STAR and the RHIC Energy Scan

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Yale University

INT Mini-workshop on the QCD Critical Point
Seattle, Washington
August 2008

Outline

- Introduction
- STAR in the Energy scan era
  - What our capabilities will be past 2010
- STAR current efforts for the energy scan
- STAR's planned measurements
- STAR's preferred run plan
- Summary and Conclusions

More than just a critical point search

Need to be careful not to just focus on Critical Point search:

- Is the Critical Point a valid concept in HI Collisions
  - Do collisions form a thermodynamic state?
  - If we don't see evidence does it mean it is not there,we looking in the wrong place, or looking for wrong signals?
  - Will semihard processes (noise) obscure the critical point (signal)?
  - Can Critical Point concept be disproved?

- We are also asking other questions:
  - What is the evolution of the unusual medium's properties with $\sqrt{s}$
  - Do any of the sQGP signatures turn off?
  - Can we see evidence of ordered transition?
  - What new surprises await in the unexplored region?

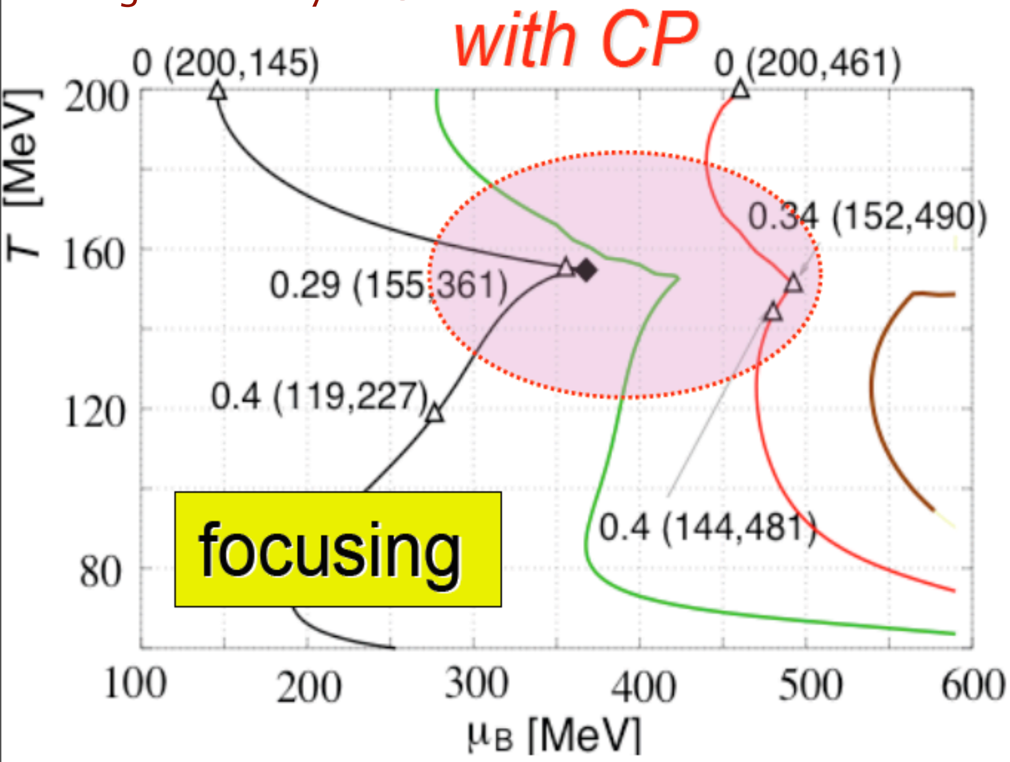
What we plan (currently) to look at

Many ideas, mostly qualitative or semi-quantitative

- Bulk properties
  - ratios, spectra (T_{ch}, T_{fo}, μ_B)
- Fluctuations & correlations of many varieties
  - K/π, $\langle p_T \rangle$, v_2 (critical point fluctuations)
  - pair correlations
- Energy dependence of flow characteristics (v_1 and v_2)
  - Collapse of proton flow (phase transition)
  - N_q scaling? (deconfinement)
  - ϕ and Ω (deconfinement)
- Signals of parity violation
- Other ideas spawned by prospect of data

If there, a critical point doesn't hide…

Image courtesy of C.Nonaka



- Hydro predicts that the evolution of the system is attracted to the critical point.
- Effect observed already for liquid-gas nuclear transition
- Focusing causes broadening of signal region - No need to run at exactly Critical Point energy

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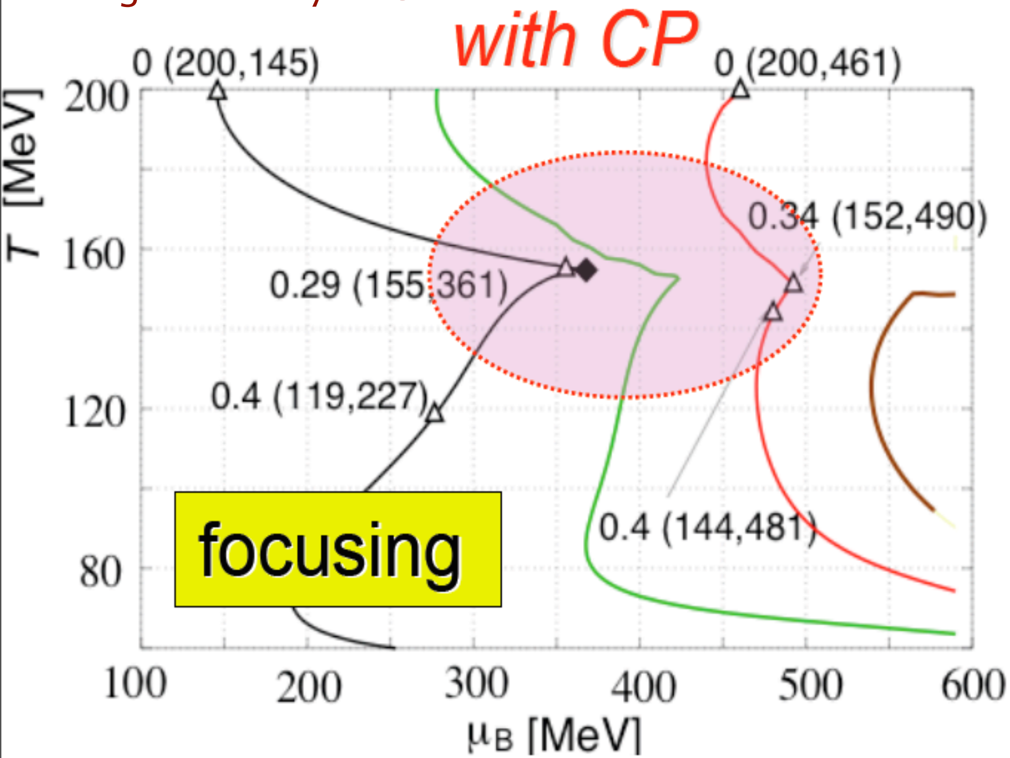

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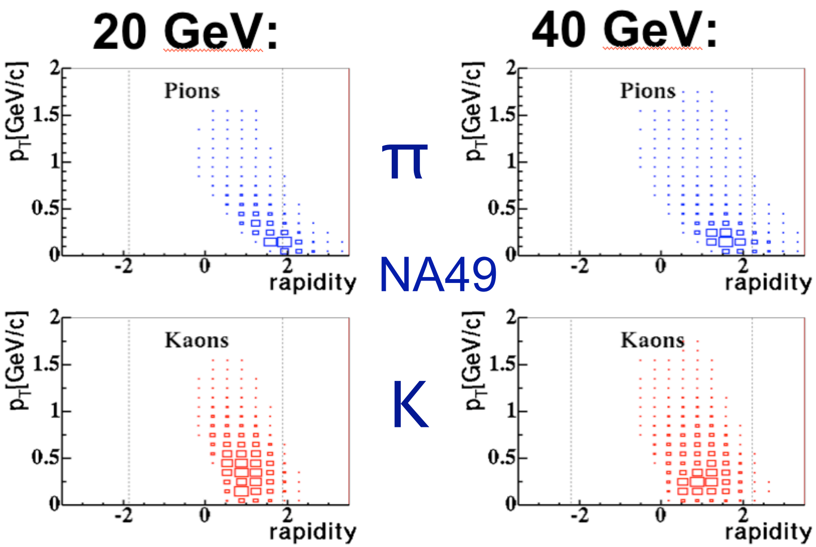
Correlation lengths expected to reach at most 2 fm (Berdnikov, Rajagopal and Asakawa, Nonaka): reduces signal amplitude, no sharp discontinuities

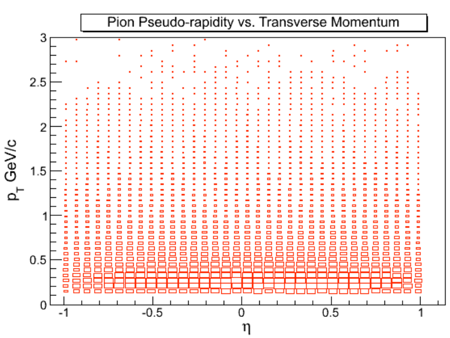
Finding evidence for a 1st order phase transition would immediately narrow location of the critical point.

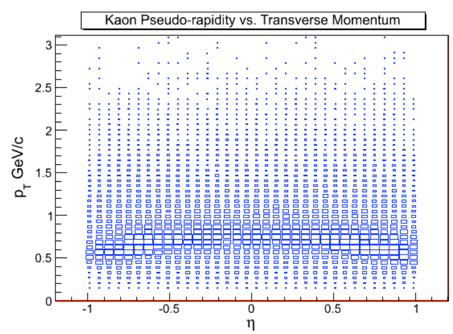
Colliders are a great choice for E-scan

Acceptance



π STAR K



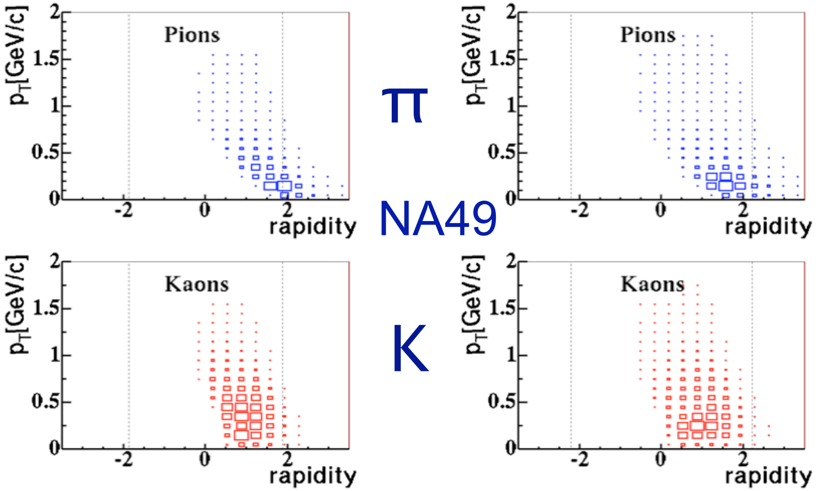


Acceptance for collider detectors is totally independent of beam energy

Colliders are a great choice for E-scan

Acceptance

20 GeV: 40 GeV:



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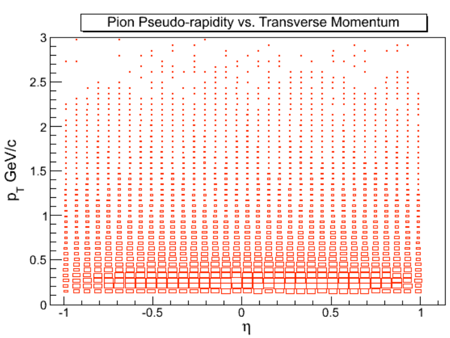

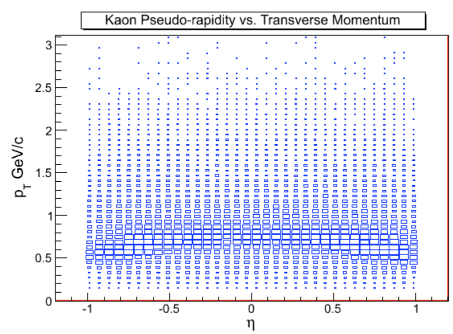

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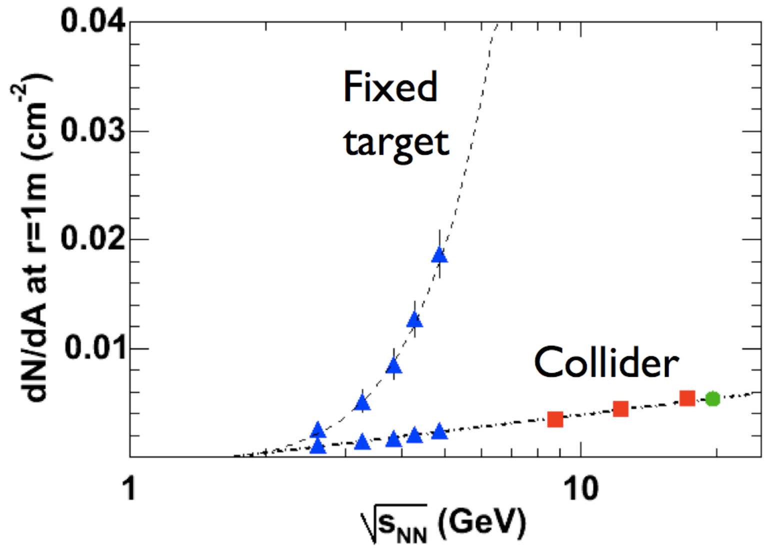
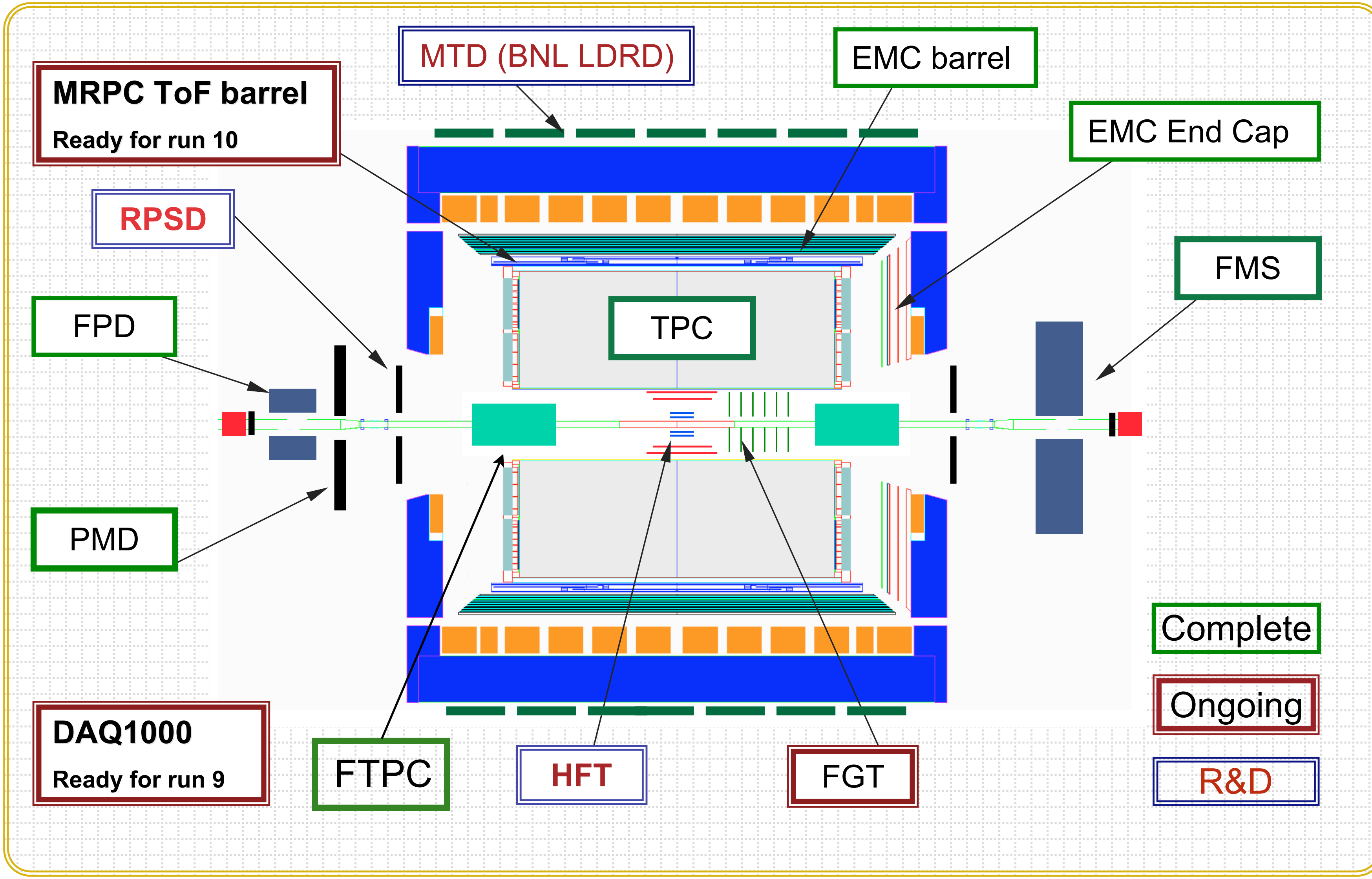


- Occupancy for collider detectors is much less dependent on beam energy
- Less problems with track merging, charge sharing hits etc..

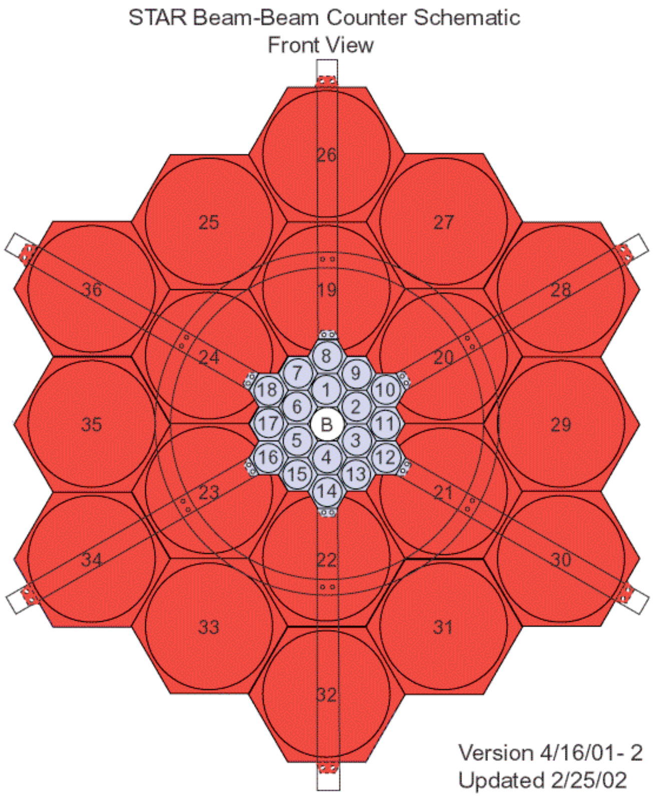
Better control of systematics

STAR post 2010



Compatibility of FTPCs and FGT/HFT being investigated - only issue if run after 2010

Triggering using BBCs



Studies indicate BBCs can be used for triggering.

No. of particles larger than that for p+p.

impact parameter	AuAu @ 5 GeV BBC Inner	AuAu @ 5 GeV BBC Outer	AuAu @ 8.75 GeV BBC Inner	AuAu @ 8.75 GeV BBC Outer
0<b<3	5	27	12	54
3<b<6	11	30	21	57
6<b<9	22	35	39	40
b>9	44	30	66	8

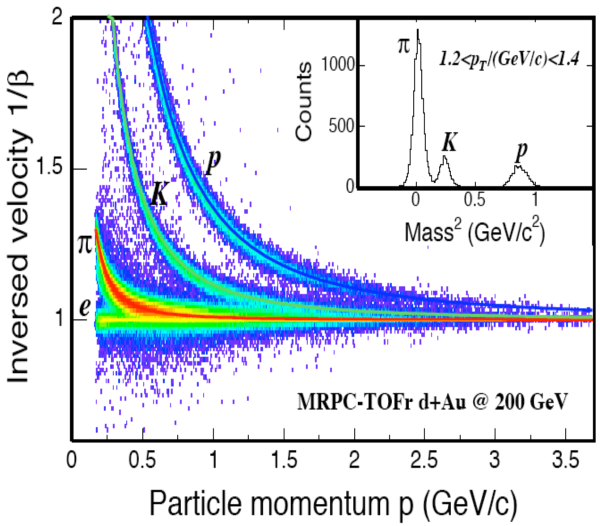
Sensitive down to single MIP hitting the detector

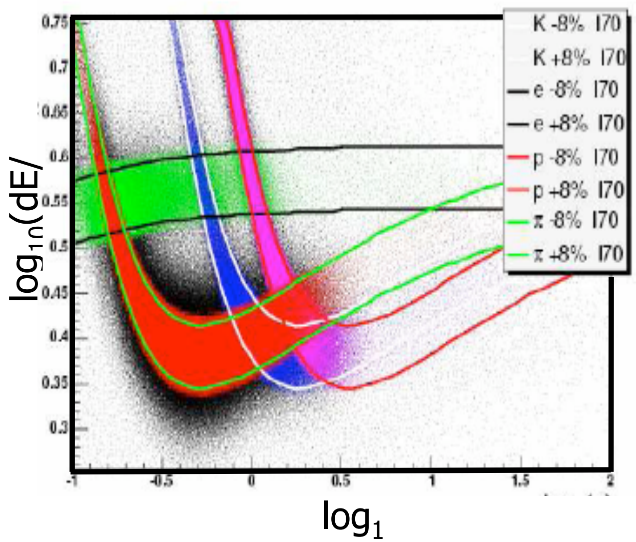
Triggering is not a problem

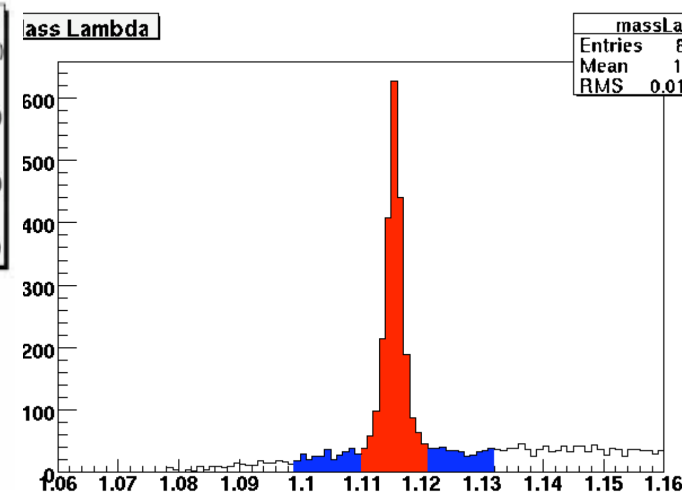
Particle identification

Use TPC+ToF(completed 2010) +EMCal+Topology

- TOF alone: (π,K) up to 1.6 GeV/c, p up to 3 GeV/c
- TOF+TPC(dE/dx, topology) up to 12 GeV (NIMA **558** (419) 2006)





