

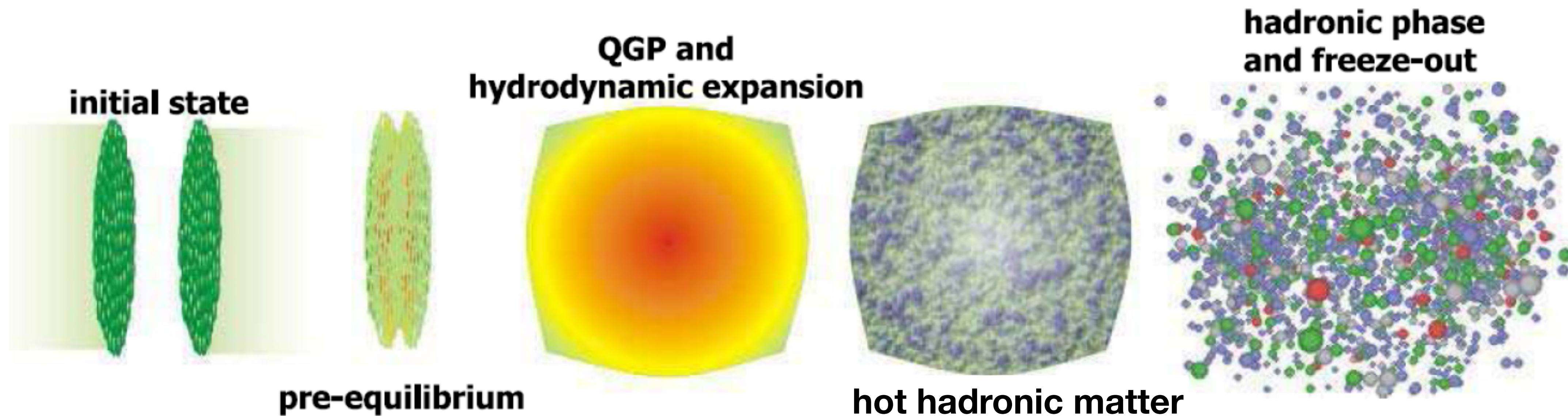


Real and virtual direct photon measurements with ALICE at the LHC

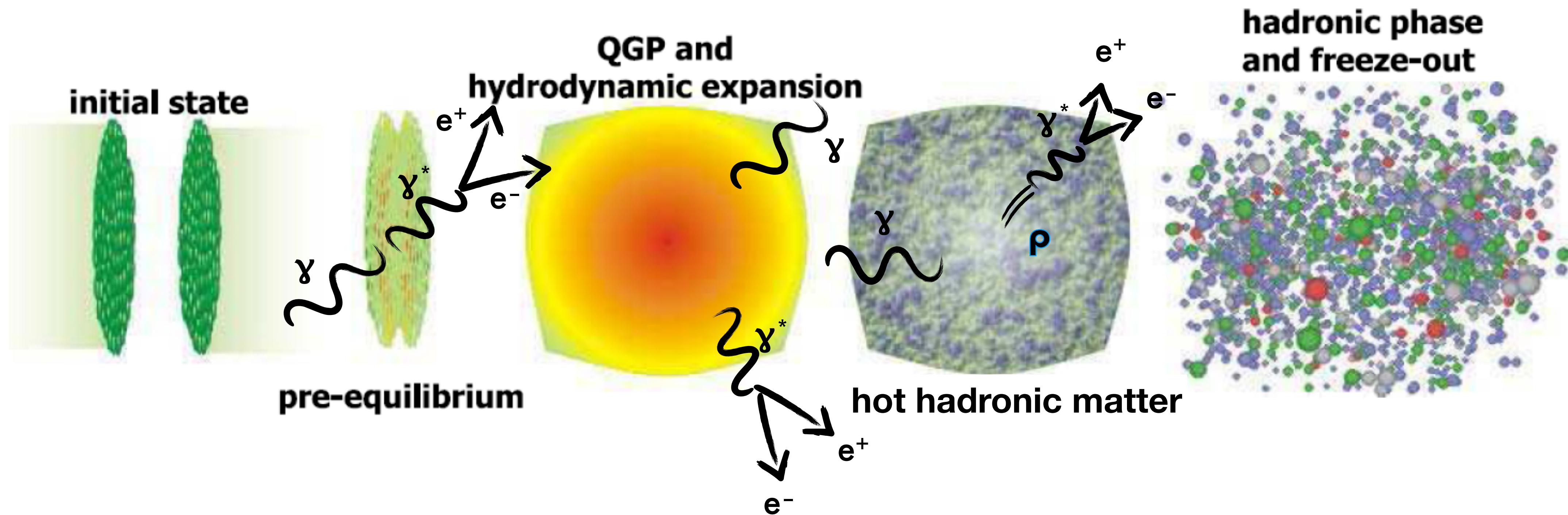
Raphaelle Bailhache
Goethe-Universitaet Frankfurt am Main, Germany

International Conference on Quantum Systems in Extreme Conditions
Bingen - 14.11.2022

The little big bang at the LHC



Why real and virtual direct photons



Produced:

- At all stages of the heavy-ion collision
- With negligible final-state interactions

→ **Carry information about the medium at the time of their emission !**

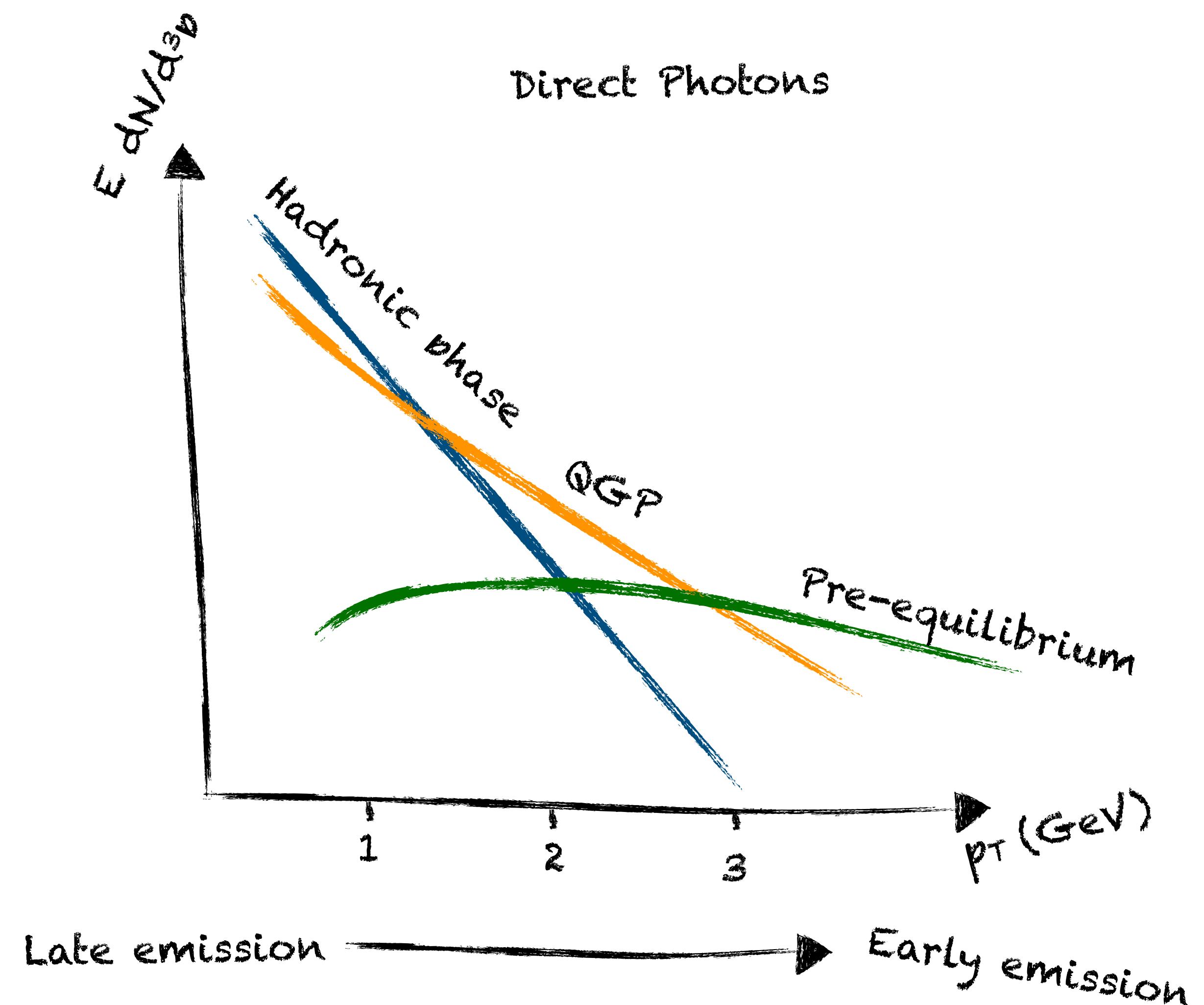
→ **Probe the whole space-time evolution of the system**

Real direct photon sources

Not from hadronic decays

- Hard scattering
(Prompt photons + possible jet-medium interaction)
- Pre-equilibrium
- Thermal from QGP
- Thermal from hot hadronic matter

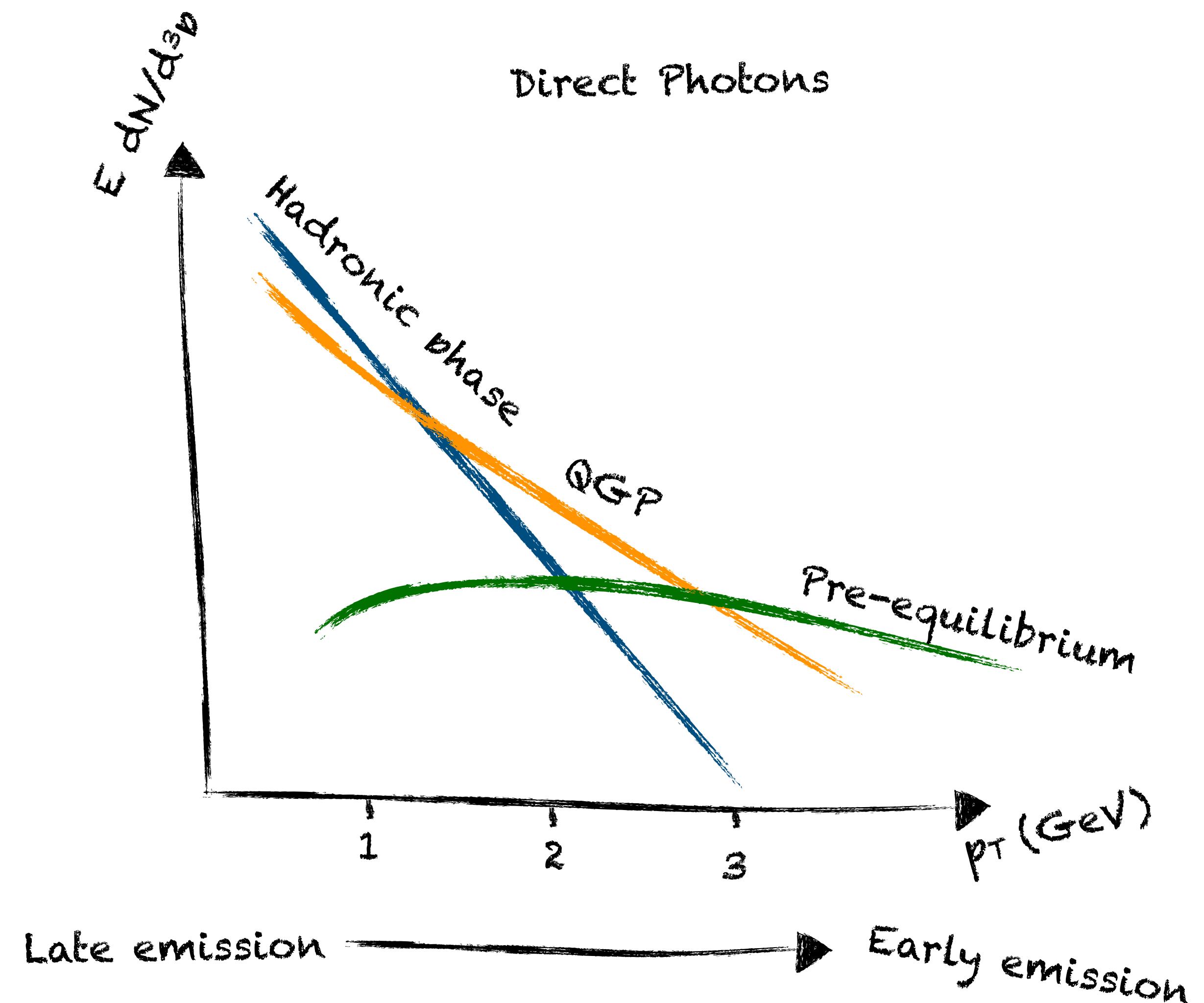
Sources populate different p_T ranges



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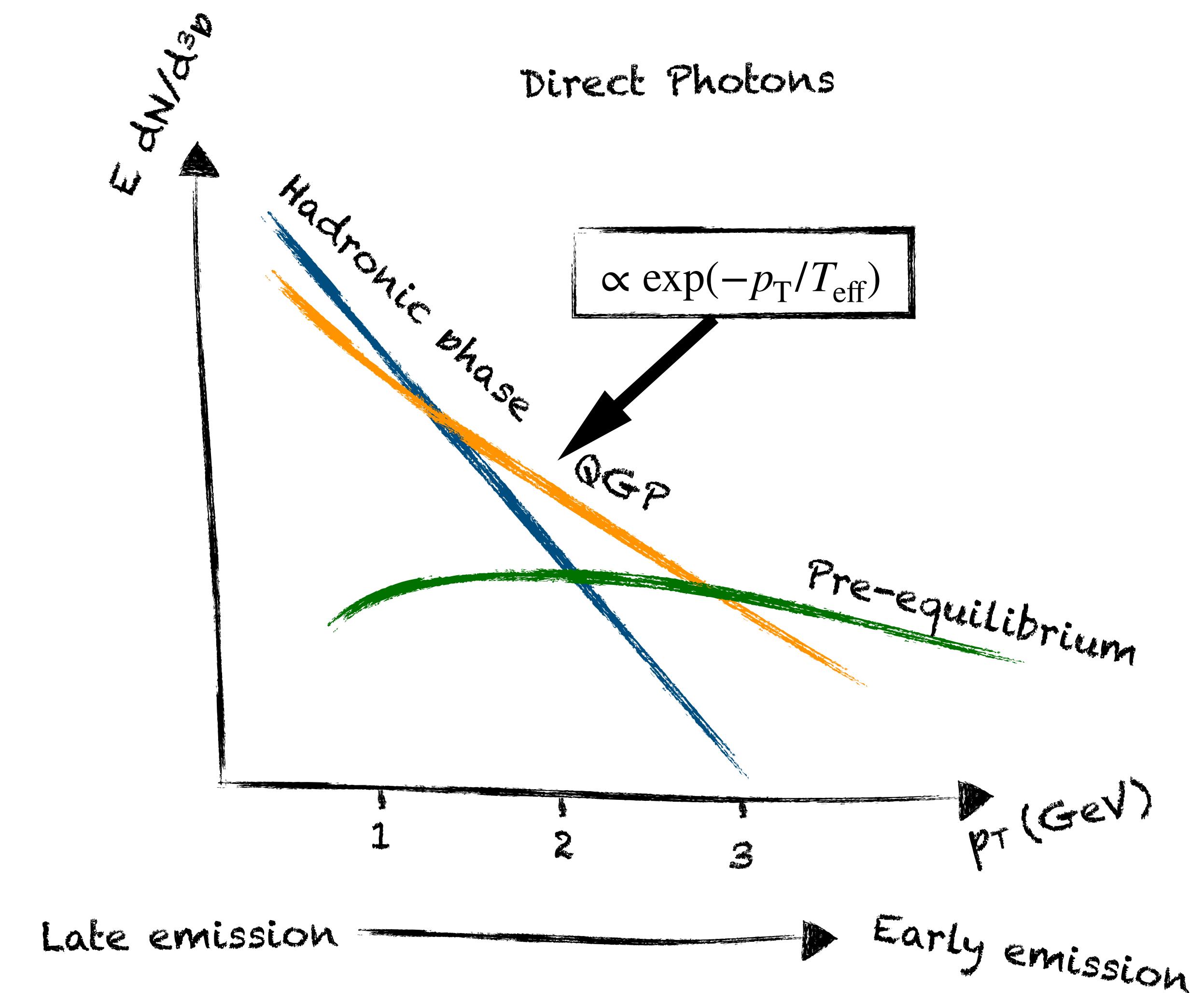
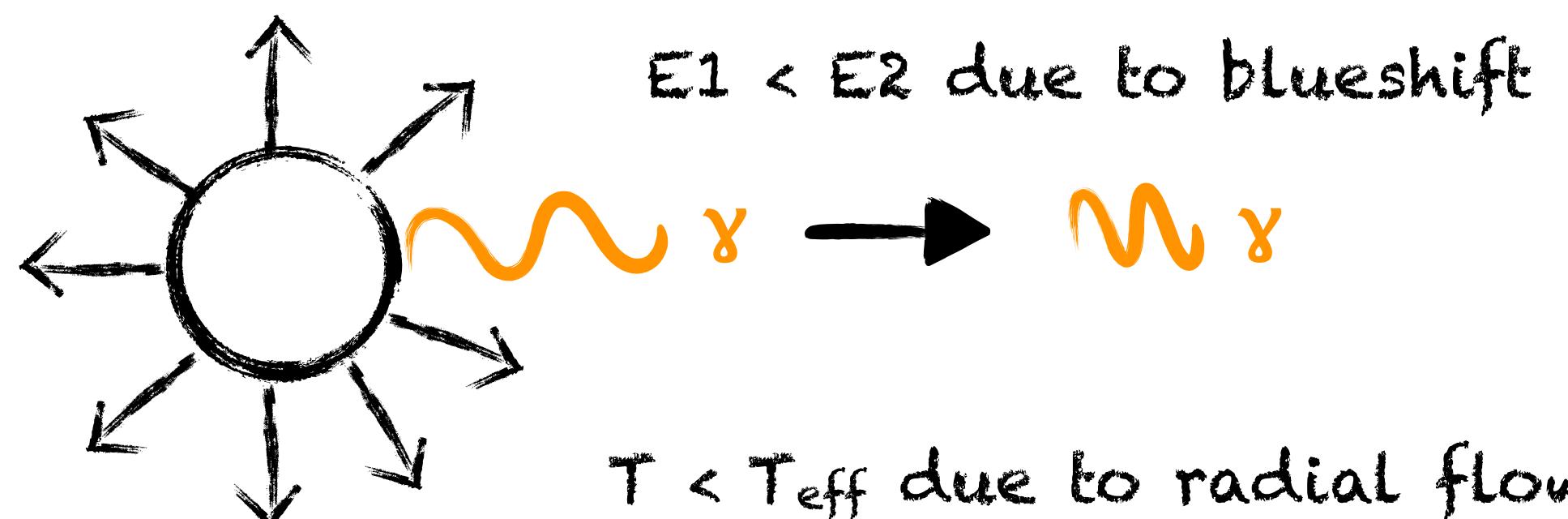
Real direct photon sources

- Hard scattering
(Prompt photons + possible jet-medium interaction)
- Pre-equilibrium
- Thermal from QGP
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Sources populate different p_T ranges

Thermal sources: inverse slope $\propto T_{\text{eff}}$

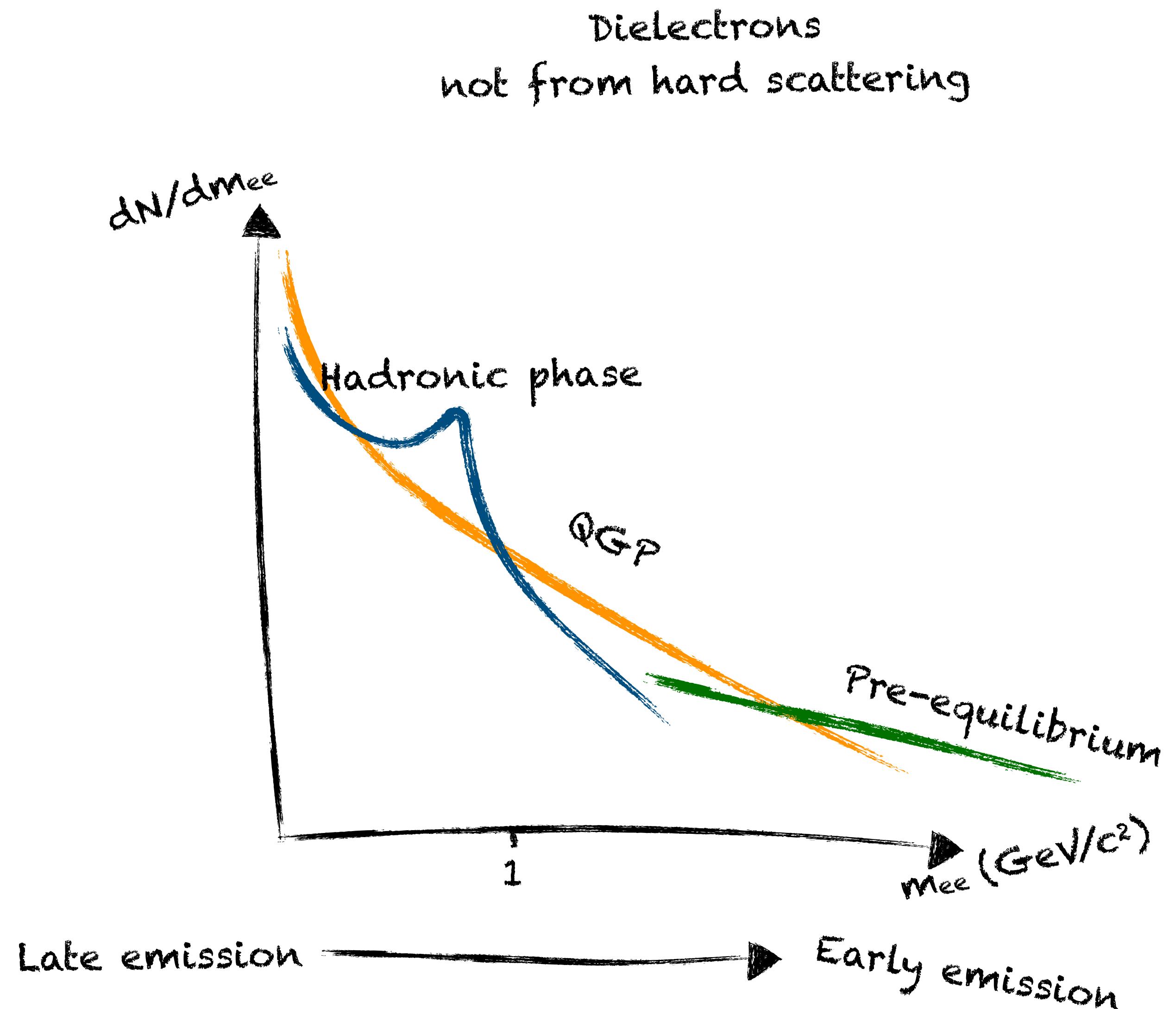
Blueshifted and averaged → Use models to interpret it



Dilepton sources

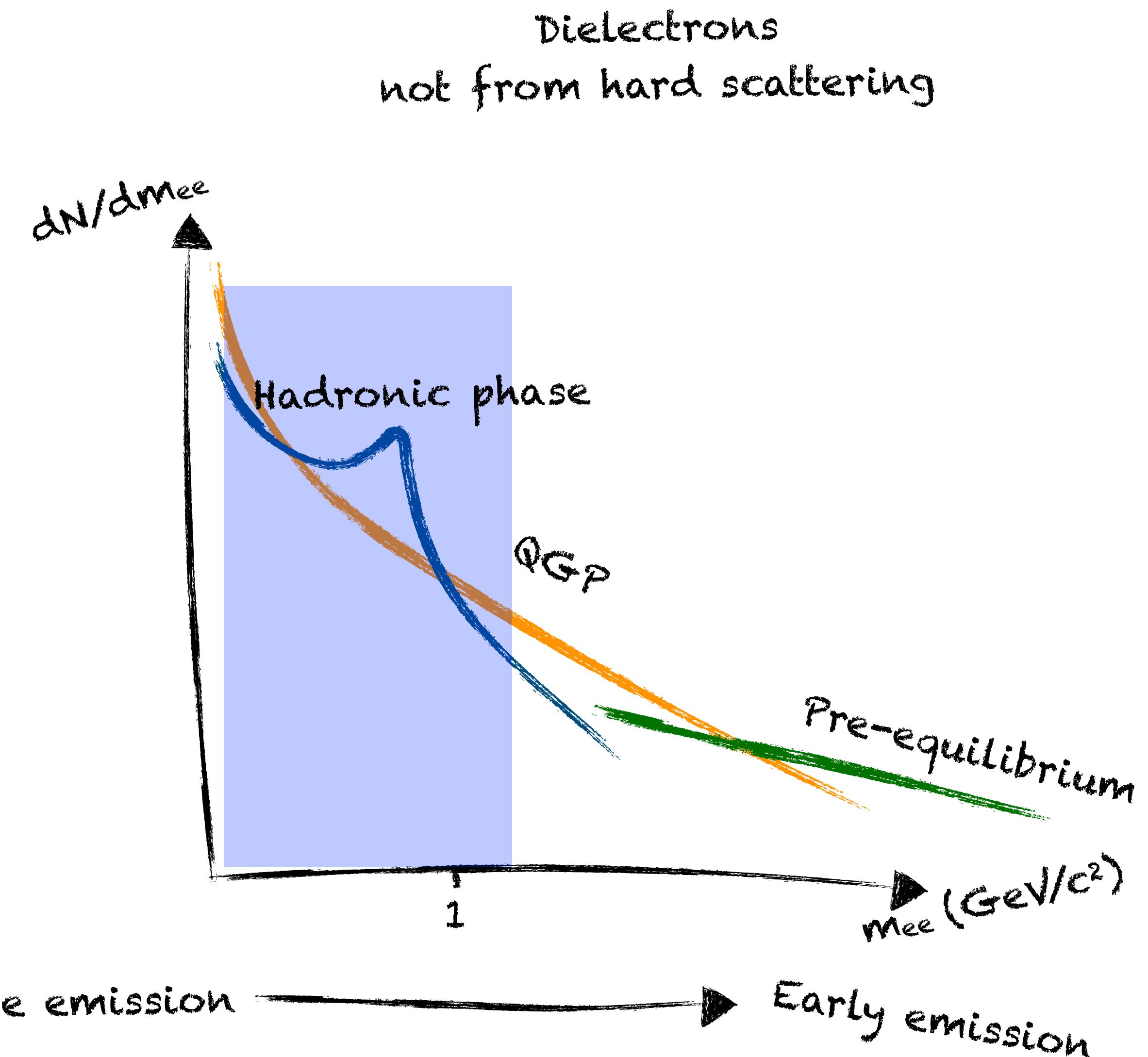
- Hard scattering
Drell-Yan small for low m_{ee} ($\leq 3 \text{ GeV}/c$) at the LHC
- Pre-equilibrium
- Thermal from QGP
- Thermal from hot hadronic matter

