Probing Hot Nuclear Matter via Moderate p_T Jets @ RHIC

Anne M. Sickles
Brookhaven

Extracting Order (and Physics) from Low to Medium Energy Jets

Anne M. Sickles
Brookhaven

More Specifically...

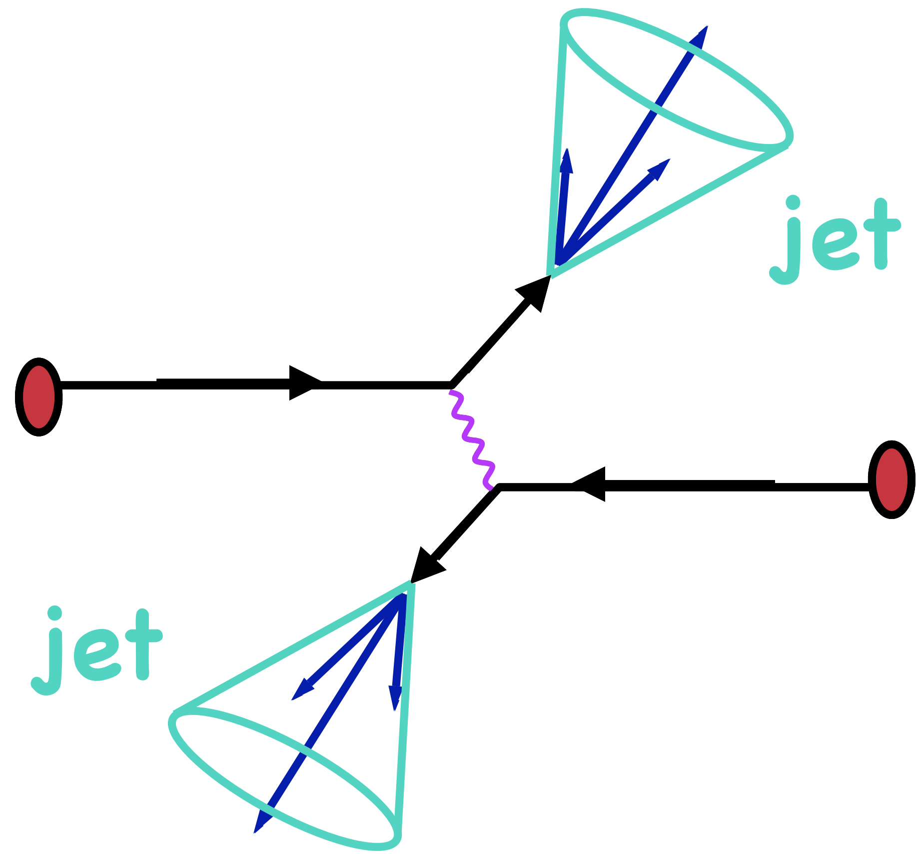
- baryon production (mostly my work)
- ridges & shoulders (gives the context to understand baryons)
- why moderate p_T phenomena still hold a lot of new information
- experimental issues that become important as the measurements become more precise

Jets in p+p Collisions

Parton Distribution Functions: Measured in Deep Inelastic Scattering

Hard Scattering Cross Section: Calculated with pQCD

Fragmentation into Hadrons: Measured in e+e- Collisions



$$\sigma^{pp->\pi^0 X} = \sum_{f_1, f_2, f} \int dx_1 dx_2 dz \; \underline{f_1^p(x_1)\, f_2^p(x_2)} \; \underline{\hat{\sigma}^{f_1 f_2 \rightarrow f+X}(x_1 p_1, x_2 p_2)} \; \underline{D_f^{\pi^0}(z)}$$

Heavy Ion Collisions

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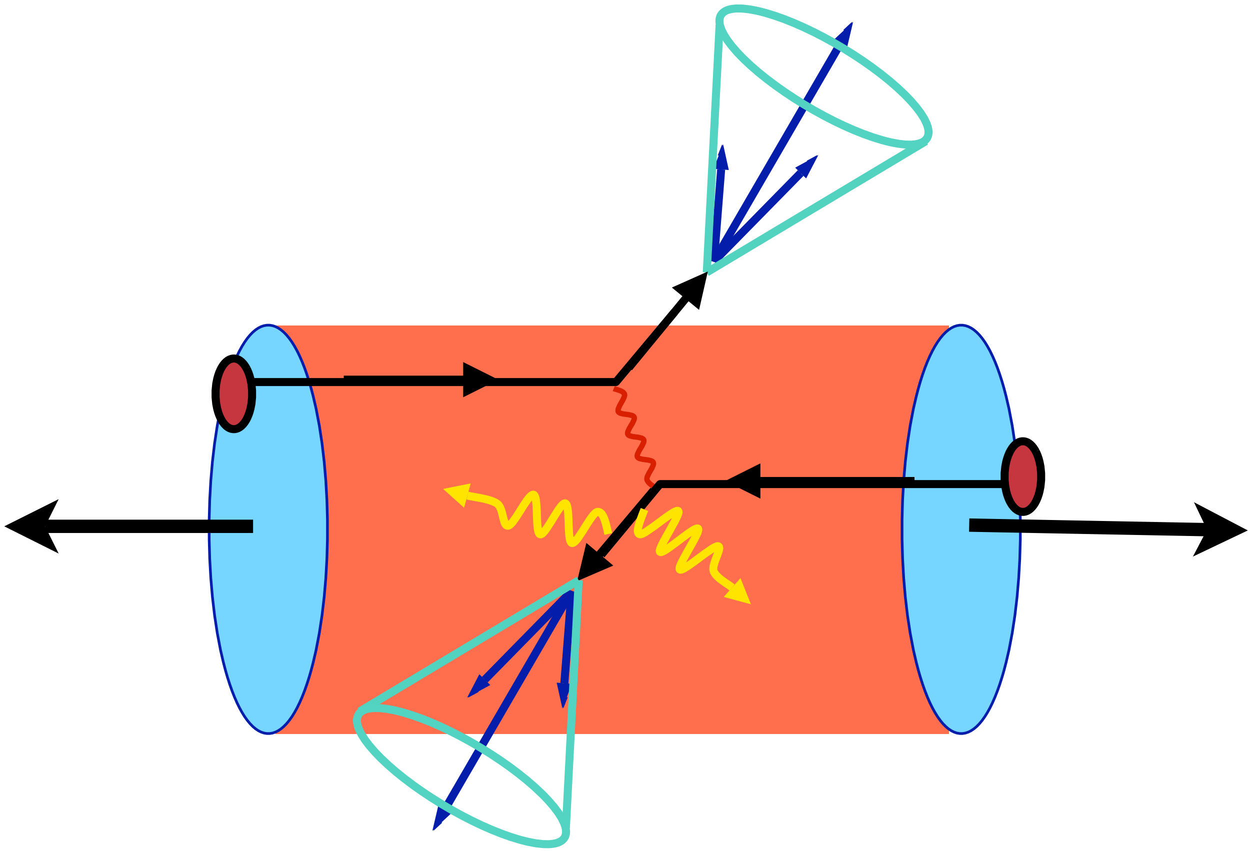

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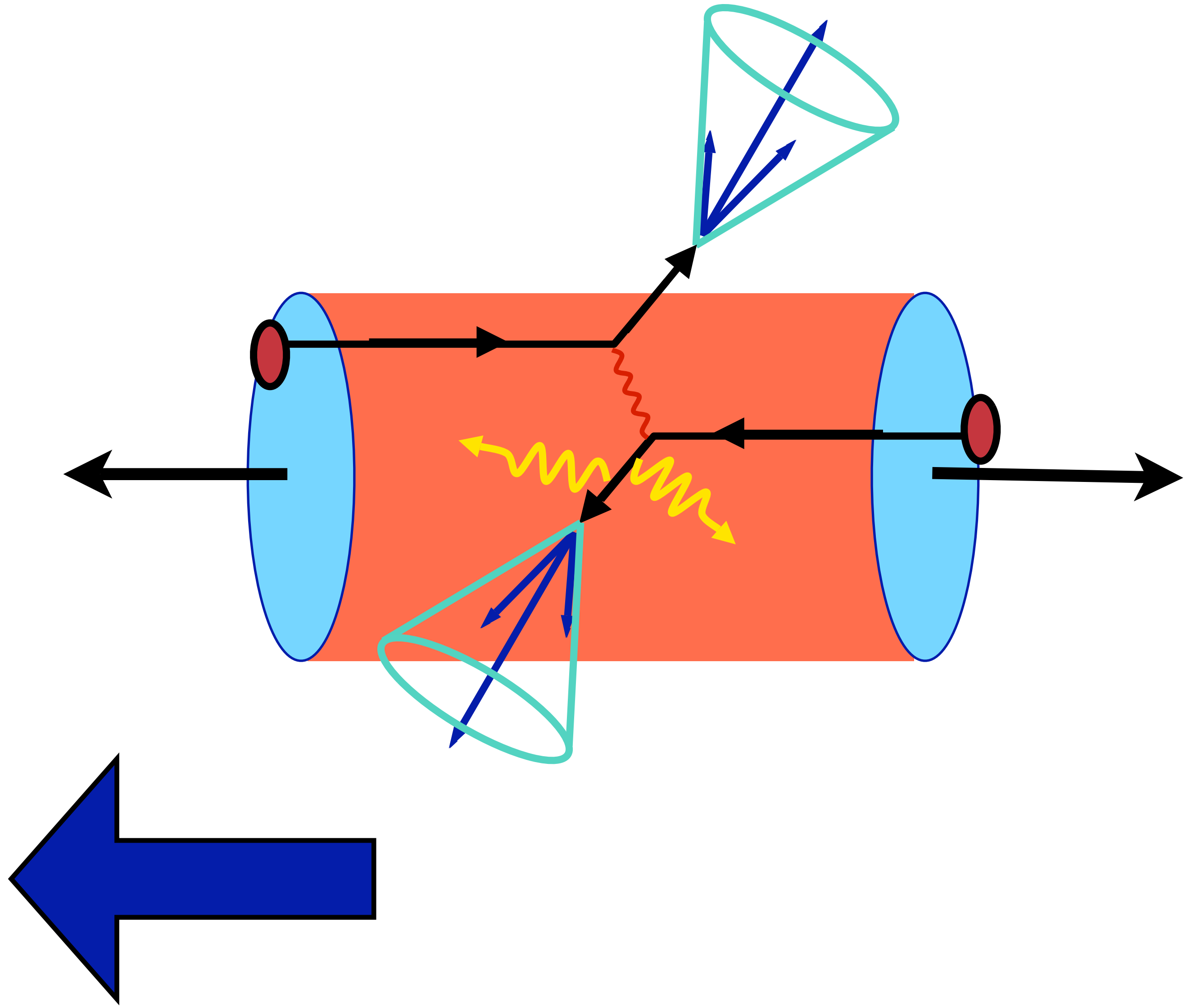
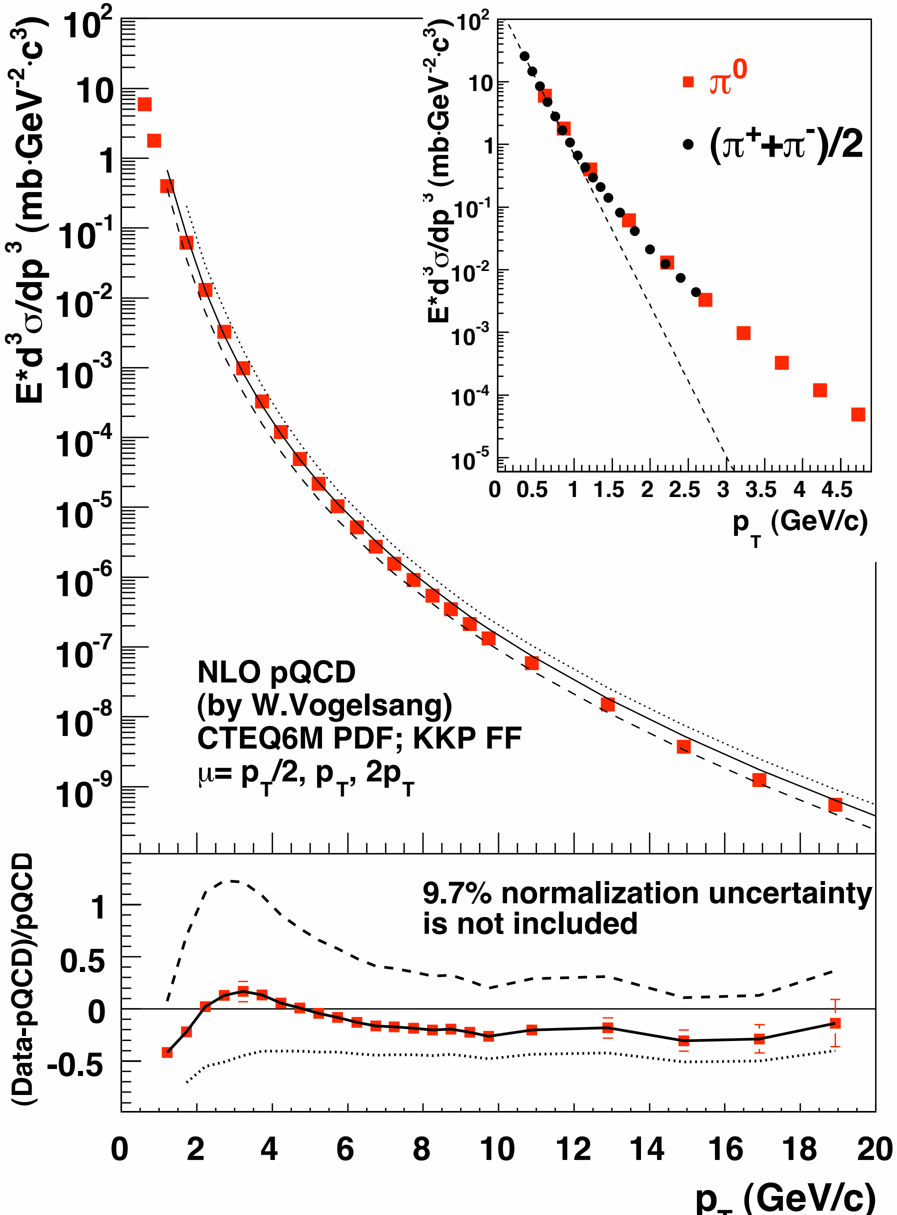
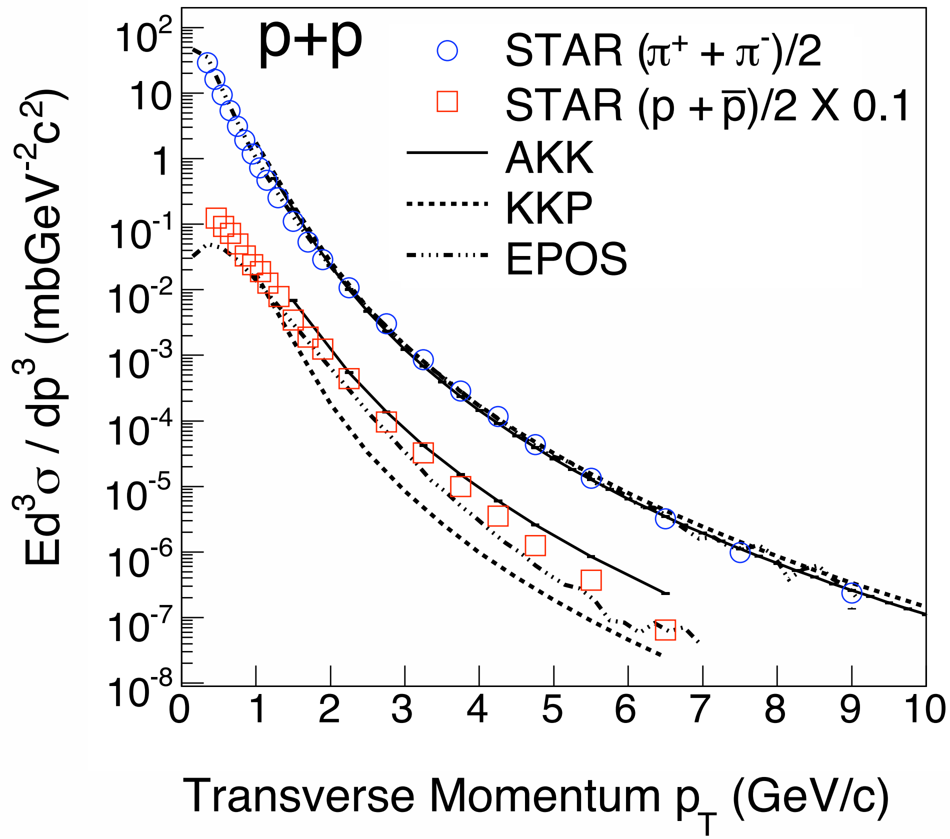


pQCD @ low p_T

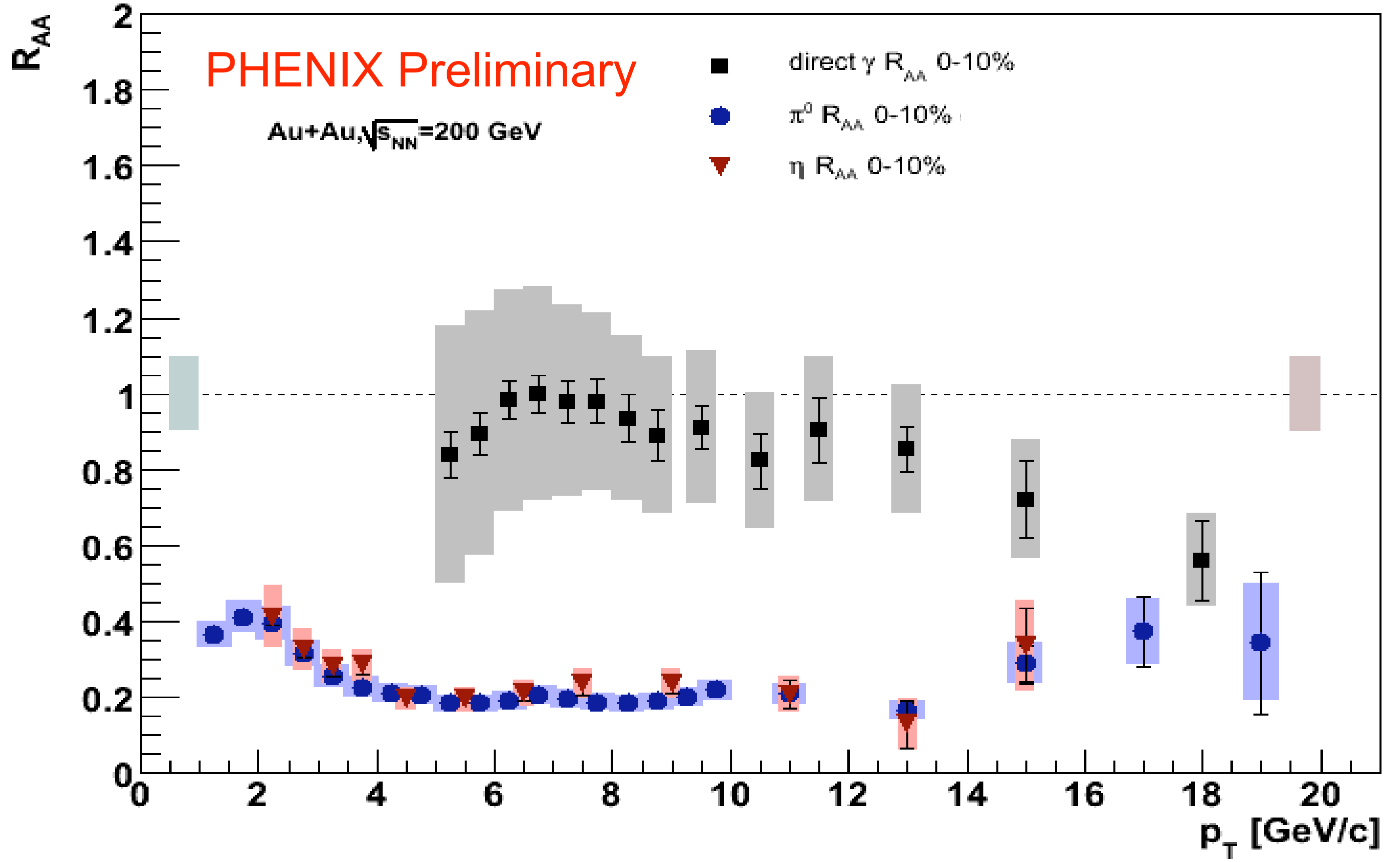




NLO pQCD describe the p+p data down to $p_T \sim$ 2GeV/c (with some uncertainty)

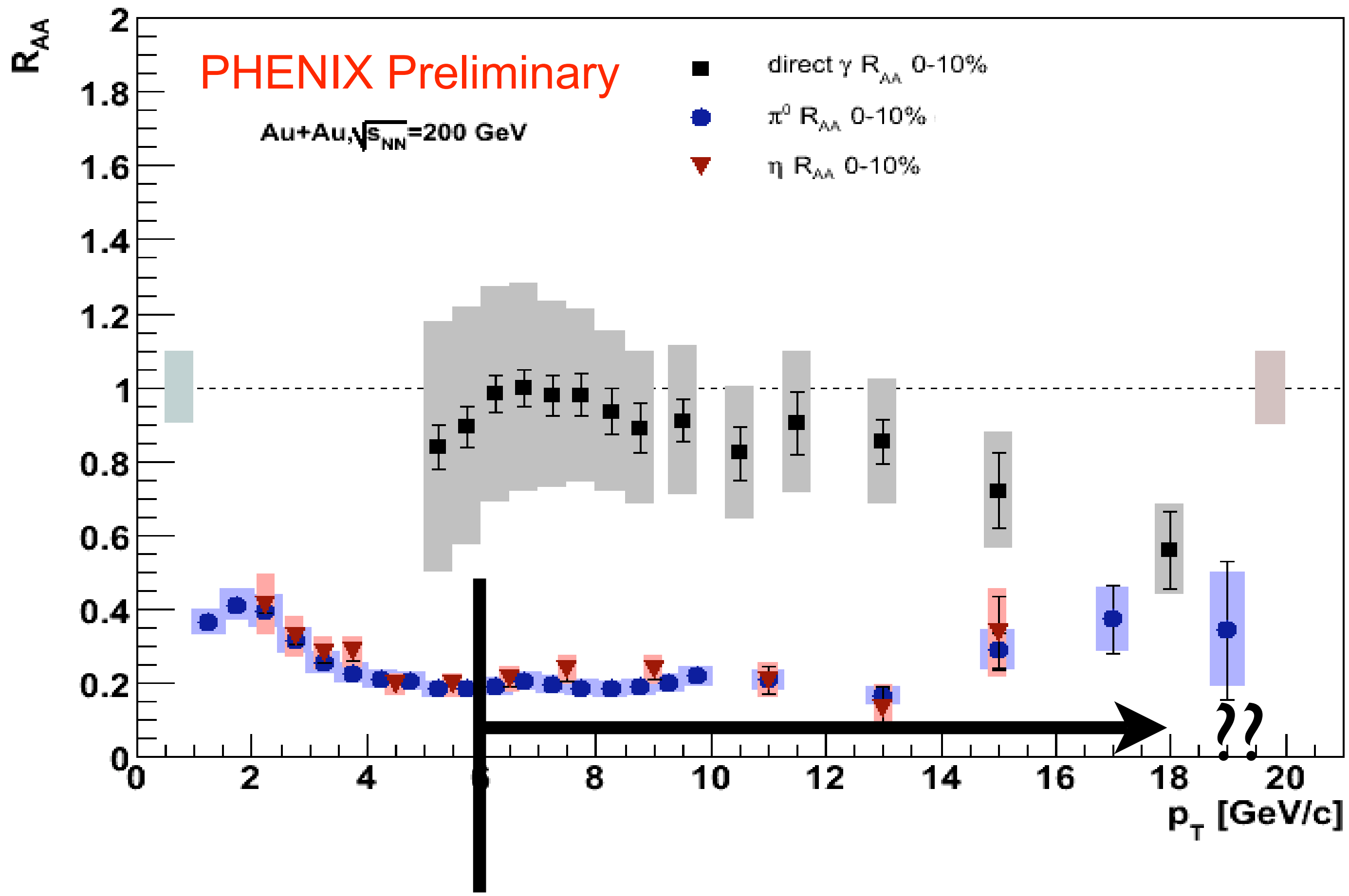
PHENIX PRD 76 051106 (2007), STAR PLB 637 (2006) 161

Au+Au: high p_T



R_{AA}
PHENIX Preliminary
Au+Au,$\sqrt{s_{NN}}$=200 GeV
direct γ R_{AA} 0-10%
π^0 R_{AA} 0-10%
η R_{AA} 0-10%
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
20
p_T [GeV/c]

Au+Au: high p_T



final state energy loss, geometrical bias

sensitive to opacity, (relatively) unmodified jets

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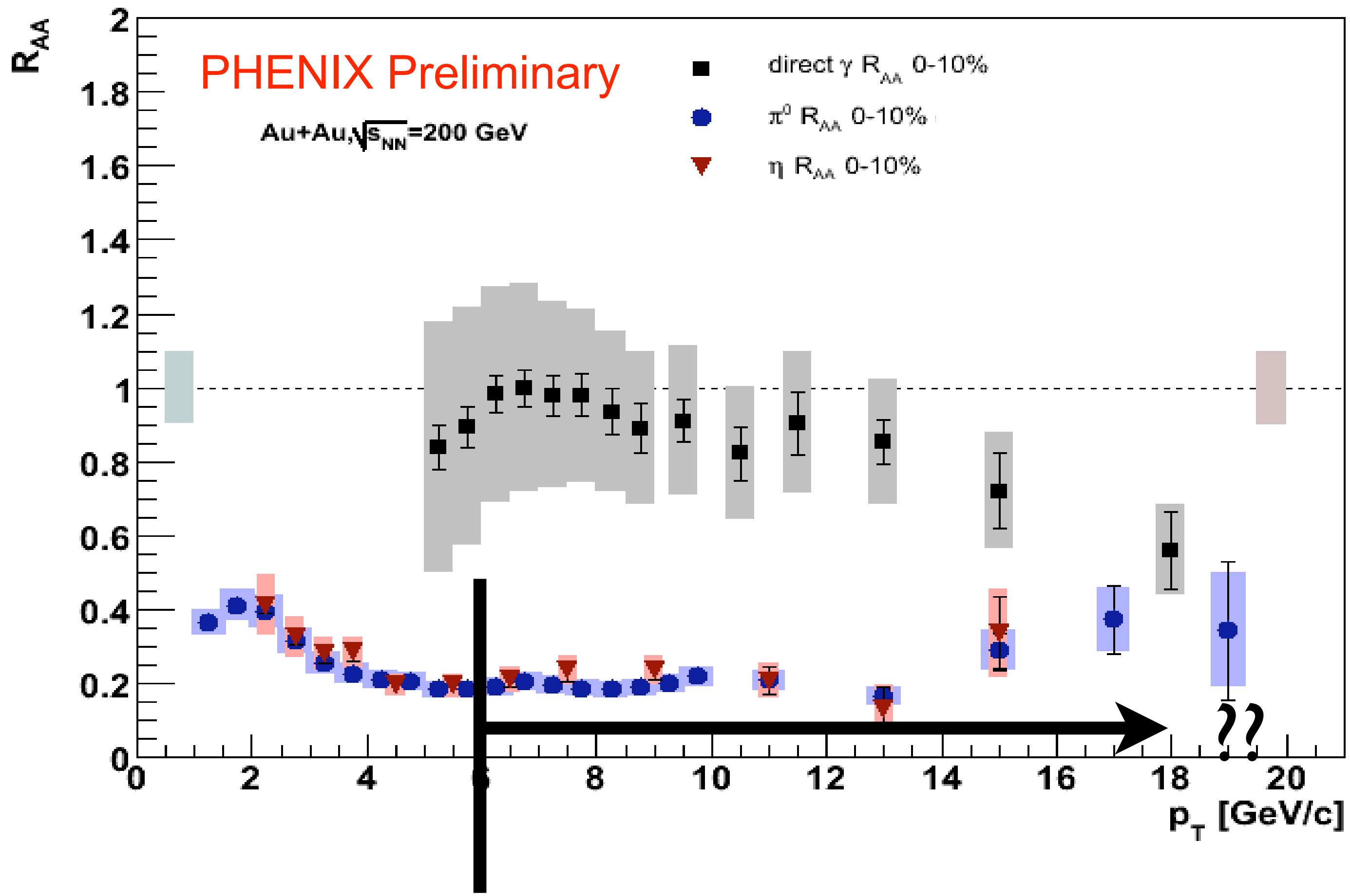


final state energy loss, geometrical bias

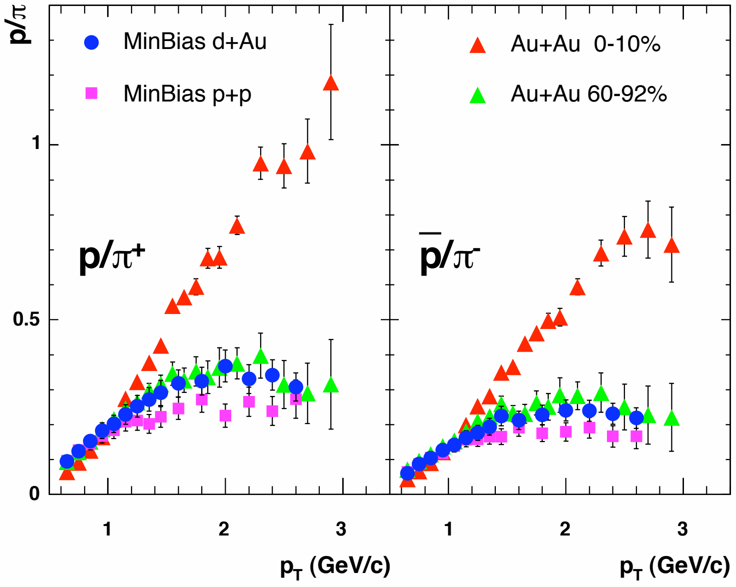
sensitive to opacity, (relatively) unmodified jets

where's the lost energy? what does that tell us about the matter?

Au+Au: Qualitatively Different

PHENIX, PRC 74 024904 (2006), J. Chen Hard Probes 2008, STAR Preliminary

Au+Au: Qualitatively Different



PHENIX, PRC 74 024904 (2006),
J. Chen Hard Probes 2008,
STAR Preliminary

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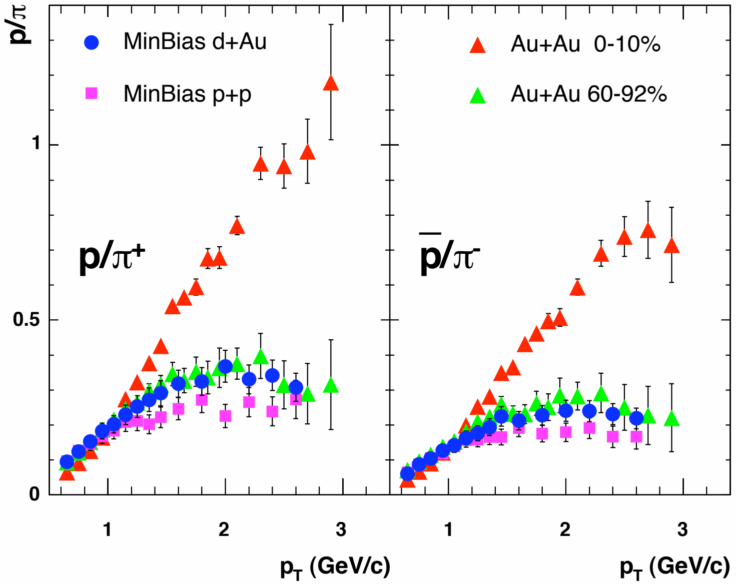

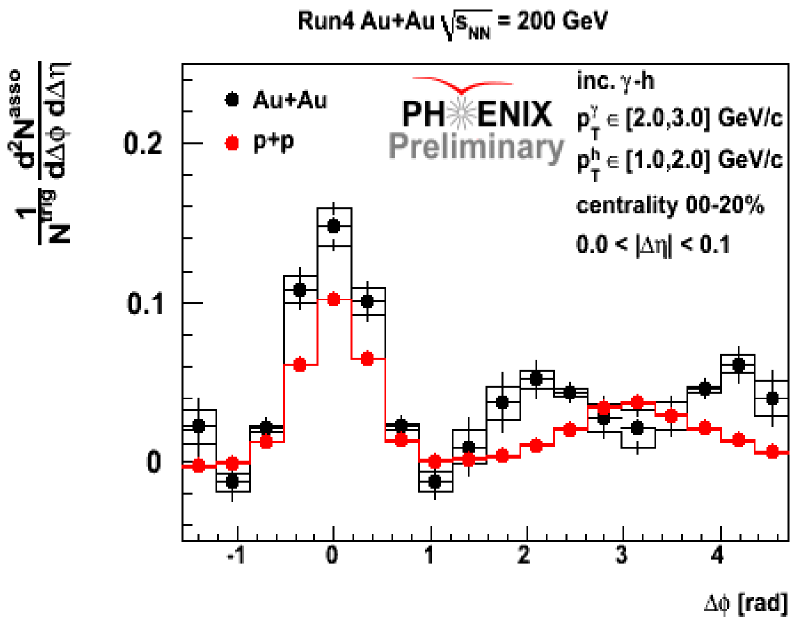

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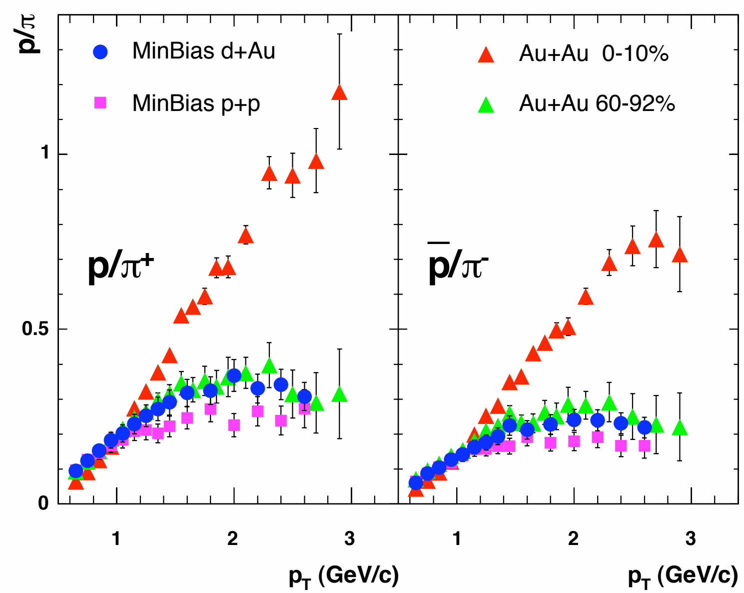

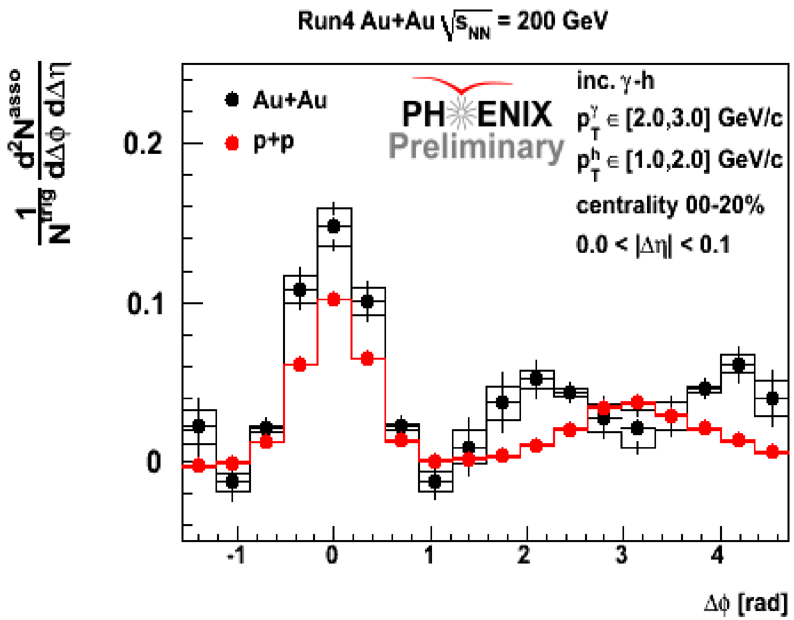

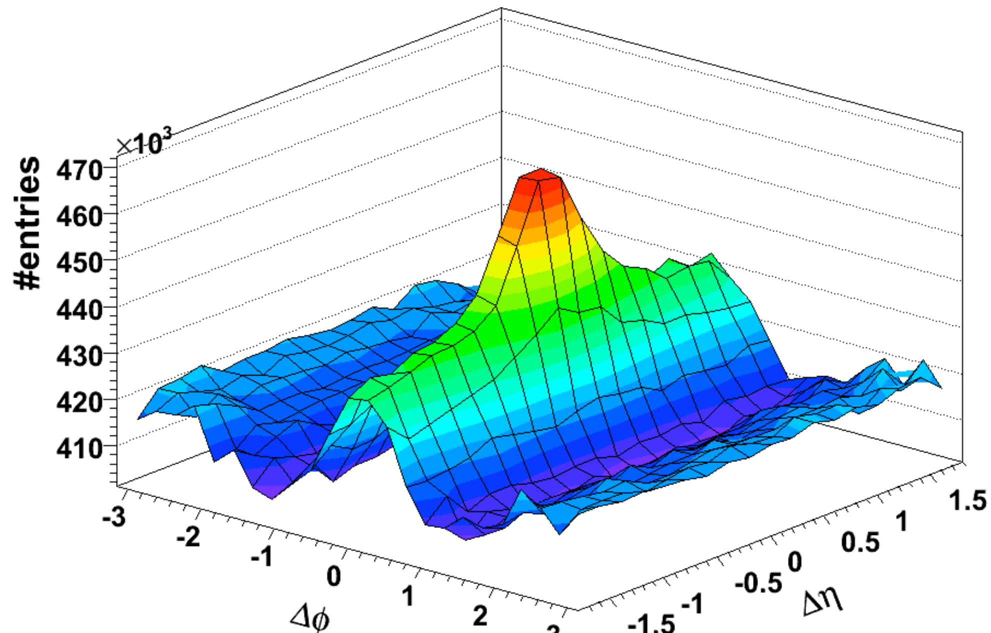

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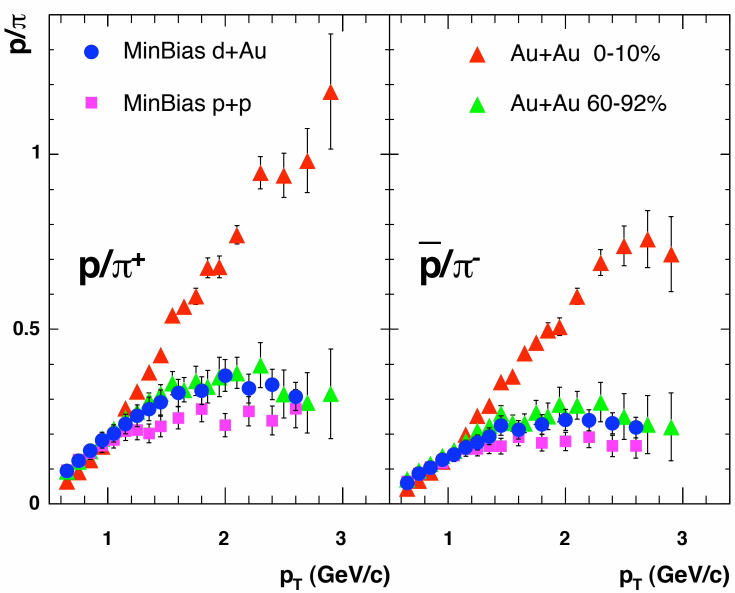

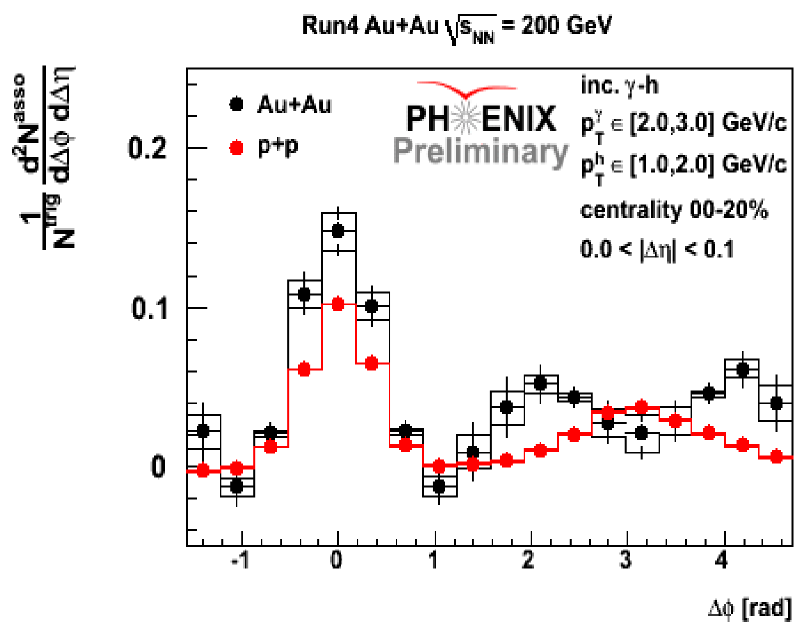

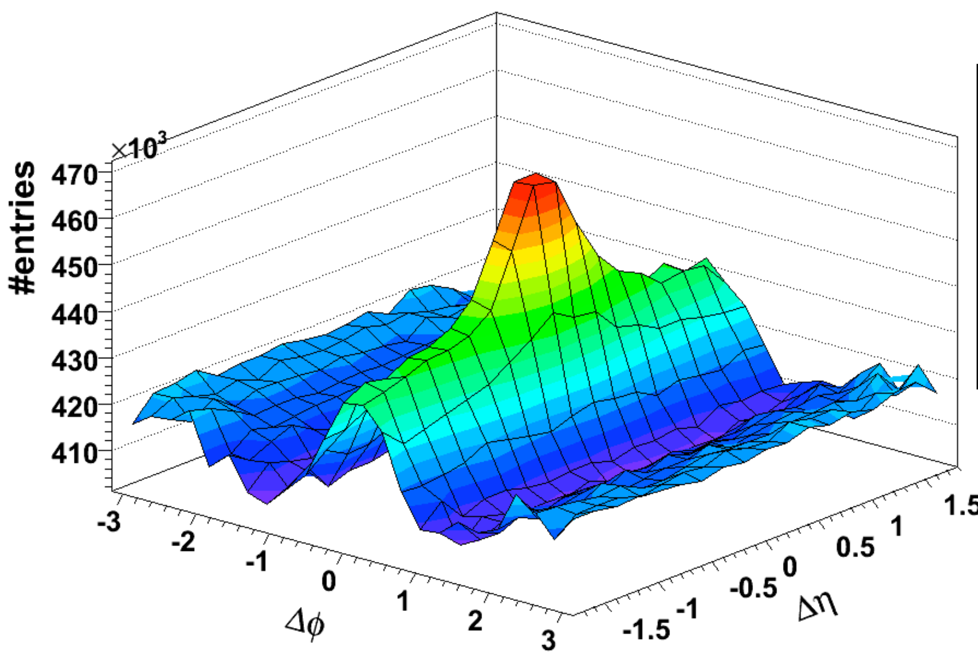

these structures might offer the chance to understand where the lost energy goes!

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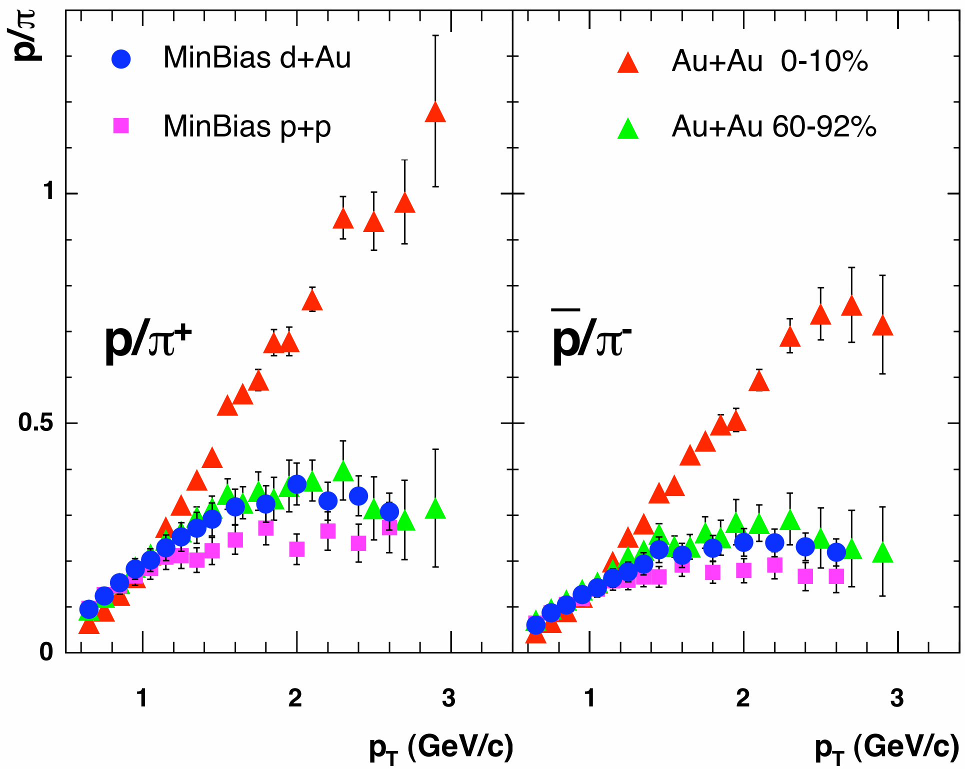
J. Chen Hard Probes 2008,
STAR Preliminary

baryon excess



Modification to fragmentation particle ratios extends to p_T ~ 5 GeV

PHENIX PRC 74 024904 (2006)

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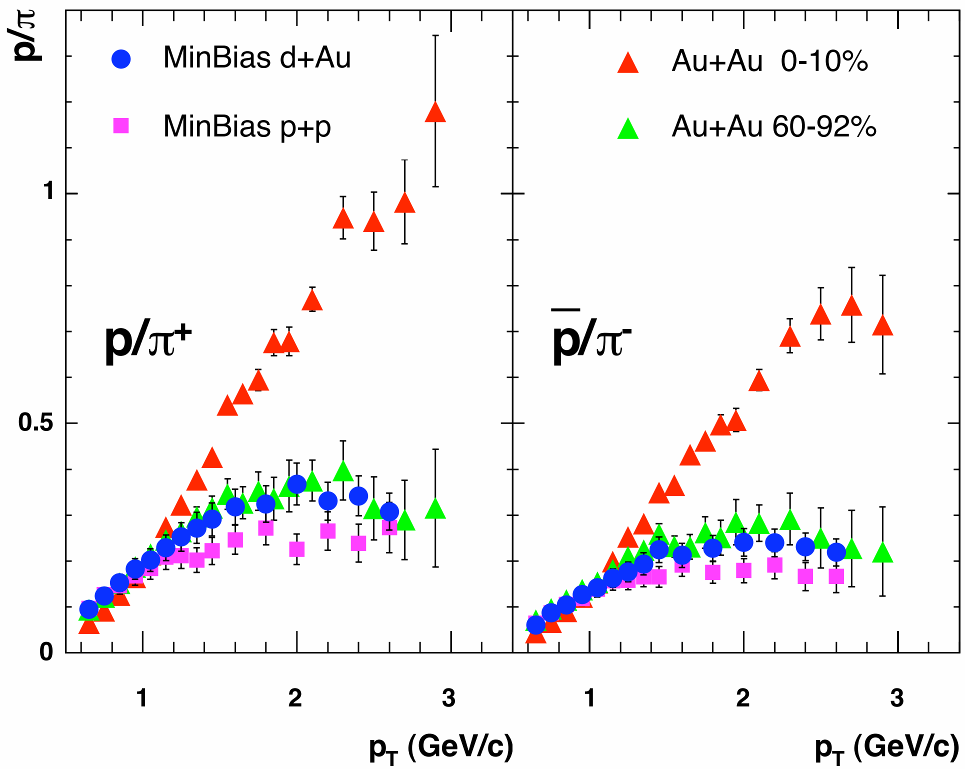
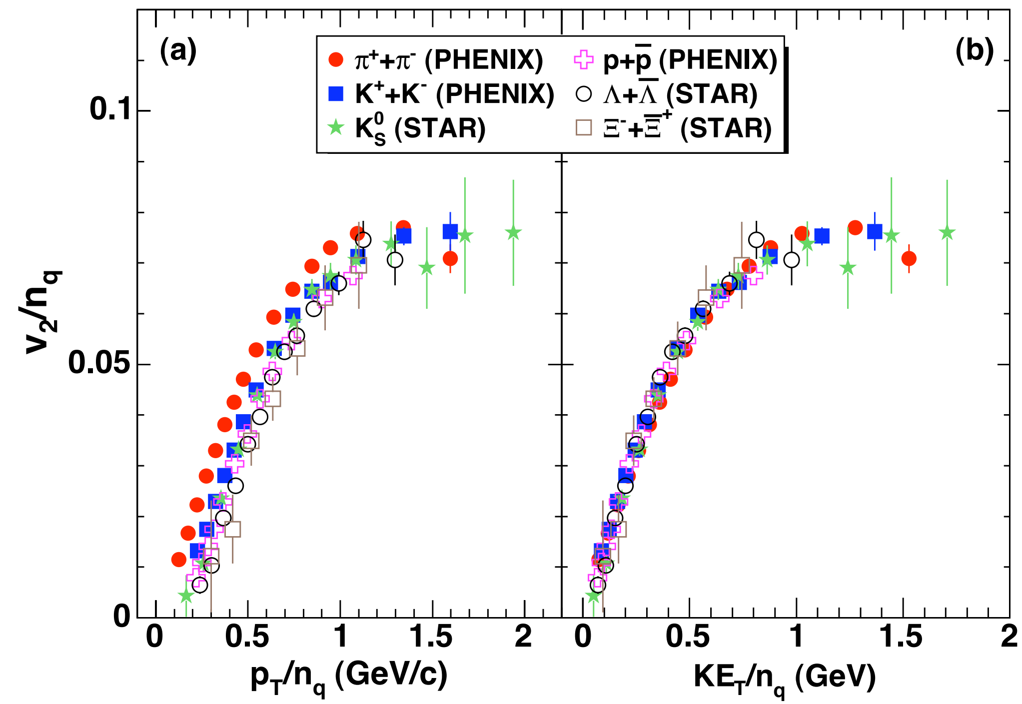


Modification to fragmentation particle ratios extends to $p_T \sim 5$ GeV

PHENIX PRC 74 024904 (2006)

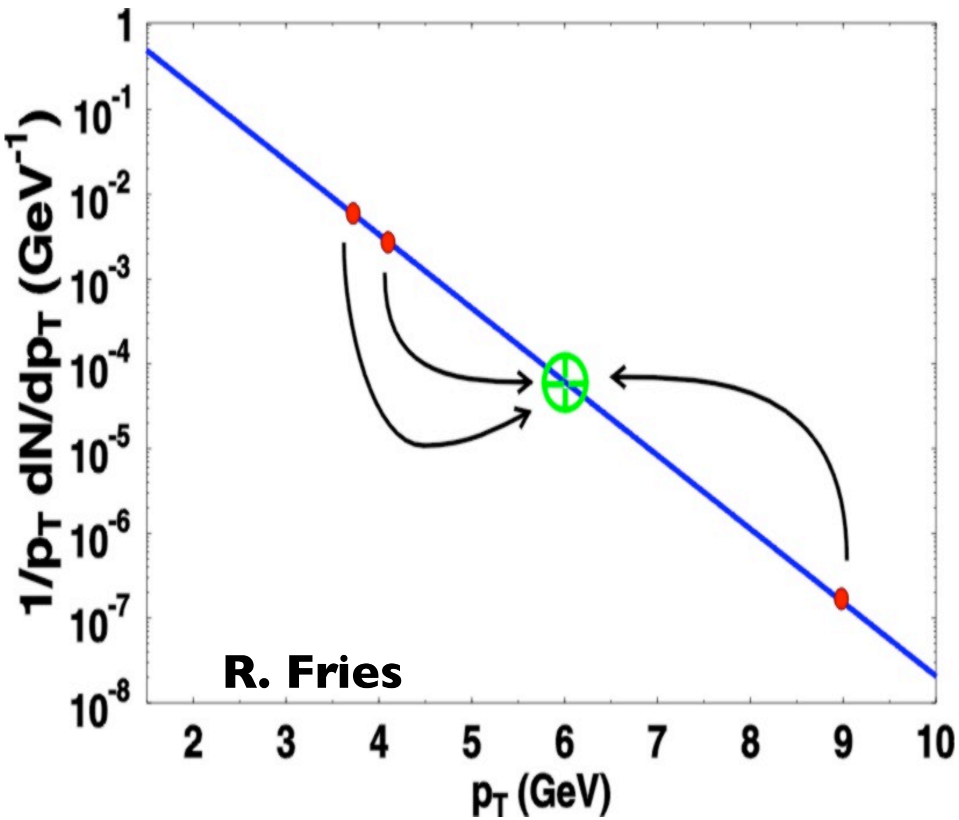


Quark Number Scaling of v2 extends to $p_T \sim 4$-6 GeV

PHENIX PRL 98 162301 (2007)

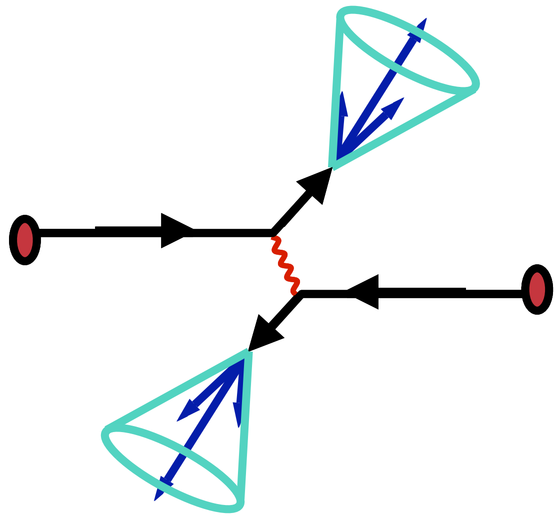
recombination models

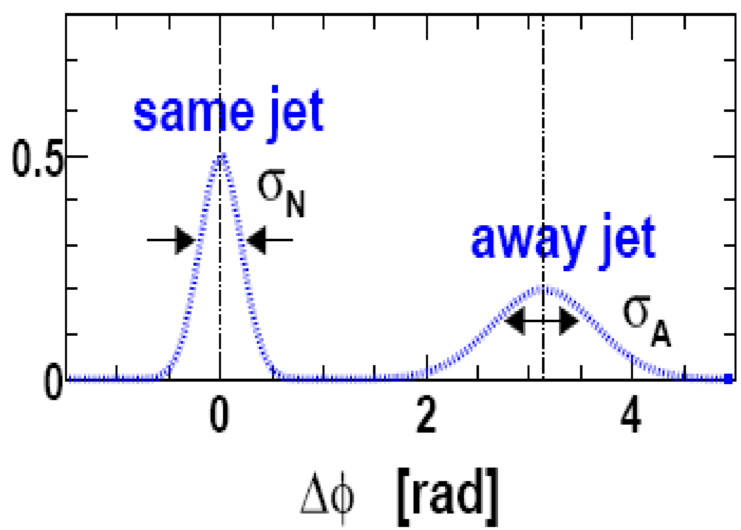
- quarks close together in phase space come together to form final state hadrons
- resulting hadron at higher p_T than parent partons, in contrast to fragmentation
- dominates for exponential parton p_T spectra
- doesn't necessarily have anything to do with jets



Fries et al., Hwa et al., Ko et al.

