Direct photon production in pp, pA and AA collisions

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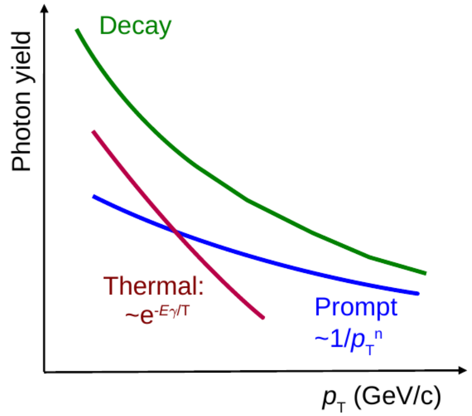
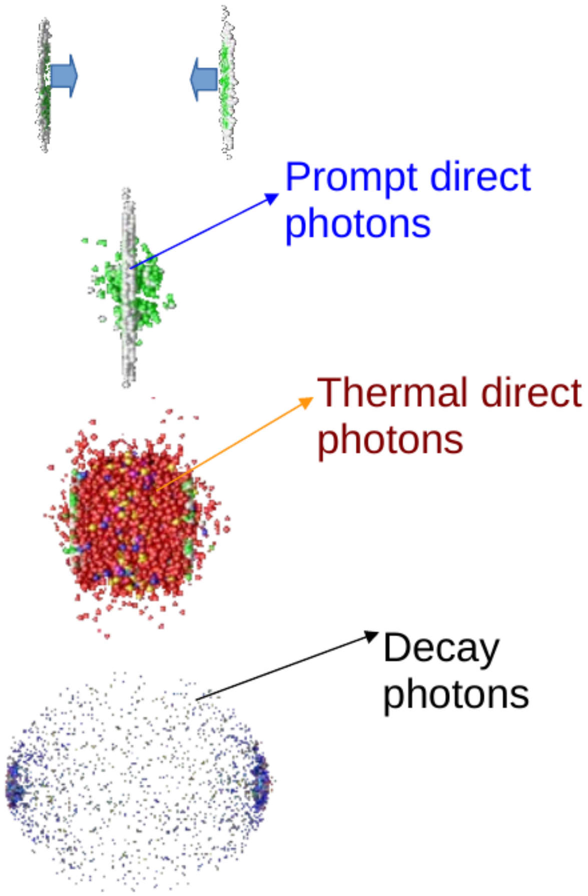
Photon classification

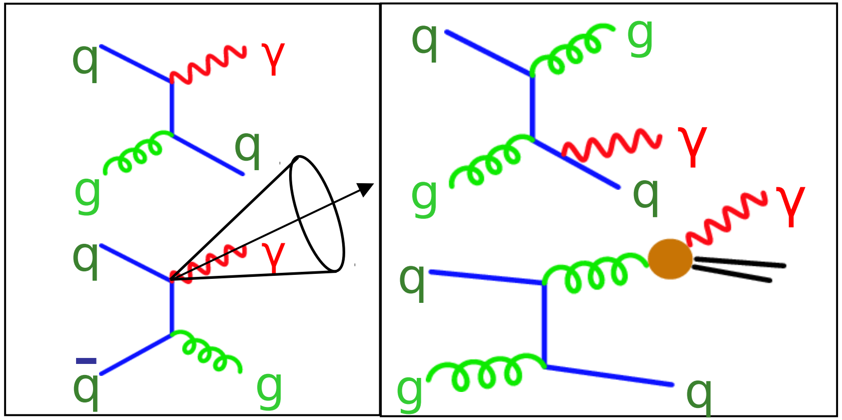
- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
  - Prompt direct photons: ones from interaction of incoming nucleons
  - Thermal direct photons: thermal radiation of hot matter
- Isolated photons: photons without hadronic activity in some cone (~0.4) around the photon
- Decay photons: photons from decays of final hadrons



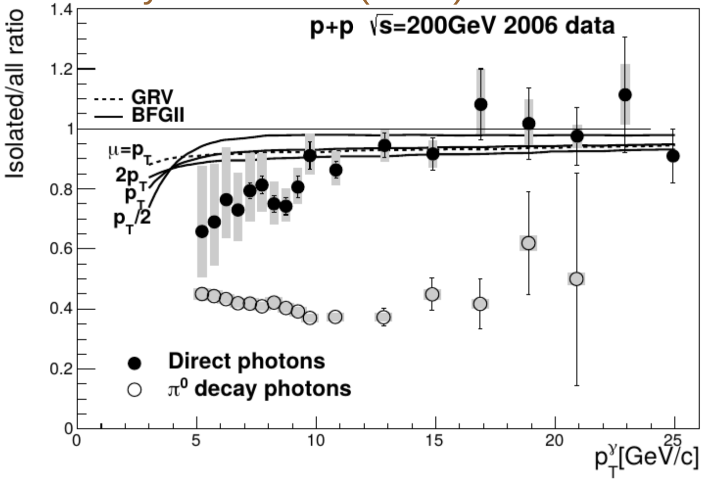


Isolated or direct photons?

- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
- Measured as a difference $N_\gamma^{dir} = N_\gamma^{incl} - N_\gamma^{dec}$
- Can not be measured in event-by-event



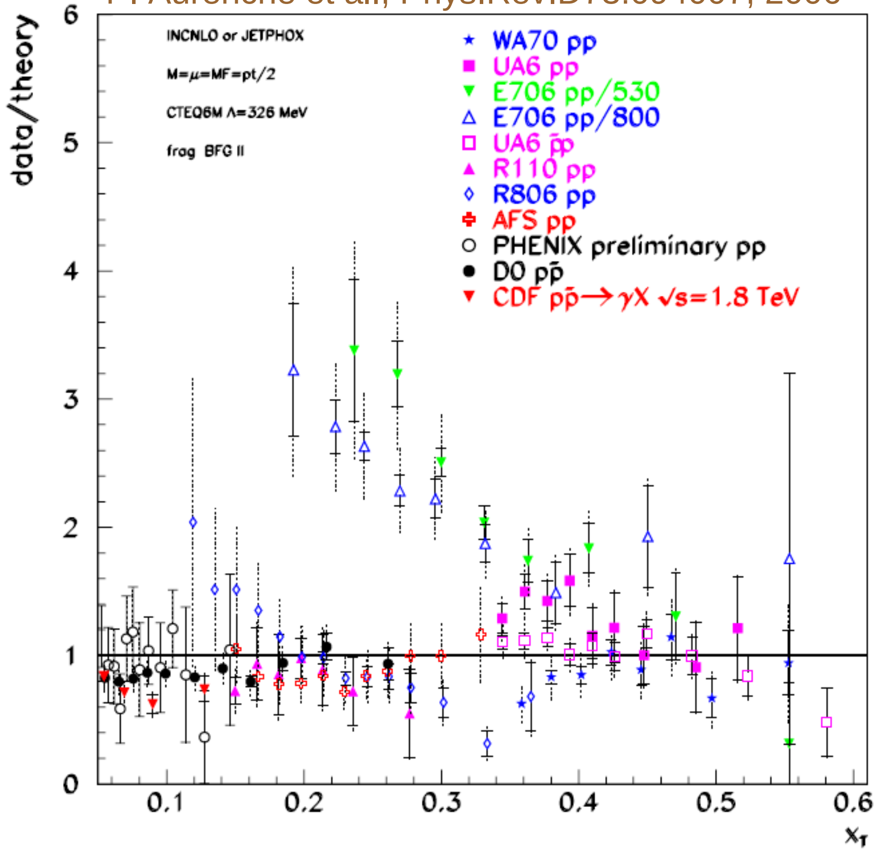
Phys.Rev.D 86 (2012) 072008



- Isolated photons: photons without hadronic activity in some cone (R~0.4) around the photon
- Can be measured in event-by-event basis
- Purity rapidly decreases with decrease at p_T<10-20 GeV/c => can not measure at lower p_T
- Difference between direct and isolated photons diminish at high p_T

Direct photons in pp collisions: low energies

P. Aurenche et al., Phys.Rev.D73:094007, 2006



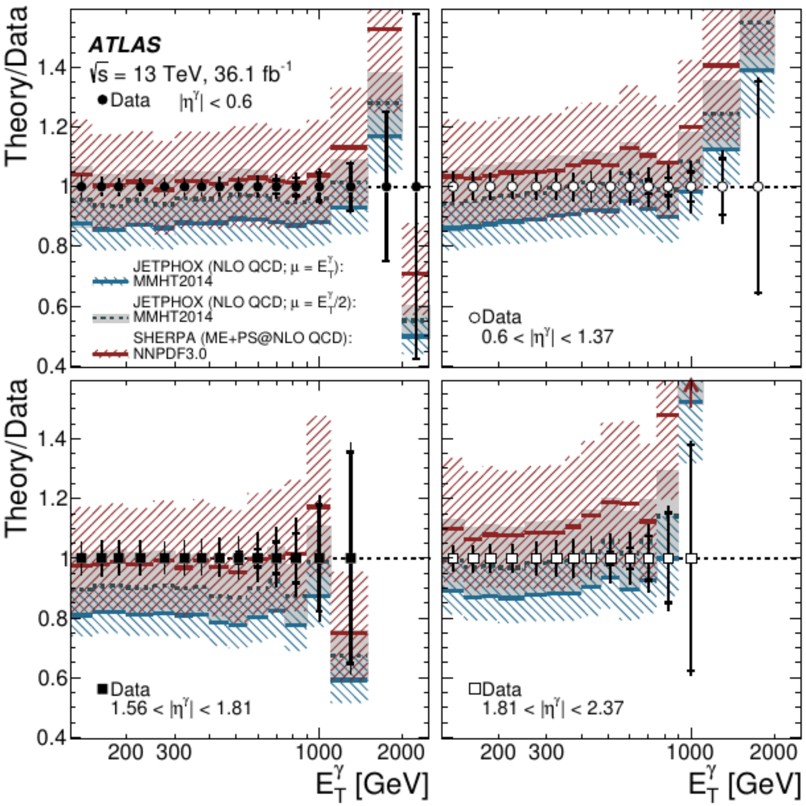
Direct photons in pp collisions:
baseline, test of resummation techniques,
input for PDF parameterization

