Direct Photon Production in Heavy Ion Reactions

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Outline

- direct photons - motivation
- theory overview
  - hard thermal loops
- experimental results
  - spectra
  - comparison to model calculations
  - elliptic flow?

What are Direct Photons?

- photons *directly* produced in scattering processes
  - not from decays (e.g. neutral pions)!
- two different major domains:
  - prompt photons
    - hard scattering processes
    - high p_T
    - information on PDFs, QCD, etc.
  - thermal photons
    - thermal production
    - low/medium p_T
    - information on early thermal state (QGP?)

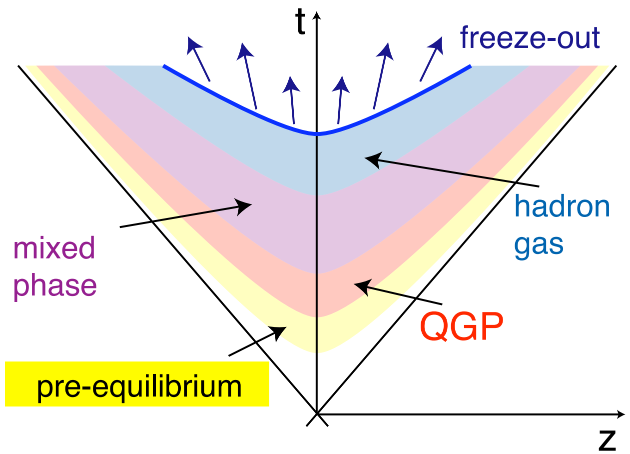
Kinetic Freeze-out Temperature

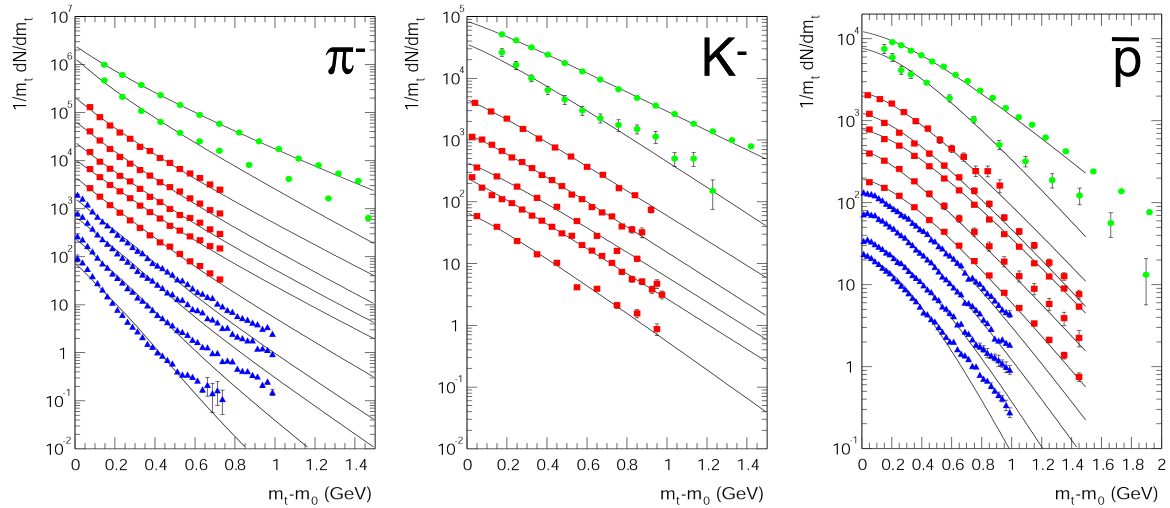
- RHIC:

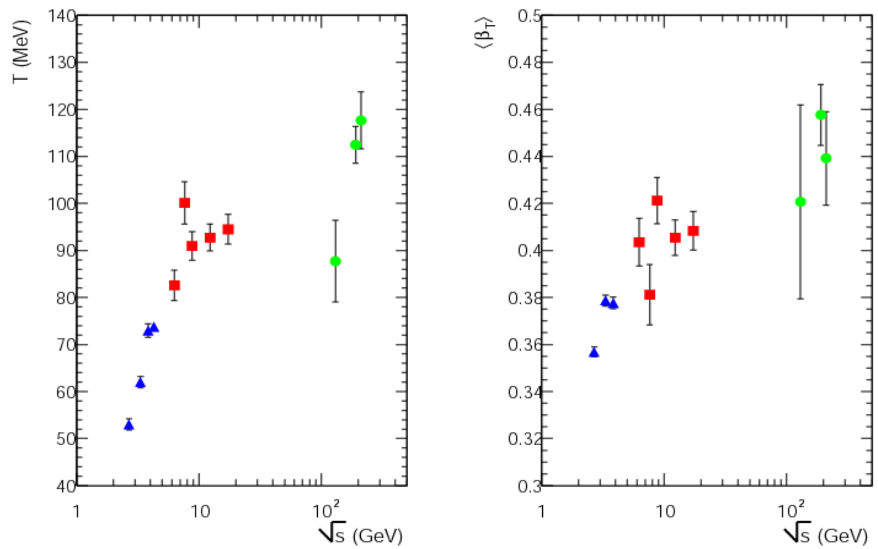
  $$T_{kin} = 100 - 120\,\mathrm{MeV}$$

  $$\beta_T = 0.4 - 0.5$$

  - latest stage of the expansion





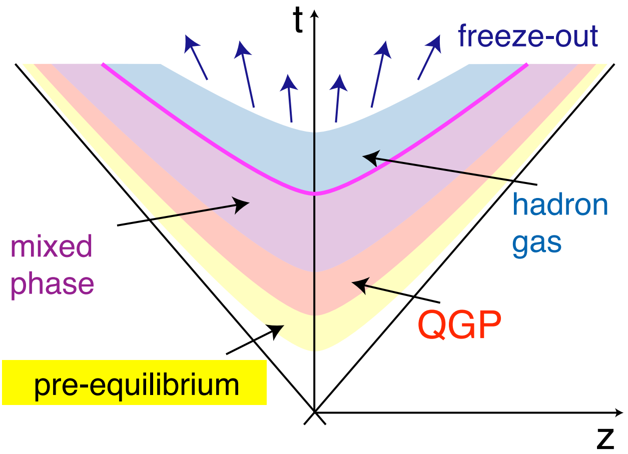


Chemical Freeze-out Temperature

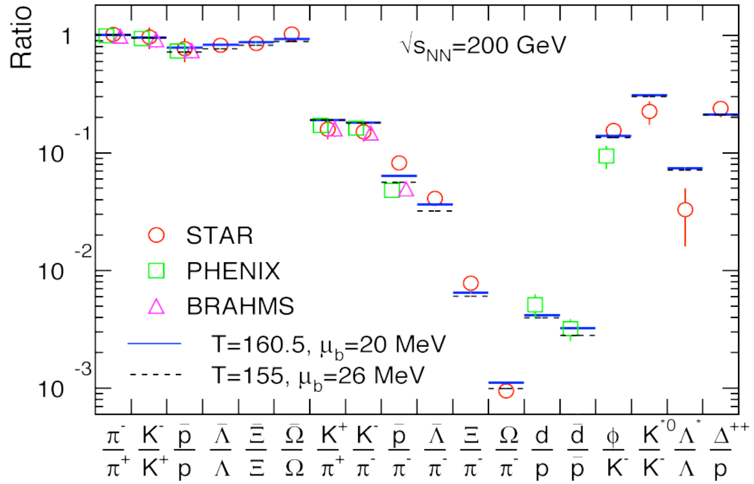
- RHIC:

