Direct Photons in p+p and A+A Collisions: A Short Introduction

Lecture week of the
Helmholtz Research School for Quark Matter Studies in Heavy Ion Collisions
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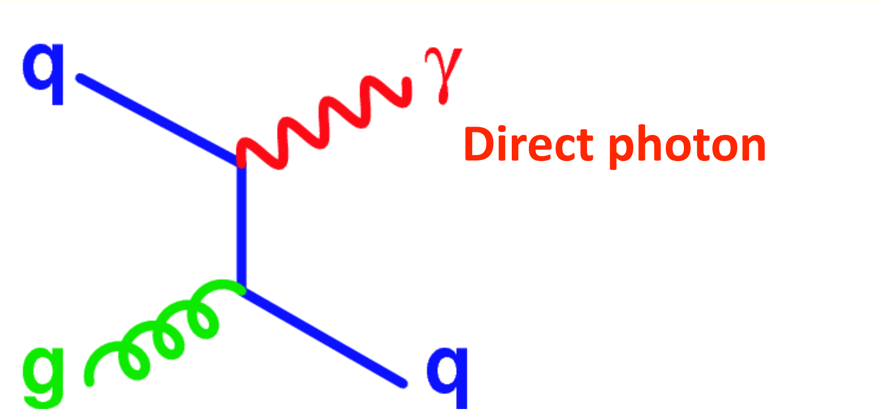
- The Internal Conversion Method
- Direct Photon Flow

Why Direct Photons?

- Direct Photons
  - Definition (heavy-ion flavor): Photons not coming from hadron decays
  - Definition (particle physics flavor): Isolated Photons
  - Difficult measurement: Large Background from $\pi^0 \rightarrow \gamma+\gamma$, $\eta \rightarrow \gamma+\gamma$
  - Exp. problem at high p_T (calorimeters, $E(\pi^0) > \sim 20$ GeV): merging of π^0 (η) decay photons

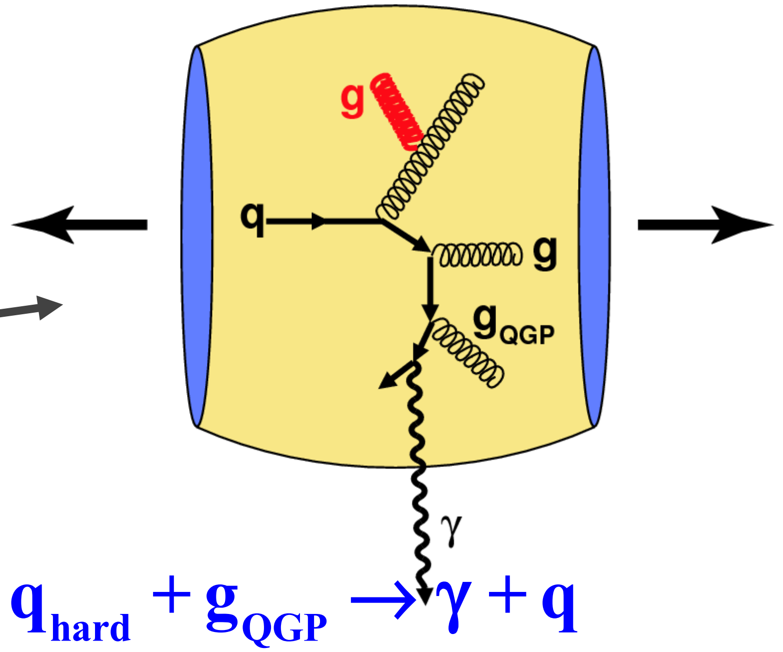


- p+p:
  - Late 1970's: Direct Photons suggested presence of point-like charged objects within hadrons
  - Test of QCD
  - Focus now on constraining gluon distribution functions
    - Quark-Gluon Compton scattering contributes at leading order (LO)
    - This is in contrast to Deep Inelastic Scattering and Drell-Yan where gluon is involved only at NLO
  - However, direct photon data often not used in global fits due to discrepancies between data and theory

Why Direct Photons in Nucleus-Nucleus Collisions? Because They Escape the Medium Unscathed!

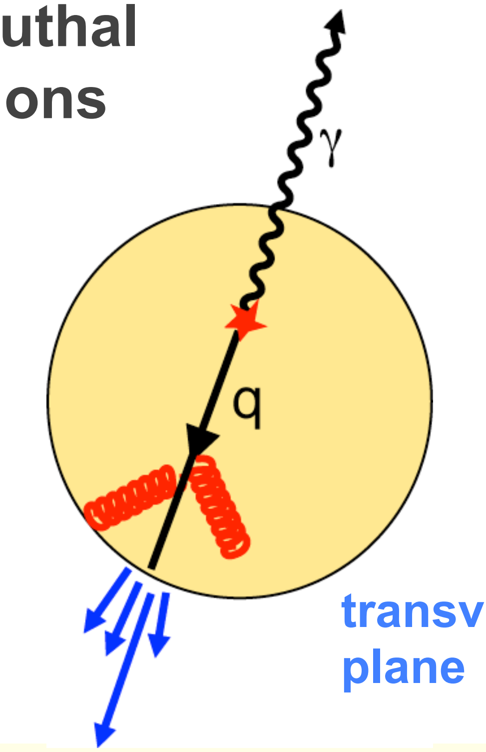
- Direct photon yields at low p_T (< 5 GeV/c)
  - Measure thermal photons
    → initial temperature of the fireball
  - Find further photon sources related to presence of the QGP (e.g. photons from jet-plasma interaction)
- Direct photon yields at high p_T
  - Confirm point-like scaling for hard processes
- Direct γ - hadron azimuthal correlations
  - p+p: measure fragmentation function
  - A+A: $E_\gamma = E_{jet}$ → study parton energy loss for partons with known initial energy

Photons from jet-plasma interaction:



$$q_{hard} + g_{QGP} \rightarrow \gamma + q$$

γ-h azimuthal correlations



transverse plane

Direct Photon Measurement: Methods

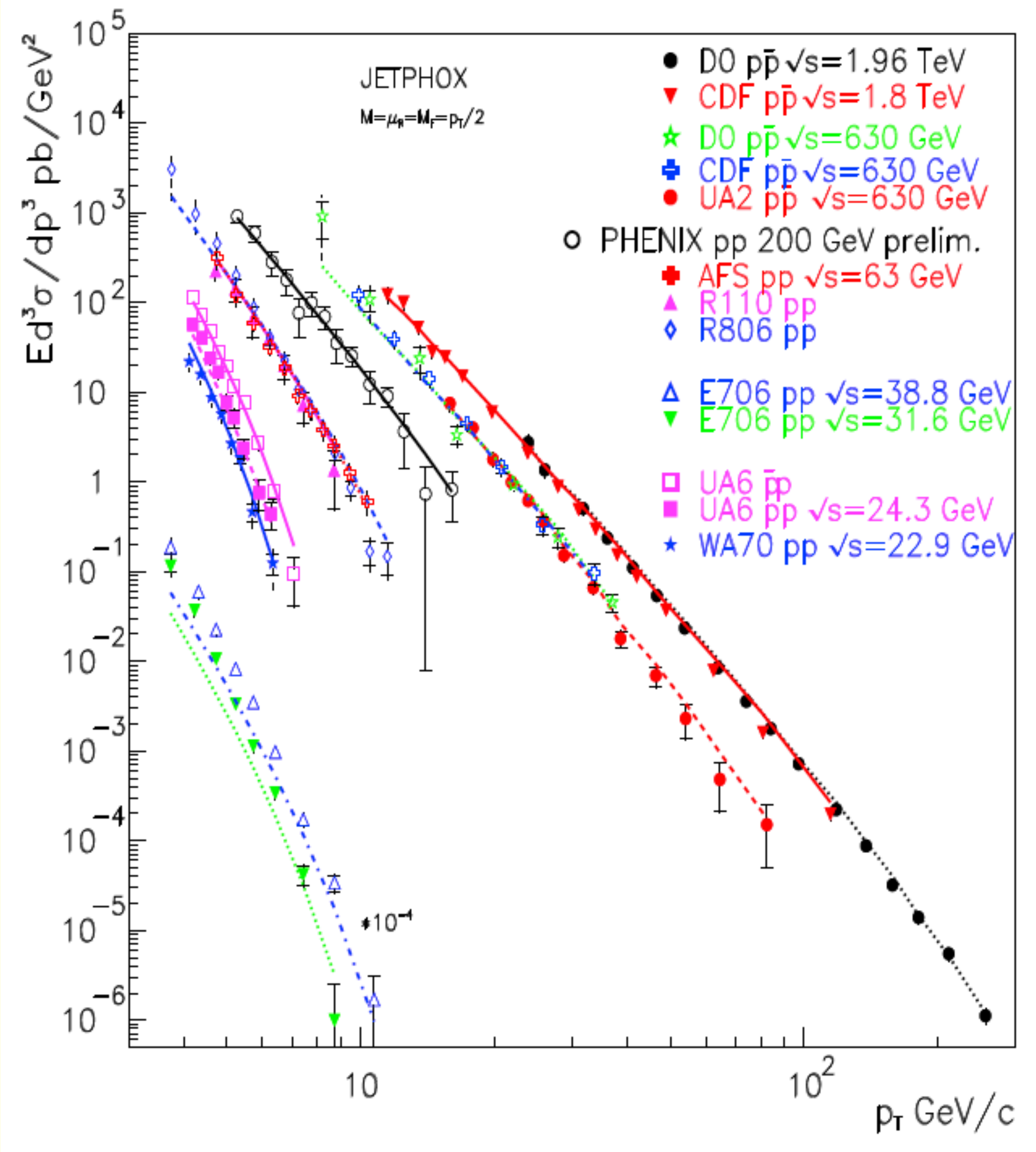
- Isolated photons + shower shape cuts

- Statistical subtraction Method
  - Measure inclusive photon spectrum and subtract photons from hadron decays
  - Inclusive photon spectrum via
    - Electromagnetic calorimeters
    - External conversion

- Hanbury Brown-Twiss (HBT) Method
  - Bose-Einstein correlation expected for direct photons
  - Direct photon yield from correlation strength

Direct Photons in p+p

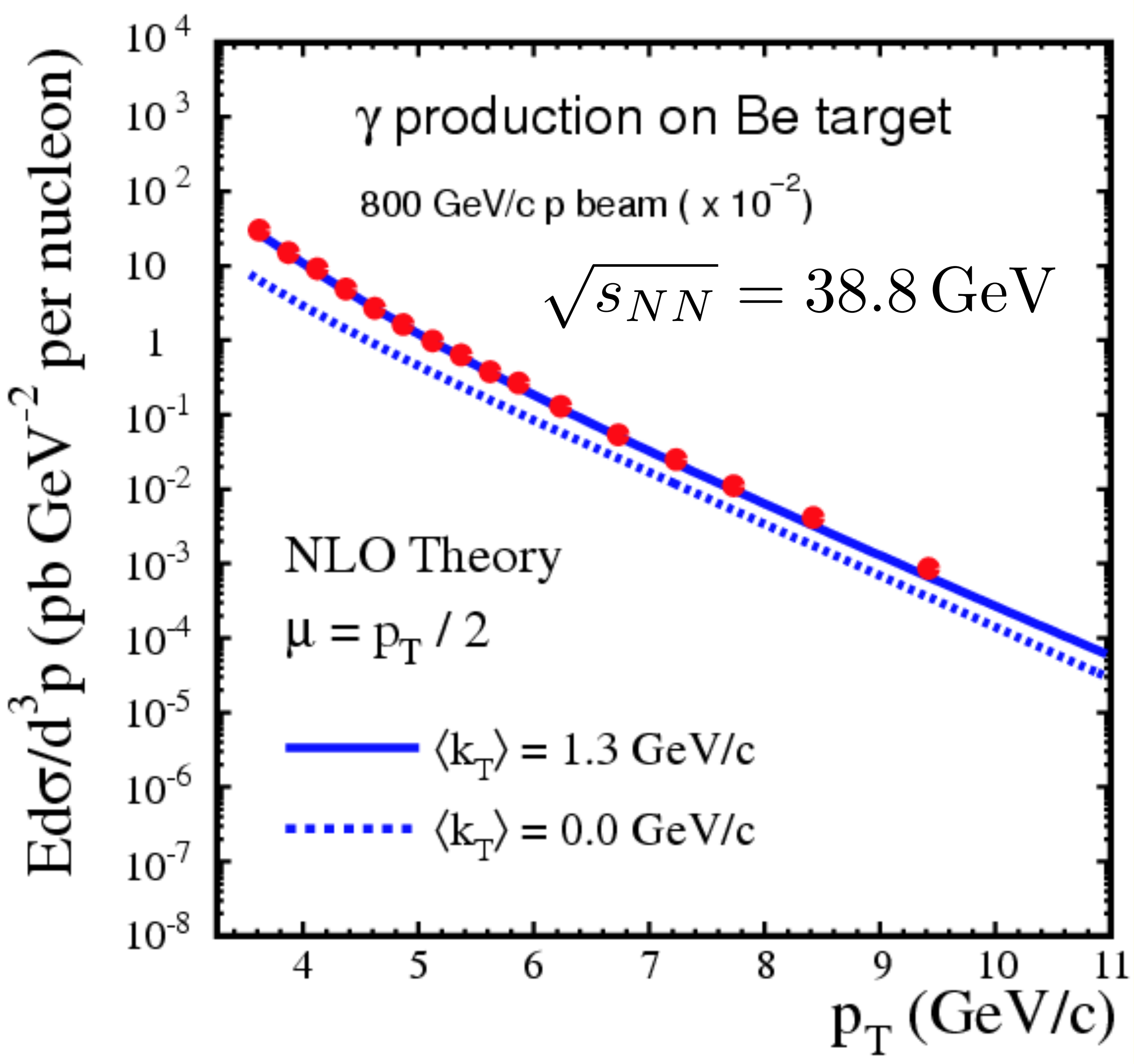
p+p(p bar) Direct Photon Data and pQCD – Status as of ~ 2006 (I)



Aurenche et al., Phys.Rev. D73 (2006) 094007

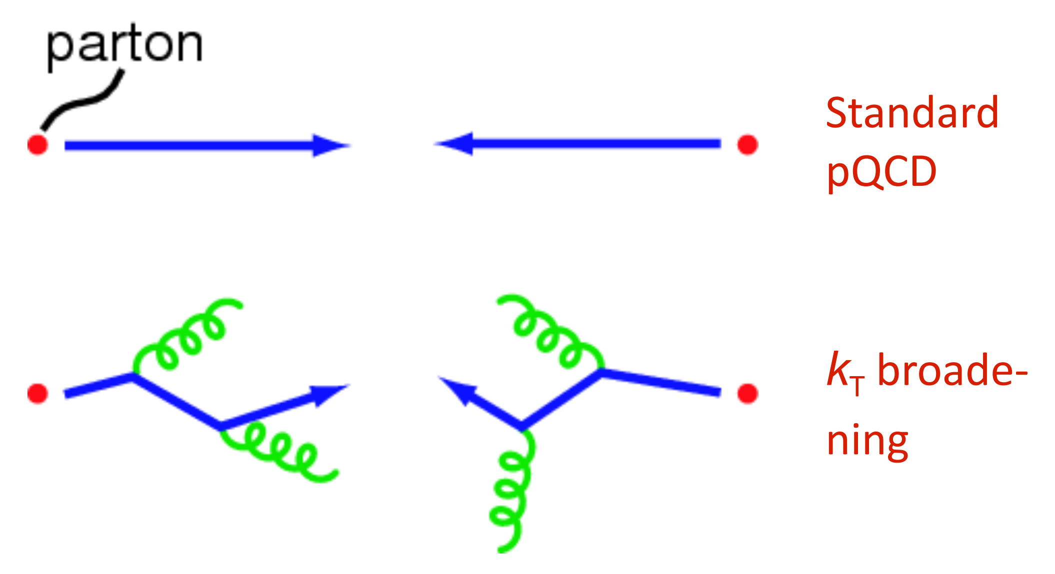
- Decent agreement at large $\sqrt{s}$
- Substantial deviations between data and NLO pQCD at small $\sqrt{s}$
- Questions:
  - Is there a systematic pattern of deviation?
  - If so, can the introduction of additional transverse momentum (k_T) of initial partons improve the agreement?
  - Are the data sets mutually consistent?

Is k_T Broadening Needed to Describe Direct Photon Data?



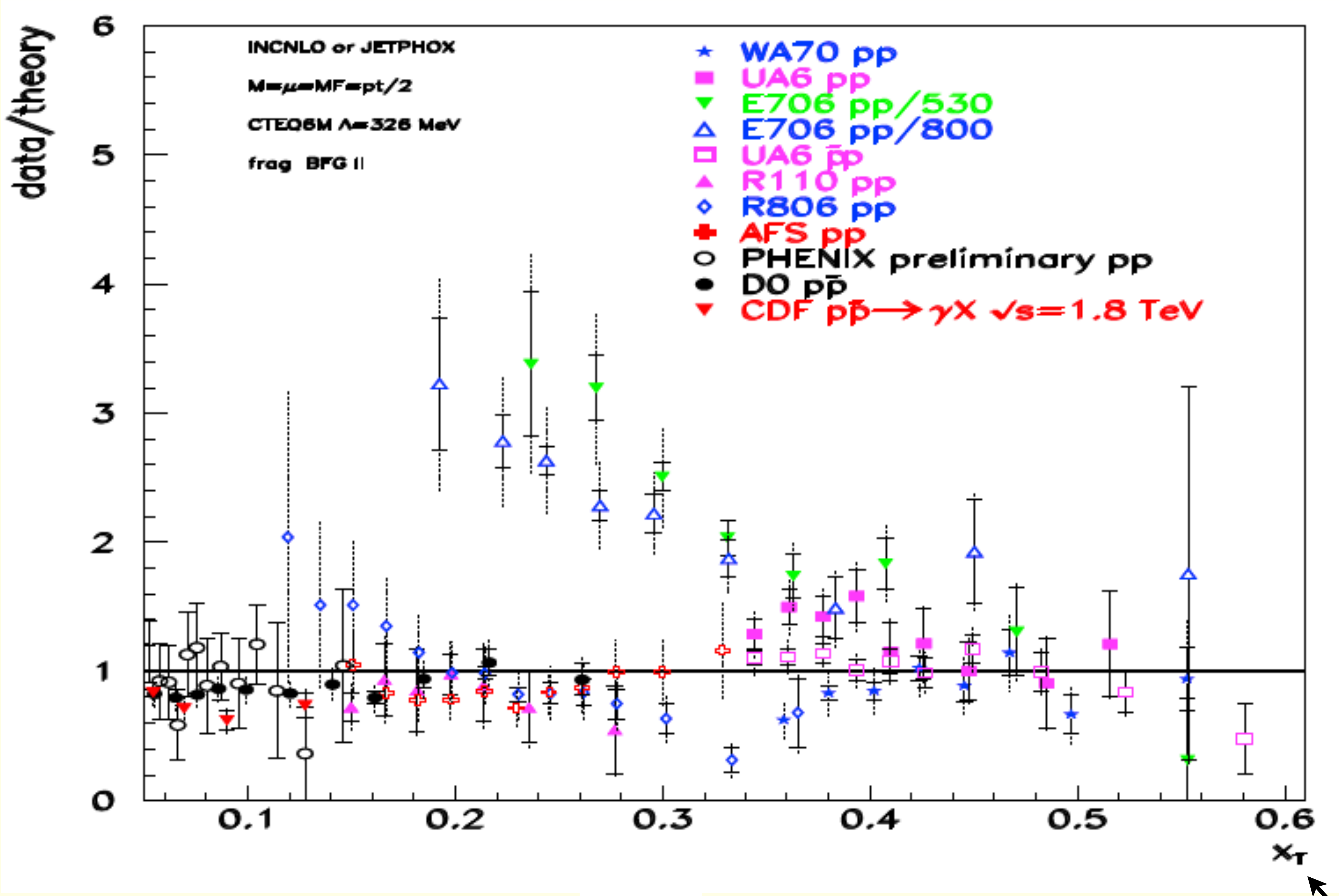
E706, Phys.Rev.D70:092009,2004

- Data from E706 fixed target experiment can be explained with $\langle k_T \rangle \approx 1.3$ GeV/c



Is there evidence for k_T broadening in p+p at larger √s ?

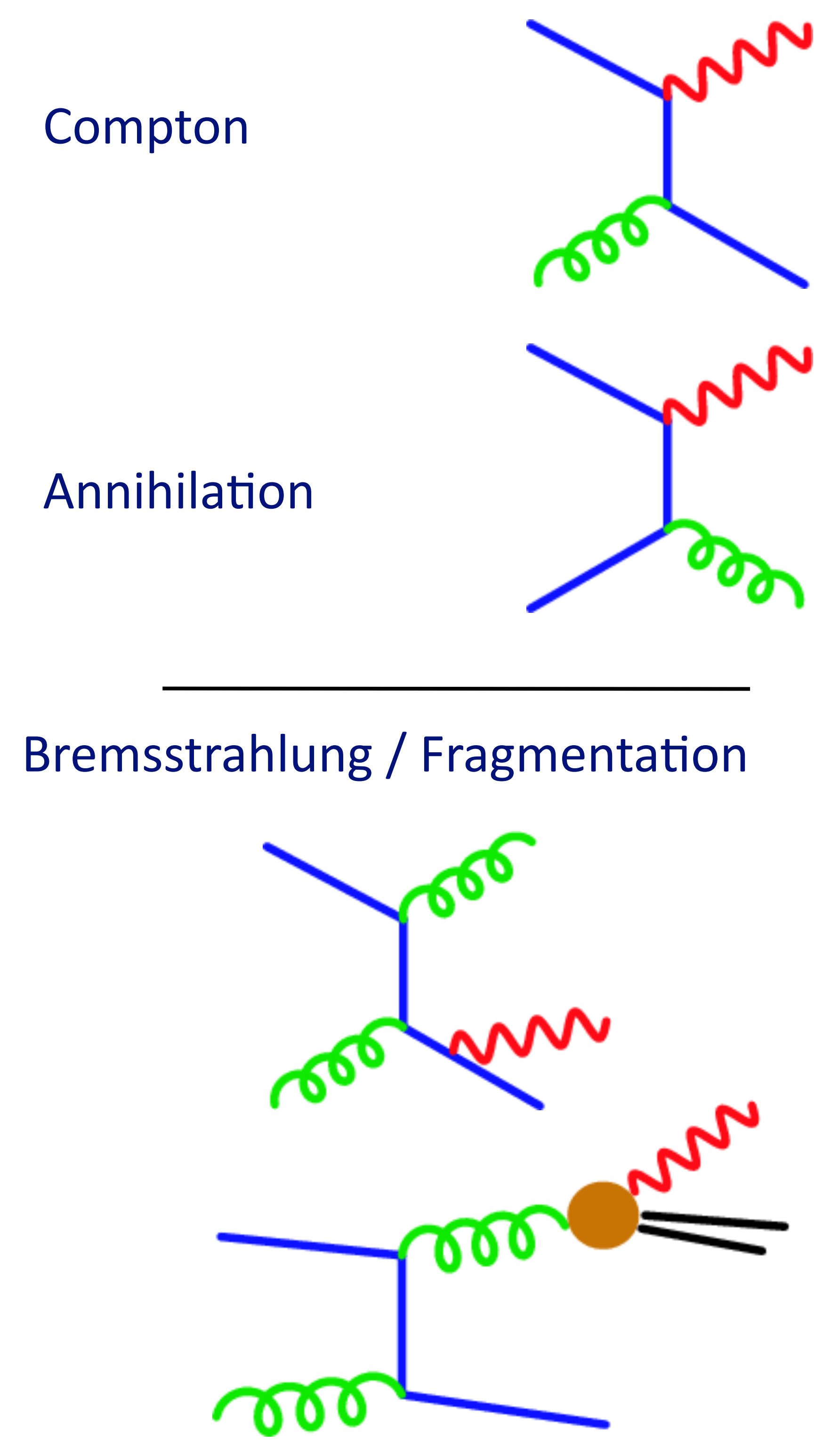
p+p(p bar) Direct Photon Data and pQCD – Status as of ~ 2006 (II)



$$x_T = 2p_T/\sqrt{s}$$

Only E706 data show strong deviation from NLO QCD.
Probably need new data at low √*s* to settle the issue.

Isolation Cuts



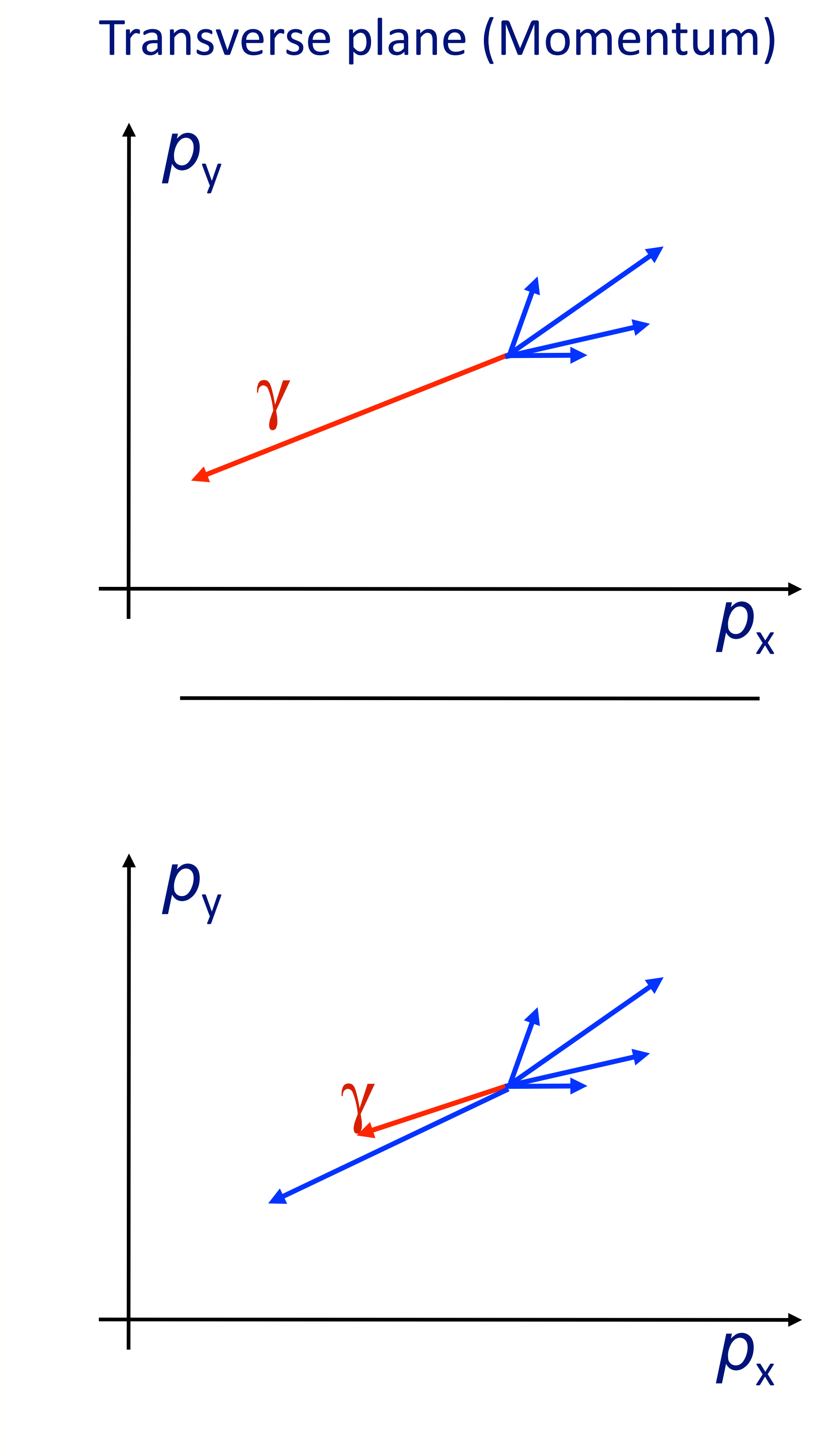
Compton

Annihilation

Bremsstrahlung / Fragmentation

⇒

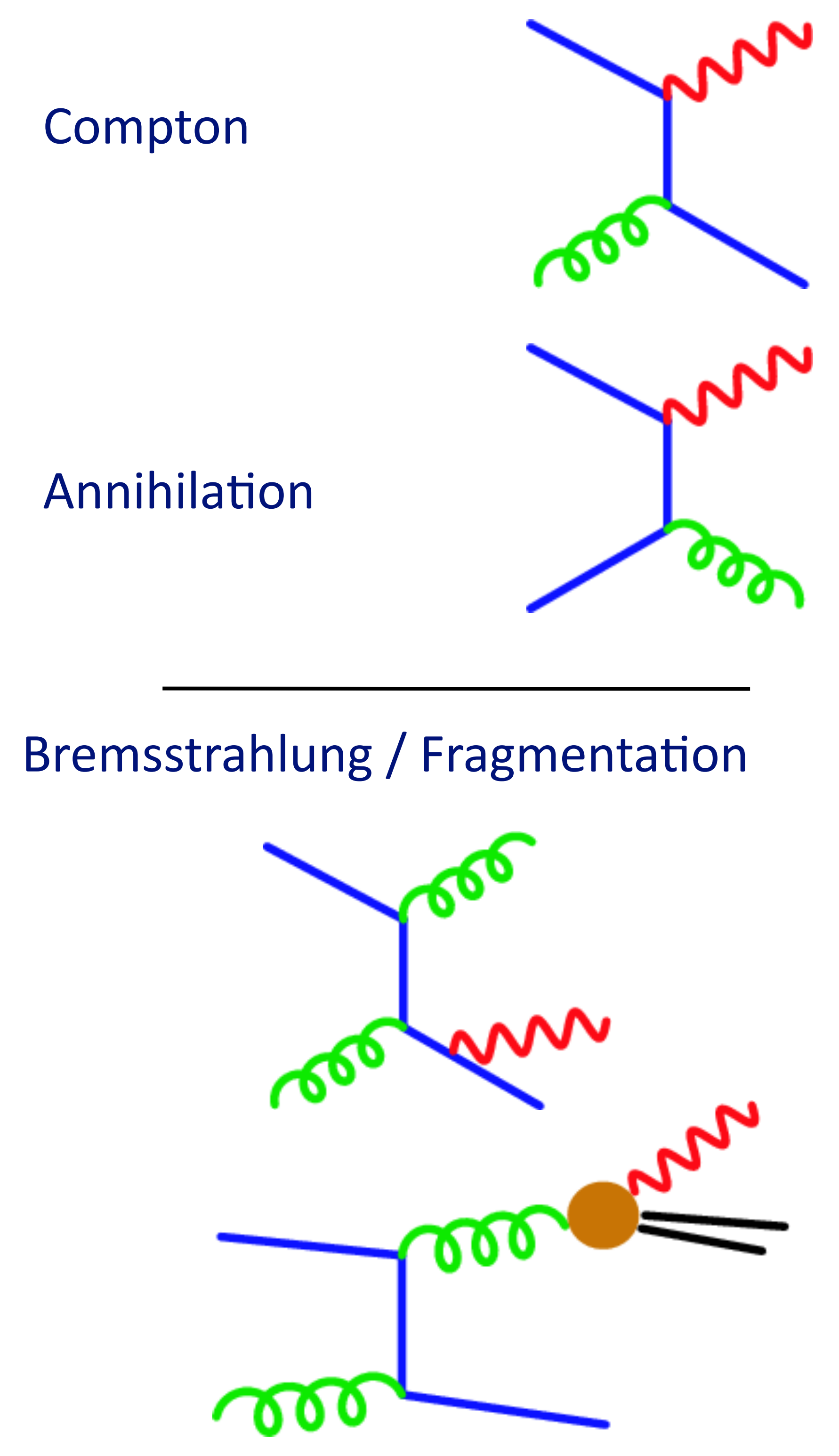
⇒



Transverse plane (Momentum)

Isolation Cuts

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



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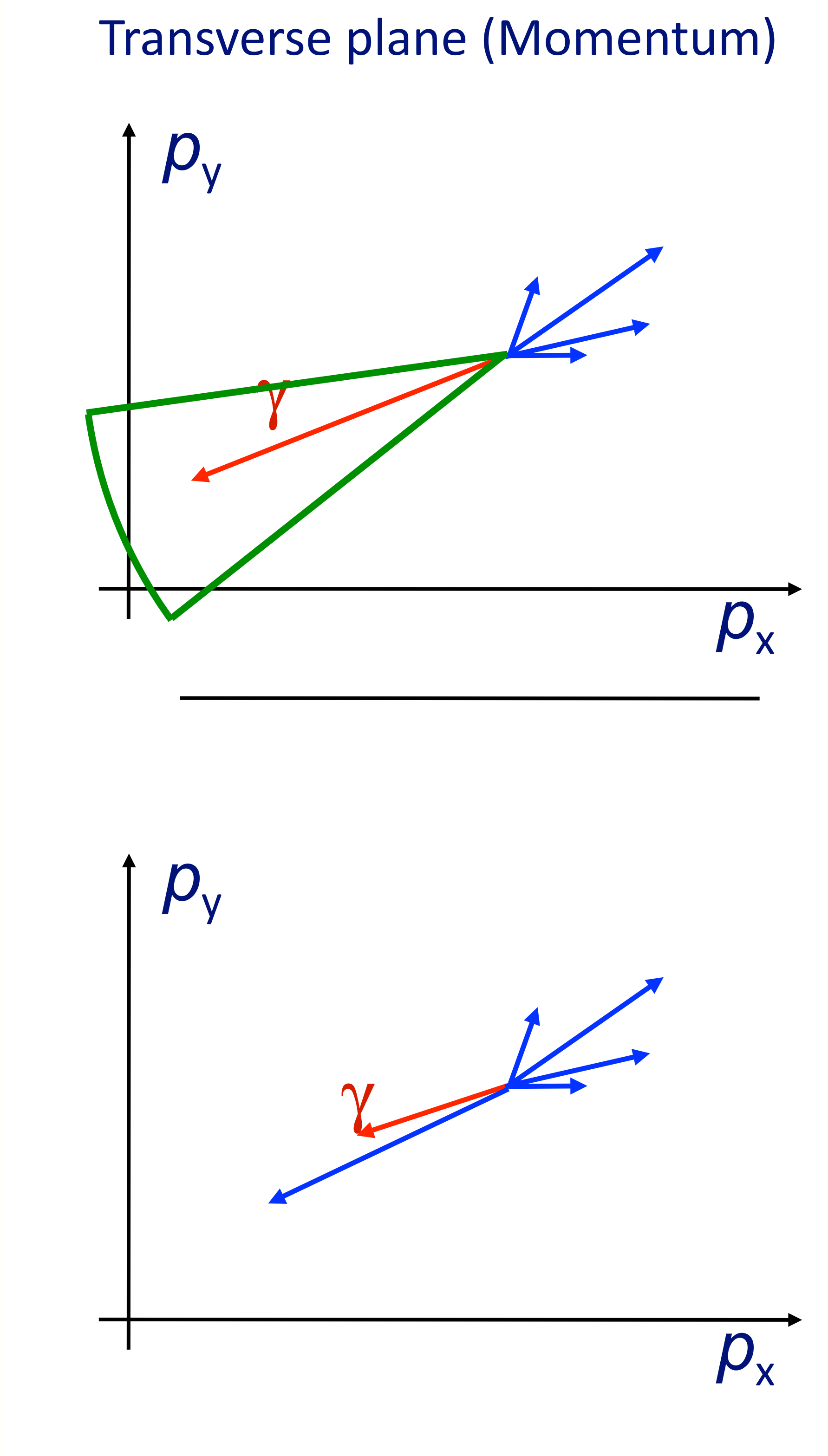
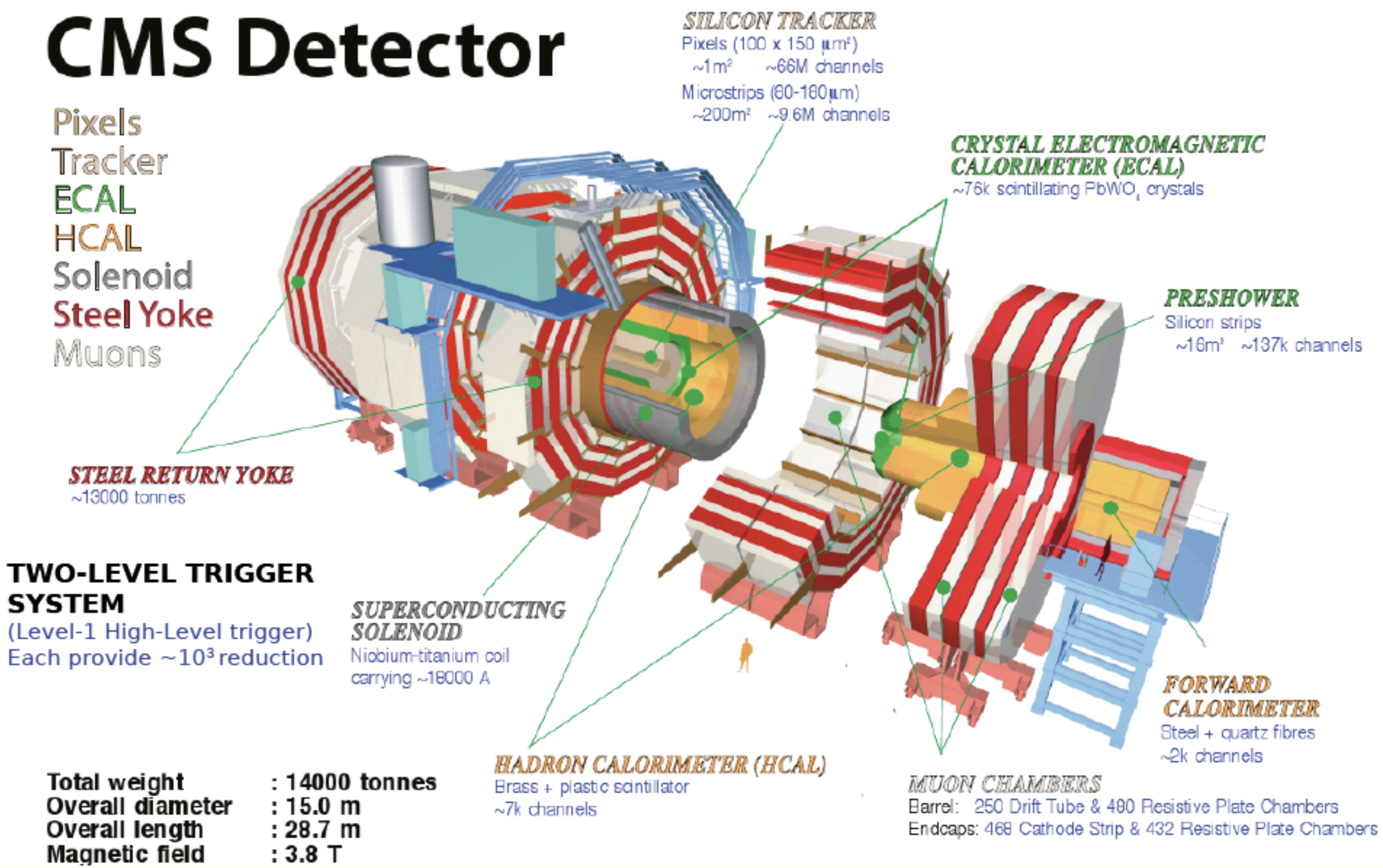


Transverse plane (Momentum)

An Example of an Isolated Photon Measurement (CMS)



TWO-LEVEL TRIGGER SYSTEM

(Level-1 High-Level trigger)

Each provide ~10^3 reduction

Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

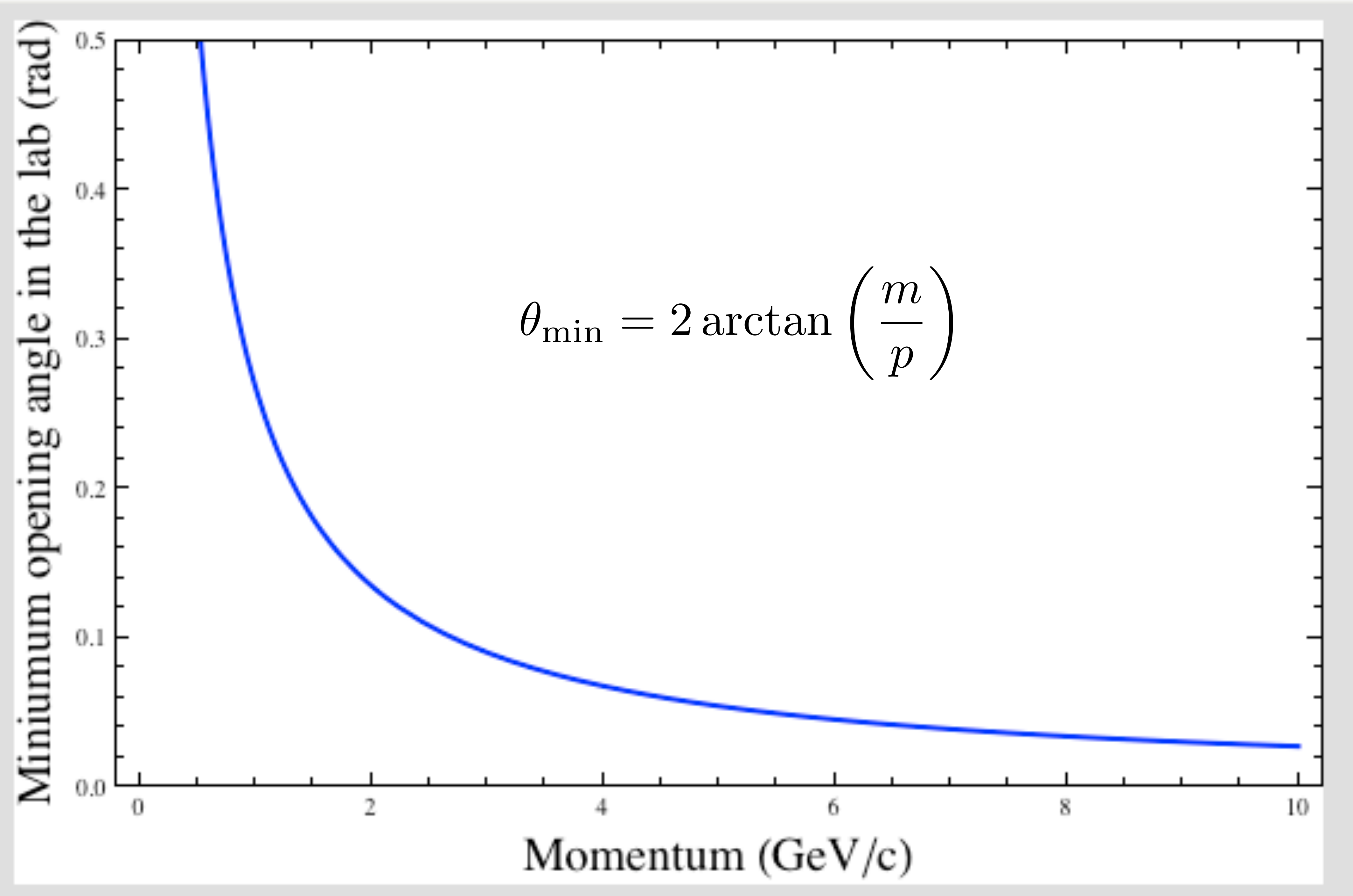
Isolated Photon Measurement (CMS): Isolation Cuts

$$R^2 = (\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2$$

- Photon candidates must satisfy three isolation requirements that reject photons produced in hadron decays
  - IsoTRK < 2 GeV/*c* in 0.04 < *R* < 0.40, excluding a rectangular strip of Δη × ΔΦ = 0.015 0.400 to remove the photon’s own energy if it converts into an e+e-
  - IsoECAL < 4.2 GeV (transverse energy in ECAL in 0.06 < *R* < 0.40, excluding again a central region for the photon)
  - IsoHCAL < 2.2 GeV (transverse energy in HCAL)
- These conditions remove the bulk of the photons from neutral meson decays

CMS, Phys.Rev.Lett. 106 (2011) 082001

[Minimum Opening Angle of π^0 Decay Photons]

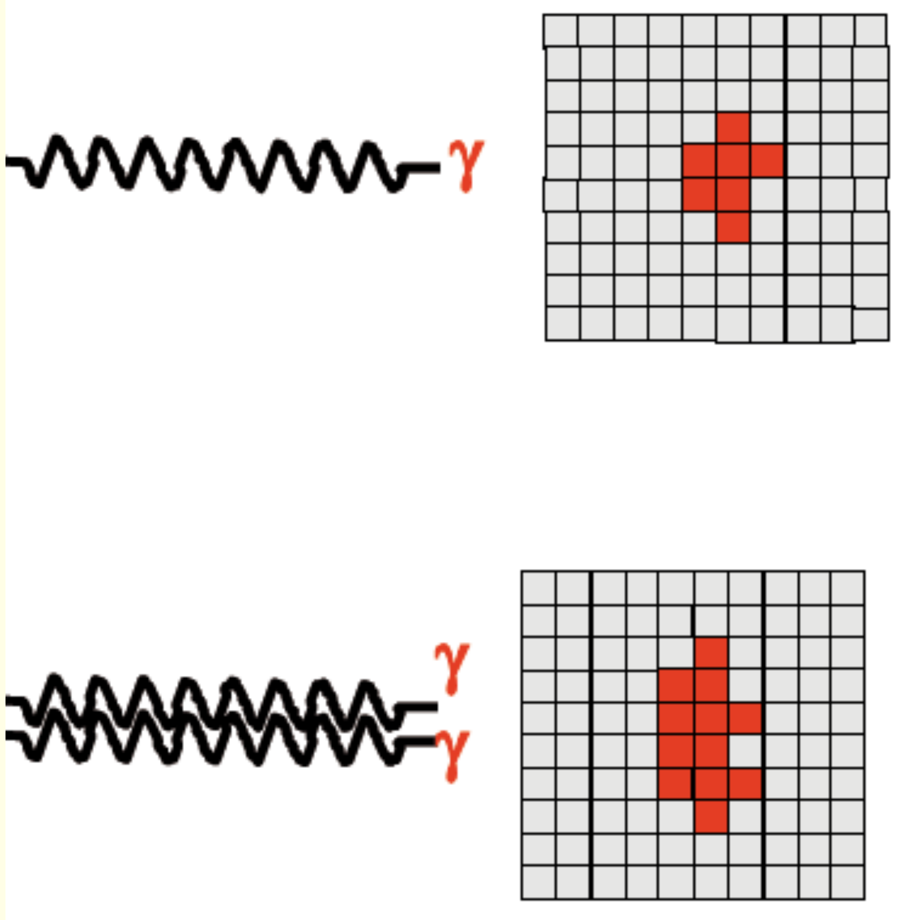


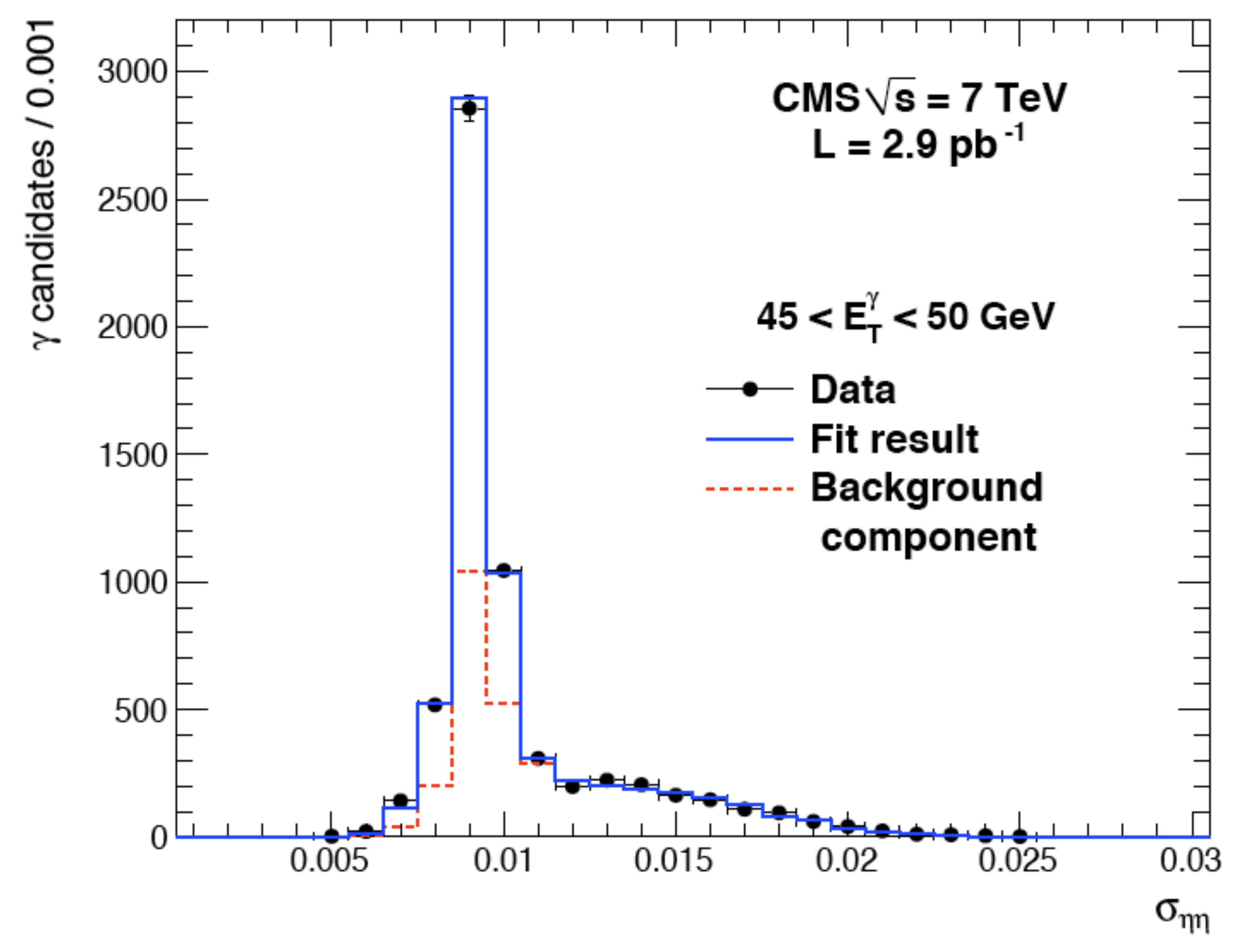
$$\theta_{\min} = 2\arctan\left(\frac{m}{p}\right)$$

Isolated Photon Measurement (CMS): Signal Extraction

$$\sigma_{\eta\eta}^2 = \sum_{i=1}^{25} w_i(\eta_i - \bar{\eta})^2 / \sum_{i=1}^{25} w_i$$

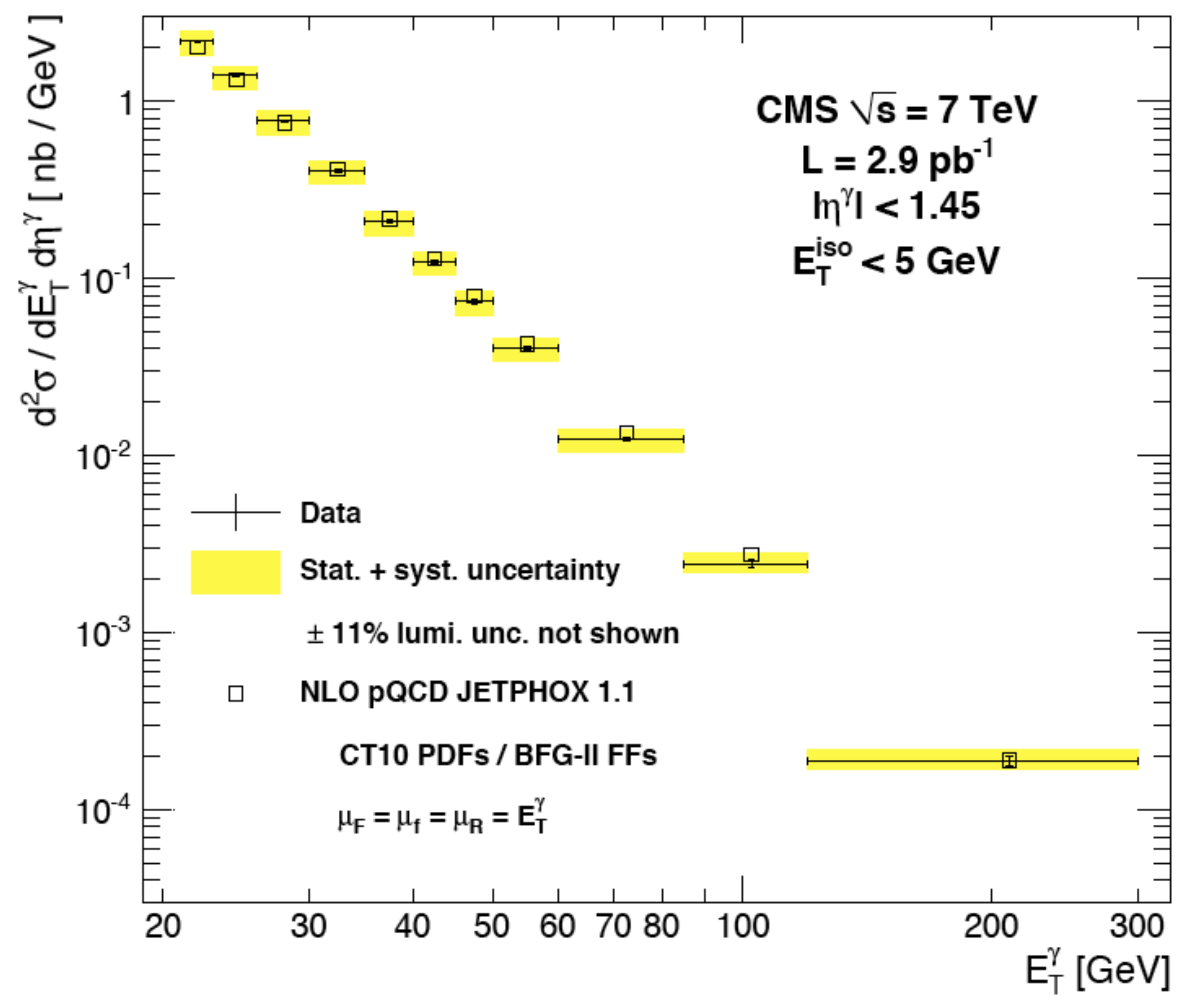
$$w_i = \max(0, 4.7 + \ln(E_i/E))$$





- Isolated photon yields extracted by fitting signal + background templates to measured shower width distribution
- Signal template from MC (Pythia + Geant)
- Background template determined in a data-driven way

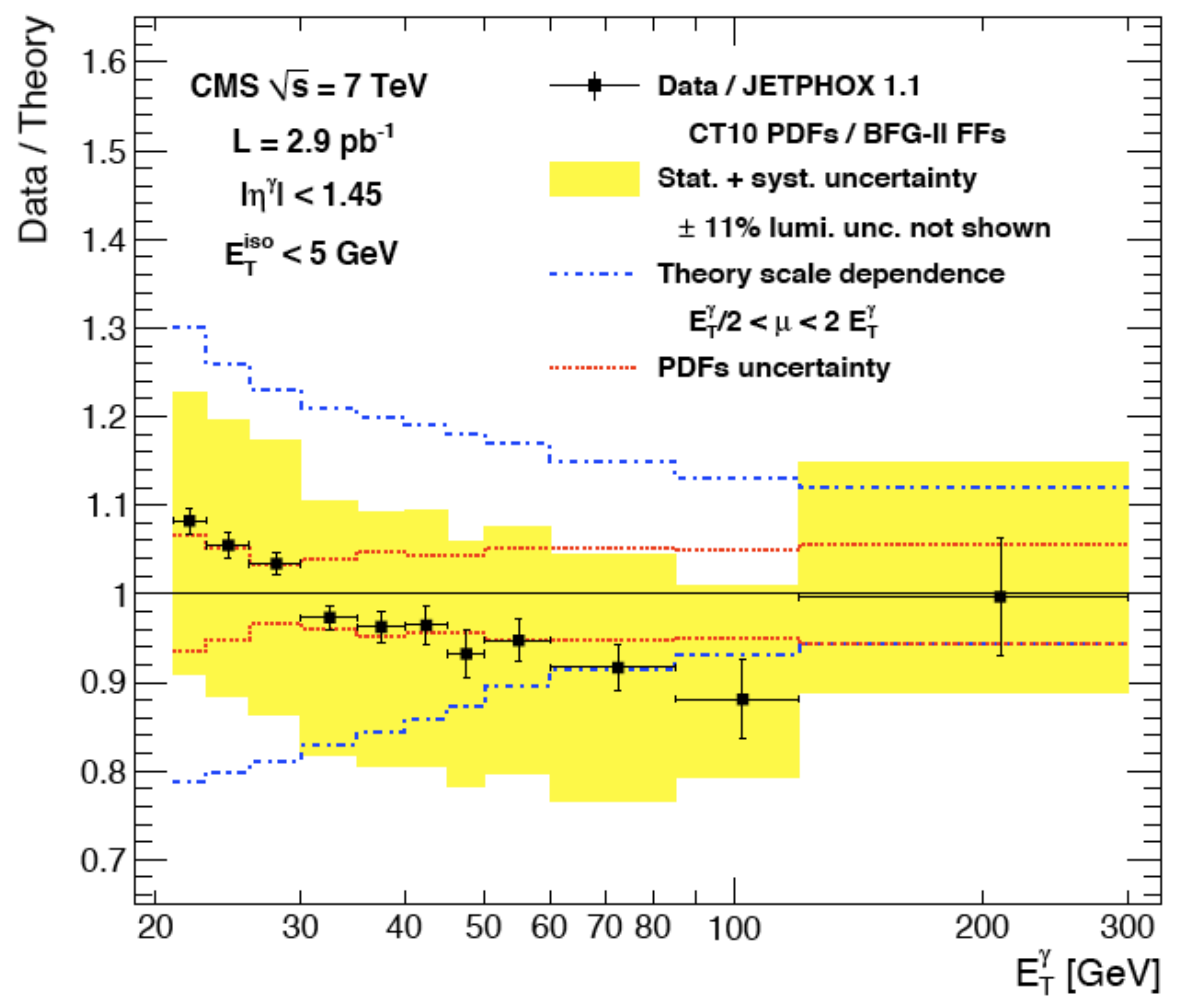
Isolated Photon Spectrum in p+p at 7 TeV (CMS)



- The photon reconstruction and selection efficiencies are determined from PYTHIA:
  $\varepsilon = 0.916 \pm 0.034$
  (rather independent of photon energy)
- Spectrum corrected for finite energy resolution

