ENHANCED DIRECT PHOTON PRODUCTION IN 200 GEV AU+AU IN PHENIX

RIKEN BNL Research Center

Stefan Bathe for PHENIX, WWND 2009

ENHANCED (WRT P+P) DIRECT PHOTON PRODUCTION IN 200 GEV AU+AU IN PHENIX

RIKEN BNL Research Center

Stefan Bathe for PHENIX, WWND 2009

ENHANCED (WRT P+P) (MID PT) DIRECT PHOTON PRODUCTION IN 200 GEV AU+AU IN PHENIX

RIKEN BNL Research Center

Stefan Bathe for PHENIX, WWND 2009

RIKEN BNL Research Center

Stefan Bathe for PHENIX, WWND 2009

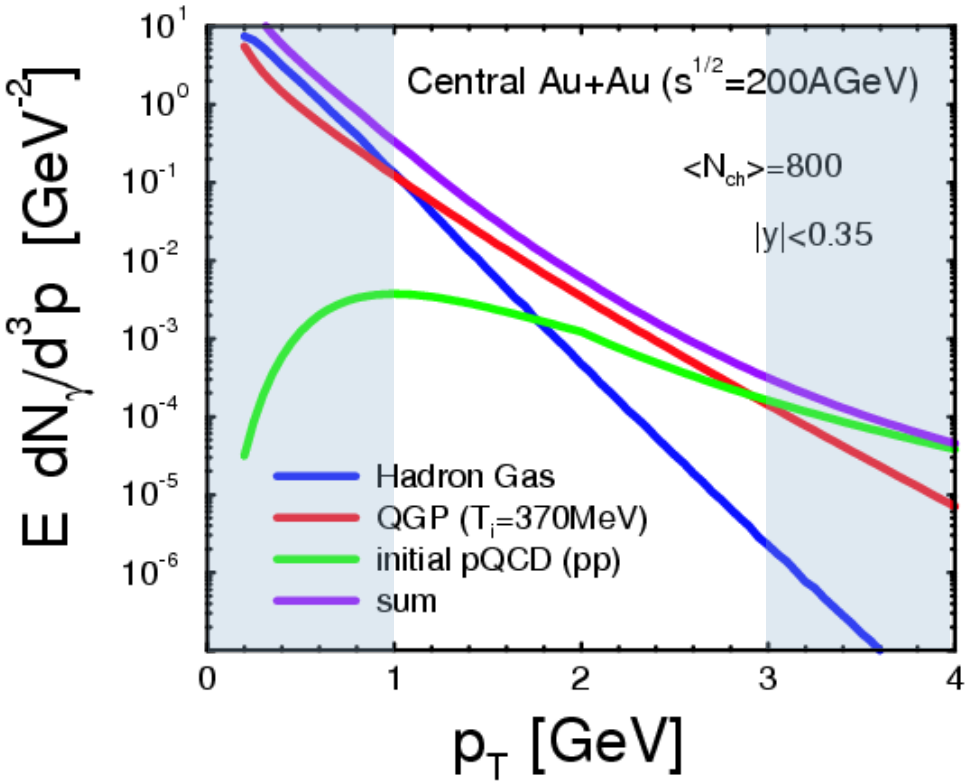
ALSO:
LOWEST PT EVER MEASURED FOR DIRECT PHOTONS IN P+P

RIKEN BNL Research Center

Stefan Bathe for PHENIX, WWND 2009

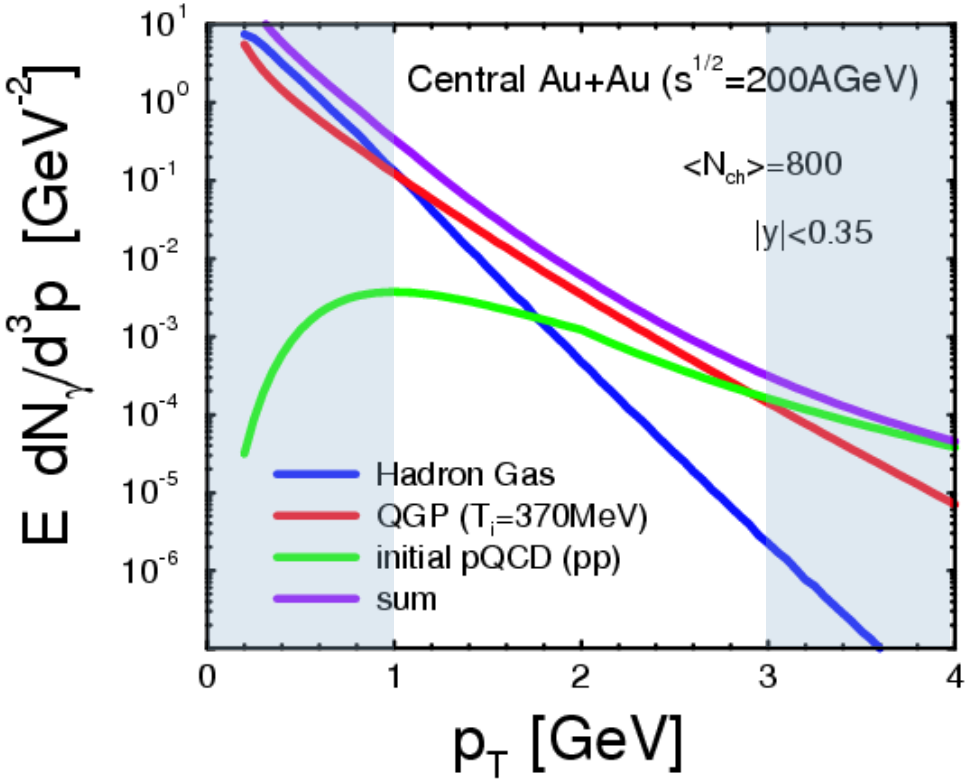
Introduction

Turbide, Rapp, Gale,
Phys. Rev. C 69 (014903), 2004



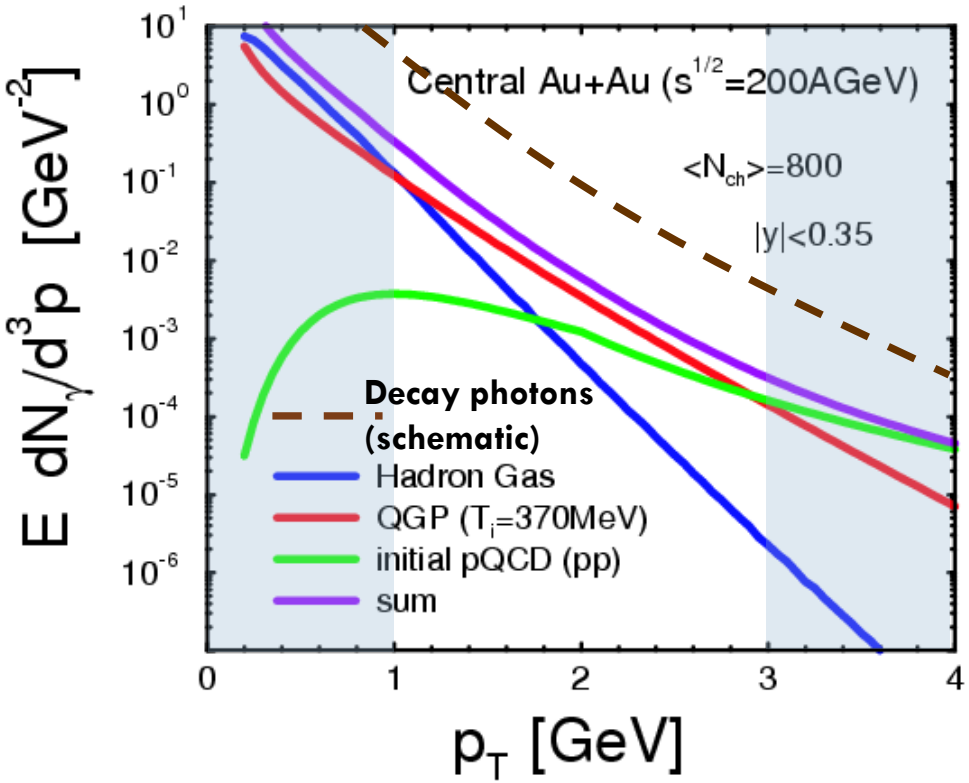
- Indications for high-density, thermalized medium at RHIC
- Expect thermal radiation
- Thermal photons from partonic phase
  - predicted to be dominant source of direct photons for 1<pT<3 GeV/c in Au+Au

Turbide, Rapp, Gale,
Phys. Rev. C 69 (014903), 2004



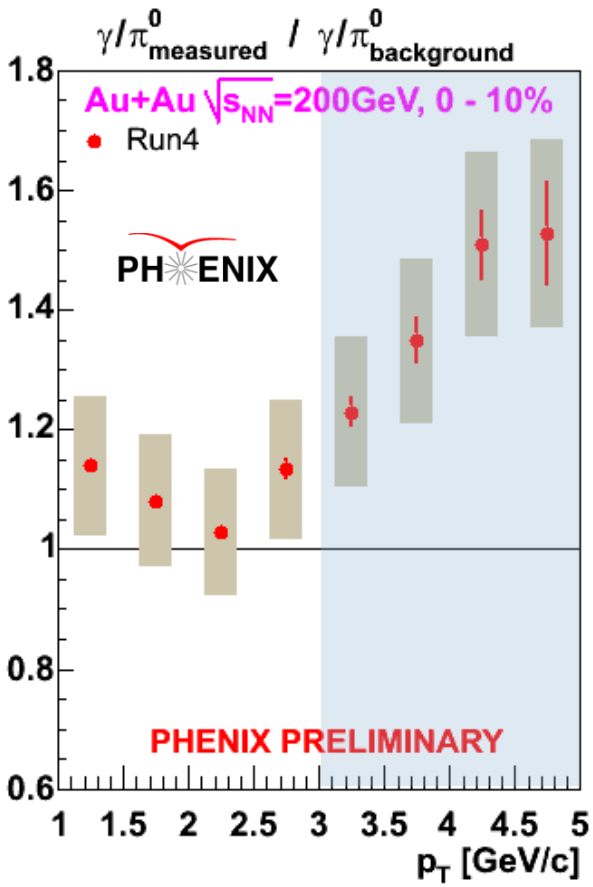
Experimental Challenge

Turbide, Rapp, Gale,
Phys. Rev. C 69 (014903), 2004



- Challenge: photon spectrum dominated by decay photons
- Conventional method:
  - Measure inclusive photons with EMCal
  - Reconstruct π^0, η from correlated photon pairs
  - $\gamma_{direct} = \gamma_{inclusive} - \gamma_{decay}$

Limit of Conventional Method

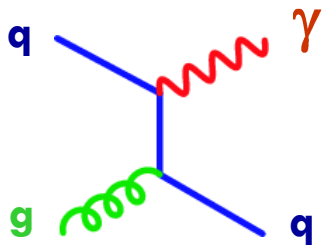


- Conventional method works well at high p_T
- But limited at low p_T where thermal photons expected

S/B ≈ Sys. Error ≈ 10%
⇒reduce background!

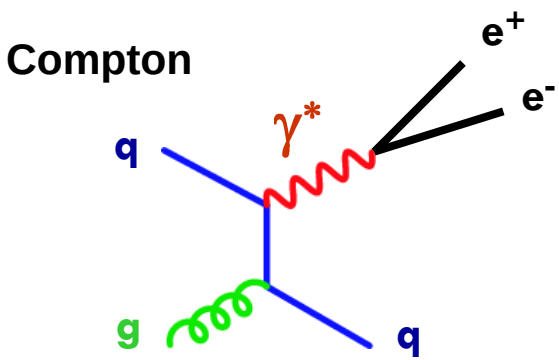
Internal Conversion Method

Compton



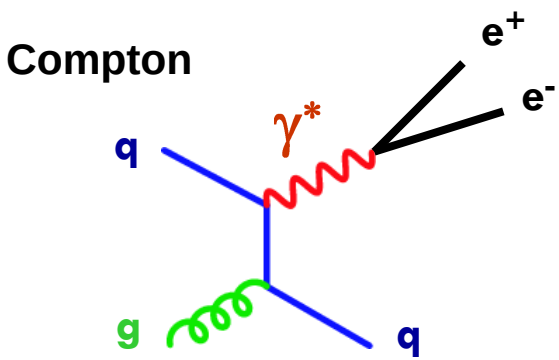
- Any source of high-E photons emits virtual photons γ^*
- γ^* convert to low-mass e^+e^-

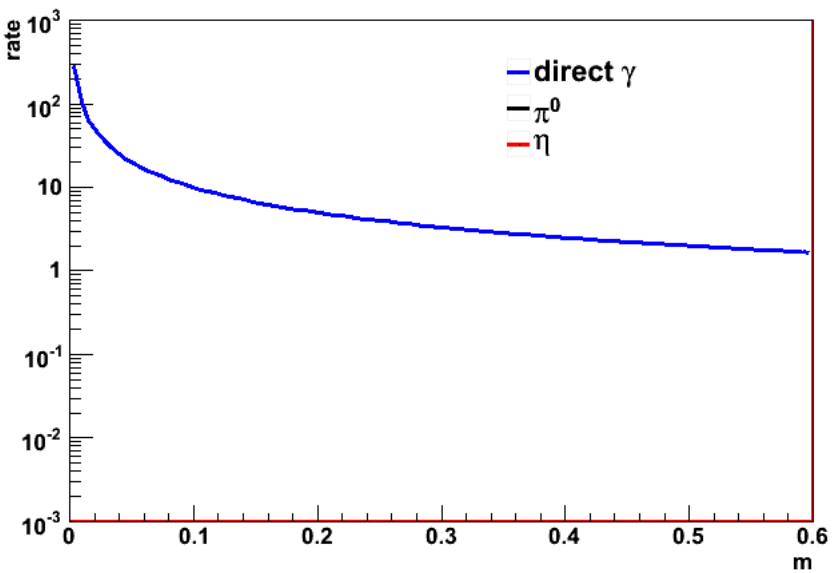
Internal Conversion Method



- Any source of high-E photons emits virtual photons γ^*
- γ^* convert to low-mass e^+e^-

