Measurement of Direct Photons at High p_T
Methods and Results

Jet Physics In Heavy Ion Collisions at the LHC
Trento
September 1st-6th 2006

Christian Klein-Bösing

IKP Münster

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Outline

- What?
- Why?
- How?

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What are Direct Photons?

- **Pragmatic definition:**
  - Anything but decay photons

inclusive photons = **decay photons** + **direct photons**

- **Difficult measurement:**

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\eta \rightarrow \gamma + \gamma$$

} large background!

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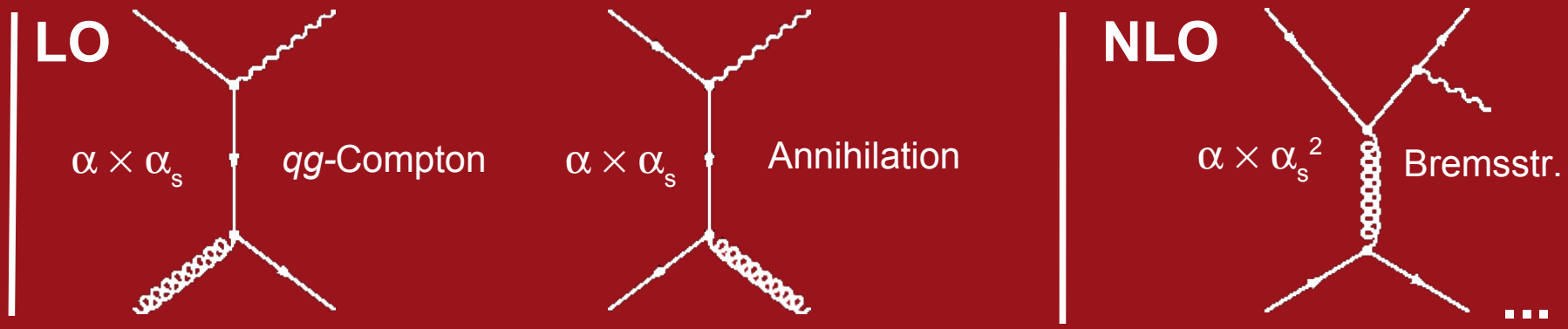
Why Direct Photons?

- **Production in p+p**
  - *Hard* (with large Q^2) parton-parton collisions e.g.:



  - Photon+Jet
  - Precision test of pQCD

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

  - Constrains gluon distribution and polarization
  - Choice of renormalization, factorization and fragmentation scales arbitrary (usually of the order of p_T)

Going from p+p to A+A

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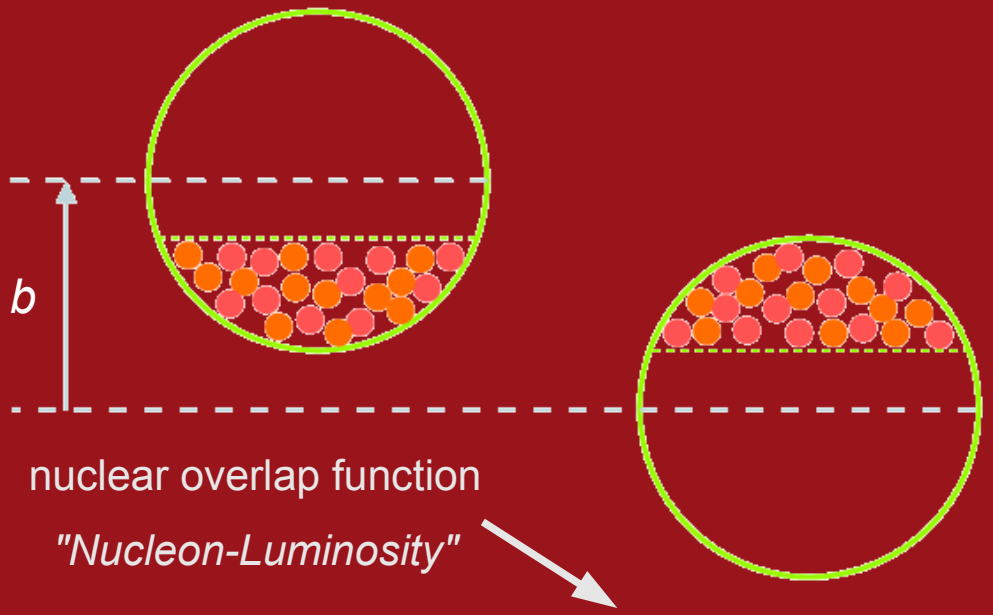
Hard Photons in A+A

- **Increased number of scattering centers**



$$\sigma_{AB}^{hard} \approx \int d^2 b \, \sigma_{NN}^{hard} \, T_{AB}(b)$$

$$\langle N_{coll} \rangle \approx \sigma_{NN} \, T_{AB}$$

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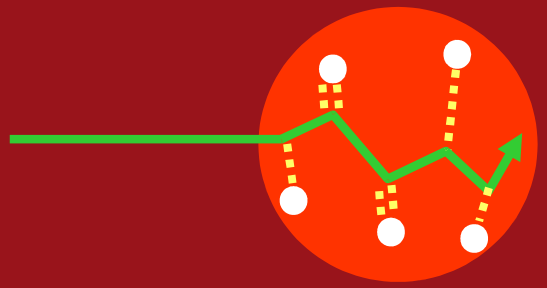
Hard Photons in A+A

- **Increased number of scattering centers**
- **Nuclear effects**
  - "Shadowing" of PDFs
  - Cronin Effect, multiple soft scattering
- **Still at parton level, but "early" reaction phase**



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

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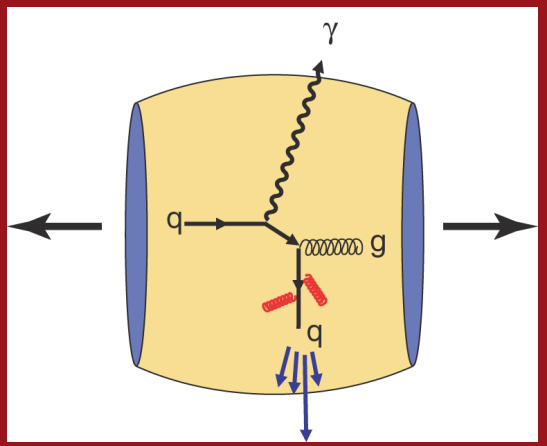
Hard Photons in A+A

- **Increased number of scattering centers**
- **Nuclear effects**
  - "Shadowing" of PDFs
  - Cronin Effect, multiple soft scattering
- **Still at parton level, but "early" reaction phase**
- **Hot and dense medium**
  - Probed by partons
  - Photons unaffected by strong interaction
  - Photons provide **in situ** control



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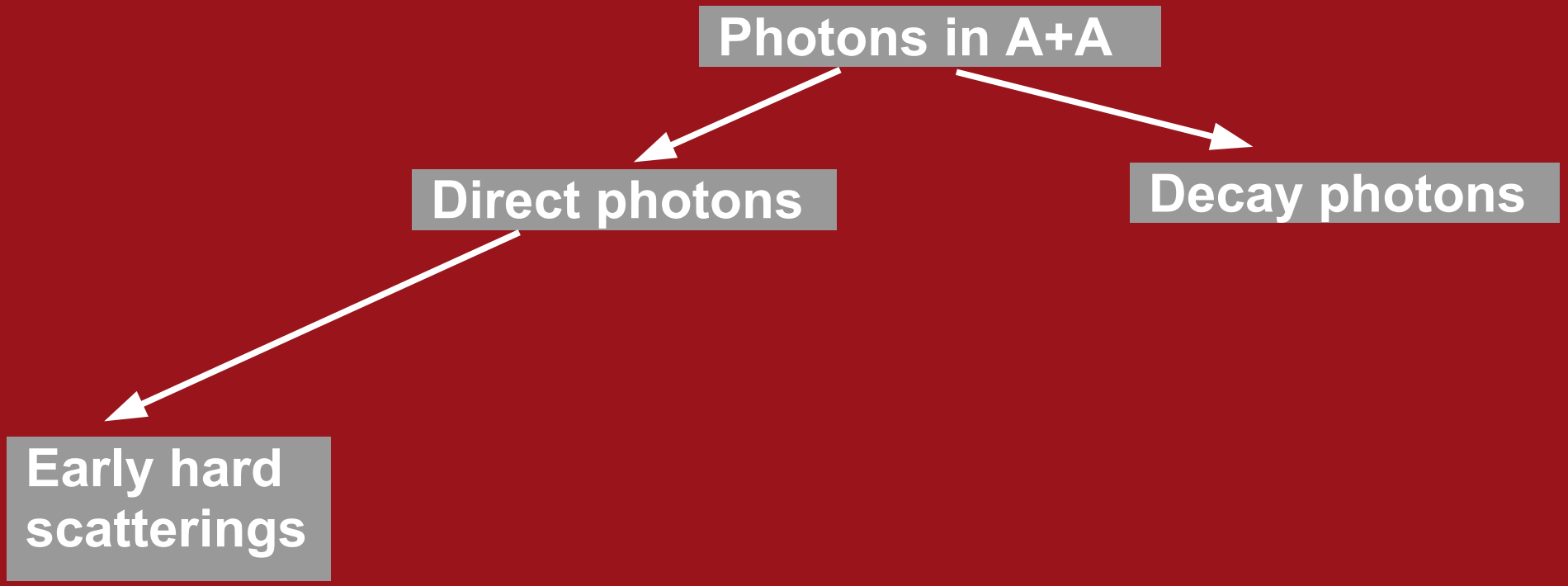
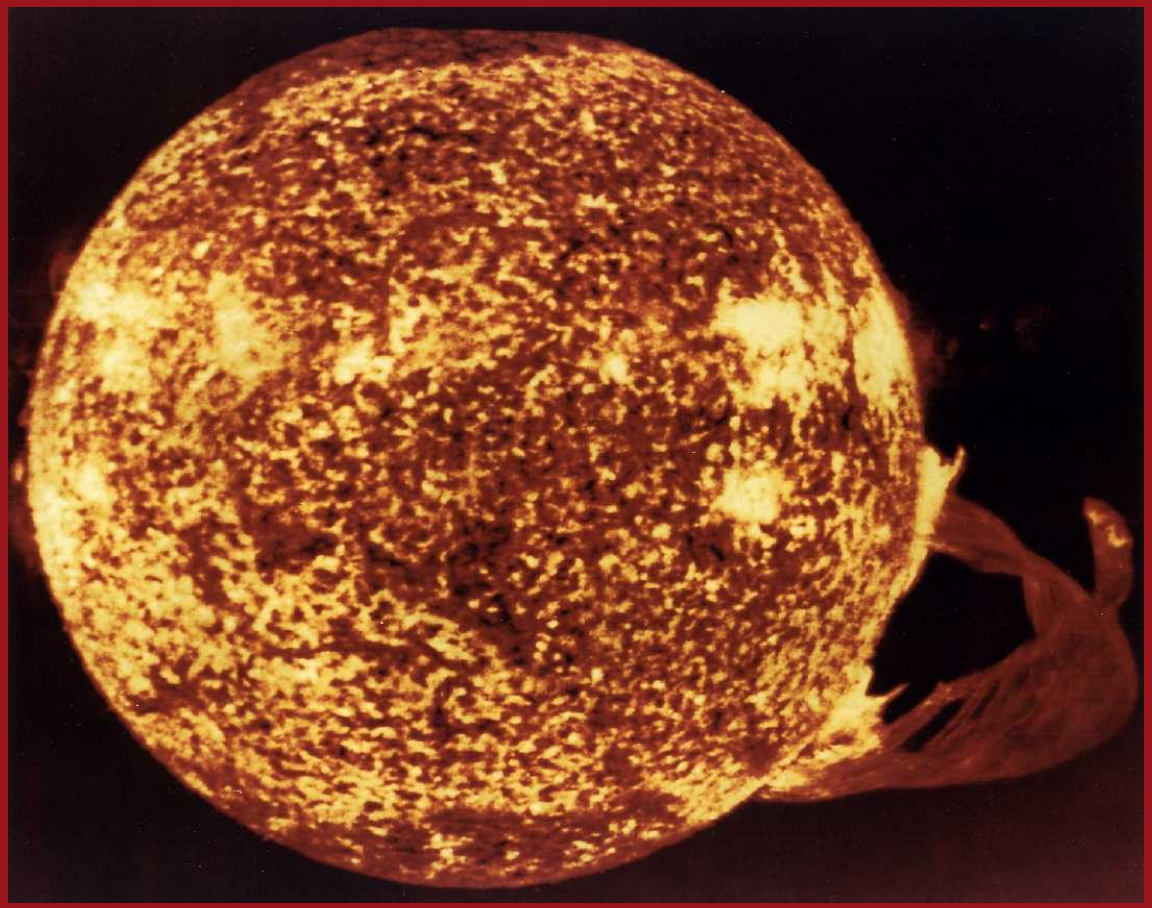
Photon Sources in A+A



Also called
prompt photons

There is more information from photons in HIC...



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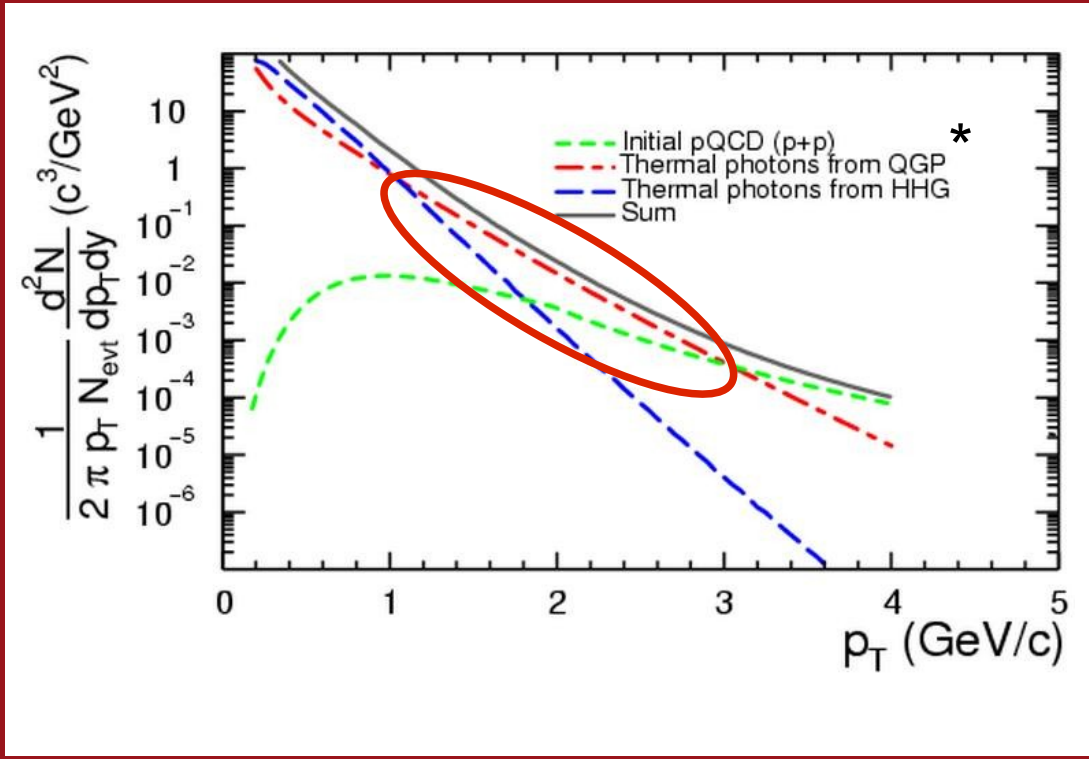
Thermal Photons in A+A



- **Thermal photons**
  - From QGP and HHG
  - Measure for initial temperature of the system (here T_i = 370 MeV)
  - Additional signature for QGP

*Turbide, Rapp, Gale:

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

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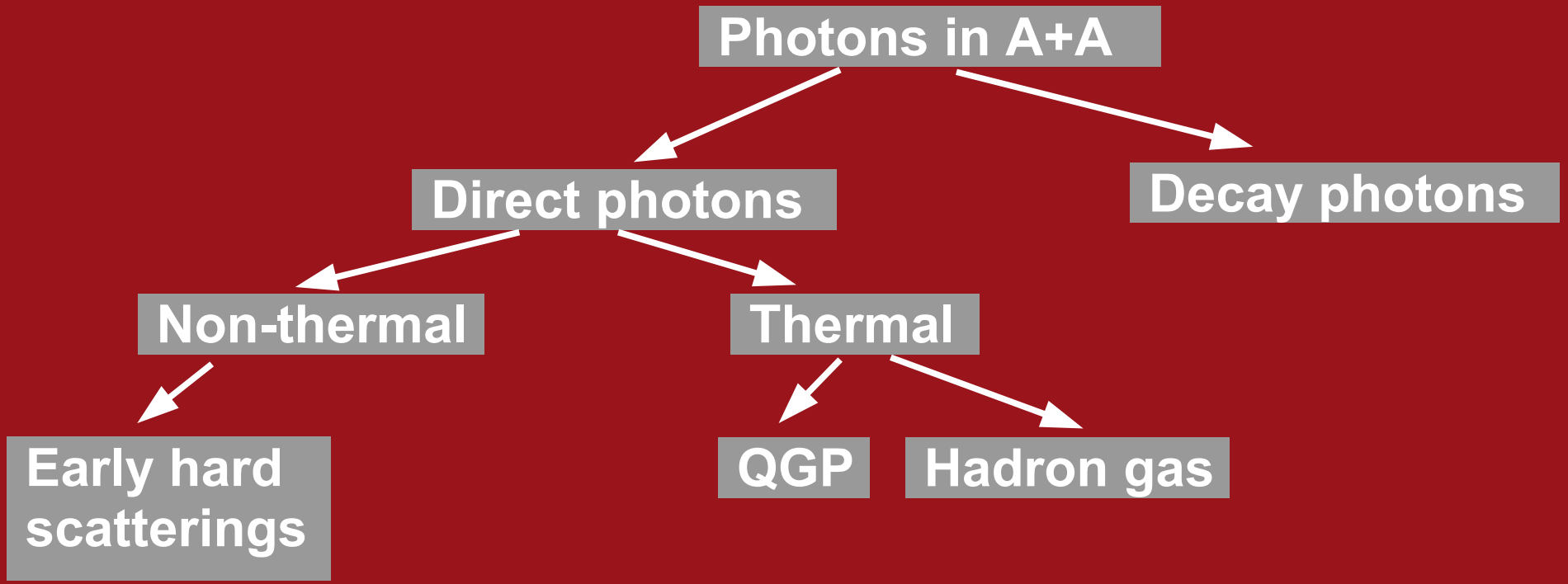
Photon Sources in A+A



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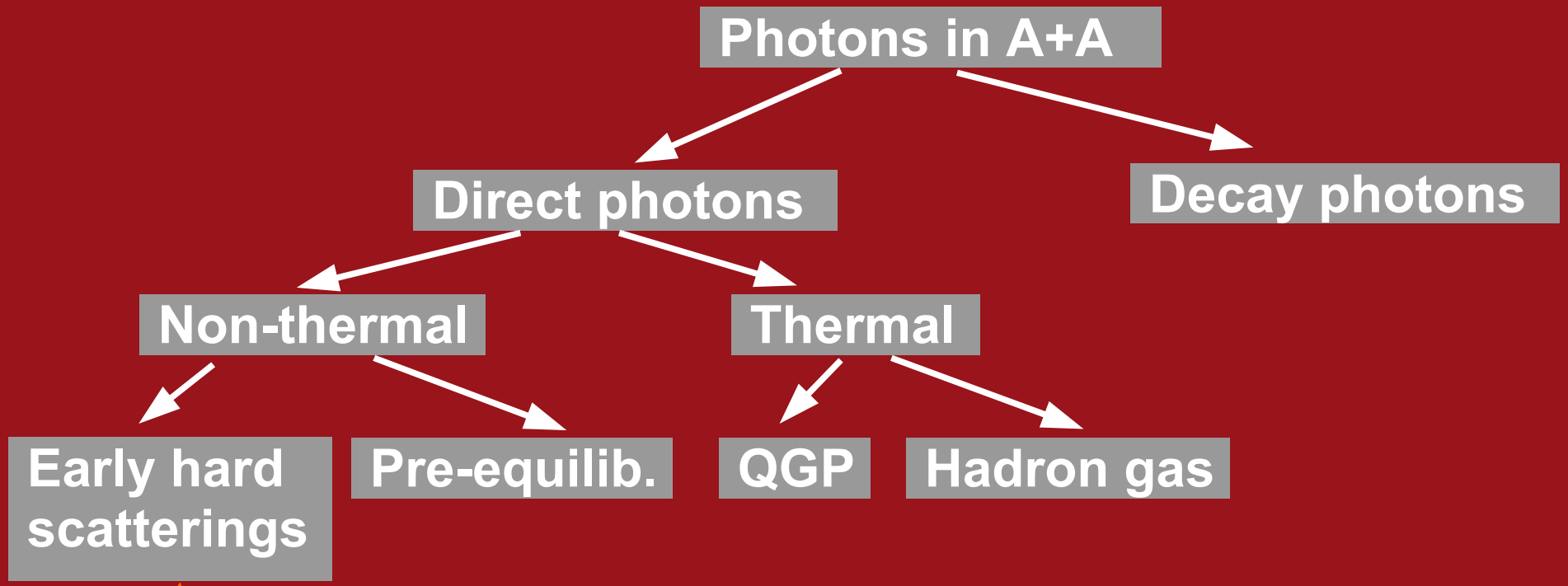
Photon Sources in A+A



