Electromagnetic Radiation in Heavy Ion Collisions

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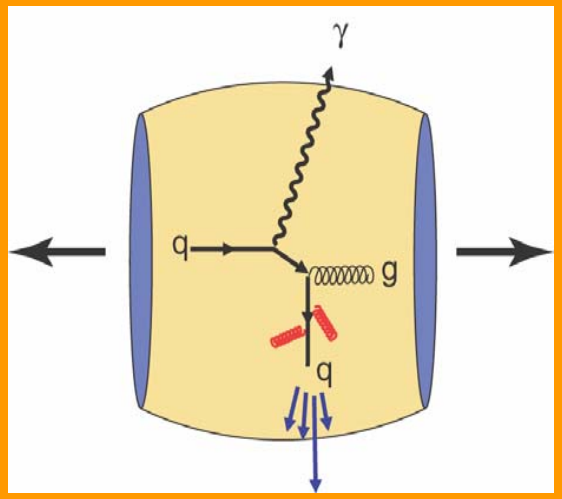
RHIC-AGS Users' Meeting, June 21, 2007

Electromagnetic Radiation: A Probe of the QGP

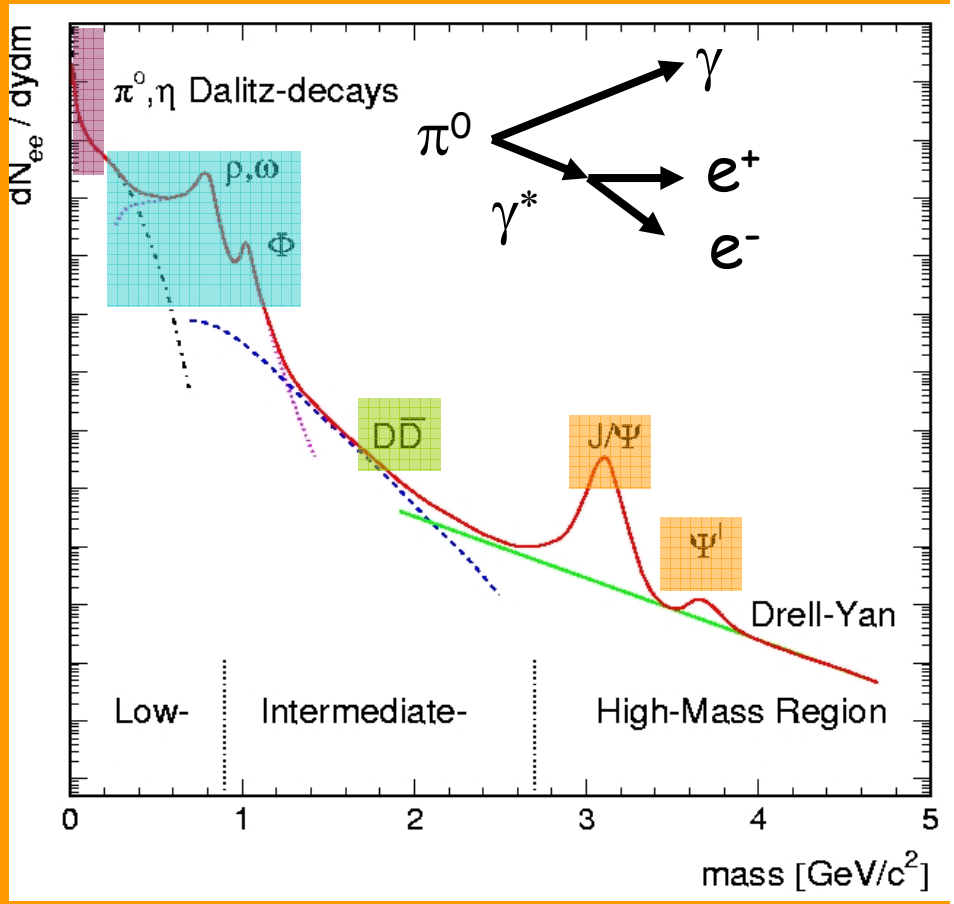
- QGP strongly interacting
- EM radiation not
  - Once produced, leaves collision region unscathed
  - Carries information about early times
  - Serves as reference for other probes



Mass Landscape of EMR

- π^0 and η Dalitz decay
  - thermal radiation from real and virtual photons
- light vector mesons and low-mass continuum
  - mass shifts, broadening, excess yield?
- open heavy flavor
  - thermal radiation
  - medium modification
- quarkonia
  - medium modification

Quarkonia: see Wei's talk



schematic dilepton mass distribution

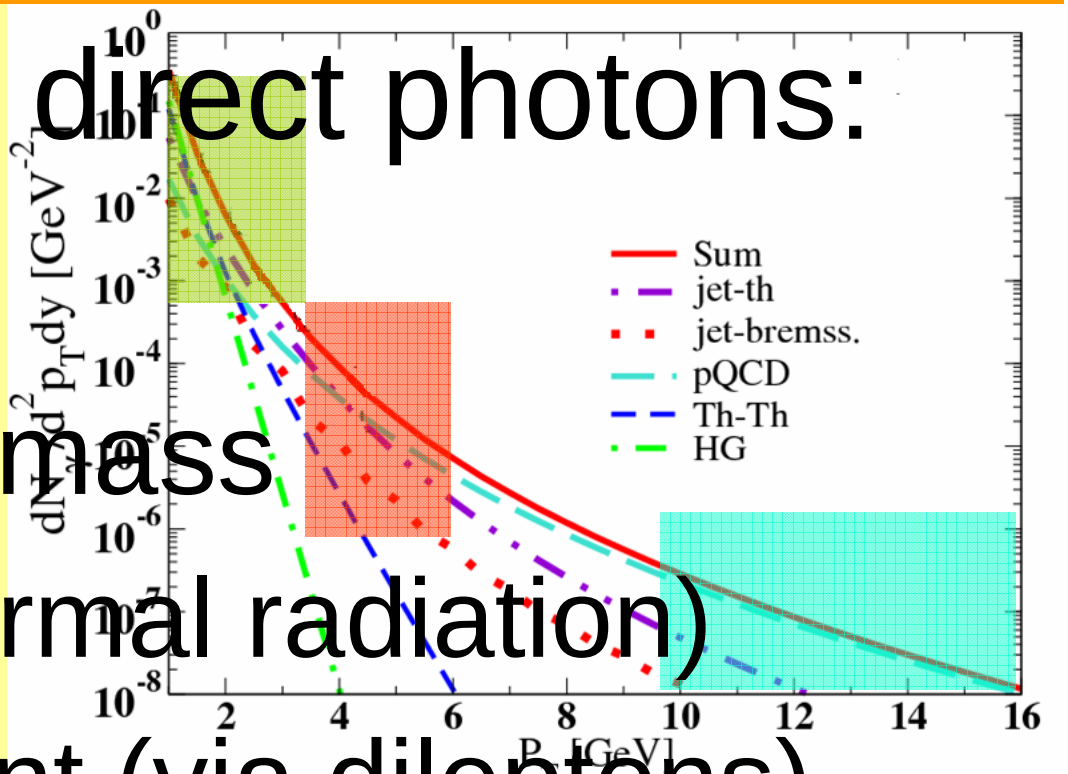
Di-leptons via charged particle tracking & PID

p_T Landscape of EMR

- Thermal radiation from the medium
  - Temperature of QGP
- Medium response to jets
  - Jet photons, induced bremsstrahlung
- Prompt photons
  - Reference for medium modification of jets

Dileptons and direct photons:

- two topics
- linked at low mass
  - physics (thermal radiation)
  - measurement (via dileptons)



C. Gale, QM05

Direct photons via EMCal

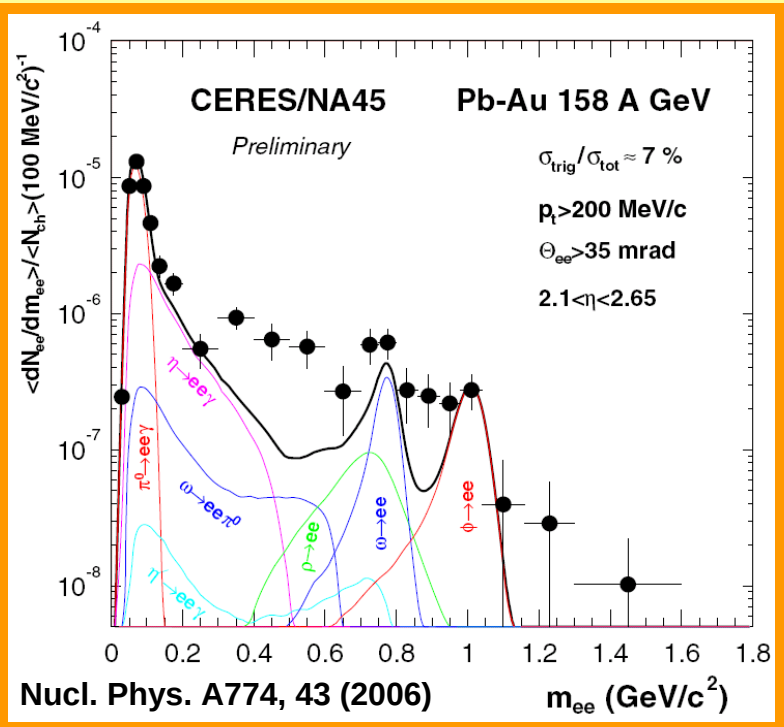
Thermal photons also by internal/external conversion!

1. Dileptons

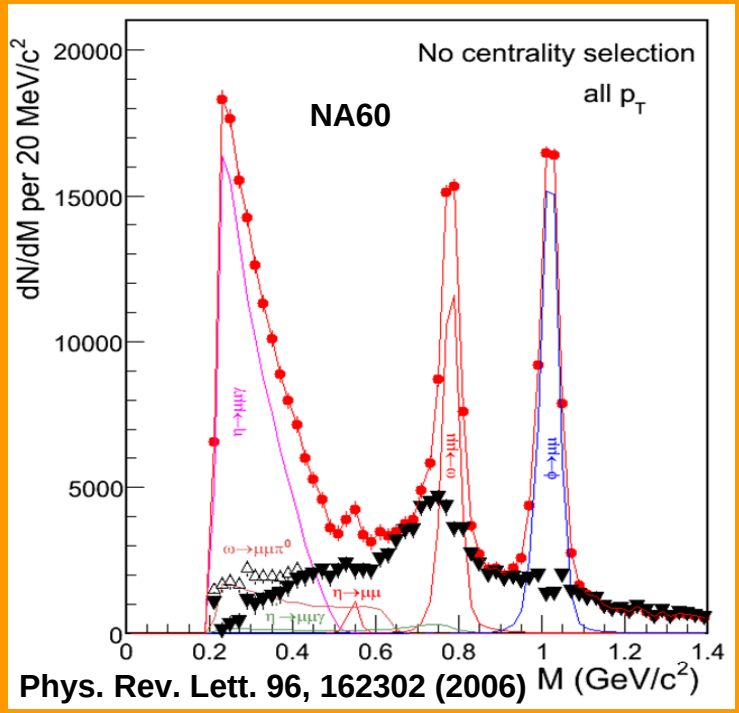
Chiral Symmetry Restoration

- One of two fundamental properties of QGP (besides deconfinement)
- Low-mass dileptons most sensitive probe
- Primarily through ρ meson decays
  - ♦ τ=1.3 fm/c (fireball 10 fm/c)
  - ♦ Most decays in medium

Low-mass excess at SPS: observed by CERES (Pb+Au) confirmed by NA60 in (In+In)



Nucl. Phys. A774, 43 (2006)

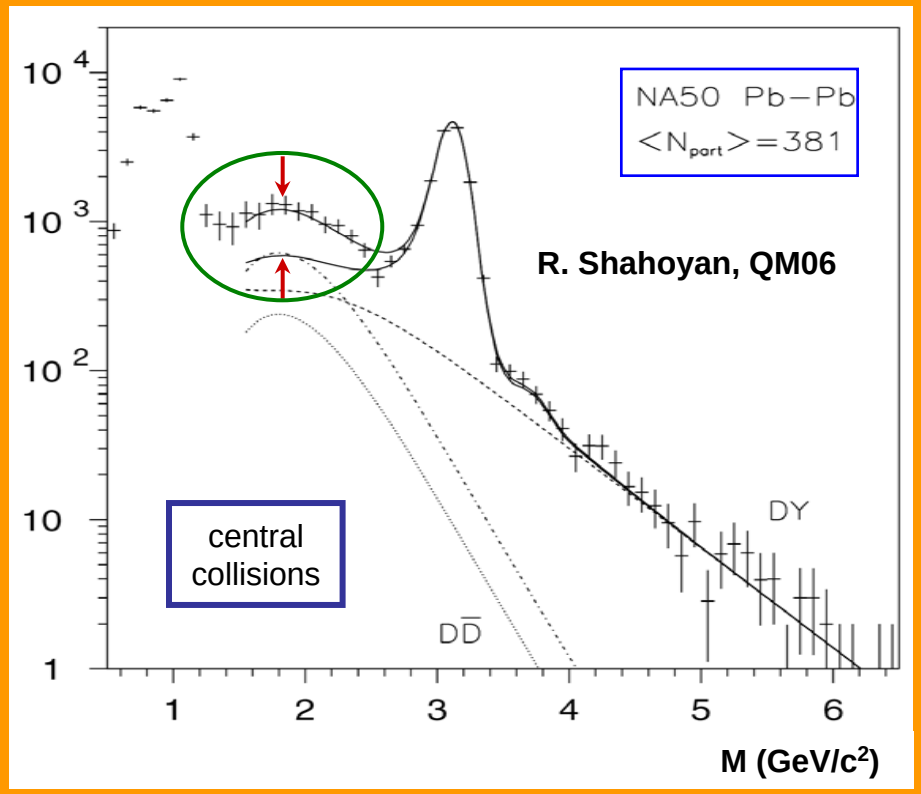


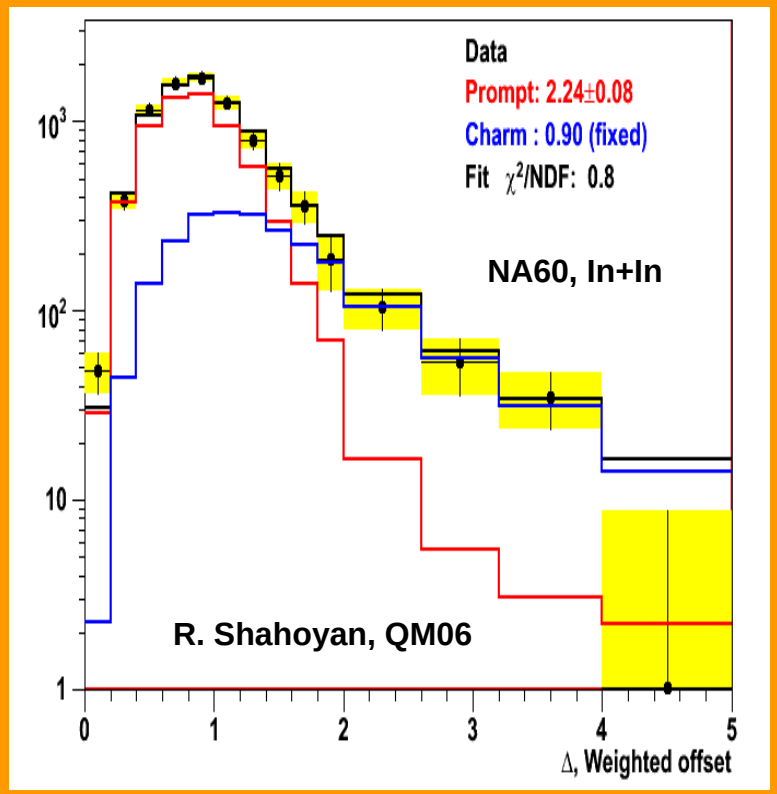
Phys. Rev. Lett. 96, 162302 (2006)