2 particle correlations

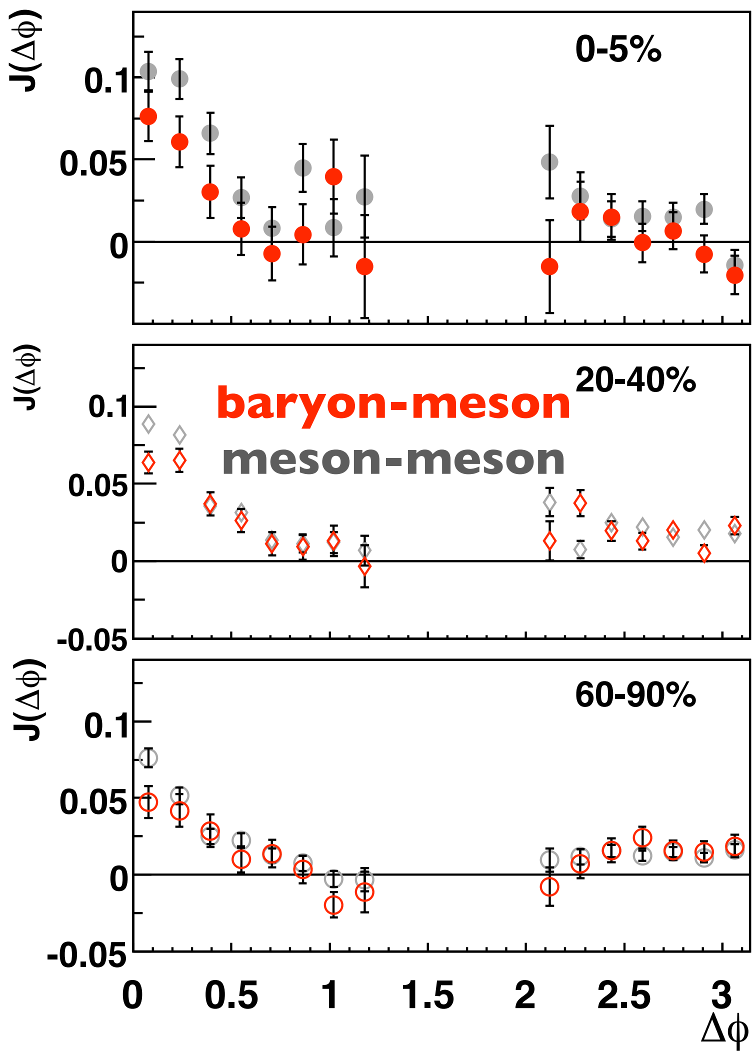




- "trigger" on high p_T particles to find a hard scattering
- count lower p_T particles to study medium interactions
- comparison of Au+Au and p+p allows measurements of matter's effect on jet properties

$\Delta\phi$: azimuthal angle around beam direction

hunting down the baryons...



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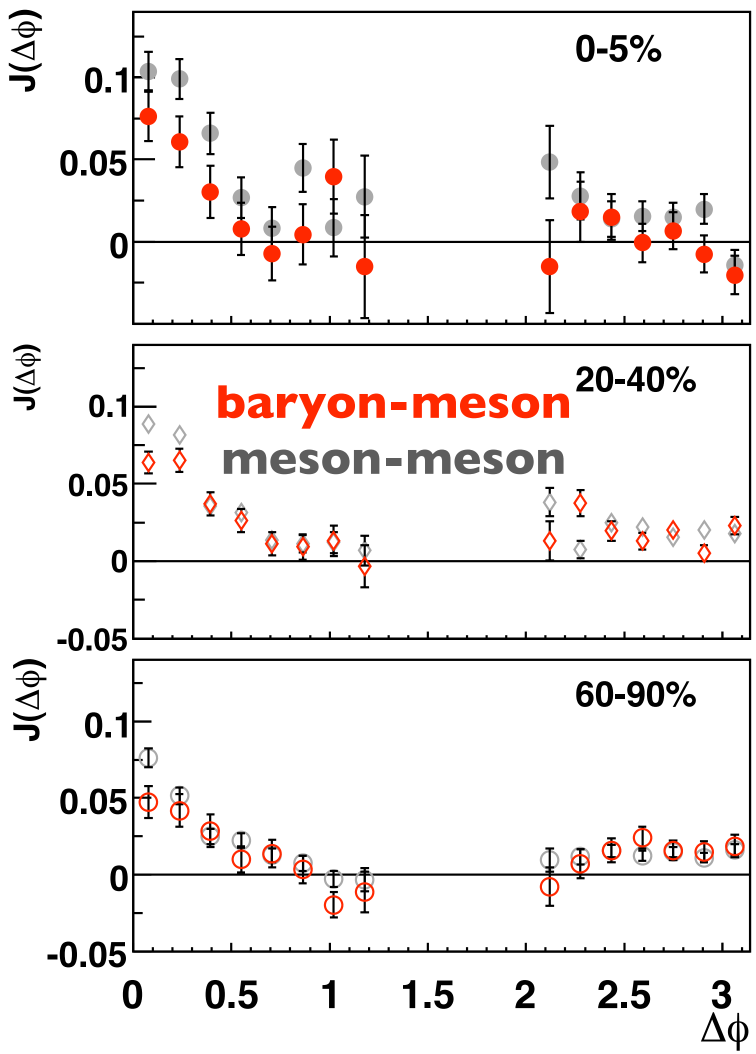
hunting down the baryons...



- are baryons associated with jet-like structures?

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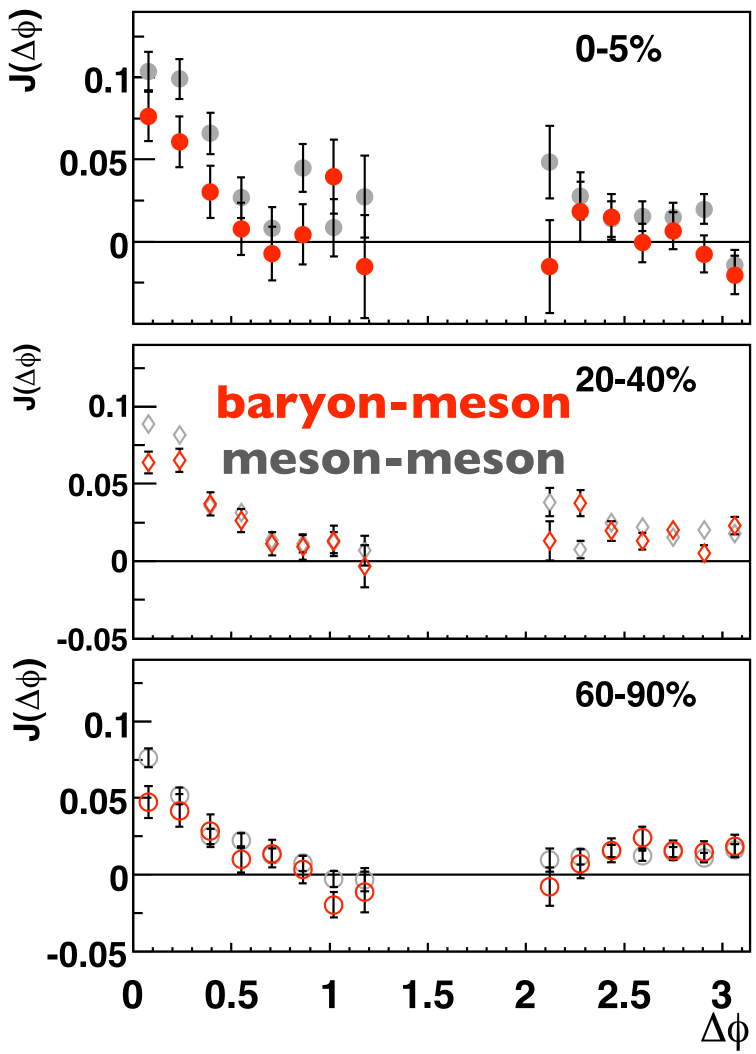
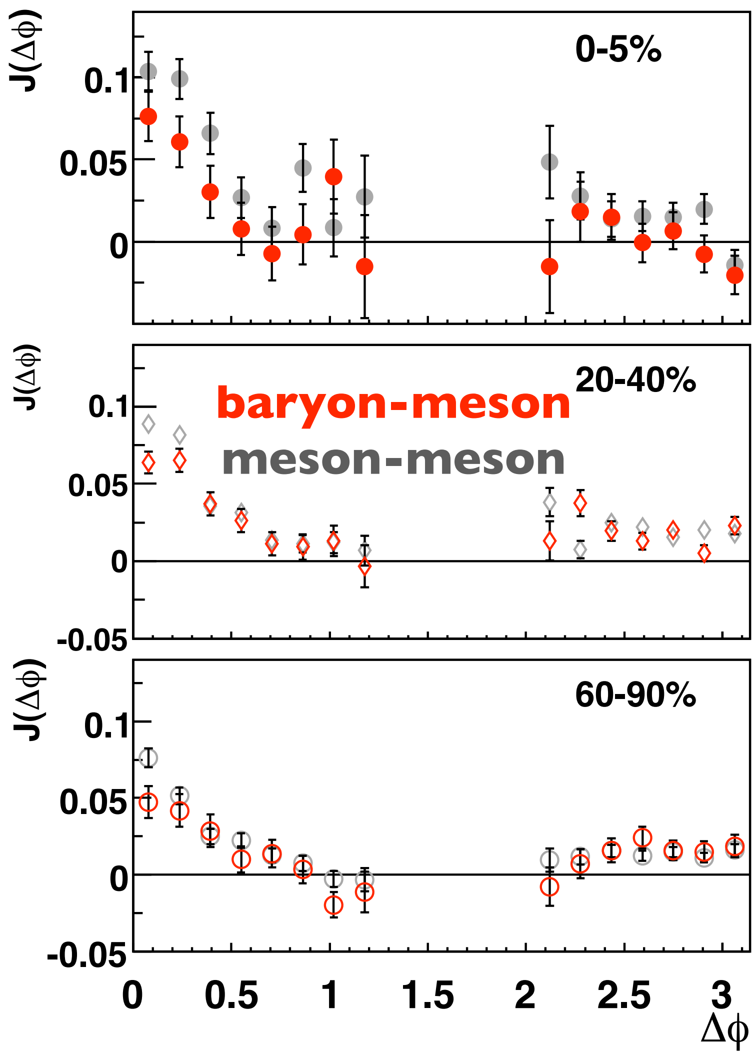


- are baryons associated with jet-like structures?
  - yes

hunting down the baryons...



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- however, the jets look different

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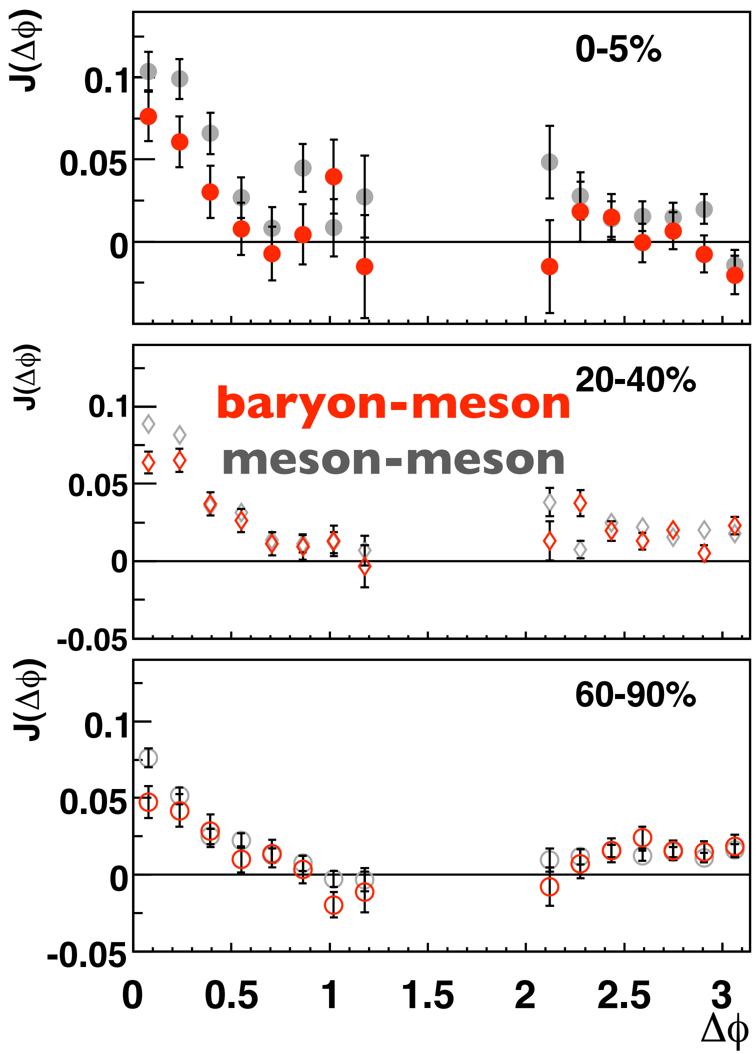

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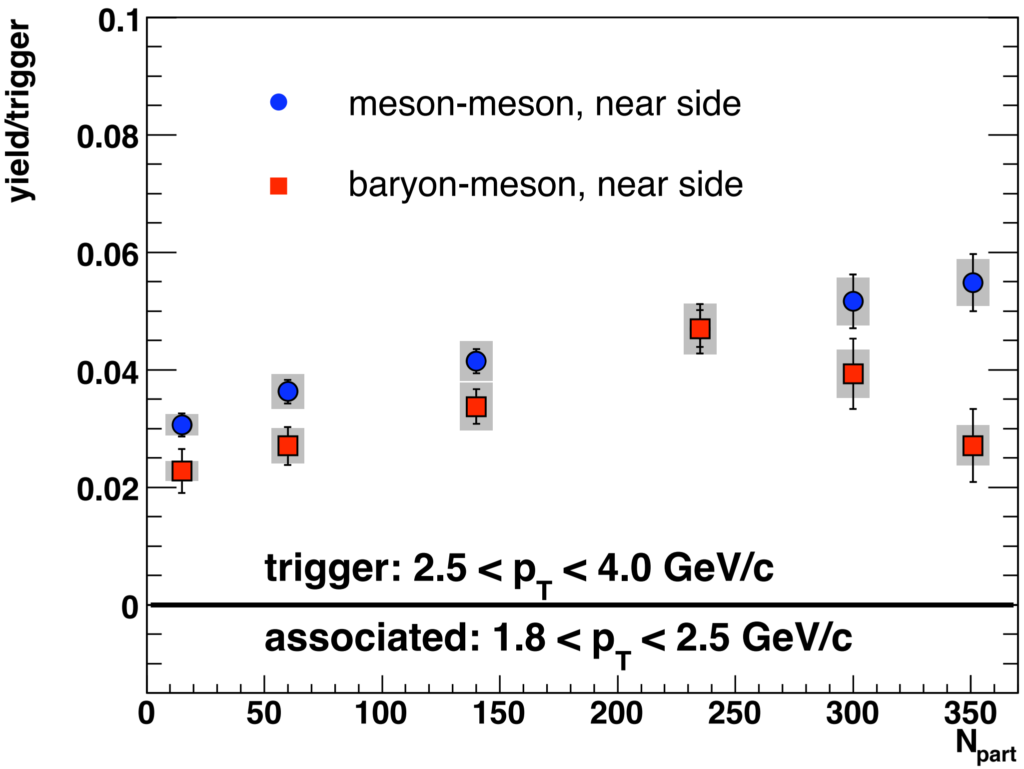

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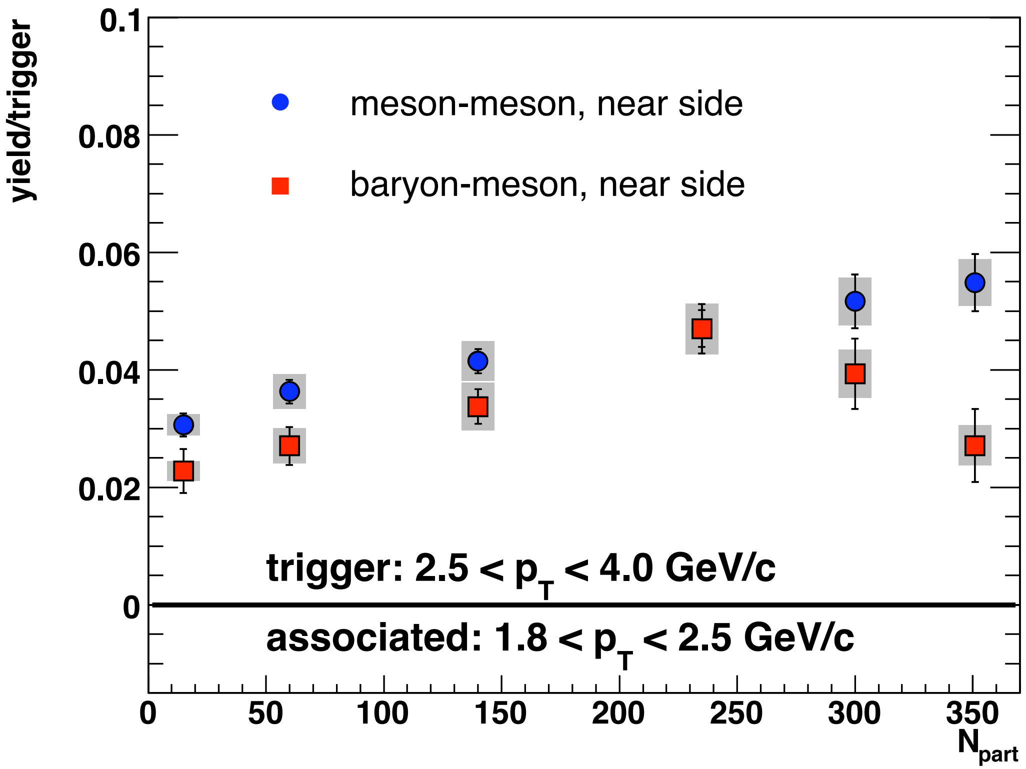

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interactions between hard parton, matter and hadron formation

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Hadron Production

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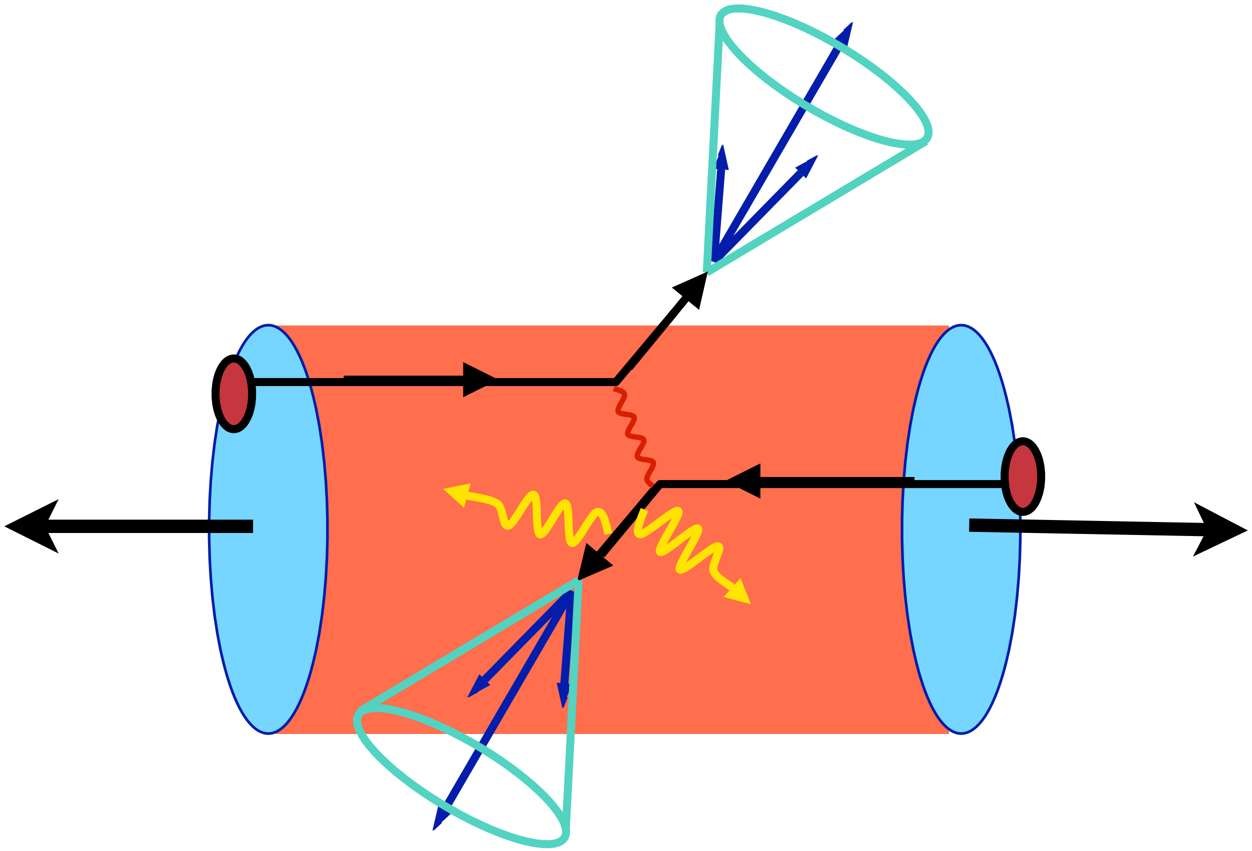

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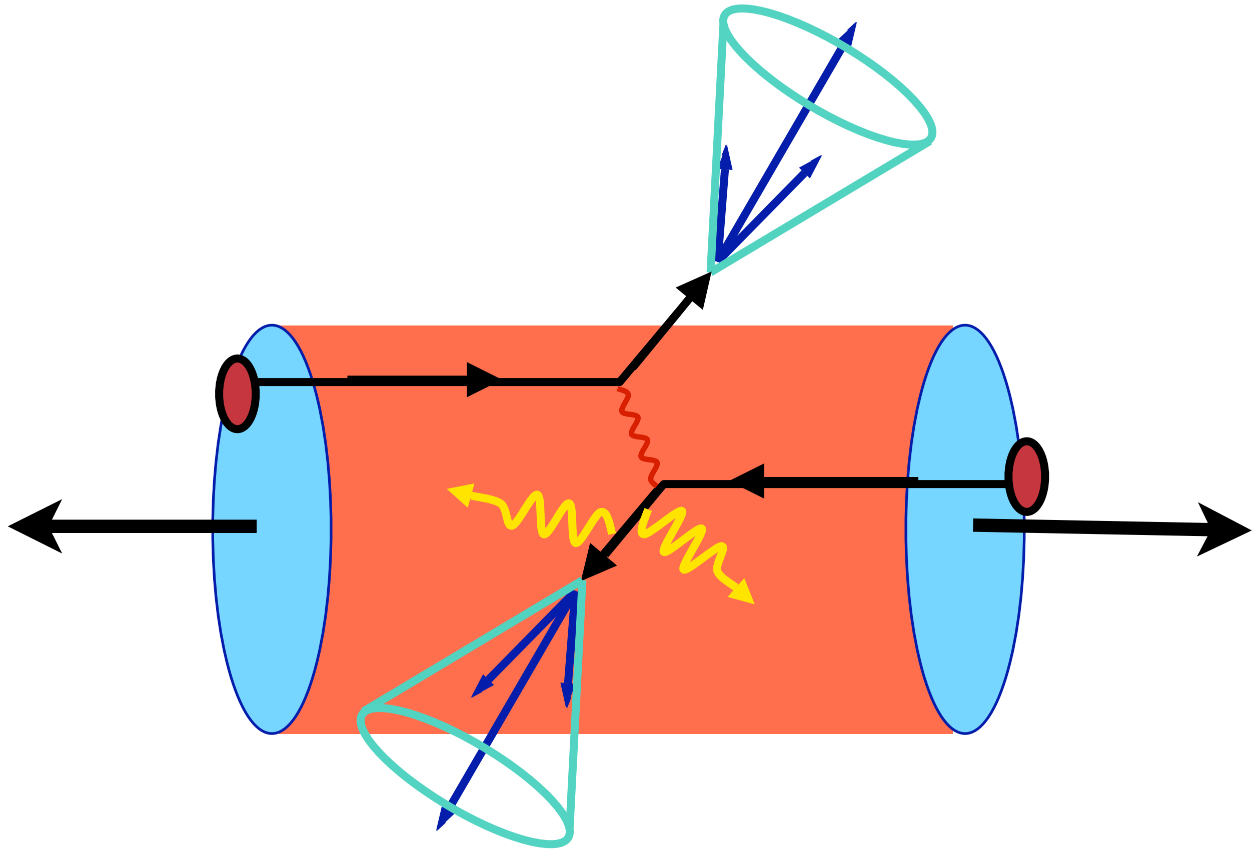

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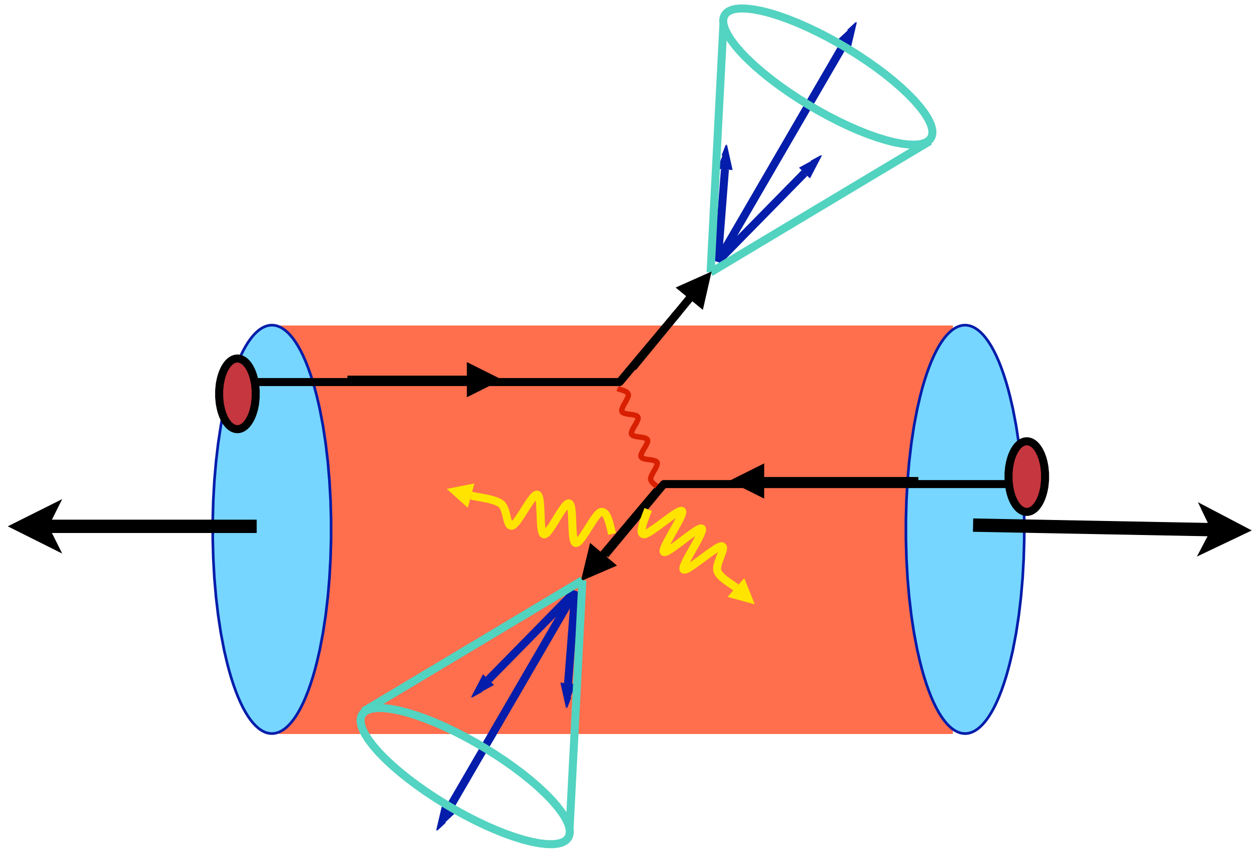
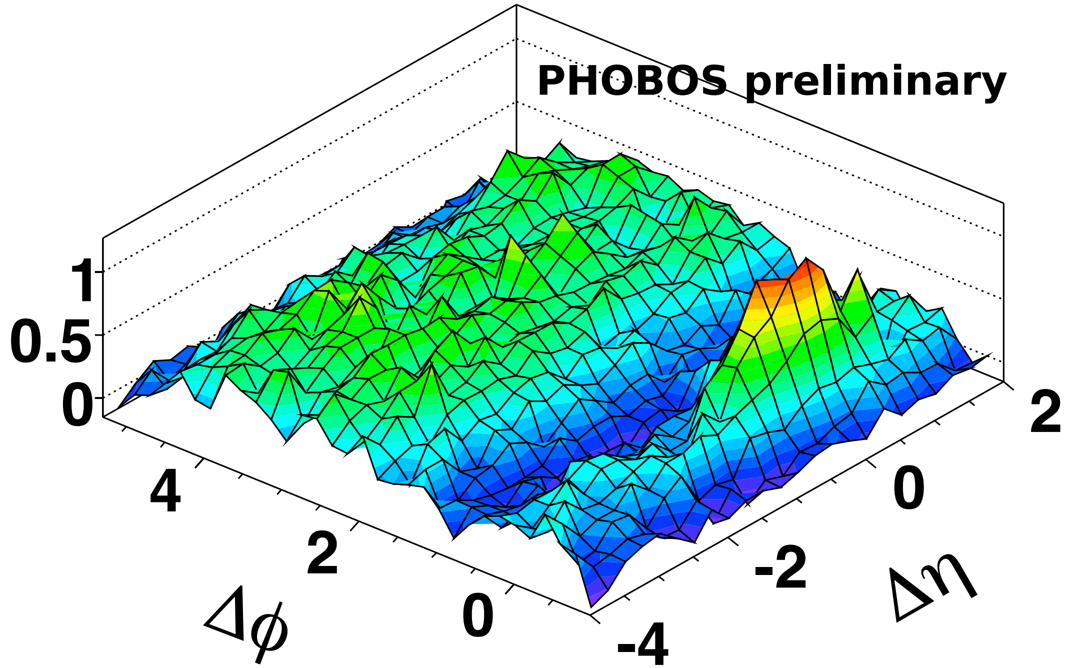


Enter the Ridge



E. Wenger QM2008

$p_{T,trig}$ >2.5GeV/c
$p_{T,assoc}$>20MeV/c

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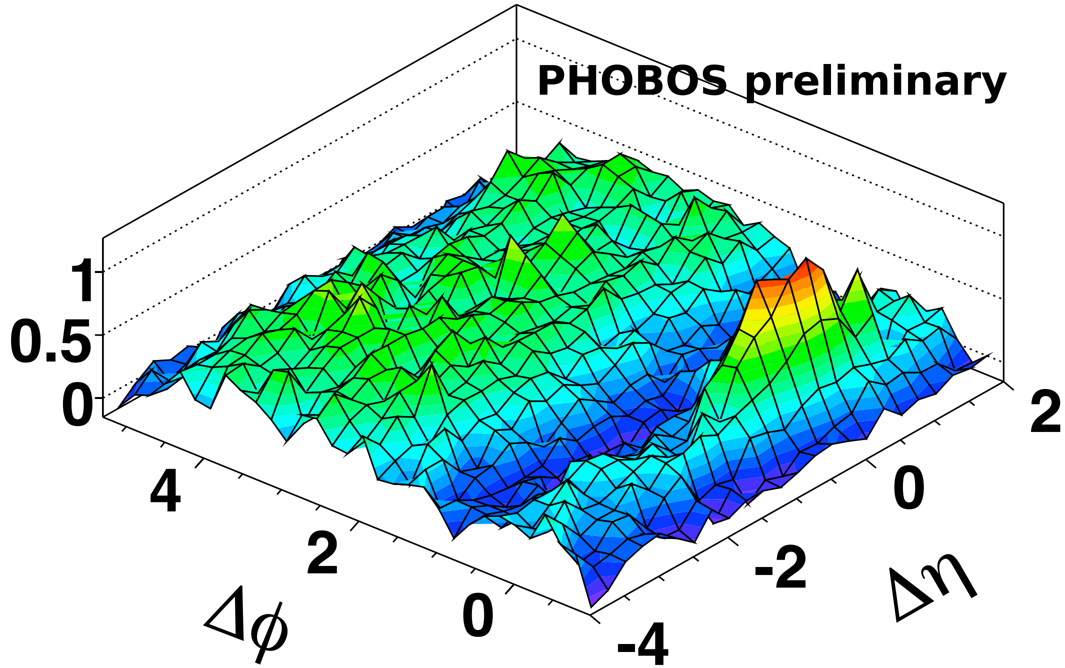

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- correlated with a jet

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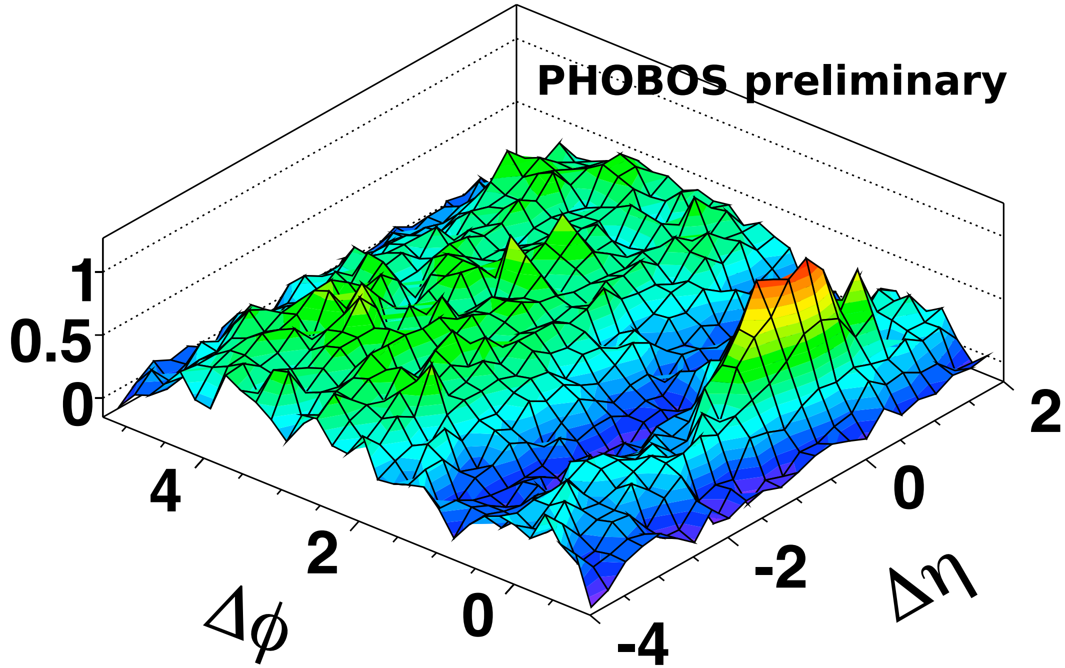

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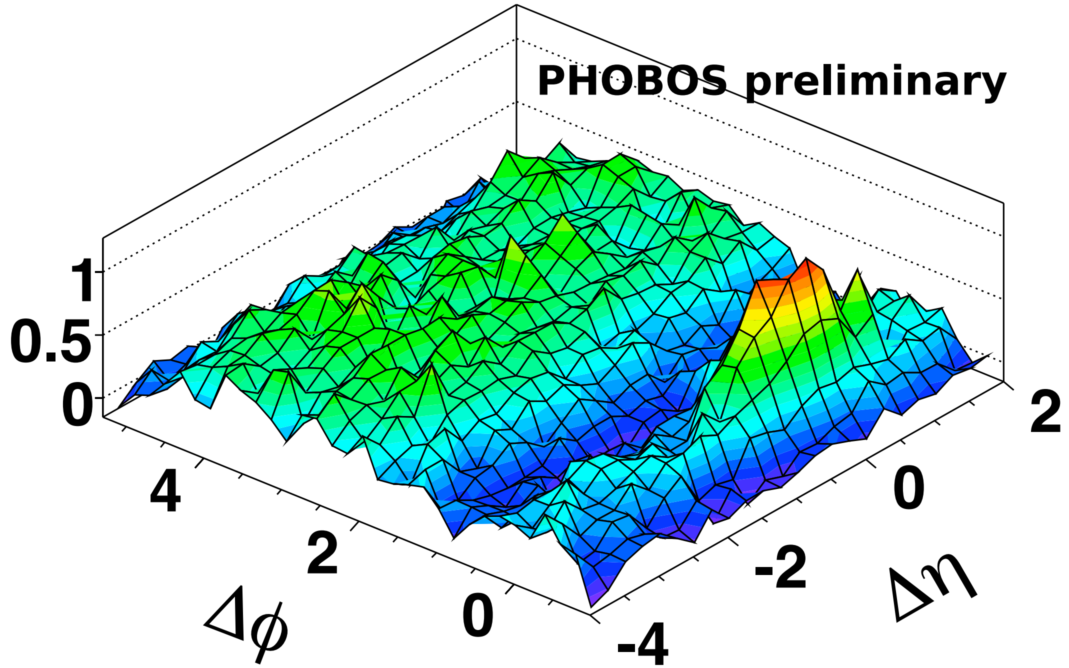
- correlated with a jet
- huge: ridge extends to $|\Delta\eta| > 4$

Enter the Ridge



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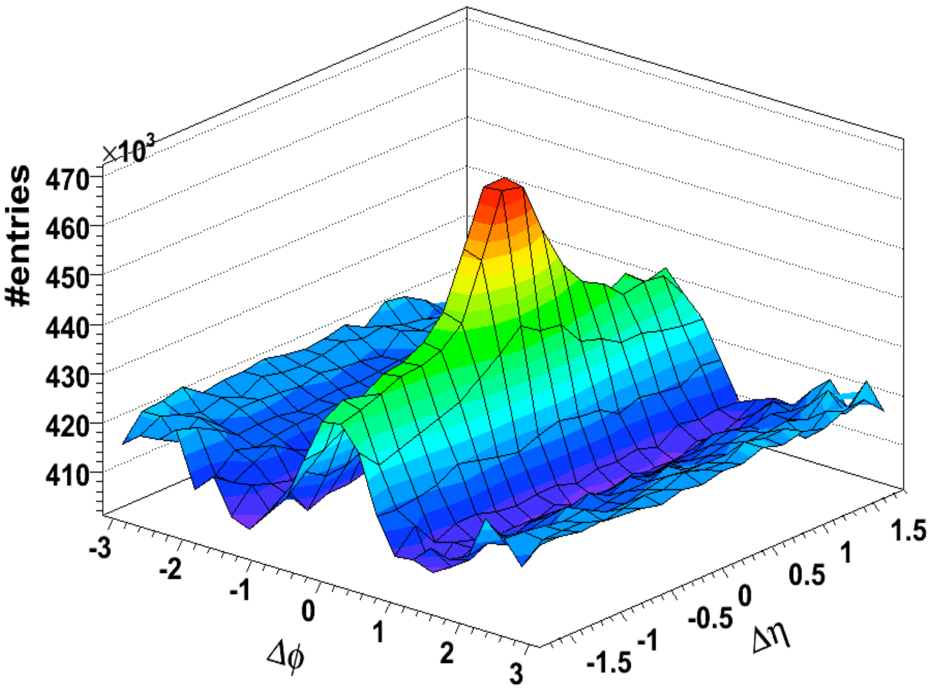
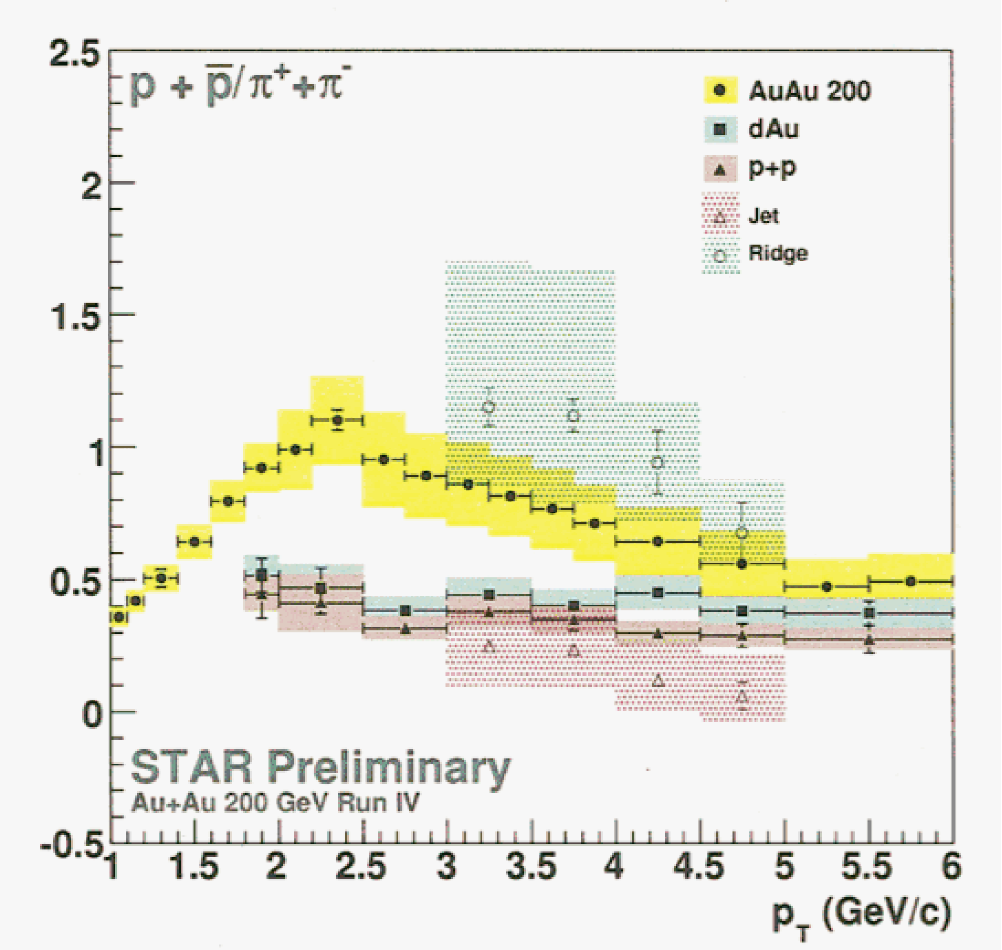
$p_{T,trig}$ >2.5GeV/c
$p_{T,assoc}$>20MeV/c

- correlated with a jet
- huge: ridge extends to |Δη| > 4
- related to baryon/meson differences in the yields?

