Direct Photon Production Measured with the PHENIX Experiment at RHIC

DPG Spring Meeting

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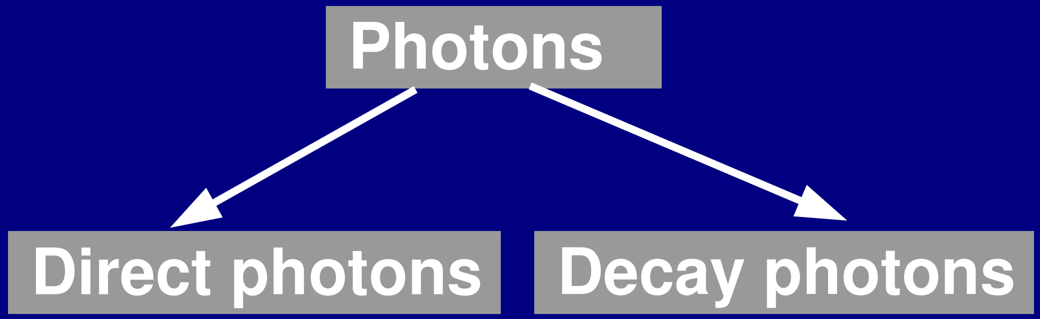
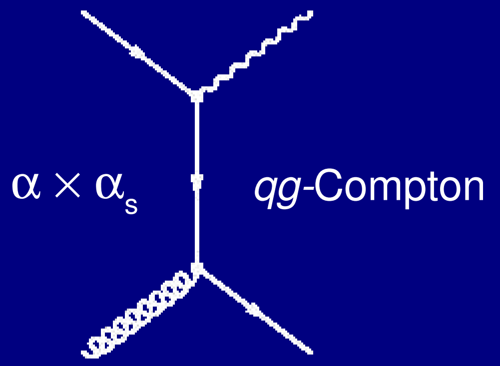
Why Direct Photons?

- **Direct photons**
  - Definition: All photons not originating from decays
- **Large background**
  - $\pi^0 \rightarrow \gamma\gamma$
  - $\eta \rightarrow \gamma\gamma$...



- **Production in p+p**
  - Hard parton collisions e.g.:



  - Photon+Jet
  - Precision test of pQCD

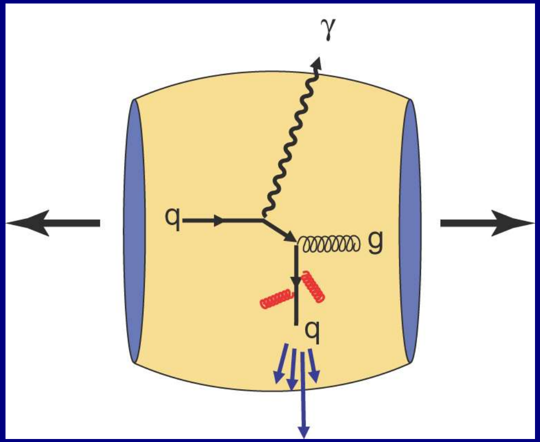
$$\frac{d^2\sigma_\gamma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \delta$$

  - Constrains gluon distribution und polarization

Direct Photons in A+A I

- **Also produced in hard parton-parton collisions**

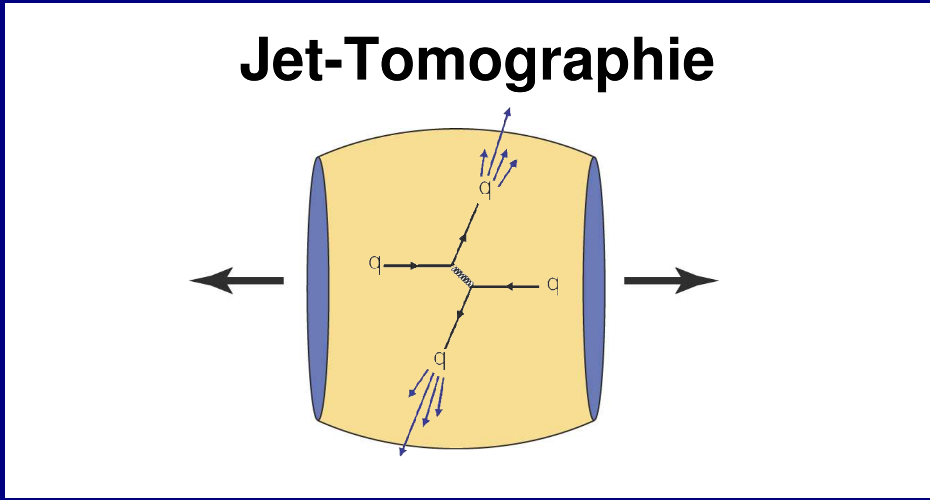
  - $$\frac{d^2\sigma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \delta$$
  - p+p: Scattering into the QCD vacuum
  - A+A: Early reaction phase
- **Not influenced by the strong interaction**
  - **In situ** control for hard scattering



Hadrons in A+A

- **Also in hard parton-parton collisions**
  - Large Q^2 ($\Rightarrow$ "Jets")
  - Dominant at high p_T
  - Factorization:

$$\frac{d^2\sigma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(q \to \pi^0)$$

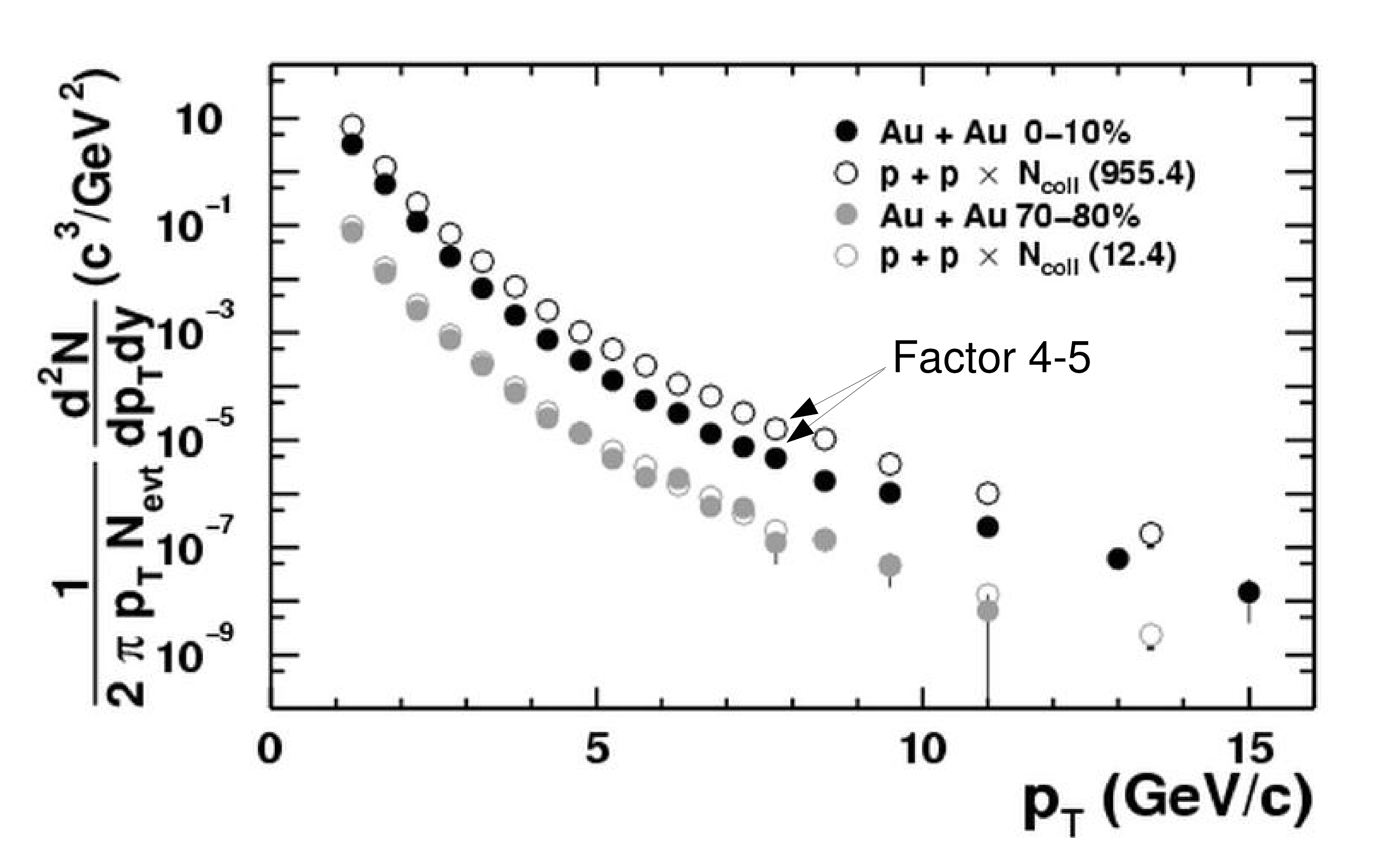


- **p+p**
  - Fragmentation into QCD vacuum
- **Au+Au**
  - Early reaction phase
  - *qg*: Probe for later stages

- **Nuclear modification factor**
  - $R_{AB} \approx 1$ (for $p_T > 2$ GeV/c)?

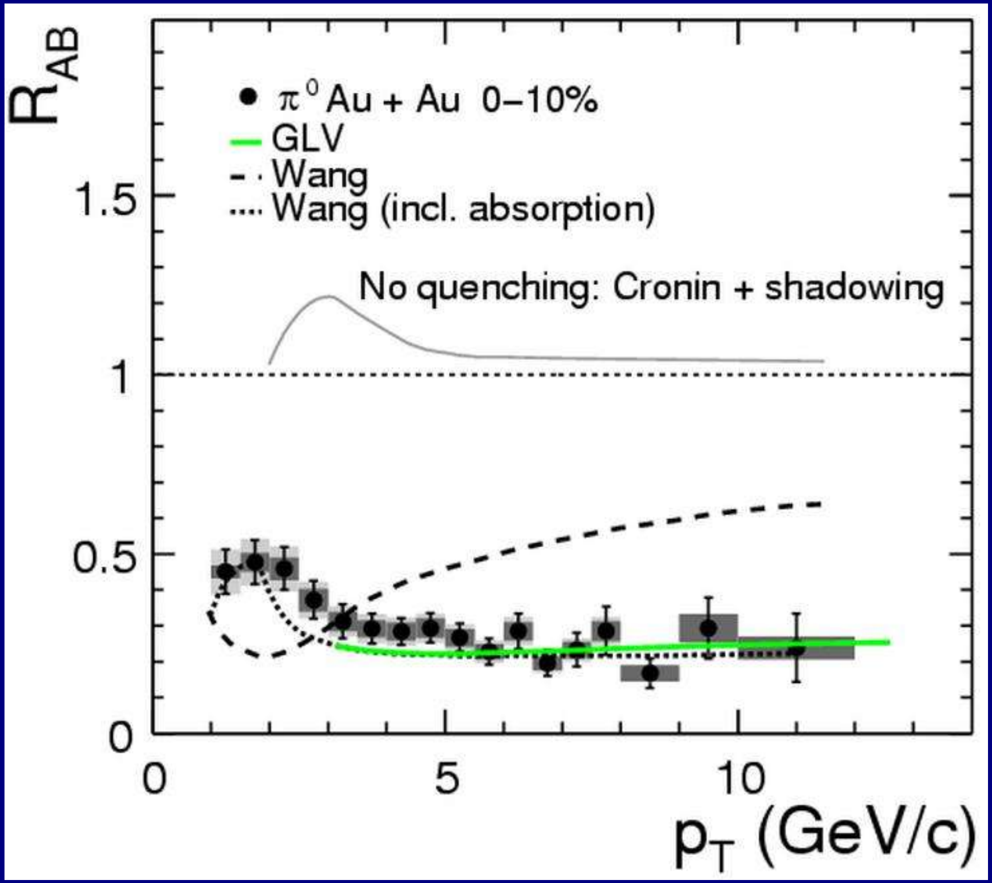
$$R_{AB} = \frac{d^2N_{AA}/dydp_T}{N_{coll}\,d^2N_{pp}/dydp_T}$$

π^0 in Au+Au



Au+Au reaction incoherent superposition of N_{coll} p+p collisions

Jet Quenching?

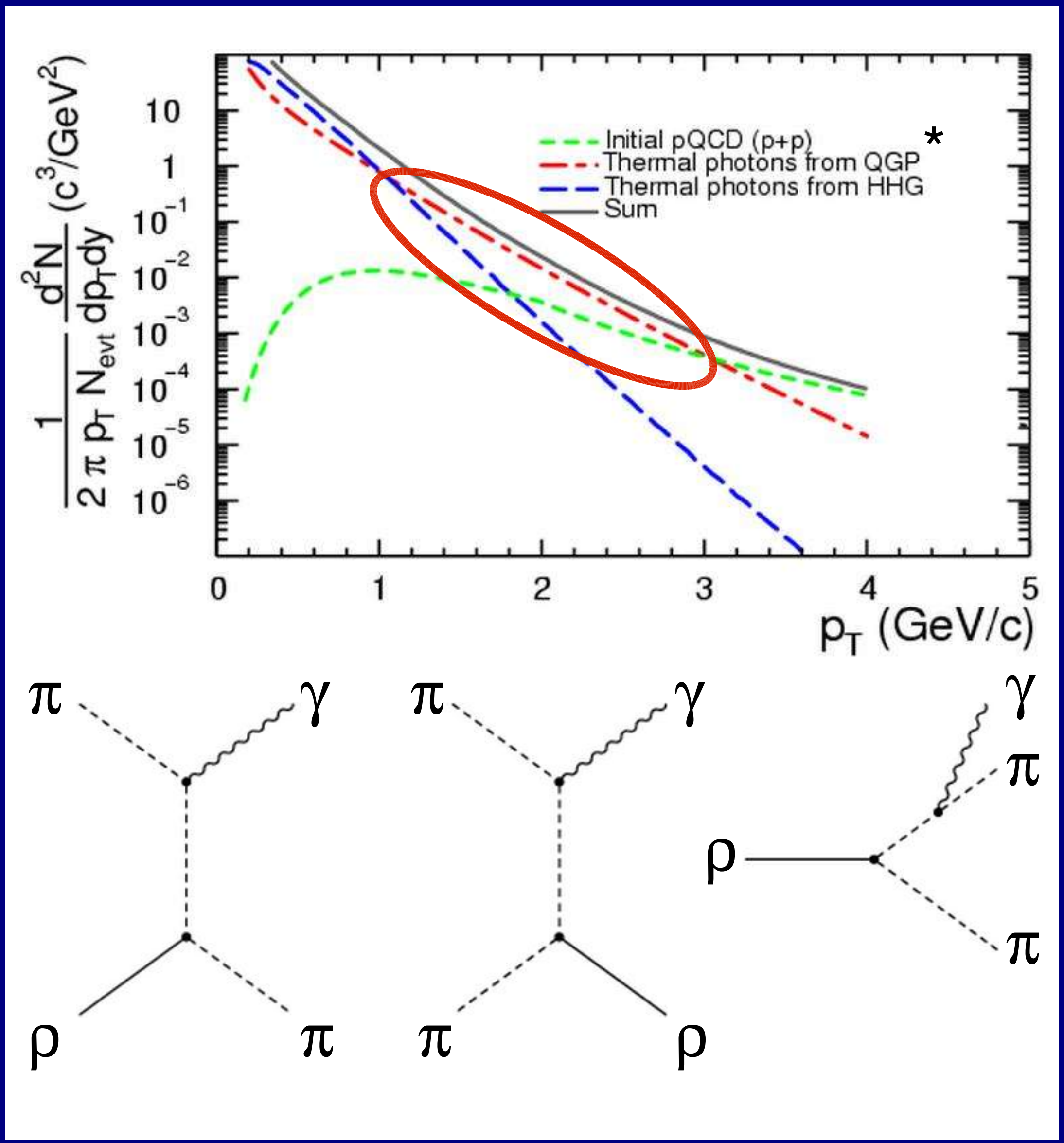


- **Parton energy loss**
  - Gluon bremsstrahlung
  - $\frac{d^2\sigma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(E \rightarrow E')$
- **Theoretical description**
  - -dE/dx ≈ 7 GeV/fm (Wang)
  - dN_g/dy ≈ 1000 (GLV)
- **Alternative explainations**
  - Modified initial state
  - N_{coll} scaling not applicable

Direct Photons provide direct control

for strong final state effect ($\frac{d^2\sigma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \delta$)!!

