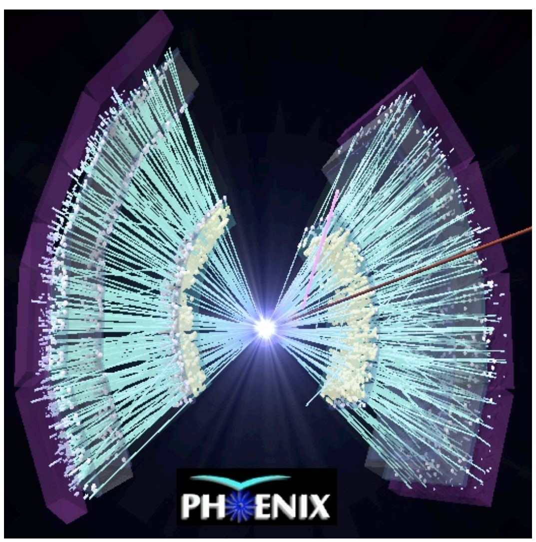
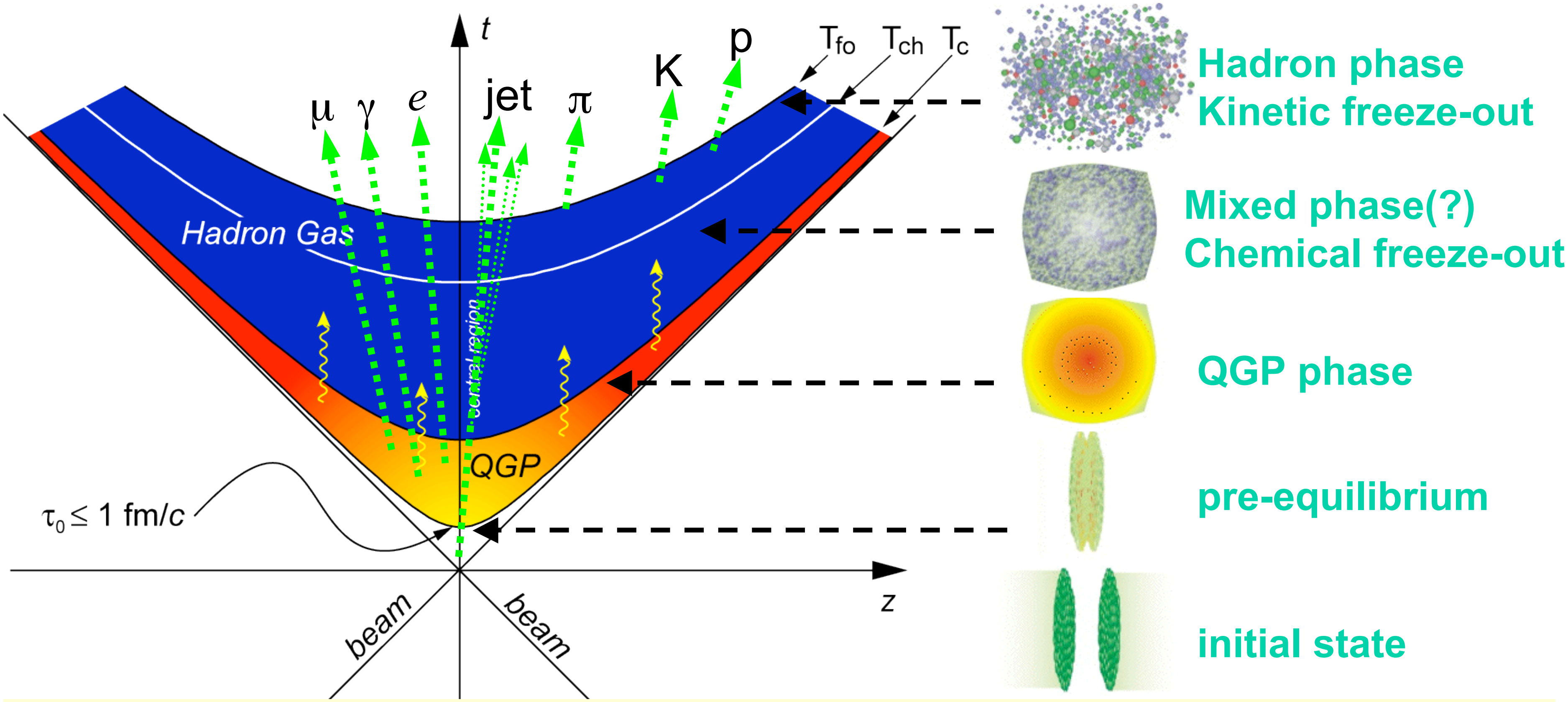
Hadron Production and Radial Flow in Au+Au Collisions at RHIC-PHENIX

Akio Kiyomichi
(RIKEN)
for the PHENIX Collaboration



Lake Louise Winter Institute 2005
February 20-26, 2005

Space-Time Evolution of System at HI Collisions

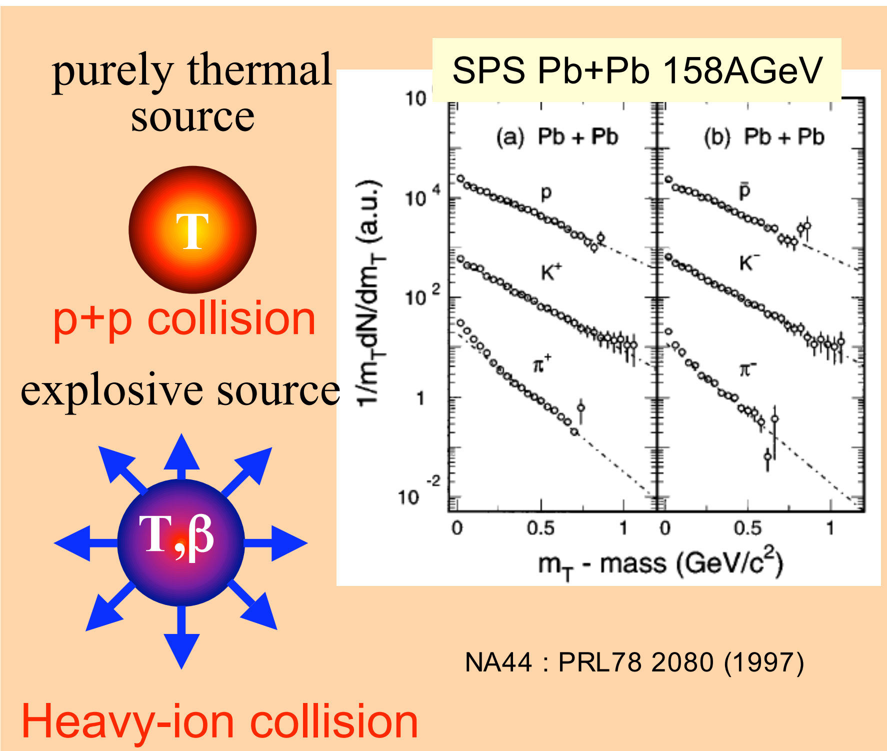


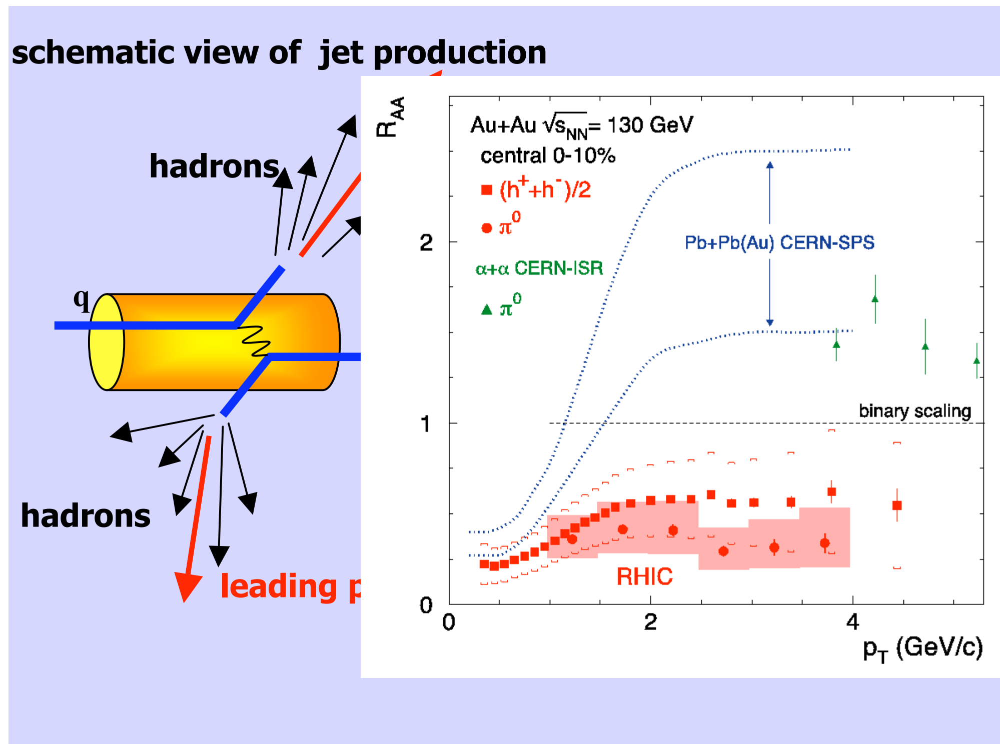
Bjorken's Space-Time Picture

- Hadrons reflect the bulk property of created system and its evolution.
  - T_{ch} - Chemical freeze-out : inelastic scattering stops ==> particle abundance determine
  - T_{fo} - Kinetic freeze-out : elastic scattering stops ==> spectra shape determine
- High-p_T hadron carry information at the early stage of the system.