Thermal Radiation

- Promise:
  initial temperature of QGP

Intermediate-mass excess at SPS:
observed by NA50 (Pb+Pb)
Shown to be prompt by NA60 (In+In)

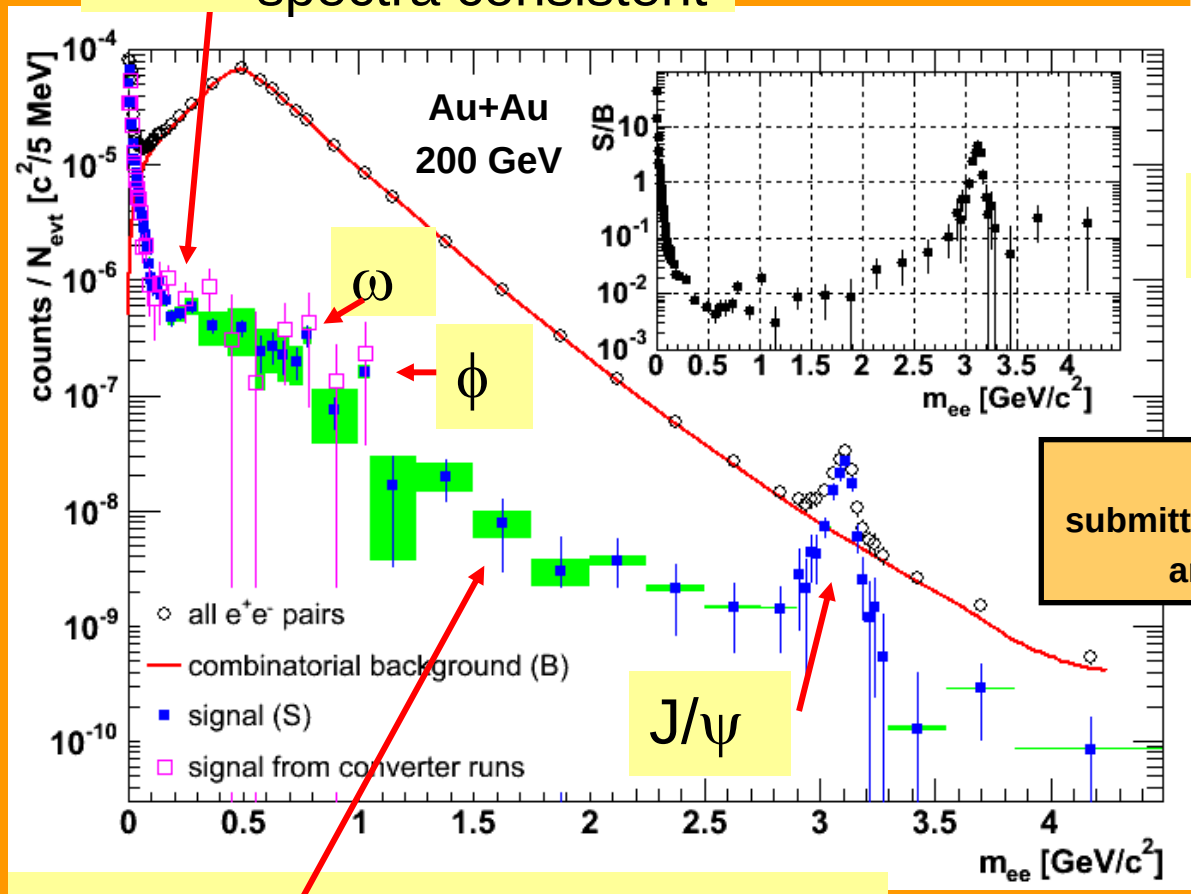




Raw Mass Distribution

Converter run

- bg 2.5x larger
- spectra consistent



Systematic error

0.25% B/S (bg substraction)

9% S (cross pair subtraction, below 600 MeV/c^2)

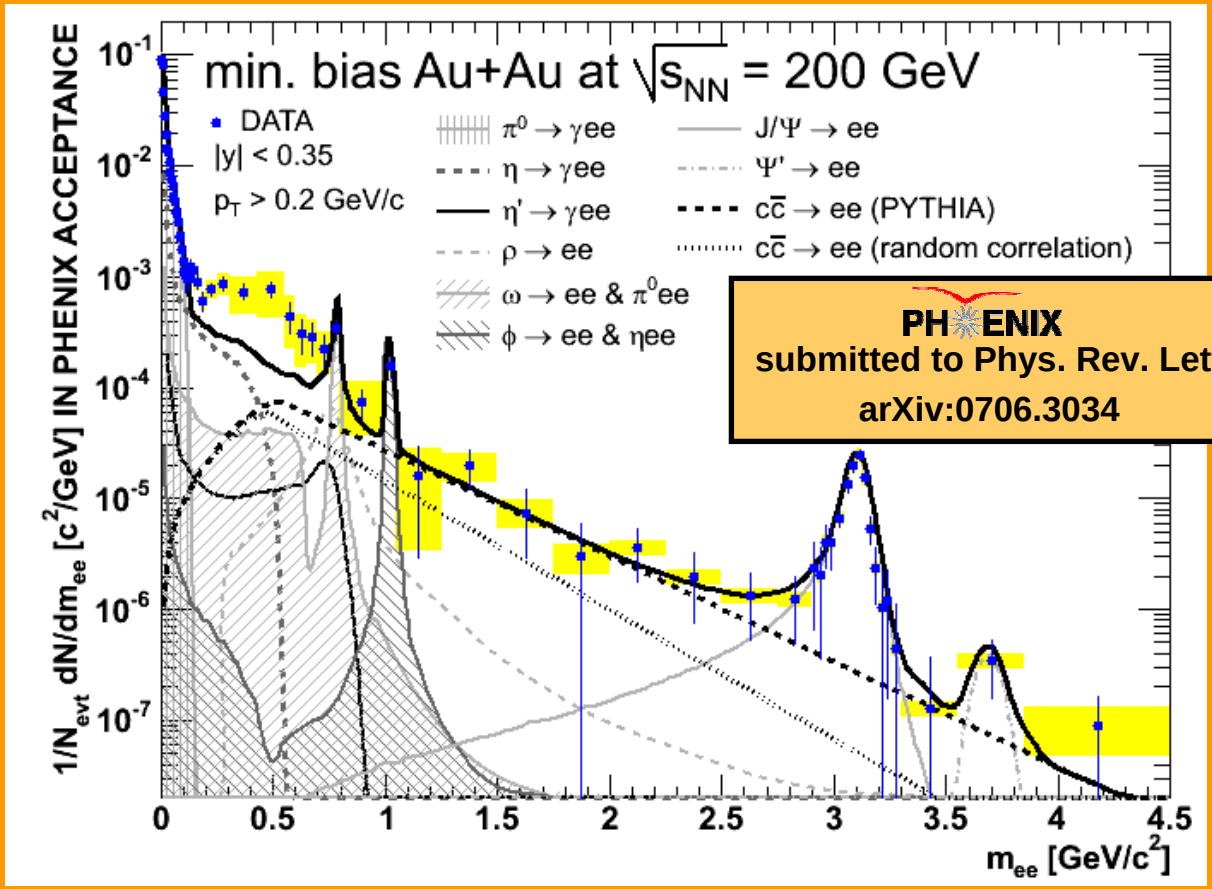
Small S/B

PHENIX
submitted to Phys. Rev. Lett
arXiv:0706.3034

Run-4
(improved analysis compared to previous preliminary result)

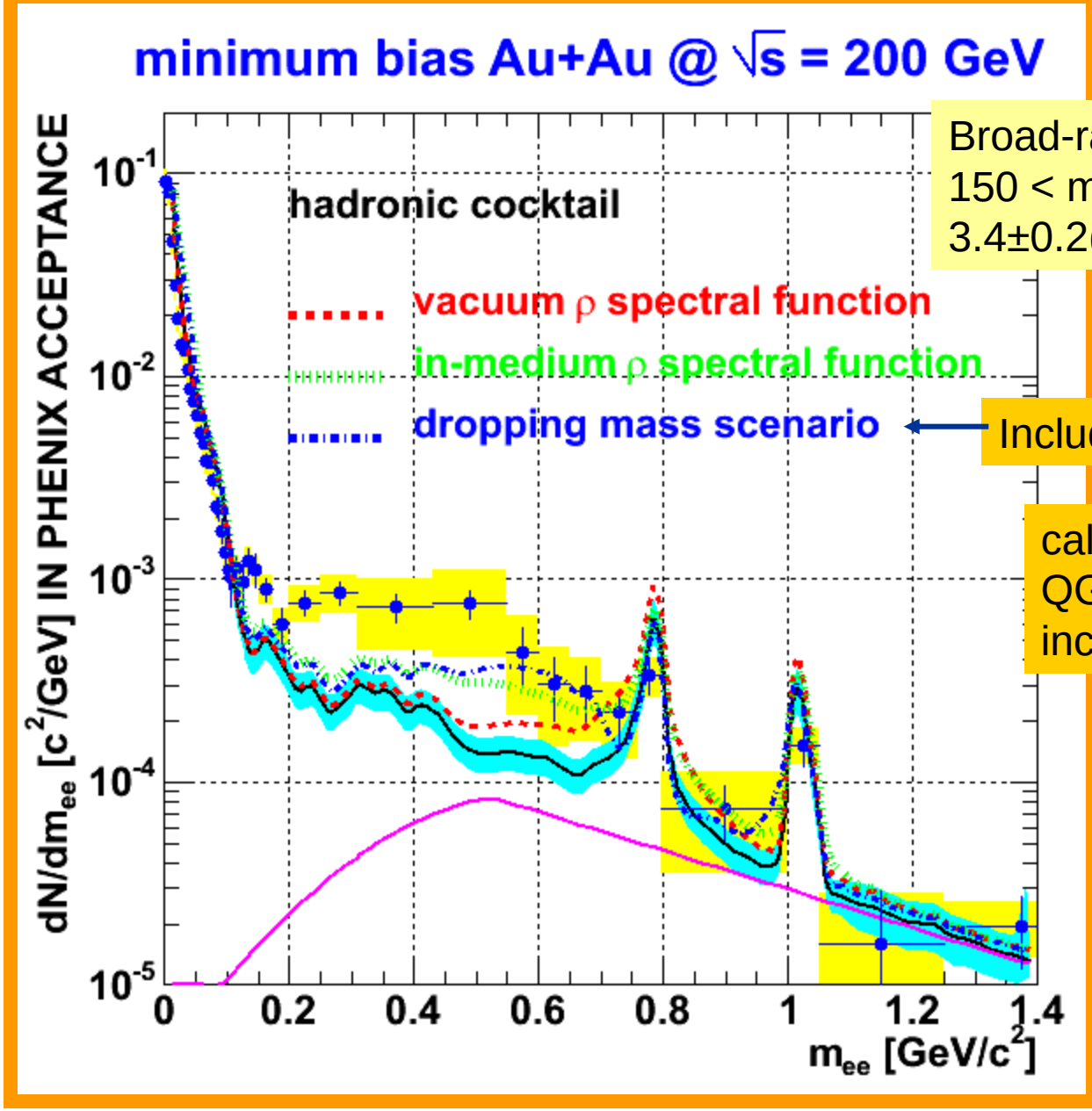
Continuum, ω, ϕ, J/ψ visible

Invariant Mass Distribution



- Low-Mass Continuum
  - enhancement in 150 <m_{ee}<750 MeV
- Intermediate-Mass
  - Consistent with Pythia
  - PYTHIA single e^- softer than p+p, but coincide with Au+Au
  - Angular correlations expected to weaken in Au+Au
  - Room for thermal contribution

Low-mass: Comparison with theory



Broad-range enhancement:
$150 < m_{ee} < 750$ MeV
3.4±0.2(stat.) ±1.3(syst.)±0.7(model)

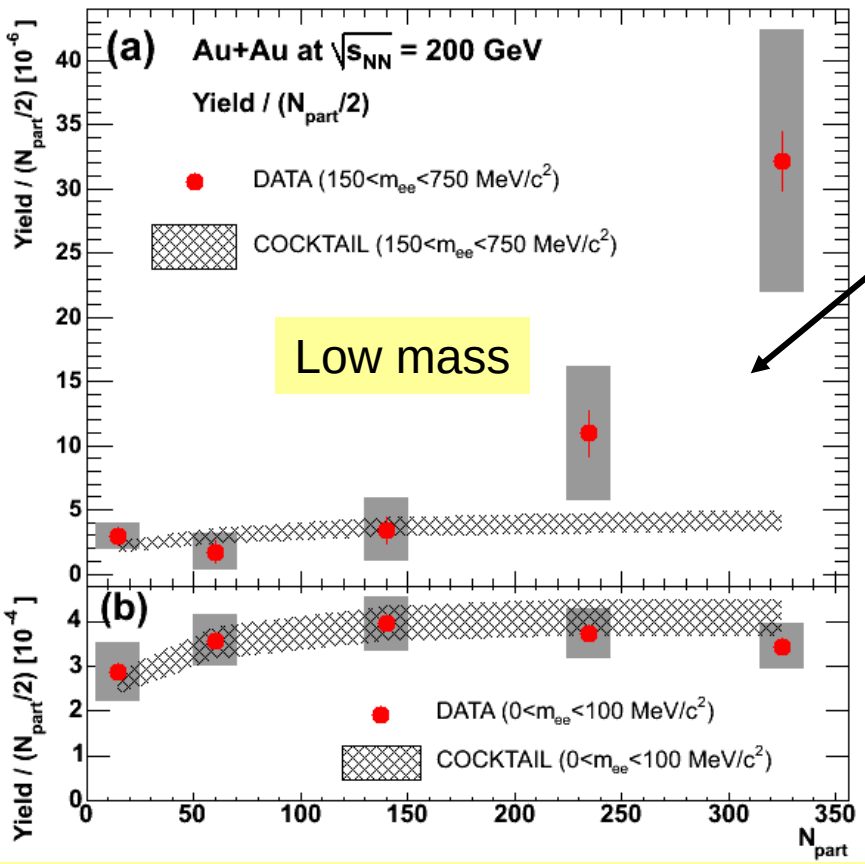
Includes chiral symmetry restoration

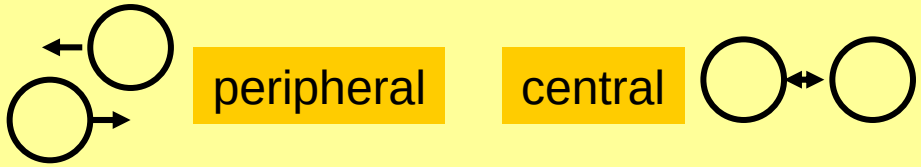
calculations for min bias, QGP thermal radiation included

R.Rapp, Phys.Lett. B 473 (2000)
R.Rapp, Phys.Rev.C 63 (2001)
R.Rapp, nucl/th/0204003

