Heavy Ion Physics and the Quark-Gluon-Plasma

Direct Photons and Dileptons

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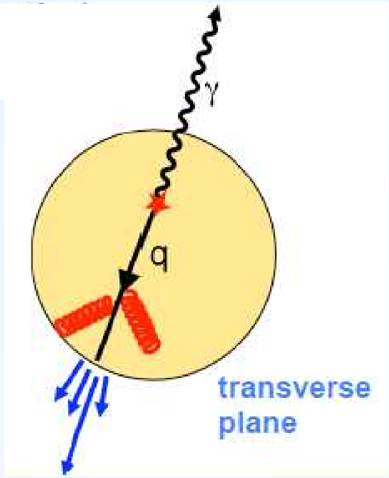
Why Direct Photons in A+A Collisions?

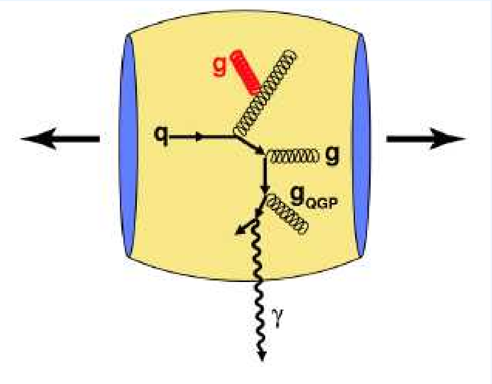
High p_T (> 6 GeV/c):

- High-p_T direct photons produced in initial hard parton-parton scatterings
- Photons leave the subsequently produced medium unaltered
- Test hard scattering predictions and measure rate of hard processes
- Direct γ-hadron azimuthal correlations
  - $E_\gamma = E_{jet}$ → study parton energy loss for partons with known initial energy



Low / Intermediate p_T:

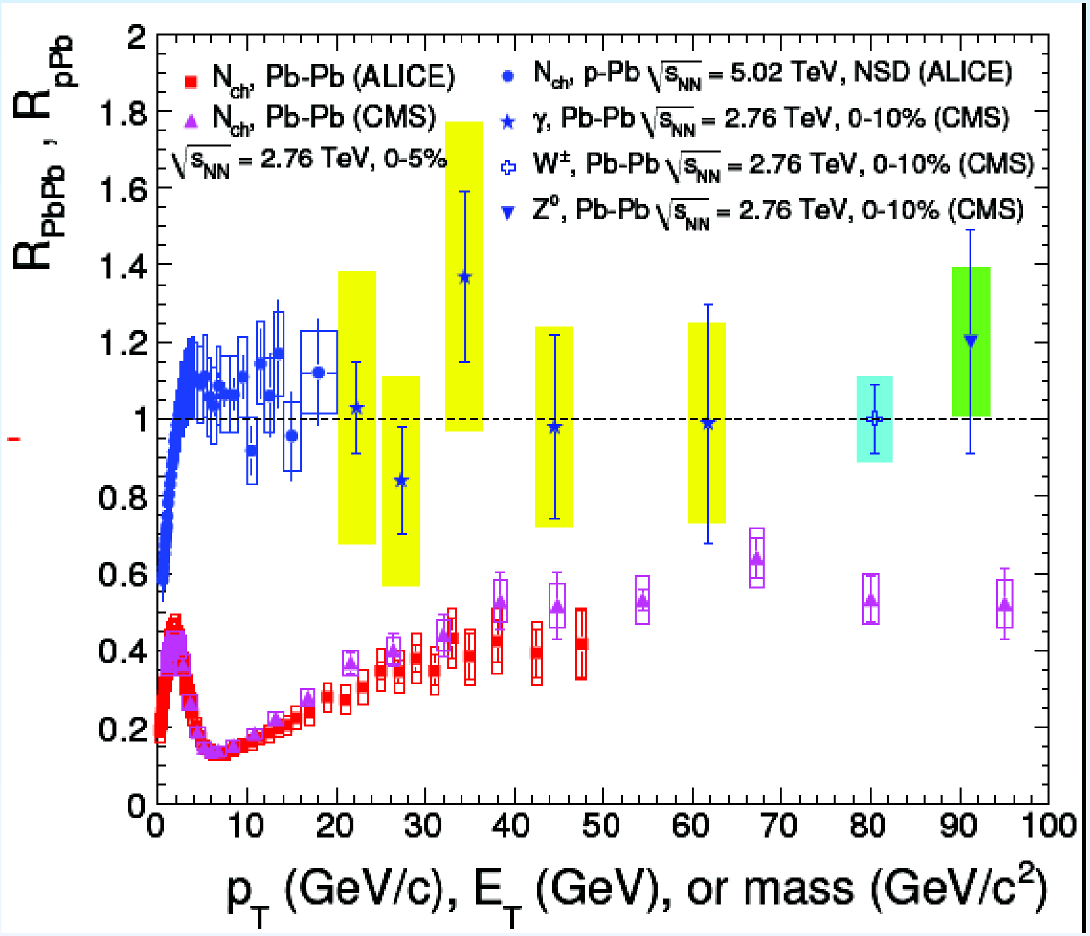
- Low-p_T thermal direct photons expected to reflect the initial temperature of the thermalized fireball
- Temperatures above T_c indicate Quark-Gluon Plasma phase
- Search for evidence for jet-plasma interactions?



Direct Photons

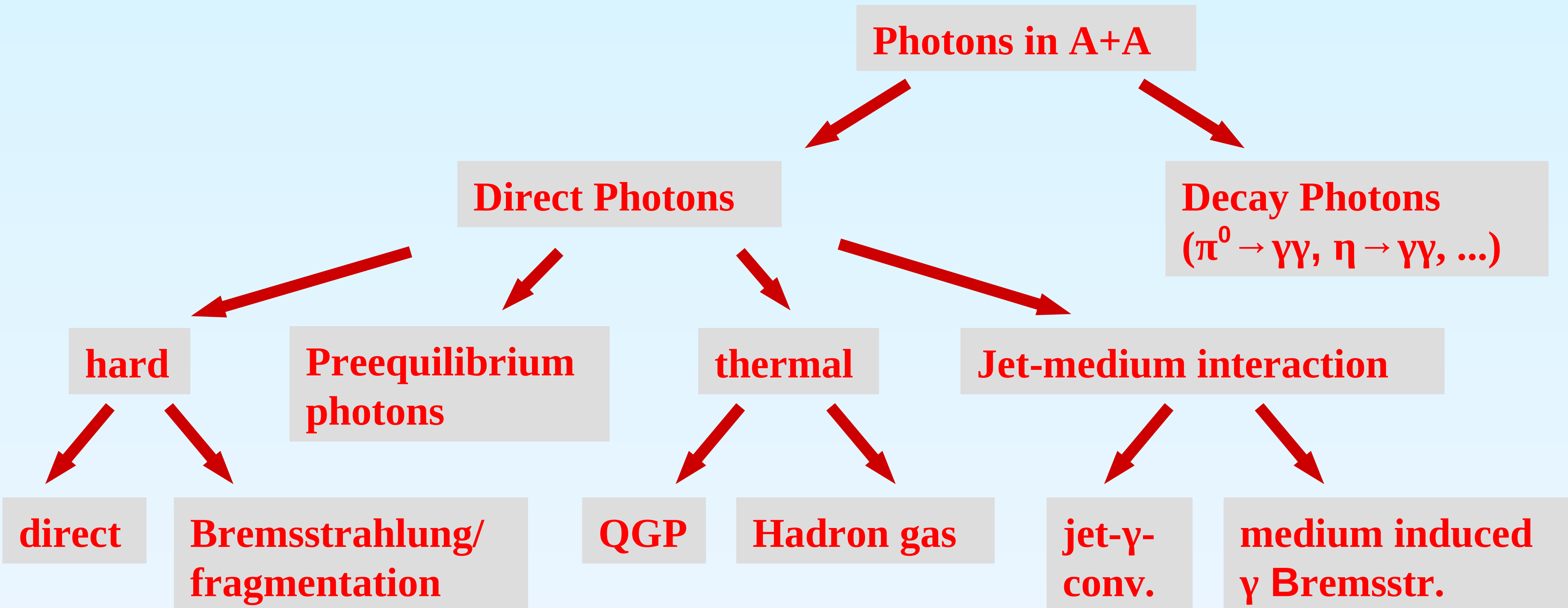
- **Often called prompt photons**
- **Definition (heavy-ion flavour):**
  Photons not coming from hadron decays
- **Definition (particle physics flavour):**
  Isolated Photons
- **Difficult measurement:**
  - Large Background from $\pi^0 \rightarrow \gamma+\gamma$, $\eta \rightarrow \gamma+\gamma$
 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

Reminder: High-p_T Direct Photons Confirm T_{AB} Scaling



ALICE: Phys.Lett.B720(2013)5262;Phys.Rev.Lett.110(2013)082302
CMS: Eur.Phys.J.C72(2012)1945;Phys.Lett.B710(2012)256277;
Phys.Lett.B715(2012)66;PAS HIN-13-004

Known and Presumed Photon Sources in A+A Collisions (I)



Known and Presumed Photon Sources in A+A Collisions (II)

Photons in A+A

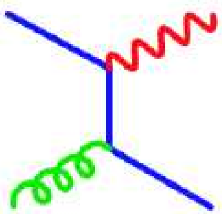
- **Direct Photons**
  - **hard**
    - **direct**
    - **Bremsstrahlung/ fragmentation**
  - **Preequilibrium photons**
  - **Q**
  - **conv.**
  - **n induced γ Bremsstr.**
- **Decay Photons** ($\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, ...)

These mechanisms are also present in pp collisions and can be calculated via pQCD

Hard direct photons:
direct component

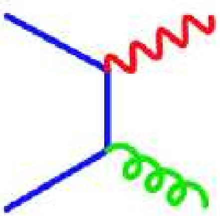
Compton

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



Annihilation

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



Known and Presumed Photon Sources in A+A Collisions (III)

Photons in A+A

Direct Photons

Decay Photons
($\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, ...)

hard

Preequilibrium photons

n

direct

Bremsstrahlung/ fragmentation

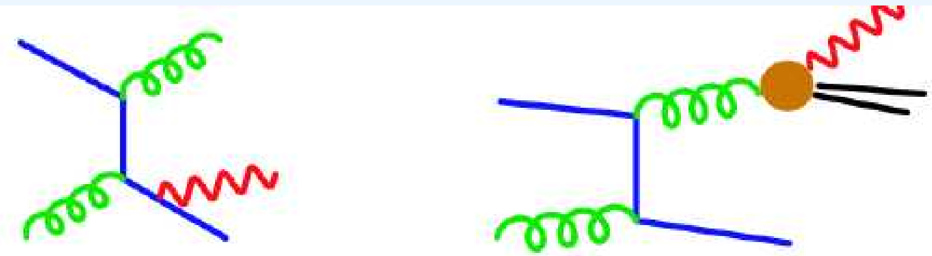
Q

conv.