Internal Conversion Method



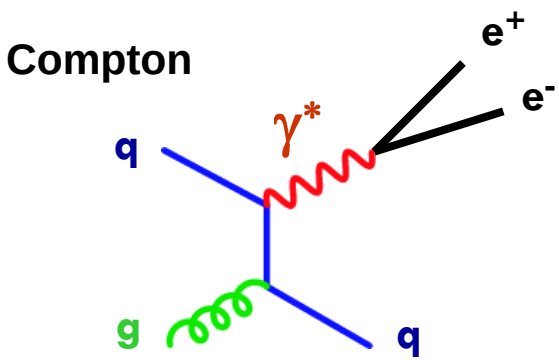


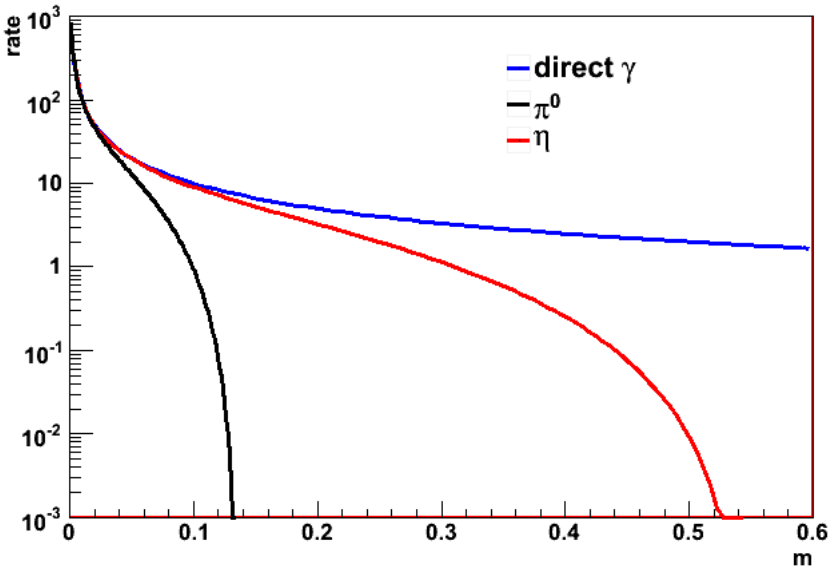
- Any source of high-E photons emits virtual photons γ^*
- γ^* convert to low-mass e^+e^-

$$\frac{d^3 n_{ee}}{dm\,dp_T\,dy} = \frac{2\alpha}{3\pi}\frac{1}{m} S \frac{d^2 n_\gamma}{dp_T\,dy}, \quad \text{for } m >> m_e$$

$$S = 1, \quad \text{for direct } \gamma$$

Internal Conversion Method





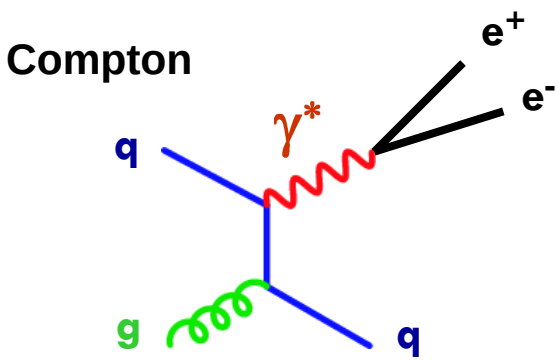
- Any source of high-E photons emits virtual photons γ^*
- γ^* convert to low-mass e^+e^-

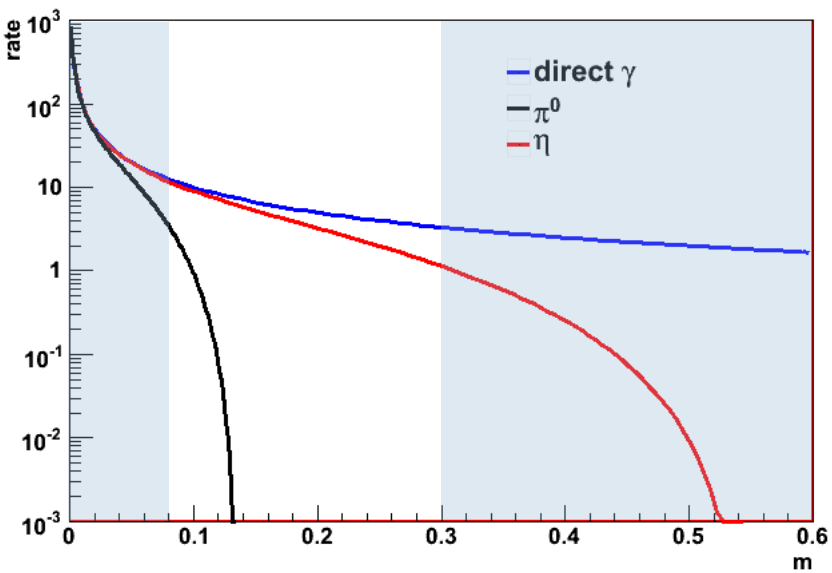
$$\frac{d^3 n_{ee}}{dm\,dp_T\,dy} = \frac{2\alpha}{3\pi}\frac{1}{m} S \frac{d^2 n_\gamma}{dp_T\,dy}, \quad \text{for } m >> m_e$$

$$S = 1, \quad \text{for direct } \gamma$$

$$S = \left|F(m^2)\right|^2 (1 - \frac{m^2}{M_h^2})^3, \quad \text{for Dalitz}$$

Internal Conversion Method





- Any source of high-E photons emits virtual photons γ^*
- γ^* convert to low-mass e^+e^-

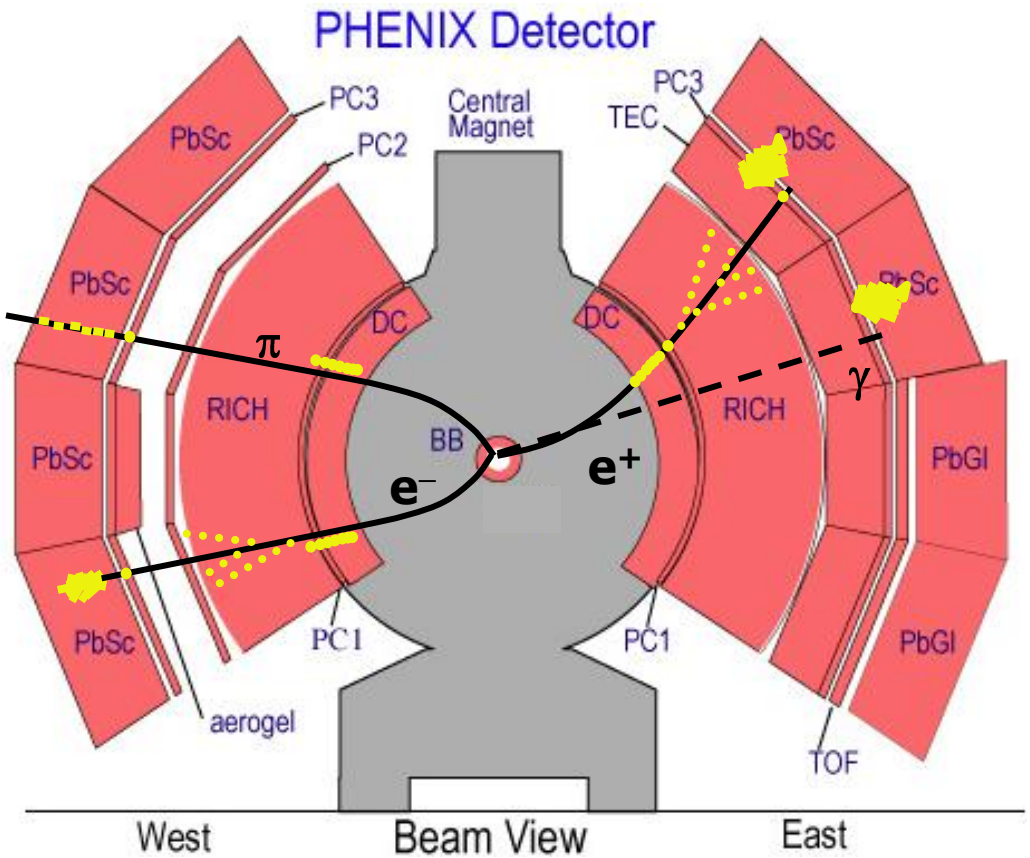
$$\frac{d^3n_{ee}}{dm\,dp_T\,dy} = \frac{2\alpha}{3\pi}\frac{1}{m} S \frac{d^2n_\gamma}{dp_T\,dy}, \quad \text{for } m >> m_e$$

$$S = 1, \quad \text{for direct } \gamma$$

$$S = \left|F(m^2)\right|^2 (1 - \frac{m^2}{M_h^2})^3, \quad \text{for Dalitz}$$

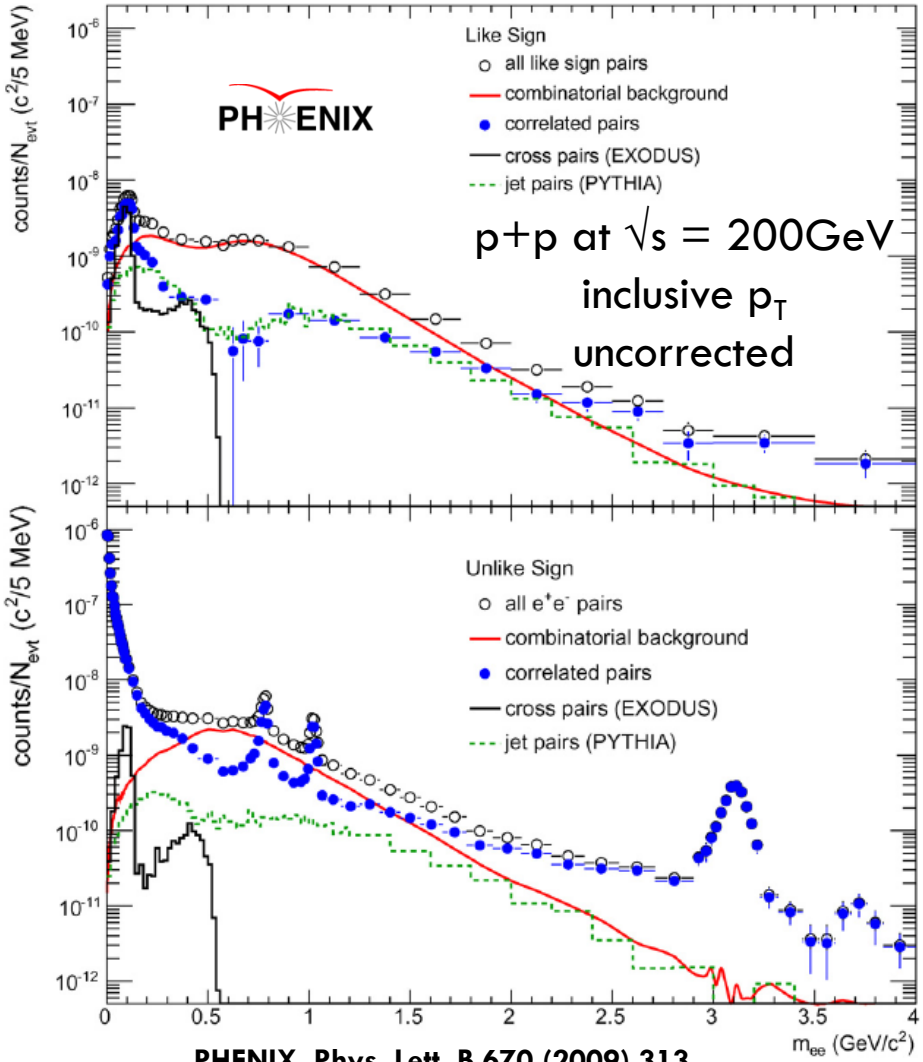
Exploit cut-off => S/B enhanced to 50%!

Detector And Data Set



- Particles
  - e^+e^- pairs, m<300 MeV
  - $1<p_T<5$ GeV
- Collision systems and energy
  - 200 GeV Au+Au, 2004, 0.8e9 events (4.9 pb^{-1} p+p equivalent)
  - 200 GeV p+p, 2005, 2.25 pb^{-1}
- Detector
  - PHENIX Central Arms
  - $|\Delta\eta|<0.35$, $2x\pi/2$
  - Conversion: 0.4% radiation length