PHENIX
submitted to Phys. Rev. Lett
arXiv:0706.3034

Centrality Dependence





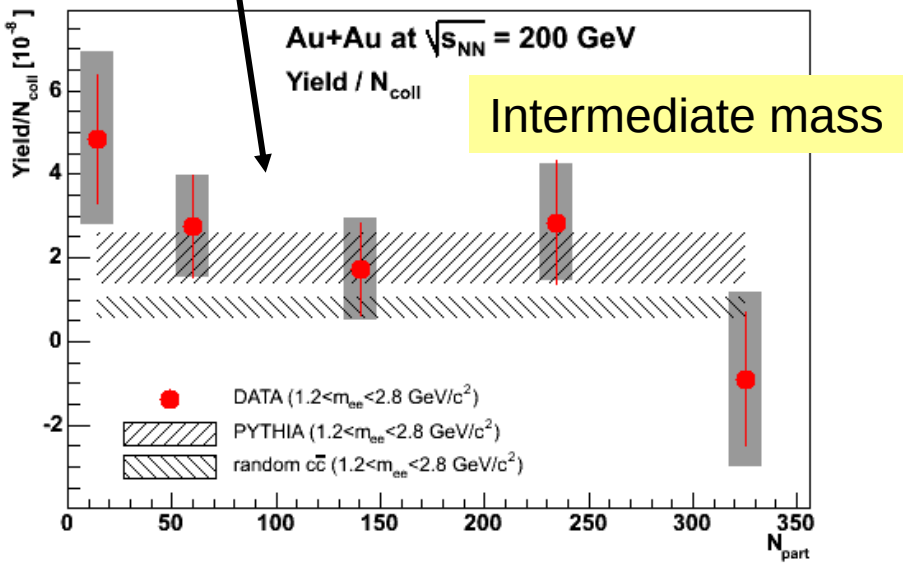
- π^0 production ~ N_{part}
- If in-medium enhancement from $\pi\pi$ or qq annihilation

→yield should increase > ~ N_{part}

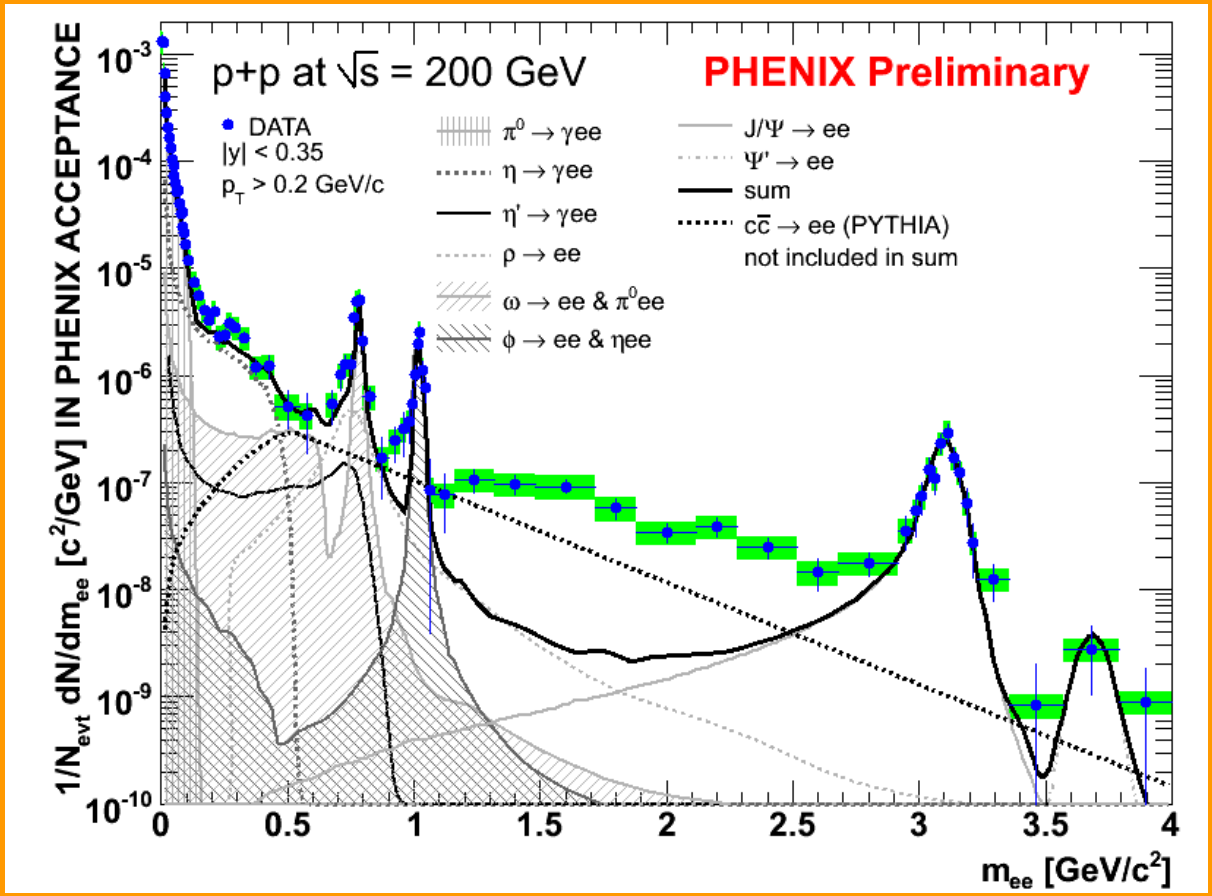
PHENIX
submitted to Phys. Rev. Lett
arXiv:0706.3034

- charm follows binary scaling

→ yield should increase ~ N_{coll}



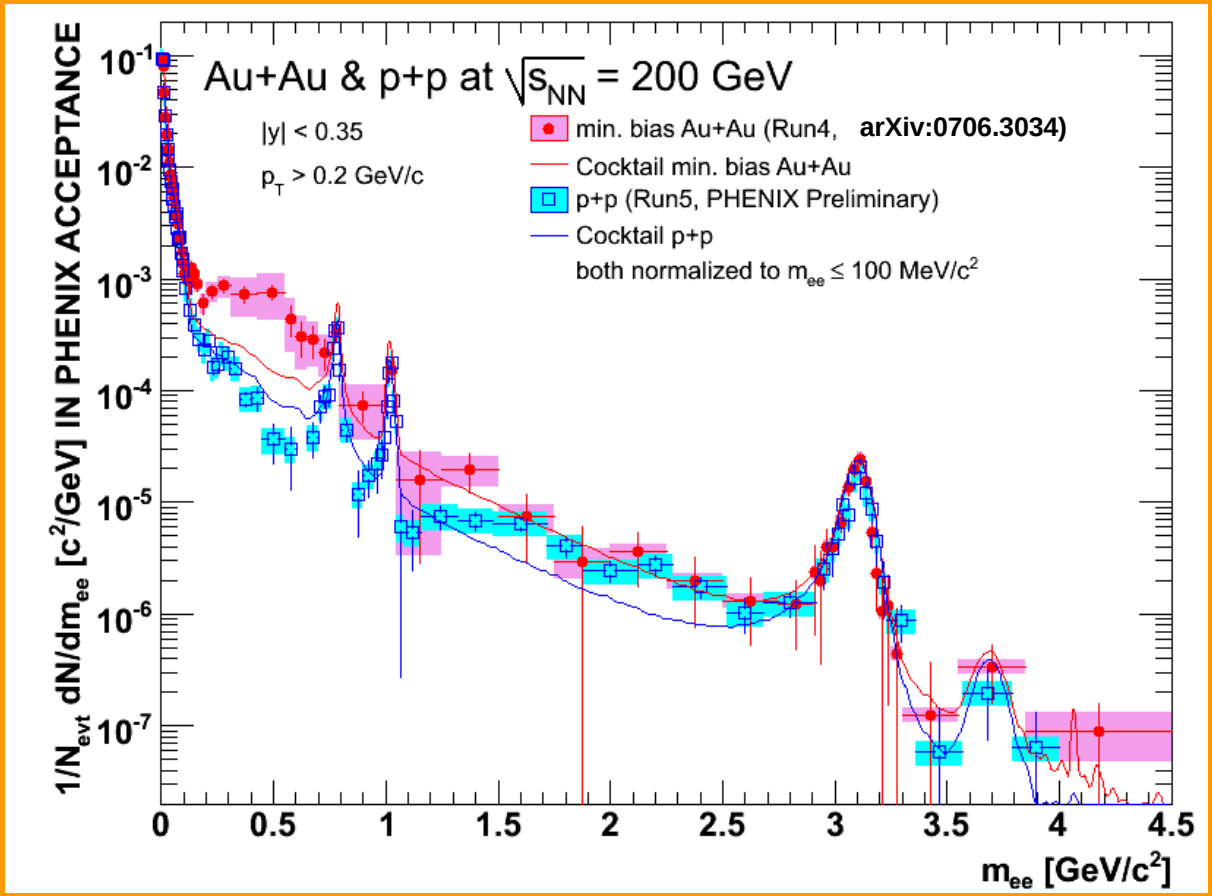
Invariant Mass Distribution in p+p



- Good agreement with hadronic cocktail except for intermediate-mass region
- N.B.: PYTHIA known to be softer than p+p data from single e^- analysis

p+p – Au+Au comparison

p+p normalized to m_{ee}<100 MeV/c^2

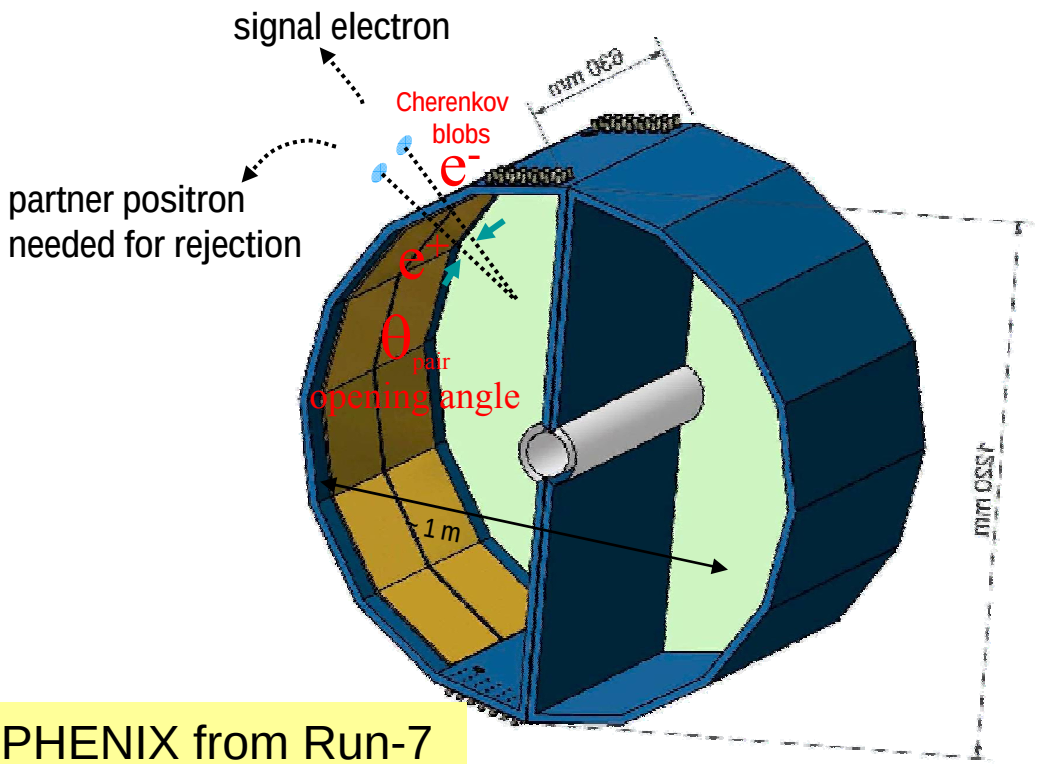


- p+p and Au+Au normalized to π^0 region
- Agreement at resonances (ω, ϕ)
- Au+Au enhancement for 0.2 < m_{ee} < 0.8 GeV

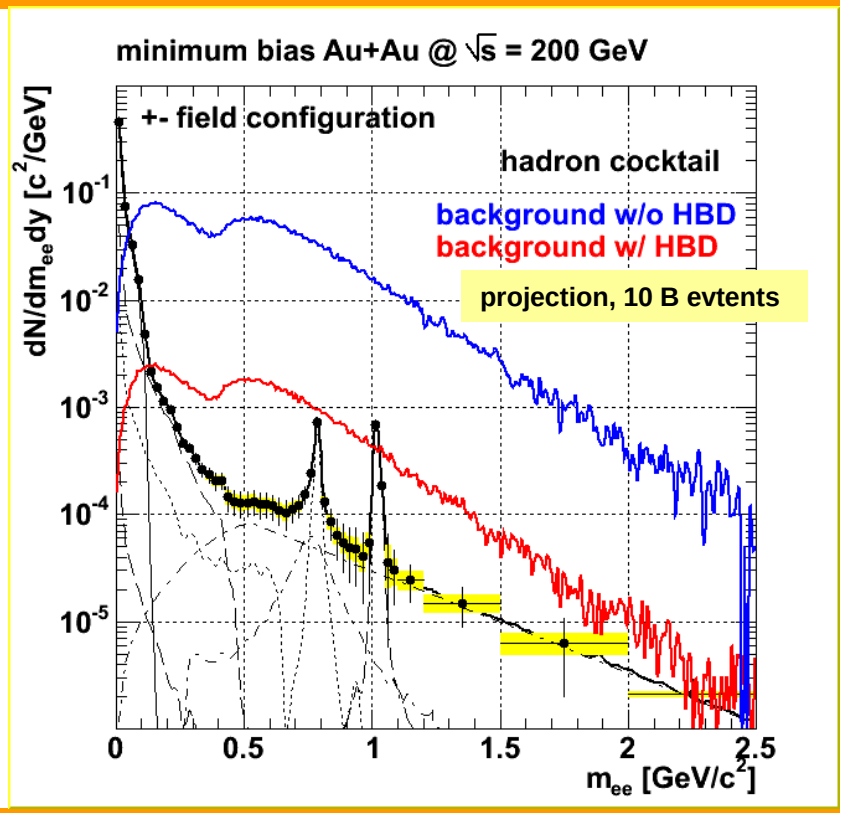
- Agreement in intermediate mass and J/Ψ just for 'coincidence' (J/Ψ happens to scale as π^0 due to scaling with N_{coll} + suppression)

The Future: Hadron Blind Detector

- Dalitz & Conversion rejection via opening angle
  - Identify electrons in field free region
  - Veto signal electrons with partner