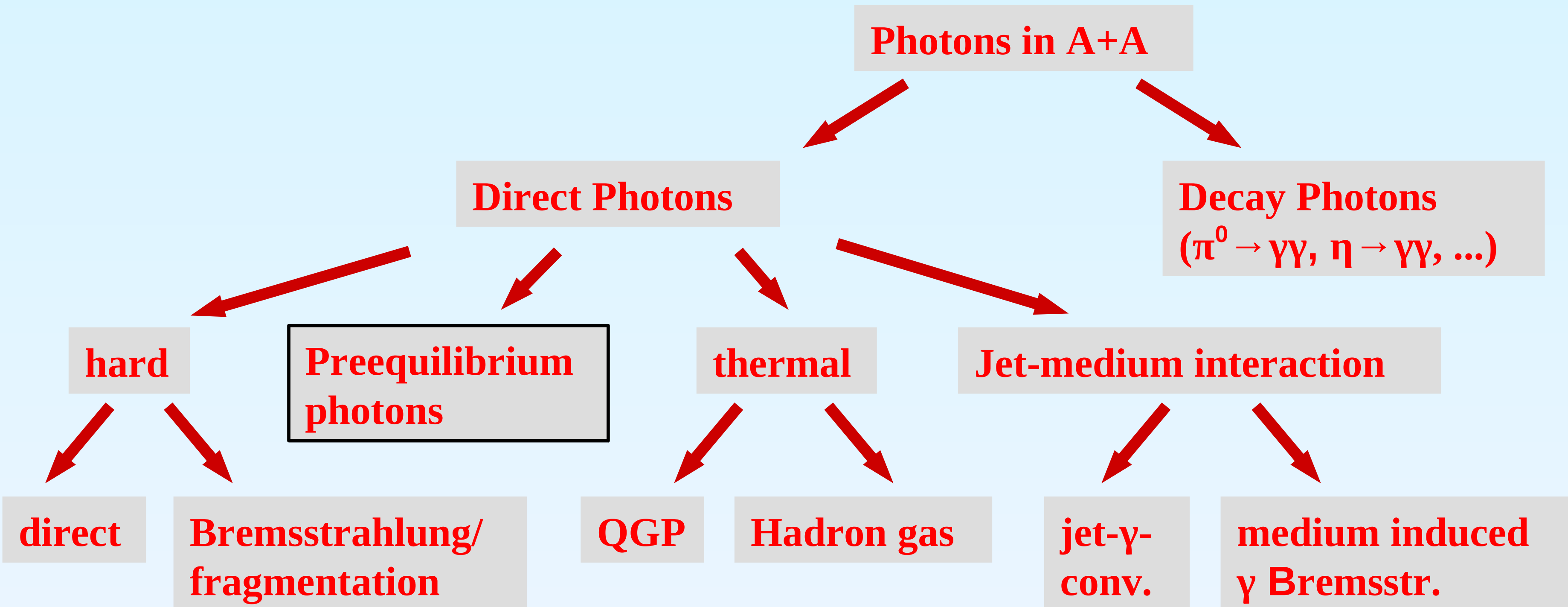
n induced
γ Bremsstr.

These mechanisms are also present in pp collisions and can be calculated via pQCD

Hard direct photons:
bremsstrahlung / fragmentation component

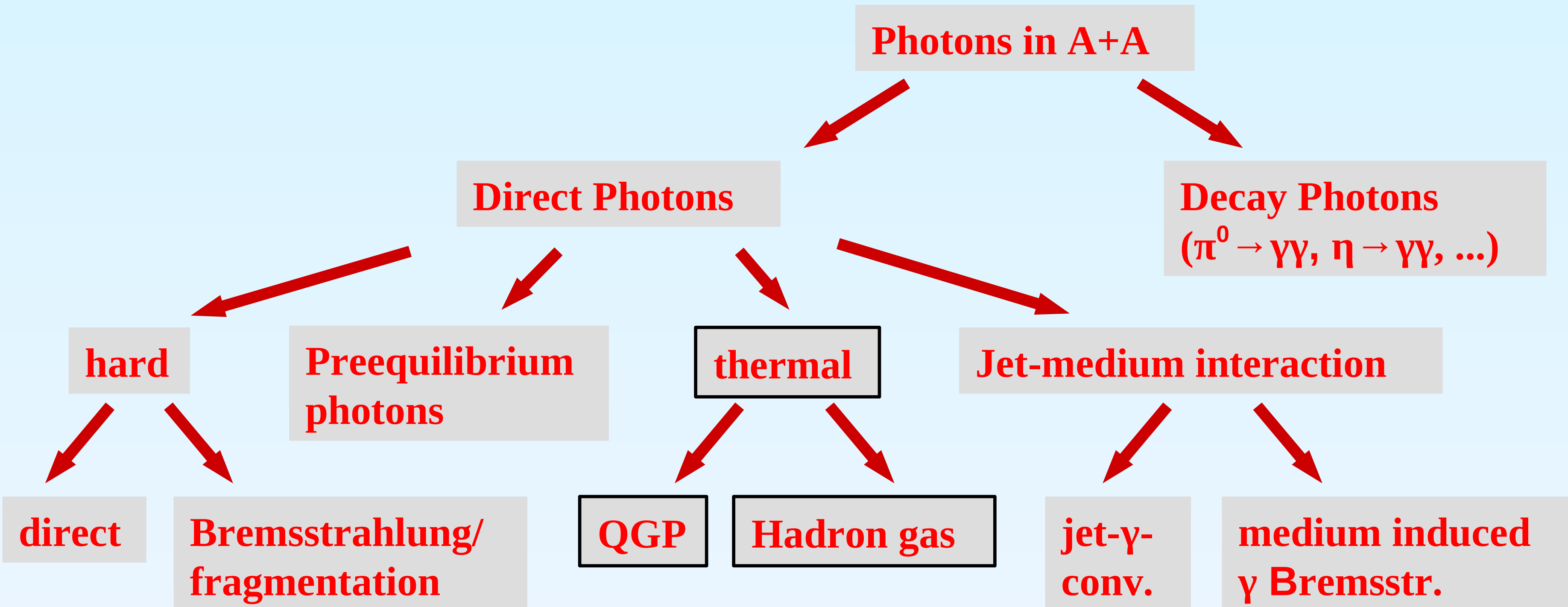


Known and Presumed Photon Sources in A+A Collisions (IV)



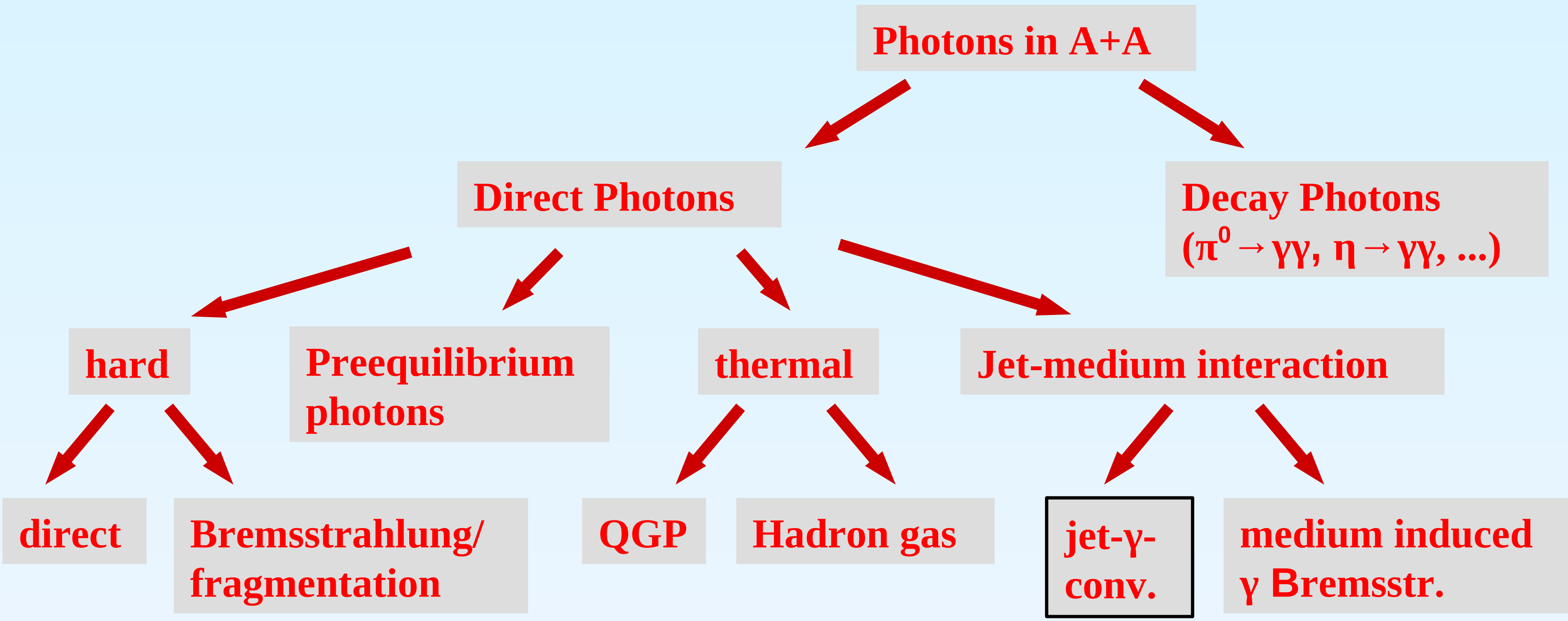
- Produced through rescattering of the primarily produced partons prior to thermalization
- Difficult to treat theoretically

Known and Presumed Photon Sources in A+A Collisions (I)



- 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 Collisions (I)



