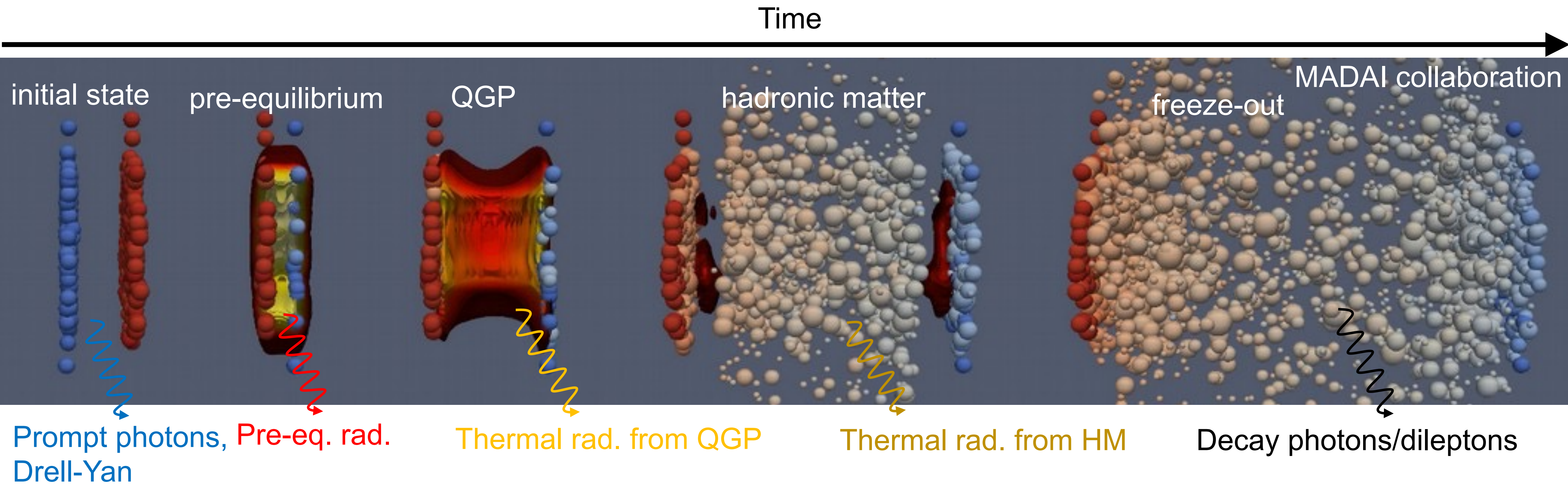
Electromagnetic probes in ALICE at the LHC

Daiki Sekihata

Center for Nuclear Study, the University of Tokyo

16.Nov.2023, Nuclear Physics Colloquium, Goethe University Frankfurt

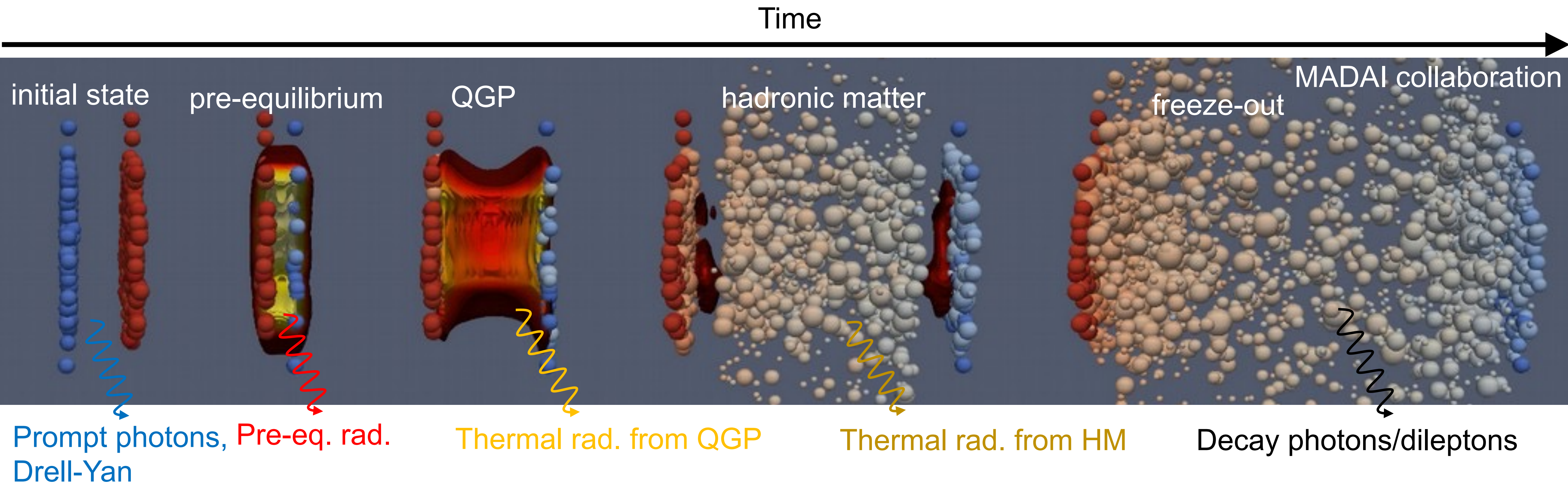
Uniqueness of EM probes



- Photons and dileptons are emitted from all stages.
- Transparent to strong interaction, unlike hadrons

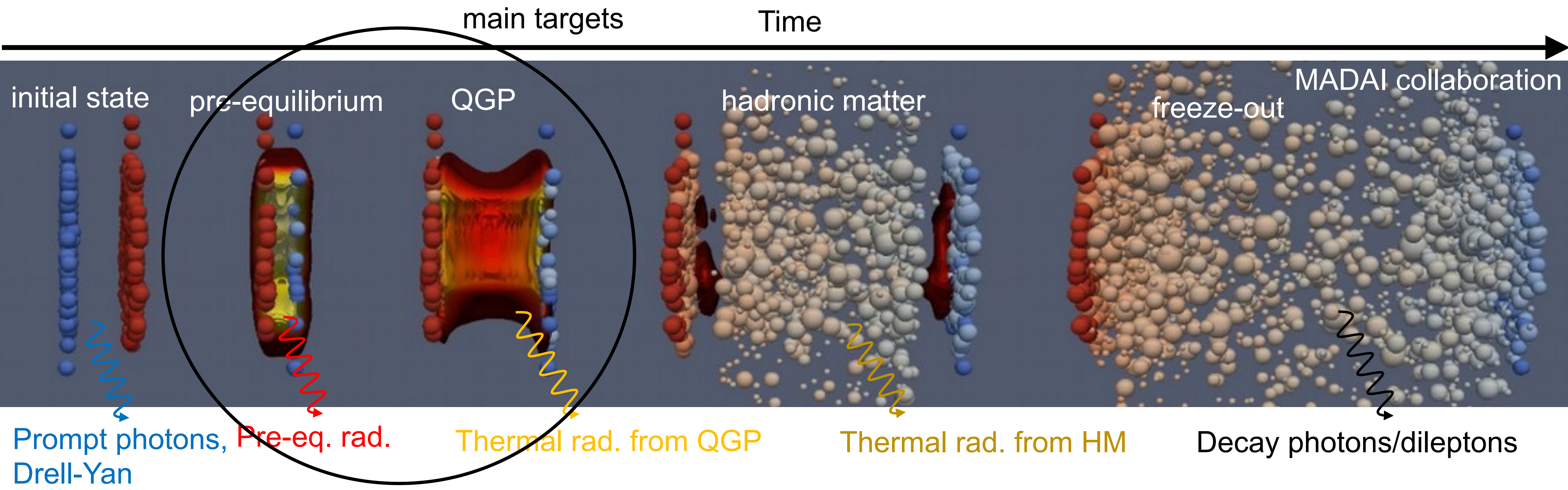
→ EM probes carry undistorted information at the time of their productions.

Physics motivations of EM probes



- Hard scatterings: modification of parton distribution function in nuclei
- Pre-equilibrium radiation: parton dynamics in pre-equilibrium and pre-hydro stage
- Thermal radiation: thermodynamical properties and space-time evolution of QGP and hadronic matter

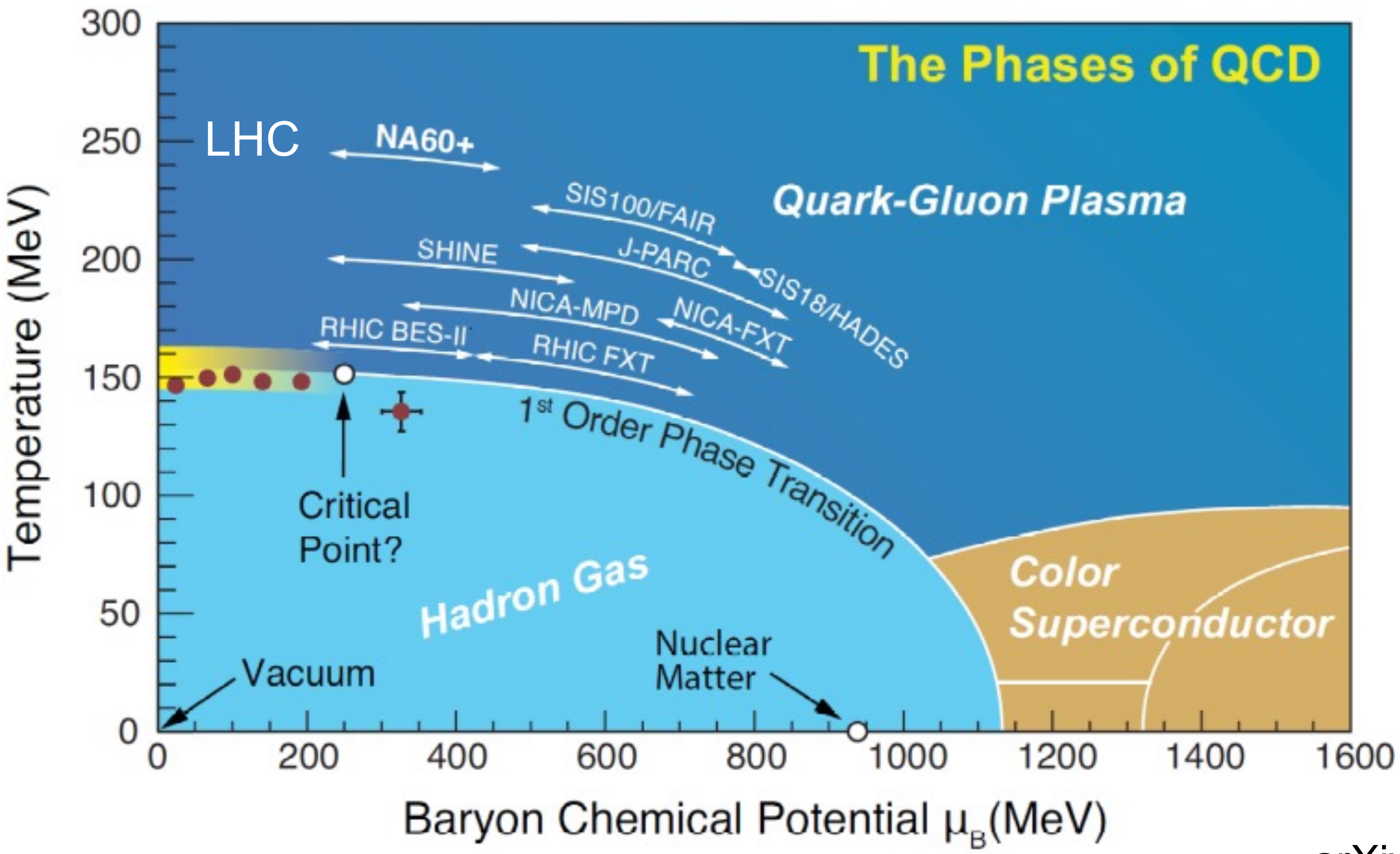
Physics motivations of EM probes



- Determine early stage of high-energy heavy-ion collisions

  → constrain theoretical models to understand space-time evolution of the collision
  e.g. average temperature over space-time, viscosity

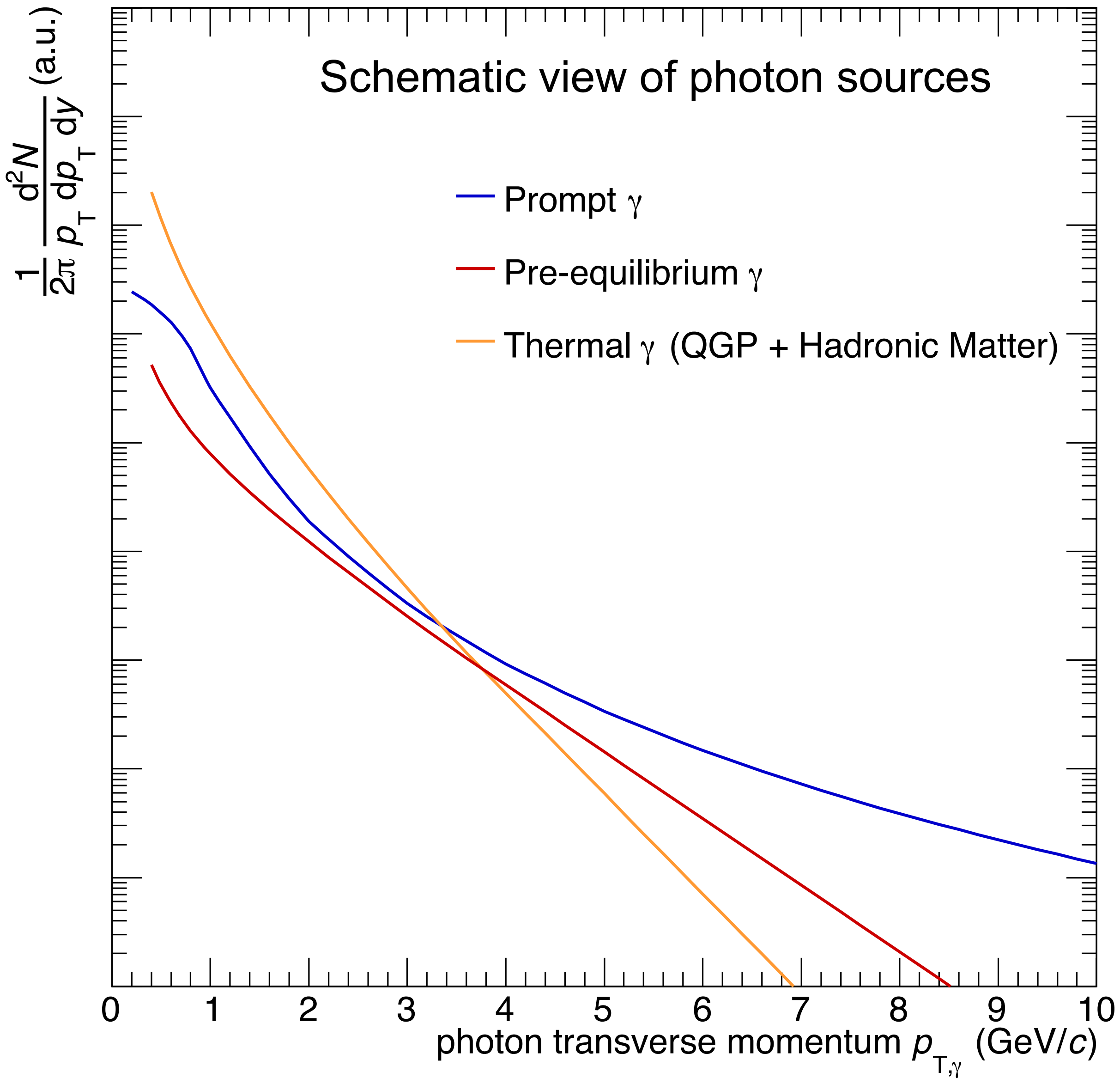
EM probes at LHC energies



arXiv:2108.11300
courtesy of Thomas Ullrich

- ALICE explores medium properties at $\mu_B = 0$.
- Largest, hottest, and longest-lived QGP

Photons



- Prompt photon from initially hard scatterings
- Pre-equilibrium photon
- Thermal photon from QGP + Hadronic Matter

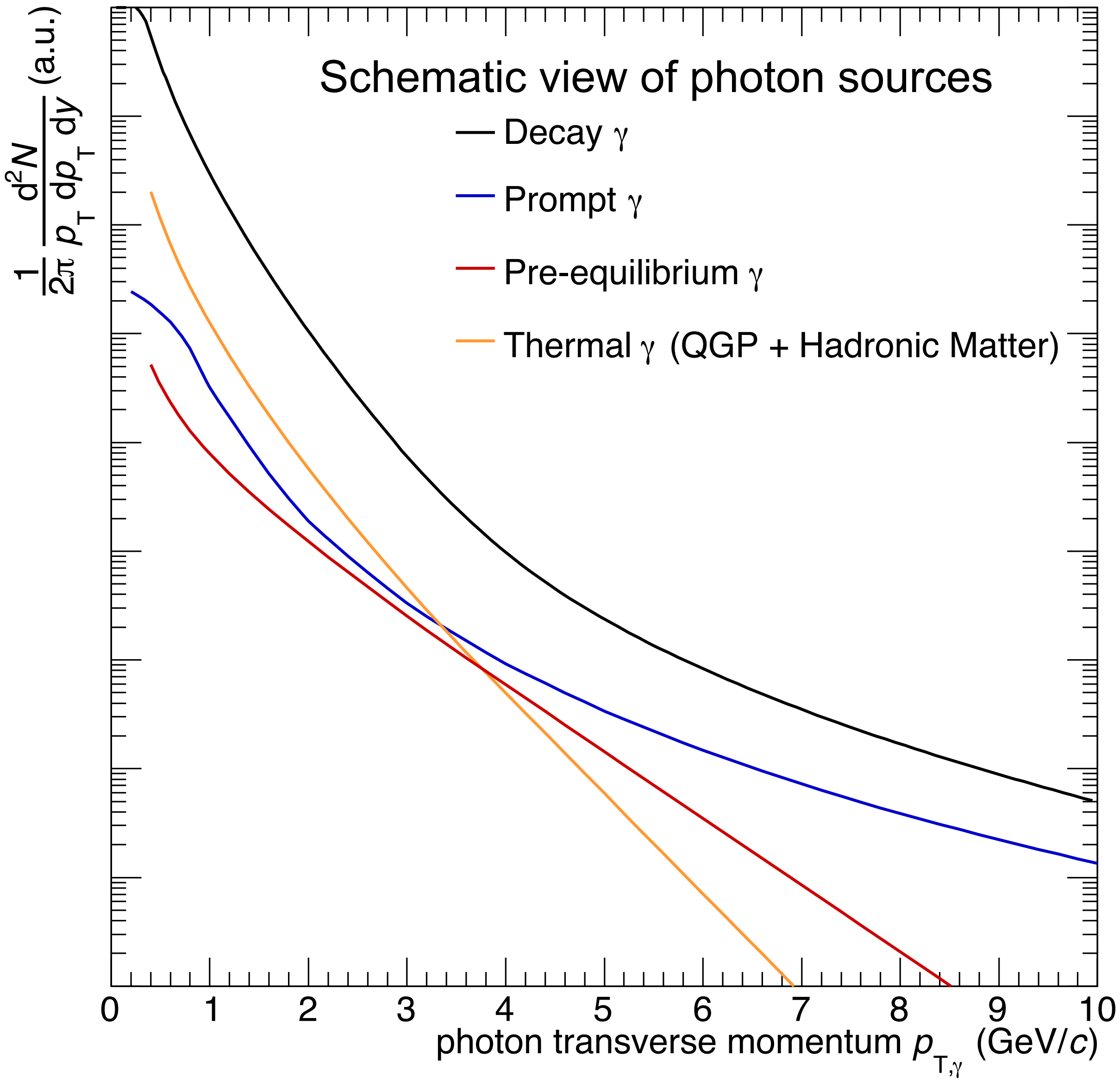
Direct photons: photons not from hadron decays

Sources are distinguishable by p_T range:

yields, v_2 and inverse slope with blueshift provide information on early stages + models

Recently, a new category is discussed.
non-prompt direct photon = total direct photon – prompt
i.e. = pre-equilibrium + thermal photons

