Light Vector Meson Results From the PHENIX Detector In pp, dAu, and AuAu Collisions at RHIC

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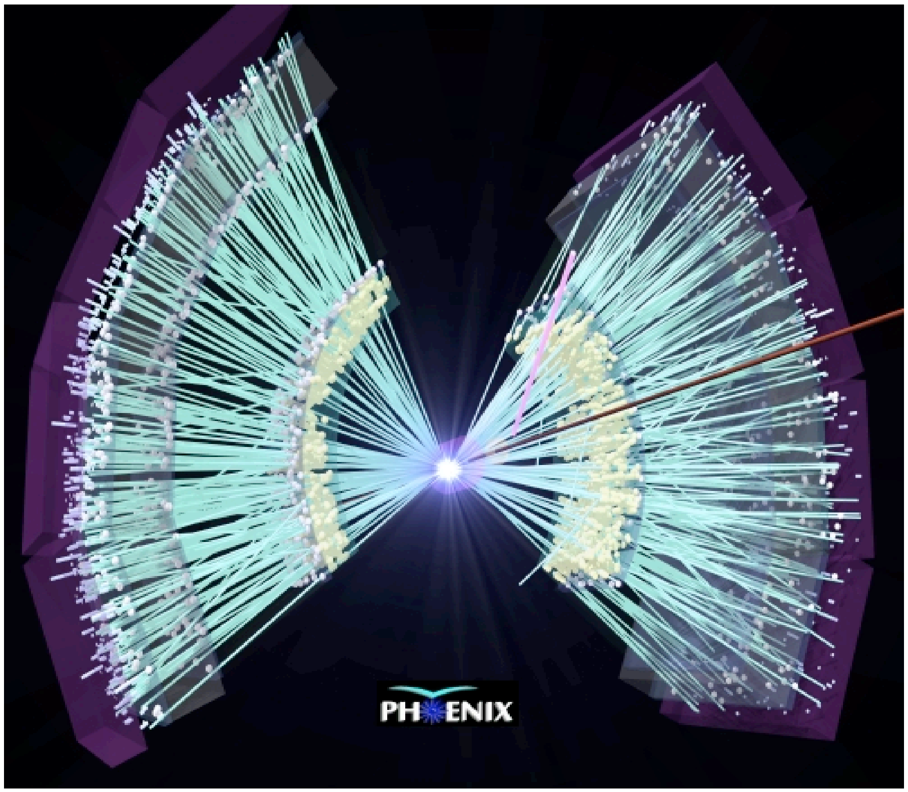
for the PHENIX Collaboration



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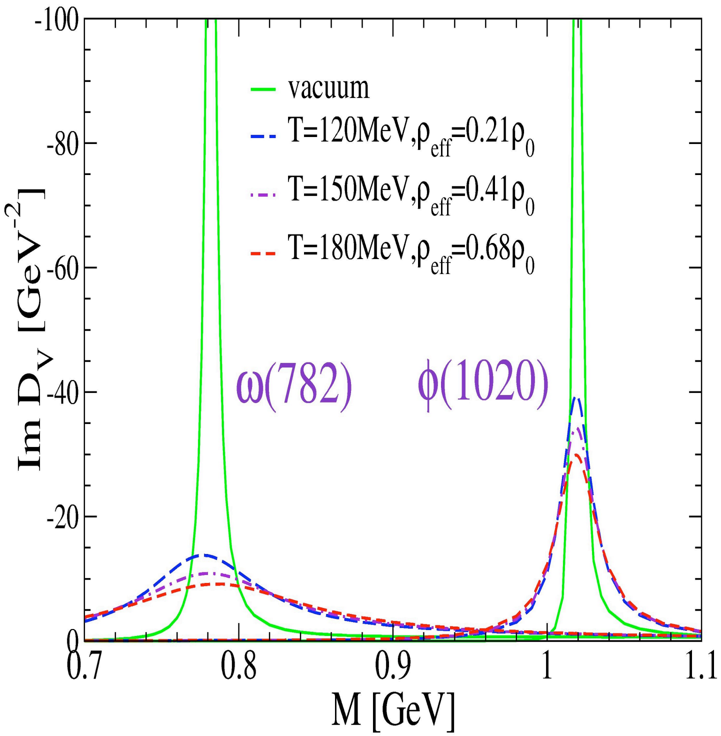
PHENIX

Outline

- **Physics Motivation**
- **Detecting the ϕ in PHENIX**
- **Line Shape Analyses for the ϕ: Au+Au and d+Au at $\sqrt{s_{NN}}$ = 200 GeV**
- **Yield Analyses for the $\phi \to K^+K^-$ in Au+Au**
  - Simple exponential fits
  - R_{cp} analysis
  - More sophisticated blast wave analysis
- **Yield Analyses for the ϕ in d+Au**
  - Compare $\phi \to K^+K^-$ and $\phi \to e^+e^-$
  - Compare per participant yields for $\phi \to K^+K^-$ in Au+Au and d+Au
- **Future ϕ Efforts in PHENIX**
  - Baseline pp studies from RHIC Run2 and Run3 data
  - Finer binned centrality analyses for $\phi \to K^+K^-$ and $\phi \to e^+e^-$ from RHIC Run4
  - Determination of the elliptic flow in $\phi \to K^+K^-$ from Run4 Au+Au data
  - Search for global polarization signal for $\phi \to K^+K^-$ in Run4 Au+Au
  - Expanded reach with new detector subsystems: MRPC/Aerogel and HBD

Physics Motivation

R. Rapp nucl-th/0204003



A theoretical prediction of how the widths of the ω and φ mesons might change as the medium temperature is raised past the chiral symmetry restoration temperature

φ Meson as a Special Probe for RHI Collisions

- $s\text{-}\bar{s}$ bound state
- sensitive to strangeness production
- small interaction cross-section with nucleons ==> retains information on production state

φ Properties

- Mass = 1.019456 +/ 0.0000020 GeV/c^2 (close to that of the proton)
- Breit-Wigner Width = 4.26 +/- 0.05 MeV (comparable to detector resolution)
- Interesting decay modes
  - $\phi \rightarrow K^+K^-$ (BR = 49.2%)
  - $\phi \rightarrow e^+e^-$ (BR = 2.96 x 10^{-4})
  - $\phi \rightarrow \mu^+\mu^-$ (BR = 2.87 x 10^{-4})

φ Experimental Observables

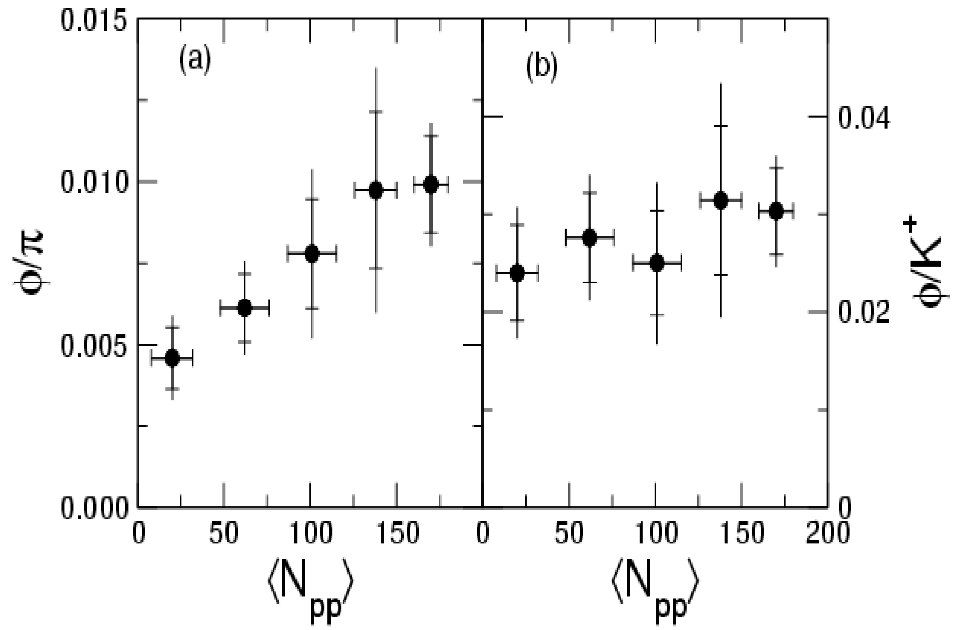
- Yield (dN/dy) as a function of transverse mass (m_T) and collision centrality
- Line shape parameters Mass and Width

Main Physics Questions

- Do the BRs change from the PDG values?
- Do the line shape parameters vary?
- Do the yields vary from expectations?

ϕ Production Topics

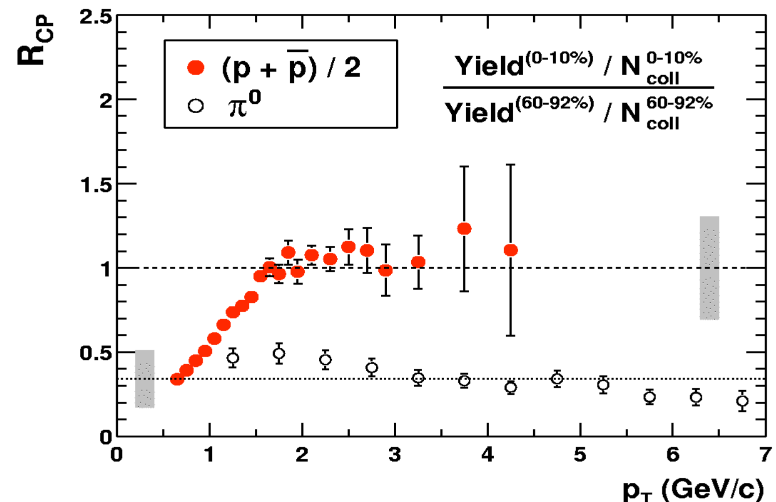
E917 Fiducial Yields for ϕ in Au+Au at $\sqrt{s_{NN}}$ = 4.87 GeV (AGS Fixed Target)



The observed yield of the ϕ relative to π appears to increase as a function of collision centrality in Au+Au collisions at the AGS.

Is the same behavior observed at RHIC? Are their differences between the d+Au and the Au+Au production ratios at RHIC?

"Baryon Anomaly" in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (RHIC)

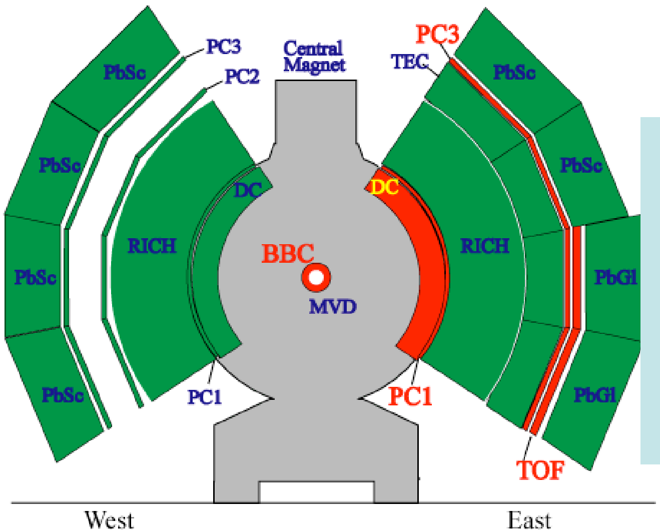


R_{CP} :Central/Peripheral Ratio
dN/dy scaled by the number of collisions

Strong suppression of π^0 yields above p_T~2 GeV/c but no suppression for proton and antiproton at intermediate p_T~(2-5 GeV/c)

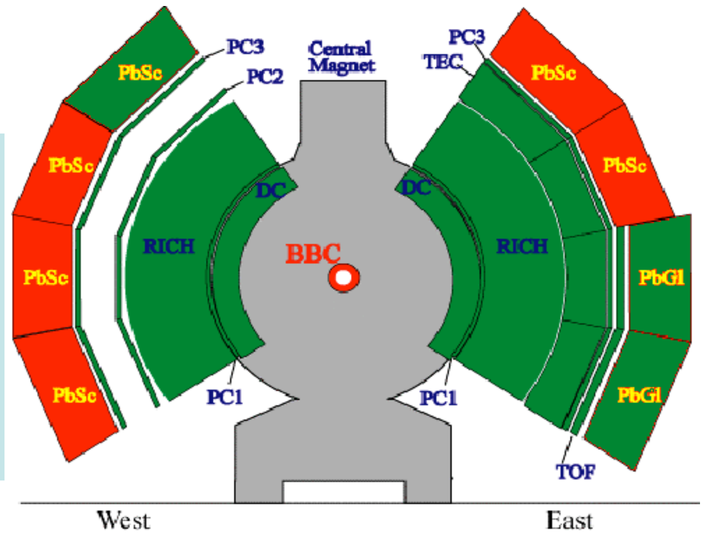
Is this anomaly a mass effect, or an effect of the meson/baryon difference between the π and the proton?