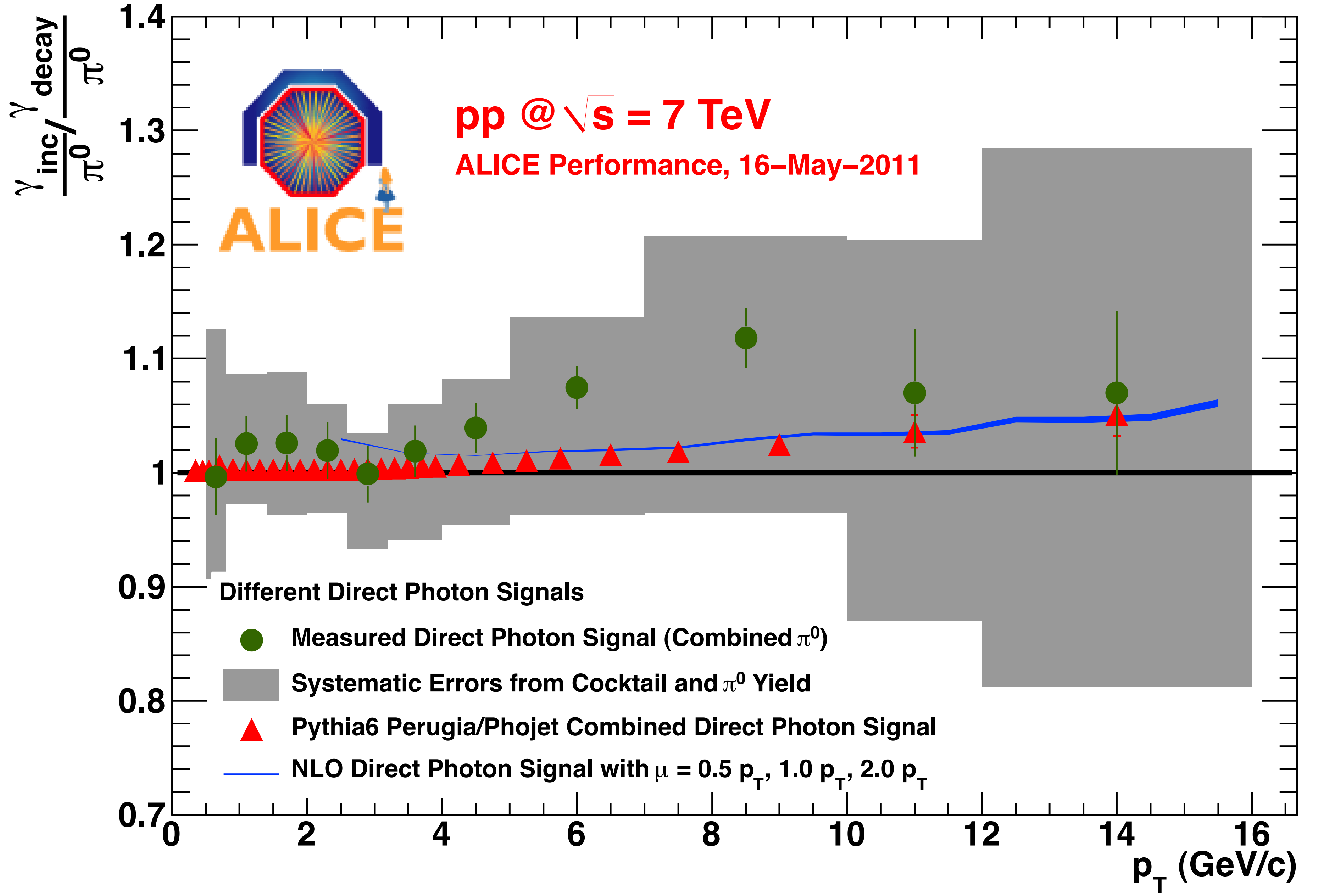
CMS, Phys.Rev.Lett. 106 (2011) 082001

Isolated Photons in p+p at 7 TeV: Agreement with NLO pQCD



P. Aurenche et al., Eur. Phys. J. C 13 (2000) 347 (http://lapth.in2p3.fr/PHOX_FAMILY).

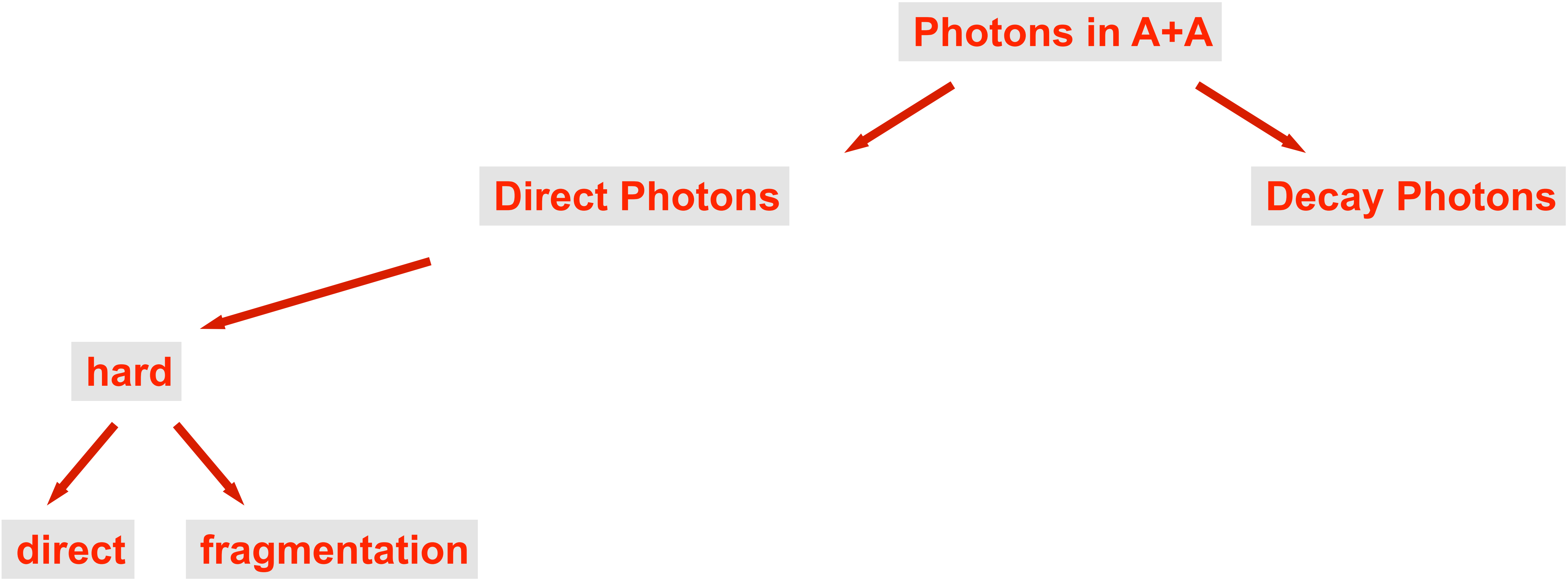
Direct Photon Search in p+p at the LHC at Low p_T: A Tough Job



Possible signal much smaller than systematic errors

Direct Photons in A+A: Overview

Known and Presumed Photon Sources in A+A



Photons in A+A

Direct Photons

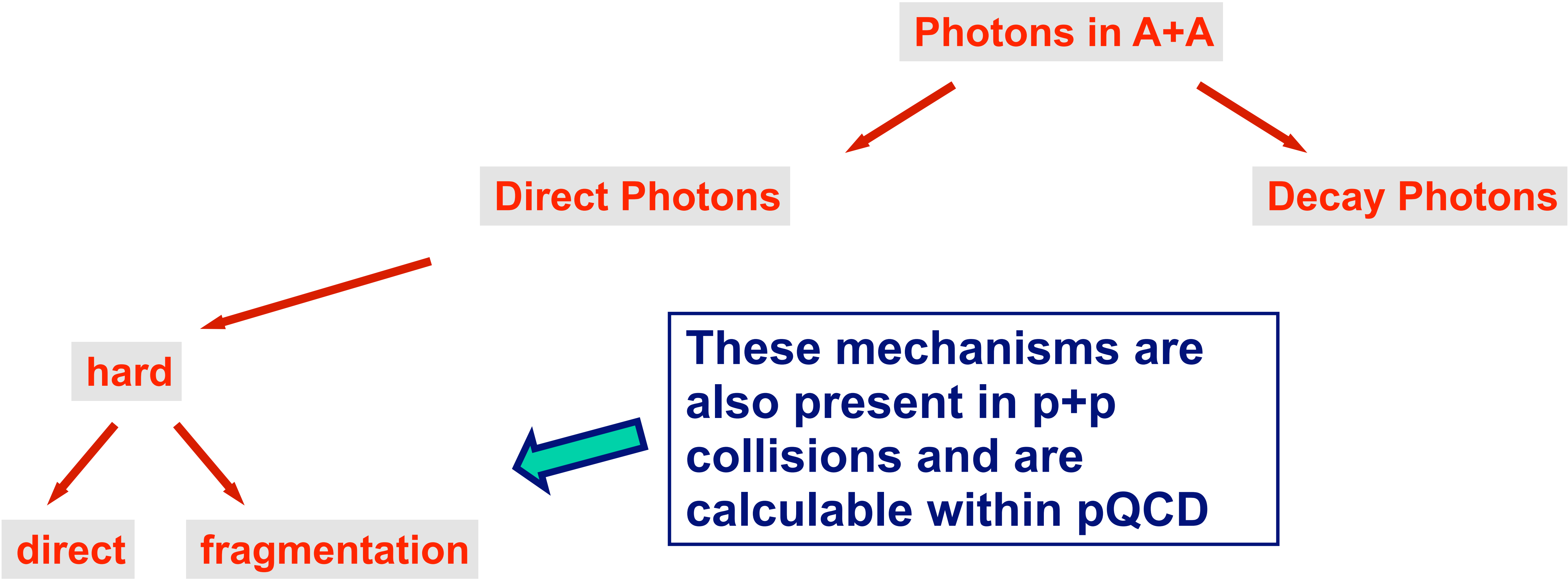
Decay Photons

hard

direct

fragmentation

Known and Presumed Photon Sources in A+A



Photons in A+A

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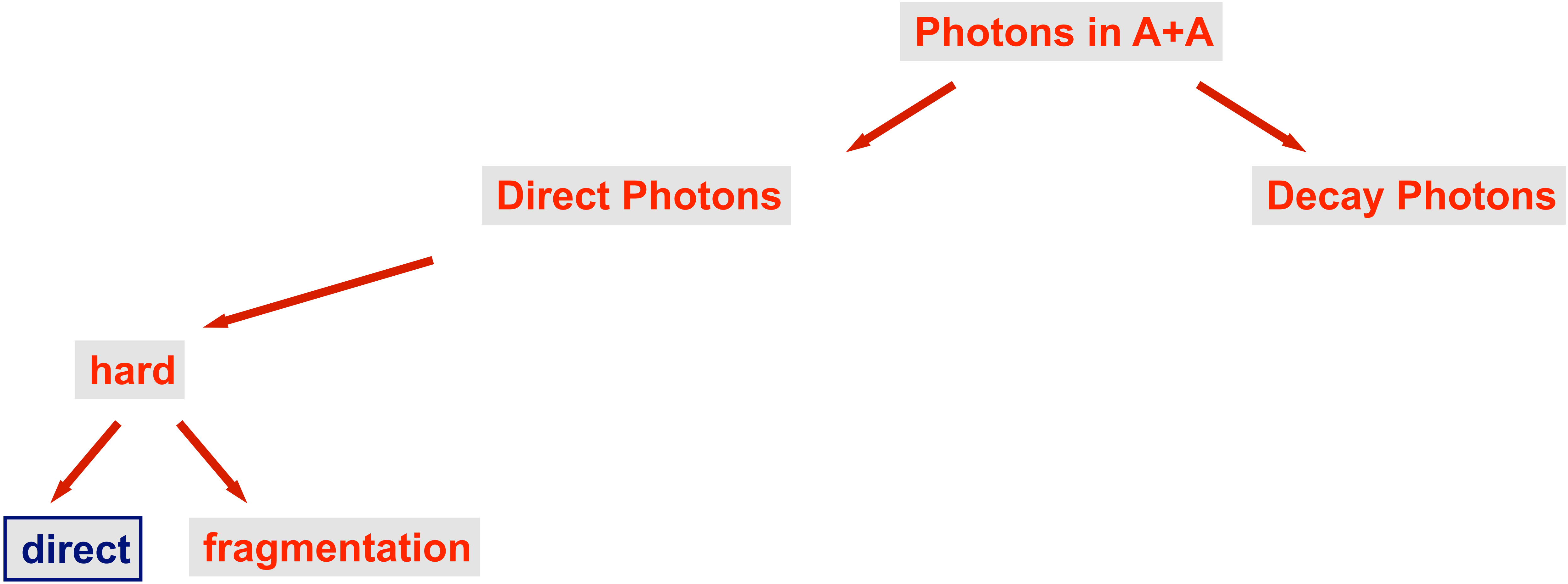
These mechanisms are also present in p+p collisions and are calculable within pQCD

Known and Presumed Photon Sources in A+A



Photons in A+A

Direct Photons

Decay Photons

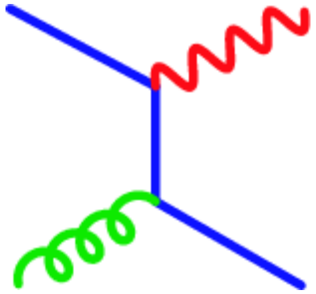
hard

direct

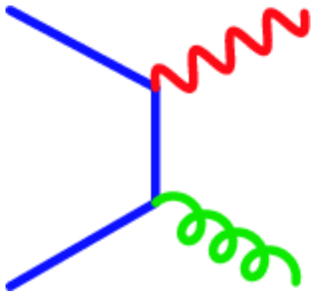
fragmentation

Hard direct photons:
direct component

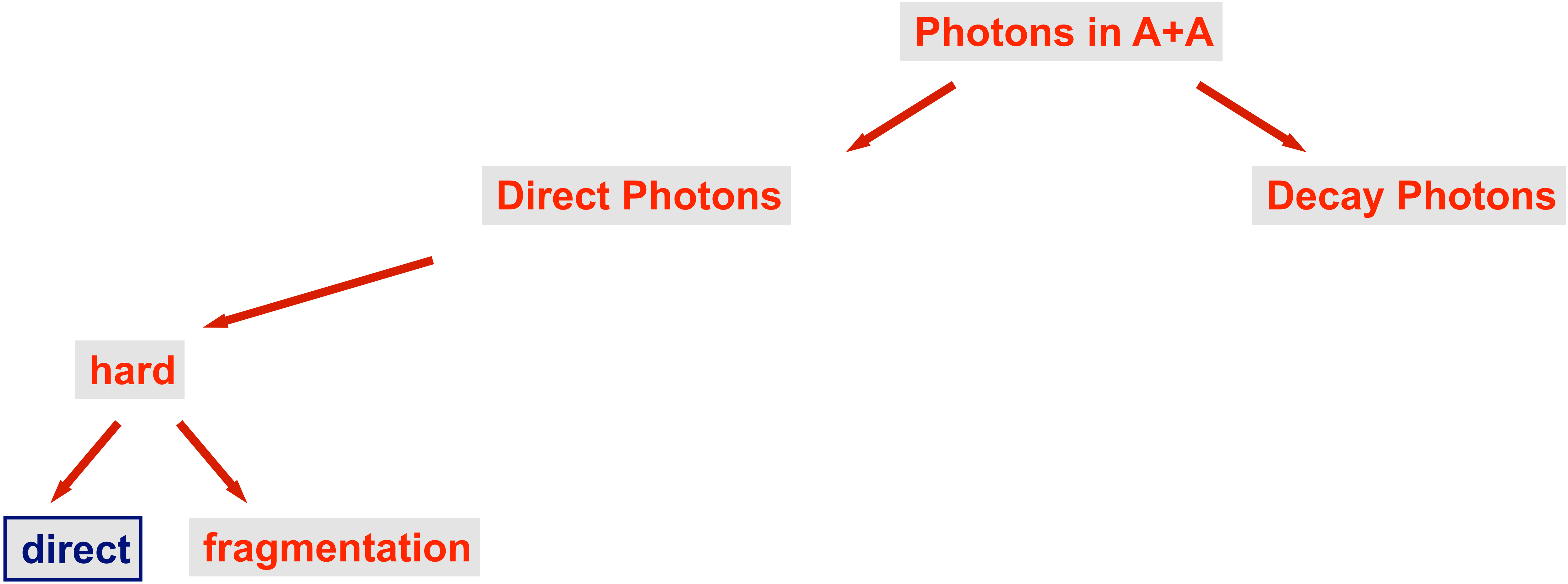
Compton



Annihilation



Known and Presumed Photon Sources in A+A



Photons in A+A

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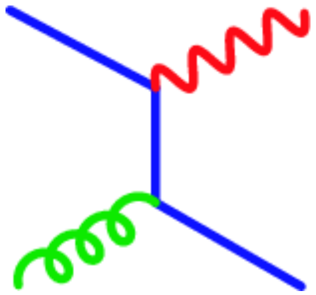
Hard direct photons:
direct component

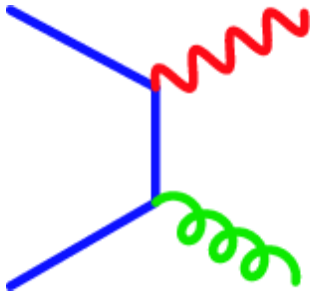
Compton

$$q + g \rightarrow \gamma + q$$



Annihilation

$$q + \bar{q} \rightarrow \gamma + g$$



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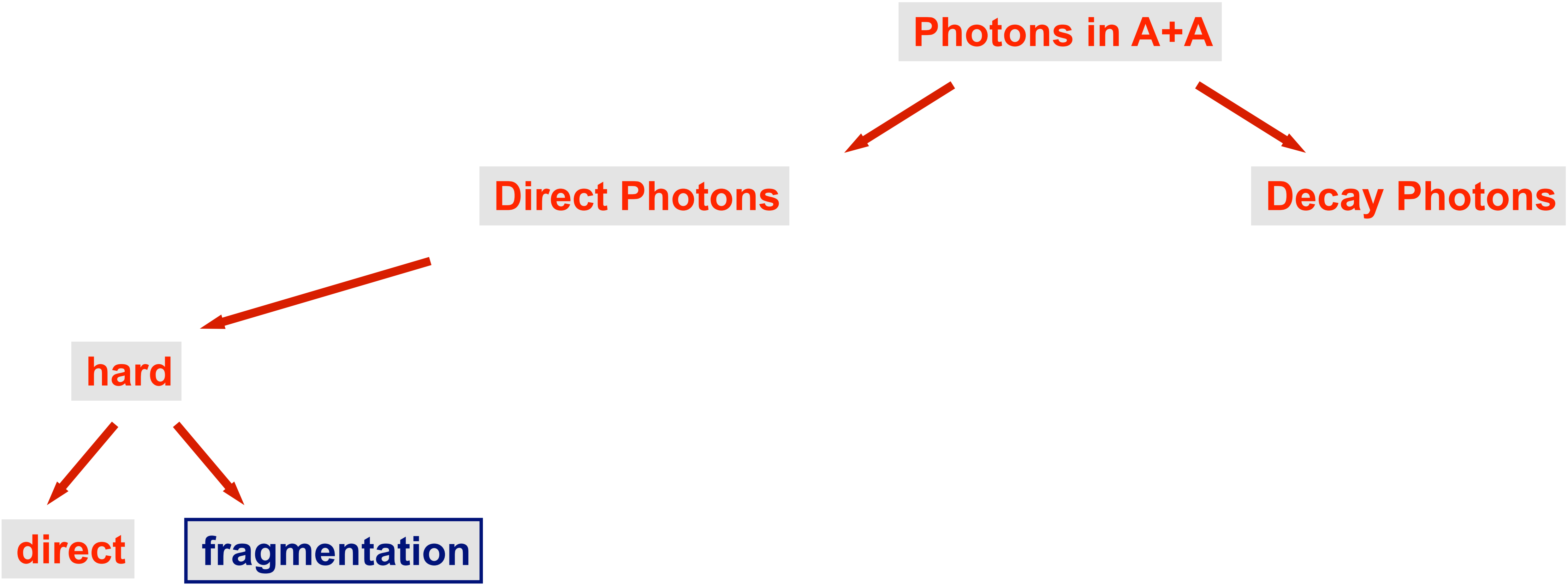


Photons in A+A

Direct Photons

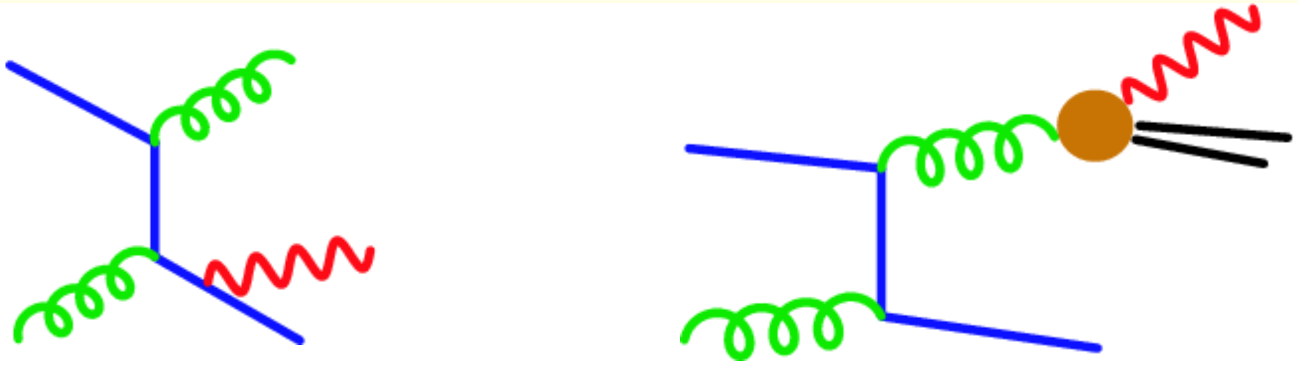
Decay Photons

hard

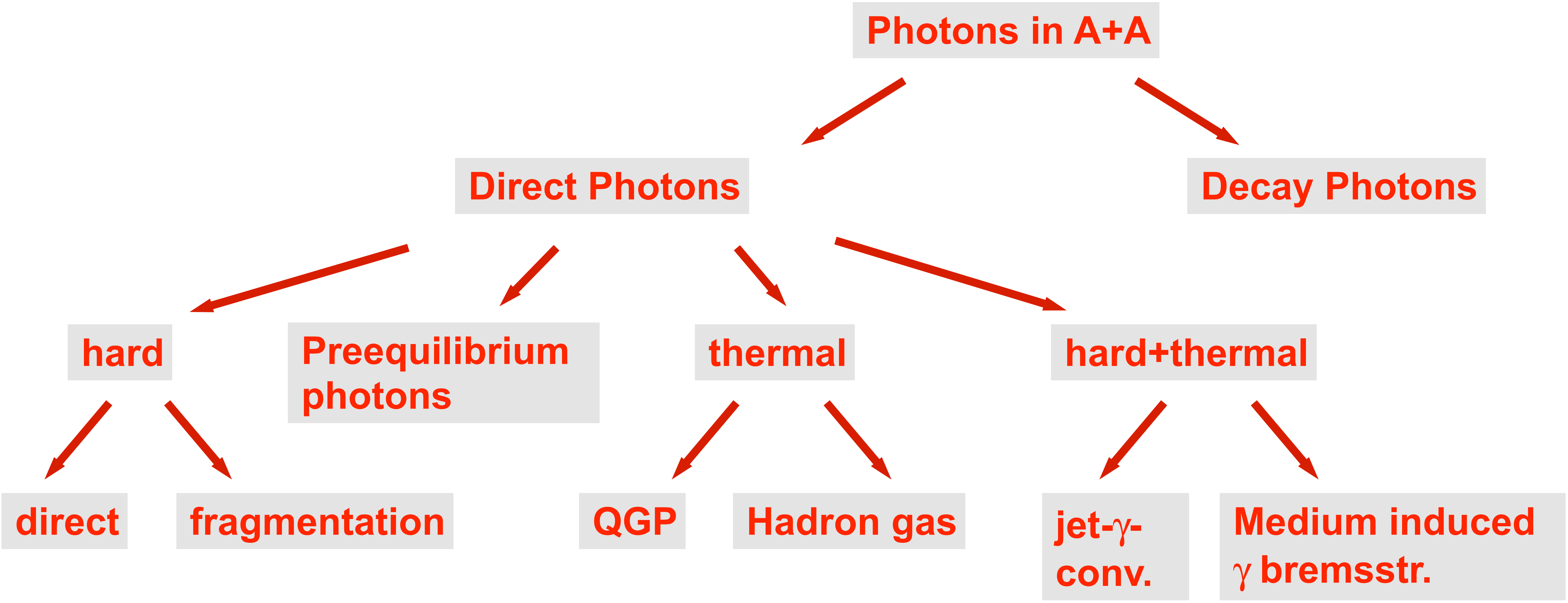
direct

fragmentation

Hard direct photons:
bremsstrahlung / fragmentation component

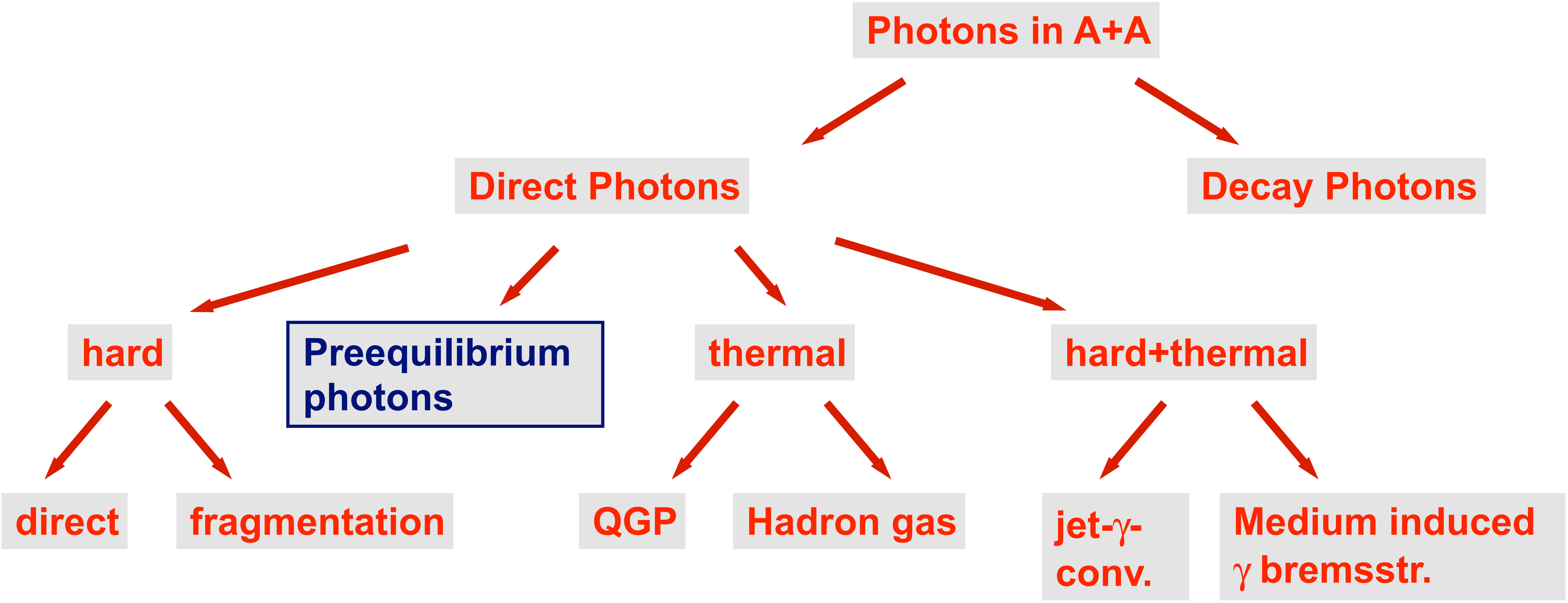


Known and Presumed Photon Sources in A+A



- Photons in A+A
  - Direct Photons
    - hard
      - direct
      - fragmentation
    - Preequilibrium photons
    - thermal
      - QGP
      - Hadron gas
    - hard+thermal
      - jet-γ-conv.
      - Medium induced γ bremsstr.
  - Decay Photons

Known and Presumed Photon Sources in A+A

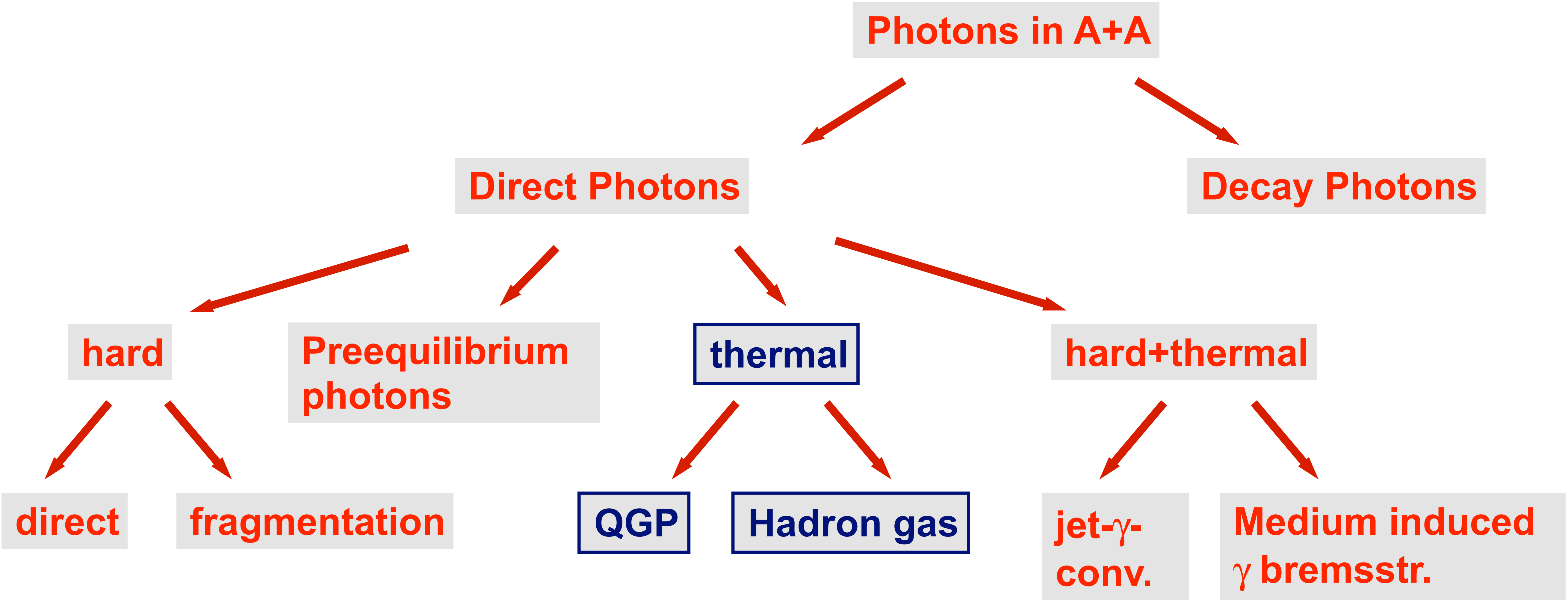


- **Photons in A+A**
  - **Direct Photons**
    - **hard**
      - **direct**
      - **fragmentation**
    - **Preequilibrium photons**
    - **thermal**
      - **QGP**
      - **Hadron gas**
    - **hard+thermal**
      - **jet-γ-conv.**
      - **Medium induced γ bremsstr.**
  - **Decay Photons**

Preequillibrium photons

- Produced through rescattering of the primarily produced partons prior to thermalization
- Difficult to treat theoretically

Known and Presumed Photon Sources in A+A



Photons in A+A

Direct Photons

Decay Photons

hard

Preequilibrium photons

thermal

hard+thermal

direct

fragmentation

QGP

Hadron gas

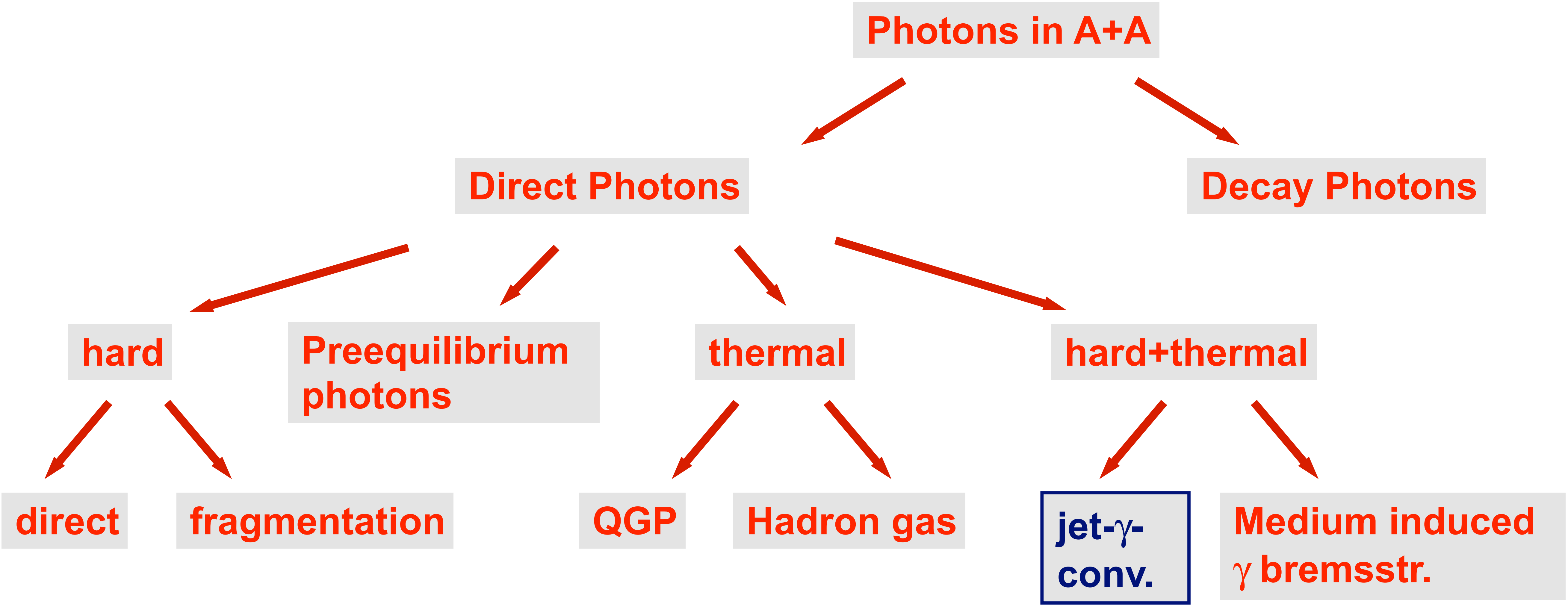
jet-γ-conv.

Medium induced γ bremsstr.

Thermal photons

- **Reflect temperature of the system, produced over entire evolution**
- **Significant direct photon source only at low p_T**

Known and Presumed Photon Sources in A+A



Photons in A+A

Direct Photons

Decay Photons

hard

Preequilibrium photons

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jet-γ-conv.

Medium induced γ bremsstr.

Hard+thermal:
Jet-Photon-Conversion

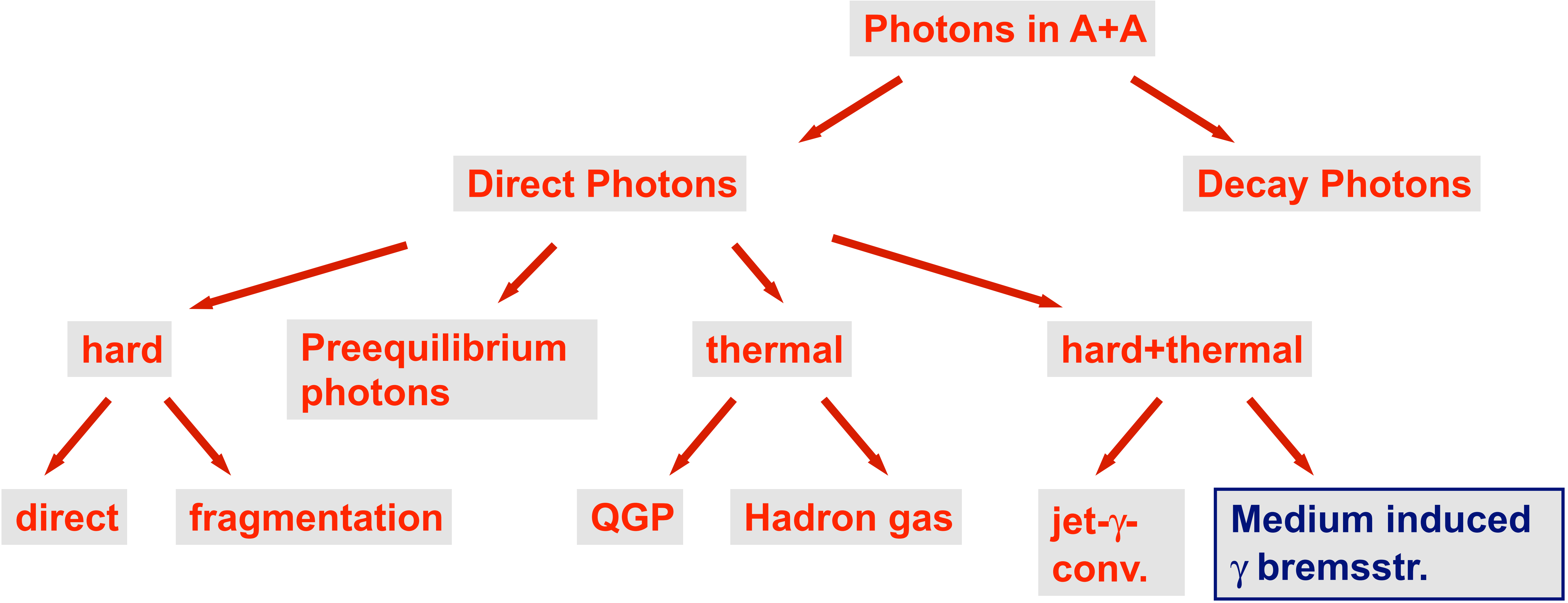
Interaction of parton from hard scattering with soft parton

$$\sigma_{\mathrm{jet}-\gamma-\mathrm{conv}} \sim \delta^3 \left(p_{\mathrm{jet}} - p_\gamma\right)$$

$$\mathbf{q}_{\mathbf{hard}} + \mathbf{g}_{\mathbf{QGP}} \rightarrow \gamma + \mathbf{q}$$

$$\mathbf{q}_{\mathbf{hard}} + \overline{\mathbf{q}}_{\mathbf{QGP}} \rightarrow \gamma + \mathbf{g}$$

Known and Presumed Photon Sources in A+A



Photons in A+A

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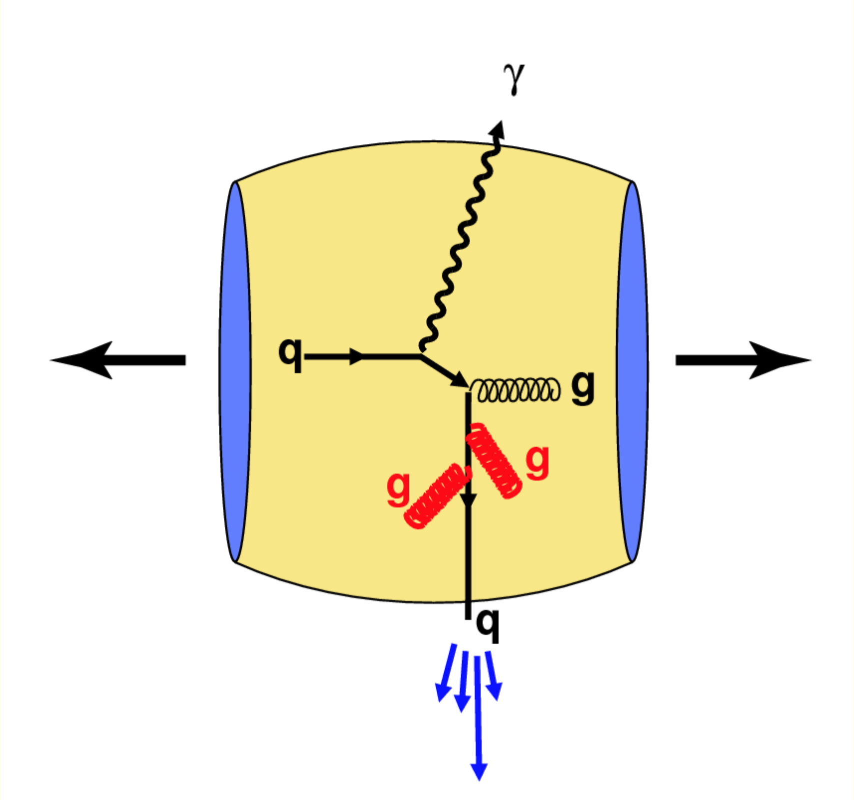
jet-γ-conv.

Medium induced γ bremsstr.

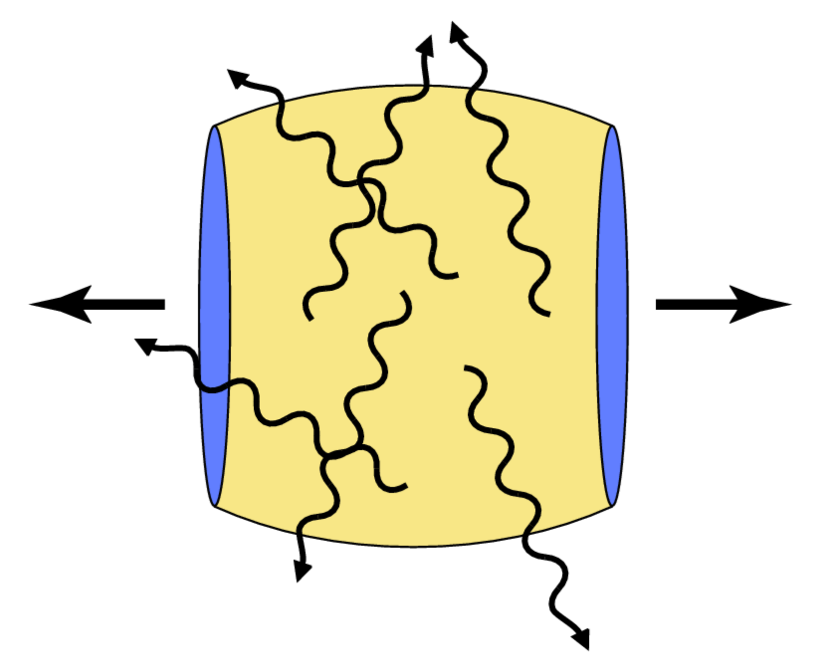
Medium induced photon bremsstrahlung

- Due to multiple scattering of quarks in the medium
- Different theoretical predictions, likely rather small contribution

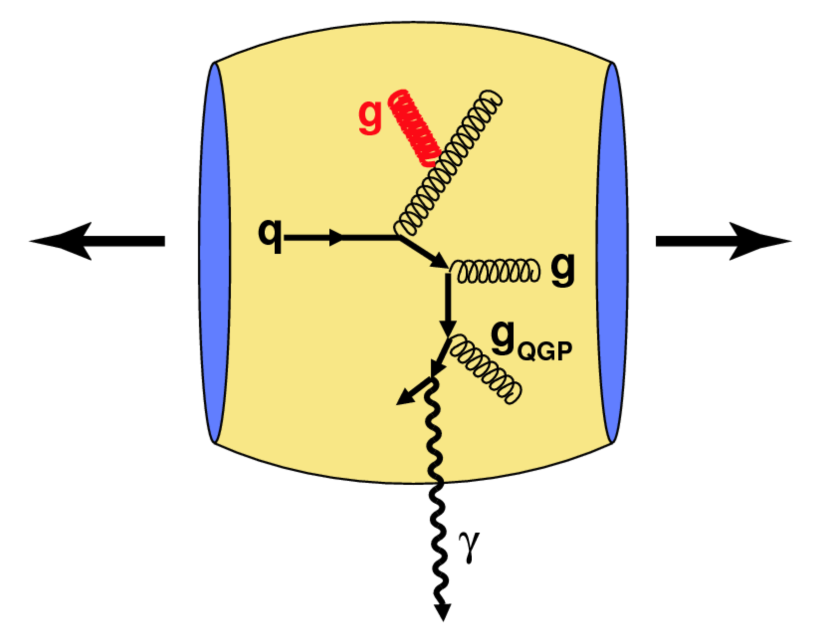
Summary: Direct Photons in A+A Collisions - Hard, Thermal, Hard+Thermal



Hard photons

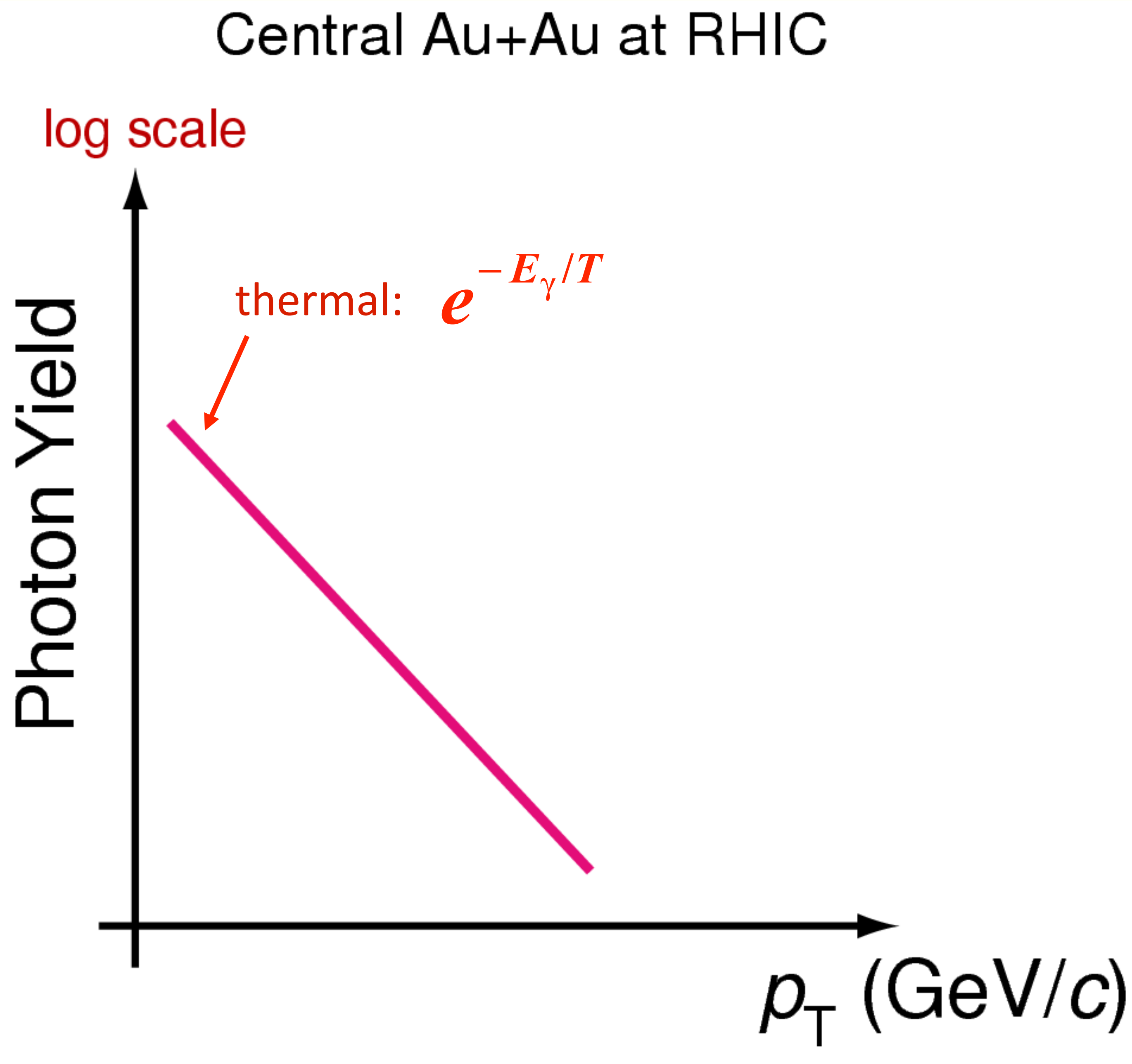


Thermal photons



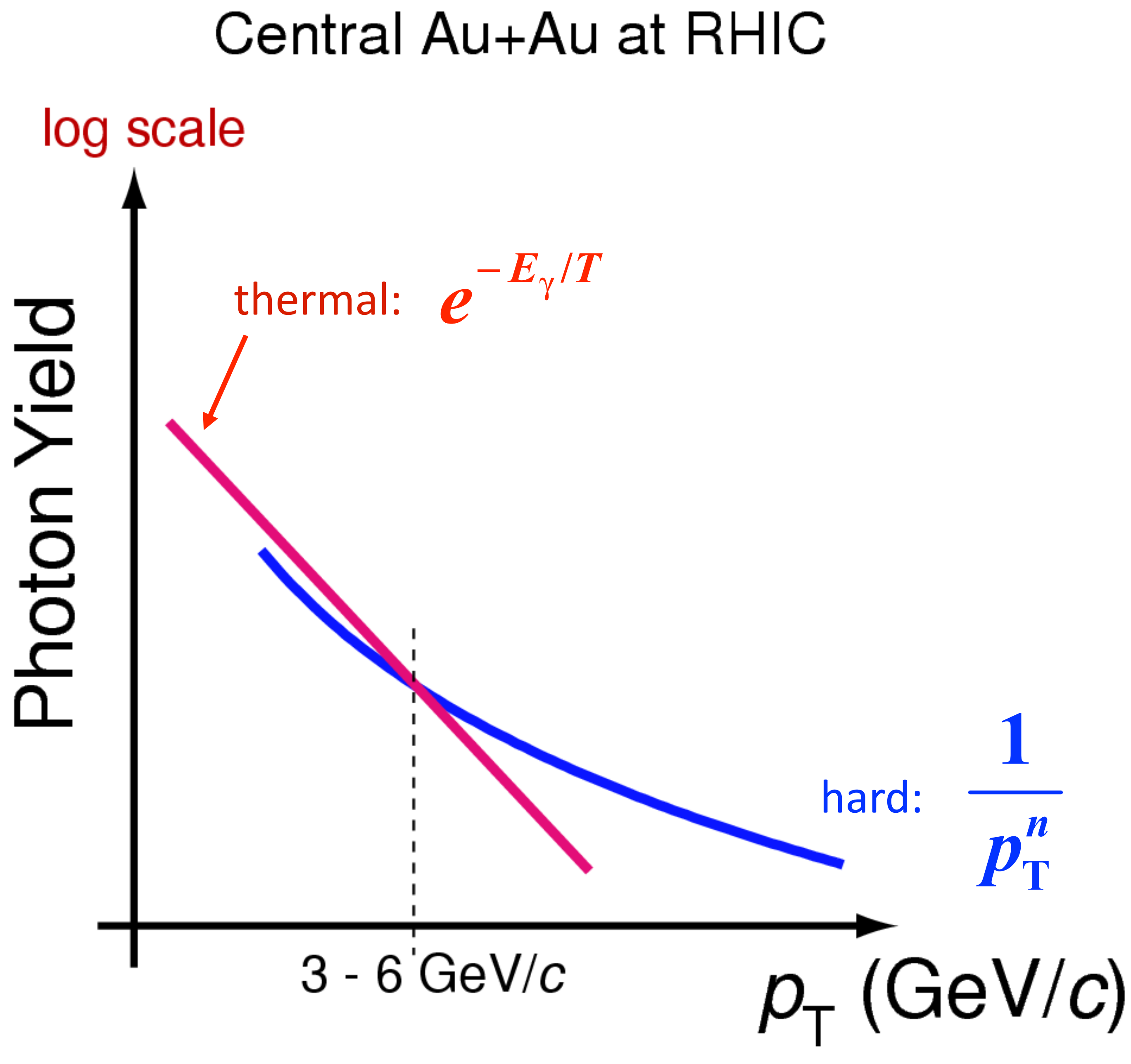
Photons form jet-plasma interaction

Schematic Photon Spectrum in A+A



- Thermal photons expected to be significant contribution below p_T ~ 3 GeV/c
- Hard photons dominant direct photon source for p_T > ~ 6 GeV/c
- Jet-photon conversion might be significant contribution below p_T ~ 6 GeV/c
- Experimental challenge: Subtraction of decay photon background

Schematic Photon Spectrum in A+A



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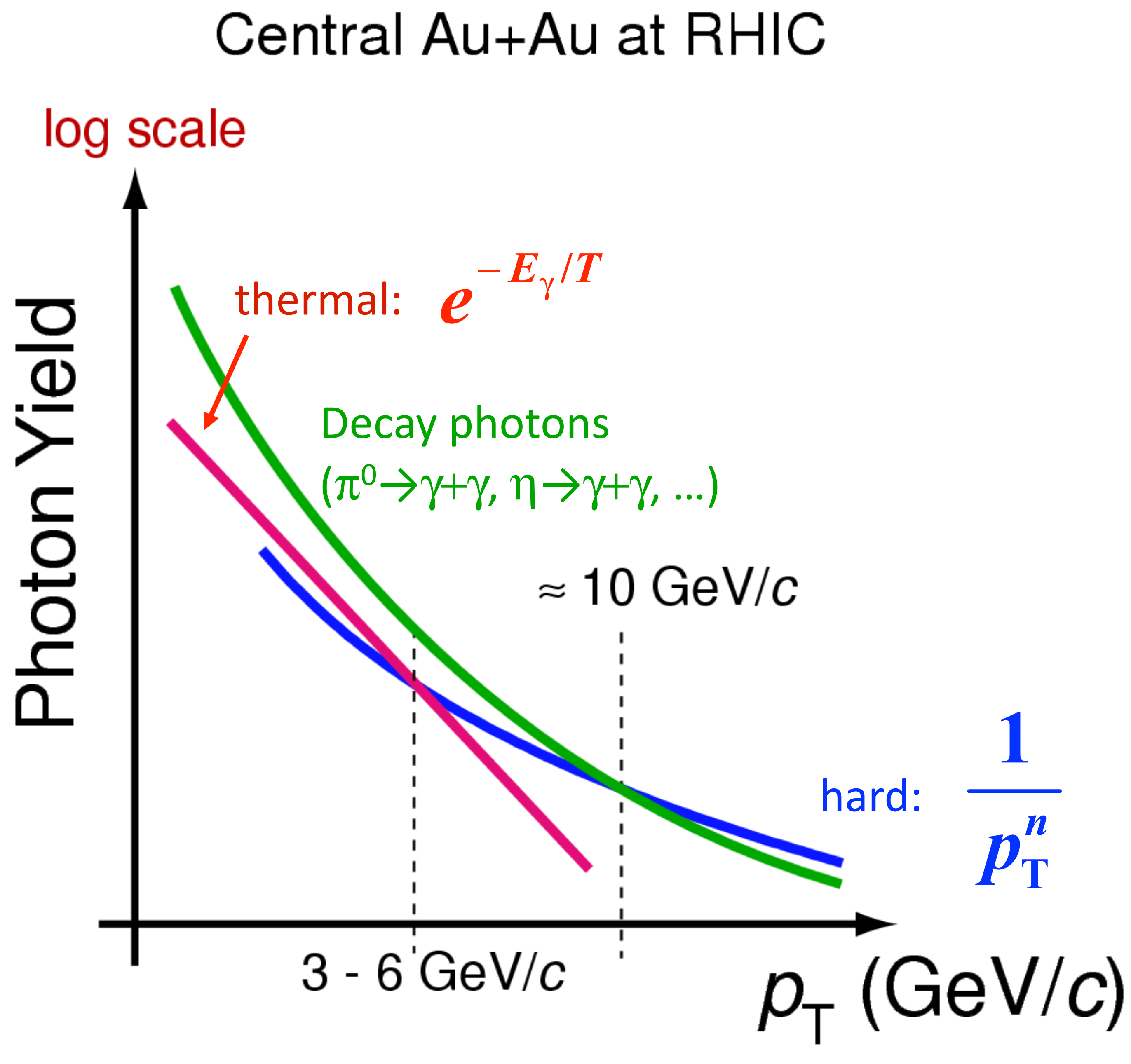

- Thermal photons expected to be significant contribution below $p_T \sim 3$ GeV/*c*
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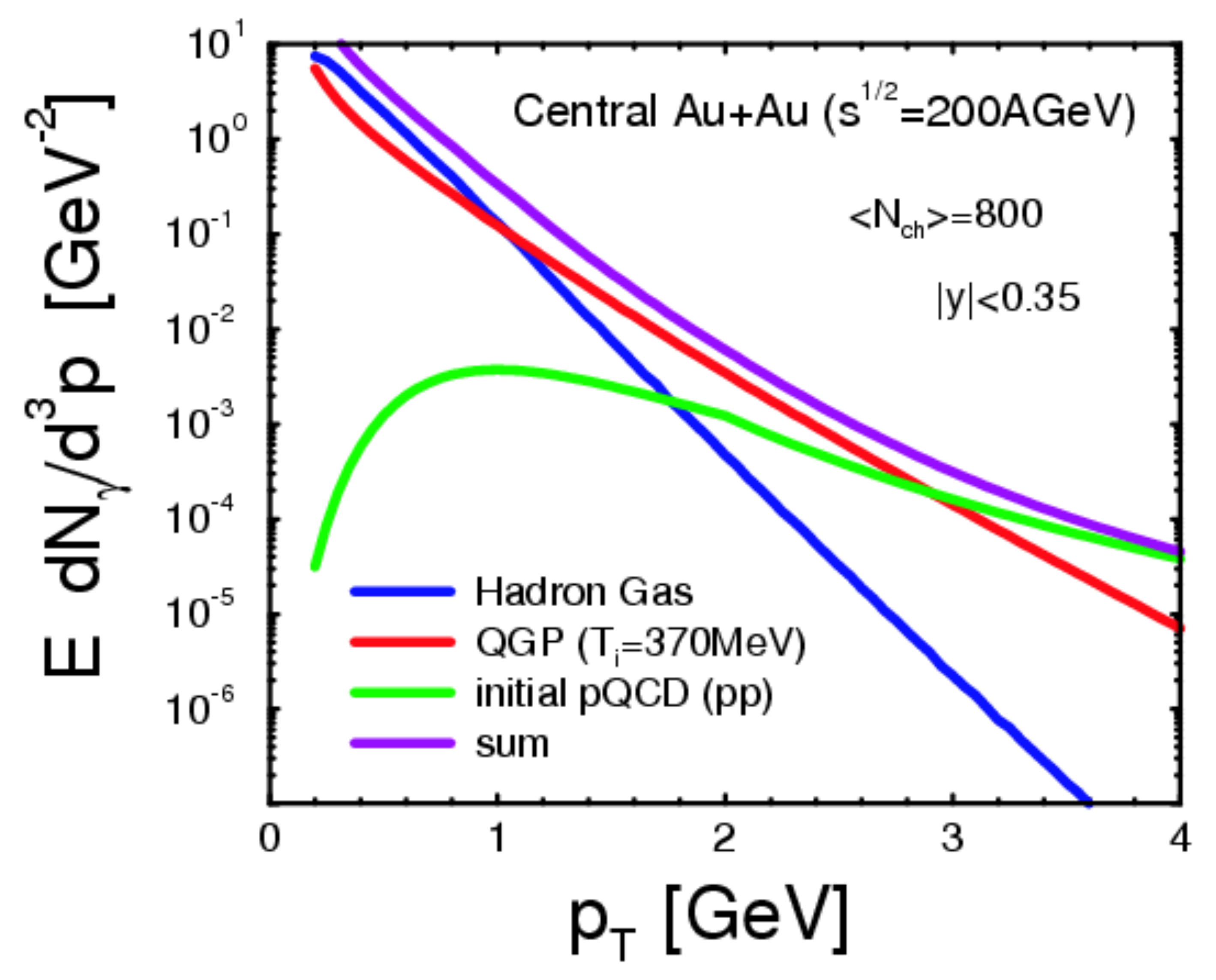
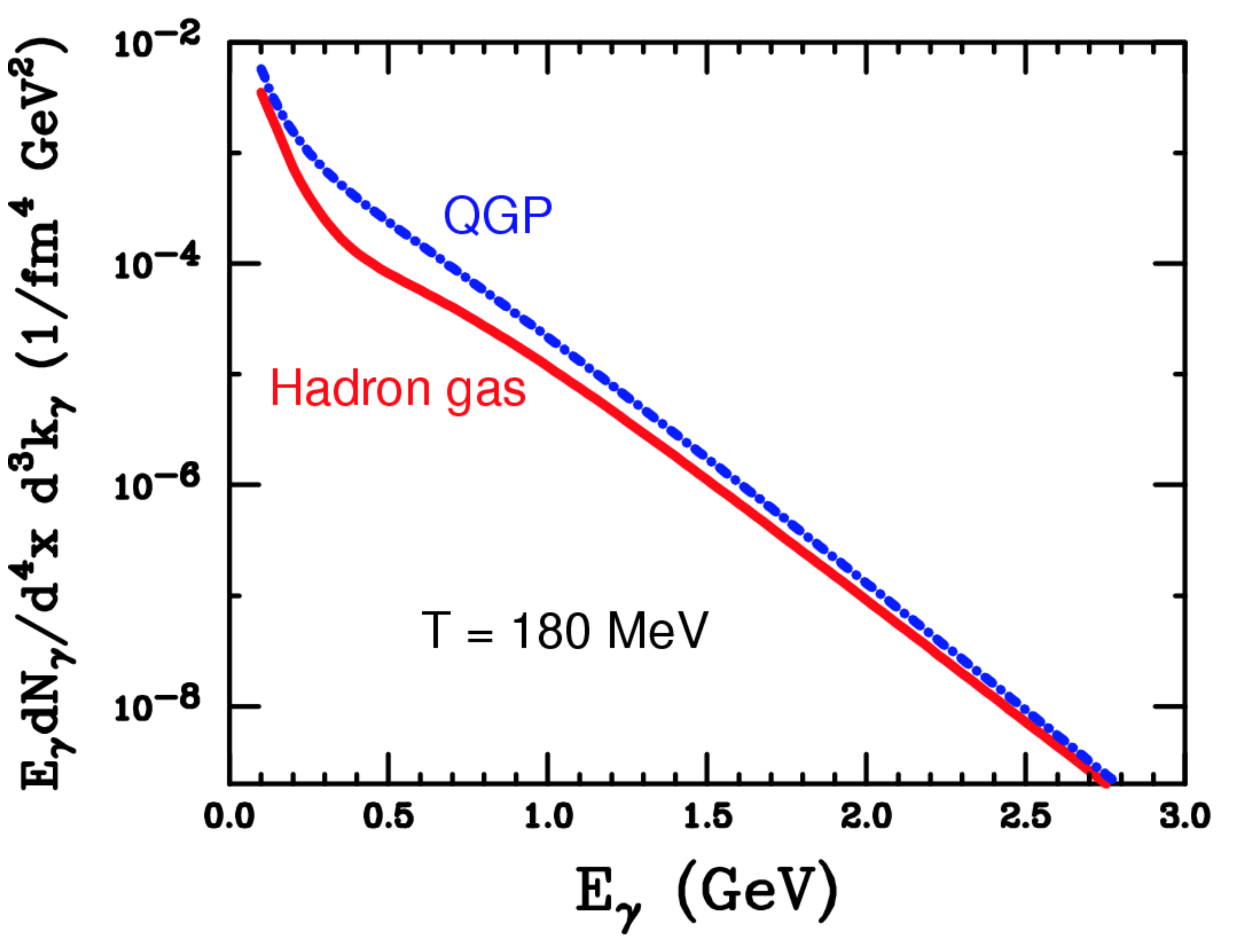
Direct Photons in A+A: Realistic Calculation



