Photon Physics @ RHIC: Highlights

BNL, June 24th, 2005

David d'Enterria
Nevis Labs, Columbia University, NY

Agenda Photon Workshop (R6)

http://www.phenix.bnl.gov/~enterria/ags_rhic_photons_05/

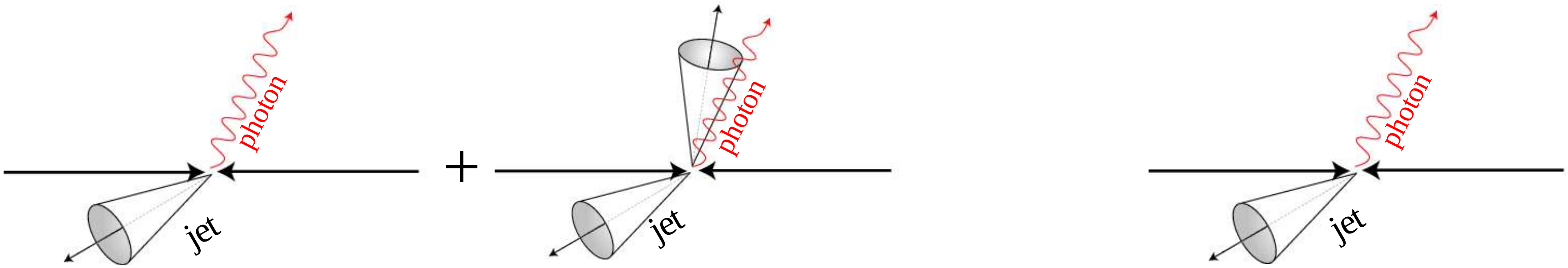
Talk :	Speaker:
"Photons in high-energy hadronic and nuclear collisions: A historical perspective" [PDF | PPT]	Paul Stankus
"Photons @ RHIC: Results from PHENIX" (EXP) [PDF | PPT]	Hisa Torii
"Photons @ RHIC: Results from STAR" (EXP) [PDF | PPT]	Marcia Maria de Moura
"Perturbative photons in p+p and A+A collisions at RHIC energies" (TH) [PDF | PPT]	Monique Werlen
"Thermal photons in A+A collisions at RHIC energies" (TH) [PDF | PPT]	Dmitri Peressounko
Coffee break	
"Photons at forward rapidities at RHIC" (TH)	Jamal Jalilian-Marian
(Joint session with the 'Femtoscopy' Workshop):	
"Light from parton cascading and jet-medium interaction in A+A at RHIC" (TH) [PDF | PPT]	Steffen Bass
"Gamma-gamma interferometry at RHIC" (EXP)	Jack Sandweiss
"Photons @ RHIC: Summary & Experimental perspectives" [PDF | PPT]	Justin Frantz

Why direct photons ?

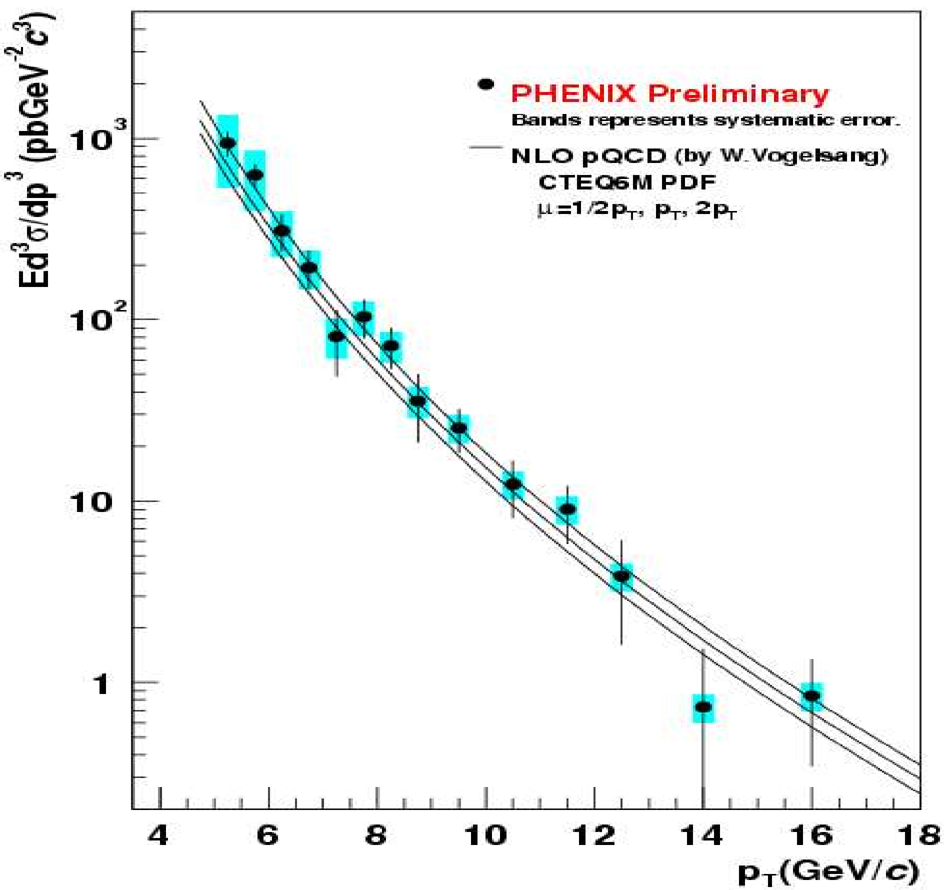
- *[Definition: direct photons = photons not coming from hadronic decays]*
- Advantages:
  - Weakly interacting. Travel unaffected to detectors after production.
  - Direct coupling to (point-like) scatterings.
  - Good theoretical understanding: γ – quark coupling precisely known (QED)
  - "Clean" probes in many QCD environments (pp, pA, AA).
- pp collisions:
  - Access to (polarized) gluon PDF (via qg Compton).
  - Testing ground of pQCD. Baseline reference for AA collisions.
- pA collisions:
  - Access to nuclear modifications of gluon PDF
  - Initial-state multiple scattering (Cronin)
  - Cold nuclear-matter effects
- AA collisions:
  t<~0.2 fm/c: perturbative photons unaffected by QCD medium (monitoring jet quenching: yields and correlations).
  t<~0.6 fm/c: secondary ("cascading") photons – thermalization mechanism
  t<~5 fm/c: thermal photons – access to medium T and EoS (!)
  $\gamma-\gamma$ correlations: space-time size of radiating source

p + p → γ + *X @ RHIC:*
Testing ground for pQCD

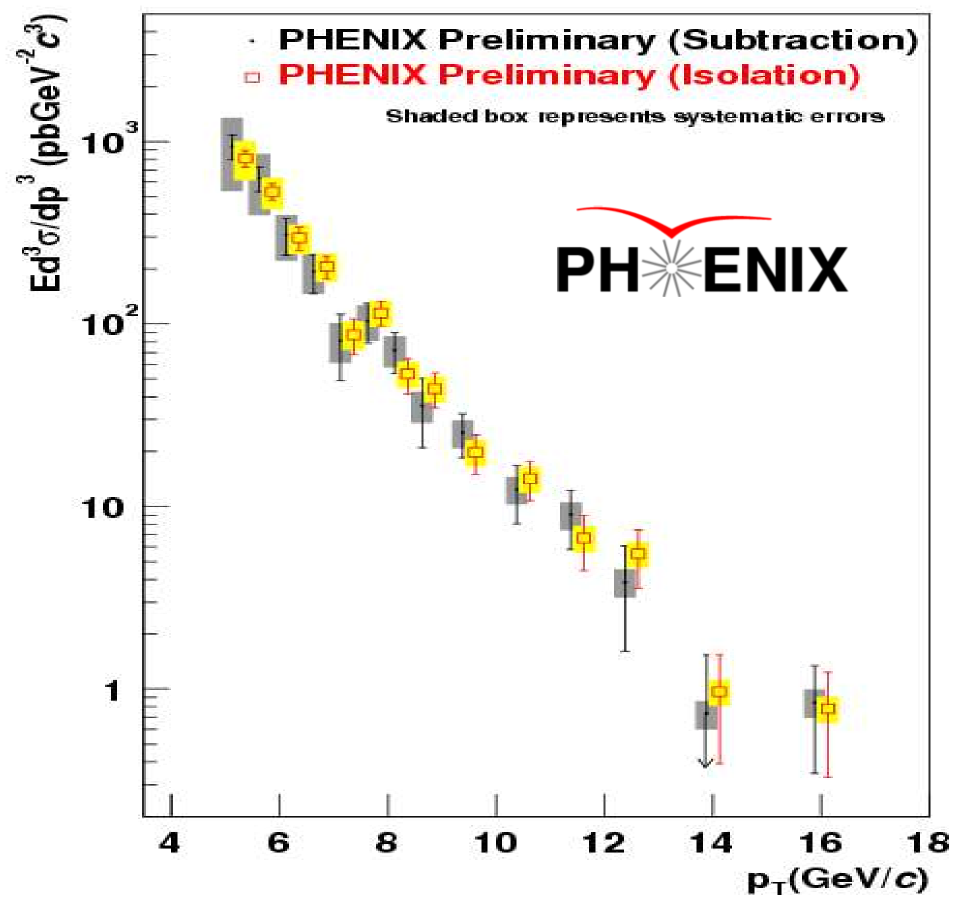
Preliminary p+p → γ+X @ $\sqrt{s}$ = 200 GeV



Hisa Torii



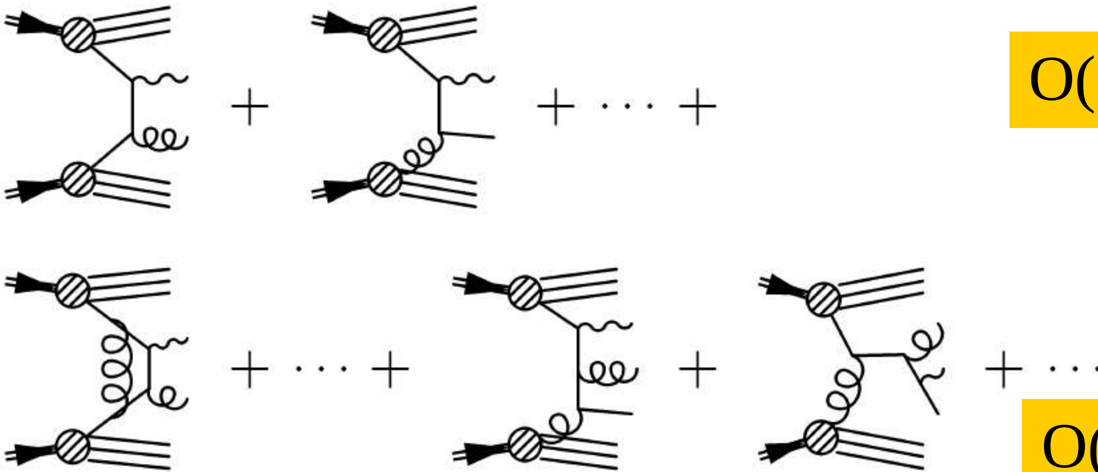
Good agreement w/ NLO pQCD [W.Vogelsang]



Isolated ~ Inclusive spectra

Direct photon components

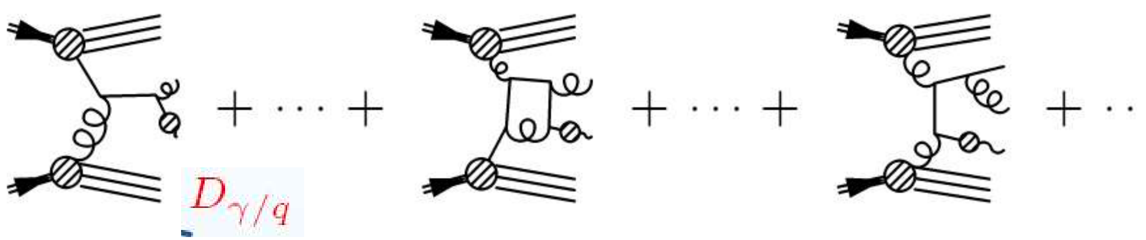
Monique Werlen



O(??$_s$) (Compton, Annihilation)

"Direct" γ

O(??$_s^2$) (NLO and higher order)

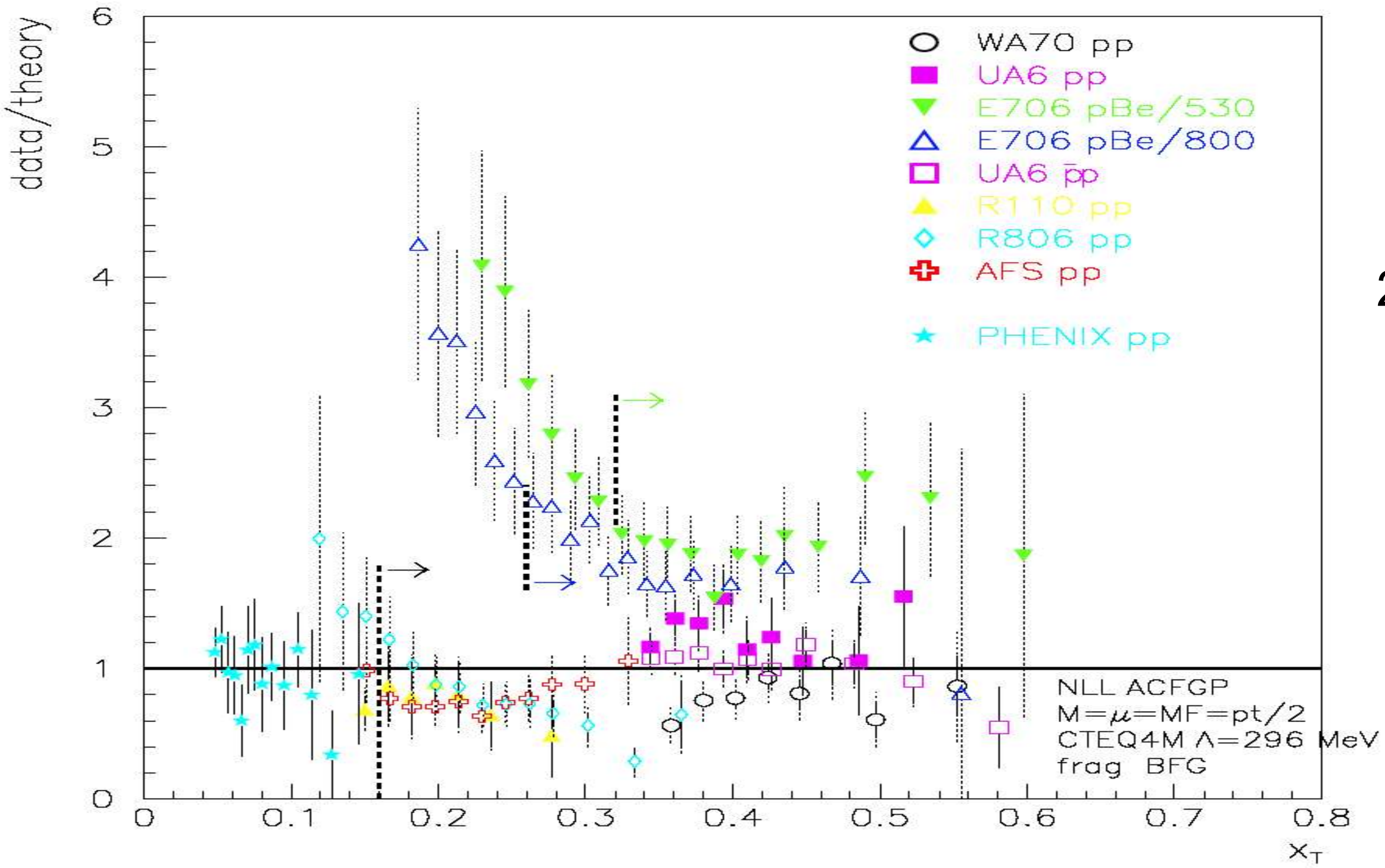


Fragmentation

Only the sum σ(D) + σ(F) is a physical observable

γ "world data" vs. state-of-the-art NLO/NLL

Monique Werlen



INCNLO

$pp, \bar{p}p \to \gamma X$

23 GeV ≤√s≤ 63 GeV

Calculations
by Annecy Group

Aurenche, Fontannaz, Guillet, Kniehl, Pilon, M.Werlen EPJC9,107 (1999)

