Direct photons in hot QCD matter what we learned and what we didn't

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International School of Nuclear Physics
40th Course
The Strong Interaction: From Quarks and Gluons to Nuclei and Stars
Erice-Sicily
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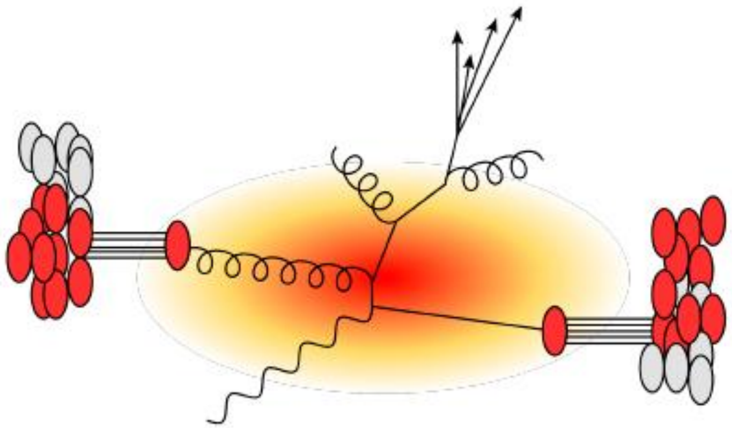
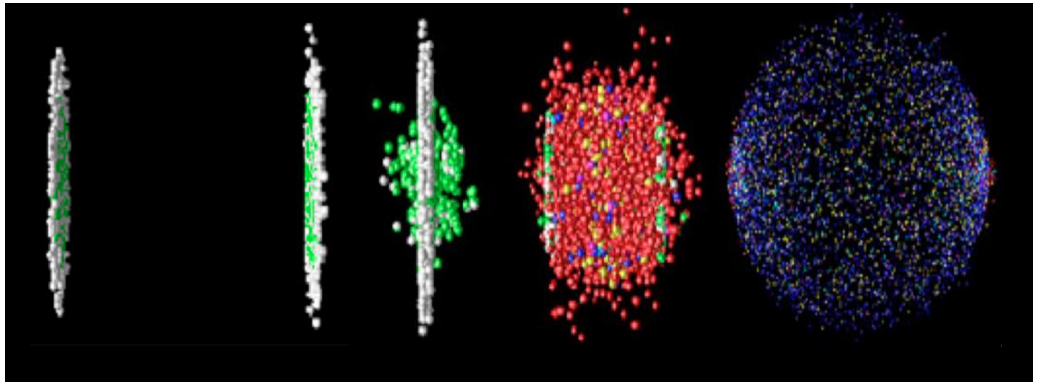
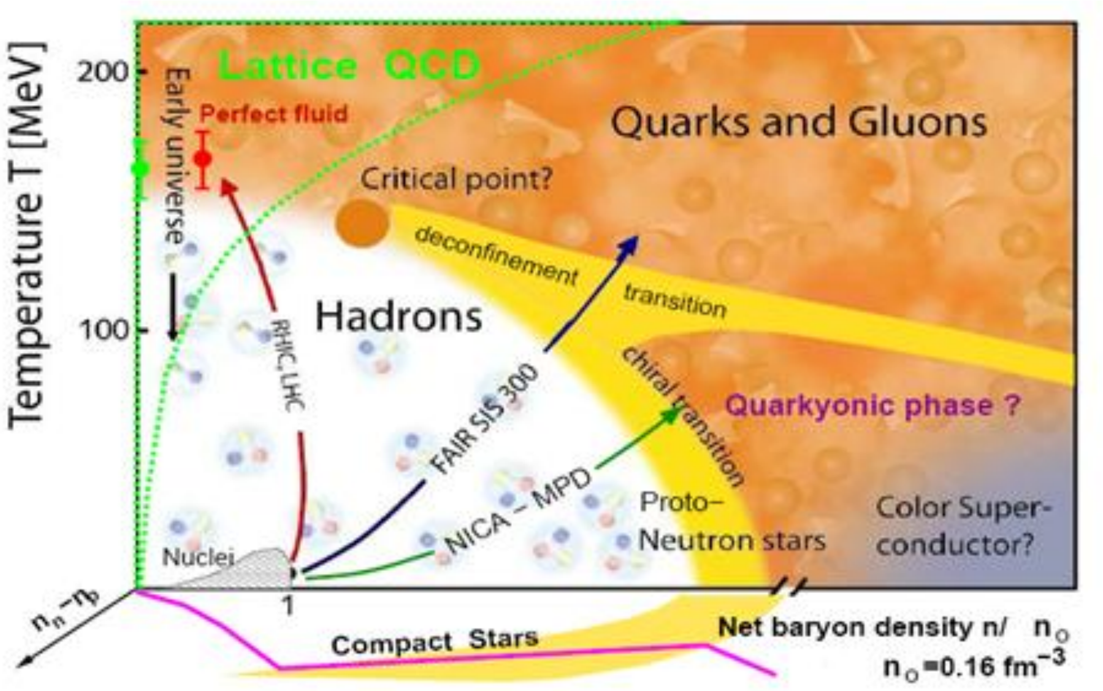
Hot QCD matter





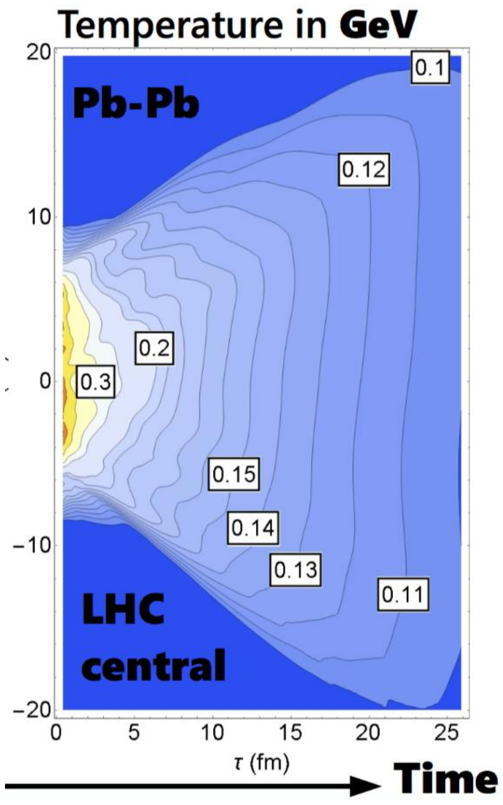


Heavy ion collisions

Phase diagram

Initial hard scattering
+ medium (high p_T)

"Thermal" radiation
(low p_T)



Stages of a heavy ion collision

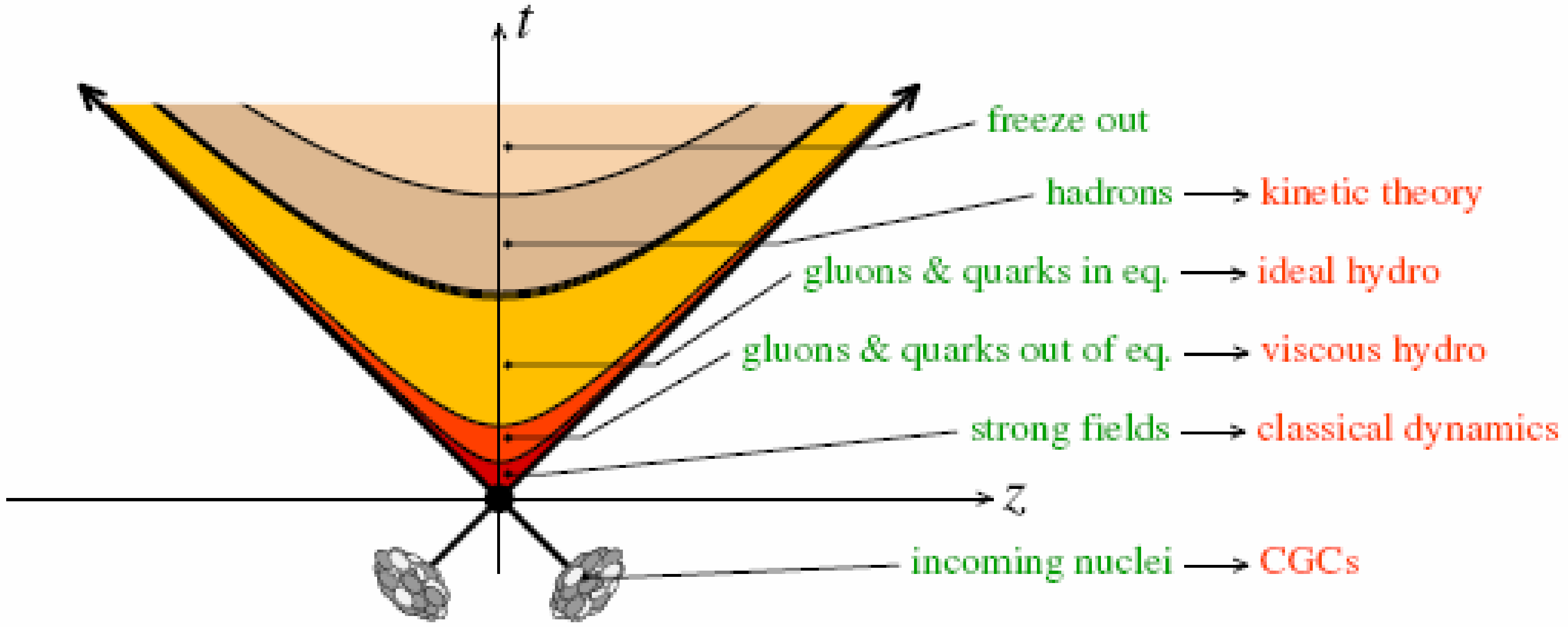
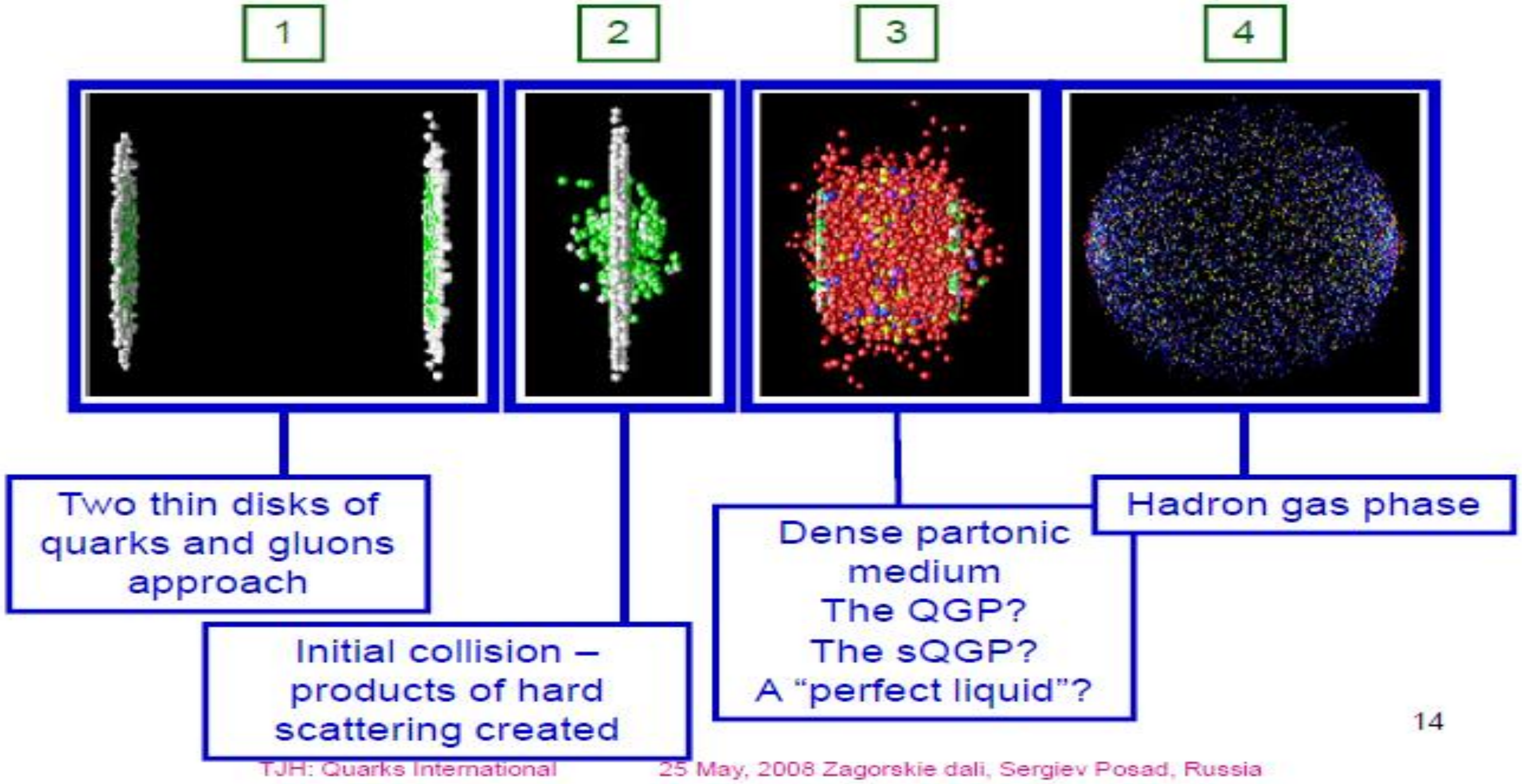


Fig. 1: Schematic representation of the various stages of a HIC as a function of time t and the longitudinal coordinate z (the collision axis). The 'time' variable which is used in the discussion in the text is the *proper time* $\tau \equiv \sqrt{t^2 - z^2}$, which has a Lorentz–invariant meaning and is constant along the hyperbolic curves separating various stages in this figure.

E. Iancu, 1205.0579

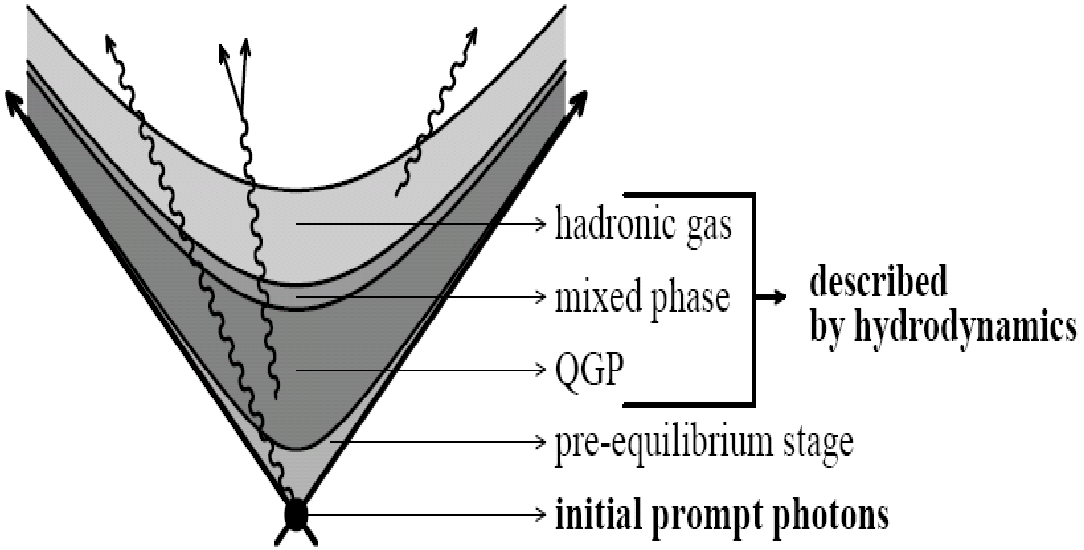
Visualization of a heavy ion collision



Three basic photon sources: pQCD, QGP, hadron gas

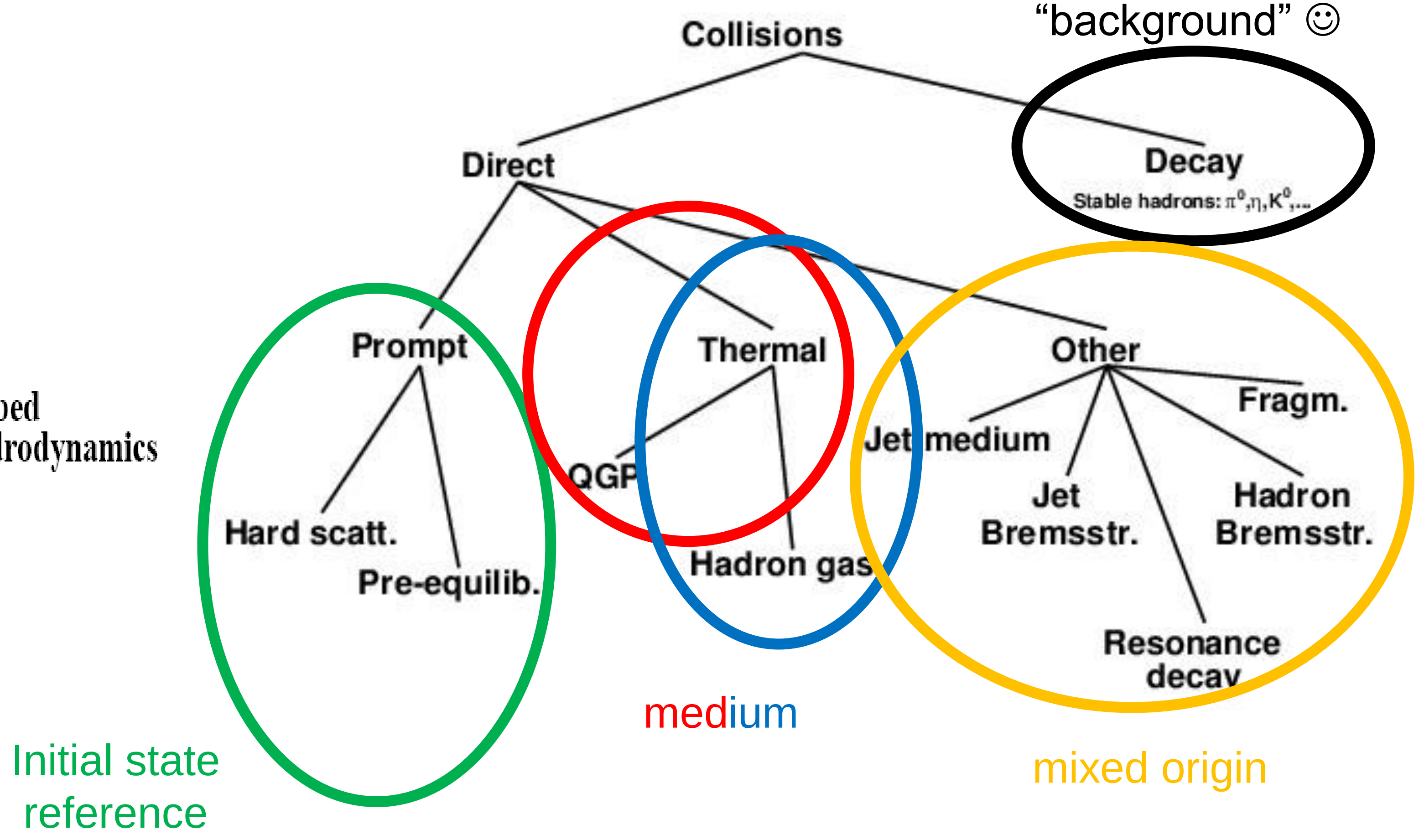
Direct photons: penetrating probe

Small, but *penetrating* signal:
once created, survives intact "forever"
$\alpha_s >> \alpha_{em}$ λ ~ 2-500 fm

