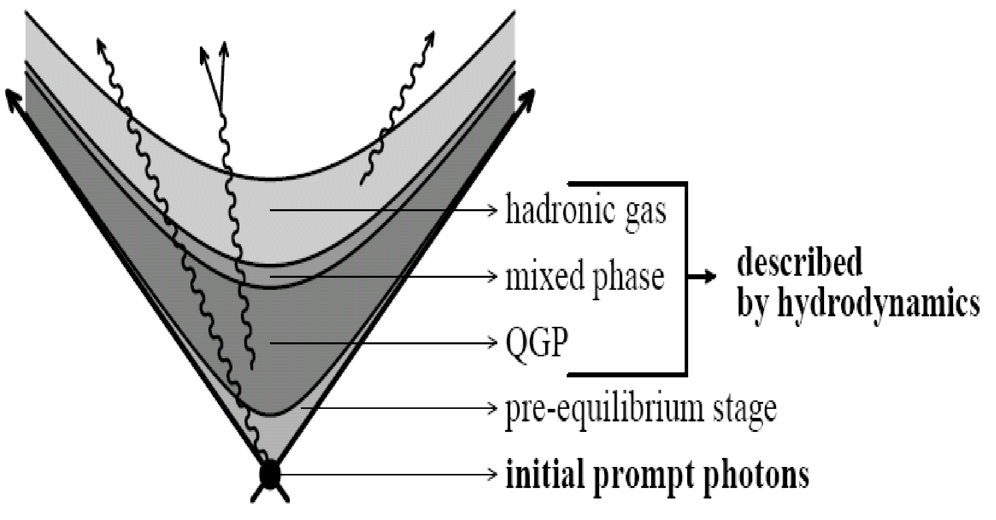
Thermal photons (and dileptons): puzzles and opportunities

G. David, BNL

Thermal photons (and dileptons): puzzles and opportunities (2nd try)

The lure:



…and then came the Grinch
whole stole QGP photons
(or did he?)

200+ years of QGP search

Volume 78B, number 1 PHYSICS LETTERS 11 Spetember 1797

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

(It's real, check it in your library or local server)

A few decades of QGP search (with “thermal” photons)

Late 70s: large initial temperatures -> large radiation from QGP (Shuryak and others)

Early 90s: “The hadron gas shines just as brightly as the QGP” (Kapusta, Lichard, Seibert)

Mid 90s: substantial radiation at SPS (WA98)

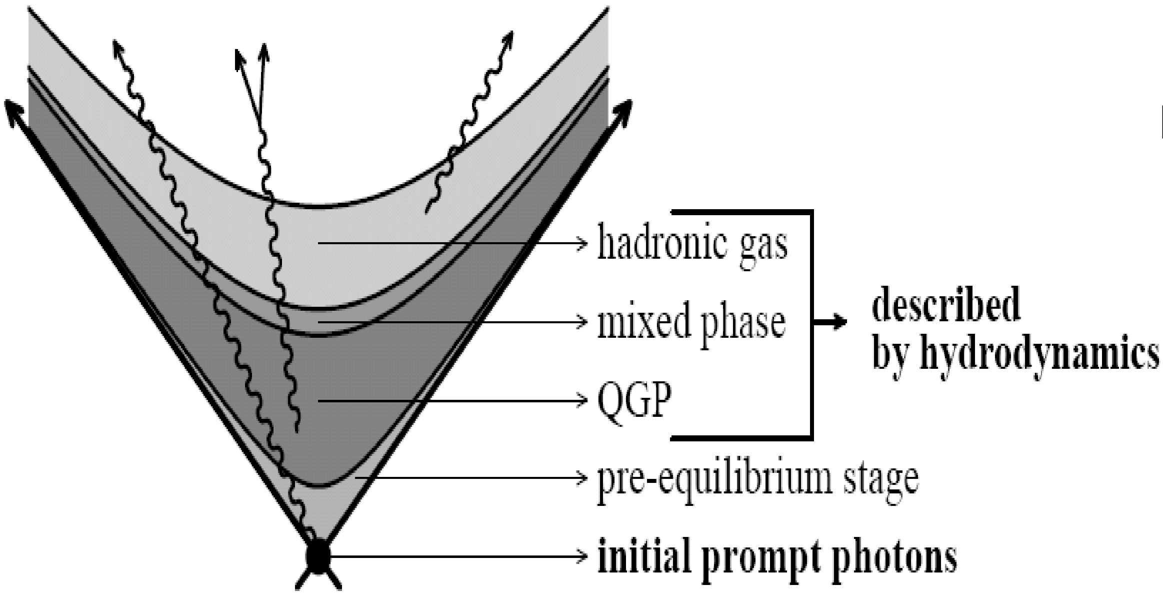
2005: large thermal yields at RHIC (PHENIX) but then

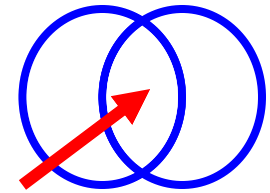
2011: large azimuthal asymmetries, too (PHENIX, then ALICE)

Conventional wisdom: large yields are produced early, when T is high
large asymmetries are produced late (fully developed flow)

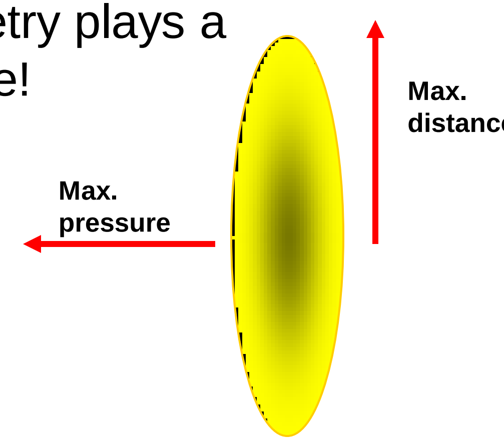
Conventional wisdom appears to be broken. Many new ideas (like “dim” plasma, prompt, non-isotropic production from magnetic fields, etc.)
At the same time, measurements are arguably the hardest in HI physics.
(How) can we sort out – falsify – theoretical scenarios?

Photons: "historians" of the evolution





Note: the overlap geometry plays a big role!



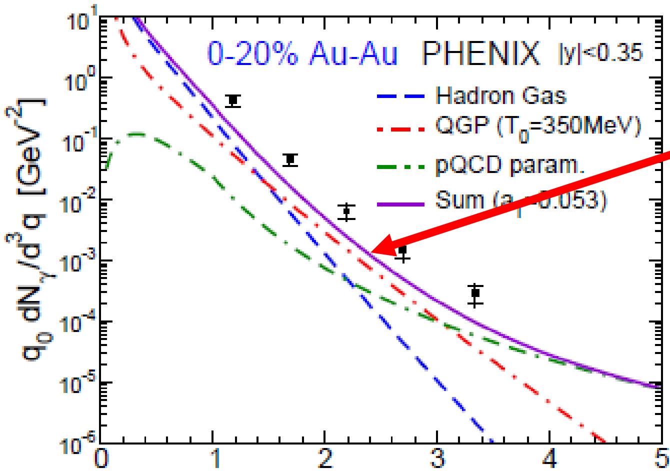
However, they come as a *small signal* on top of final state hadron decays ($\alpha_{em} << \alpha_s$) → *difficult to disentangle*

At a few GeV, direct photons are only about 10% of inclusive photons (at higher p_T hadron suppression helps)

Measurement techniques: direct identification (no pair to make a hadron, or $\gamma \rightarrow e^+e^-$) or statistical subtraction of decay γ (only possibility at very high multiplicites)

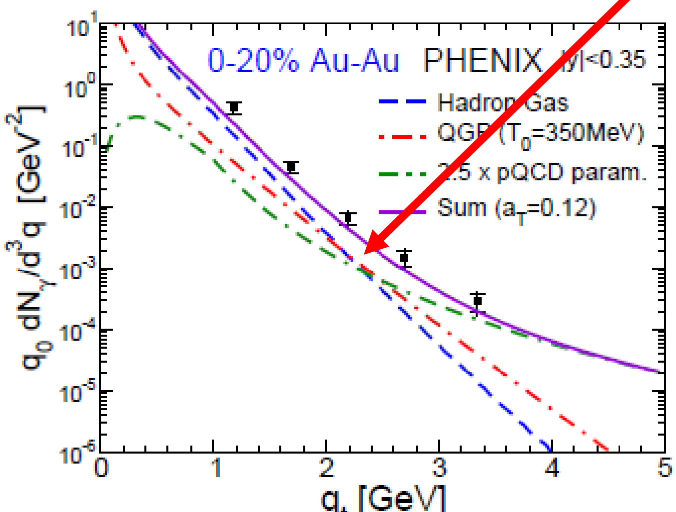
The “puzzle” in a nutshell
high yields and high v2 couldn’t be reconciled (so far)

Recall: “high yield -> early emission, high anisotropy -> late emission”

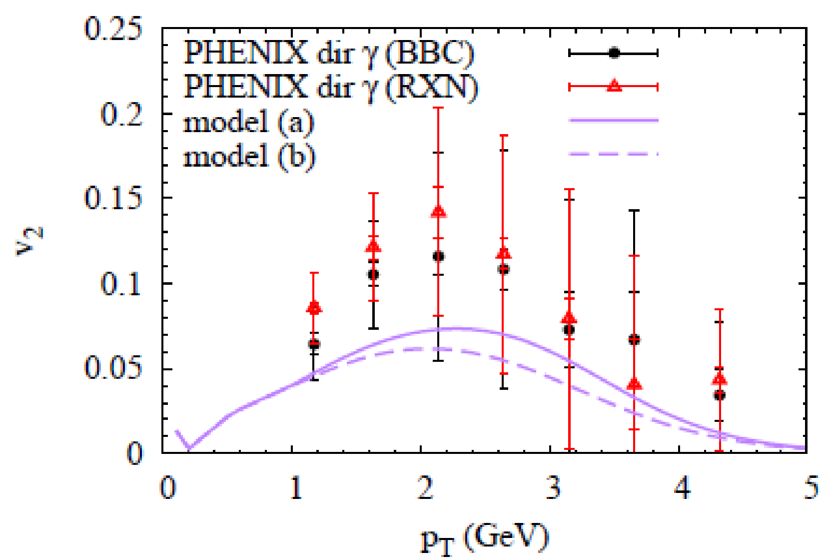


“QGP window”, small a_T

“QGP window” closed, large a_T

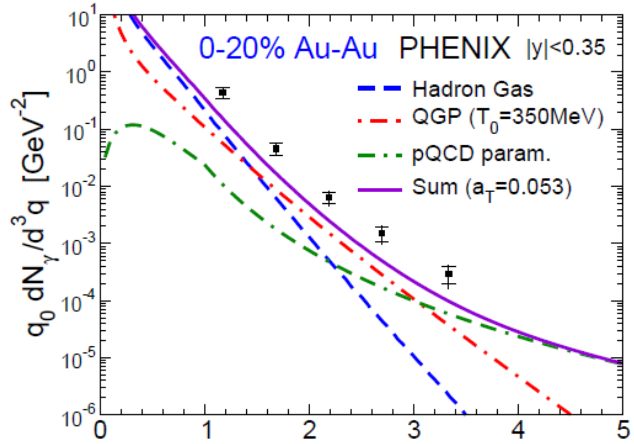


Fireball model:
  boosts rates, but doesn’t
  add enough anisotropy
Rates: initial conditions,
  flow: expansion dynamics)



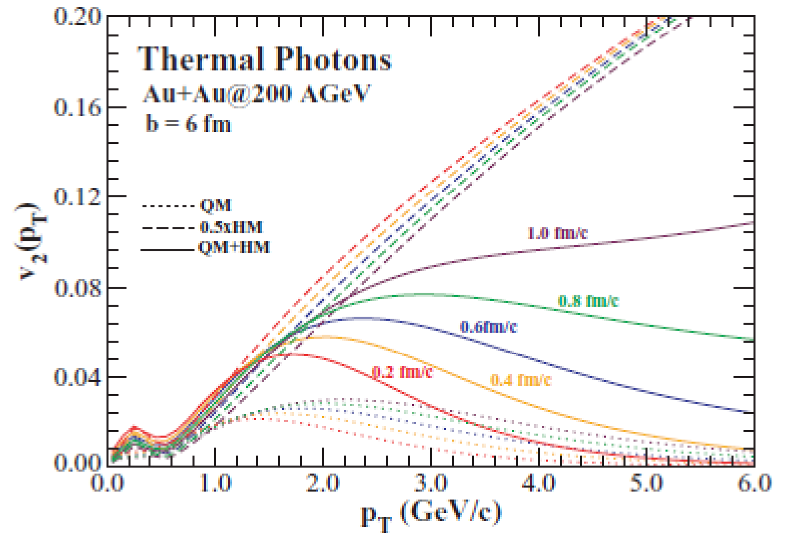
PRC 84, 054906 (2011)

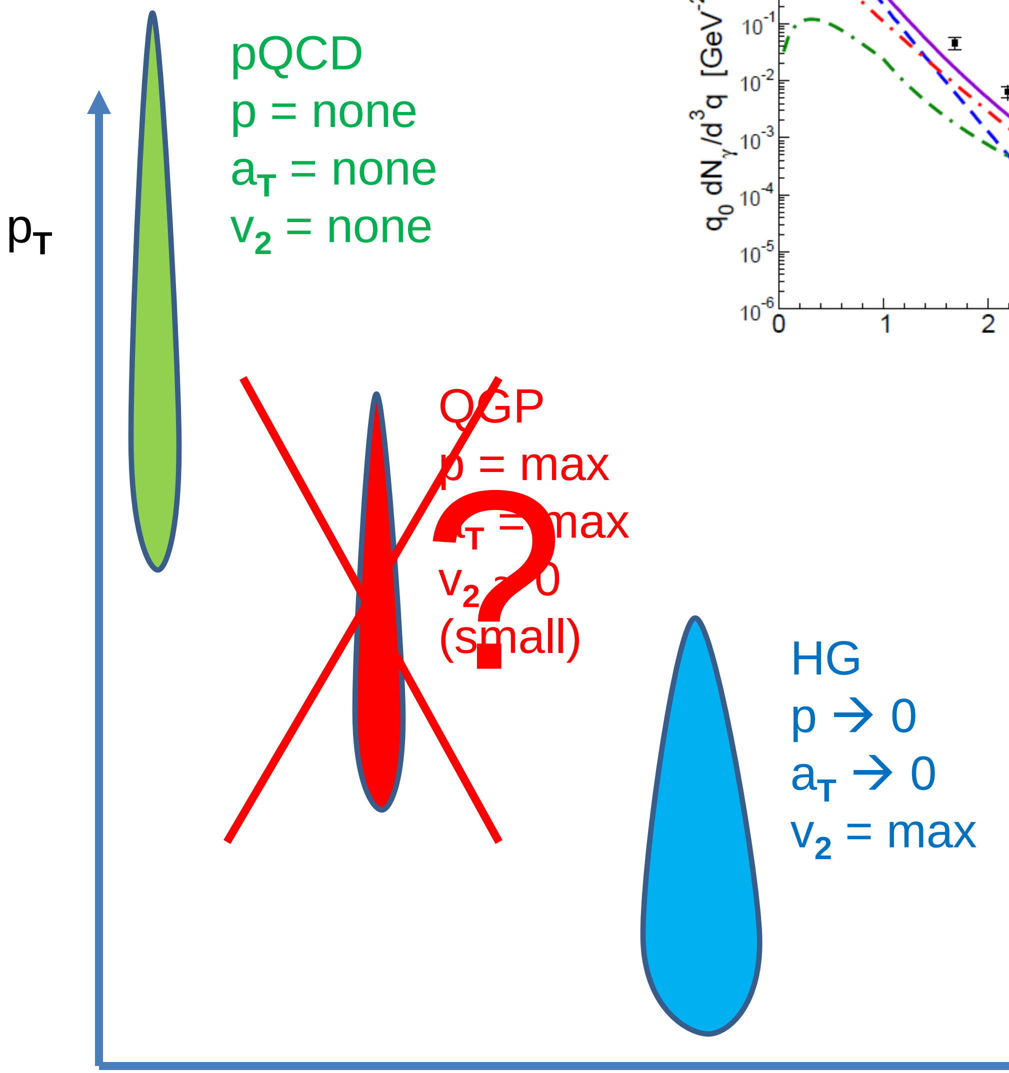
Main sources (simplified)