L.E. Gordon and W. Vogelsang,
Phys. Rev. D 48 (1993) 3136; Phys. Rev. D 50 (1994) 1901
developed technique to perform joined recoil and threshold resummations

P. **Aurenche et al.,**
Phys.Rev.D73:094007, 2006
developed package Jetphox
https://lapth.cnrs.fr/PHOX_FAMILY/jetphox.html

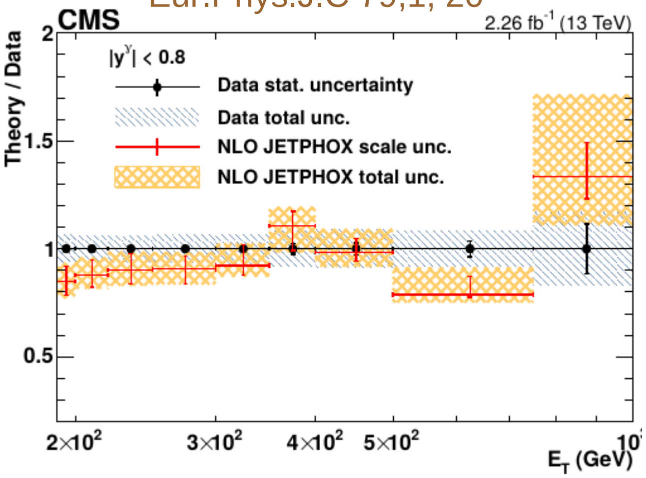
Isolated photons in pp at LHC

ATLAS Collaboration, Phys. Lett. B 770, 473

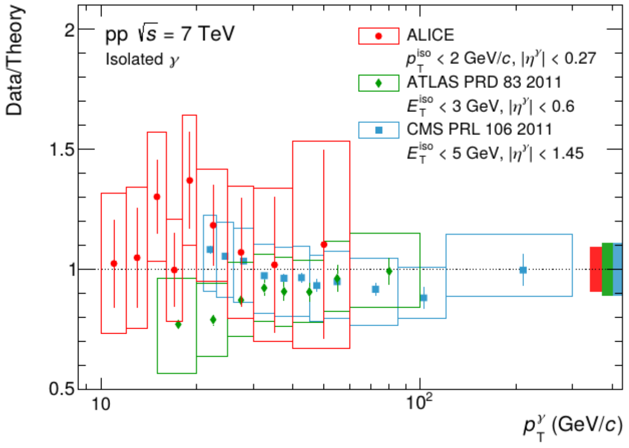


- Isolates photon production well reproduced with NLO pQCD calculations
- Good agreement between LHC experiments

CMS collaboration,
Eur.Phys.J.C 79,1, 20



ALICE collaboration,
Eur.Phys.J.C 79 (2019) 11, 896

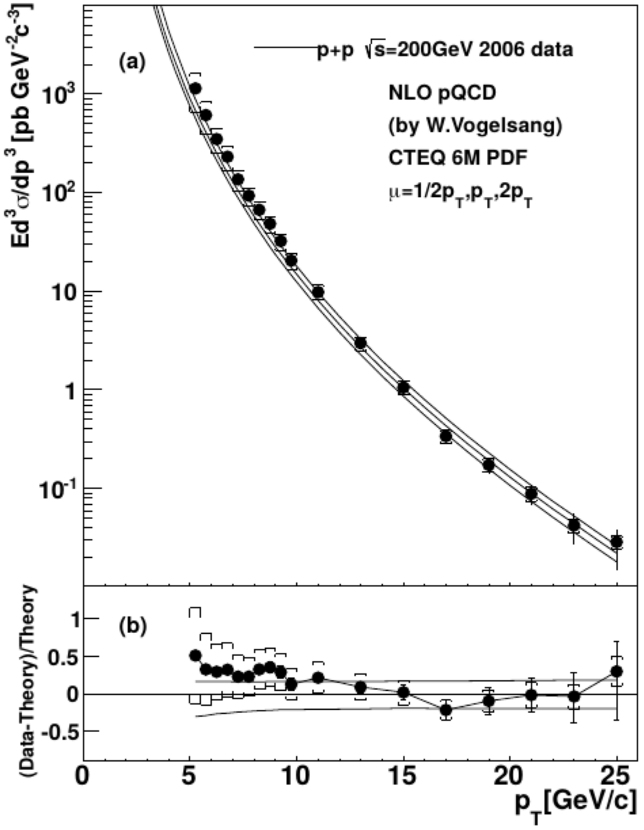


Direct photons in pp at low p_T

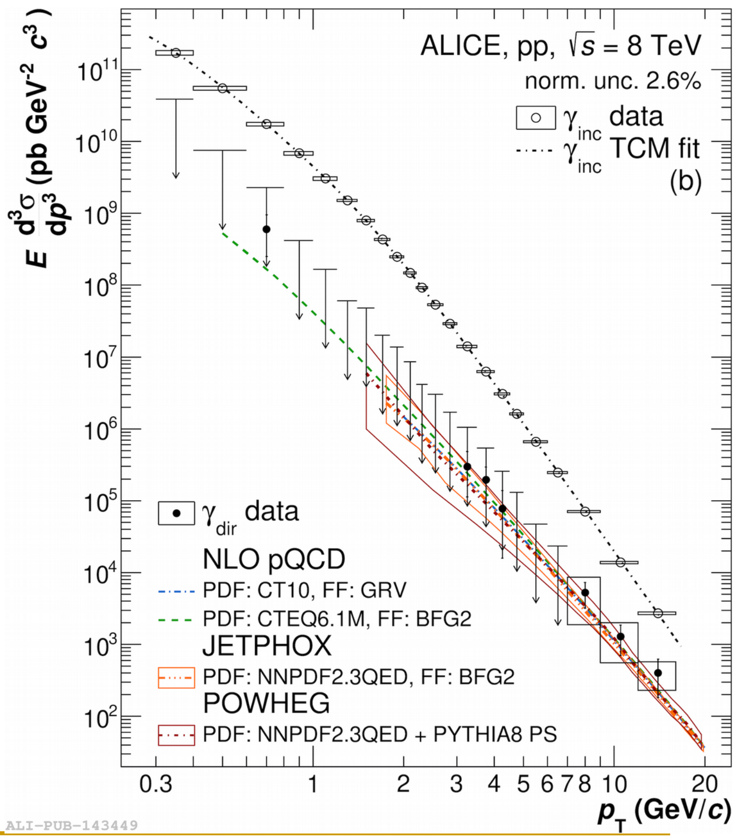
Low-p_T direct photon production in pp collisions is reproduced with NLO calculations

=> Have calibrated baseline

Phys.Rev.D 86 (2012) 072008



Phys. Rev. C 99, 024912 (2019)

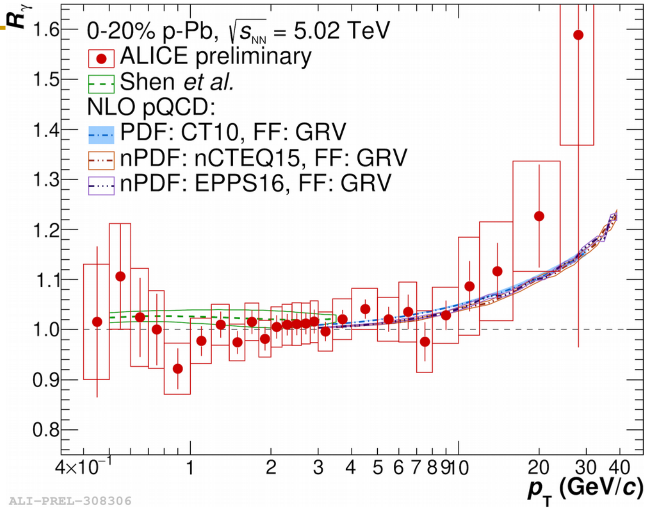


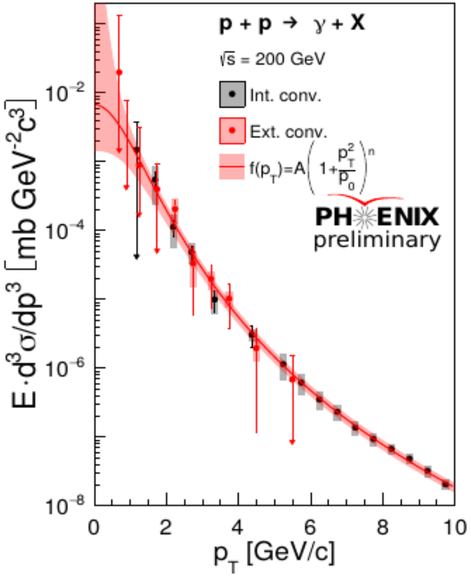
Production in small systems

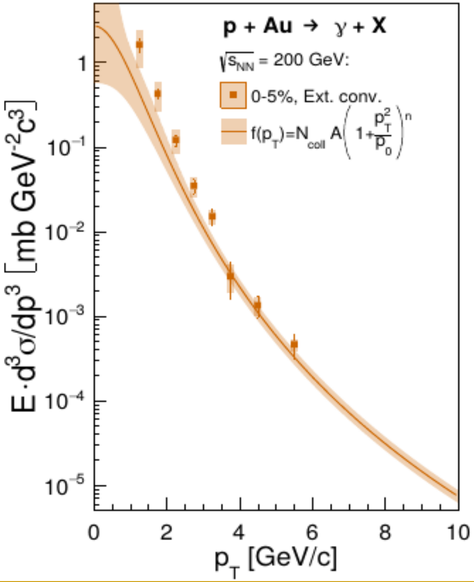
In p+Au collisions with high multiplicity (central) PHENIX observed excess of direct photons at low p_T<4 GeV/c w.r.t. scaled pp

