Recent results on direct photon and low mass dilepton production

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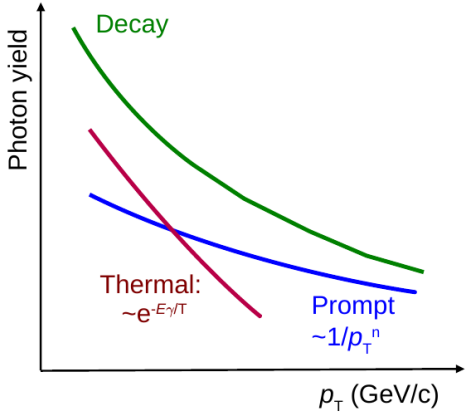
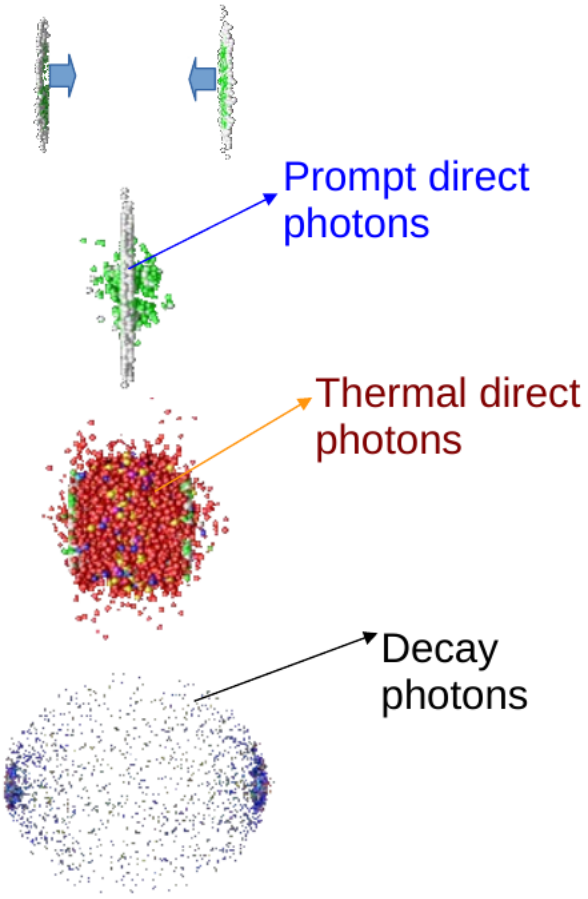
Photon classification

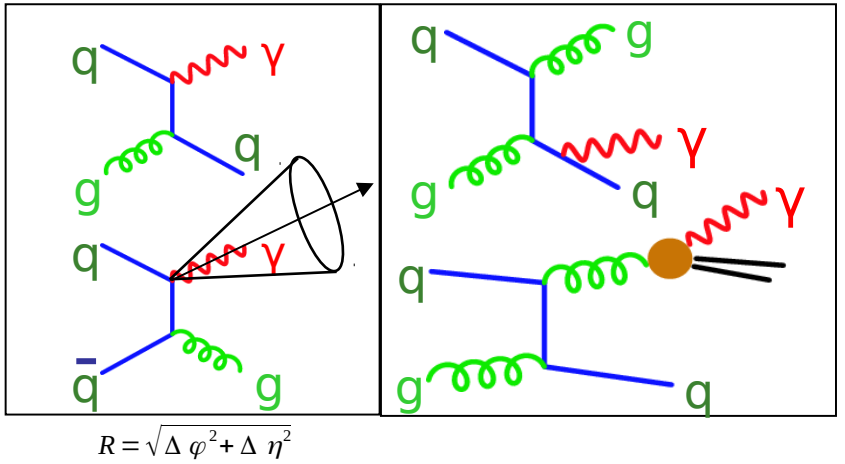
- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
  - Prompt direct photons: ones from interaction of incoming nucleons
  - Thermal direct photons: thermal radiation of hot matter
- Decay photons: photons from decays of final hadrons





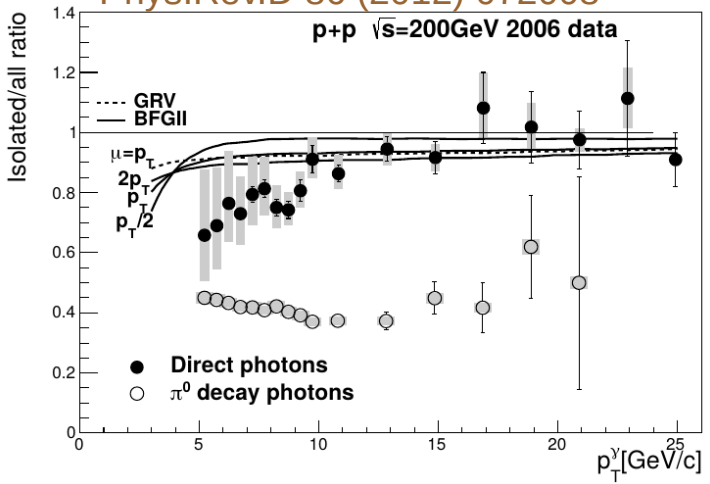
Isolated and direct photons

- **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 identified event-by-event



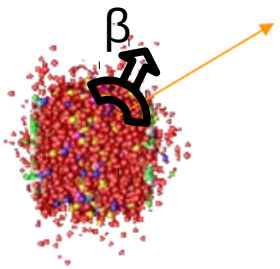
$R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$

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

Real and virtual photons



$$E_\gamma \frac{d^3N_\gamma}{d^3p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}$$

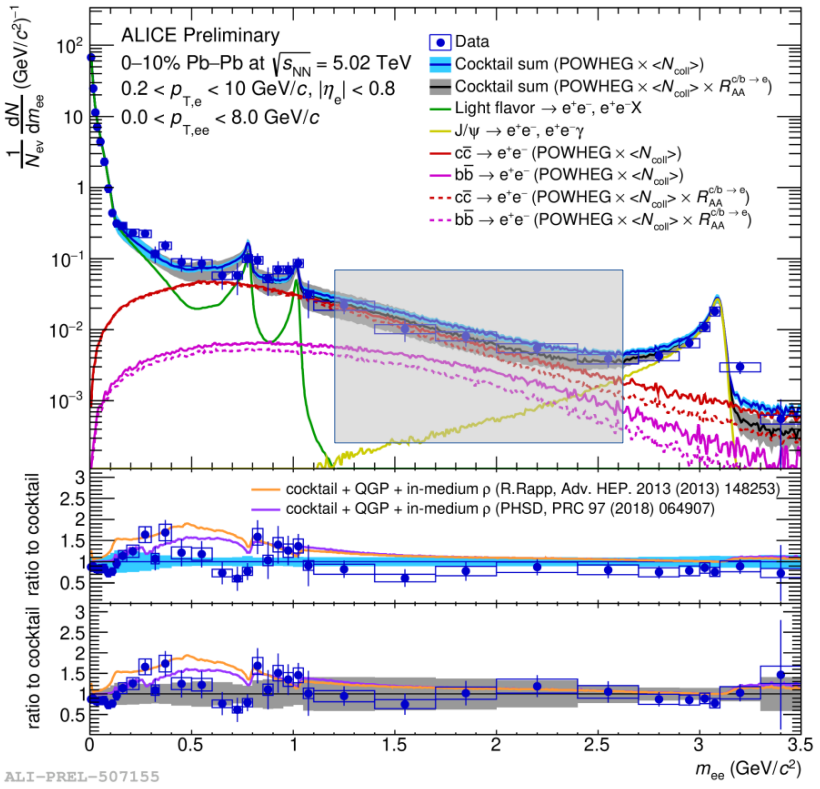
$$T_{\text{eff}} = \sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}} \times T$$

Real photons:

- Thermal contribution significant at p_T<3-5 GeV/c
- Slope strongly affected by collective flow
- Integrate contributions from pre-equilibrium phase till hadronic gas freeze-out