$$T = 160\,\mathrm{MeV}, \quad \mu_B = 20\,\mathrm{MeV}$$

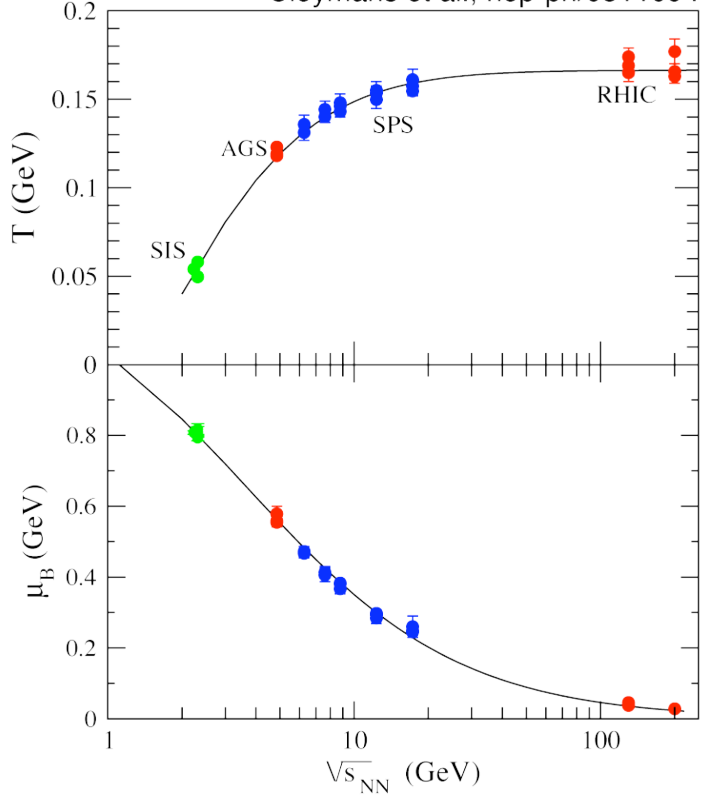
  – close to critical temperature



Andronic et al., nucl-th/0511071

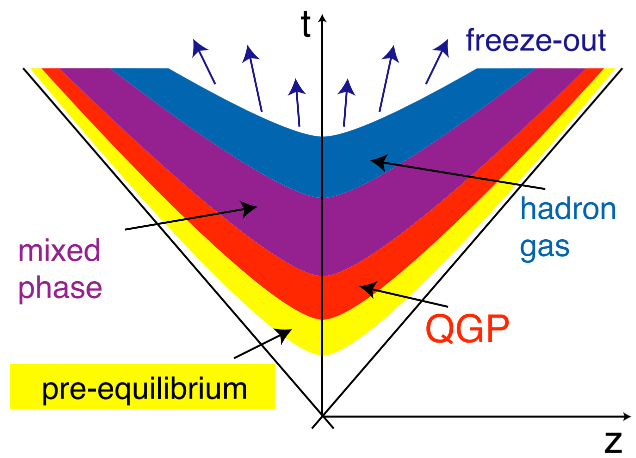


Cleymans et al., hep-ph/0511094



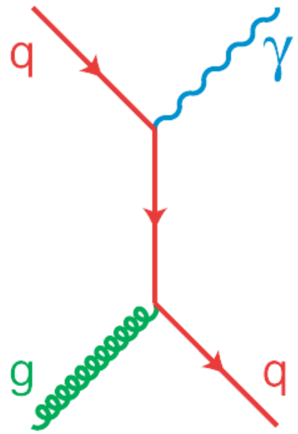
Thermal Photons as Thermometer

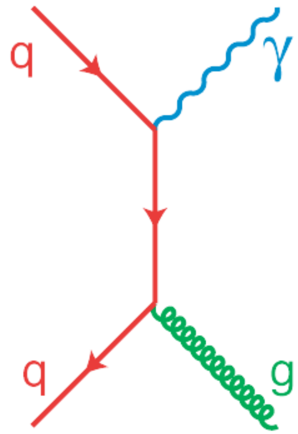
- momentum distributions for thermal system should reflect temperature
  - hadron momentum distributions determined at freeze-out (latest stage of the evolution = low temperature)
- photons do not interact strongly, photon emission from all phases (also early phase)
  - direct photons from thermal source contain information from initial temperature
  - theoretical calculation needs to fold photon rates with evolution of collision system

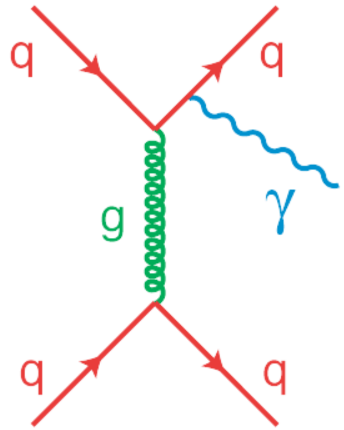


Prompt Photons

- produced in hard scatterings of quarks and gluons
- lowest order
  - quark-gluon-Compton
  - quark-antiquark-annihilation
- next order
  - Bremsstrahlung
- calculable in pQCD
- soft corrections
  - intrinsic k_T ?
  - K-factor ?







Thermal Photon Rates (Lowest Order)

- matrix elements from Feynman diagrams
- convolute with parton momentum distributions

$$\frac{dN}{d^4x d^3p} = \frac{1}{(2\pi)^3 2E} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_3}{(2\pi)^3 2E_3}$$

$$\times\, n_1(E_1) n_2(E_2) \left[1 \pm n_3(E_3)\right]$$

$$\times \sum_i \left\langle |M|^2 \right\rangle (2\pi)^4 \delta(p_1 + p_2 - p_3 - p)$$

- thermal distributions (BE or FD):

$$n_i(E_i) = \frac{1}{\exp(E_i/T) \pm 1}$$

Thermal Photon Rates (example)

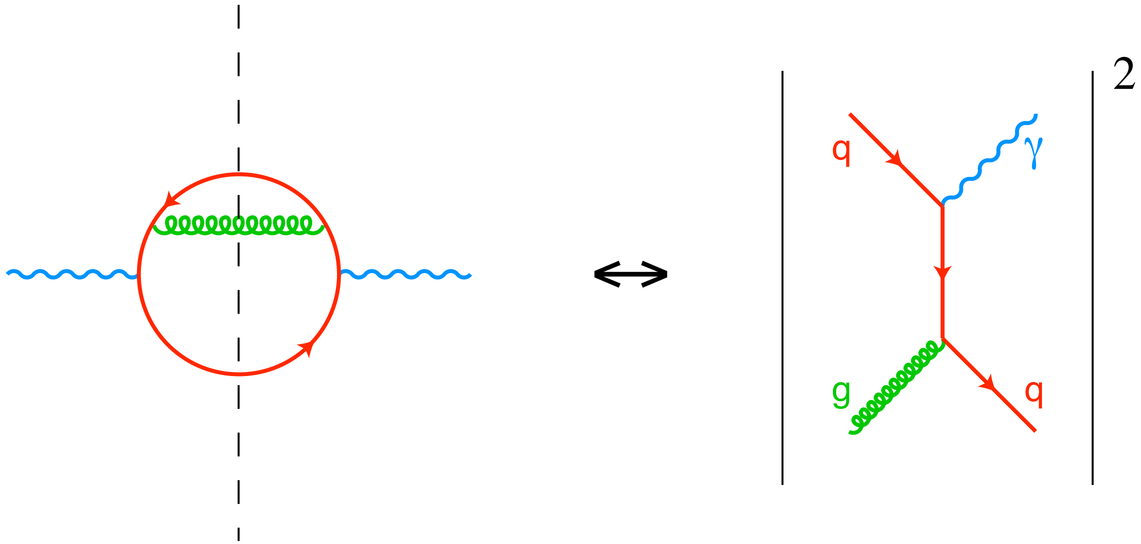
- rate for quark-gluon Compton

$$\frac{dN}{d^4x d^3p}(qg \to q\gamma) = \frac{5}{9}\frac{\alpha\alpha_S}{6(\pi)^2}T^2\exp(-E/T) \times \left[\ln\frac{4ET}{k_c^2} + 0.046\right]$$

- similar expression for other diagrams
  - higher orders (e.g. Bremsstrahlung): $\alpha \cdot \alpha_S^2$

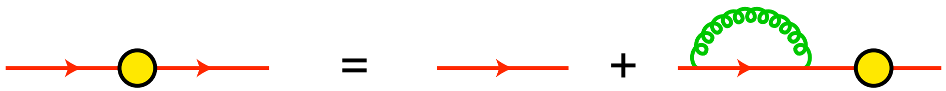
Alternative Approach (Finite T Field Theory)

- relate photon rate to polarization tensor (photon self-energy) $$\frac{dN}{d^4x d^3p} = -\frac{1}{(2\pi)^3 E} \frac{1}{\exp(E/T) - 1} \Im \left[\Pi^{\mu}_{\mu}(E) \right]$$
  - expression valid for all orders in α_s
- self-energy contains loop-diagrams:



Hard Thermal Loops

- IR-divergent diagrams at finite T
- possible solution: include medium effects in propagators and vertices:
- Hard Thermal Loops (HTL)
  - define Dyson-Schwinger equation



- separation of scales for weak coupling (g << 1)
  - hard scale $\approx$ T use bare propagator
  - soft scale $\approx$ gT use HTL-resummed propagator

Hard Thermal Loops

- appropriate in high temperature limit
  - 1-loop diagrams with hard momentum in the loop, but only soft external momenta
- HTL propagator corresponds to effective propagator in medium
  - effective quark mass, in-medium dispersion relation
- for calculations, use HTL-resummed propagators as in ordinary perturbation theory

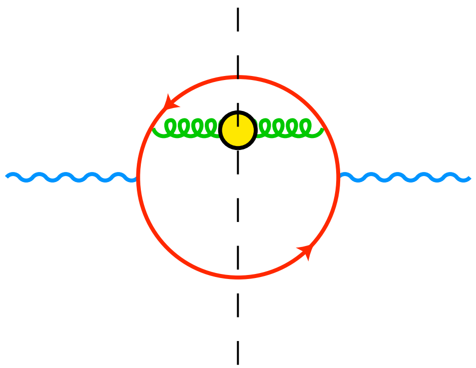
Higher Orders

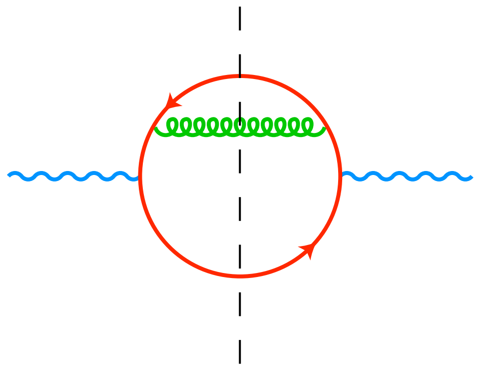
- e.g. Bremsstrahlung
  - naive expectation for weak coupling limit (high T)

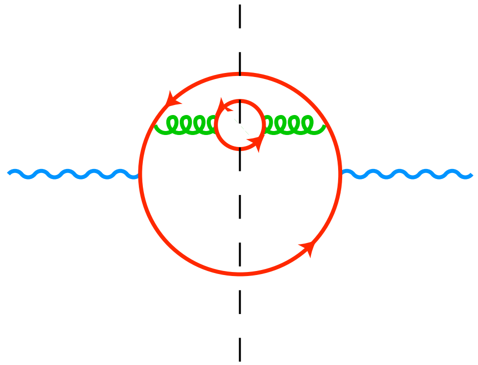
    $$\alpha \cdot \alpha_S^2 \ll \alpha \cdot \alpha_S$$

  - HTL diagram contains contributions from different orders
  - medium effects enhance higher order diagrams
    - multiply rates by factor

    $$\frac{T^2}{m_{\text{eff}}^2} \propto \frac{1}{\alpha_S}$$

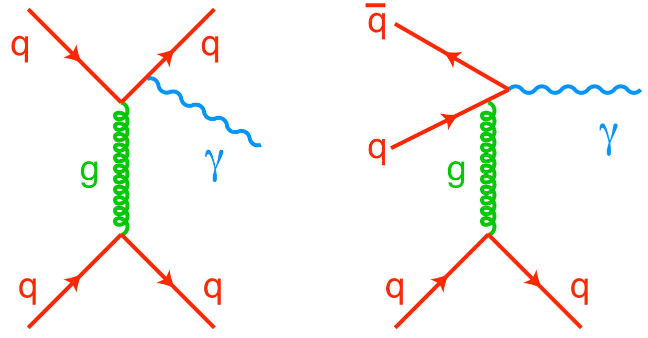




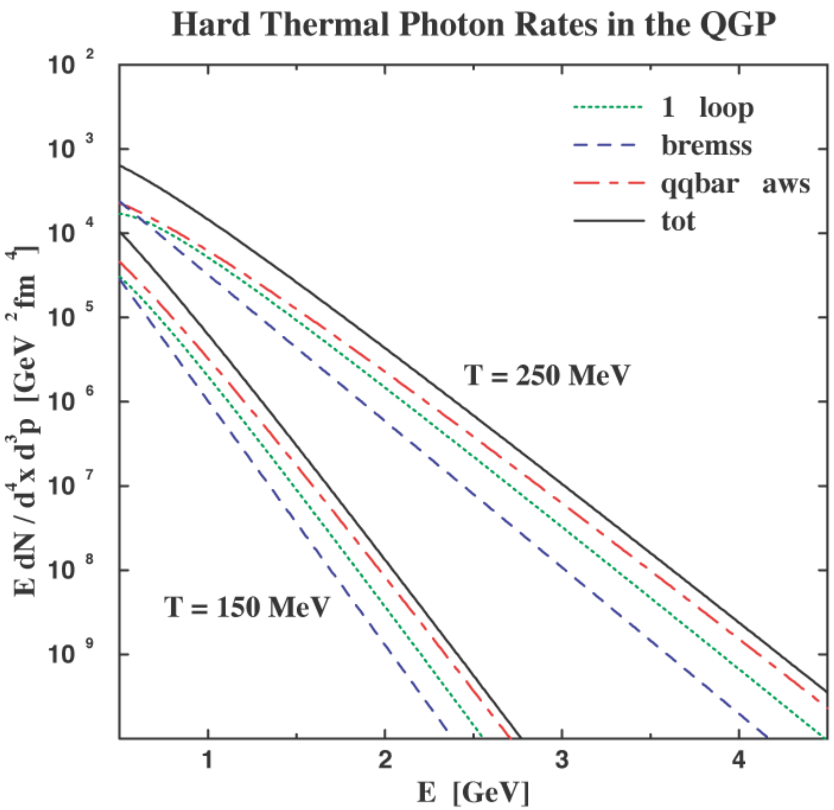


Higher Order Diagrams

- at finite temperature next order of similar magnitude!
  - Bremsstrahlung
  - annihilation with scattering
    - photon radiated from off-shell quark
  - increases photon yield from QGP
- still higher orders may also contribute at similar order of magnitude

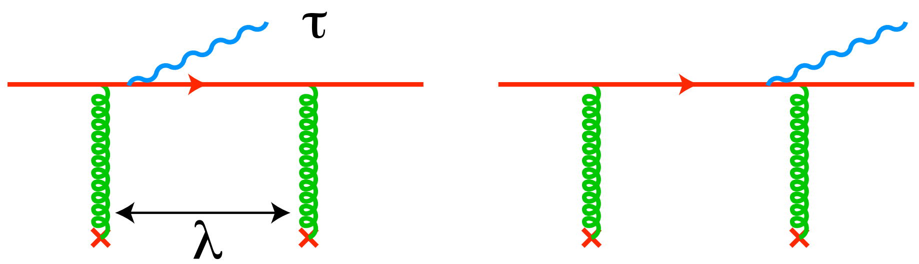


Bremsstrahlung   annihilation with scattering



Higher Order Diagrams and Interference

- need to study all orders
  - also destructive interference possible
- Landau-Pomeranchuk-Migdal effect



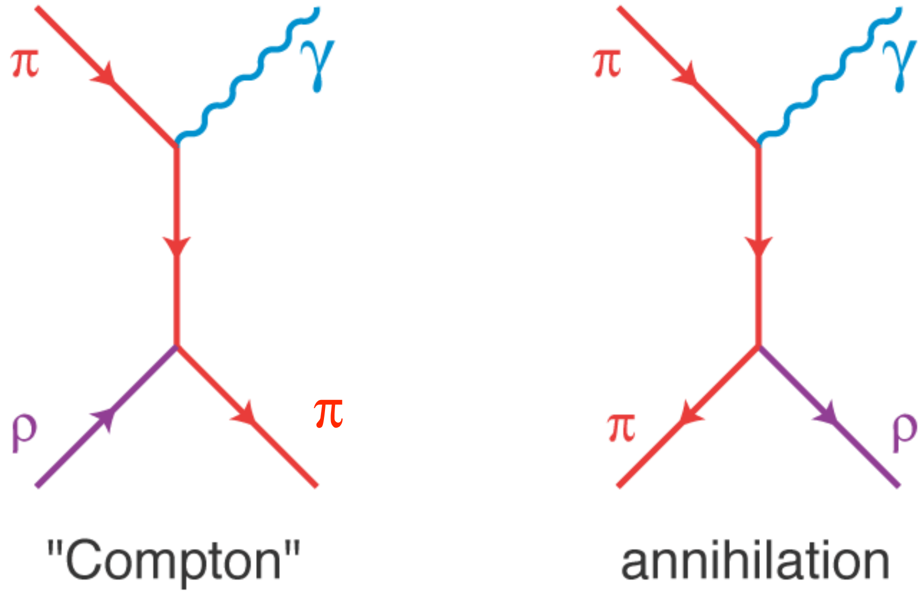
  - interference depends on formation time and mean free path

$$\tau \geq \lambda$$

- calculations including LPM effect yield finite results for all orders

Photons from Hadron Gas

- calculations need effective theory
  - similar diagrams using hadrons
- most important
  - annihilation and Compton-like diagrams involving rho mesons
  - modifications due to intermediate resonances
  - large uncertainties: e.g. medium modifications of hadrons