PRC 84, 054906 (2011)

PRC 79, 021901 (2009)



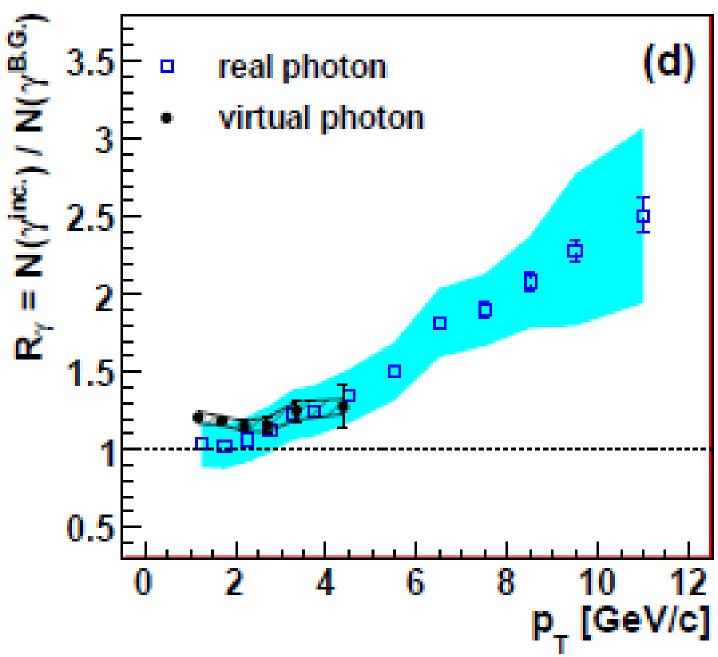


Direct photons – experimental issues / 1

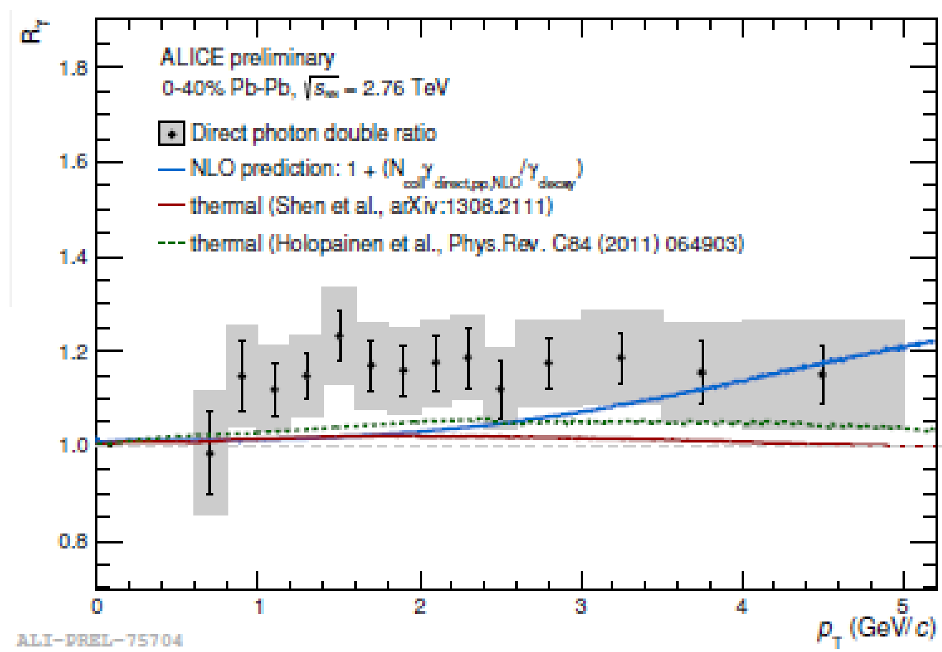
Small signal (O(10%)) over a large (hadron decay) background, at low p_T
Traditional calorimetry doesn't work well
→ insufficent resolution, PID, directionality, instrumental backgrounds

$R\gamma = N^{inc}/N^{dec}$, ratio of inclusive over decay (bg) photons

PHENIX



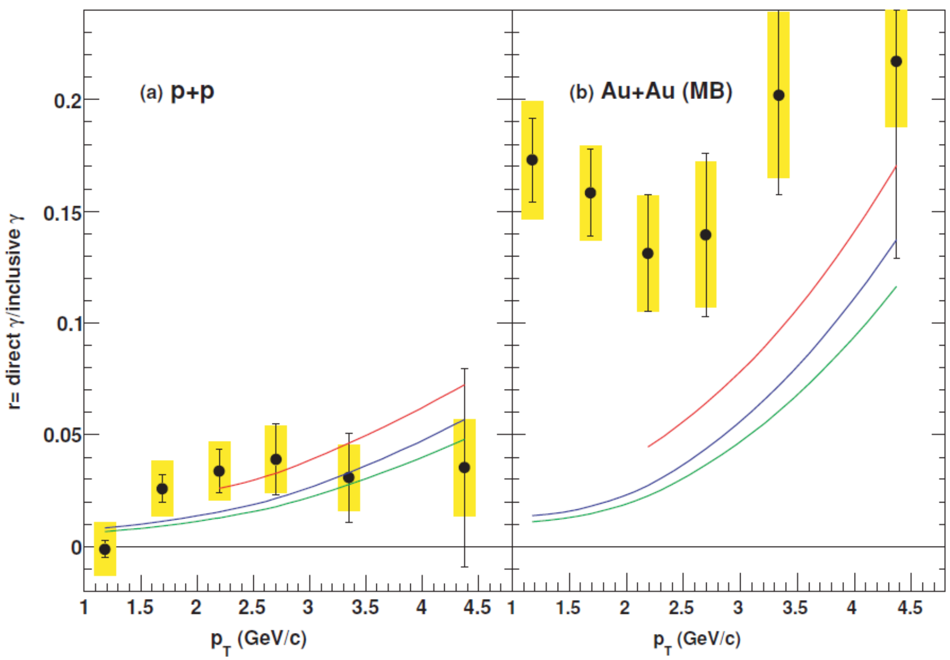
ALICE



The dirty secret: R_γ is hard to do, easily biased, and mostly in one direction – up!

Direct photons – experimental issues / 2

Yield (almost vanishing in p+p, PRC 81, 034911)
(Plotted here: essentially $R_\gamma - 1$)

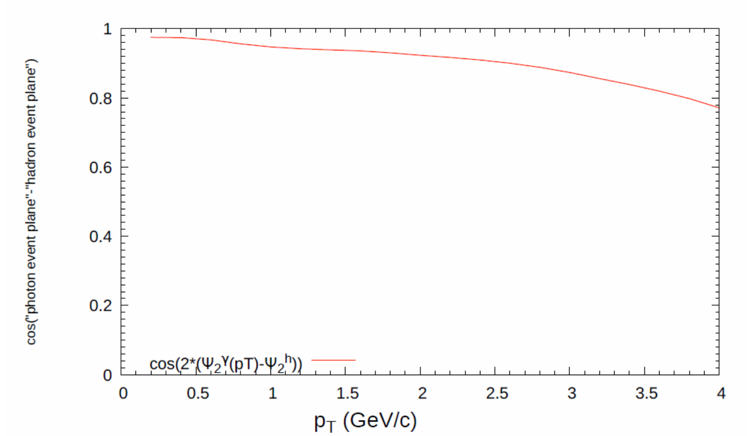


Flow:

$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma(p_T)v_2^{\gamma,\mathrm{inc}} - v_2^{\gamma,\mathrm{bg}}}{R_\gamma(p_T) - 1}$$

Very small!

with possible decorrelation of photonic and hadronic reaction planes:



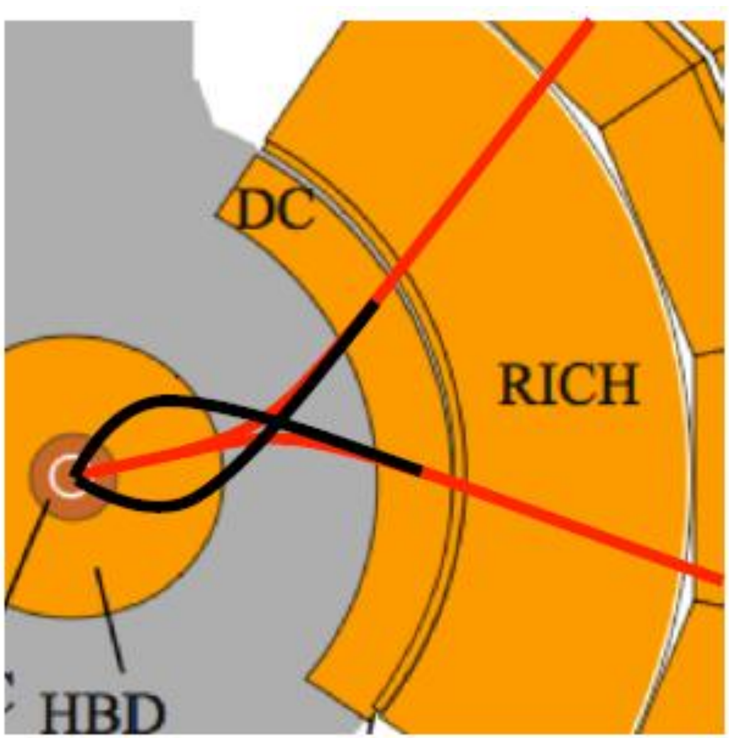
(J.-F. Paquet)

Nowadays ALICE, PHENIX, STAR all use external or internal conversion photons for low p_T

How: identifying (external) conversion photons

Example: PHENIX (PRL 109, 122302 (2012))
PHENIX is special because DC has to assume track origin (vertex)
The way we handle this: "Alternate Tracking Model"

- → calculate momenta of e^+ e^- assuming they come from a/ vertex b/ HBD backplane
- → calculate invariant mass of e^+e^- pairs with both
- → for true photons, true momenta M_{inv} ~ 0, otherwise M_{inv} > 0



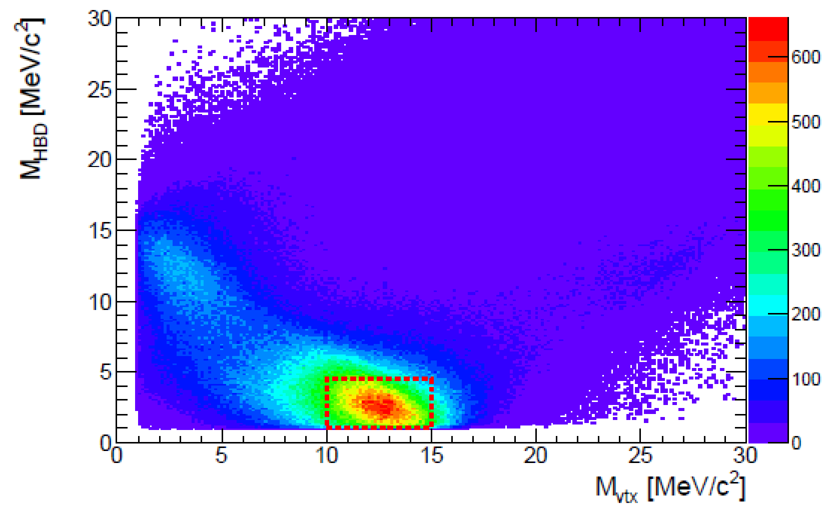


FIG. 2. A view of the cut space used for the conversion photon identification. The mass as calculated under the standard reconstruction algorithm (vtx) is plotted on the horizontal axis, while the mass as calculated under the alternate track model (HBD) is plotted on the vertical axis. The red dotted box indicates the region used to identify photon conversions.

Enhancement of direct photon yield (PHENIX)

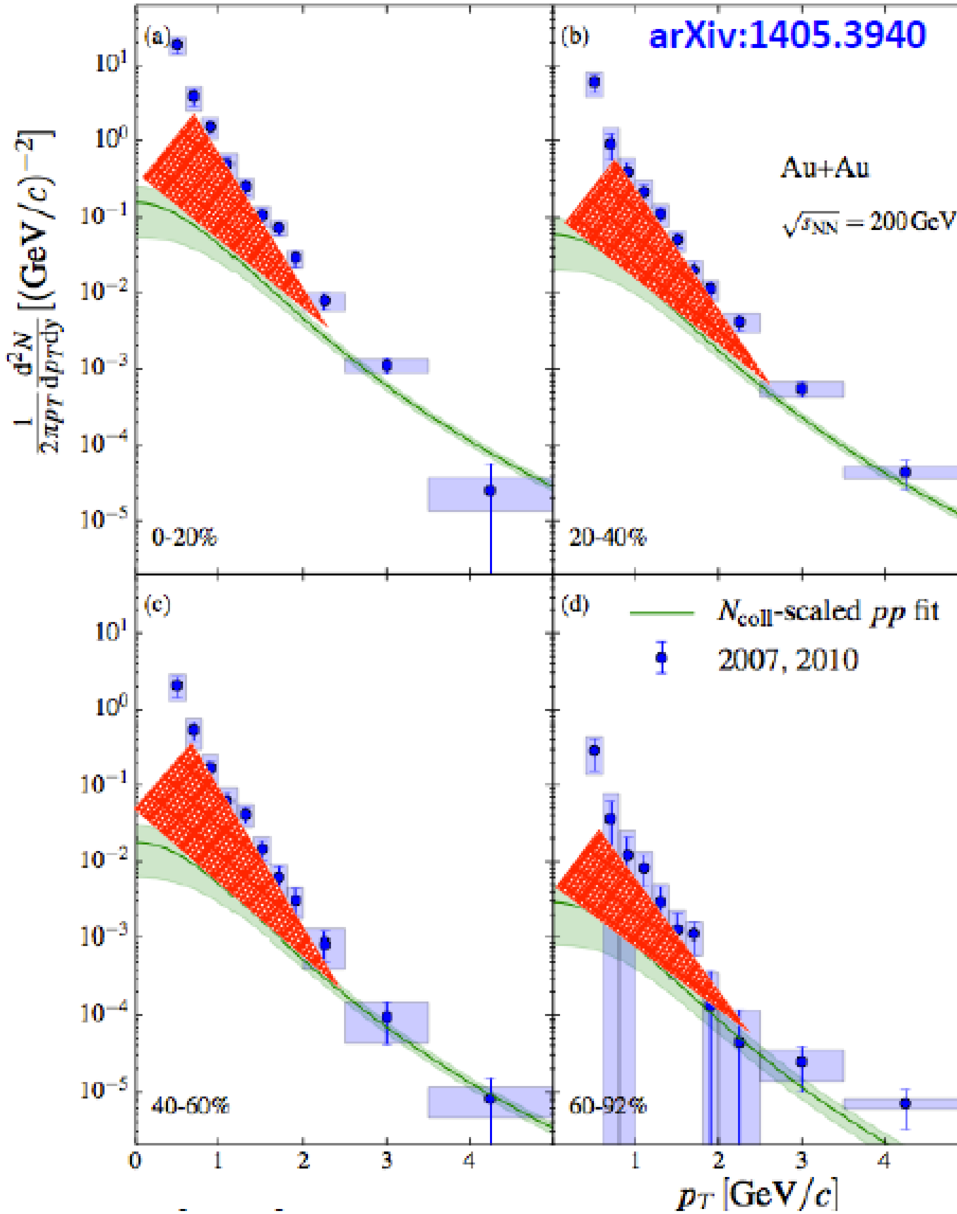
$$\gamma^{\text{direct}} = (R_\gamma - 1)\gamma^{\text{hadron}}$$

1405.3940

Enhancement over pp rates
(assumed "thermal", or
"originated in the medium")

External conversion method

Red area is the excess
(but pp – the green band –
is fit extrapolation below 2GeV)



Excess photon yield vs theories (PHENIX)

All theory curves are postdictions

Transport model (PHSD, Linnyk…)

Fireball model (van Hees…)