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

Window for thermal photons from QGP in this calculation:
p_T = 1 - 3 GeV/c

Photon Rates in HG and QGP



- Final thermal photon spectrum: QGP and HG photon rates convoluted with space-time evolution of the reaction
- Very similar thermal photon rates for QGP and hadron gas at same temperature *T*

QGP rates: Arnold, Moore, Yaffe (2001)
HG rates: Turbide, Rapp, Gale (2004)

Measurement of Direct Photons in A+A Collisions

Measurement of Direct Photons with the Subtraction 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, …
- Finally:
  Subtract decay background from inclusive photon spectrum

Pocket formula:

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

$$\Rightarrow \frac{\gamma_{\pi^0}^{\text{decay}}}{\pi^0} = \frac{2}{n-1} \approx \mathbf{0.28\ \text{at RHIC}}$$

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}$$

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Direct Photons: Statistical Subtraction Method

$$\pi^0 \to \gamma + \gamma, \;\; \eta \to \gamma + \gamma, \;\; \ldots$$

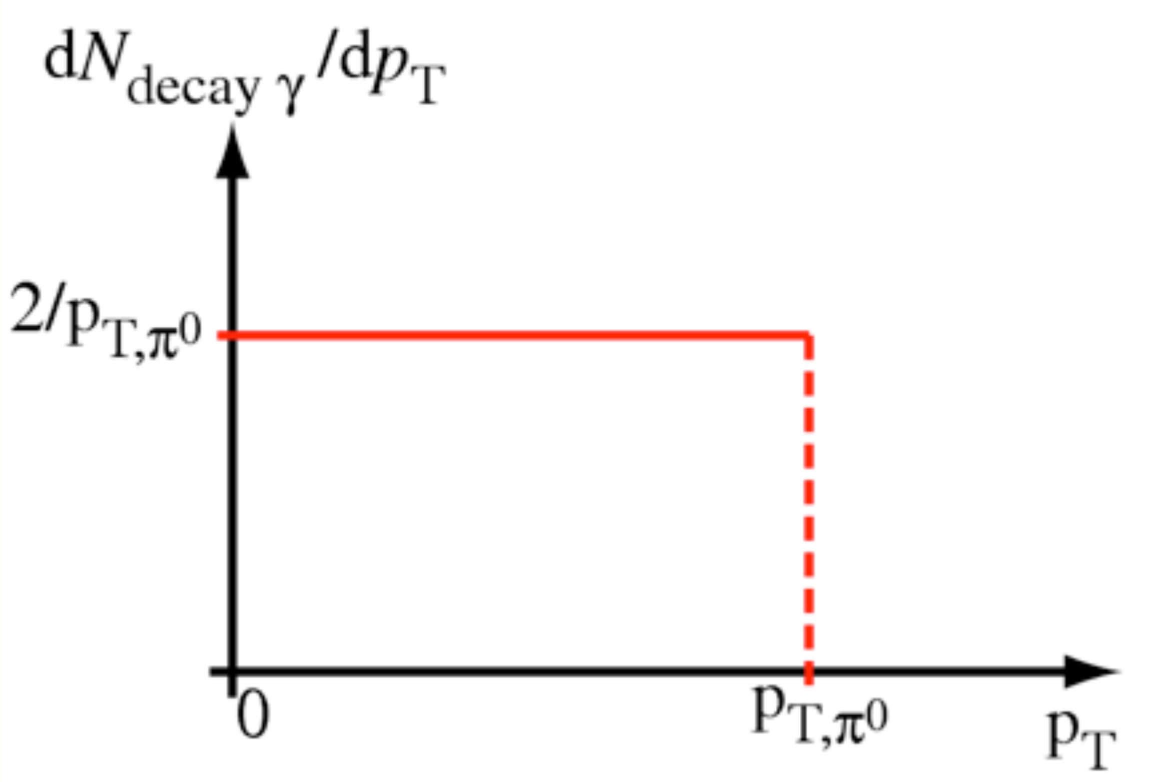
$$\begin{aligned}\gamma_{\mathrm{direct}} = \gamma_{\mathrm{inclusive}} - \gamma_{\mathrm{backgr}} &= \left(1 - \frac{\gamma_{\mathrm{backgr}}/\pi^0}{\gamma_{\mathrm{inclusive}}/\pi^0}\right) \cdot \gamma_{\mathrm{inclusive}} \\ &= (1 - 1/R) \cdot \gamma_{\mathrm{inclusive}}\end{aligned}$$

with $$R = \frac{\gamma_{\mathrm{inclusive}}}{\gamma_{\mathrm{backgr}}} = 1 + \frac{\gamma_{\mathrm{direct}}}{\gamma_{\mathrm{backgr}}} \equiv \frac{(\gamma_{\mathrm{inclusive}}/\pi^0)_{\mathrm{meas}}}{(\gamma_{\mathrm{backgr}}/\pi^0)_{\mathrm{calc}}}$$

Calculated based on measured π^0 and η spectrum (includes ω, η', … decays)

Systematic errors (e.g. energy scale non-linearity) partially cancel in this ratio

Pocket Formula for Decay Photons



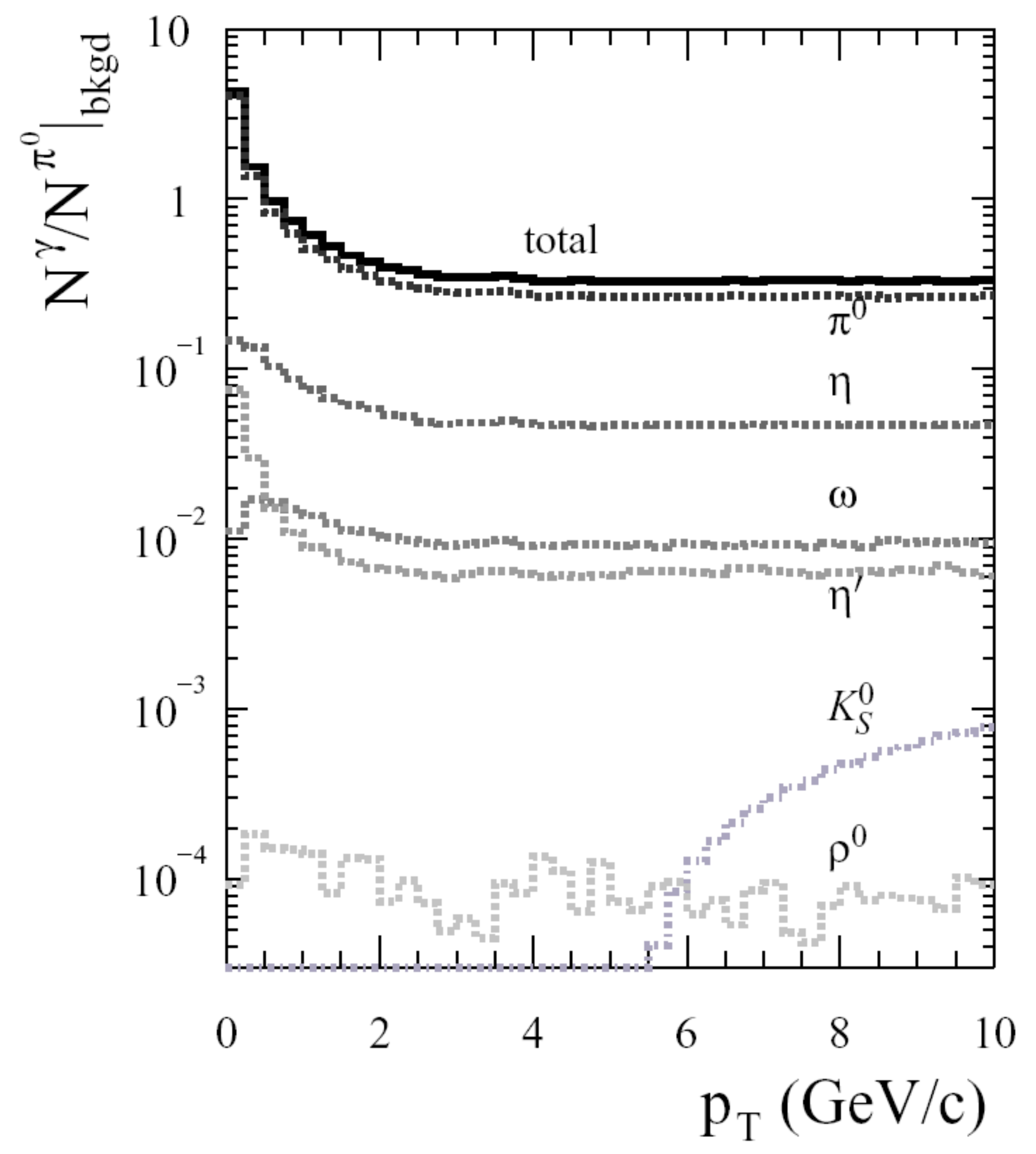
Decay photon p_T distribution
for π^0's with a given trans. momentum

$$g(p_T, p_{T,\pi^0}) \approx \begin{cases} 2/p_{T,\pi^0}, & p_T < p_{T,\pi^0} \\ 0, & \text{else} \end{cases}$$

For $\displaystyle \frac{1}{p_T}\frac{dN_{\pi^0}}{dp_T} \propto p_T^{-n}$:

$$\left.\frac{\gamma_{\text{decay}-\pi^0}}{\pi^0}\right|_{p_T} = \frac{\int_{p_T}^{\infty} g(p_T, p_{T,\pi^0})\, \frac{dN_{\pi^0}}{dp_{T,\pi^0}}\, dp_{T,\pi^0}}{p_T^{-n+1}} = \frac{2 \cdot \int_{p_T}^{\infty} p_{T,\pi^0}^{-n}\, dp_{T,\pi^0}}{p_T^{-n+1}} = \frac{2}{n-1}$$

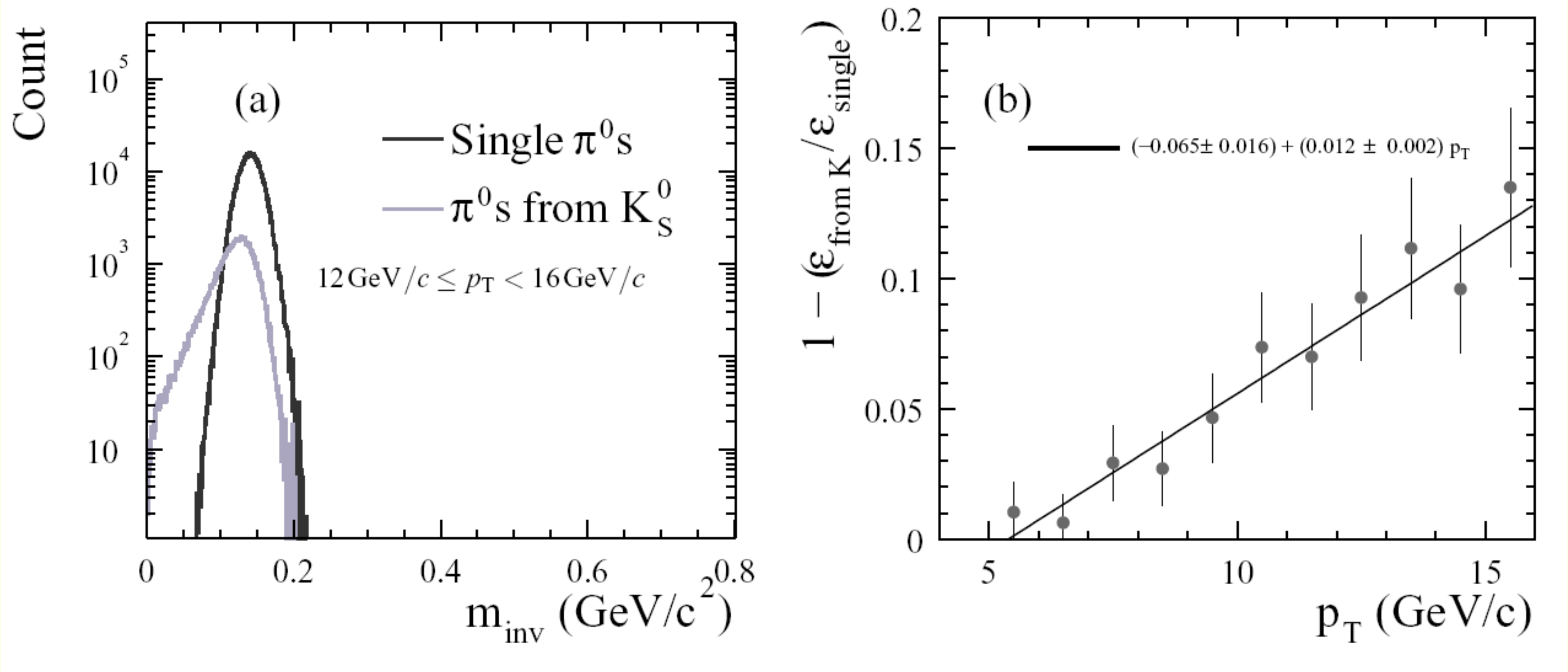
Decay Photon Calculation



- Simple Monte Carlo code
- Pure kinematics (no detector simulation needed)
- ~96% of the background photons from π^0 and η decays

Background Photons from $K_s^0 \longrightarrow \pi^0 + \pi^0$

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



$$K_s^s : c\tau_0 = 2.67\,\mathrm{cm} \qquad L_{\mathrm{lab}} = v \cdot \gamma \cdot \tau_0 = \beta \cdot \gamma \cdot \tau_0 \cdot c \qquad \beta \cdot \gamma = \frac{p}{mc}$$

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

Formula for Fully Corrected Inclusive Photon Spectrum

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

Formula for Fully Corrected Inclusive Photon Spectrum

Fraction of charged clusters

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

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Fraction of neutral background (neutron, anti-neutrons)

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efficiency

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efficiency

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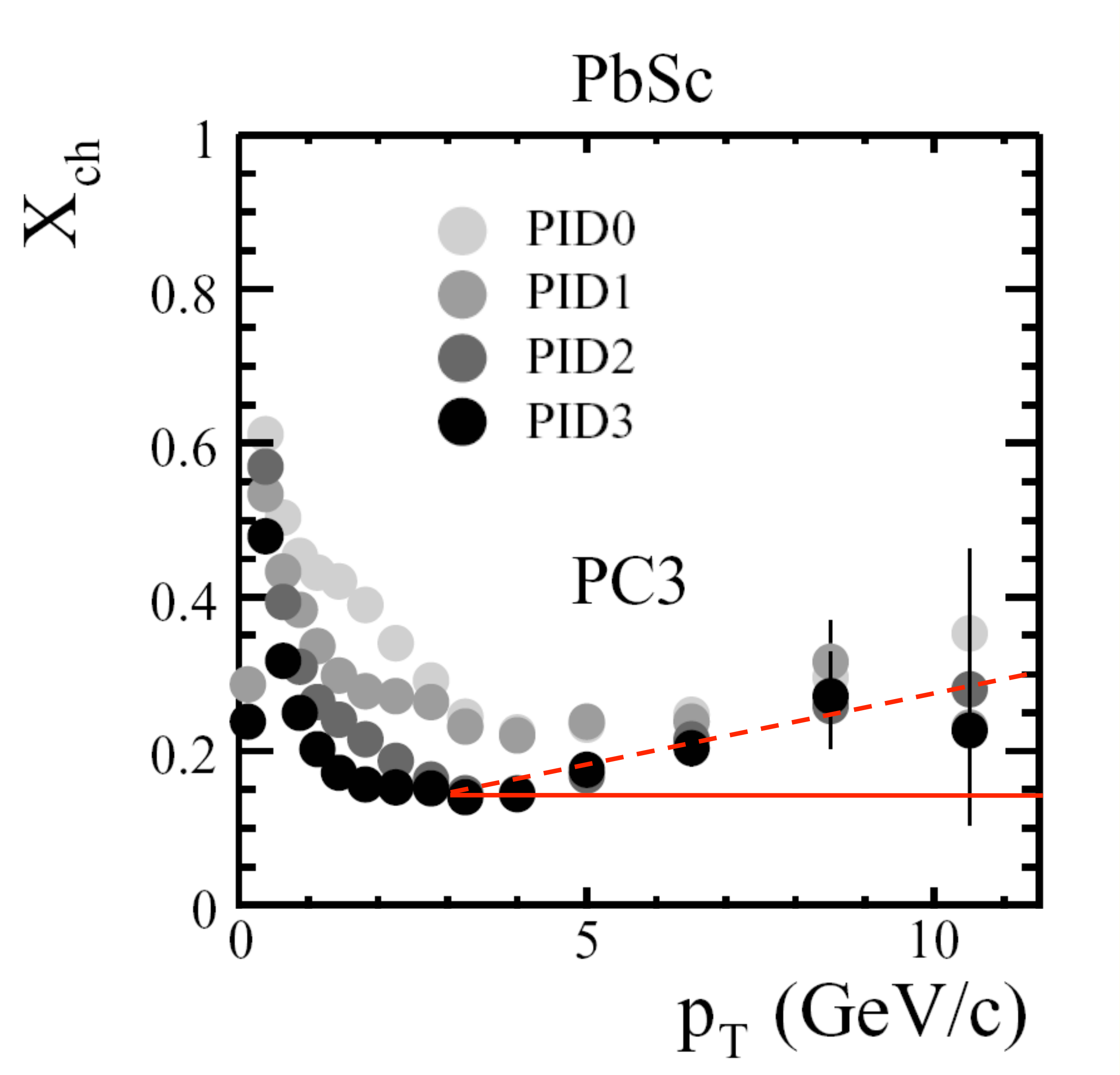
efficiency

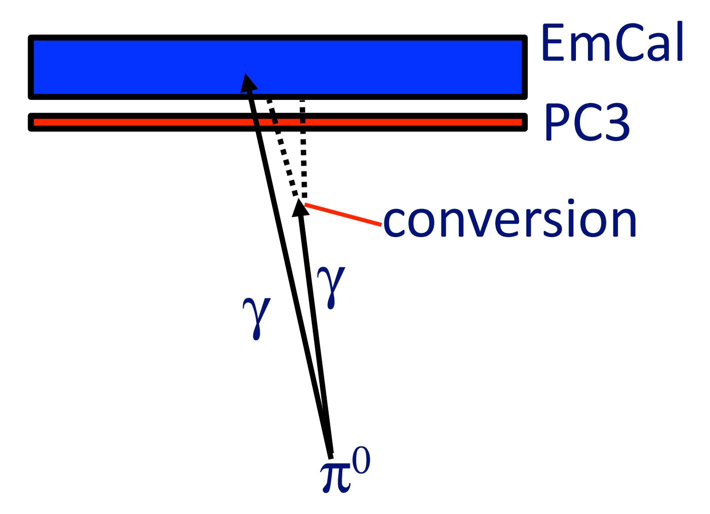
acceptance

photon conversion

Charged Background: X_{ch}

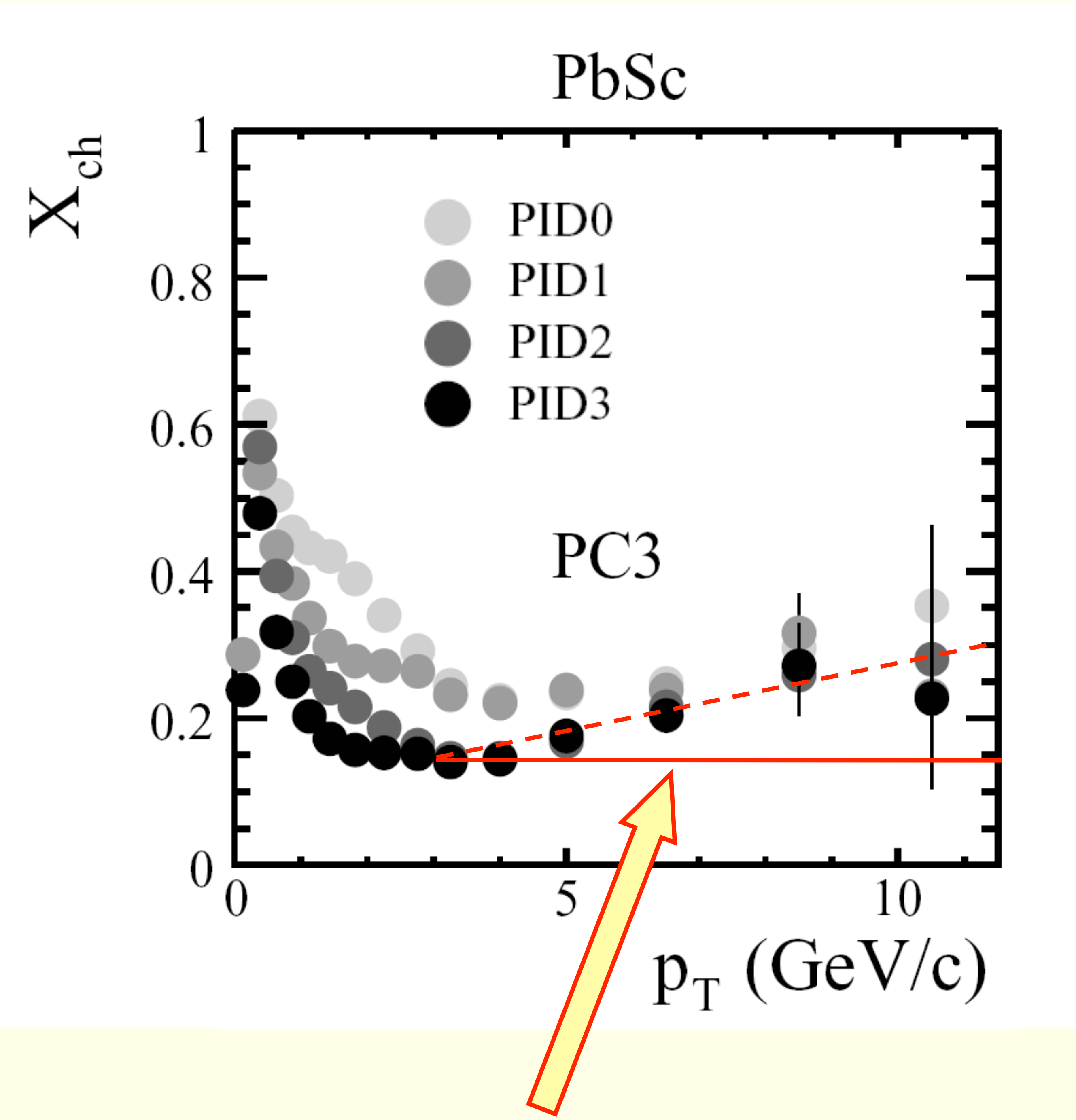


- X_{ch} > 0 at high p_T largely due to photon conversion
- Artificial decay photon-charged hit (PC3) correlations at high p_T:



final correction

Charged Background: X_{ch}



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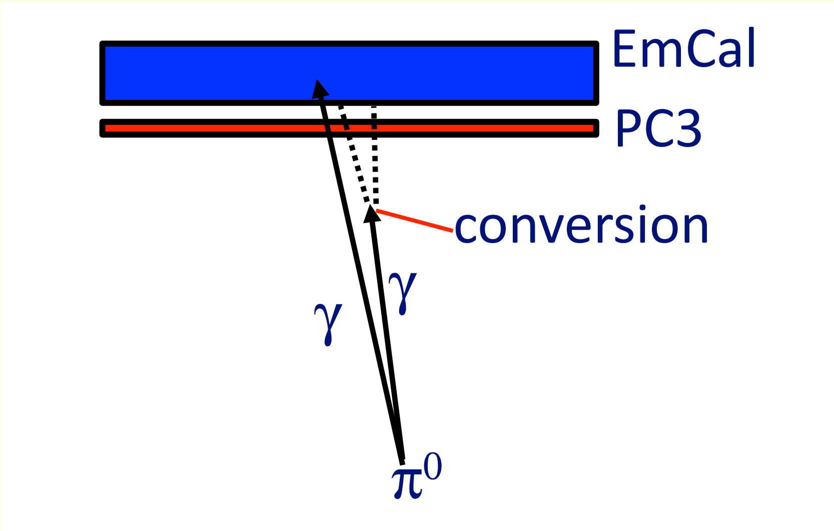

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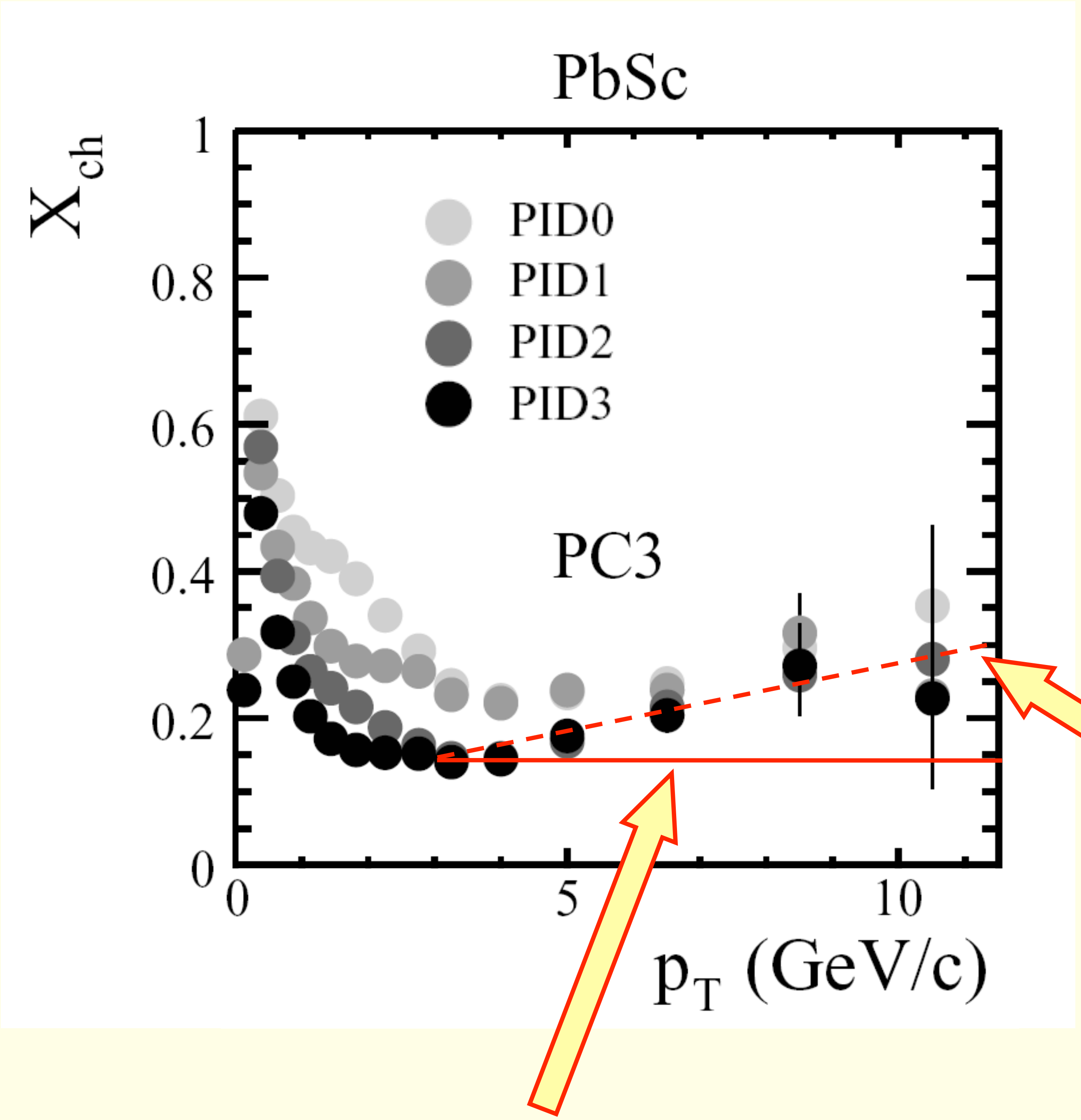

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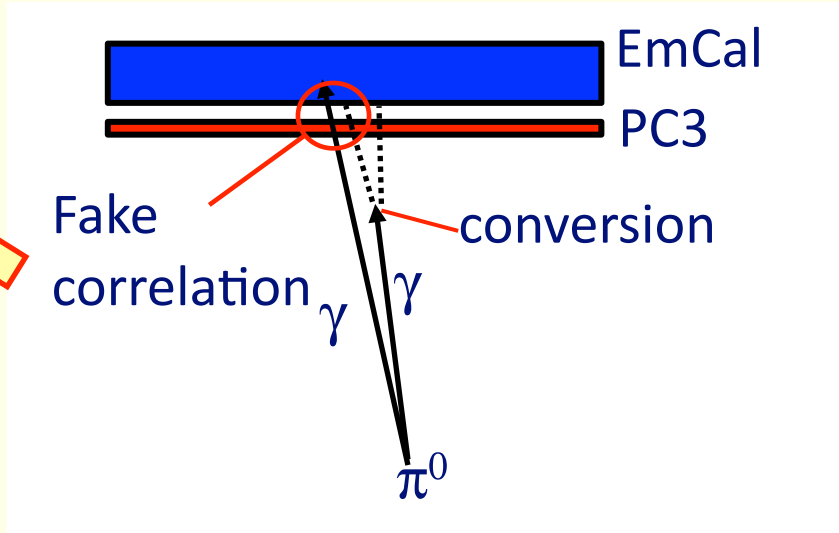
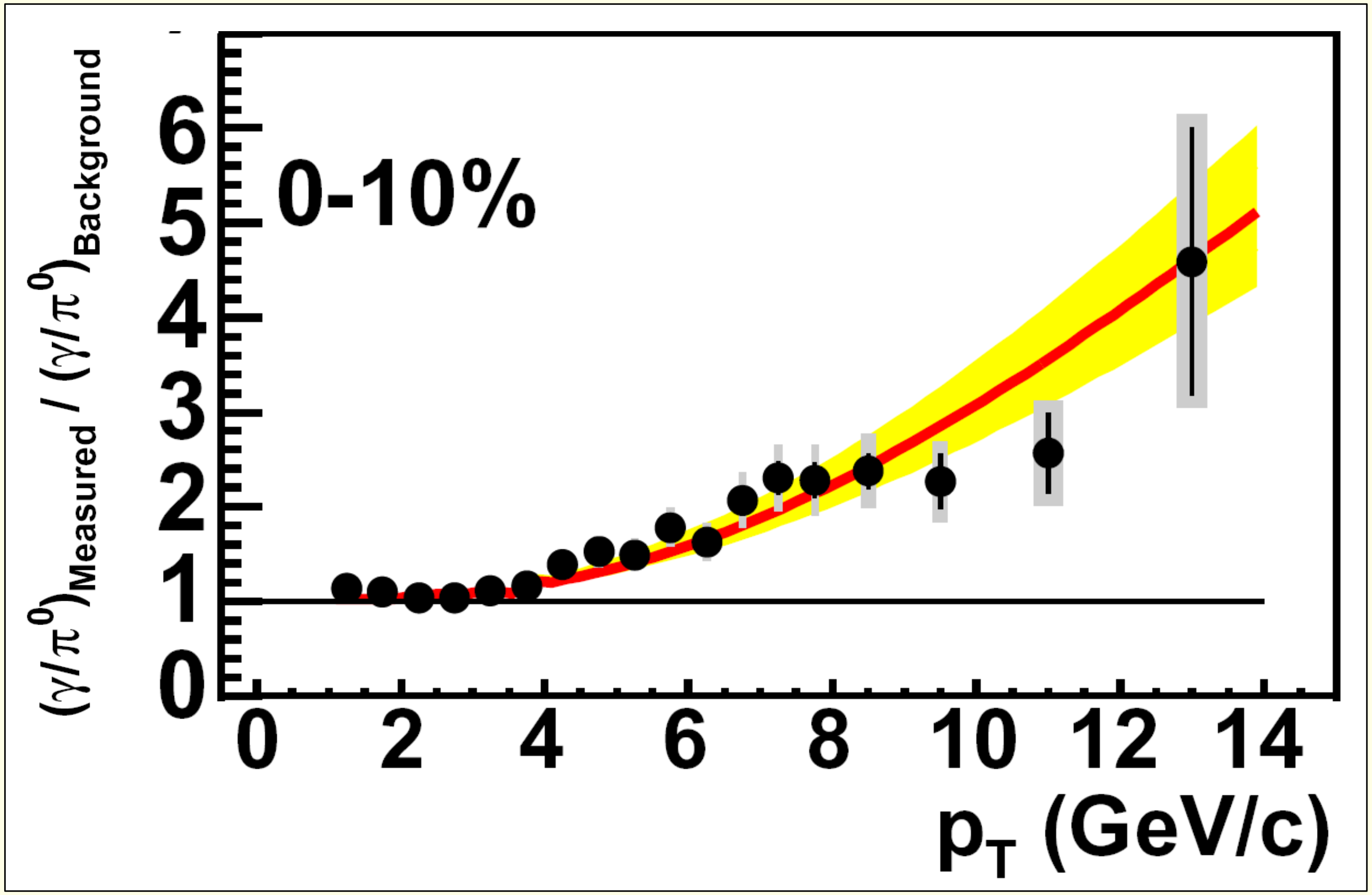


Neutral Background: X_{nn}

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

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

Result: Double Ratio



Multiply Inclusive Photon Spectrum by the double ratio to obtain direct-photon spectrum (and add sys. errors of the inclusive photon spectrum which cancelled in the double ratio)

Systematic Uncertainties of the Subtraction Method

[talk by Andreas Arend]

- π^0 measurement
  - Peak extraction
  - Yield correction (acceptance + efficiency)
  - Energy scale

- Inclusive photon measurement
  - Non-photon background
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Non-linearity in the EM calorimeter is also crucial. It is vital, for instance, that two 3 GeV photons have the identical response as one 6 GeV photon.

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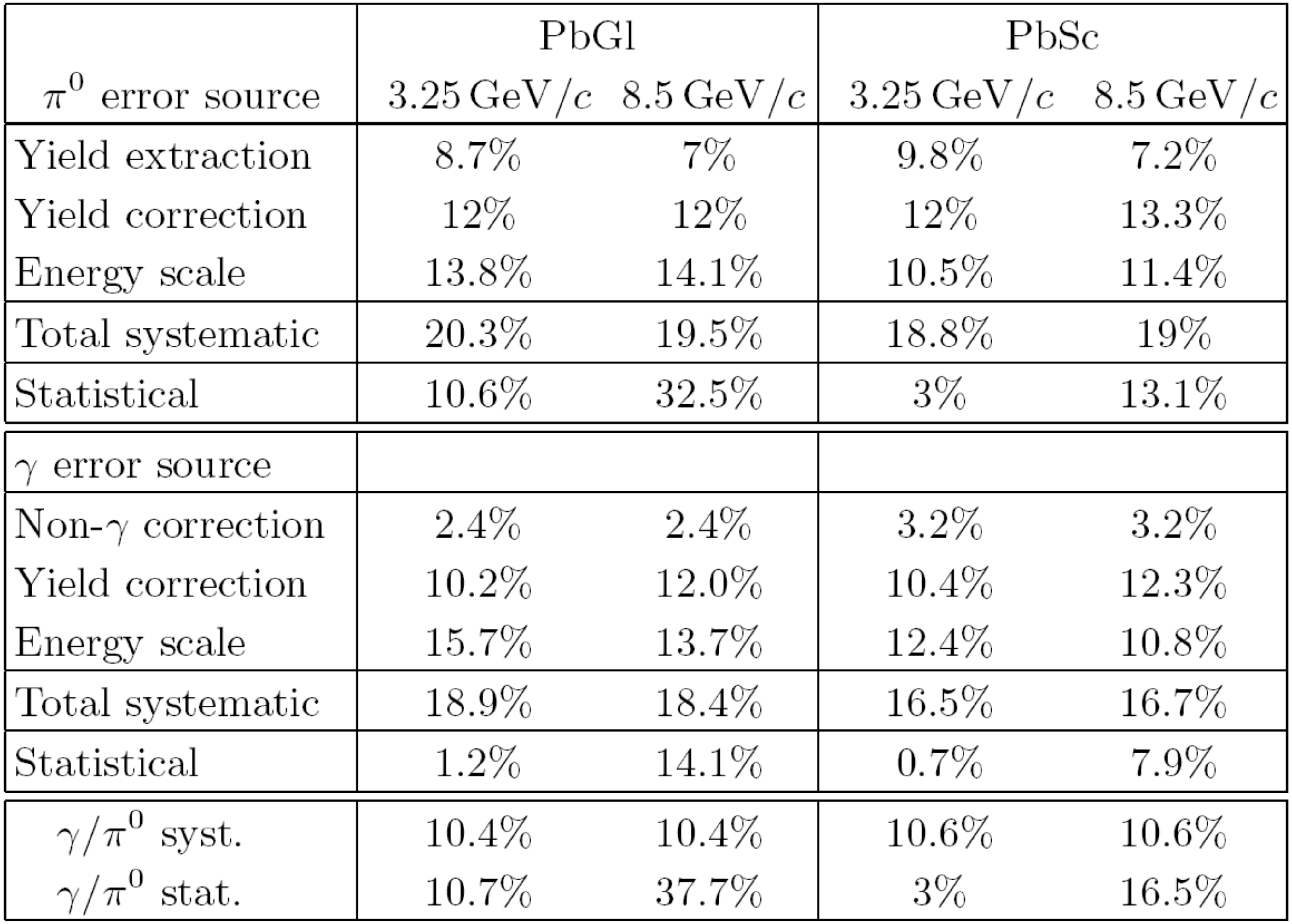
  - Energy scale

Many systematic uncertainties of π^0 and photon measurements are highly correlated!

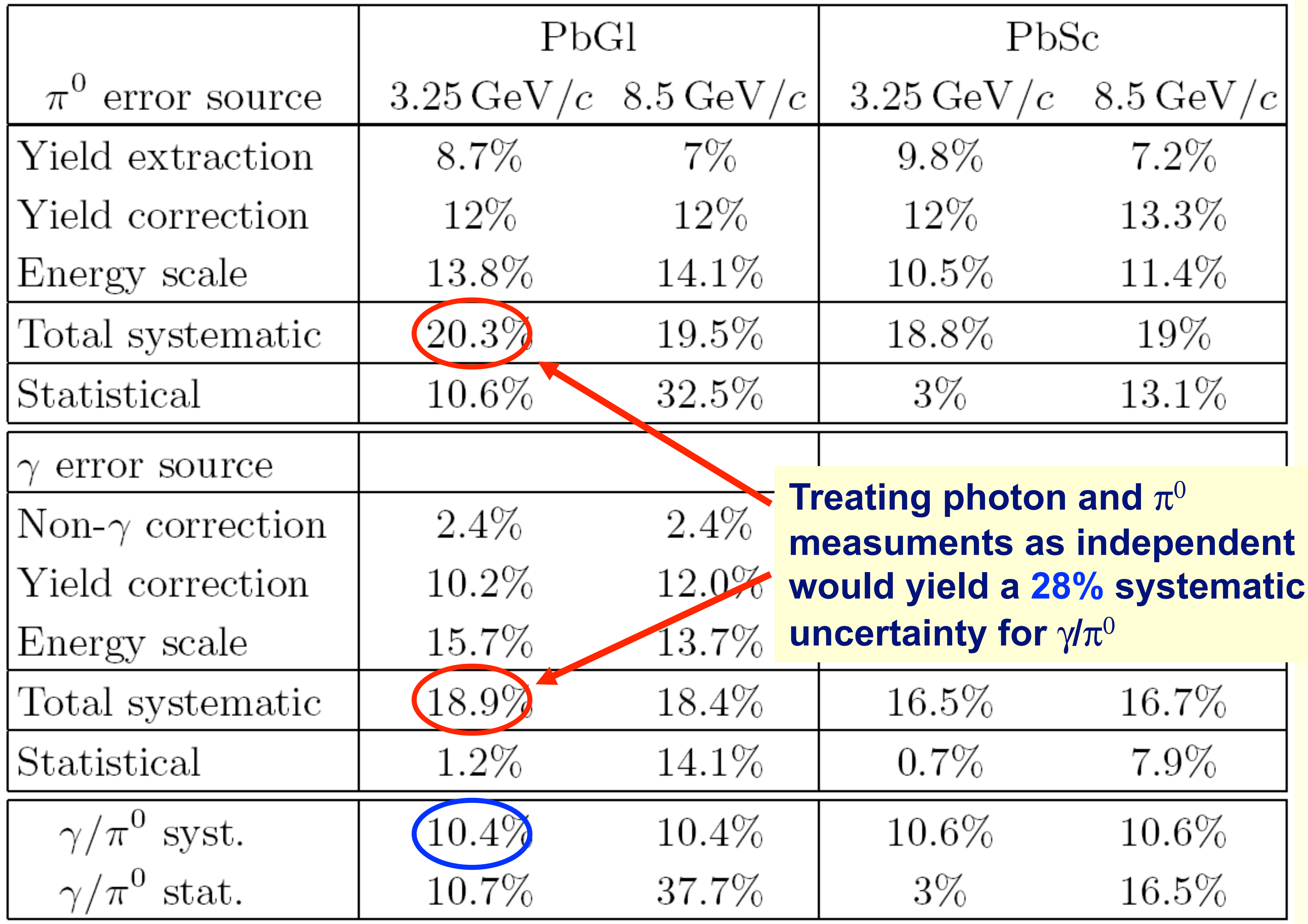
Non-linearity in the EM calorimeter is also crucial. It is vital, for instance, that two 3 GeV photons have the identical response as one 6 GeV photon.

Systematic Uncertainties
(Example: PHENIX, Run-2 Au+Au)



	PbGl		PbSc	
π^0 error source	3.25 GeV/c	8.5 GeV/c	3.25 GeV/c	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%	3.2%	3.2%
Yield correction	10.2%	12.0%	10.4%	12.3%
Energy scale	15.7%	13.7%	12.4%	10.8%
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%

Systematic Uncertainties (Example: PHENIX, Run-2 Au+Au)



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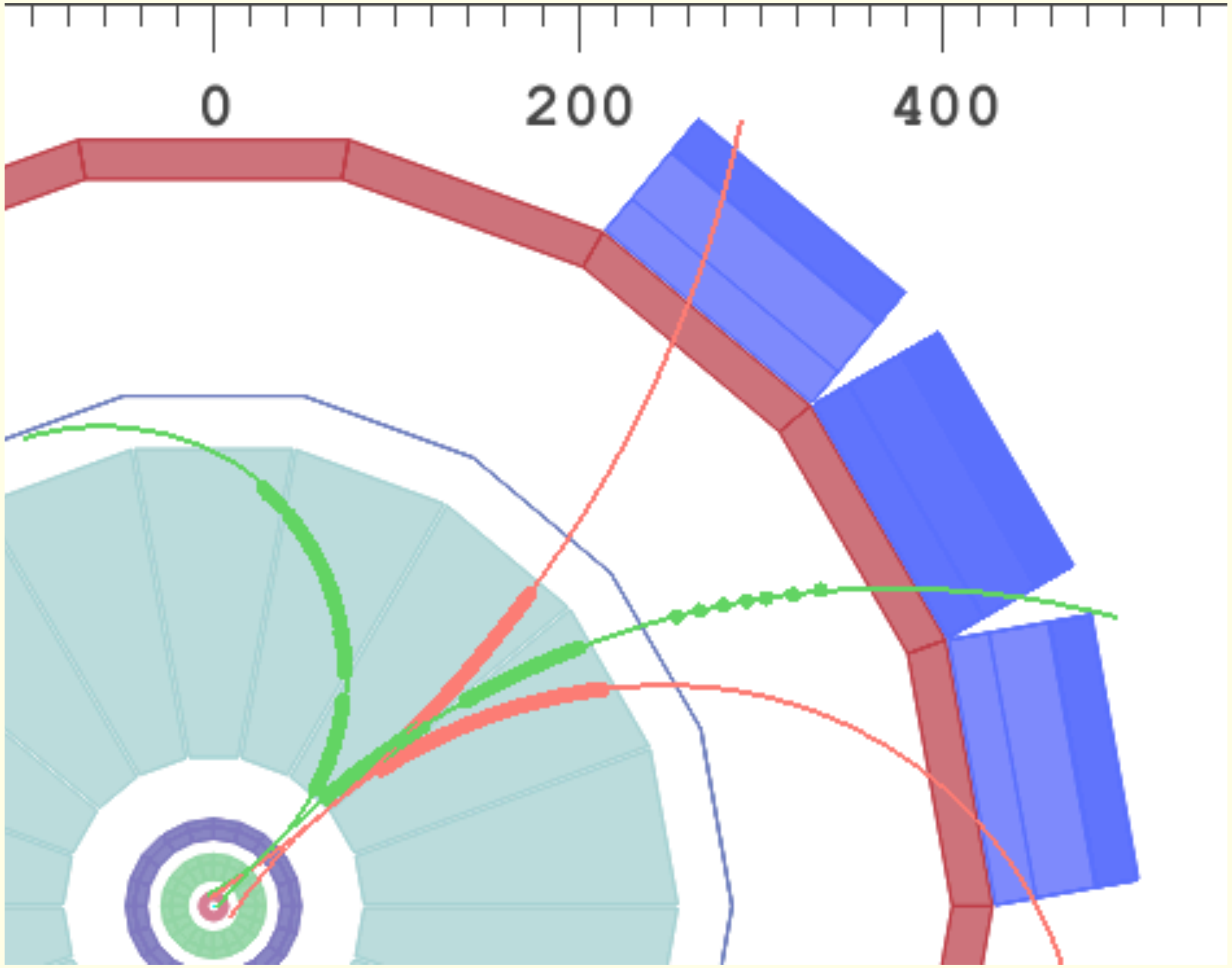
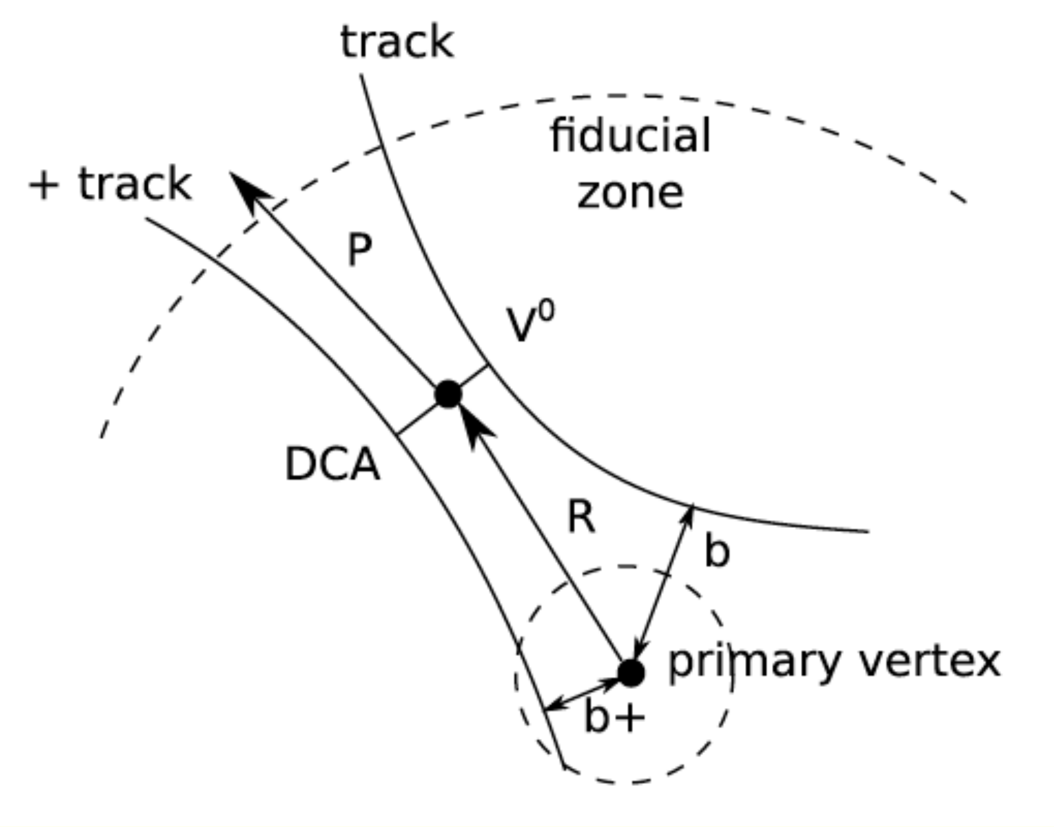
Treating photon and π^0 measuments as independent would yield a 28% systematic uncertainty for γ/π^0

Measuring Photons via Conversions



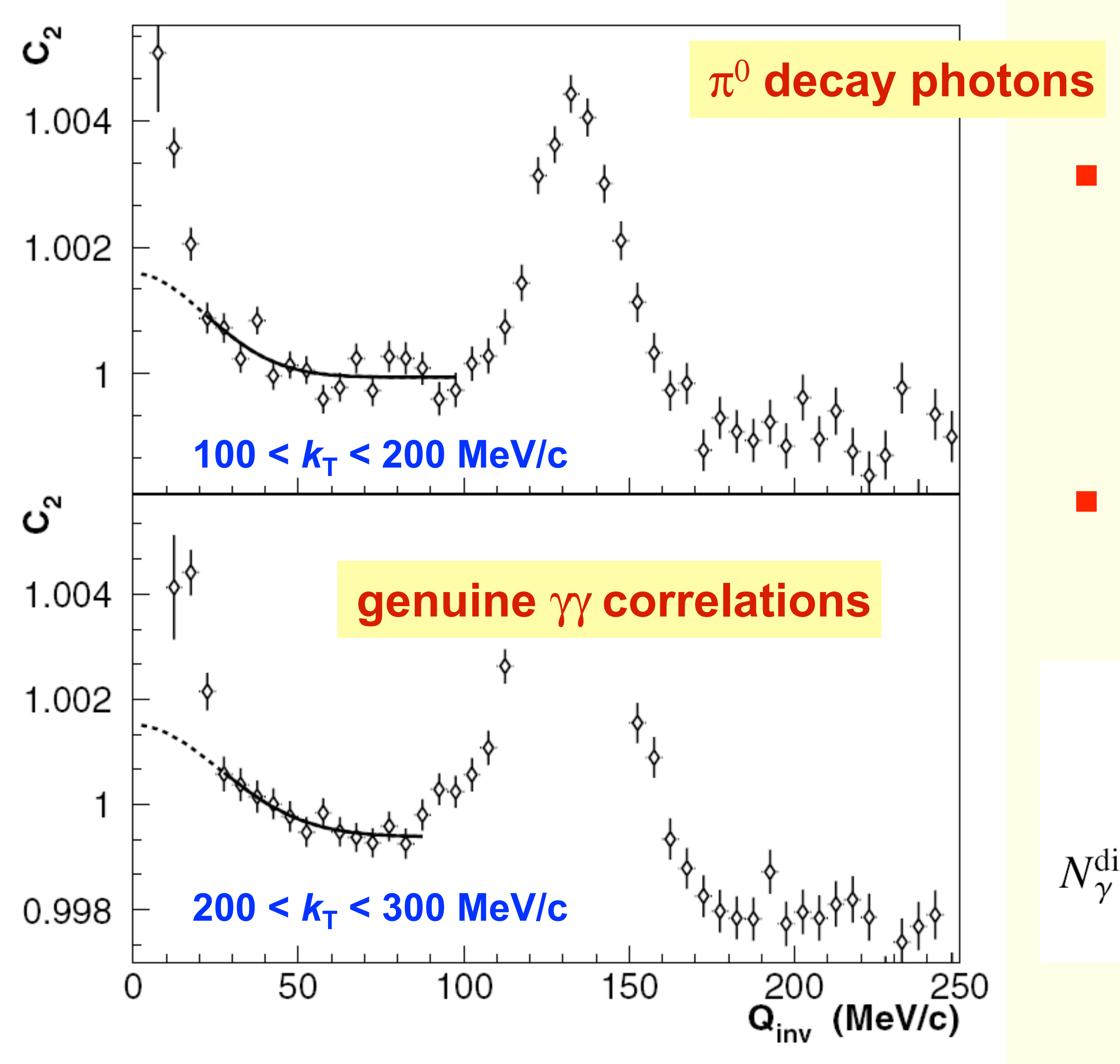


ALICE: photon conversion probability
~ 8% up to the middle of the TPC

Advantage of the conversion method:
Better resolution and higher purity of the photon sample at low p_T

Direct Photon Measurement via γγ-HBT

Background effects



Central Pb+Pb at √s=17.2 GeV

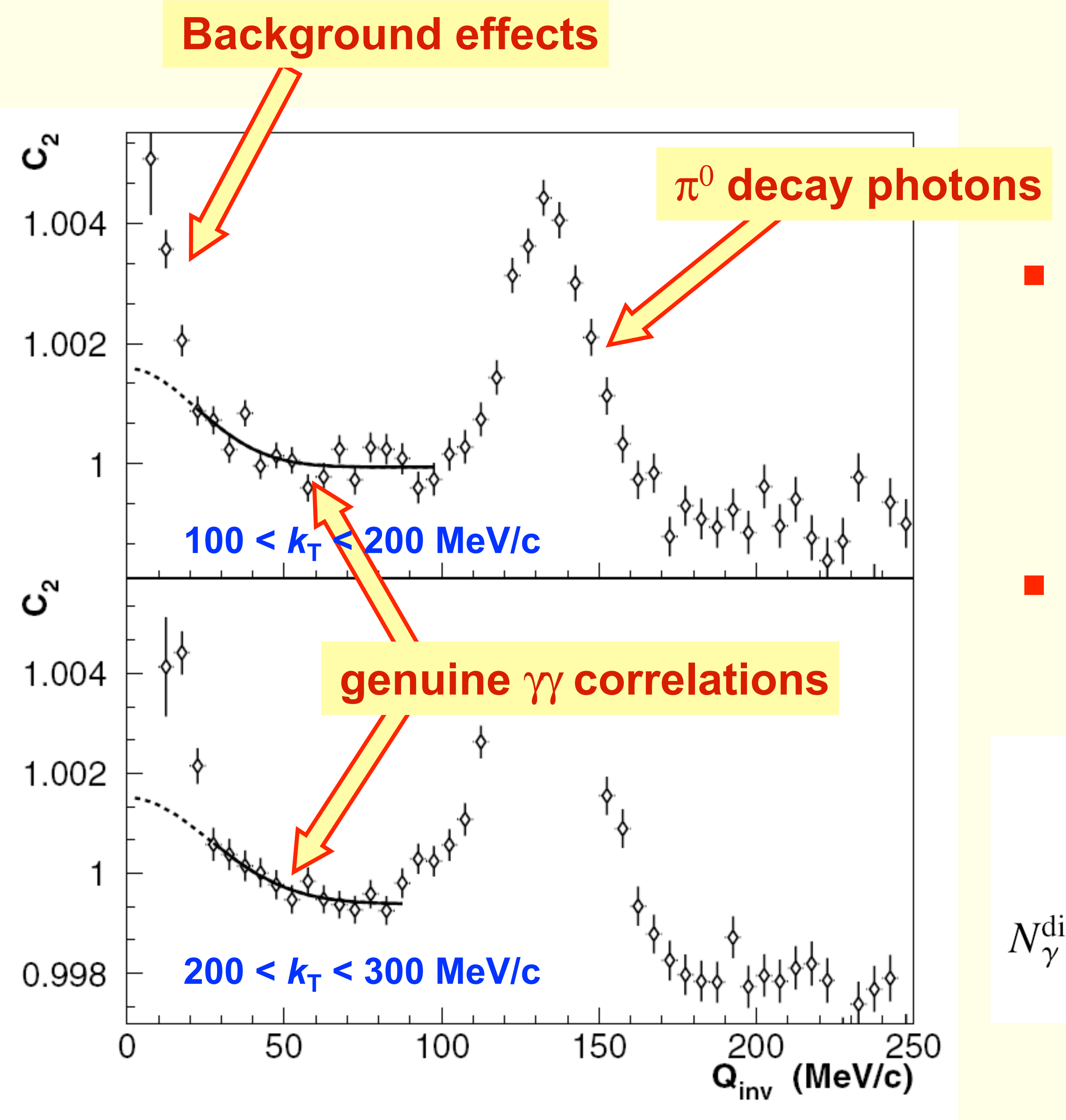
- Two-photon correlations observed and attributed to Bose-Einstein correlations
- Direct photon yield extracted from correlation strength:

$$C_2(Q_{\text{inv}}) = A[1 + \lambda_{\text{inv}} \exp(-R_{\text{inv}}^2 Q_{\text{inv}}^2)]$$

$$N_\gamma^{\text{direct}}/N_\gamma^{\text{total}} = \sqrt{2\lambda} = \sqrt{8\lambda_{\text{inv}} K_T R_O/\sqrt{\pi}\,\text{Erf}(2K_T R_O)}$$