Detecting the ϕ in PHENIX



momentum resolution
$\sigma_p/p \sim$ 1% $\oplus$ 1% p

Leads to ~1 MeV pair resolution for $\phi \to K^+K^-$
Compare Γ_ϕ = 4.24 MeV

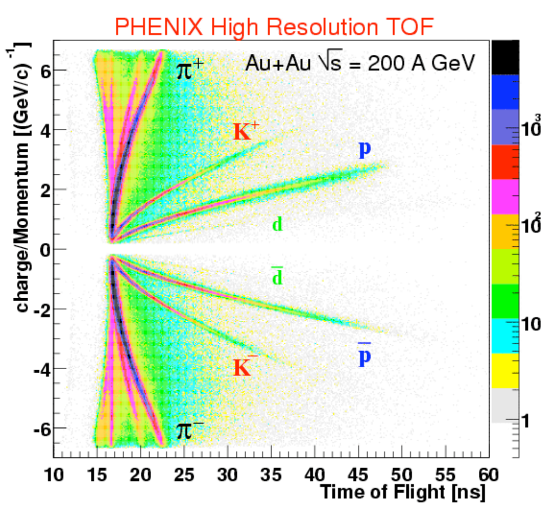


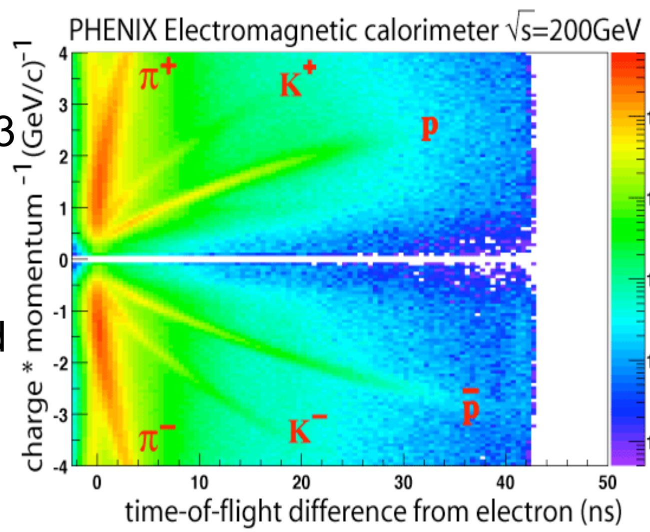
TOF resolution **120 ps**

$\phi \to K^+K^-$ uses TOF-TOF, EMCal-EMCal, and TOF-EMCal
East Arm only for Run2
East + West Arms for Run3

$\phi \to e^+e^-$ uses RICH, EMCal-EMCal in East-West, East-East, and West-West

EMCal resolution 450 ps

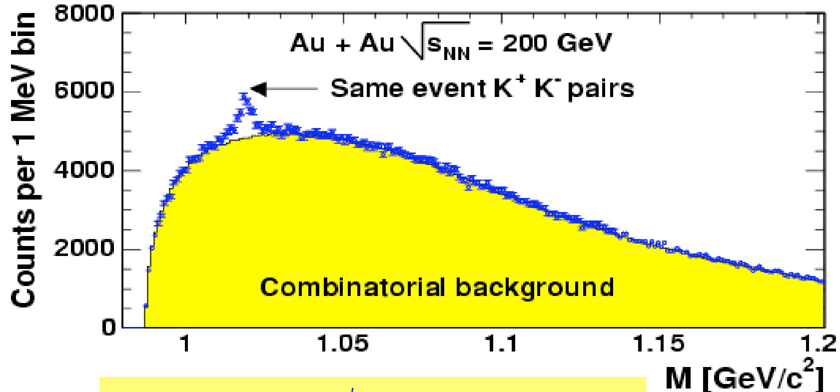




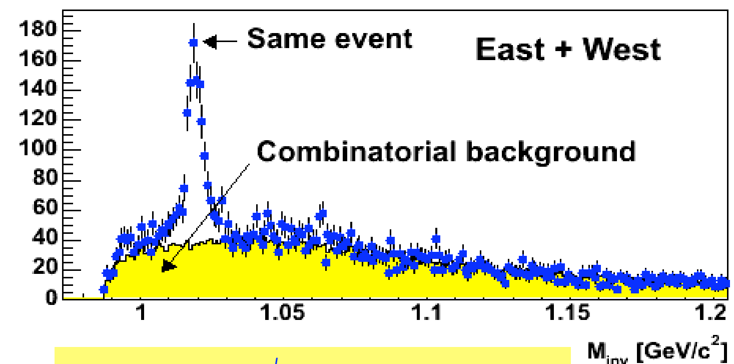
Data Samples

- **Data sets:** Au+Au 200 GeV, data taken during RHIC Run2 (2001/2002)
  d + Au 200 GeV, data taken during RHIC Run3 (2003)

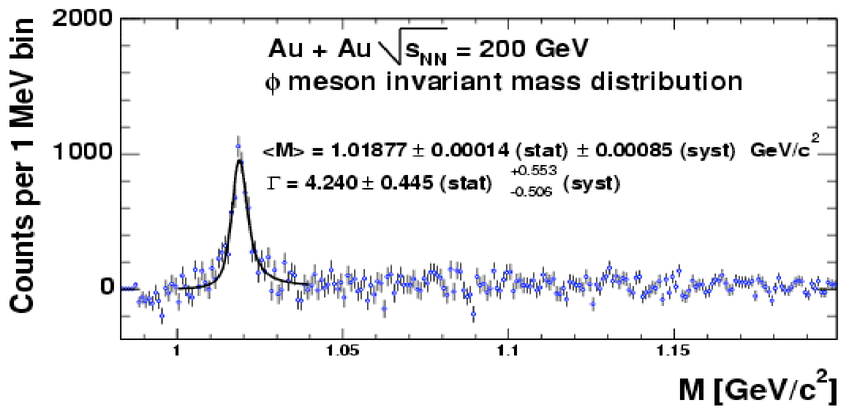
- **Statistics:** analyzed 20 M minimum bias (MB) events for Run2
  analyzed 54 M minimum bias events for Run3

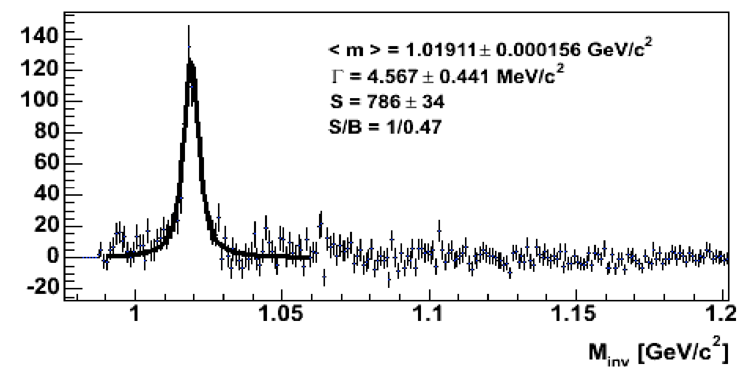


Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



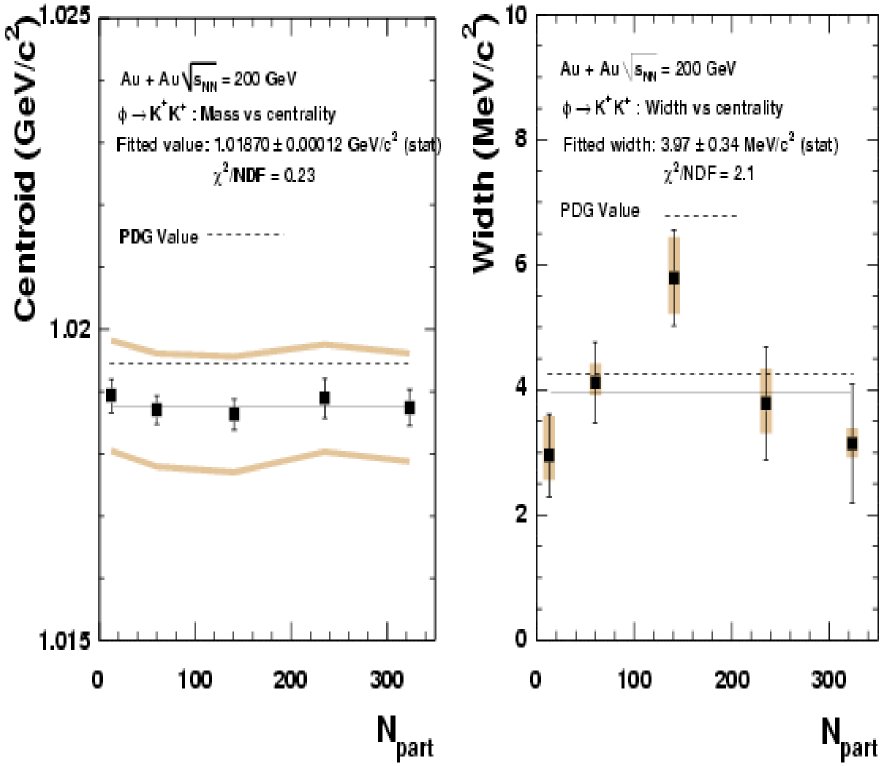
d + Au at $\sqrt{s_{NN}}$ = 200 GeV



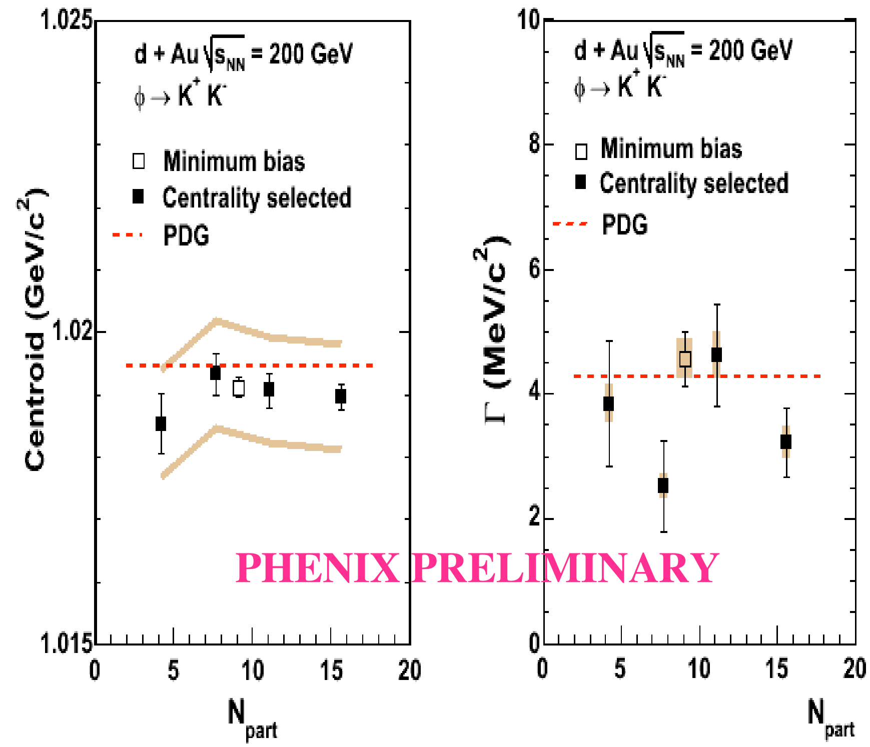


Line Shape Analysis for the ϕ

Au + Au at $\sqrt{s_{NN}}$ = 200 GeV



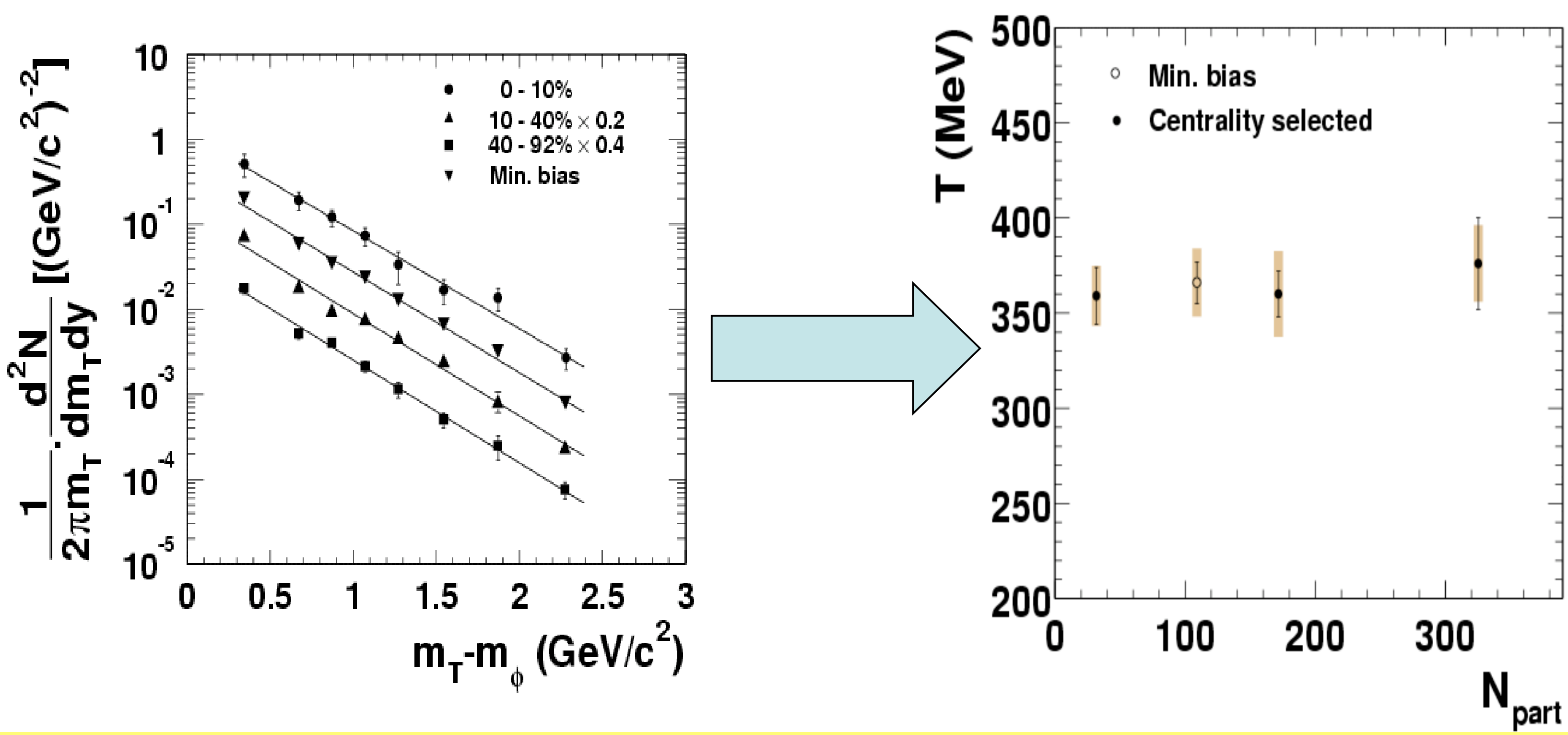
d + Au at $\sqrt{s_{NN}}$ = 200 GeV



M_ϕ = 1.01870 +/- 0.00012 GeV/c²
Γ_ϕ = 3.97 +/- 0.34 MeV/c²
Consistent with PDG values
No evidence of a centrality dependence