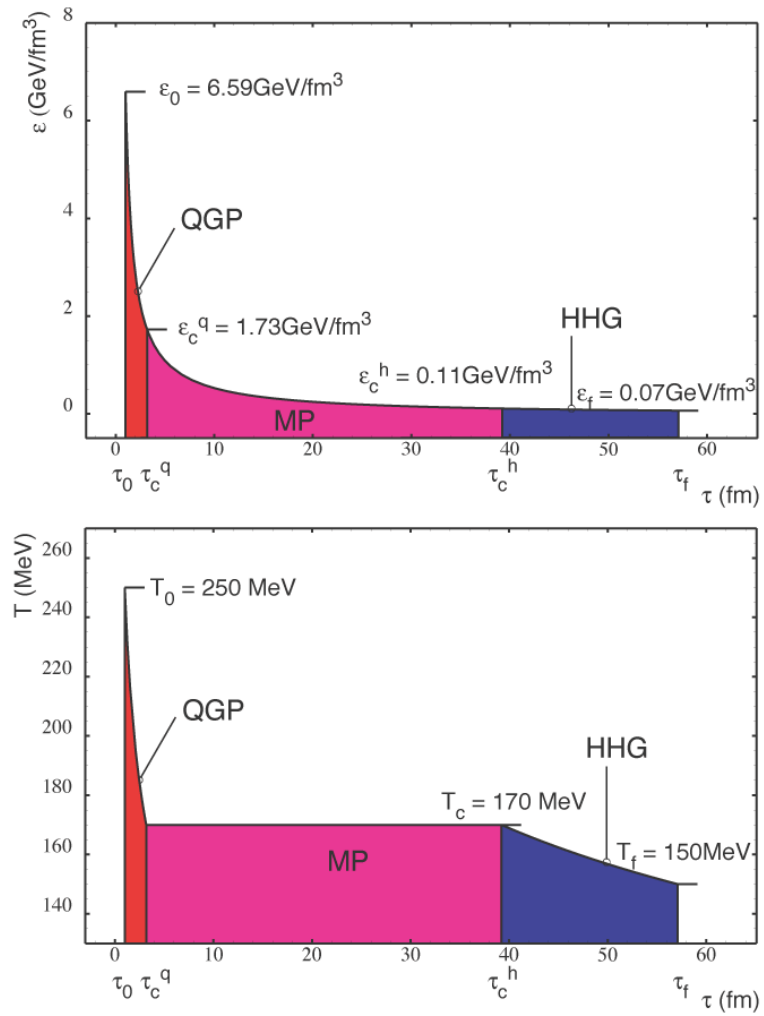
- parameterized numerical results,

e.g.:
$$\frac{dN}{d^4x d^3p}(\pi\rho \to \pi\gamma) \approx T^{2.4} \exp\left[-\frac{1}{(2TE)^{3/4}} - \frac{E}{T}\right]$$

Thermal Photons from Heavy-Ion Reactions

- photon rates have to be folded with temperature history T(t)
- hydrodynamic evolution uses
  - equation of state
  - initial temperature
  - critical temperature

- comparison to experimental data needs subtraction of prompt photons first

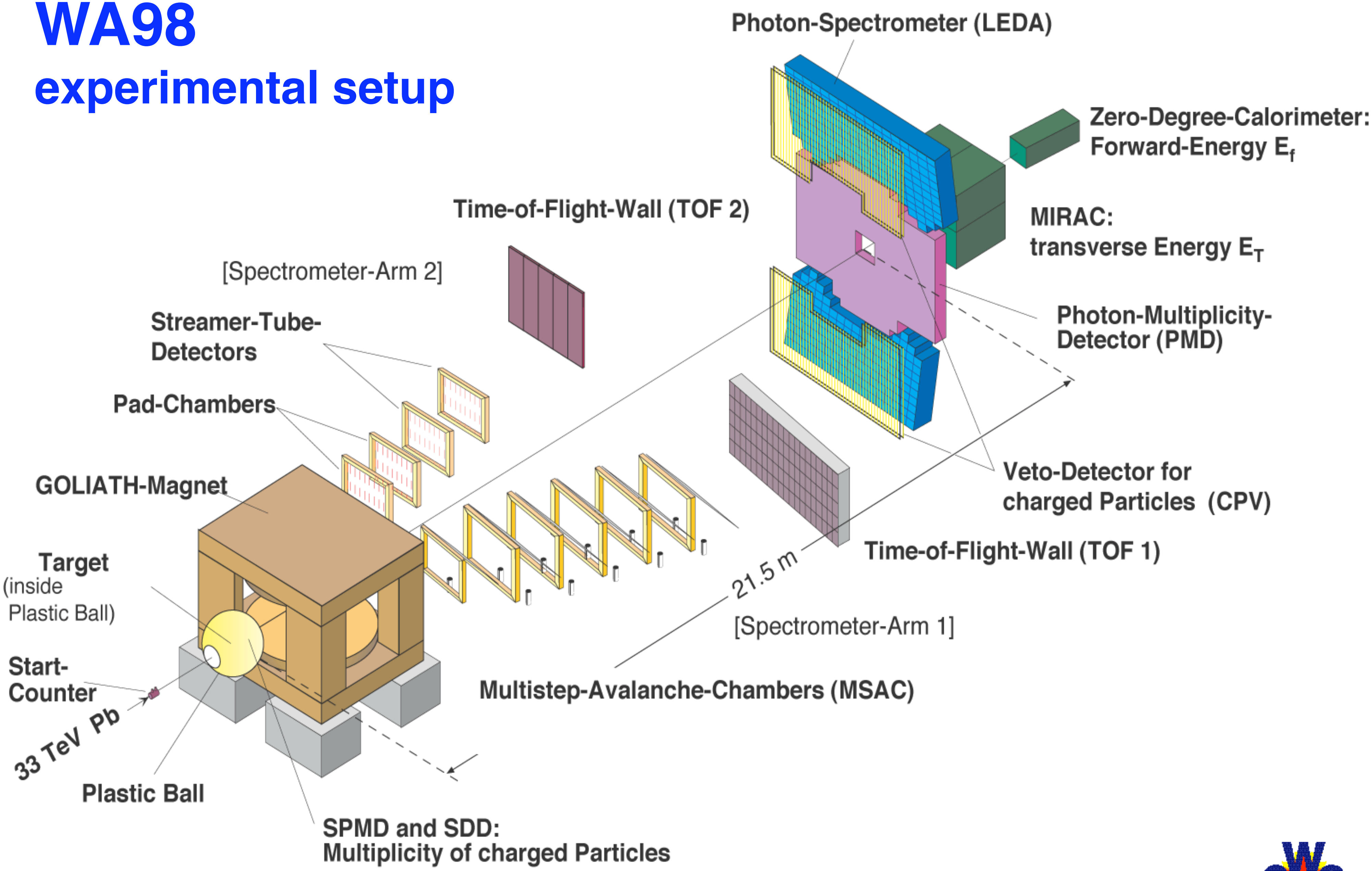


Direct Photon Measurement

- undisturbed signal
  - little interaction with surrounding matter
    - different from hadronic signals
  - direct information on early state
    - PDFs
    - initial thermal state

- experimentally very challenging
  - background of photons from hadron decays (neutral mesons)
  - small signal expected
    - EM vs strong interaction
  - especially difficult in heavy ion reactions
    - high multiplicity
    - neutral meson extraction difficult
    - tagging of individual direct photons not possible