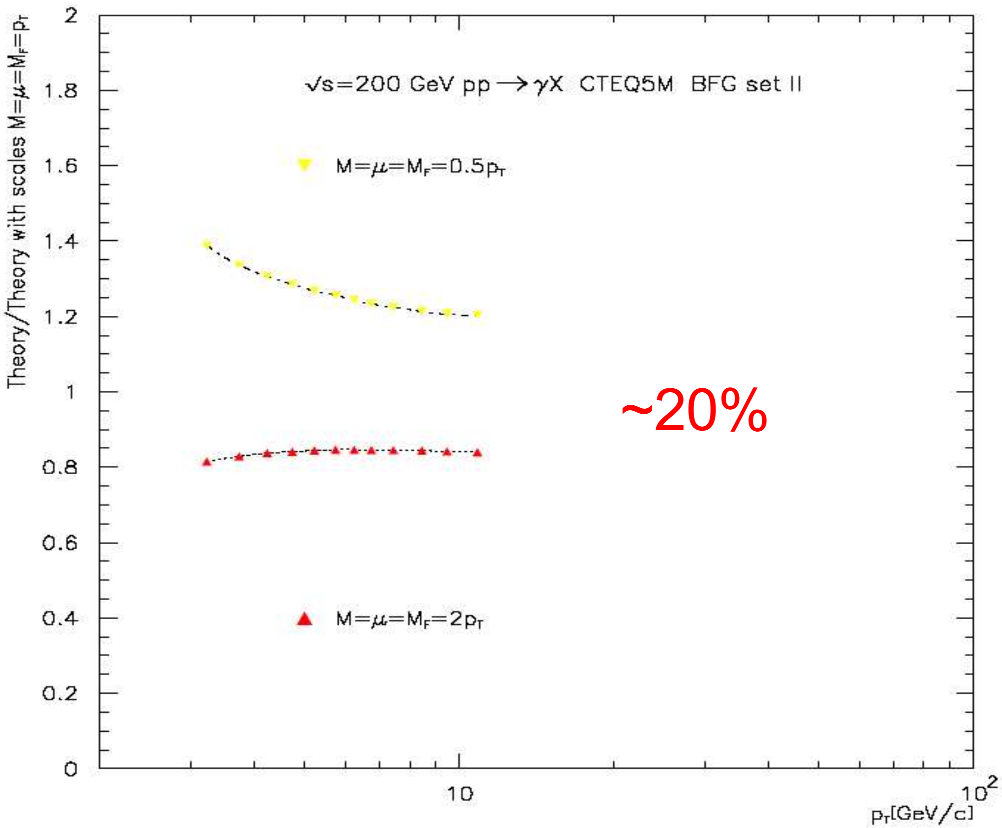
- PHENIX preliminary data in very good agreement w/ NLO QCD predictions (like most of ISR & fixed target data).
- Enhanced pBe (E-706) production: non-perturbative k_T + Cronin ? (partially) accounted for by latest NLL gluon resummation calculations ?

Theoretical uncertainties at RHIC

Monique Werlen

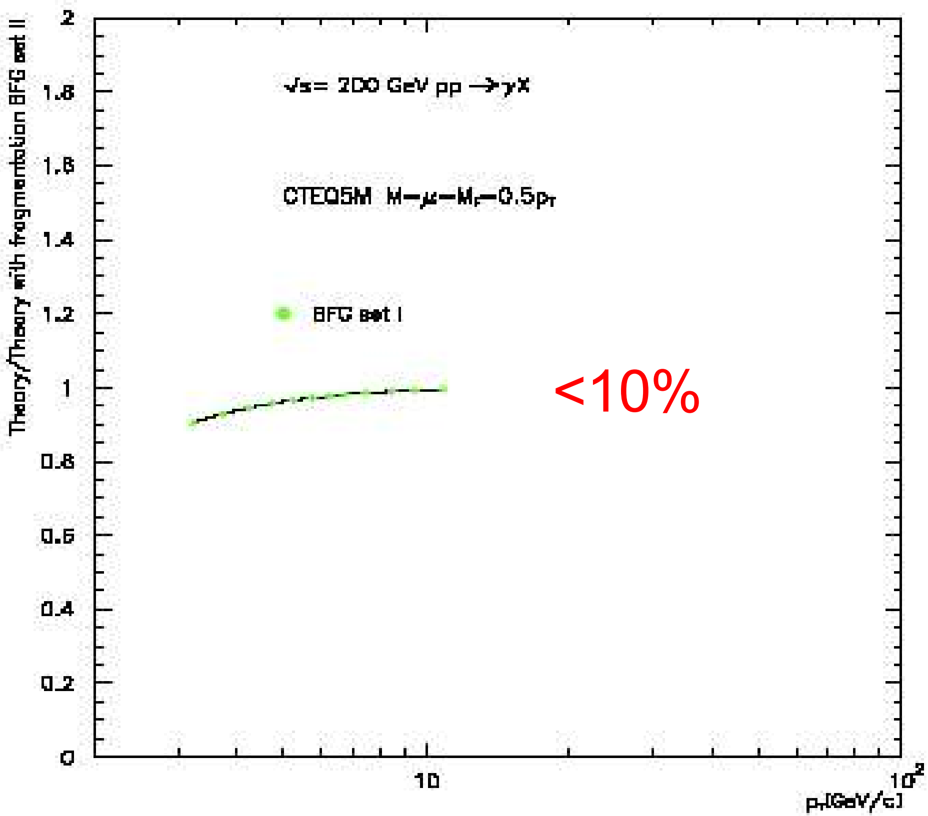
- Relatively small:

Scales uncertainty



~20%

Fragmentation BFGI/BFGII



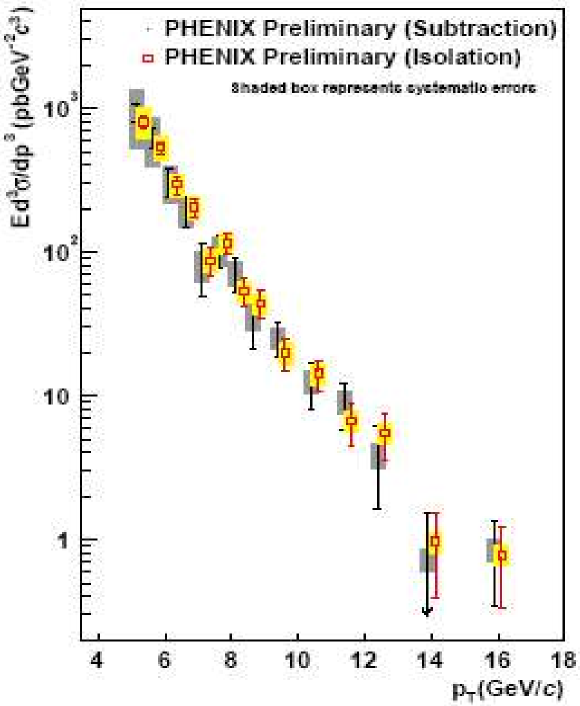
<10%

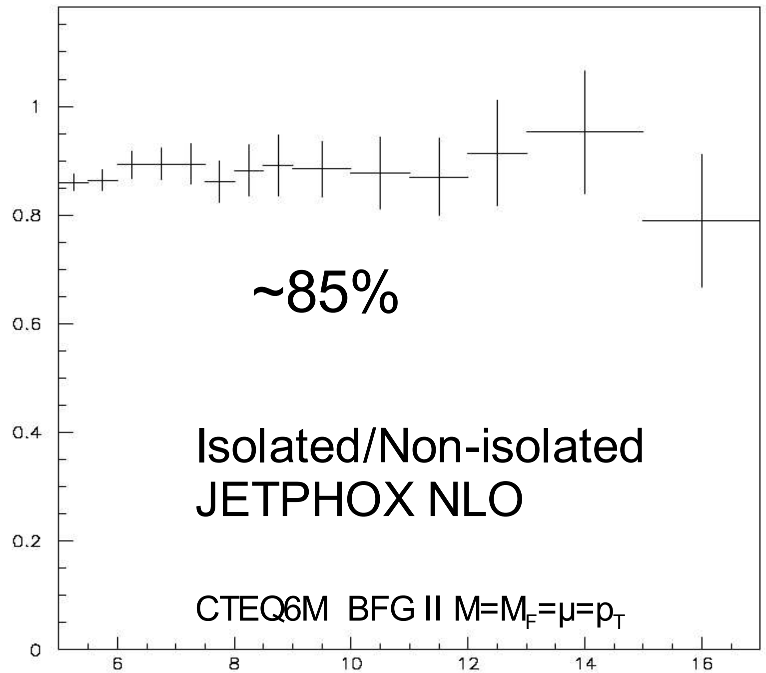
Isolated versus non-isolated photons

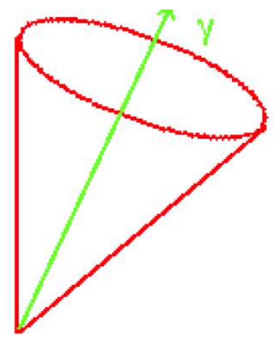
Monique Werlen

- Handle on the γ fragmentation component via "isolation cut" measurement (important also for AA studies of possible (?) γ energy loss):

K.Odaka hep-ex/0501066







in a cone around photon with:

$R=\sqrt{\Delta\eta^2 + \Delta\phi^2}$ =0.5

E_T (parton) ? E_T max =0.1$E_?$

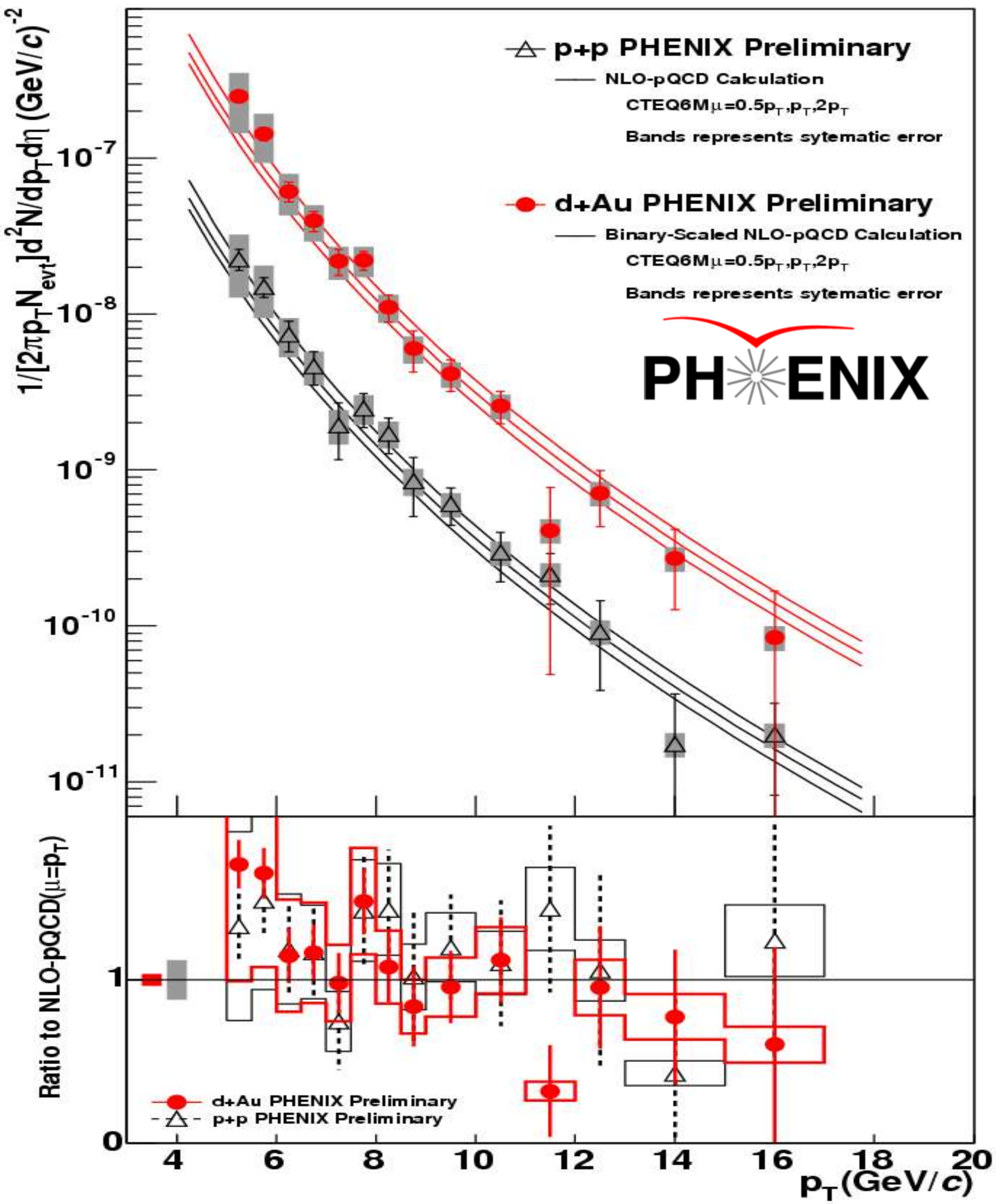
- Isolated spectrum: yield depends on applied isolation criteria.
- Inclusive ≈ isolated (for R=0.5): Small non-isolated production in data and theory @ RHIC

d + Au → γ + *X @ RHIC:* *Probing cold nuclear-matter medium*

Preliminary d+Au → γ+X @ $\sqrt{s_{NN}}$ = 200 GeV

Hisa Torii

- The analysis method is similar to p+p
- NLO pQCD Calculation
  p+p collisions [W.Vogelsang]
- CTEQ6M + GRV
- Scale(renormalization and factorization scale) 0.5,1.0,2.0p_T
- Averaged number of collisions (8.42) from the Glauber model was multiplied to the calculation.