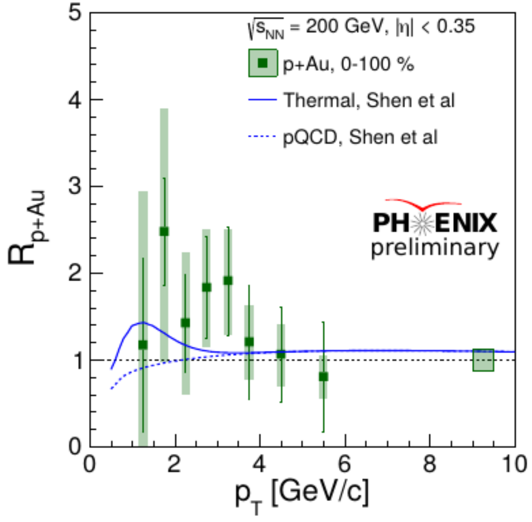
ALICE did not observe excess in p+Pb collisions within uncertainties

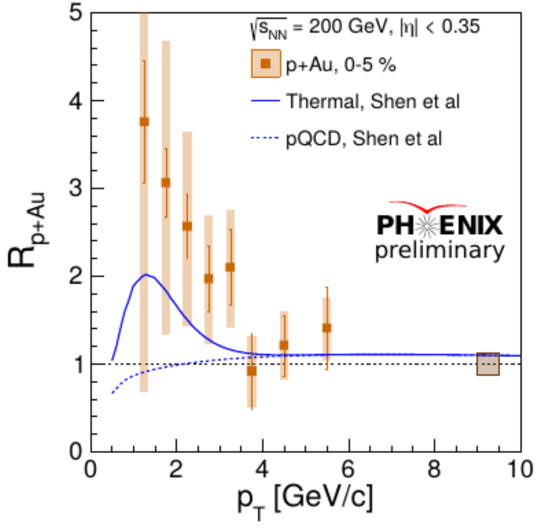
Is it thermal emission or bias to MPI interactions with higher bremstrahlung yield? How to distinguish mechanisms?











PHENIX: V. Khachatryan, J.Phys.Conf.Ser. 1602 (2020) 1, 012015
ALICE: N. Schmidt, PoS HardProbes2018 (2018) 183, e-Print:1812.08104

Direct photon spectrum in AA collisions

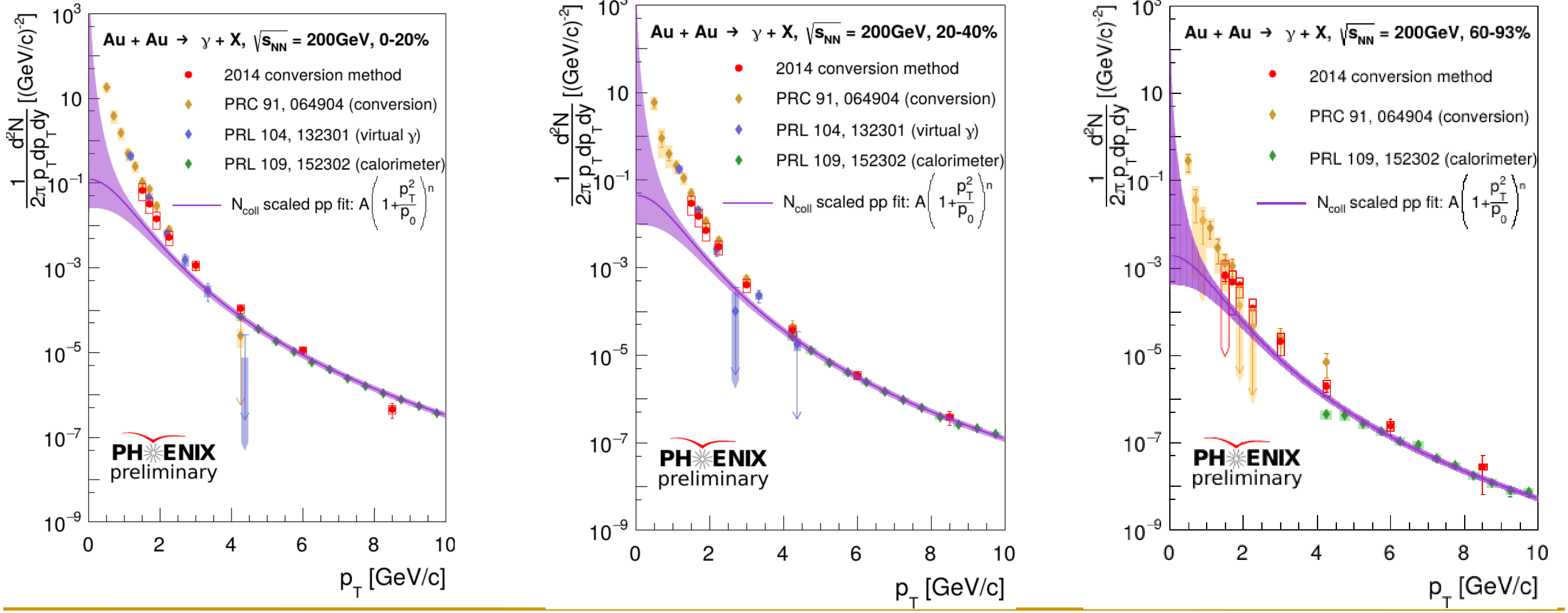
Prompt and thermal photons in AA collisions

At high p_T yield agrees with one in pp scaled with N_{coll}

At low p_T< 3 GeV/c clear excess, larger in central collisions

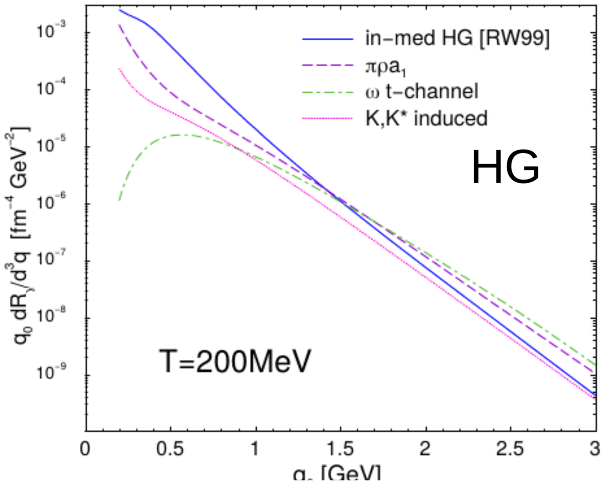
=>thermal radiation

W. Fan,
EPJ Web of Conf. 182, 02041I



Hydrodynamic models

S. Turbide, R. Rapp, and C. Gale, PRC 69(2004) 014903

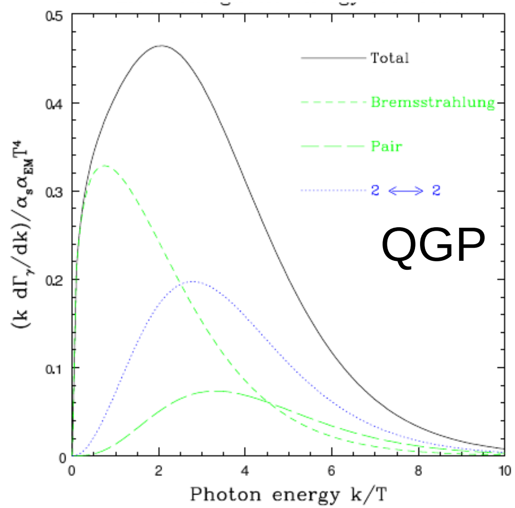


Thermal photon spectrum is integral of emission rate R_γ over space-time occupied by hot matter

$$\frac{d^3 N^{\gamma,therm}}{dyd^2k_T} = \int_\Omega dV\, dt R_\gamma\left(k, T(x), \mu(x), u(x)\right)$$

Hydrodynamic model provides temperature T, baryon chemical potential μ and four-velocity u.