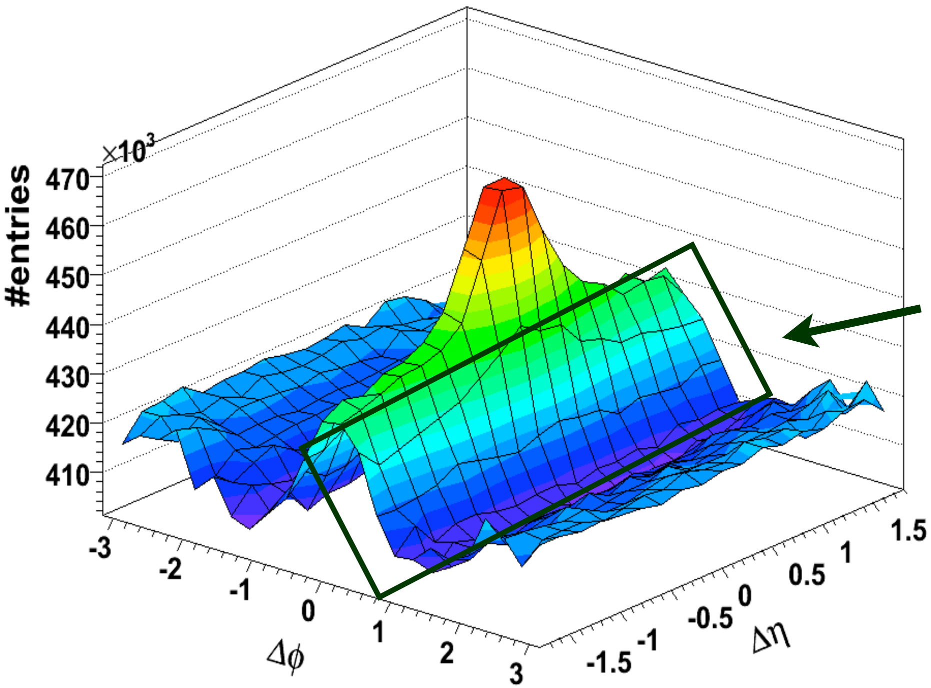
baryons in the ridge



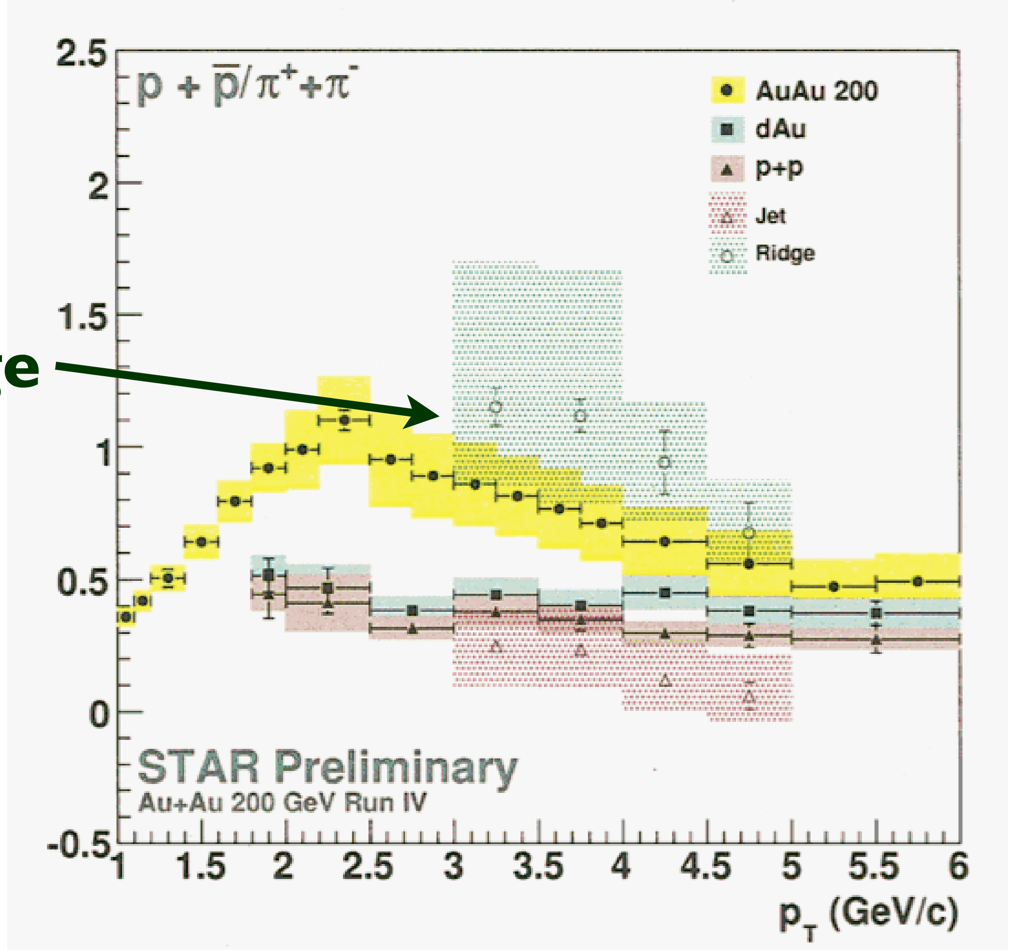


C. Suarez, QM08

baryons in the ridge



ridge



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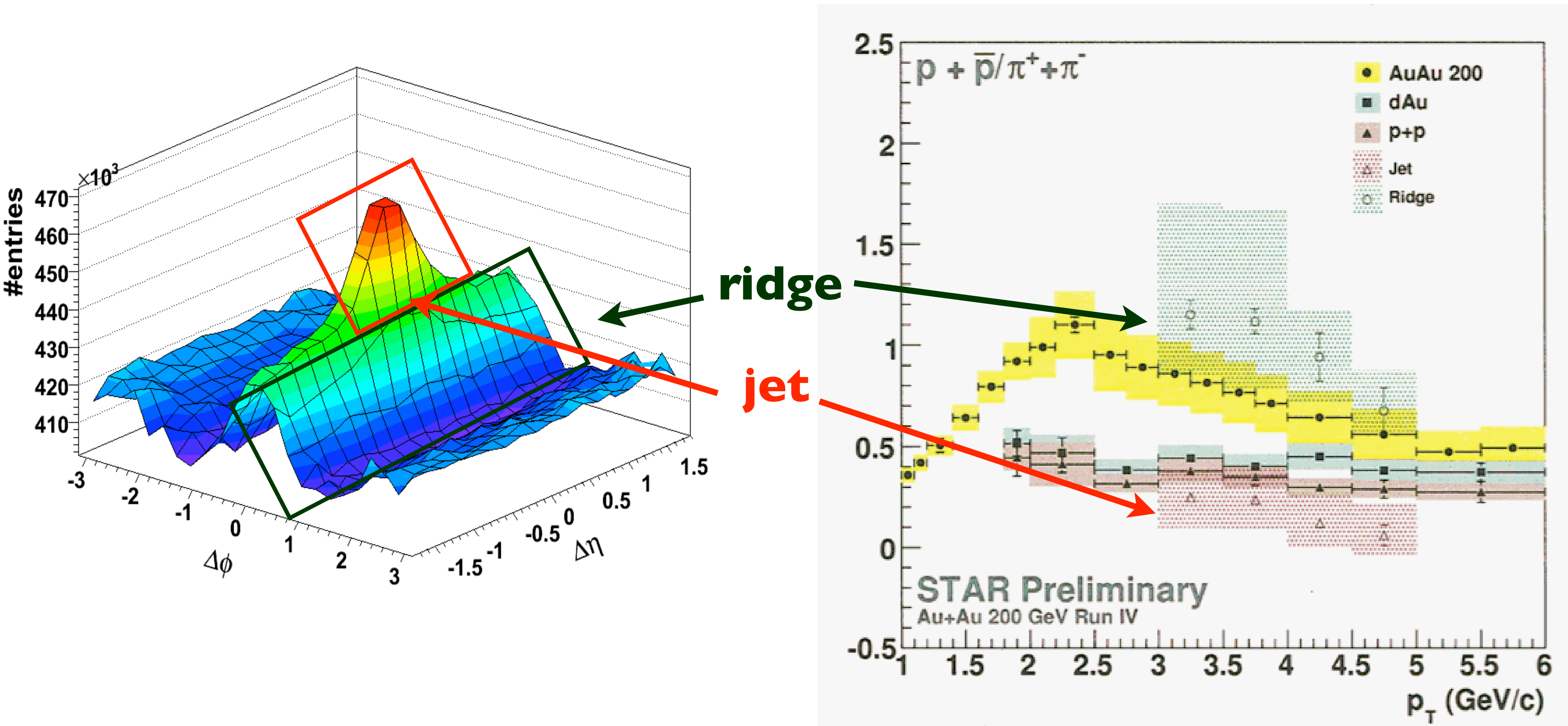

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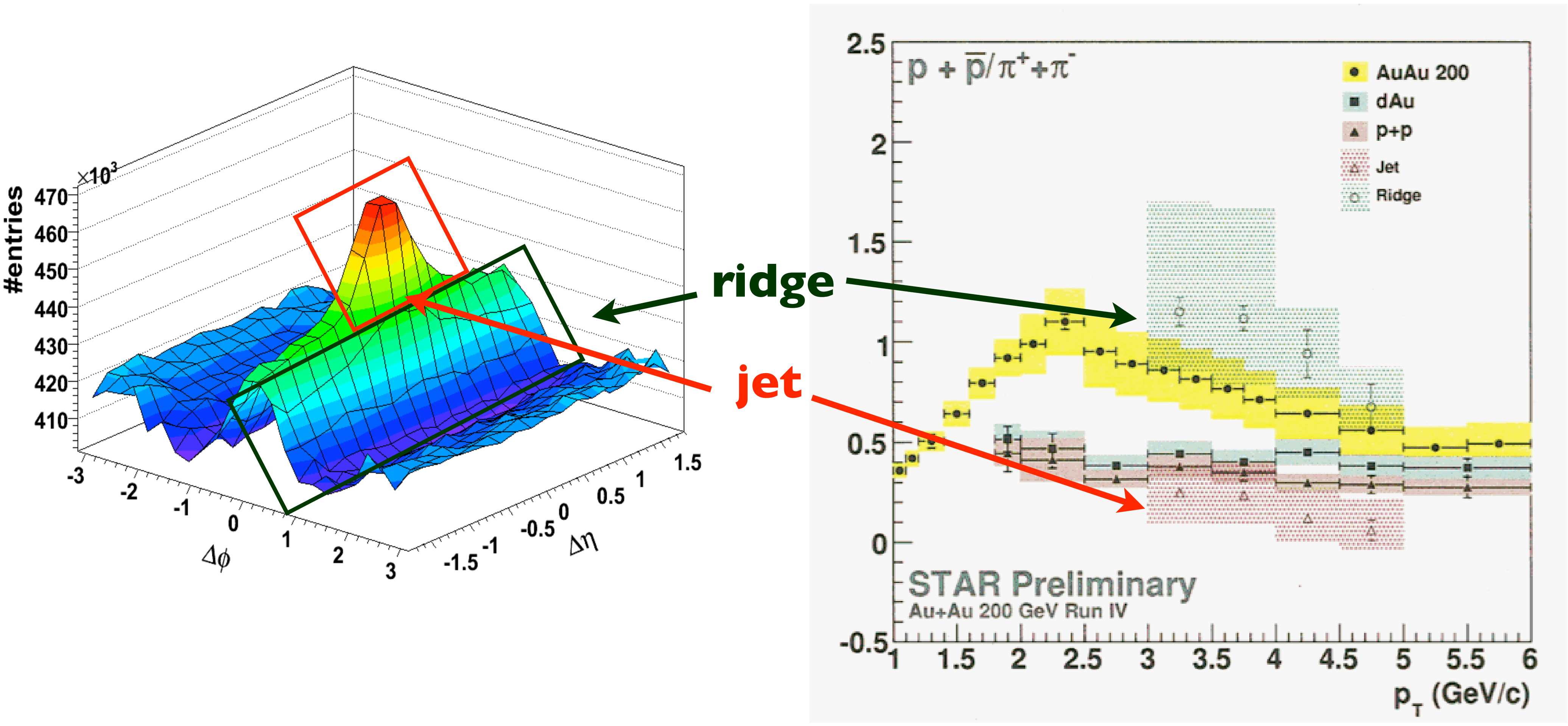
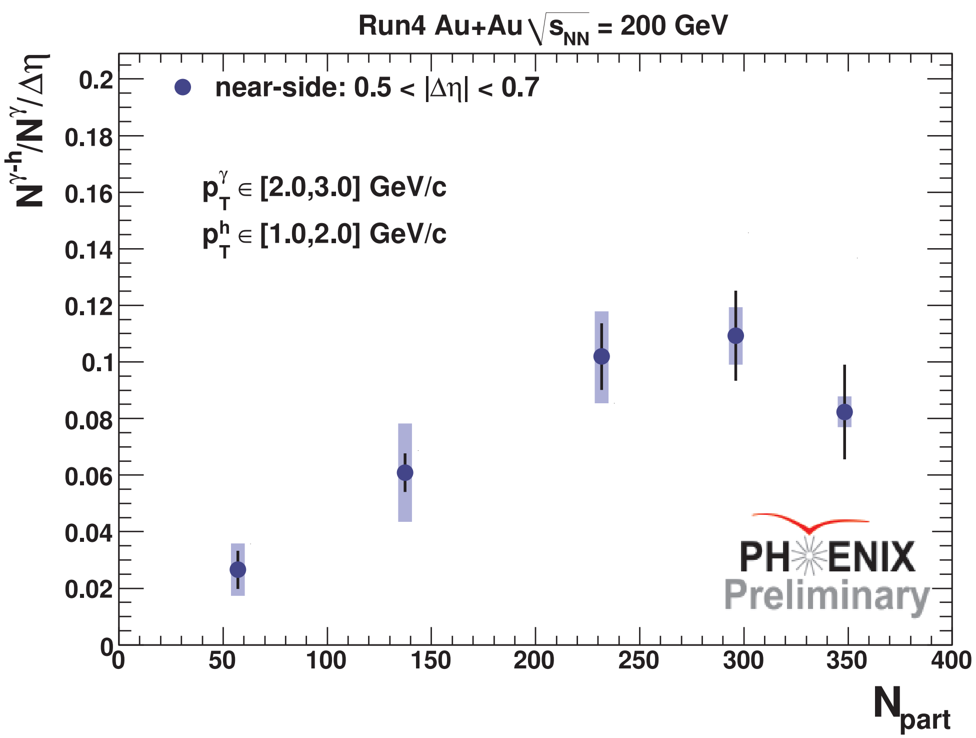


excess baryons in the ridge, jet particle ratios ~unmodified

C. Suarez, QM08

ridge yield vs. centrality



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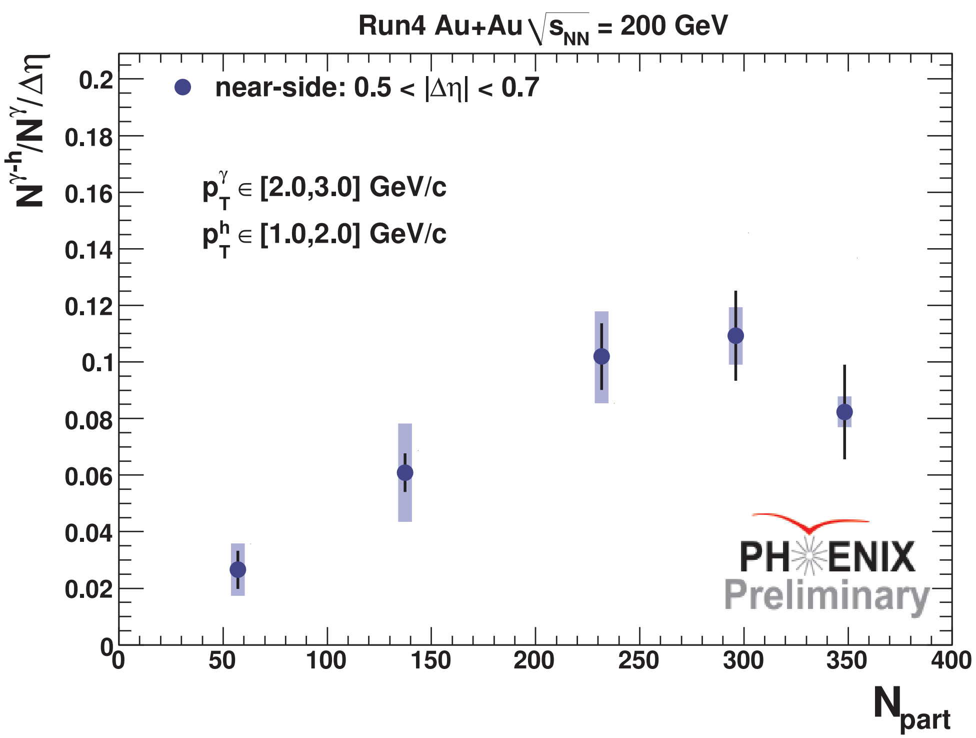

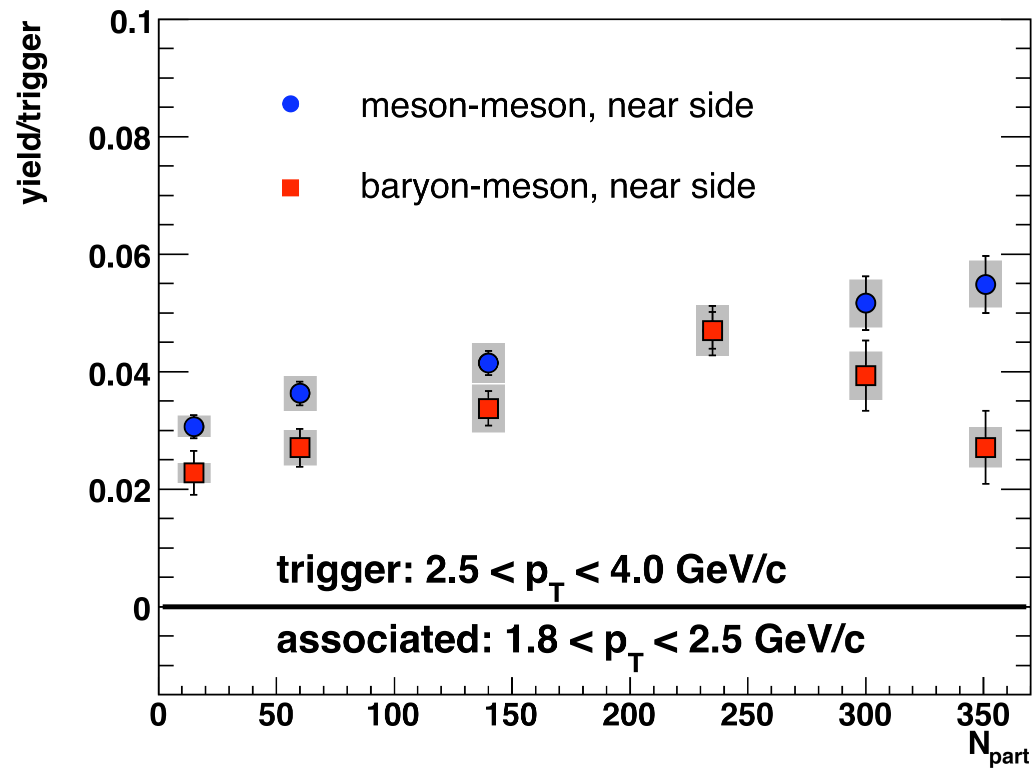

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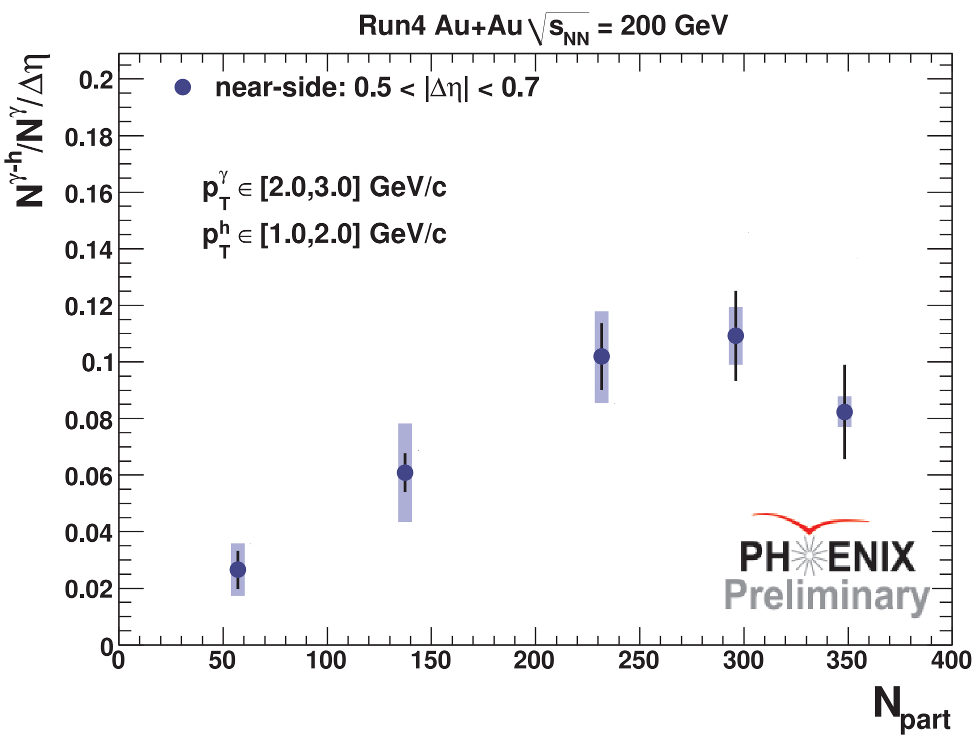

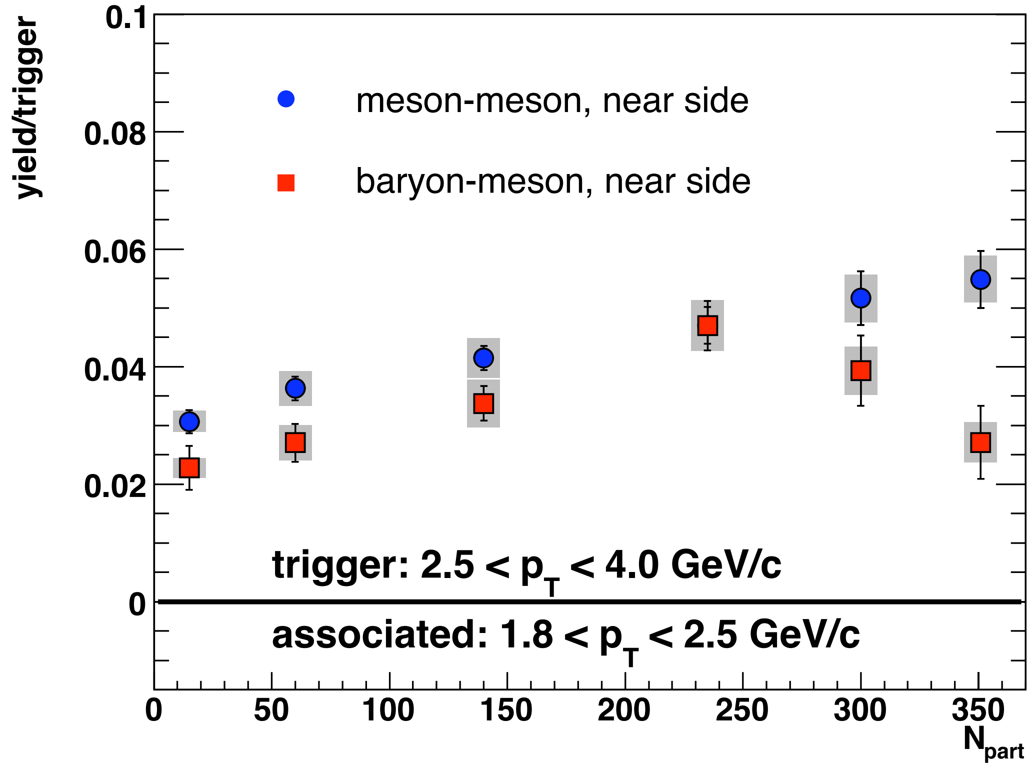

- baryon trigger = ridge trigger

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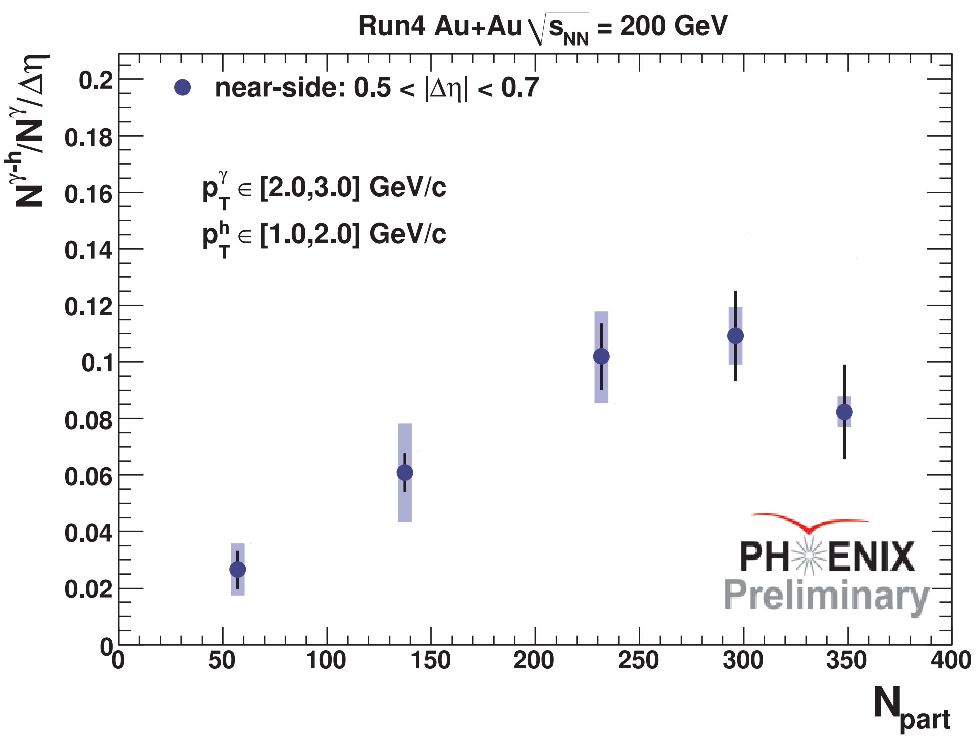
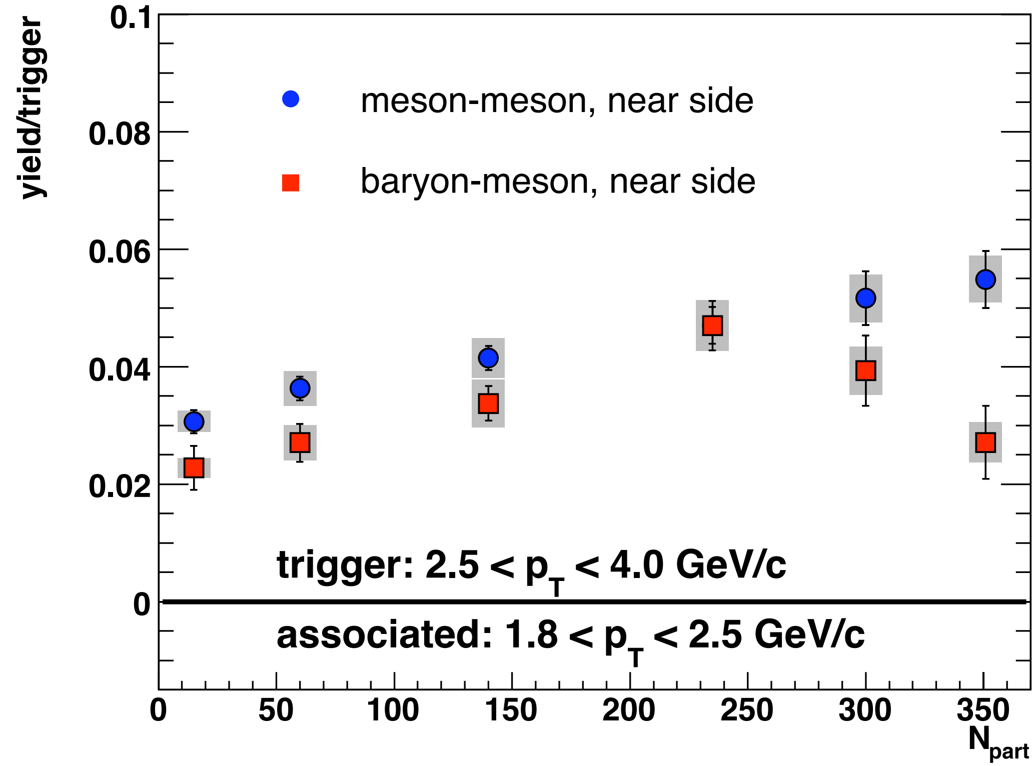
ridge yield vs. centrality





- baryon trigger = ridge trigger
  - most of the time PHENIX misses the jet (σ_{ridge} >> σ_{PHENIX})

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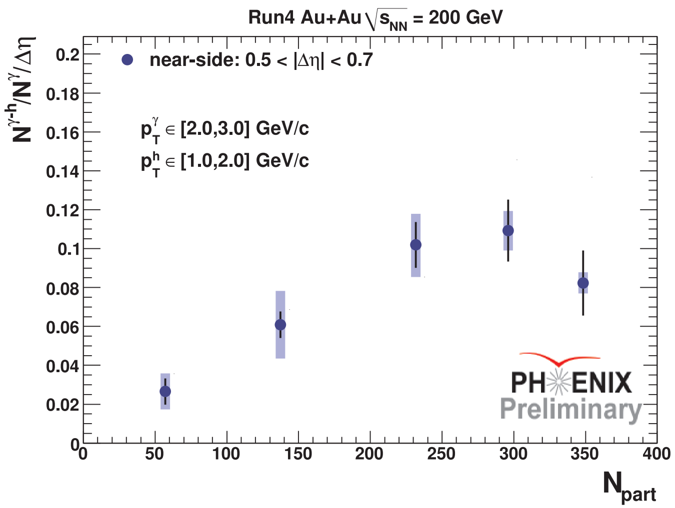
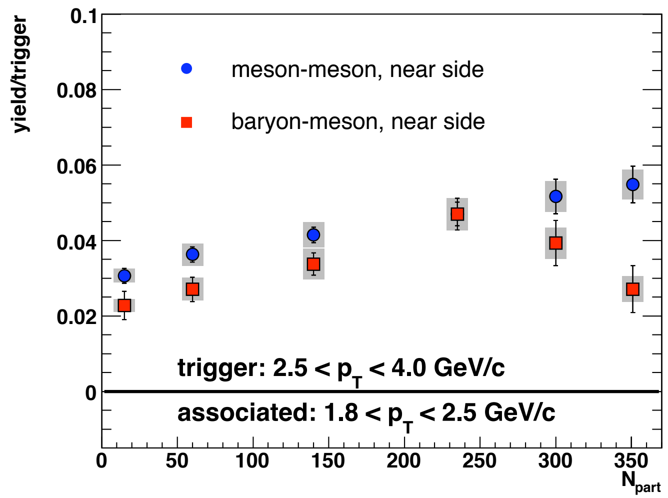
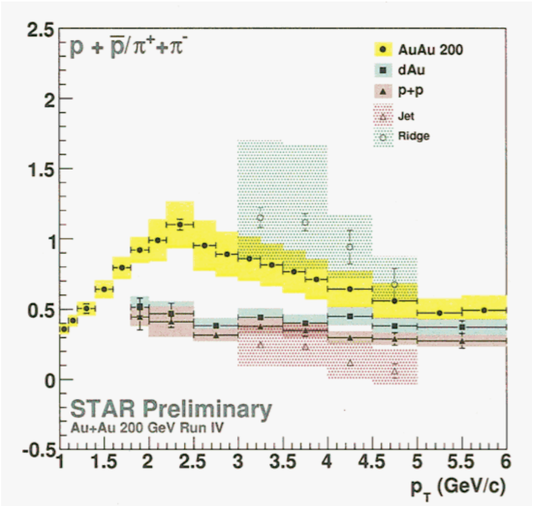
qualitative vs. quantitative







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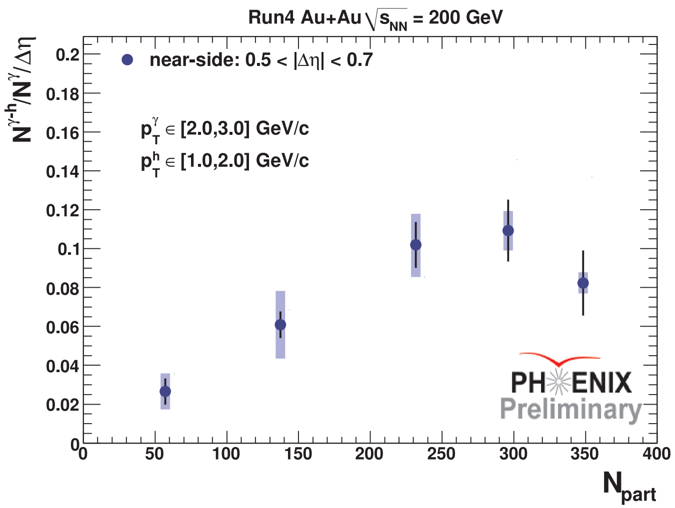
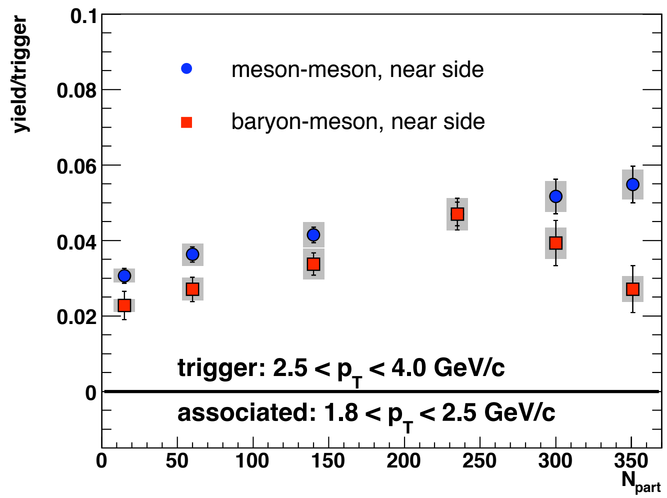
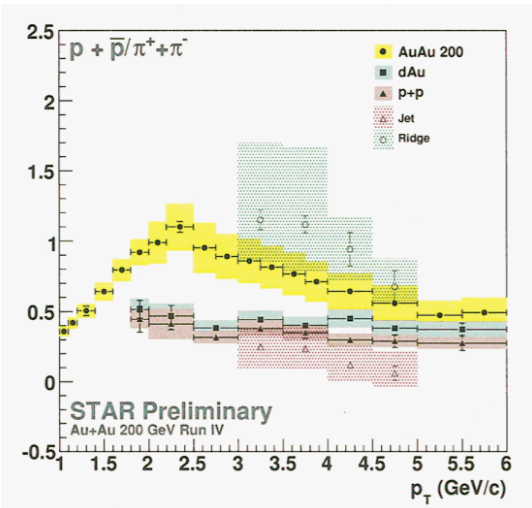
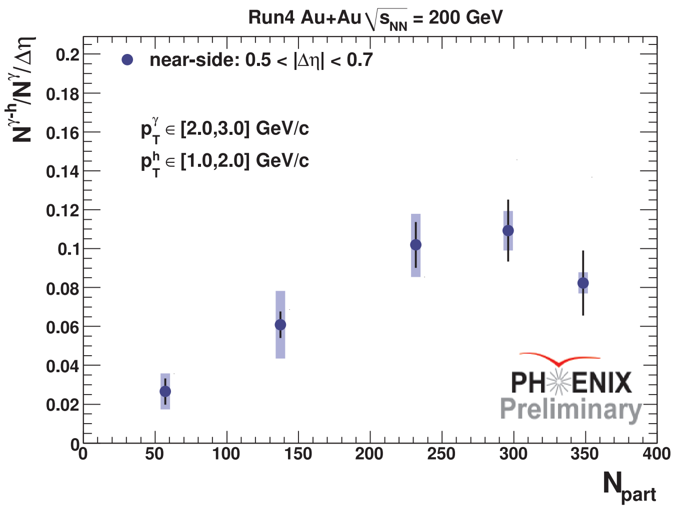


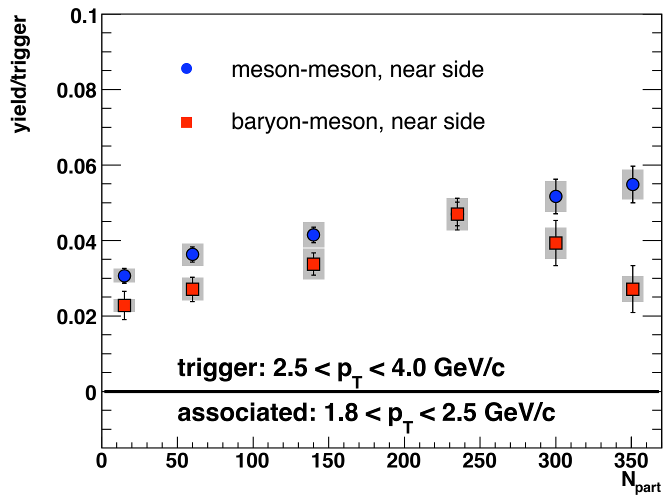


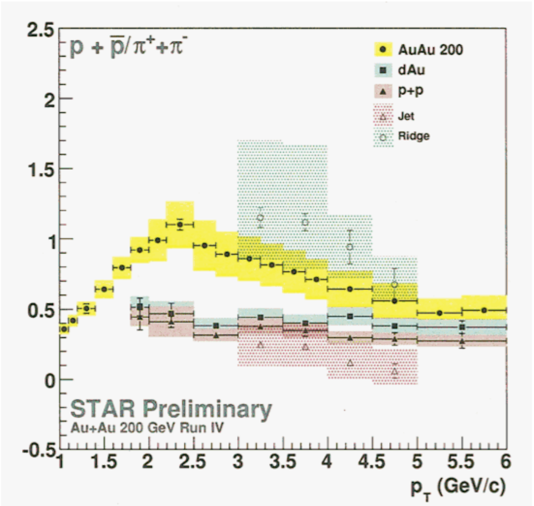


particles	decay γ-hadrons	baryon-meson	hadron-baryon/meson
associated p_T	1-2GeV/c	1.8-2.5GeV/c	3-5GeV/c
η	0.5|Δη|<0.7	|η|<0.35	? (wider than PHENIX)

qualitative vs. quantitative



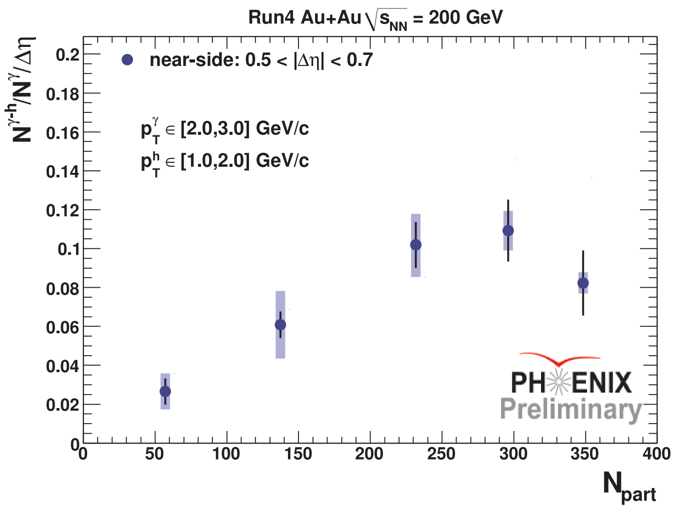


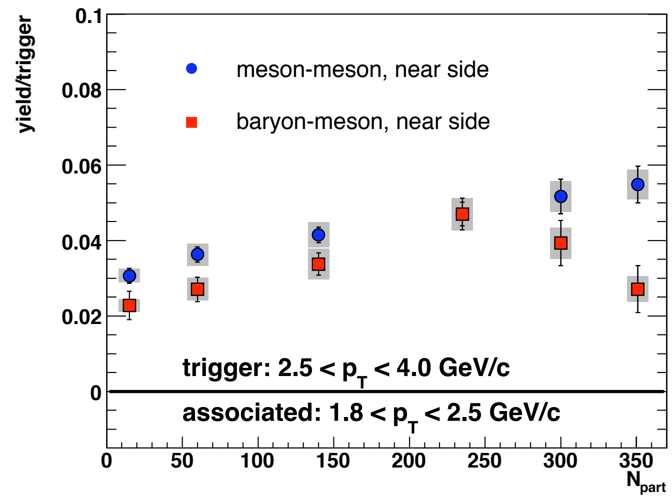


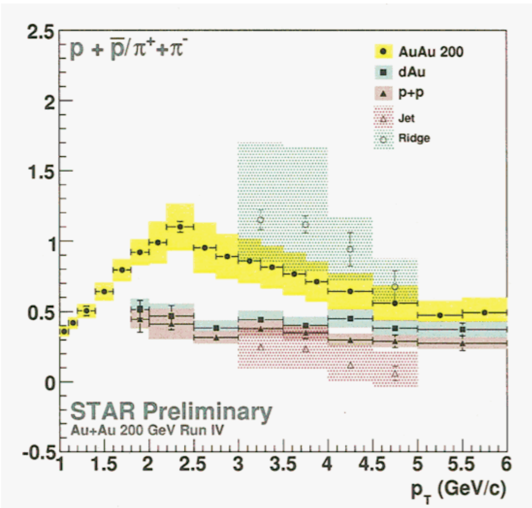
particles	decay γ-hadrons	baryon-meson	hadron-baryon/meson
associated p_T	1-2GeV/c	1.8-2.5GeV/c	3-5GeV/c
η	0.5|Δη|<0.7	|η|<0.35	? (wider than PHENIX)

- quantitative comparisons require the same particles in the same p_T/centrality bins

qualitative vs. quantitative







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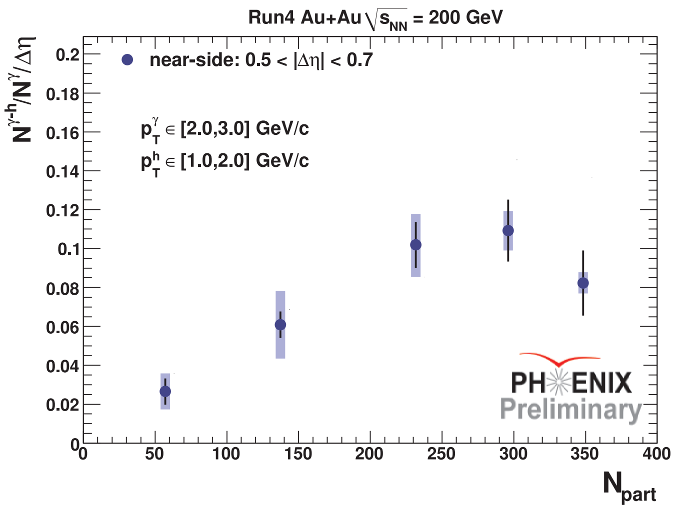
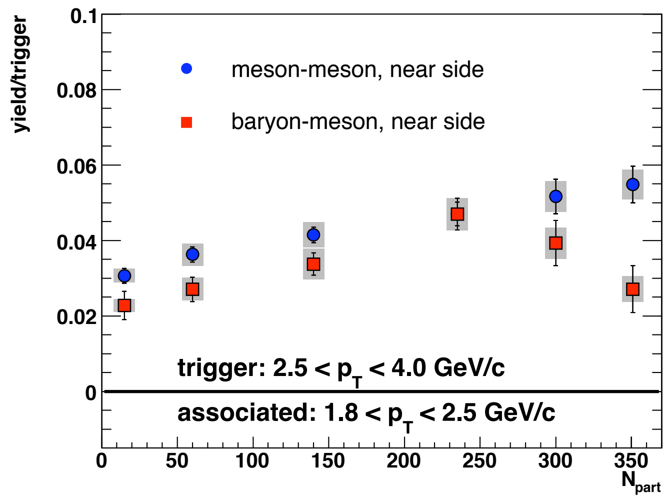
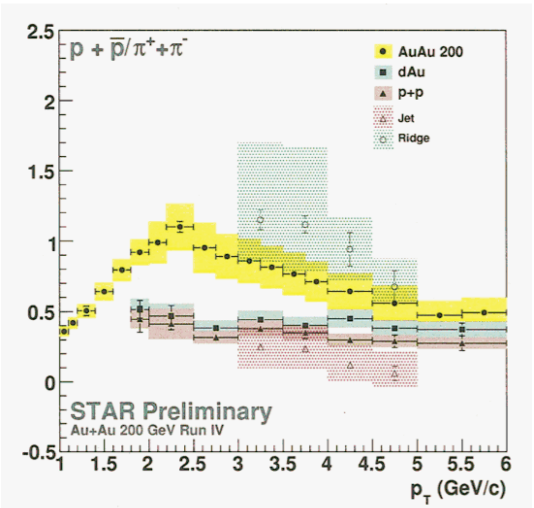
qualitative vs. quantitative







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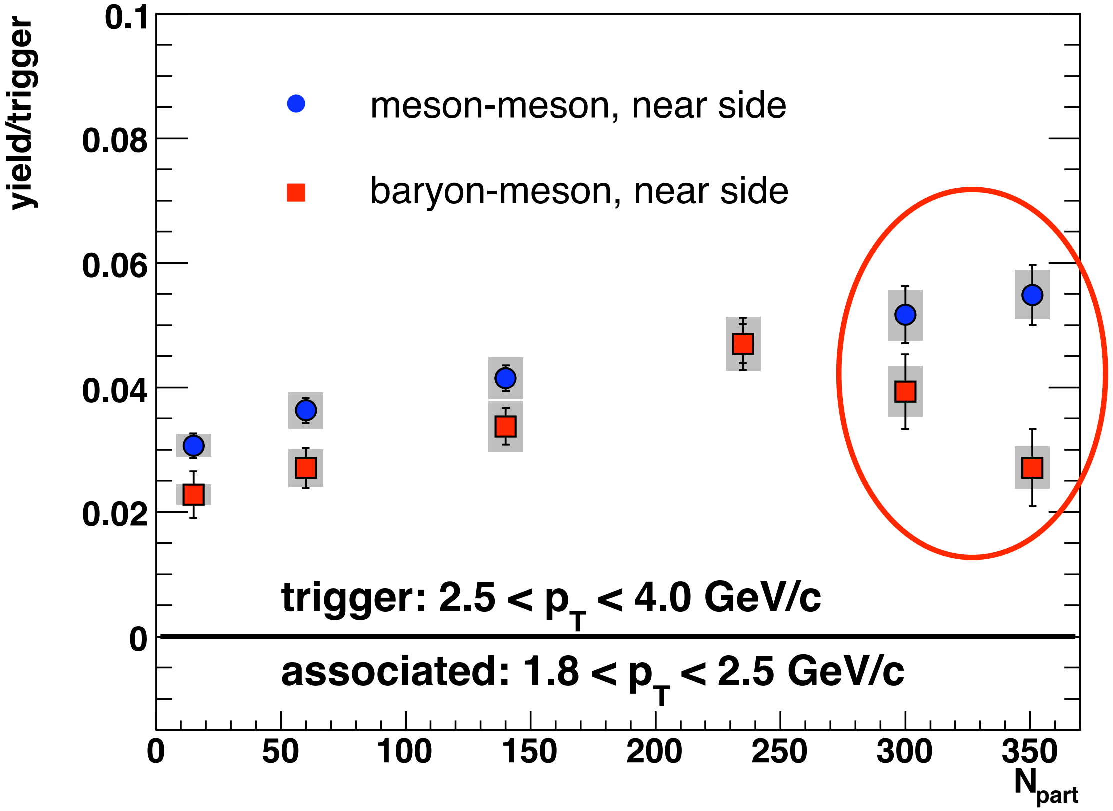
- quantitative comparisons require the same particles in the same p_T/centrality bins
- identified particles!

we might be missing something interesting!

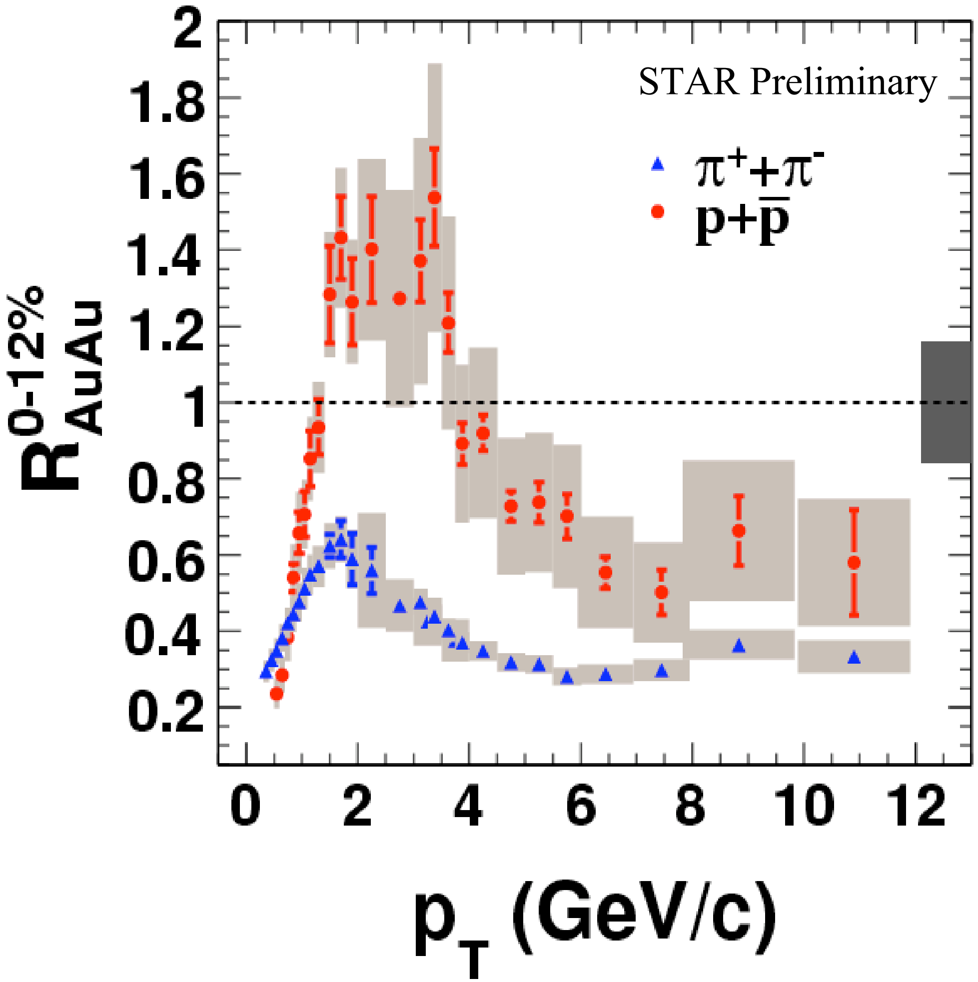
most central collisions



- big drop off in the number of mesons associated with a small angle baryon
- is this something else? baryons without a ridge or a jet?