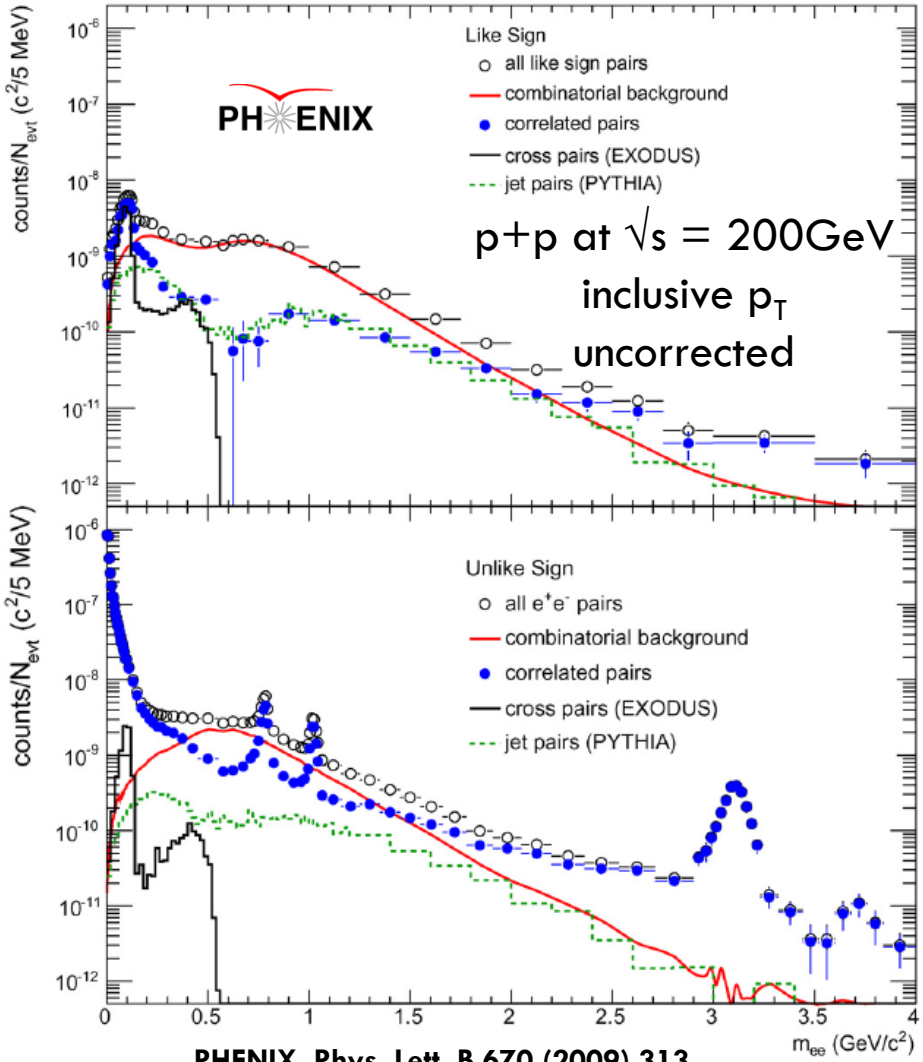
Signal-Background Pair Separation



PHENIX, Phys. Lett. B 670 (2009) 313

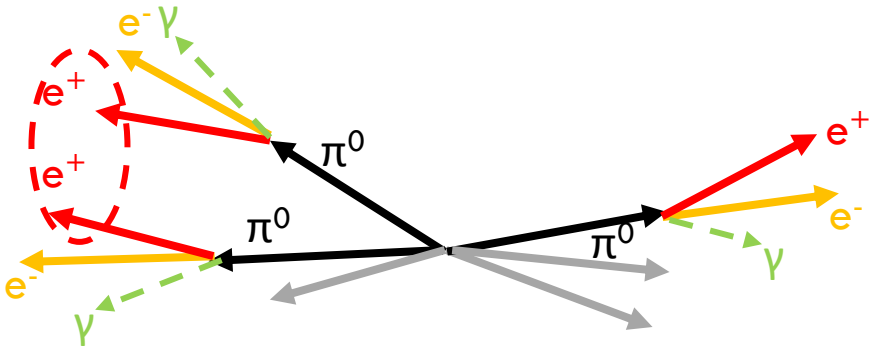
- Material conversion pairs removed by cut on orientation in magnetic field
- Combinatorial background removed by mixed events (0.25% syst. uncertainty in Au+Au)

Signal-Background Pair Separation

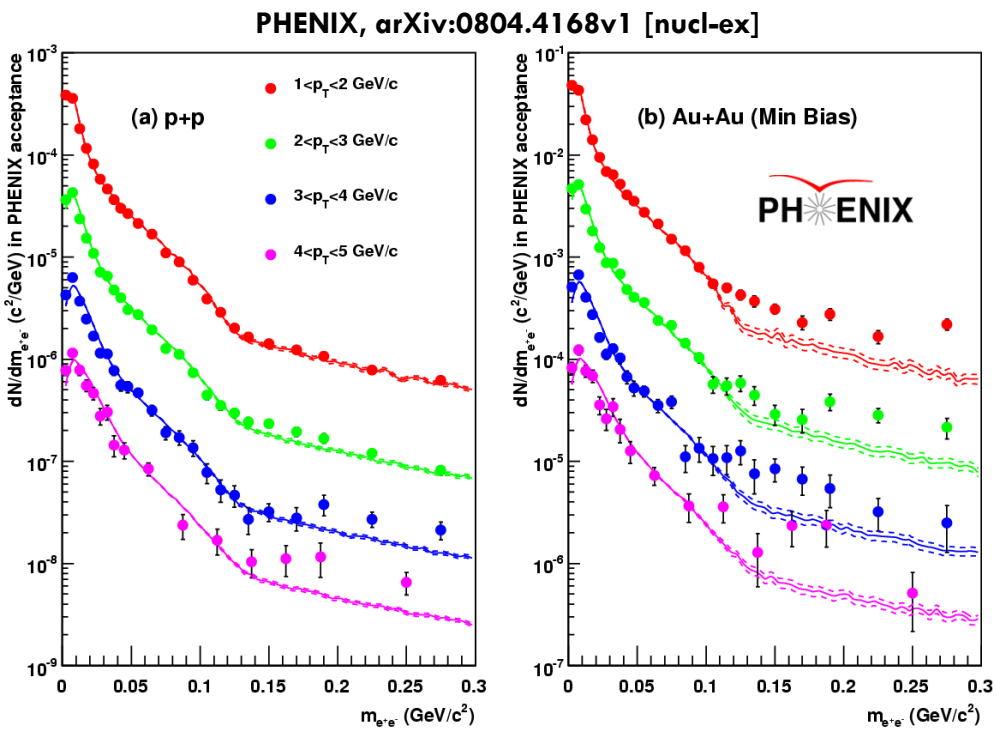


PHENIX, Phys. Lett. B 670 (2009) 313

- Material conversion pairs removed by cut on orientation in magnetic field
- Combinatorial background removed by mixed events (0.25% syst. uncertainty in Au+Au)
- additional correlated background:
  - cross pairs from decays with four electrons in final state
  - particles in same jet (low mass)
  - or back-to-back jet (high mass)
- well understood from MC



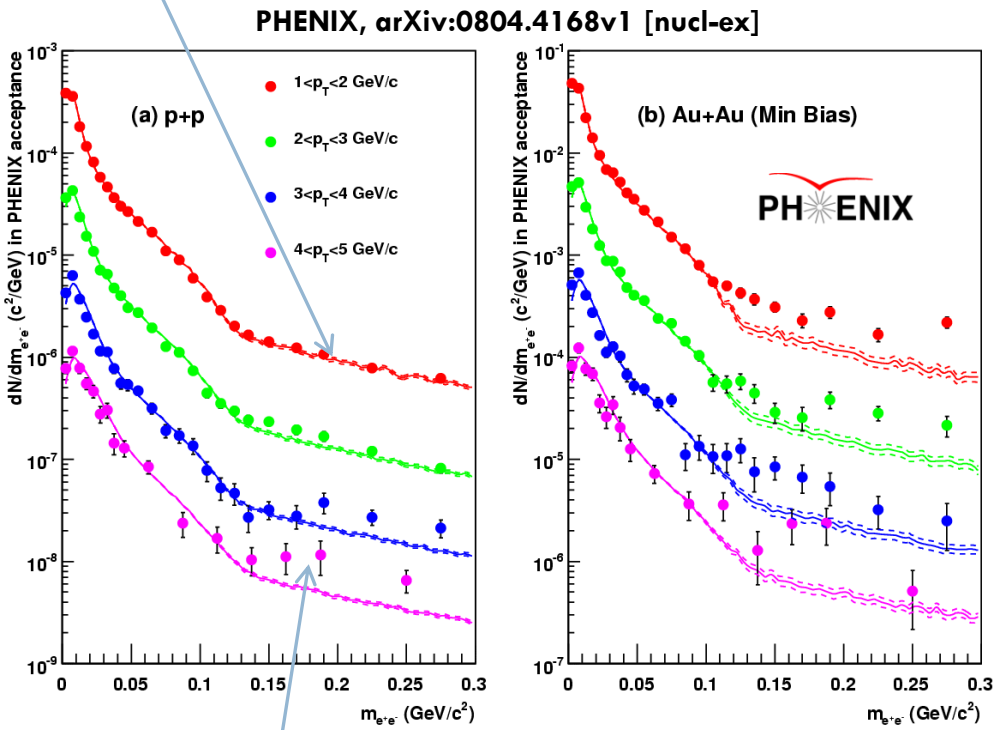
Direct Photon Signal



- Corrected mass spectra (points)
- Compared to "cocktail" of hadronic decays (lines)
- Cocktail normalized to data for m<30 MeV
- "knee" at 100 MeV from π^0 cut-off
  - 80% background reduction

Direct Photon Signal

p+p consistent w/ bckgrnd for lowest p_T



Small excess at higher p_T for $m>m_{\pi 0}$

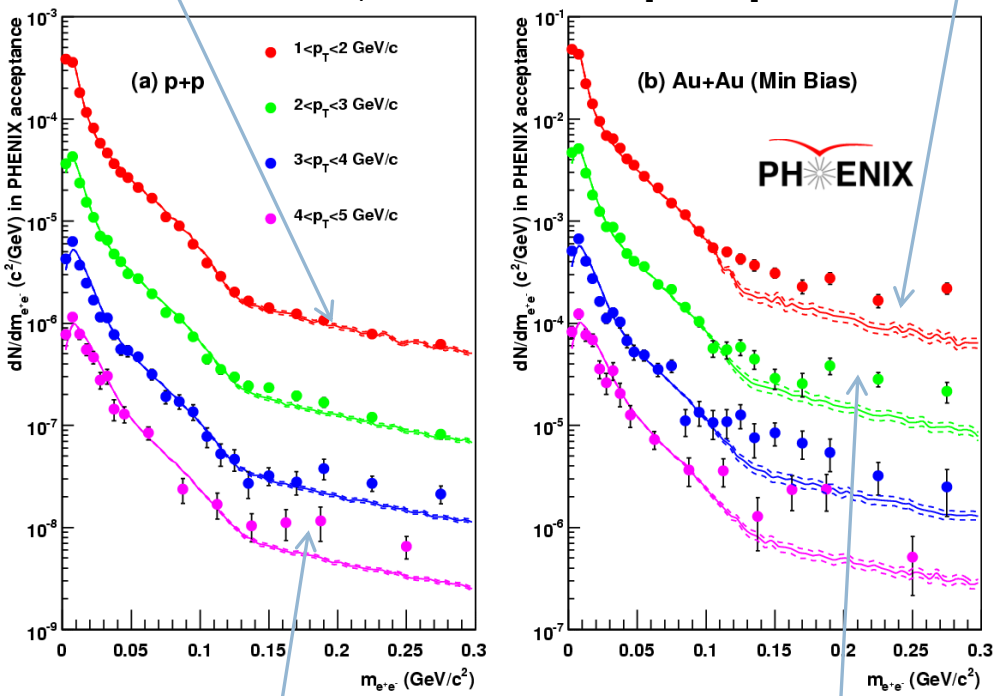
- Corrected mass spectra (points)
- Compared to "cocktail" of hadronic decays (lines)
- Cocktail normalized to data for m<30 MeV
- "knee" at 100 MeV from π^0 cut-off
  - 80% background reduction

Direct Photon Signal

p+p consistent w/ bckgrnd for lowest p_T

Au+Au much larger excess at all p_T

PHENIX, arXiv:0804.4168v1 [nucl-ex]

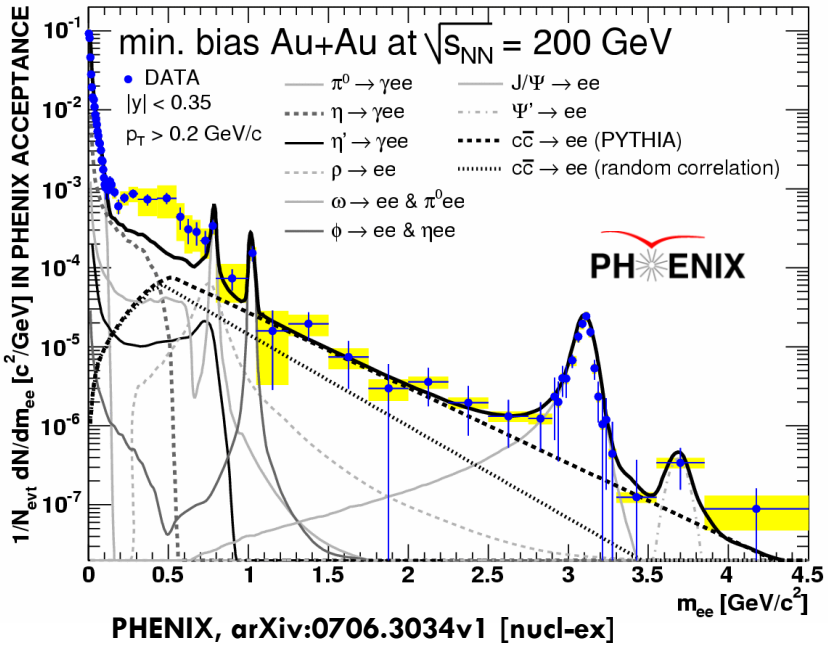


Small excess at higher p_T for $m>m_{\pi 0}$

Indicates enhanced production of virtual photons

- Corrected mass spectra (points)
- Compared to "cocktail" of hadronic decays (lines)
- Cocktail normalized to data for m<30 MeV
- "knee" at 100 MeV from π^0 cut-off
  - 80% background reduction