P. Arnold, G. D. Moore, L. G. Yaffe, JHEP12(2001) 009

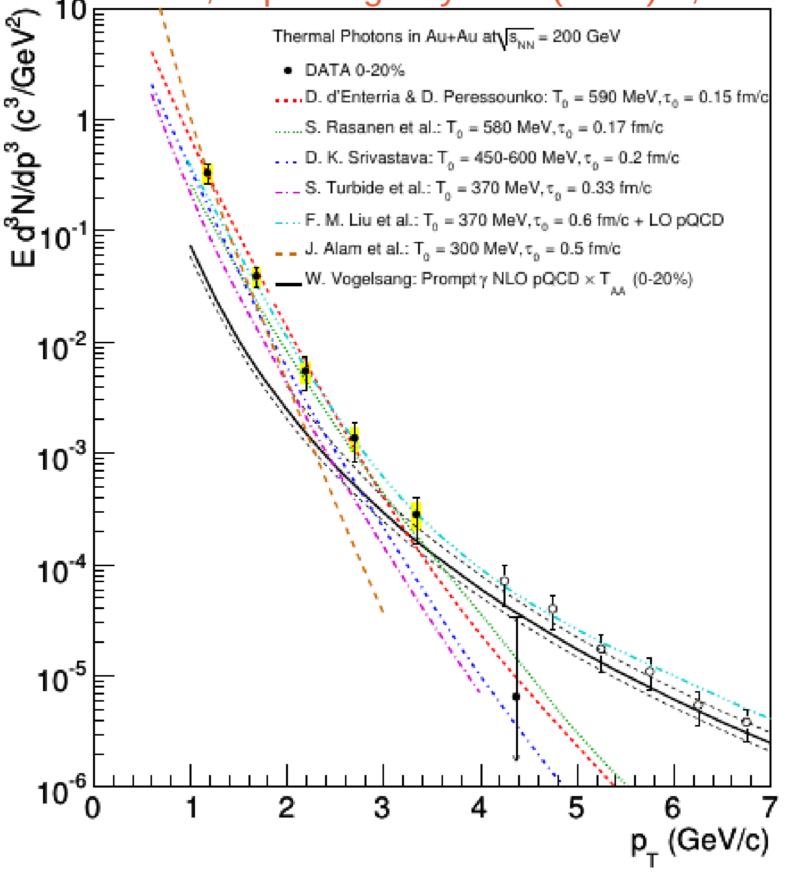


Photon emission rate $$E\frac{dR}{d^3p} = \frac{-2}{(2\pi)^3}\mathrm{Im}\Pi^{R,\mu}_{\mu}\frac{1}{e^{E/T}-1}$$

How photon emission rate behaves close to critical point? Increase as other susceptibilities?
As size of fireball << photon mean free path, thermal photon yield should increase with R_γ

Direct photon spectrum in AA collisions

G. David,Rept.Prog.Phys. 83 (2020) 4, 046301



Final state of hydro model is fixed with final hadron spectra.
No clear way how to choose initial time of hydro evolution => use different speculations.

Thermal photon yield rapidity increase with T (as T^4) => choosing smaller initial time => starting evolution at higher T results in higher thermal photon yield.

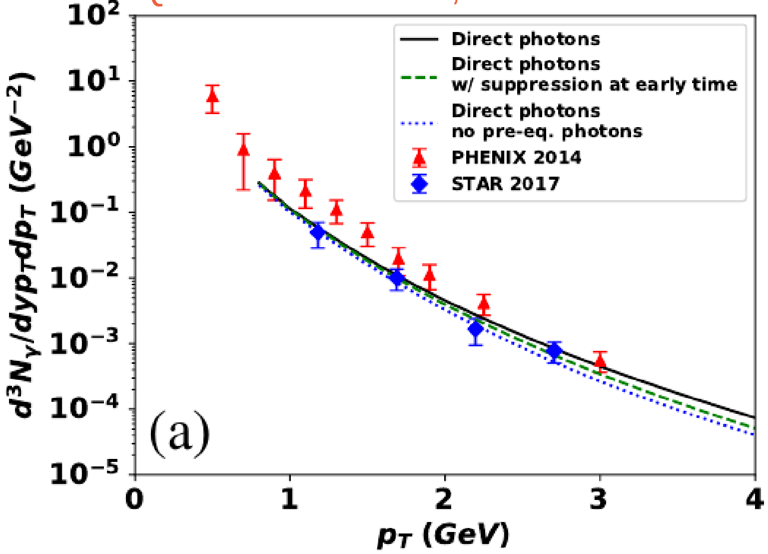
How to choose initial time for hydro evolution?

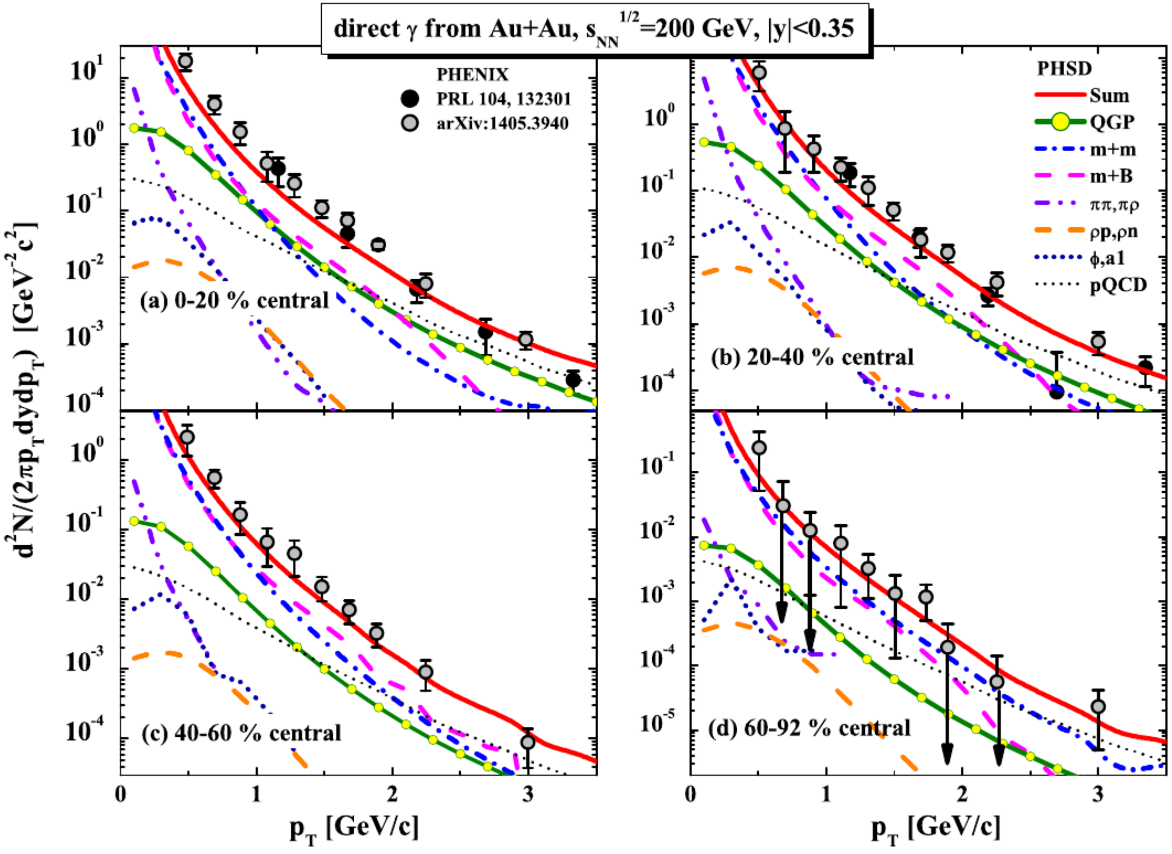
Direct photons at RHIC

O. Linnyk, W. Cassing, E.L. Bratkovskaya
Phys.Rev.C 89 (2014) 3, 034908

Available hydrodynamic and and transport (PHSD) models tuned to reproduce final hadron spectra predict 2-5 times smaller direct photon yield.

C.Gale, J-F. Paquet, B. Schenke, C. Shen, Quark Matter 2019, arxiv 2002.05191



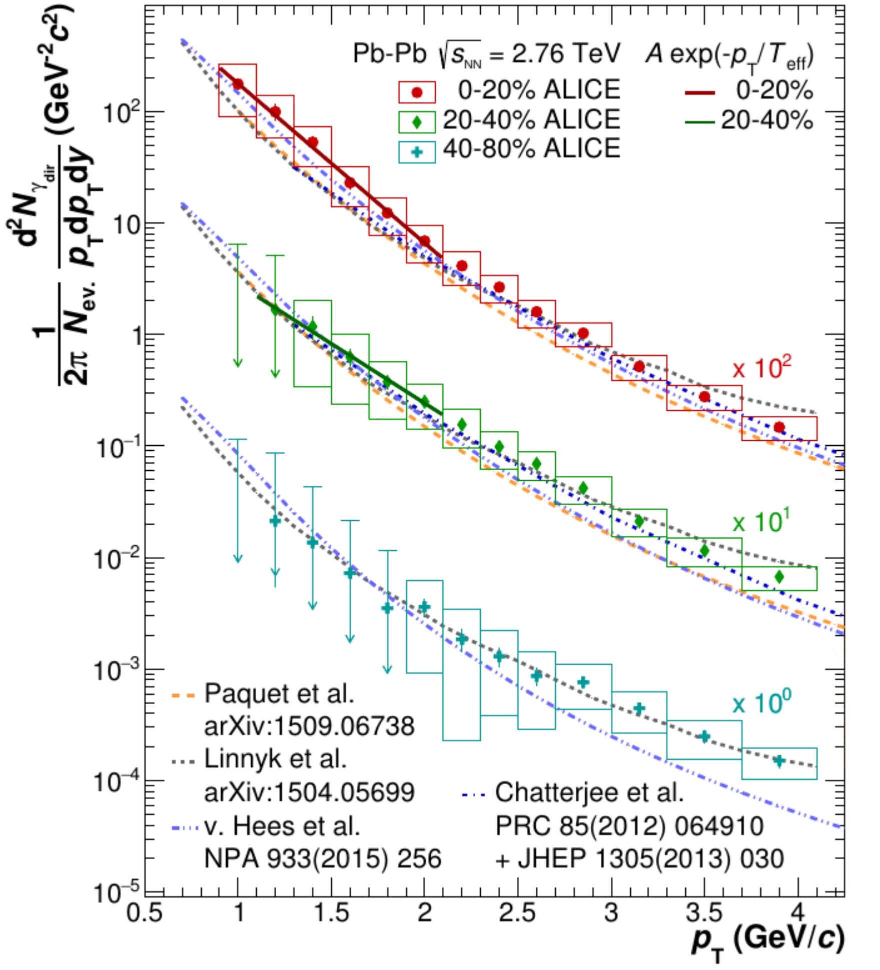


Direct photons at LHC

J. Adam et al., Phys.Lett.B 754 (2016) 235-248

Similar to RHIC energies, hydrodynamic and transport calculations predict smaller yield which, although agree with data within uncertainties.