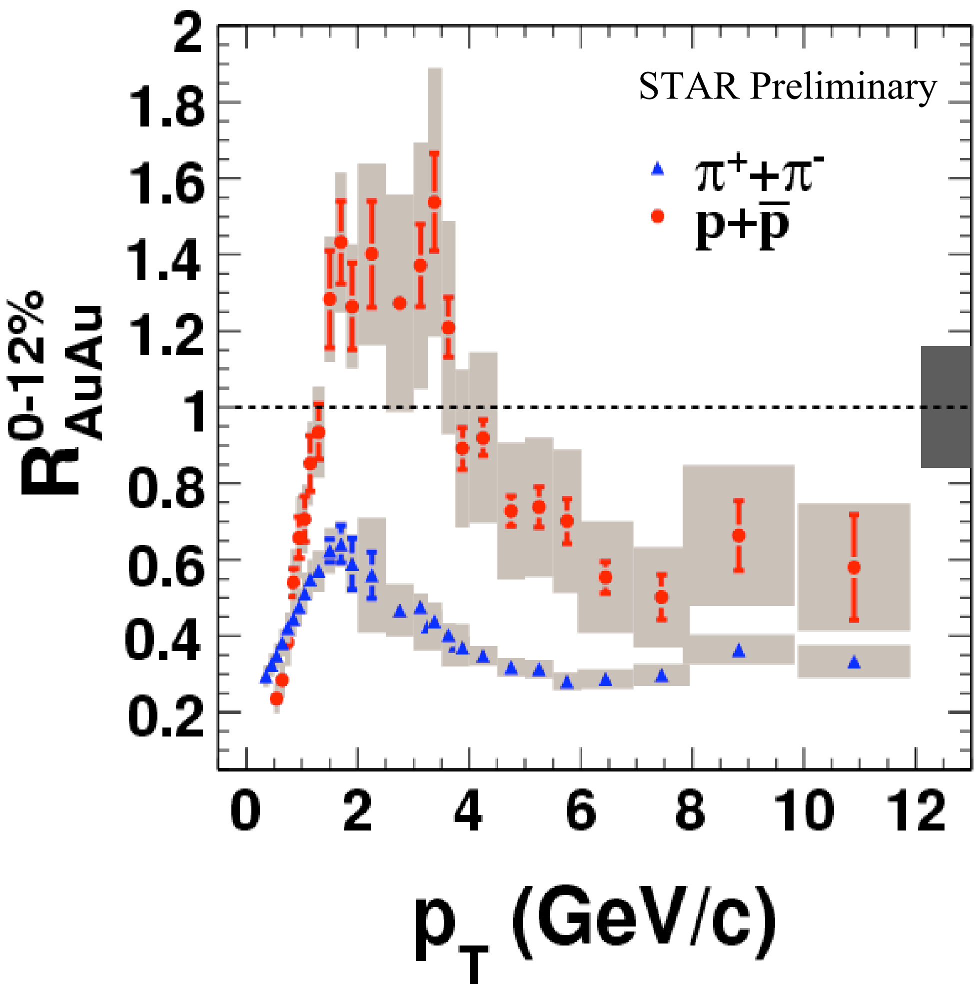
PHENIX, PLB 649 359 (2007)

other baryon anomalies



- even @ high p_T, baryon/meson differences persist!
- however, baryons should if anything be more suppressed because of the larger gluon color factor

other baryon anomalies

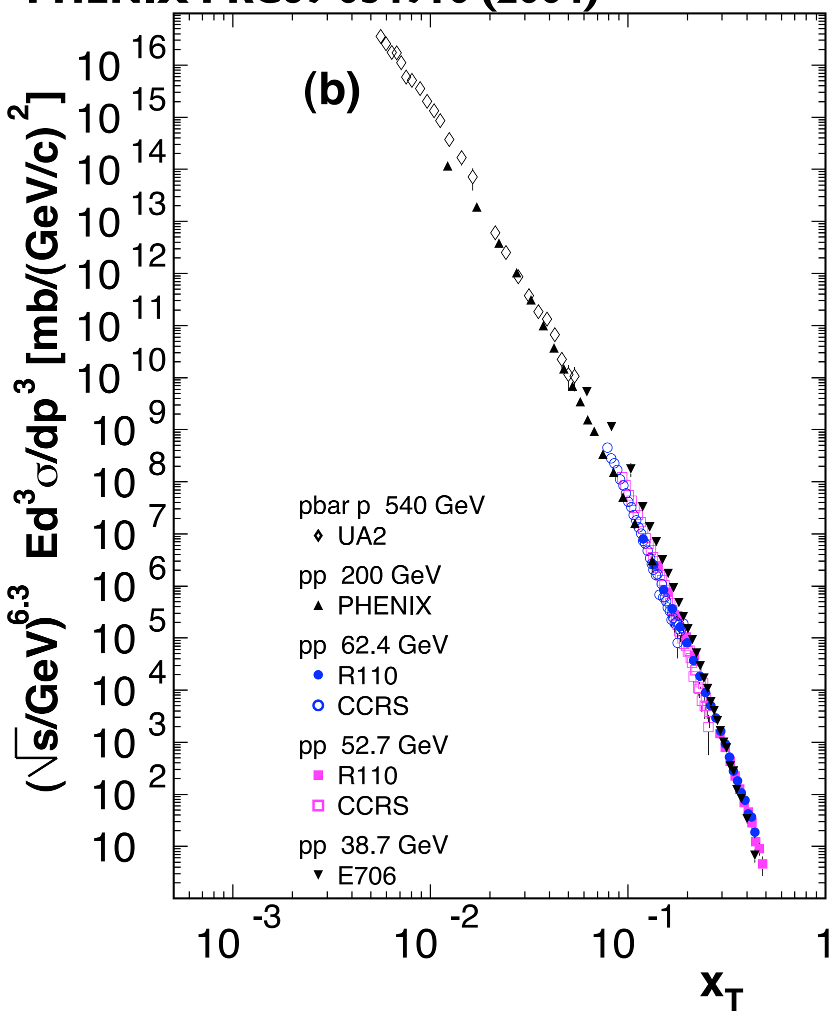


- even @ high p_T, baryon/meson differences persist!
- however, baryons should if anything be more suppressed because of the larger gluon color factor

are baryons coming from somewhere else?

spectra shapes: p+p

PHENIX PRC69 034910 (2004)

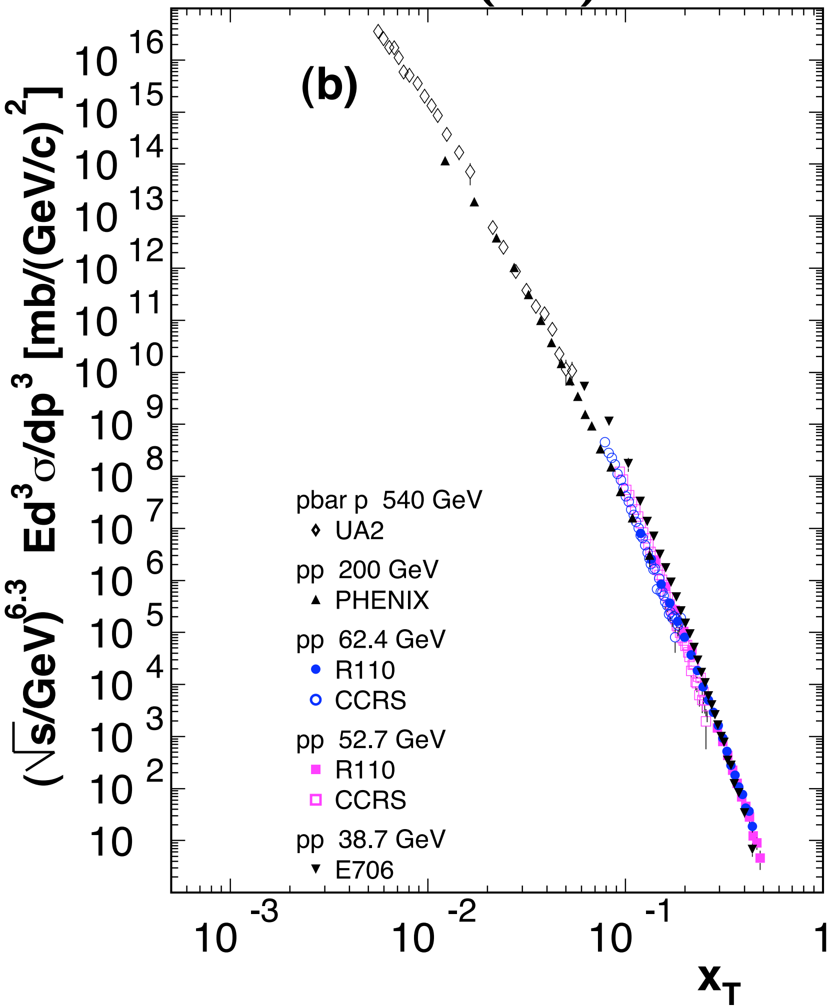


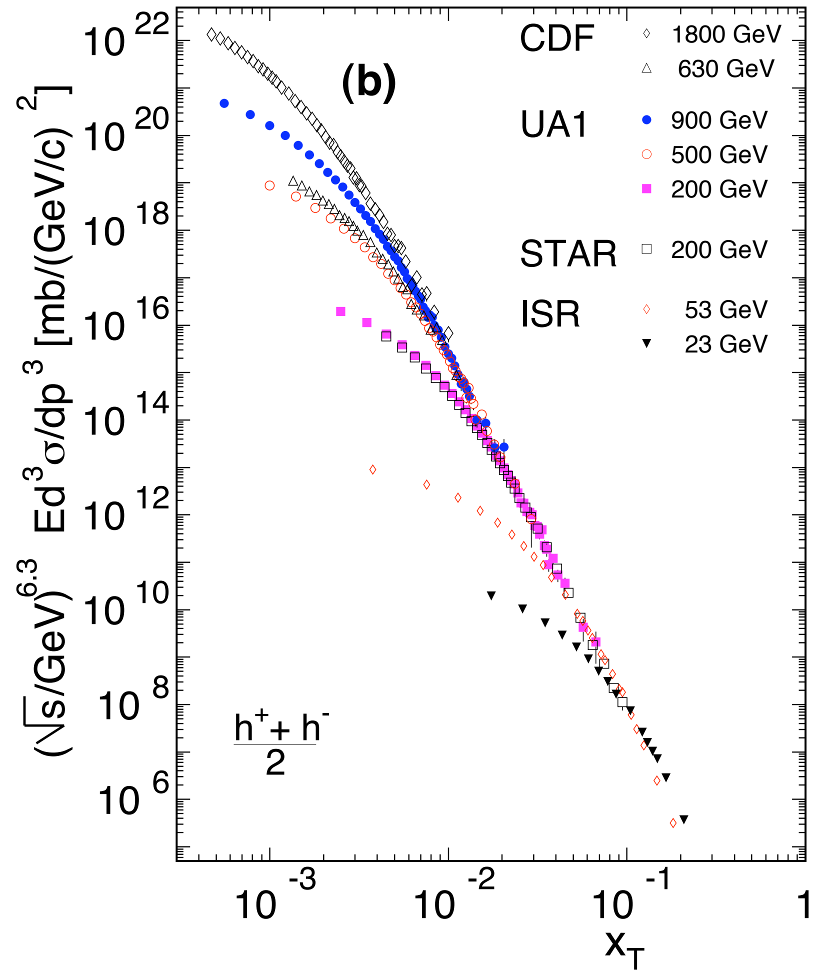
$x_T = 2p_T/s^{1/2}$

spectra shapes: p+p

$x_T = 2p_T/s^{1/2}$

PHENIX PRC69 034910 (2004)





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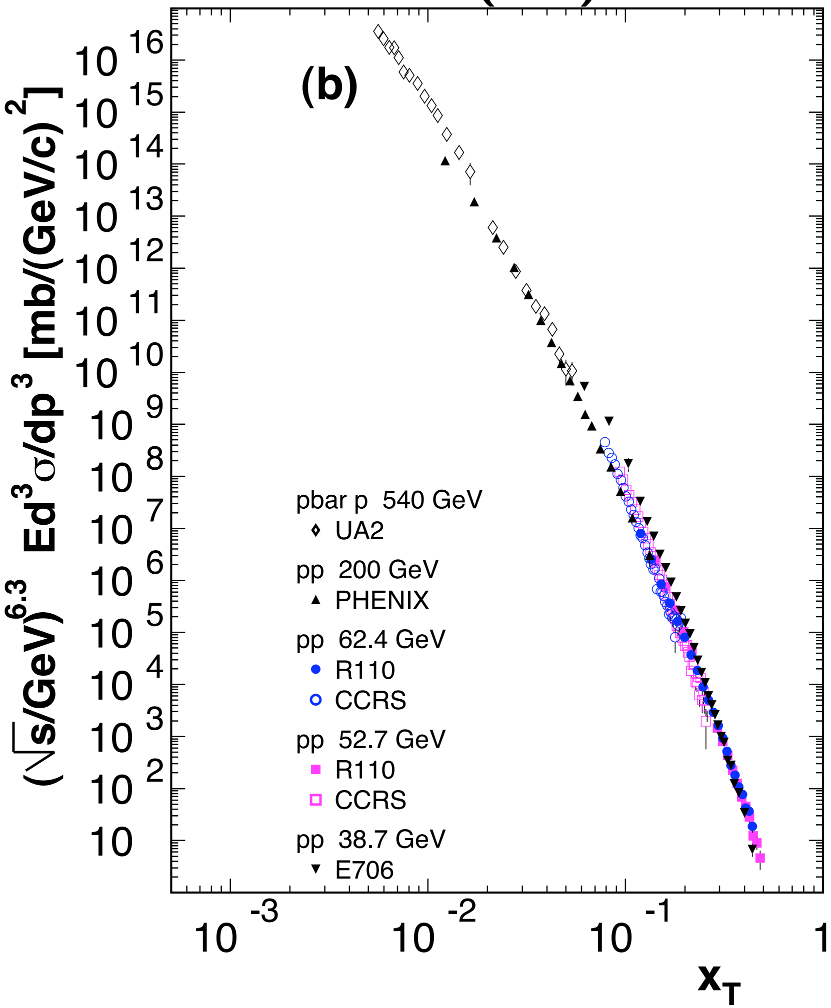
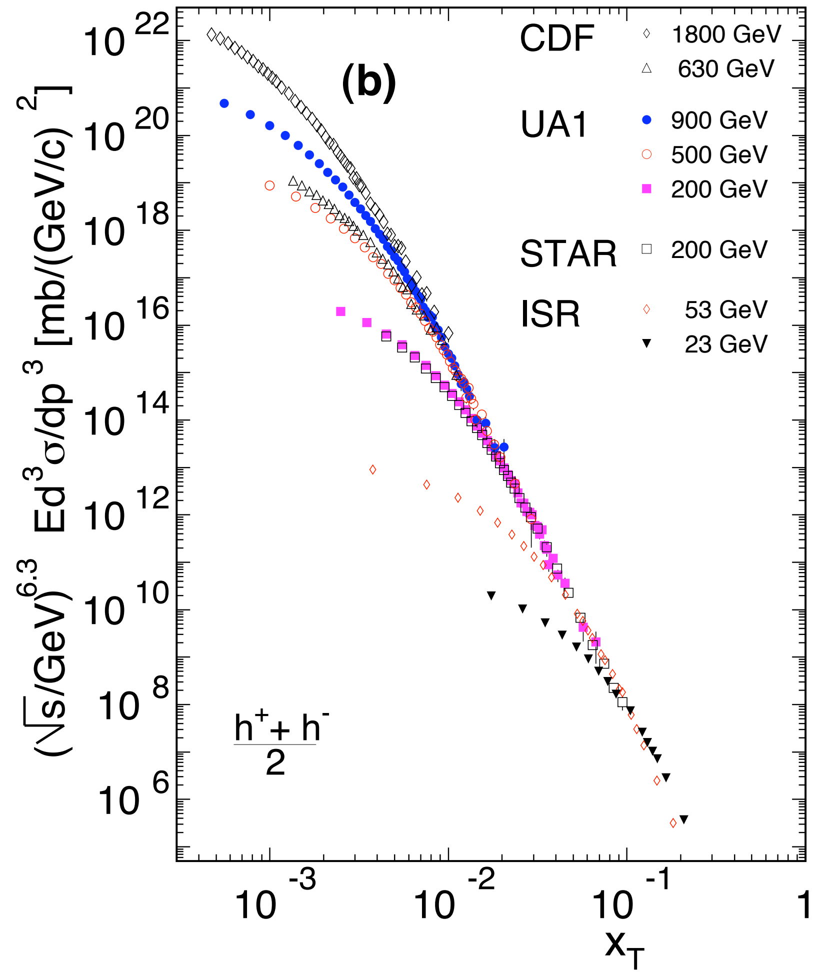
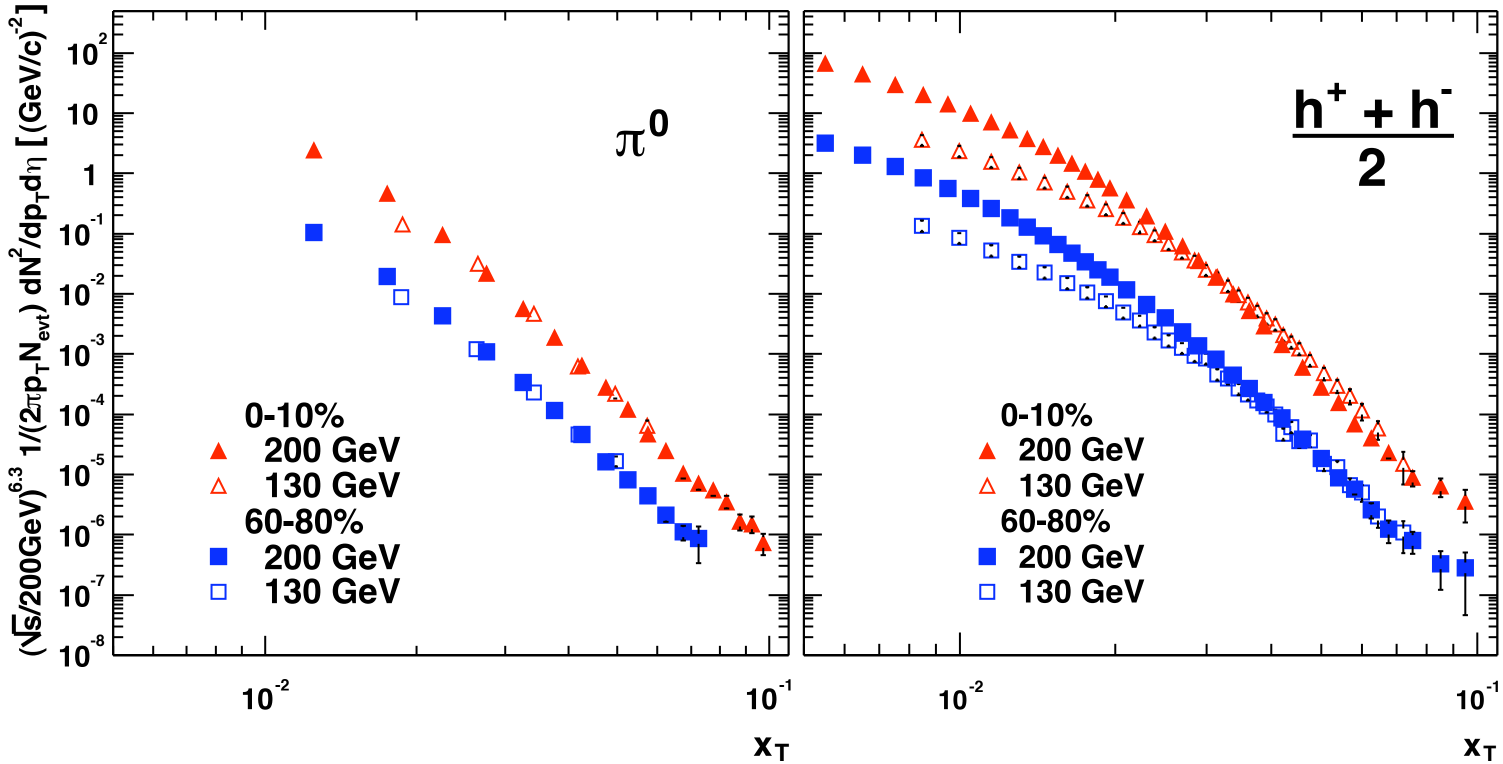




π^0 & hadron production scale with constant power

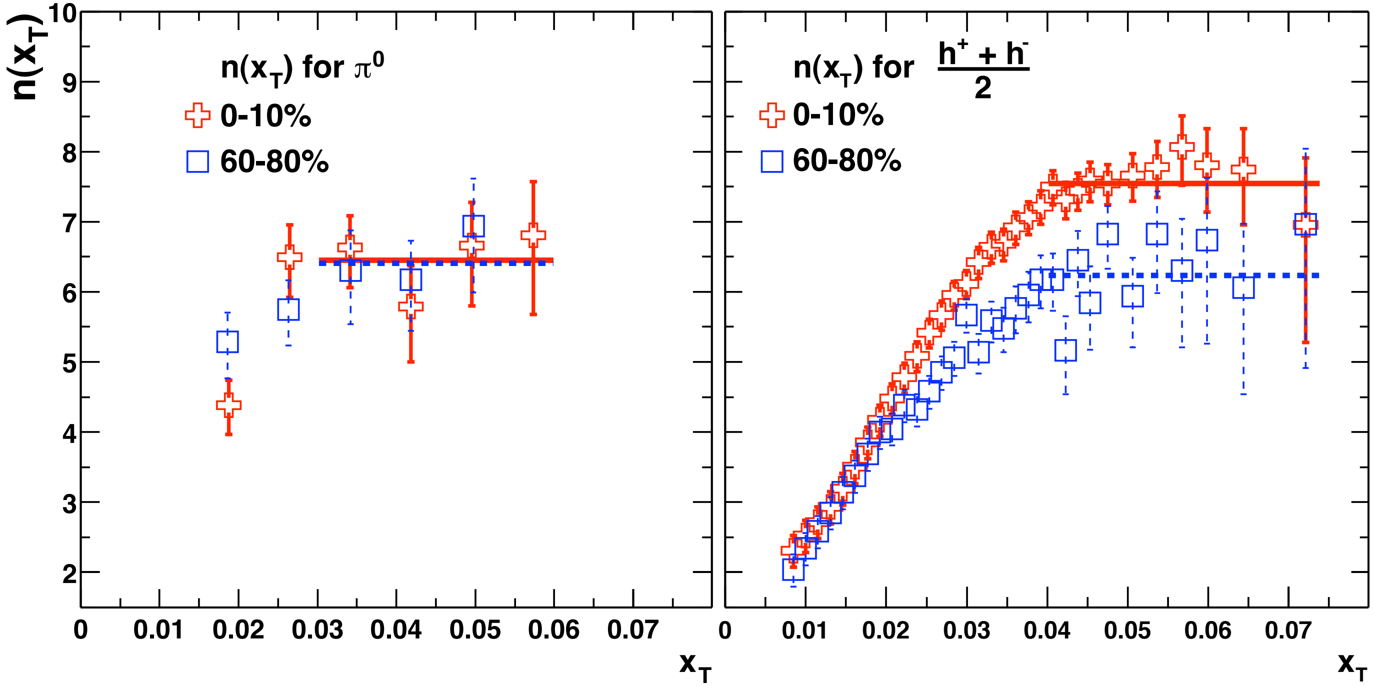
spectra shapes: Au+Au

PHENIX PRC69 034910 (2004)



π^0: same scaling as in p+p
hadrons: significant deviations from scaling

more quantitatively

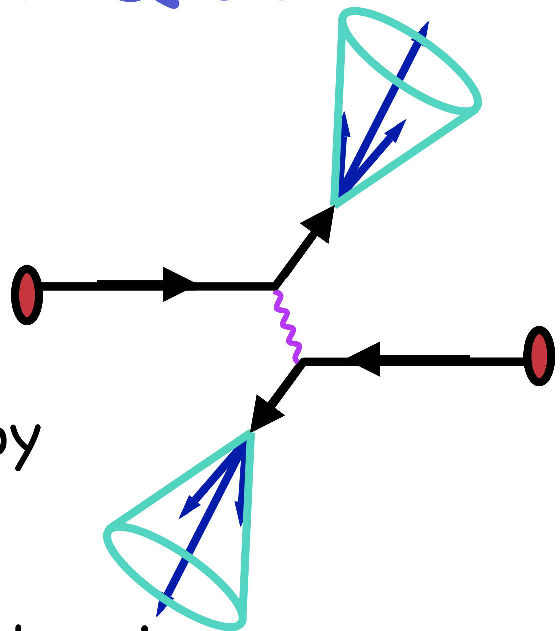


$$n(x_T) = \frac{log(yield(x_T, 130GeV)/yield(x_T, 200GeV))}{log(200/130)}$$

- baryons raise the effective power at fixed x_T
- why?

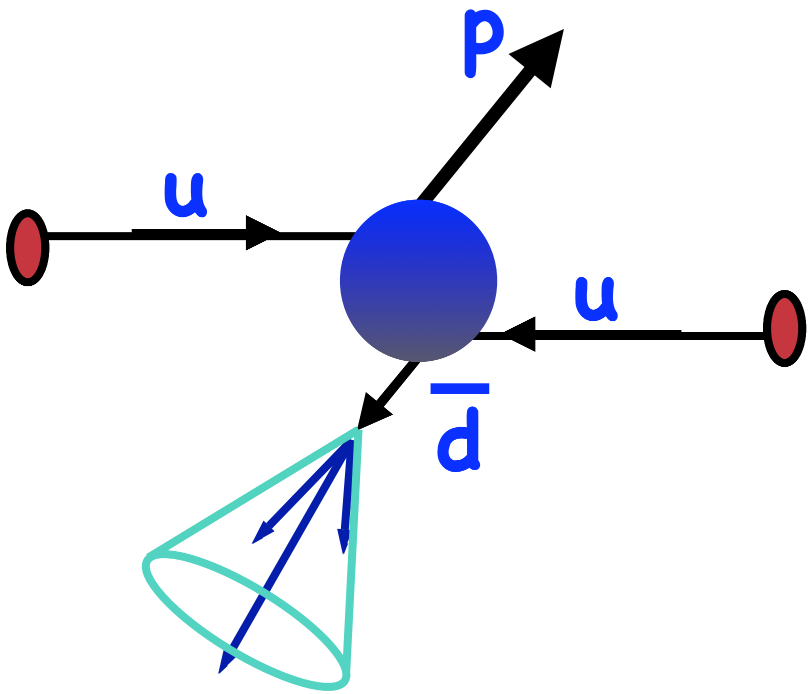
PHENIX PRC69 034910 (2004)

Hadron Production in QCD



- 2→2 quark or gluon scattering followed by fragmentation
  - understood as creating quark/anti-quark pairs which form hadrons
  - works well for mesons
- however baryoon production is suppressed
  - 3 quarks are needed
  - however, this suppression could increase sensitivity to novel QCD processes...

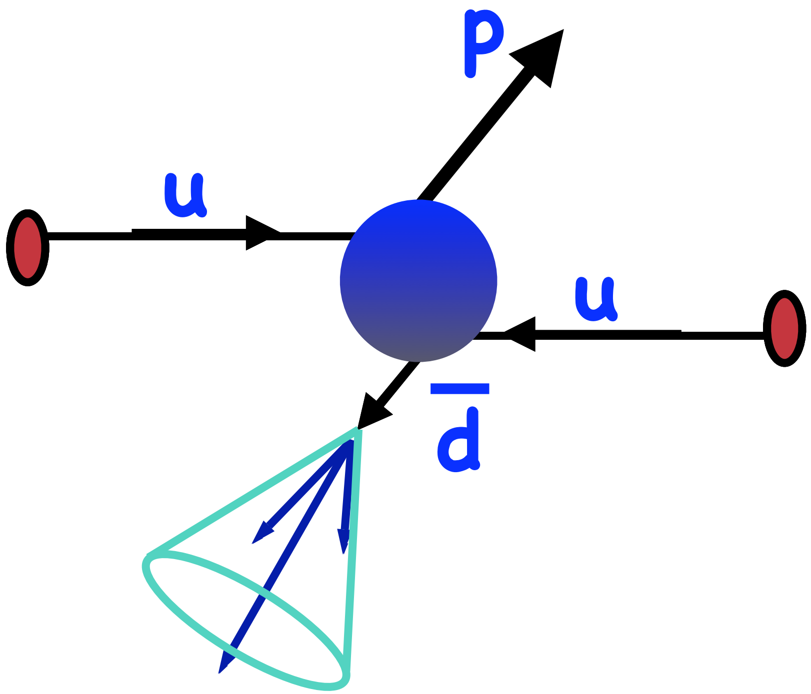
direct proton production



$uu \rightarrow p\bar{d}$

Brodsky, AS
PLB 668 111 (2008)

direct proton production



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- color singlet proton directly produced within hard subprocess

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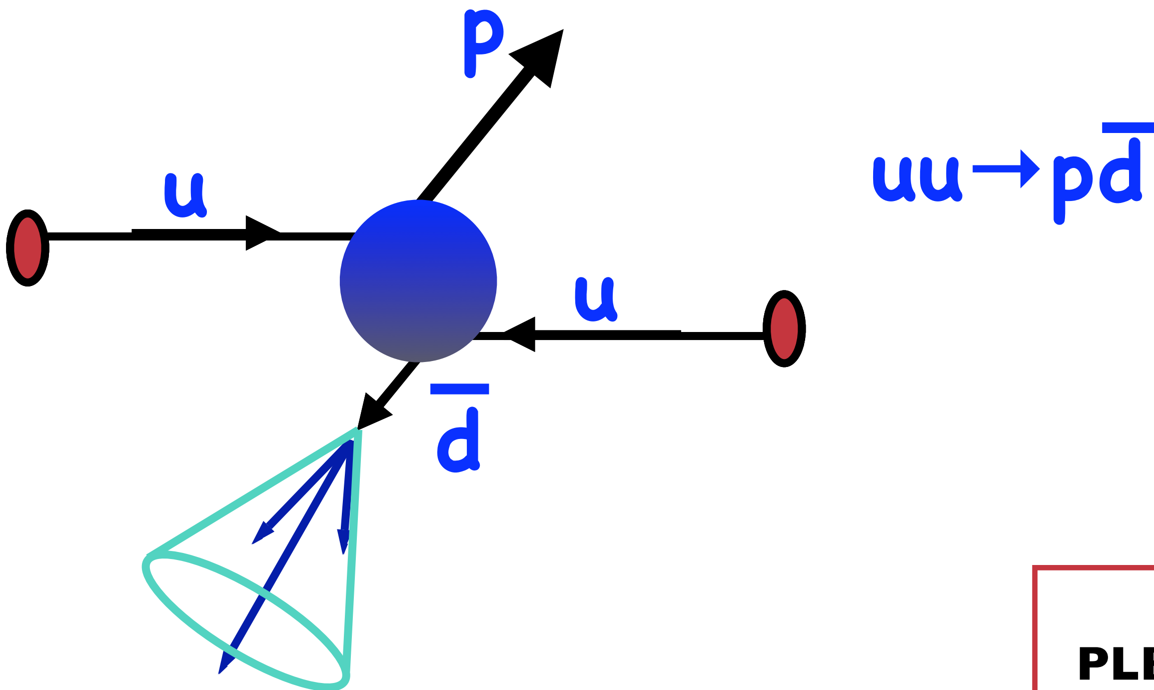
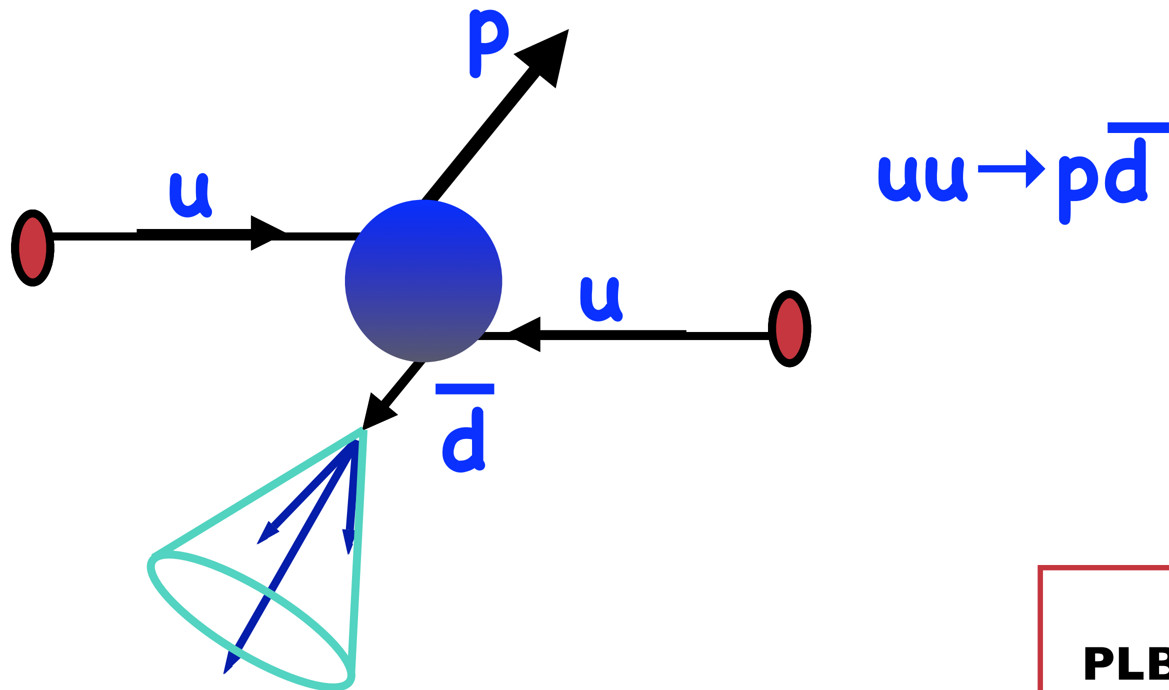


Brodsky, AS
PLB 668 111 (2008)

- color singlet proton directly produced within hard subprocess
- higher twist effect, but could be dominant within p_T range of interest

direct proton production



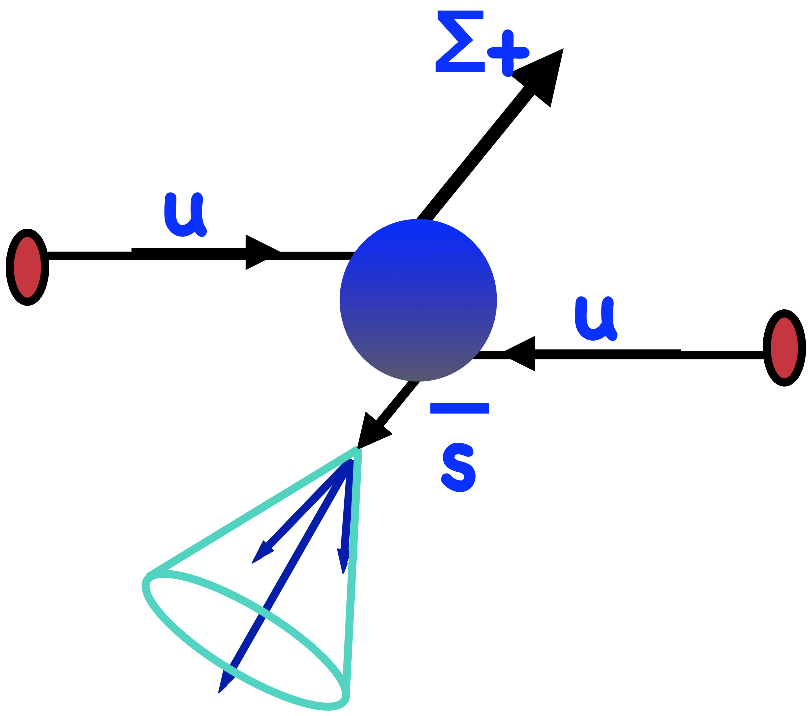
Brodsky, AS
PLB 668 111 (2008)

- color singlet proton directly produced within hard subprocess
- higher twist effect, but could be dominant within p_T range of interest
- size of proton decreases with increasing p_T: **color transparent**
  - proton exits collision region without interacting, like a direct γ

how would you test this?

Brodsky, AS
PLB 668 111 (2008)

how would you test this?



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Brodsky, AS
PLB 668 111 (2008)

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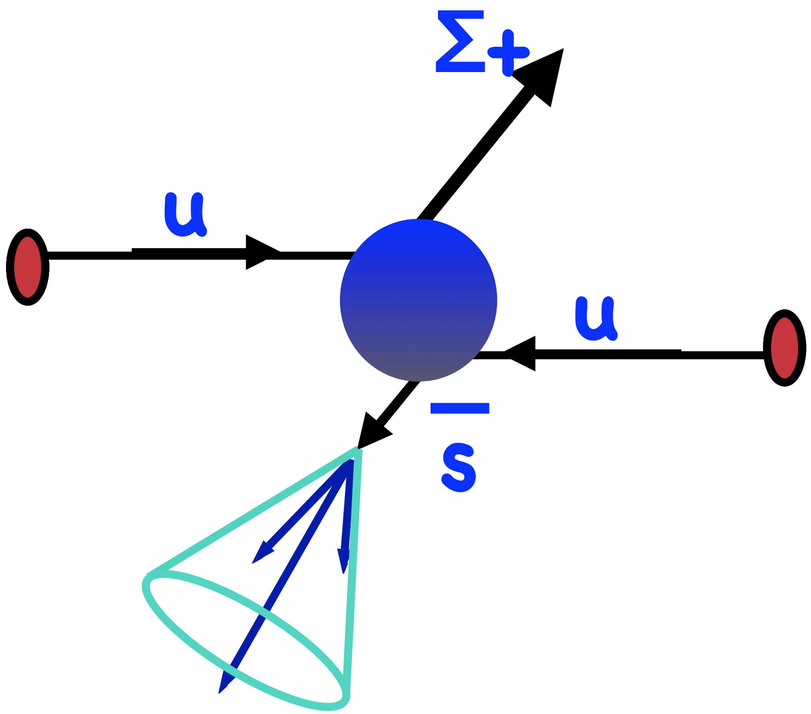

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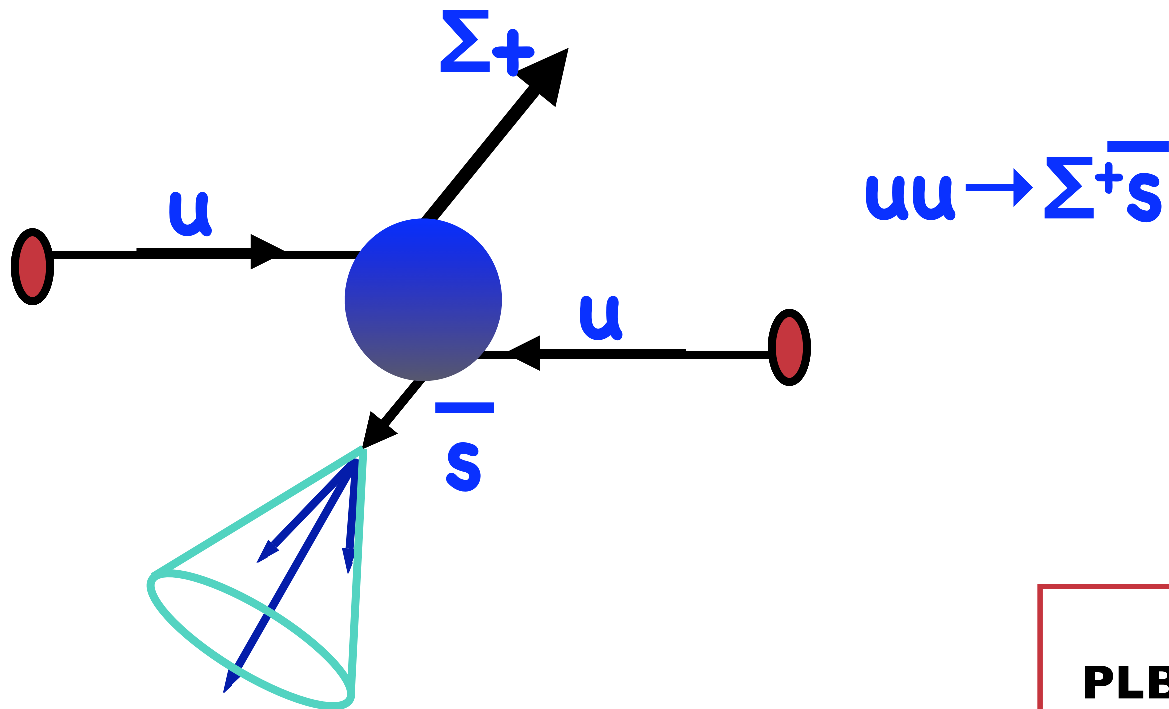
Brodsky, AS
PLB 668 111 (2008)

- can also make strange baryons: signature balancing strangeness will be on in recoil jet

how would you test this?

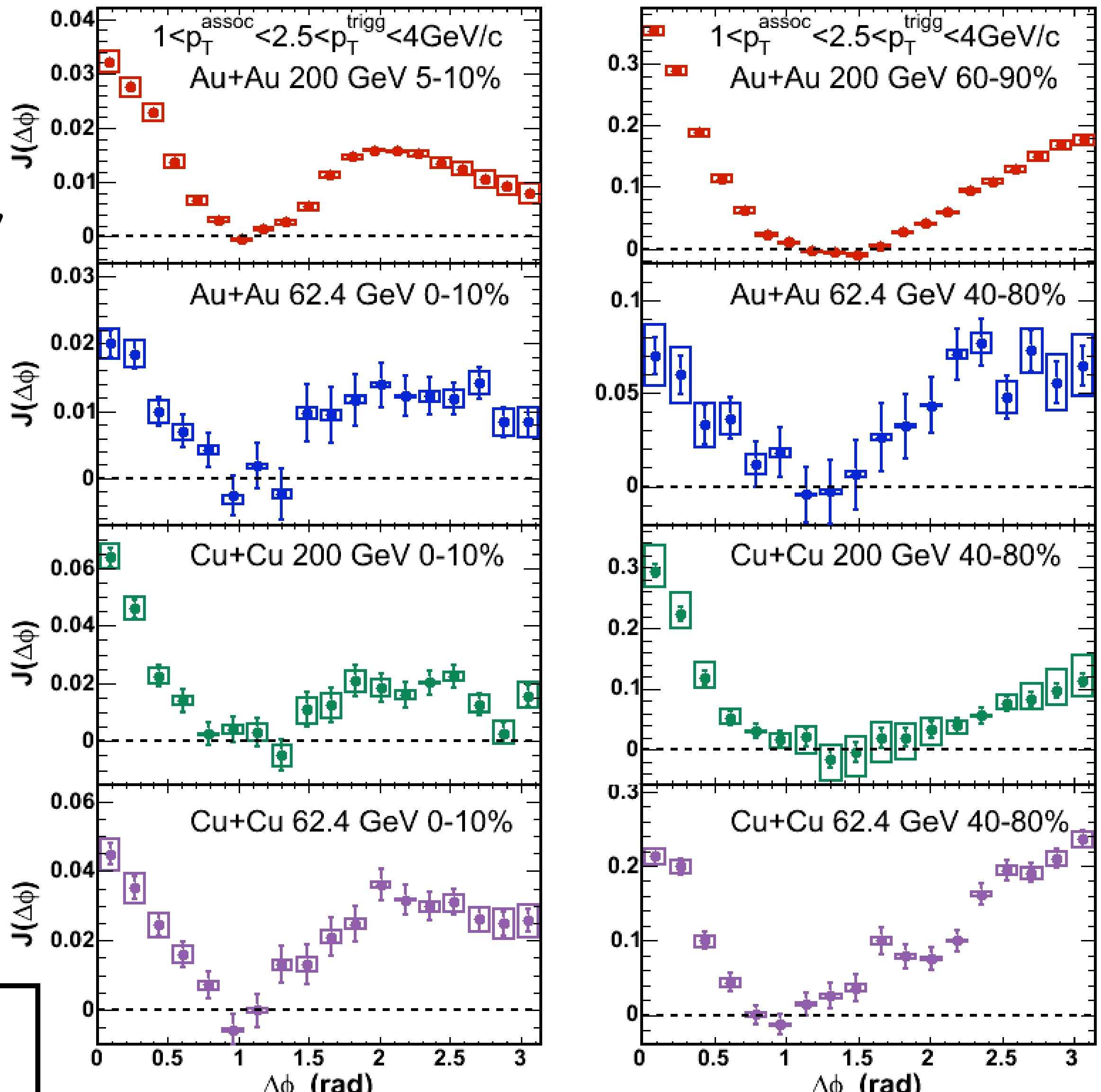


Brodsky, AS
PLB 668 111 (2008)

- can also make strange baryons: signature balancing strangeness will be on in recoil jet
- in contrast, in hard fragmentation picture: balancing strangeness will be close, in same jet

Shoulder

PRL 98 232202 (2007)



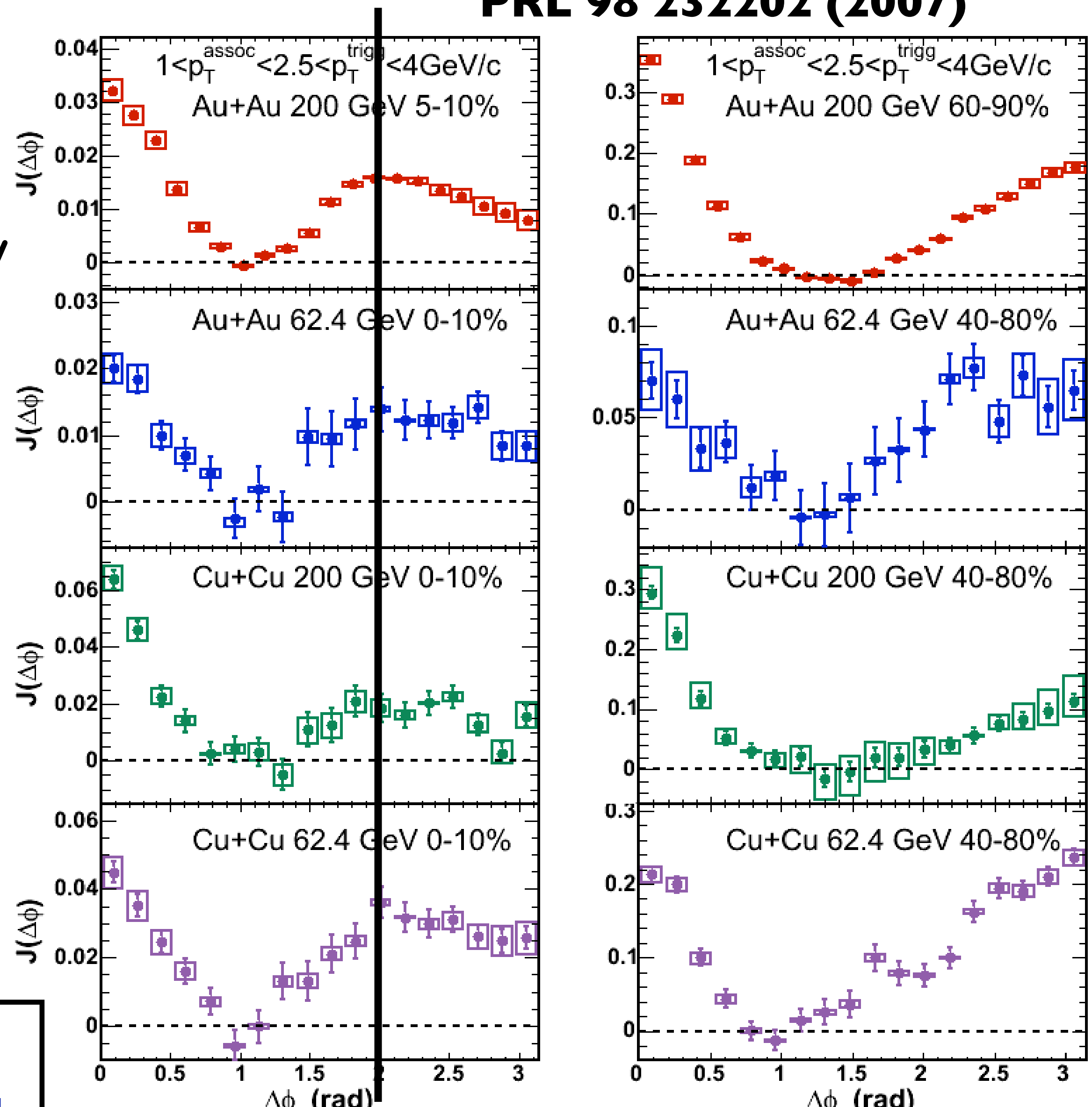
- persists to low energies/ small systems
- peak position nearly constant

is this one modified structure or two distinct peaks?

Shoulder

PRL 98 232202 (2007)

- persists to low energies/ small systems
- peak position nearly constant



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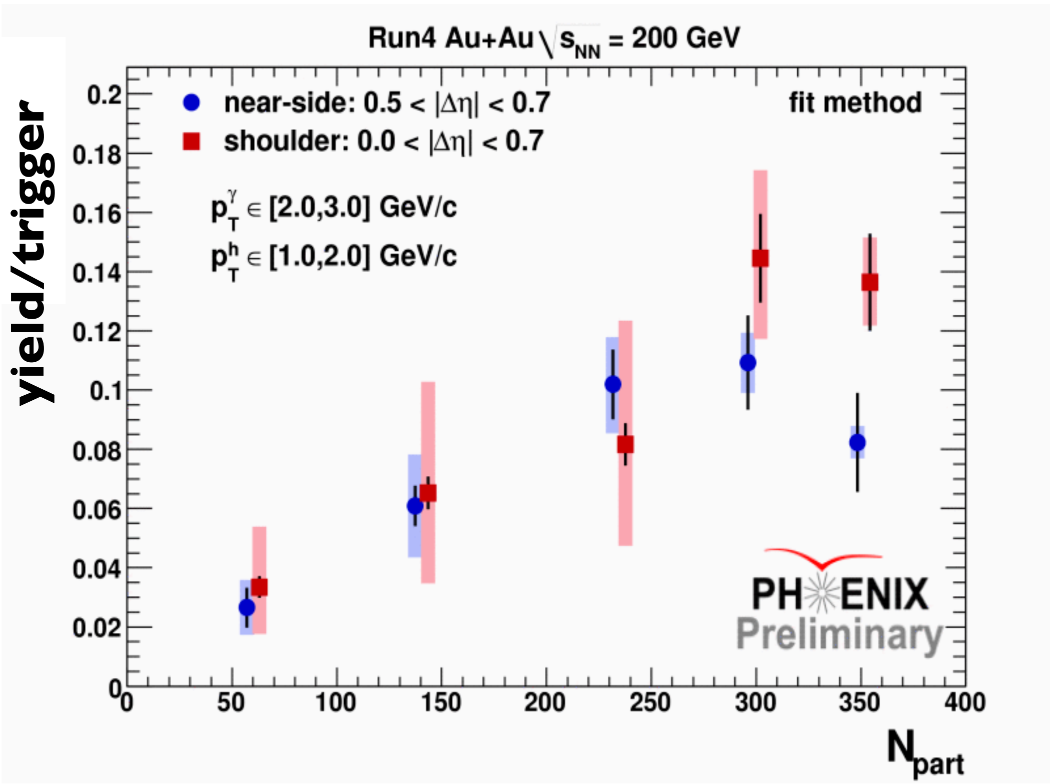
Ridge & Shoulder: very similar

J. Chen Hard Probes 2008

Ridge & Shoulder: very similar



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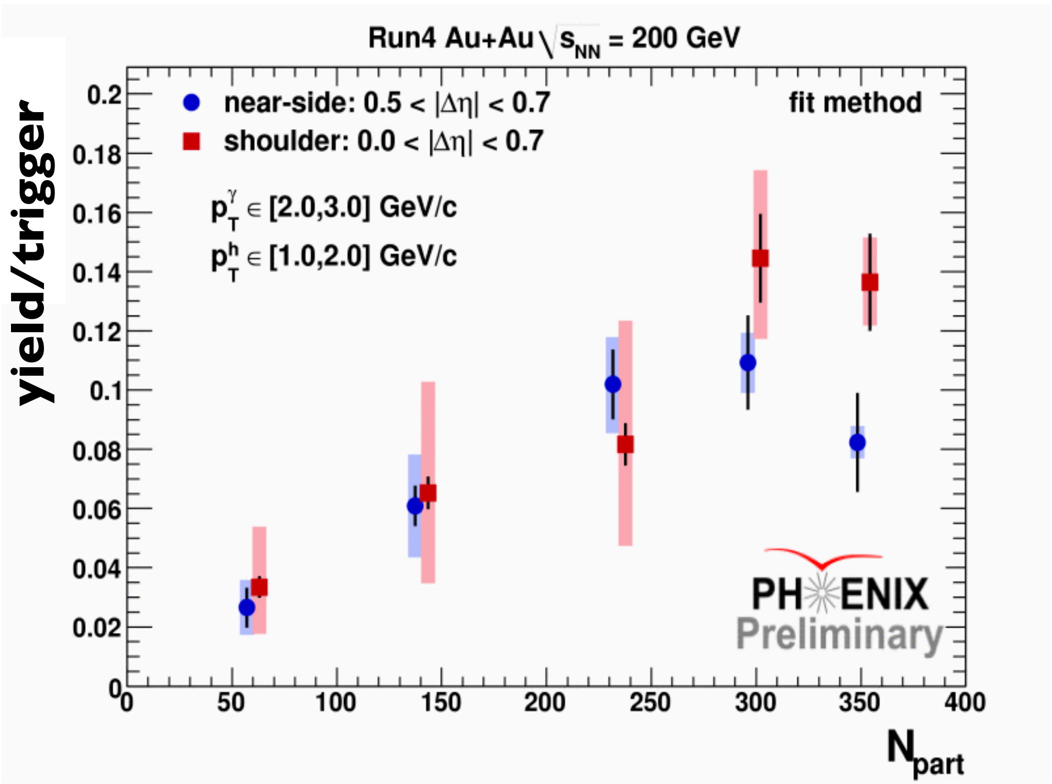

why should these be similar at all? coincidence?