Hard+thermal:
Jet-Photon-Conversion

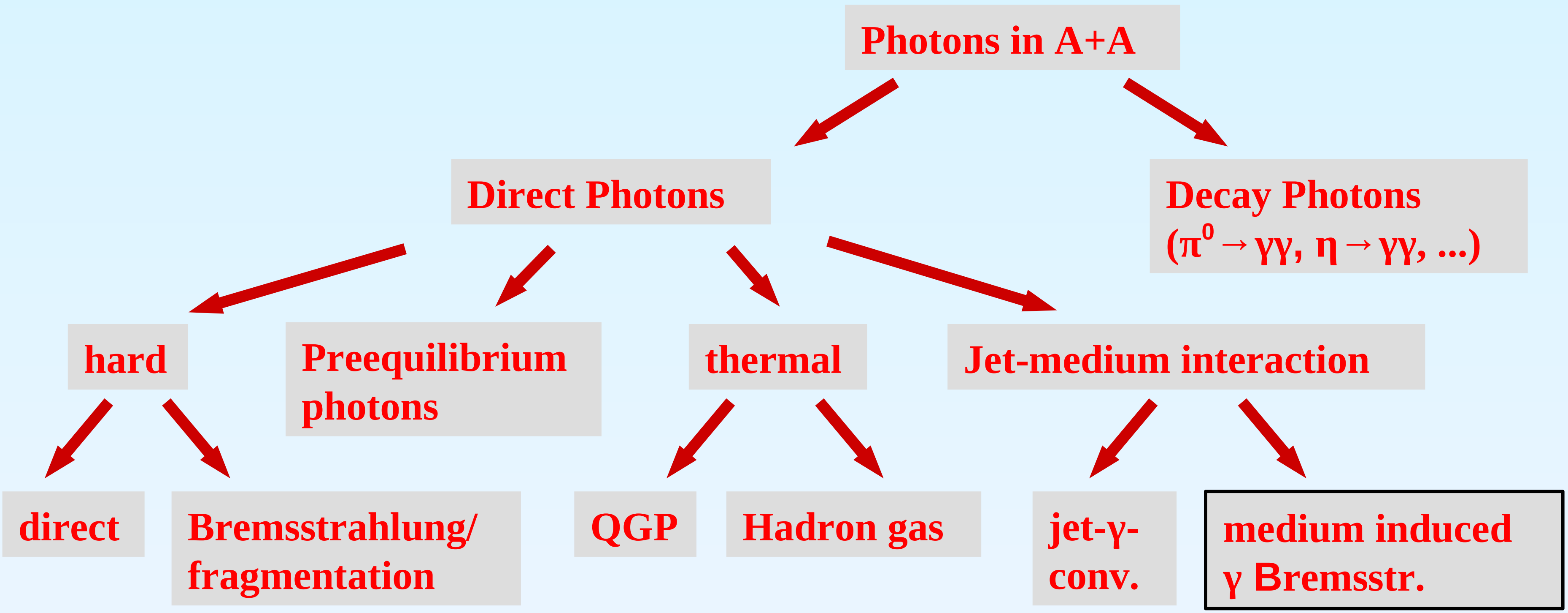
Interaction of parton from hard scattering with soft parton

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

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

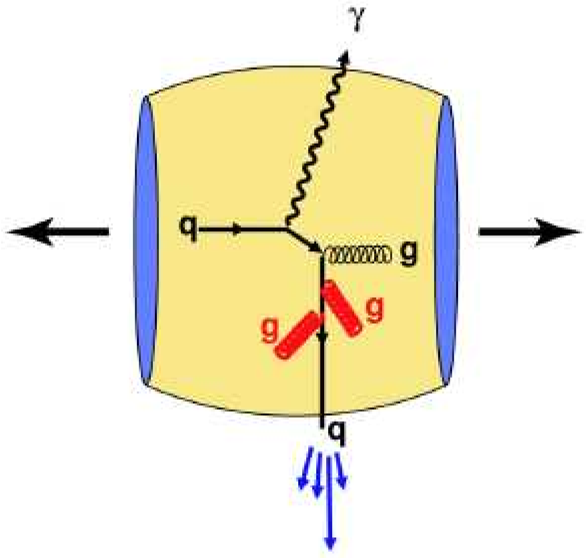
$$q_{hard} + \bar{q}_{QGP} \rightarrow \gamma + g$$

Known and Presumed Photon Sources in A+A Collisions (I)

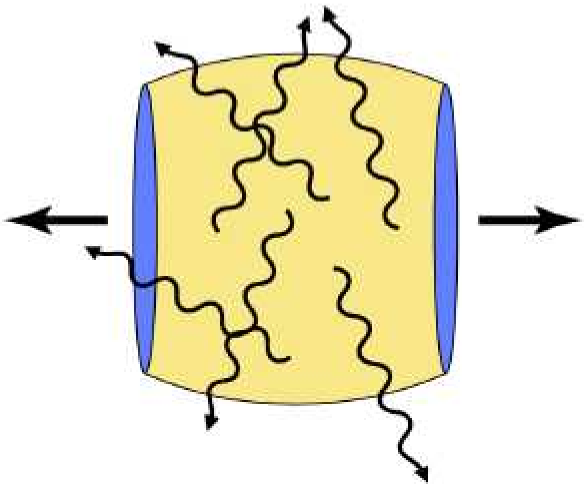


- Due to multiple scattering of quarks in the medium
- Different theoretical predictions, likely rather small contribution

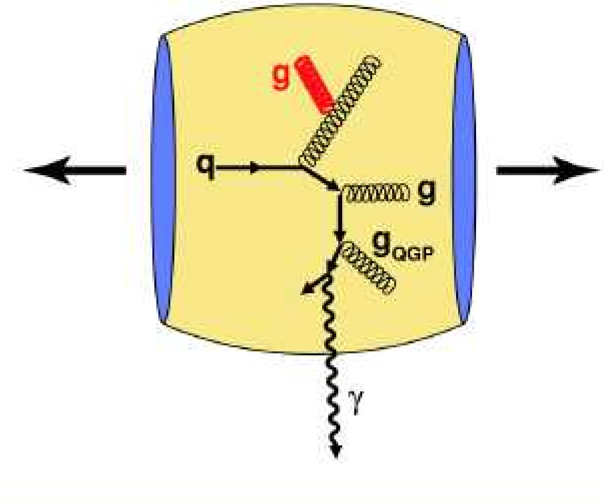
Summary: Direct Photons in A+A Collisions: Hard, Thermal, Hard+Thermal Hard