Sources populate different mass ranges
Mass not blueshifted



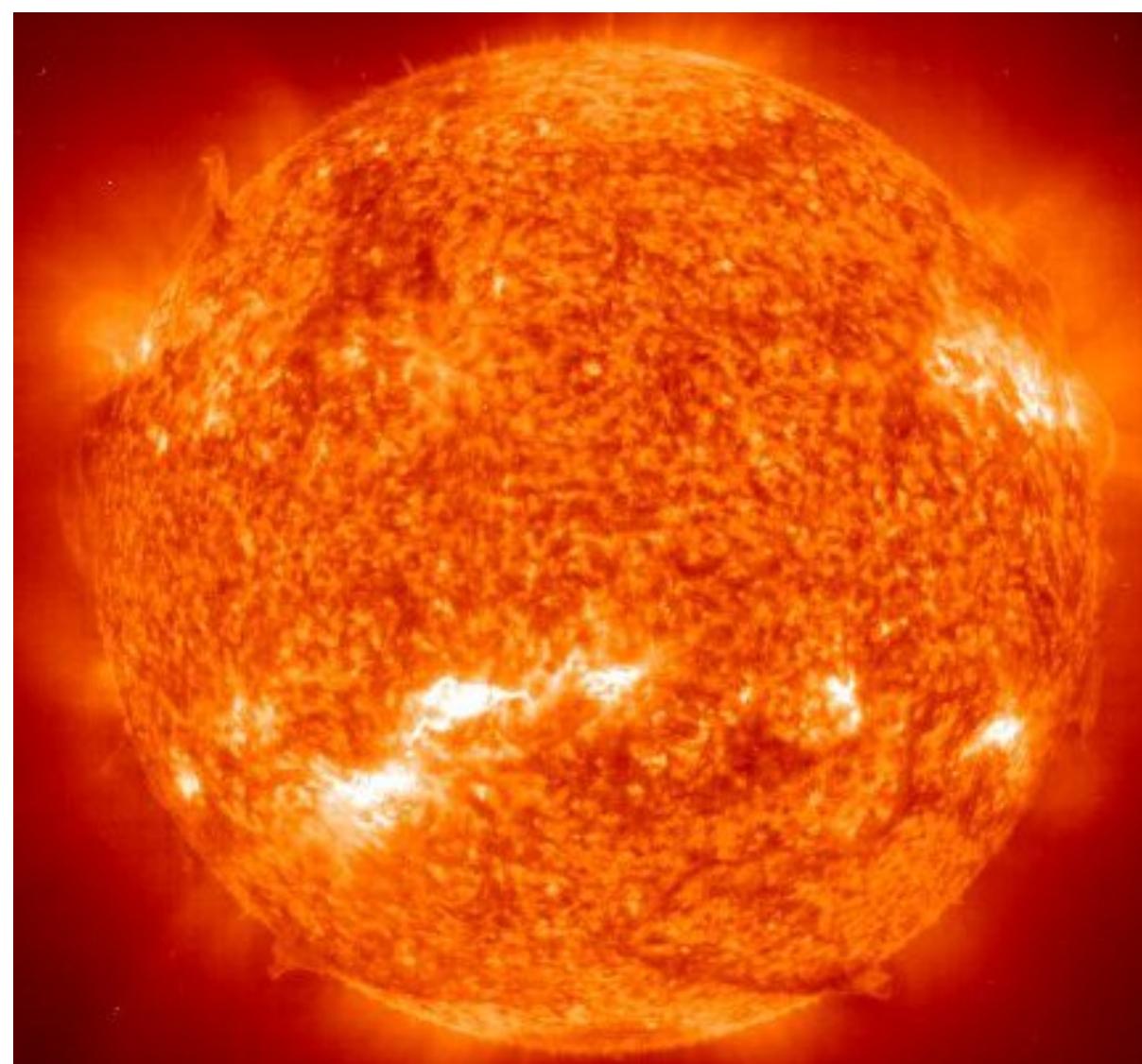
Low invariant mass (LMR)

- $\rho \rightarrow \gamma^* \rightarrow e^+e^-$
produced thermally in the hot hadronic matter
- Modifications of ρ spectral function in the hot medium
Related to the chiral symmetry restoration at high T



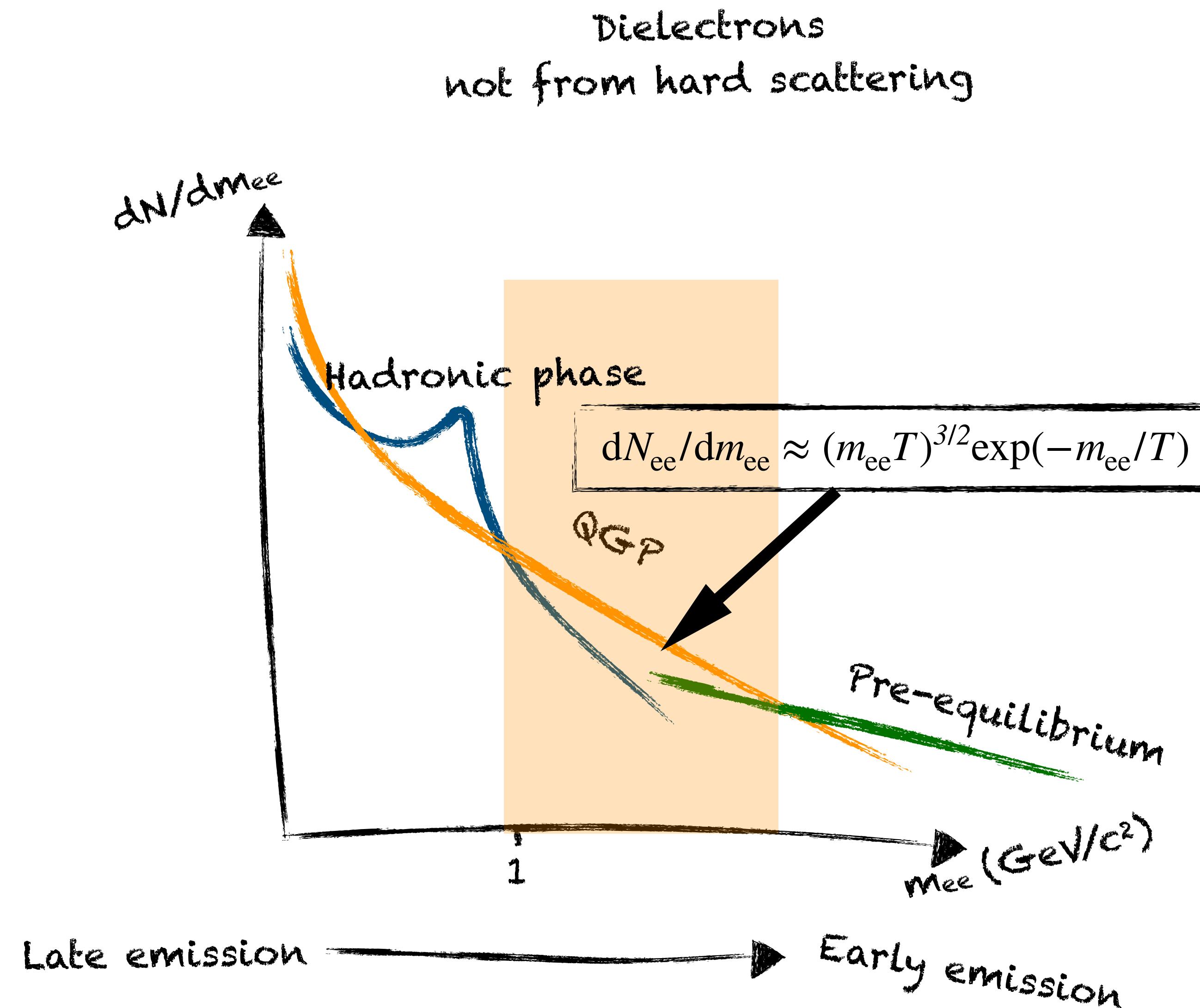
Intermediate invariant mass (IMR)

Black-body radiation from QGP
integrated over space-time

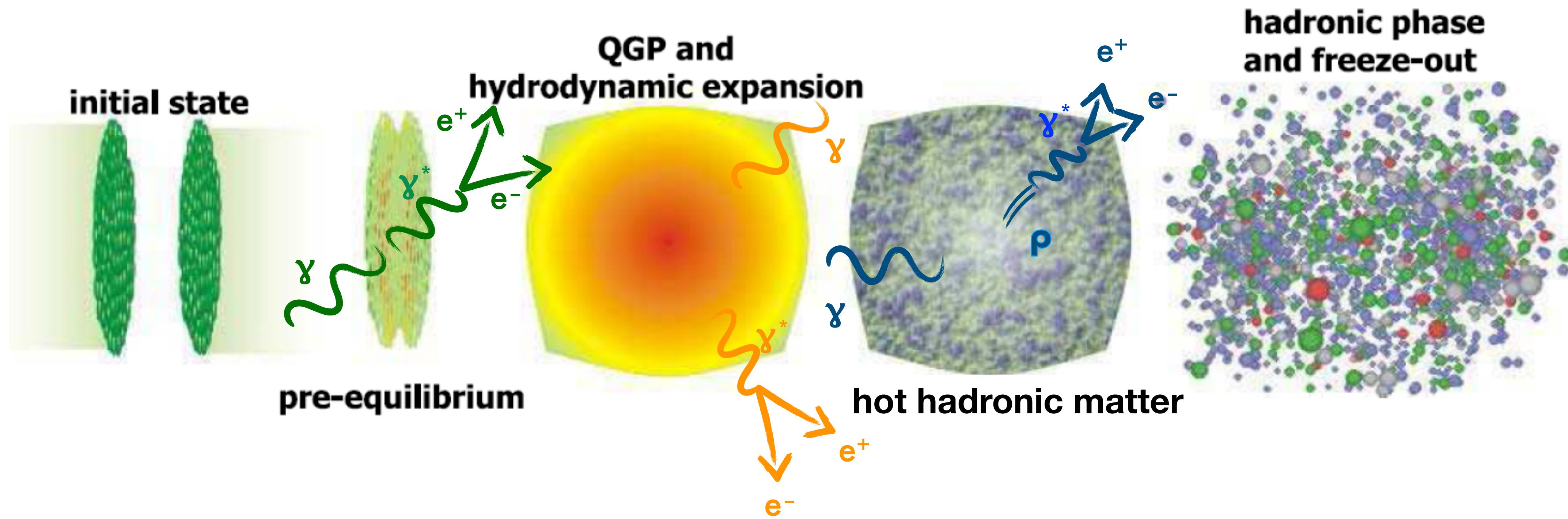


$$\text{Static source} \approx e^{-E/T}$$

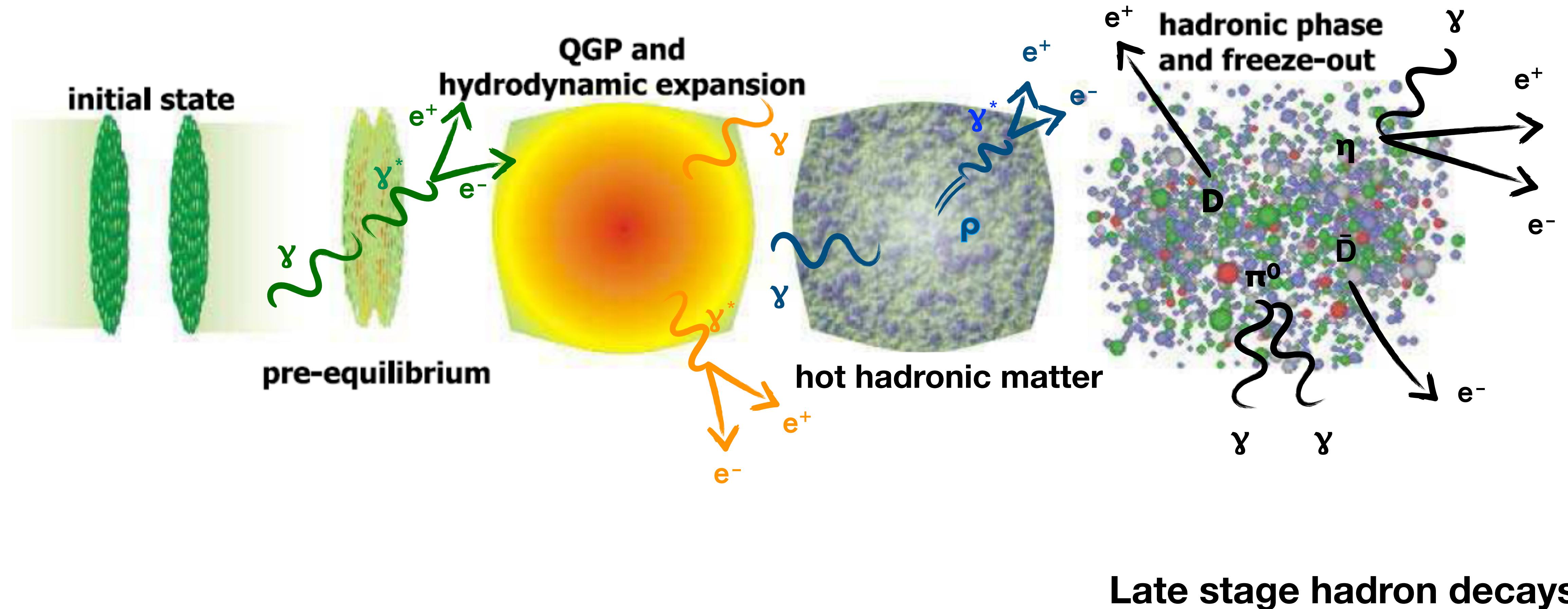
→ Access to early average QGP temperature
No blueshift



The sources



The sources and background



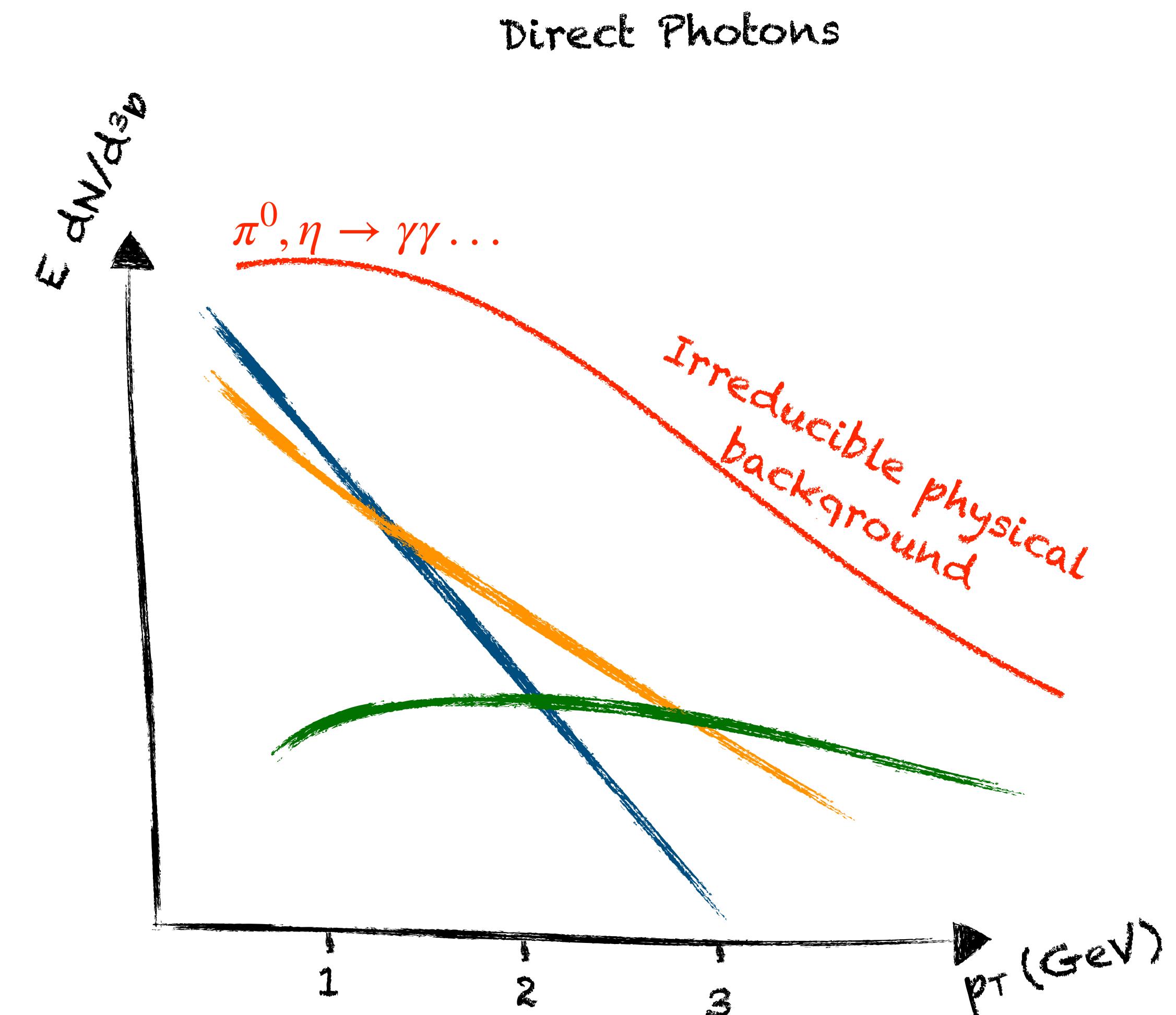
The backgrounds

- **Dileptons: combinatorial background**
 - Do not know the origin of e^\pm
→ Combine all possible e^+e^- pairs
- **Real and virtual γ : irreducible physical backgrounds**
 - Light-flavour hadron decays:
 $\pi^0 \rightarrow \gamma\gamma$ or γe^+e^- , $\eta \rightarrow \gamma\gamma$ or γe^+e^- ..
 - Correlated heavy-flavour (HF) hadron decays:
 $c\bar{c} \rightarrow D\bar{D} \rightarrow e^+e^-XY$

The backgrounds

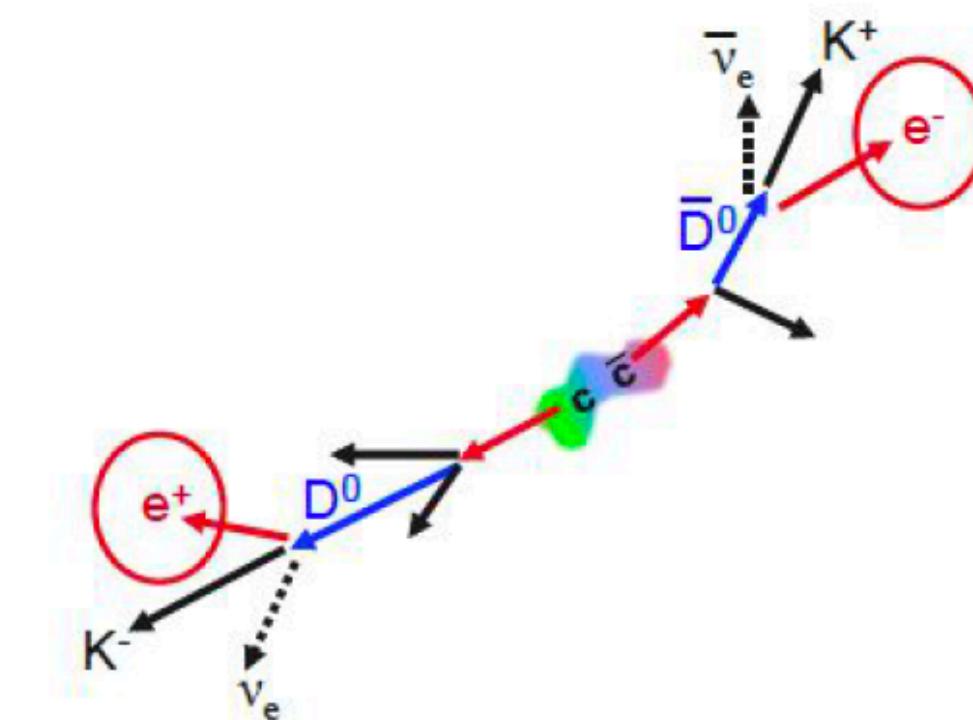
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Estimated with $\pi^0, \eta\dots$ measurements + decay kinematic
→ **Hadronic cocktail**



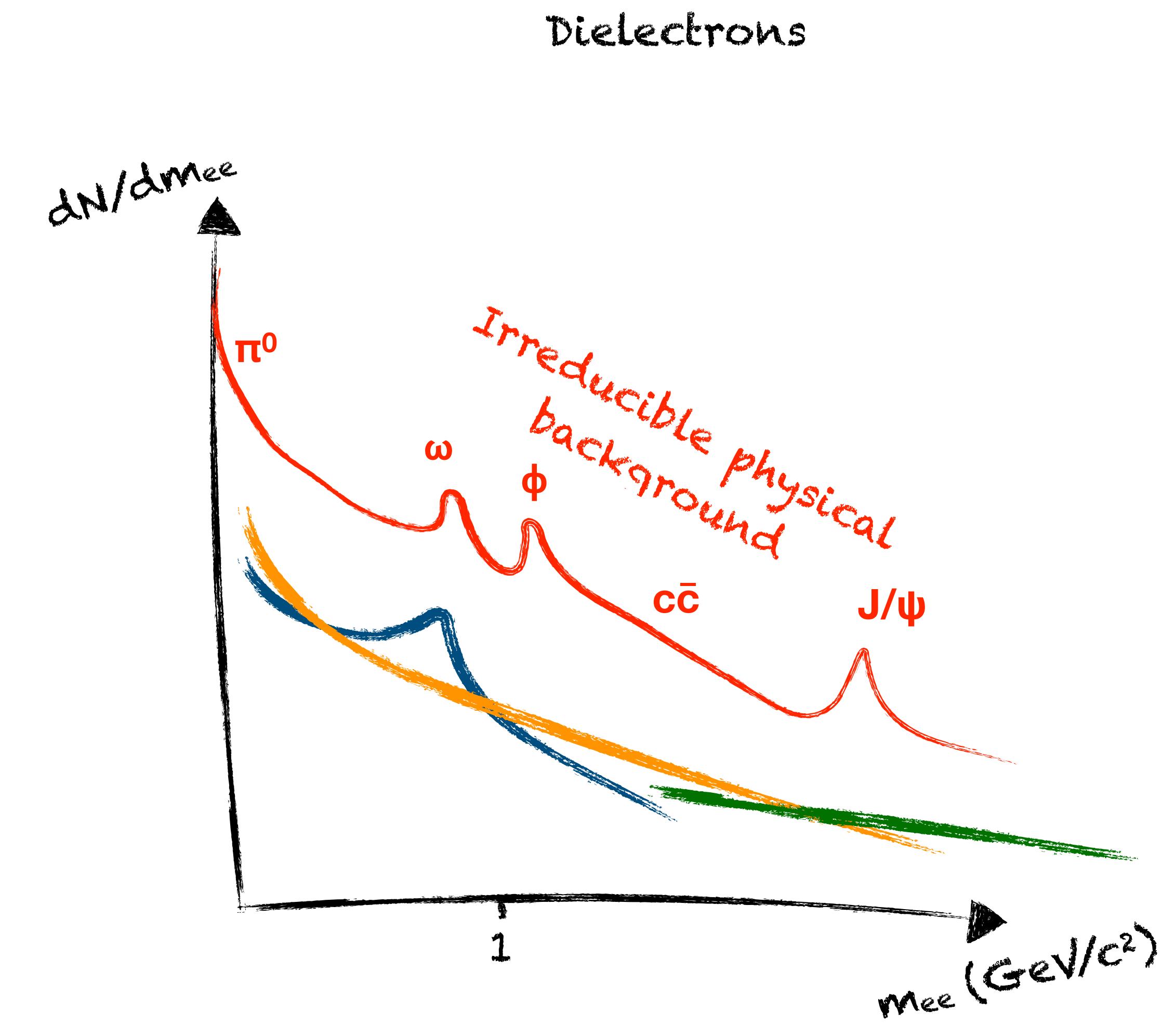
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 $c\bar{c} \rightarrow D\bar{D} \rightarrow e^+e^-XY$



very large heavy-flavour background at the LHC !