M_ϕ(min bias) = 1.01911 +/- 0.00016 GeV/c²
Γ_ϕ (min bias) = 4.57 +/- 0.44 MeV/c²
Consistent with PDG values
No evidence of a centrality dependence

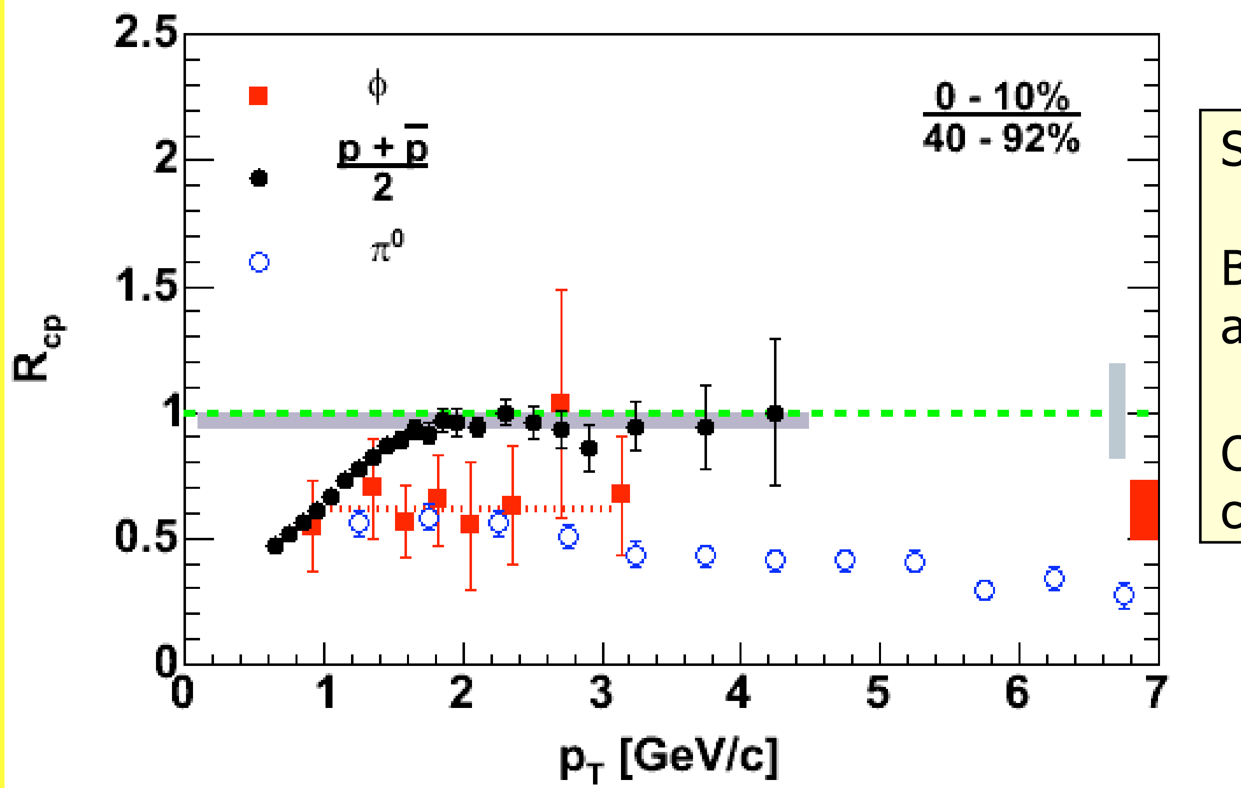
I:Yield Analysis for the ϕ in Au + Au



Transverse mass spectra fitted with exponential in m_T , three centrality bins are used
Extracted inverse slope parameter (“Temperature”) is independent of centrality
Results are same when three subsystem combination data sets are fitted separately

II:Yield Analysis for the ϕ in Au + Au Compare to π^0 and protons in R_{CP}

$$R_{cp} = \frac{\text{Yield }(0-10\%)/N_{coll}(0-10\%)}{\text{Yield }(40-92\%)/N_{coll}(40-92\%)}$$

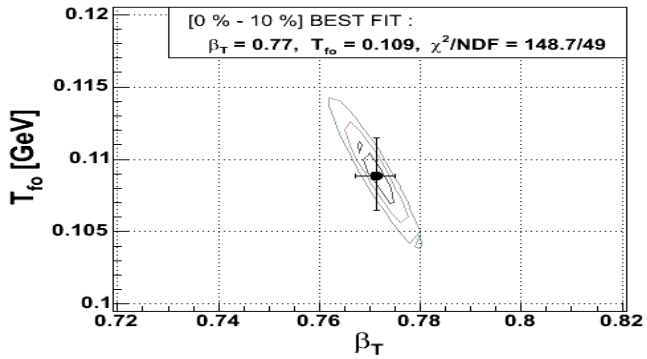


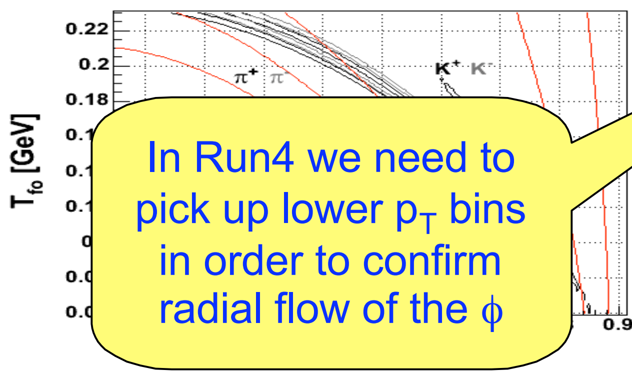
Similar behavior for ϕ and π

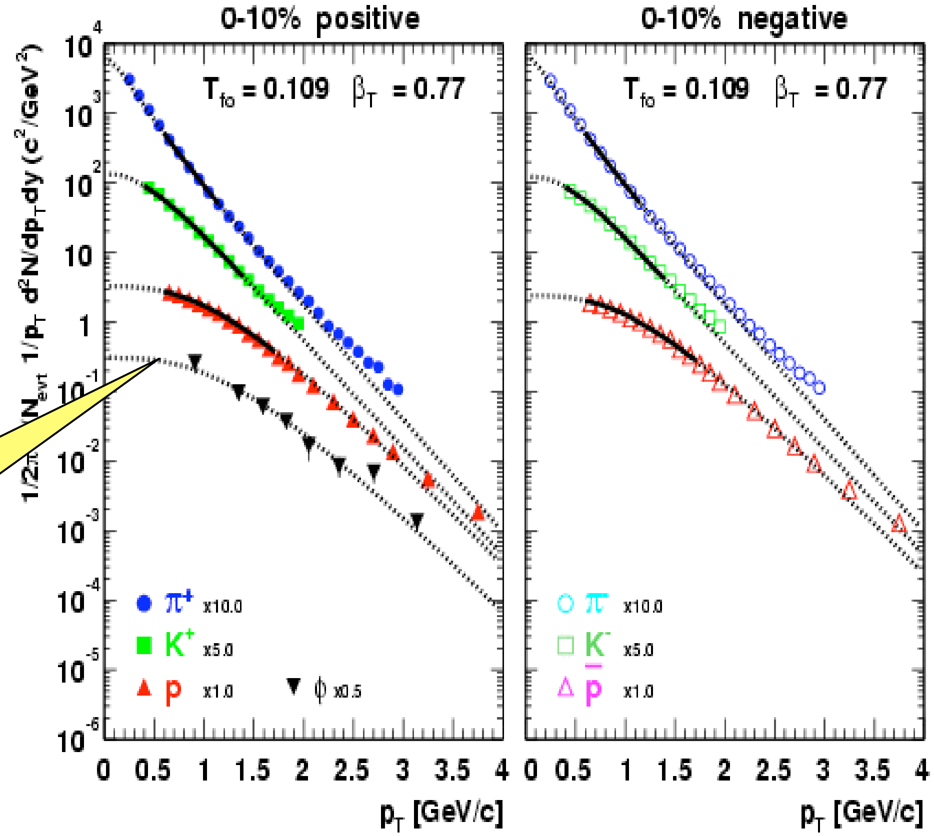
Baryon anomaly not a mass effect

Consistent with quark coalescence models

III:Yield Analysis for the ϕ in Au + Au Compare to π , kaons, and protons in flow



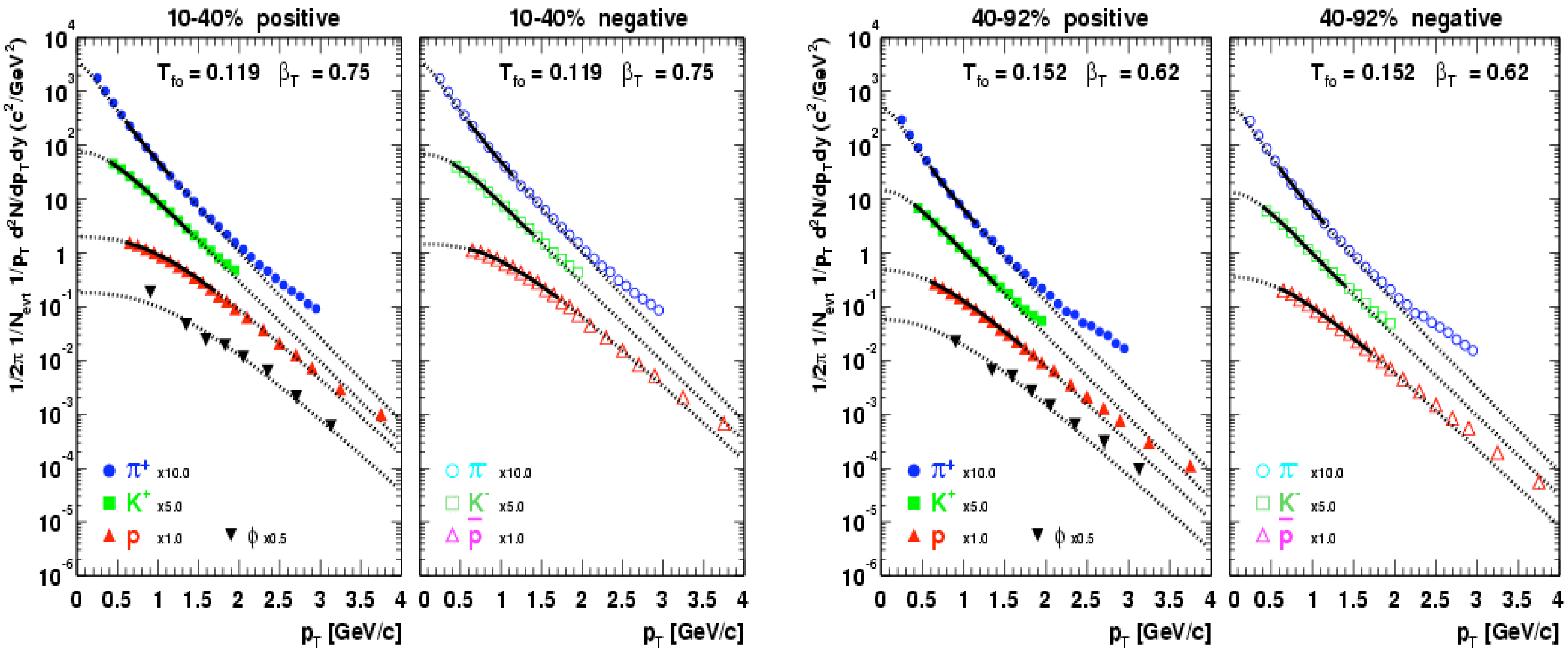




(same model as in Peter Seyboth talk)