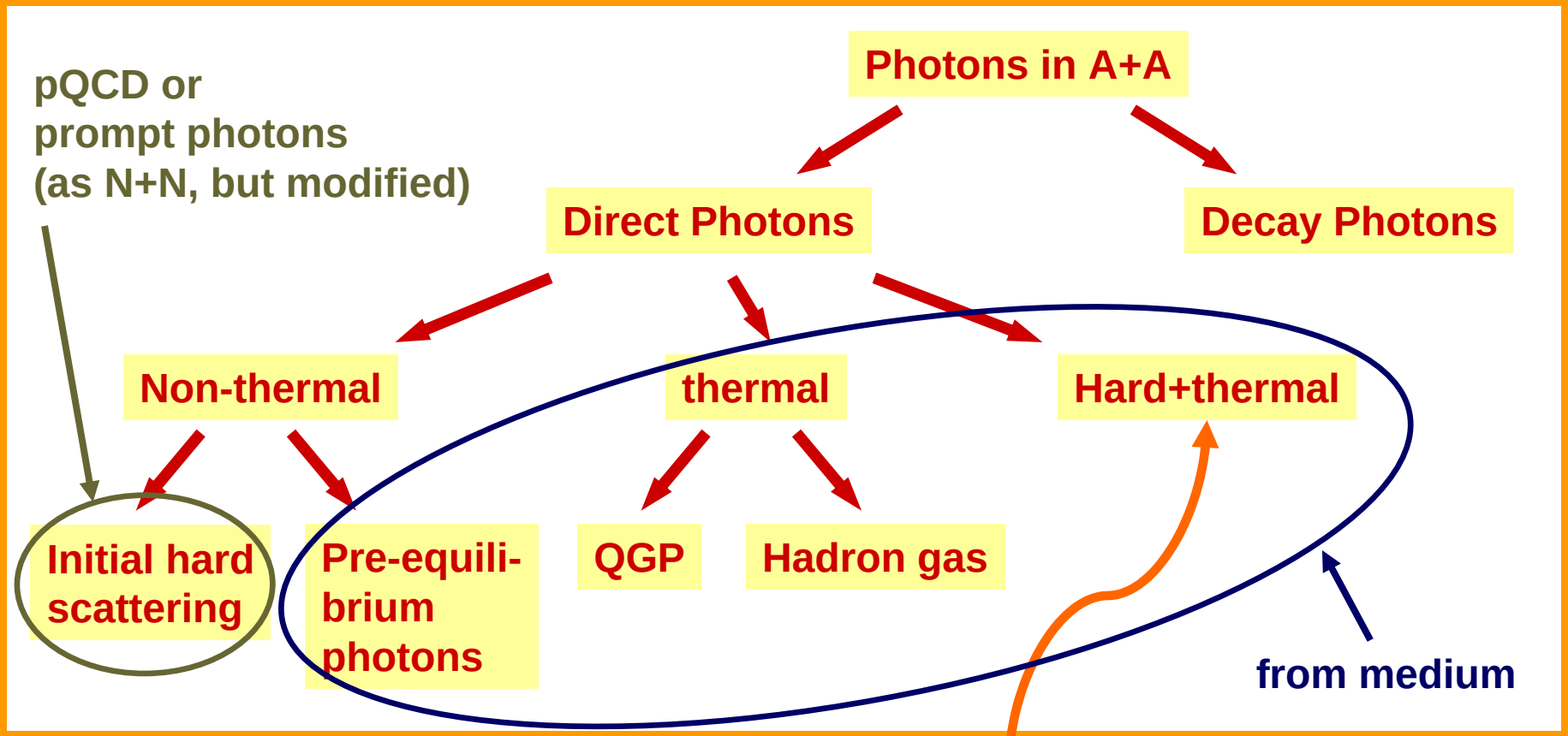


PHENIX from Run-7



2. Direct Photons

Photon Sources in A+A



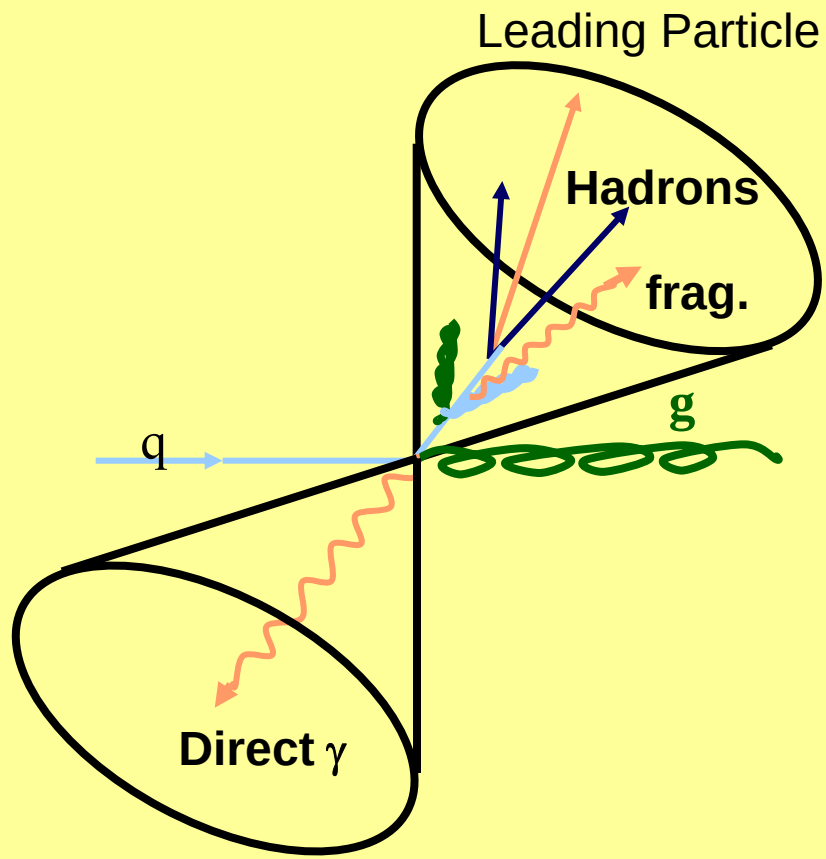
Interaction of hard parton with QGP

1) $\mathbf{q_{hard}} + \overline{\mathbf{q}}_{\mathbf{QGP}} \rightarrow \gamma + \mathbf{g}$ and $q_{hard} + g_{QGP} \rightarrow \gamma + q$

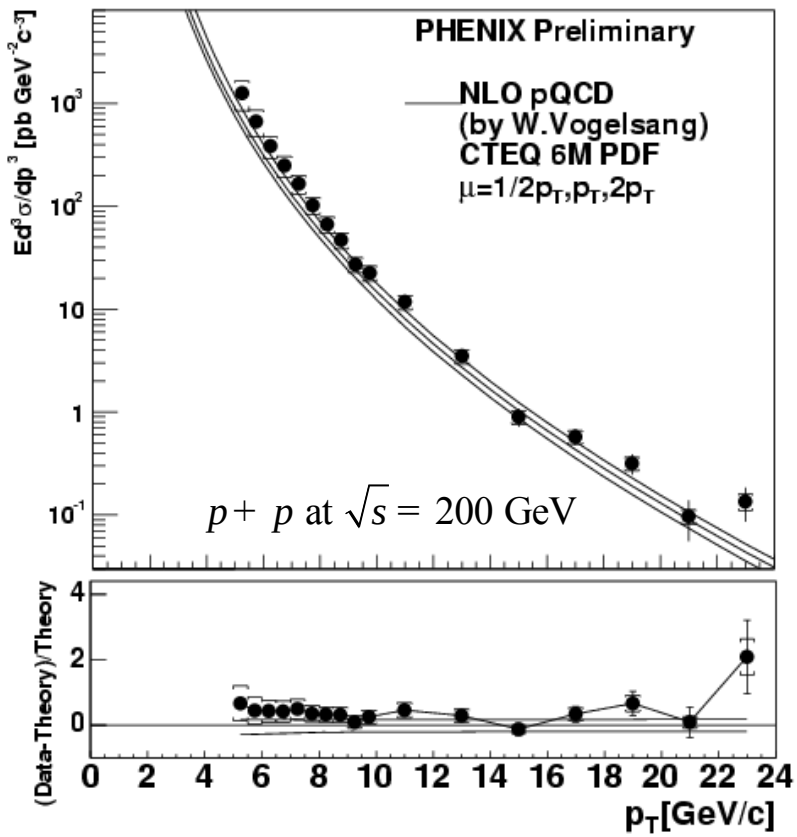
2) Medium induced photon bremsstrahlung

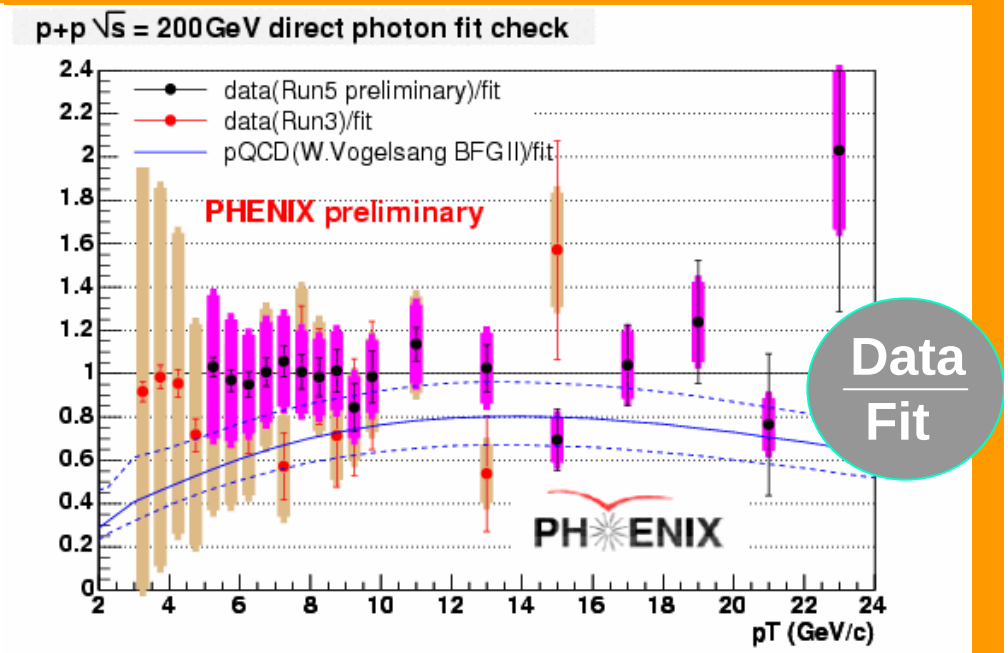
Measurement

- Large background from decay photons $\pi^0 \rightarrow \gamma + \gamma$
- Three methods
  - 1: Statistical
    - Measure inclusive photons
    - Measure main sources of decay photons (π^0, η)
    - Calculate spectrum of decay photons from measurement
    - Subtract decay photons from inclusive photons
    - applied at all p_T
  - 2: Conversion
    - similar to dilepton measurement
    - Low p_T only
  - 3: Isolation
    - Can be applied in p+p and very-high-p_T Au+Au



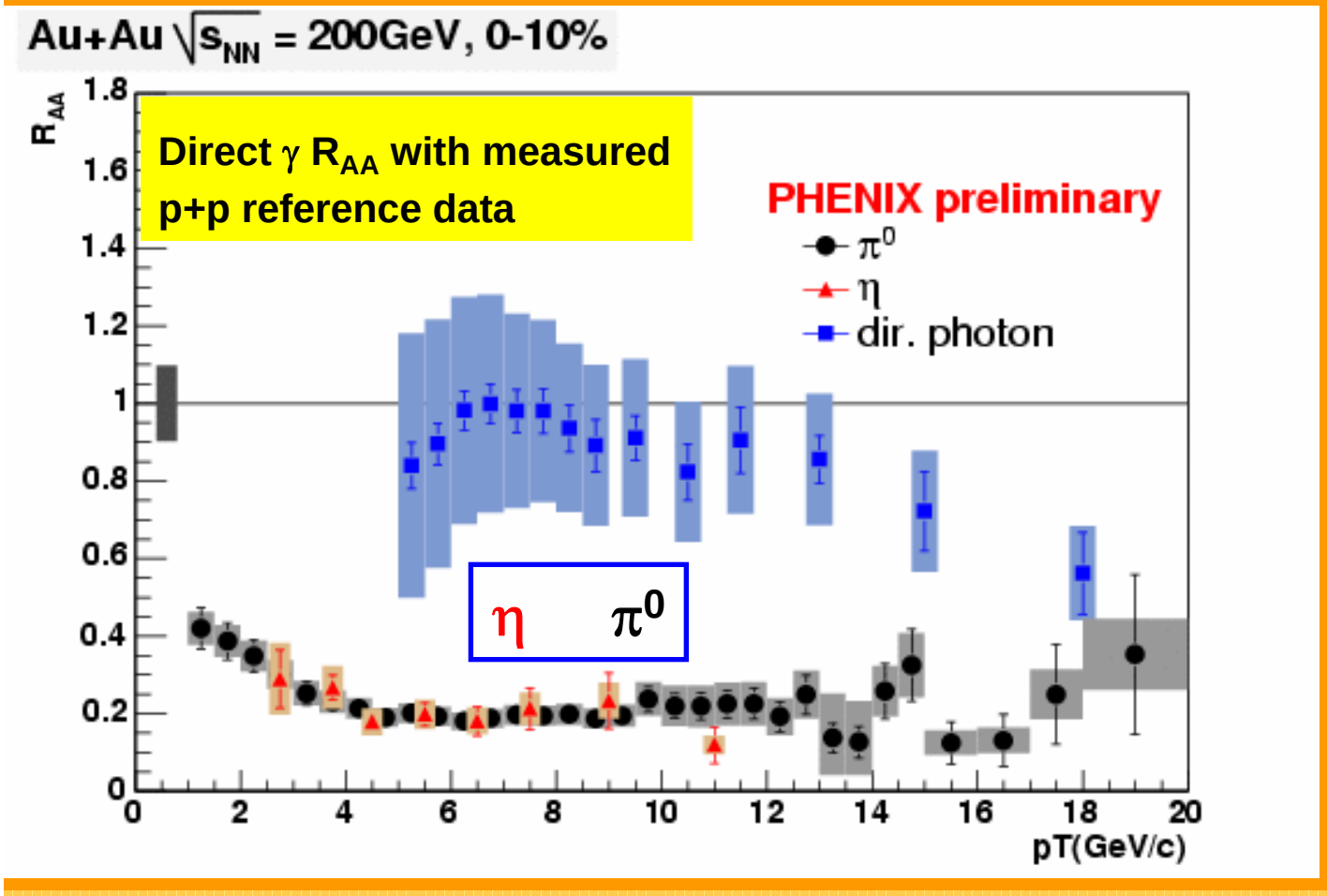
p+p from Run-5





While data and pQCD calculation consistent, data tend to be higher than pQCD by at least 20%, increasing to low and high p_T

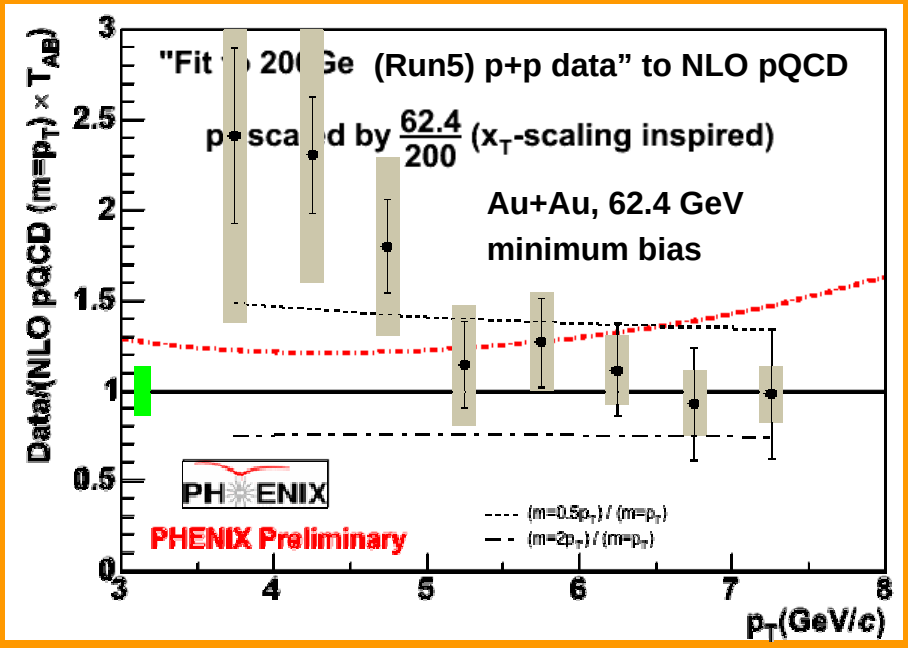
R_{AA} with measured p+p reference



Direct photons and π^0 touch at highest p_T

- Still consistent with
  - final state effect for π^0 and initial state effect for direct photons
  - Modification of structure function?
    - different for π^0 and direct photons

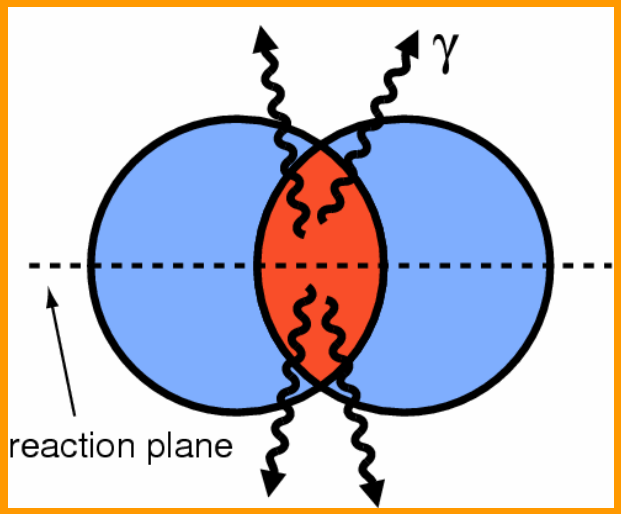
Direct Photons in 62.4 GeV Au+Au



- Modification of structure function can be tested at smaller p_T (20 GeV->~10 GeV) by going to smaller collision energy (200 GeV->62 GeV)
- Advantage: independent detector systematics (no cluster merging)
- Caveat: other direct photons sources come into play

