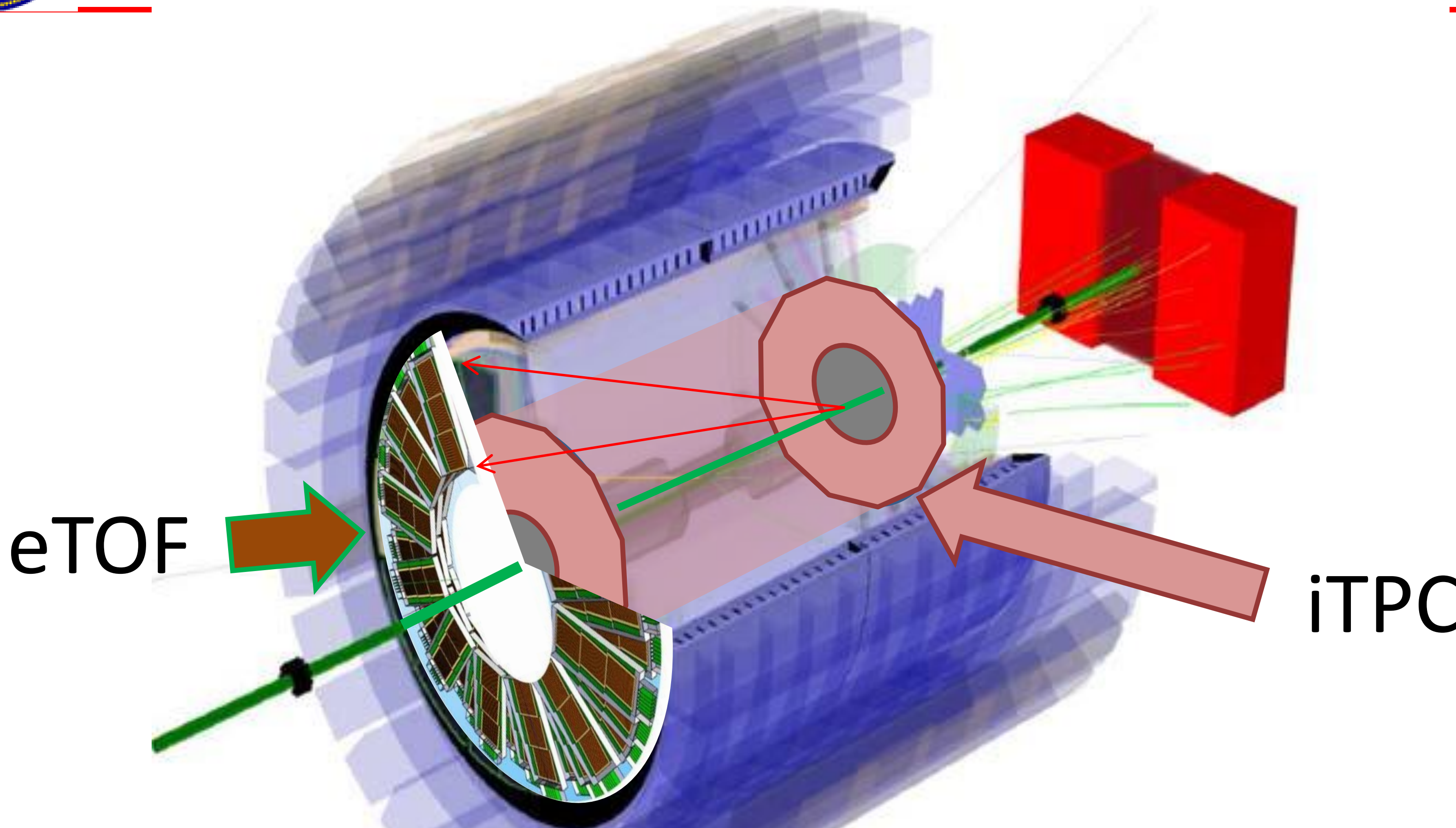
Fixed Target Physics in BES II with Detector Upgrades



Daniel Cebra
University of California - Davis

RHIC Runs at or Below Nominal Injection Energy:

1. Au+Au 19.6 GeV 2001	100 k events
2. Cu+Cu 22.4 GeV 2005	250 k events
3. Au+Au 9.0 GeV 2007	0 events
4. Au+Au 9.2 GeV 2008	7 k events
5. Au+Au 7.7 GeV 2010	4 M events
6. Au+Au 11.5 GeV 2010	12 M events
7. Au+Au 5.5 GeV 2010	0 events
8. Au+Au 19.6 GeV 2011	36 M events
9. Au+Au 5.0 GeV 2011	1 event
10. Au+Au 14.5 GeV 2014	20 M events

History of Fixed-Target Analysis

- Analysis of the background triggers began in 2008.

- Developing the Beam Energy Scan I Proposal ➔ could not afford to seriously miscalculate the number events.

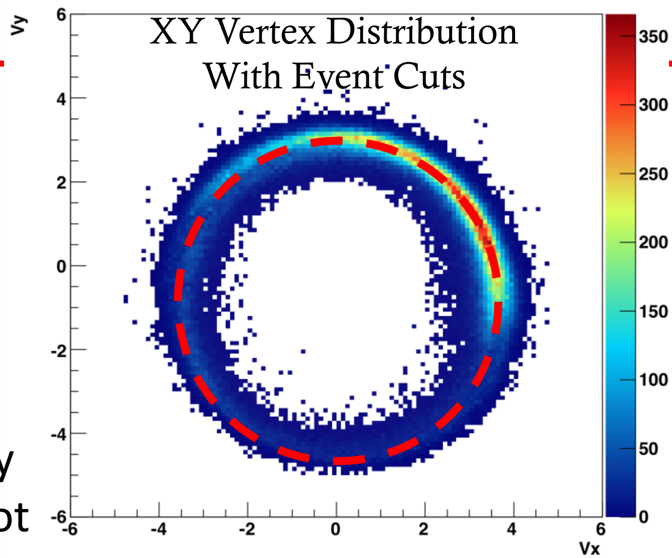
- Effort was aimed at understanding the background.

- Later realized we could develop a physics program.

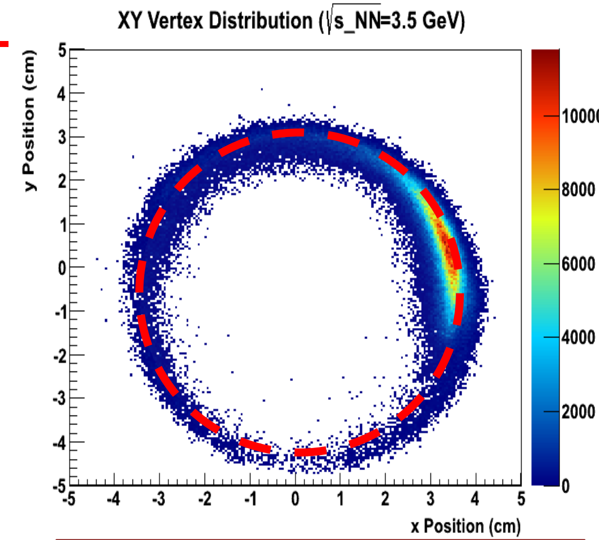
- In 2014, we installed an internal gold target.

- Parasitic tests in 2014. Directed beam tests in 2015.

7.7 GeV Au+Au (2010)

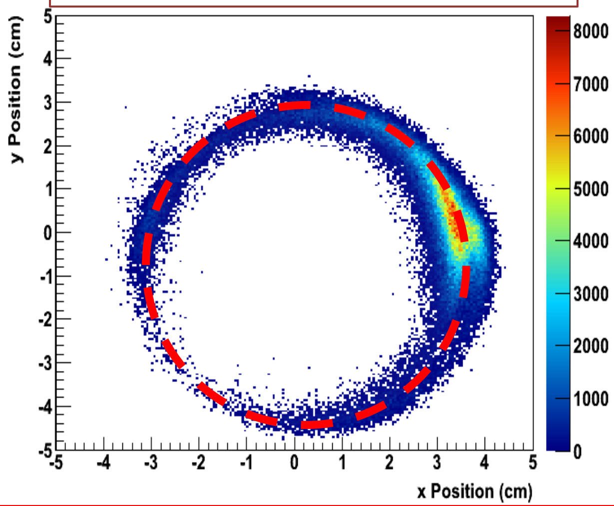


11.5 GeV Au+Au (2010)

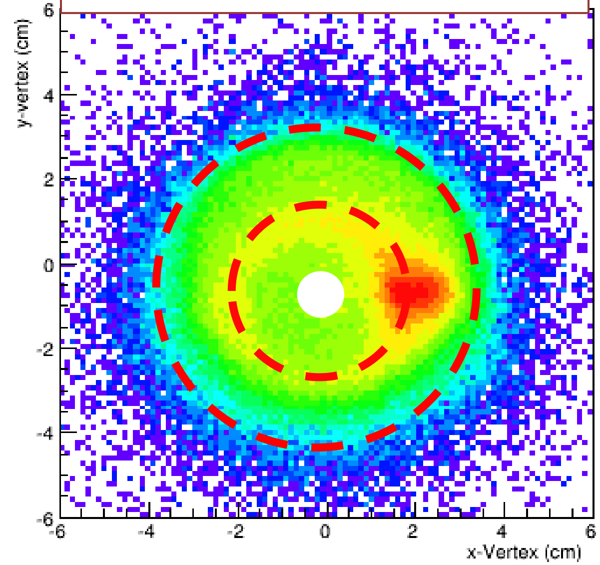


Note:
there is consistently a bright spot to the positive *x* value in the plane of the beam

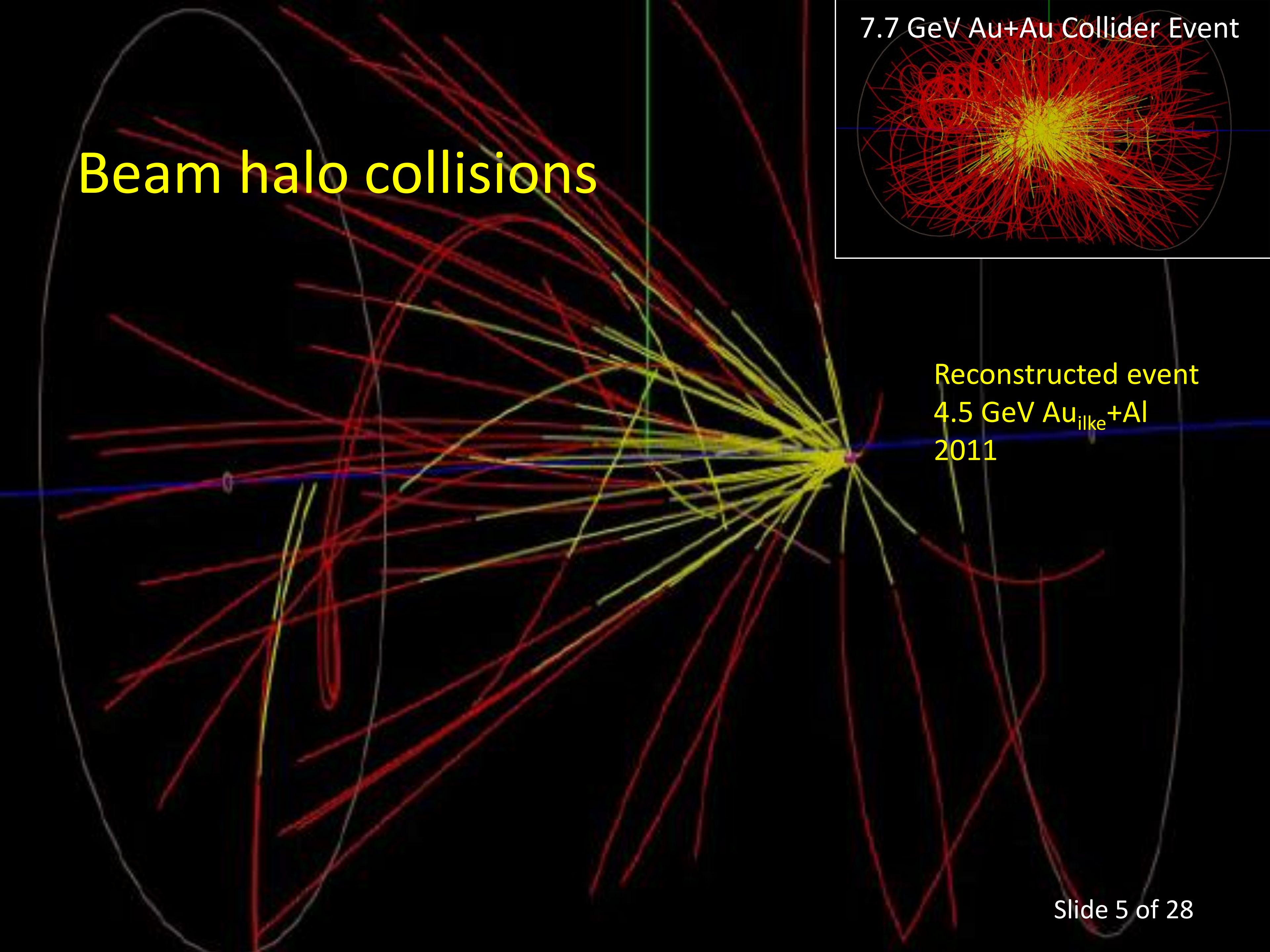
19.6 GeV Au+Au (2011)



14.5 GeV Au+Au (2014)

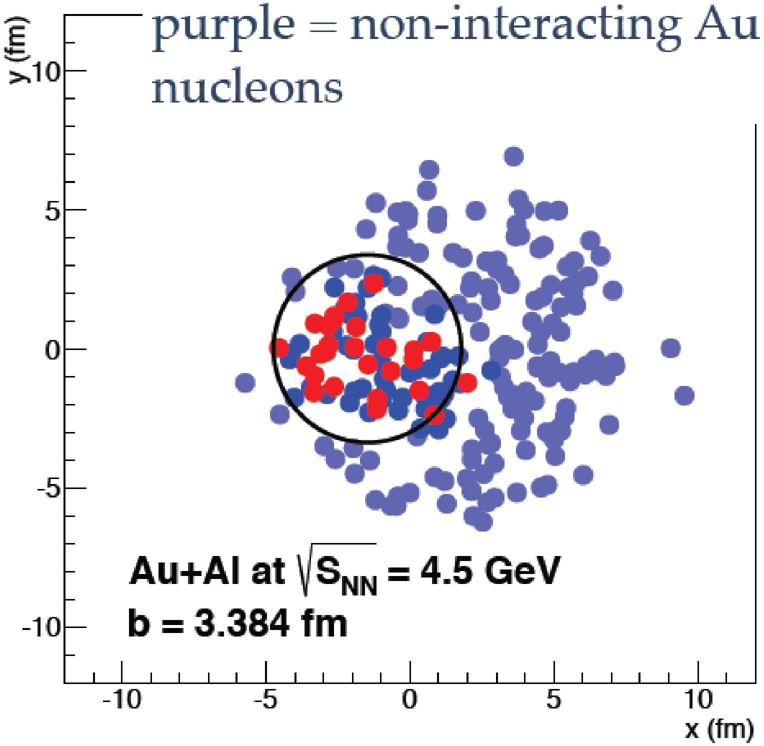


Beam halo collisions



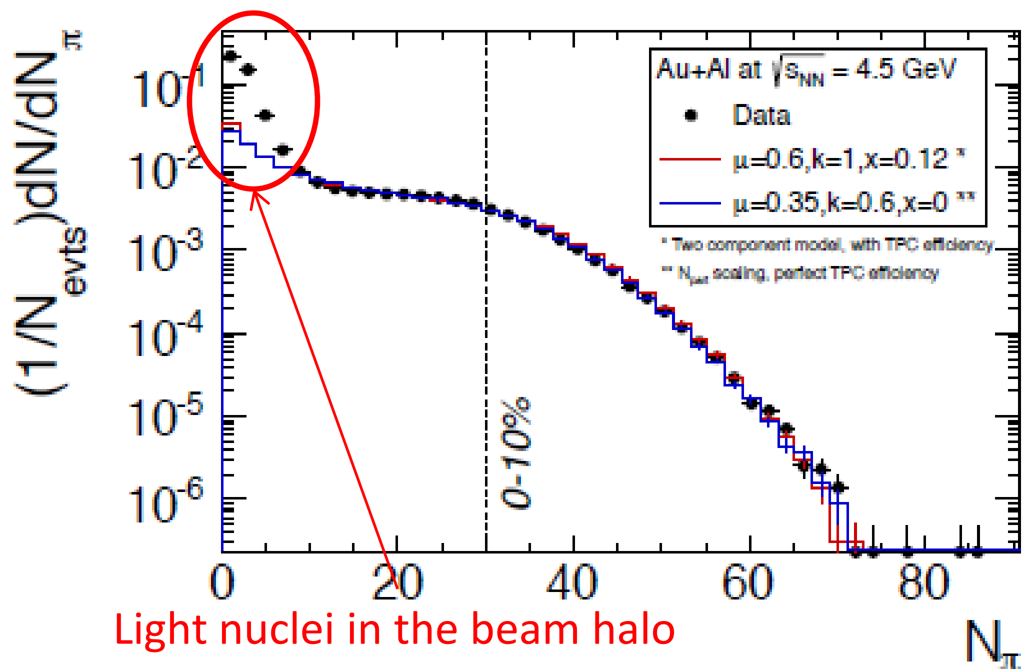
Glauber Model of Au+Al -- Centrality

red = interacting Al nucleons
blue = interacting Au nucleons
purple = non-interacting Au nucleons



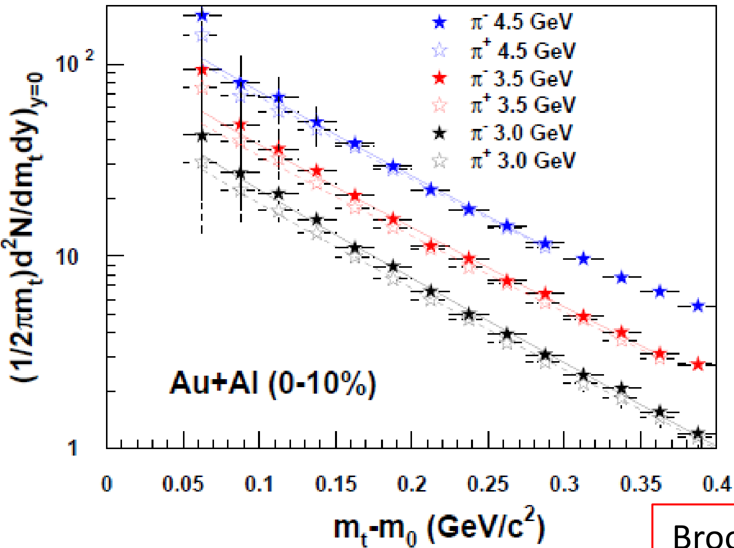
For top 10% central collisions:

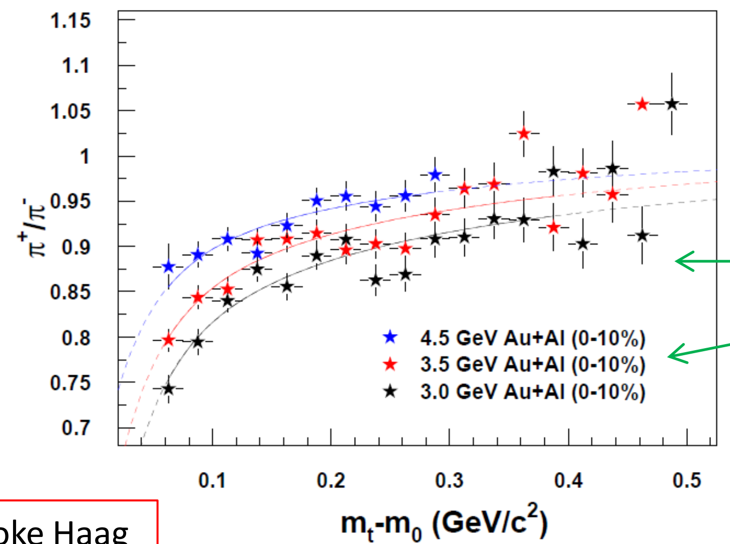
- 13 protons from Al
- 14 neutrons from Al
- 22 protons from Au
- 33 neutrons from Au

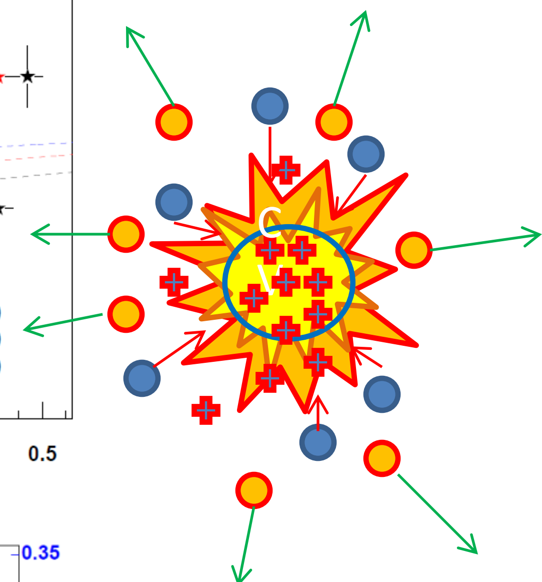


35 protons with a radius of 3.4 fm
➔ Coulomb Potential = 15 MeV

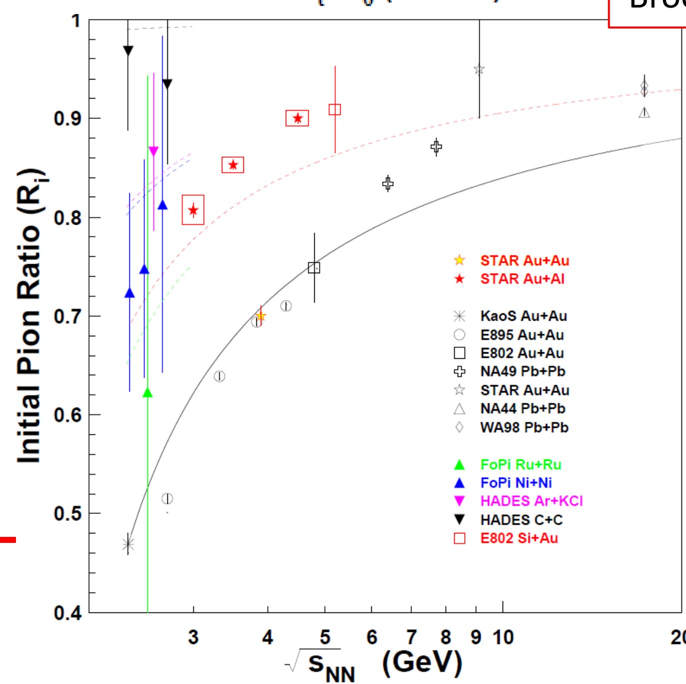
Physics Results: Spectra, Ratios, and Coulomb Analysis