pQCD or
„prompt“ photons

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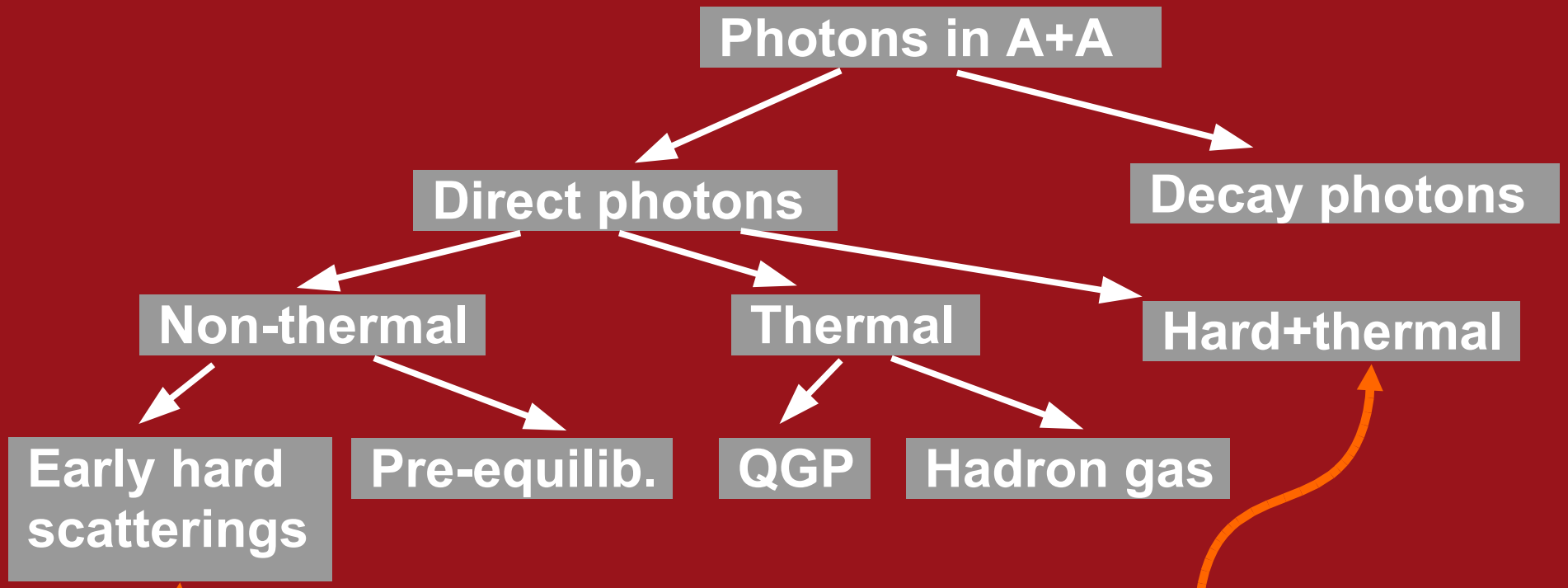
Photon Sources in A+A



pQCD or
„prompt“ photons

Interaction of hard partons with the QGP

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

2) Medium induced photon bremsstrahlung

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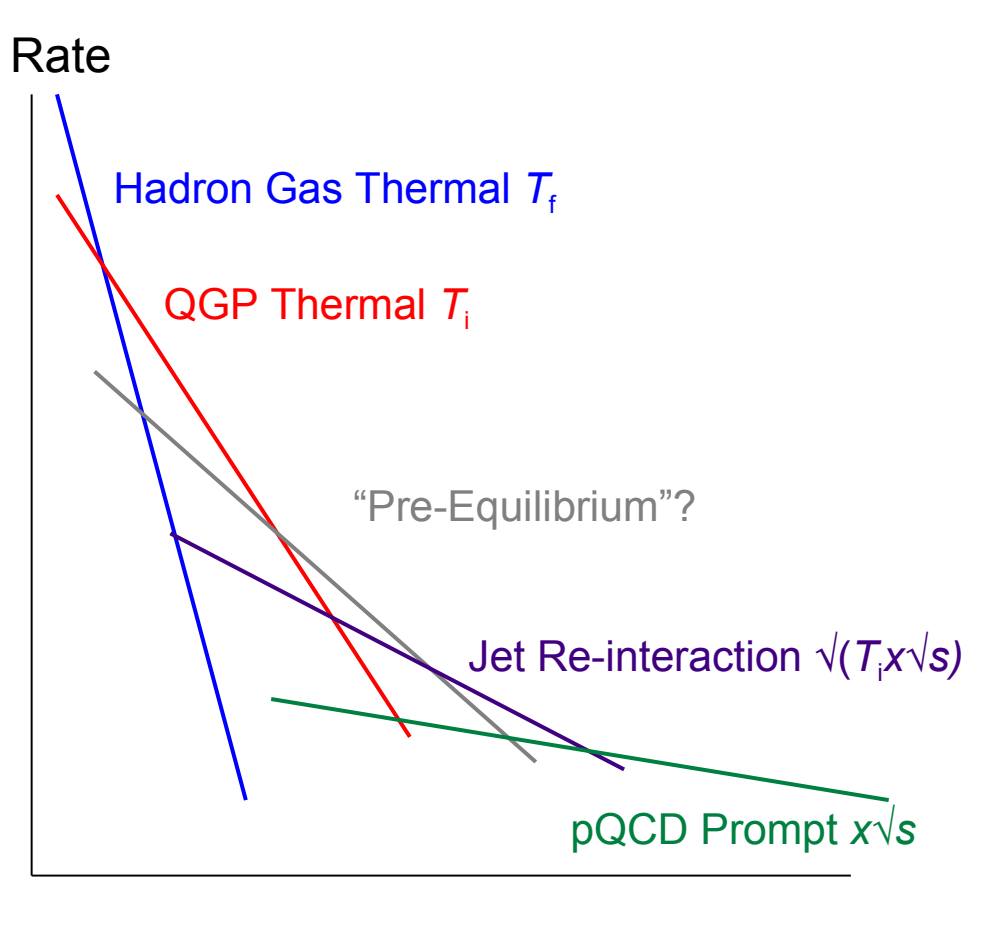
Summary



The promise and the peril:
Photon signal is very ambiguous!

- **Direct photons in p+p**
  - Precision test of pQCD
  - Do not suffer from fragmentation
  - Direct (LO) access to gluon polarization
- **Direct photons in A+A**
  - Carry information of all stages of the reaction
  - In situ control of hard scattering at high p_T
  - Thermal radiation from QGP and HHG at low p_T
  - Additional photons:
    - Pre-equlibrium
    - Jet – plasma interactions

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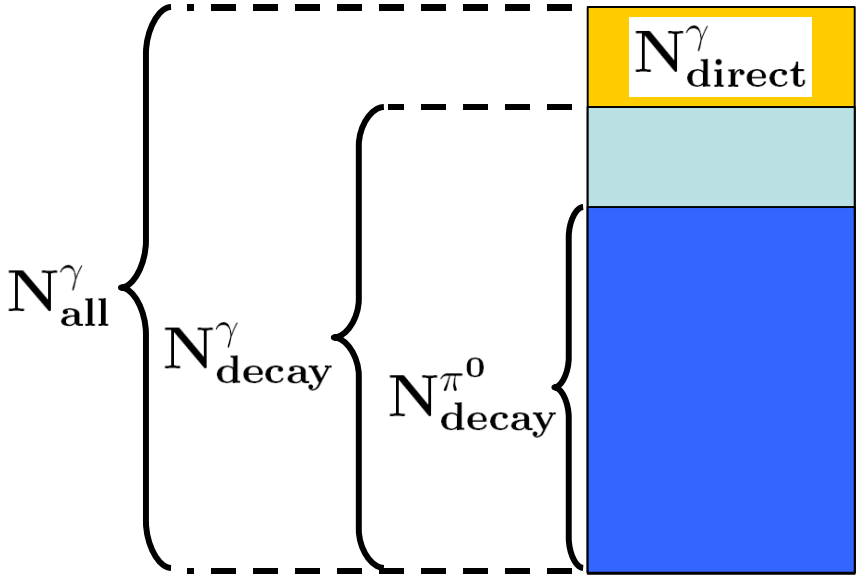
How to measure Direct Photons

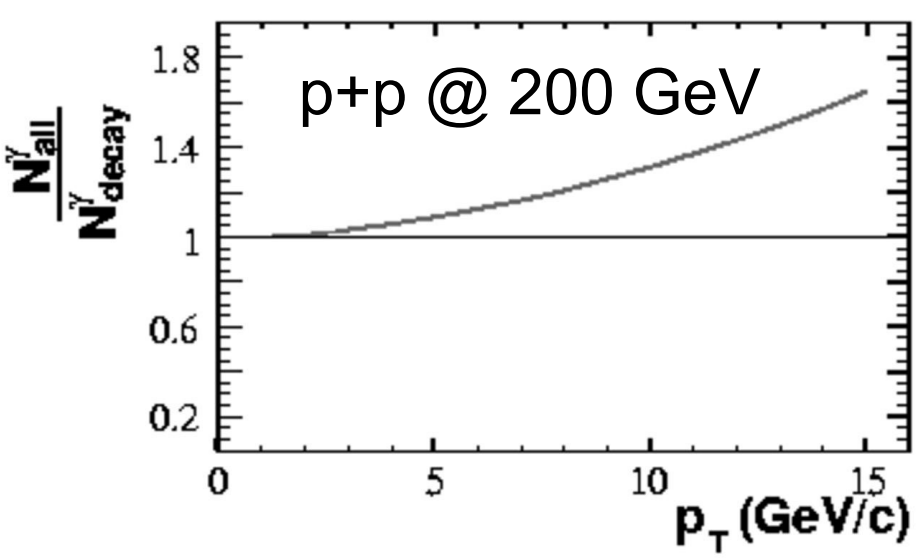
- **Inclusive Photons**

$$N^{\gamma}_{all} = N^{\gamma}_{direct} + N^{\gamma}_{decay}$$

- **Challenge to separate signal from decay background**
  - Mainly $\pi^0 \rightarrow \gamma\gamma$
- **Direct separation**
  - event-by-event isolation cuts
- **Statistical separation**
  - Compare measured inclusive γ to expected decay γ

$$N^{\gamma}_{direct} = N^{\gamma}_{all} - N^{\gamma}_{decay}$$





PHENIX

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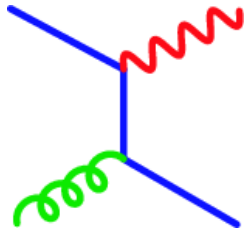
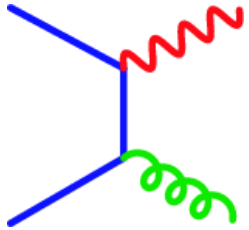
Isolation Cuts

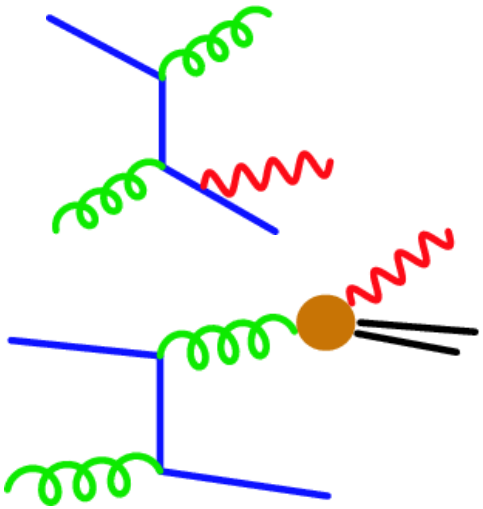
Compton



Annihilation



Bremsstrahlung



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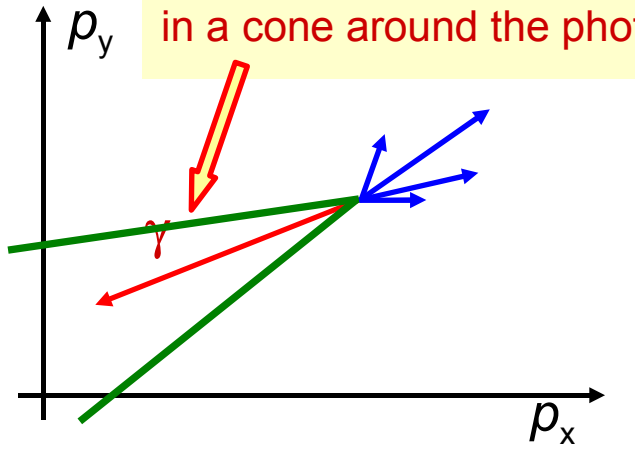
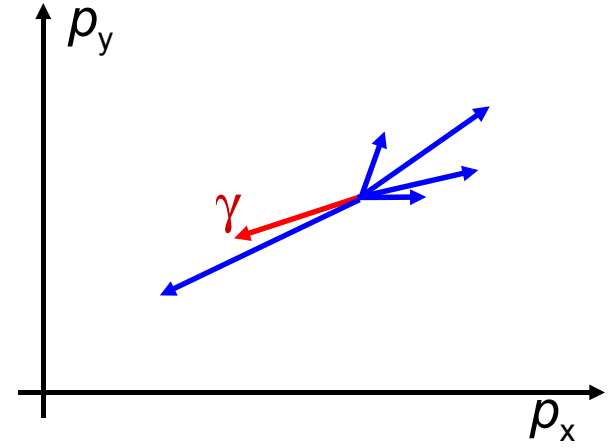
Isolated direct photons:
Limit on transverse energy E_T
in a cone around the photon





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Example of Isolation Cuts

- **Cone radius:** $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- **Fermilab experiments (p+$\bar{p}$ at $\sqrt{s}$ = 1.8 TeV):**
  - CDF: $E_T < 5$ GeV for $R < 0.65$
  - D0: $E_T(R \leq 0.4) - E_T(R \leq 0.2) < 2$ GeV

For a meaningful comparison with NLO pQCD, the experimental isolation cut needs to be translated into a theoretical cut.

This is not trivial.

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Subtraction Method

- **Determine inclusive photon spectrum**
  - Calorimeter
  - Tracking of conversion photons
- **Extract signifcance of direct photon signal**
  - Cocktail Method
  - HBT correlation strength
  - Internal conversions

$$\gamma_{direct} = \gamma_{inclusive} - \gamma_{decay}$$
$$= \left(1 - \frac{\gamma_{decay}}{\gamma_{inclusive}}\right)\gamma_{inclusive}$$
$$= (1 - 1/R)\,\gamma_{inclusive}$$

e.g with $R = \frac{(\gamma_{inclusive}/\pi^0)_{meas}}{(\gamma_{decay}/\pi^0)_{calc}}$

***R* contains the statistical and systematic significance of the direct photon signal**

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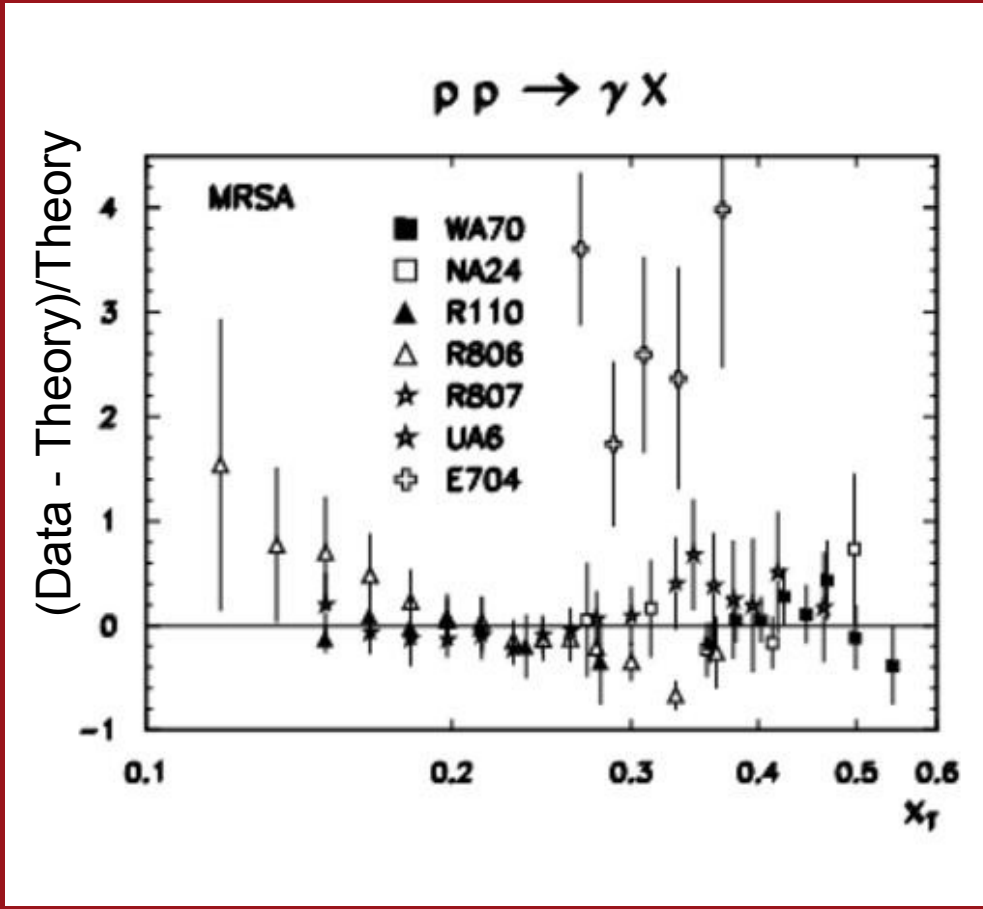
Measurements in p+p



W. Vogelsang J. Phys. G23 (1997)

- **First measurement in the late 1970s**
  - Today: $\sqrt{s_{NN}}$ = 19.3 – 1800 GeV
- **Momentum fraction of probed parton relevant**

$$x \approx x_T = \frac{2p_T}{\sqrt{s}}$$

- **Open issues/uncertainties**
  - Analysis cuts
  - Arbitrary choice of scales
  - Additional intrinsic k_T needed?
  - Gluon **PDF** poorly known
  - **FF($g/q \to \gamma$)**

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Direct Photon Measurement in A+A

- **Challenging**
  - Large decay background
  - High multiplicities
- **Two measurements:**
  - WA98:
    - Pb+Pb @ $\sqrt{s_{NN}}$ = 17.2 GeV
    - PRL **85** (2000) 3595
  - PHENIX:
    - Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
    - PRL **94** (2005) 232301

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- **Similar Methods**
  - Subtraction

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

  - Compare inclusive Photons to expectation from decay photons (Cocktail)

$$R = \frac{\gamma_{meas}}{\gamma_{bkgd}} = \frac{\left(\gamma/\pi^0\right)_{meas}}{\left(\gamma/\pi^0\right)_{bkgd}}$$

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Direct Photon Measurement in A+A

- **Challenging**
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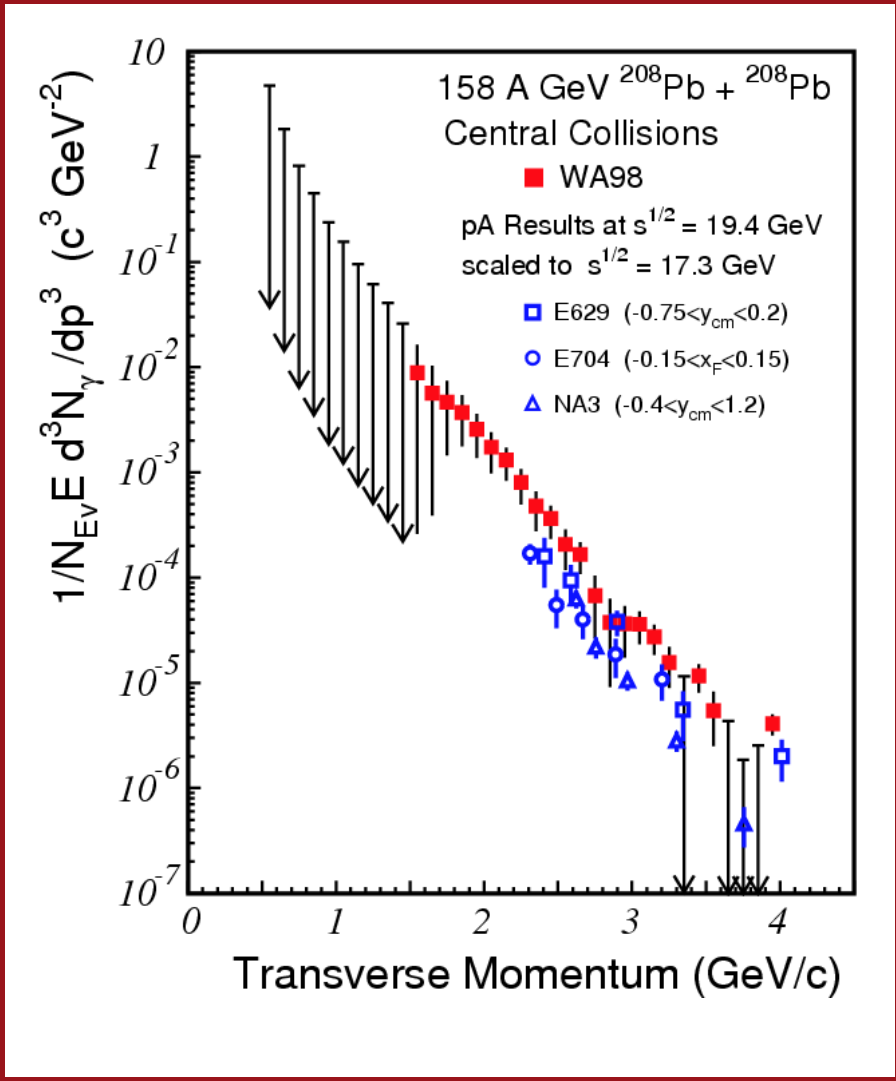

Details of the first Direct Photon Measurement at RHIC (Cocktail Subtraction)

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Measurement of Direct Photons with Cocktail Method

- **Get clean inclusive photon sample**
- **Measure p_T spectrum of π^0 and η mesons with high accuracy**
- **Calculate number of decay photons per π^0**
  - Done with Monte-Carlo
  - m_T scaling for (η), η', ω, …
- **Extract direct photon signal**
- **Finally:**
  Subtract decay background from inclusive photon spectrum

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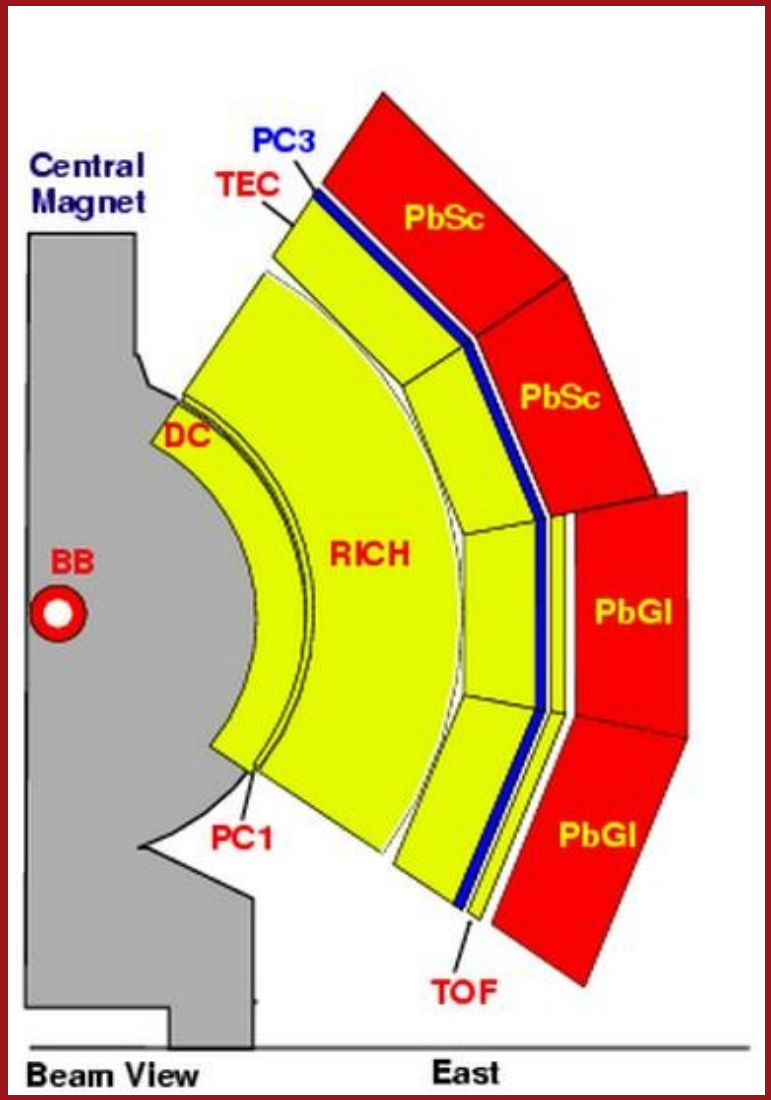
Direct Photon Measurement



