Hadron Production at Intermediate p_T at RHIC

Tatsuya Chujo
Vanderbilt University
for the PHENIX Collaboration

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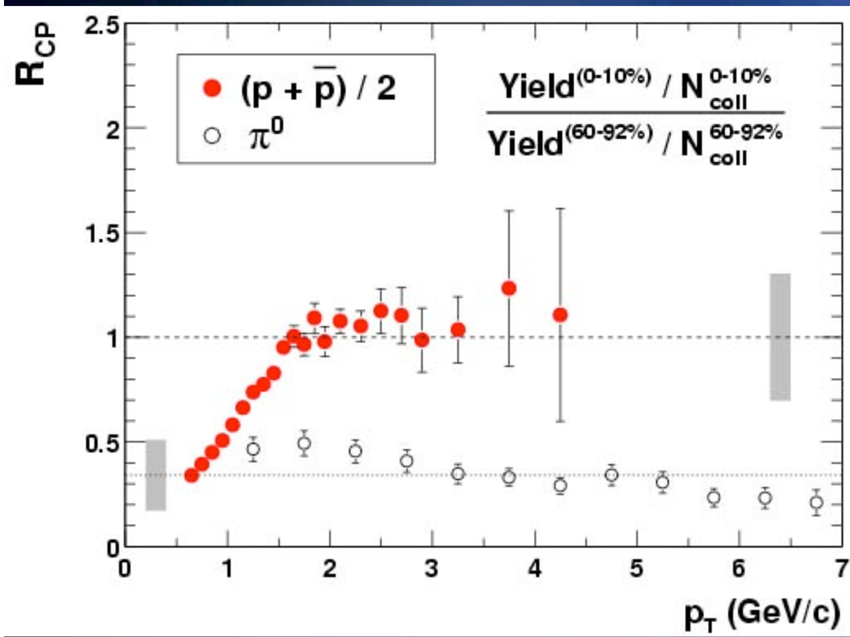
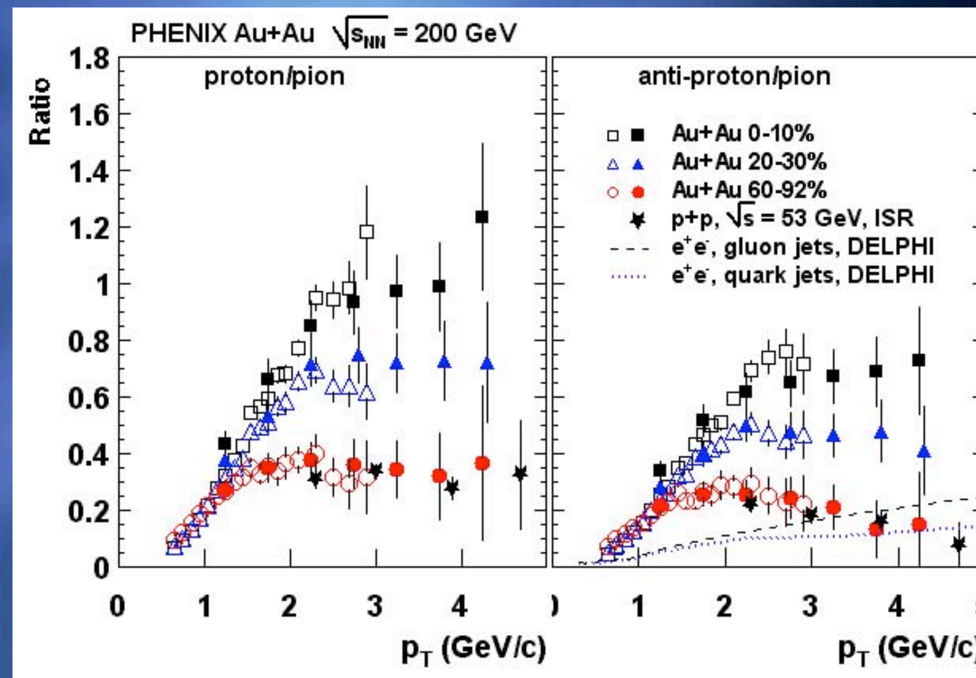
Outline

1. Motivation
   - Baryon anomaly intermediate p_T (2-5 GeV/c) at RHIC.
2. Experimental data in Au+Au $\sqrt{s_{NN}}$=200 GeV
   1) ϕ meson (N_{coll} scaling property, R_{cp})
   2) Meson vs. baryon R_{cp}.
   3) Jet correlation with PID trigger.
   4) Models vs. data (hydro+jet, recombination).
3. Proton and antiproton production in Au+Au $\sqrt{s_{NN}}$=62.4 GeV
4. Summary and outlook

1. Baryon Anomaly at RHIC

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



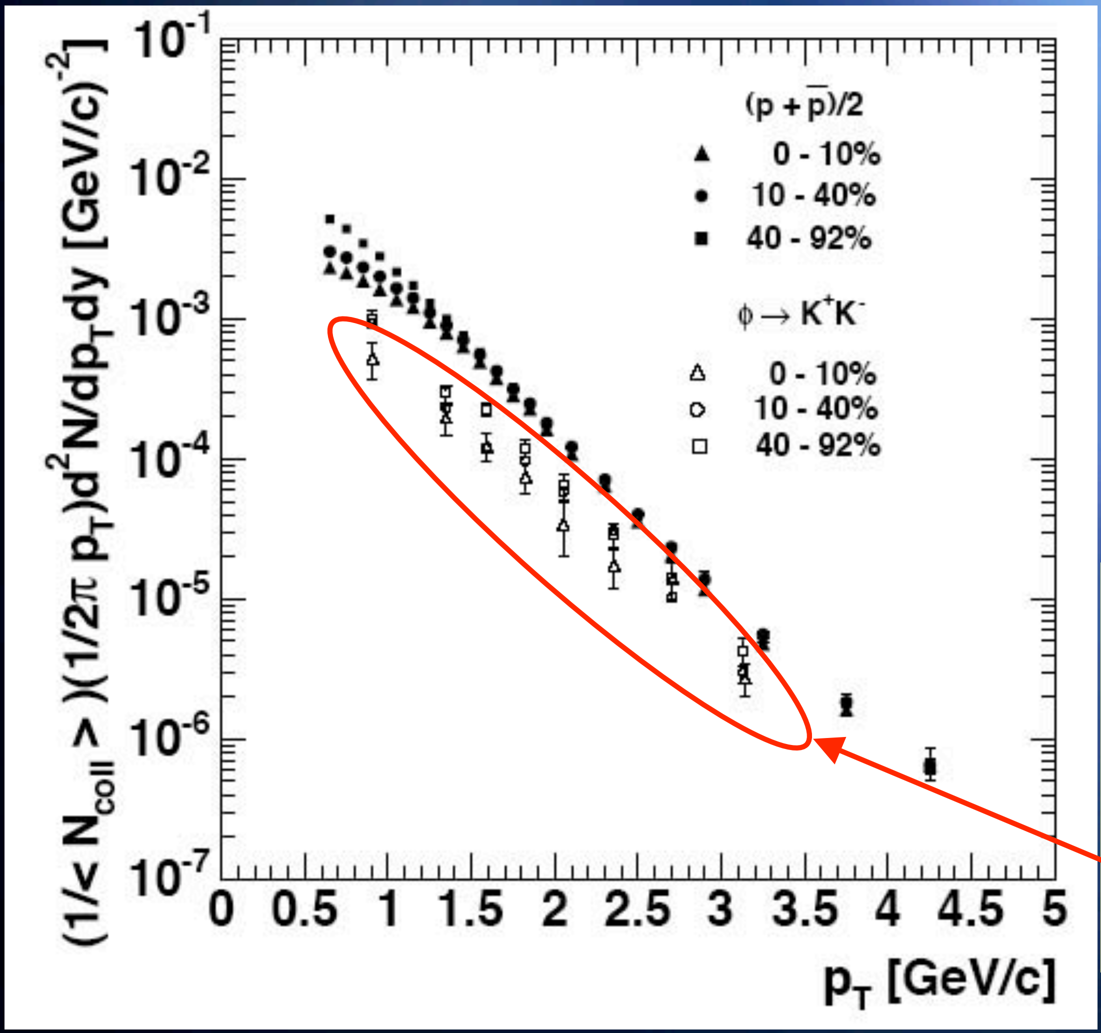


p, pbar : No suppression,
N_{coll} scaling at
1.5 GeV - 4.5 GeV
π^0: Suppression

- **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.

2.1 Scaling properties of $\phi(1020)$

proton, pbar: PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004)
ϕ: PHENIX final data, will be submitted to PRC.



ϕ meson:

- Similar mass as proton, but meson.

→ Ideal test particle whether the observed baryon anomaly is a mass effect or not.