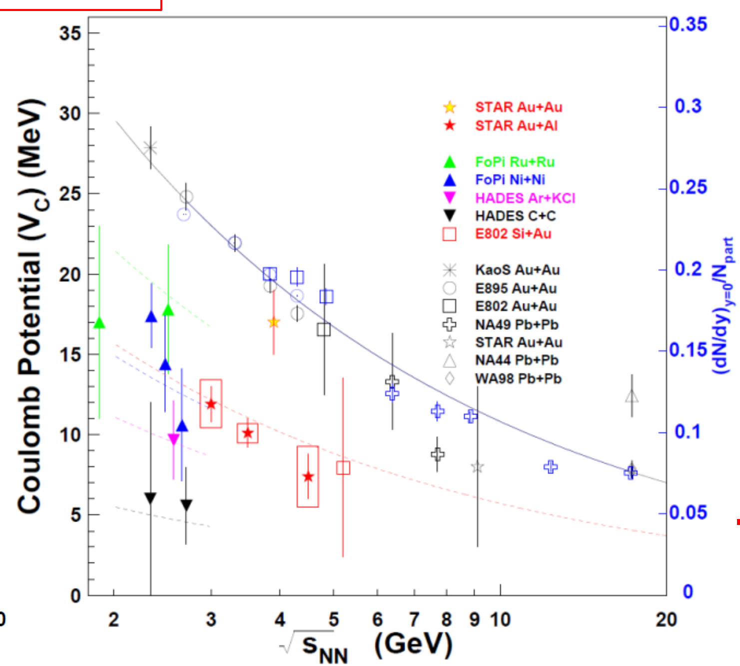






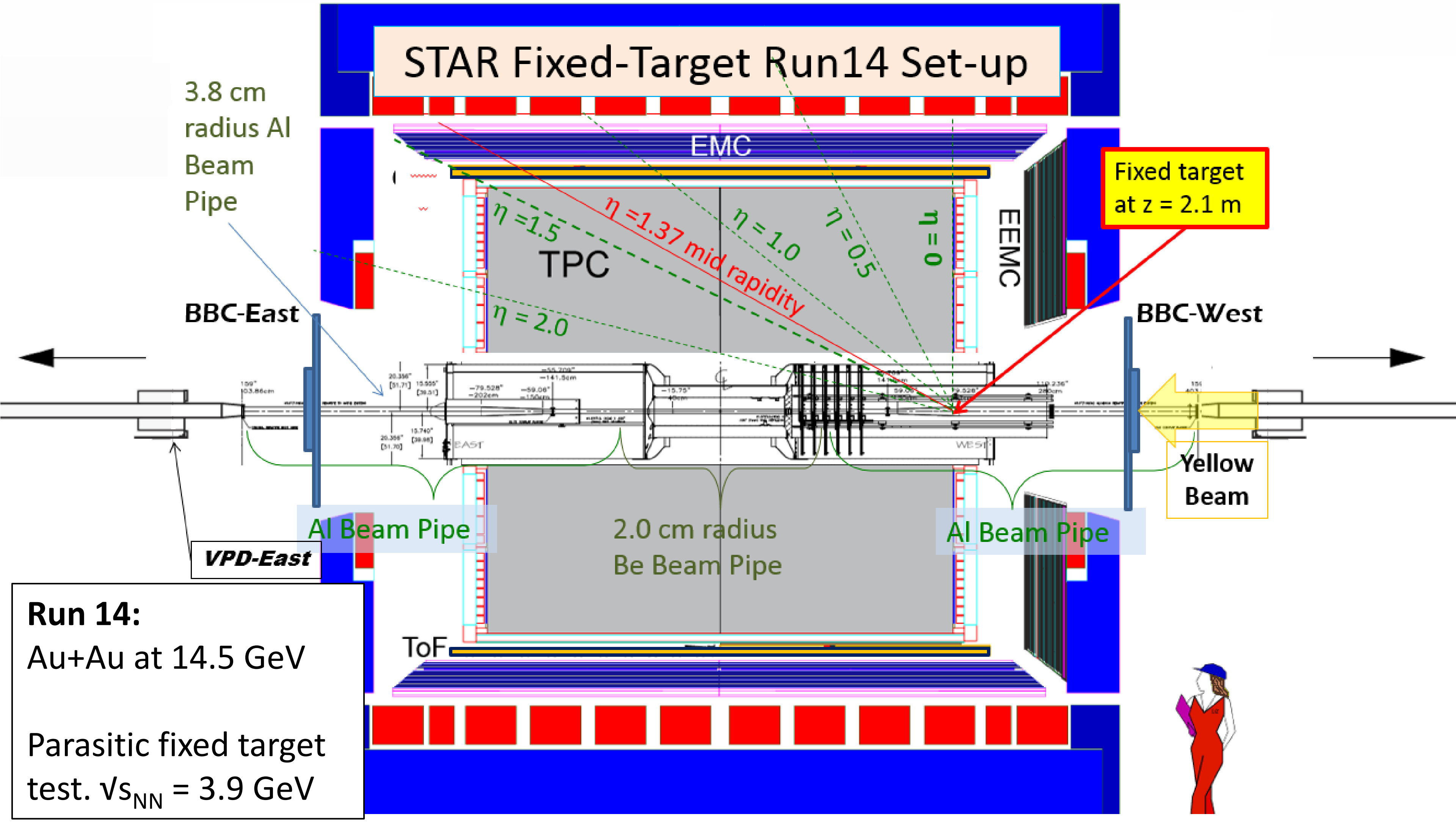
Brooke Haag





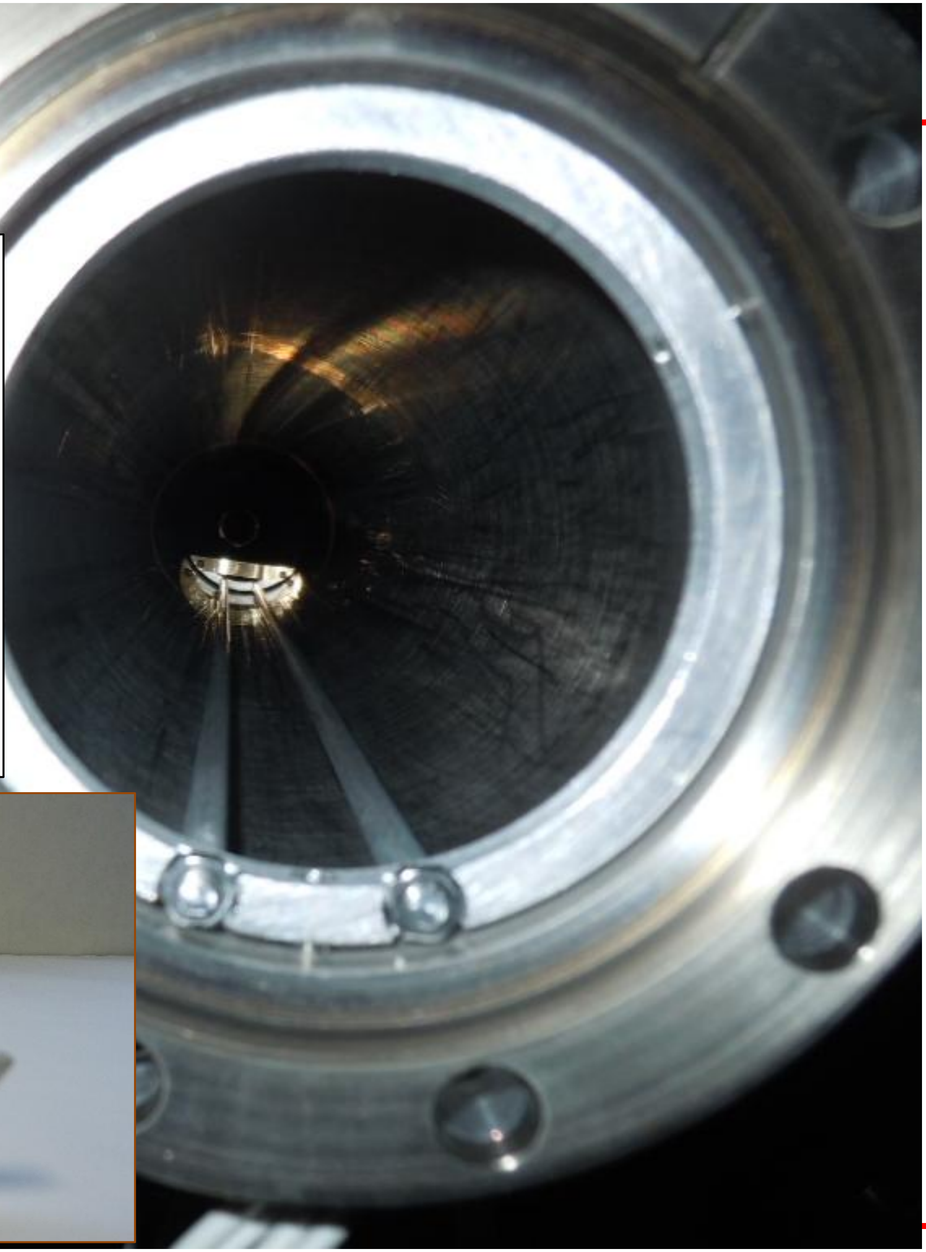
Coulomb force adds an extra push to the π^+ and pull the π^- back a little

RHIC Fixed-Target Test Runs 2014 and 2015



Run 14:
Au+Au at 14.5 GeV

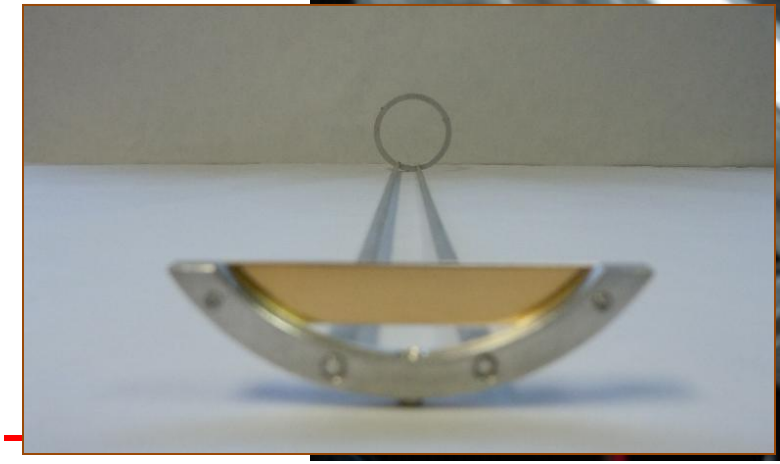
Parasitic fixed target test. $\sqrt{s_{NN}}$ = 3.9 GeV



The target foil is held 2.0 cm (1.7 cm in 2015) below the center of the beam pipe.

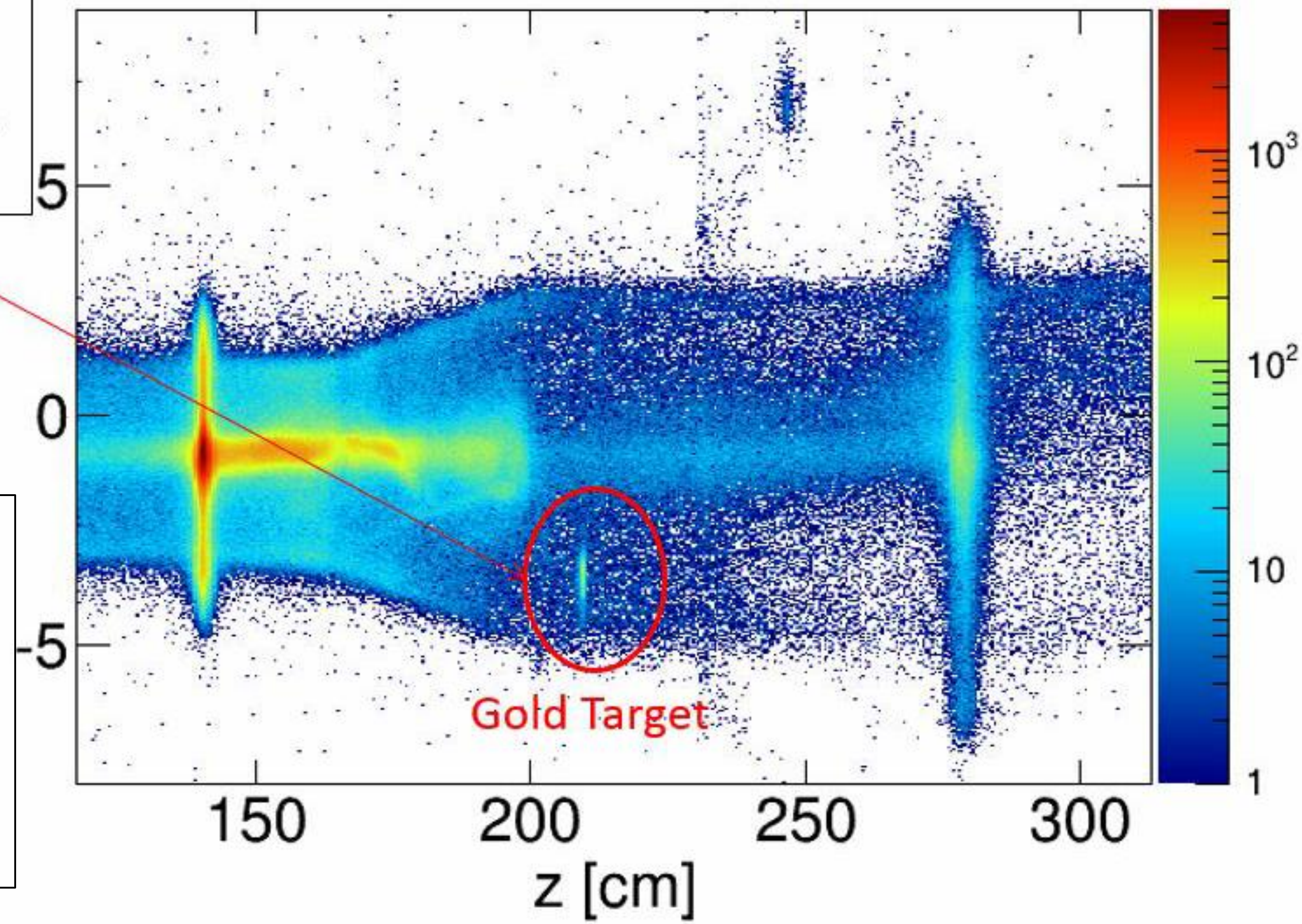
The foil is 1 mm thick (4%).

In 2015, the 3 mm overhang makes the target a defining aperture.



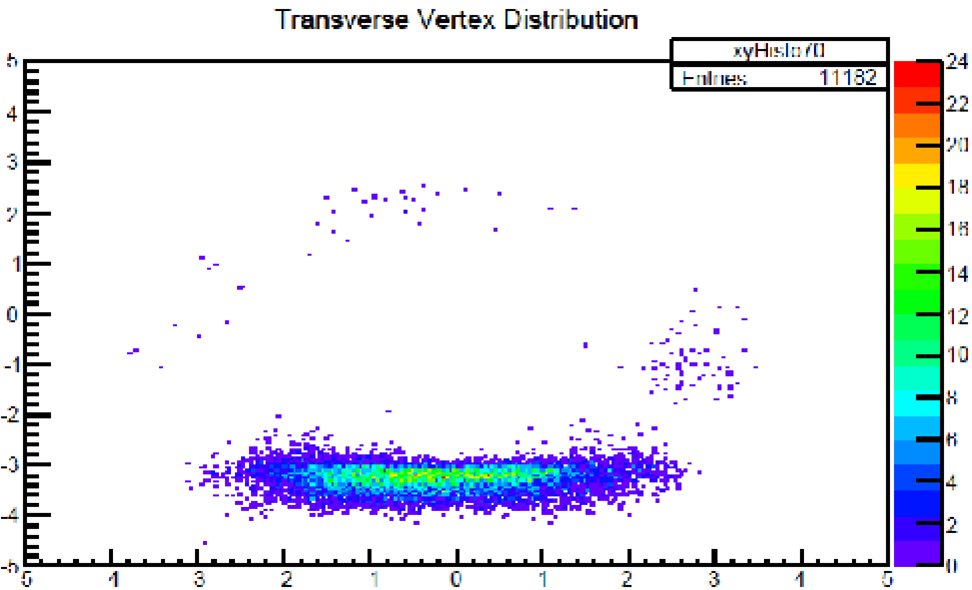
Imaging the Gold Target - 2014

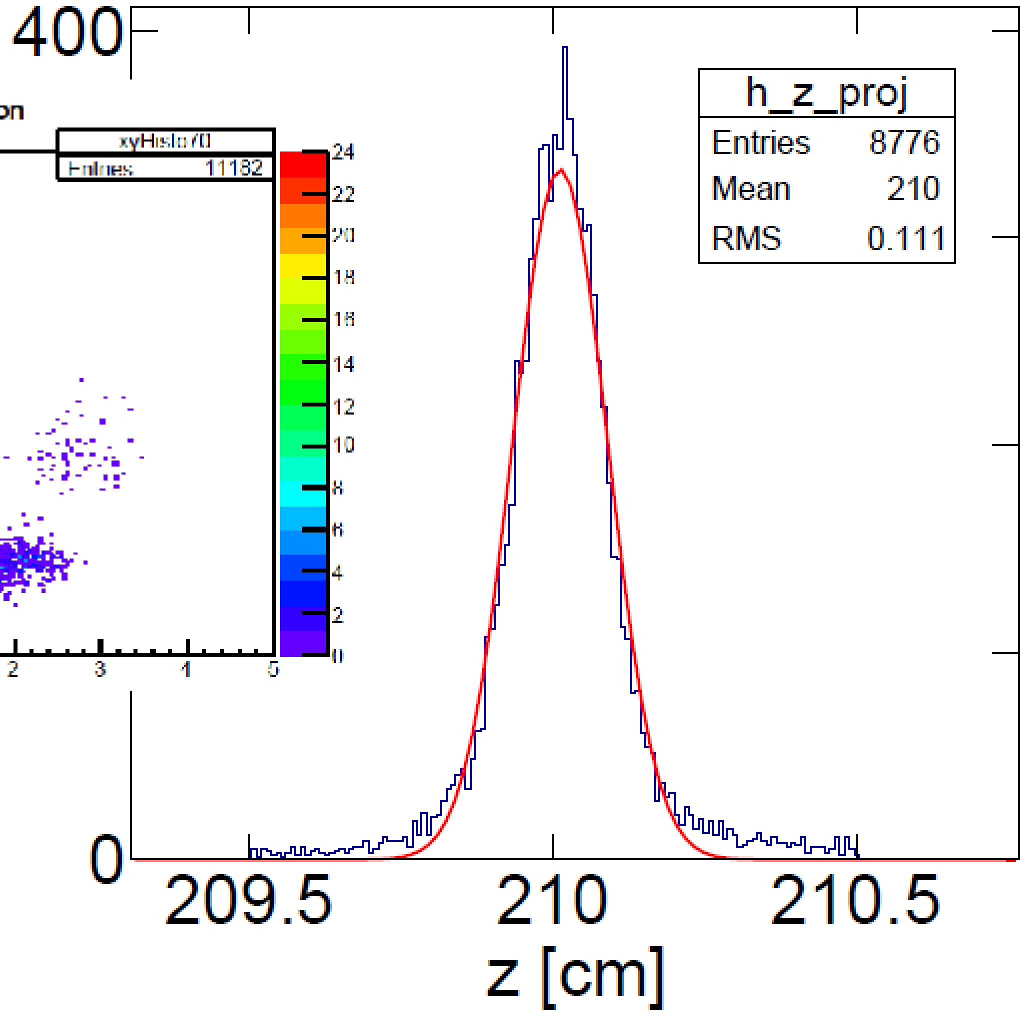
Lots of background, but the target events are evident



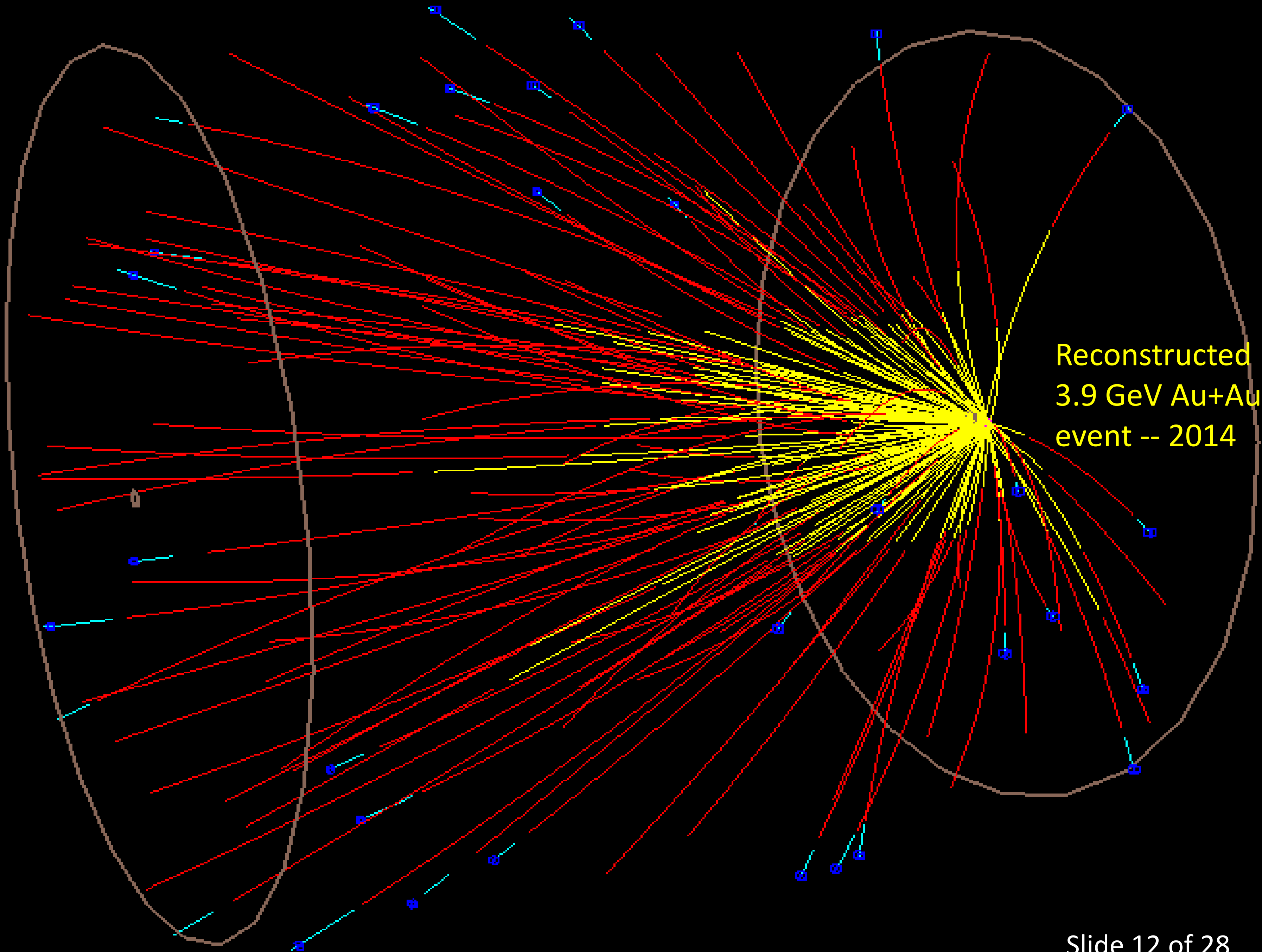
During three weeks of running RHIC for 14.5 GeV Au+Au collisions, target events taken with background

Au+Au @ **3.9 GeV**

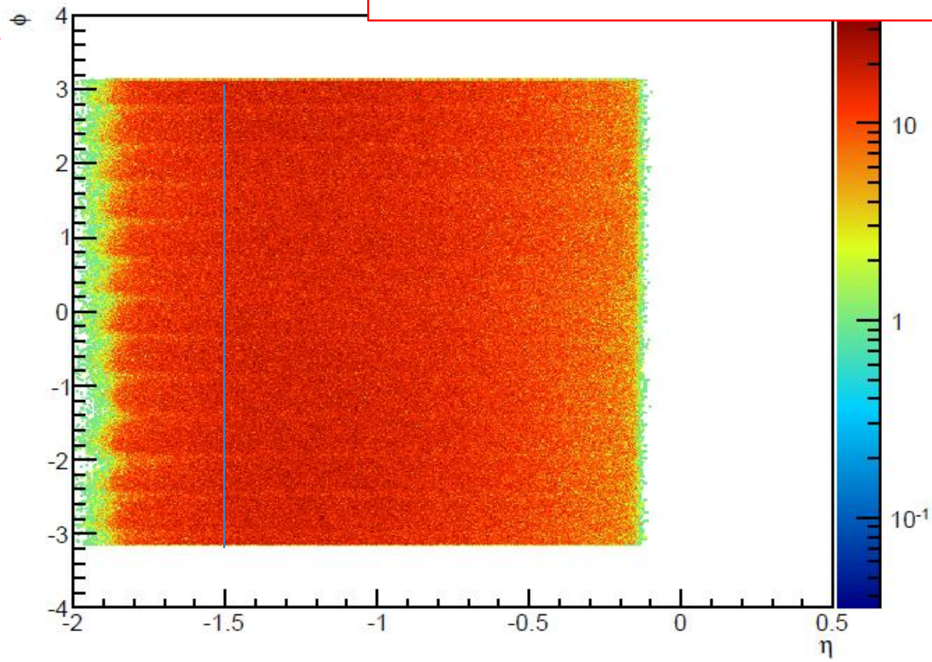


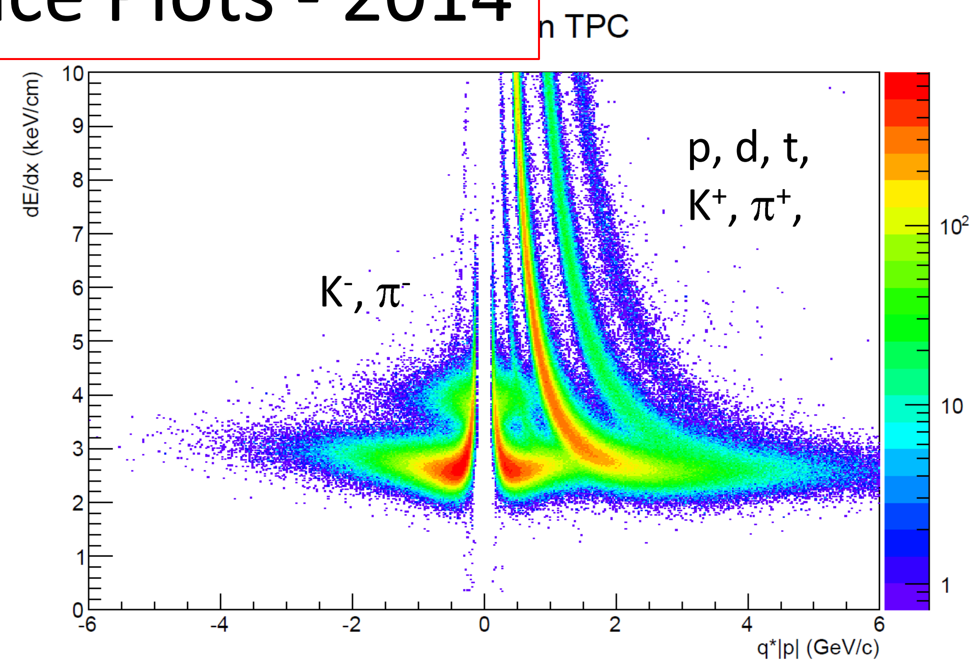


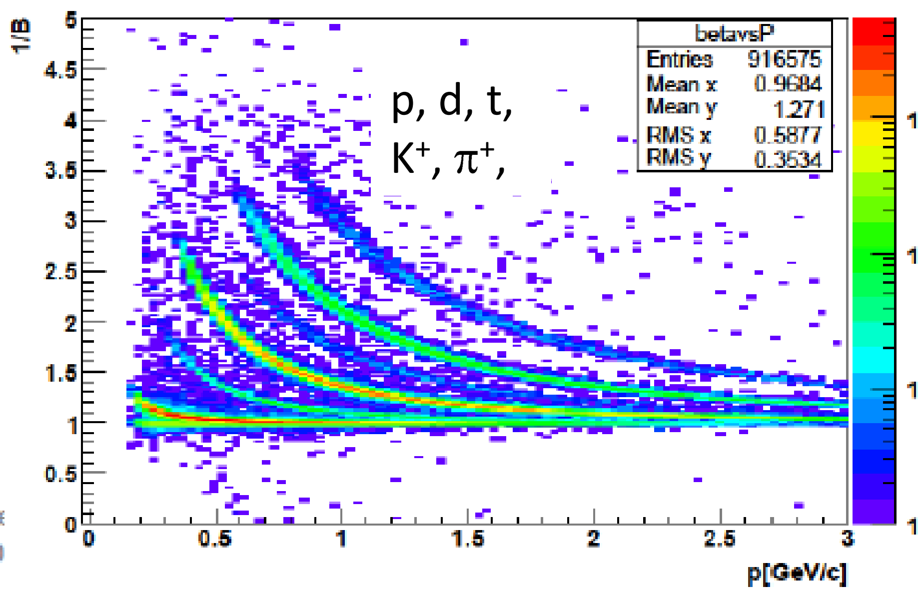
In three weeks of running, ~10,000 Au+Au events at 3.9 GeV were recorded