- Result still suffers from large uncertainties
- Needs higher-statistics run and p+p measurement at same energy
- Ideally structure function measurement in p+A

Direct Photon Elliptic Flow

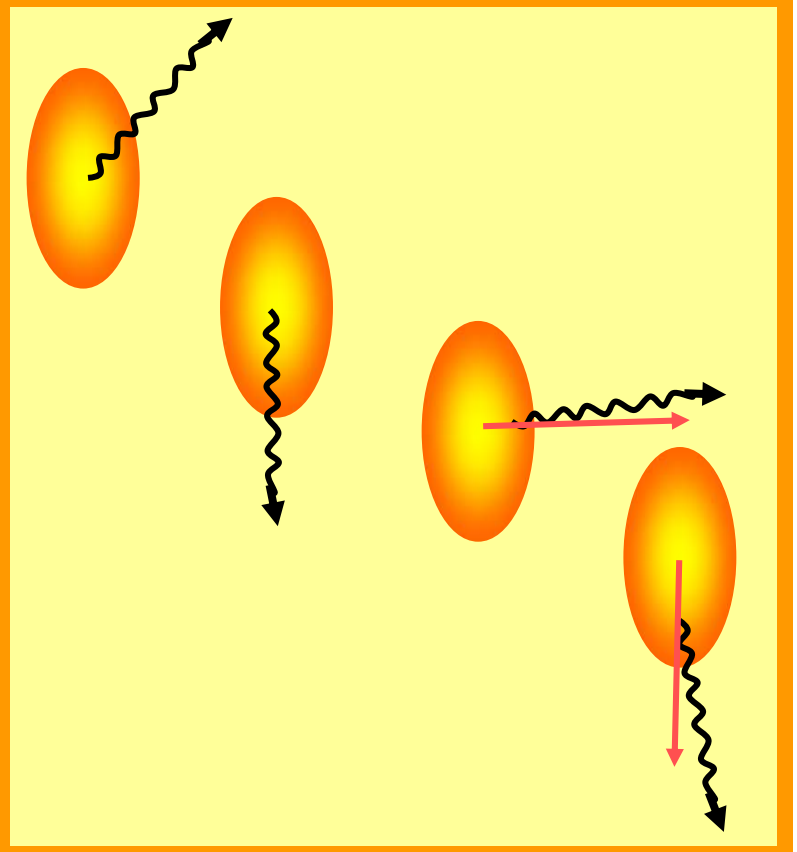


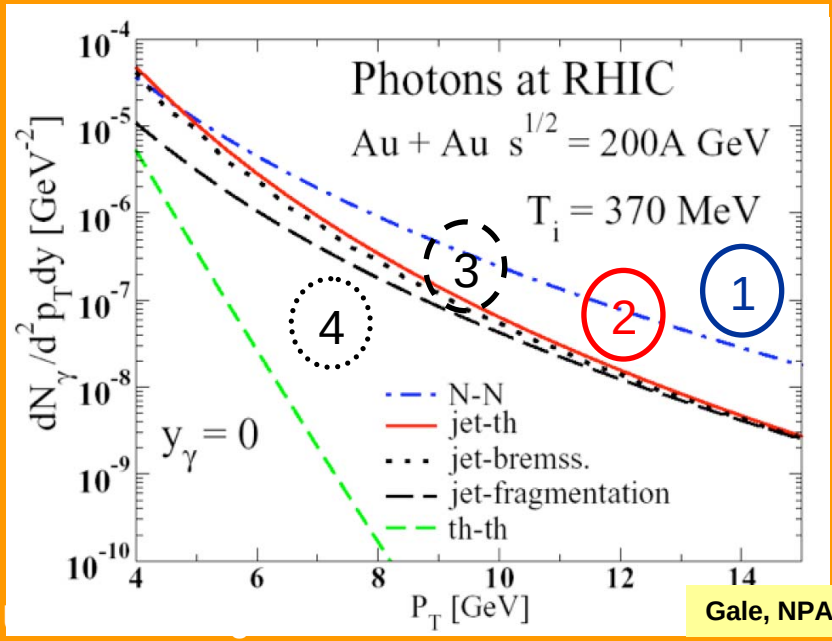
- Jet-photons and induced photon bremsstrahlung: out-of-plane, negative v_2
- Jet-quenching → less fragmentation photons: in-plane, positive v_2

Elliptic flow helps to disentangle various contributions

Disentangling the contributions

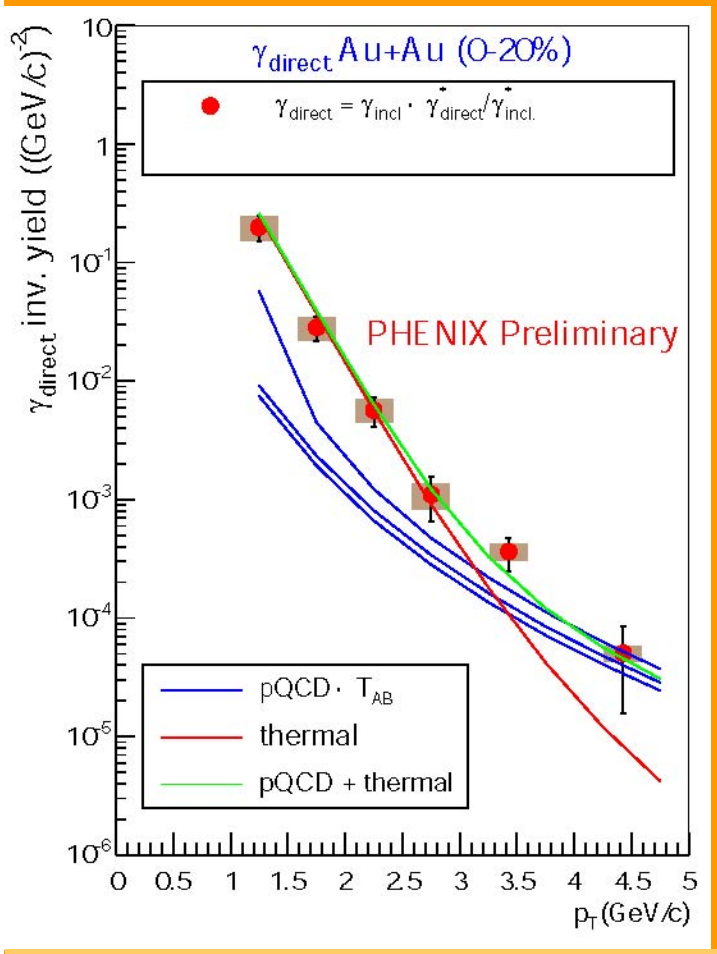
contribution	softer	v_2	isol.
1 compton, annihi.	↓	=0	yes
2 jet-thermal	↓	<0	yes
3 fragmentation	↓	>0	no
4 induced. brems.	↓	<0	no





Gale, NPA 785, 93c (2007)

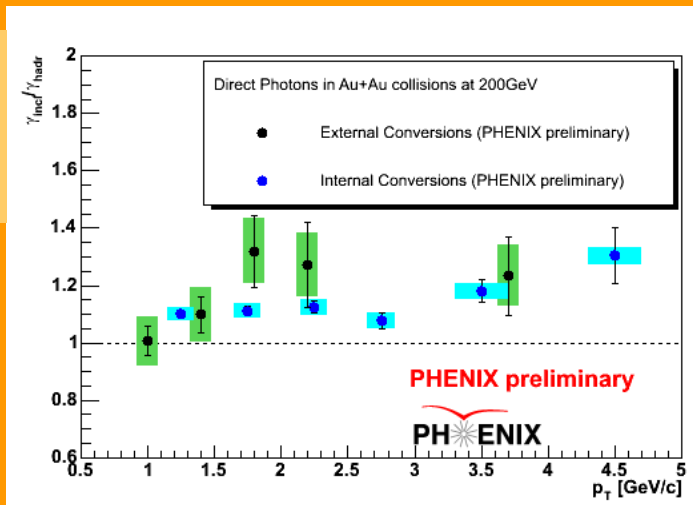
Towards thermal photons: conversion measurements

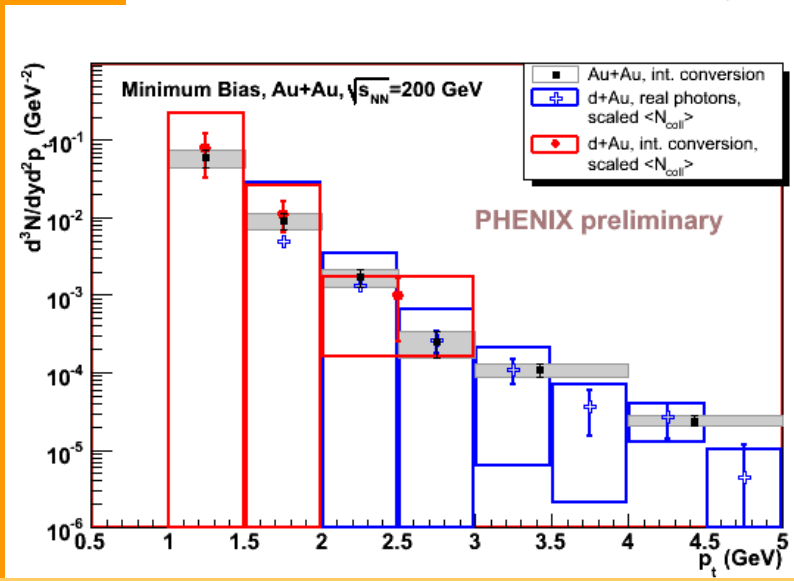


Internal conversion in Au+Au

Needs p+p reference measurement

Confirmation from external conversion

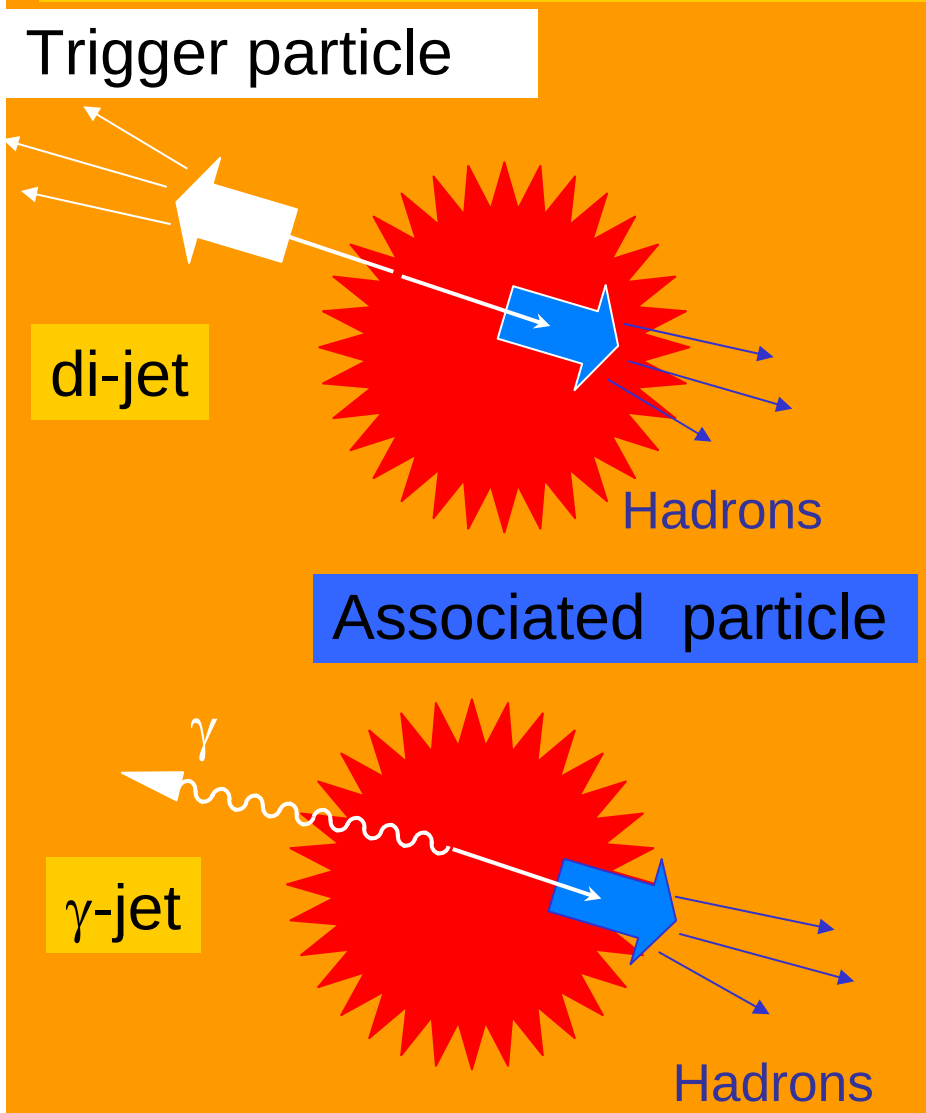




Internal conversion in d+Au

Still too large uncertainties to make a conclusion

Photon-tagged Jets

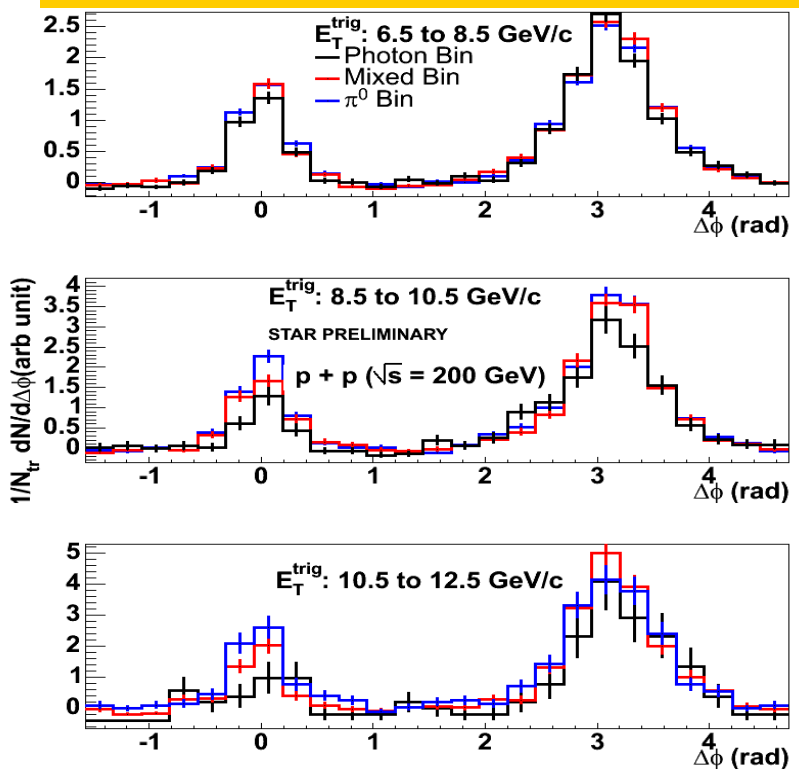


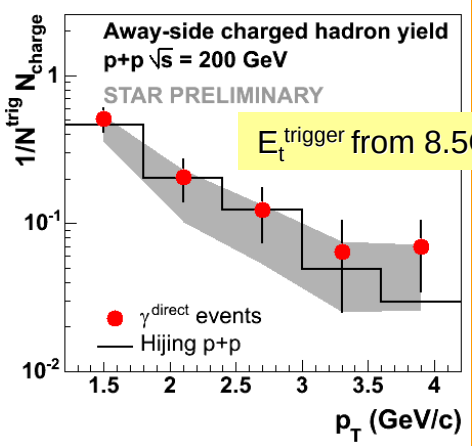
Because of energy loss, di-jet measurement suffers from surface bias