Photons



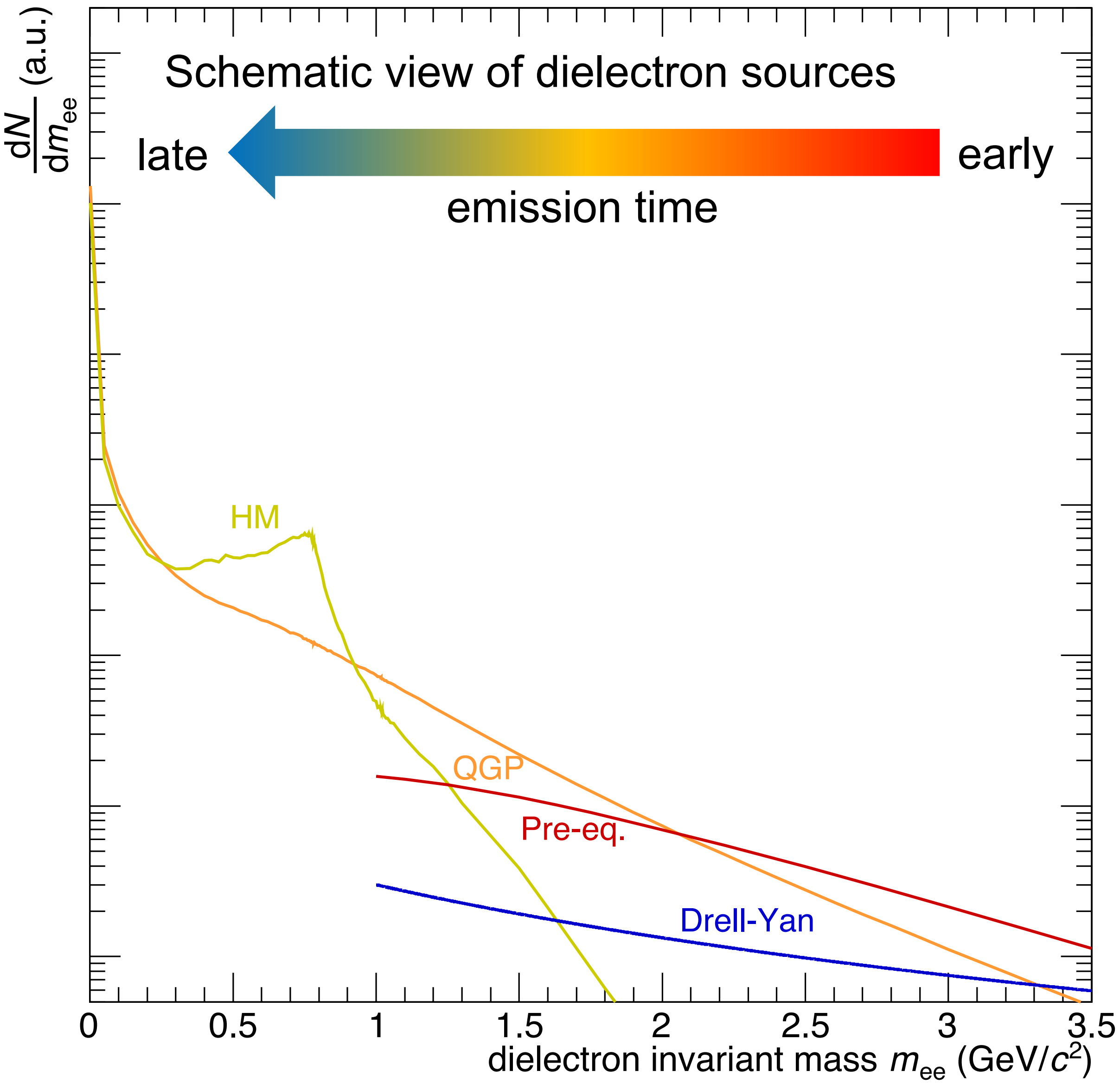
- Prompt photon from initially hard scatterings
- Pre-equilibrium photon
- Thermal photon from QGP + Hadronic Matter
- Large background from hadron decays

Direct photons: photons not from hadron decays

Experimentally, measurements are limited by systematic uncertainties. $\pi^0, \eta \rightarrow \gamma\gamma$

Recently, a new category is discussed.
non-prompt direct photon = total direct photon – prompt
i.e. = pre-equilibrium + thermal photons

Dielectrons $\gamma^* \to e^+e^-$

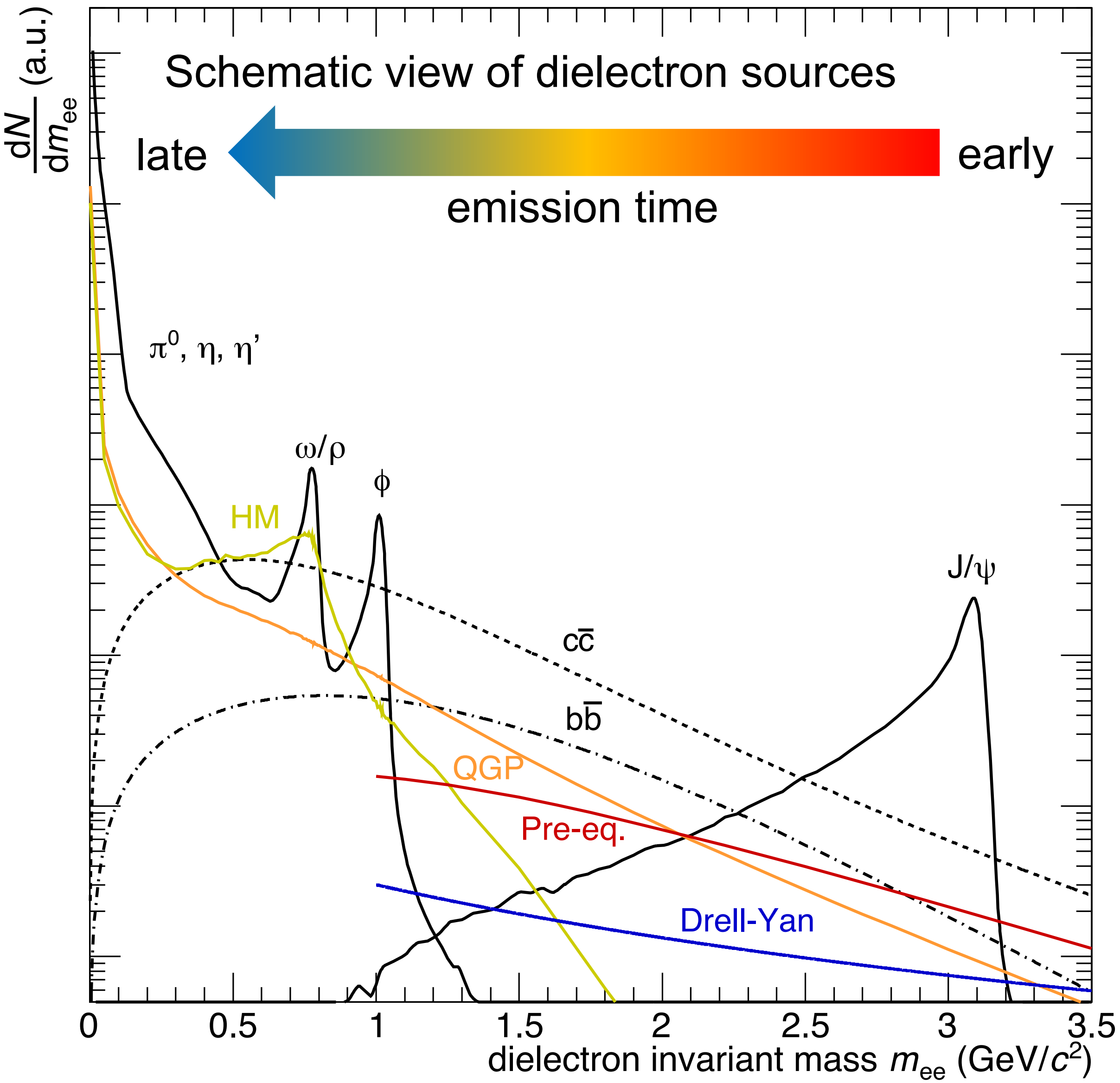


- Drell-Yan
- Pre-equilibrium radiation
- Thermal radiation

Additional variable: pair invariant mass
→ serves as a clock

Inverse slope without blueshift provides direct information on averaged temperature

Dielectrons $\gamma^* \rightarrow e^+e^-$



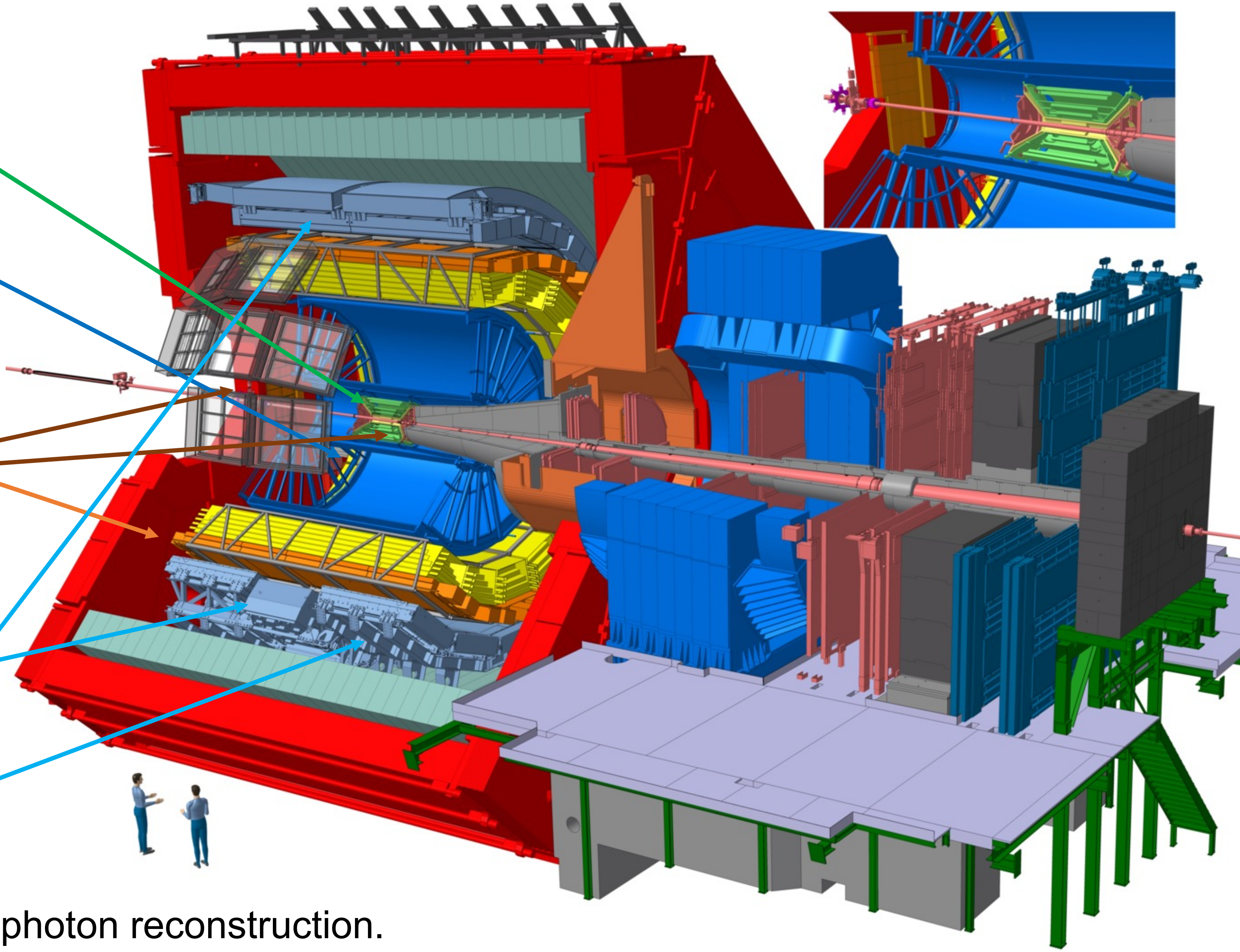
- Drell-Yan
- Pre-equilibrium radiation
- Thermal radiation
- Hadronic decays

Additional variable: pair invariant mass
→ serves as a clock

Dielectrons suffer from statistics and physical background.
Especially, dielectron from correlated HF hadron decays is huge background for thermal radiation from QGP.

ALICE detectors at the LHC

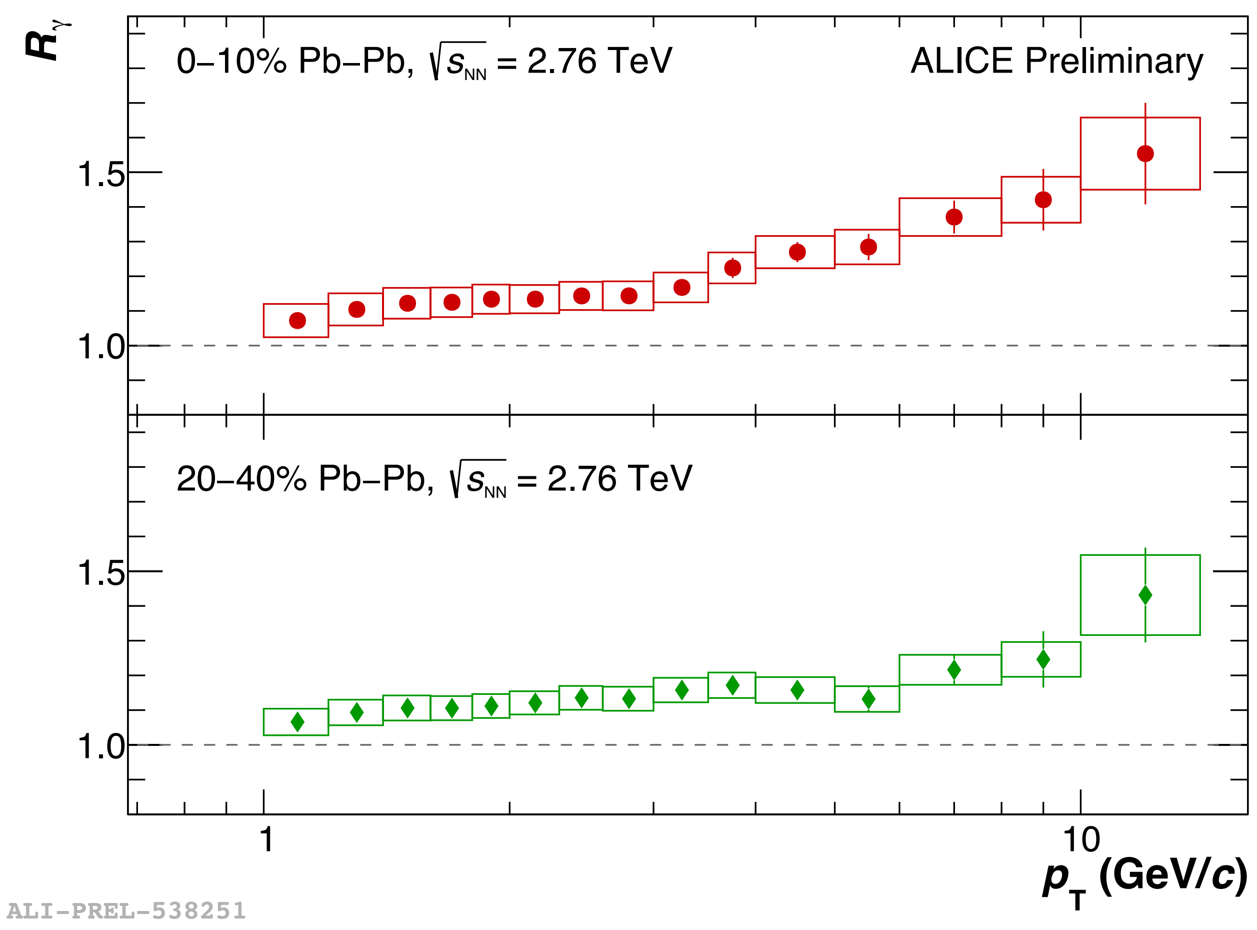
- Inner Tracking System (ITS)
  - Vertexing
  - Tracking
- Time Projection Chamber (TPC)
  - Tracking
  - Particle identification
- Time of Flight (TOF)
  - Particle identification
- V0 at forward/backward rapidity
  - Triggering
  - Multiplicity determination
- Photon Spectrometer (PHOS)
  - $PbWO_4$ crystals, homogenous calo.
- EMCal/DCal
  - Pb + scintillator, sampling calo.



Photon Conversion ($\gamma \rightarrow e^+e^-$) is also used for photon reconstruction.

Direct photons

Direct photon excess ratio in Pb-Pb at 2.76 TeV



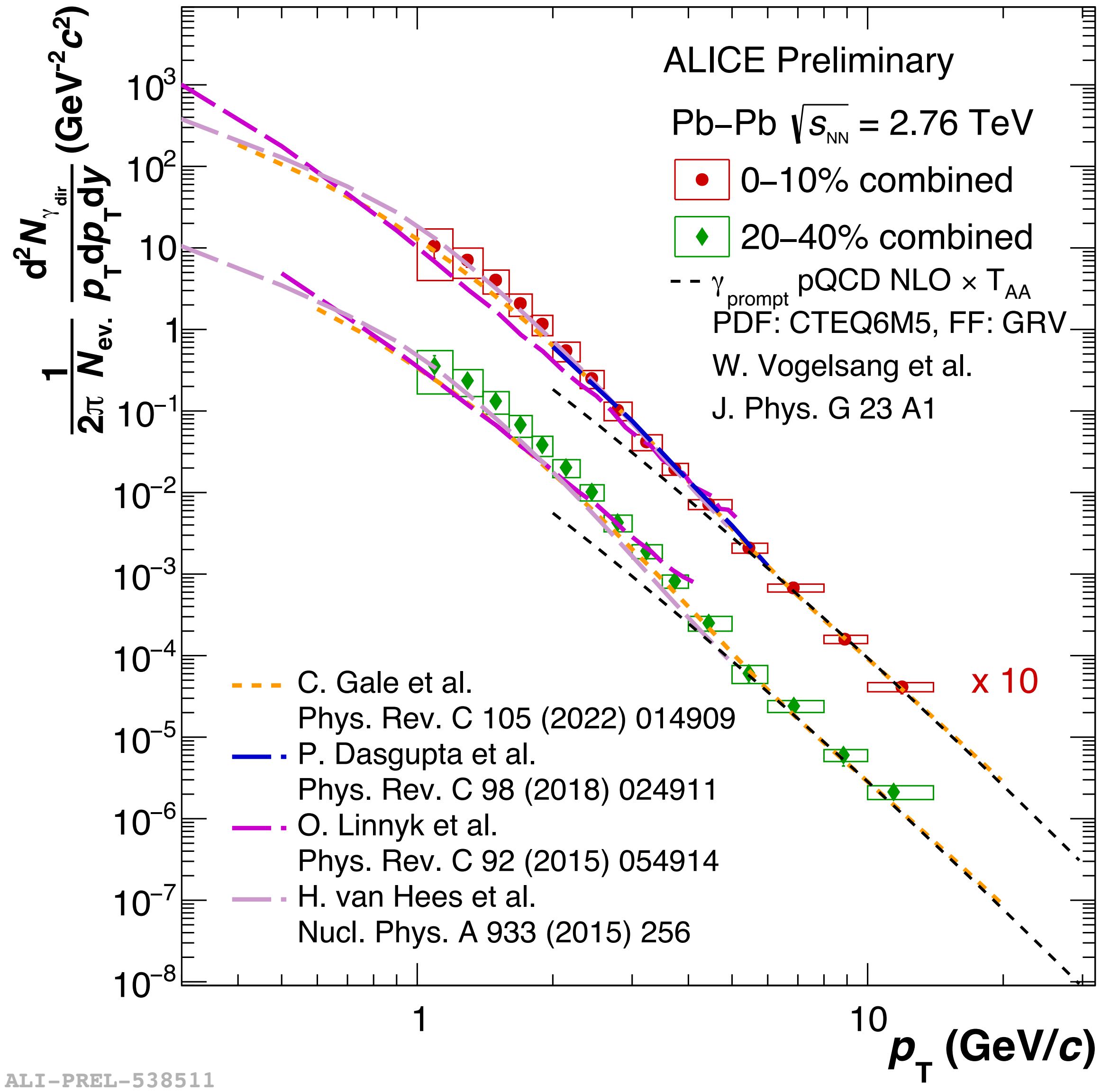
$$\gamma^{\mathrm{dir}} = \gamma^{\mathrm{inc}} - \gamma^{\mathrm{decay}} = \gamma^{\mathrm{inc}} \cdot \left(1 - \frac{1}{R_\gamma}\right)$$

$$R_\gamma = \frac{\gamma^{\mathrm{inc}}}{\gamma^{\mathrm{decay}}} = \frac{(\gamma^{\mathrm{inc}}/\pi^0)_{\mathrm{data}}}{(\gamma^{\mathrm{decay}}/\pi^0)_{\mathrm{cocktail}}}$$