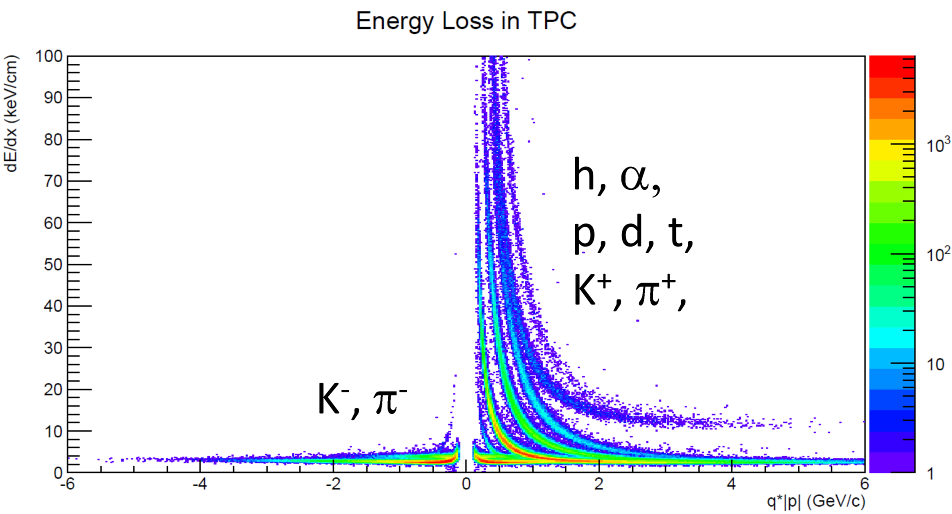

Reconstructed
3.9 GeV Au+Au
event -- 2014

Basic Performance Plots - 2014



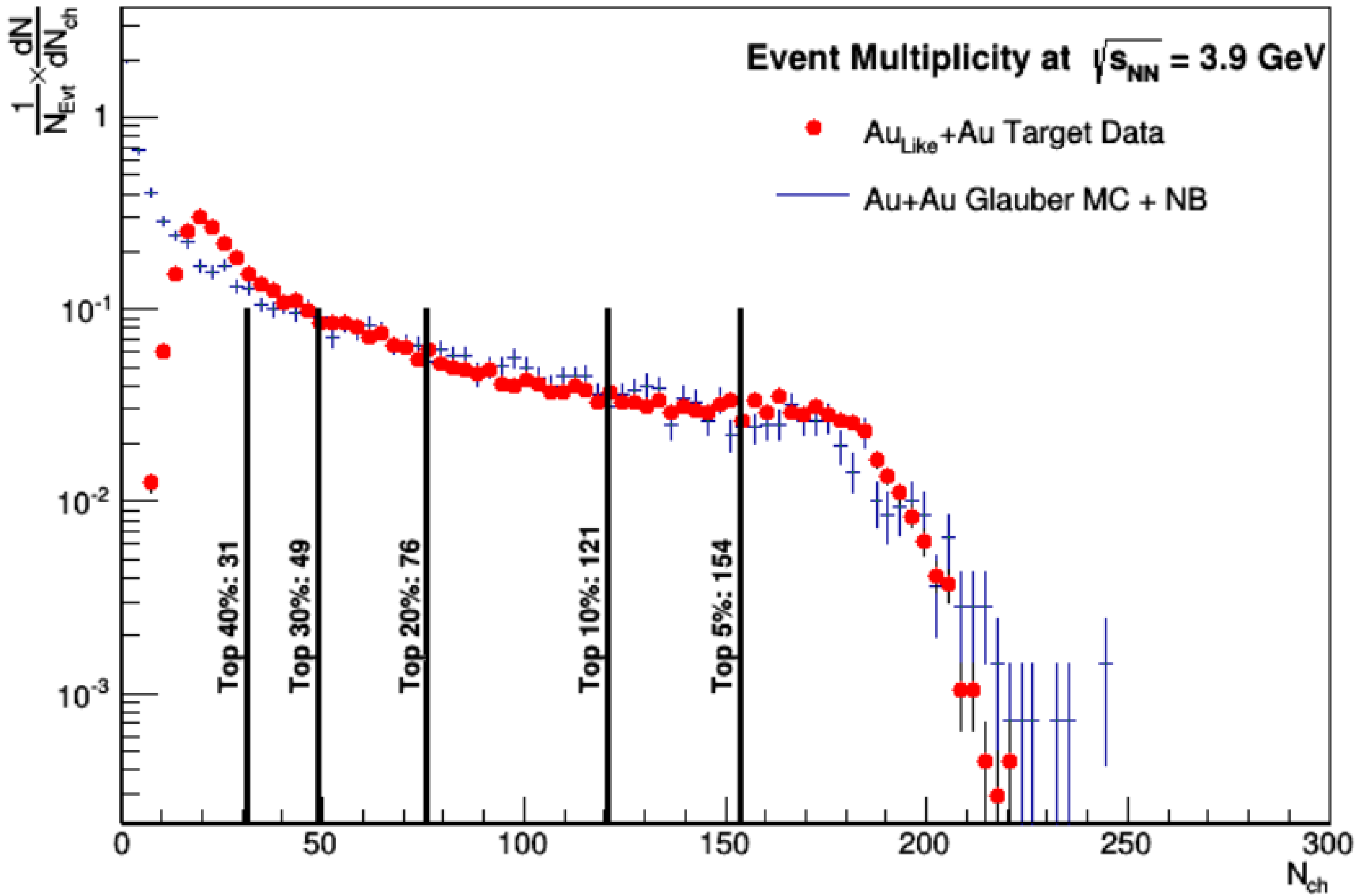




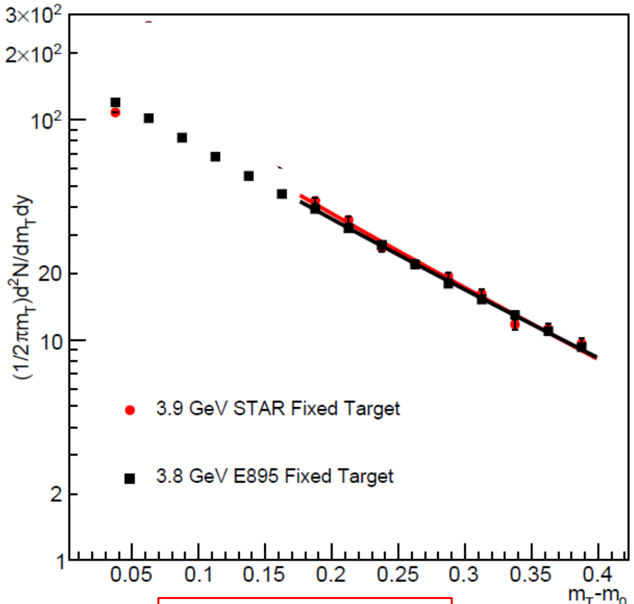


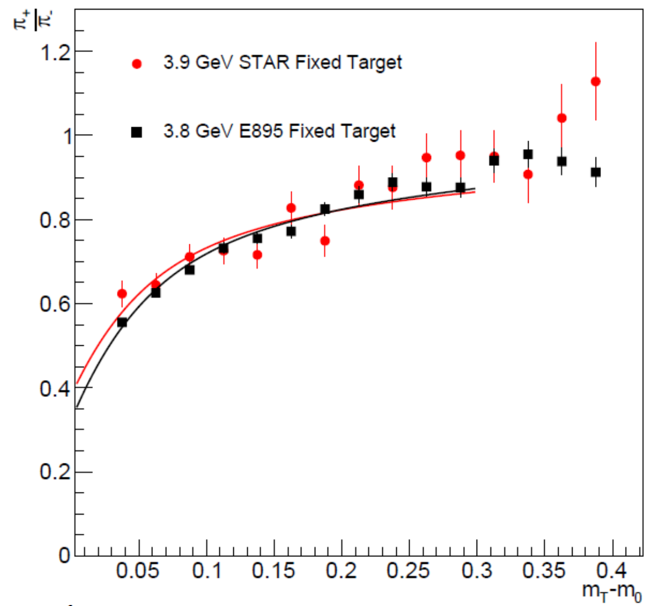
R Upgrades
China

Centrality Determination - 2014

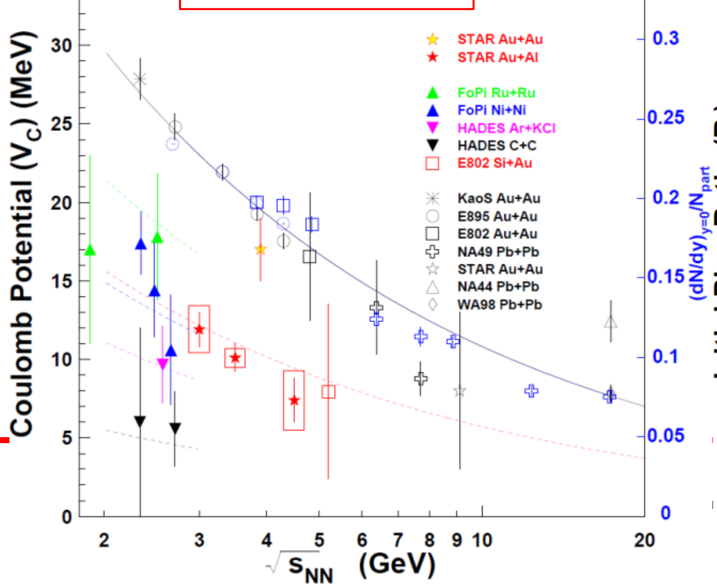


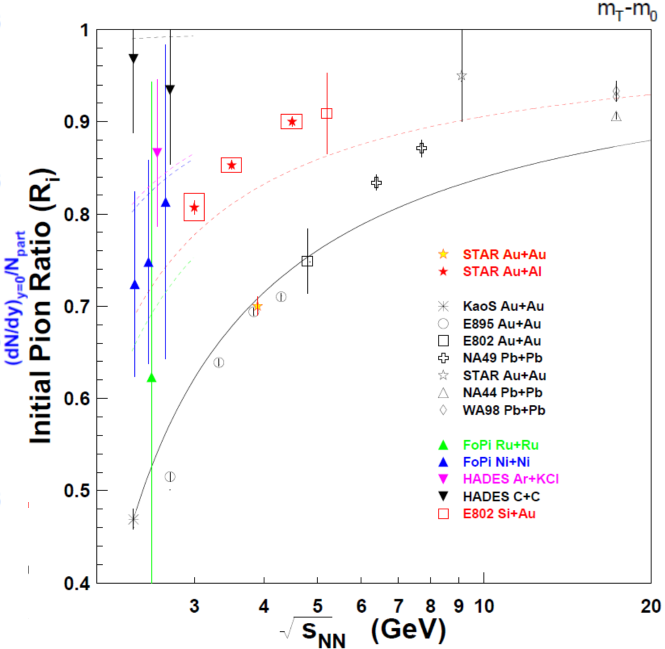
Physics Results: Spectra, Ratios, and Coulomb Analysis

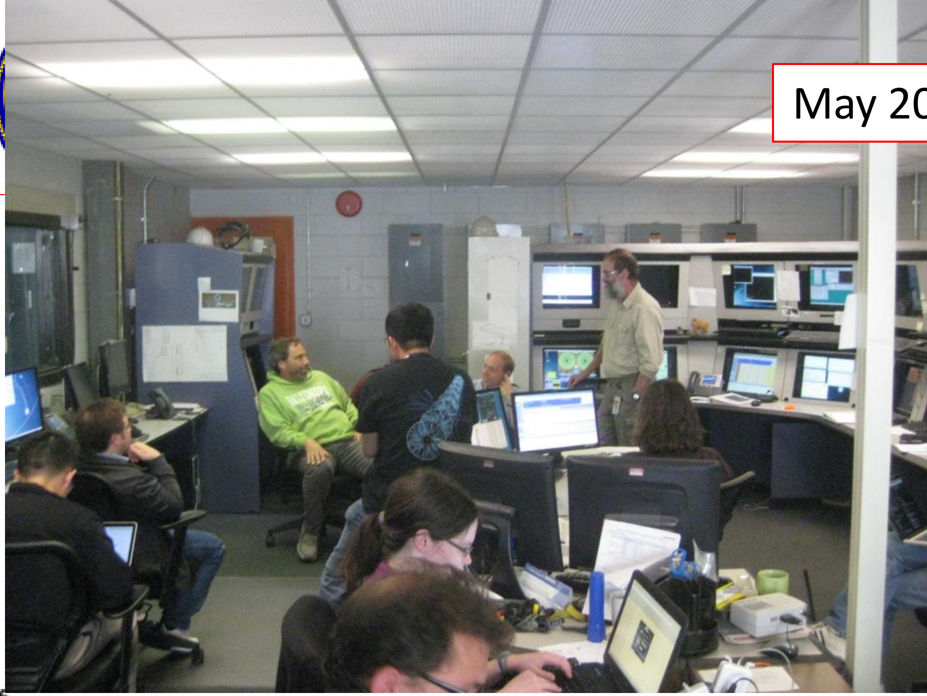


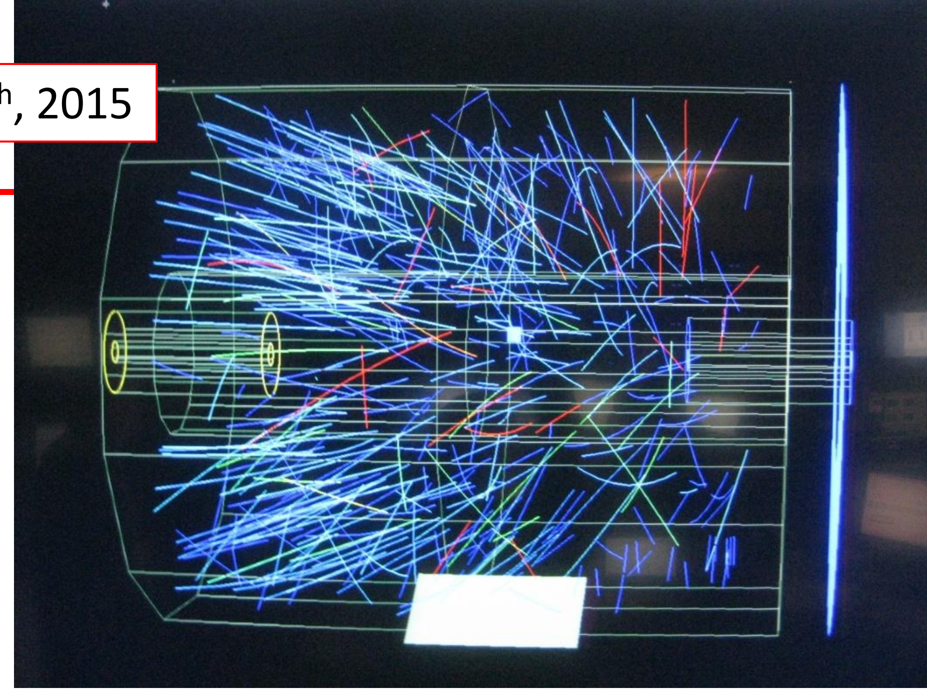


Kathryn Meehan

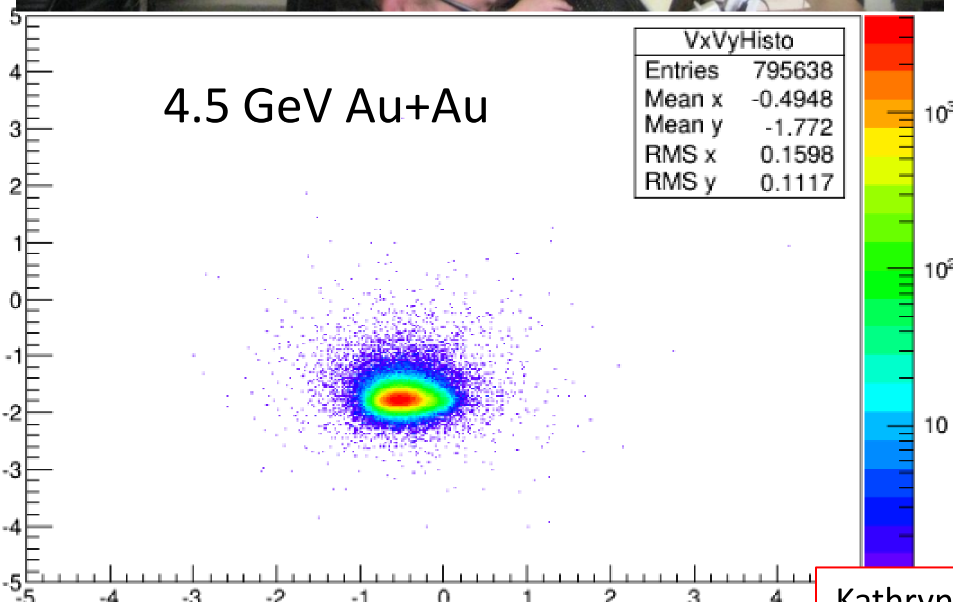


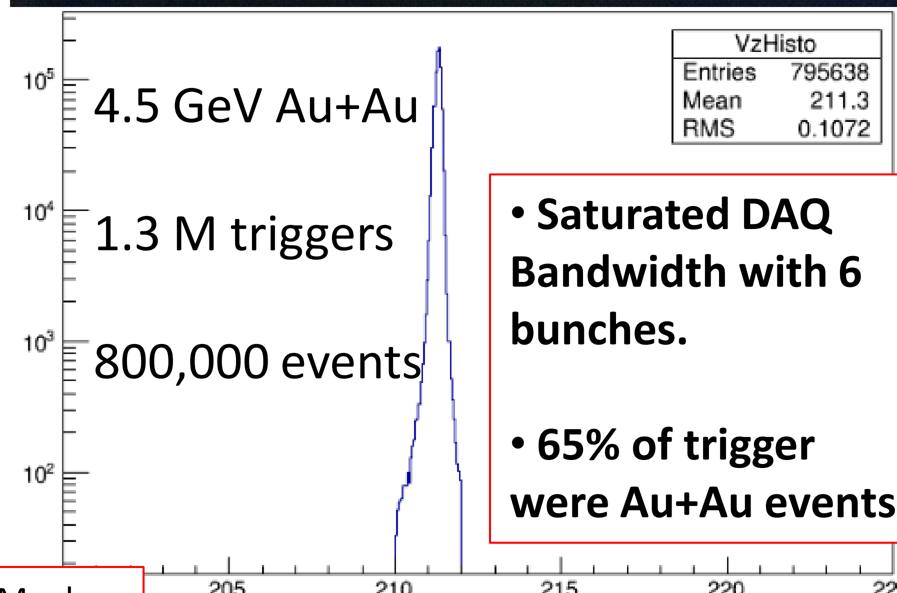






May 20th, 2015

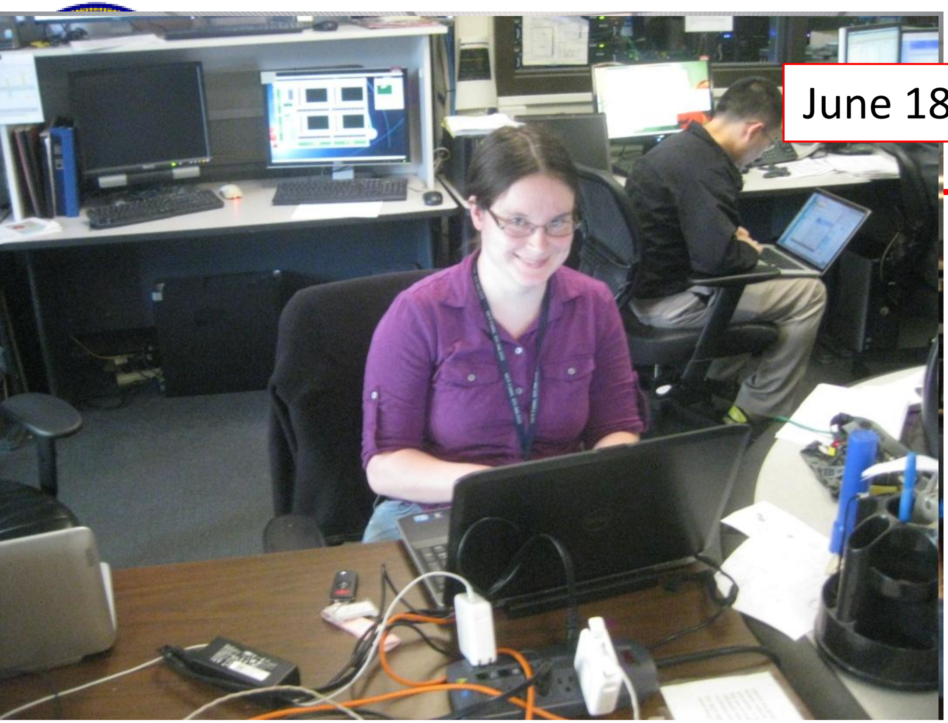


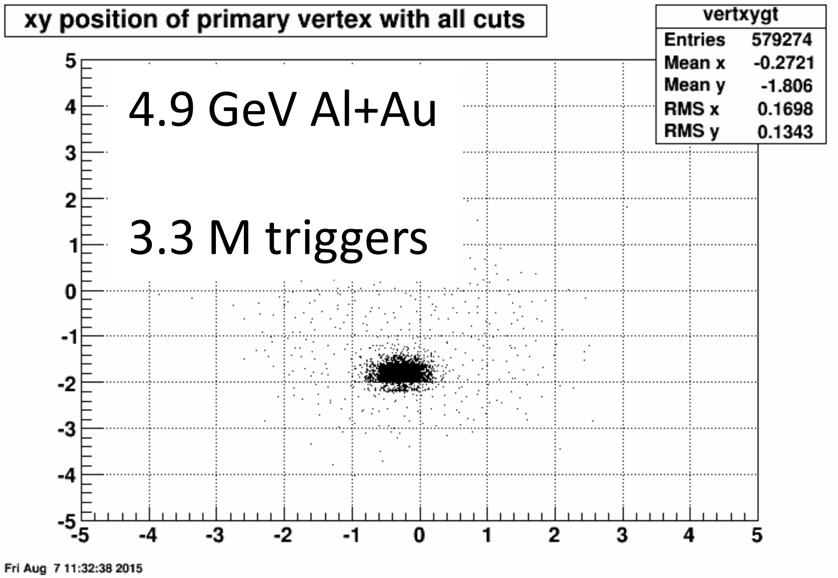


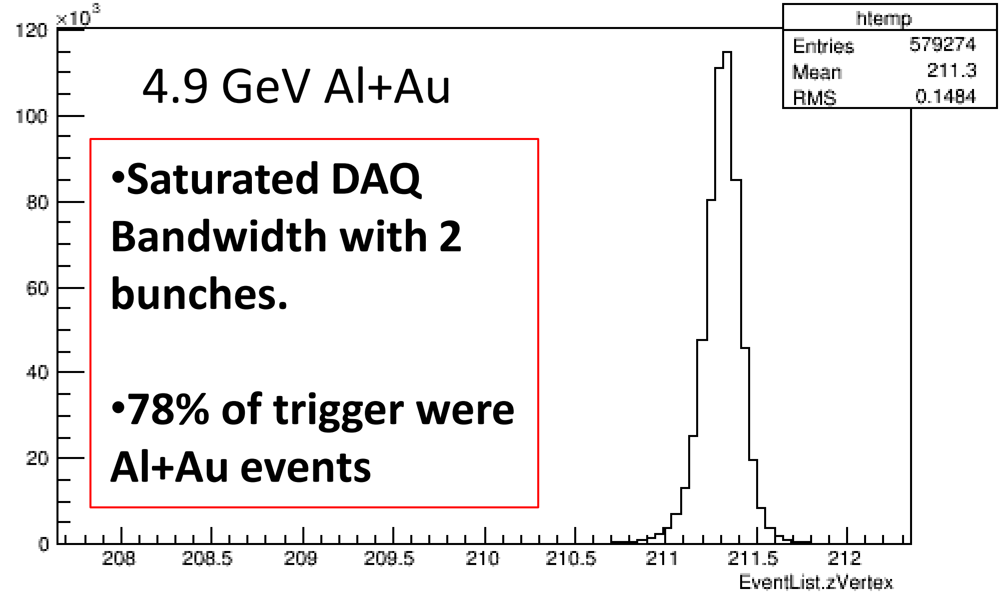
Kathryn Meehan

- **Saturated DAQ Bandwidth with 6 bunches.**
- **65% of trigger were Au+Au events**