WA98, Phys. Rev. Lett. 93 (022301), 2004

Direct Photon Measurement via $\gamma\gamma$-HBT



Background effects

π^0 decay photons

genuine $\gamma\gamma$ correlations

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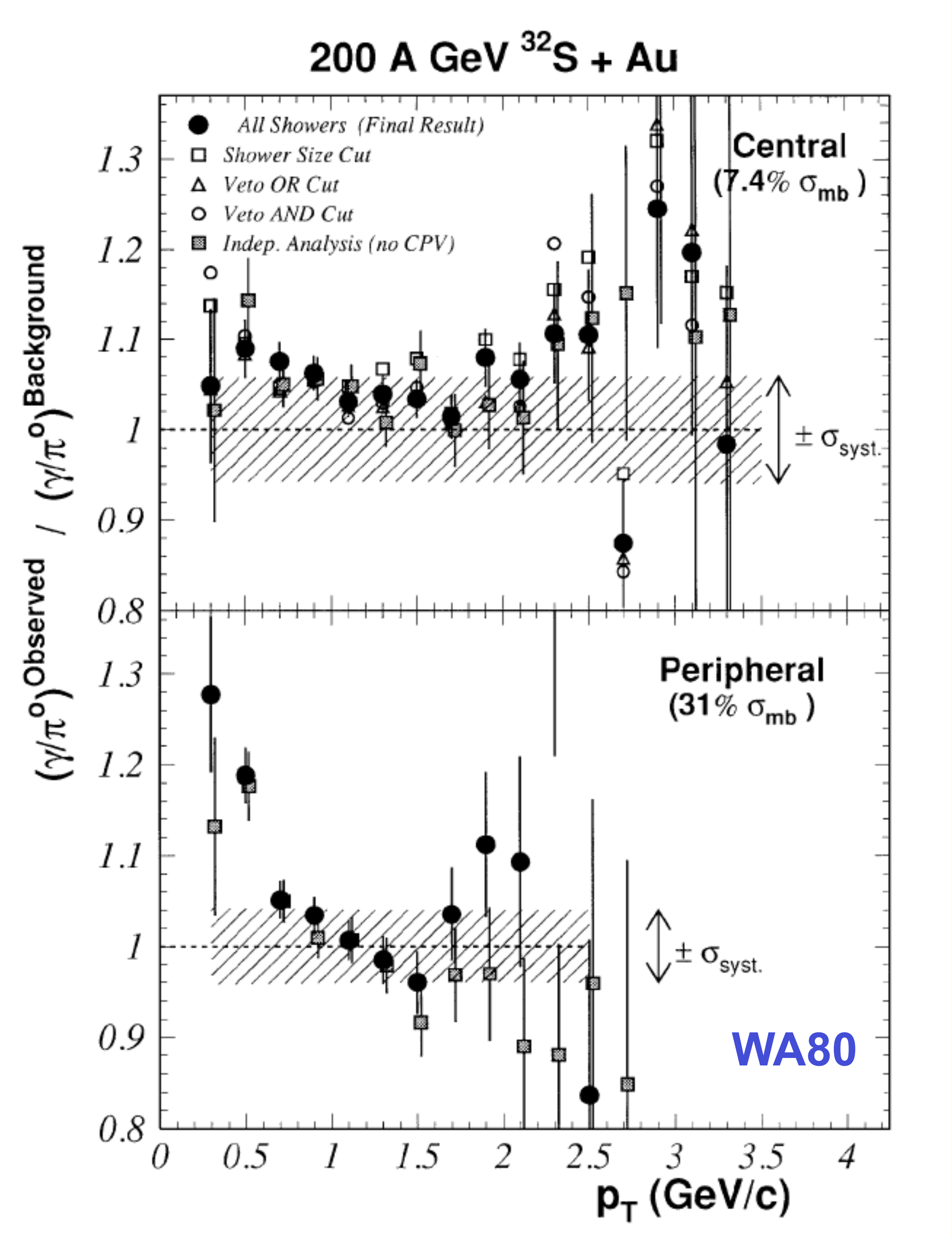
Results on Direct Photon Production in A+A Collisions (Measured With Real Photons)

Early CERN SPS Results: Upper Limits



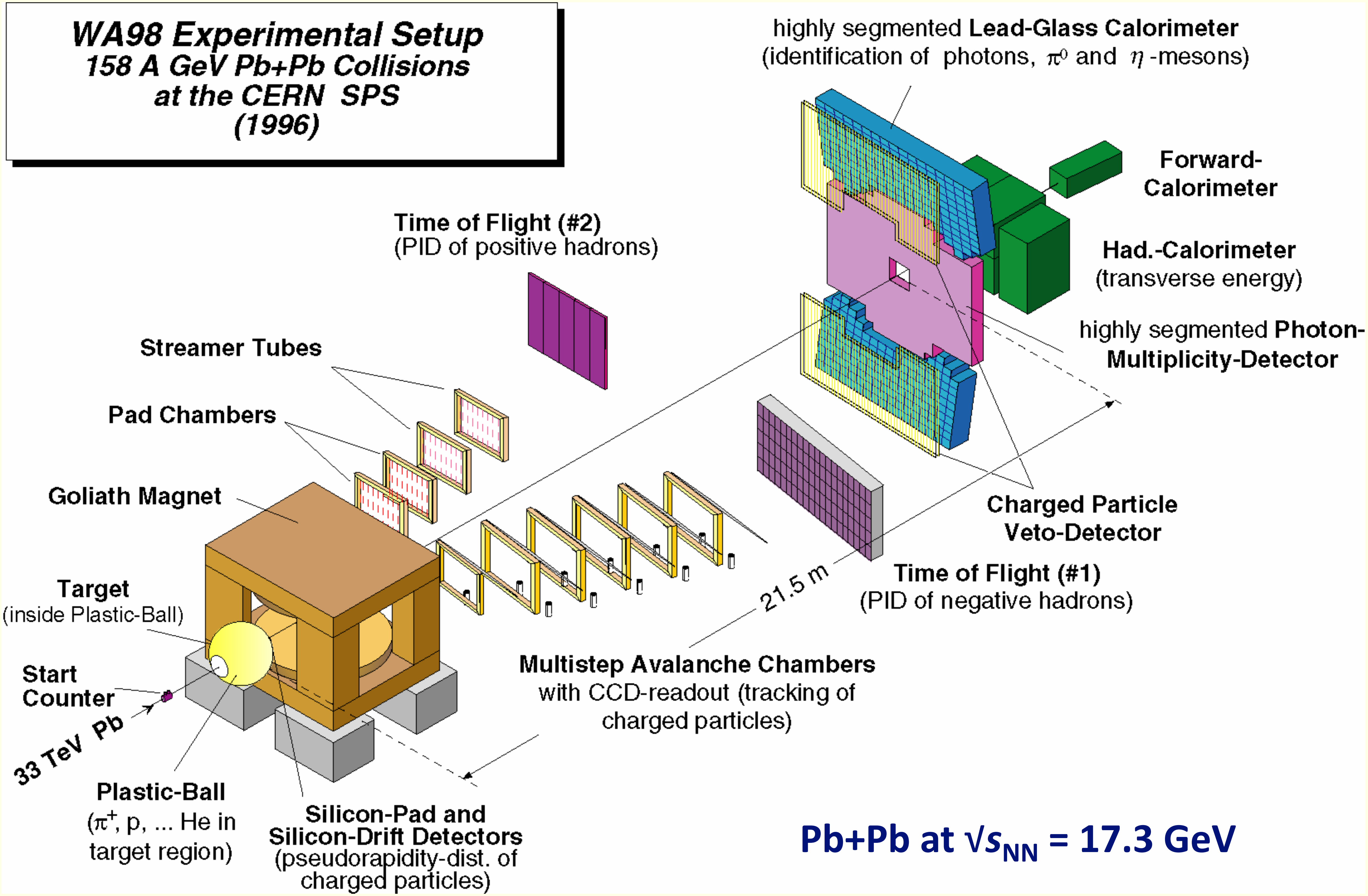
on γ_{direct} / $\gamma_{background}$

Experiment	p_T (GeV/c)	System	Upper limit
HELIOS 2[1]	0.1 – 1.5	p-W, O-W, S-W	13%
WA80[2]	0.4 – 2.8	O-Au	15%
CERES[3]	0.4 – 2.0	S-Au	14%
WA80[4]	0.5 – 2.5	S-Au	12.5%

1. Z.Phys.C46:369-376,1990
2. Z.Phys.C51:1-10,1991
3. Z.Phys.C71:571-578,1996
4. Phys.Rev.Lett.76:3506-3509,1996

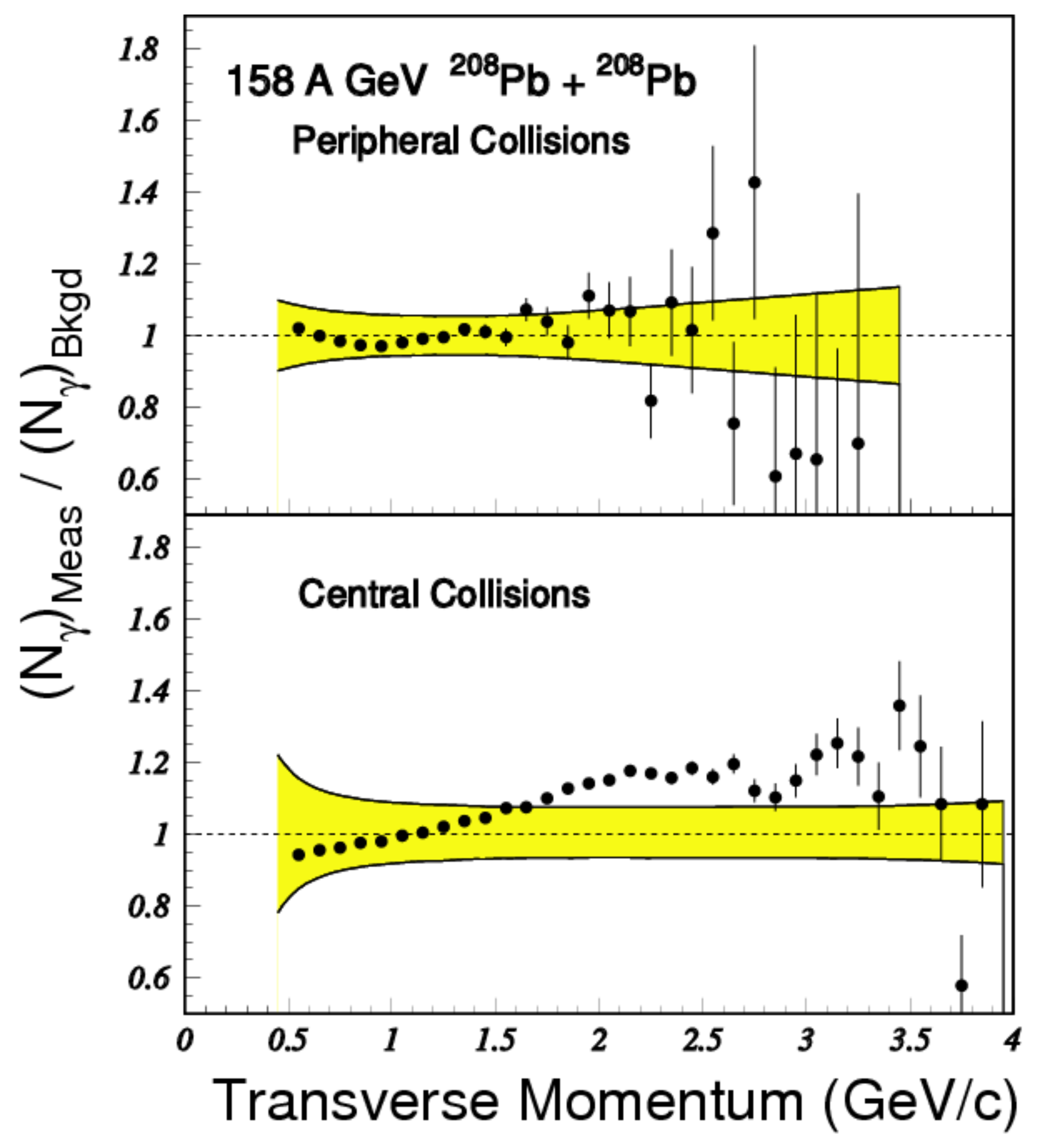
Early fixed target experiments at the CERN SPS only gave upper limits

WA98 Experiment



Pb+Pb at $\sqrt{s_{NN}}$ = 17.3 GeV

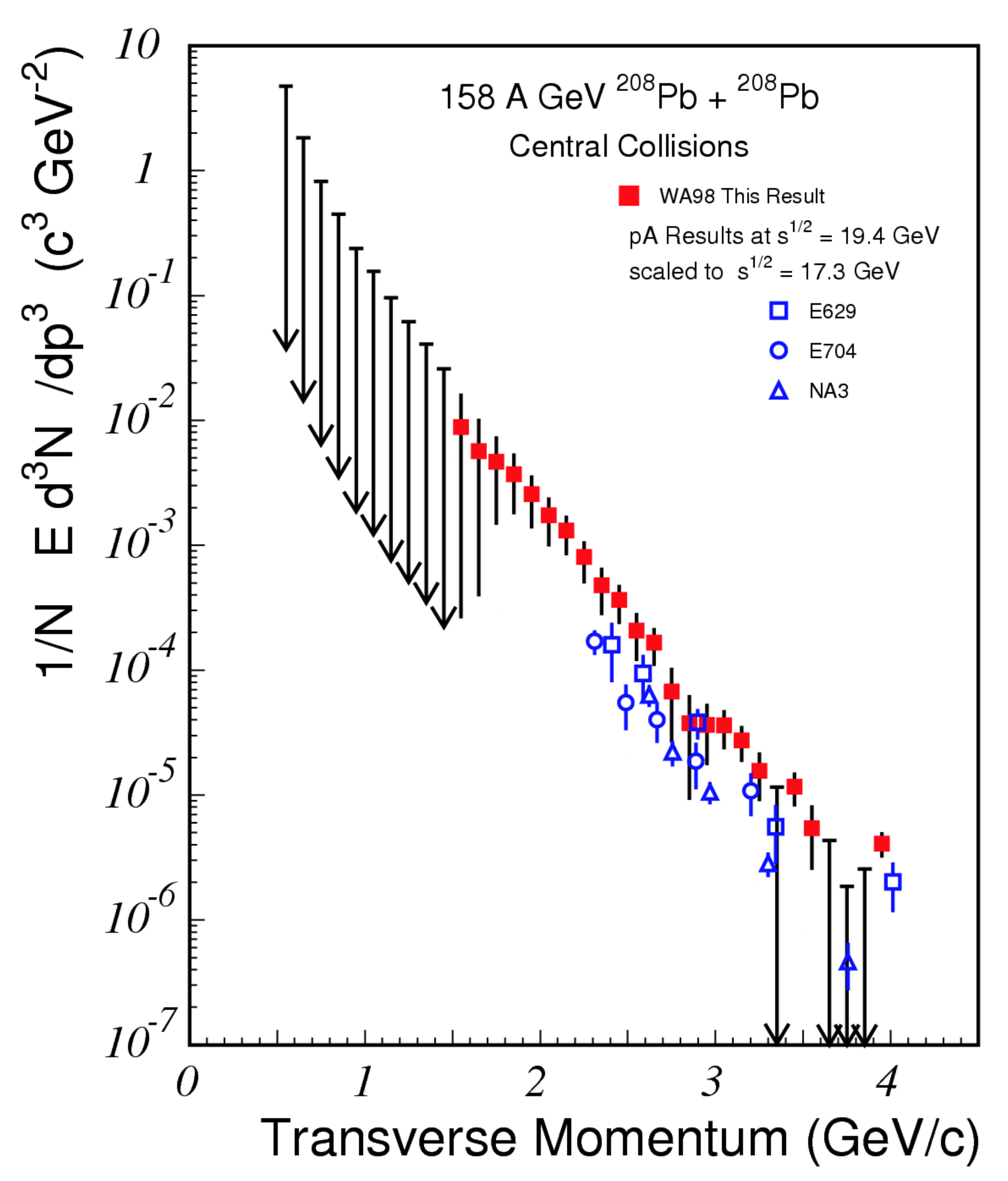
WA98 Result on Direct Photons



- **No signal within errors in peripheral collisions**
- **20% direct photon excess at high p_T in central Pb+Pb collisions at CERN SPS**

Phys.Rev.Lett.85:3595-3599,2000

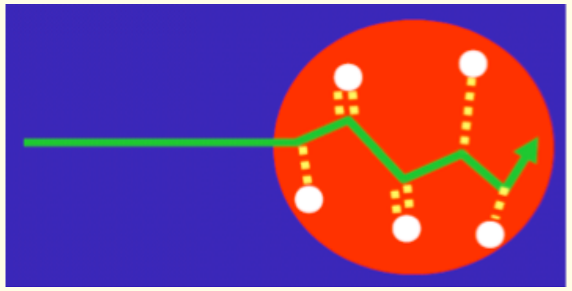
WA98 Direct Photon Spectrum: Hard Scattering + Nuclear k_T Broadening ?



- Better p+p and p+A measurement desirable

- Very unlikely that Pb+Pb spectrum is just hard scattering

Cronin-effect:
Multiple soft scattering in p+A prior to hard scattering ("nuclear k_T")



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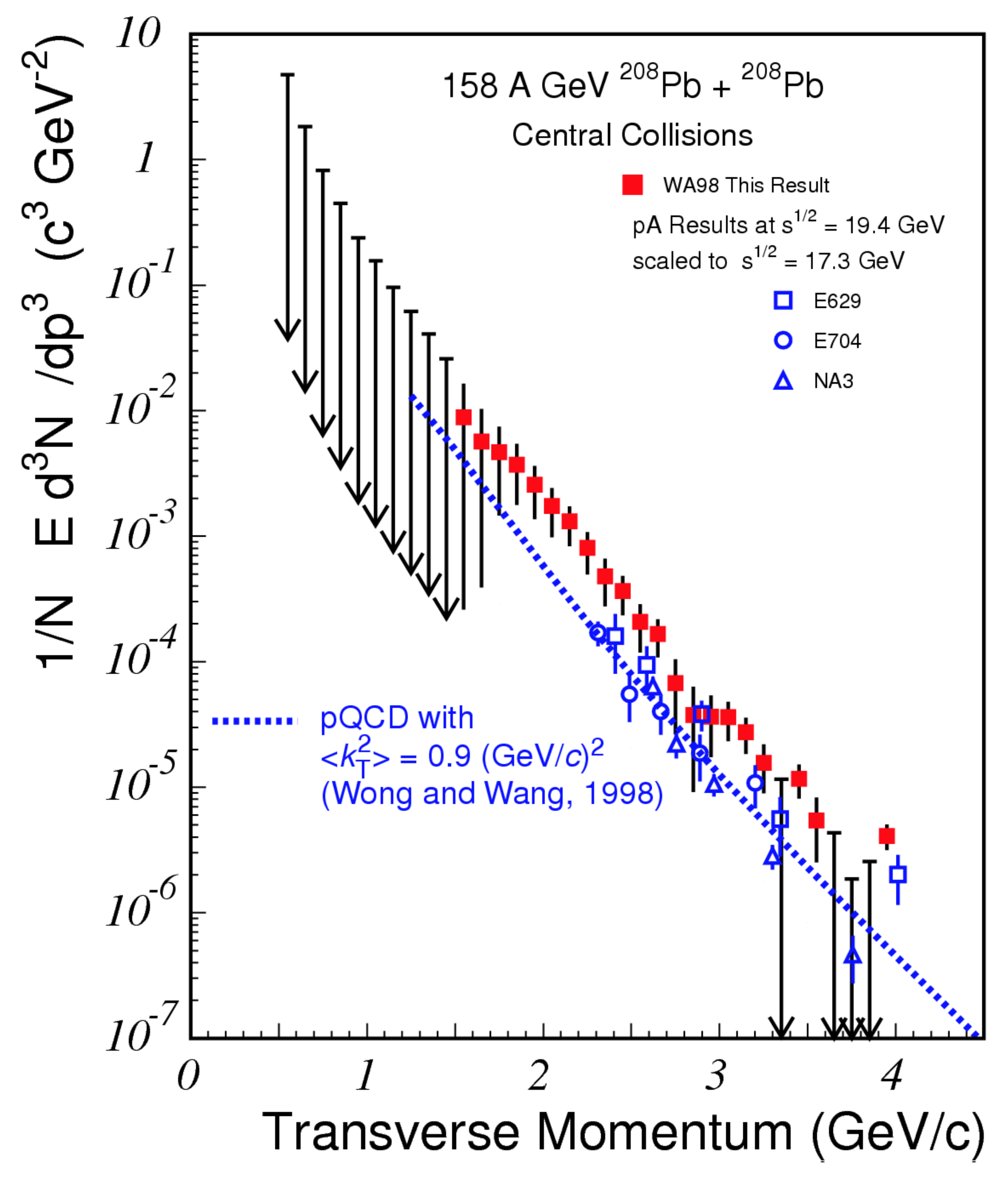

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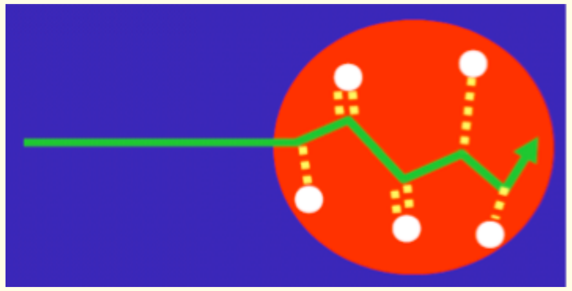

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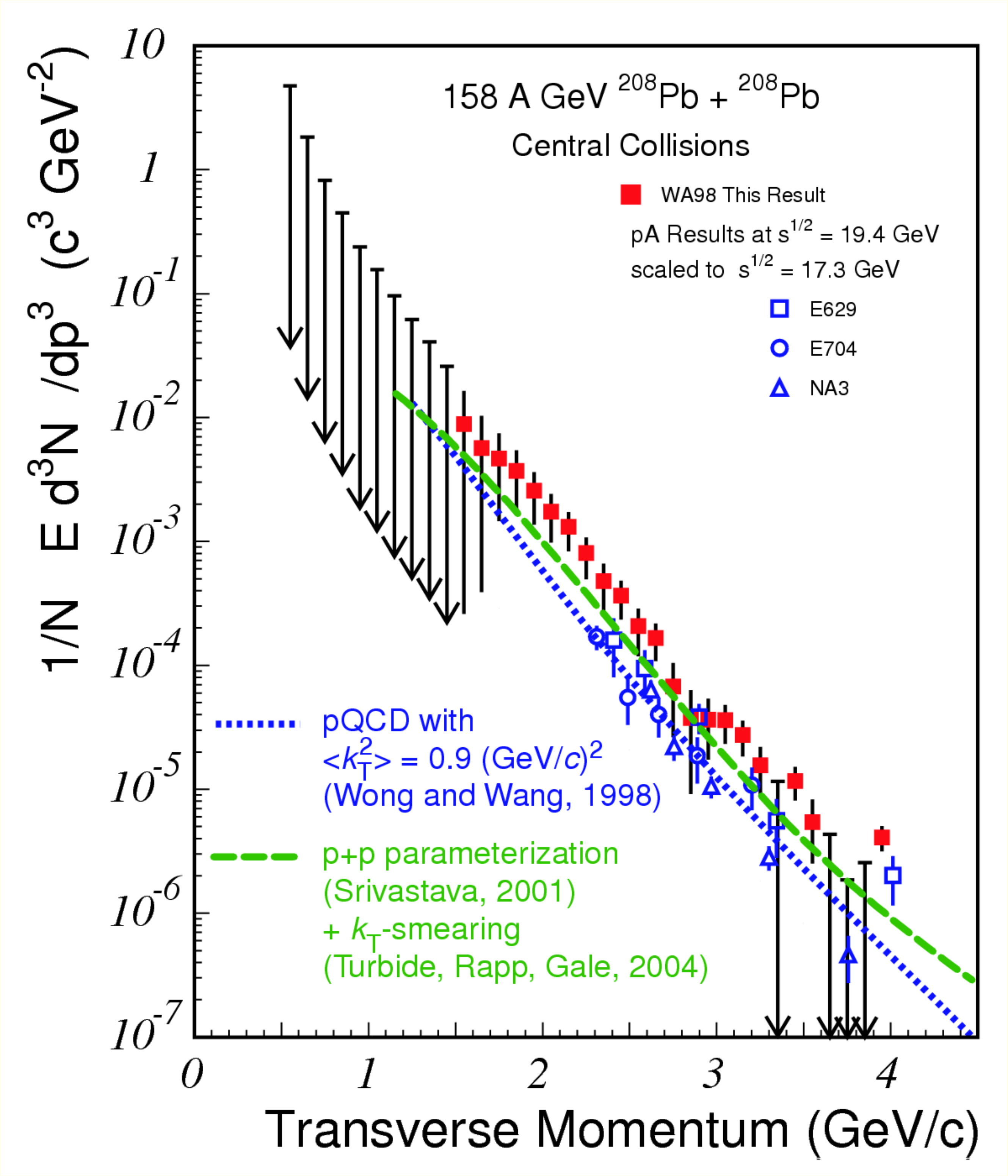

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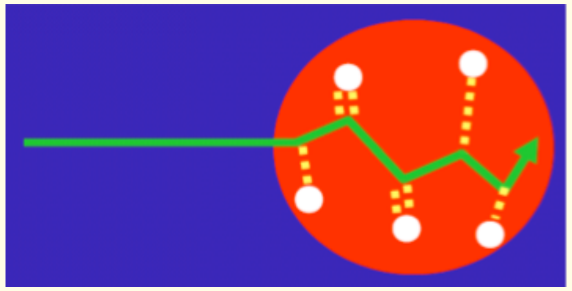
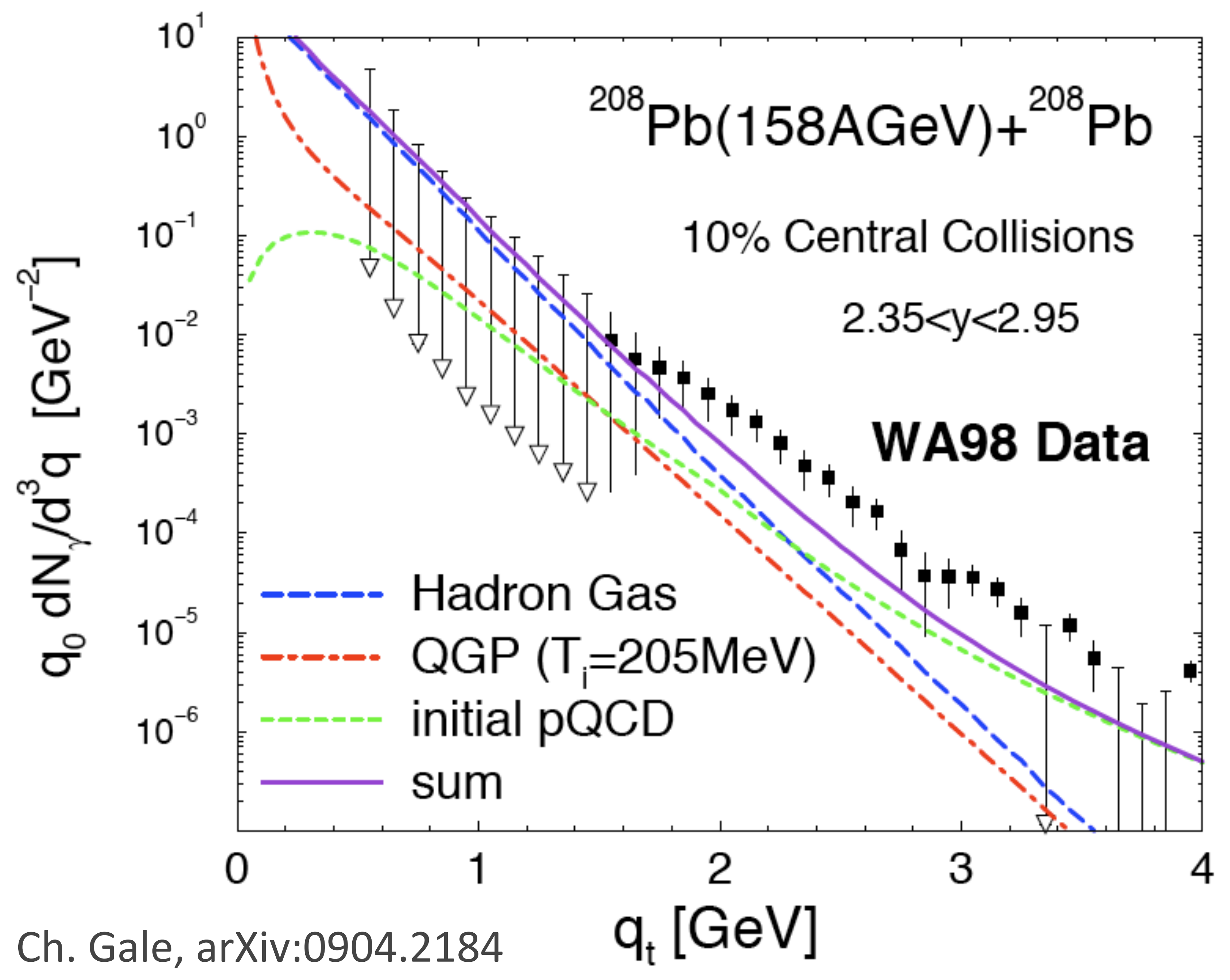


Interpretation of the WA98 Data



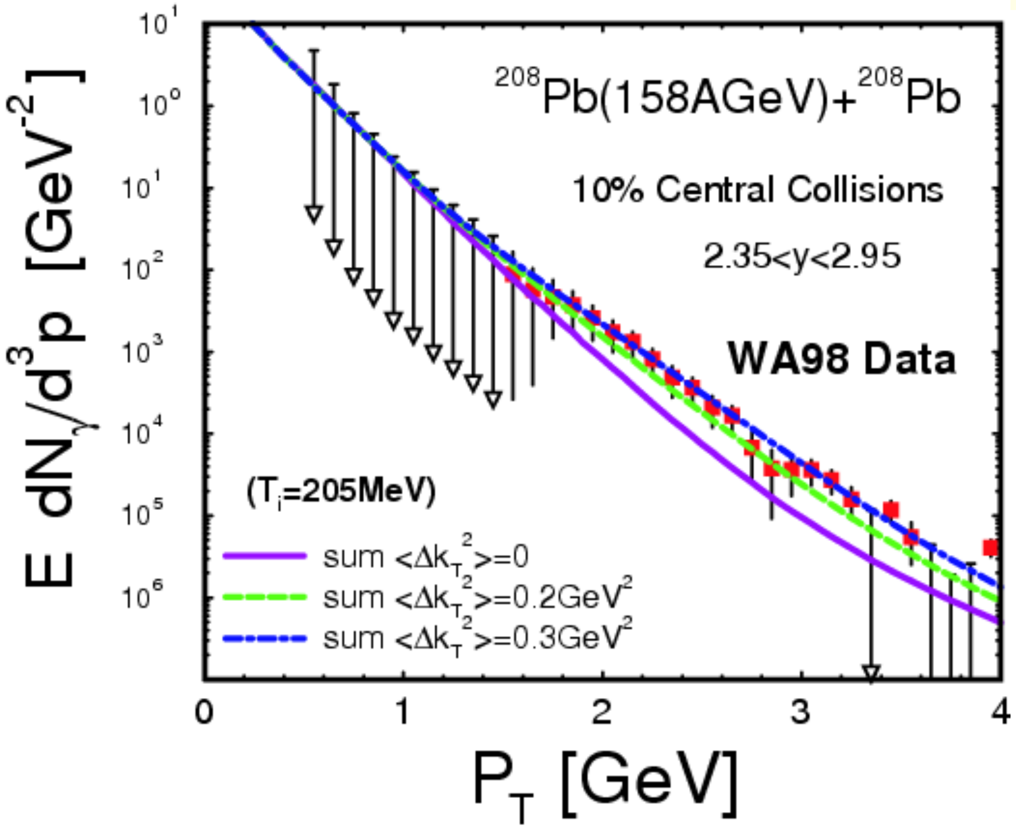
Ch. Gale, arXiv:0904.2184

Interplay between T ad k_T, contribution from QGP small

Direct Photons at CERN SPS: T or k_T ?

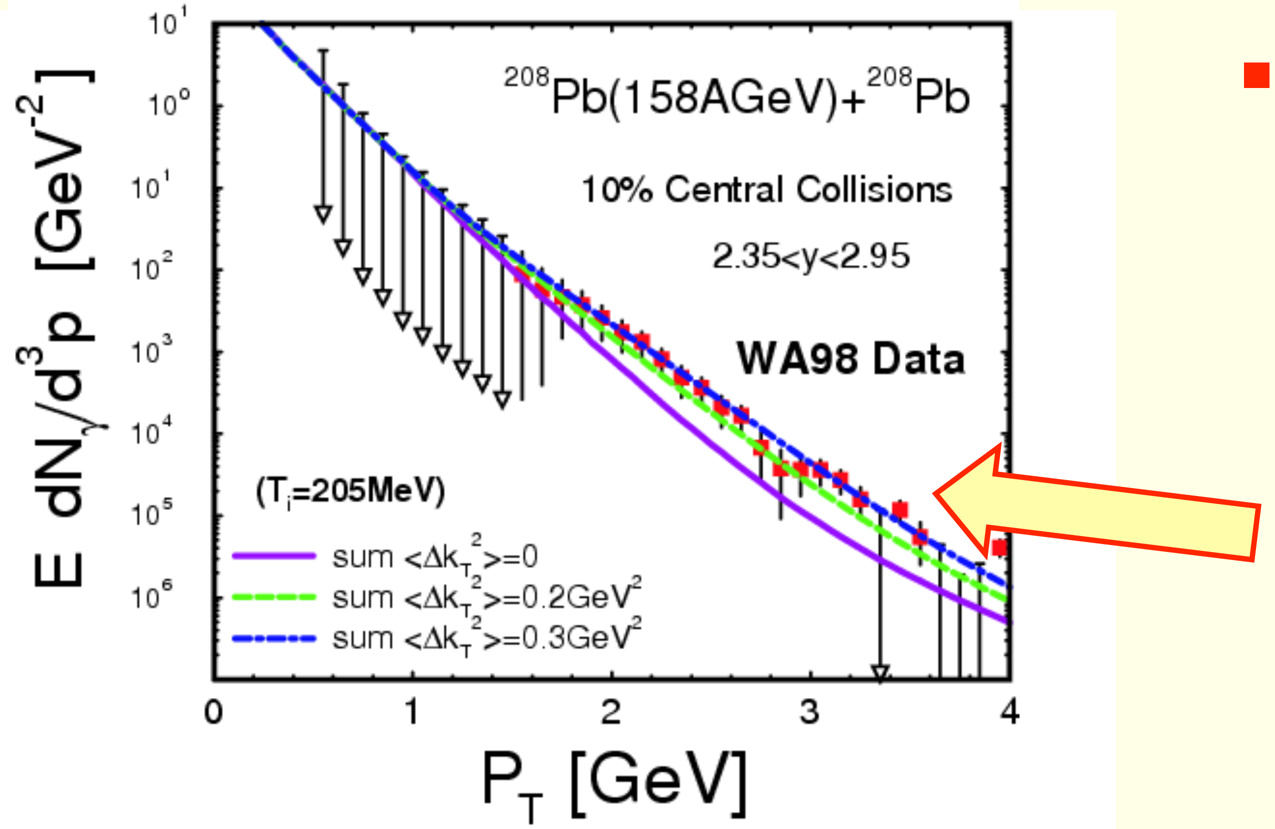
Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

Direct Photons at CERN SPS: T or k_T ?



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

Direct Photons at CERN SPS: T or k_T ?



- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons

Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

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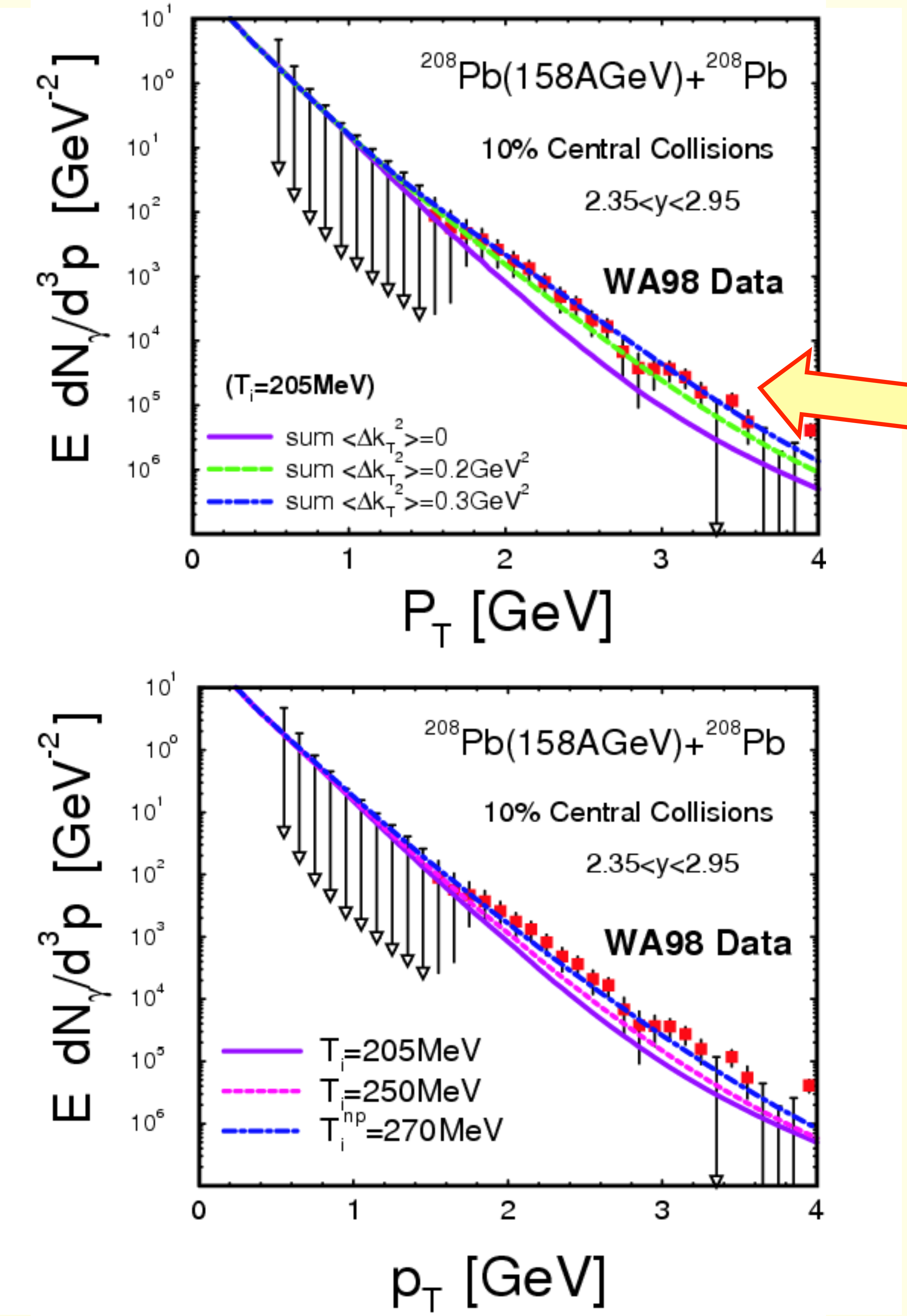

Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

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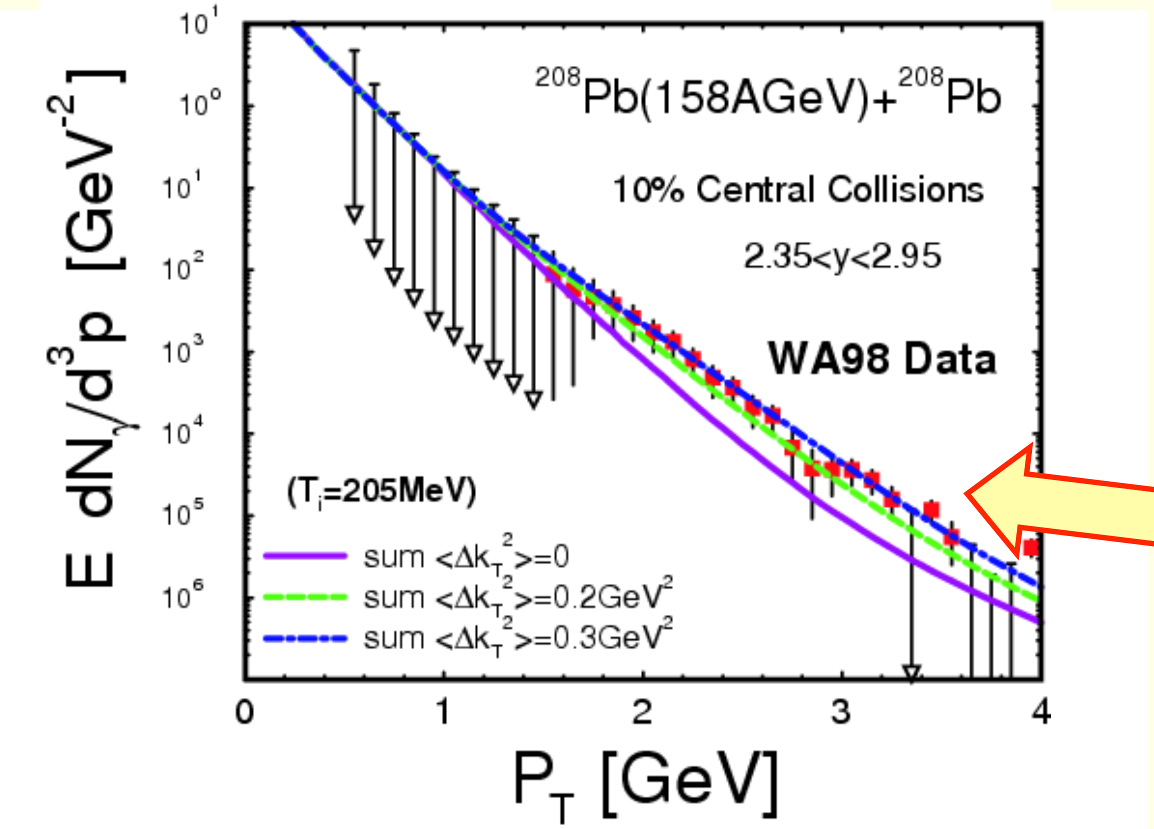
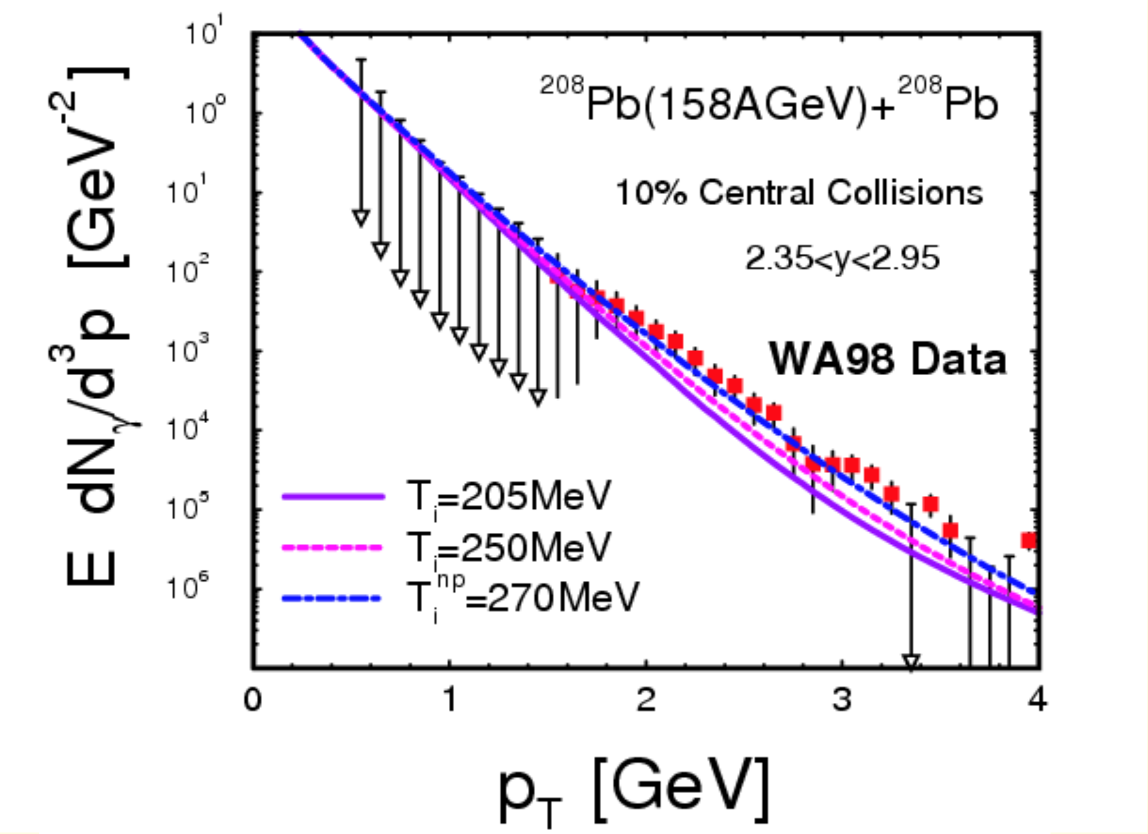




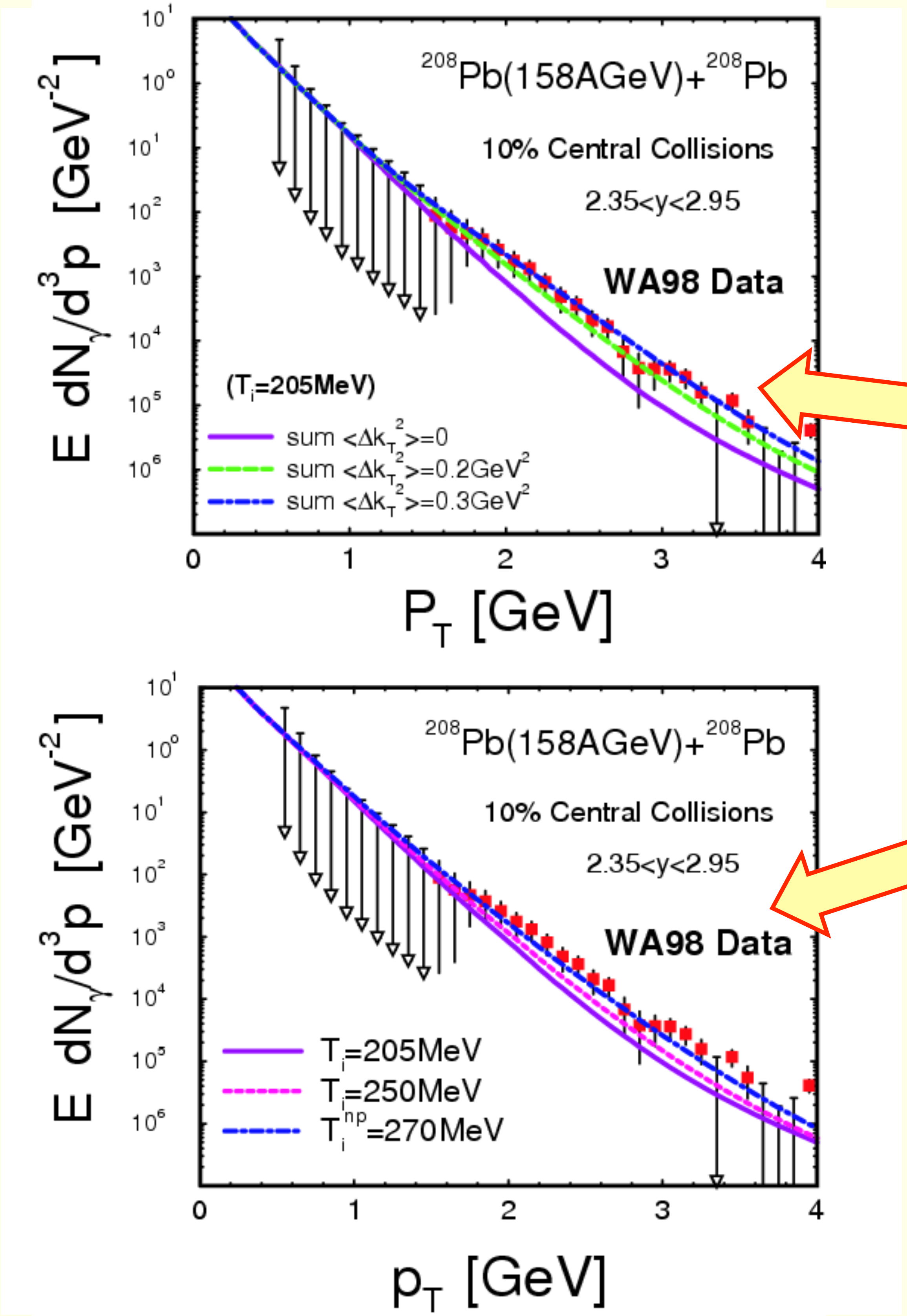
Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
- Data described with initial temperature T_i = 205 MeV

  + some nuclear k_T broadening

  (Cronin-effect)

Direct Photons at CERN SPS: T or k_T ?



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

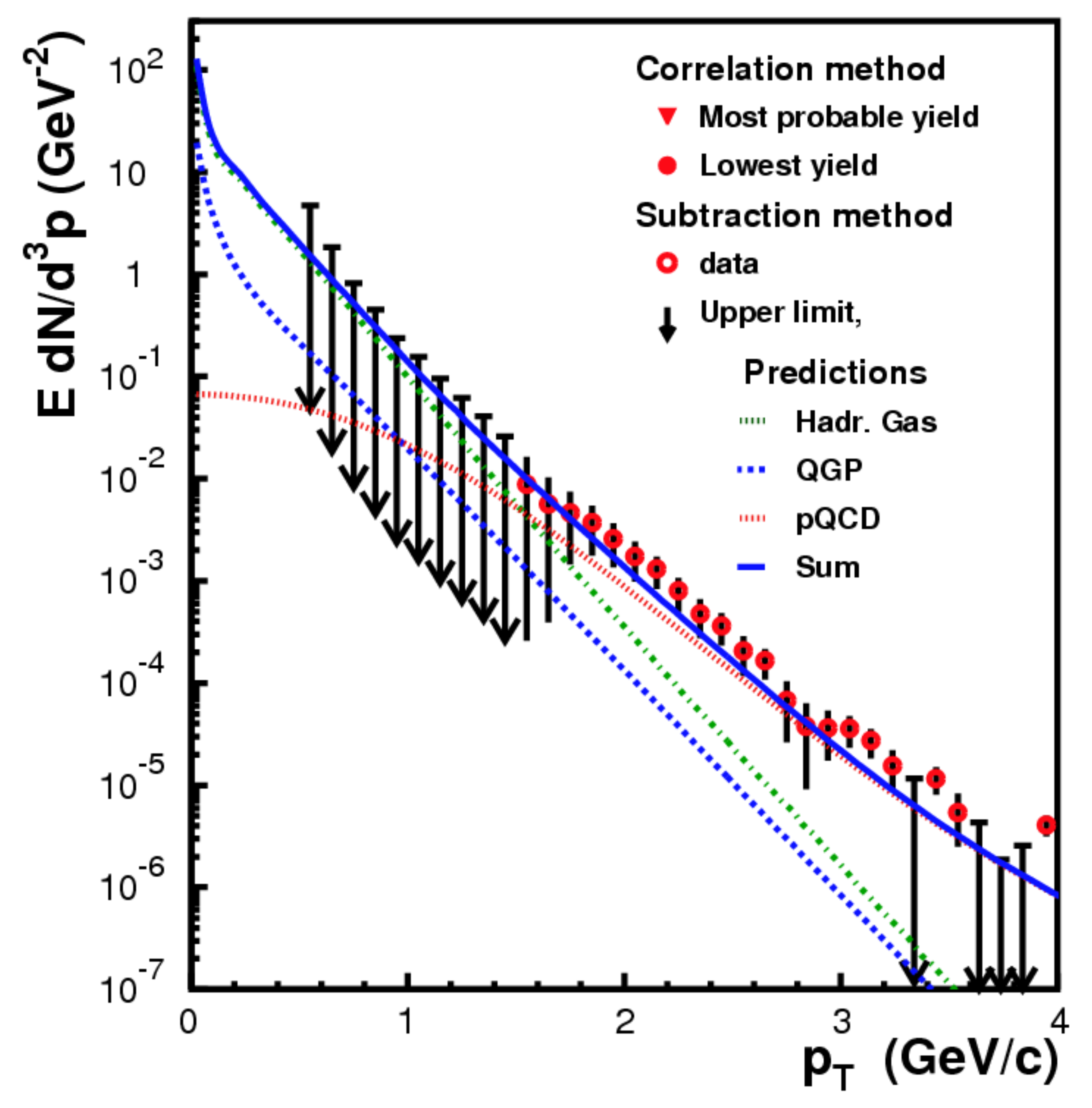
- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
- Data described with initial temperature T_i = 205 MeV

  + some nuclear k_T broadening

  (Cronin-effect)
- Data also described without k_T broadening but with high initial temperature

  (T_i = 270 MeV)

WA98: New low-p_T Points



WA98, Phys. Rev. Lett. 93 (022301), 2004

- Two-photon correlations observed and attributed to Bose-Einstein correlations of direct photons
- Correlation strength used to extract direct photon signal at low p_T
- Possible explanation: photon bremsstrahlung from hot hadron gas

  (Lui, Rapp, nucl-th/0604031)

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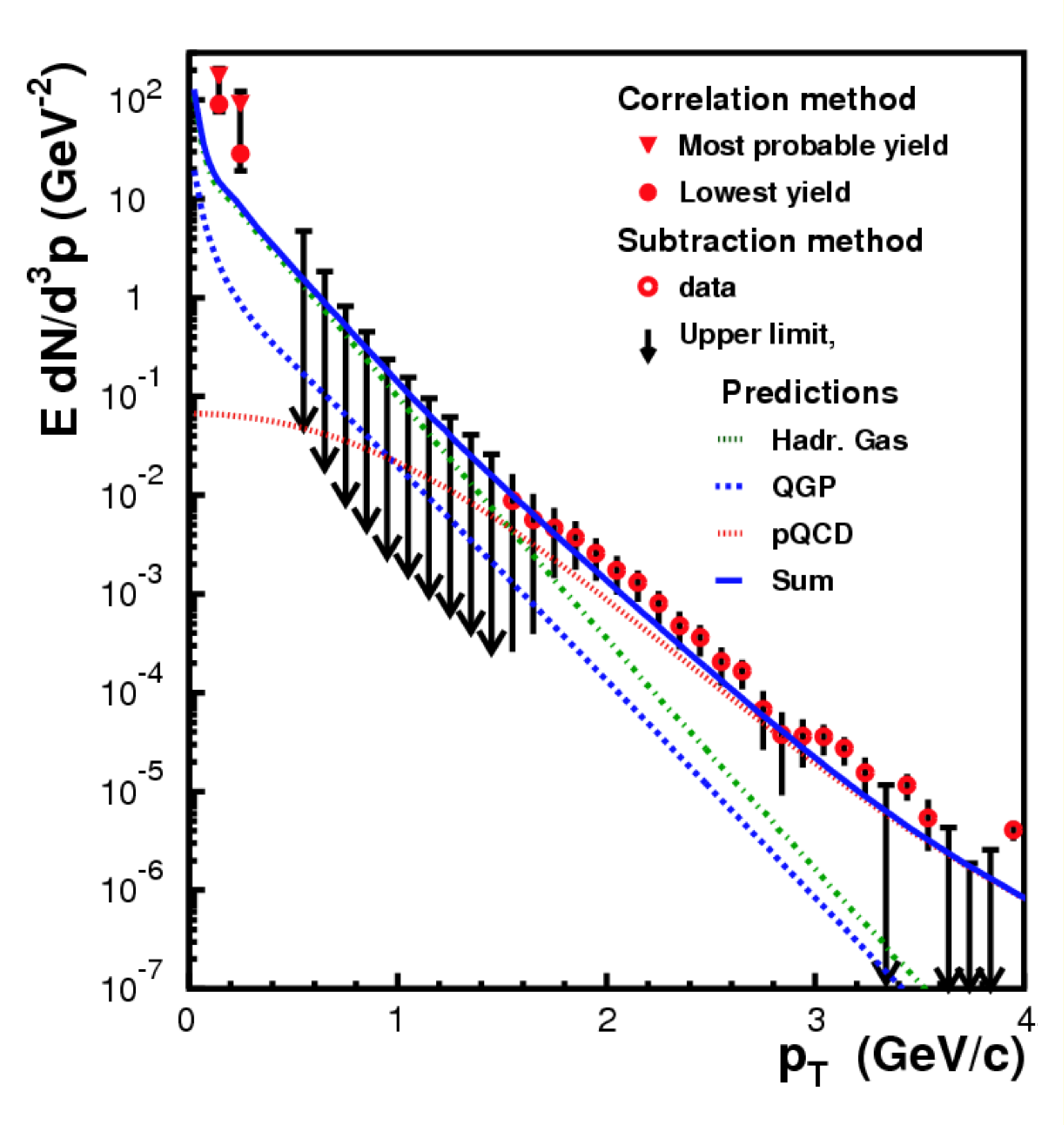

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- Possible explanation: photon bremsstrahlung from hot hadron gas

(Lui, Rapp, nucl-th/0604031)

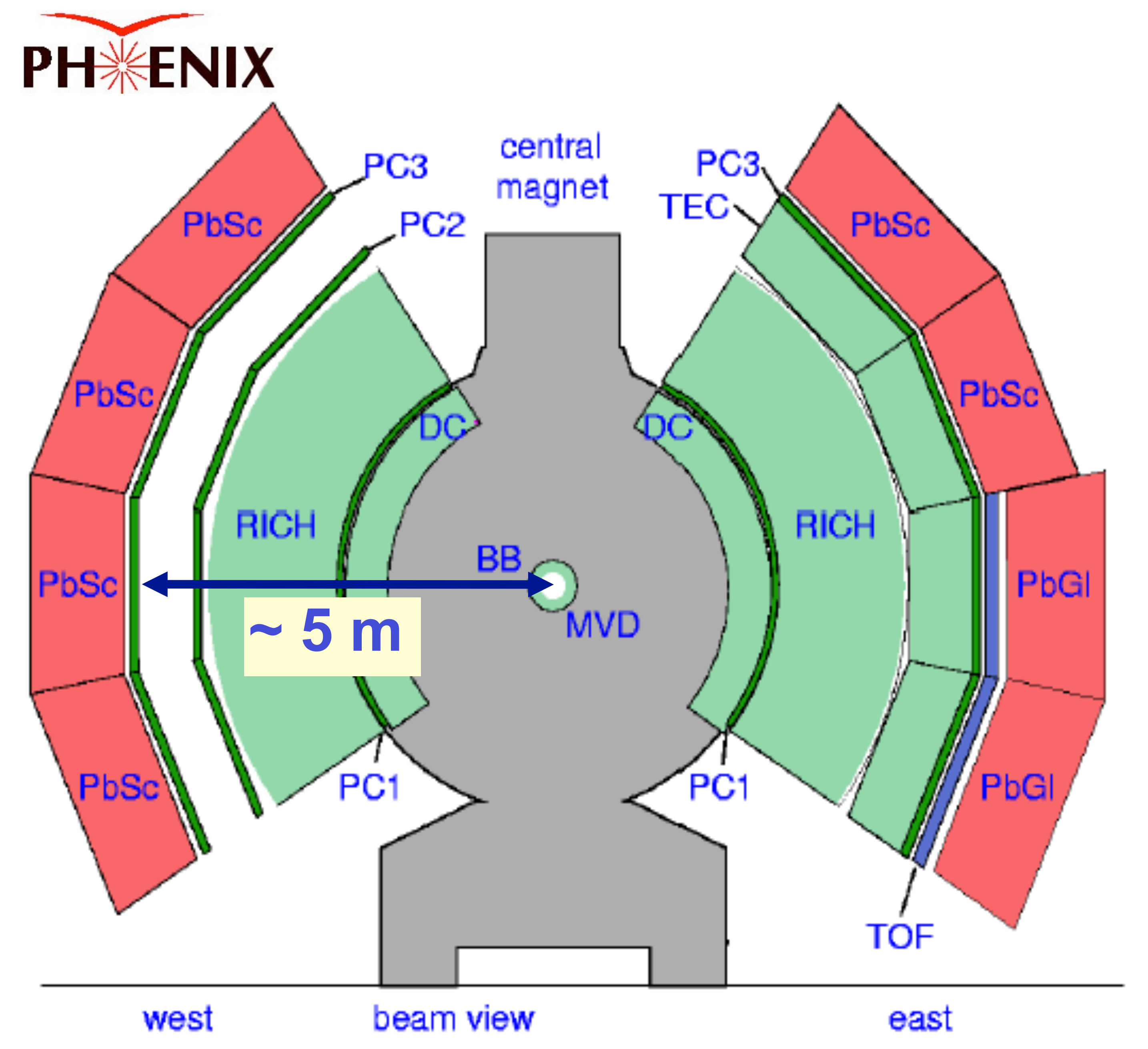
Direct Photons at CERN SPS: Conclusions

Data can be described under a variety of different assumptions, e.g.:

Turbide, Rapp, Gale (Phys.Rev.C69:014903,2004)	**QGP + HG + pQCD with k_T**	**T_i = 205 MeV, τ_0 = 1 fm/c**
	QGP + HG + pQCD without k_T	**T_i = 250 - 270 MeV, τ_0 = 0,5 fm/c**
Renk (Phys.Rev.C67:064901,2003)	**QGP + HG + pQCD**	**250 < T_i < 370 MeV, 0,5 < τ_0 < 3 fm/c**
Svrivastava (nucl-th/0411041)	**QGP + HG + pQCC (Bjorken hydro)**	**T_i = 335 MeV, τ_0 = 0,2 fm/c**
Huovinen, Ruuskanen, Räsänen (Nucl. Phys. A 650 (227) 1999)	**QGP + HG + pQCD (Non-boost inv. hydro)**	**T_i = 214 - 255 MeV**
	Pure HG + pQCD (Non-boost inv. hydro)	**T_i = 213 - 234 MeV**

- Data consistent with QGP picture, but also with pure HG picture
- Large variations in extracted initial temperature T_i (however, most models give $T_i > T_c$)

PHENIX: Photon and Electron Detectors



Pseudorapidity coverage : |η| < 0.35

- EMCal:
  PbSc (6 sectors) + PbGl (2 sectors)
- PbSc :
  - Highly segmented lead scintillator sampling calorimeter
  - Module size:
    5.5 cm x 5.5 cm x 37 cm
- PbGl:
  - Highly segmented
    lead glass Cherenkov calorimeter
  - Module size:
    4.0 cm x 4.0 cm x 40 cm
- Ring Imaging Cherenkov Detector (RICH):
  - Electron identification (together with E/p matching in EMCal)
  - No signal for charged pions with p < 4.6 GeV/c

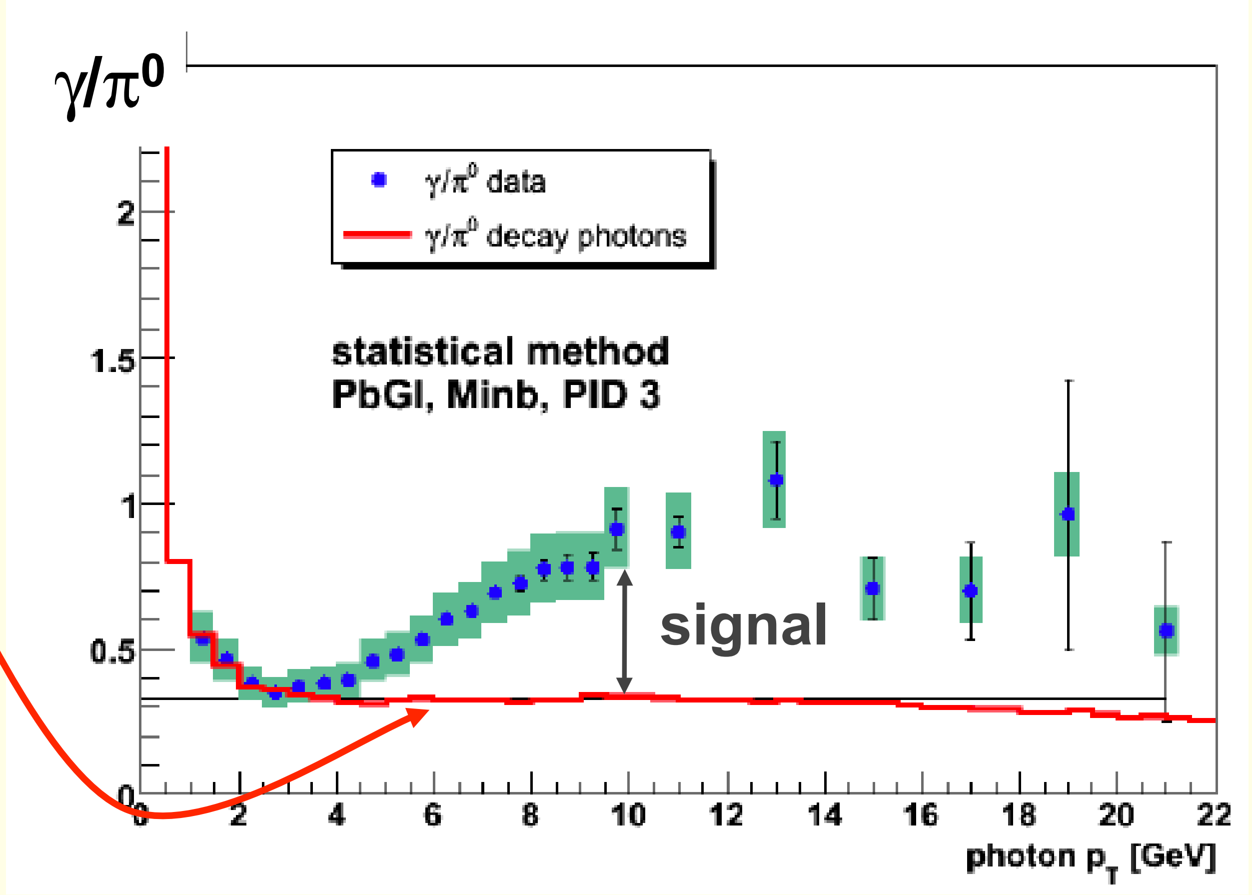
How Do We Measure Direct Photons in PHENIX?