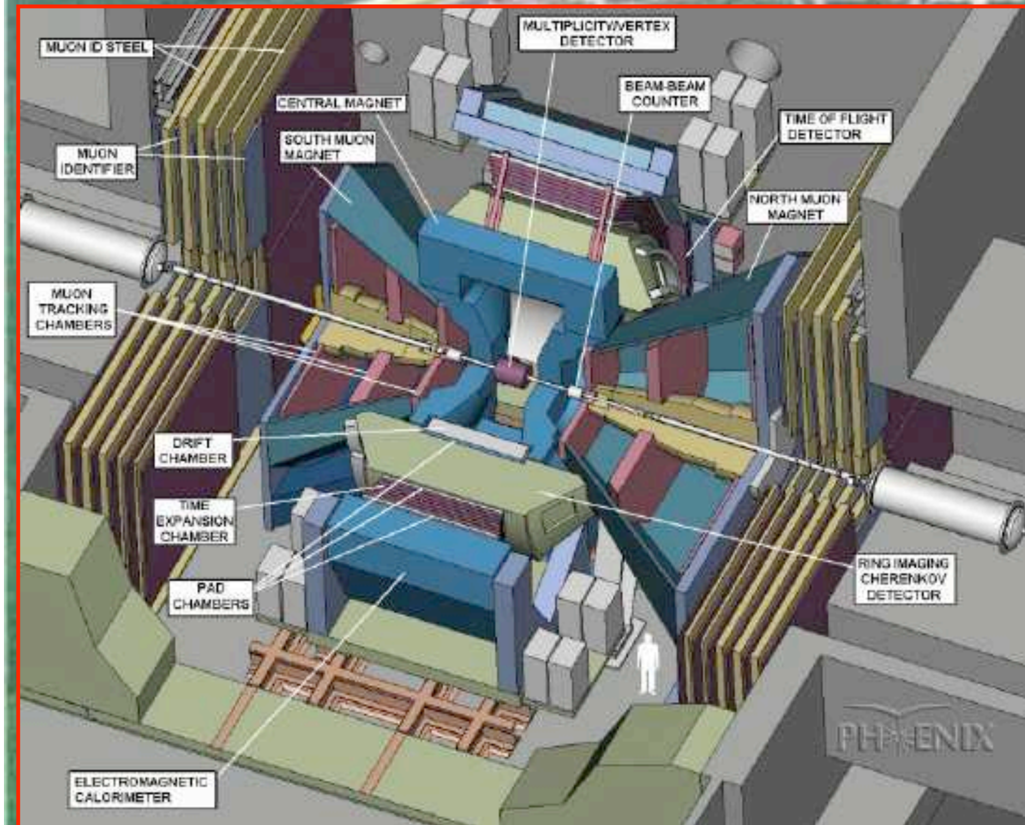
What could we learn by Hadron measurements

- Soft process
  - Hydrodynamic Collective Expansion (radial flow)
  - Hadron spectra may fit by hydrodynamical model.
- Hard scattering
  - High-p_T hadron may interact with medium





Relativistic Heavy Ion Collider (RHIC)



BRAHMS

Run	Year	Species	$\sqrt{s}$ [GeV]	$\int L dt$
01	2000	Au+Au	130	$1 \mu b^{-1}$
02	2001/2002	Au+Au	200	$24 \mu b^{-1}$
		p+p	200	$0.15 pb^{-1}$
03	2002/2003	d+Au	200	$2.74 nb^{-1}$
		p+p	200	$0.35 pb^{-1}$
04	2003/2004	Au+Au	200	$241 \mu b^{-1}$
		Au+Au	62.4	$9 \mu b^{-1}$
05	2004/2005	Cu+Cu	200	

New machine at BNL

First Heavy-ion Collider

- Operational since 2000
- 3.83 km, two rings
- 4 experiments

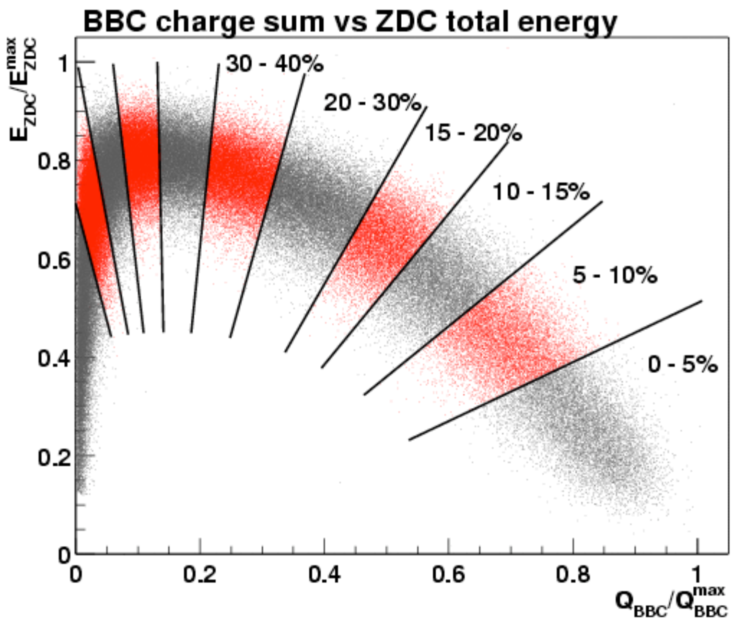
Species

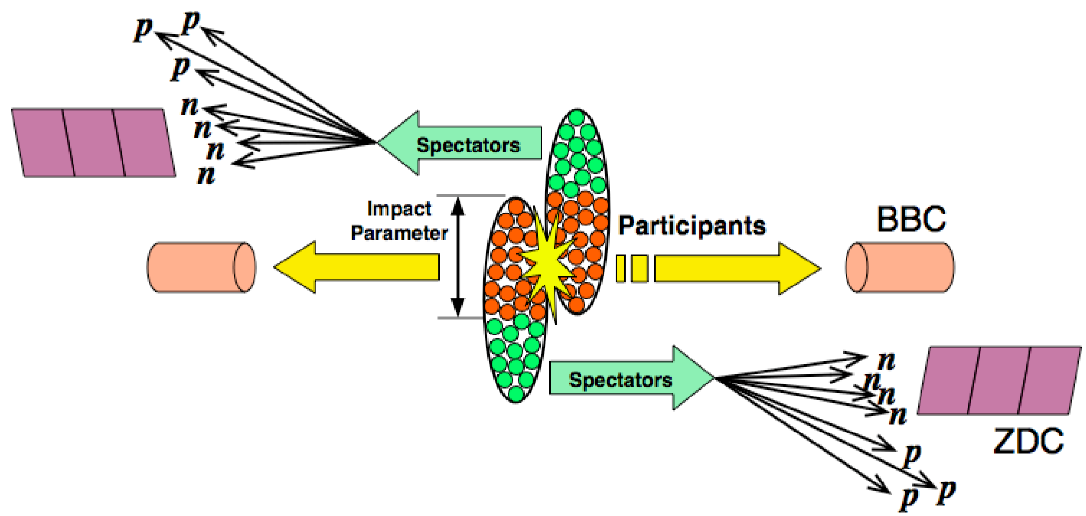
- Au+Au, d+Au, p+p, Cu+Cu

Luminosity

- Au-Au: 2×10^{26} cm^{-2} s^{-1}
- p-p : 2×10^{32} cm^{-2} s^{-1} (*polarized*)

Event Selection



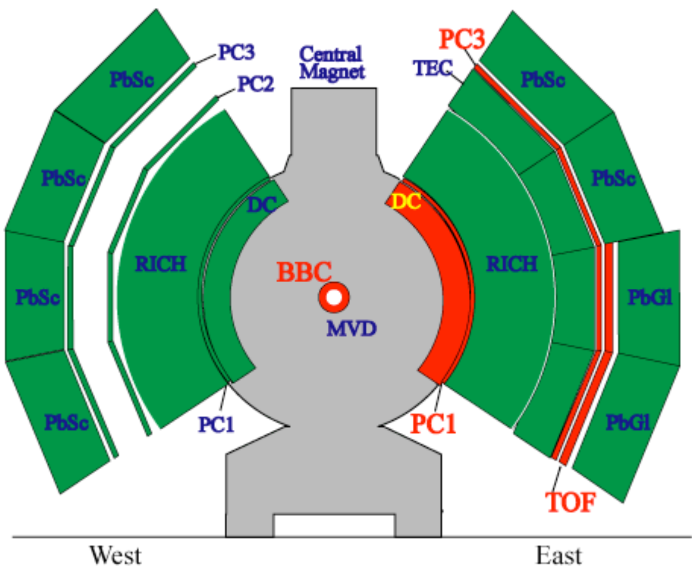


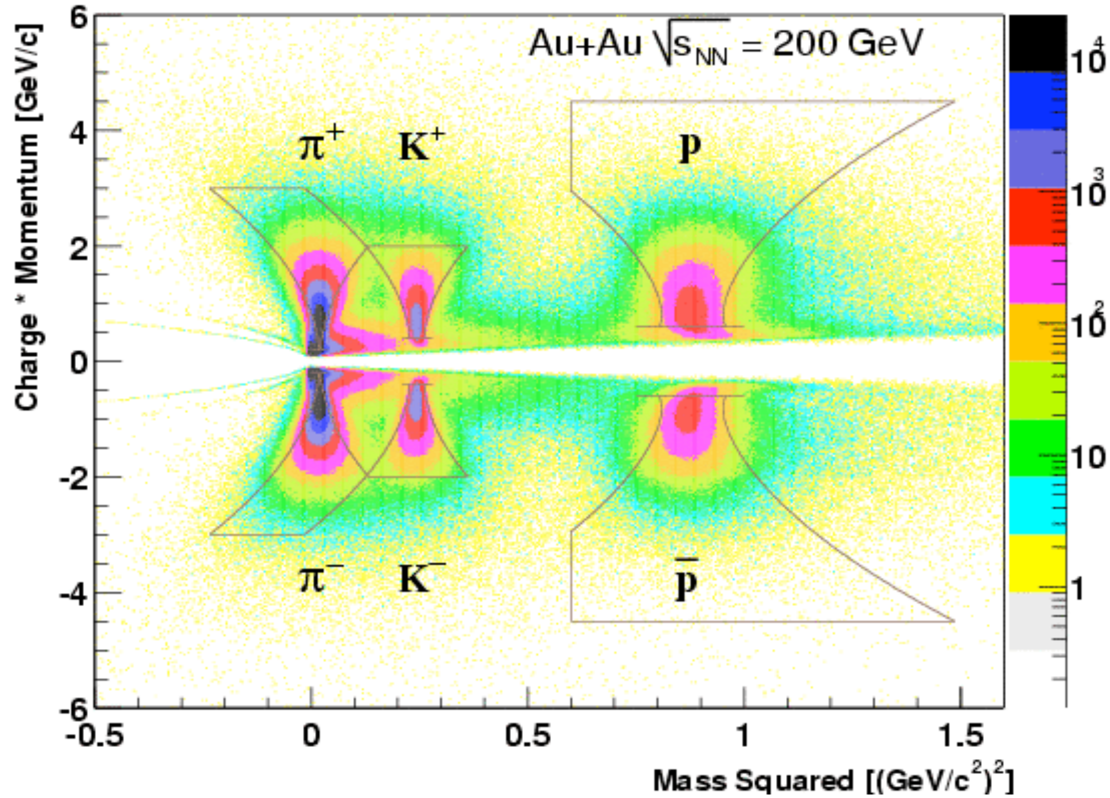
Centrality	$\langle T_{AuAu} \rangle$ (mb^{-1})	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
0- 5%	25.37 ± 1.77	1065.4 ± 105.3	351.4 ± 2.9
0-10%	22.75 ± 1.56	955.4 ± 93.6	325.2 ± 3.3
5-10%	20.13 ± 1.36	845.4 ± 82.1	299.0 ± 3.8
10-15%	16.01 ± 1.15	672.4 ± 66.8	253.9 ± 4.3
10-20%	14.35 ± 1.00	602.6 ± 59.3	234.6 ± 4.7
15-20%	12.68 ± 0.86	532.7 ± 52.1	215.3 ± 5.3
20-30%	8.90 ± 0.72	373.8 ± 39.6	166.6 ± 5.4
30-40%	5.23 ± 0.44	219.8 ± 22.6	114.2 ± 4.4
40-50%	2.86 ± 0.28	120.3 ± 13.7	74.4 ± 3.8
50-60%	1.45 ± 0.23	61.0 ± 9.9	45.5 ± 3.3
60-70%	0.68 ± 0.18	28.5 ± 7.6	25.7 ± 3.8
60-80%	0.49 ± 0.14	20.4 ± 5.9	19.5 ± 3.3
60-92%	0.35 ± 0.10	14.5 ± 4.0	14.5 ± 2.5
70-80%	0.30 ± 0.10	12.4 ± 4.2	13.4 ± 3.0
70-92%	0.20 ± 0.06	8.3 ± 2.4	9.5 ± 1.9
80-92%	0.12 ± 0.03	4.9 ± 1.2	6.3 ± 1.2
60-92%	0.35 ± 0.10	14.5 ± 4.0	14.5 ± 2.5
min. bias	6.14 ± 0.45	257.8 ± 25.4	109.1 ± 4.1