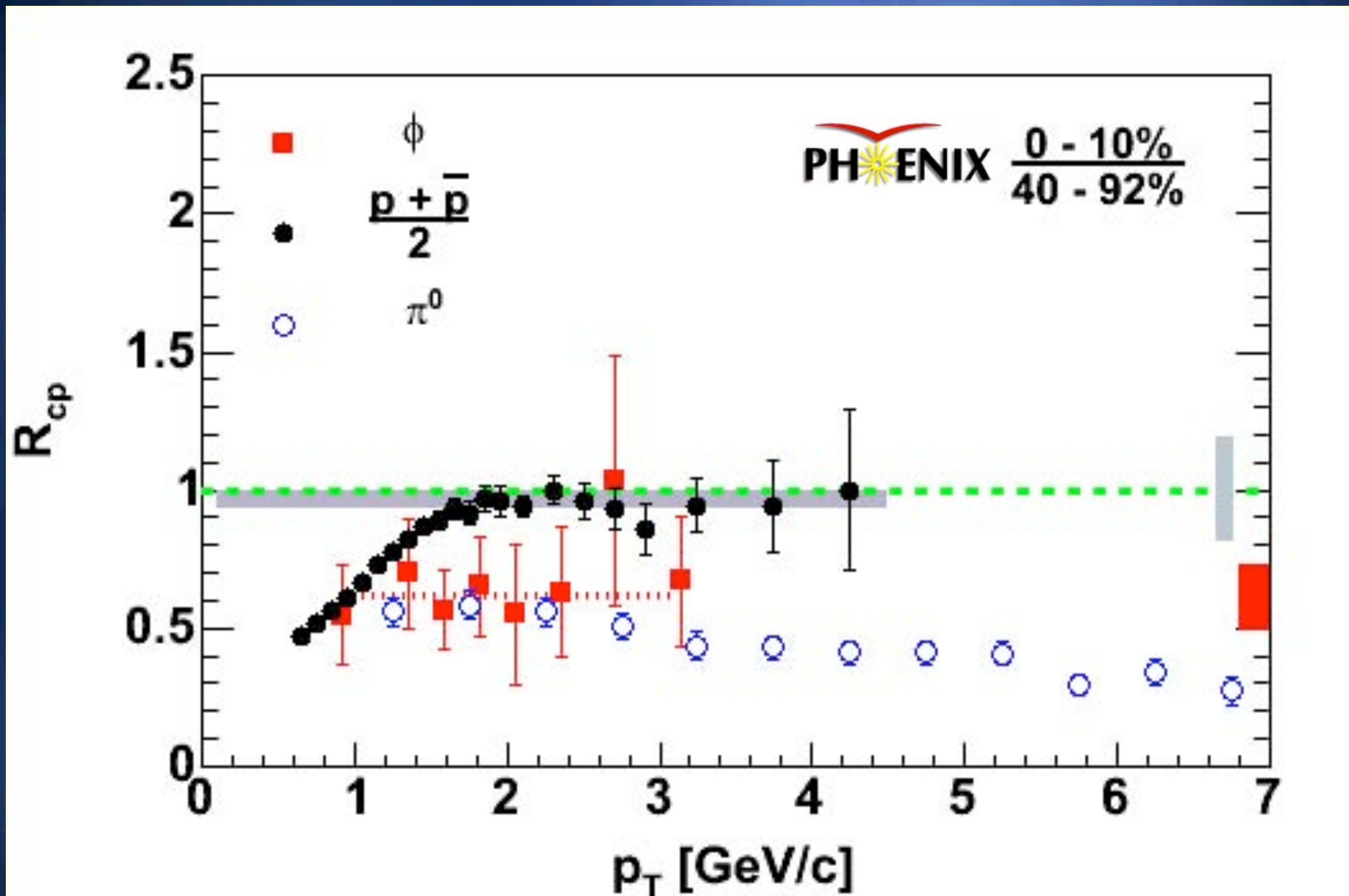
p, pbar:

low p_T (< 1.5 GeV/c): different shape due to the radial flow, intermediate p_T: Ncoll scaling

ϕ:

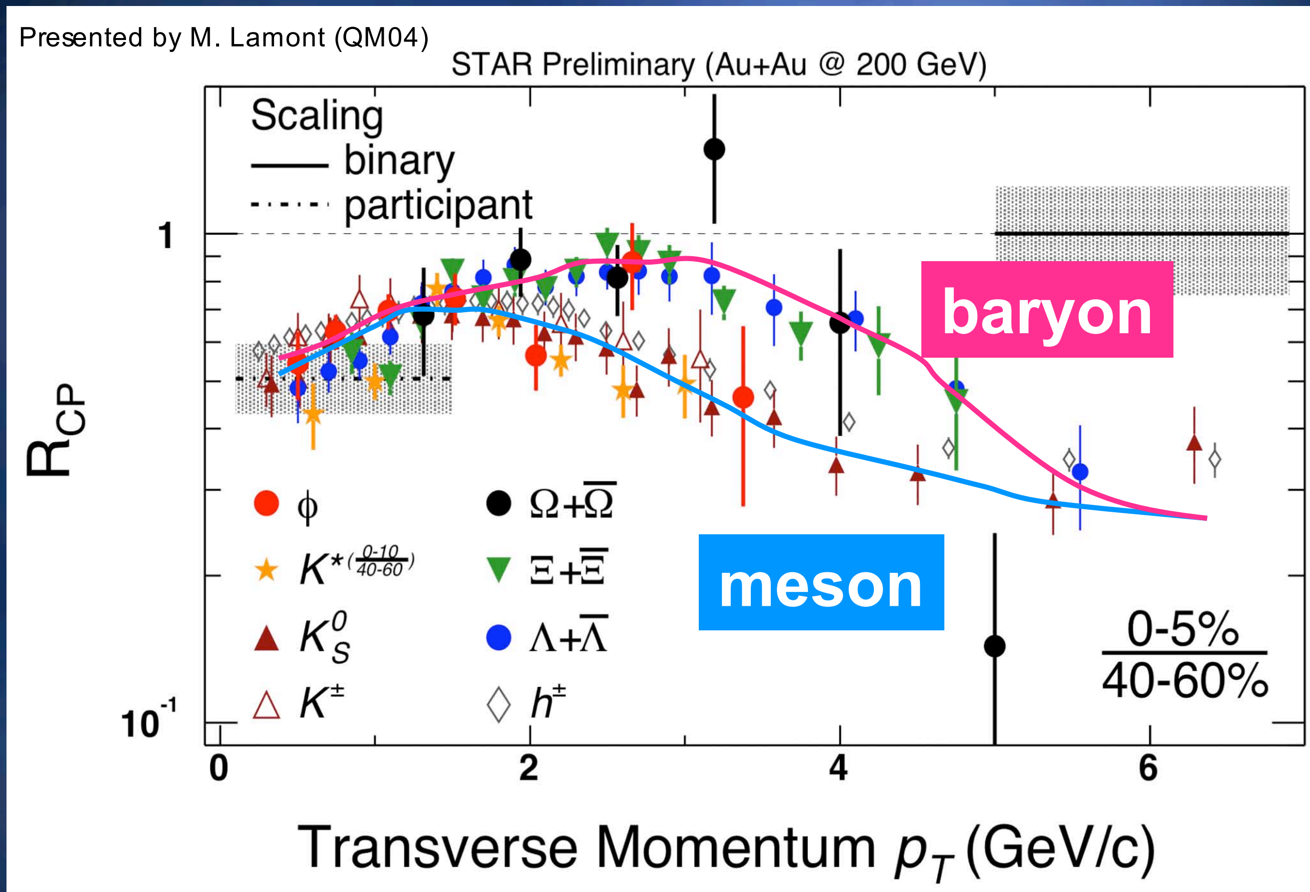
does not scale with N_{coll}

R_{cp} of ϕ meson



- **Followed the π^0 data points, not protons!**
- **Indicates the absence of suppression of proton at intermediate p_T is not a mass effect.**