Virtual photons:

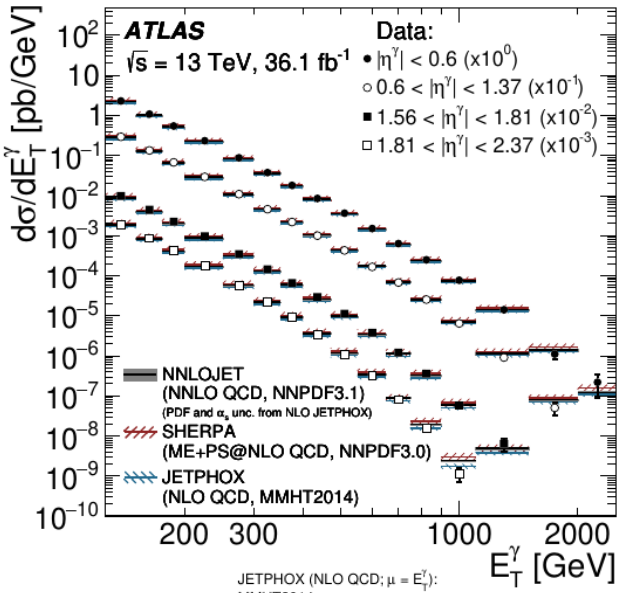
- Intermediate mass region provides true temperature
- May contain pre-equlibrium contribution

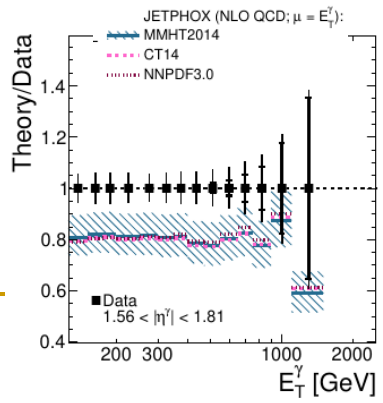


$$\frac{dN}{dM_{ee}} \propto (M_{ee}\,T)^{3/2} e^{-M_{ee}/T}$$

Prompt photons

ATLAS: JHEP2019, 203 (2019)



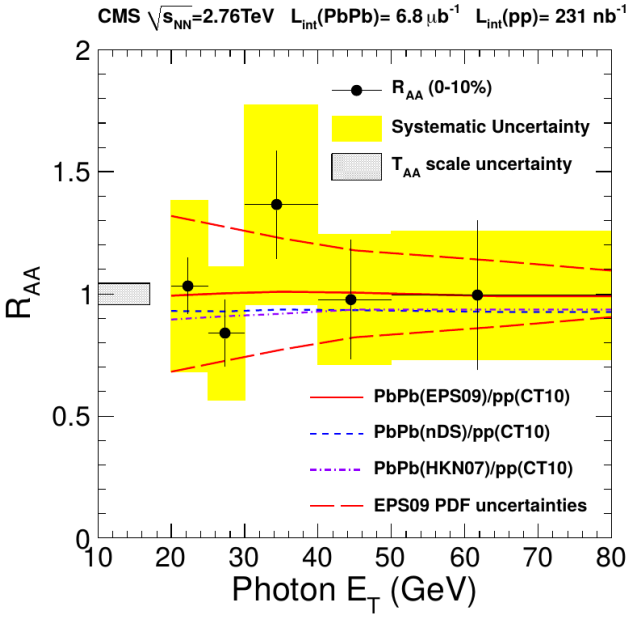


Prompt photon contribution: high-p_T part of the spectrum is reproduced with NLO calculations with ~10% accuracy in pp collisions
AA collisions: pp with nPDF and Glauber model

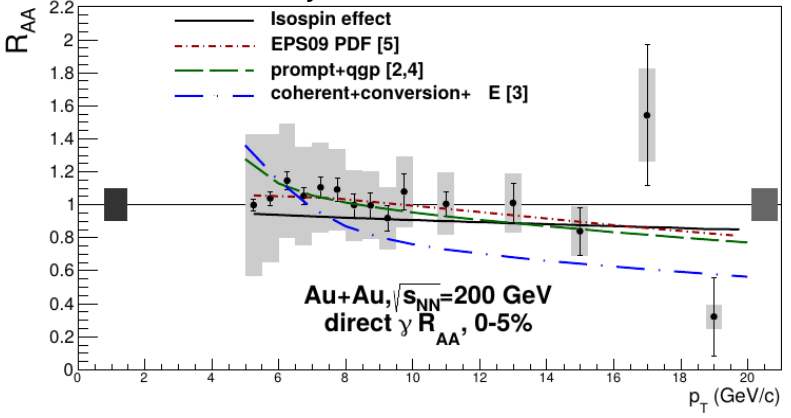
pp:input for PDF global fits

AA: control of initial state, input for nPDF

CMS: Phys.Lett.B 710 (2012) 256



PHENIX: Phys. Rev. Lett. 109 152302

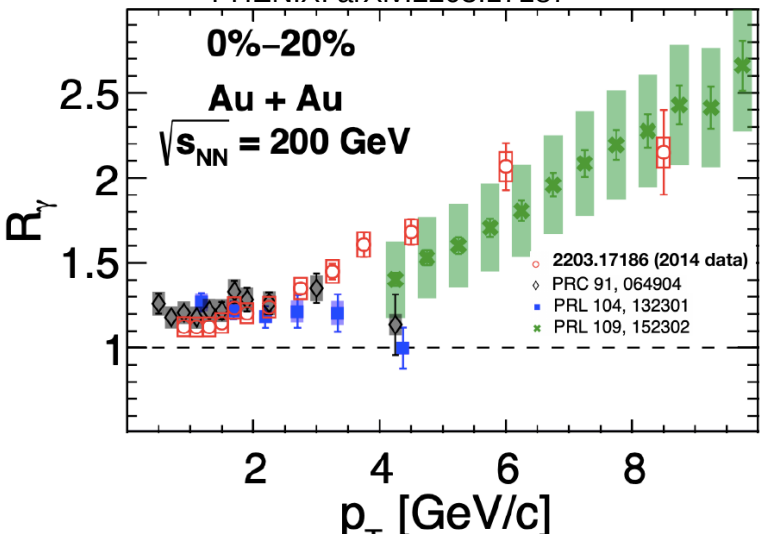


Thermal photon spectrum

Subtract prompt photon contribution using (extrapolated) spectrum in pp at same energy

Good agreement between different methods (statistical subtraction, tagging, photons in calorimeter, converted photons, internal conversion)

