Strong Parton-Dense Medium Interactions at RHIC

Paul Stankus

Oak Ridge National Lab

JLab Hall C Summer Workshop

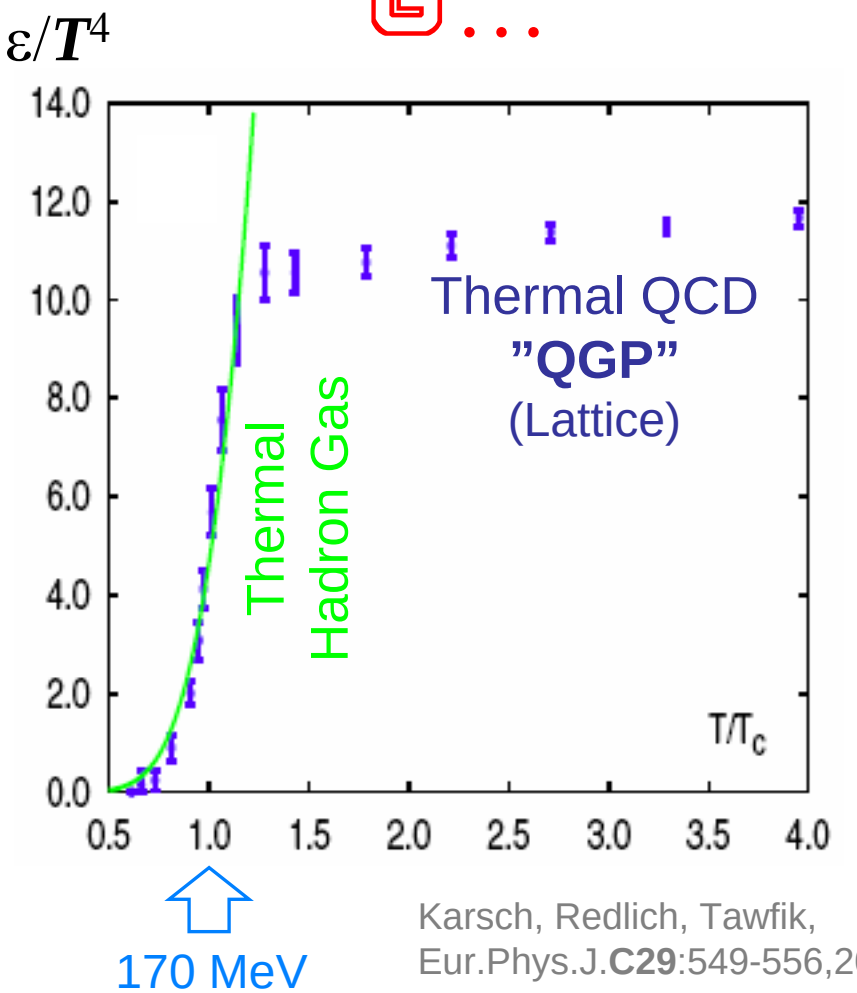
Aug 25, 2006

THERMAL QCD

What is it?

And where can I get some?

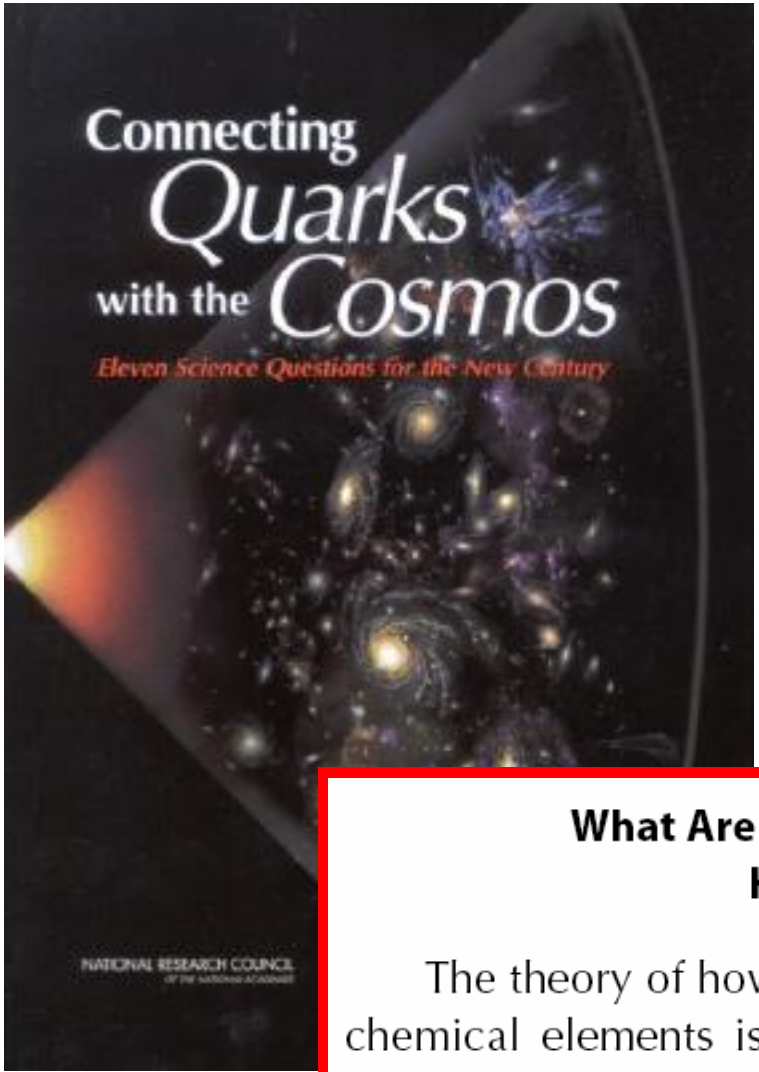
IN THE BEGINNING...



Karsch, Redlich, Tawfik, Eur.Phys.J.**C29**:549-556,2003

"In 1972 the early universe seemed hopelessly opaque…conditions of ultrahigh temperatures…produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly…" Frank Wilczek, Nobel Lecture (RMP 05)

"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma." David Gross, Nobel Lecture (RMP 05)



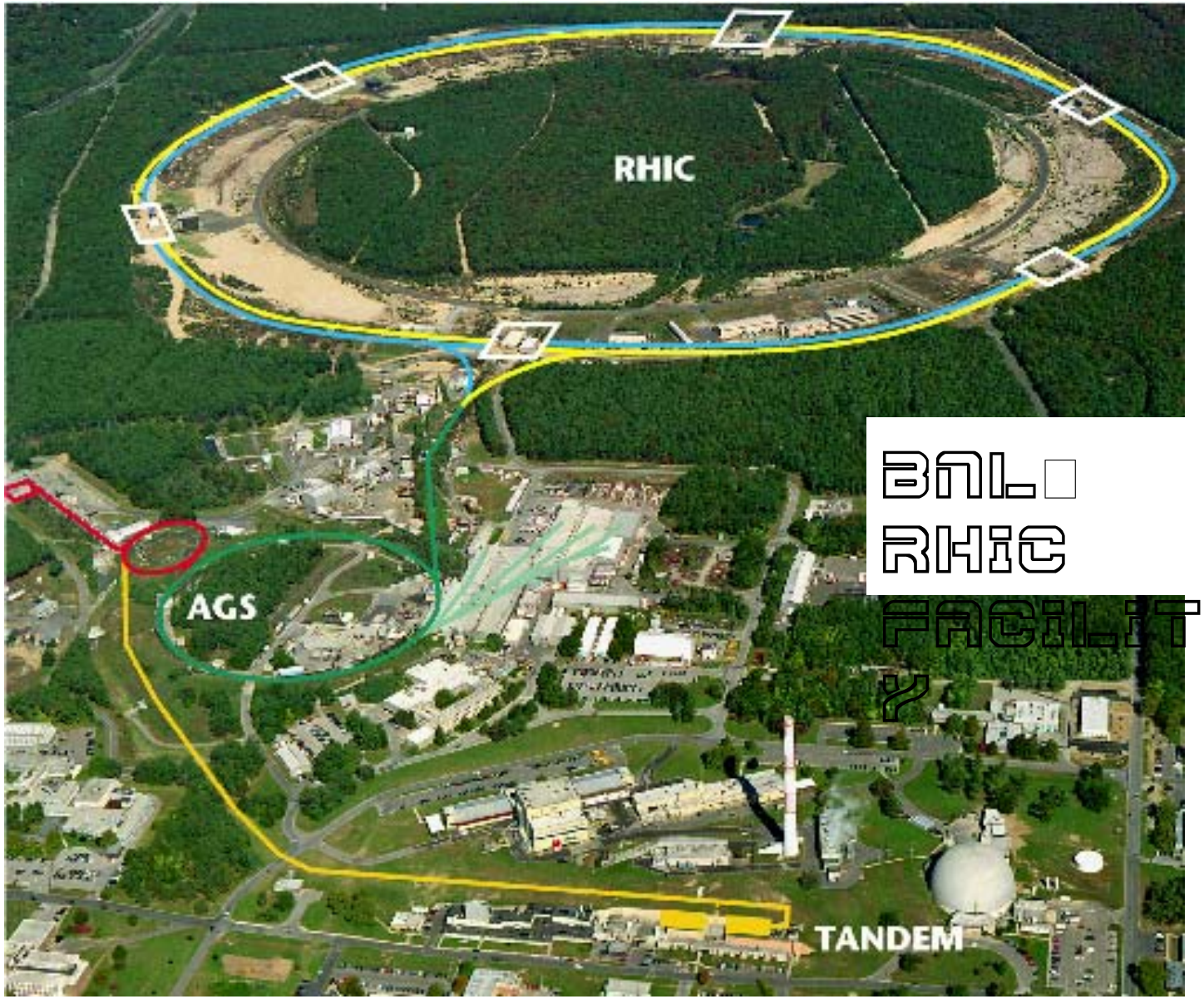
NATIONAL RESEARCH COUNCIL REPORT

ELEVEN SCIENCE QUESTIONS FOR THE NEW CENTURY

What Are the New States of Matter at Exceedingly High Density and Temperature?

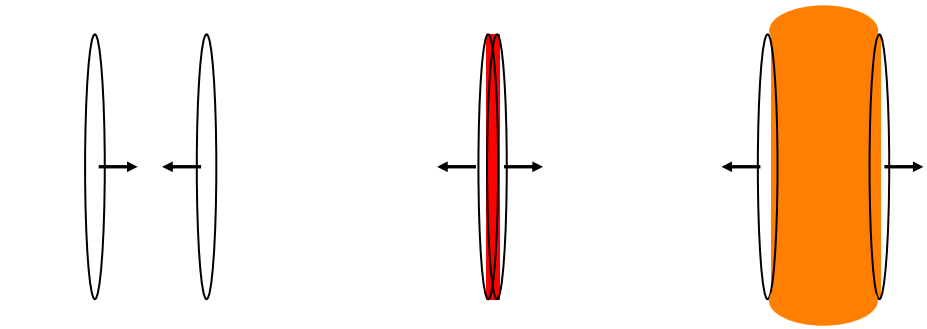
QUESTION □ IS:

The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may dissolve into an undifferentiated soup of quarks and gluons, which can be probed in heavy-ion accelerators. Densities beyond nuclear densities occur and can be probed in neutron stars, and still higher densities and temperatures existed in the early universe.