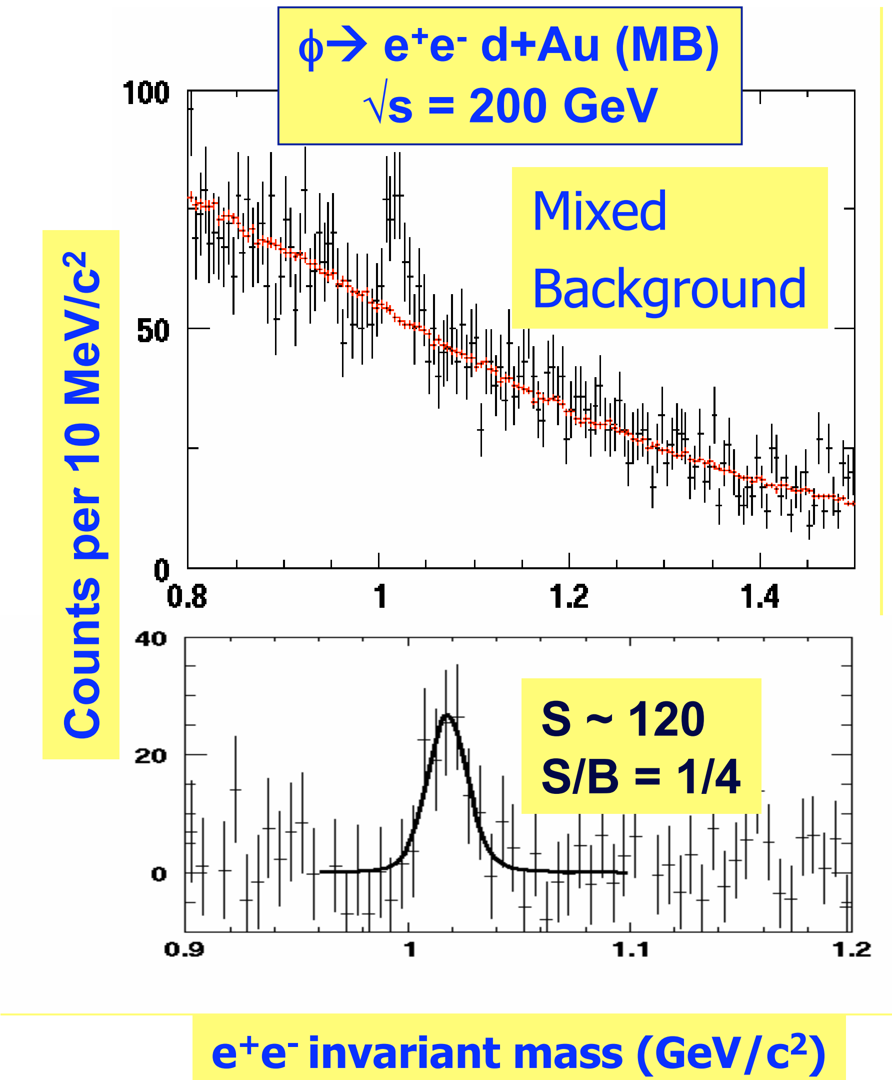
- Hydrodynamic model fits to most central bin: **PHENIX (nucl-ex/0410012)**
  - Simultaneous fit of π,K,p and anti-particles: <u>“predict” ϕ shape (shown above)</u>
  - Simultaneous fit of π,K,p and anti-particles *and* ϕ
- Both sets of fits can be described by T_{fo} = 109 Mev and $\langle\beta_T\rangle$ = 0.77

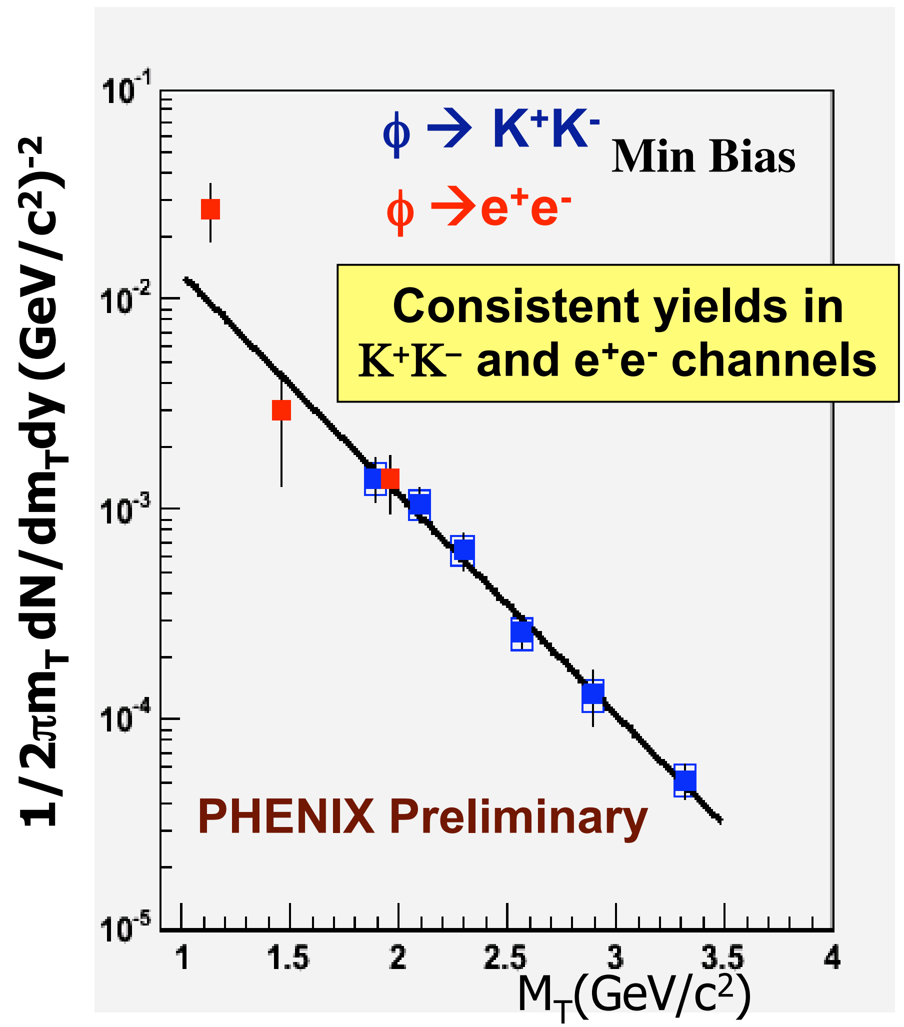
III:Yield Analysis for the ϕ in Au + Au
Compare to π , kaons, and protons in flow



- Extend model fits to two other centrality bins
  - Simultaneous fit of π,K,p and anti-particles: "predict" ϕ shape (shown above)
- For each centrality bin all spectra shapes can be described by common T_{fo} and $<\beta_T>$ (with same caveat for more ϕ low p_T bins)
- T_{fo} and $<\beta_T>$ are anti-correlated, varying slowly with centrality

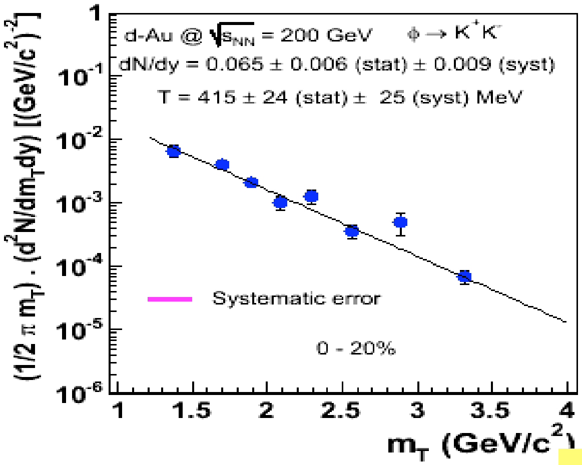
Yield Analysis for the ϕ in d + Au
Compare K^+K^- and e^+e^- Channels

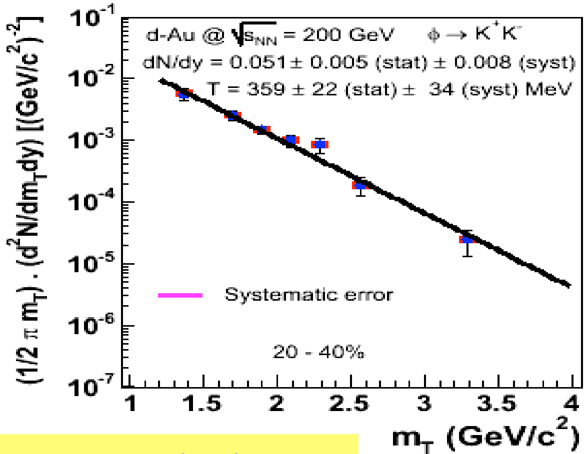




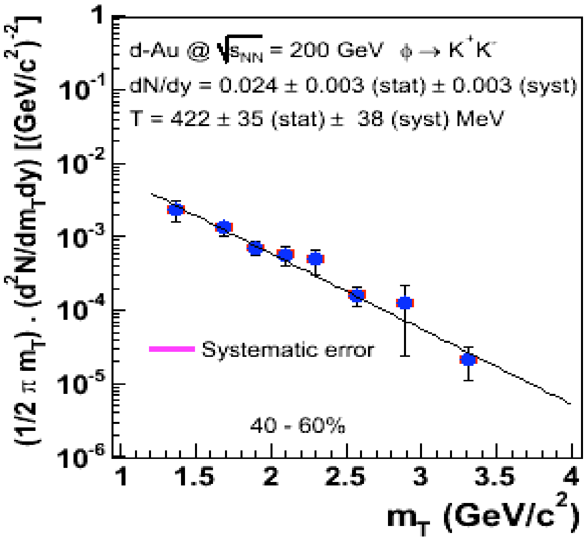
Yield Analysis for the ϕ in d + Au

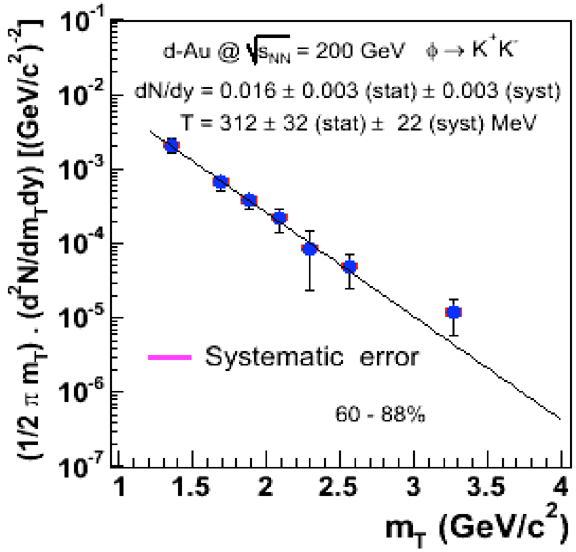
Extract K^+K^- dN/dy and T Parameters in 4 Centrality Bins





PHENIX Preliminary





For 3 most central bins the inverse slope parameter T average is 400 MeV

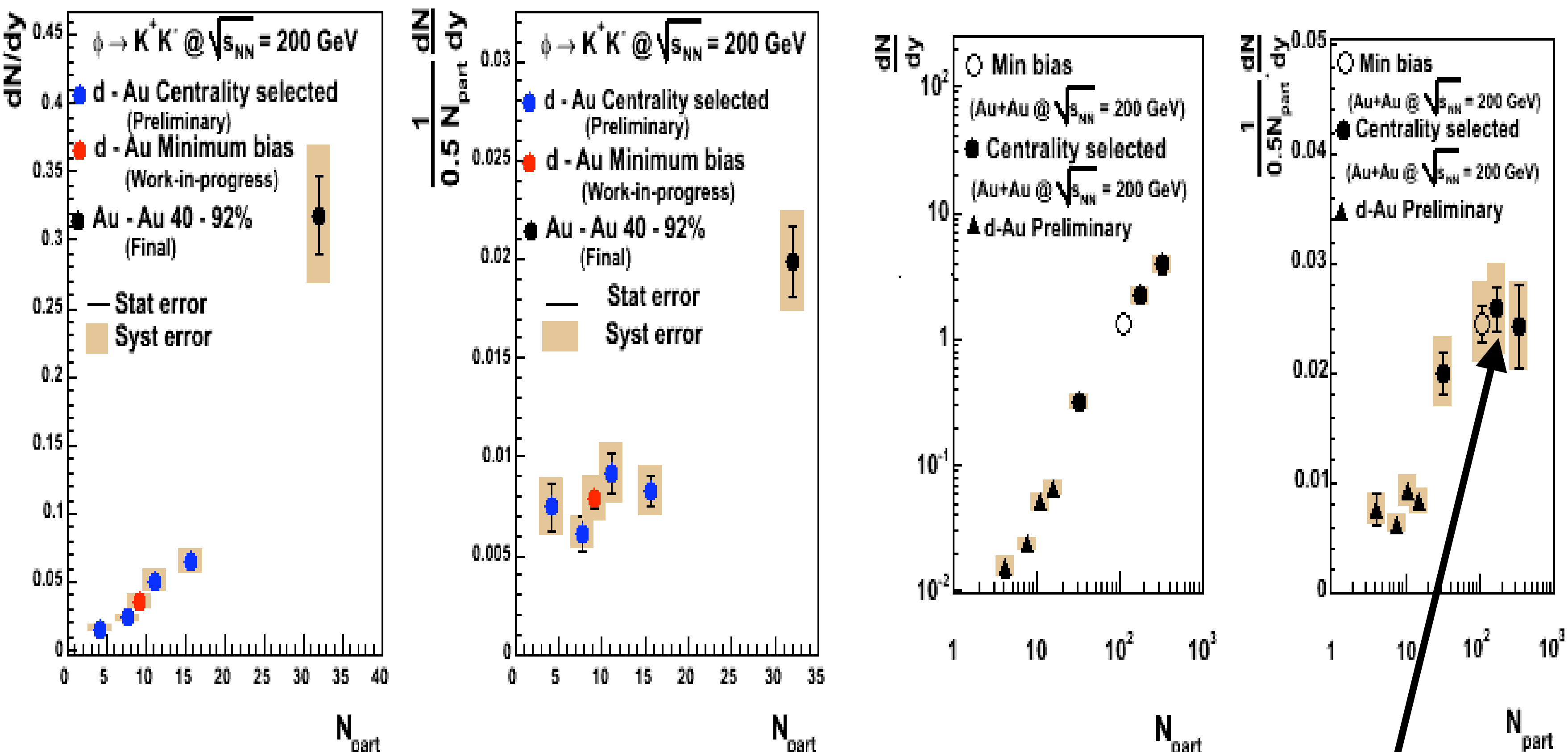
For the most peripheral bin the inverse slope T = 312 MeV