- If $R_\gamma > 1$, direct photon signal

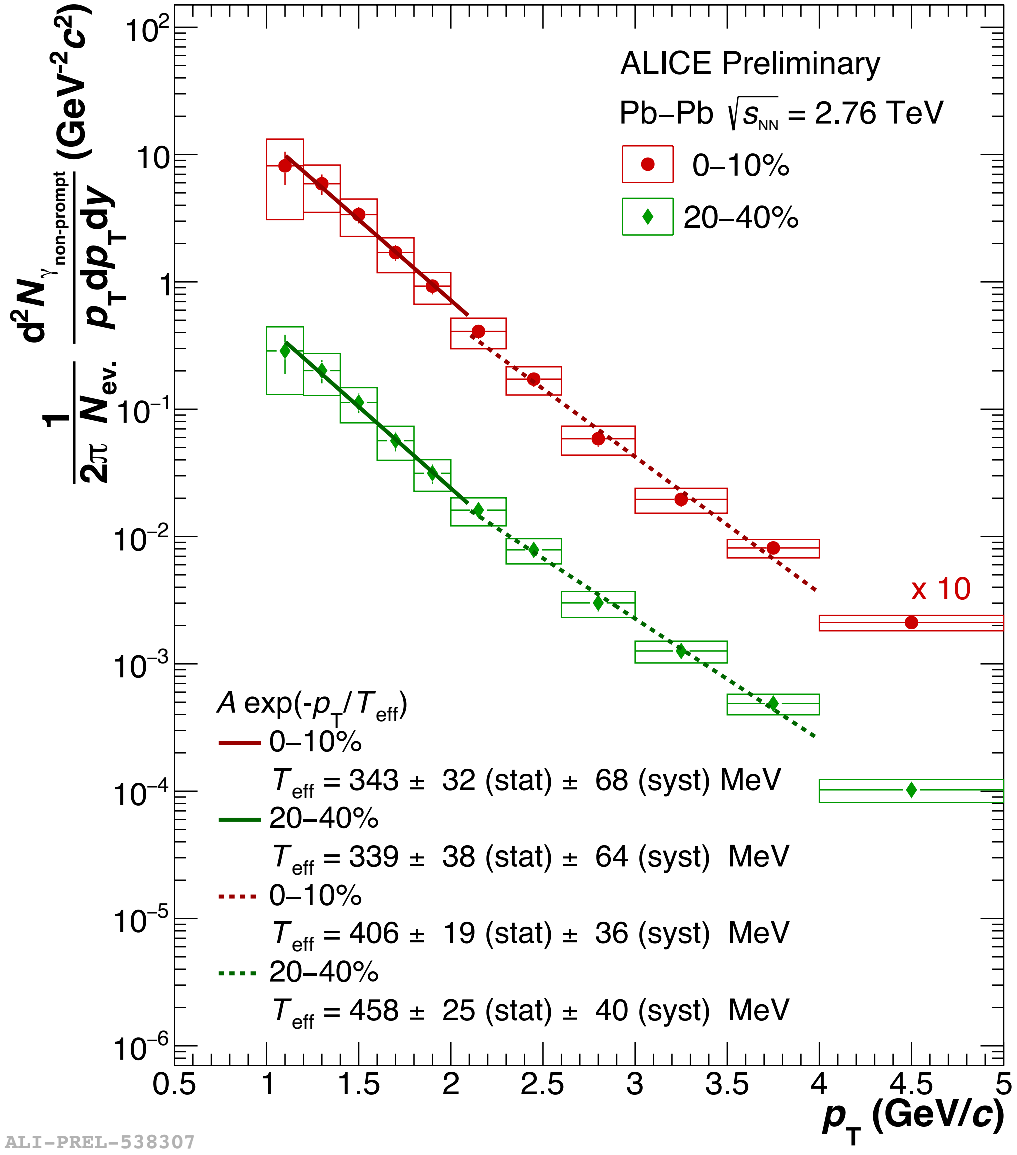
- Improved results from the previous publication (PLB 754 (2016) 235-248)
  - Larger statistics : 20M events in 0-10%
  - Material budget correction (arXiv:2303.15317)

Direct photons p_T spectra in Pb-Pb at 2.76 TeV



- Improved results from the previous publication (PLB 754 (2016) 235-248)
  - Larger statistics : 20M events in 0-10%
  - Material budget correction (arXiv:2303.15317)
- Most precise direct photon results in ALICE ever
- Consistent with NLO pQCD calculation at high p_T
- Excess of direct photon production beyond pQCD calculation for $p_T < 4$ GeV/c
  - Thermal + pre-eq. photons

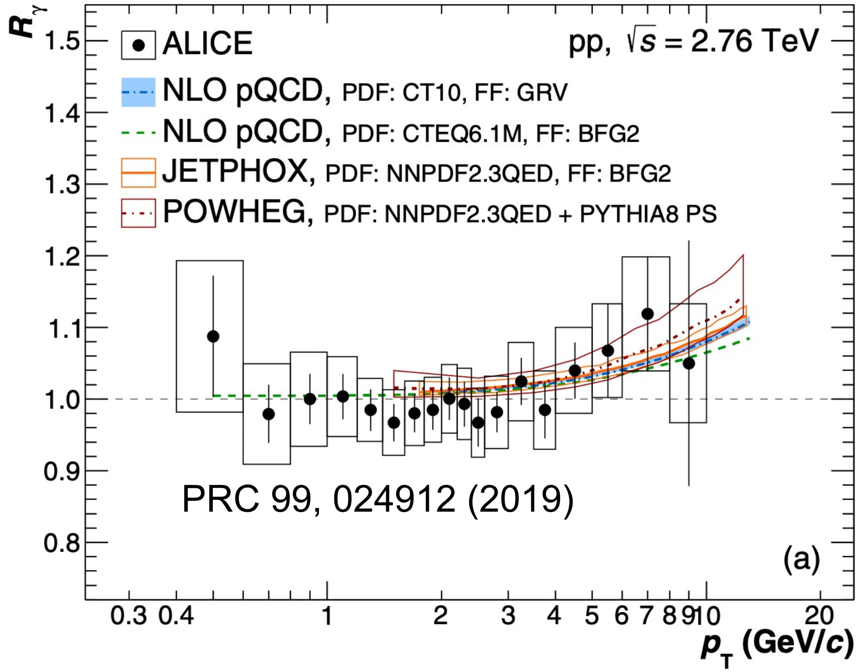
Inverse slope parameter T_{eff} of nonprompt direct photon



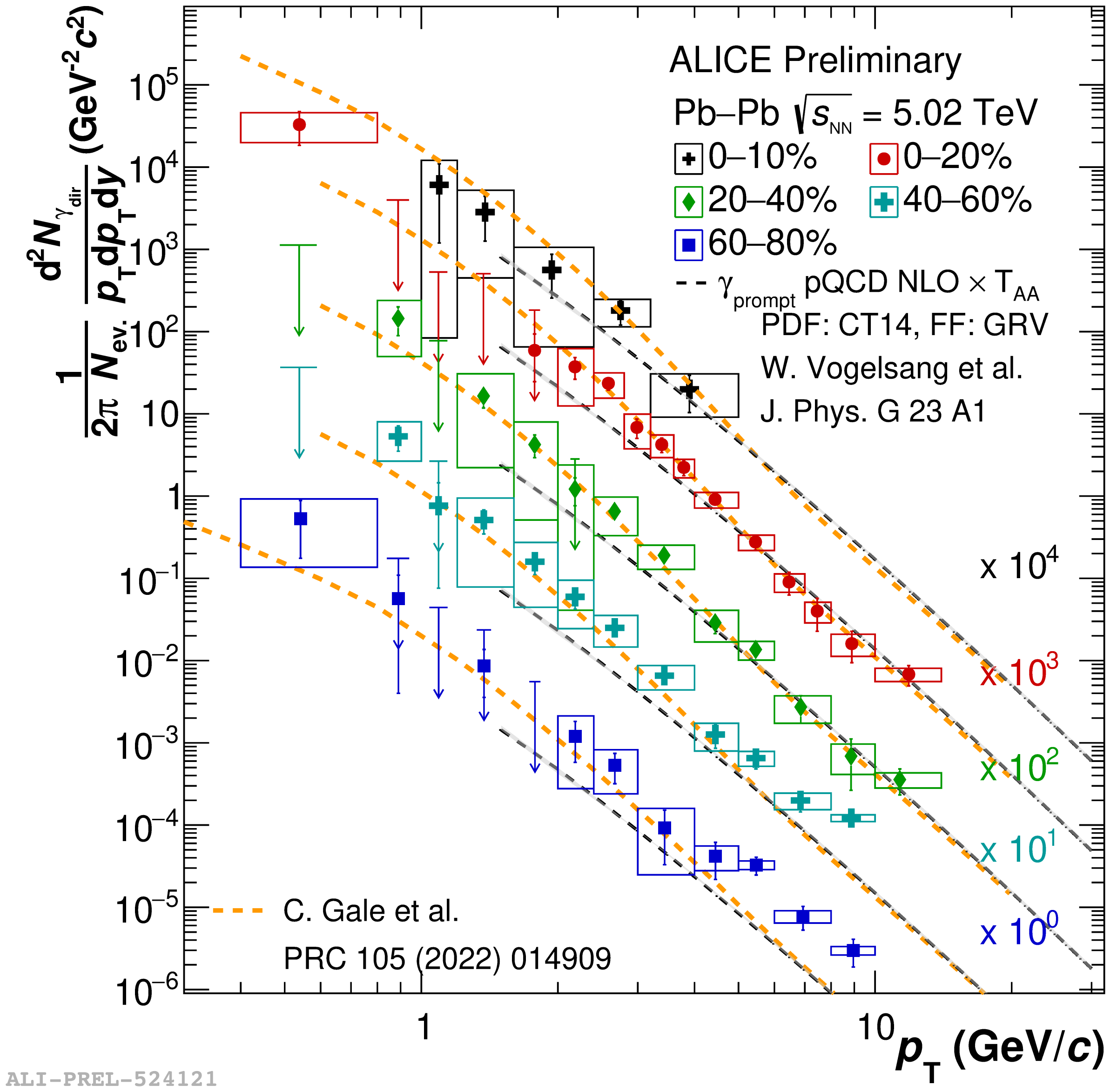
- Average temperature over space-time evolution
  - early temperature
  - expansion velocity (i.e. blue shift)
- First nonprompt direct photon at the LHC
  - $\gamma^{nonprompt} = \gamma^{direct} - \gamma^{pQCD}$
  - importance of pp ref.

Ideally, one should measure

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

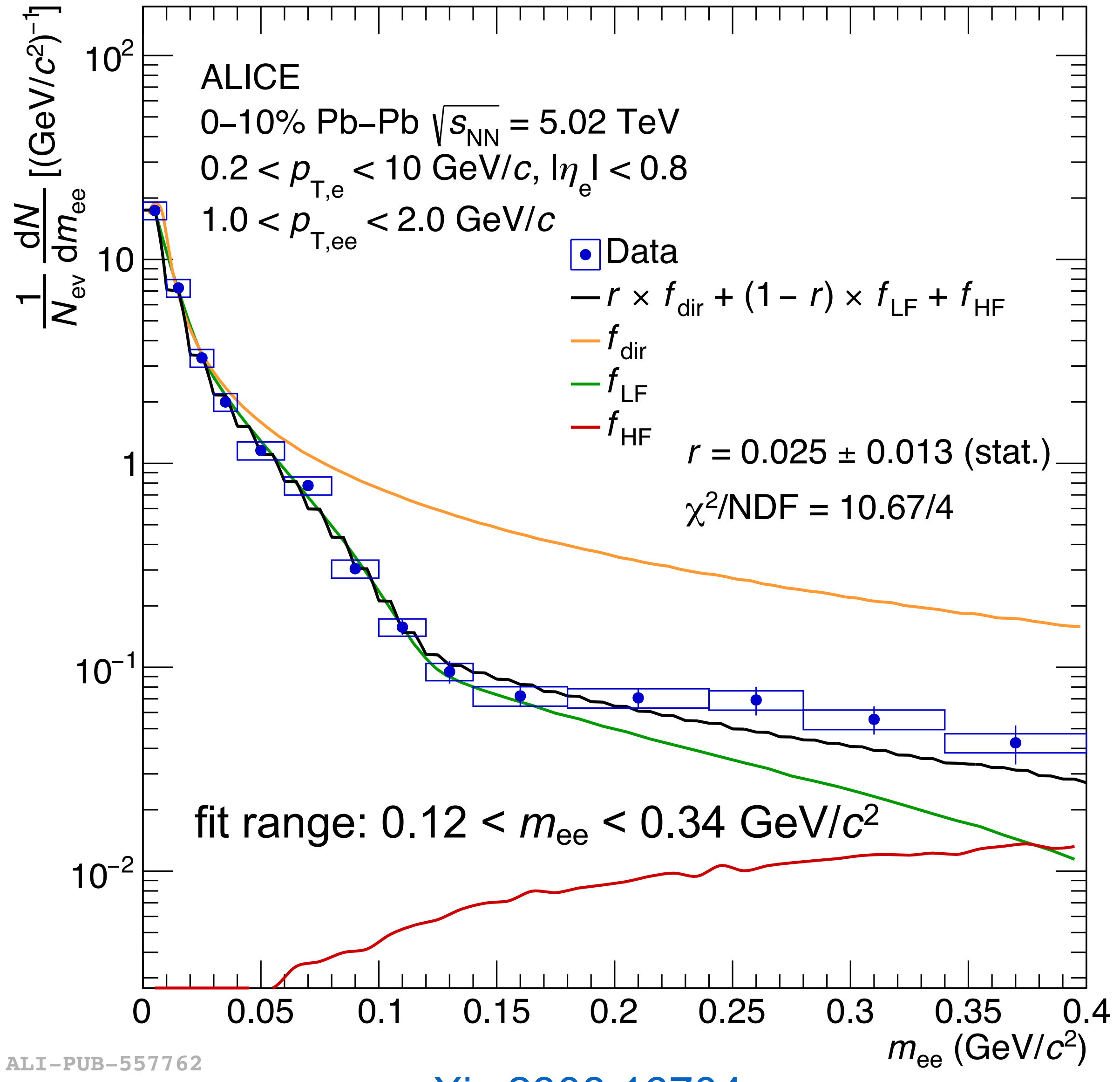


Direct photon p_T spctra in Pb-Pb at 5.02 TeV



- Consistent with NLO pQCD calculation at high p_T
- Consistent with the latest model PRC 105 (2022) 014909
  - Prompt + pre-eq. + thermal photons
- Outlook: analyzing full statistics in Pb-Pb at 5.02 TeV
  - 100M events in 0-10%
  - 90M events in 30-50%
    -- v_2 measurement

Extracting direct photon signal from dielectron m_{ee} spectrum



- Template fit with 3 components
  - Light-flavor (measured p_T spectra in ALICE and decayer)
  - Heavy-flavor (fixed to measured m_{ee} and $p_{T,ee}$ spectra)
  - Dielectrons associated with real photons by Kroll-Wada

$$\frac{d^2N}{dm_{ee}dp_T} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{dN}{dp_T}$$

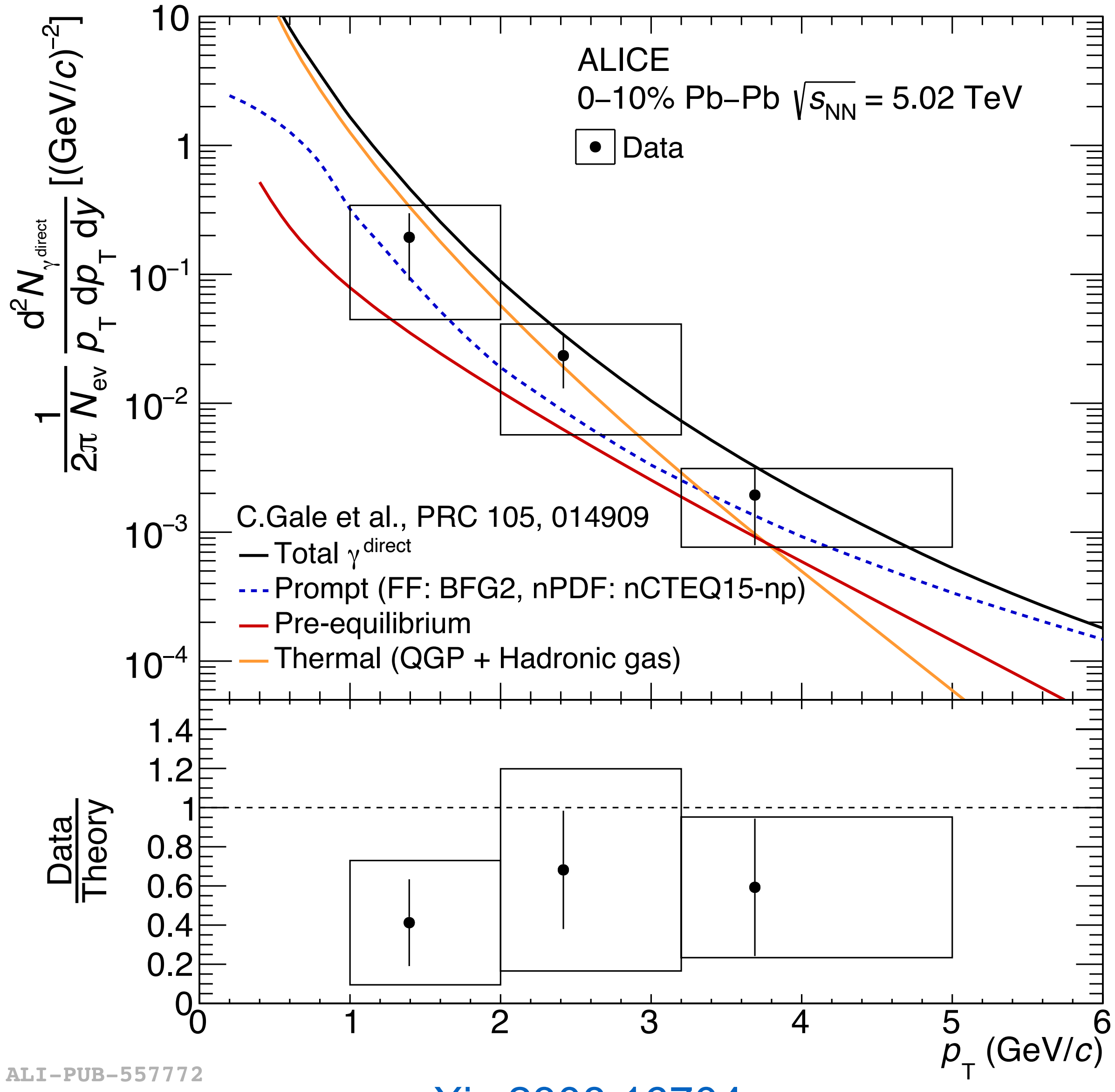
N.M. Kroll and Walter Wada, Phys. Rev. 98, 1355

  - $dN/dm_{ee} = r \times f_{dir} + (1-r) \times f_{LF} + f_{HF}$
  - r : only free parameter for direct photon fraction

- Advantage : select m_{ee} window above π^0 mass
  - 85% of decay photons is from π^0.
  - Main background for direct photons: $\eta \to e^+e^-\gamma$

arXiv:2308.16704

Direct photon production in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



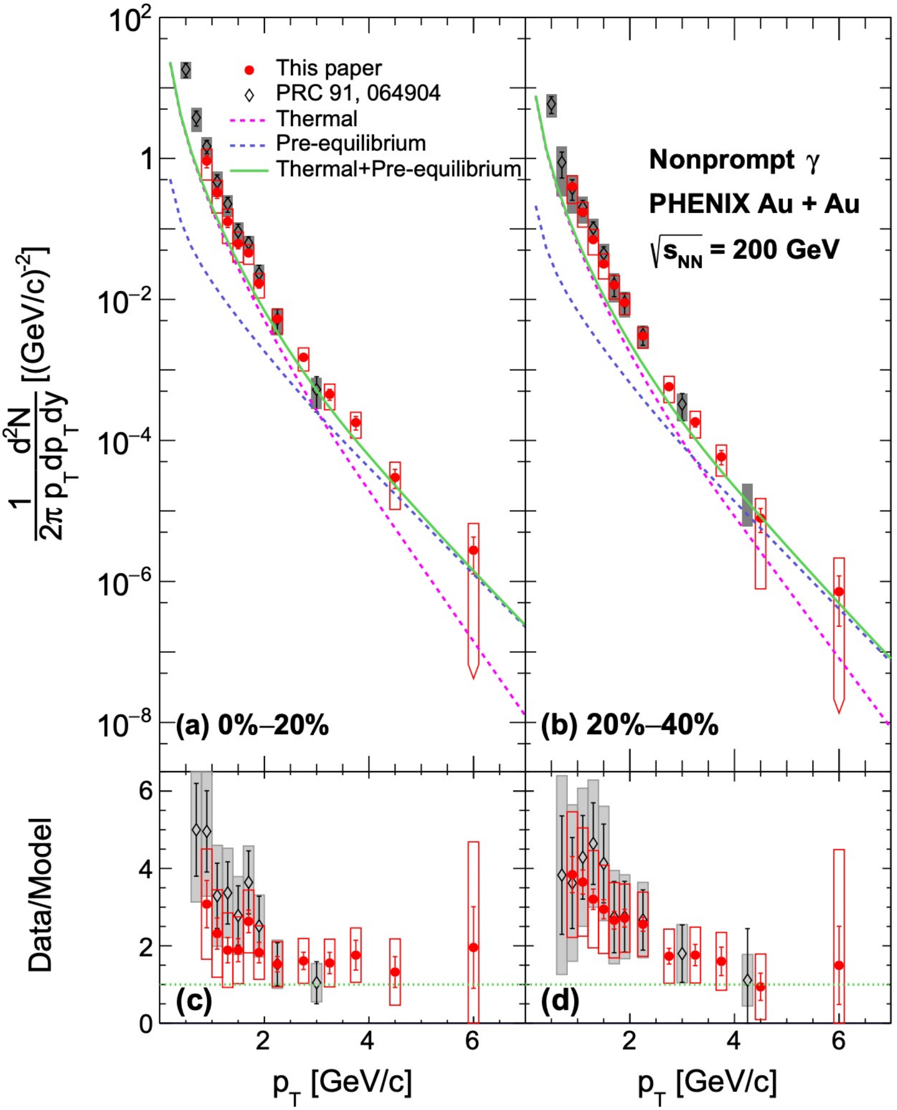
- First direct photon measurement via dielectrons in Pb–Pb collisions with ALICE

- Compared with the latest model
  - Including photons from all stages:
    Prompt + pre-equilibrium + thermal photons
  - Describes ALICE data within experimental uncertainties
  - Tend to be upper edge of uncertainty