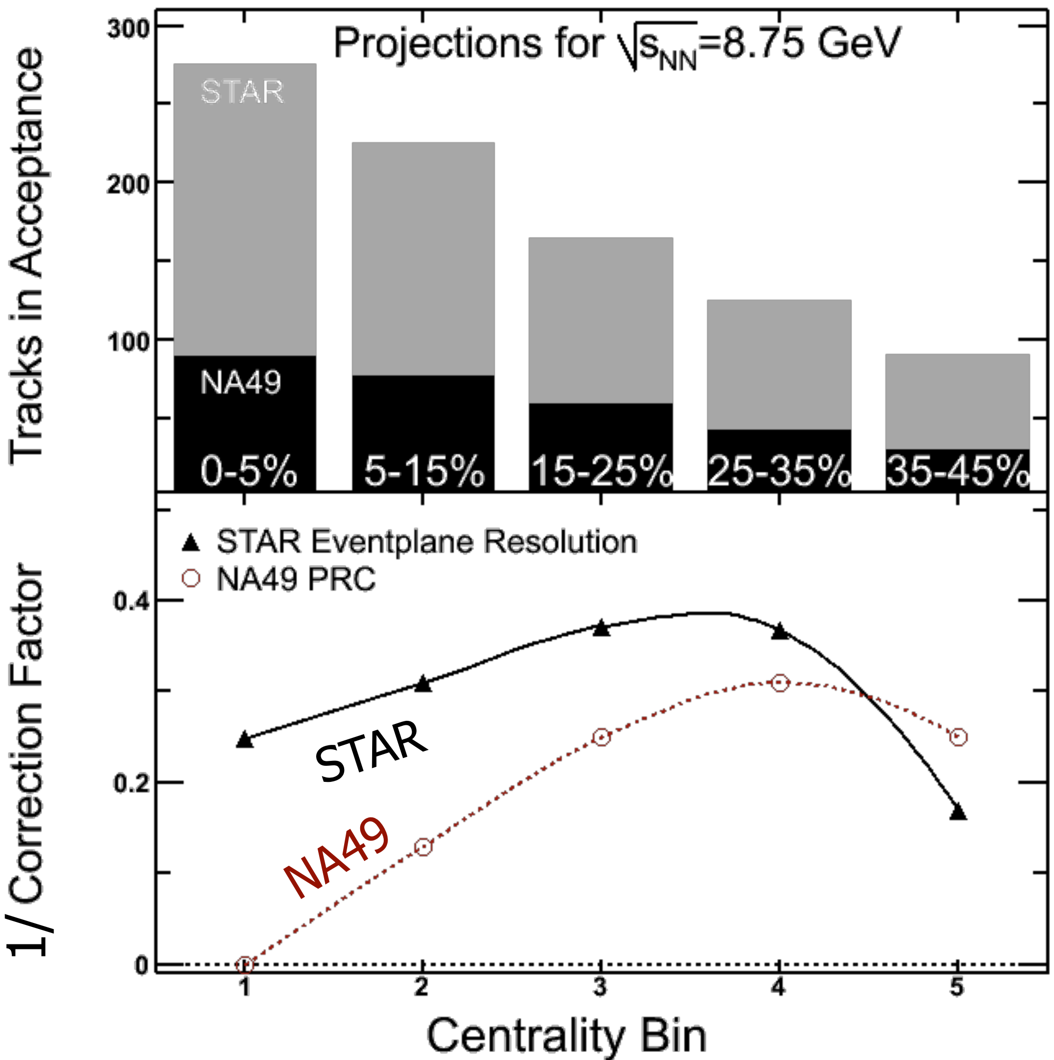


Have track by track identification over large p_T, y range

- necessary for fluctuation measures

Good quality PID spectra and ratios (μ_B and T)

Event-plane resolution



NA49 flow PRC used less than 500K events per energy

Better resolution than NA49 so smaller errors for same event count

Estimates used:

- v_2 from NA49
- dN/dy using 1.5*N_{part}/2
- Tracks with |y|<0.5 (can probably do better)
- Events passed through simulators

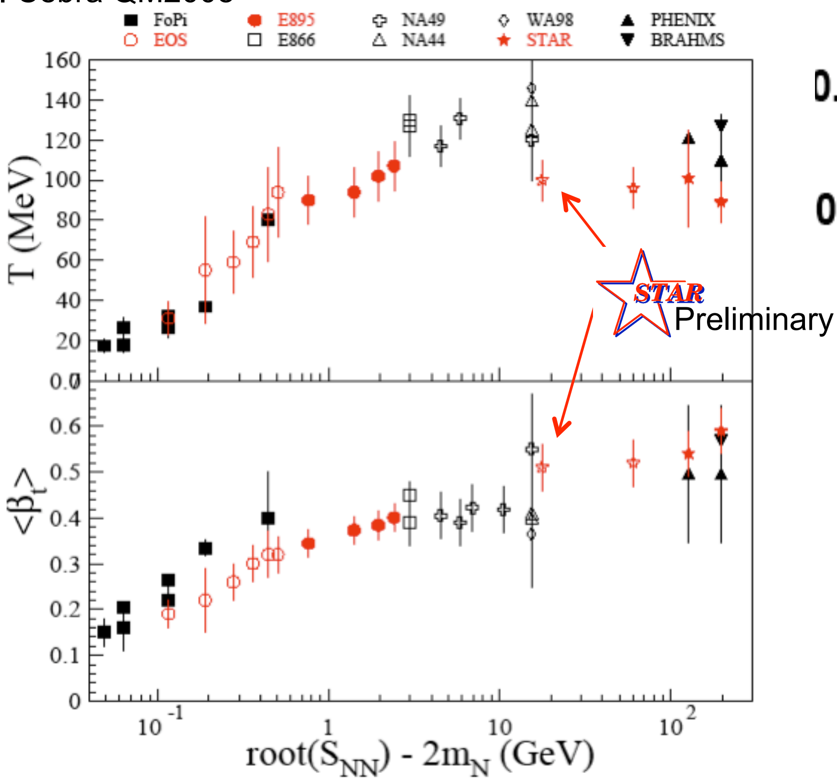
Big improvement on v_2 measurements possible

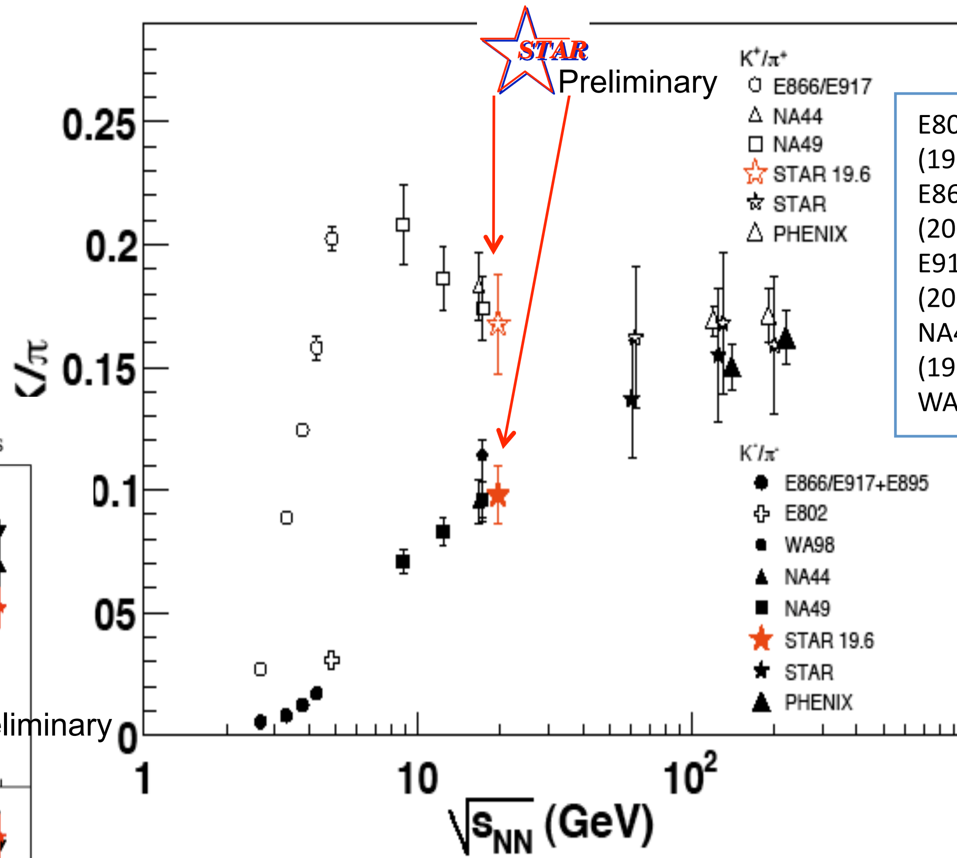
Energy scan actually started year 1

2001: 19.6 GeV Au+Au

- Total recorded events = 175466
- Events with good vertex = 42412
- 10% centrality events = 5106

D. Cebra QM2008





E802 PRL81, 2650 (1998)
E866 PLB476, 1 (2000)
E917 PLB490, 53 (2000)
NA44 PLB471, 6 (1999)
WA98 PRC67,

Sufficient data to extract ratios, flow velocity, HBT radii, v_2

All data fit into systematics

2008 low energy beam test

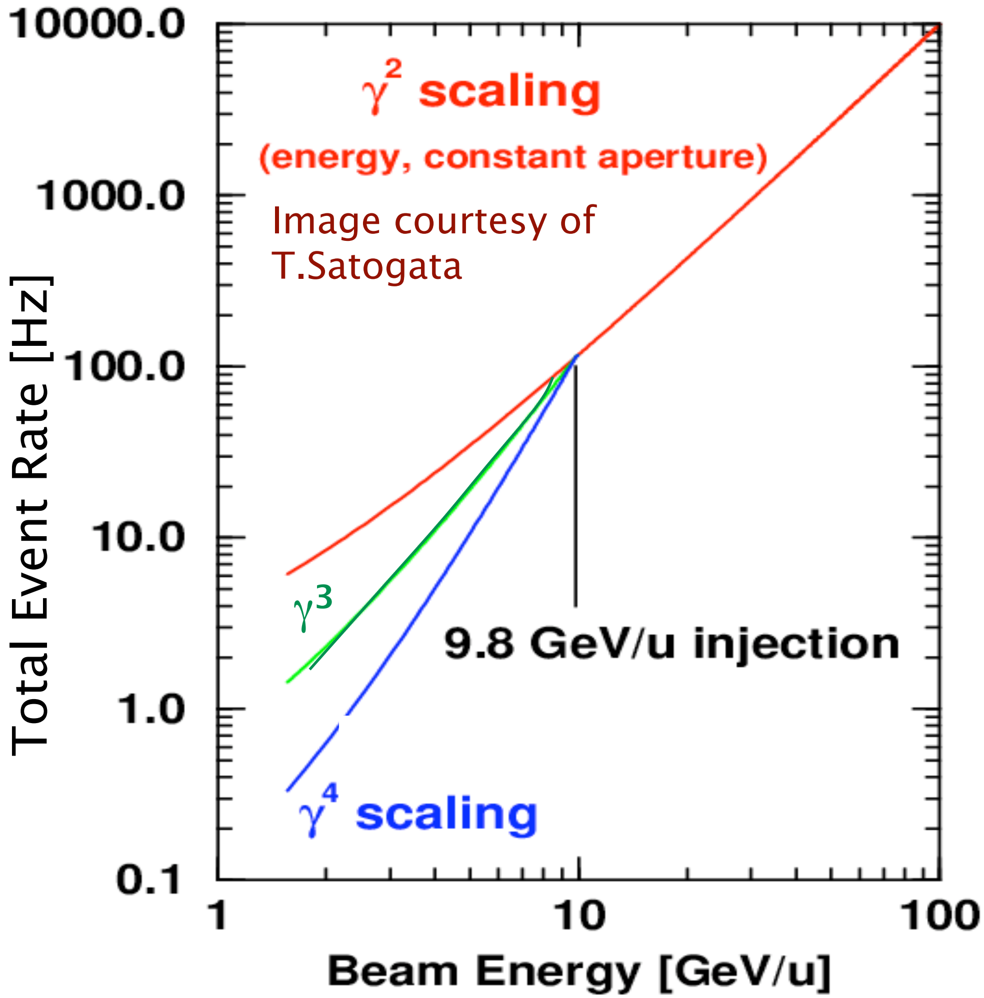
Again injecting and colliding Au+Au $\sqrt{s_{NN}}$ = 9.2 GeV

- Setup and experimental DAQ problems with new harmonic number h=366 solved.
- Stable running with collisions at STAR ⇒ Data!!
  - Couldn't cog simultaneously at PHENIX and STAR⇒limited data :-(
  - This problem will be fixed in the future by choosing a slightly different energy

Short test at Injecting Au+Au @ $\sqrt{s_{NN}}$ = 5 GeV

- Interrupted by power supply problems but did allow study of some beam characteristics.
- Additional important work needs to be done in Run 9.

Luminosity is the key issue



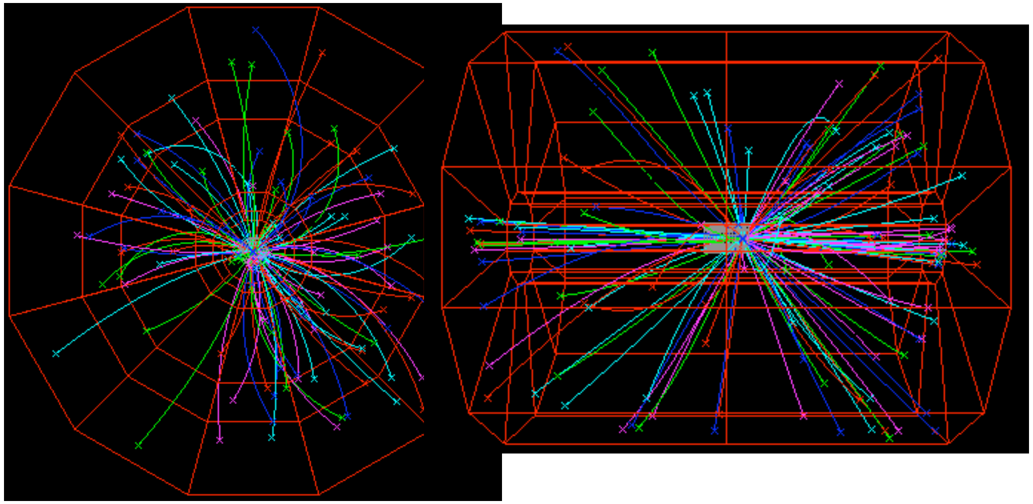
Expect to reach γ^3 rate even at lowest energies

Determined collision rate for 2008 9 GeV Au+Au test to be ~1Hz.

Rate can be increased by:

- factor 2 by adding more bunches - only 56 used for tests (max 120).
- factor 3-6 by operating with higher charge in bunches.
- factor few by running in continuous injection mode
- electron cooling in RHIC (?)

Collisions Au+Au $\sqrt{s_{NN}}$ = 9 GeV



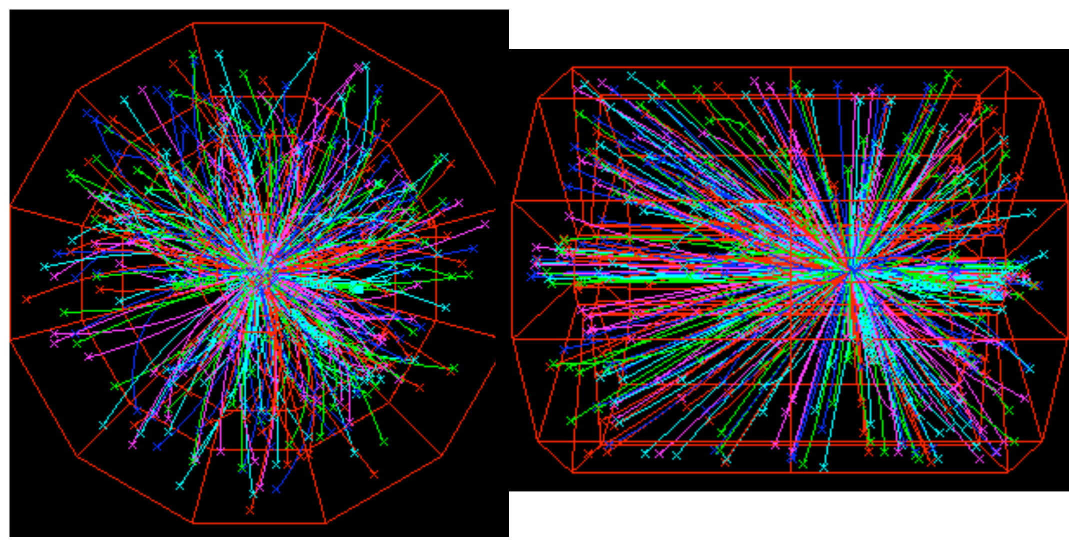
From 2 days of running:
203395 triggers

~3500 good events

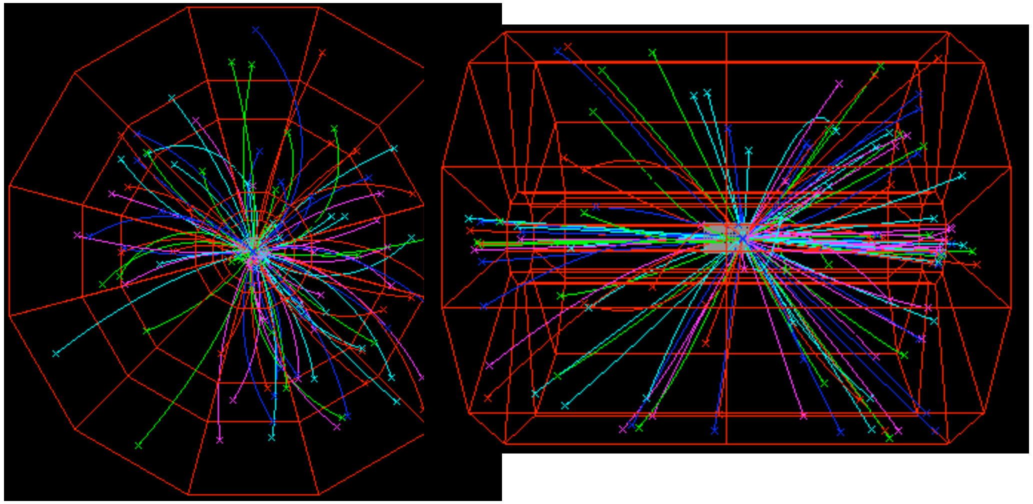
(good≡ primary vertex along beamline and within acceptance)

Still learning about trigger:

Some events were empty - trigger thresholds too low (shouldn't happen again)



Collisions Au+Au $\sqrt{s_{NN}} = 9$ GeV



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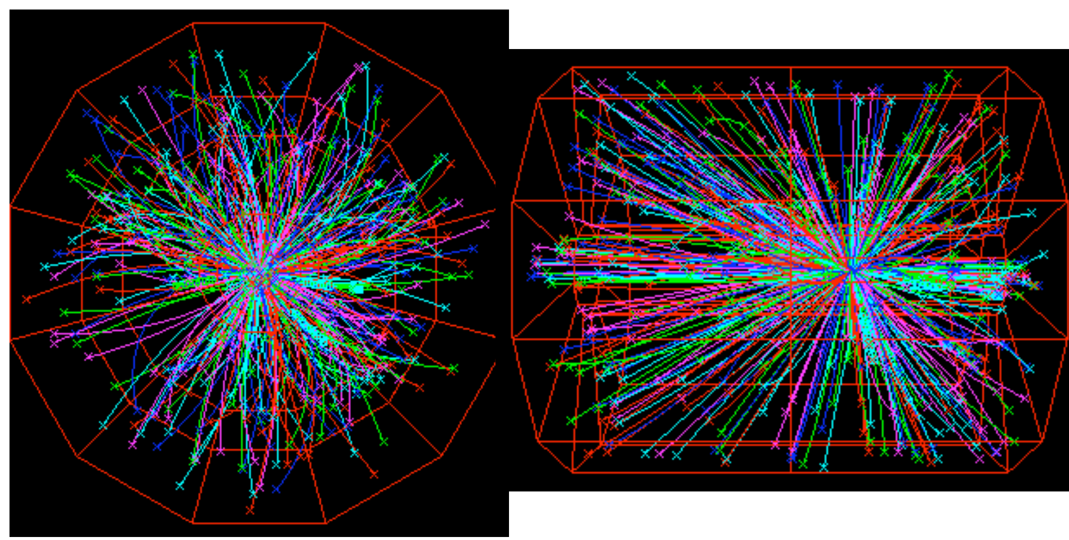
Unambiguous beam+beam events



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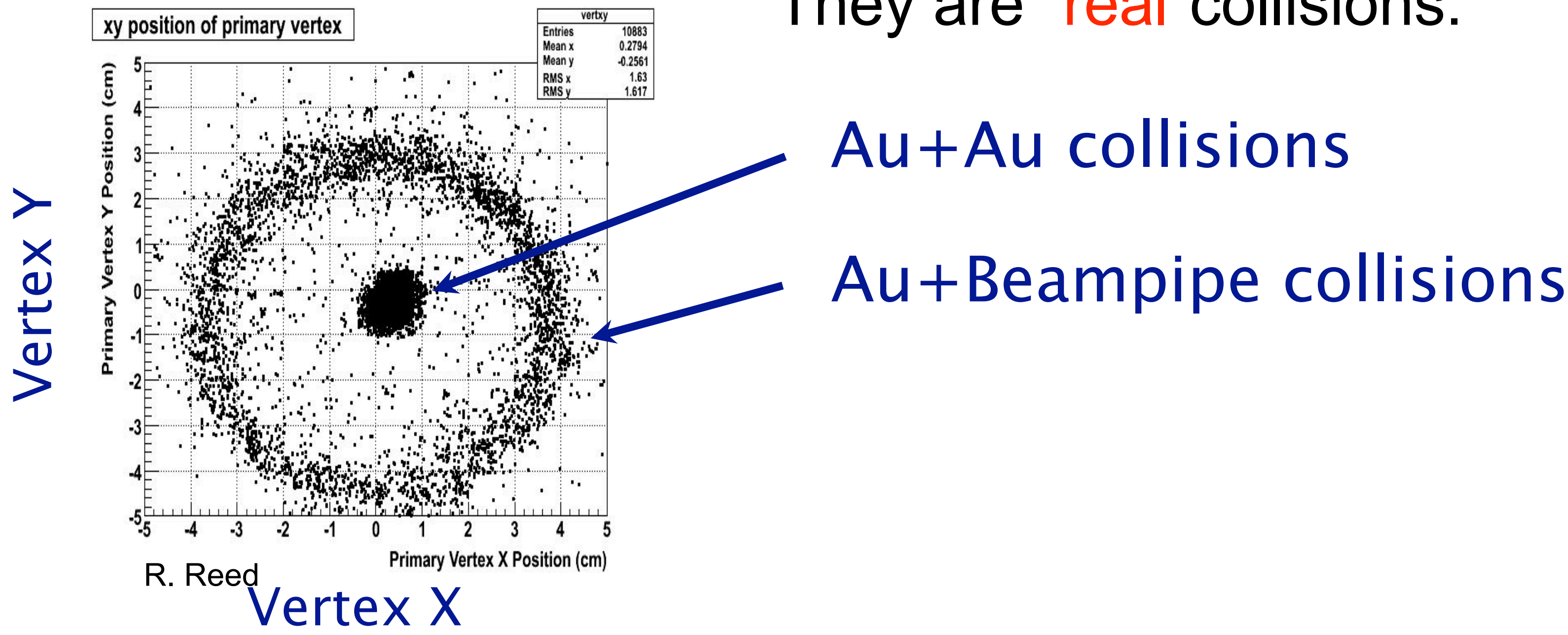
What about other bad triggers?

Investigated primary vertex location:



R. Reed

They are "real" collisions.