No trigger surface bias for direct photon tagged jets

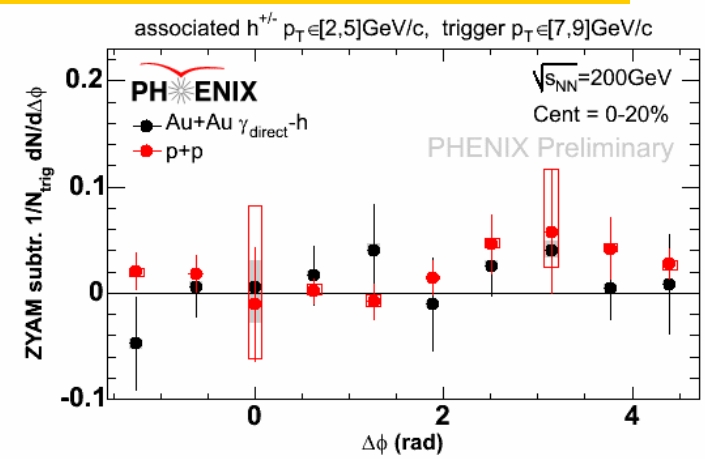
Direct photon is measure of jet energy

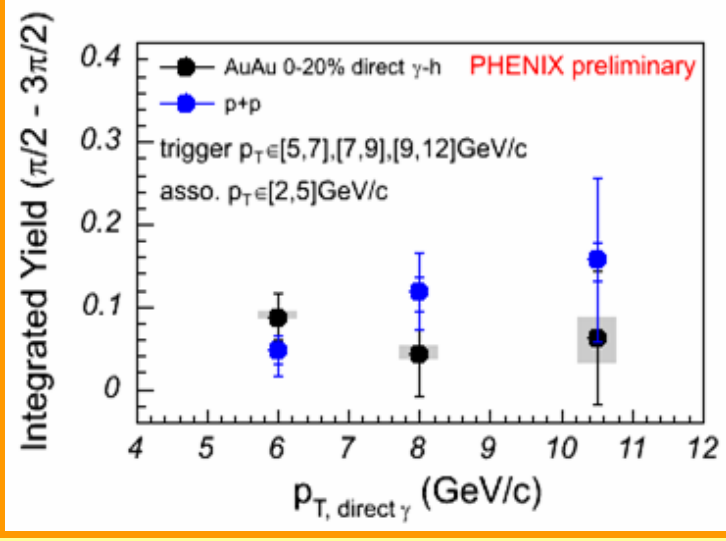
First γ-jet results





$E_t^{trigger}$ from 8.5GeV/c to 10.5 GeV





- Both STAR and PHENIX have first γ-jet results
- So far more proof-of-principle than precise measurements
- Need higher-statistics run

Summary and Outlook

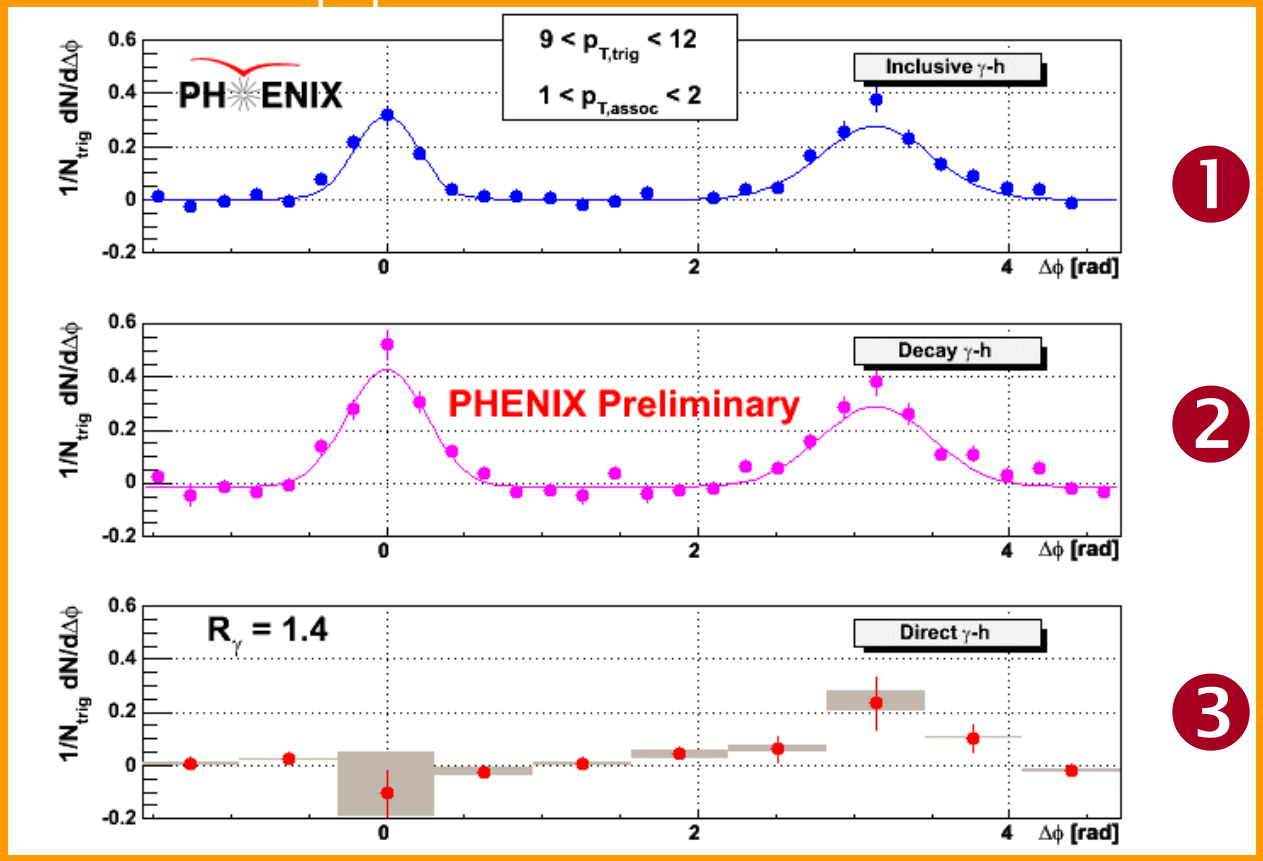
- Electromagnetic radiation in HI collisions comprises two subfields
  - Dileptons
  - Direct photons
- Coupled at low mass by physics and measurement techniques
- EMR provides enormous physics potential, but measurement and its interpretation extremely challenging
- Future high-luminosity runs combined with detector and machine upgrades will allow great advances

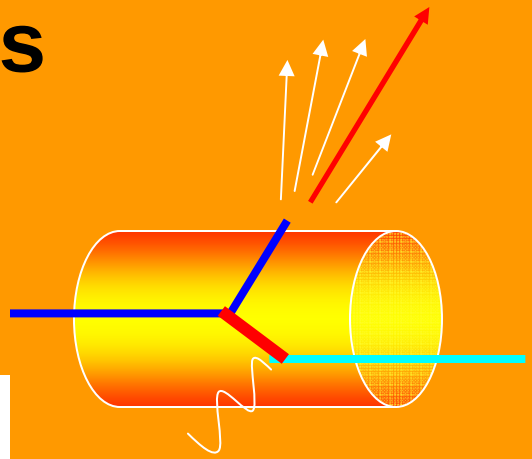
Extra Slides

γ-Jet Correlations

$$Y_{inclusive-h} = \left(\frac{\gamma_{decay}}{\gamma_{inclusive}}\right) Y_{decay-h} + \left(\frac{\gamma_{direct}}{\gamma_{inclusive}}\right) Y_{direct-h}$$