Hard photons

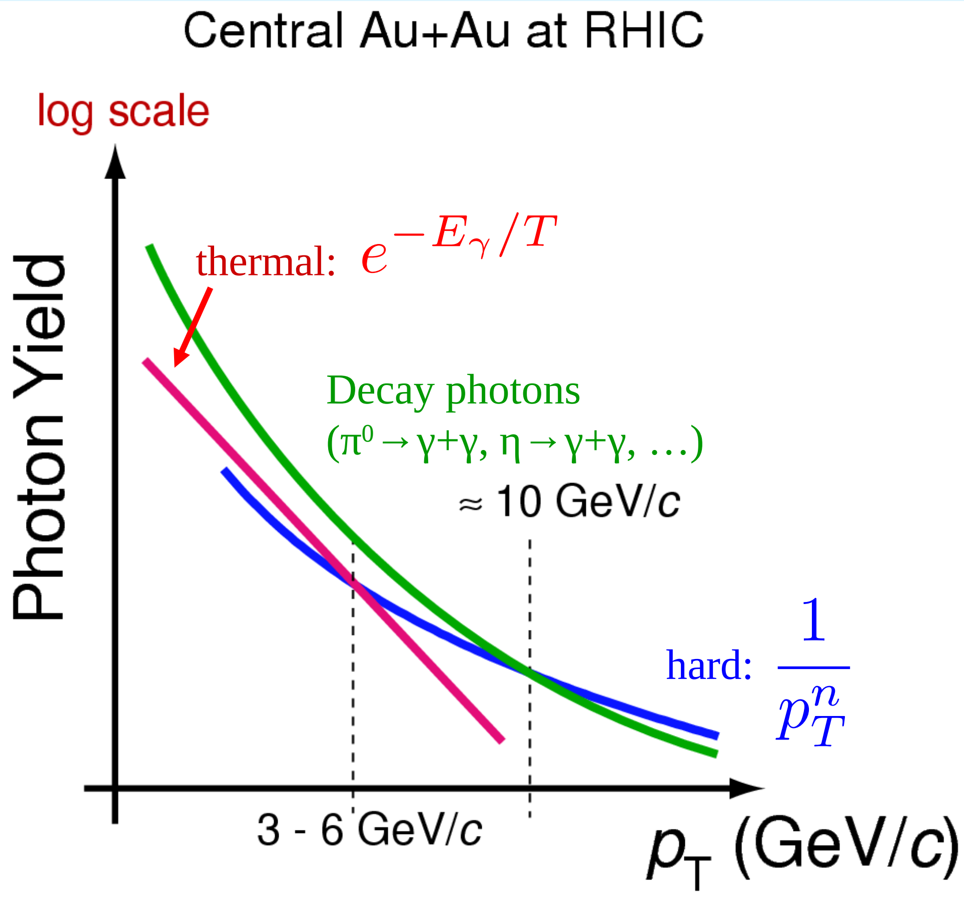


Thermal photons



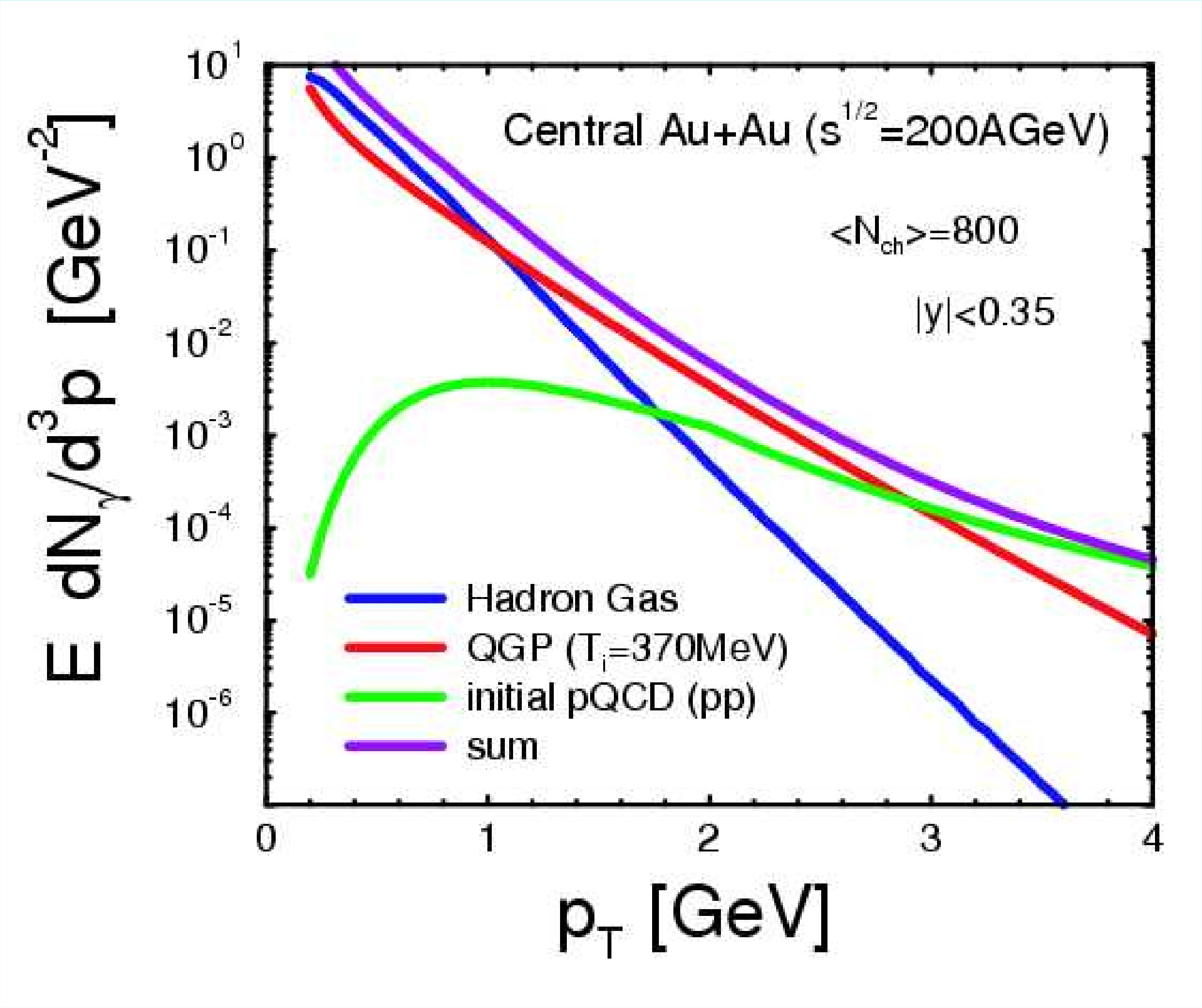
Photons from jet-plasma interaction

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*

Calculation: Sources of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV



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

Direct Photons in A+A Collisions: Measurements

- **So far (2013) only three measurements in the p_T range where thermal photons might be an important source**
  - Central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV (WA98)
  - Central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)
  - Central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2760 GeV (ALICE, preliminary)

- **After an photon excess has been established experimentally, one needs to figure out whether there is a contribution from thermal direct photons. This needs theoretical guidance.**

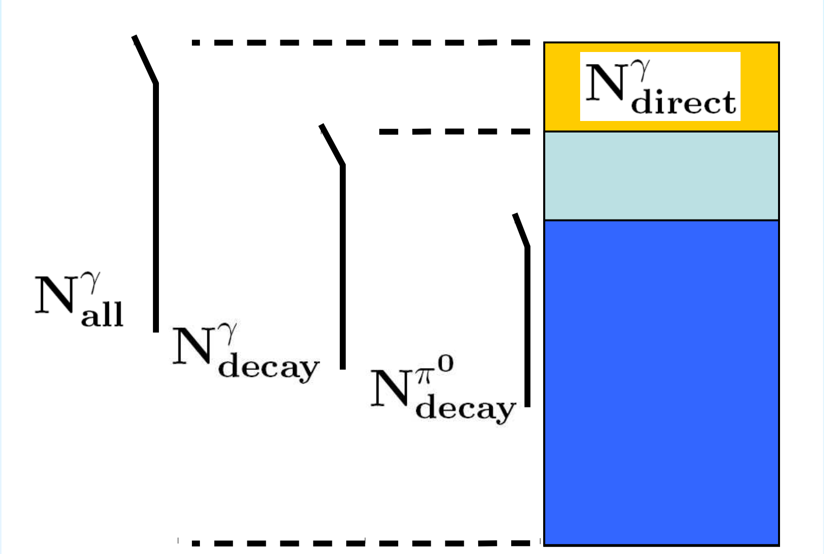
- Experimental methods:
  - Measure photons with electromagnetic calorimeter (WA98, PHENIX)
  - Measure photons via external conversion in e^+e^- pairs (ALICE)
  - Measure virtual photons ($\gamma^* \rightarrow e^+e^-$),

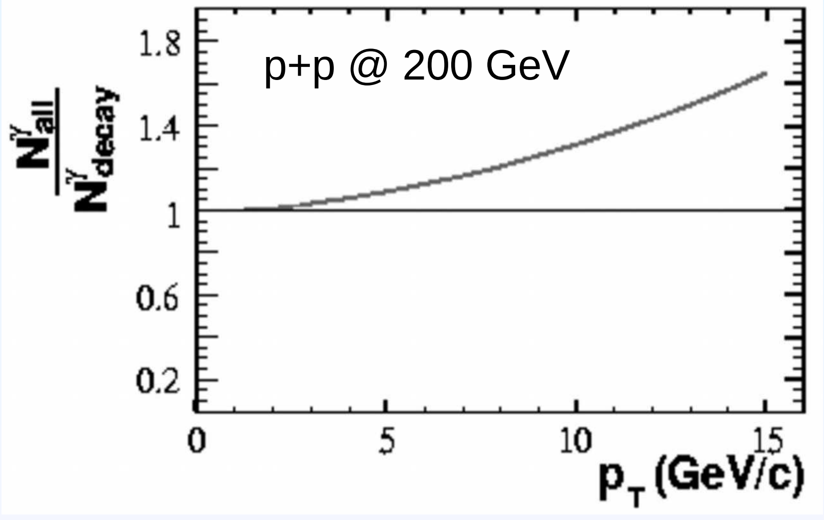
    and assume (PHENIX)

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

Direct Photon Measurement: Subtraction Method

- **Inclusive photons**
  - $N_{incl} = N_{direct} + N_{decay}$
- **Challenge to separate signal from background**
  - Mainly $\pi^0 \rightarrow \gamma + \gamma$
- **Direct separation**
  - Isolation cuts
- **Statistical separation**
  - Compare measured inclusive γ with expected decay γ (cocktail)
  - $N_{direct} = N_{incl} - N_{decay}$





Subtraction Method (I)

- Determine the inclusive photon spectrum
  - Calorimeter measurement
  - External conversion photons
  - Account for contamination with charged and neutral hadrons
    - Tracking detectors, PID cuts (TOF, shower shape), simulation

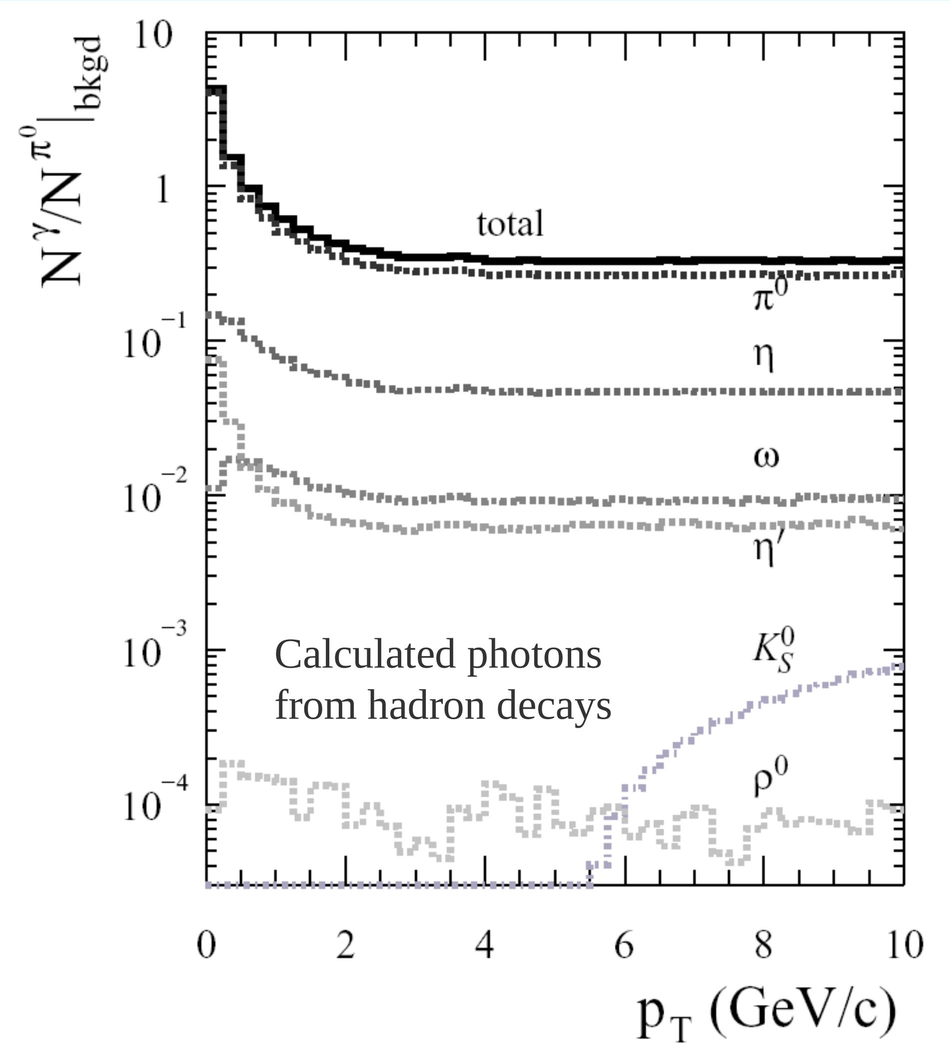
- Extract significance of the direct photon signal
  - Cocktail method
  - HBT correlation strength
  - Internal conversions

$$\begin{aligned}\gamma_{direct} &= \gamma_{incl} - \gamma_{decay} \\ &= \left(1 - \frac{\gamma_{decay}}{\gamma_{incl}}\right)\gamma_{incl} \\ &= (1 - 1/R) \cdot \gamma_{incl}\end{aligned}$$