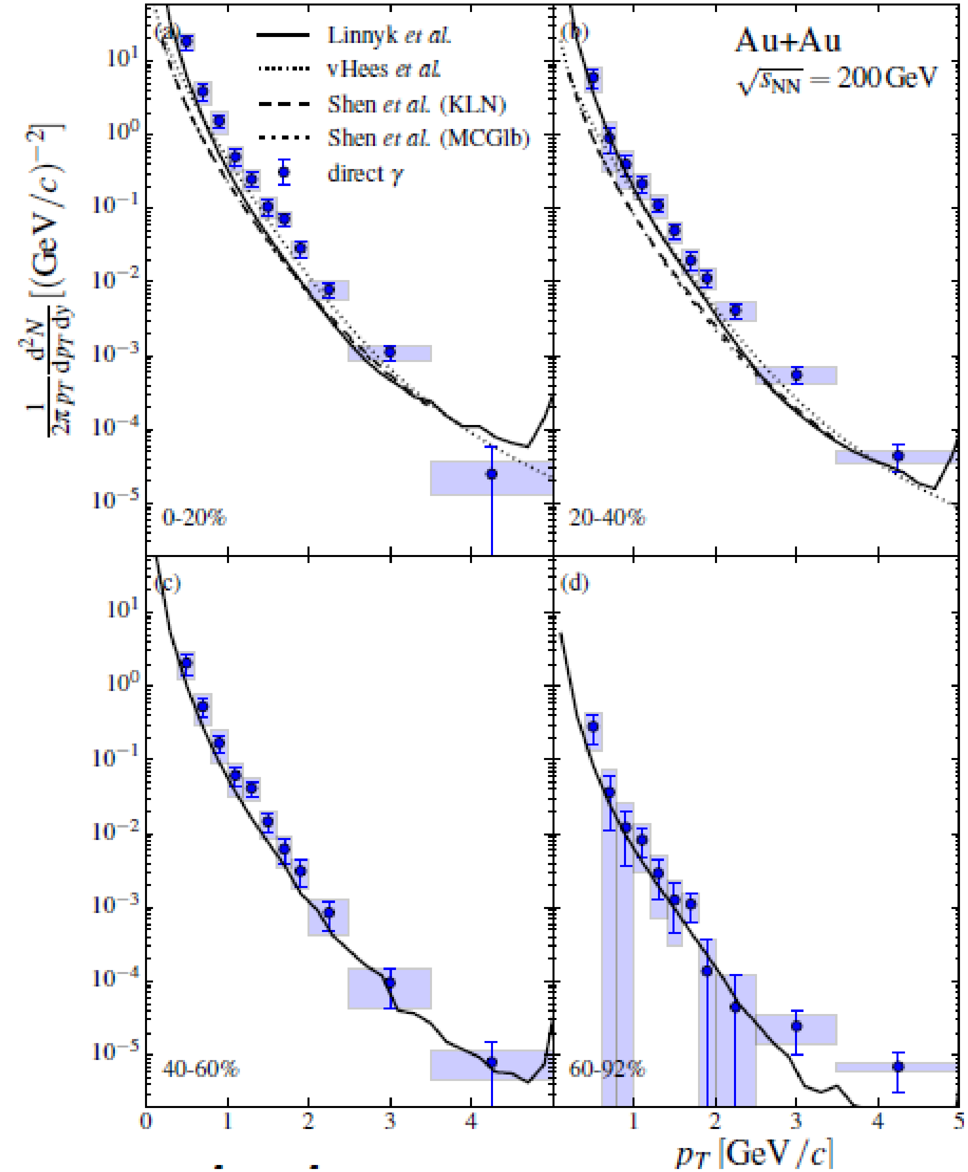
Hydro (Shen…)

T_{ini} between 300-600MeV

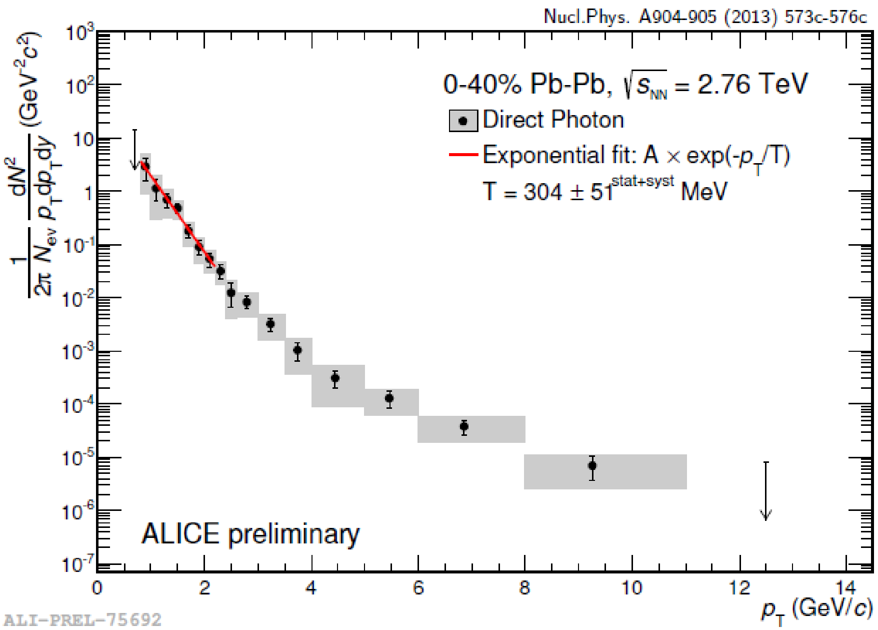
Shapes similar (OK, not too bad)
yields underestimated

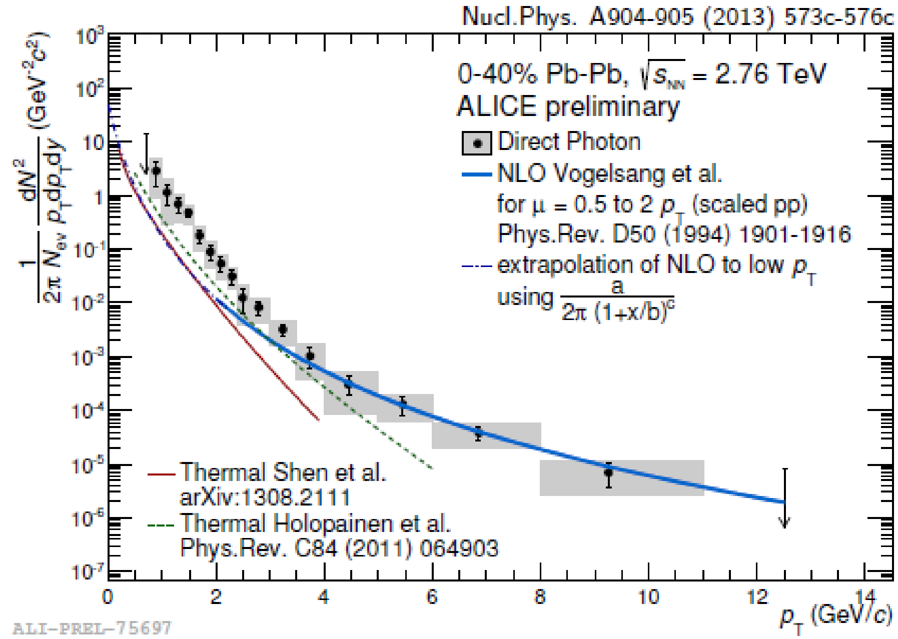
Inverse slopes (T_{eff}) 240-260 MeV,
no significant centrality dependence
Is this a meaningful quantity?

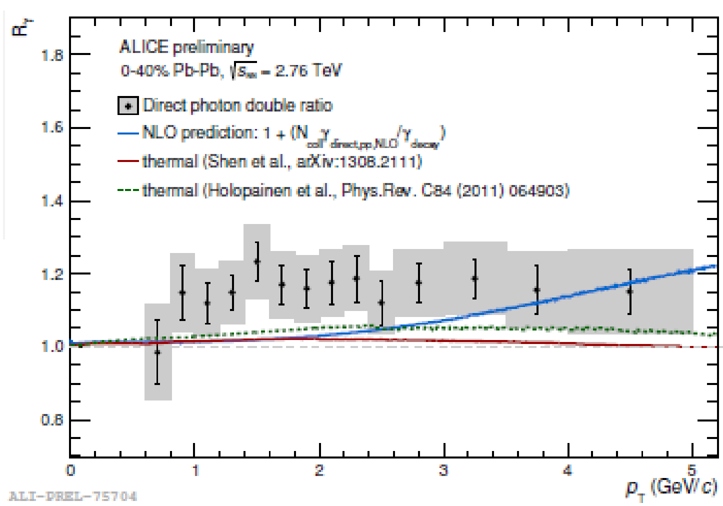
arXiv:1405.3940



Yields vs theory (ALICE)





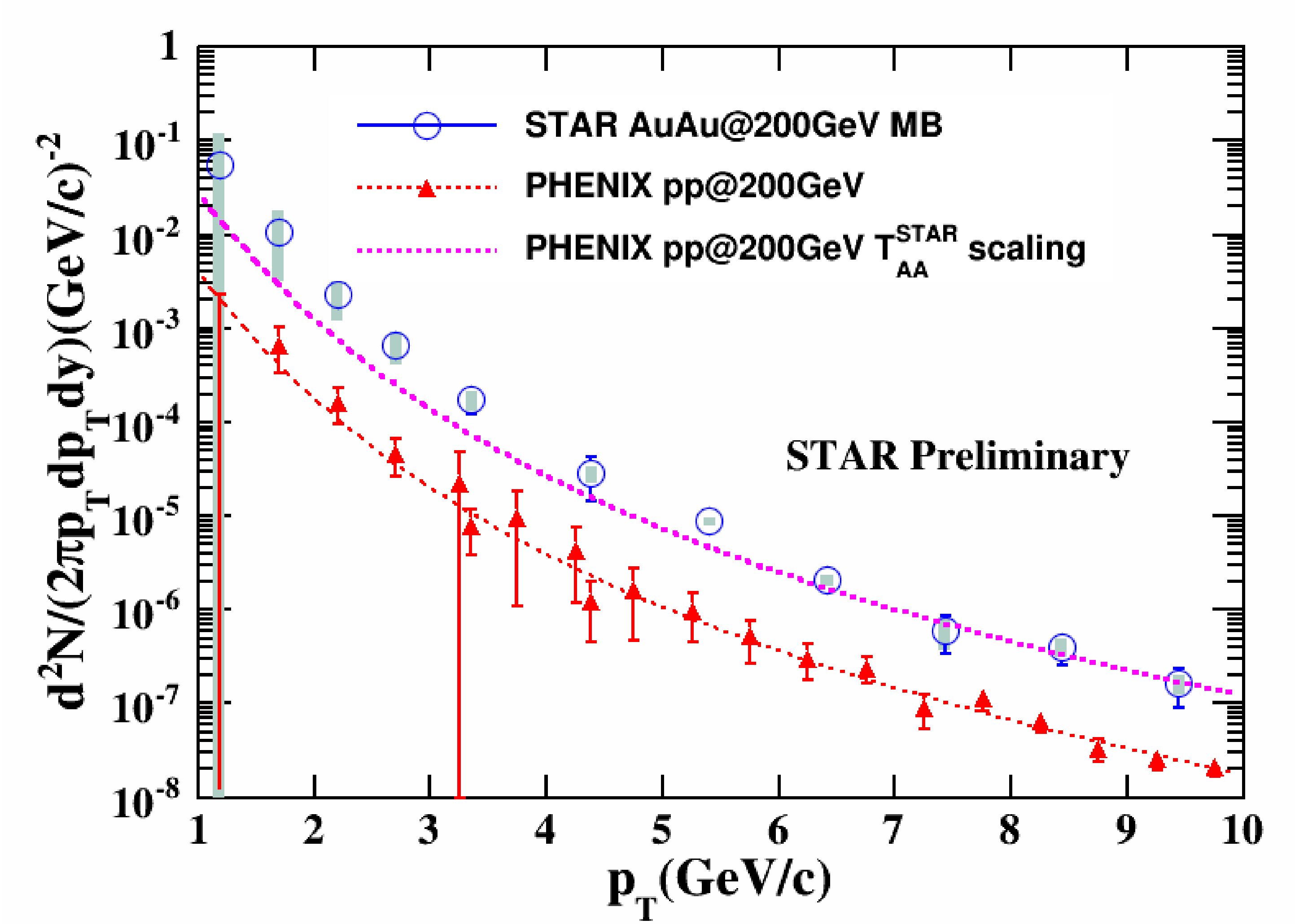


(Recall Rγ and its uncertainties!)

T_{eff} ~ 300MeV
How meaningful is this?

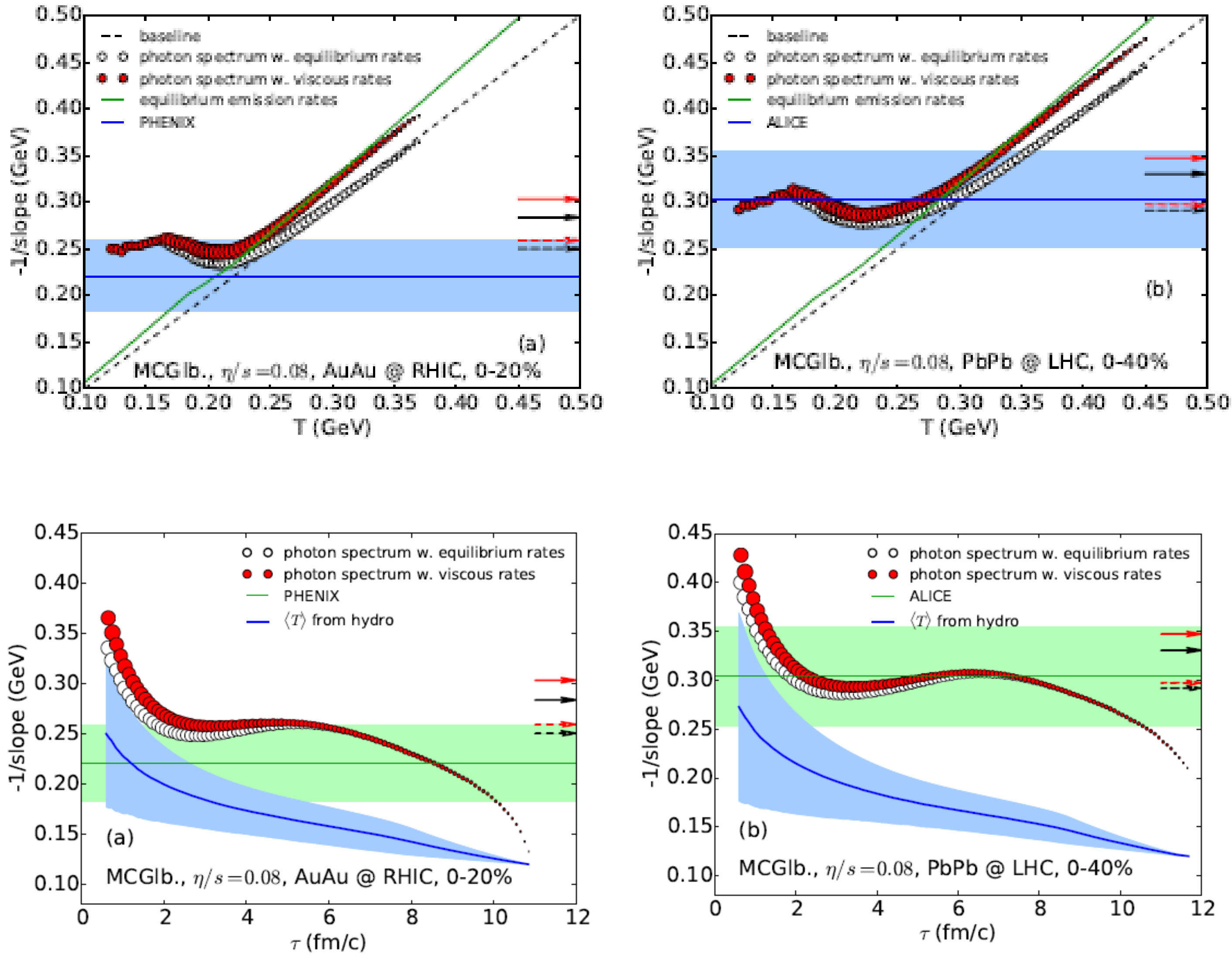
STAR: internal conversion photons

I'm not aware of a T_{eff} fit



(Bingchu Huang, TPD2014)

Effective temperature vs true (and time)



After ~2fm/c T_{eff} significantly blue-shifted by radial flow

What does yield vs centrality tell us?