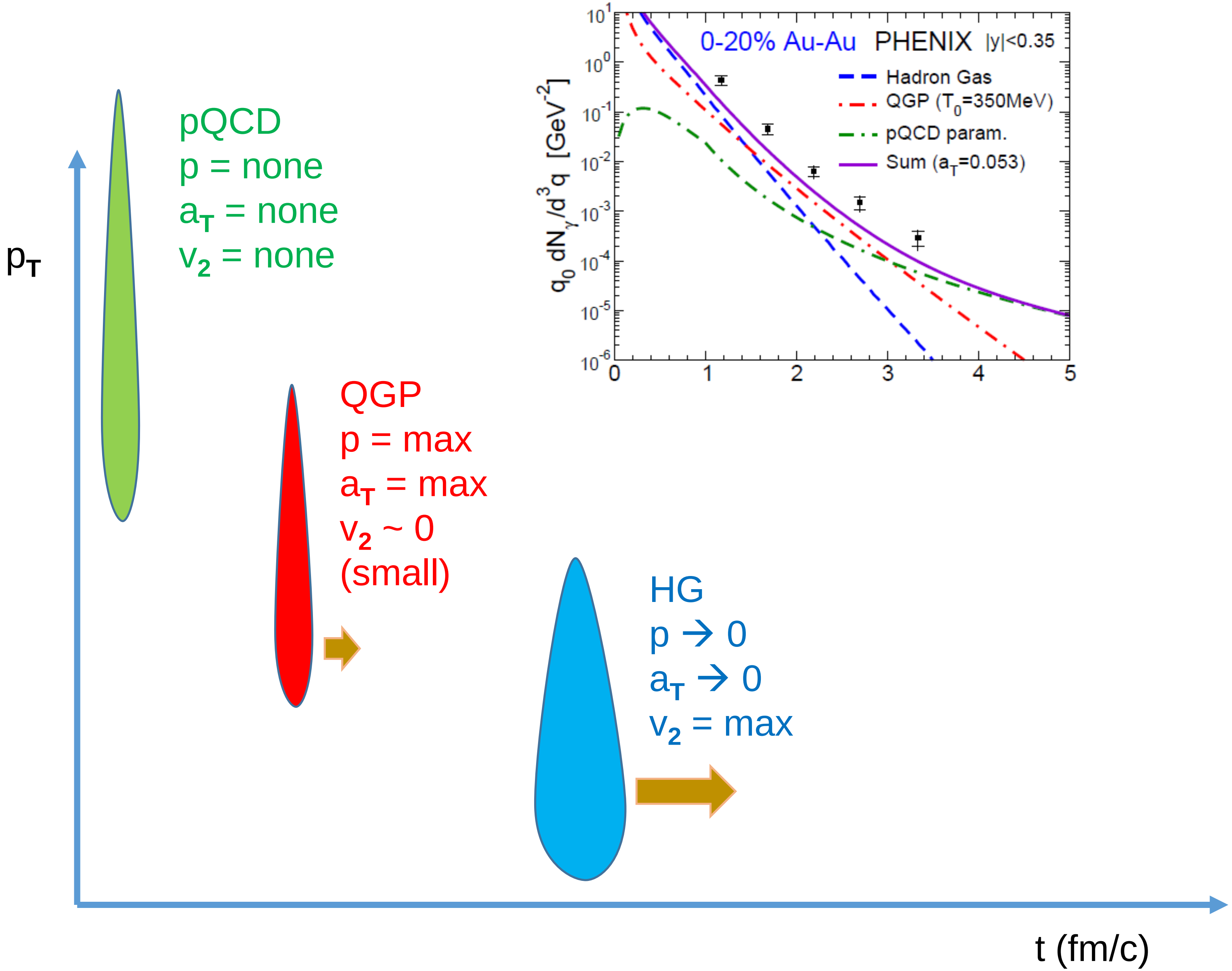


Nomenclature

About 90% of all "background" ☺



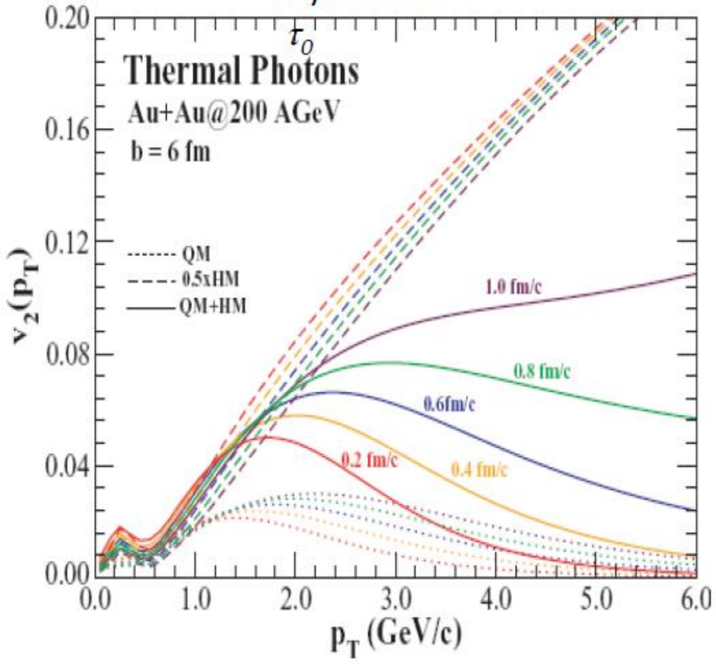
Dominant photon sources: p_T vs time (simplified)



In principle one can try to deconvolute the individual contributions starting from the highest p_T

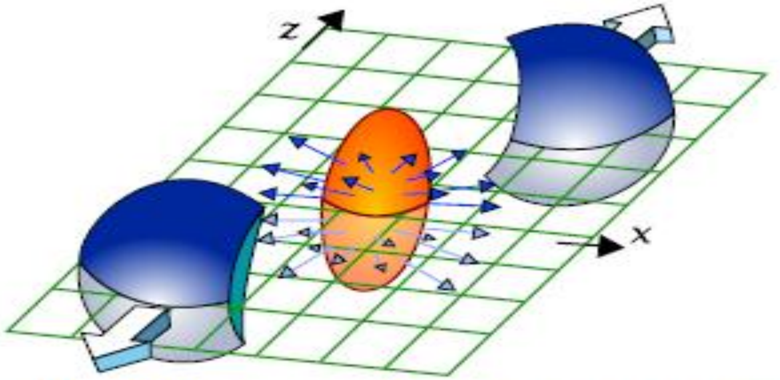
The emitting medium evolves, too!
(Anisotropic emission)

Hydro after τ_0

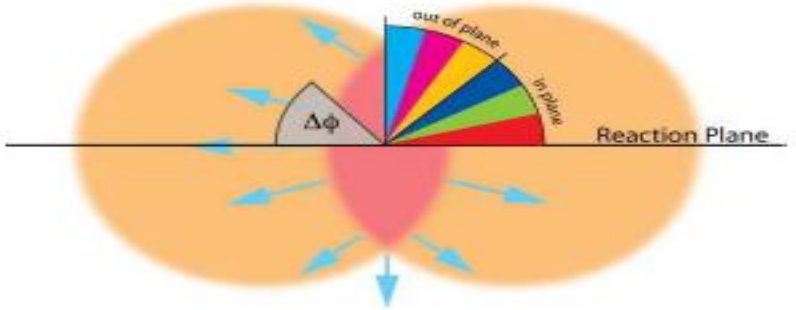


Azimuthal emission pattern – from spatial to momentum anisotropy

Shortest path to surface (vacuum): largest pressure gradient



Flow: Initial spatial anisotropy converts to momentum anisotropy (v_2)



Red initial short pathlength

Cyan long pathlength

R_{AA} wrt. reaction plane $\sim$ R_{AA} wrt. path length

$$R_{AA}(p_T, \Delta\Phi) \approx R_{AA}(p_T) \times \frac{N(p_T, \Delta\Phi)}{\sum_i N(p_T, \Delta\Phi_i)}$$

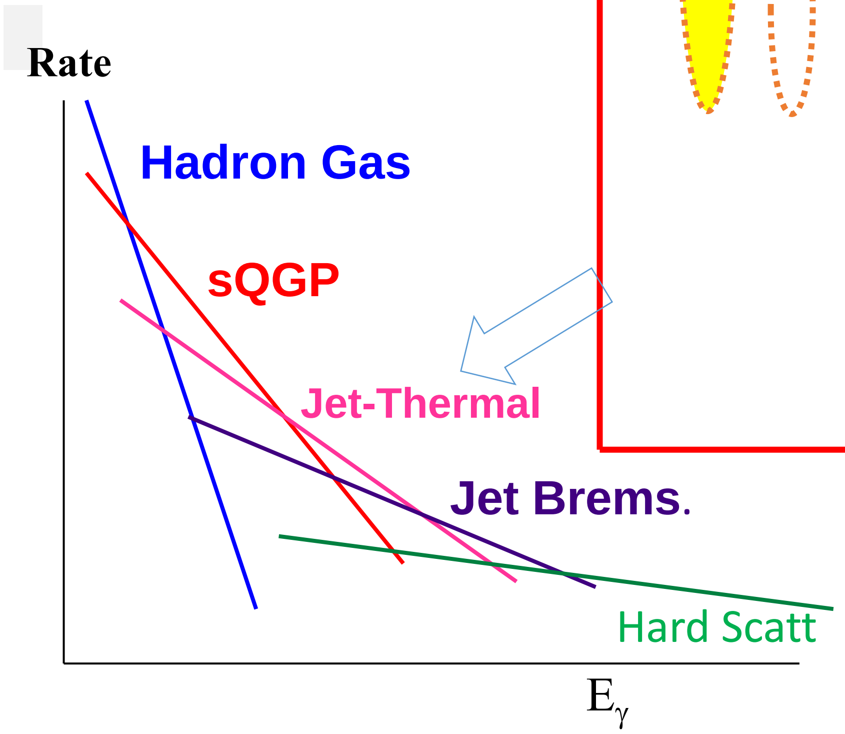
$$N(p_T, \Delta\Phi_i) \approx N(1 + 2v_2 \cos(2\Delta\Phi_i))$$

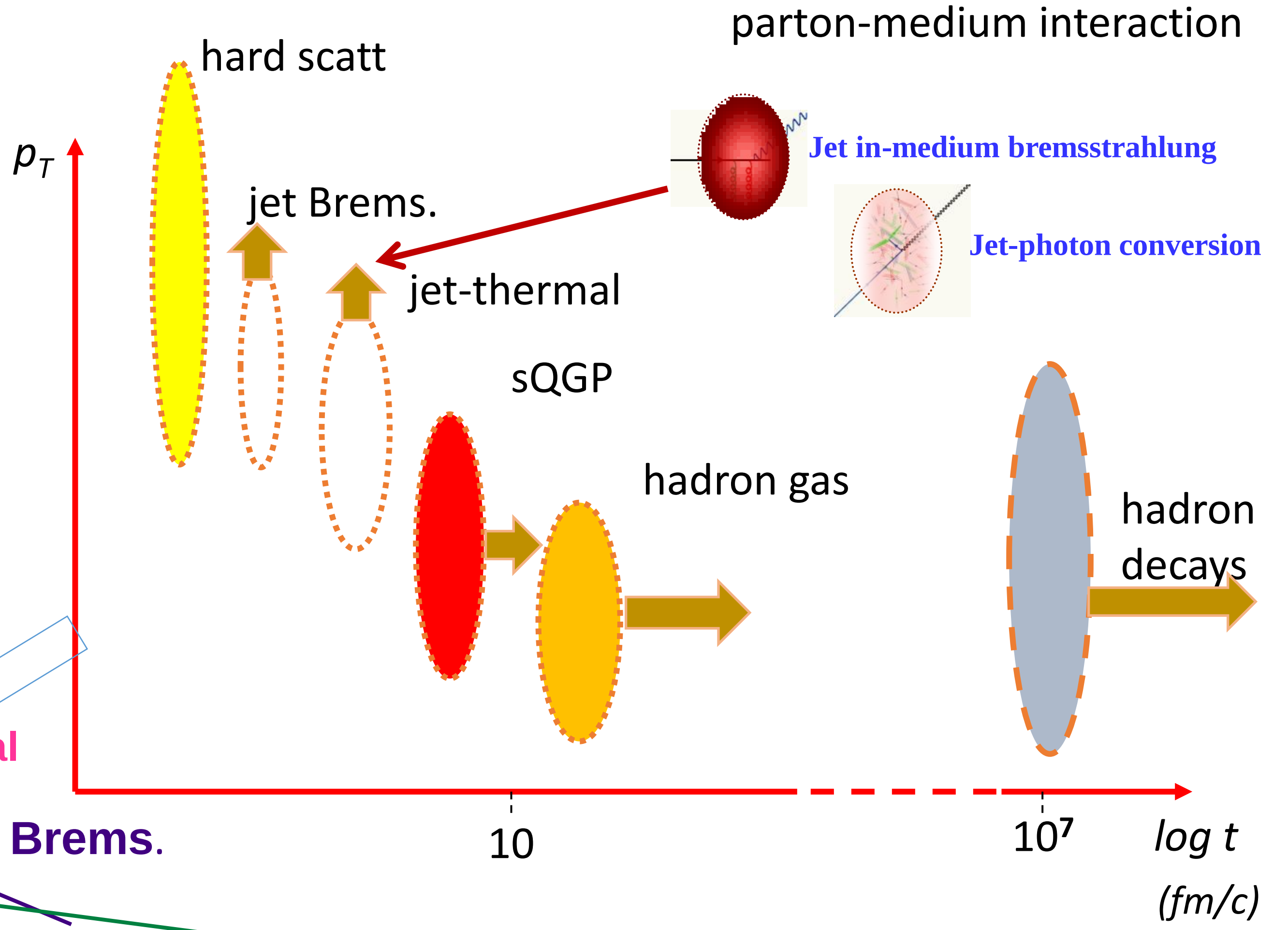
More sources…

Jet fragmentation,
Jet-thermal interaction
(jet-photon conversion)
Initial magnetic field
Bremsstrahlung (hadron gas)
…???

Obviously each new source makes the deconvolution from a single, integrated spectrum more difficult

See e.g., Turbide, Gale, Jeon and Moore, PRC 72, 014906 (2005)



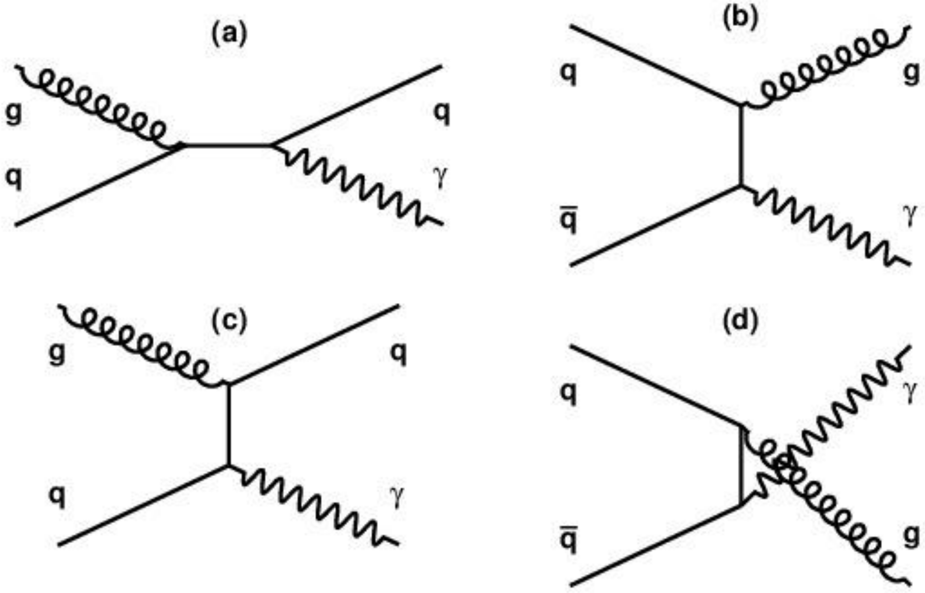


The historians of the collision.

Direct photons: basic processes

Partonic (2→2)
Initial hard scattering, QGP

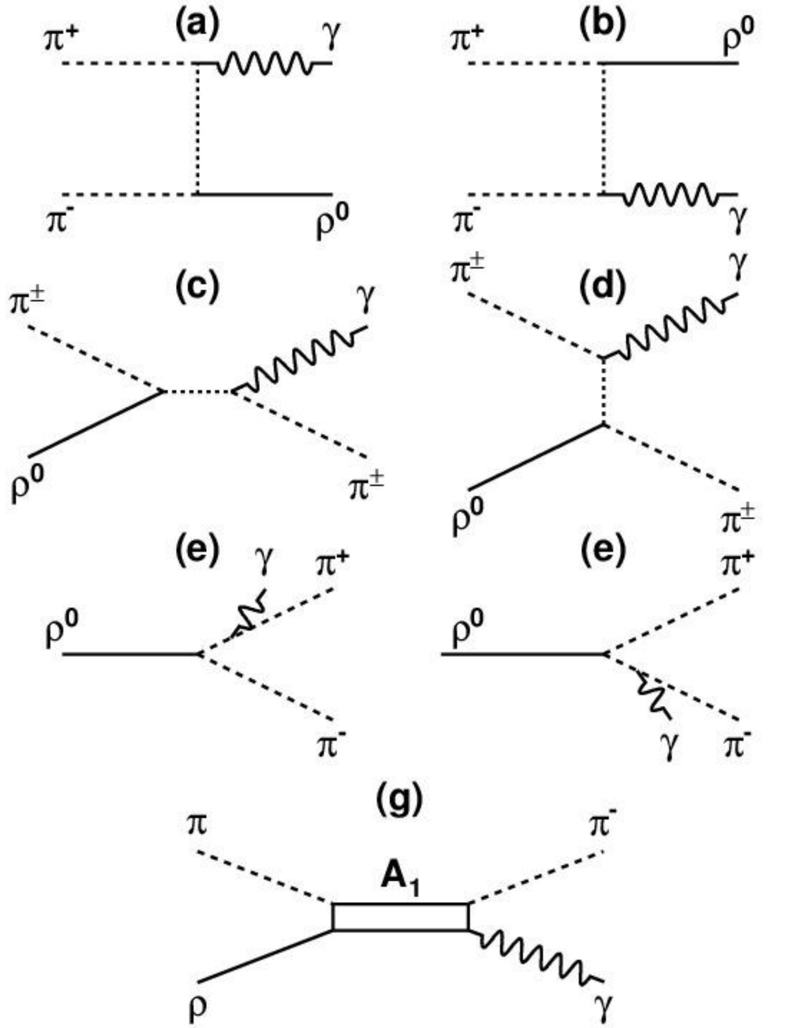
Processes similar, distributions different
(PDF vs "thermal")



Compton-scattering

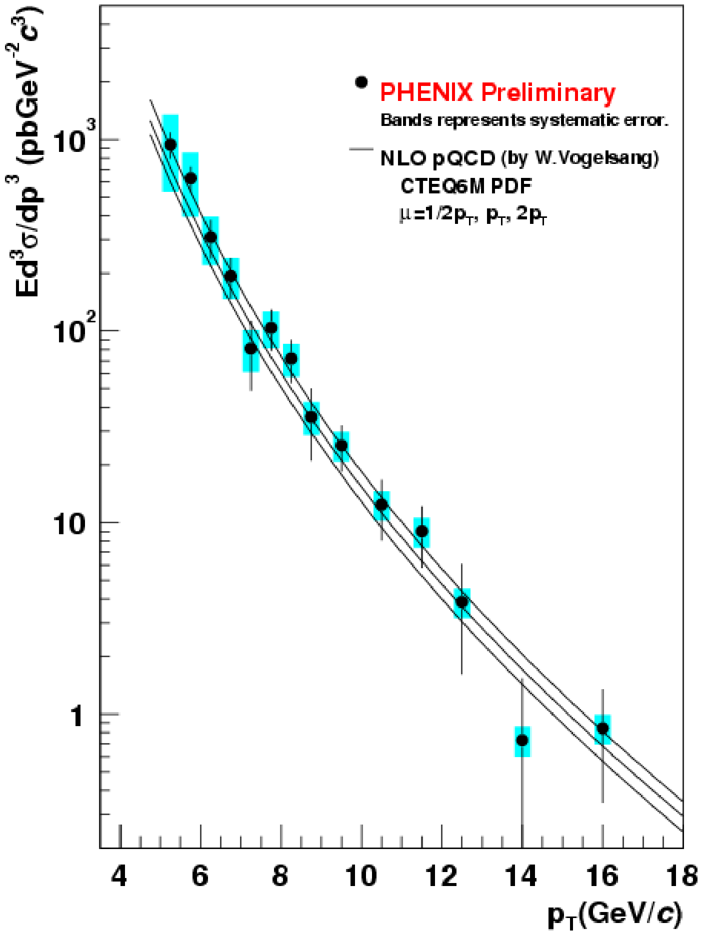
Annihilation

Hadronic
(hadron gas until kinetic "freezout")