Direct Photons in A+A II

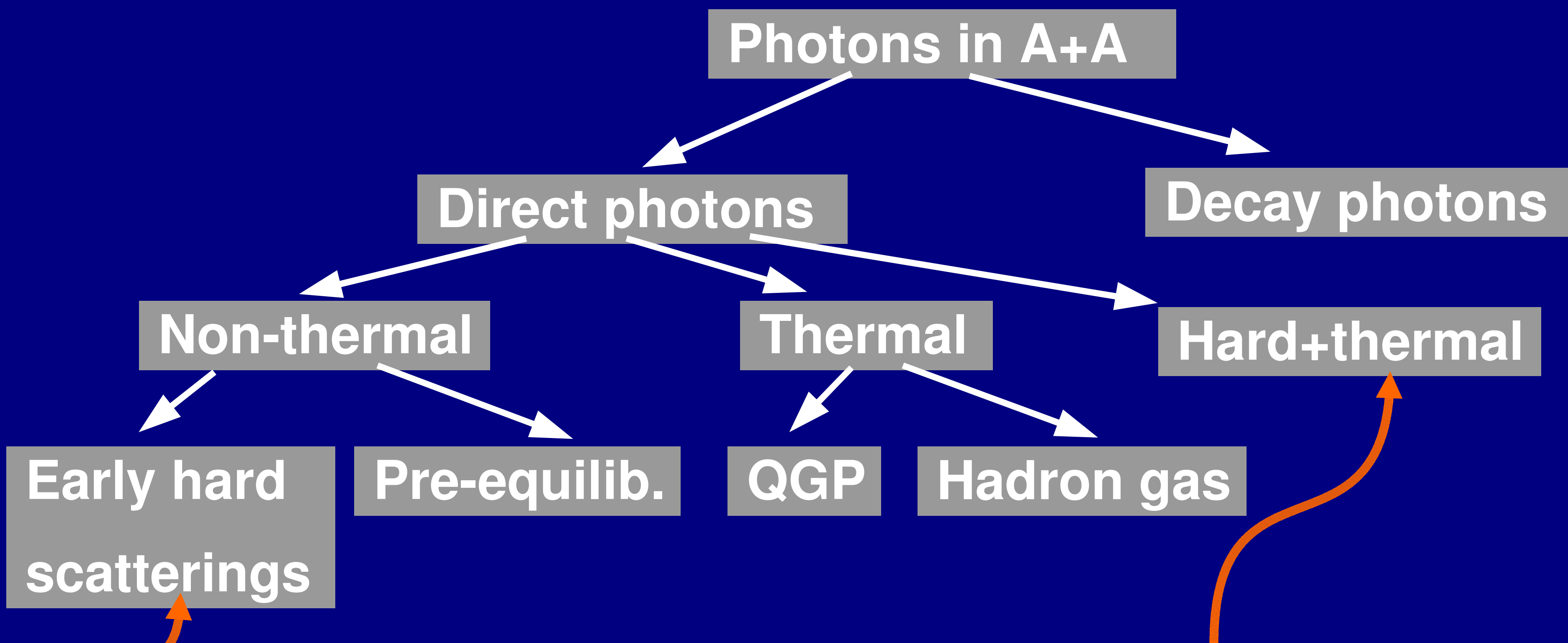


- **Thermal photons**
  - Thermal *qg* and hadron distributions
  - Static rates ⊗ T(τ)
  - Measure for temperature of the system
  - Additional signature for QGP

*Turbide, Rapp, Gale:

Phys. Rev. **C** 69:014903, 2004

Photon Sources in A+A

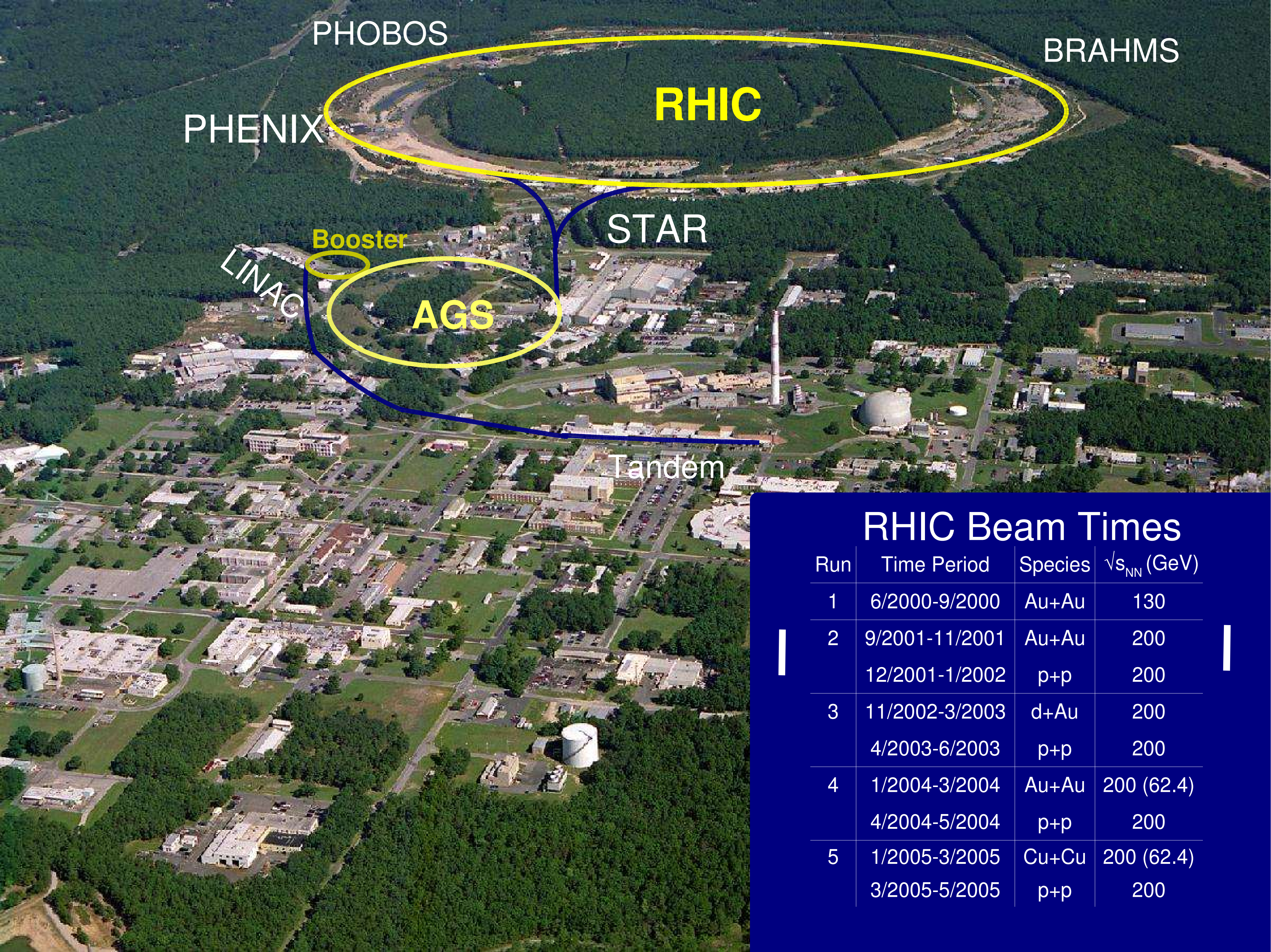


pQCD or
„prompt“ photons

Interaction of hard partons with the QGP

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

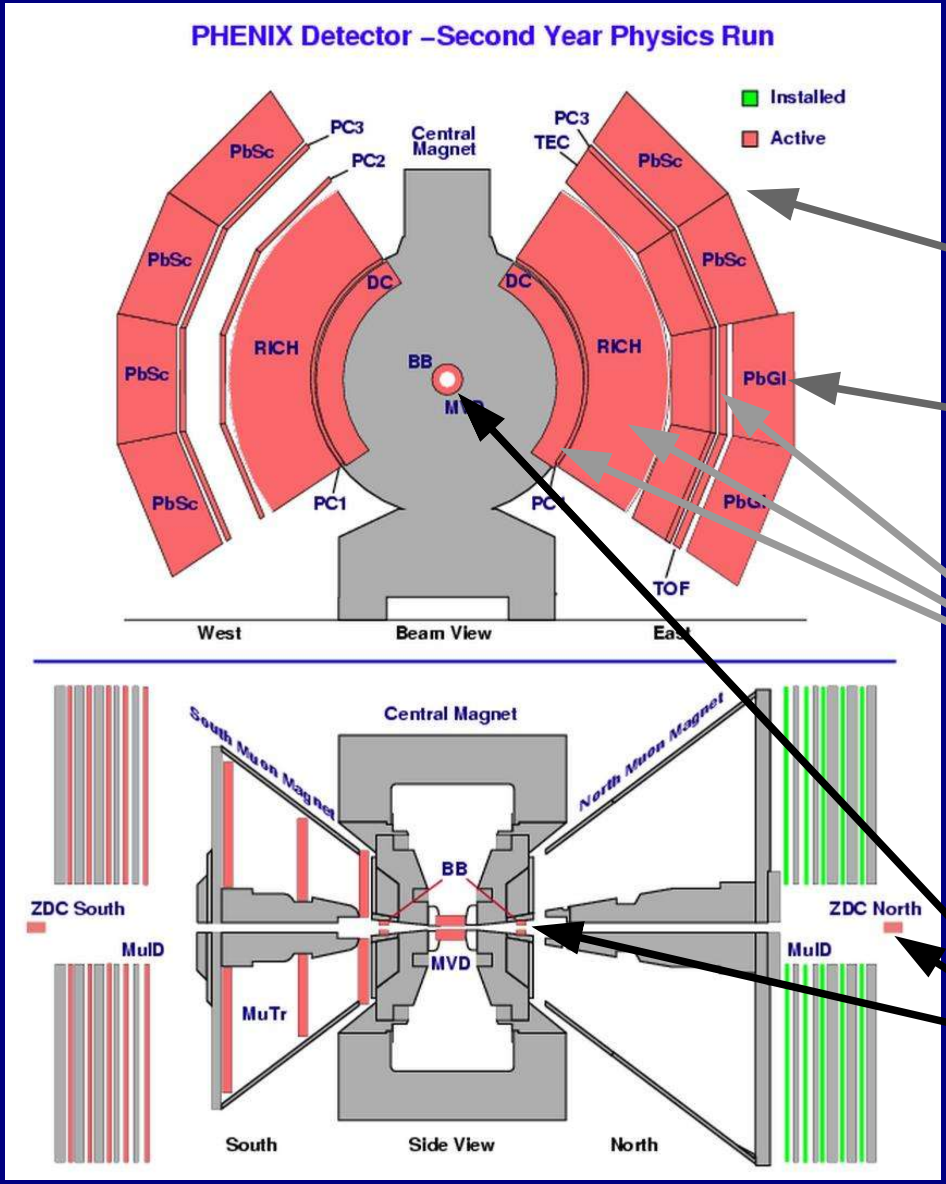
2) Medium induced photon bremsstrahlung



RHIC Beam Times

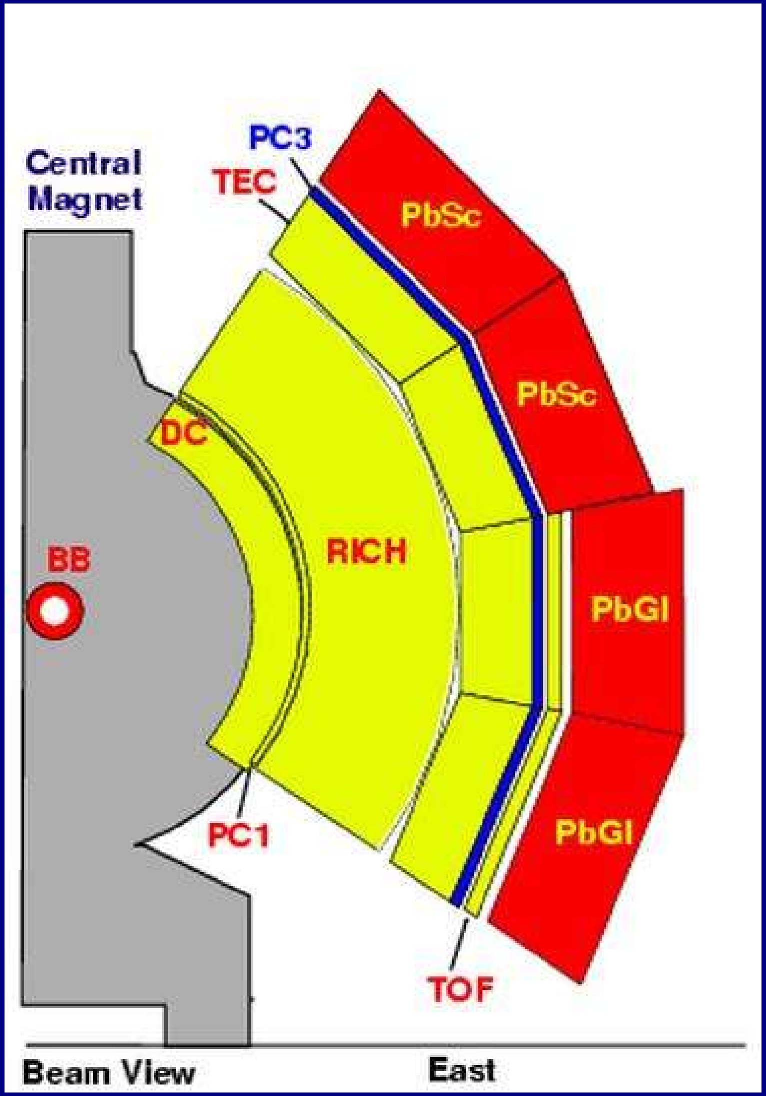
Run	Time Period	Species	$\sqrt{s_{NN}}$ (GeV)
1	6/2000-9/2000	Au+Au	130
2	9/2001-11/2001	Au+Au	200
	12/2001-1/2002	p+p	200
3	11/2002-3/2003	d+Au	200
	4/2003-6/2003	p+p	200
4	1/2004-3/2004	Au+Au	200 (62.4)
	4/2004-5/2004	p+p	200
5	1/2005-3/2005	Cu+Cu	200 (62.4)
	3/2005-5/2005	p+p	200