2.2 Compilation on R_{cp} from STAR



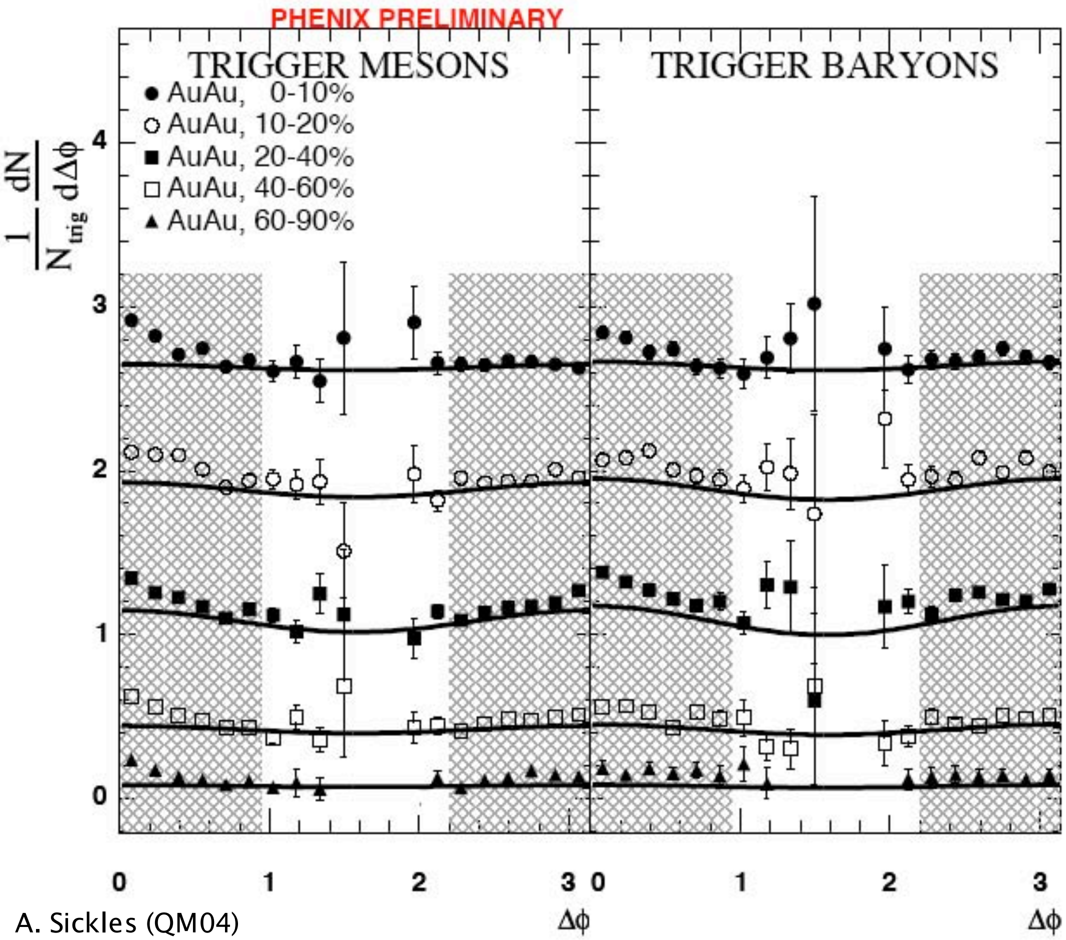
- **Two distinct groups in R_{cp} , i.e. meson and baryon, not by particle mass.**
- **Separate at p_T ~ 2 GeV/c and come together at 5 GeV/c.**

2.3 Mid-p_T protons from fragmentation?

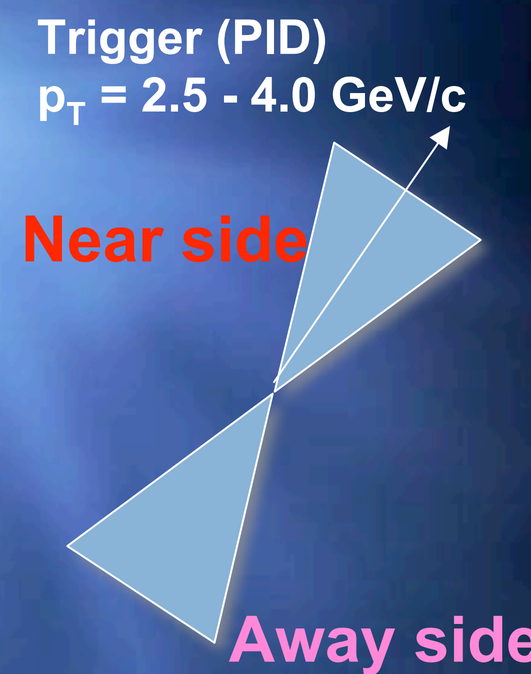
- Intermediate p_T is the transition region from soft to hard process.
- What is the origin of proton and antiproton production at the intermediate p_T?
- Note: Recombination model of purely thermal quarks implies the observed baryon excess comes from soft, not from fragmentation (no jet partner hadrons).

→ **Jet correlation with identified particle trigger (p+pbar, π+K) are employed in Au+Au and d+Au.**

Jet Correlation with PID trigger



A. Sickles (QM04)

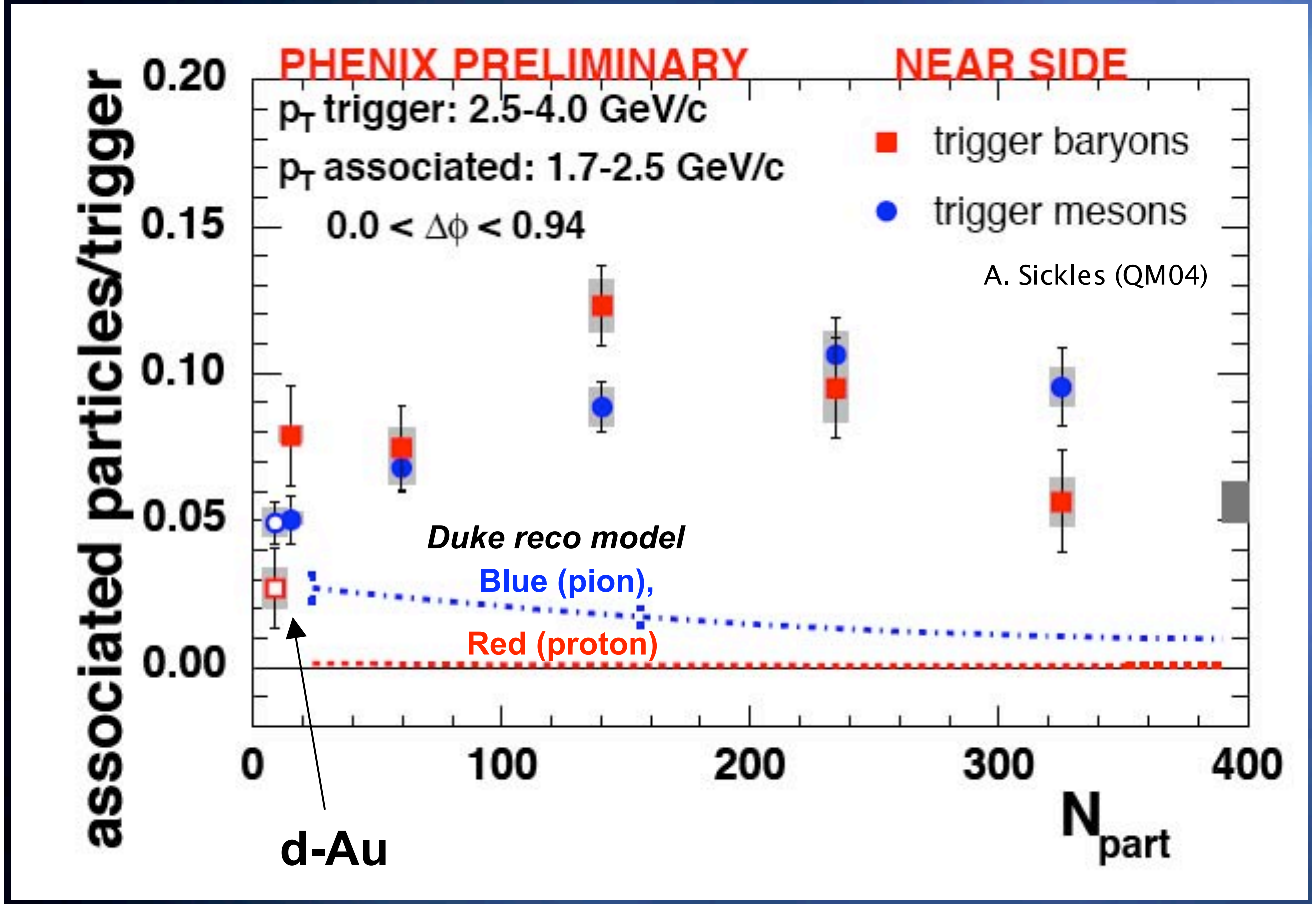


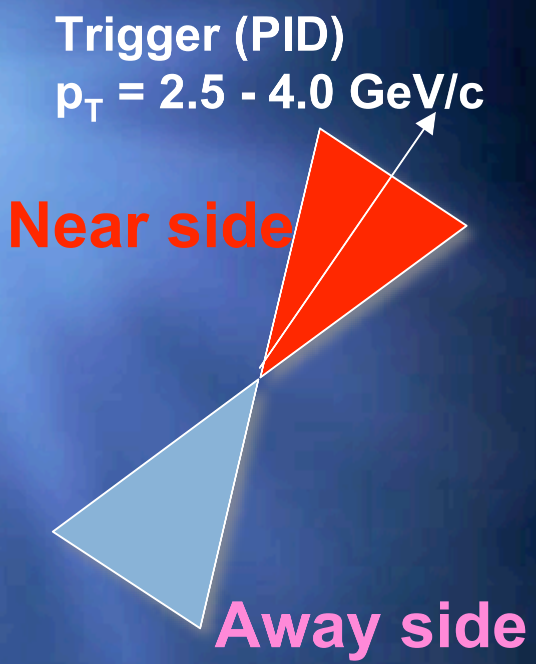
*Line: calculated combinatorial BG modulated by the measured v_2.

Count associated low p_T particles with PID mid-p_T trigger

- Near side: Number of jet associated particles from same jet.
- Away side: Number of fragments from opposing jet.