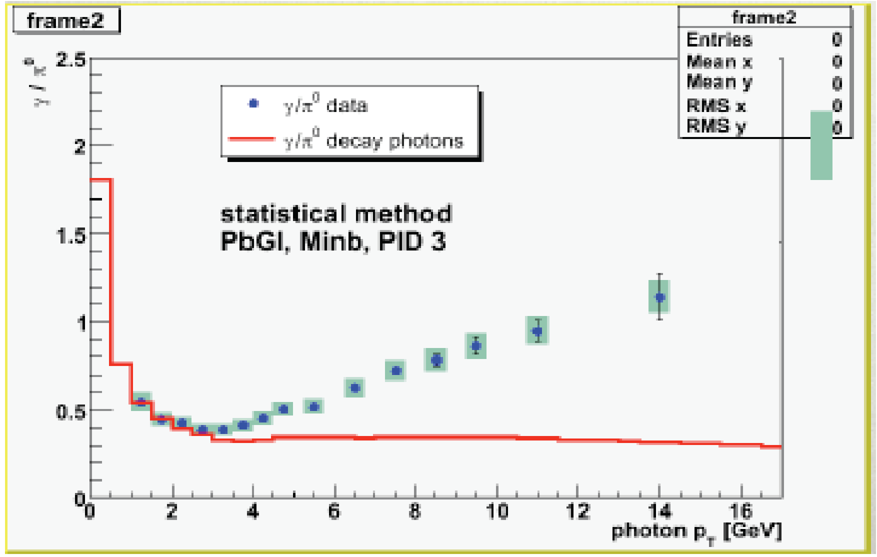
Ways to present direct photon results: spectrum, γ/π and the $R\gamma$

Spectrum:
complete information,
but many syst. errors

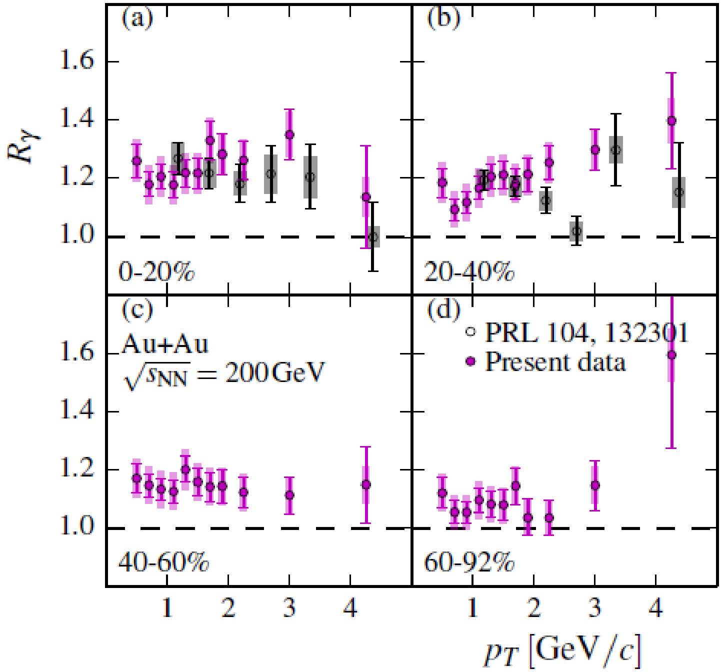


γ/π^0

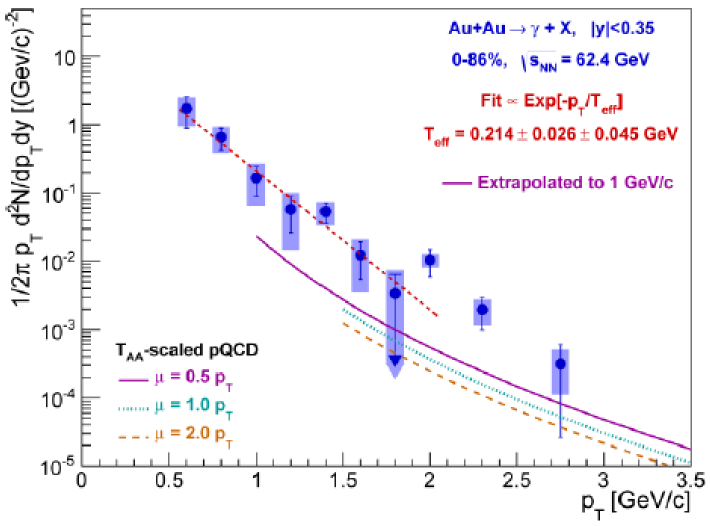
Less information, but more robust w.r.t. errors.
These two presentations encode similar information



$$R_\gamma = \frac{\gamma^{\mathrm{incl}}}{\gamma^{\mathrm{hadron}}} = \frac{\langle \varepsilon_\gamma f \rangle \left(\frac{N_\gamma^{\mathrm{incl}}}{N_\gamma^{\pi^0,\mathrm{tag}}} \right)_{\mathrm{Data}}}{\left(\frac{\gamma^{\mathrm{hadron}}}{\gamma^{\pi^0}} \right)_{\mathrm{Sim}}}$$



Ways to present effects of the medium: T_{eff}, R_{AA}, flow…



T_{eff}

exponential fit

to low p_T part

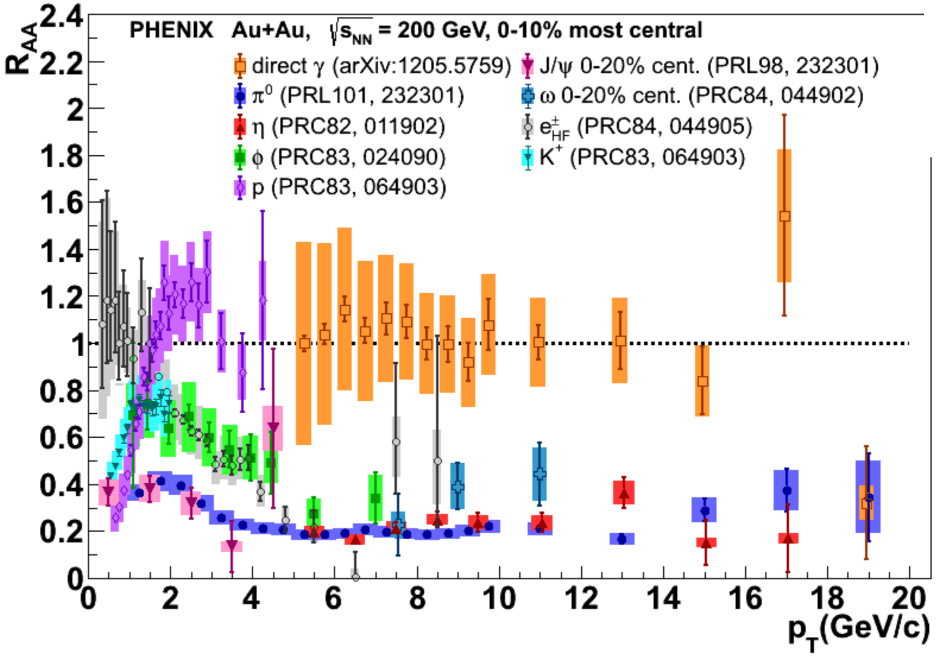
(fit range, etc…)

R_{AA}

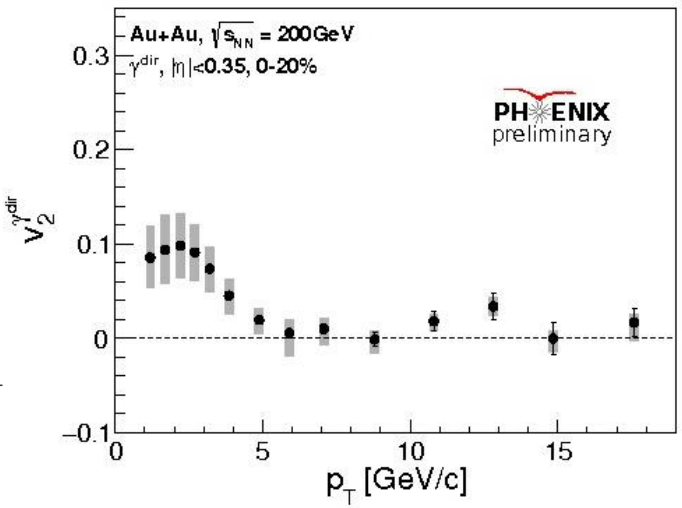
(nuclear modification factor)

ratio of yields in *AA* divided by expected yields from scaled *pp*

$$R^a_{AA}(p_T) = \frac{(1/N^{evt}_{AA})d^2N^a_{AA}/dp_T dy}{(\langle N_{coll}\rangle/\sigma^{inel}_{pp})d^2\sigma^a_{pp}/dp_T dy}$$



$$\frac{dN(\ldots)}{d\phi} = \left\langle \frac{dN(\ldots)}{d\phi} \right\rangle \left(1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)]\right)$$



v_n (*n*-th order "flow")

Fourier-coefficient

of azimuthal distribution

(azimuthal asymmetry)

Some promises of direct, real photons

Binary scaling: proof of sanity → *is R_{AA} a robust observable, is the Glauber model valid?*

Jet energy scale, E_{loss} → *"calibrate" the initial energy of a hard scattered parton*

Initial temperature → *the inverse slope of the spectrum will be dominated by emission at earliest times*

Thermal radiation from the QGP → *does the QGP "outshine" the hadron gas – or vice versa?*

Time-dependent η/s → *ratios of Fourier-coefficients of azimuthal asymmetries of emission (not discussed)*

Initial magnetic field → *centrality dependence of emission anisotropies (not discussed)*

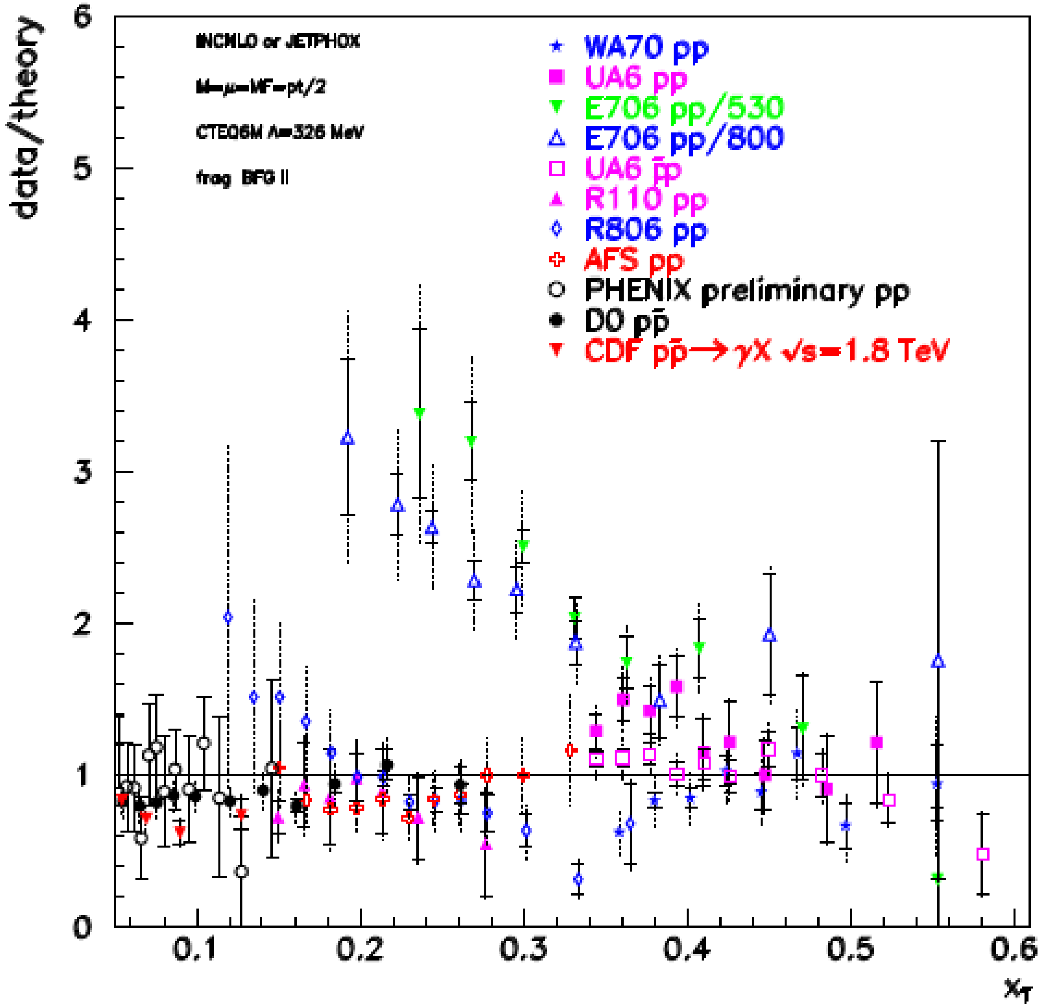
Role of initial state → *how fast is thermalization (briefly touched only)*

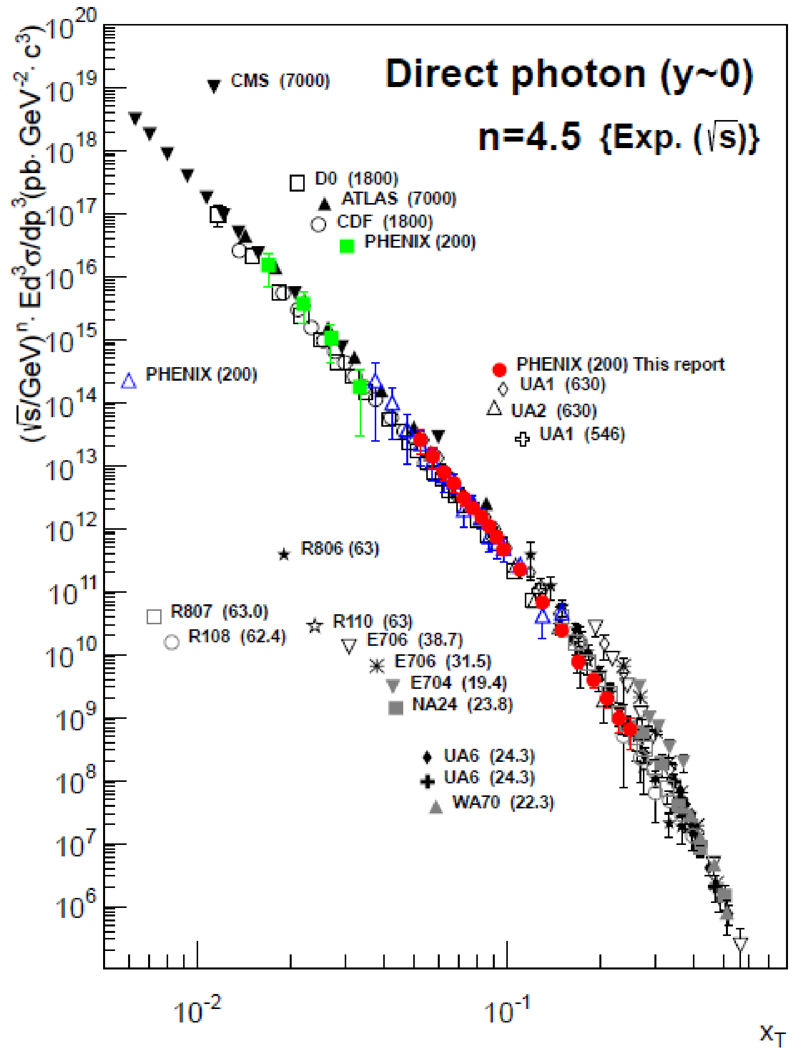
Initial geometry → *magnitude and centrality dependence of azimuthal asymmetries*

"Historians" of the entire collision, including expansion dynamics → *can various sources be isolated?*

Provide major surprises → ***you bet!***

Testing hot QCD matter: you need a reliable probe (pp)

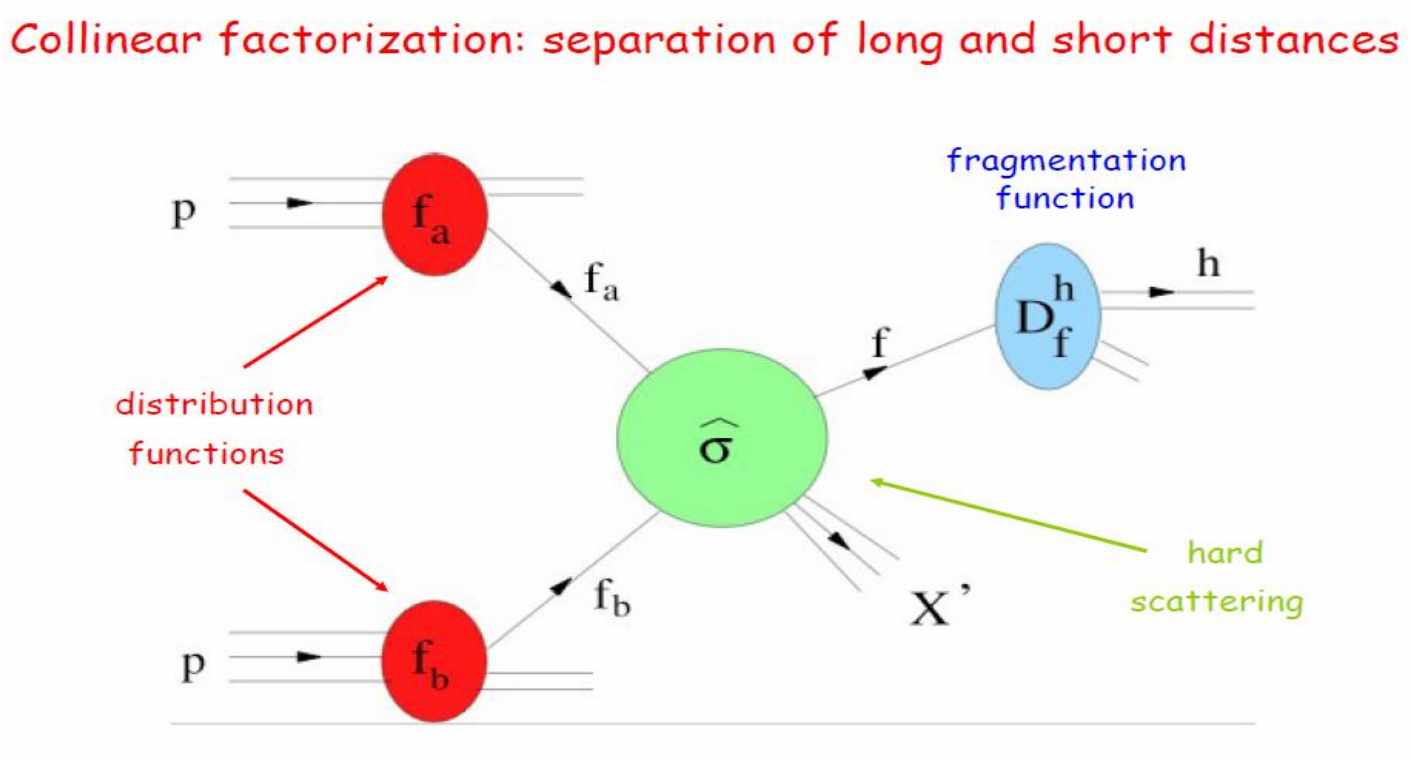


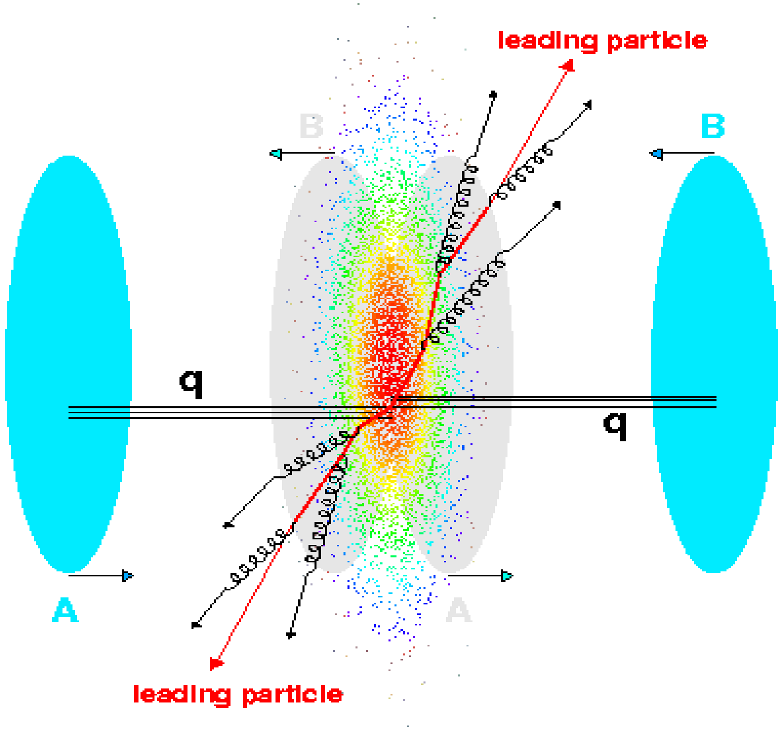


Data well described by NLO calculations

The basic question in AA collisions at high p_T

This factorization works well in p+p. What is different when relativistic nuclei collide?