PHENIX @ RHIC



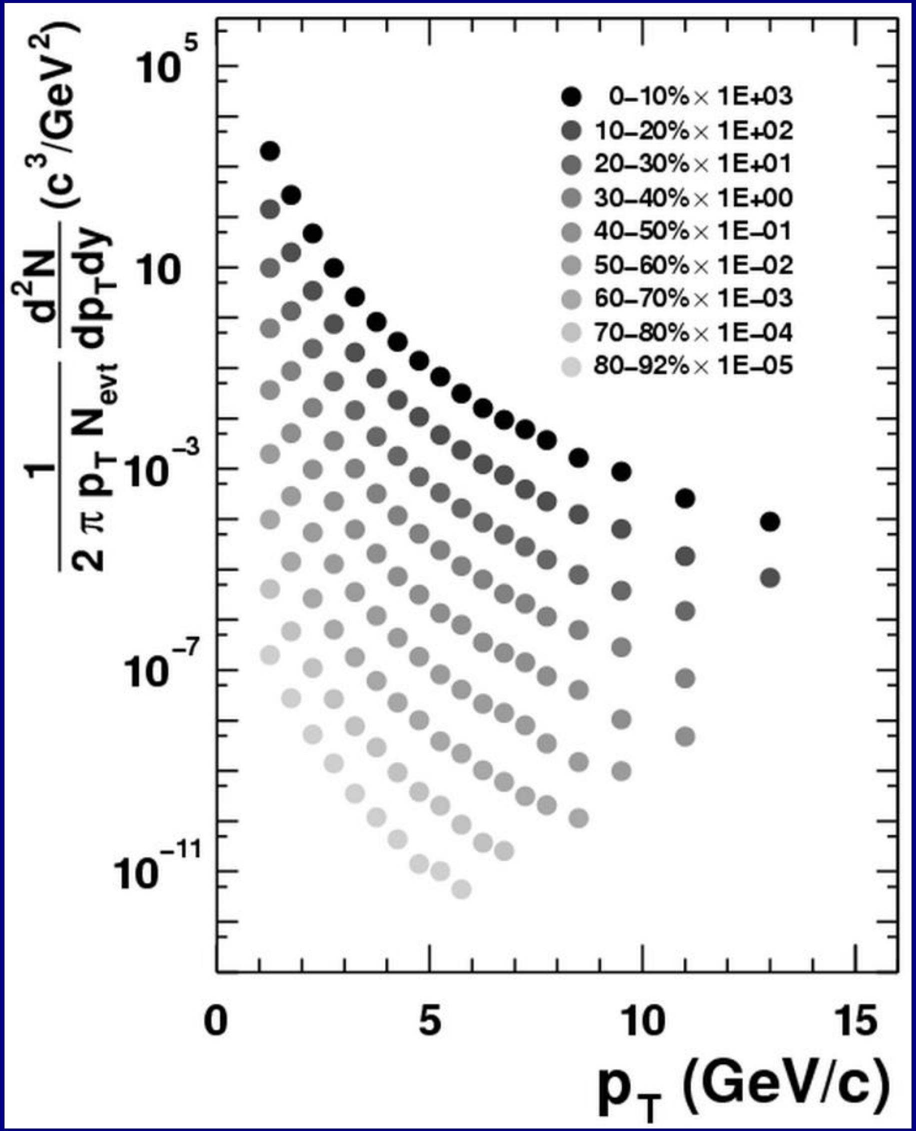
- **Calorimetry/EMCal**
  - Photons/electrons
  - 6 sectors lead-scintillator sandwich calorimeter
  - 2 sectors leadglas Cherenkov calorimeter
- **Tracking/PID**
  - PC, DC / RICH, TOF
  - Charged hadrons, dileptons
- **Muon PID and tracking**
- **Global detectors**
  - BBC, ZDC
  - Trigger, vertex and centrality

Measurement of Direct Photons



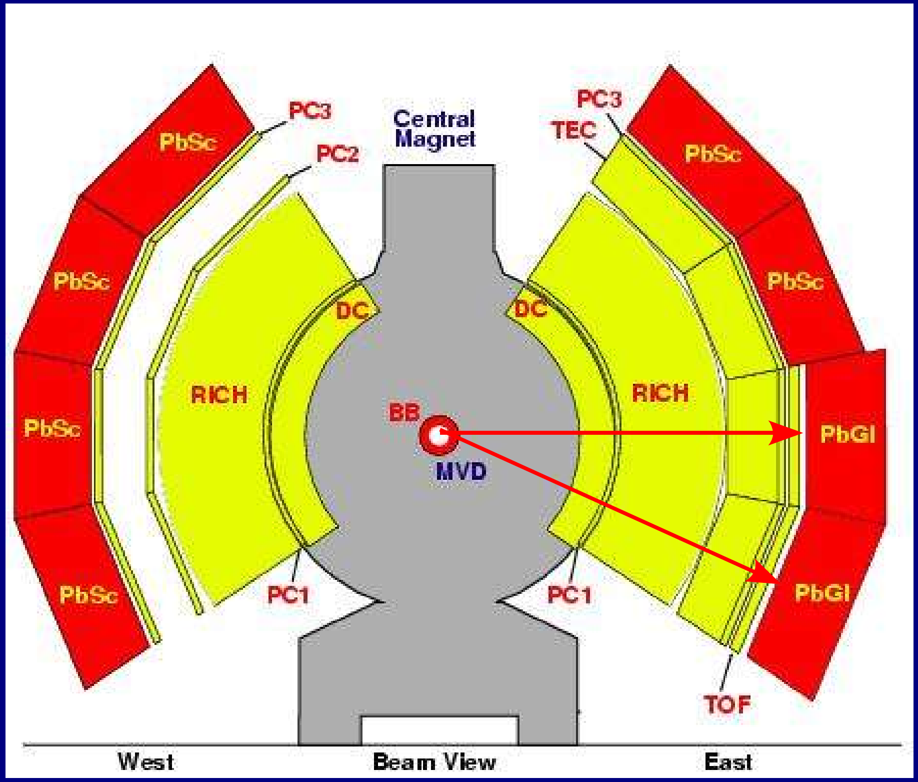
- **Photon candidates**
  - All EMCal clusters after PID-cuts
  - Contaminated with charged particles (CPV) and neutrons

Inclusive Photons



- **Corrections**
  - Charged particles (CPV)
  - Neutrons and anti-neutrons (simulation)
  - Acceptance and Efficiency
  - Conversion losses
- **Combined PbGl/PbSc result**
- **Including all decay photons**
  - $\pi^0 \to 2\gamma$ (main contribution)
  - $\eta \to 2\gamma$....

π^0 and η @ PHENIX



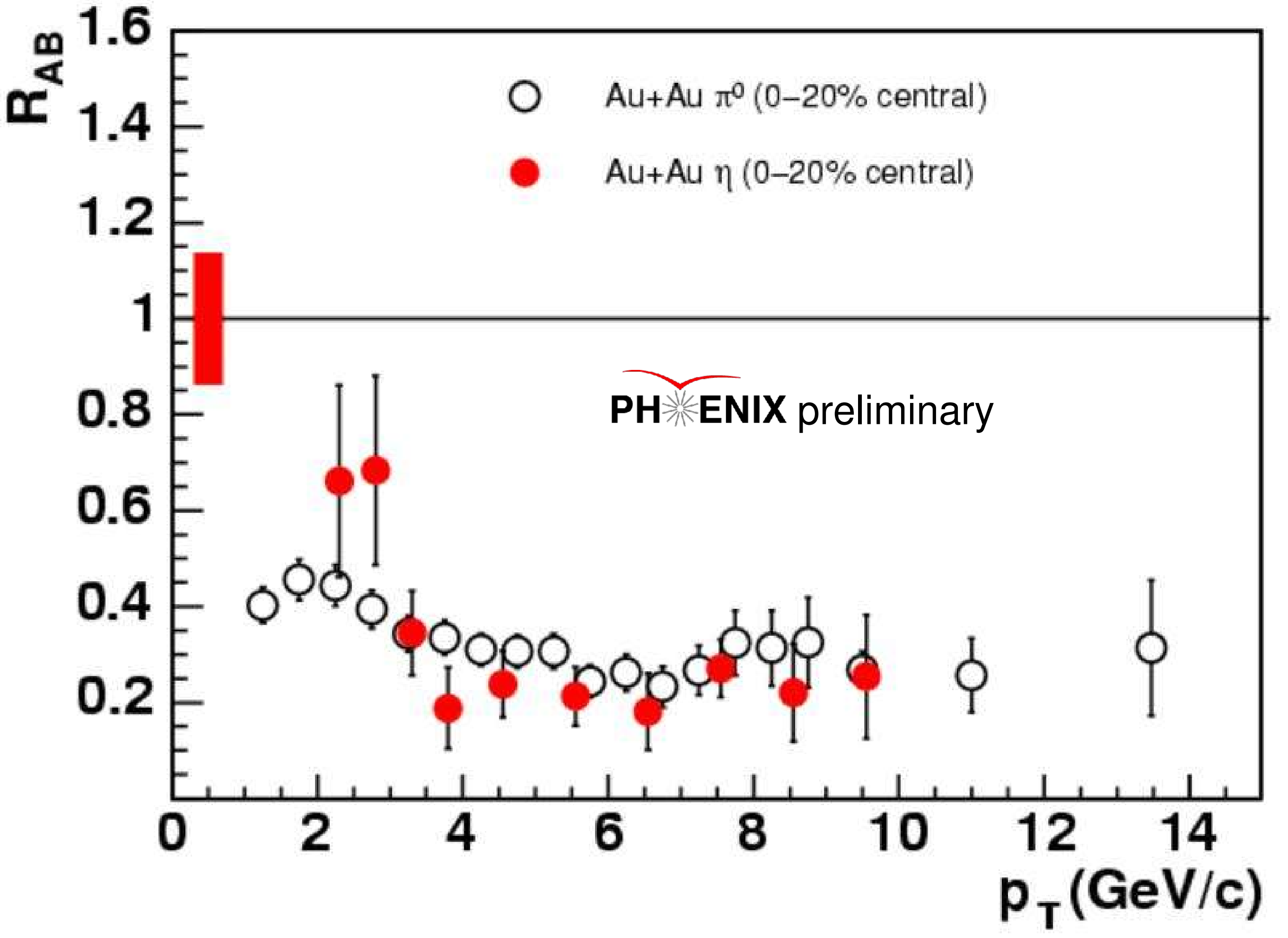
- Background in direct photon measurement
- "Hadronic" probe

- Reconstruction via $\pi^0(\eta)\rightarrow 2\gamma$
  - Invariant mass

$$m_{inv}=\sqrt{2E_1E_2(1-\cos\theta)}=135(548)\,\mathrm{MeV}$$

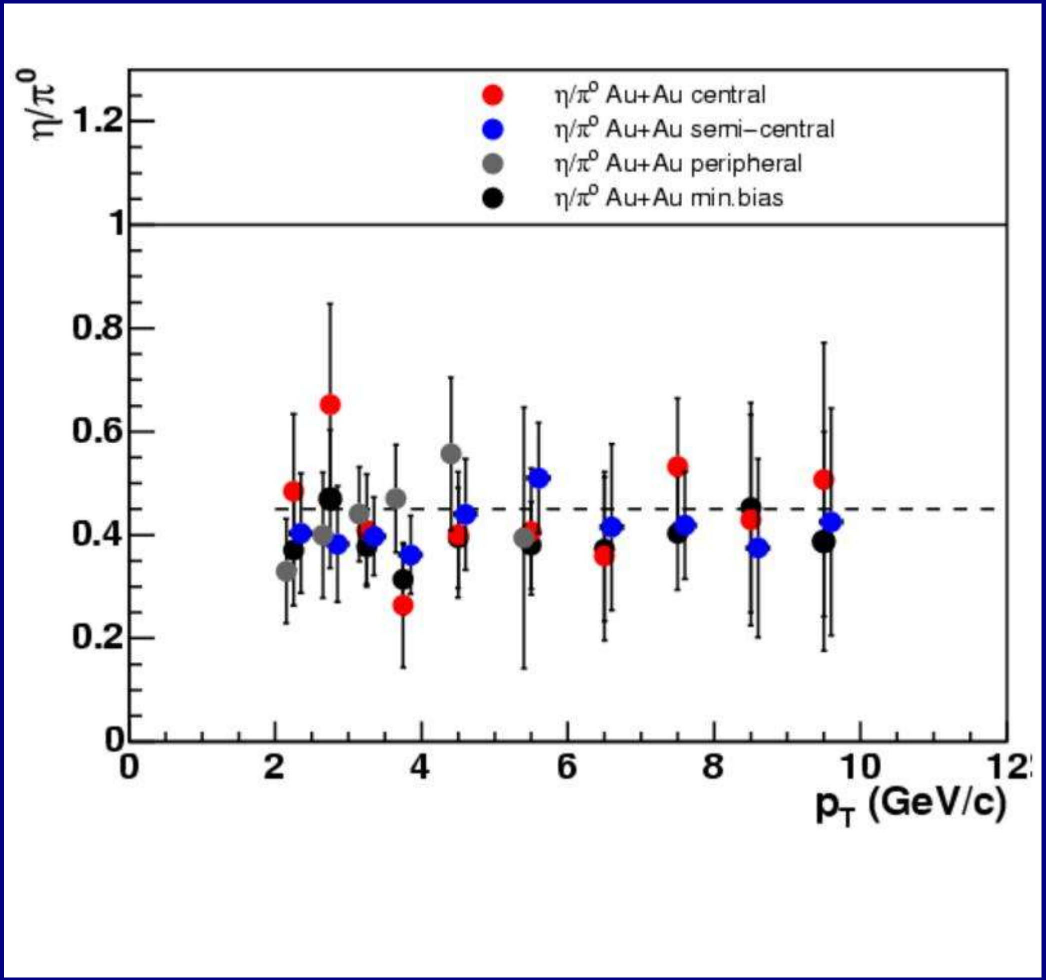
- Combinatorial background
  - $N_{\gamma\gamma} = N_\gamma\,(N_\gamma - 1)/2$ pair comb.