- **Photon candidates**
  - 6 Sectors PbSc sandwich
  - 2 Sectors PbGl Cherenkow
- **Charged particles with PC3**

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Formula for Fully Corrected Inclusive Photon Spectra

fraction of neutral background (neutron, anti-neutrons)

fraction of charged clusters

$$\left.\frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{incl}} = \frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \cdot \frac{(1 - X_{\mathrm{n\bar{n}}}) \cdot (1 - X_{\mathrm{ch}})}{\varepsilon_\gamma \cdot a_\gamma \cdot c_{\mathrm{conv}}} \cdot \frac{\Delta N_{\mathrm{cluster}}}{\Delta p_{\mathrm{T}} \Delta y},$$

efficiency

acceptance

photon conversion

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Formula for Fully Corrected Inclusive Photon Spectra

fraction of charged clusters

$$\left.\frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{incl}} = \frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \cdot \frac{(1 - X_{\mathrm{n\bar{n}}}) \cdot (1 - X_{\mathrm{ch}})}{\varepsilon_\gamma \cdot a_\gamma \cdot c_{\mathrm{conv}}} \cdot \frac{\Delta N_{\mathrm{cluster}}}{\Delta p_{\mathrm{T}} \Delta y},$$

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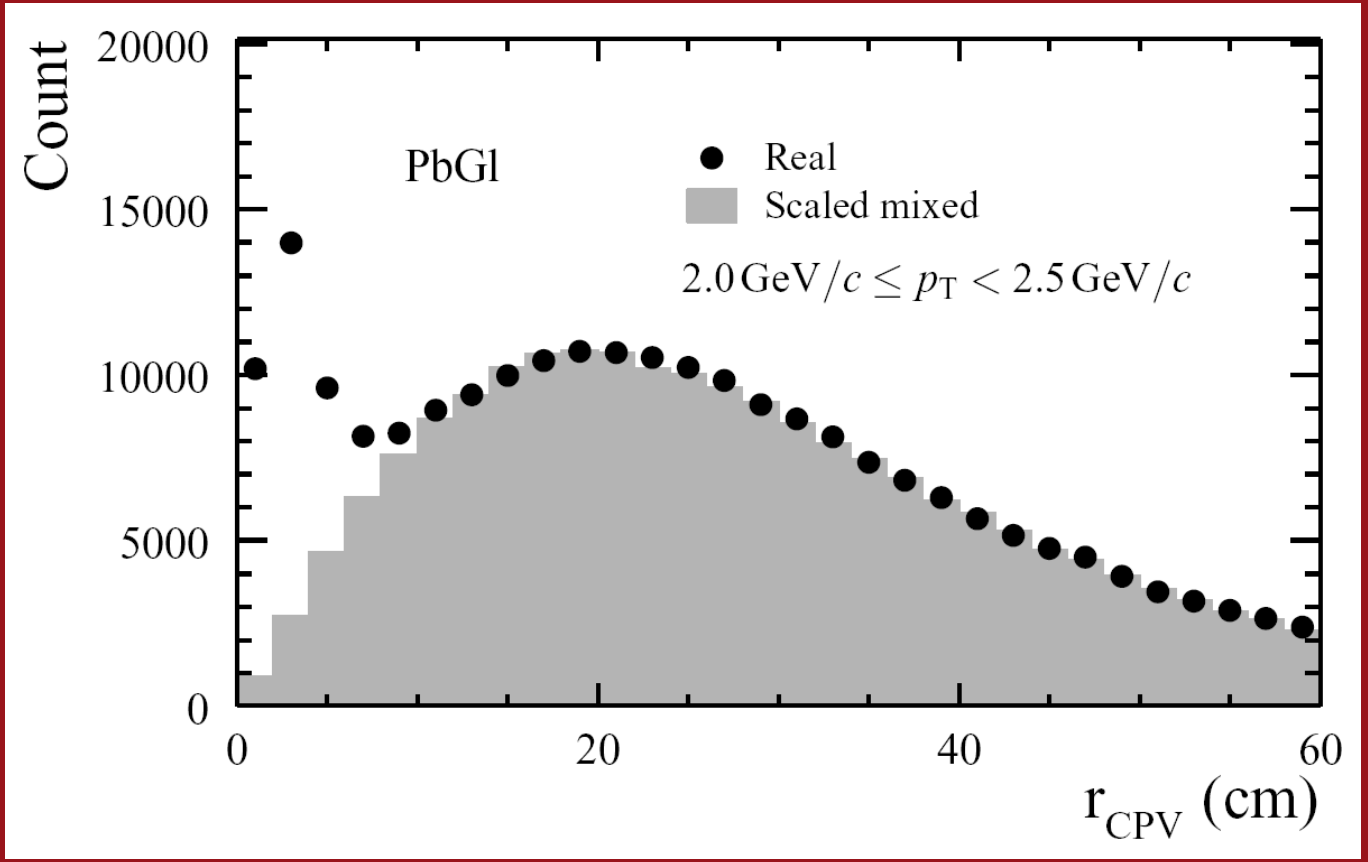
PC3 – EMCal Correlation



- r_{CPV}: distance to closest PC3 hit projection
- Random associations of PC3 and EMCal hits subtracted (event mixing)
- Background scaled to match real distribution at r_{CPV} > 30 cm

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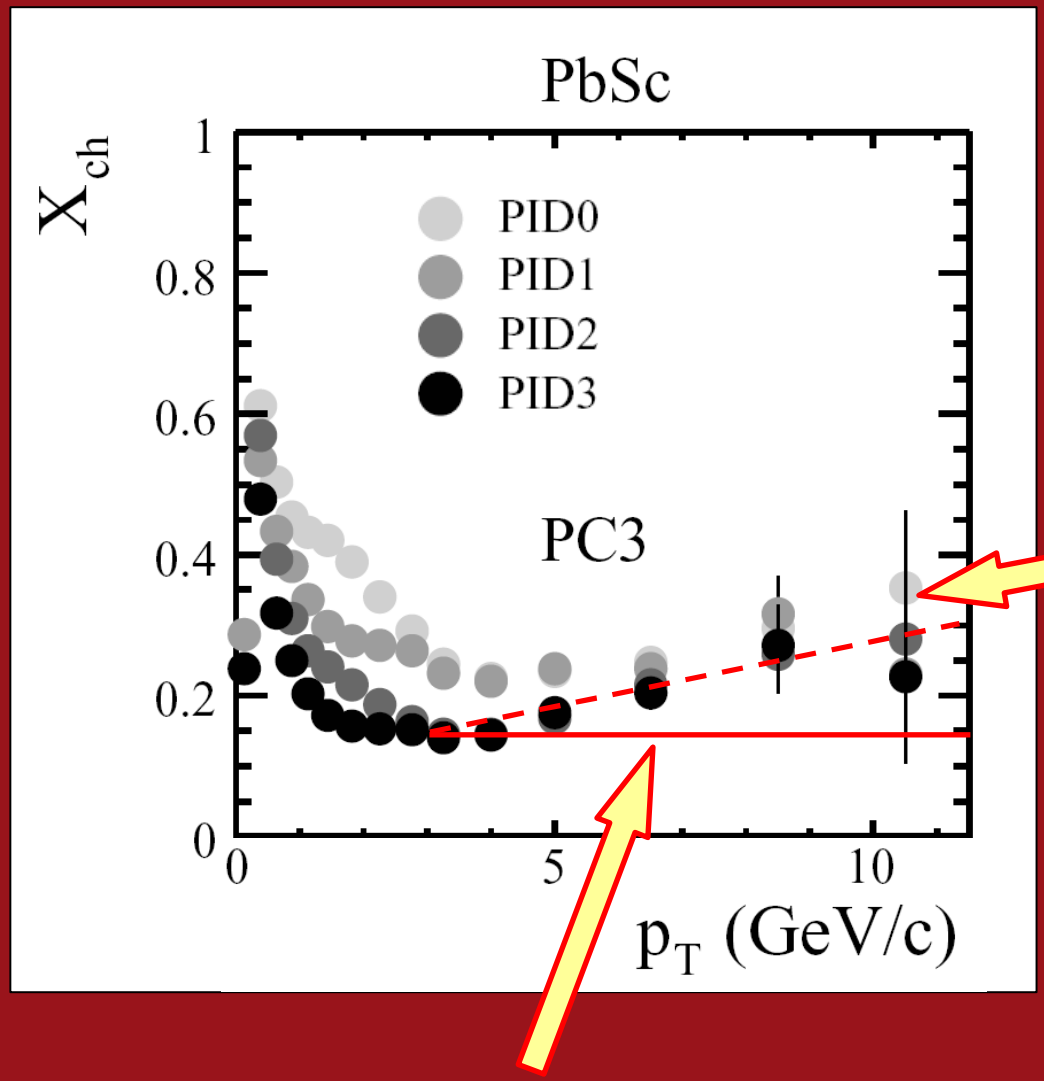
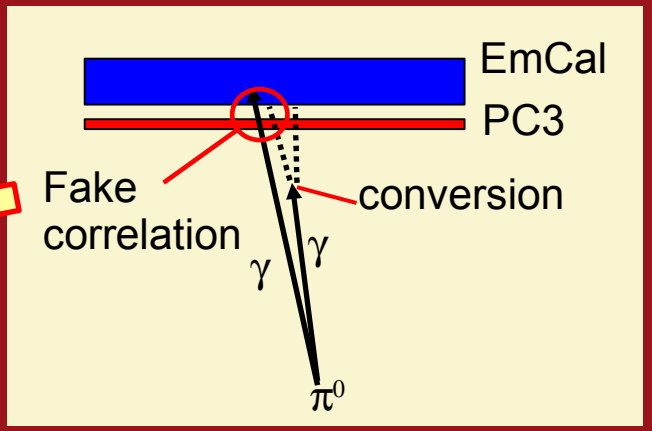
Charged Background: X_{ch}



final correction

- $X_{ch} > 0$ at high p_T largely due to photon conversion
- Artificial decay photon-PC3 correlations at high p_T:



- Verified with DC tracks
  - Closer to beam pipe
  - Less conversions
- MUST not be corrected: bias towards decay photons

Formula for Fully Corrected Inclusive Photon Spectra

fraction of neutral background (neutron, anti-neutrons)

$$\left.\frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{incl}} = \frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \cdot \frac{(1 - X_{\mathrm{n\bar{n}}}) \cdot (1 - X_{\mathrm{ch}})}{\varepsilon_\gamma \cdot a_\gamma \cdot c_{\mathrm{conv}}} \cdot \frac{\Delta N_{\mathrm{cluster}}}{\Delta p_{\mathrm{T}} \Delta y},$$

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Neutral Background: X_{nn}

- Background from neutrons and antineutrons needs to be simulated (PISA)
- Input neutron and anti-neutron spectra “determined” from measured proton and anti-proton spectra

$$\left.\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}\right|_{\bar{\mathrm{n}}} = \left.\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}\right|_{\bar{\mathrm{p}}},$$

$$\left.\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}\right|_{\mathrm{n}} = \left.\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}\right|_{\bar{\mathrm{p}}} + \left(\left.\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}\right|_{\mathrm{p}} - \left.\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y}\right|_{\bar{\mathrm{p}}} \right) \frac{A-Z}{Z}$$

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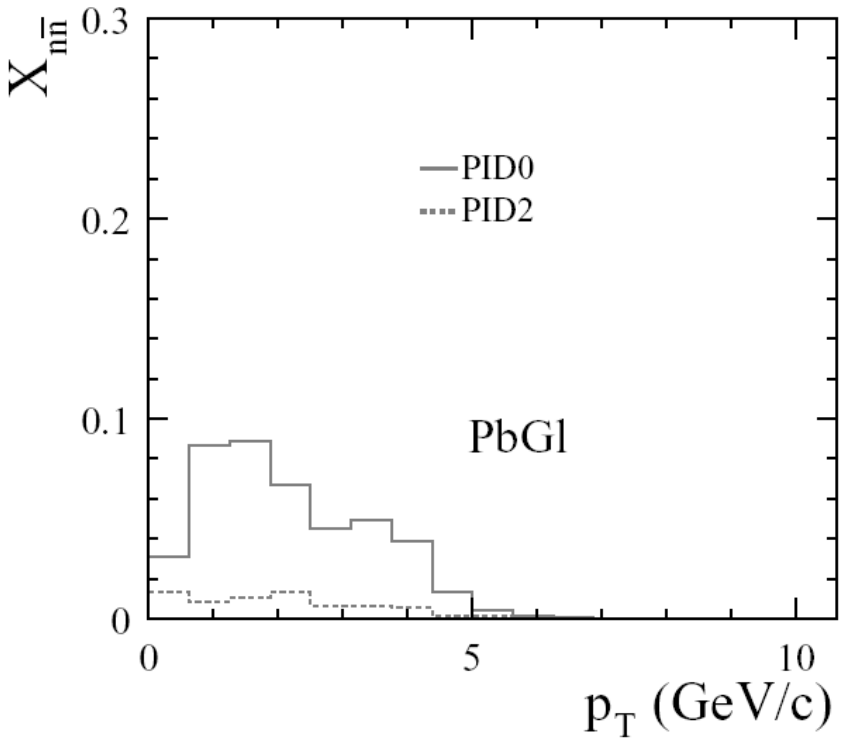
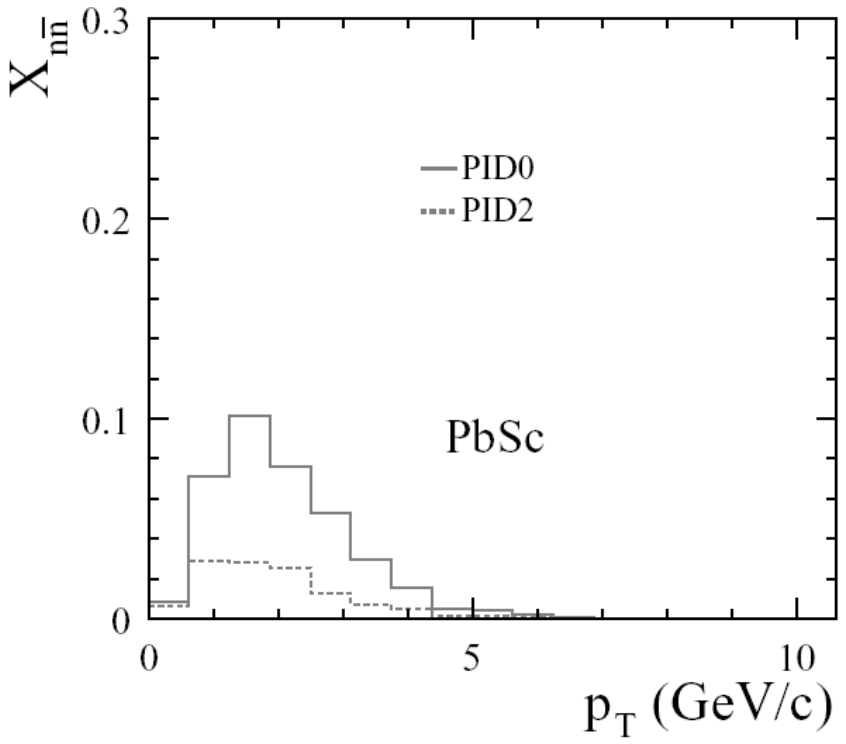
Simulation Results for X_{nn}





- **Neutral background negligible after TOF and shower shape cut (PID2)**

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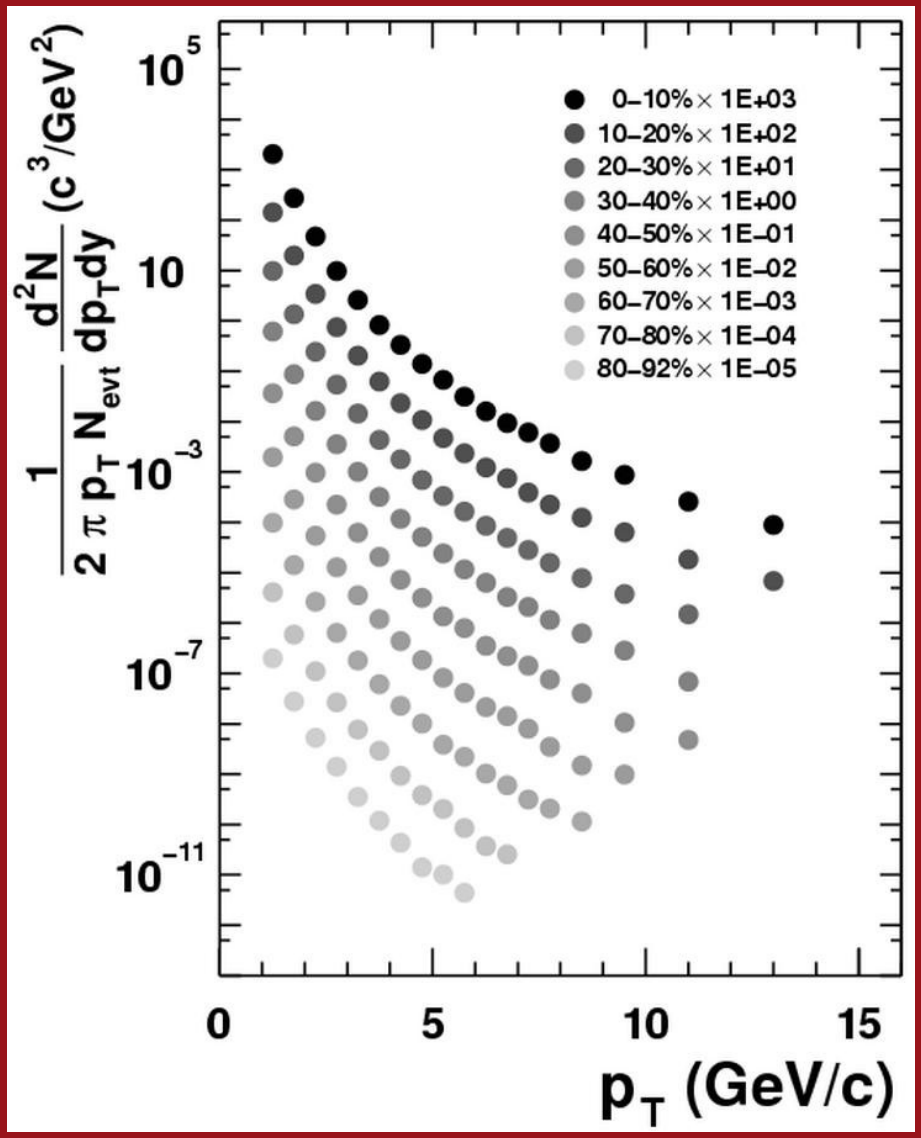
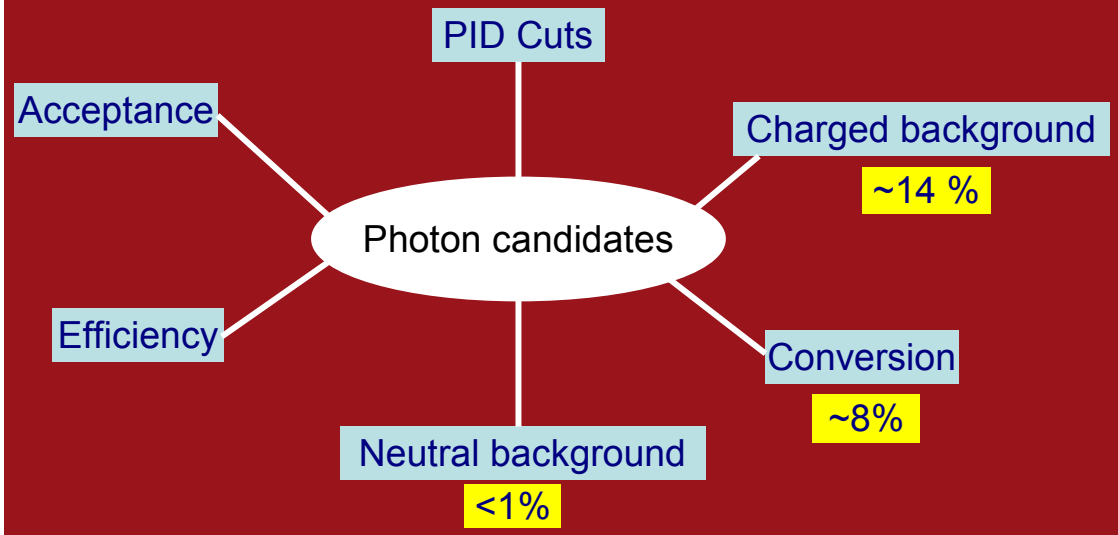
Inclusive Photons





- **Suffers from calorimeter resolution and background at low p_T**
  - Alternative approach via tracking of conversions ($\gamma \rightarrow e^+e^-$)
  - See talk by S. Bathe