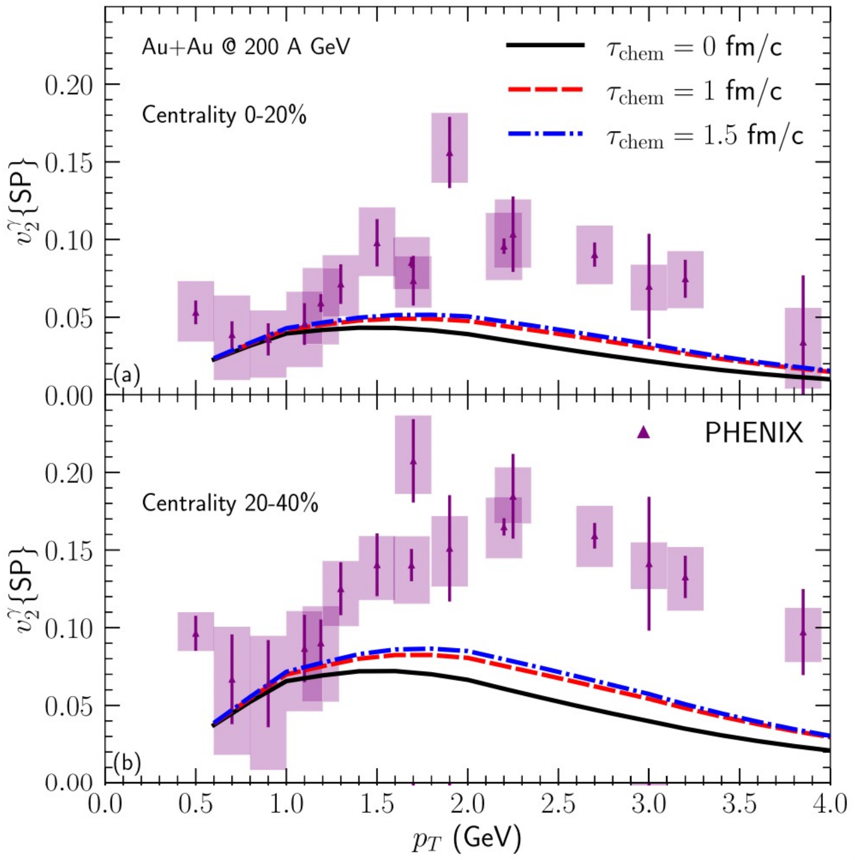
arXiv:2308.16704

Direct photon puzzle

Originally, suggested by PHENIX at RHIC



arXiv:2203.17187

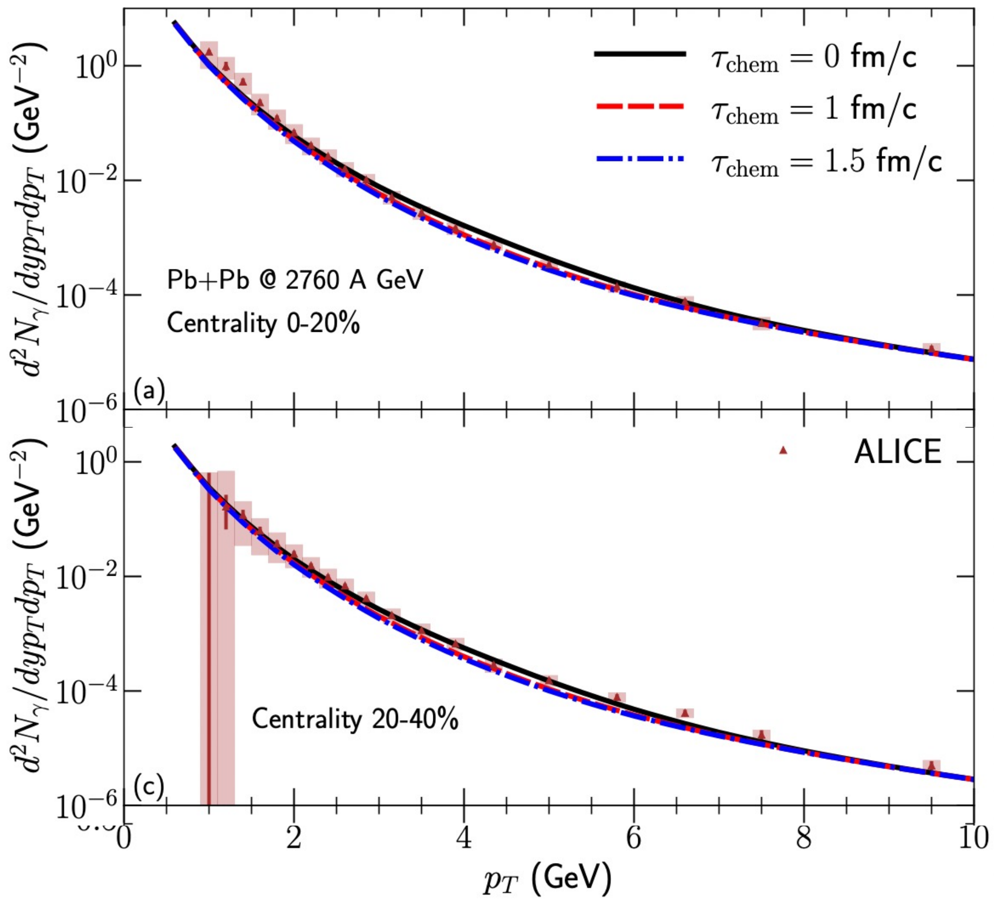


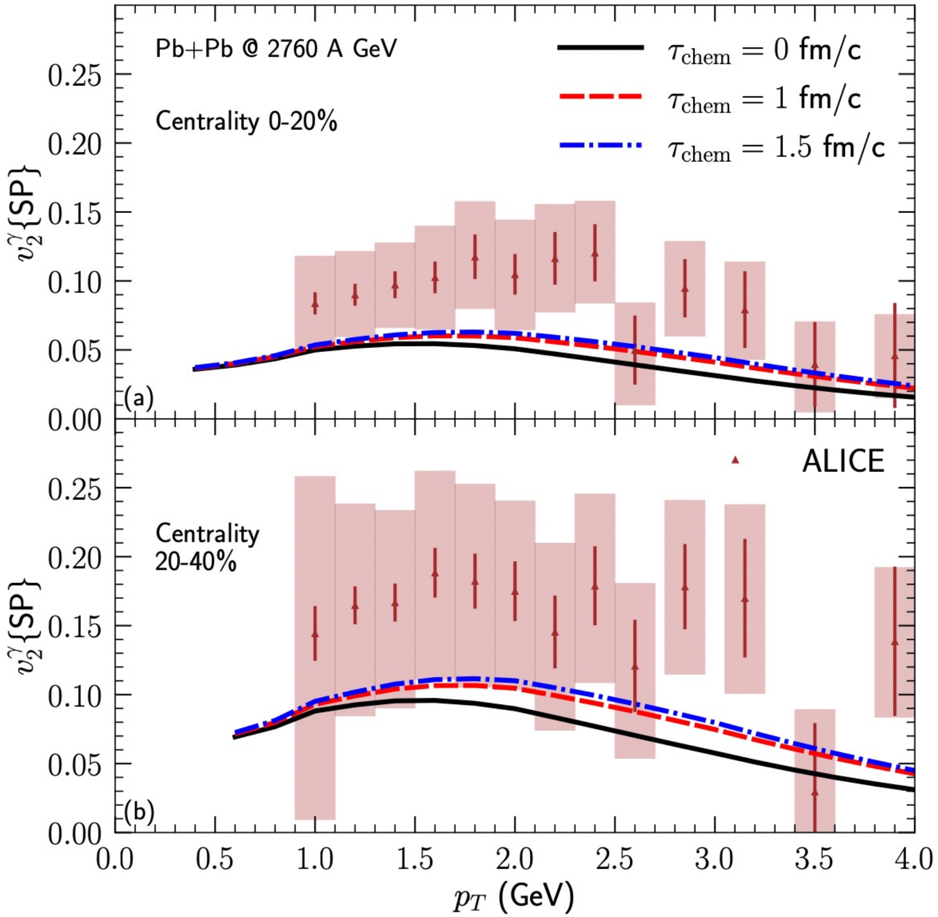
PRC 105, 014909 (2022)

- Large yield: early stage emission from hot medium
- Large v_2: late stage emission when collectivity evolves
- Theoretical model cannot reproduce the large yield and the large v_2 simultaneously.

Direct photon puzzle at the LHC

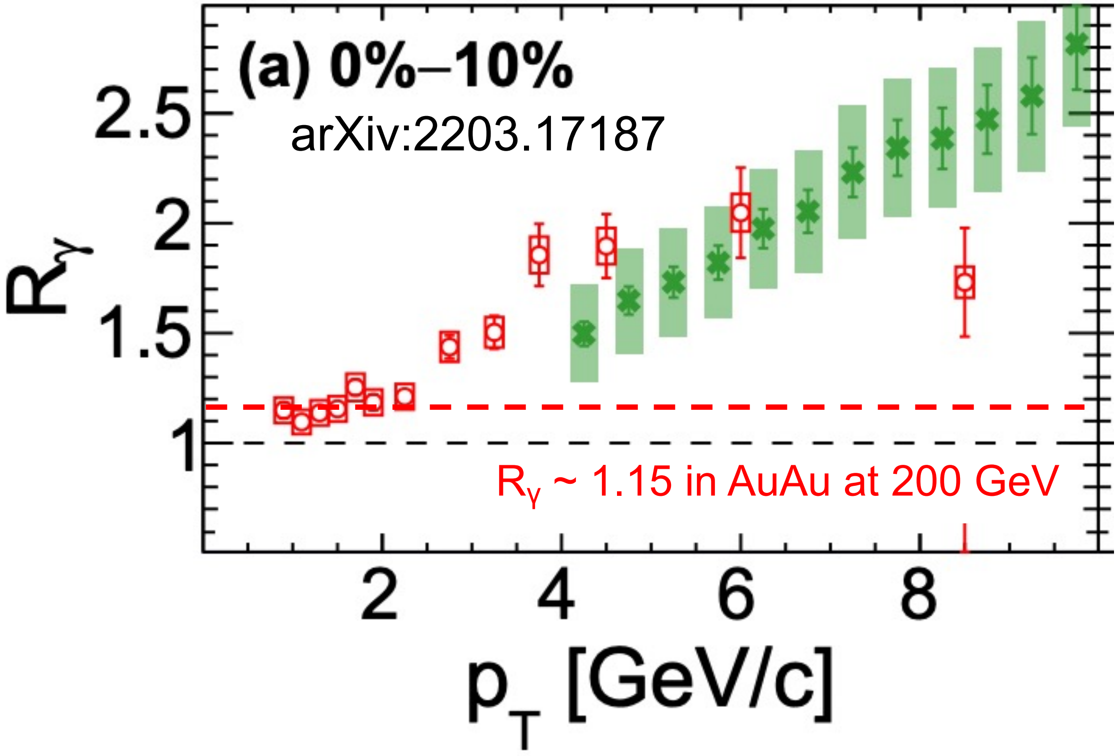
PRC 105, 014909 (2022)

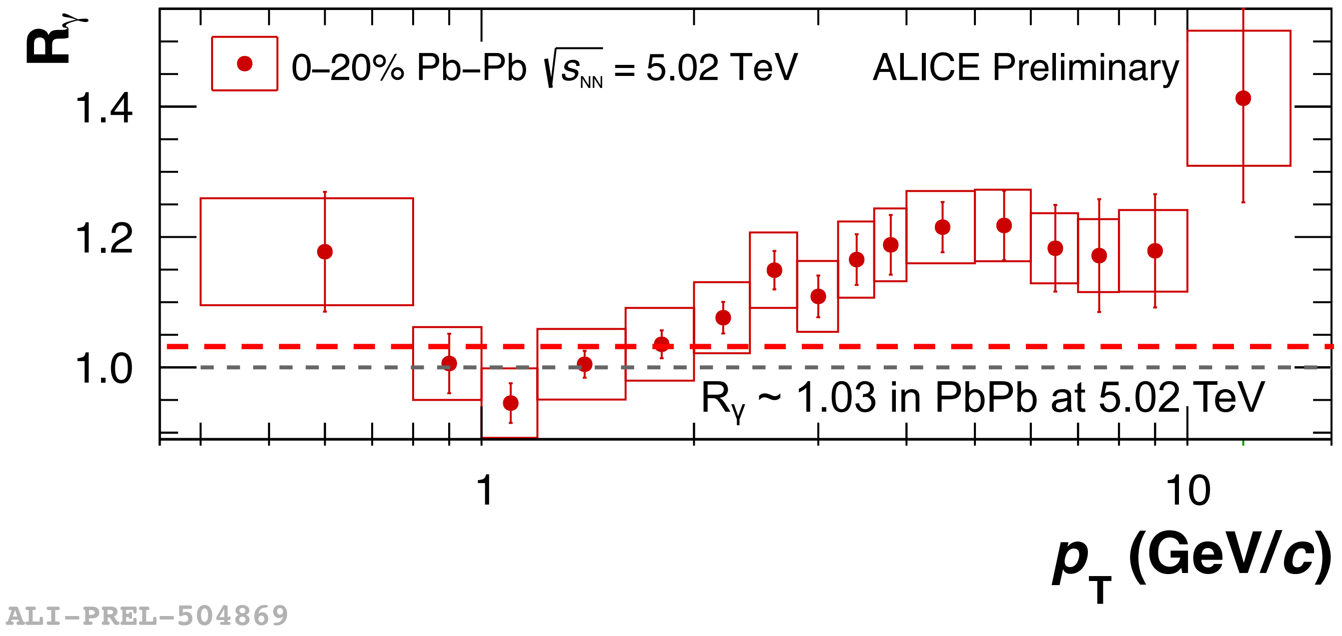




- Direct photon puzzle is not observed within our experimental uncertainties.
- Let's hope that huge statistics in Run 3 improves our measurements.

Another difficulty at the LHC

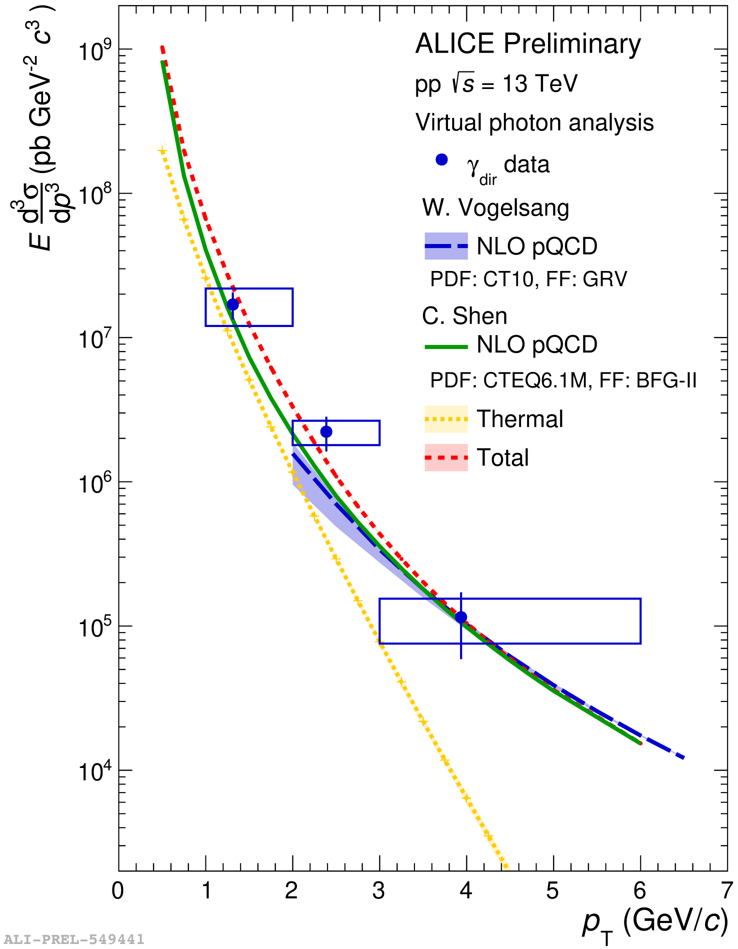




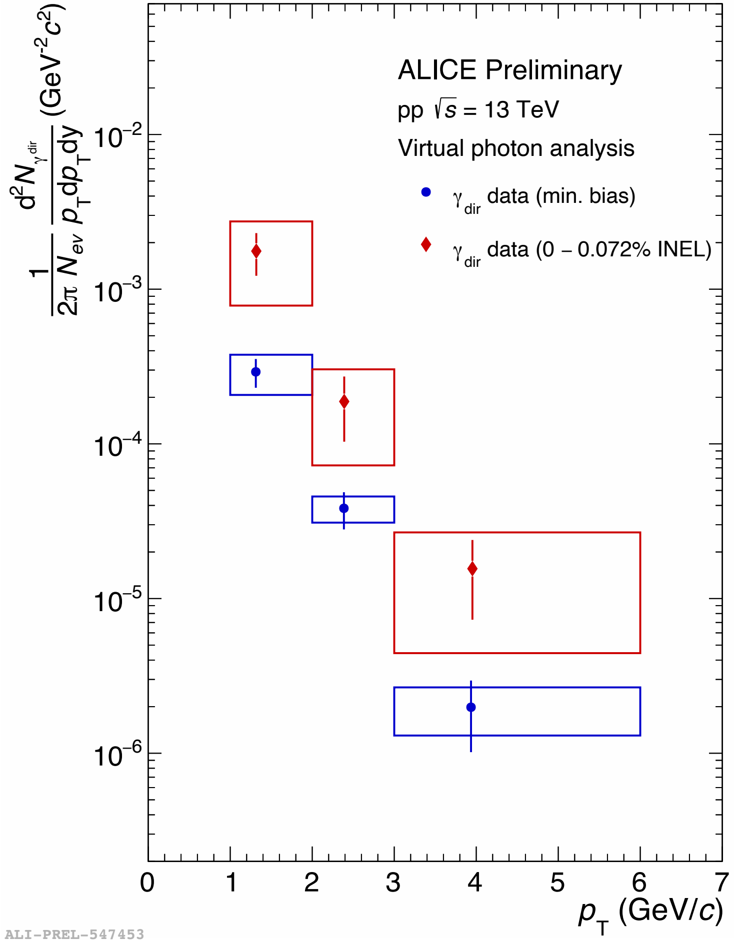
- R_γ ~ 1.15 in PHENIX, and R_γ ~ 1.03 in ALICE at low p_T
- At higher collision energies, π^0 from mini jets may feed decay photons at low p_T.
- v_n measurement is challenging in ALICE due to the smaller R_γ.

Search for thermal radiation in small systems

minimum-bias pp collisions



minimum-bias pp collisions
high-multiplicity pp collisions



with virtual photon technique

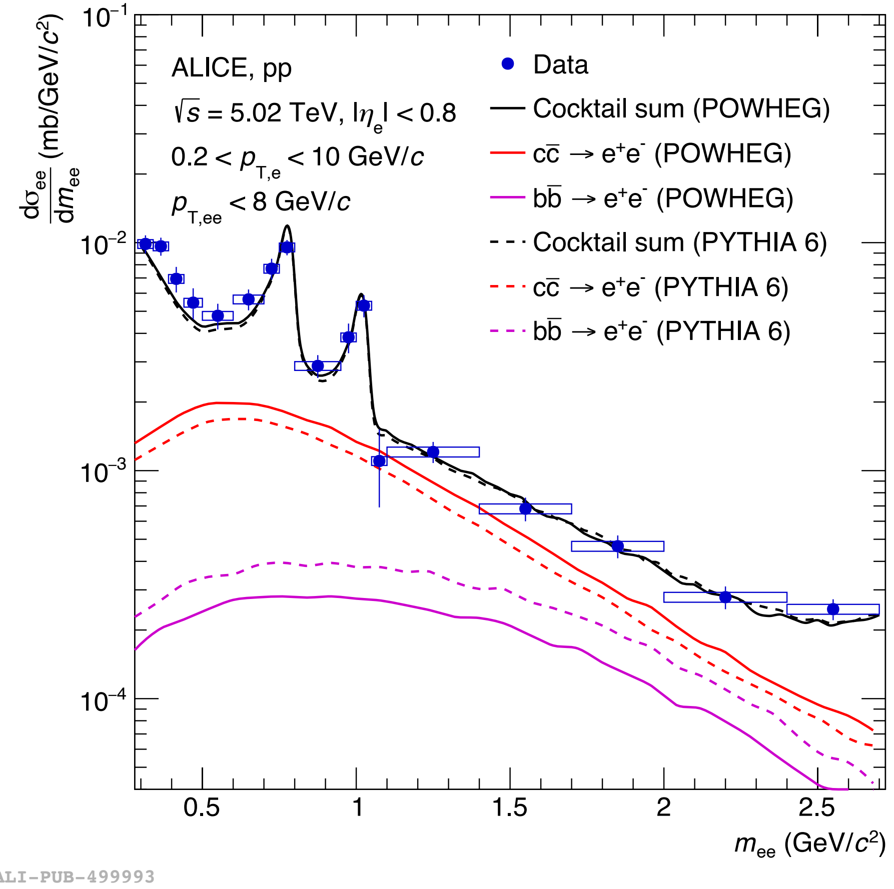
- First measurement of direct photons in small systems at low p_T in ALICE
  - Direct photon fraction r = 0.01 ~ 0.03
- Data can be reproduced by both prompt only and prompt + thermal radiation in MB pp collisions.
- Significant increase of direct photon yields in high-multiplicity pp collisions
  - Challenging to calculate photon productions in HM pp collisions