R_{AB} for π^0 and η



Same behavior dispite different masses

m_T-Scaling

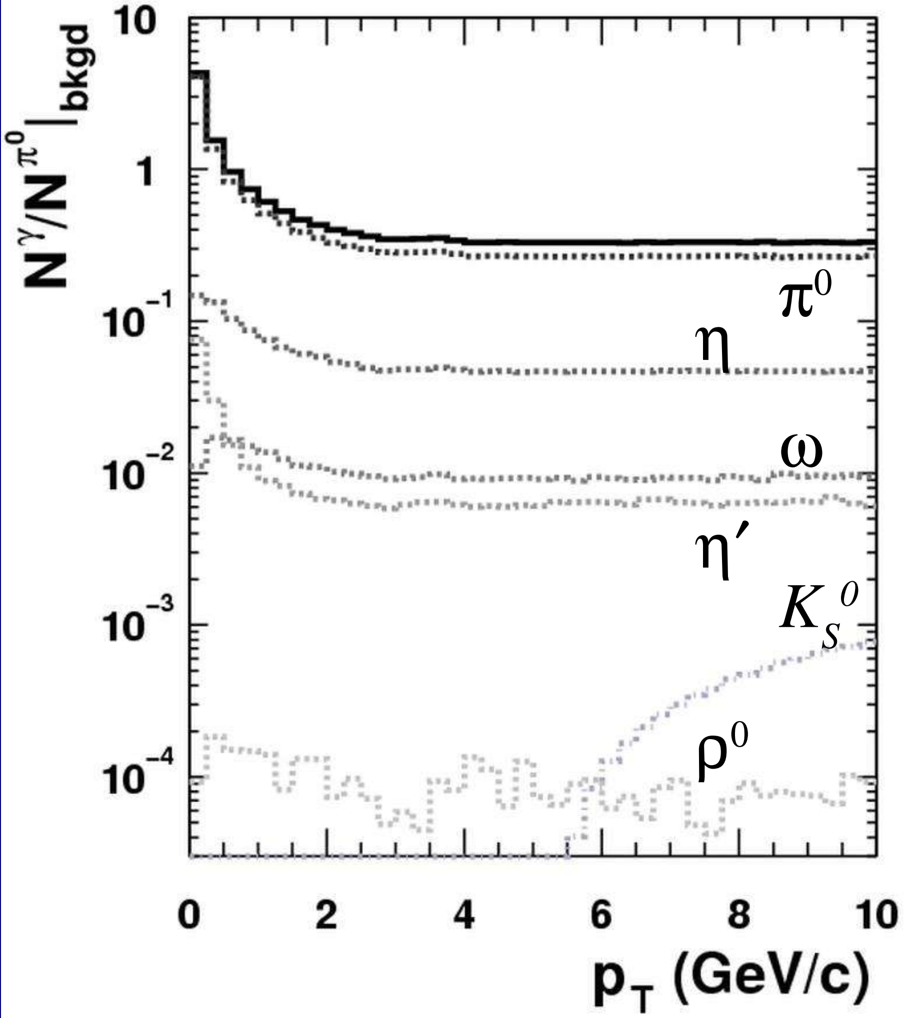


- **Empirical observation:**
  - Similar hadron spectra as a function of $m_T = \sqrt{p_T^2 + m_0^2}$

$$E\frac{d^3\sigma_h}{dp^3} = C_h f(m_T)$$

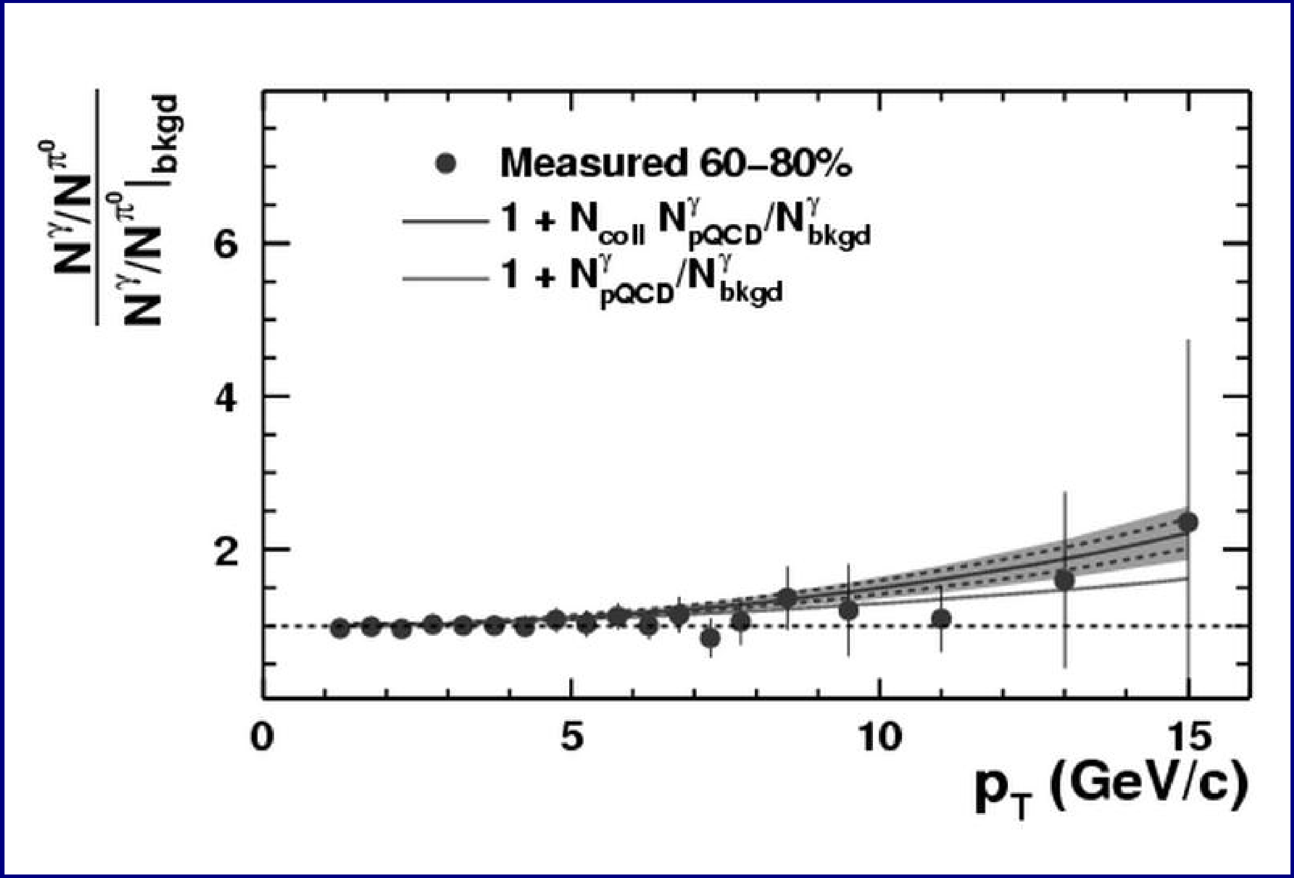
- **Confirmed with η and π⁰**
  - In p+p, d+Au and Au+Au
  - $C_h = 0.45 \pm 0.05$

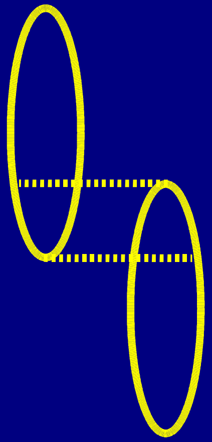
Decay Background



- **$\pi^0 \rightarrow 2\gamma$ main contribution**
  - Including $\eta \rightarrow 3\pi^0$ etc.
- **Simulation of decays**
  - $\pi^0 \rightarrow \gamma\gamma, e^+e^-\gamma$
  - $\eta \rightarrow \gamma\gamma, \pi^+\pi^-\gamma$
  - $\omega \rightarrow \pi^0\gamma$ ...
  - $\eta' \rightarrow \rho^0\gamma$ ...
  - $K_S^0 \rightarrow (\pi^0\pi^0)$

$\gamma_{meas}/\gamma_{bkgd}$ in Au+Au Collisions





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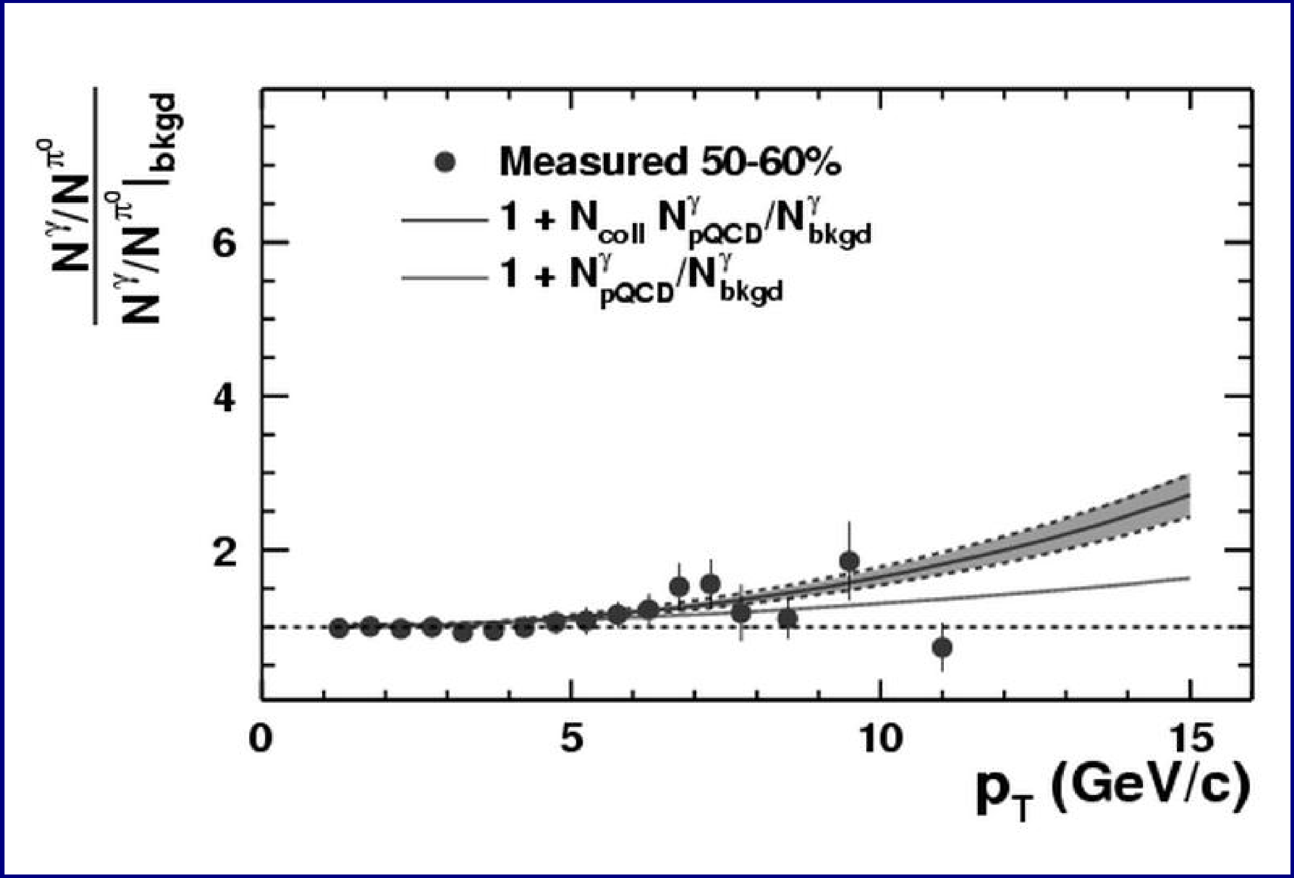

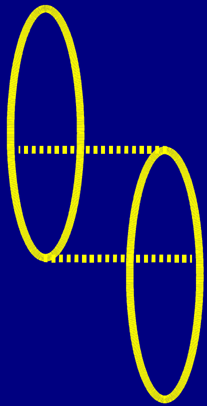

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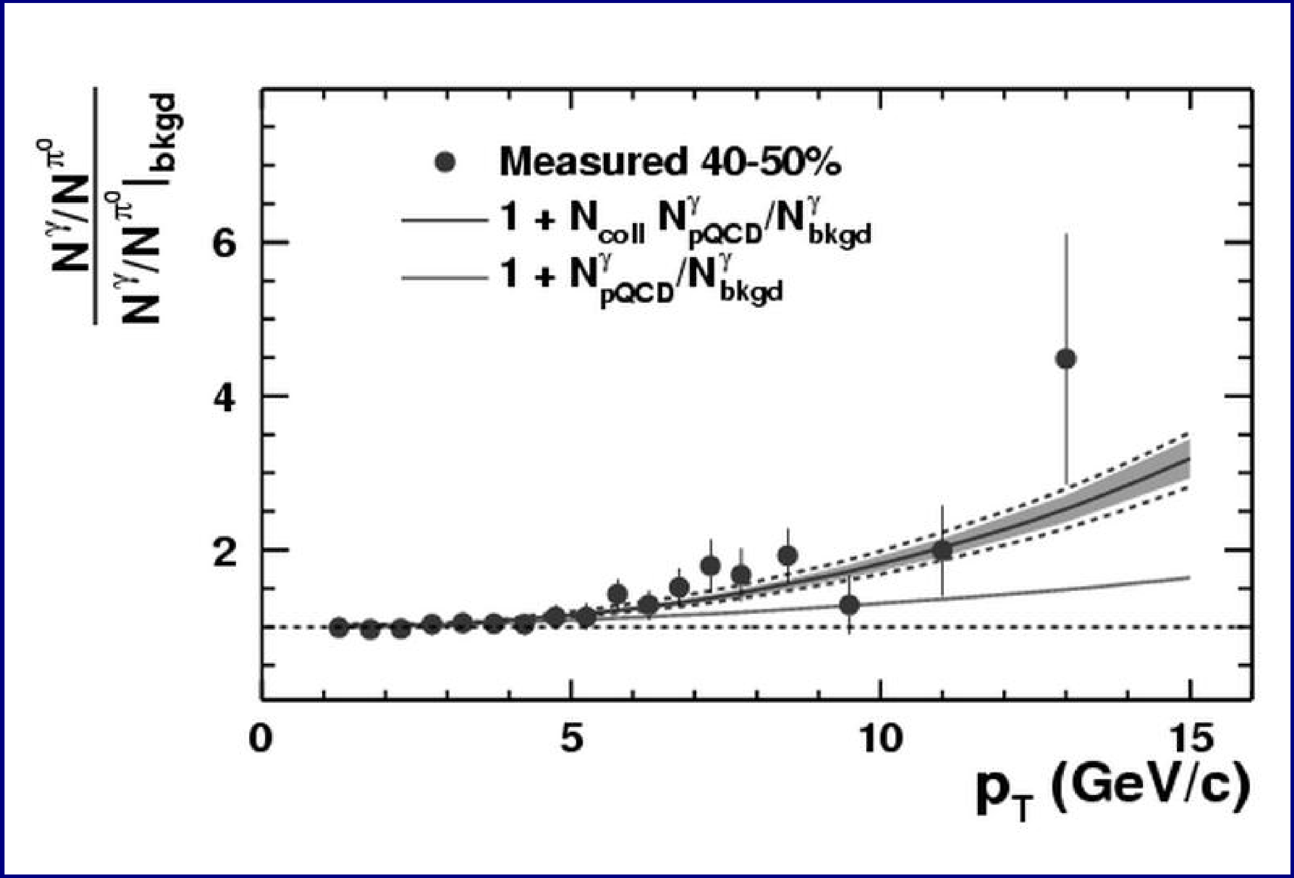