With extracted dN/dy multiplicities we can compare the ϕ production as a function of the number of participants N_{part}

I: Compare Yields for the ϕ in d+Au and Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

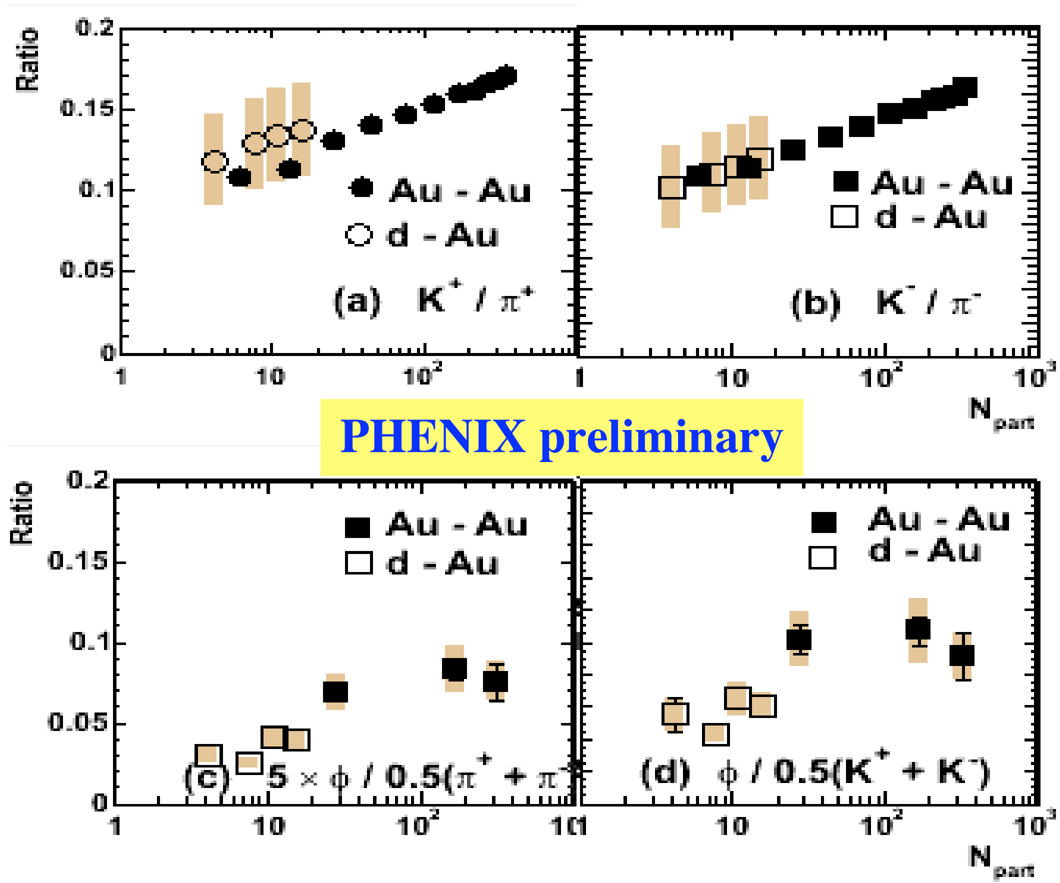
Lower range of N_{part}

Complete range of N_{part}



The ϕ yield per participant in Au+Au is at least a factor of 3 higher than in d+Au !

II: Compare Yields for the ϕ in d+Au and Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

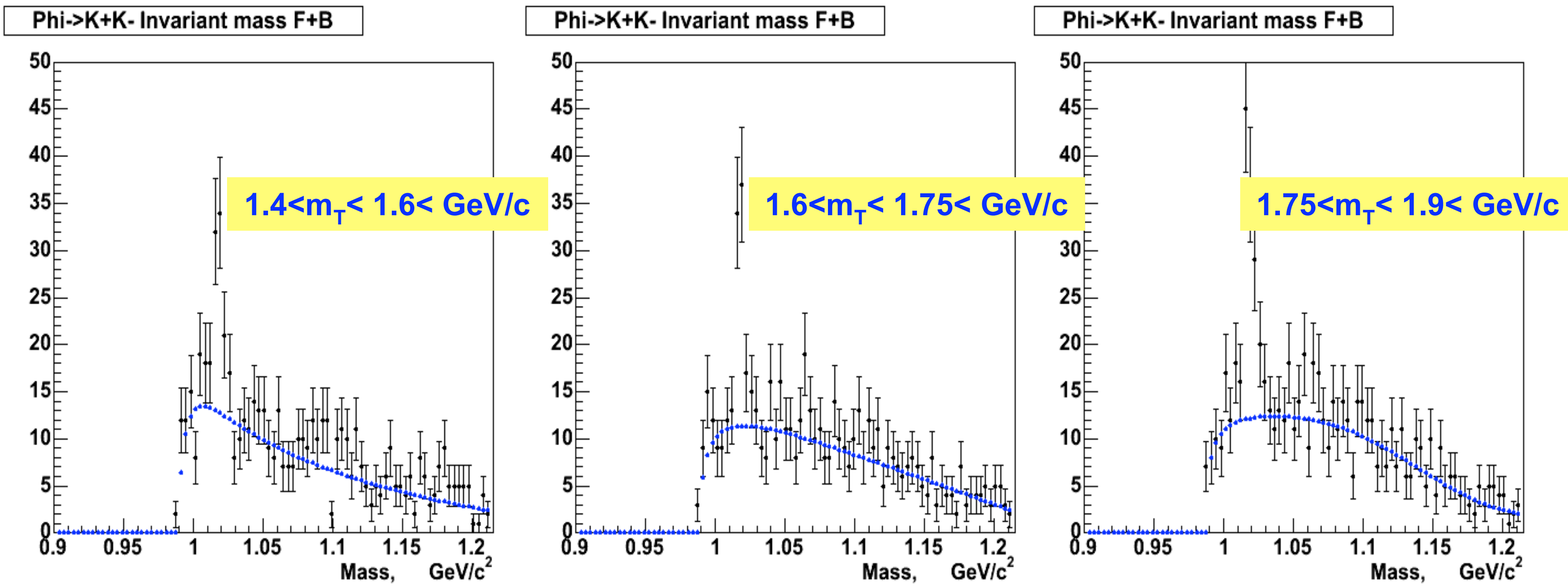


The ϕ yield per π and per K in Au+Au is about a factor of 2 higher than in d+Au

Future ϕ Analysis Effort in PHENIX
The past is prolog

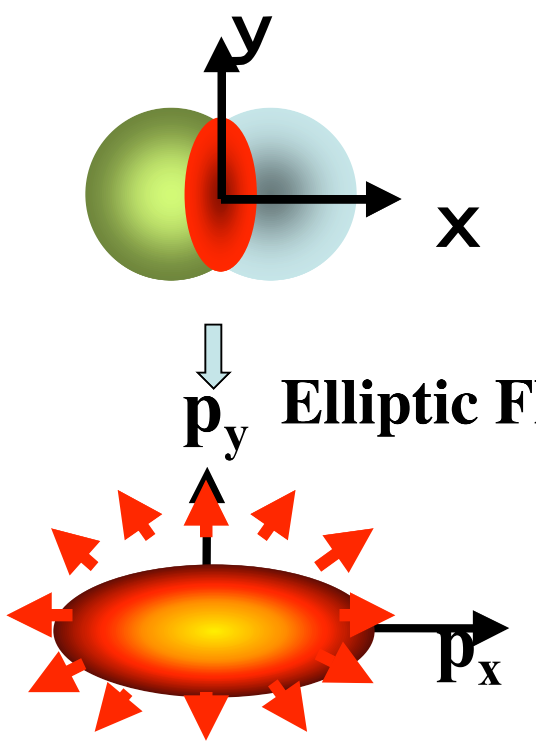
The $\phi \to K^+K^-$ in Run2 pp as Detected in PHENIX

Sample Invariant Mass Spectra
Detector Acceptance/Efficiency Corrections Not Included

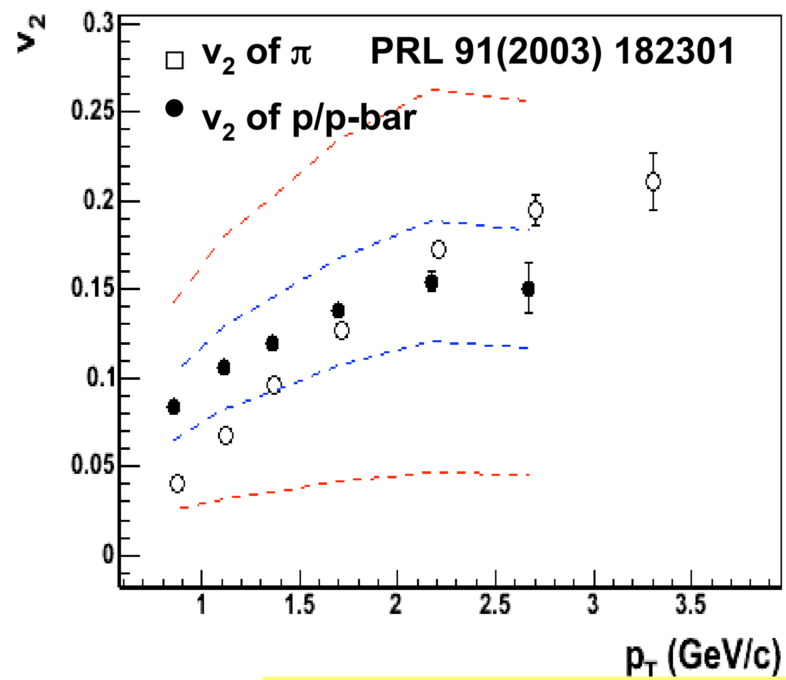


Analysis of Run2 pp data nearly completed
Expect to be able to do R_{dA} and R_{AA} for ϕ in near future

Does the ϕ Manifest Elliptic Flow? Expect to get answer from Run4 data



Feasibility study for observing the v_2 of the ϕ in PHENIX at RHIC for Run4



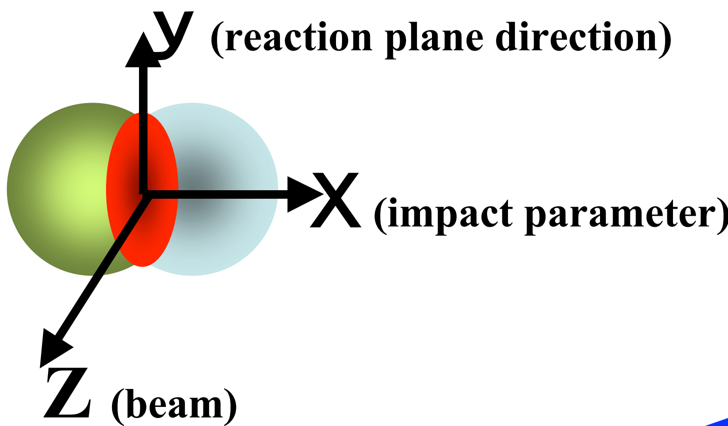
For non-central collisions the initial spatial anisotropy transforms to an anisotropy in the emission directions in the reaction plane. This emission anisotropy is scaled as a v_2 coefficient in an azimuthal Fourier expansion.

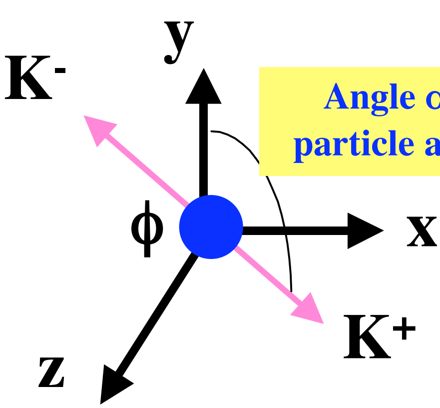
Run2 (Au + Au): Predicted statistical error (~70%) on ϕ [assuming $v_2(\phi) = v_2(\pi^-)$]

Run4 (Au + Au) @ 10x Run2 Predicted statistical error on ϕ [assuming $v_2(\phi) = v_2(\pi^-)$]

Does the ϕ Manifest Global QGP Polarization?