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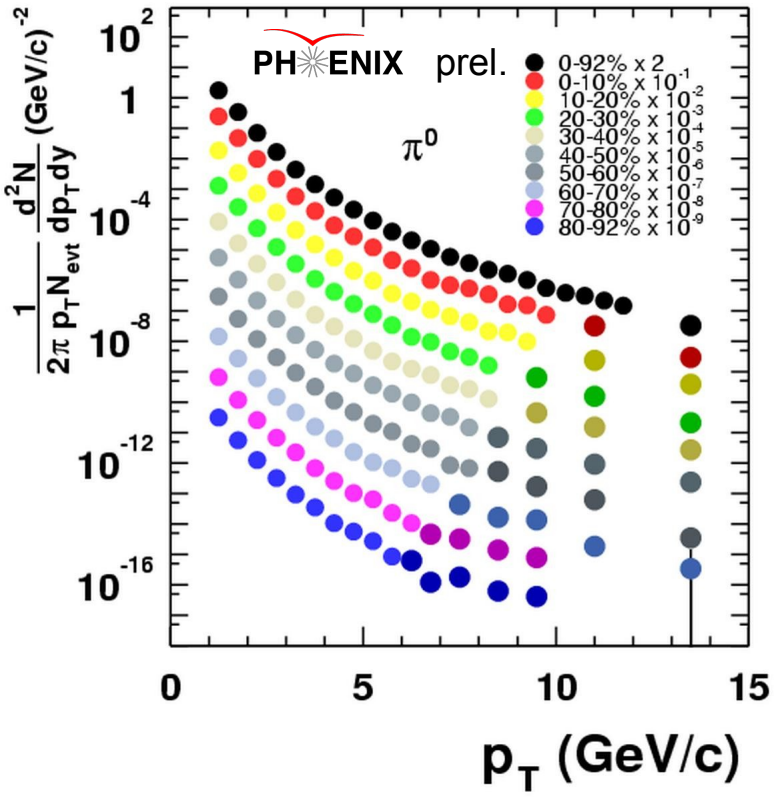
π^0 and η @ PHENIX

PRL **91**,072301 (2003) + high p_T triggered data



- **Reconstructed via 2γ decay**
- **Same suppression pattern**
  - PRL 96 202301 (2006)
  - Factor 5 in central Au+Au
  - Reduced decay background for direct γ measurement

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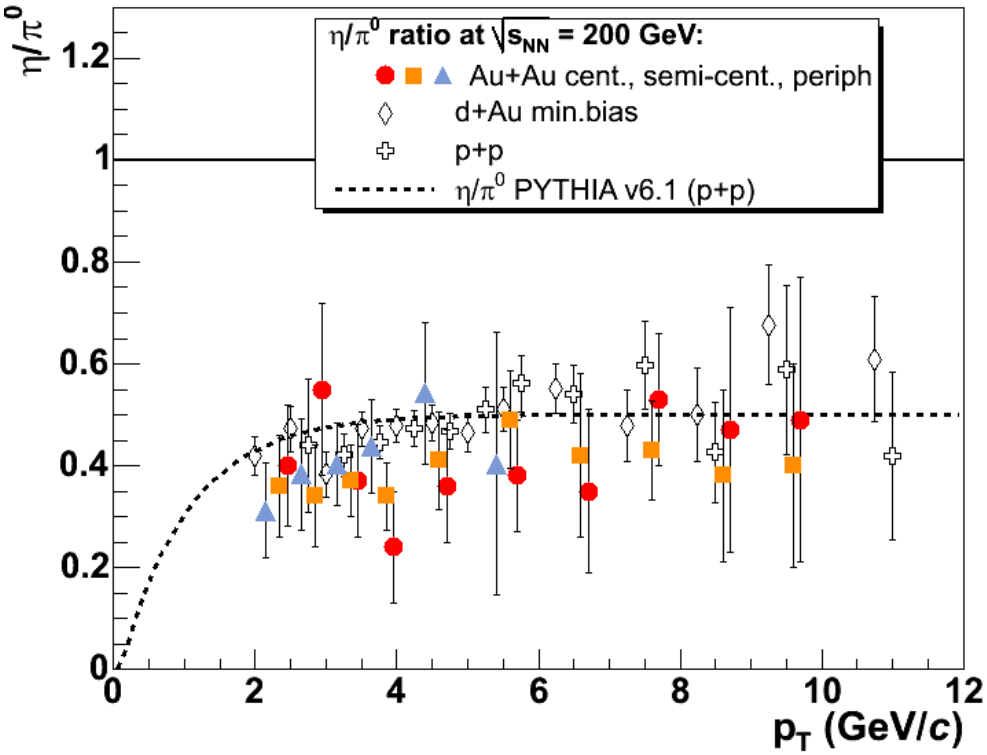

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- **Same suppression pattern**
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  - Reduced decay background for direct γ measurement
- **m_T-scaling works for η**

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

  - C_η ~ 0.45 for all species (p+p, d+Au, Au+Au) and centralities

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Measurement of Direct Photons with Cocktail Method

- **Get clean inclusive photon sample**
- **Measure p_T spectrum of π^0 and η mesons with high accuracy**
- **Calculate number of decay photons per π^0**
  - Done with Monte-Carlo
  - m_T scaling for (η), η', ω, …
- **Extract direct photon signal**
- **Finally:**
  Subtract decay background from inclusive photon spectrum

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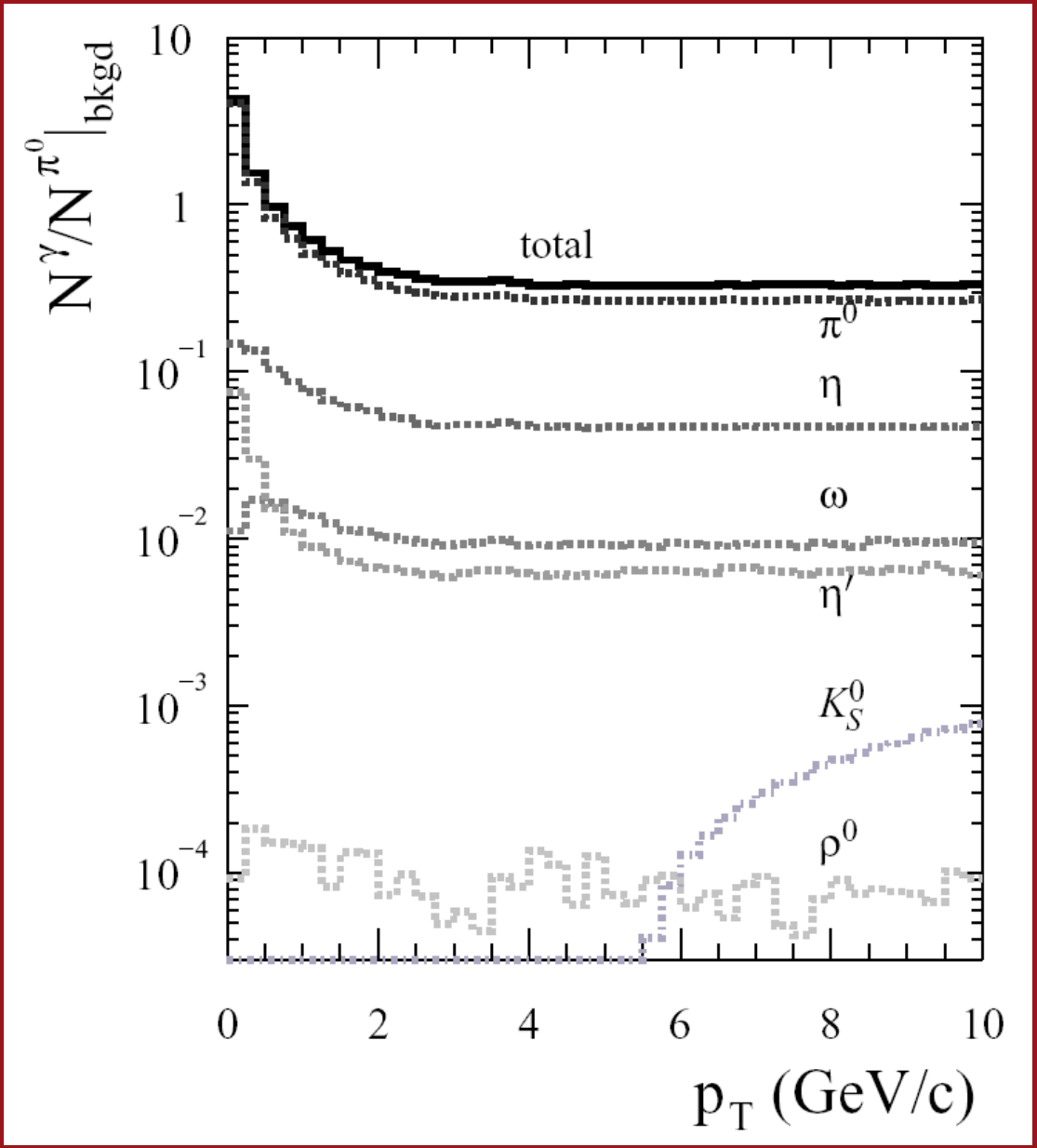
Decay Photon Background



- **Reference to compare:**

$$R = \frac{\gamma_{meas}}{\gamma_{bkgd}} = \frac{\left(\gamma/\pi^0\right)_{meas}}{\left(\gamma/\pi^0\right)_{bkgd}}$$

- **~96% background γ from π^0 and η (measured)**
- **Pocket formula:**

$$\frac{1}{p_T}\frac{dN^{\pi^0}}{dp_T} \propto 1/p_T^n$$

$$\rightarrow \frac{\gamma_{\pi^0}^{decay}}{\pi^0} = \frac{2}{n-1} \approx 0.29$$

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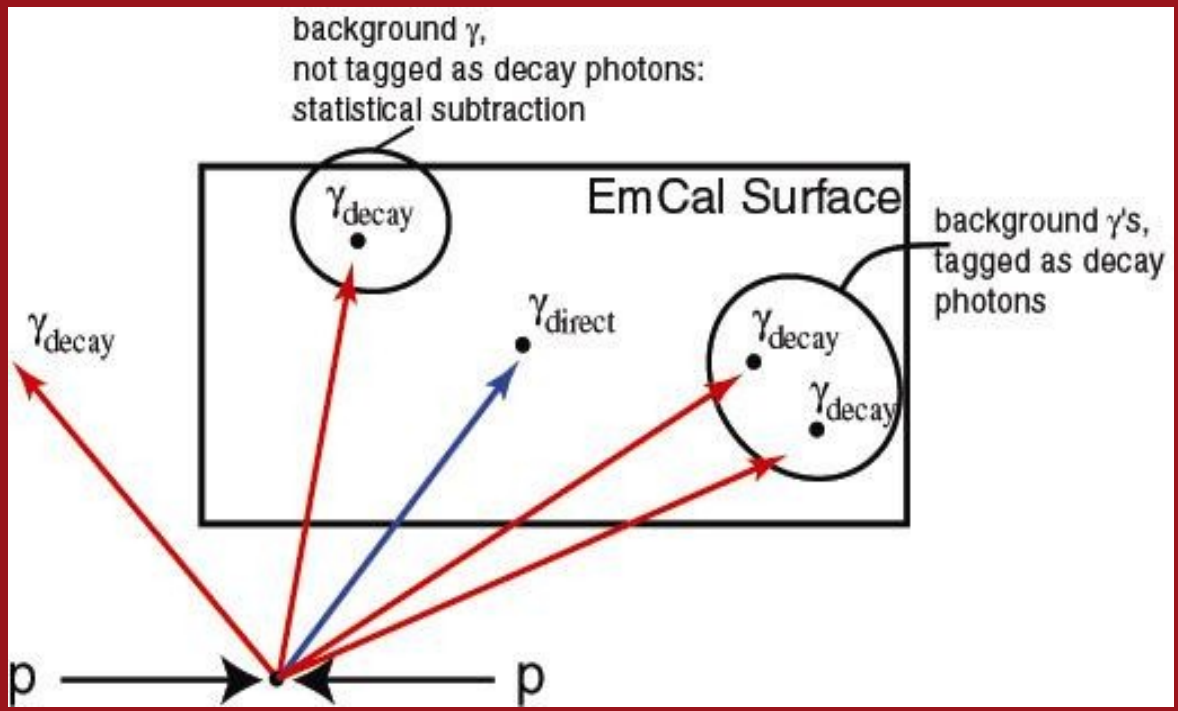
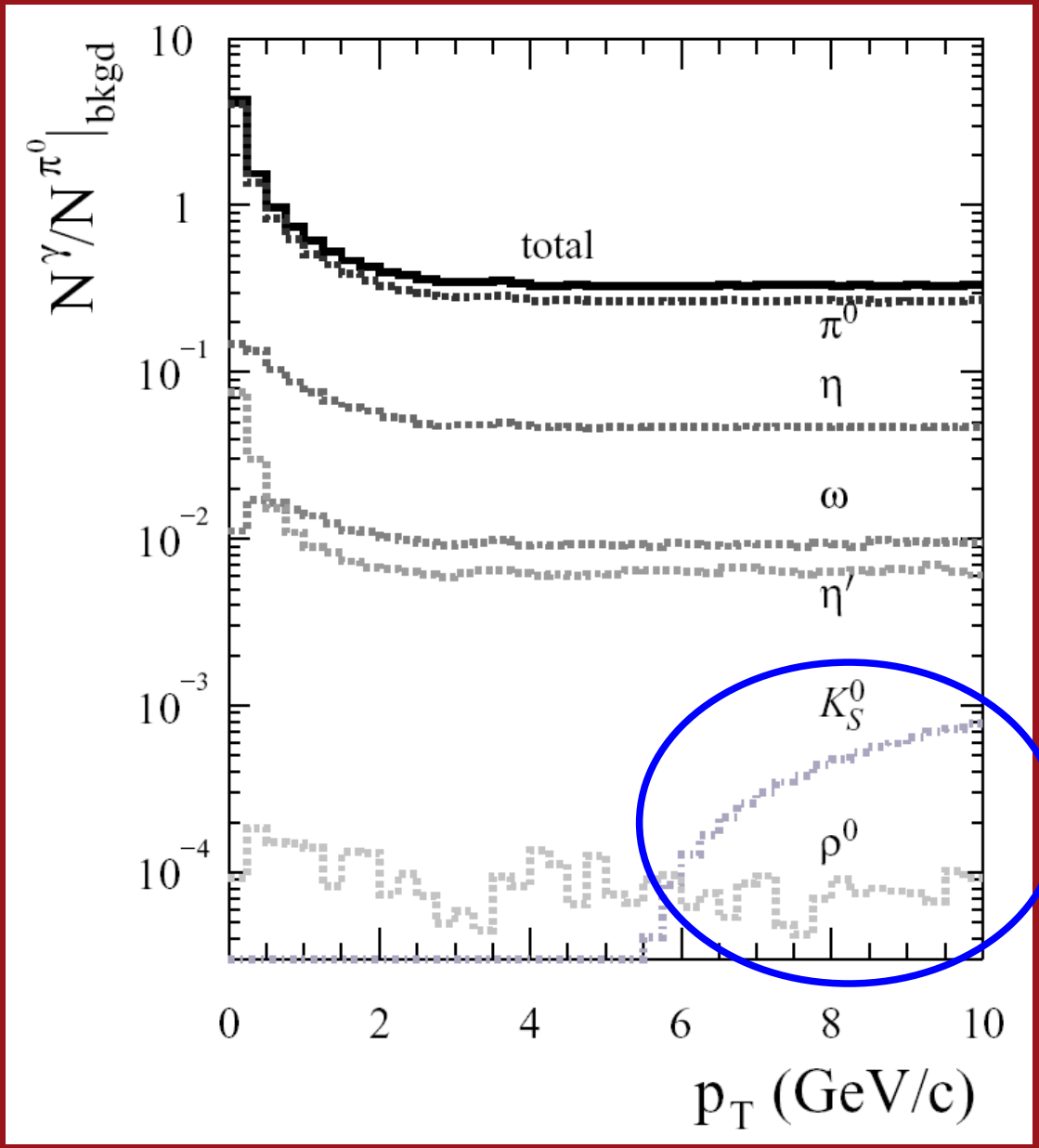
Side-Remark: π^0 and η tagging

- In low multiplicity environments the S/B ratio can be improved by accepting only those photons as direct photon candidates that don't form an inv. mass in the π^0 or η range (needs to be done in MC and real events)
- In central A+A collisions the number of random associations is too high for this approach



Decay Photon Background



- **~96% background γ from π^0 and η (measured)**
  - π^0 also includes $\eta \rightarrow (\pi^0\pi^0)$
- **Other hadrons via m_T-scaled π^0 spectra**
- **Monte Carlo based on JETSET**
  - $\pi^0 \rightarrow \gamma\gamma,\ e^+e^-\gamma$
  - $\eta \rightarrow \gamma\gamma,\ \pi^+\pi^-\gamma$
  - $\omega \rightarrow \pi^0\gamma \ldots$
  - $\eta' \rightarrow \rho^0\gamma \ldots$
  - $K_S^0 \rightarrow (\pi^0\pi^0)$

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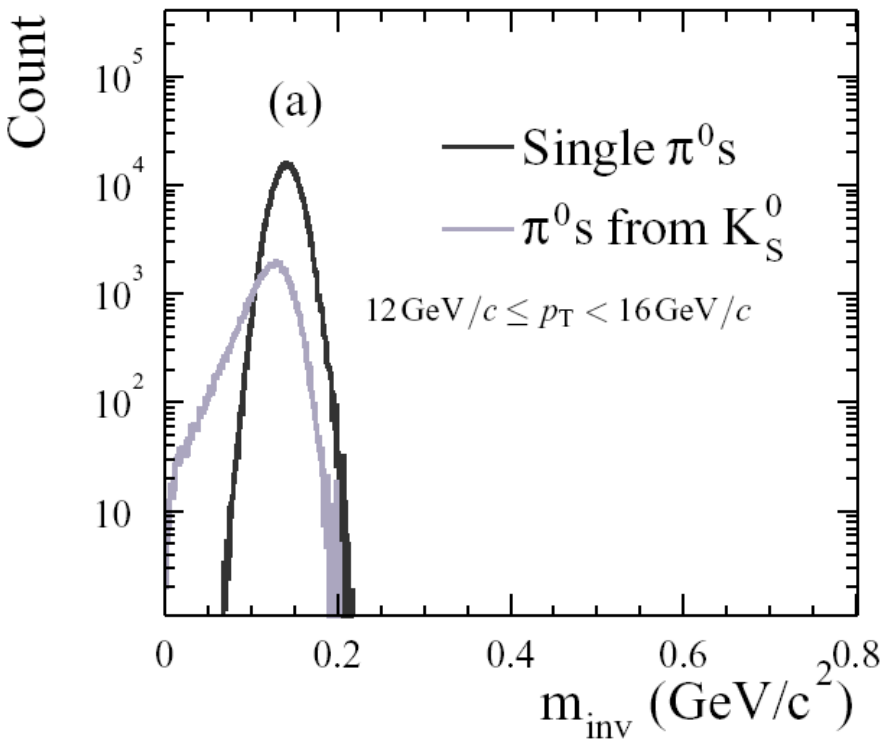
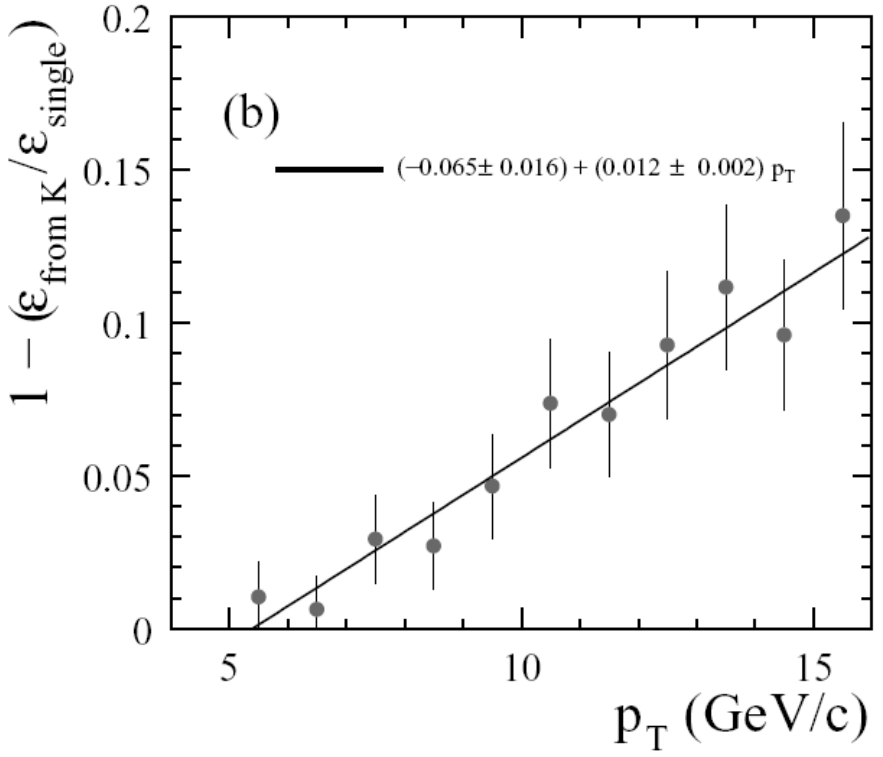
Background Photons from K_s^0

Probability to miss a π^0 from $K_s^0 \rightarrow \pi^0+\pi^0$
in the π^0 reconstruction due to displaced decay vertex