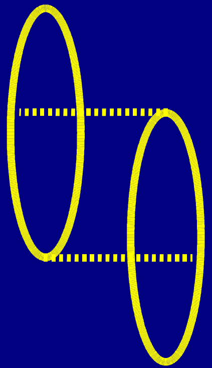

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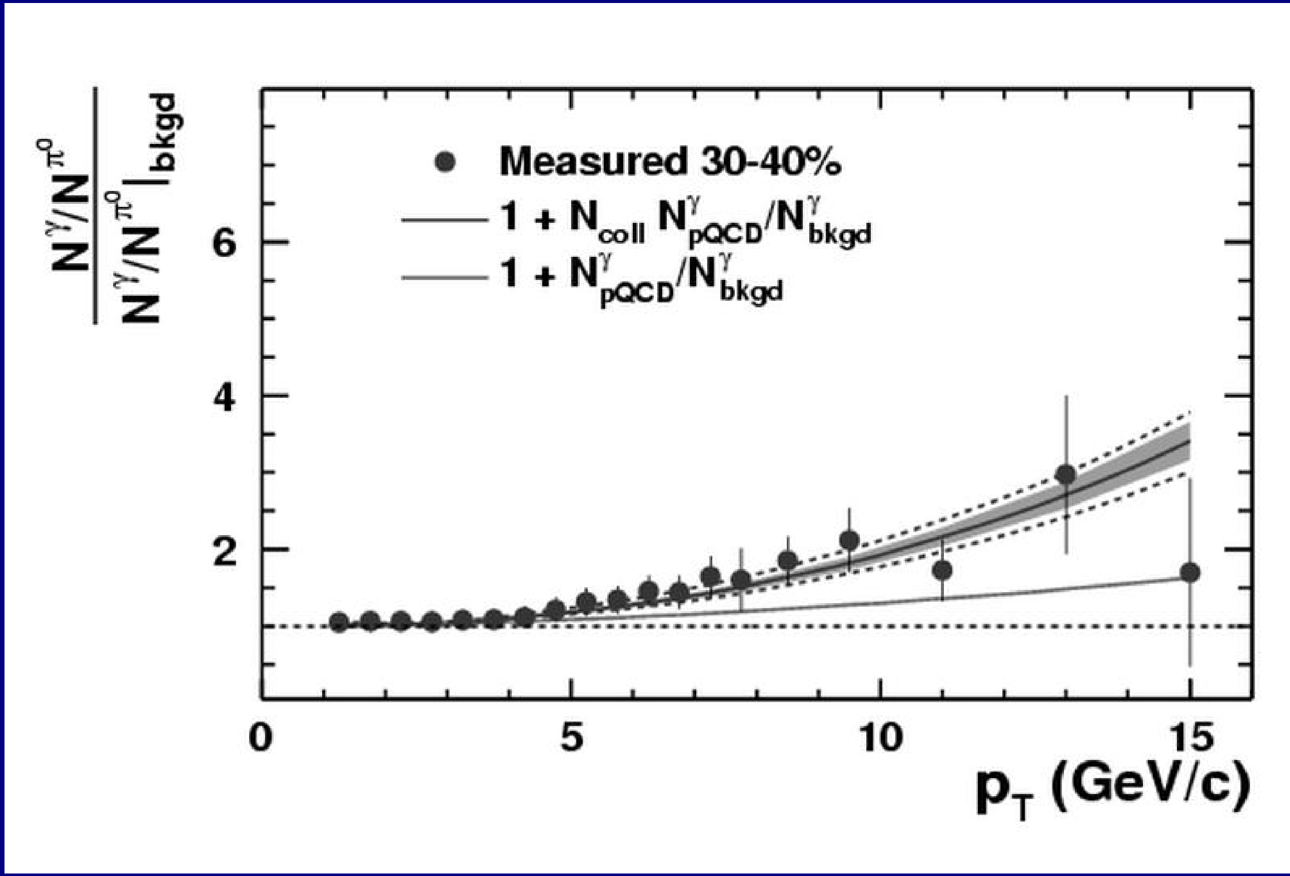

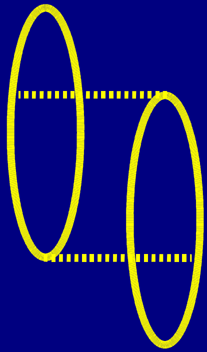

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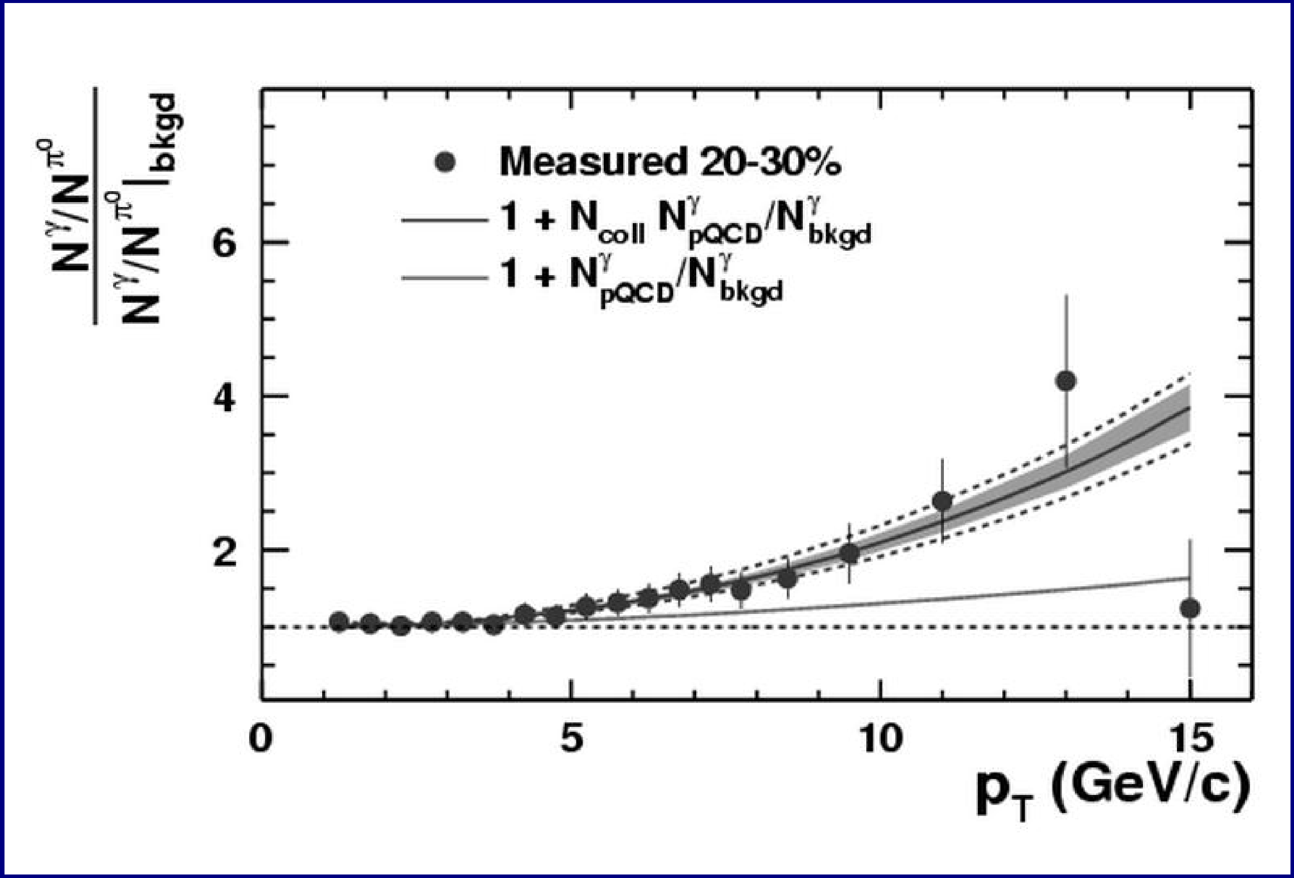

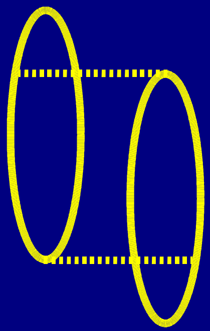

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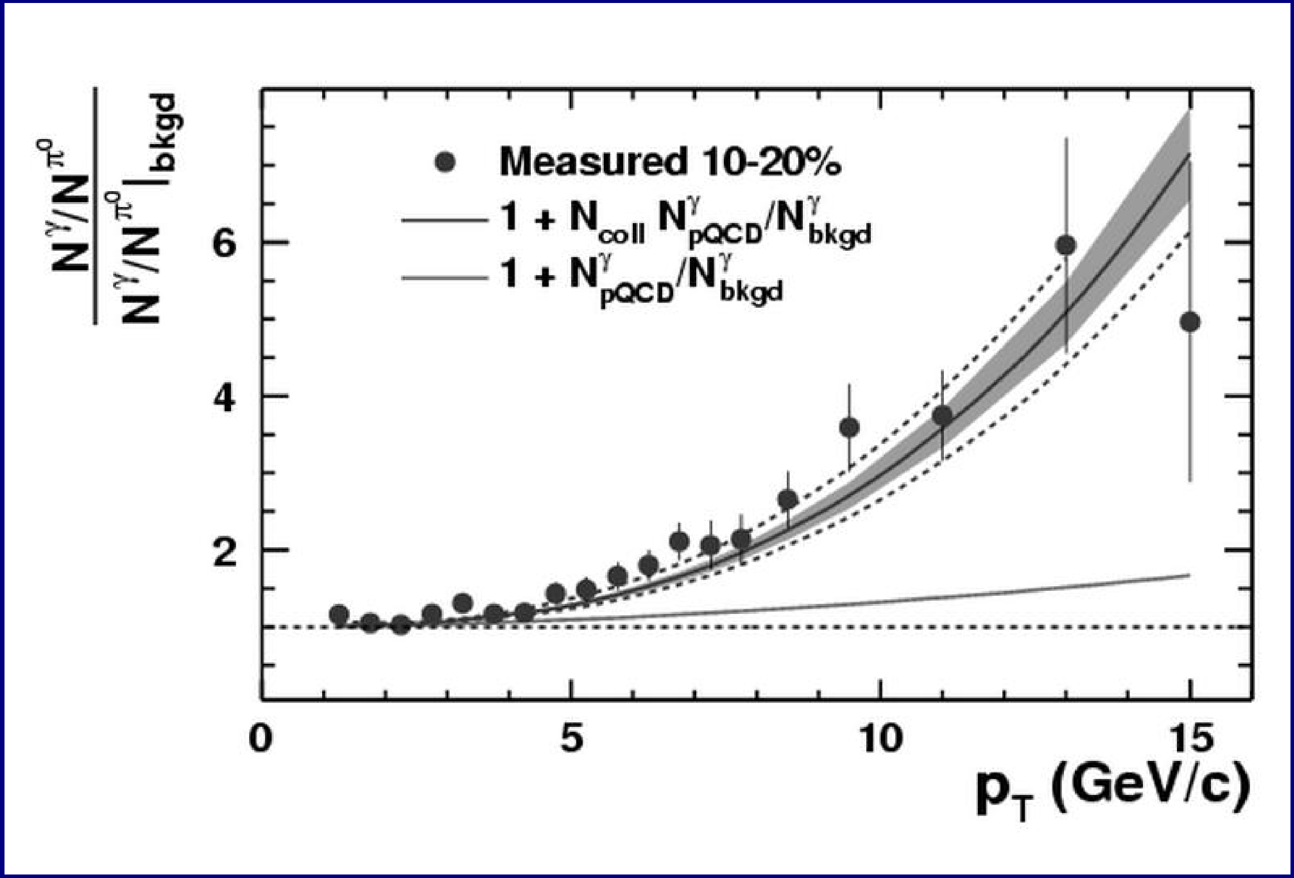

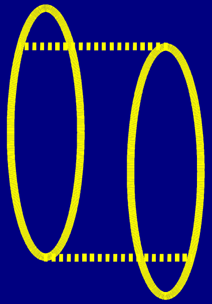

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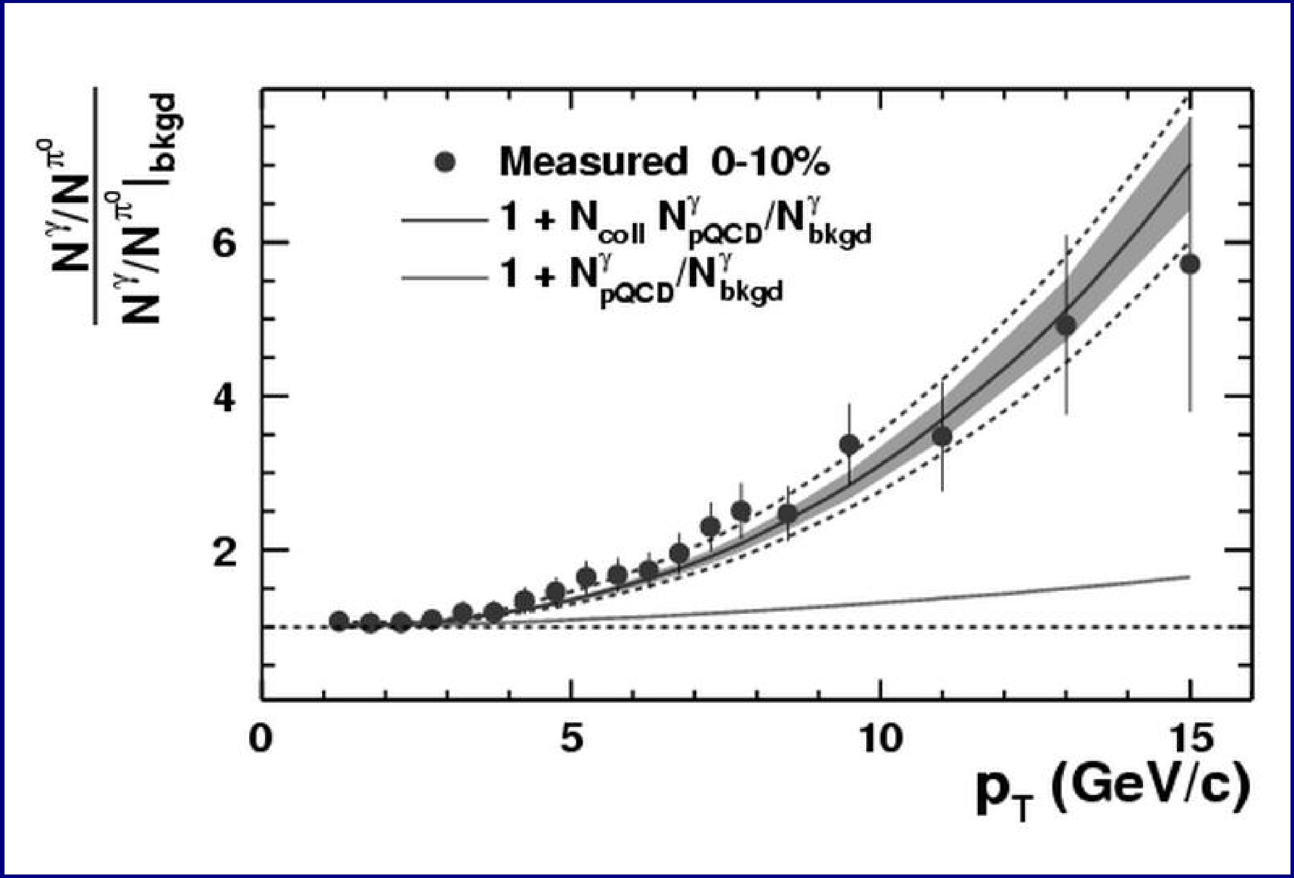
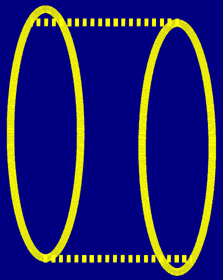
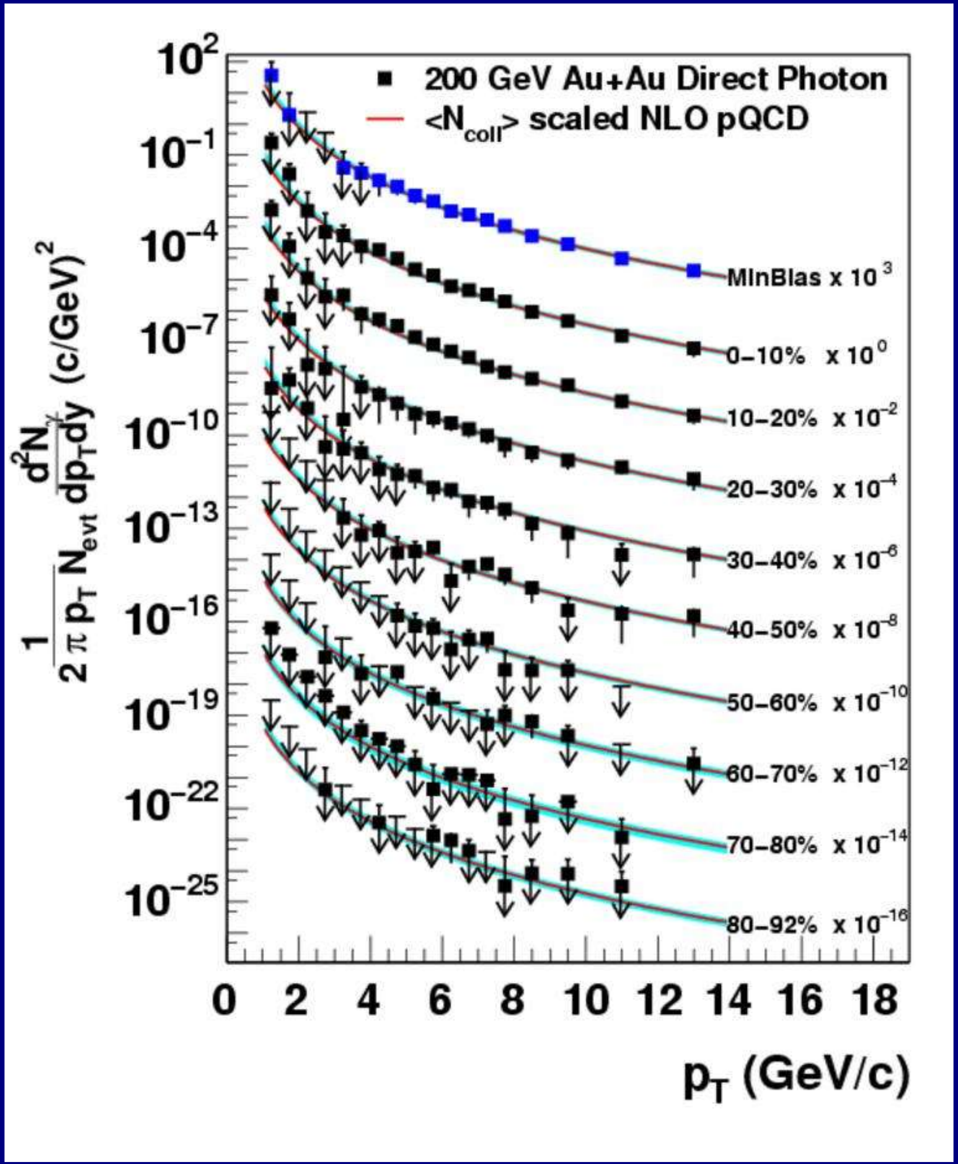