Yield ~ N^{α}, α = 1.48 (irrespective of lower integration limit)

Model predictions:

PHSD → α ~ 1.5 (1311.0279)

hydro → α ~ 1.67 – 1.9 (dependent on int. limit 1308.2440)

glasma → α ~ 1.47 – 2.2

strong B field → no number, but yield decreasing with centrality!

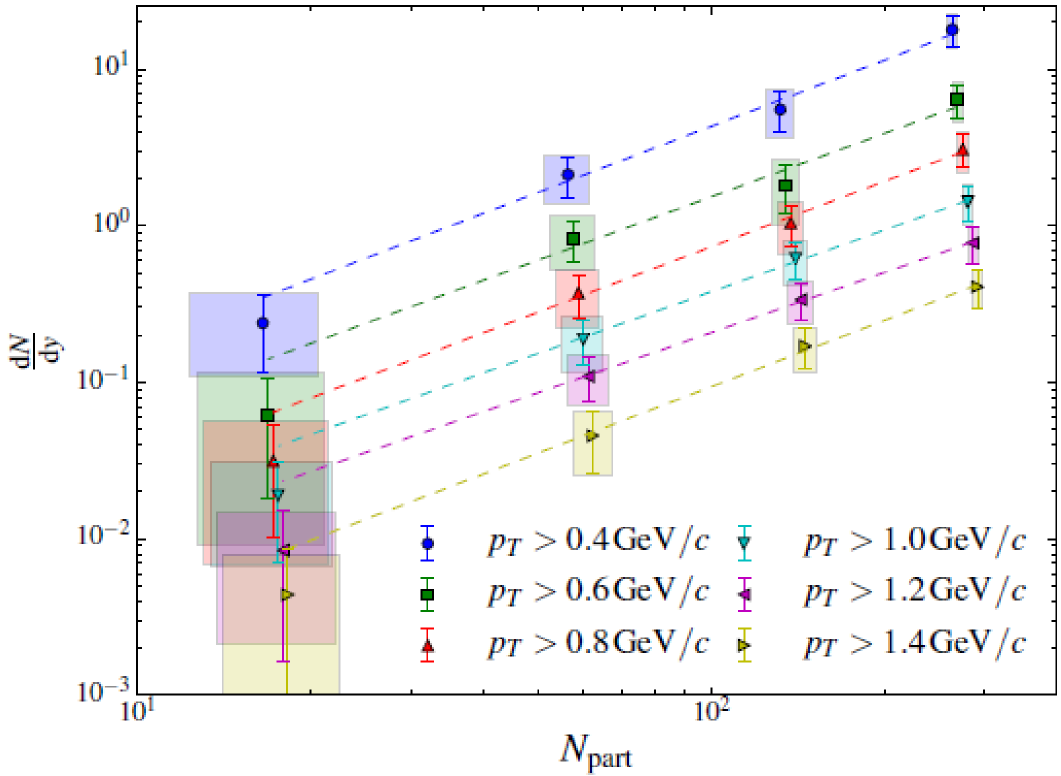
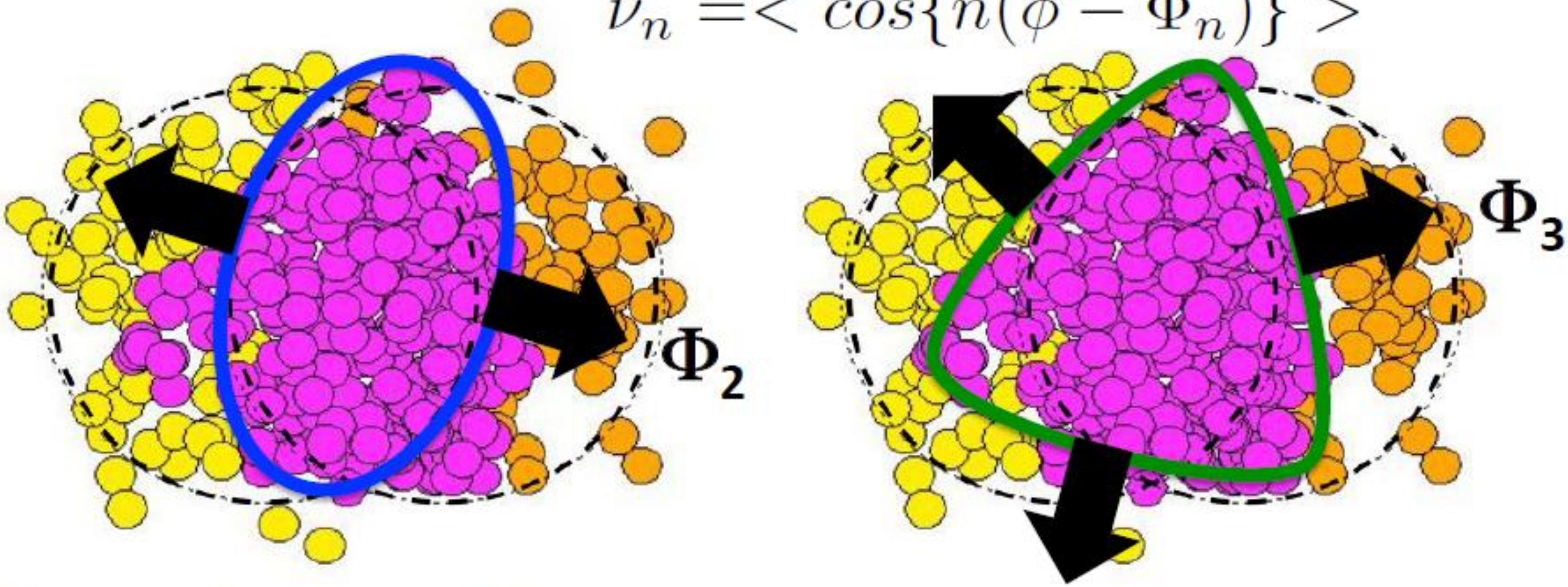


FIG. 9. Integrated thermal photon yields as a function of N_{part} for different lower p_T integration limits. The dashed lines are independent fits to a power-law.

Now to the flow…

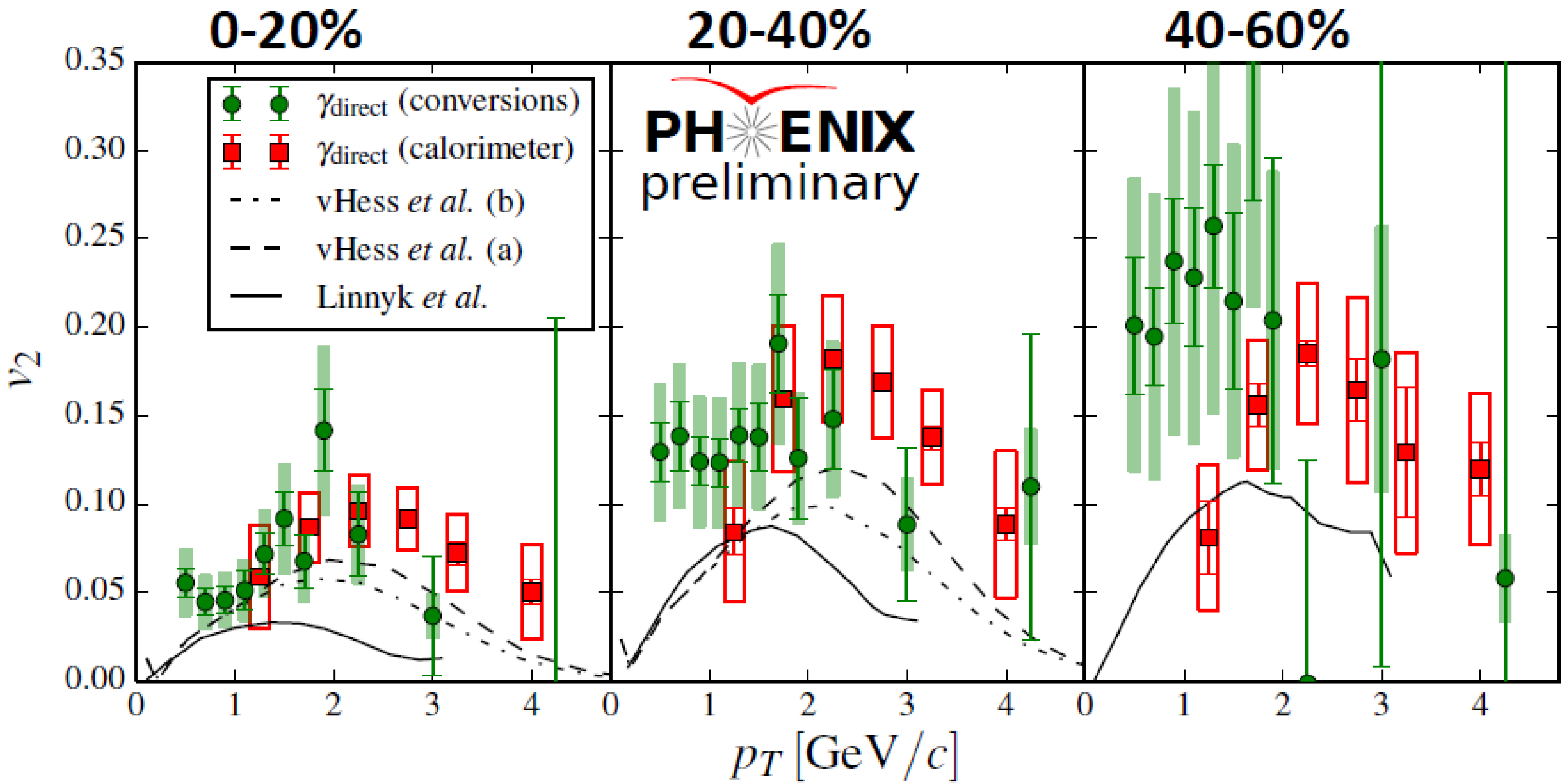
$$\frac{dN}{d(\phi - \Psi_n)} = N_0[1 + 2\sum_{n=1}^{\infty} v_n cos\{n(\phi - \Phi_n)\}]$$

$$\nu_n =< cos\{n(\phi - \Phi_n)\} >$$



Dominant component is v_2;
v_3 comes from participant fluctuations, viscosity dampens higher order terms.

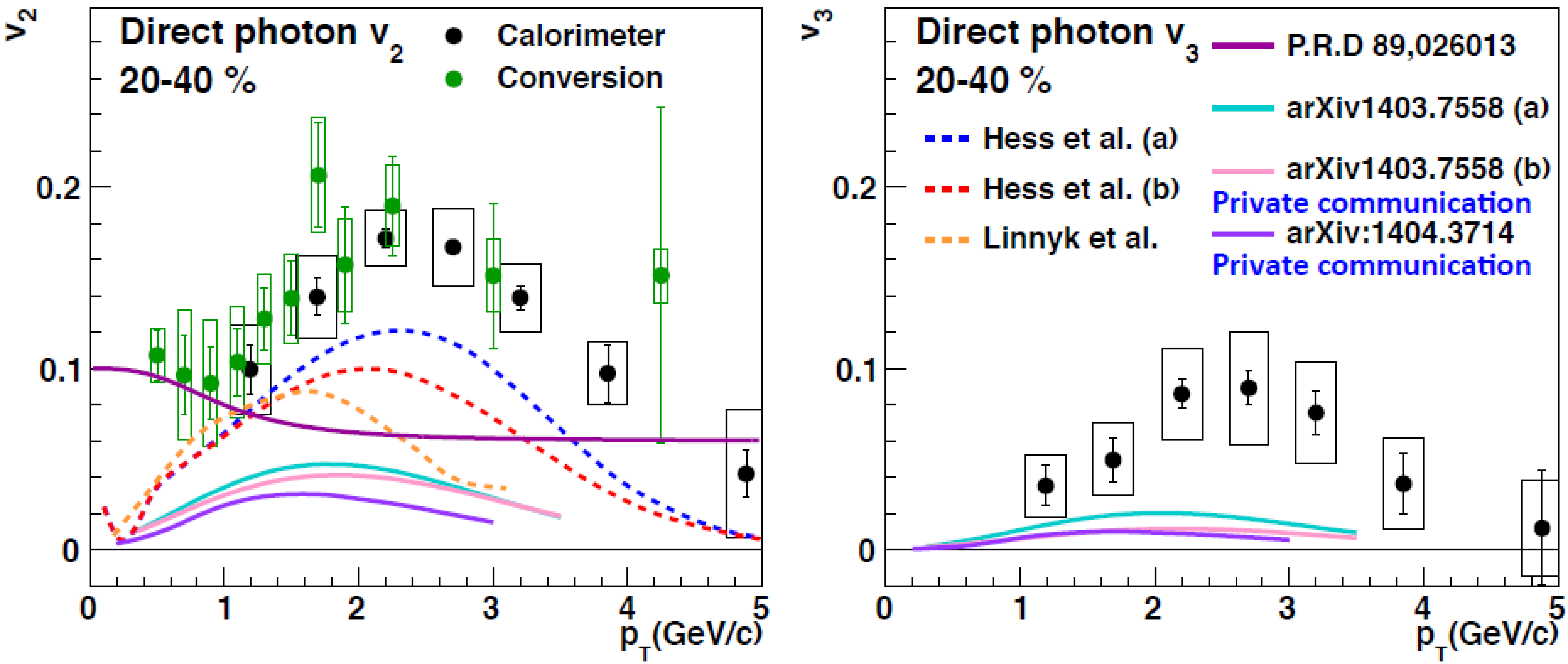
PHENIX: v_2 vs theory



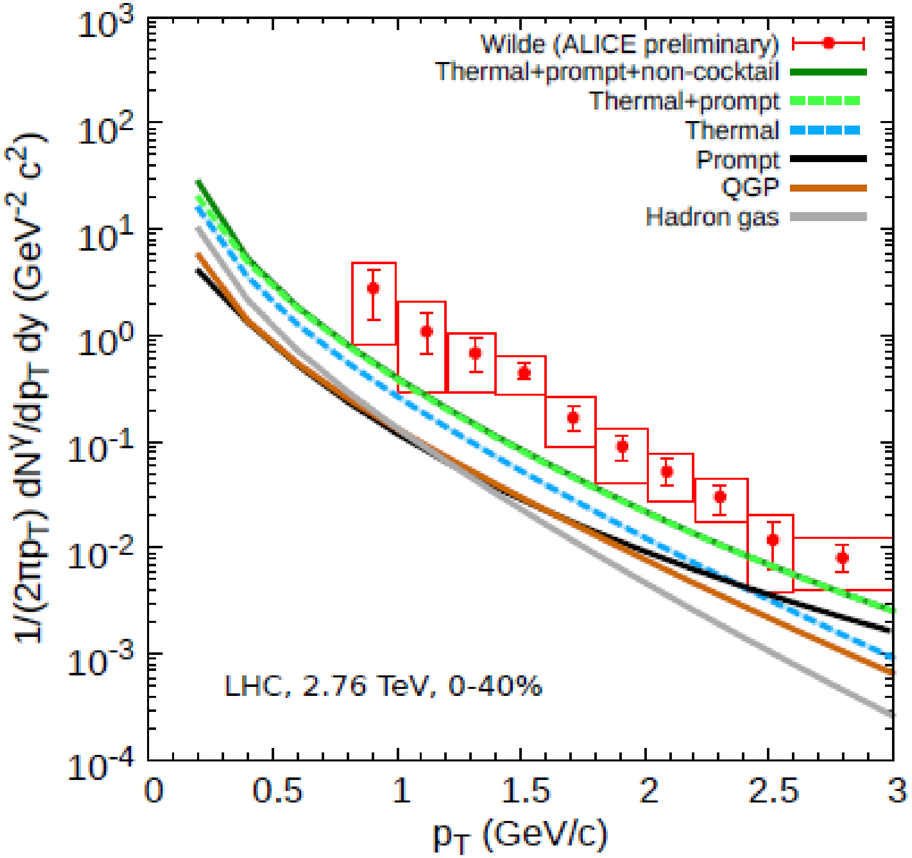
Two different analyses (different detectors), comparable results
Theory typically underestimates the data
Is the “flattening out” at very low p_T real?

