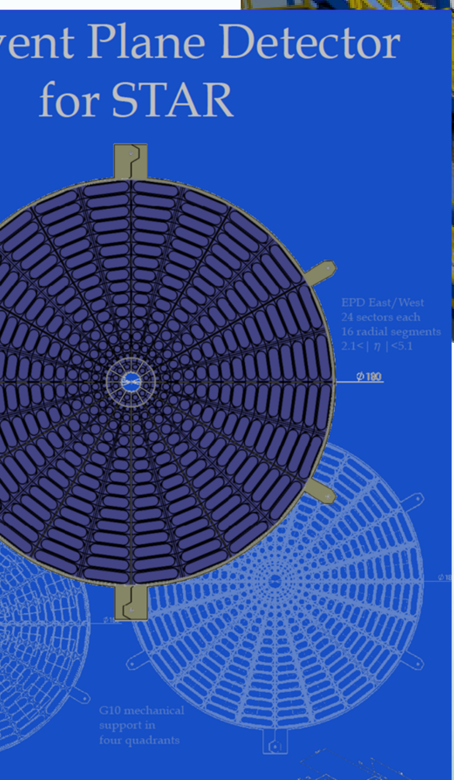
- NA49 → onset of deconfinement = $\sqrt{S_{NN}}$ = 7.7GeV Phys. Rev. C77, 024903 (2008),
  - < 7.7 GeV not possible in collider mode
- Using just the iTPC upgrade → energy range from 3 to 4.5 GeV
- eTOF upgrade allows $\sqrt{S_{NN}}$ = 3-7.7 GeV





EPD

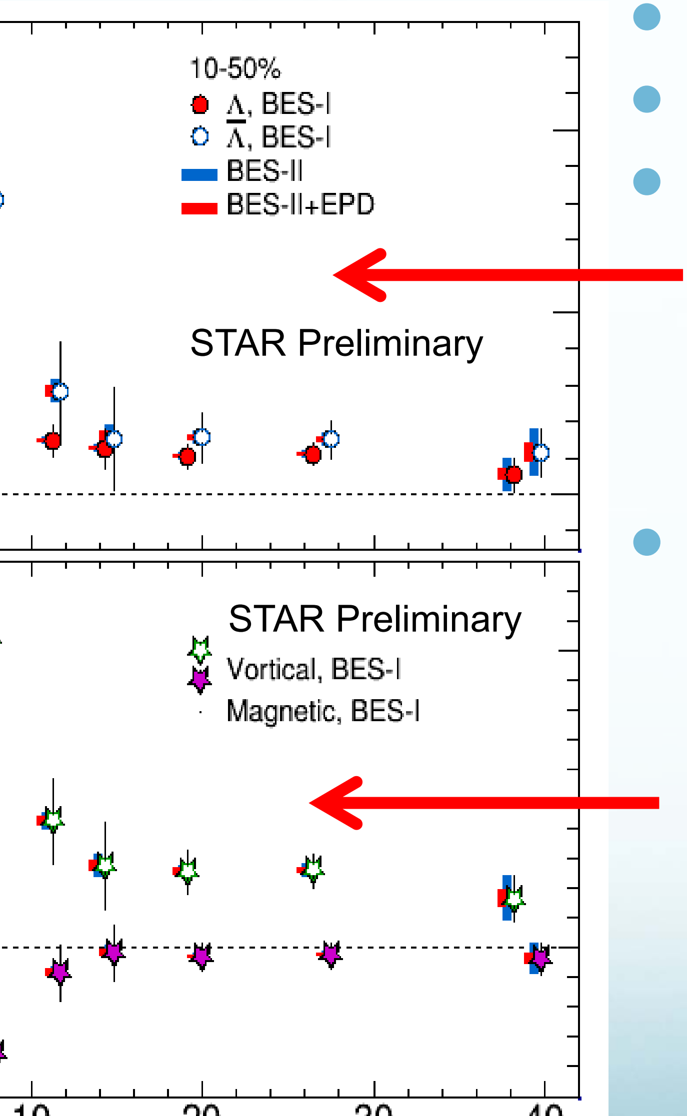




$2.1 < |\eta| < 5.1$

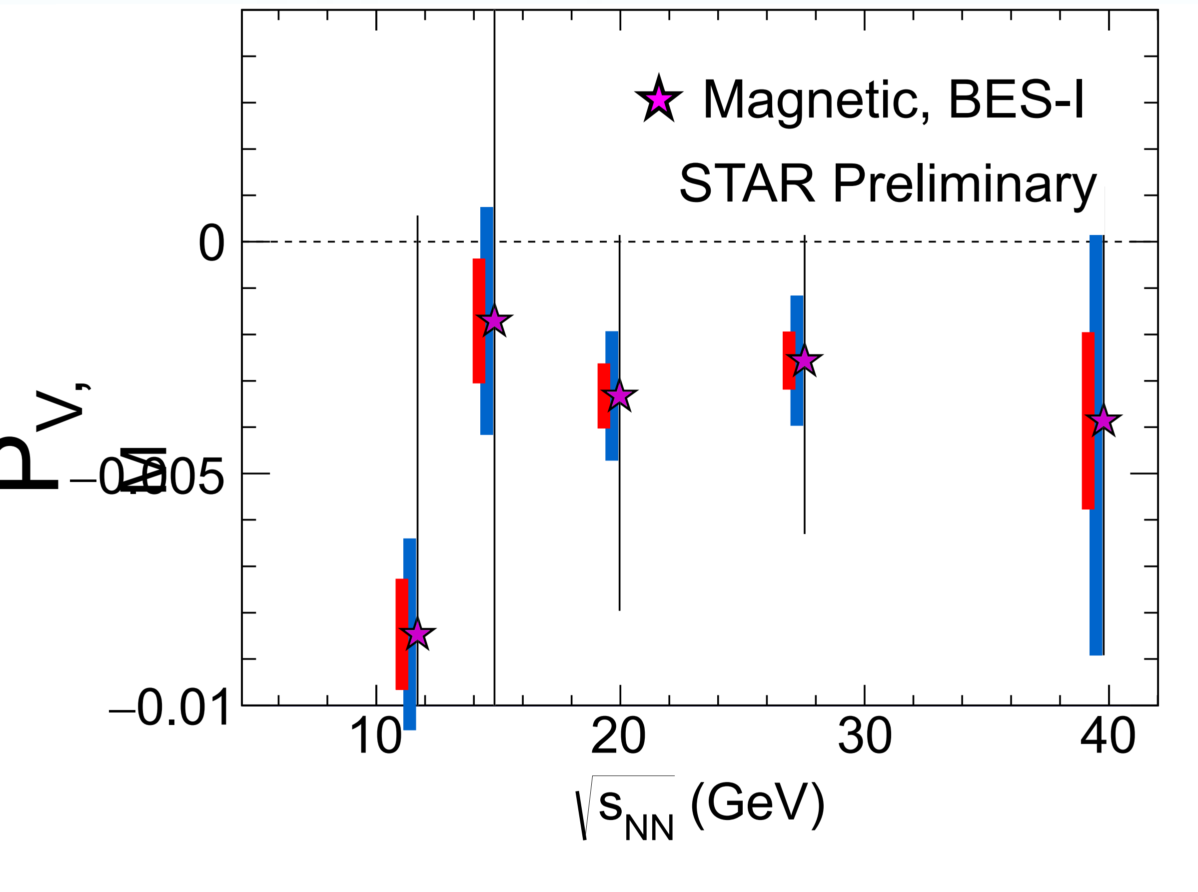
- Greatly improved Event Plane info (especially 1st-order EP)
- Determine Centrality outside mid-rapidity
- Better trigger & background reduction

EPD Improvements



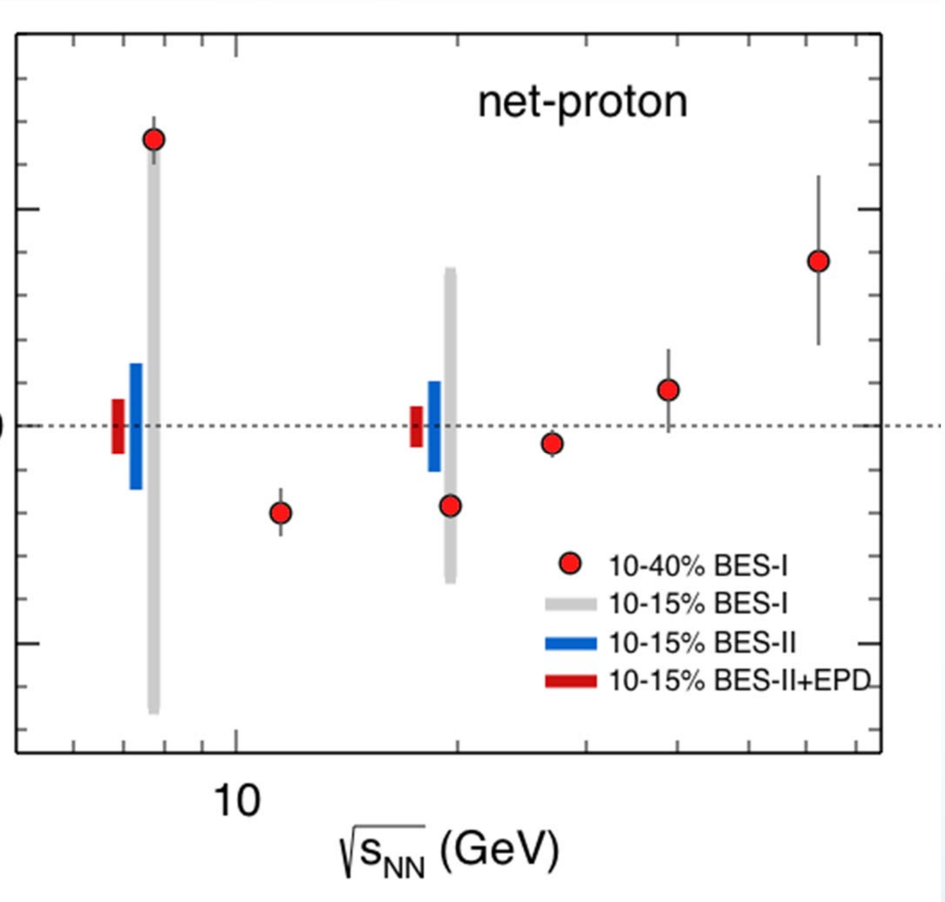
- **BES-II**
- **BES-II + EPD**
- The **average polarization** of $\bar{\Lambda}$ and Λ from 20-50% central collisions
  - No feed-down effects → Stat uncertainty only
- The **vortical and magnetic contributions** to Λ and $\bar{\Lambda}$ emitted directly from the hot zone created in a heavy ion collision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



ning we can see that the current results are not significant for $\sqrt{s_{NN}} \geq$
eV
crease in statistics and EPD allow for a ~3σ effect
ves an independent measure of B, key for CME/CVE verification