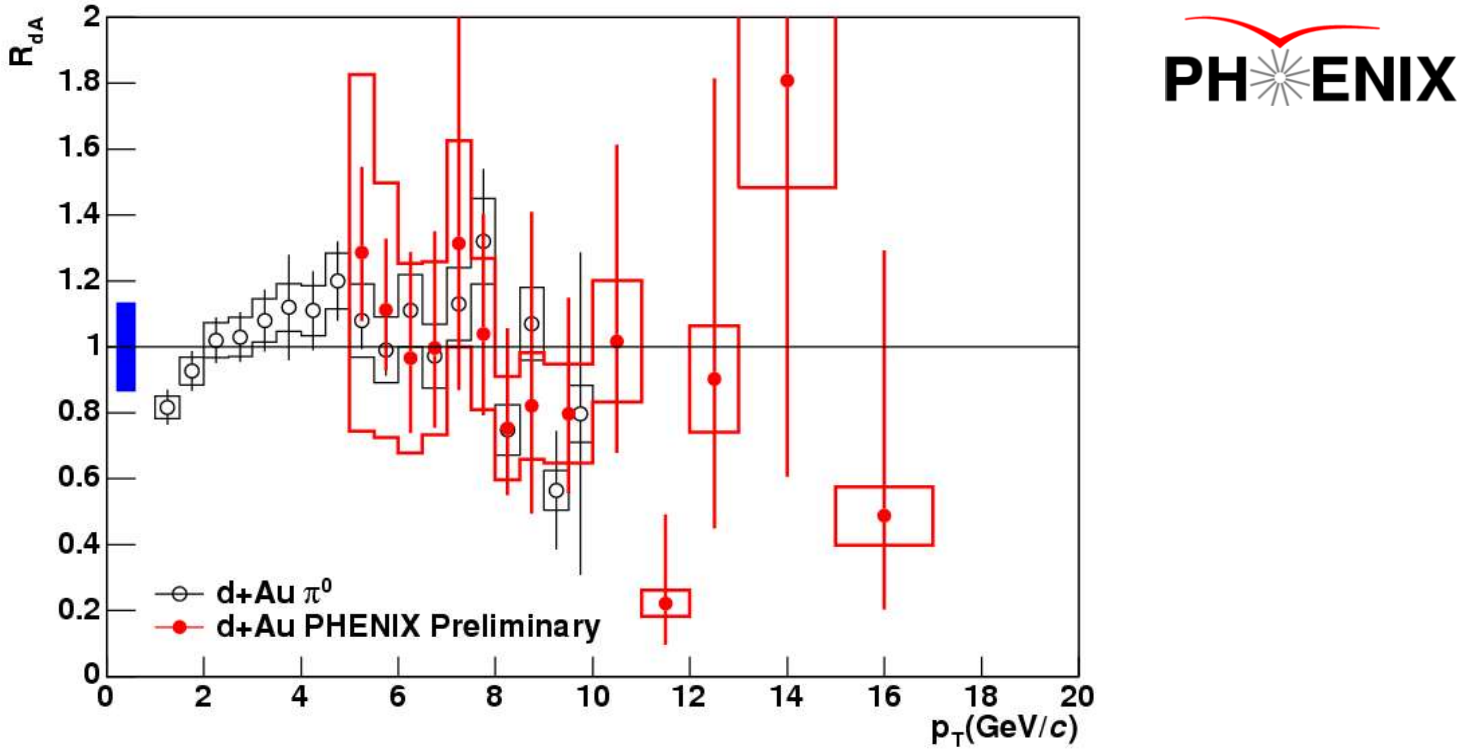
Result consistent with the binary – scaled NLO-pQCD calculation

Nuclear effects in d+Au @ $\sqrt{s_{NN}}$ = 200 GeV

Hisa Torii

- Nuclear Modification Factor:

$$R_{dA} = \frac{\left[d^2N_{dA}/dp_T d\eta dN_{evt}\right]}{\langle N_{coll}\rangle / \sigma_{pp}^{inel} \times \left[d^2\sigma_{pp}/dp_T d\eta\right]}$$



Consistent with ~1. No modification within errors

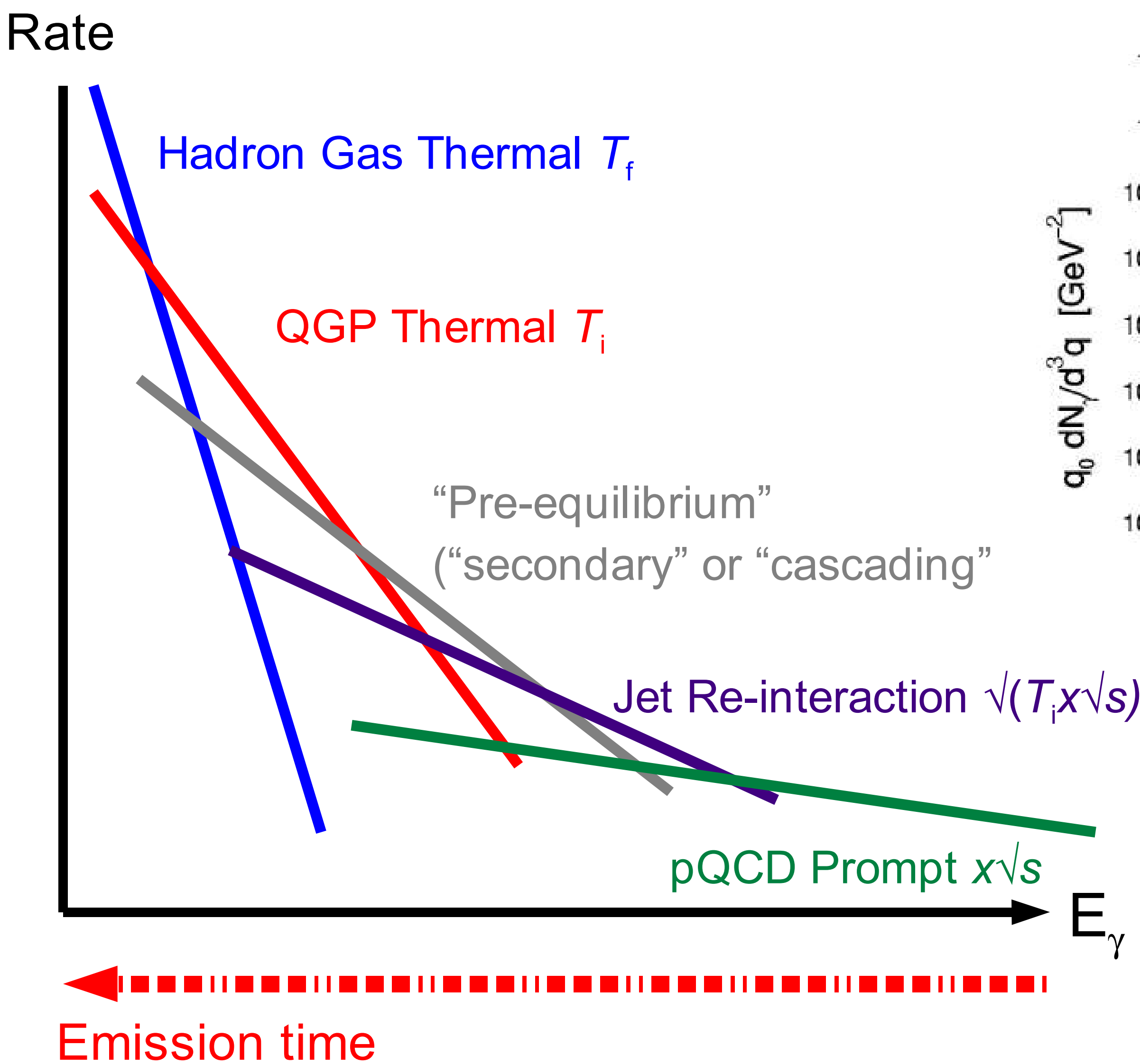
Small or null Cronin as measured in π^0

A + A → γ + *X*:
Probing hot & dense QCD medium

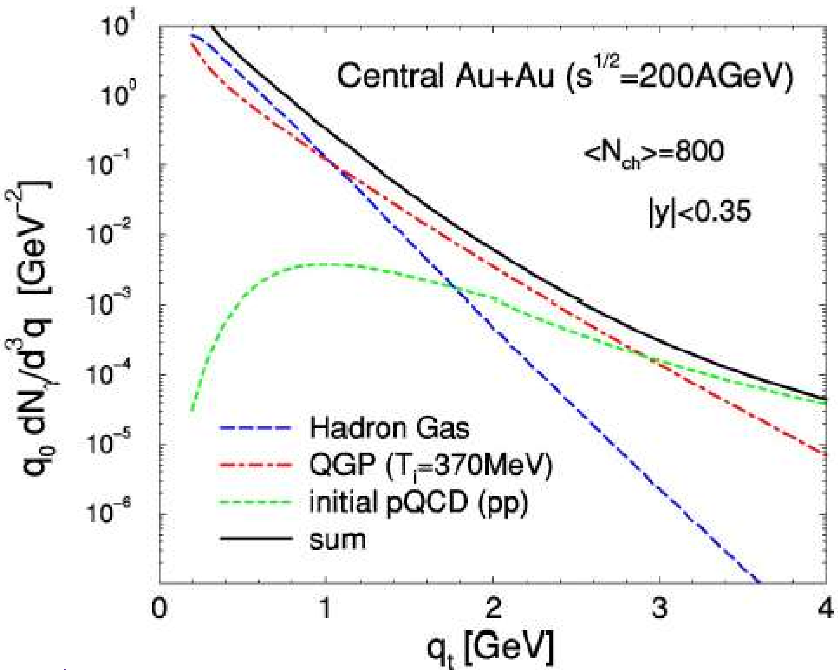
Photons in AA @ RHIC: different contributions

Paul Stankus

- Photons = sum of emission from the entire history of nuclear collision:



PHYSICAL REVIEW C **69**, 014903 (2004)

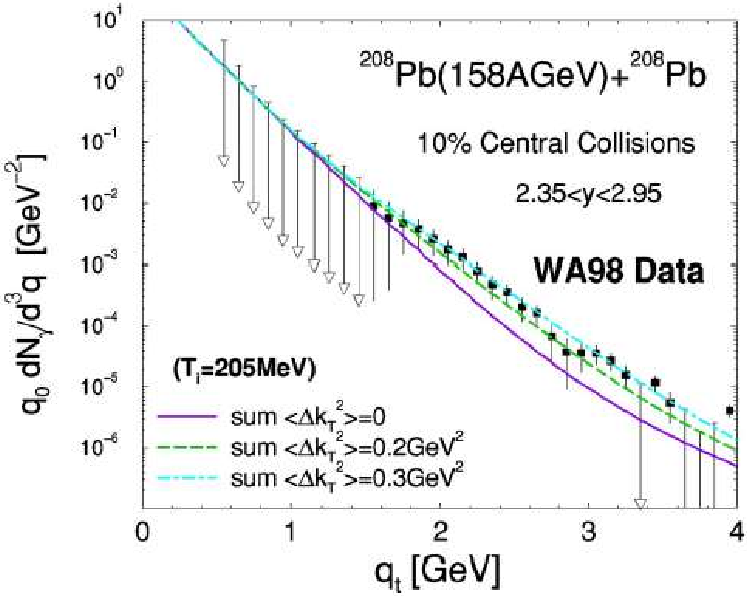


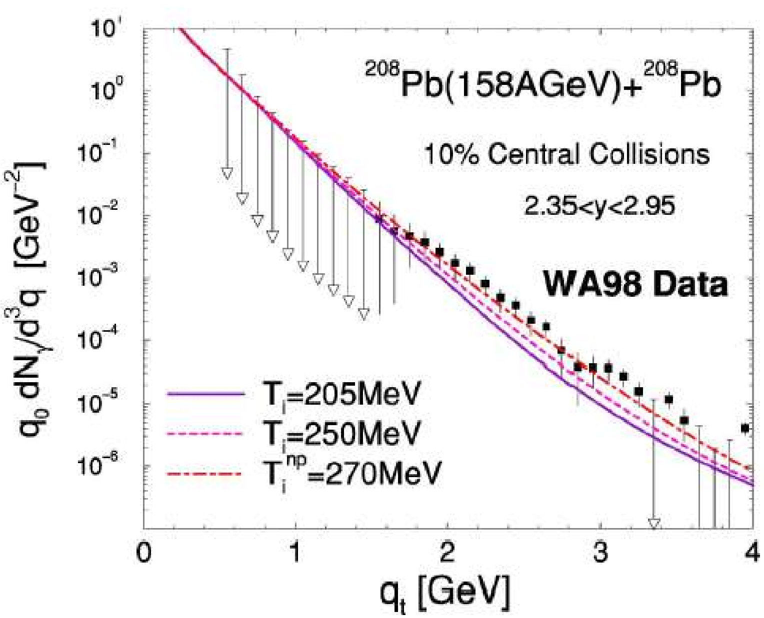
Turbide, Rapp, Gale

Photons in AA: the pre-RHIC (fixed-target) era

Paul Stankus

- Summary:





1. The early days had more enthusiasm than rigor.
2. In S+Au upper limits on thermal photons were used to set limits on initial temperatures; weak evidence for high # d.o.f.
3. Direct photon spectrum (ie upper *and* lower limits) observed in heavier Pb+Pb collisions.
4. Thermal radiation from boosted Hadron Gas may dominate thermal radiation from cooler QGP.
5. Ambiguity between pQCD sources with intrinsic plus nuclear k_T effects, and hotter thermal sources. More definitive pQCD calculations would be a great help.
6. Limiting initial temperatures in Pb+Pb possible, not yet done.

AuAu → γ(π⁰) +X @ $\sqrt{s_{NN}}$ = 130, 62.4 GeV (STAR)

Marcia Moura

- Measurement obtained from γ conversion in TPC
- e^+ and e^- are selected through dE/dx

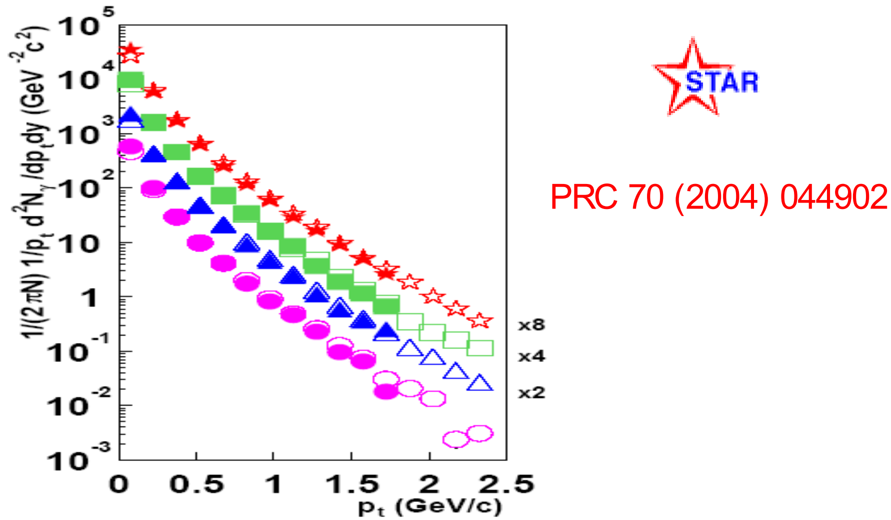
Efficiency

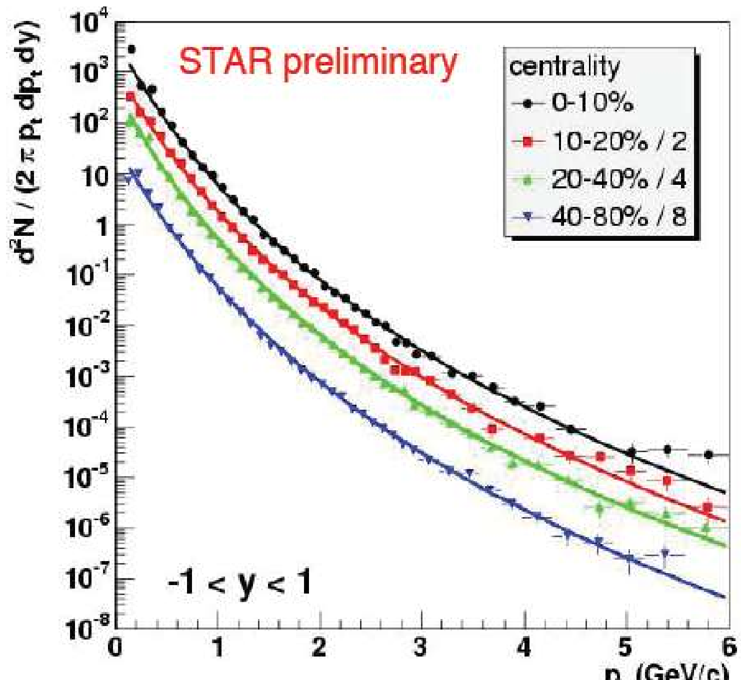
- γ ~ 2%
- π^0 ~ 0.04%

Goes lower in p_T than PHENIX meas.
(important ! see later)