- Intermediate and high p_T:
  Real photons with EMCal
  - Statistical Subtraction
    (typically no isolation cut)

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}$$

$$= \left(1 - \frac{\boxed{\gamma_{\text{decay}} / \pi^0}}{\gamma_{\text{inclusive}} / \pi^0}\right) \cdot \gamma_{\text{inclusive}}$$

Calculated based on measured π^0 und η spectra

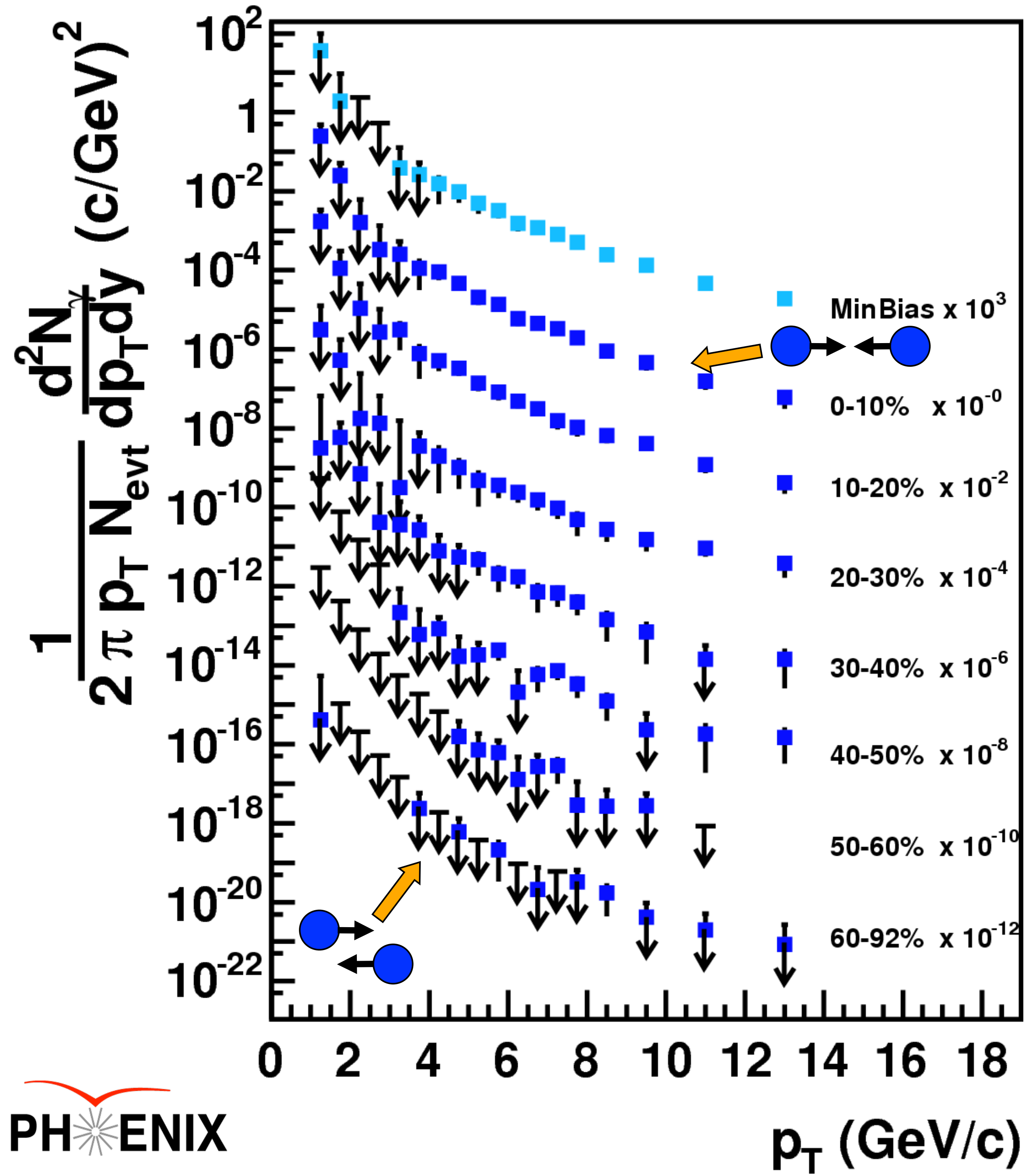


- Low p_T:
  Virtual photons ($\gamma^* \to e^+e^-$) with RICH (internal conversion)
  - Assumption:

$$\frac{\gamma_{\text{direct}}}{\gamma_{\text{inclusive}}} = \left.\frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}}\right|_{m_{ee} < 30\,\text{MeV}}$$

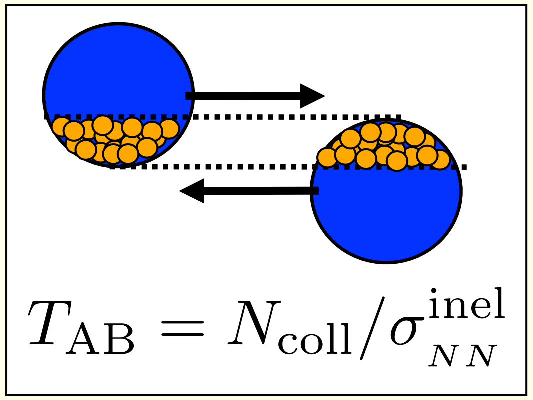
Direct-Photon Spectra in Au+Au

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (RHIC run 2)



Phys.Rev.Lett.94:232301,2005

T_{AB} : increase in parton-luminosity per event (p+p → Au+Au)



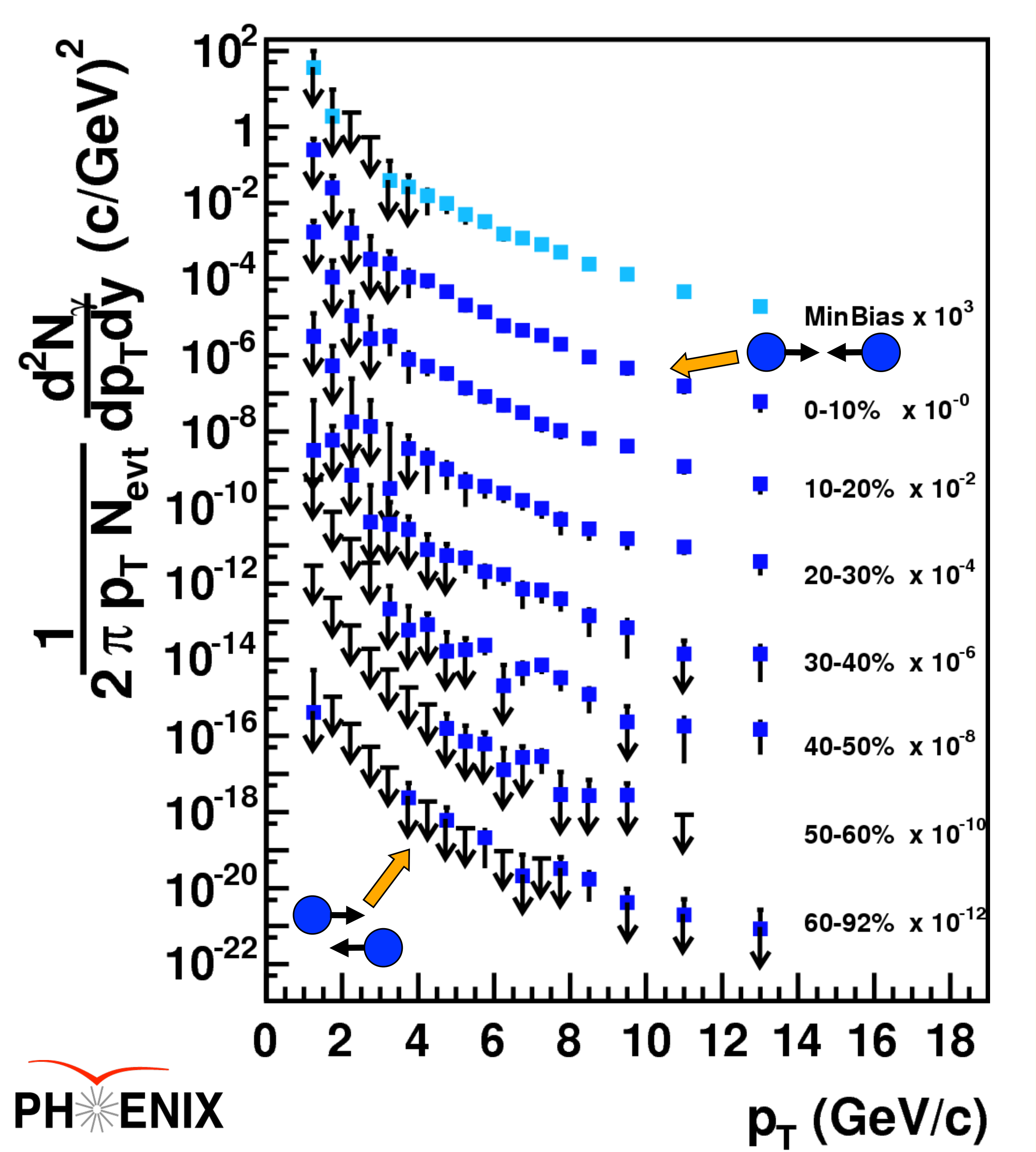
$$T_{AB} = N_{\mathrm{coll}}/\sigma_{NN}^{\mathrm{inel}}$$

0 – 10%:
$\langle N_{coll} \rangle$ = 955 ± 94

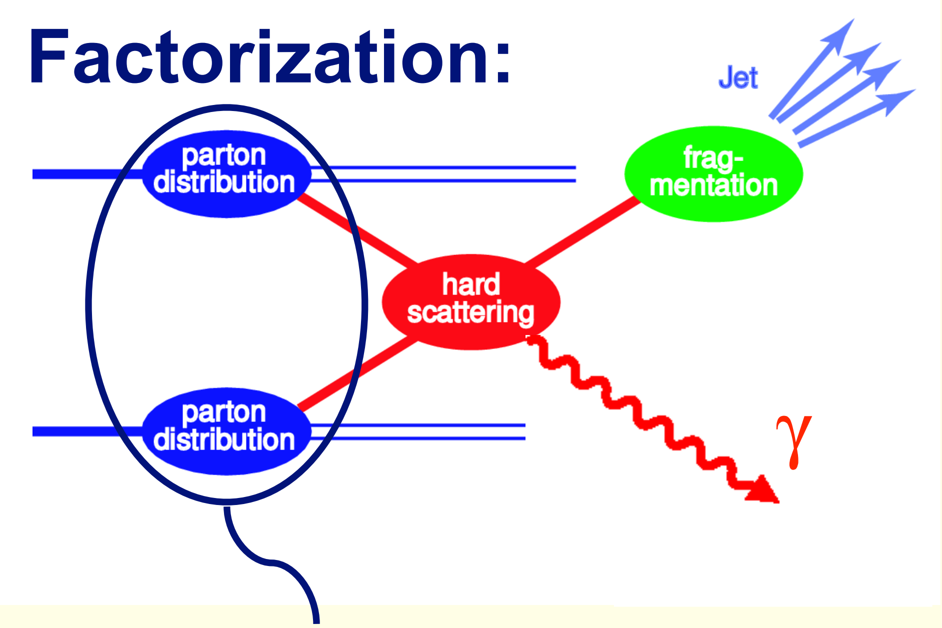
60 – 92%:
$\langle N_{coll} \rangle$ = 14.5 ± 4

Direct-Photon Spectra in Au+Au

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (RHIC run 2)



Phys.Rev.Lett.94:232301,2005



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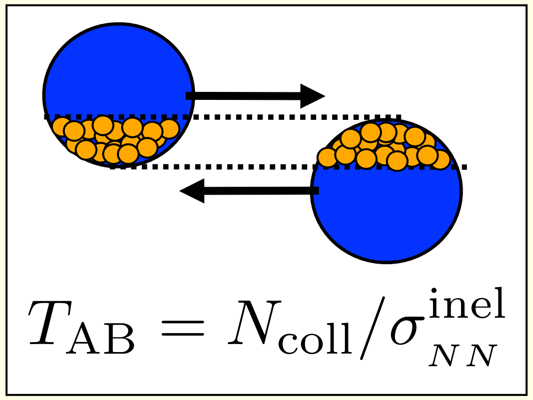

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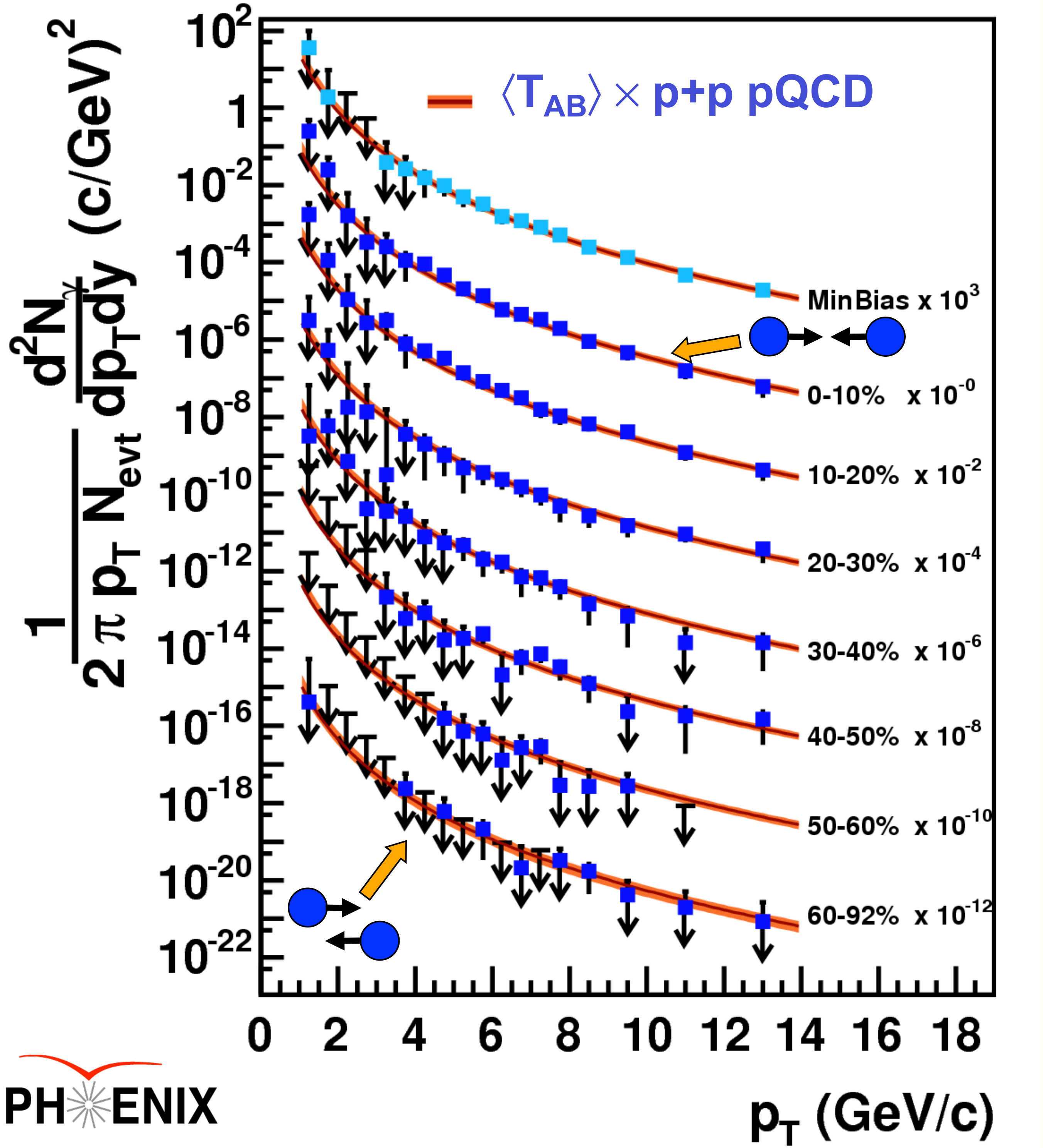
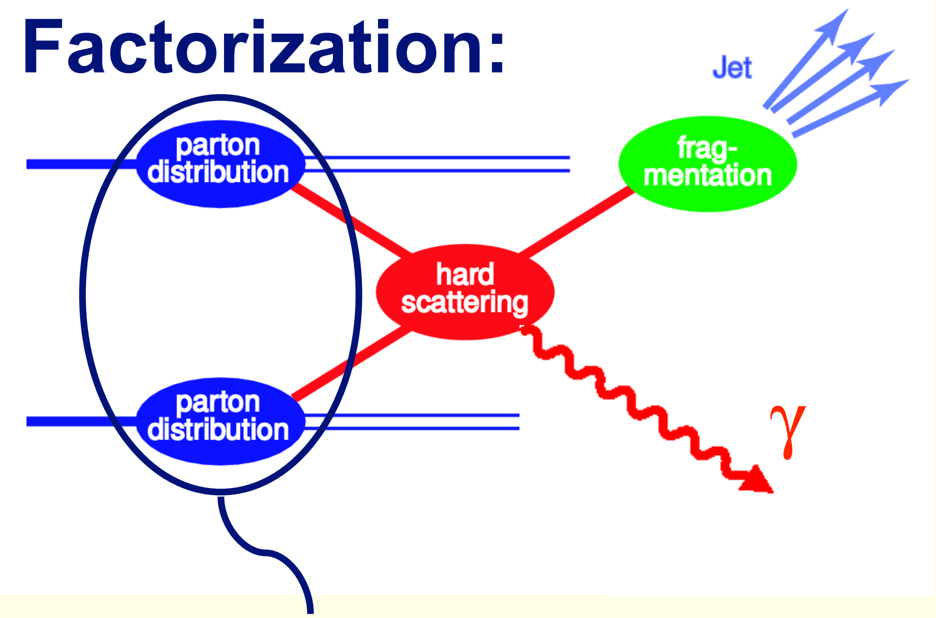
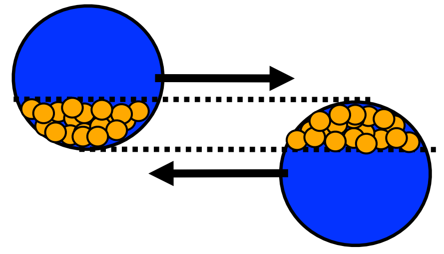


Phys.Rev.Lett.94:232301,2005

Factorization:



T_{AB} : increase in parton-luminosity per event (p+p → Au+Au)



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60 – 92%:
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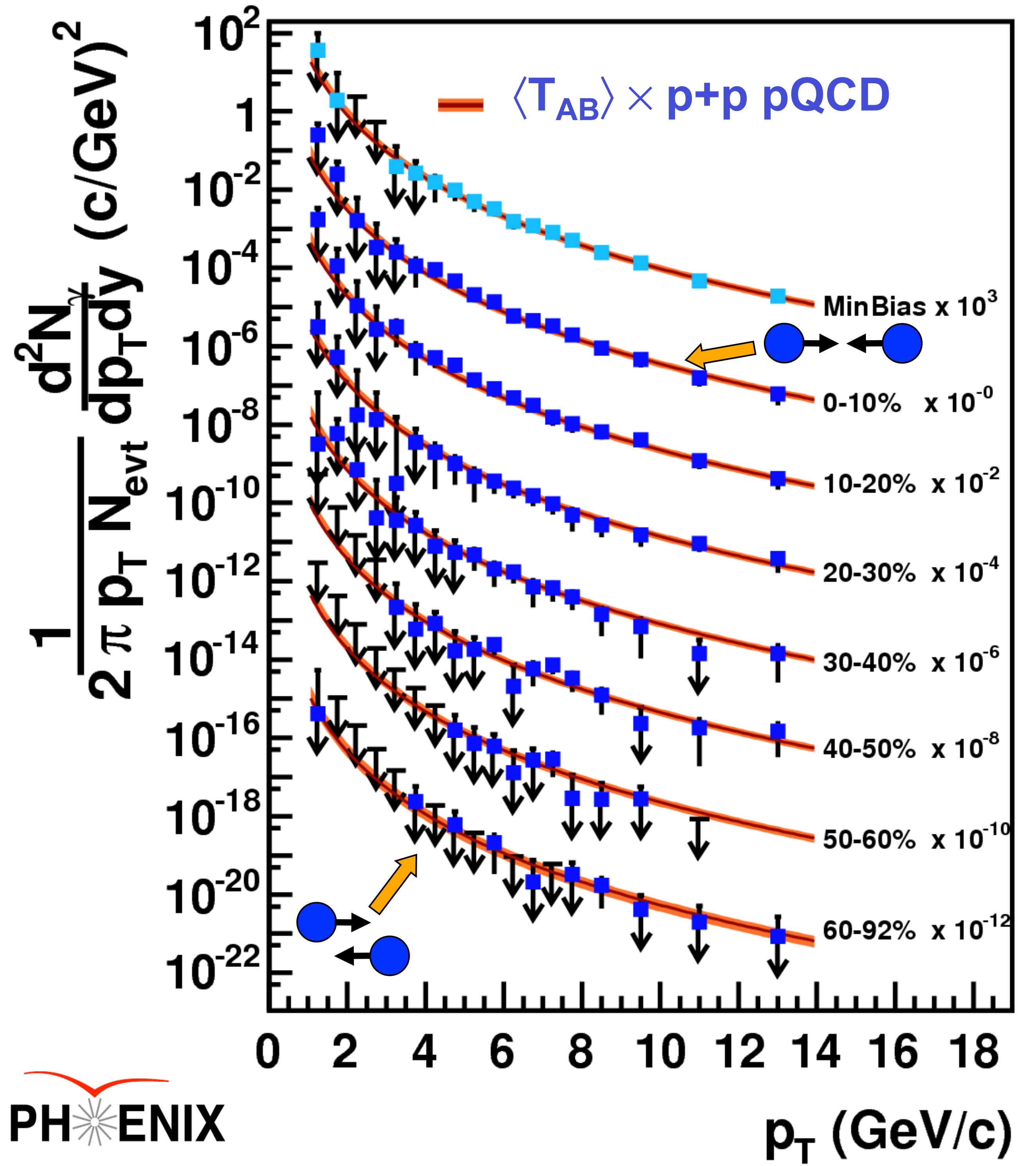
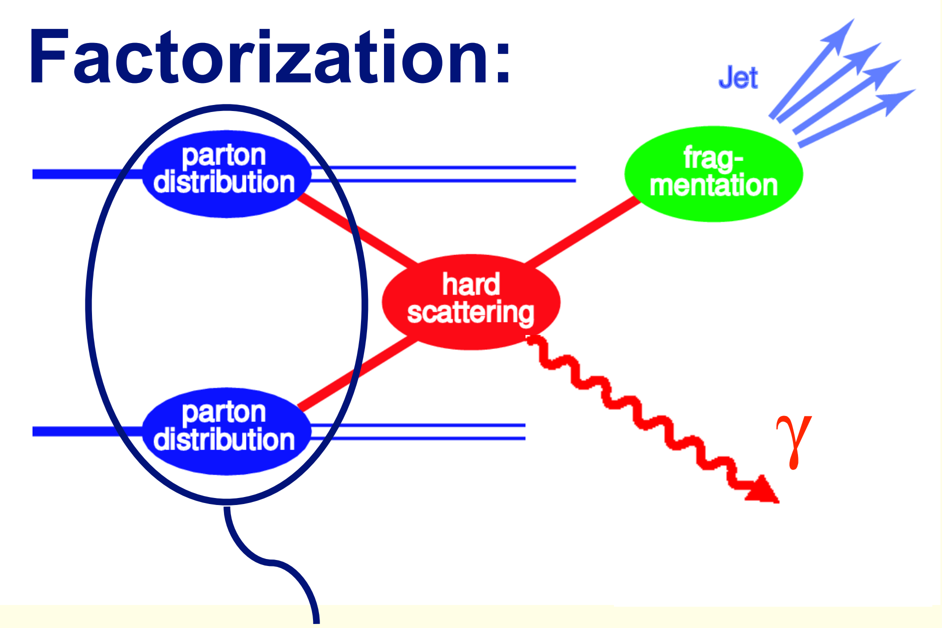
Direct-Photon Spectra in Au+Au

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (RHIC run 2)

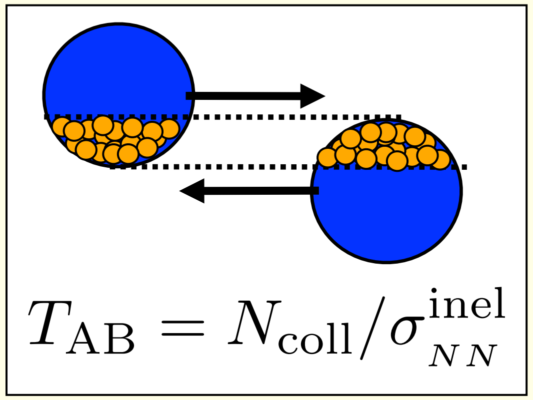


Phys.Rev.Lett.94:232301,2005

Factorization:



***T_{AB}* : increase in parton-luminosity per event (p+p → Au+Au)**



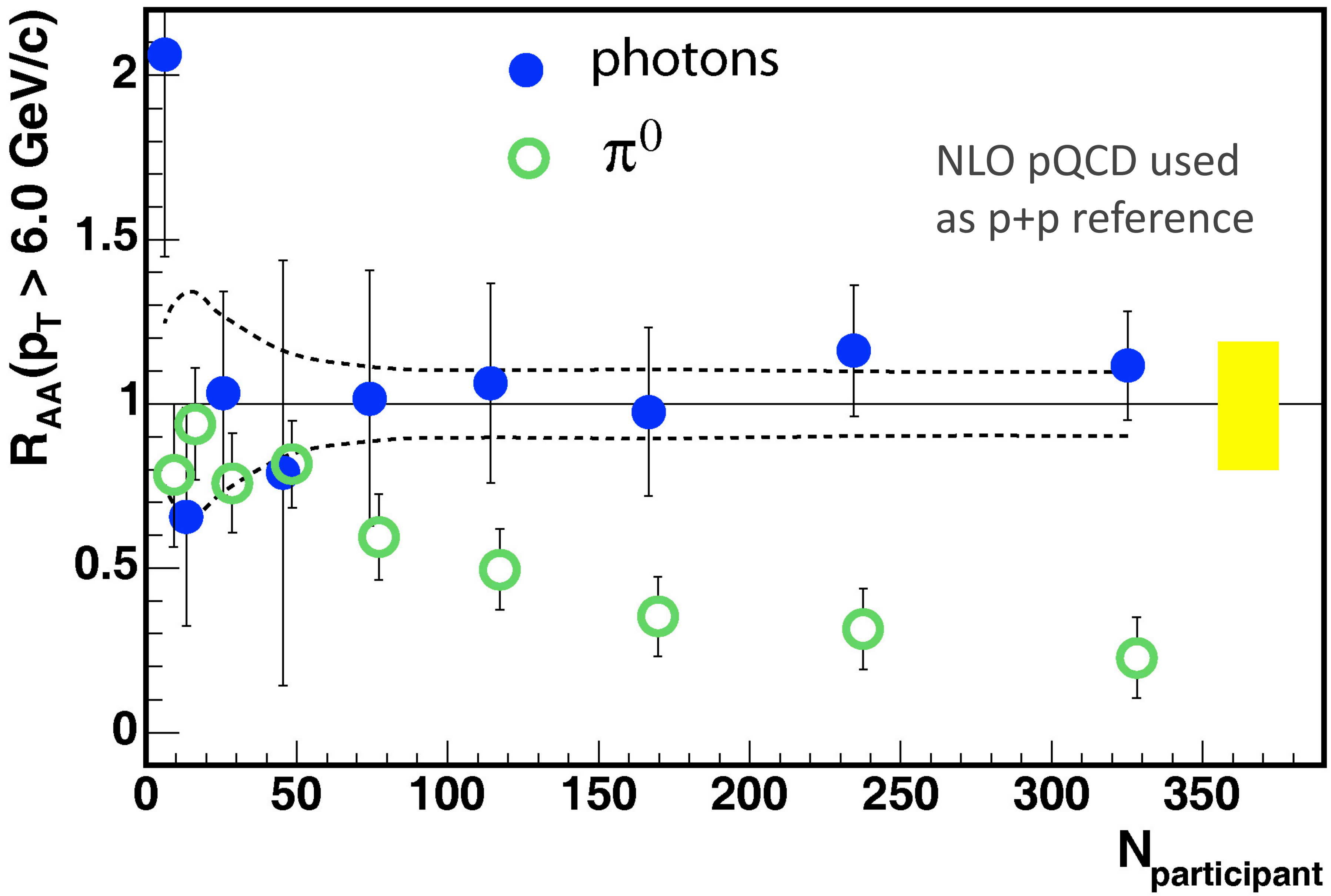
$$T_{AB} = N_{\mathrm{coll}} / \sigma_{NN}^{\mathrm{inel}}$$

0 – 10%:
$\langle N_{coll} \rangle$ = 955 ± 94

60 – 92%:
$\langle N_{coll} \rangle$ = 14.5 ± 4

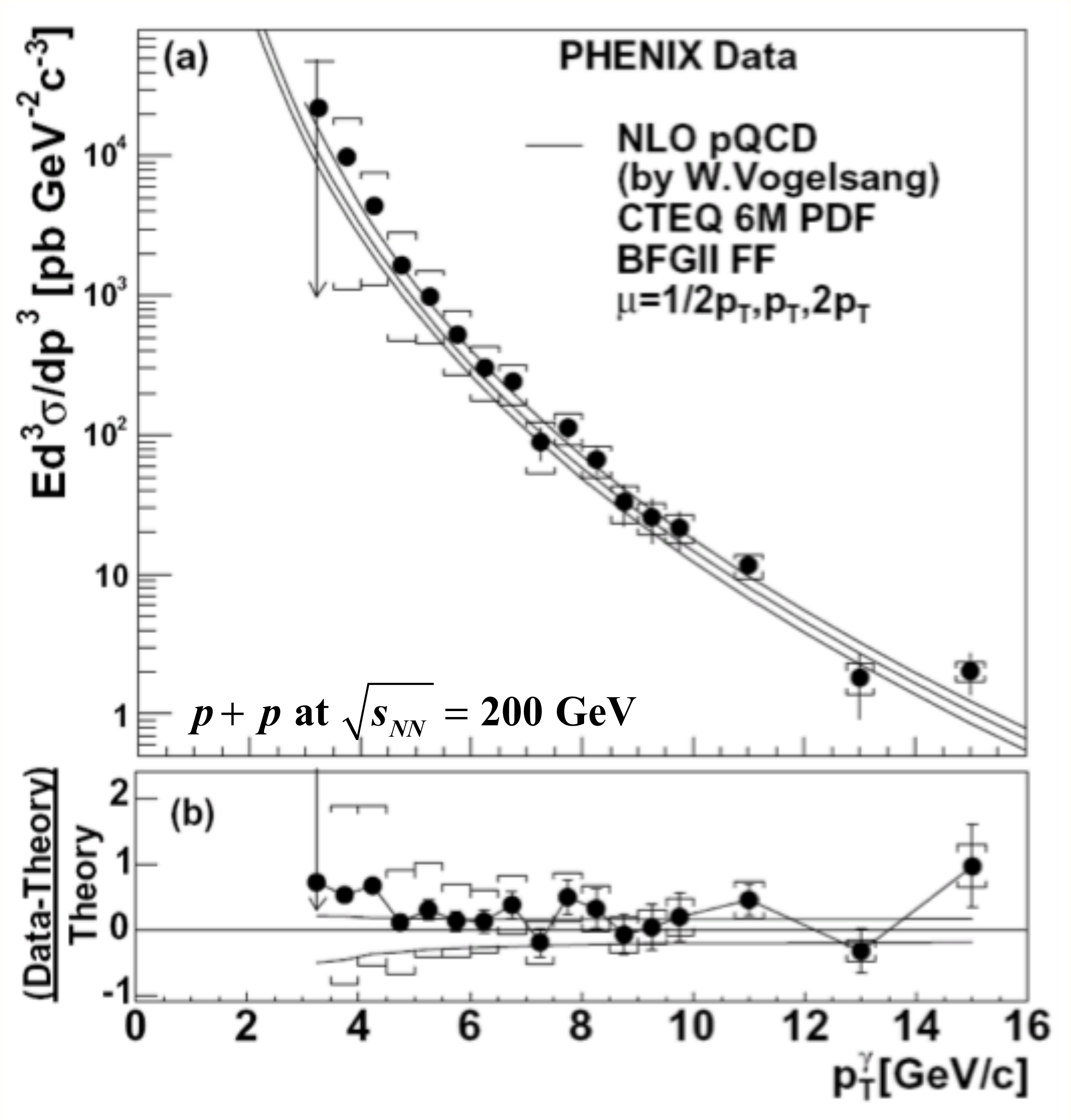
- **High-p_T direct photons scale with $\langle T_{AB} \rangle$**
- **No indication of nuclear effects**

Centrality Dependence of the Direct Photon and π^0 R_{AA} in Au+Au Collisions at 200 GeV



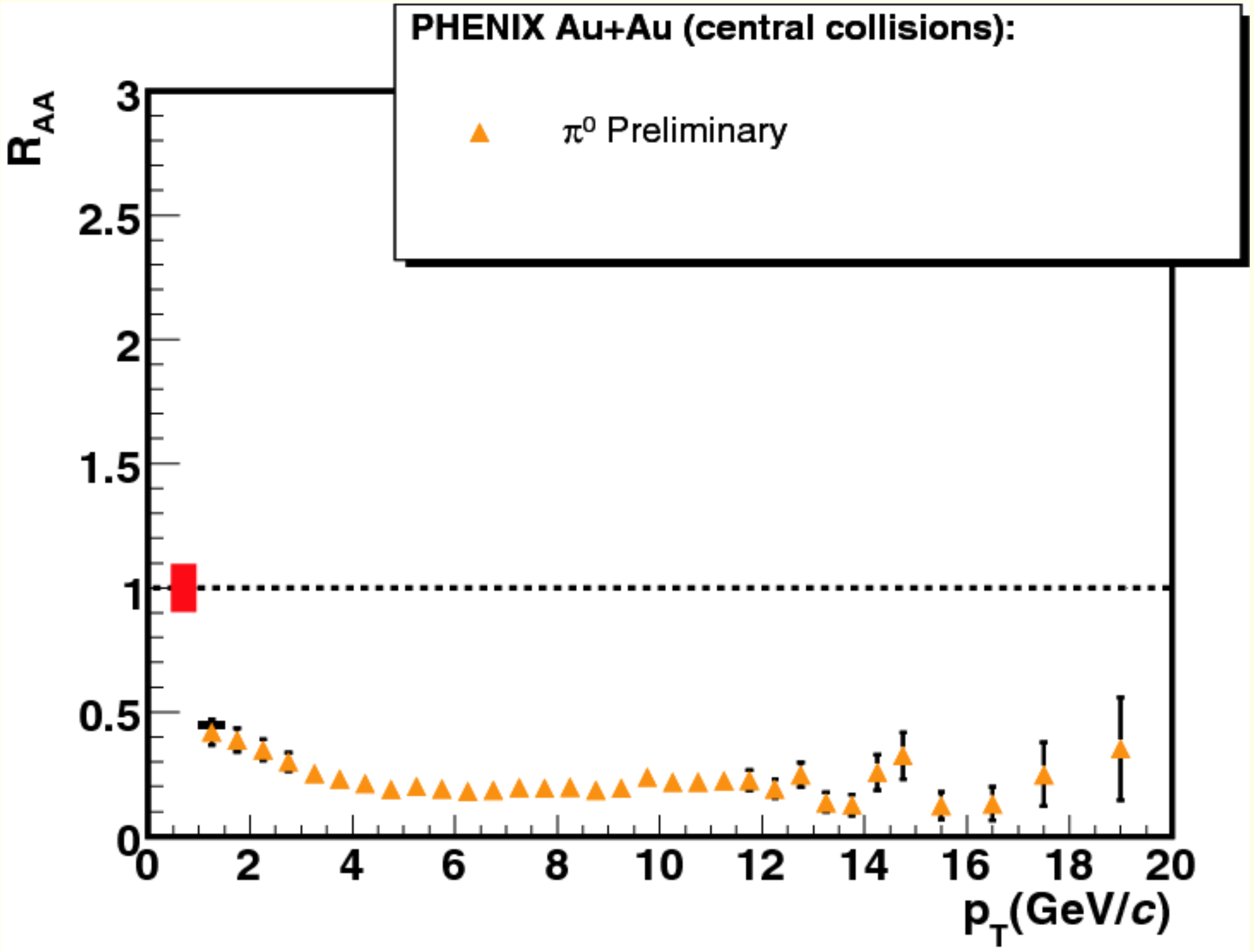
Direct photons follow T_{AB} scaling

Direct-Photon Production in p+p at $\sqrt{s}$ = 200 GeV



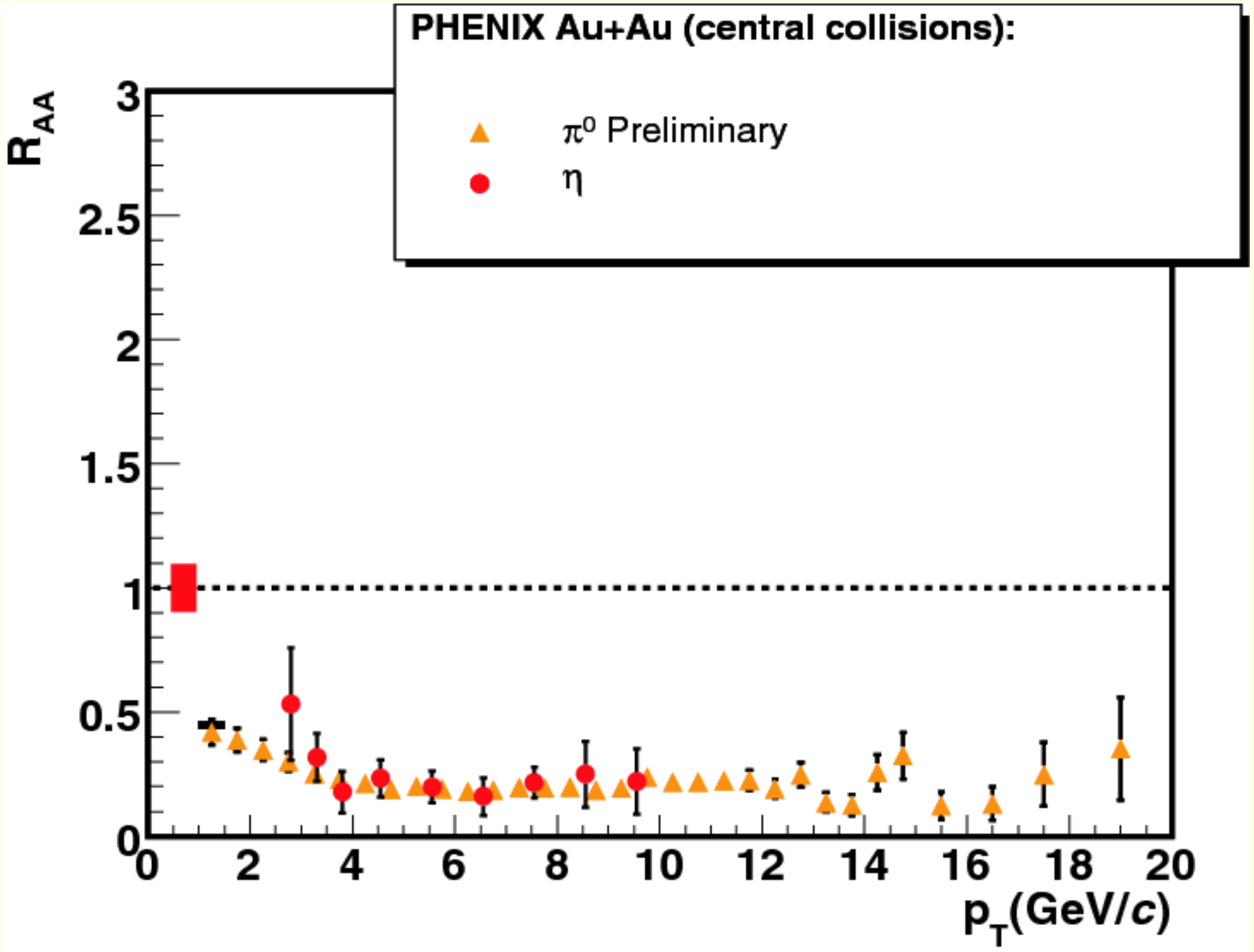
- Direct-photon data in p+p at $\sqrt{s}$ = 200 GeV consistent with NLO pQCD
- No need for additional k_T broadening

Hadron Suppression: A Final State Effect!



$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T(A+A)}{\langle T_{AA}\rangle \times \mathrm{d}\sigma/\mathrm{d}p_T(p+p)}$$

Hadron Suppression: A Final State Effect!



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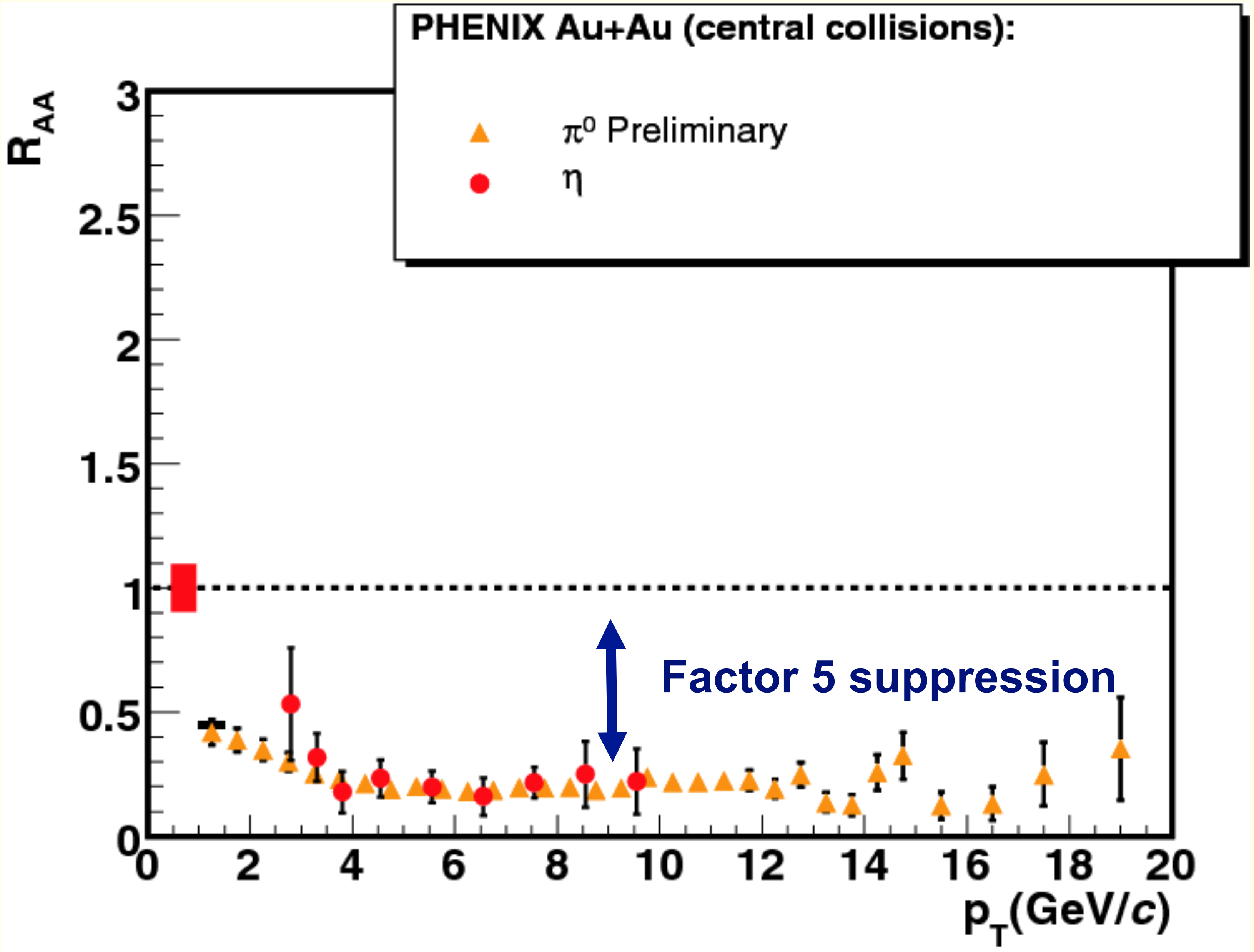

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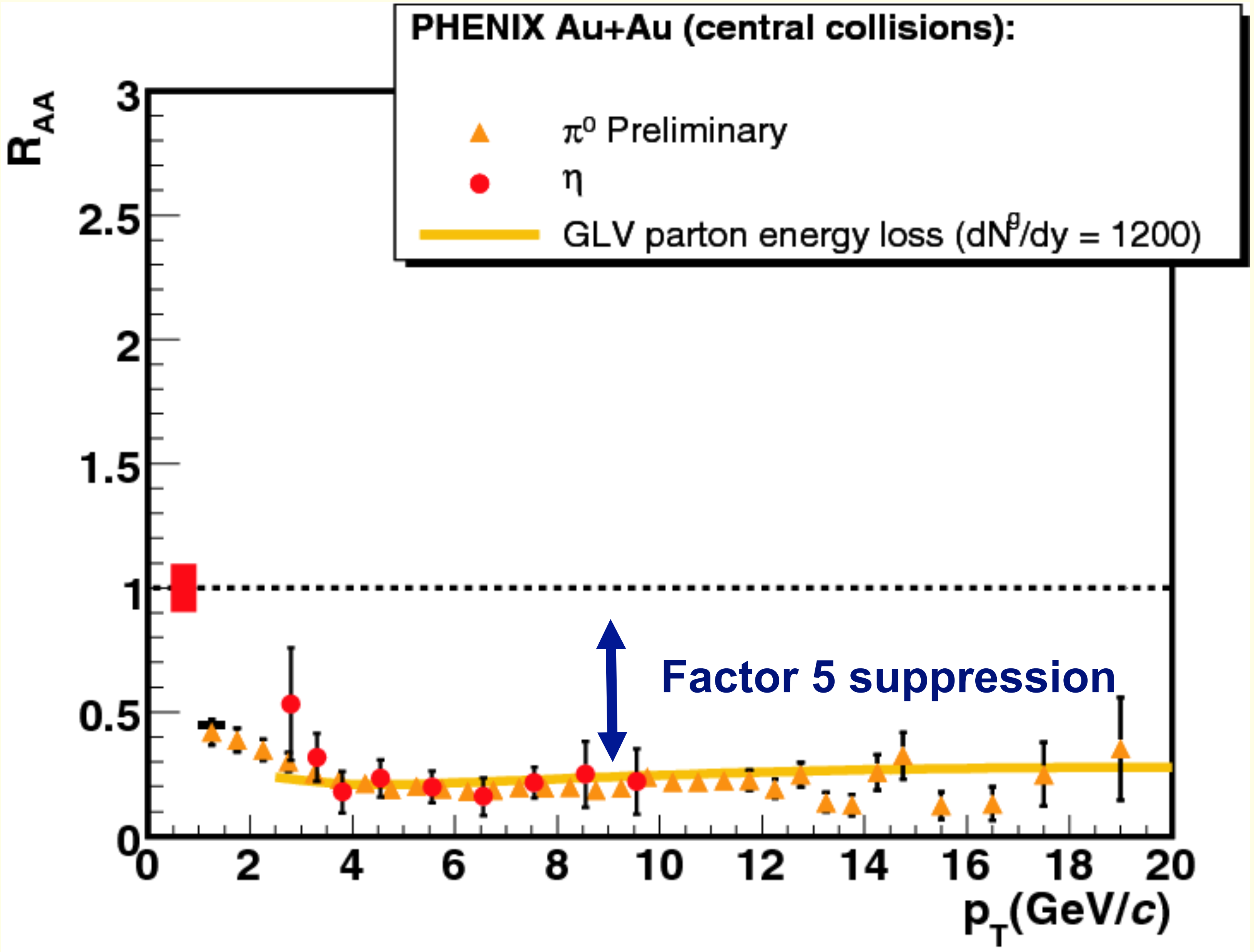

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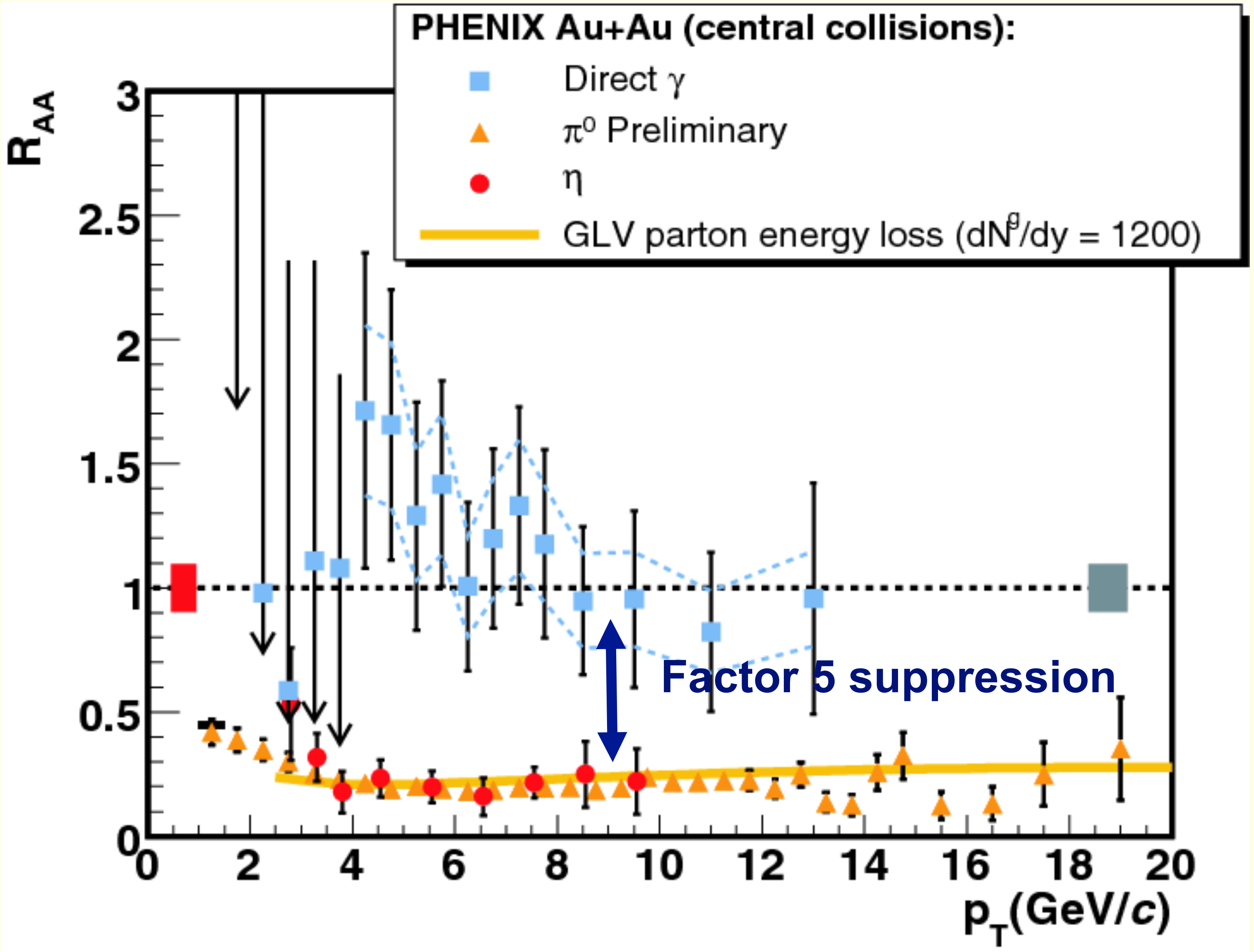