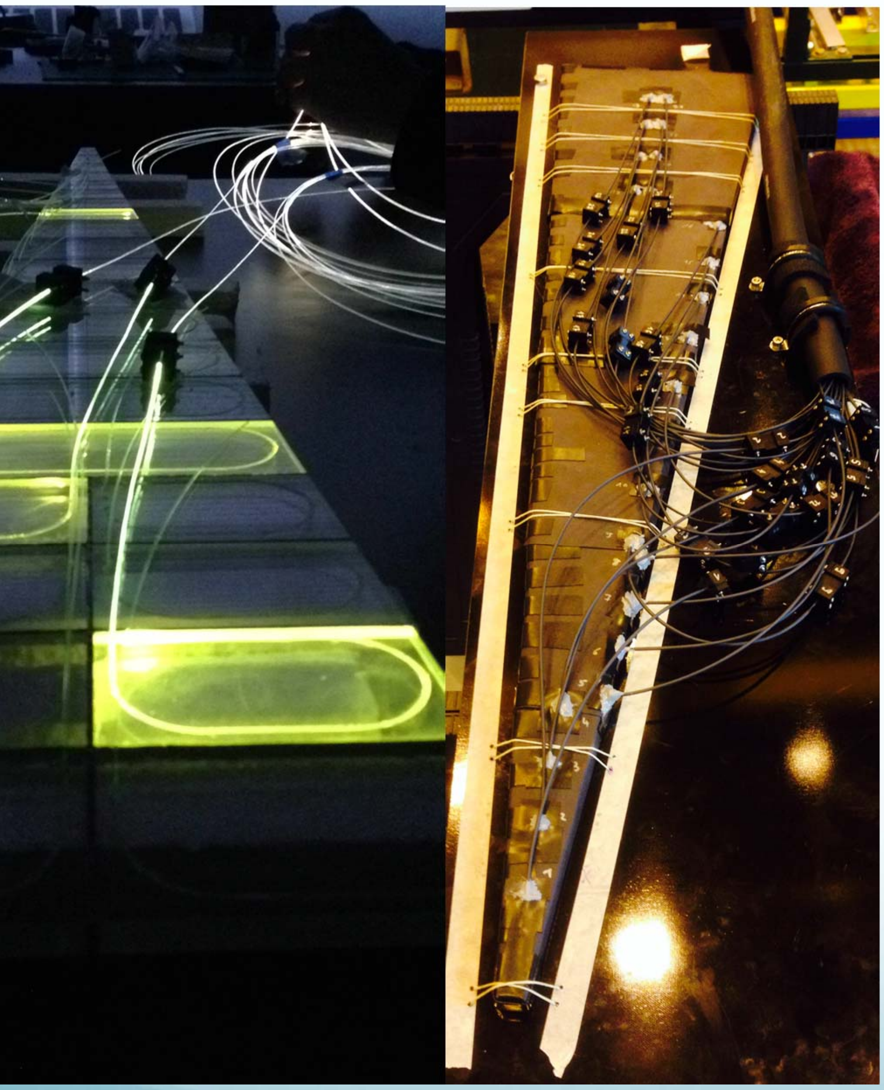
EPD Improvements



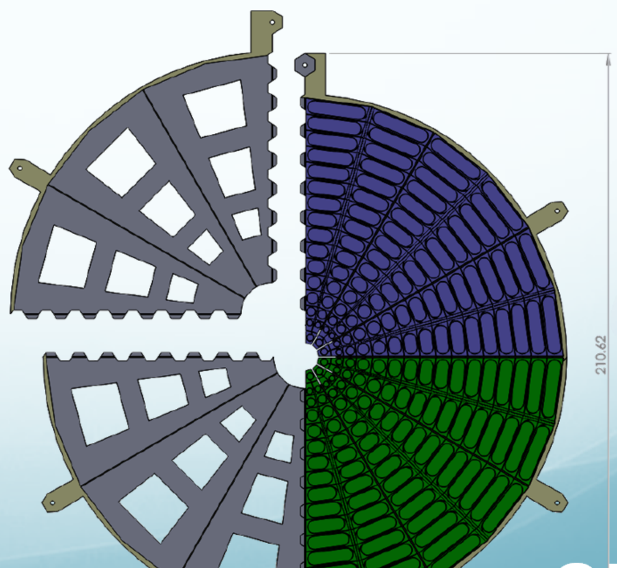
- Net proton v_1 versus $\sqrt{s_{NN}}$ at mid-rapidity
  - BES I data from 10-40%
- The grey bars indicate what the error bars would have been with a narrow centrality

I Data
II
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

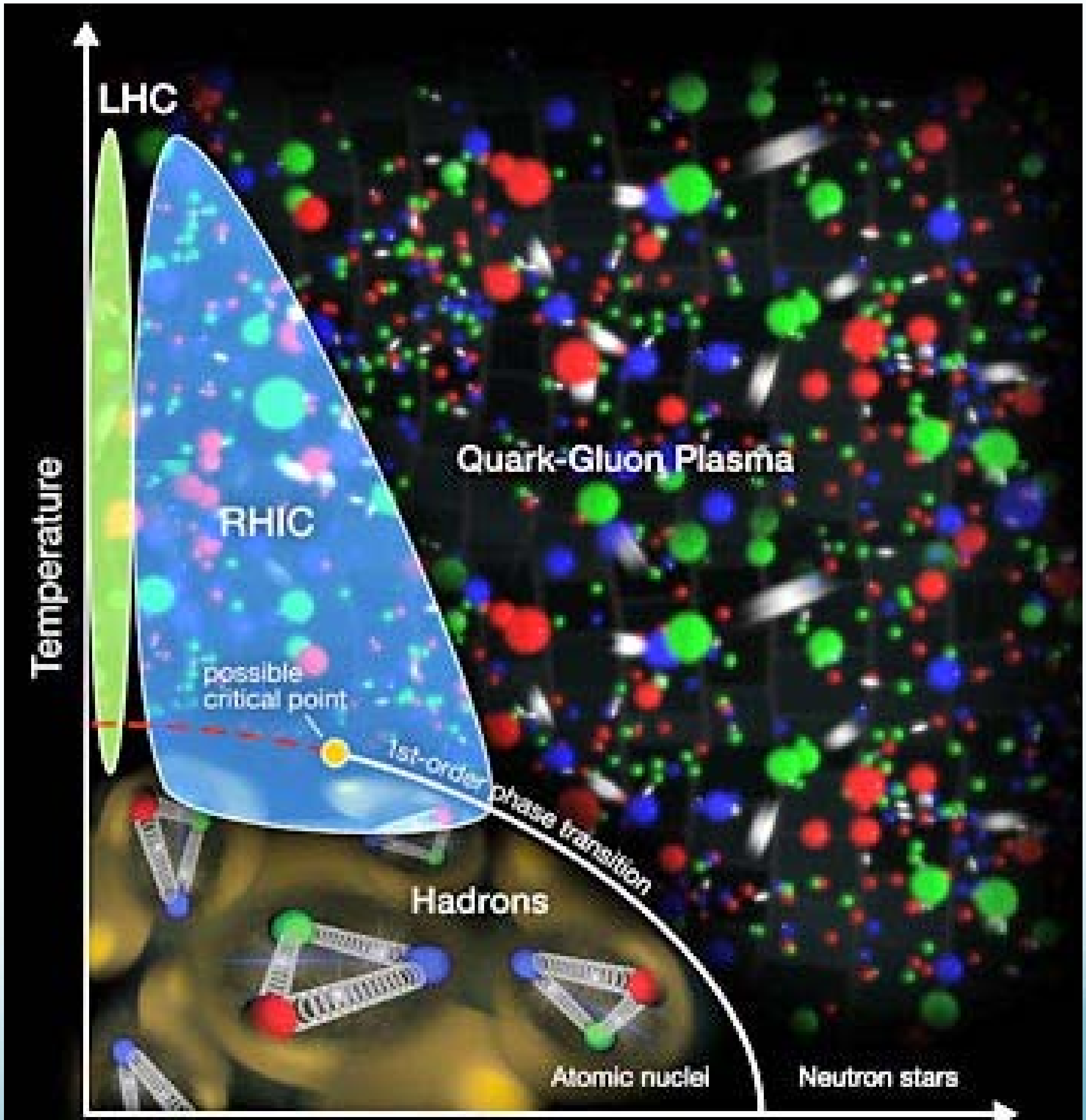


From 7.7 GeV →510 GeV

C is an
zingly versatile
hine

GeV (and below!)
udy QCD phase
ram →

GeV polarized
ons to study the
structure of the
on



R_{pA} in Drell Yan + Direct Photon

See Elke-Caroline Aschenauer's talk later today!

undamental 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

ee the RHIC Cold QCD Plan at: Arxiv:1602.03922

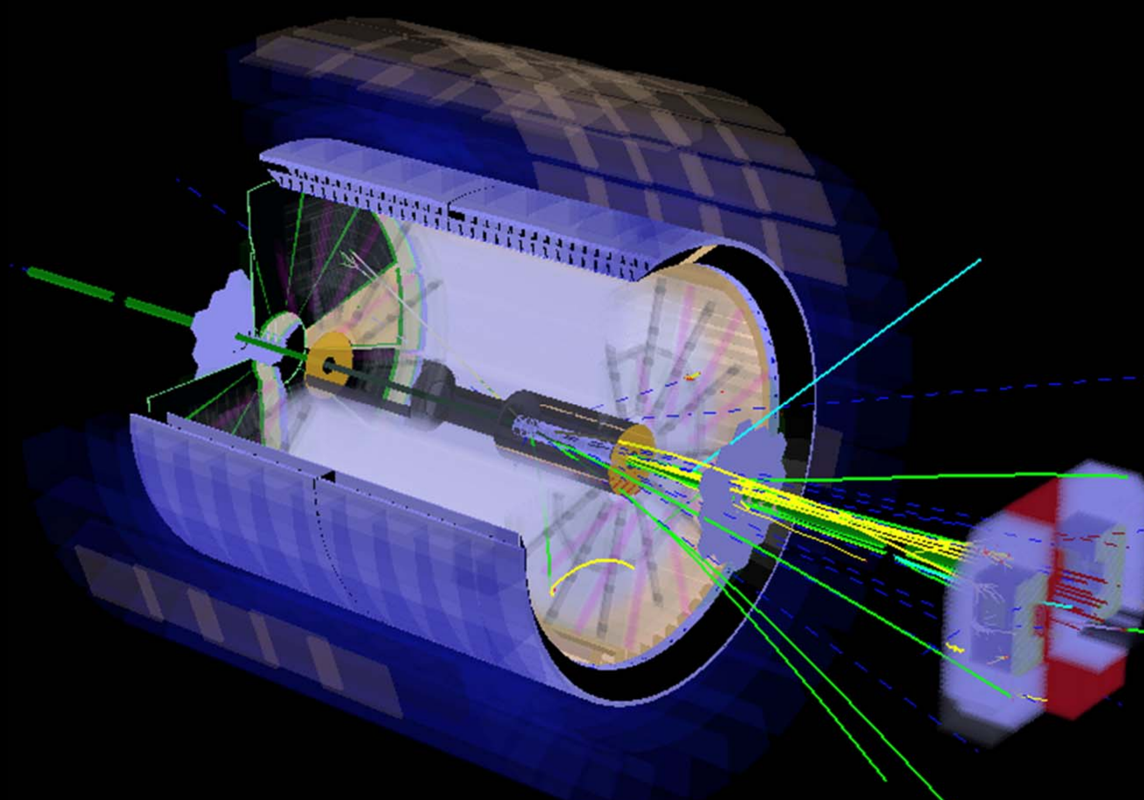
FCS and FTS

oposed FCS+FTS provide access to very small x

- Facilitates investigations into the dynamics and nonlinear evolution effects in the regime of high gluon-density.

orward
alorimeter
ystem

orward
racking System



Forward Calorimeter System (FCS)

Uses the refurbished PHENIX sampling ECal

- **EM resolution ~8%/√E**

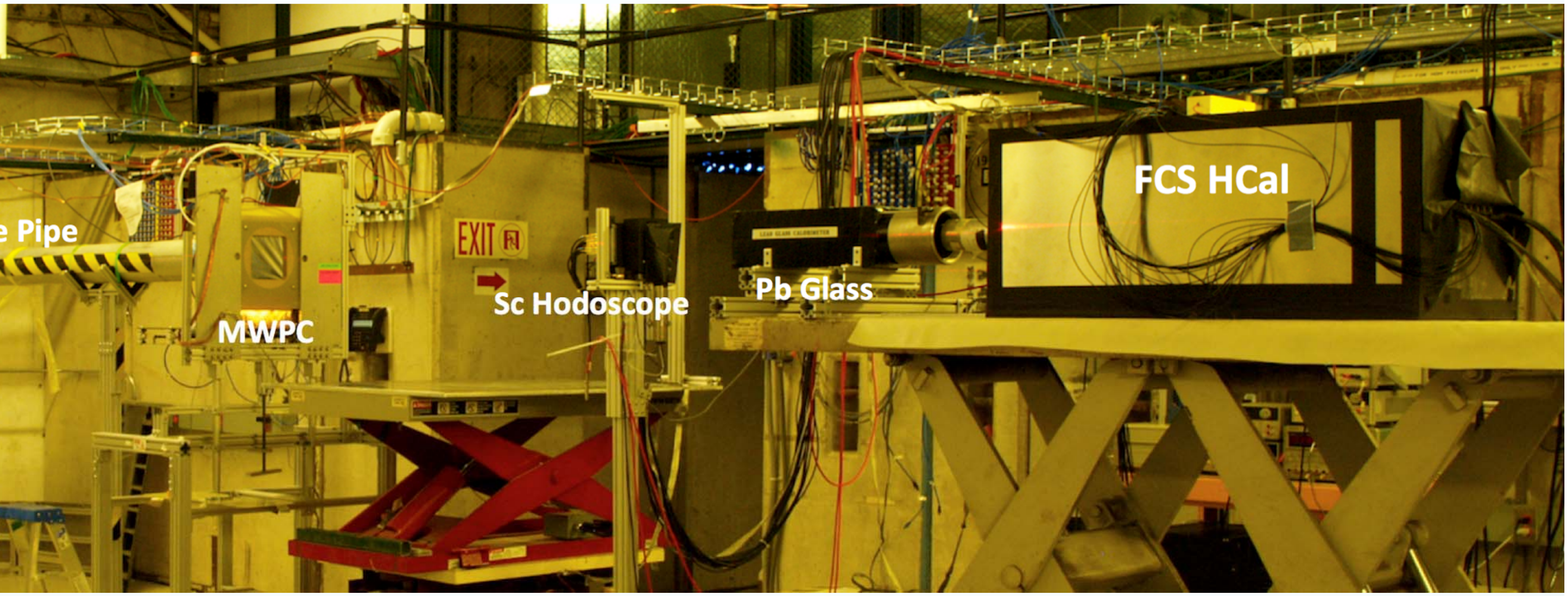
Hadronic calorimeter is a sandwich Pb scintillator plate sampling type