Hope to get answer from Run4 data





Angle α between decay particle and reaction plane

Rest frame decay of the ϕ
Kaon kinetic energy 16 MeV

Global Polarization Signal of the QGP
Liang and Wang, nucl-th/04011101 (11/25/04)

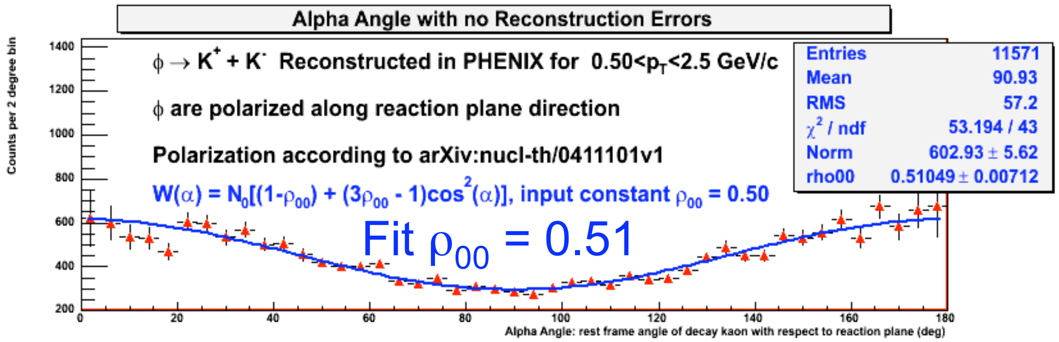
Vector meson decay particles aligned w.r.t. reaction plane direction in rest frame
<u>Alignment depends on hadronization scenarios</u>
Induces a decay angular distribution

$$W(\alpha) = 0.75[\ (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\alpha\ ]$$

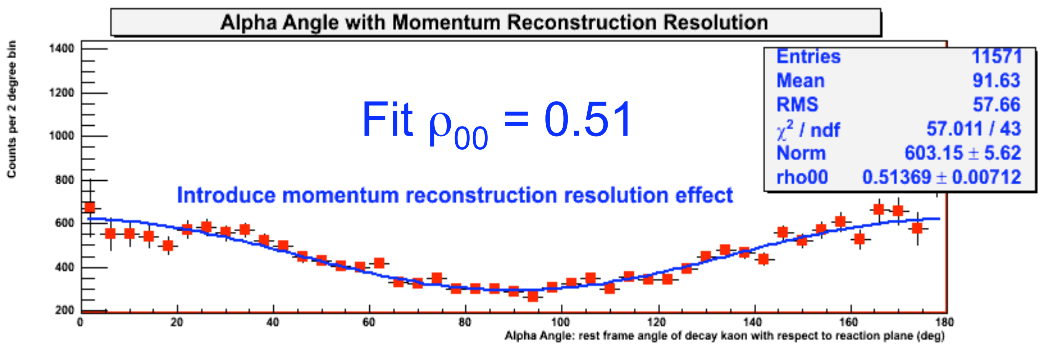
ρ_{00} is spin density matrix element
$0 \leq \rho_{00} \leq 1$
$\rho_{00} = 1/3$ means no polarization
ρ_{00} may be parameterized as a function of ϕ p_T
$\rho_{00} = \rho_{000} + (1/3 - \rho_{000})(2/\pi)\mathrm{atan}(p_T/a_0)$
ρ_{000} = polarization at $p_T = 0$, $a_0 = 0.5$ GeV/c

Question: Is the PHENIX detector sensitive to a polarization signal in the ϕ, given the fiducial acceptance of PHENIX and the actual reconstruction resolutions in PHENIX?

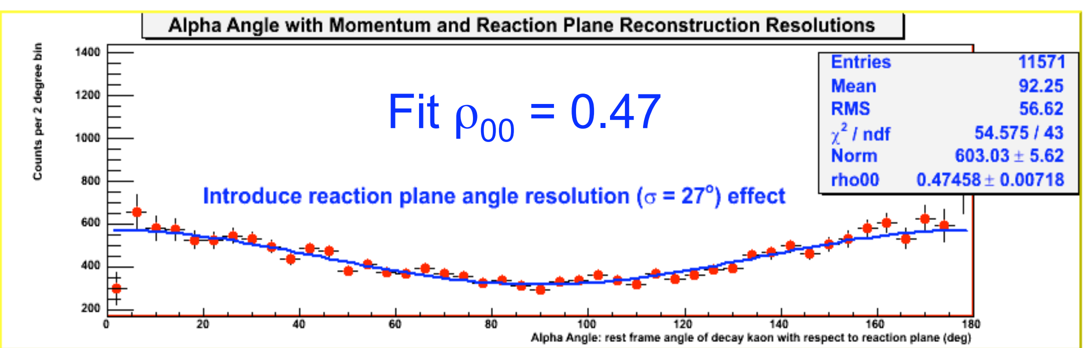
Does the ϕ Manifest QGP Polarization?
<u>Simulation Studies</u> of PHENIX Sensitivity



1) Reconstruct 11.6K ϕ decays
Exact PHENIX geometry model
Perfect momentum reconstruction
Perfect reaction plane angle
<u>Recover input polarization parameter</u>



2) Realistic momentum reconstruction
Still perfect reaction plane angle
<u>No change in fit parameter</u>



3) Realistic momentum reconstruction
Realistic reaction plane angle
<u>Only small change in fit parameter</u>

Answer: It looks promising to detect a significant ϕ polarization pending S/B simulations

PHENIX High p_T PID Upgrade

Aerogel & MRPC Time-of-Flight

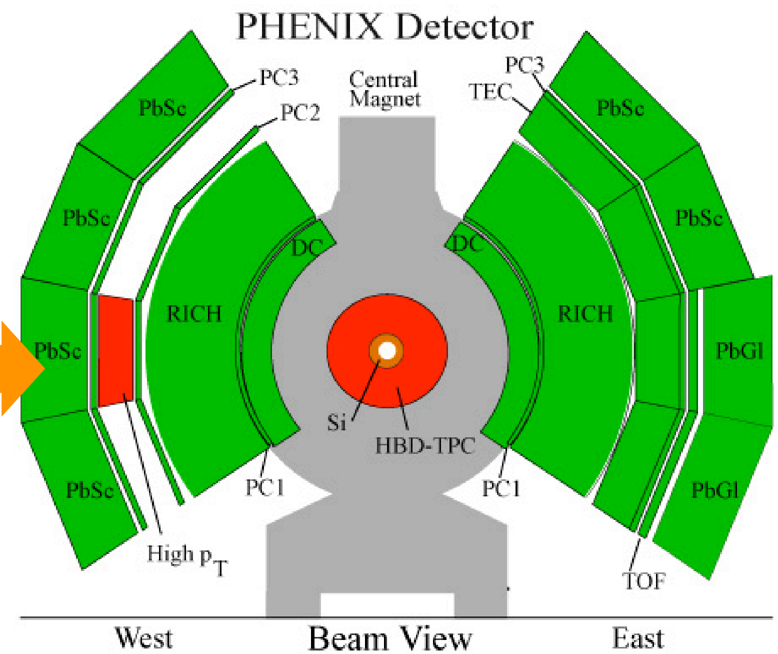
- Together with the Aerogel, TOF and RICH, we can extend the PID to 10 GeV/c
- **Coverage: ~ 4 m^2 in PHENIX west arm**

AEROGEL Cherenkov detector:

- n = 1.0113.
- Completed full installation for Run5.

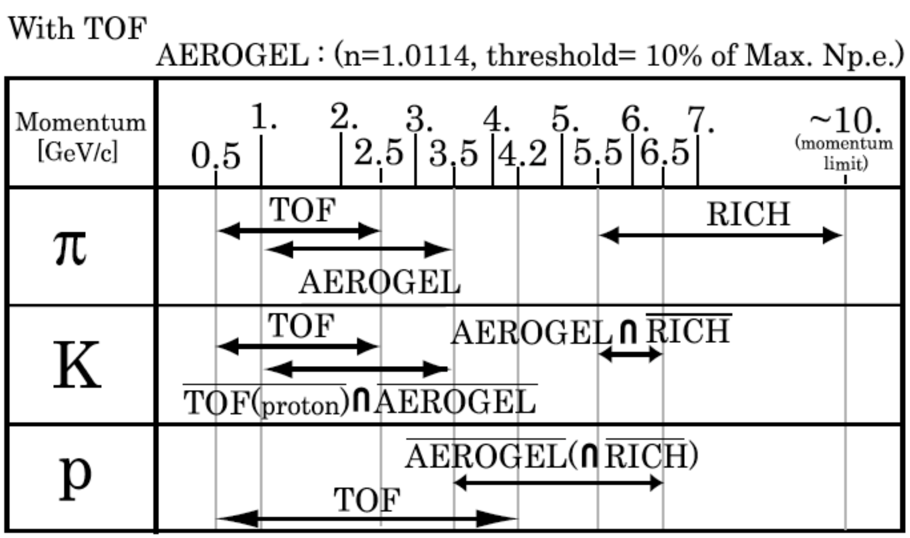
Additional TOF counter is required for K/p separation below 5 GeV/c.

Decided to use MRPC technology for TOF taking advantage of STAR's experiences



Extension of Charged Hadron PID Capability
Will be operational in PHENIX for RHIC Run6

		Pion-Kaon separation	Kaon-Proton separation
TOF	σ~100 ps	0 - 2.5	- 5
RICH	n=1.00044 γth~34	5 - 17	17 -
Aerogel	n=1.01 γth~8.5	1 - 5	5 - 9

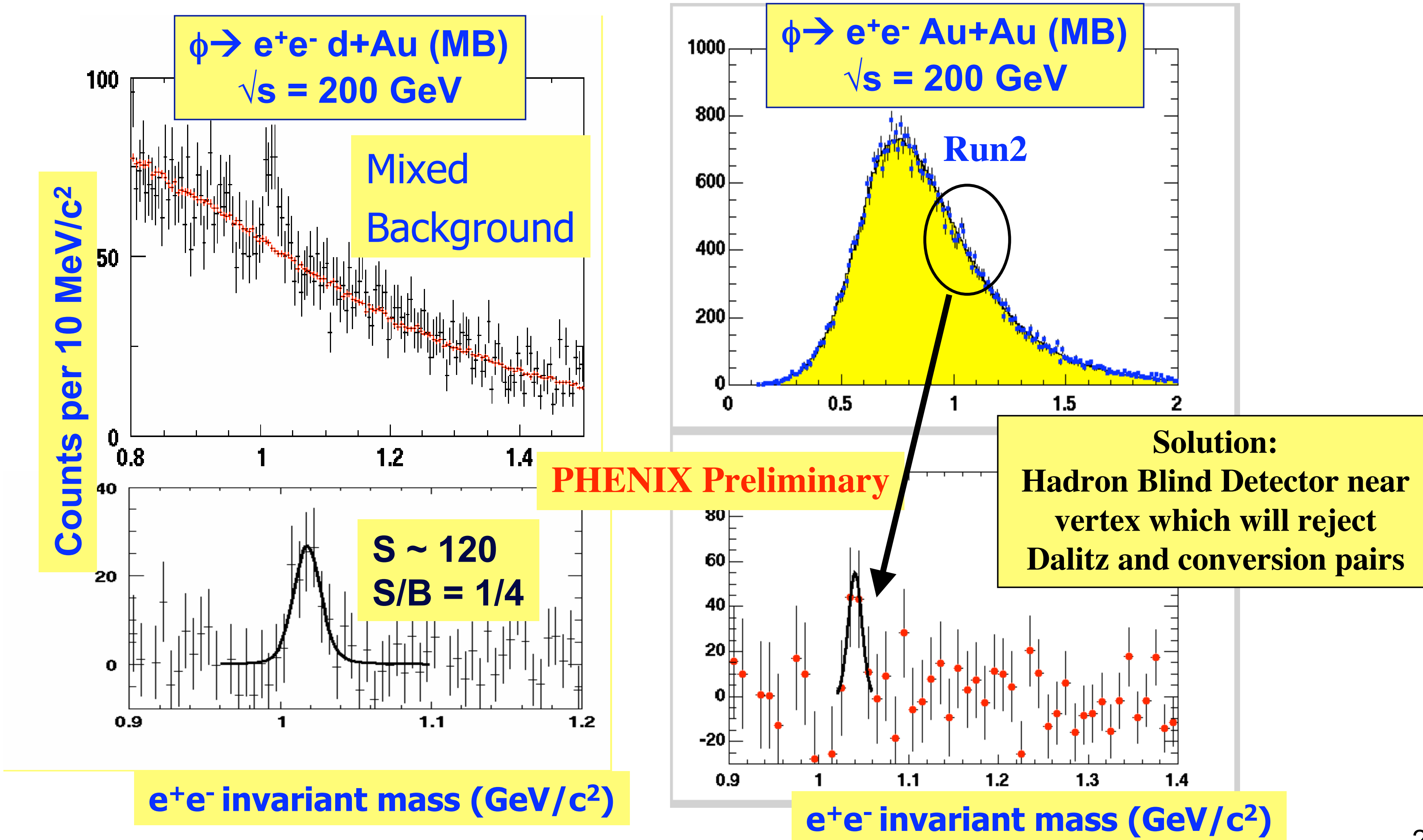


Aerogel together with TOF can extend PID range to 10 GeV/c

Without TOF, no K-proton separation at p_T < 5 GeV/c

Added reach in K momentum will significantly increase the signal of the ϕ in PHENIX

