Overview of direct photon measurements at the LHC

Daiki Sekihata

Center for Nuclear Study, the University of Tokyo

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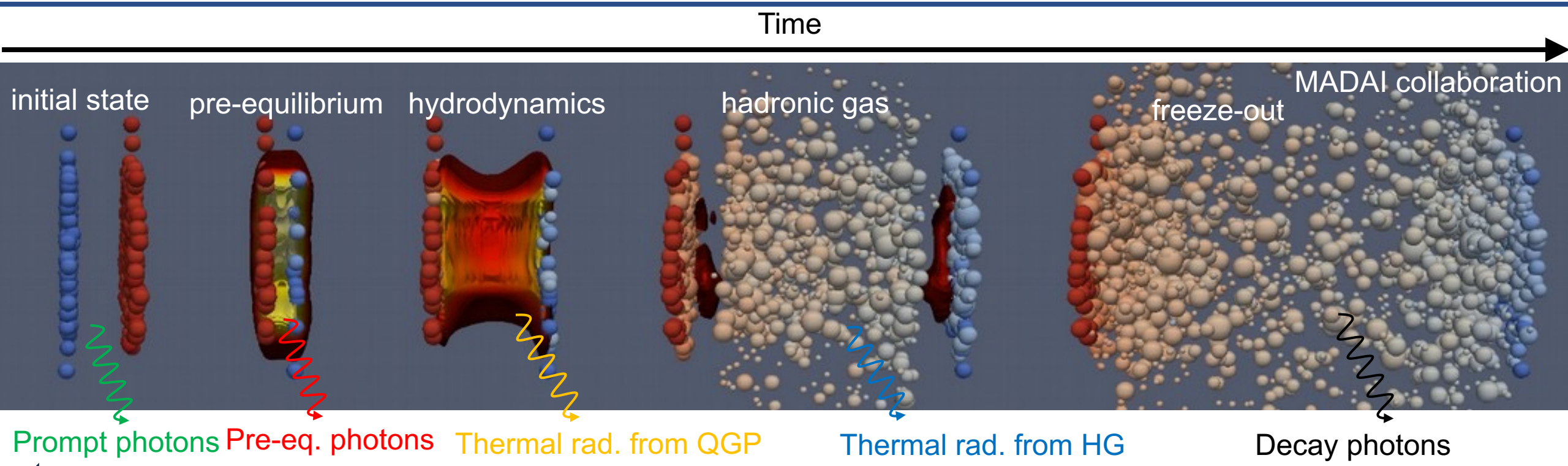
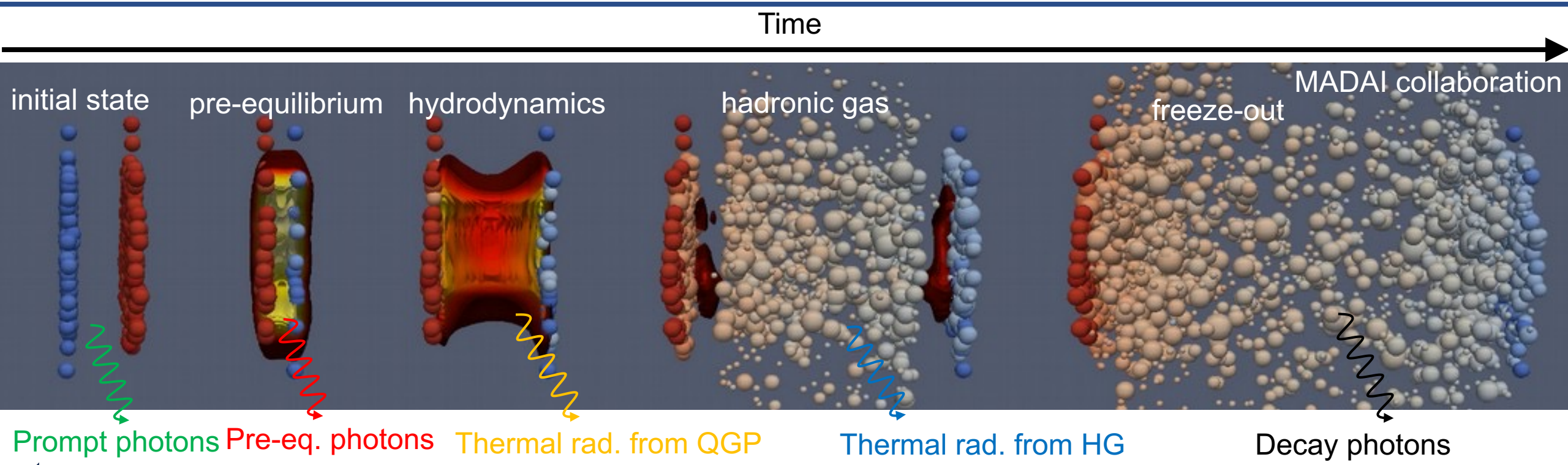
Space-time evolution of high-energy heavy-ion collision



What we want to do : “go backward in time”

- We want to understand the properties of strongly interacting matter.
- EM probes carry undistorted information at early stage of the collision without strong interaction.

Physics motivation of photon measurement

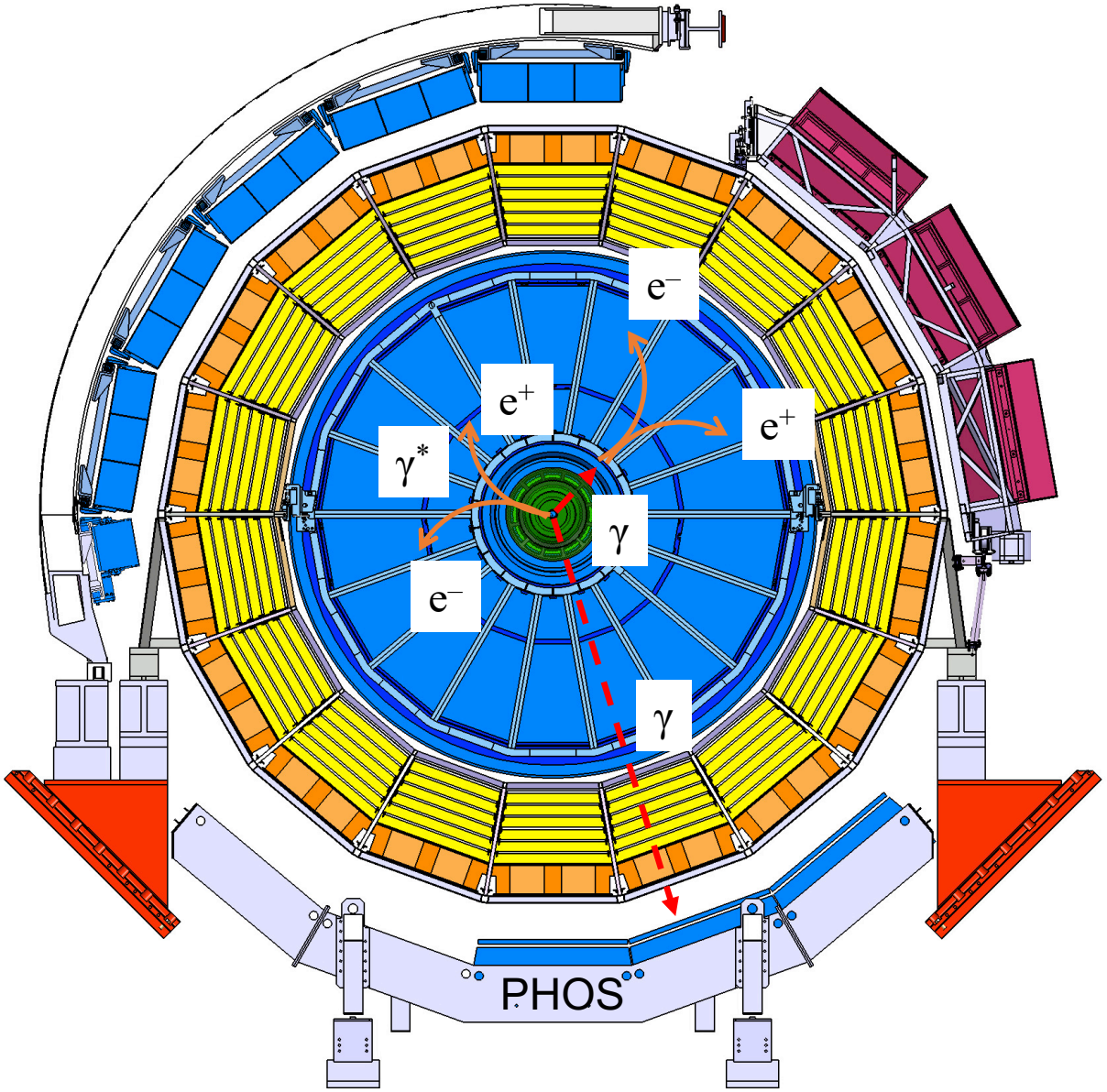


What we want to do : “go backward in time”

- Thermal radiation: thermodynamical properties of the medium
- Pre-equilibrium radiation: how quarks are produced from purely gluonic system and how they equilibrate
- Prompt photon: determine initial state of colliding nuclei

However, direct photons are experimentally hidden under decay photons.

Direct photon measurement at the LHC



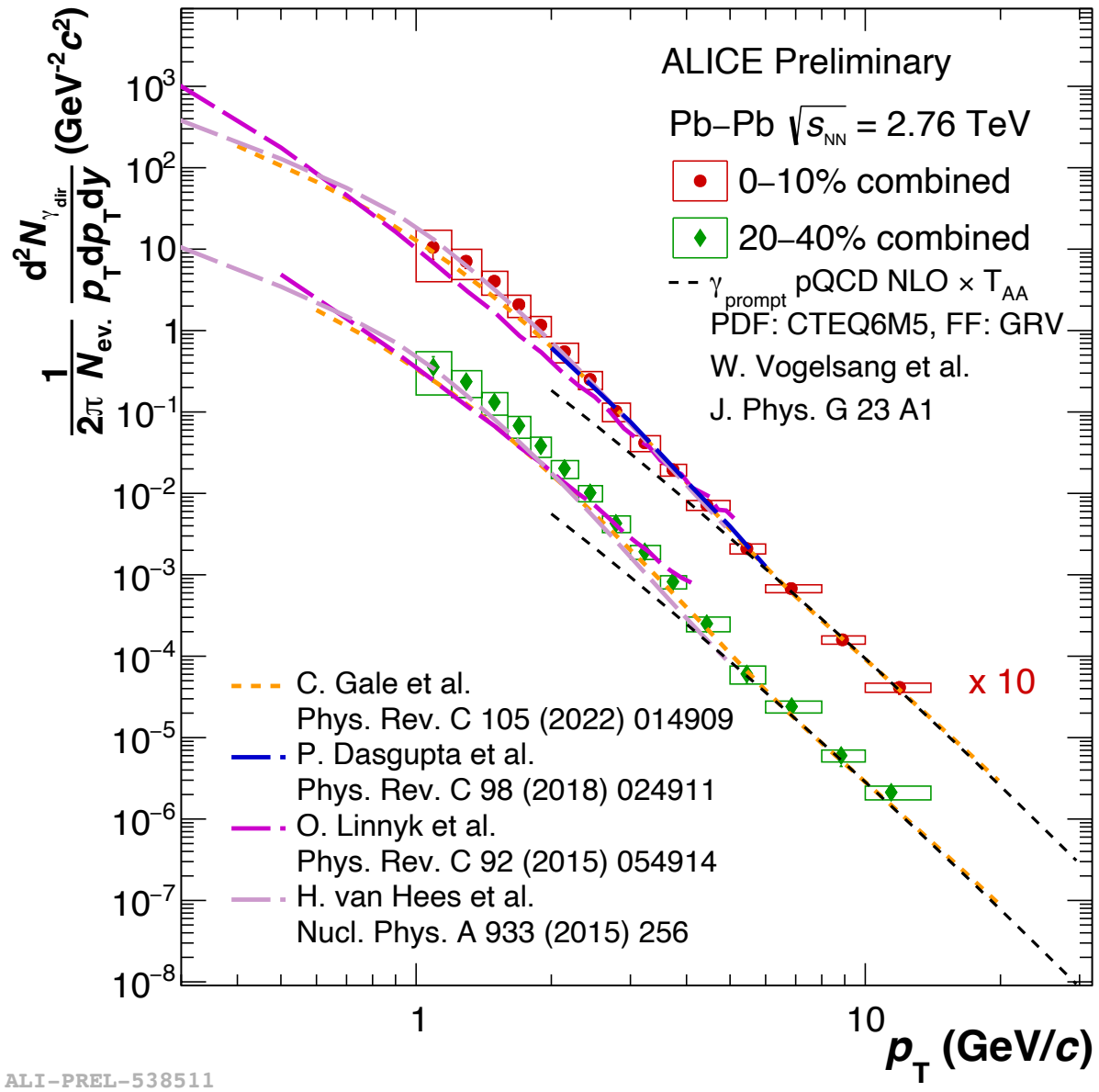
cross section of ALICE detectors

- PCM (Photon Conversion Method, γ→ee)
  - conversion probability : 8.5 %
  - $|\eta| < 0.9$, $0 < \varphi < 2\pi$
- PHOS (Photon Spectrometer)
  - homogenous calorimeter
  - Moliere radius : 2.2 cm ($PbWO_4$ crystals)
- Complementally, virtual photon technique ($\gamma^* \rightarrow ee$)
  - associated dielectron with real photon
  - equivalent to real photon at massless limit

$$R_\gamma = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}}, \quad \gamma_{\mathrm{direct}} = \gamma_{\mathrm{incl}} - \gamma_{\mathrm{decay}} = (1 - \frac{1}{R_\gamma}) \cdot \gamma_{\mathrm{incl}}$$