- **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



ested the response to hadrons, electrons and muons
- 3 < E < 32 GeV
- Successful test results from 2012

leally reconstructed $E = E_{EMCal} + E_{HCal}$

Vith E dependent weighting of E_{EMCal} energy measured

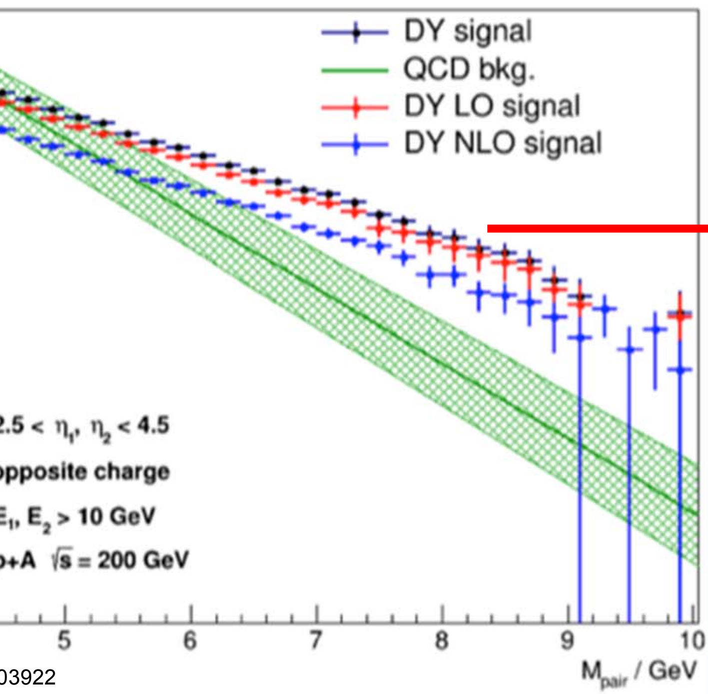
/h ratio ~0.95

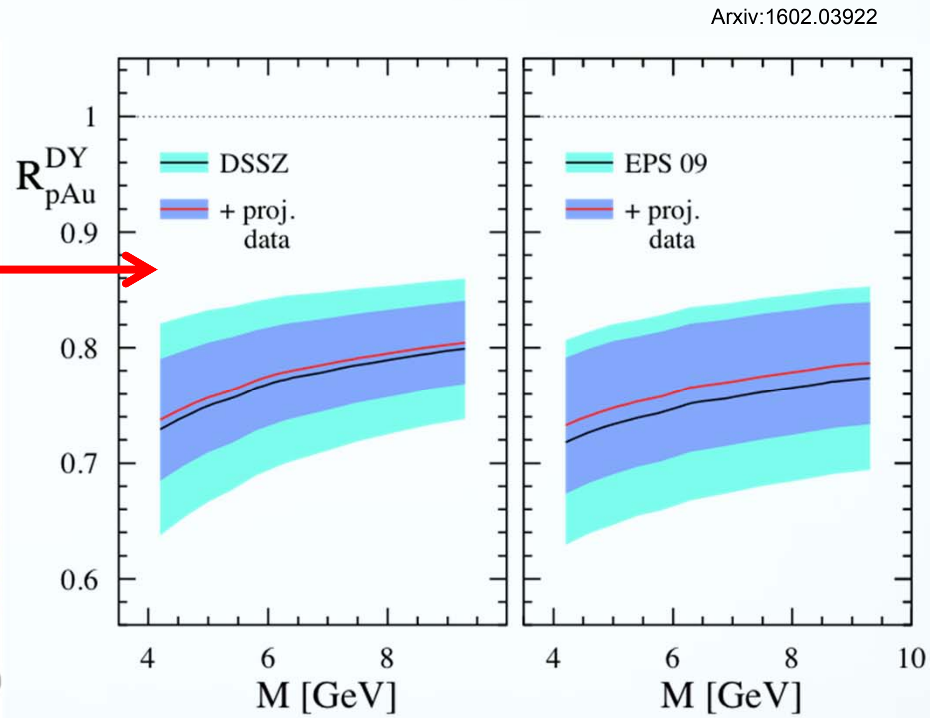
- Constant above 10 GeV

Forward Tracking System (FTS)

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

A dependence of nuclear PDFs

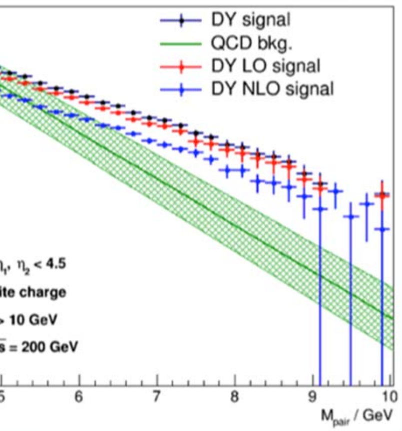


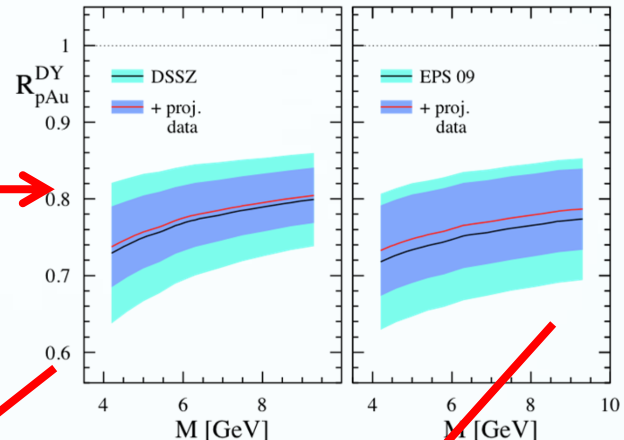


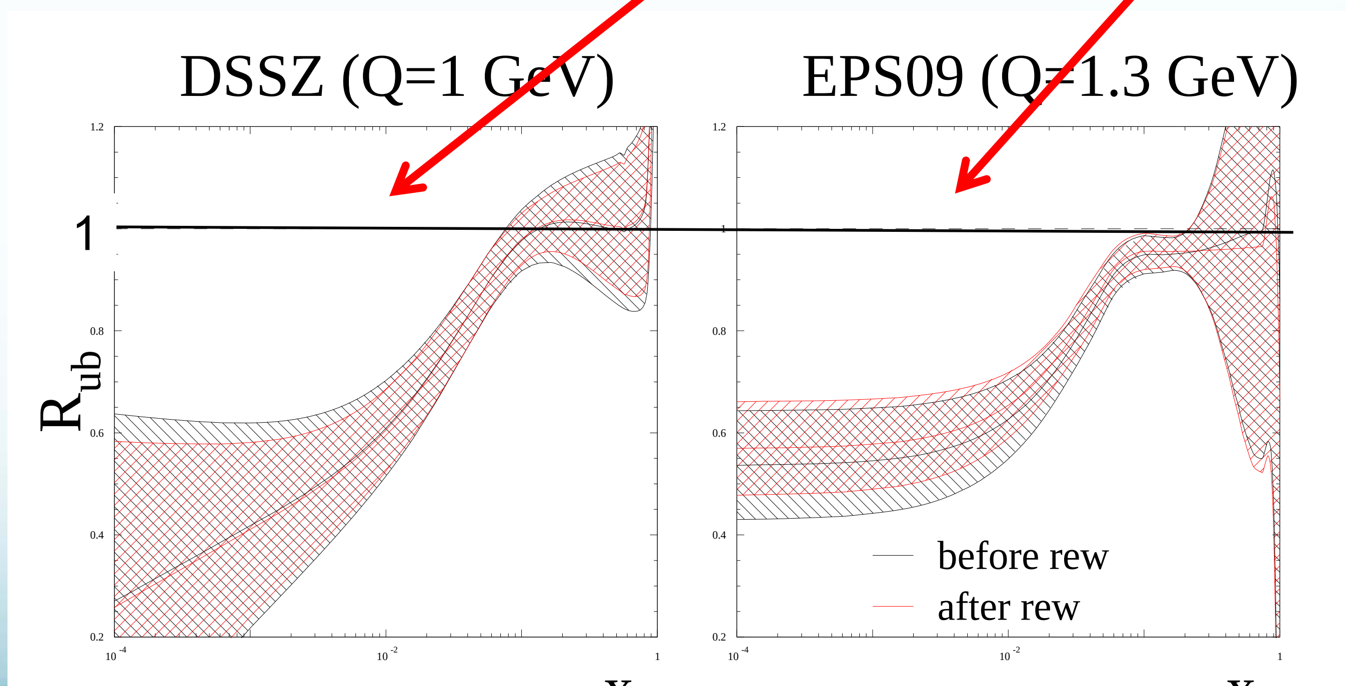
measurement:
llenge is to suppress
ronic background while
ntaining high electron
ciency

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







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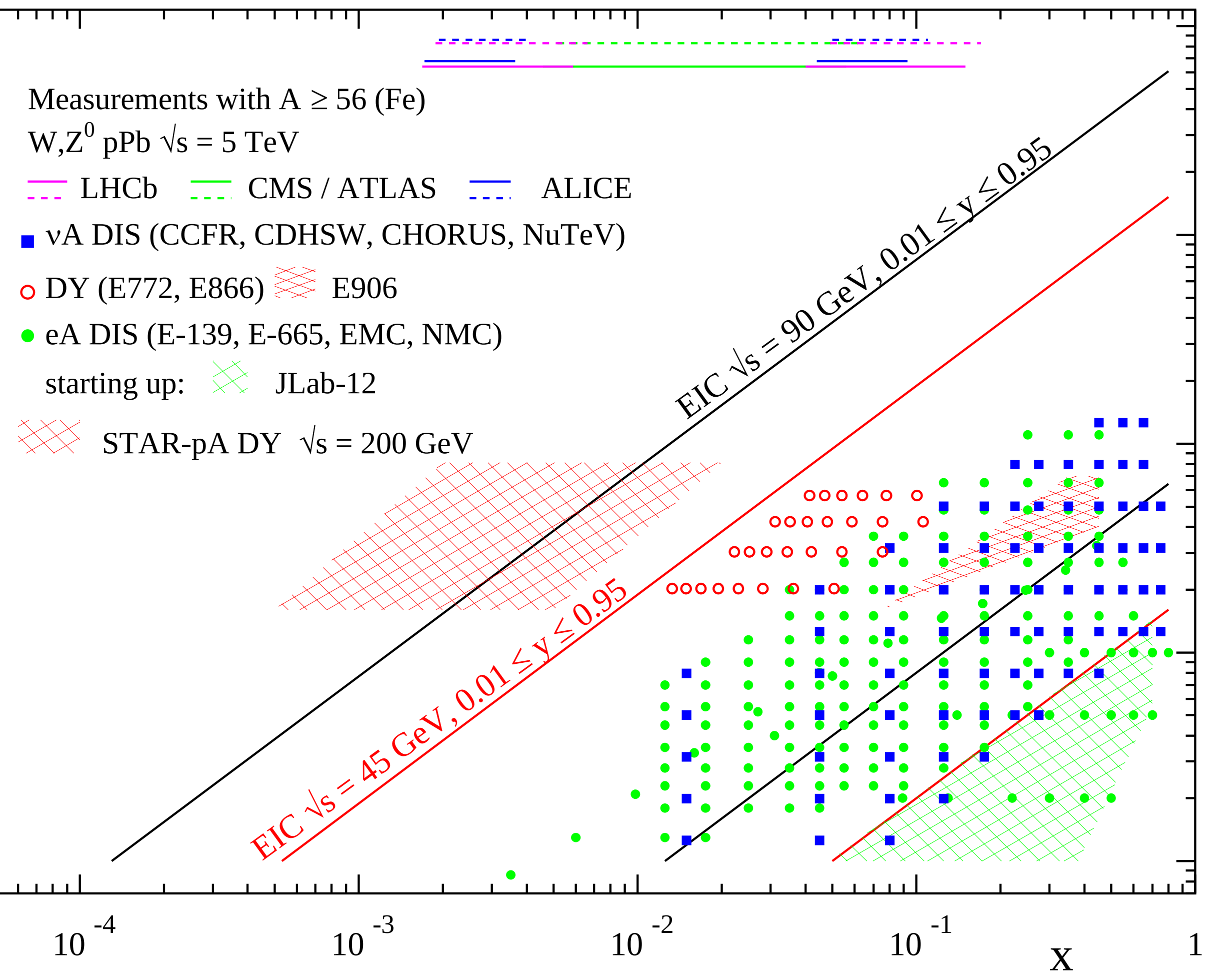
Kinematic Coverage in x–Q^2