- Error bars: statistical only
- Systematic uncertainty: 20%
- Combinatorial background has been subtracted
- Other contributions, such as Λ decays, were verified to be negligible

Centrality dependence





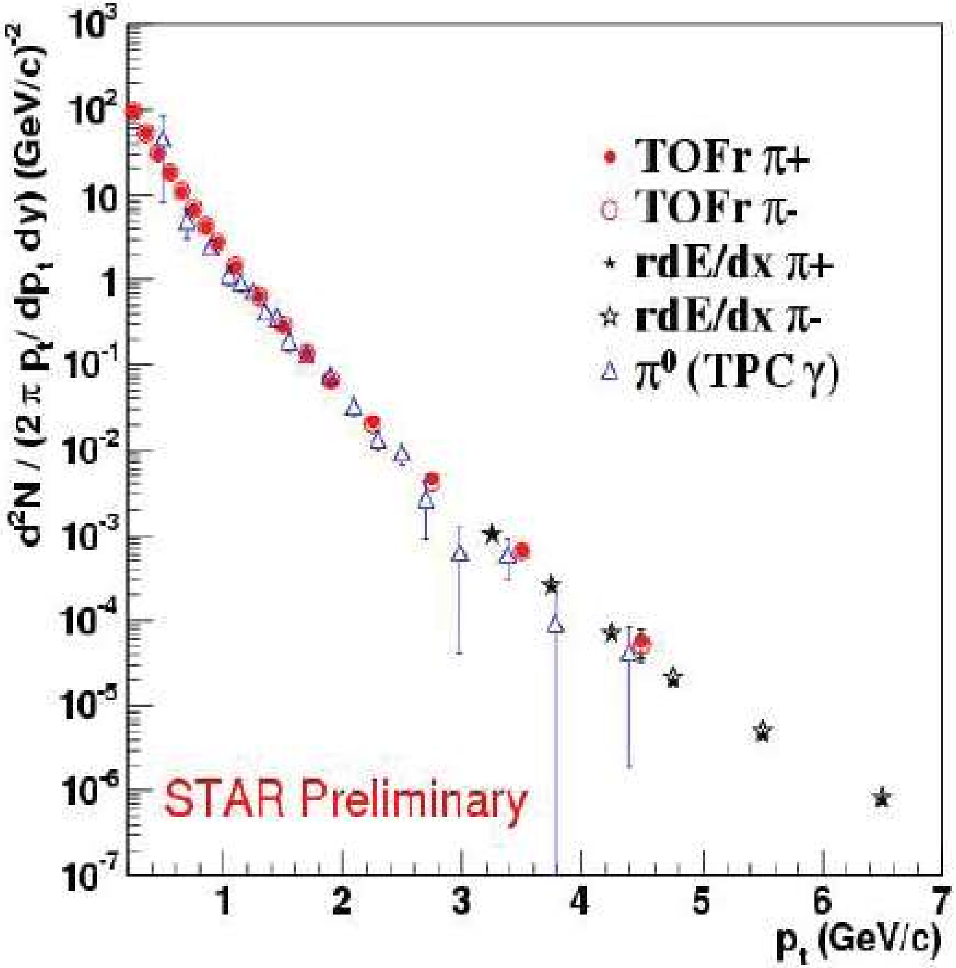
AuAu → π^0 +X @ $\sqrt{s_{NN}}$ = 62.4 GeV (STAR)

Marcia Moura

- Direct photons accessible (hopefully soon) after subtraction of measured π^0 (and other meson) decays:

- Each point is the gaussian fit of the 2γ invariant mass distribution for a given p_T
- ~10 MeV width, depending on p_T
- Systematic uncertainty of 30%

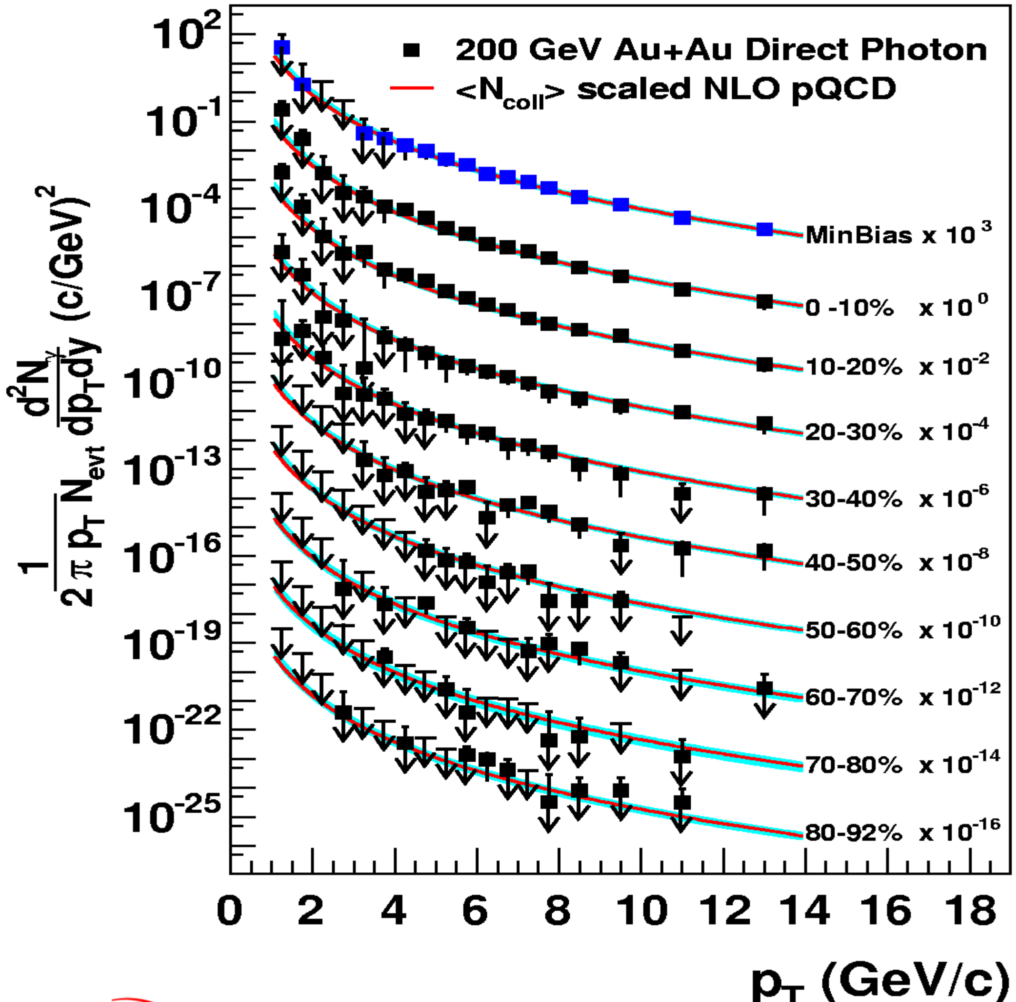
Comparison of π^0 to π^+ and π^- from STAR TPC *dE/dx* and TOFr shows good agreement.



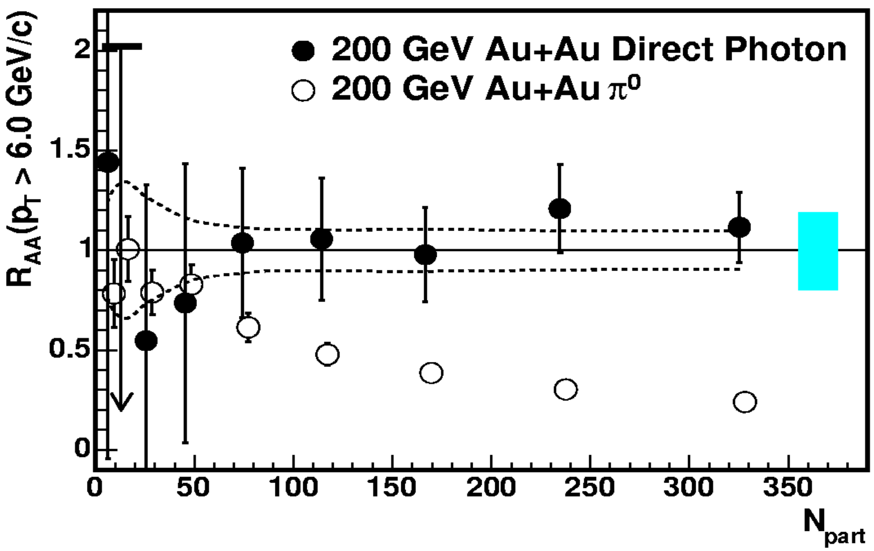
Au+Au → γ+X @ $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)

Hisa Torii

- Direct photon production in Au+Au (all centralities) consistent w/ p+p incoherent scattering ("N_{coll}-scaled" pQCD) predictions:



$$R_{AA}(p_T, y; b) = \frac{\text{“hot/dense QCD medium”}}{\text{“QCD vacuum”}} = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T},$$



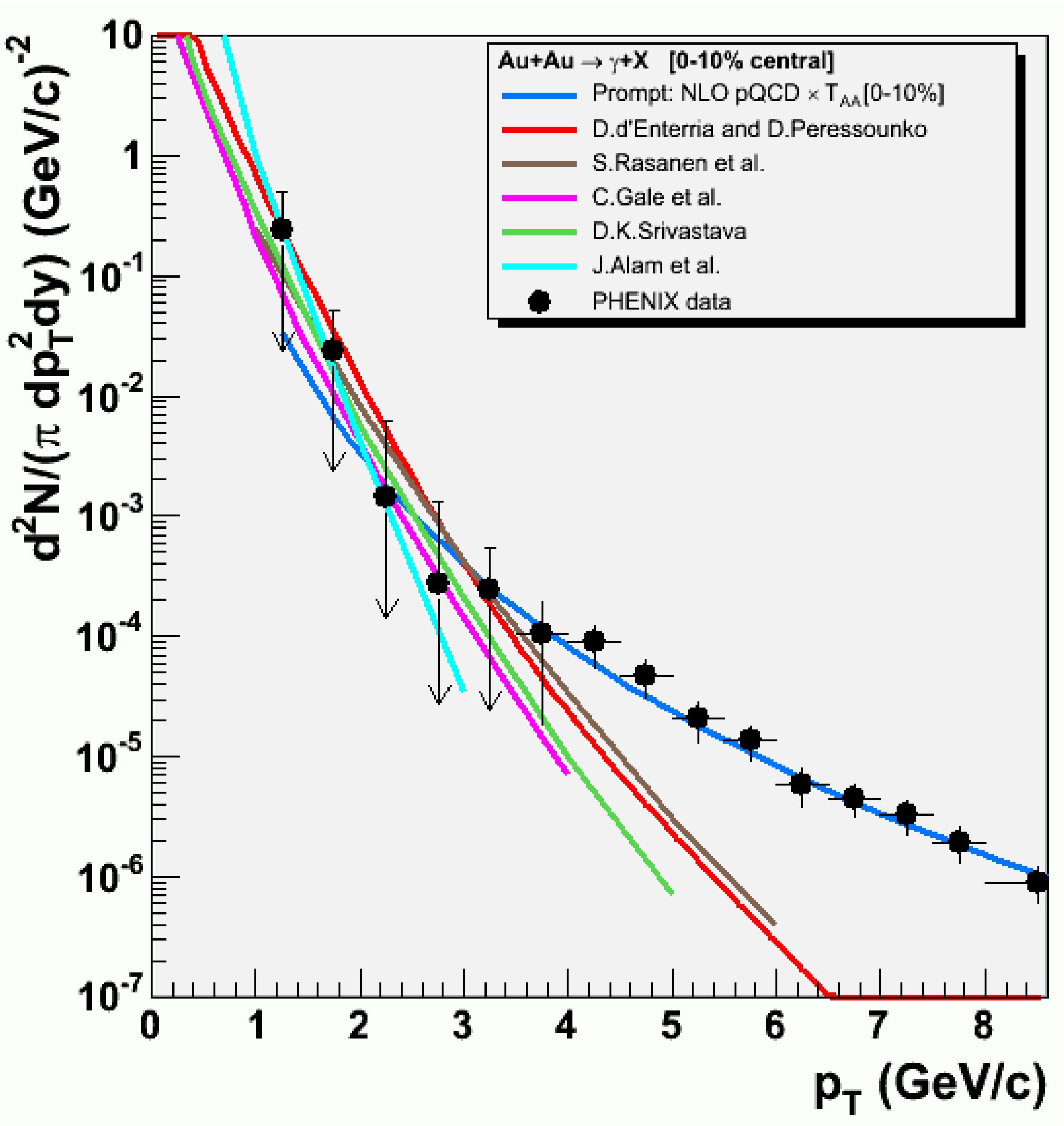
- Direct photon production in Au+Au unmodified by QCD medium.

PHENIX To appear in PRL nucl-ex/0503003

Au+Au → γ+X @ 200 GeV. Theory vs data: prompt + thermal

Dmitri Peressounko

- PHENIX 0-10% AuAu photons compared to 5 hydro (+ pQCD) calculations:



All calculations predict considerable thermal contribution for p_T < 3 GeV

All calculations agree with current (upper limit) data.

Calculations with similar initial time (temperature) result in similar spectra. Dependence on used emission rates & details of description of evolution is modest.