Difficult to estimate (need to know $D\bar{D}$ correlation...) → Other method needed



Photon measurements in ALICE

Real photons:

- Photon conversion in the detector material (PCM)

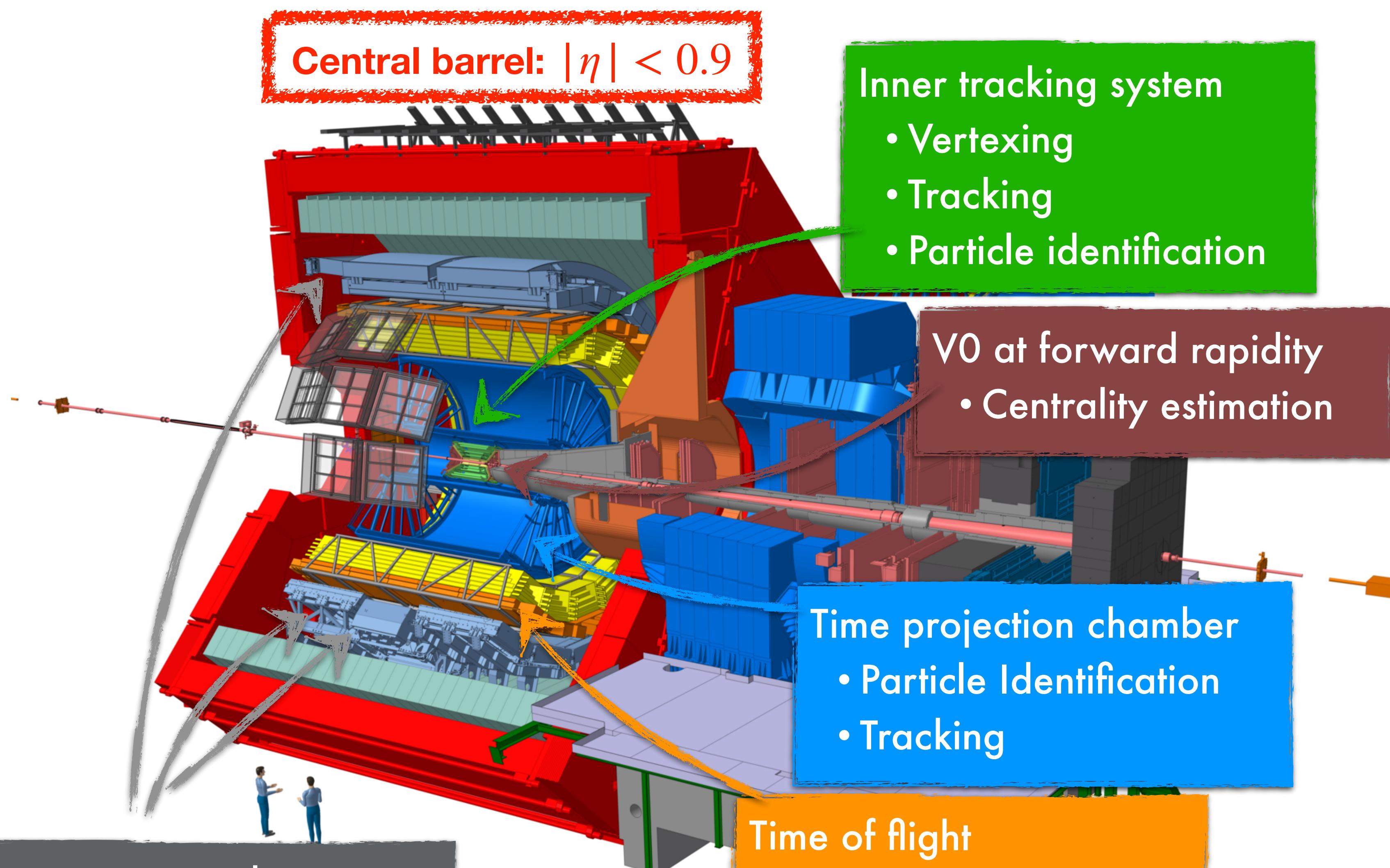
$$\gamma X \rightarrow e^+ e^-$$

- Measurement with calorimeters

Virtual photons:

- Prompt dielectrons ($\gamma^* \rightarrow e^+ e^-$) at midrapidity

Central barrel: $|\eta| < 0.9$



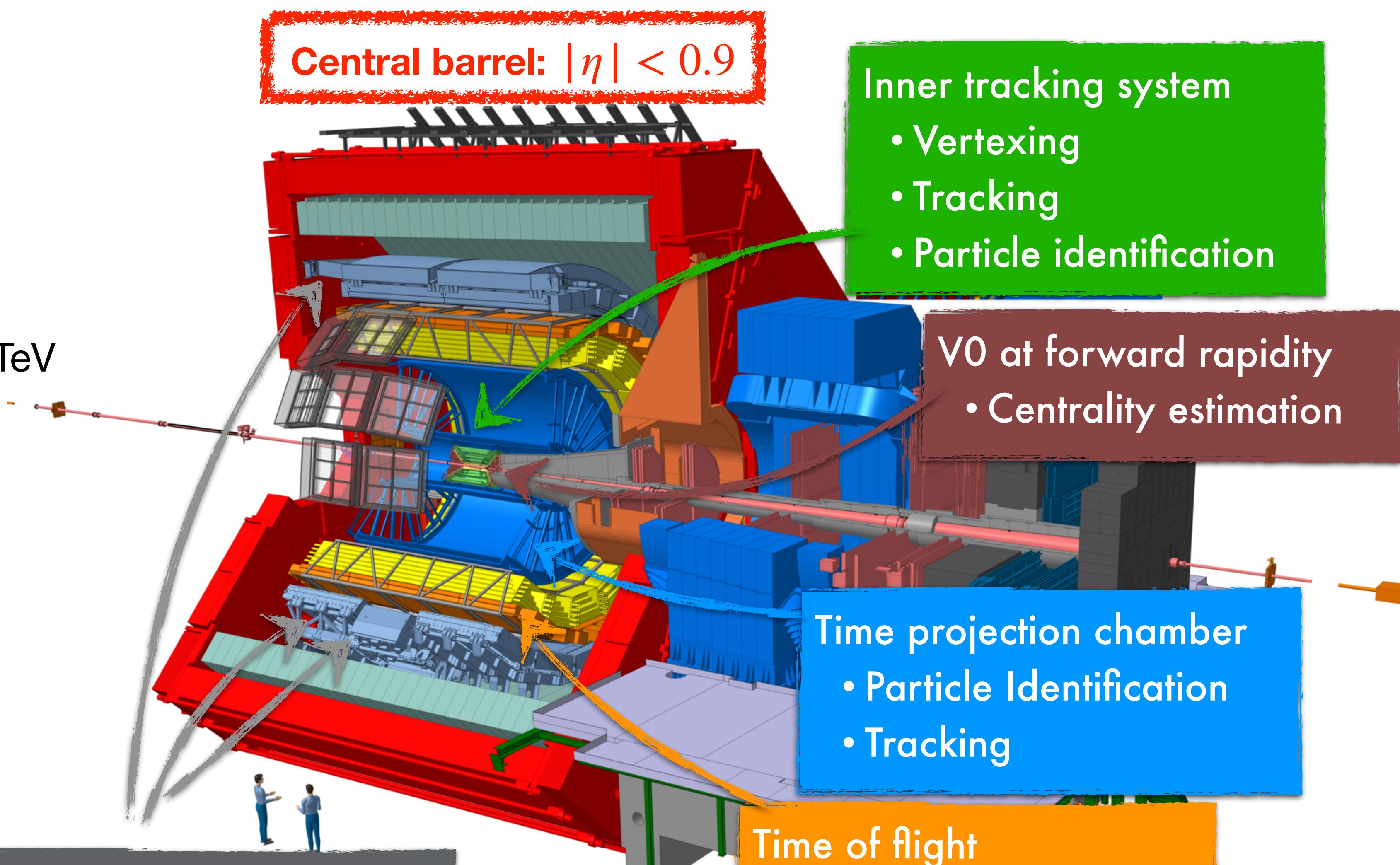
Photon measurements in ALICE

Data in this presentation:

Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

- Minimum bias (2015)
- Triggered 0-10% and 30-50% most central events (2018)

Central barrel: $|\eta| < 0.9$



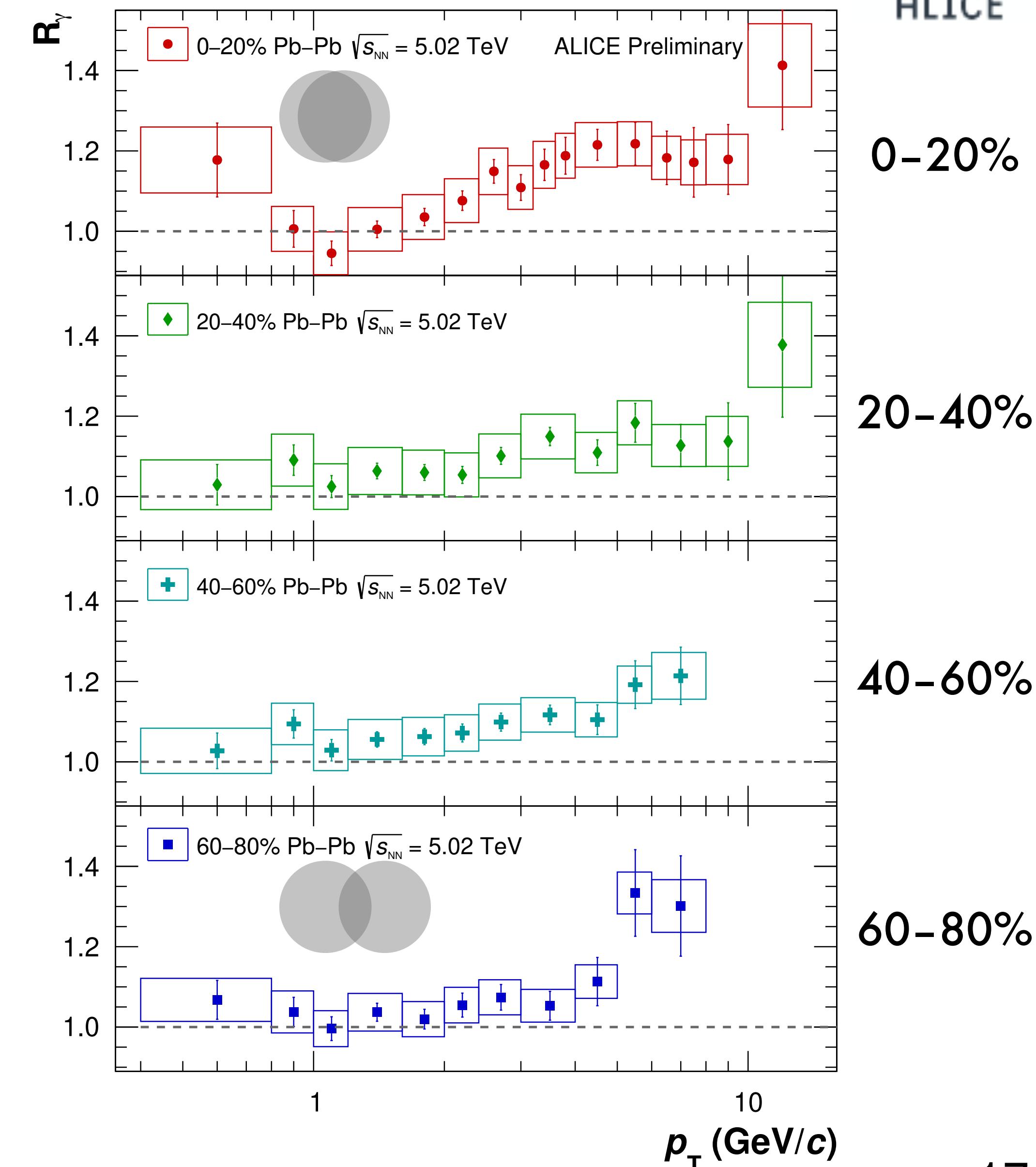
Real photons

Measured via photon conversion method (PCM)

$$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \rightarrow \text{Direct photons if } > 1$$

γ_{inc} = all photons (inclusive)

γ_{decay} = photons from hadronic decays (cocktail calculations)



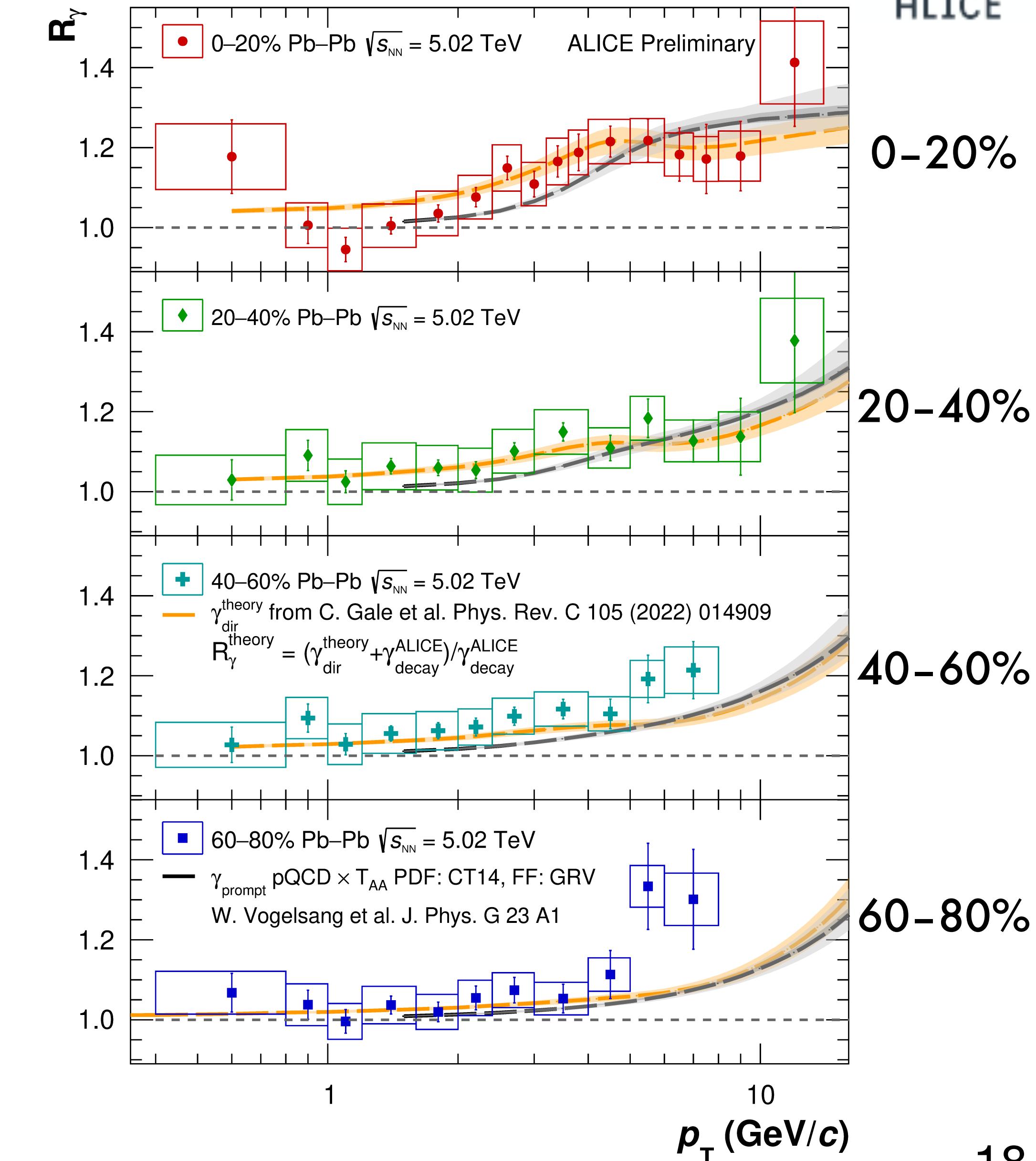
Real photons

Measured via photon conversion method (PCM)

$$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \rightarrow \text{Direct photons if } > 1$$

Data consistent with:

- **Prompt photon from NLO pQCD calculations**
pp collisions scaled with the number of binary nucleon-nucleon collisions (N_{coll})
 - **Hydrodynamical calculations containing:**
 - Pre-equilibrium
 - Thermal
 - Prompt photons
- Small excess predicted at intermediate/low p_T



Real photons

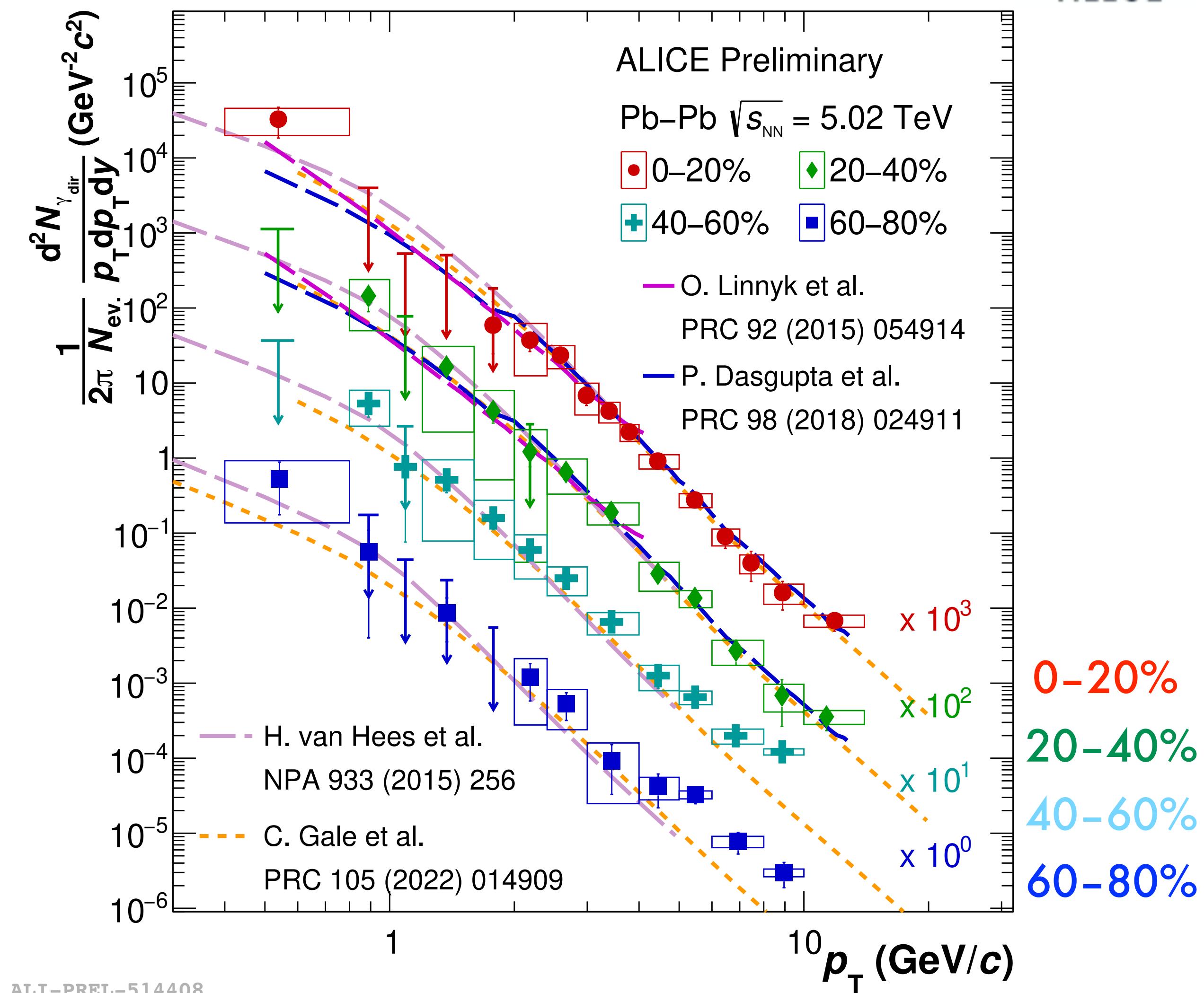
Direct photon spectra:

$$\gamma_{\text{dir}} = \gamma_{\text{inc}} \times \left(1 - \frac{1}{R_\gamma}\right)$$

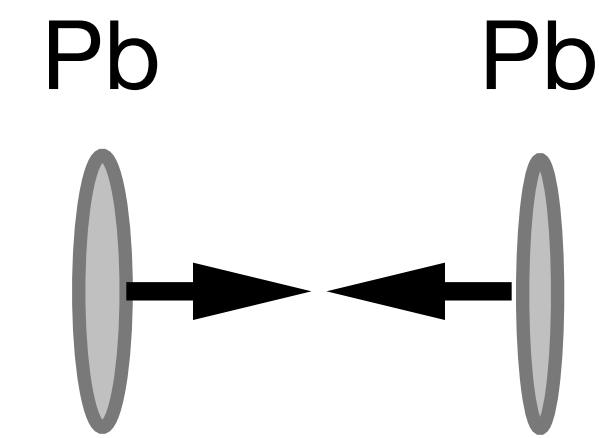
Upper limits where data consistent with 0

Data well described by different models

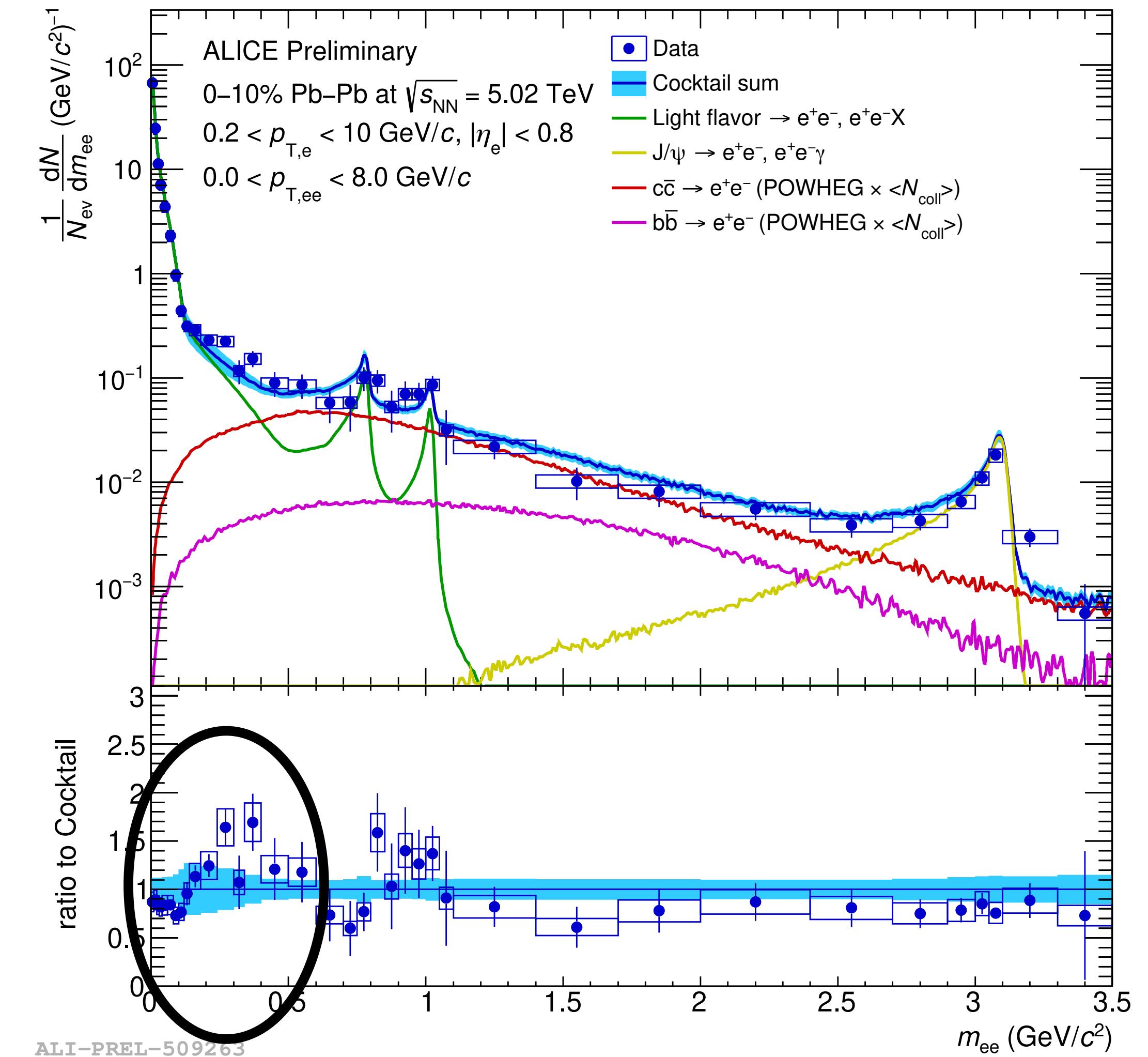
→ No sensitivity yet to the different implementations



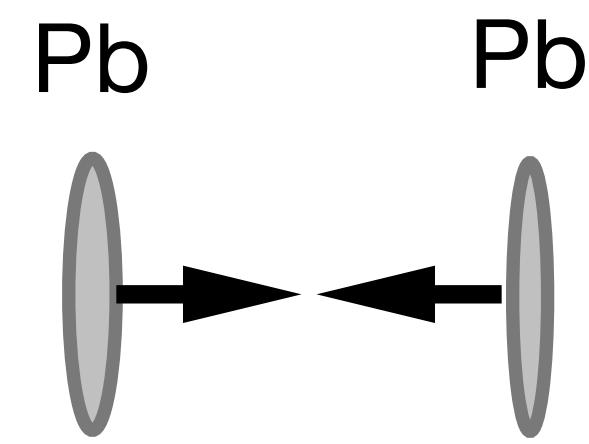
Dielectrons



- e^+e^- spectrum compared to hadronic cocktail
- Hint for excess at masses $< 0.5 \text{ GeV}/c^2$