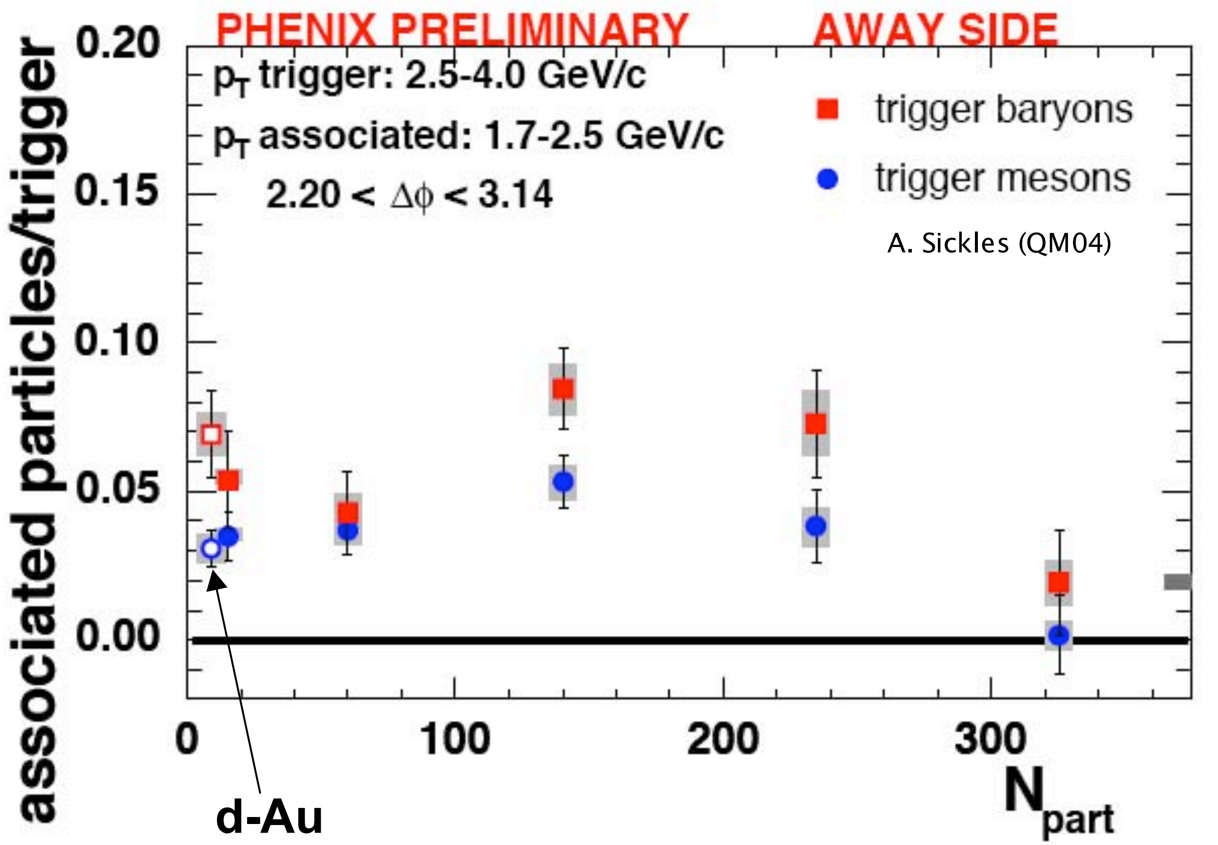
Jet correlation: near side

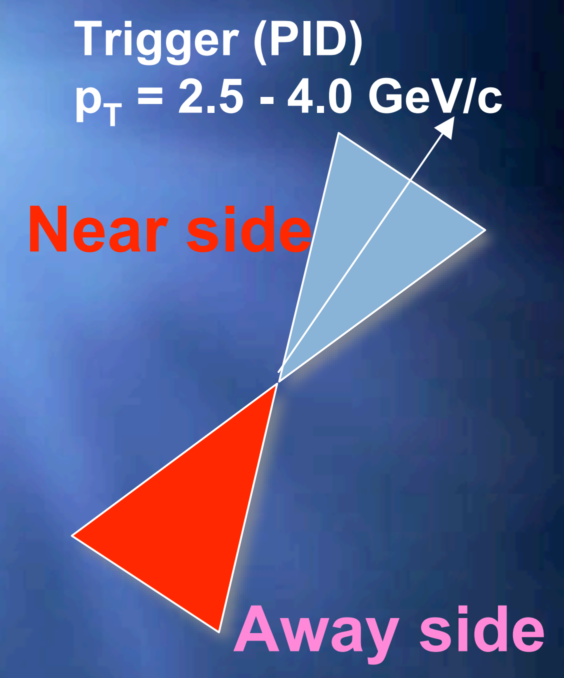




- **No apparent difference on jet partner yield** between trigger baryons and mesons, perhaps except most central Au+Au for baryons.
- Suggested intermediate p_T baryon arises from a fragmentation from jet.

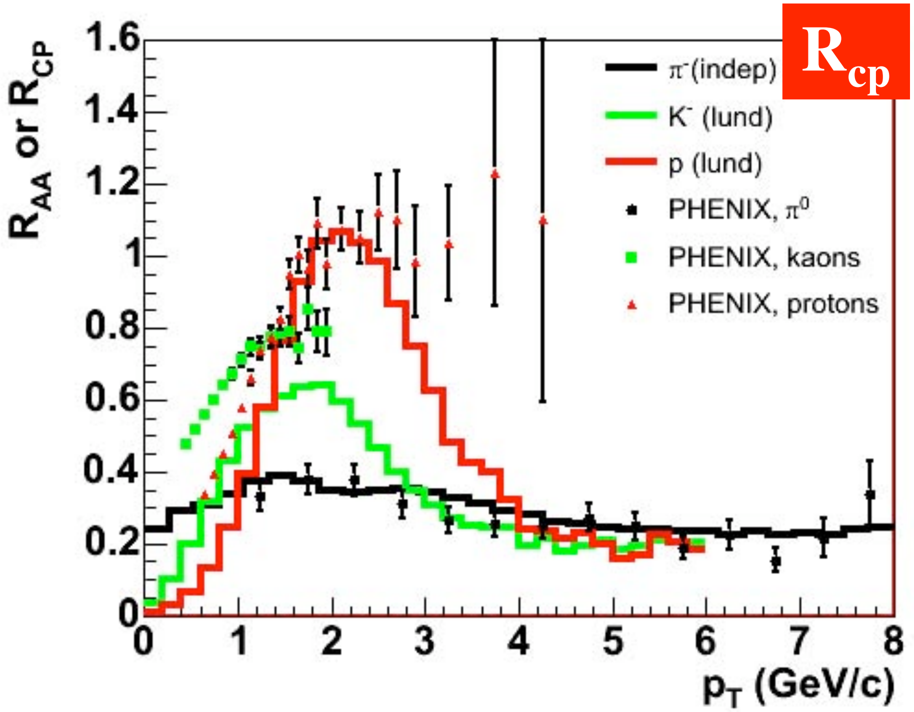
Jet correlation: away side

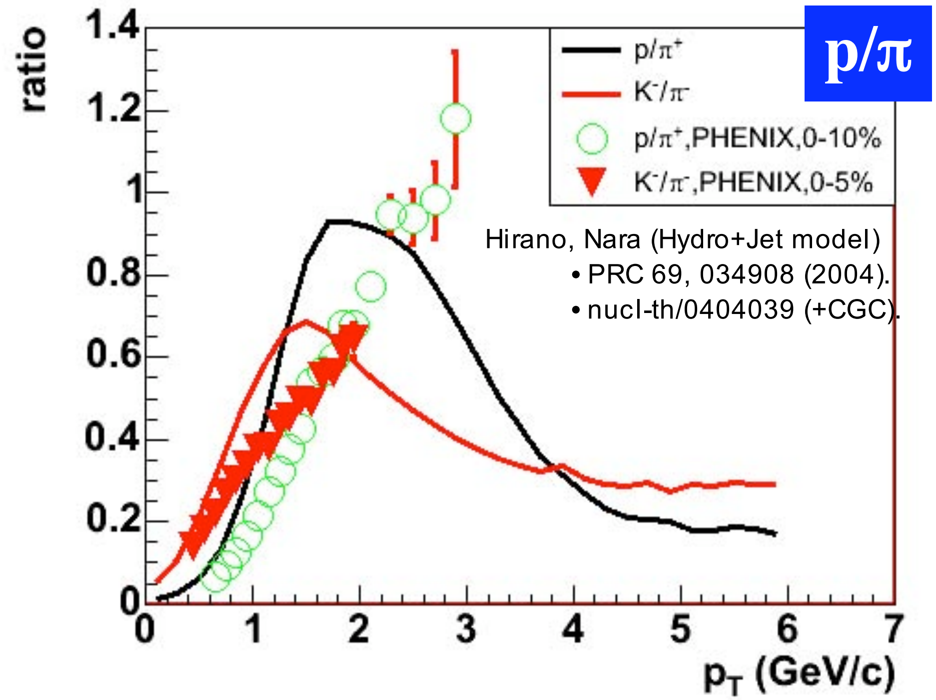




- Meson and baryon are comparable and decreasing at most central Au+Au collisions.
- In agreement with the disappearance/ broadening of back-to-back jet correlation in central Au+Au.