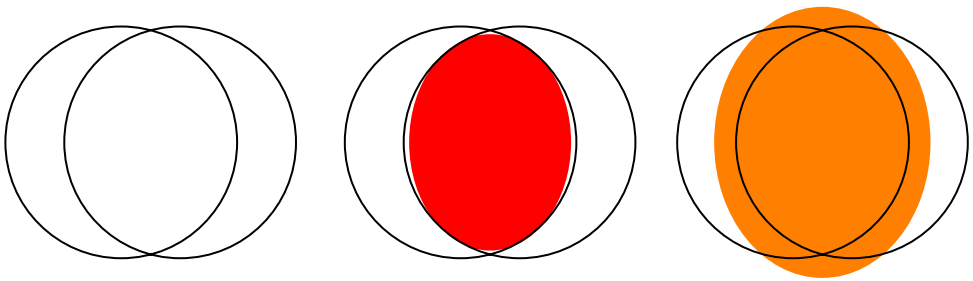


Also: BNL-AGS, CERN-SPS, CERN-LHC

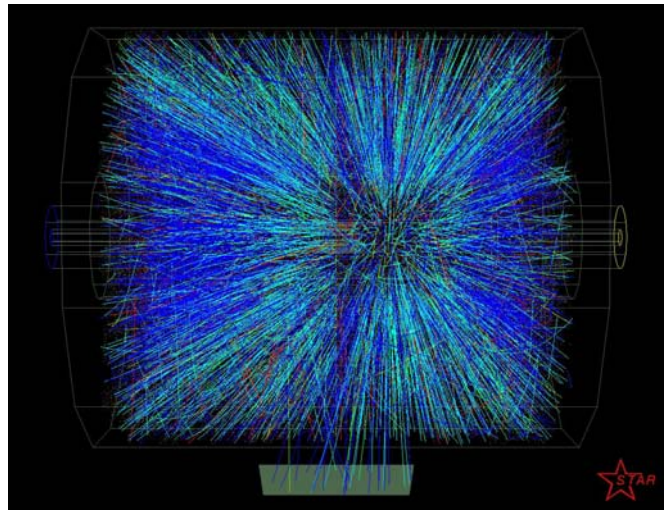
Side-to-Beam View

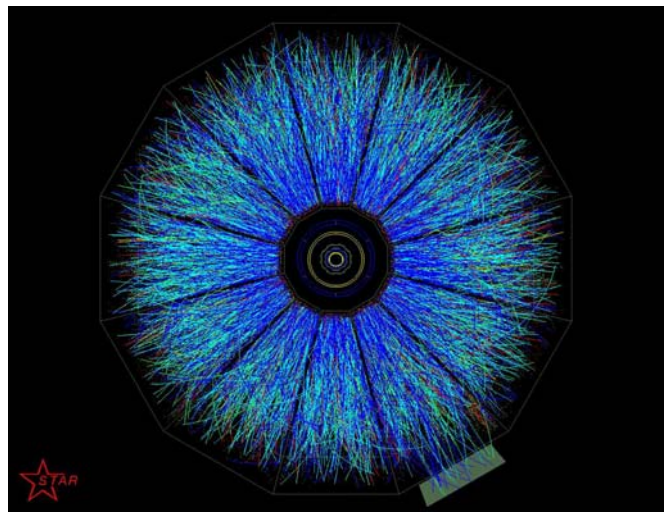


Along the Beam View

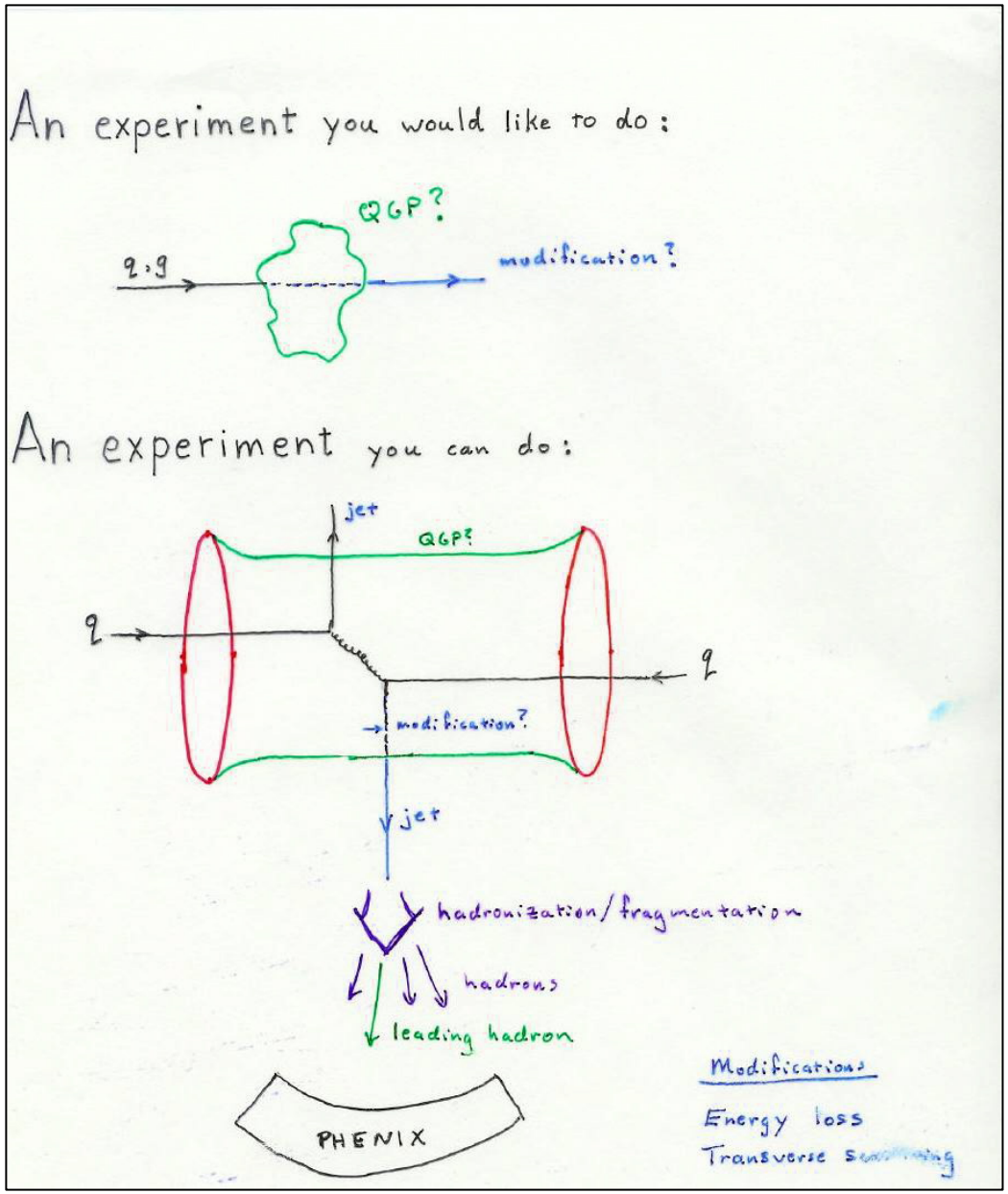


STAR Experiment at RHIC



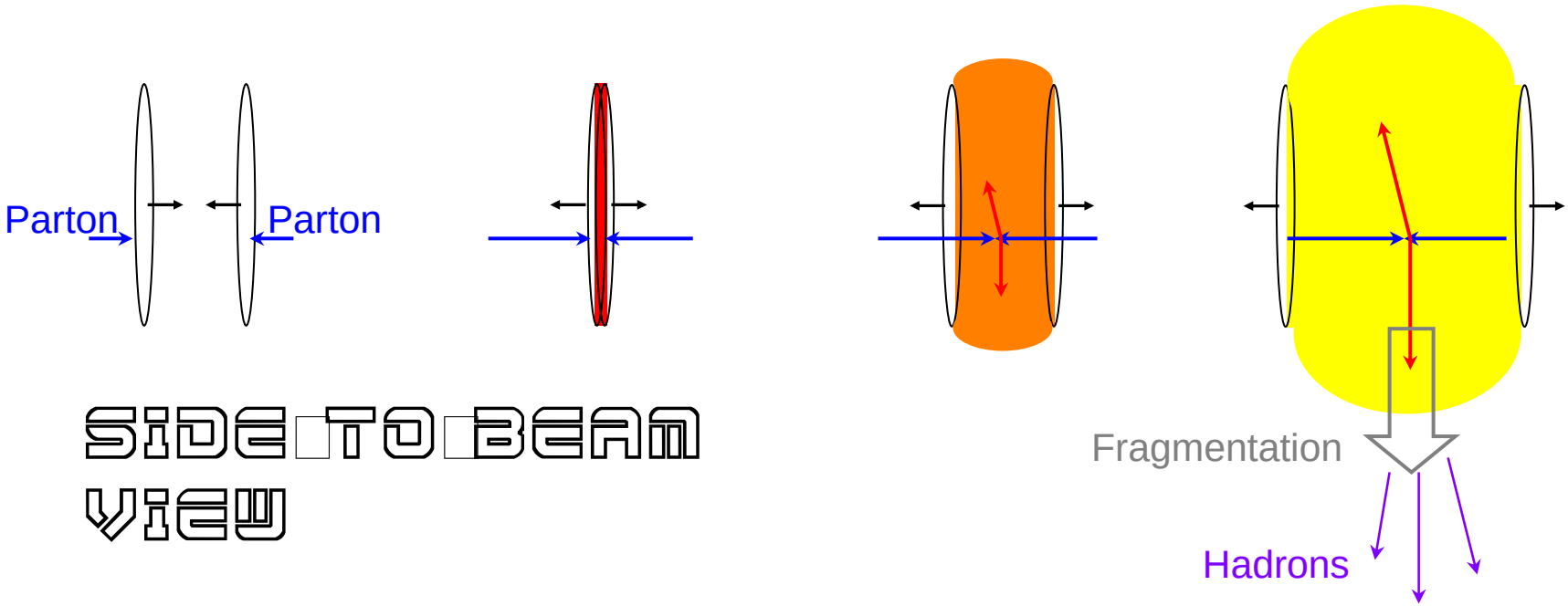


Au-Au at $\sqrt{s_{nn}}$ = 200 GeV

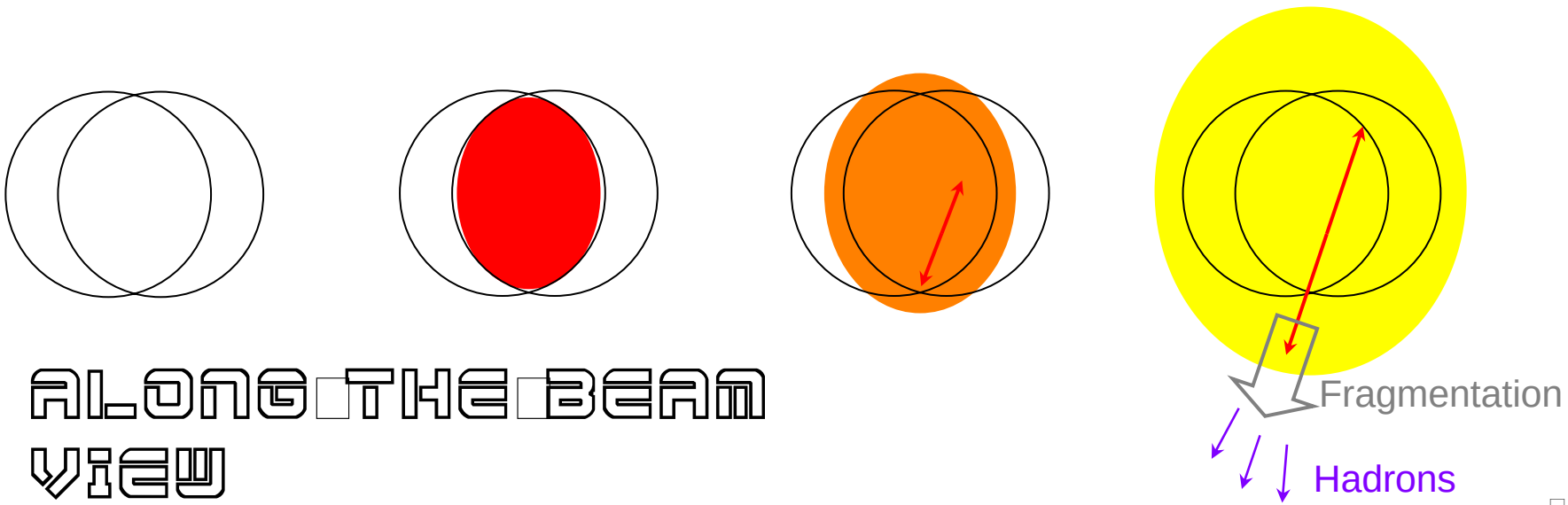


Early hand-drawn version of a now-ubiquitous cartoon

FIRST SHOWN IN



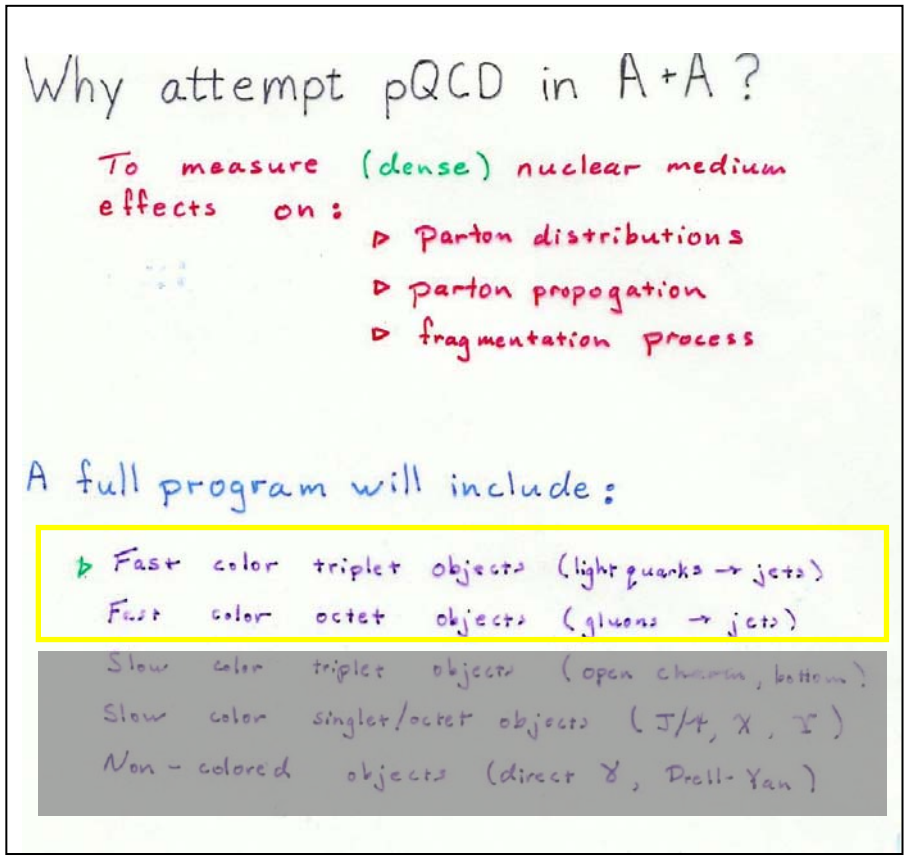
Side to beam view



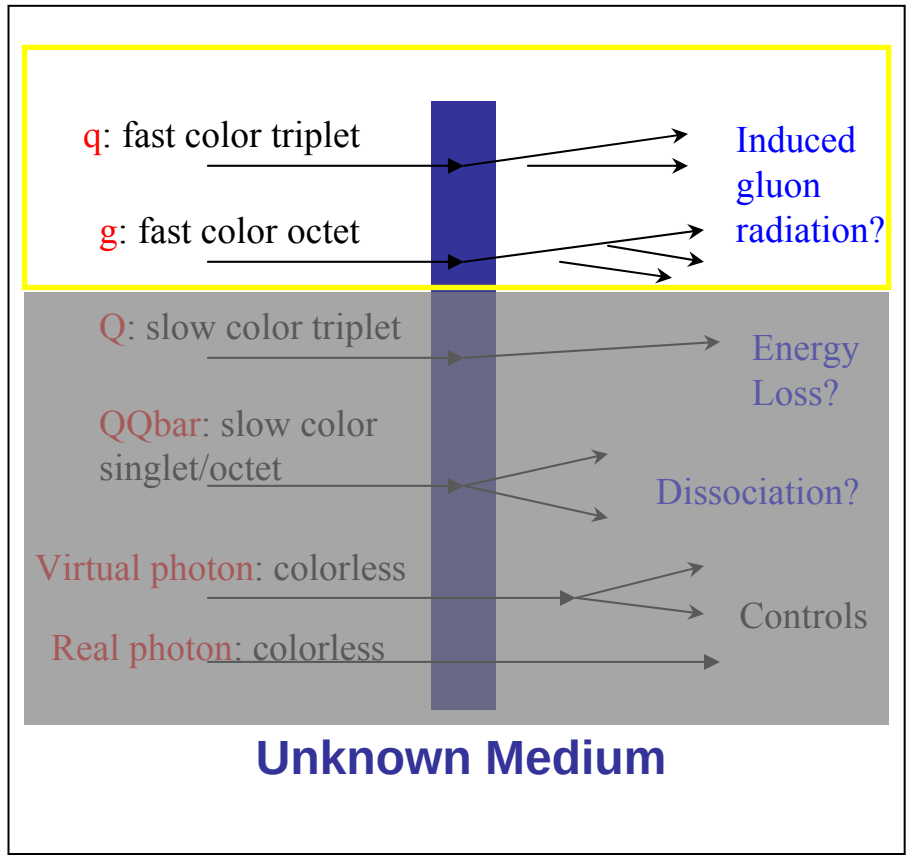
Along the beam view

A PALLET OF PROMPT PROBES

The **most general** way to classify QCD probes is by speed and color multiplet; different combinations give rise to different classes of high-Q^2 observables:



Version 1997



Version 2003

Today's talk

HIGH p_T SINGLE HADRONS

Binary Collision Scaling

How many outcomes from one bunch crossing at a p+p collider?

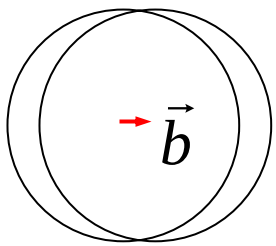
$$\frac{dN^{\text{Bunch+Bunch}}}{dp_T} = \frac{d\sigma^{\text{p+p}}}{dp_T} \int_{\text{Single Crossing}} L$$