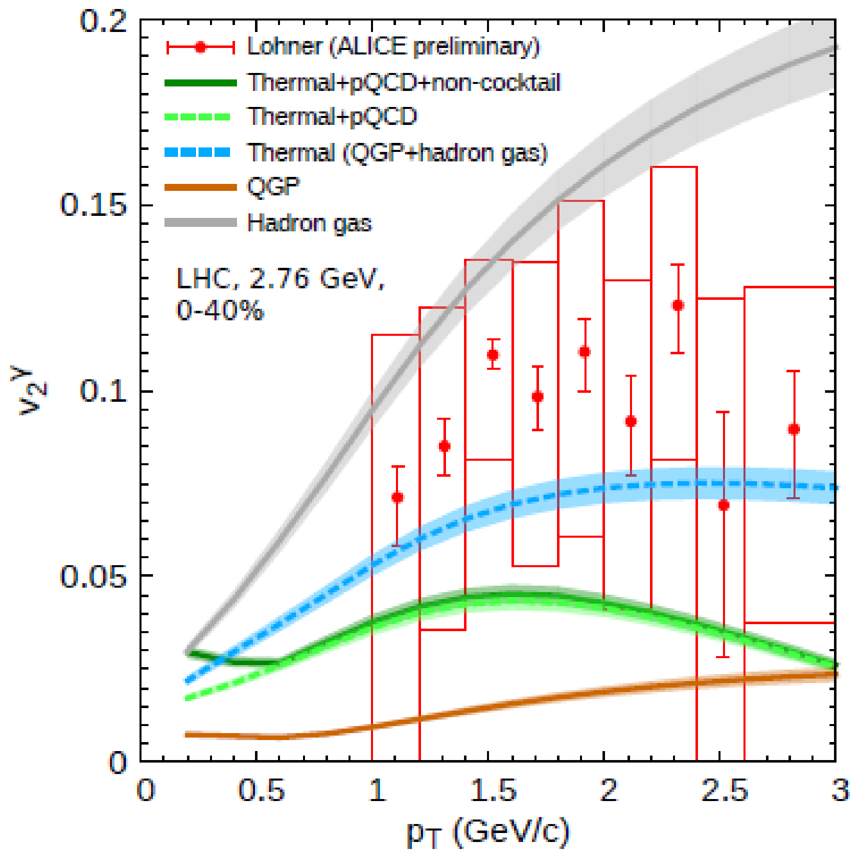
One way to get high v_2 at low p_T

B. Muller, Wu, Yang (1308.6568)
Photons from magnetic field
→ azimuthal asymmetry
Upper limit only



Yields and flow vs theory (ALICE)



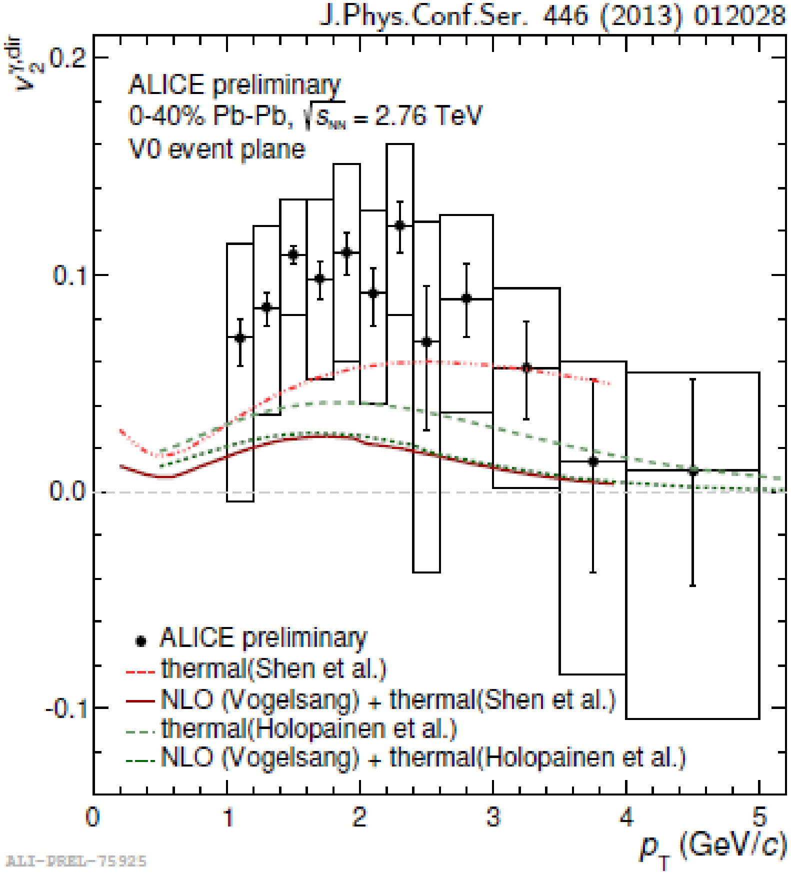


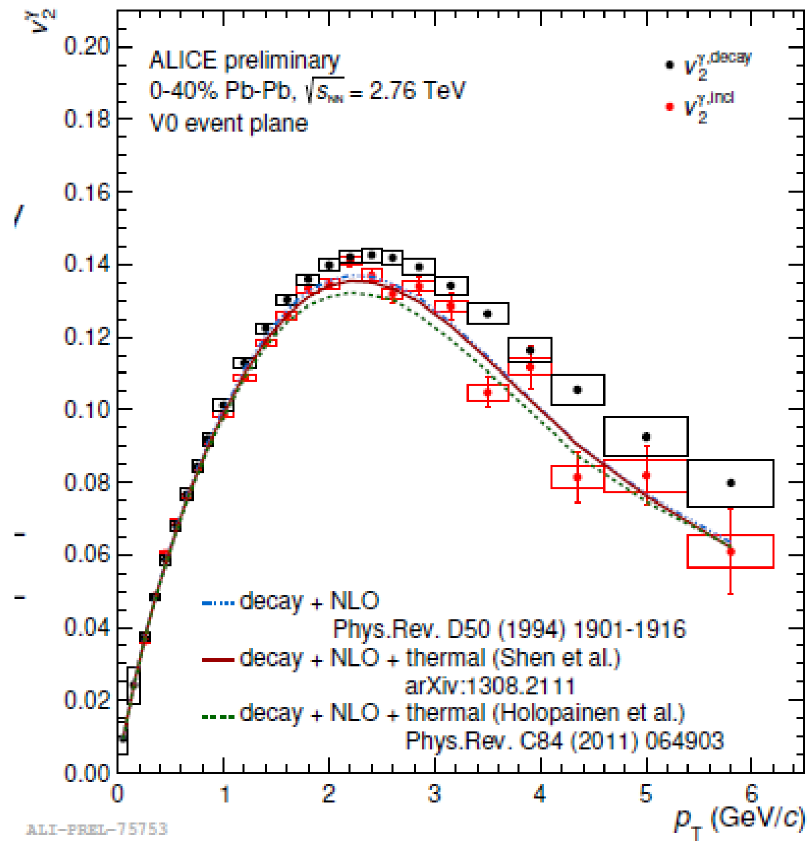
(Gale, TPD2014)

ALICE: getting very cautious

Hot Quarks 2012

TPD2014

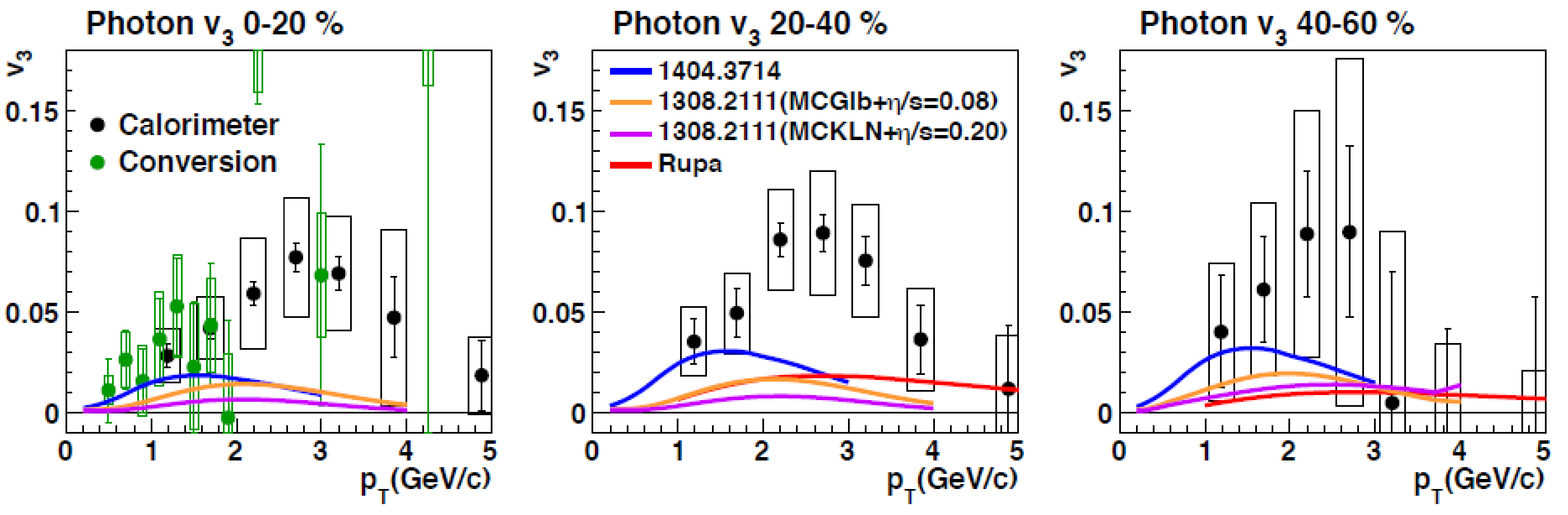




As for flow, "no statement on the existence of (the) direct photon puzzle can be made at this stage" (F. Bock, TPD2014)

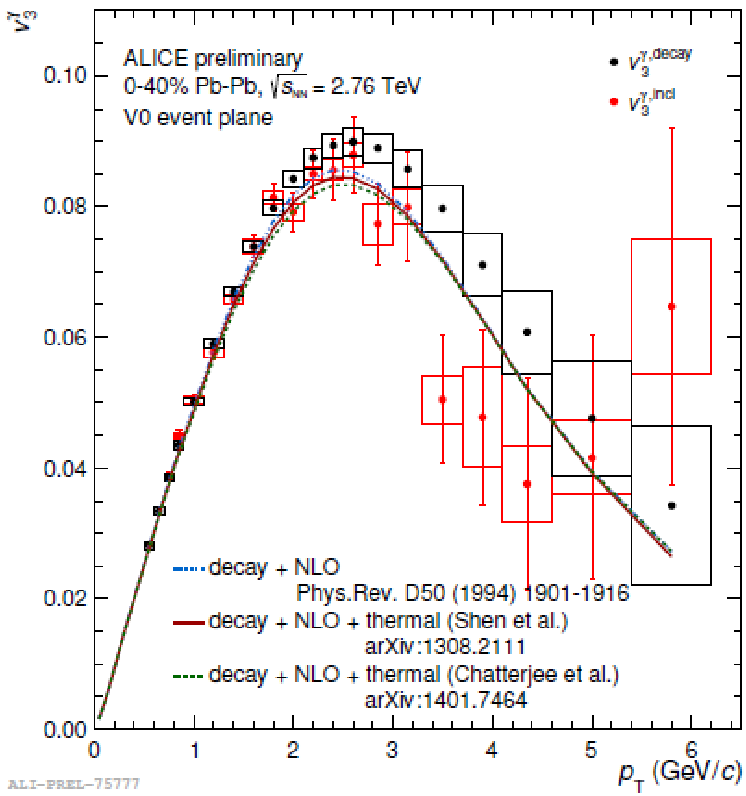
(The basic issue: small Rq with large uncertainties, correlated components, proper propagation of errors)

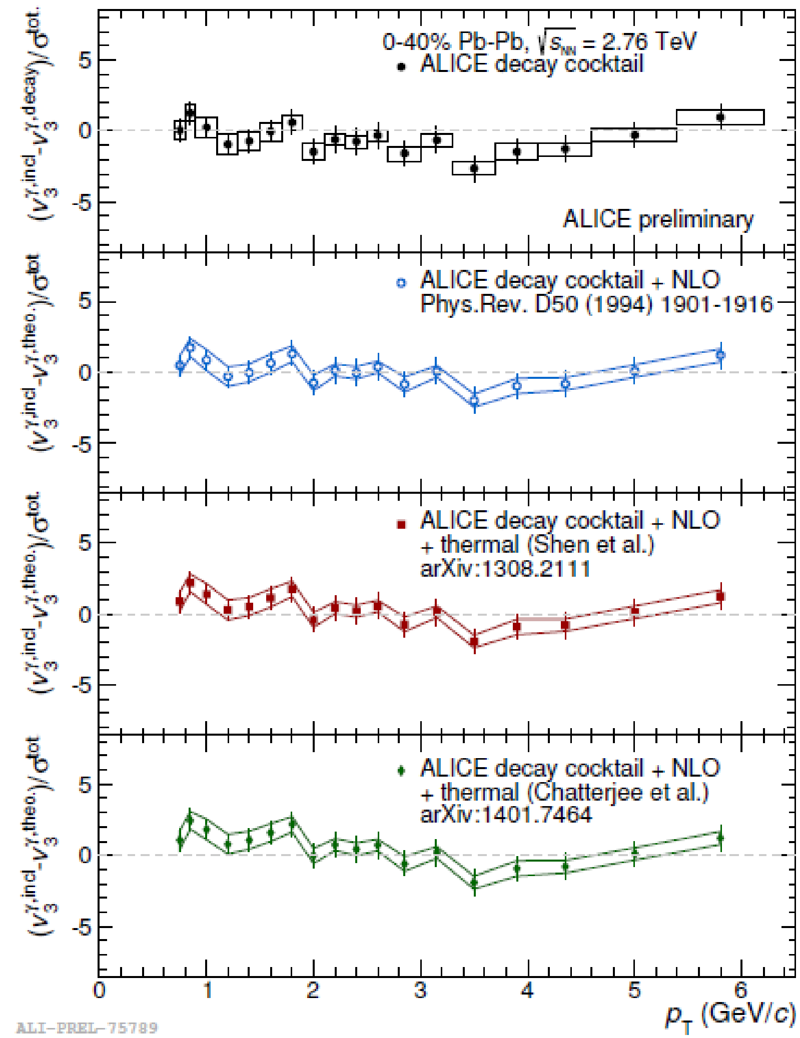
PHENIX: direct photon v_3



1404.3714 – Vujanovic, Paquet, Denicol, Luzum, Schenke, Jeon, Gale
1308.2111 – Shen, Heinz, Paquet, Kozlov, Gale
Rupa Chatterjee, private communication

ALICE: photon v3 (indirectly)





- Very small contribution from thermal v_3
- No significant deviation from 0 in region of interest between 1-3 GeV/c

(F. Bock, TPD2014)