Dielectrons

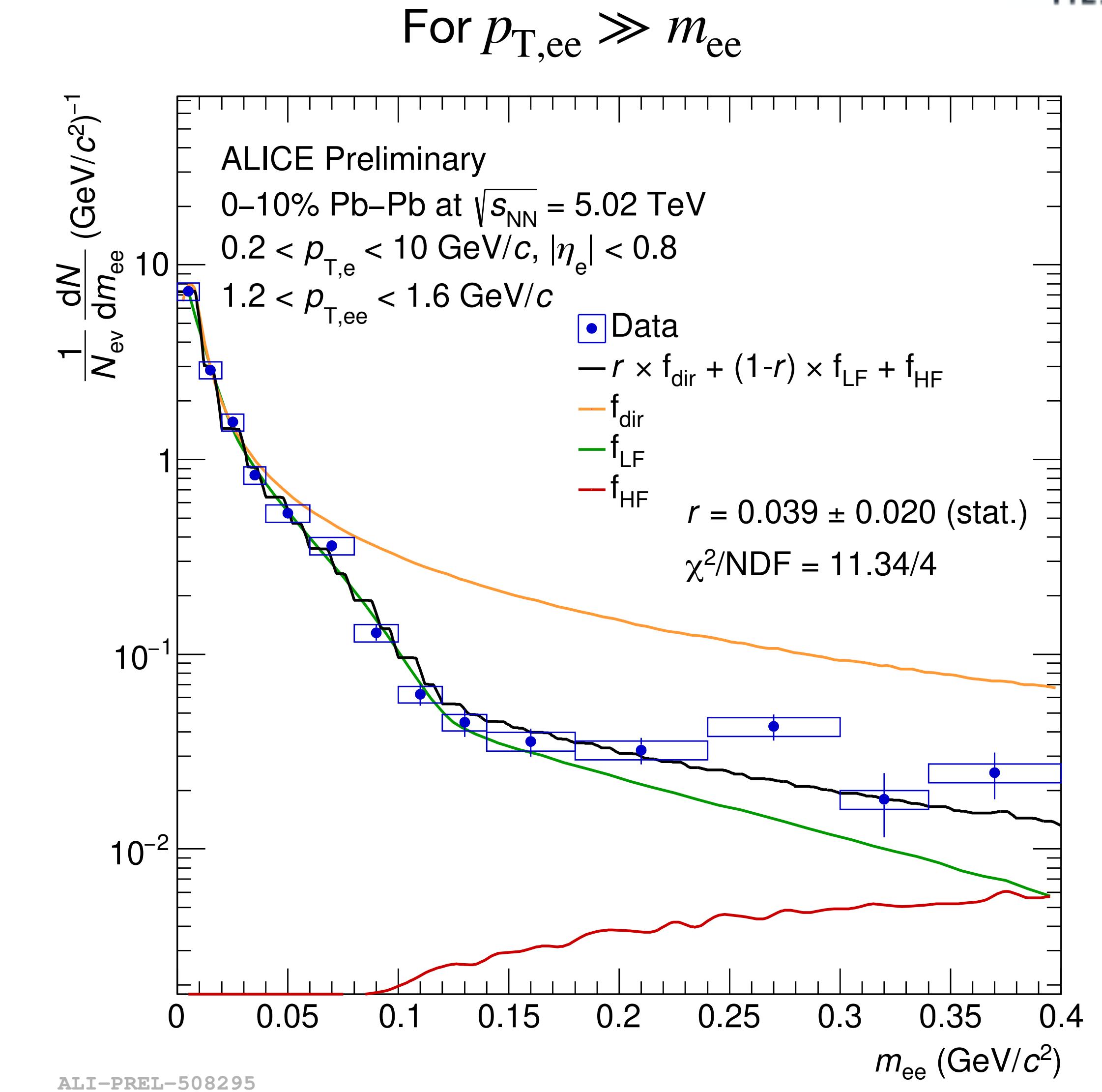


Extract direct photon fraction r ($= \frac{\gamma_{\text{dir}}^*}{\gamma_{\text{inc}}^*} \Big|_{m_{ee} \rightarrow 0} = \frac{\gamma_{\text{dir}}}{\gamma_{\text{inc}}}$)

by fitting the m_{ee} distribution above the pion mass:

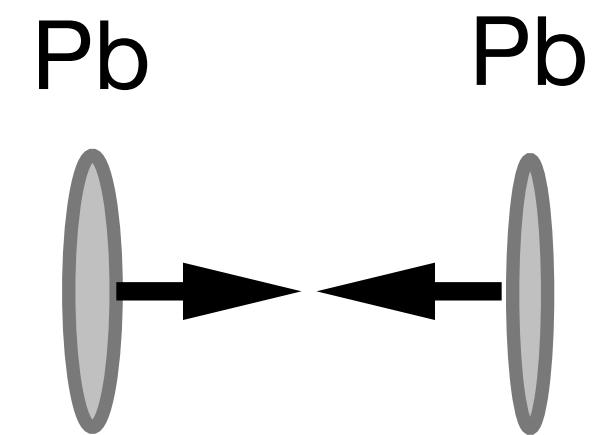
$$f_{\text{fit}} = r \times f_{\text{dir}} + (1 - r) \times f_{\text{LF}} + f_{\text{HF}}$$

Direct Light flavour Heavy flavour



ALI-PREL-508295

Dielectrons



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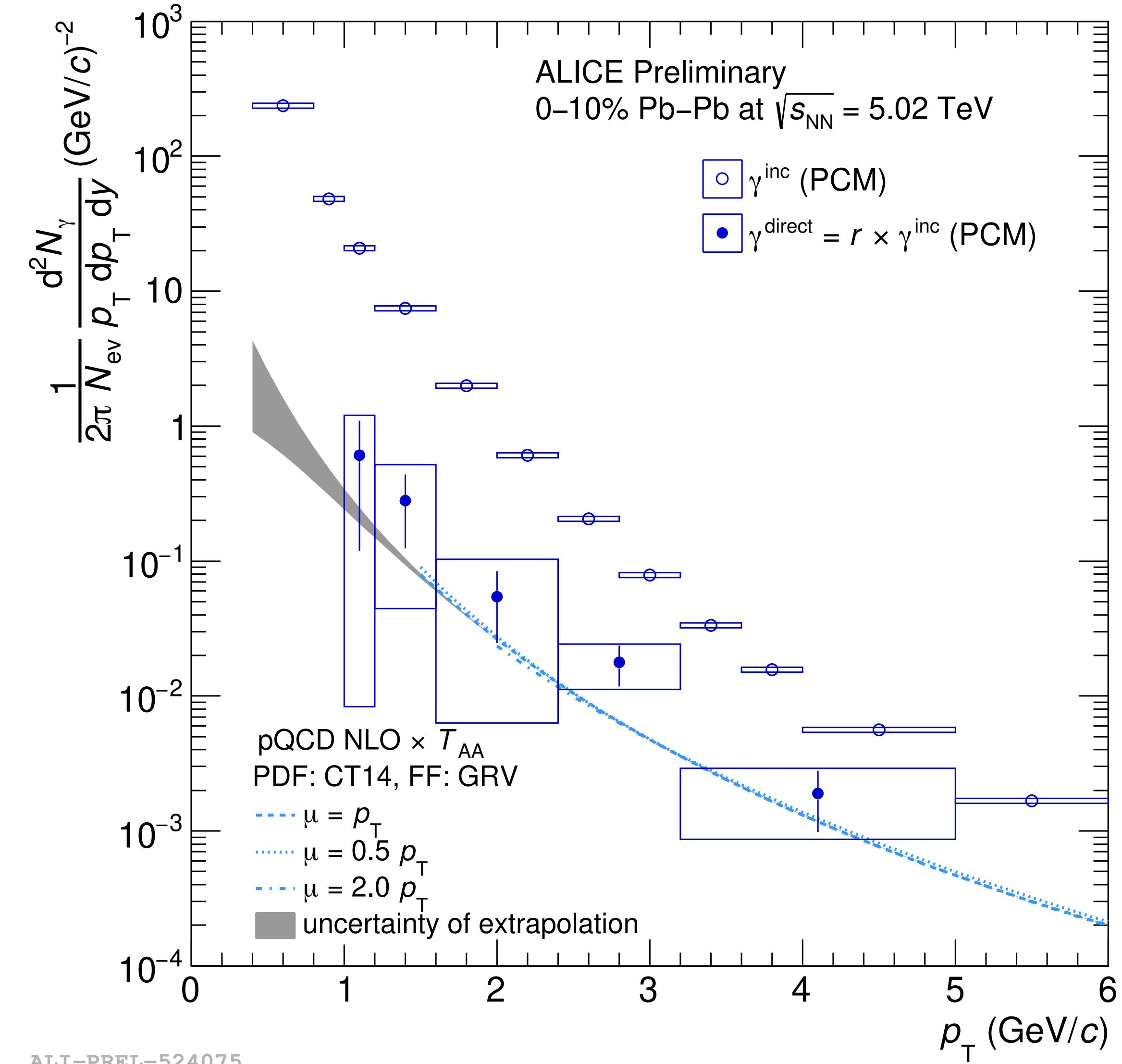
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Direct

Light flavour

Heavy flavour

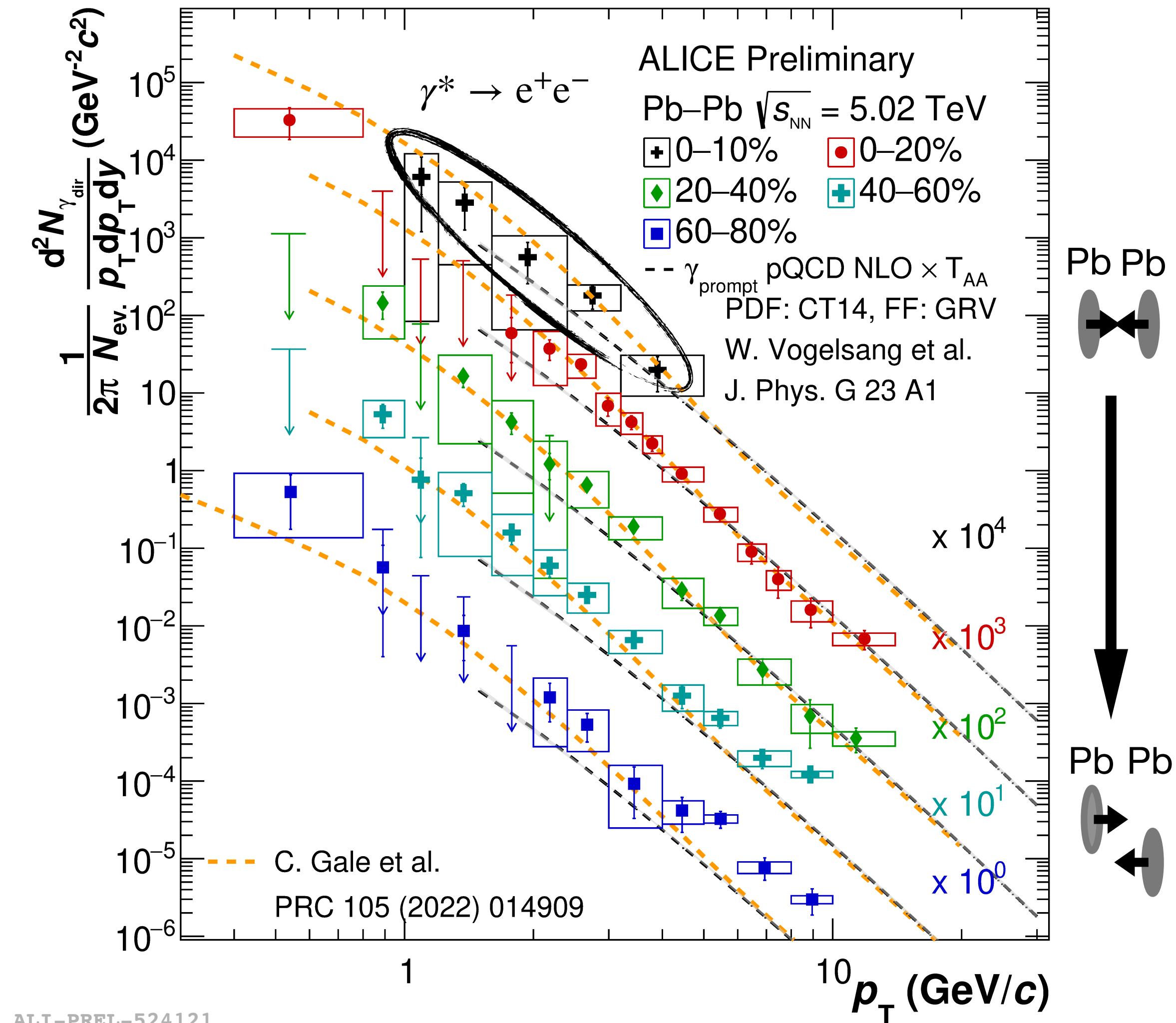
→ Direct real photon spectrum as $r \times \gamma_{\text{inc}}(\text{PCM})$



Direct real photons

- Latest direct photon measurements in **Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$** by ALICE
- Data consistent with both:
 - pQCD prompt photon calculations at high p_T
 - State-of-the-art model including pre-equilibrium and thermal γ**
- Current data uncertainties still large

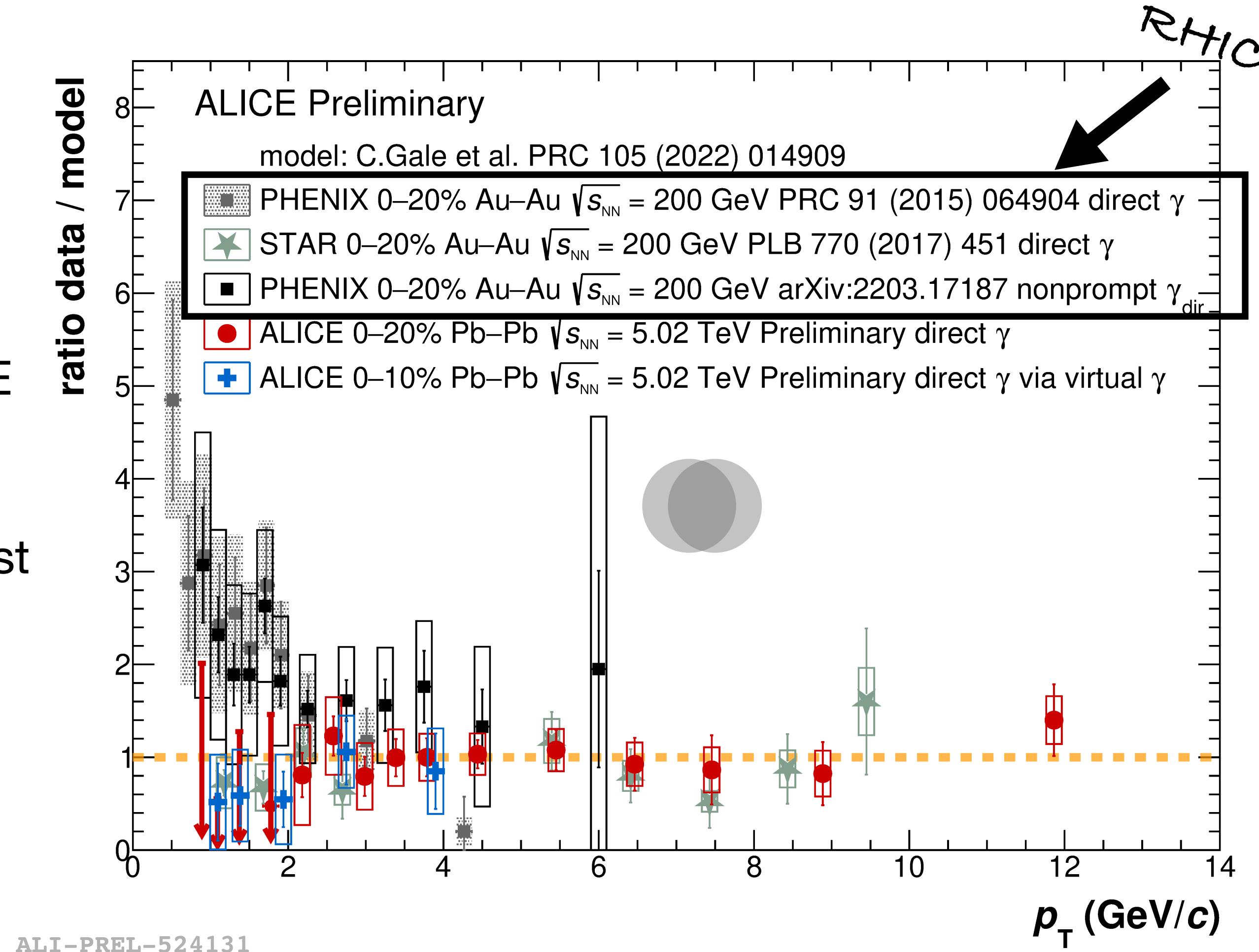
Results also in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$
 ALICE, Phys. Lett. B 754 (2016) 235; ALICE, Phys. Lett. B 789 (2019) 308



Direct photons at the LHC and at RHIC

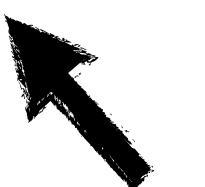


- Comparison of direct photon results to their respective state-of-the-art model calculations
- No puzzling discrepancy of yields between new ALICE measurements and state-of-the-art model
- Slight tension at low p_T for the PHENIX data in the past
- Future: interesting to see if there is a puzzle that involves the flow of direct photons



ALI-PREL-524131

Direct photon HBT



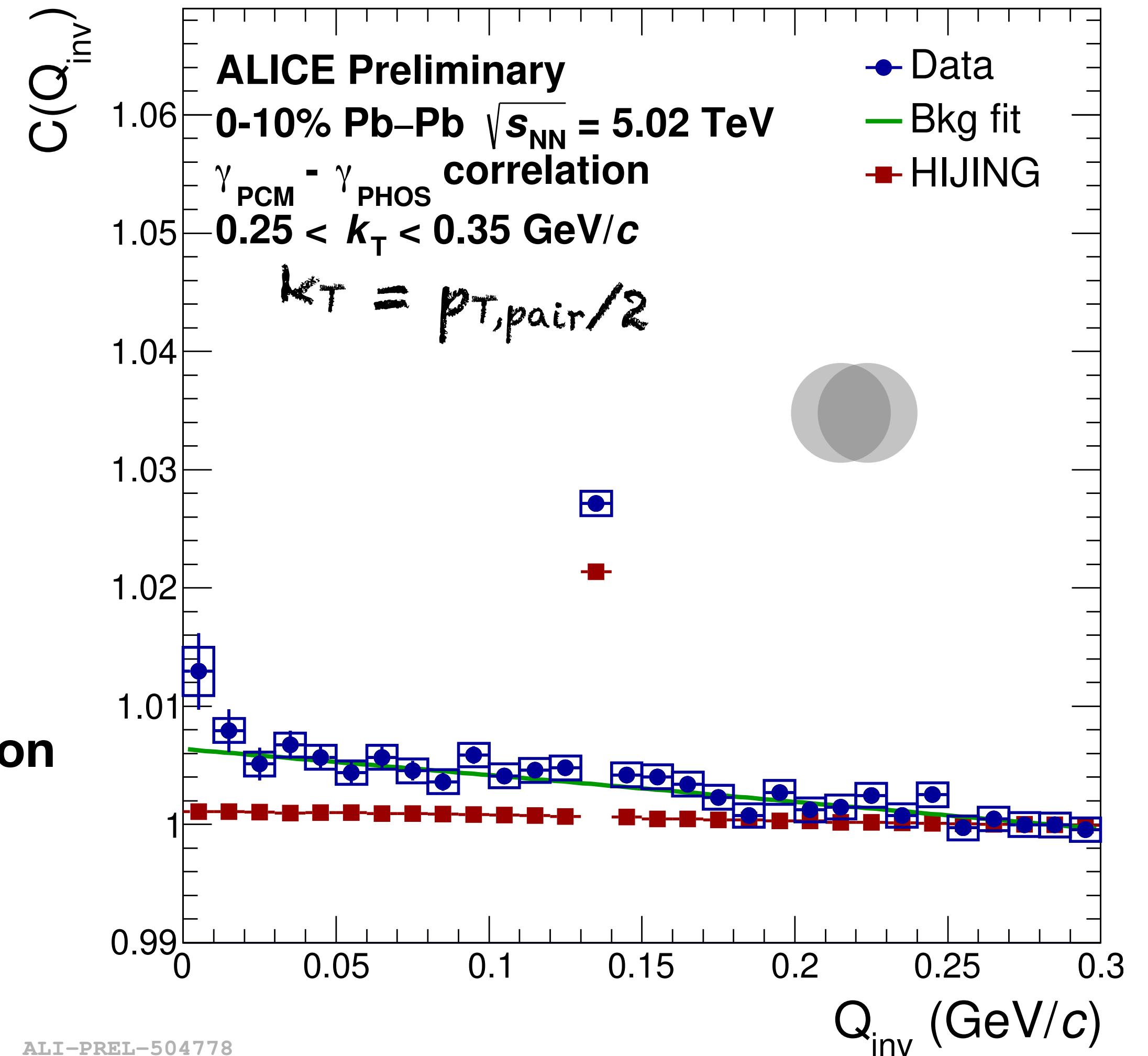
Hanbury Brown Twiss correlation

- Measure $\gamma\gamma$ momentum correlation with one γ with PCM and one γ in calorimeter
- Correlation function:

$$C(Q_{\text{inv}}) = \frac{Q_{\text{inv,SE}}}{Q_{\text{inv,ME}}}$$

$Q_{\text{inv}} = m_{\gamma\gamma}$ from same events (SE) and mixed events (ME)

Sensitive to size of emitting source and direct photon fraction



Direct photon HBT



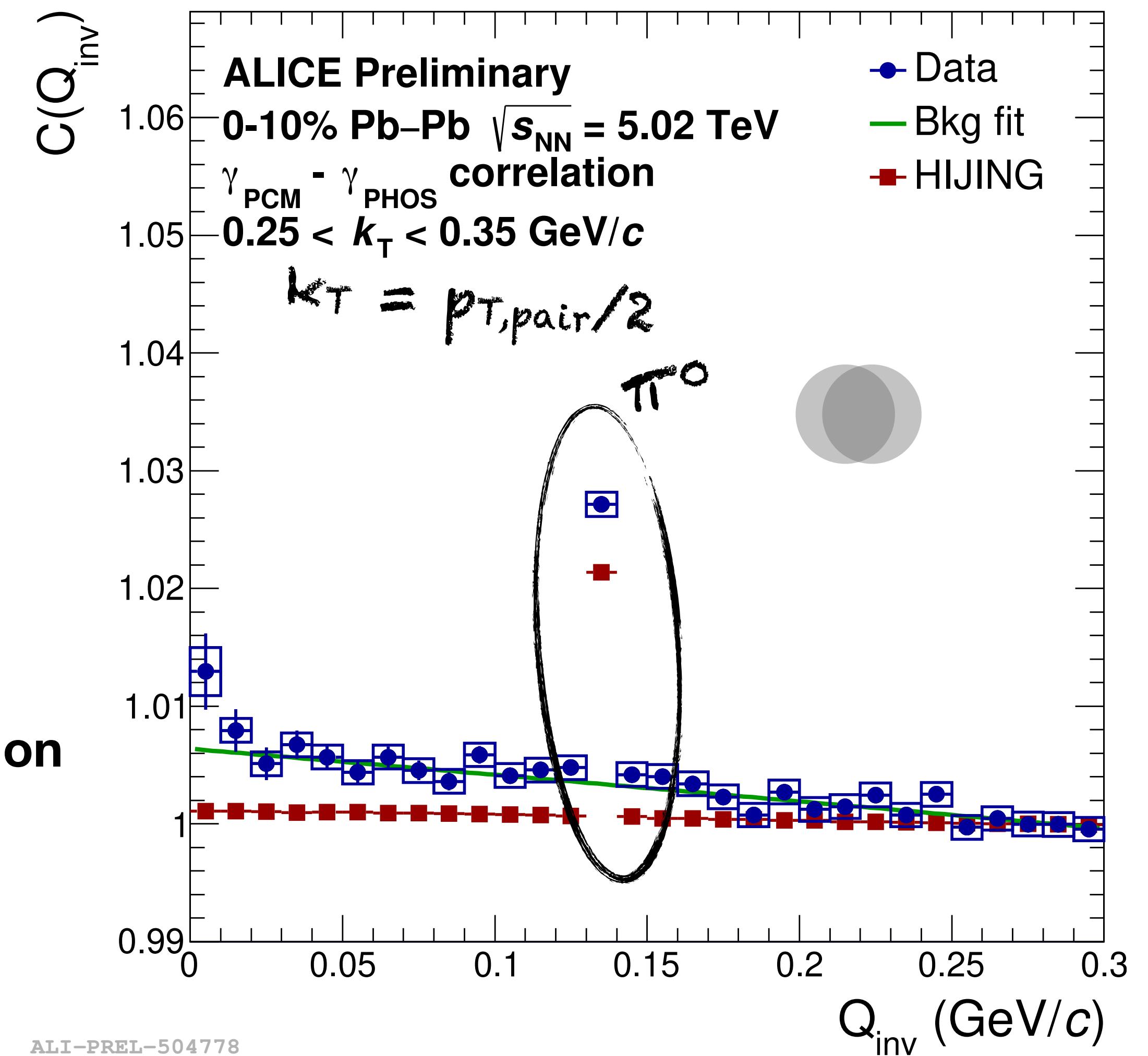
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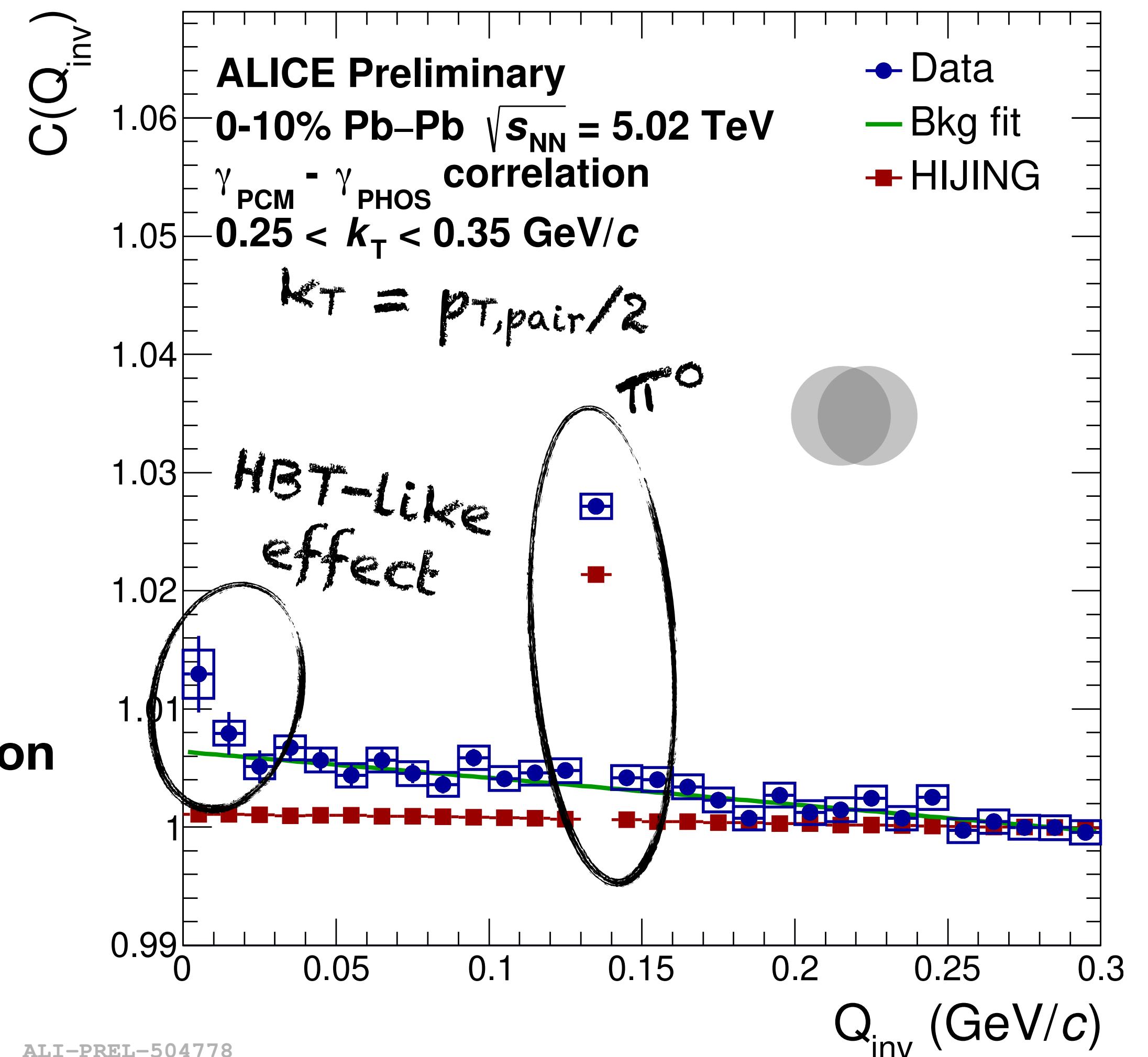
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Sensitive to size of emitting source and direct photon fraction