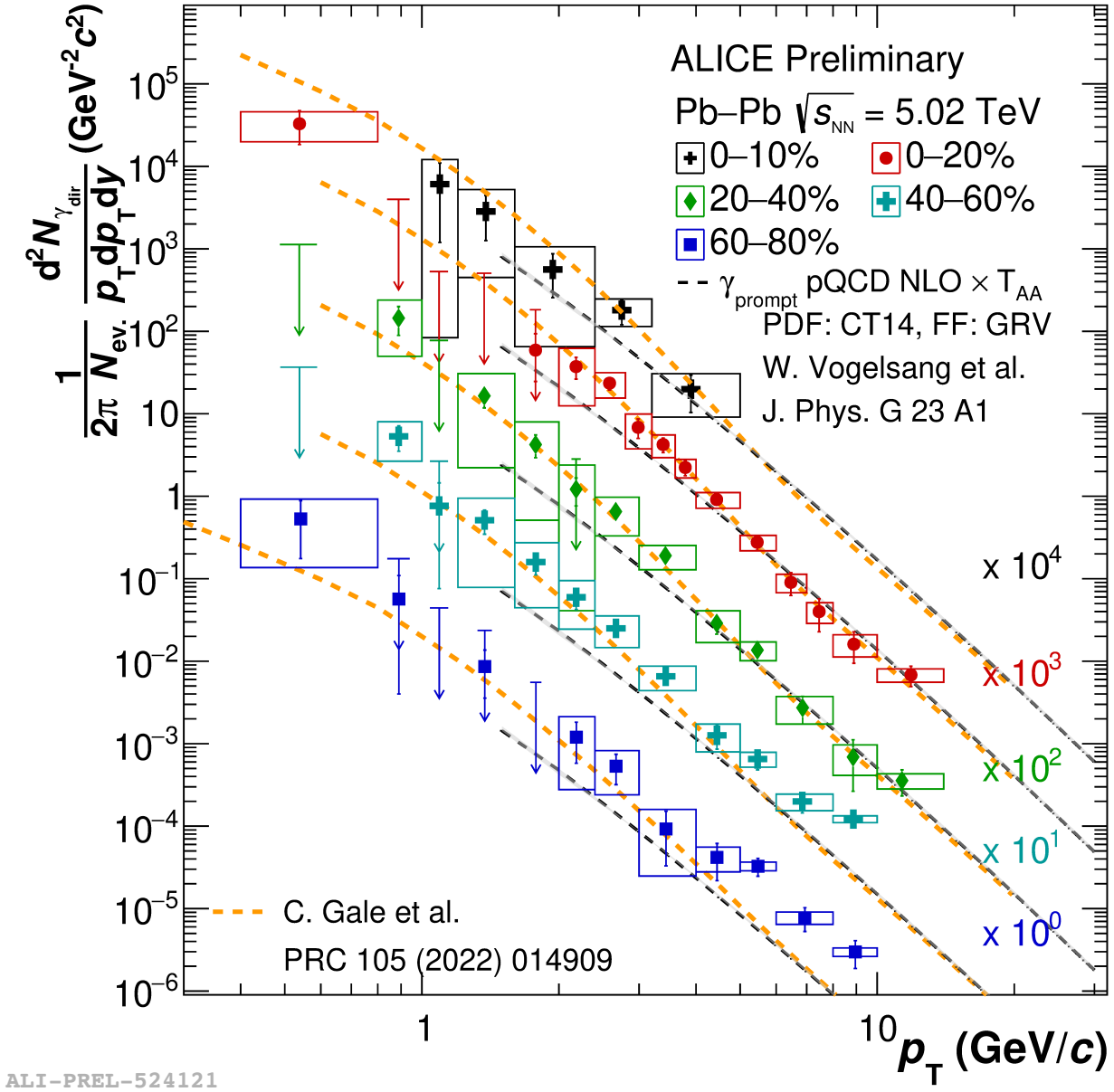
ATLAS/CMS are dedicated to measure high-energy photons
i.e. isolated photons for $E_\gamma > 10$ GeV

Direct photon measurements in Pb-Pb at 2.76 TeV



- Improved results compared to the previous publication (PLB 754 (2016) 235-248)
  - larger statistics : 20M events in 0-10%
  - data-driven material budget correction (arXiv:2303.15317)
- Good agreement with pQCD at high p_T
  - standard candle for measurement
- Excess beyond pQCD at low p_T

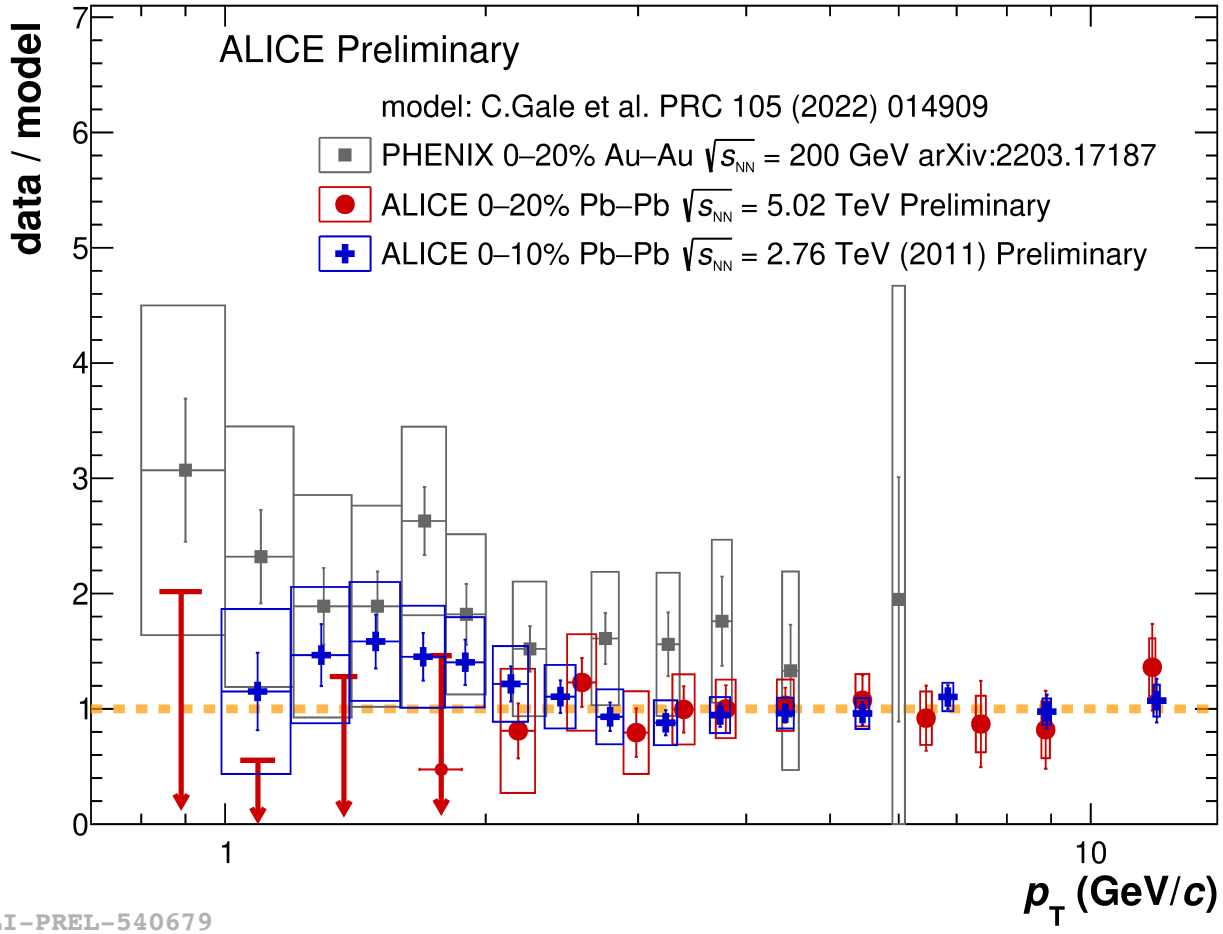
Direct photon measurements in Pb-Pb at 5.02 TeV



ALI-PREL-524121

- Highest collision energy in 2015 data
  - 80M events in 0-80%
- Comparison to different models:
  - C. Gale et al. : EM radiation from all stages including pre-equilibrium
  - W.Vogelsang et al. : NLO pQCD x N_{coll}
- Analysis with larger data in 2018 is ongoing.

Data/theory ratio of direct photon measurements



PHENIX : ratio of nonprompt direct photon yields
ALICE : ratio of direct photon yields

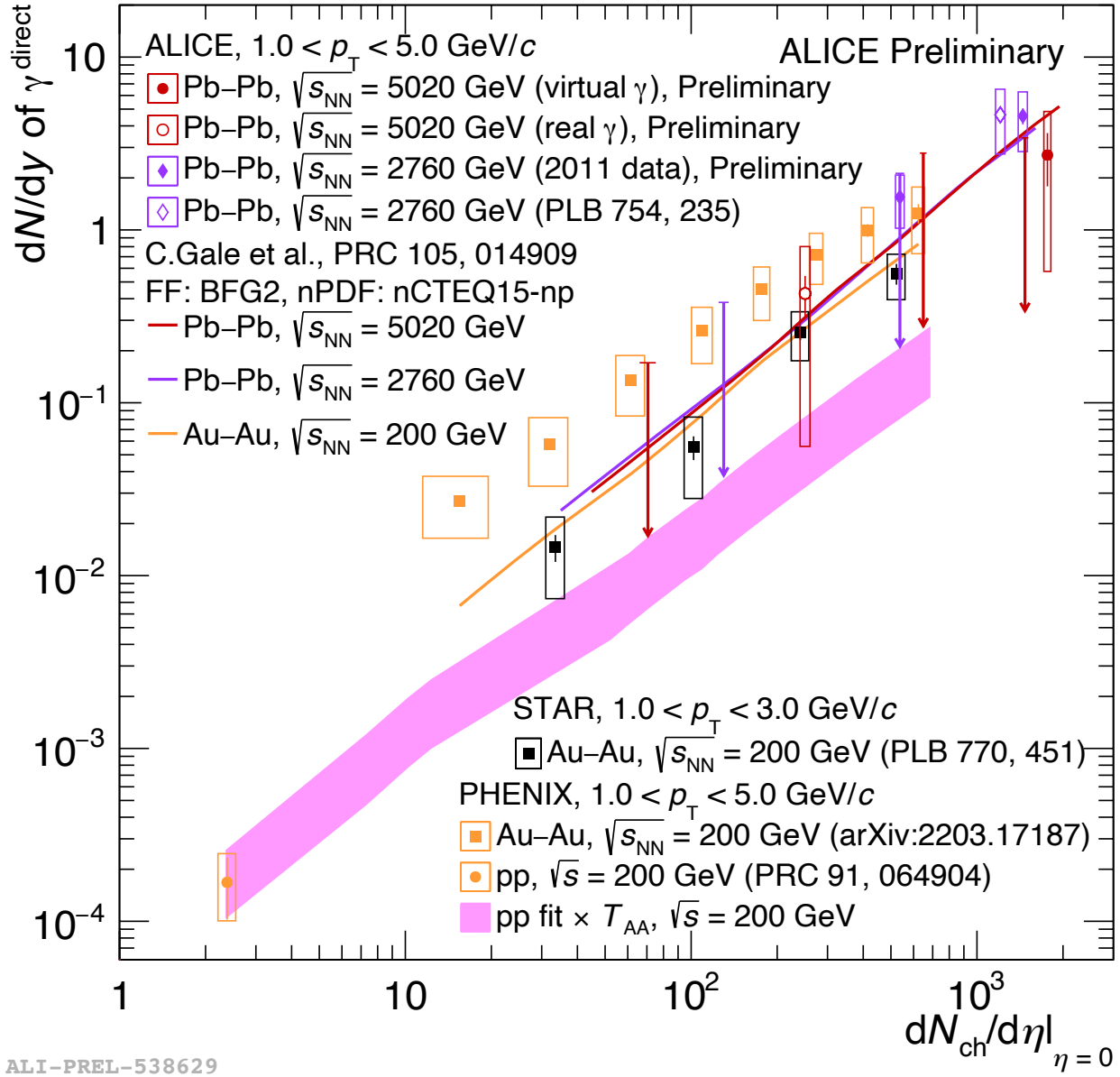
- data/model ratio at 3 collision energies

- At low p_T, the ratios indicate ordering
  - 200 GeV > 2.76 TeV > 5.02 TeV
  - (Of course, all 3 ratios are consistent within experimental uncertainties)

It is interesting to understand whether the ordering exists or not.