Look ahead: photon v_2/v_3 as measure of η/s

1403.7558

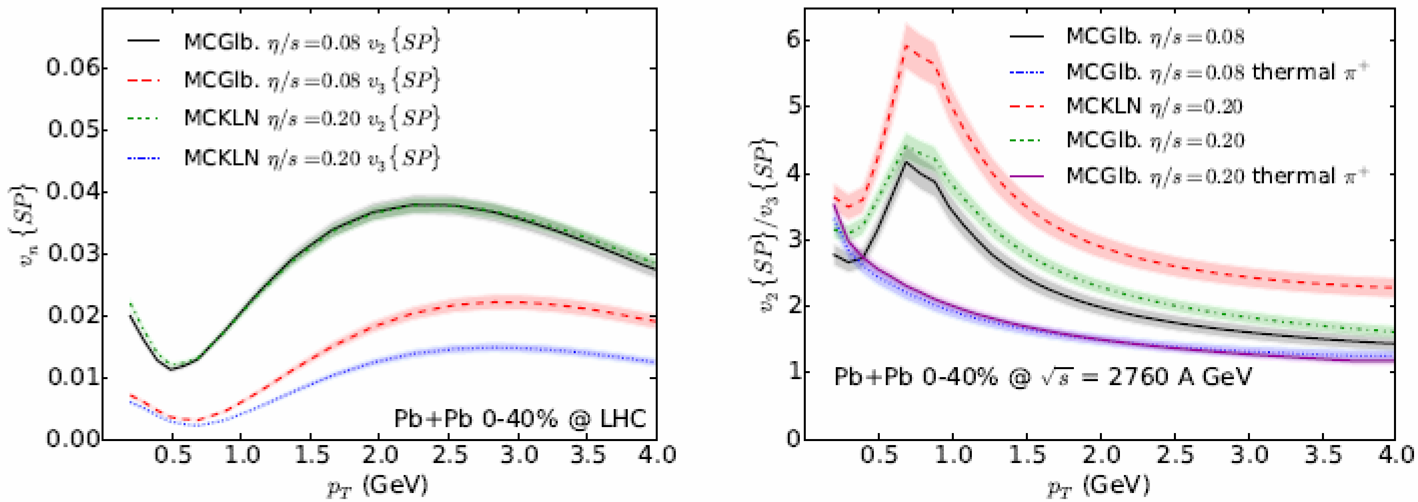
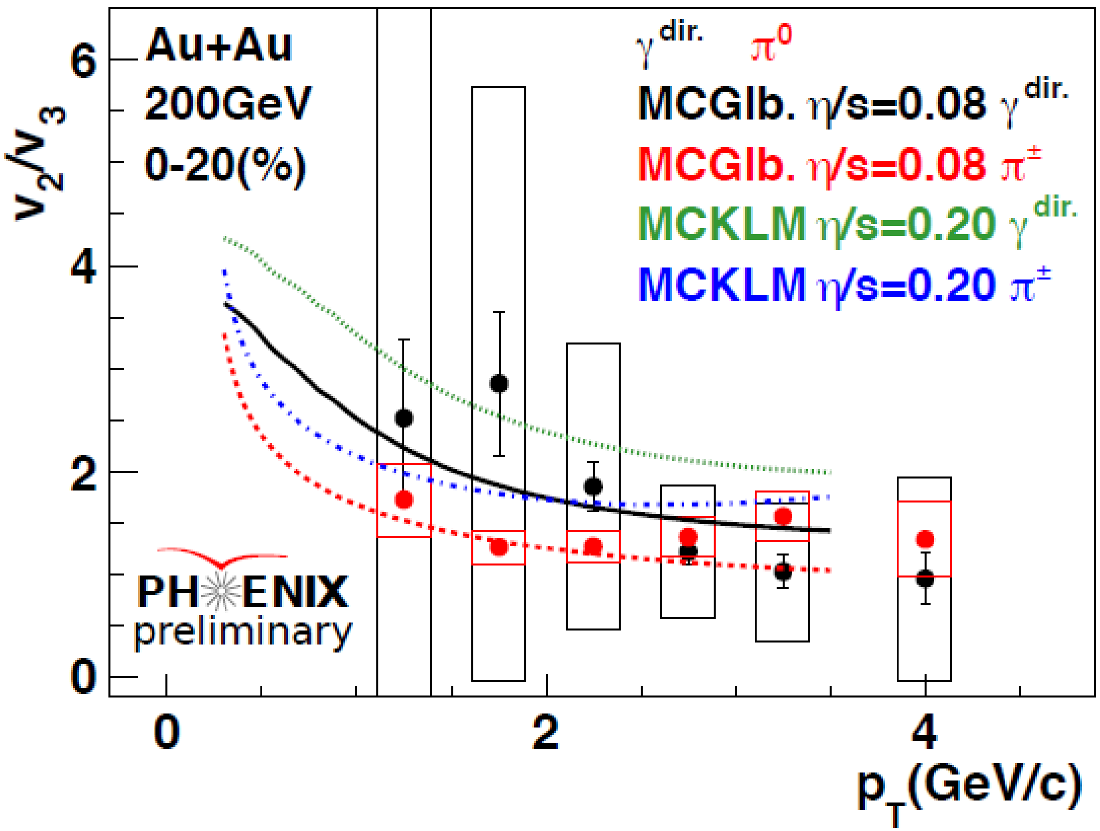


Figure 3. Left panel: p_T-differential $v_{2,3}\{\text{SP}\}$ of thermal photons at 0-40% centrality in Pb + Pb collisions at $\sqrt{s}$ = 2.76 A TeV. Right panel: The corresponding ratio $v_2\{\text{SP}\}/v_3\{\text{SP}\}$ as a function of p_T compared with the same ratio for thermal π^+.

State-of-the-art calculations of thermal photon anisotropic flow, $v_n\{\text{SP}\}$ ($n = 2, 3$), use event-by-event viscous hydrodynamic simulations to account for event-by-event quantum fluctuations in the initial state. Shear viscosity suppresses photon $v_n\{\text{SP}\}$, with viscous corrections to the photon production rates dominating this suppression. For both the p_T-integrated and p_T-differential anisotropic flows, the ratio $v_2^\gamma\{\text{SP}\}/v_3^\gamma\{\text{SP}\}$ shows stronger sensitivity to the specific shear viscosity of the QGP for thermal photons than for charged hadrons. This ratio increases with η/s because the viscous suppression of v_n increases with the harmonic order n. Since the ratio $v_2^\gamma\{\text{SP}\}/v_3^\gamma\{\text{SP}\}$ is insensitive to photon sources that carry zero anisotropic flow, such as prompt photons, the experimental measurements of this ratio for direct photons will shed new and more direct light on the specific shear viscosity of the thermal medium formed after the end of prompt photon emission, but well before most of finally emitted hadrons are set free.

A first attempt on v_2/v_3



Theory curves: private communication by Ch. Shen, Ch. Gale, J.-F. Paquest, U. Heinz as in 1403.7558, Calculated for RHIC.

Systematic errors grossly overestimated
Recall: individually both v_2 and v_3 are way off (too low) in theories
-> but the ratio can still in principle make sense

Some more RHIC, LHC v_2, v_3

1308.2111
(Shen, Heinz, Paquet, Kozlov, Gale, updated Dec 22, 2014)

Warning: this is scalar product, not reaction plane

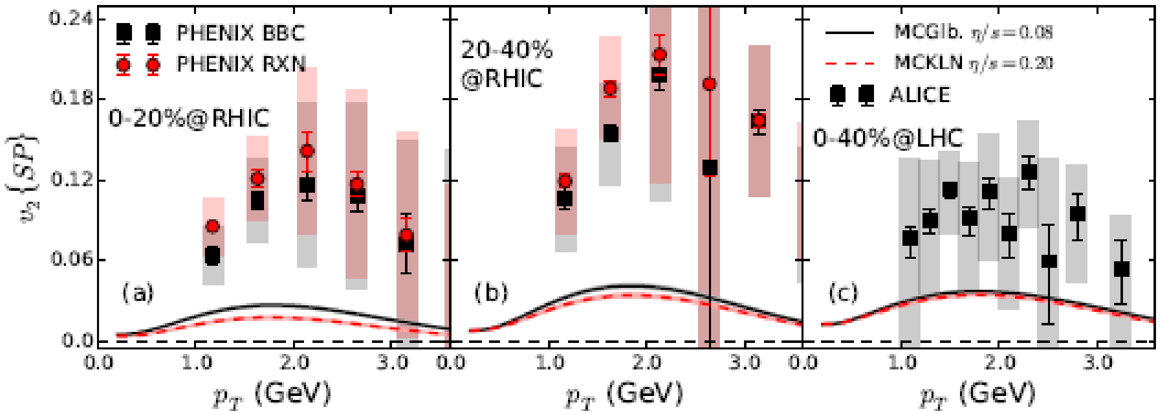


FIG. 2. (Color online) Comparison of direct photon (prompt + thermal (QGP+HG)) elliptic flow from event-by-event viscous hydrodynamics with recent experimental data from (a) 0-20% and (b) 20-40% central 200 A GeV Au+Au collisions at RHIC [18] and (c) from 0-40% central 2.76 A TeV Pb+Pb collisions at the LHC [20]. Solid black (dashed red) lines correspond to MCGlb (MCKLN) initial conditions evolved with a shear viscosity $\eta/s=0.08$ (0.2), respectively.

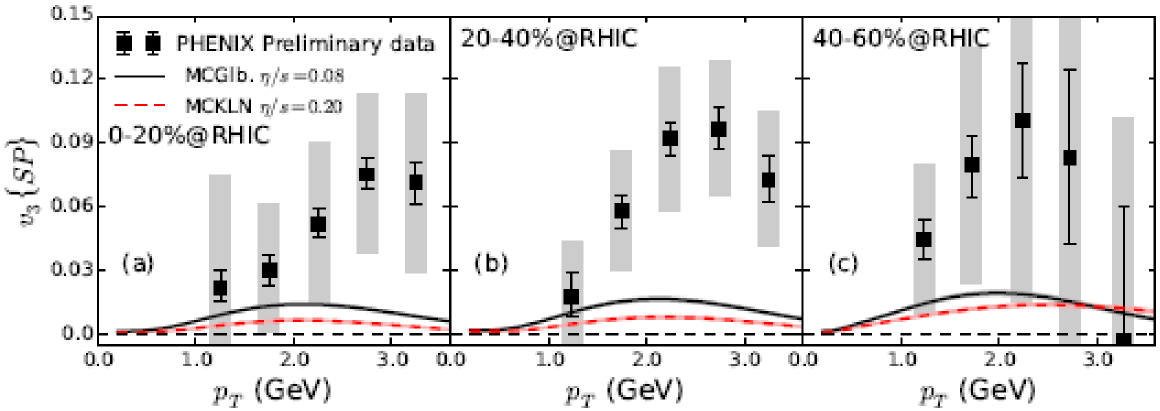
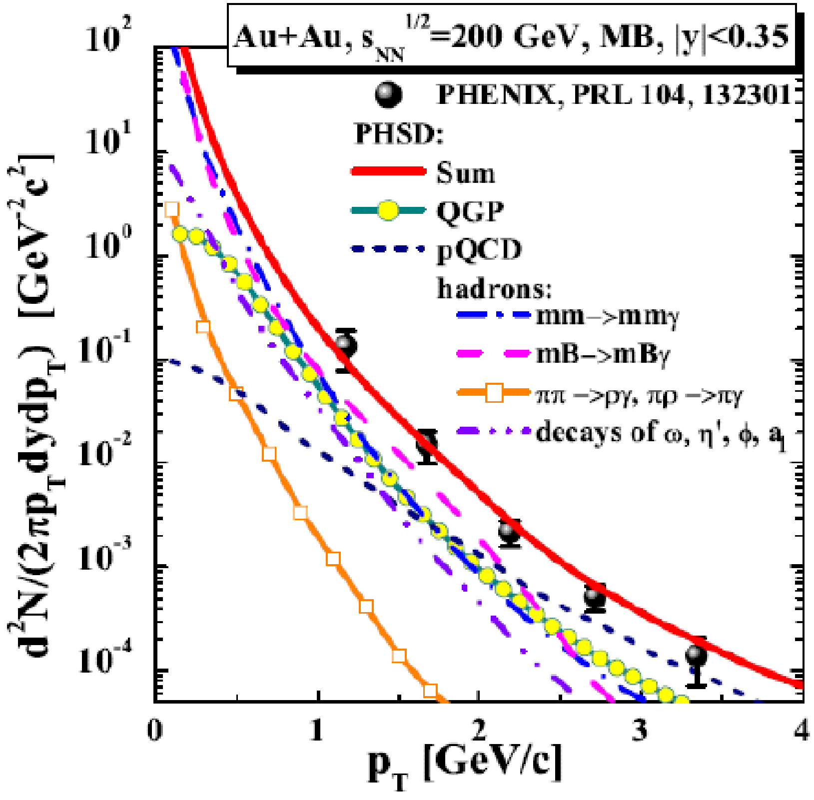
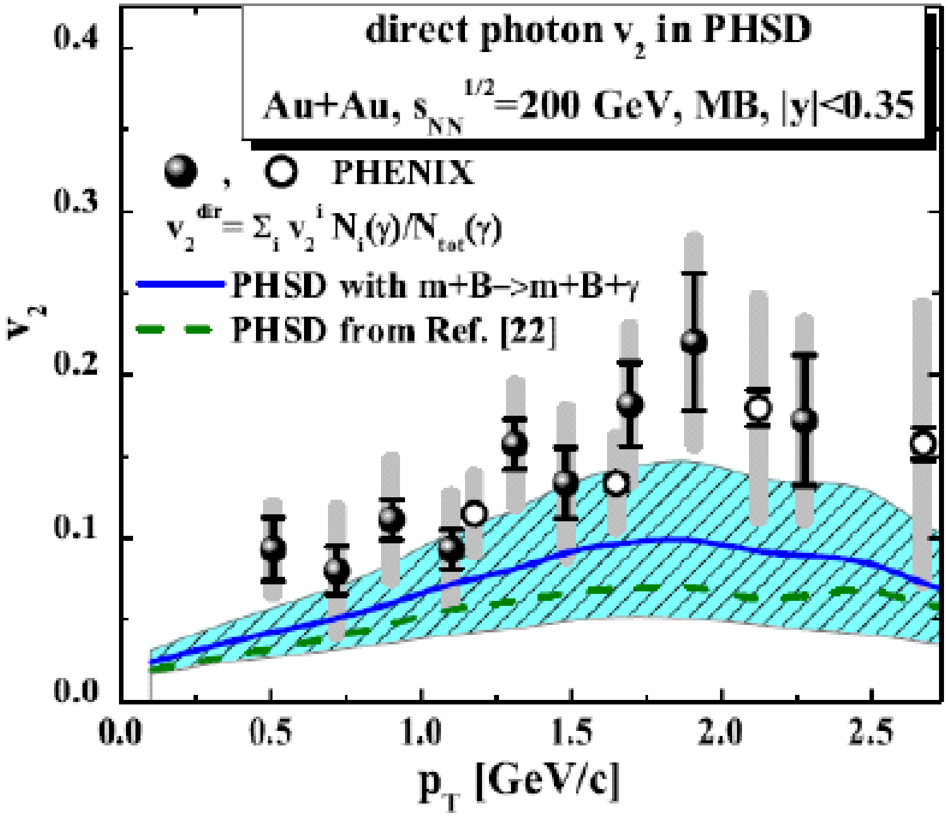


FIG. 3. (Color online) Similar to Fig. 2 but for triangular flow. Direct photon (prompt + thermal (QGP+HG)) triangular flow from event-by-event viscous hydrodynamics is compared with recent preliminary data from the PHENIX Collaboration [46] for 200 A GeV Au+Au collisions at RHIC, at (a) 0-20%, (b) 20-40%, and (c) 40-60% centrality.