Centrality selection:

- Use charge sum of Beam-Beam Counter (BBC) and energy deposit of Zero-degree calorimeter (ZDC) in minimum bias events.
- Extracted N_{coll} (# of binary collisions), N_{part} (# of participants), T_{AuAu}(nuclear overlap function) based on Glauber model.

Charged Hadron PID

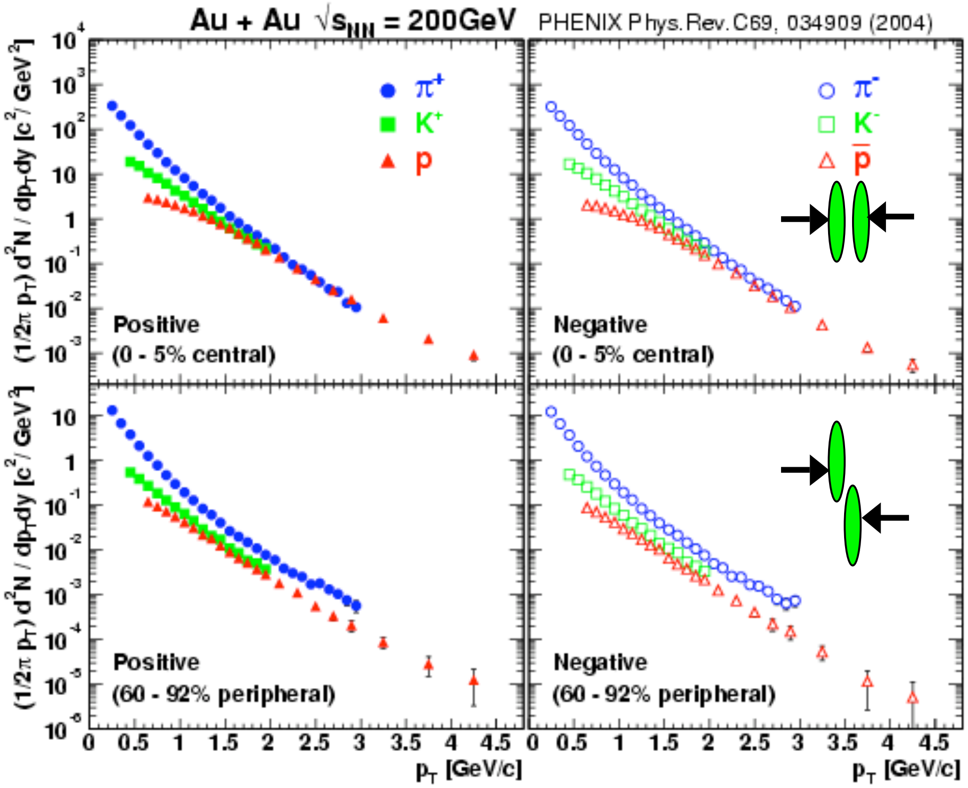




- **Detectors for hadron measurement.**
  - DCH+PC1+TOF+BBC
  - $\Delta\phi = \pi/4$, $-0.35 < \eta < 0.35$

- **Charged Hadron PID by TOF**
  - $0.2 < \pi < 3.0$ GeV/c
  - $0.4 < K < 2.0$ GeV/c
  - $0.6 < p < 4.5$ GeV/c

p_T Spectra, mean p_T vs. N_{part}



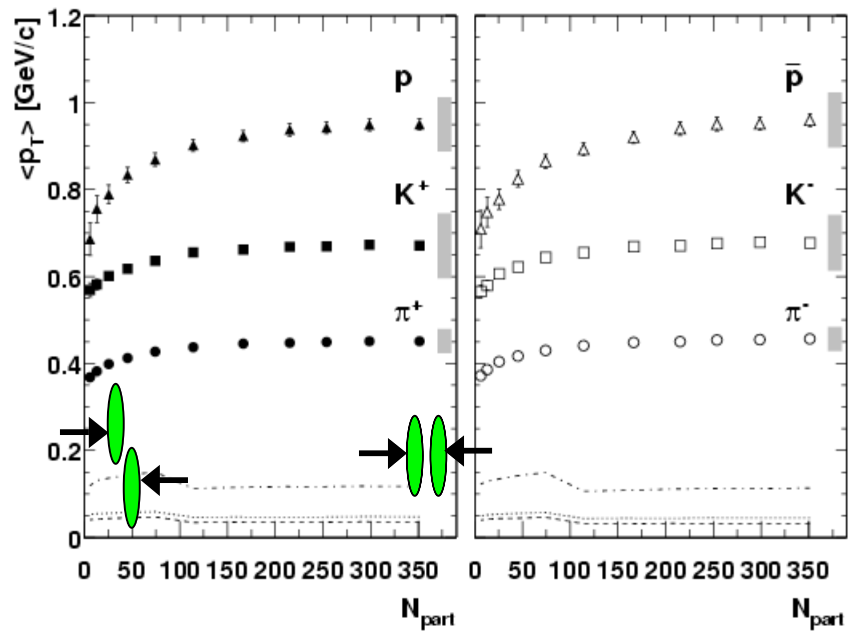
Central

- Low p_T slopes increase with particle mass.
- Proton and anti-proton yields equal the pion yield at high p_T.

Peripheral

- Mass dependence is less pronounces.
- Similar to pp.

- Increase from peripheral to mid-central, and then saturate from mid-central to central for all particle species.
- Observed clear mass dependence.
- **Indicative radial expansion.** **(consistent with hydro picture)**



Blast-wave model fit

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

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

- Phenomenological hydrodynamical model
- Local thermal equilibrium + collective expansion.
- Freeze-out temperature (T_{fo}) and radial flow velocity (β_T)
- Include resonance effect.

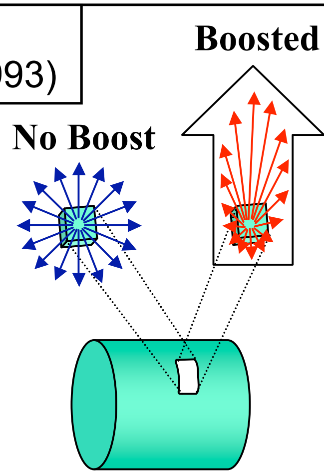
Blast wave model
E. Schnedermann et al., PRC48 2462 (1993)

$$E\frac{d^3n}{dp^3} \propto \int_\sigma e^{-(u^\nu p_\nu)/T_{th}} p^\lambda d\sigma_\lambda$$

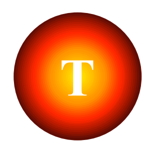
$$u^\nu(t,r,z=0) = (\cosh\rho, \vec{e}_r\sinh\rho, 0)$$

$$\rho = \tanh^{-1}\beta_r$$

$$\beta_r = \beta_s\, f(x,p) = \beta_s (r/R)^n$$

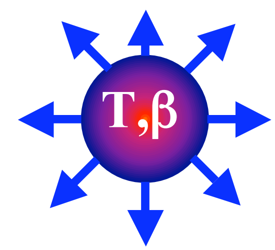


purely thermal source



p+p collision

explosive source



Heavy-ion collision

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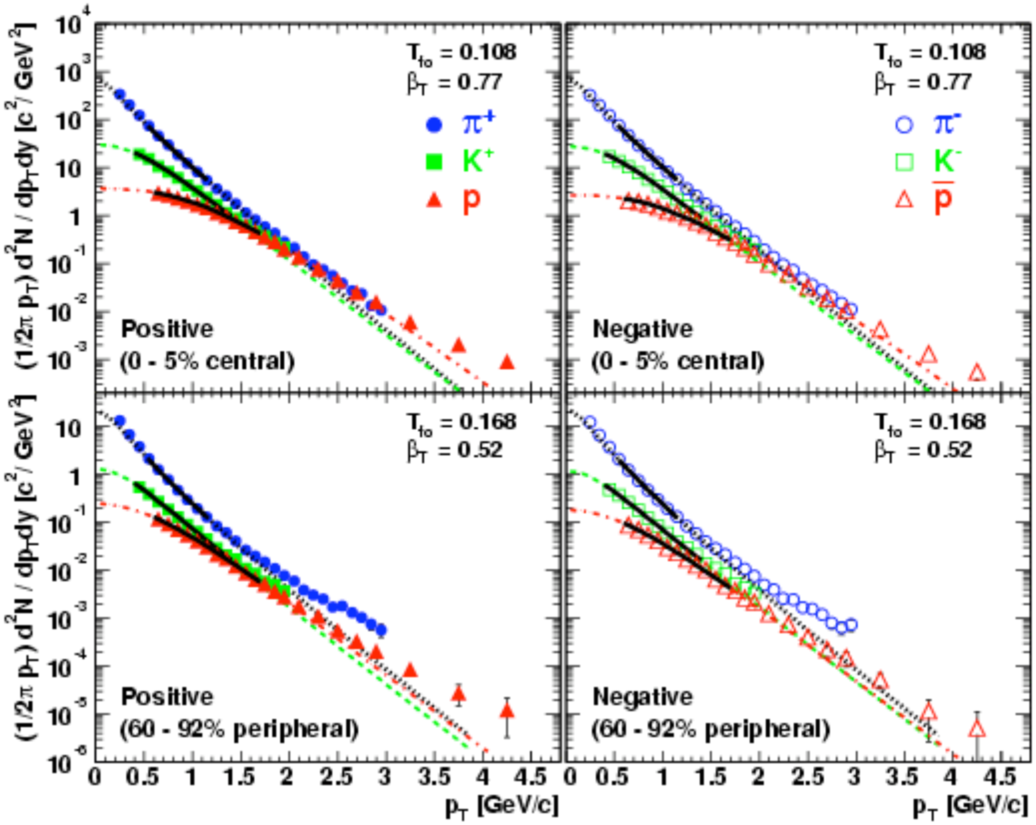
Fitting the p_T spectra