WA98
experimental setup



Direct Photon Measurement

- photon detection
  - lead glass calorimeter (LEDA)
    - segmented (10000 modules)
      - ➡suited for high particle density
    - good resolution at reasonable costs

$$\frac{\sigma_E}{E} = \frac{5.5\%}{\sqrt{E}} + 0.8\%$$

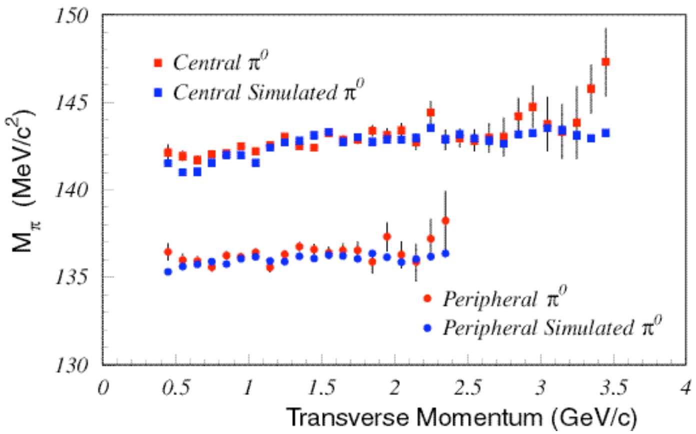
  - charged particle veto detector
    - $16 m^2$ streamer tubes
    - pad readout

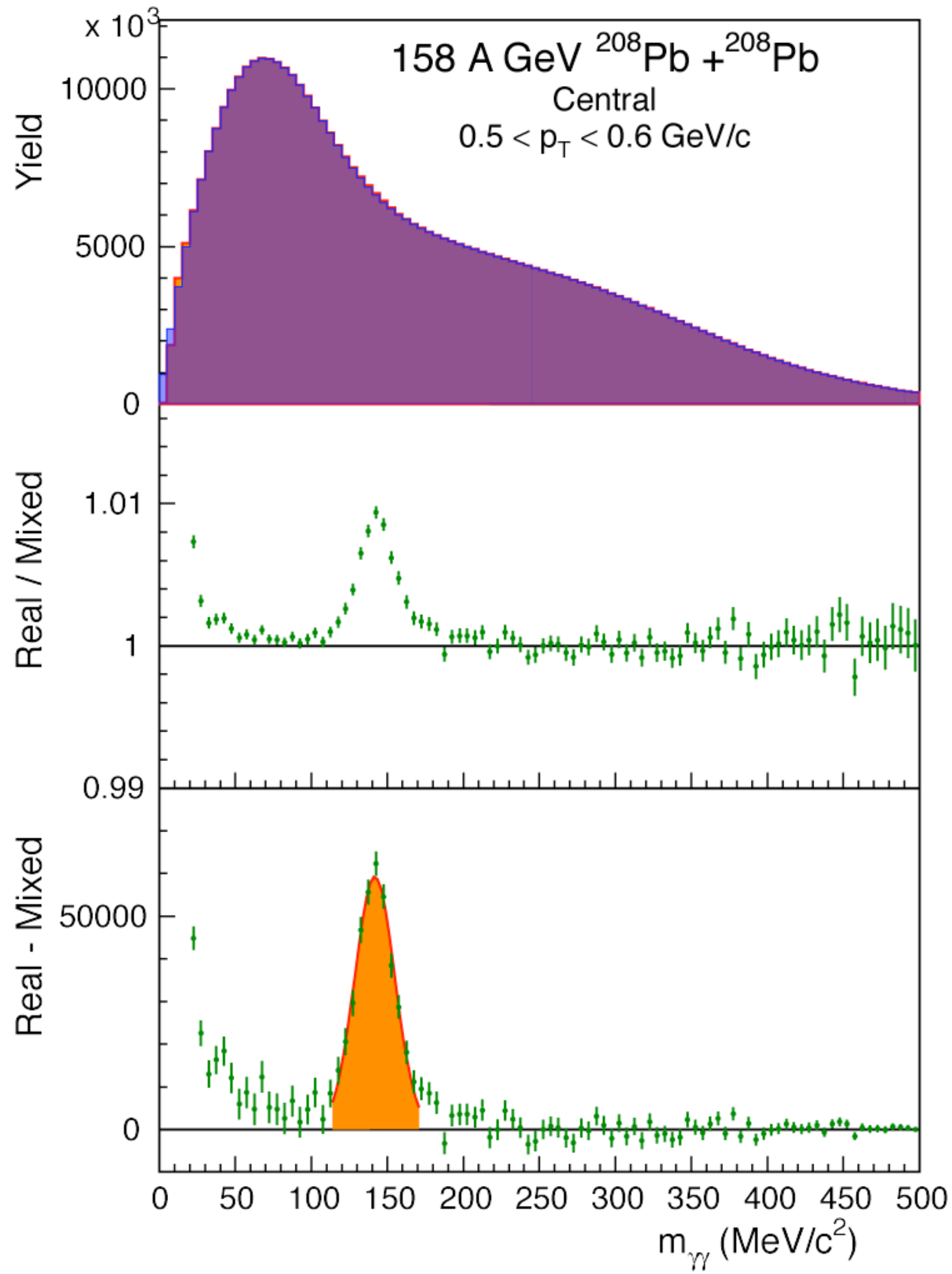
- statistical identification of direct photons
  - measurement of inclusive photons
  - measurement of neutral mesons (π^0, η) in the same data set
    - simulation of hadronic decay photons
  - direct photons from subtraction

$$N_\gamma^{direct} = \left(N_{\gamma-candidate}^{inclusive} - N_{\gamma-candidate}^{target-out} \right) \times$$
$$\times \left(1 - r_{charged}\right) \cdot \varepsilon \cdot \left(1 - r_{n,\bar{n}}\right) \cdot k_{acc} - N_\gamma^{decay}$$

Reconstruction of Neutral Pions

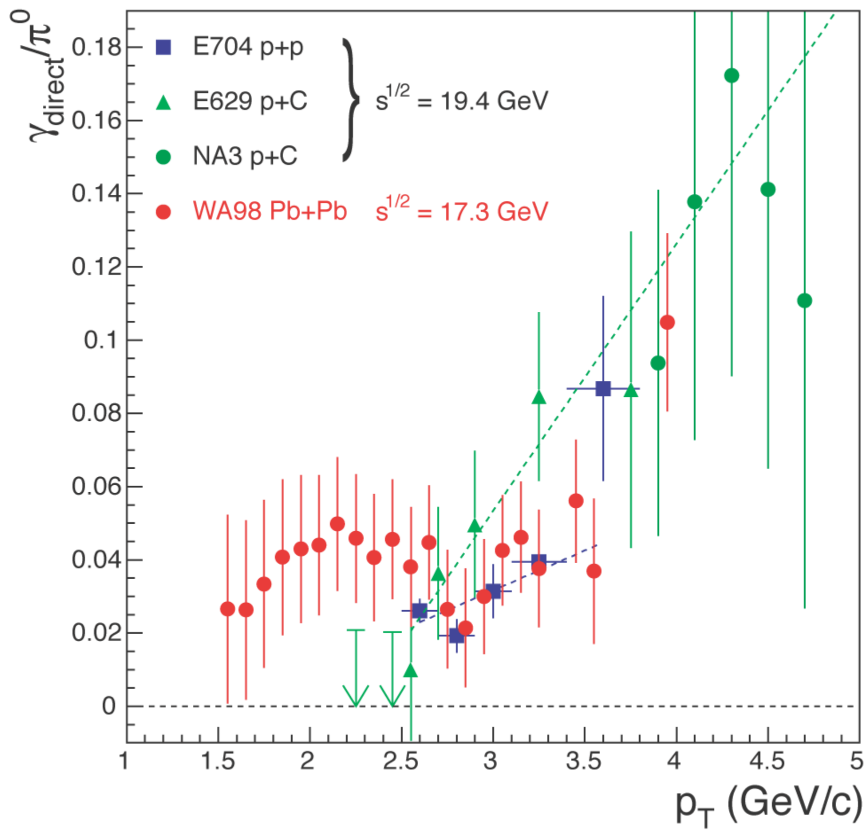
- combination of all pairs of photon candidates
  - invariant mass distributions
- background by event mixing
- similar correction as for photons
  - no direct influence of charged hadrons and (anti)neutrons
- good agreement with simulations