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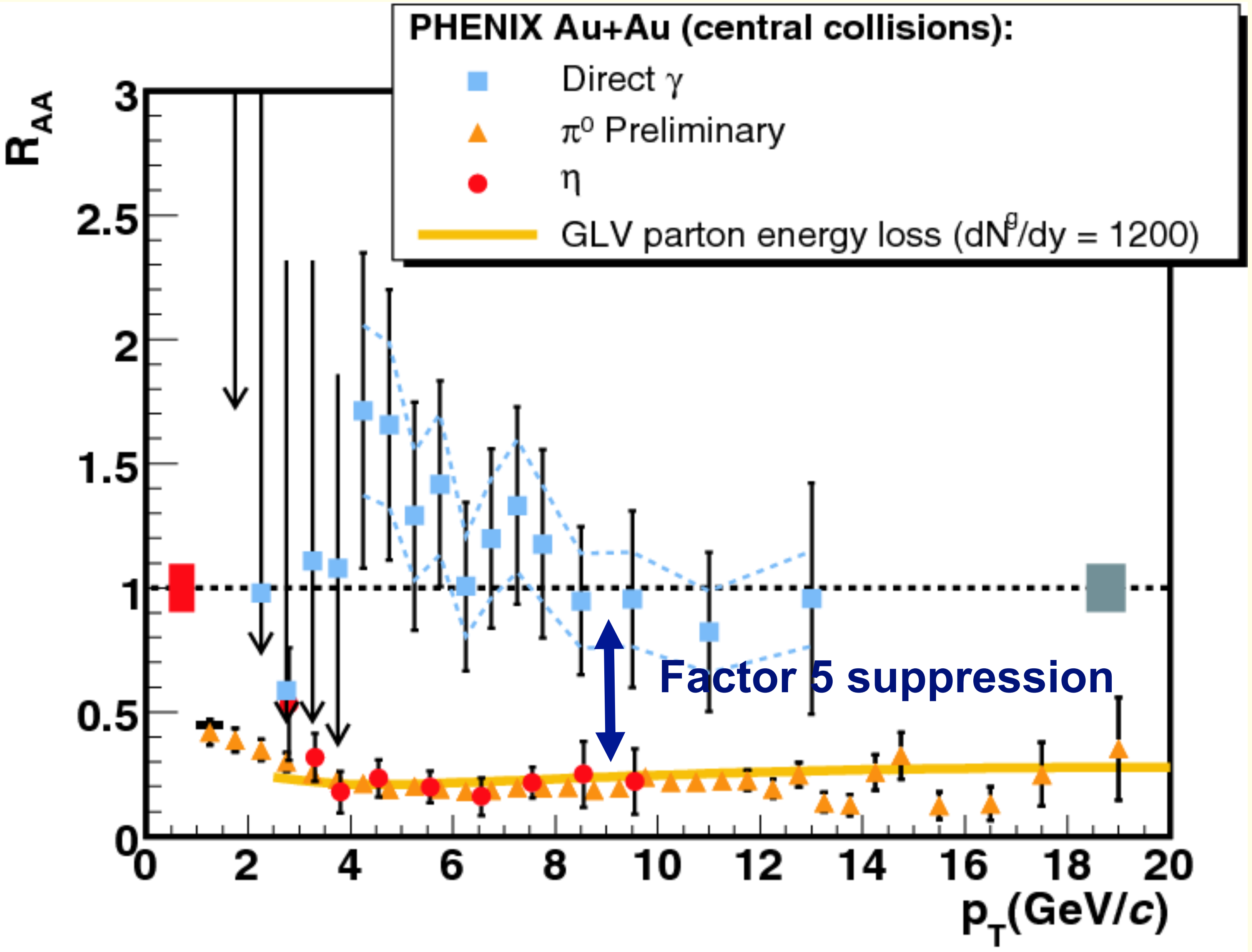
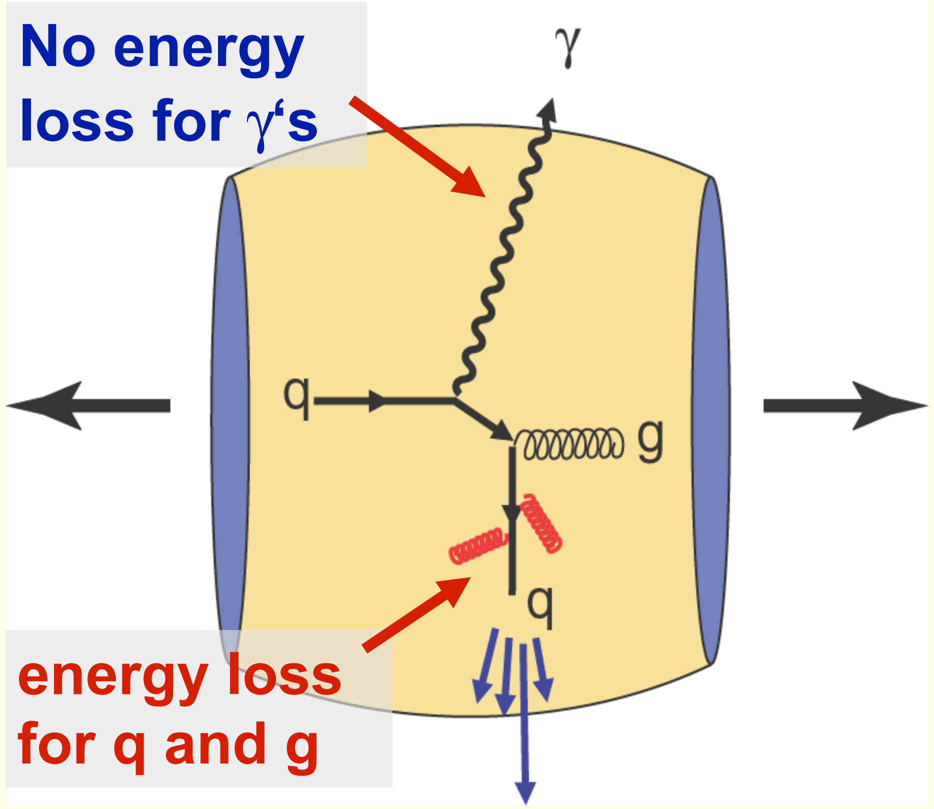


Factor 5 suppression

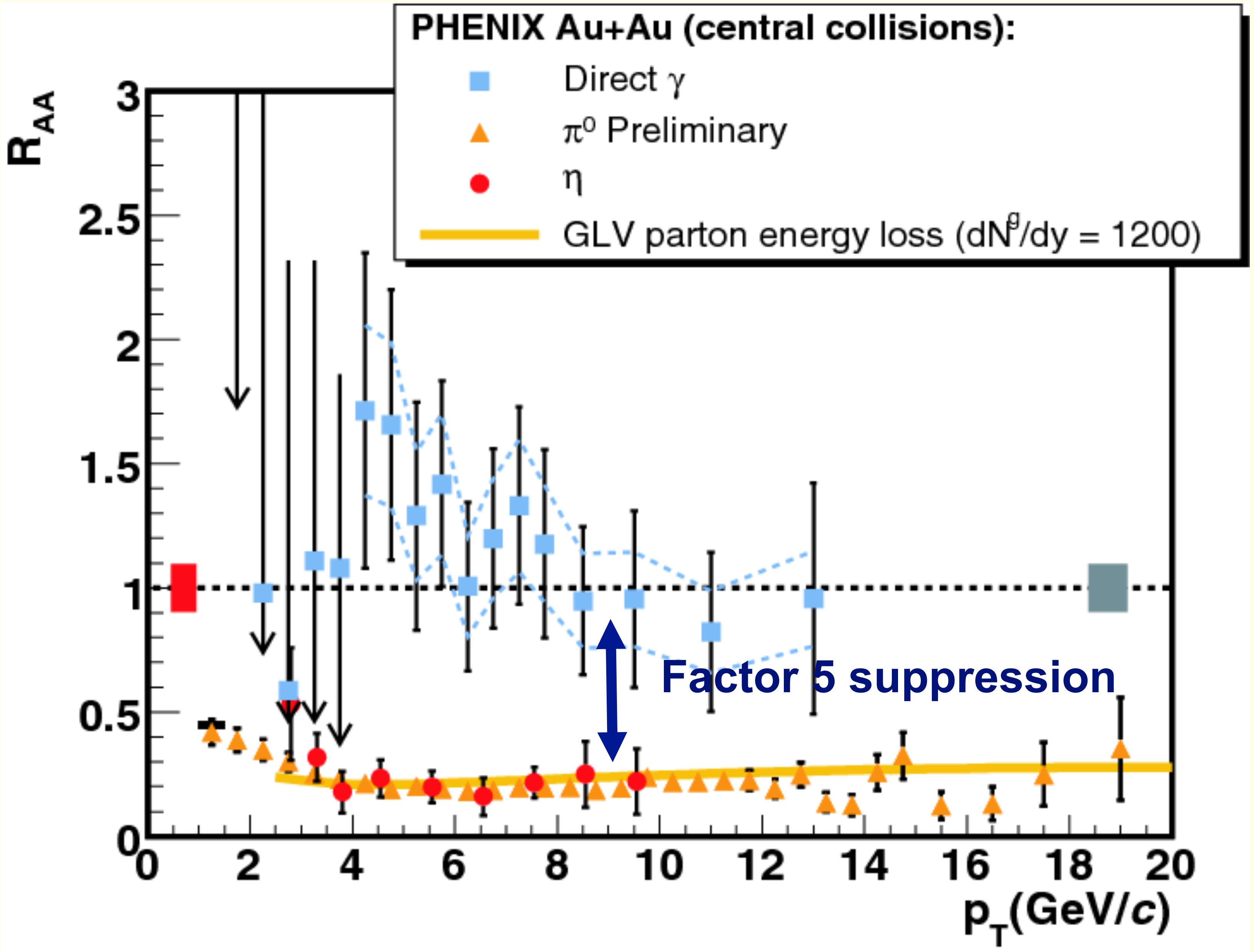
$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T(A+A)}{\langle T_{AA}\rangle \times \mathrm{d}\sigma/\mathrm{d}p_T(p+p)}$$



No energy loss for γ's

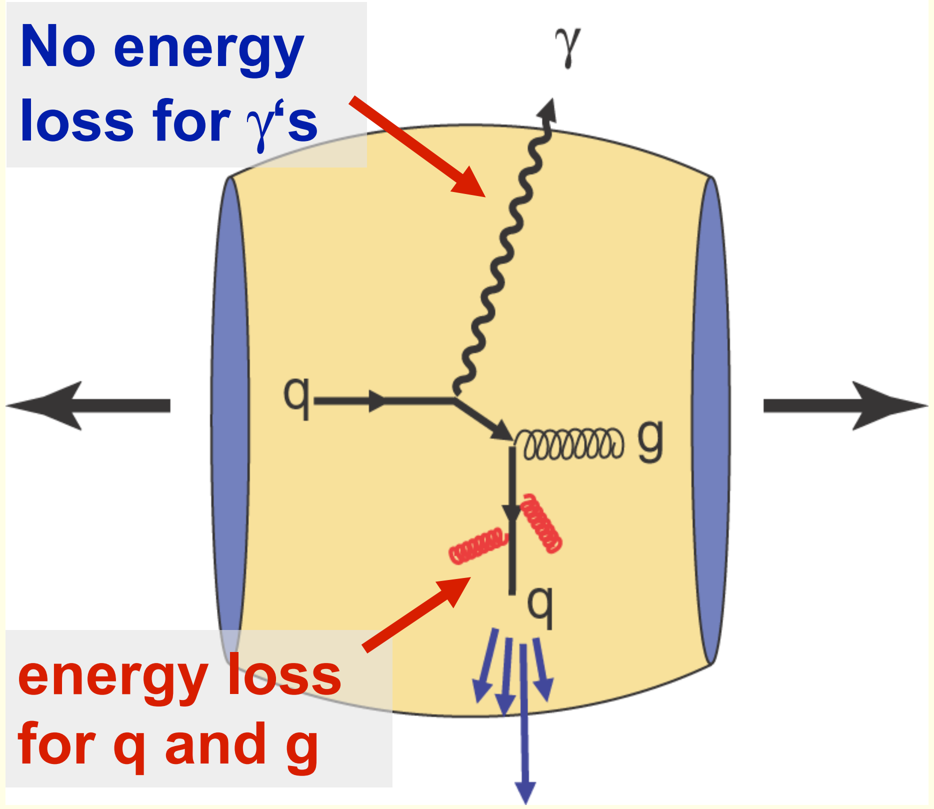
energy loss for q and g

Hadron Suppression: A Final State Effect!



Factor 5 suppression

$$R_{AA} = \frac{dN/dp_T(A+A)}{\langle T_{AA}\rangle \times d\sigma/dp_T(p+p)}$$

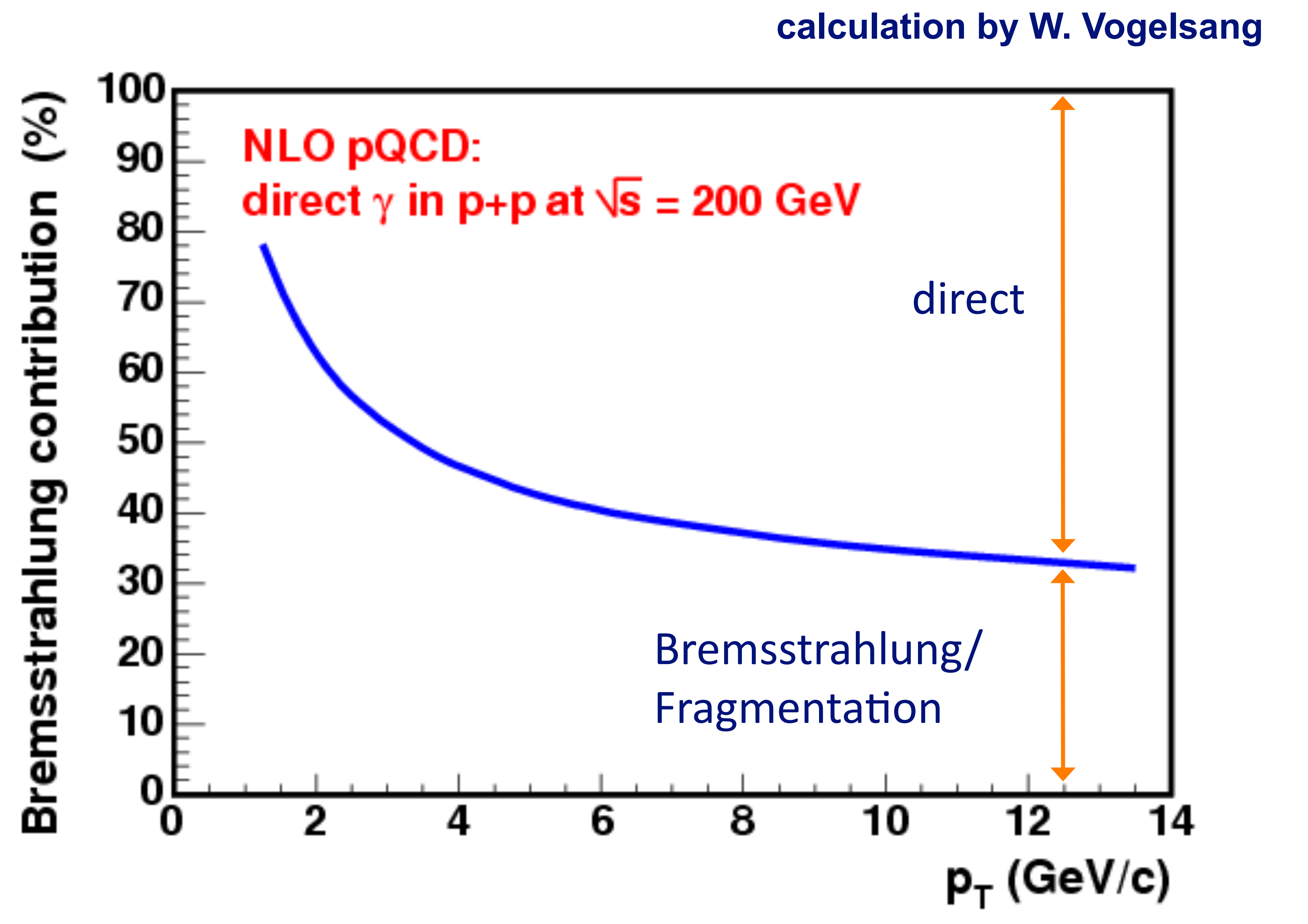


No energy loss for γ's

energy loss for q and g

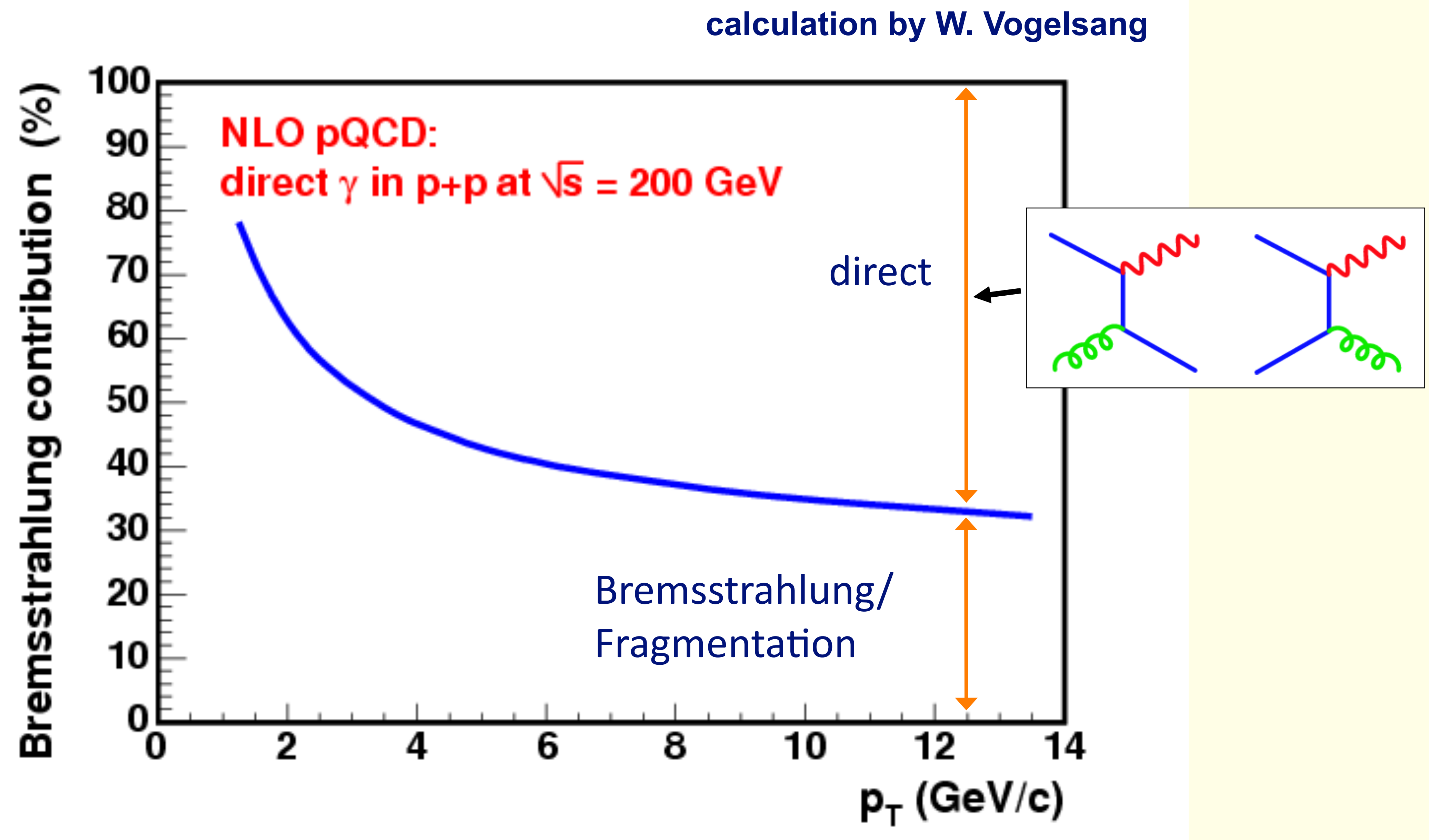
Hadrons are suppressed whereas direct photons are not: Evidence for parton energy loss (as expected in the QGP)

pQCD: Bremsstrahlung/Fragmentation Component



- Bremsstrahlung/fragmentation contribution large
- Suppression of bremsstrahlung/fragmentation contribution expected in A+A

pQCD: Bremsstrahlung/Fragmentation Component


calculation by W. Vogelsang

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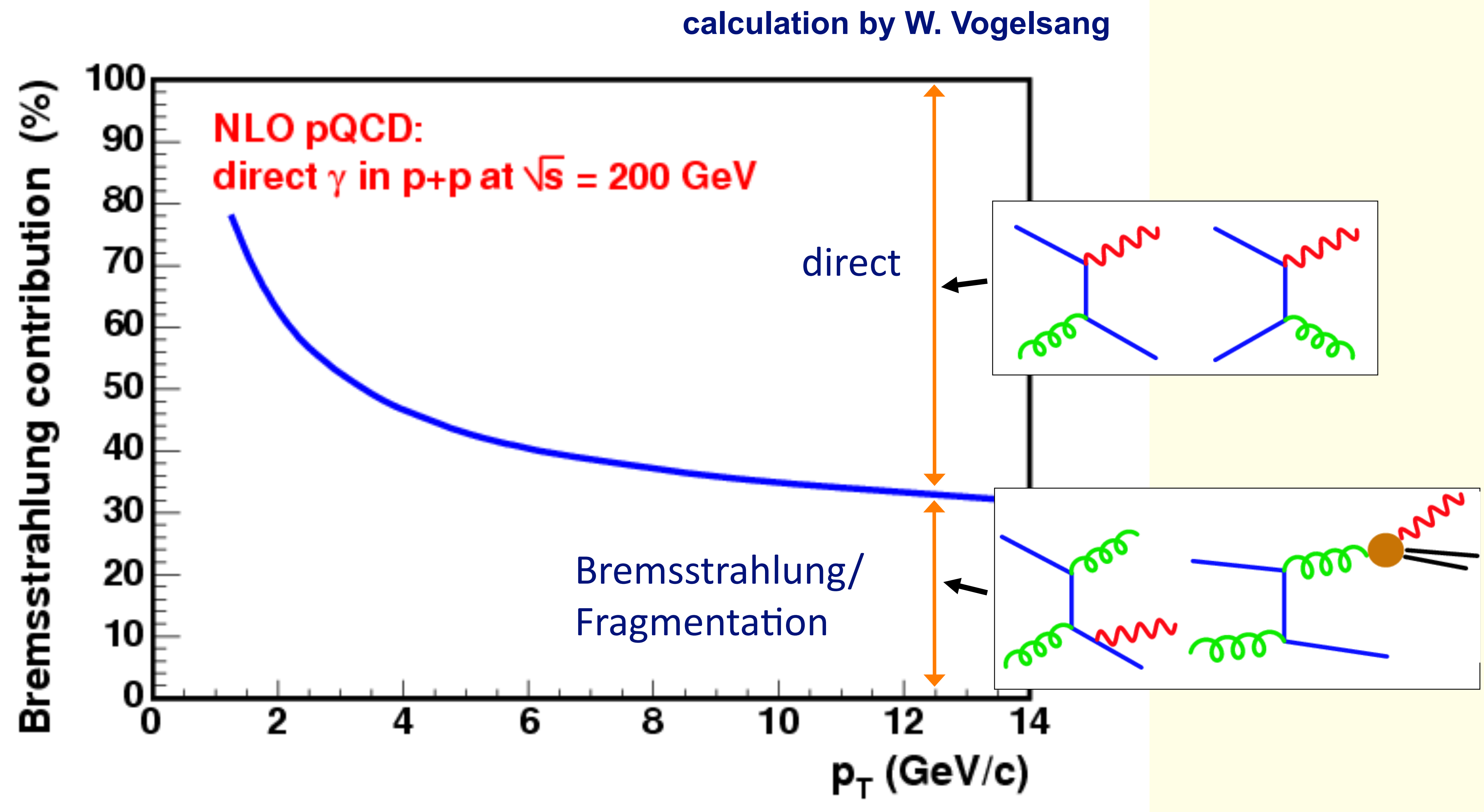
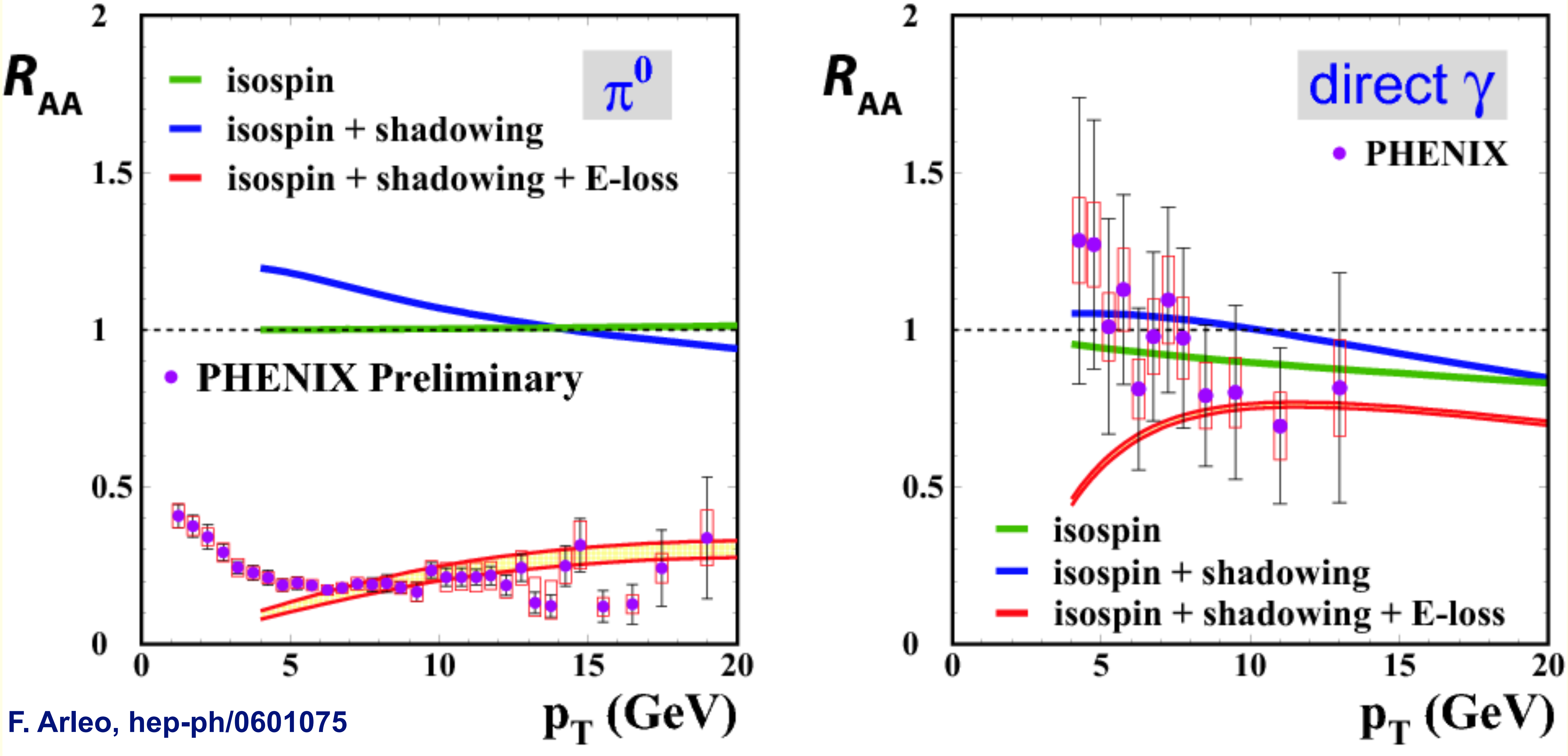


calculation by W. Vogelsang

- Bremsstrahlung/fragmentation contribution large
- Suppression of bremsstrahlung/fragmentation contribution expected in A+A

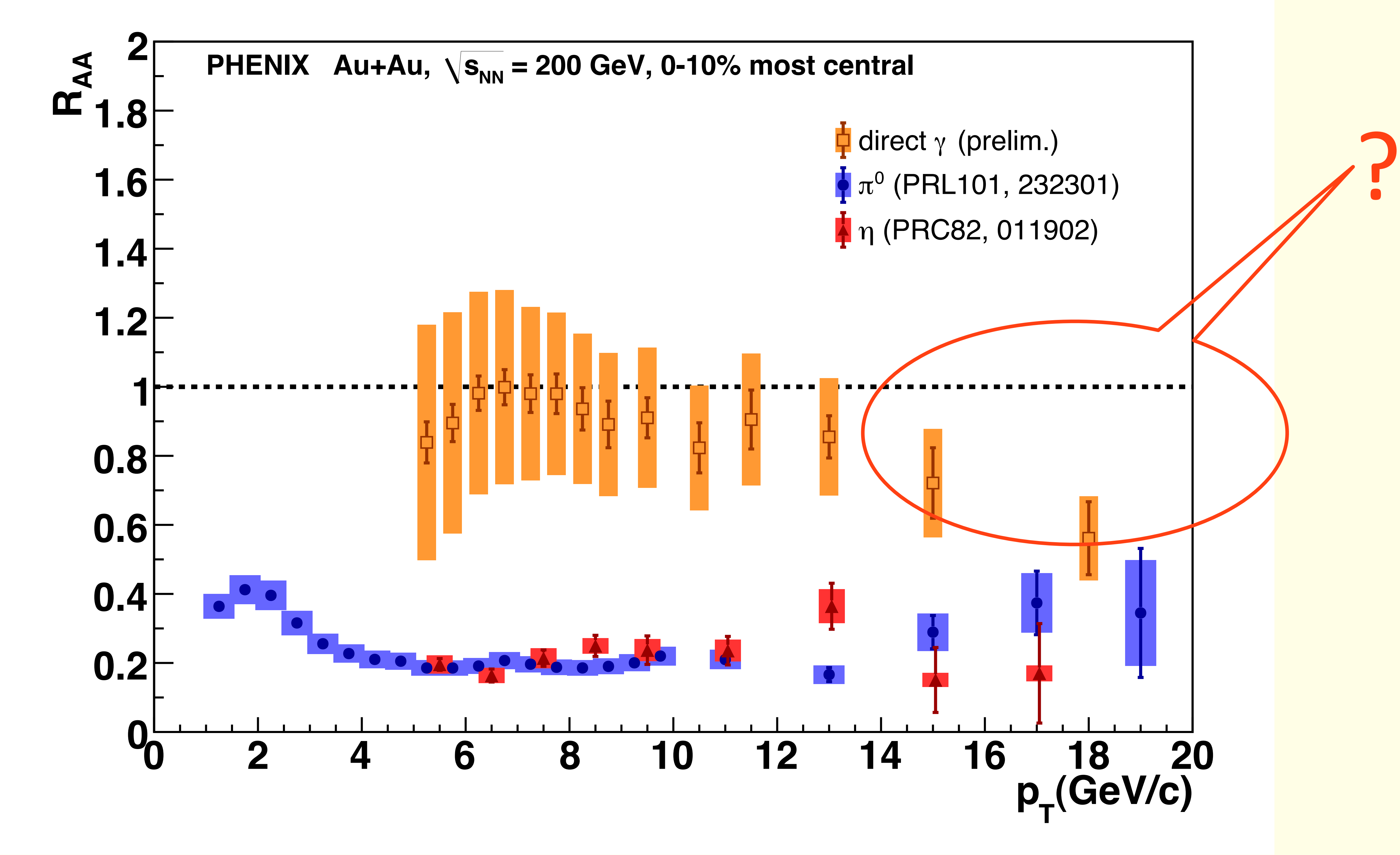
Effect of Parton Energy Loss



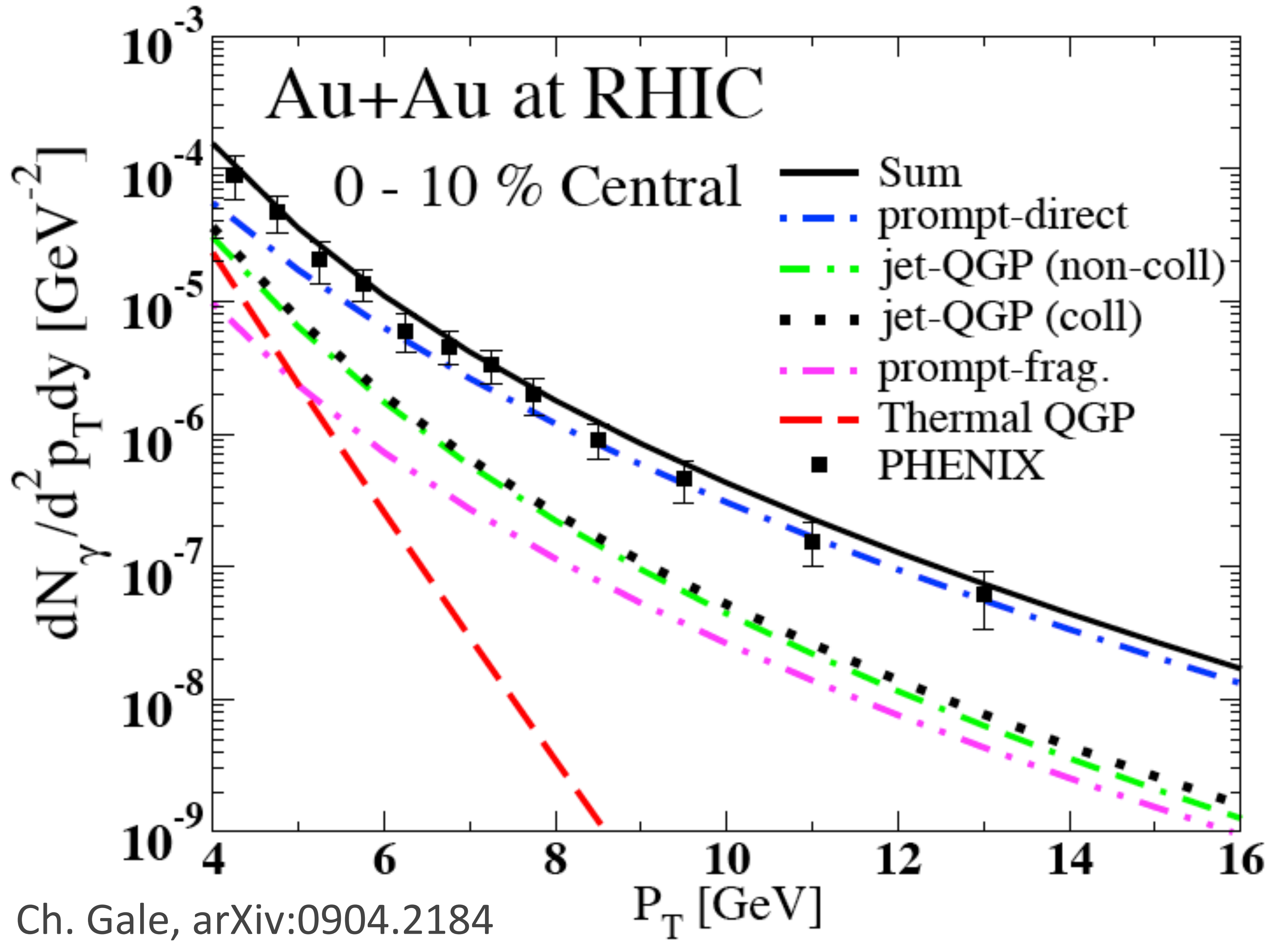
F. Arleo, hep-ph/0601075

- 20-30% reduction of direct photon R_{AA} expected due to parton energy loss
- Consistent with PHENIX data

The Puzzle of the Preliminary Direct Photon R_{AA} at high p_T (PHENIX, Run 4 Au+Au data)



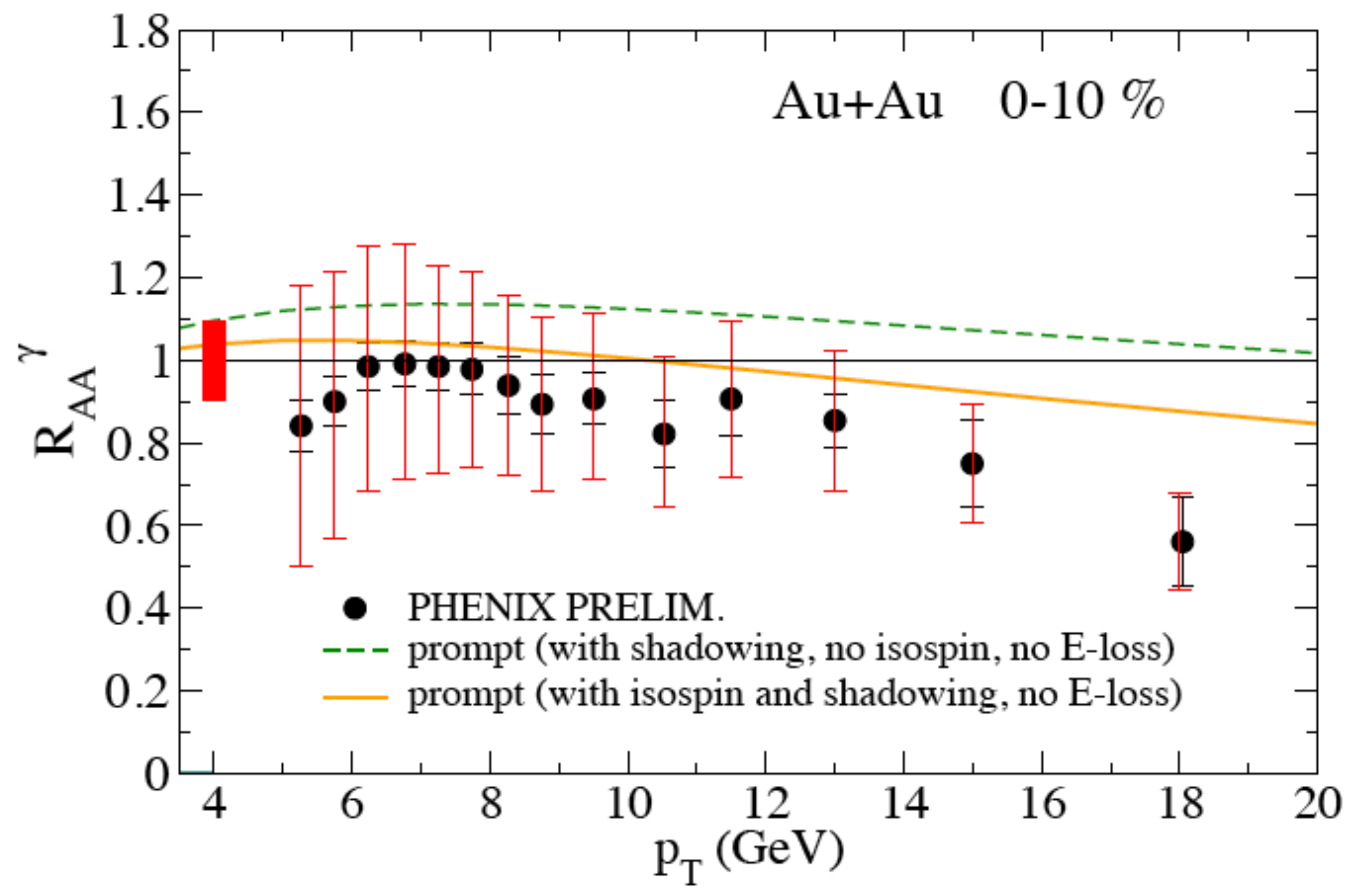
Interpretation of the Direct-Photon Spectrum at RHIC (p_T > 4 GeV/*c*) (I)



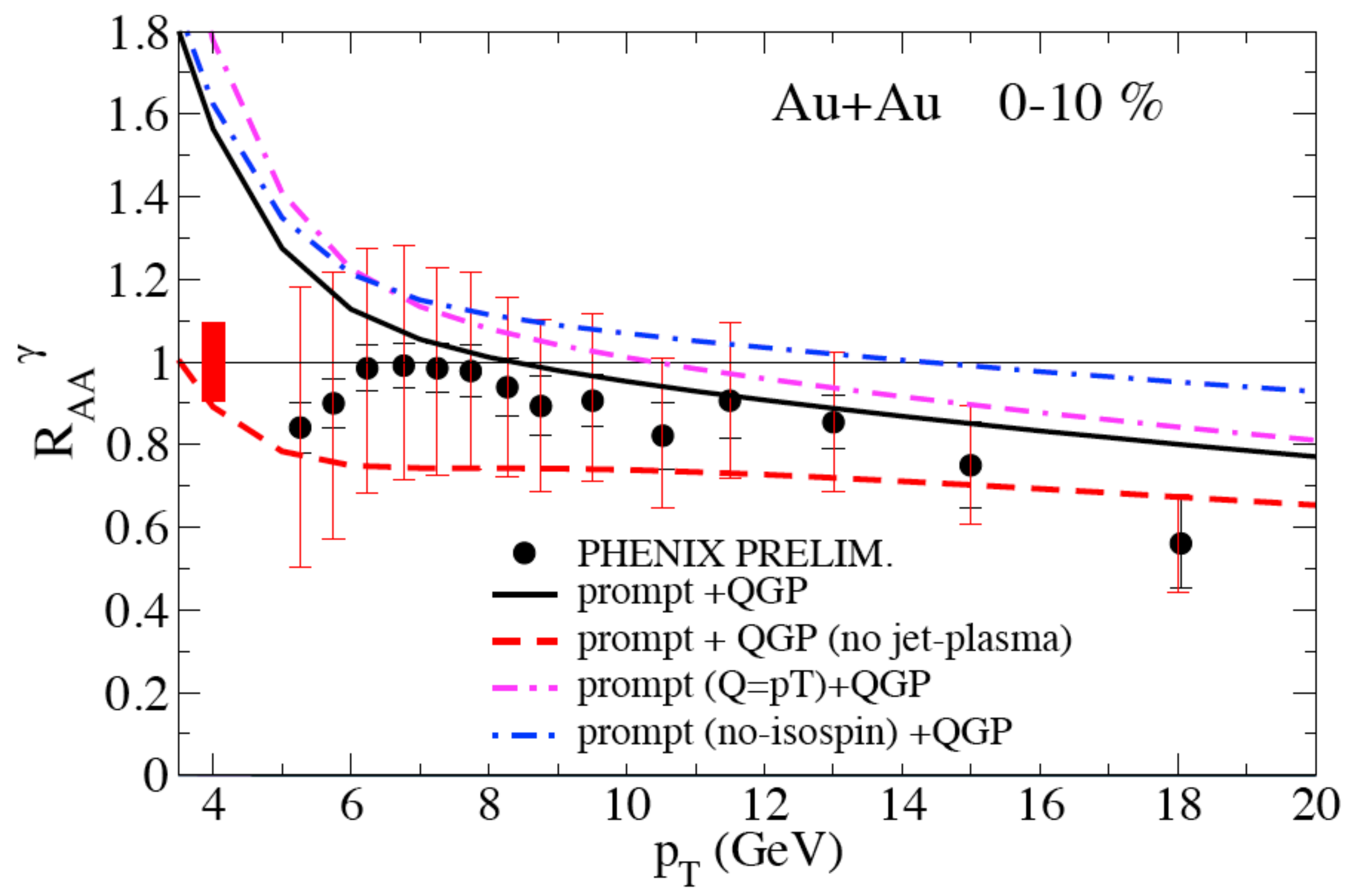
Ch. Gale, arXiv:0904.2184

Indication for relevance of photons from jet-plasma interactions for p_T < 6 GeV/*c* ?

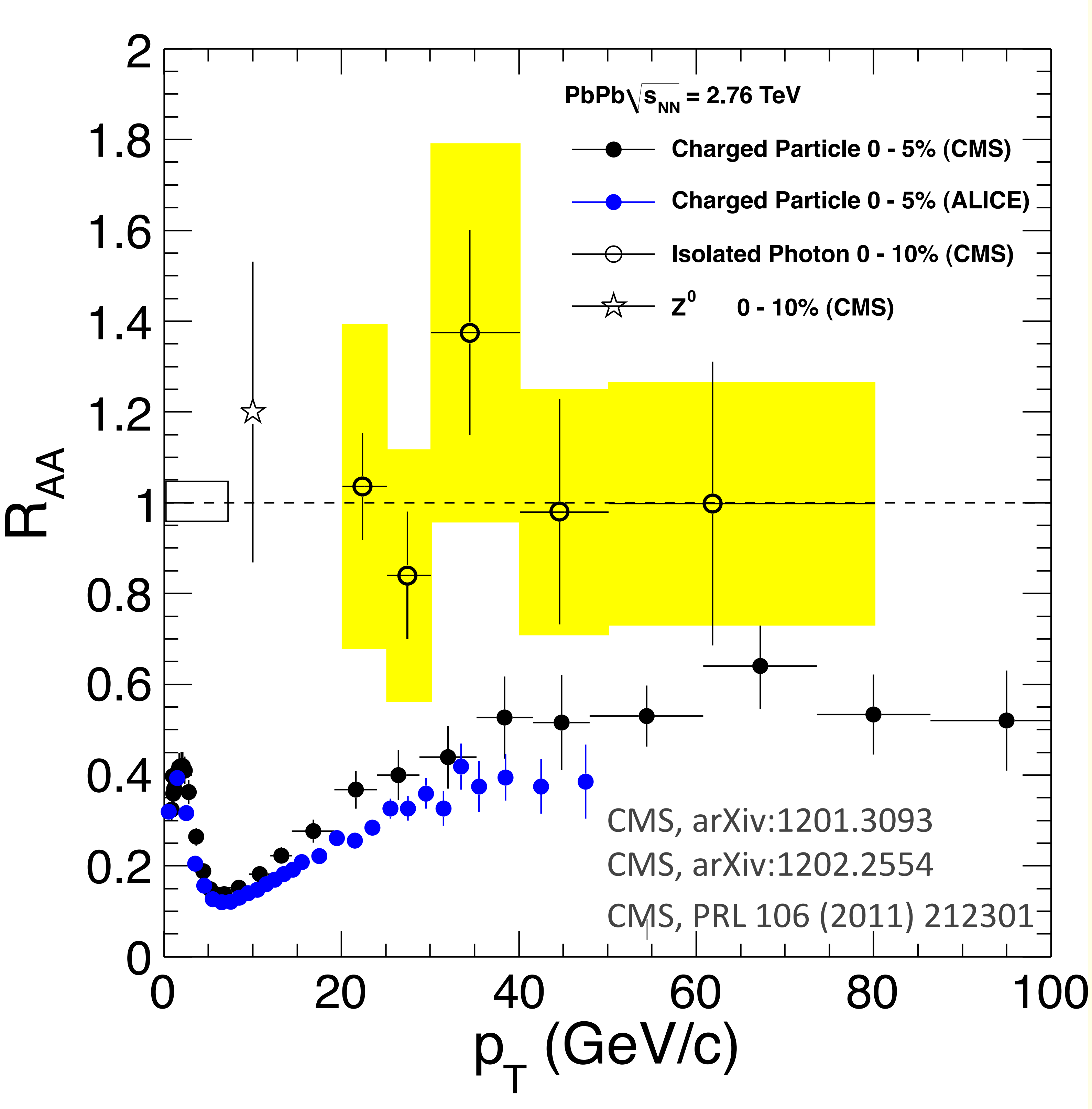
Interpretation of the Direct-Photon Spectrum at RHIC (p_T > 4 GeV/c) (II)



Interpretation of the Direct-Photon Spectrum at RHIC ($p_T > 4$ GeV/c) (III)

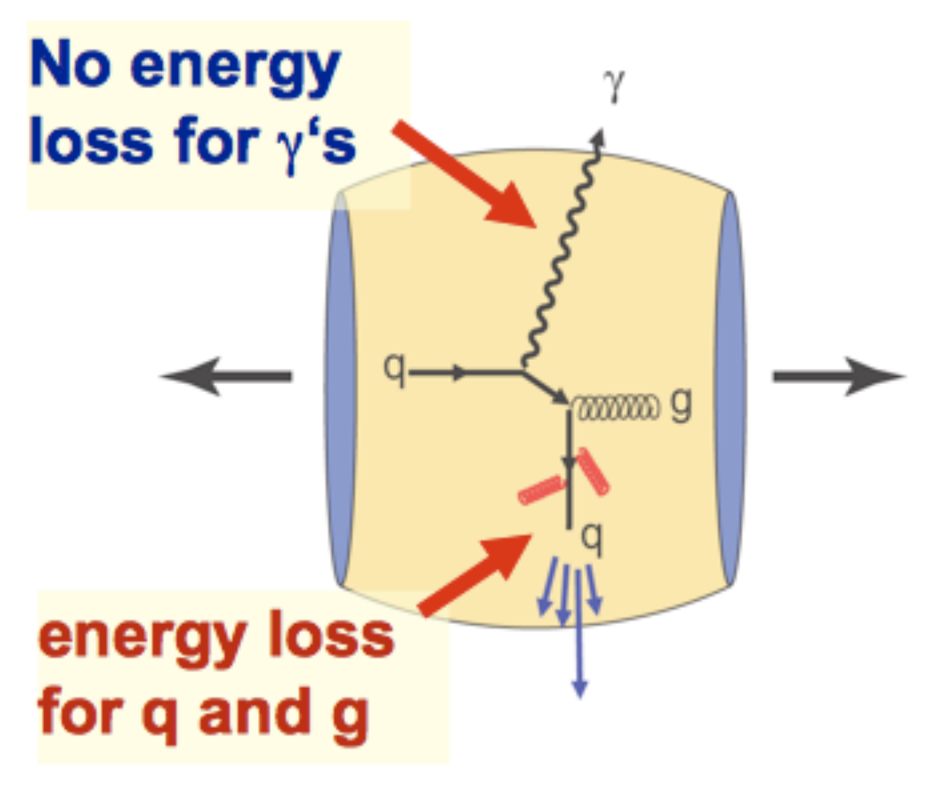


Pb+Pb at the LHC: Test of T_{AA} Scaling With Prompt Photons (and Z Bosons)



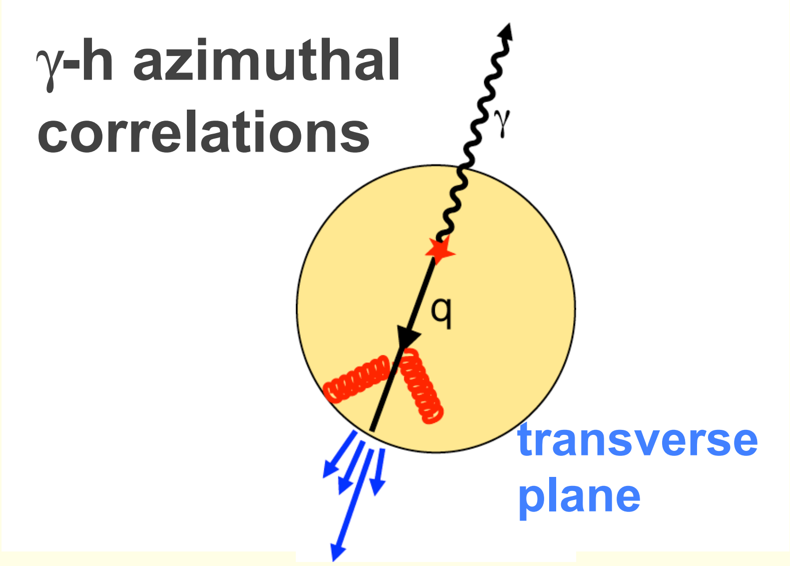
CMS, arXiv:1201.3093
CMS, arXiv:1202.2554
CMS, PRL 106 (2011) 212301

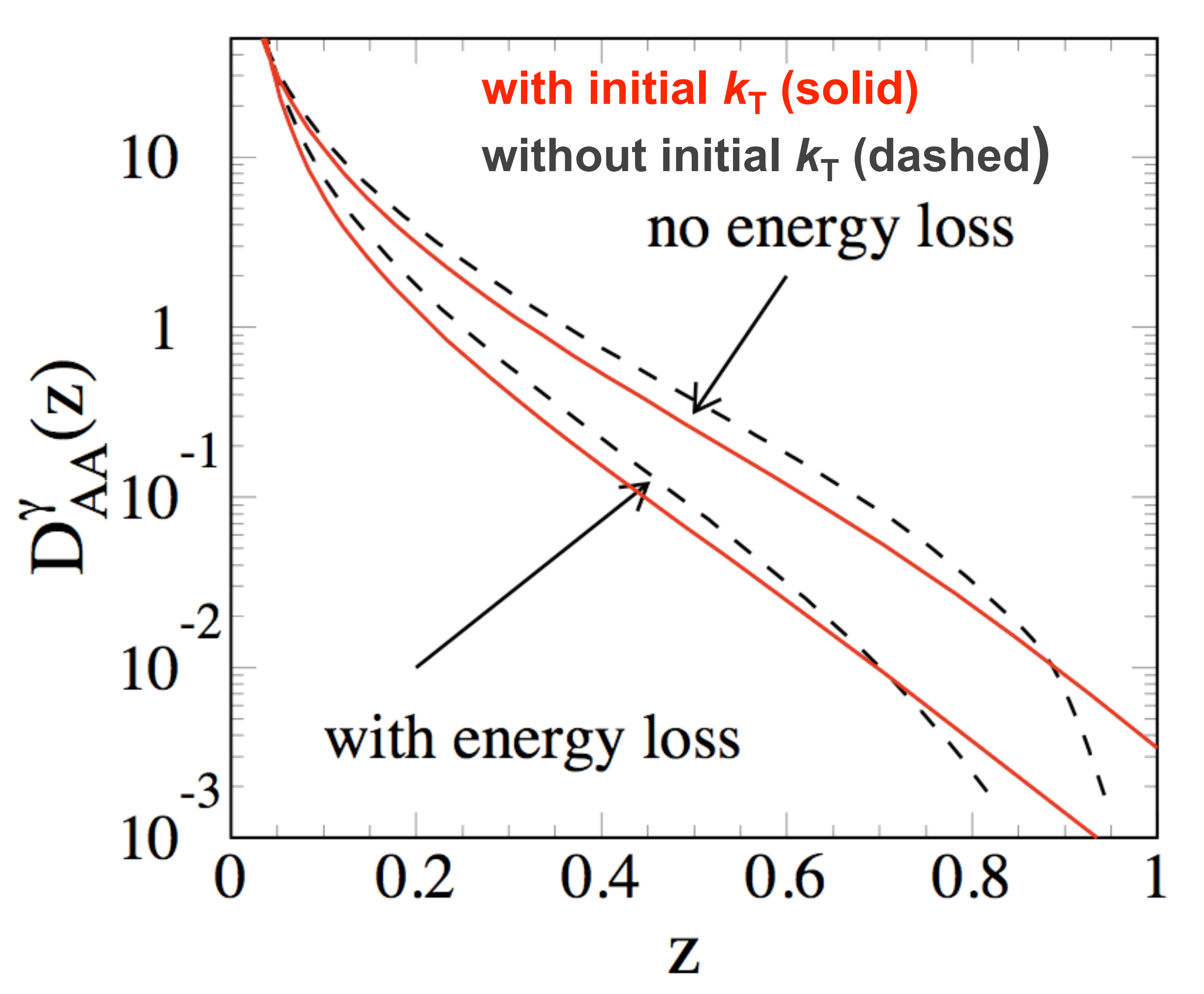
$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T(A+A)}{\langle T_{AA}\rangle \times \mathrm{d}\sigma/\mathrm{d}p_T(p+p)}$$



Prompt Photons (and Z^0's) are not suppressed: Strong Evidence for Parton Energy Loss Picture

γ-Triggered Away-Side Correlations: Basic Idea





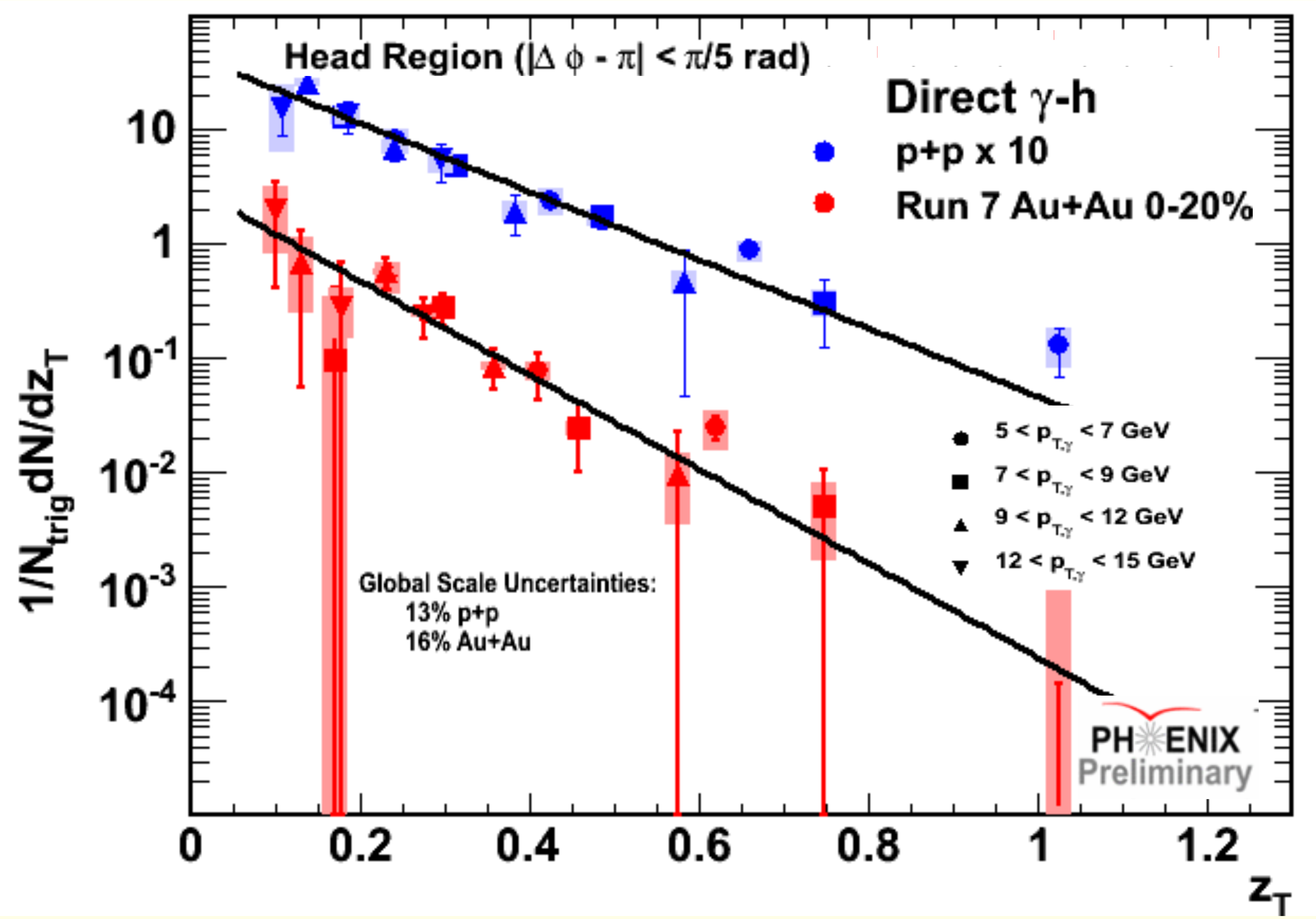
Wang, Huang, Phys.Rev.C55:3047-3061,1997