Minimize contribution from hard process

- $(m_T - m_0) < 1$GeV
- → **π : p_T < 1.2GeV/c,**
- → **K : p_T < 1.4GeV/c,**
- → **p : p_T < 1.7GeV/c**

Simultaneous fit to spectra of π,K,p

- T_{fo} : 60~240MeV , **2**MeV each
- β_T : 0.00~0.90, **0.01** each

More fine mesh in small region:

- T_{fo} : 90~130MeV , **1**MeV each
- β_T : 0.70~0.82, **0.002** each

PHENIX Au+Au 200GeV:

- **Most central: T_{fo} = 108MeV, $\langle\beta_T\rangle$ = 0.57**
- **Peripheral: T_{fo} = 168MeV, $\langle\beta_T\rangle$ = 0.27**

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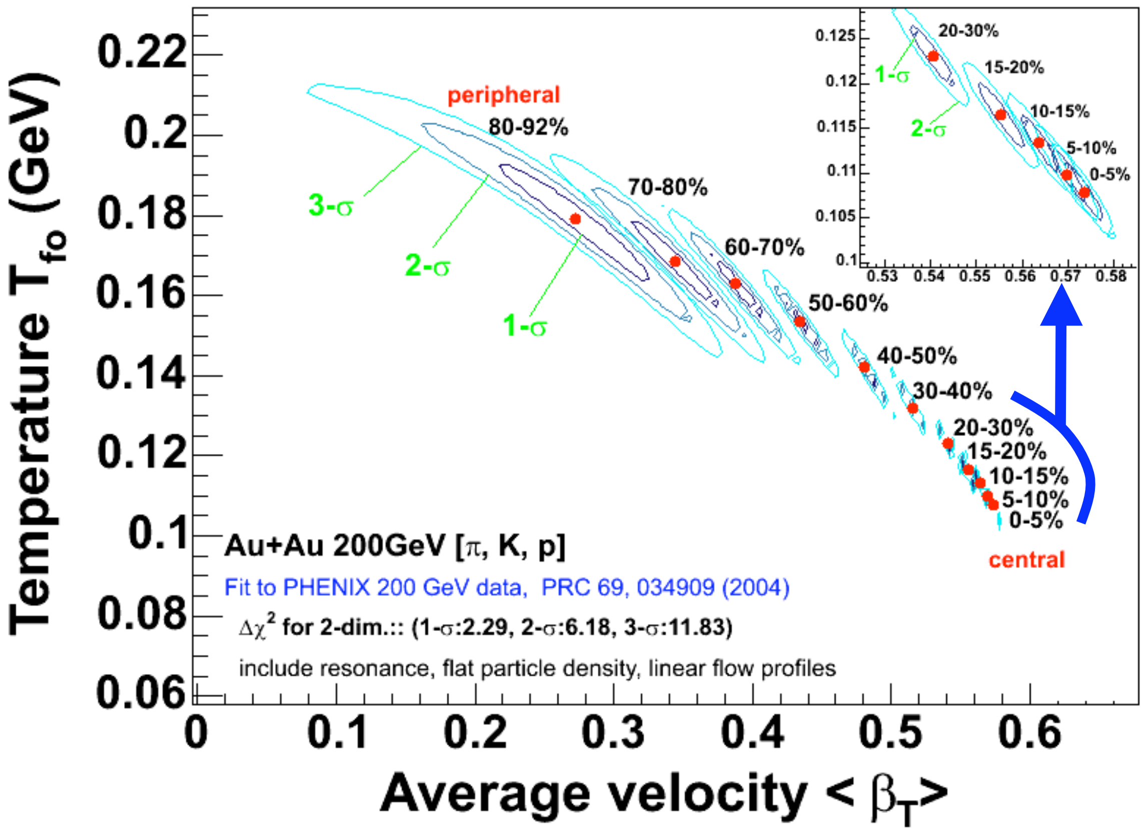
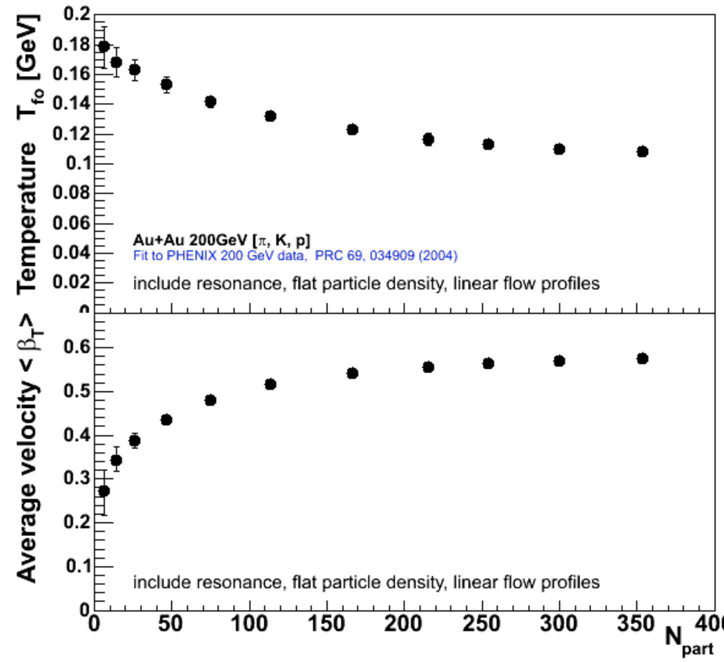
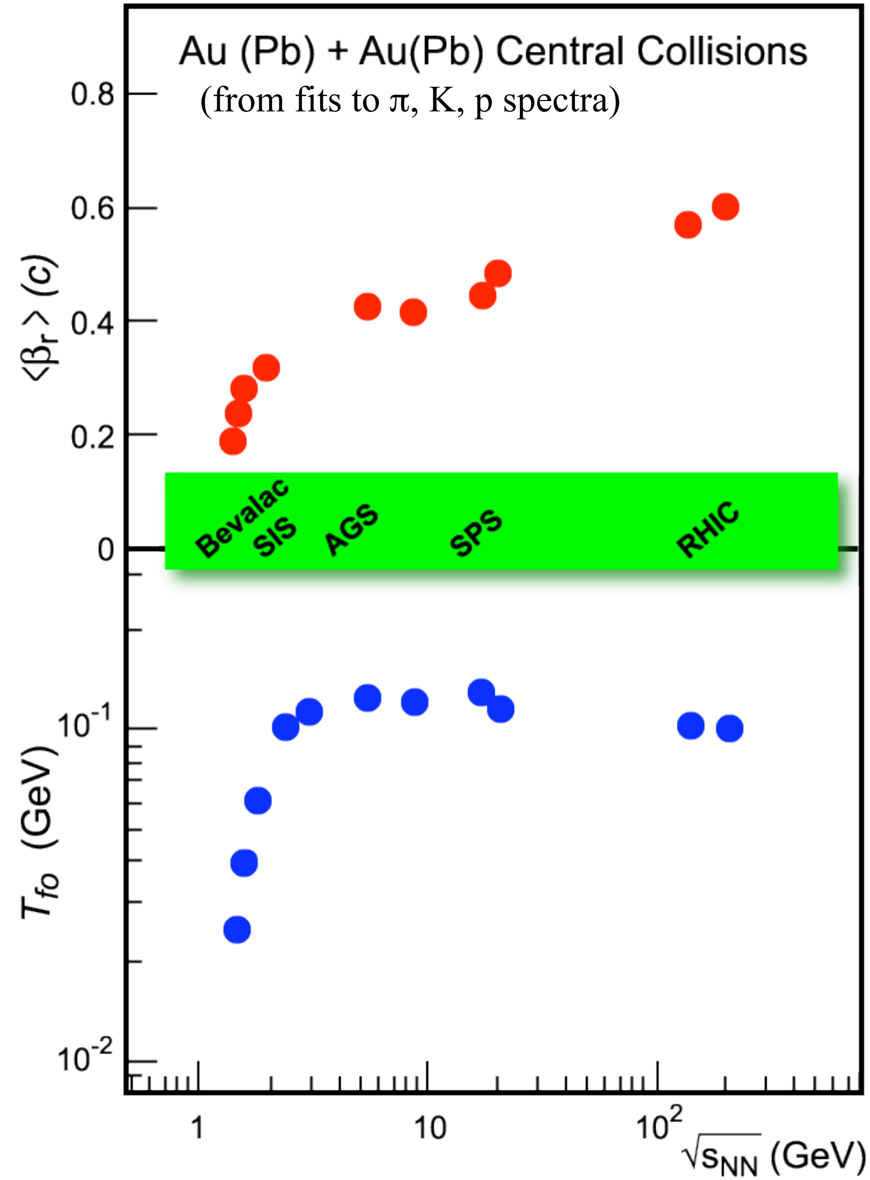
Centrality dependence of T_{fo} and $<\beta_T>$





- N_{part} dependence of expansion is observed:
  - @central: saturate
  - @peripheral : $N_{part} \rightarrow 0$, **T_{fo} increase, $<\beta_T> \rightarrow 0$**