PHSD

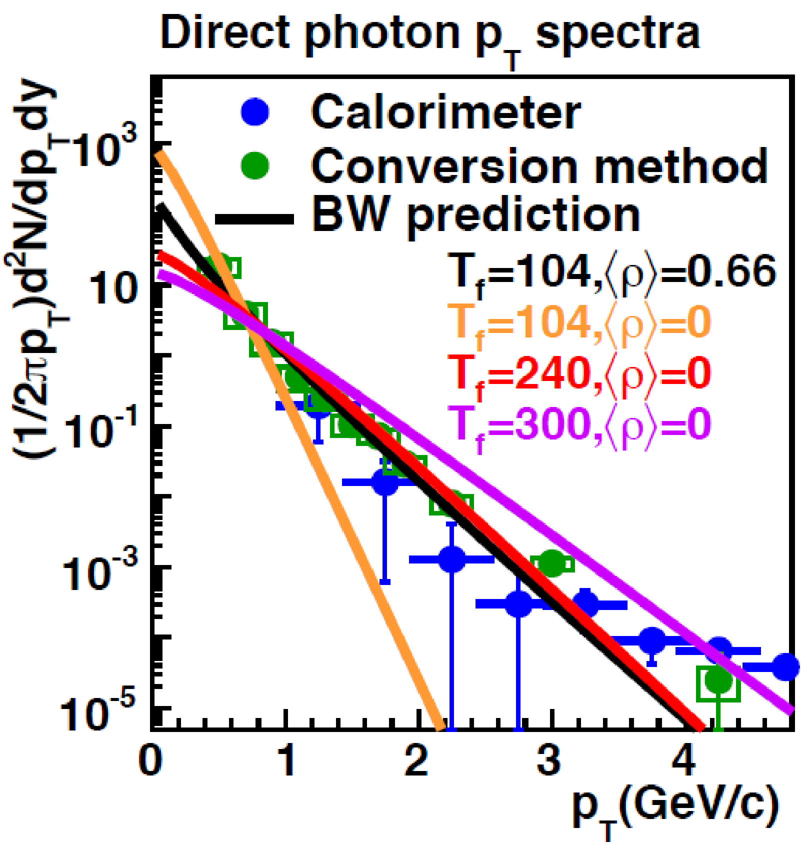




(Linnyk, EMMI RRTF2014)

More exotic scenarios

Blast Wave fit
(“photons are just zero mass hadrons”)



Photons from dipole radiation
(Biro et al, 1503.06628)

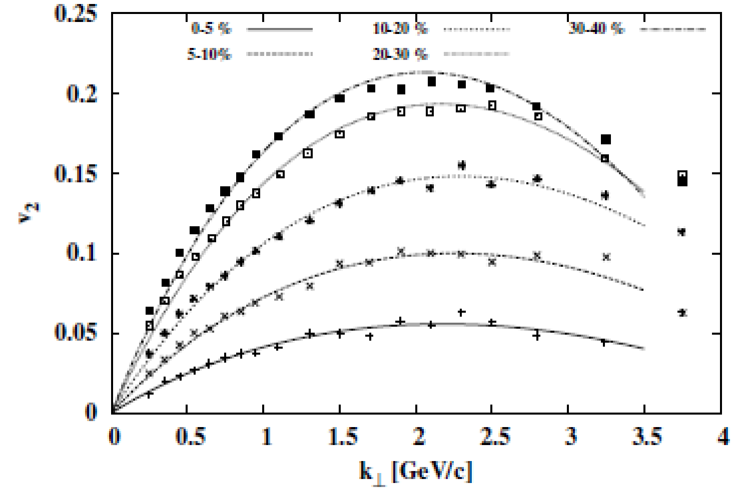


Fig. 2: Inclusive photon elliptic flow measured by ALICE group of LHC in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV for several centrality classes [22]

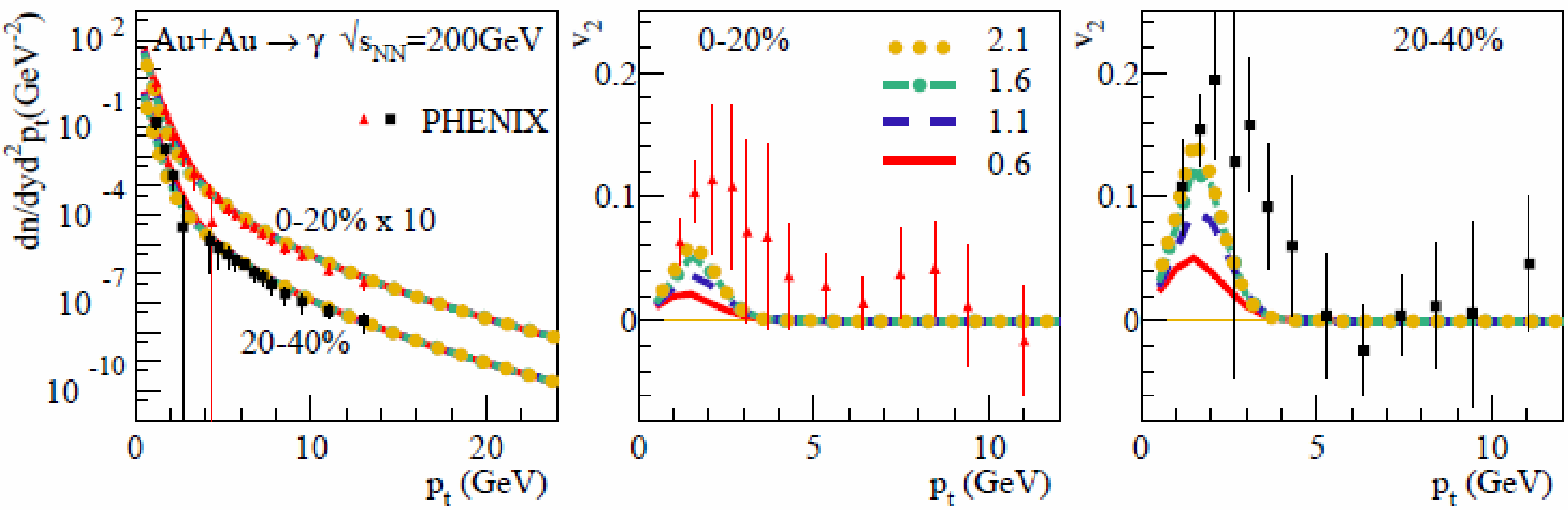
Abstract In this paper we demonstrate that radiation patterns could cause flow-like behaviour without any reference to hydrodynamic description. For that purpose we use a statistical ensemble of radiating dipoles, motivated by the investigation of the equivalent photon yield produced by decelerating charges. For the elliptic asymmetry factor, v_2, we find a reasonable agreement with experimental data.

Direct photon flow – play with time

F.-M. Liu

Early hydro initial time, QGP forms considerably later
(0.6 f/c vs QGP formation times up to 2.1 f/c)
→ early emission (no flow part) was overestimated

arXiv:1212.6587



Q: what is the emission between τ_{hydro} and τ_{QGP}? Apparently unanswered
(looks a bit like a "**fiat**" type theory so far → fine for the trees
but where's the forest?)

Conformal anomaly

(Basar, Kharzeev, Skokov, PRL 109, 202303 (2012))

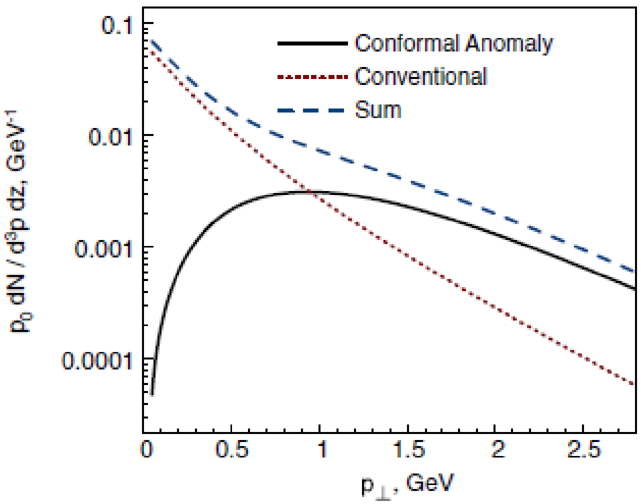


FIG. 3 (color online). The transverse momentum spectra of the produced direct photons for $C_\zeta = 2.5$ calculated for minimum bias Au-Au collisions; see text for details.

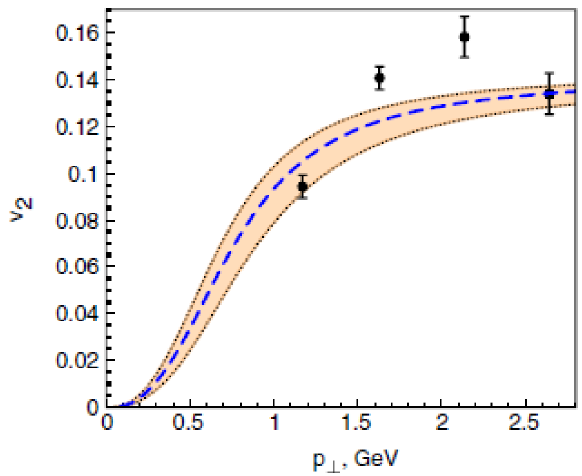


FIG. 2 (color online). The azimuthal anisotropy v_2 of the direct photons for different values of bulk viscosity corresponding to C_ζ in the range of 2.5–5 calculated for minimum bias Au-Au collisions. The dashed line represents the results with $C_\zeta = 4$. The black dots are the data from the PHENIX Collaboration [25] for minimum bias Au-Au collisions at $\sqrt{s} = 200$ GeV.

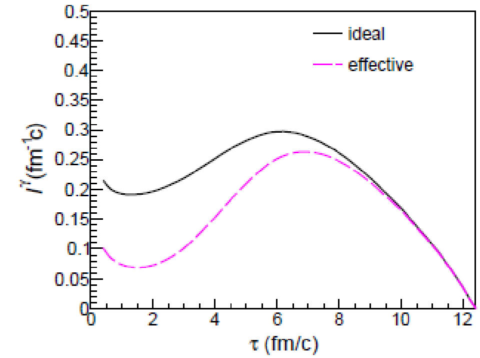
Less radiation from QGP?

Monnai 1504.00406

Quasi-particle effective model, lower d.o.f. in plasma

→ decreasing rates, increasing v_2

(thermal photons emitted later)



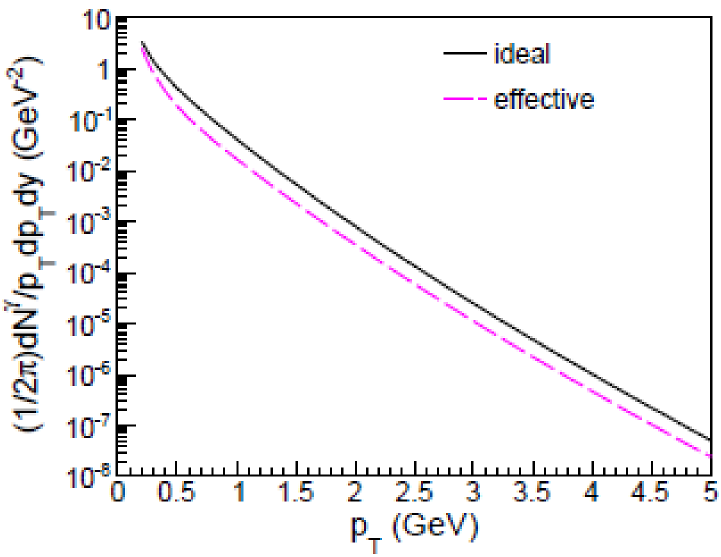


FIG. 4. (Color online) Thermal photon p_T spectrum with effective distributions (dashed line) compared to that with ideal distributions (solid line).

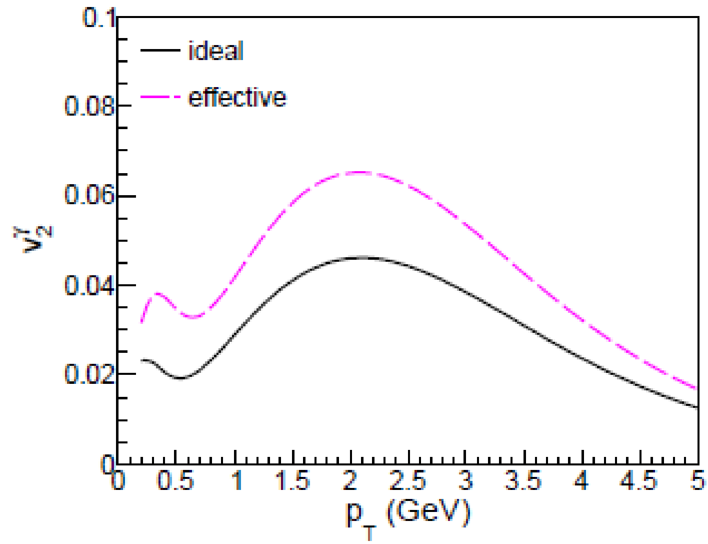


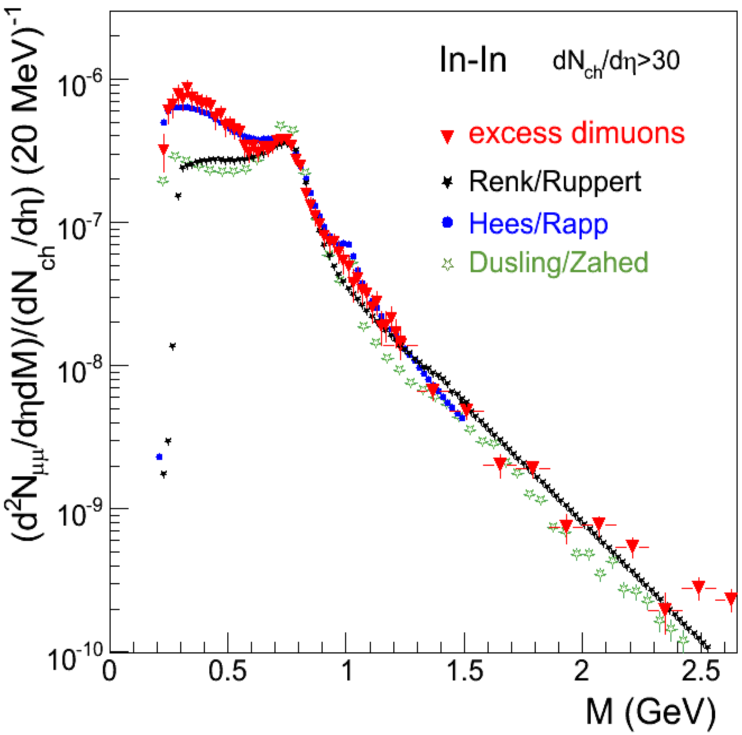
FIG. 3. (Color online) Thermal photon elliptic flow with effective distributions (dashed line) compared to that with ideal distributions (solid line).

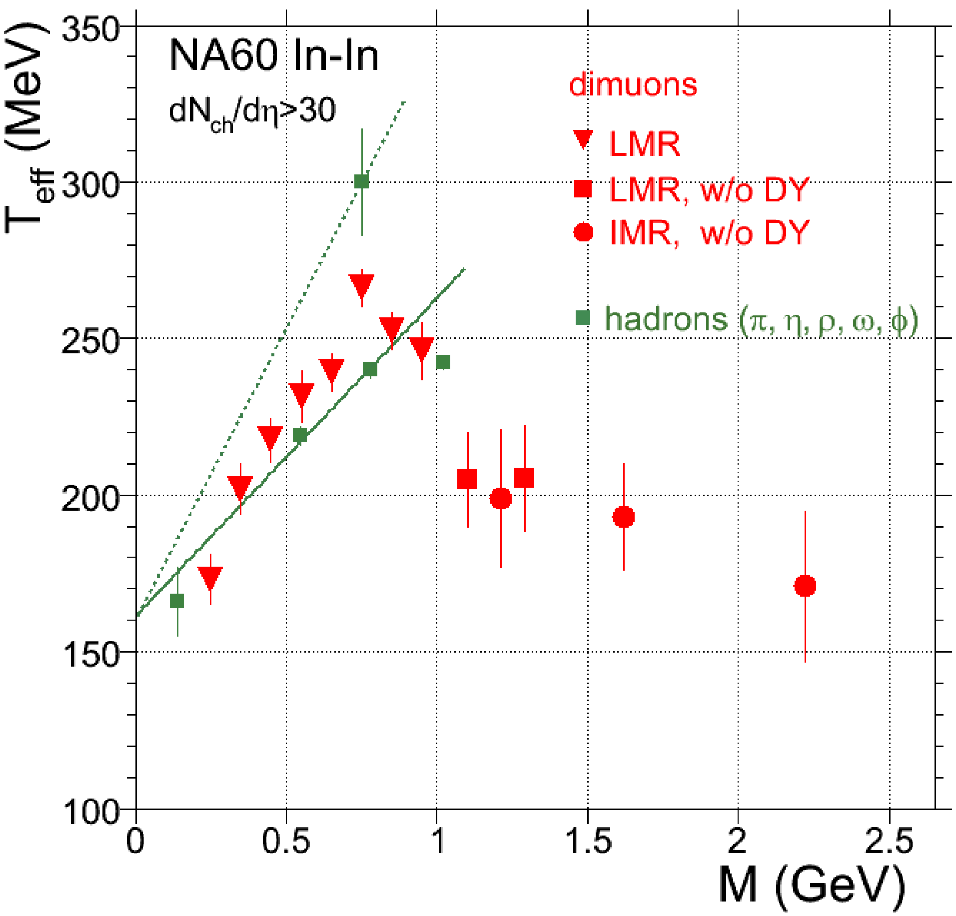
Dileptons: an additional degree of freedom -- mass

(But the measurement is even more difficult without a dedicated experiment!)