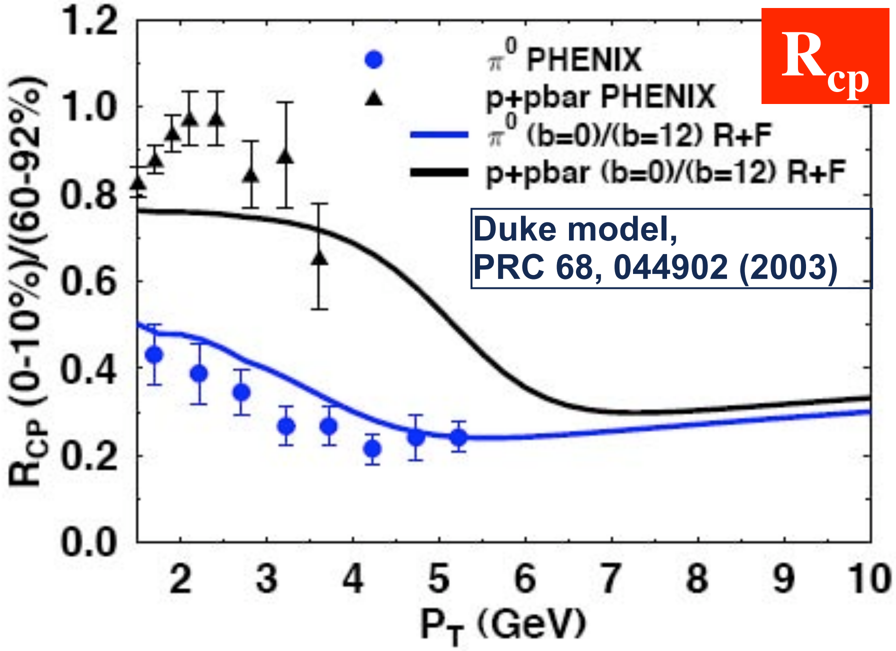
2.4 Hydro+Jet vs. data

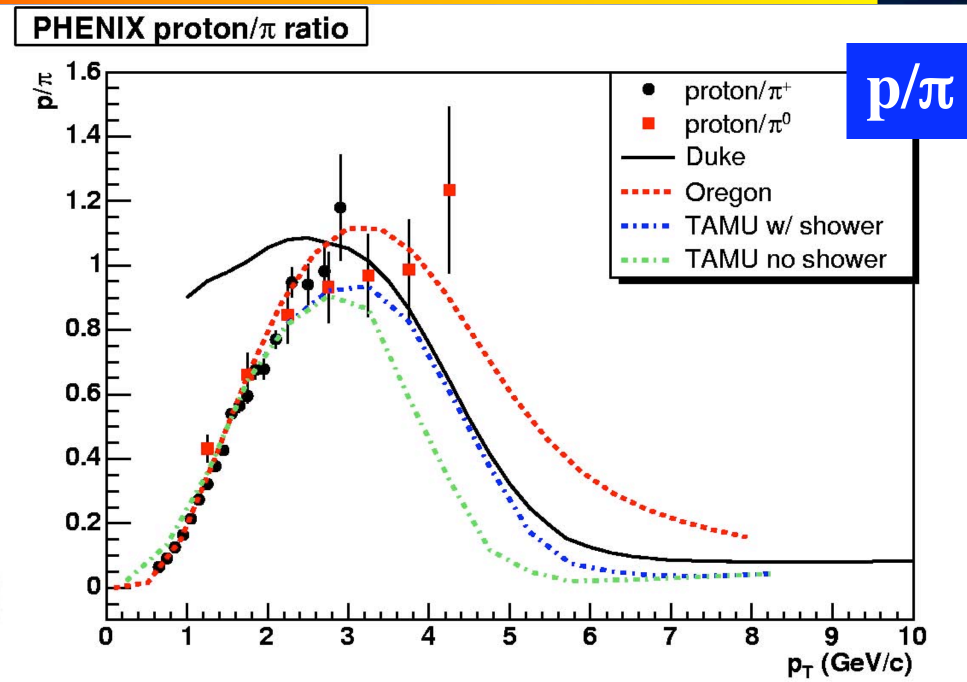




- **Excellent agreement in π^0 suppression pattern.**
- **Trend in Rcp(p) and p/pi ratio are right, but quantitative disagreement with data.**
- **Challenging for ϕ and K* due to the mesons with large mass.**
  → Explained by the less interaction cross section?

Recombination Models vs. data





- Qualitative agreement with R_{cp} (proton) data.
- Better description when (thermal - hard) is included, which supports the experimental result on jet correlations.

3. p, pbar production $\sqrt{s_{NN}}$ = 62.4 GeV

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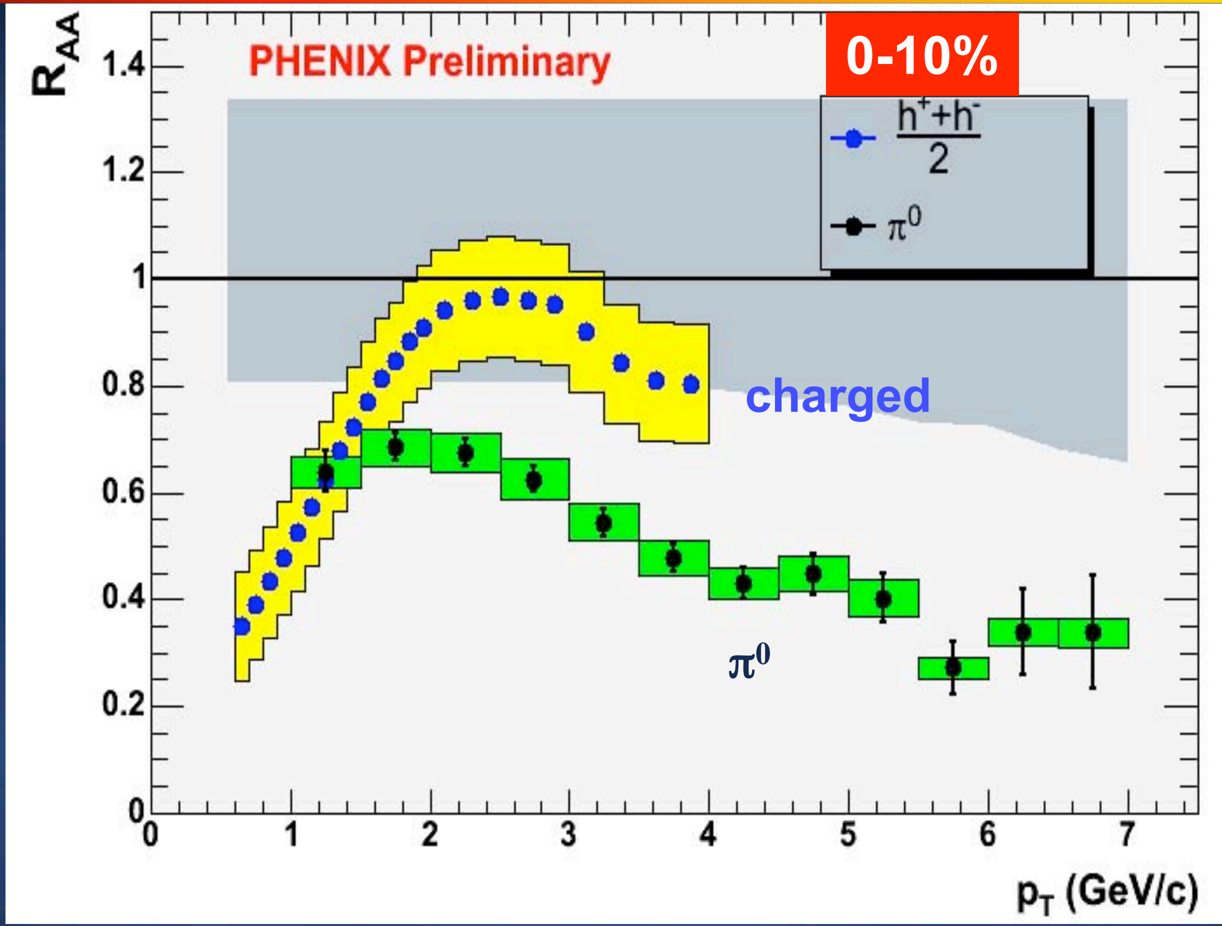
Why 62.4 GeV?