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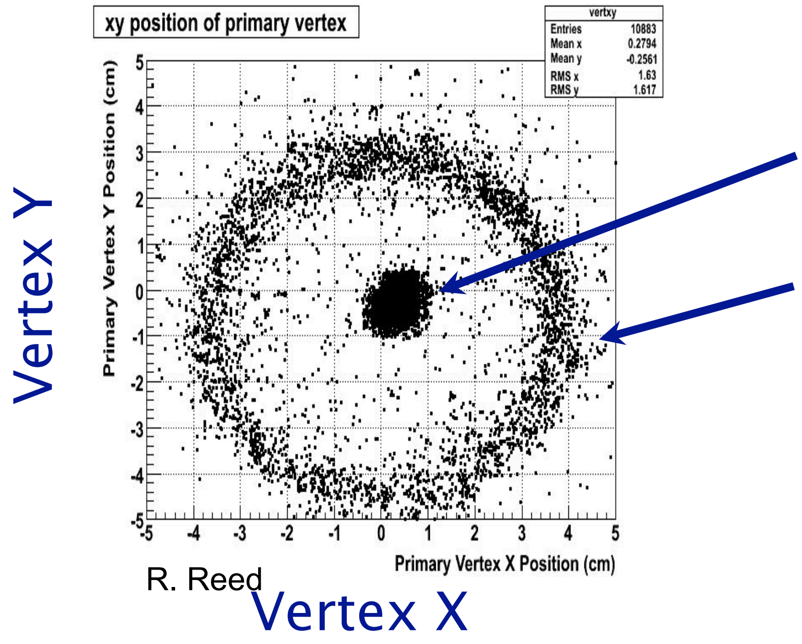

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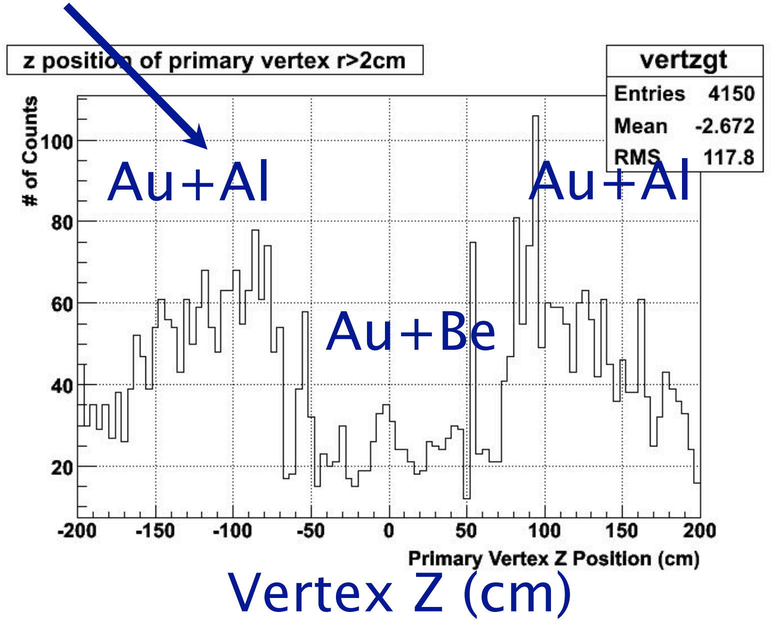

Can see the change in beampipe material and thickness

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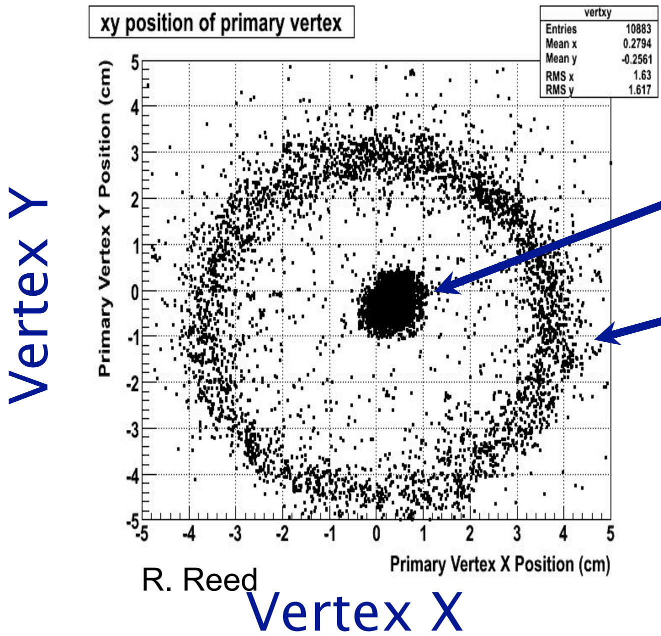

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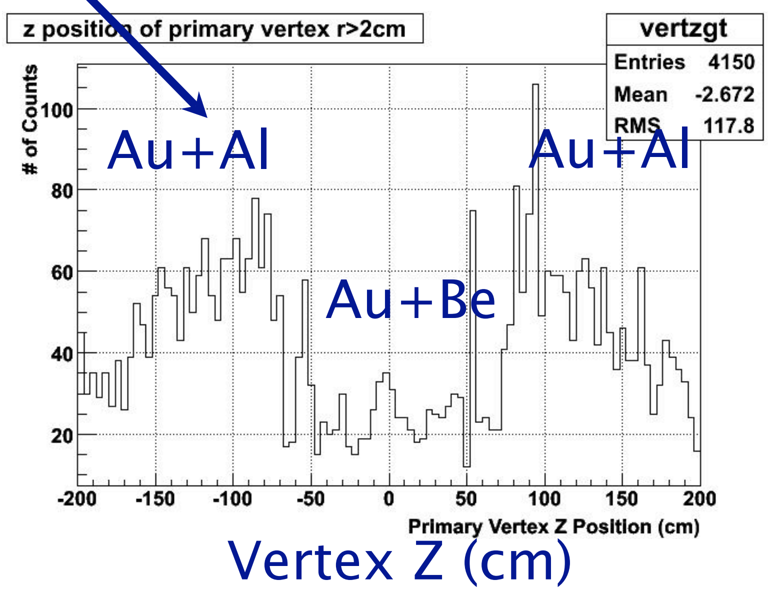
Au+Au collisions

Au+Beampipe collisions



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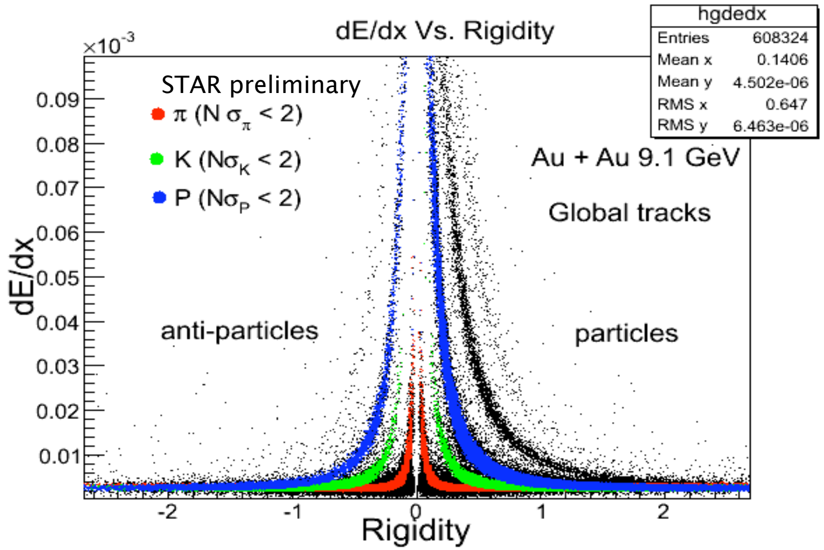
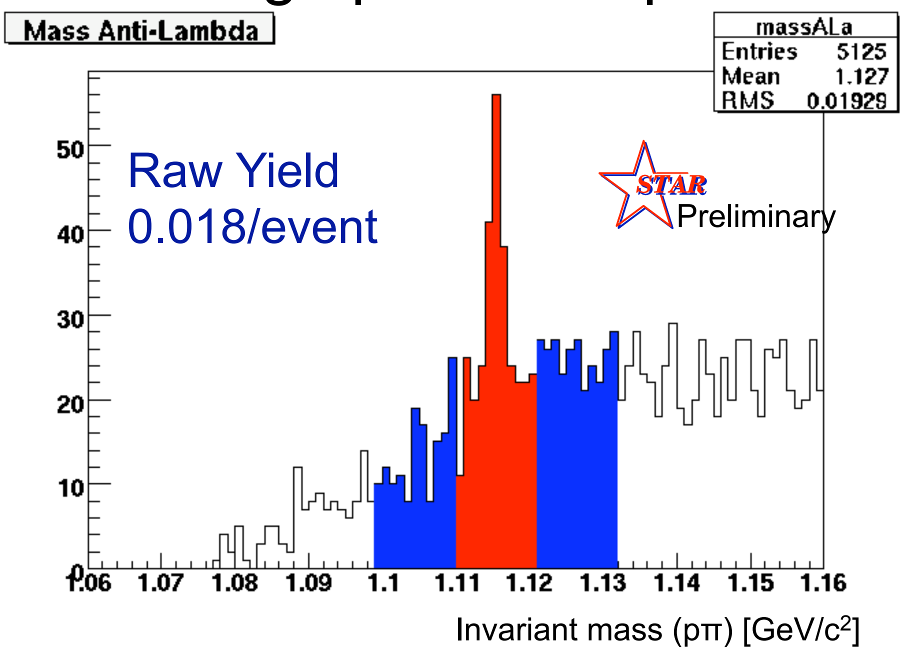
Since event rate so low plan to leave trigger as is and filter offline

Au+Au $\sqrt{s_{NN}}$=9 GeV



Clean PID for π, K, p + anti-particles

All strange particles up to $\bar{\Lambda}$



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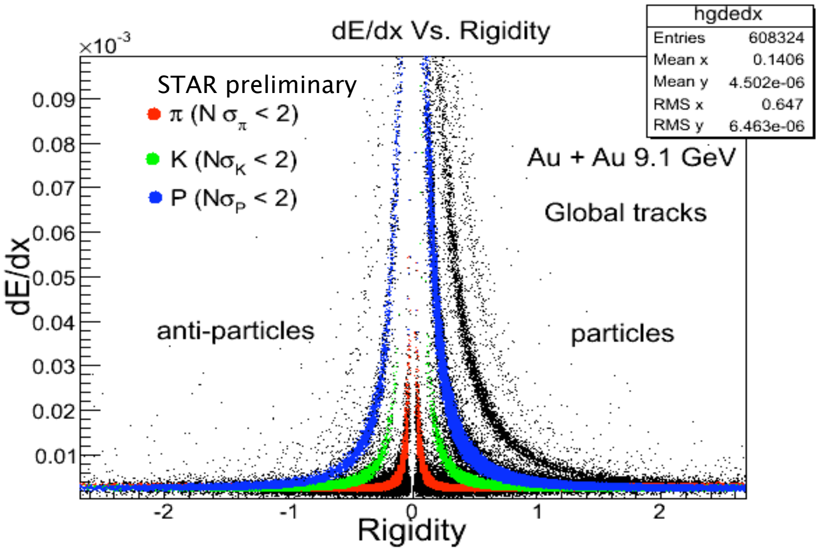

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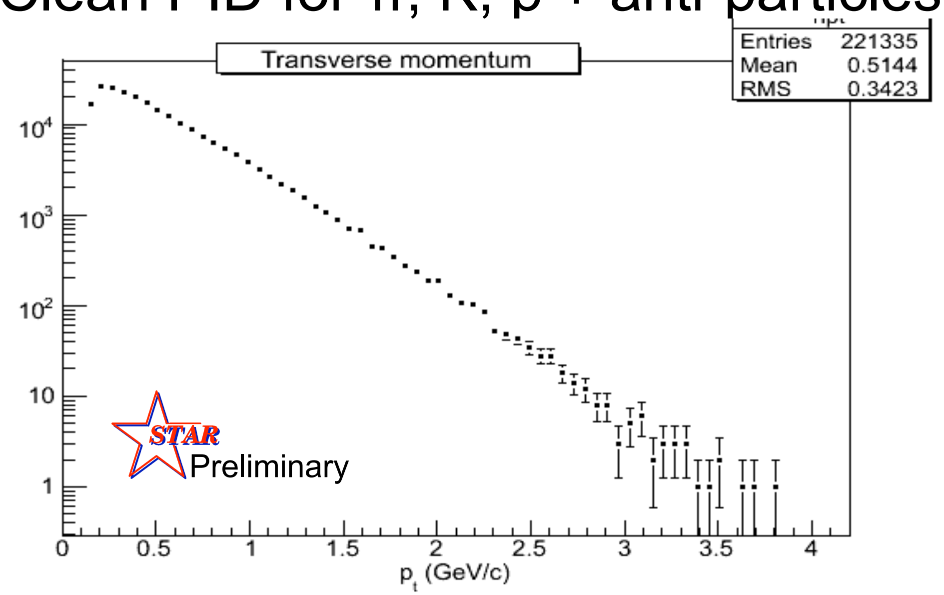

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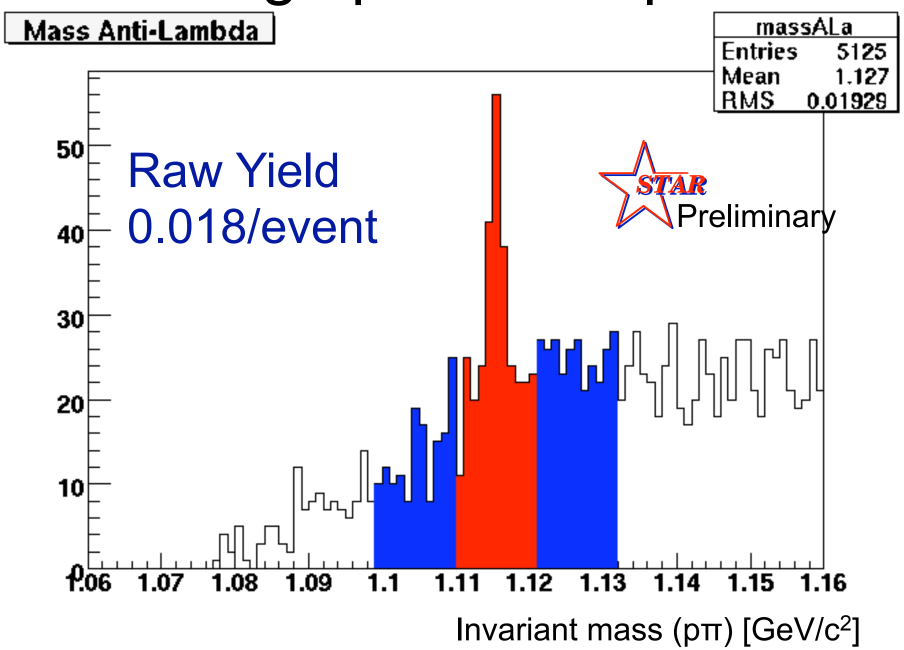


Uncorrected charged particle mid-rapidity p_T spectra out to ~4GeV/c.

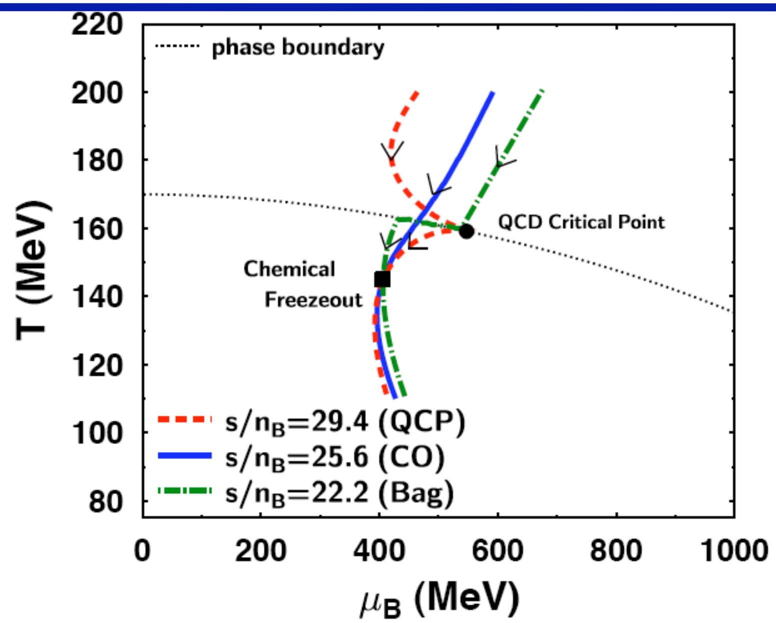
(Not corrected.
Can't extract physics yet)

μ_B/T trajectories and the Critical Point

μ_B/T ($\bar{p}/p$):

- Increases monotonically for cross-over/1st order
- Decreases for C.P.

- If hadron emission occurs over a finite range in T see measurable effect on ratio



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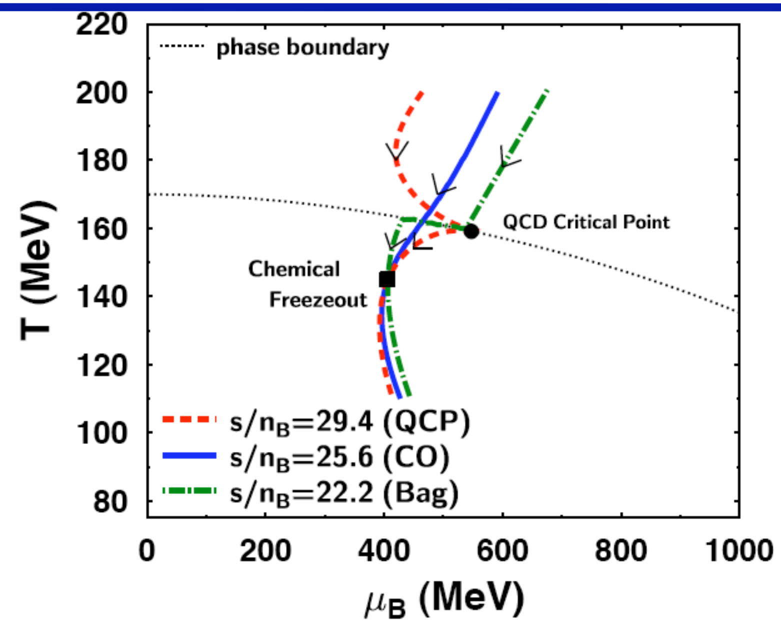
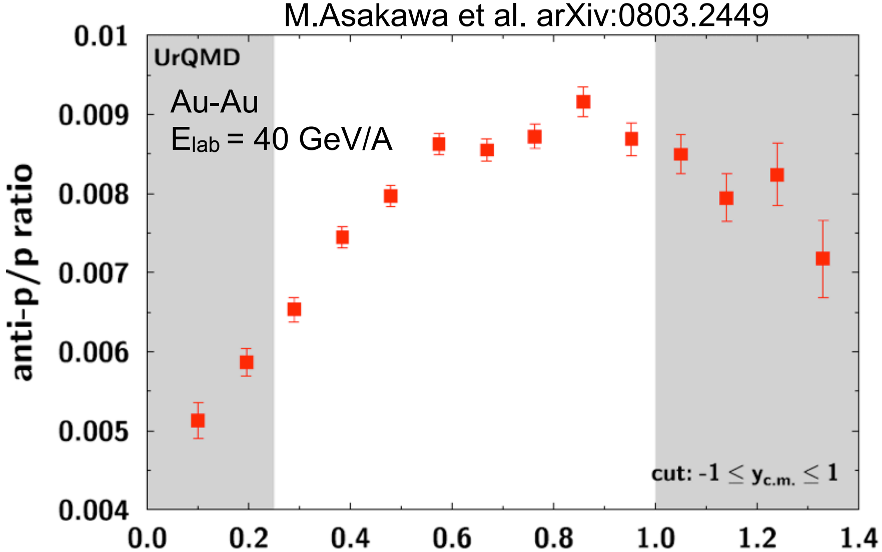
- Sampling in y_T preferentially selects on emission time.

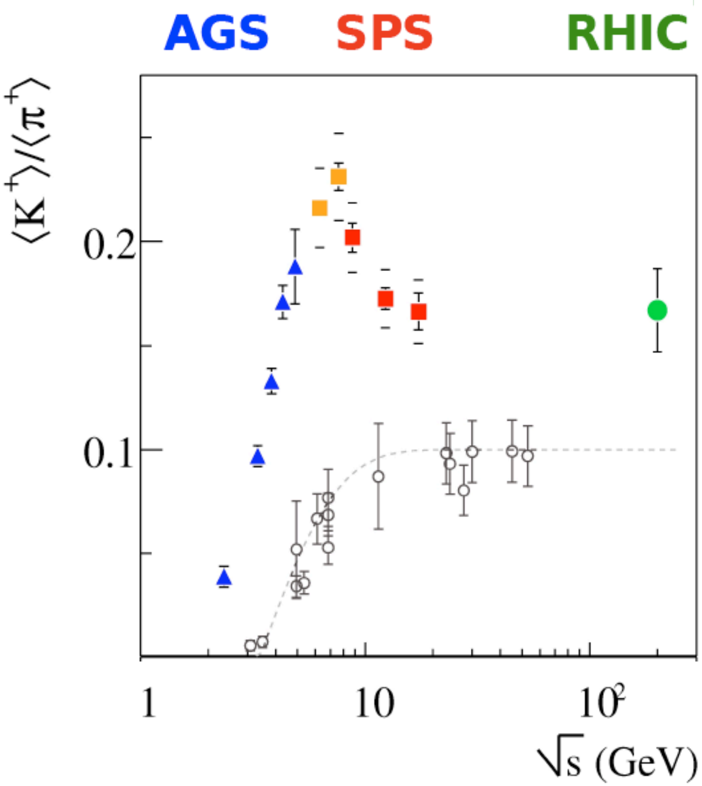
- High $y_T \rightarrow$ early emission



M.Asakawa et al. arXiv:0803.2449



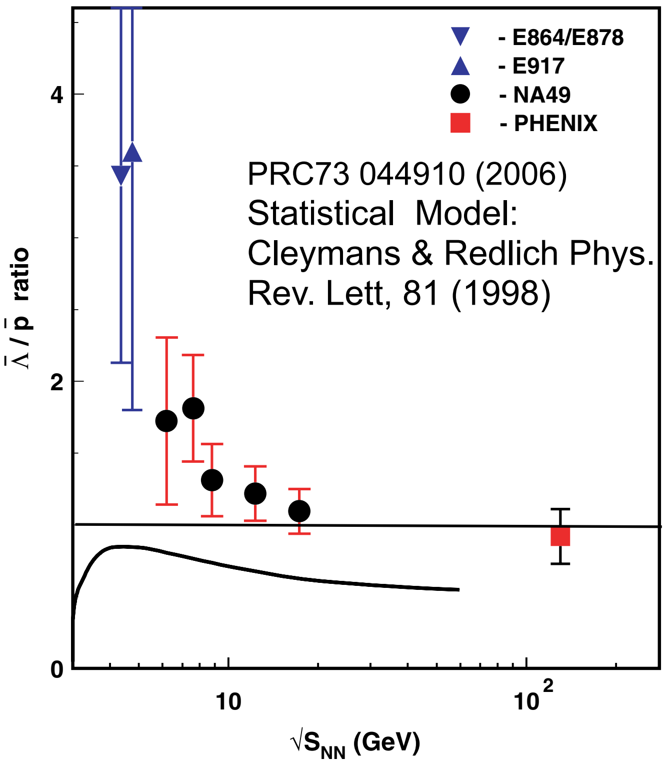
$\bar{s}/\bar{q}$ production



$$\frac{\bar{\Lambda}}{\bar{p}} \approx \frac{\bar{s}}{\bar{q}} \approx \frac{K^+}{\pi^+}$$

Is this the same physics?

Anti-baryon annihilation?