PHENIX: arXiv:2203.17187



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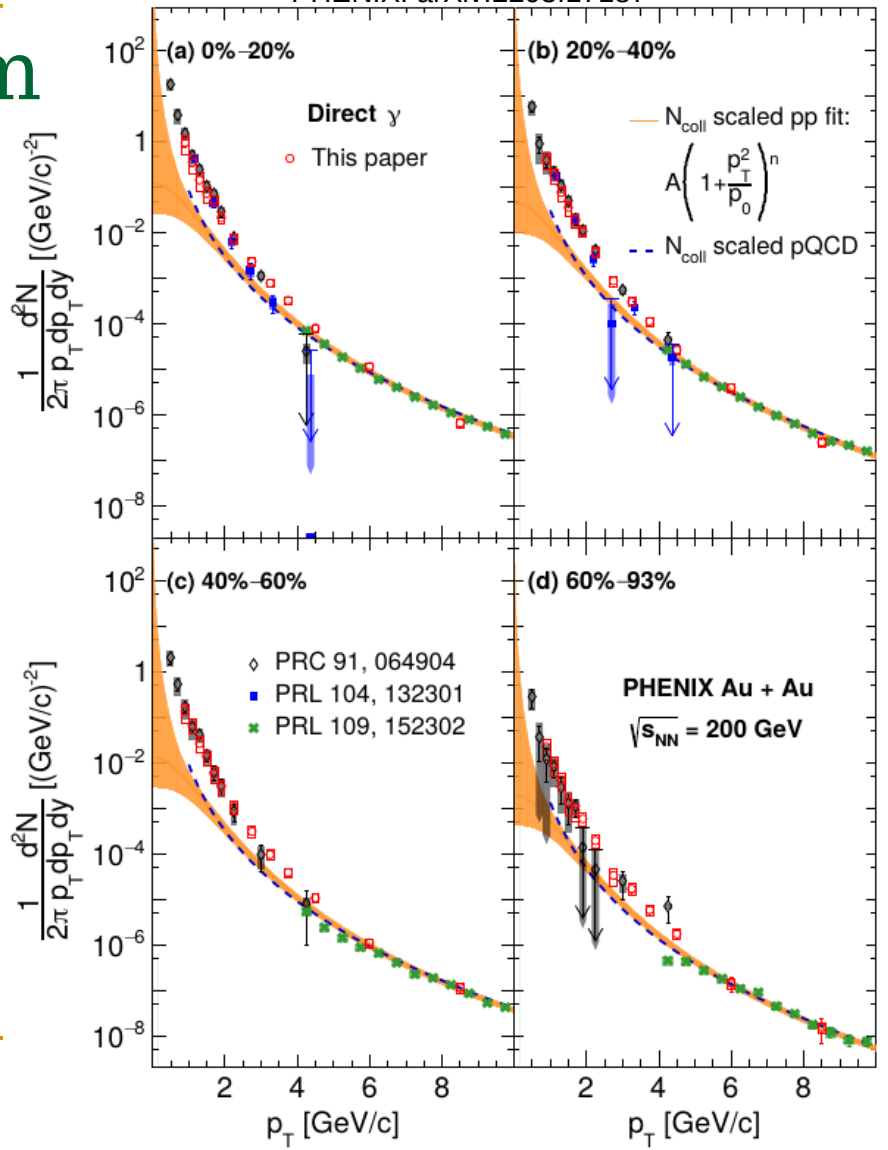
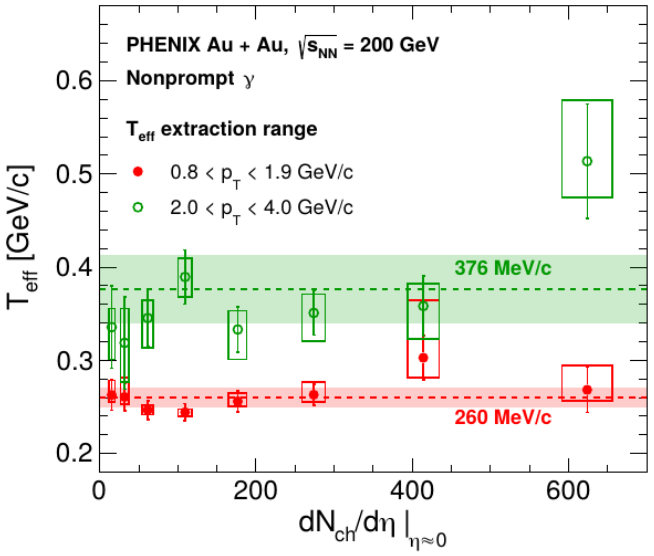


Centrality dependence of slope and yield

- Fit (subtracted) thermal photon spectrum in 2 p_T ranges
  - Lower p_T range provides smaller "Temperature"
  - No significant centrality dependence.

PHENIX: arXiv:2203.17187



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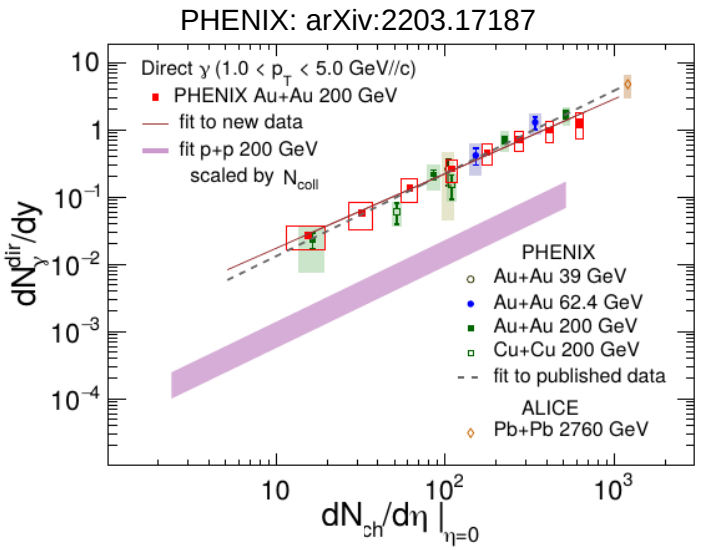


$$\frac{dN_\gamma}{dy} = \int_{p_{T,\min}}^{p_{T,\max}} \frac{dN_\gamma^{\mathrm{dir}}}{dp_T dy} dp_T = A \times \left(\frac{dN_{\mathrm{ch}}}{d\eta}\right)^{\alpha}$$

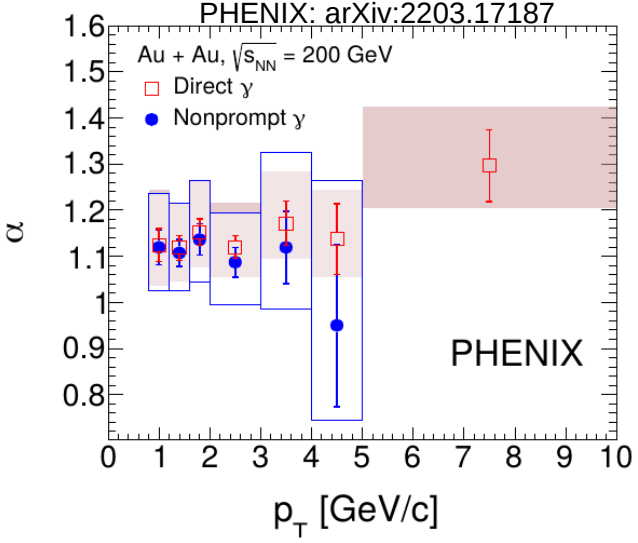
Scaling of direct photon yields in different p_T

- p_T < 2 GeV/c: similar scaling from 39 GeV to 2.76 TeV
- p_T > 2 GeV/c: different at 2.76 TeV (~30% higher)
- α is independent of p_T

Comparison to theory

$$\frac{dN_\gamma}{dy} = A(p_T)\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha(p_T)}$$

PHENIX: arXiv:2203.17187

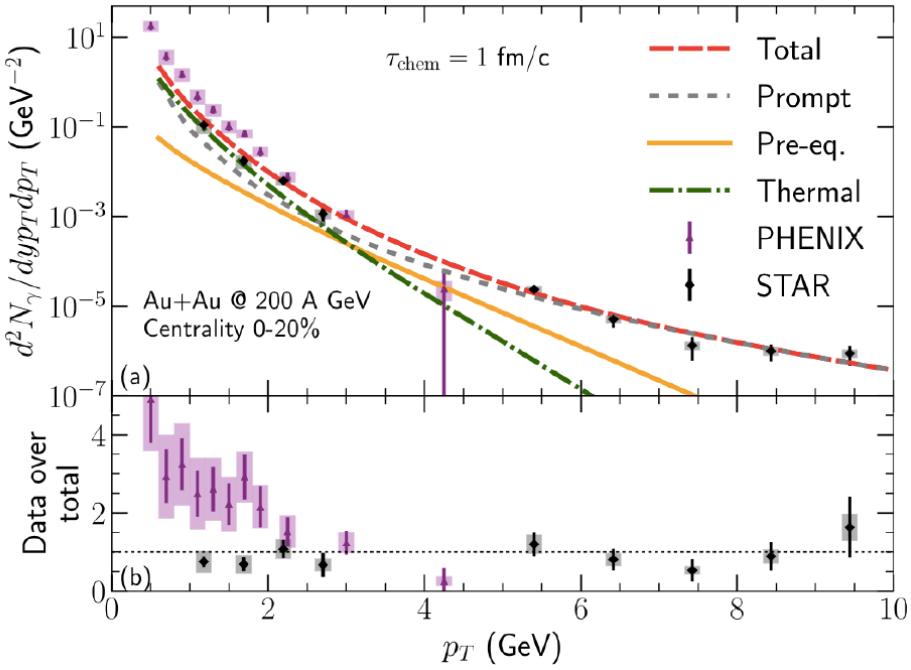


Shen, Heinz, Paquet, Gale, PRC 89, 044910 (2014)