Assume we can treat a nuclear collision just like a p+p bunch crossing:

$$\frac{dN^{A+A}}{dp_T} = \frac{d\sigma^{\text{p+p}}}{dp_T} \int_{\text{Single A+A}} L(\vec{b}) = \frac{dN^{\text{p+p}}}{dp_T} \underbrace{\sigma^{\text{p+p}}_{\text{Inelas}} \int_{\text{Single A+A}} L(\vec{b})}_{\text{Number of p+p collsions}} = \frac{dN^{\text{p+p}}}{dp_T} \left\langle N_{\text{Binary}} \right\rangle_{\vec{b}}$$

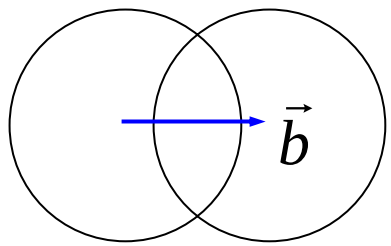
$$R_{\text{AA}} \equiv \frac{\dfrac{dN^{A+A}}{dp_T}}{\dfrac{dN^{\text{p+p}}}{dp_T} \left\langle N_{\text{Binary}} \right\rangle_{\vec{b}}}$$

Null Observable



Central e.g. 0-10%

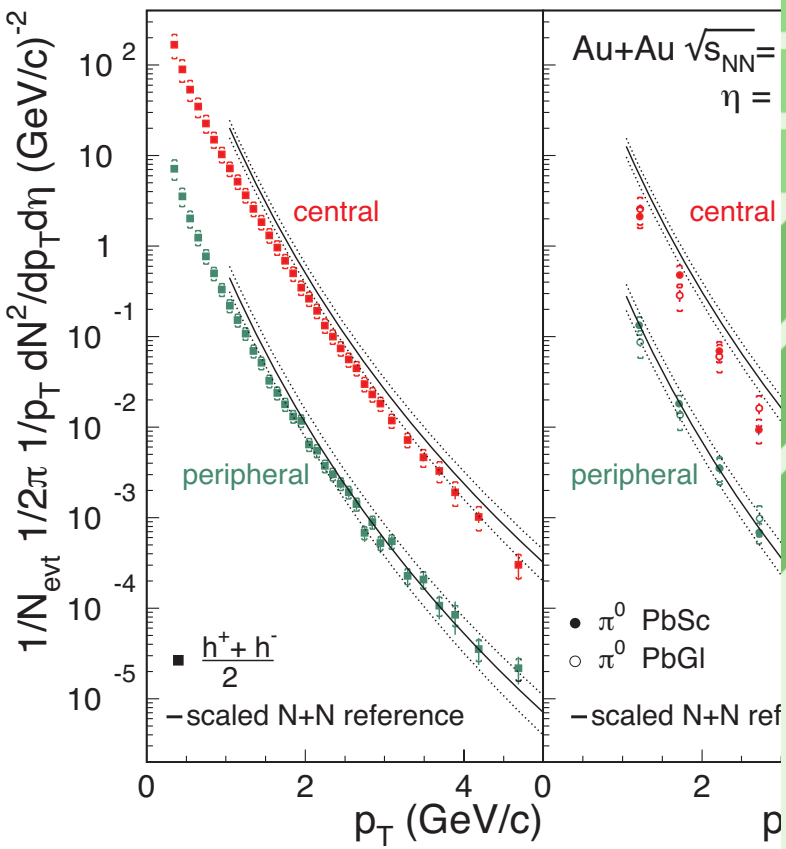
$\langle N_{\text{Binary}} \rangle \sim 900$



Peripheral 60-95%

$\langle N_{\text{Binary}} \rangle \sim 10$

Discovery of "Jet Quenching"

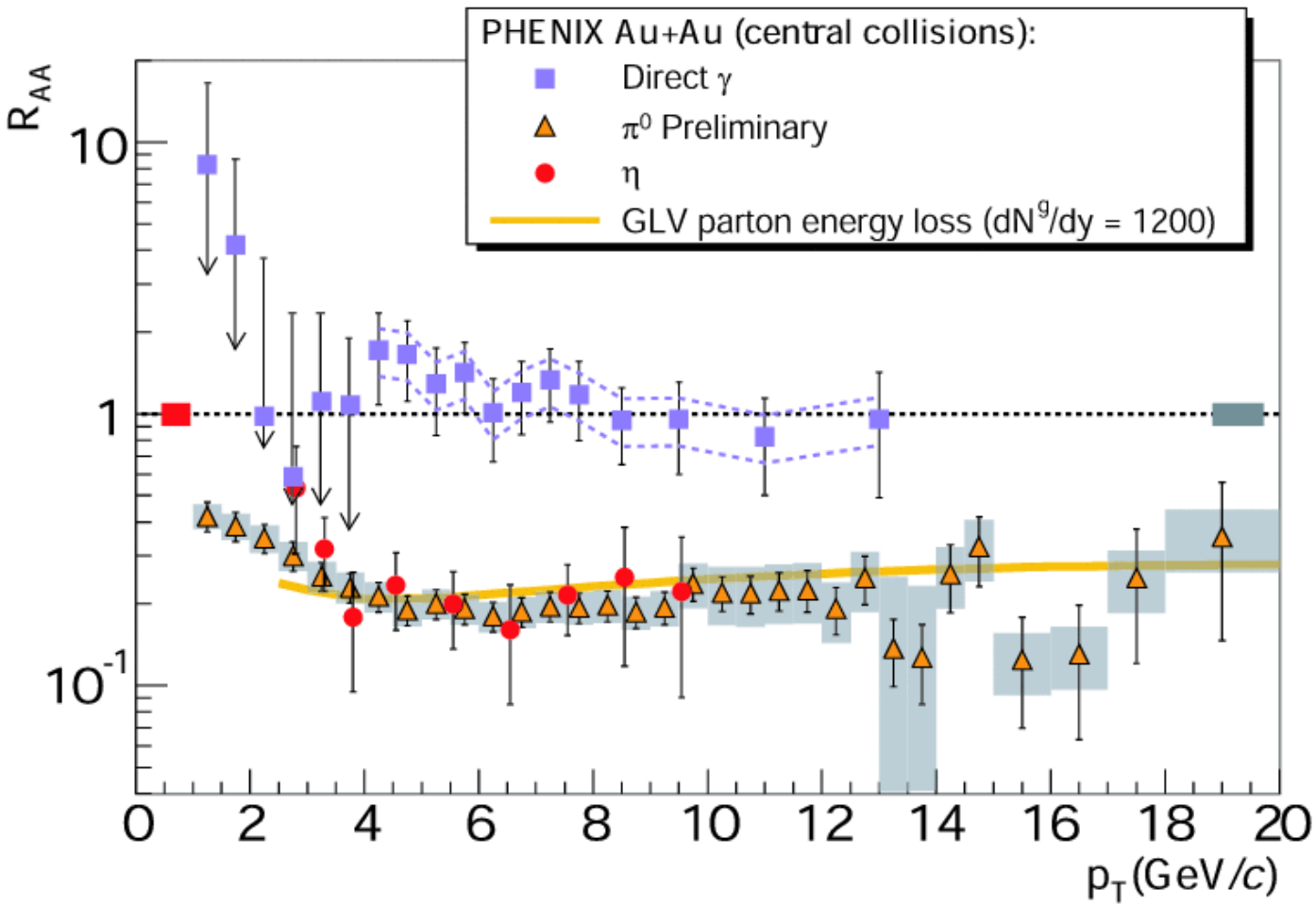


PHENIX PRL88, 02301 (2002)

Direct Photons: Mesons at *Very* High p_T

Direct photons show *no* effect, as expected; confirms binary scaling logic.

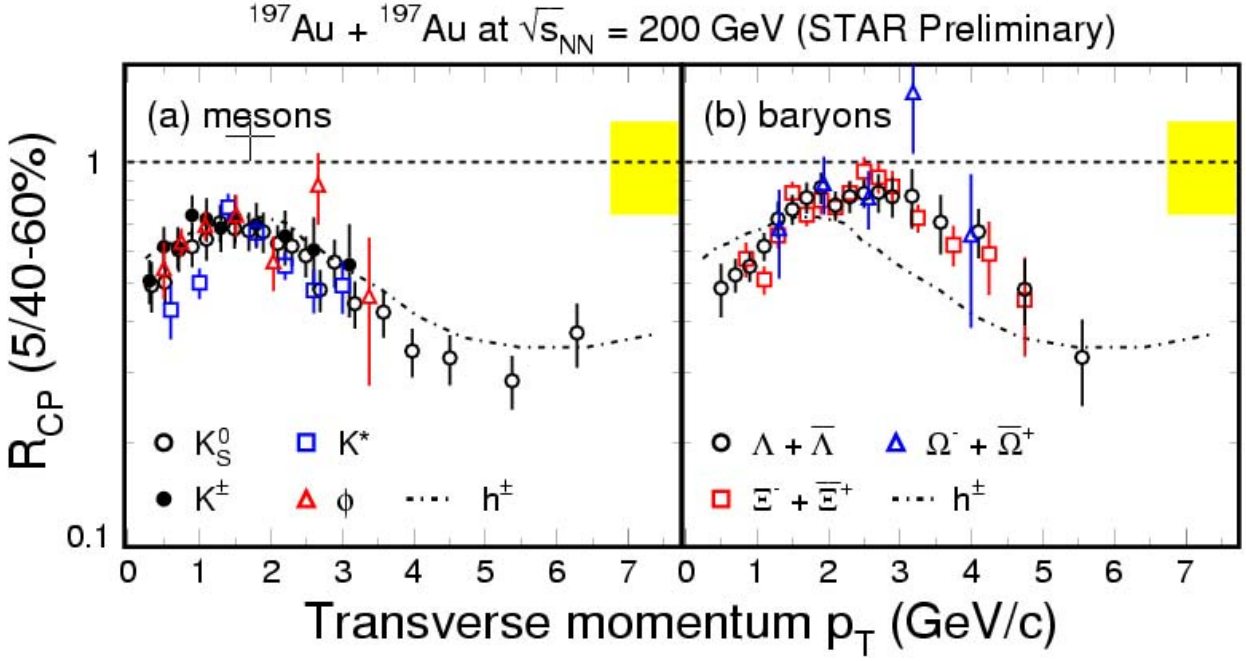
Meson suppression continues out to highest measurable momenta.