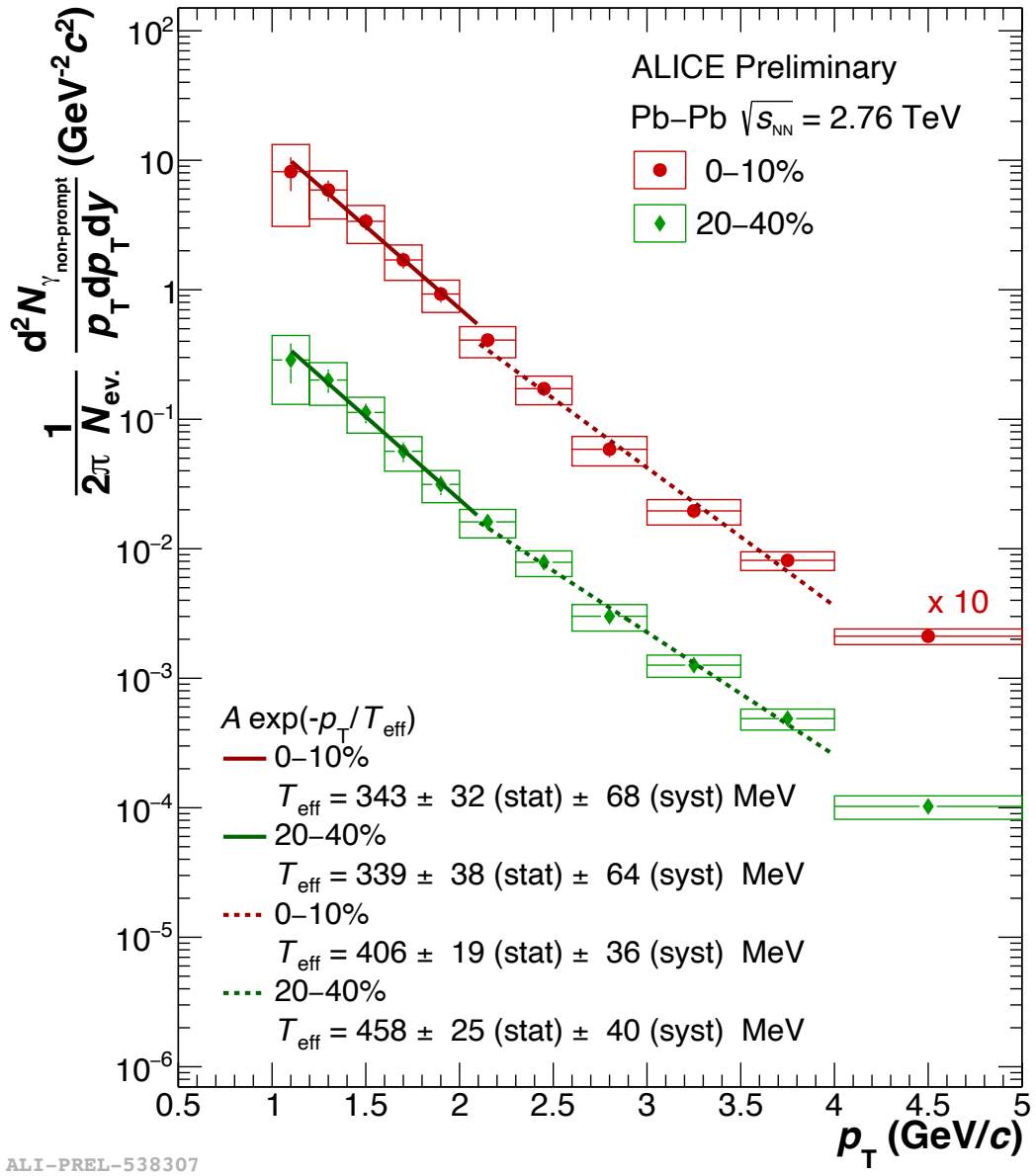
If so, how can the model be understood/improved?

Scaling of direct photon yields



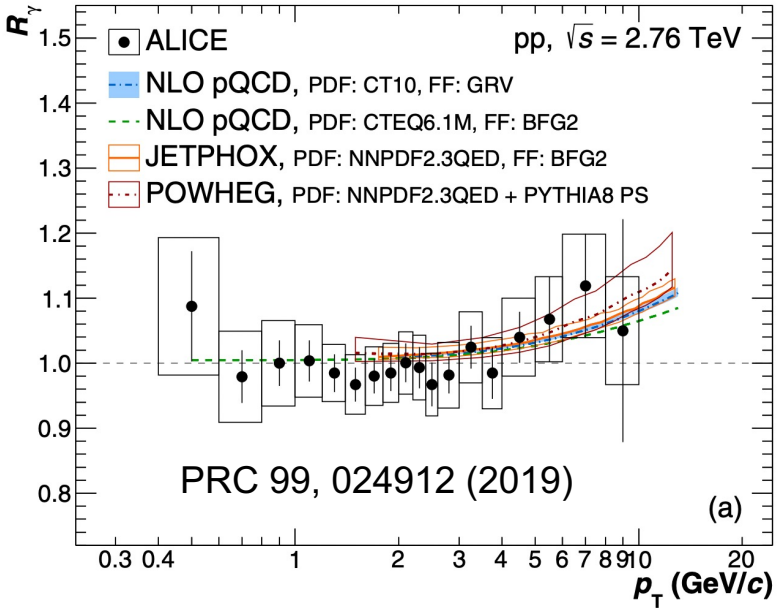
- Originally, suggested by PHENIX
- ALICE data is consistent with the theoretical model
- PHENIX data is higher than the theoretical model
- Discrepancy between PHENIX and STAR is not clear yet.
  - Precise ALICE data at $dN_{ch}/d\eta$ ~ 100 would help to disentangle.

Inverse slope parameter T_{eff} of nonprompt direct photon

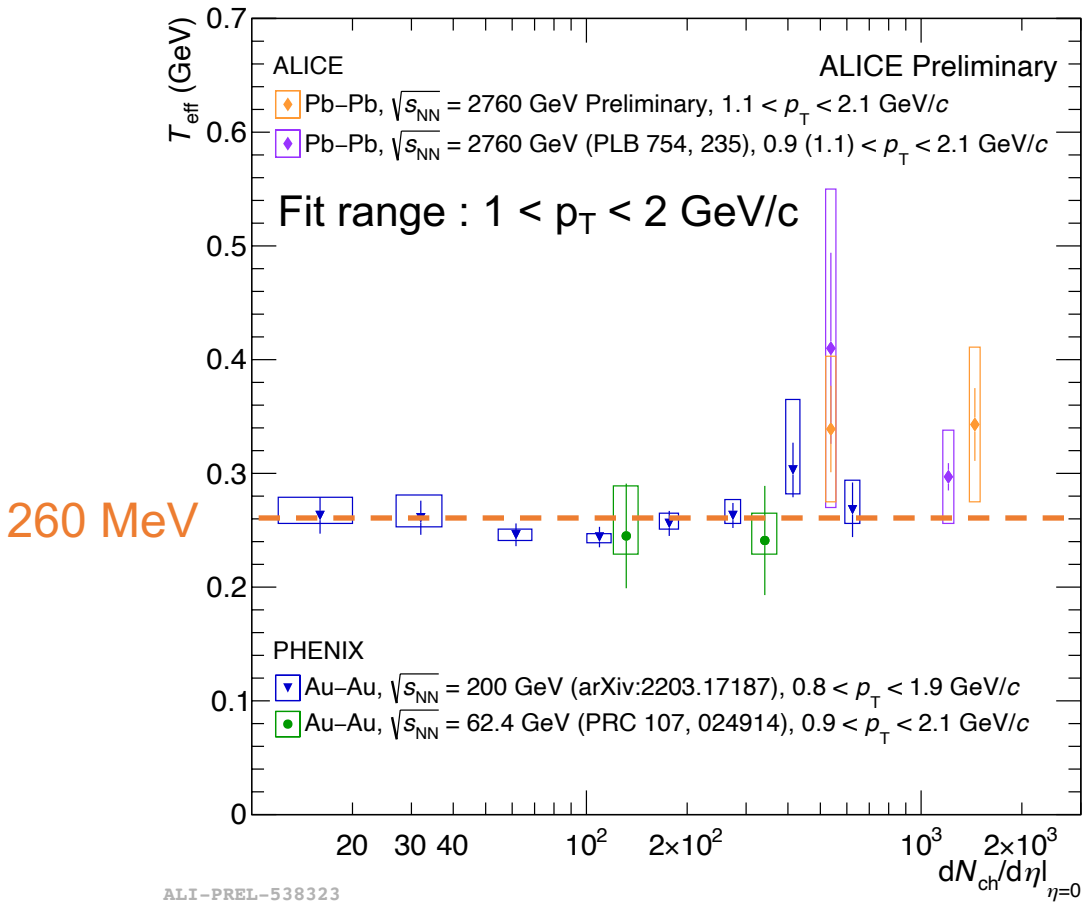


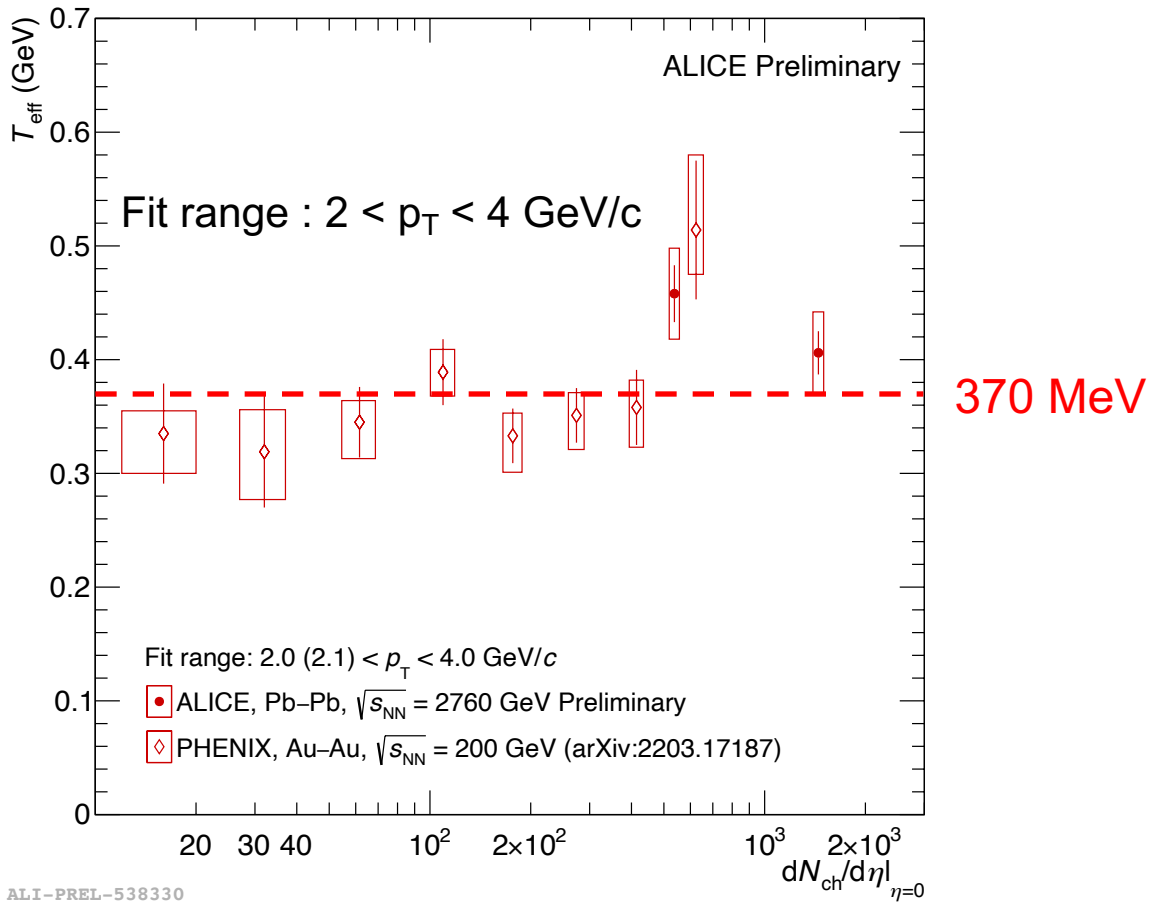
- Averaged temperature over space-time evolution
  - early temperature
  - expansion velocity (i.e. blue shift)
- First nonprompt direct photon at the LHC
  - $\gamma^{\text{nonprompt}} = \gamma^{\text{direct}} - \gamma^{\text{pQCD}}$ due to missing pp ref. at the same energy
  - importance of pp ref.