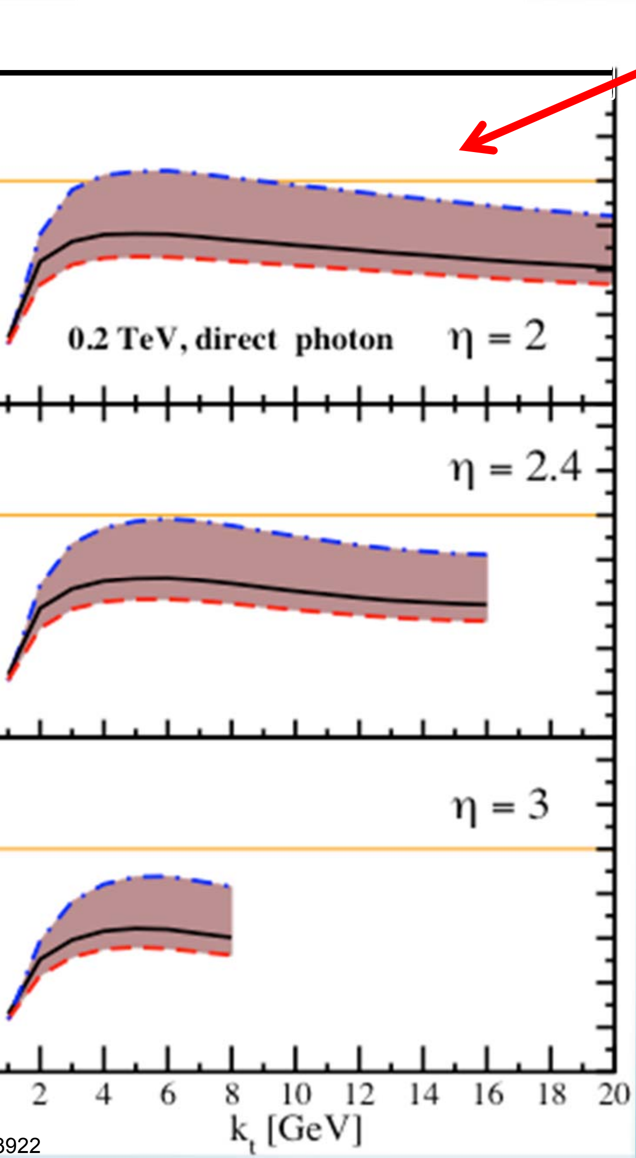
Past, Present, and Future Experiments Capabilities



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

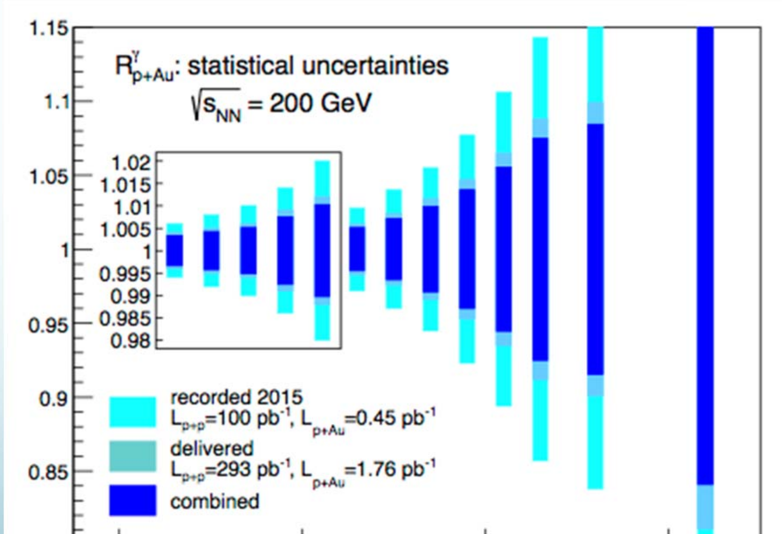
- Nuclear modifications already significantly reduced
- At intermediate Q^2, DY at RHIC will extend the low-x reach by nearly one decade compared to EIC

Gluon Saturation



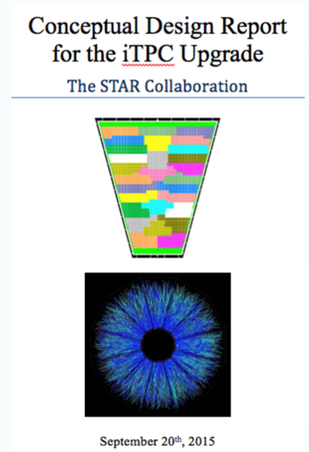
A: Q_{0A}^2 [GeV^2], p: Q_{0p}^2 [GeV^2]
A: 0.67, p: 0.168
A: 0.50, p: 0.168
A: 0.60, p: 0.20

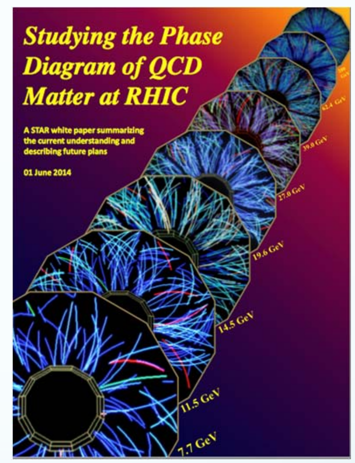
- Measurements so far in p(d)+A collisions have strongly interacting initial+ final states
  - Complicates theoretical treatment
- Remove final state strong interaction by using γ and DY electrons

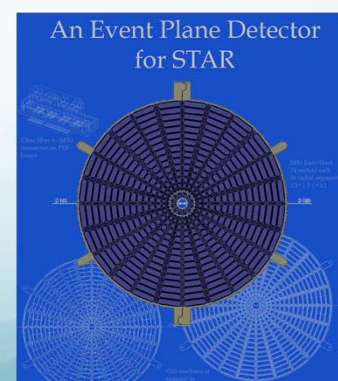


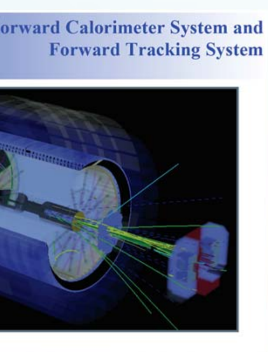
Summary

- 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





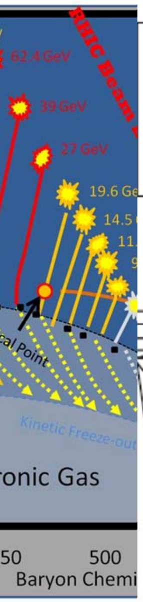


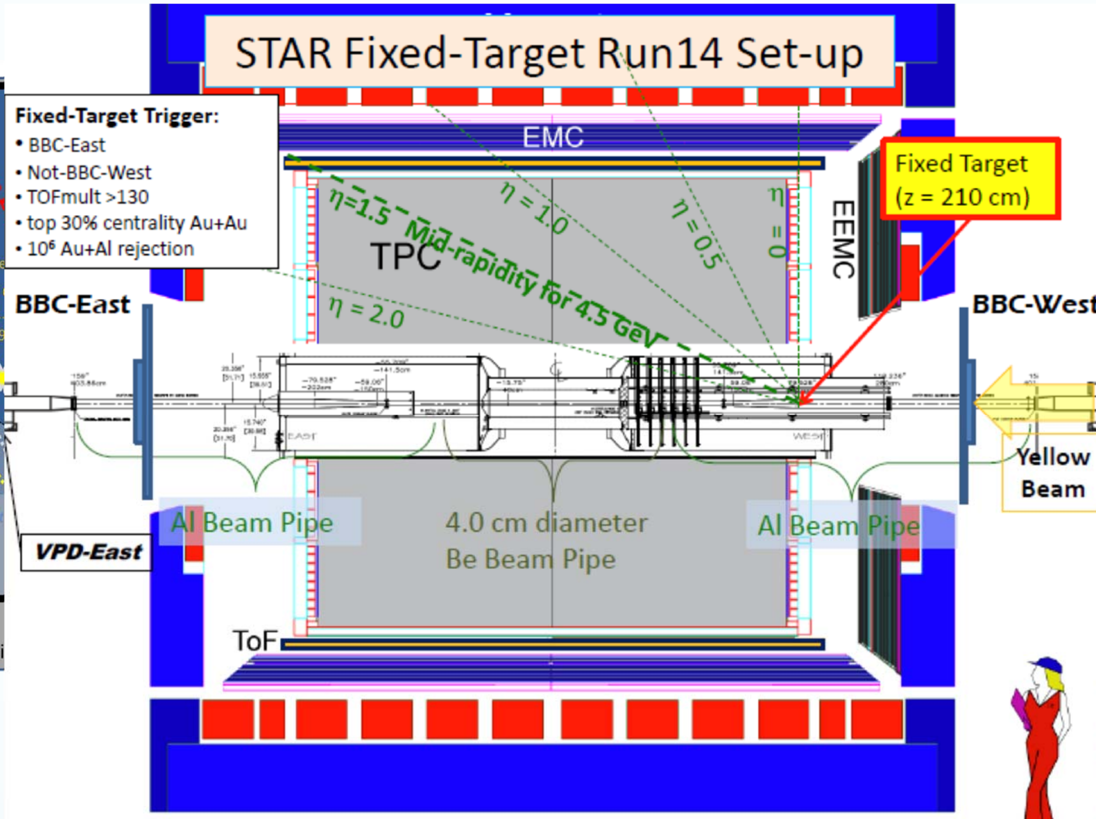


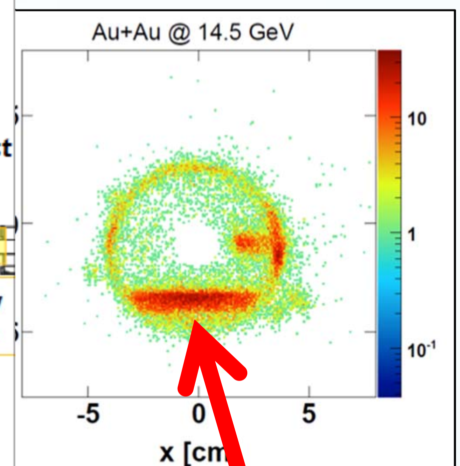
Back up

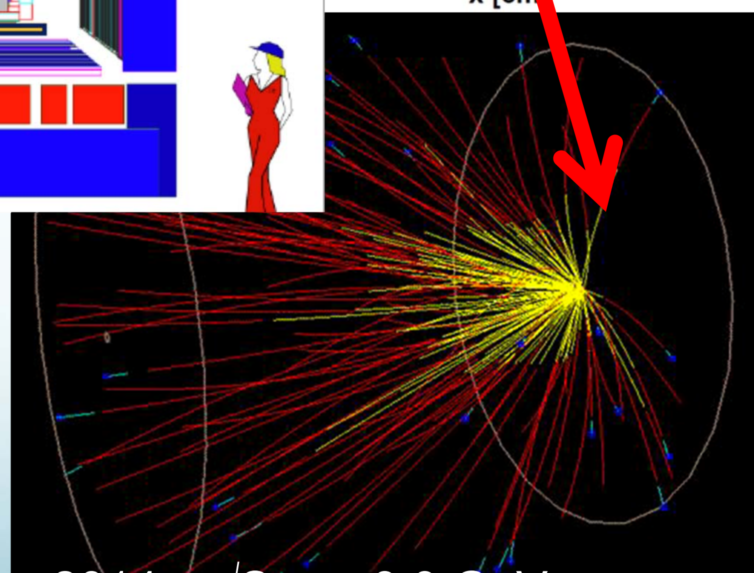
BES-I → BES-II

See Kathryn Meehan's talk on Tuesday!