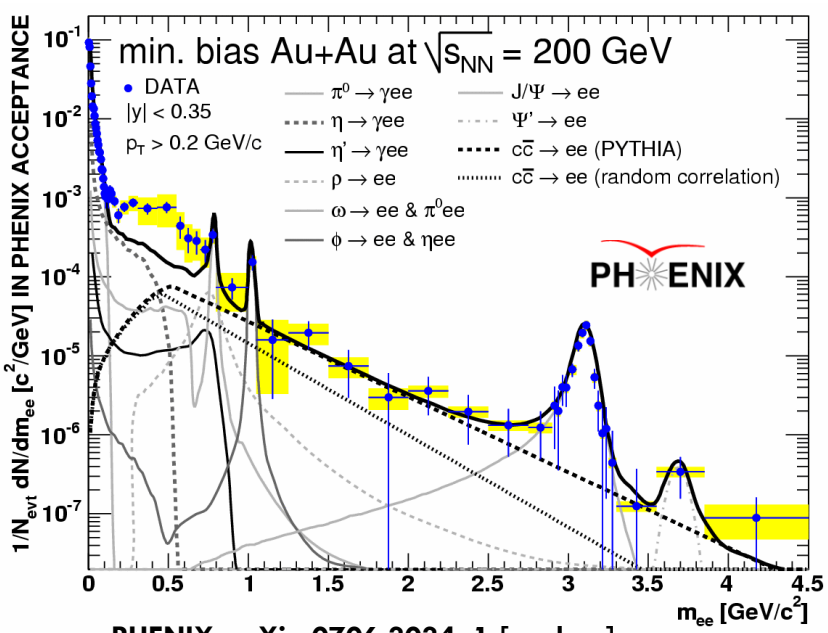
Direct γ vs. Low-Mass Enhancement



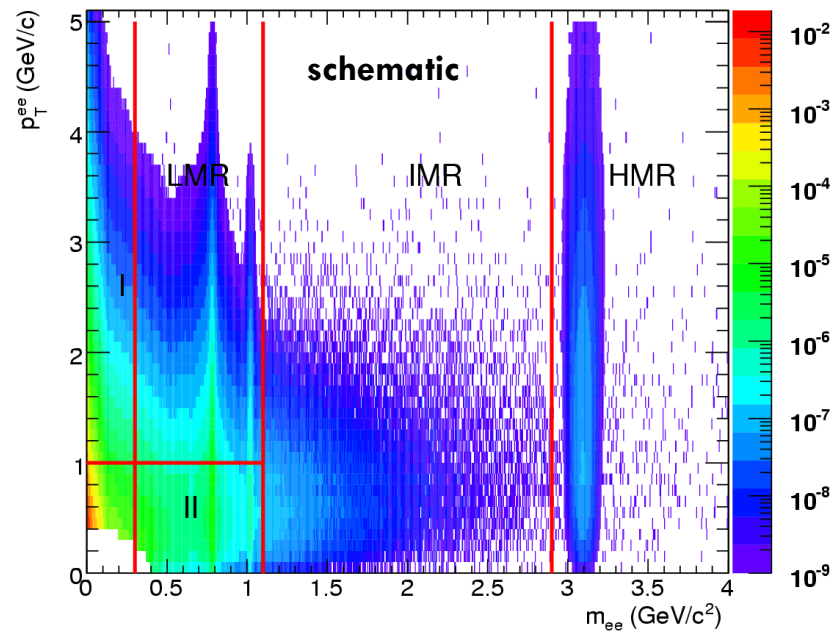
PHENIX, arXiv:0706.3034v1 [nucl-ex]

- Low mass enhancement seen in Au+Au
  - Inclusive p_T, region II

Direct γ vs. Low-Mass Enhancement



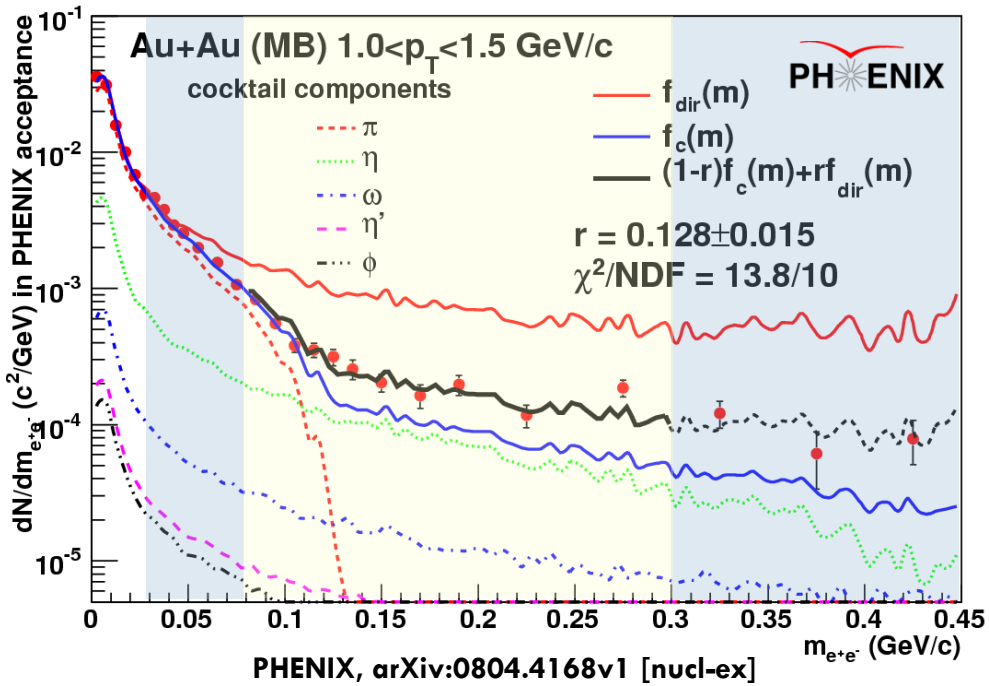
PHENIX, arXiv:0706.3034v1 [nucl-ex]



- Low mass enhancement seen in Au+Au
  - Inclusive p_T, region II

- Kinematic region II:
  - Expected to be dominated by hadronic gas phase
- Kinematic region I:
  - Quasi-real virtual photons

Extracting Direct γ Signal



- Two-component fit

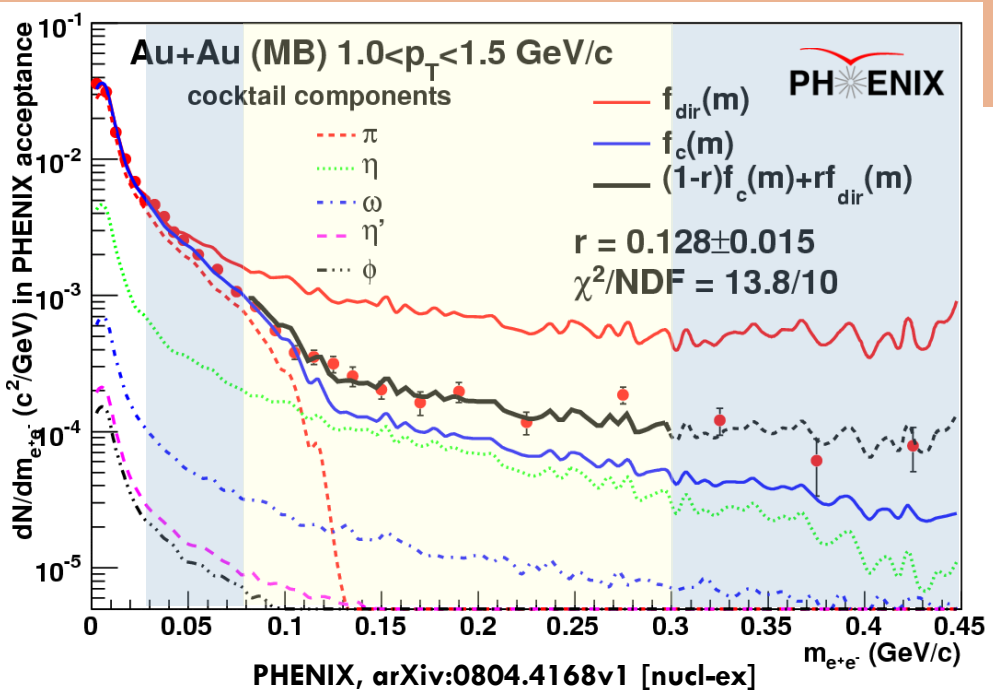
$$f(m) = (1-r)\, f_c(m) + r f_{dir}(m)$$

  - f_c: shape of cocktail
  - f_{dir}: shape of direct photon
  - r: fit parameter
  - f_c, f_{dir}: separately normalized to data for m<30 MeV

Extracting Direct γ Signal

Reminder: $$\frac{d^3 n_{ee}}{dm dp_T dy} = \frac{2\alpha}{3\pi}\frac{1}{m} S \frac{d^2 n_\gamma}{dp_T dy}, \quad \text{for } m >> m_e \qquad S = 1, \quad \text{for direct } \gamma$$

$$S = \left|F(m^2)\right|^2 (1 - \frac{m}{M_h^2})^3, \quad \text{for Dalitz}$$

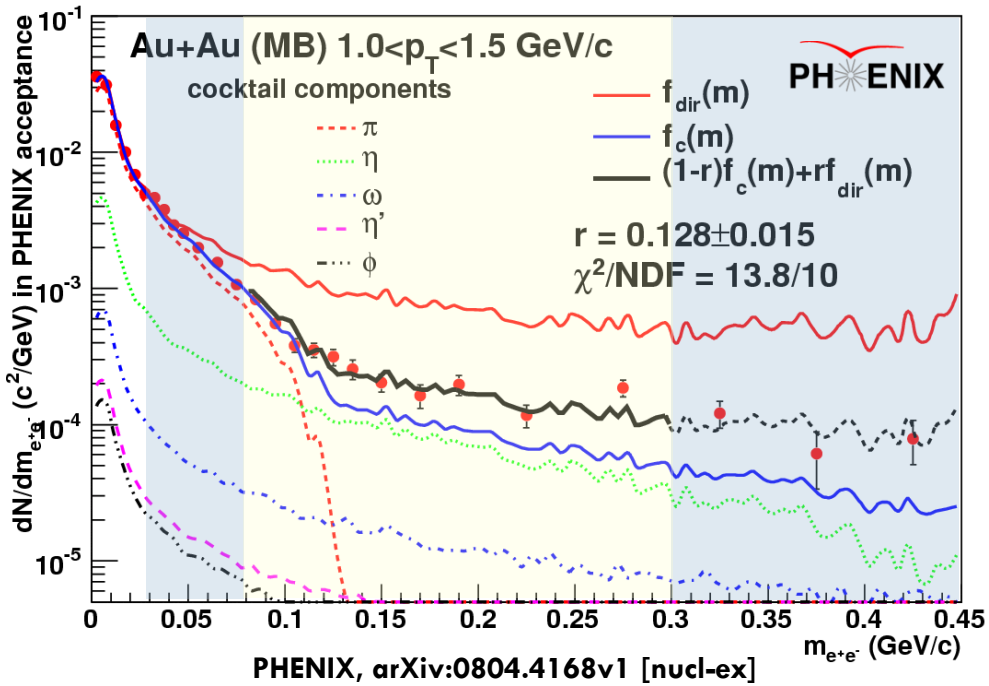


- Two-component fit

$$f(m) = (1-r) f_c(m) + r f_{dir}(m)$$

  - f_c: shape of cocktail
  - f_{dir}: shape of direct photon
  - r: fit parameter
  - f_c, f_{dir}: separately normalized to data for m<30 MeV

Extracting Direct γ Signal



- Two-component fit

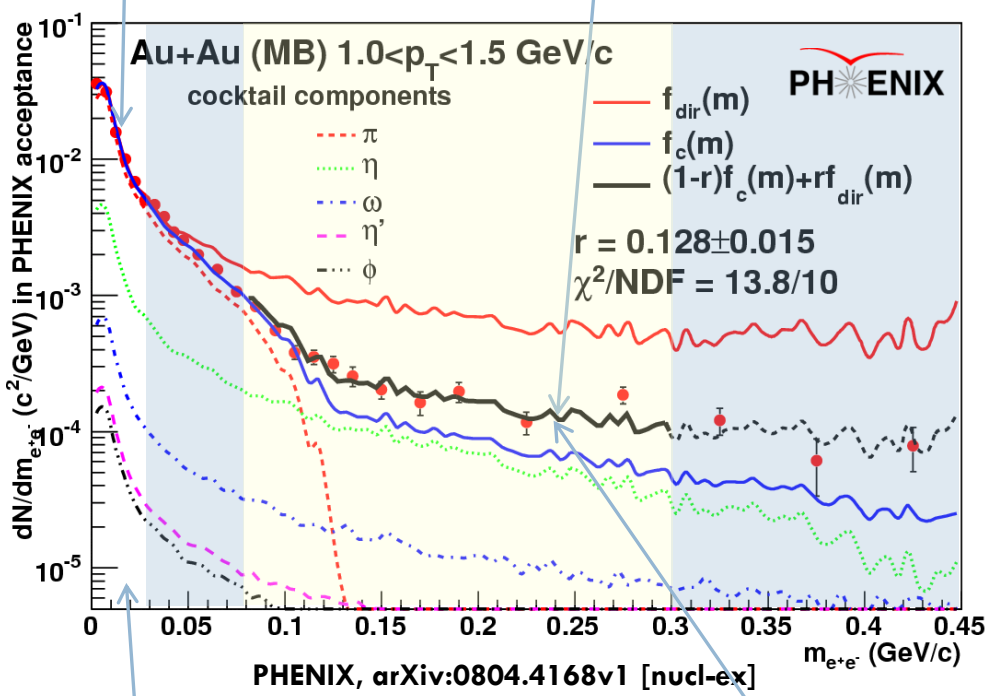
$$f(m) = (1-r)\, f_c(m) + r f_{dir}(m)$$

  - f_c: shape of cocktail
  - f_{dir}: shape of direct photon
  - r: fit parameter
  - f_c, f_{dir}: separately normalized to data for m<30 MeV