Measurements by WA98 in Pb—Pb at lower energy

WA98, Phys. Rev. Lett. 93 022301

Raphaelle Bailhache



Relative momentum

Direct photon HBT



At low Q_{inv} , quantify direct photon HBT signature by fitting with:

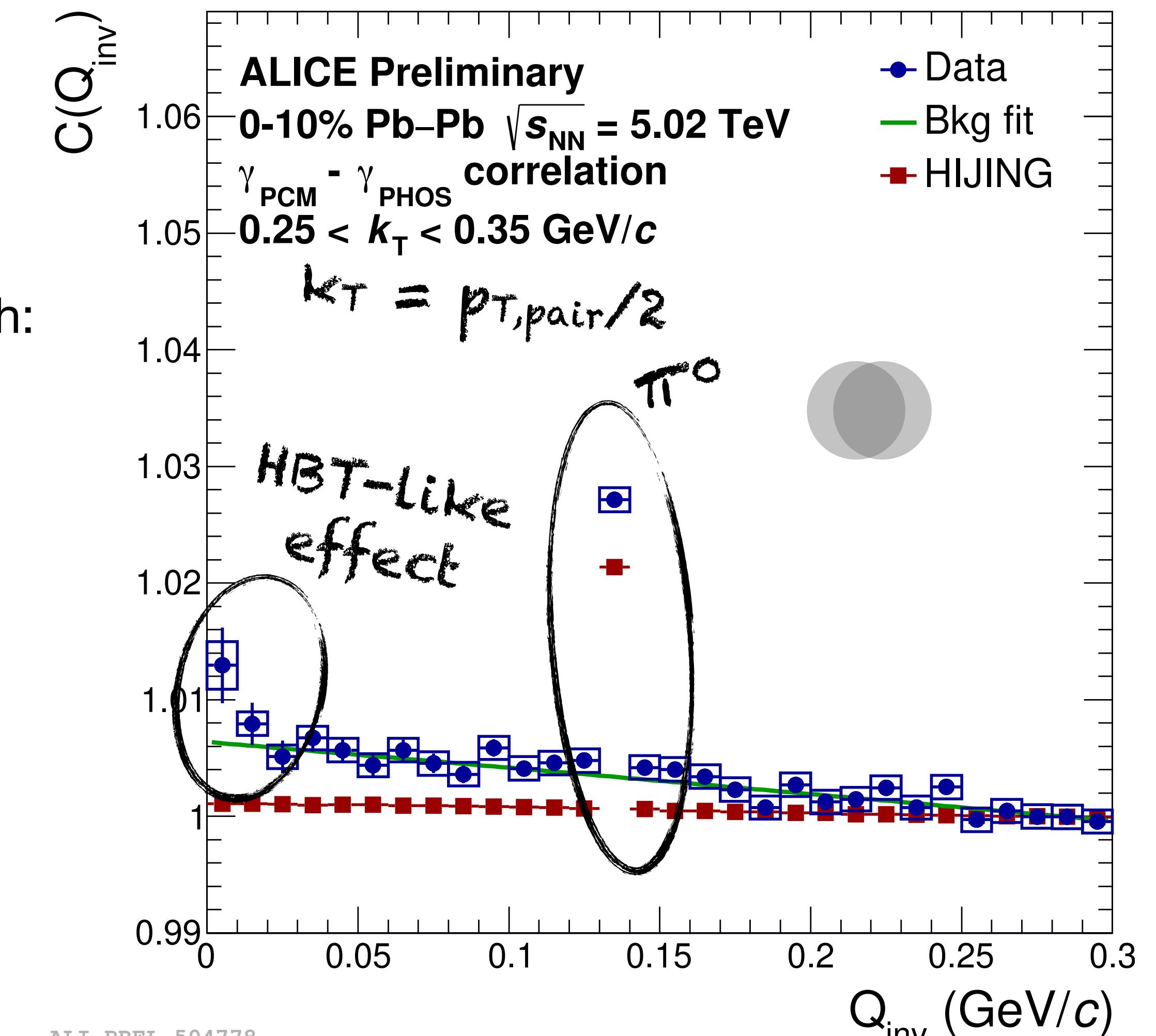
$$C(Q_{\text{inv}}) = 1 + \lambda_{\text{inv}} \exp(-R_{\text{inv}}^2 Q_{\text{inv}}^2)$$

*Correlation strength
related to γ_{dir} fraction*

Source size

Measurements by WA98 in Pb-Pb at lower energy

WA98, Phys. Rev. Lett. 93 022301



Direct photon Hanbury Brown Twiss correlation



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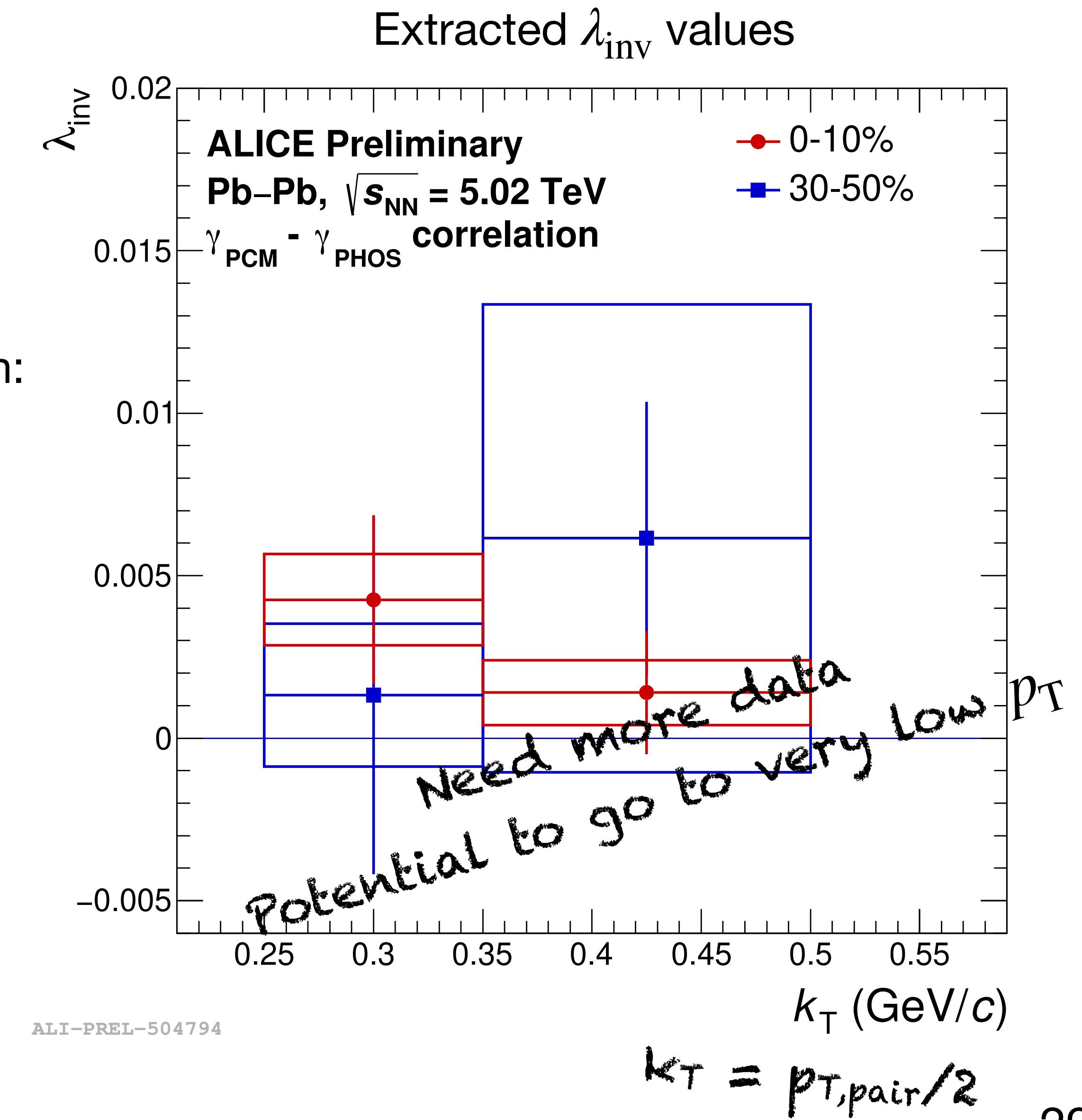
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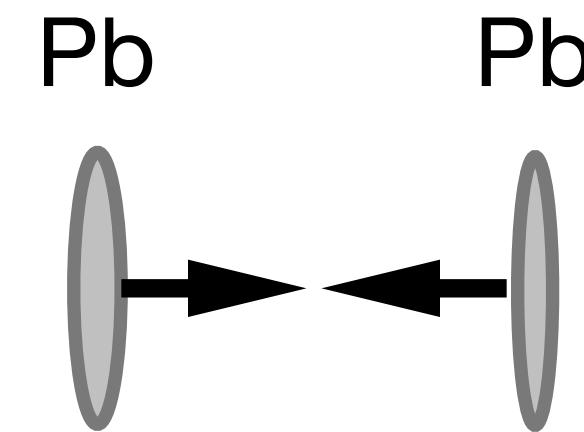
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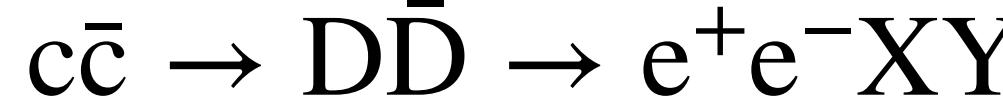
WA98, Phys. Rev. Lett. 93 022301



Dielectrons - higher masses

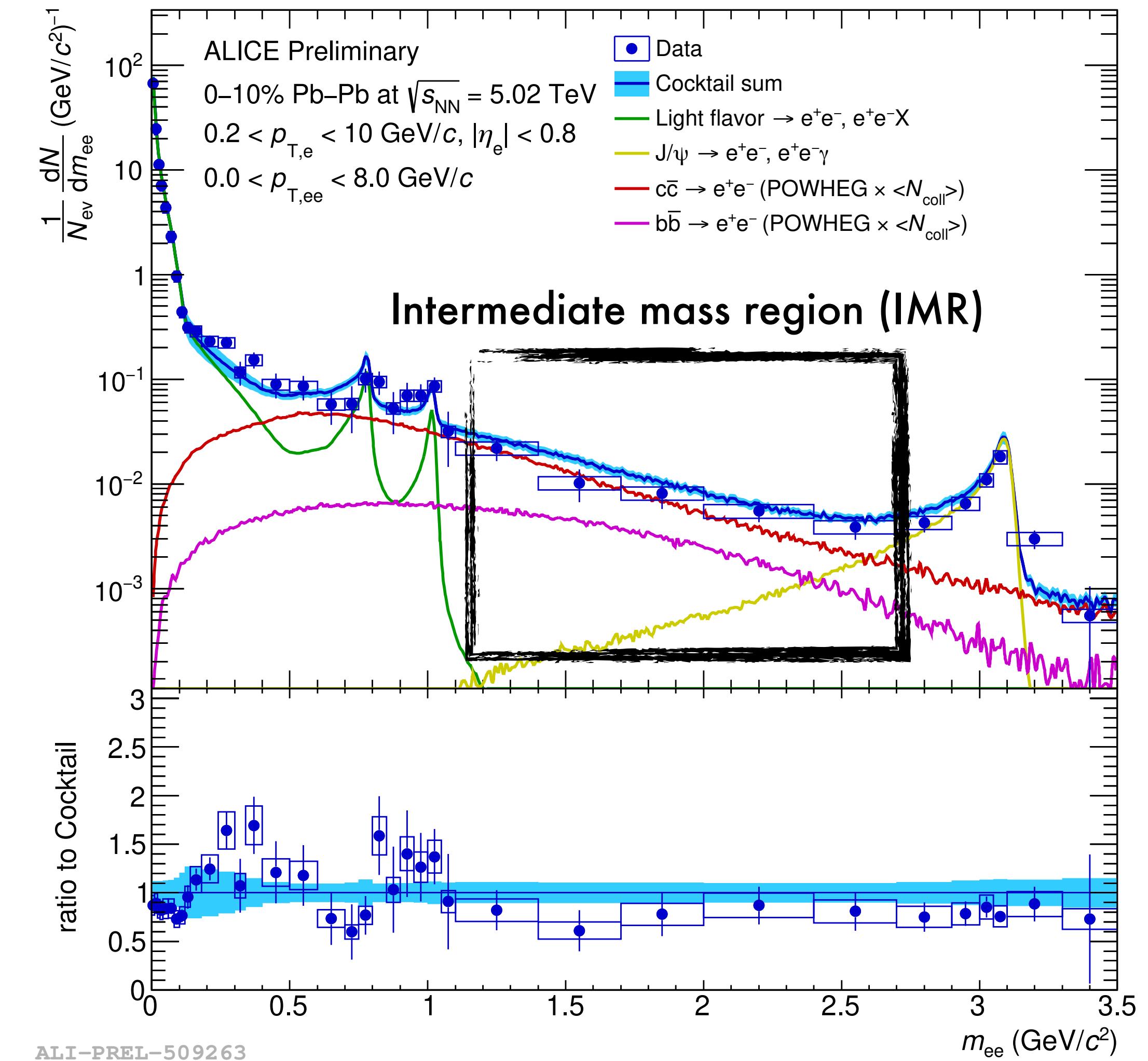


- e^+e^- spectrum compared to hadronic cocktail
- **Dominant contribution from correlated heavy-flavour (HF) hadron decays:**

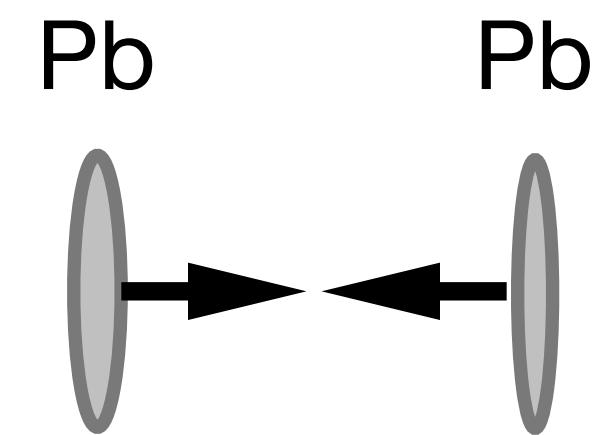


Here calculated from proton-proton collisions
scaled with N_{coll} neglecting energy loss in QGP...

But expect medium effects !



Dielectrons - higher masses



- e^+e^- spectrum compared to two hadronic cocktails

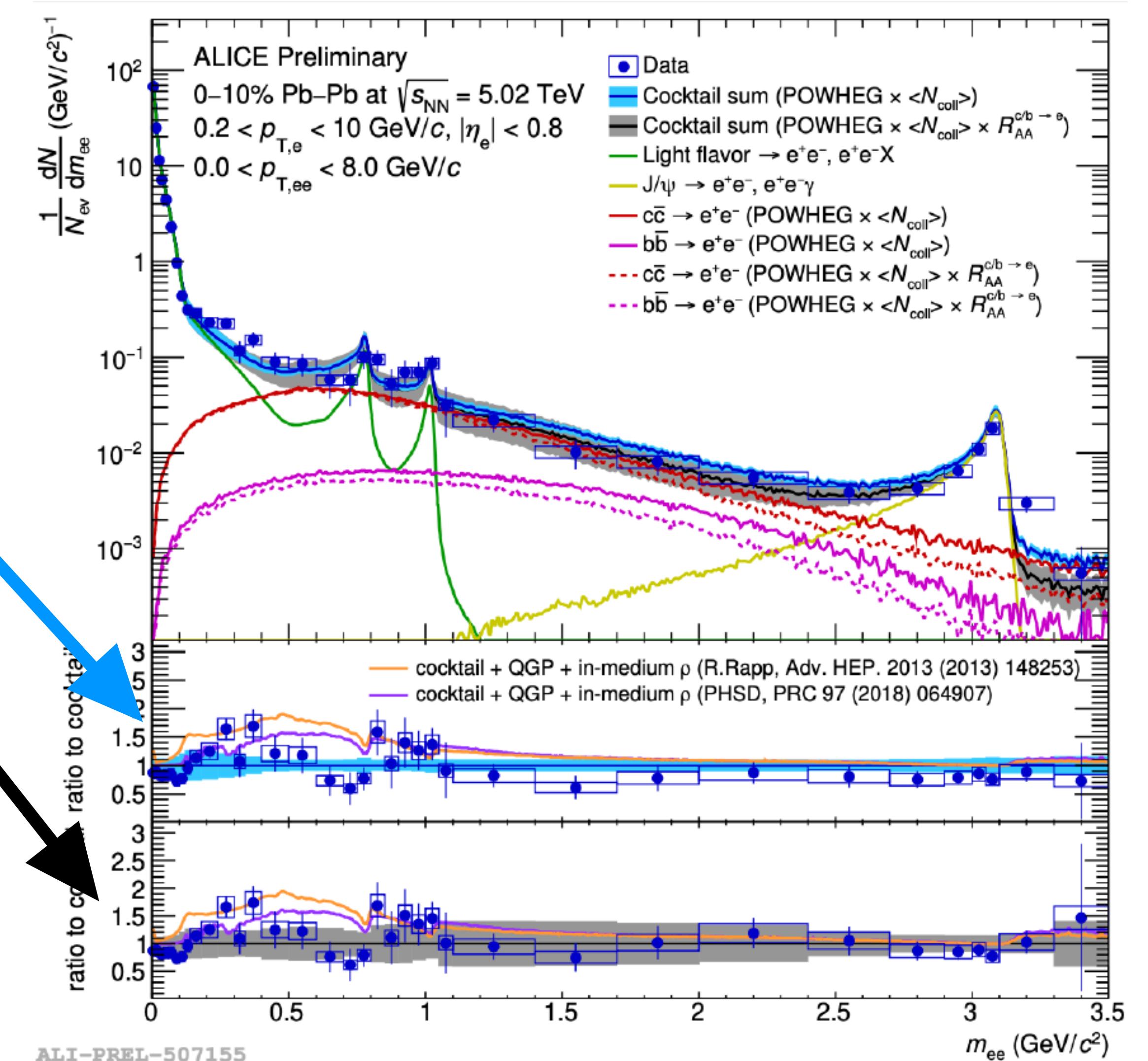
- Heavy-flavour from pp collisions (N_{coll} scaled)

- Heavy-flavour including $c, b \rightarrow e^\pm$ measurements

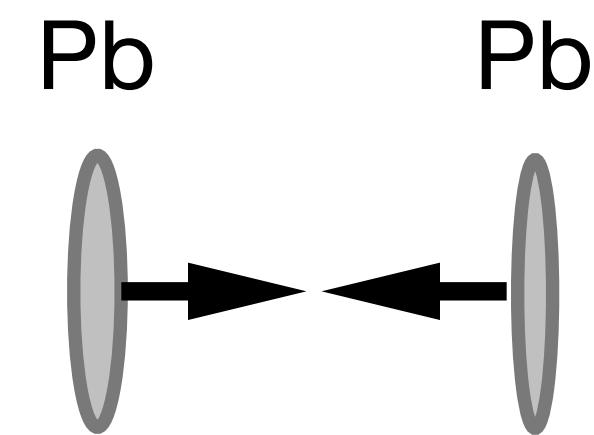
→ Imply some model dependence
going from single $e^\pm \rightarrow e^+e^-$ pairs

→ Better agreement with R_{AA} based cocktail

But large uncertainties !