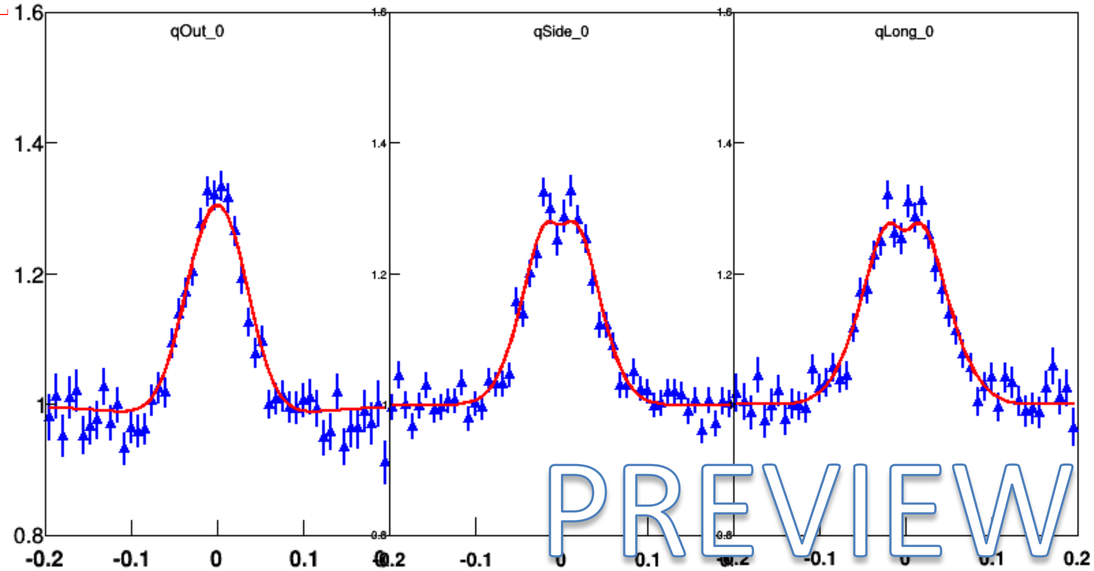
June 18th, 2015

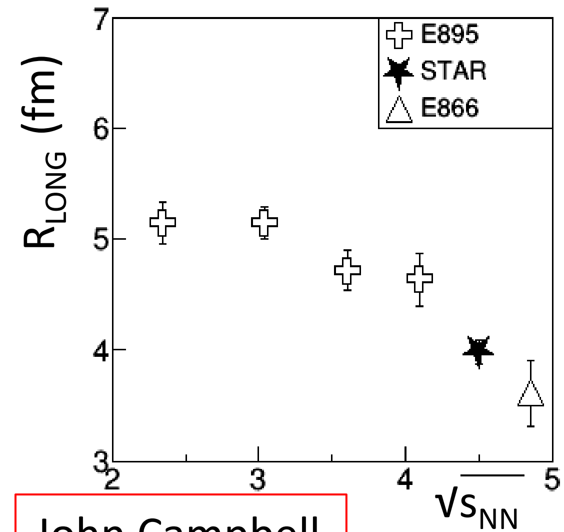




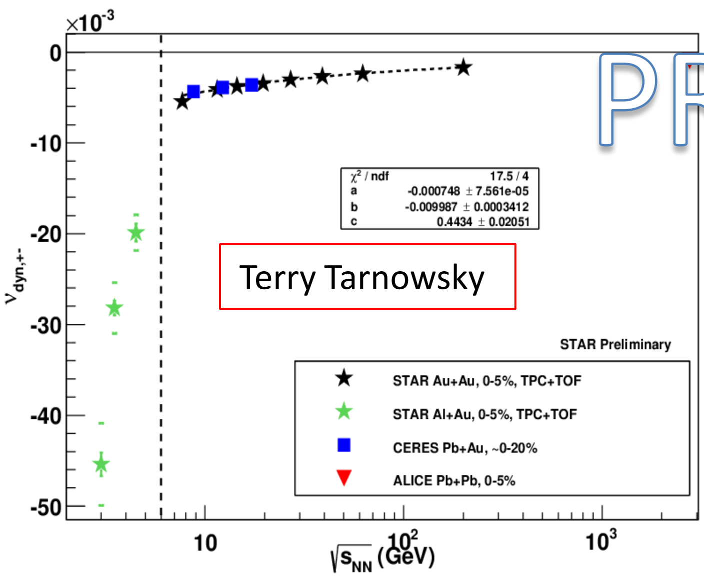


Physics results: Fluctuations and Correlations

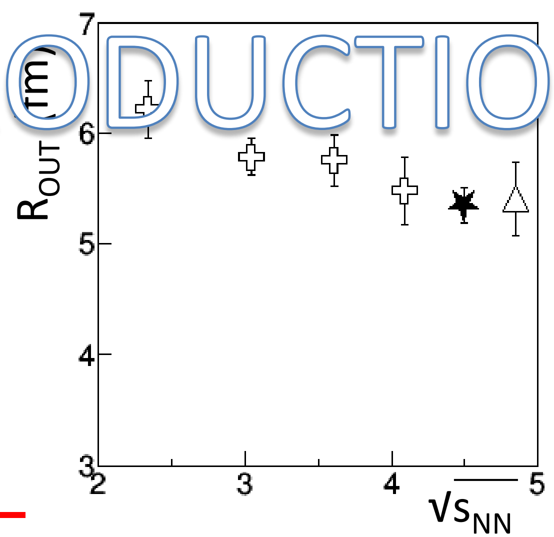


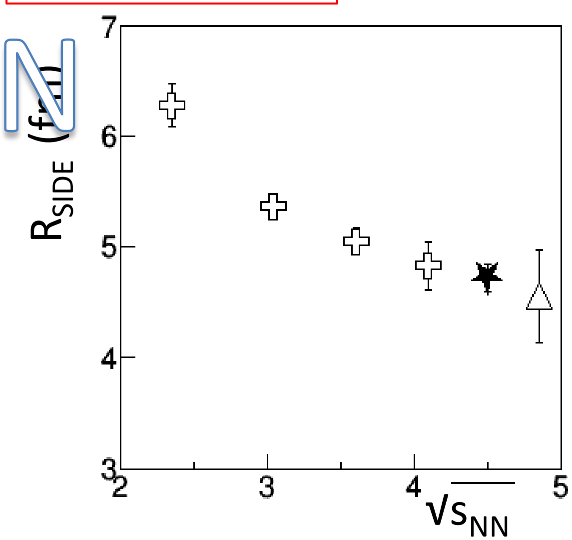


John Campbell

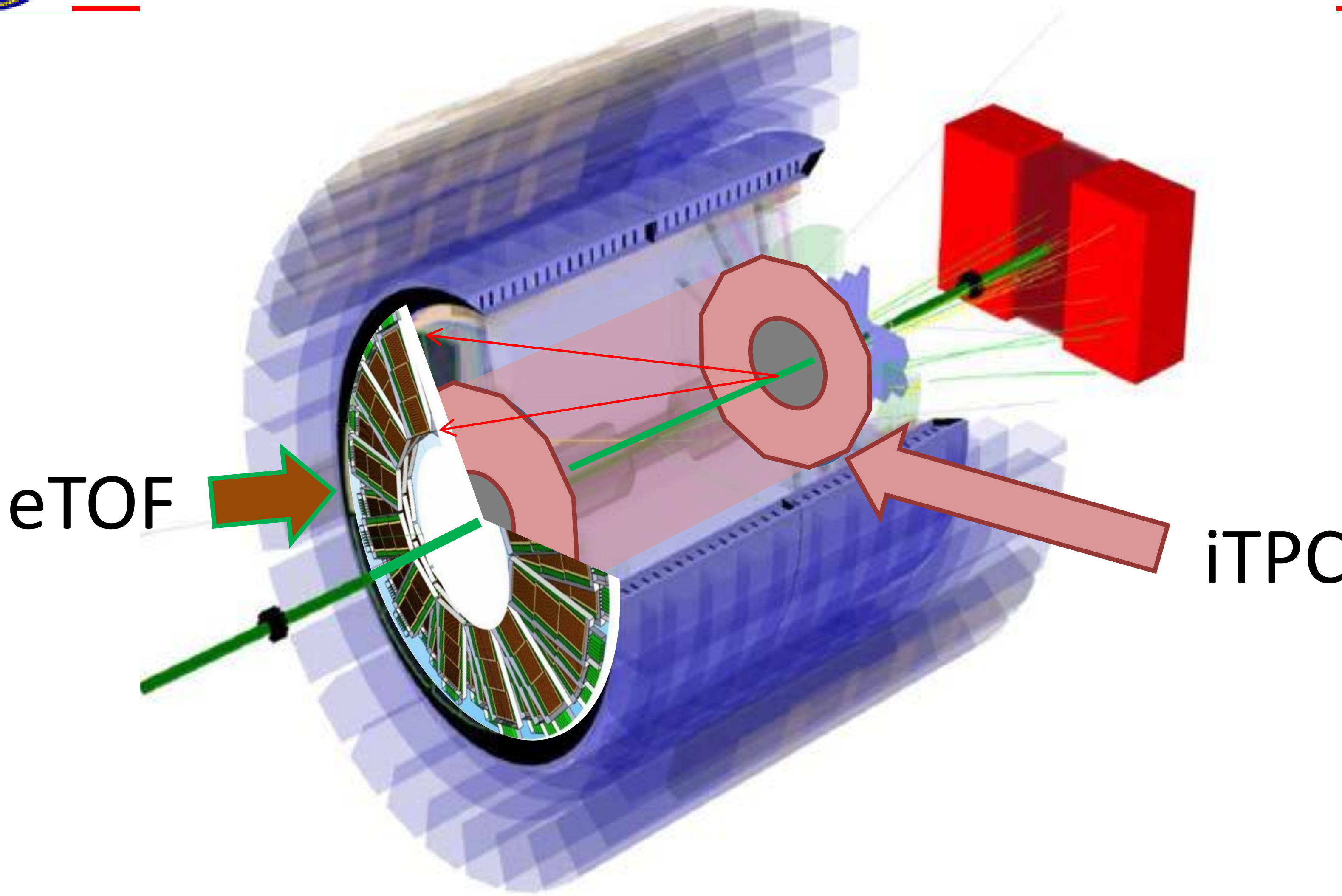


Terry Tarnowsky





Fixed Target Physics in BES II with Detector Upgrades



Upgrade Capabilities

- Low p_T acceptance ➔ Determined by the minimum hit requirement (10)
  - Current TPC p_T > 120 MeV/c
  - iTPC – p_T > 70 MeV/c

- Momentum Resolution:
  - Mostly determined by track length, only improves with the square root of samples

- Pseudorapidity Acceptance ➔ Limited by 10 hit requirements

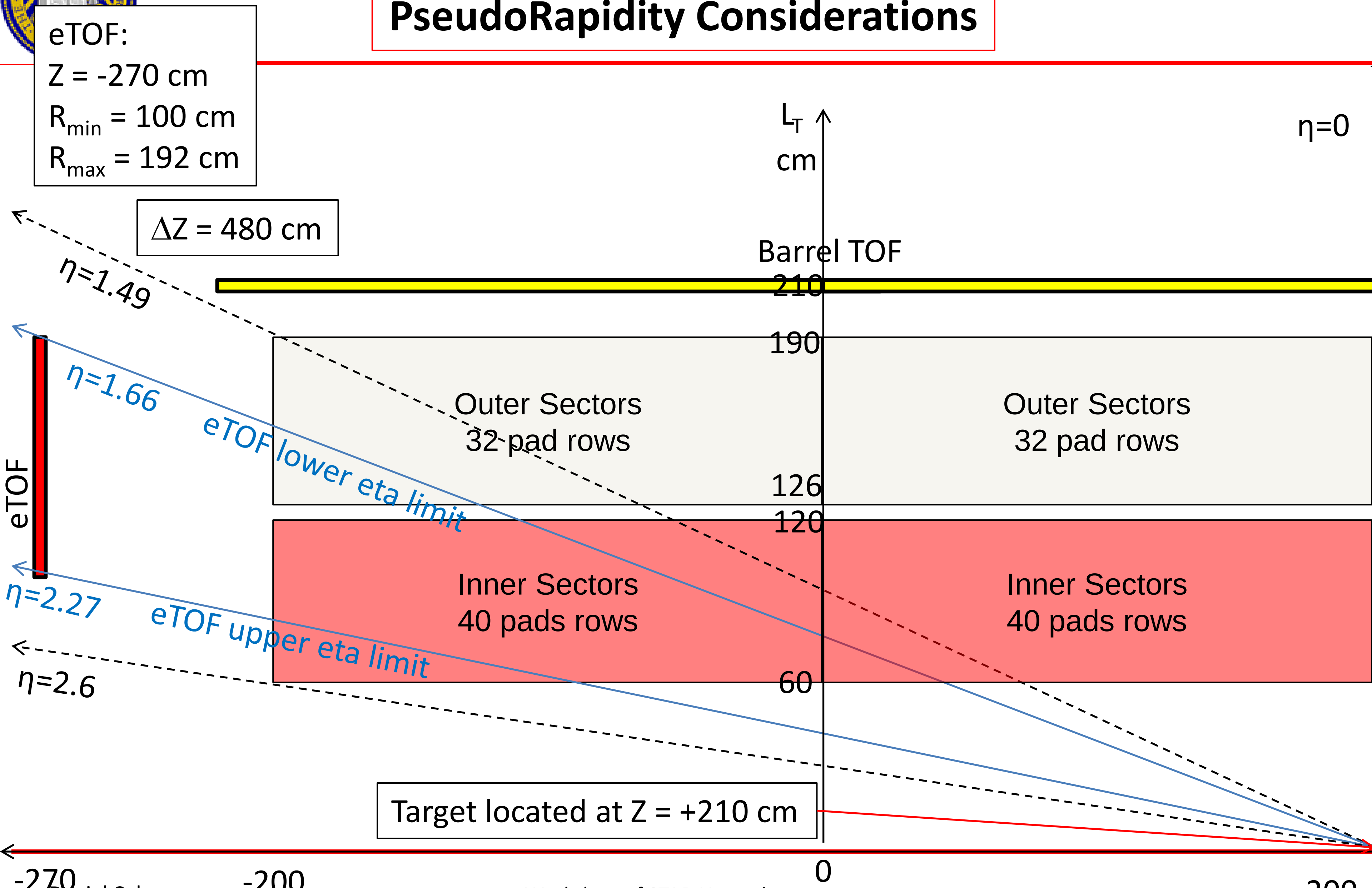
- Particle Identification:
  - *dE/dx* Resolution
  - ToF Resolution

$$\sigma_{dEdx} = 0.47 N^{-0.46} (Ph)^{-0.32} (dE/dx)_{trunc}$$

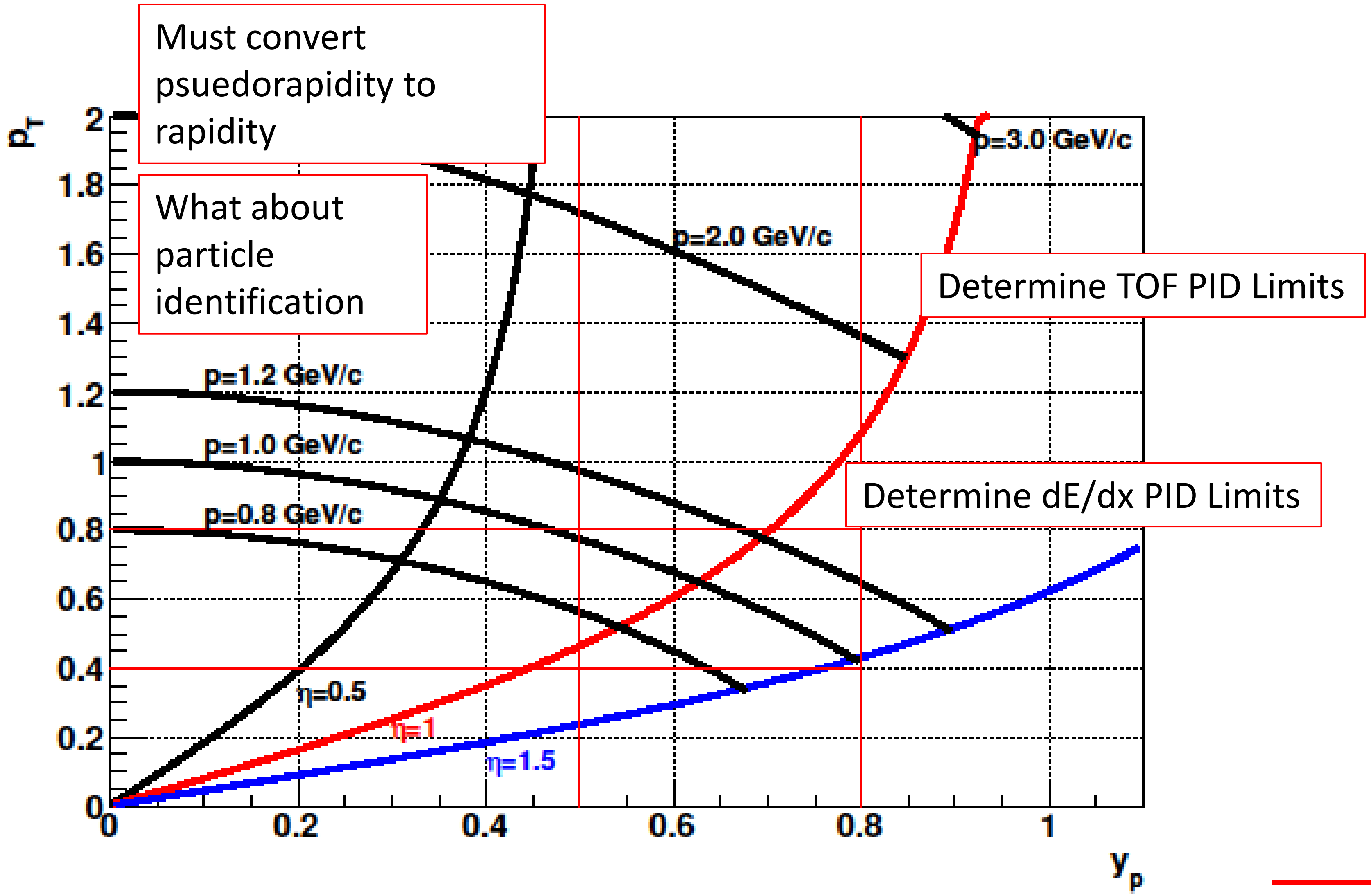
$$TOF = d/\beta c$$

$$t + \Delta t = \frac{d}{c}\left(\frac{1}{\beta} + \delta\frac{1}{\beta}\right)$$

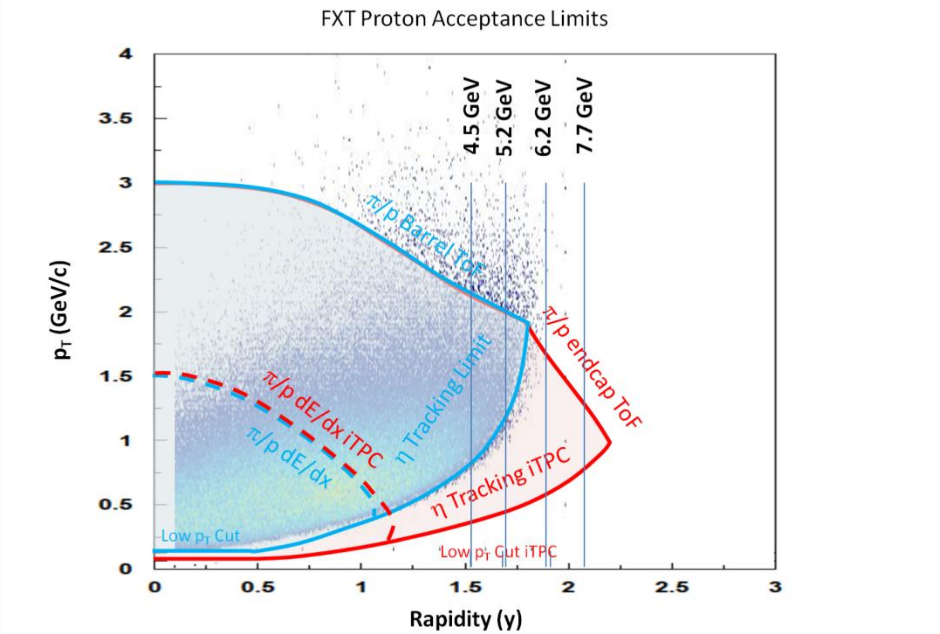
Internal Fixed Target PseudoRapidity Considerations

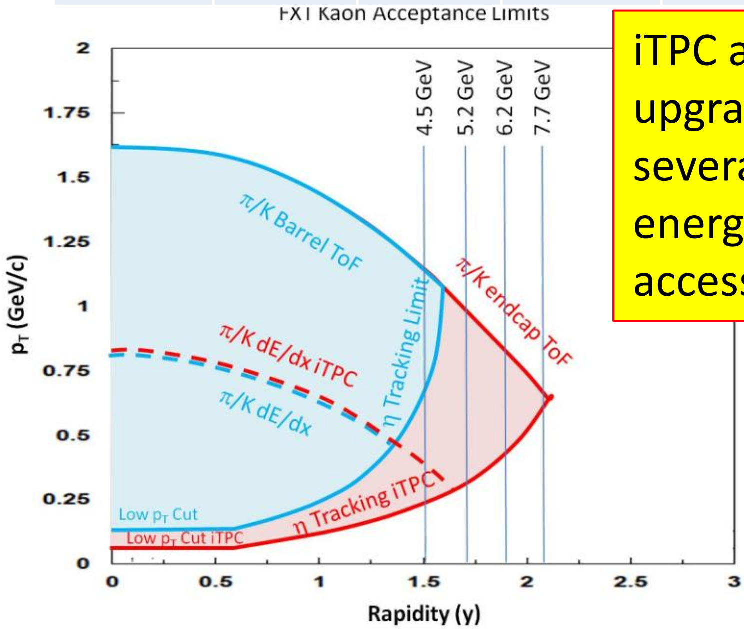


Conversion of psuedorapidity to rapidity -- Protons

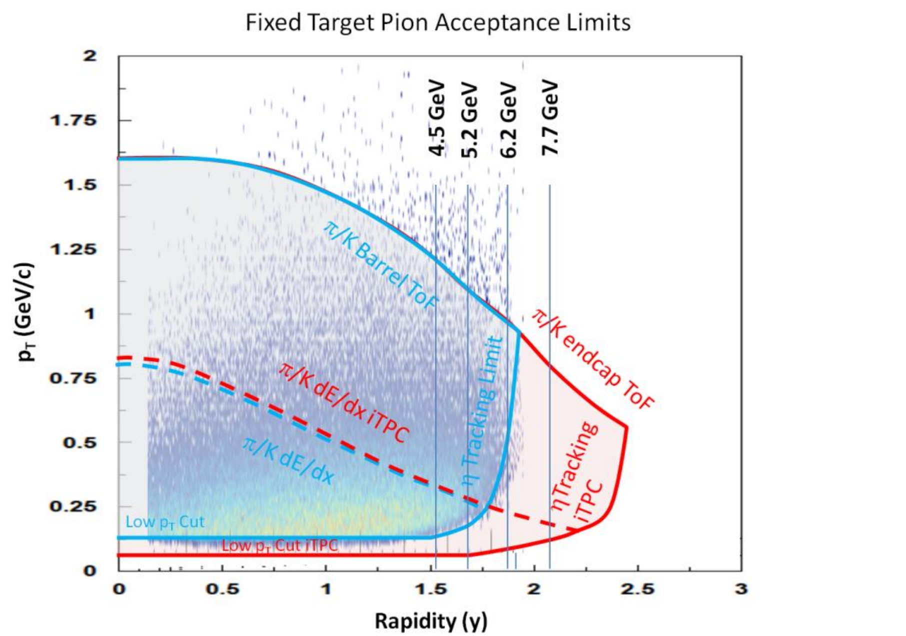


Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	**7.7**	30.3	2.10	420
39	**6.2**	18.6	1.87	487
27	**5.2**	12.6	1.68	541
19.6	**4.5**	8.9	1.52	589
14.5	**3.9**	6.3	1.37	633
11.5	**3.5**	4.8	1.25	666
9.1	**3.2**	3.6	1.13	699
7.7	**3.0**	2.9	1.05	721





iTPC and eTOF upgrades make several key energies accessible



BESII FXT Physics Program

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

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

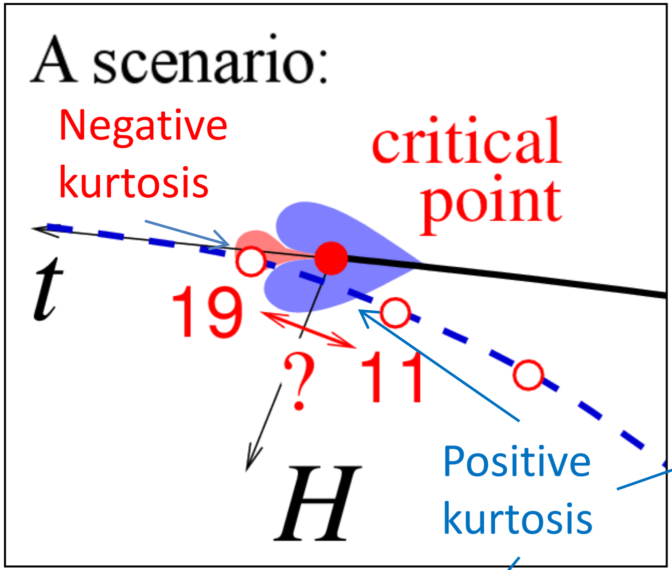
Criticality:
- Higher moments
- Particle Ratio Fluctuations

Chirality:
- Dilepton studies

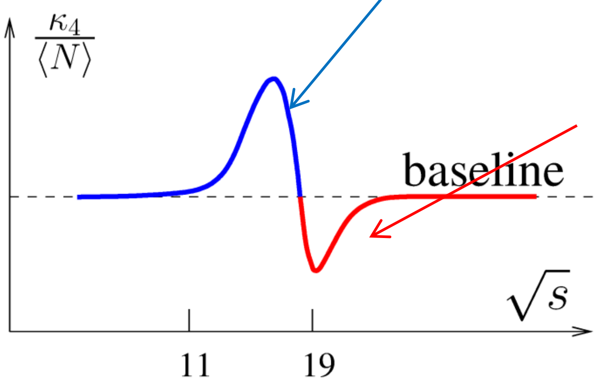
No measurements in this energy range

Hypernuclei:
- $^{3}_{\Lambda}H$ Lifetime and excitation function

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

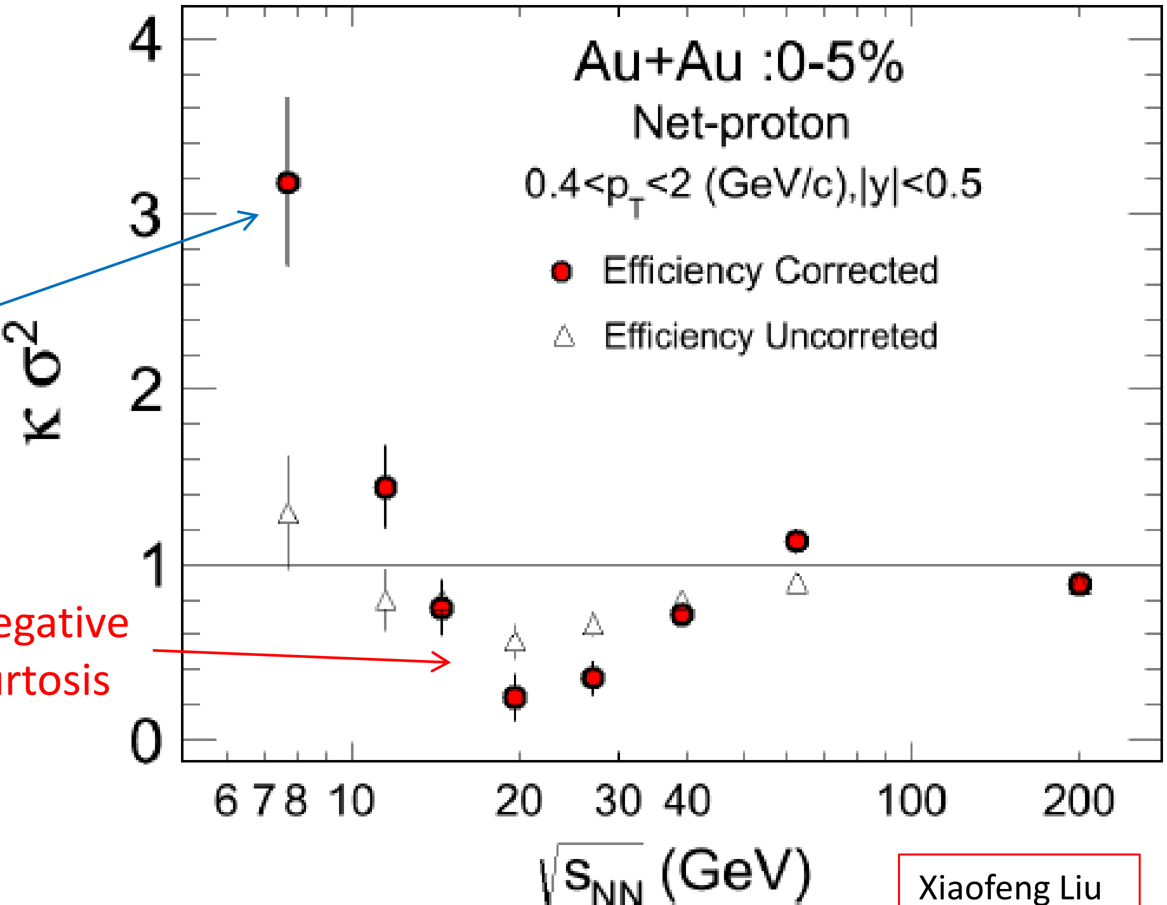


Misha Stephanov



STAR results show a fall and rise of the fluctuation variable. Need lower energy data.