- p+p:
  (Effective) jet fragmentation functions can be extracted from γ-hadron azimuthal correlations (modulo initial k_T effect)
- A+A:
  Modification of fragmentation function provides information on parton energy loss
- Variables:

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

$$D(z_T) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}N(z_T)}{\mathrm{d}z_T}$$

γ-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au



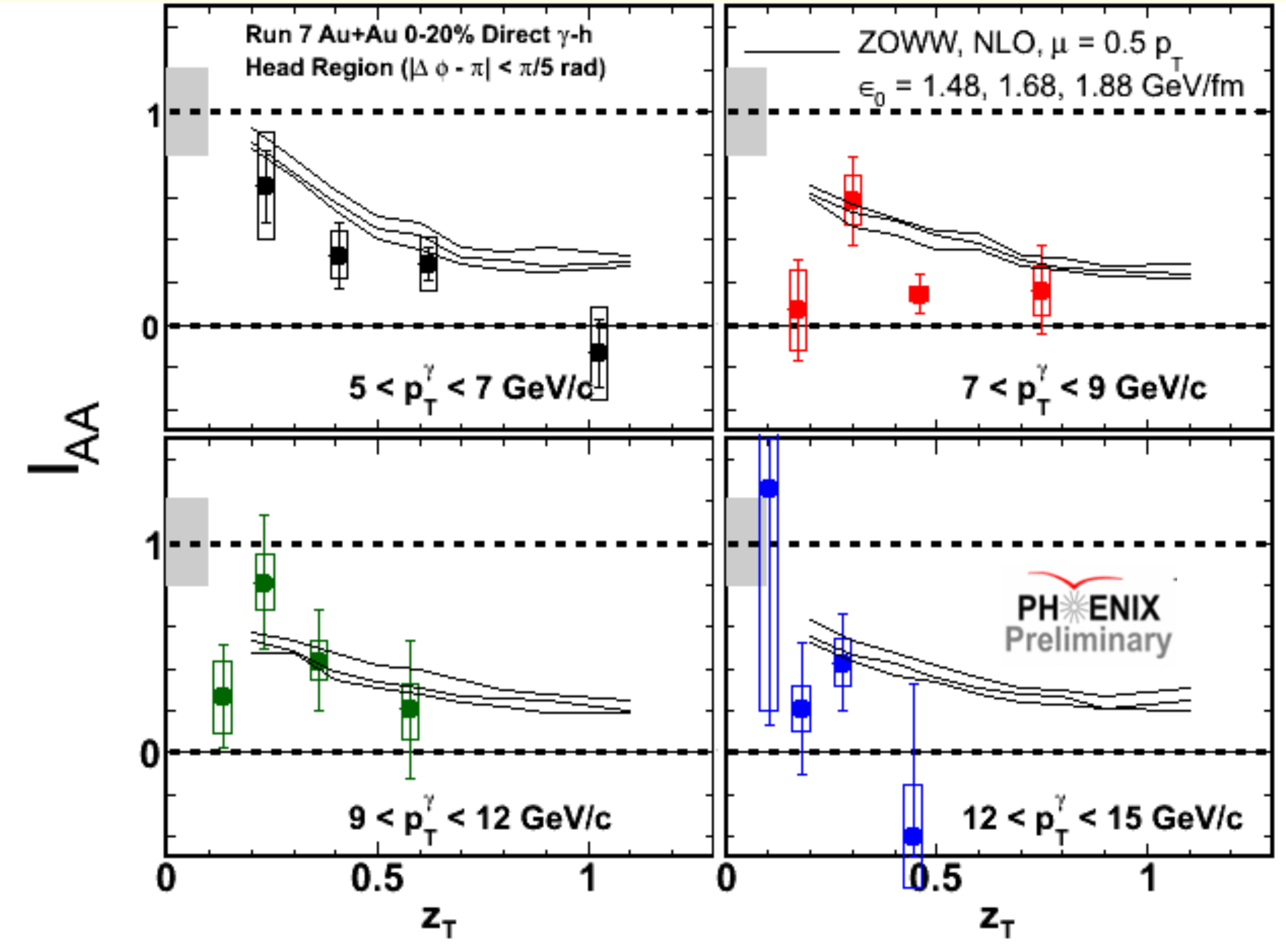
- Fit effective FF's with

$$\frac{dN}{dz_T} = Ne^{-bz_T}$$

- p+p: $b = 6.89 \pm 0.64$
- Au+Au: $b = 9.49 \pm 1.37$
- Difference reflects influence of the medium

γ-Triggered Away-side Correlations: Results

$I_{AA} = D_{AA}(z_T) / D_{pp}(z_T)$



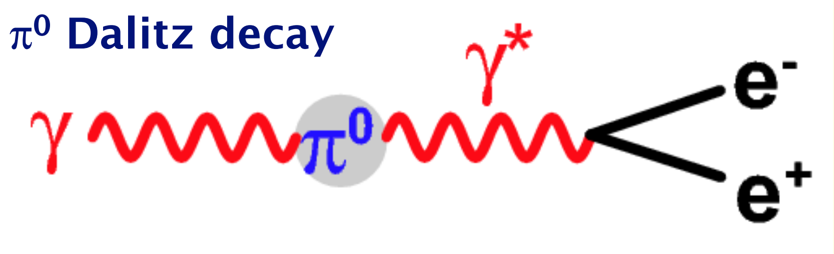
- Different z_T regions probe different regions of the fireball (arXiv:0902.4000v1)
- Agreement with NLO pQCD + parton energy loss: Indication that energy loss in different regions of the fireball is understood

NLO calculation:
Zhang et al. (ZOWW), arXiv:0902.4000v1

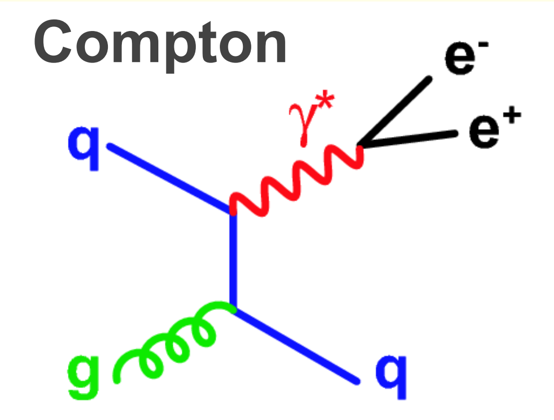
The Internal Conversion Method

Direct Photons via Internal Conversion

- Motivation:
  Measure where thermal photons are expected and calorimetric measurements are difficult
- Internal conversion
  - Any source of real photons also emits virtual photons
  - Well known example:



  - Rate and m_{ee} distribution calculable in QED (Kroll-Wada formula)
- Hadron decays: $m_{ee} < M_{\text{hadron}}$
- Essentially no such limit for point-like processes



Improve signal-to-background ratio by measuring e^+e^- pairs with $m_{ee} > \sim M_{\text{pion}}$

Kroll-Wada Formula

Number of virtual photons per real photon (in a given $\Delta\eta\ \Delta\phi\ \Delta p_T$ interval):

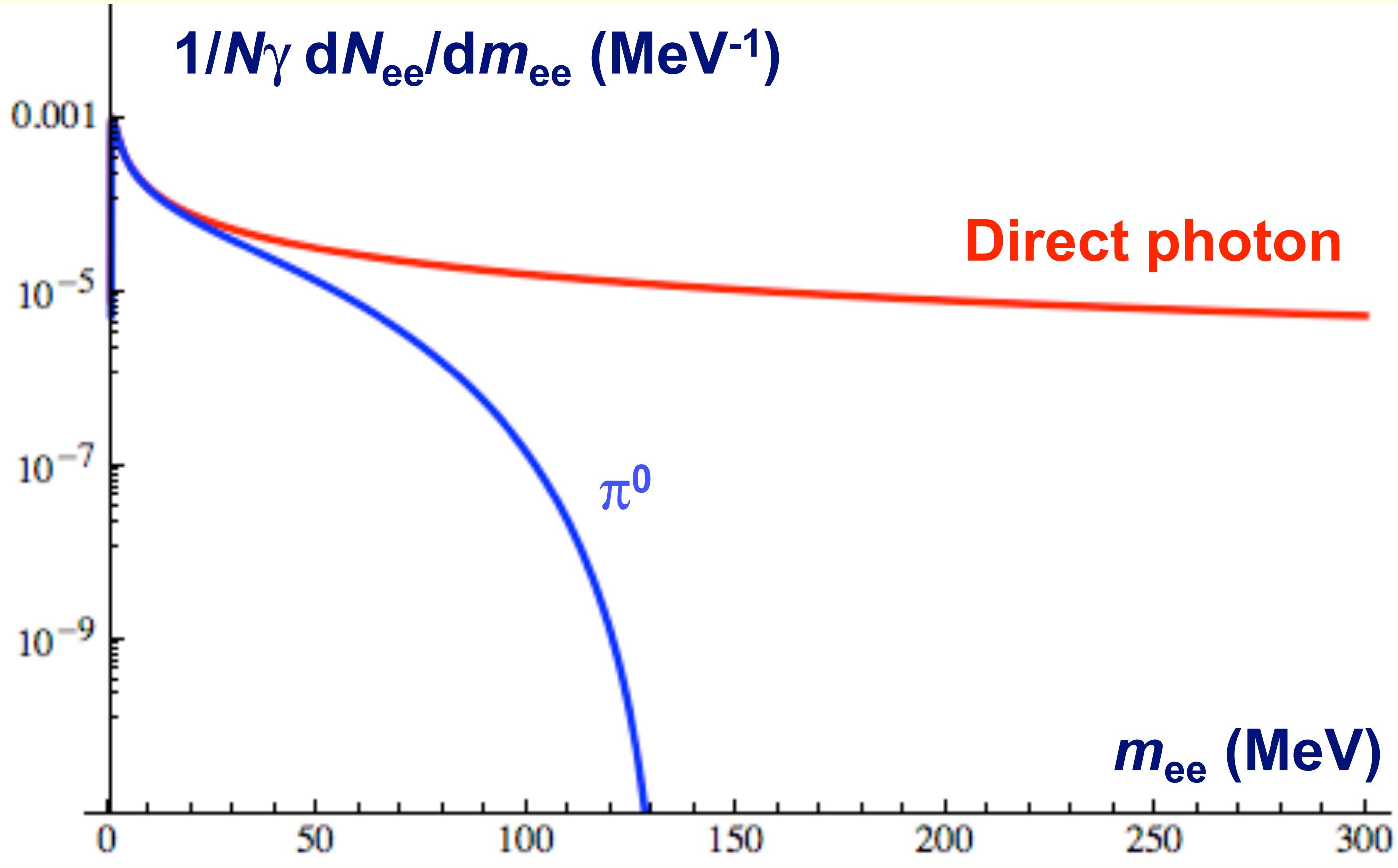
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

Hadron decay:

$$S = |\underbrace{F(m_{ee}^2)}_{\text{form factor}}|^2\left(1-\frac{m_{ee}^2}{M_h^2}\right)^3$$

Point-like process:

$$S \approx 1$$
$$(\text{for } p_T^{ee} \gg m_{ee})$$



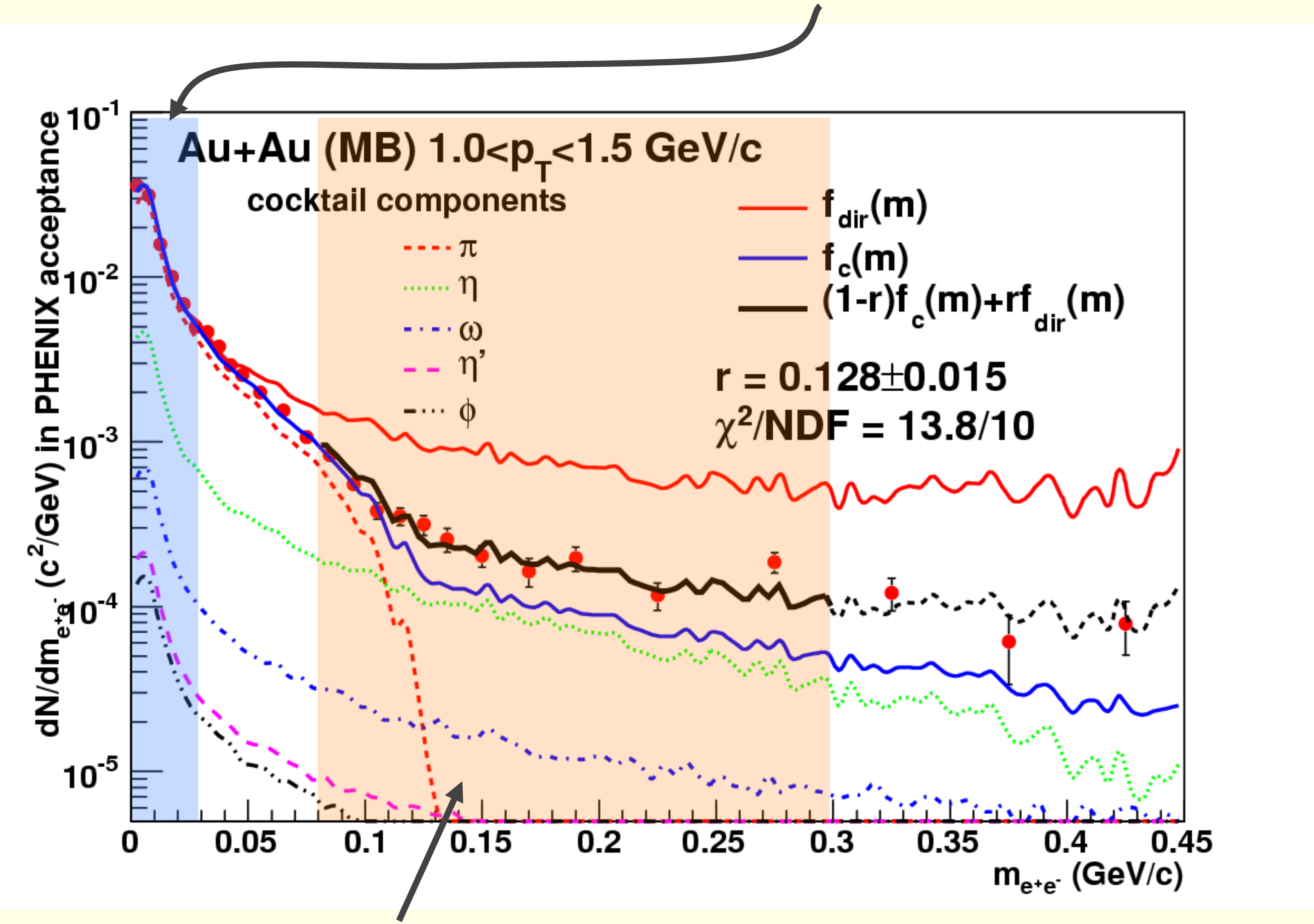
About 0.001 virtual photons with $m_{ee} > M_{\text{pion}}$ for every real photon

→ Avoid the π^0 background at the expense of a factor 1000 in statistics

Extraction of the Direct Photon Signal: Two-Component Fit

$$f(m_{ee}) = (1-r) \cdot f_{\mathrm{cocktail}}(m_{ee}) + r \cdot f_{\mathrm{direct}}(m_{ee})$$

Separately normalized to data at m_{ee} < 30 MeV



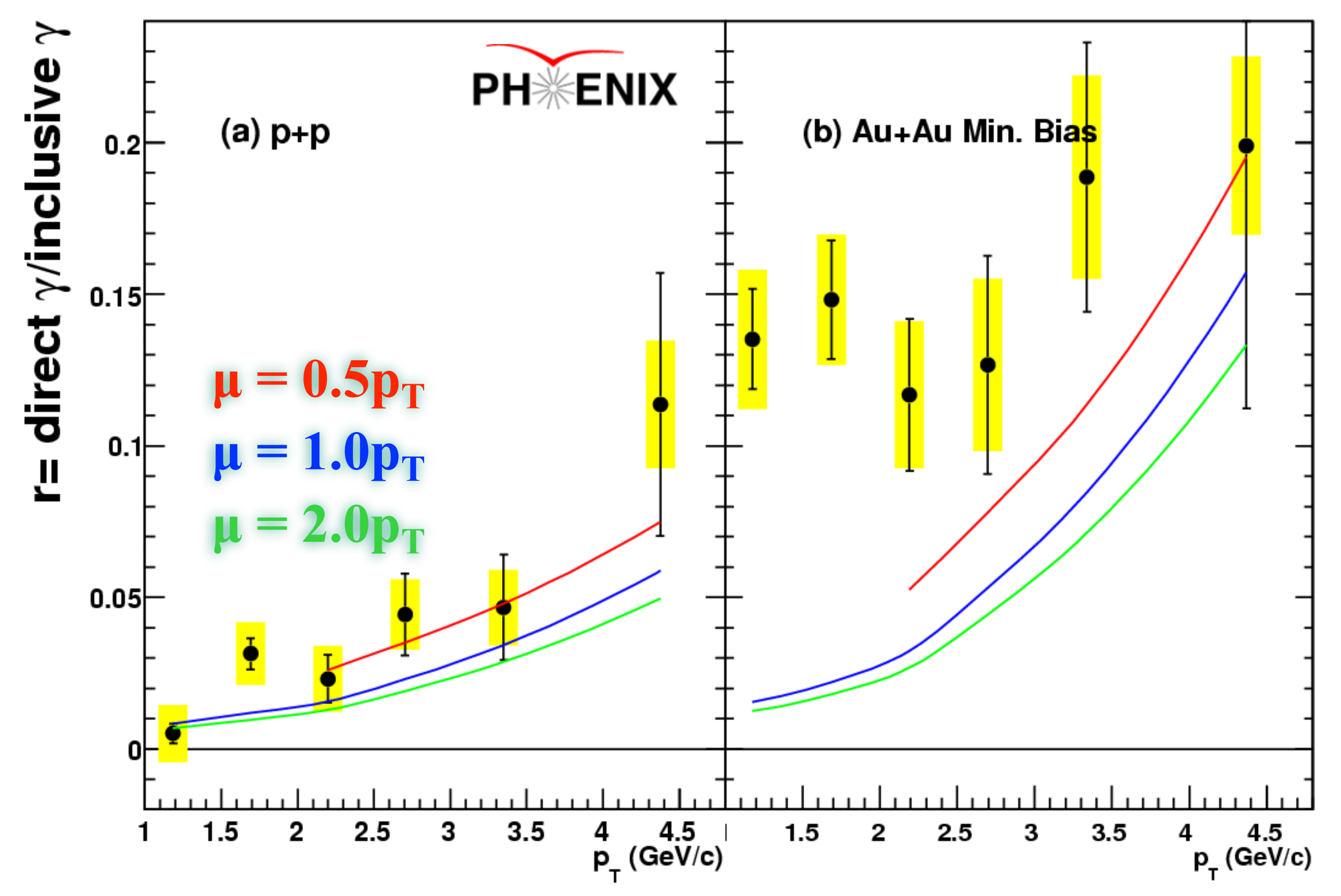
Fit range: 80 < m_{ee} < 300 MeV

- Interpret deviation from hadronic cocktail (π, η, ω, η', ϕ) as signal from virtual direct photons
- Extract fraction *r* with two-component fit

$$r = \left. \frac{\gamma^*_{\mathrm{direct}}}{\gamma^*_{\mathrm{inclusive}}} \right|_{m_{ee} < 30\,\mathrm{MeV}}$$

- Fit yields good χ^2/NDF (13.8 / 10)

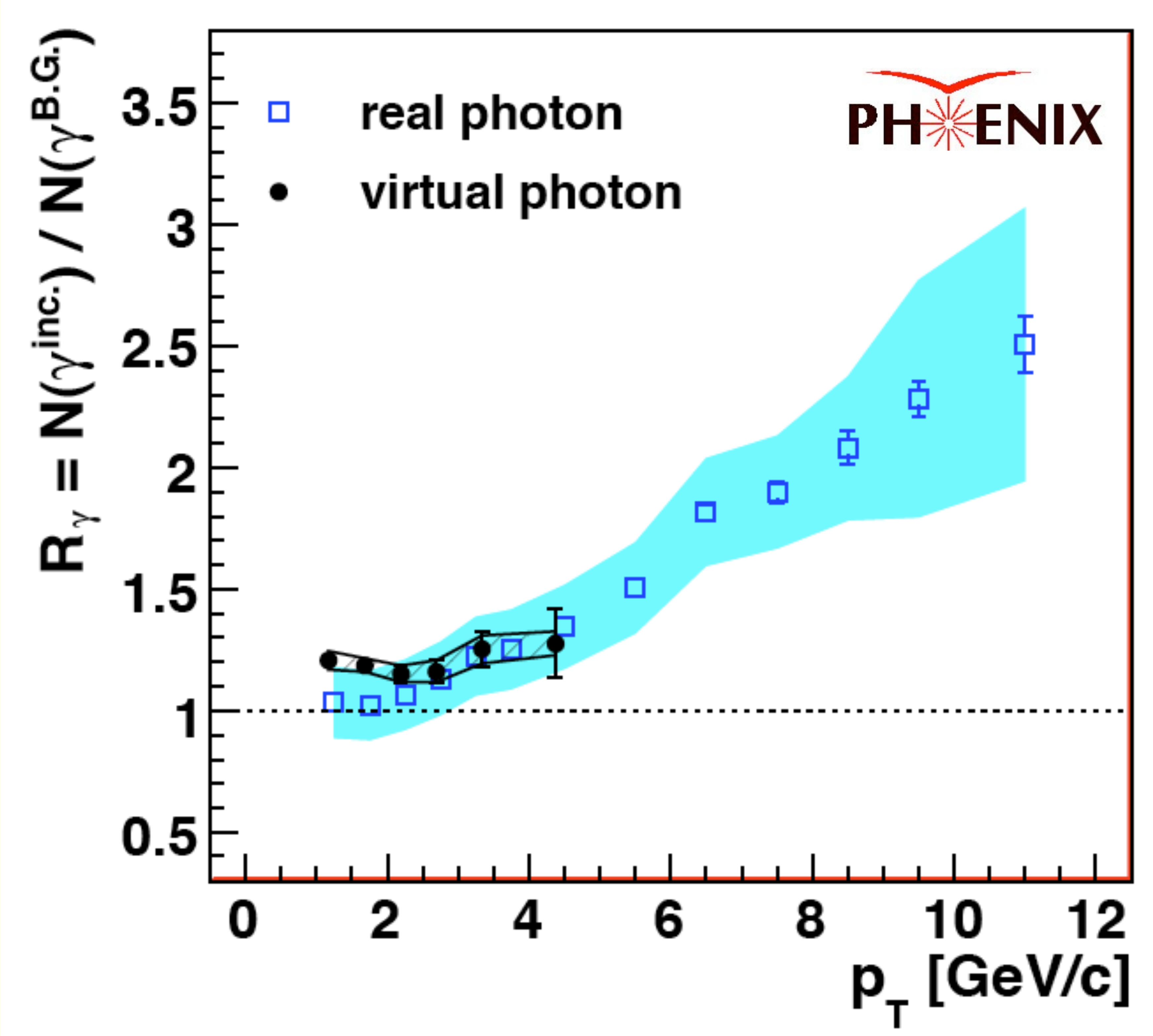
Direct Photon Fraction in p+p and Au+Au at $\sqrt{s_{NN}} = 200$ GeV



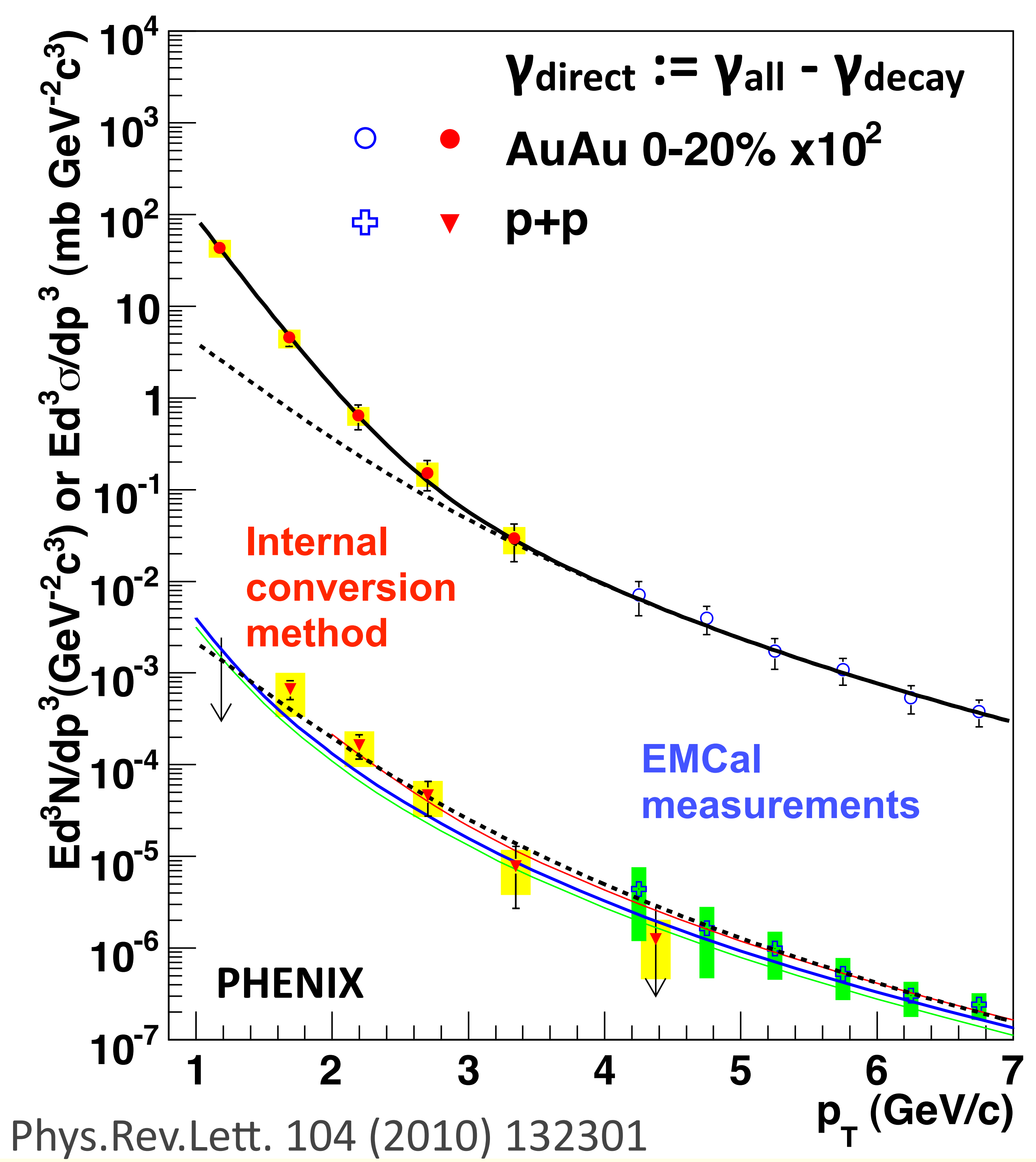
PHENIX, Phys.Rev.Lett. 104 (2010) 132301, (arXiv:0804.4168)

- Lowest p_T ever measured in p+p
- Comparison to NLO pQCD (colored lines)
- p+p: Agreement
- Au+Au:
  Strong enhancement
  at low p_T

Comparison Between the Internal Conversion Method and the Calorimeter Measurement



Low p_T Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP



Phys.Rev.Lett. 104 (2010) 132301

- p+p: spectrum described with

$$f_{p+p}(p_T) = A \cdot (1 + p_T^2 / b)^{-n}$$

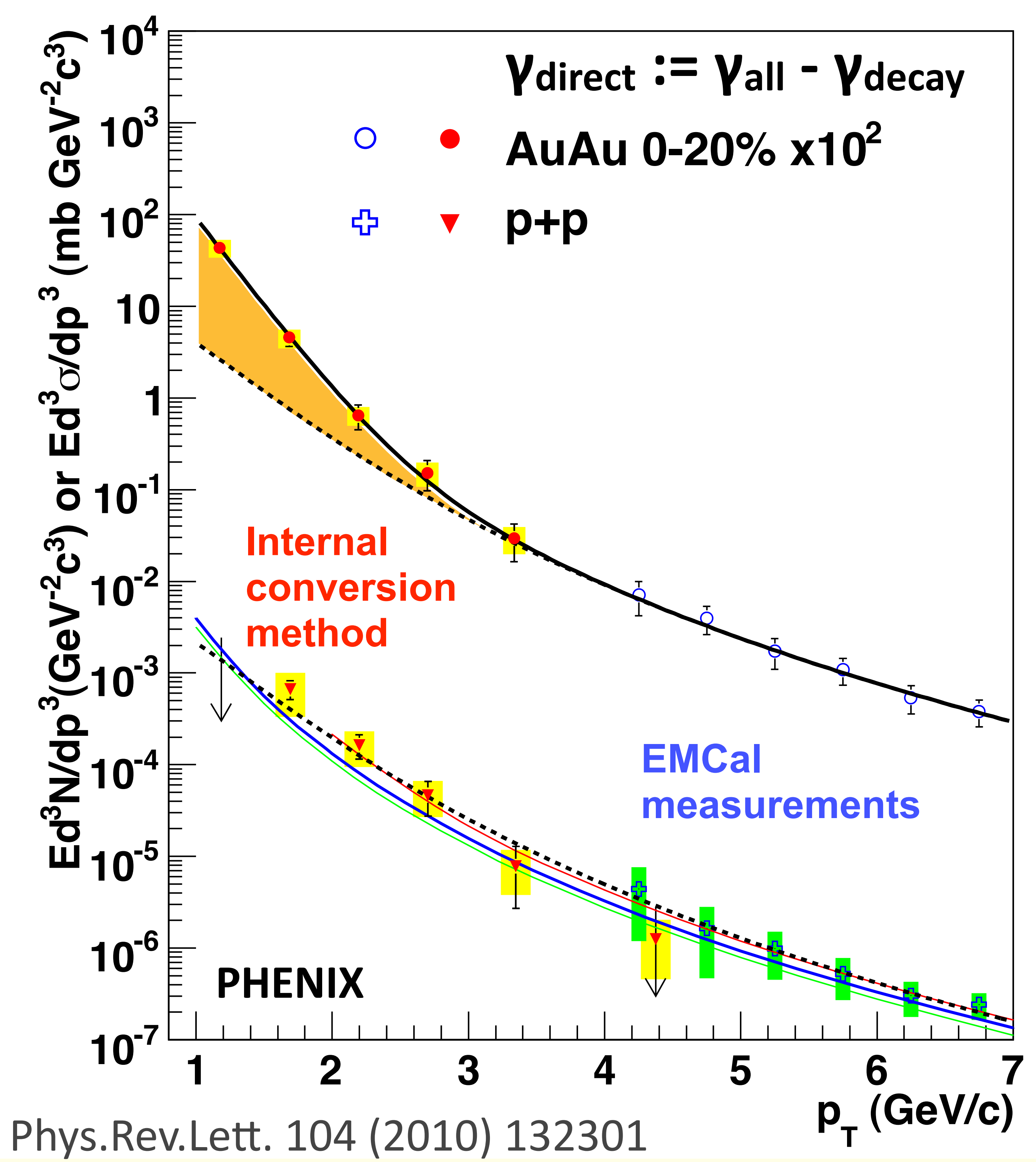
- Au+Au:
Enhancement above p+p described by an exponential (as expected for a thermal source)

$$f_{Au+Au}(p_T) = \frac{N_{\text{coll}}}{\sigma_{\text{NN}}^{\text{inel}}} \times f_{p+p}(p_T) + B \times e^{-\frac{p_T}{T}}$$

- Slope parameter (0-20%):
$T = (221 \pm 23 \pm 18)$ MeV

Expected to be a lower limit for the initial temperature!

Low p_T Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP



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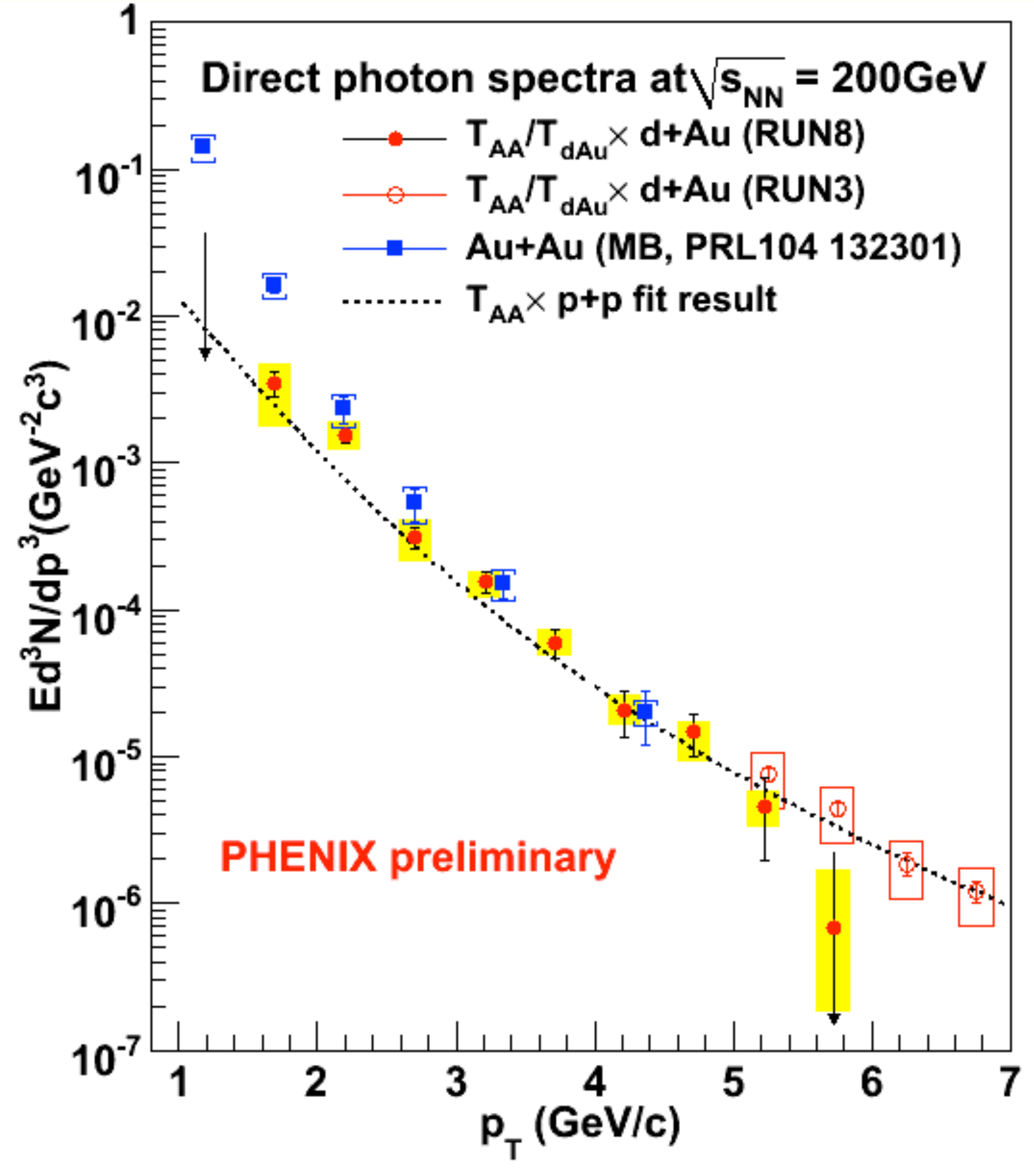
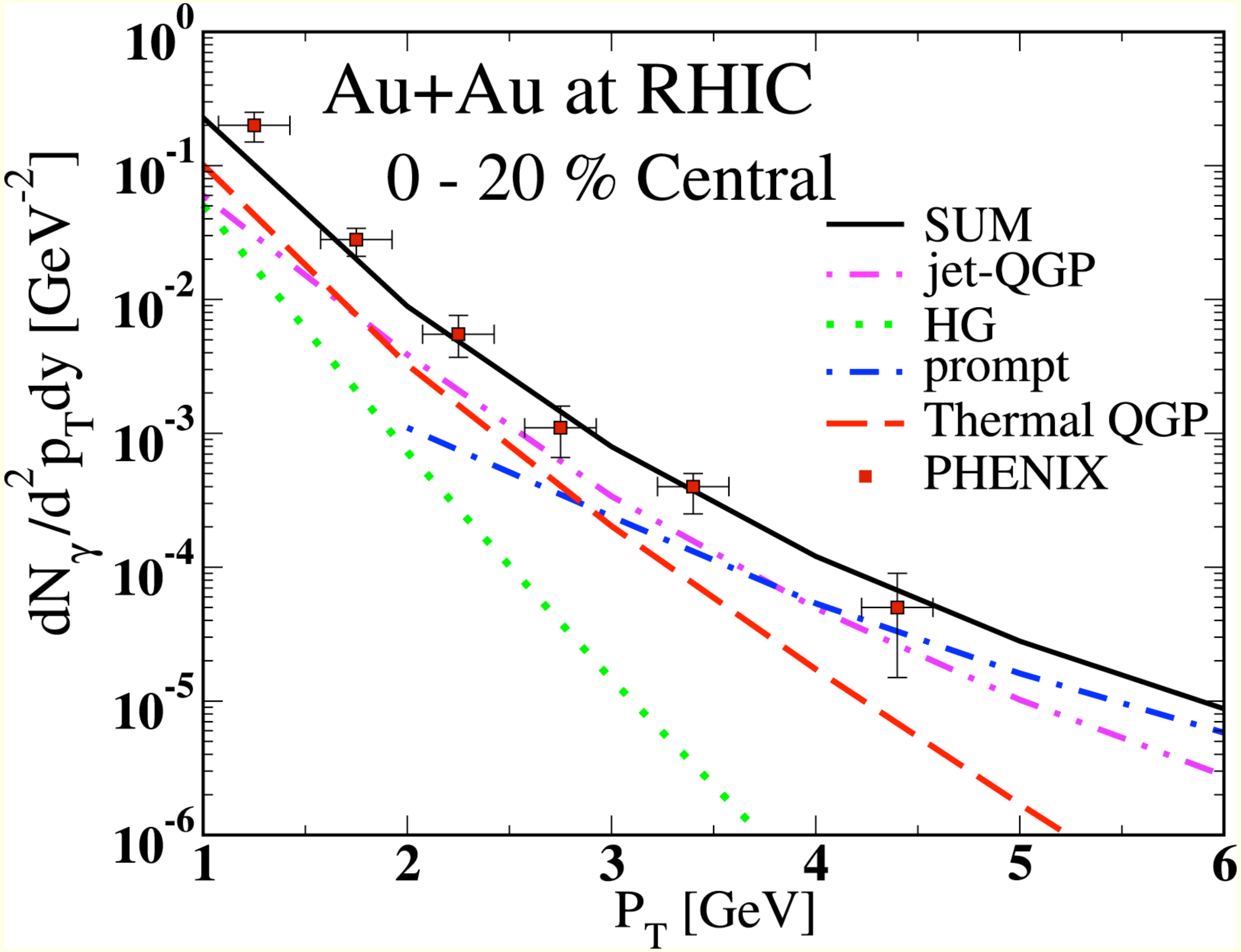
Critical d+Au Check: No exponential excess in d+Au



Model Comparison

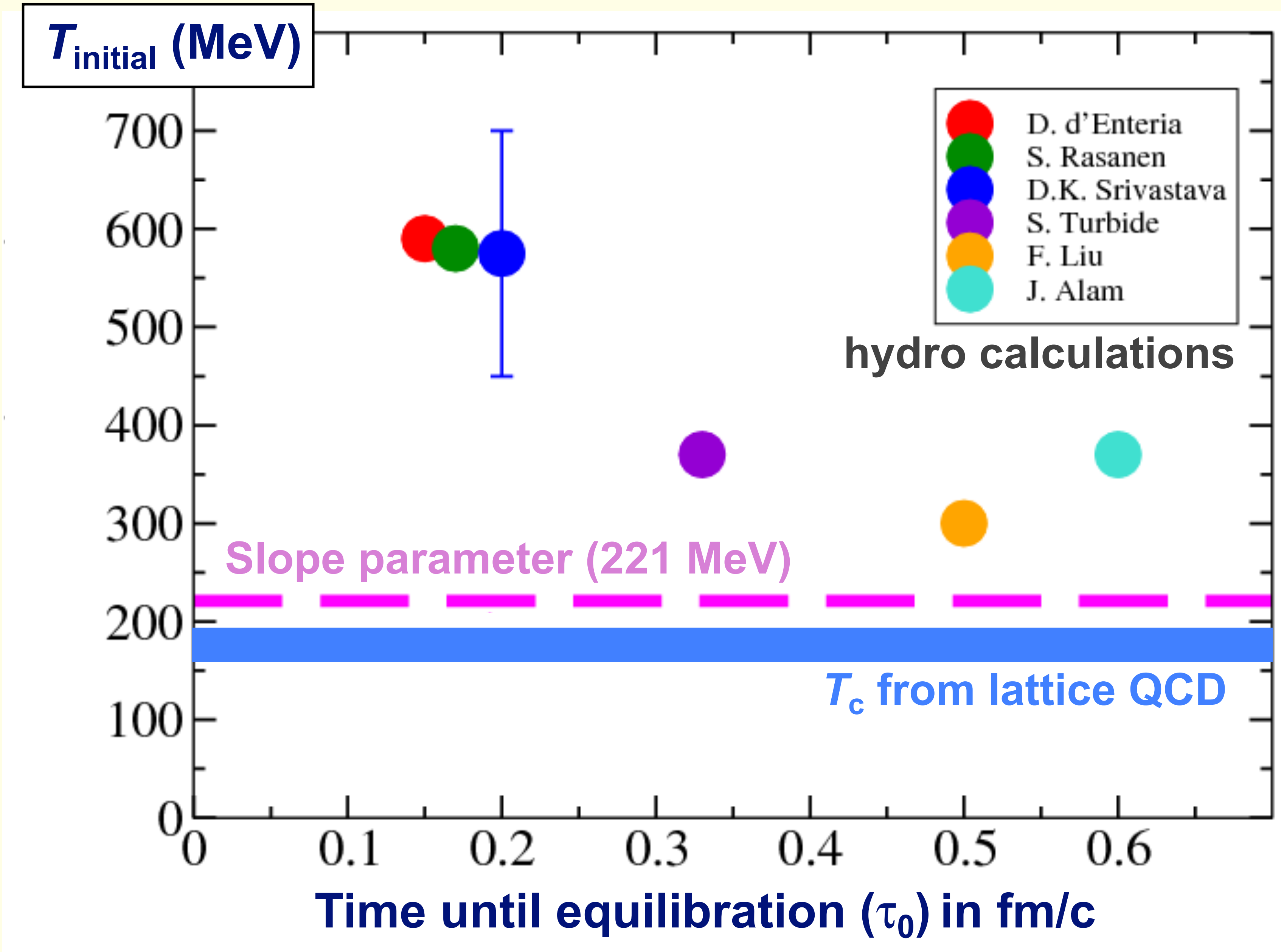


C. Gale, arXiv:0904.2184v1

- Model space-time evolution with ideal hydro
- This calculation (arXiv:0904.2184v1)
  - Hydro starts early (τ_0 = 0.2 fm/*c*) to take pre-equilibrium photons into account
  - Thermal equilibrium expected at τ_0 = 0.6 fm/*c* (T_initial = 340 MeV)
  - Photons from jet-plasma interaction needed
- $T_\text{initial} > T_c \approx$ 170 - 190 MeV → evidence for the formation of a quark-gluon plasma

Similar conclusions for essentially all hydro models on the market

PHENIX Low p_T Direct Photon Data: Comparison with Different Hydro Models

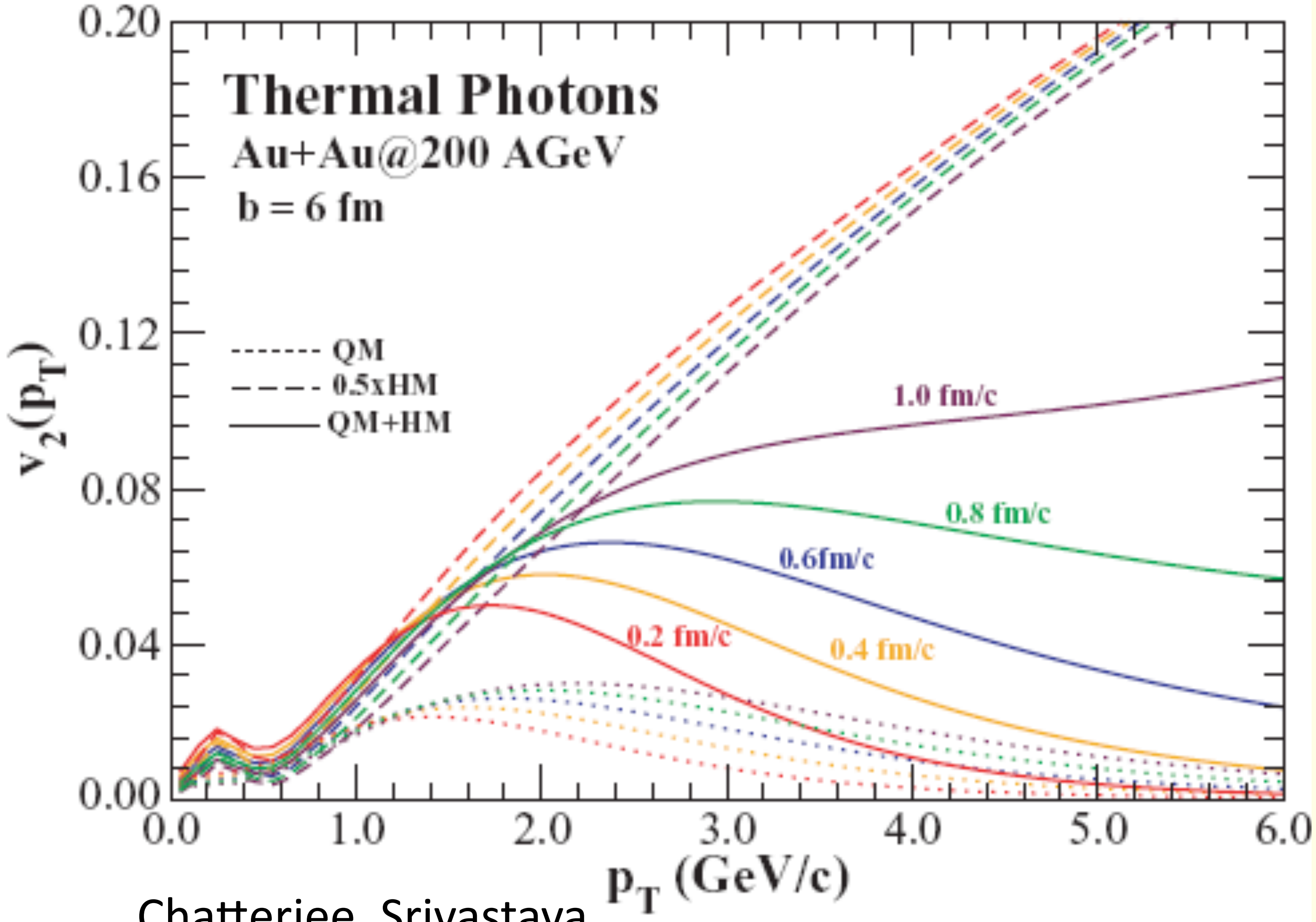


Initial temperature above T_c in all models

Direct Photon Flow

Direct photon v_2 further constrains T_i

Hydro after τ_0



Chatterjee, Srivastava
PRC79, 021901 (2009)

- expected v_2 :
  - prompt photons: 0 (time zero)
  - thermal photons

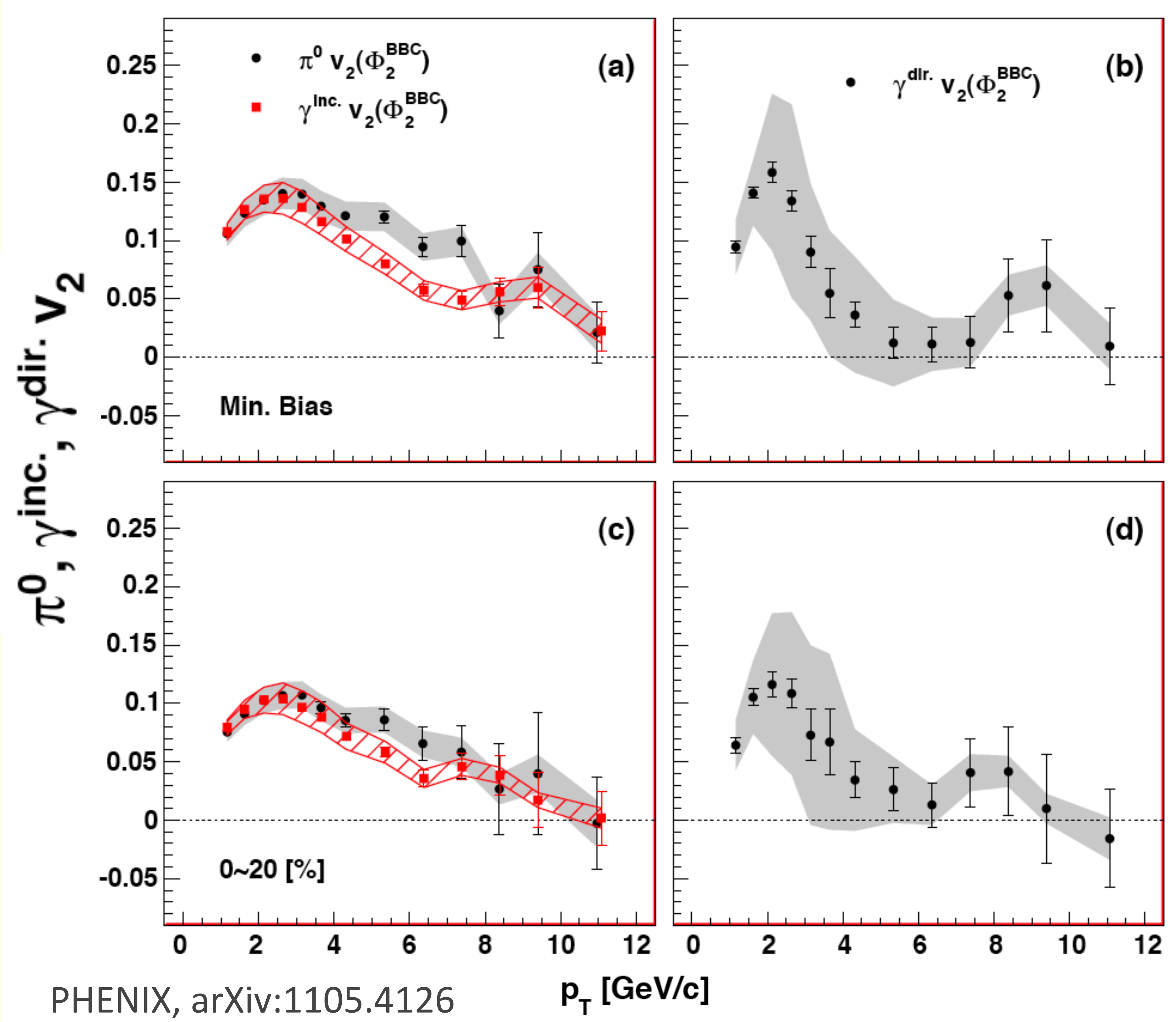
early

late

small
(flow not built up)

large
(like hadrons)

Significant Elliptic Flow of Direct Photons Found in Au+Au at 200 GeV for $p_T < 3$ GeV/c



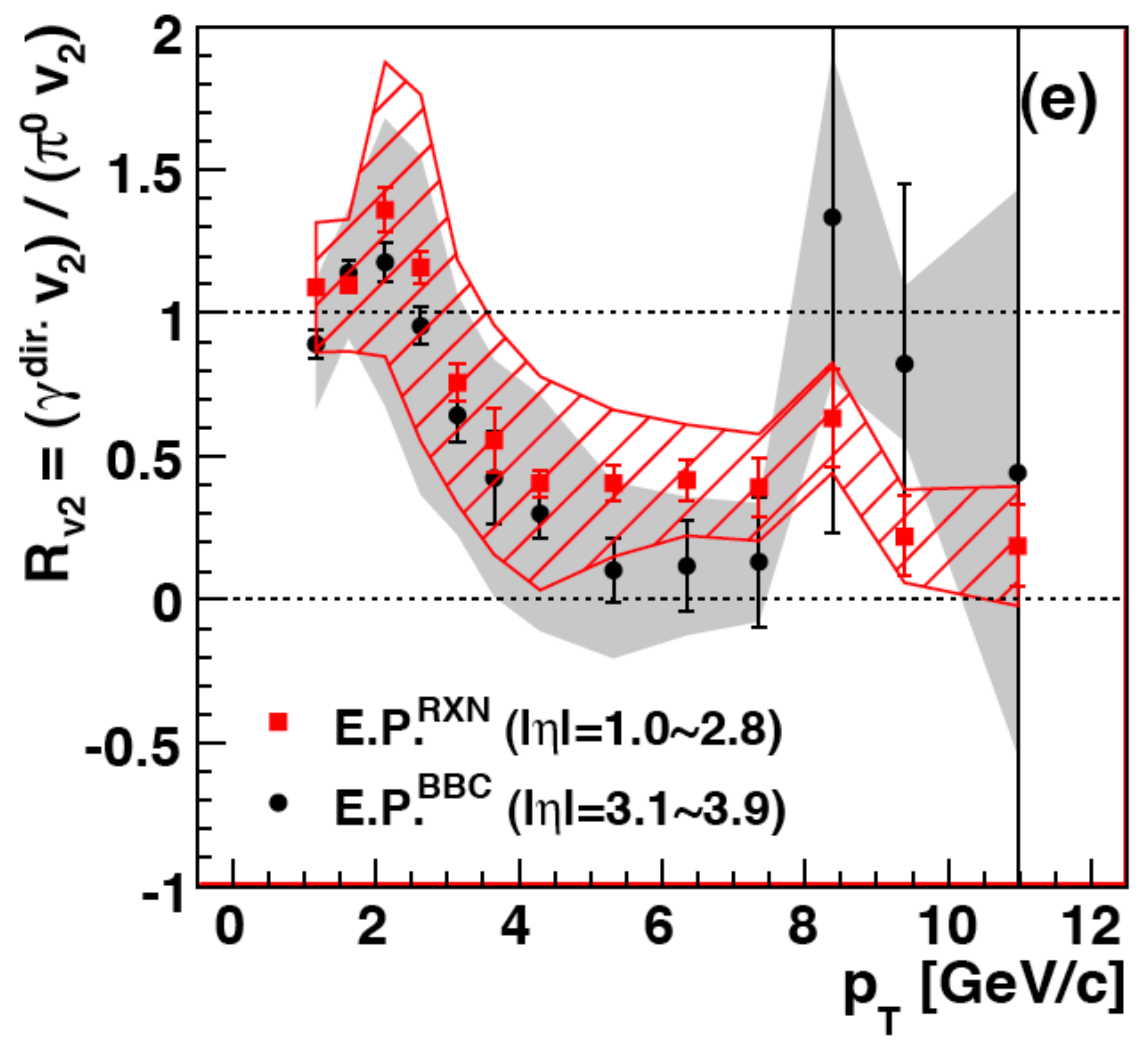
PHENIX, arXiv:1105.4126

$$v_2^{\text{dir}} = \frac{R_\gamma v_2^{\text{inc}} - v_2^{\text{decay}}}{R_\gamma - 1}$$

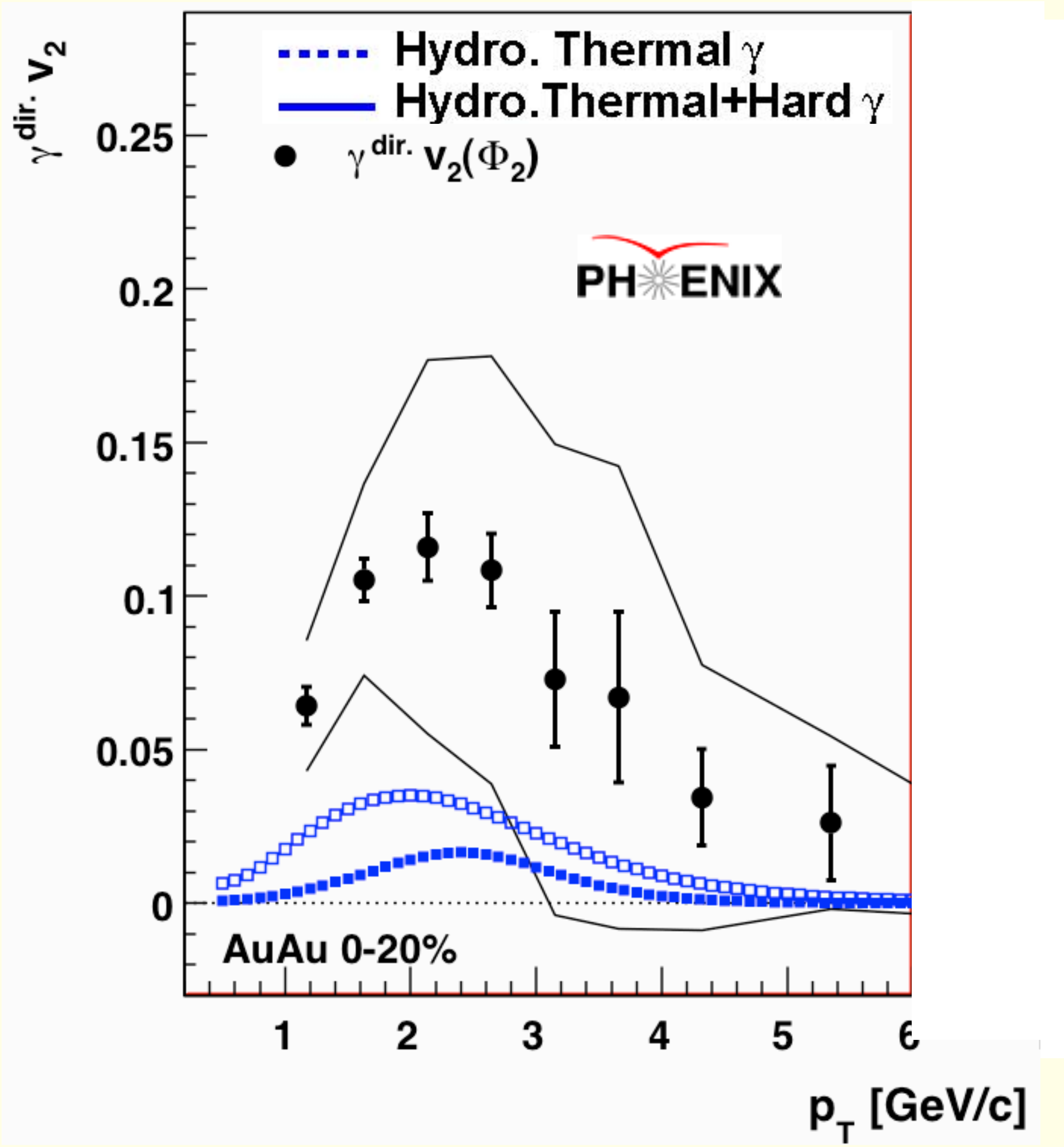
$$R_\gamma = \frac{\gamma^{\text{inc}}}{\gamma^{\text{decay}}}$$

v_2^{inc} from calorimeter measurement

Direct Photon v_2 at p_T = 2 GeV/c as larger as for Pions

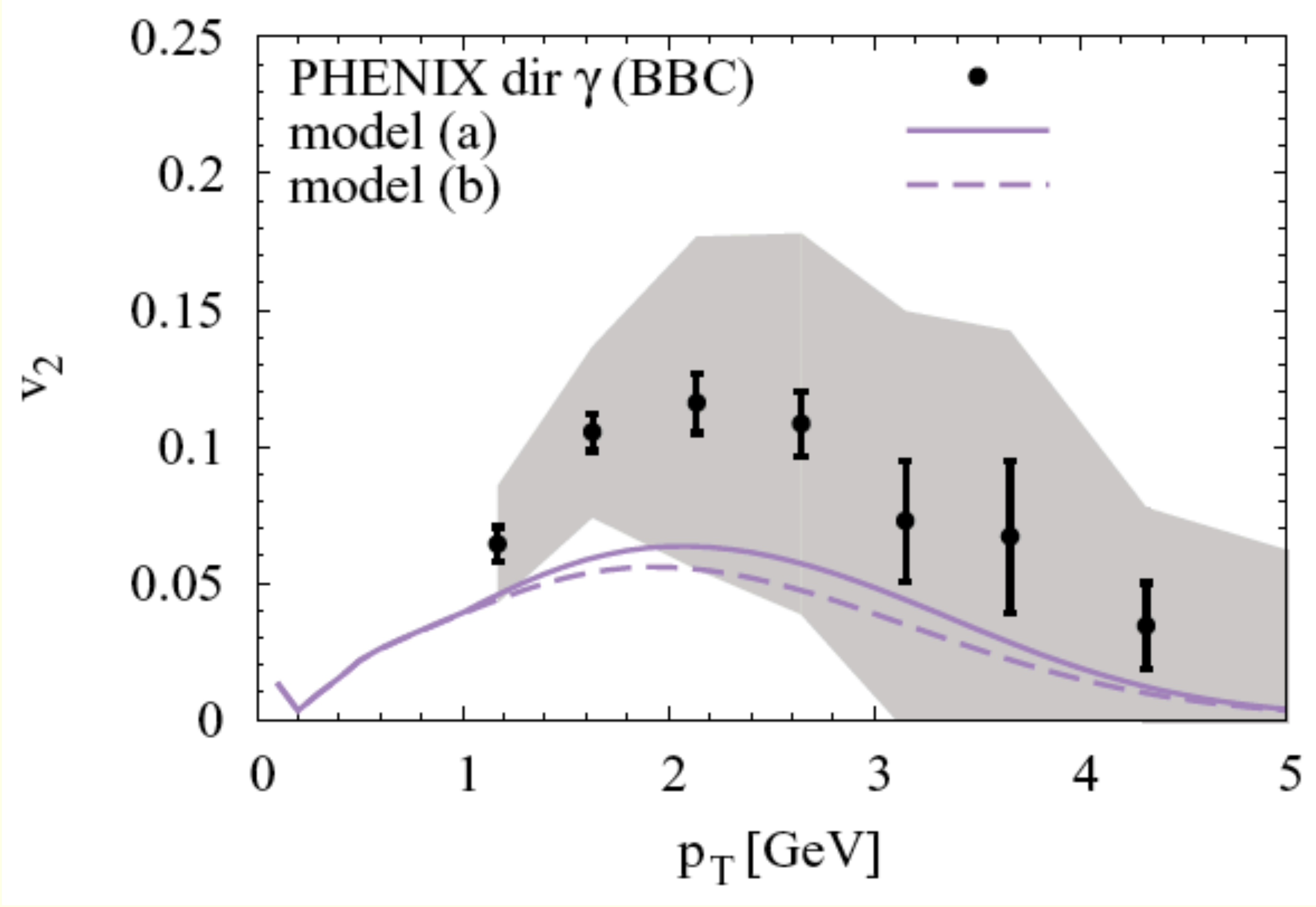


Theory Comparison: A Big Puzzle (!?)