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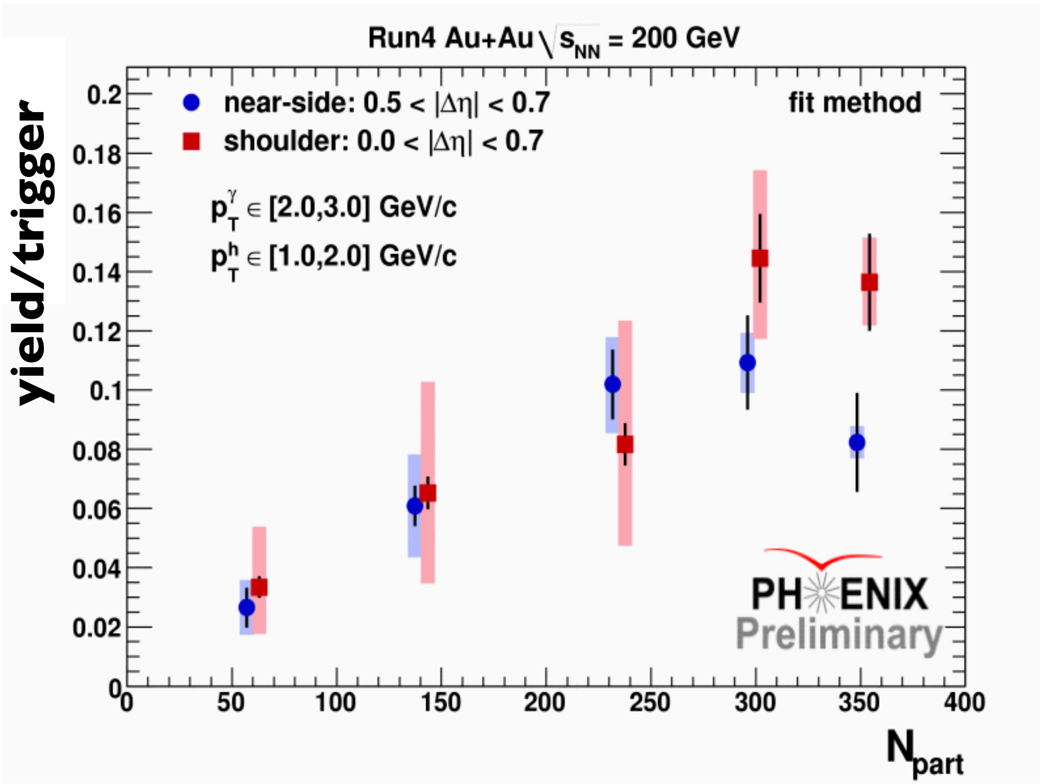

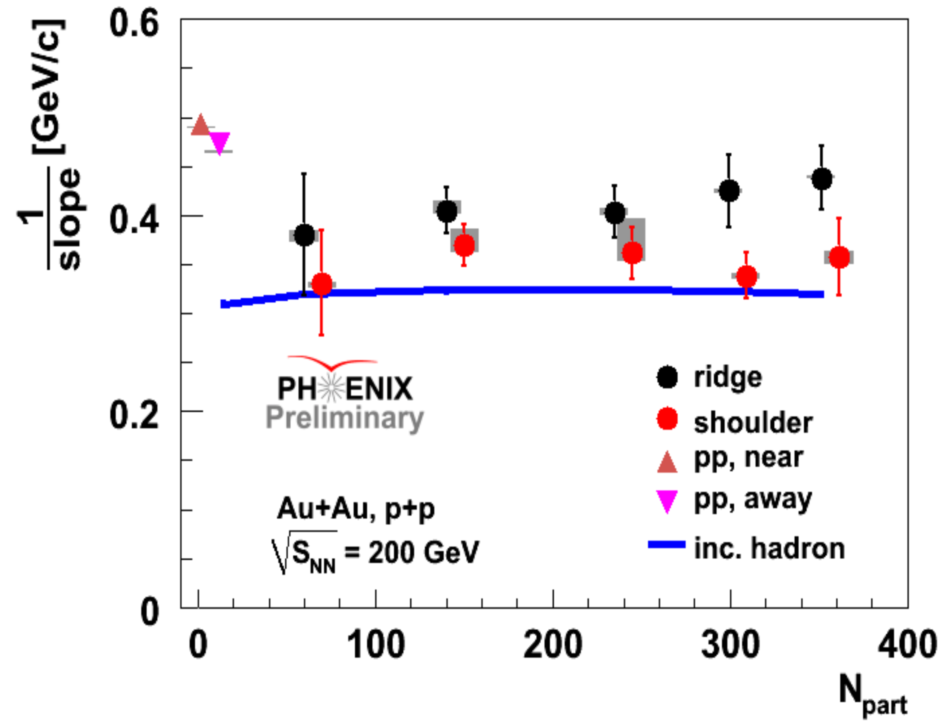

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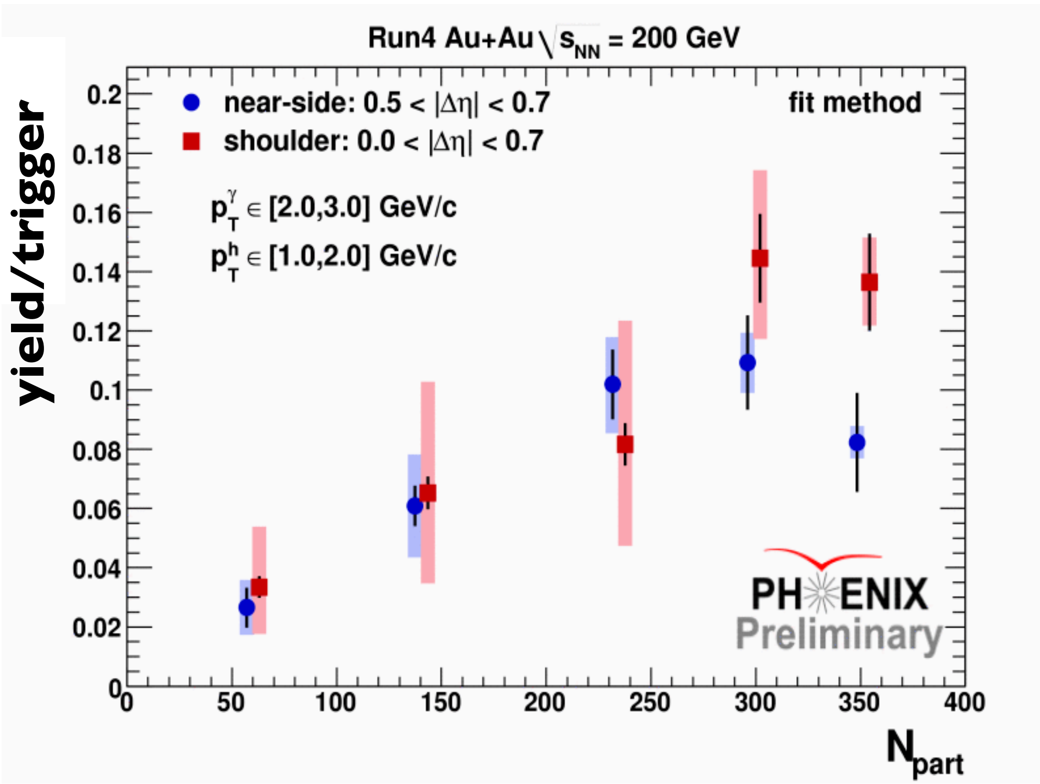

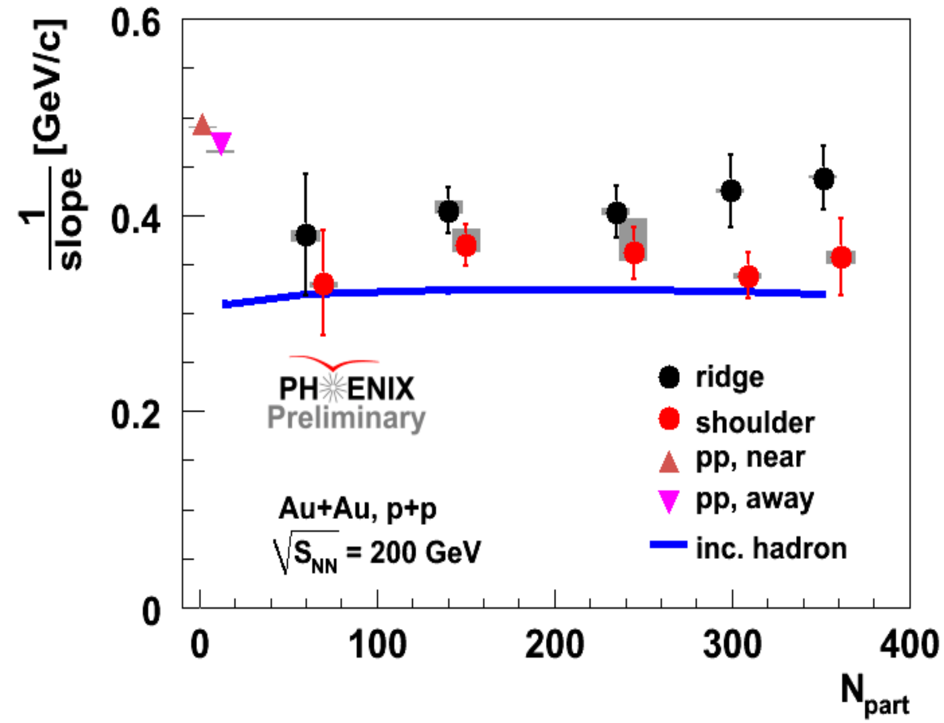

why should these be similar at all? coincidence?

similar p_T dependence -- ridge slightly harder, surface bias?

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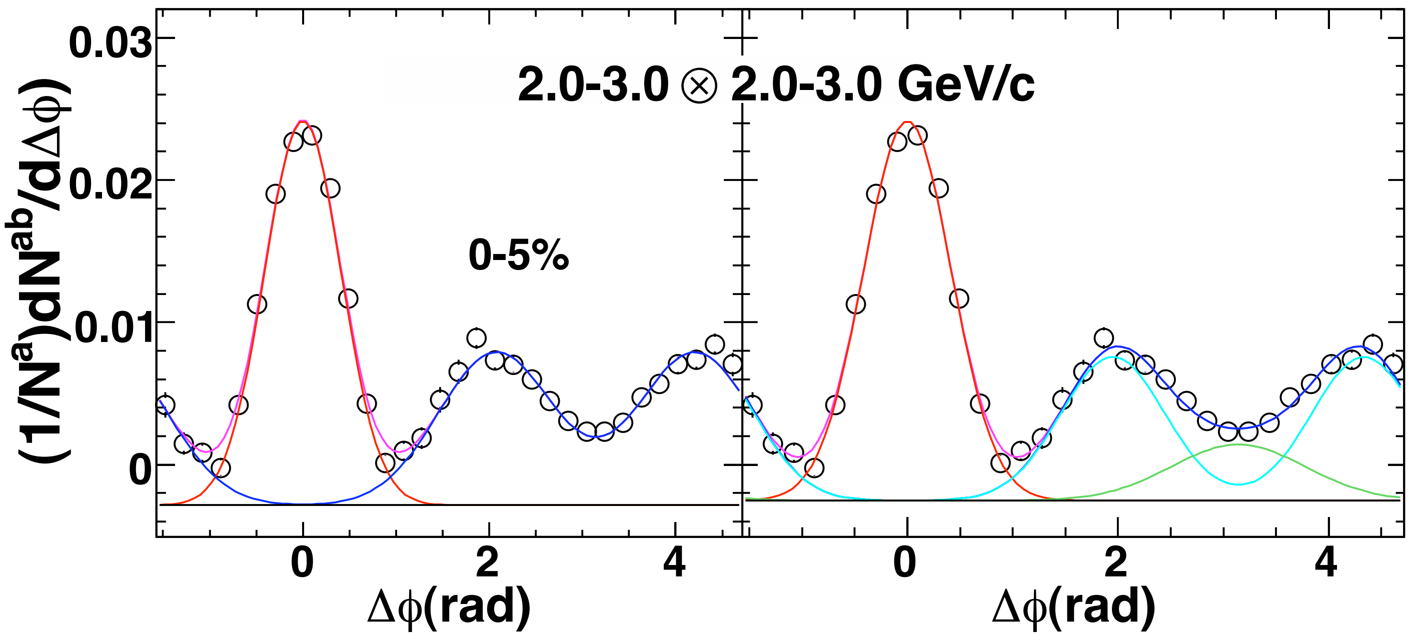
structure of away side

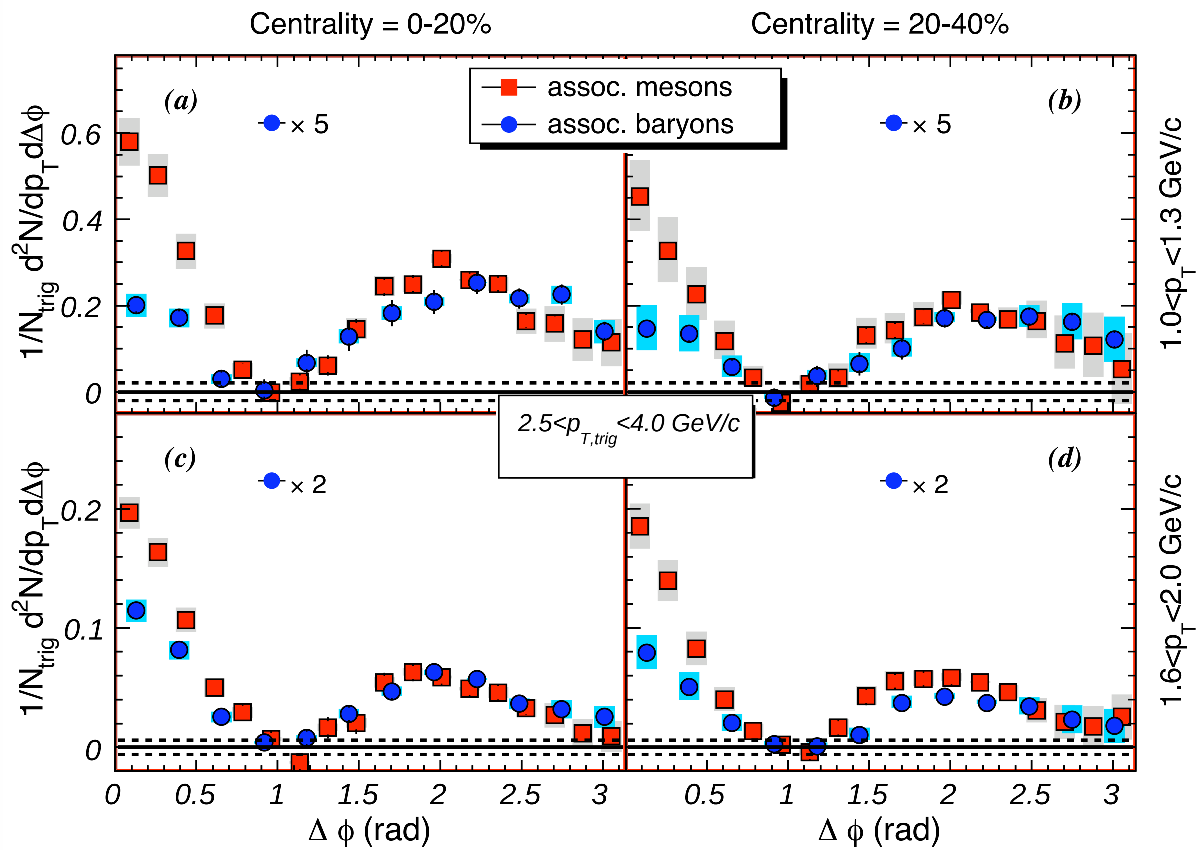


PHENIX,
PRC 78 014901 (2008)

- is a division of the away side into a "normal" di-jet and a shoulder structure supported by the data?

baryons on the away side

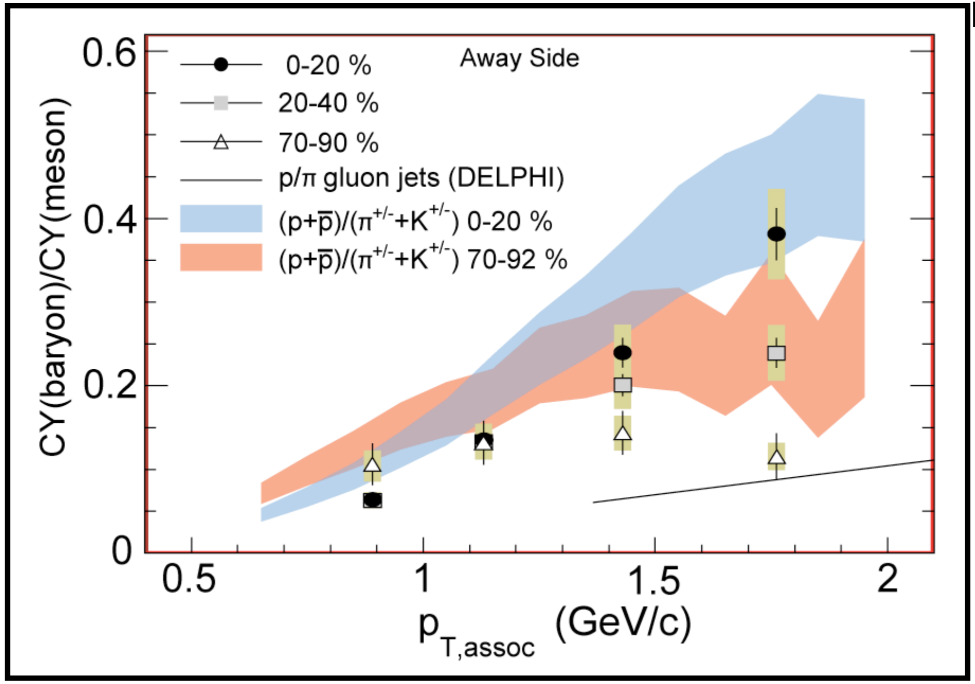
PHENIX PRL 101 082301 (2008)



- enhanced baryons in the shoulder as well!
- no $\Delta\phi$ dependence to baryon/meson ratio

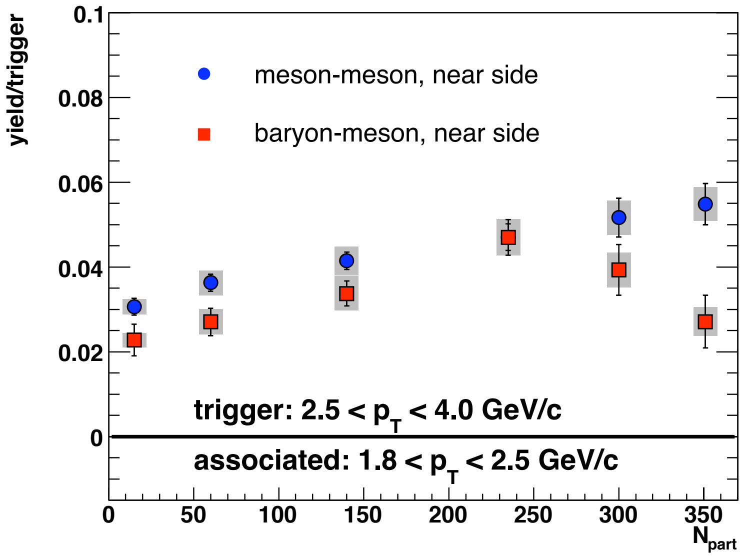
baryons in the away side

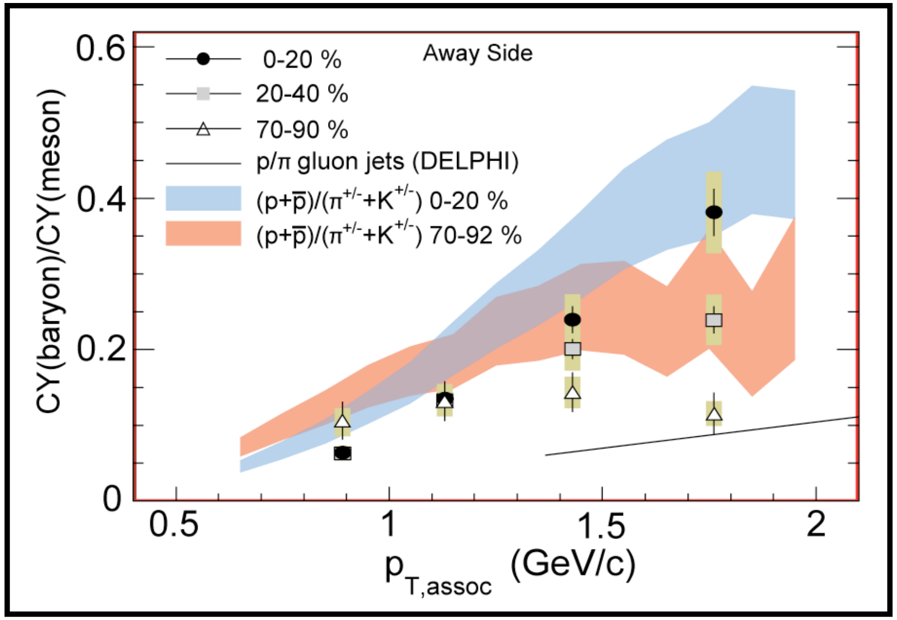
PHENIX PRL 101 082301 (2008)



- away side baryons are enhanced
  - central collisions associated B/M approaches single particle B/M ratio
- centrality dependence however, different

Au+Au: Qualitatively Different





PHENIX, PLB 649 (2007) 359,
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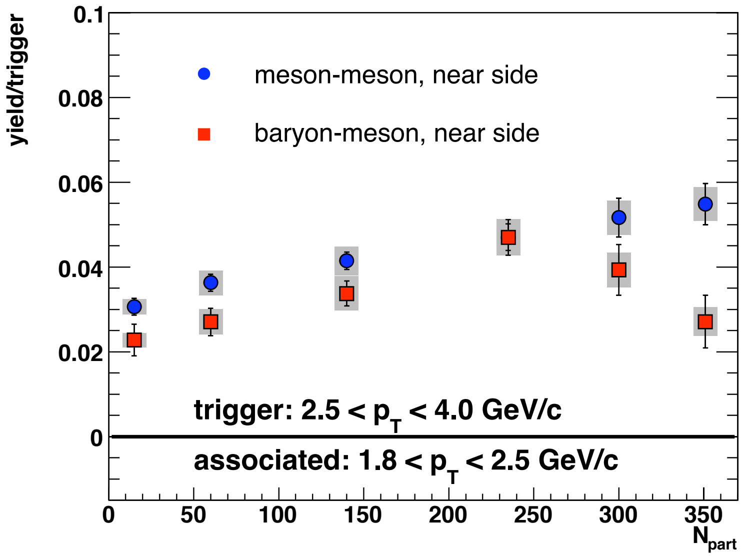
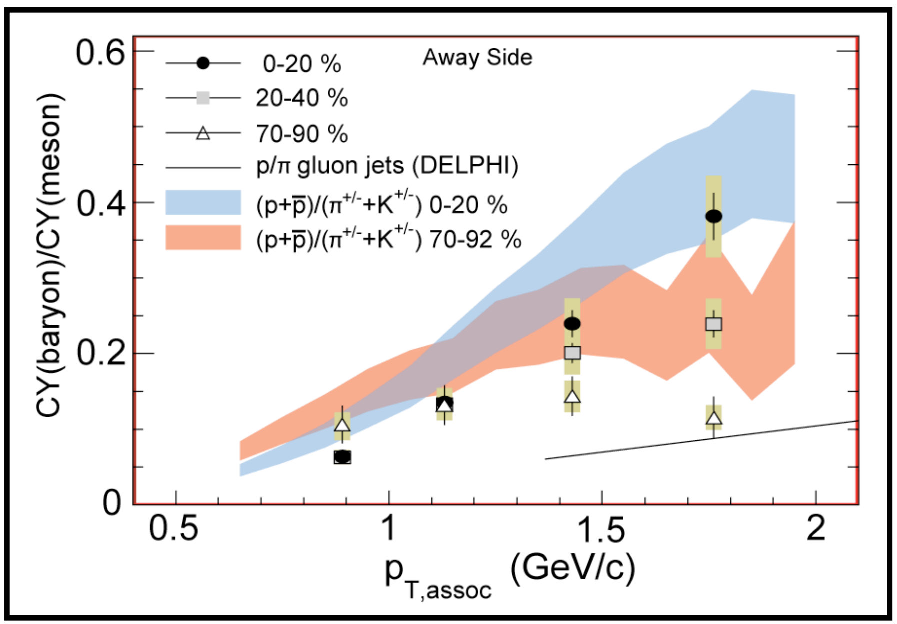
PHENIX PRL 101 082301 (2008)

Au+Au: Qualitatively Different

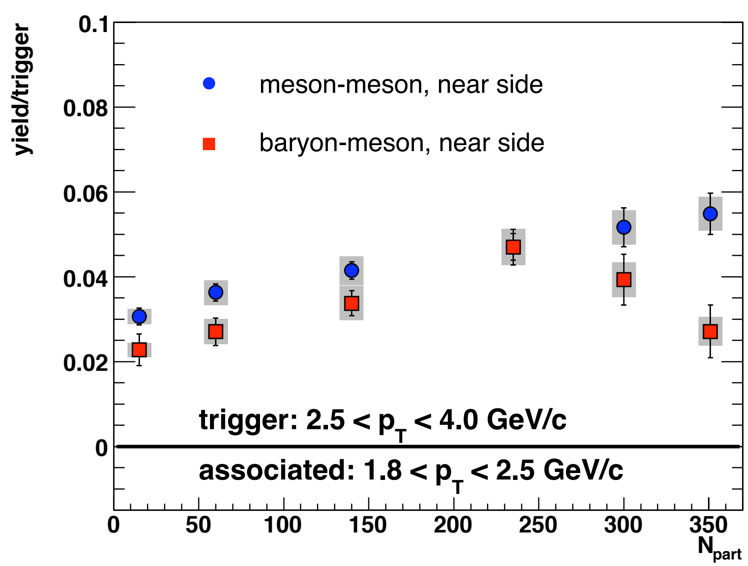


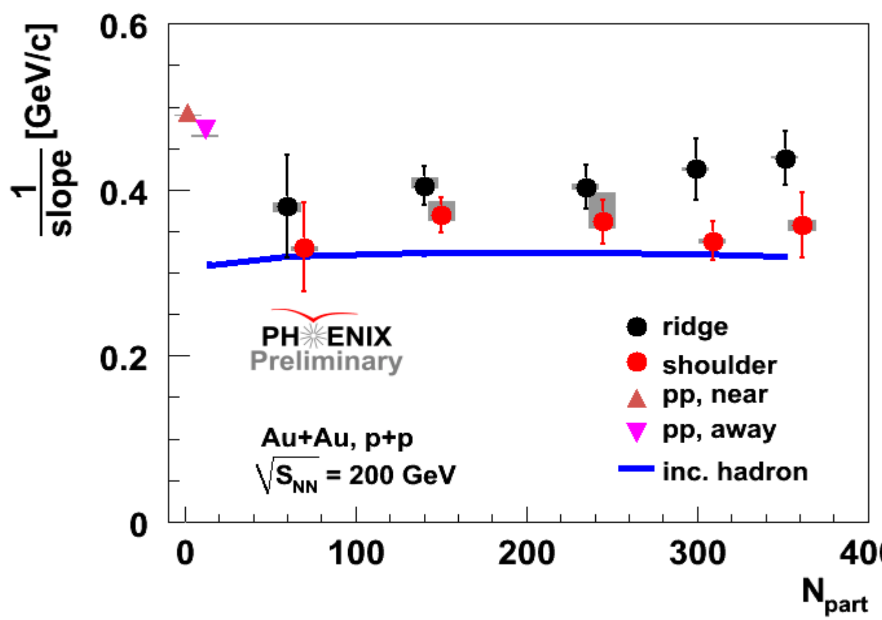


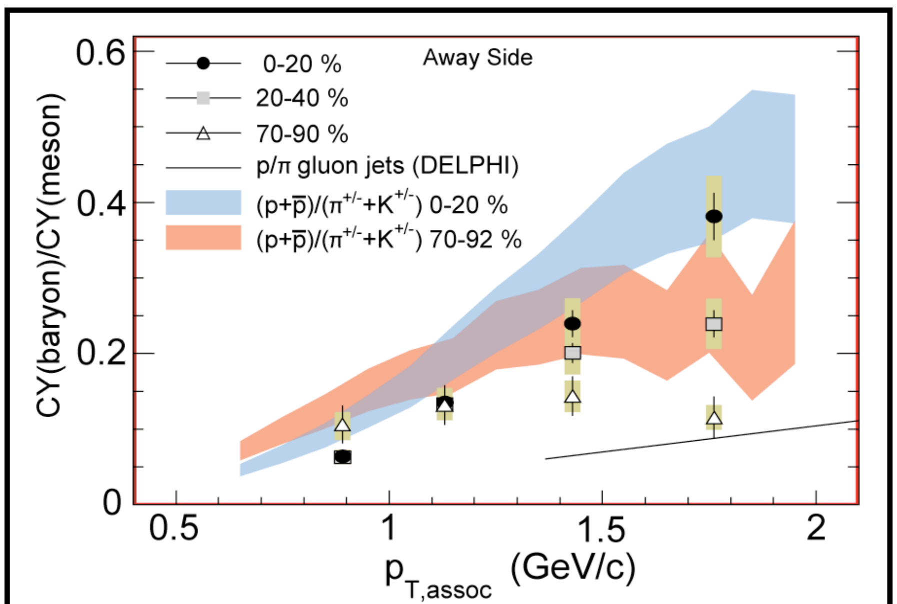
moderate p_T jets acquire medium properties

PHENIX, PLB 649 (2007) 359,
J. Chen Hard Probes 2008,
PHENIX PRL 101 082301 (2008)

Au+Au: Qualitatively Different







moderate p_T jets acquire medium properties

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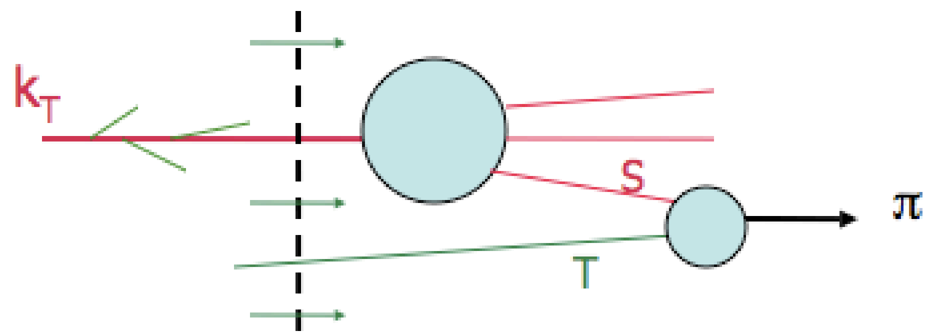
PHENIX PRL 101 082301 (2008)

Hard/Soft Recombination

Hwa, Yang...



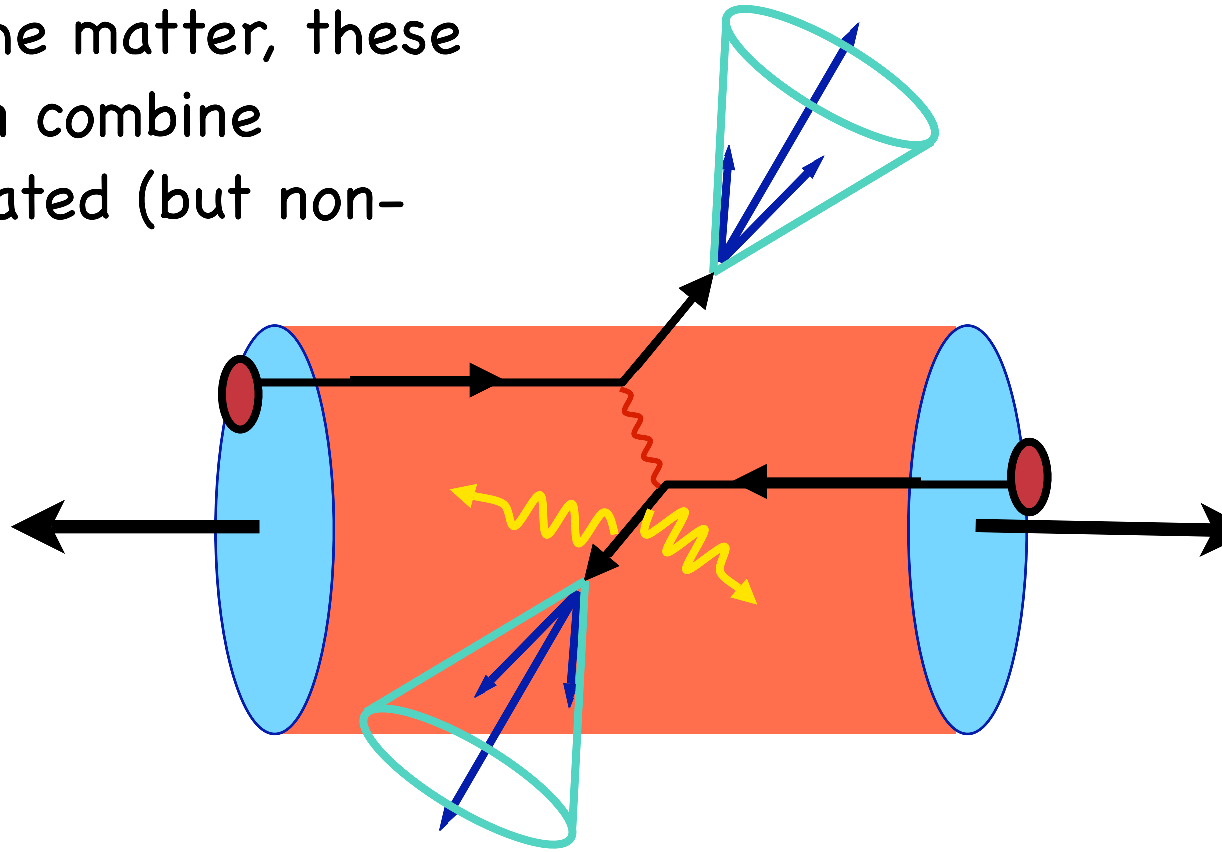
- two kinds of quarks:
  - shower, from the hard parton
  - thermal, from the matter
- jet hadrons can include both types of quarks
  - adds energy (thermal quarks) to the jet

drawing R. Hwa

jets could heat up the matter

Fries et al. PRL 94 122301(2005)
PHENIX PRL 101 082301 (2008)

- jet loses energy which creates a localized “hot spot” in the matter, these heated partons can then combine together to form correlated (but non-jet hadrons)



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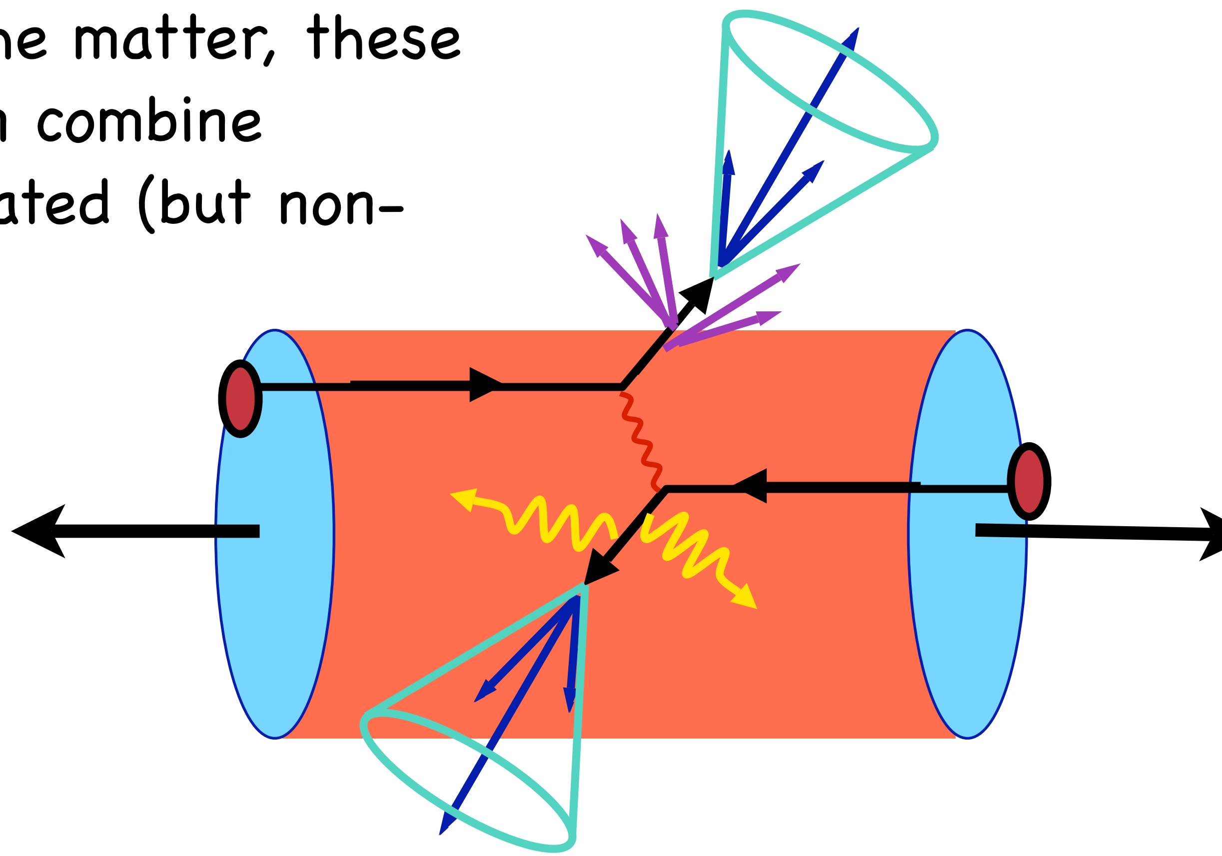

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PHENIX PRL 101 082301 (2008)

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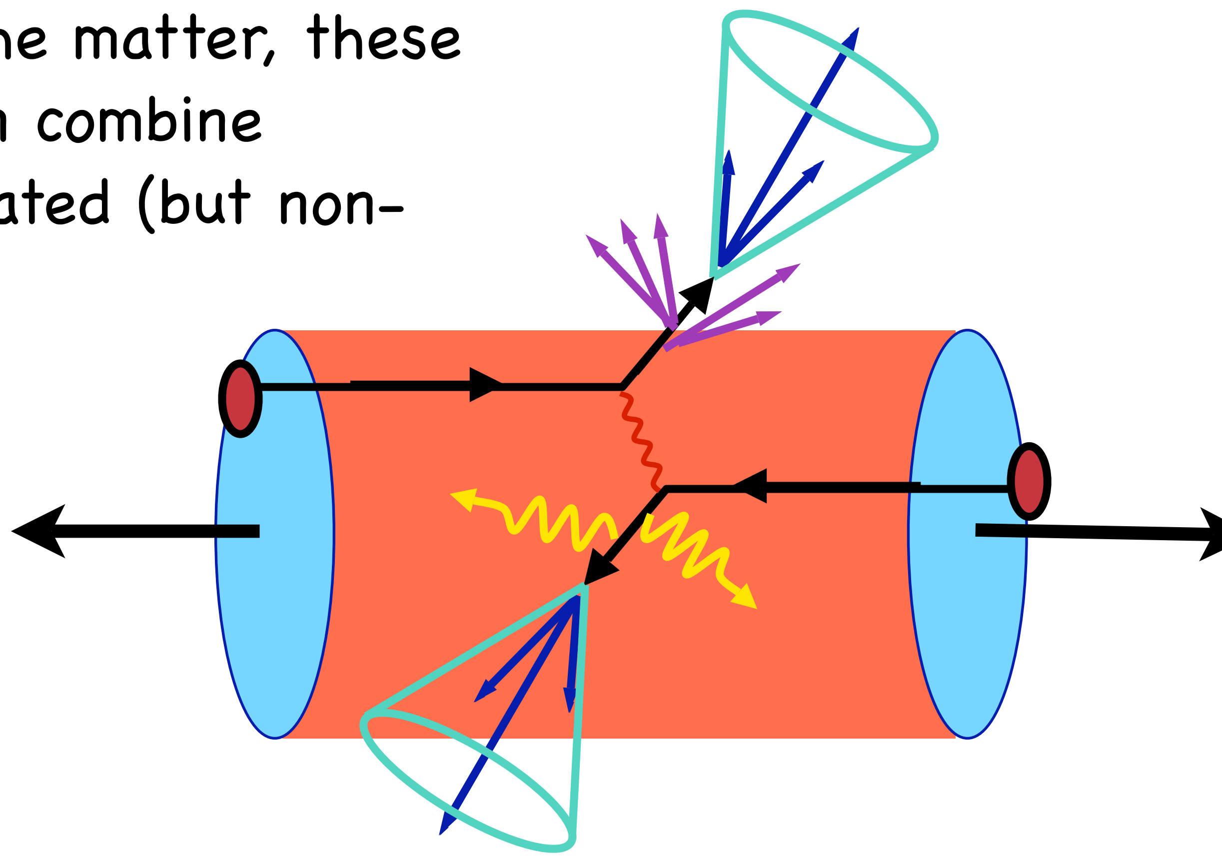
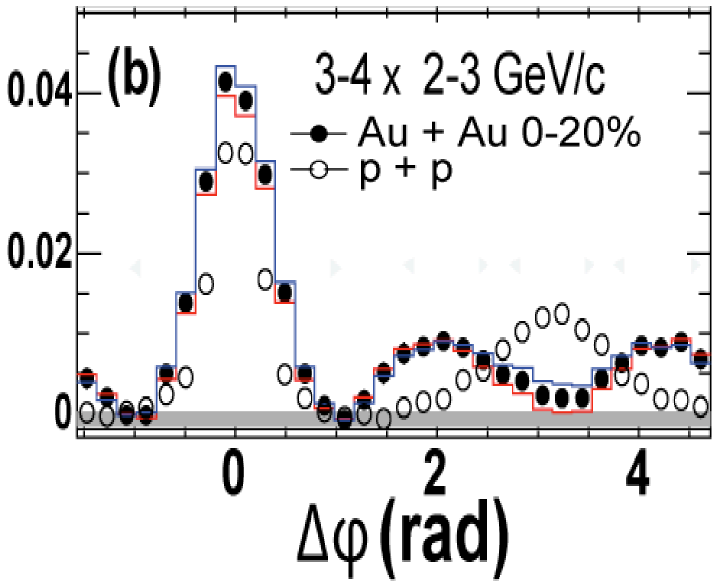
experimental question: how does the Σ correlated p_T compare to $p_{T,parton}$?