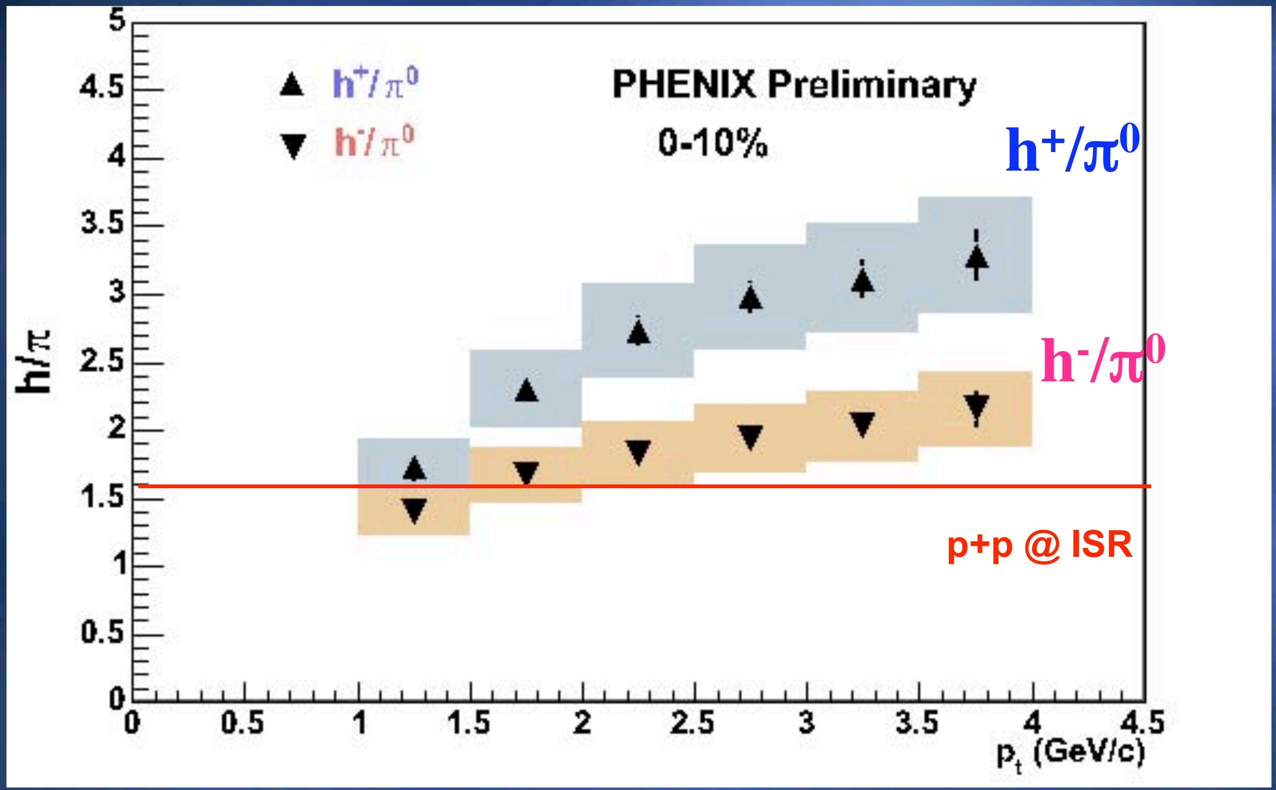
1) Located in the middle between SPS(17GeV) and RHIC top energy (200 GeV) in $\sqrt{s_{NN}}$ (log scale).
2) Many reference data from ISR.
3) Provide a constraint on jet quenching model.
4) Allow to study the excitation function of baryon production/transport, further constrain on various models for hadron production at intermediate p_T.

62.4 GeV R_{AA} : Charged hadron and π^0



- Common reference p+p→charged+X is used, instead of ISR π^0 reference.
- π^0 yield is divided by (charged reference)/1.6.
- **Clear difference between charged and π^0 at intermediate p_T up to 4 GeV/c.**
- Suggests a large proton contribution in this p_T region, as seen in 200 GeV data.

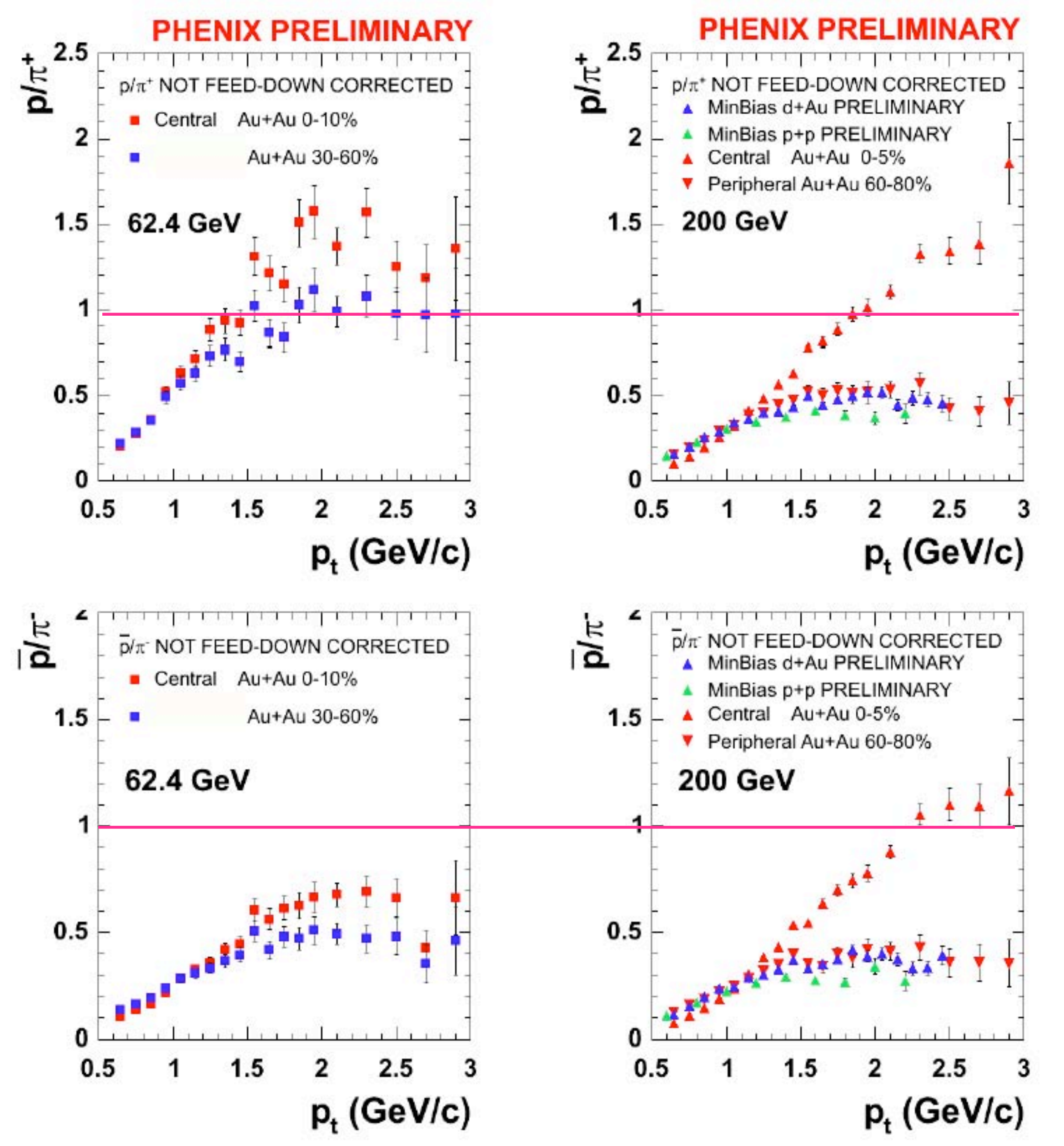
h^+/π^0 and h^-/π^0 ratios @ 62 GeV



- Monotonic increase for both ratios at measured p_T, starting from 1.6.
- **Difference between negative and positive hadron to π^0 ratio.**

p/π^+, pbar/π^- ratios @ 62 GeV

- **Large proton contribution** at intermediate p_T 62.4 GeV.
- **Less antiproton** in central collisions at 62.4 GeV than 130/200 GeV.
- **Indicating more baryon transport and less p-pbar pair production at 62 GeV than 200 GeV.**
- The 62 GeV p_T spectra will tell us more about the excitation function of chemical properties, scaling and radial flow at RHIC (stay tuned!).



4. Summary

- Experimental data seems to have a better agreement with a recombination model with thermal-hard parton interactions.
- Important difference between Hydro+Jet and recombination model is the origin of flow, i.e. partonic flow or hadronic flow?
- Discriminatory measurements are essential to understand the hadron production at intermediate p_T.
  - High statistics identified trigger particle correlations.
  - v_2 for ϕ meson.
  - Charm: v_2 and R_{cp} for D meson, J/ψ.
  - Hadron PID (especially baryons) at higher p_T up to 10 GeV/c to study the fragmentation region at RHIC.