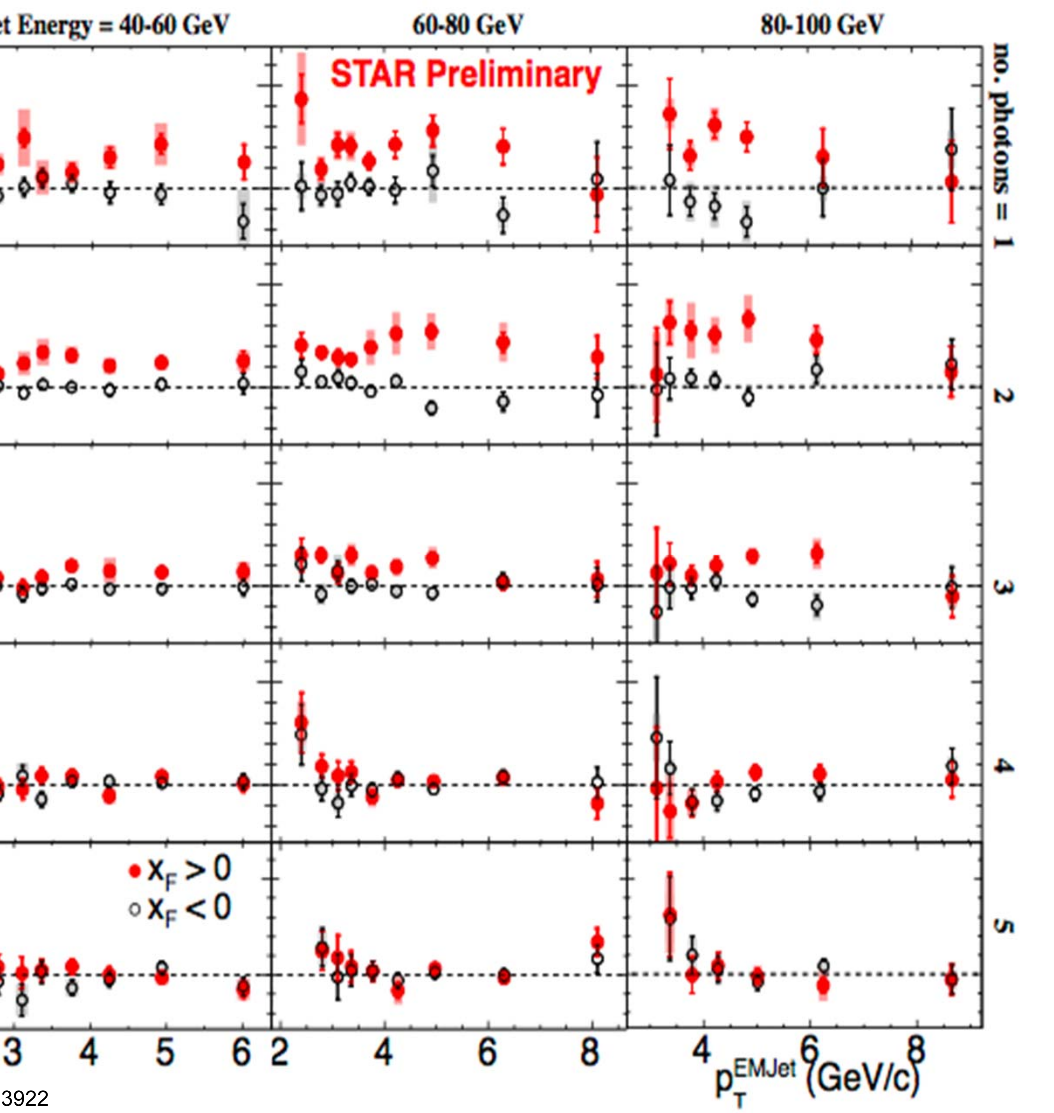






- et inserted into beam pipe
- run done parasitically
- lo interference w/collider mode data
- More efficient →small dedicated runs

Single Spin Asymmetries



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

FTS allows π^+/π^-

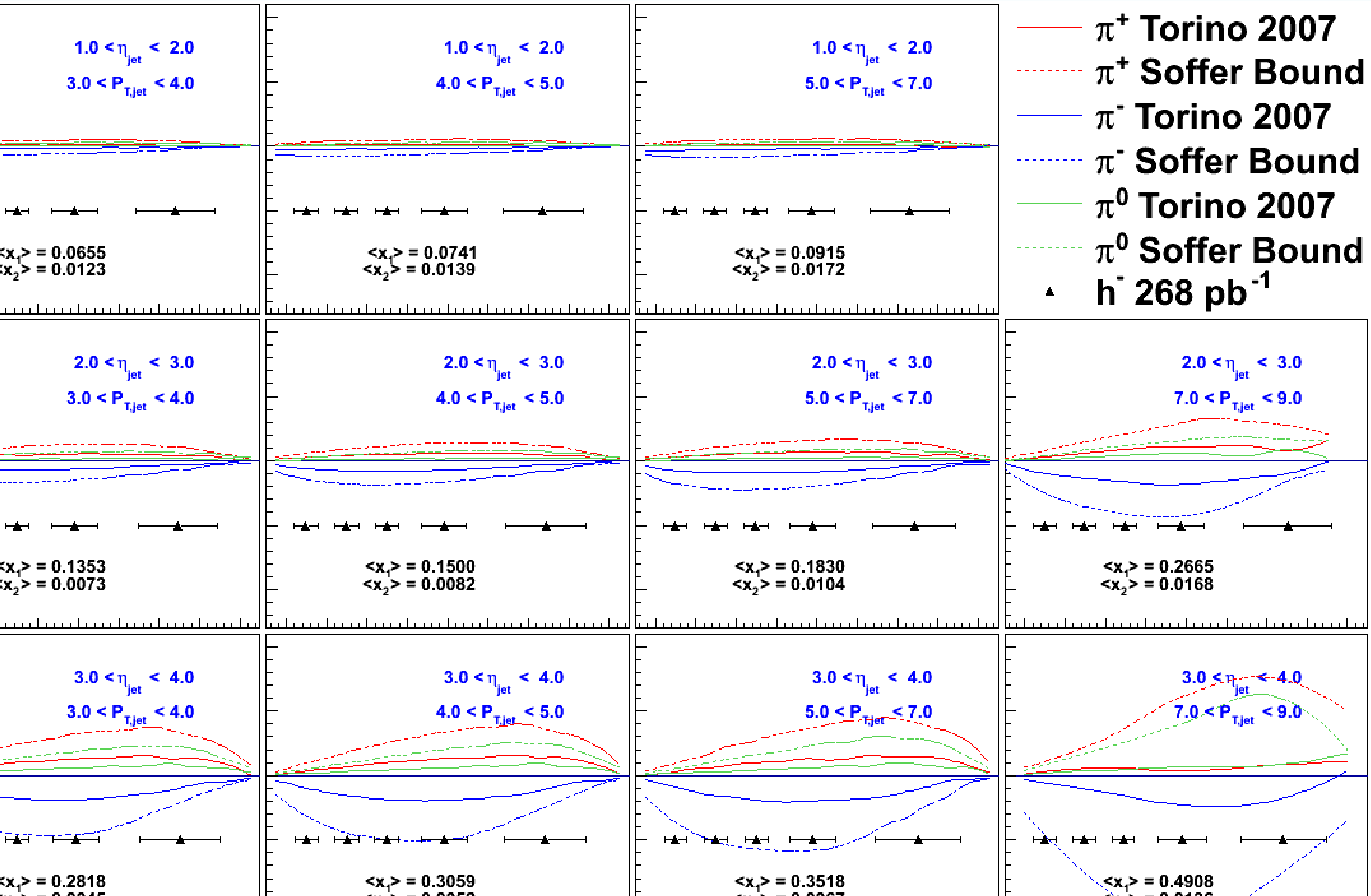
Calorimeters only allow π^0

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

Results show the process is not 2-2

- Diffraction?

Collins

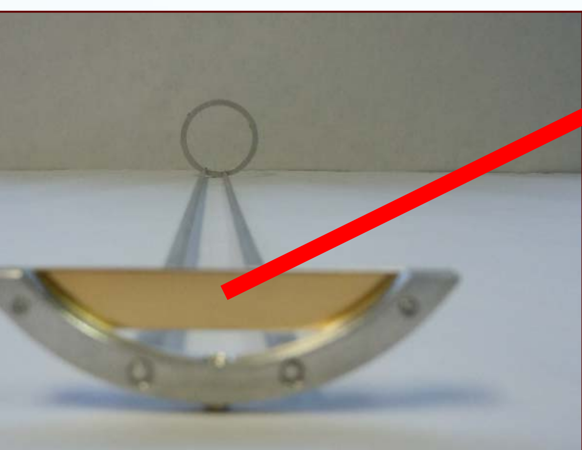


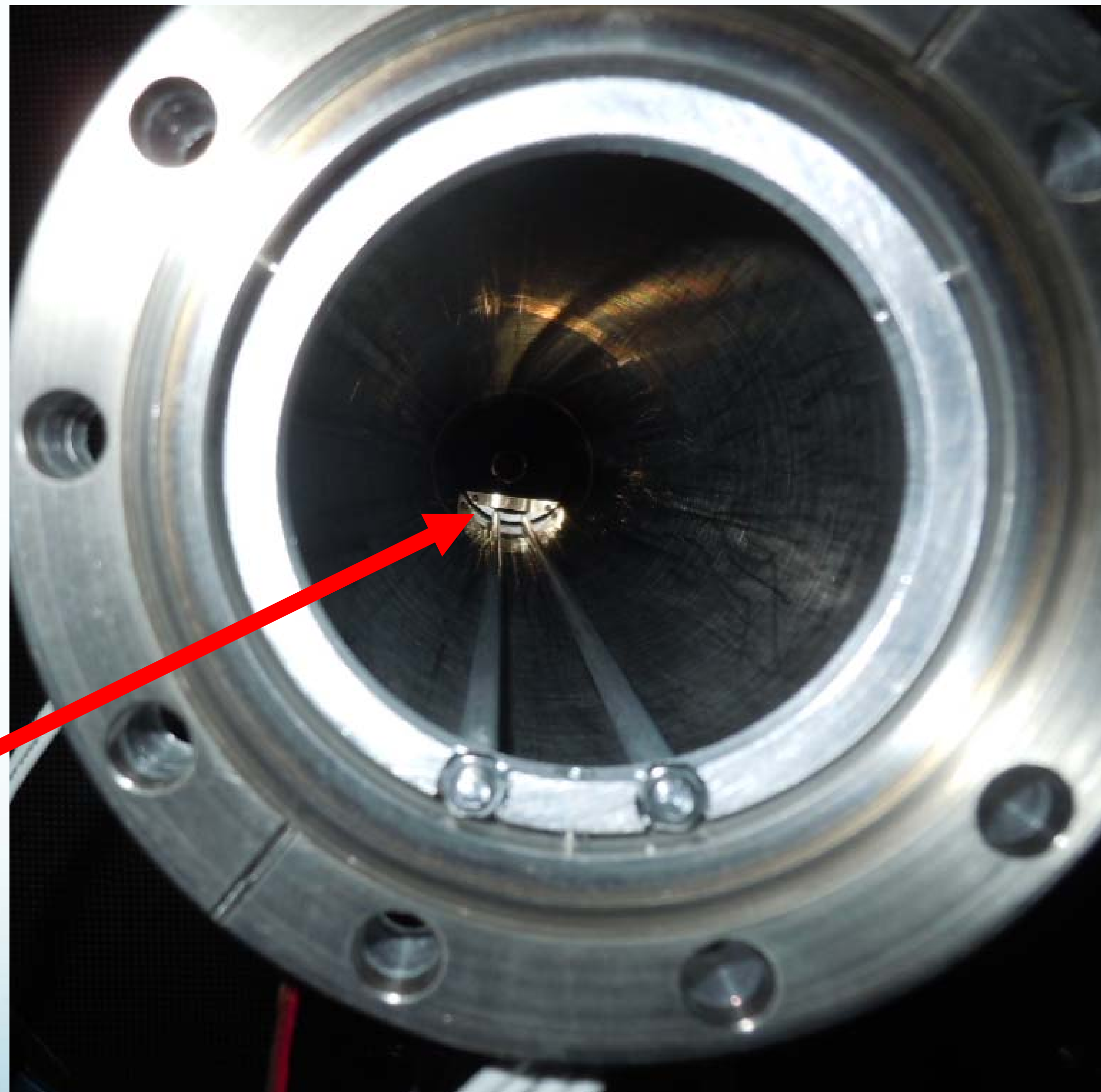
π+ Torino 2007
π+ Soffer Bound
π- Torino 2007
π- Soffer Bound
π0 Torino 2007
π0 Soffer Bound
h- 268 pb-1
1.0 < η jet < 2.0
3.0 < P T,jet < 4.0
<x1> = 0.0655
<x2> = 0.0123
1.0 < η jet < 2.0
4.0 < P T,jet < 5.0
<x1> = 0.0741
<x2> = 0.0139
1.0 < η jet < 2.0
5.0 < P T,jet < 7.0
<x1> = 0.0915
<x2> = 0.0172
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
3.0 < η jet < 4.0
4.0 < P T,jet < 5.0
<x1> = 0.3059
3.0 < η jet < 4.0
5.0 < P T,jet < 7.0
<x1> = 0.3518
3.0 < η jet < 4.0
7.0 < P T,jet < 9.0
<x1> = 0.4908