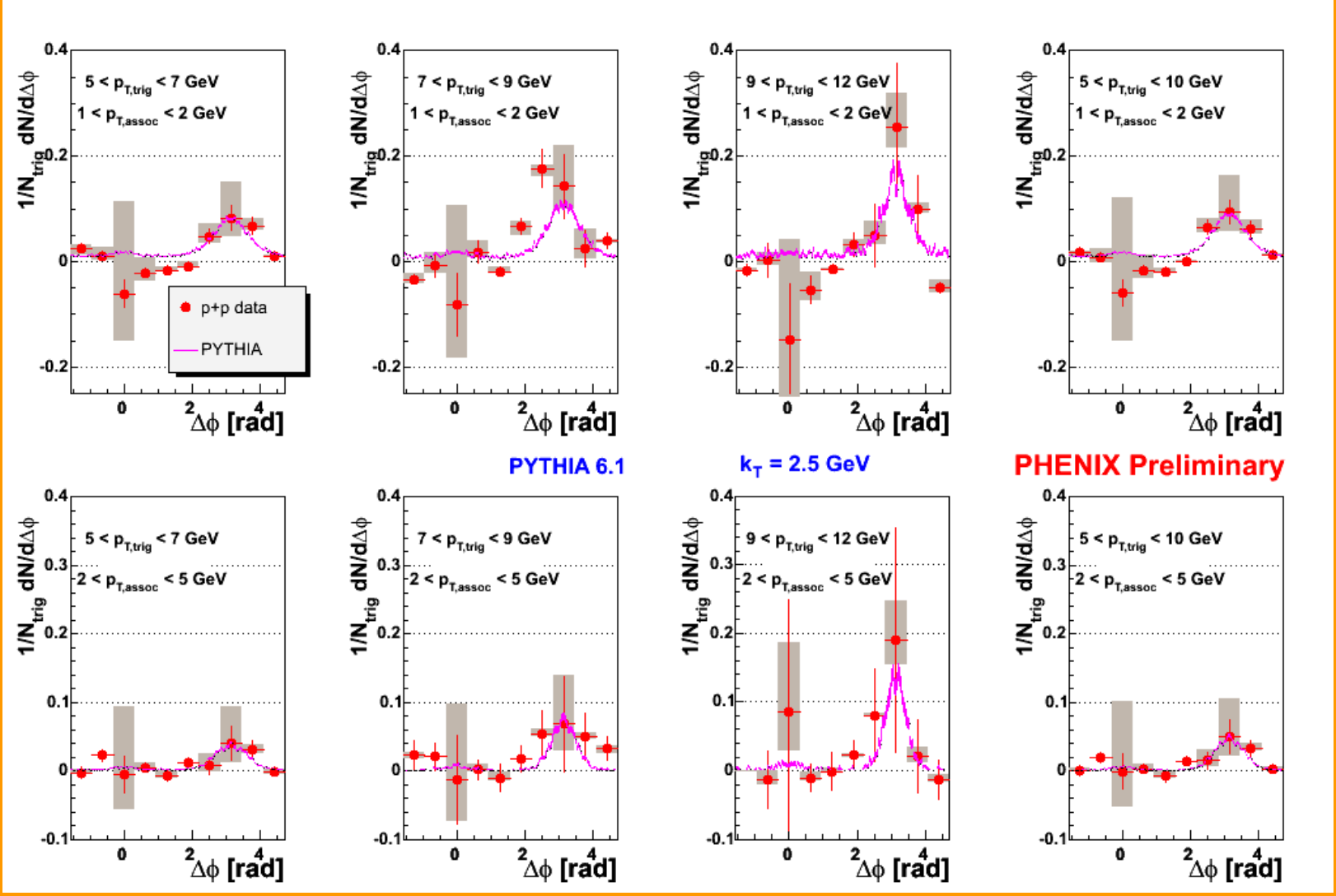
p+p collisions at 200 GeV



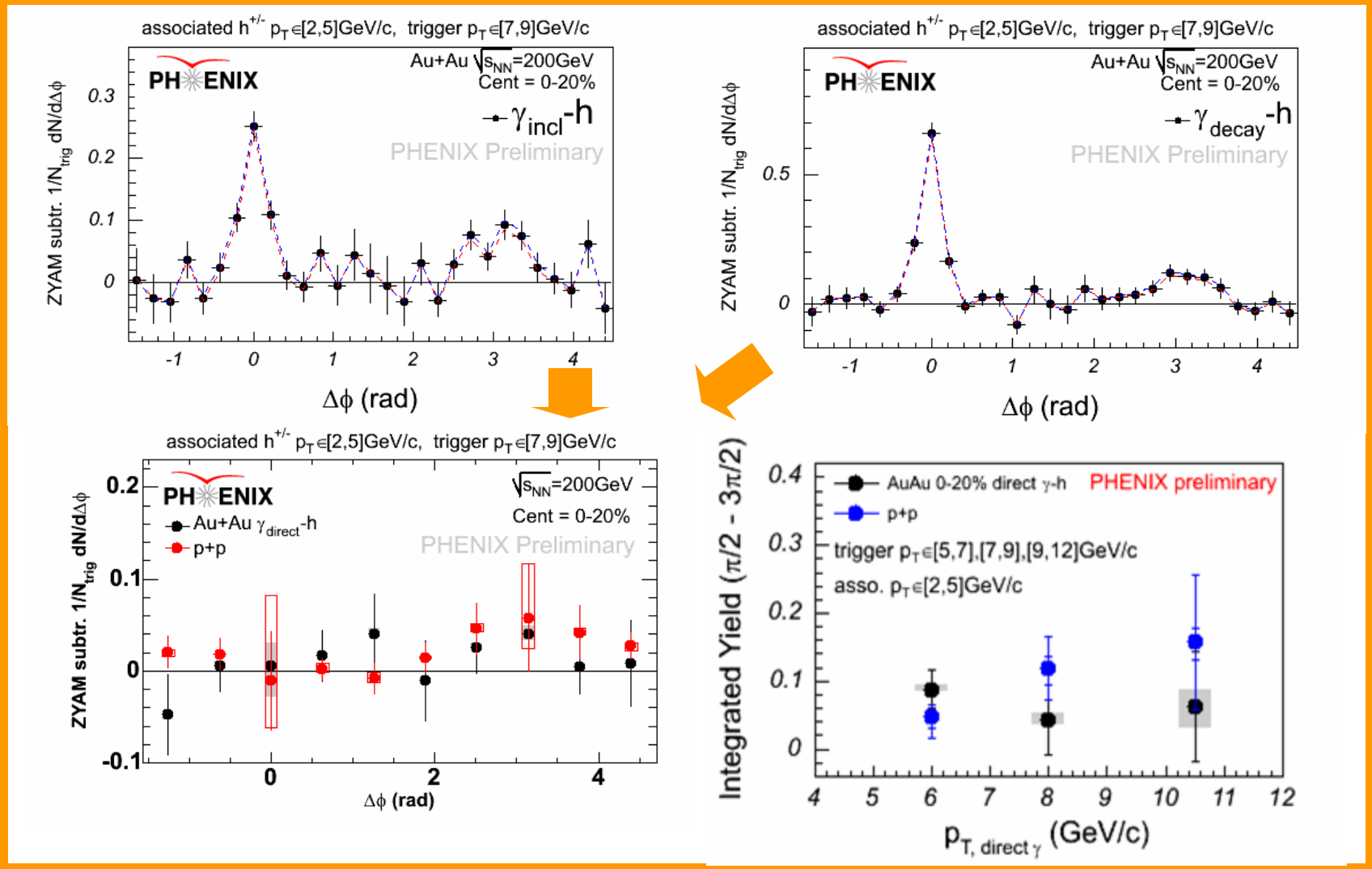


1. Inclusive γ-h
2. Decay γ-h contribution (via π^0-hadron)
3. Direct γ-h !

Comparison to Pythia



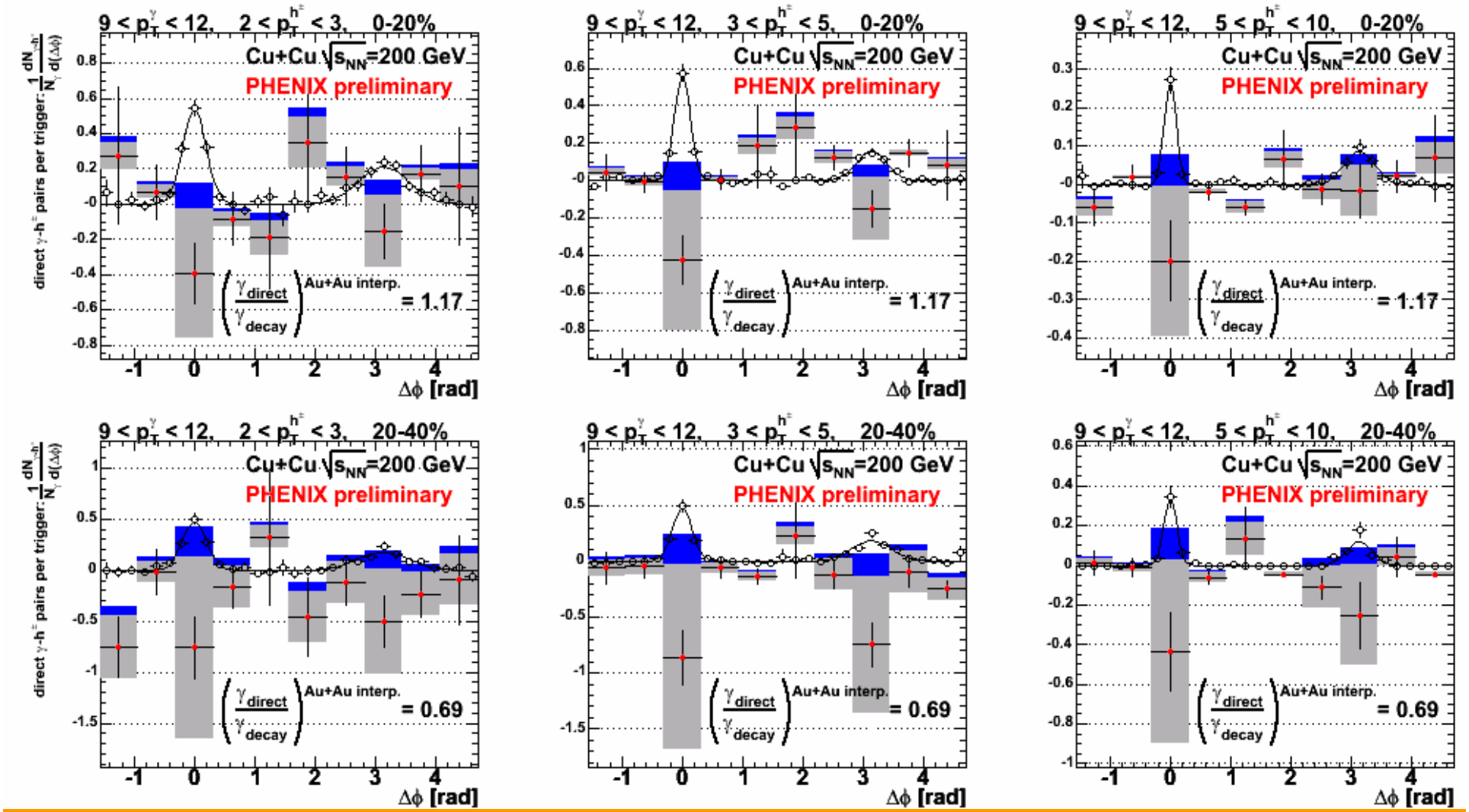
γ-Jet Correlations in AuAu



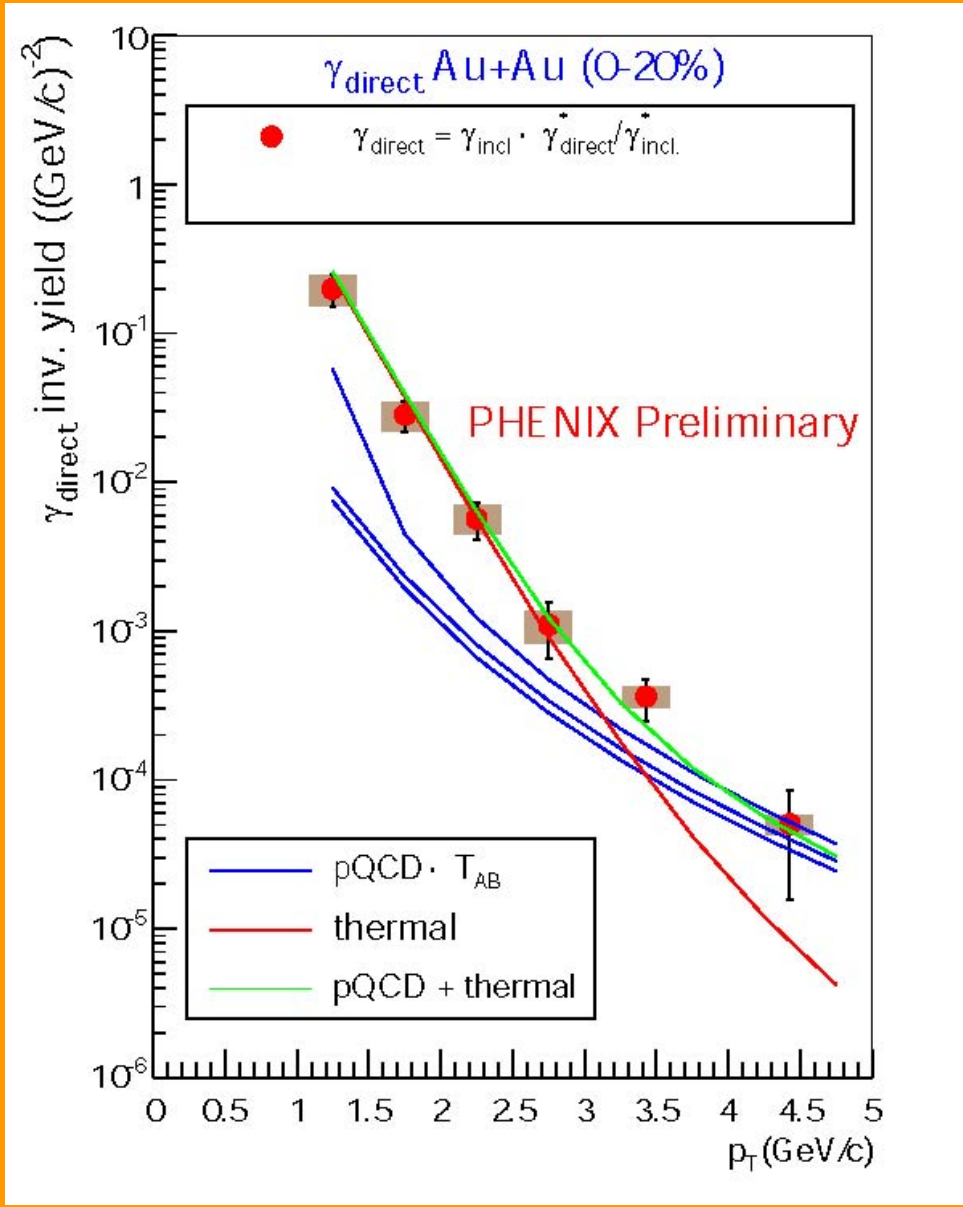
PHENIX Cu+Cu – jet E-scale

systematic from R_γ

systematic from subtraction method



The Spectrum



Compare to NLO pQCD

- L.E.Gordon and W. Vogelsang
- Phys. Rev. D48, 3136 (1993)

- above (questionable) pQCD

Compare to thermal model

- D. d'Enterria, D. Perresounko
- nucl-th/0503054

2+1 hydro

T_0^{ave}=360 MeV(T_0^{max}=570 MeV)

τ_0=0.15 fm/c

- data above thermal at high p_T

Compare to thermal + pQCD

- data consistent with thermal + pQCD

- Needs confirmation from *p+p* measurement

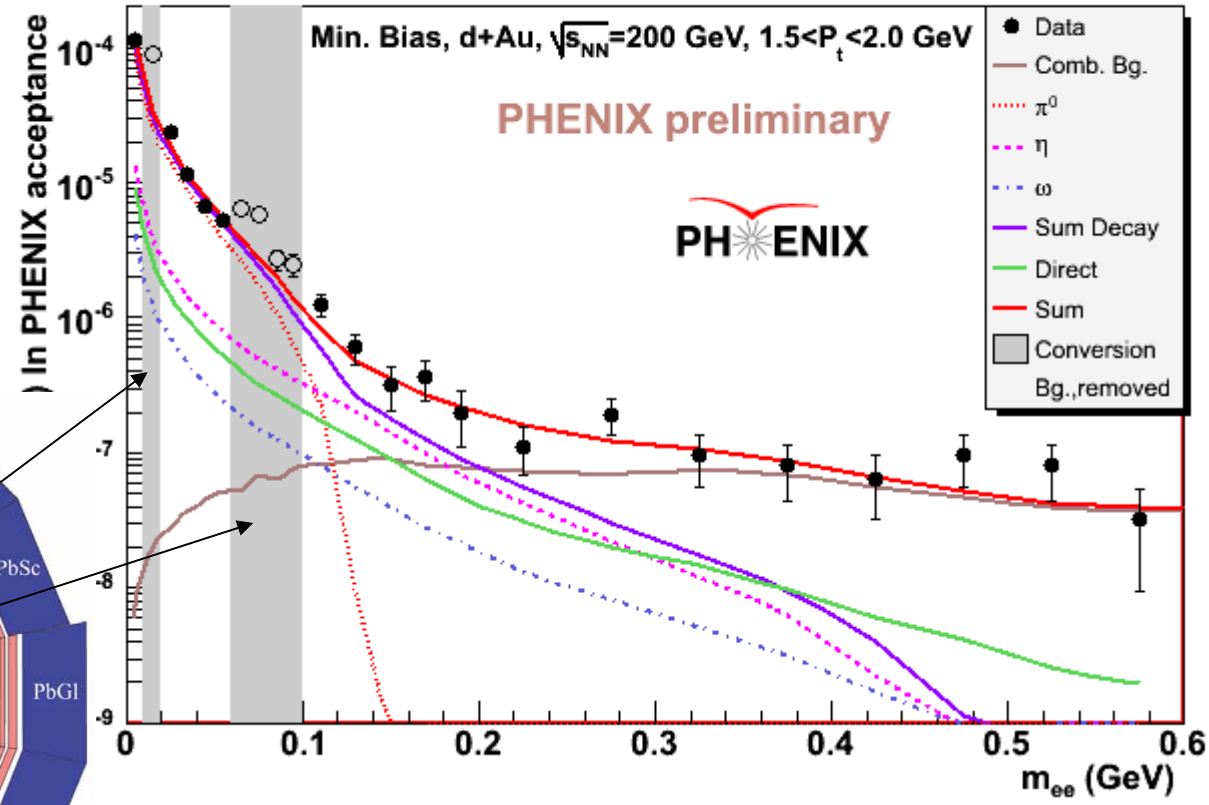
Internal conversion: d+Au

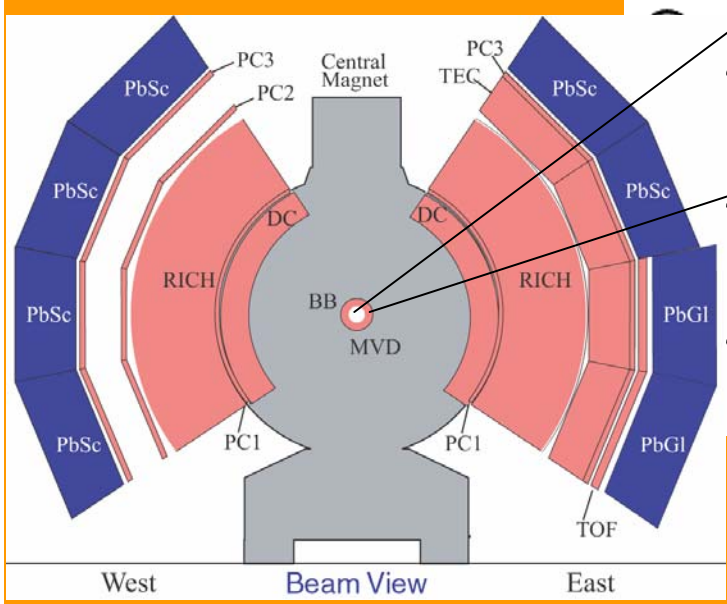
Fit measured mass spectrum with function:

$$\frac{dN}{dm_{ee}} = a\left(\frac{dN^{\pi}}{dm_{ee}} + \frac{dN^{\eta}}{dm_{ee}} + \frac{dN^{\omega}}{dm_{ee}} + b\frac{dN^{dir}}{dm_{ee}}\right) + \frac{dN^{BG}}{dm_{ee}}$$