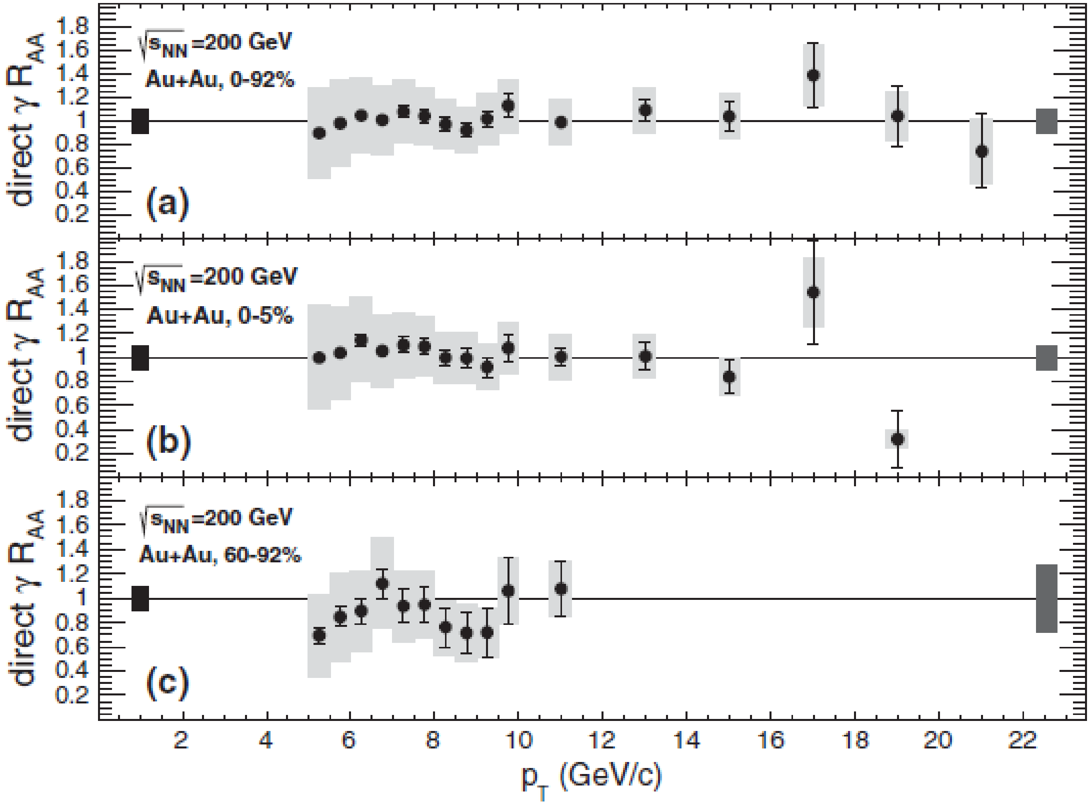


Are PDFs the same? And the relevant processes?
(How) do partons lose energy in the medium?
Any other change in the fragmentation?
Leading particle: our favorite jet proxy

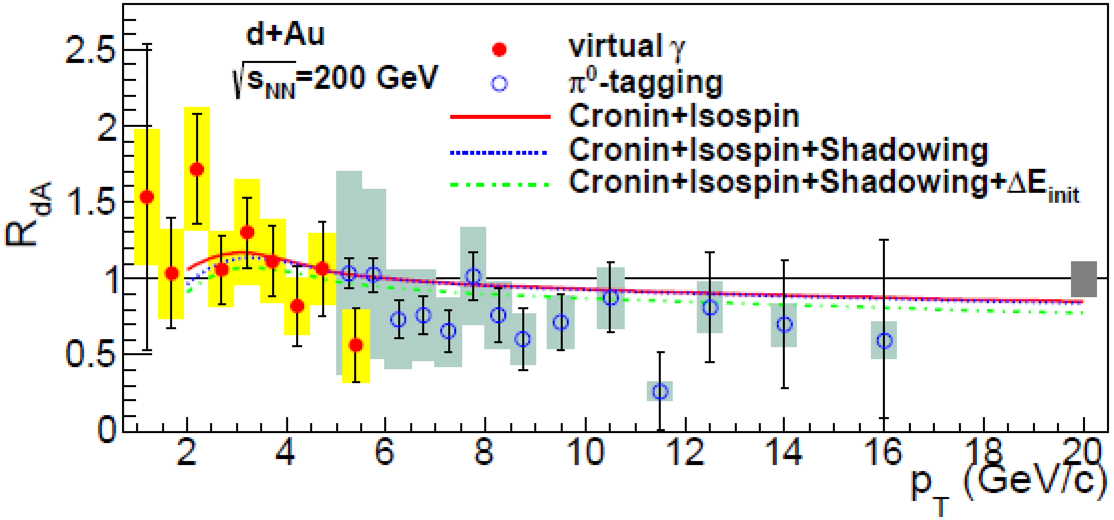
High pT (isolated) photons are immune to the medium

In A+A collisions, while hadrons are strongly suppressed,
and in a p_T-dependent way, photons appear to be unaffected

PHENIX PRL 109, 152302 (2012)



PRC 87, 054904 (2013)



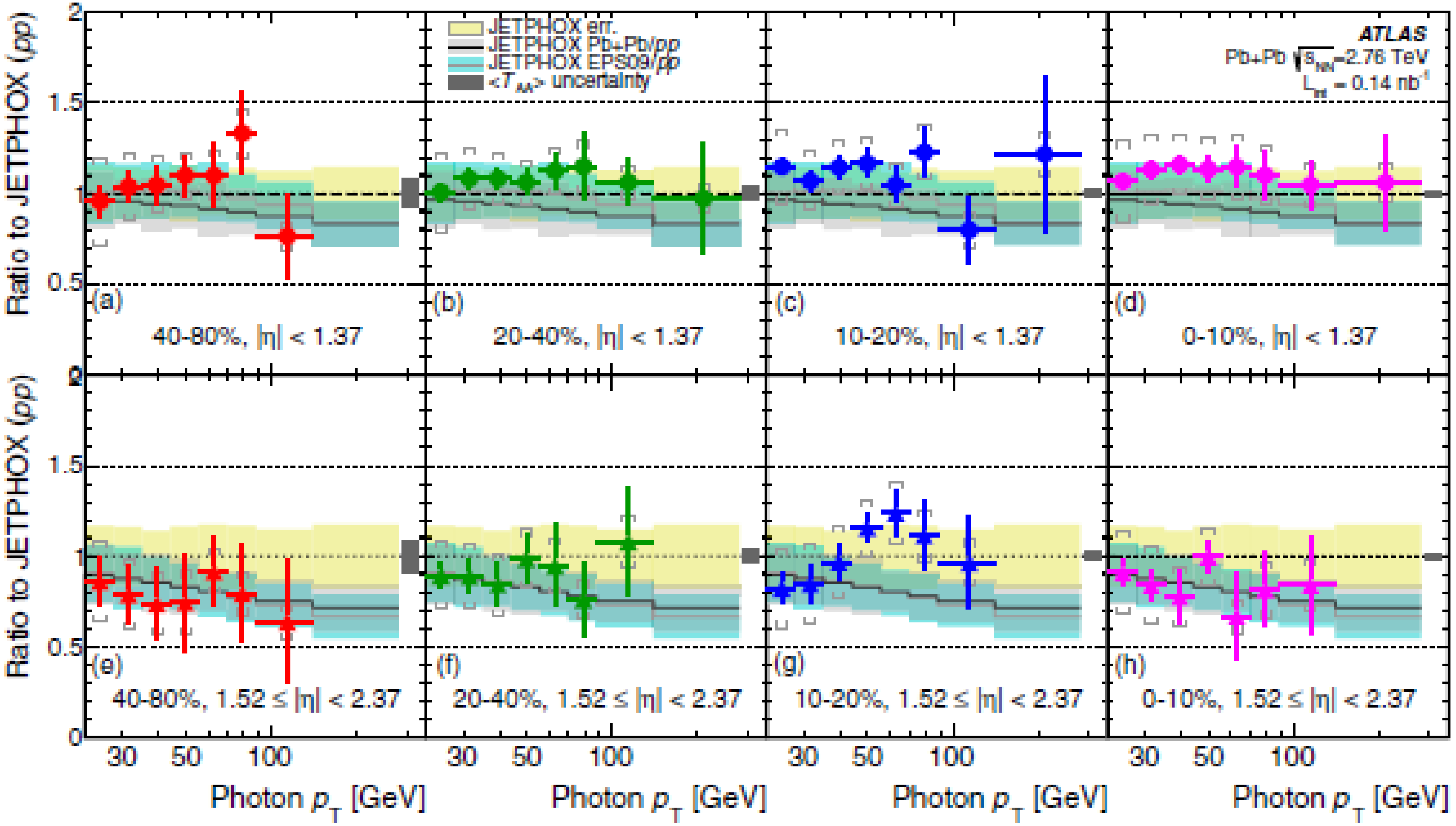
Watch out for the slight deviation from unity
due to the isospin effect

All right, this is MB, but stay tuned!
(And don't forget: centrality is non-trivial in very asymmetric collisions!)

ATLAS, Pb+Pb

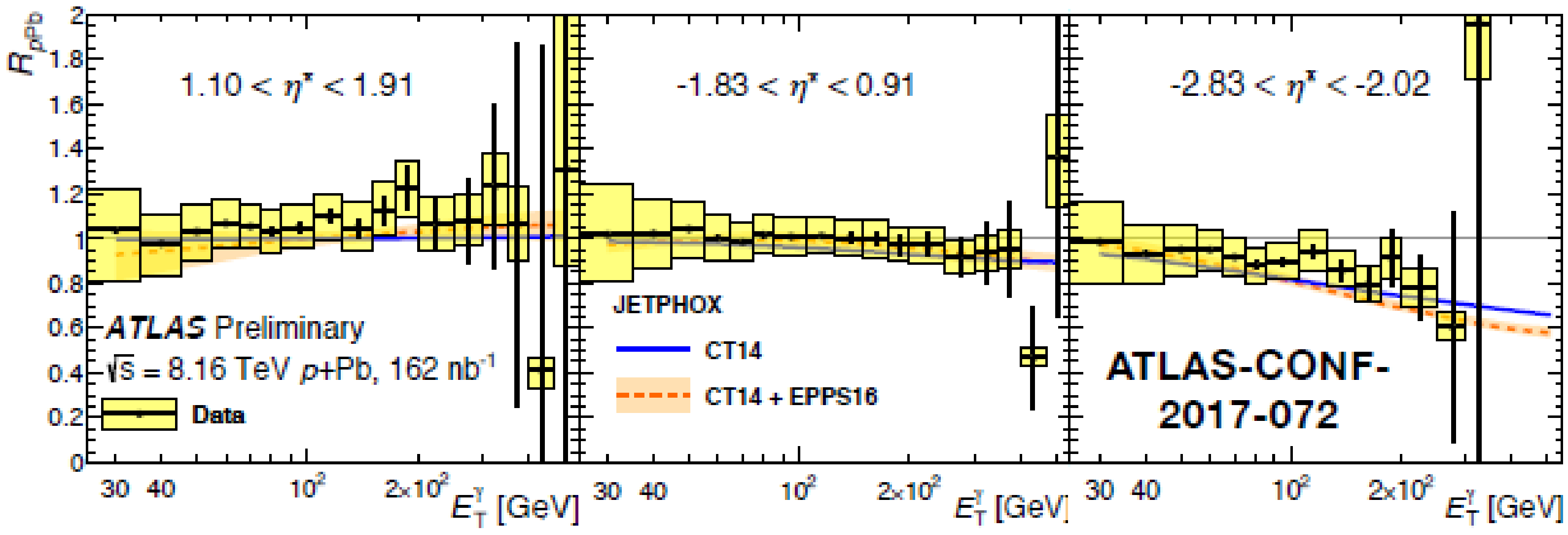
ATLAS, PRC 93, 034914 (2016)

At midrapidity, consistent with 1; fw some depletion
PbPb – includes isospin effect (n/p) - EPS09 includes neutron skin effect

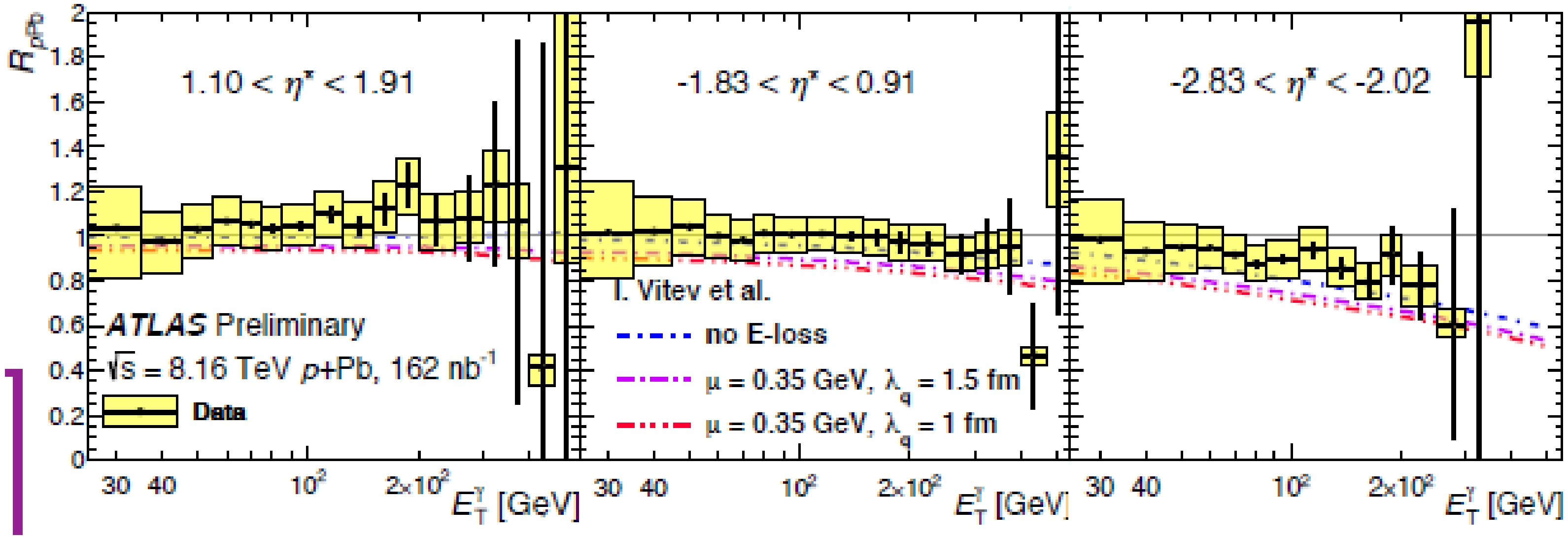


ATLAS, p+Pb

Photon R_{AA} unity even for very asymmetric collisions (some deviation at high rapidity: gluon PDF's?)



➡ *favorable comparison to pQCD & nPDF*

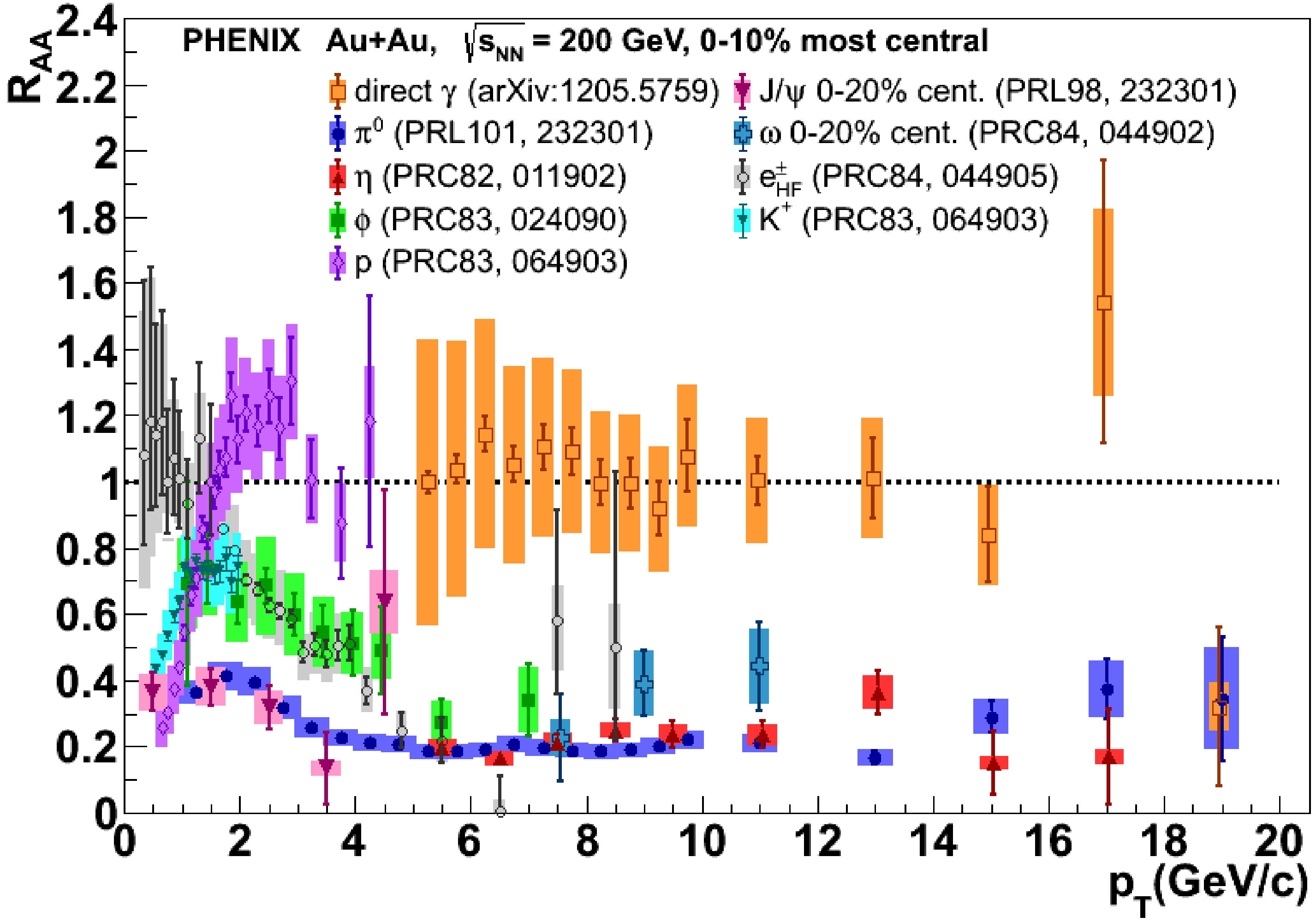


High pT photons: immune to the medium

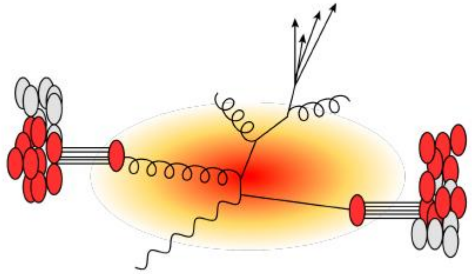
Hard scattered partons lose energy → fragmentation hadrons are suppressed, but photons are insensitive to medium effects → will be the decisive tool or "centrality" in pA (small-on-large) collisions (***but that's a completely different talk -- GD, Pos(INPC2016)345***)

PHENIX
"T-shirt plot"

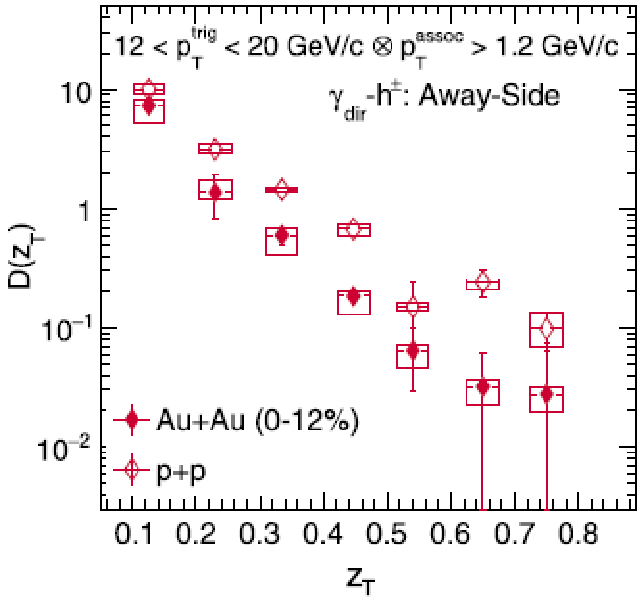
Strong evidence for parton energy loss in medium
as well as validity of the Glauber-model in large-on-large collisions