High p_T PID Upgrade

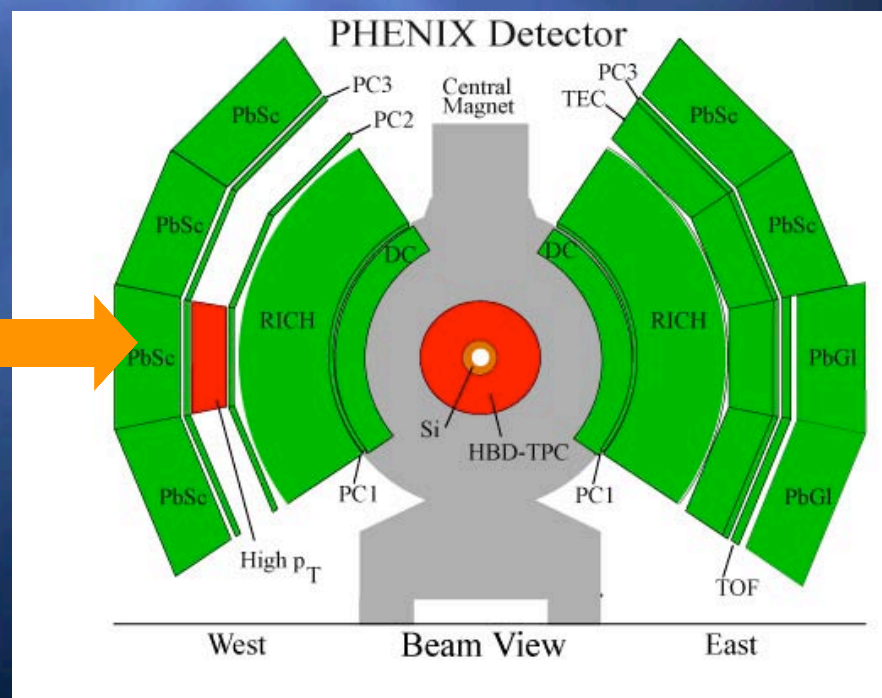
		Pion-Kaon separation	Kaon-Proton separation
TOF	σ~100 ps	0 - 2.5	- 5
RICH	n=1.00044 γth~34	5 - 17	17 -
Aerogel	n=1.01 γth~8.5	1 - 5	5 - 9

Aerogel & MRPC-TOF

- Together with the Aerogel, TOF and RICH, we can extend the PID **beyond 5 GeV/c.**
- **Coverage: ~ 4 m^2 in west arm.**

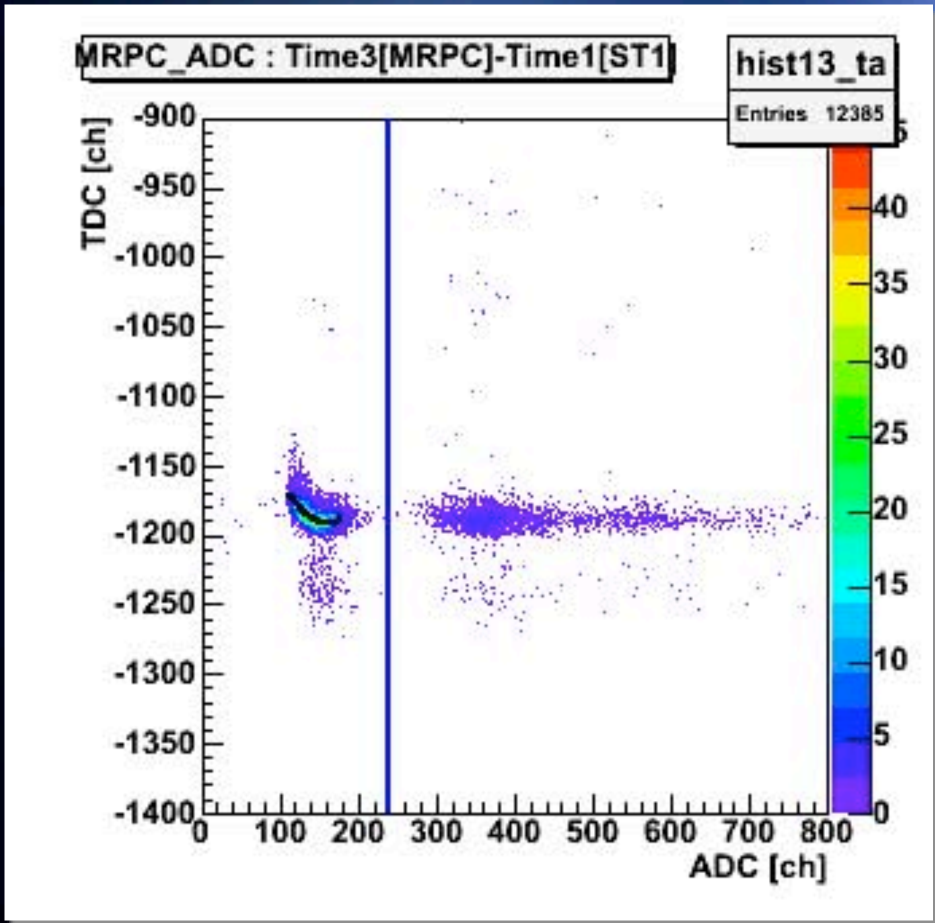
AEROGEL:
- **Full installation for Run5.**

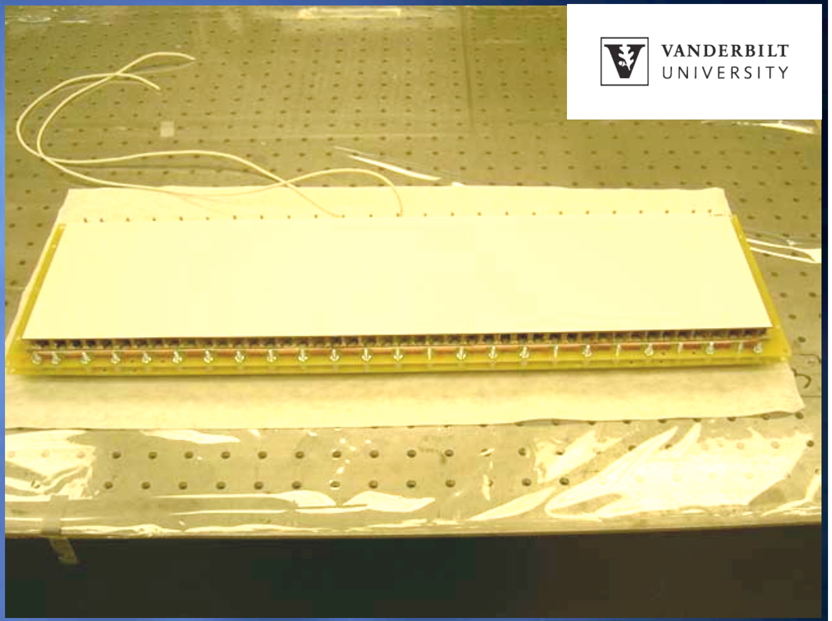
MRPC-TOF:
- **Prototype installation in Run5**
- **Physics run in Run6.**

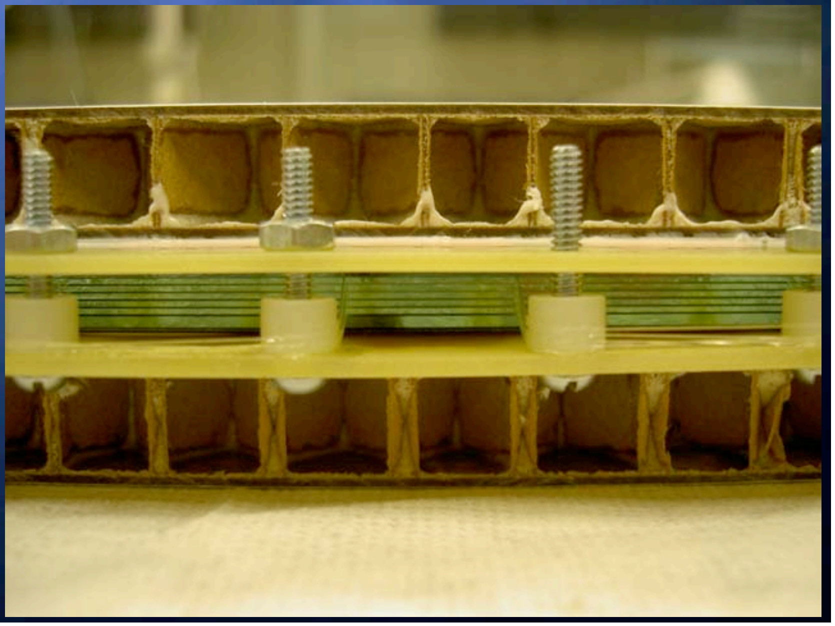


MRPC-TOF Prototype Test

Prototype Test @ KEK (June 1-8, 2004)







TOF resolution: 85 ps achieved.

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12 Countries; 57 Institutions; 460 Participants*

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
LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecòle des Mines at Nantes, Nantes

Germany — University of Münster, Münster

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
University of Tokyo, Bunkyo-ku, Tokyo
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