Direct Photon Spectra

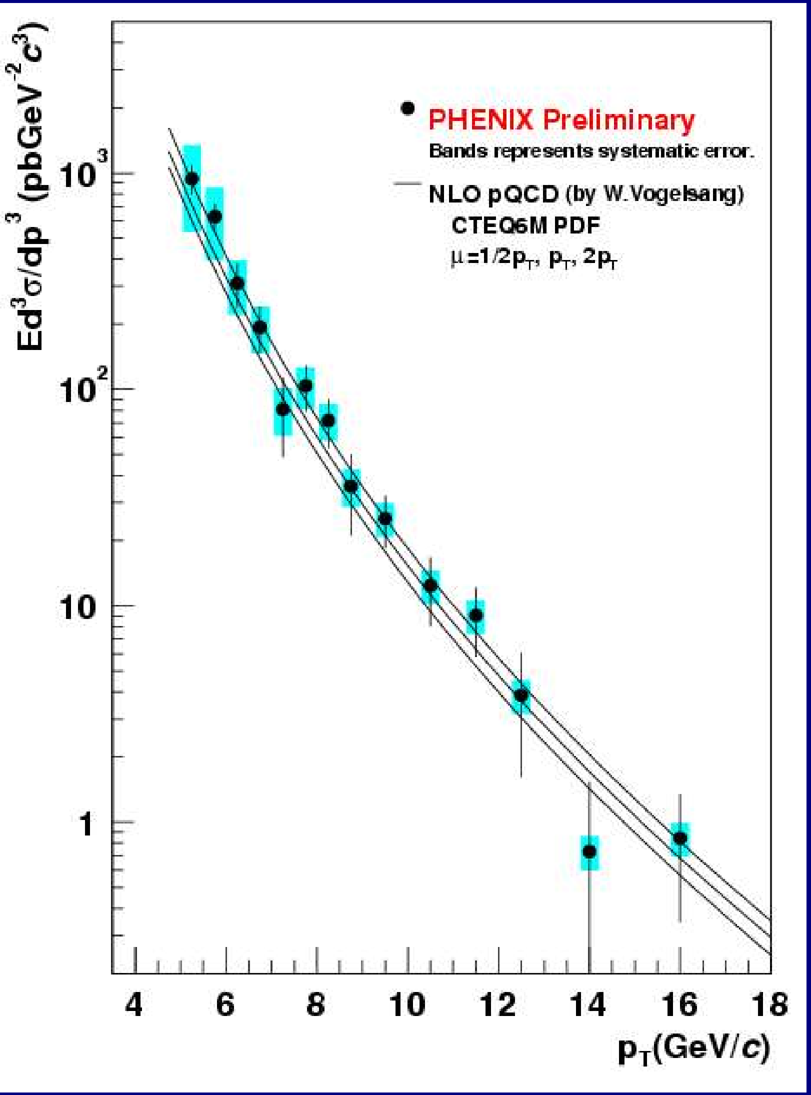


- Direct photon yield

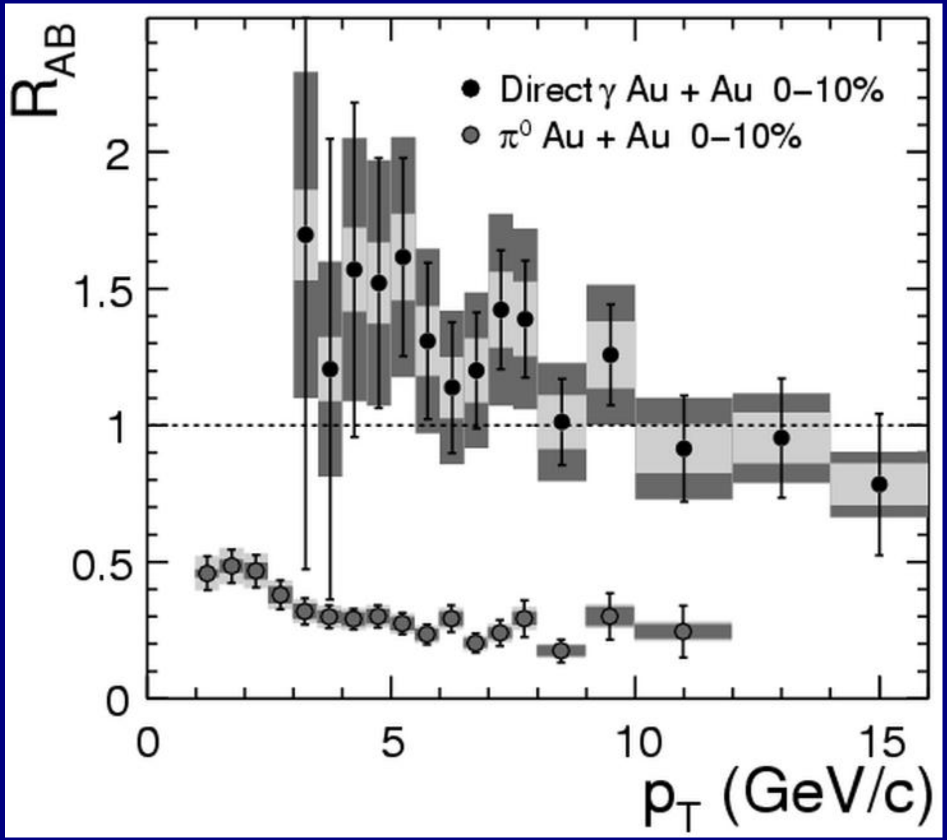
$$\frac{d^2N}{dp_T\,dy}_{direct} = \left(1 - \frac{\gamma_{bkgd}}{\gamma_{meas}}\right) \frac{d^2N}{dp_T\,dy}_{incl}$$

- Consistent with scaled p+p calculation

Direct Photons in p+p @ 200 GeV



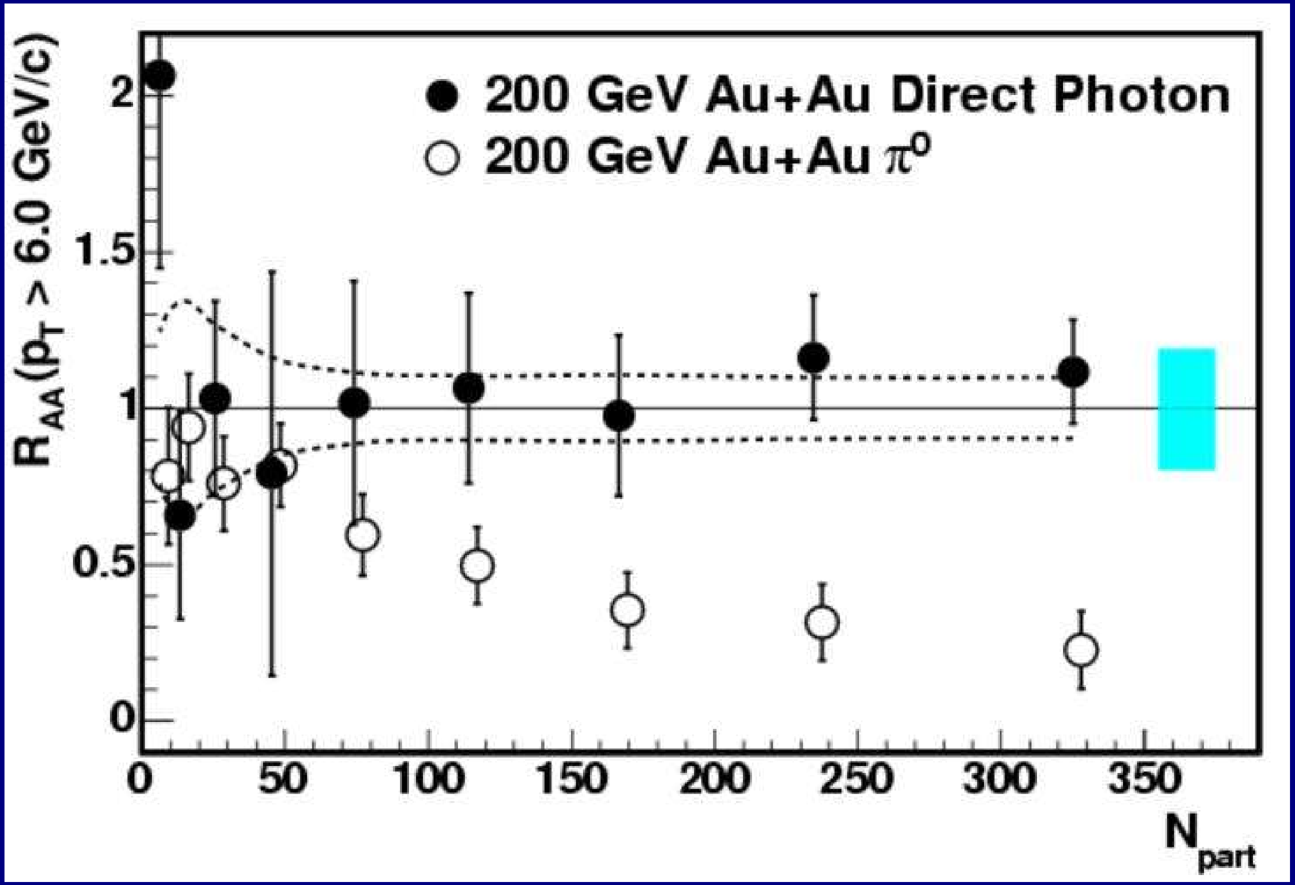
R_{AB} for Direct Photons vs. π^0



- **R_{AB} for direct photons**
  - Comparison on linear scale
- **Direct photons are not suppressed**
  - Initial state **not** responsible for π^0 deficit
  - $$\frac{d^2\sigma}{dp_T\,dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(E \rightarrow E')$$

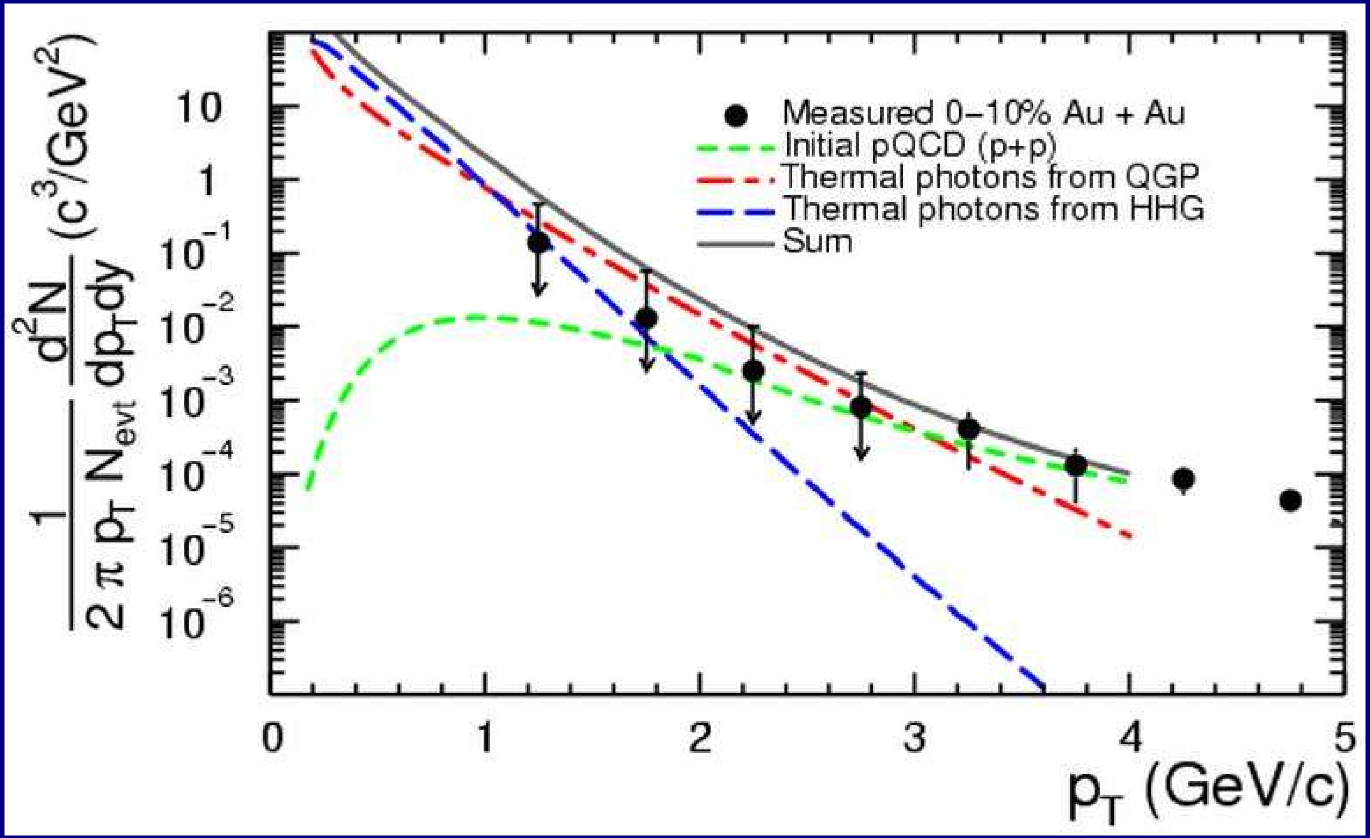
$$R_{AB} = \frac{d^2N_{AA}/dydp_T}{N_{coll}\,d^2N_{pp}/dydp_T}$$

Centrality Dependence



PHENIX

Thermal Signal?