$$\gamma_{AA}^{\text{Nonprompt}} = \gamma_{AA}^{\text{direct}} - \langle N_{\text{coll}} \rangle \times \gamma_{pp}^{\text{direct}}$$



Effective temperature vs. charged particle multiplicity

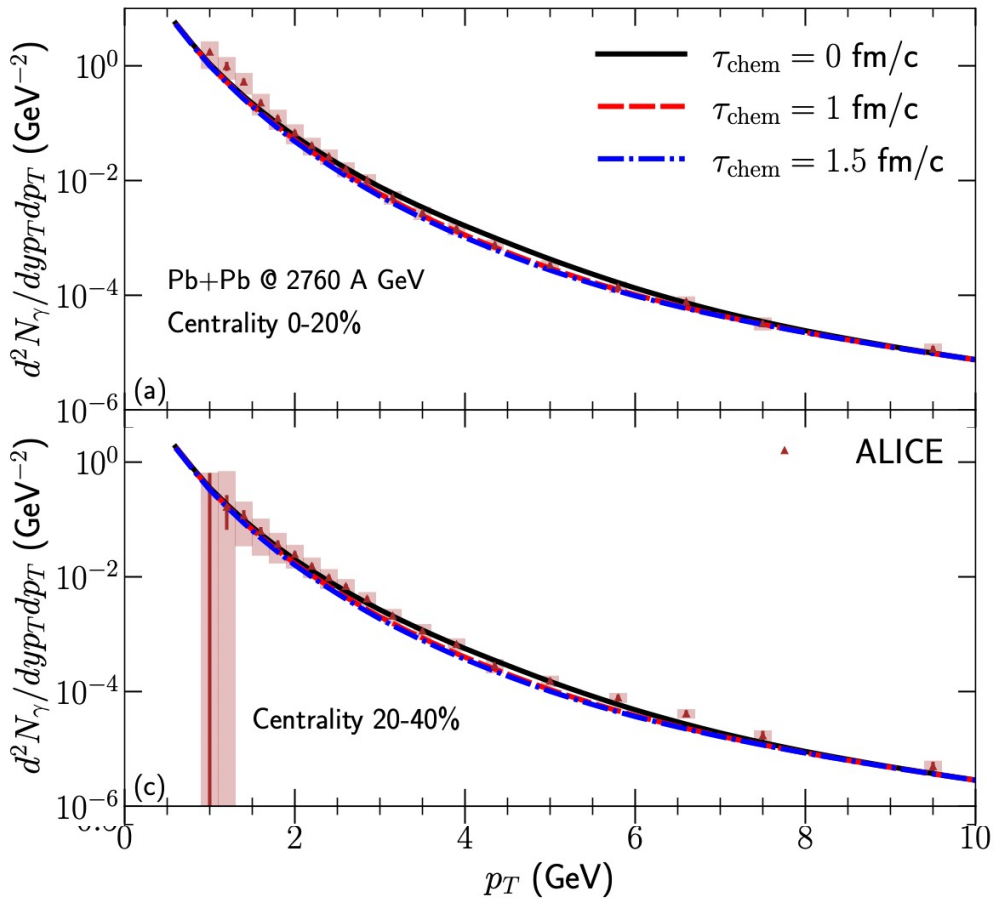


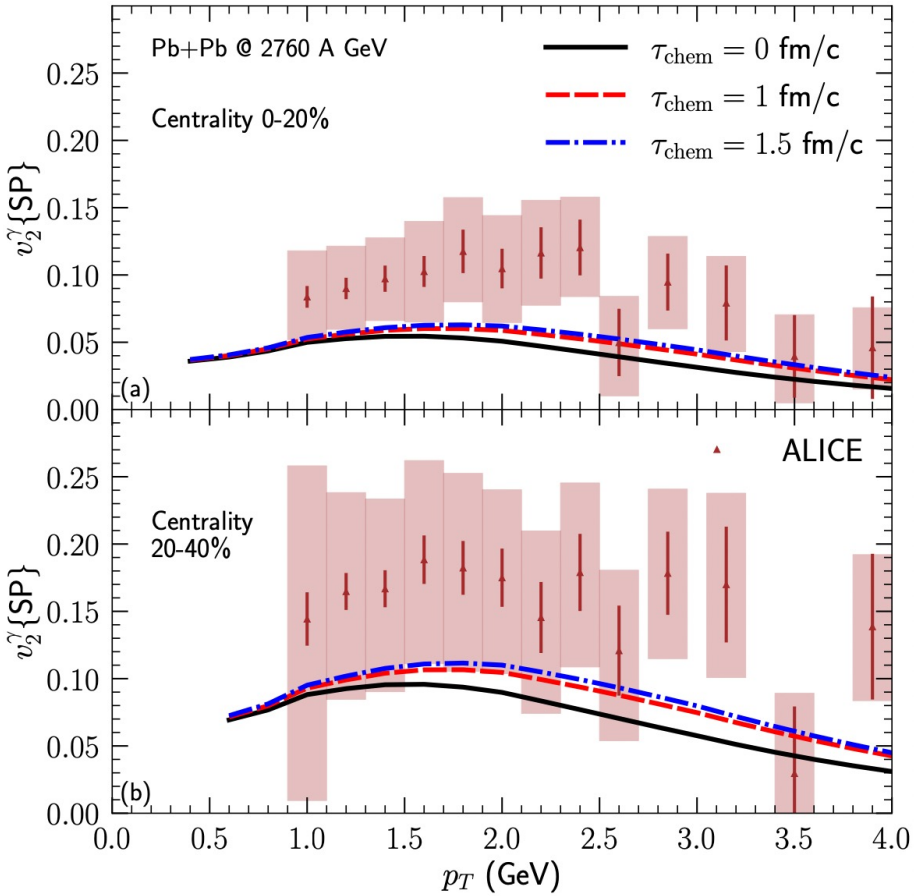


- T_{eff} clearly increase with p_T. → This suggests that photon emissions from earlier stages start to dominate.
- Considering the uncertainties on the data, possible increase of T_{eff} with $dN_{ch}/d\eta$ is not excluded.

Status of direct photon puzzle at the LHC

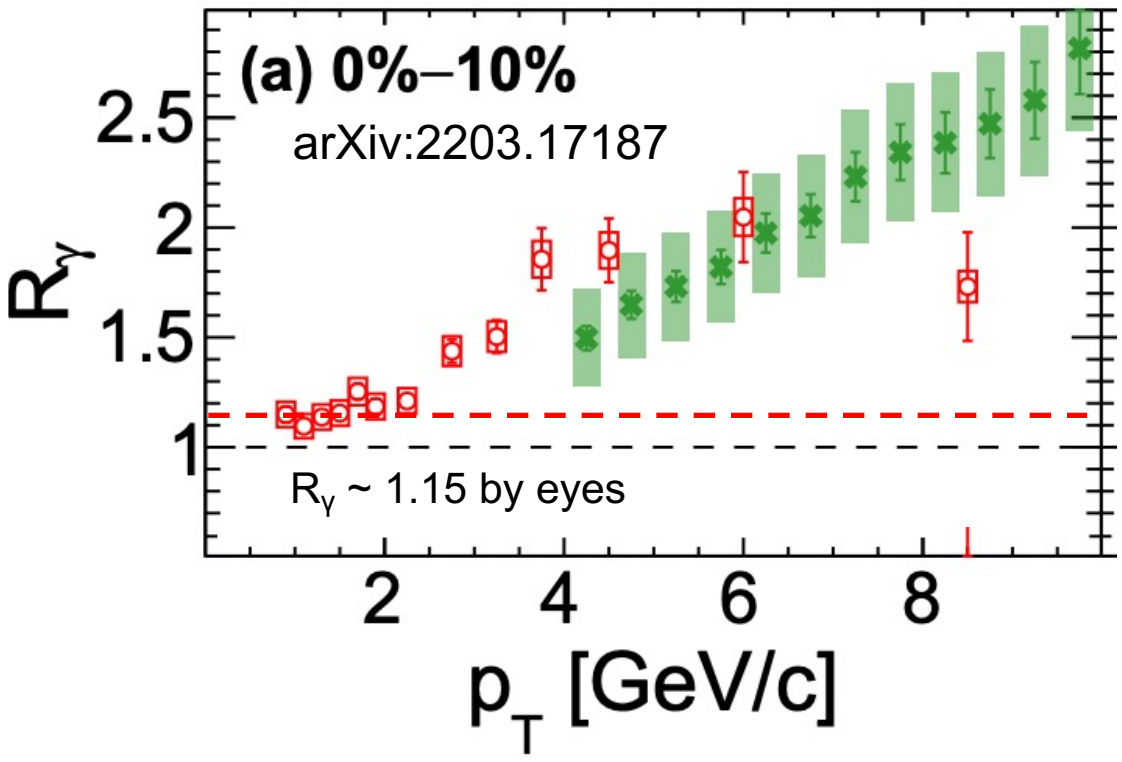
PRC 105, 014909 (2022)

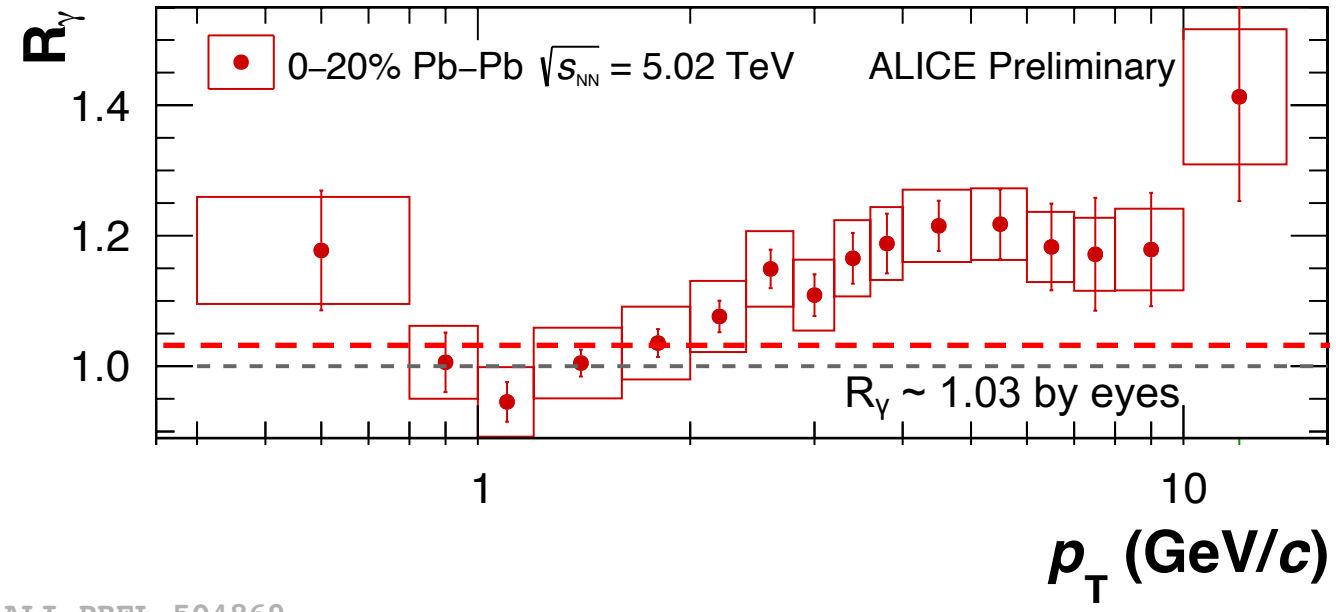




- No direct photon puzzle within the experimental uncertainties (2010 data)
  - material budget uncertainty: 4.5%, missing η meson measurement in old data
- ALICE has all ingredients to reduce uncertainties now!
  - material budget uncertainty : 2.5%, η/π^0 ratio can be constructed by $\left(\frac{\eta}{\pi^0}\right)_{\rm Pb–Pb} = \left(\frac{\eta}{\pi^0}\right)_{\rm pp} \times R_{\rm flow} = \left(\frac{\eta}{\pi^0}\right)_{\rm pp} \times \frac{\left(\frac{\rm K^{\pm}}{\pi^{\pm}}\right)^*_{\rm Pb–Pb}}{\left(\frac{\rm K^{\pm}}{\pi^{\pm}}\right)^*_{\rm pp}}$,