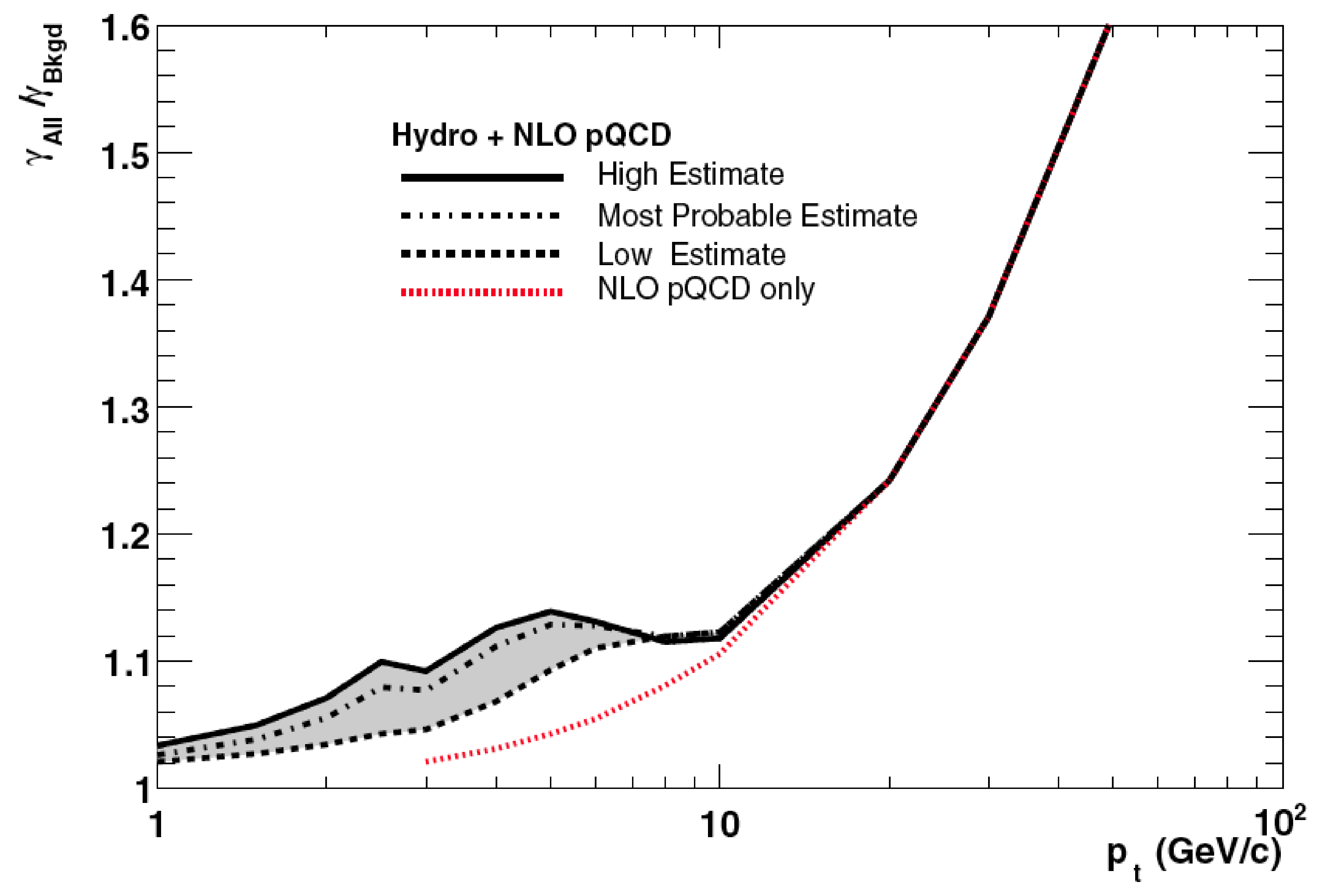
Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

Hendrik van Hees, Charles Gale, Ralf Rapp,
Phys.Rev. C84 (2011) 054906



Slope of low p_T direct photons spectrum points to early emission, v_2 suggests late emission from mixed/hadronic phase

Expected Thermal Photon Signal (from ALICE Physics Performance Report II)



Stay tuned for low p_T direct-photon data from the LHC!

Extra Slides

Direct Photons in A+A collisions – Why?

Photons escape the medium unscathed

$\Rightarrow$

High p_T photons

- test hard scattering predictions
- measure rate of hard processes

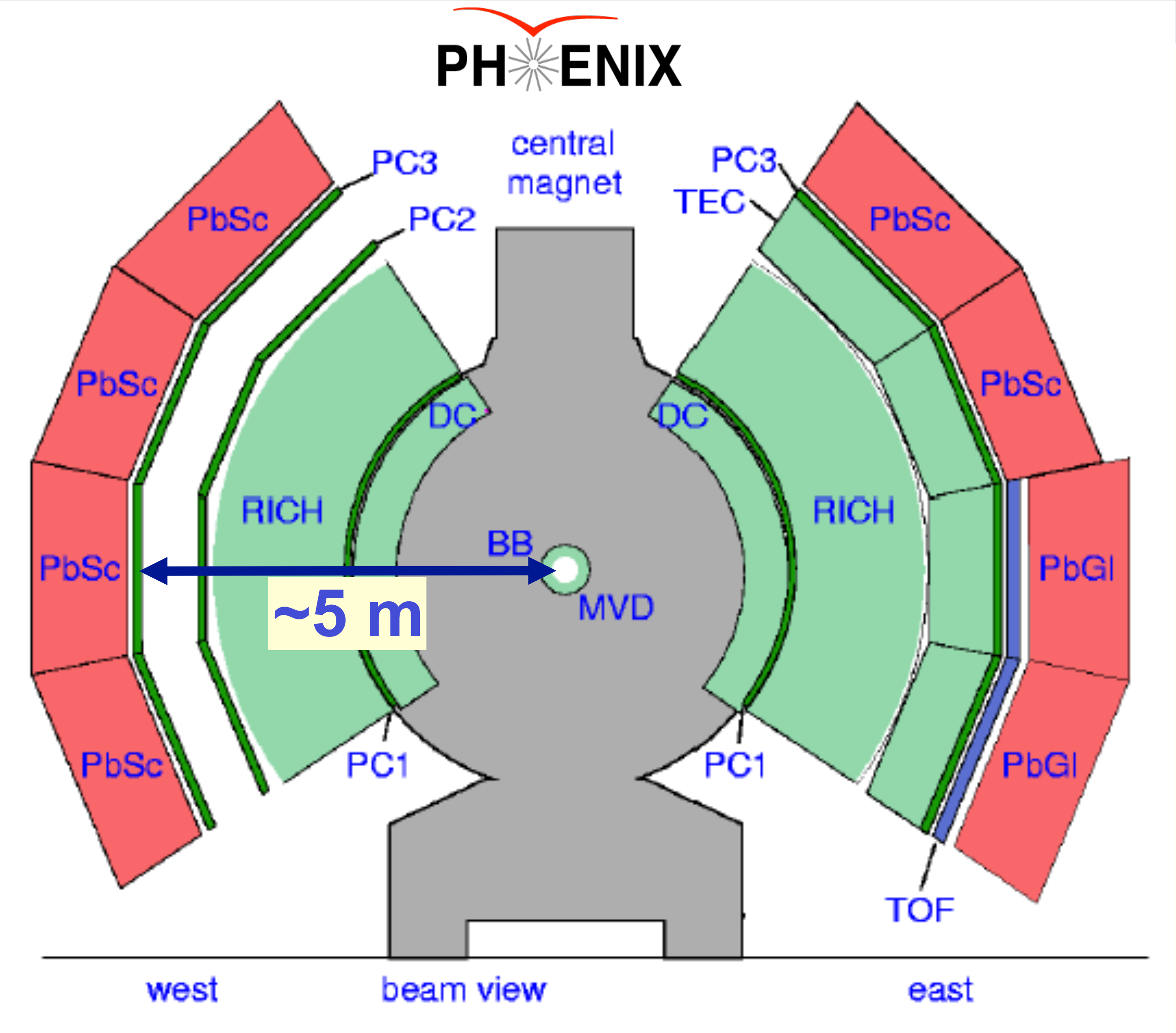
Control Measurement

Low p_T photons

- reflect the initial temperature of the thermalized fireball ($T_i > T_c \Rightarrow$ QGP)
- could indicate jet-plasma interactions

Thermometer

RHIC: Relativistic Heavy Ion Collider



PHENIX:

- **Real photons with electromagnetic calorimeters**
- **Virtual photons ($\gamma^* \to e^+e^-$) with Ring Imaging Cherenkov**

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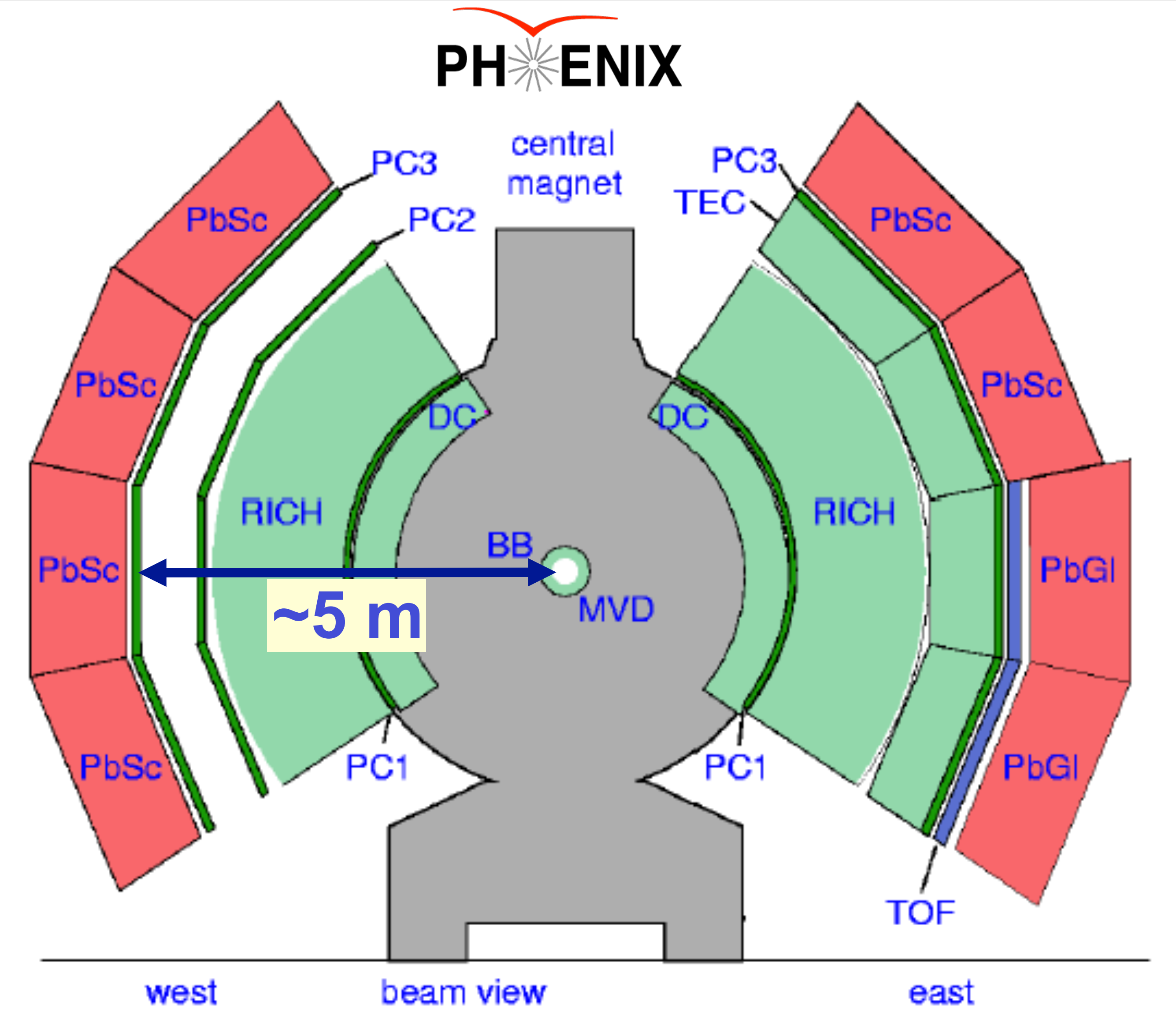

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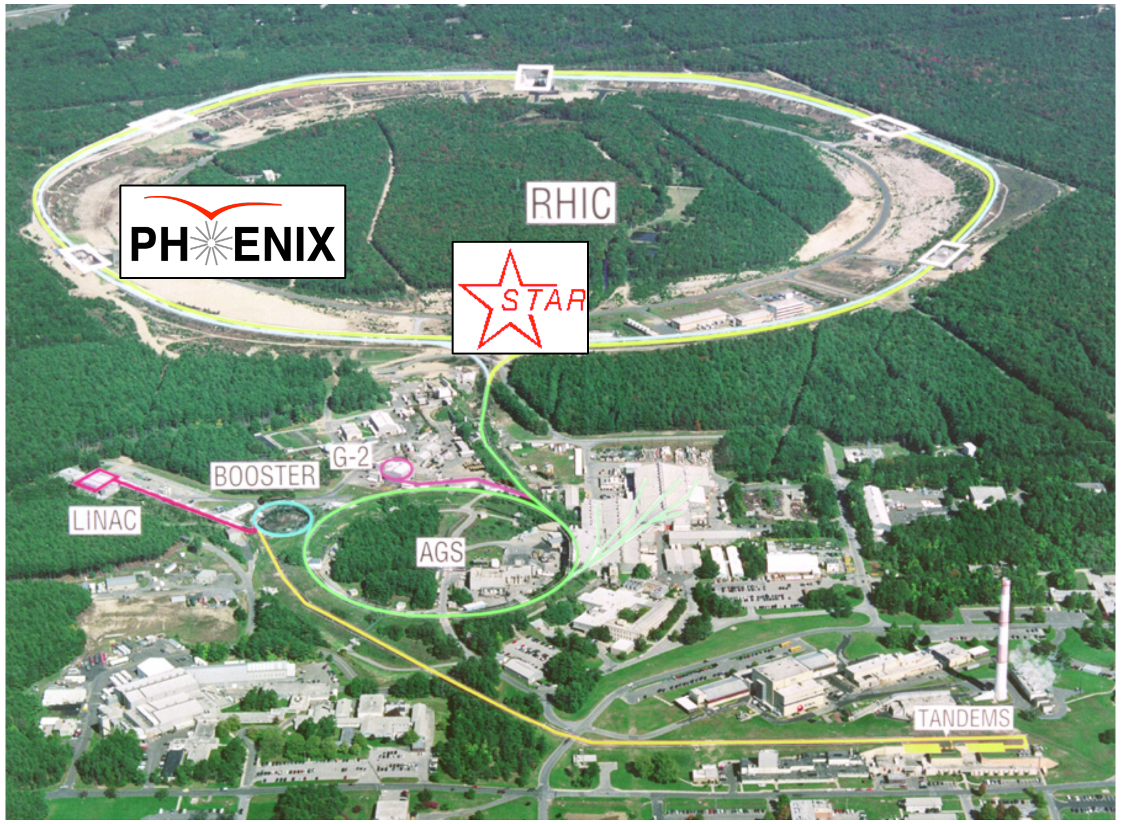

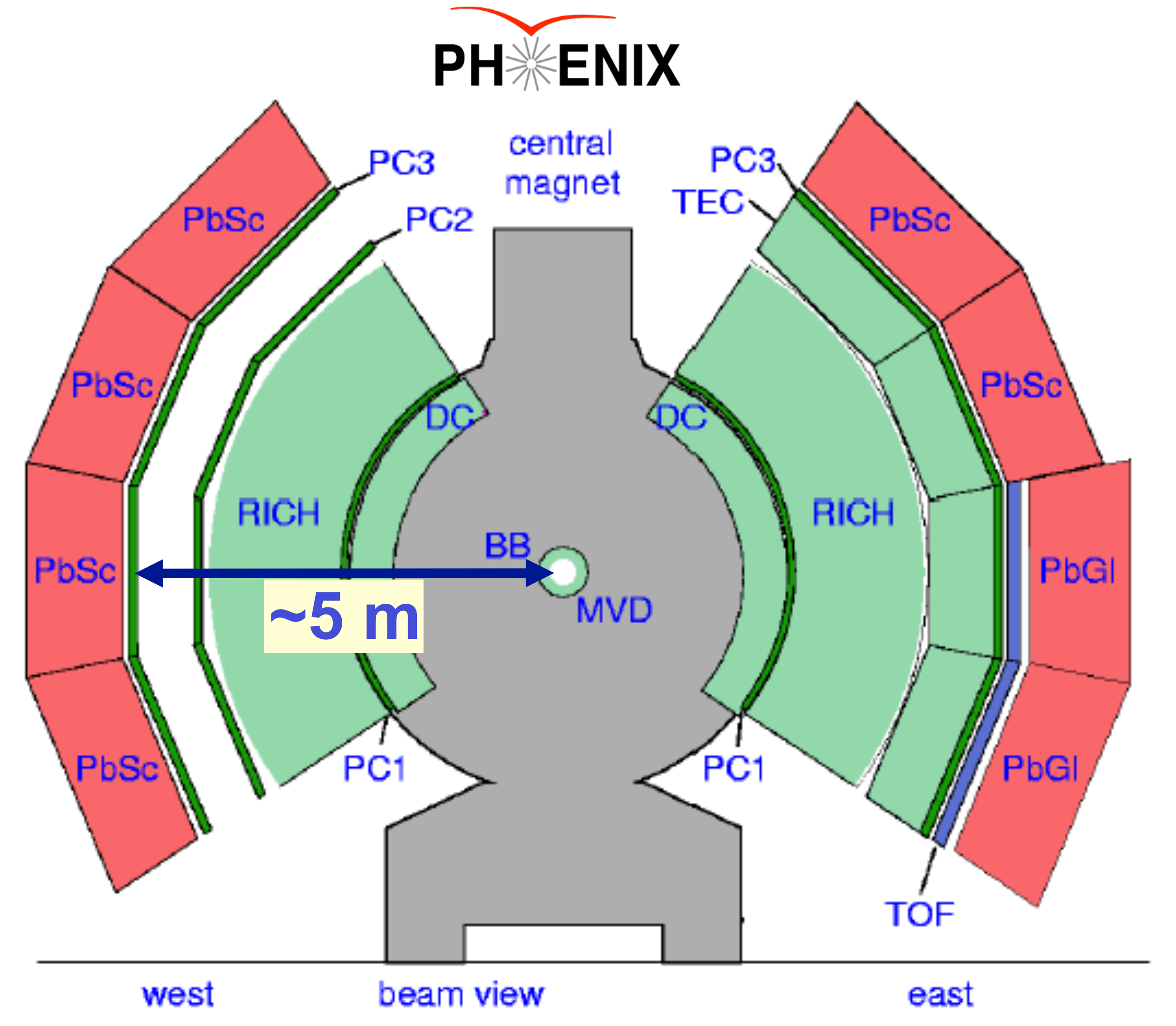

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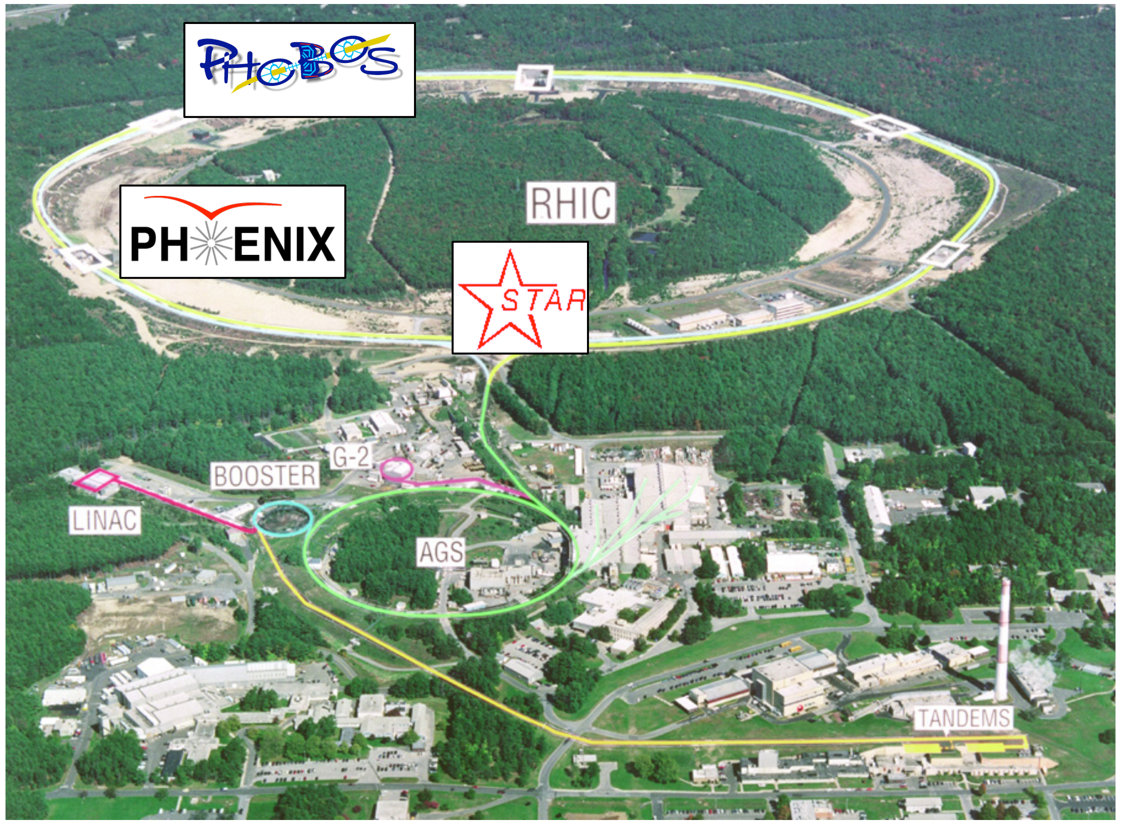

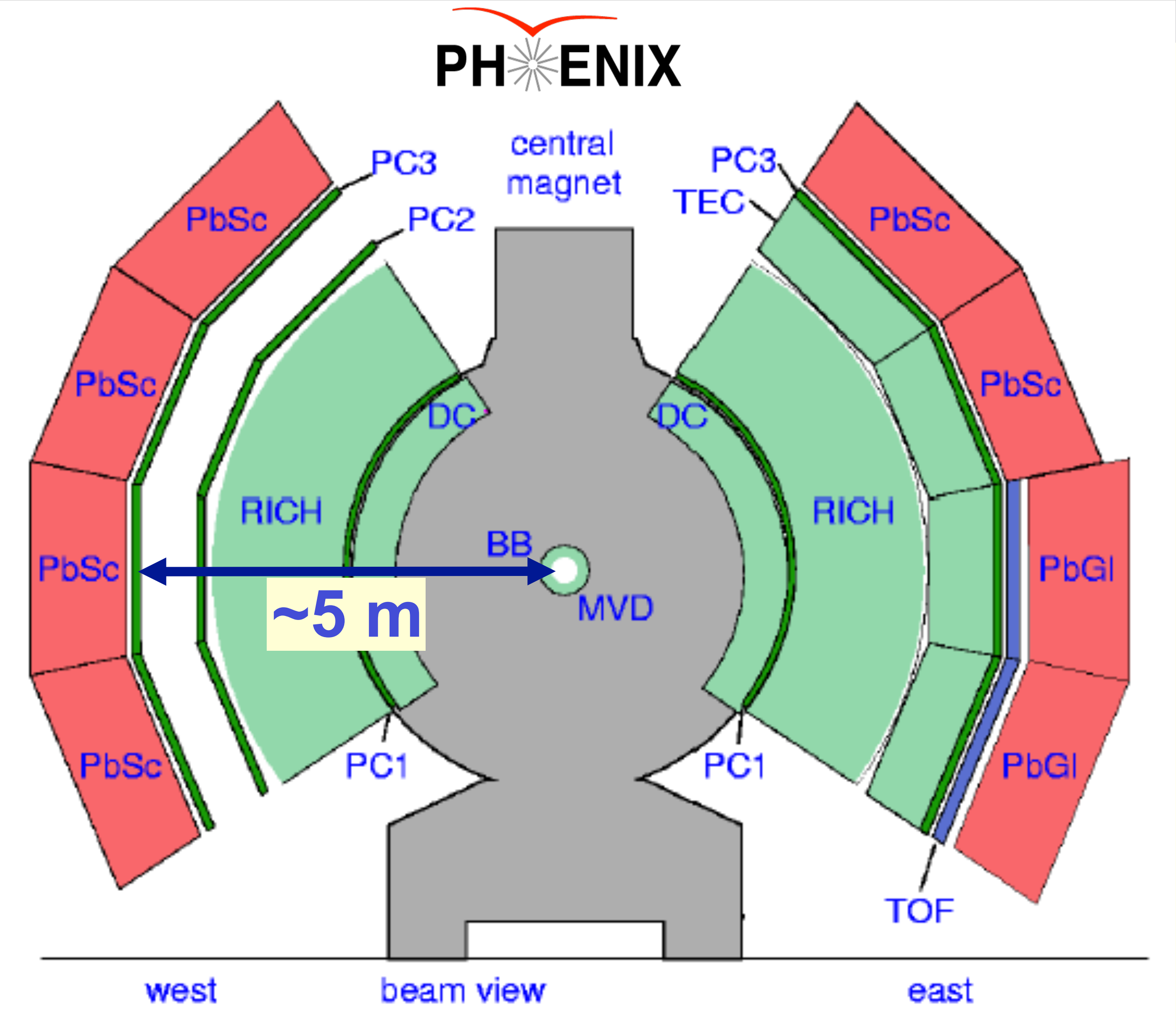

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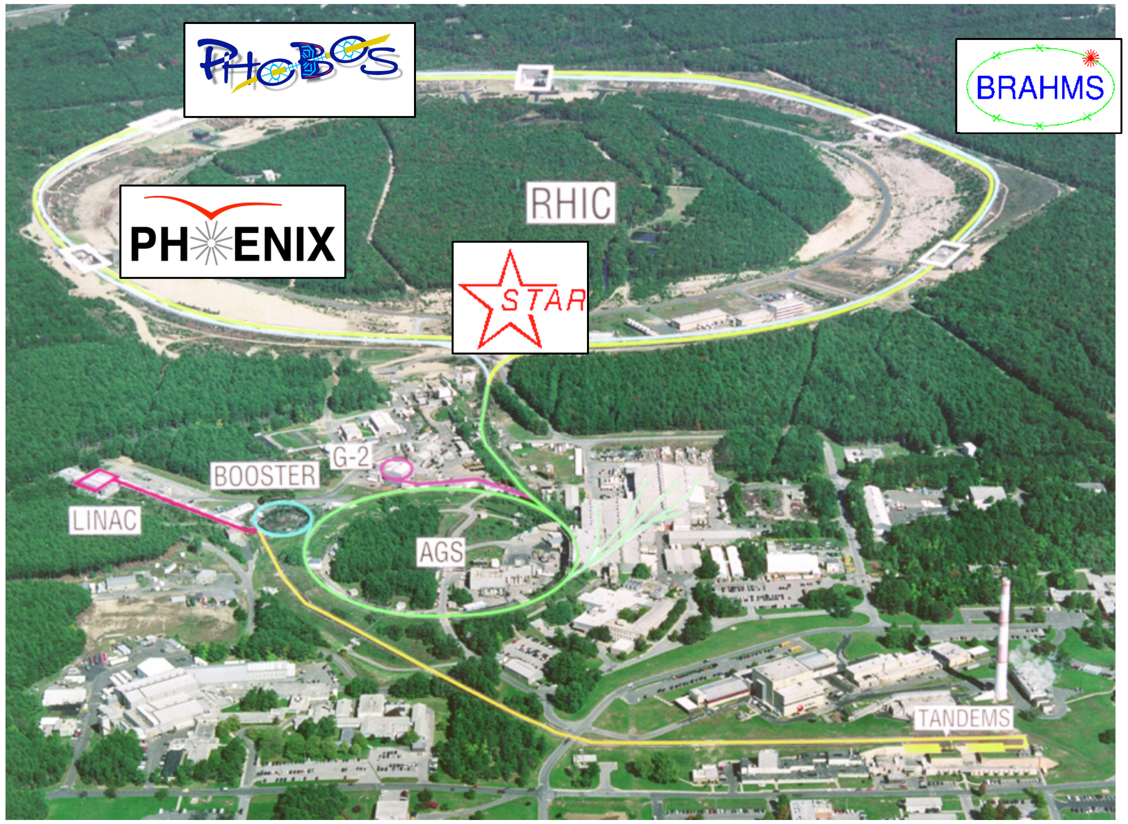

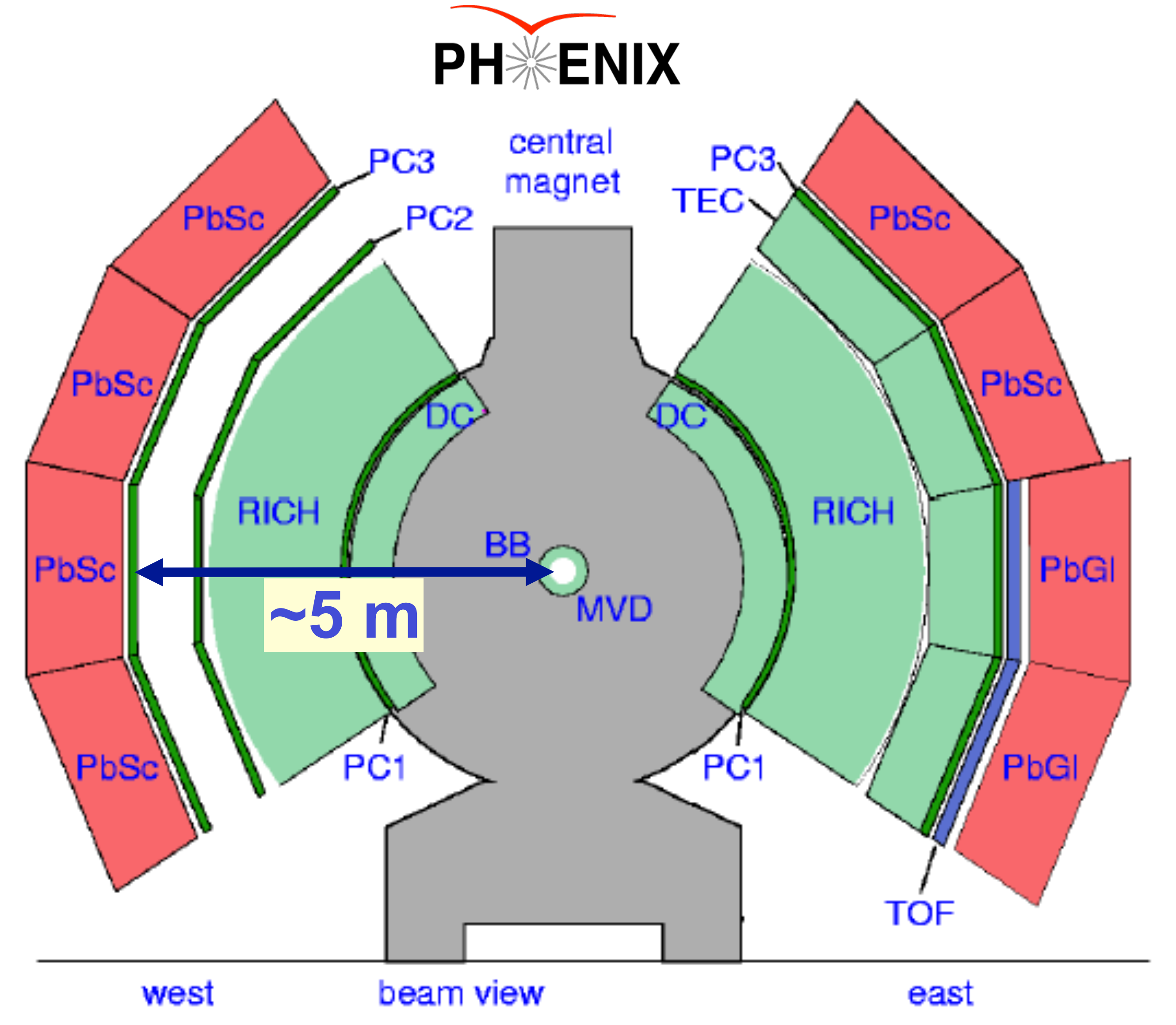

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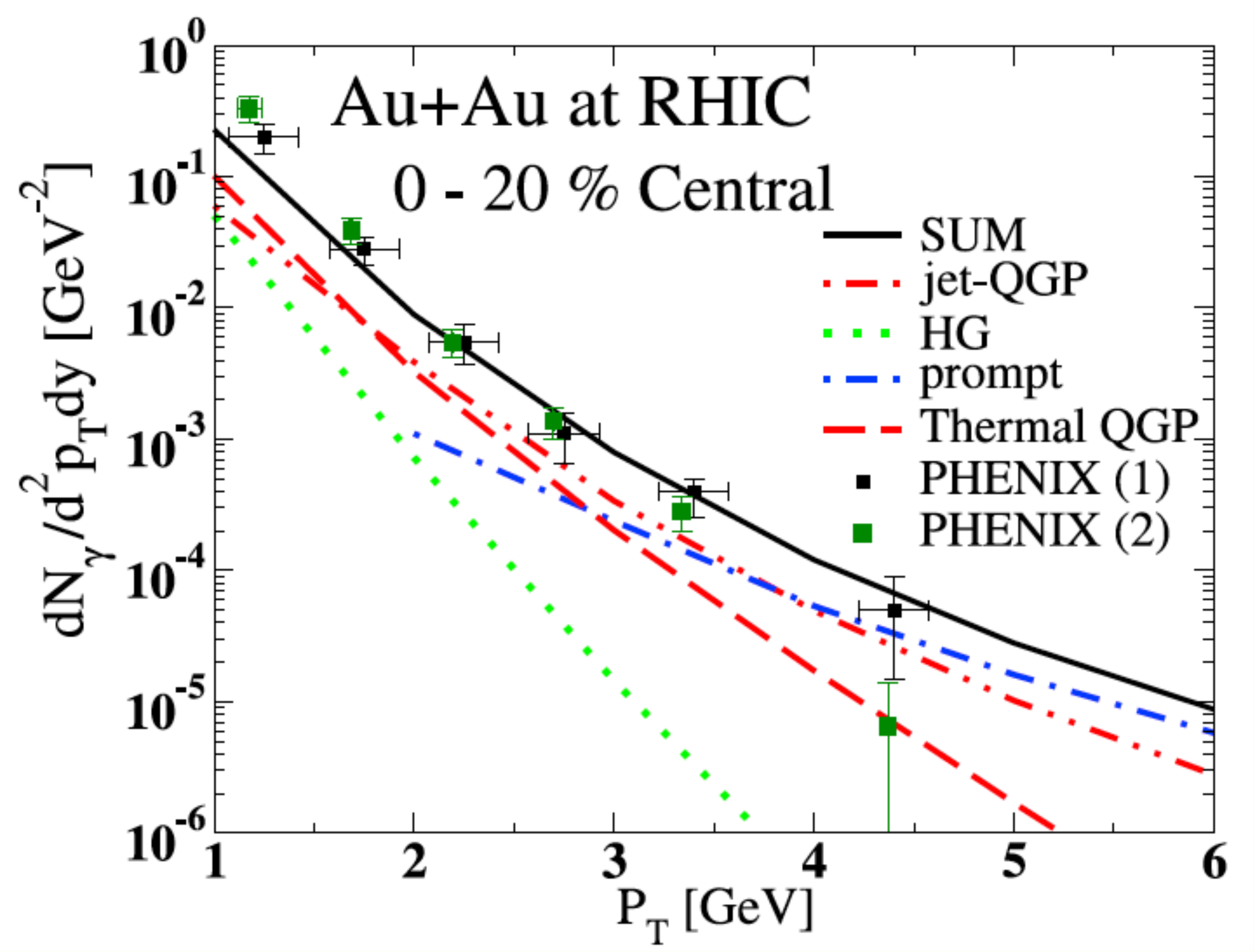
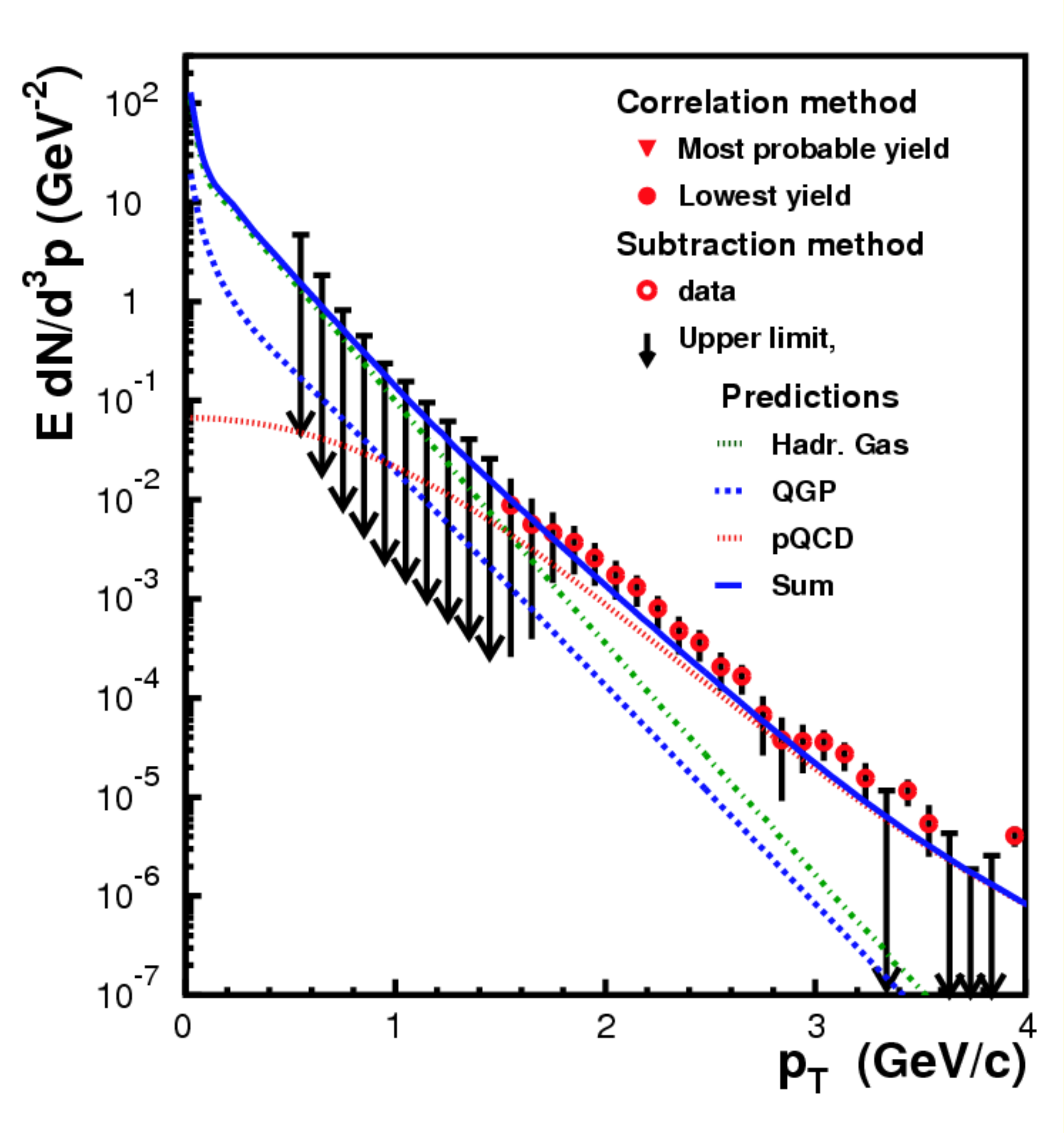

Au+Au at RHIC
0 - 20 % Central
SUM
jet-QGP
HG
prompt
Thermal QGP
PHENIX (1)
PHENIX (2)
$dN_\gamma/d^2p_T dy$ [GeV^{-2}]
P_T [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
2
3
4
5
6

Limitations of the Different Methods



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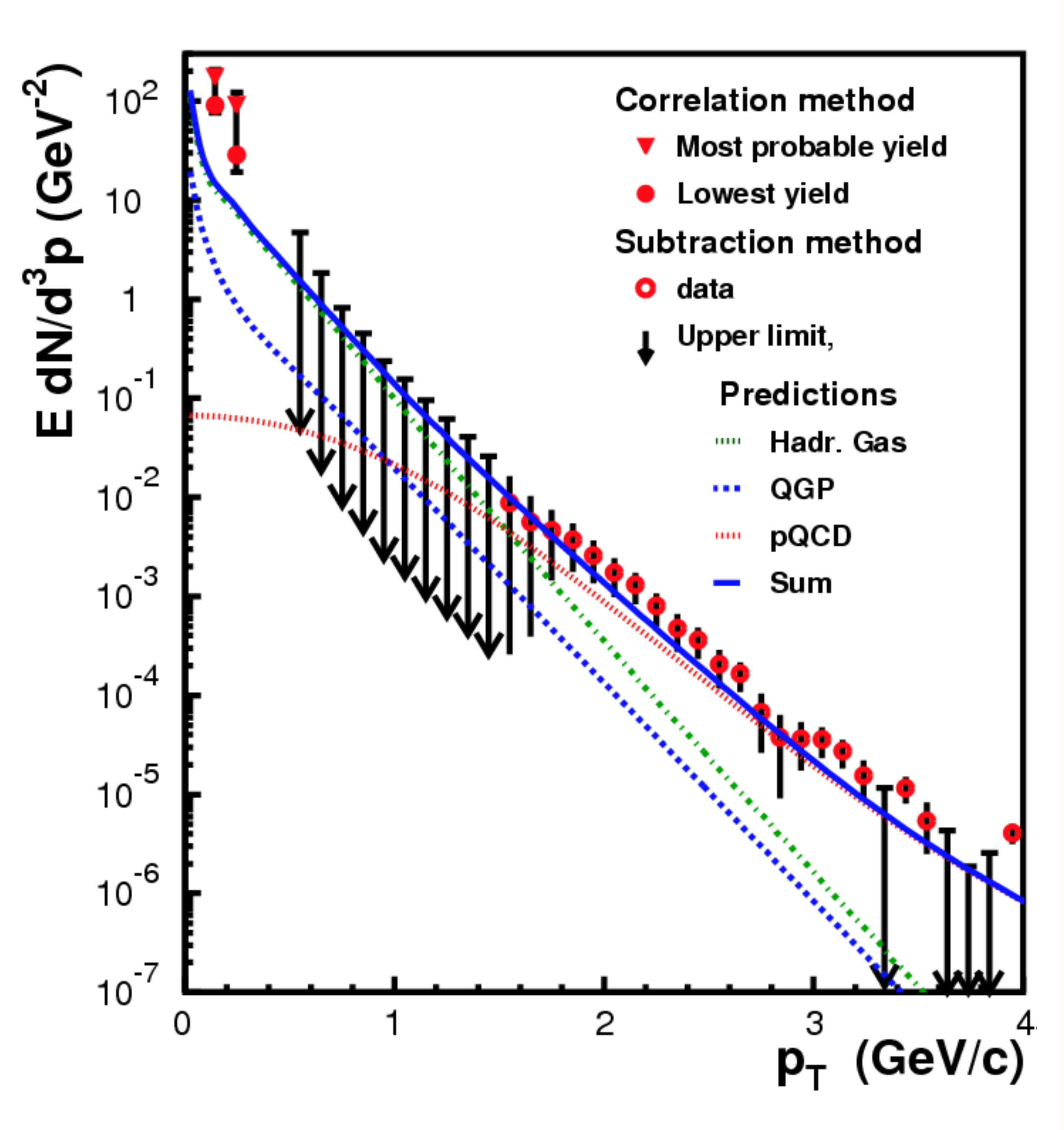

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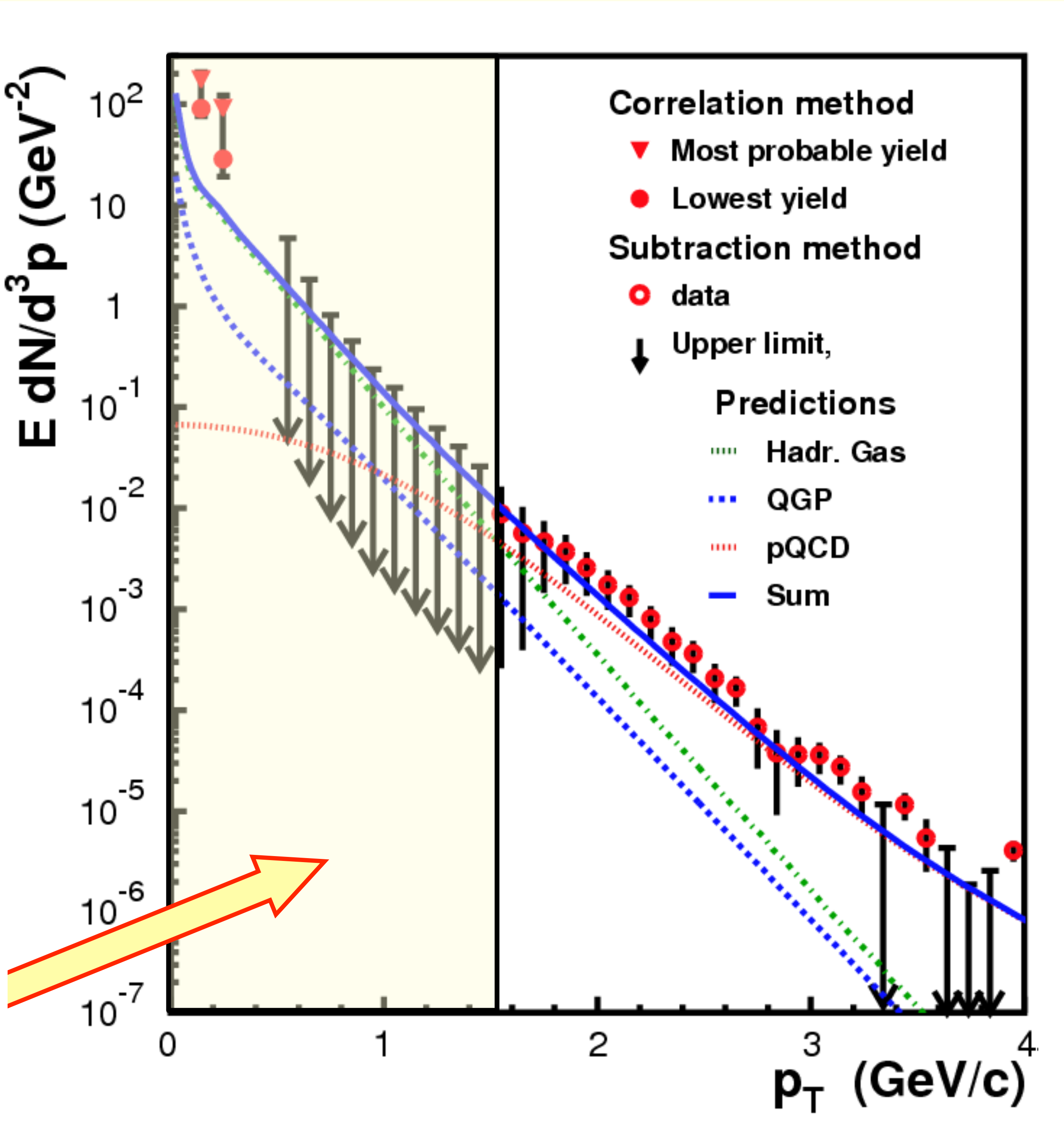
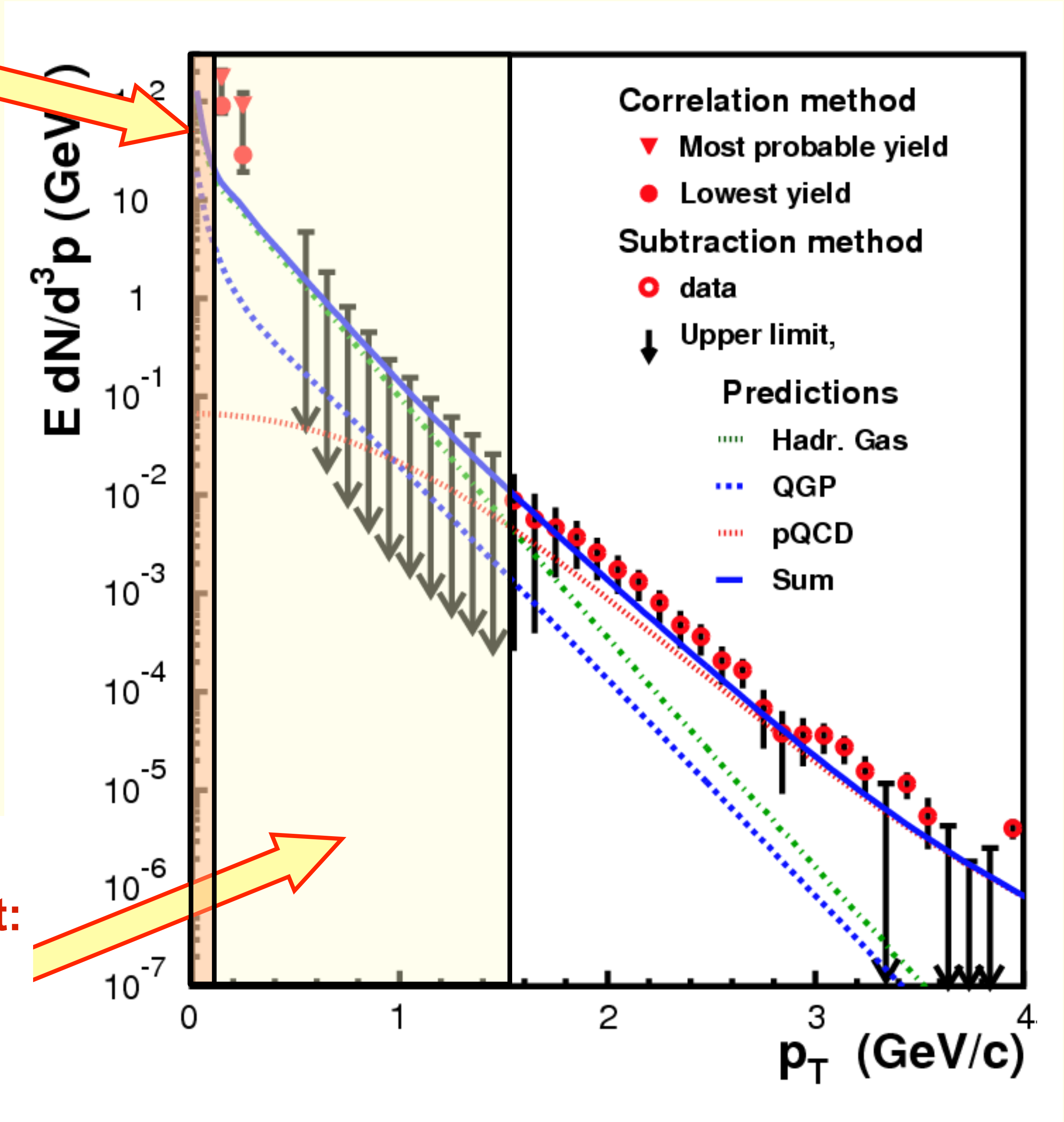


Subtraction method at low p_T largely limited by uncertainty of π^0 measurement:

- **Energy Scale**
- **Reconstruction Efficiency**
- **Peak Extraktion**

Limitations of the Different Methods

Low p_T limitation of HBT method:
Huge charged particle background
(p_T for MIP's ~ 100 MeV)



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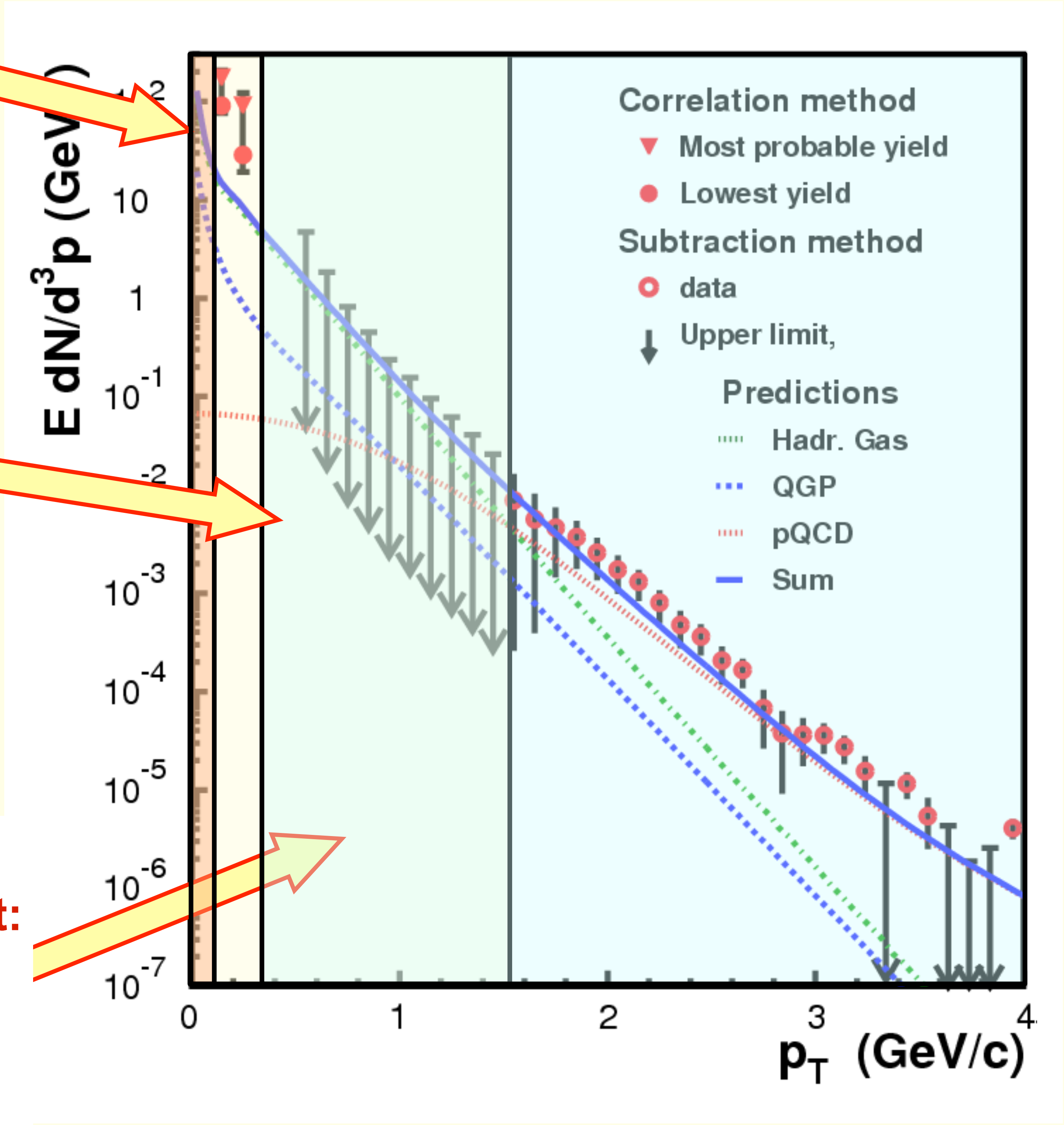
High p_T limitation of HBT method:
Hit distance cut of $D > 20$ cm (cluster splitting!) limits usable Q_{inv} range



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