$K_S^0: c\tau_0 = 2.67\ \mathrm{cm}$ $\qquad L_{Lab} = \beta\gamma c\tau_0$ $\qquad \beta\gamma = \frac{p}{m_0 c}$

p	1 GeV/c	5 GeV/c	10 GeV/c
$\langle L_{Lab} \rangle$	5,37 cm	26,9 cm	53,7 cm

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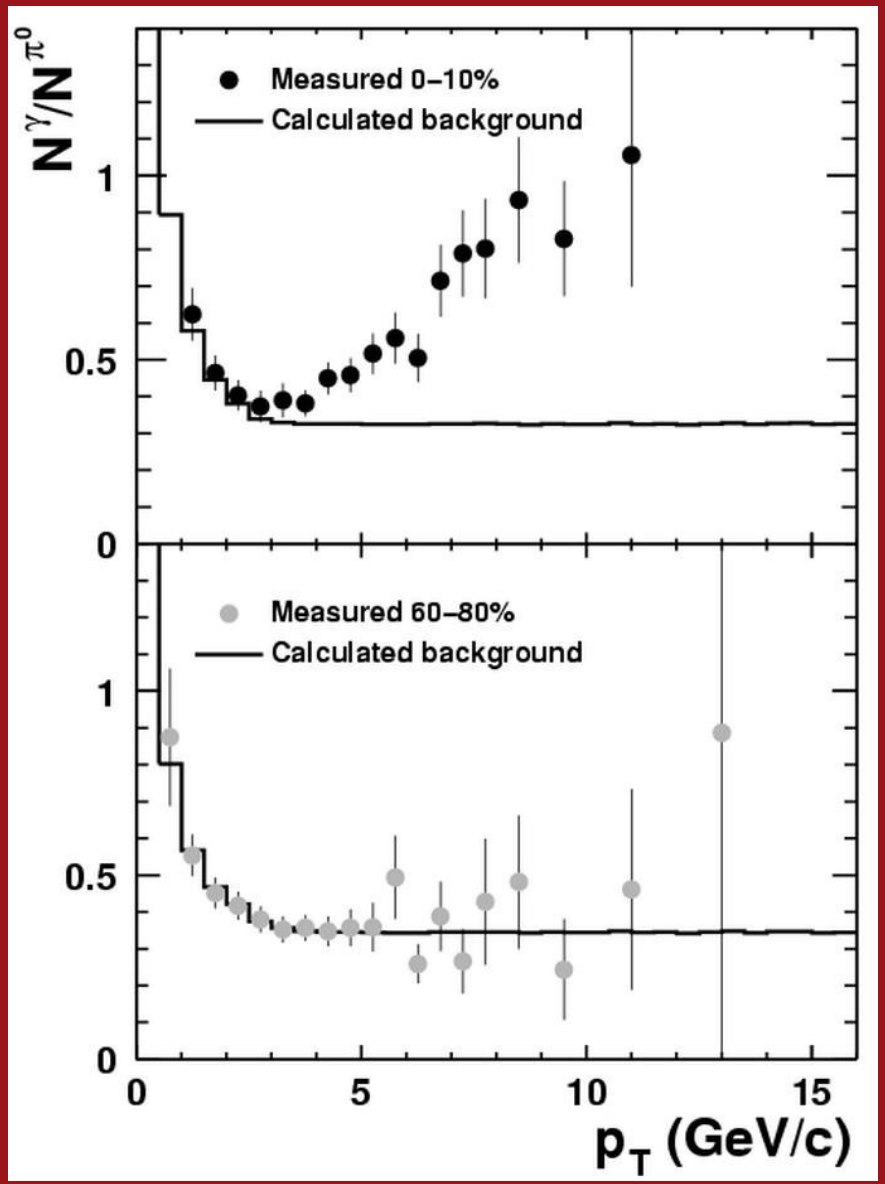
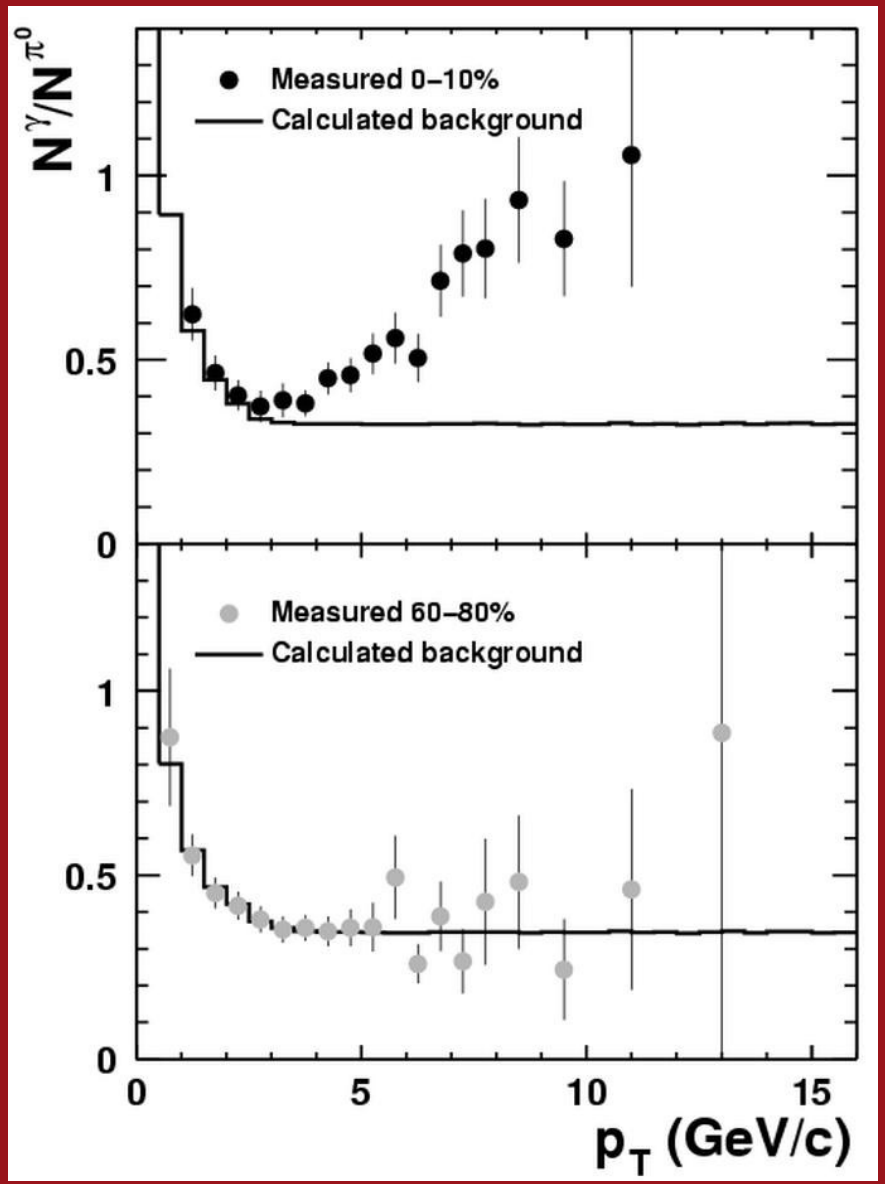
Direct Photon Signal



Direct Photon Signal



- **Double ratio *R* gives signifcance of the signal**

$$\frac{\left(\gamma/\pi^0\right)_{meas}}{\left(\gamma/\pi^0\right)_{decay}} = \frac{\gamma_{meas}}{\gamma_{decay}}$$

- **Many systematics cancel**
  - Energy scale
  - Photon efficiency and acceptance
  - Photon conversion

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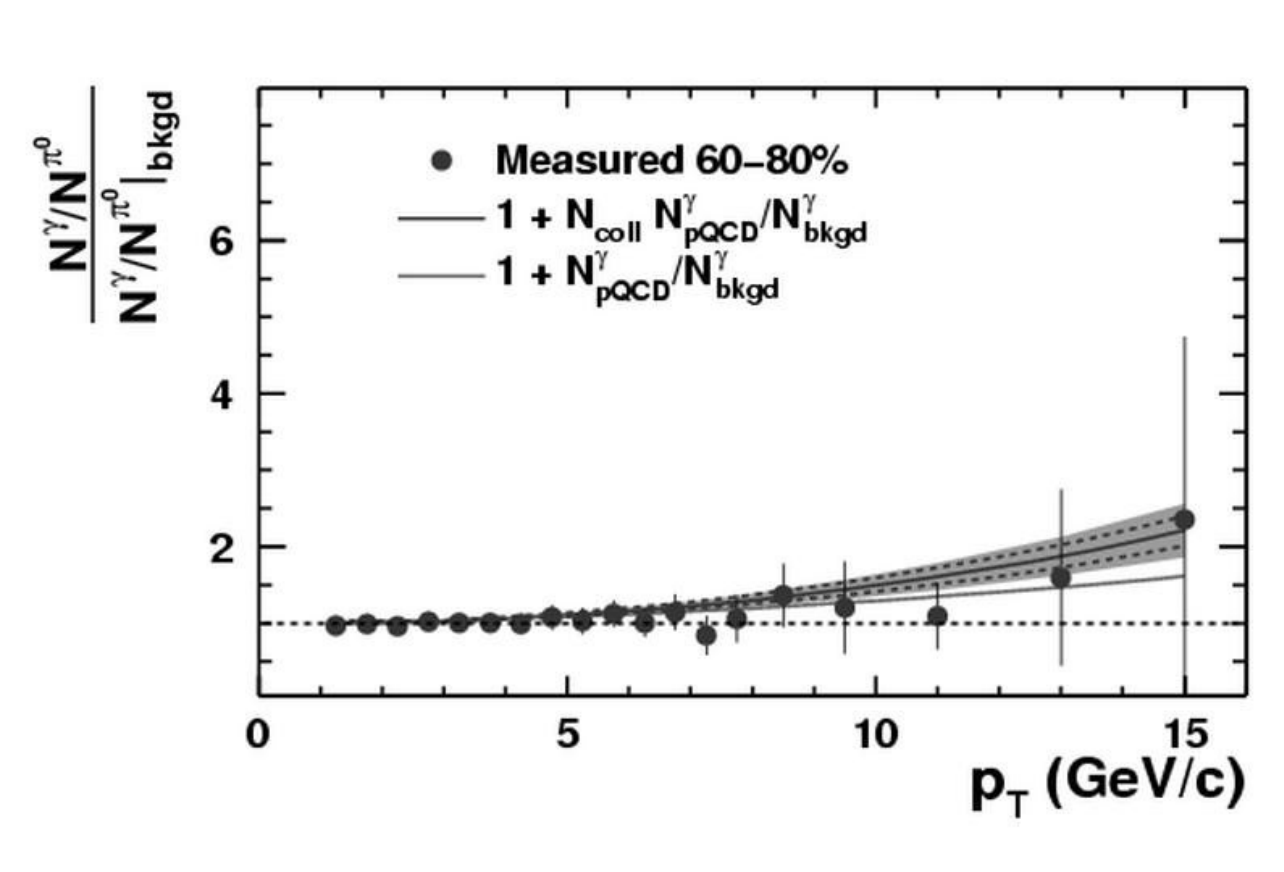
Uncertainties in PHENIX-Run2 Au+Au

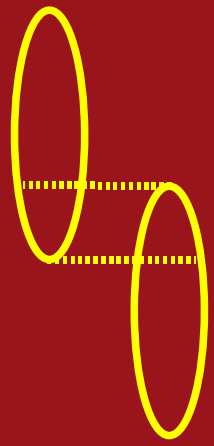
π^0 error source	PbGl 3.25 GeV/c	PbGl 8.5 GeV/c	PbSc 3.25 GeV/c	PbSc 8.5 GeV/c
Yield extraction	8.7%	7%	9.8%	7.2%
Yield correction	12%	12%	12%	13.3%
Energy scale	13.8%	14.1%	10.5%	11.4%
Total systematic	20.3%	19.5%	18.8%	19%
Statistical	10.6%	32.5%	3%	13.1%
γ error source				
Non-γ correction	2.4%	2.4%		
Yield correction	10.2%	12.0%		
Energy scale	15.7%	13.7%		
Total systematic	18.9%	18.4%	16.5%	16.7%
Statistical	1.2%	14.1%	0.7%	7.9%
γ/π^0 syst.	10.4%	10.4%	10.6%	10.6%
γ/π^0 stat.	10.7%	37.7%	3%	16.5%

Treating photon and π^0 measurements as independent would yield a 28% systematic uncertainty for γ/π^0

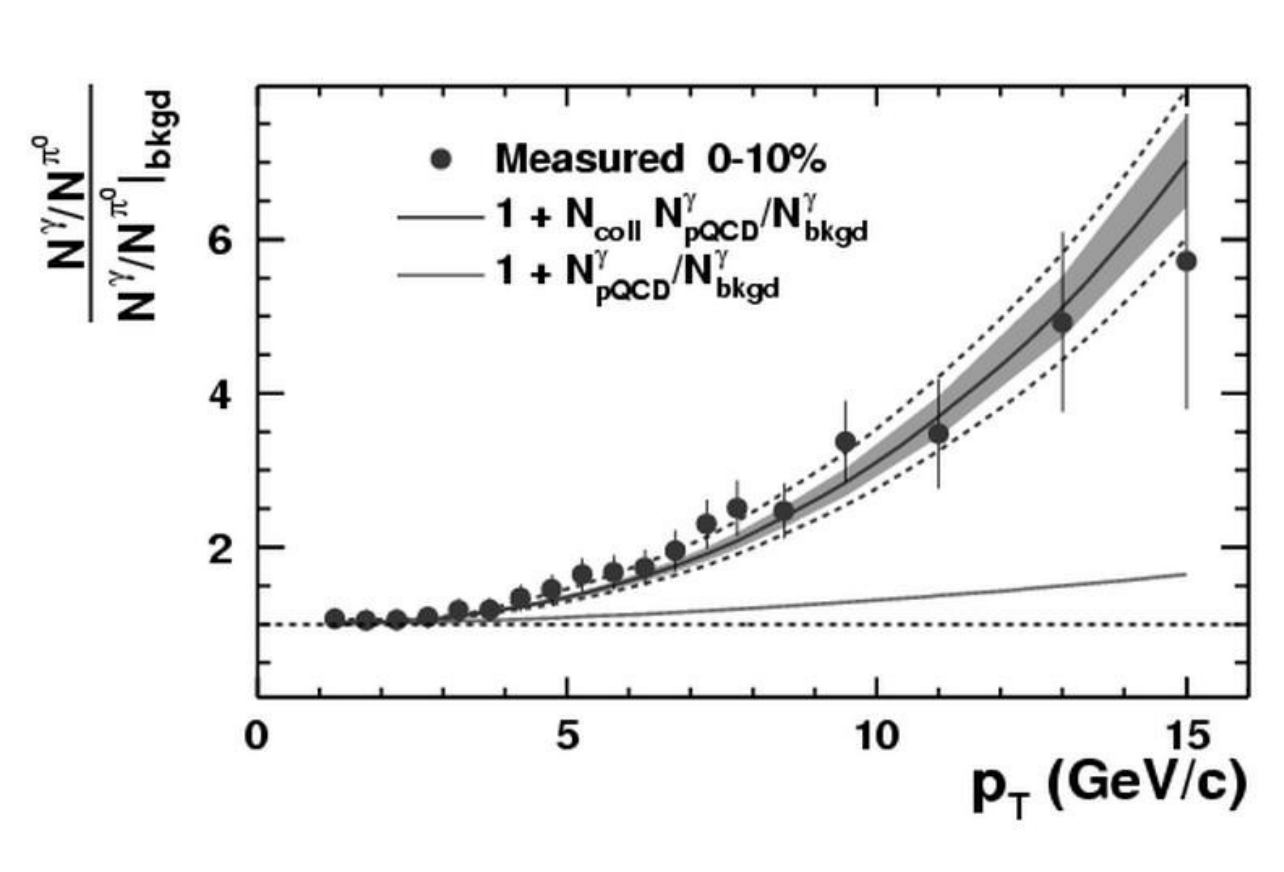
PRL **94** (2005) 232301

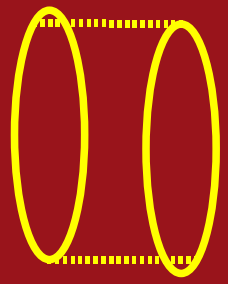
$\gamma_{meas}/\gamma_{incl}$





$\gamma_{meas}/\gamma_{incl}$





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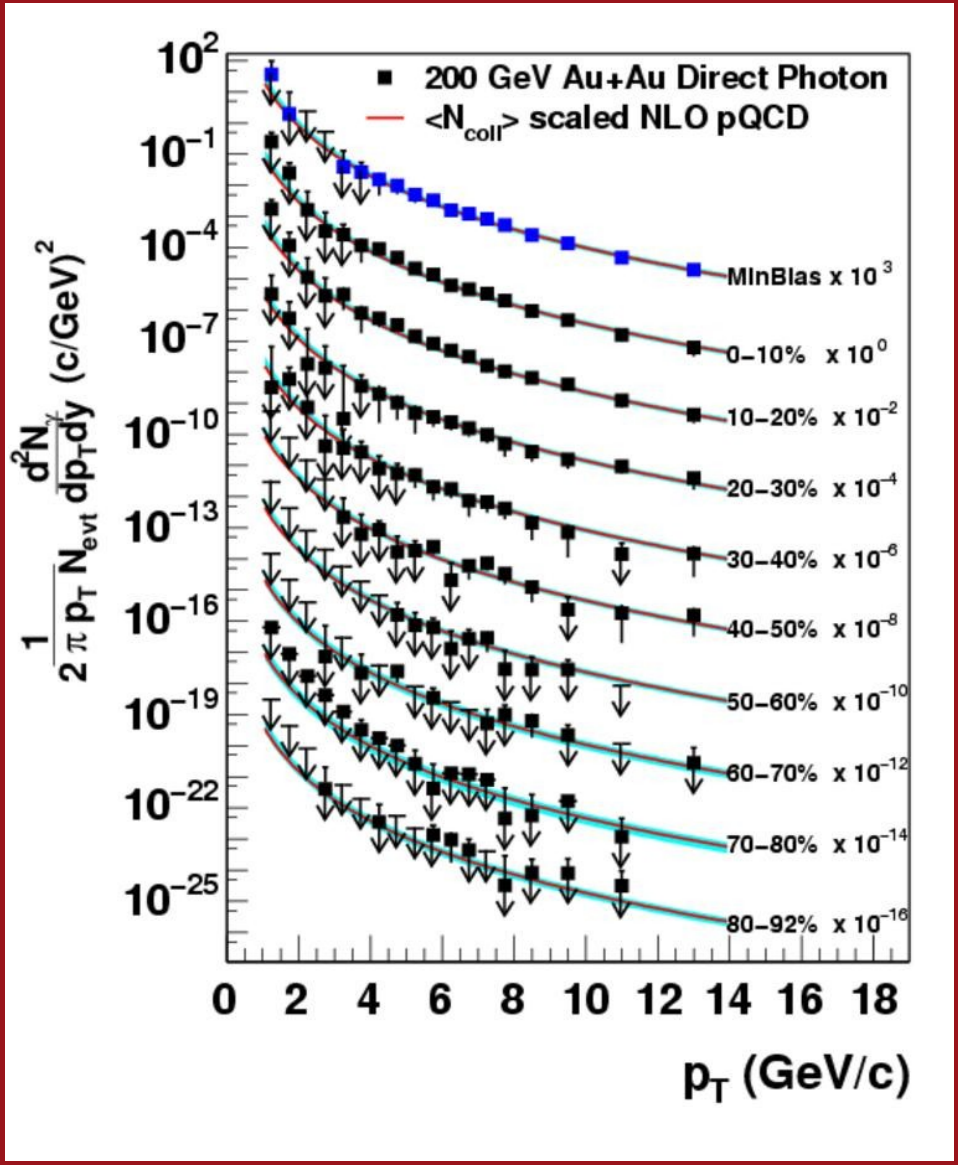
  Subtract decay background from inclusive photon spectrum

Direct Photon Spectra



- Direct photon yield

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

- Consistent with scaled p+p calculation

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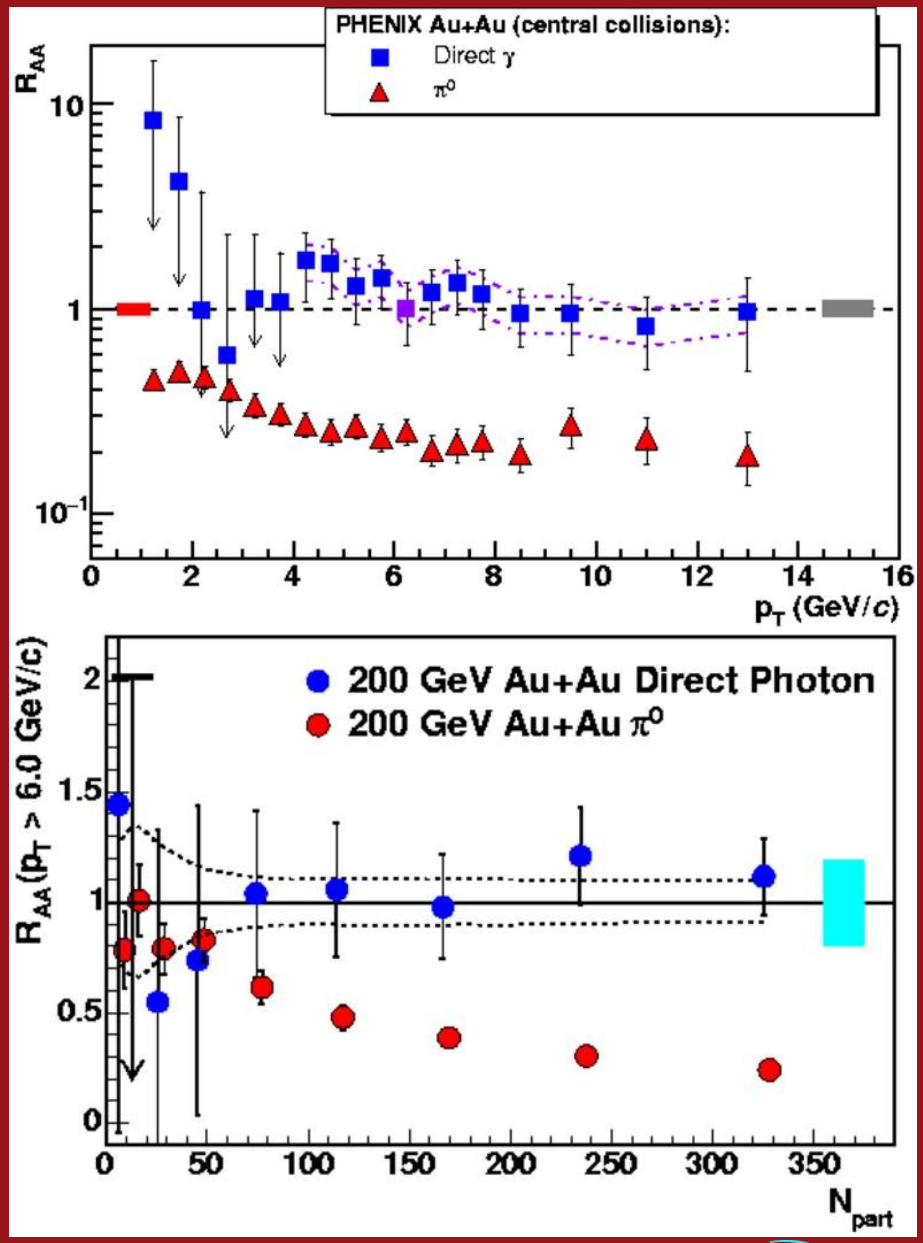
R_{AA} for direct γ vs. π^0

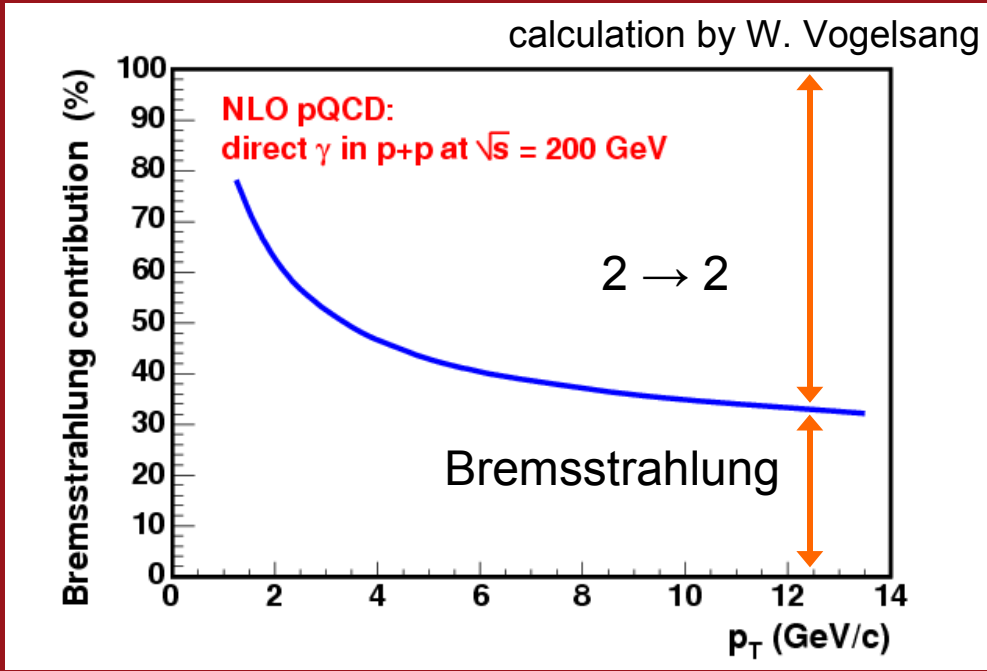


- **R_{AA} for direct photons**
  - Comparison on linear scale

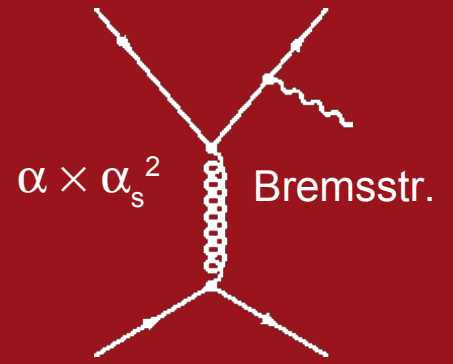
$$R_{AA} = \frac{d^2 N_{AA}/dydp_T}{T_{AA}\, d\sigma_{pp}/dydp_T}$$

- **Direct photons are not suppressed**
  - Initial state **not** responsible for π^0 deficit
  - $\frac{d^2\sigma}{dp_T dy} = \int \mathrm{PDF} \times \mathrm{pQCD} \times \mathrm{FF}(E \to E')$

But...