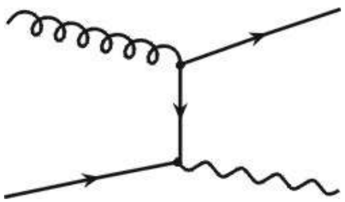
Theory vs data: prompt + (cascade) + thermal

Steffen Bass

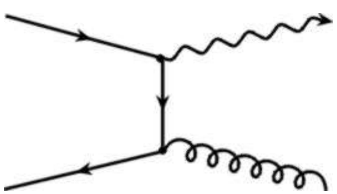
- Photon yield very sensitive to parton-parton rescattering

relevant processes:

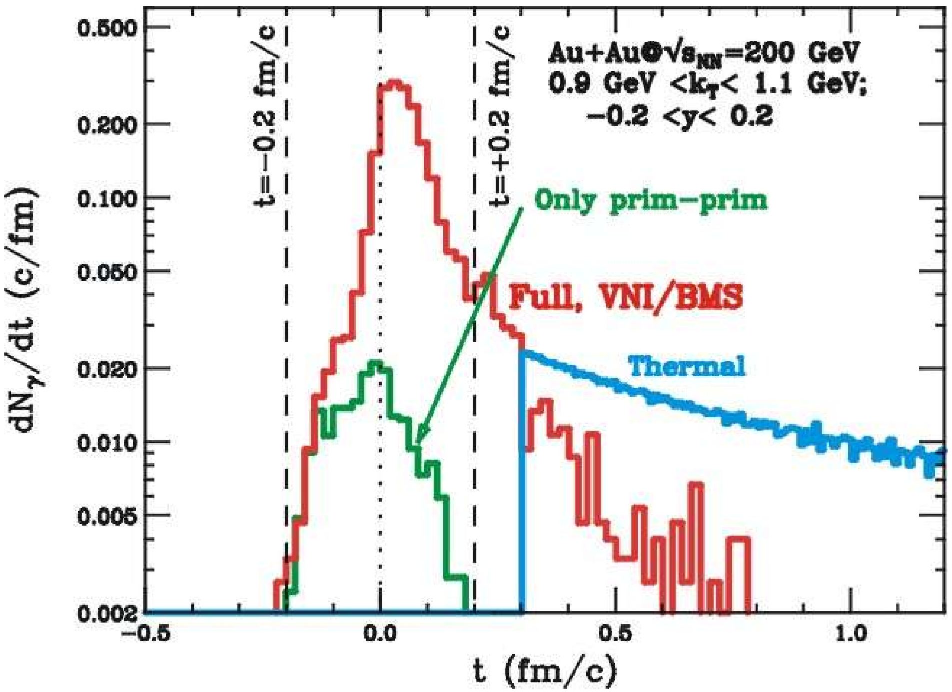
•Compton: **q g → q γ**



•annihilation: **q qbar → g γ**



•bremsstrahlung: **q* → q γ**



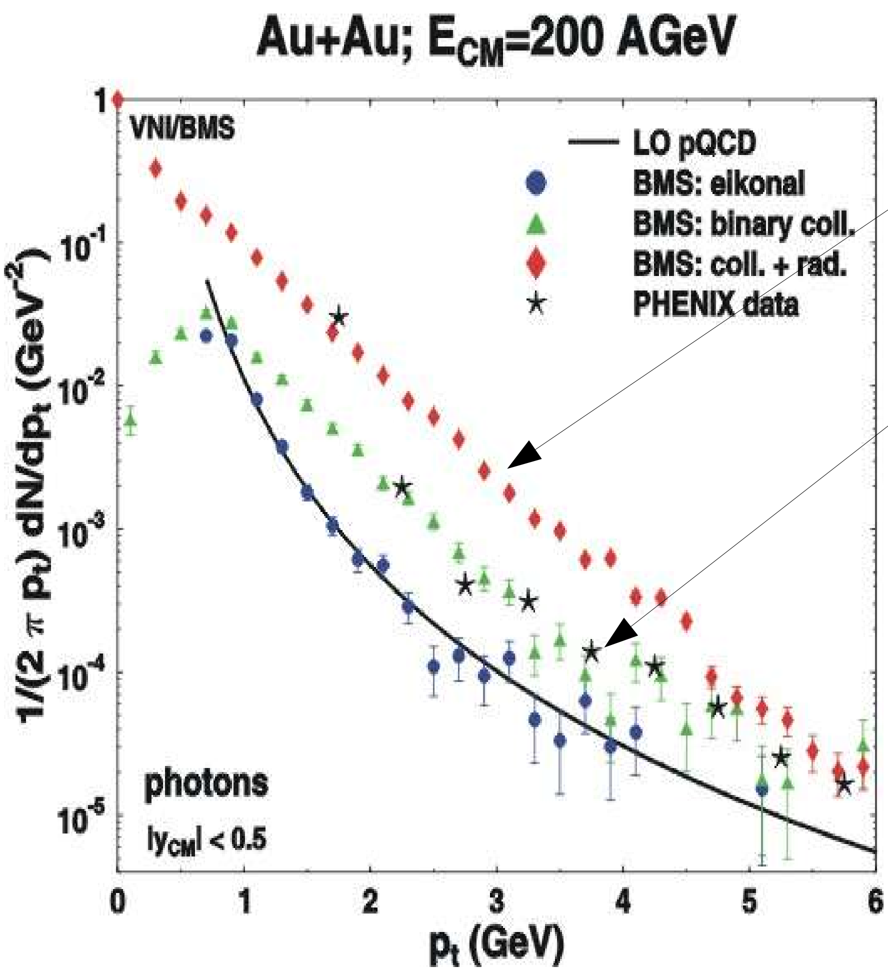
• Short emission time in the PCM, 90% of photons before 0.3 fm/c

Hydrodynamic calculation with τ_0=0.3 fm/c allows for a smooth continuation of emission rate

Theory vs data: prompt + (cascade) + thermal

Steffen Bass

- LPM destructive interference important !



PCM w/o LPM:

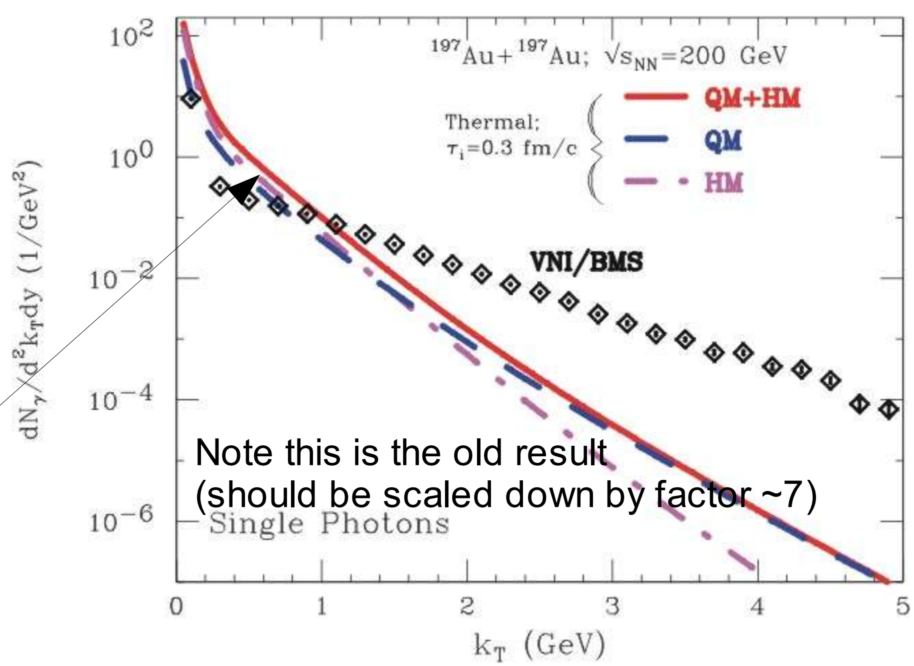
Large overprediction of γ yield

PCM with LPM:

γ yield for p_t < 6 GeV strongly reduced

strong p_t dependence of LPM suppression

good agreement with data



below ~3 GeV/c, need to take thermal contributions into account

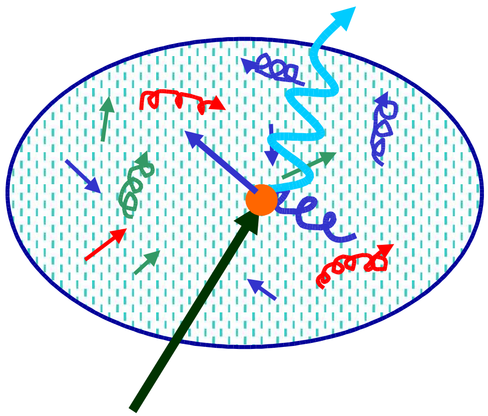
Theory vs data: extra jet-photon contribution

Steffen Bass

- Latest calculations by Duke group:

plasma mediates

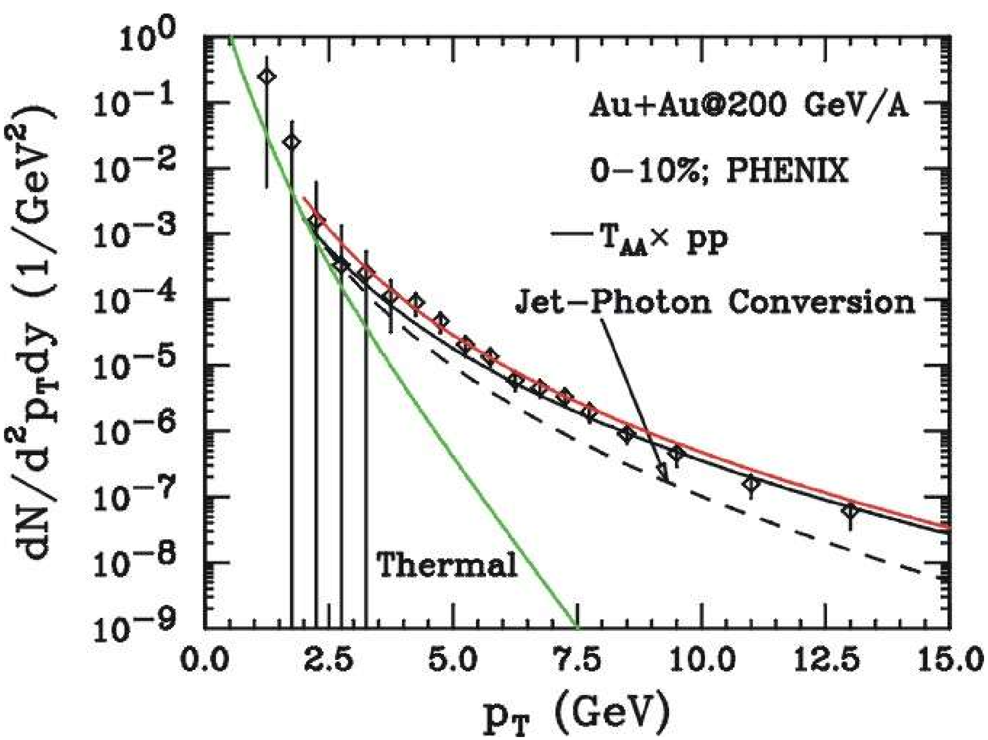
a jet-photon conversion:



Fries, Muller, Srivastava
PRL 90 132301 (2003)

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

[Fries, Mueller & Srivastava, ms in preparation]



jet passing through the medium:

large energy loss: jet quenching.

electromagnetic radiation (real & virtual photons) from jet-medium interactions.

can escape without rescattering

use as probe of energy loss?

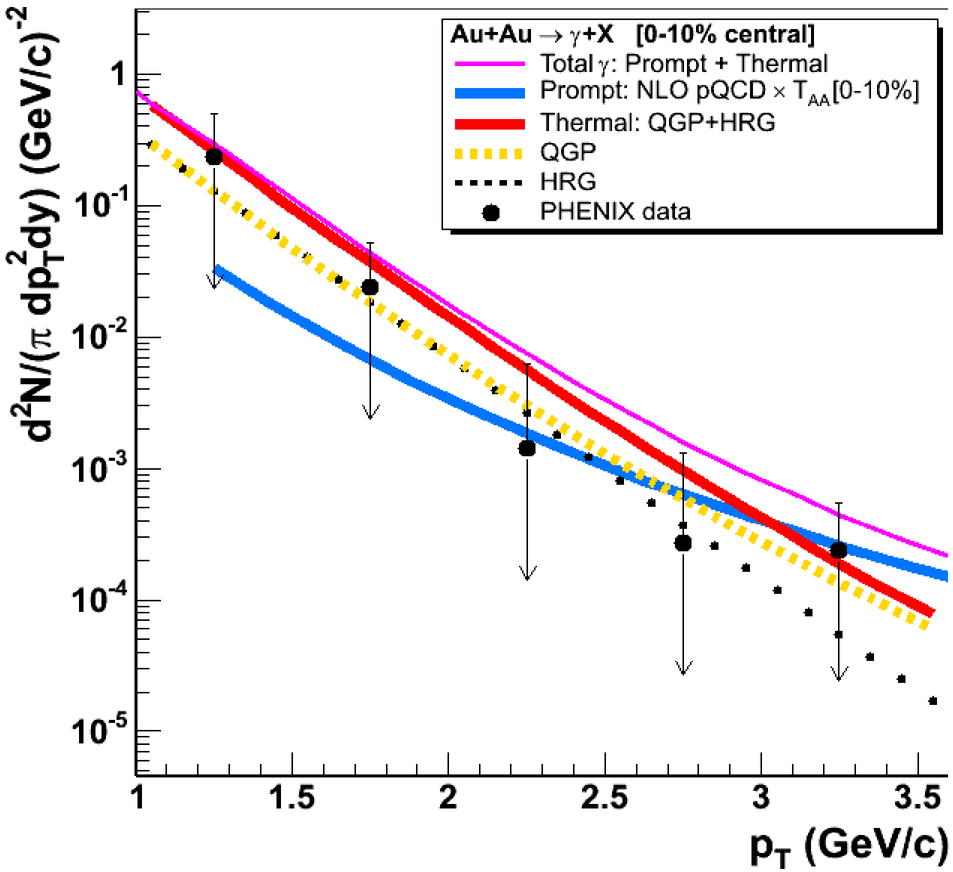
Reduced effect compared to previous calculations (consistent K-factors for γ and jets now).

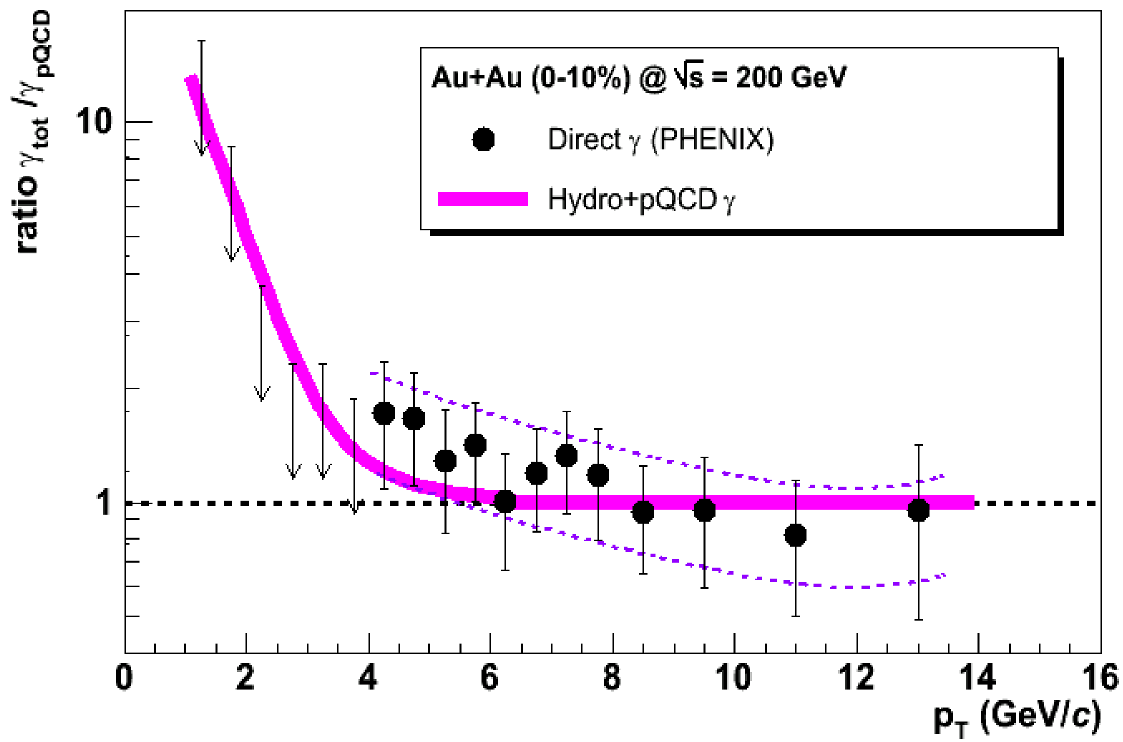
For p_t<6 GeV, FMS photons give still significant contribution to photon spectrum: 50% @ 4 GeV

Back to the "thermal region" (p_T ~ 1 – 4 GeV/c)

Dmitri Peressounko

- Current upper limits in p_T = 1 – 4 GeV/c consistent w/ possible thermal γ comp.