Negative kurtosis



Xiaofeng Liu

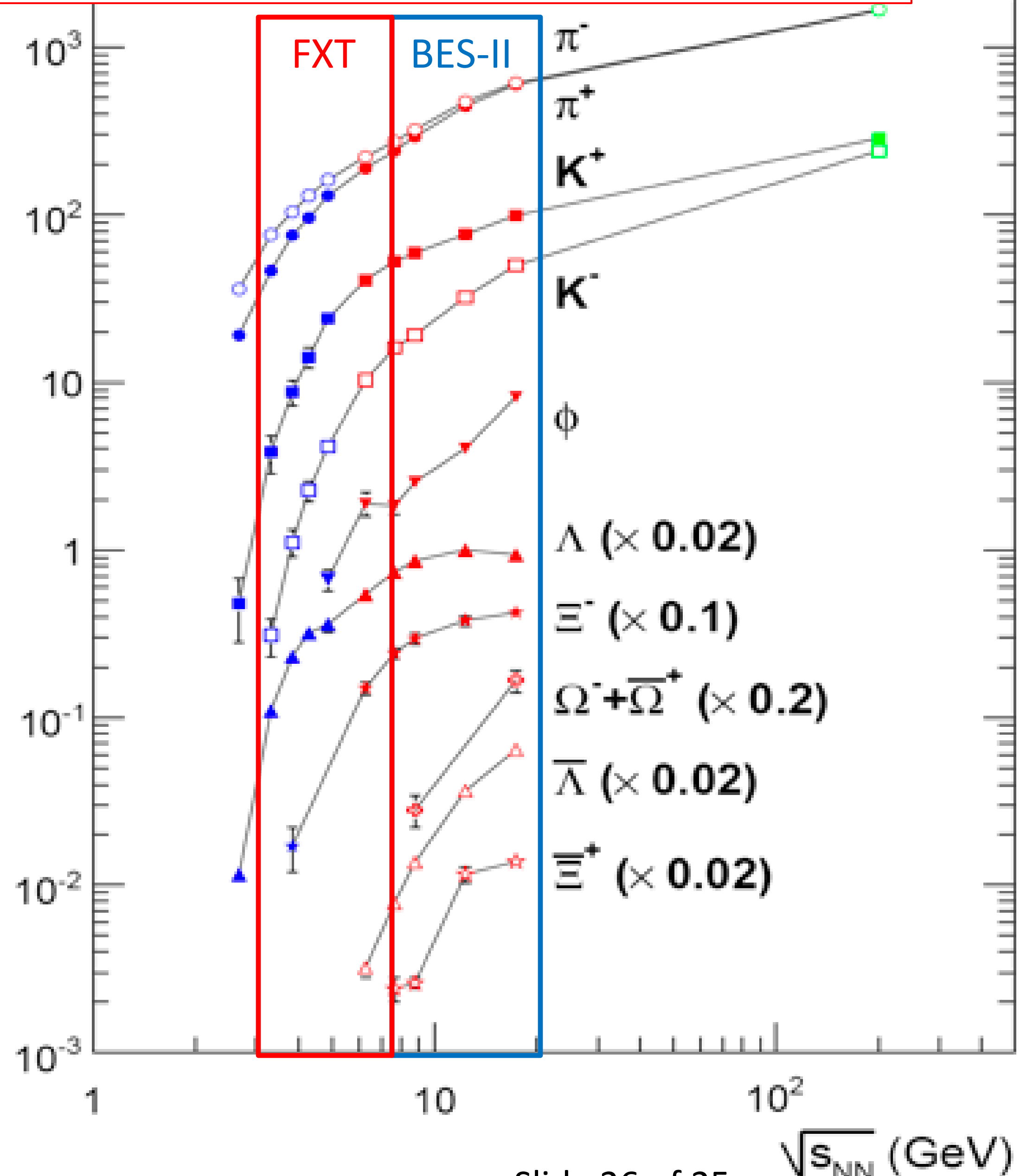
Yields of Hadrons → Mapping the Phase Boundary

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

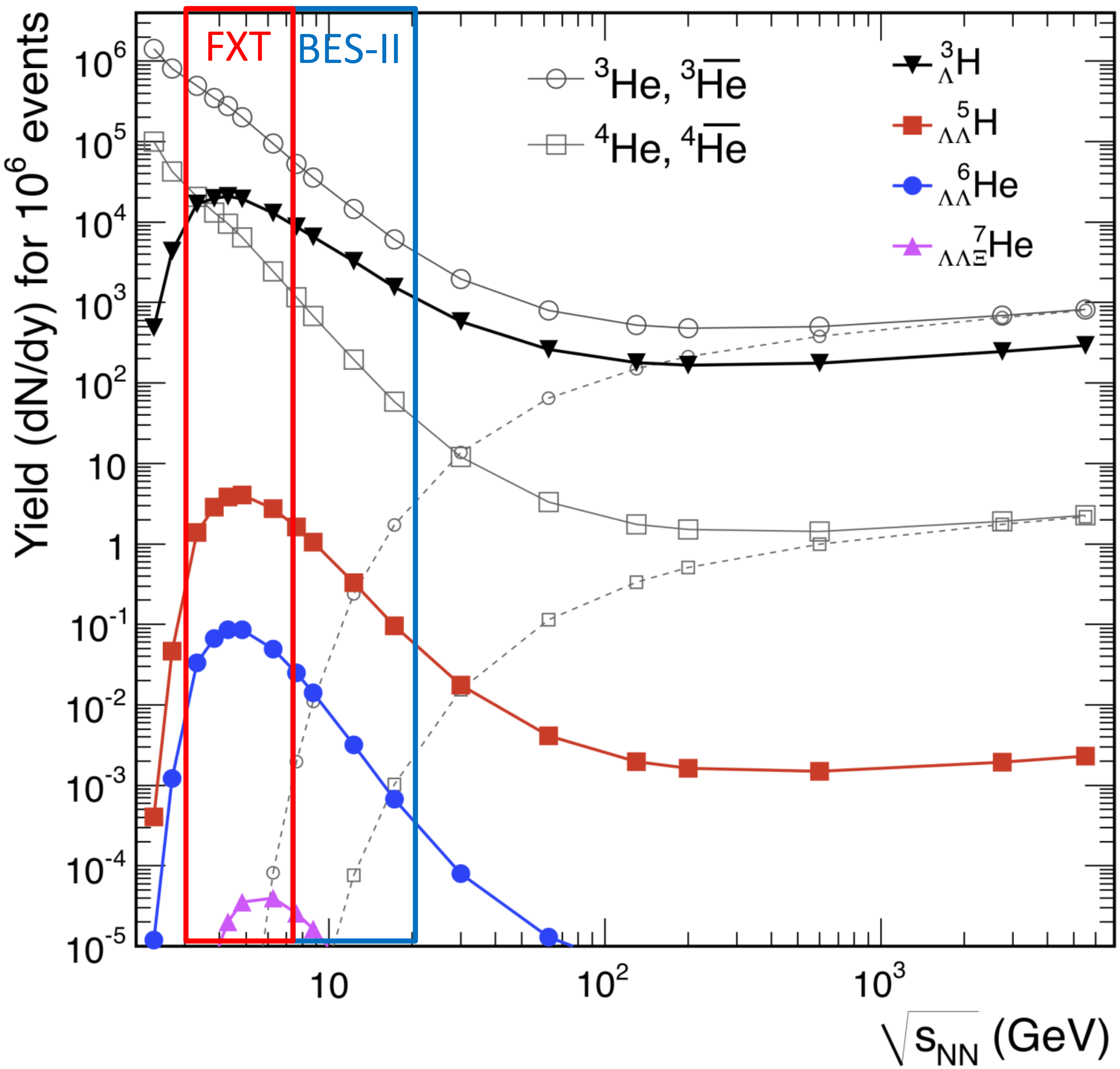


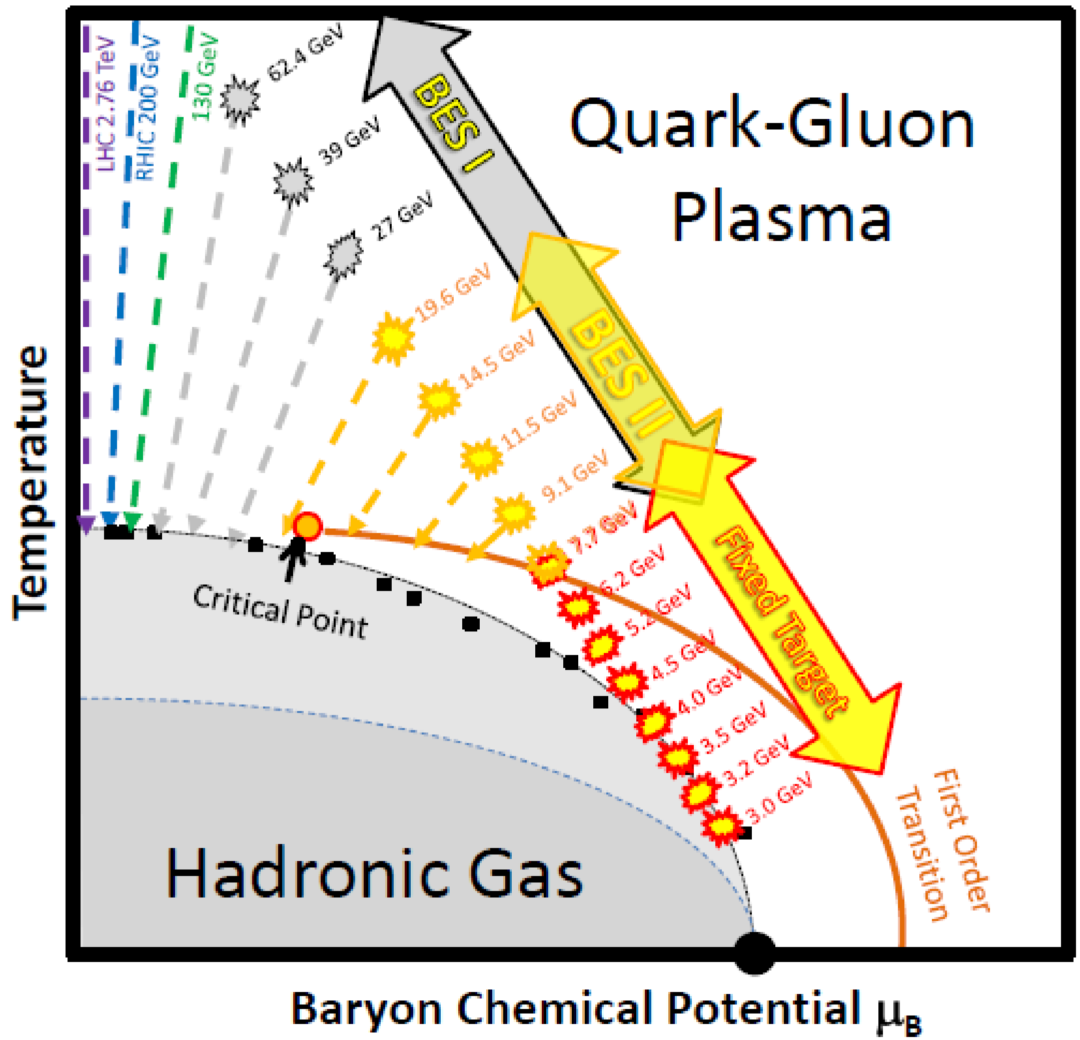
Hypernuclei

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



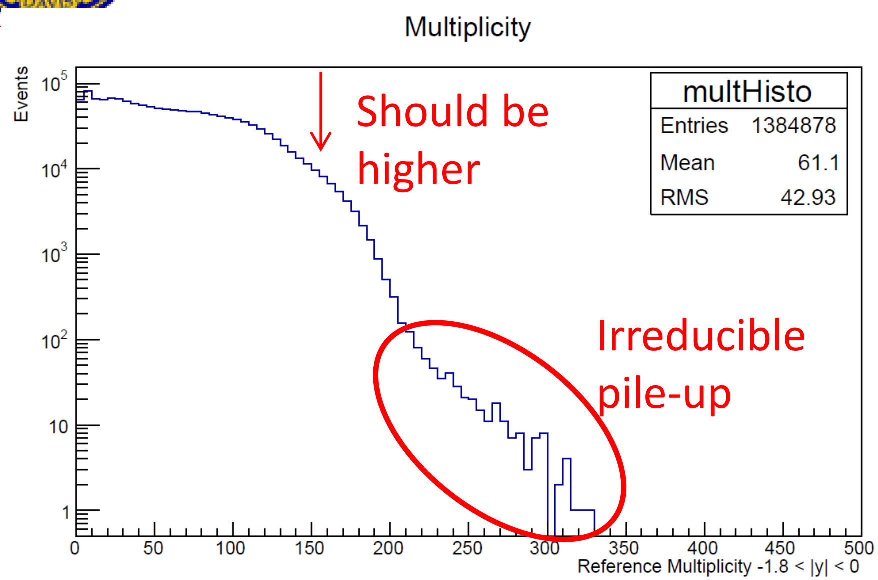


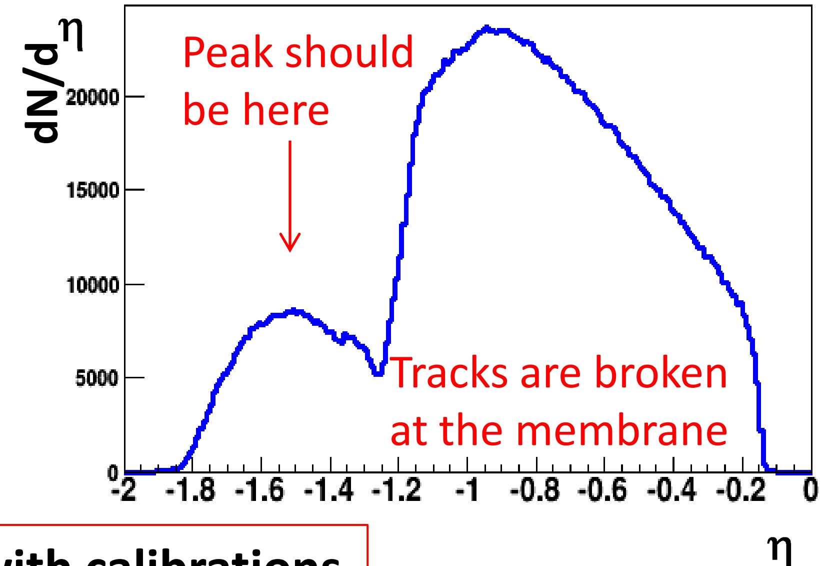
Conclusions:

- BES program is designed to study the phase diagram of QCD matter
- Need to access lower energy range to study all region of the phase diagram
- Fixed Target program along with key upgrades allows us to scan from 19.6 to 3.0 GeV (200-720 MeV in μ_B)

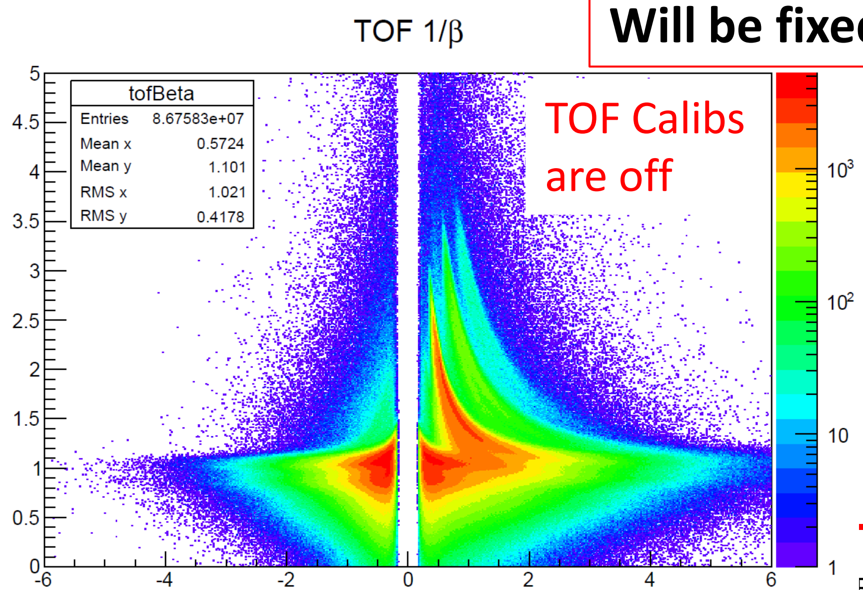
Extra Slides

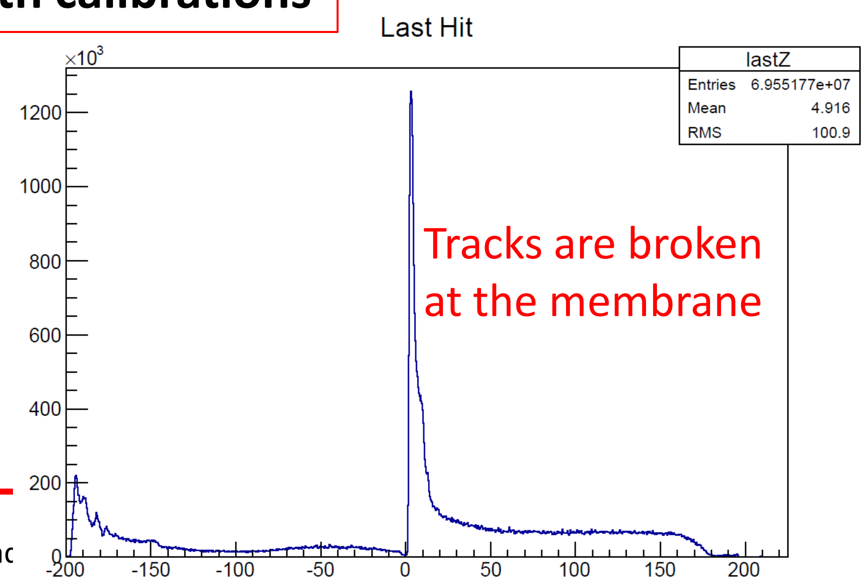
The 2015 Test Run data are all still "Preview Data" ➔ There are known issues





Will be fixed with calibrations

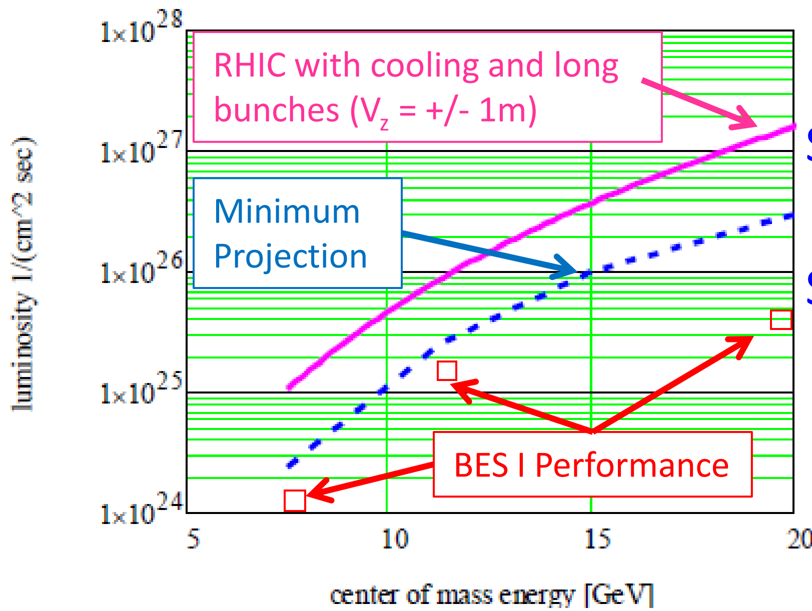




Low Energy Electron Cooling at RHIC

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 5 – 20 GeV

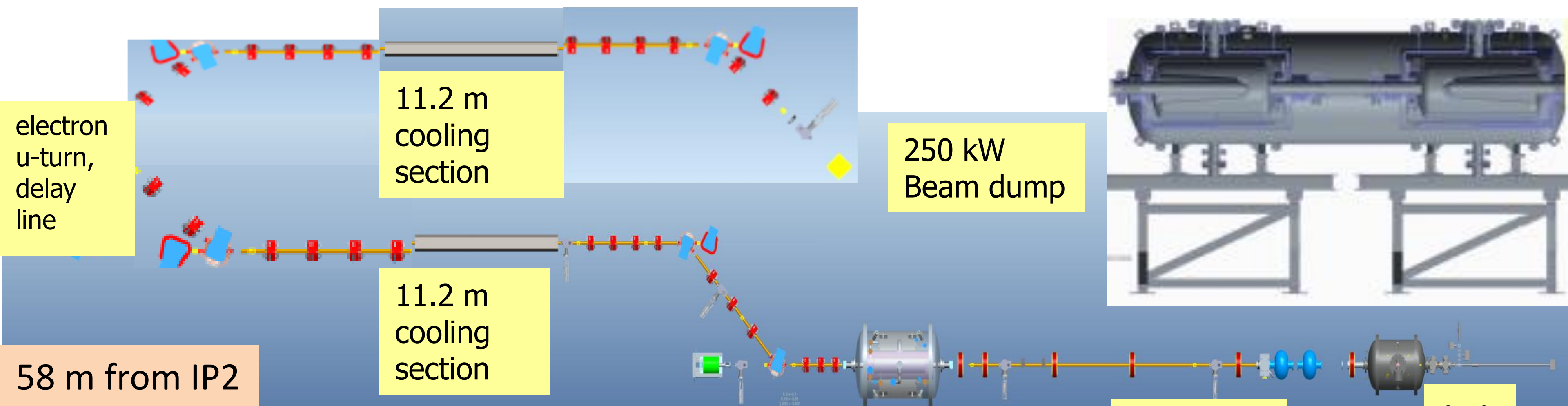
Long Bunches increase luminosity by factor of 2-5