Target Design 2014 and 2015
remove

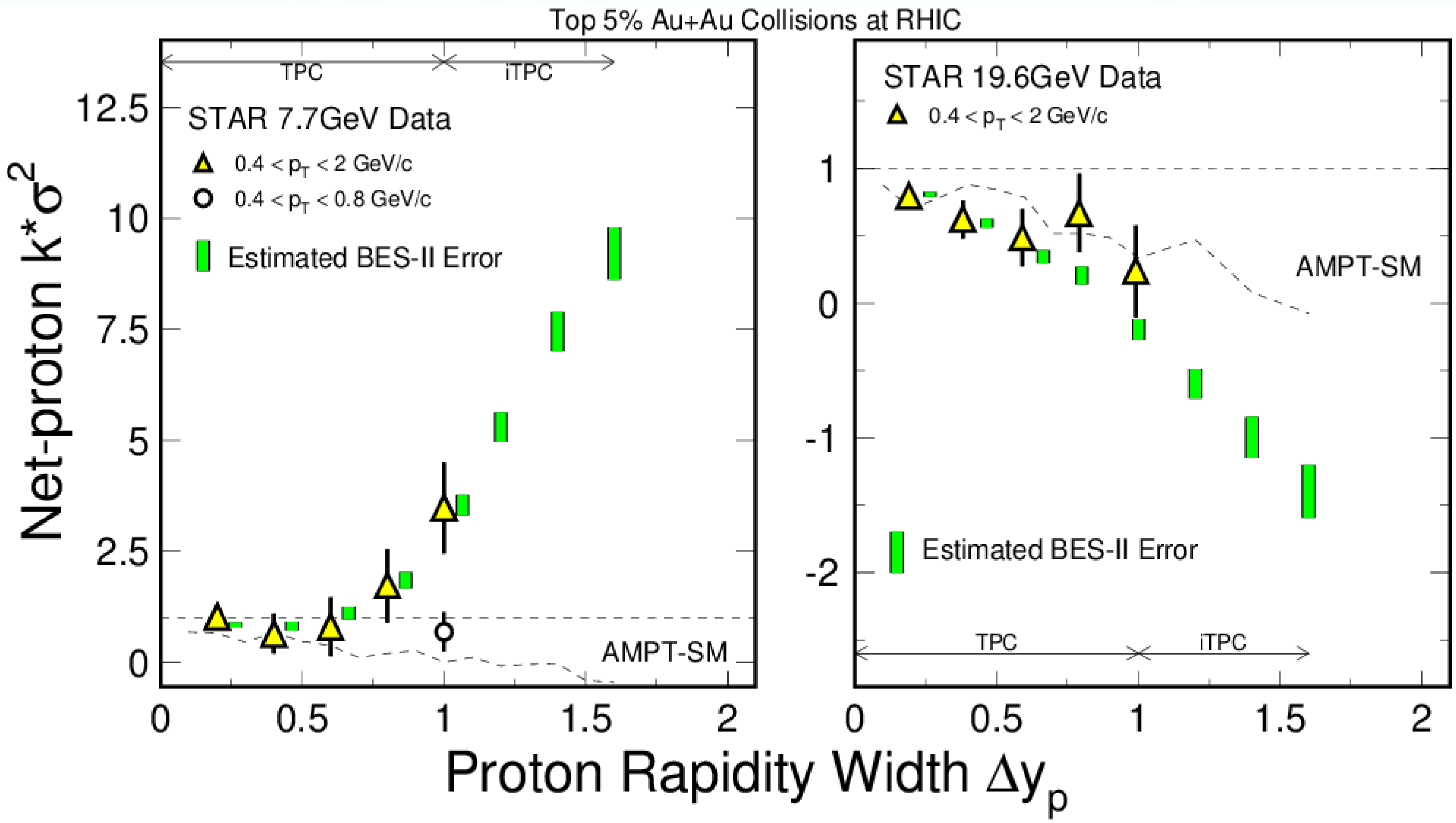
get design:

- old foil
- mm Thick
- 1 cm High
- 4 cm Wide
- 10 cm from IR





Net-proton cumulants in BES-II



S-I has revealed a non-trivial energy dependence
pidity length of the correlation is important

asure as function of Δy_p in wide range is needed to
ablish true nature of correlation → iTPC

Planned BES II Measures

ollision Energies (GeV):	7.7	9.1	11.5	14.5	19.6
hemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
bservables	Millions of Events Needed				
$_{CP}$ up to p_T 4.5 GeV	NA	NA	160	92	22
lliptic Flow of ϕ meson (v_2)	100	150	200	300	400
ocal Parity Violation (CME)	50	50	50	50	50
irected Flow studies (v_1)	50	75	100	100	200
sHBT (proton-proton)	35	40	50	65	80
et-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
ileptons	100	160	230	300	400
roposed Number of vents:	**100**	**160**	**230**	**300**	**400**

ES Phase I – What have We Learned

he BES at RHIC spans a range of μ_B that could contain features of the
D phase diagram.

ignatures consistent with a parton dominated regime either disappear,
e significance, or lose sufficient reach at the low energy region of the
n.

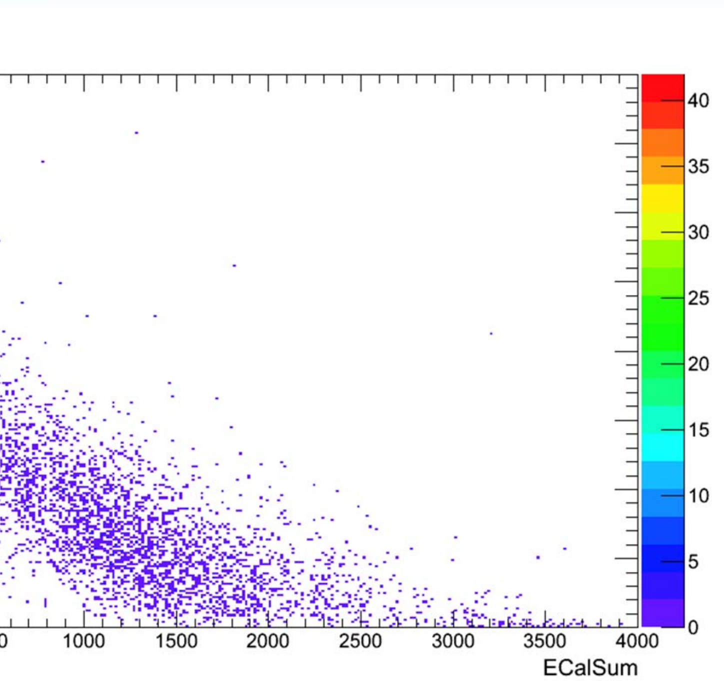
ilepton mass spectra show a broadening consistent with models
uding hadron gas and quark-gluon plasma components

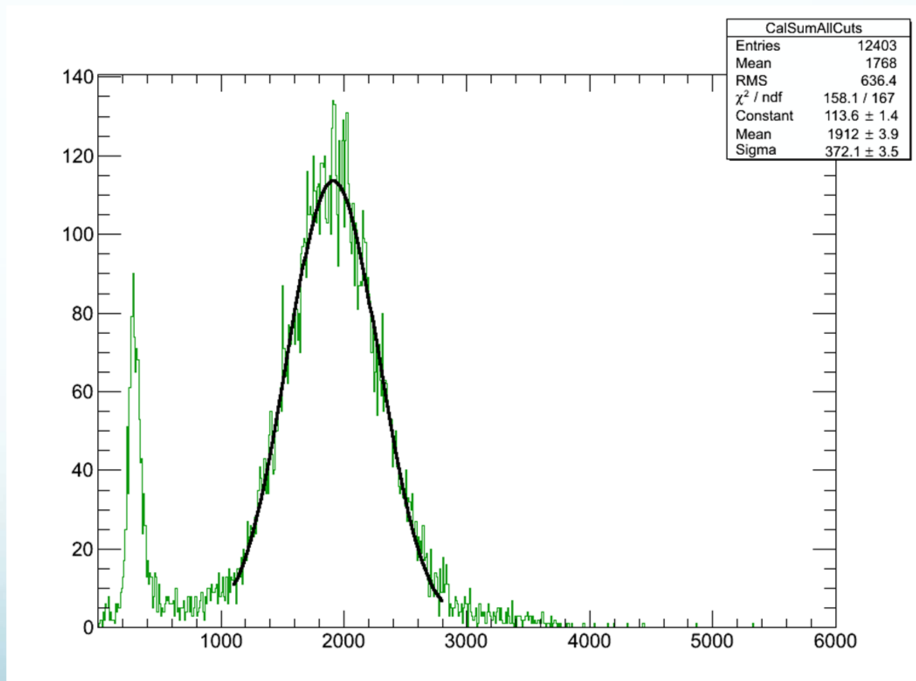
here are indicators pointing towards a softening of the equation of state
ch can be interpreted as evidence for a first order phase transition.

he higher moment fluctuation is sensitive to critical phenomena, but
se analyses place stringent demands on the statistics.

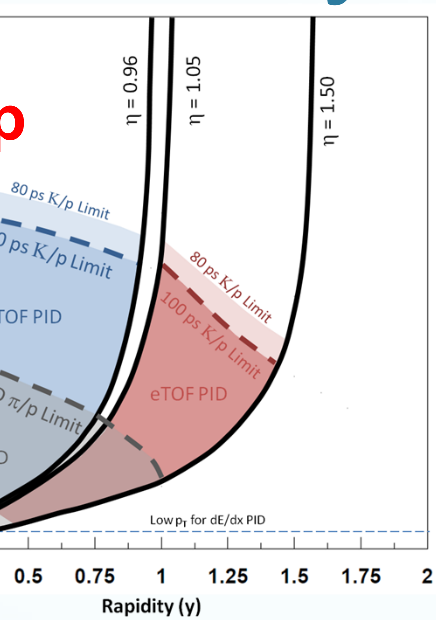
Response of the FCS prototype module to hadrons

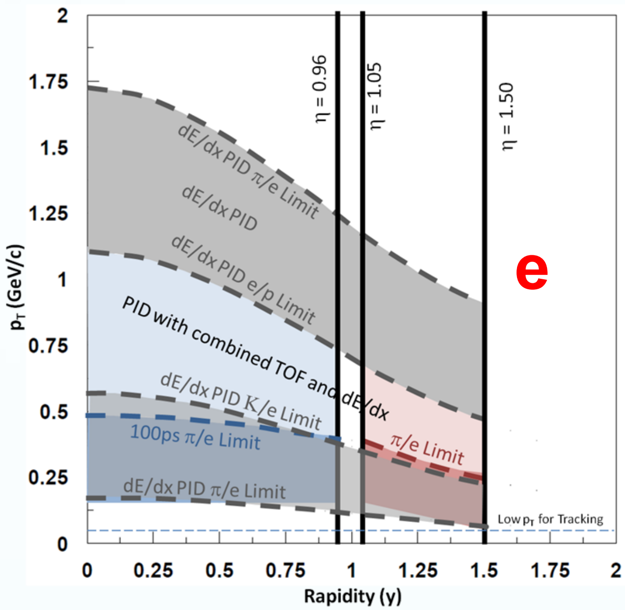
nergy deposition in HCal section (Y-axis) vs energy
eposition in EMCal section (X-axis) for 12 GeV hadrons
eft panel). A weighted sum of the energy deposited in
MCal and HCal section for 12 GeV hadrons (right
anel).