Shoulder Sources

Data: Double Peak



AdS/CFT: Correlations from Neck region

PHENIX, PRC 78 014901 (2008), Noronha et al. arXiv:0807.1038, Neufeld arXiv:0807.2996

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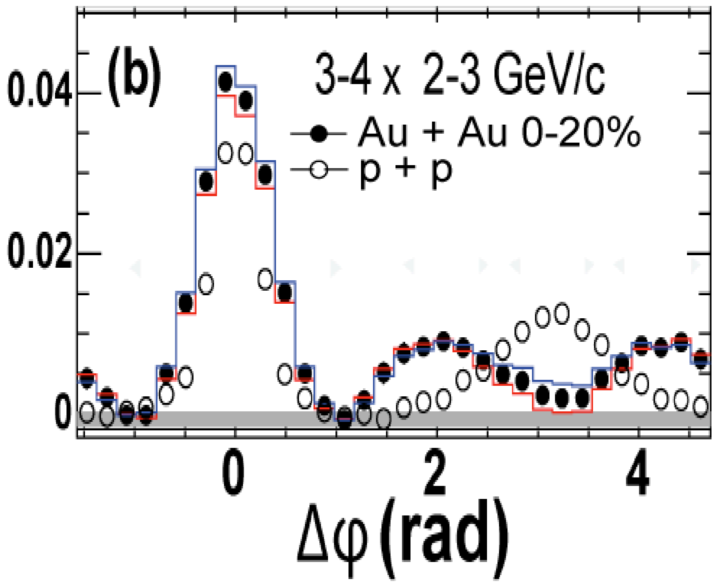

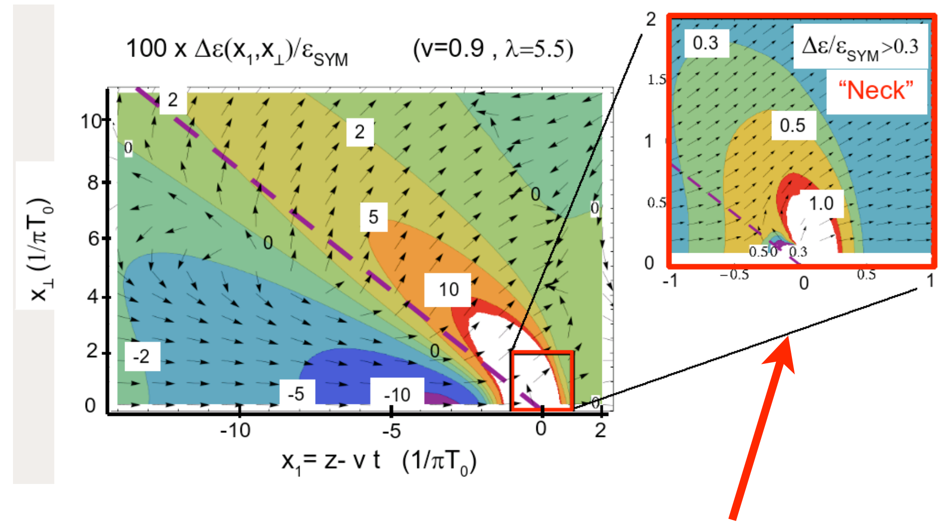

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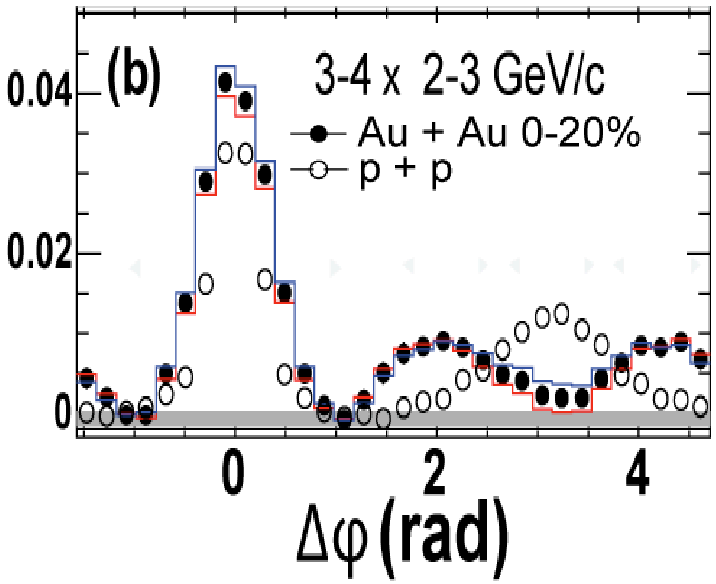

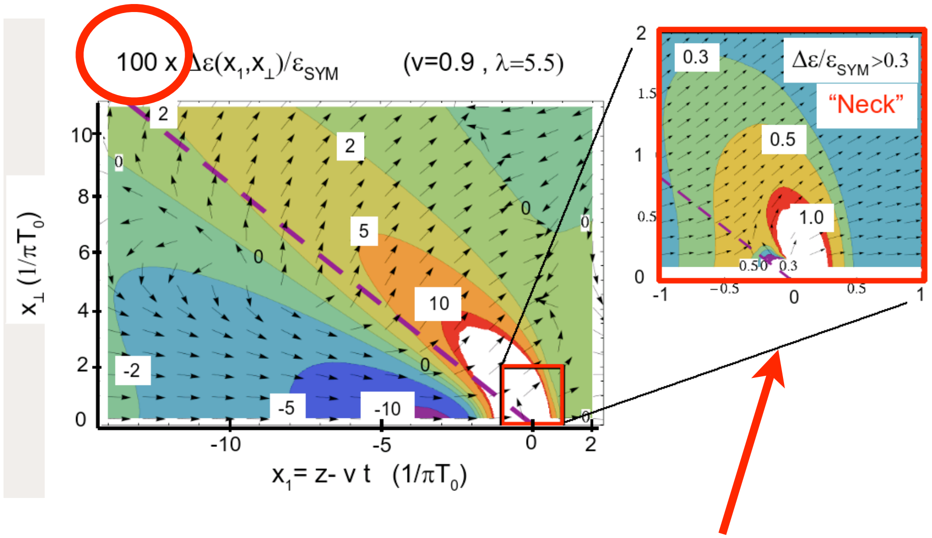

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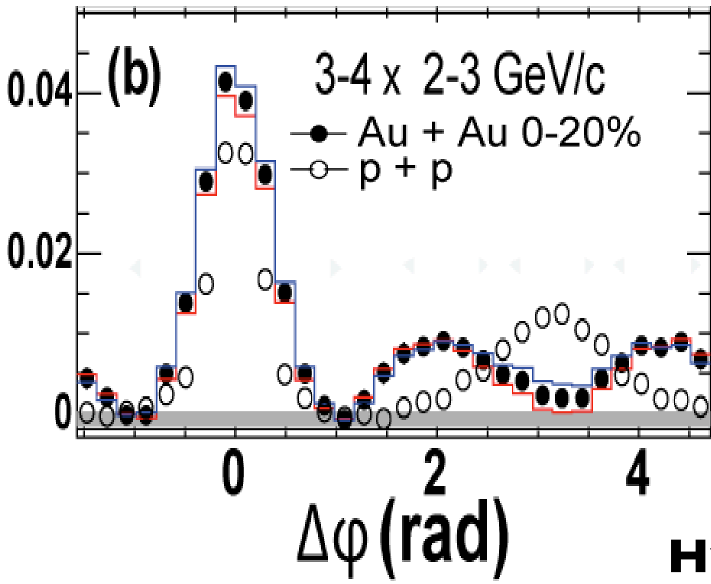
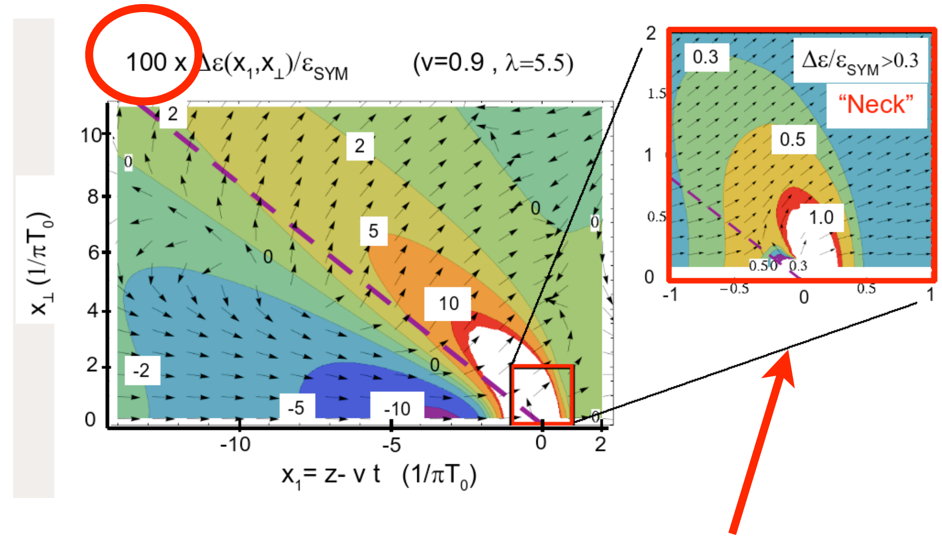
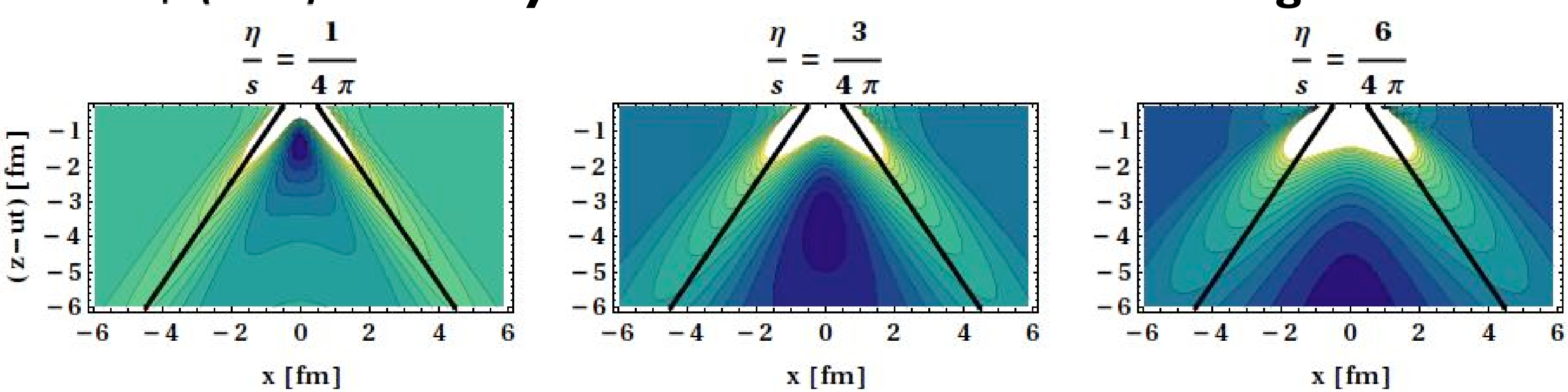




AdS/CFT: Correlations from Neck region

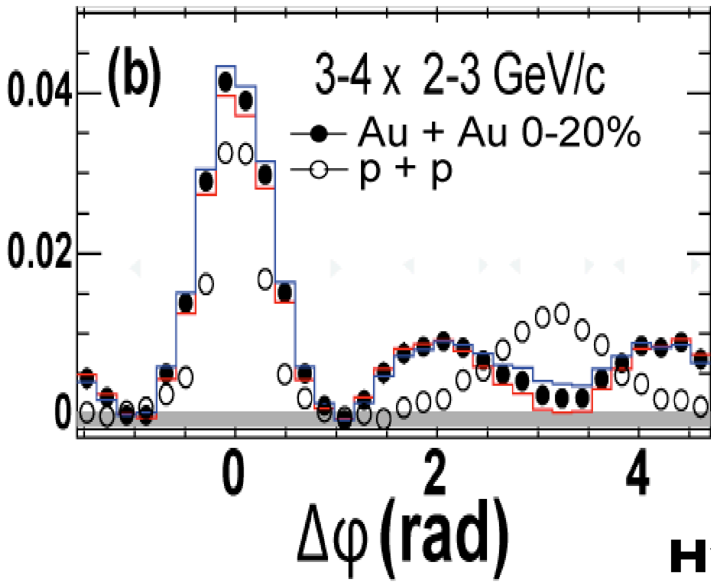
Hydro: Mach Cone width & strength sensitive to η/s

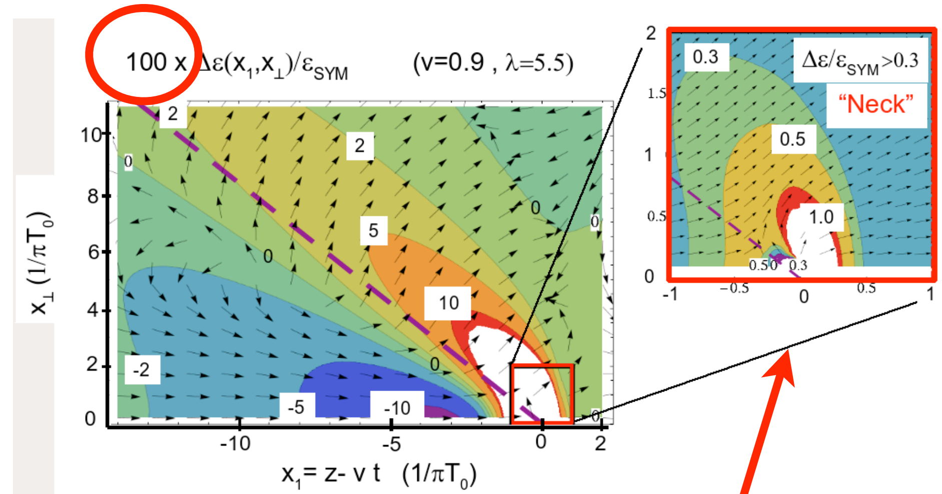


PHENIX, PRC 78 014901 (2008), Noronha et al. arXiv:0807.1038, Neufeld arXiv:0807.2996

Shoulder Sources

Data: Double Peak





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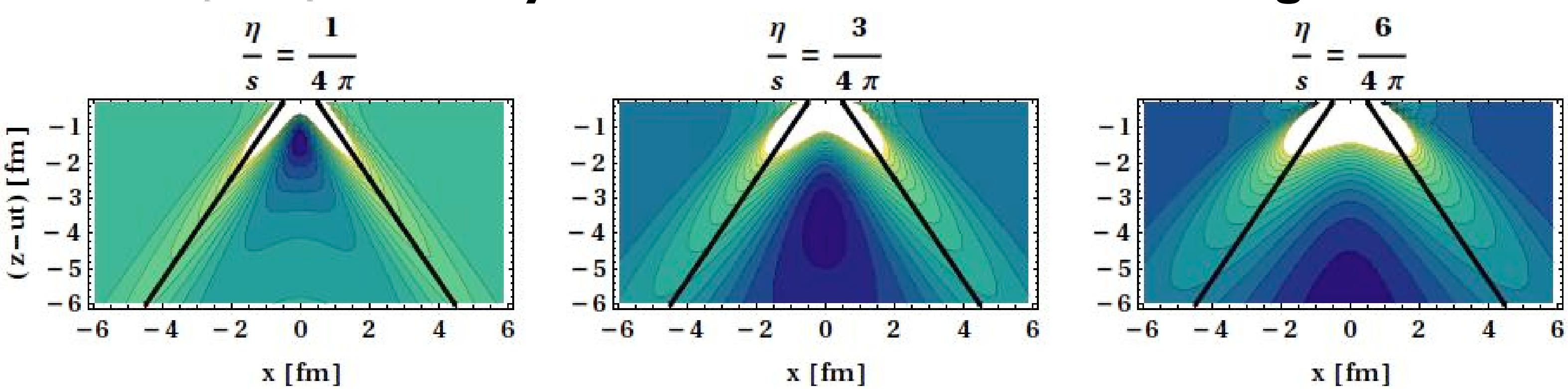
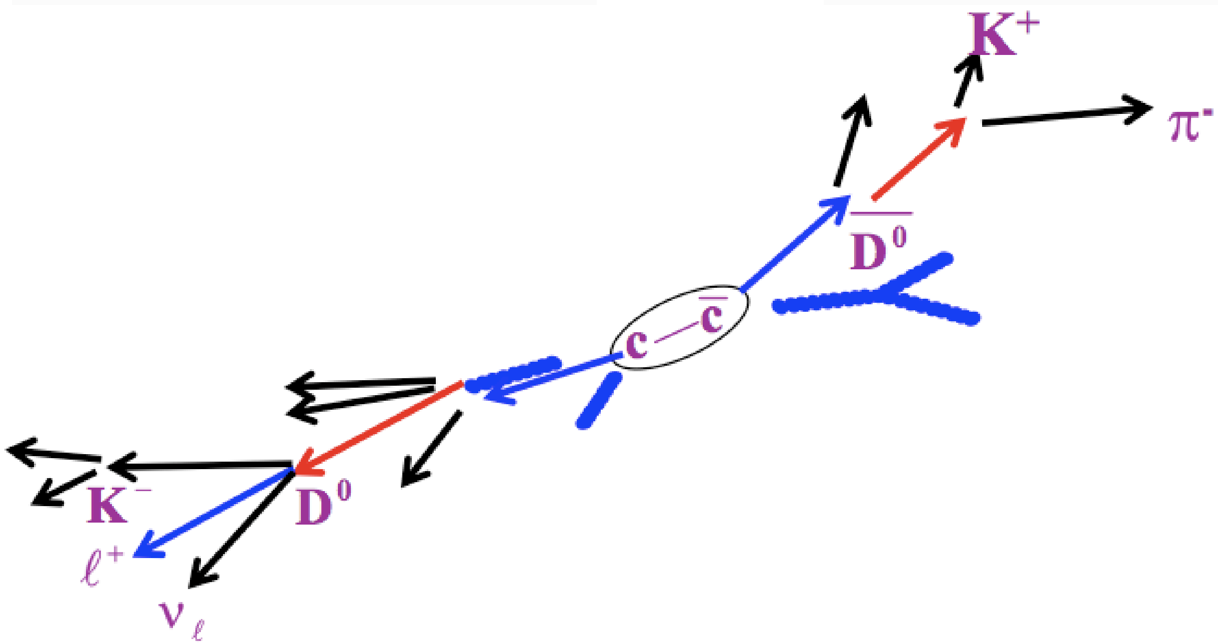


Heavy quark correlations should help discriminate!

PHENIX, PRC 78 014901 (2008), Noronha et al. arXiv:0807.1038, Neufeld arXiv:0807.2996

heavy quarks via semileptonic decays



Decay	Branching Ratio
$D^{\pm} \rightarrow e + X$	16.0%
$D^{0} \rightarrow e + X$	6.5%

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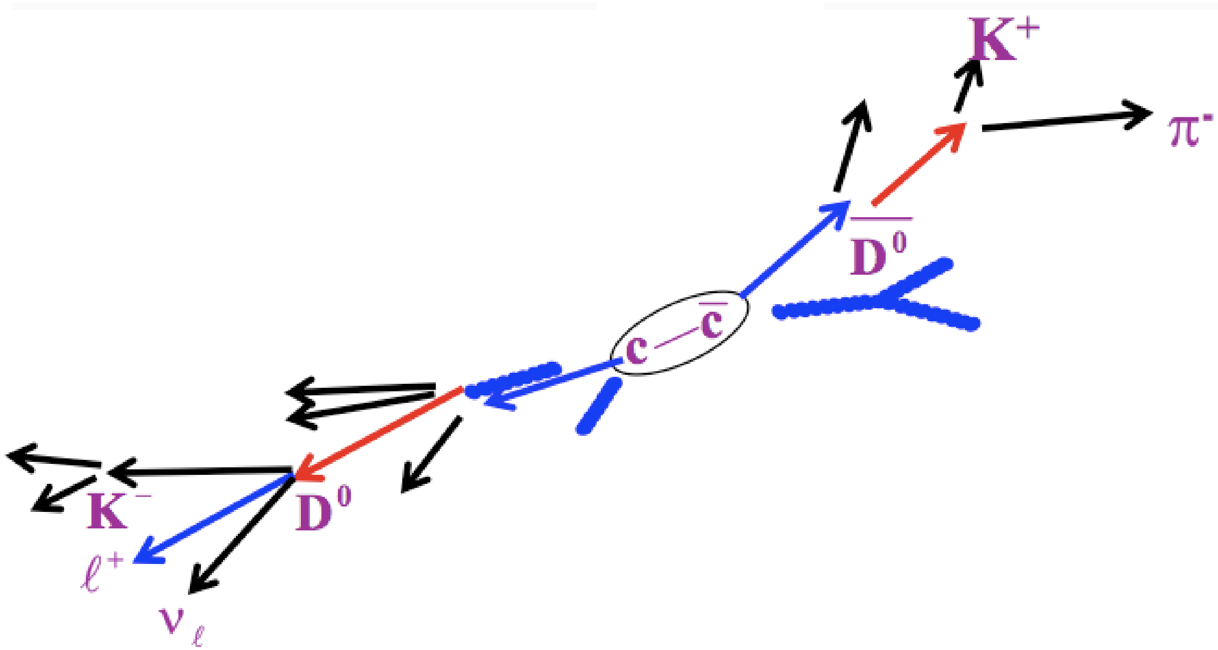

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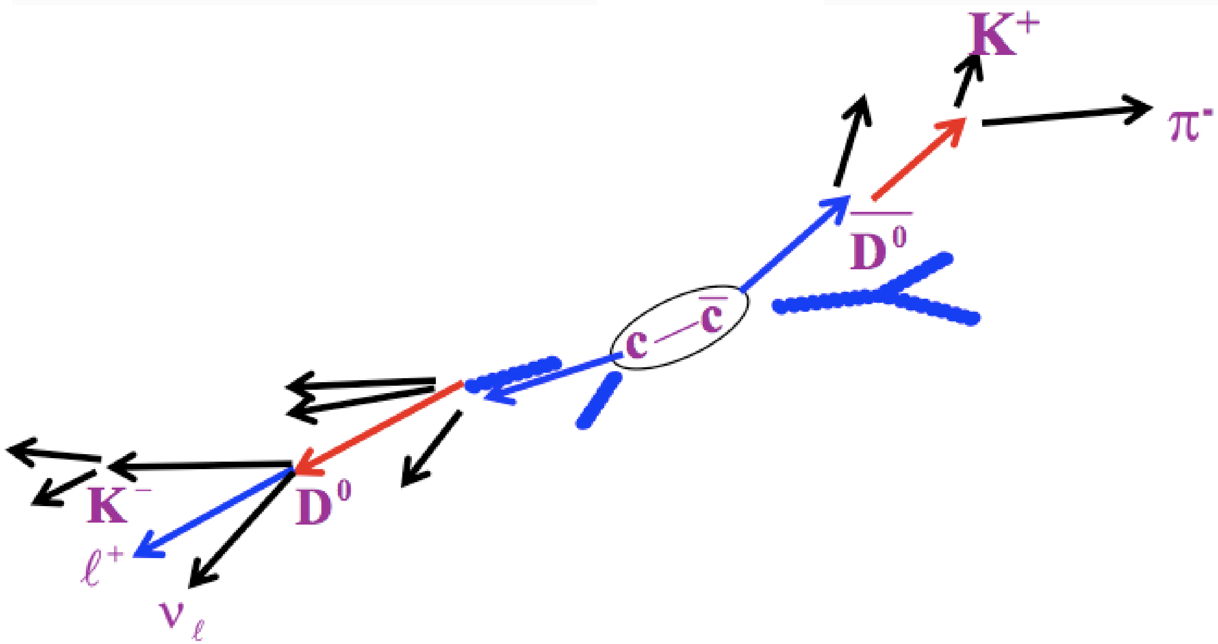

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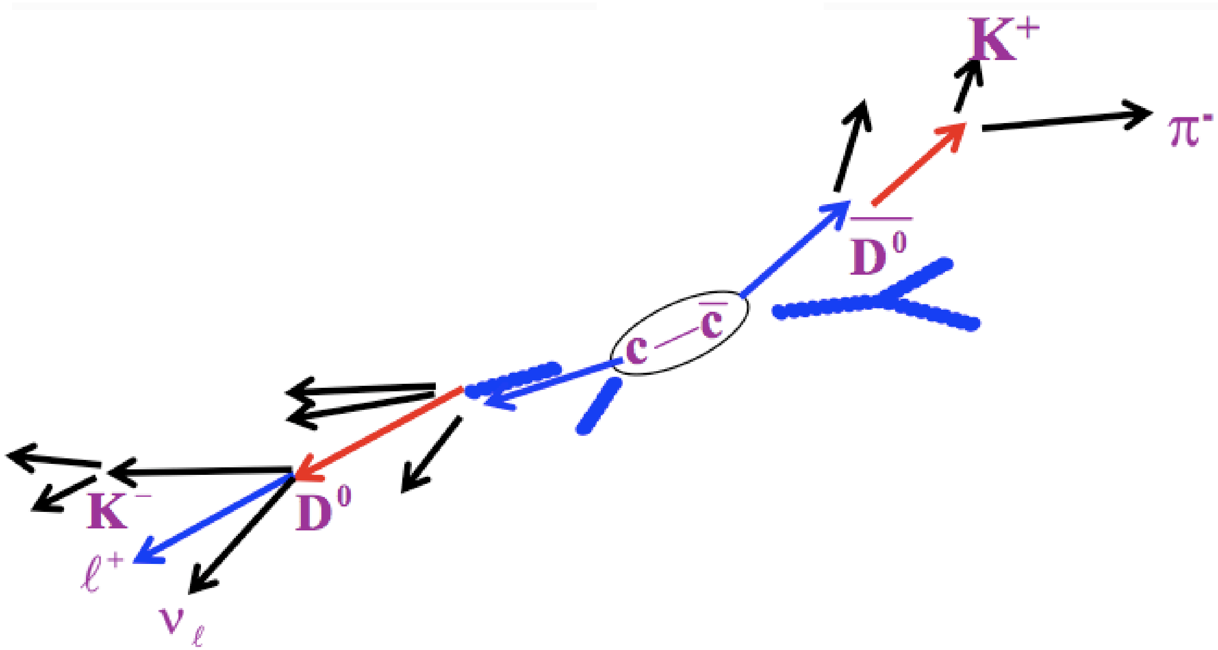

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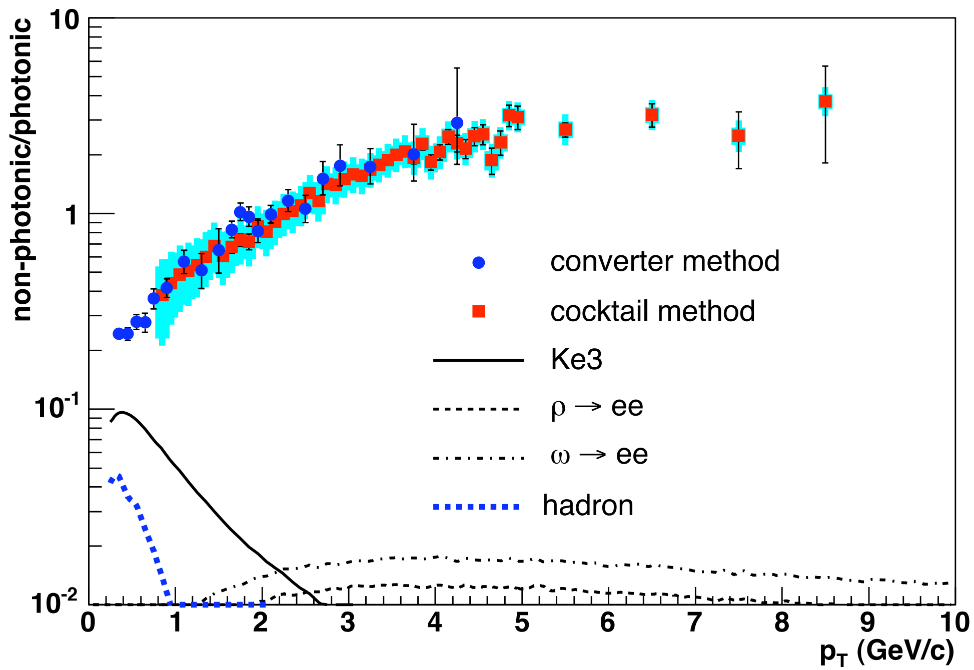
- away side: recoil heavy quark, longer medium path length

electron-hadron correlations

Run 5 p+p

R_{HF} = heavy flavor $e^{\pm}$/photonic $e^{\pm}$



PHENIX, PRL 97 252002 (2006)

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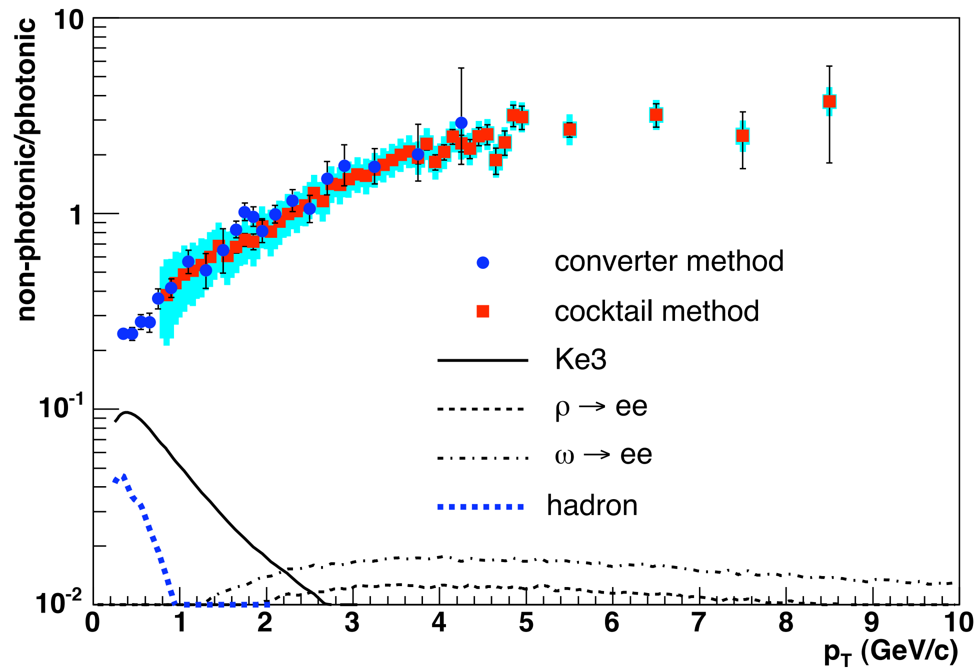

PHENIX, PRL 97 252002 (2006)

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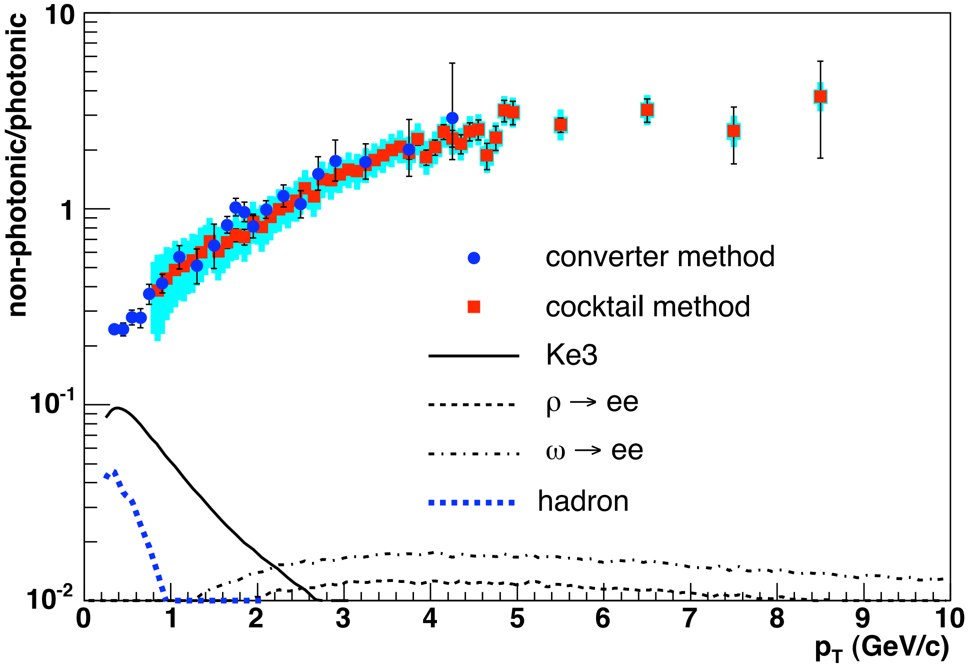

PHENIX, PRL 97 252002 (2006)

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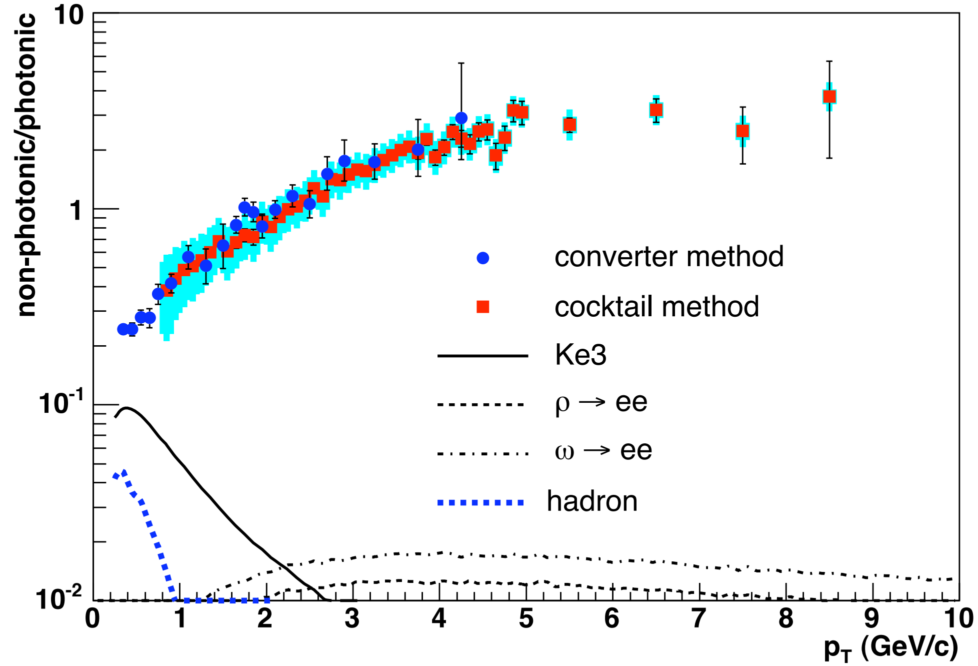

PHENIX, PRL 97 252002 (2006)

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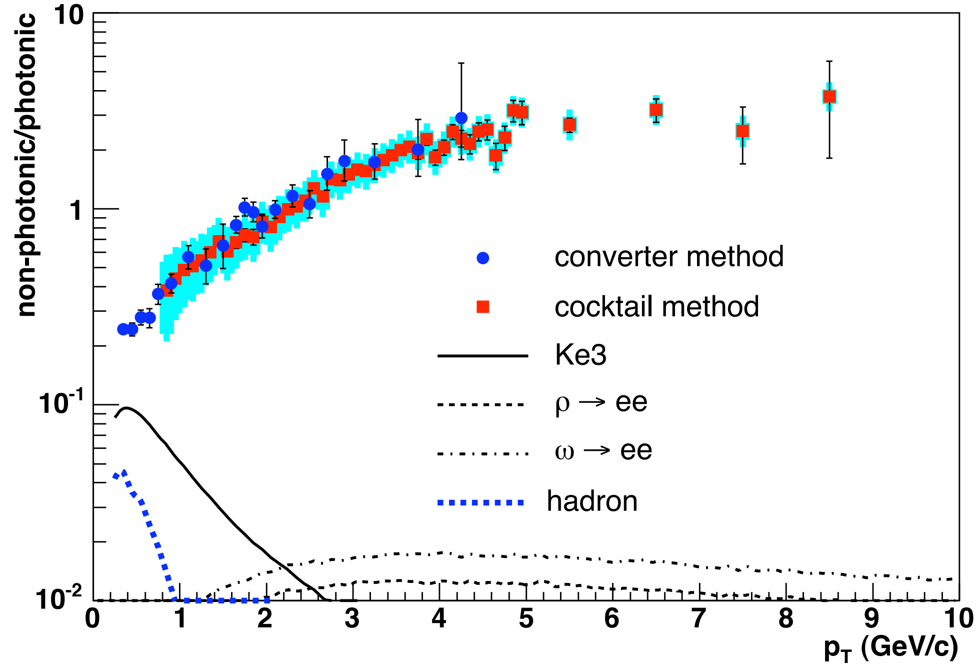
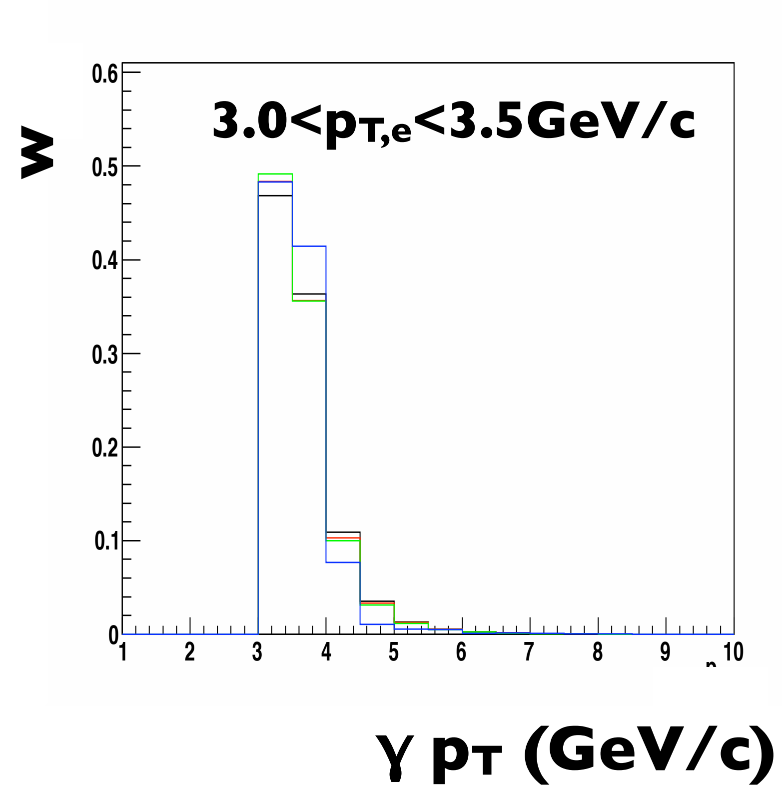


$$Y_{e_{HF}-h} = \frac{(R_{HF}+1)Y_{e_{incl}-h} - Y_{e_{phot}-h}}{R_{HF}}$$

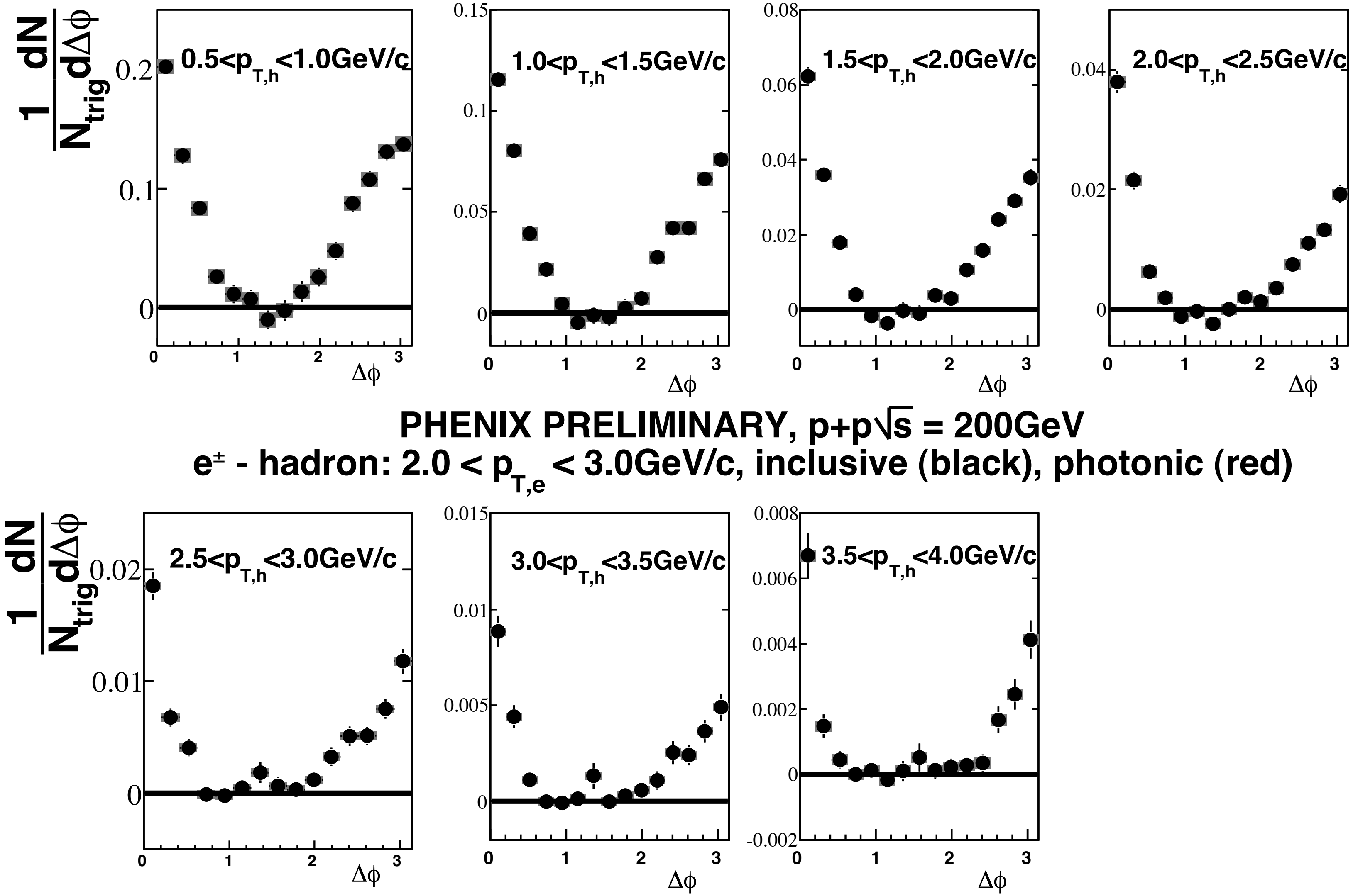
PHENIX, PRL 97 252002 (2006)

e_{phot}-h correlations

- e_{phot}: Dalitz decays and decay γ conversions, both from light mesons
- photons also come from light meson decays
- use simulations to map between $e_{phot}(p_T)$ & $\gamma(p_T)$
  - $e_{phot}(p_{Ti})$-h = Σ_j $w(p_{Ti,j})$ $\gamma(p_{Tj})$-h
- dominated in both cases by daughter e_{phot}/γ that carry most of the meson p_T



e-h jet functions



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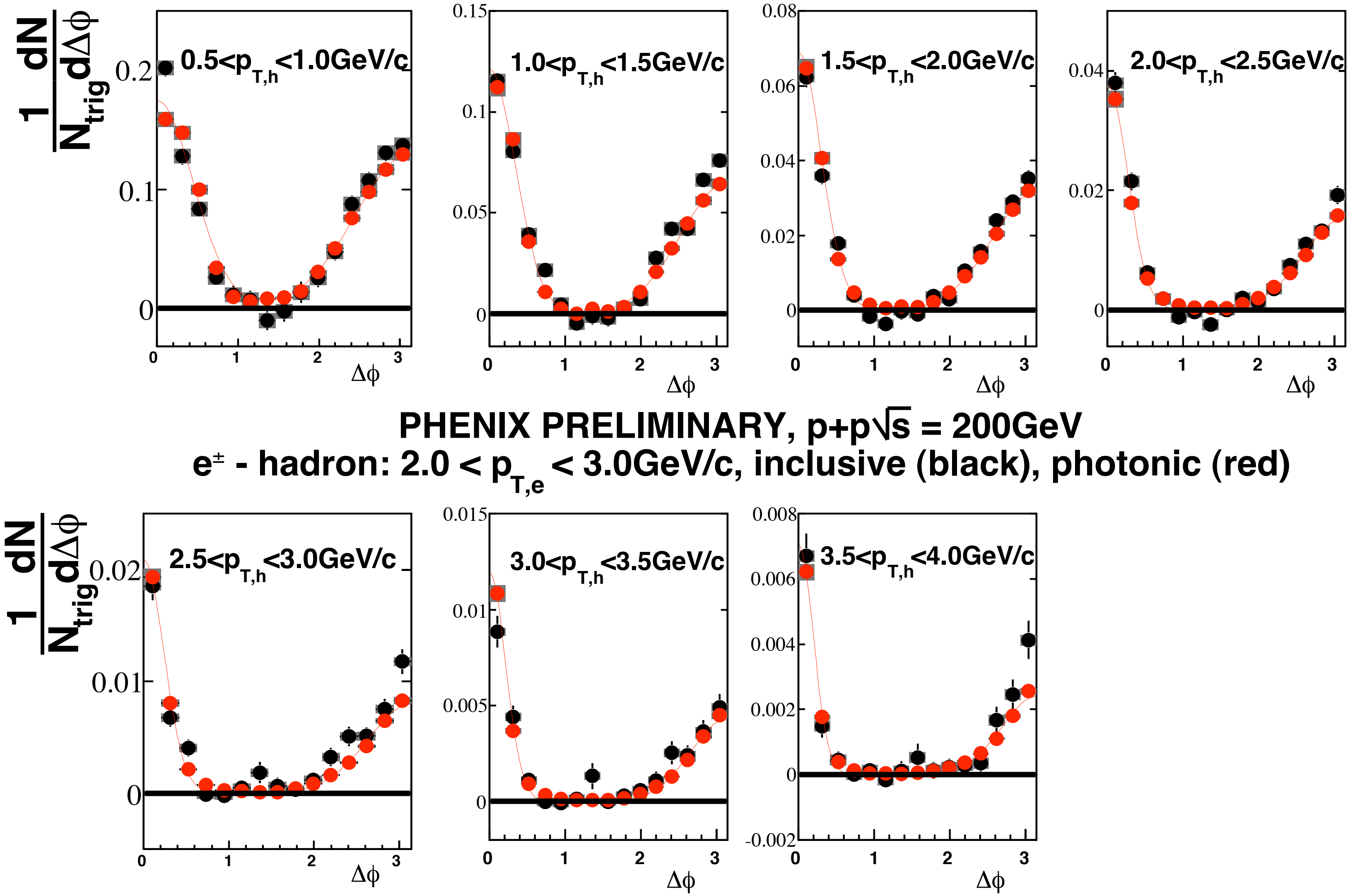
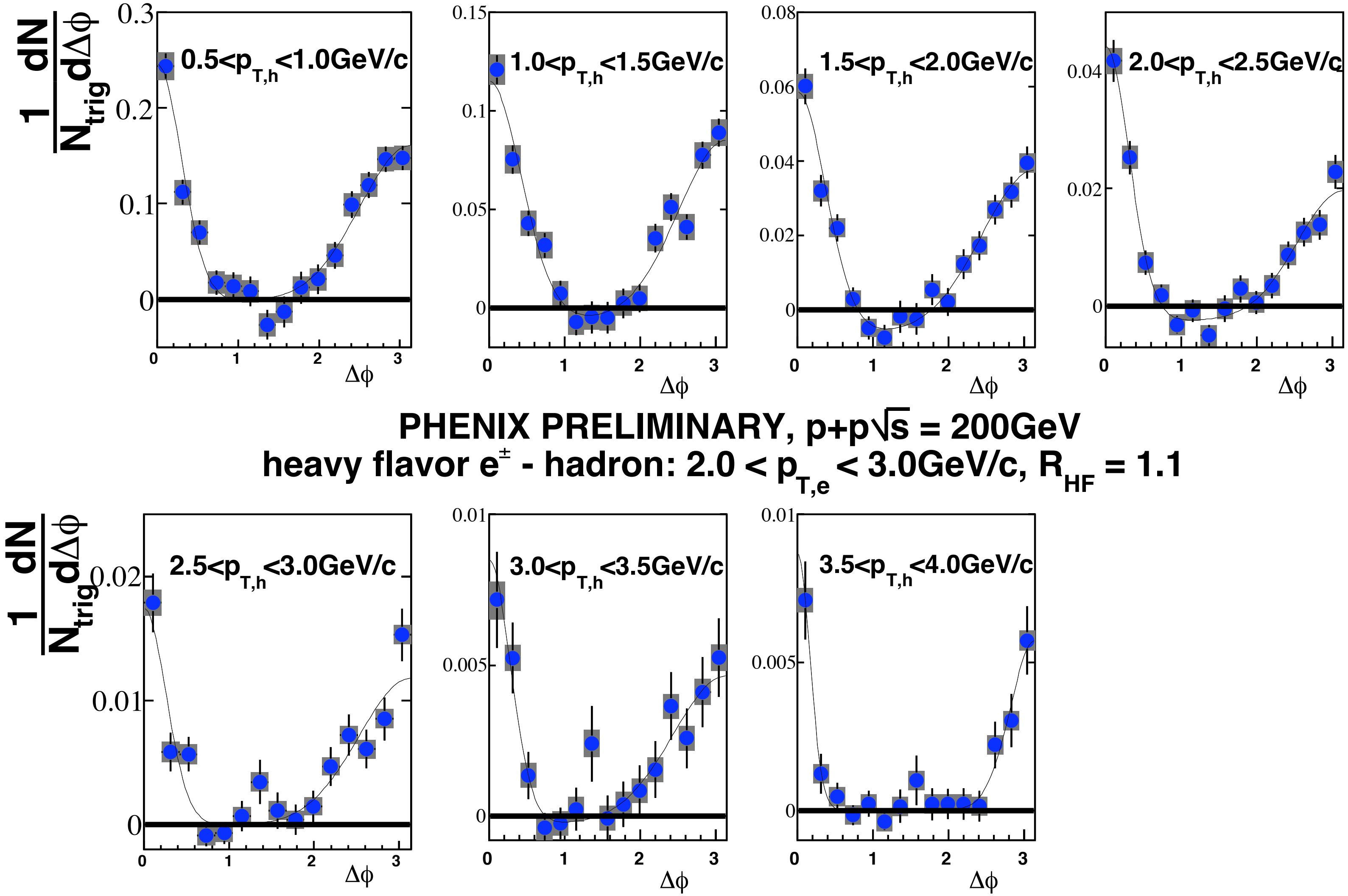


e_{HF}-h jet functions



e_{HF}-h jet functions

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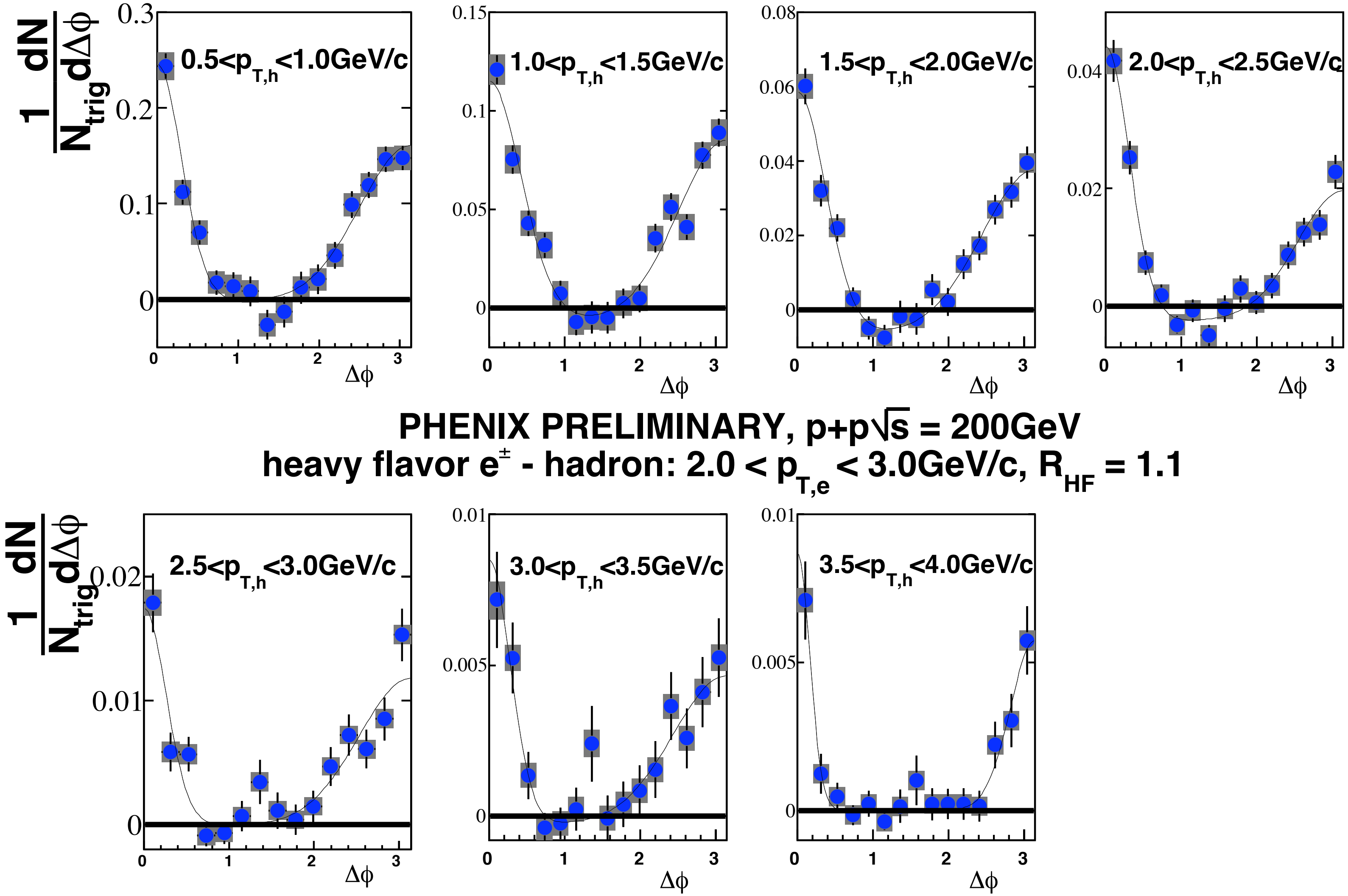
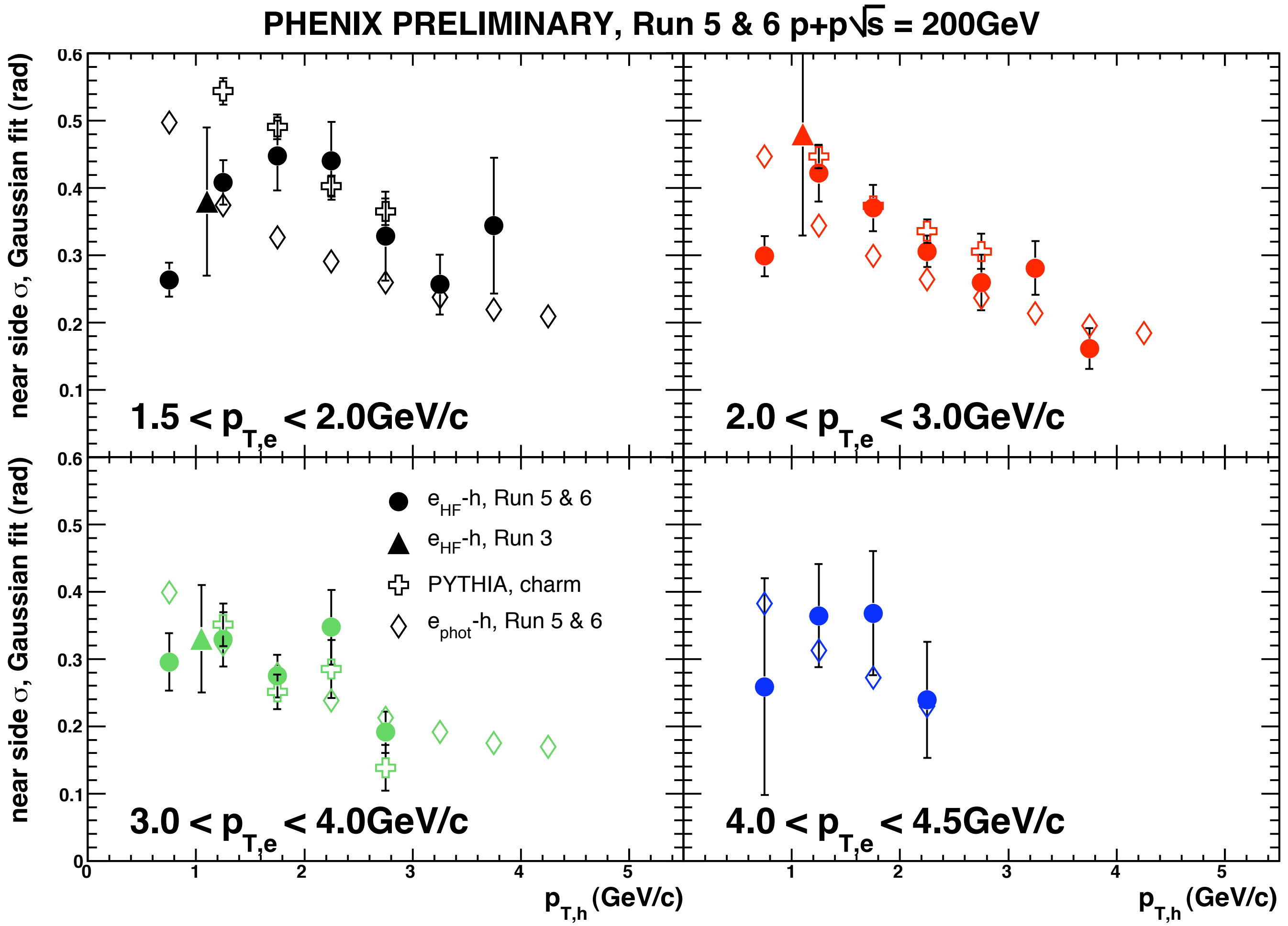


widths: sanity check



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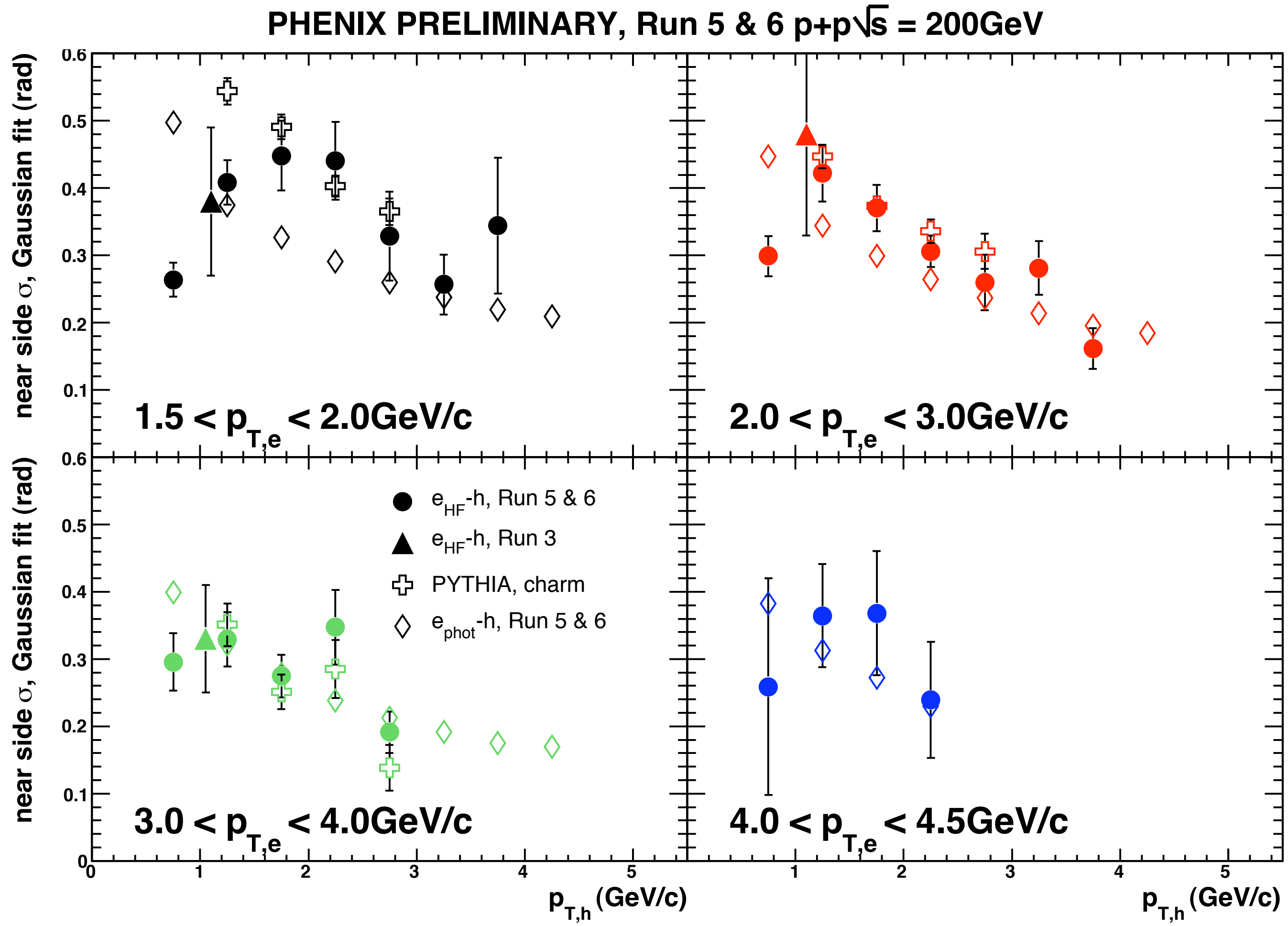