- **... Shouldn't we see some suppression:**



- **Consider also multiple scattering and gluon/photon formation time**

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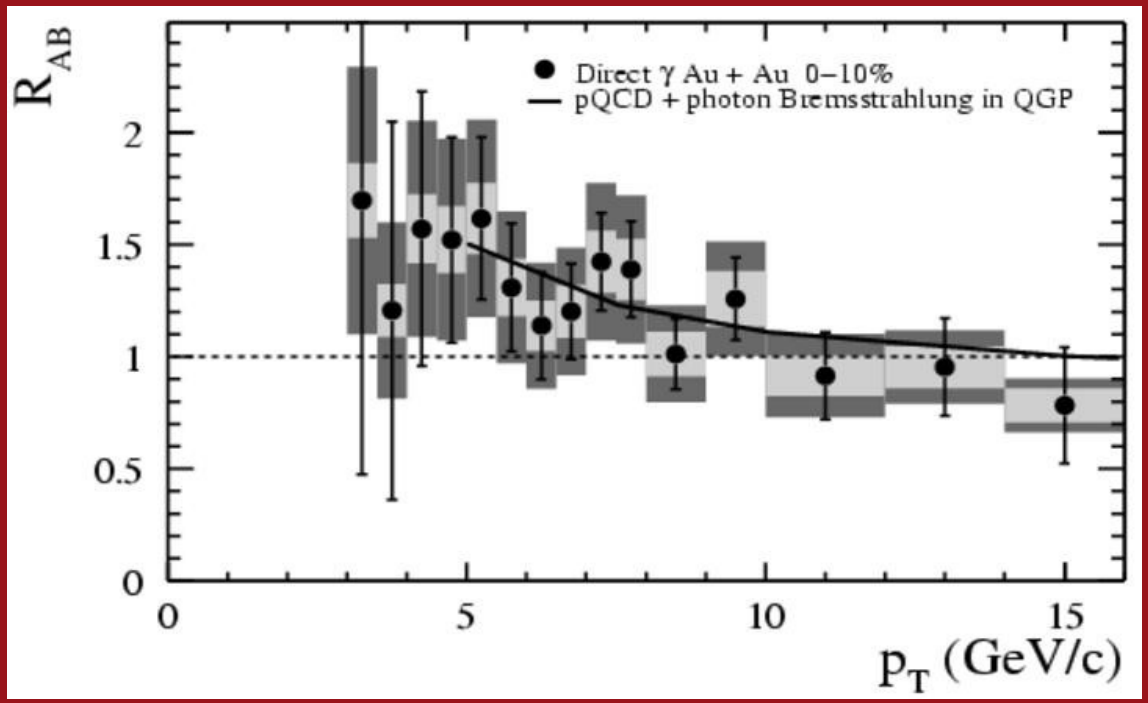
Bremsstrahlung of hard scattered Quarks



- **Including multiple scattering and energy loss**
  - Zakharov JETP Lett. 80 (2004)
- **Only pQCD reference, need p+p**
- **d+Au for nuclear effects**

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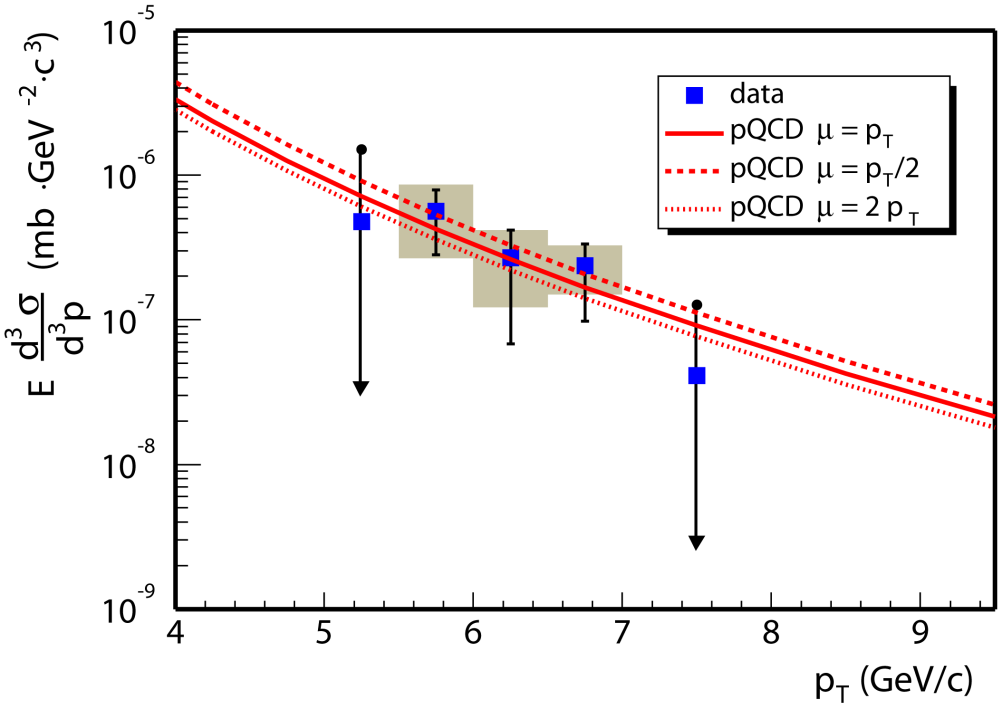
Direct Photons Run02 p+p



- **Cocktail subtraction with tagging**
  - 900 M Events ~ 41 nb^{-1}
- **Only three significant points**
- **Confirmation of pQCD**

Phys. Rev. D71, 071102 (2005)

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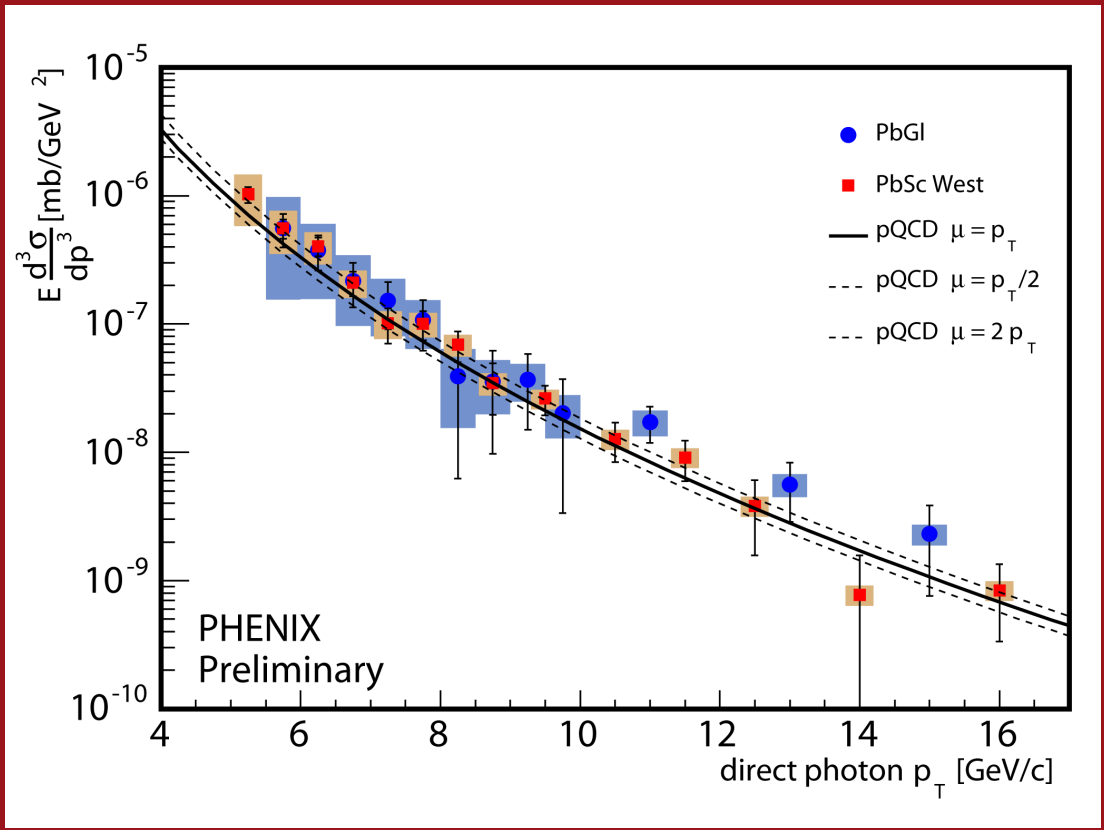
Direct Photons Run03 p+p



- **Cocktail subtraction**
  - 10*Run02 ~ 0.35 pb^{-1}
- **Two independent analyses**
- **Very good agreement with pQCD**

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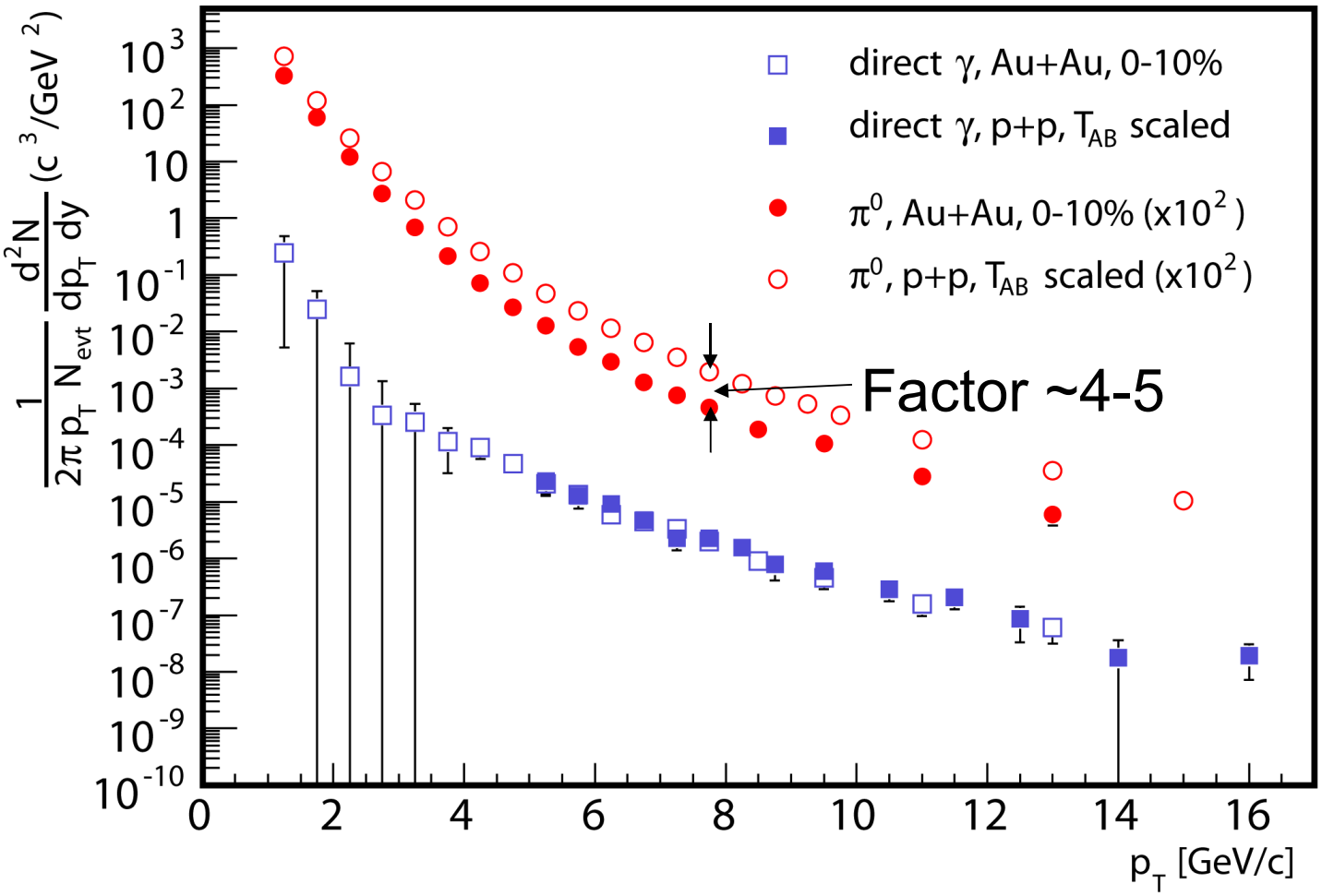
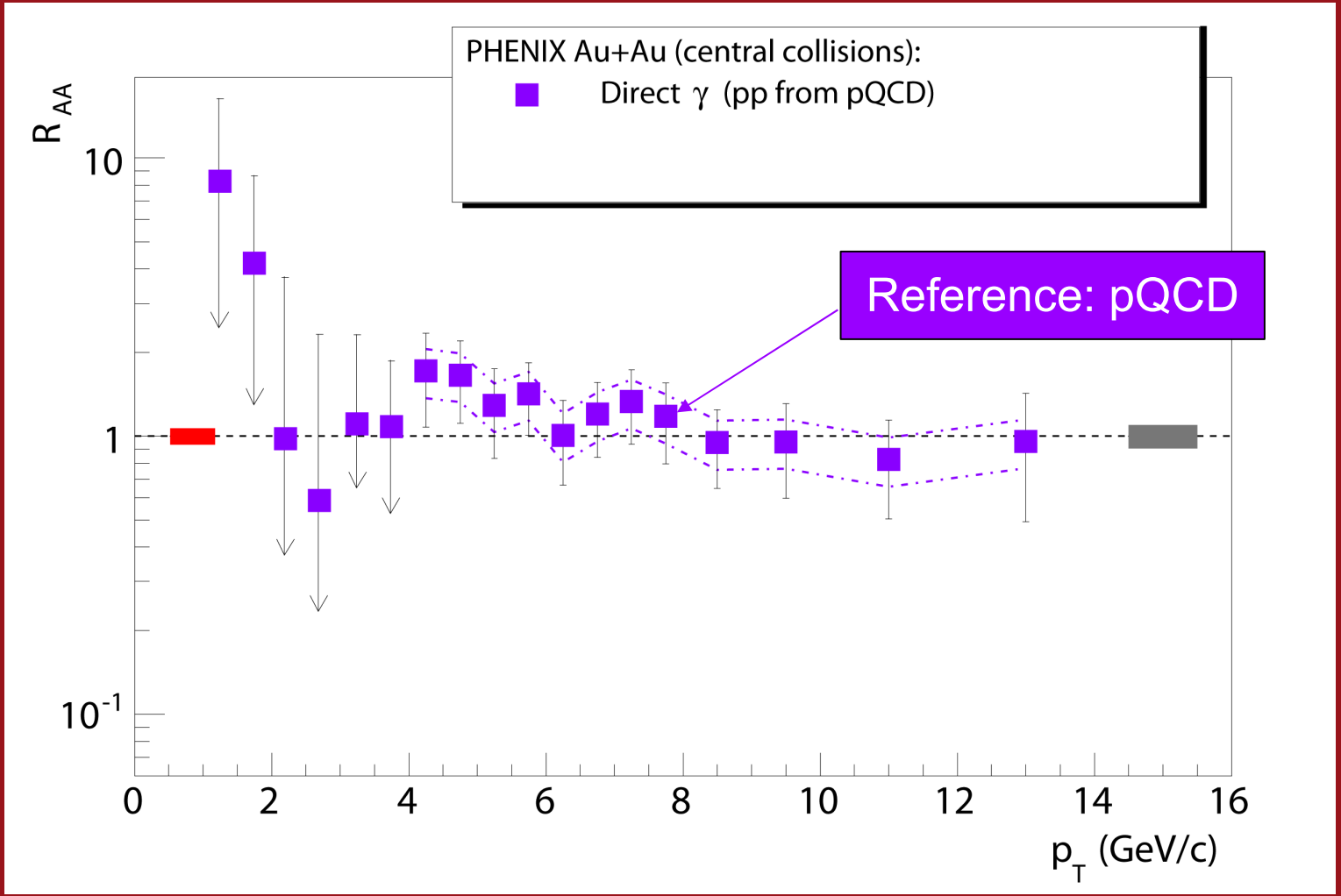
Spectra in p+p vs. Au+Au

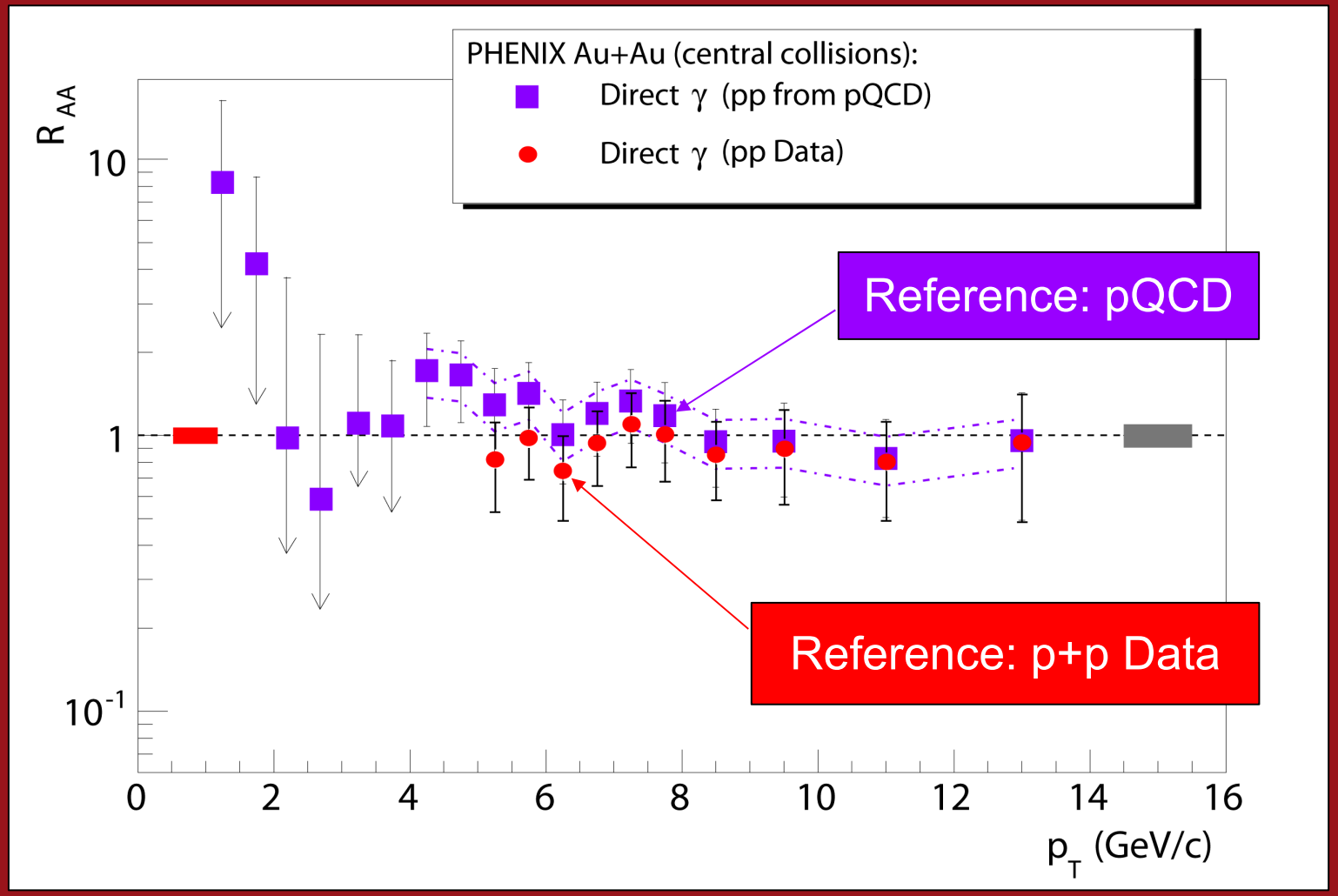


T_{AB} -scaling works perfect also with measured direct γ

Direct Photon R_{AA}



Direct Photon R_{AA}



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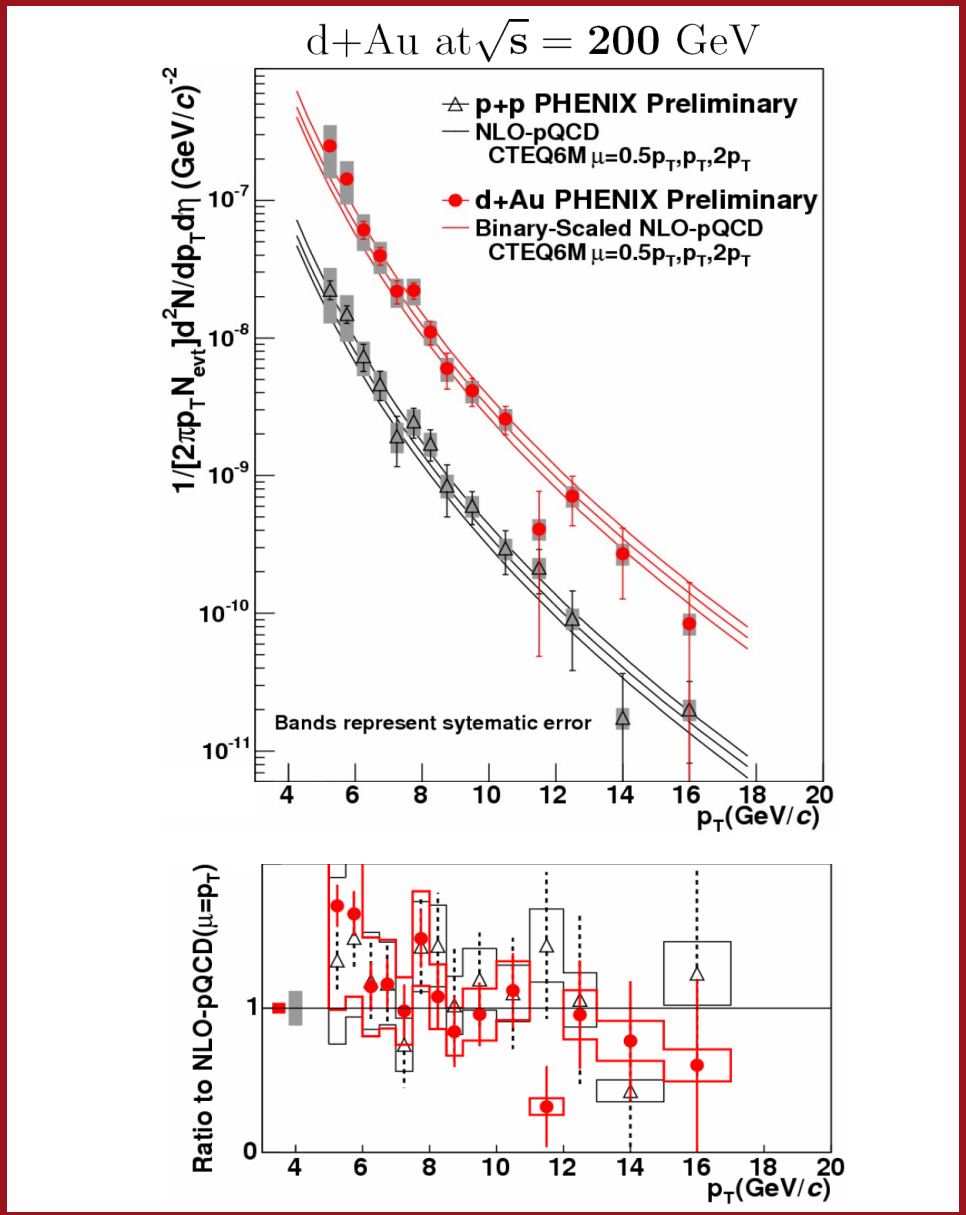
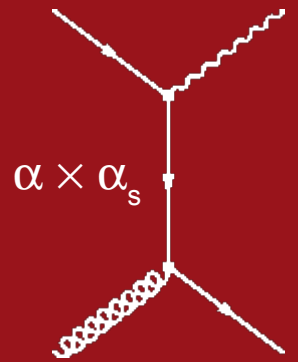
Nuclear Effects in d+Au?