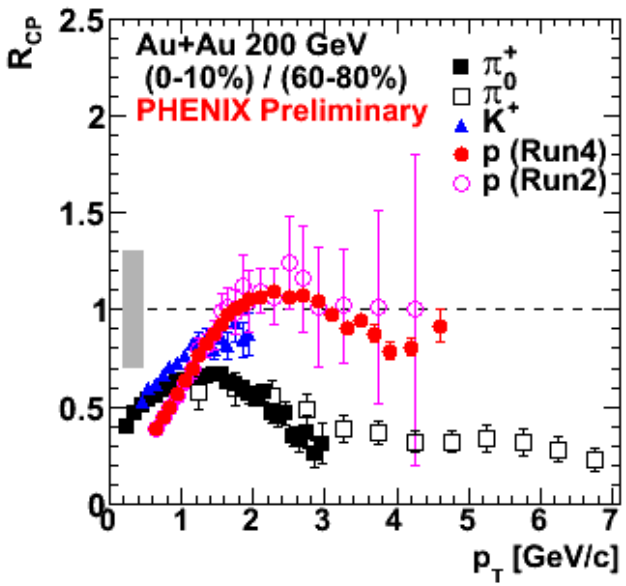


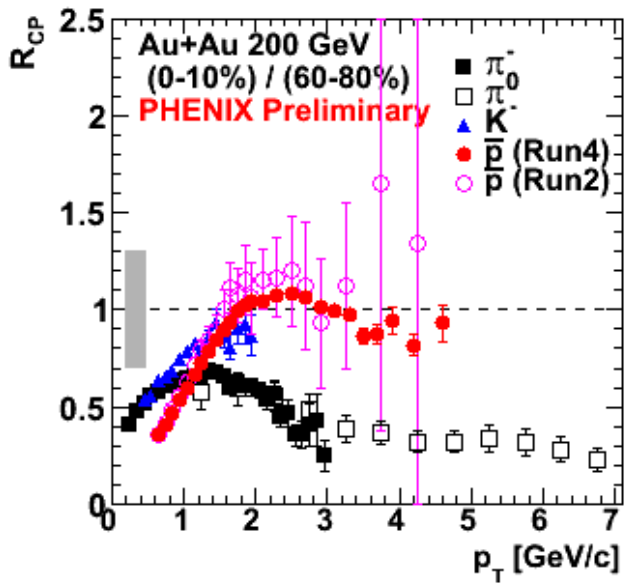
Baryons vs Mesons

Markedly different suppression patterns! below ~6 GeV/c.

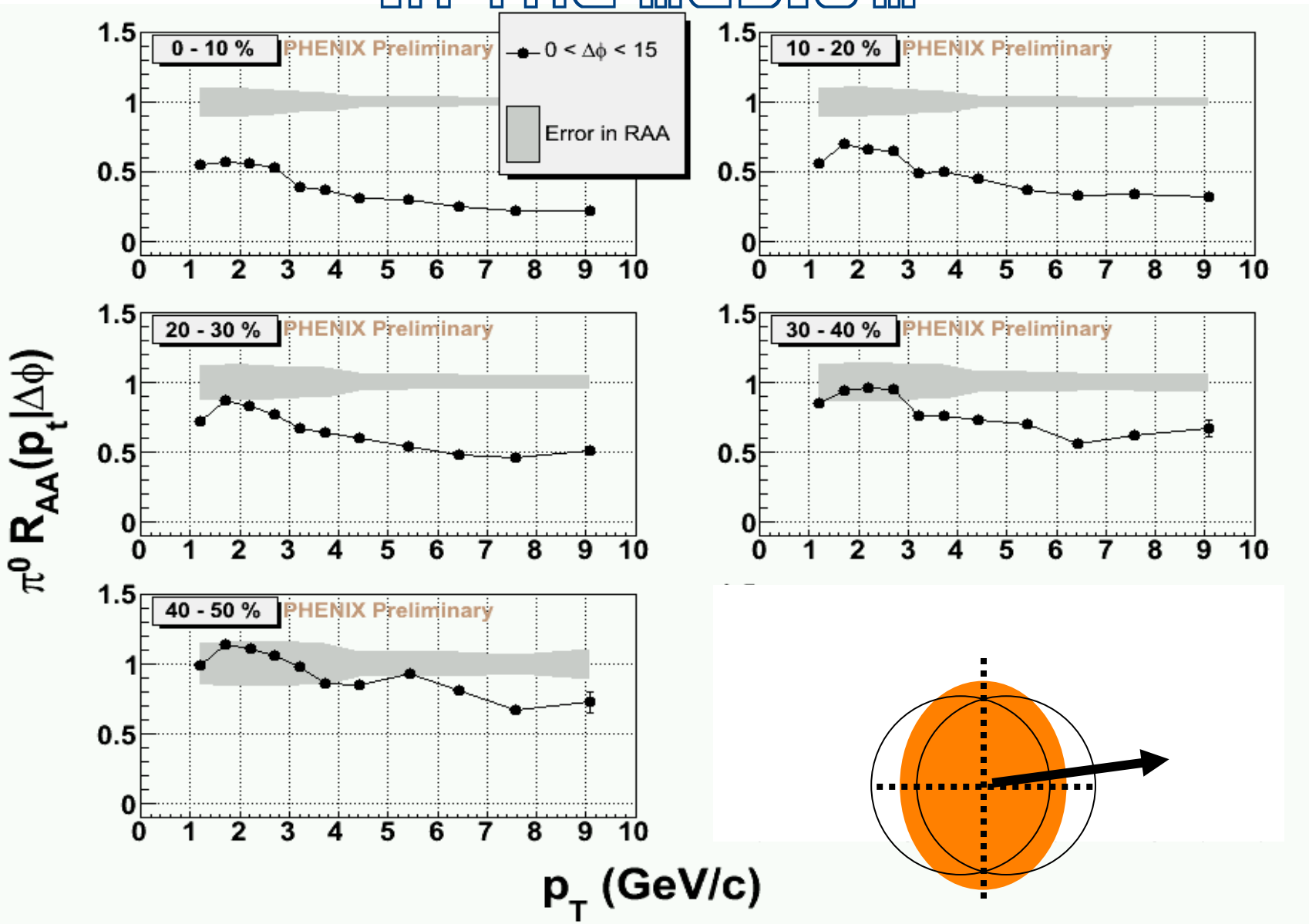
Large change in M/B ratio; change in hadronization process?