D.d'E. & D.Peressounko
(in preparation)

- Caveat 1: Upper limits only as of now (data could be lower).
- Caveat 2: Prompt γ reference used is NOT real p+p data but NLO pQCD: Large uncertainties below p_T ~ 4 GeV/c (unknown contribution of dominant jet bremsstralung component). Need direct p+p measurement for p_T< 4 GeV/c

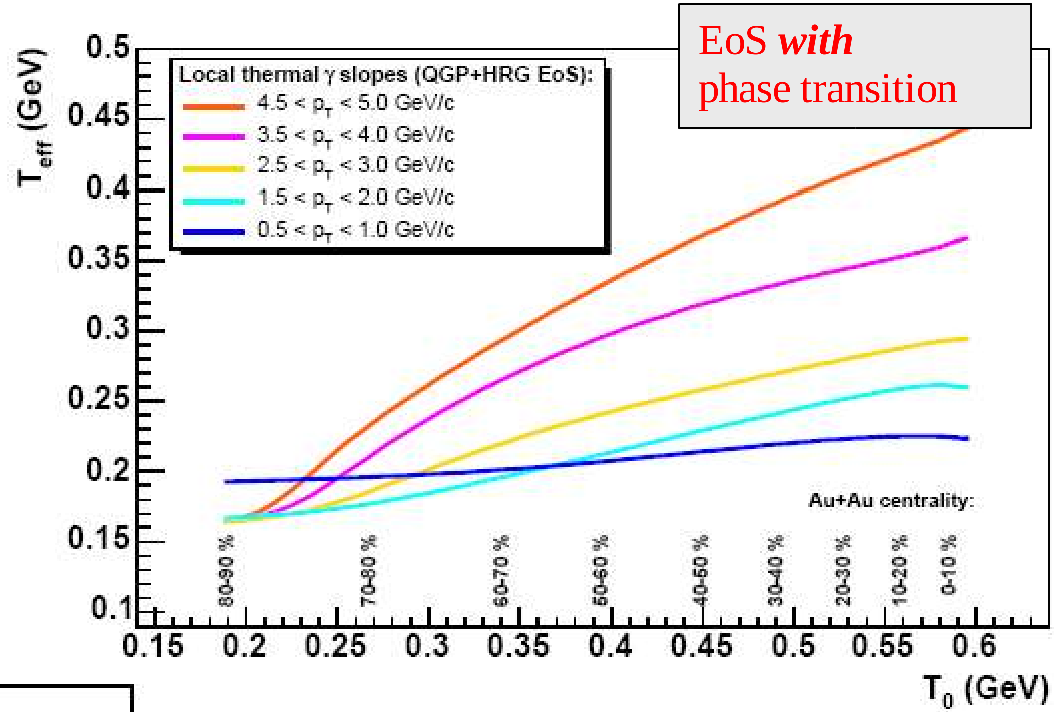
QGP temperature from thermal γ

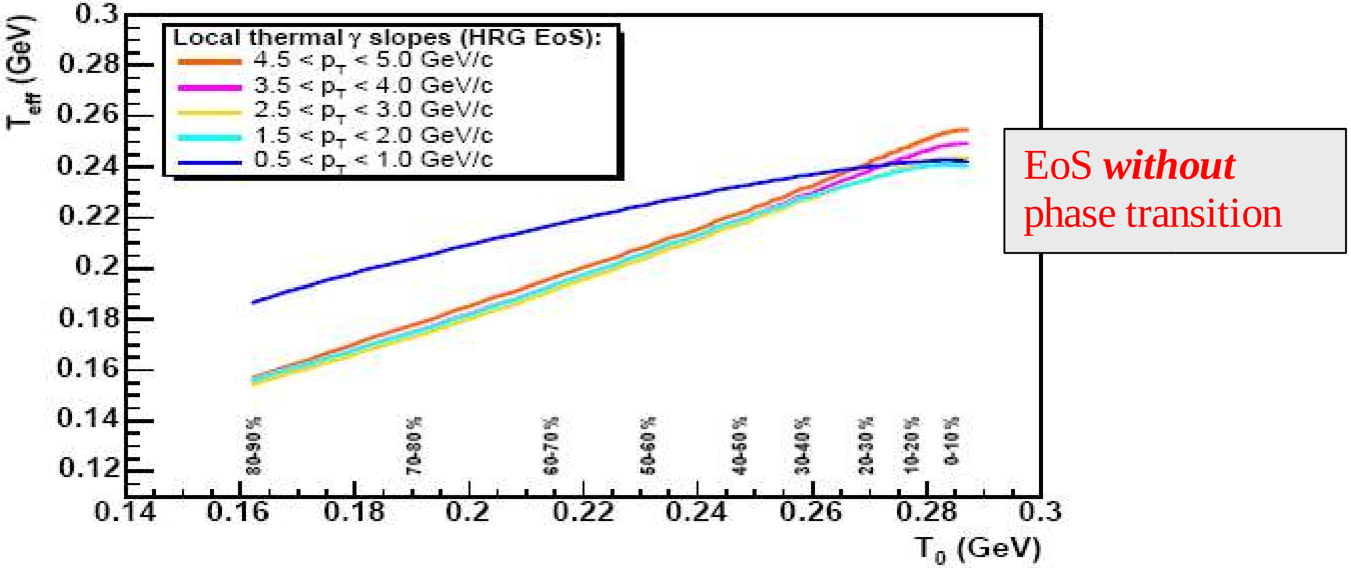
Dmitri Peressounko

- Good correlation between exponential photon slope and initial temperature:
- T_{eff} dominated by hottest phase

Small smearing of effective temperature due to:

- Final thickness of matter
- Temperature gradients T(r)
- Collective velocity





D.d'Enterria and D.Peressounko, nucl-th/0503054

QGP "EoS" from thermal γ & hadron multiplicities (I)

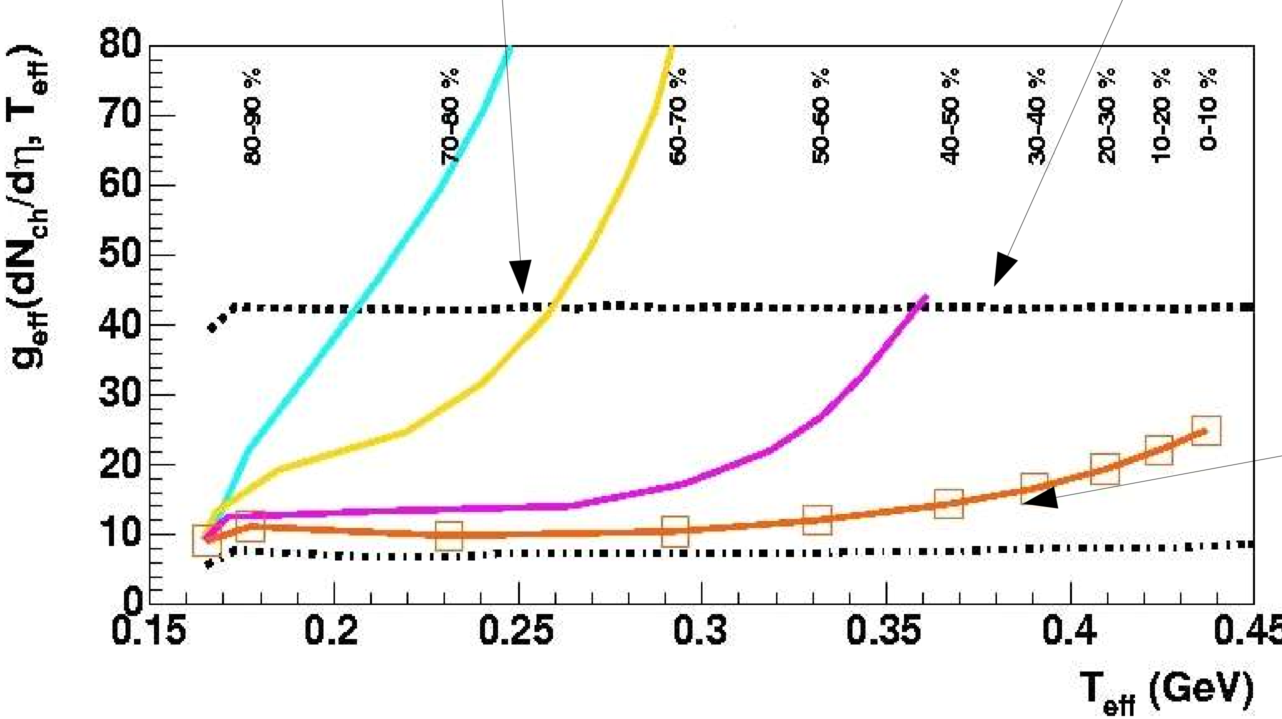
Dmitri Peressounko

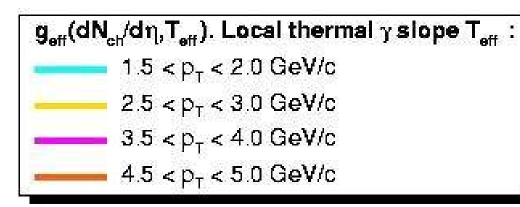
- Access EoS correlating thermal γ slopes (temperature) & hadron multiplicities ($dN_{ch}/d\eta \propto$ entropy in isentropic expansion) measured in diff AuAu centralities.
- Evolution of the effective # of degrees of freedom, g(s,T), with centrality:

$$g_{hydro}(s_0,T_0) = \frac{45}{2\pi^2}\frac{s_0}{T_0^3}(\hbar c)^3$$

$$g_{eff}(dN_{ch}/d\eta,T_0) = \frac{100}{\pi^2}\frac{dN_{ch}/d\eta}{A_T\tau_0\, T_0^3}(\hbar c)^3$$

- $g_{hydro}(s,T) \sim 42$ (QGP) for all centralities: AuAu-200 GeV (medium too "hot", even periph.)





- ideal-gas QGP "plateau" in # d.o.f. should be observable in the data.

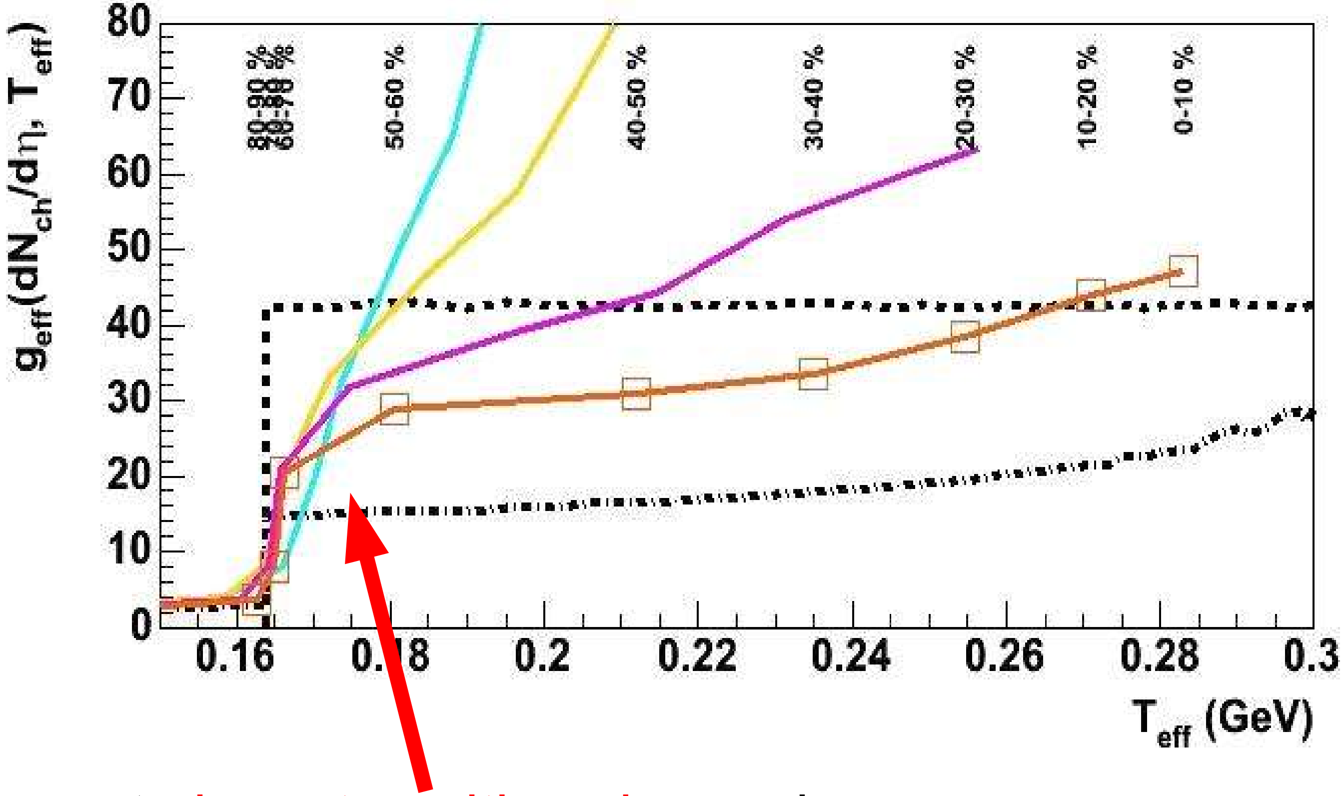
D.d'E. & D.Peressounko
nucl-th/0503054

QGP "EoS" from thermal γ & hadron multiplicities (II)

Dmitri Peressounko

- AuAu @ 200 GeV produces "too hot" medium (QGP for all centralities). Insensitive to any centrality-dependent change due to QCD phase transition.
- Preliminary hydro calculations for AuAu @ 62 GeV :

$\tau_i = 4R/\gamma$ = 0.45 fm/c



D.d'E. & D.Peressounko (in preparation)