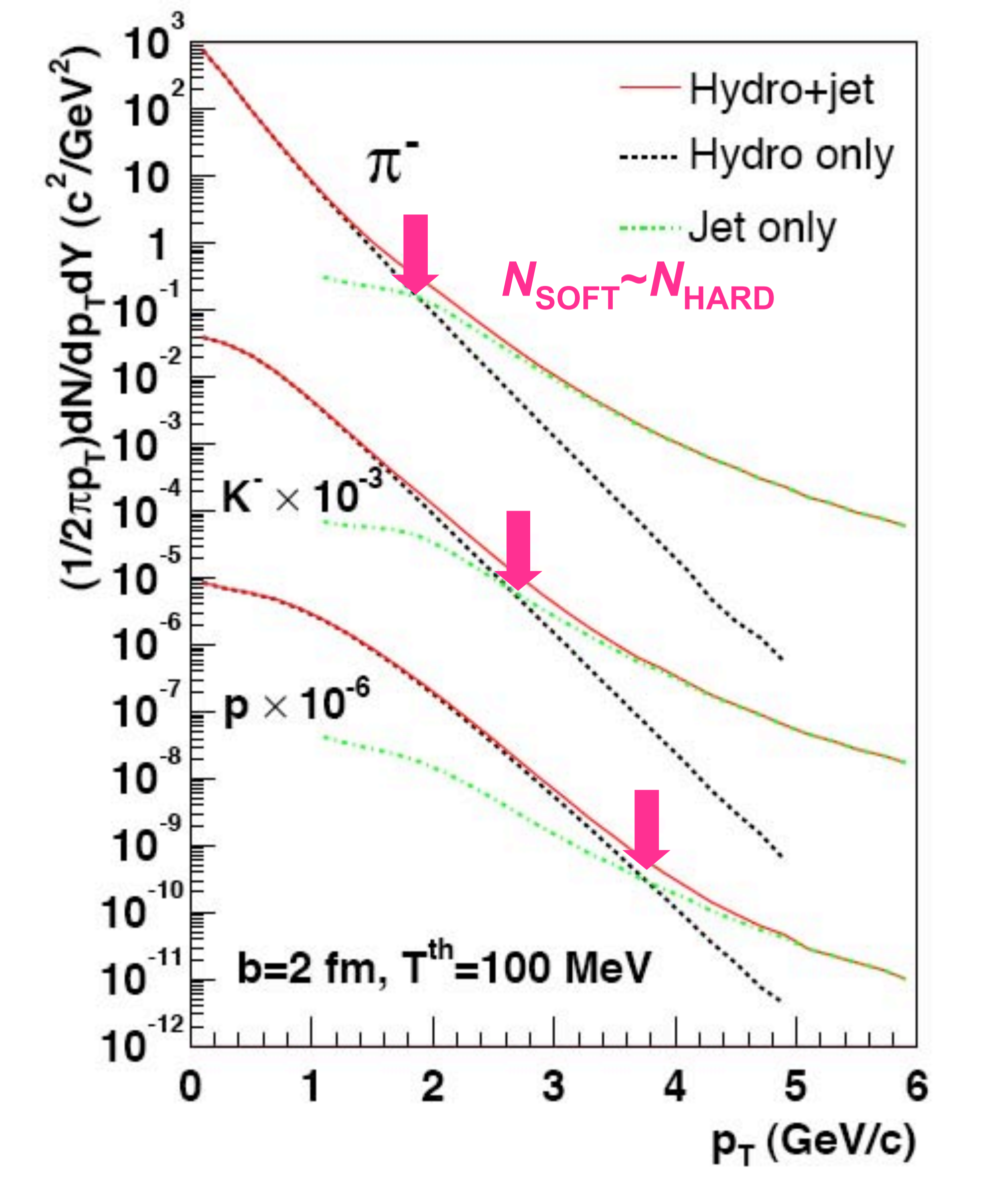
Sweden — Lund University, Lund

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
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
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

*as of July 2002

Backup Slides

Hybrid model: Hydro + Jet



Hirano, Nara (Hydro+Jet model)
- PRC 69, 034908 (2004).
- nucl-th/0404039 (+CGC).

- **3D Hydro calculation.**
- **Required QGP type EOS in order to reproduce p_T spectra and elliptic flow.**
- **Jet quenching included.**
- **Hydro push thermal distribution to higher pT at hadronic stage (mass effect).**

$T=T_c$, $\langle v_T \rangle \sim 0.25c$
$T=100$ MeV, $\langle v_T \rangle \sim 0.55c$

- **Intermediate p_T = 2 - 4 GeV/c**
  - π : hard region
  - p : soft region

$$p_{T,\text{cross}} \sim \begin{array}{l} 1.8 \ \text{GeV}/c \ \text{for} \ \pi \\ 2.7 \ \text{GeV}/c \ \text{for} \ K \\ 3.7 \ \text{GeV}/c \ \text{for} \ p \end{array}$$

Quark Recombination Models

Quarks in a densely populated phase space combine to form the final state hadrons.

1. **Duke model (Fries, Muller, Nonaka, Bass)**
   Exponential thermal quark distribution, fragmentation for high pT (w/ eloss).
   Relative normalization (recombination ↔ fragmentation).
   No gluons in the system.
   Parameterized collective flow developed in the partonic phase (v_T~0.55c at $T=T_c$).

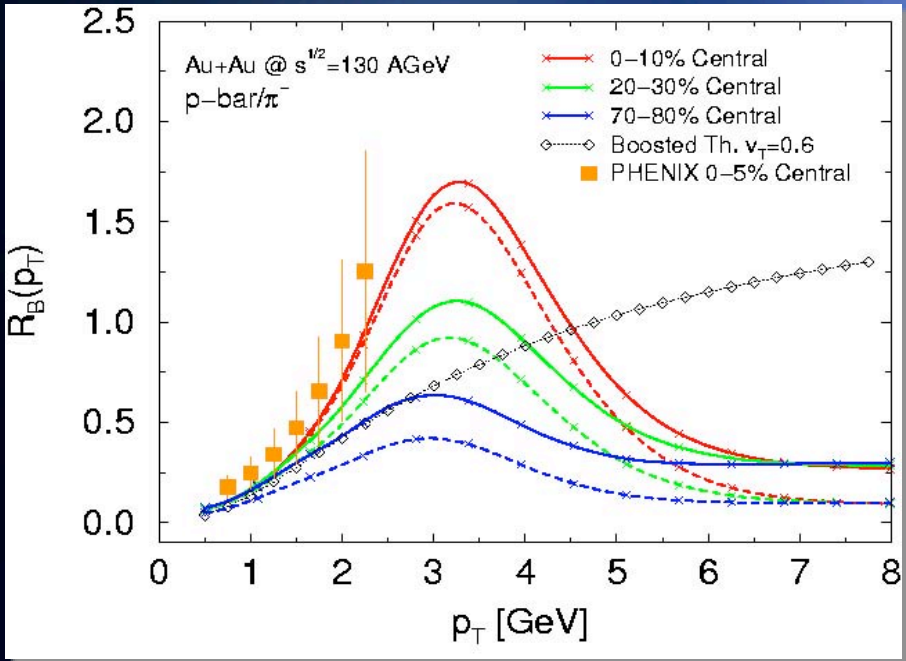
2. **Oregon model (Hwa and Yang)**
   All hadrons arise from recombination (NO fragmentation).
   Hard partons are allowed to fragment into a shower of partons.
   e.g.) thermal-thermal, thermal-shower, shower-shower (for mesons).

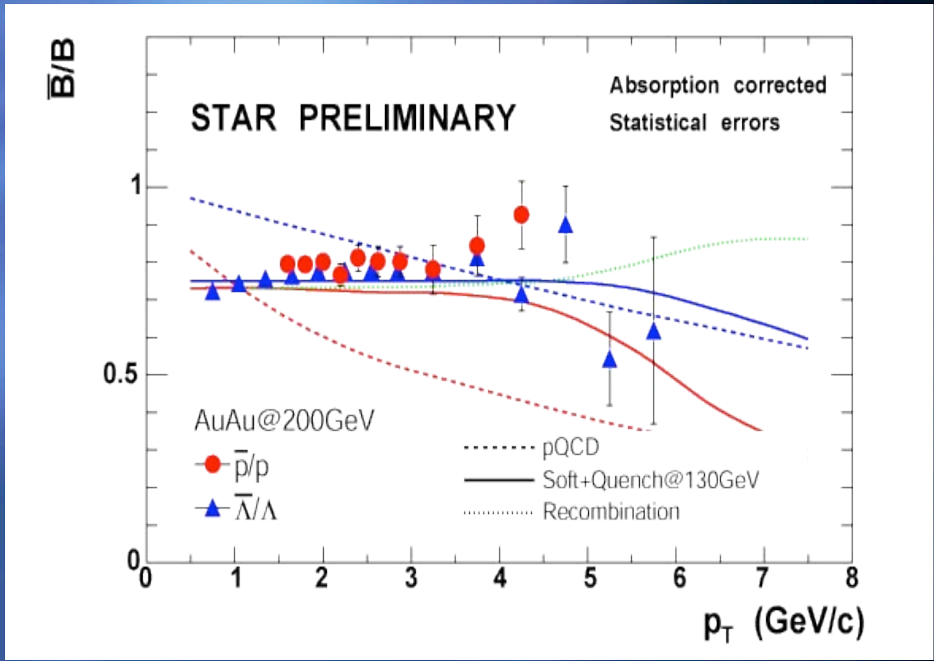
3. **Texas model (Greco, Ko, Levai)**
   Allow recombination of hard partons with thermal partons by Monte-Carlo.
   Taking into account decays (e.g. $\rho \rightarrow 2\pi$) which produces low pt pions.

Recombination Model References

- **Duke Model**
  - R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, PRL 90, 202303 (2003).
  - R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, PRC 68, 044902 (2003).
- **Oregon Model**
  - R.C. Hwa, C.B. Yang, PRC 67, 034902 (2003).
  - R.C. Hwa, C.B. Yang, nucl-th/0401001.
- **TAMU Model**
  - V. Greco, C.M. Ko, P. Levai, PRL 90, 202302 (2003).
  - V. Greco, C.M. Ko, RPC 68, 034904 (2003).

Another Scenarios...





- *pQCD does not reproduce Bbar/B vs. p_T.*
- *Baryon Junction Mechanism ?* (Vitev, Gyulassy PRC 65, 041902, 2002)
- Different formation time between baryons and mesons ?

ϕ R_{cp} by STAR