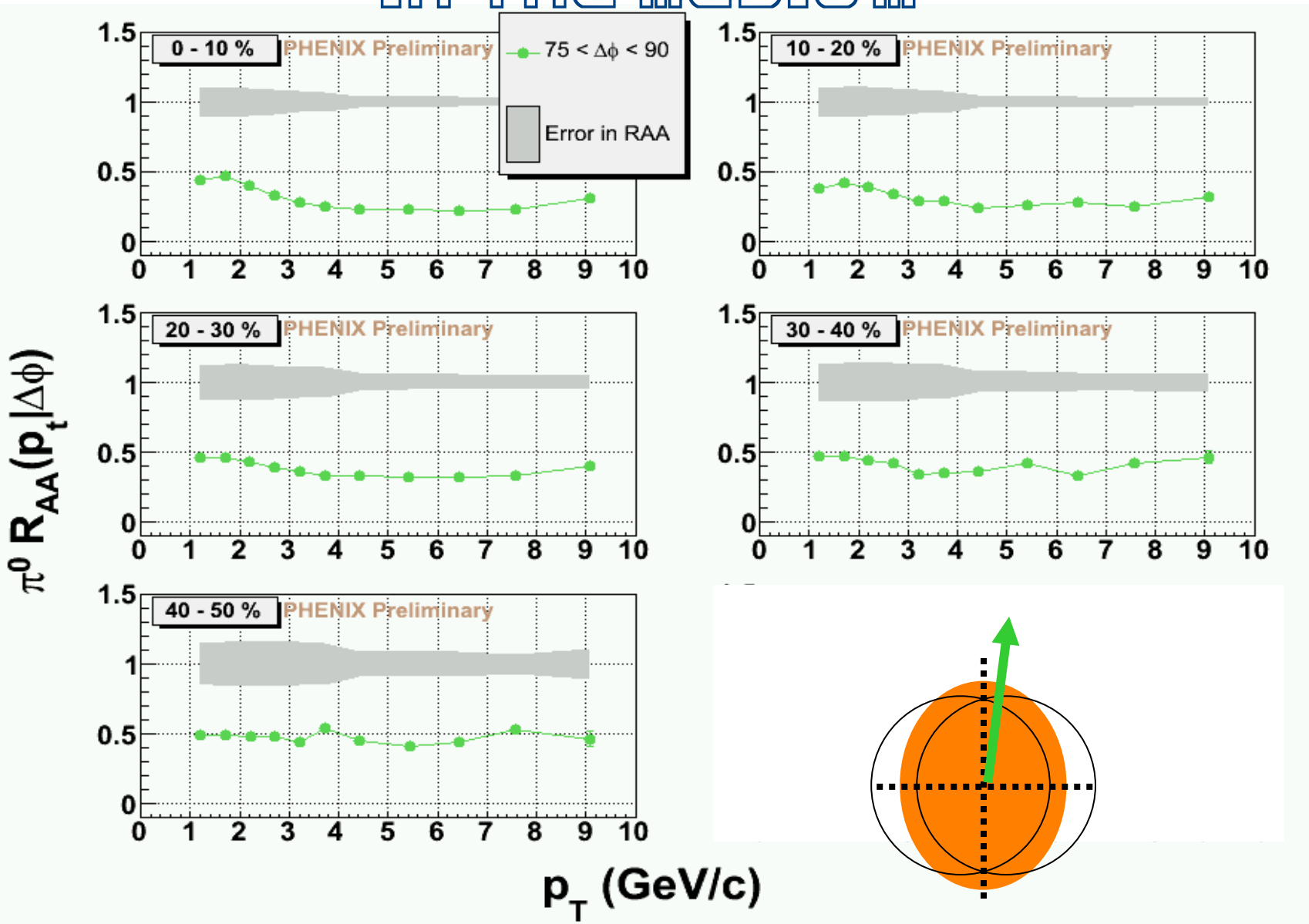




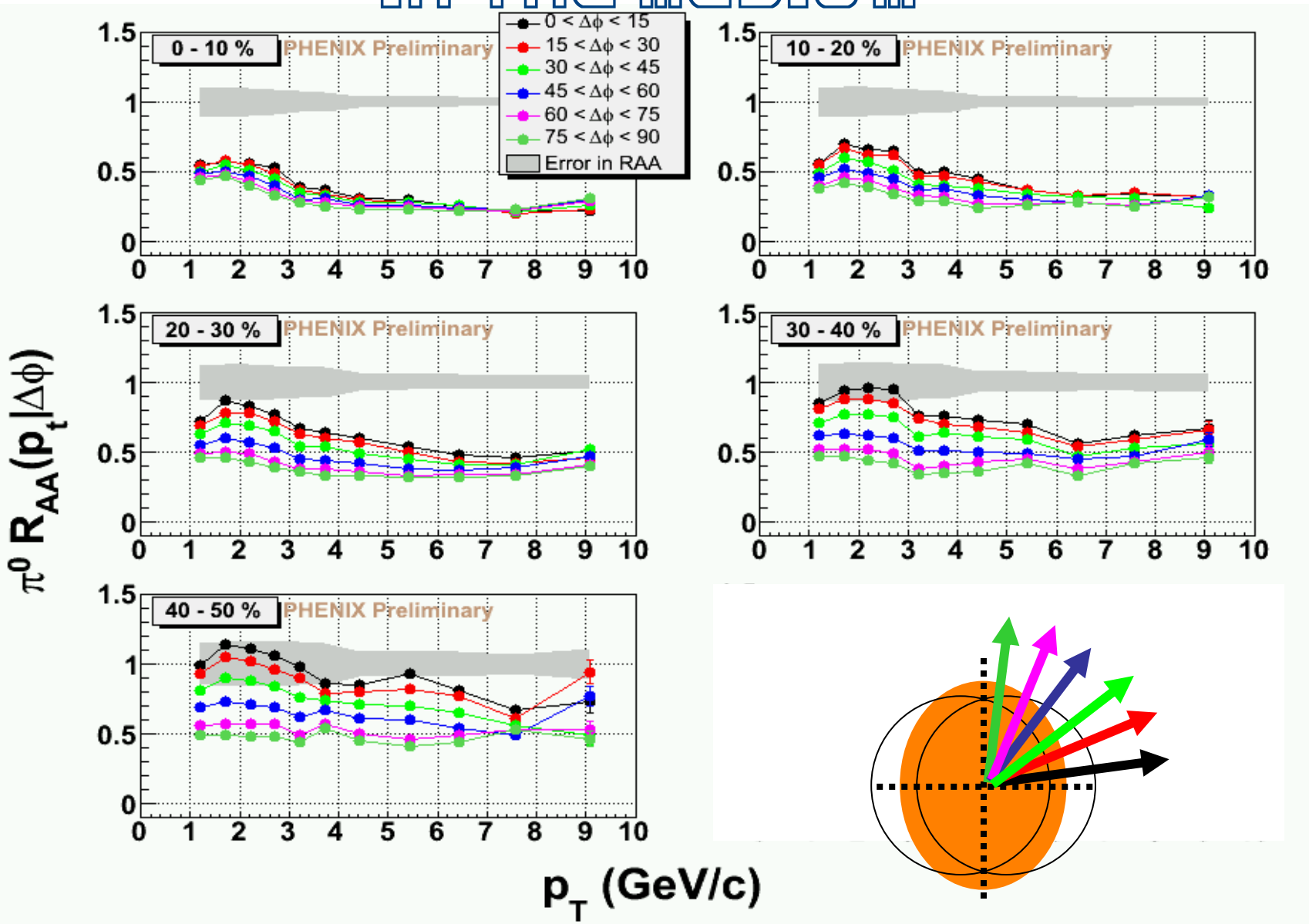
Dependence on path length in the medium



Dependence on path length in the medium



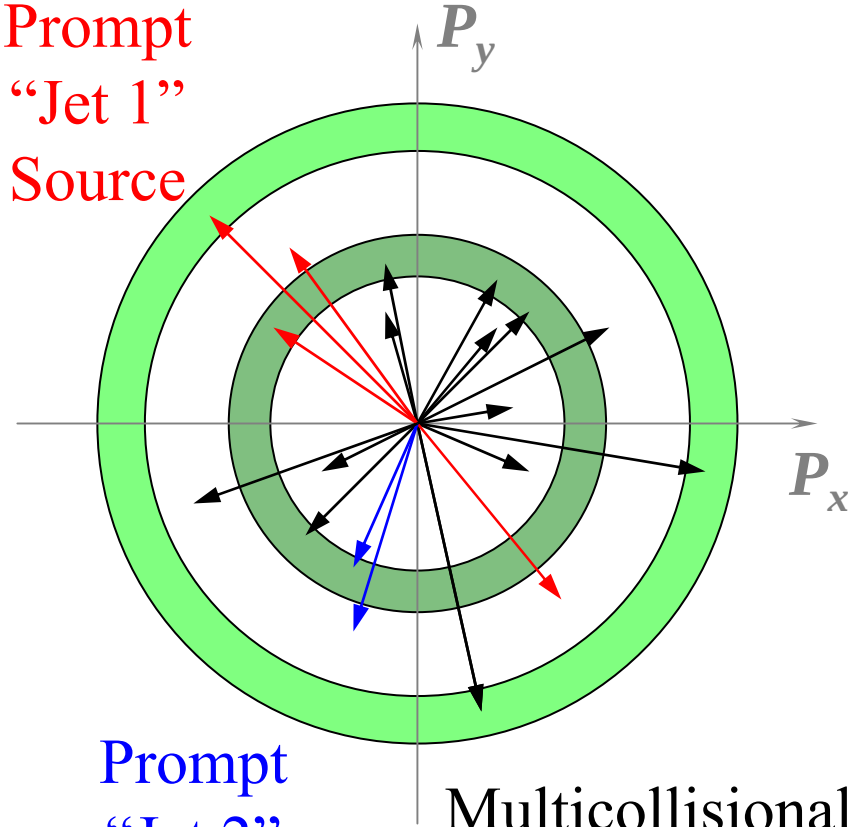
Dependence on path length in the medium



HIGH p_T HADRON PAIRS

COUNTING PAIRS

Prompt "Jet 1" Source

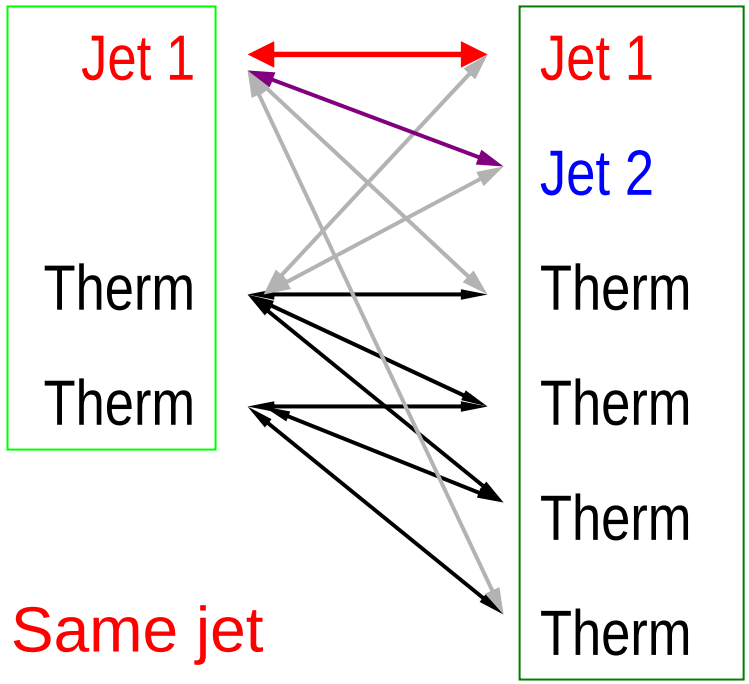


Prompt "Jet 2" Source

Multicollisional/ Hydrodynamic/ "Thermal" Source

Particles A from high-p_T "Trigger" bin

Particles B from low-p_T "Partner" bin

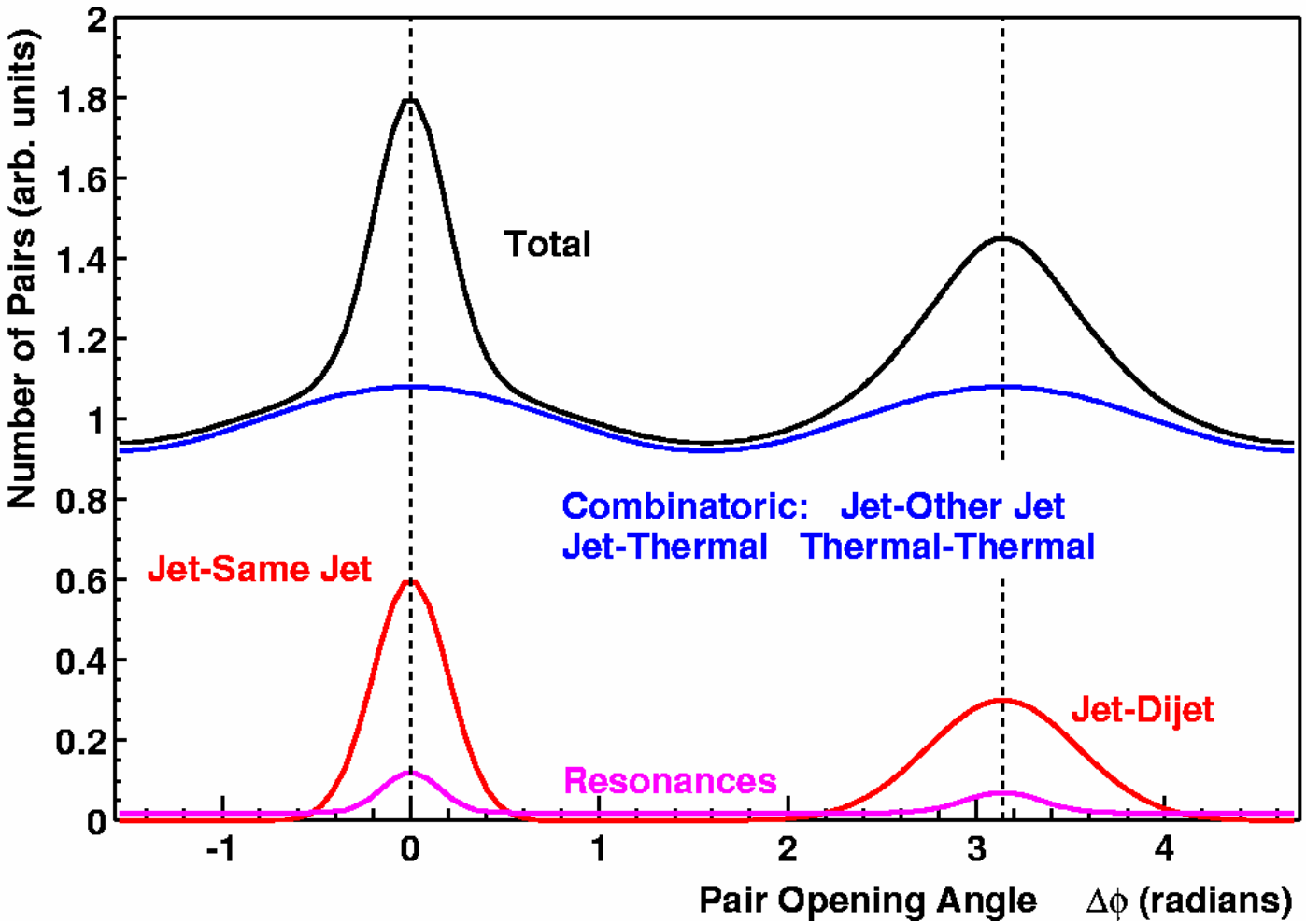


Same jet

Unrelated jets

Jet-Thermal

Thermal-Thermal



PARTICL
TYPE
TRIGGER
P_T

H± □□H±

C: □□□□□

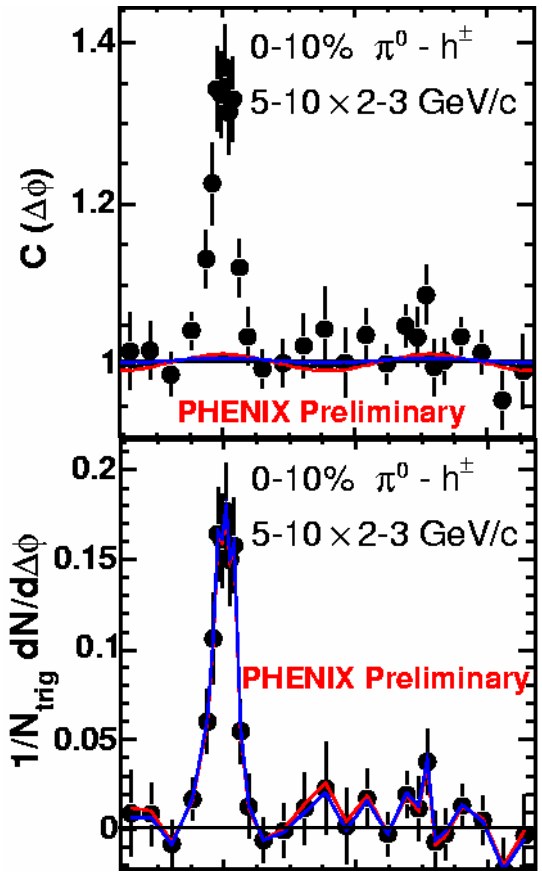
T: □□□
GEV

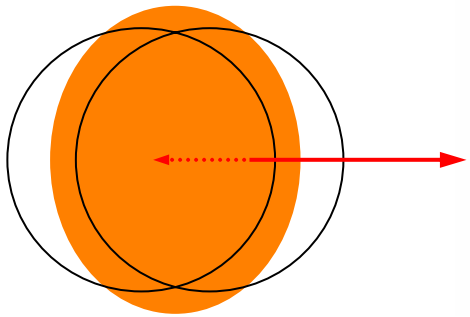
P: □□□
GEV

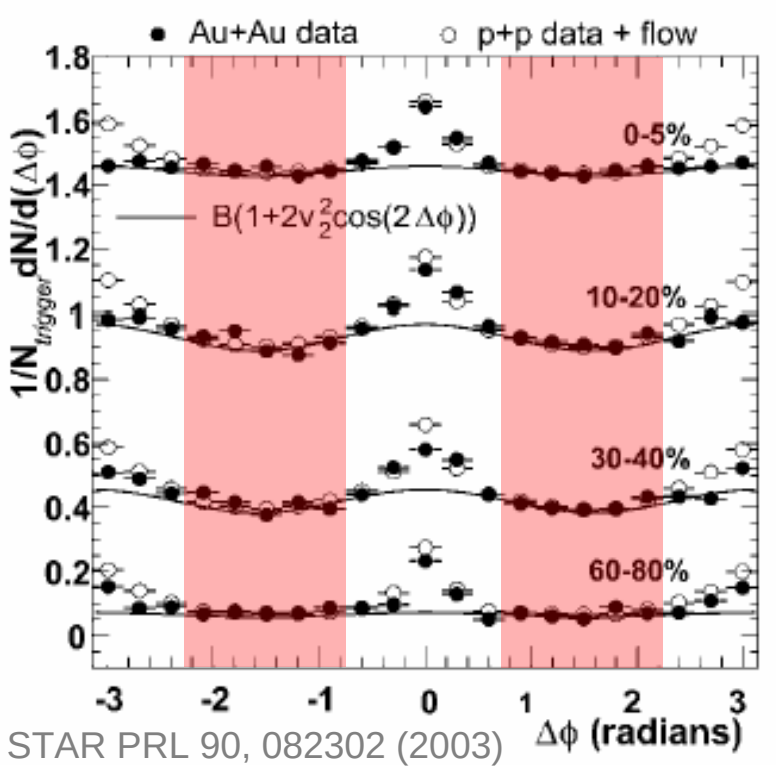
EVENT
CENTRALIT
PARTNER
P_T

□□

Away-side disappearance

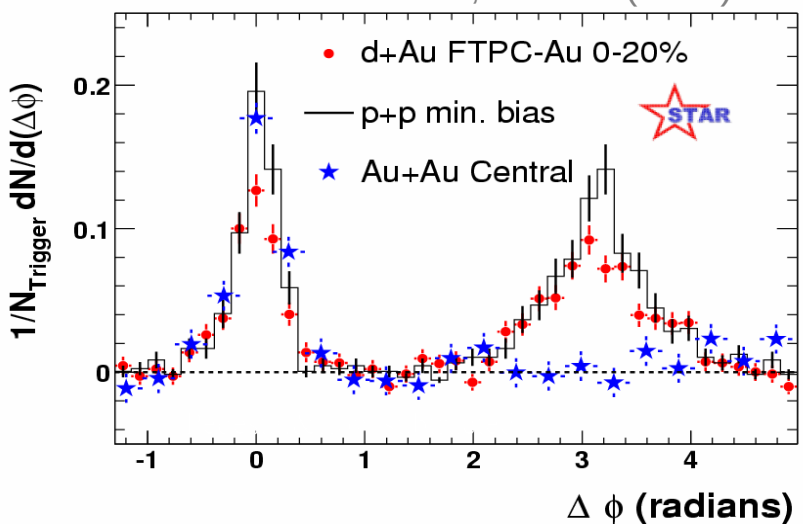






STAR PRL 90, 082302 (2003)