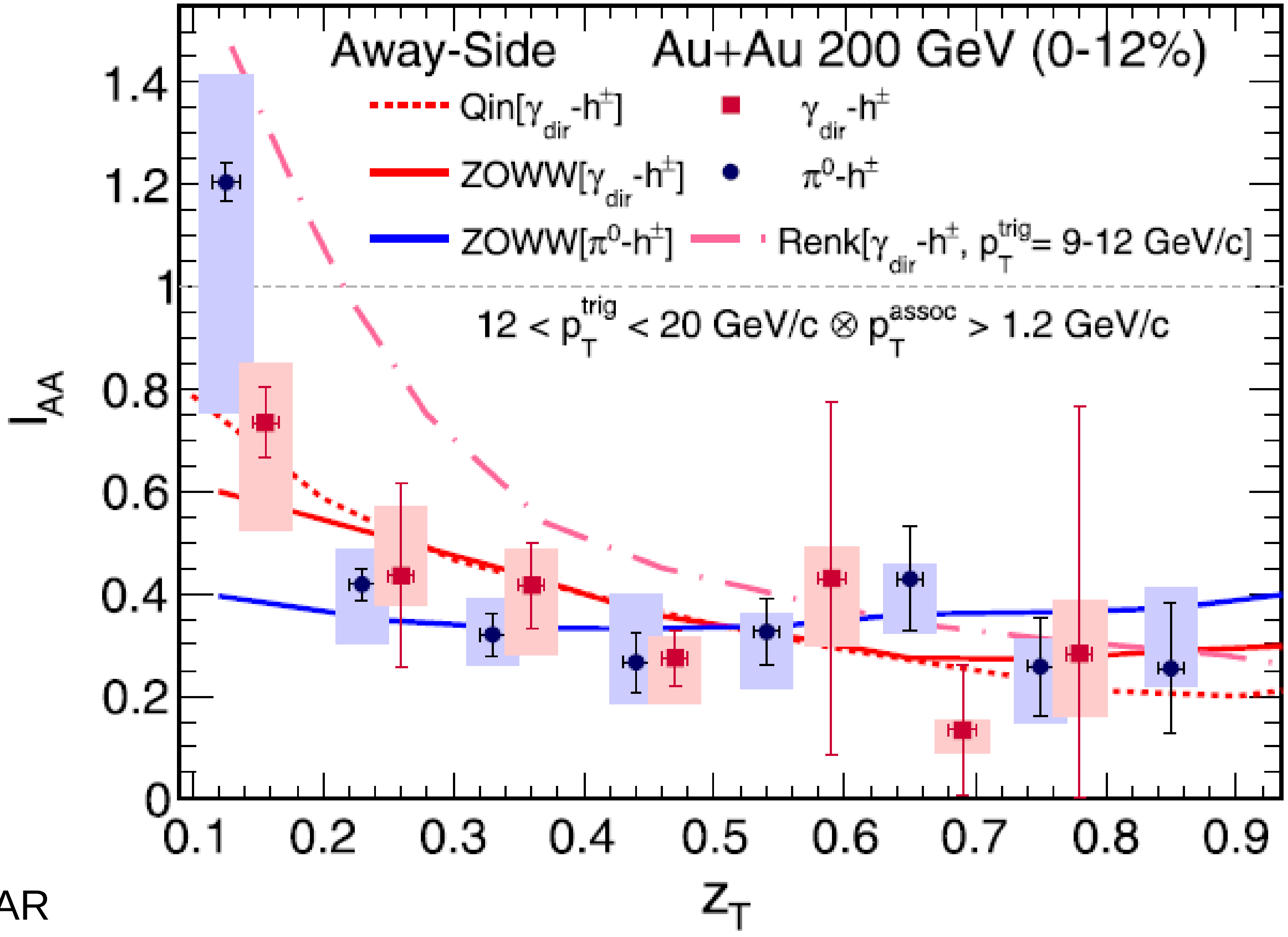


High pT photons: calibrating parton energy loss



Photon triggered hadron-correlations:
fragmentation function proxy
Dramatic change in Au+Au

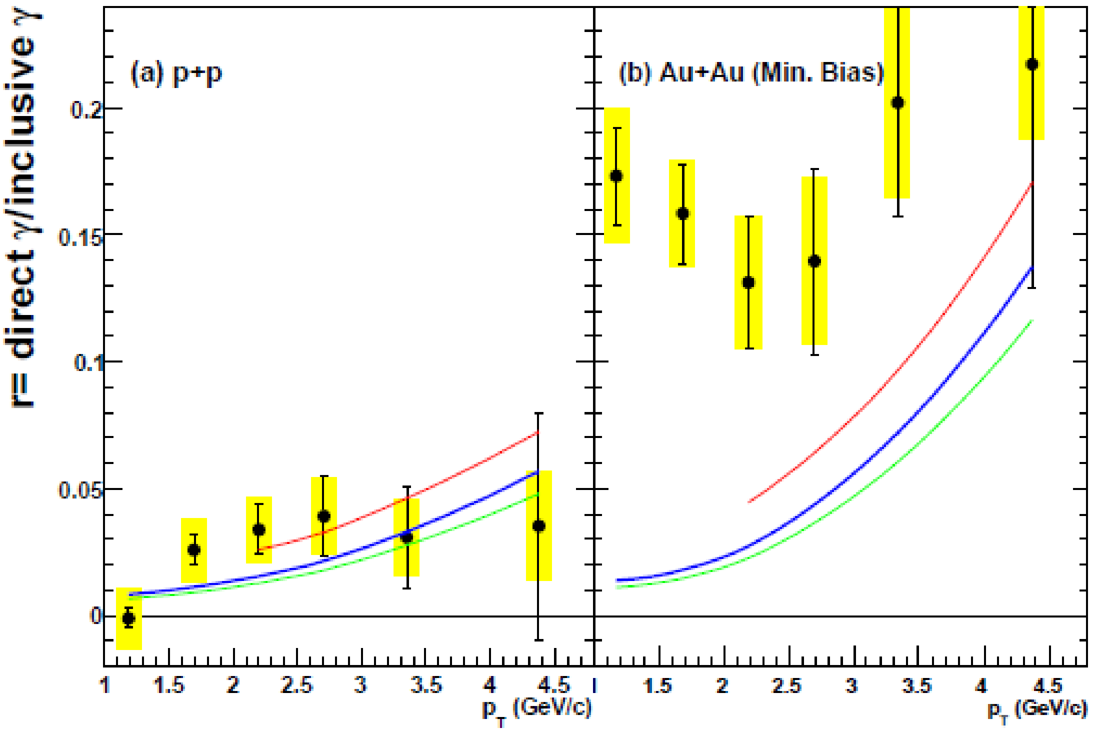




STAR
PLB 760 (2016) 689

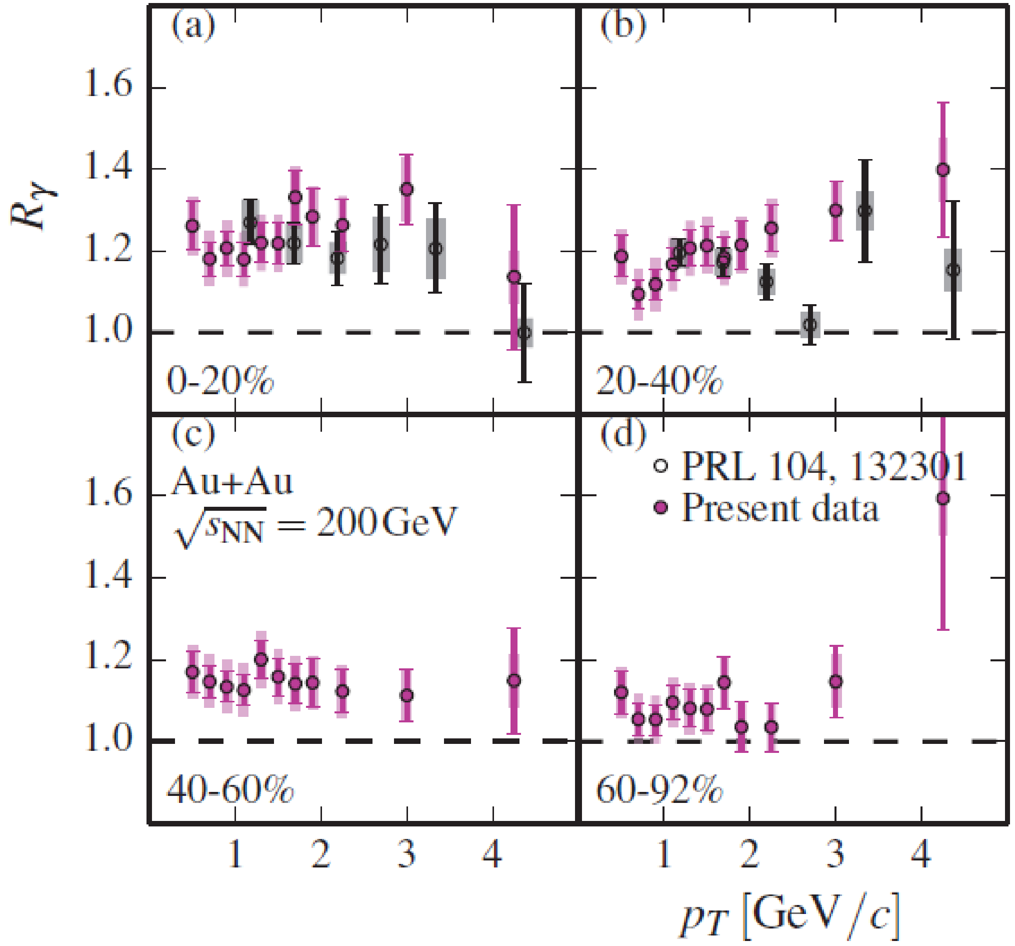
Low pT (“thermal”) photons – RHIC, Au+Au

PHENIX, PRL 104, 132301 (2010)



Virtual photons. Note that this result is in “tension” with the published STAR result

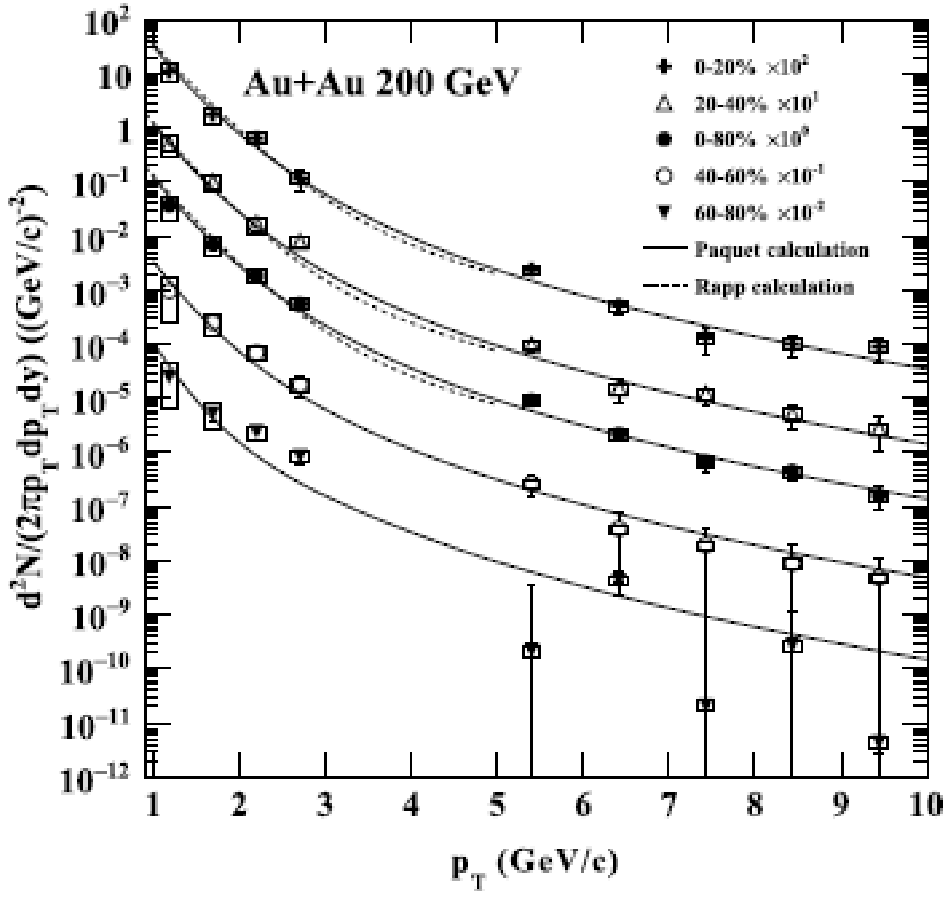
Real photons, measured with external conversion
Consistent with virtual photon result (PHENIX)



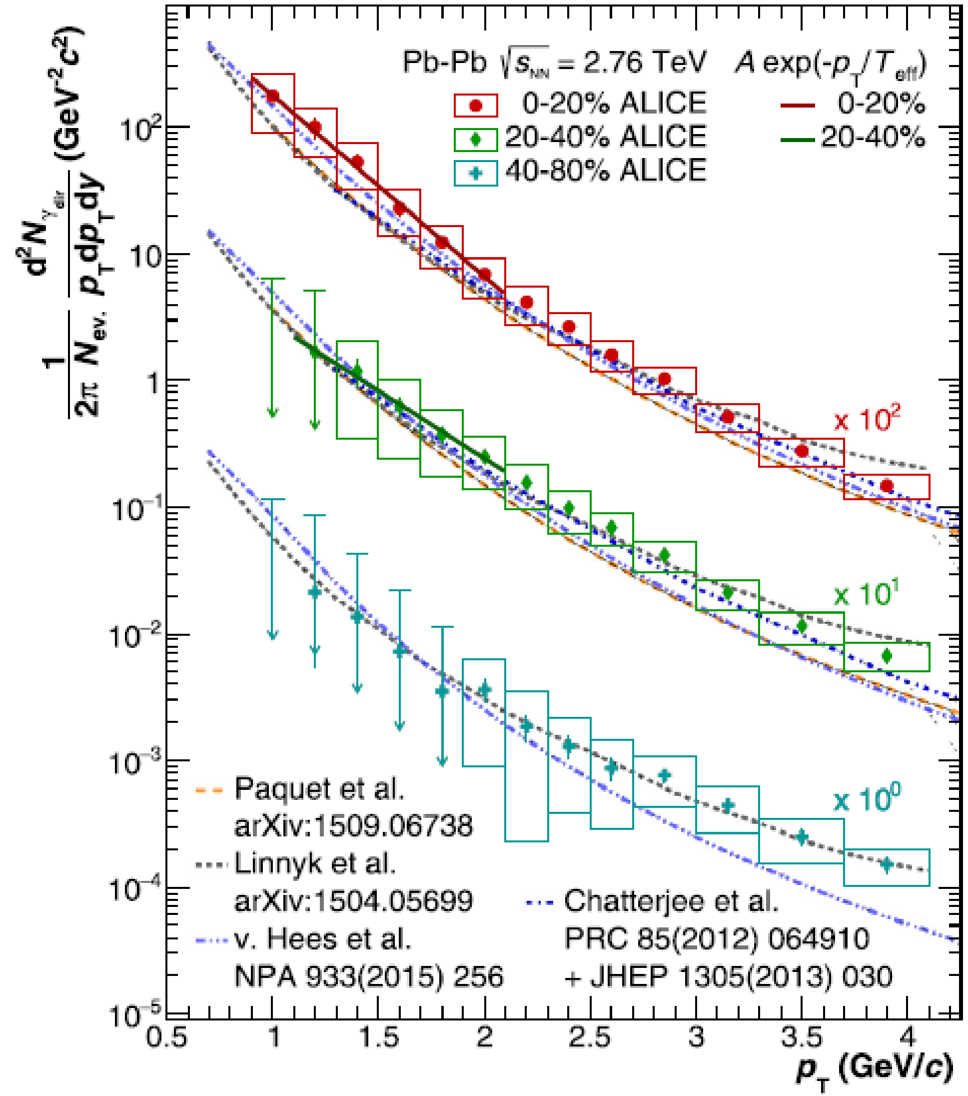
Low pT ("thermal") photons – RHIC, LHC

Everybody sees some excess (apparently exponential) above simple scaled p+p – the argument is only how much is it – and what's the origin?

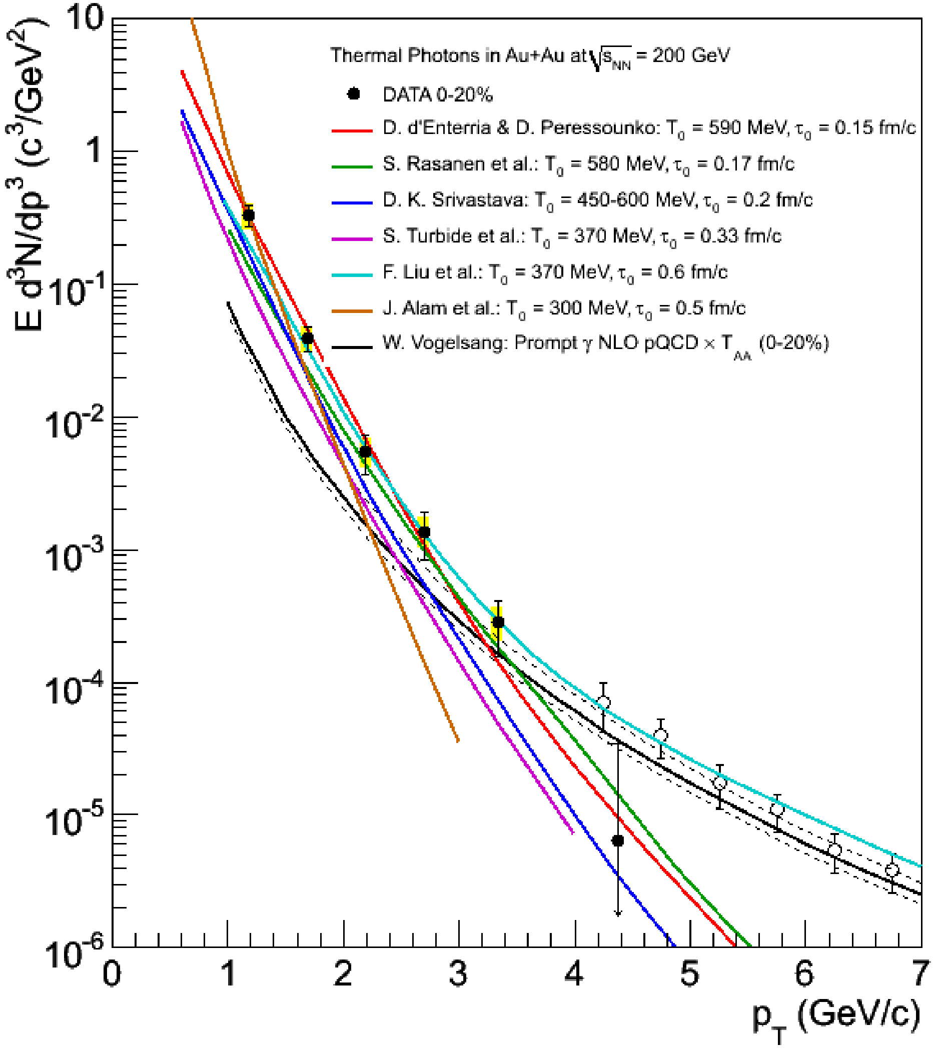
STAR, PLB 770 (2017) 451

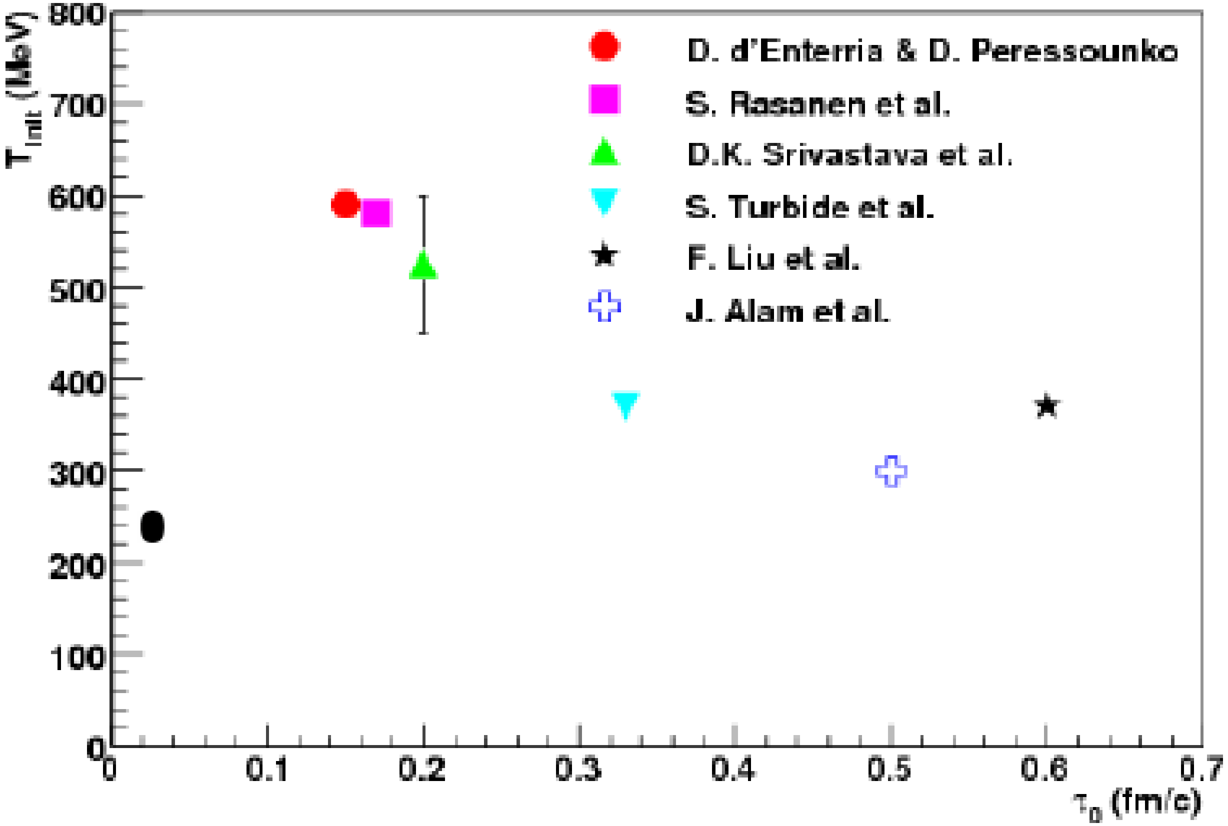


ALICE, PLB 754 (2016) 235



“Thermal” photons: is it really temperature?