- Directly sensitiv to gluon PDF (CGC?)



- No effect at high p_T
- Similar to high p_T π^0

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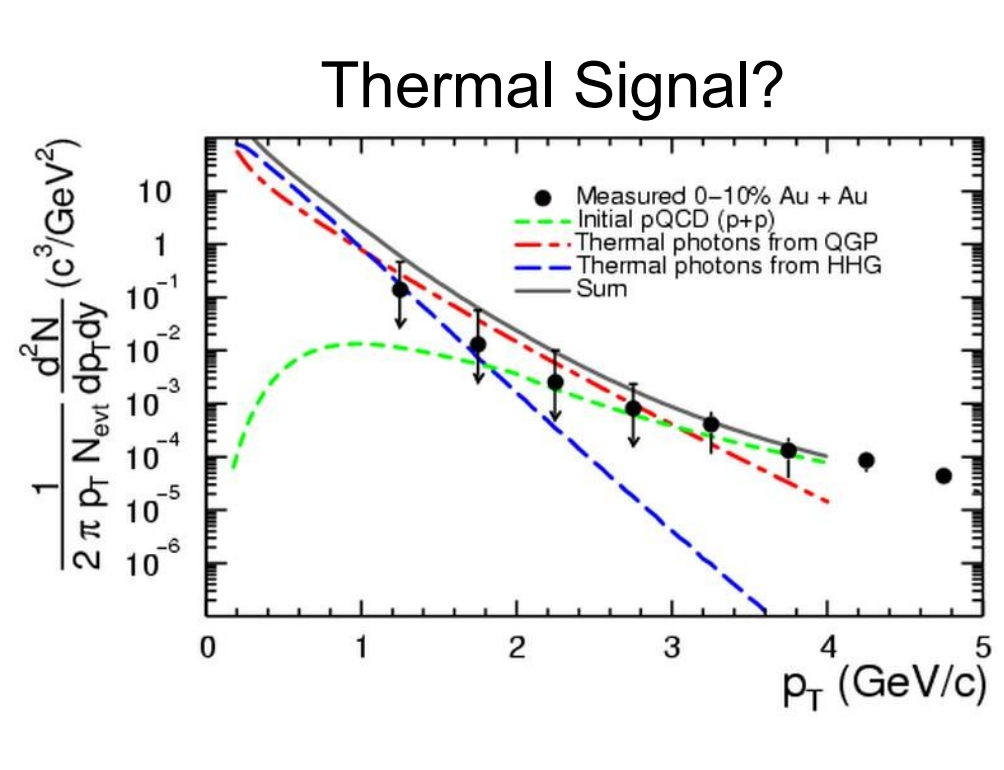
What we missed in this talk?



- **Many interesting effects at lower p_T**
- **Need refined methods**
  - Conversions (internal and external)
  - HBT correlation strength
  - Reaction plane dependence
- **See S. Bathe's talk**

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Summary

- **No suppression of direct photons at high p_T in central Au+Au reactions at PHENIX/RHIC**
  - Direct control for hard scattering and strong energy loss of partons
- **First measurement of direct photons in p+p nearly 30 years ago, in HIC only 6 years (WA98)**
  - At the moment only the very high p_T part (a.k.a the scaled p+p part) is theoretically under control/understood!!
  - Again 30 years needed?

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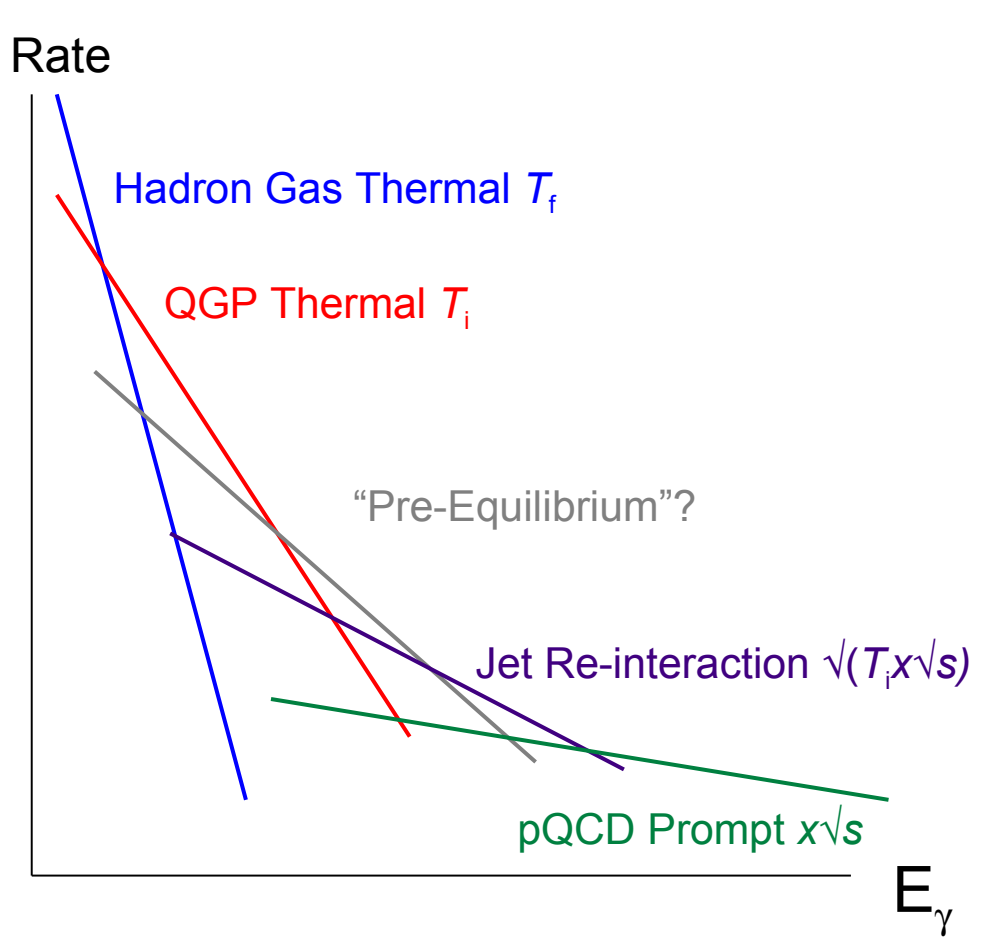
30 years needed? No!



Turn all experimental knobs!!

- **A wealth of data available and analyzed right now!**
  - with new methods
  - Au+Au (x10 Run02)
  - p+p (x100 Run03)
  - Cu+Cu
  - 22 GeV, 62 GeV, 200 GeV
  - ...
- **And will be coming with**
  - LHC
  - RHIC upgrades

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Thanks

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Isolation Cut in PHENIX

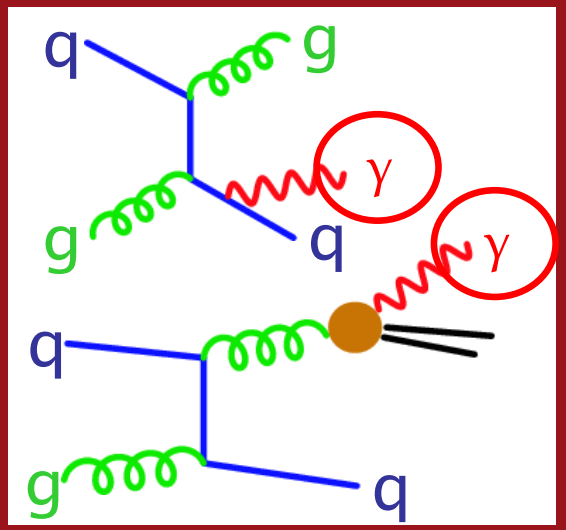
- **What fraction of direct photons is isolated?**

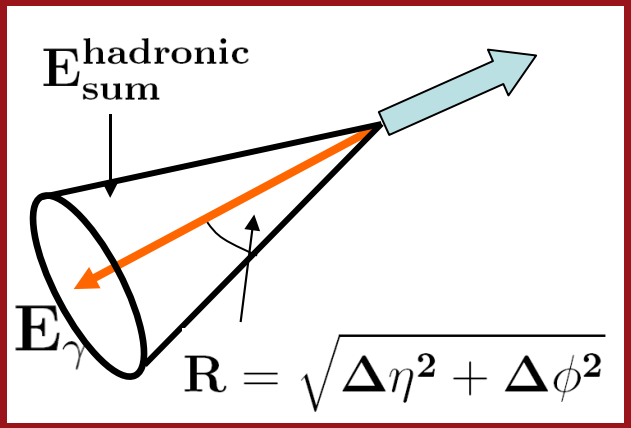
$$E^{hadronic}\left(R<0.5\,\mathrm{rad}\right) < 0.1\times E_{\gamma}$$

  - Isolation cut should remove Bremsstrahlung

- **Difficult to estimate efficiency of isolation cut:**
  - Underlying event (soft physics)
  - Limited acceptance

Bremsstrahlung





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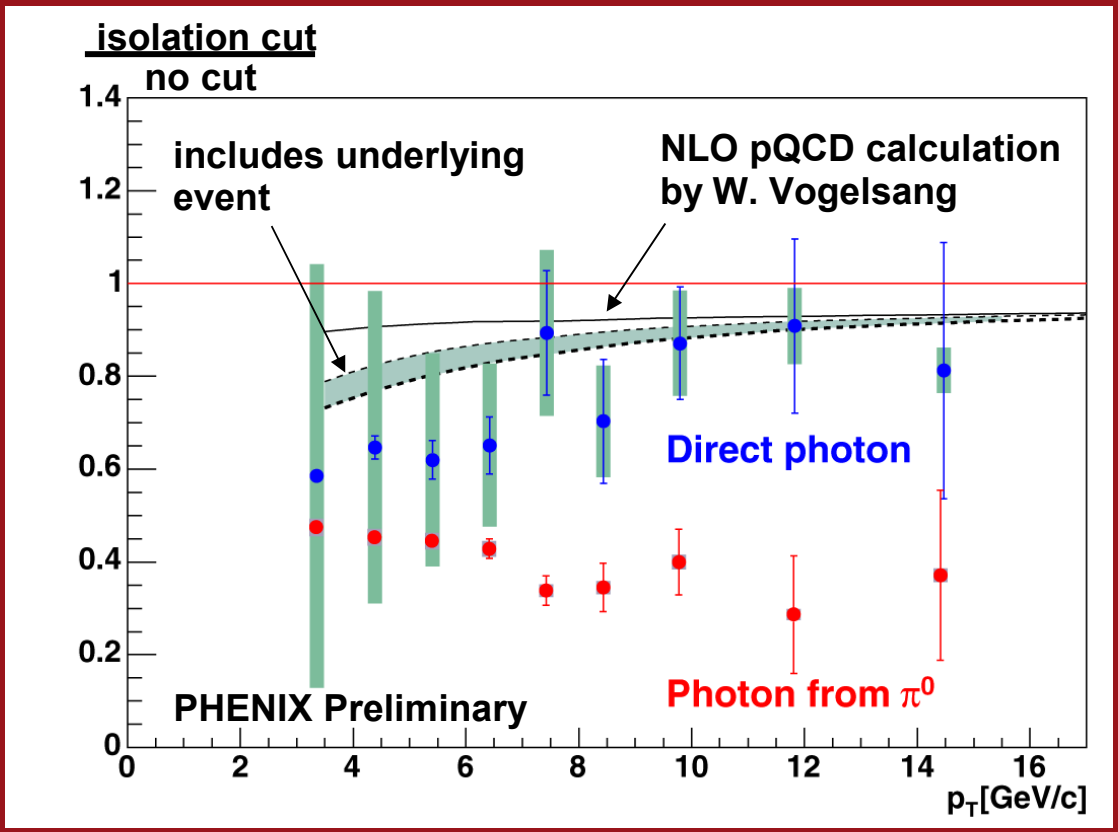
Results



- **Isolation cut affects photons from π^0**
- **Large uncertainties**
  - Bigger effect on direct γ at lower p_T? (expected)
  - Better aggreement when including underlying event?
- **RHIC Run06 p+p**
  - Integrated lumi ~ 45 pb^{-1}
  - Factor 100!!

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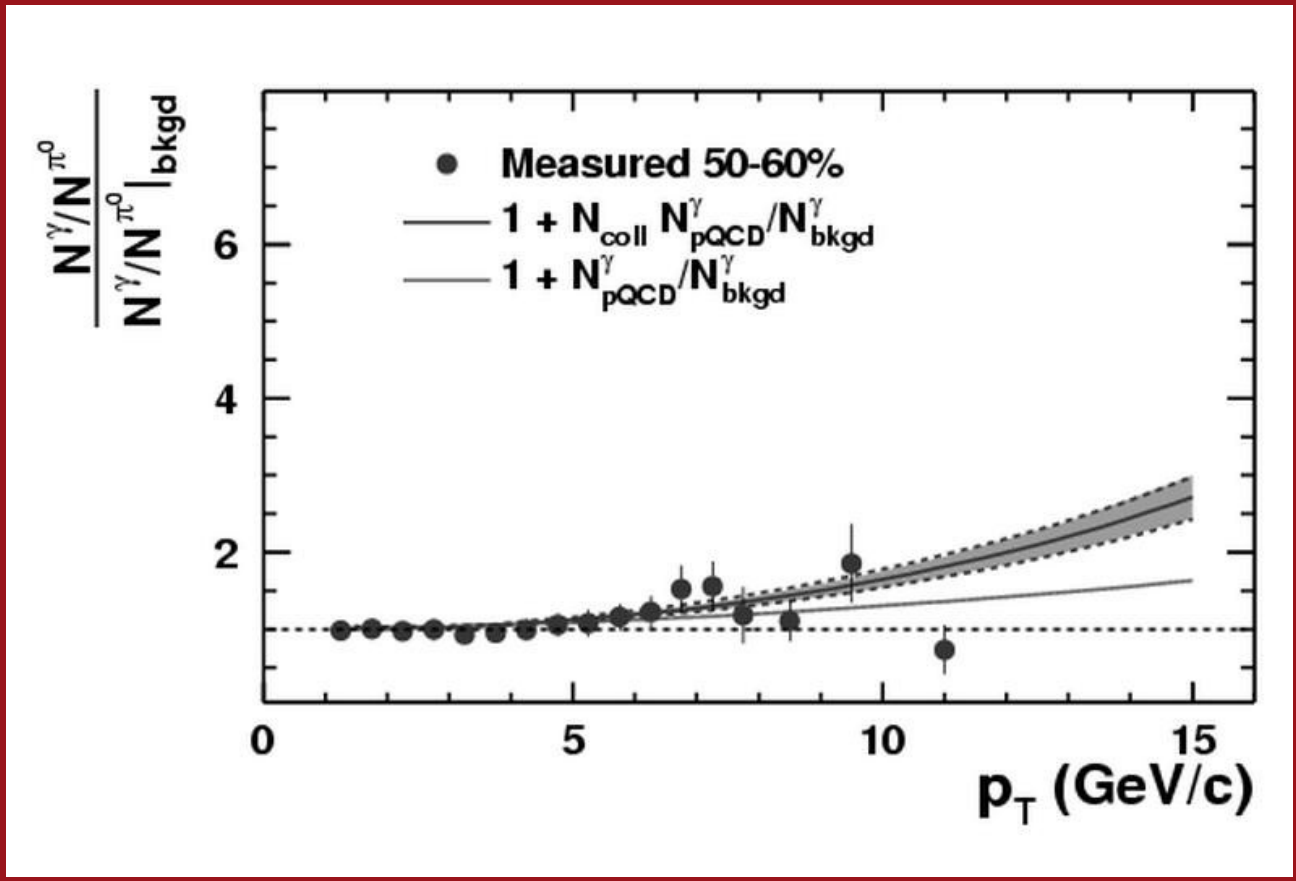
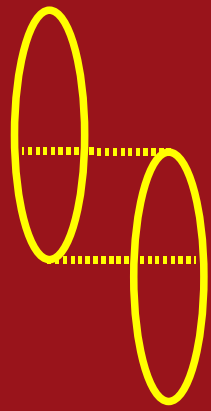
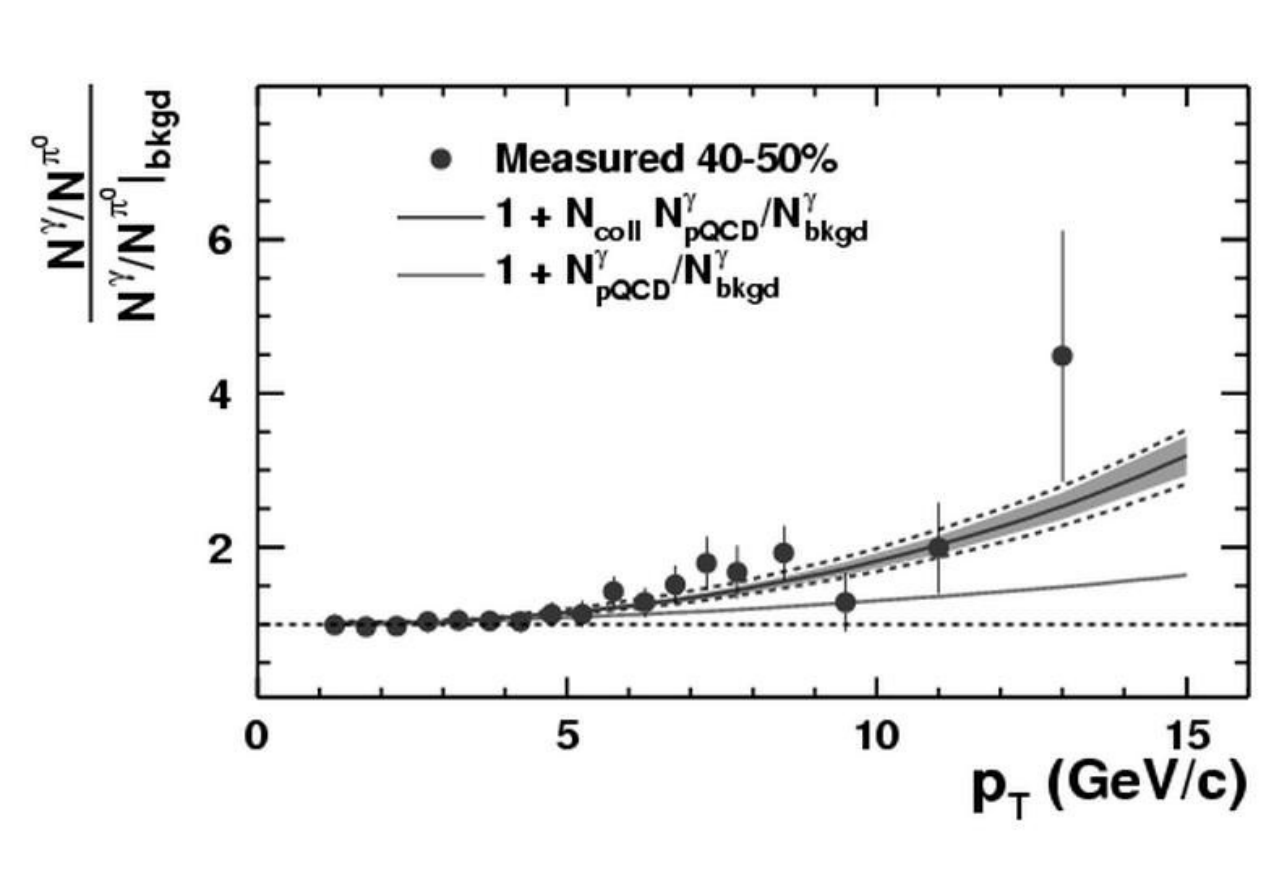
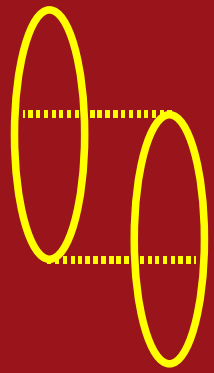
$\gamma_{meas}/\gamma_{incl}$