R contains the statistical and systematic significance of the direct photon signal e.g. with:

$$R = \frac{\gamma_{incl}/\pi^0\big|_{meas}}{\gamma_{decay}/\pi^0\big|_{calc}}$$

Subtraction Method (II)
The Decay Background



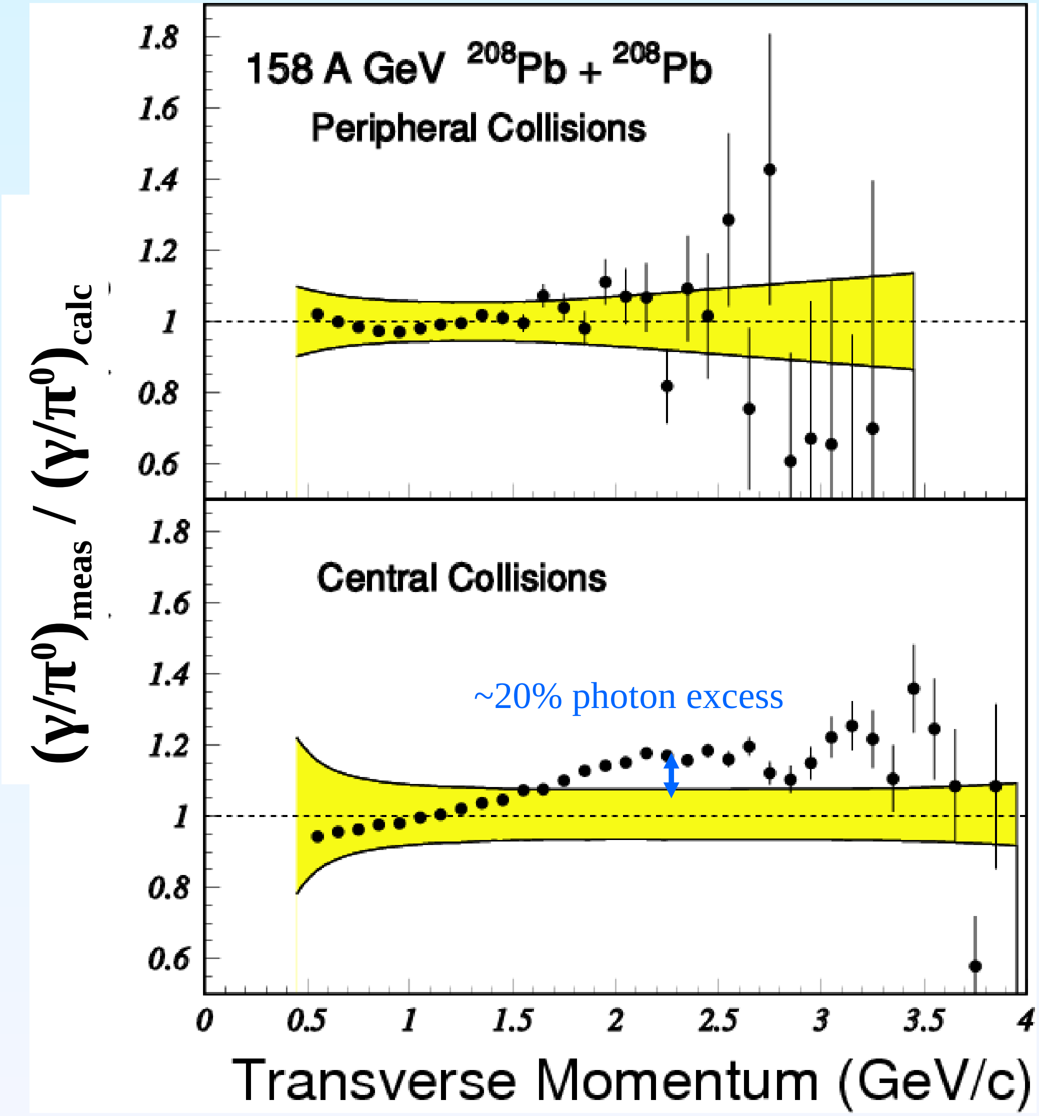
- **Reference for double ratio:**

$$R = \frac{\gamma_{incl}/\pi^0|_{meas}}{\gamma_{decay}/\pi^0|_{calc}}$$

- **Calculated based on measured π and η spectra**
  - 96% of background
  - All other mesons via m_T scaled π^0 spectra

WA98, nucl-ex/0006007

Direct Photon Measurement by WA98 (SPS)



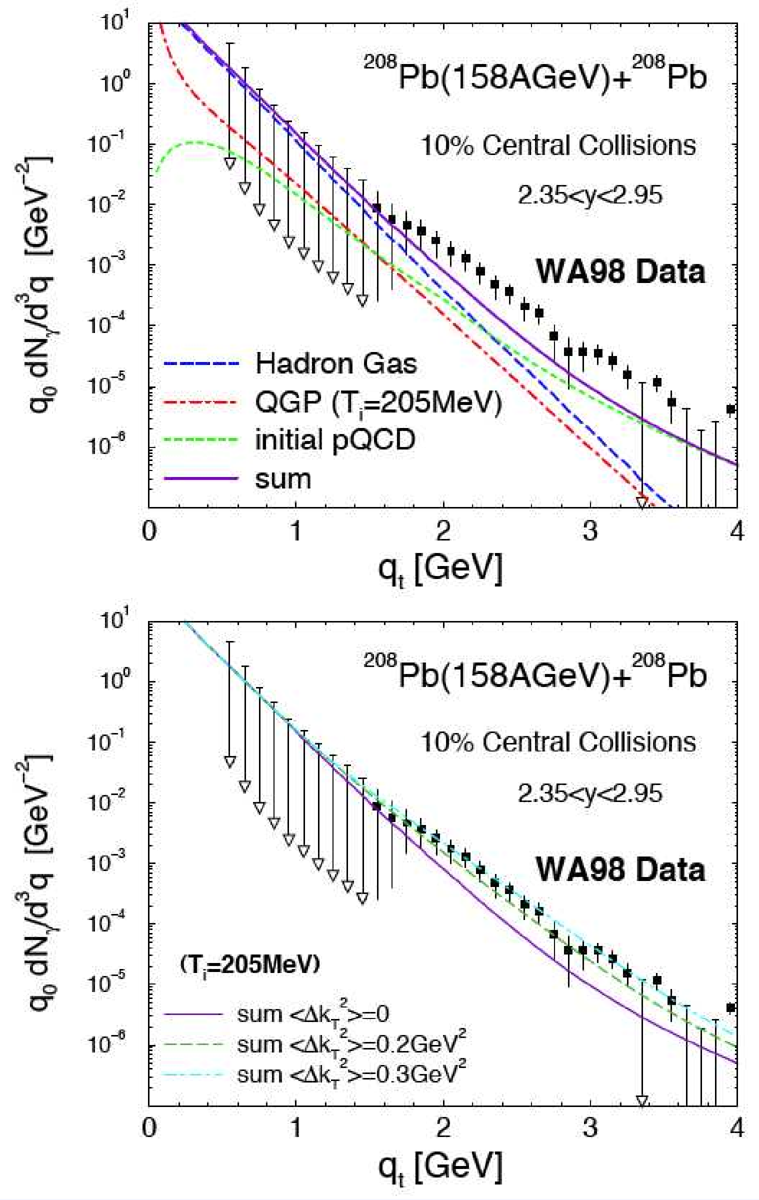
- No signal in peripheral collisions
- 20% photon excess in central Pb+Pb collisions

158 AGeV Pb + Pb:

$$\sqrt{s_{NN}} = 17,3 \text{ GeV}$$

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

Interpretation of the WA98 Data (SPS)



Ch. Gale, arXiv:0904.2184

Theoretical ingredients:

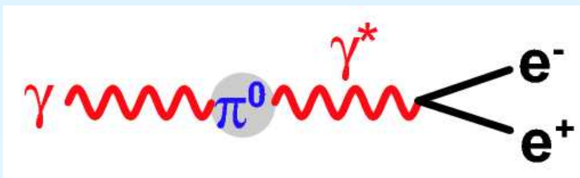
- (schematic) fireball evolution
- Photon emission rates from a gas of hadrons
- Photon emission rates from the QGP complete to leading order in α_s
- Estimate of the Cronin effect deduced from p+A collisions

Conclusions:

- Data consistent with QGP scenario ($T_i \approx 200 - 270$ MeV), however, QGP contribution is small
- Data also consistent with hadronic scenario (Cronin enhancement alone could explain the data)

Internal Conversion Method

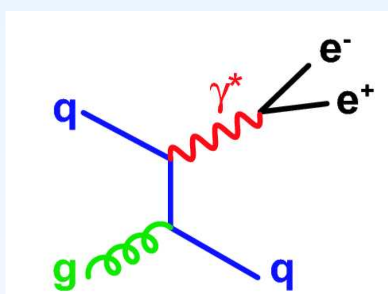
- **Internal conversion**
  - Any source of real photons also emits virtual photons
  - Well known example:



- Rate and m_{ee} distribution calculable in QED
  (Kroll-Wada formula, see next slide)

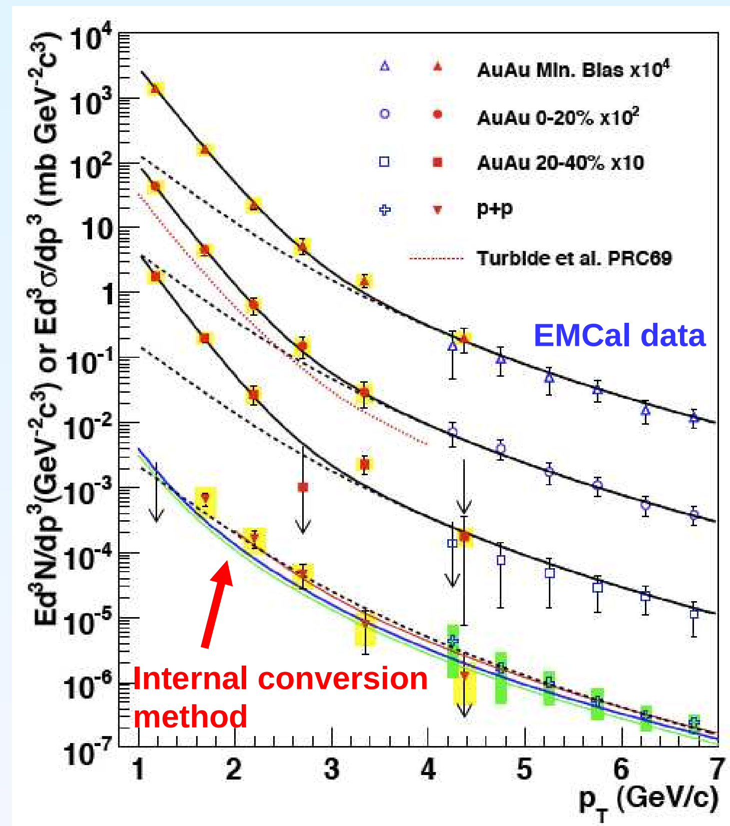
- Hadron decays: $m_{ee} < M_{hadron}$

- Essentially no such limit for point-like processes



- **Motivation**
  - Measure direct photons where thermal photons dominate and calorimeter measurements are difficult