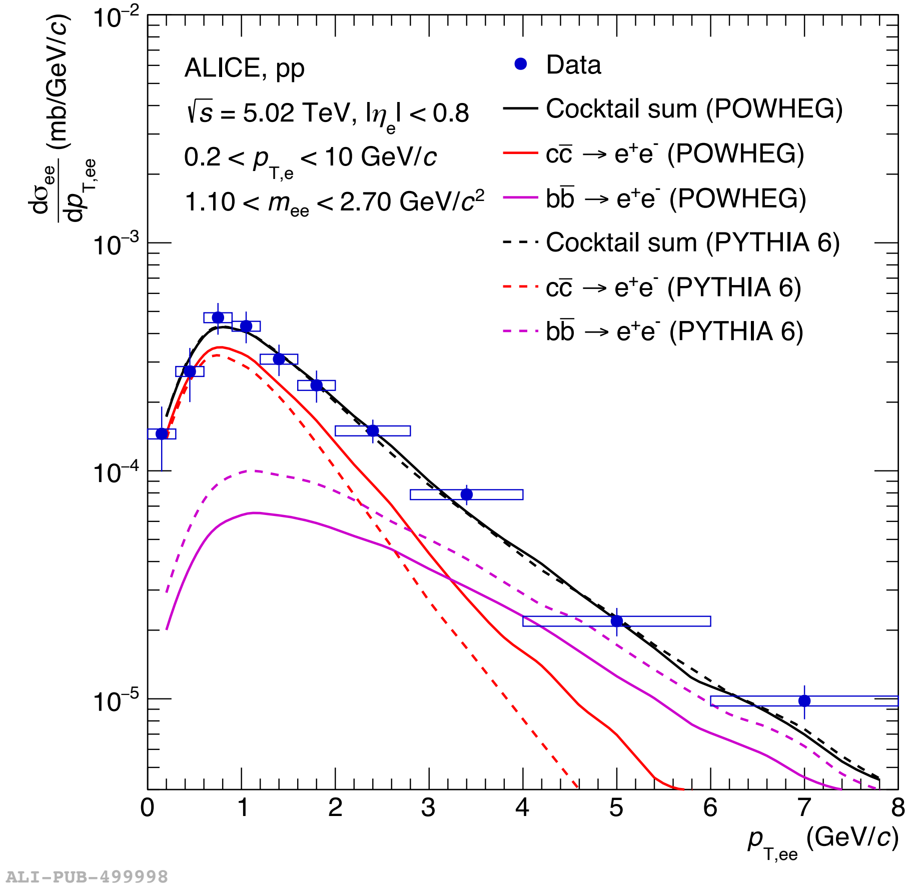
Dielectrons

Reminder : dielectrons from correlated HF hadron decays are main background for thermal radiation from QGP in the intermediate mass region.
→ First, let's look at pp results in the IMR. ($1.1 < m_{ee} < 2.7$ GeV/c^2)

Dielectron in pp at $\sqrt{s}$ = 5.02 TeV

PRC 102, 055204 (2020)



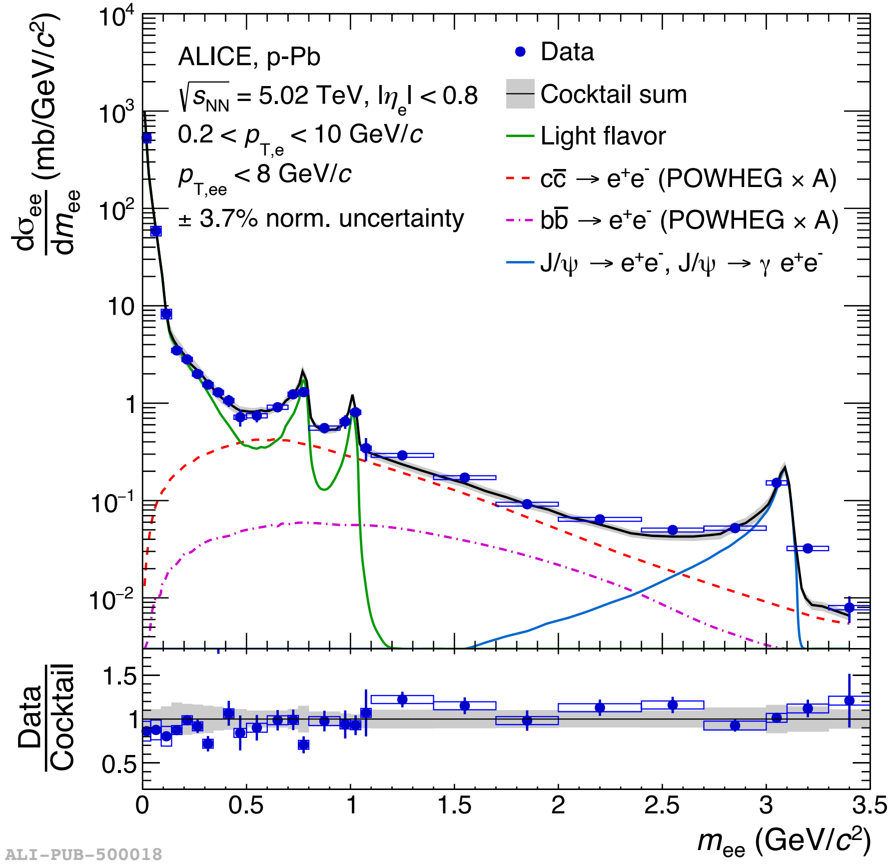


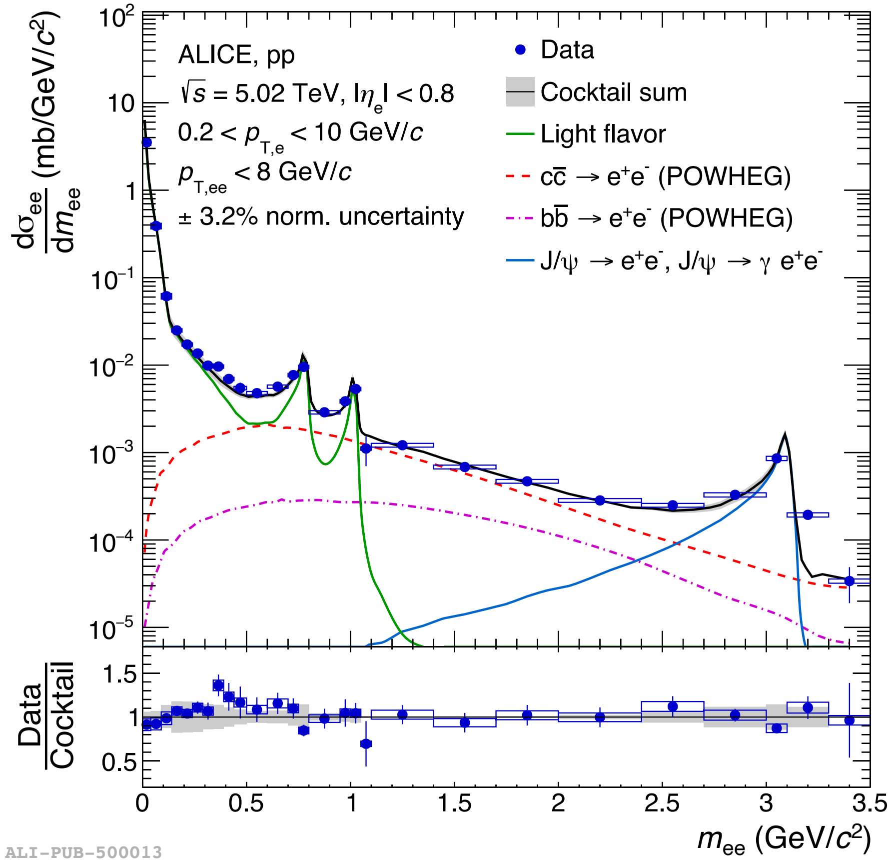
- Charm and beauty contributions are determined by template fit in 2D (m_{ee}, p_{Tee}).

  → vacuum baseline for p-Pb and Pb-Pb at the same energy.

Dielectron in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

PRC 102, 055204 (2020)

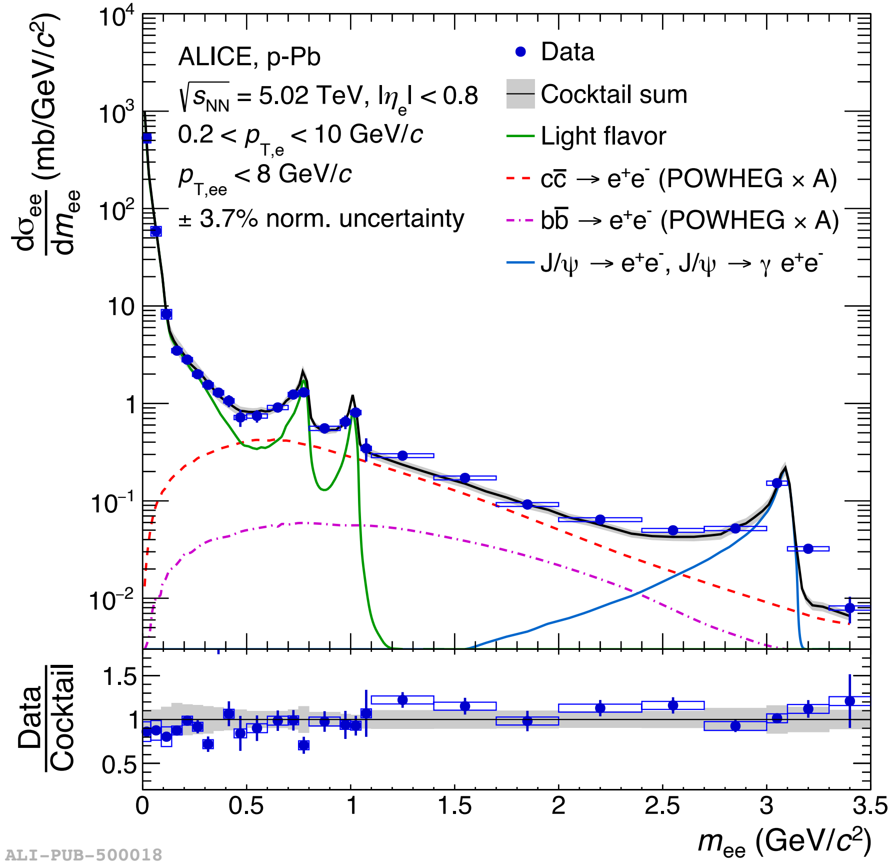


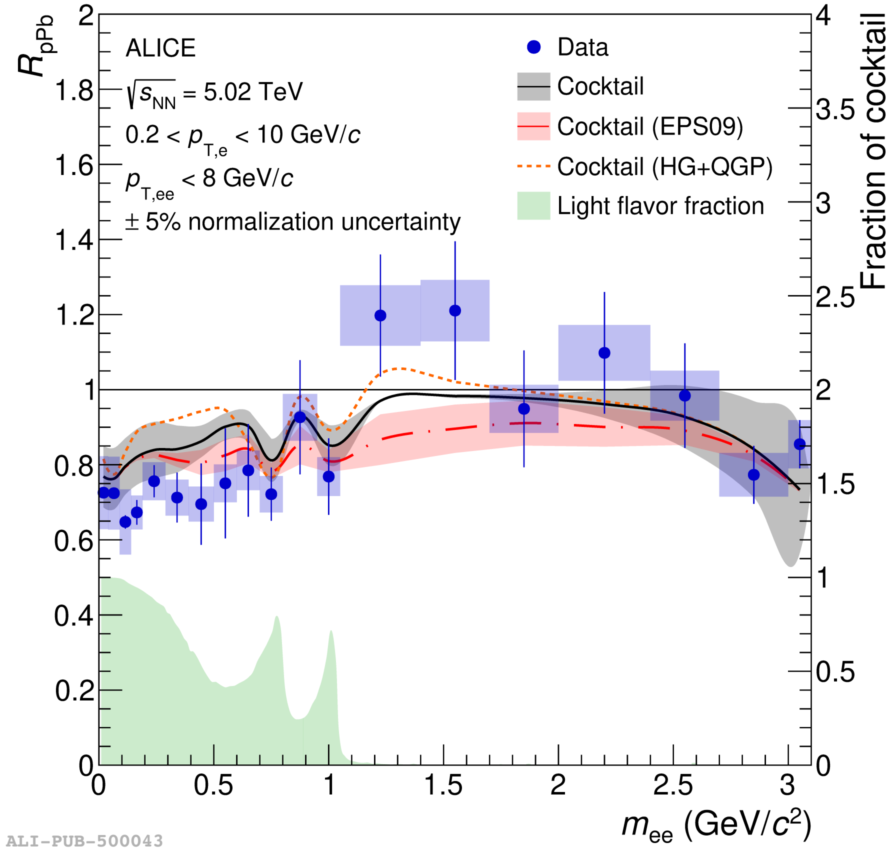


- Motivation in p-Pb : cold nuclear matter effect (shadowing), search for thermal radiation

Dielectron in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

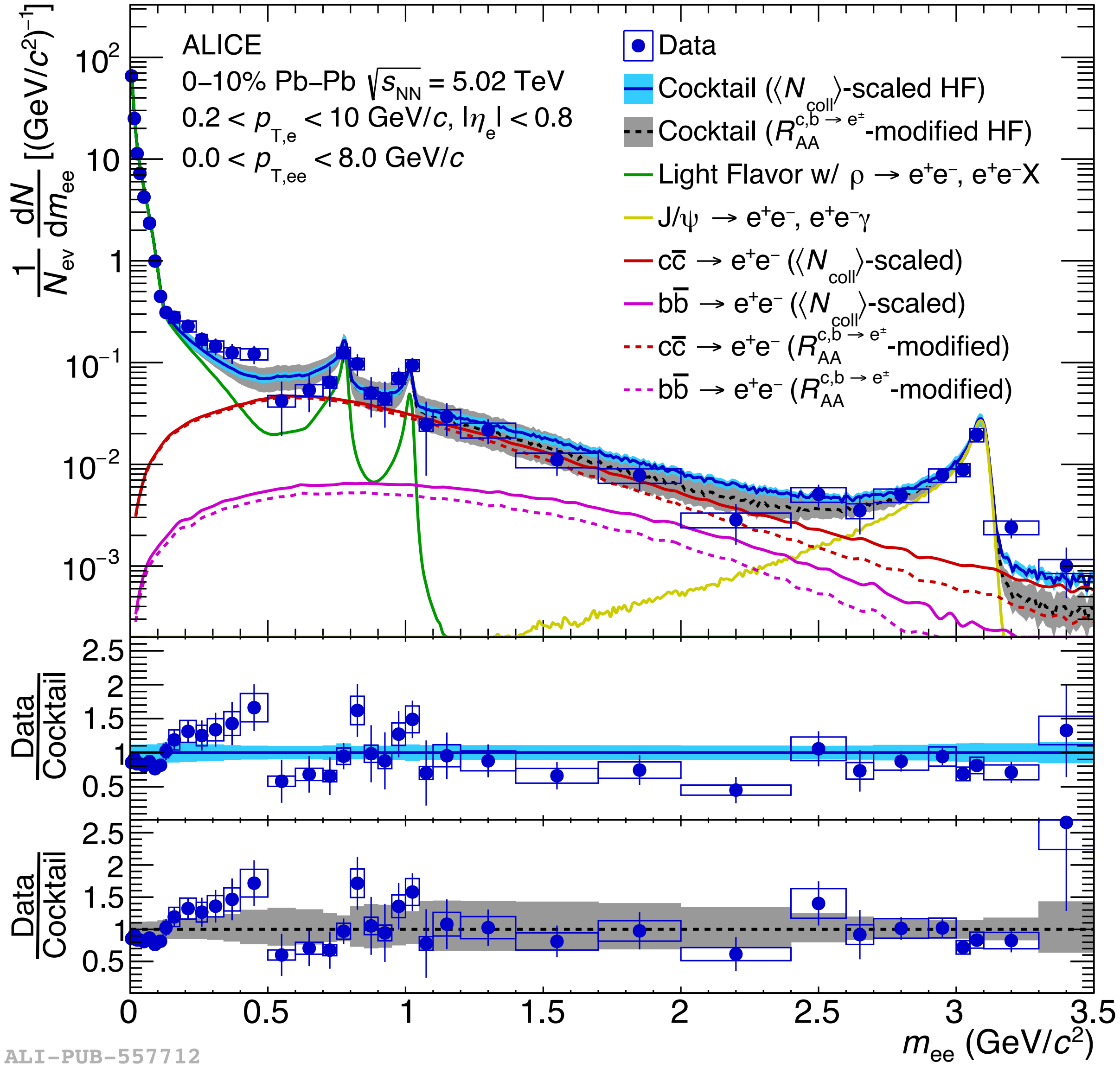
PRC 102, 055204 (2020)





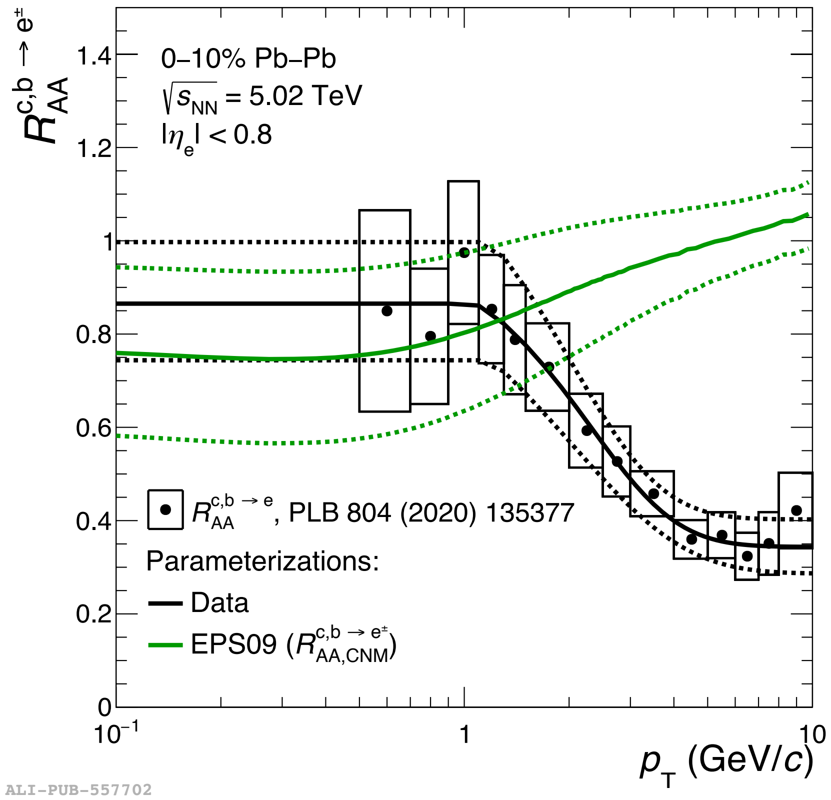
- Motivation in p-Pb : cold nuclear matter effect (shadowing), search for thermal radiation
- R_{pA} is described by N_{coll}-scaled HF cocktail. But, also compatible with cocktail with shadowing and cocktail with thermal radiation.