HG	QGP	pQCD
$\alpha_{HG} \approx 1.23$	$\alpha_{QGP} \approx 1.83$	$\alpha_{pQCD} \approx 1.25$

relative contribution varies with p_T

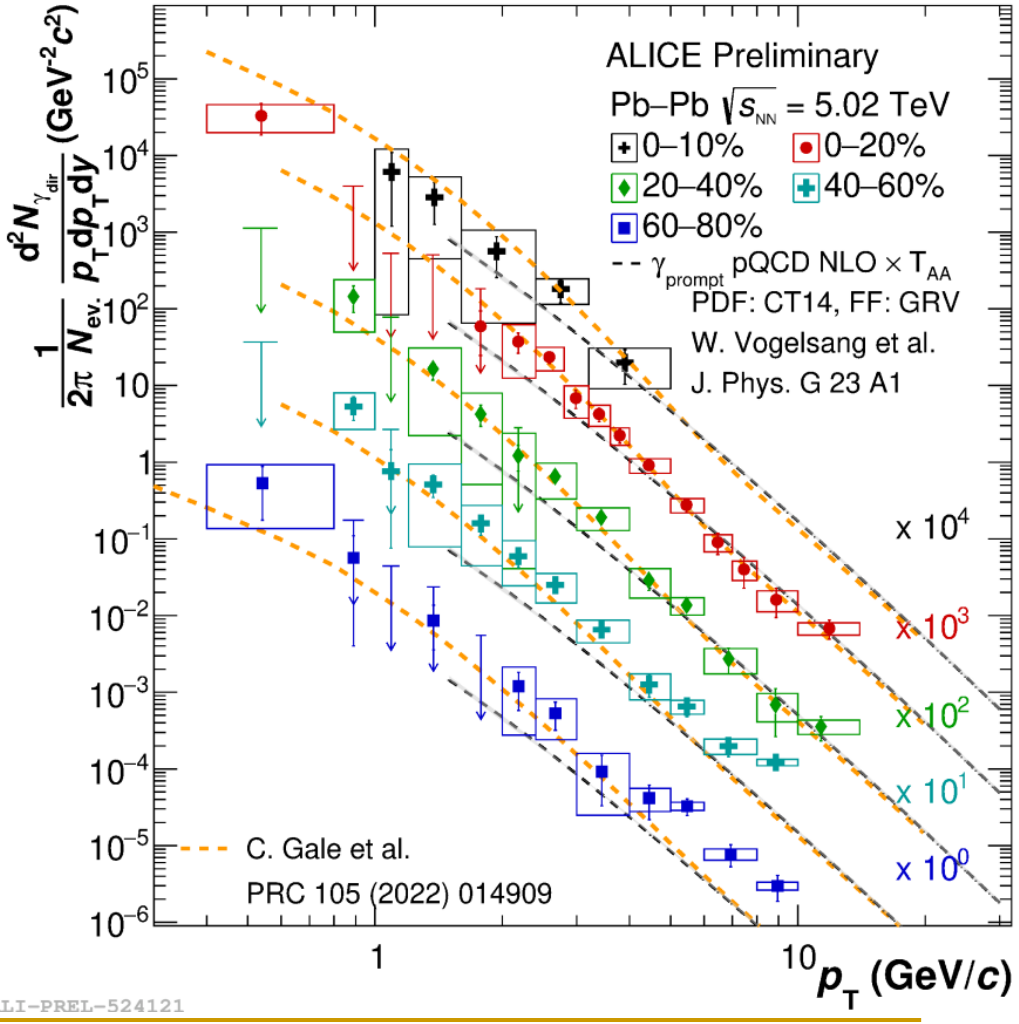
C. Gale, J-F. Paquet, B. Schenke, C. Shen
Phys.Rev.C 105 (2022) 1, 014909



- PHENIX: yield for $p_T < 2$ GeV/c factor 2–4 above model predictions
- STAR: consistent with theory predictions
- Discrepancy between PHENIX and STAR

Direct photons at LHC

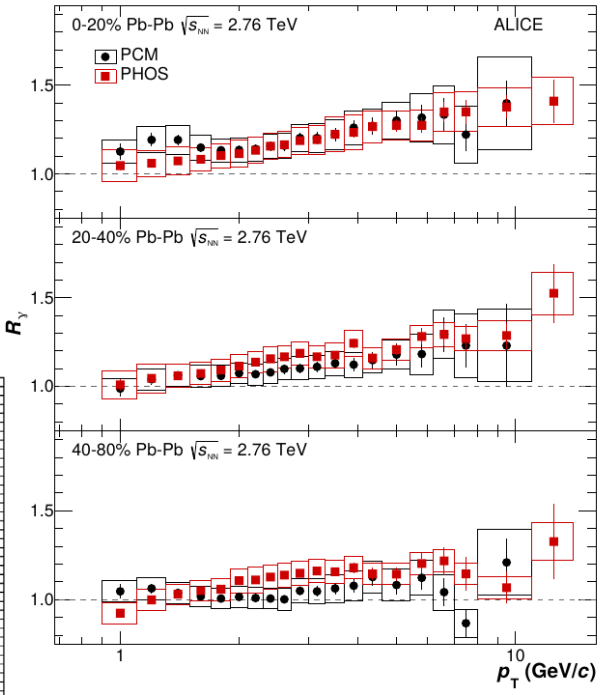
- First measurement of direct photons in Pb-Pb at 5.02 TeV
- Virtual photon method 0-10%
- Real photons with conversion reconstruction (other centralities)
- High p_T: prompt photons consistent with pQCD expectation
- Low p_T: data consistent with model containing in prompt and thermal photons

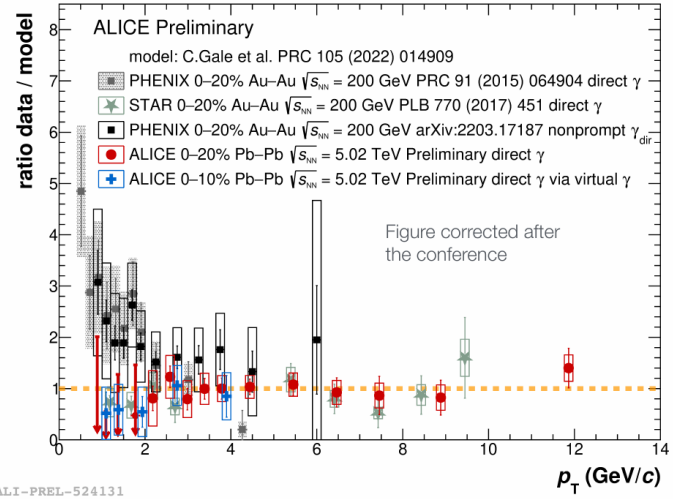


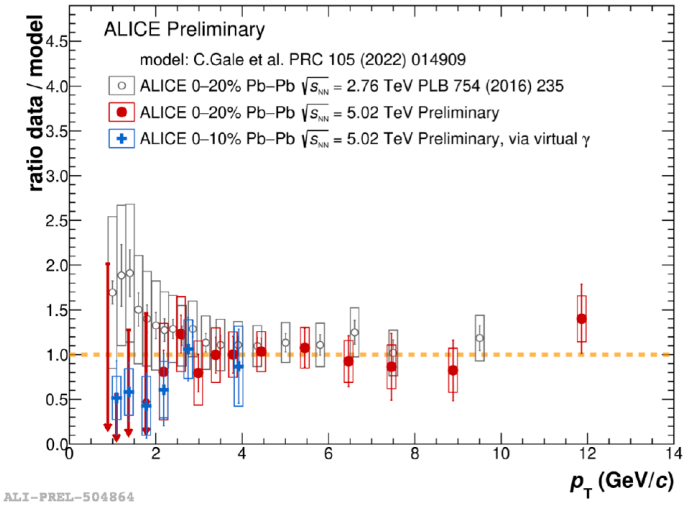
LHC: comparison to theory

- New ALICE 5.02 data consistent with theory predictions
- Conversion method now uses self-normalized material budget estimate