Hadron Gas models cannot reproduce this peak/large ratio

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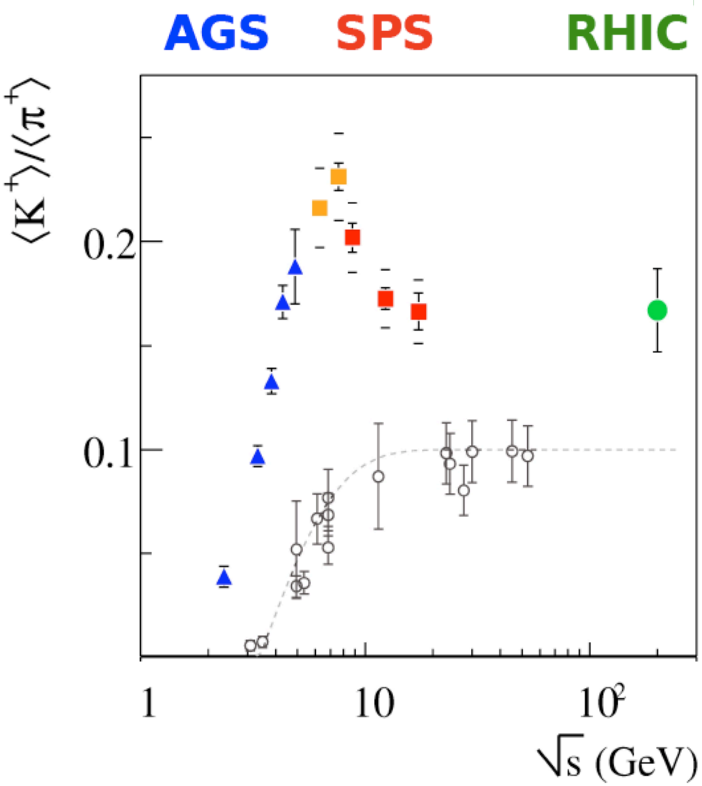

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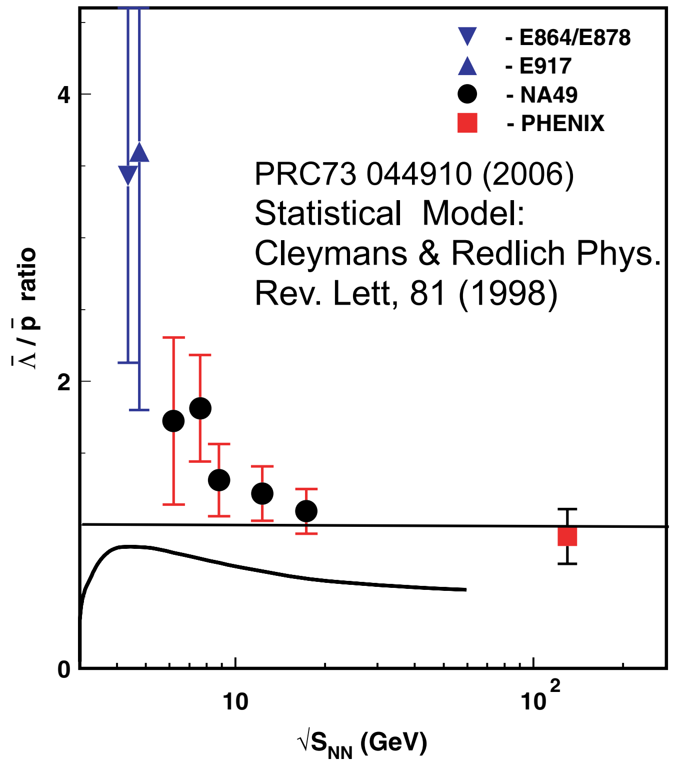


Hadron Gas models cannot reproduce this peak/large ratio

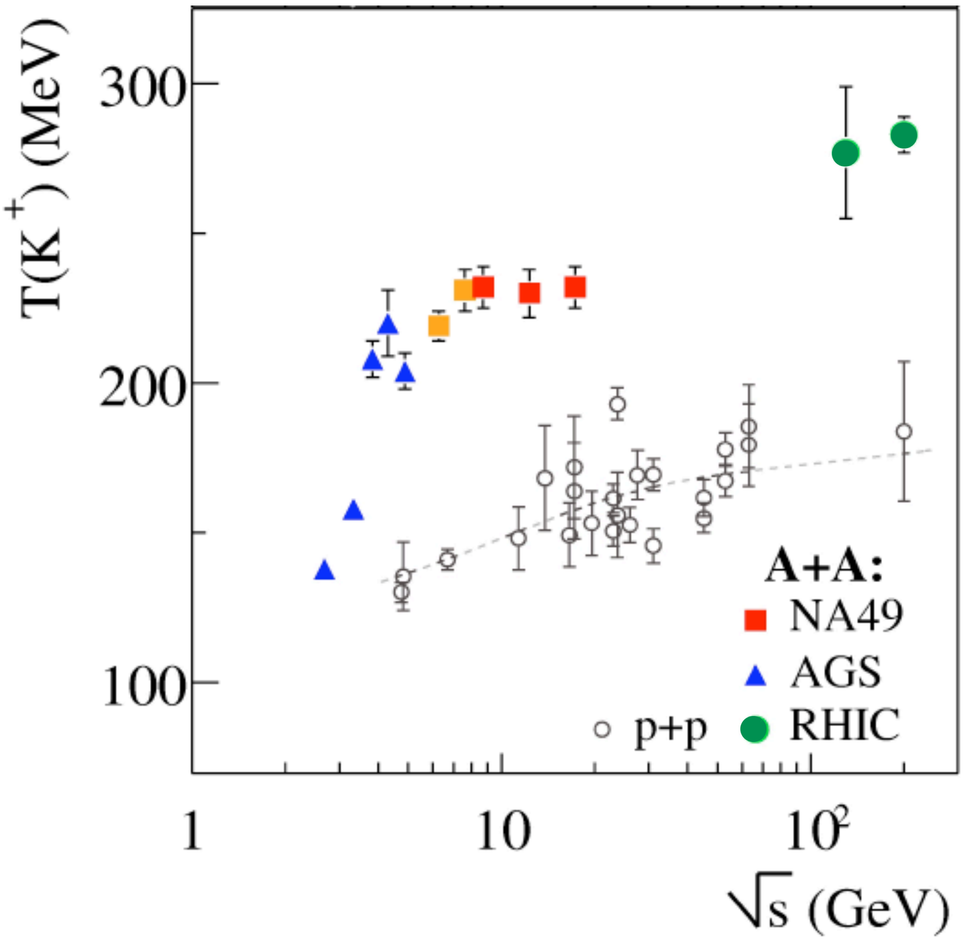
1 Million events gives few thousand $\bar{\Lambda}$ reconstructed at lowest $\sqrt{s}$

We can investigate in detail and fill in the gap at higher energies

Inverse slopes of K^+ p_T spectra

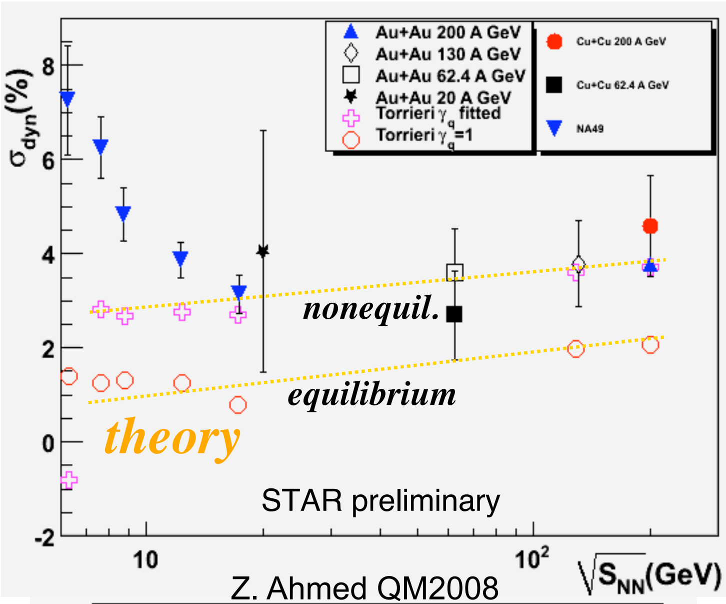
There is also an apparent plateau in $T(K^+)$ around the same $\sqrt{s}$.

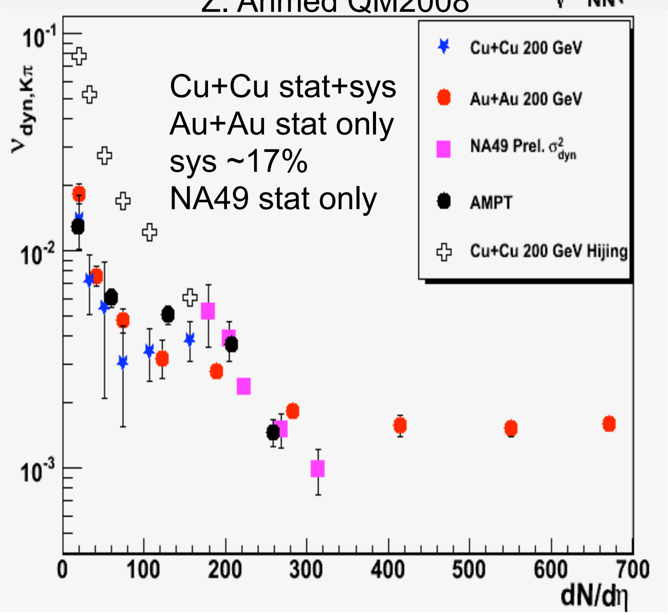
How far does this plateau extend?



Again STAR will fill in the gap.

K/π fluctuations





Current STAR results consistent with NA49 at $\sqrt{s_{NN}}$ ~ 20 GeV.

At higher energies results consistent with γ_q =1.6 (from fit) but not with equilibrium scenario (γ_q=1)

Georgio Torrieri;nucl-th/0702062(2007)

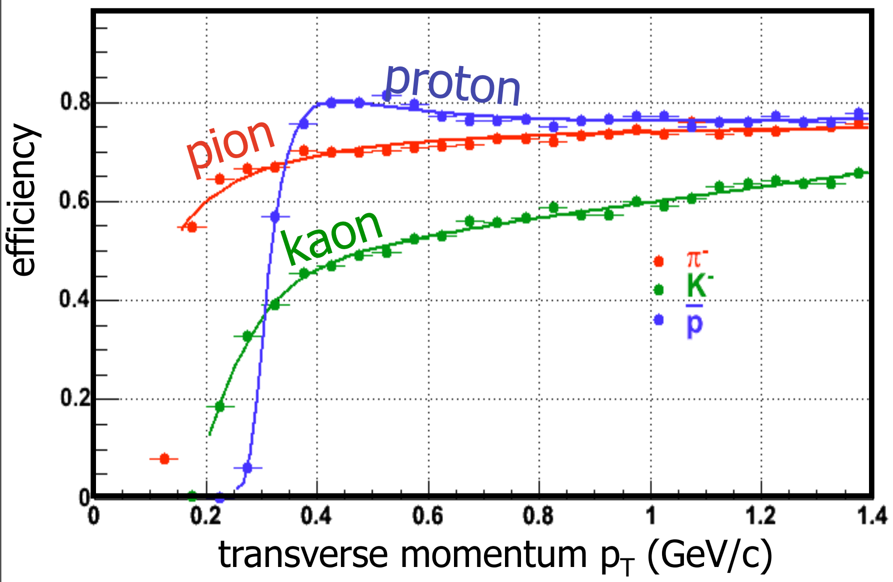
The fluctuations scale with dN/dη rather than energy or system size.

At lower dN/dη:
- HIJING - too high
- AMPT (HIJING+rescattering) - good agreement

Challenges for K/π fluctuation measures

Need to measure ALL K and π

Issue 1:



- decays: $K^+ \rightarrow \mu^+ \nu_\mu$ (cτ=3.7 m)
  ⇒ low tracking efficiency

- PID cuts reduce efficiency further
  ⇒ reco. < 50% of all kaons

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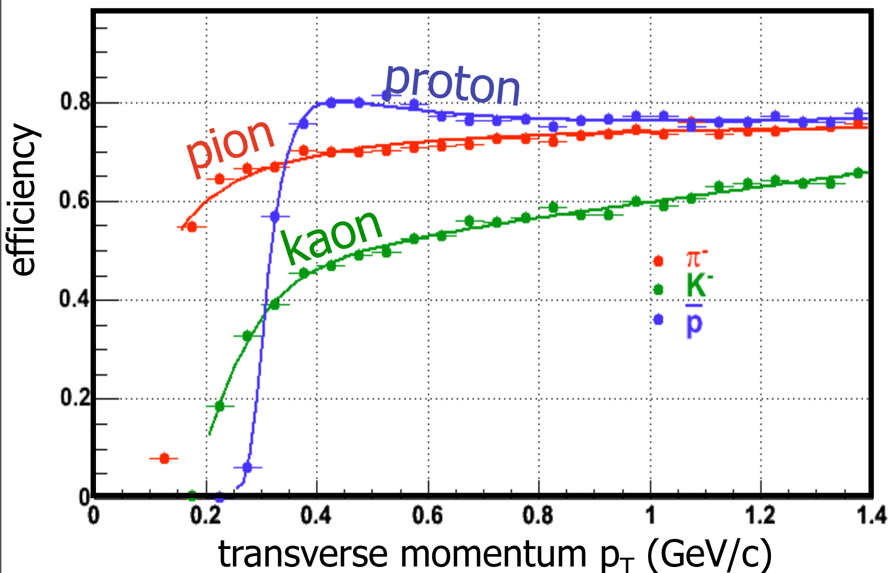

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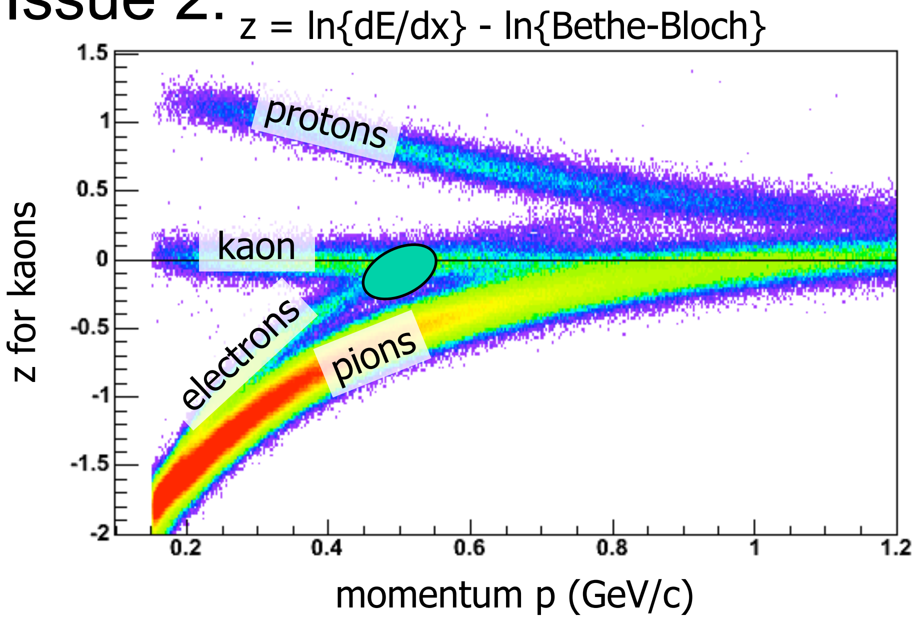

Misidentification using TPC dE/dx

$\pi \leftrightarrow K$, $\pi \rightarrow e$ identified as K.

$K/\pi \rightarrow (K+1)/(\pi-1)$ or $(K-1)/(\pi+1)$

K/π fluctuations distorted

- 0.5% swapping: width ⇩5%
- signal is only 4%!

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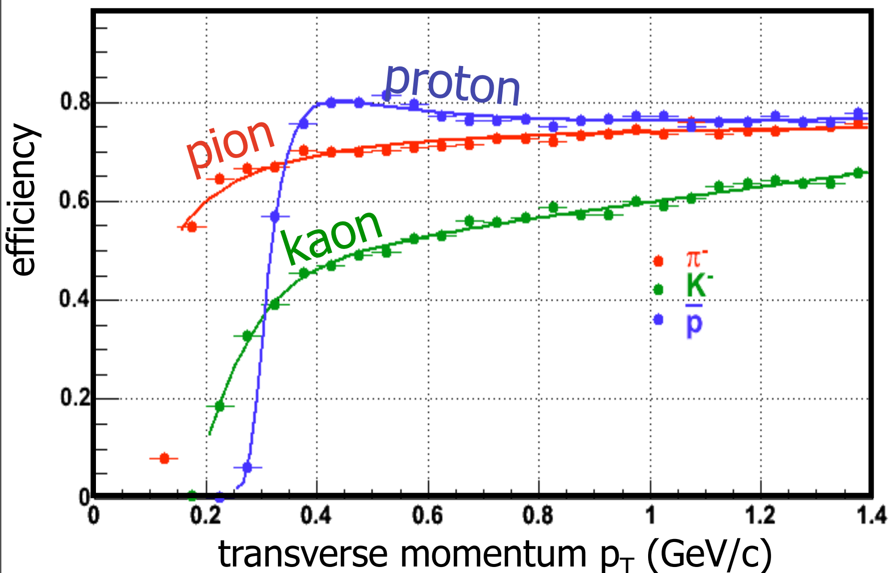

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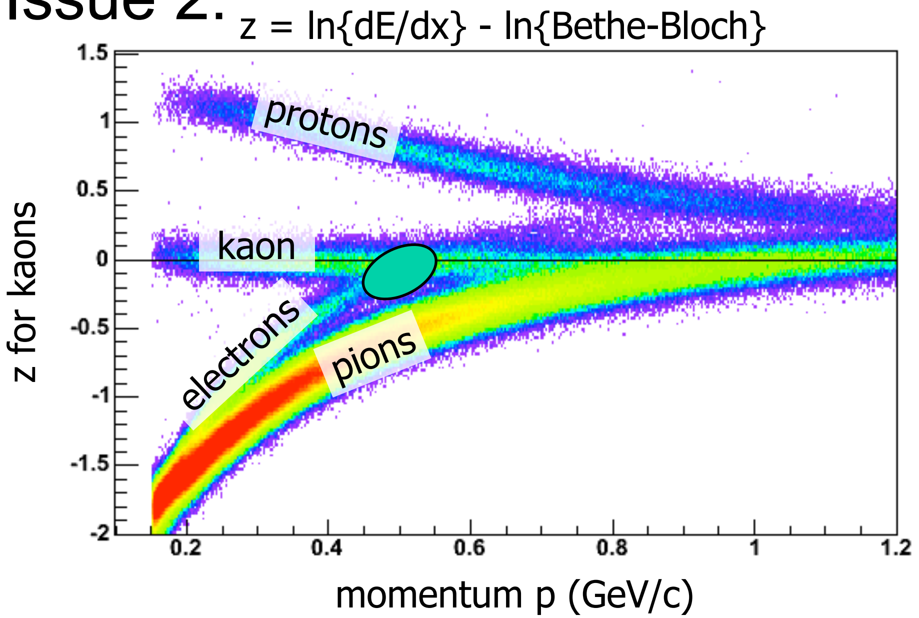

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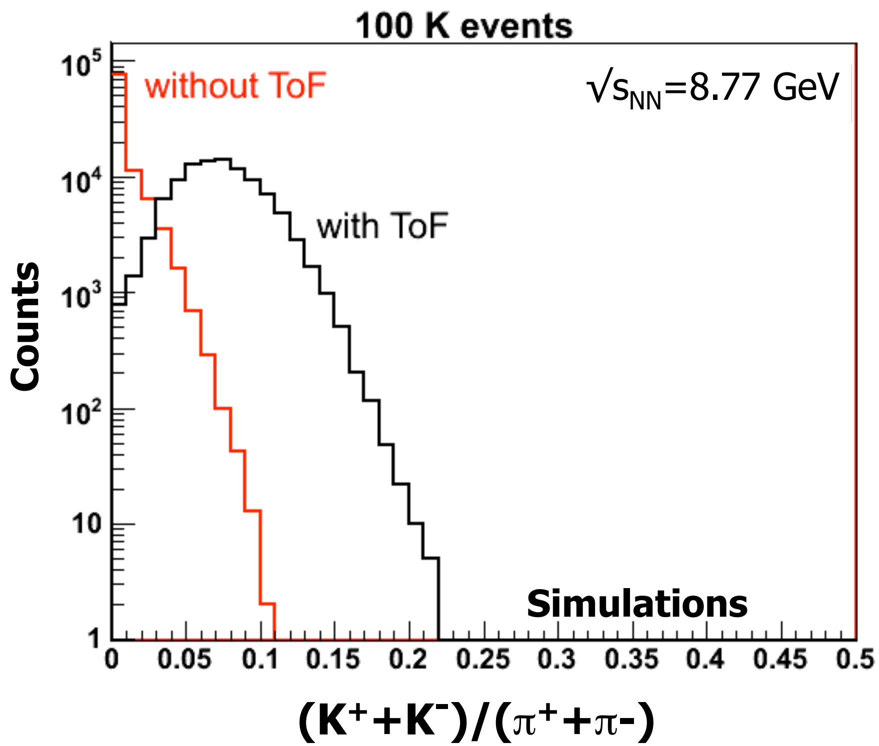
ToF is essential

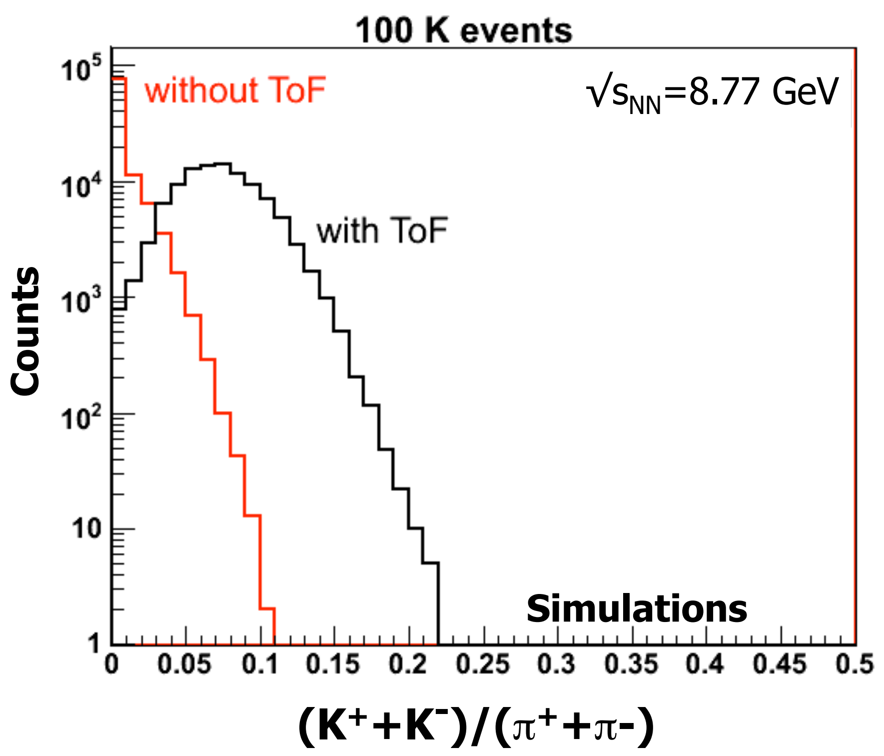
K/π measure with ToF

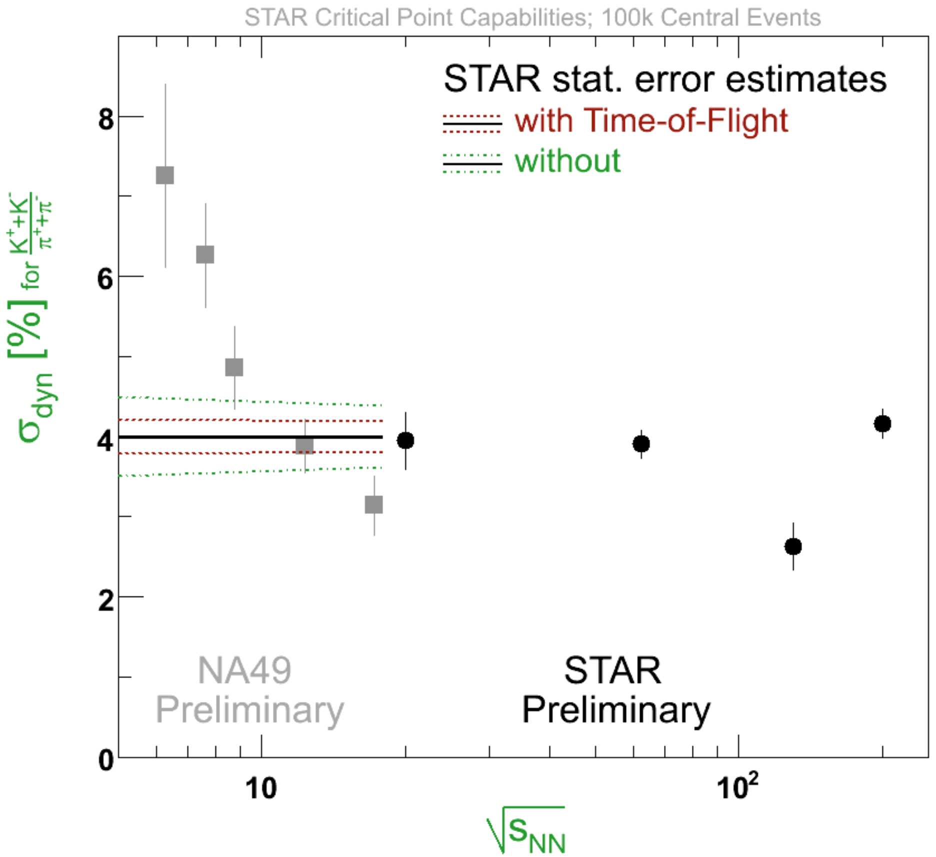


With ToF can improve:

- momentum range
- purity

K/π measure with ToF





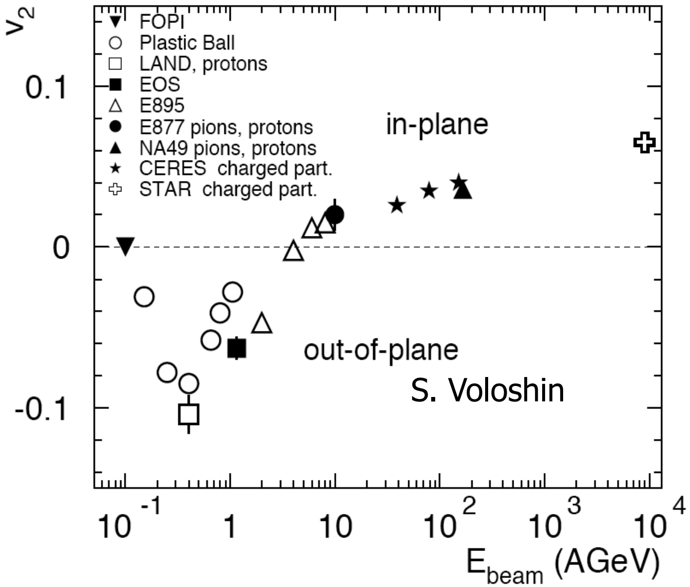
With ToF can improve:

- momentum range
- purity

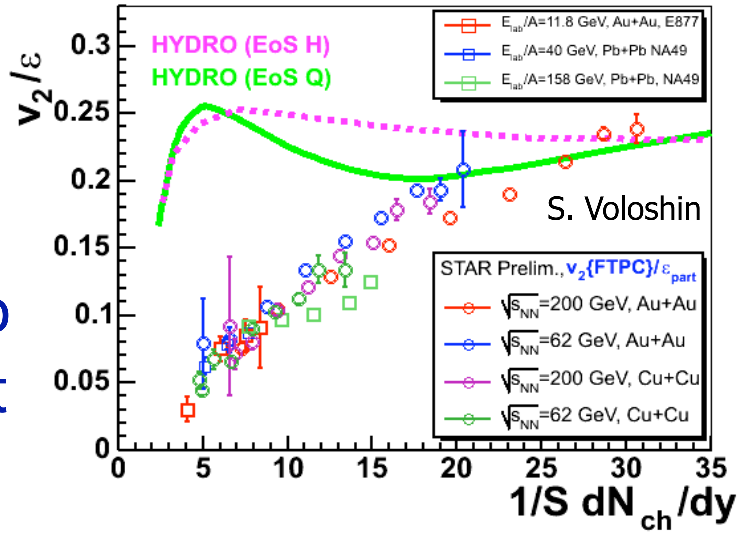
Au+Au 100k central $\sqrt{s_{NN}}$=8.77 GeV statistical errors:

- without ToF ≈ ±11% (relative)
- with ToF ≈ ±5% (relative)

Understanding the origin of v_2



- v_2 grows with $\sqrt{s}$
- v_2/ε appears to reach hydro limit at top $\sqrt{s}$



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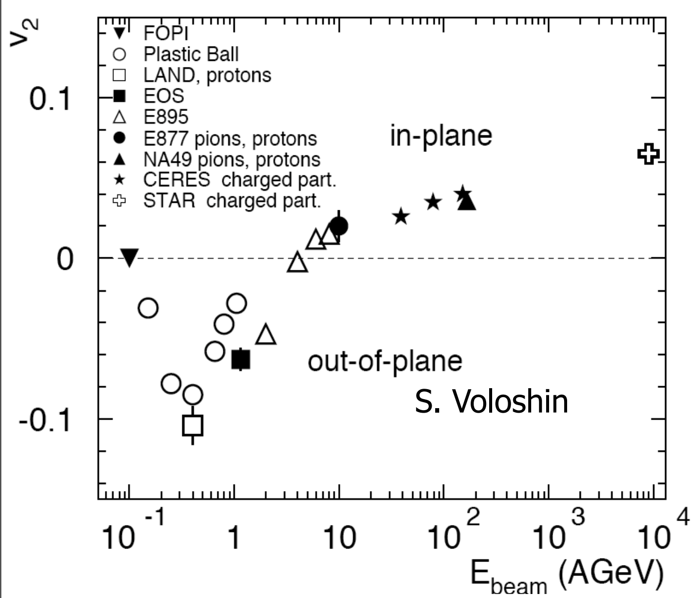

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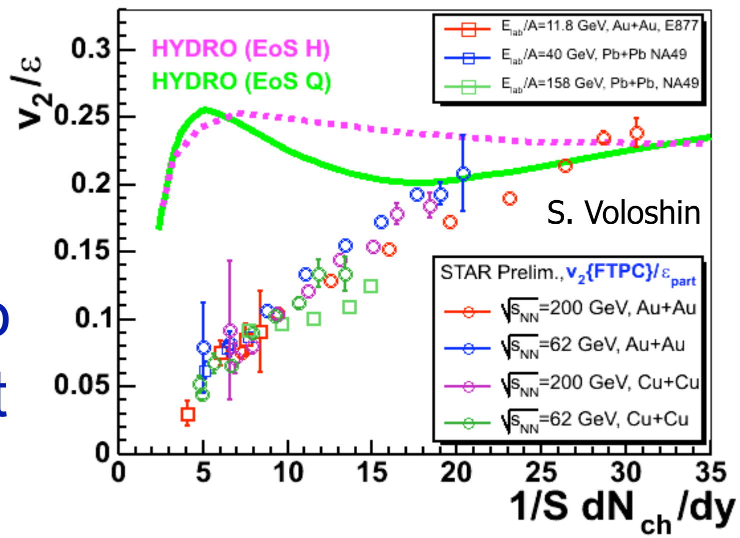
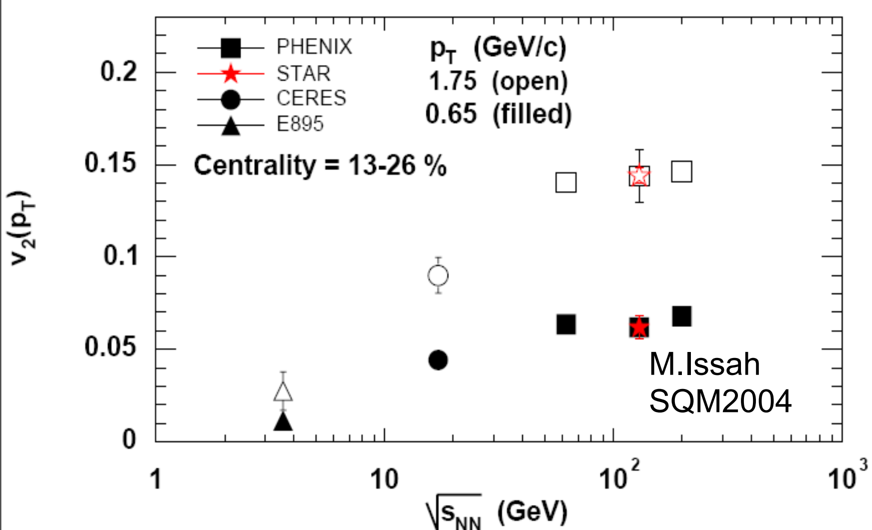
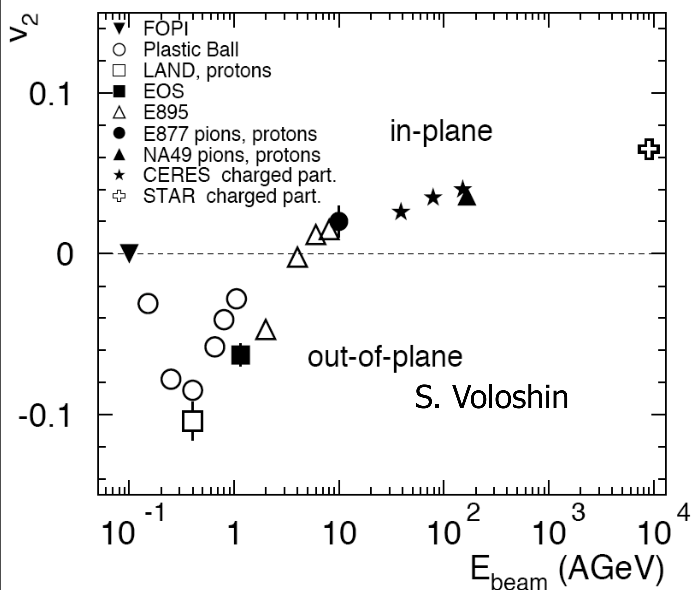




- v_2 at fixed p_T appears to saturate

- Evidence of softening of EoS due to phase transition?

Understanding the origin of v_2



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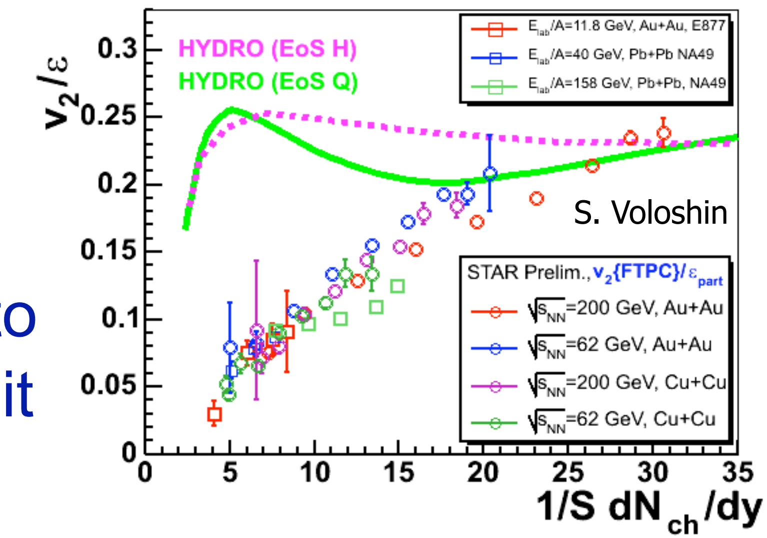

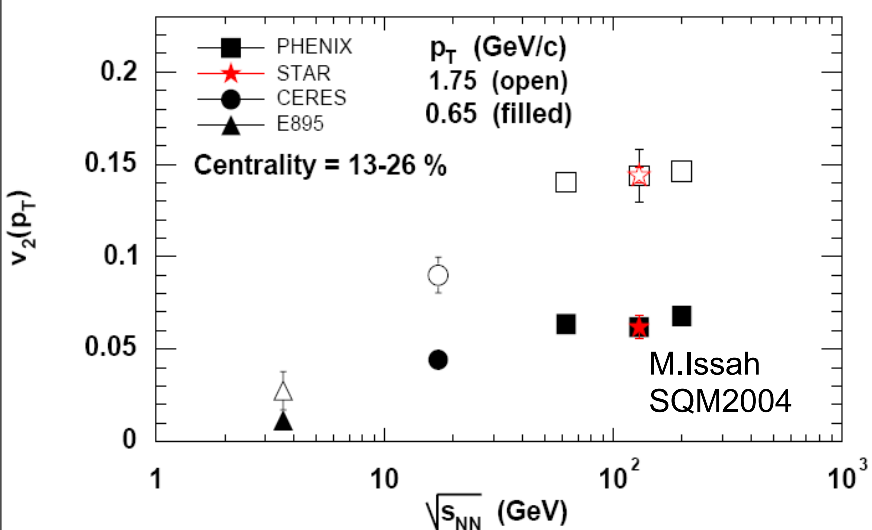

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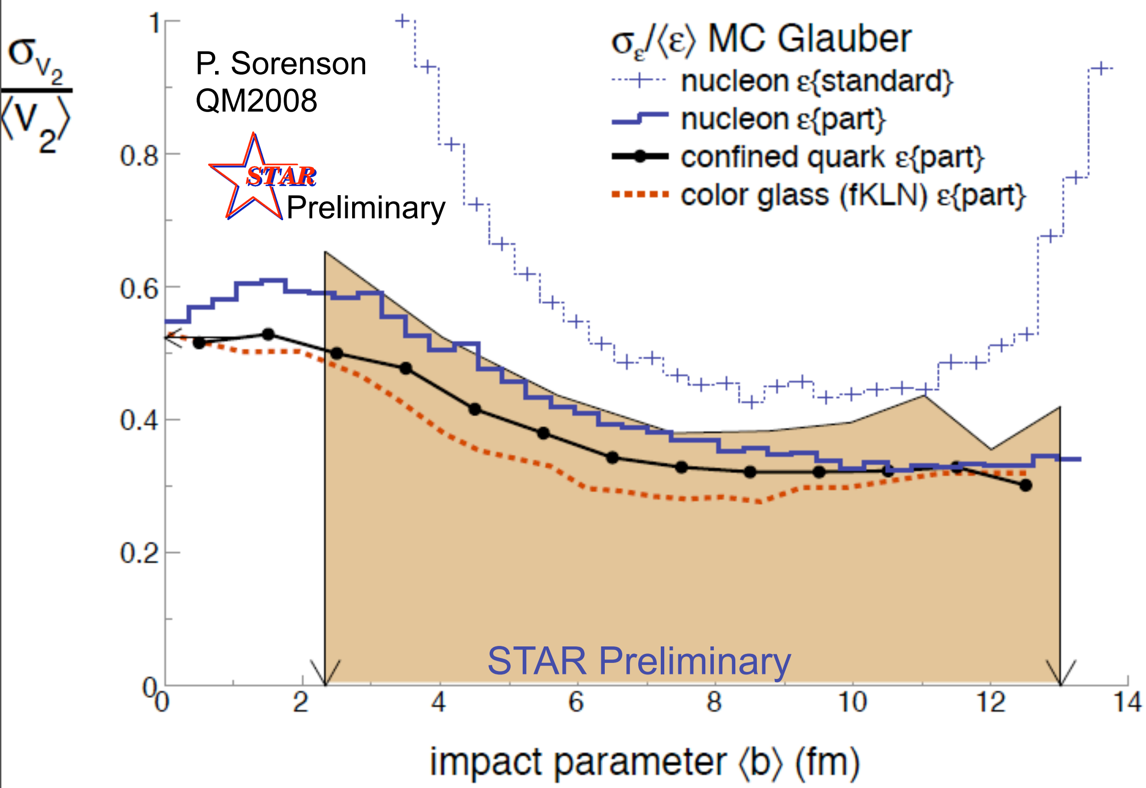
Energy dependence gives important guidance to theoretical interpretation

v_2 fluctuations

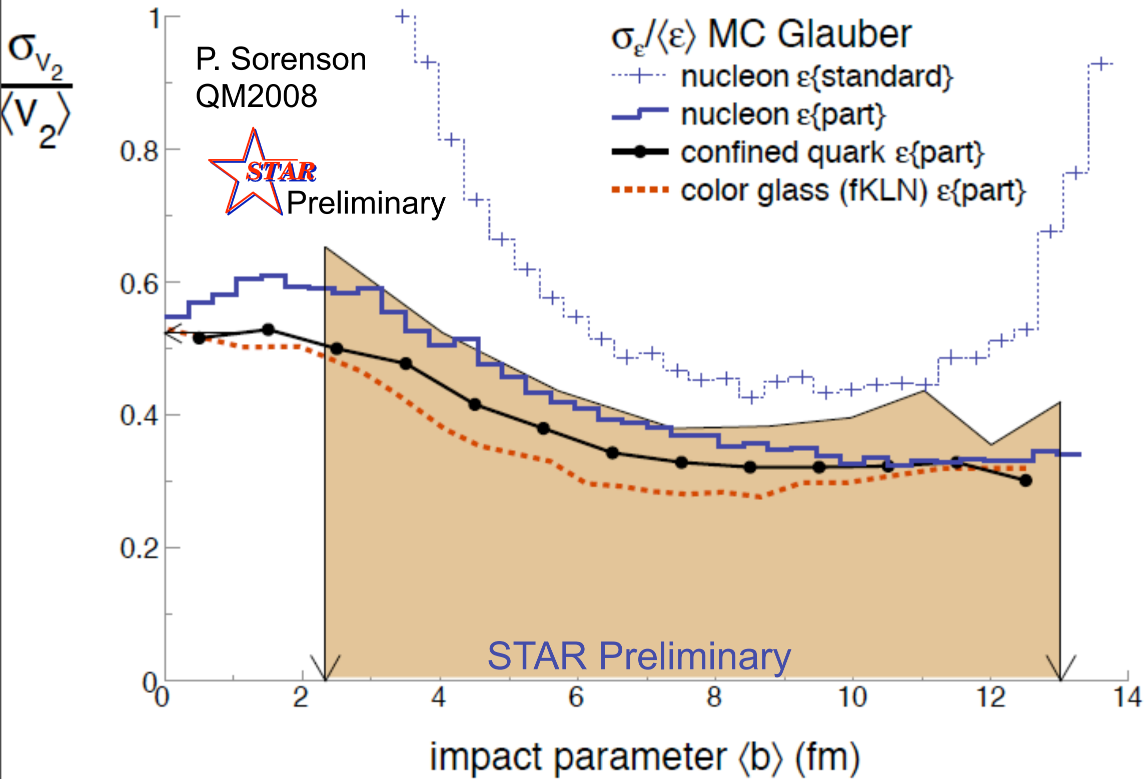


Upper limit challenges models of initial eccentricity fluctuations

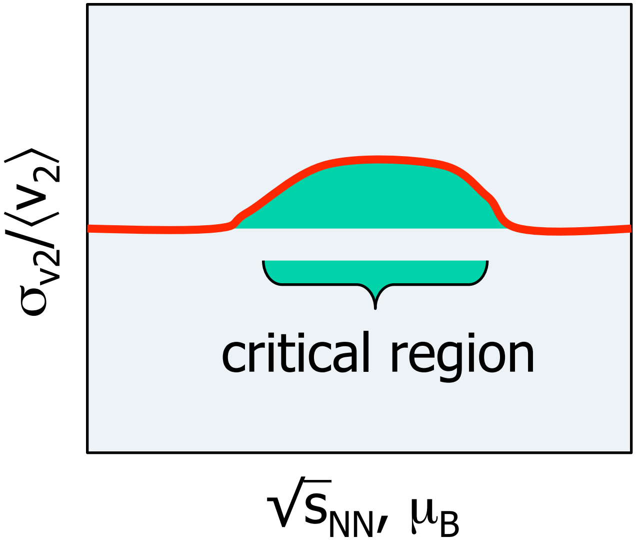
Nucleon Glauber - no room for other fluctuations/correlations

Data calls for different model of initial eccentricity (e.g. CGC)

v_2 fluctuations



Near critical point fluctuations should be big - need calculations



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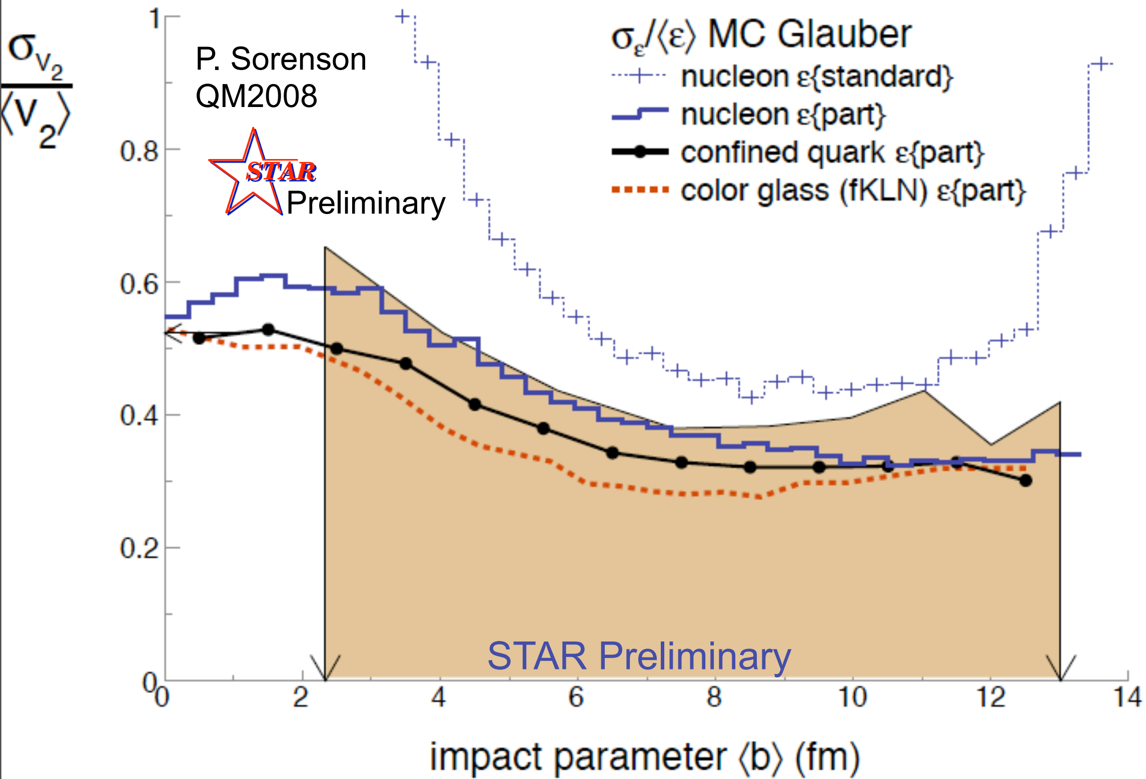

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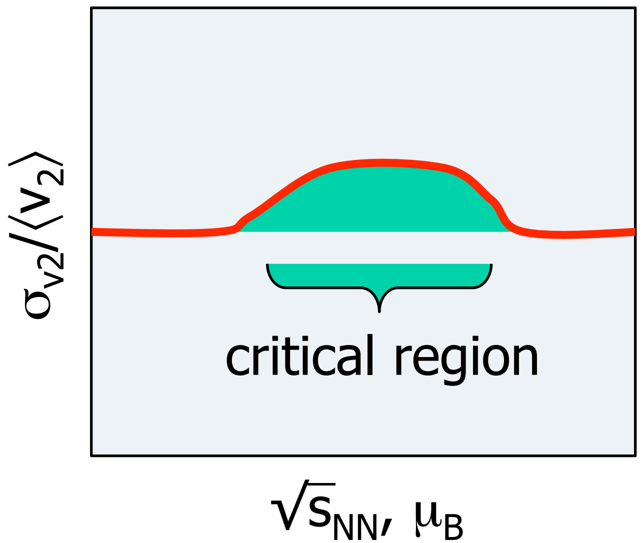

Upper limit challenges models of initial eccentricity fluctuations

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Data calls for different model of initial eccentricity (e.g. CGC)

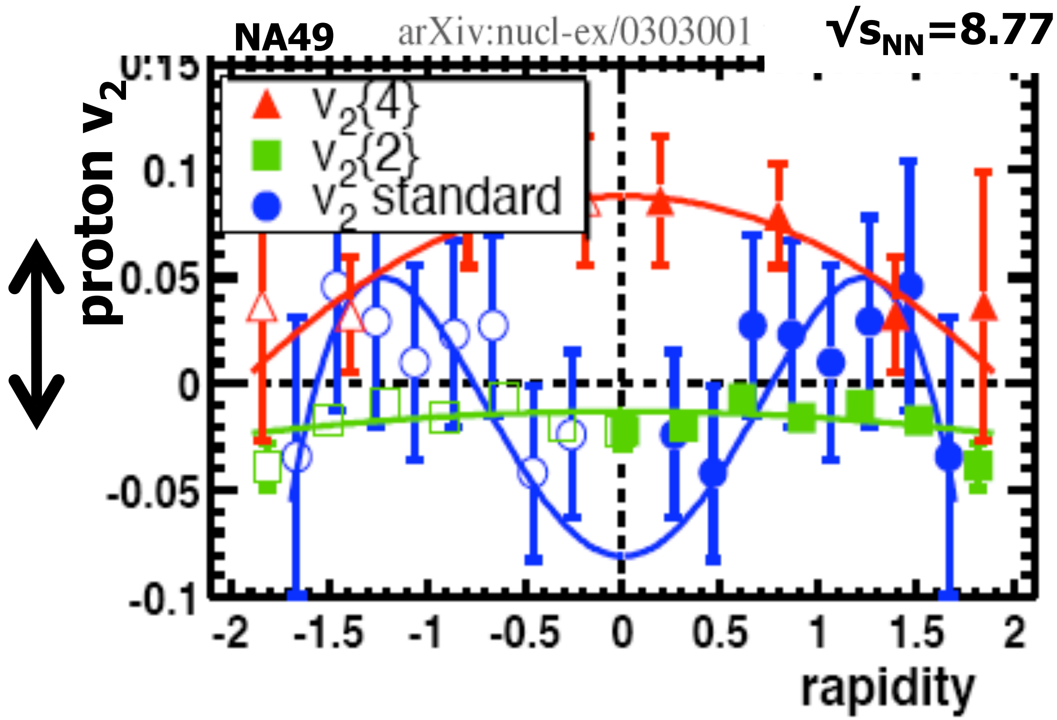
Measurement relies on central limit theorem, need acceptance - i.e. STAR

"Collapse" of proton v_2

Signature of phase transition (Stöcker, E. Shuryak)?