Beam energy dependence

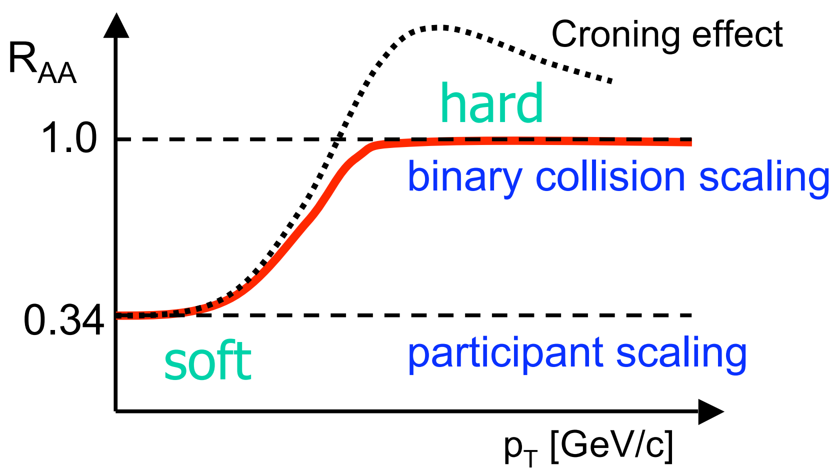


- Most central event of Au+Au or Pb+Pb.
- Radial flow:
  - Increases with beam energy
  - $<\beta_T>$~0.55 at RHIC
- Temperature:
  - saturate from AGS,
  - 100~120MeV

Nuclear Modification Factor R_{AA} , R_{CP}

Qualify the # of binary collisions

$$R_{AA}(p_T) = \frac{\mathrm{Yield}_{AuAu} / \langle N^{AuAu}_{\mathrm{coll}} \rangle}{\mathrm{Yield}_{pp} / \langle N^{pp}_{\mathrm{coll}} \rangle} \approx R_{CP}(p_T) = \frac{\mathrm{Yield}_{central} / \langle N^{central}_{\mathrm{coll}} \rangle}{\mathrm{Yield}_{peripheral} / \langle N^{peripheral}_{\mathrm{coll}} \rangle}$$

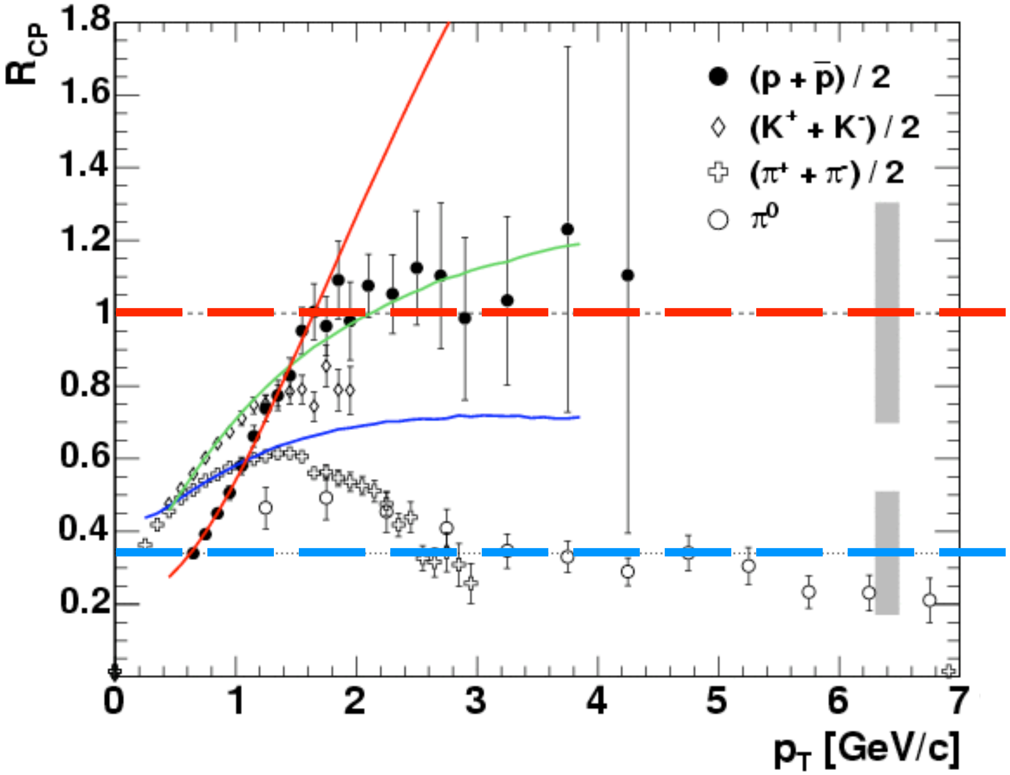


- Total multiplicity : N_{part} scaling
  - Low-p_T region (p_T < 2GeV/c)
- Jets: N_{coll} scaling
  - High-p_T in high energy collision.

Expected behavior:

- From N_{part} scaling at low-p_T to N_{coll} scaling at high-p_T region.

Central-to-Peripheral Ratio (R_{CP}) vs. p_T



$$R_{CP} = \frac{\mathrm{Yield}^{0\text{-}10\%} / \langle N_{coll}^{0\text{-}10\%} \rangle}{\mathrm{Yield}^{60\text{-}92\%} / \langle N_{coll}^{60\text{-}92\%} \rangle}$$

N_{coll} scaling

* Shaded boxes : N_{part}, N_{coll} determination errors.

N_{part} scaling

Line: extend Blast-wave fit

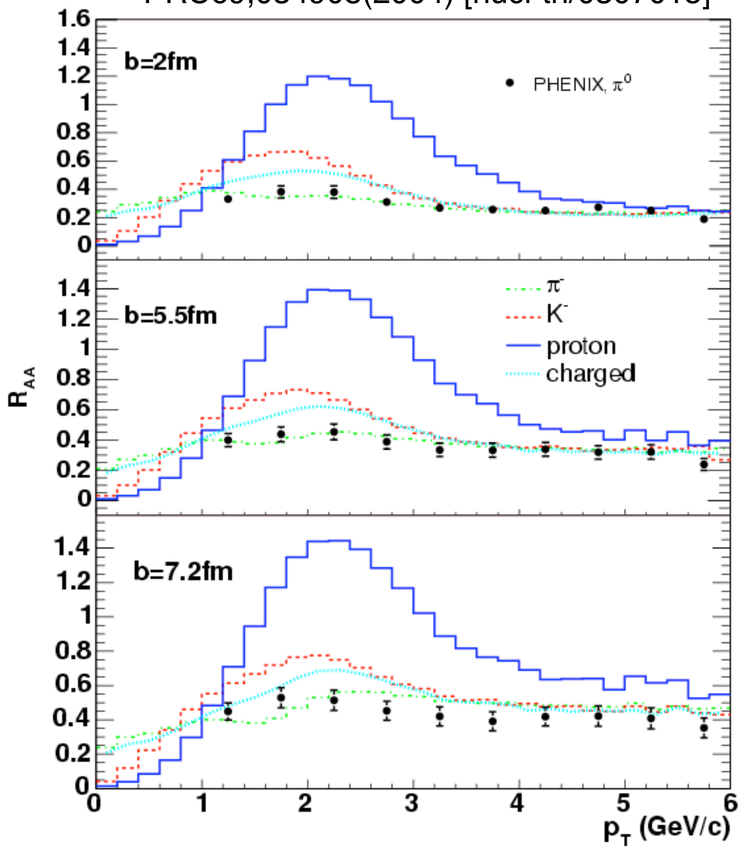
Depend on particle species

- Stray off the hydrodynamical curve at high-pt.
- Proton,anti-proton: **No suppression**, N_{coll} scaling
- π: **suppression**

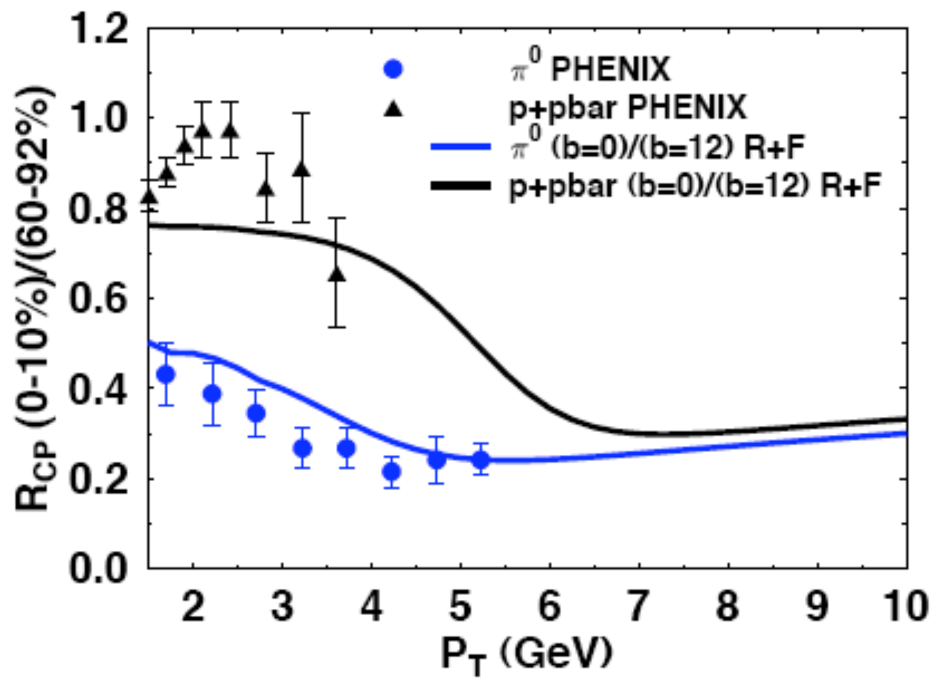
Theoretical explanations: hydro+jet model, quark recombination model

Hydro+Jet and Recombination

Hirano, Nara (Hydro + Jet Model)
PRC69,034908(2004) [nucl-th/0307015]



Fries, Muller, Nonaka, Bass (Fragmentation/Recombination model)
PRC68,044902(2003) [nucl-th/0306027]



- Qualitative agreement in pion suppression and proton non-suppression.
- Both model predict that proton suppress at ~6GeV/c.

Conclusion

- Results of identified charged hadron spectra.
  - Au+Au 200GeV: Phys.Rev.C69 034909(2004)
- Hydro-dynamical model fit to the spectra with resonance decay effect.
  - N_{part} dependence of expansion is observed
  - For the most central:
    - **Au+Au 200GeV: T_{fo} = 108MeV, $\langle\beta_T\rangle$ = 0.57**
- High-p_T hadron production
  - Observed strong pion suppression at high p_T in central.
  - No suppression for proton.

  There are several theories and discussing.