Na60

flow in the hadronic phase,
fferent and approximately
ant T_{eff} at high masses
nic vs partonic sources?)





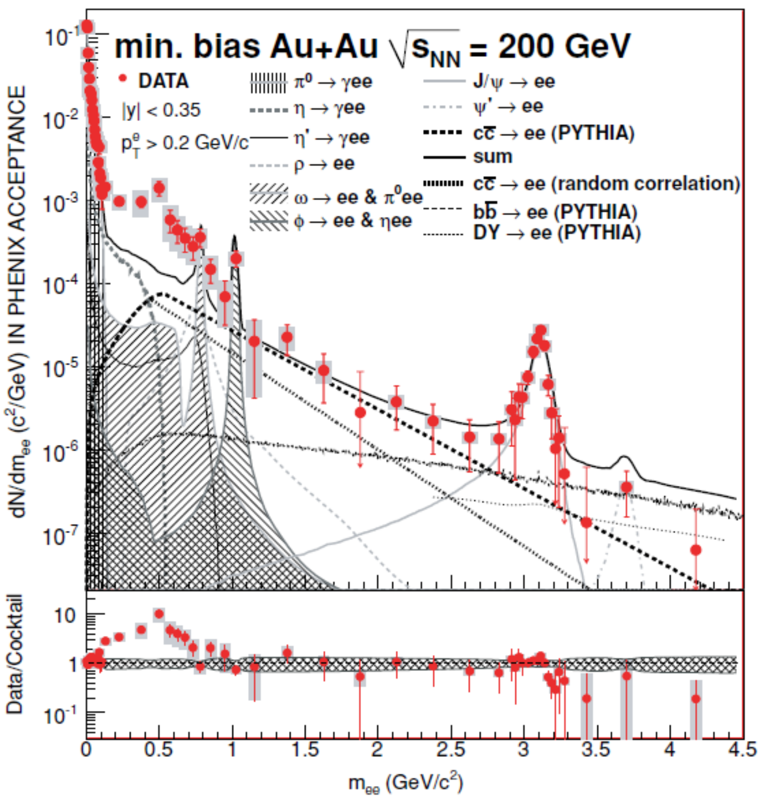
Eur. Phys. J. C 59 (2009) 607; CERN Courier 11/2009

Low mass dileptons: a major issue

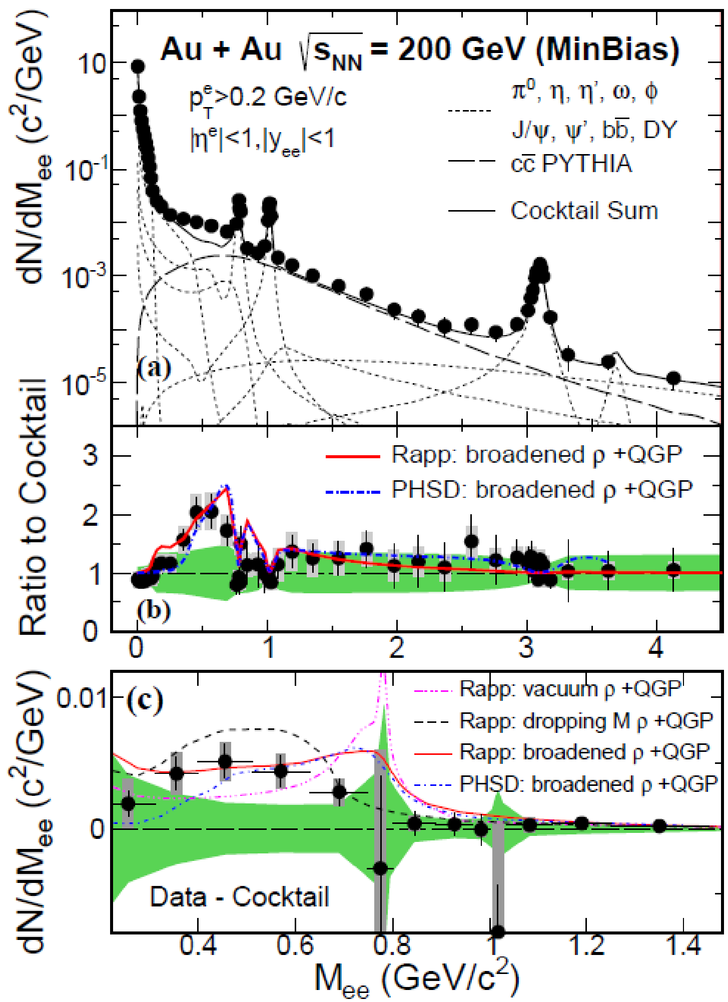
Discrepancy between the RHIC experiments:

PHENIX

PHYSICAL REVIEW C **81**, 034911 (2010)



STAR



Waiting for final (HBD) results from PHENIX

STAR: dielectron v_2

PRC 90, 064904 (2014)

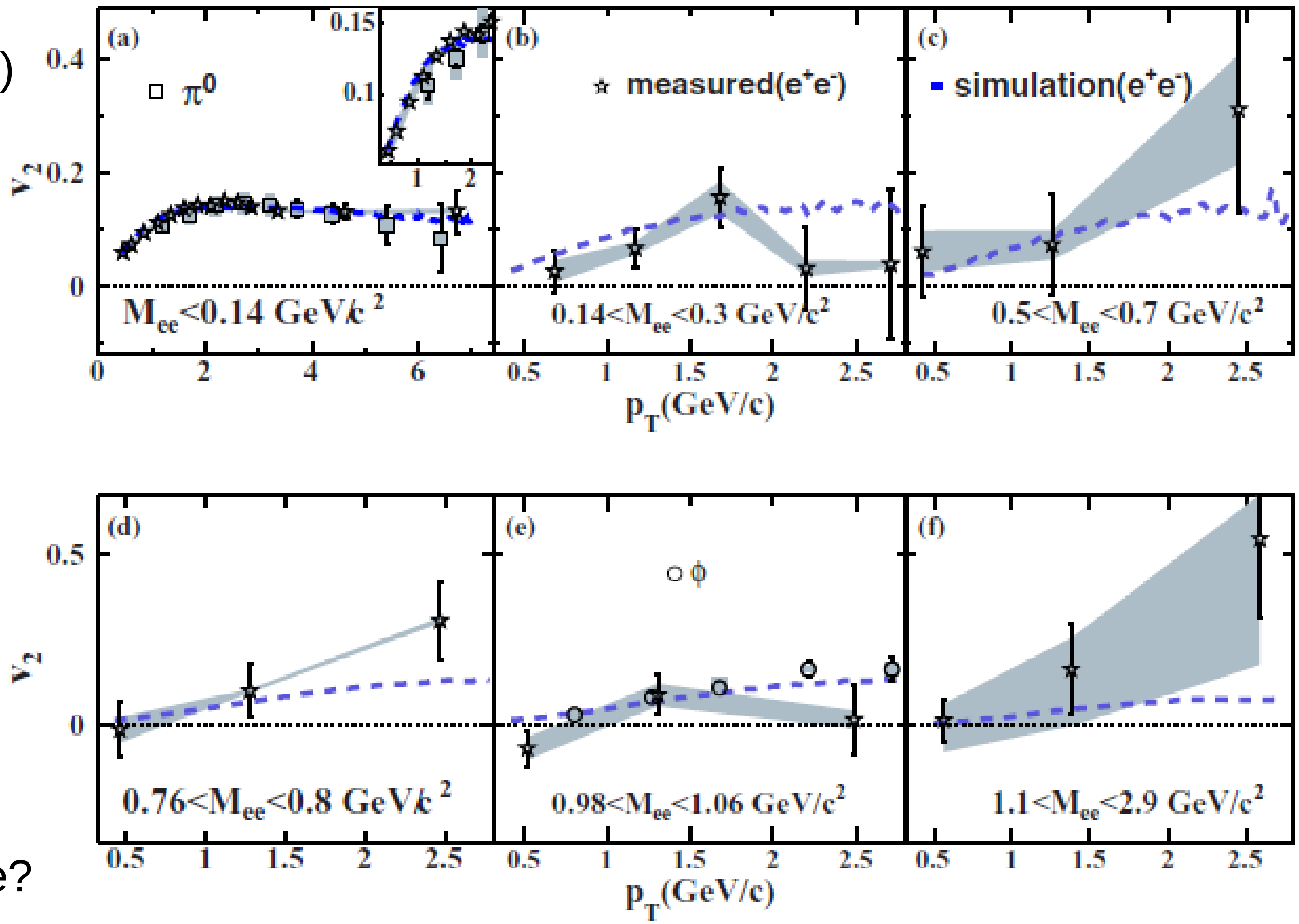
EP from the same rapidity

In the low mass (<1.1) region consistent with π^0, η, ω, ϕ decay contributions

Thermal dielectron rates comparable to Dalitz rates! (better S/B)

In 1.1 < M_{ee} < 2.9 consistent with ccbar contribution

Would a v_2 of virtual photons be possible?



Issues, opportunities?

These measurements live and die on S/B ($R\gamma$), where B is now irreducible:
it means physics – not instrumental – background
(e.g. real photons from decay of real π^0-s)

Cocktail needs to be known very precisely down to very low p_T (normalization?)
→ integrated yield? Asymptotic ratios? Validity of m_T scaling?

Improve understanding of error correlations (spoils promising v_n/v_m measurements)

Long, but potentially rewarding shot: direct photon HBT
→ could differentiate between pre-QGP and late HG sources

Event plane from photons, far in η? (Still strongly biased by hadrons!)

Collision energy and species systematics

*External conversion is the "technique du jour". Could systematics be improved by measuring with **converters of various thickness** (in current and future experiments)? I think it would.*

Where does this leave us? (Summary)

Substantial radiation from the QGP disfavored (??? Some surprise, if true…)

Very early, pre-hydro, anisotropic sources? (Can explain rates?)

Dim (gluonic) plasma, delayed freeze-out?

Most of the yield from the hadronic phase?

Some new explanations in the works? ☺

Experimentally: the crucial point is to improve R_γ (a.k.a. S/B)
→ very hard short of a dedicated electromagnetic probes experiment

The fantastic richness of the signal (escaping freely, carrying information on the entire history of the collision) is also a tremendous curse…

(Or a challenge worth taking up! ***A dedicated experiment would help****…)*

Backup, extras

Chun Shen

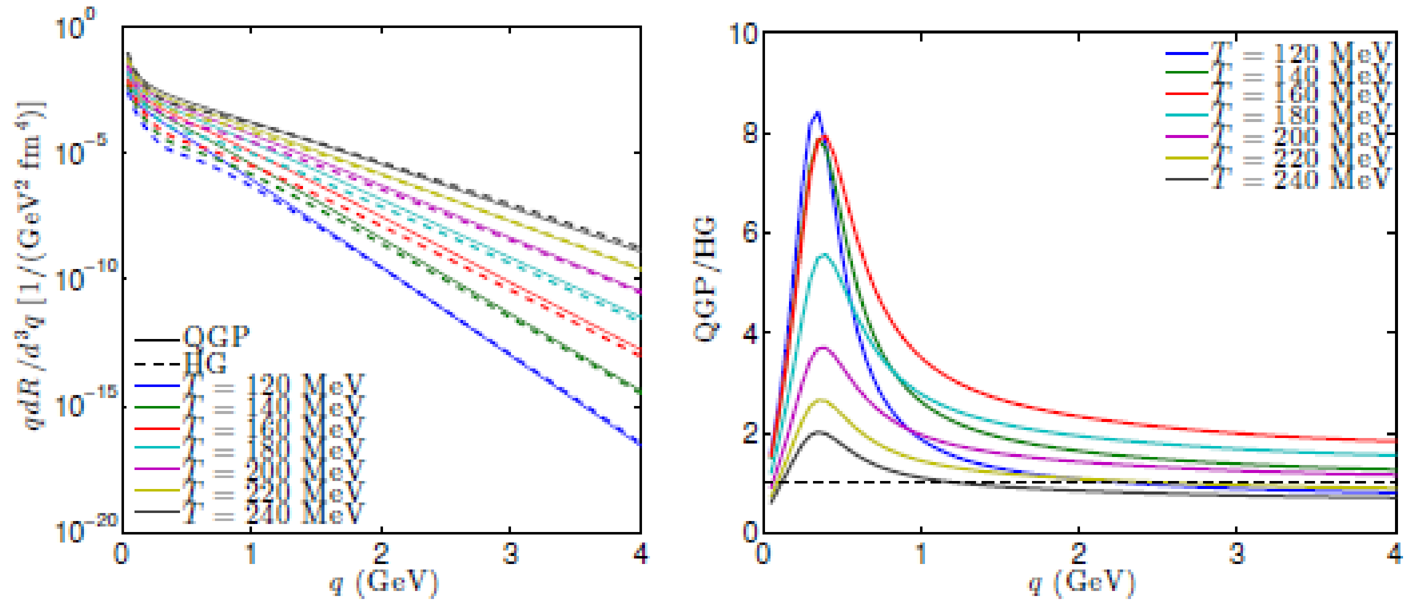


Figure 17.1: The comparison of photon production rates between QGP and HG phase in the transition temperature regions.

Chun Shen

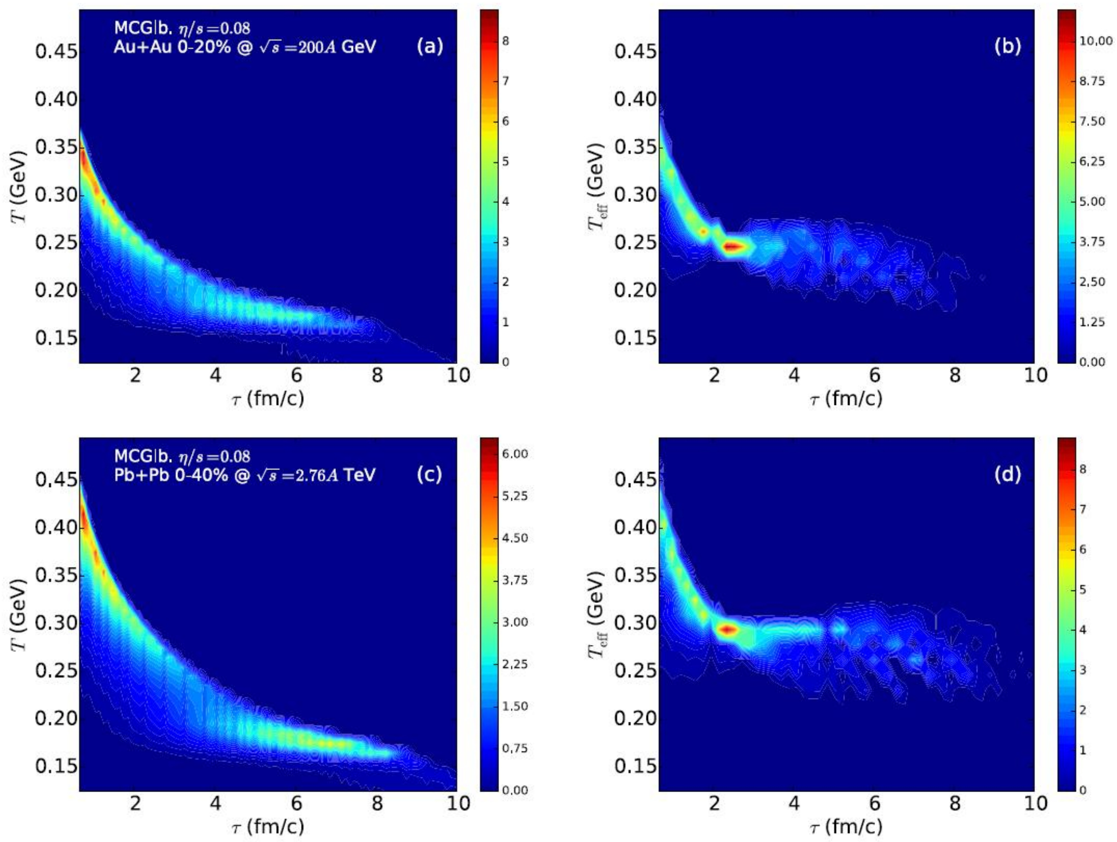


Figure 18.5: Similar to Fig. 18.4, but rate transition temperature region is chosen for 150 MeV < $T_{...}$ < 170 MeV