Problem: Different analysis different results.
$v_2\{4\} \neq v_2\{2\} \neq v_{2stand}$

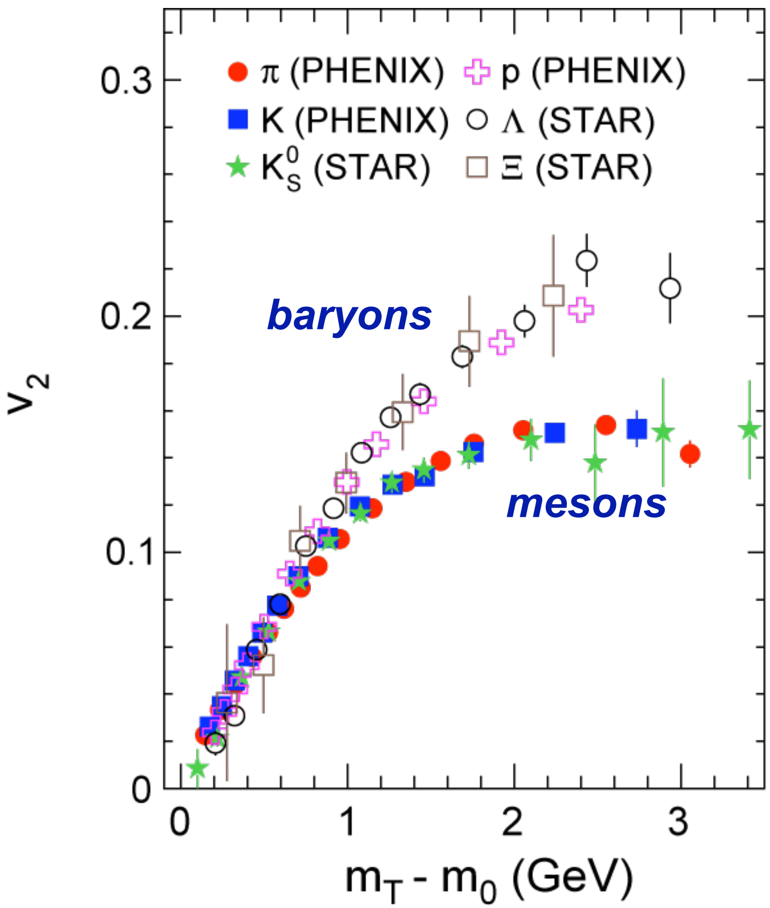
Results need to be reconfirmed.



Is difference due to non-flow and fluctuations or phase transitions?

Can help determine answer by measuring both v_2 and fluctuations in same detector

v_2 and de-confinement



- At low m_T-m_0 PID v_2 follows hydro. type scaling

- ϕ and Ω have large v_2 but small hadronic scattering cross-sections (not shown)

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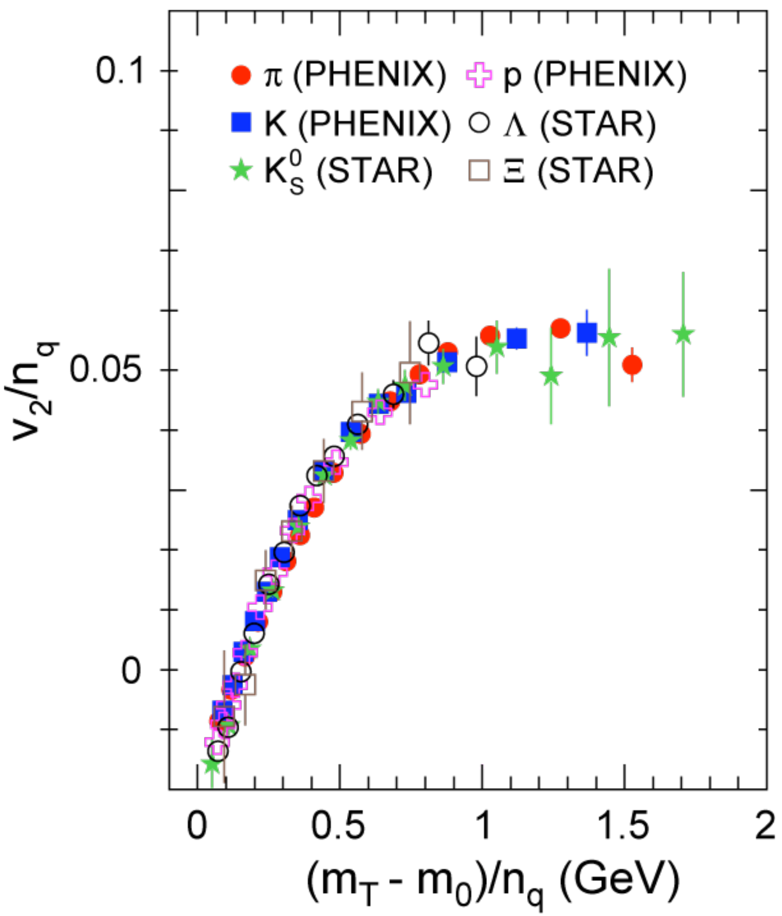

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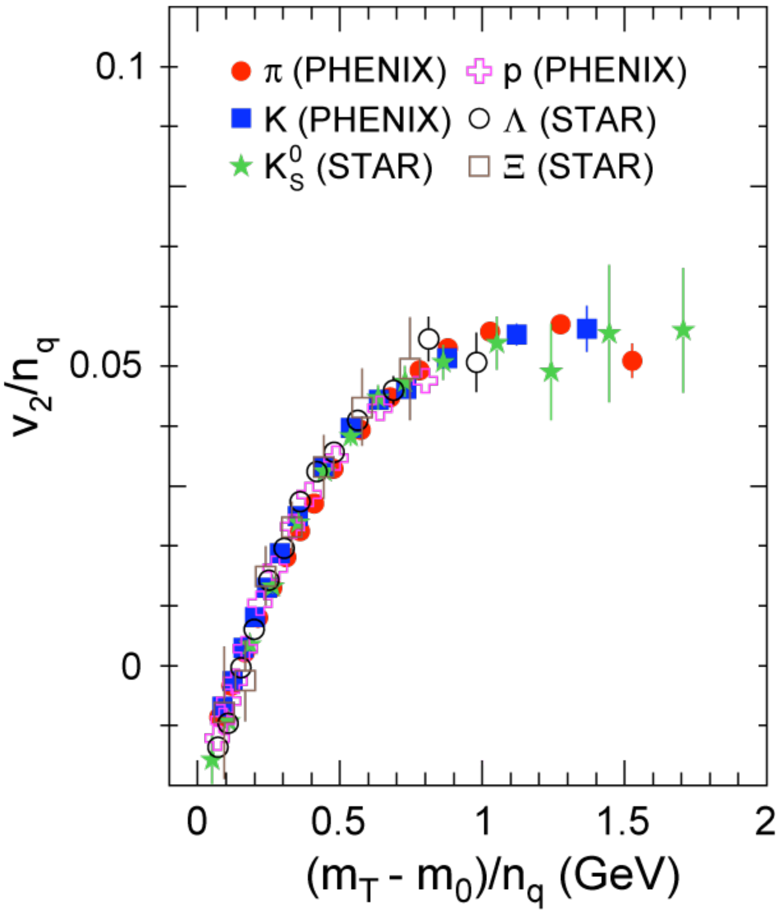

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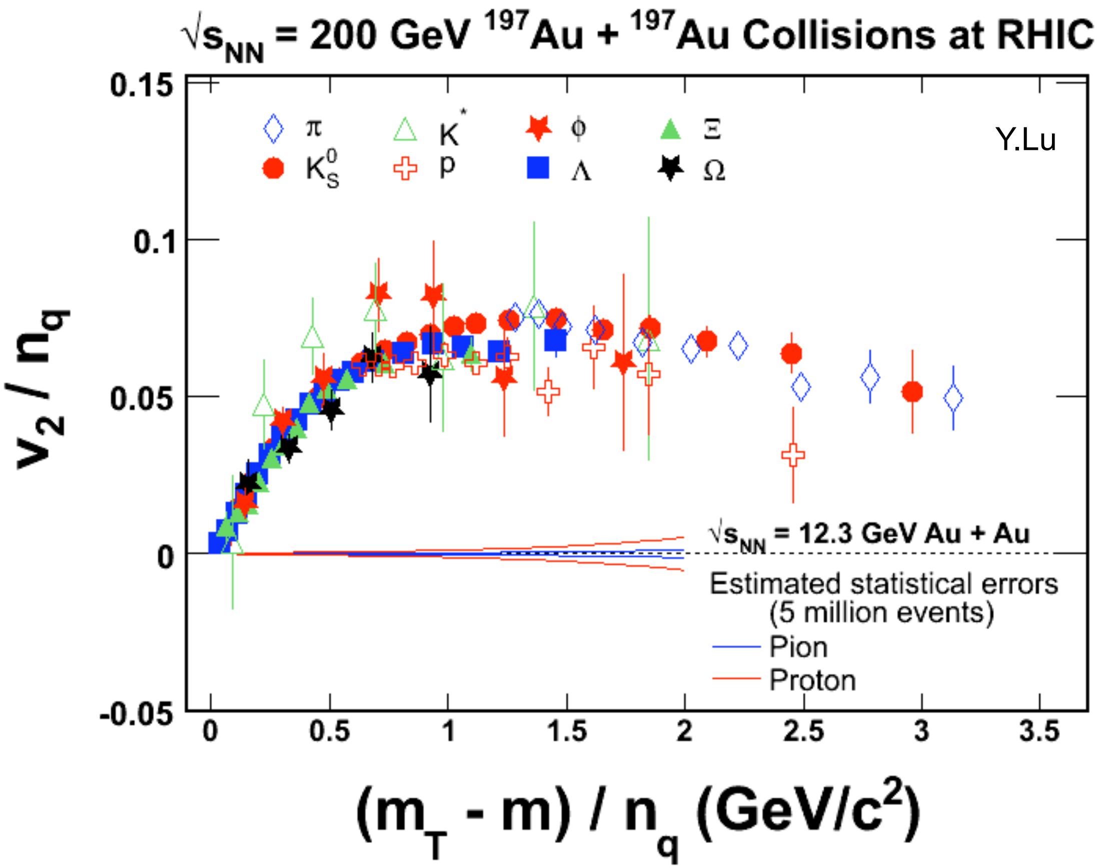
Do these effects turn off at lower energies?
- sufficient stats. with several million events (few days at 9 GeV)

Can we show this is not a hadronic effect?

Statistical error on v_2 with PID

Assuming 5 M Au+Au events at √s=12.3 GeV



0-43.5% measurements up to $(m_T-m)/n_q$ ~ 2 GeV is promising.

Systematic errors will dominate

Parity violation

In non-central collisions:

large orbital angular momentum

(magnetic fields)+ deconfined phase

⇒ strong P violating domains

Kharzeev et al. PRL 81 (1998) 512, and PRD 61 (2000) 111901

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⇒ Preferential emission of like sign particles in the direction of the angular momentum i.e. opposite sides of the reaction plane.

(Voloshin PRC 70 (2004) 057901)

$$\frac{dN_{\pm}}{d\phi} \sim 1 + 2a_{\pm} sin(\phi - \Psi_{RP})$$

the asymmetry

$\langle a_{\pm} \rangle = 0$ so measure $\langle a_{\alpha} a_{\beta} \rangle$

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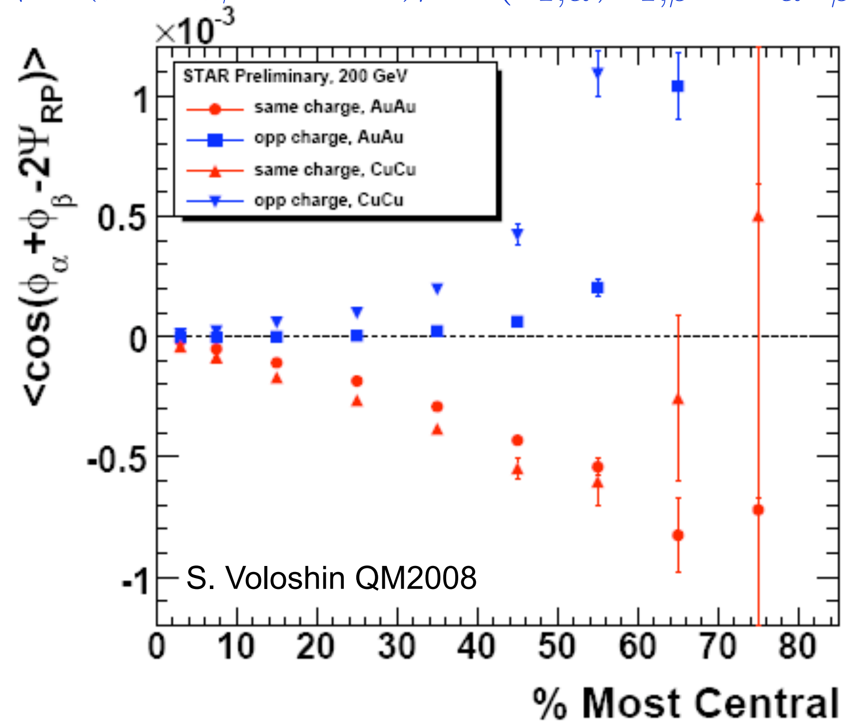

Possible signal in non-central event

$\langle a_{\alpha} a_{\beta} \rangle$ - P-even so may contain other effects

Under investigation

Parity violation

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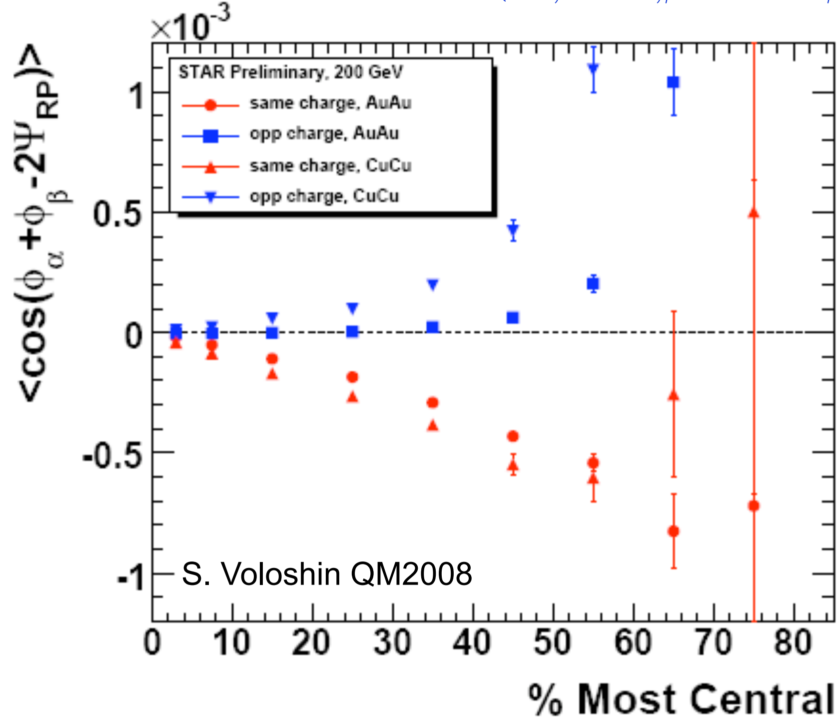

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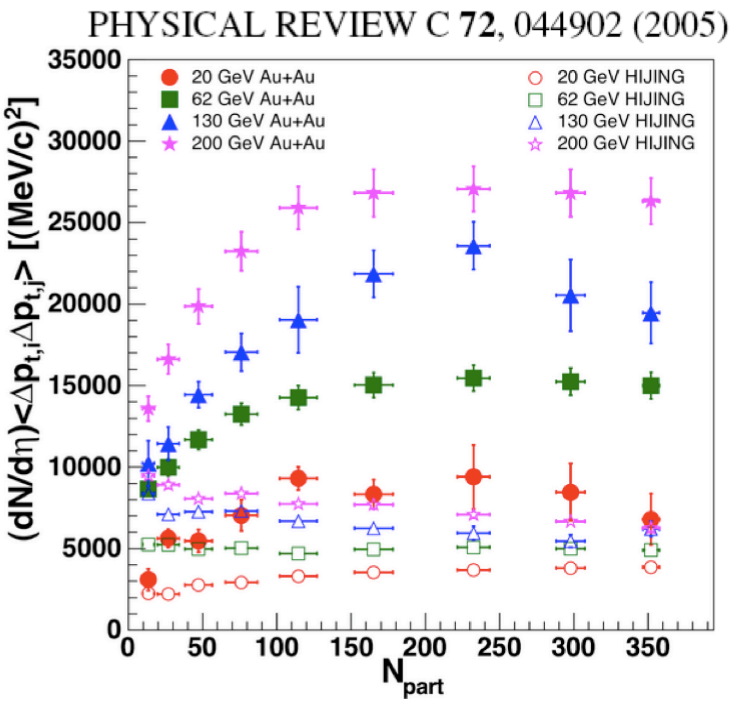
Possible signal in non-central event

$\langle a_\alpha a_\beta \rangle$ - P-even so may contain other effects

Under investigation

B-field+deconfinement → strong threshold effect → BES

⟨p_T⟩ fluctuations



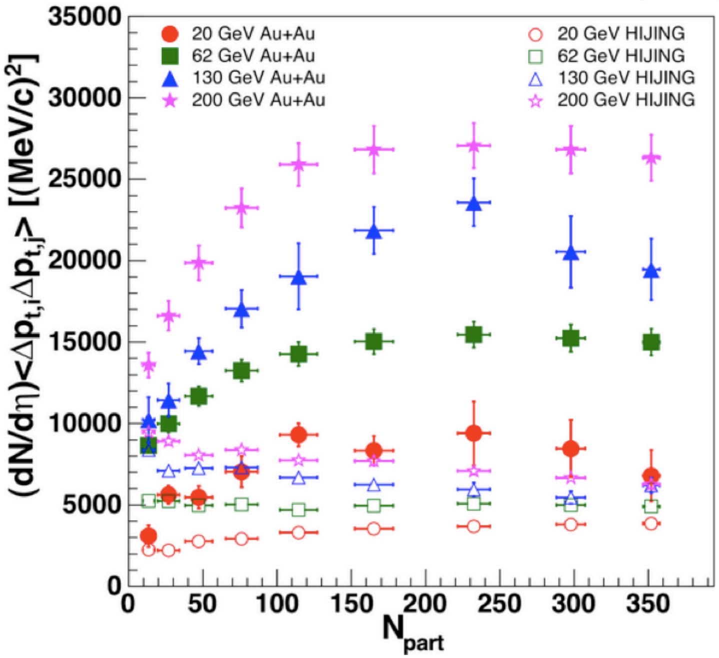
Non-statistical fluctuations are observed for all energies.

They increase with $\sqrt{s}$ and are larger than predicted by HIJING.

The fluctuation*dN/dη plateau for more central events.

⟨p_T⟩ fluctuations

PHYSICAL REVIEW C **72**, 044902 (2005)

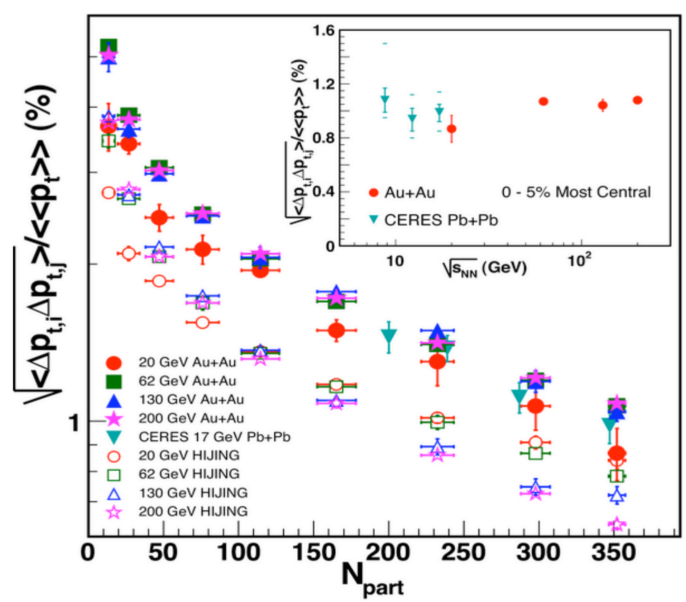


Non-statistical fluctuations are observed for all energies.

They increase with √s and are larger than predicted by HIJING.

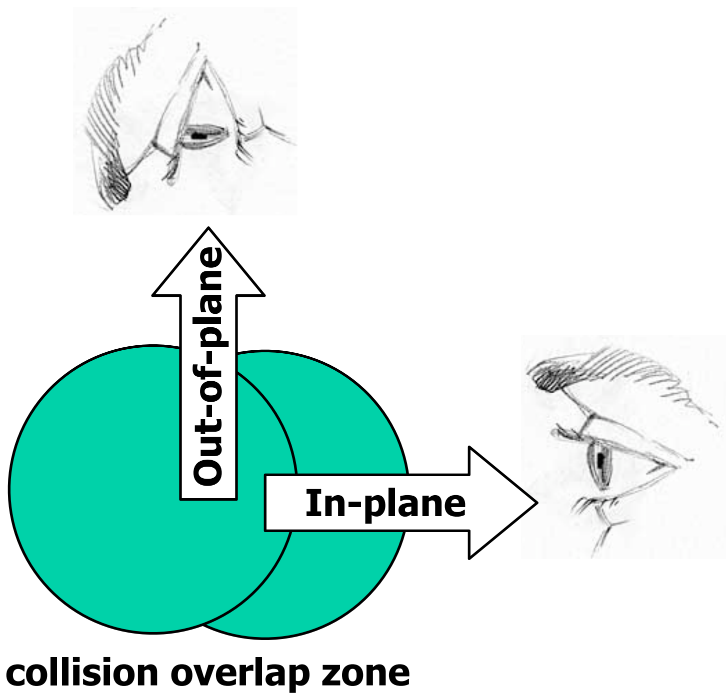
The fluctuation*dN/dη plateau for more central events.