PHENIX, arXiv:0804.4168v1



More Details on the Internal Conversion Method: Kroll-Wada Formula

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

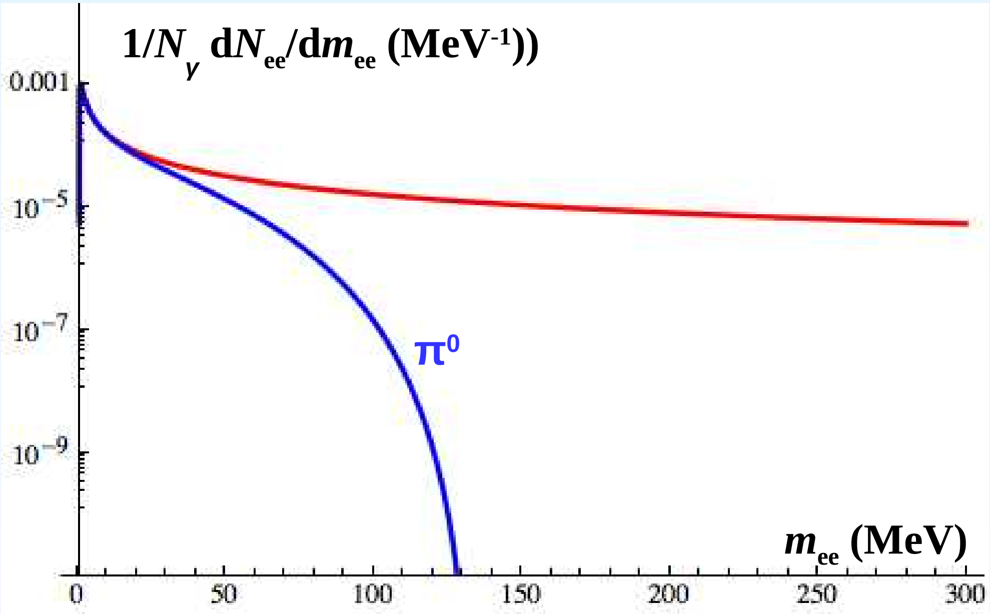
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

Hadron decay:

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

Point-like process:

$$\underbrace{S = 1}_{\text{holds for } p_{T,ee} >> m_{ee}}$$



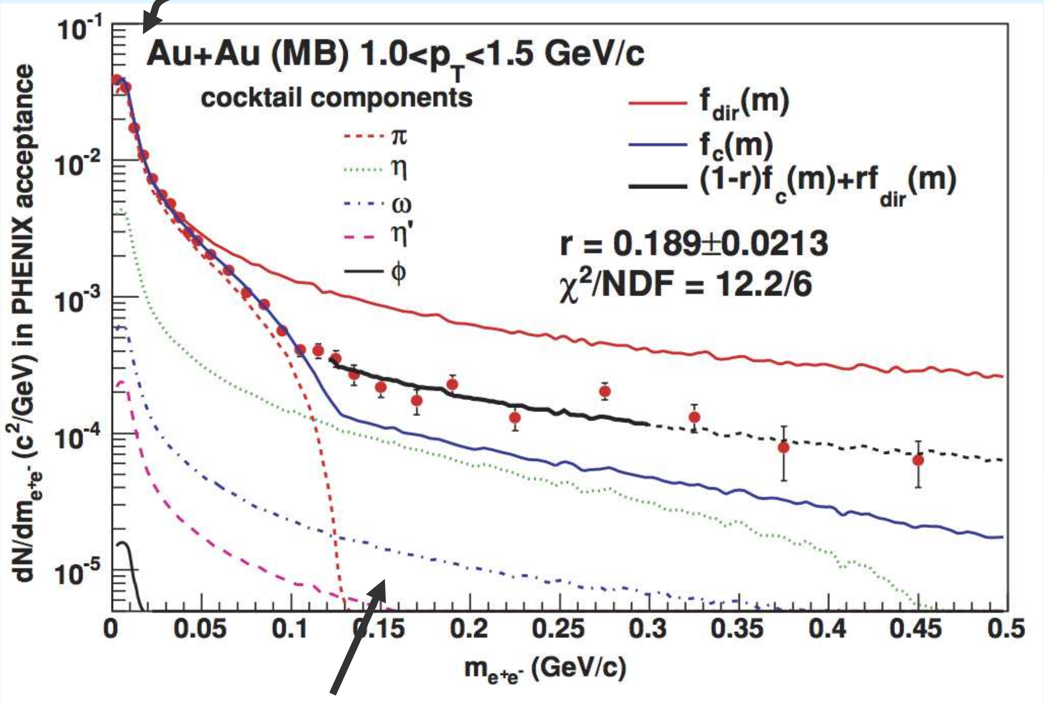
PHENIX measurement:
$80 < m_{ee} < 300$ MeV

→ **There are 0.002 e+e- pairs with $80 < m_{ee} < 300$ MeV for every real photon**

Extraction of the Direct Photon Signal: Two-Component Fit

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

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



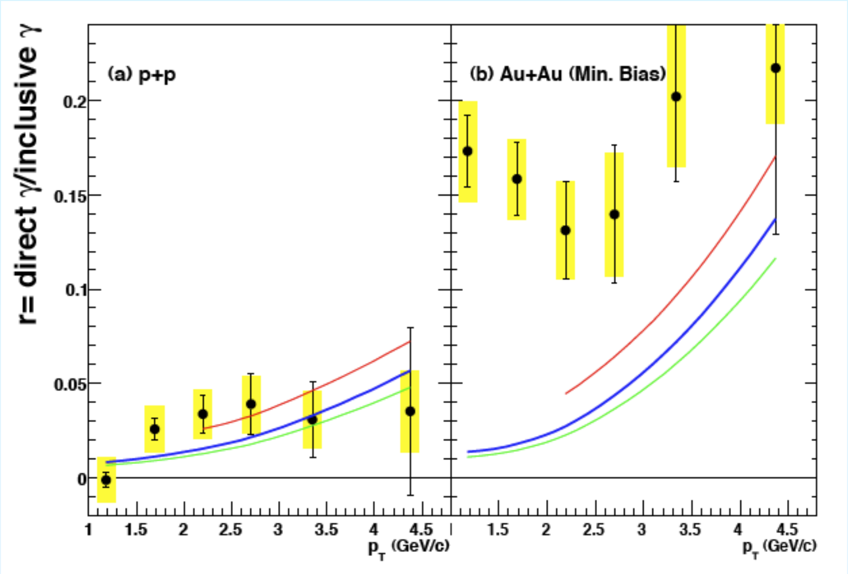
Fit range: 120 < m_{ee} < 300 MeV

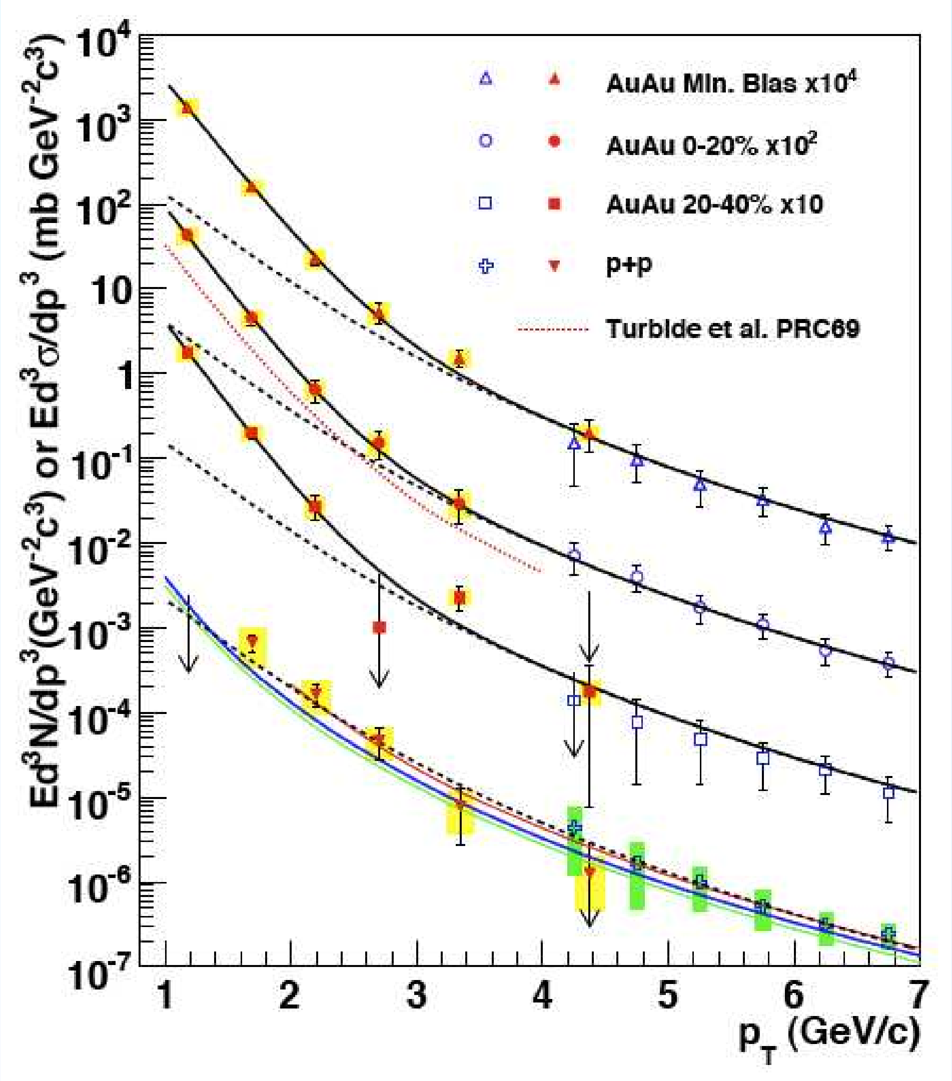
- **Electrons identified with RICH and EMCAL**
- **Combinatorics via mixed event**
- **Interpret deviation from hadronic cocktail as signal from virtual direct photons**
- **Clear excess over cocktail shape**
- **Direct photons can account for this enhancement**
- **Excess given by fit with free parameter**

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

- χ^2/NDF: (12.2 / 6)