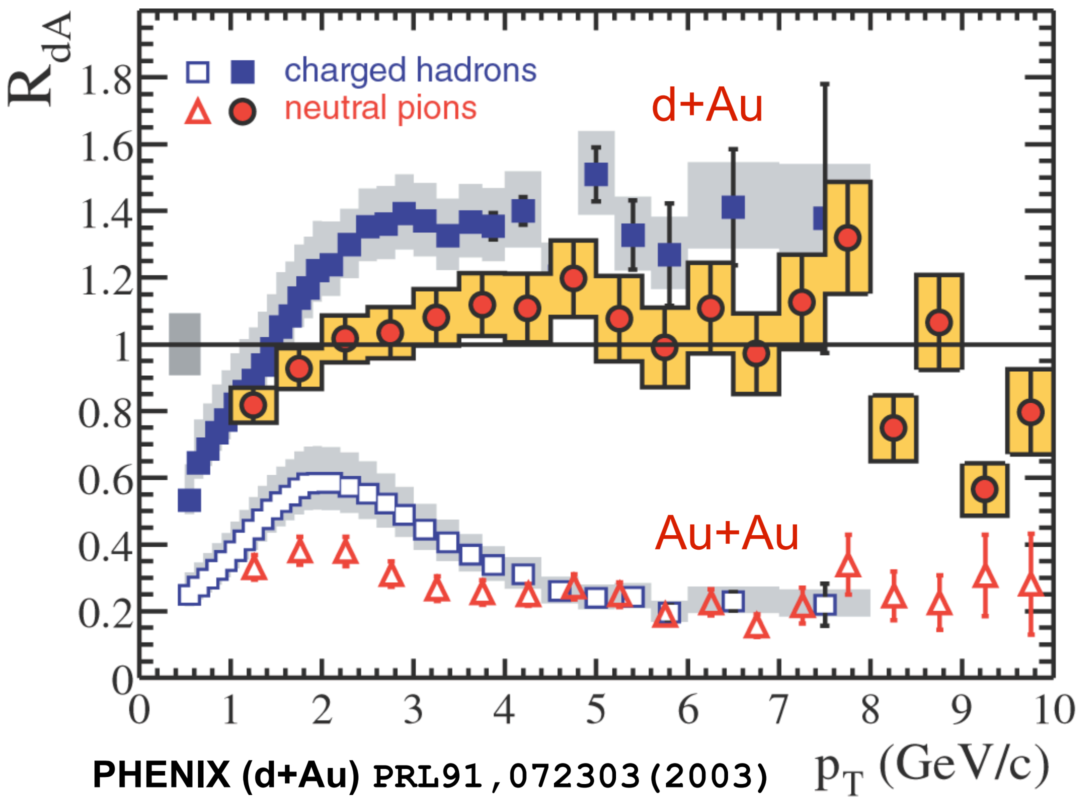
High-p_T PID upgrade : Aerogel & MRPC-TOF

- PID beyond 5GeV/c.

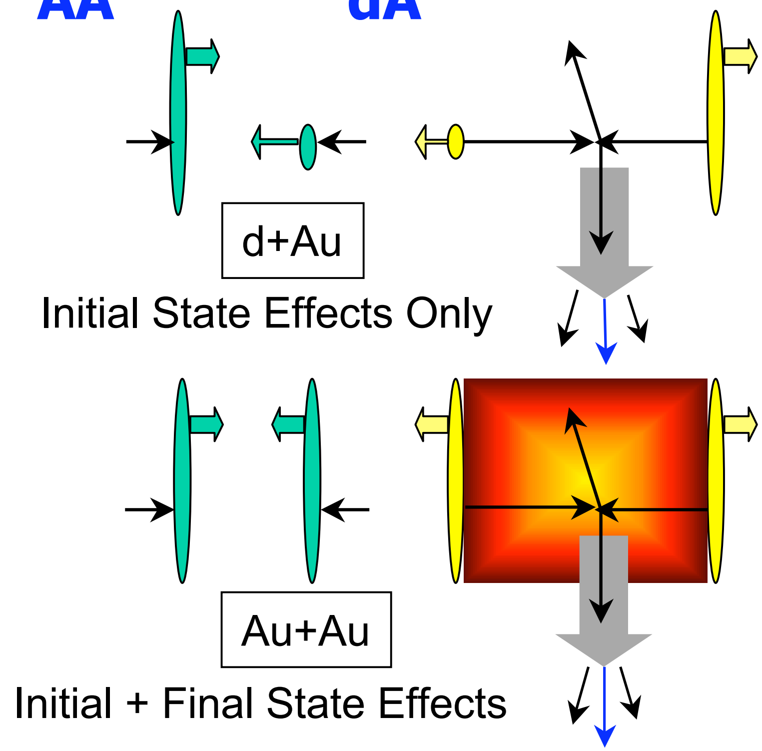

PHENIX
PHENIX Experiment

Spare

d+Au Collisions: R_{AA} vs. R_{dA}



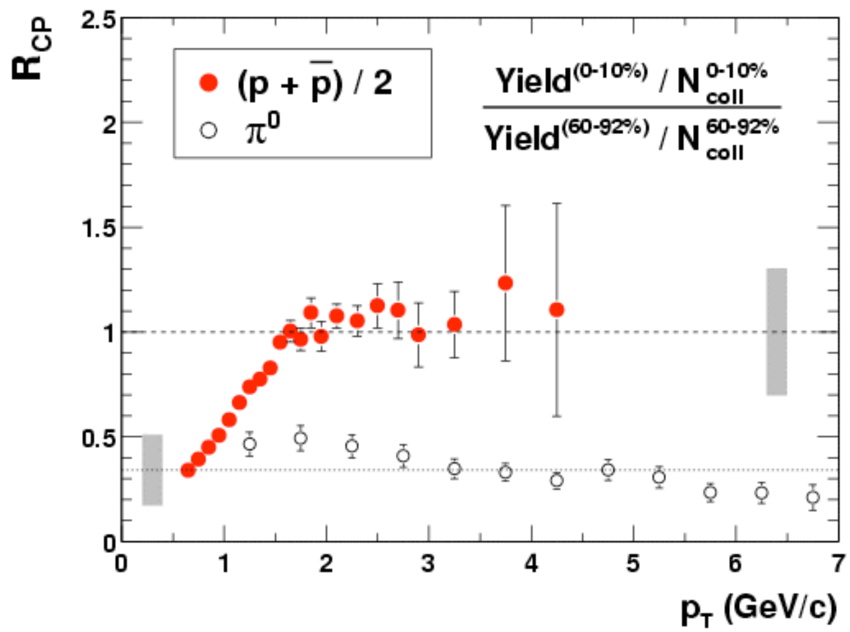
PHENIX (d+Au) PRL91,072303(2003)

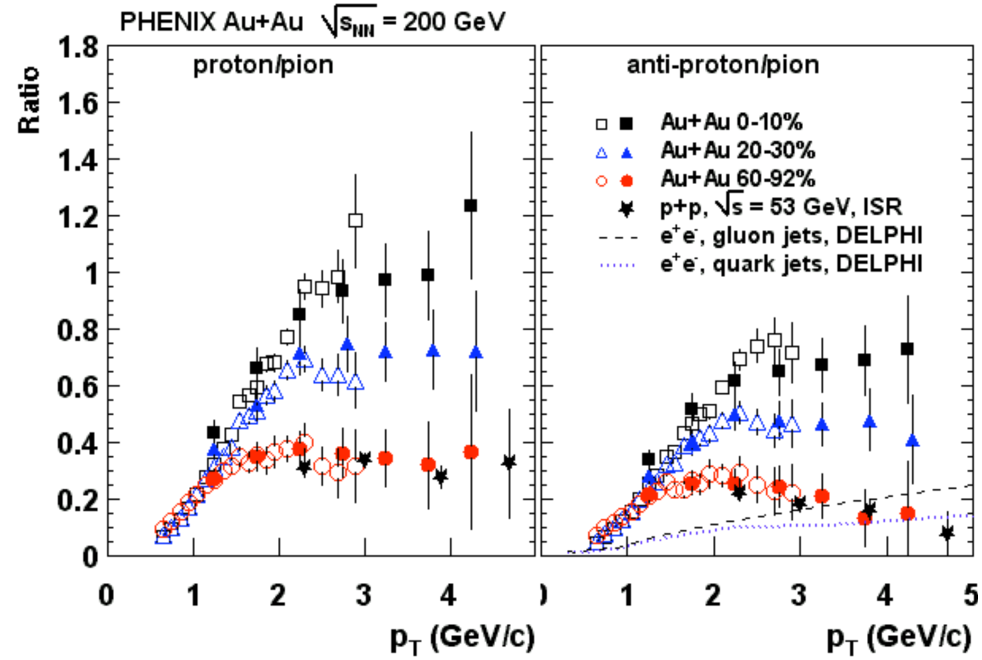


- π^0 and charged are largely suppressed in central Au+Au at high p_T.
- No Suppression in d+Au, instead small enhancement observed !
- d-Au results rule out CGC (initial sate effect) as the explanation for high p_T suppression of hadrons in AuAu central.

Baryon Anomaly at RHIC

PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004)