- $\sigma_{HF} > \sigma_{phot}$, D decays broaden near side

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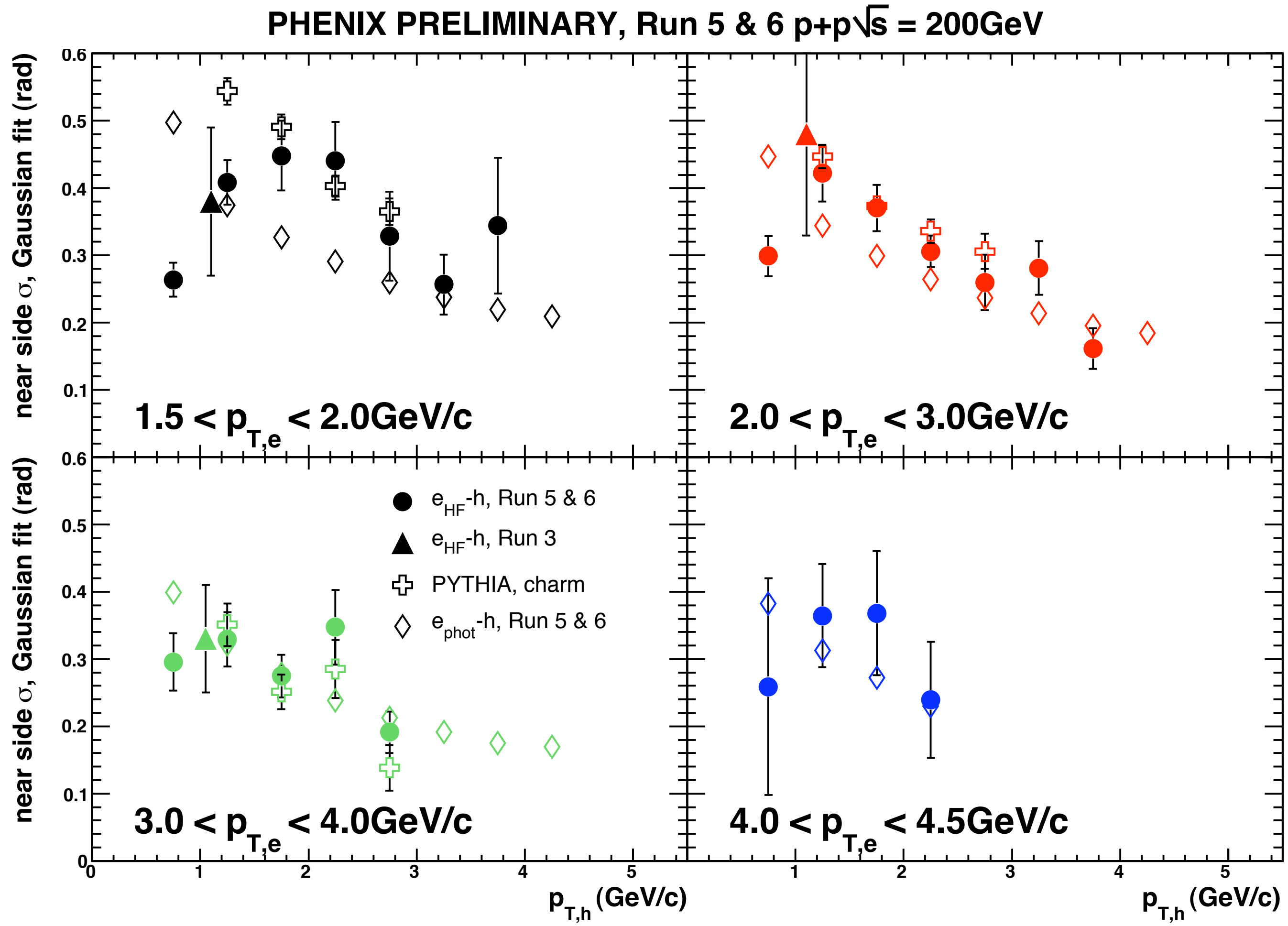

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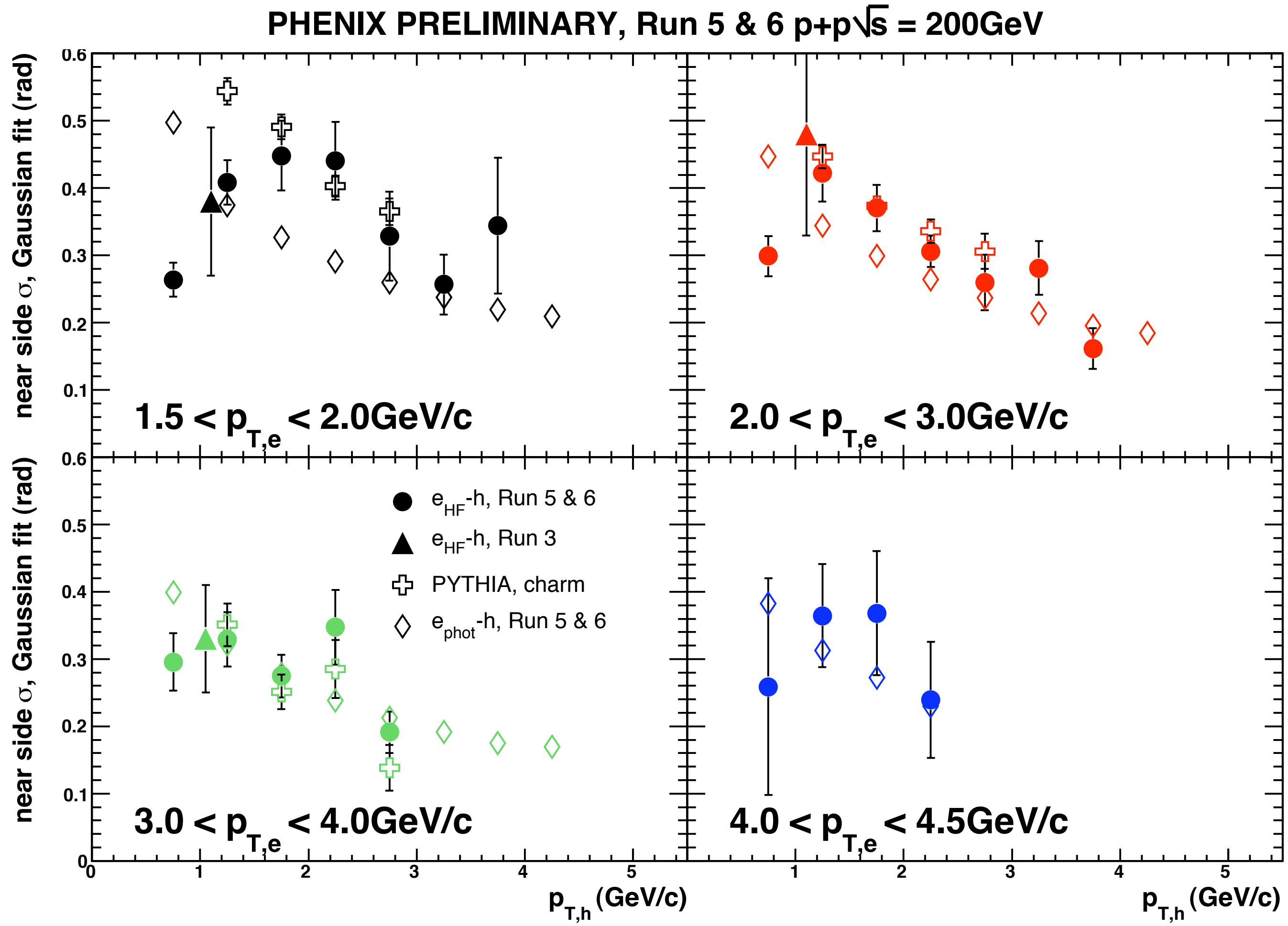
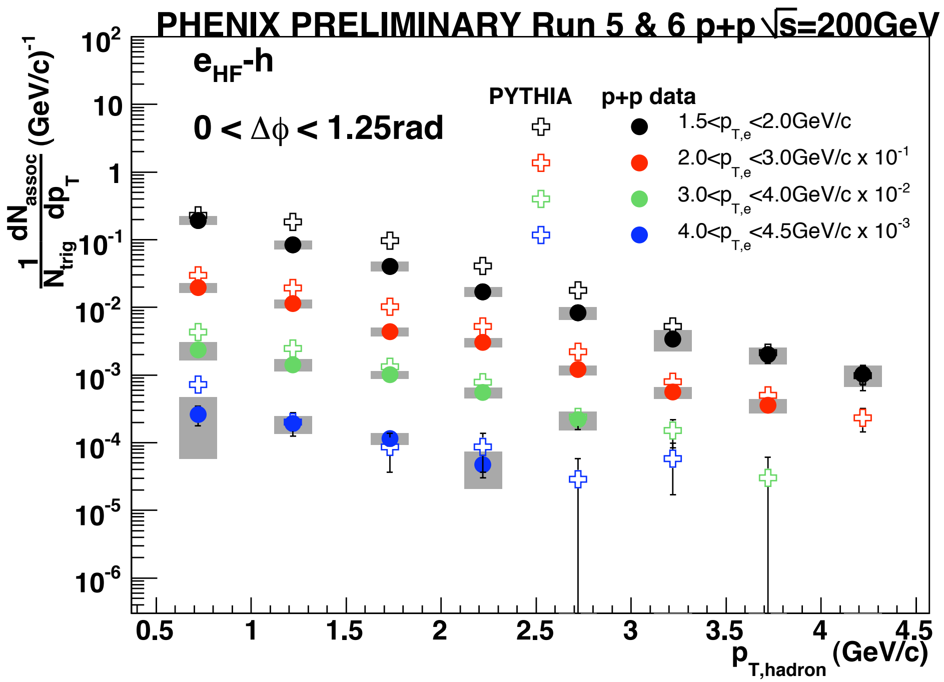
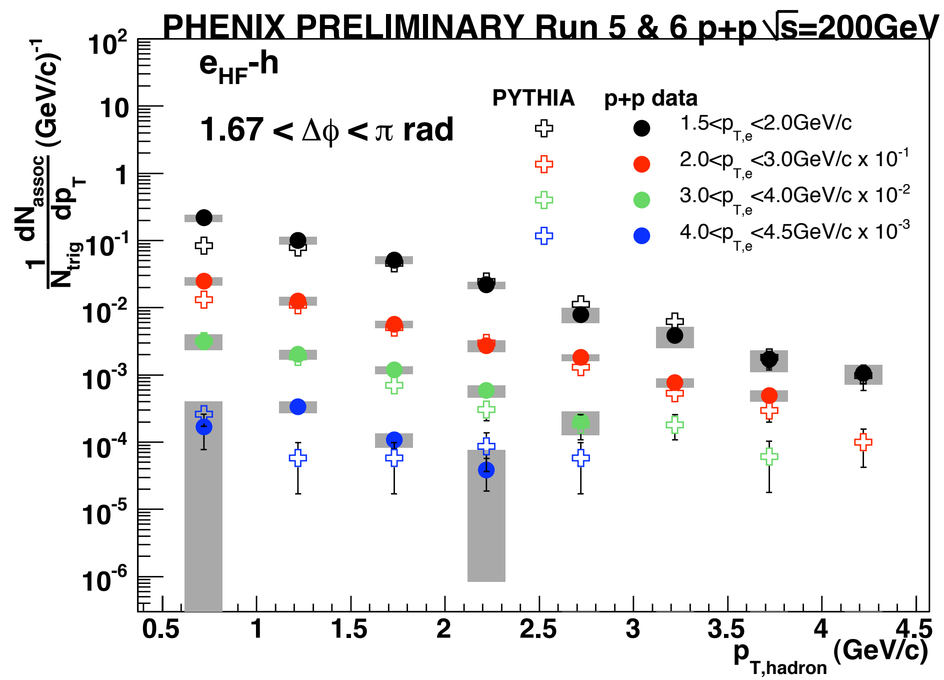


- $\sigma_{HF} > \sigma_{phot}$, D decays broaden near side
- σ_{HF} consistent with σ_{PYTHIA} (charm production)
- agreement w/ Run 3 PHENIX result

conditional yields

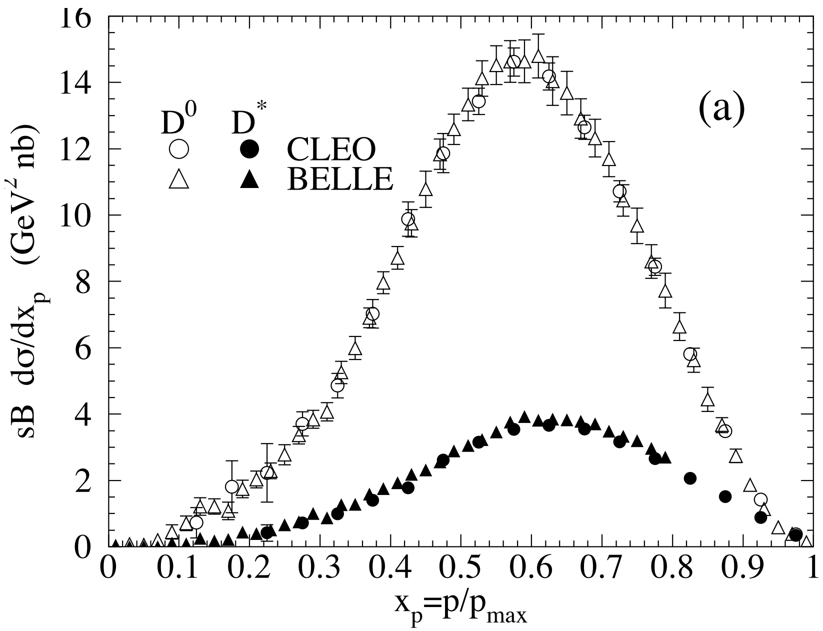


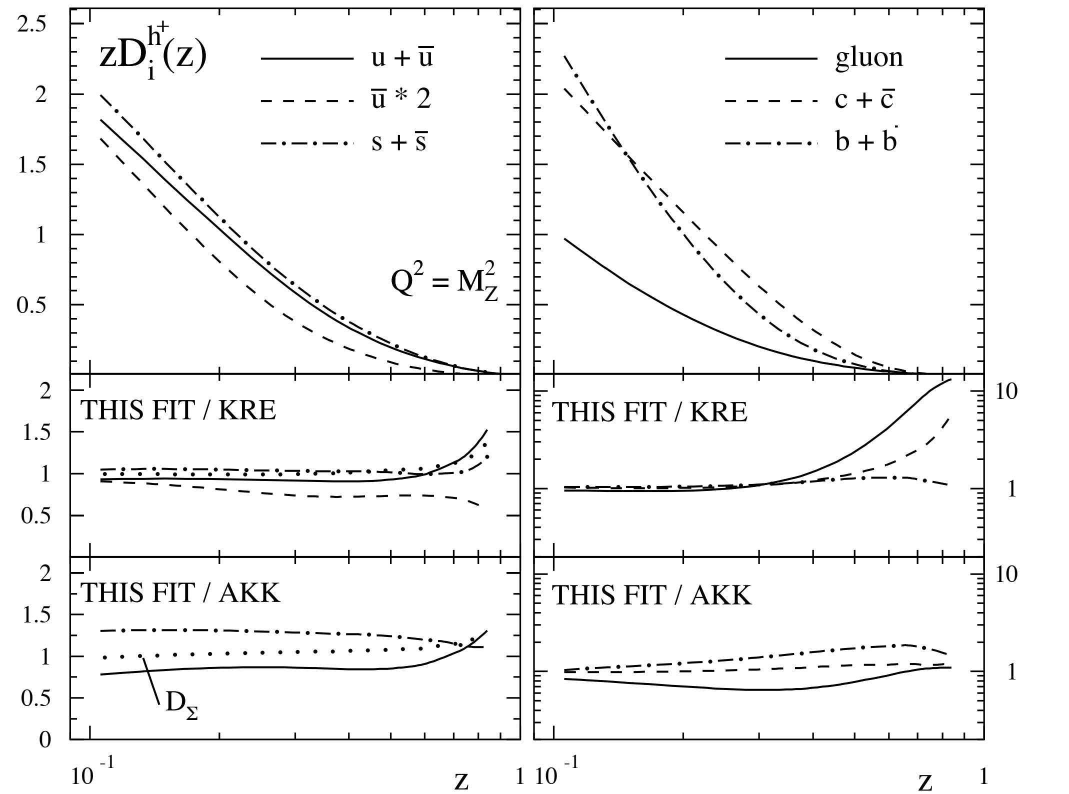


- near side, D decay dominated, especially at high pT
- away side, mix of hadrons from D decays and fragmentation

***PYTHIA, charm production, default parameters**

charm fragmentation



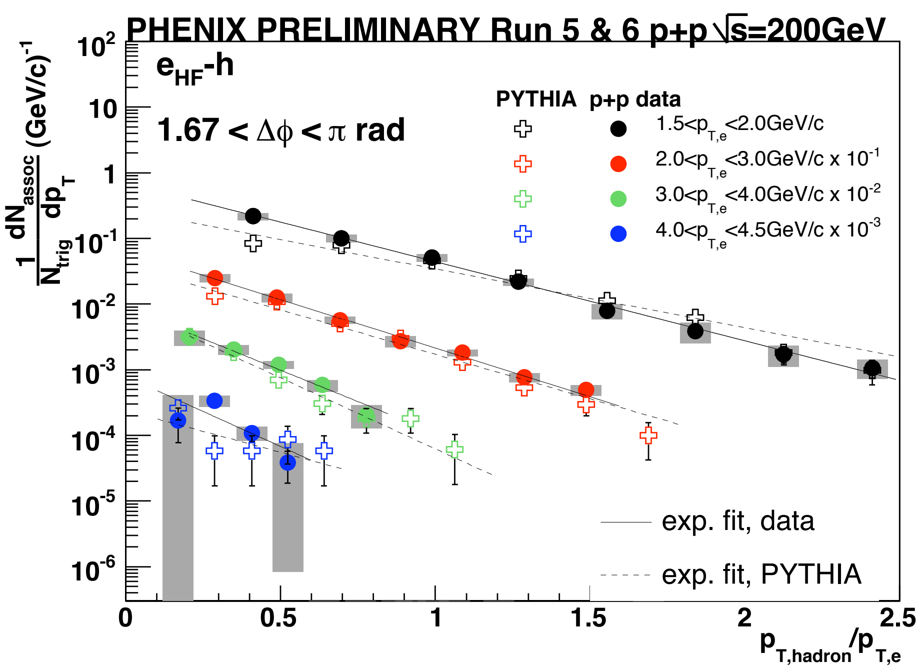


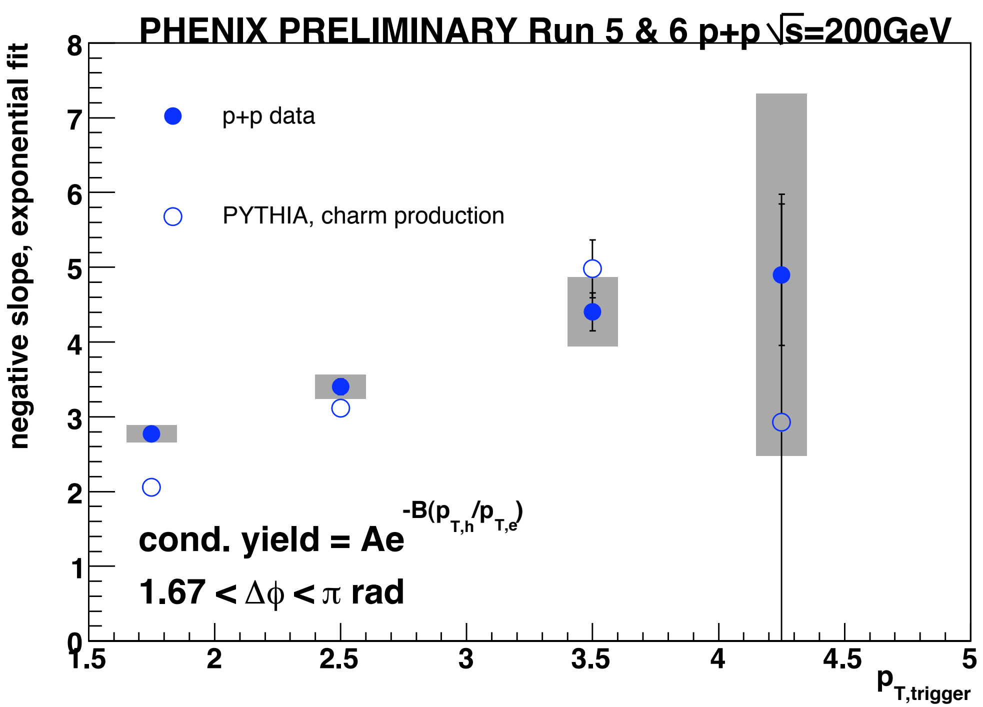
- D carries most of the charm p_T
- charm → light hadron fragmentation softer than gluon → light hadron

Part. Data Book

de Florian et al PRD 76 074033 (2007)

away side compared to light jets





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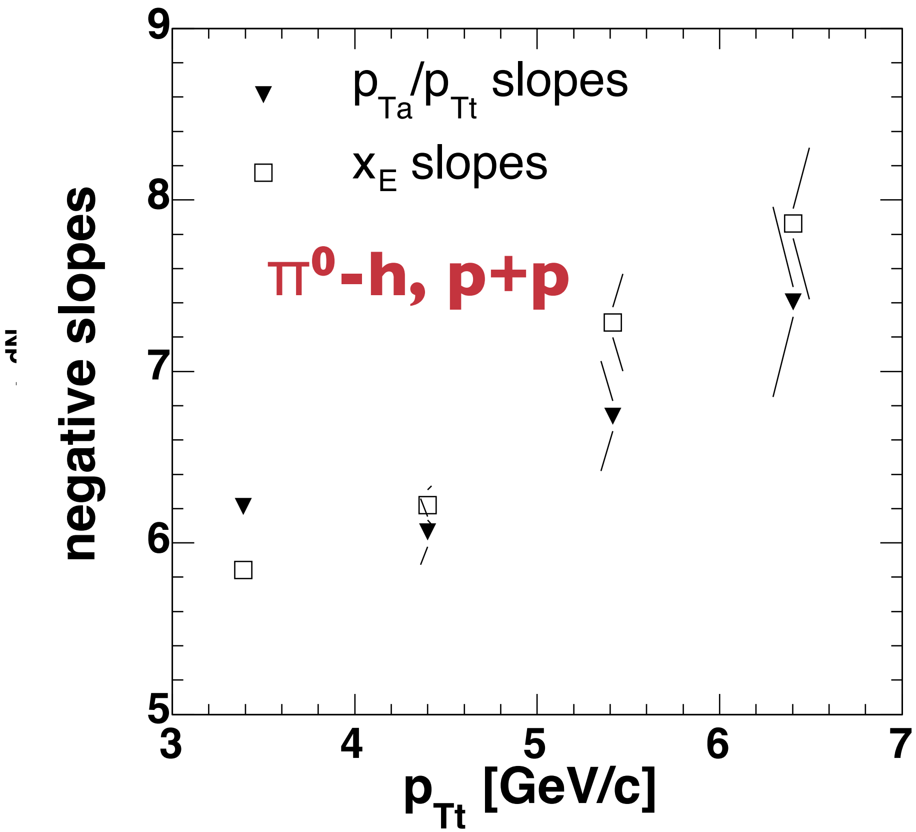

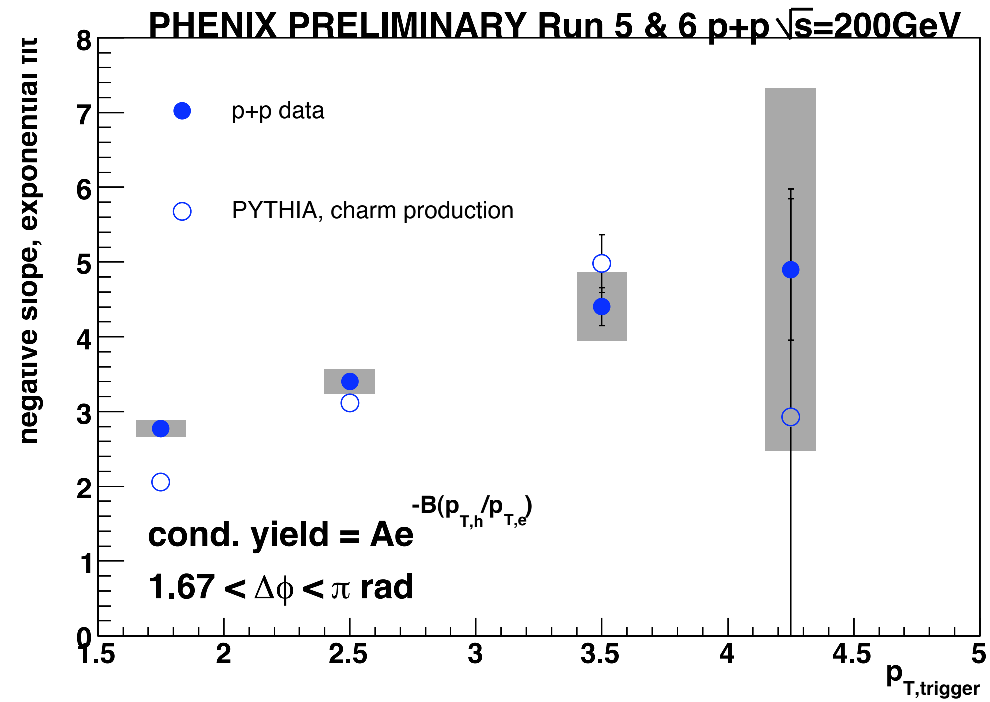

PHENIX PRD 74 072002 (2006)

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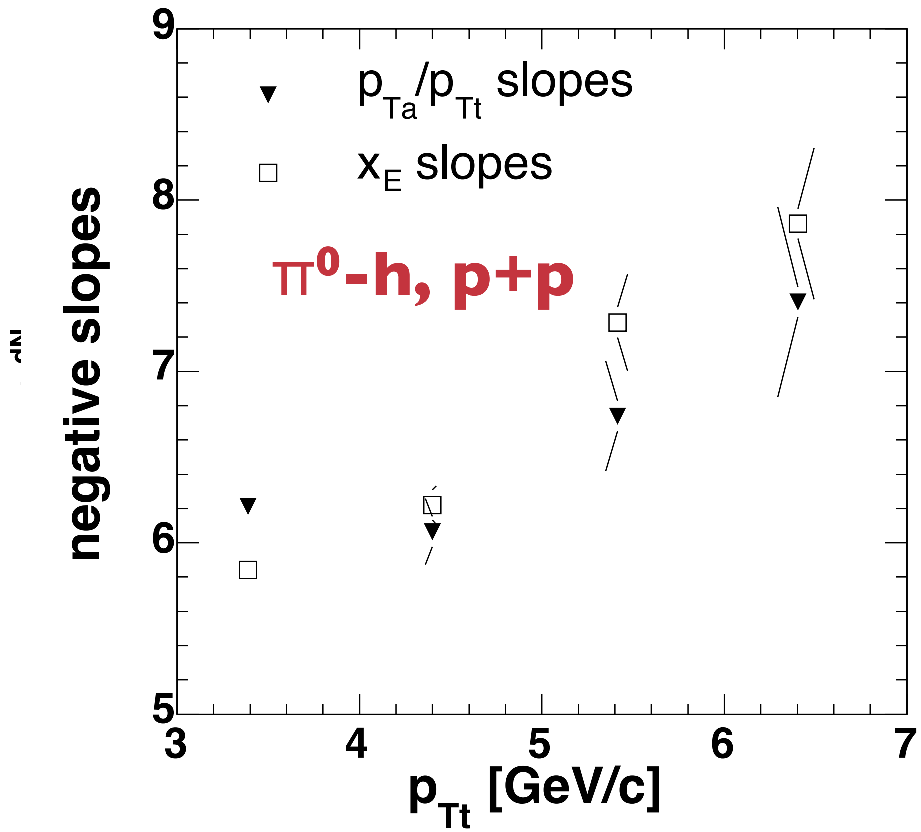
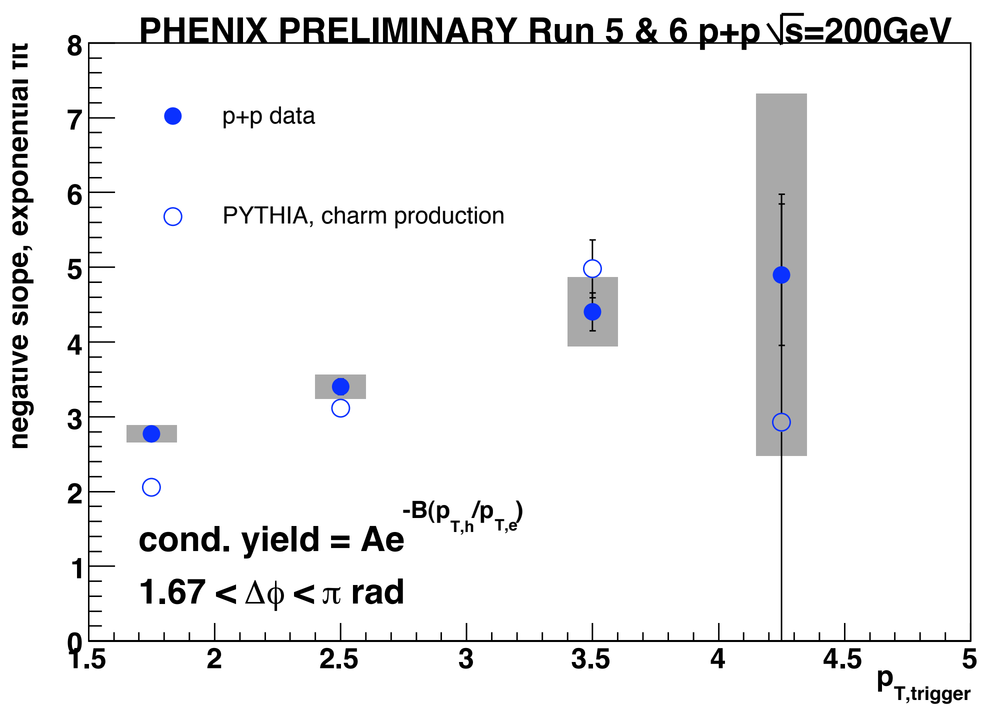
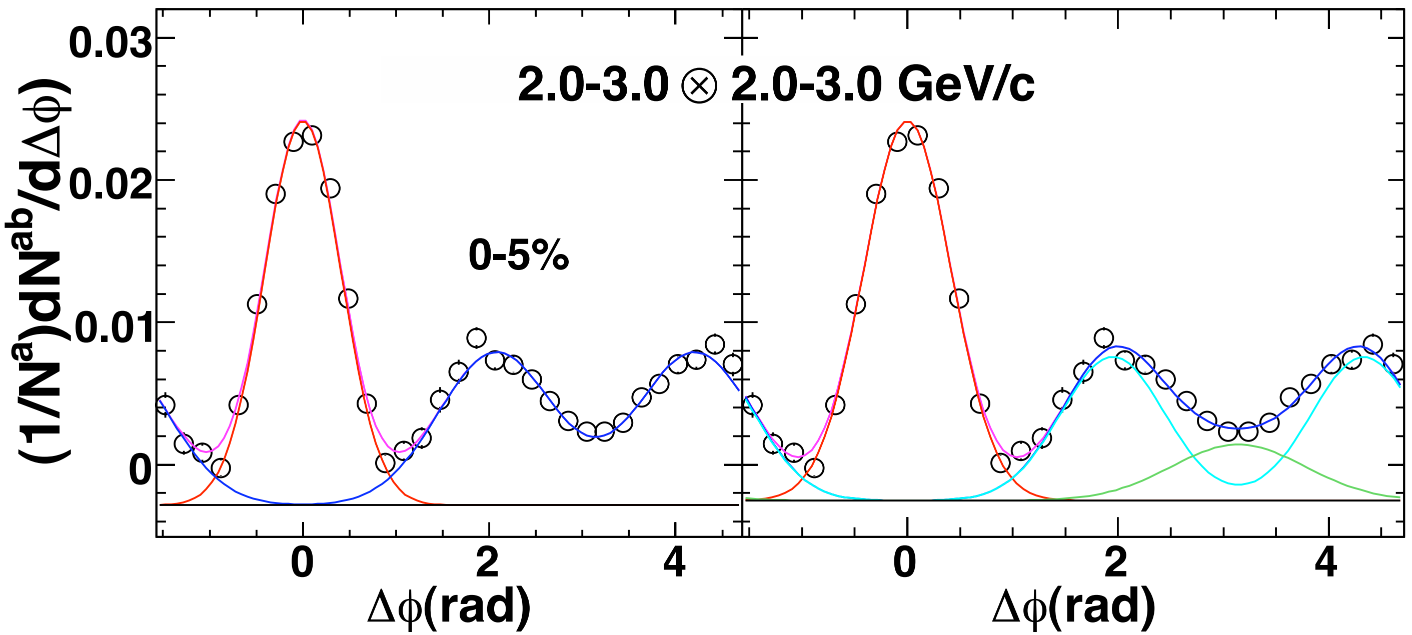




PHENIX PRD 74 072002 (2006)

e_{HF}-h harder @ same $p_{T,trig}$

beyond ZYAM



PHENIX,
PRC 78 014901 (2008)

- ZYAM: zero-yield-at-minimum, assume $\Delta\phi$ region without signal
- ZYAM not a good assumption for moderate p_T
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  - fitting not an optimal way to find the background either (lots of overlapping Gaussians)

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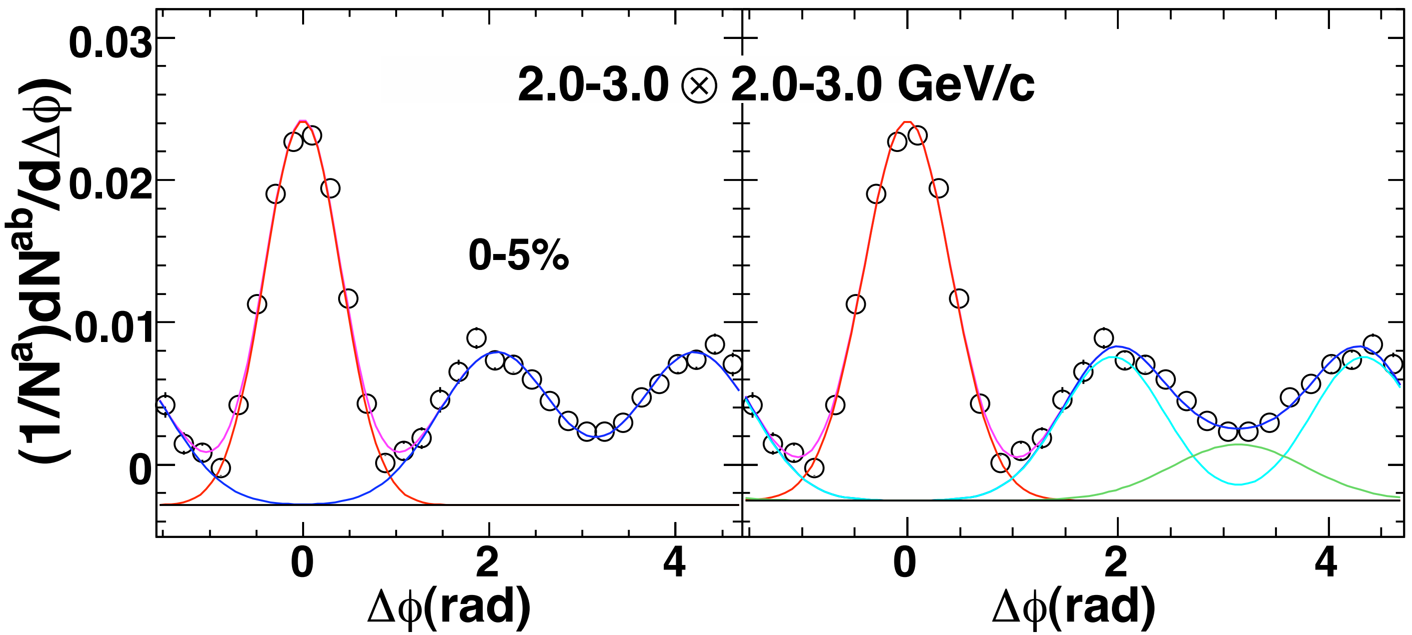

PHENIX, PRC 78 014901 (2008)

fit background

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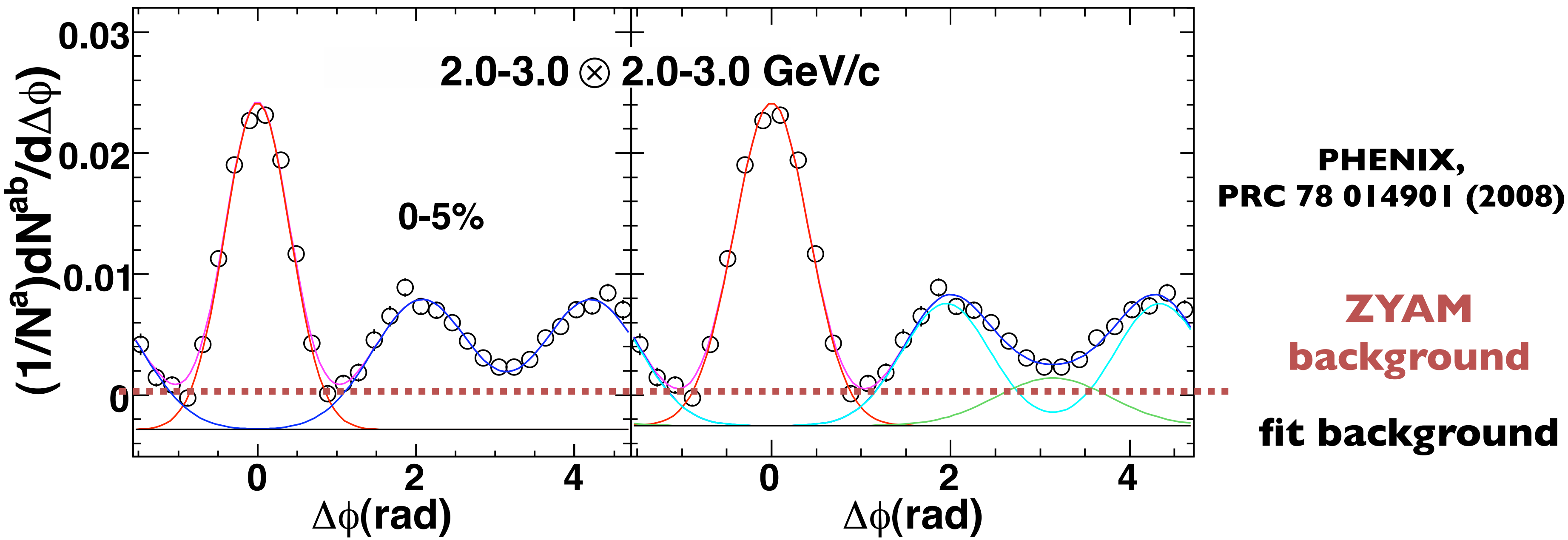

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absolute background subtraction

**PHENIX, PRC 71 051902 (2005),
AS et al, nucl-ex/072007**

absolute background subtraction

- random background rate: <n_{trig}><n_{part}>

PHENIX, PRC 71 051902 (2005), AS et al, nucl-ex/072007

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PHENIX, PRC 71 051902 (2005),
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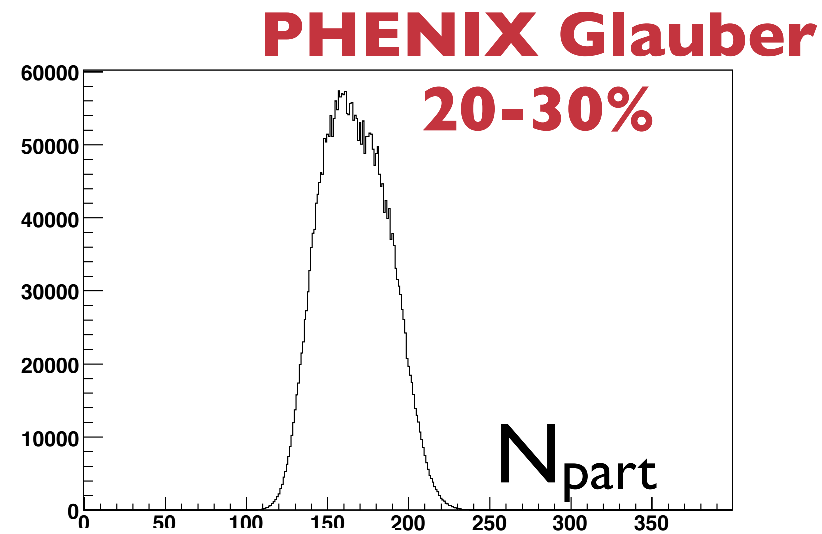
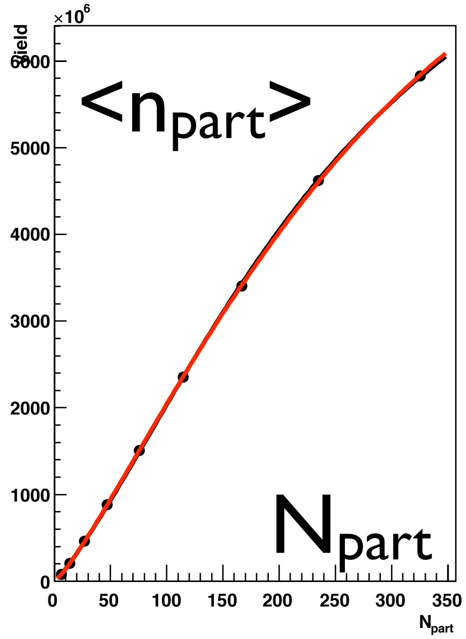
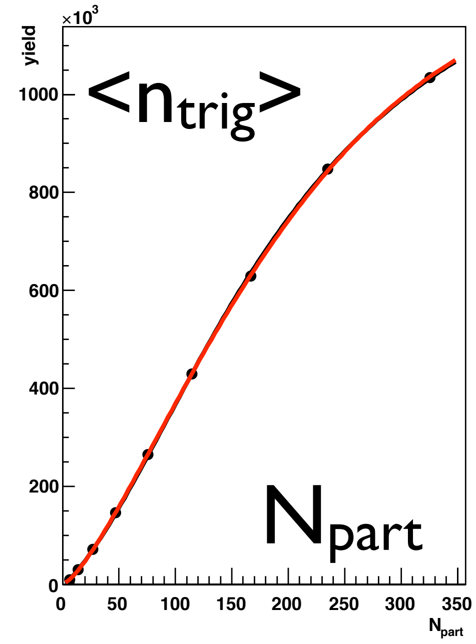
  - $\rightarrow$ background rate: $\xi \langle n_{trig} \rangle \langle n_{part} \rangle$
    - no ZYAM, fitting needed

PHENIX, PRC 71 051902 (2005),
AS et al, nucl-ex/072007

calculating ξ







calculating ξ

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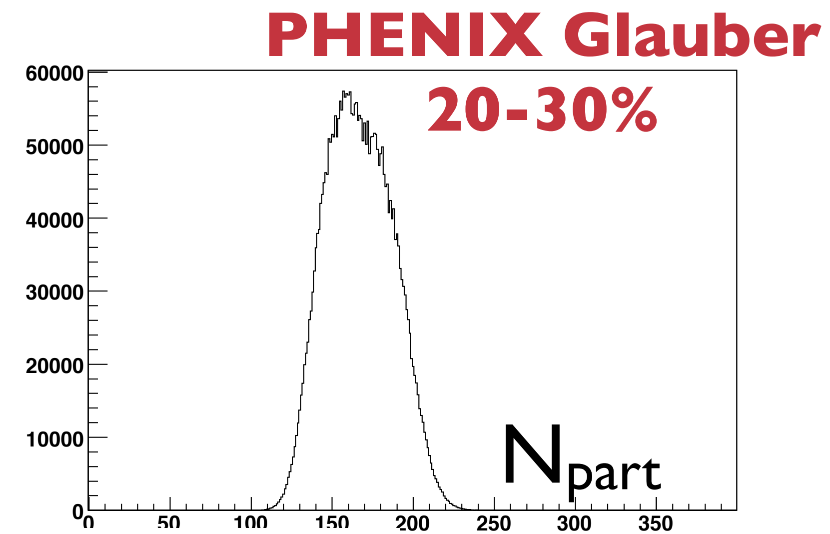

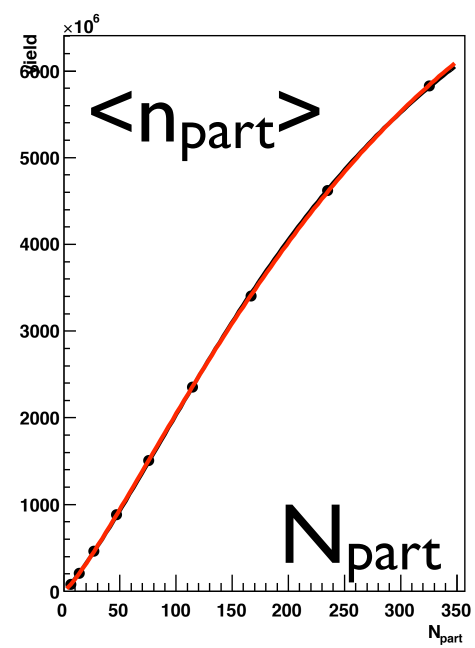

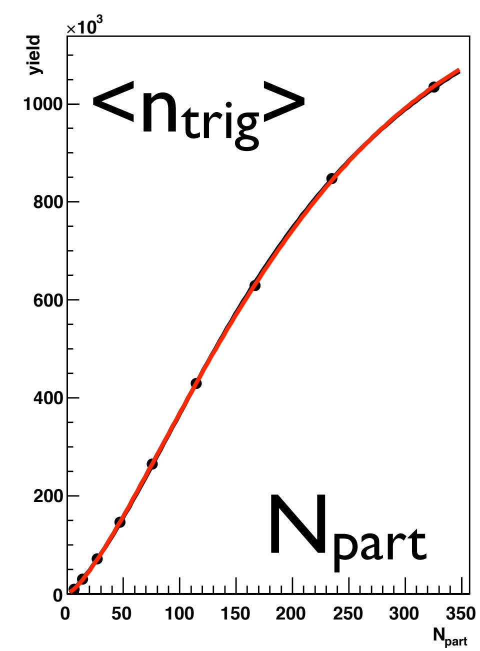

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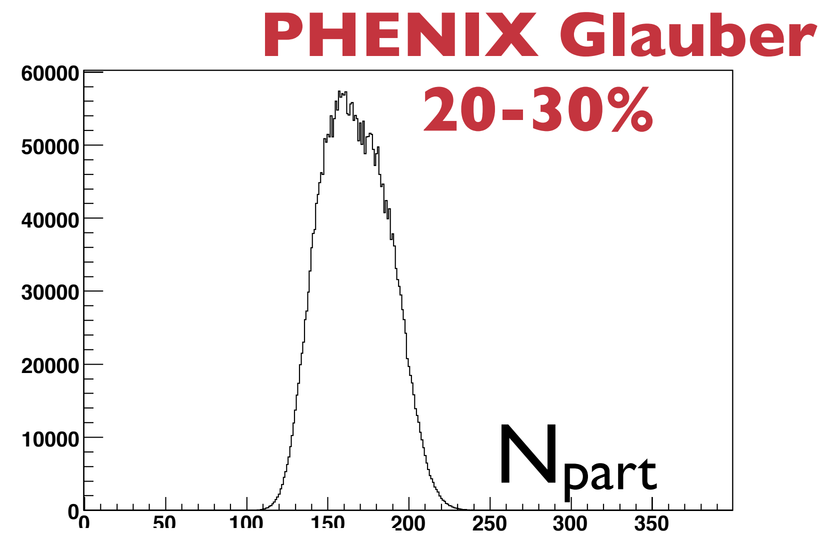