Another difficulty at the LHC



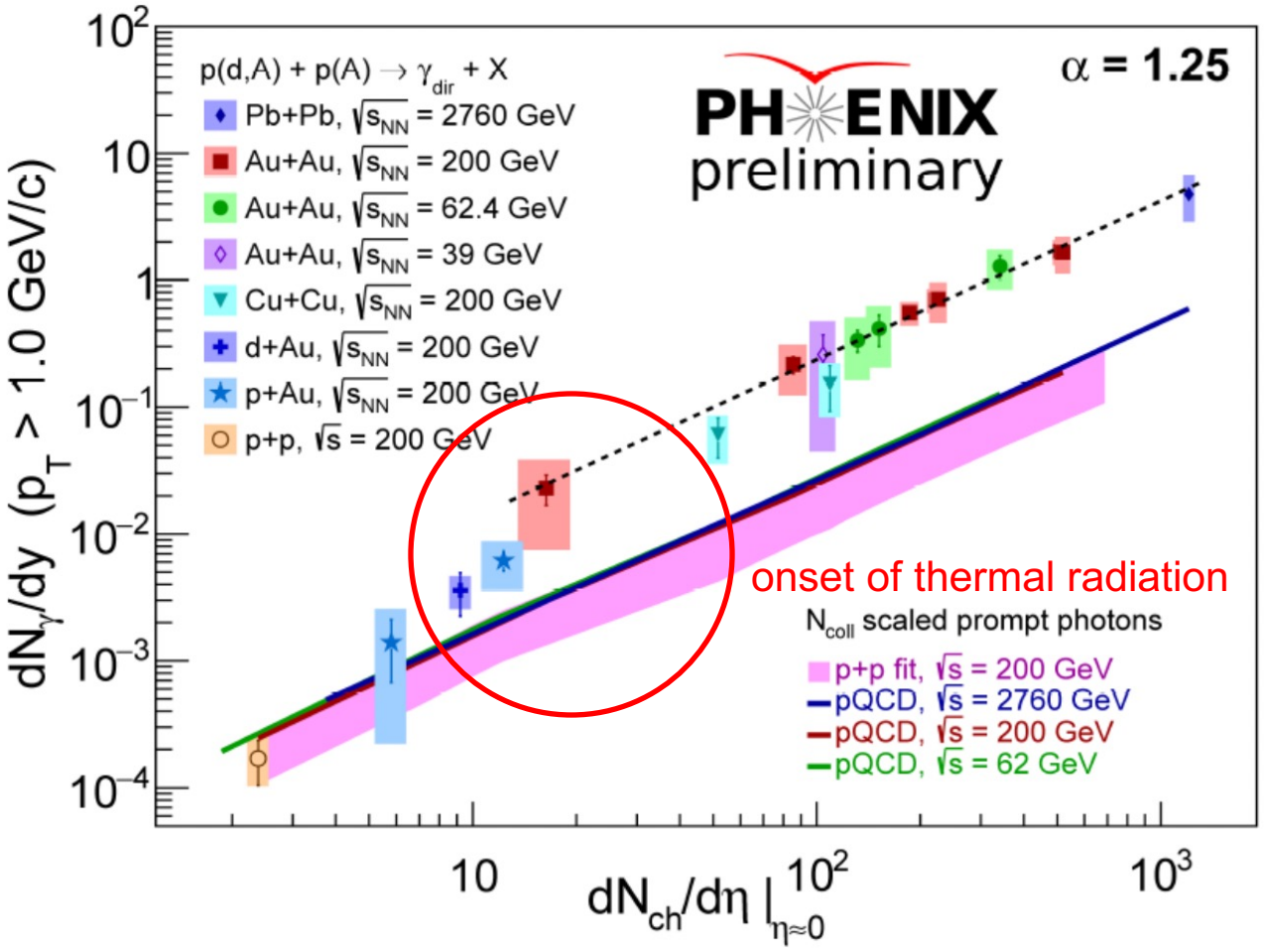


- R_γ ~ 1.15 in PHENIX, and R_γ ~ 1.03 in ALICE at low p_T
- At higher collision energies, π^0 from mini jets may feed decay photons at low p_T.
- v_n measurement is challenging in ALICE due to the smaller R_γ.

Future prospects for direct photon measurements at the LHC

- High-multiplicity pp collisions. Expected luminosity ~ 200 pb^{-1} in ALICE
- OO and pO collisions in 2024 (or 2025, strongly depends on LHC schedule)
- Low B field run in ALICE (B = 0.2 T). Expected luminosity ~ 3 pb^{-1}
- Tungstate wires installed for material budget calibration in ALICE
- ALICE3 from 2035

Search for thermal radiation in high-multiplicity pp collisions



- Expect L_{int} = 200 pb^{-1} in pp at 13.6 TeV
- Multi-differential analyses in Run 3
  - charged particle multiplicity
  - sphericity
    - -- naively, thermal radiation expected in isotropic events
- A key is η meson measurement at low p_T.
  - constrain hadronic cocktail

A paper for direct photons via dielectron in pp at 13 TeV is under preparation.
ALICE aims to publish data points at $dN_{ch}/d\eta$ = 7 and 30.

LHC plan in Run 3

http://lhc-commissioning.web.cern.ch/performance/Run-3-targets.htm

Run 3 luminosity targets

Indicative!

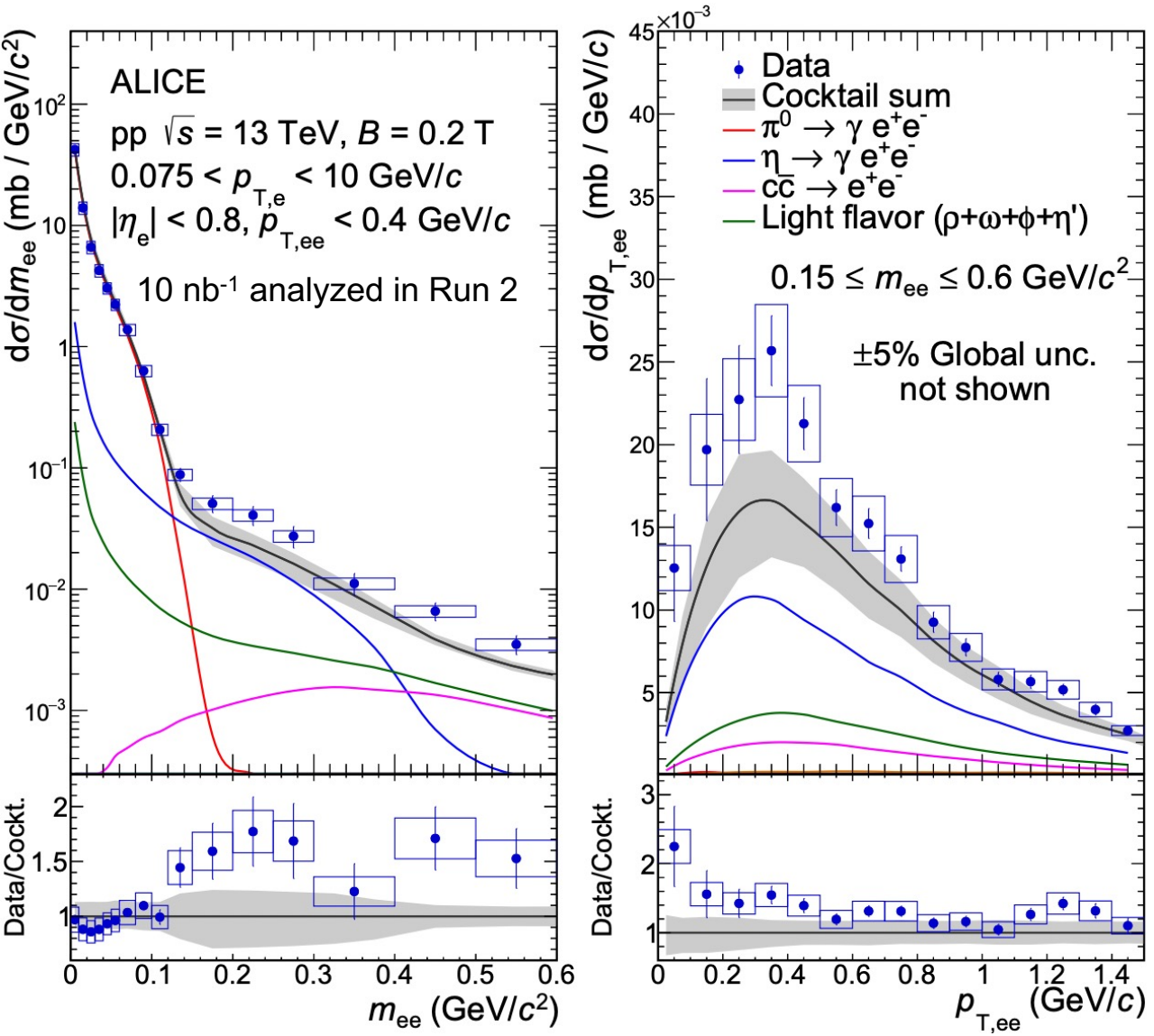
Mode	GPDs	LHCb	ALICE
p-p	250/fb	25 - 30/fb (~50/fb by LS4)	200/pb
Pb-Pb	7/nb (13/nb by LS4)	1/nb (2/nb by LS4)	7/nb (13/nb by LS4)
p-Pb	0.5/pb (~1/pb by LS4)	0.1/pb (~0.2/pb by LS4)	0.25/pb (~0.5/pb by LS4)
O-O	0.5/nb	0.5/nb	0.5/nb
p-O	LHCf 1.5/nb	2/nb	

ALICE took 400 nb^{-1} of pp data at B = 0.2 T on 11-12.July.2023.

Experiments also require HI reference pp data at 5.x TeV

Updated January 2022 (Run 3: 2022 - 2025)