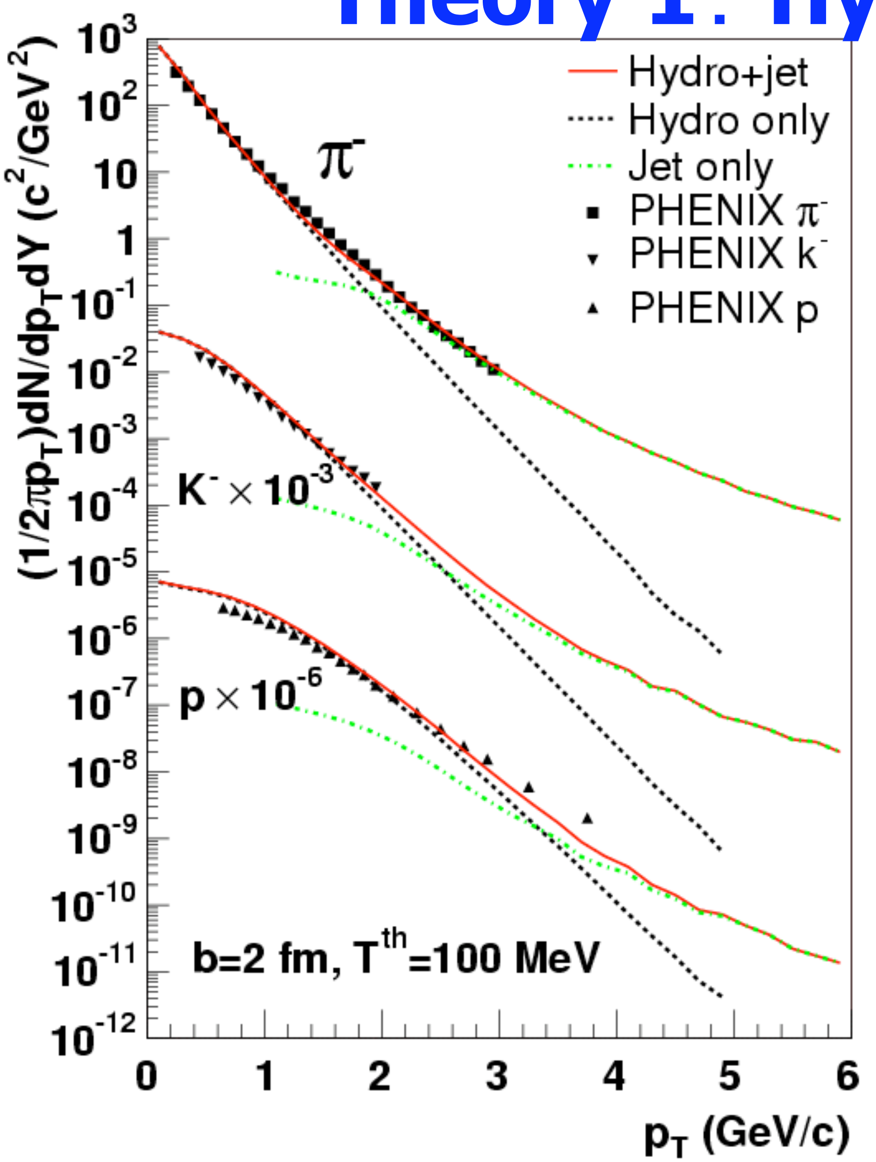




p, pbar : No suppression,
N_{coll} scaling at
1.5 GeV - 4.5 GeV
π^0: Suppression

- **Factor ~3 enhancement on both p/π and pbar/π ratios in central Au+Au** compared to peripheral Au+Au, p+p at Intermediate p_T.
- Peripheral Au+Au at high p_T: Consistent with gluon/quark jet fragmentation and IRS data.

Theory 1：Hydro + Jet Model



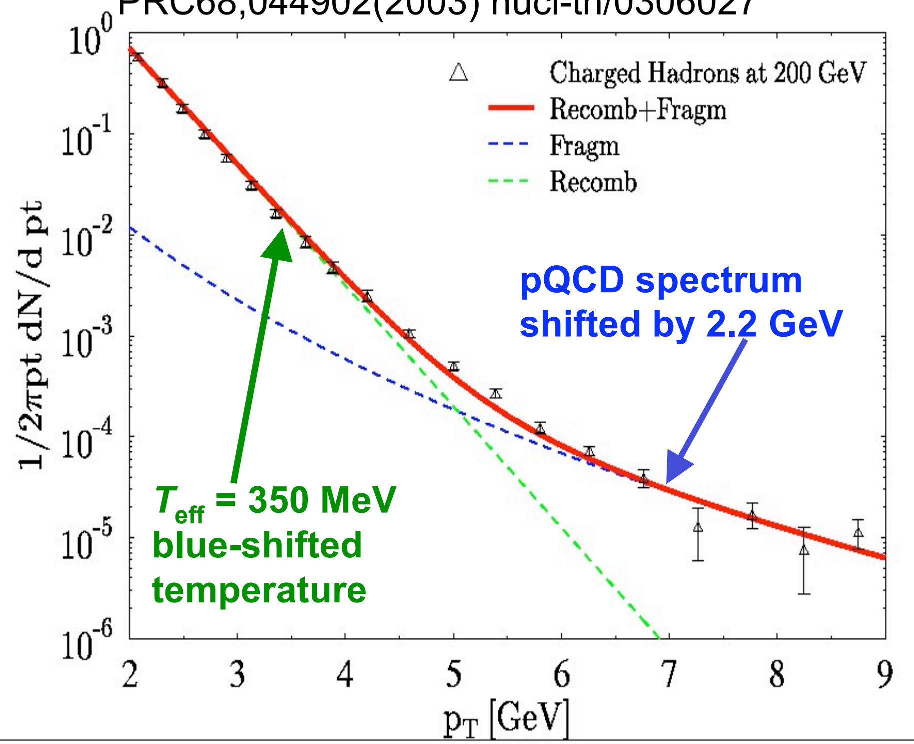
Hirano, Nara (Hydro + Jet Model)
PRC69,034908(2004) [nucl-th/0307015]

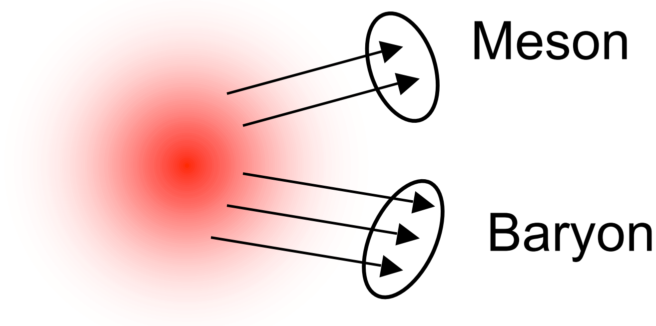
- **Explicit 3D Hydrodynamical calculations (including QGP in EOS)**
- **Tuned jet quenching effect to reproduce the suppression factor in π^0 data.**

- Hydrodynamics can describe p_T spectra up to ~ 2 GeV/c.
- **Jet contributions from 2 GeV/c.**

Theory 2: Recombination Model

Fries, Muller, Nonaka, Bass (Fragmentation/Recombination model)
PRC68,044902(2003) nucl-th/0306027



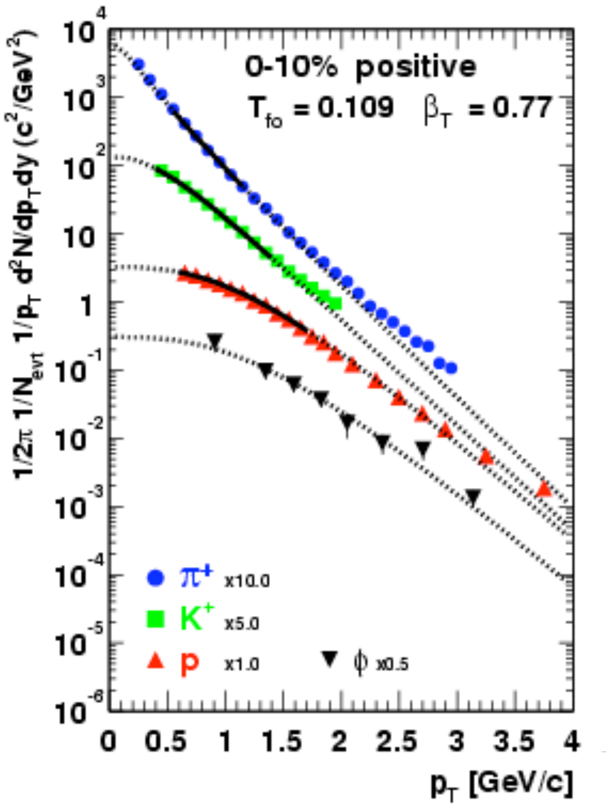


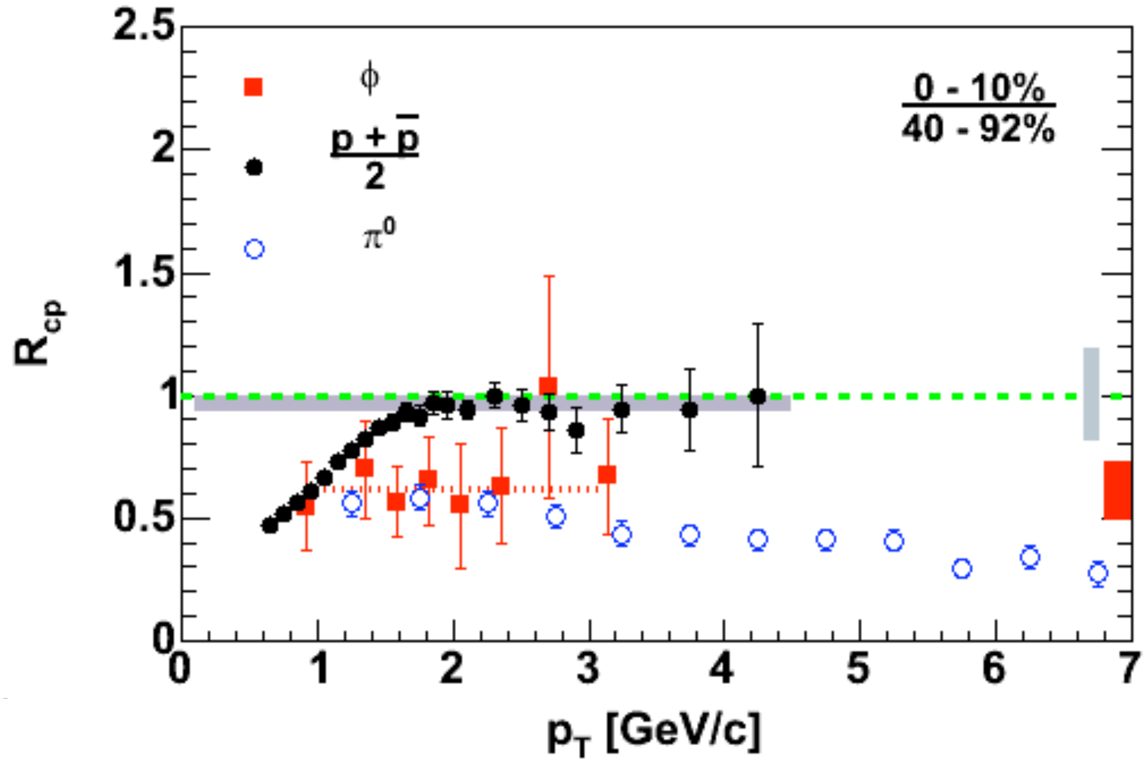
$$\frac{dN_M}{p_T dp_T} = C_M \cdot w(p_T/2)^2$$

$$\frac{dN_B}{p_T dp_T} = C_B \cdot w(p_T/3)^3$$

- Quarks and anti-quarks recombine into hadrons locally "at an instant"
  - $q\bar{q}$ → **Meson**
  - **qqq → Baryon**
- Thermal part (quark only) and power law tail (quarks and gluons) from pQCD.
- Modification of fragmentation function "$D_{i\to h}(z)$" by energy loss of partons.
- Competition between recombination and fragmentations mechanism.
- **Quark degrees of freedom** play an important role.