Dielectron in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



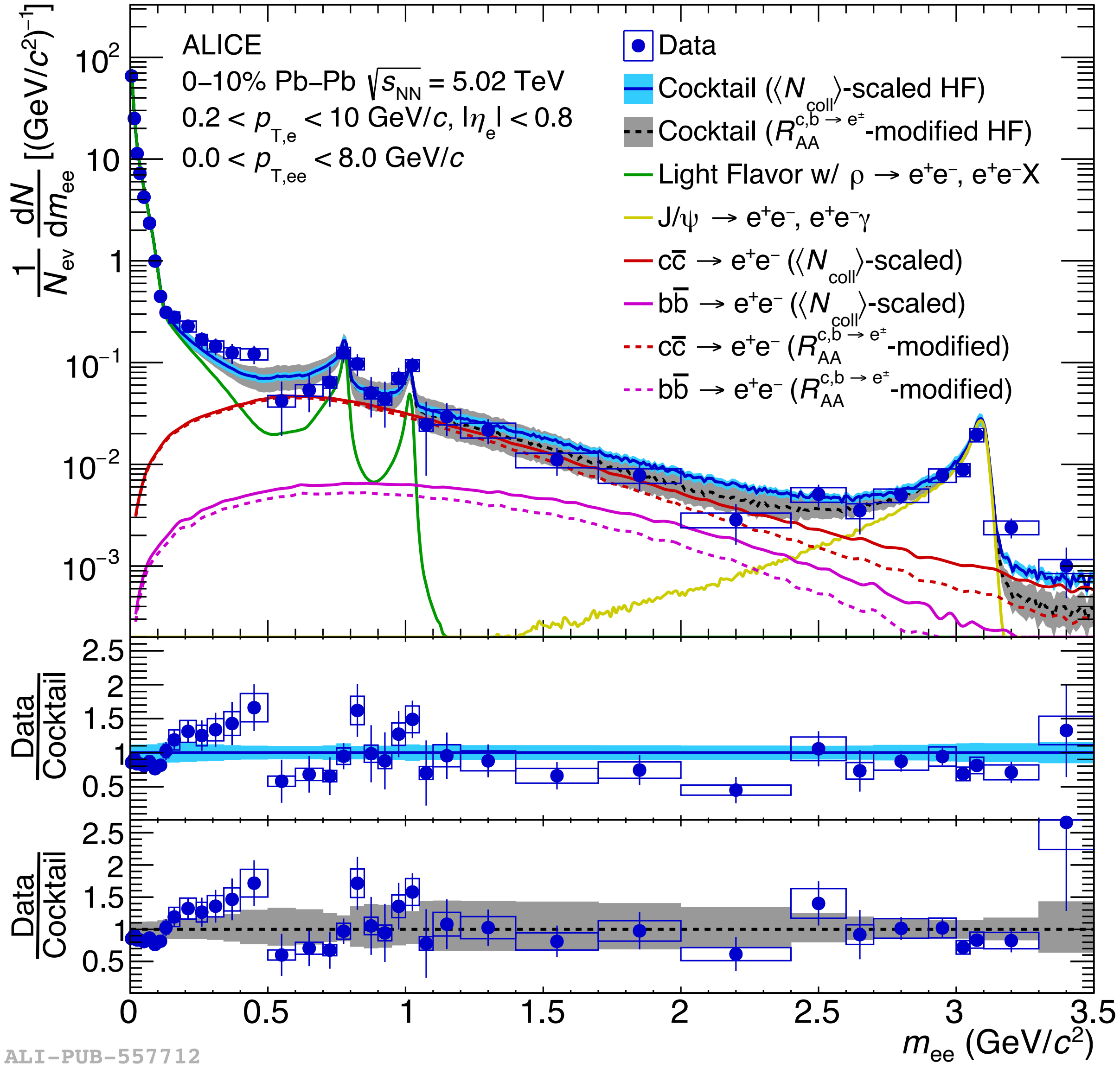
- Comparison to hadronic cocktails
  - N_{coll}-scaled heavy-flavor (HF) (PRC 102 (2020) 055204)
  → at the edge of uncertainties

- Electrons from HF are modified in the final state in PbPb



arXiv:2308.16704

Dielectron in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

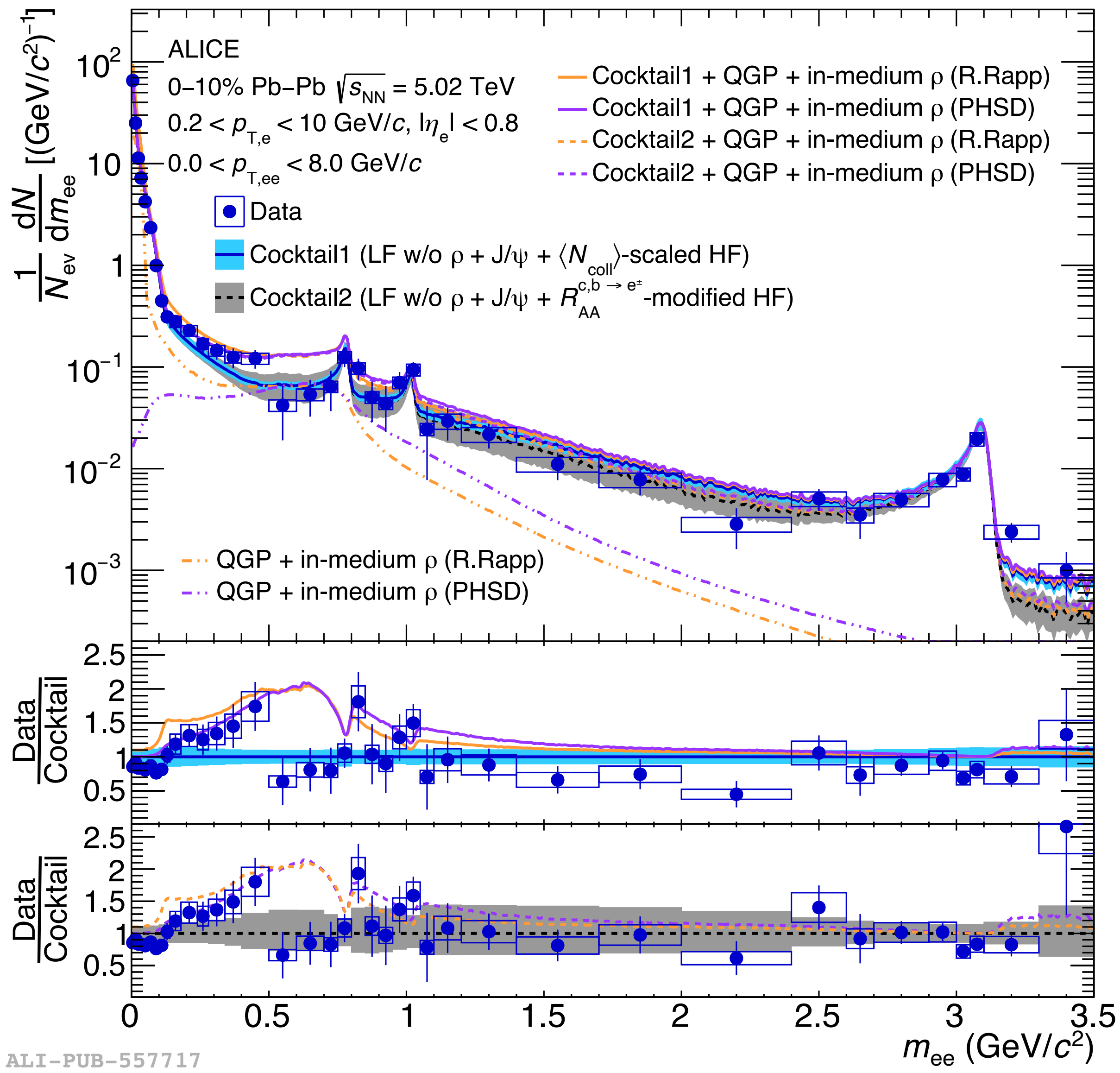


arXiv:2308.16704

- Comparison to hadronic cocktails
  - N_{coll}-scaled heavy-flavor (HF) (PRC 102 (2020) 055204)
  → at the edge of uncertainties

  - Modified HF by R_{AA} of c/b→e
  → Agreement improved. But, large cocktail uncertainty due to extra modification.

Dielectron in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

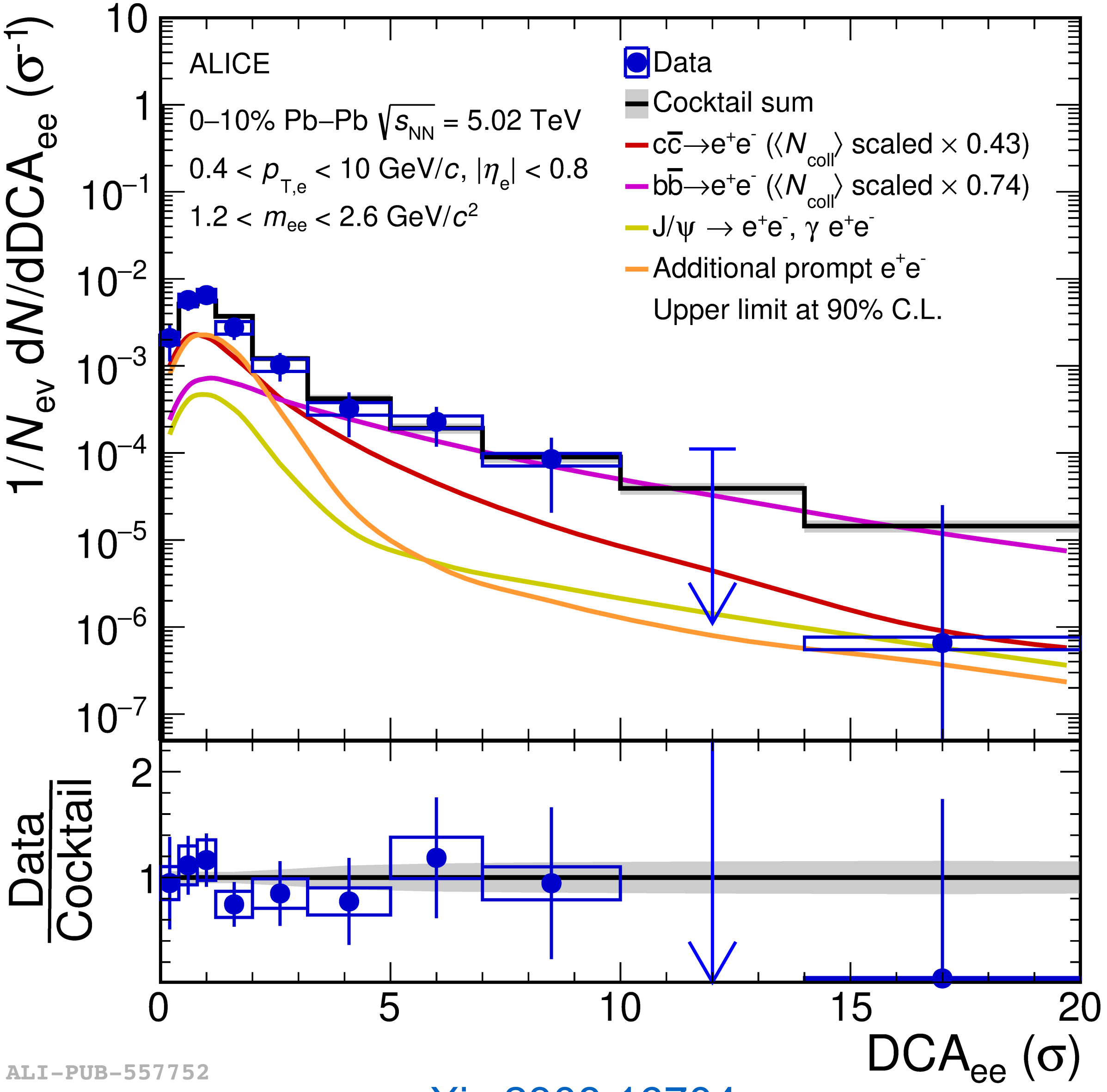


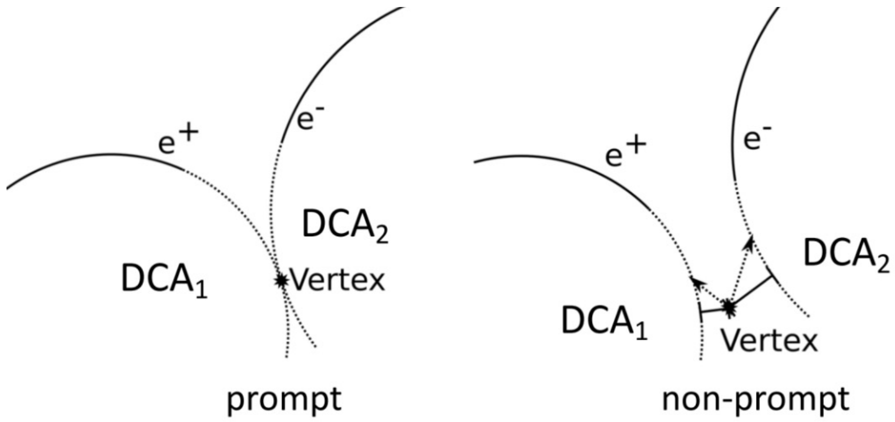
- Comparison to hadronic cocktails
  - N_{coll}-scaled heavy-flavor (HF) (PRC 102 (2020) 055204)
  → at the edge of uncertainties

  - Modified HF by R_{AA} of c/b→e
  → Agreement improved. But, large cocktail uncertainty due to extra modification.
  QGP radiation is not distinguishable due to the large uncertainty.
  Need cocktail-independent method to extract QGP signal

arXiv:2308.16704

First DCA_{ee} analysis in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

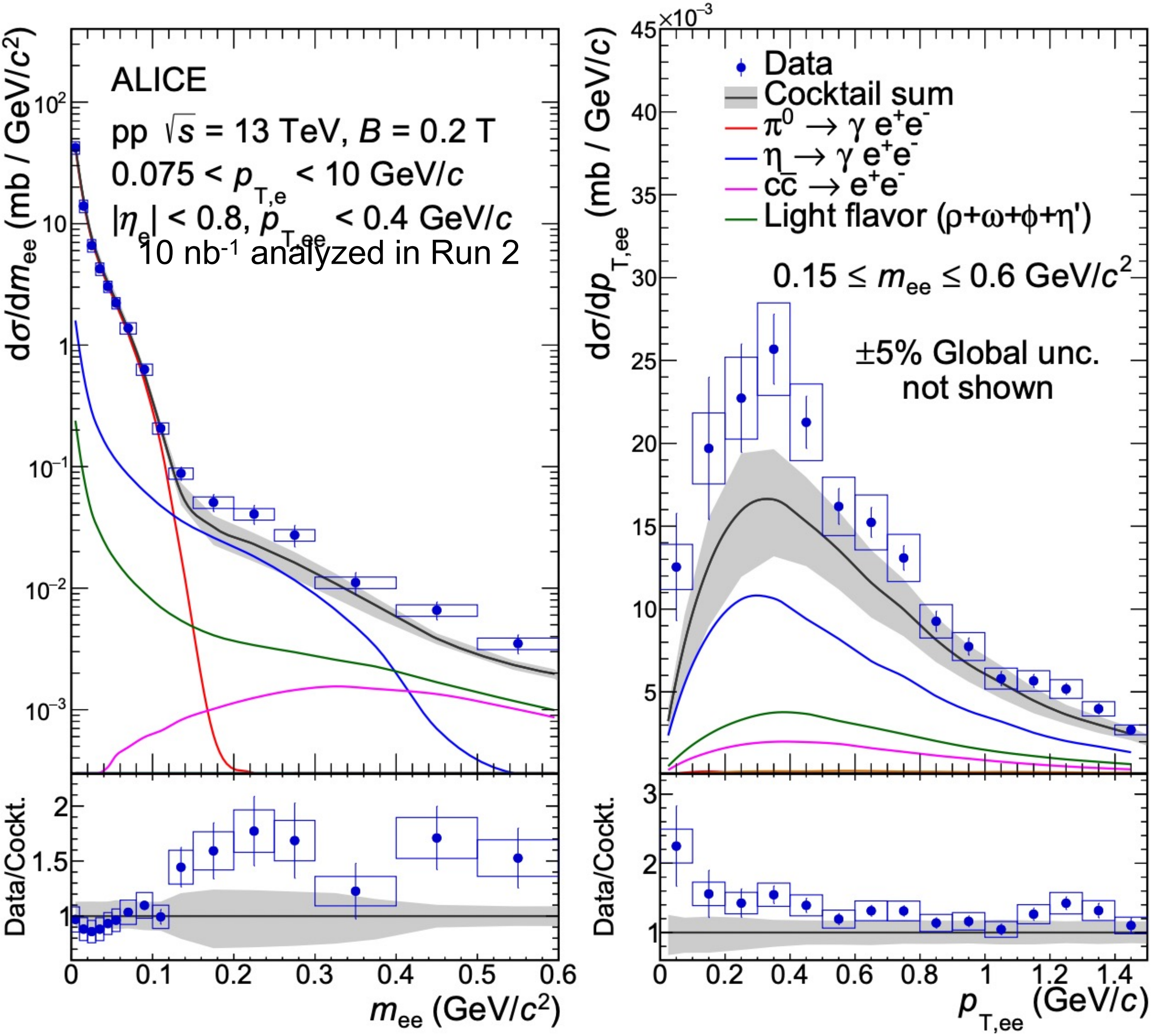
- First DCA_{ee} analysis in Pb-Pb collisions
  - Template fit in 1.2 < m_{ee} < 2.6 GeV/c^2

- Scaling factors to obtain the best fit are:
  - Beauty: [0.74 ± 0.24 (stat.) ± 0.12 (syst.)] x $\langle N_{coll} \rangle$
  - Charm: [0.43 ± 0.40 (stat.) ± 0.22 (syst.)] x $\langle N_{coll} \rangle$
  - Thermal: 3.17 ± 3.81 (stat.) ± 0.35 (syst.) w.r.t. Rapp model

arXiv:2308.16704

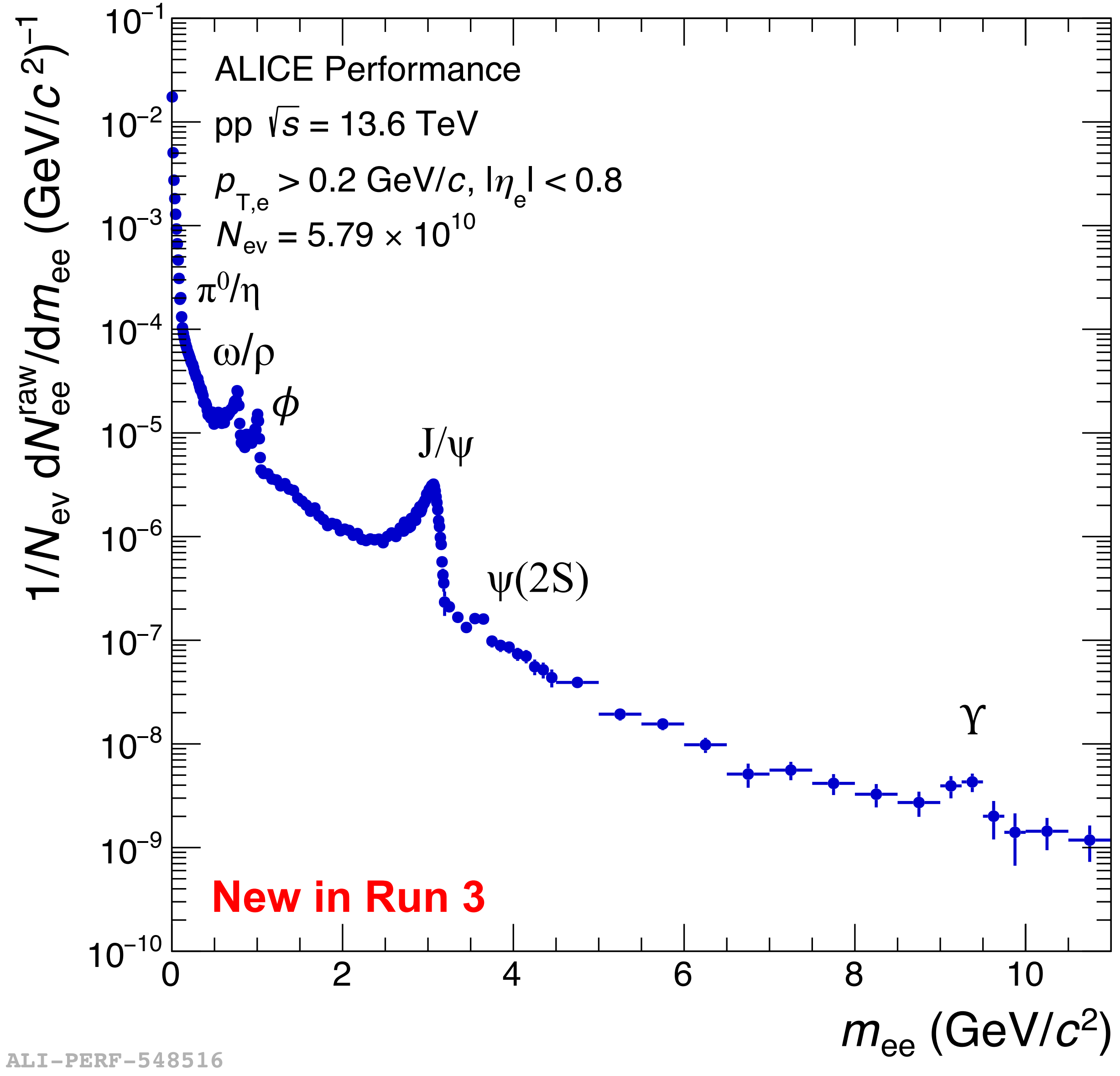
Soft dielectron excess in pp at 13 TeV

PRL 127, 042302 (2021)



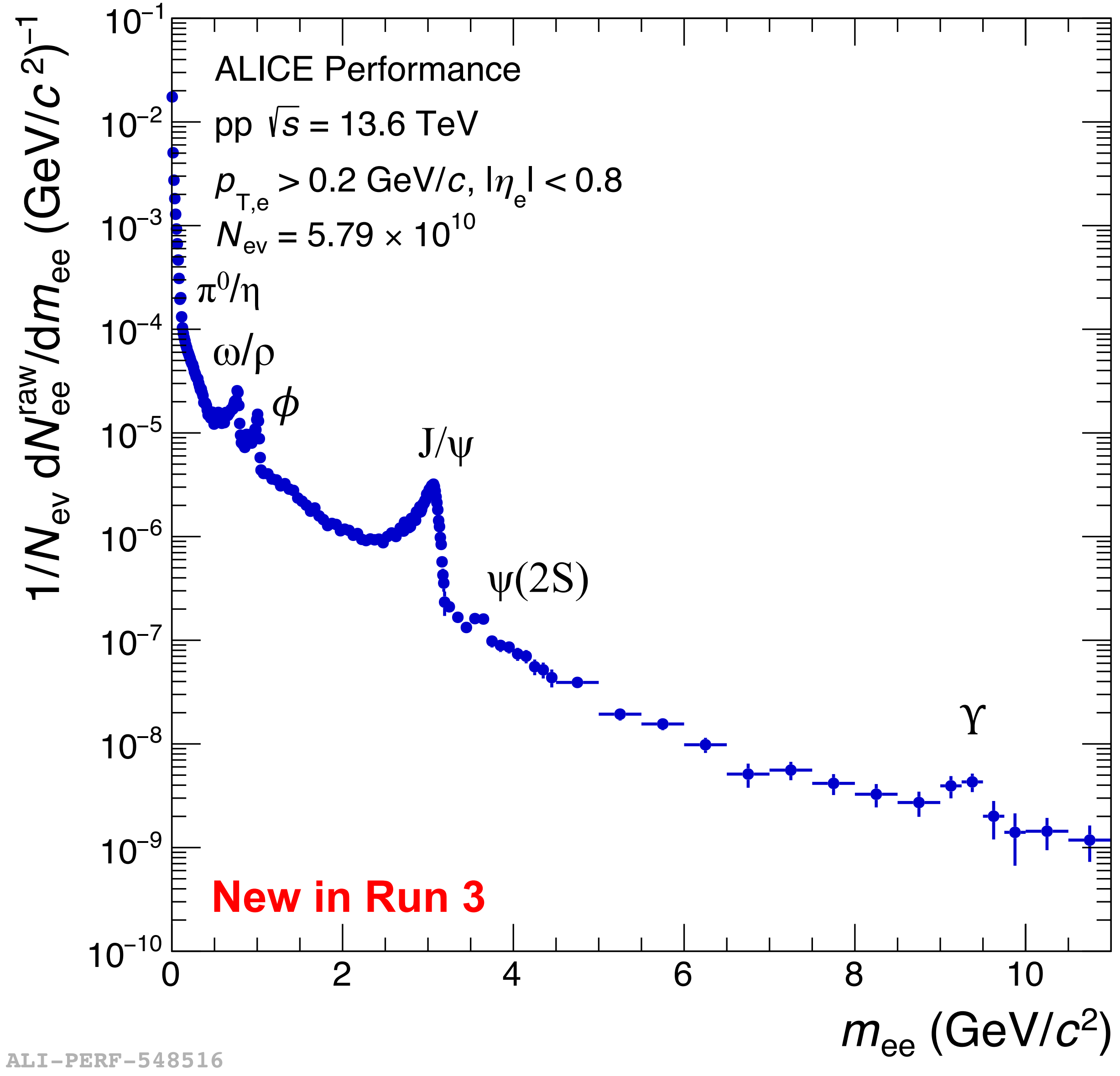
- Dedicated to EM probes at very low p_T in ALICE
  - Thanks to new ITS, minimum $p_{T,e}$ can be extended to lower value.
  - Key is η meson at low pT
- Expect L_{int} ~ 3 pb^{-1} with B = 0.2T in pp at 13.6 TeV
  - 300 times more data than that in Run 2
- 0.5 pb^{-1} available for physics analyses in Run 3