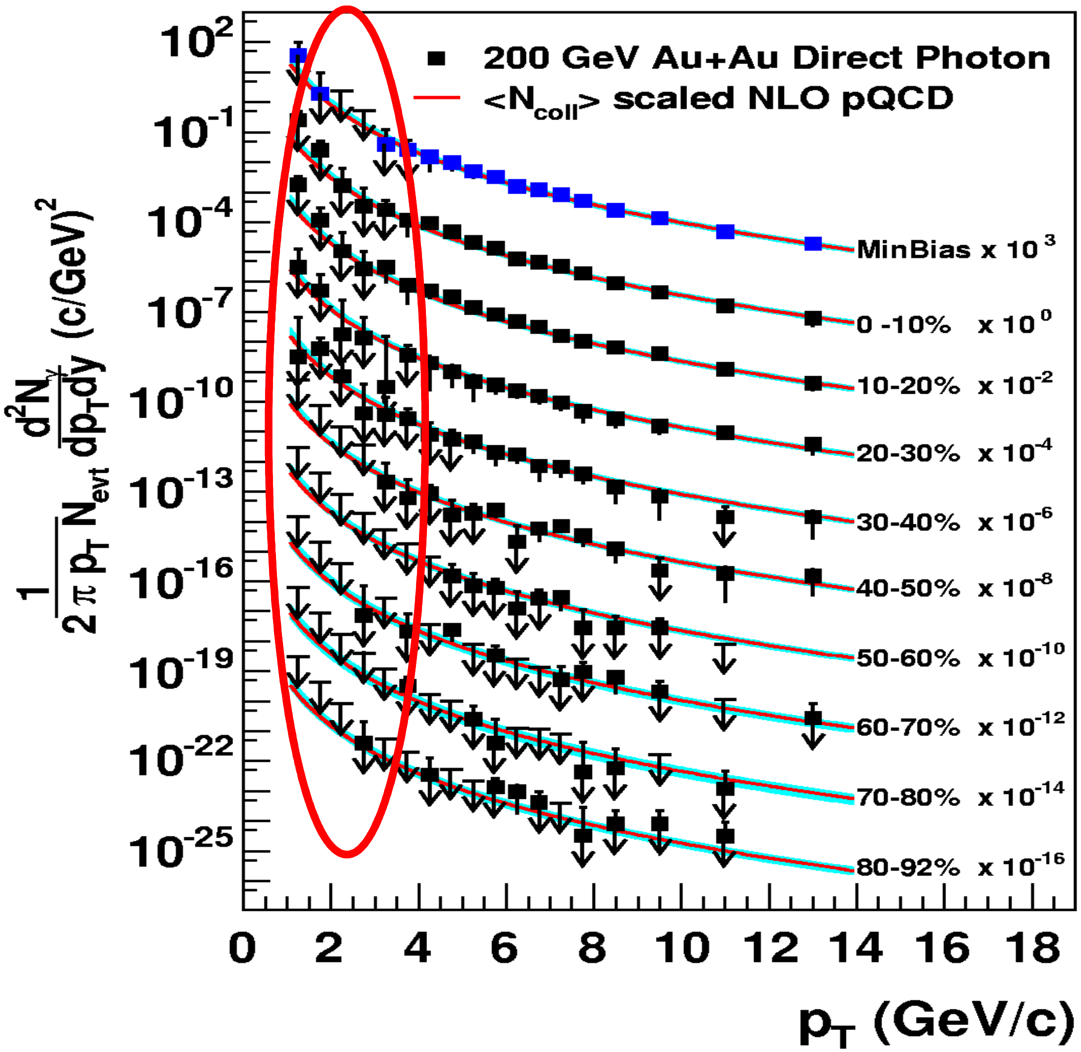
- Apparent phase transition change in $g_{eff}(dN_{ch}/d\eta, T_{eff})$ for centrality 50-60%
- Should show up in more central collisions for lighter / lower-$\sqrt{s}$: AuAu, CuCu @ 62 GeV. AuAu, p+p @ $\sqrt{s}$ = 40 GeV (RHIC-II) ?

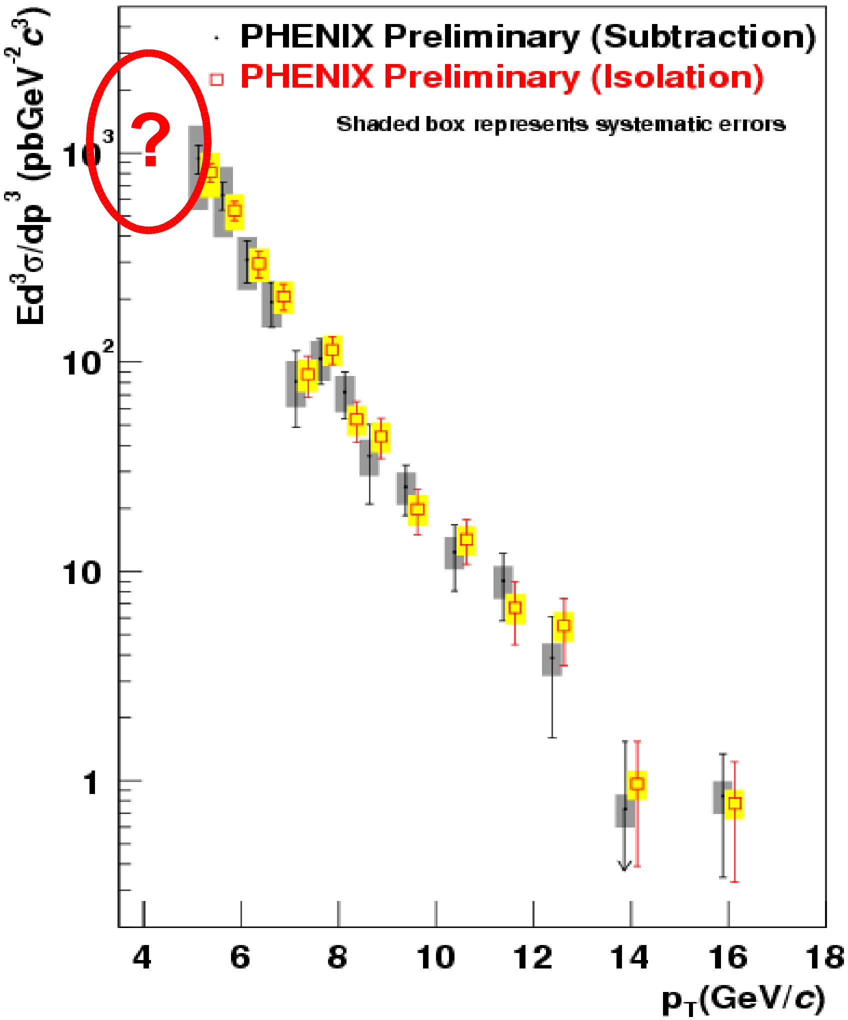
Reducing systematics at low p_T !

- Isolating the thermal component requires:

  (i) small systematic uncertainties in AA and pp !

  (ii) within $p_T \sim 1 - 4$ GeV/c !



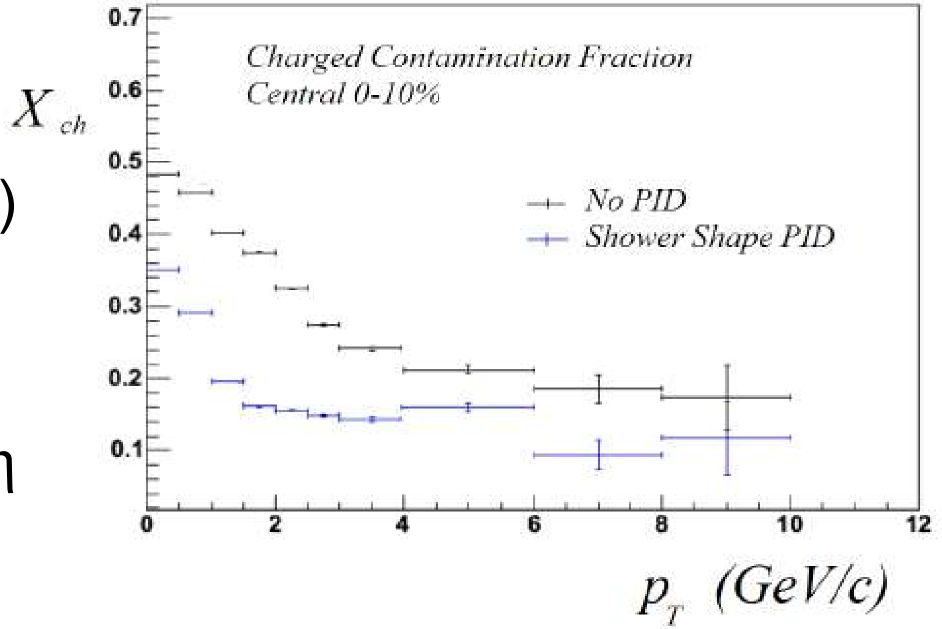


"Tips" from the expert (I): Dominating systematics

Justin Frantz

- EM Calorimeter "Base Method": Count Cal Hits
- PHENIX Calorimeters (seg. $\Delta\phi\Delta\theta \sim 0.01^2$) PbSc/Gl MidRap
- STAR Calorim. (BC seg. $\Delta\phi\Delta\theta \sim 0.05^2$ MidRap, ECC ForwardRap seg smaller)

- Limitations at low p_T :
- Hadronic showers (50% @ p_t < 1GeV)
- Resolution ($\sigma_E/E = A/\sqrt{E}+B$)
- Cluster splitting effects
- Decay bckgd: Acceptance for π^0 and η



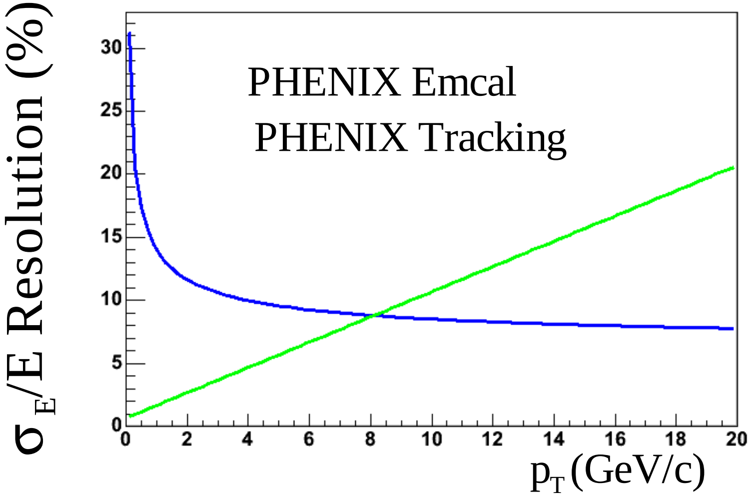
- Systematic errors for photon 10-15%, π^0 14-18%
- High p_T: dominated by Energy Scale and Efficiency
- Low p_T : large hadron contamination

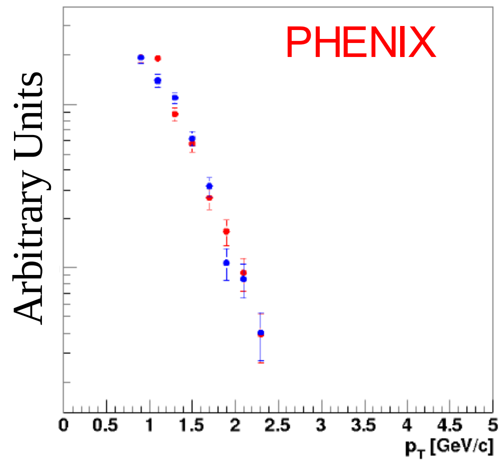
“Tips” from the expert (II): Going lower in p_T

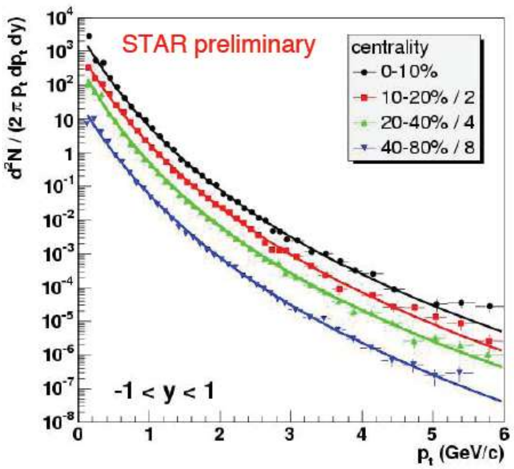
Justin Frantz

- Use the conversion measurement ! (e^{+-} ID runs out @ 5 Gev/c)
- Energy Resolution has opposite behavior:

Ex.: photon yields @ 62.4 GeV







At low p_T < ~3 GeV systematics smaller. Total systematics 13% (STAR)

- Factor of 10^{2-4} loss in statistics won’t hurt in Run-4.
- In the region of overlap with EMCal measurements, reduce γ energy scale uncertainty by “combining” rate normalization.
- Extend *p+p* --> γ measurement to low p_T (need baseline in “interesting” region !)
- **Result:** Constrain thermal rates below 4 GeV **and** confirm/deny jet-medium enhancement

Many exciting topics in photon physics

Paul Stankus
Justin Frantz

- Summary:

  The central interest in thermal direct photons continues in RHIC and LHC nuclear collisions. But photon production, as well as W and Z production, touches on a wide range of physics topics beyond QCD thermodynamics:

- γ-h correlations: calibrated away-side energy. separation angular jet shape differences btw Bremss., Compton π^0 bkg. Also difference in flow contribution of γ-h angular correlation shape.
- Reaction plane dependent direct γ analysis. Measure direct γ flow directly (may be 0). Constrain path dependencies.
- Direct photon- (and Z-) tagged jet fragmentation
- Jet+medium-induced direct photons
- Investigate the approach to thermal equilibrium (parton cascade)
- Beam-stopping collective bremstrahlung
- Source size via $\gamma\gamma$ HBT correlations
- ...

Backup slides

Energy loss in Au+Au→ γ+ X @ √s = 200 GeV ?

(Part of the) prompt photons can be distorted by the dense QCD medium (esp. in the region p_T< 4 GeV/c).

Photon production in p+p @ 200 GeV:

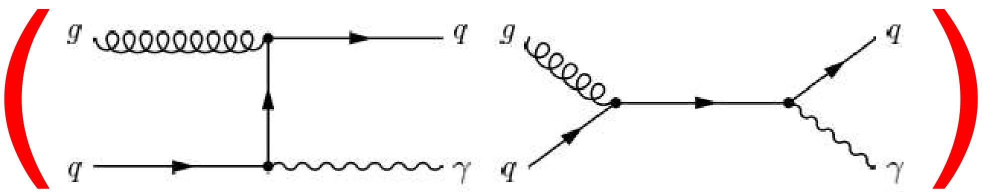


Figure 2.1: Compton diagrams.

+

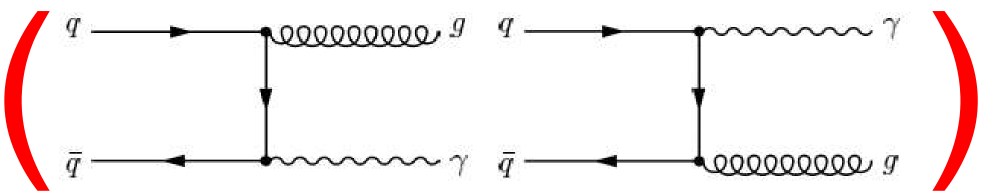


Figure 2.2: Annihilation diagrams.