Low B field run in ALICE

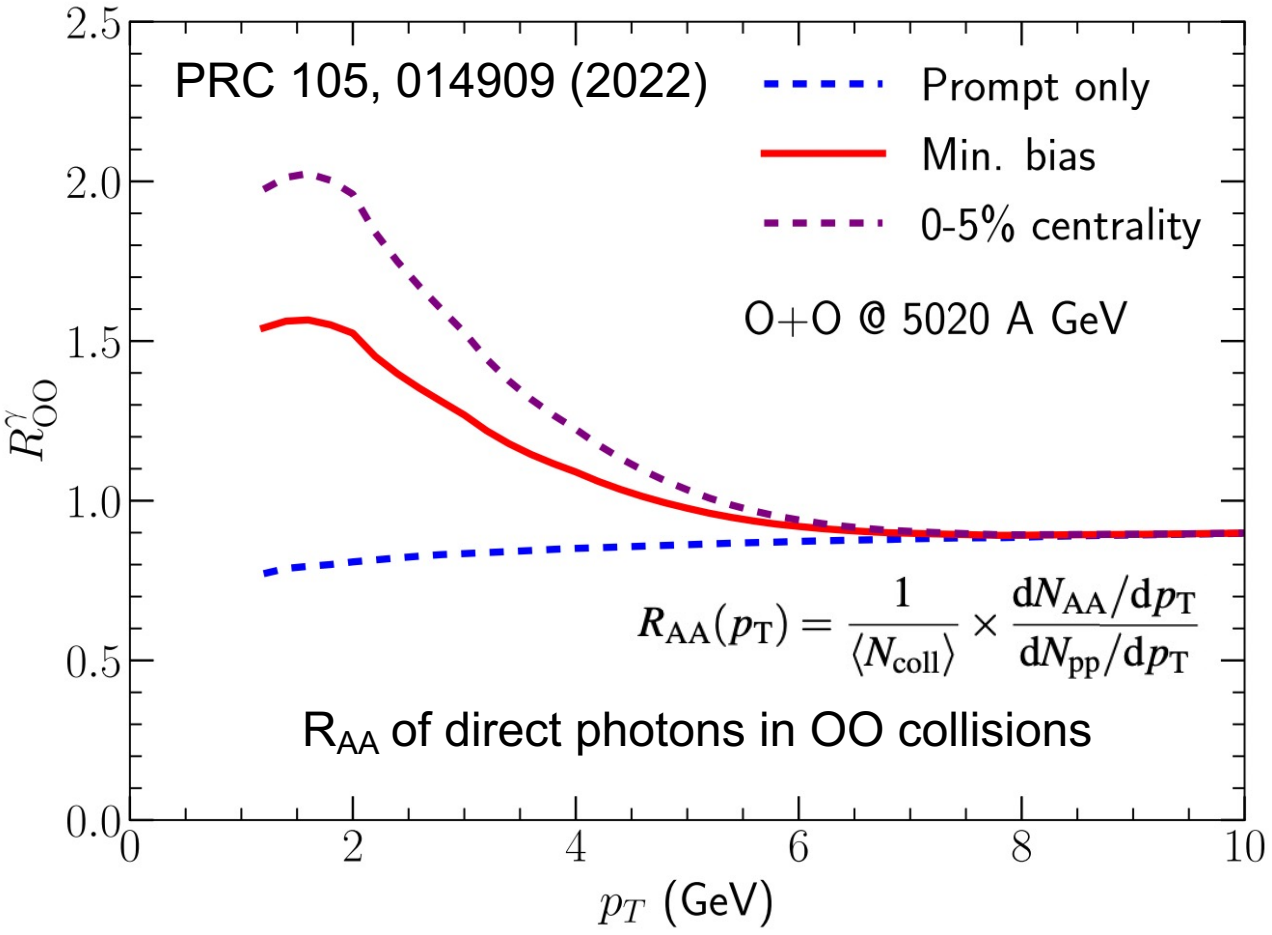


- Dedicated to EM probes at very low p_T in ALICE
  - Thanks to new ITS, minimum $p_{T,e}$ can be extended to lower value.
  - A key is η meson at low pT
- Expect L_{int} ~ 3 pb^{-1} with B = 0.2T in pp at 13.6 TeV
  - 300 times more data than that in Run 2
- Recorded 400 nb^{-1} on 11-12.July.2023

Soft dielectron excess
PRL 127, 042302 (2021)

OO and pO collisions at the LHC

arXiv:2103.01939



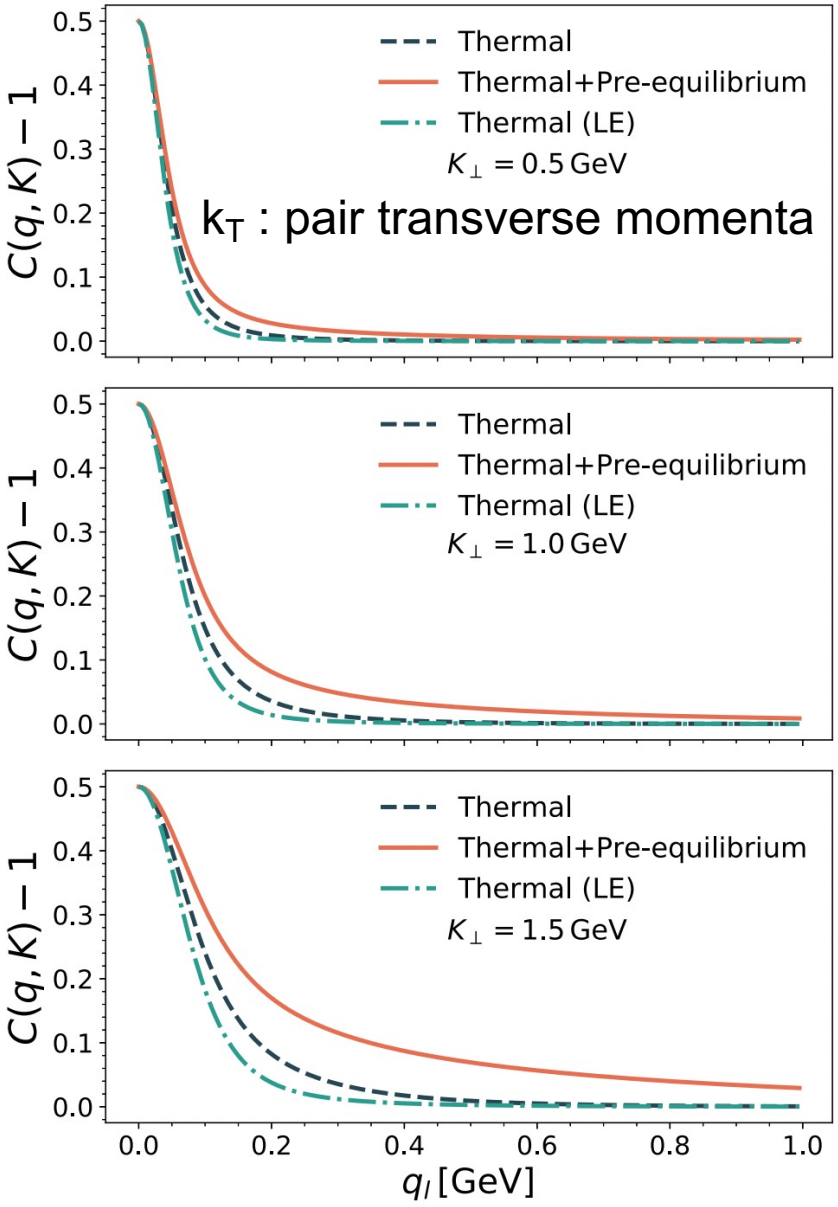
R_{AA} of direct photons in OO collisions

Expected luminosity for ALICE:
L_{OO} = 0.5 ~ 1.0 nb^{-1}, L_{pO} = 5 ~ 10 nb^{-1}

- Multiplicity scan in 3 < $dN_{ch}/d\eta$ < 150
  - ”small system” but AA geometry
- Measure direct photon yields at $dN_{ch}/d\eta$ ~ 10
  - onset of thermal radiation is expected.
  - same multiplicity but different collision system
- If thermal photon excess is large, we can measure direct photon v_2 in OO.

Bose-Einstein correlation between 2γ

PRC 102, 024915 (2020)

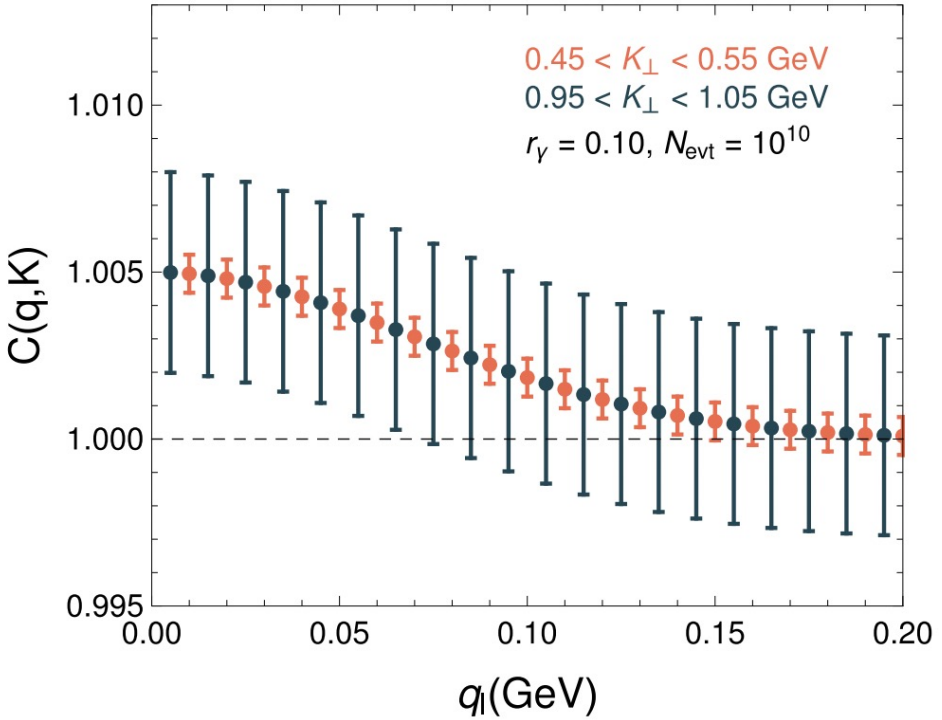


k_T : pair transverse momenta

relative momentum along beam axis

- Sensitive to system size of emission source
- A key to differentiate emission sources
- higher k_T : earlier emission
  - high k_T is essential to access pre-equilibrium and thermal radiation from QGP
  - require very high statistics

Projection at the end of Run 4 (13 nb^{-1})