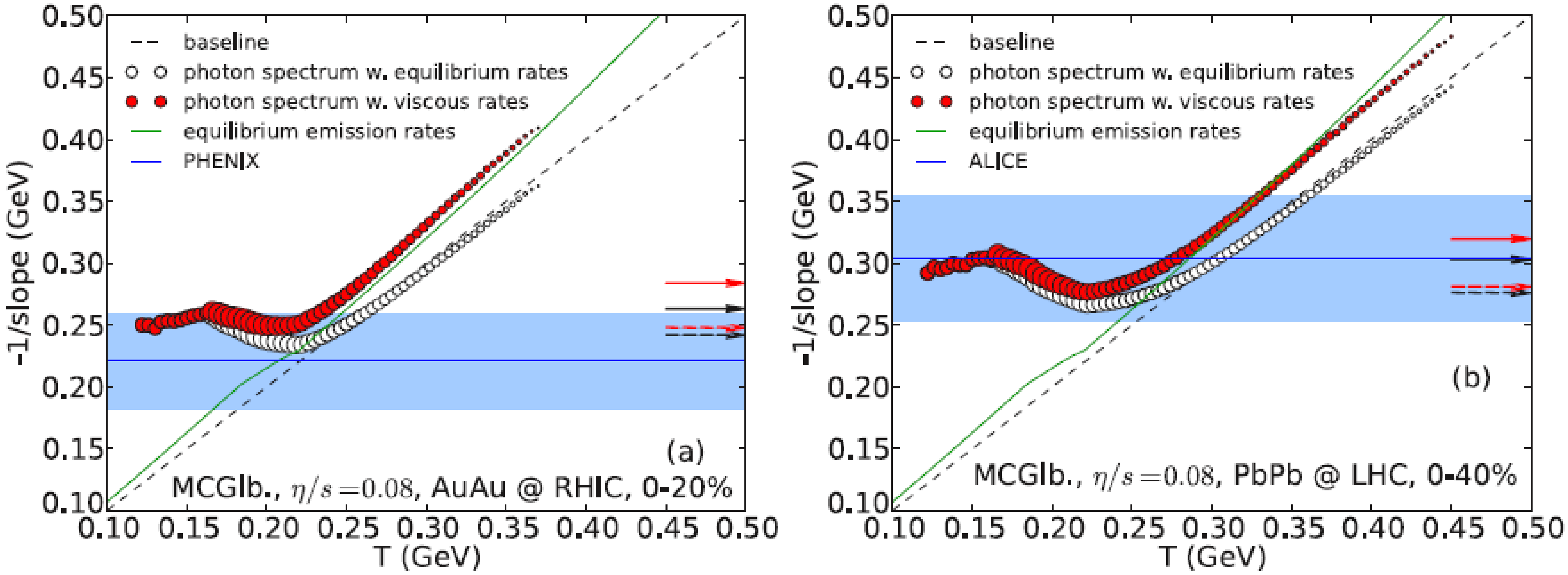
“Temperature” vs “initial time” (start of hydro evolution)

Shown in a zillion different versions, same conclusion: direct photon spectra alone, while important, not sufficient constraint on temperature – or “temperature”…

Temperature, effective temperature, inverse slope

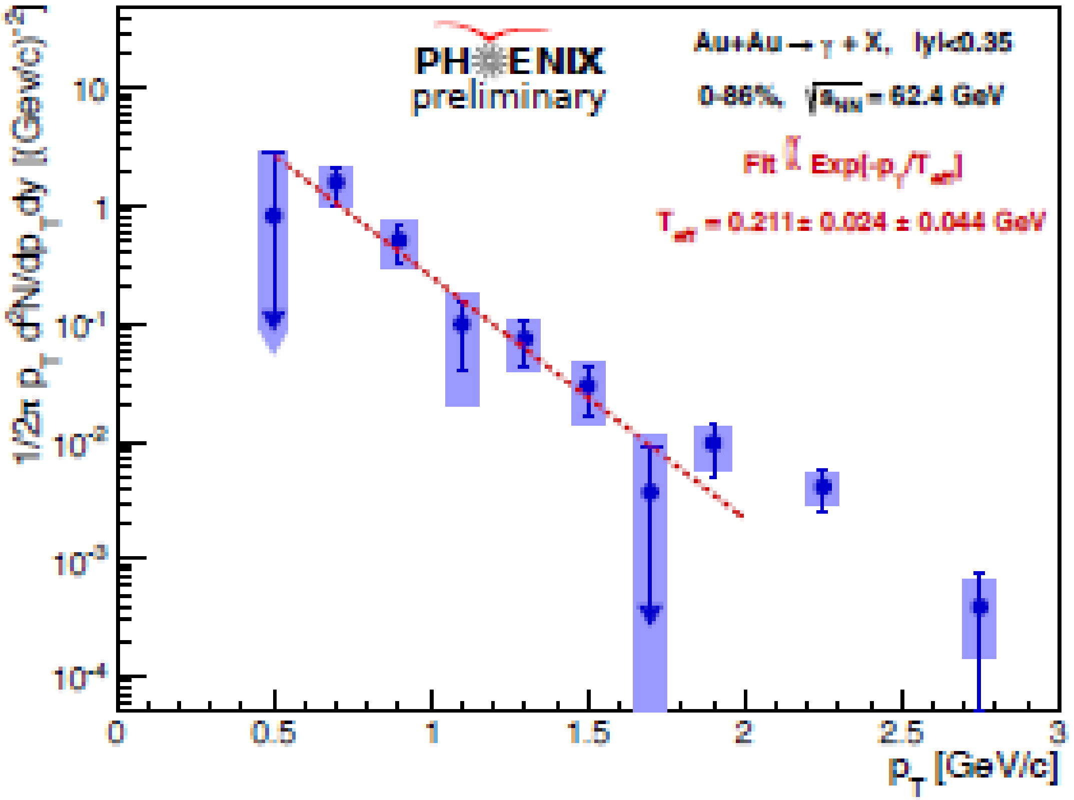
System evolution followed in a specific hydro model. Apparent inverse slope vs true instantaneous temperature. Size of blobs: instantaneous production rate.

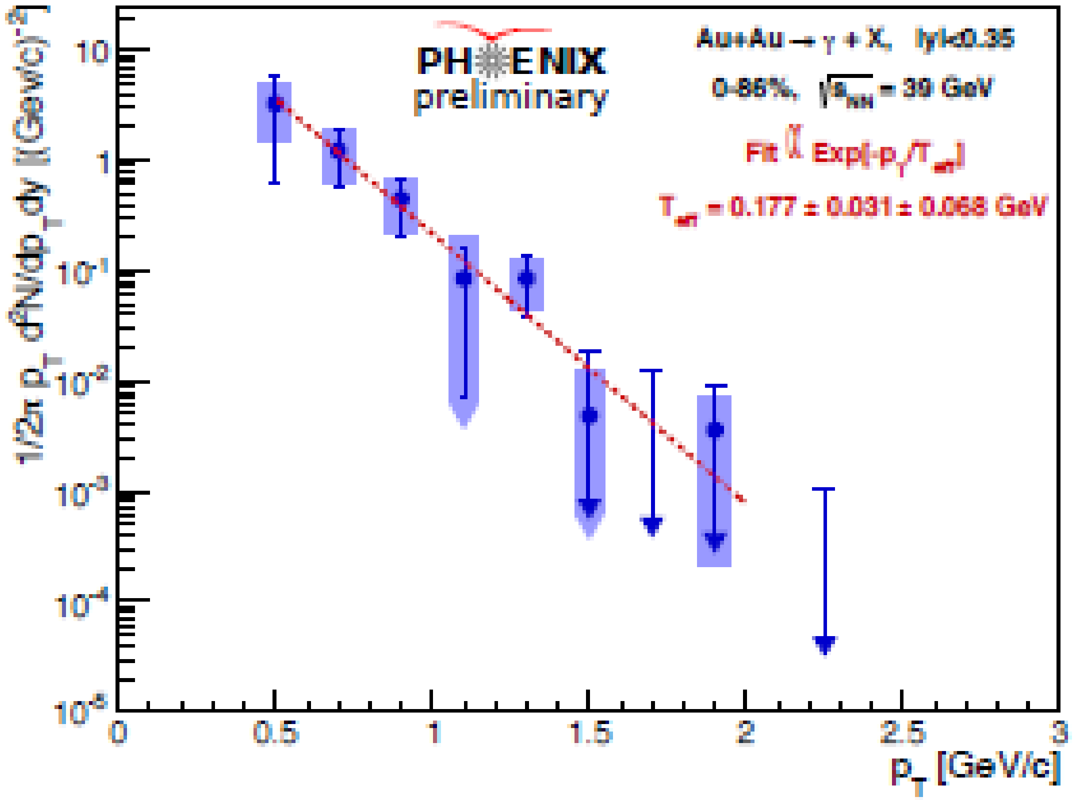
PRC 89, 044910 (2014)



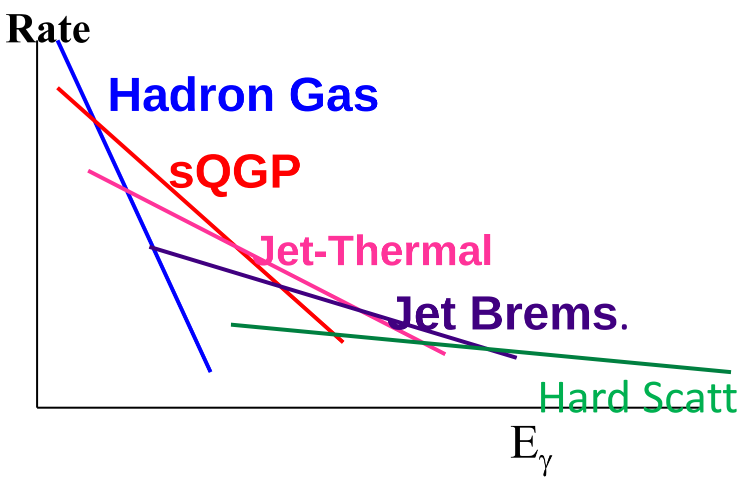
T_{eff}: where do you fit the spectra?

It's hard to argue that a single exponential is a good fit; which region do you fit anyway?

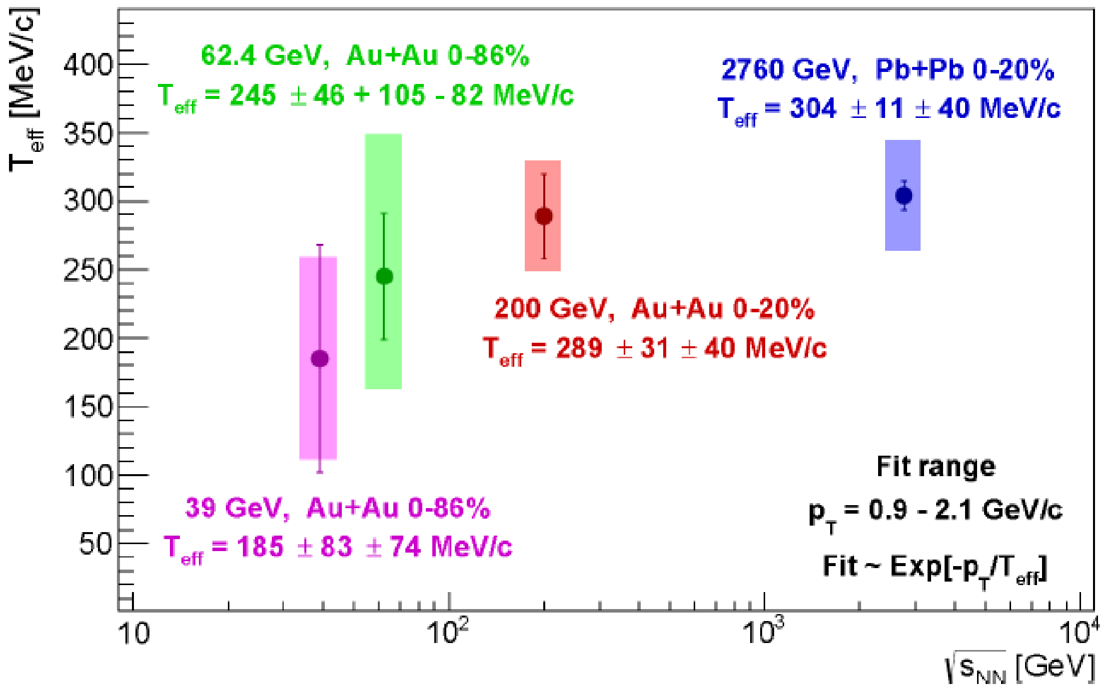


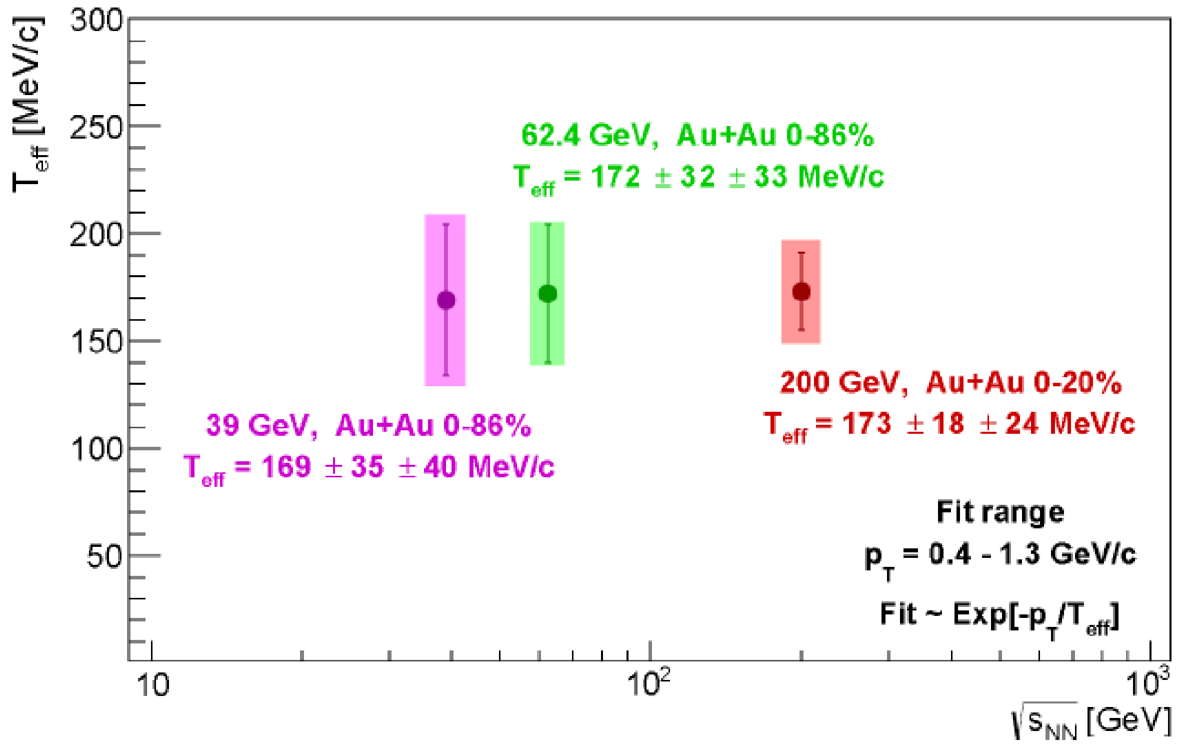


T_{eff}: where do you fit the spectra?



Remember: temperature, radial boost, dominant physics mechanisms – all change with time!
Fitting the envelope of this convolved does not give you a simple, ordinary "temperature"!