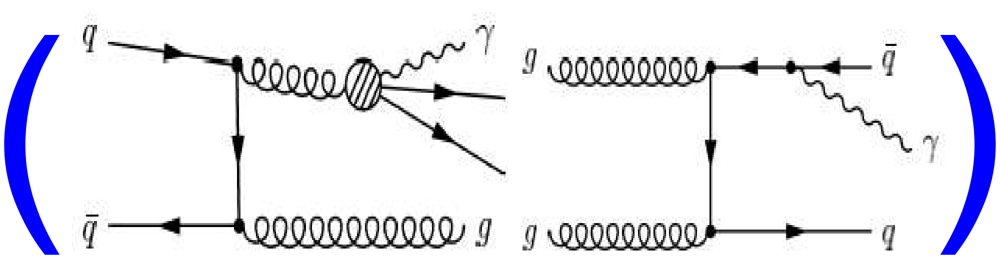
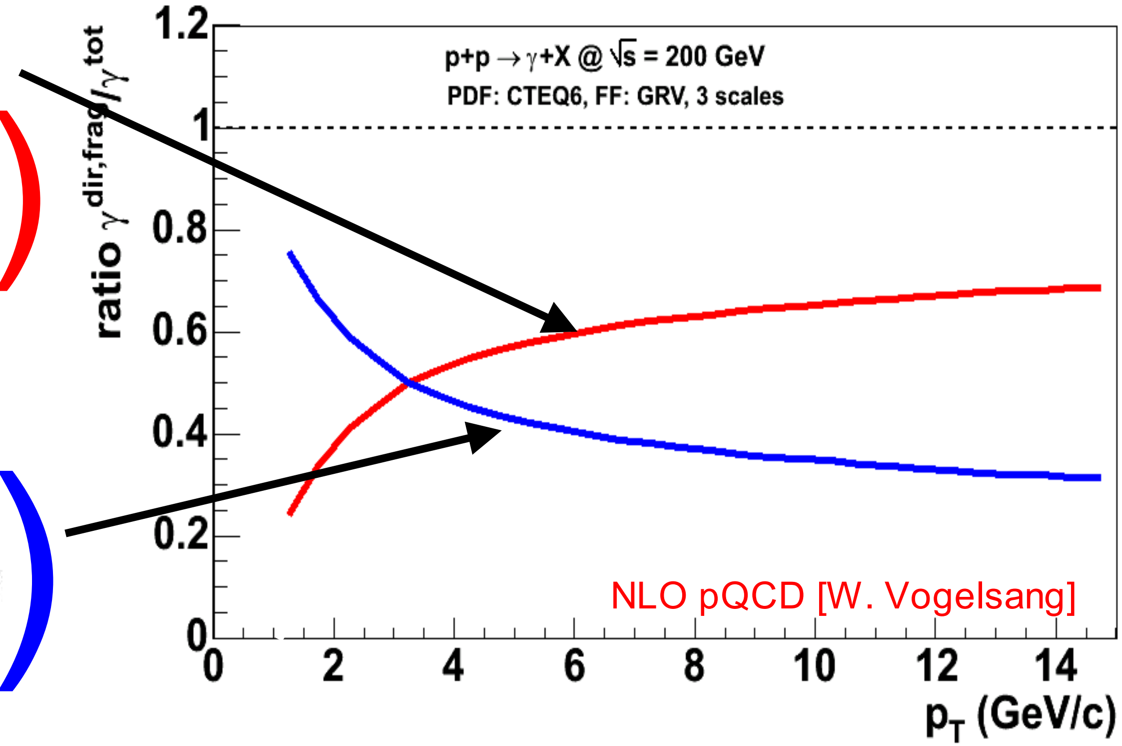


Figure 2.3: Bremsstrahlung diagrams.

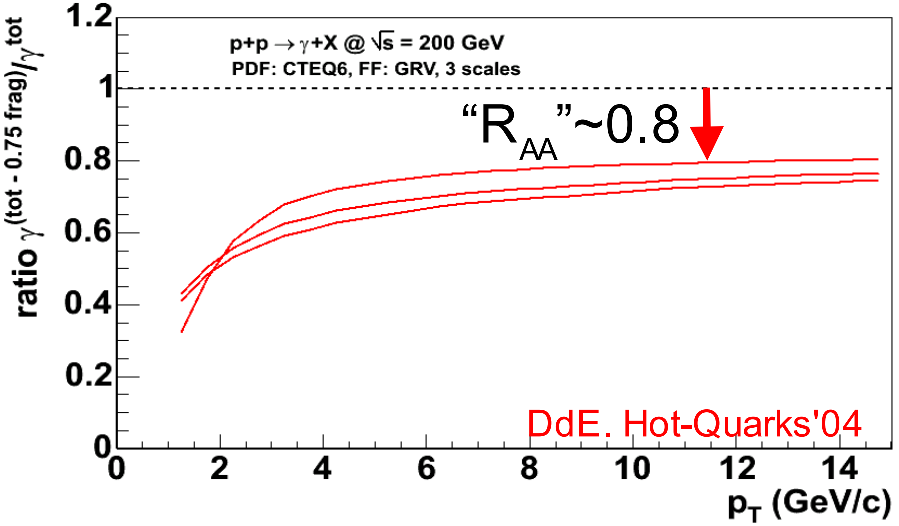
Below $p_T \approx$ 4. GeV/c dominated by γ from collinear q,g fragmentation



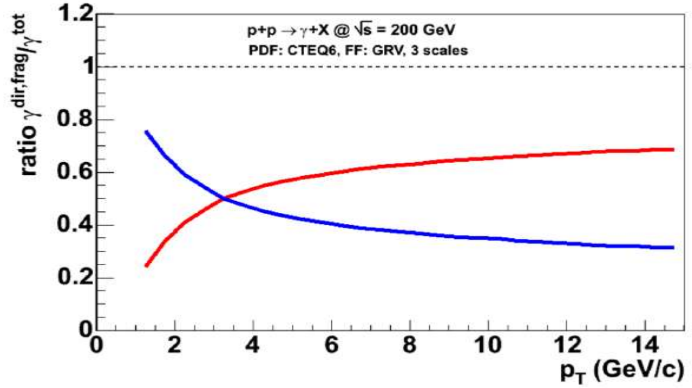
"Tips" from the expert (II): photon energy loss ?

Justin Frantz

- Any (bremsstrahlung) photon energy loss ?

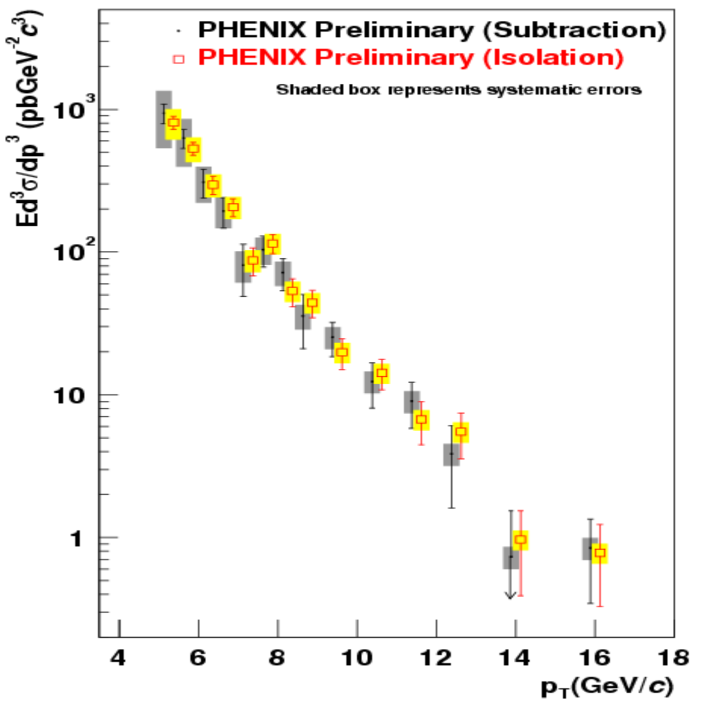


pQCD Brems ~ 20%



- *p+p* Preliminary Comparison between isolation/non-iso method: null Brems?
- Plenty of room in those systematics

- Make real R_{AA} (with p+p γ–it's all there!) More precise also look for nuclear effects (k_T, Cronin)?



Theoretical models

Monique Werlen

NLO codes

	type of code	Direct	Fragmentation
INCNLO (*)	I/FO	NLO	NLO
Vogelsang, Gordon (*)	I/FO	NLO	NLO
Owens et al. (*)	G/FO	NLO	LO
Frixione, Vogelsang	G/FO	NLO	LO
JETPHOX (*)	G/FO	NLO	NLO

I : Inclusive
G : Generator
FO : Fixed Order

(*) http://wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/main.html

Threshold resummation:(*) Catani et al.
(*) Kidonakis, Owens

Guillet, DIS04

Disentangling "thermal" γ from quenched prompt γ

Step 1: Measure p+p → γ(isolated) + *X*
down to p_T = 1 GeV/c
with uncertainties ~10%

Handle on γ from qg-Compton, qqbar annihilation

Step 2: Measure p+p → γ(total) + *X*
down to p_T = 1 GeV/c
with uncertainties ~10%

Handle on fragmentation γ production

Step 3: Measure Au+Au → γ(total) + *X*
down to p_T = 1 GeV/c
with uncertainties ~10%

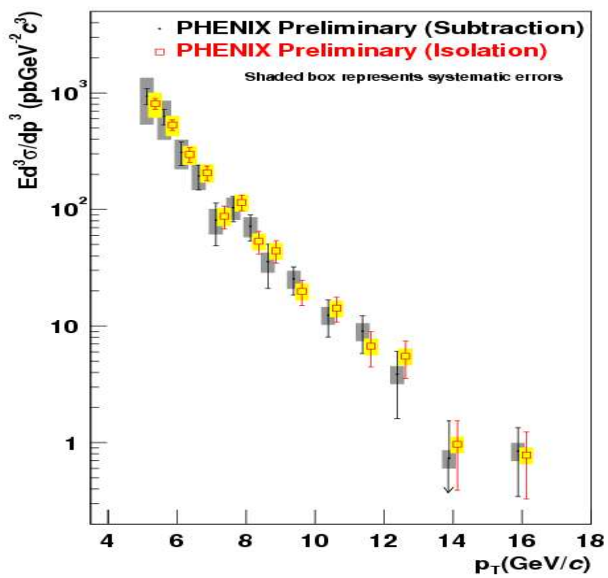
Step 4: (AuAu γ_{total}) – T_{AB}•(pp $\gamma_{isolated}$)

Upper limit on thermal spectrum.

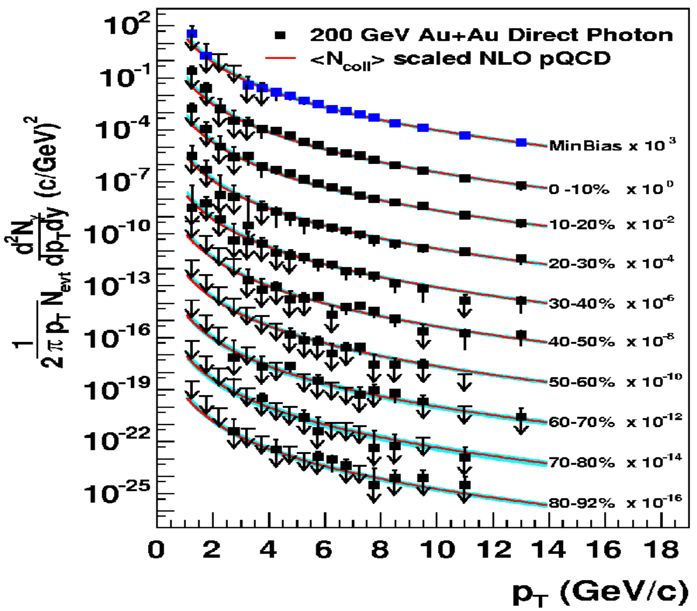
Step 5: (AuAu γ_{total}) – T_{AB}•(pp γ_{total})

Lower limit on thermal spectrum.

Current best p+p γ data:

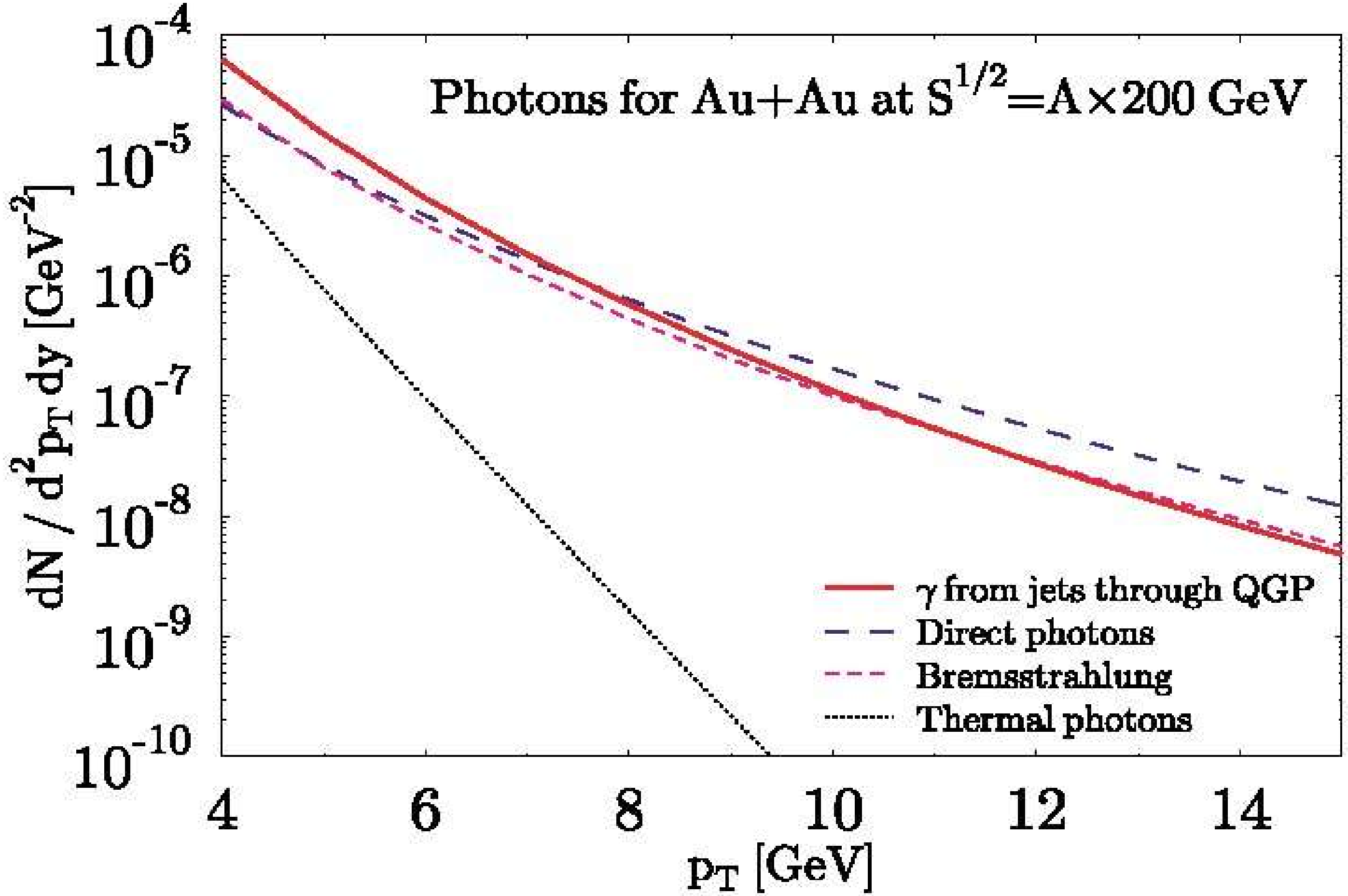


Current best Au+Au γ data:



Photons from quark jets in the medium ?

- Duke group predictions for Compton & annih. of fast quark in medium
- LO for photons (& not most recent thermal photon rates)
- But NLO (K = 2.5) for jets, no energy loss taken into account ...
  Effect probably overestimated



Fries, Muller, Srivastava
PRL 90 132301 (2003)

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

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