Do we miss some important source of direct photons?
Do we underestimate emission rates?



Direct photons at low colliding energies

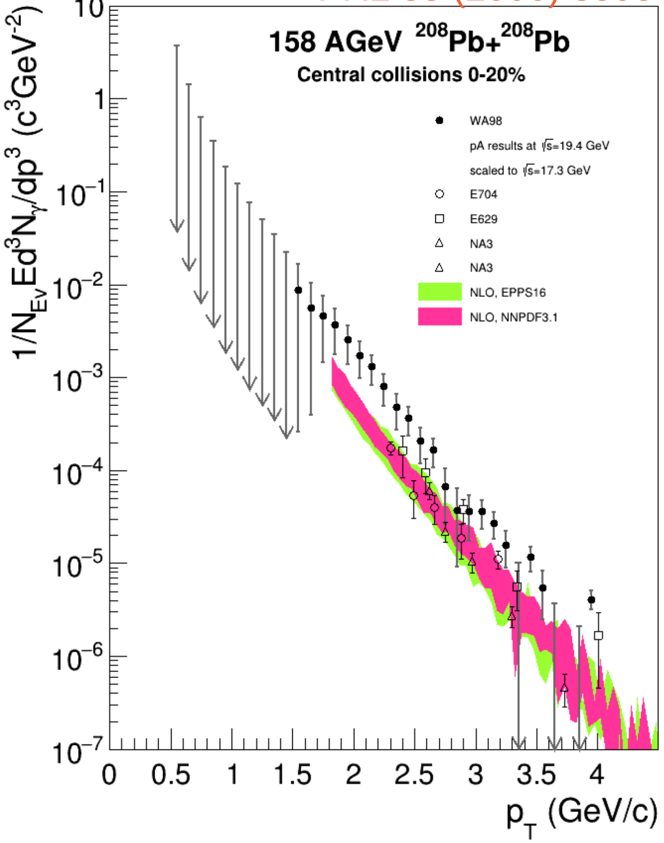
For colliding energies SPS, NICA, FAIR prompt photon contribution do not dominate at high p_T

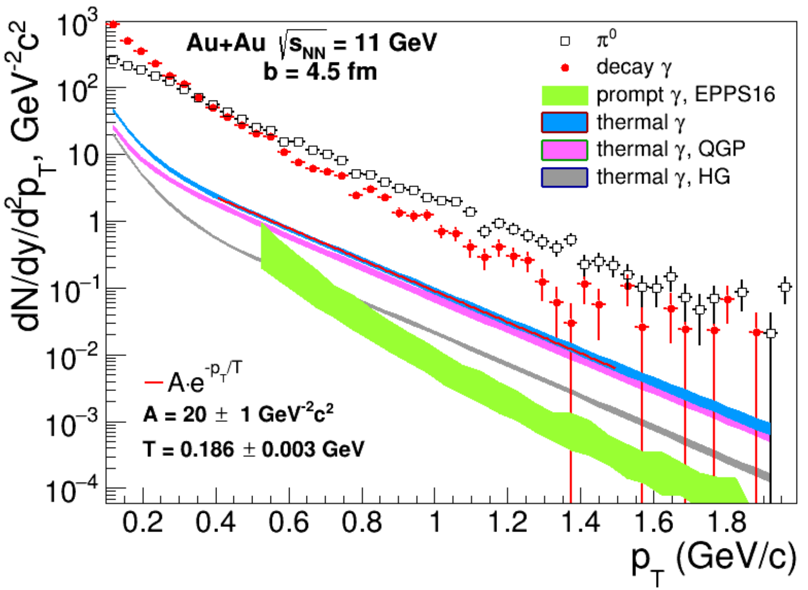
=> Possibility to explore high p_T tail of quark spectrum

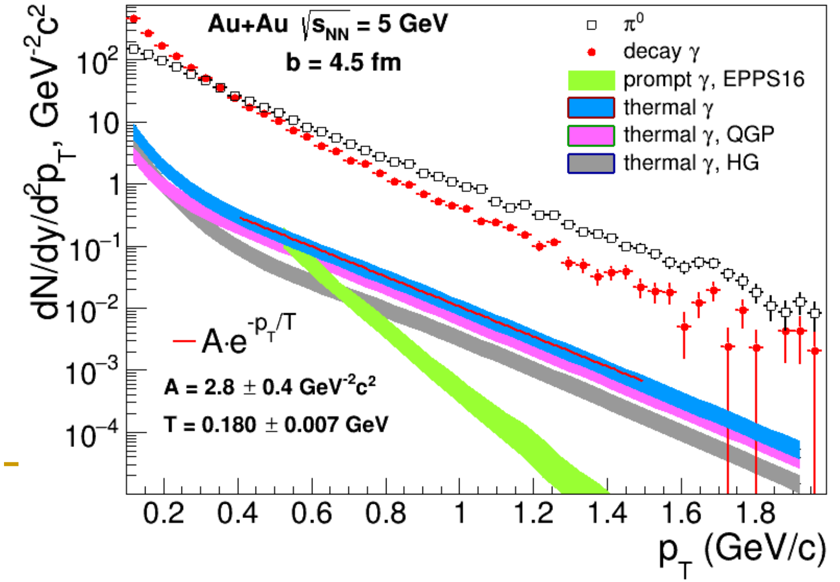
=> To which extend hydro + emission at equilibrium applicable?

=> Use transport approach?

M.M. Aggarwal et al., PRL 85 (2000) 3595



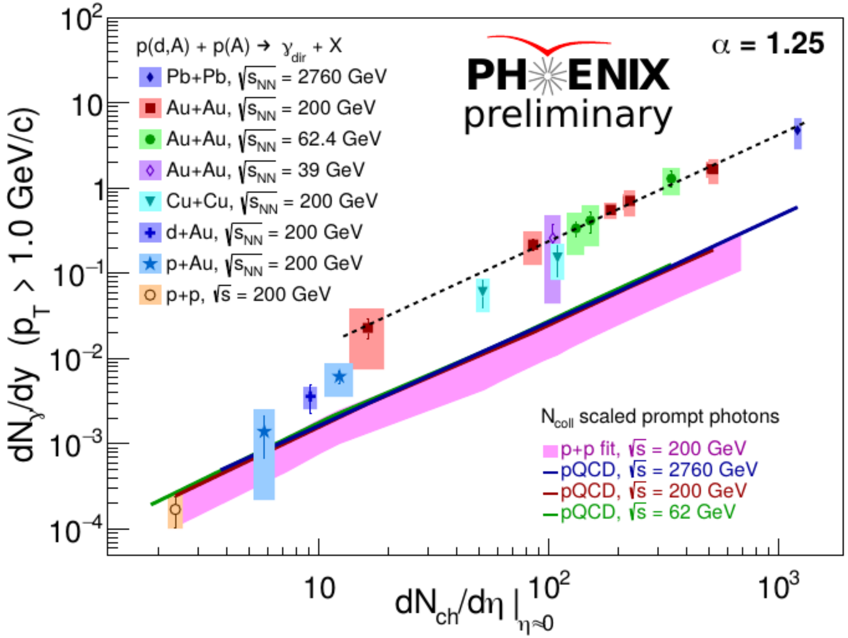


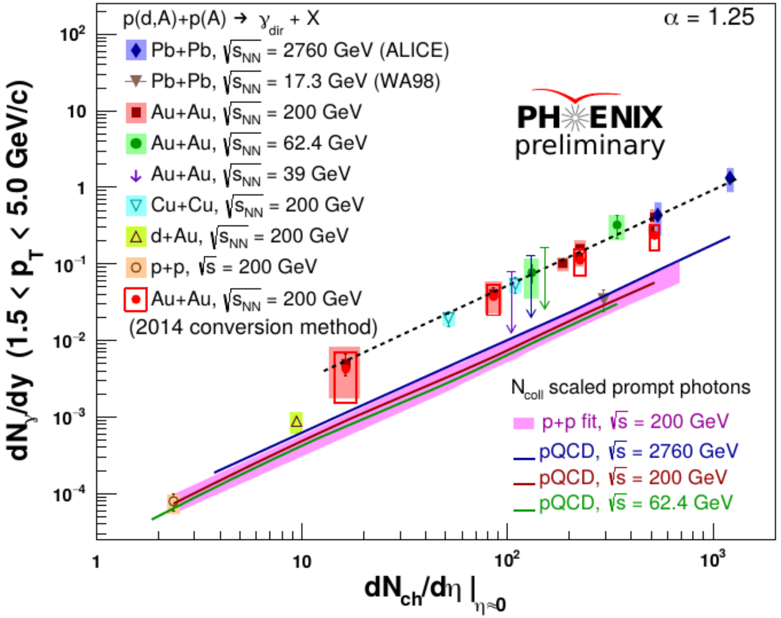


Scaling of direct photon yield

PHENIX observed scaling of direct photon yield with charged particles multiplicity with smooth transition from light to heavy systems