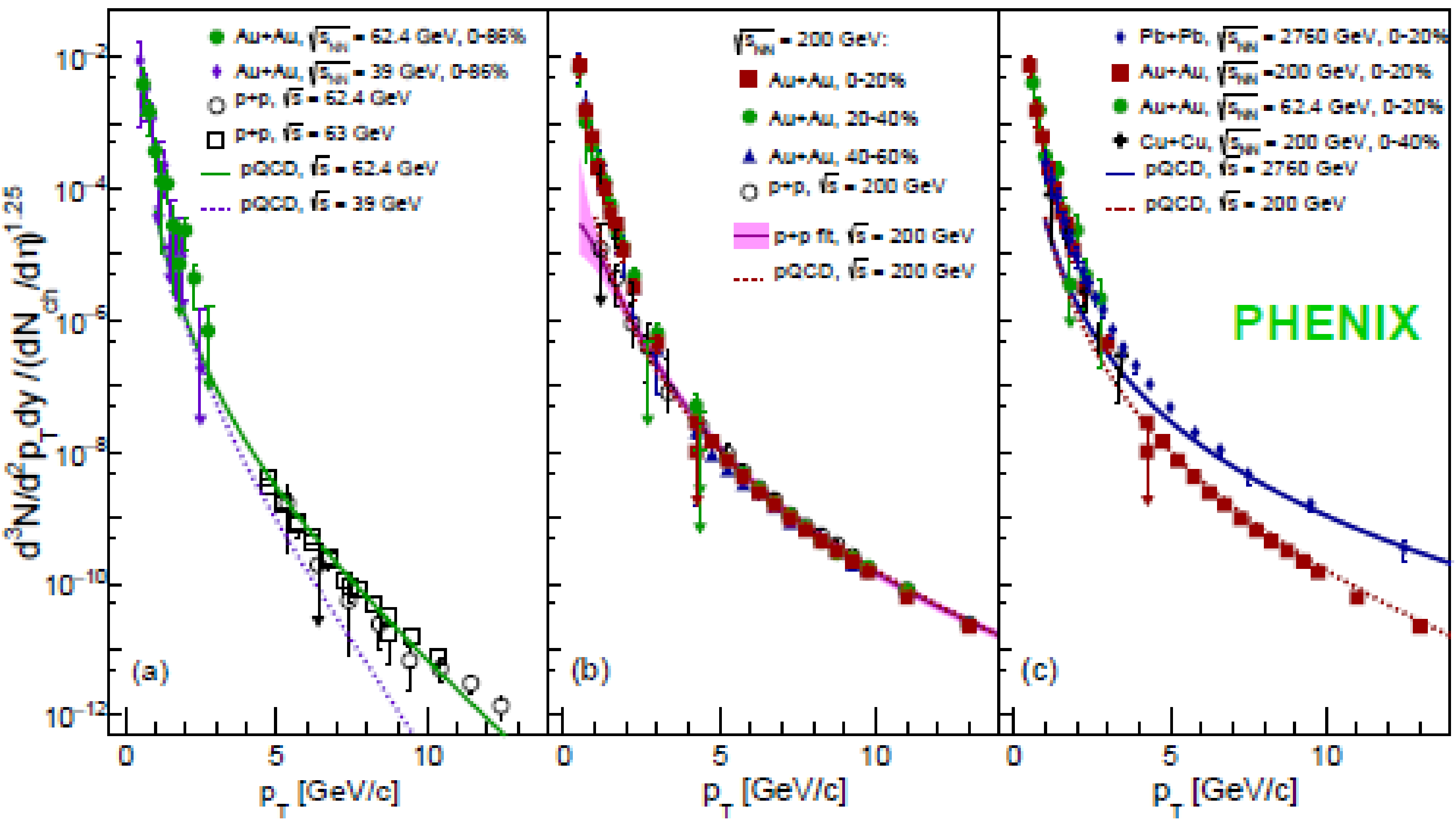




Probably mostly hadron gas

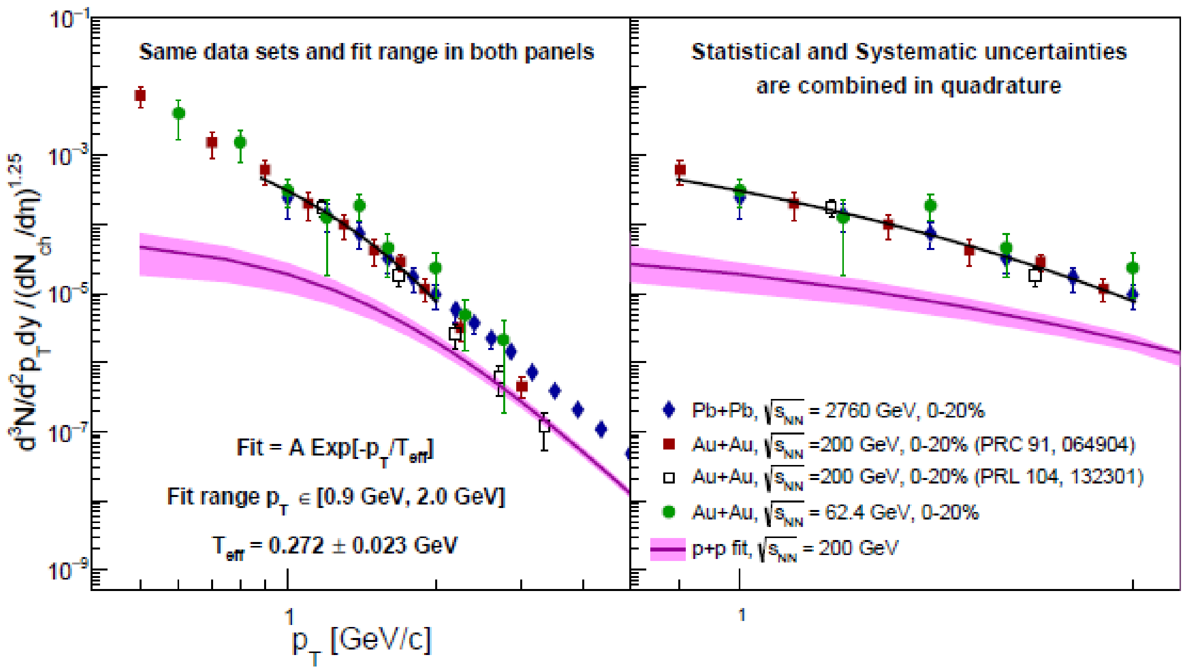
"Scaling"

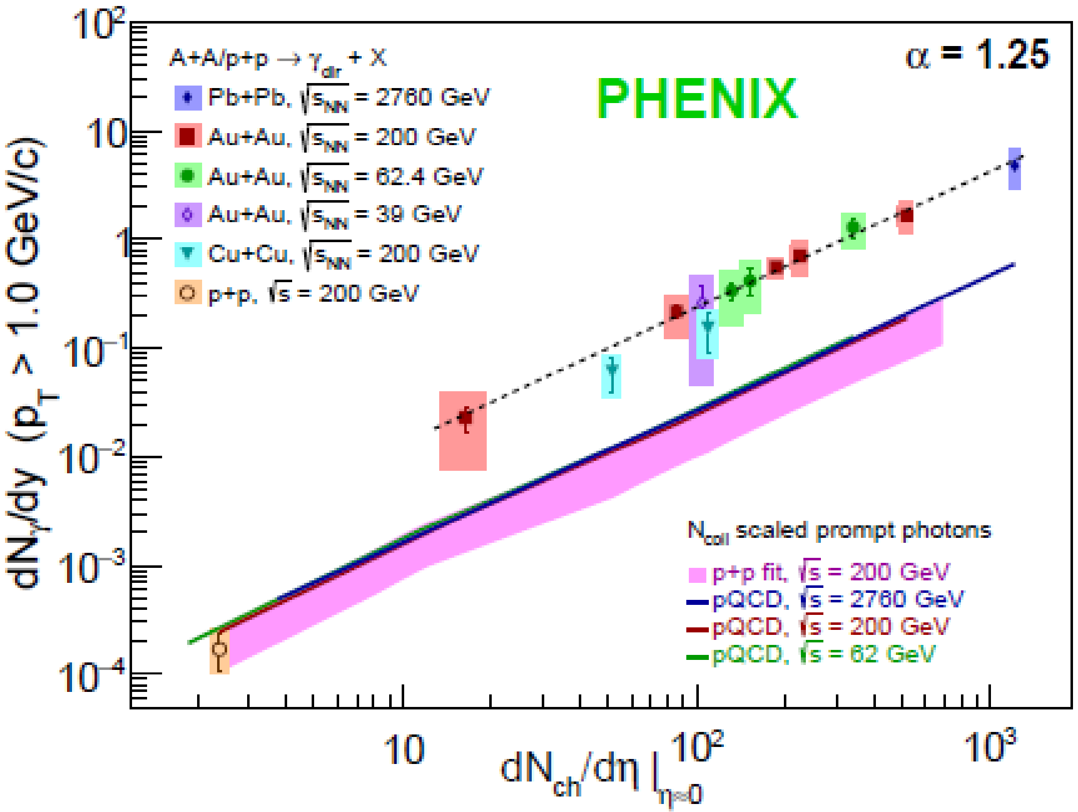
Basic idea: compare photon yields in a wide range of colliding systems and energies;
do it in terms of an experimental observable ($dN_{ch}/d\eta$) rather than Glauber-based N_{part} or N_{coll}



"Scaling"

Yields normalized by $(dN_{ch}/d\eta)^{1.25}$





In this narrow range (0.9-2.0 GeV) one single exponential fits well across large range of collision energies

Integrated yields > 1.0 GeV/c
From >CuCu to PbPb, 62 to 2760 GeV
Large-on-large, very different from pp (or pA)

Most photons produced at late time, which is universal (as opposed to initial state?)

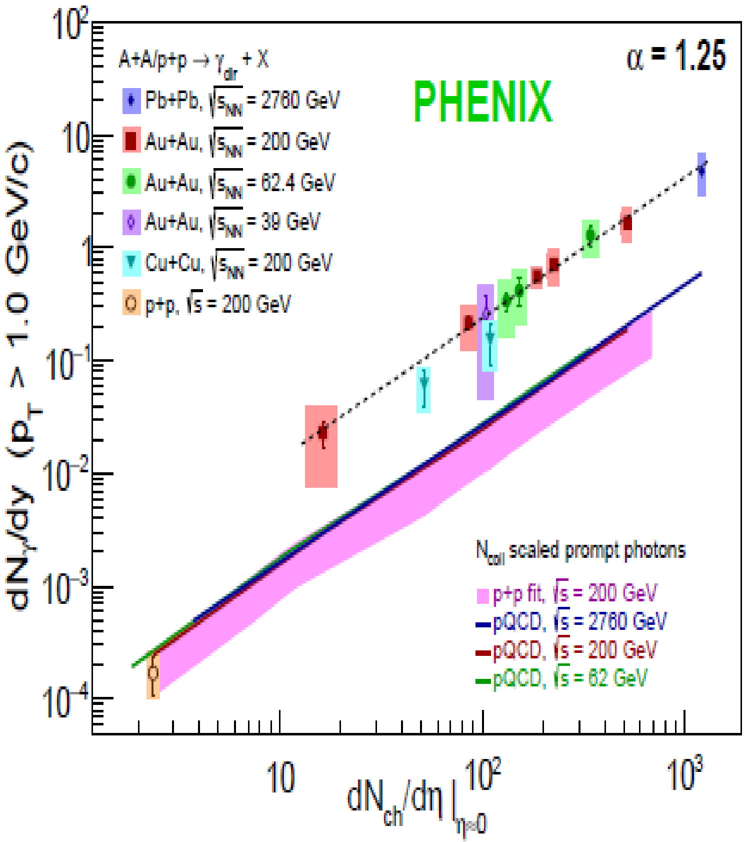
Before we get carried away…

We are talking about 2 orders of magnitude in integrated yield, about the same in $dN_{ch}/d\eta$

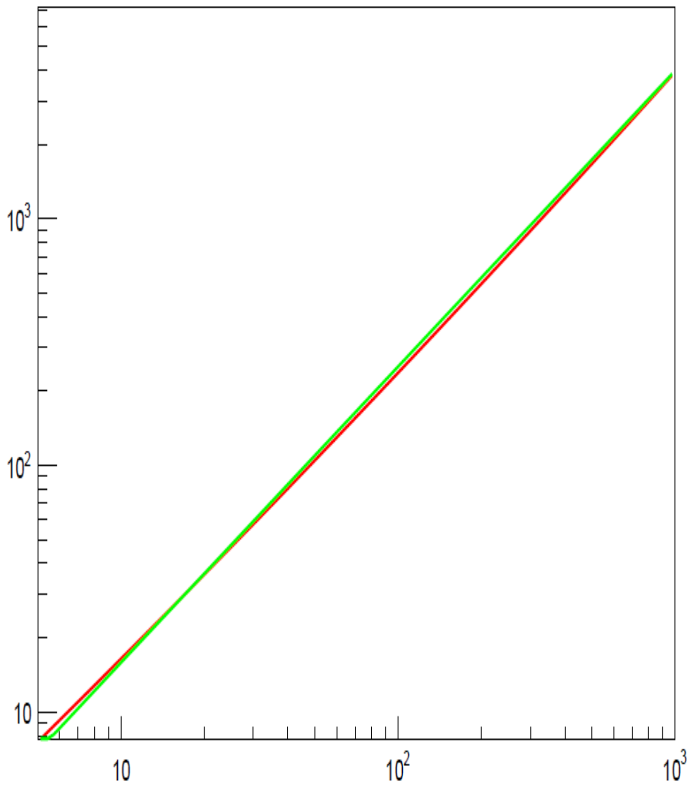
Could you (or the data) differentiate between these two curves? (one is $x^{1.2}$, the other $x + x^{4/3}$ suggesting two completely different underlying scenarios)

This second curve is similar to the one suggested by ***Feinberg, 1974(!)***

Also, it could be interpreted as an extra photon source proportional to volume * lifetime

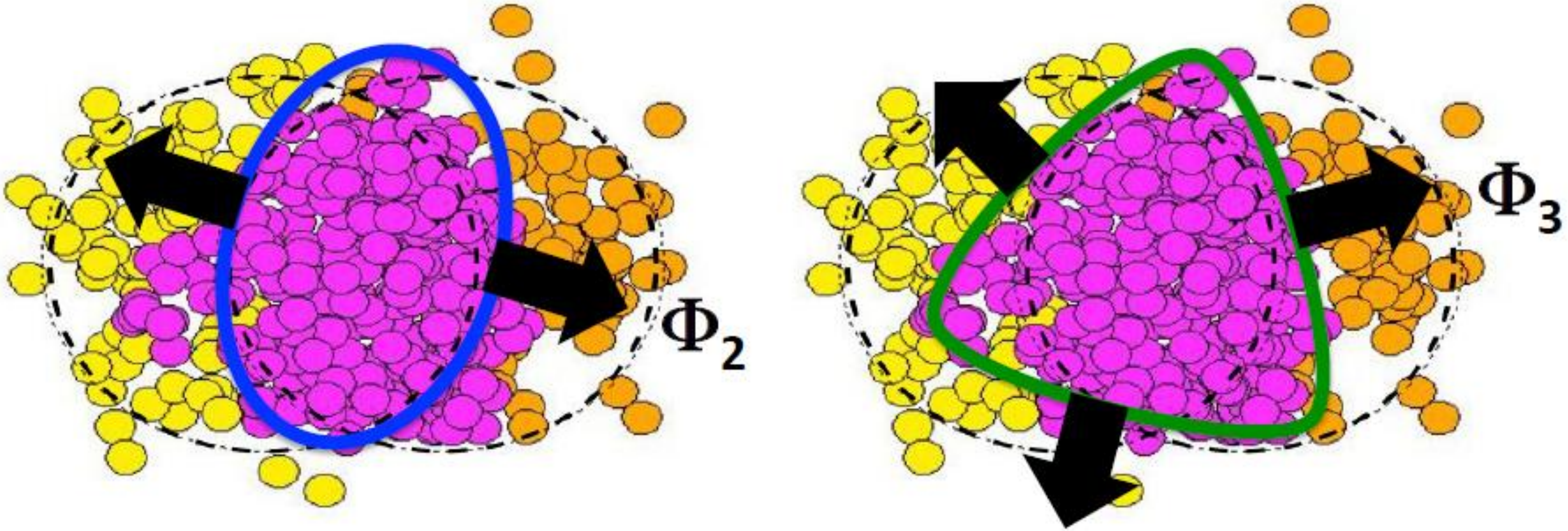


The two curves are the two fits in the region of interest



Principal message: photon production in AA over a large range of sizes and energies can be described empirically with a simple 2-parameter function!

Second and third order asymmetries

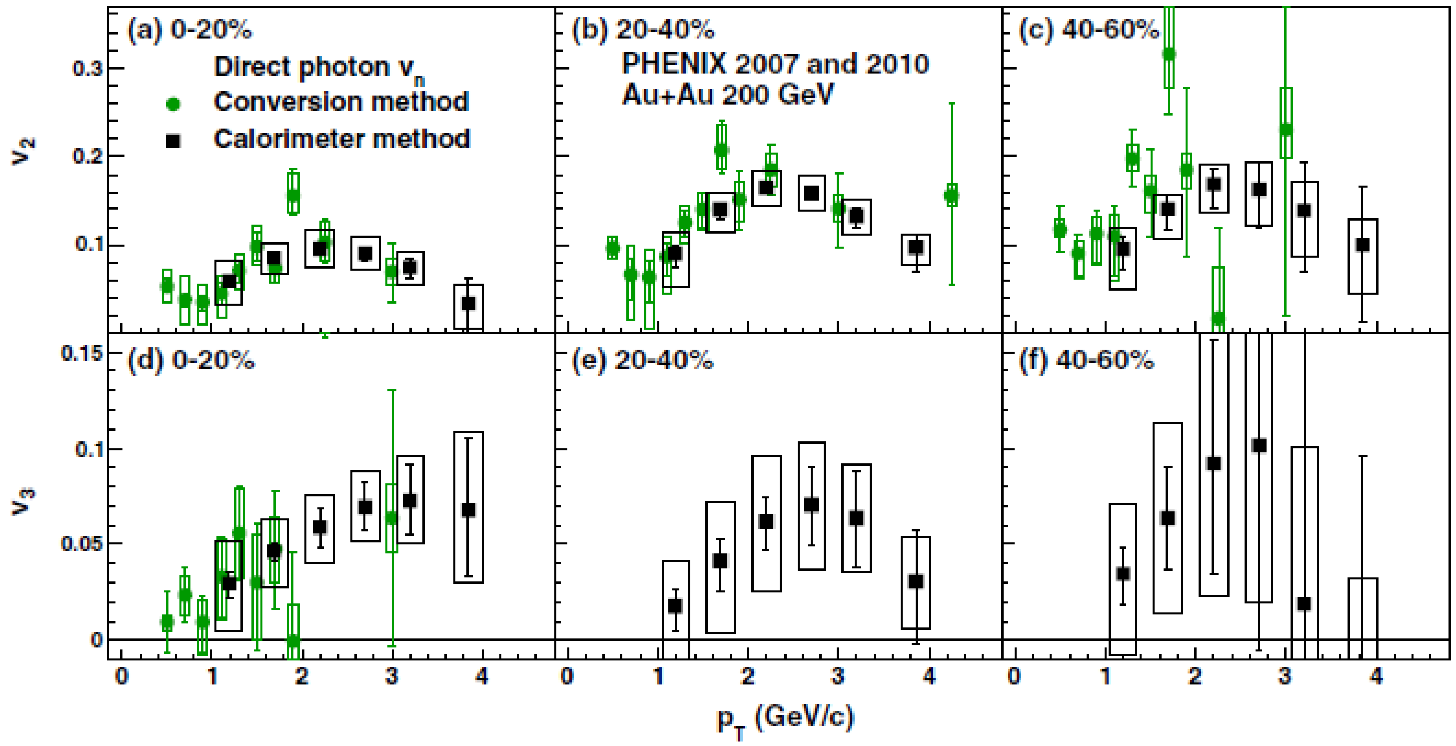


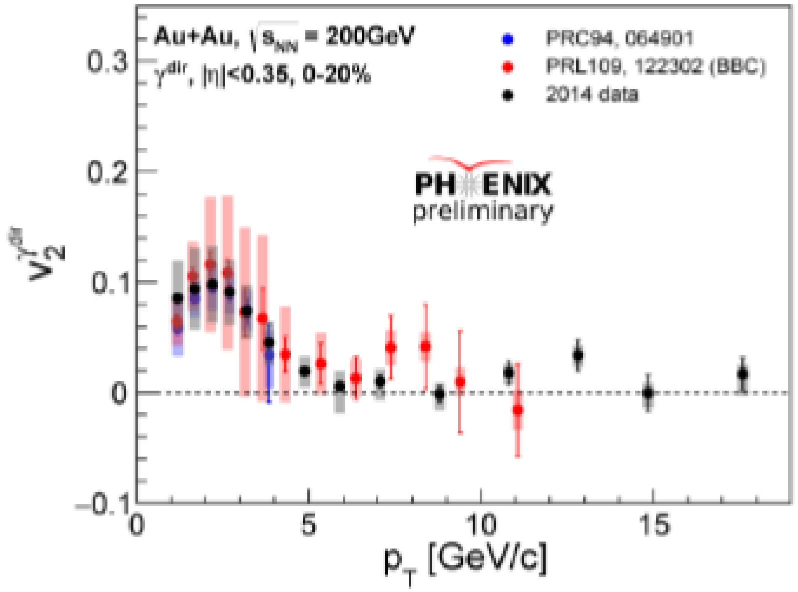
Higher frequencies are damped faster → ratios of v_2/v_3 for photons (earlier) vs hadrons (later) can provide a clue on viscosity

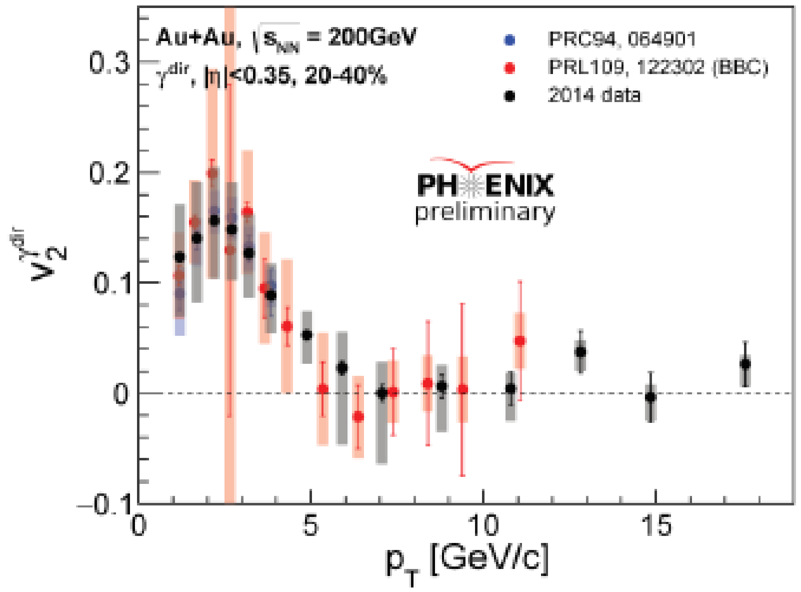
Photon "flow" – PHENIX / RHIC

PHENIX, PRC 94, 064901

$$v_2^{\gamma,\mathrm{dir}} = \frac{v_2^{\gamma,\mathrm{inc}} R_\gamma - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}.$$