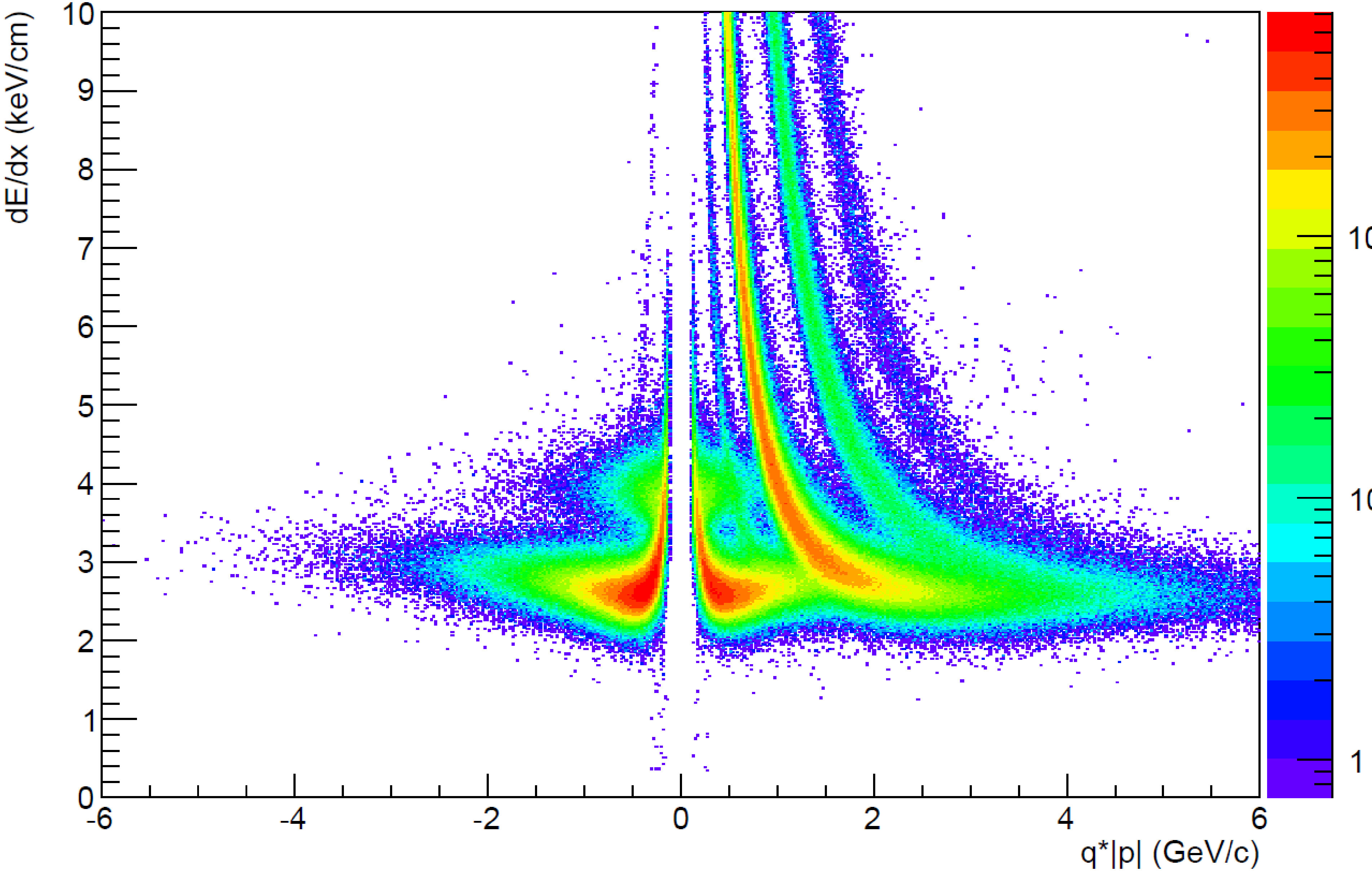
Stage I
$\sqrt{s_{NN}}$ = 5-9 GeV

Stage II -- 3 MeV booster cavity
$\sqrt{s_{NN}}$ = 9-20 GeV

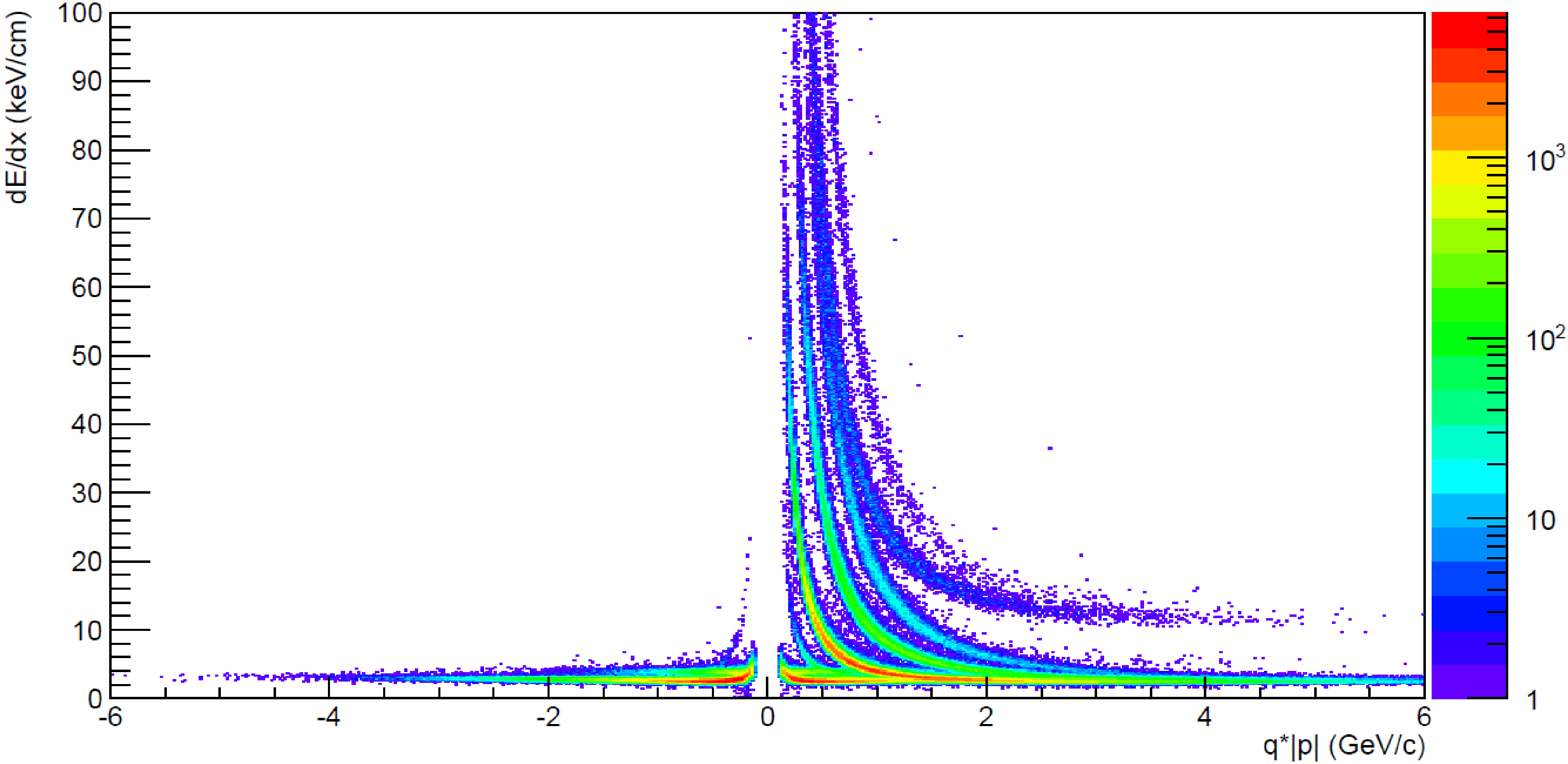
100 MHz SRF Gun

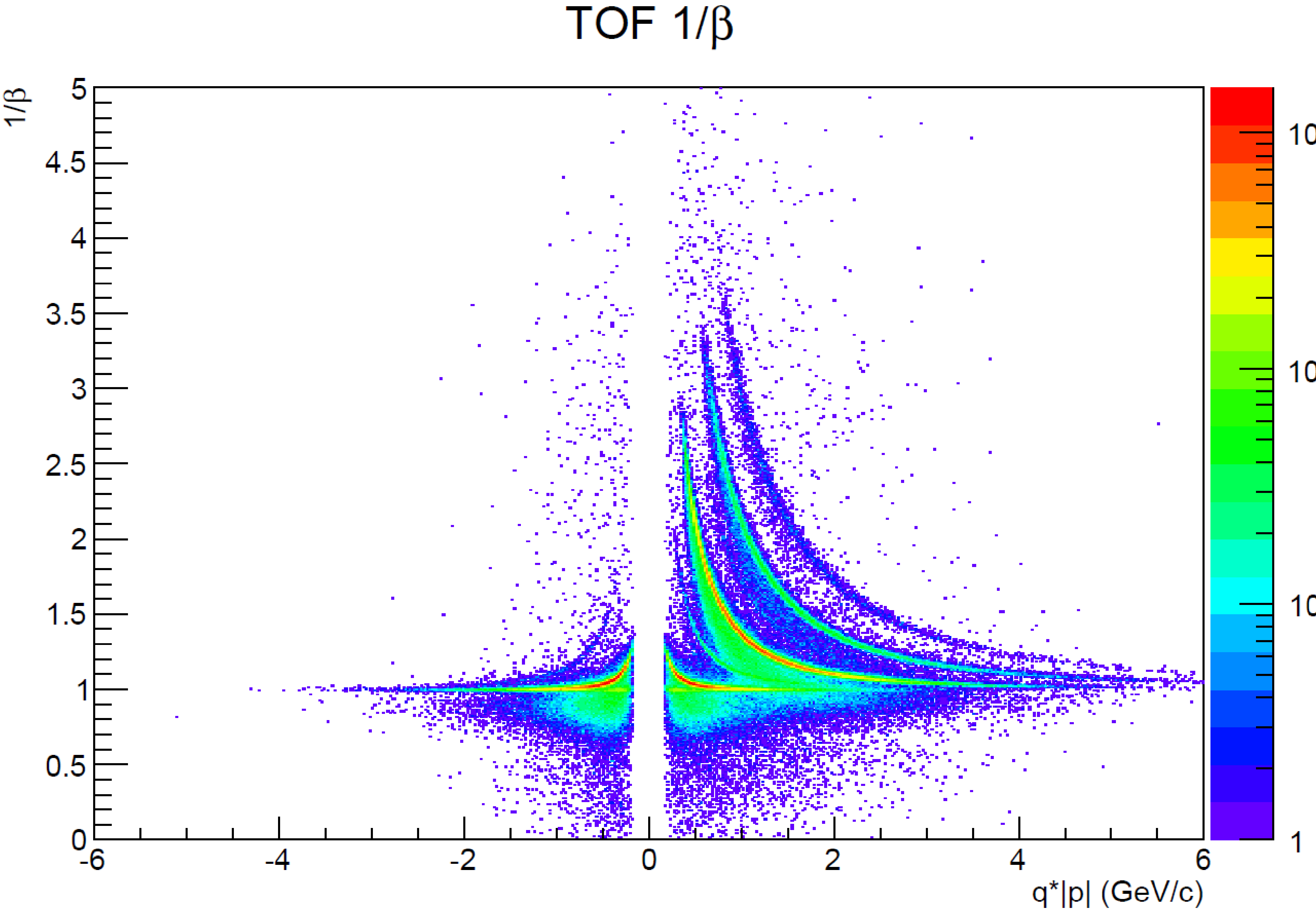


Energy Loss in TPC

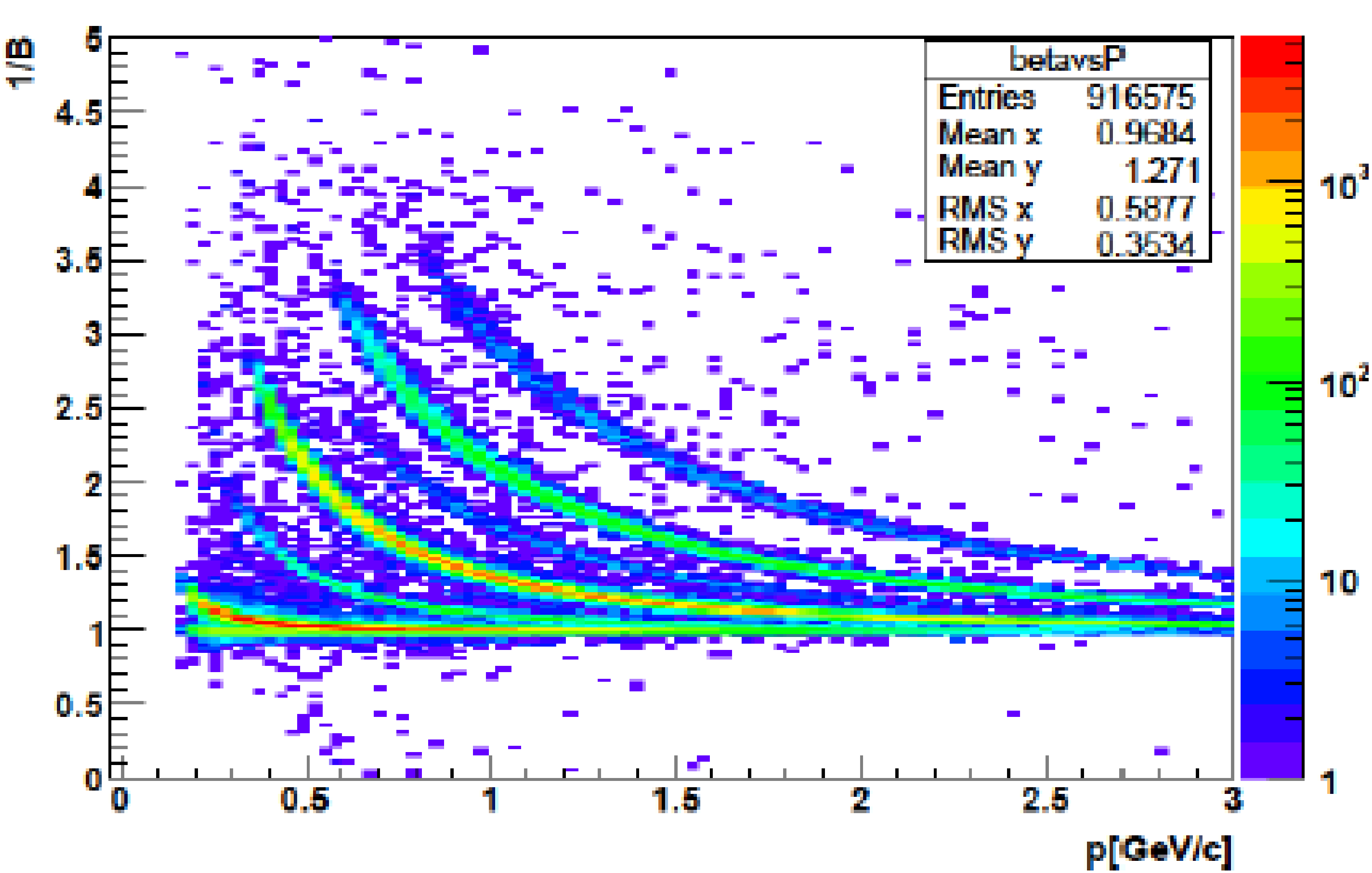


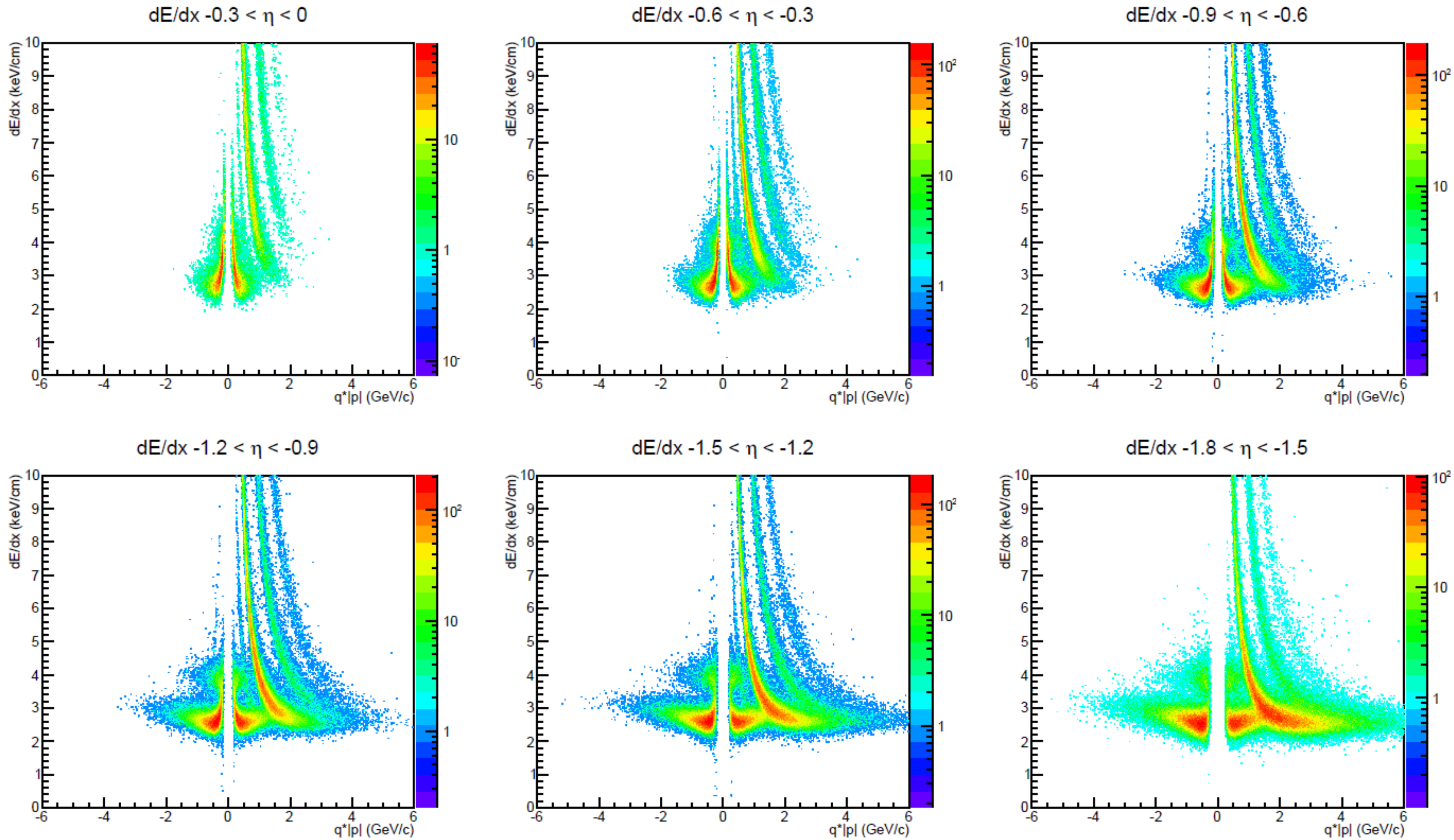
Energy Loss in TPC



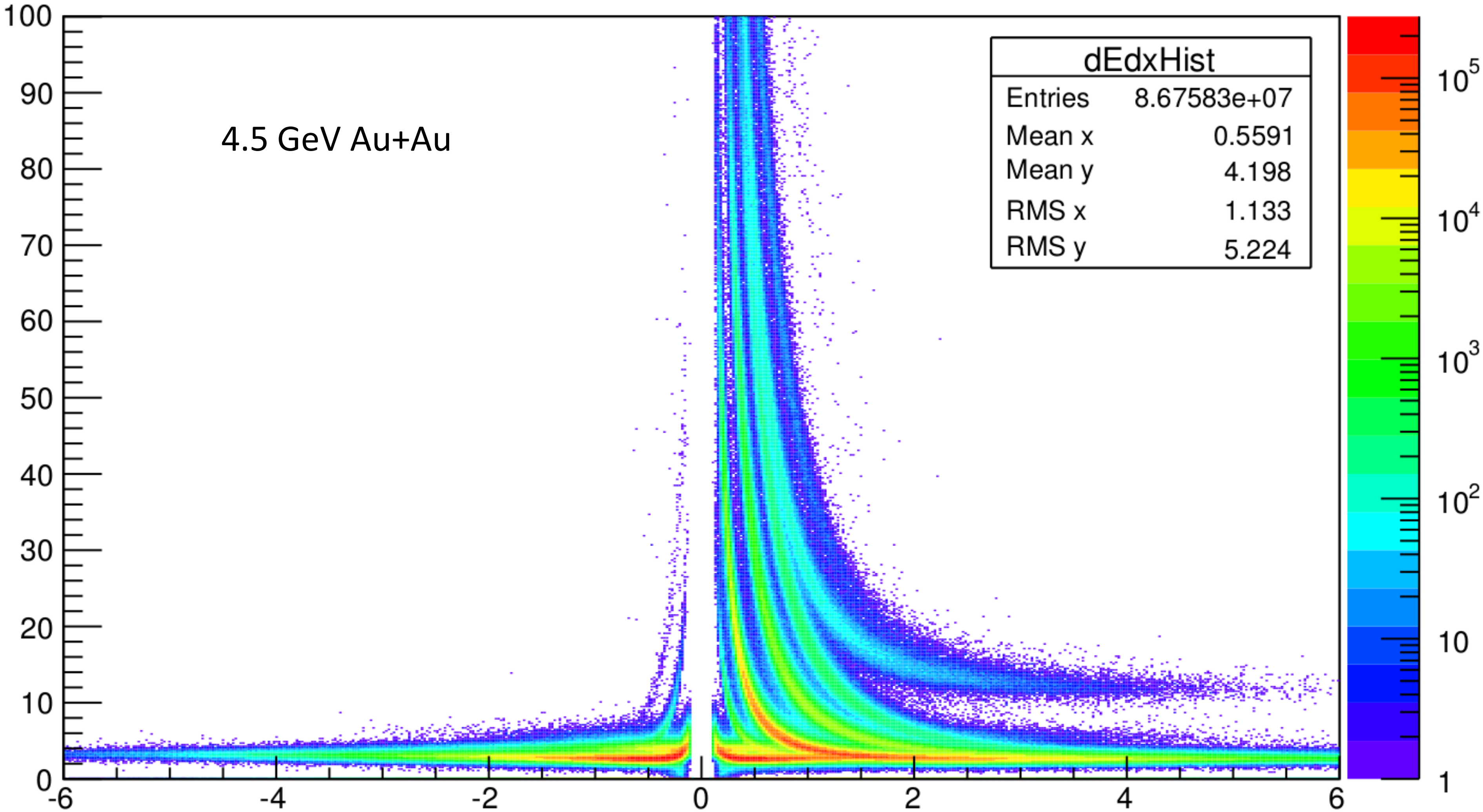


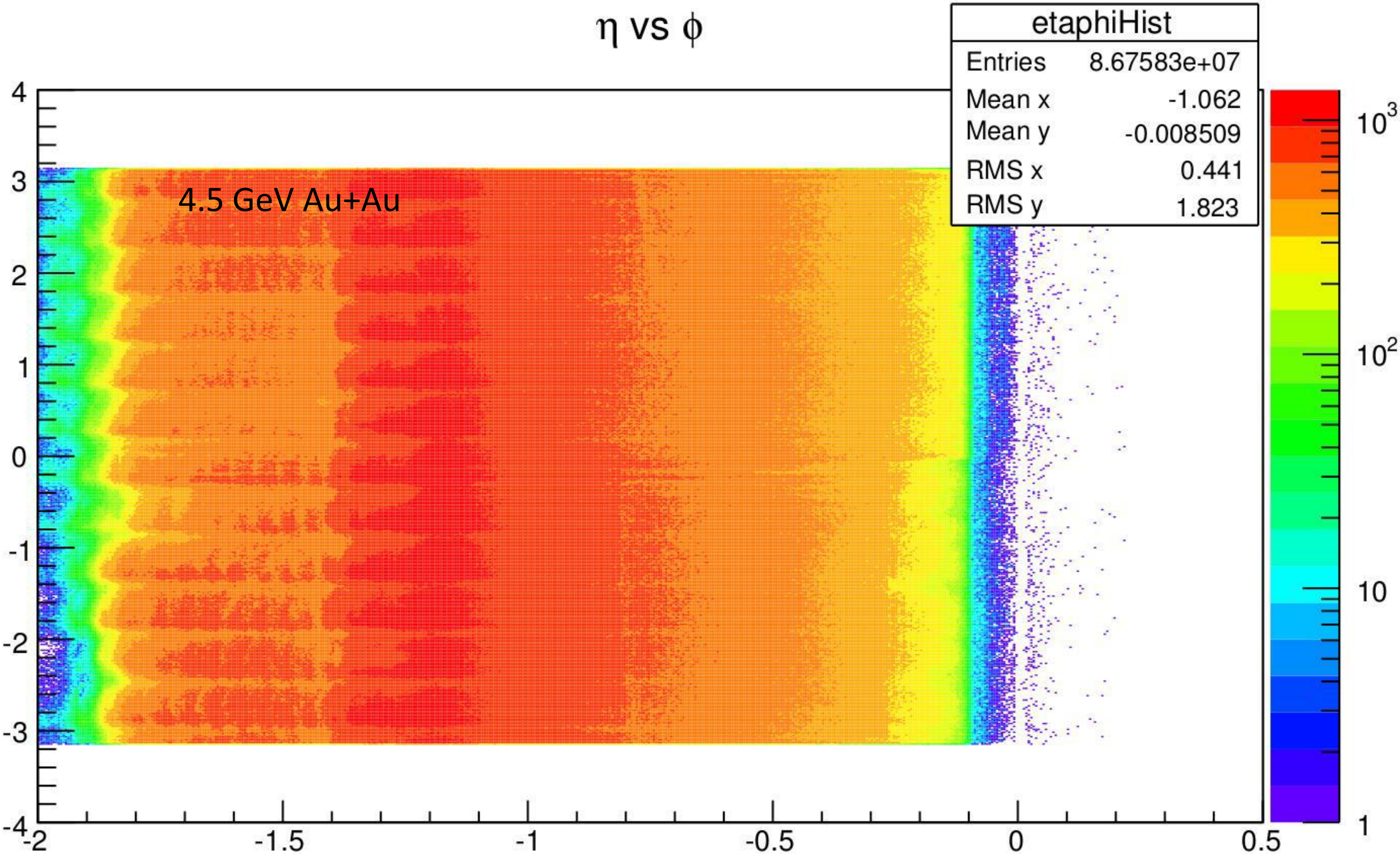
TOF 1/β
1/β
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-6
-4
-2
0
2
4
6
q*|p| (GeV/c)
1


betavsP
Entries 916575
Mean x 0.9684
Mean y 1.271
RMS x 0.5877
RMS y 0.3534
1/B
p[GeV/c]

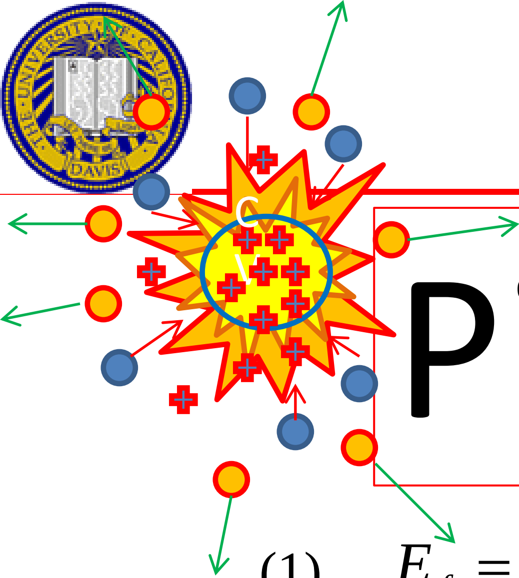

dE/dx -0.3 < η < 0
dE/dx -0.6 < η < -0.3
dE/dx -0.9 < η < -0.6
dE/dx -1.2 < η < -0.9
dE/dx -1.5 < η < -1.2
dE/dx -1.8 < η < -1.5
dE/dx (keV/cm)
q*|p| (GeV/c)

Energy Loss in TPC





η vs ϕ
etaphiHist
Entries 8.67583e+07
Mean x -1.062
Mean y -0.008509
RMS x 0.441
RMS y 1.823
4.5 GeV Au+Au
4
3
2
1
0
-1
-2
-3
-4
-2
-1.5
-1
-0.5
0
0.5
10^3
10^2
10
1



Pion Ratios

(1) $$E_f = E_i \pm V_C$$

Coulomb Potential

(2) $$R_f(E_f) = \boxed{\frac{E_f - V_C}{E_f + V_C} \frac{\sqrt{(E_f - V_C)^2 - m^2}}{\sqrt{(E_f + V_C)^2 - m^2}}} \frac{n^+(E_f - V_C)}{n^-(E_f + V_C)}$$

Jacobian

(3) $$\frac{n^+(E_f - V_C)}{n^-(E_f + V_C)} = \boxed{\frac{A^+(e^{(E_f + V_C)/T_\pi} - 1)}{A^-(e^{(E_f - V_C)/T_\pi} - 1)}}$$

Bose-Einstein Formulae

(4) $$V_{eff} = V_C(1 - e^{-E_{\max}/T_p})$$

$$\boxed{E_{\max} = \sqrt{(m_p p_\pi / m_\pi)^2 + m_p^2} - m_p}$$

Energy where the proton is faster then the pions with a given momentum

$$V_C = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$$

Glauber 0-5% Au+Au ➔ Coulomb potential of 68+68 within a radius of 7 fm = 28 MV

Glauber 0-10% Au+Al ➔ Coulomb potential of 22+13 within a radius of 3.4 fm = 15 MV

There are 22 protons from gold in the overlap region

Experiment	System	Energy (GeV)	Coulomb Potential	Initial Pion Ratio
KaoS	Au+Au	2.2	27.8 +/- 1.3	0.469 +/-0.011
E866	Au+Au	4.8	16.3 +/- 1.9	0.771 +/- 0.011
WA98	Pb+Pb	17.3	9.8 +/- 0.6	0.934 +/- 0.004
STAR	Au+Au	39	6.6 +/- 8.7	0.977 +/- 0.021
STAR	Au+Al	4.5	8.0 +/- 1.2	0.910 +/- 0.005
STAR	Au+Al	3.5	11.5 +/- 0.7	0.878 +/- 0.004
STAR	Au+Al	3.0	14.4 +/- 1.2	0.830 +/- 0.008

Nucleonic Resonances and Pions

Consider the numbers:

Nucleon-Nucleon Interactions:

$$n + n \rightarrow 7(\Delta^- + p) : 1(\Delta^0 + n)$$

$$p + p \rightarrow 7(\Delta^{++} + n) : 1(\Delta^+ + p)$$

$$p + n \rightarrow 1(\Delta^0 + p) : 1(\Delta^+ + p)$$

Charged Pion Decay Channels:

$$\Delta^{++} \rightarrow p + \pi^+$$

$$\Delta^+ \rightarrow n + \pi^+$$

$$\Delta^0 \rightarrow p + \pi^-$$

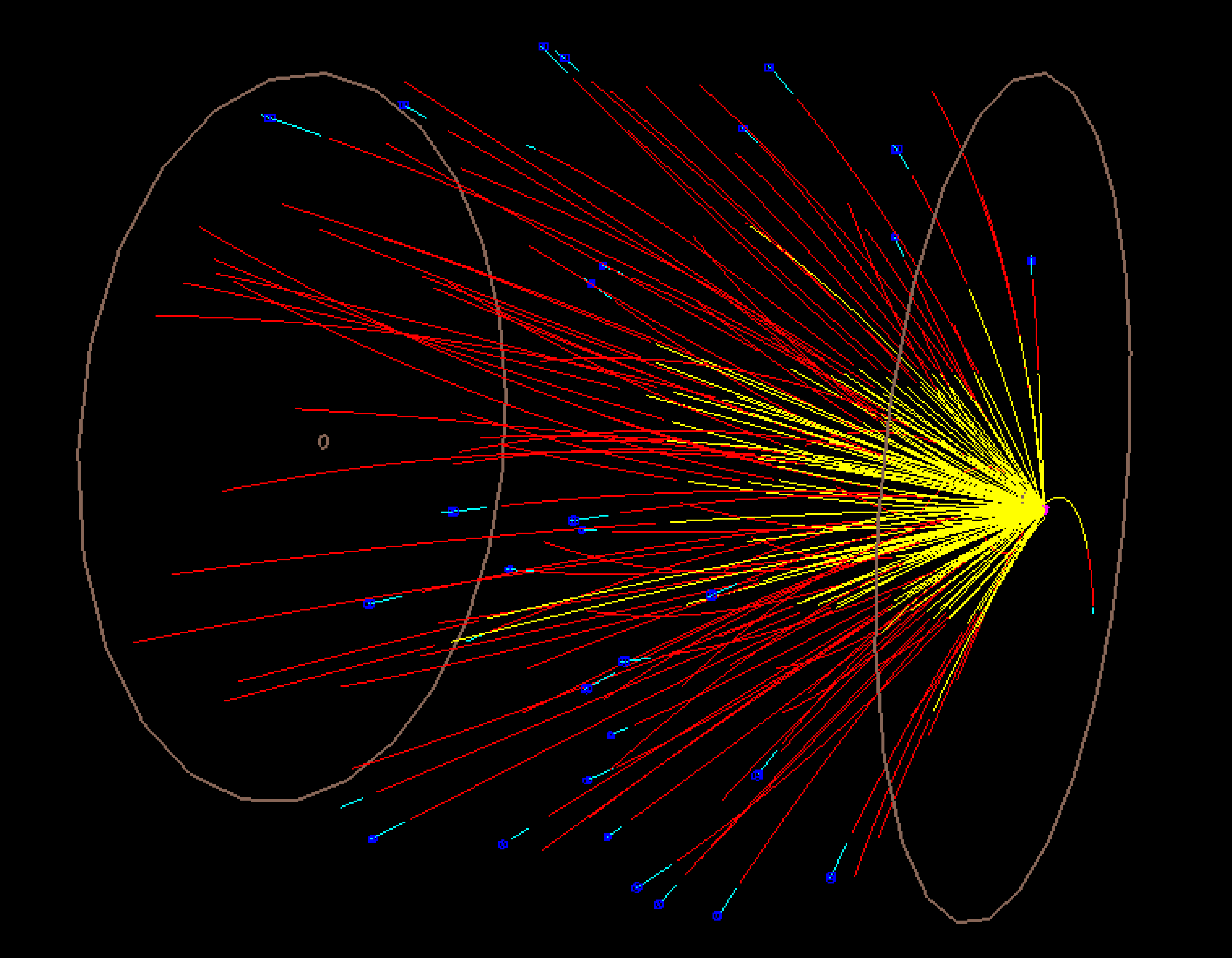
$$\Delta^- \rightarrow n + \pi^-$$

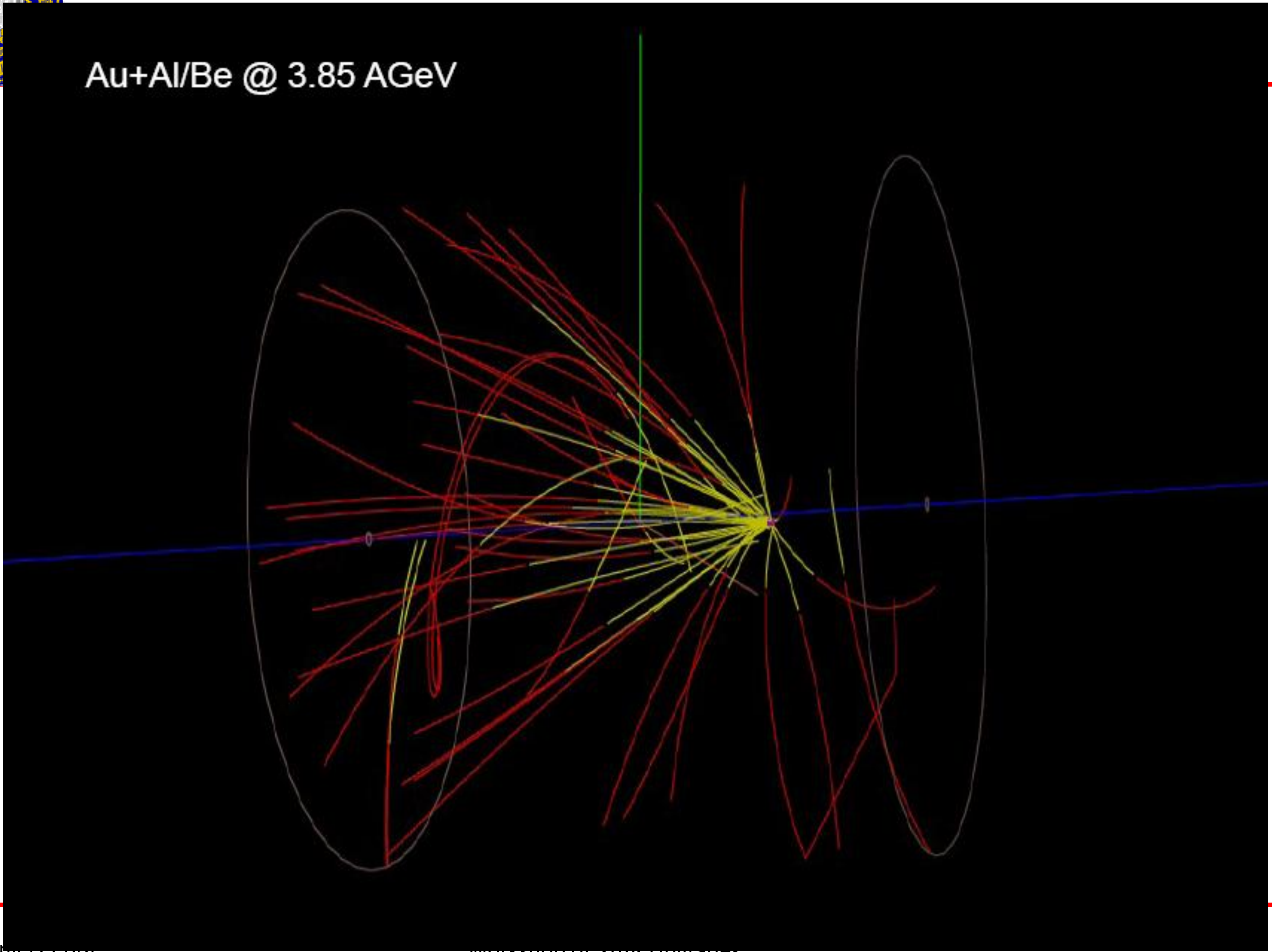
0-5% Au +Au $\rightarrow$ Glauber Model predicts $\langle N_{part} \rangle = 354$

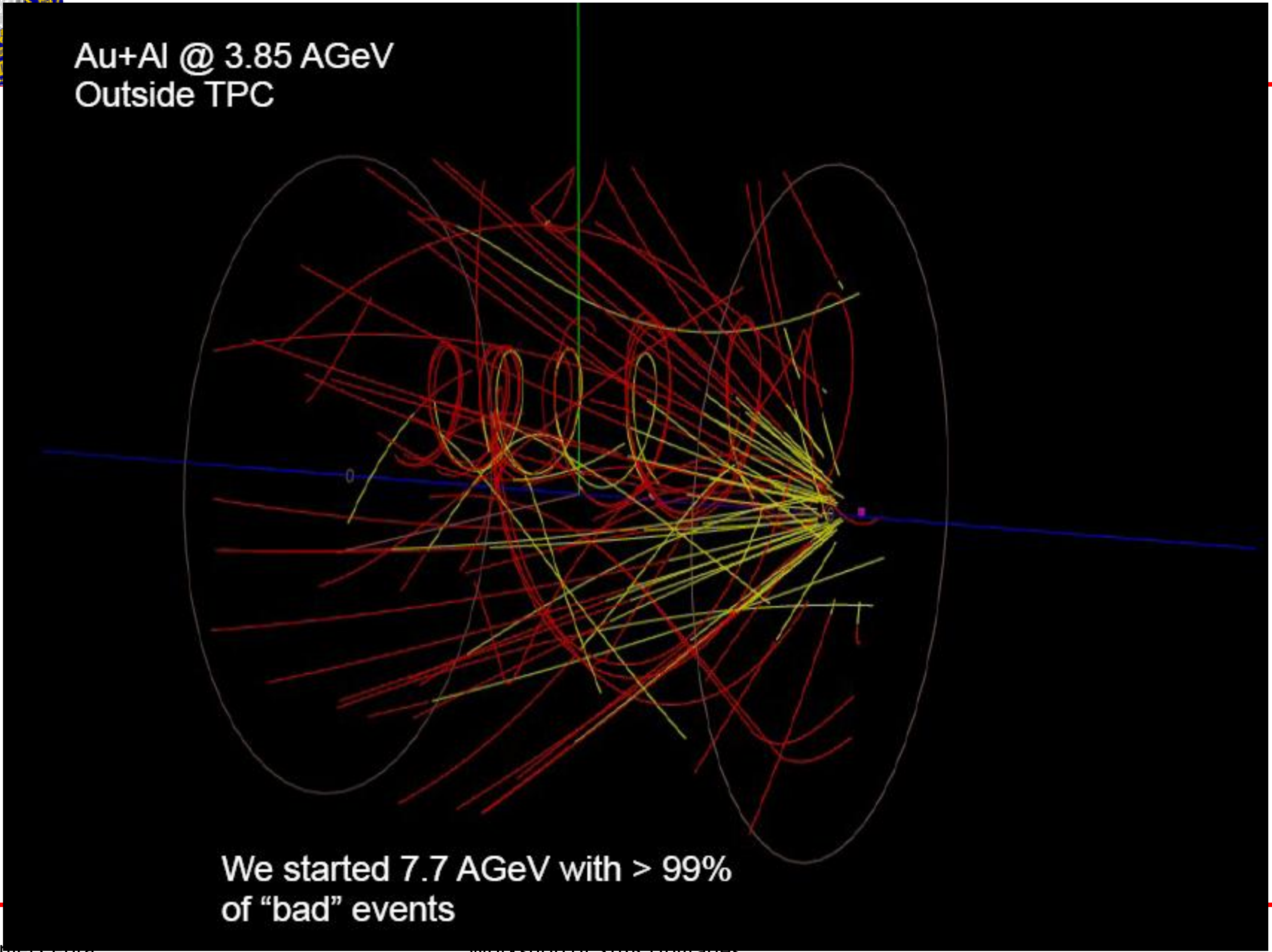
$\rightarrow$ more neutrons than protons, 218 : 136

More neutron interactions $\rightarrow$ more Pi-minus than Pi-plus

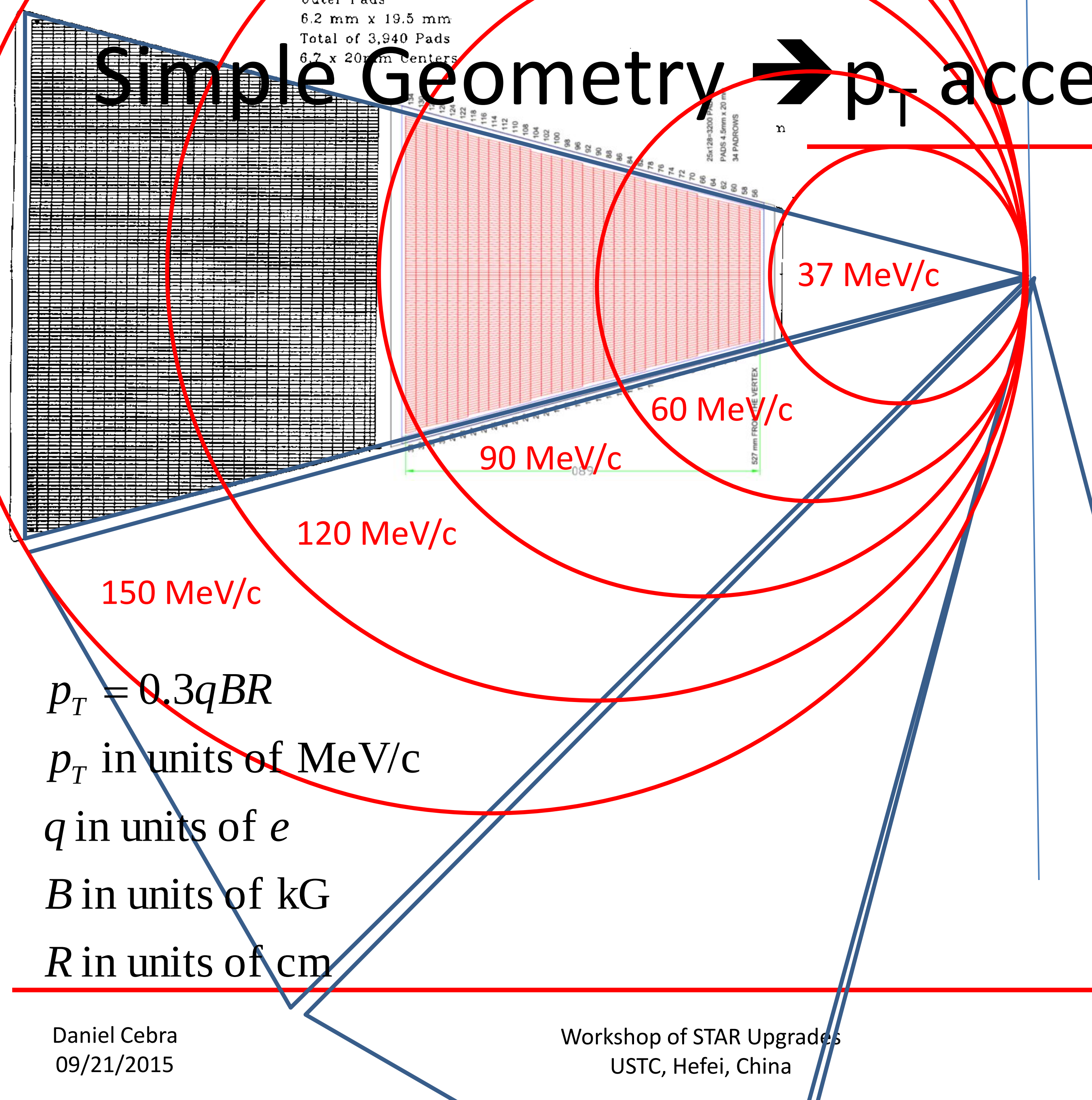
(2.27:1)


0


Au+Al/Be @ 3.85 AGeV


Au+Al @ 3.85 AGeV
Outside TPC
We started 7.7 AGeV with > 99%
of “bad” events

Simple Geometry ➔ p_T acceptance



$$p_T = 0.3qBR$$

p_T in units of MeV/c

q in units of e

B in units of kG

R in units of cm

STAR Low p_T acceptance is dependent on the track quality cuts.

Minimum of 10 hits for a track

Quality tracks require at least 25 hits.

Current TPC low p_T limit is 112.5 MeV/c

iTPC low p_T limit is 71 MeV/c

Momentum Resolution

$$(\delta k)^2 = (\delta k_{res})^2 + (\delta k_{ms})^2$$

$$k \equiv 1/R$$

$$p\cos\lambda = p\sin\theta = p_T = 0.3qBR$$

$$(\delta k_{res}) = \frac{\sigma_t \sqrt{720}}{s^2 \sqrt{n+4}}$$

Tracking Term

$$(\delta k_{ms}) = \frac{q(0.016)}{\sqrt{sX_0}\,\beta}$$

Multiple Scattering Term

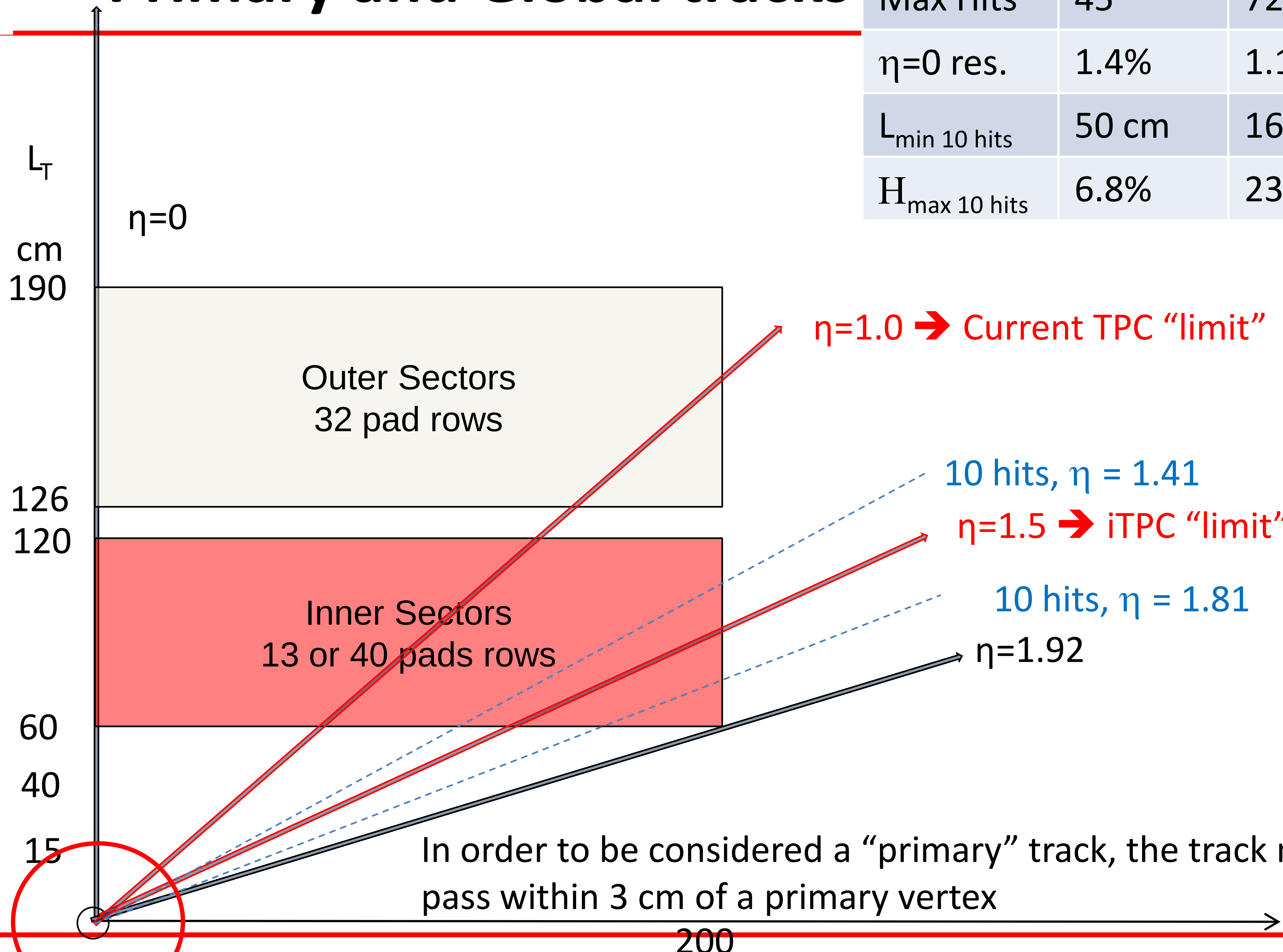
p = momentum (MeV/c)
σ_t = transverse resolution
q = charge of the particle (e)
B = magnetic field (kG)
n = number of spatial measures
s = track length
X_0 = radiation length
β = velocity

For STAR, the predicted momentum resolution is 1.4% at p_T of 400 MeV at mid-rapidity (from res. and ms terms). From tracking the resolution gets about 0.8% worse for each additional GeV

At STAR, resolution is 3% at 100 MeV

Primary and Global tracks

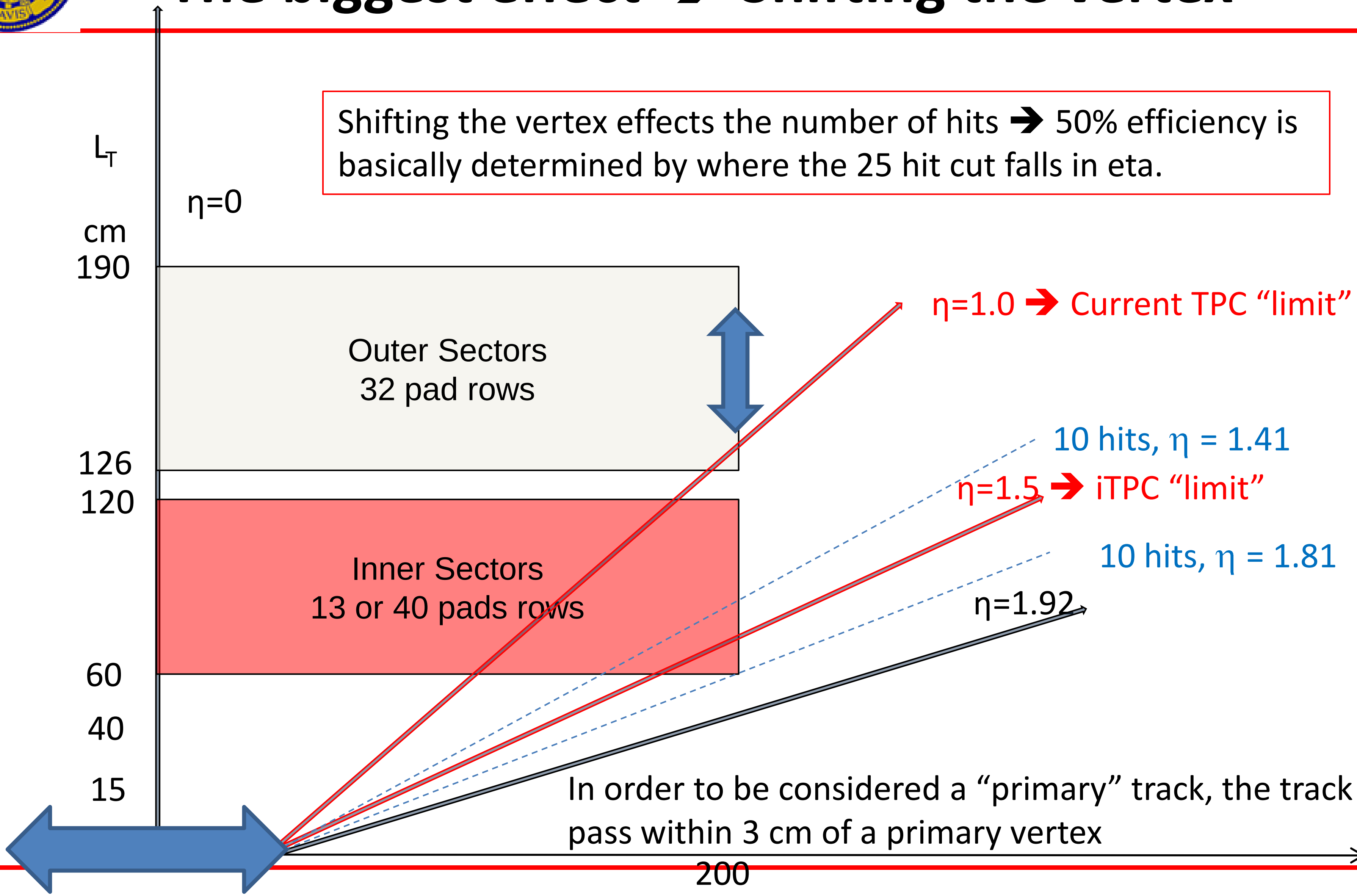
	Current	iTPC
Max Hits	45	72
η=0 res.	1.4%	1.1%
$L_{min\ 10\ hits}$	50 cm	16 cm
$H_{max\ 10\ hits}$	6.8%	23%



In order to be considered a "primary" track, the track must pass within 3 cm of a primary vertex

The biggest effect ➔ Shifting the vertex

Shifting the vertex effects the number of hits ➔ 50% efficiency is basically determined by where the 25 hit cut falls in eta.



In order to be considered a “primary” track, the track m
pass within 3 cm of a primary vertex

dE/dx Resolution

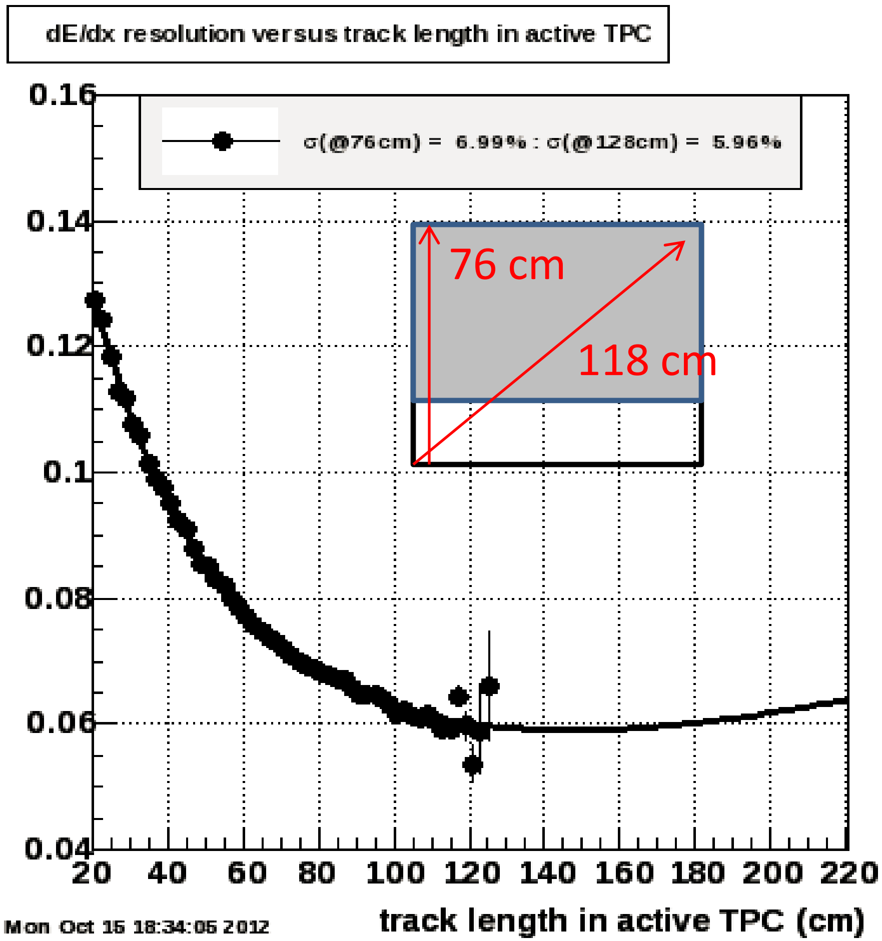
From Allison and Cobb, Ann. Rev. Nucl. Part. Sci. 30, 253 (1980)

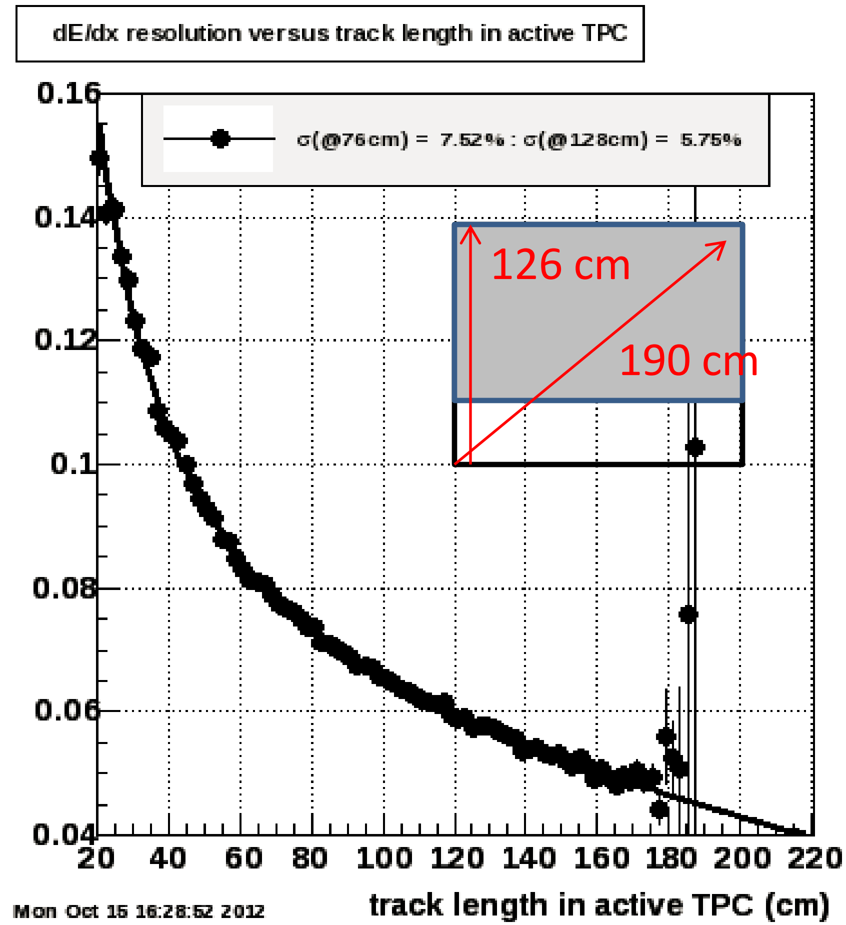
$$\sigma_{dEdx} = 0.47 N^{-0.46} (Ph)^{-0.32} (dE/dx)_{trunc}$$