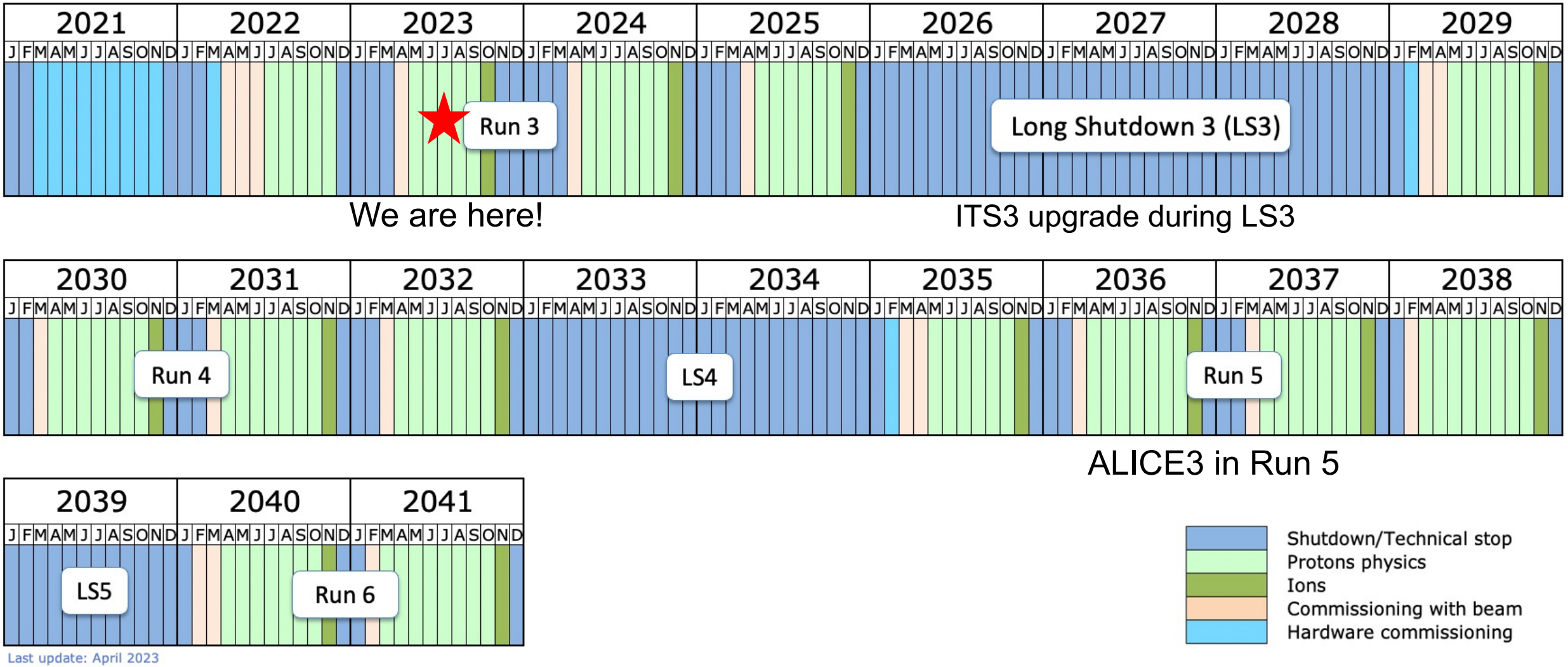


Beyond 2035

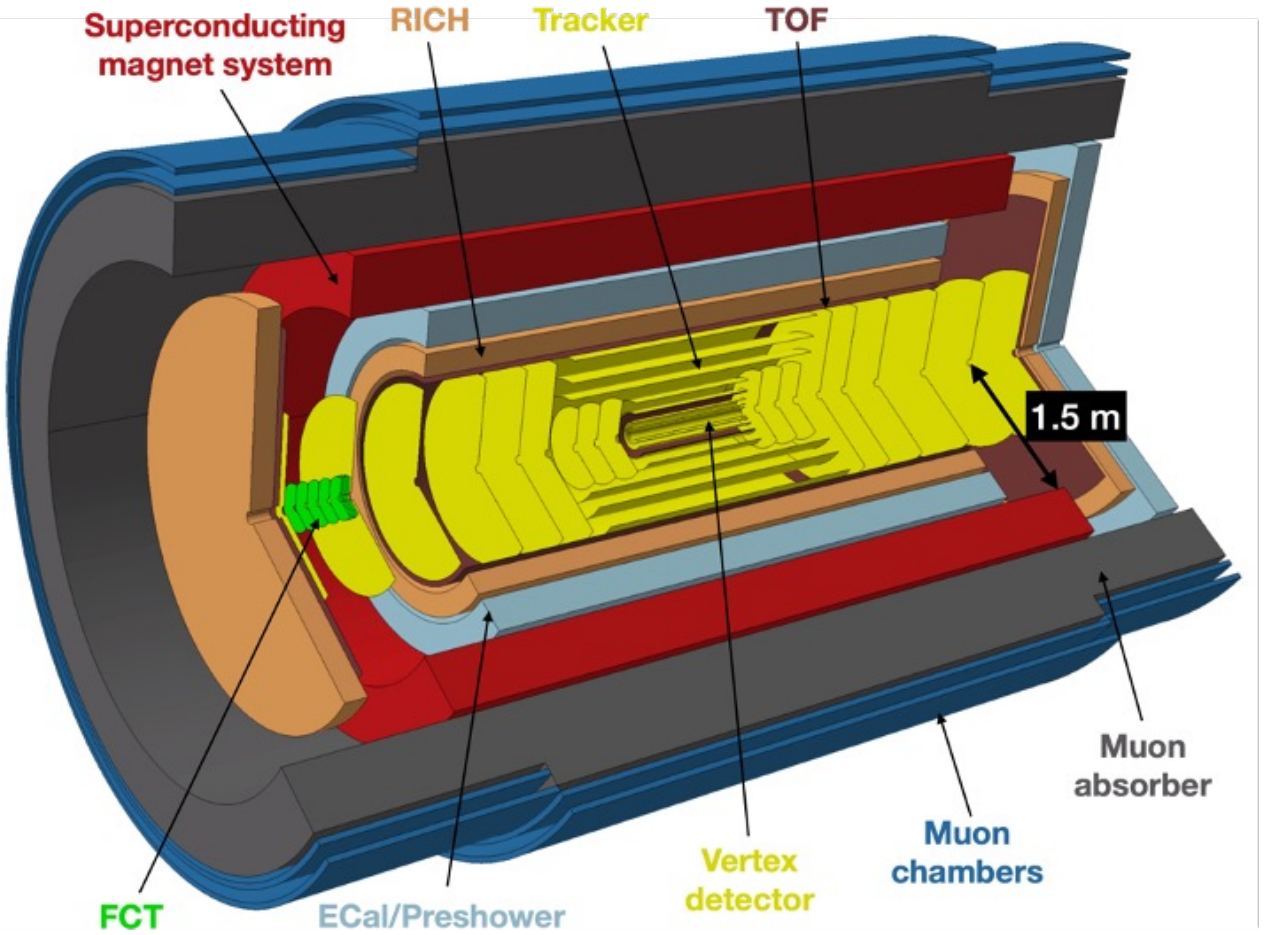
http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

Longer term LHC schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.

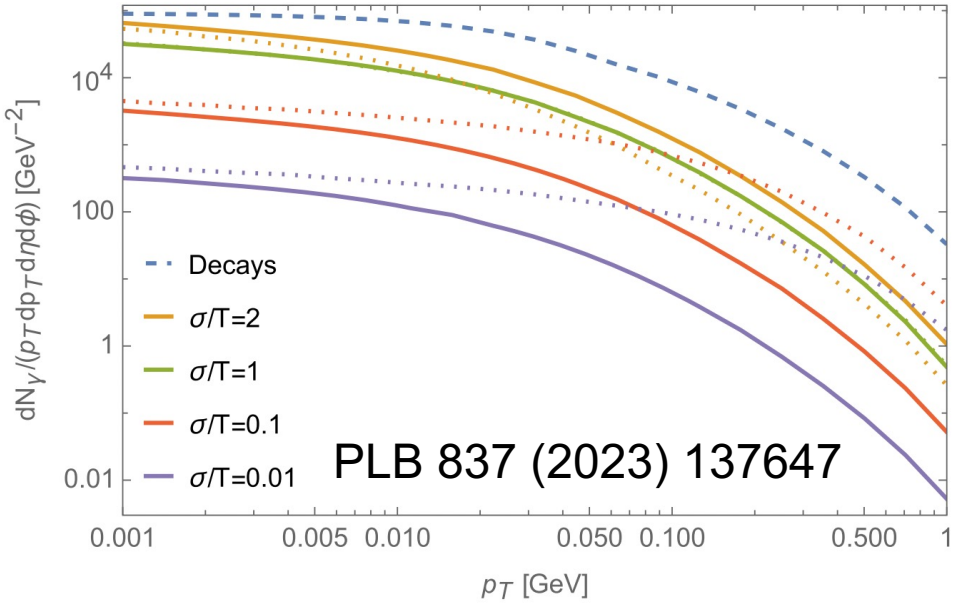


ALICE3



arXiv:2211.02491

- Advanced silicon technology
  - High-rate data acquisition
  - Precise vertexing
  - Strong particle identification at low p_T
- E.g., electrical conductivity with photons/dileptons
  - $p_T << T_{QGP}$ is relevant regime.
  - 2γ correlation is an attractive way.



Summary

- Direct photons have been measured in different collision systems and energies at the LHC.
- No direct photon puzzle due to experimentally large uncertainty at the LHC.
  - Stay tuned for yields and $v_{2,3}$ in larger Pb-Pb data taken in 2018.
  - Smaller material budget uncertainty and new approach to constrain η/π^0 ratio

- Next topic in Run 3 and 4 will be:
  - pre-equilibrium photons
  - Search for thermal radiation in small system with multi-differential analyses

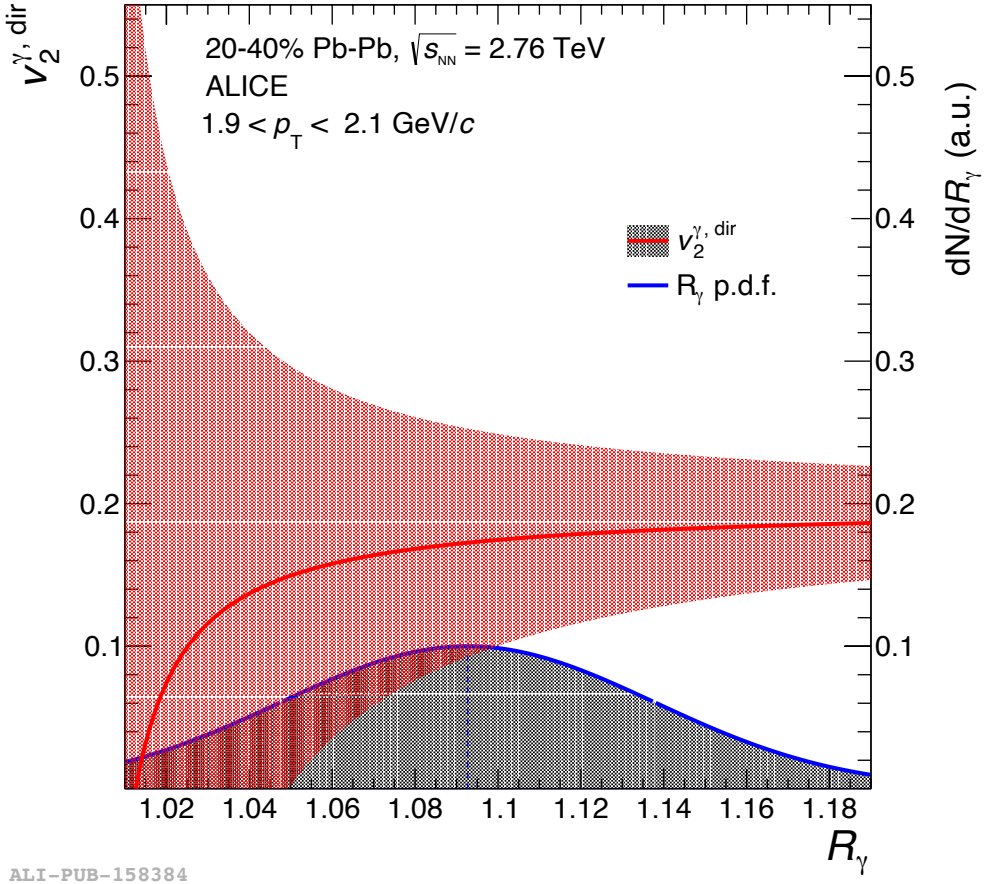
- Beyond 2035 with ALICE3:
  - Differentiate emission sources with HBT correlation as a function of k_T
  - Low-p_T photon << T_{QGP} can be accessed by HBT.

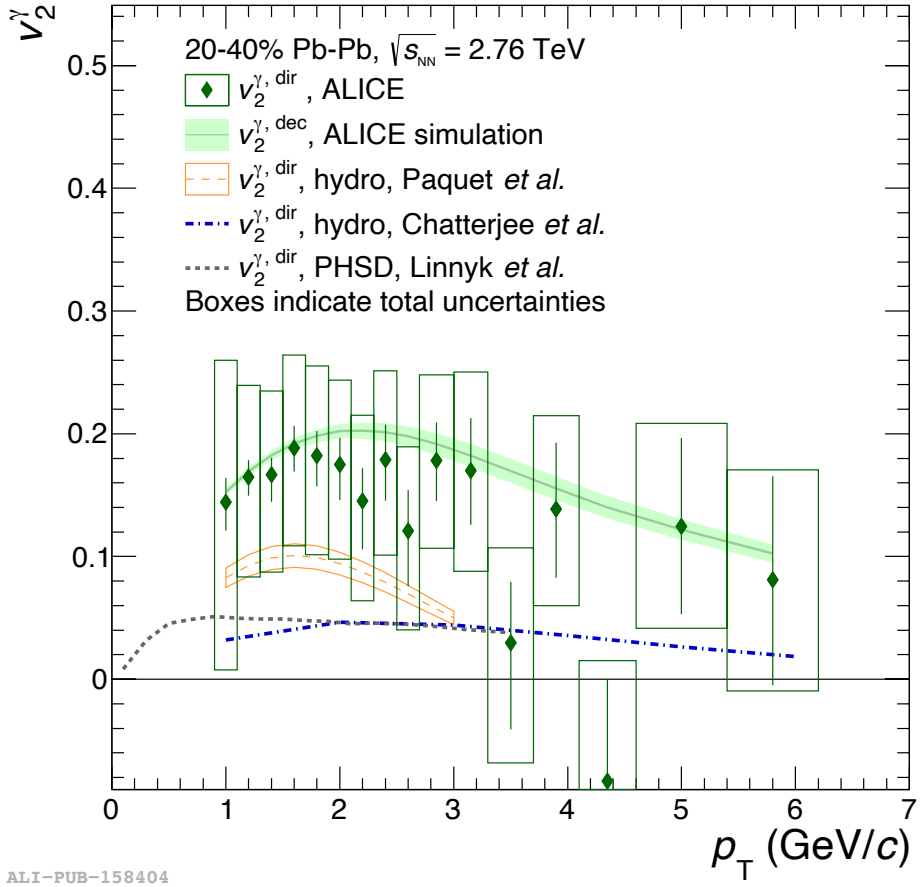
backup

- backup

Direct photon v_2

Phys. Lett. B 789 (2019) 308





- Smaller R_γ leads the larger uncertainty of direct photon v_2.