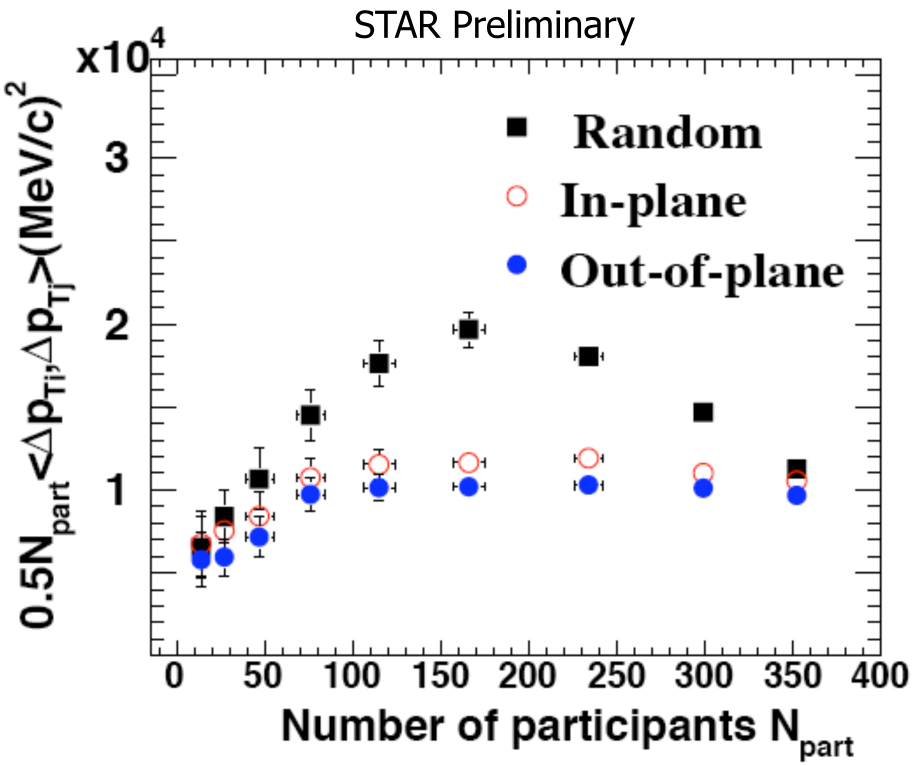
When scaled by ⟨p_T⟩ the energy dependence is removed but still higher than HIJING.



Challenges for $\langle p_T \rangle$ fluctuation measures

Acceptance





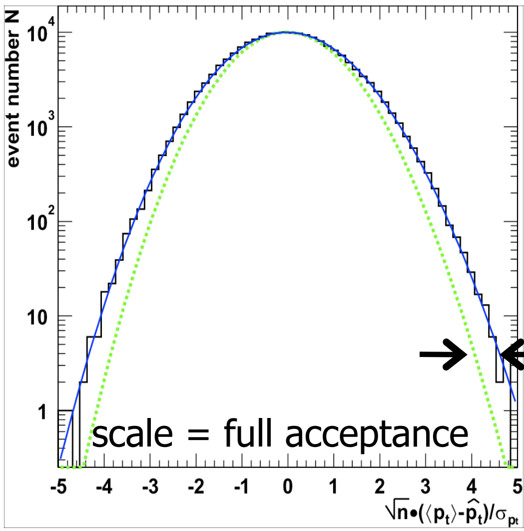
Elliptic flow can enhance apparent fluctuations

Need 2π coverage

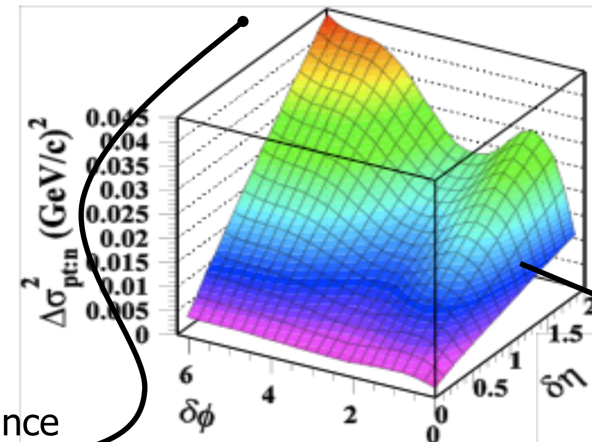
More advanced tools

Differential analyses have been developed at RHIC

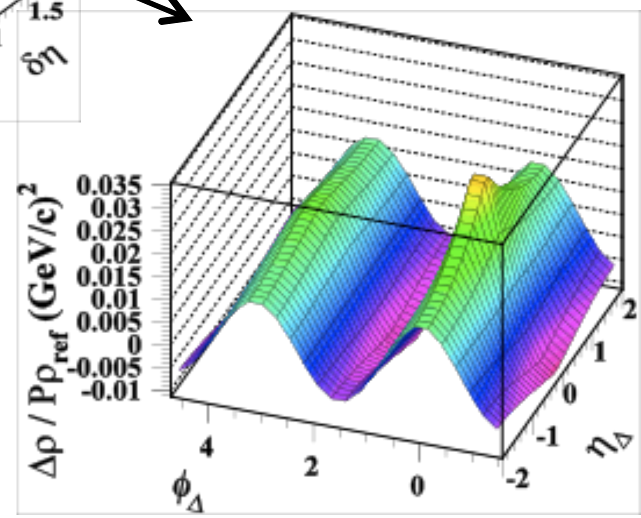
fluctuations



variance excess



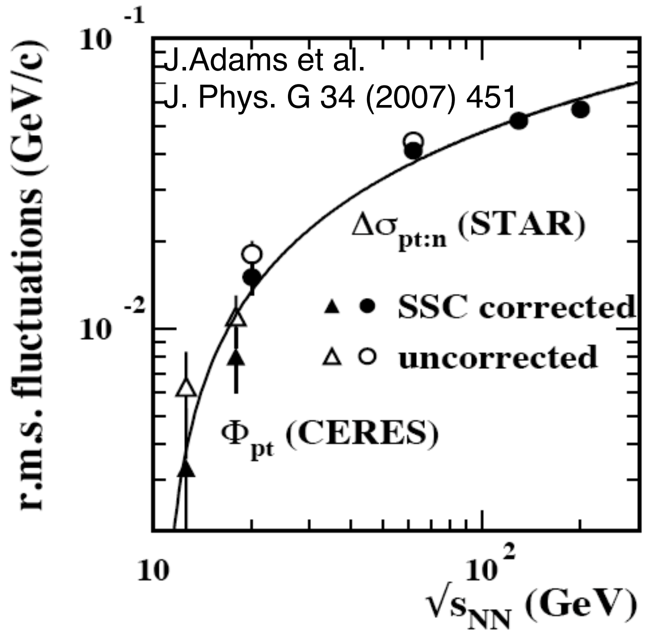
correlations



Allow a more detailed investigation of fluctuation measures

Rely heavily on acceptance and statistics

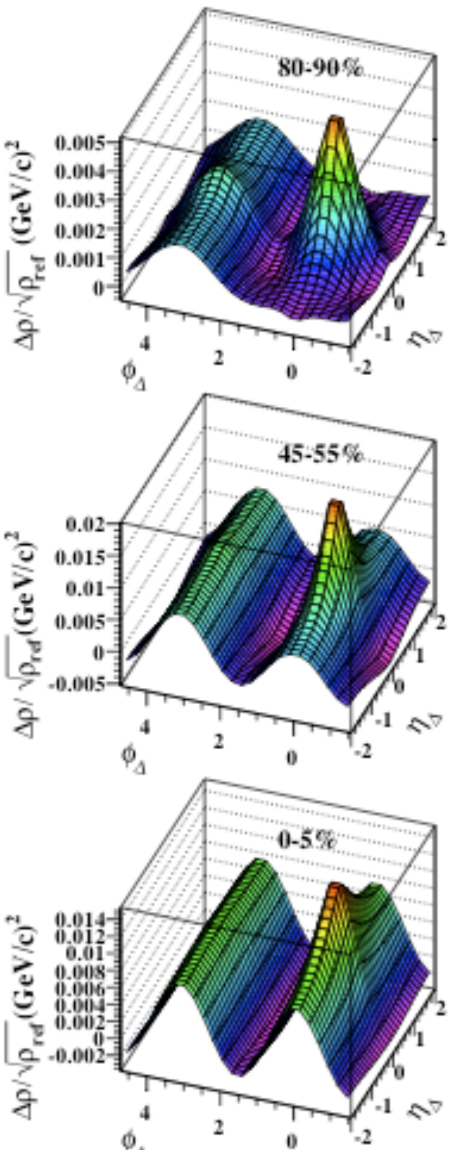
$\langle p_T \rangle$ fluctuations - a closer look



The $\langle p_T \rangle$ fluctuations appear to rise a log($\sqrt{s_{NN}}$).

Need to fill in the gap to check.

$\langle p_T \rangle$ fluctuations - a closer look



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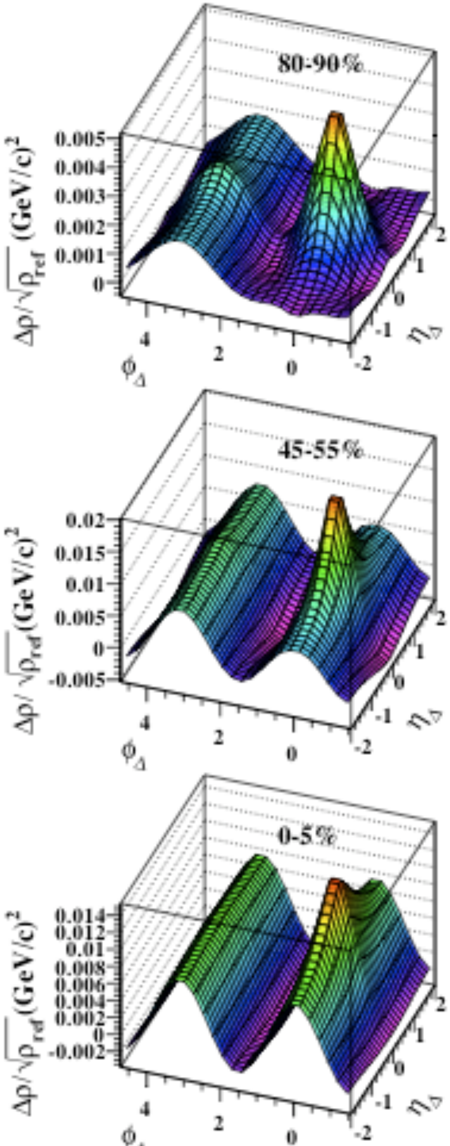
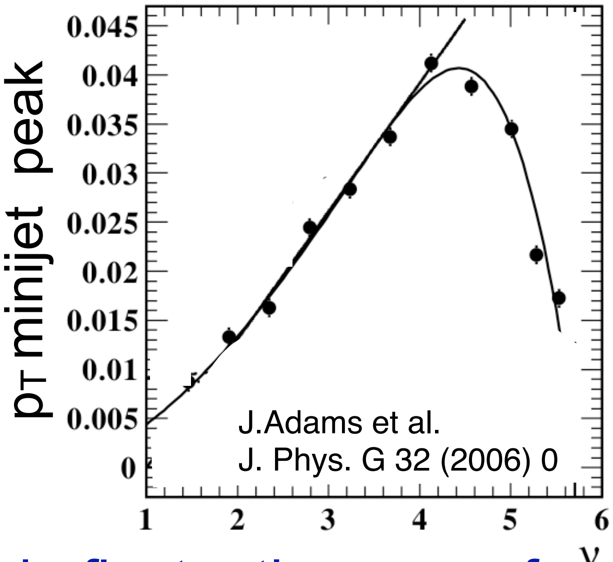
Increase in fluctuations as a function of centrality are concentrated in a near-side peak.

These correlations, elongated in η_Δ but focused in θ_Δ, are identified as mini-jets

J.Adams et al. J. Phys. G 32 (2006) 0

$\langle p_T \rangle$ fluctuations - a closer look





Increase in fluctuations as a function of centrality are concentrated in a near-side peak.

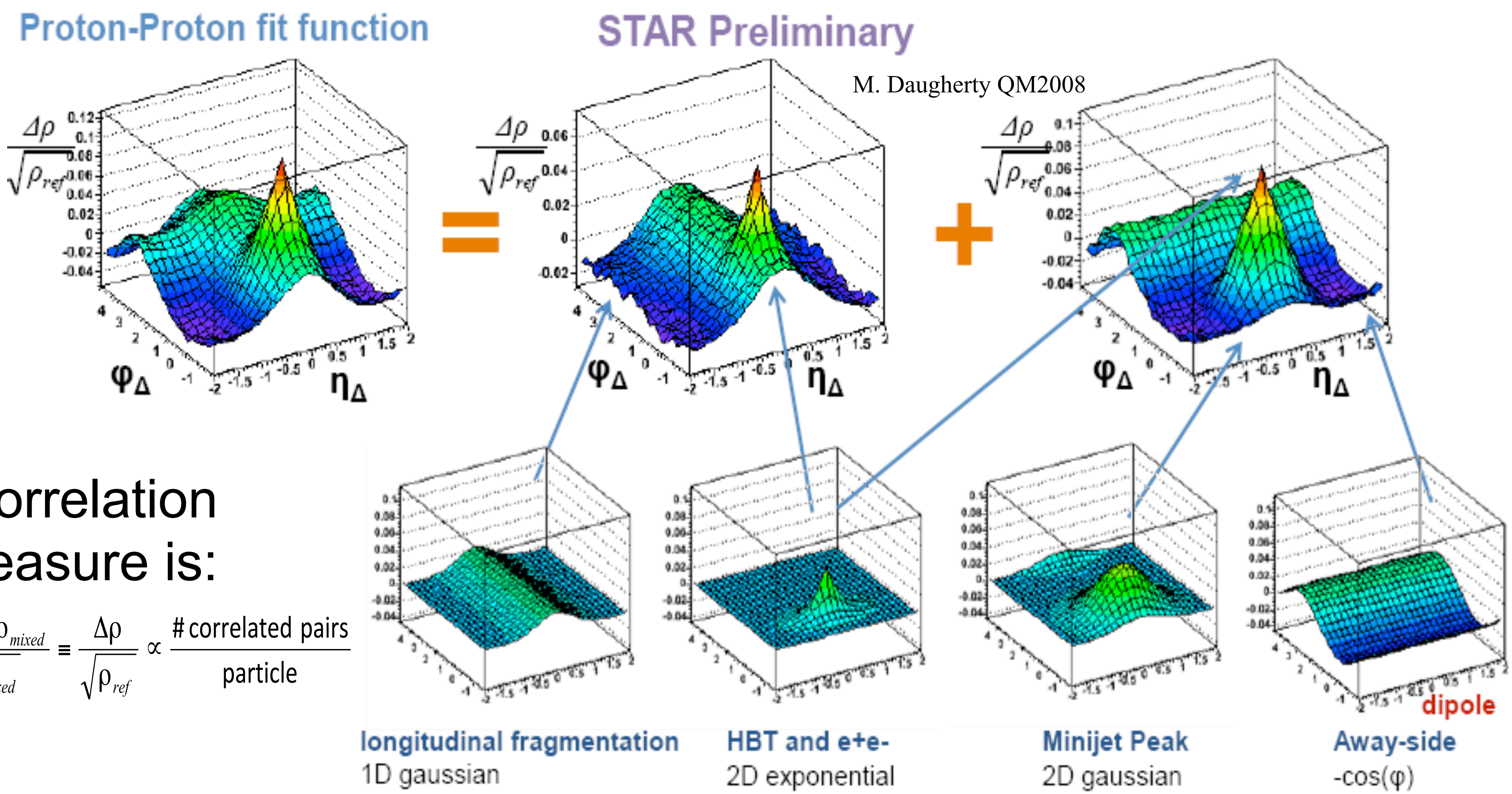
These correlations, elongated in η_Δ but focused in θ_Δ, are identified as mini-jets

Amplitude of peak follows N_{bin} scaling except most central events

J.Adams et al. J. Phys. G 32 (2006) 0

Pair correlations in p+p

Pair densities $\rho(\eta_1-\eta_2,\varphi_1-\varphi_2)$ for *all possible pairs* in same and mixed events.

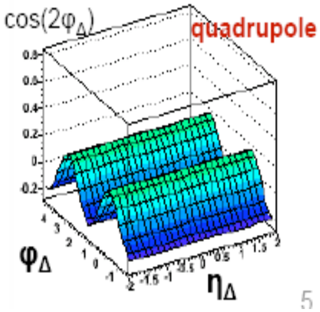


Correlation measure is:

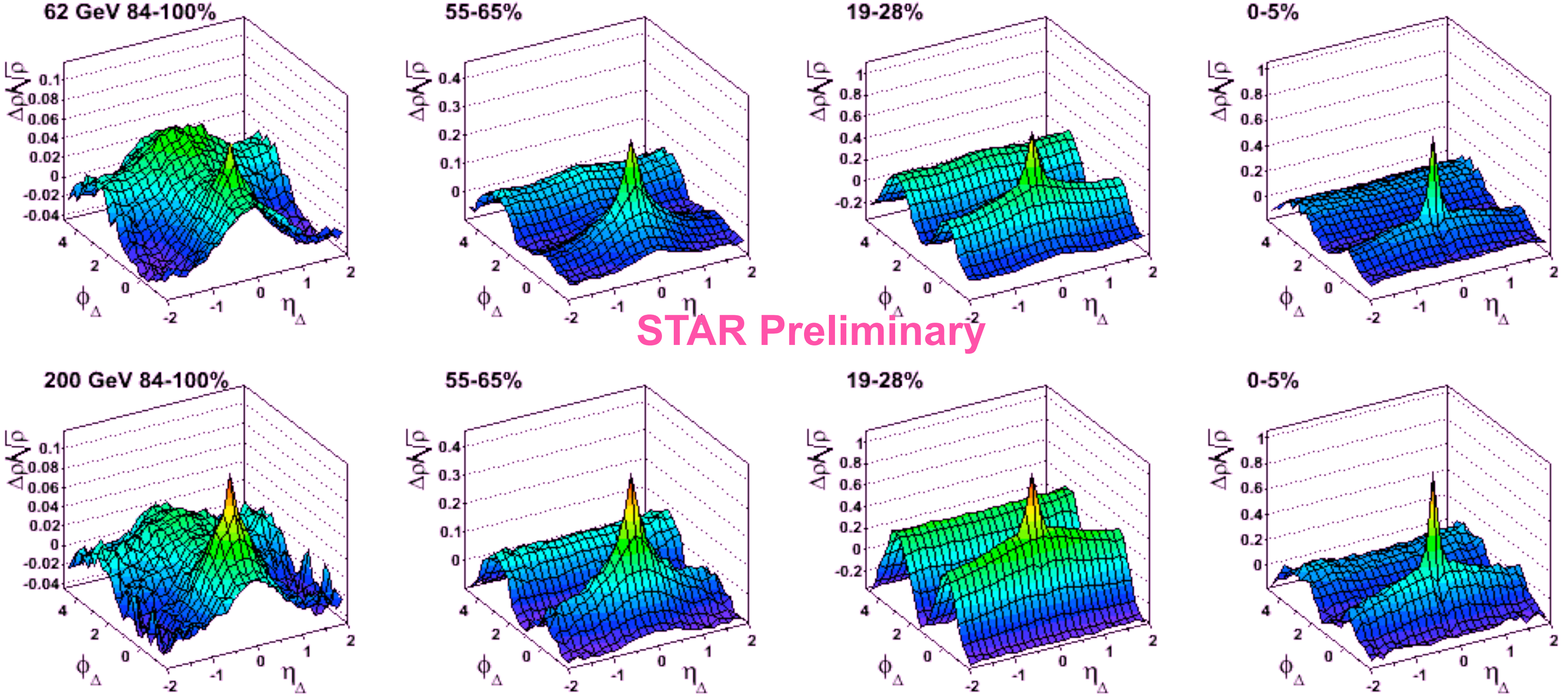
$$\frac{\rho_{same}-\rho_{mixed}}{\sqrt{\rho_{mixed}}} \equiv \frac{\Delta\rho}{\sqrt{\rho_{ref}}} \propto \frac{\#\,\text{correlated pairs}}{\text{particle}}$$

Au+Au 200 GeV pair correlations

Fit to p+p function + cos(2φ_Δ) (quadrupole term (aka flow))



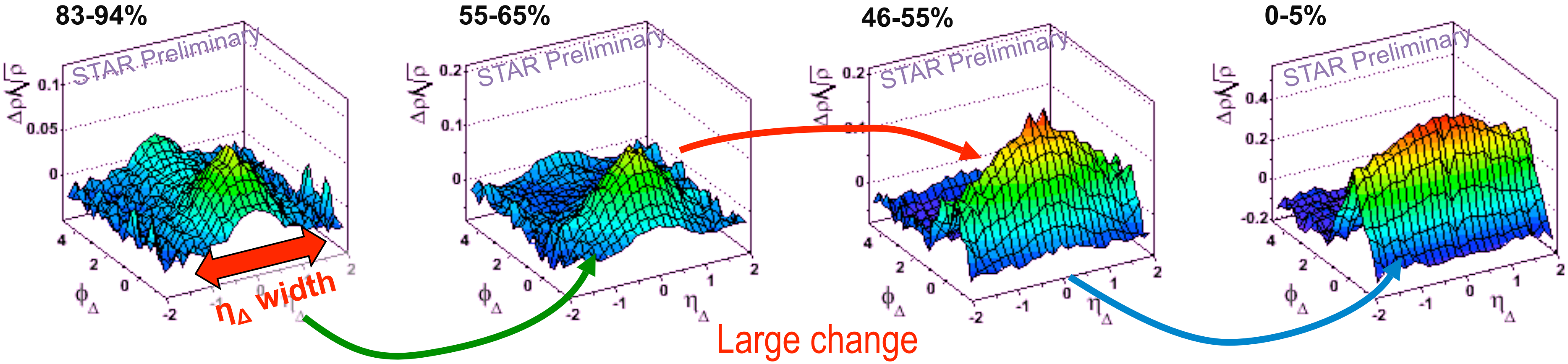
Fits result in ~zero residuals



M. Daugherty QM2008

A low p_T ridge

Same-side peak



Little shape change from peripheral to 55% centrality

Large change within ~10% centrality

Smaller change from transition to most central

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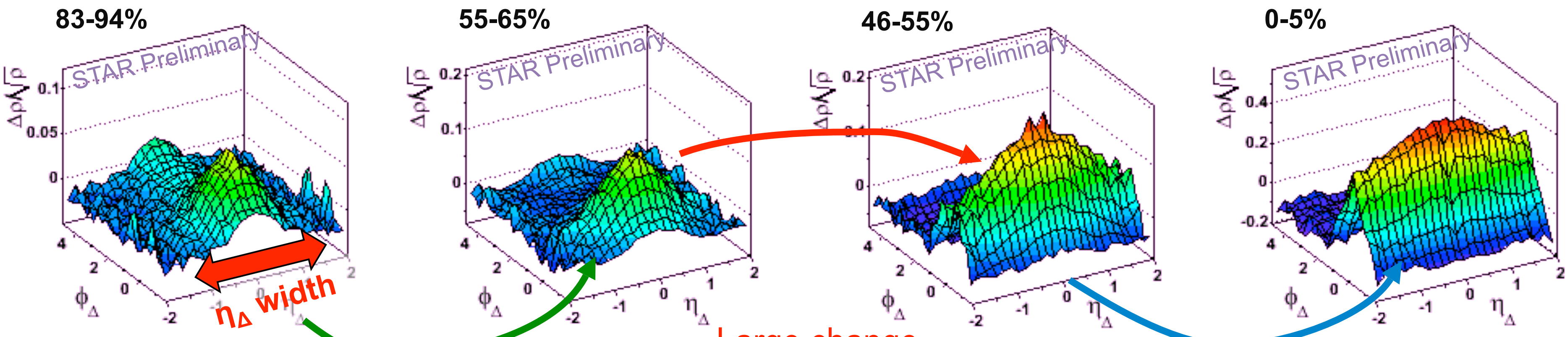