N = number of dEdx samples
P = pressures in atomspheres
h = pad length (in cm)

$$\sigma_{dEdx} = 5.4 (L)^{-0.37} \%$$

Detector	N	h(cm)	P(atm)	expected	Observed
PEP TPC	183	0.4	8.5	2.9%	3.4%
MARK II	72	0.83	1.0	7.0%	7.2%
ALEPH	340	0.4	1.0	4.3%	5.1%
DELPHI	L = 0.76 m		1.0	6.0%	5.5%
EOS	128	1.2	1.0	4.8%	5.5%
STAR	44	1.15/1.95	1.0	6.8%	7.0%
ALICE	L = 1.65 m		1.0	5.5%	5.7%


dE/dx resolution versus track length in active TPC
σ(@76cm) = 6.99% : σ(@128cm) = 5.96%
76 cm
118 cm
0.16
0.14
0.12
0.1
0.08
0.06
0.04
20 40 60 80 100 120 140 160 180 200 220
Mon Oct 15 18:34:05 2012
track length in active TPC (cm)


dE/dx resolution versus track length in active TPC
σ(@76cm) = 7.52% : σ(@128cm) = 5.75%
126 cm
190 cm
0.16
0.14
0.12
0.1
0.08
0.06
0.04
20 40 60 80 100 120 140 160 180 200 220
Mon Oct 15 16:28:52 2012
track length in active TPC (cm)

Tabulating dE/dx PID

eta	0	0.5	0.9	1	1.1	1.2	1.3	1.4	1.5
dE/dx length	79.0	89.1	113.2	91.0	65.1	39.8	27.2	22.2	18.3
dE/dx resolu.	6.8%	6.4%	5.7%	6.3%	7.4%	9.3%	11.1%	12.2%	13.3%
π/p sep.	1.45	1.46	1.49	1.47	1.43	1.36	1.29	1.25	1.21
pT	1.45	1.30	1.04	0.95	0.86	0.75	0.66	0.58	0.52
rapidity (y)	-	0.41	0.70	0.76	0.81	0.84	0.86	0.88	0.90
iTPC length	126.0	142.1	180.6	163.6	143.5	123.1	116.3	101.1	80.0
iTPC $\sigma_{dE/dx}$	6.4%	6.0%	5.4%	5.7%	6.0%	6.5%	6.6%	7.1%	7.9%
π/p sep.	1.47	1.48	1.50	1.49	1.48	1.46	1.46	1.44	1.41
pT	1.47	1.31	1.05	0.97	0.89	0.81	0.74	0.67	0.60
rapidity (y)	0	0.41	0.70	0.77	0.82	0.87	0.92	0.95	0.98

Particle Identification by TOF

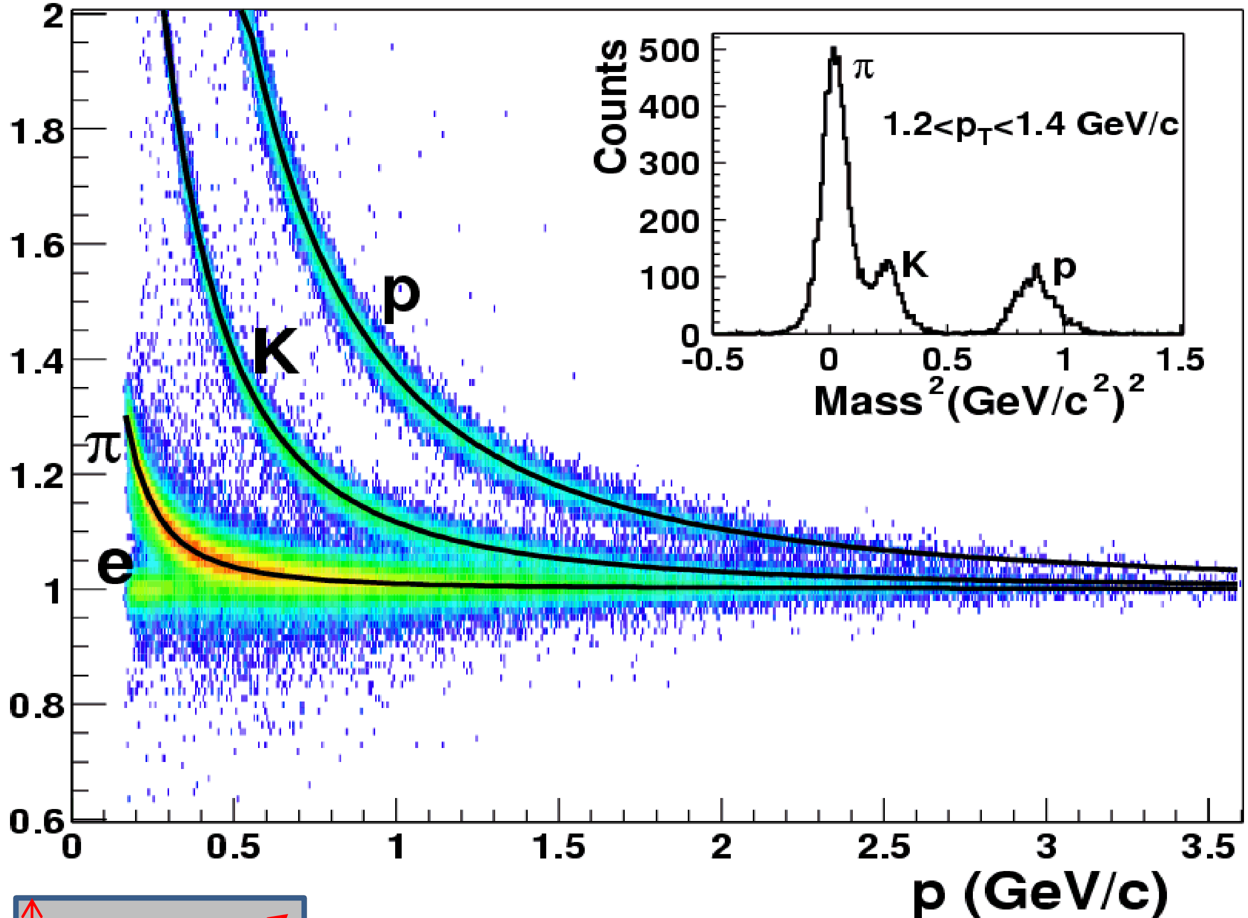
$$TOF = d / \beta c$$

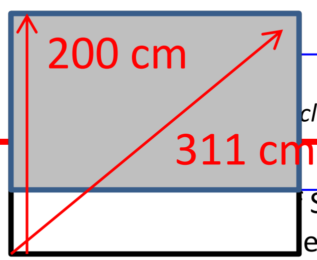
$$t + \Delta t = \frac{d}{c}\left(\frac{1}{\beta} + \delta\frac{1}{\beta}\right)$$

Δt = 50 ps

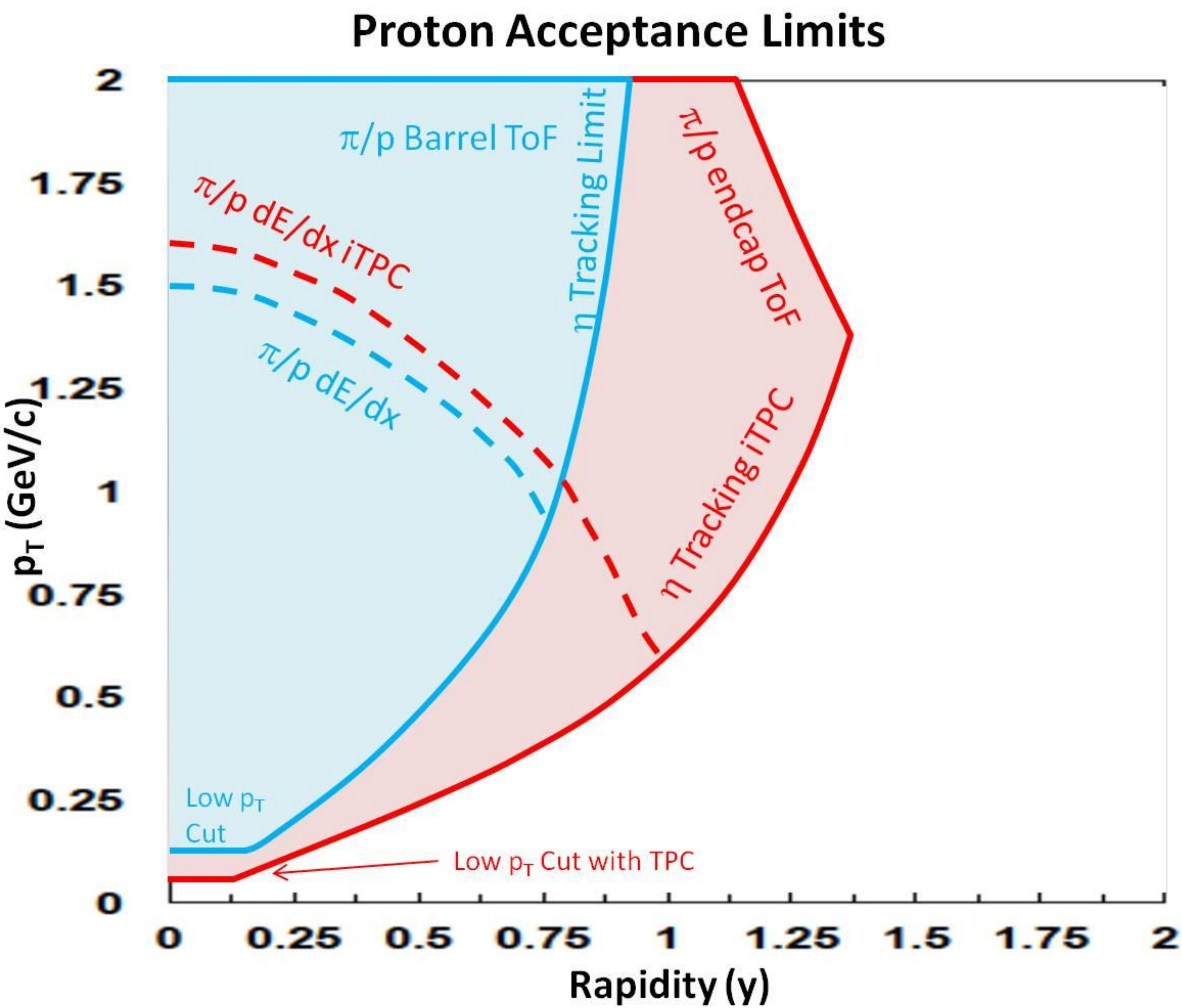
At η=0:
π/k is 1.5 GeV/c
k/p is 3.0 GeV/c

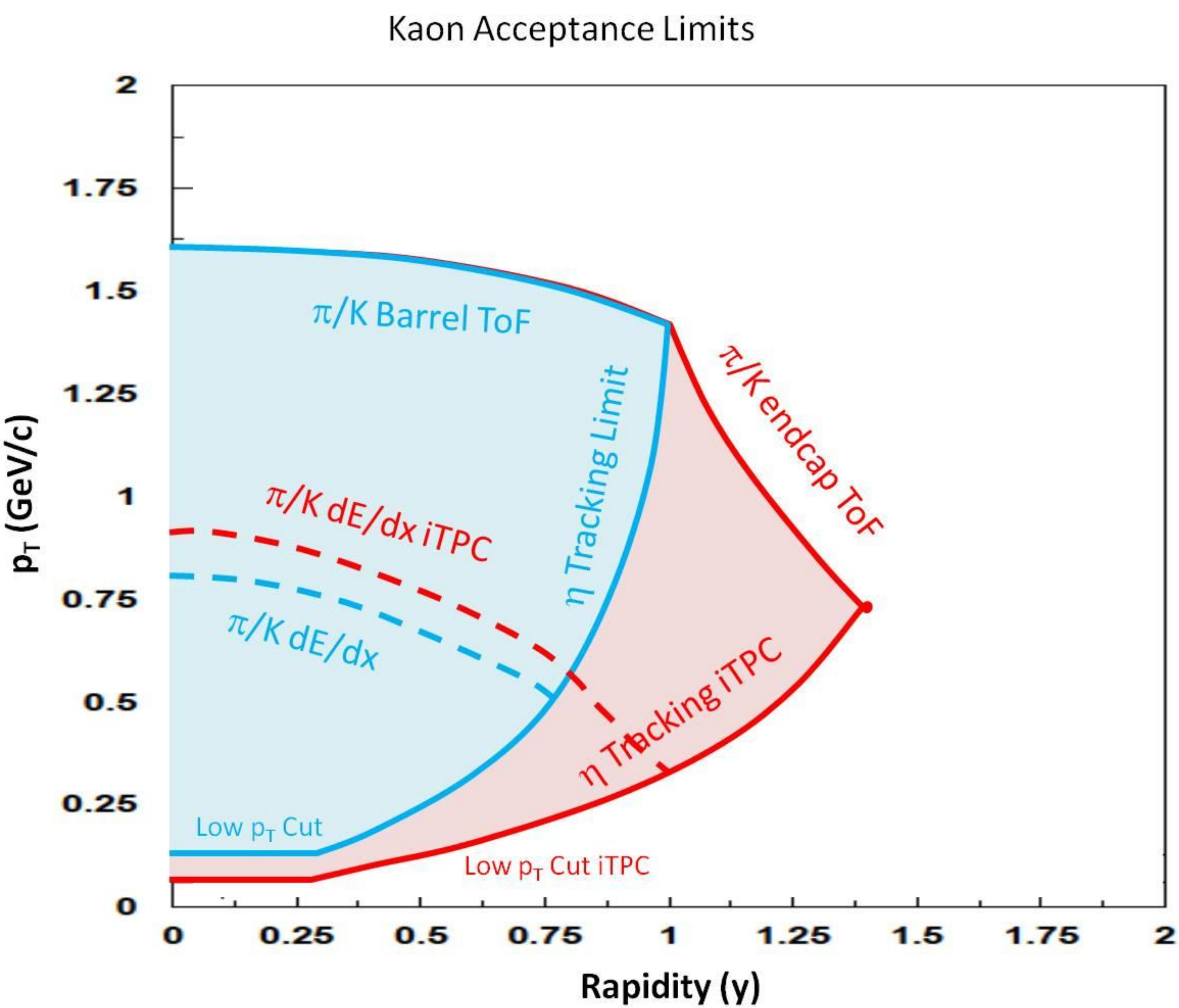
Flight path varies with η



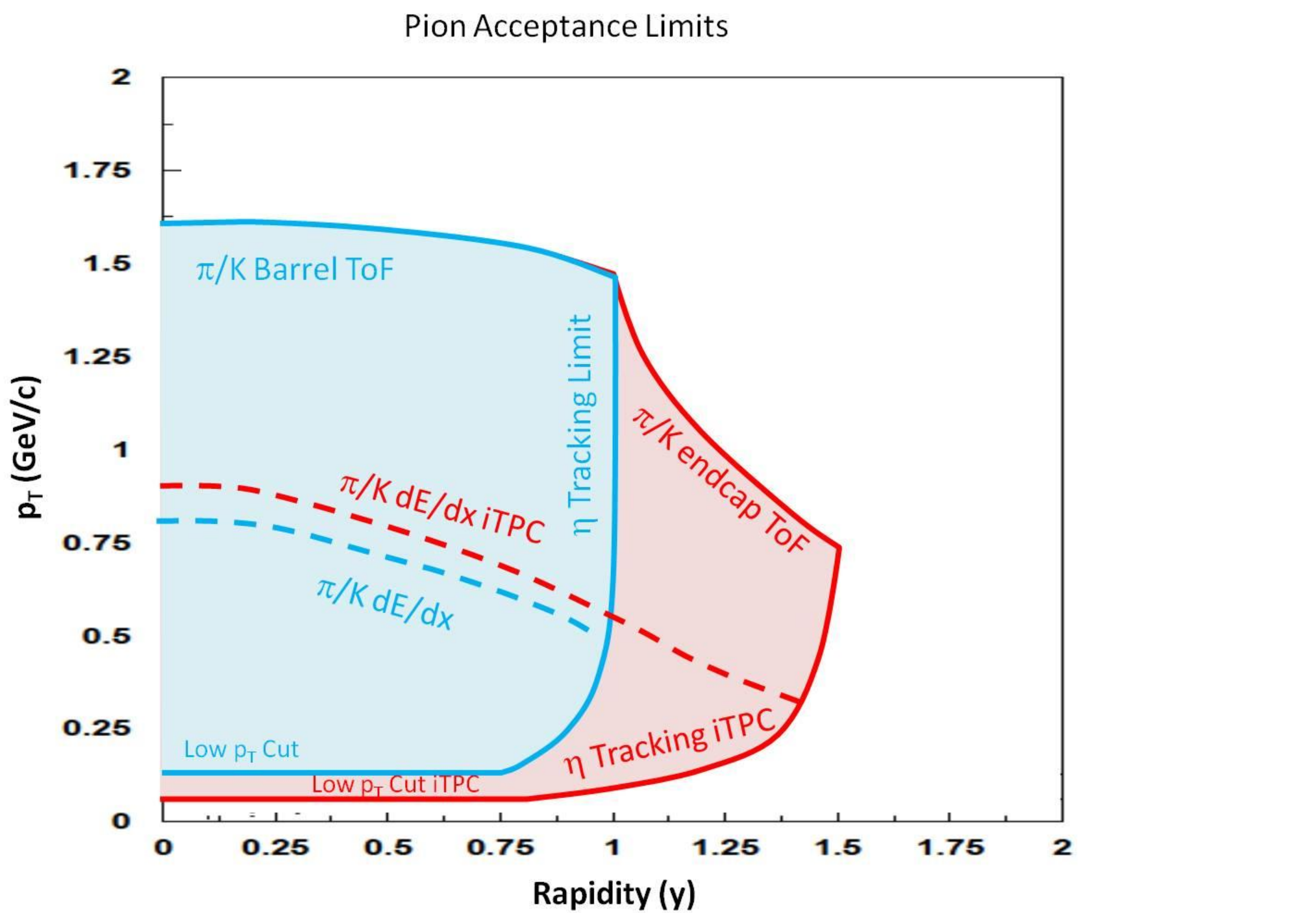


cl-ex/0309012


Proton Acceptance Limits
π/p Barrel ToF
η Tracking Limit
π/p endcap ToF
π/p dE/dx iTPC
π/p dE/dx
η Tracking iTPC
Low p_T Cut
Low p_T Cut with TPC
p_T (GeV/c)
Rapidity (y)
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2

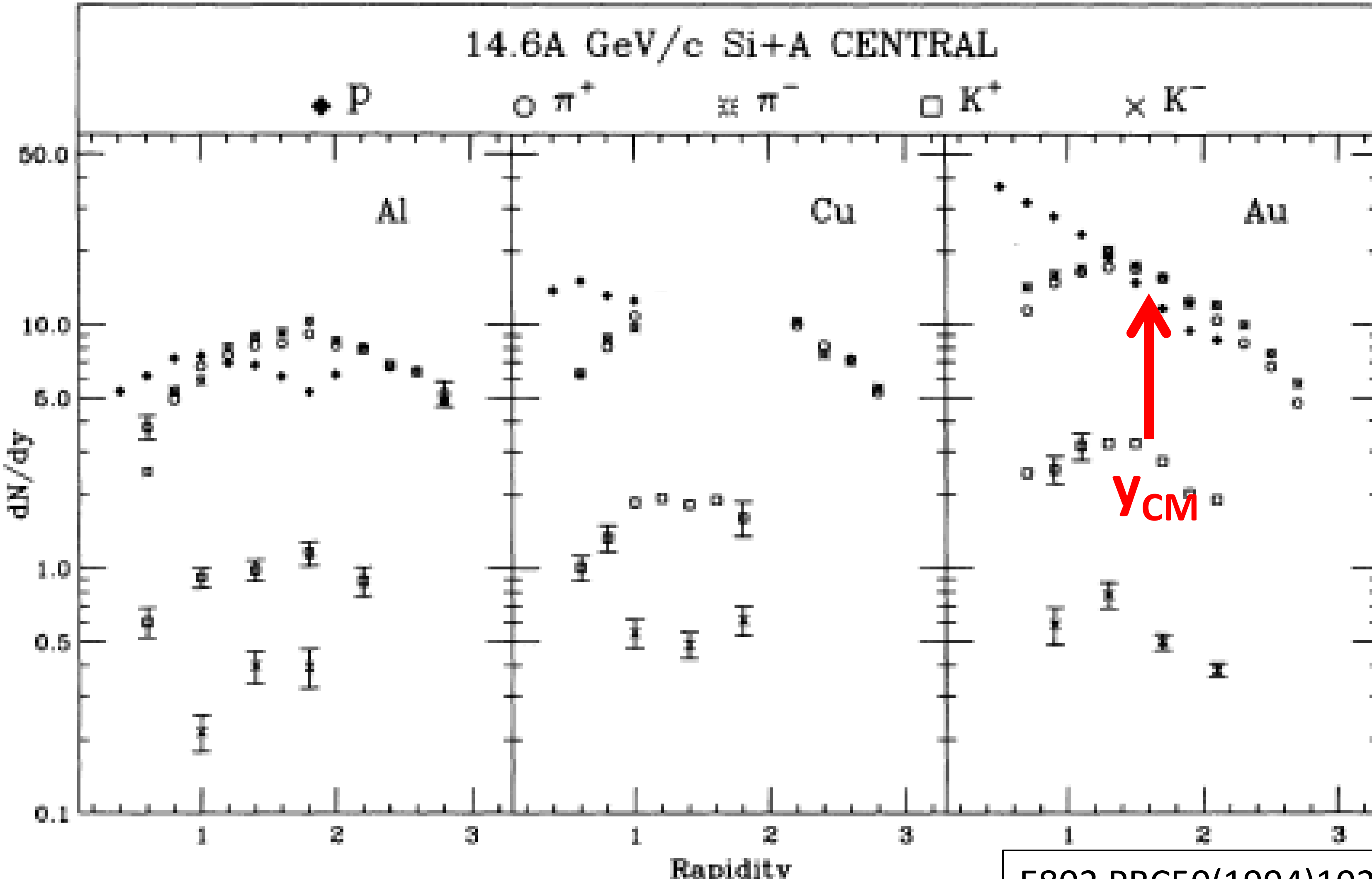


Kaon Acceptance Limits
π/K Barrel ToF
η Tracking Limit
π/K endcap ToF
π/K dE/dx iTPC
π/K dE/dx
η Tracking iTPC
Low p_T Cut
Low p_T Cut iTPC
p_T (GeV/c)
Rapidity (y)
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2



Pion Acceptance Limits
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
p_T (GeV/c)
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Rapidity (y)
π/K Barrel ToF
η Tracking Limit
π/K endcap ToF
π/K dE/dx iTPC
π/K dE/dx
η Tracking iTPC
Low p_T Cut
Low p_T Cut iTPC

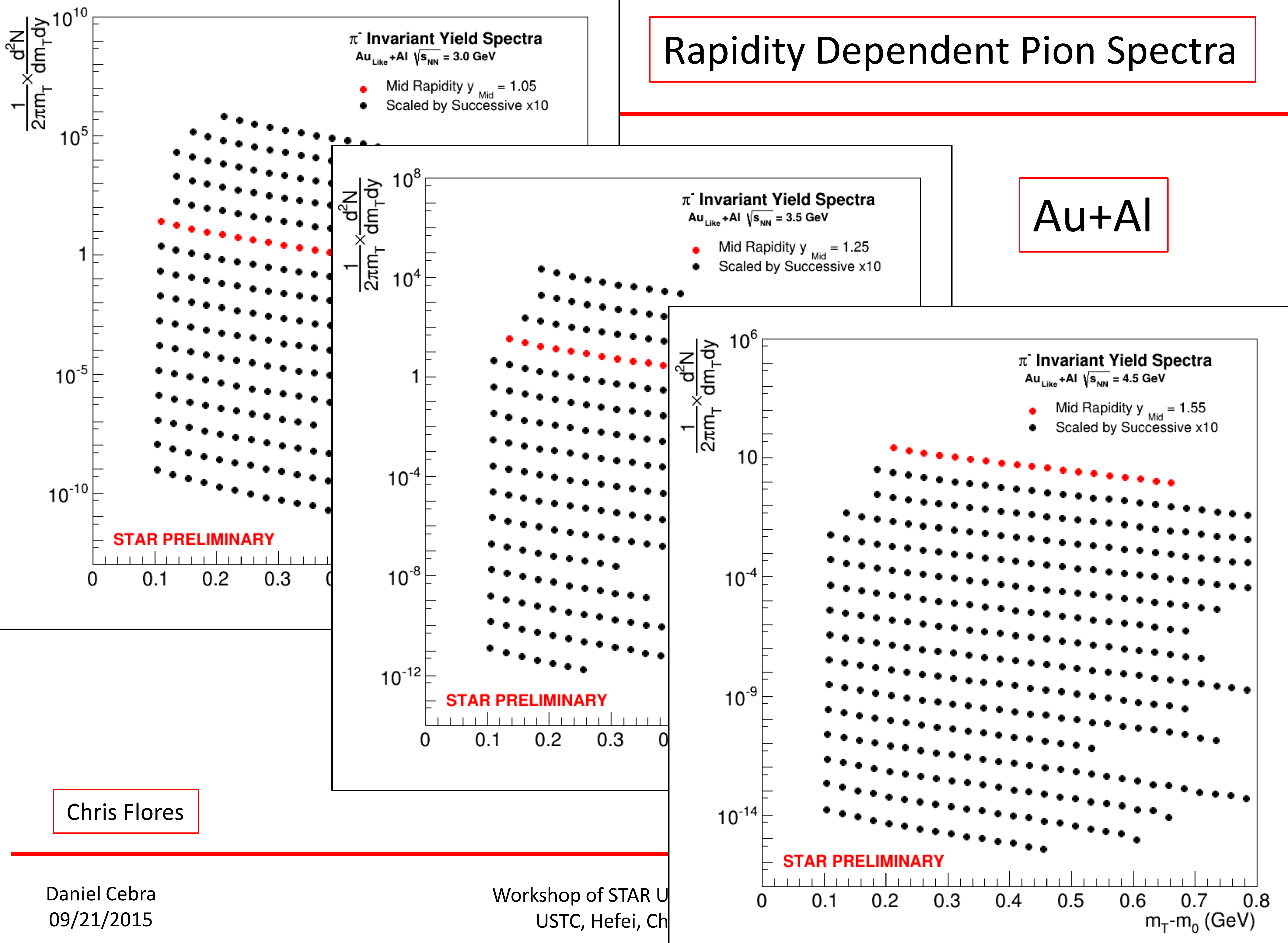
5.5 GeV Si + Au --- E802 Results



E802 PRC50(1994)1024

Rapidity Dependent Pion Spectra

Au+Al



Chris Flores

Pion Rapidity Density Distributions

Au+Al

- Unfortunately, we can not really determine the location of the maximum.
- We need to also have the inverse kinematics → Al+Au