Dielectrons - higher masses



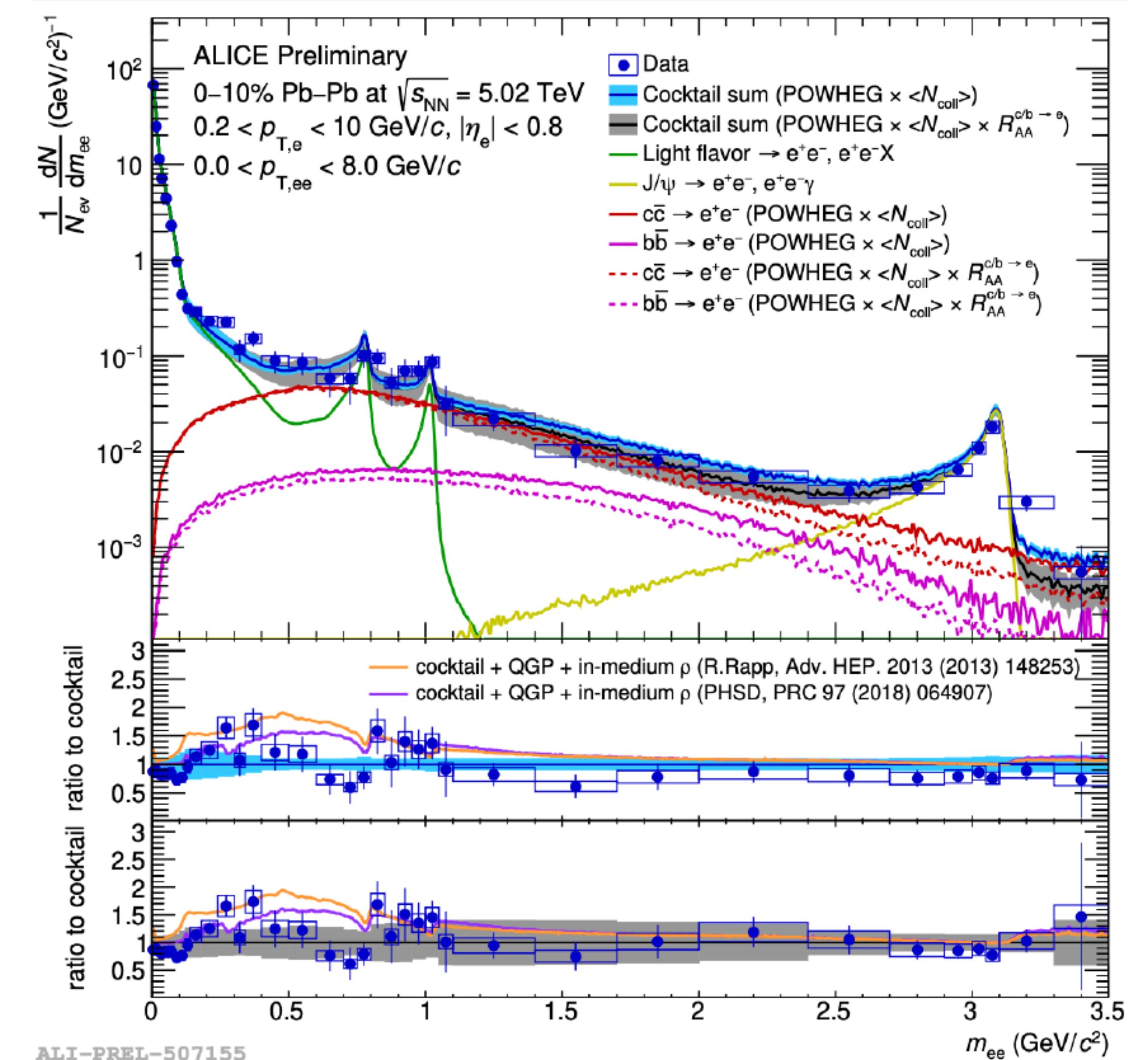
- e^+e^- spectrum compared to two hadronic cocktails

- **Models including thermal radiations:**

- R. Rapp: fireball + hadronic many body system
- PHSD: transport model

→ Predict very small excess for $m_{ee} > 0.5 \text{ GeV}/c^2$

→ **Need experimental handle to suppress HF !**



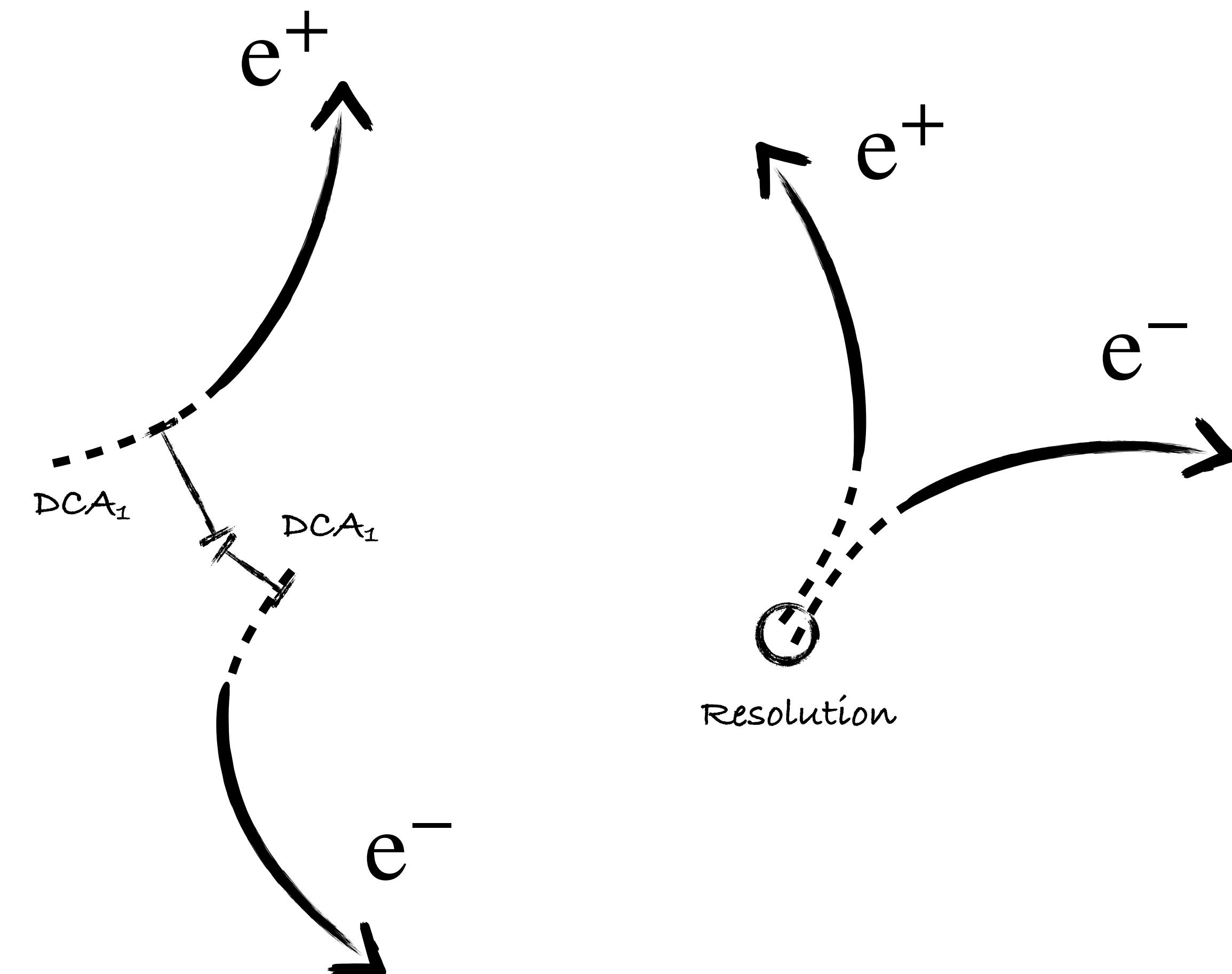
Topological separation of 1^+1^- sources

Use Distance-of-closest approach to primary vertex

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

With $DCA_{1/2}$ normalised to respective resolution

Need good/excellent detector pointing resolution



First steps in pp and Pb–Pb collisions by ALICE (Runs 1&2)
ALICE JHEP 1809 (2018) 064

Non-prompt: Heavy-flavour
Large decay length of D-B hadrons

Prompt: thermal ...

Dielectrons - DCA

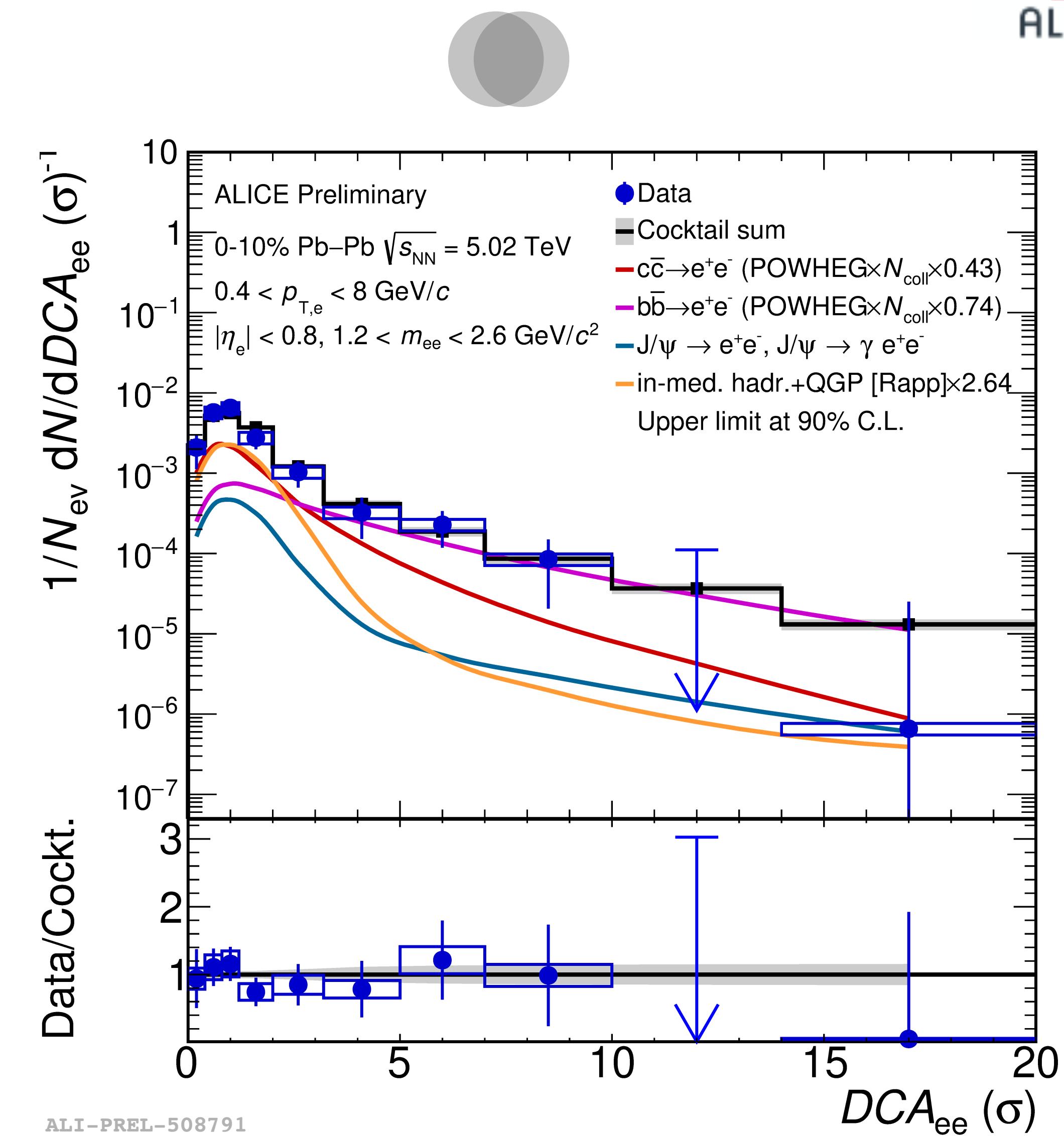


Dielectron DCA spectrum in the IMR

- **Beauty contribution** at large DCA values
 $c\tau \approx 500 \mu\text{m}$ (fixed at large DCA and $p_{T,\text{ee}}$)
- **Charm contribution** at intermediate DCA values
 $c\tau \approx 150 \mu\text{m}$
- **Prompt thermal contribution** at small DCA values
- **J/ψ mixture of prompt and non-prompt**
fixed by J/ψ measurements

Simultaneous fit of the data with $c\bar{c}$ and thermal contribution

Result consistent with charm suppression
and additional thermal source



Dielectrons - DCA

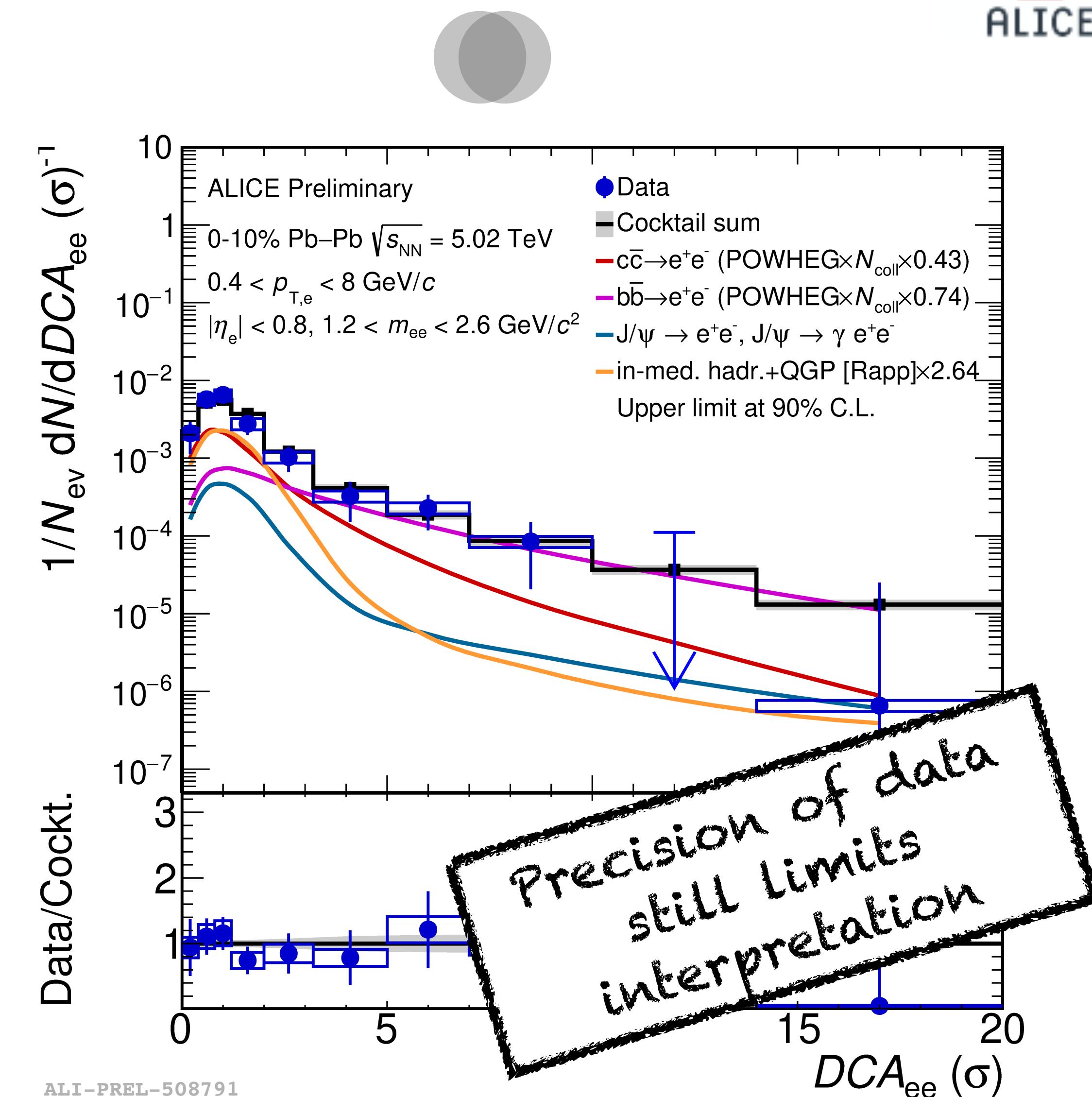


Dielectron DCA spectrum in the IMR

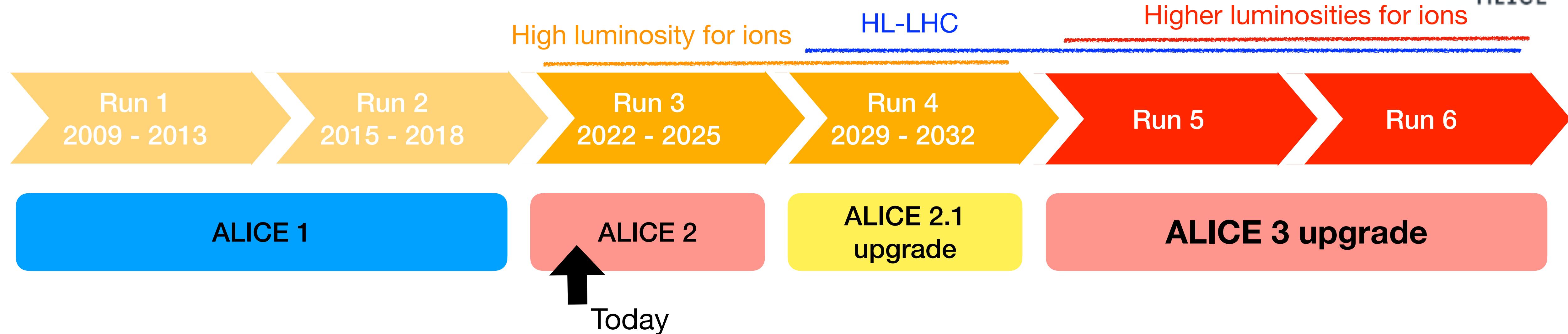
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Simultaneous fit of the data with $c\bar{c}$ and thermal contribution

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ALICE timeline



ALICE 2 upgrades

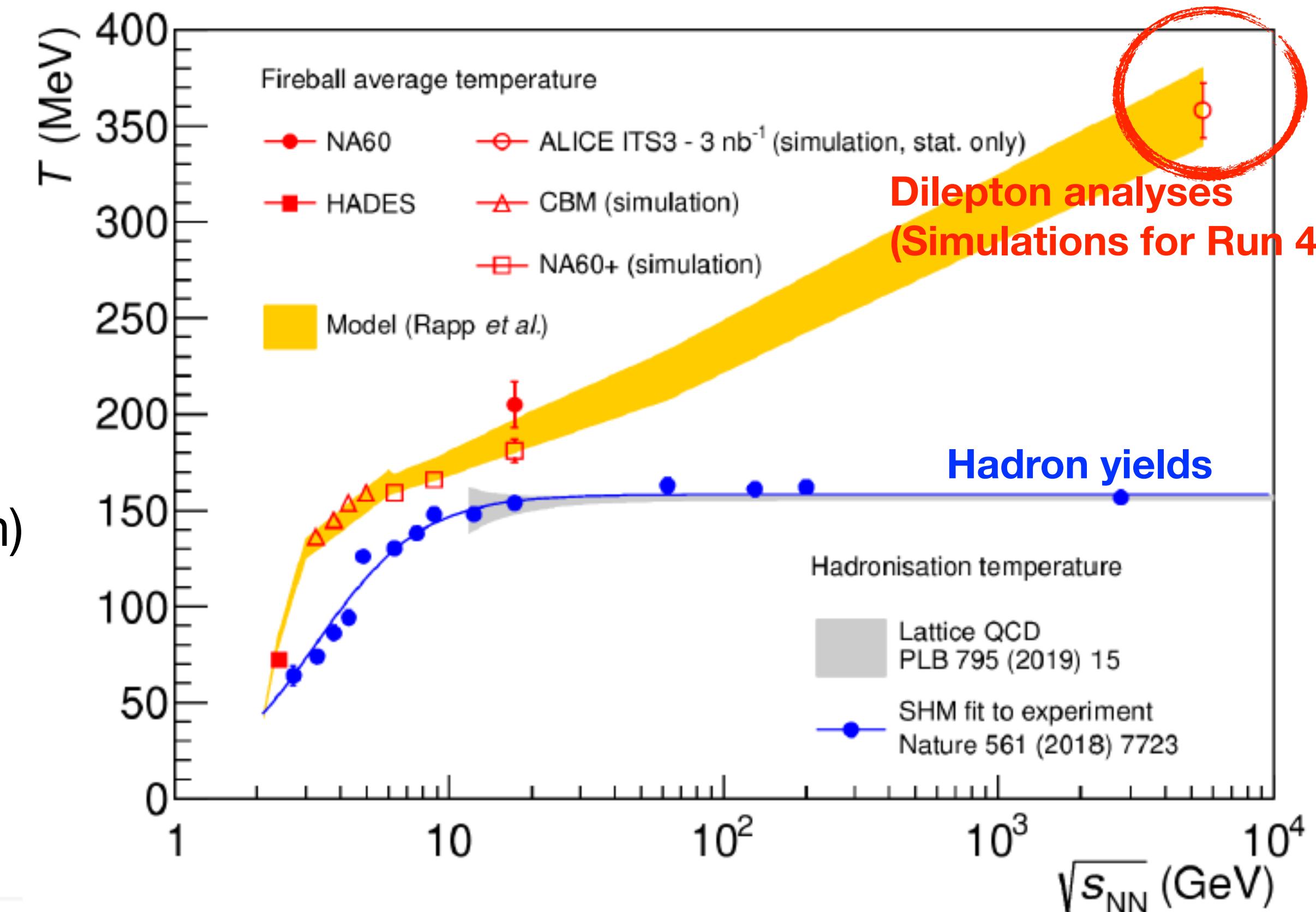
- **Increased read out rate up to a factor 100**
 - Expect 13 nb^{-1} integrated luminosity for Pb—Pb (Run 3+4)
- **Improved pointing resolution**
 - by factor 3-6 (Run 3)
 - And again factor 2 (Run 4)
- Will benefit DCA_{ee} analysis !

Physics prospects Runs 3 & 4



At the end of Run 4:

- First time-averaged T of the QGP:
 - Dielectron at mid-rapidity
 - Dimuons at forward-rapidity
- Patterns indicative of chiral symmetry restoration (dilepton)
- More precise real photon measurements (v_2 , yield)



NA60, AIP Conf. Proc. 1322 (2010) 1, 1-10
HADES, Nature Physics 15 (2019) 10, 1040-1045
ALICE, CERN-LHCC-2019-018
CBM, Nucl. Phys. A 982 (2019) 163
NA60+, SPSC-EOI-019

R. Rapp et al., Phys. Lett. B 753 (2016) 568
T. Galatyuk et al., Eur. Phys. J. A52 (5) (2016) 131
Lattice QCD, Phys. Lett. B 795 (2019) 15
SHM, Nature 561 (2018) 7723, 321-330



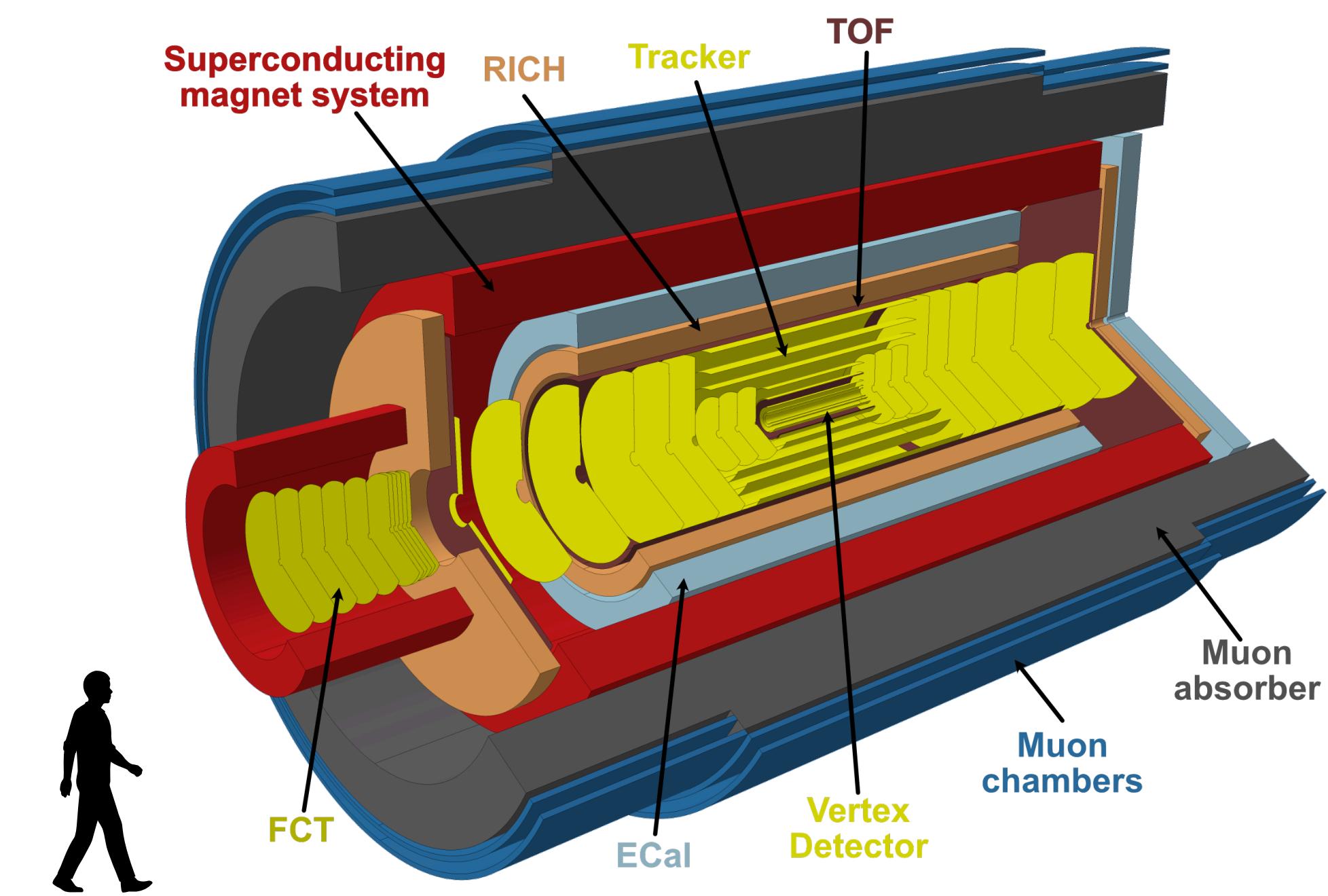
Beyond Run 4: ALICE 3



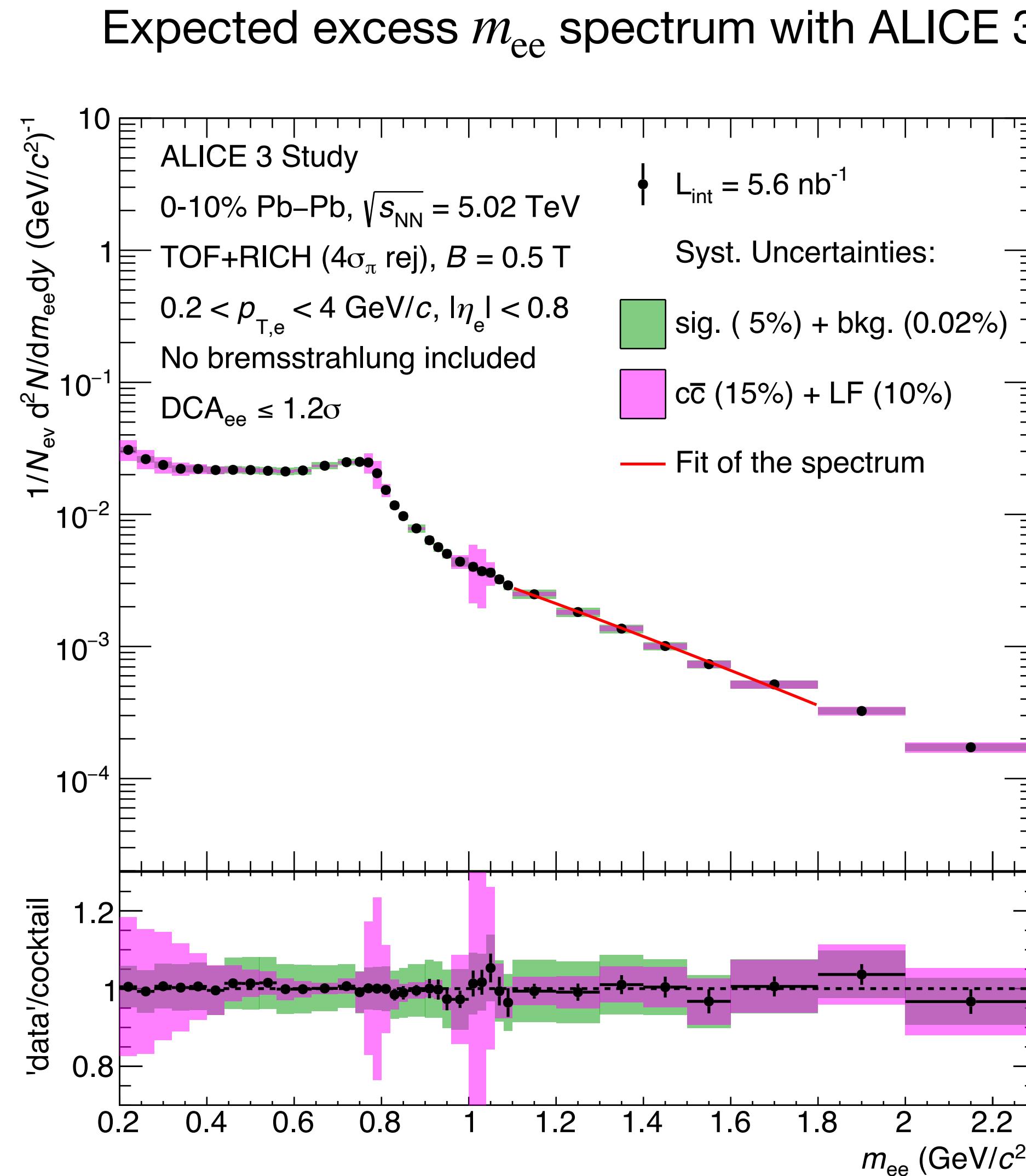
Next-generation LHC heavy-ion experiment ALICE 3:

- Compact all-silicon tracker with high-resolution vertex detector
- Particle identification $\gamma, e^\pm, \mu^\pm, K^\pm, \pi^\pm$
- Over large acceptance ($-4 < \eta < 4$)
- Down to very low p_T

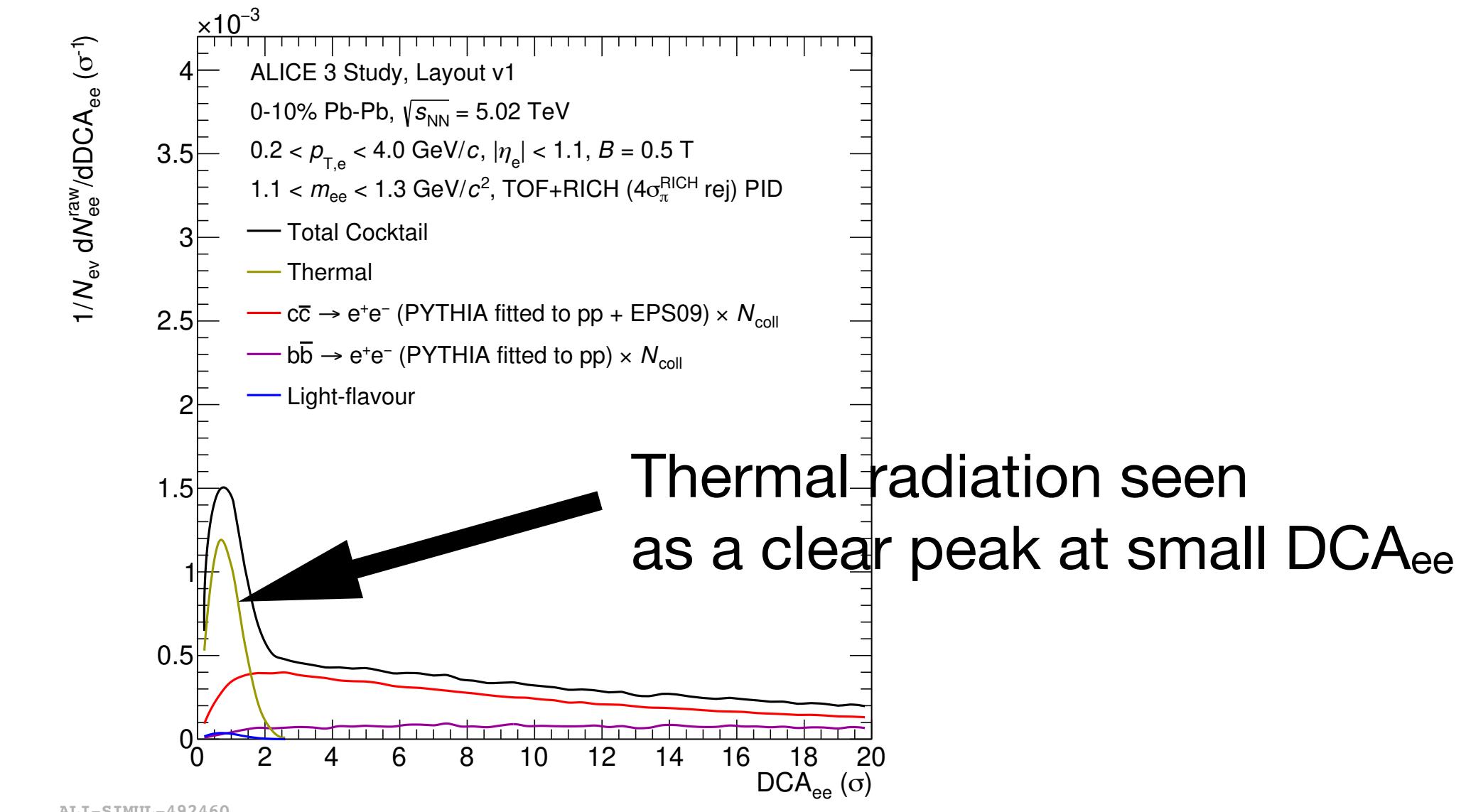
Letter of Intent reviewed by the LHCC in March 2022



Time dependence of early temperature



Expected DCA_{ee} distribution in IMR

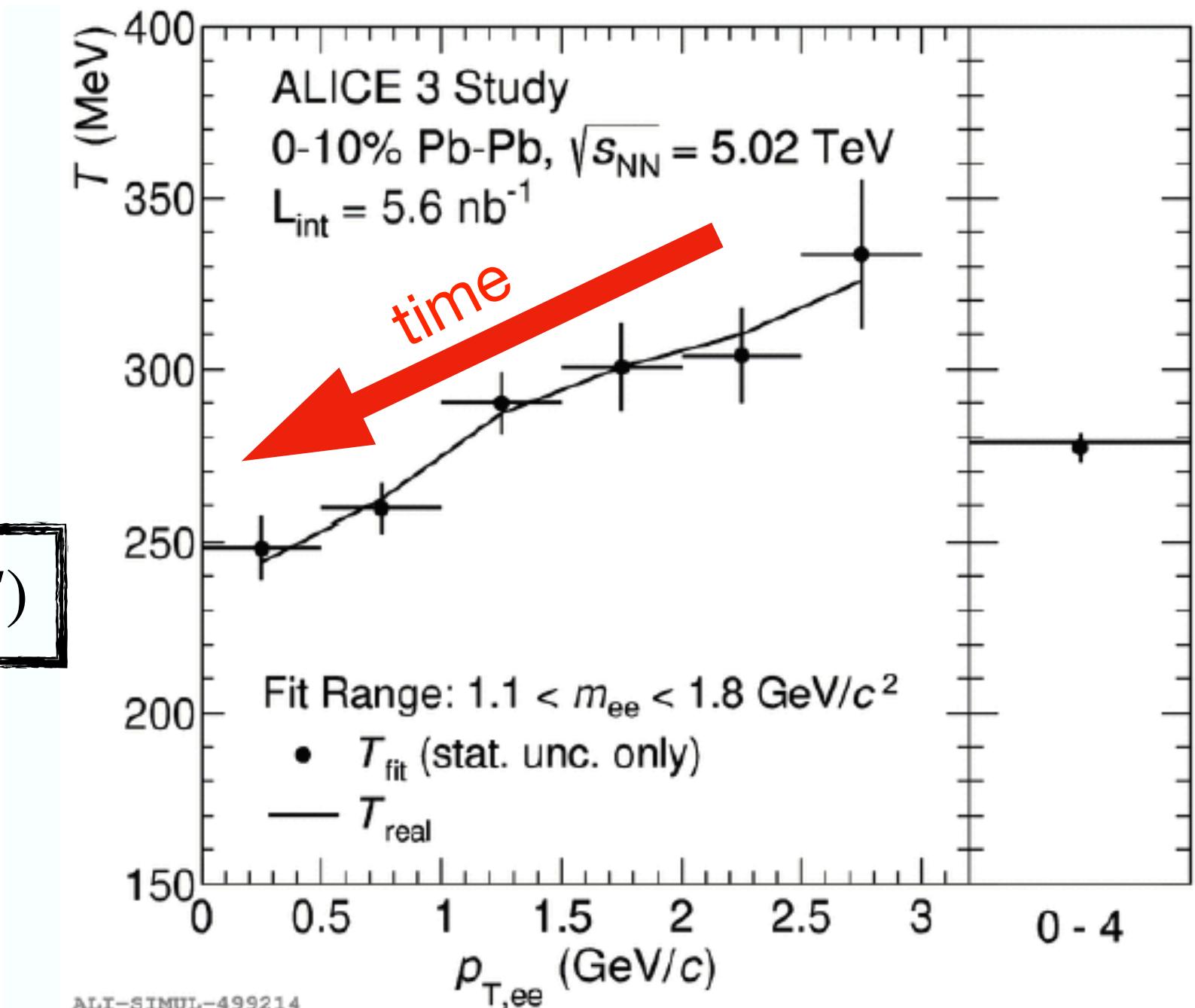
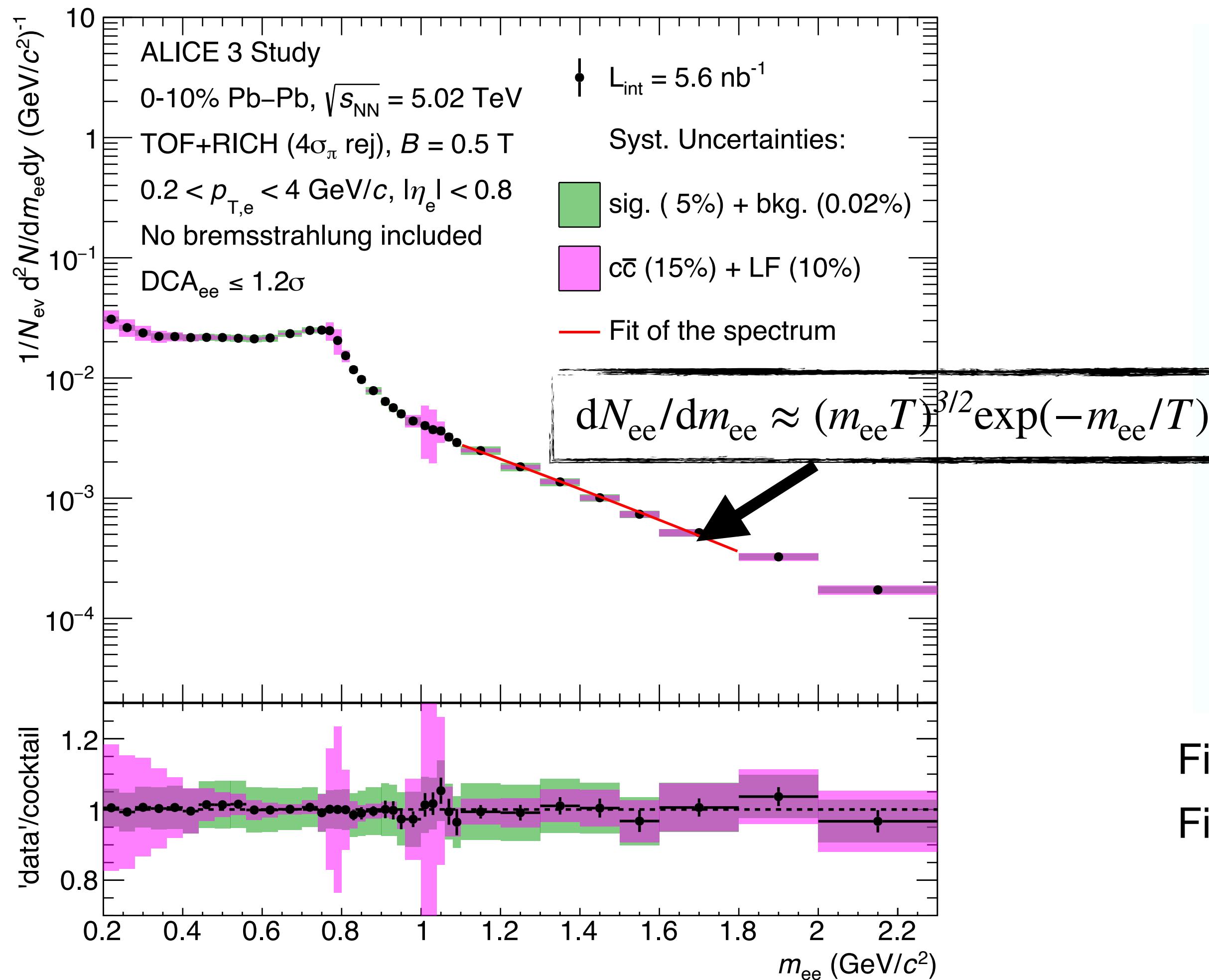


- Suppress HF hadron decays with max DCA_{ee} cut
- Expected excess after subtraction of hadronic cocktail and remaining background from correlated HF
- One month of Pb—Pb data taking



Time dependence of early temperature

Expected excess m_{ee} spectrum with ALICE 3



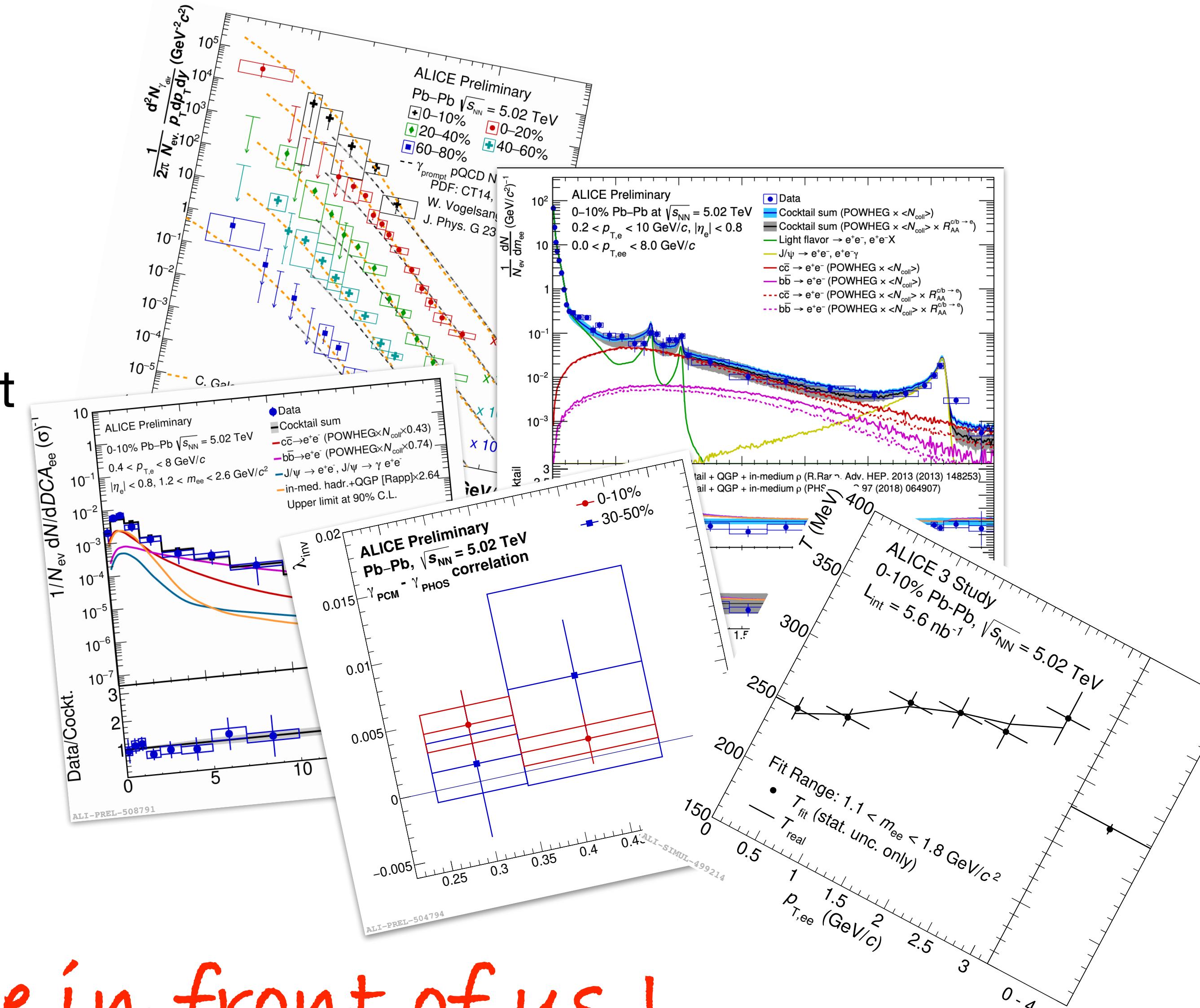
Fit of m_{ee} spectrum \rightarrow Average temperature
 Fit for different $p_{T,ee}$ windows \rightarrow Probe time dependence of T

Summary

Real and virtual photon measurements key to understanding different phases of heavy ion collisions

Direct photon yields from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from ALICE in agreement with state of the art models

- Different experimental techniques under investigation to extend measurements



Exciting time in front of us !

Back-up

Heavy-flavour modification in AA

Single e^\pm : $c, b \rightarrow e^\pm$

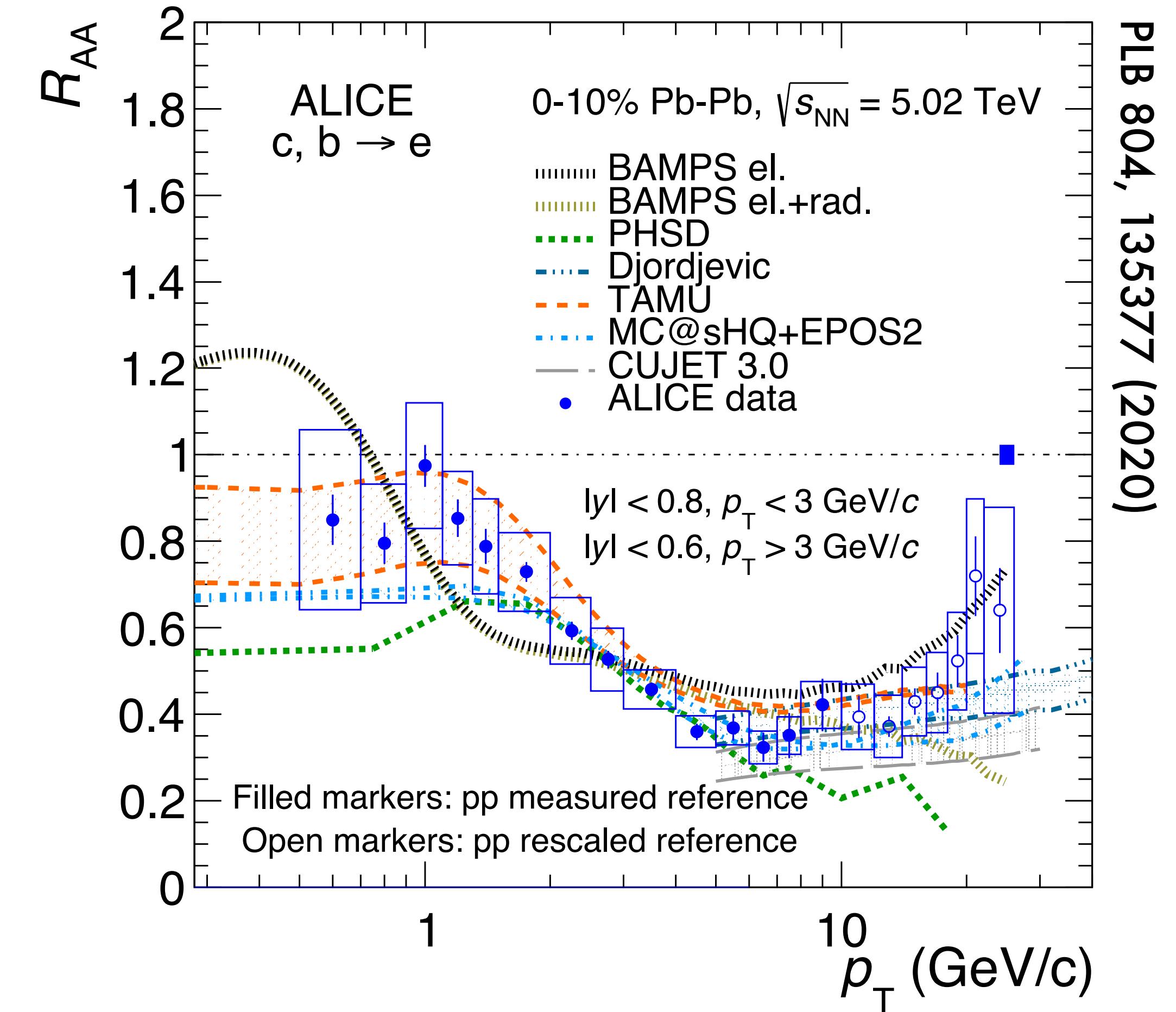
$$R_{AA} = \frac{1}{N_{\text{coll}}} \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy} \rightarrow \neq 1 \text{ if modifications}$$

Modifications due to

- Initial state effects: cold nuclear matter (CNM)
- Final state effects: in medium energy loss....