$\gamma_{meas}/\gamma_{incl}$





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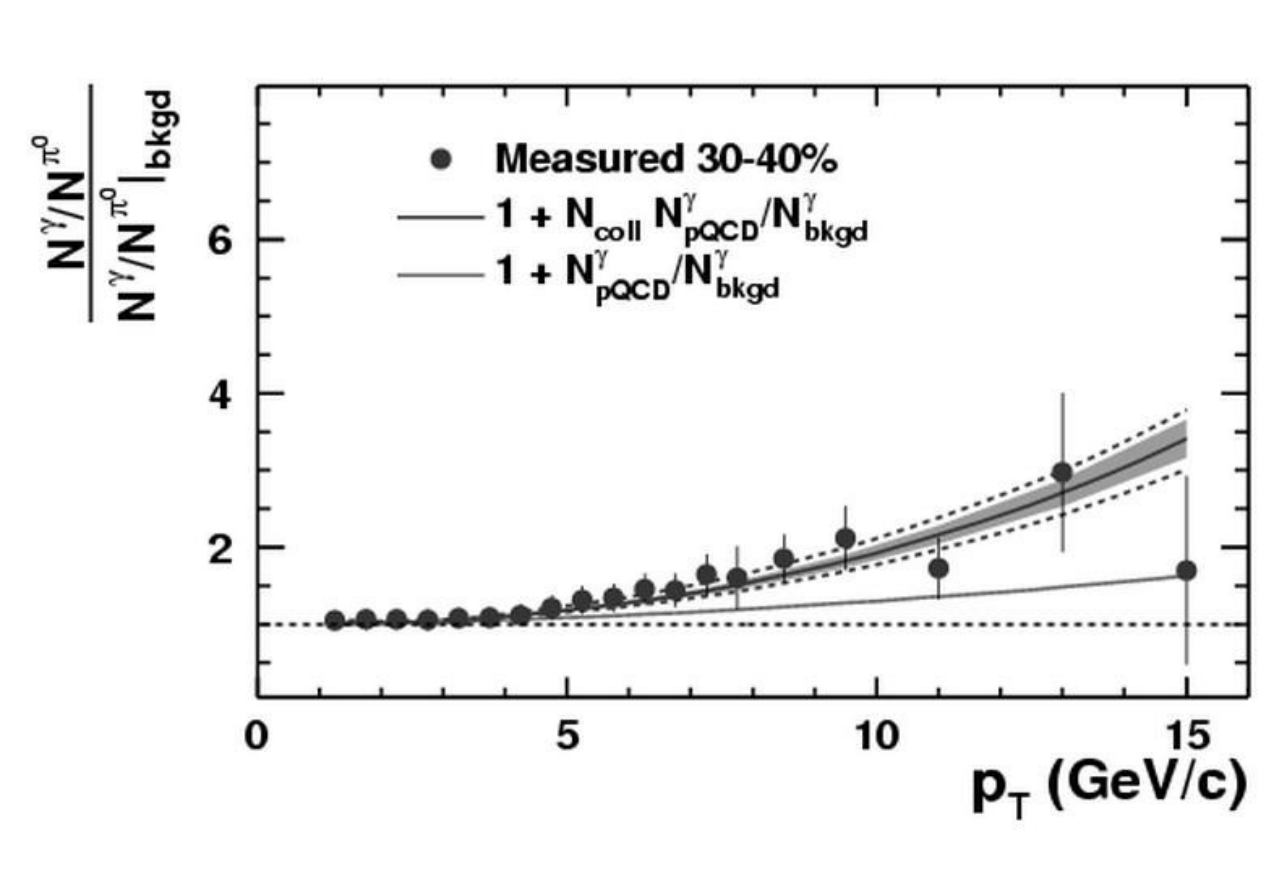
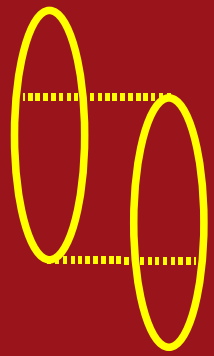
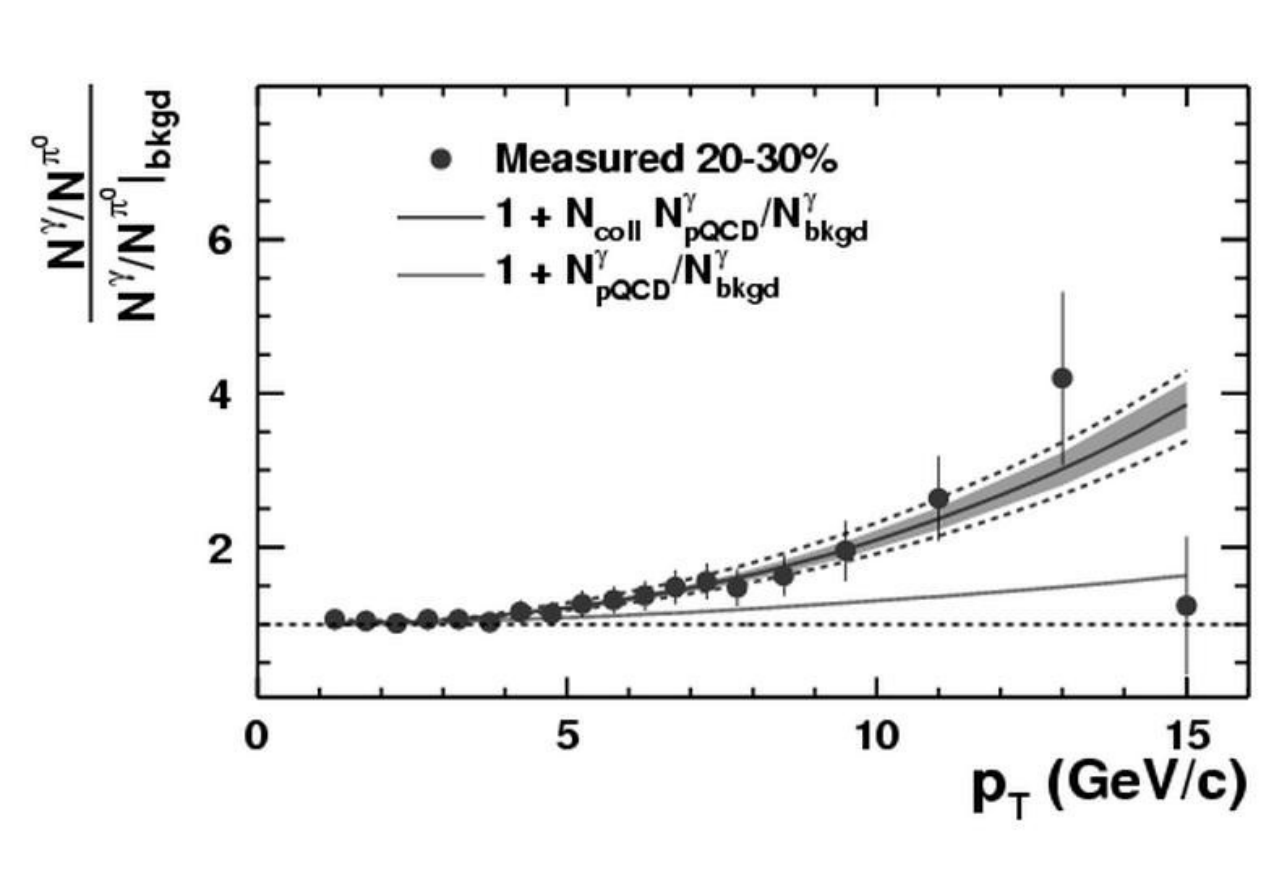
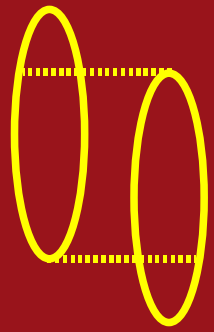
$\gamma_{meas}/\gamma_{incl}$





$\gamma_{meas}/\gamma_{incl}$





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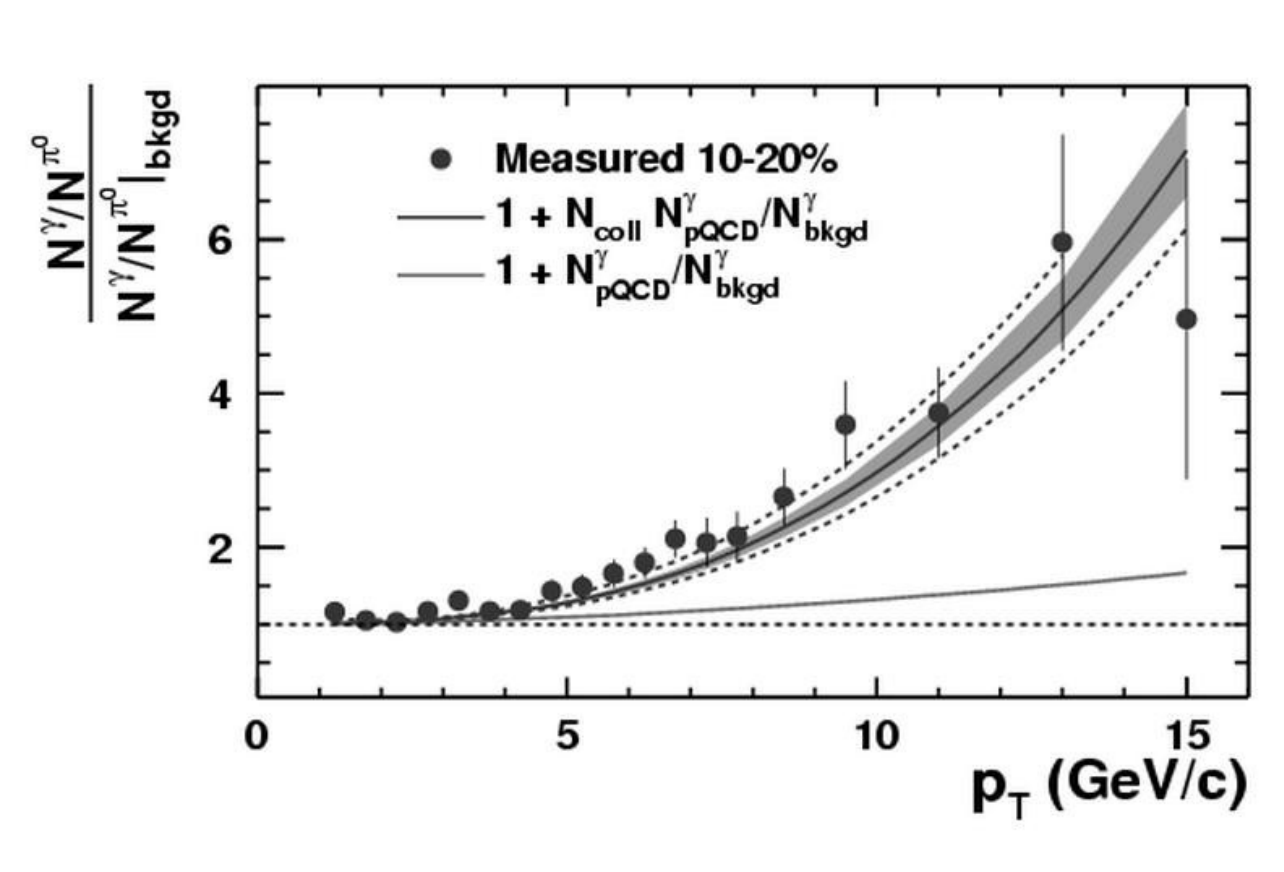
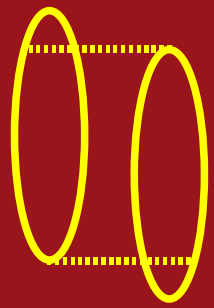
$\gamma_{meas}/\gamma_{incl}$





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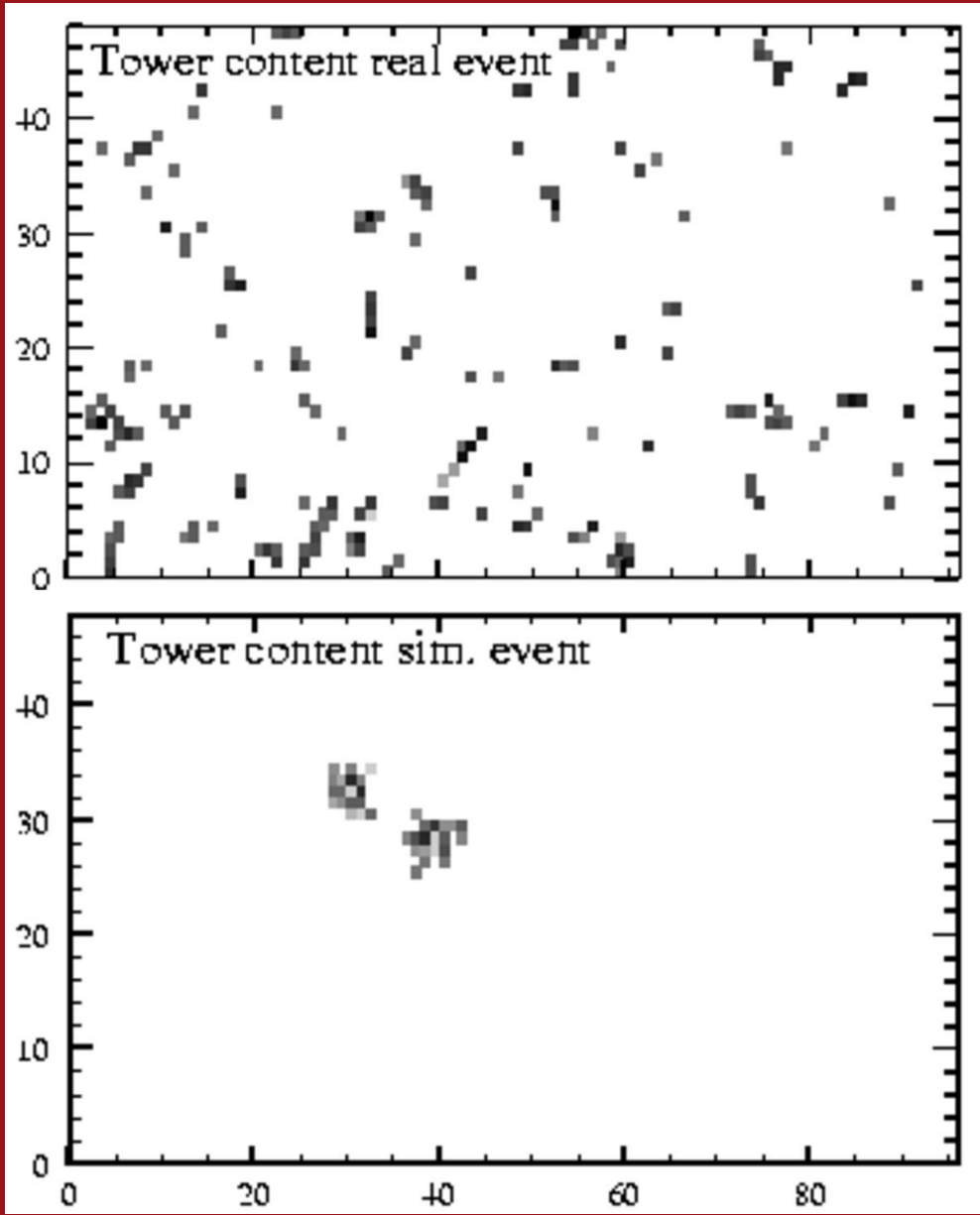
Efficiency via Embedding



- **Embedding of simulated particles into REAL events**
- **Most realistic conditions**
  - Exact event topology
  - Crucial for high multiplicity (cluster overlap)
  - Exactly the same cuts/code for real and merged events
- **Done for π^0,γ and neutrons**

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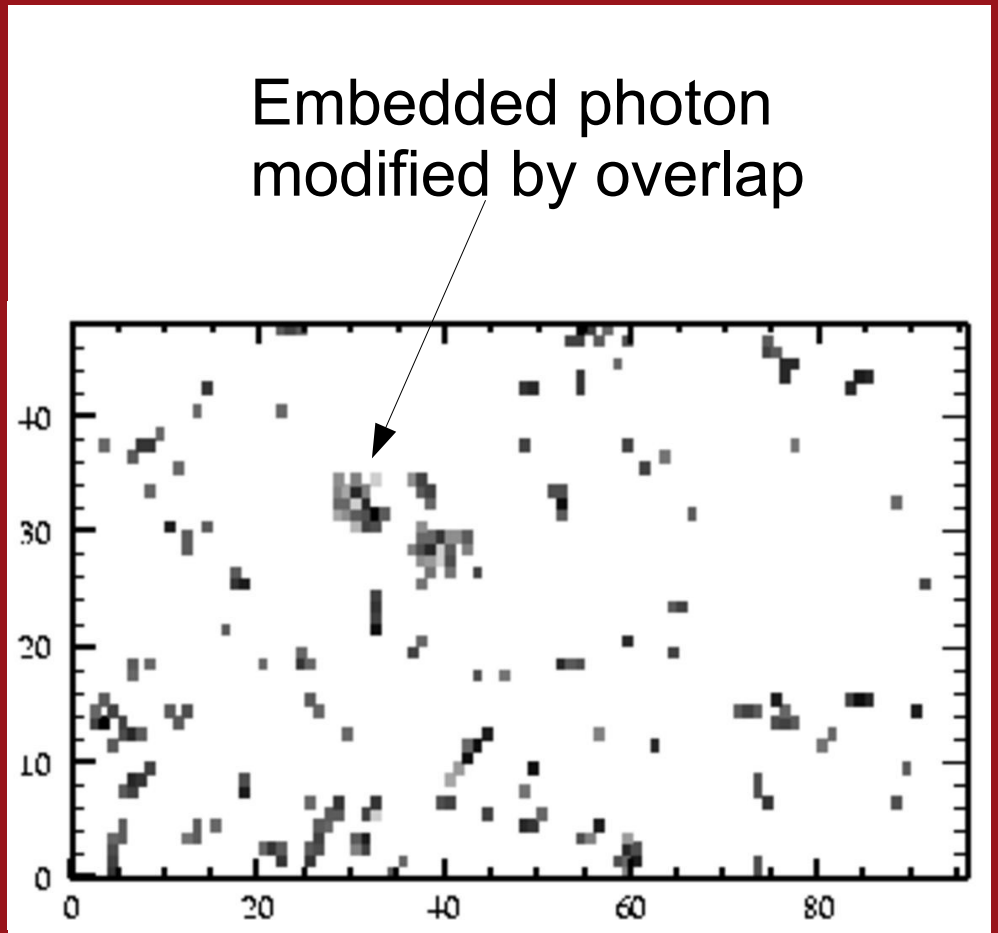
Efficiency via Embedding



- **Embedding of simulated particles into REAL events**
- **Most realistic conditions**
  - Exact event topology
  - Crucial for high multiplicity (cluster overlap)
  - Exactly the same cuts/code for real and merged events
- **Done for π^0,γ and neutrons**
  - Single photon efficiency:
    - Including module cuts
    - ~95% (PbSc)
    - ~80% (PbGl)

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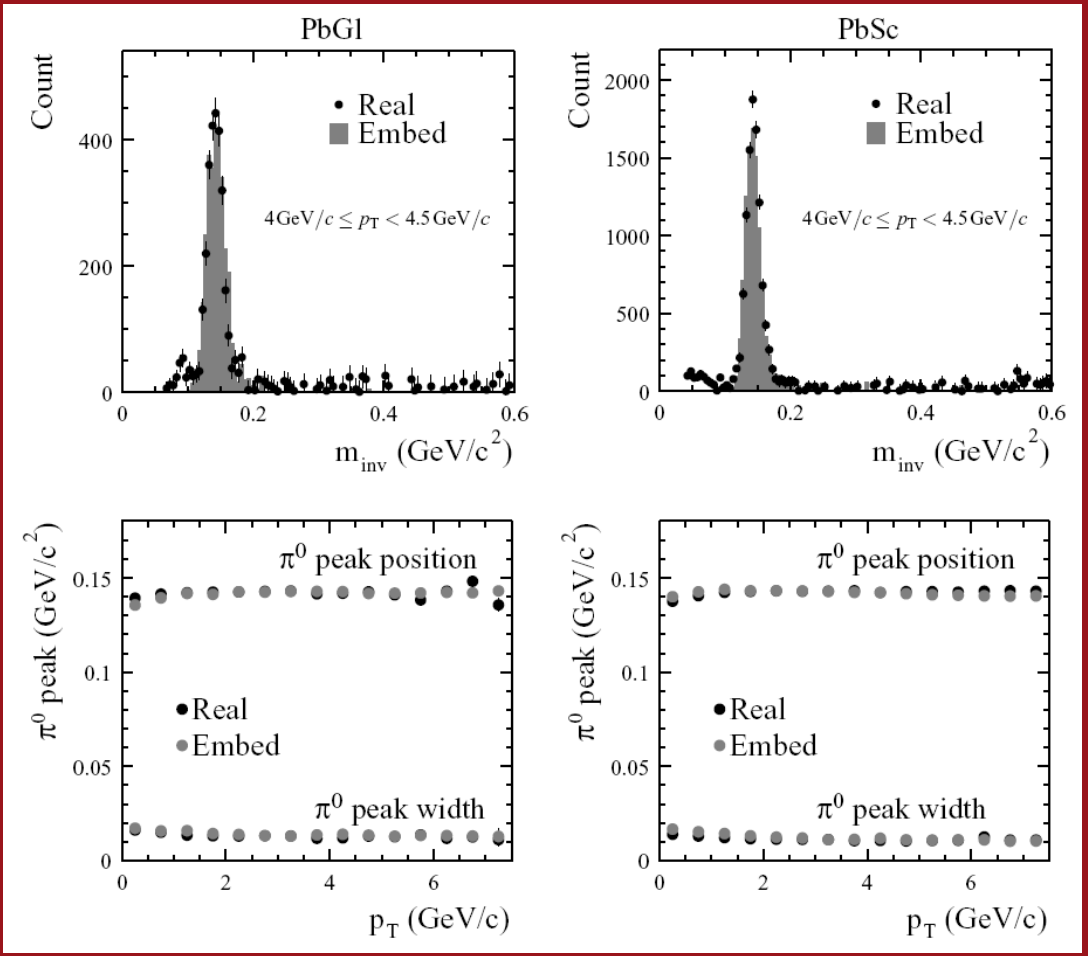
An Important Cross Check



- Efficiency simulation reproduces π^0 peak positions and widths over the entire p_T range