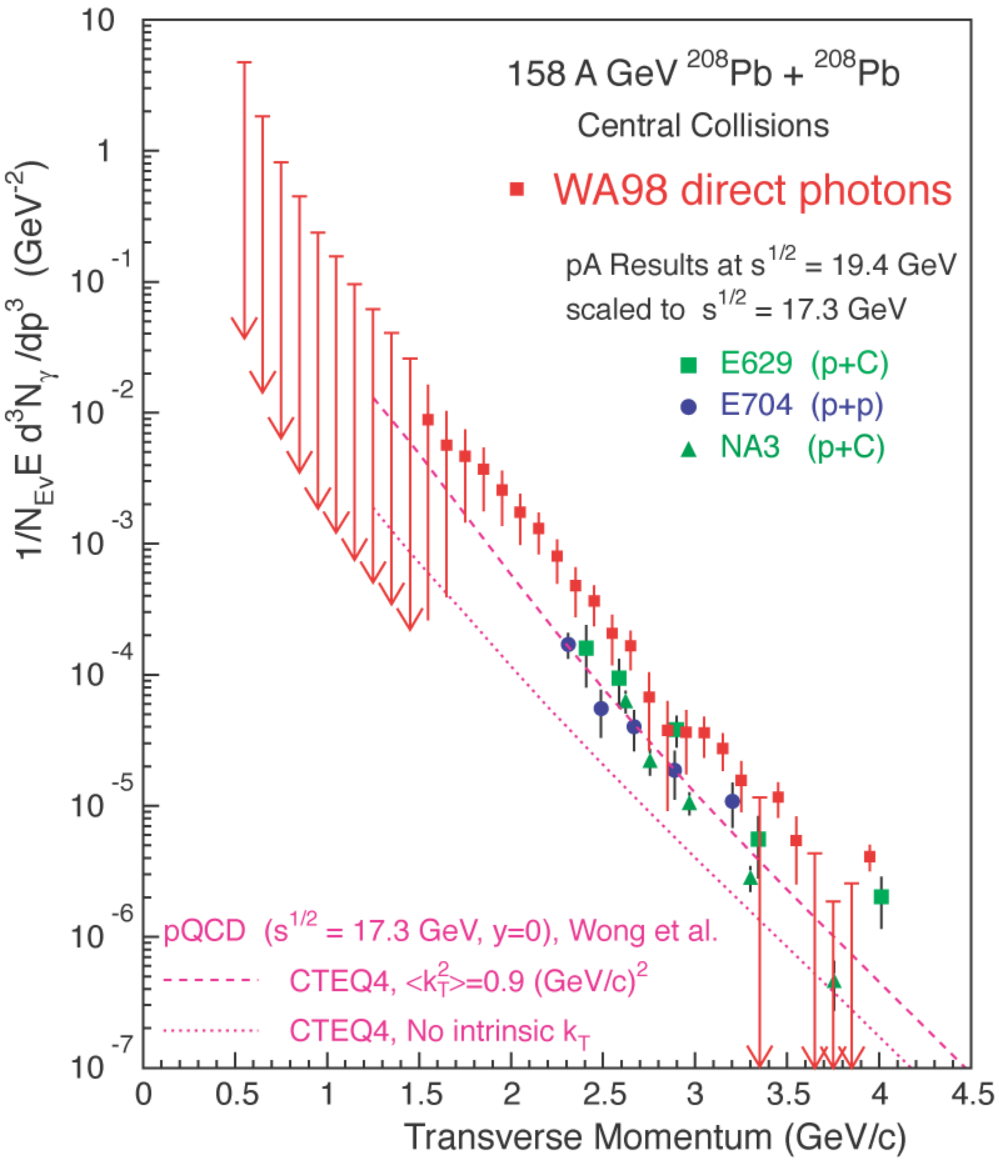
Direct Photons – Experiment

- difficulties in comparing to p+A
  - uncertainty of scaling
- alternative: γ/π^0
  - more robust with respect to scaling for energy and system size
  - other uncertainties: nuclear effects in meson production?
- significant excess relative to expectation from p+A for p_T<2.5 GeV/c



Direct Photons – Experiment

- first measurement of direct photons in ultrarelativistic heavy ion reactions
- comparison with extrapolations of p+A reactions
  - hard scattering important
  - small excess even at high p_T
    - not only hard scattering?
- naive extrapolation from pp not sufficient
  - thermal contribution?
  - other modifications?



Hydrodynamic Model

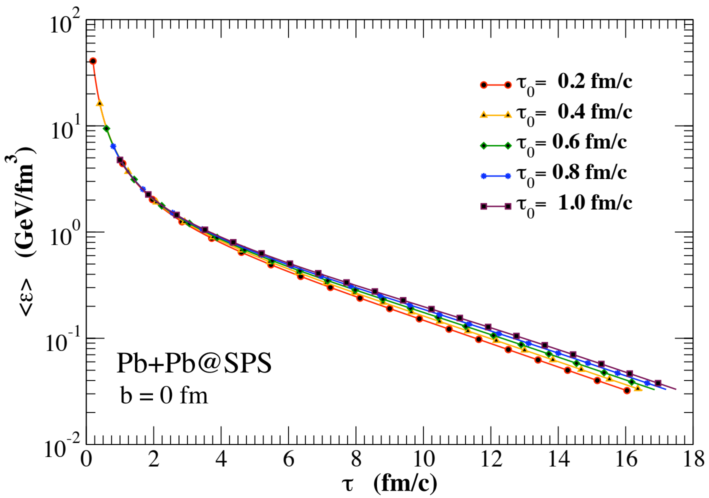
- recent calculation
  - R. Chatterjee et al. (arXiv: 0902.1036)
- entropy tuned to describe hadron multiplicities and spectra
- phase transition