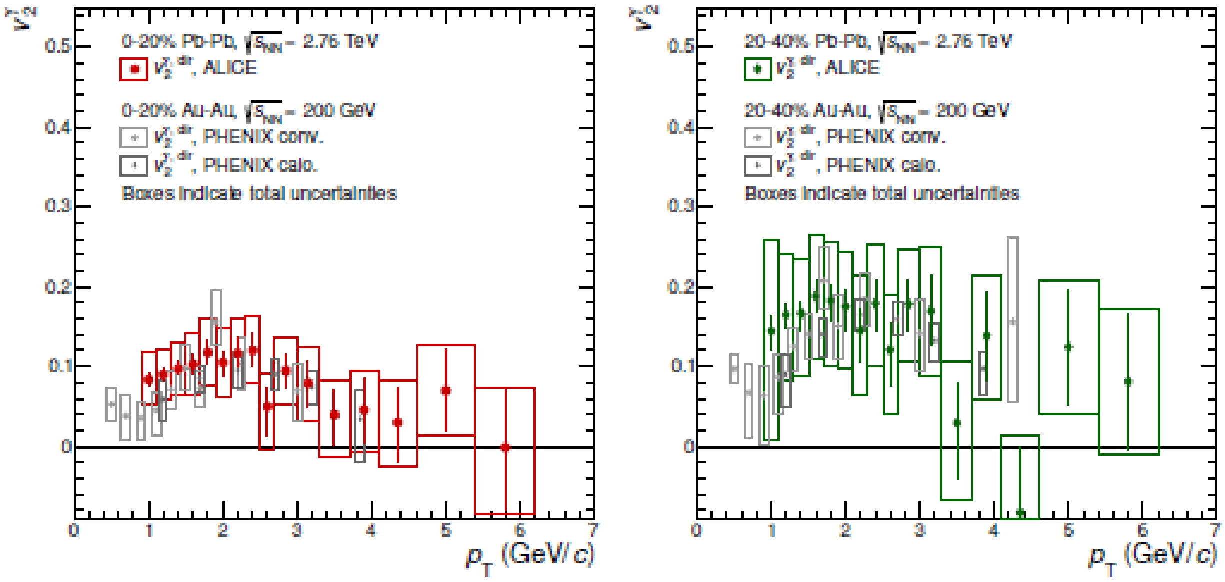






Three methods, confirmed, now up to very high p_T (no flow, as expected)

Photon "flow" – ALICE / LHC



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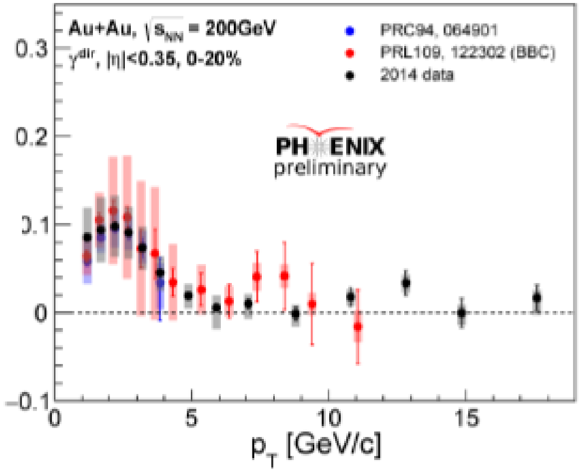
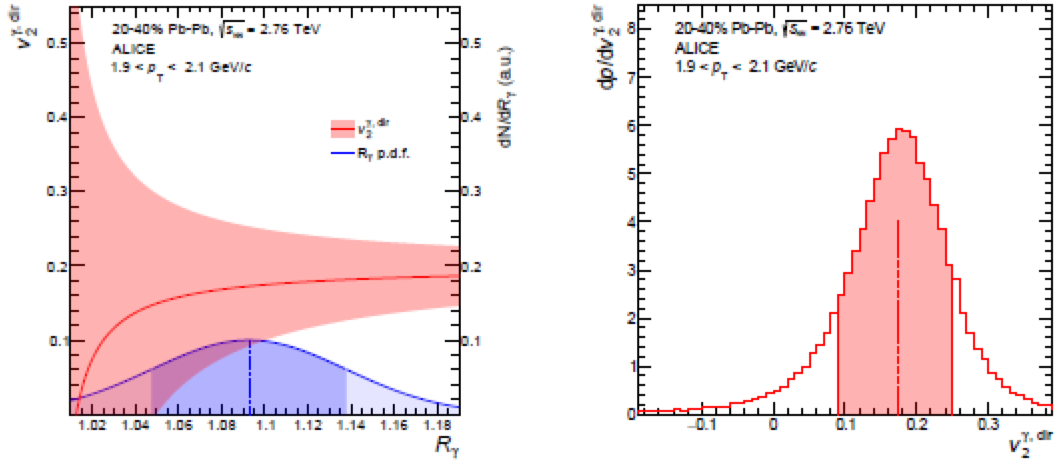
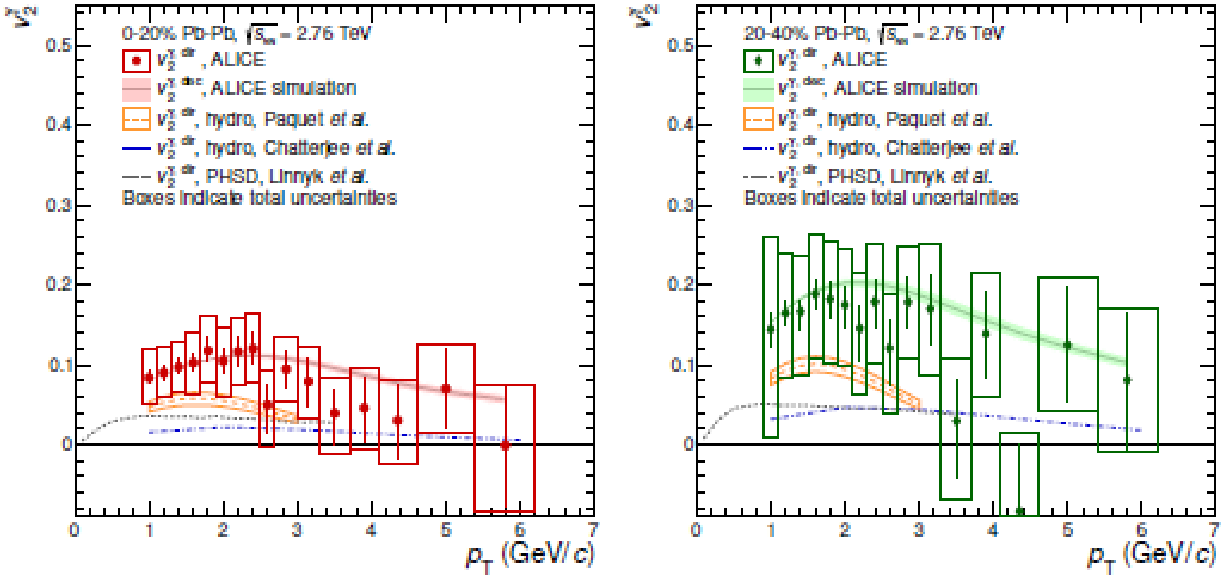






Large systematics: the measurement lives or dies on R_γ

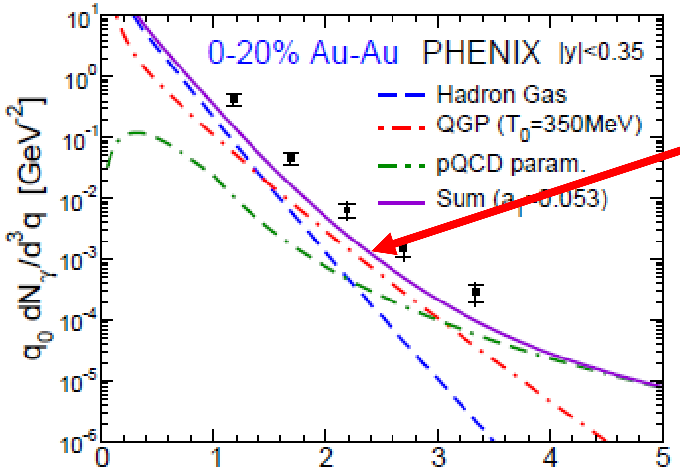
The “direct photon puzzle” in a nutshell
high yields and high v2 couldn’t be reconciled (so far)

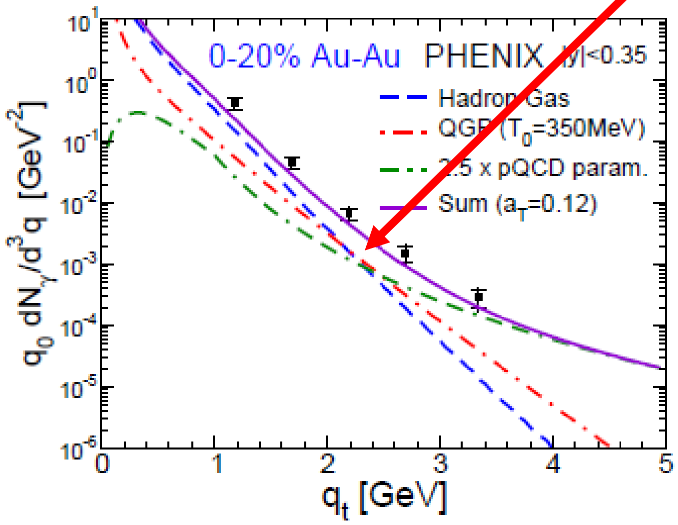
Issue since 2011

PRC 84, 054906 (2011)

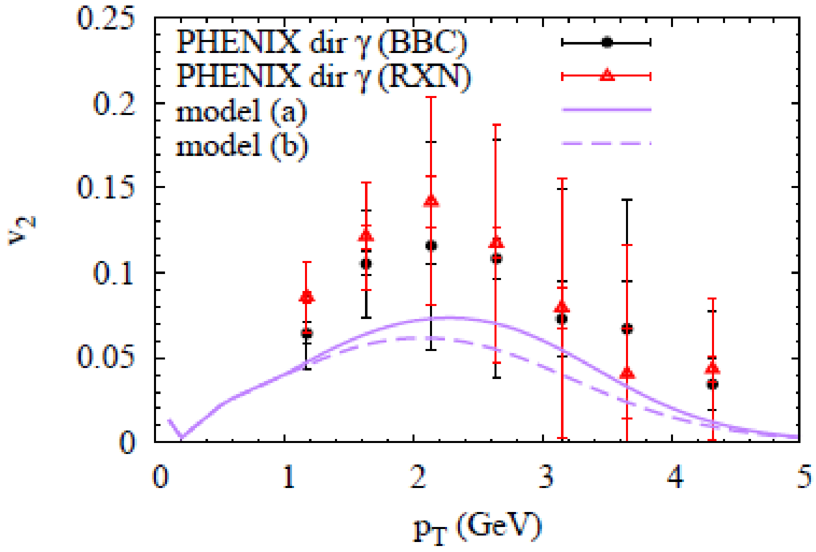
“QGP window”, small a_T

“QGP window” closed, large a_T





Fireball model:
  boosts rates, but doesn’t
  add enough anisotropy
Rates: initial conditions,
  flow: expansion dynamics)



"Direct photon puzzle" in a nutshell

- Thermal photons (HG+QGP), pQCD with fireball scenario

- H.van Hees, C. Gale, R. Rapp PRC 84 054906 (2011)
- Include finite initial flow at thermalization
- Include resonance decays and hadron-hadron scattering
- Blue shift of HG spectrum included

- Microscopic transport (PHSD)

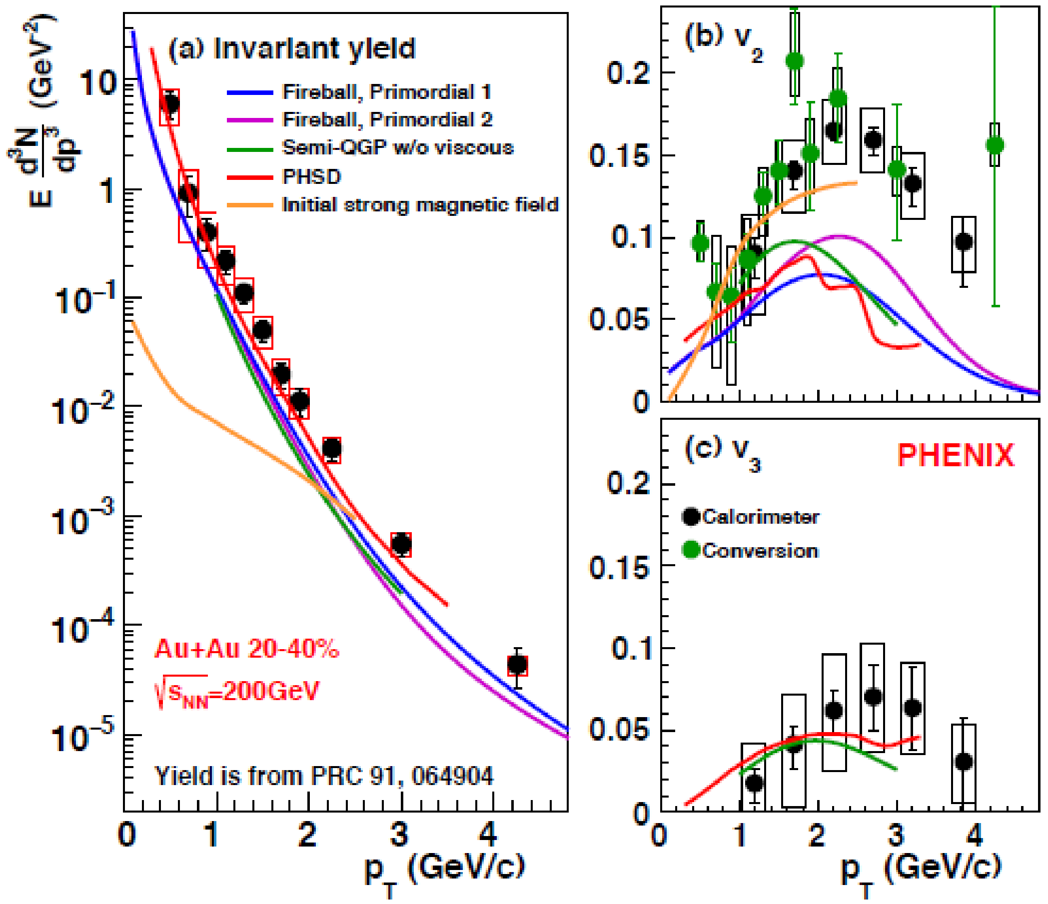
- O. Linnyk, W. Cassing, E.L. Bratkovskaya, PRC 89, 034908 (2014)
- Parton-Hadron-String dynamics
- Include large contribution from hadron-hadron interaction in HG using Boltzmann transport
- Include thermal photons from QGP

- Enhanced emission from non-equilibrium effects (glasma, etc.)

- C. Gale et al., PRL114, 072301 + priv.comm. with Y Hidaka and J-F. Paquet
- Semi-QGP is the QGP near T_c
- Annihilation and Compton processes around hadronization time are naturally included

- Enhanced early emission from magnetic field

- G. Basar, D. E. Kharzeev, V. Skokov, PRL 109 202303 (2012)
- Initial strong magnetic field produces anisotropy of photon emission
- magnetic field + thermal photons (lattice QCD)



Plenty of new ideas

The main problem is at the heart of the "direct photon promise":

- while *hadronic* observables mostly *constrain* only your *final state* (but not much the dynamics how you got there) *direct photons* force you to get the *entire evolution* – rates and expansion – right at the same time

- nevertheless, any scenario in the end should explain *hadrons and photons* simultaneously!

Initial state effects – including nPDFs, pre-equilibrium processes, glasma, etc. became important players

Radiation from the *hadron phase* (even after decoupling) emphasized more and more

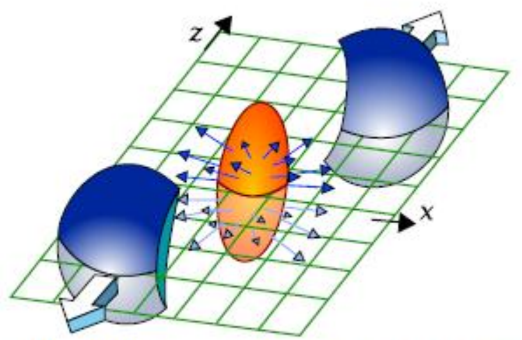
Role of the QGP deprecated???

- that's quite ironic: once upon a time we thought it is going to be the dominant source

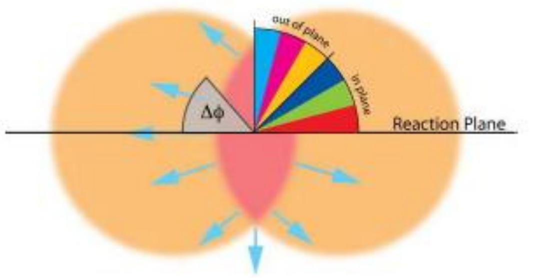
Whatever the truth, current mainstream models emphasize

- either very early asymmetries and expansion, or very late production, or a combination of both

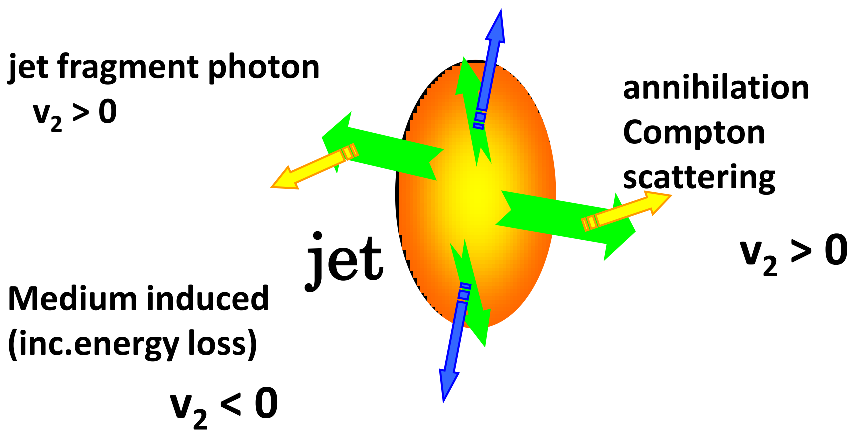
Promise open: "history" → differentiating between sources?



Flow: Initial spatial anisotropy converts to momentum anisotropy (v_2)

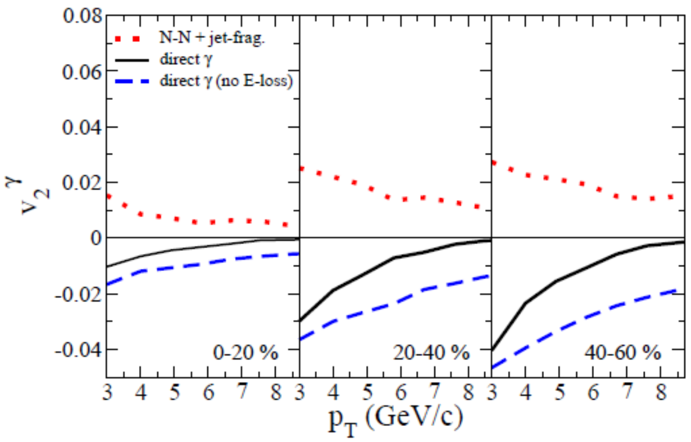


Red initial short pathlength
Cyan long pathlength



Sources	p_T	v_2	v_3	v_n t-dep.
Hadron-gas	Low p_T	Positive and sizable	Positive and sizable	→
QGP	Mid p_T	Positive and small	Positive and small	↗
Primordial (jets)	High p_T	~zero	~zero	→
Jet-Brems.	Mid p_T	Positive	?	↘
Jet-photon conversion	Mid p_T	Negative	?	↘
Magnetic field	All p_T	Positive down to p_T=0	Zero	→

0904.2184



Some promises of direct, real photons

Binary scaling: proof of sanity → ***kept***

Jet energy scale, $E_{\mathbf{loss}}$ → ***kept***

Initial temperature → ***broken***

Thermal radiation from the QGP → ***broken***

Time-dependent η/s → ***open***

Initial magnetic field → ***open***

Role of initial state → ***open***

Initial geometry → ***open***

"Historians" of the entire collision, including expansion dynamics → ***very model-dependent so far***

Provide major surprises → ***kept, for sure!***

Summary

High p_T region well understood
→ Glauber-model valid in large-on-large collisions
→ Will serve as centrality measure in small-on-large collisions
(disclaimer: until now only partially accepted by the community)

Low p_T region not well understood (extremely hard measurement)
→ substantial extra source (over pp) is unquestionable
→ origin (pre-equilibrium? QGP? hadron gas?) unclear
→ apparent simple behavior (2 parameters!) in a wide range of systems and energies surprising

Historians of the collision, but deconvolution is extremely hard

No relativistic heavy ion experiment is optimized for low p_T real photons (not dileptons)

It's a challenging journey – and a dedicated real photon experiment would certainly help…