STAR PRL 91, 072304 (2003)

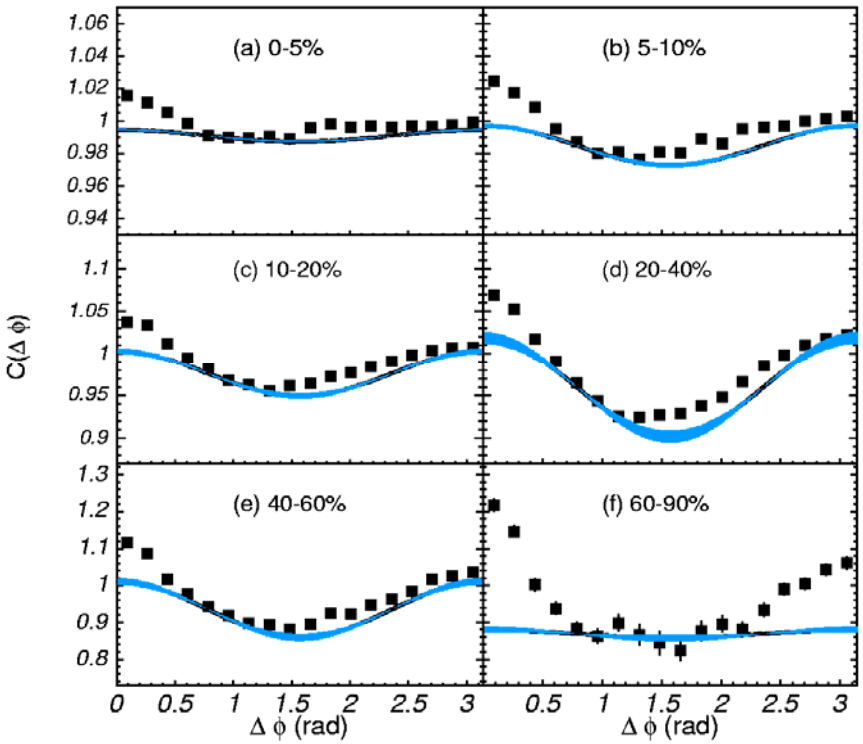


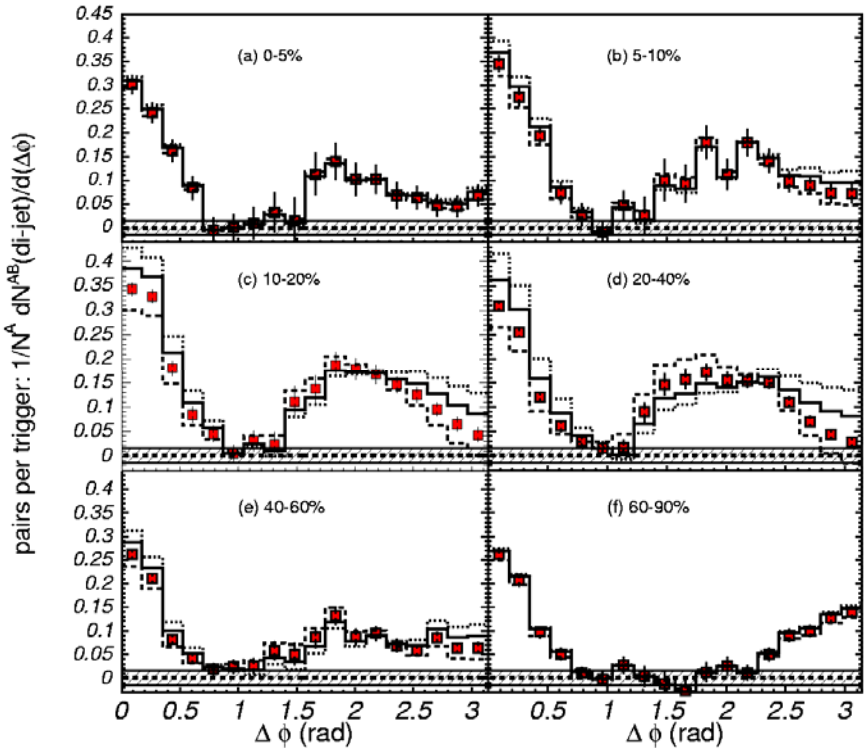
π□□□H±
C: □□□□□
T: □□□□
P: □□□

H± □□□H±
C:
T: □□□
P: □□P_T TRIG

□□

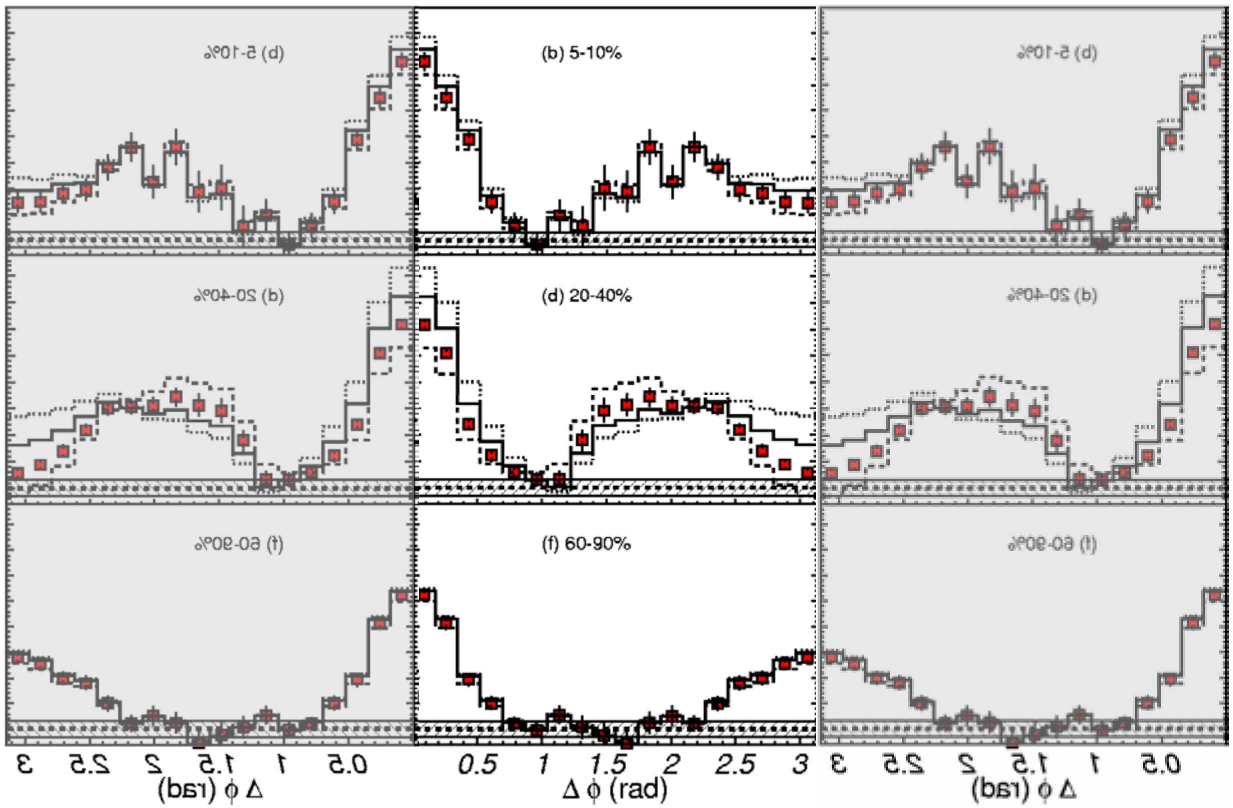
Away-side broadening and [illegible]





PHENIX PRL 97, 052301 (2006)

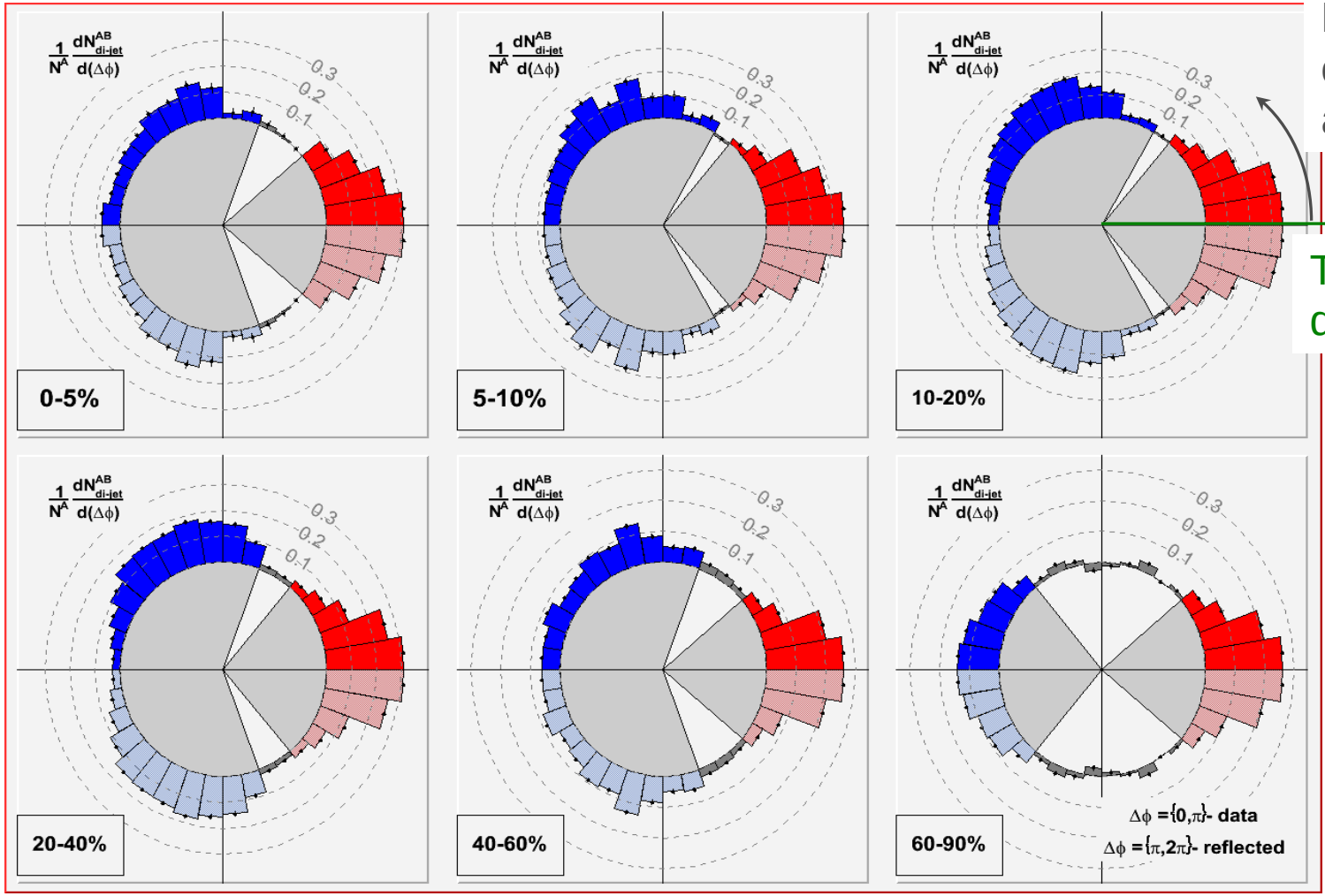
H± □□ H± | C:
T: □□□ □ □ | P: □ □ □□□

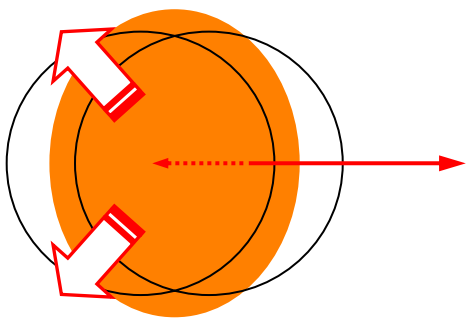


NEAR SIDE PEAK

AWAY SIDE PLATEAU DIP

K± K±	C:
T:	P:

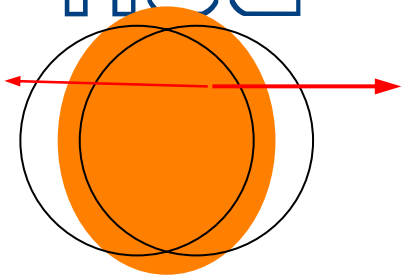


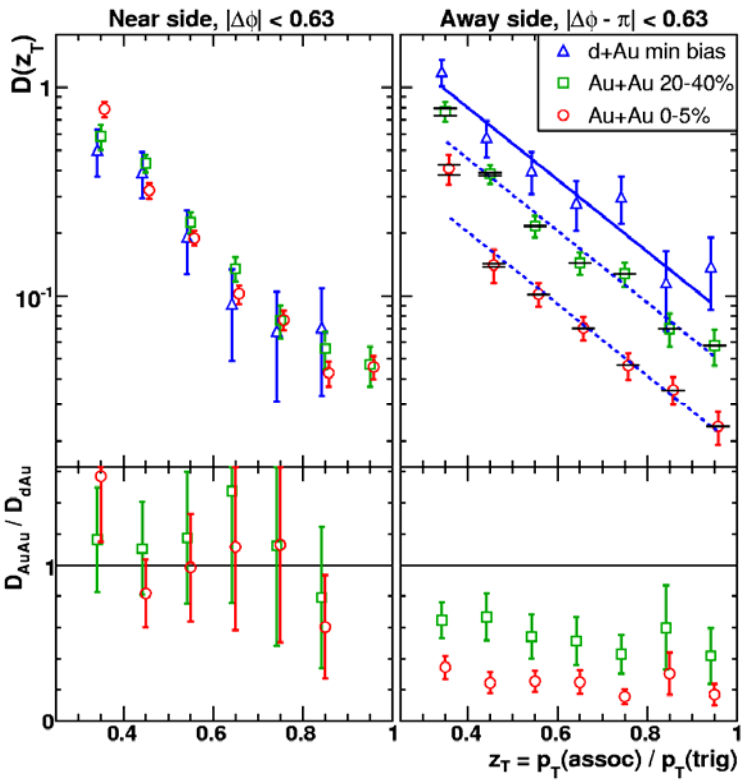


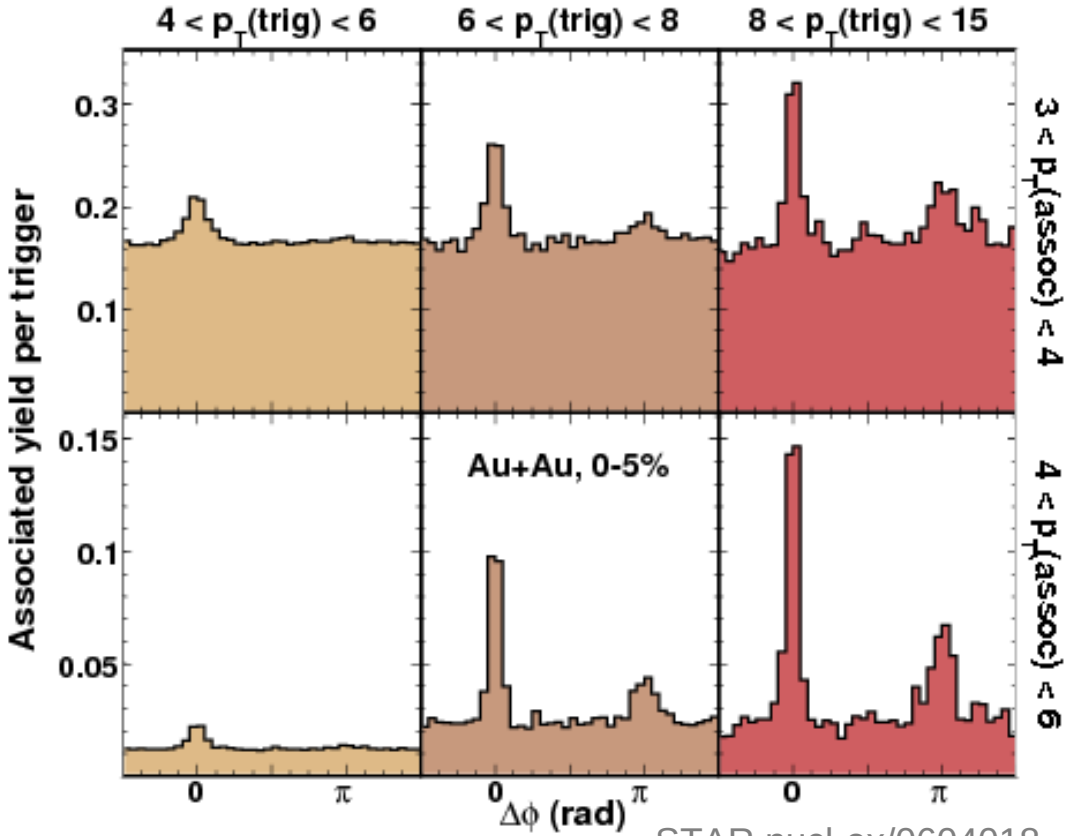
Suggestive of…

Cherenkov cones?
Mach cones?

Away Side Reappearance







STAR nucl-ex/0604018.

At much higher trigger particle pT the away side peak in central Au+Au reappears -- “punches through”?

The shape of the away-side yield spectrum is the same as that from d+Au; surprise?

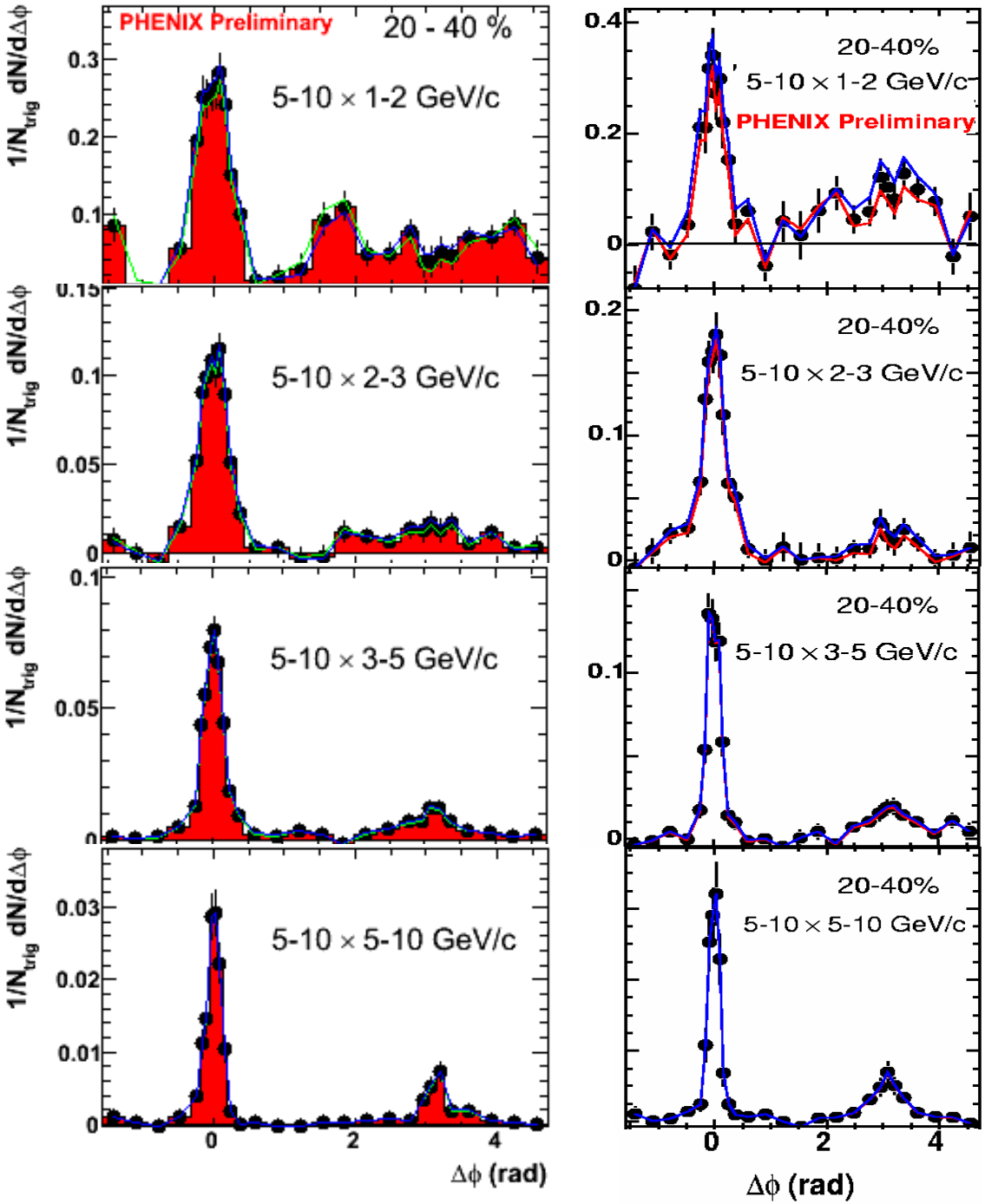
Fix p_T trig Raise p_T assoc

H± H±

C:

T:

P: vario vs

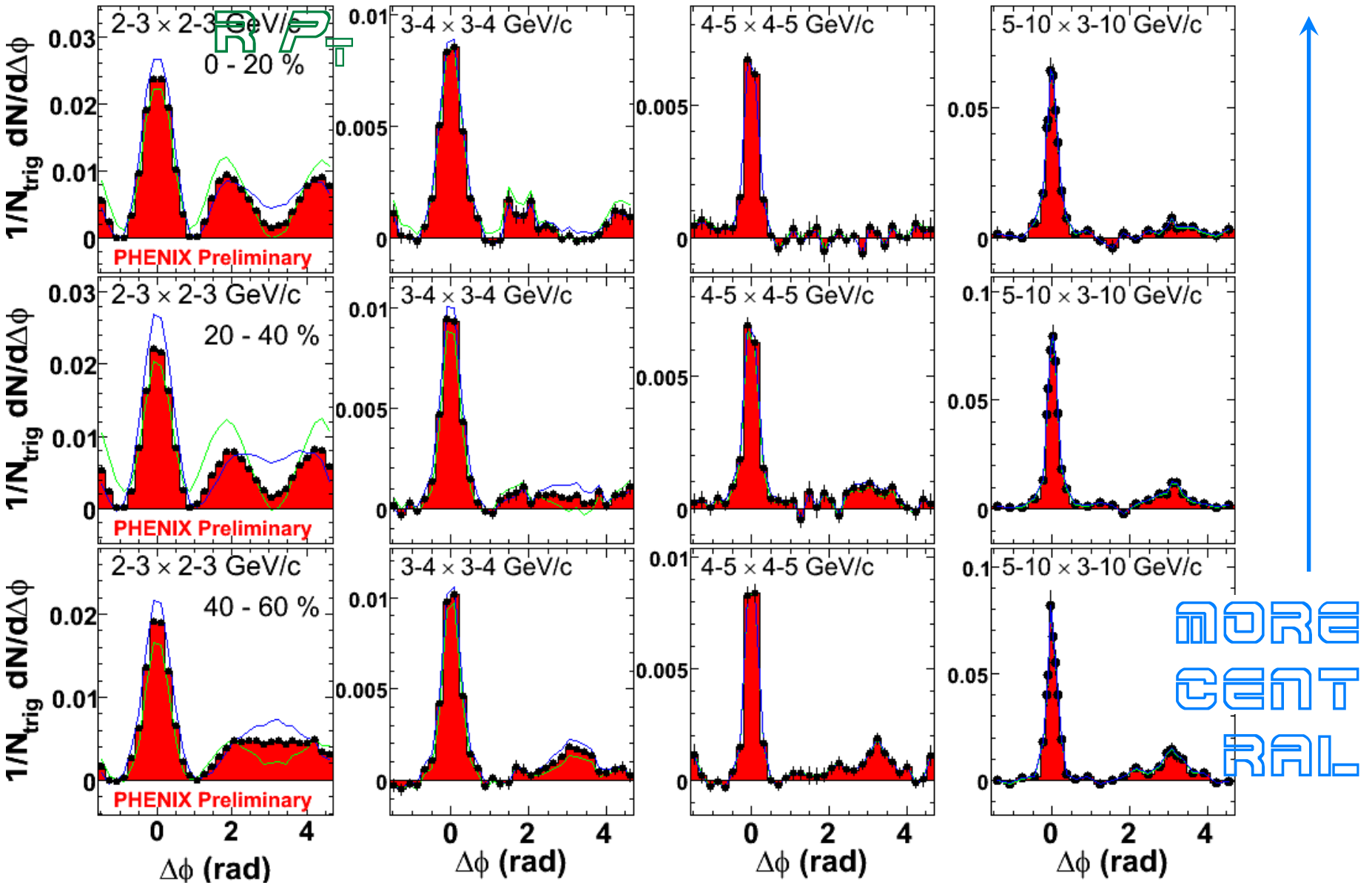


π H±

C:

T:

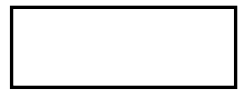
P: vario vs


HIGHER R_T
2-3 × 2-3 GeV/c
0 - 20 %
3-4 × 3-4 GeV/c
4-5 × 4-5 GeV/c
5-10 × 3-10 GeV/c
20 - 40 %
40 - 60 %
PHENIX Preliminary
$1/N_{trig}\ dN/d\Delta\phi$
$\Delta\phi$ (rad)
MORE CENTRAL