Extracting Direct γ Signal

Normalization
m<30 MeV

Fit
80<m<300 MeV



normalization preserves meaning of *r* as real direct photon fration

r entirely determined in fit region where S/B enhanced by factor 5

- Two-component fit

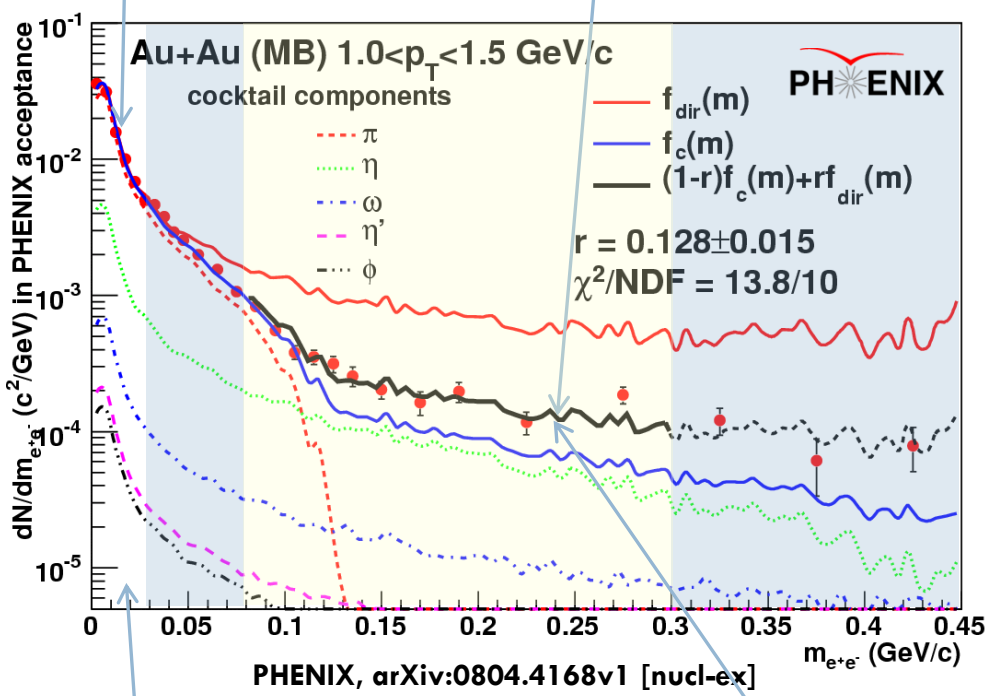
$$f(m) = (1-r)\, f_c(m) + r f_{dir}(m)$$

  - f_c: shape of cocktail
  - f_{dir}: shape of direct photon
  - r: fit parameter
  - f_c, f_{dir}: separately normalized to data for m<30 MeV

Extracting Direct γ Signal

Normalization
m<30 MeV

Fit
80<m<300 MeV



normalization preserves meaning of *r* as real direct photon fration

r entirely determined in fit region where S/B enhanced by factor 5

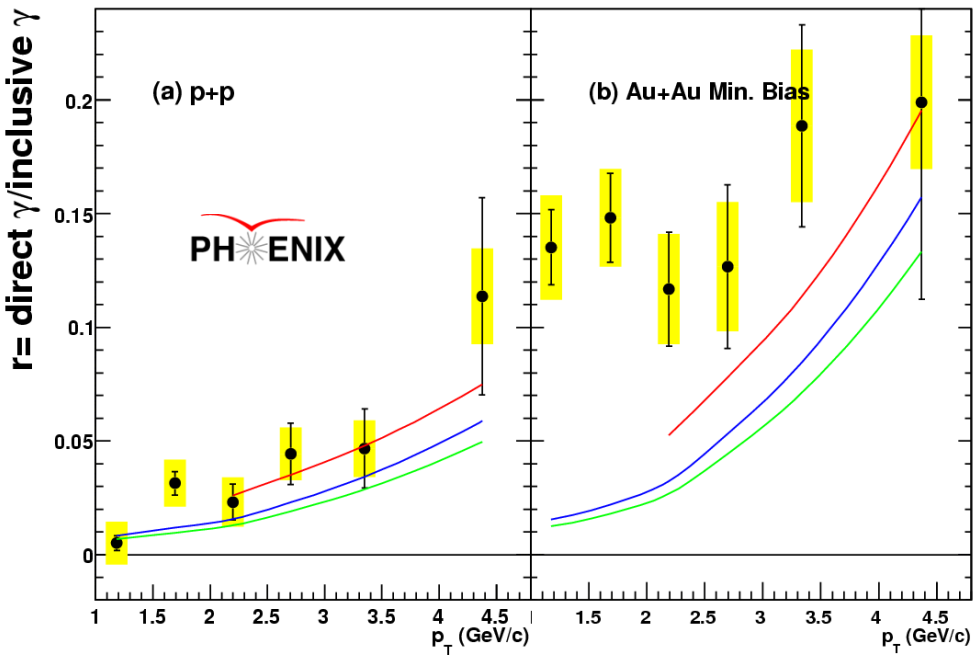
- Two-component fit

$$f(m) = (1-r)\, f_c(m) + r f_{dir}(m)$$

  - f_c: shape of cocktail
  - f_{dir}: shape of direct photon
  - r: fit parameter
  - f_c, f_{dir}: separately normalized to data for m<30 MeV

Data follow expected shape for direct photons

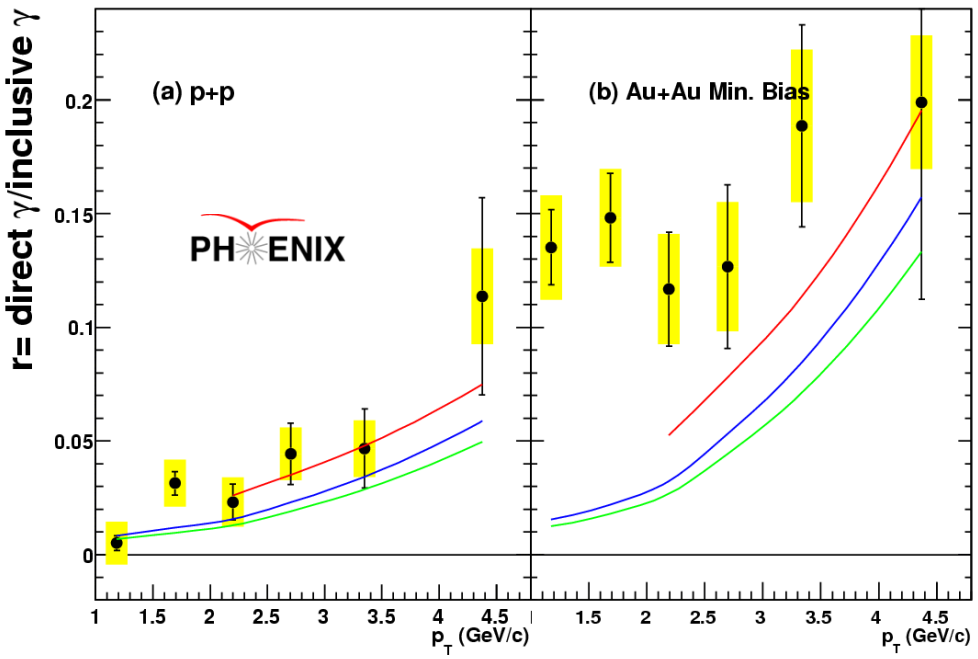
Direct Photon Fraction



PHENIX, arXiv:0804.4168v1 [nucl-ex]

- Direct photon fraction compared to NLO pQCD (lines, three scales)
- p+p
  - consistent with pQCD
- Au+Au:
  - enhanced above pQCD

Direct Photon Fraction



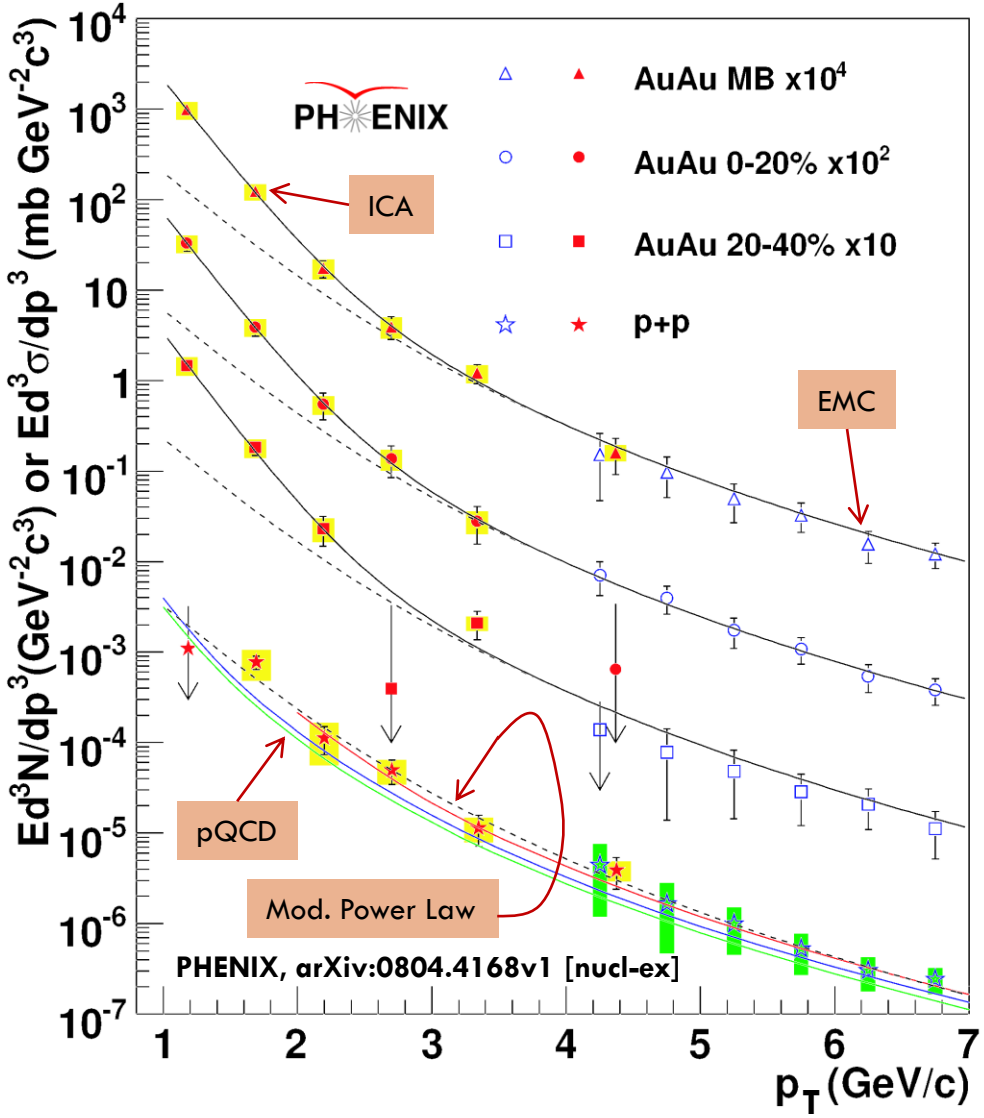
PHENIX, arXiv:0804.4168v1 [nucl-ex]

- Direct photon fraction compared to NLO pQCD (lines, three scales)
- p+p
  - consistent with pQCD
- Au+Au:
  - enhanced above pQCD
- Systematic uncertainties
  - **shape** difference measured
  - η/π^0 ratio largest source of uncertainty: 7% (17%) pp (AuAu)
  - Other sources contribute only few % as cocktail normalized to data (no absolute measurement)

Direct Photon Yield p+p

- Convert *r* into direct γ yield
  - $dN_{\gamma_{direct}}(p_T) = r \times dN_{\gamma_{inclusive}}(p_T)$
  - $dN_{\gamma}^{incl} = N_{ee}^{data} \times (dN_{\gamma}^{c} / N_{ee}^{c})$
  - Ratio of γ/e^+e^- for m<30 MeV same for any source
  - Syst. uncertainty of γ_{incl} 14%
    - From e^+e^- pair acceptance

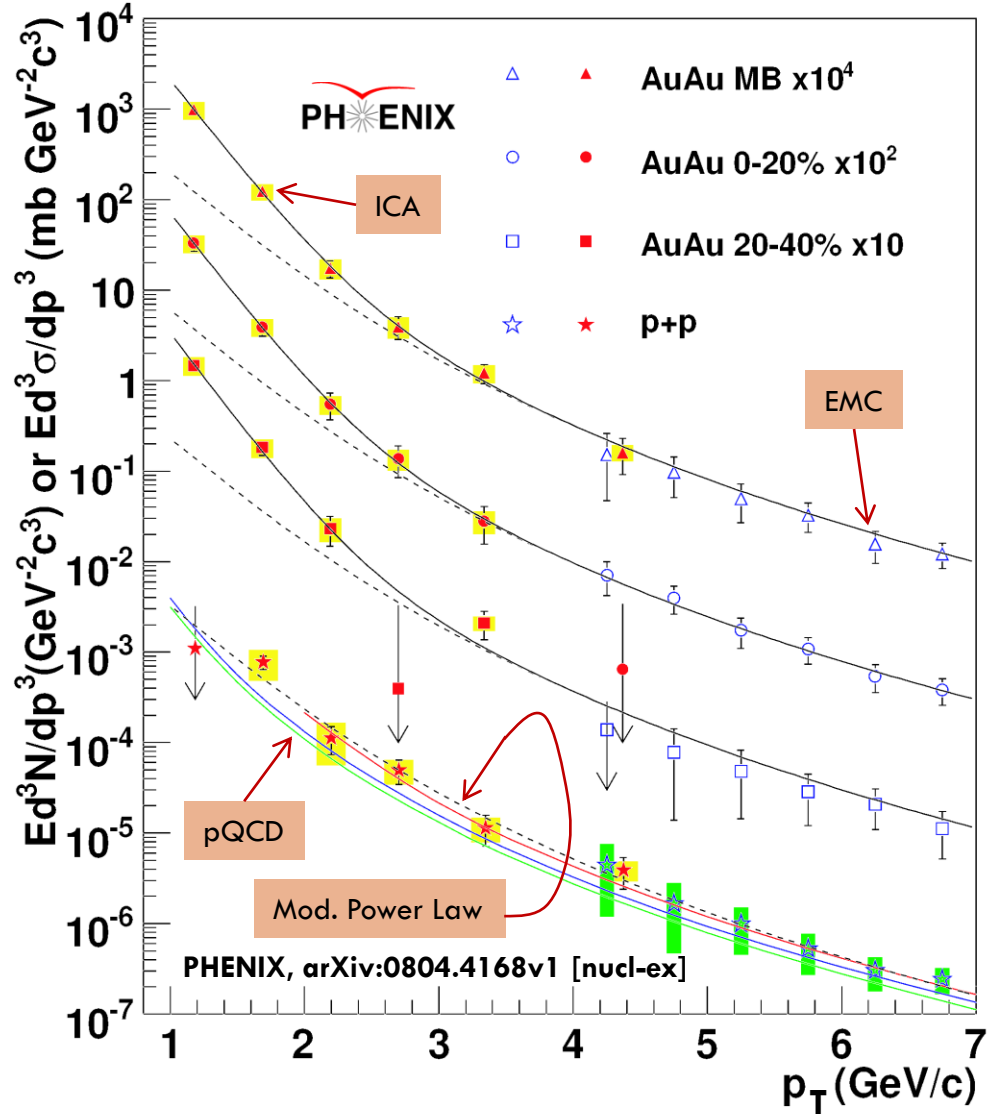
Direct Photon Yield p+p



- Convert *r* into direct γ yield
  - $dN_{\gamma_{direct}}(p_T) = r \times dN_{\gamma_{inclusive}}(p_T)$
  - $dN_{\gamma}^{incl} = N_{ee}^{data} \times (dN_{\gamma}^{c} / N_{ee}^{c})$
  - Ratio of γ/e^+e^- for m<30 MeV same for any source
  - Syst. uncertainty of γ_{incl} 14%
    - From e^+e^- pair acceptance