Calculation consistent with upper limits

Summary and Outlook

- Strong suppression of neutral pions at high p_T in central Au+Au collisions at RHIC compared to the p+p reference
- No suppression of direct photons at high p_T in central Au+Au reactions (Direct control for hard scattering!!)
- Dense, partonic medium in central Au+Au collisions consistent with all observations
- Factor 10 more data from last Au+Au run, analysis of d+Au data (Cronin effect), low p_T region via photon conversions

Brazil University of São Paulo, São Paulo

China Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing

France LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecòle des Mines at Nantes, Nantes

Germany University of Münster, Münster

Hungary Central Research Institute for Physics (KFKI), Budapest
Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest

India Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay

Israel Weizmann Institute, Rehovot

Japan Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
Rikkyo University, Tokyo, Japan
Tokyo Institute of Technology, Tokyo
University of Tsukuba, Tsukuba
Waseda University, Tokyo

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Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul

Russia Institute of High Energy Physics, Protovino
Joint Institute for Nuclear Research, Dubna
Kurchatov Institute, Moscow
PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg

Sweden Lund University, Lund

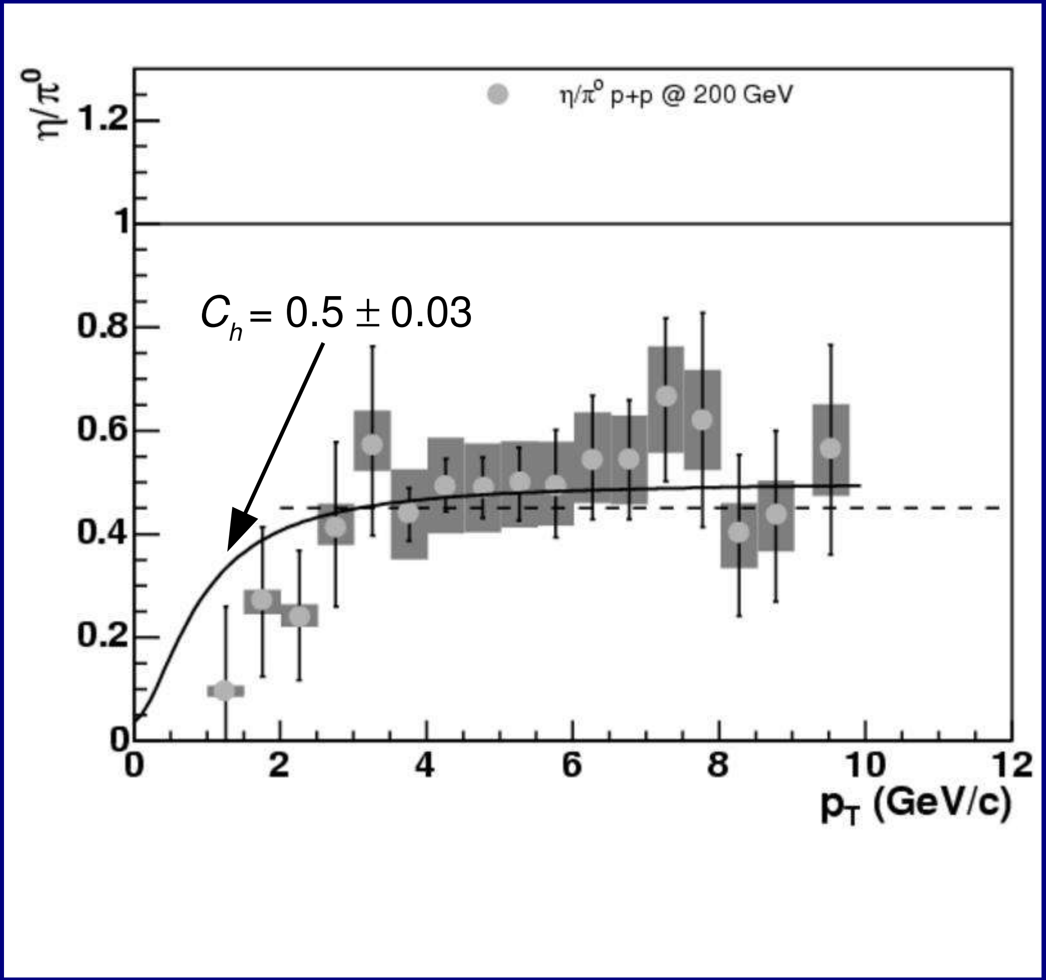
*12 Countries; 58 Institutions; 480 Participants**

*as of January 2004

USA Abilene Christian University, Abilene, TX
Brookhaven National Laboratory, Upton, NY
University of California - Riverside, Riverside, CA
University of Colorado, Boulder, CO
Columbia University, Nevis Laboratories, Irvington, NY
Florida State University, Tallahassee, FL
Florida Technical University, Melbourne, FL
Georgia State University, Atlanta, GA
University of Illinois Urbana Champaign, Urbana-Champaign, IL
Iowa State University and Ames Laboratory, Ames, IA
Los Alamos National Laboratory, Los Alamos, NM
Lawrence Livermore National Laboratory, Livermore, CA
University of New Mexico, Albuquerque, NM
New Mexico State University, Las Cruces, NM
Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
Oak Ridge National Laboratory, Oak Ridge, TN
University of Tennessee, Knoxville, TN
Vanderbilt University, Nashville, TN

Backup Slides

m_T-Scaling



- **Empirical observation:**
  - Similar hadron spectra as a function of $m_T = \sqrt{p_T^2 + m_0^2}$

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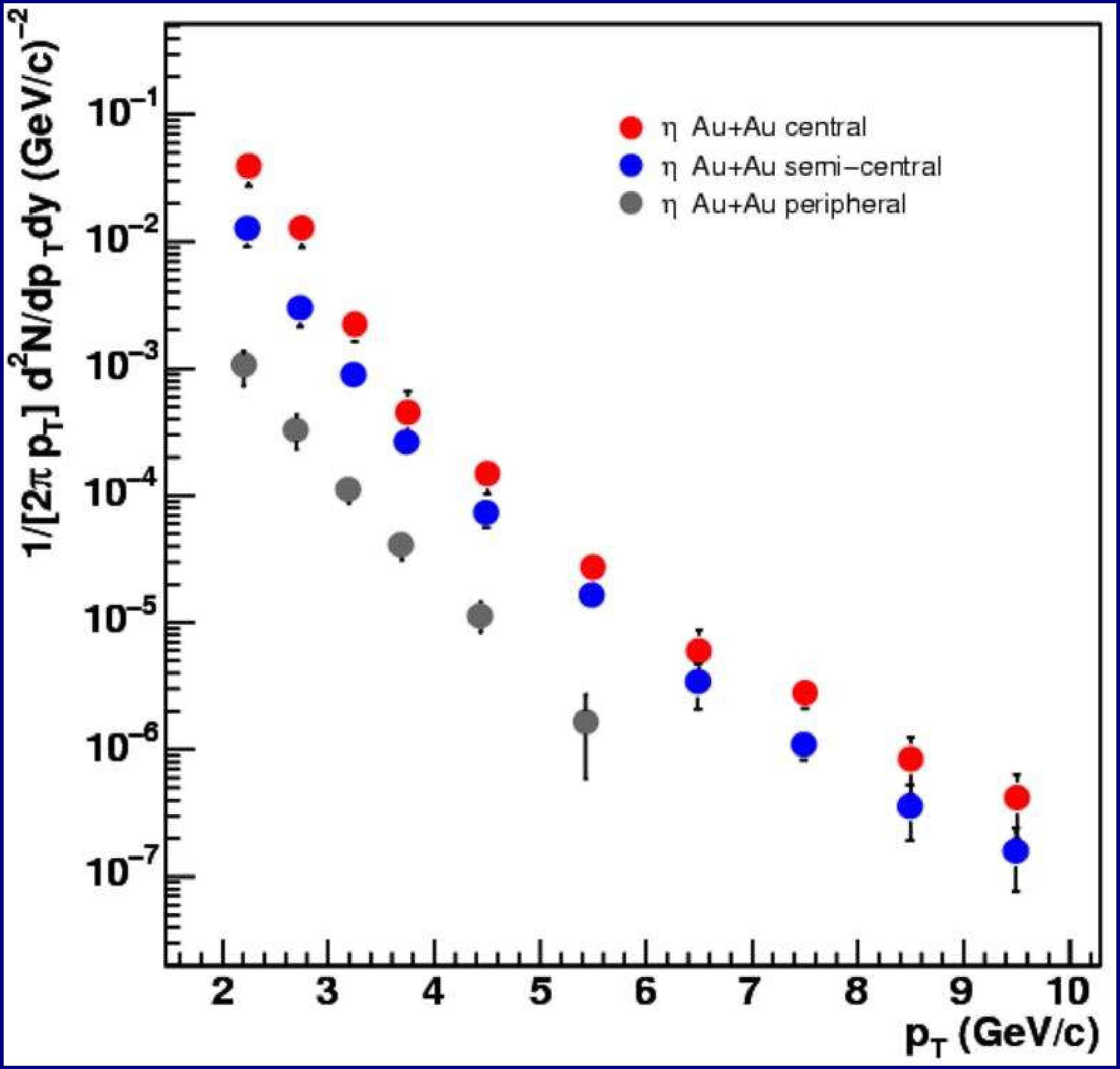
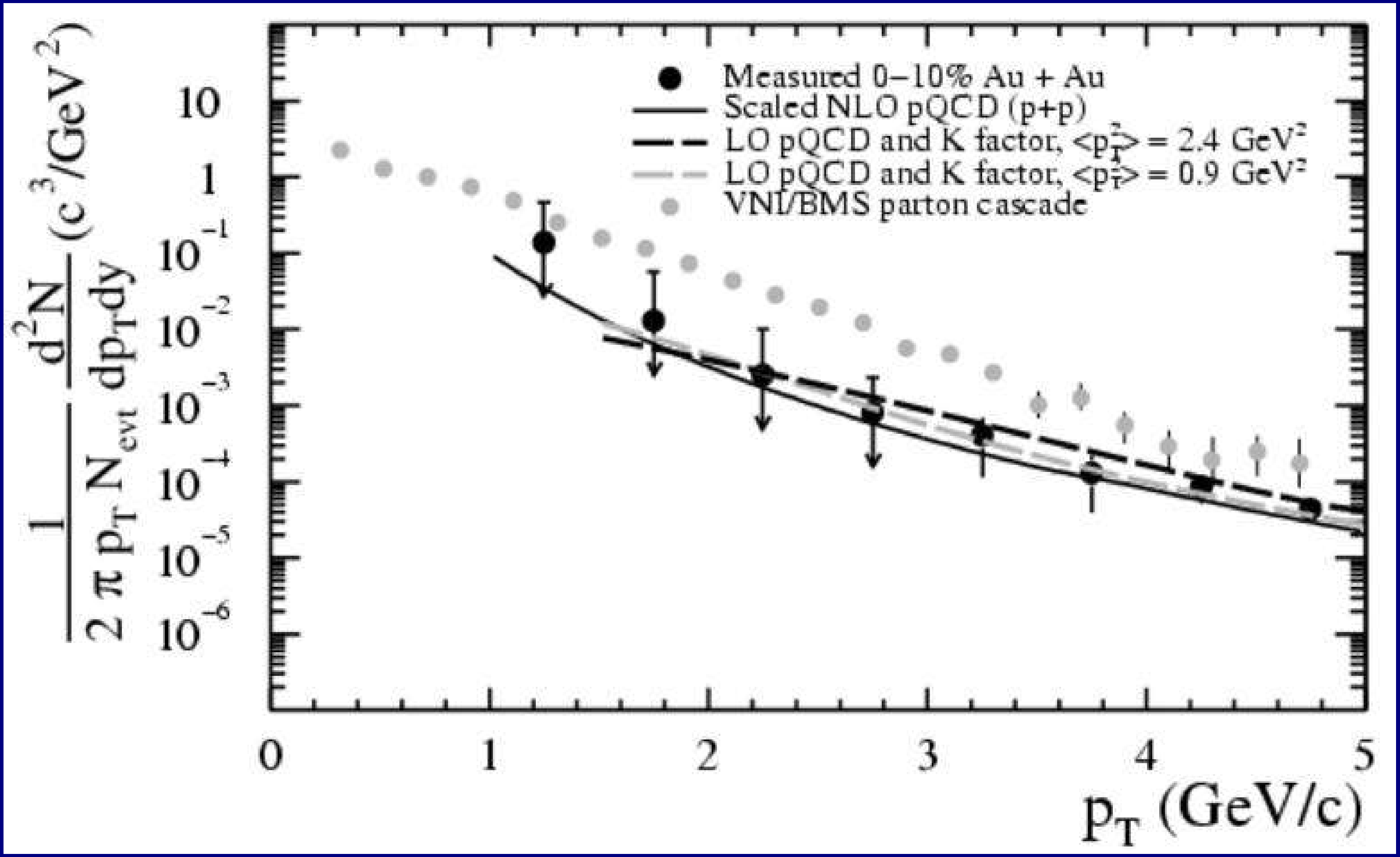
- **Confirmed with η and π^0**
  - In p+p, d+Au and Au+Au
  - $C_h = 0.45 \pm 0.05$

η Spektren im EMCal

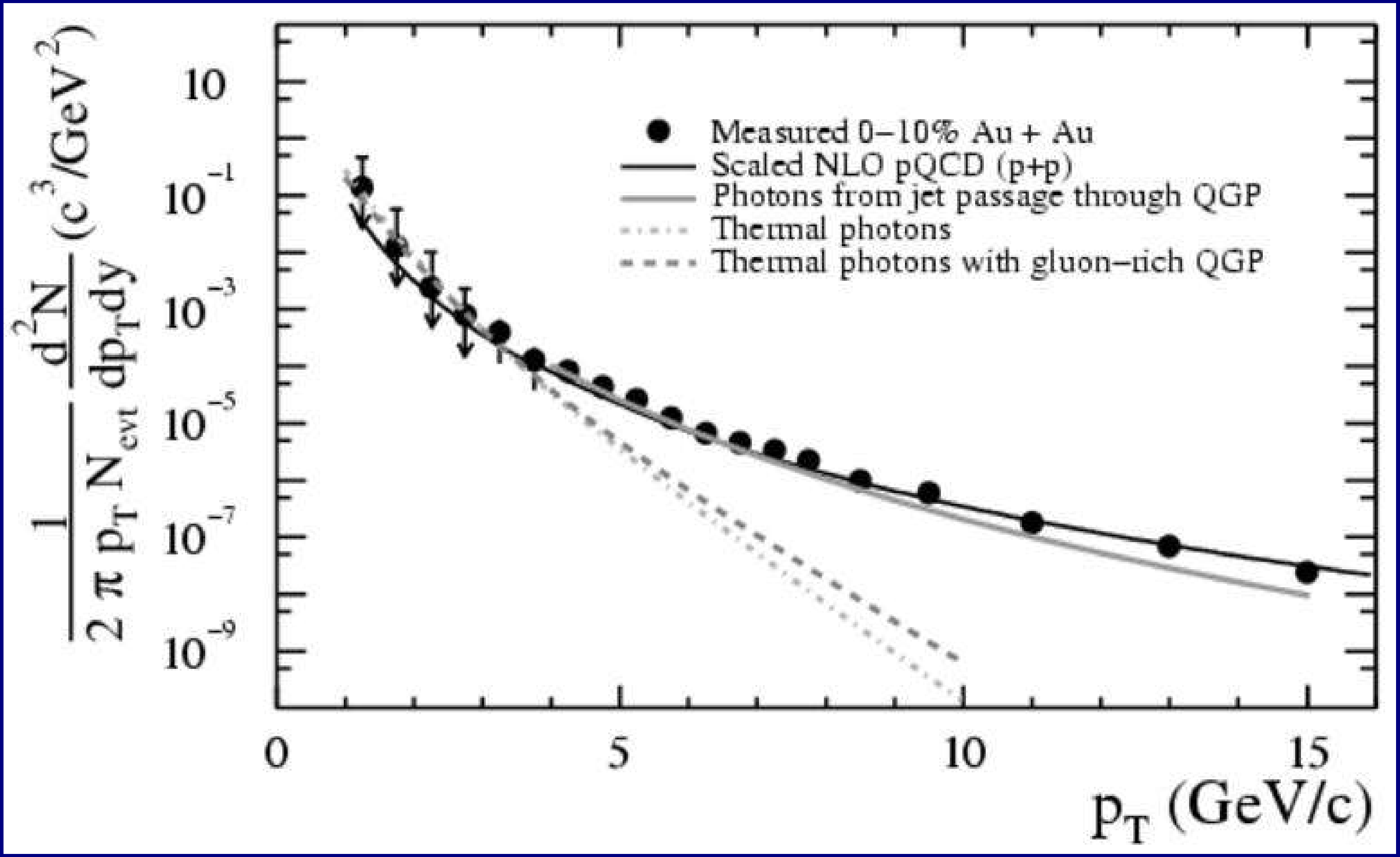


Intrinsic k_T and Parton Cascade?