Because of Dalitz and photon conversion electrons, the Combinatoric Background (CB) in the ϕ di-electron channel is painfully high

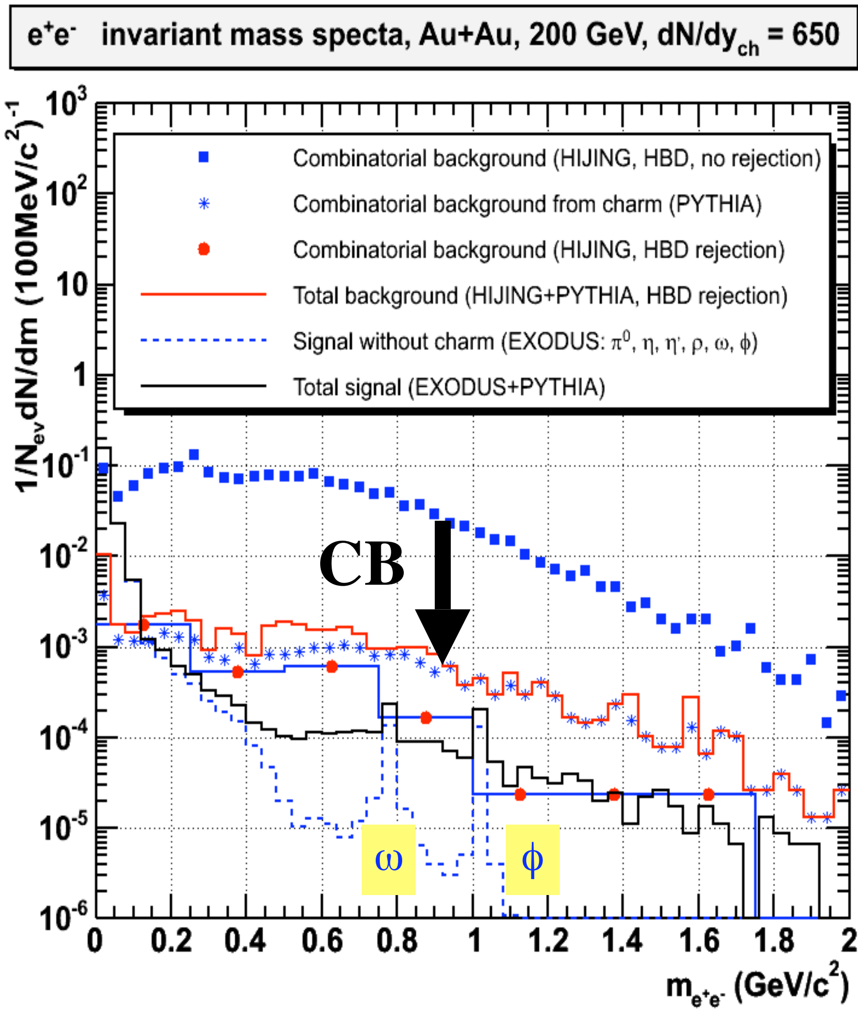


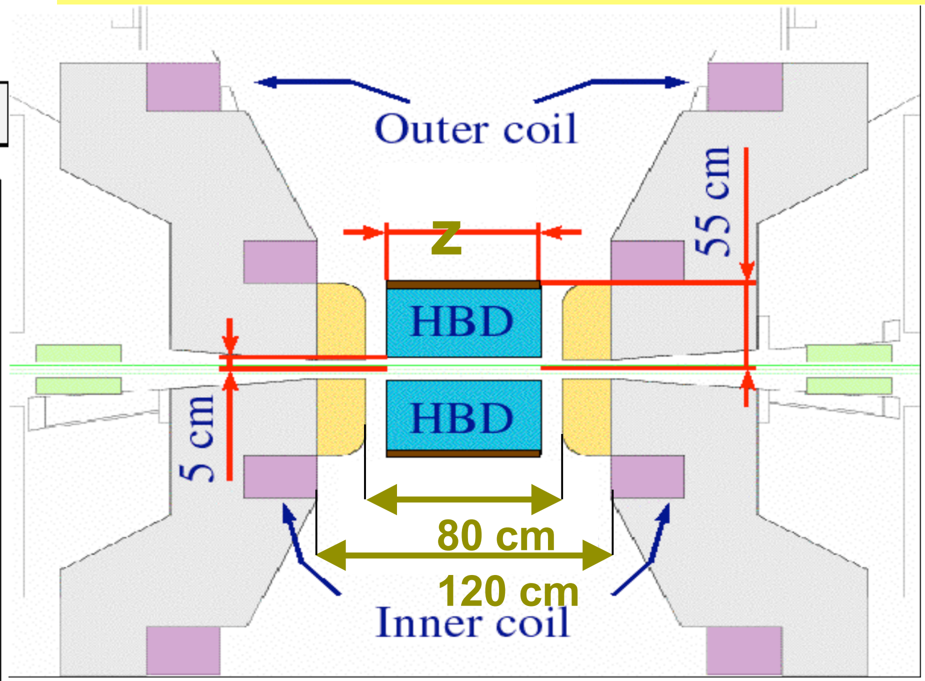
Solution:
Hadron Blind Detector near vertex which will reject Dalitz and conversion pairs

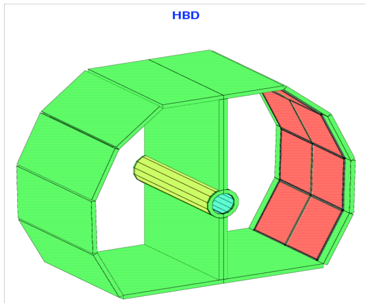
Proposed Hadron Blind Detector for Electron Background Suppression

Detector Modeled in GEANT Simulation
Factor of 50 reduction in CB for Au+Au !

Detector Inserted into PHENIX Vertex Region







Summary and Outlook

- PHENIX measured $\phi \to K^+K^-$ in Au+Au and d+Au at $\sqrt{s_{NN}}$ = 200 GeV
  - No mass shift is observed as a function of centrality in either system
    Mass centroid is constant to within less than 1 MeV
  - No width broadening is observed as a function of centrality
    Width broadening is less than 2 MeV
  - Exponential fits show a constant slope parameter as a function of centrality except for the most peripheral bin in d+Au
  - Yield of ϕ per participant in Au+Au jumps (~3x) compared to d+Au
    Ratios ϕ/π and ϕ/K are larger (~2x) in Au+Au compared to d+Au
  - R_{cp} of the ϕ in Au+Au is consistent with that of the π^0 rather than the protons
    Indicates that the baryon anomaly is not a mass effect
  - A blast wave model parameterization fit for the charged hadrons reproduces the p_T spectrum of the ϕ with the same T_{fo} and $\langle\beta_T\rangle$ for each centrality bin
- PHENIX measured $\phi \to e^+e^-$ for minimum bias d+Au
  - Transverse spectrum consistent with that of $\phi \to K^+K^-$
- Future effort in PHENIX for the ϕ
  - Results for $\phi \to K^+K^-$ from RHIC Run2 pp should be available soon
  - Expect to see 10x as many ϕ (i.e. ~50K) in Run4 Au+Au; (Run5 Cu+Cu in progress)
    Should enable measurement of the v_2 of the ϕ, and possibly a ϕ polarization
  - Detector upgrades will significantly extend range of ϕ measurements and e^+e^-

Brazil University of São Paulo, São Paulo
China Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing
France LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
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Hungary Central Research Institute for Physics (KFKI), Budapest
Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest
India Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay
Israel Weizmann Institute, Rehovot
Japan Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
Rikkyo University, Tokyo, Japan
Tokyo Institute of Technology, Tokyo
University of Tsukuba, Tsukuba
Waseda University, Tokyo
S. Korea Cyclotron Application Laboratory, KAERI, Seoul
Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul
Russia Institute of High Energy Physics, Protovino
Joint Institute for Nuclear Research, Dubna
Kurchatov Institute, Moscow
PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg
Sweden Lund University, Lund

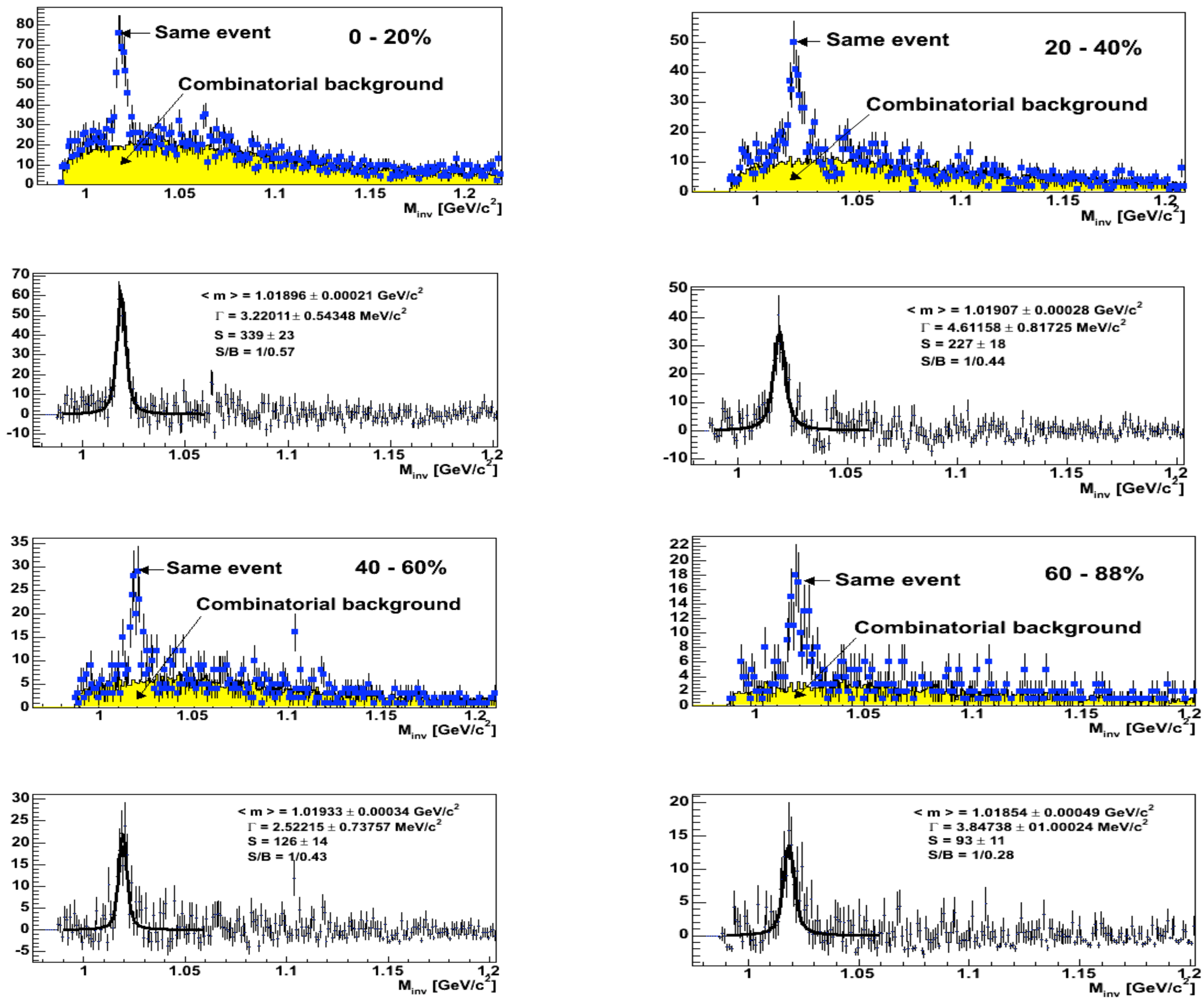
*12 Countries; 58 Institutions; 480 Participants**

** as of January 2004*

USA Abilene Christian University, Abilene, TX
Brookhaven National Laboratory, Upton, NY
University of California - Riverside, Riverside, CA
University of Colorado, Boulder, CO
Columbia University, Nevis Laboratories, Irvington, NY
Florida State University, Tallahassee, FL
Florida Technical University, Melbourne, FL
Georgia State University, Atlanta, GA
University of Illinois Urbana Champaign, Urbana-Champaign, IL
Iowa State University and Ames Laboratory, Ames, IA
Los Alamos National Laboratory, Los Alamos, NM
Lawrence Livermore National Laboratory, Livermore, CA
University of New Mexico, Albuquerque, NM
New Mexico State University, Las Cruces, NM 26
Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
Oak Ridge National Laboratory, Oak Ridge, TN
University of Tennessee, Knoxville, TN
Vanderbilt University, Nashville, TN