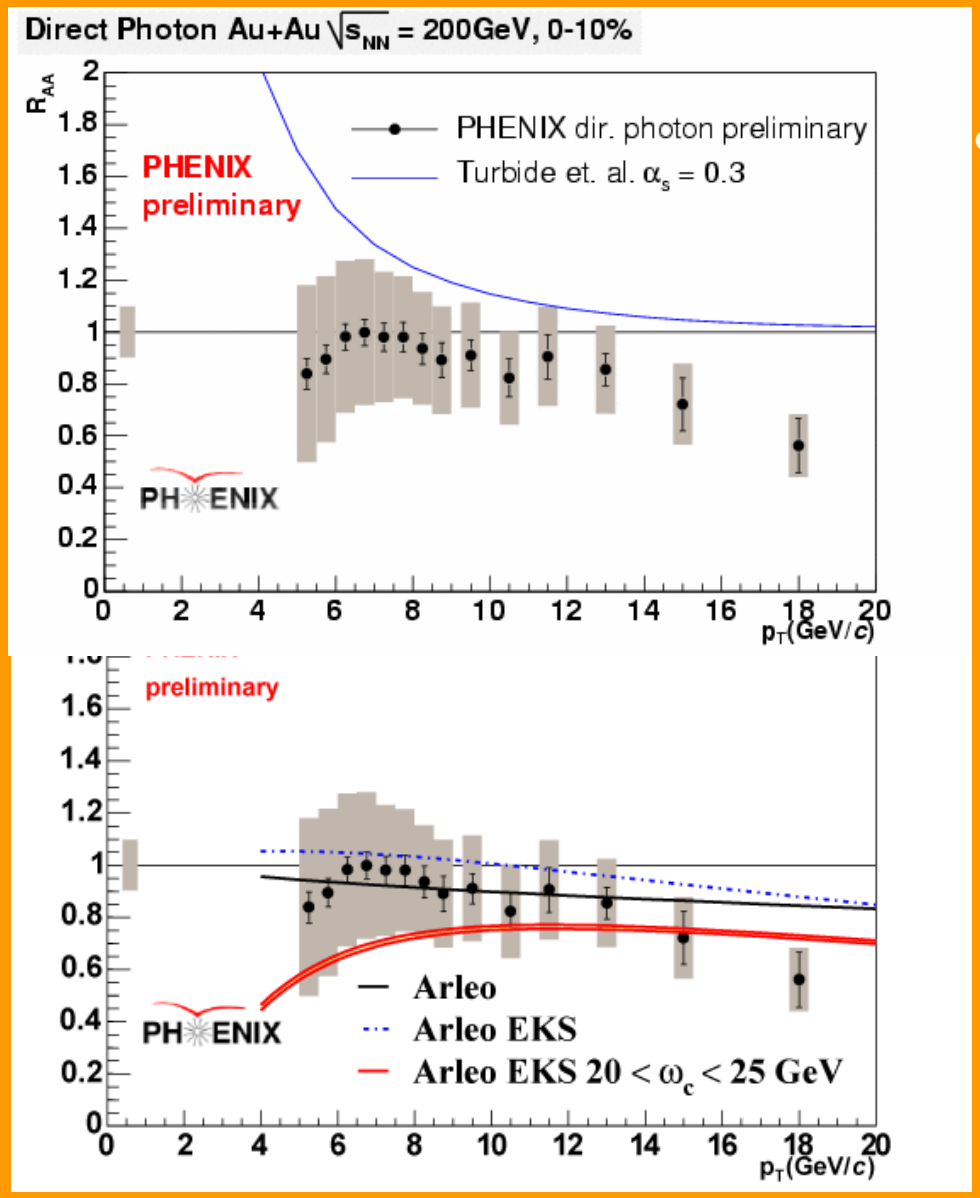
a **- absolute normalization**

b **– fraction of direct photons:**

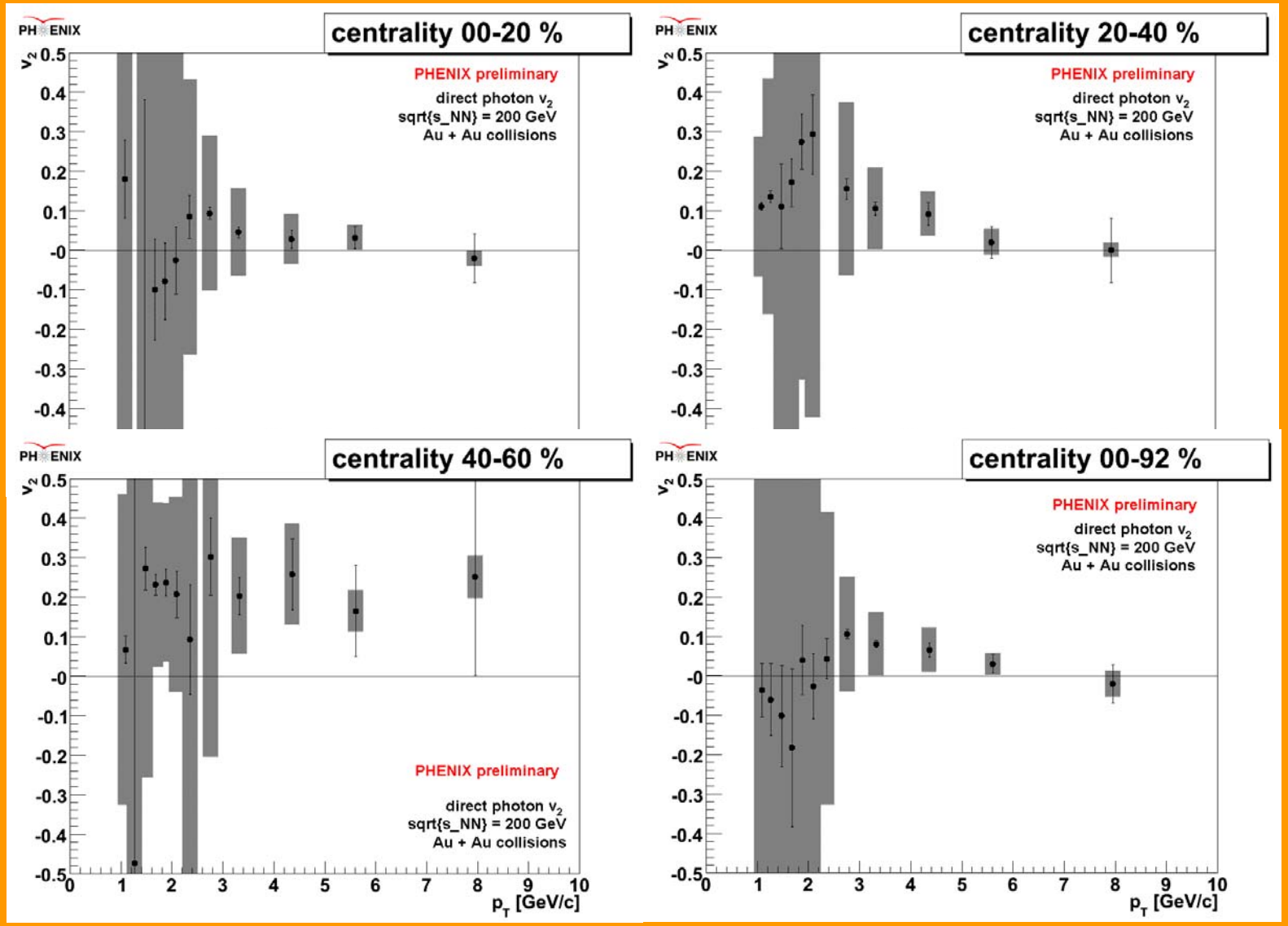




Comparison to Theory



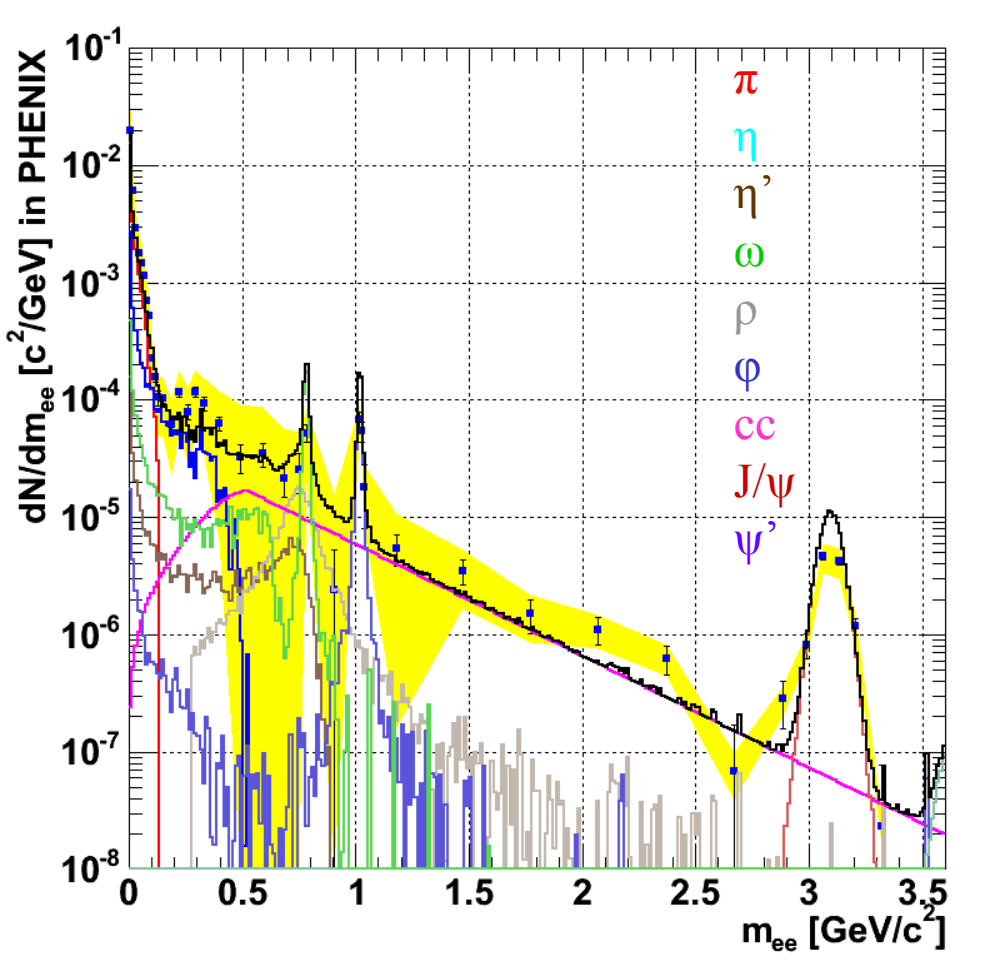
- Turbide et al.
  - Jet photons + pQCD + thermal
  - AMY formalism for jet-quenching of fragmentation photons
  - Data systematically below theory
  - Phys. Rev. C72 (2005) 014906 + private communication
- F. Arleo
  - pQCD photons only
  - High-p_T suppression due to isospin effect, shadowing, and energy loss
  - BDMPS for jet-quenching
  - JHEP 0609 (2006) 015



Systematic errors mostly from R:
large background of decay photons at low p_T

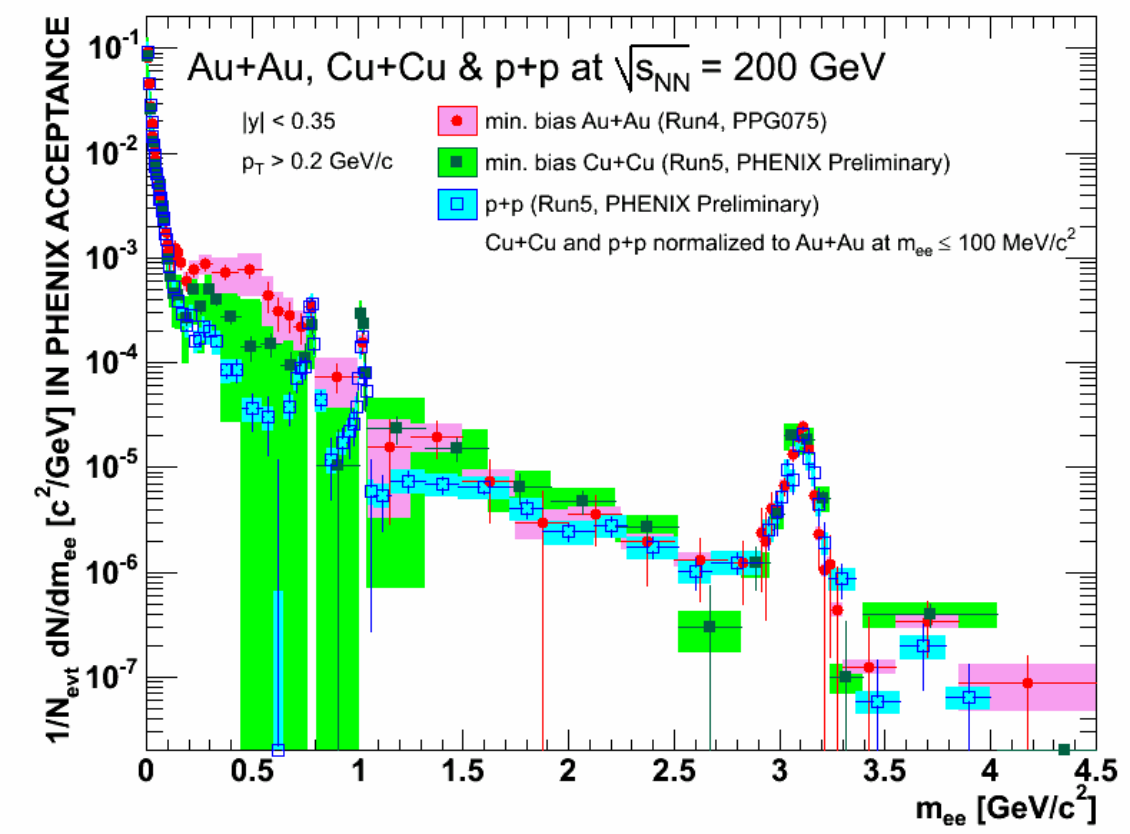
v_2 consistent with zero

Cu+Cu, 200 GeV, PHENIX preliminary



Caveat: different acceptance cuts than in Au+Au and p+p, so not directly comparable

Cu+Cu, 200 GeV, PHENIX preliminary

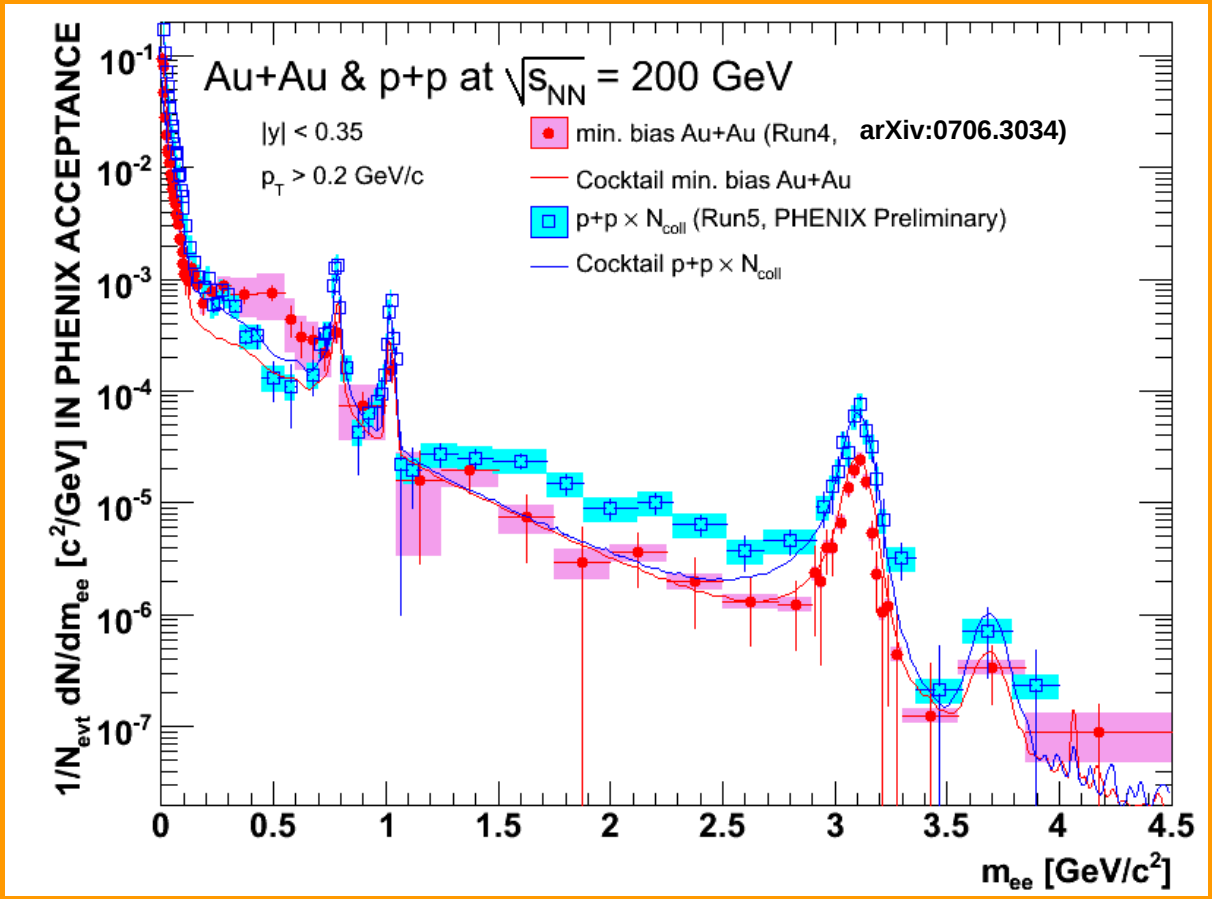


Caveat: different acceptance cuts than in Au+Au and p+p, so not directly comparable

p+p–Au+Au comparison

both normalized to m_{ee}<100 MeV/c^2

p+p multiplied by $N_{part}/2$ | p+p multiplied by N_{coll}



- p+p and Au+Au normalized to π^0 region
- Agreement at resonances (ω, ϕ)
- Au+Au enhancement for 0.2- m_{ee} < 0.8 GeV

- Agreement in intermediate mass and J/Ψ just for 'coincidence' (J/Ψ happens to scale as π^0 due to scaling with N_{coll} + suppression)

The Quark-Gluon Plasma and Heavy Ion Collisions

- In everyday life, forces get weaker when one pulls things apart

- Not so for the strong force . . .