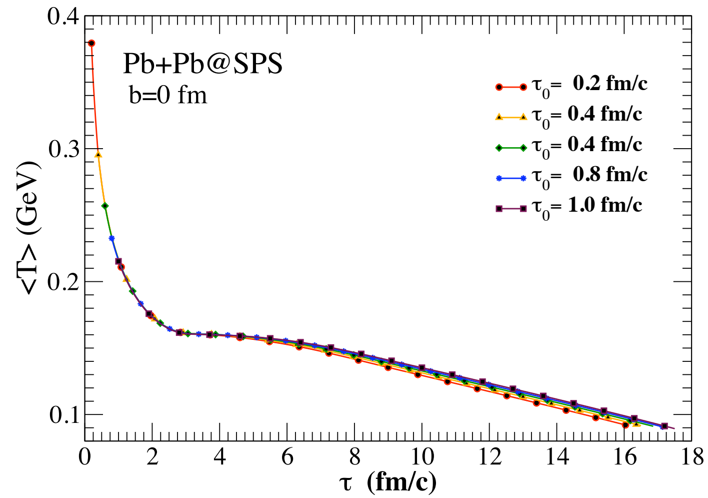
$$T_c = 164\,\mathrm{MeV}$$

- vary equilibration time

$$\tau_i = 0.2 \ldots 1.0 \text{ fm}/c$$

  - strongest impact on thermal photons
- add NLO prompt photon yields





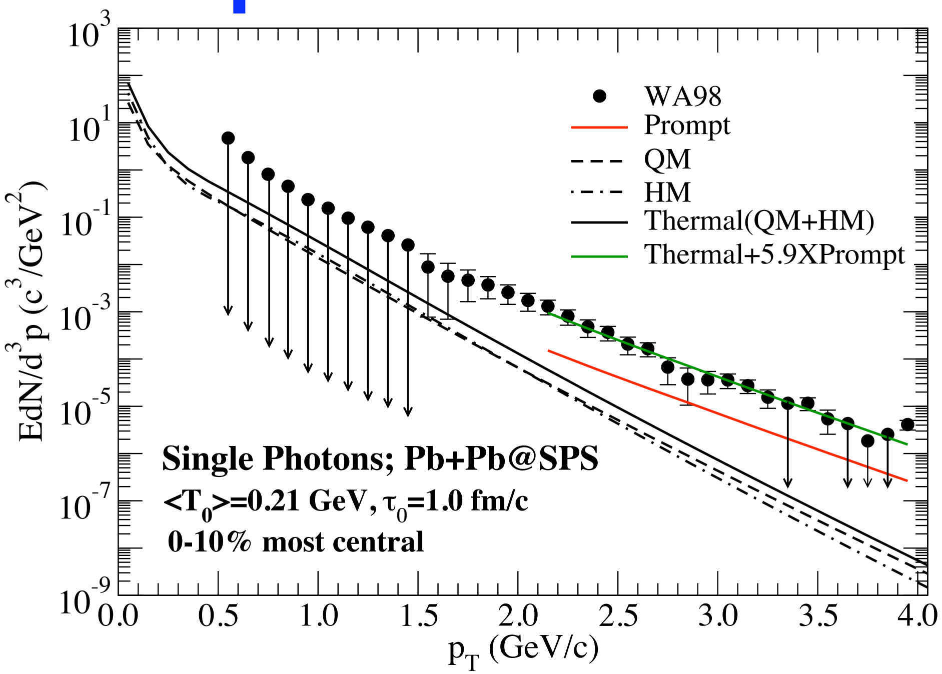
Direct Photons Model Comparison

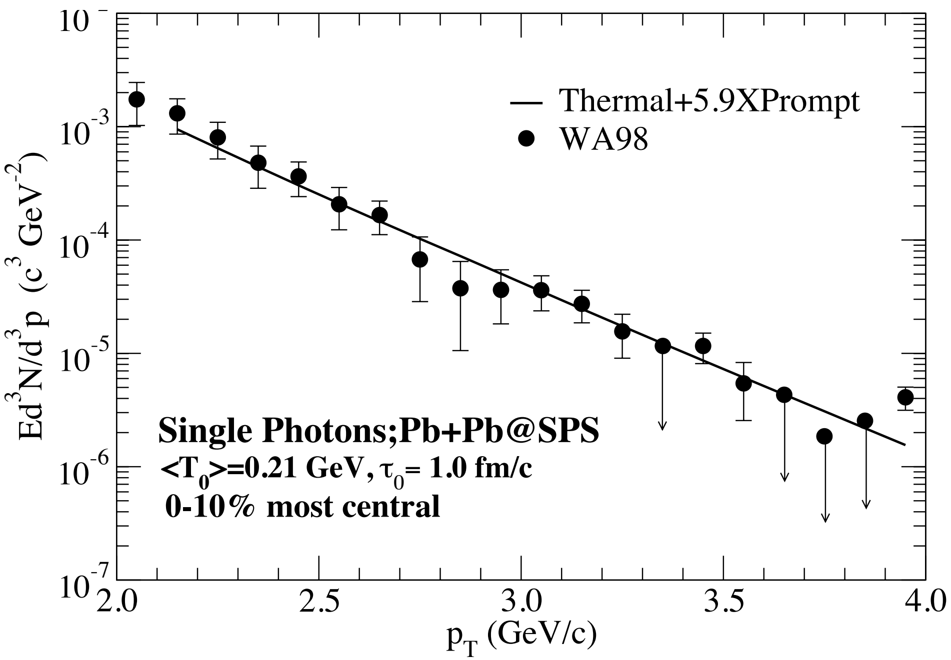
- standard equilibration time

$$\tau_i = 1.0\ \mathrm{fm}/c$$

$$\Rightarrow T_i = 210\mathrm{MeV}$$

- requires large K-factor for prompt photons
  - pQCD uncertainties at low beam energy (nuclear k_T?)
- how to treat pre-equilibrium non-prompt photon emission?