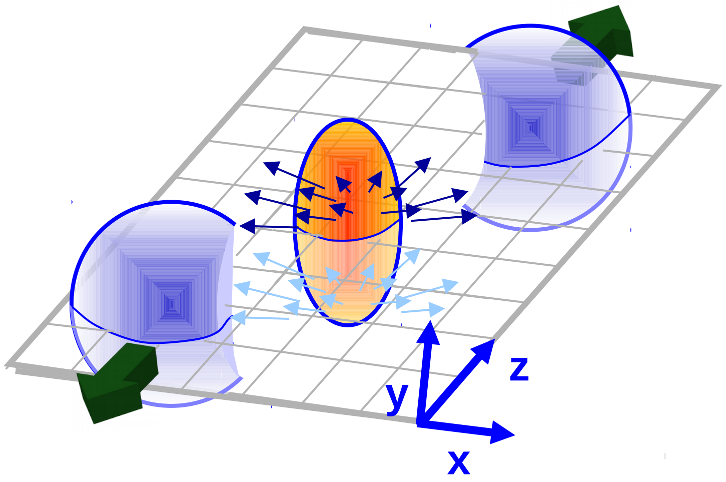
A. Adare et al., PHENIX Collaboration, Phys.Rev.Lett. 123 (2019) 2, 022301, 1805.04084





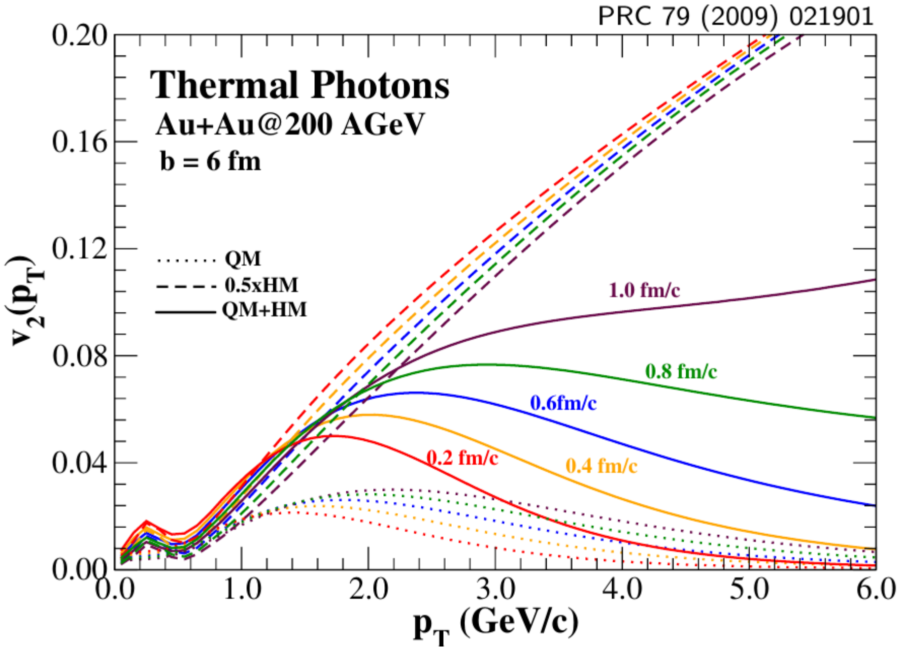
Why STAR and WA98 both measured ~5 times smaller yields?

Direct photon flow in AA collisions



Collective expansion transforms initial spacial asymmetry of fireball to asymmetry in momentum space.

$$\frac{dN}{d\phi}=1+2v_1\cos(\phi-\Psi_{RP})+2v_2\cos[2(\phi-\Psi_{RP})]+2v_3\cos[3(\phi-\Psi_{RP})]+\dots$$



Thermal photons, emitted early from hotter fireball carry smaller collective flow than those, emitted at later stages.

=> one can test development of collective flow with direct photons.

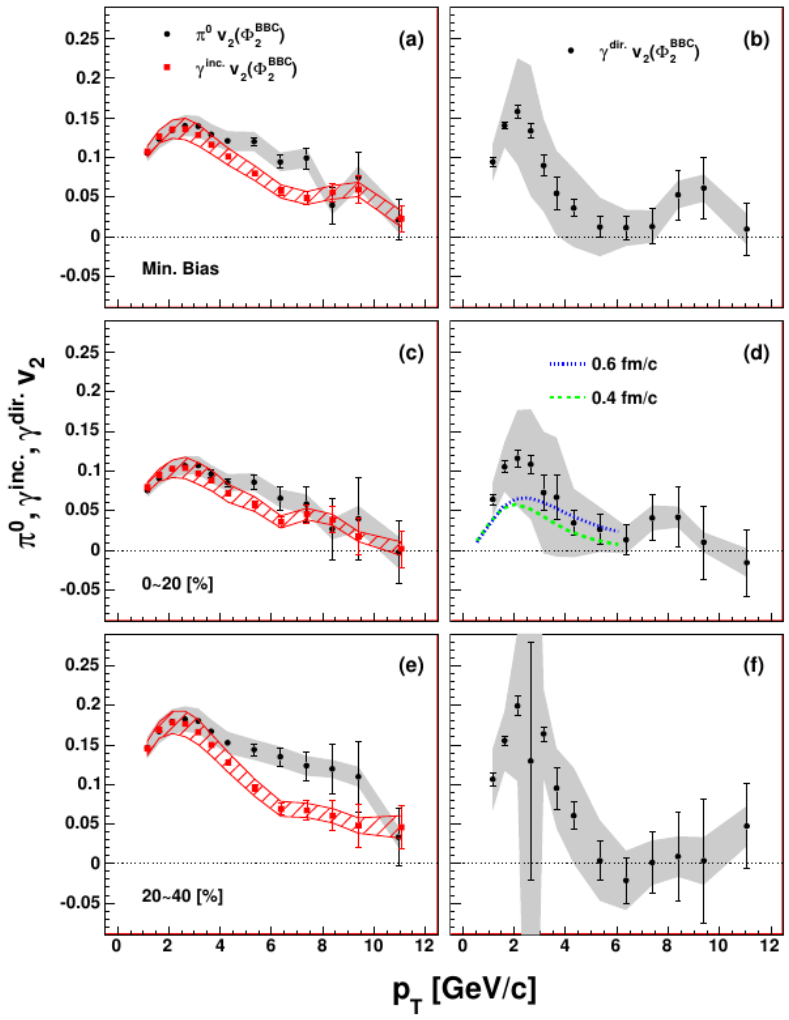
A. Adare et al., PRL 109, 122302

Direct photon flow at RHIC

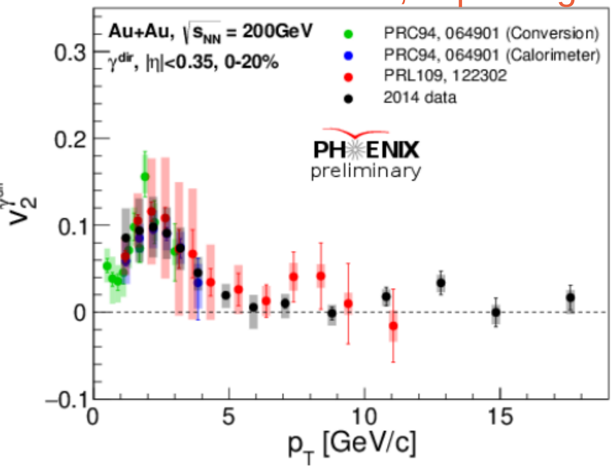
$$v_2^{\gamma,dir} = \frac{R_\gamma v_2^{\gamma,inc} - v_2^{\gamma,dec}}{R_\gamma - 1} \qquad R_\gamma = \frac{N_\gamma^{inc}}{N_\gamma^{dec}}$$

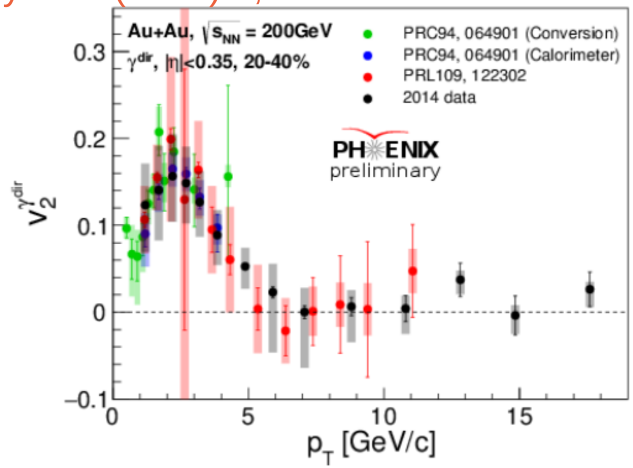
Direct photon flow in Au+Au collisions comparable to flow of decay photons and considerably stronger than predicted by hydro models