$$A(1+p_T^2/b)^{-n}$$

Direct Photon Yield p+p

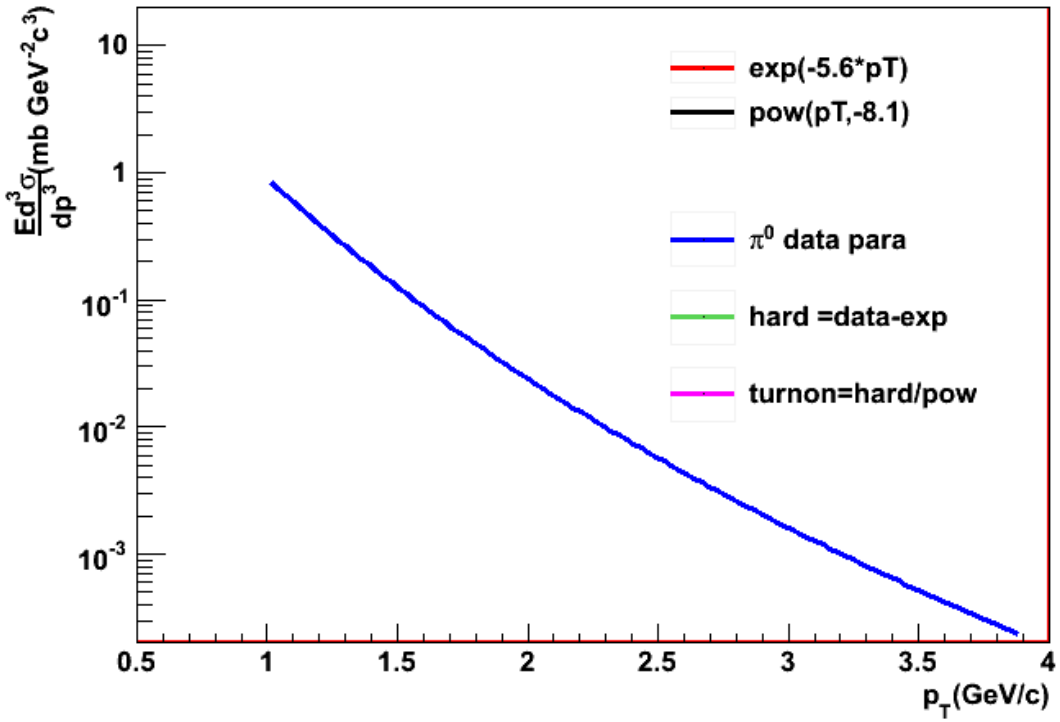


- Convert *r* into direct γ yield
  - $dN_{\gamma_{direct}}(p_T) = r \times dN_{\gamma_{inclusive}}(p_T)$
  - $dN_{\gamma}^{incl} = N_{ee}^{data} \times (dN_{\gamma}^{c} / N_{ee}^{c})$
  - Ratio of γ/e^+e^- for m<30 MeV same for any source
  - Syst. uncertainty of γ_{incl} 14%
    - From e^+e^- pair acceptance
- p+p
  - pQCD consistent with data for p_T>2 GeV
  - Well described with modified power law: $A(1+p_T^2/b)^{-n}$

Excursion

Significance of modified power law

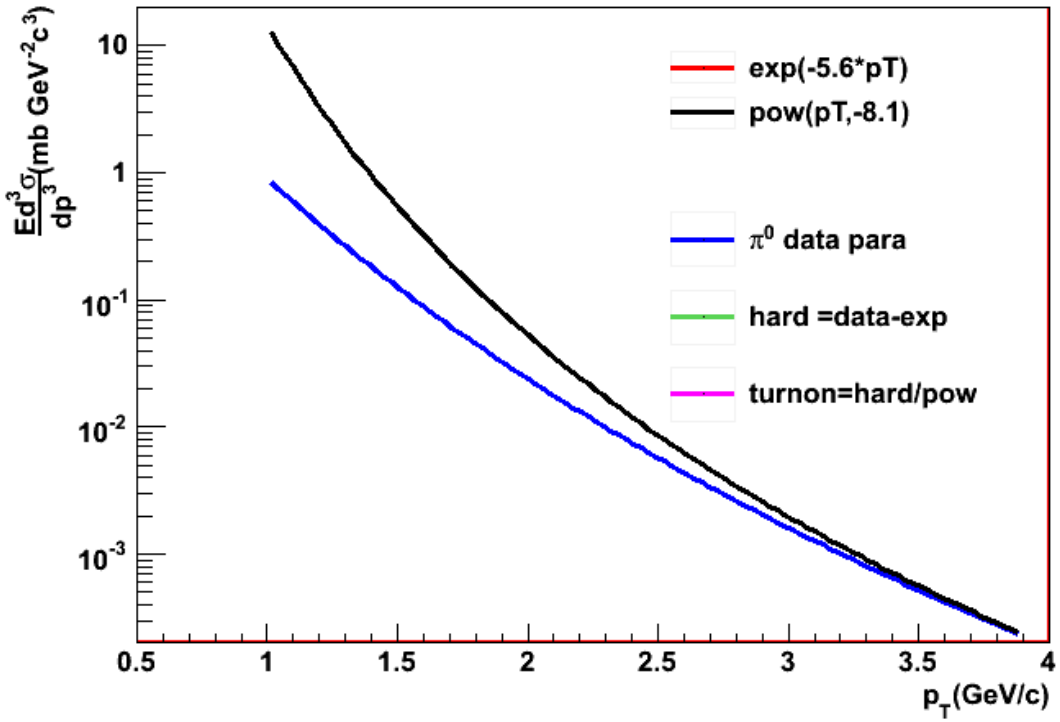
Onset of Hard Scattering



π^0 : **PHENIX PRL 98, 172302 (2007)**

- Example : π^0 production
- Data parameterized by

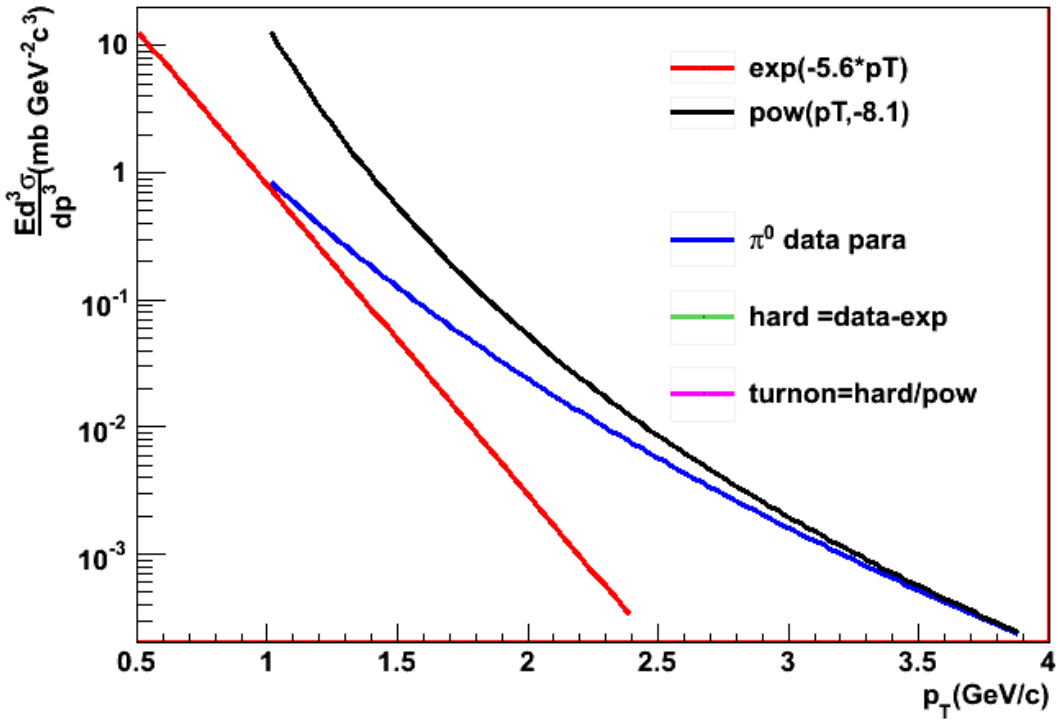
Onset of Hard Scattering



π^0 : **PHENIX PRL 98, 172302 (2007)**

- Example : π^0 production
- Data parameterized by
  - power law at high p_T

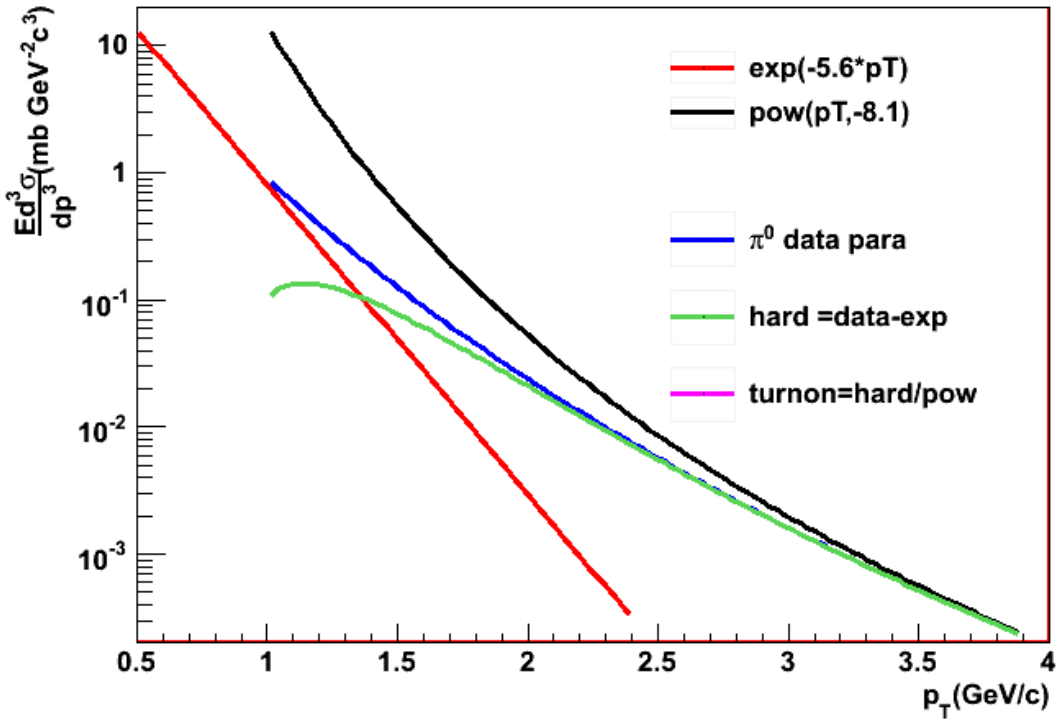
Onset of Hard Scattering



π^0 : **PHENIX PRL 98, 172302 (2007)**

- Example : π^0 production
- Data parameterized by
  - power law at high p_T
  - exponential at low p_T
  - Woods-Saxon transition
- exponential dies out at high p_T
- Power law diverges at low p_T