ALICE, Phys.Lett.B 754 (2016) 235

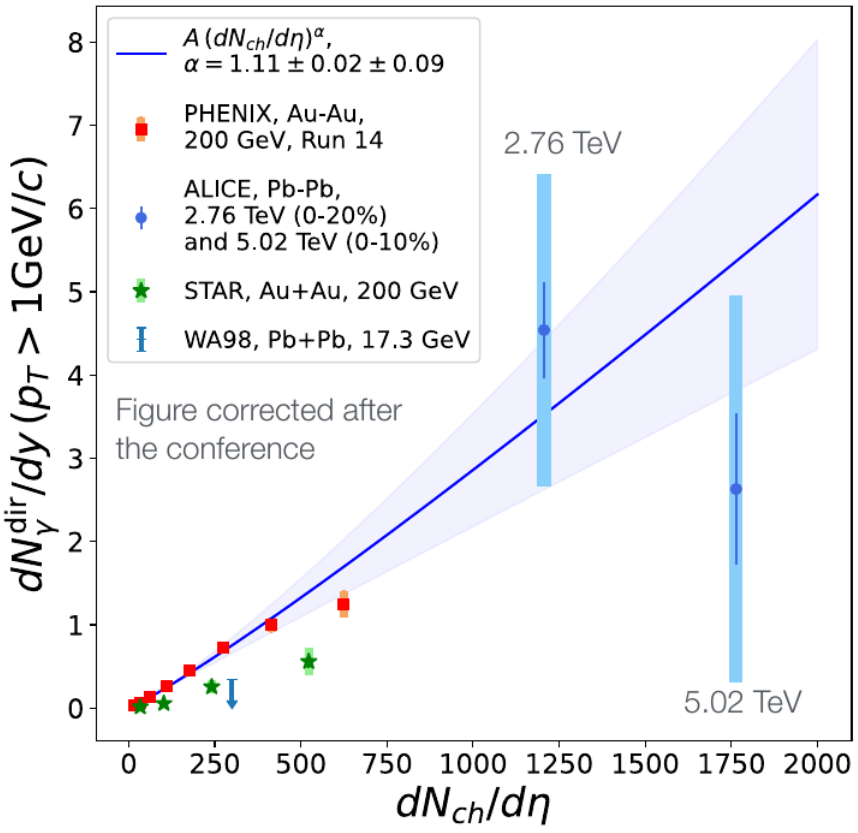






Scaling with charged multiplicity

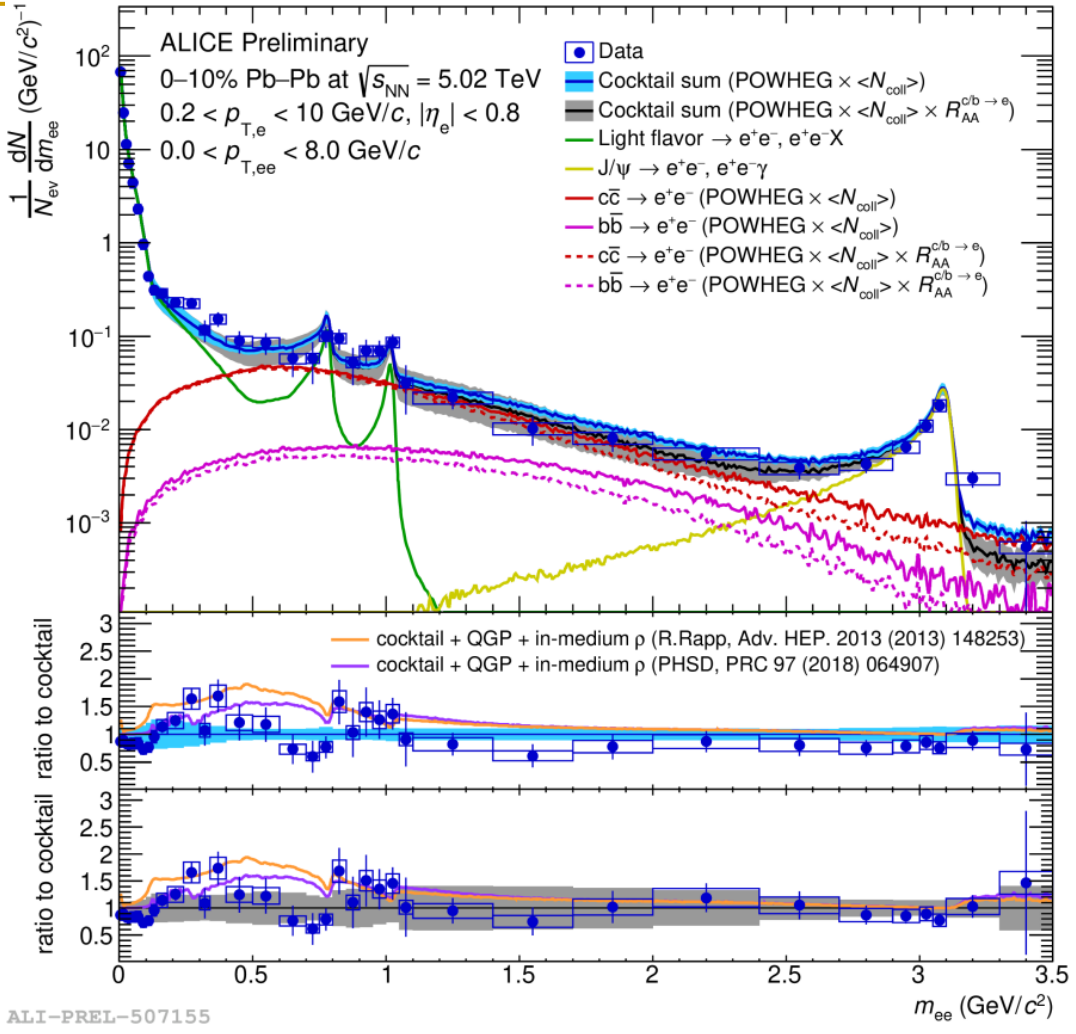
K.Reygers, 2212.01220



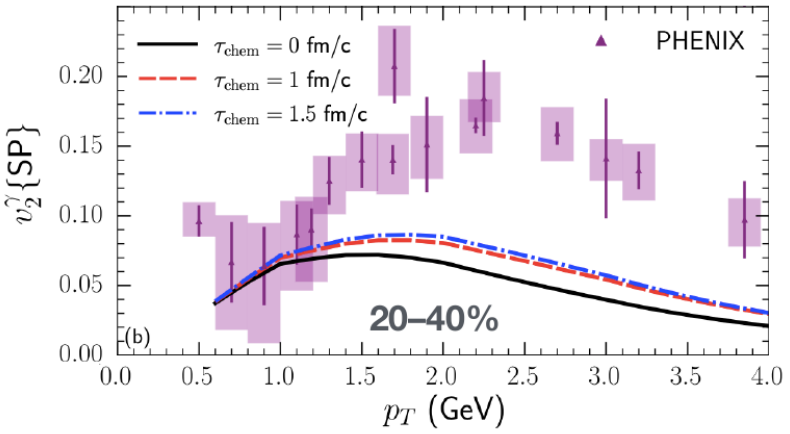
- New ALICE data consistent both with PHENIX extrapolation
- Also consistent with STAR extrapolation