Internal Conversion Methods: Results PHENIX at RHIC





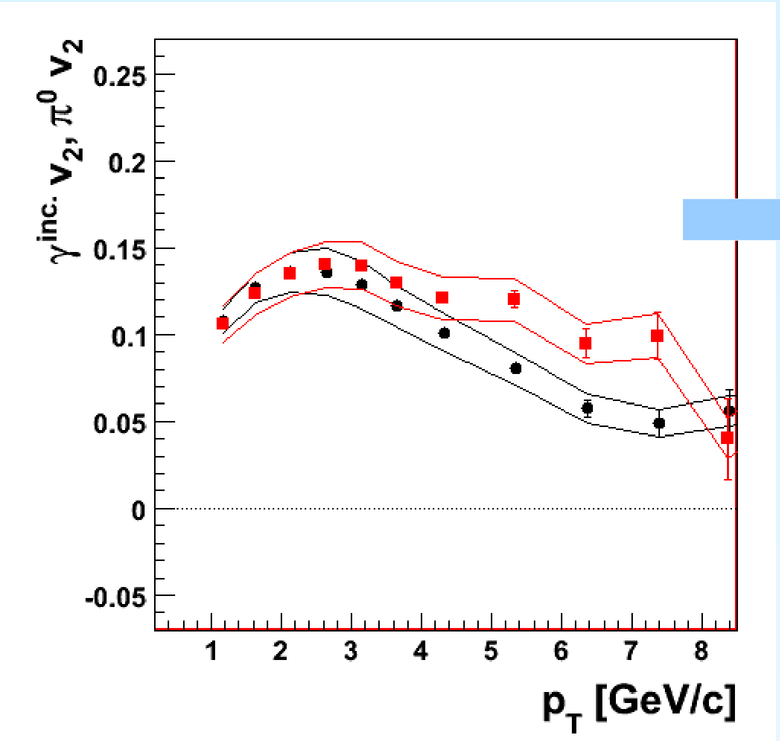
- Enhancement in Au+Au above p+p described by an exponential (as expected for a thermal source)

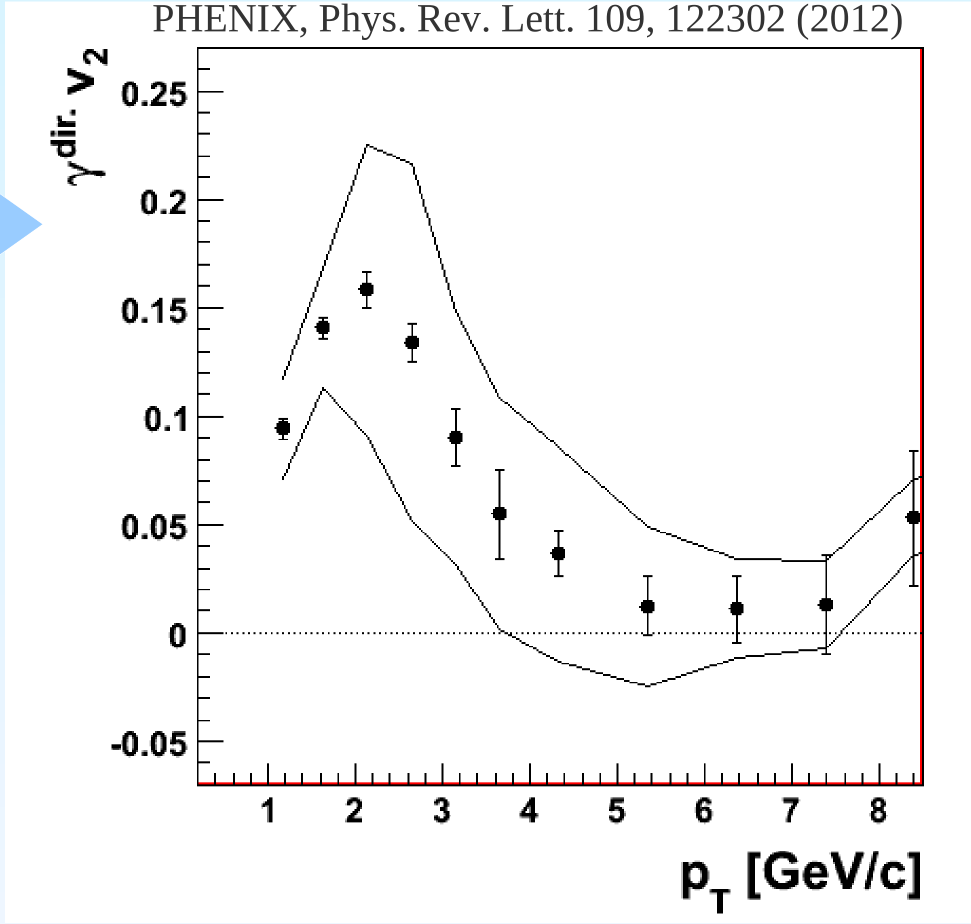
$$Y_{Au+Au} = N_{\mathrm{coll}} \cdot Y_{p+p} + A \cdot e^{-p_T/T}$$

- Slope parameter (0-20%): T = (221 ± 23 ± 18) MeV
- Initial temp. from hydro: T_i = 300 … 600 MeV

Expected to be a lower limit for the initial temperature T_i!

Direct Photon v_2 (PHENIX @ RHIC)



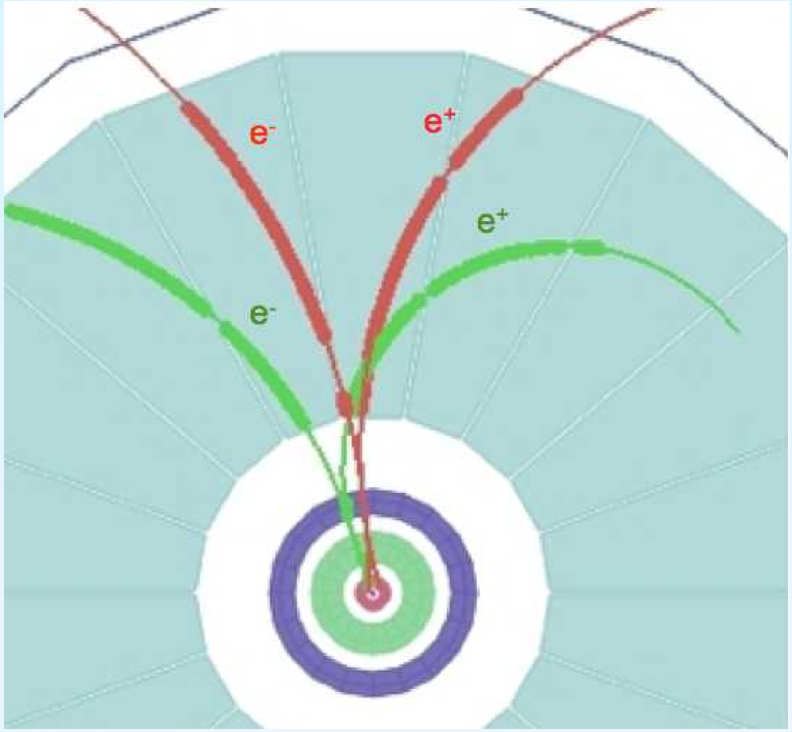


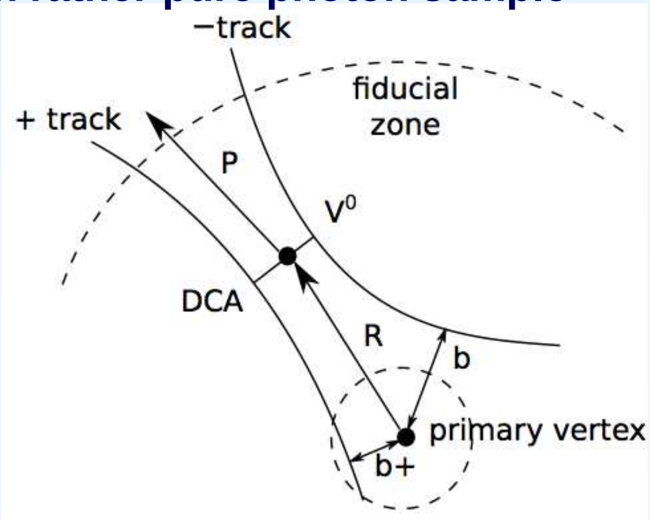
$$v_2^{\mathrm{dir.}\,\gamma} = \frac{R_\gamma \cdot v_2^{\mathrm{incl.}} - v_2^{\mathrm{decay.}\,\gamma}}{R_\gamma - 1}$$

Large direct photon v_2 is a challenge to theory because most thermal photons are expected to be created early (when the temp. is largest and) when v_2 has not fully built up

ALICE: Measuring Photons with Conversions
Reconstruction of Secondary Vertices (V0's) (I)

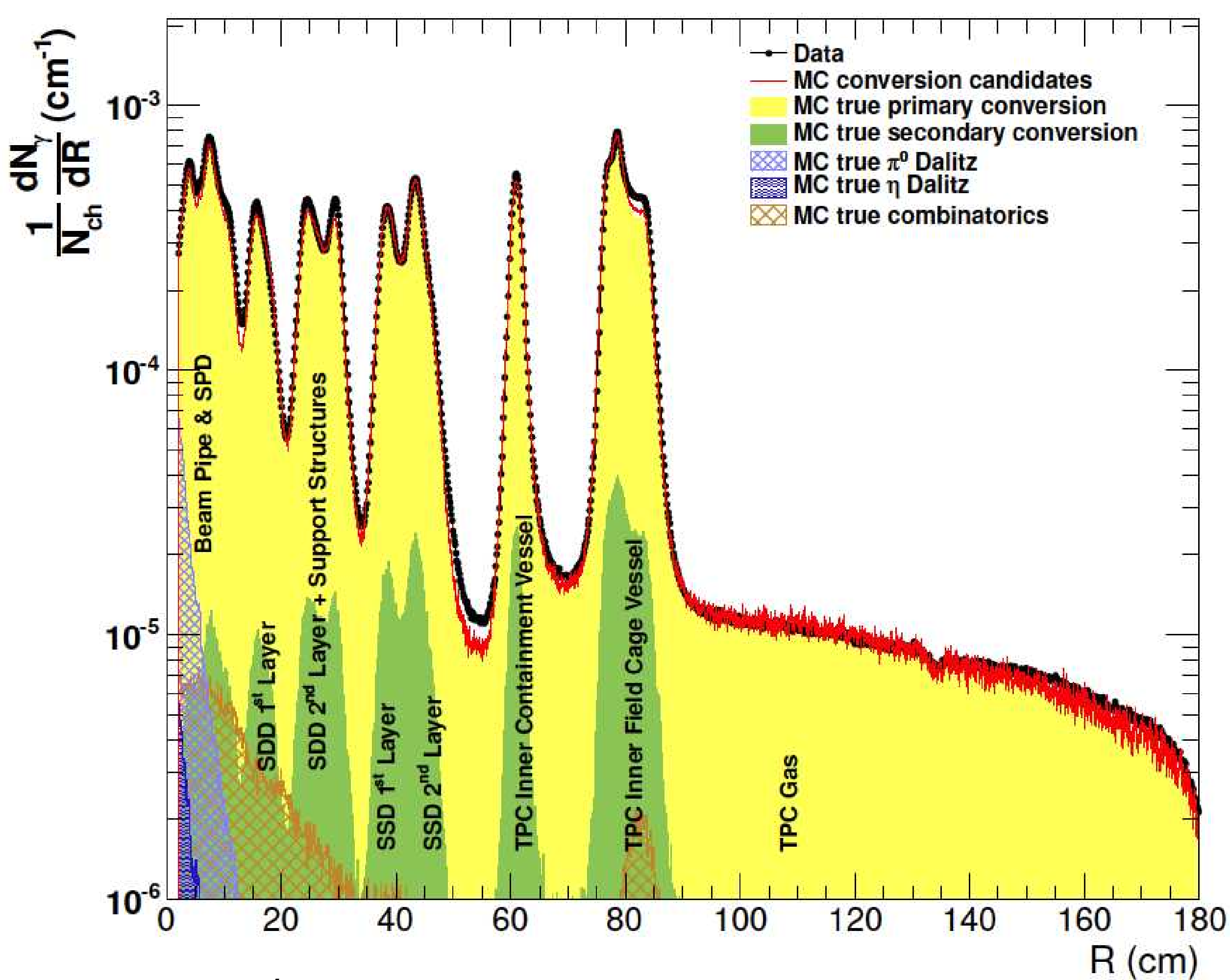
- **Charged tracks with large impact parameter b**
- **Accept pairs of such tracks with small distance of closest approach (DCA) as V0**
- **V0's mainly from**
  - $K_S^0 \rightarrow \pi^+\pi^-$ ($c\tau$ = 2.7 cm)
  - $\Lambda \rightarrow p+\pi$ ($c\tau$ = 7.9 cm)
  - converted γ's
- **Cuts based on decay kinematics and electron ID to obtain rather pure photon sample**