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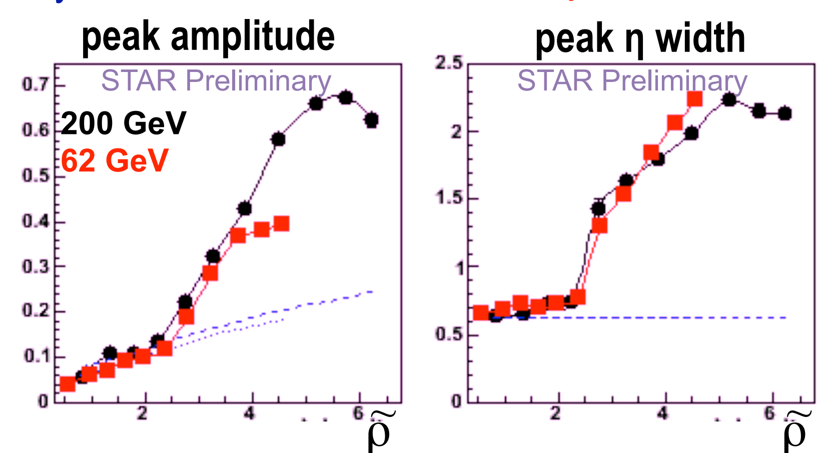
Large change within ~10% centrality

Smaller change from transition to most central

Sharp transition in peak and width at ρ ~ 2.5 for both 62 and 200 GeV



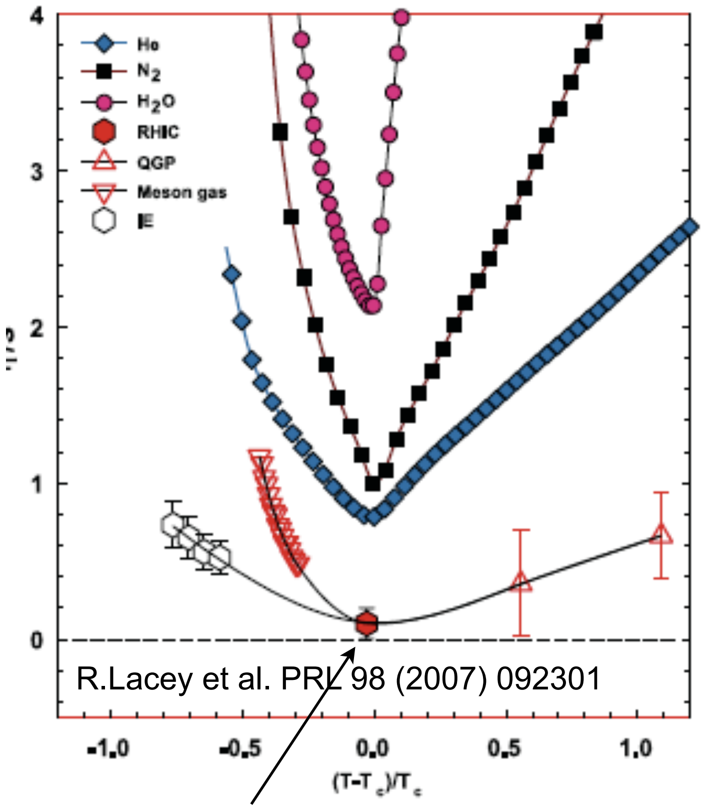
Transverse particle density $\tilde{\rho} = \frac{3}{2}\frac{dN_{ch}}{d\eta}/S$

M. Daugherty QM2008

What causes this rapid transition?

(not observed in p_T correlations)

η/s and the Critical Point

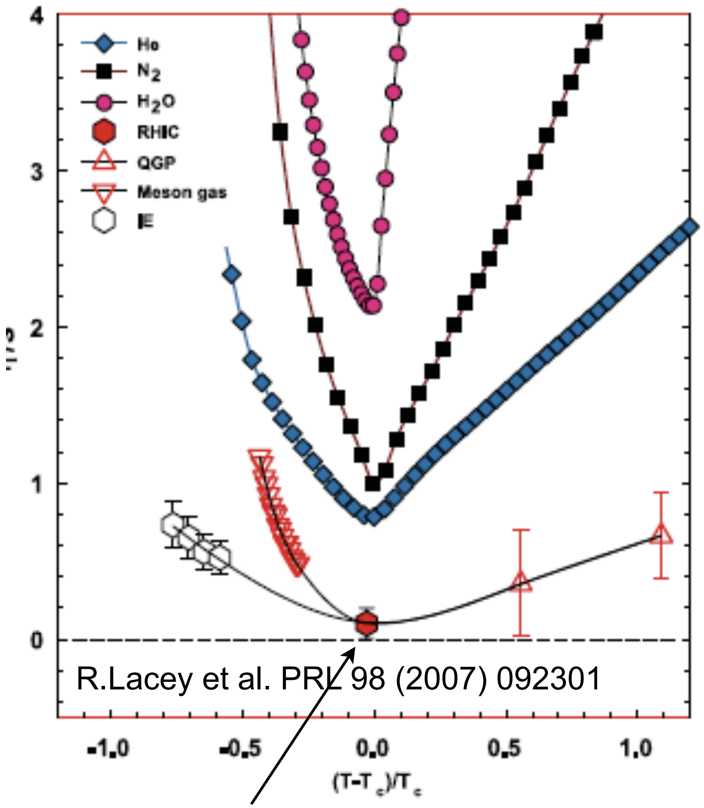


What is T?

- Near critical temperature η/s is a minimum.
- Need to sit near T_C while system evolves for this η/s to dominate
- If critical point acts as an attractor low η/s values may indicate we are close

Current estimates from 200 GeV data are near lower bound

η/s and the Critical Point



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Estimates possible with BES:

Elliptic flow

H.-J. Drescher et al. Phys. Rev. C76 (2007) 024905
R.Lacey et al. PRL 98 (2007) 092301

$$\frac{\eta}{s} \sim T\lambda_f c_s$$

p_T fluctuations

S.Gavin, M.Abdel-Aziz PRL 97 (2006) 16302

$$\frac{\eta}{s} \sim \nu T$$

STAR's beam energy scan proposal

First scan aiming to cover wider range $\sqrt{s_{NN}}$ from 6-40 GeV

- Lower energies will focus on phase transition properties
- Higher energies will focus on disappearance of the partonic medium.
- Also beam development at 5 GeV, expanding on work in Run 9.

Lower energies will be as close as possible to SPS while allowing, where possible, for collisions at both experiments

- Energy choices can be modified if theoretical guidance appears.

STAR's current energy scan proposal

14 weeks physics+1 week commissioning

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Rate (Hz)	Events	Duration (days)
5.0	550	0.5	Test	7
6.1	491	1.4	1M	23
7.7	410	2.7	2M	20
8.6	385	4	2M	15
12.3	300	10	5M	15
17.3	229	25	10M	12
27	151	30	10M	7
39	112	50	10M	6

Current "best guess" for optimization of run time and physics

Summary

The most exciting discovery potential of the beam energy scan is locating the critical point or 1st order phase transition

- K/π, $\langle p_T \rangle$, v_2 (critical point fluctuations)
- Pair correlations
- Energy dependence of flow characteristics (v_1 and v_2)

Guaranteed results:

- Narrowing of region where exotic medium effects (dis)appear
  - Sizemlable v_2 of φ and Ω
  - N_q scaling of v_2
  - Parity violation
- Detailed systematics help close the open theory issues referenced in the RHIC “white papers”
- Significant extension and improvement over existing SPS

Need more detailed predictions from theory - this workshop!

STAR and RHIC are ready for a focused low energy run ASAP

A second low energy run

After analysis of first data set we propose a second scan focused on specific energies

- Energies and physics topics will be chosen to explore in more depth the most interesting regions found in the first scan.
- Luminosity upgrades will be useful at the lowest energies *unless* first scan indicates those regions are not interesting.

Guaranteed results:

To be predicted once data from the first scan is analyzed.

Low energy beam tests

2006: One day of machine studies with protons

- Center of mass energy - 22 GeV
  - Magnet settings appropriate for Au+Au $\sqrt{s}$ ~ 9 GeV equivalent to fixed target with ~40 AGeV beam.
- Results were very encouraging!

2007: Injecting and colliding Au+Au @ $\sqrt{s_{NN}}$ = 9.2 GeV

- Running below design injection energy for the first time
- Same magnetic rigidity as 2006 low energy proton test
- Overall, the run was a major success!
  - For the first time at RHIC, the RF frequency limits could not accommodate 360 RF buckets.

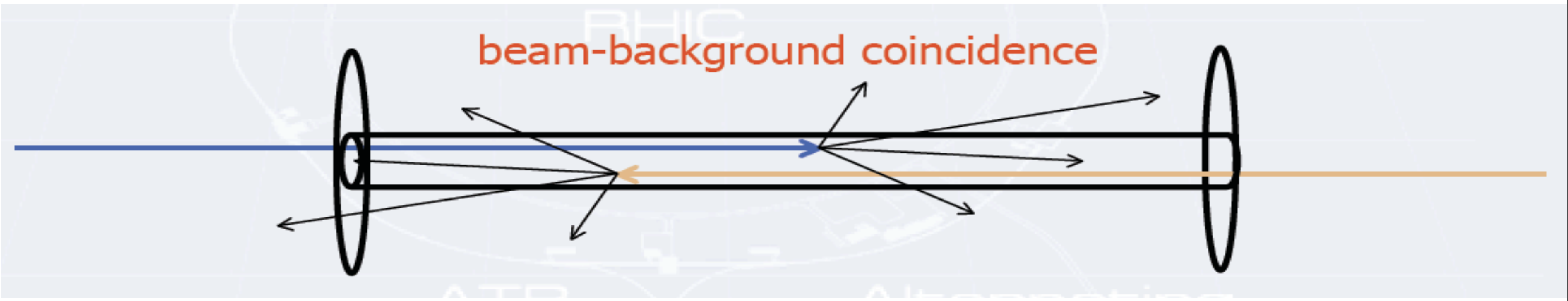
Both tests successful for accelerator and STAR

Analysis of Au+Au $\sqrt{s_{NN}}$=9 GeV data

Preliminary (during run) conclusions very optimistic

BUT: in 2500 events on tape fewer than 1% vertices reconstructed

During 2008 d+Au run a contribution to the BBC coincidence rate from beam-background coincidence was identified:



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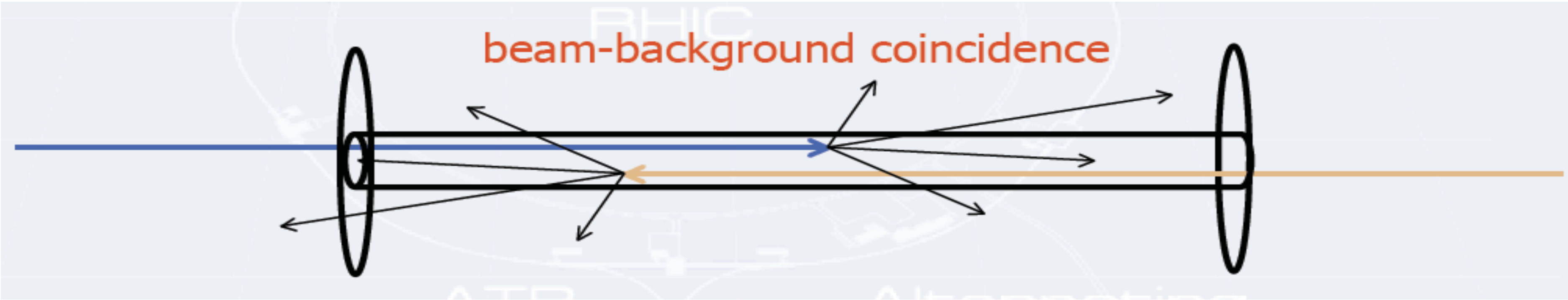
BUT: in 2500 events on tape fewer than 1% vertices reconstructed

During 2008 d+Au run a contribution to the BBC coincidence rate from beam-background coincidence was identified:



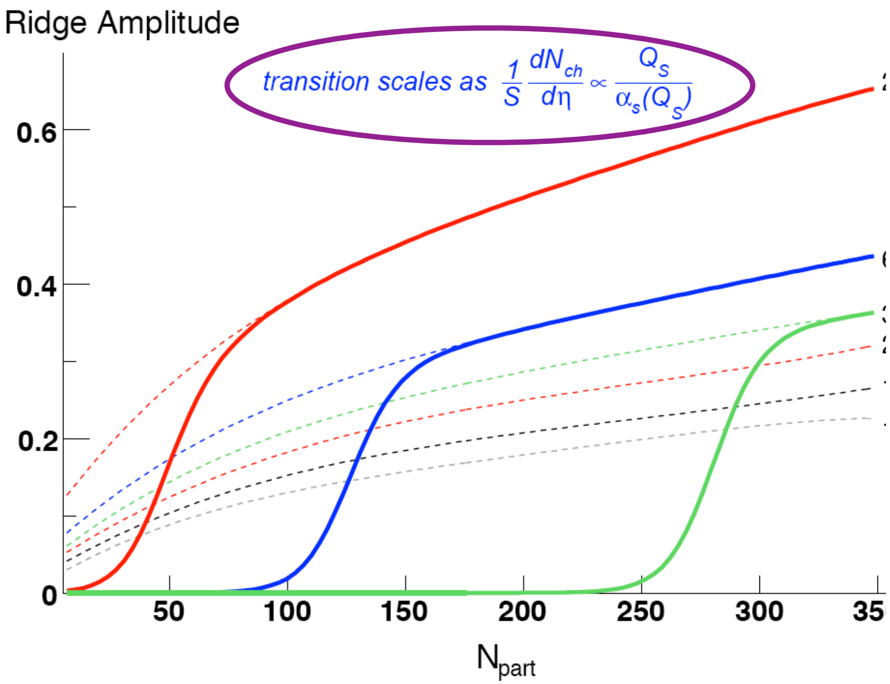
- Background explained almost entire event rate during the low energy test
- Actual event rate was unknown and could be very low
- Time for physics program may therefore have been underestimated
- BBC alone is not a good measure of luminosity for the low energy run

Need another test run - try BBC&&CTB/TOF trigger

Low p_T ridge prediction

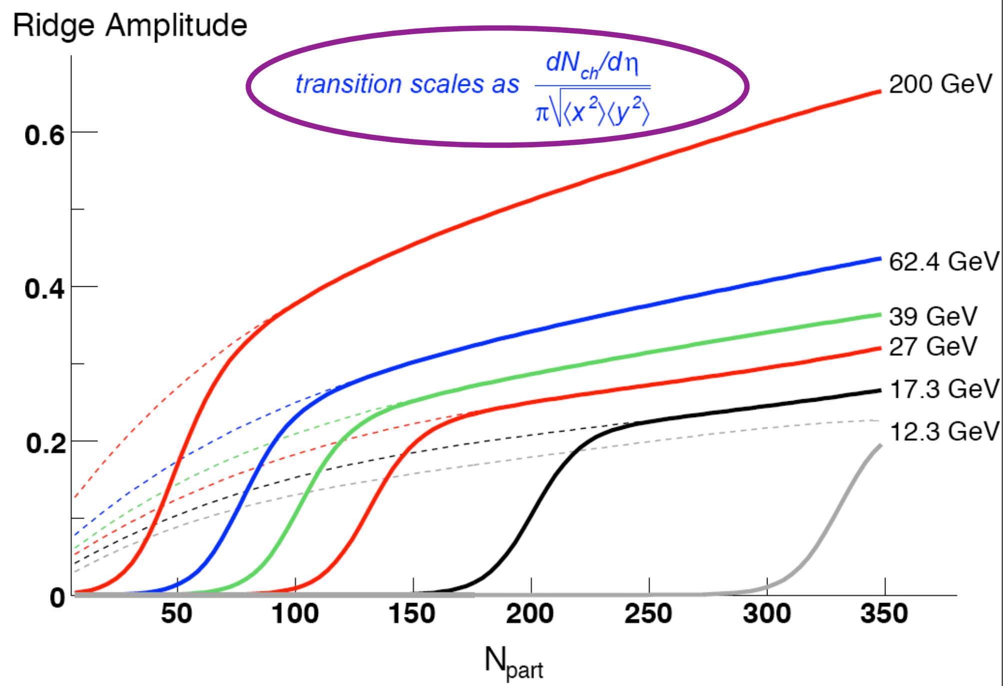
Low p_T caused by Glasma flux tube radiation + flow?
QGP boundary may be mapped by “turn on” of this ridge

A. Dumitru et al. arXiv:0804.3858



Saturation physics motivated
onset related to energy density

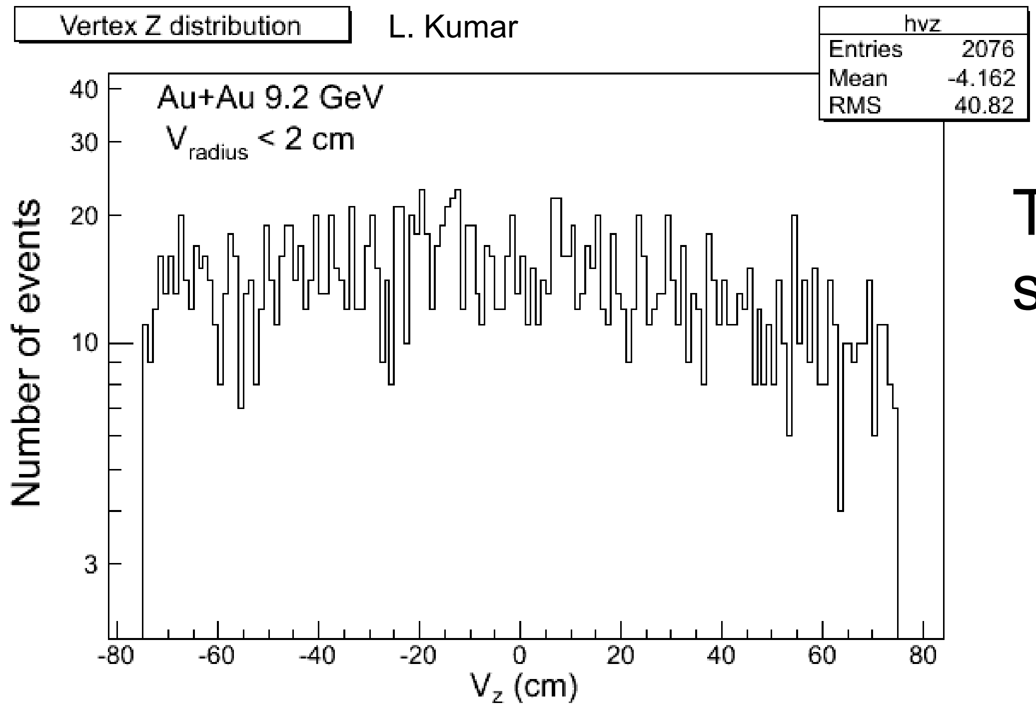
- ridge gone below $\sqrt{s_{NN}} \approx 35$ GeV



Collisional Low Density Limit
onset related to particle density

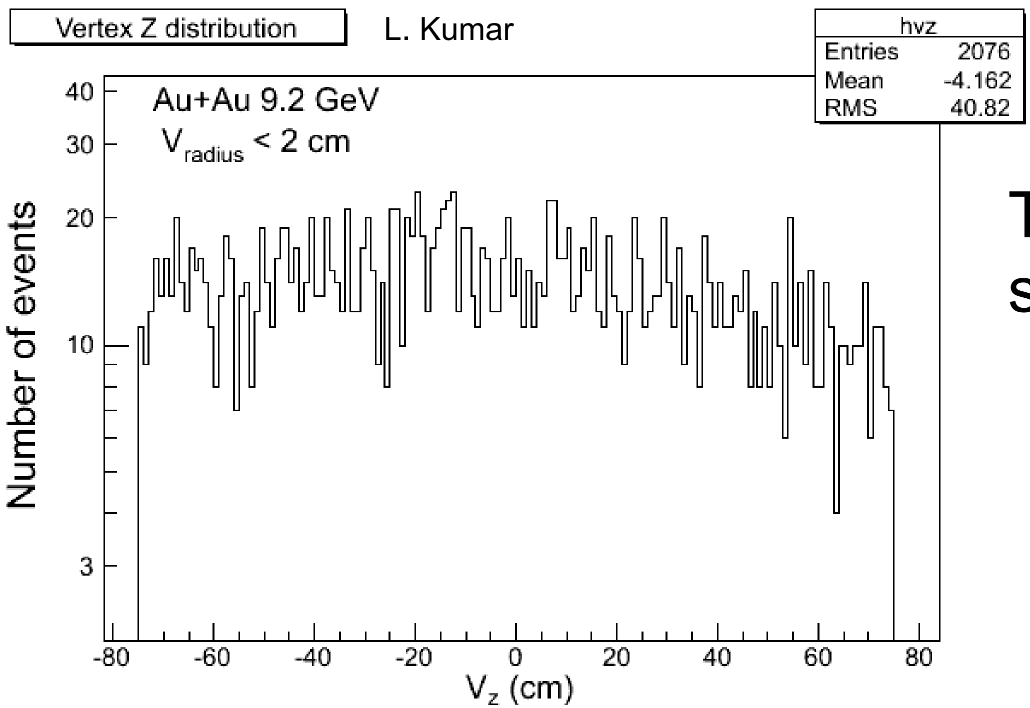
- ridge gone below $\sqrt{s_{NN}} \approx 13$ GeV

Event characteristics

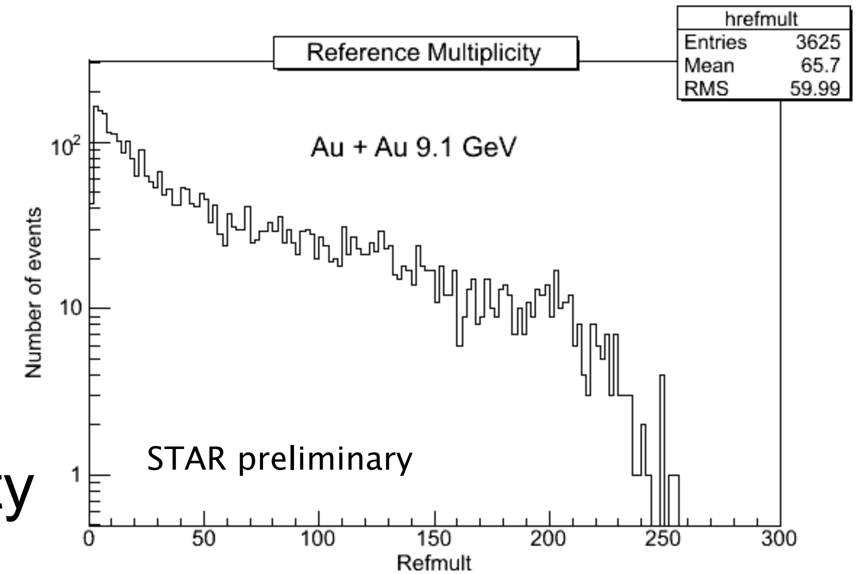


The primary vertex location is spread over a large range in z

Event characteristics



The primary vertex location is spread over a large range in z



- We obtain a reasonable min-bias distribution
- Need to investigate low multiplicity trigger/vertex finding efficiency
  - Don't get 100% of cross-section?

Raw multiplicity

What energies to pick?