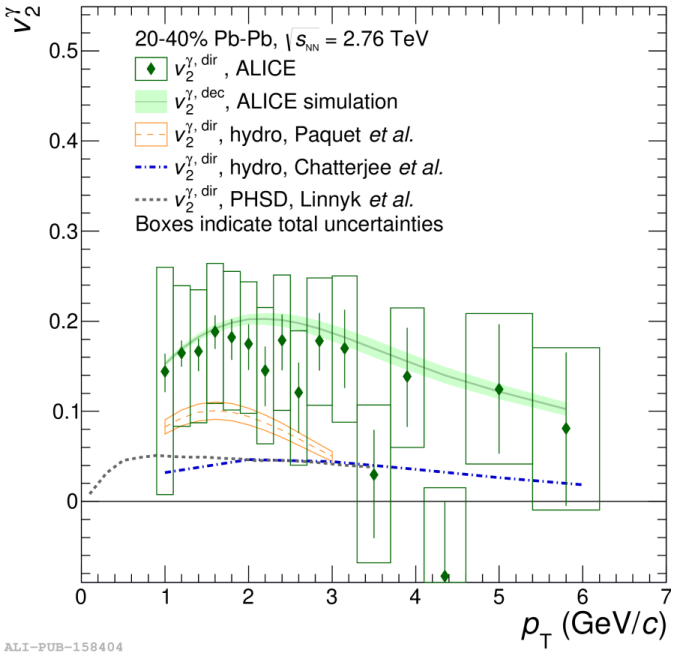
Dileptons at LHC

- Hint for an excess at low m_{ee}
  - Consistent with additional thermal radiation from the medium
- Need to control heavy-flavour background
  - DCA_{ee} studies in Pb-Pb
- Extract fraction of direct photons by fitting the m_{ee} spectra (m_{ee} < 0.4 GeV/c^2)
- No significant excess at medium mass region 1.1<m_{ee}<2.5 GeV/c^2



Photon flow puzzle

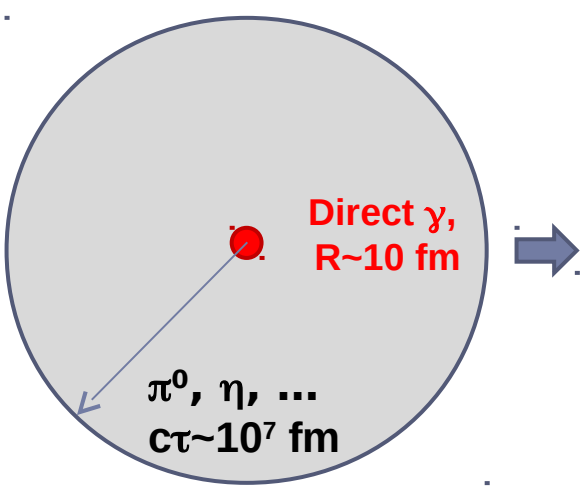


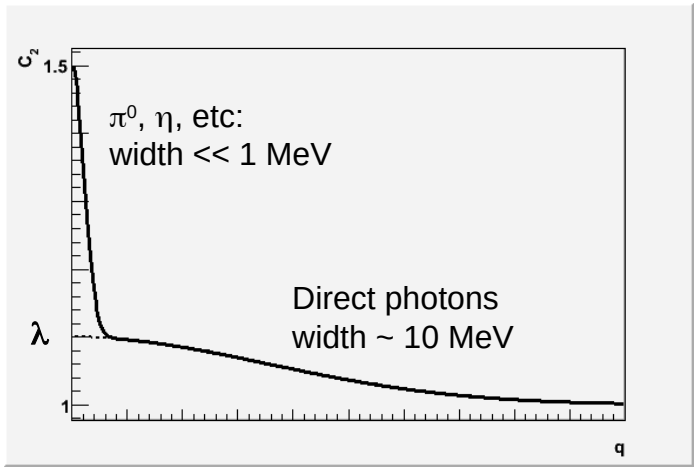


- PHENIX: $v_2^\gamma \sim v_2^\pi$ and much larger than theory predictions
- ALICE: $v_2^\gamma \sim v_2^\pi$, statistically consistent with predictions

$$v_n^{dir} = v_n^{decay} + \frac{R}{R-1}\left(v_n^{incl} - v_n^{decay}\right)$$

Direct photon Bose-Einstein correlations



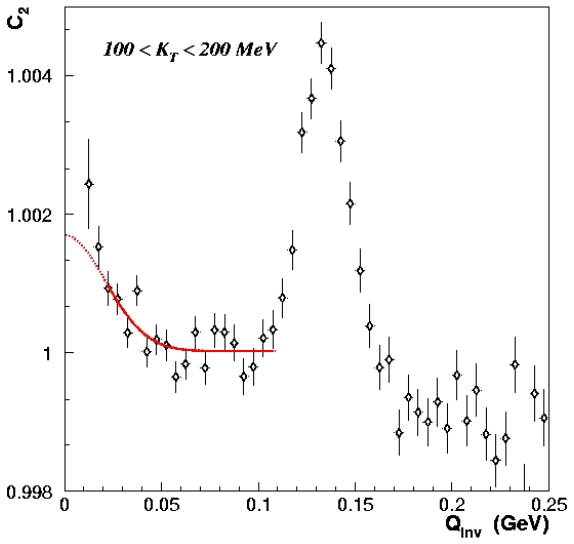


- No need to select direct photons: correlations between decay-decay or decay-direct have tiny width
- Space-time dimensions of hot matter
- Correlation strength reflects proportion of direct photons

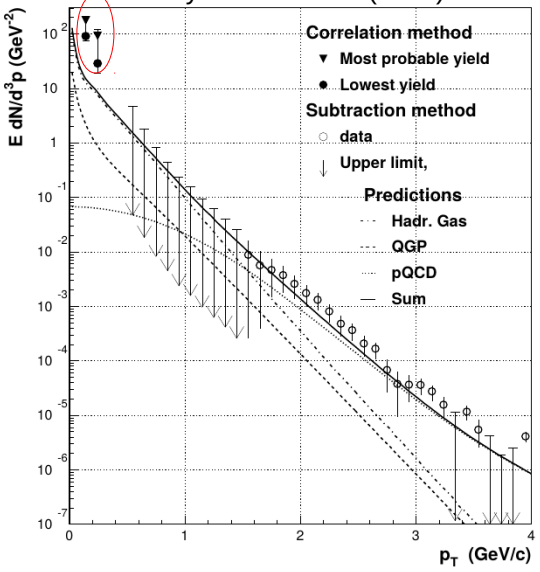
$$\lambda = \frac{1}{2}\frac{N^{Direct\ pairs}}{N^{All\ pairs}} = \frac{1}{2}\left(\frac{N_{\gamma}^{dir}}{N_{\gamma}^{all}}\right)^{2} \sim 10^{-3}$$

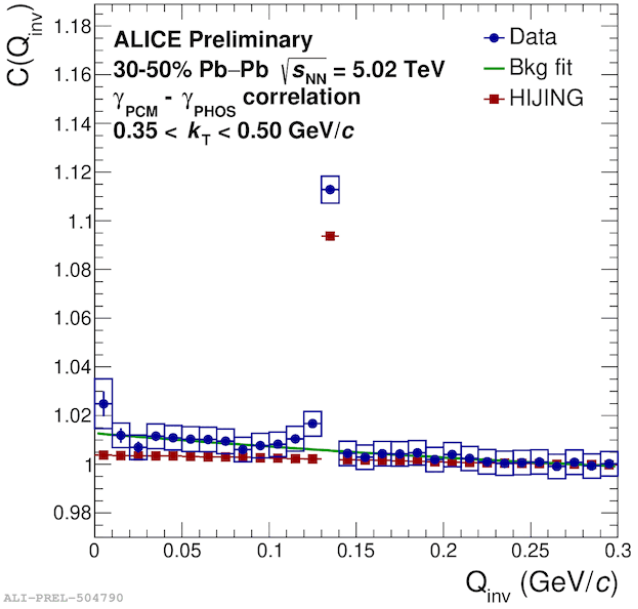
Direct photon Bose-Einstein correlations