A. Dumitru, L. Frankfurt, L. Gerland, et al. Phys. Rev. C64 (2001) 054909
S. A. Bass, B. Muller, and D. K. Srivastava. Phys. Rev. Lett. 90 (2003) 082301

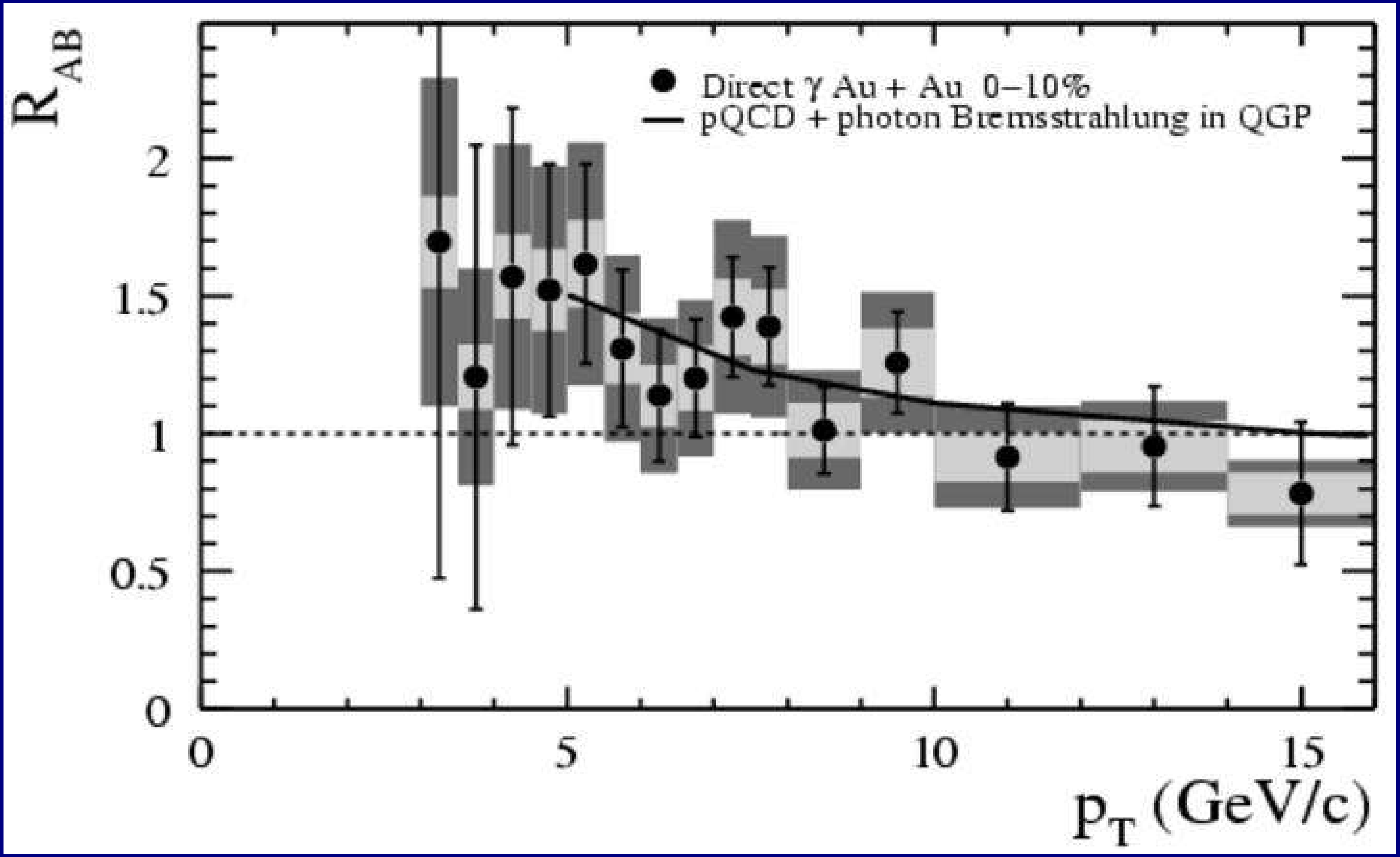
Hard + Soft?



R. J. Fries, B. Muller, and D. K. Srivastava. Phys. Rev. Lett. 90 (2003) 132301

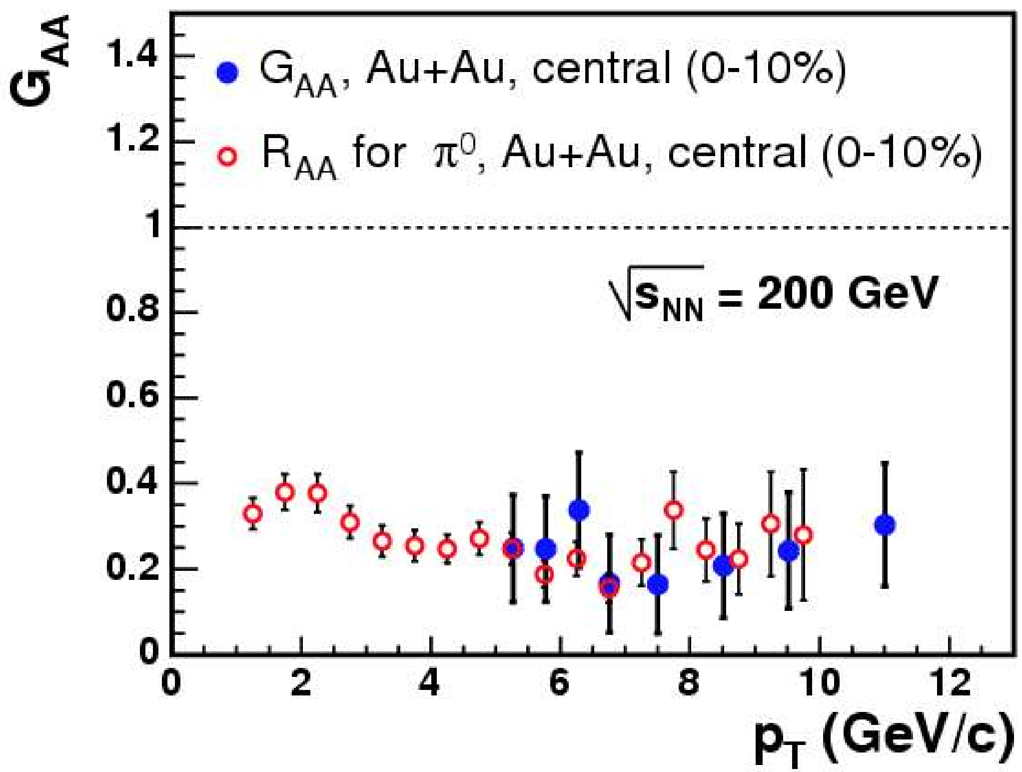
F. Arleo et al. hep-ph/ 0311131, 2003

Photon Bremsstrahlung?



B. G. Zakharov. JETP Lett. 80 (2004) 1

G_{AAg}



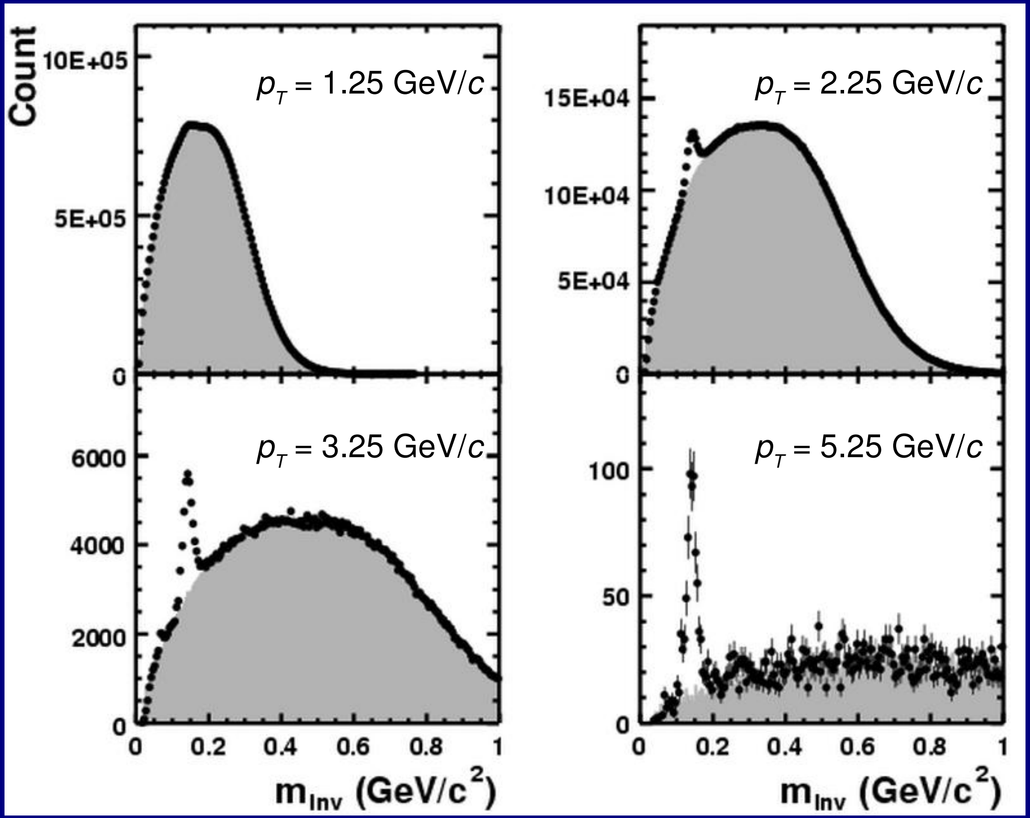
K. Reygers Habilitation WWU Münster

- **Idee:**
  - Photonen als Maß für harte Streuung
  - Definiere Größe G_{AA} analog zu R_{AA}

$$G_{AA} = \frac{(\gamma_{direct}/\pi^0)_{p+p}}{(\gamma_{direct}/\pi^0)_{A+A}}$$

- **Modellunbahängig**
- **Wenn Photonen mit N_{coll} skalieren:** $G_{AA} = R_{AA}$

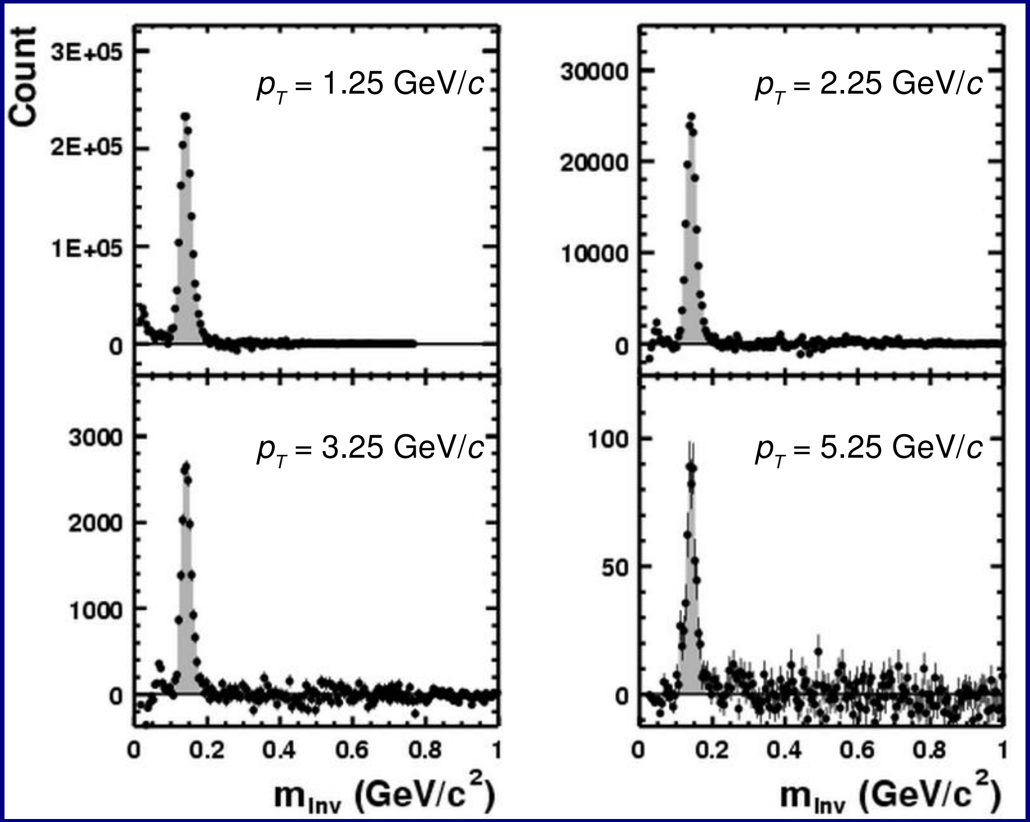
π^0-Extraktion



- **Untergrundbestimmung via "Mixed Events"**
  - Kombination von Photonen aus versch. Ereignissen
  - A priori unkorreliert
  - Ähnliche Multiplizität, Vertex nötig

28 M minimum-bias Ereignisse (PbGl)

π^0-Extraktion



- **Unkorrigierte Spektren**
  - Real – Mixed
  - Integration im Peakbereich
- **Korrekturen**
  - Geometrische Akzeptanz
  - Rekonstruktionseffizienz
    - Orts-/Energieauflösung
    - Cuts
    - Schauerüberlapp....

28 M minimum-bias Ereignisse (PbGl)