First raw m_{ee} spectrum in Run 3



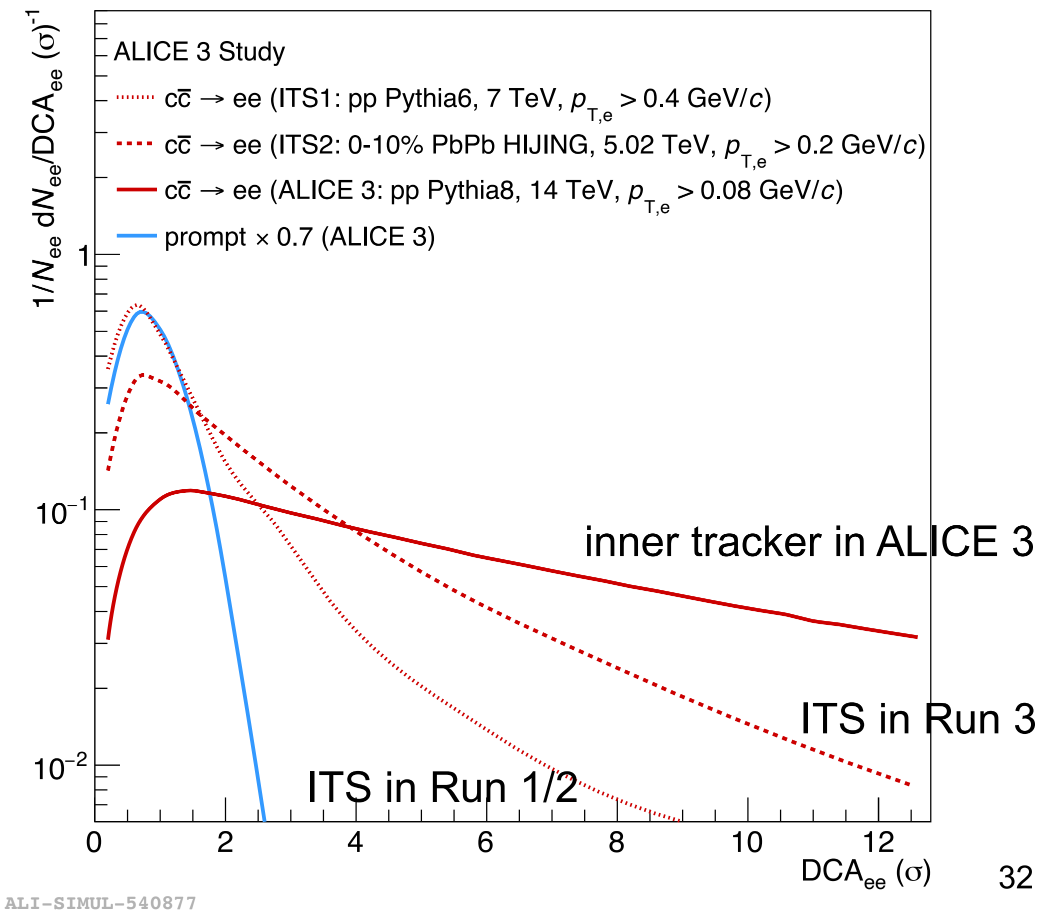
- ALICE recorded huge statistics in 2022 and 2023.
  - 0.97 pb^{-1} analyzed for the left plot
  - 0.03 pb^{-1} in Run 2
- Clear dielectron signals in pp at 13.6 TeV
  - π^0 and η Dalitz decays
  - $\omega/\rho/\phi$ peak
  - J/ψ and ψ(2S) peak
  - ϒ peak
  - HF continuum in the intermediate and high mass regions

First raw m_{ee} spectrum in Run 3

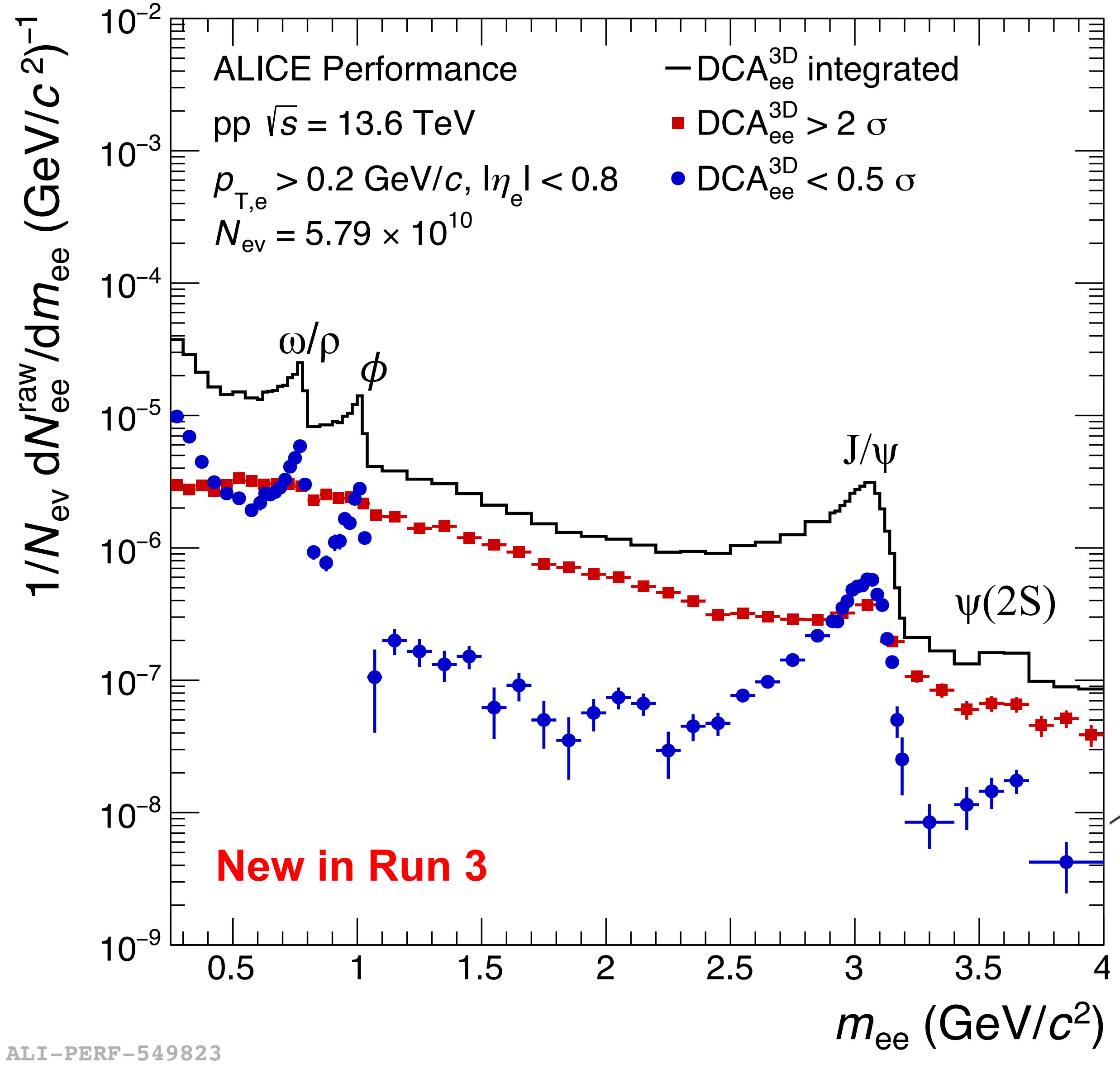


- ALICE recorded huge statistics in 2022 and 2023.
  - 0.97 pb^{-1} analyzed for the left plot
  - 0.03 pb^{-1} in Run 2

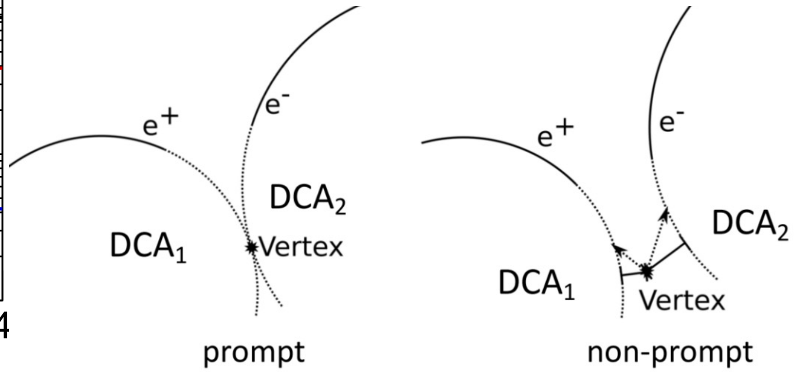
DCA$_{ee}$ spectra with new ITS



Separation power with DCA_{ee} in Run 3



- ALICE recorded huge statistics in 2022 and 2023.
  - 0.97 pb^{-1} analyzed for the left plot
  - 0.03 pb^{-1} in Run 2
- Strong separation power of DCA_{ee}
  - Prompt dielectrons with $DCA_{ee} < 0.5\ \sigma$
    - -- LF + prompt J/ψ + possible thermal radiation
  - Non-prompt dielectrons with $DCA_{ee} > 2.0\ \sigma$
    - -- HF + non-prompt J/ψ



$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

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 0.5 pb^{-1} in pp at 13.6 TeV with 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)

Beyond 2035

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

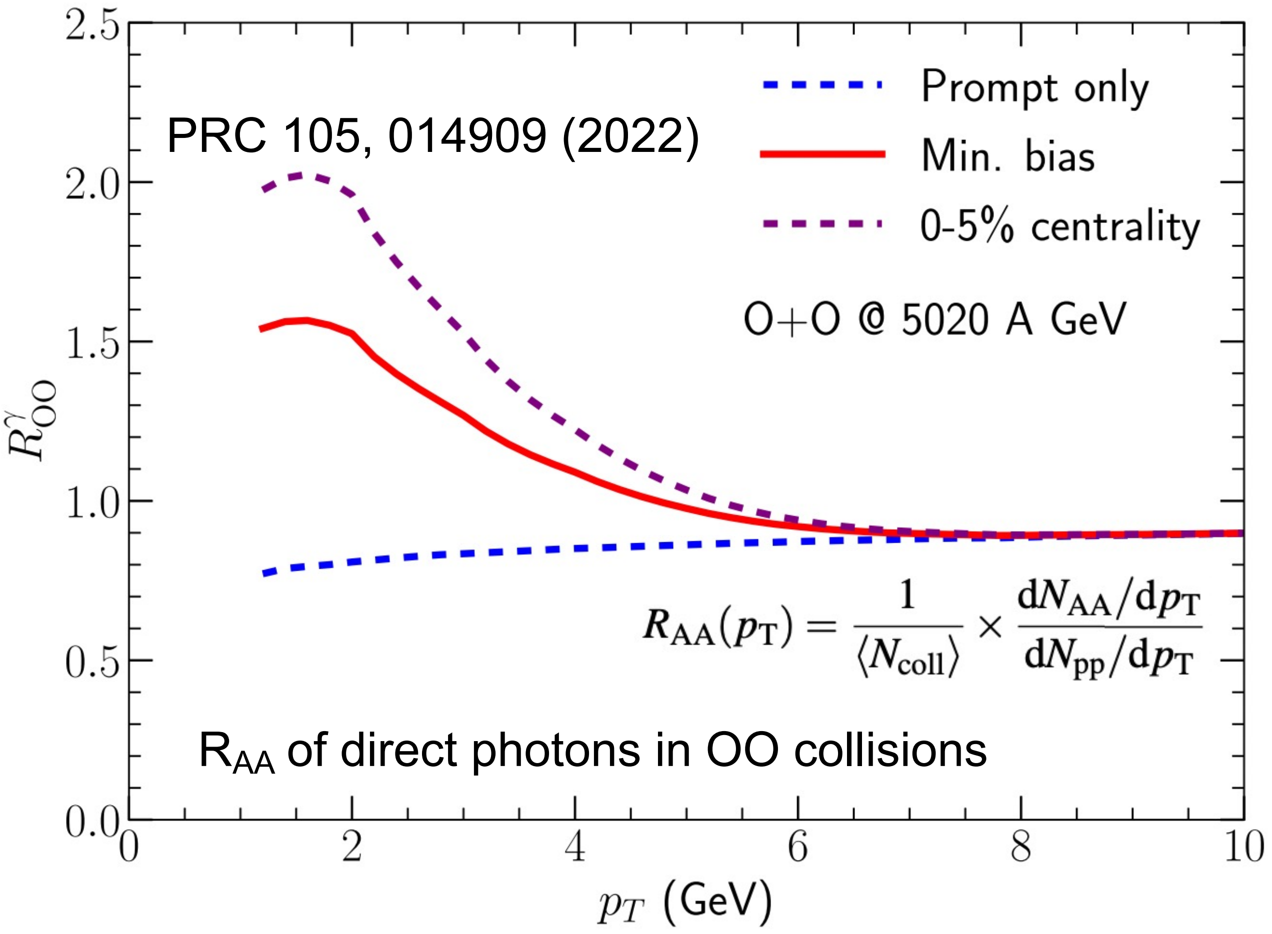
Longer term LHC schedule

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.

Last update: April 2023

OO and pO collisions at the LHC

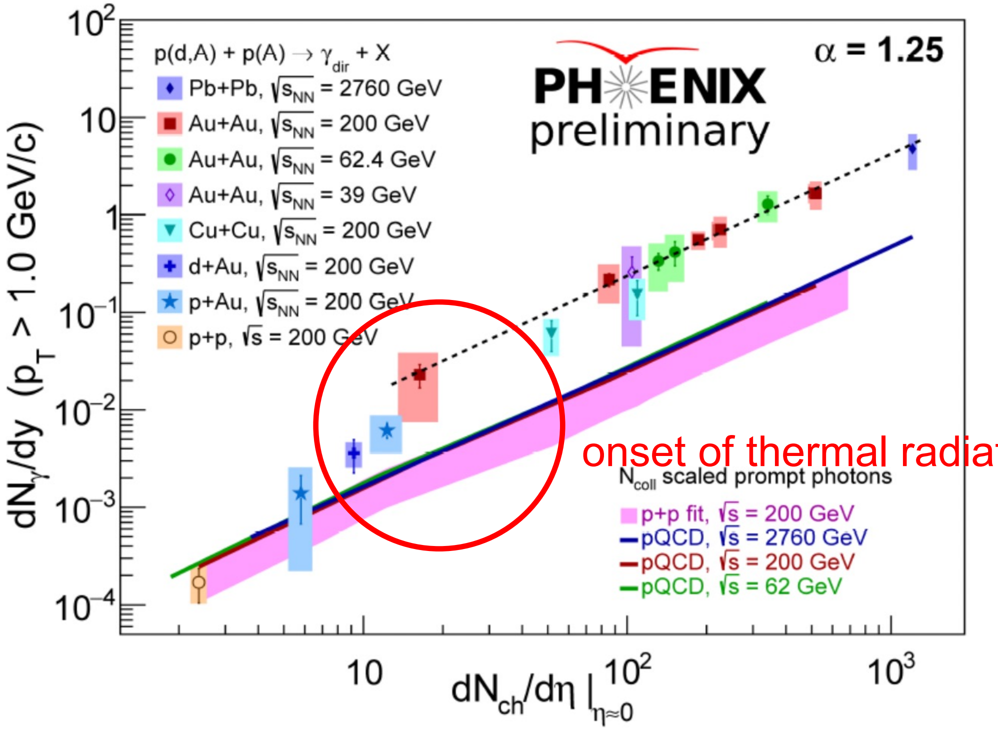
arXiv:2103.01939



R_{AA} of direct photons in OO collisions

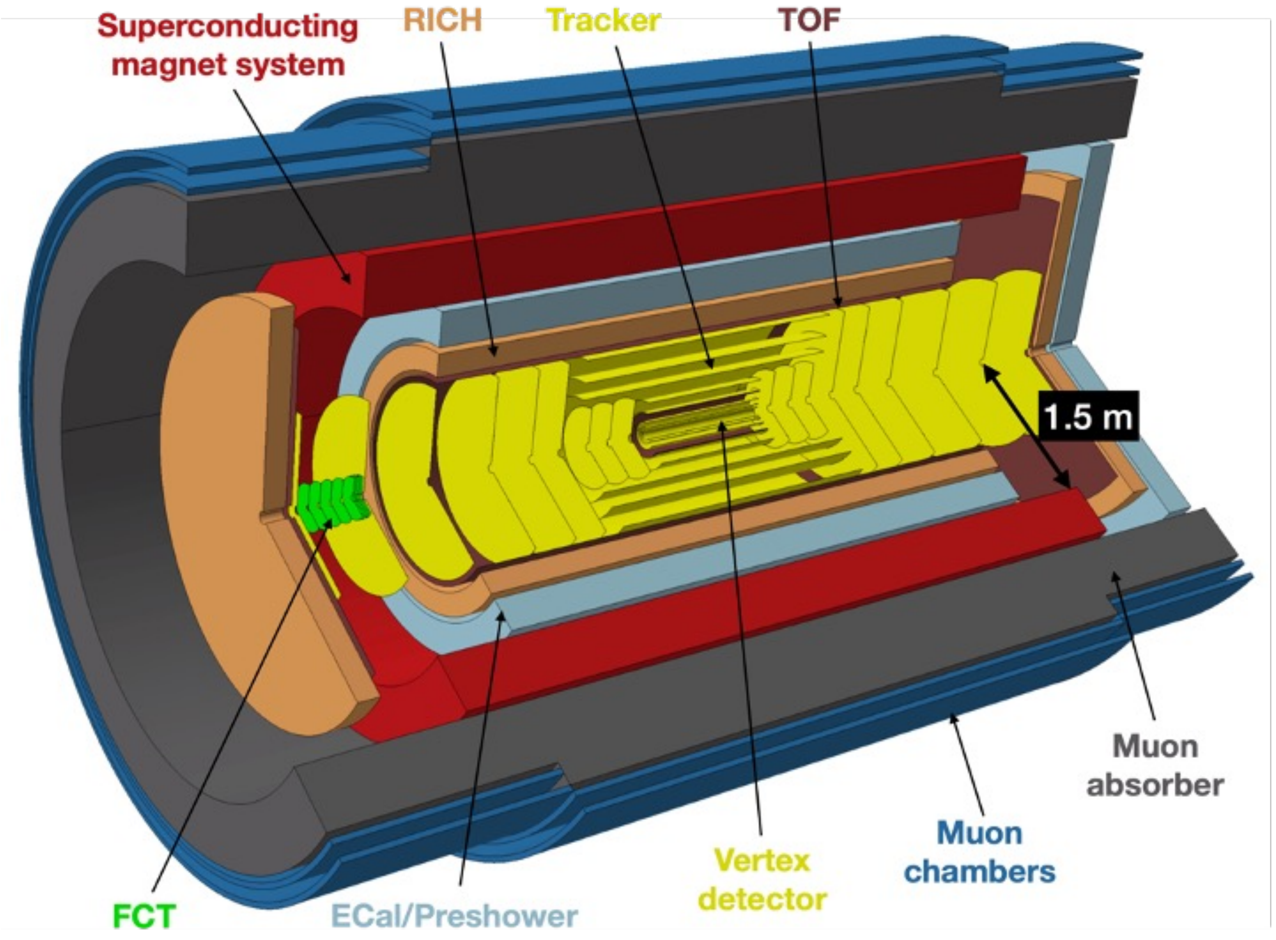
Expected luminosity for ALICE:
$L_{OO} = 0.5 \sim 1.0\ nb^{-1}$, $L_{pO} = 5 \sim 10\ nb^{-1}$

- Multiplicity scan in $3 < dN_{ch}/d\eta < 150$
  - "small system" but AA geometry
- Direct photons at $dN_{ch}/d\eta \sim 10$
  - onset of thermal radiation
  - same multiplicity but different collision system