WA98: Phys.Rev.Lett. 93 (2004) 022301



WA98: Phys.Rev.Lett. 93 (2004) 022301





- WA98 extracted correlation radius and *lower limit* of direct photon yield
  - Fortunate experimental setup: fixed target, EM calorimeter at 21m from IP
  - Good resolution and photon identification, large distance between clusters
- ALICE made first attempt with pairs converted photon-PHOS
  - Some hint of correlation is observed

Conclusions

- Direct photon yield measured in pp, pA, dA, and AA collisions at RHIC and LHC energies
- Several methods developed which provide excellent agreement
- RHIC: considerable discrepancy between PHENIX and STAR
- Comparison with theory PHENIX yield 2-3 times higher than theory predictions, other experiments agree within uncertainties

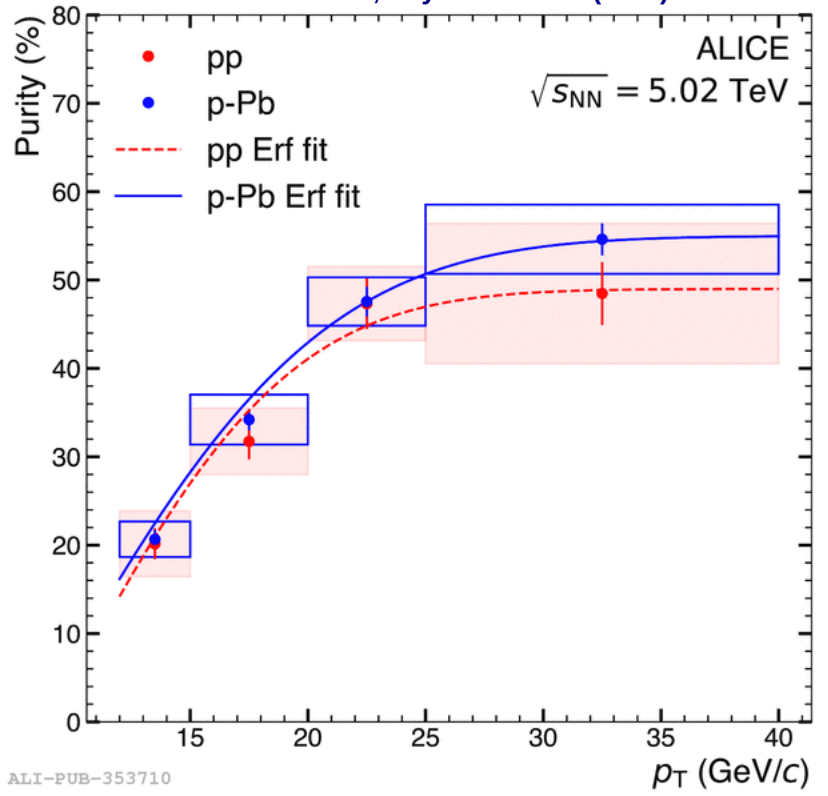
Backup slides

Isolated photons

$$\frac{\mathrm{d}^2\sigma^{\gamma}}{\mathrm{d}p_{\mathrm{T}}^{\gamma}\,\mathrm{d}\eta} = \frac{1}{\mathscr{L}\varepsilon_{\mathrm{trig}}\mathscr{C}}\frac{\mathrm{d}^2N_n^{\mathrm{iso}}}{\mathrm{d}p_{\mathrm{T}}^{\gamma}\,\mathrm{d}\eta}\frac{P}{\varepsilon_{\gamma}^{\mathrm{iso}}}$$

- The most delicate part – calculation of purity
- Photons identified using shower shape, which might be affected by jet environment
  - Template fits
  - Selecting regions with or without contamination
- Hard to extend measurements below ~10 GeV/c with reasonable accuracy

ALICE collaboration, Phys Rev C 102 (2020) 044908



Statistical method

Direct photons is the difference between measured inclusive and estimated decay photons:

$$N_{\gamma}^{dir} = N_{\gamma}^{incl} - N_{\gamma}^{decay}$$

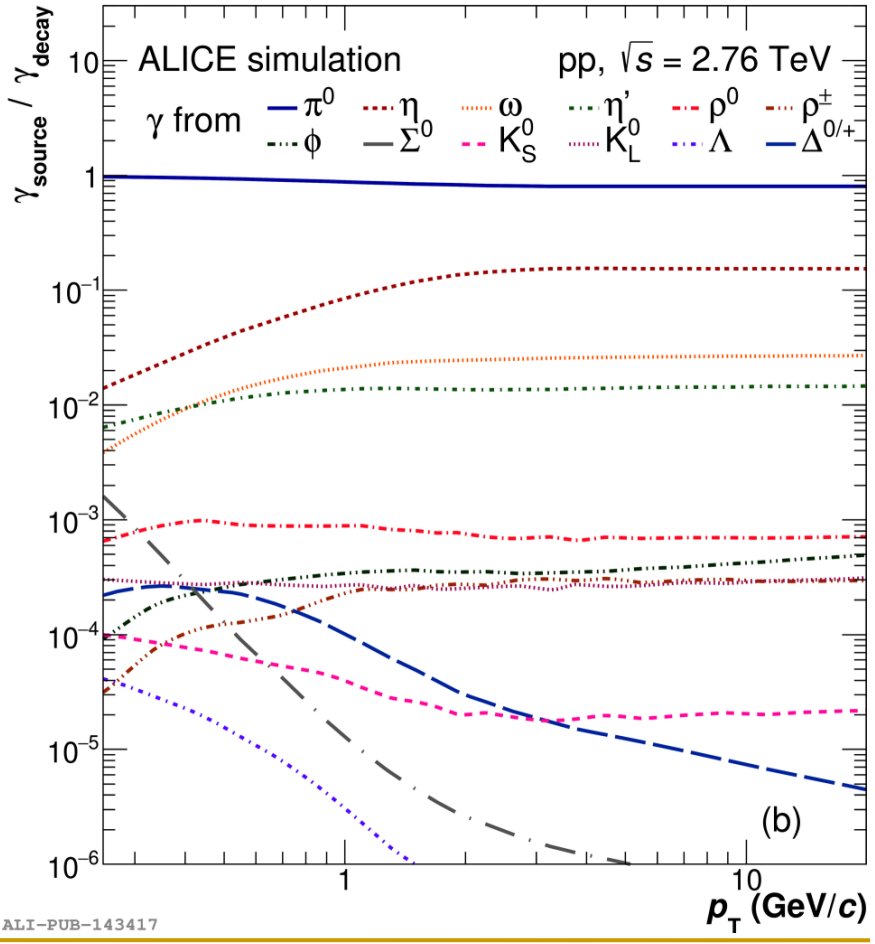
Measure intermediate ratio where the largest sys. uncertainties cancel:

$$R_{\gamma} = \frac{N_{\gamma}^{incl} / N_{\pi}^{measured}}{N_{\gamma}^{decay} / N_{\pi}^{simulated}} \approx \frac{N_{\gamma}^{incl}}{N_{\gamma}^{decay}}$$