Measurements with different methods agree



G. David,Rept.Prog.Phys. 83 (2020) 4, 046301



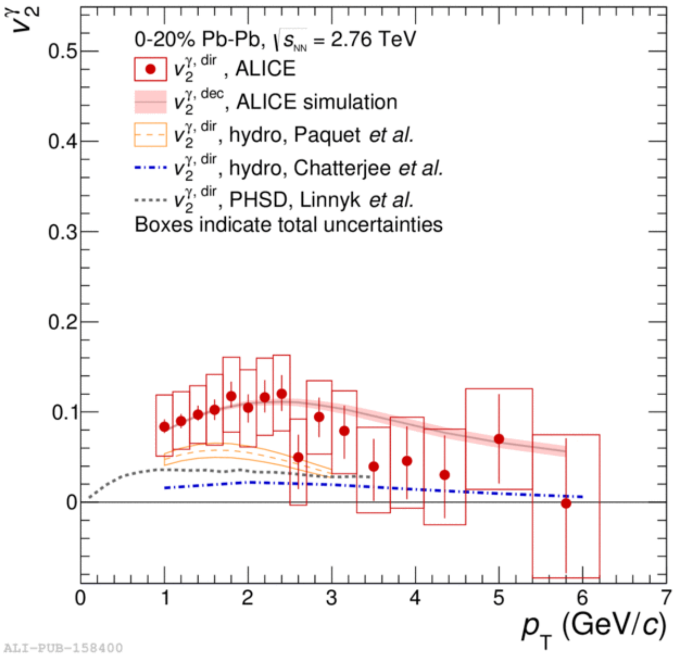


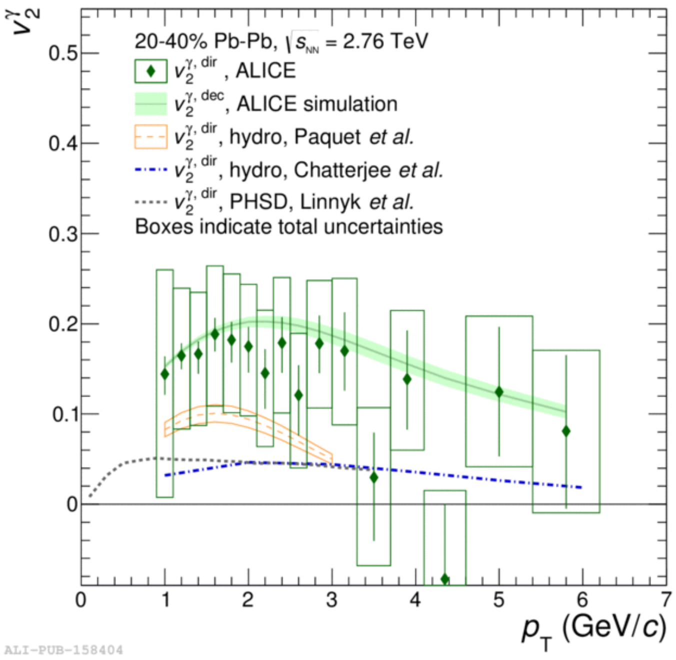
Direct photon flow at LHC

Phys.Lett.B 789 (2019) 308-322

At LHC direct photon v_2 also comparable with v_2 of decay photons at p_T<3 GeV/c

$v_2^{\gamma,dir}$ compatible with $v_2^{\gamma,dir} = 0$ within 1.4(1.0)σ in p_T range ($0.9 < p_T < 2.1$ GeV/c)
No deviation beyond 2σ from theory observed for $v_2^{\gamma,dir}$





Ideas to solve direct photon flow puzzle (1)

Suppress emission at the early stage of collision

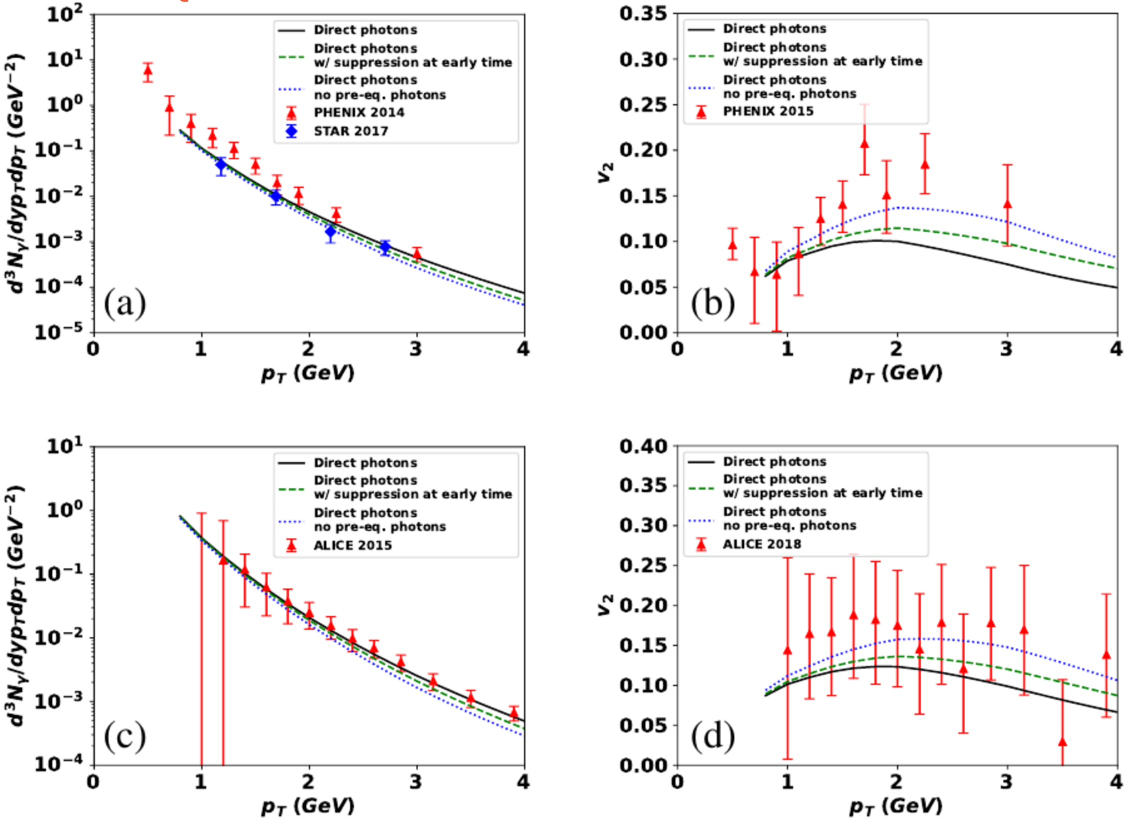
Akihiko Monnai, Phys. Rev. C90, 021901 (2014),arXiv:1403.4225

C. Gale, Y. Hidaka, Sangyong Jeon, S. Lin, J.-F. Paquet, R.D. Pisarski, D. Satow, V.V. Skokov, and G.Vujanovic, Phys. Rev. Lett. 114, 072301 (2015), arXiv:1409.4778

C.Gale, J-F. Paquet, B. Schenke, C. Shen, Quark Matter 2019, arxiv 2002.05191

Further reduce total photon yield, increasing discrepancy with measured spectra

C.Gale, J-F. Paquet, B. Schenke, C. Shen, Quark Matter 2019, arxiv 2002.05191



Ideas to solve direct photon flow puzzle (2)

Photon emission in the presence of strong magnetic field

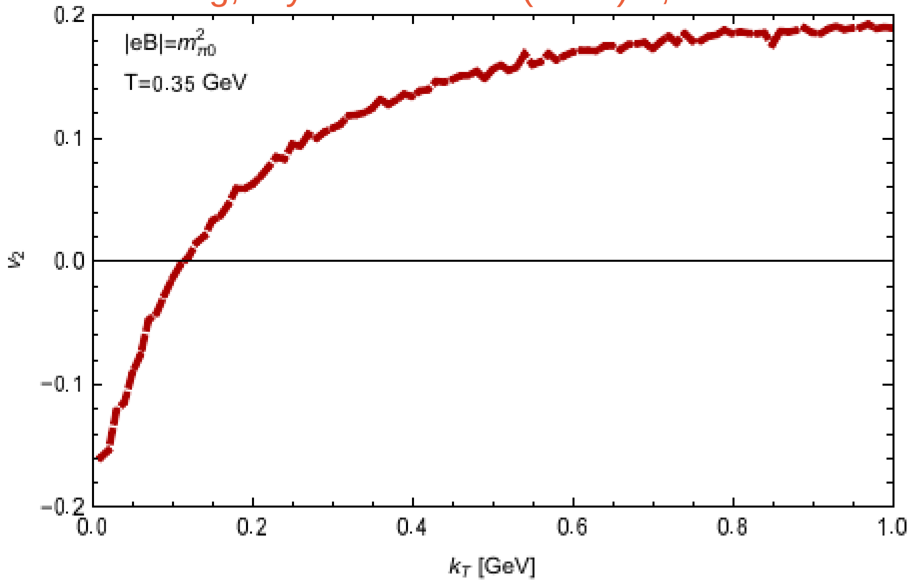
G. Basar, D. Kharzeev and V. Skokov, Phys. Rev. Lett. 109, 202303 (2012), arXiv:1206.1334

A. Bzdak and V. Skokov, Phys. Rev. Lett. 110, 192301 (2013), arXiv:1208.5502

X. Wang, I.A. Shovkovy, L. Yu, M. Huang,Phys.Rev.D 102 (2020) 7, 076010

How to explain large value of v_3?