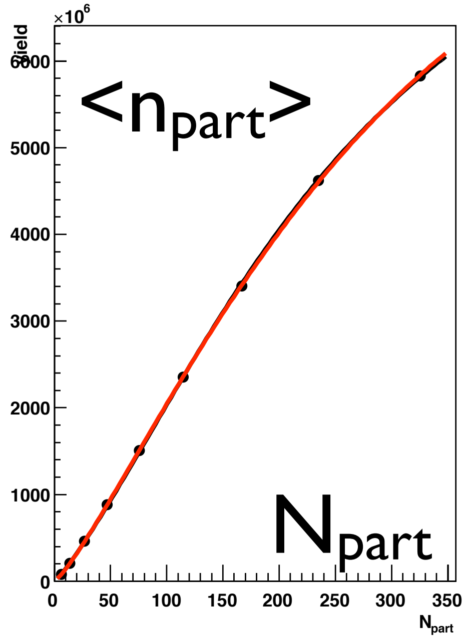

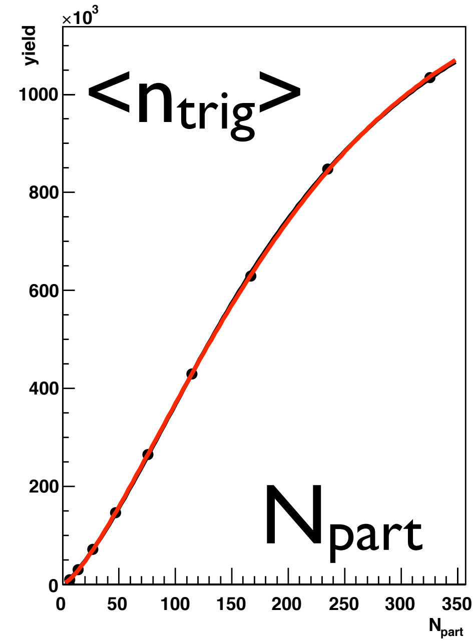

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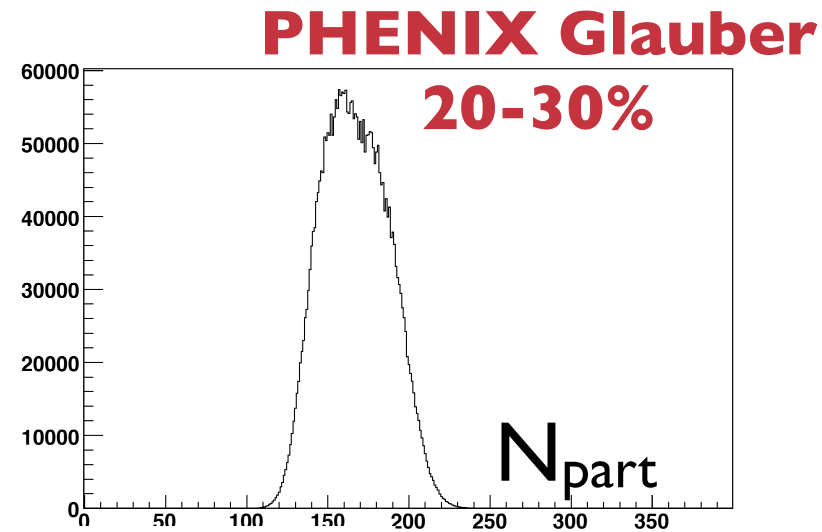

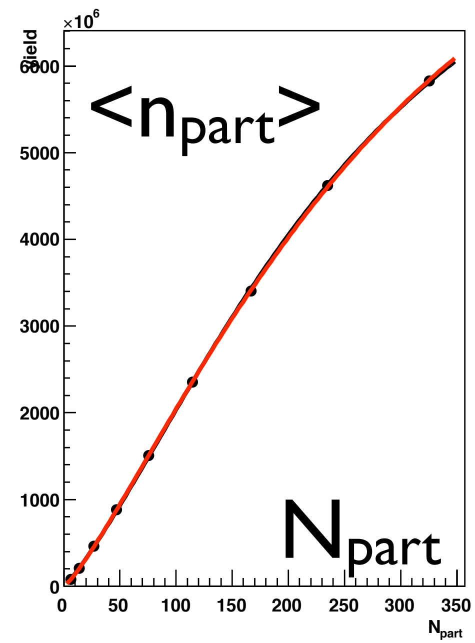

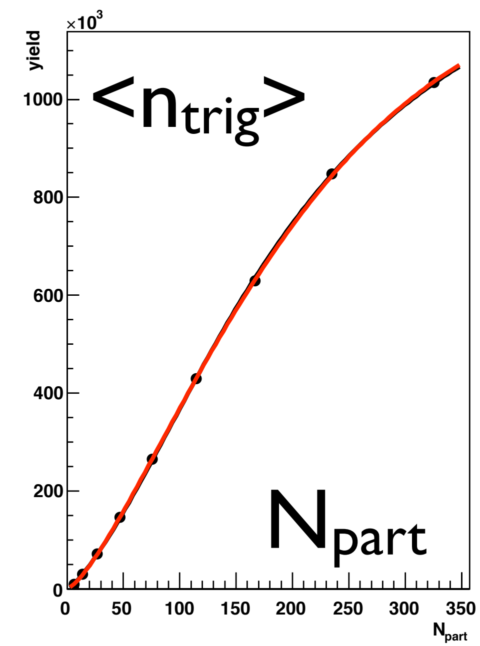

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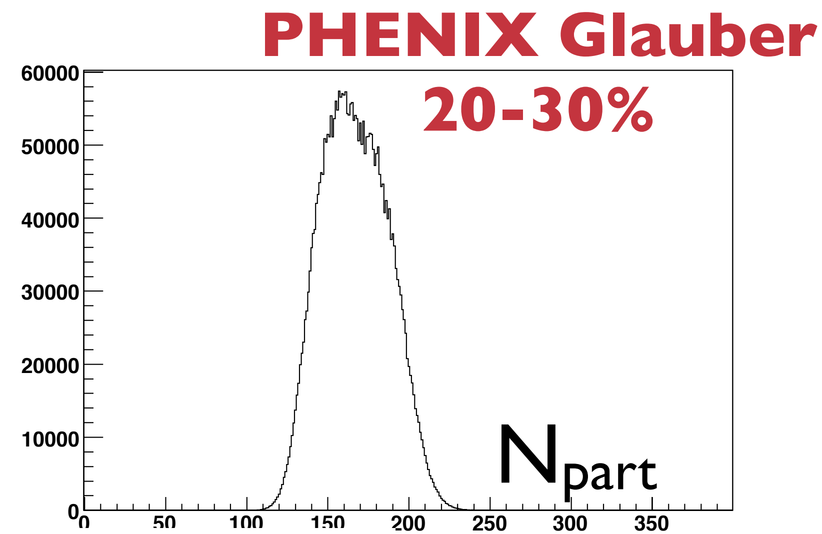

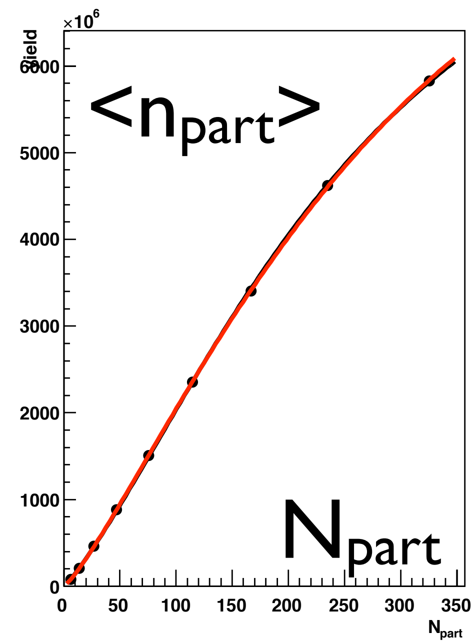

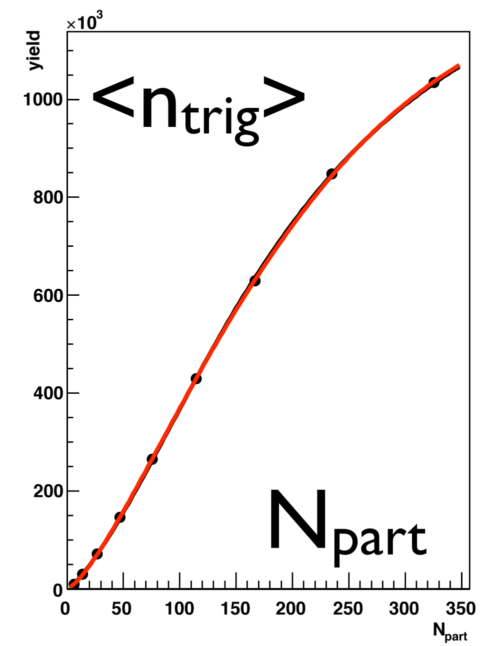

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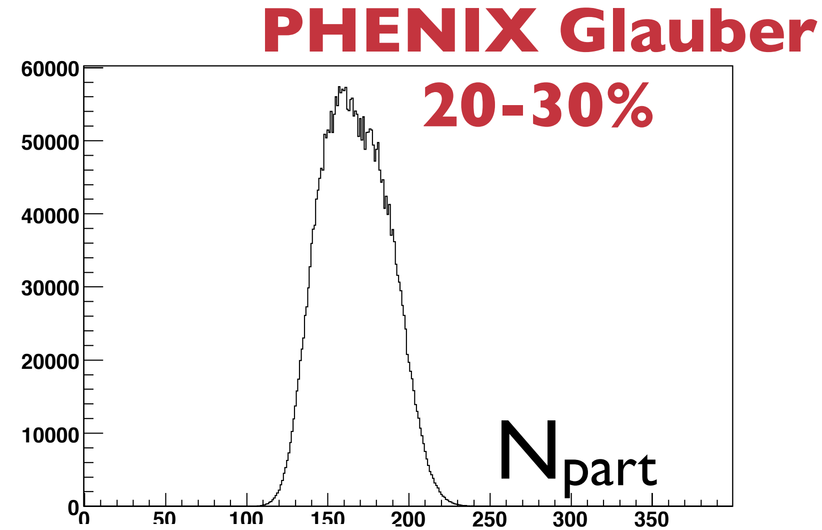
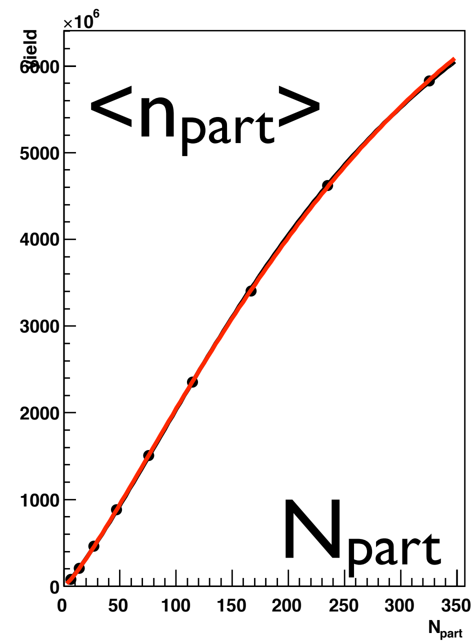
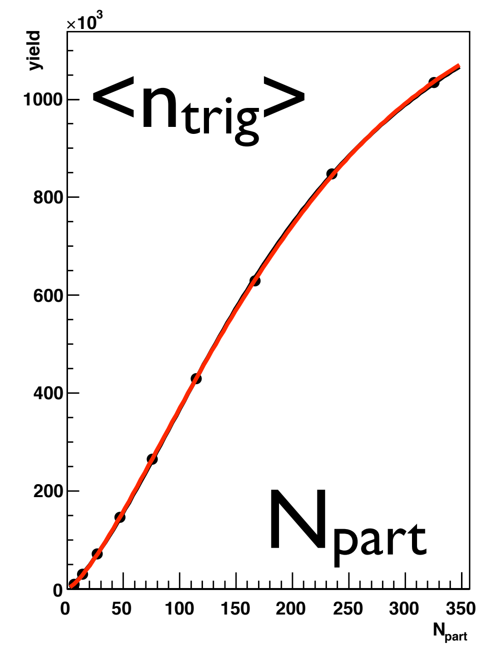
- repeat many times







Conclusions

Conclusions

- matter responds to the passage of a fast parton
  - energy transport, η/s, sound speed, surface bias, coupling strength
- hadrons: probably formed via recombination
  - balance between losing & picking up energy?
- baryons: medium response & recombination
  - possible contributions from higher twist production

Where Next?

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  - ridge, shoulder, jet many p_T & centrality bins

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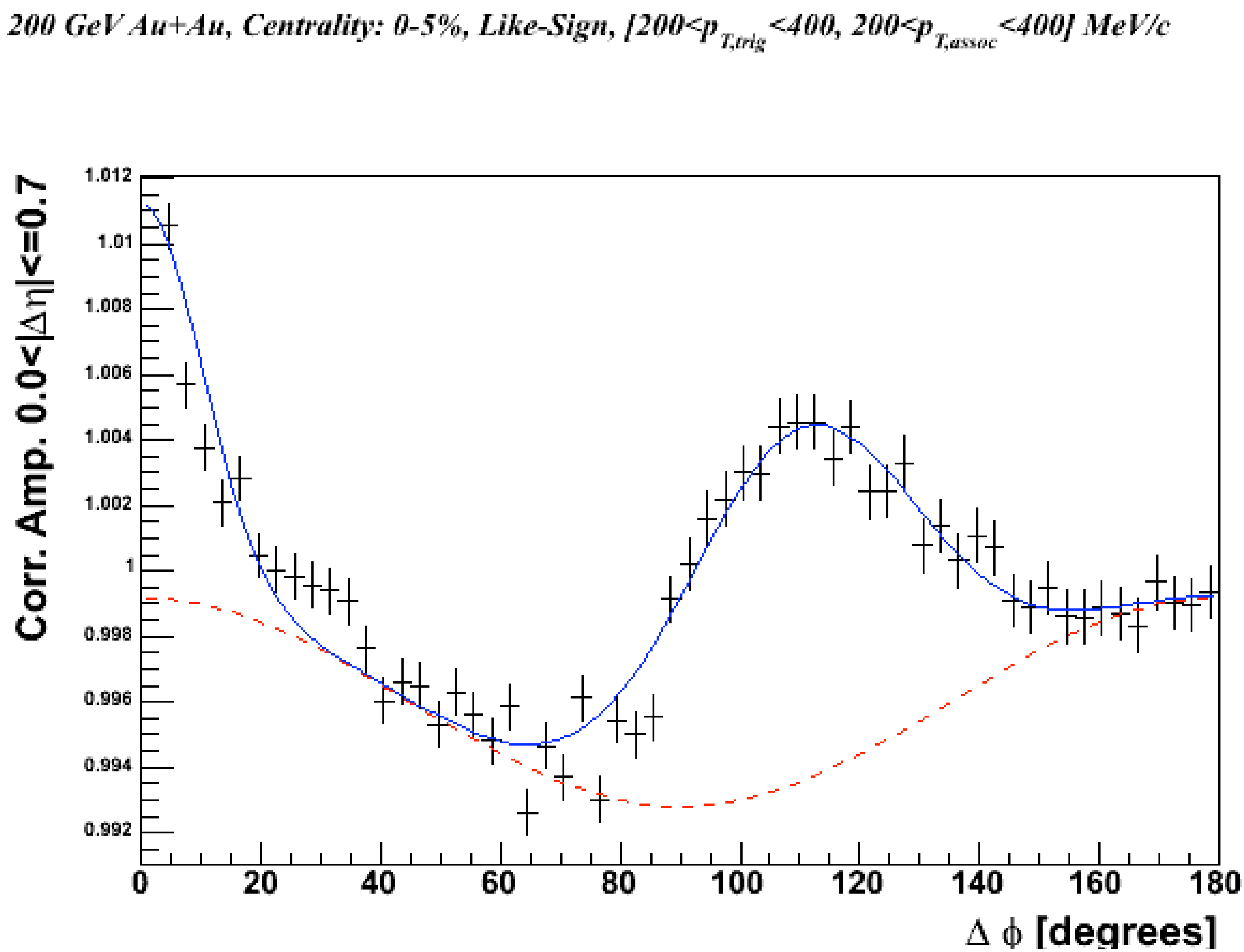
  - identified particle spectra: x_T distributions

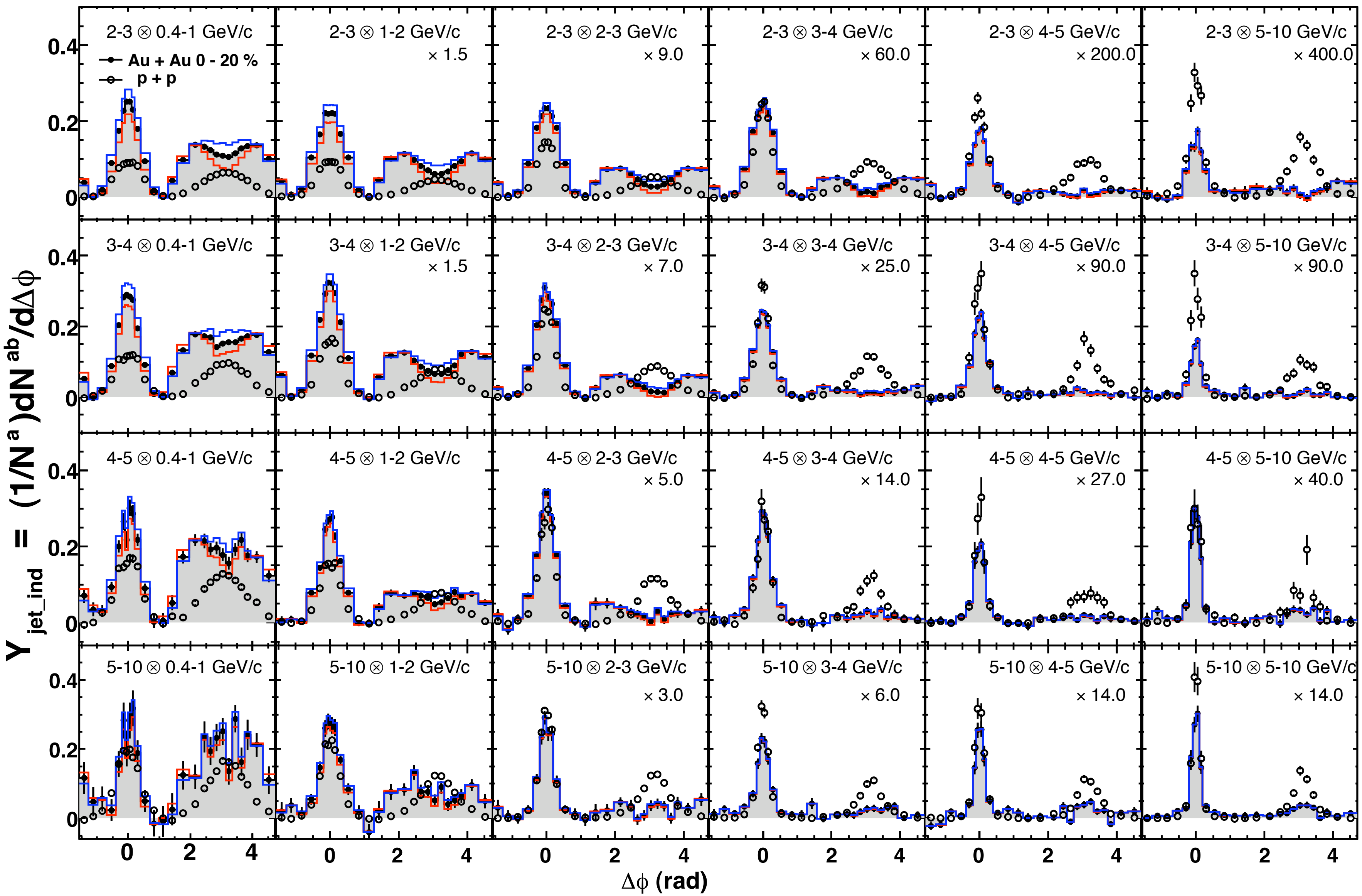
BACKUPS

very low p_T

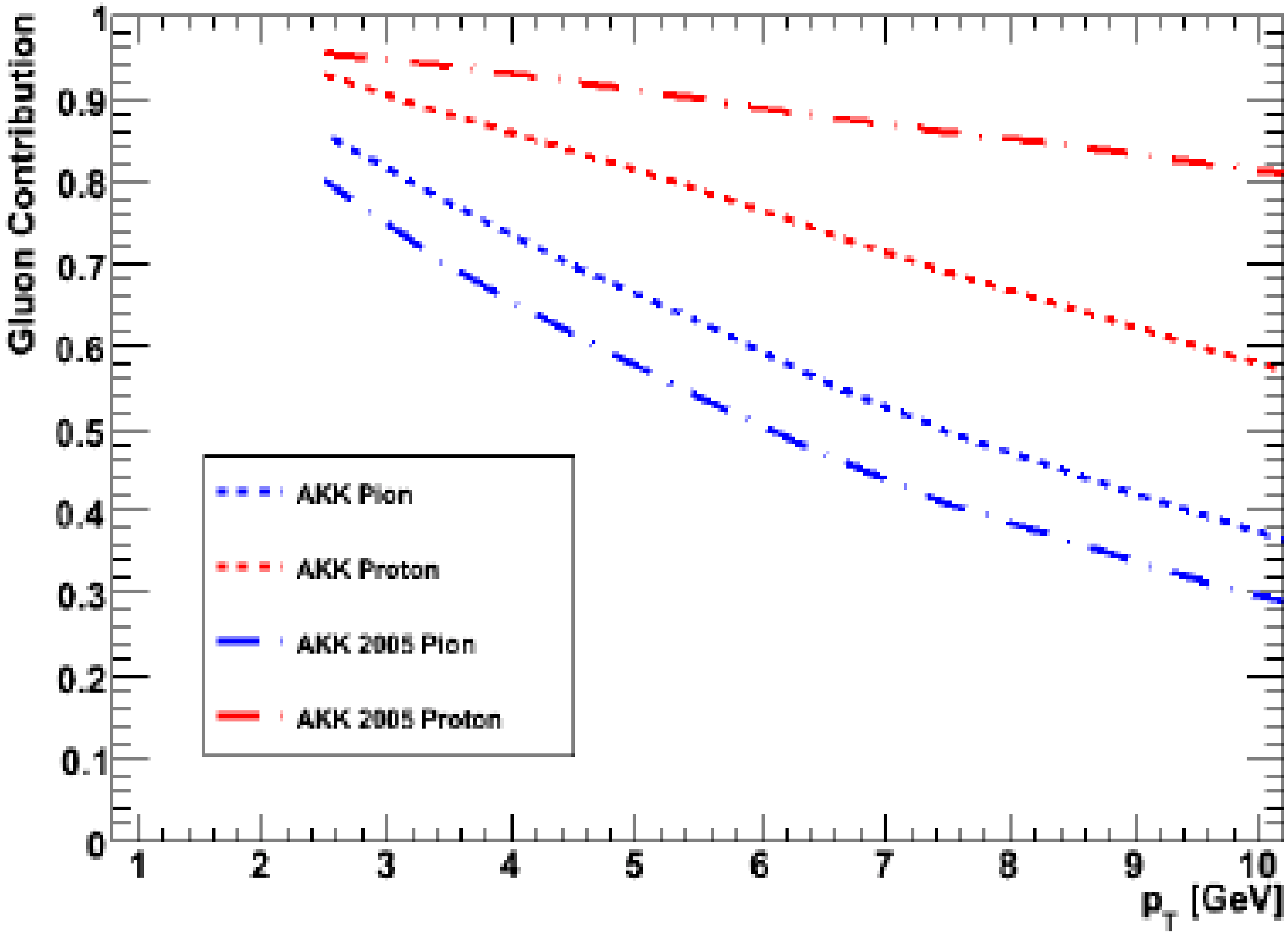


- ridge & sh
trigger

- maybe this means the matter has these properties w/o the jet, the jet just picks them up via coupling


2-3 ⊗ 0.4-1 GeV/c
Au + Au 0 - 20 %
p + p
2-3 ⊗ 1-2 GeV/c
× 1.5
2-3 ⊗ 2-3 GeV/c
× 9.0
2-3 ⊗ 3-4 GeV/c
× 60.0
2-3 ⊗ 4-5 GeV/c
× 200.0
2-3 ⊗ 5-10 GeV/c
× 400.0
3-4 ⊗ 0.4-1 GeV/c
3-4 ⊗ 1-2 GeV/c
× 1.5
3-4 ⊗ 2-3 GeV/c
× 7.0
3-4 ⊗ 3-4 GeV/c
× 25.0
3-4 ⊗ 4-5 GeV/c
× 90.0
3-4 ⊗ 5-10 GeV/c
× 90.0
4-5 ⊗ 0.4-1 GeV/c
4-5 ⊗ 1-2 GeV/c
4-5 ⊗ 2-3 GeV/c
× 5.0
4-5 ⊗ 3-4 GeV/c
× 14.0
4-5 ⊗ 4-5 GeV/c
× 27.0
4-5 ⊗ 5-10 GeV/c
× 40.0
5-10 ⊗ 0.4-1 GeV/c
5-10 ⊗ 1-2 GeV/c
5-10 ⊗ 2-3 GeV/c
× 3.0
5-10 ⊗ 3-4 GeV/c
× 6.0
5-10 ⊗ 4-5 GeV/c
× 14.0
5-10 ⊗ 5-10 GeV/c
× 14.0
$Y_{jet\_ind} = (1/N^a)dN^{ab}/d\Delta\phi$
Δφ (rad)
0.4
0.2
0
2
4

AKK: Old vs. New

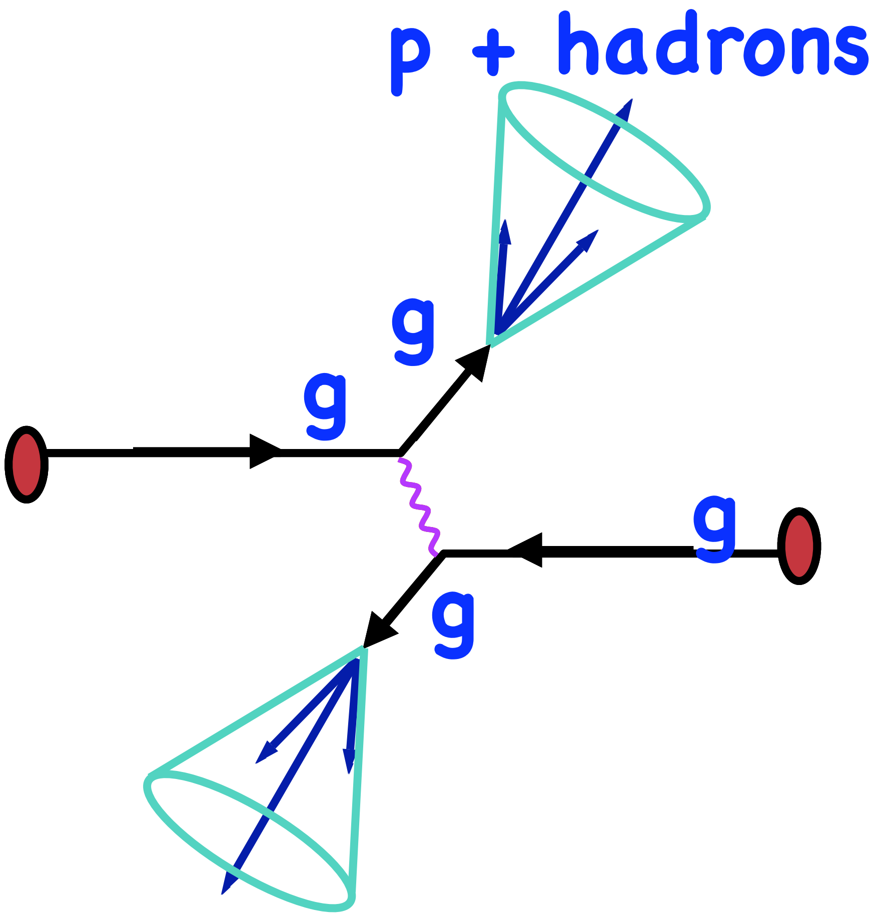


Direct vs. Conventional Protons

Direct vs. Conventional Protons

Conventional Production:

Proton with Other Jet Fragments



Direct vs. Conventional Protons

Conventional Production:

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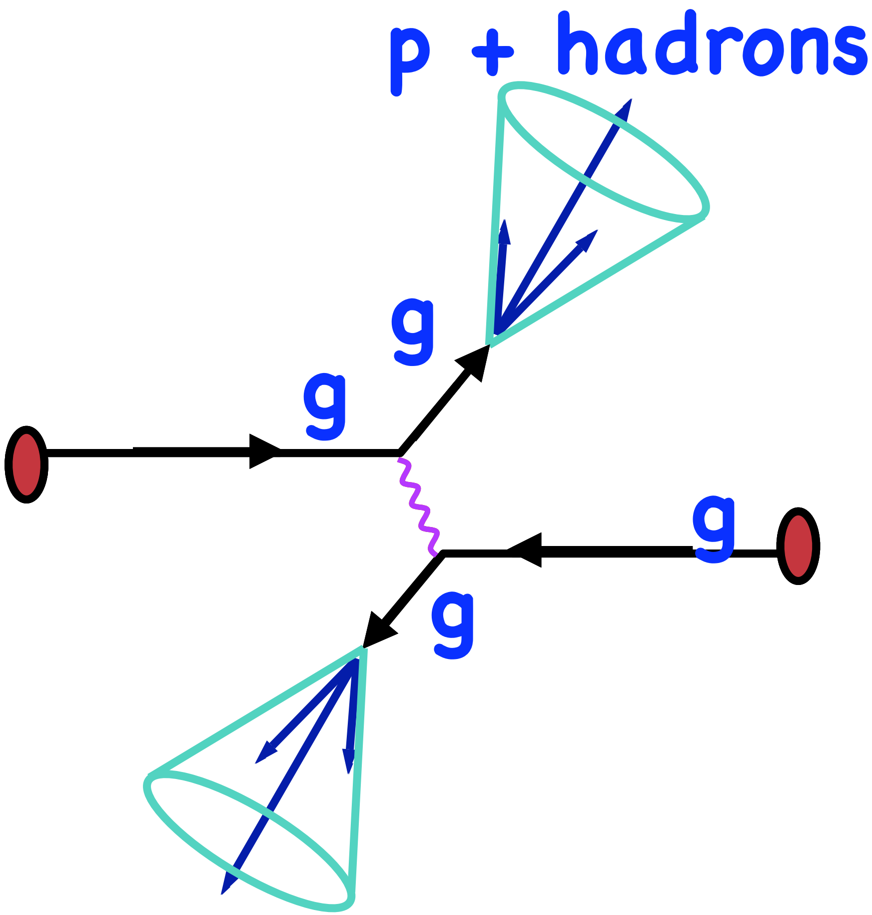
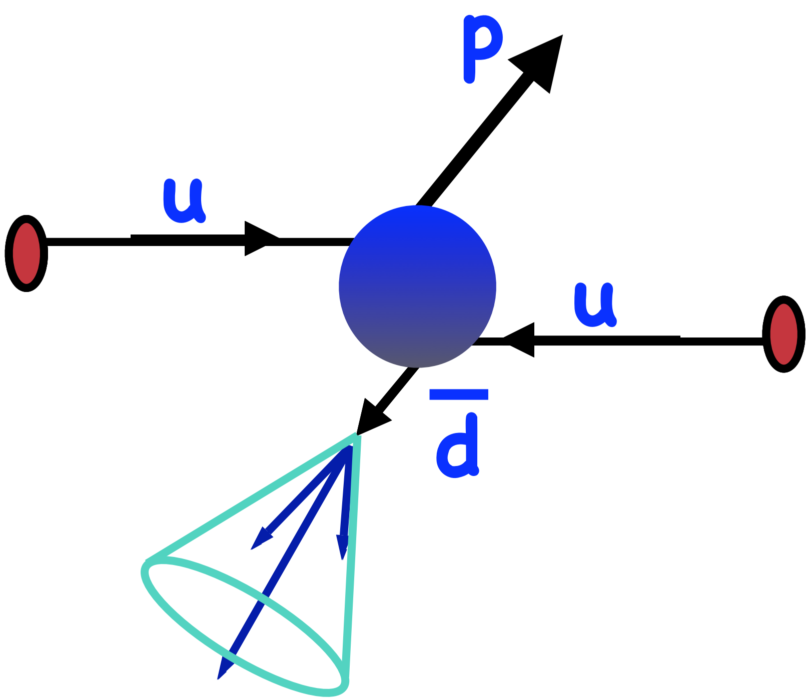


Direct Production:

Isolated Protons



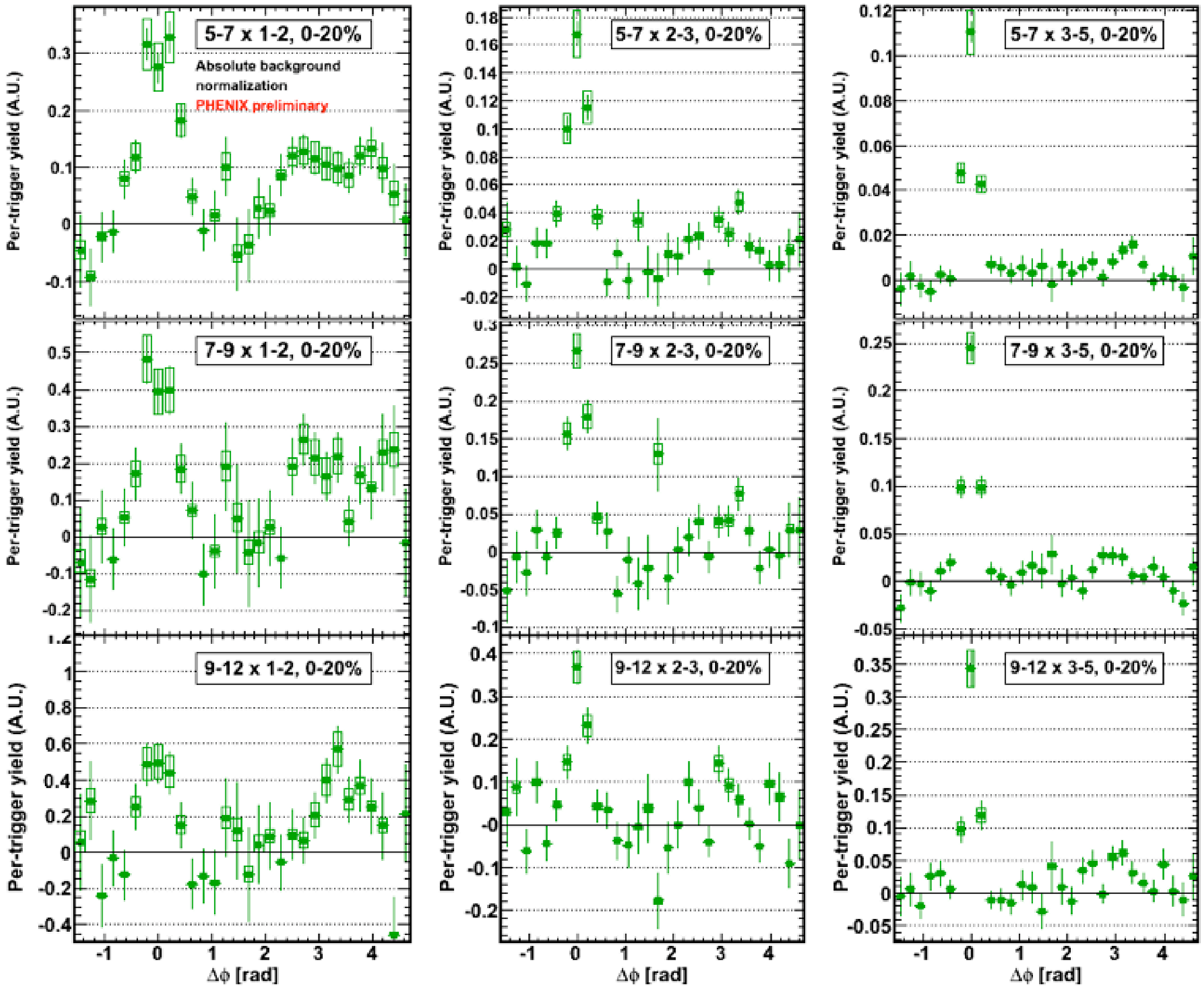
The most important discriminant of the twist of a pQCD subprocess in a hard hadronic collision is the scaling of the inclusive cross section

$$\frac{d\sigma}{d^3p/E}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^n}$$

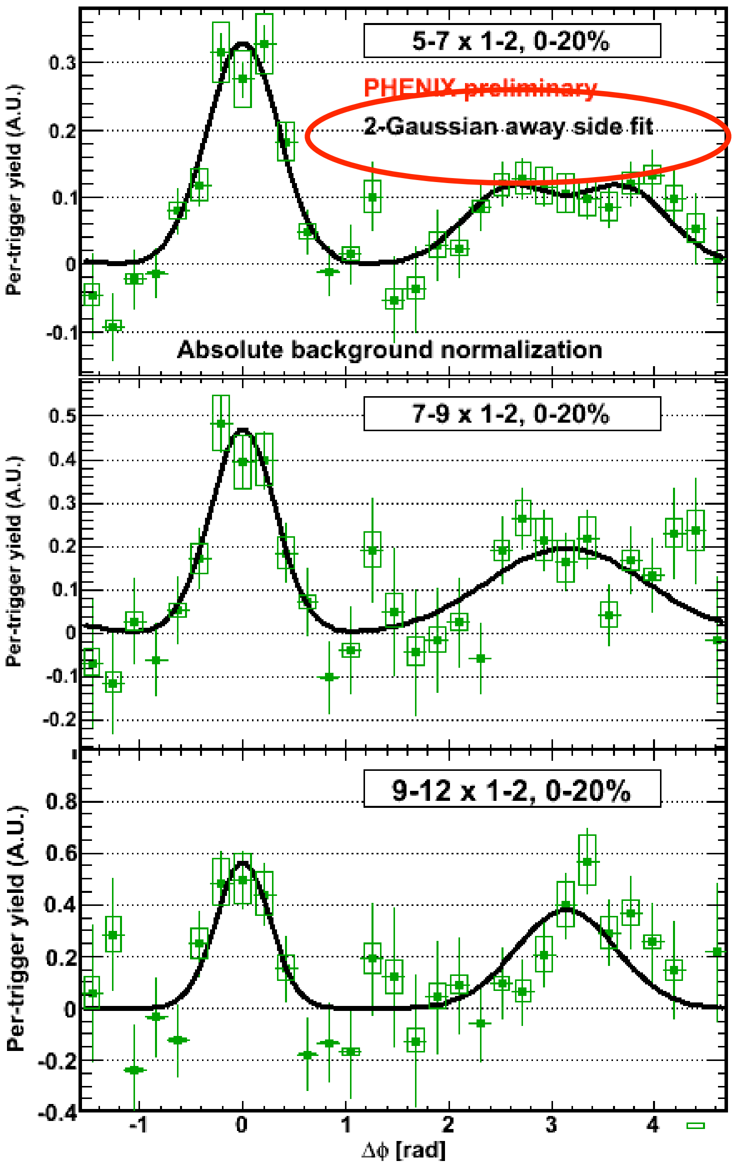
at fixed $x_T = 2p_T/\sqrt{s}$ and θ_{cm} In the original parton model [19] the power

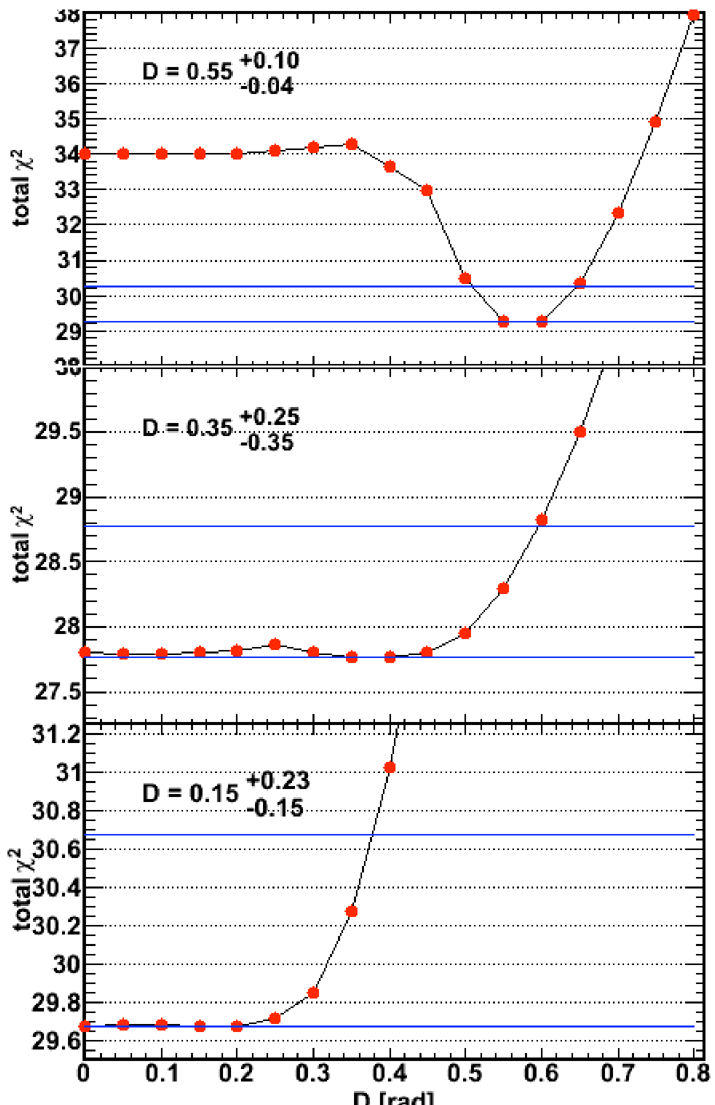
π^0-hadron correlations

- meson trigger
- high trigger p_T



π^0-hadron correlations



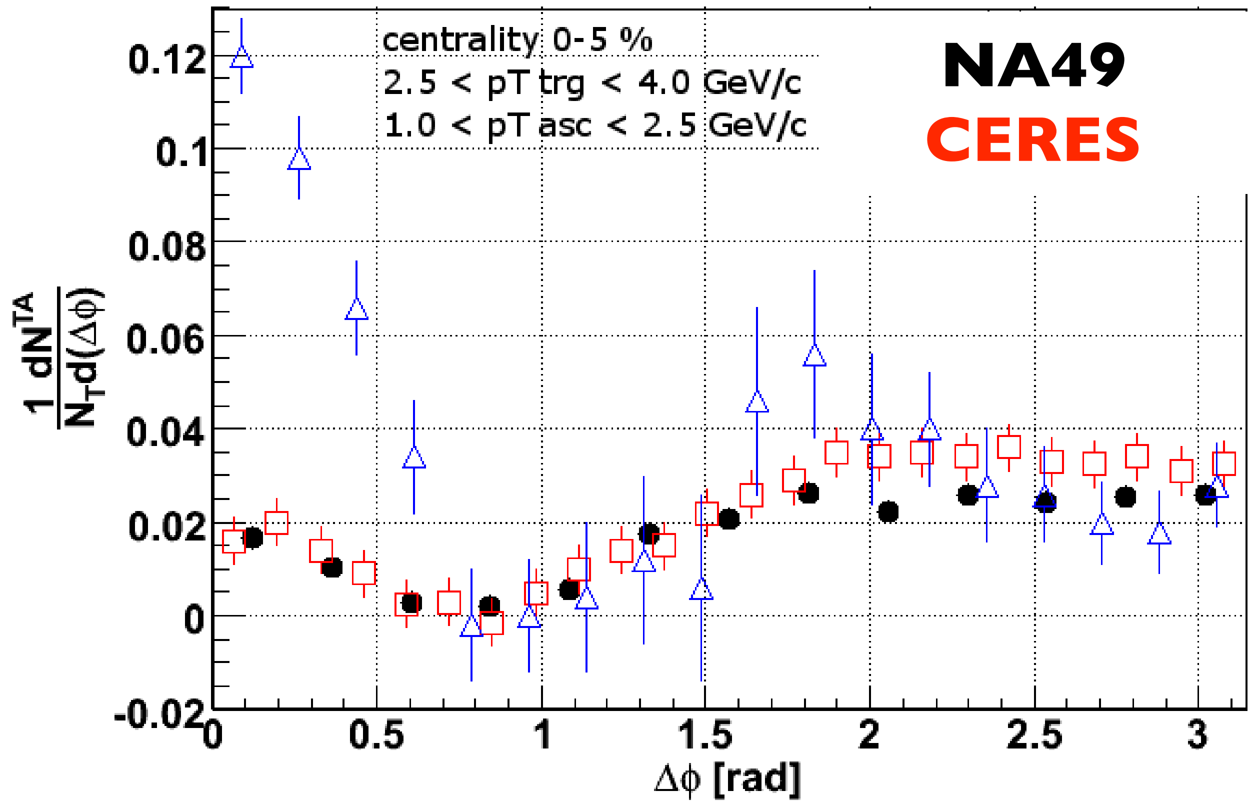


do these data constrain D with a three Gaussian fit? punch through + shoulder

A. Adare Hot Quarks 2008

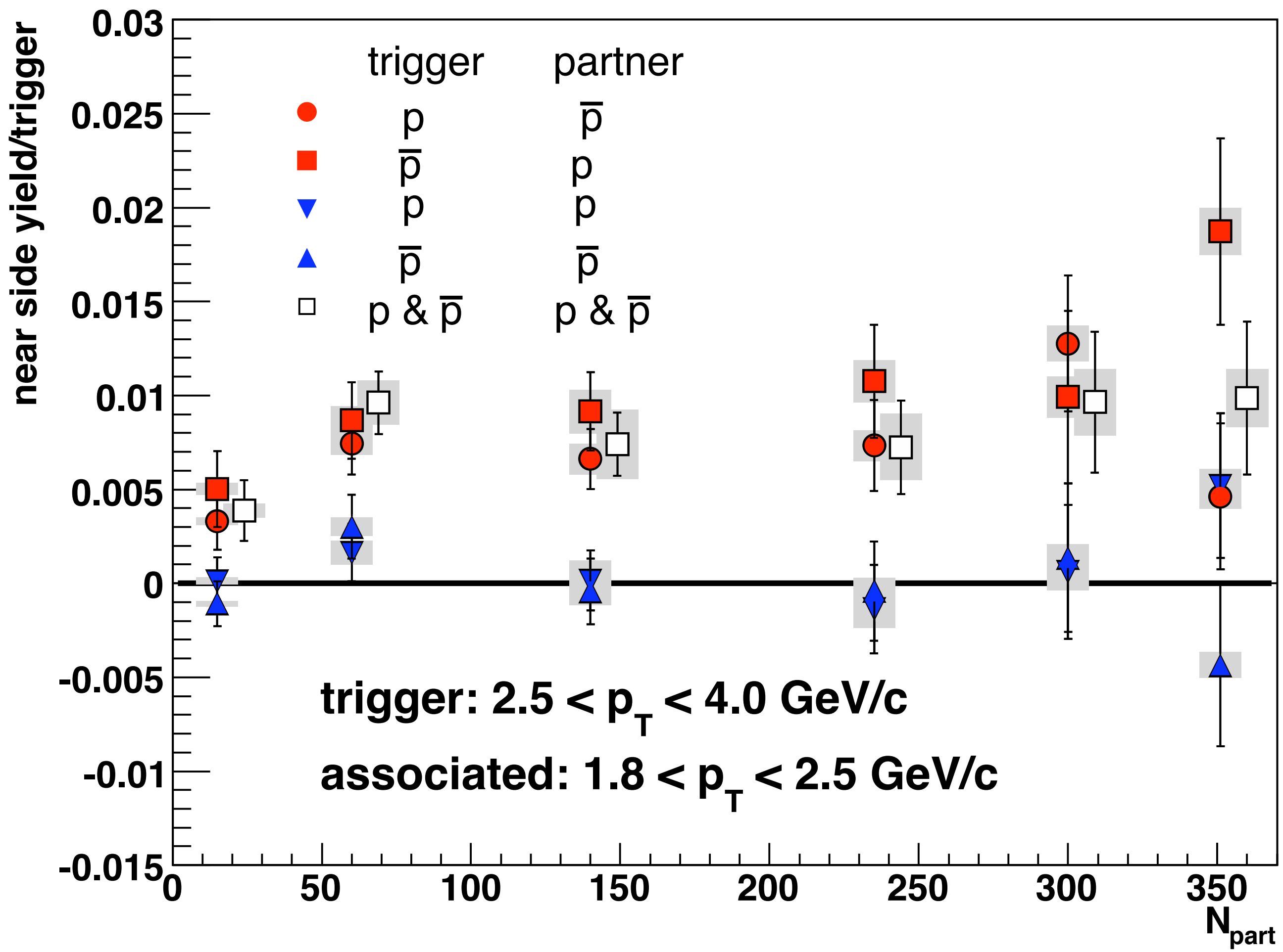
Mach cone @ SPS energies?

M. Szuba QM2008



- challenge to hydro/Mach cone models
- what about the ridge?
- importance of intermediate energy scan @ RHIC

near jet-less measurement?



- consistent with local baryon number conversvation
- like jets, but not necessarily recombination models, or direct processes