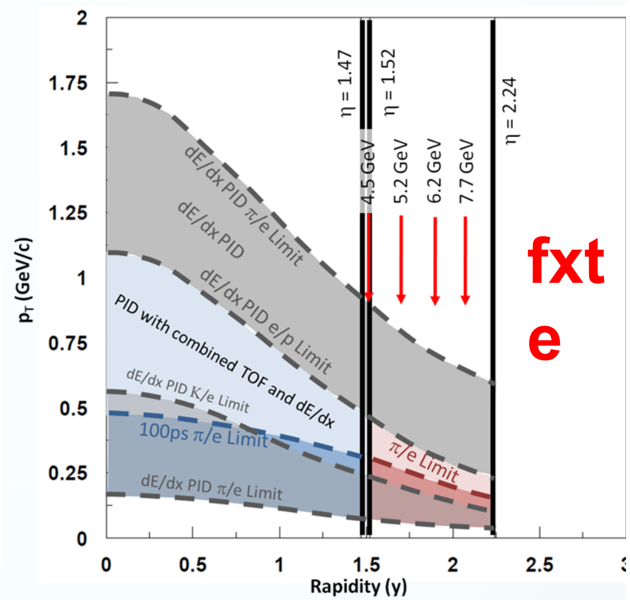


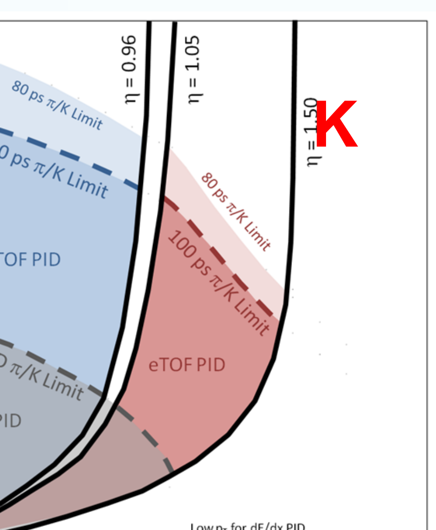


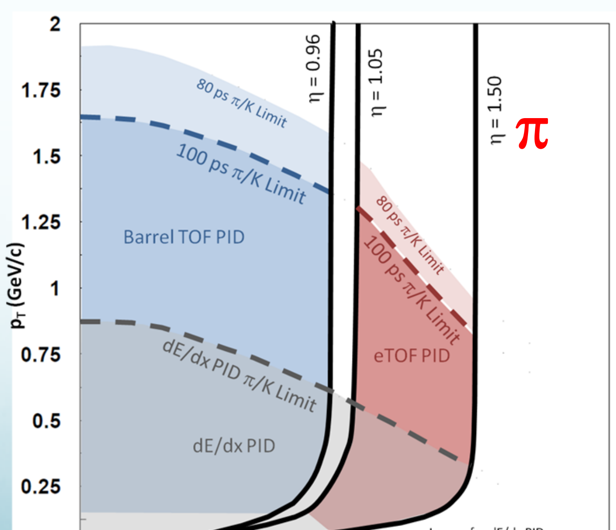
y – p_T Map Colider











Low Energy Electron Cooling at RHIC

rove
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energy
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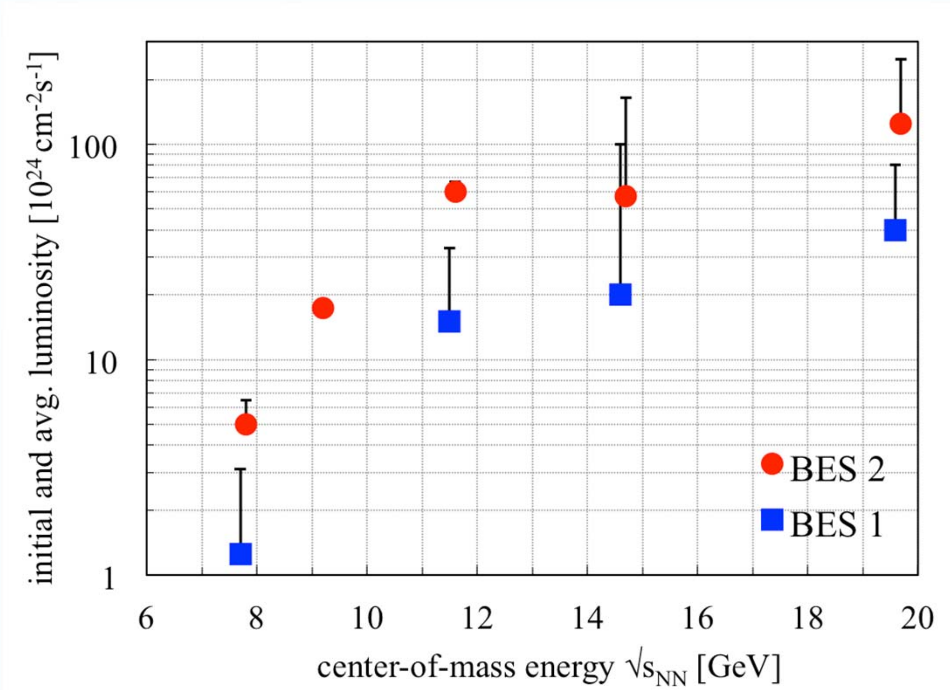
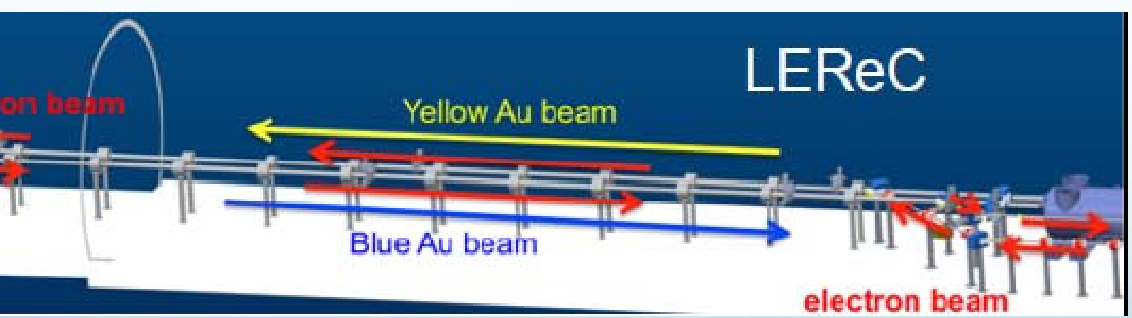
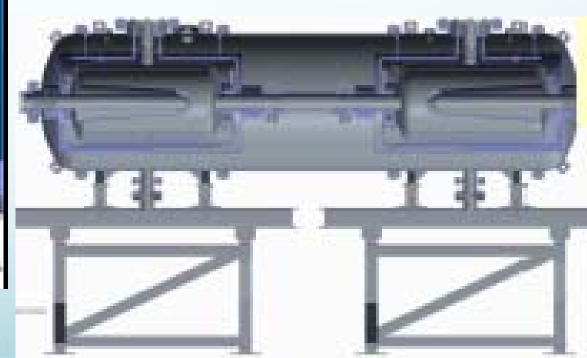


- Start with 14.5 and 19,6 3X improvement
- Following year, 7.7, 9.1, and 11.5. 4X improvement with eCooling
- Run 24 weeks



m IP2

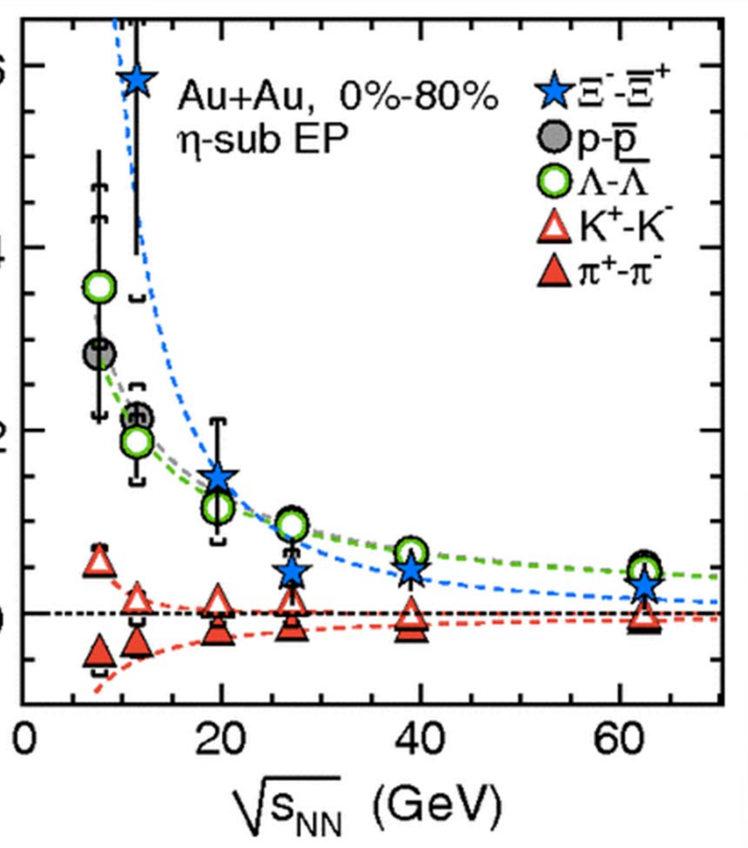
100 MHz SRF Gun



STAR BES-I

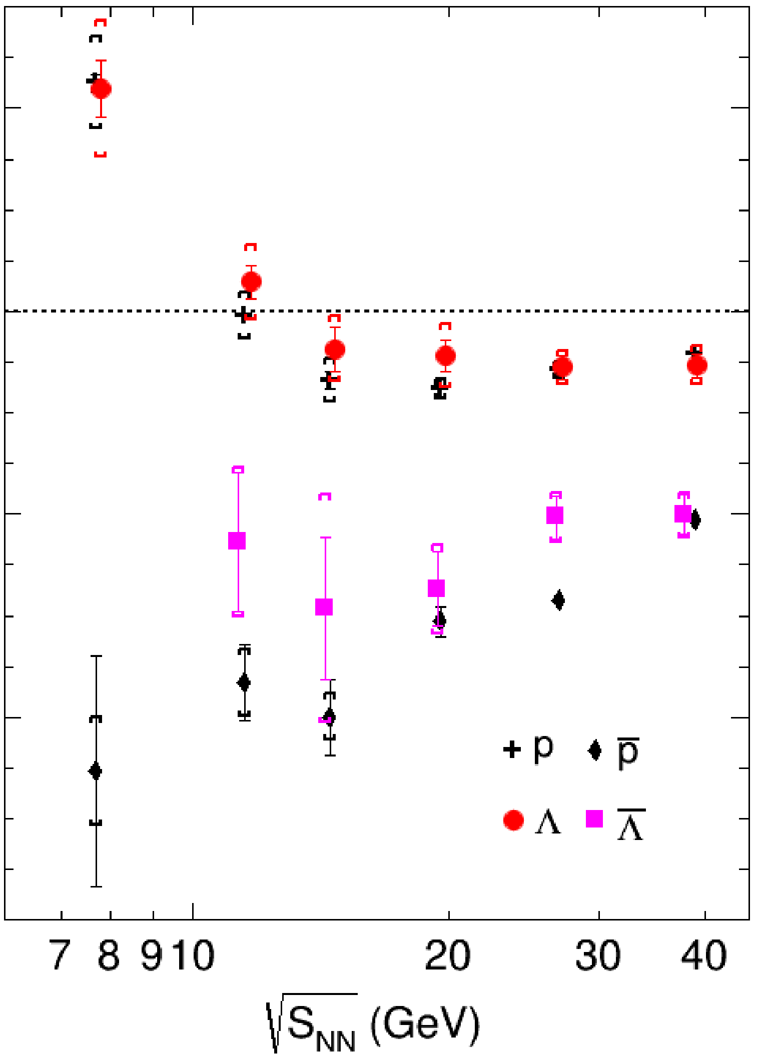
Turn-off of sQGP signatures

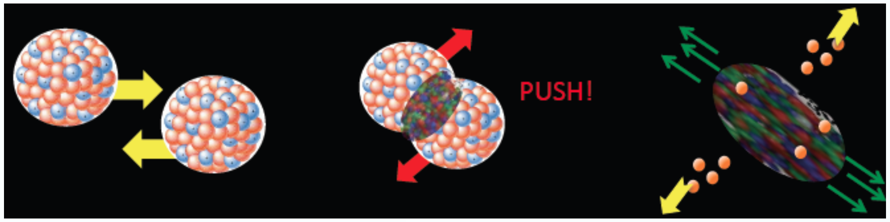
Phys.Rev.Lett. 110 (2013) 142301



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

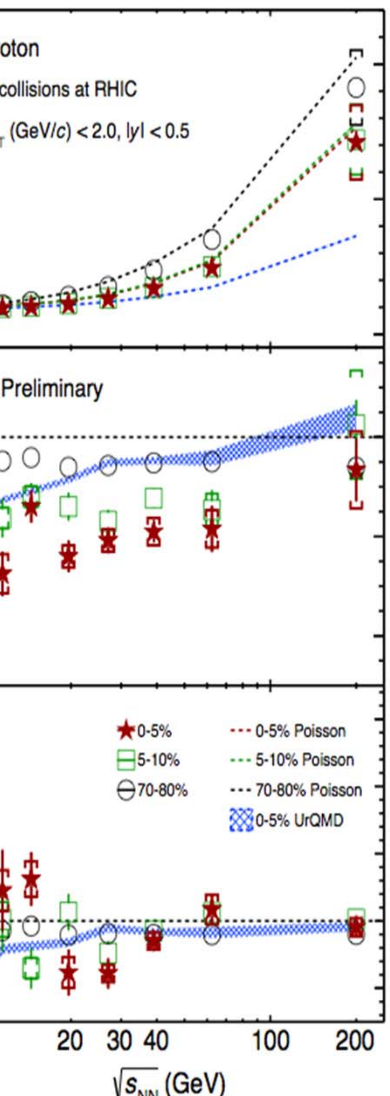
Search for Phase Transition : directed flow