Both influence the e^+e^- pairs differently (factorise or not)

→ Imply some model dependence going from $e^\pm \rightarrow e^+e^-$



Heavy-flavour modification

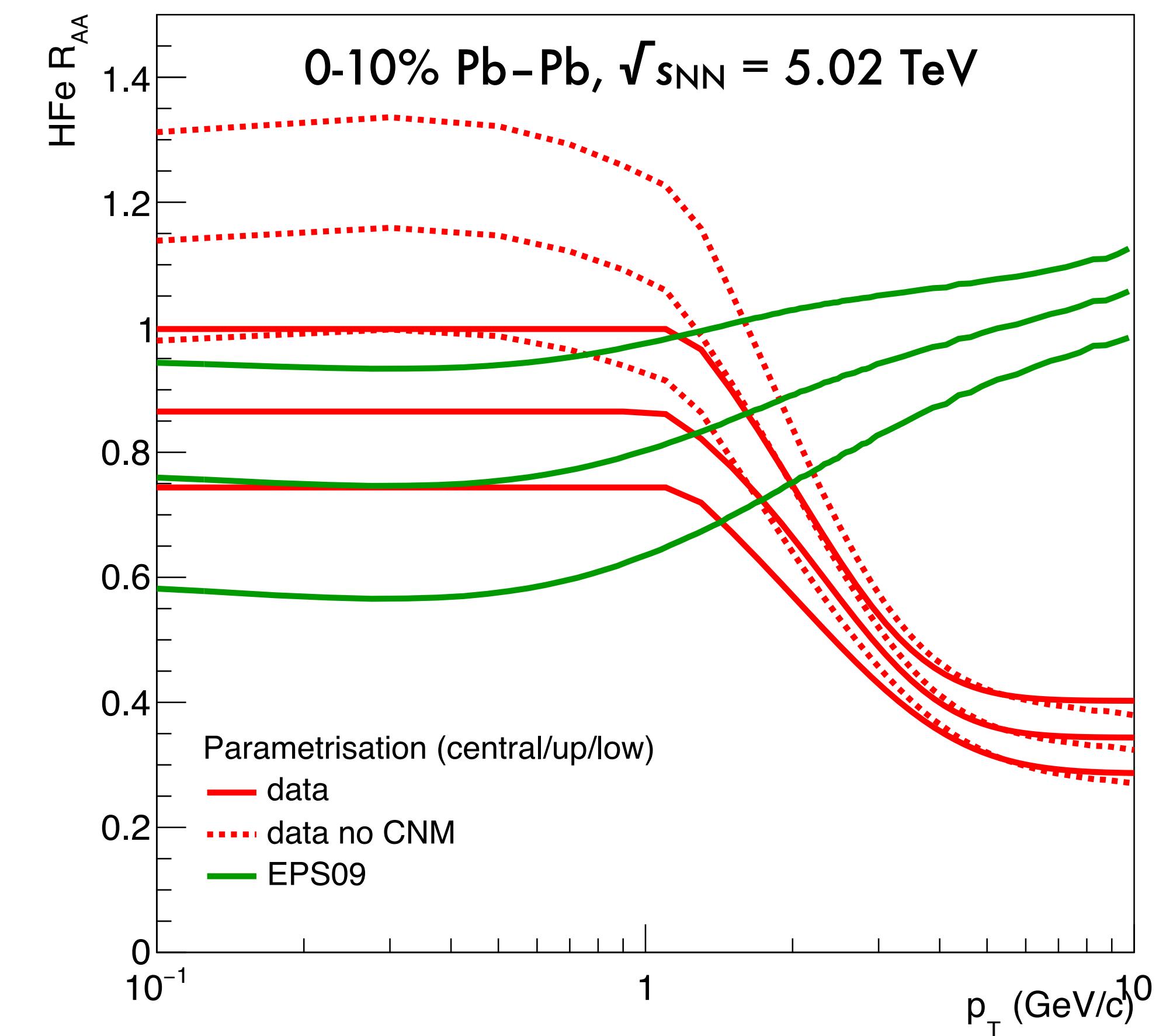
Modifications of single HF electrons

- Initial state: cold nuclear matter (CNM)
- Final state: in medium energy loss

Both effects influence the dielectron in a different way

Disentangle two effects using CNM (EPS09)* calculations

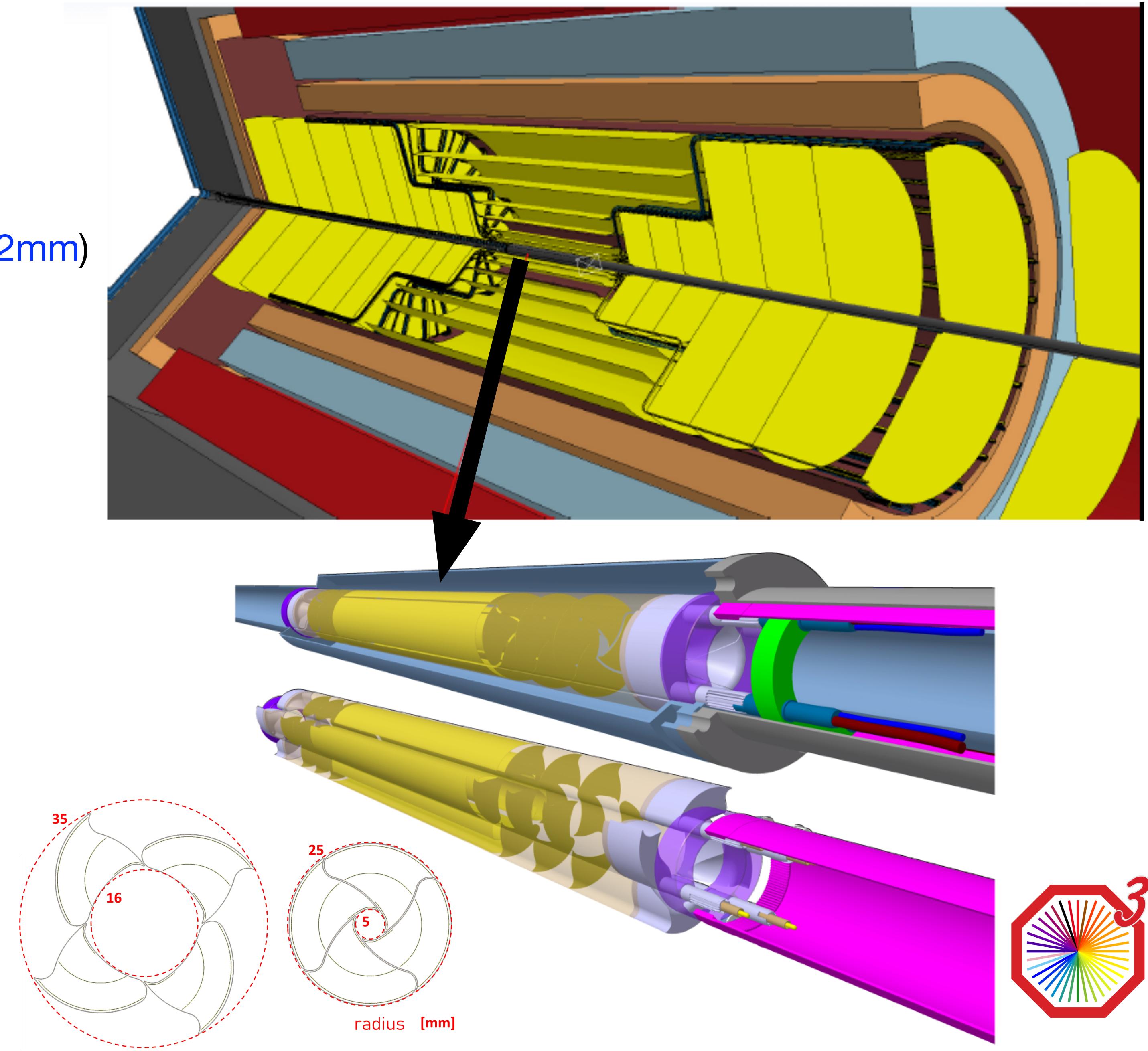
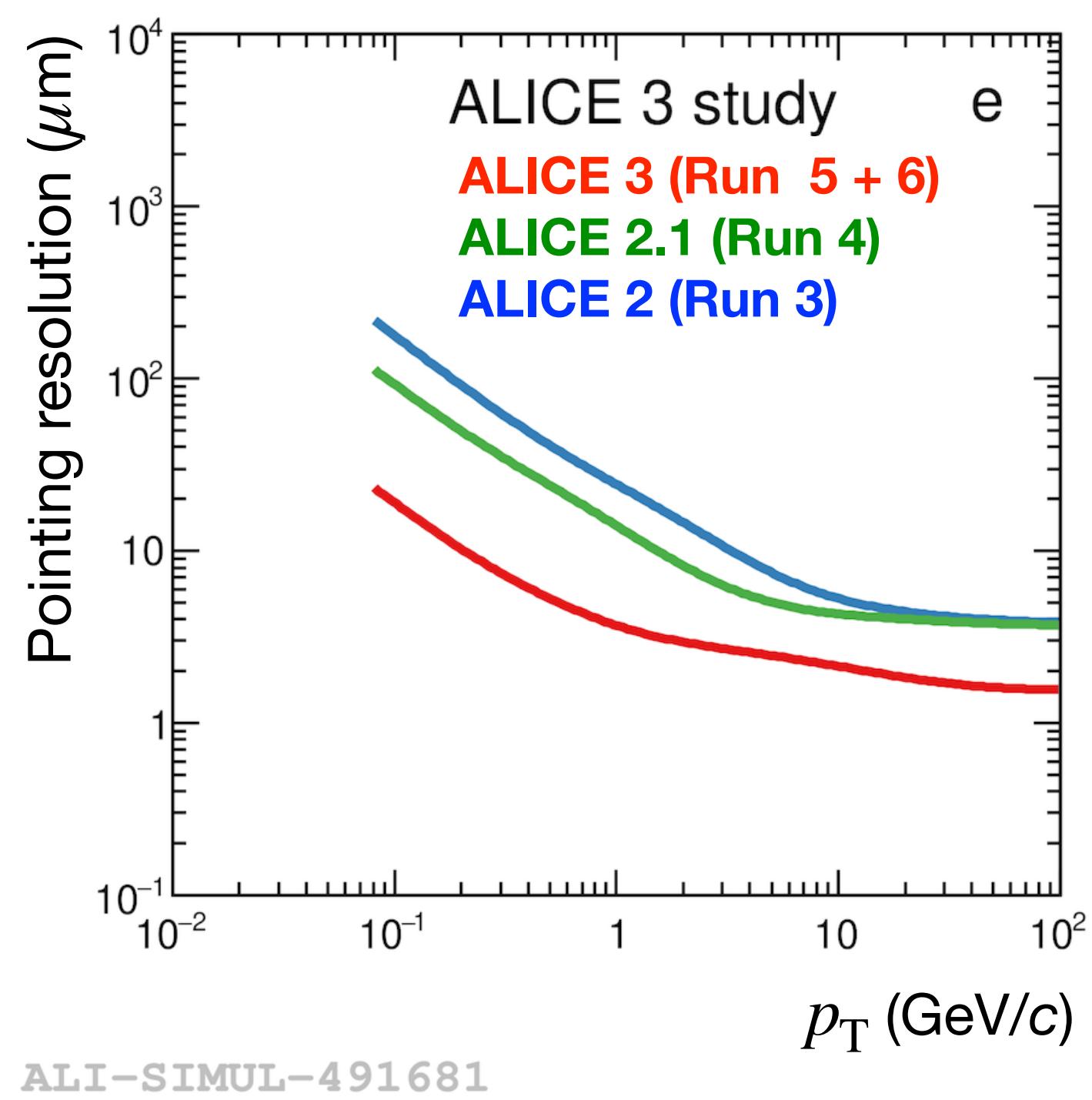
Calculate as a function of m_{ee} and $p_{T,ee}$
within toy Monte Carlo model



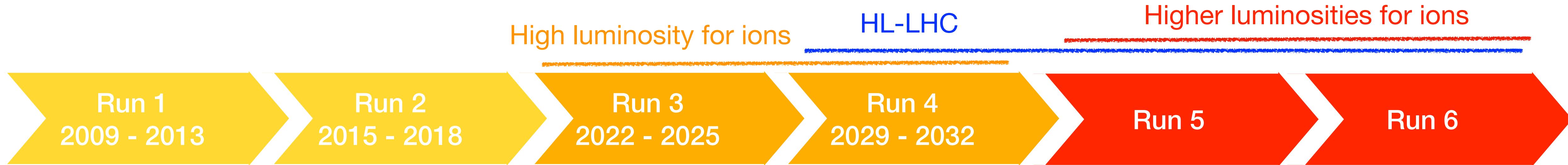
* Eskola et al., JHEP 04, 065

Tracker

- Position of first layer at mid-rapidity:
 $r = 5 \text{ mm}$ (ALICE Run 4: 18 mm; ALICE Run 3: 22mm)
- Achieved with a retractable vertex detector inside of the beam pipe in secondary vacuum



LHC schedule



Collision systems

pp, pPb, Pb—Pb

pp, pPb
Xe—Xe, Pb—Pb

pp, pO, OO
pPb, Pb—Pb

pp, pPb
Pb—Pb

pp, pA?, AA

pp, pA?, AA

Pb—Pb luminosity limited by LHC

up to $1 - 2 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$

Run 4 → HL-LHC

- Push pp luminosity to $\approx 4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

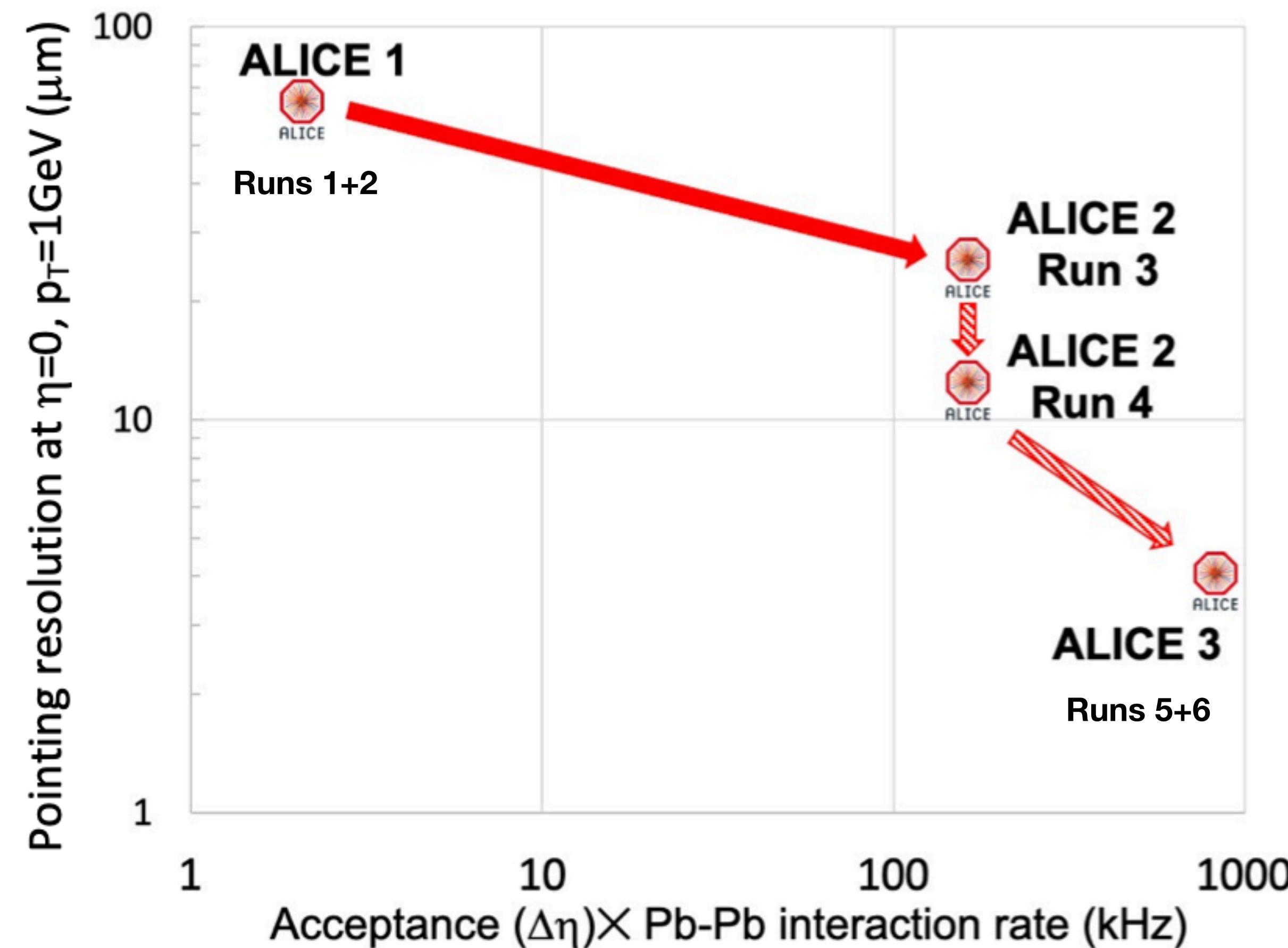
Run 3 → high luminosity for ions ($\approx 7 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$) and OO

- Improved collimation systems
- Ion luminosities now limited by bunch intensities from injectors

Beyond Run 4: ALICE 3



Improved pointing resolution
and effective statistics (Run 5 + 6)



D.Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009

Direct real photons



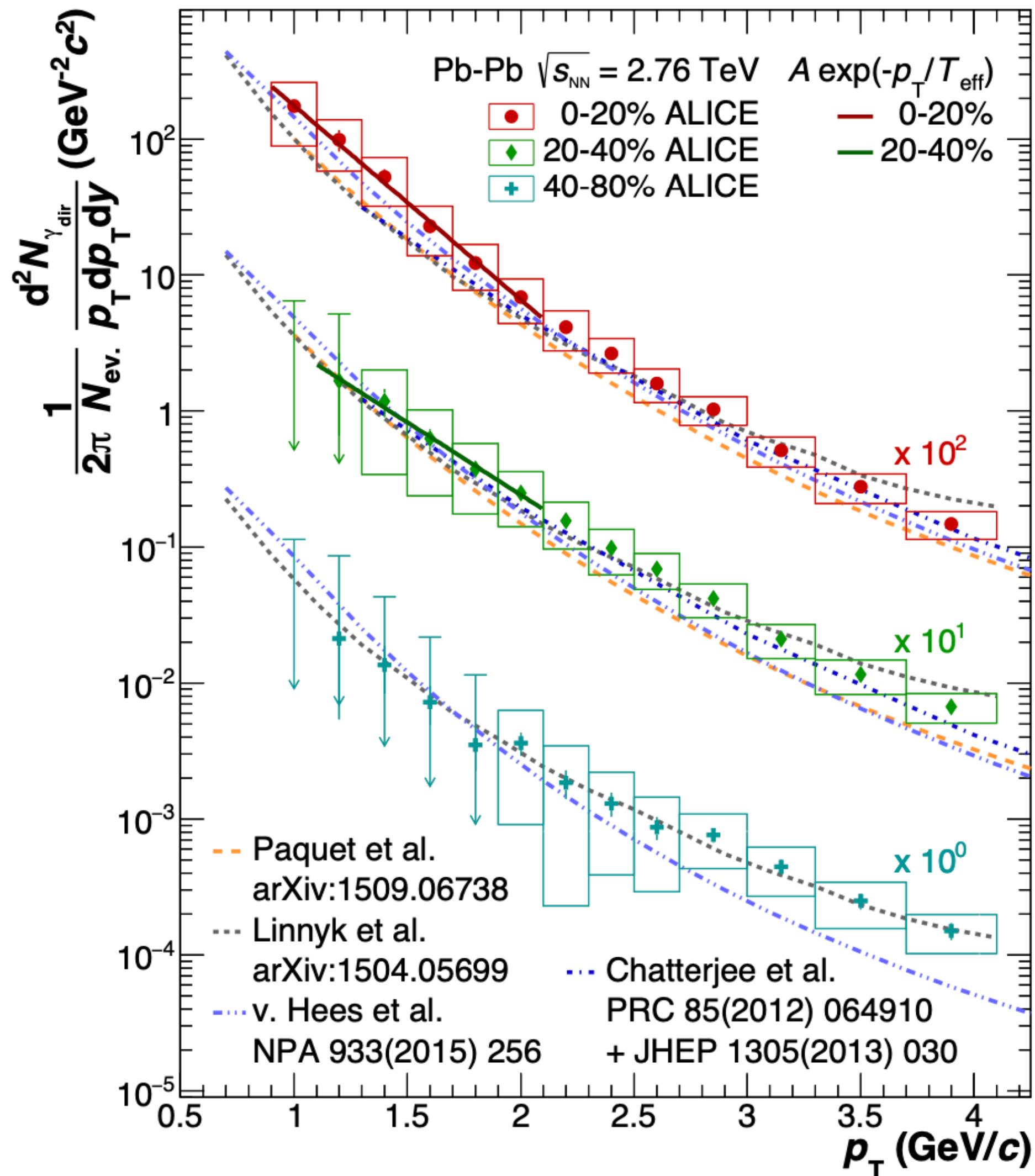
Same measurements at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$:

0-20%: Inverse slope $T_{\text{eff}} = 297 \pm 12(\text{stat}) \pm 41(\text{syst})$

Models allow then to estimate T of medium

→ Need to reduce uncertainties (yield, v_2) to constrain models

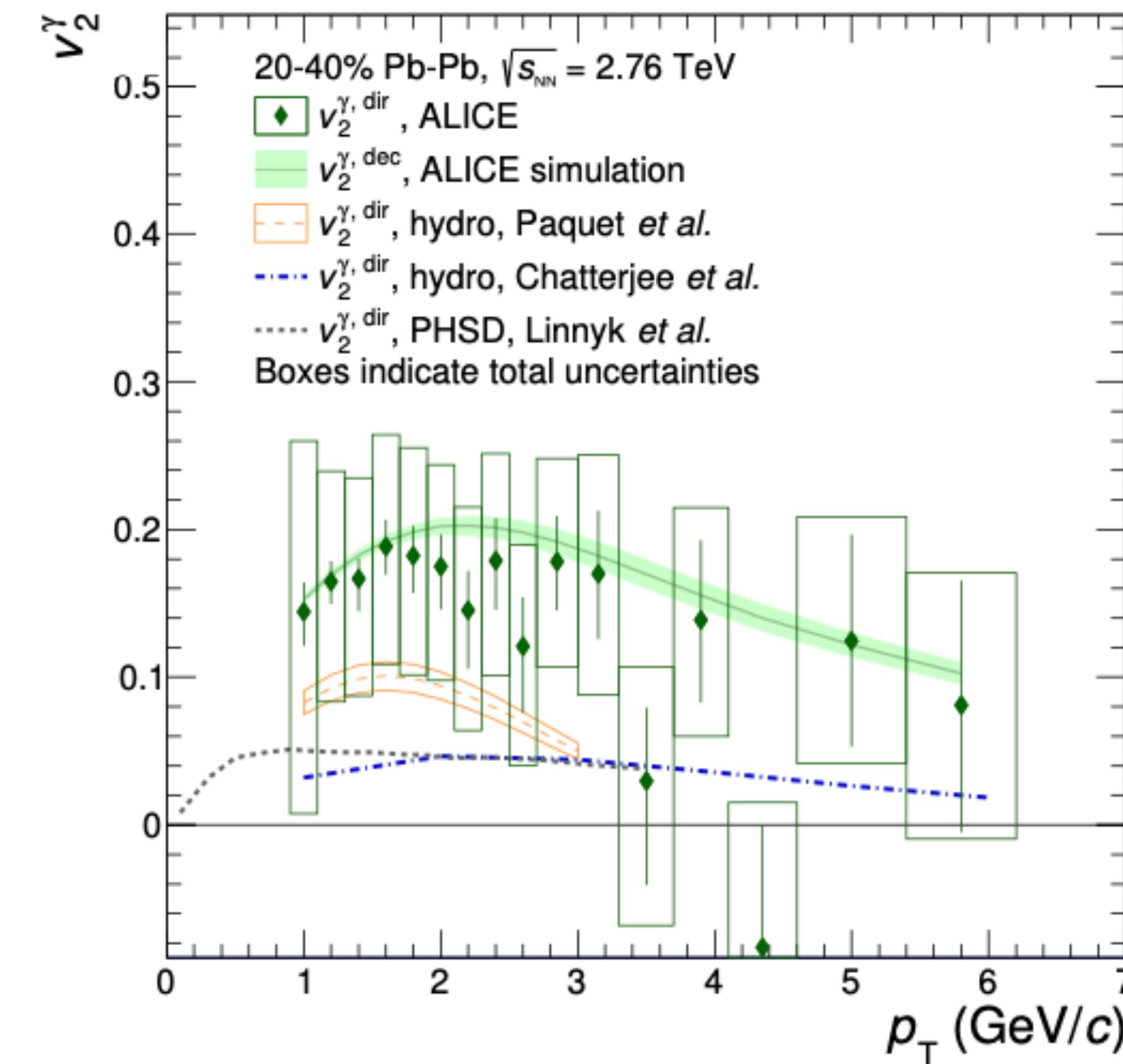
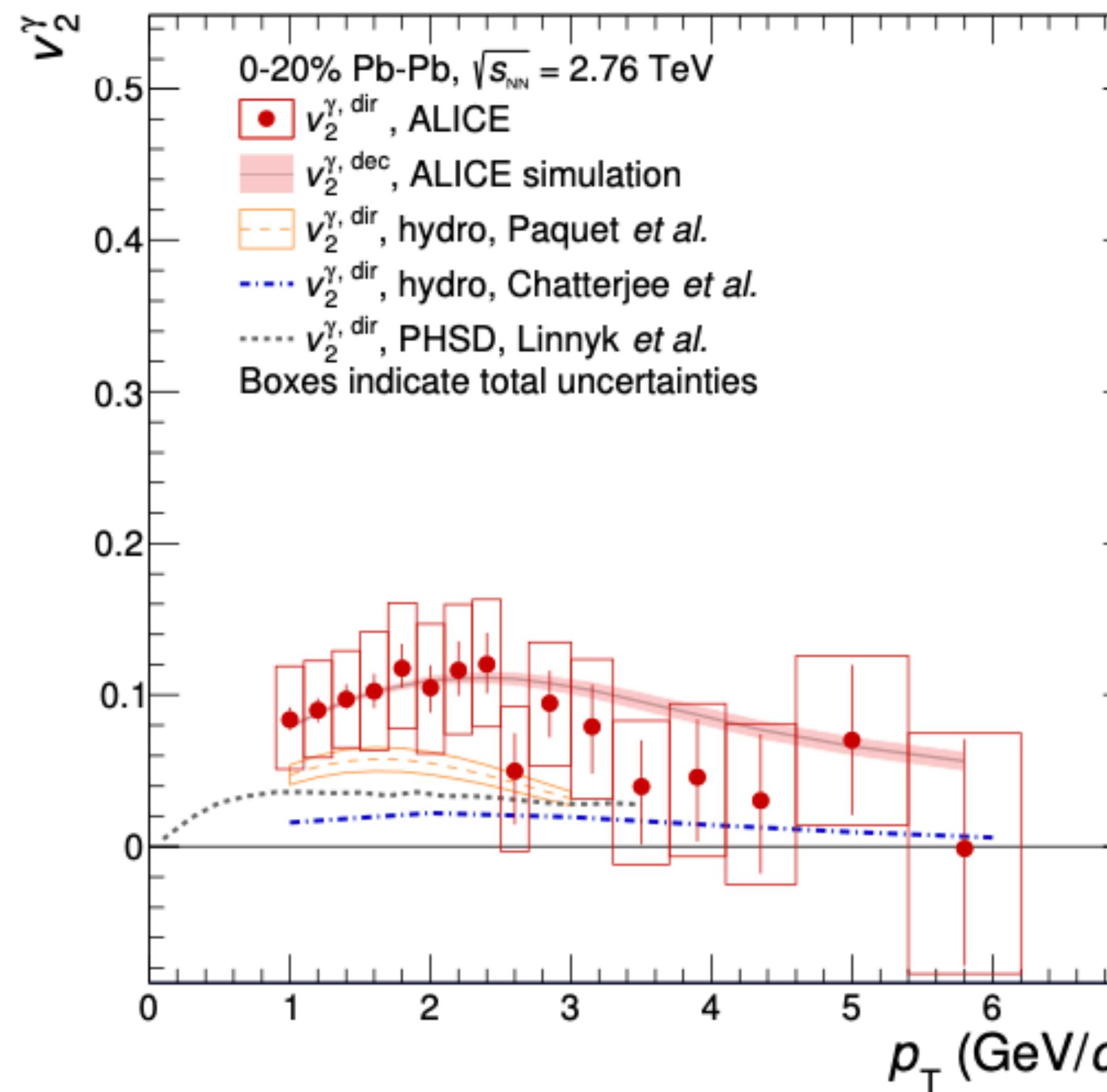
Pb—Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$



Direct real photons



Pb—Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$



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

Direct photons at the LHC



- Comparison of direct photon results to their respective state-of-the-art model calculations
- No puzzling discrepancy of yields between new ALICE measurements and state-of-the-art model