Onset of Hard Scattering

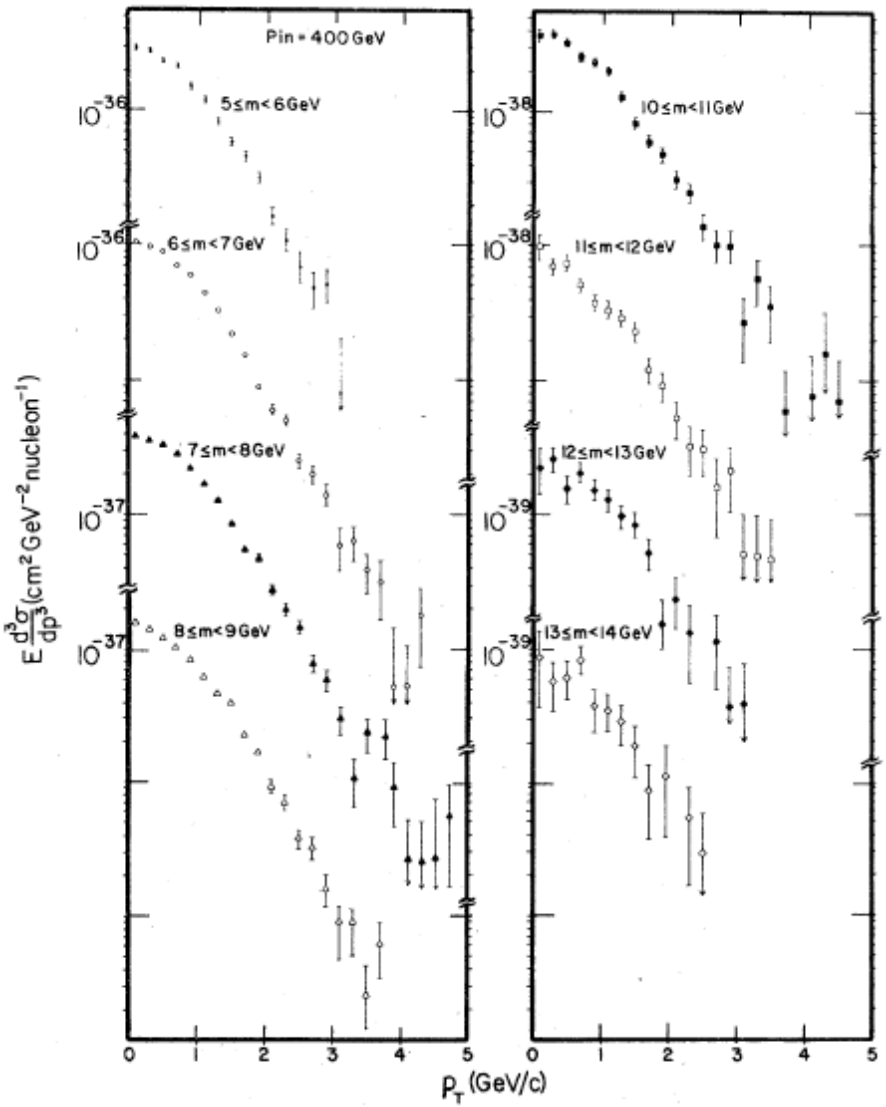


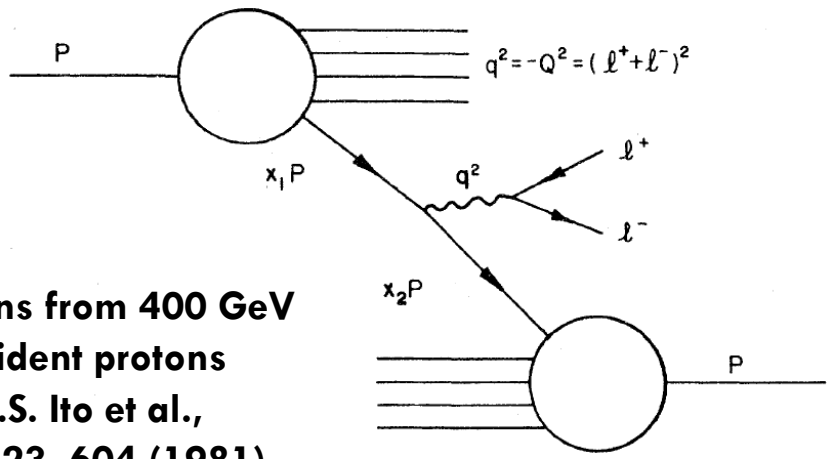
π^0 : PHENIX PRL 98, 172302 (2007)

- Example : π^0 production
- Data parameterized by
  - power law at high p_T
  - exponential at low p_T
  - Woods-Saxon transition
- exponential dies out at high p_T
- Power law diverges at low p_T

Power law must break down

Hard Scattering in Drell-Yan



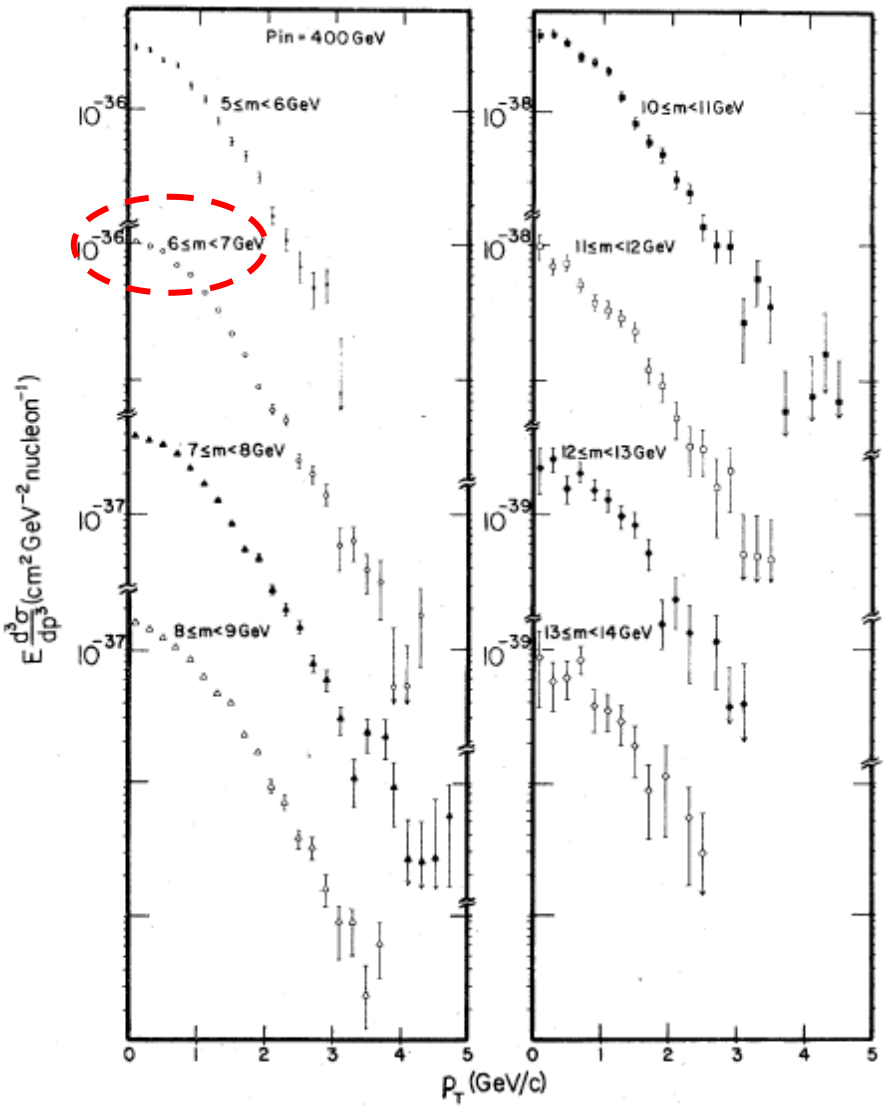


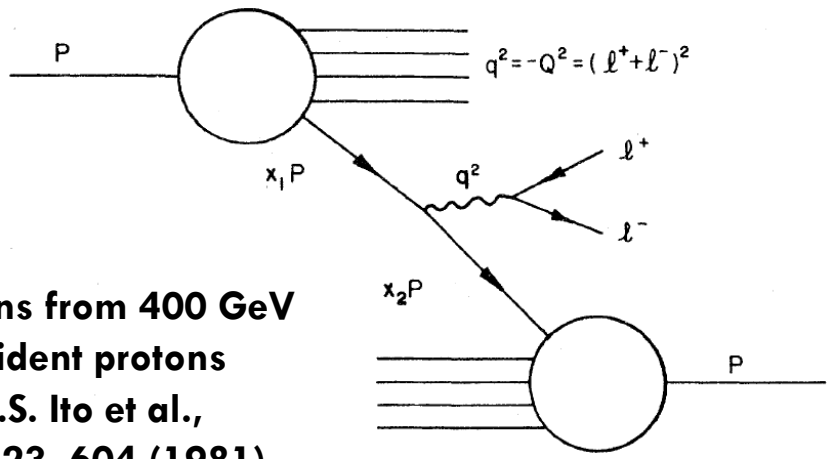
Dimuons from 400 GeV incident protons
A.S. Ito et al., PRD123, 604 (1981)

- Drell-Yan cleaner than direct g
  - No strongly interacting particle in vertex
- Well described by modified power law

$$E\frac{d^3\sigma}{dp^3} \propto \frac{1}{[1+(p_T/p_0)^2]^6}$$

Hard Scattering in Drell-Yan



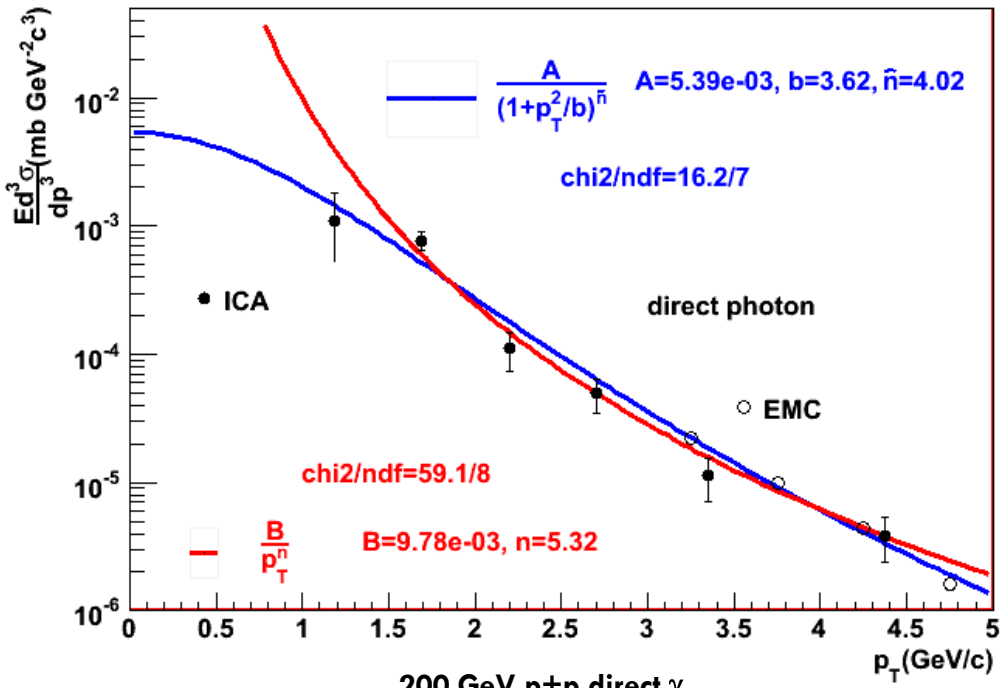


Dimuons from 400 GeV incident protons
A.S. Ito et al., PRD123, 604 (1981)

- Drell-Yan cleaner than direct g
  - No strongly interacting particle in vertex
- Well described by modified power law

$$E\frac{d^3\sigma}{dp^3} \propto \frac{1}{[1+(p_T/p_0)^2]^6}$$

Modified vs. Unmodified Power Law



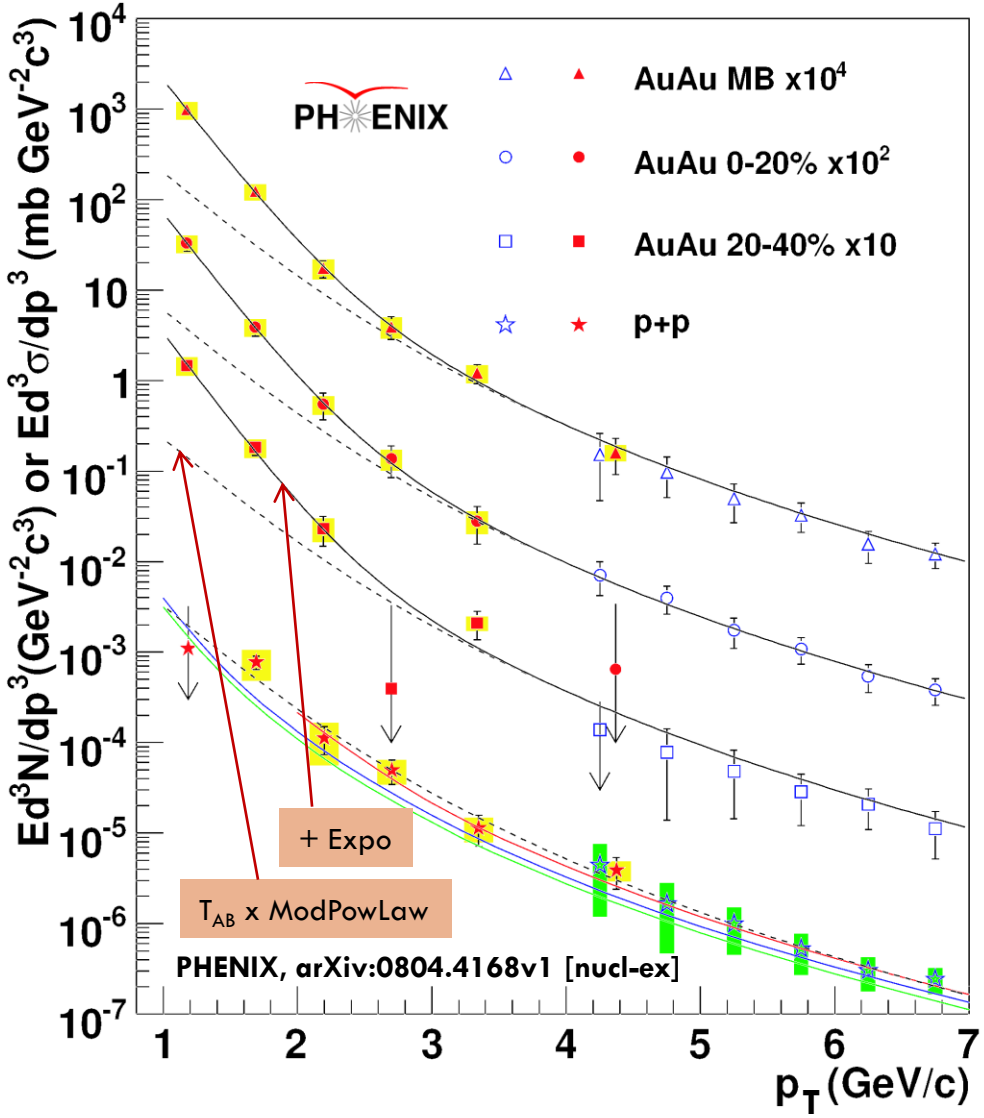
200 GeV p+p direct γ
Statistical uncertainties only
Data points: PHENIX, arXiv:0804.4168v1 [nucl-ex]

- Fit p+p direct γ from $1<p_T<5$ GeV
  - both ICA and EMC
- Modified power law better fit