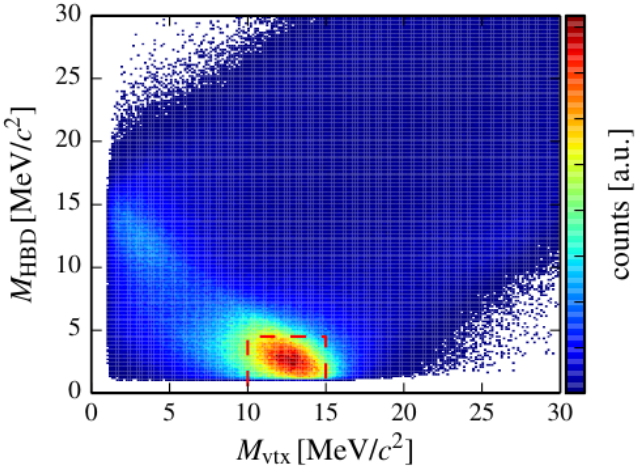
Having ratio, calculate direct photon spectrum

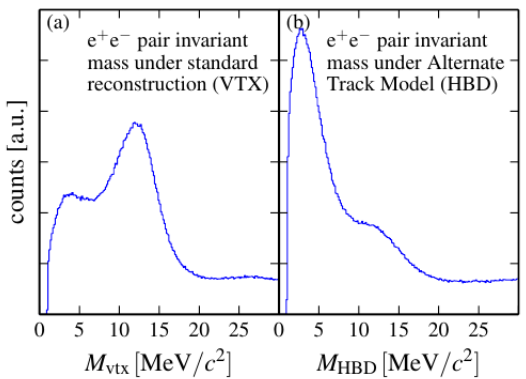
$$N_{\gamma}^{dir} = N_{\gamma}^{incl} \frac{R_{\gamma} - 1}{R_{\gamma}}$$

ALICE collaboration, Phys.Rev.C 99 (2019) 2, 024912



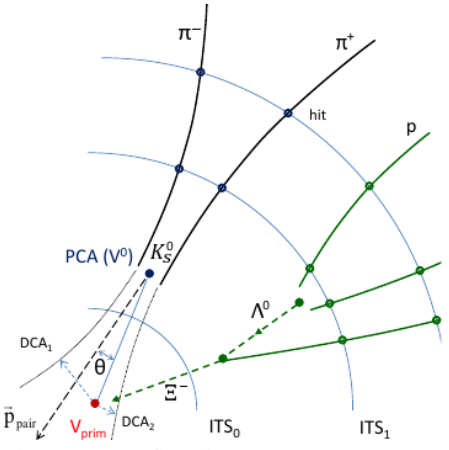
Photon conversion

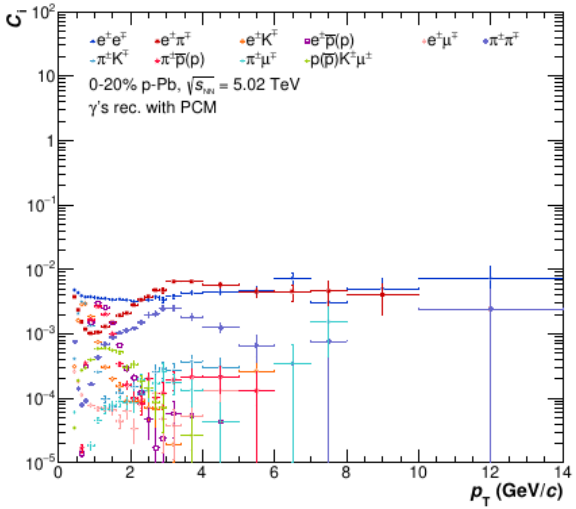


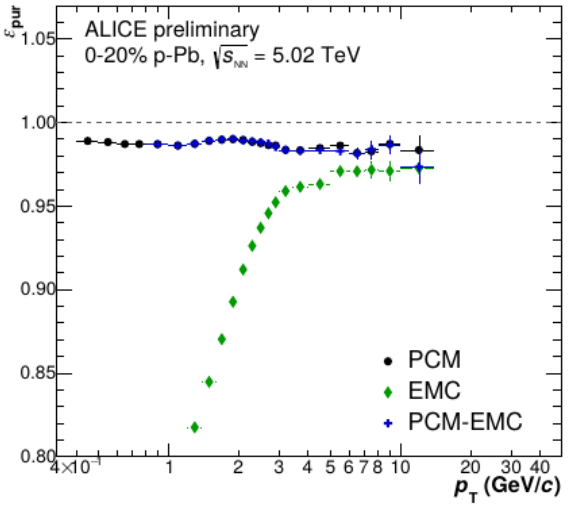


1% uncertainties of photon purity

Photons converted on detector material and reconstructed as e^+e^- pair in tracking system



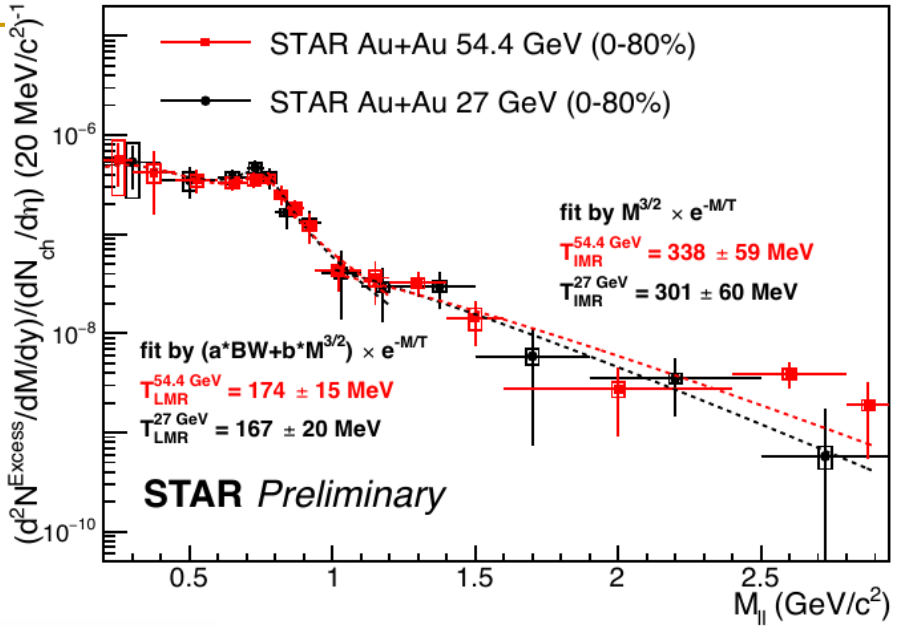


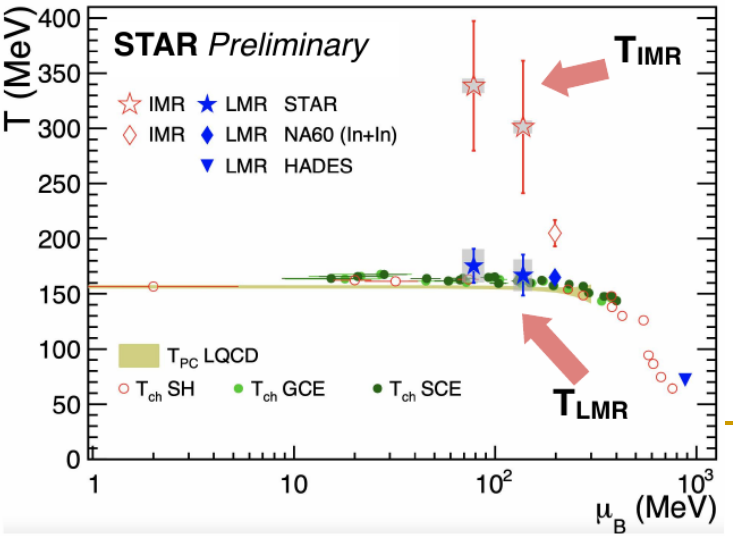


PhD thesis N.Schmidt, Goethe U., Frankfurt, 2021

Dileptons in STAR

- Precision di-lepton spectra measured with Au+Au 27 GeV (2018) and 54.4 GeV data (2017)
- blue-shift free average temperatures extracted: IMR systematically above LMR temperature





IMR