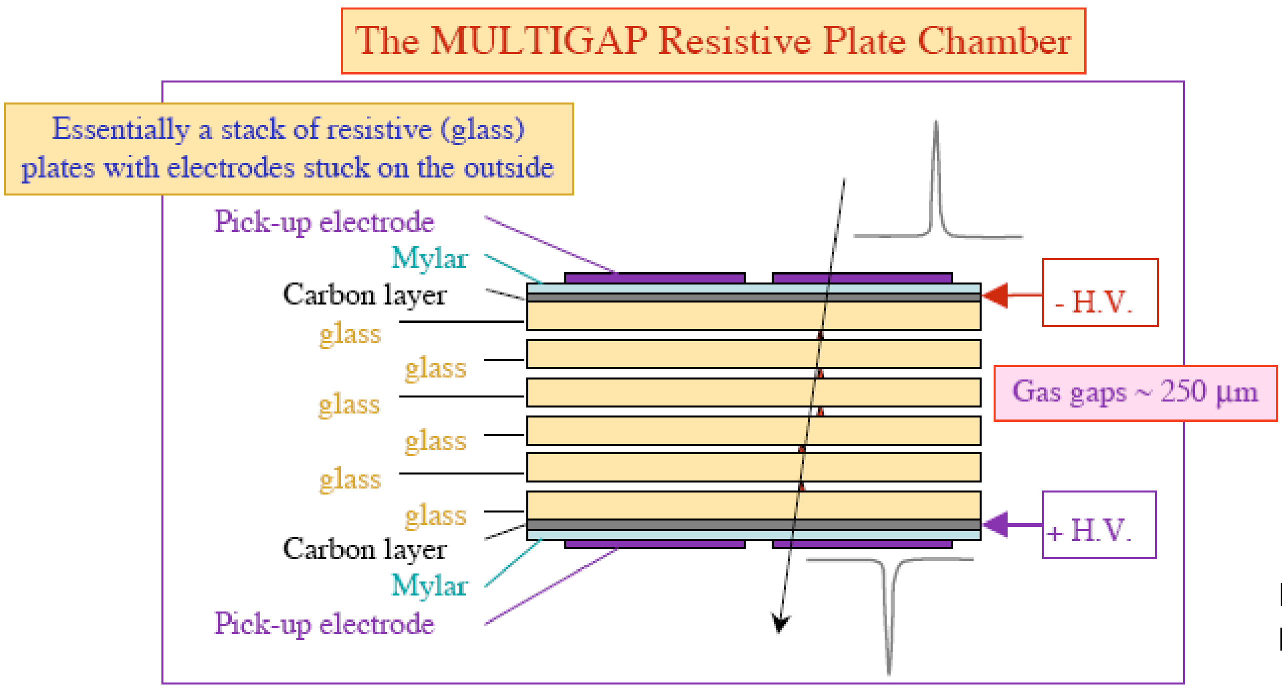
Back up slides

Line shape analysis: Centrality dependence



MRPC: Multi-gap Resistive Plate Chamber

- A stack of resistive plates (glass) with electrodes stuck on the outside.
- Internal glass plates electrically floating, take and keep correct voltage by electrostatics and flow of electrons and ions produced in gas avalanches.
- Resistive plates transparent to fast signals, induced signals on external electrodes is sum of signals from all gaps (also, equal gain in all gaps)
- Operated in avalanche mode for TOF detector.



From QM2001 (ALICE-TOF) poster by Crispin Williams.

Blast-wave Analysis

$$\frac{1}{m_T}\frac{dN}{dm_T} = A\int_0^R f(r)\,r\,dr\,m_T\,\mathrm{I}_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)\mathrm{K}_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right)$$

$$\rho(r) = \tanh^{-1}(\beta_T)\cdot r/R$$

$\mathbf{I_0}$, $\mathbf{K_1}$: modified Bessel function

Ref:Sollfrank,Schnedermann,Heinz,PRC48(1993)2462

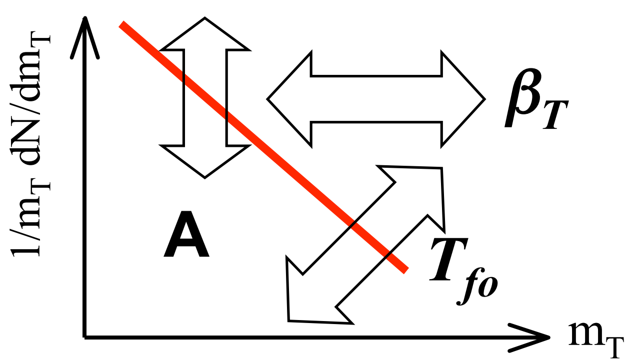
Use linear flow rapidity profile and constant particle density

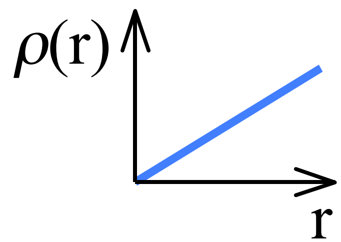
Parameters:

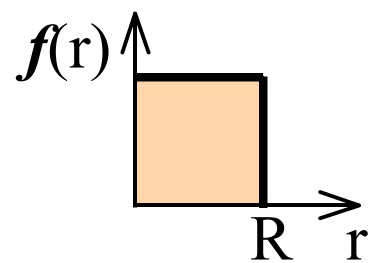
normalization **A**

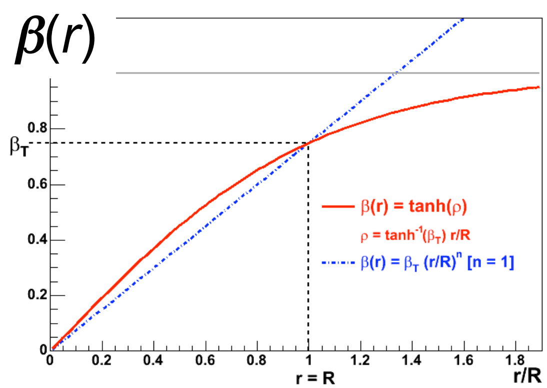
freeze-out temperature T_{fo}

surface velocity β_T









Average flow velocity:

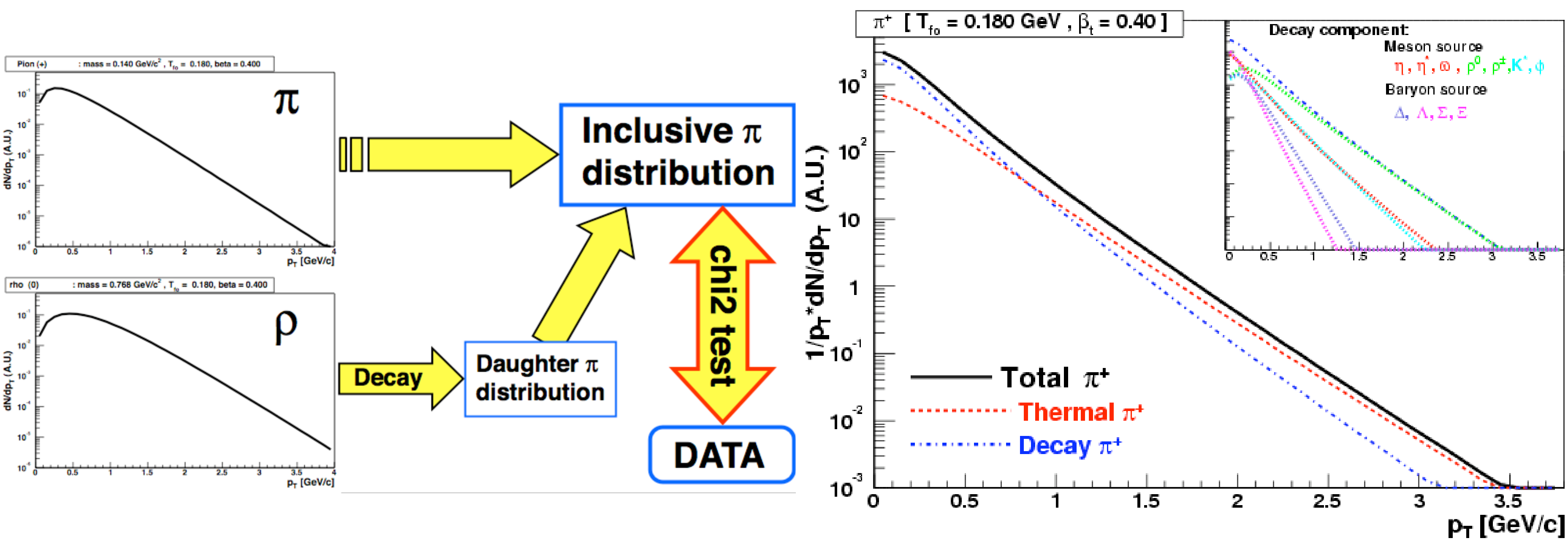
$$\langle\beta_T\rangle = \frac{\int_0^R \beta(r)\,r\,dr}{\int_0^R r\,dr}$$

$$\beta(r) = \tanh\rho(r)$$

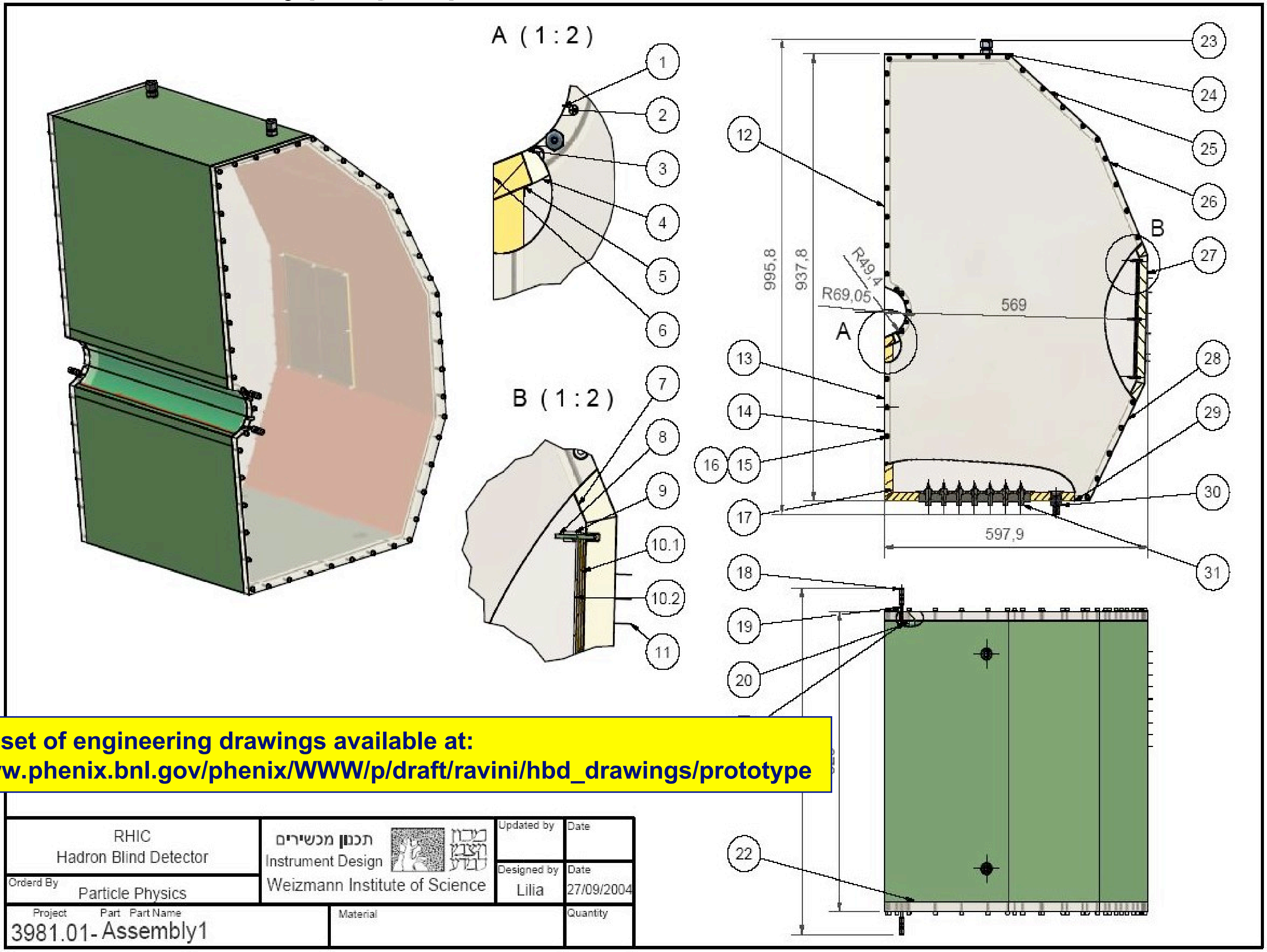
(Work by Akio Kiyomichi)

Model fit with resonance feed down

1. Generate resonances with p_T distribution determined by each combinations of T_{fo}, β_T.
2. Decay them and obtain p_T spectra of π,K,p.
3. Particle abundance calculated with chemical parameters
   T_{ch} = 177MeV, μ_B = 29MeV (200GeV), T_{ch} = 176MeV, μ_B = 41MeV(130GeV)
   Ref:P.Braun-Munzinger et al,PLB518(2001)41.
4. Merge and create inclusive p_T spectra. → χ^2 test



Full scale HBD Prototype design
Prototype proposed for Run6 installation



Complete set of engineering drawings available at:
https://www.phenix.bnl.gov/phenix/WWW/p/draft/ravini/hbd_drawings/prototype