ϕ meson



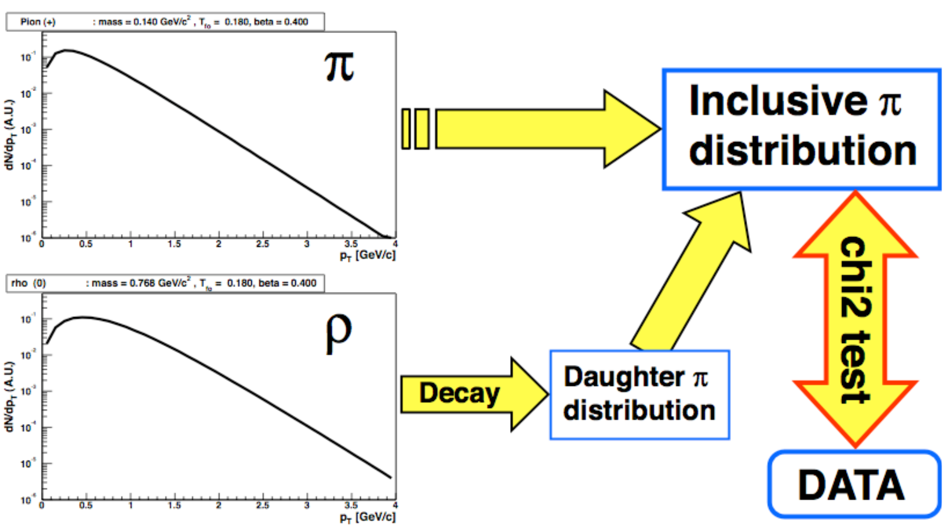


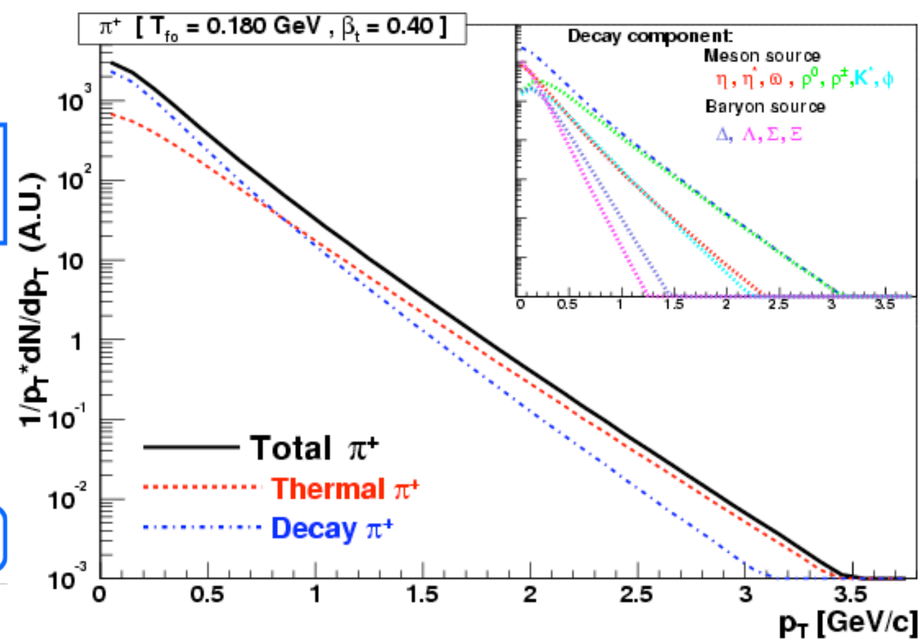
ϕ meson:

- Similar mass as proton.
- Followed the π^0 data points, not protons!

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





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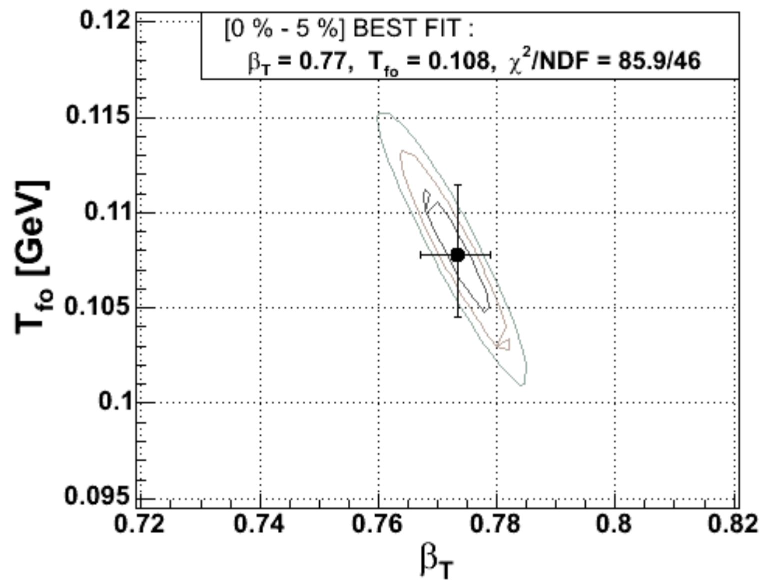
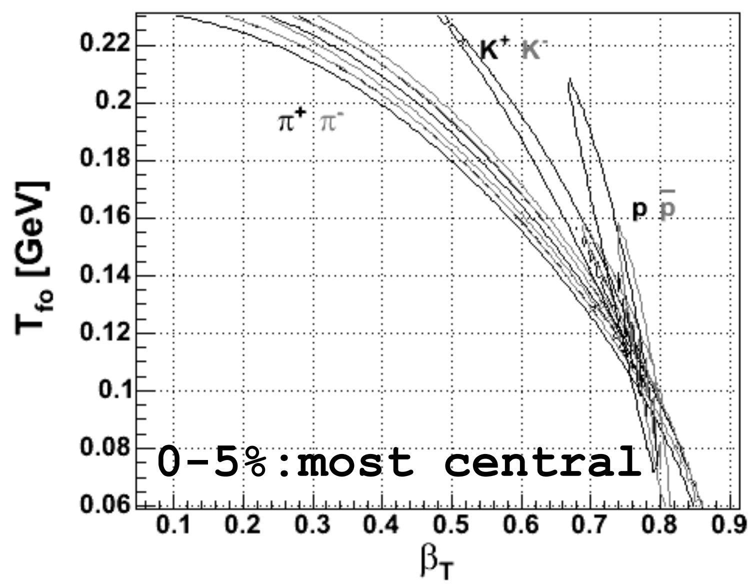
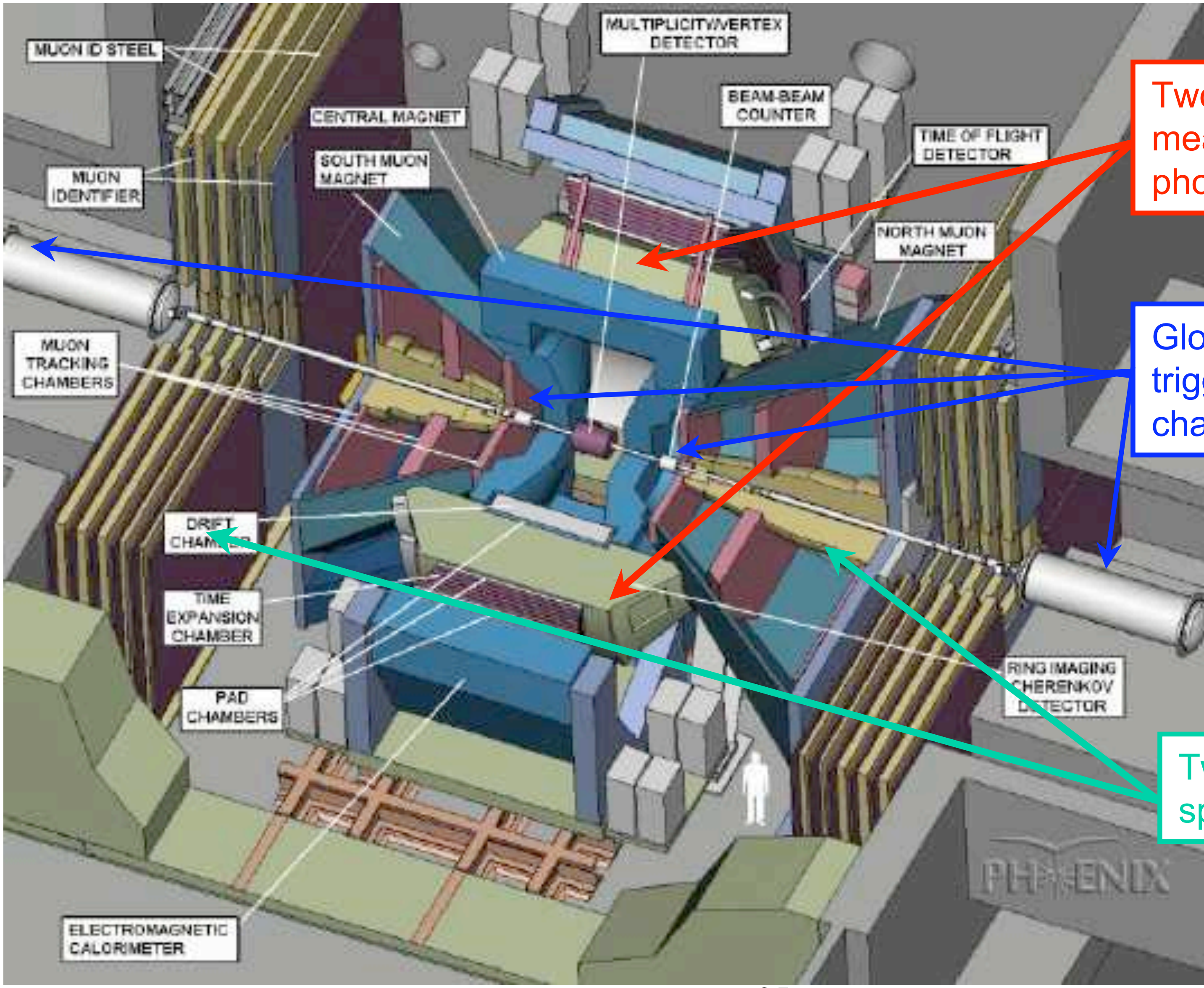
χ^2 contours in parameter space T_{fo} and β_T

- Upper figure show the χ^2 test result of simultaneous fitting for most-central spectra.
- Lower figure show χ^2 contours for each particles.
- There are strong anti-correlation between T_{fo} and β_T.





PHENIX Experiment



Two central arms to measure electron, photon, and hadrons

Global detectors for trigger and event characterization

Two forward muon spectrometers

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