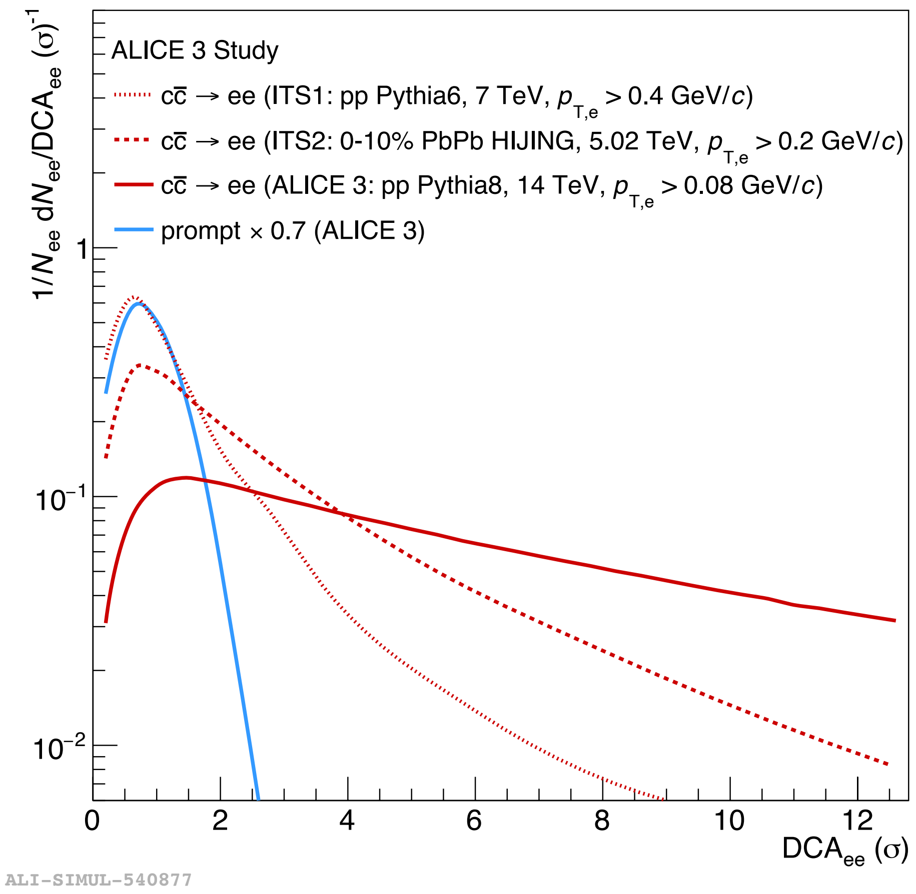


ALICE3

arXiv:2211.02491



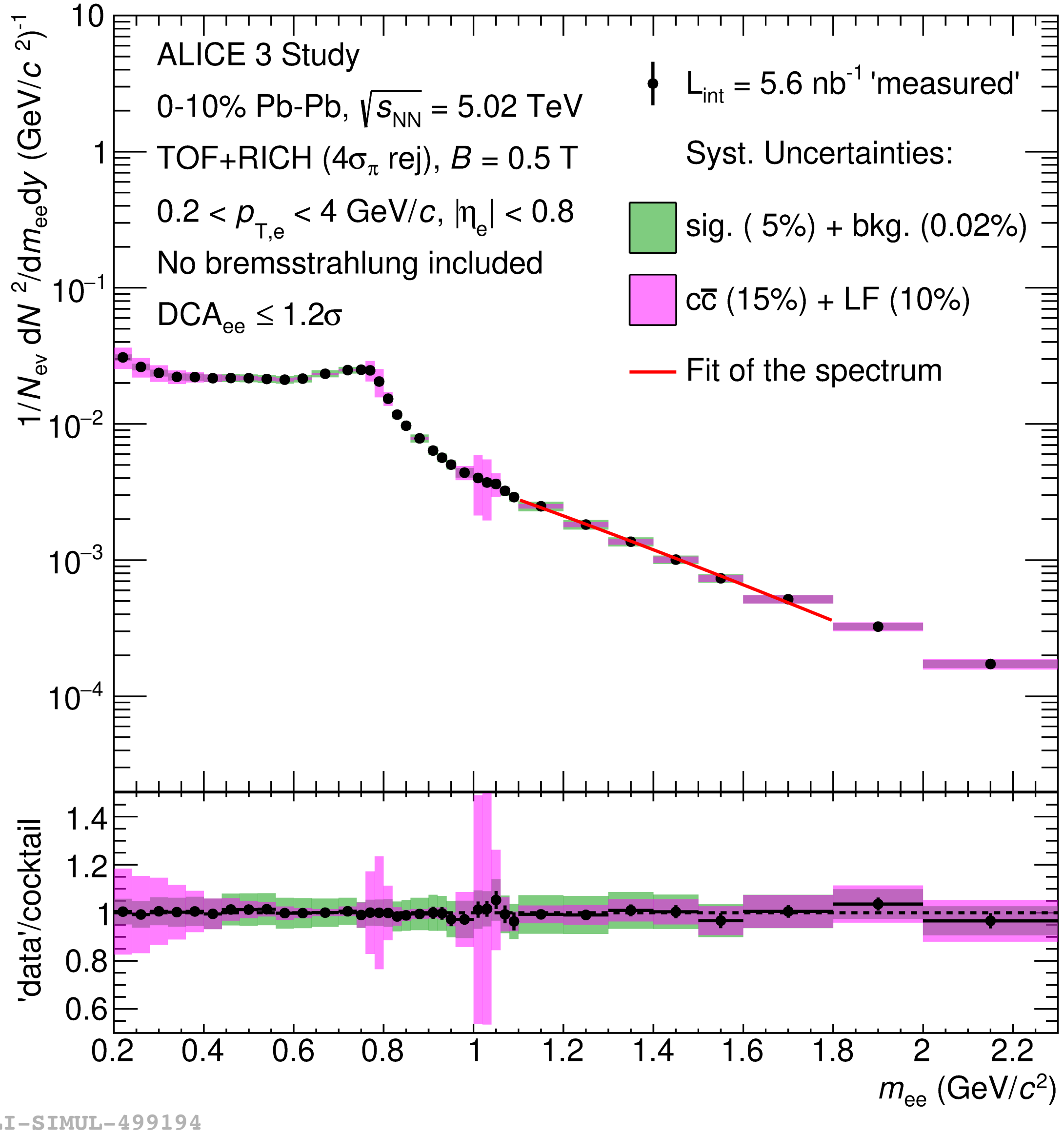
- Advanced silicon technology
  - High-rate data acquisition
  - Precise vertexing with retractable tracker
  - Strong particle identification at low p_T



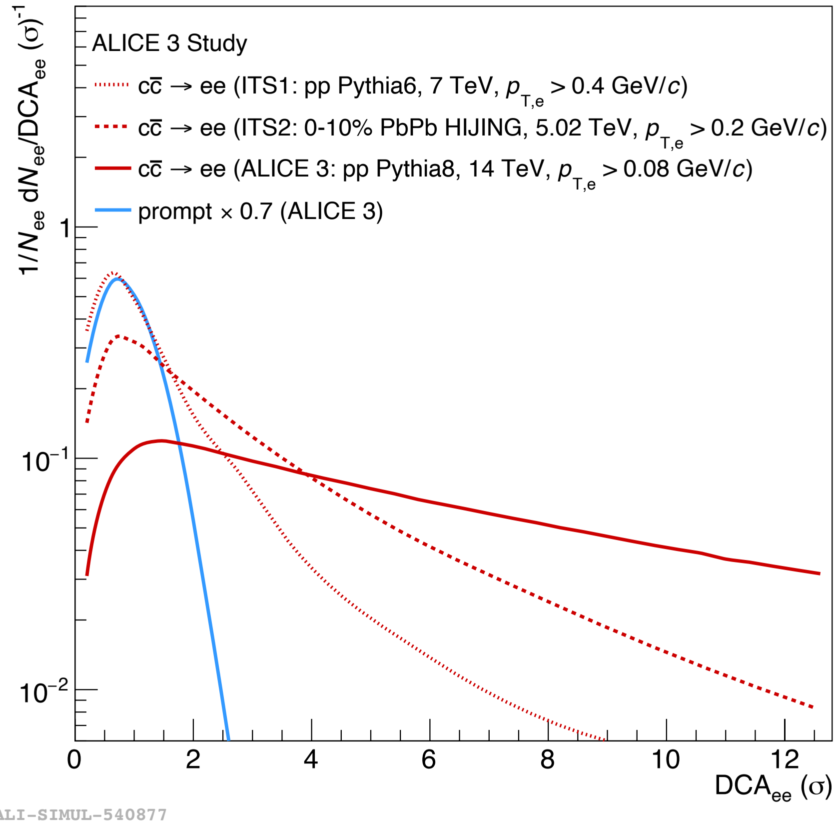
allow us to measure EM probes more precisely

Dielectron in ALICE 3

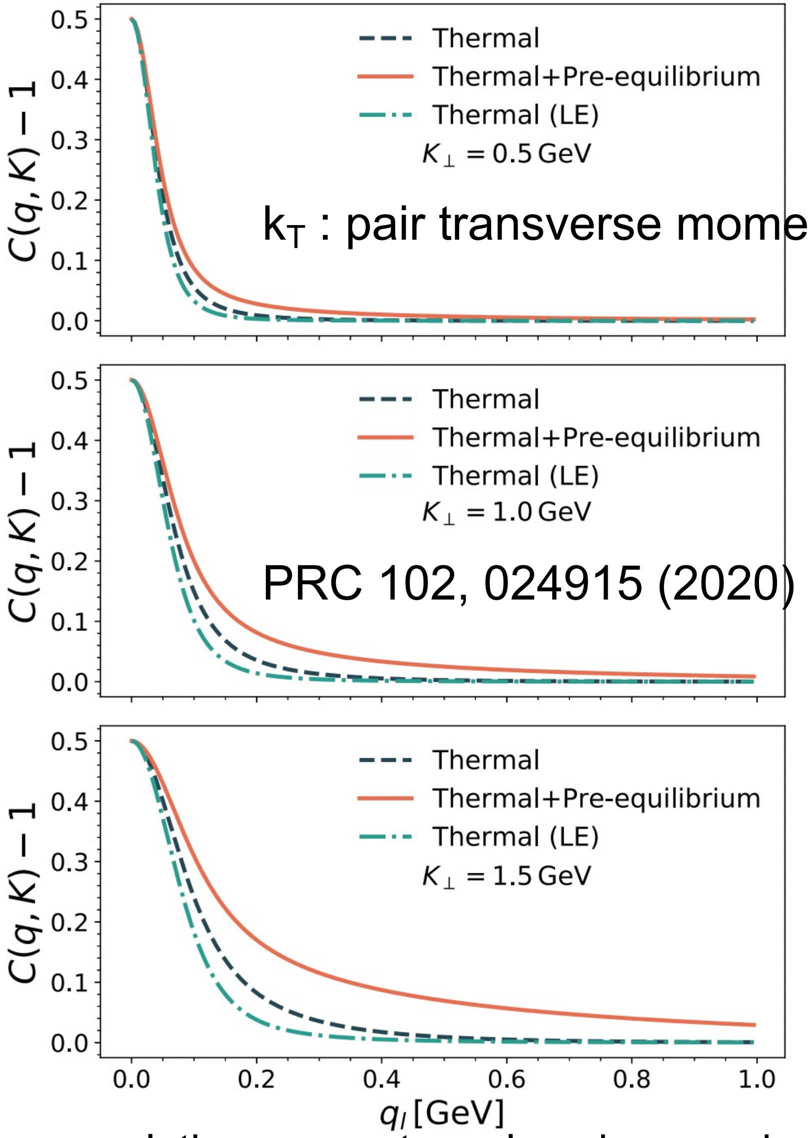
arXiv:2211.02491



- Pre-eq. and thermal radiation with high precision
- Chiral mixing (ρ-a_1)
- charm rejection with retractable tracker



Bose-Einstein correlation between 2γ



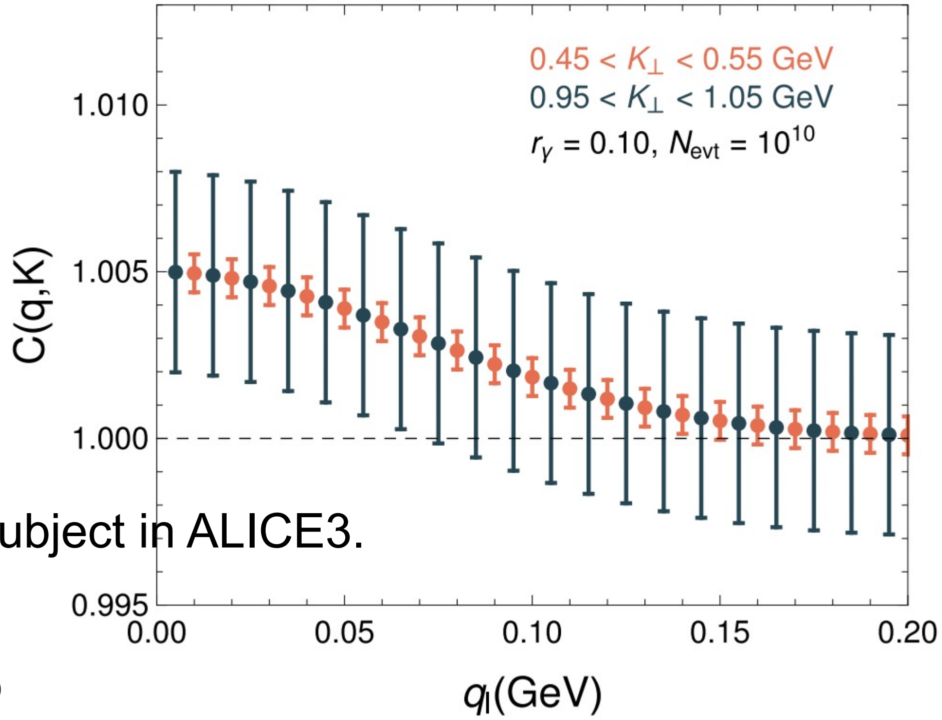
k_T : pair transverse momenta

PRC 102, 024915 (2020)

relative momentum along beam axis

- Sensitive to system size of emission source
- 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})



2γ correlation is a good subject in ALICE3.

Summary

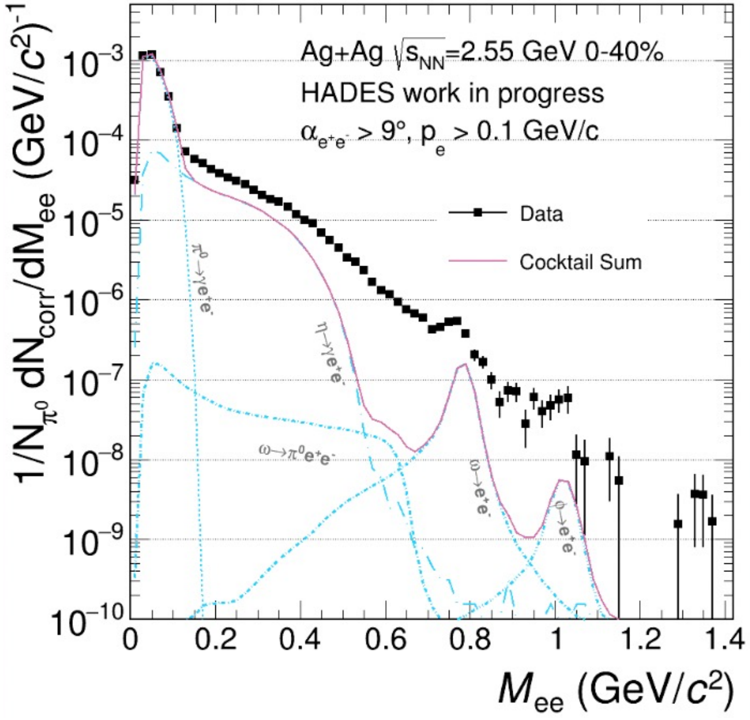
- ALICE published EM results in Run 1 and Run 2.

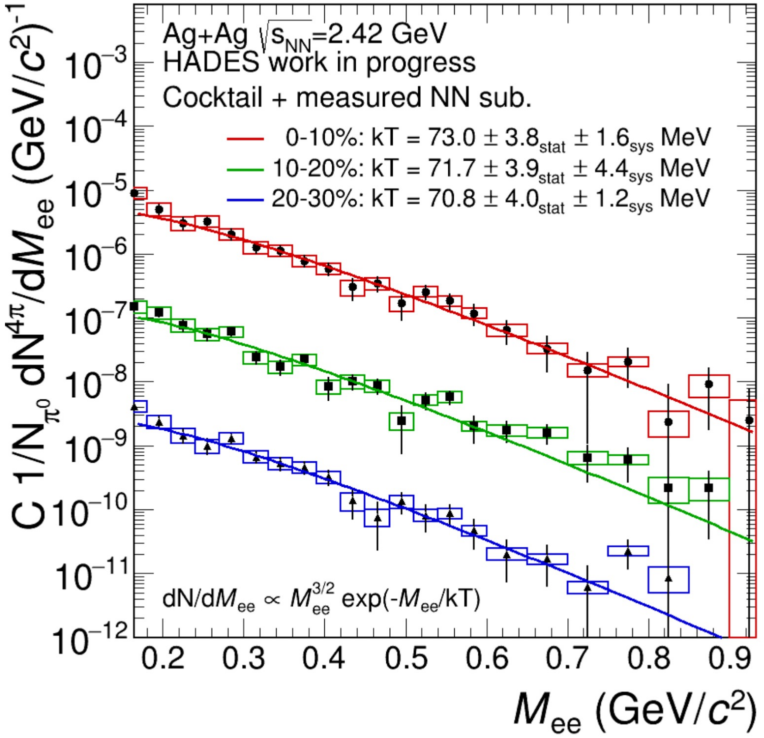
- Thanks to high statistics and precise vertexing, EM probes will provide:
  - Thermal radiation from QGP and viscosity
  - Pre-equilibrium radiation
  - Chiral mixing
  - Electric conductivity
  - Differentiate emission source with 2γ correlation

backup

High density region : HADES experiment

Nature Physics vol.15, 1040-1045 (2019)
[QM2023 poster]



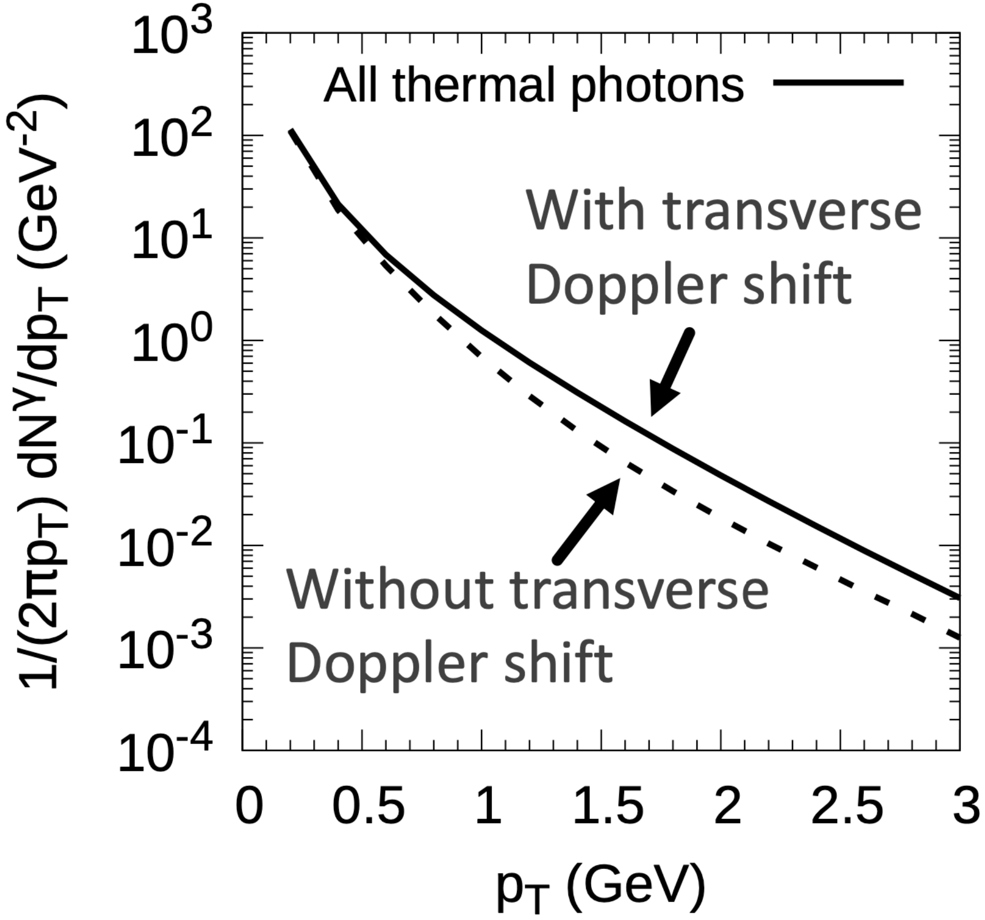


$$\frac{dN}{dM_{ee}} \propto M_{ee}^{3/2} \exp(-M_{ee}/T)$$

- T = 70MeV at HADES

Interpretation of inverse slope T_{eff}

arXiv:2205.12299
arXiv:2305.10669



- Local effect is large, but global effect is small.