End of Excursion

Back to data

Direct Photon Yield Au+Au



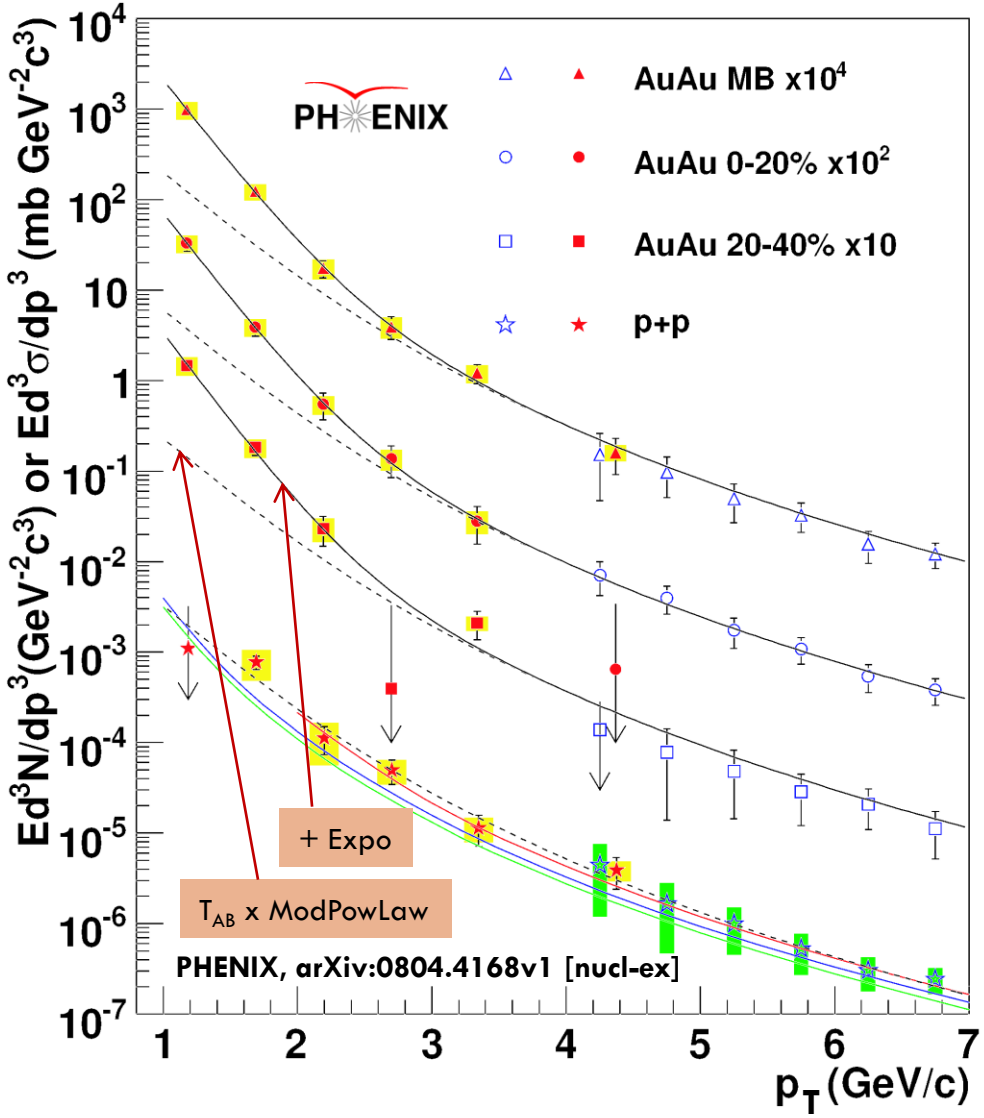
- Au+Au enhanced above

  $T_{AB}A(1+p_T^2/b)^{-n}$ (= p+p)

  for 1<pT<3 GeV

- Fit with $T_{AB}A(1+p_T^2/b)^{-n}+Be^{-\frac{p_T}{T}}$

Direct Photon Yield Au+Au



- Au+Au enhanced above

  $T_{AB}A(1+p_T^2/b)^{-n}$ (= p+p)

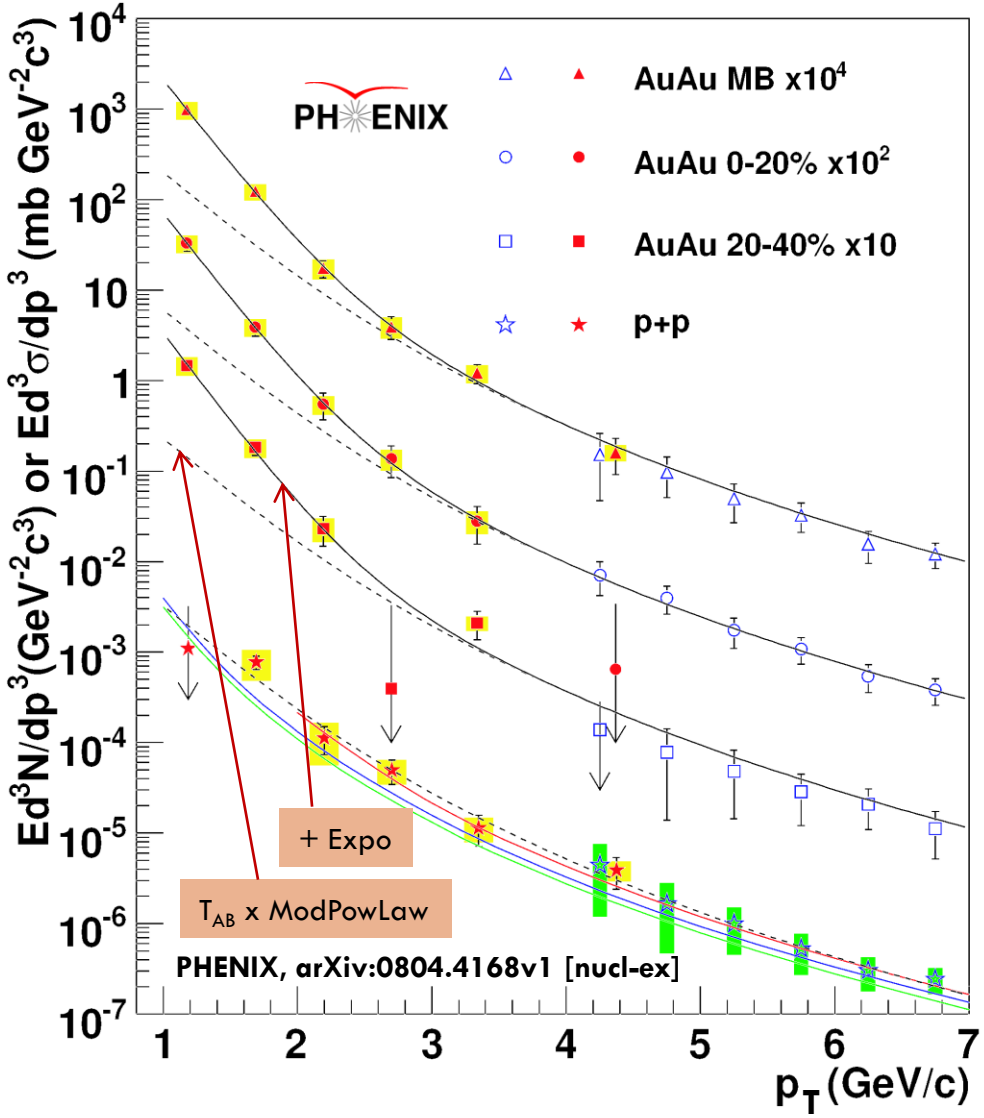
  for 1<pT<3 GeV

- Fit with $T_{AB}A(1+p_T^2/b)^{-n}+Be^{-\frac{p_T}{T}}$

Enhancement consistent with exponential

centrality	$dN/dy(p_T > 1\text{GeV}/c)$	$T(\text{MeV})$	χ^2/DOF
0-20%	$1.10 \pm 0.20 \pm 0.30$	$221 \pm 23 \pm 18$	3.6/4
20-40%	$0.52 \pm 0.08 \pm 0.14$	$215 \pm 20 \pm 15$	5.2/3
MB	$0.33 \pm 0.04 \pm 0.09$	$224 \pm 16 \pm 19$	0.9/4

Direct Photon Yield Au+Au



- Au+Au enhanced above

  $T_{AB}A(1+p_T^2/b)^{-n}$ (= p+p)

  for 1<pT<3 GeV

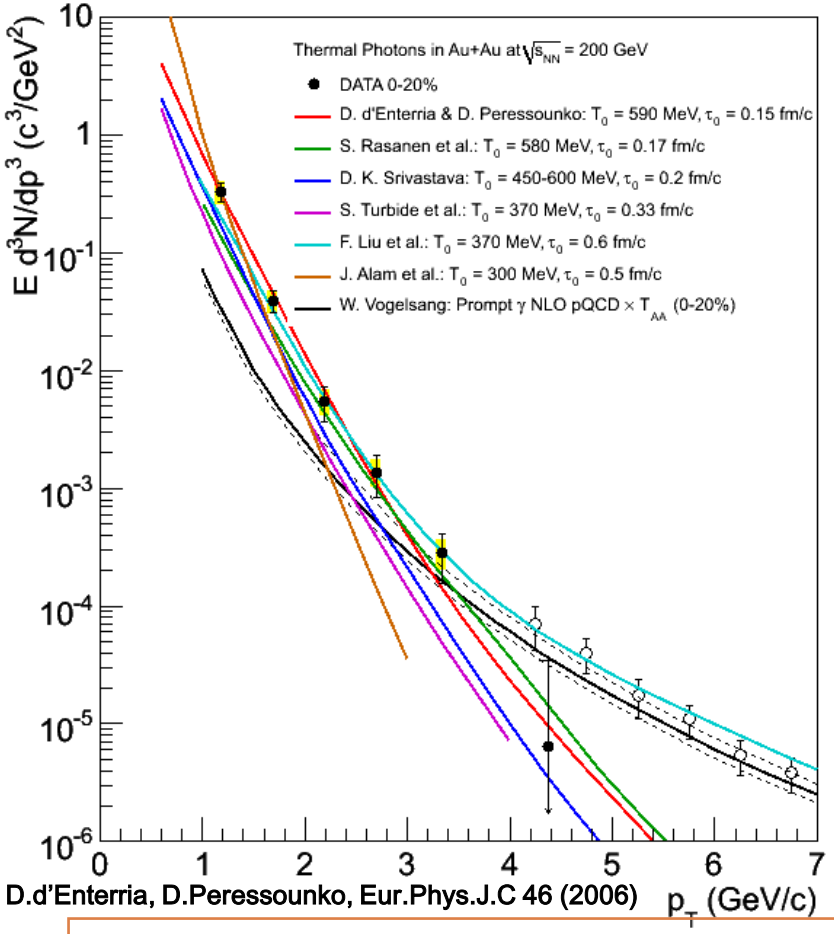
- Fit with $T_{AB}A(1+p_T^2/b)^{-n}+Be^{-\frac{p_T}{T}}$

Enhancement consistent with exponential

centrality	$dN/dy(p_T > 1\mathrm{GeV}/c)$	$T(\mathrm{MeV})$	χ^2/DOF
0-20%	$1.10 \pm 0.20 \pm 0.30$	$221 \pm 23 \pm 18$	3.6/4
20-40%	$0.52 \pm 0.08 \pm 0.14$	$215 \pm 20 \pm 15$	5.2/3
MB	$0.33 \pm 0.04 \pm 0.09$	$224 \pm 16 \pm 19$	0.9/4

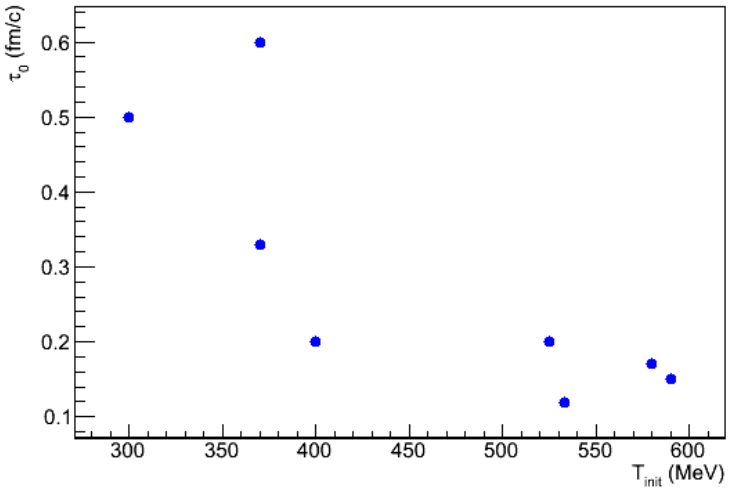
If p+p fit with pure power law T→T+24 MeV (central)

Model comparison



D.d'Enterria, D.Peressounko, Eur.Phys.J.C 46 (2006)

- Au+Au = pQCD + exp.
  - →T = 221 ± 23 (stat) ± 18 (sys)
- Initial temperatures and times from theoretical model fits to data:
  - 0.15 fm/c, 590 MeV (d'Enterria et al.)
  - 0.17 fm/c, 580 MeV (Rasanen et al.)
  - 0.2 fm/c, 450-660 MeV (Srivastava et al.)
  - 0.33 fm/c, 370 MeV (Turbide et al.)
  - 0.6 fm/c, 370 MeV (Liu et al.)
  - 0.5 fm/c, 300 MeV (Alam et al.)



From data: $T_{ini} > 220$ MeV $> T_C$

From models: $T_{ini} = 300$ to 600 MeV

$\tau_0 = 0.15$ to 0.6 fm/c

Summary

- Measured e^+e^- pairs
  - m<300 MeV
  - 1<pT<5 GeV
  - p+p and Au+Au
- p+p
  - small excess over hadronic background
- Au+Au
  - much larger excess
- Treated excess as internal conversion of direct photons
- Extracted direct photon yield

Summary

- Measured e^+e^- pairs
  - m<300 MeV
  - 1<pT<5 GeV
  - p+p and Au+Au
- p+p
  - small excess over hadronic background
- Au+Au
  - much larger excess
- Treated excess as internal conversion of direct photons
- Extracted direct photon yield
- p+p
  - Lowest p_T ever measured for direct photon in p+p
  - Consistent with NLO pQCD
  - But indicates turn-over
- Au+Au
  - Spectrum shape above T_{AA} scaled p+p exponential
  - T=221+-23+-18MeV
  - Consistent with hydro models
    - T_{init}=300-600 MeV
    - τ_0=0.6-0.15fm/c
- Analysis ongoing for d+Au