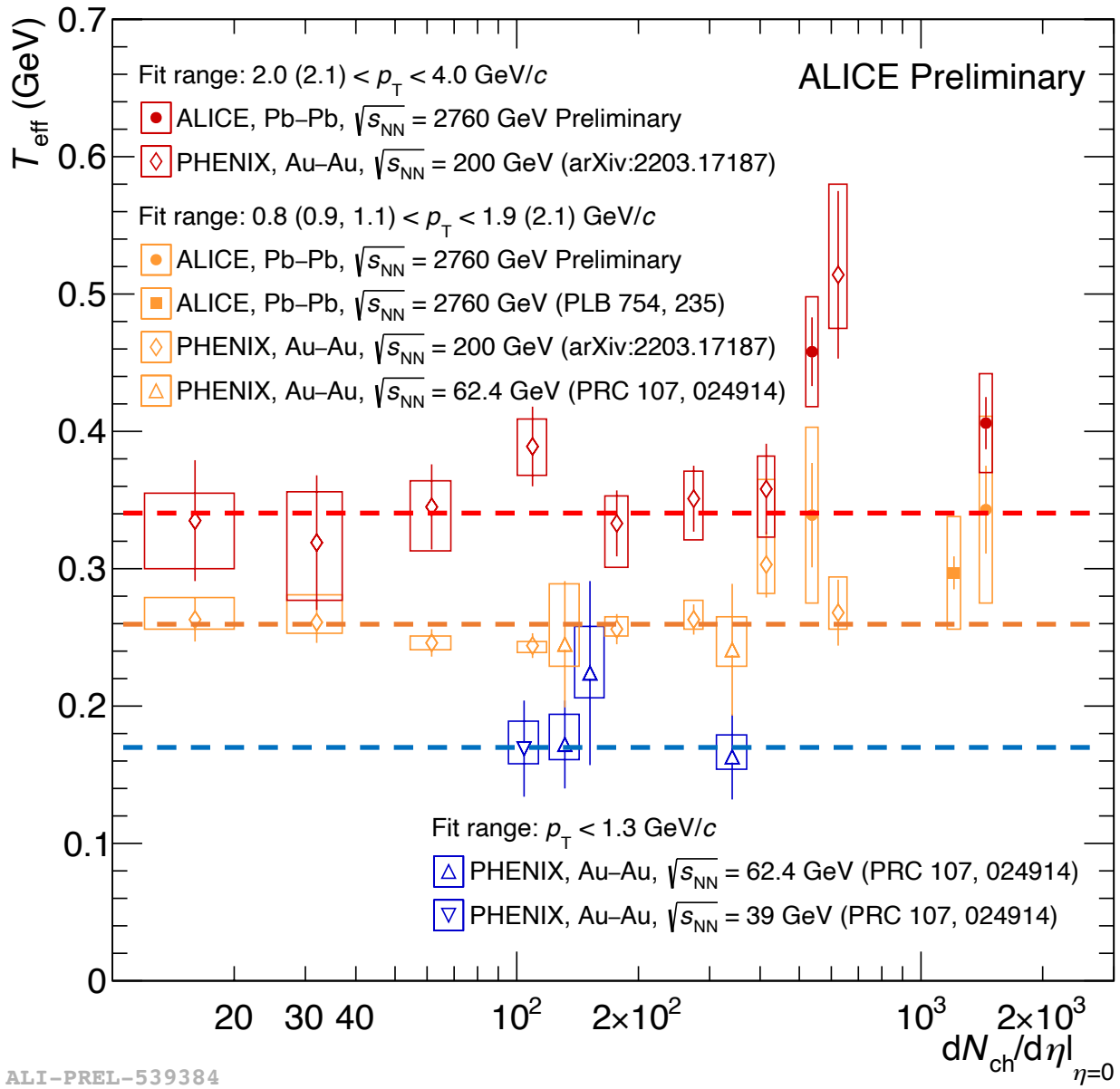
$$v_2^{\gamma,\mathrm{inc}} = \frac{N_{\gamma,\mathrm{dir}}}{N_{\gamma,\mathrm{inc}}} v_2^{\gamma,\mathrm{dir}} + \frac{N_{\gamma,\mathrm{dec}}}{N_{\gamma,\mathrm{inc}}} v_2^{\gamma,\mathrm{dec}}$$

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

References

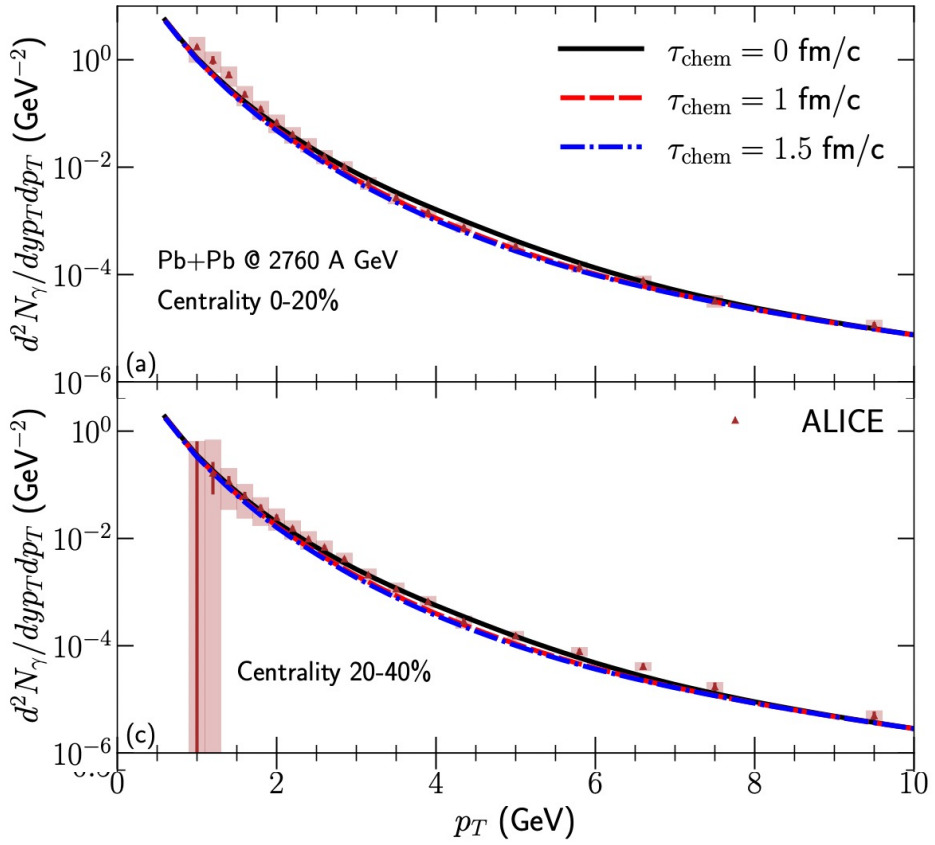
- Phys. Lett. B 754 (2016) 235-248
- Phys. Lett. B 789 (2019) 308
- Phys. Rev. C 99, 024912
- arXiv:2303.15317
- Phys. Lett. B 837 (2023) 137647
- PHYSICAL REVIEW C 91, 024908 (2015)
- PHYSICAL REVIEW C 103, 024904 (2021)
- arXiv:2211.04384
- Physics Letters B 785 (2018) 14–39

Inverse slope in different fitting range

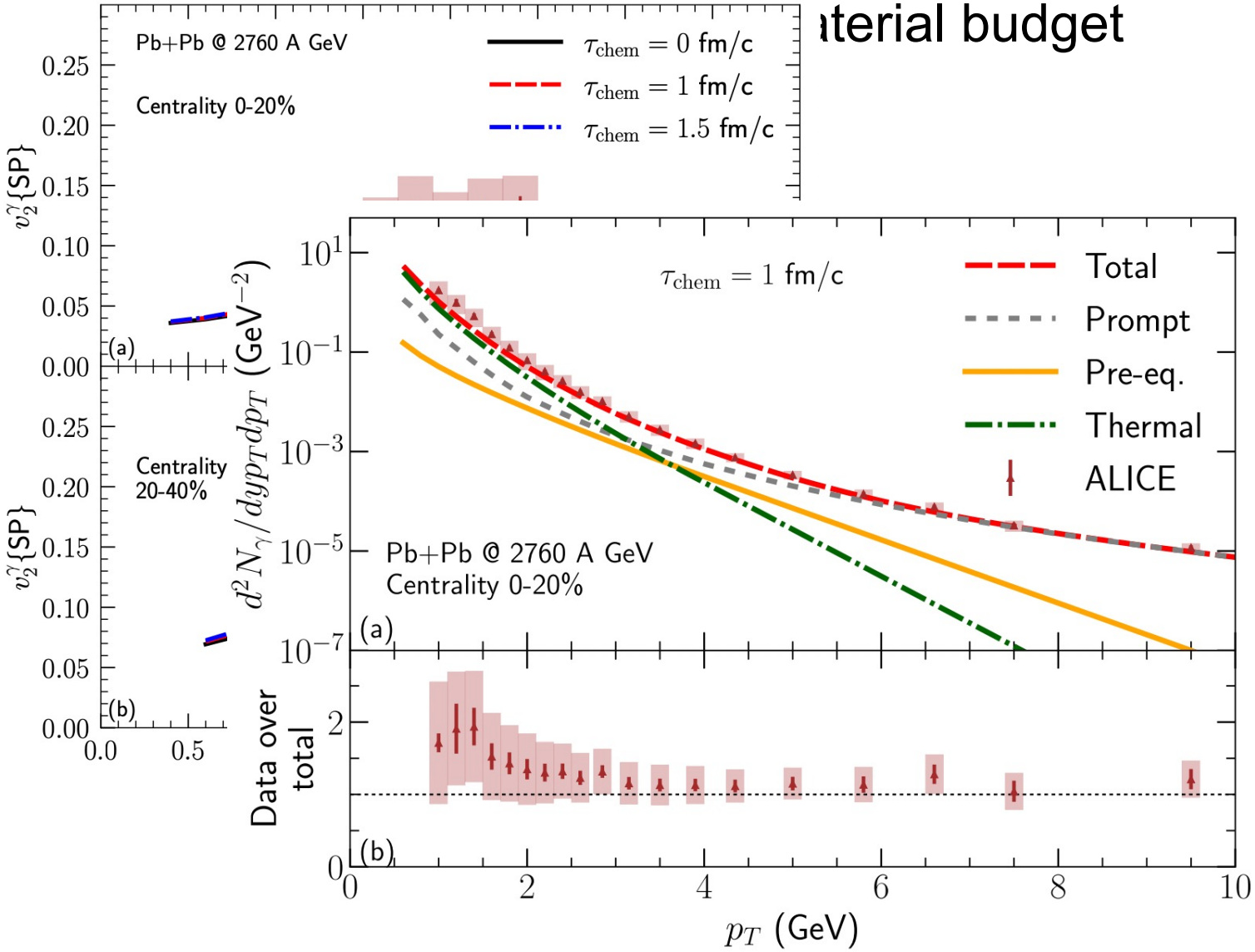


- $1 < p_T < 2$ GeV/c : hadronic gas + blue shift

Direct photon puzzle at the LHC PRC 105, 014909 (2022)

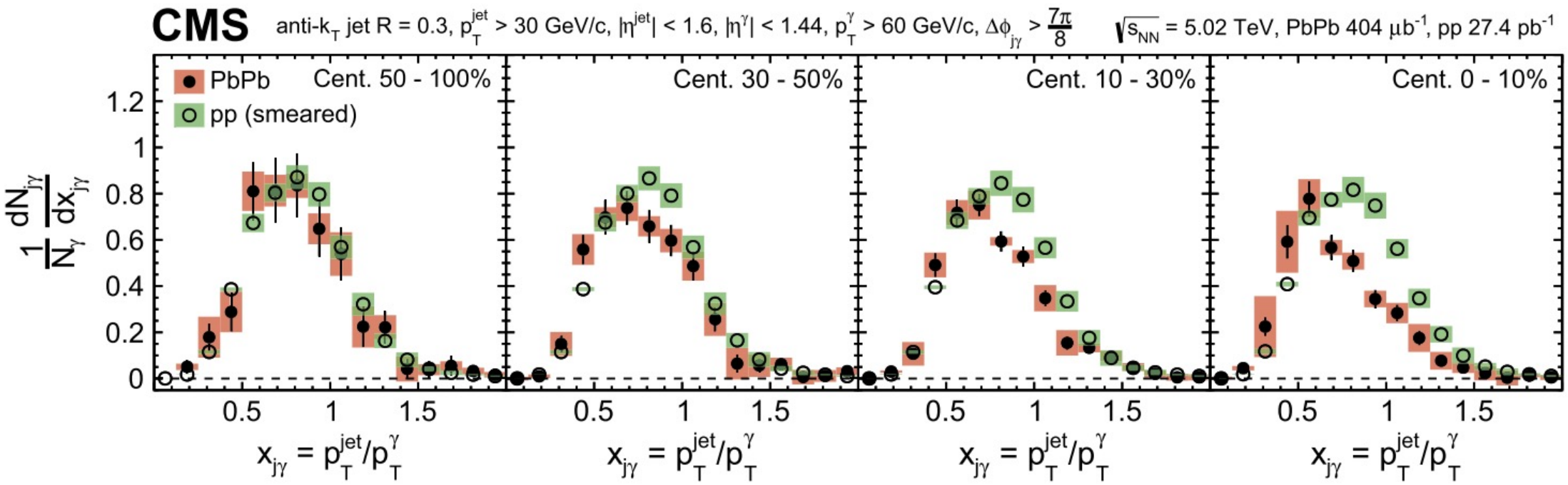


aterial budget



photon-jet momentum imbalance

PLB 785 (2018) 14–39



- Photon energy is reference for parton energy loss in the QCD medium.
- Direct access to transport coefficient of the QCD medium.

$$x_{j\gamma} = p_T^{jet} / p_T^{\gamma}$$