X. Wang, I.A. Shovkovy, L. Yu, M. Huang,Phys.Rev.D 102 (2020) 7, 076010

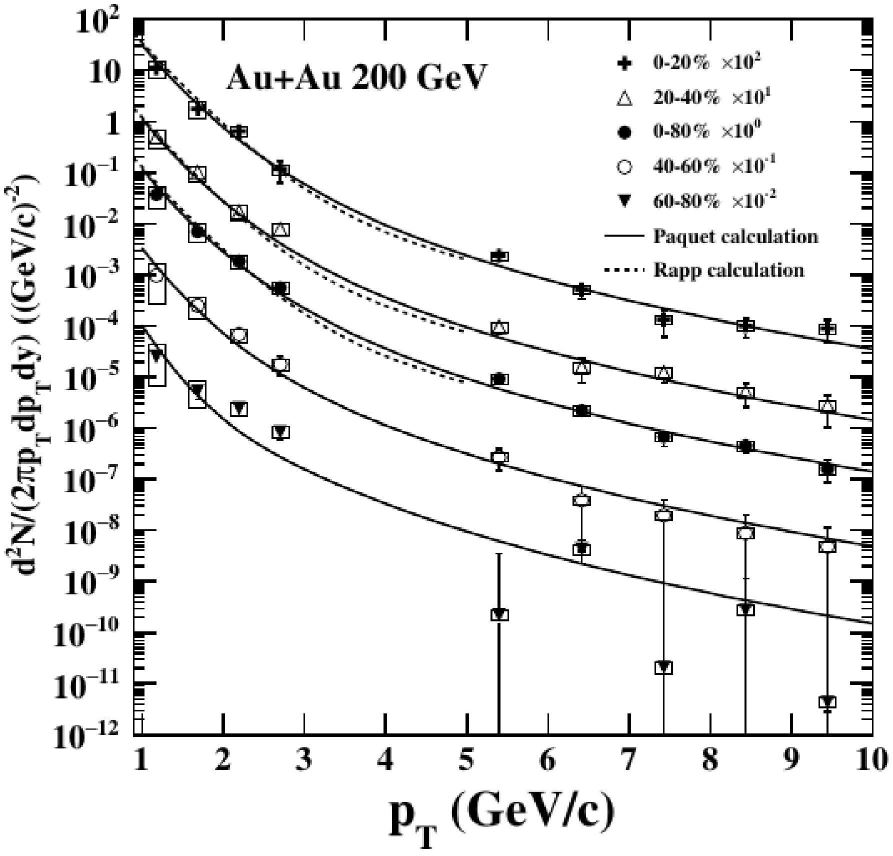


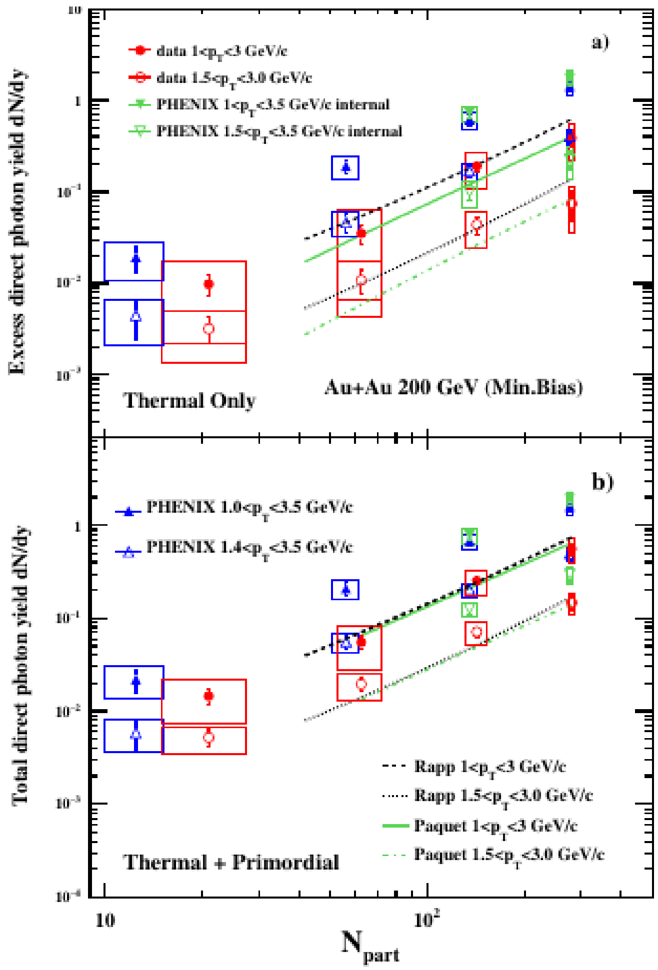
Questions (instead of conclusions)

- Do we have excess of direct photons in high-multiplicity pA collisions? If yes:
  - Is it thermal radiation, bias to MPI processes, anything else?
  - What is expected baseline of prompt photons in AA collisions?
- Hydrodynamic and transport models predict 2-5 times smaller thermal photon yield. What could be the reason?
- How thermal photon emission rate (related to conductivity) change in vicinity of critical point? Should we expect thermal photon flush?
- Low energy AA collisions probably provide possibility to explore high-p_T part of thermal photon spectrum p_T>5-10 T
  - What it proper approach to describe photon spectrum?
  - Access to momentum distribution of quarks in hot matter?
- Collective flow puzzle
  - Absence of emission at initial stages (a-la glasma): further decrease yield, increasing discrepancy with data
  - Synchrotron radiation: how to explain large v_3?

Dedicated experiment for direct photon measurement (small material of inner detectors with known material budget, high granularity and good resolution calorimeter) is highly appreciated

STAR vs PHENIX



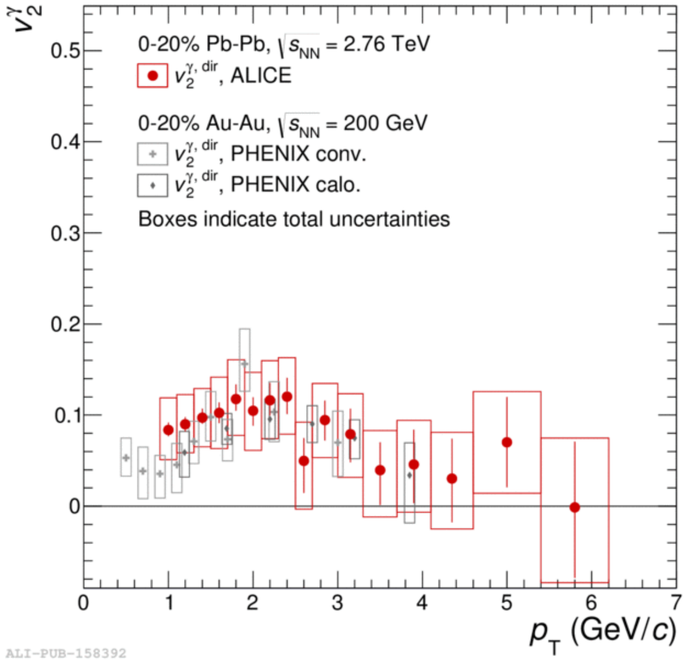


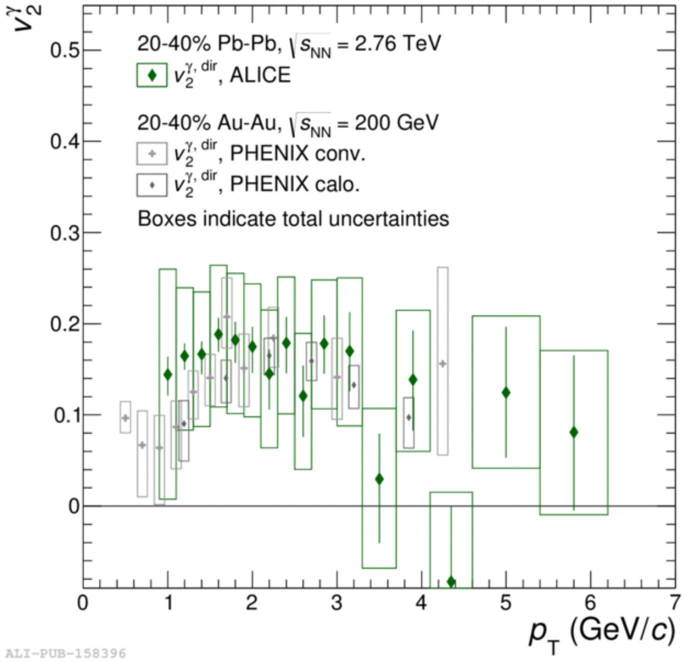
L. Adamczyk et al. (STAR),Phys. Lett. B770, 451–458 (2017)

Comparison with direct photon flow at RHIC and LHC

Phys.Lett.B 789 (2019) 308-322

$$\left(v_2^{\gamma,dir}\right)_{LHC} \approx \left(v_2^{\gamma,dir}\right)_{RHIC}$$





Inclusive photon flow