Direct Photons Model Comparison

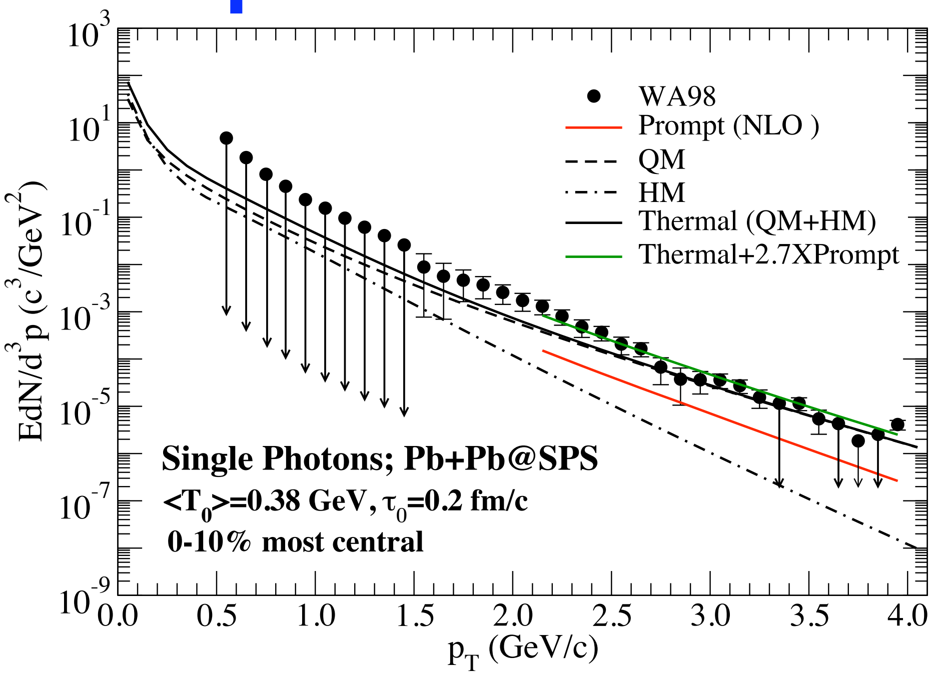
- early equilibration time

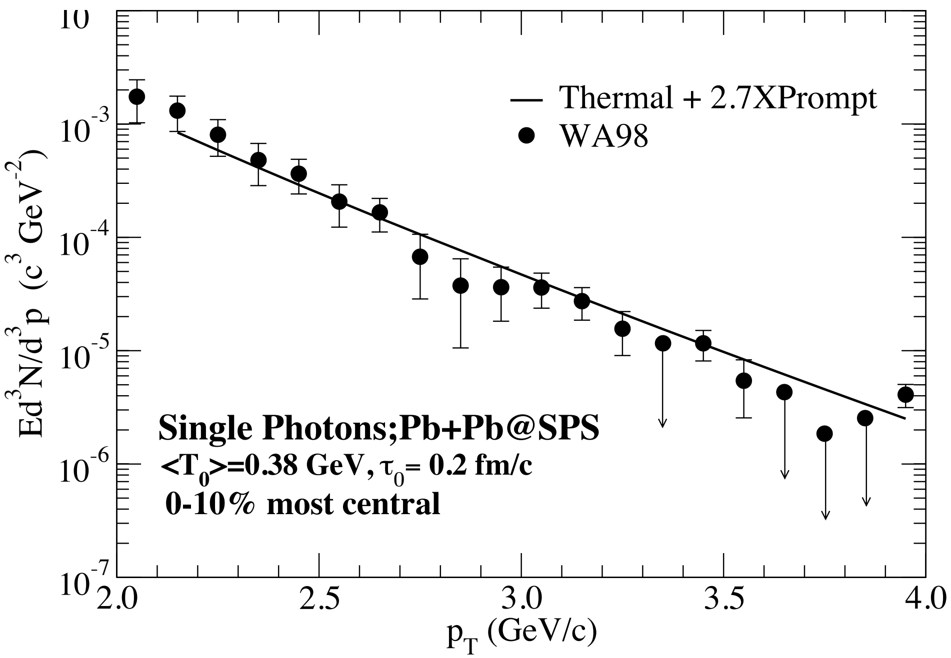
$$\tau_i = 0.2 \text{ fm}/c$$

$$\Rightarrow T_i = 380\text{MeV}$$

- more reasonable K-factor for prompt photons

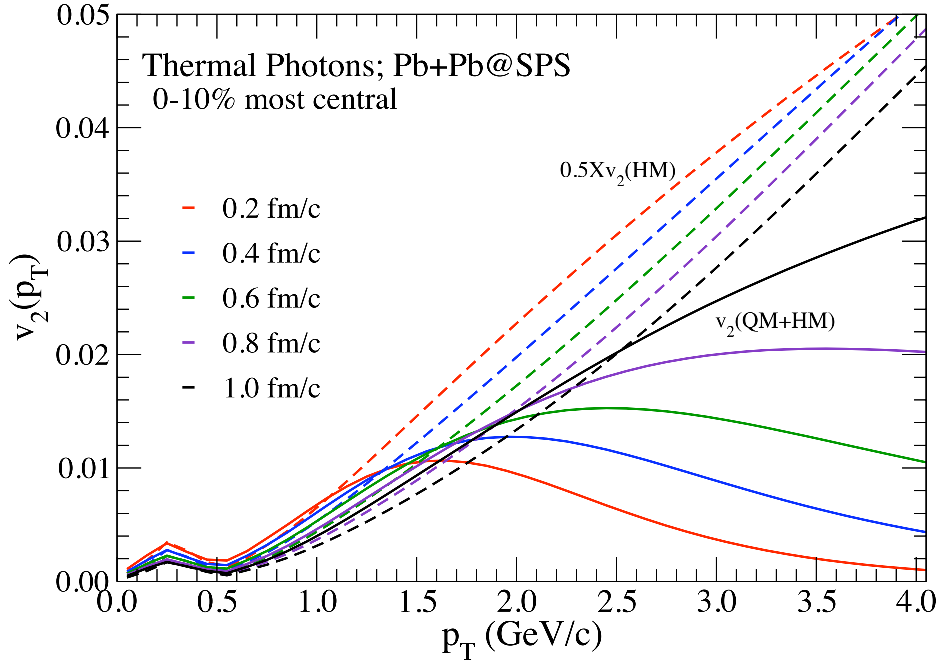
- other observables to distinguish scenarios?

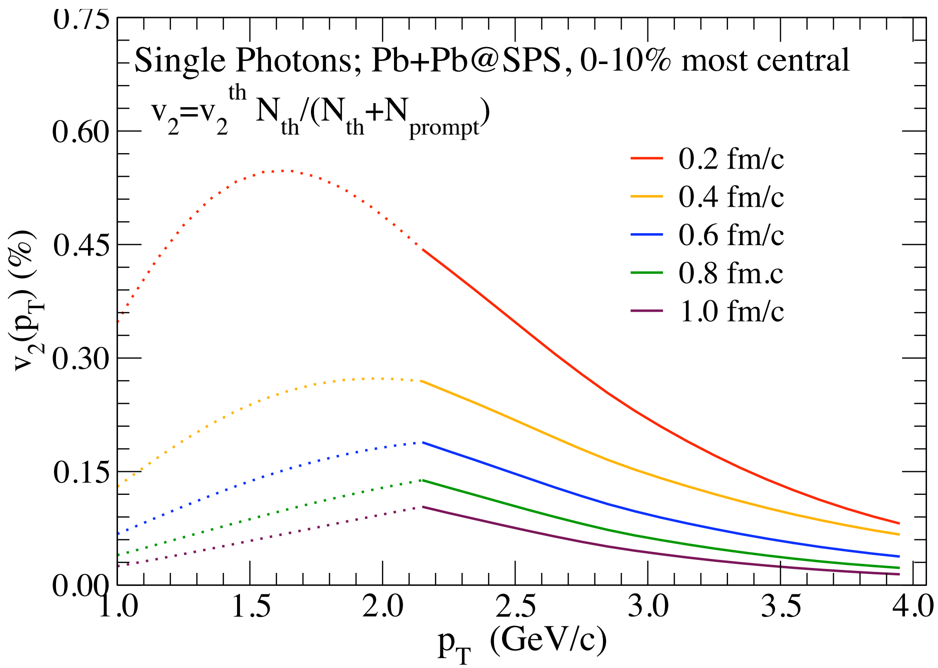




Direct Photon Elliptic Flow

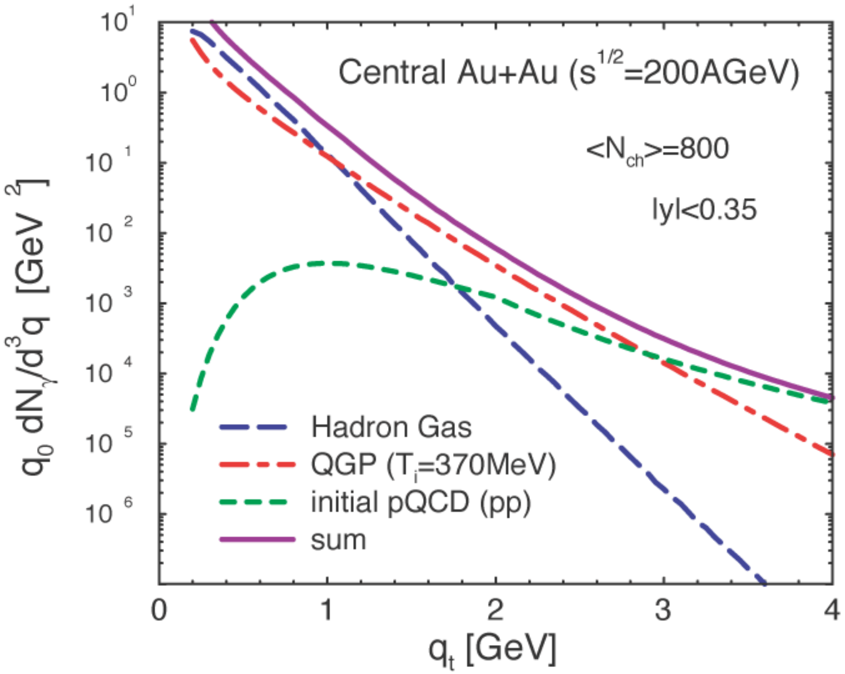
- elliptic flow probes (relatively) early equilibration
- thermal photons are dominated by very early times
  - early equilibration reduces elliptic flow of direct photons at high p_T
- prompt photons dilute elliptic flow
- elliptic flow can discriminate scenarios
  - flow values very small!

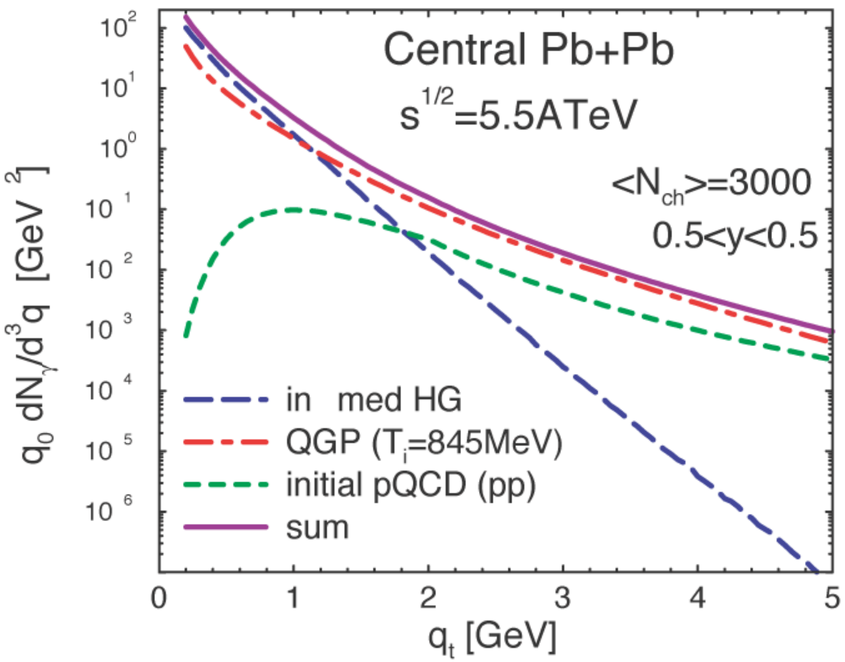




RHIC and LHC

- low energy data suffer from overlap of prompt and thermal photon yields
- easier to disentangle at higher energies?
  - experimentally not easier!
- Calculations (Gale&Rapp)
  - thermal + prompt (including nuclear k_T)
- RHIC
  - pQCD dominates above 3 GeV/c
  - preliminary data with new method
- LHC
  - larger window for thermal radiation?





Summary

- thermal photons contain information about initial temperature
- status of theory: HTL resummed diagrams to all orders in α_s including LPM effect
- experimental results
  - SPS: possibly seen
    - difficult from overlap of prompt photons
  - RHIC: under investigation
    - small QGP window (1 – 3 GeV/c)
  - LHC: QGP visible!?
- direct photon elliptic flow an interesting observable!
- future of thermal photon measurements
  - (internal) conversion measurements?
  - direct photon interferometry?