- 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

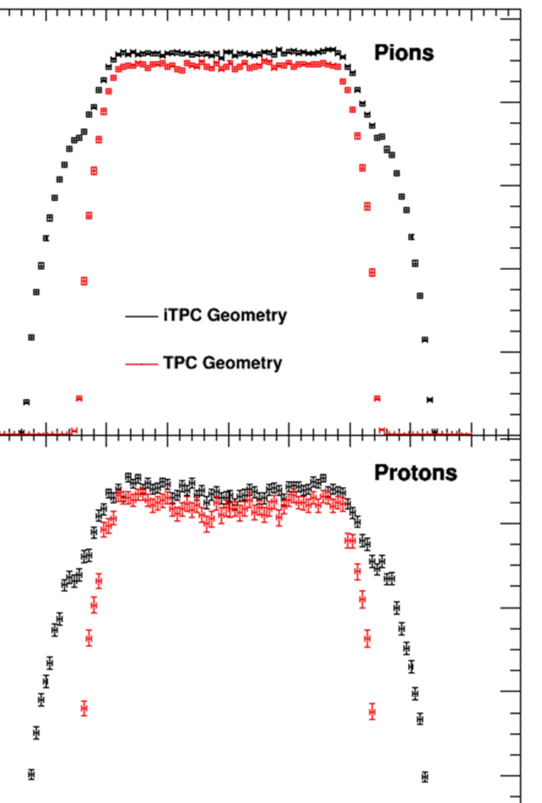


- Looking for fluctuation in S and κ
- σ2/M increases with increasing energy, consistent with Poisson expectation
- Non-monotonic behavior of net-proton κσ2 seen in top 5% central collisions
- Peripheral collisions show smooth trend
- UrQMD (no Critical Point), shows suppression at lower energies - due to baryon number conservation
- Uncertainties requires better measurements – motivation for BES II

iTPC Improved performance

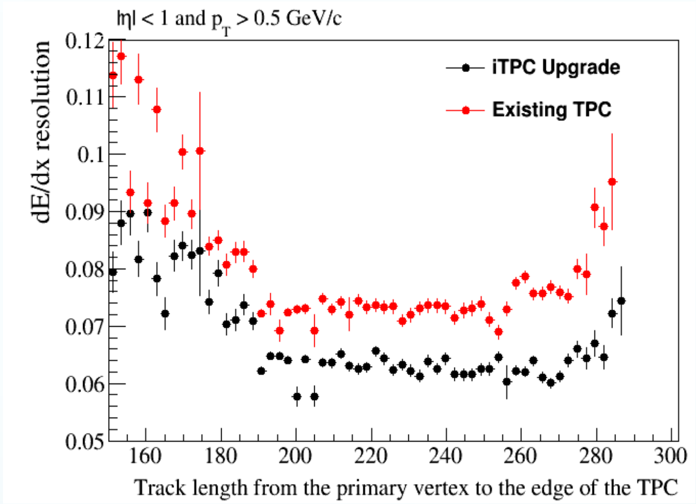
se rapidity coverage |η| < 1 to
5

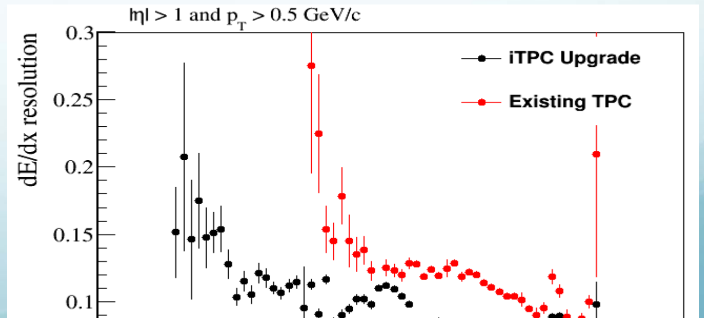
sed efficiency for |η| >1 both in
particle specieS



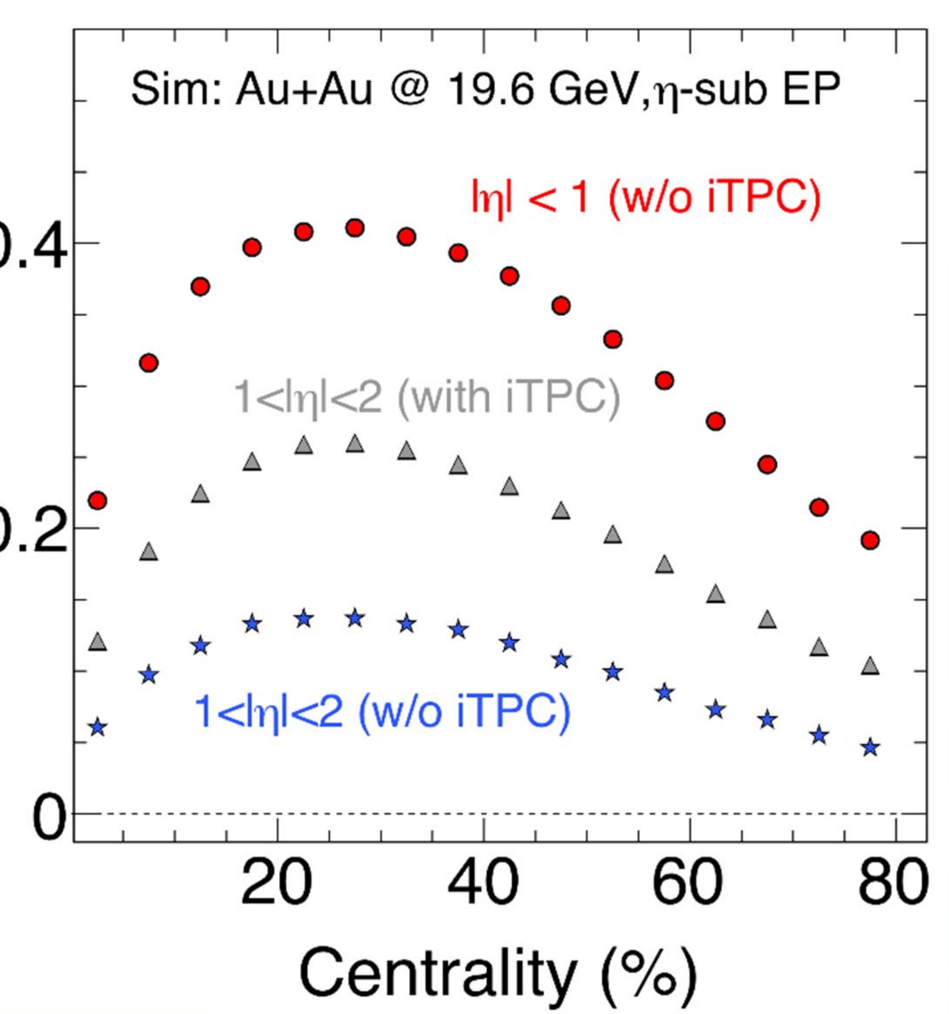
Improved dE/dx

7.5->6.2%



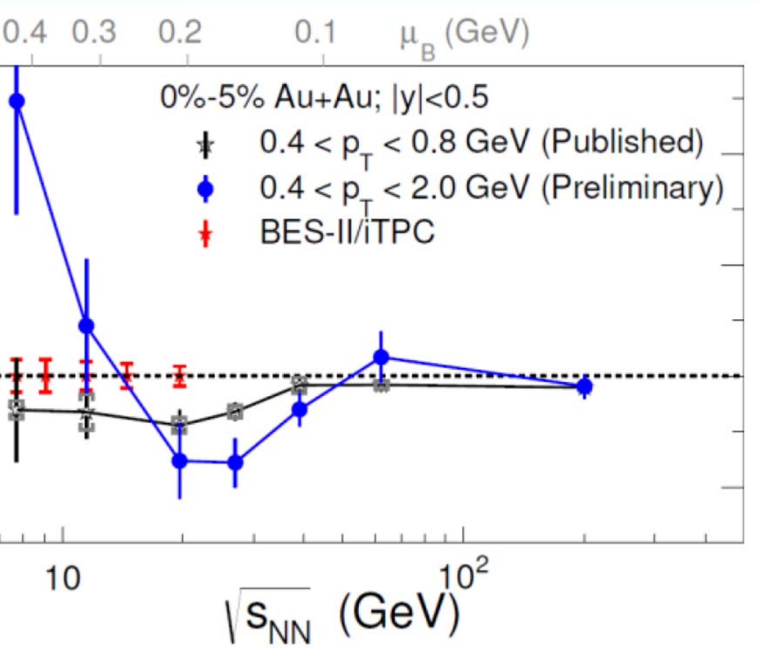


iTPC

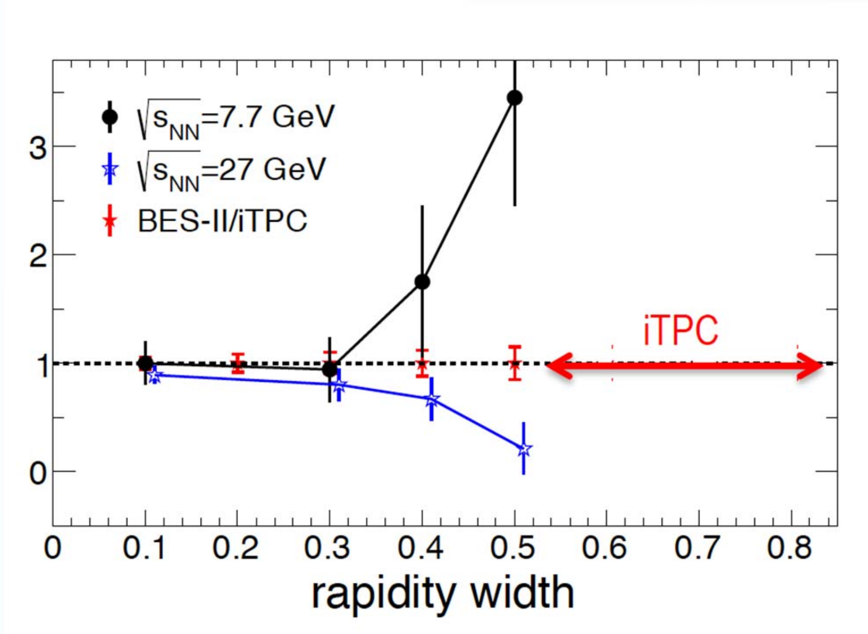


Sim: Au+Au @ 19.6 GeV,η-sub EP
|η| < 1 (w/o iTPC)
1<|η|<2 (with iTPC)
1<|η|<2 (w/o iTPC)
0.4
0.2
0
20
40
60
80
Centrality (%)

iTPC



0.4 0.3 0.2 0.1 μ_B (GeV)
0%-5% Au+Au; |y|<0.5
0.4 < p_T < 0.8 GeV (Published)
0.4 < p_T < 2.0 GeV (Preliminary)
BES-II/iTPC
10
10^2
$\sqrt{s_{NN}}$ (GeV)



$\sqrt{s_{NN}}$=7.7 GeV
$\sqrt{s_{NN}}$=27 GeV
BES-II/iTPC
iTPC
0 1 2 3
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
rapidity width

BES-I White paper