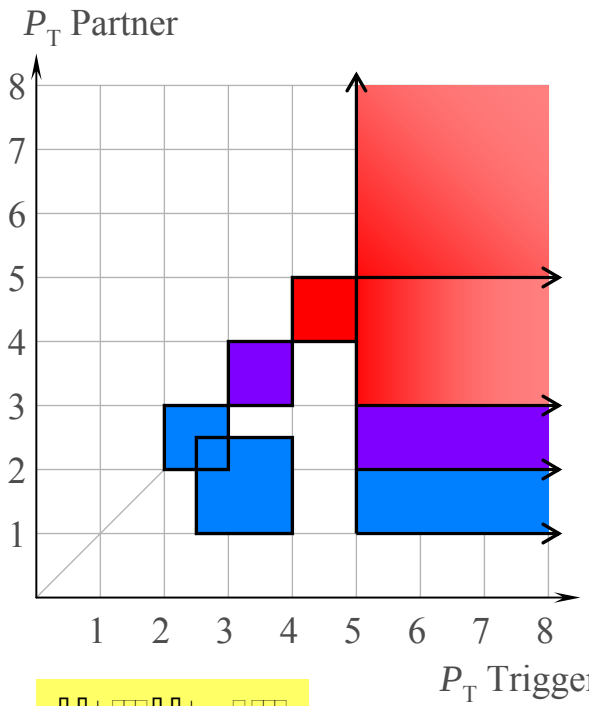
Away-side peak visible

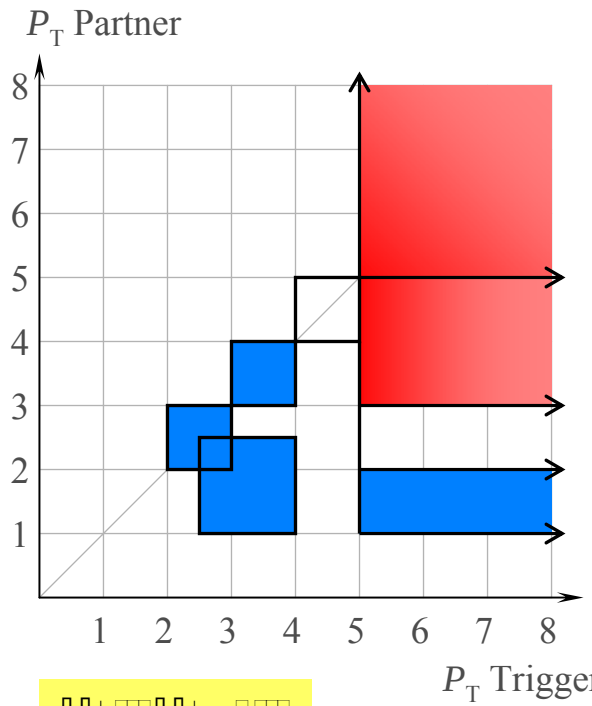
Away-side shoulders visible

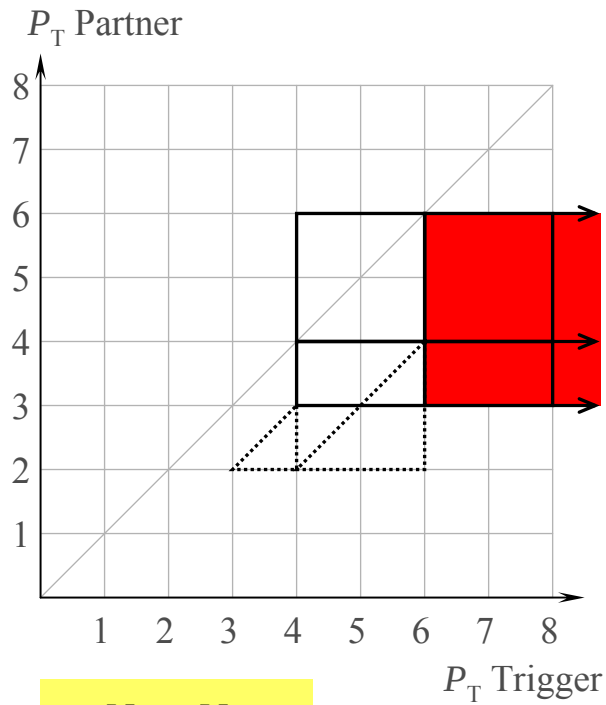
Both visible



Neither visible







SEVERAL DISTINCT REGIONS

STAR PRL 90, 082302 (2003)

PHENIX PRL 97, 052301 (2006)

STAR nucl-ex/0604018.

Conclusions

General

Nuclear collisions at RHIC energies create hard-scattered partons *in situ*, which act as probes of the created medium

High p_T Single Hadrons

Dramatic suppression (x5) of hadrons produced in central Au+Au collisions, evidence for dense/opaque medium

Baryons much less suppressed than mesons in mid-p_T range

Can measure path-length dependence through geometry

…continued

High p_T hadron pairs

Trigger on the presence of a jet, see what happens to the fragmentation partners

Away-side disappearance at mid-p_T

Away-side broadening/shoulder peaks at low $p_T^{Partner}$

Away-side reappearance at high $p_T^{Trigger}$

All this … and more…

Heavy flavor, flavor-dependent correlations, three-particle correlations, direct photon correlations, rapidity structure….

BACKUP MATERIAL

SINGLES PAIRS

$$\frac{dN^A}{d\phi_A} \propto 1 + 2v_2^A \cos 2(\phi_A - \Psi_{RP}) \quad \text{same for } B$$

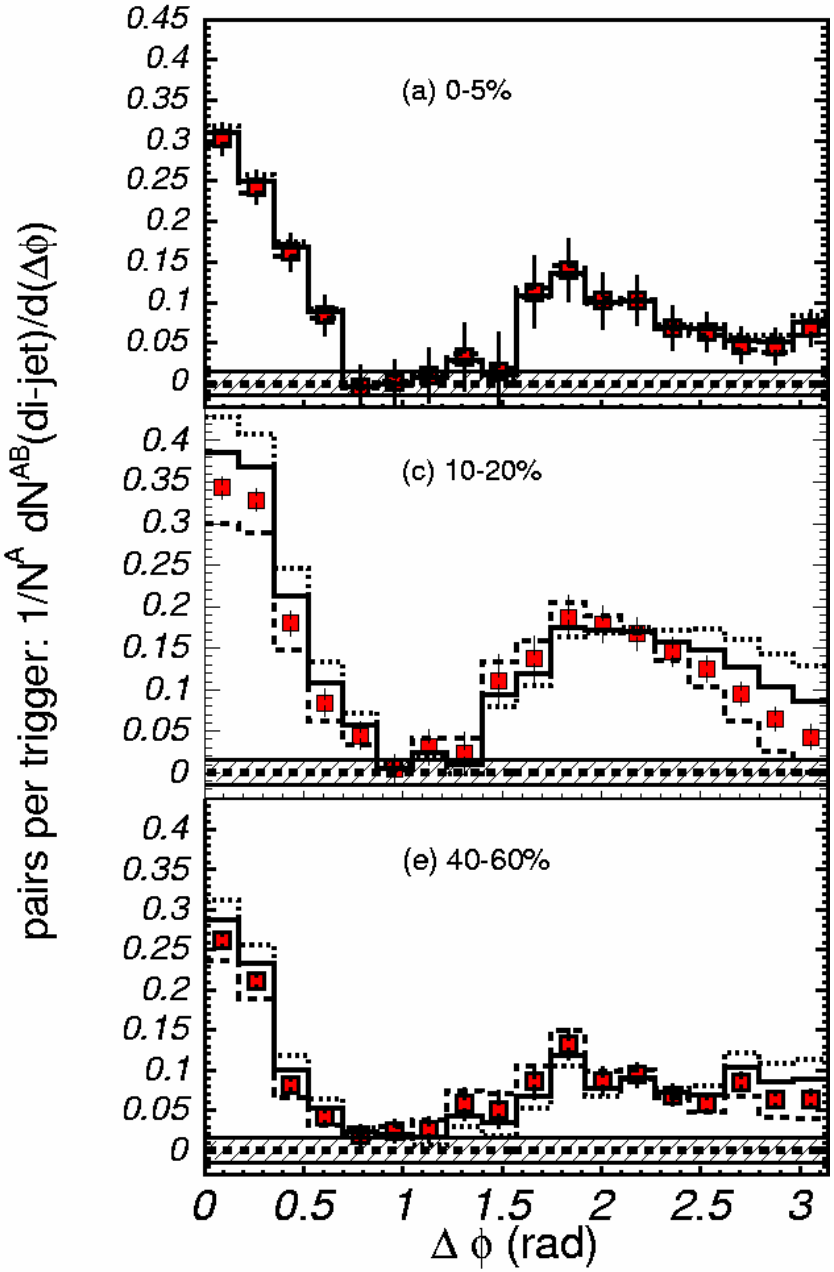
$$\frac{dN^{AB}}{d(\Delta\phi)} = \underbrace{b_0\left[1 + 2\left\langle v_2^A v_2^B \right\rangle \cos(2\Delta\phi)\right]}_{\text{Therm-Therm Jet-Therm Jet-Other Jet}} + \underbrace{J(\Delta\phi)}_{\text{Same-Jet Pairs}}$$

combinatoric "Background Pairs"

b_0 Background Level — Fix by matching, fitting, combinatoric+

$J(\Delta\phi)$ Jet-Induced Pairs — Fragmentation and medium response

$$\underbrace{\frac{dN^{AB}}{d(\Delta\phi)}}_{\text{Pairs}} \propto \underbrace{\frac{1}{N_A}\frac{dN^{AB}}{d(\Delta\phi)}}_{\text{Conditional Yield}} \propto \underbrace{\frac{dN^{AB}/d(\Delta\phi)\ \text{same-event}}{dN^{AB}/d(\Delta\phi)\ \text{mixed-event}}}_{\text{Correlation Function}}$$



H± □□ H±

C: □□□□

T: □□□ □ □

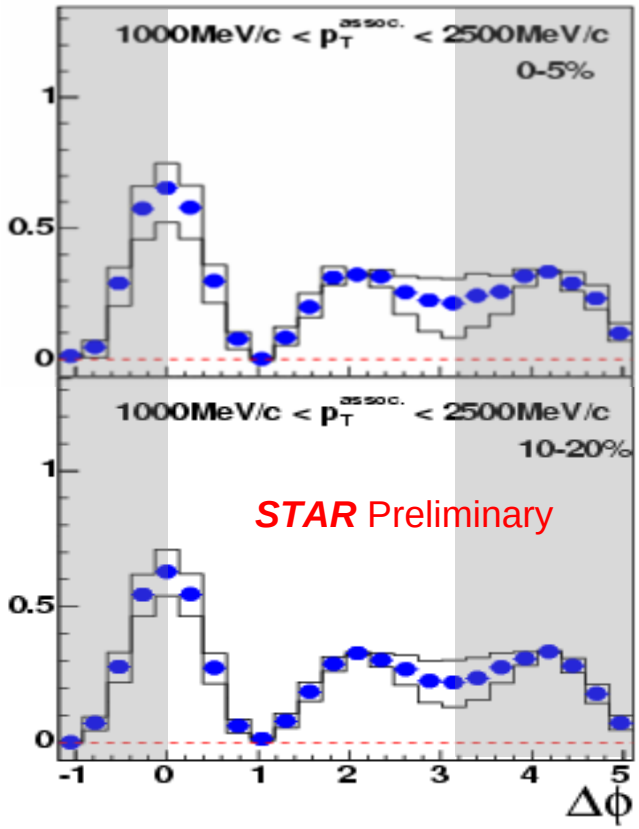
P: □ □ □□□

H± □□ H±

C: □□□□□

T: □□□ □ □

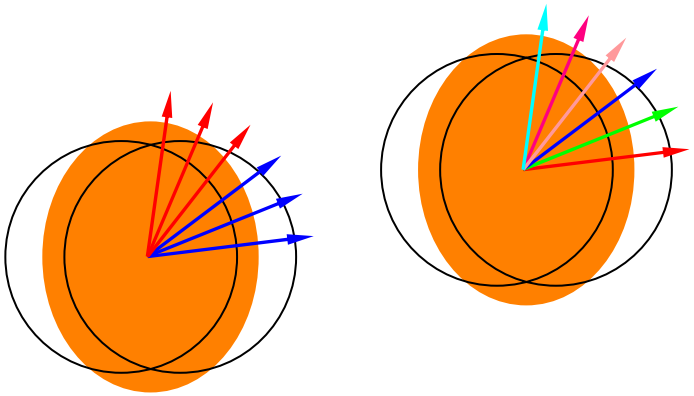
P: □ □ □□□

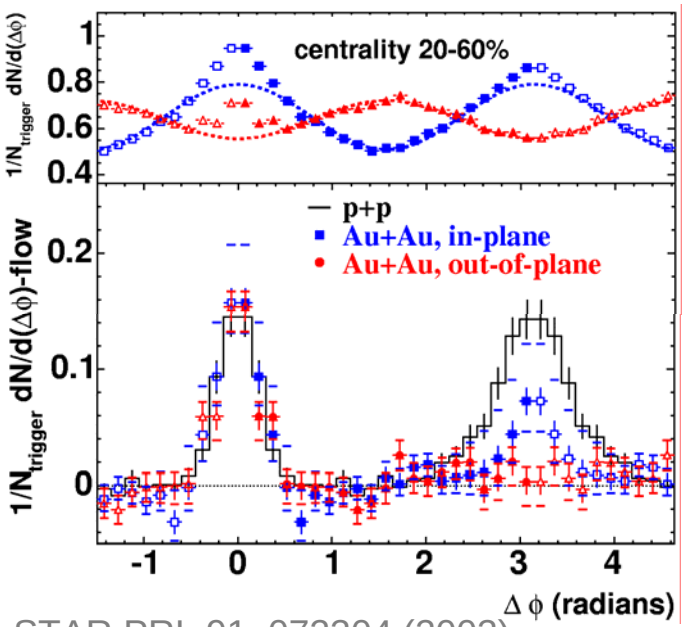


STAR "QM05 Focus" C. Gagliardi

PHENIX nucl-ex/0507004 submitted to PRL

□□





STAR PRL 91, 072304 (2003)