Photon conv. probability in ALICE (for R < 180 cm):
p_{conv} = 8.5% for p_T > ~3 GeV/c

ALICE: Measuring Photons with Conversions
Reconstruction of Secondary Vertices (V0's) (II)

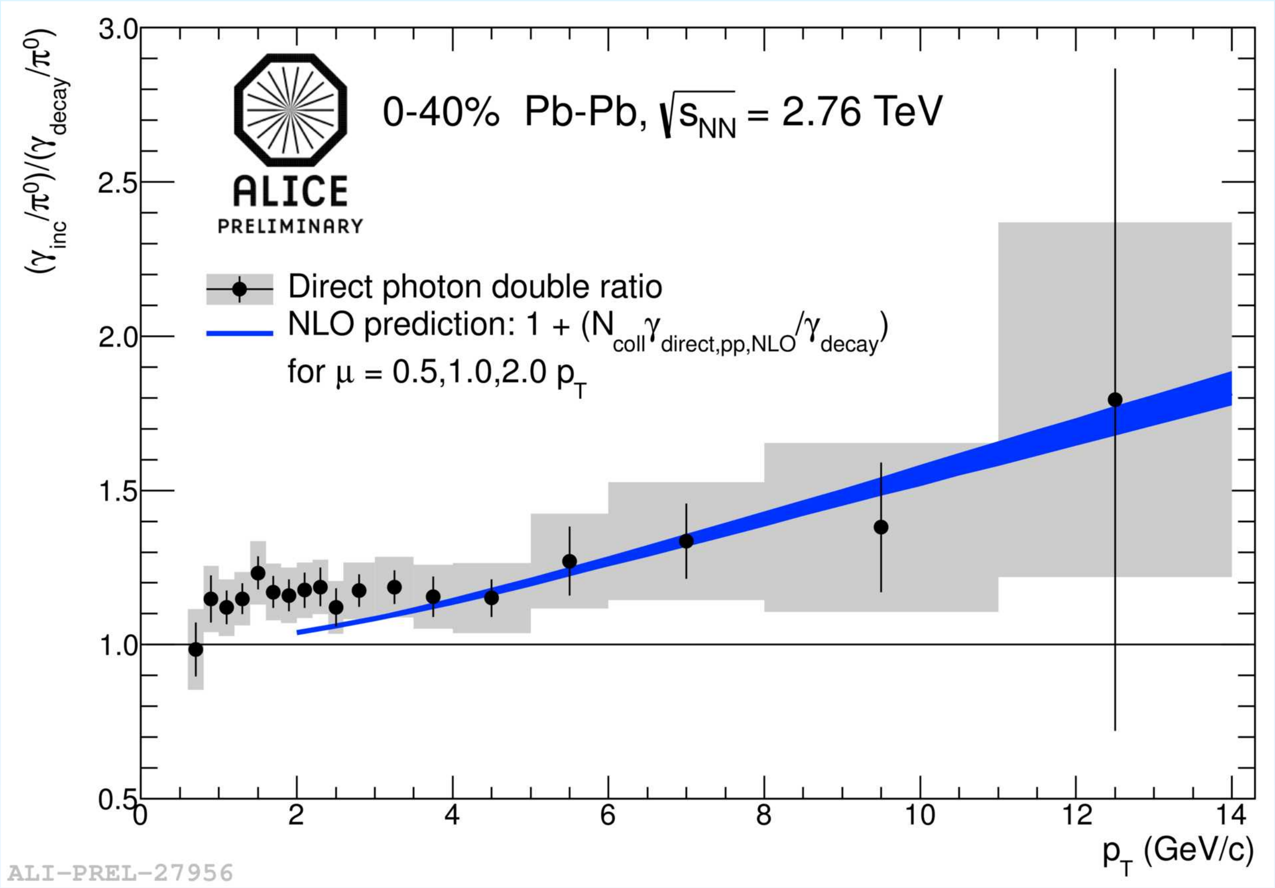


Poor energy resolution for calorimeters at low p_T, use tracking of photon conversion products: $\gamma + A \rightarrow e^+e^-$

Requires precise knowledge of material budget.

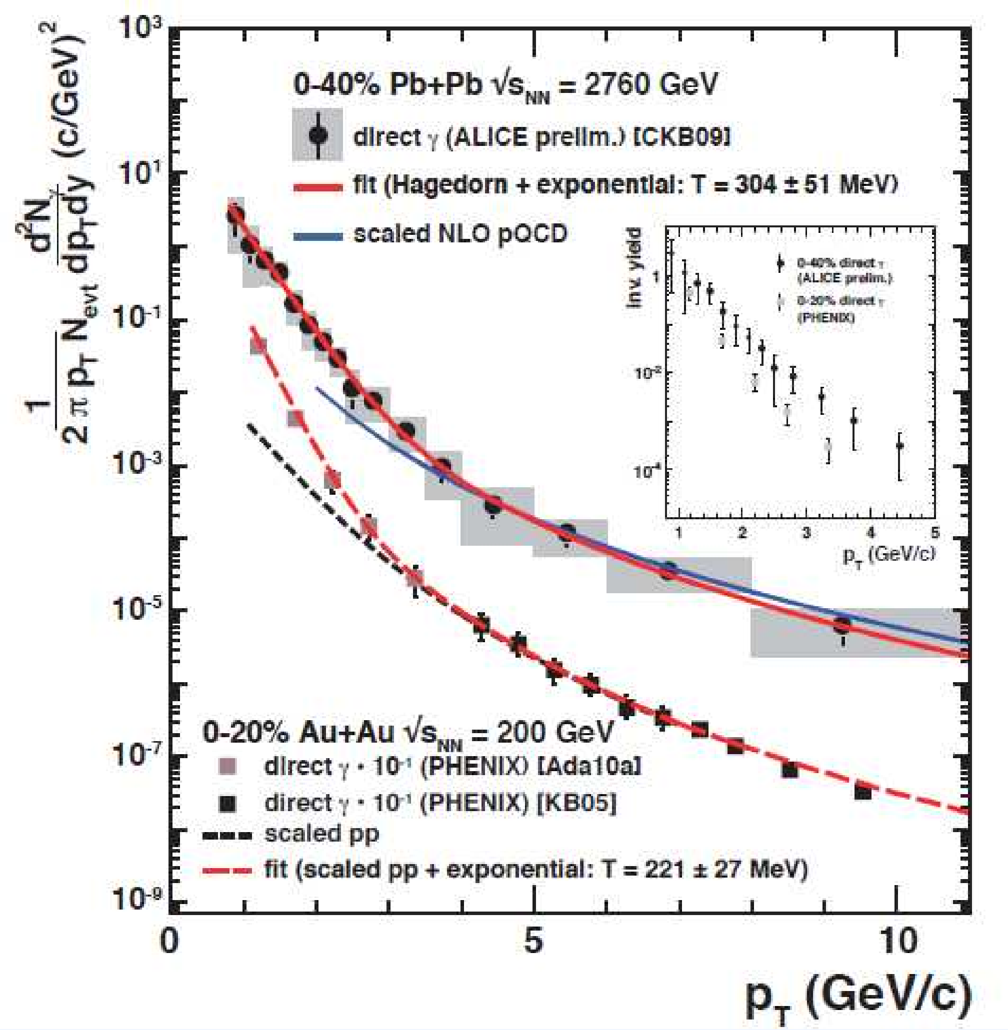
ALICE 1.8 m/X_0 = 11.4% ± 0.5%

Pb+Pb at 2.76 TeV (ALICE): Photon Excess in Central Collisions



- Photon excess of about 15-20% (for 1 < p_T < 5 GeV/*c*)
- Comparison with pQCD: Significant thermal photon component below 3 GeV/*c*

Pb+Pb at 2.76 TeV (ALICE): Direct Photon Spectra



- **ALICE at LHC**
  - Exponential fit for p_T < 2.2 GeV/c
  - inv. slope T_{LHC} = 304 ± 51 MeV
- **PHENIX at RHIC**
  - T_{RHIC} = 221 ± 27 MeV
  - 0-20% Au-Au at $\sqrt{s_{NN}}$ = 200 GeV
    PHENIX PRL 104:132301 (2010)
- **Slope above T_c ≈ 160 MeV at RHIC and LHC**
  → Early emission from QGP?
- **First indication of thermal radiation at LHC**
  - Average slope/effective temperature ≈ 40% higher than at RHIC.

Take-Home Message

- **Direct Photons escape the medium basically unaffected**
  - Probe various stages of the reaction
  - Difficult measurement against large background from decay photons
- **Early phase probed at highest p_T**
  - Confirm validity of binary scaling
  - Strong final state effect in hadron suppression
- **Low p_T**
  - Access to thermal radiation
  - First observation at RHIC, confirmed at LHC with higher effective slope
  - Interpretation complicated