Dielectrons with ALICE in Run 2 & 3

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FSP ALICE

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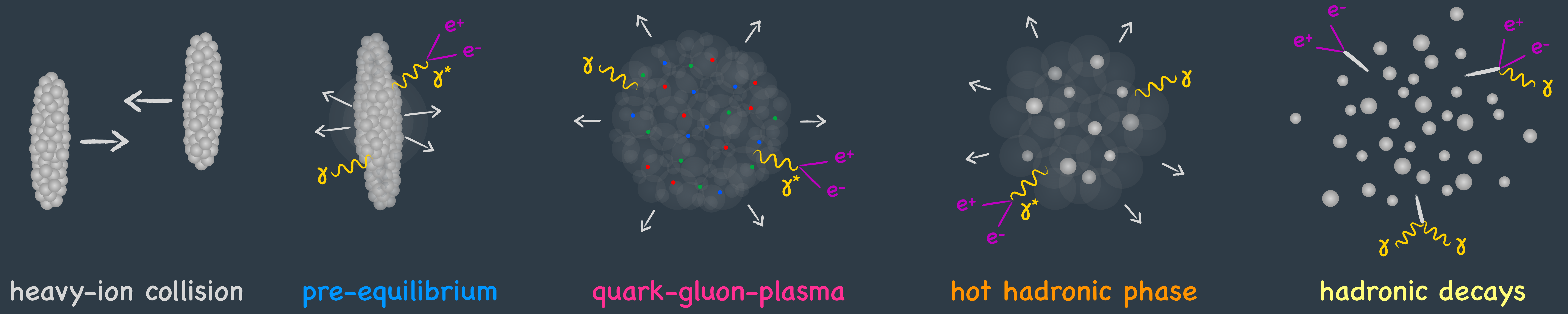
Outline

- Motivation: dielectrons in heavy-ion collisions
- Dielectron analysis of central Pb–Pb collisions in Run 2 (2015 - 2018)
- Upgrades of the ALICE detector for LHC Run 3
- First look at dielectrons in pp & Pb–Pb collisions in Run 3 (2022 - ongoing)

Motivation

Dielectrons in Heavy-Ion Collisions



Dielectrons (correlated e^+e^- pairs):

- Created in all stages of the collision
- Do not interact strongly (no final-state interactions)
- Carry information about their production mechanism into the detector

→ ideal probes to study the properties of strongly-interacting matter, produced in heavy-ion collisions

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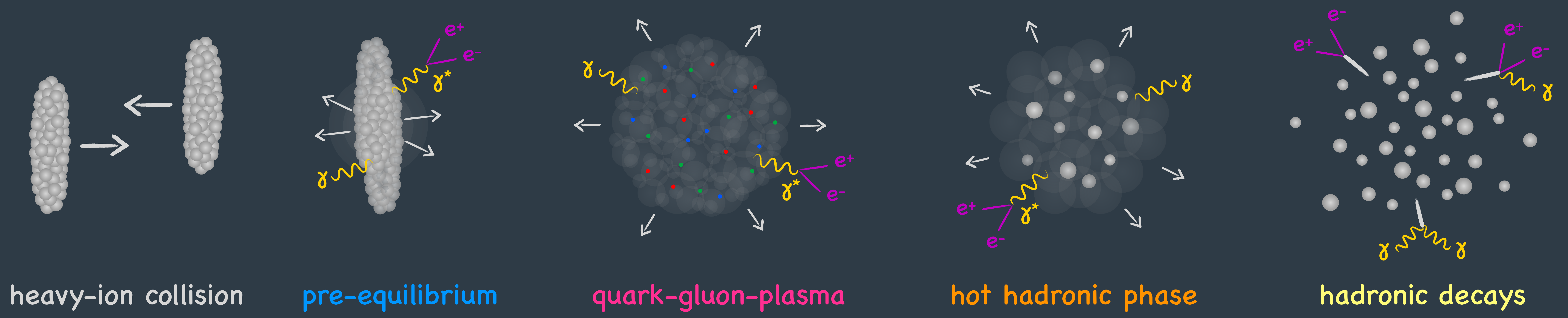
Dielectrons in Heavy-Ion Collisions



Heavy-ion (Pb–Pb) collisions:

- Chiral-symmetry restoration (modification of spectral function for vector mesons)
- Thermal radiation throughout the medium evolution
- De-correlation of heavy-flavor pairs in the medium
- Constrain the space-time evolution of the collision

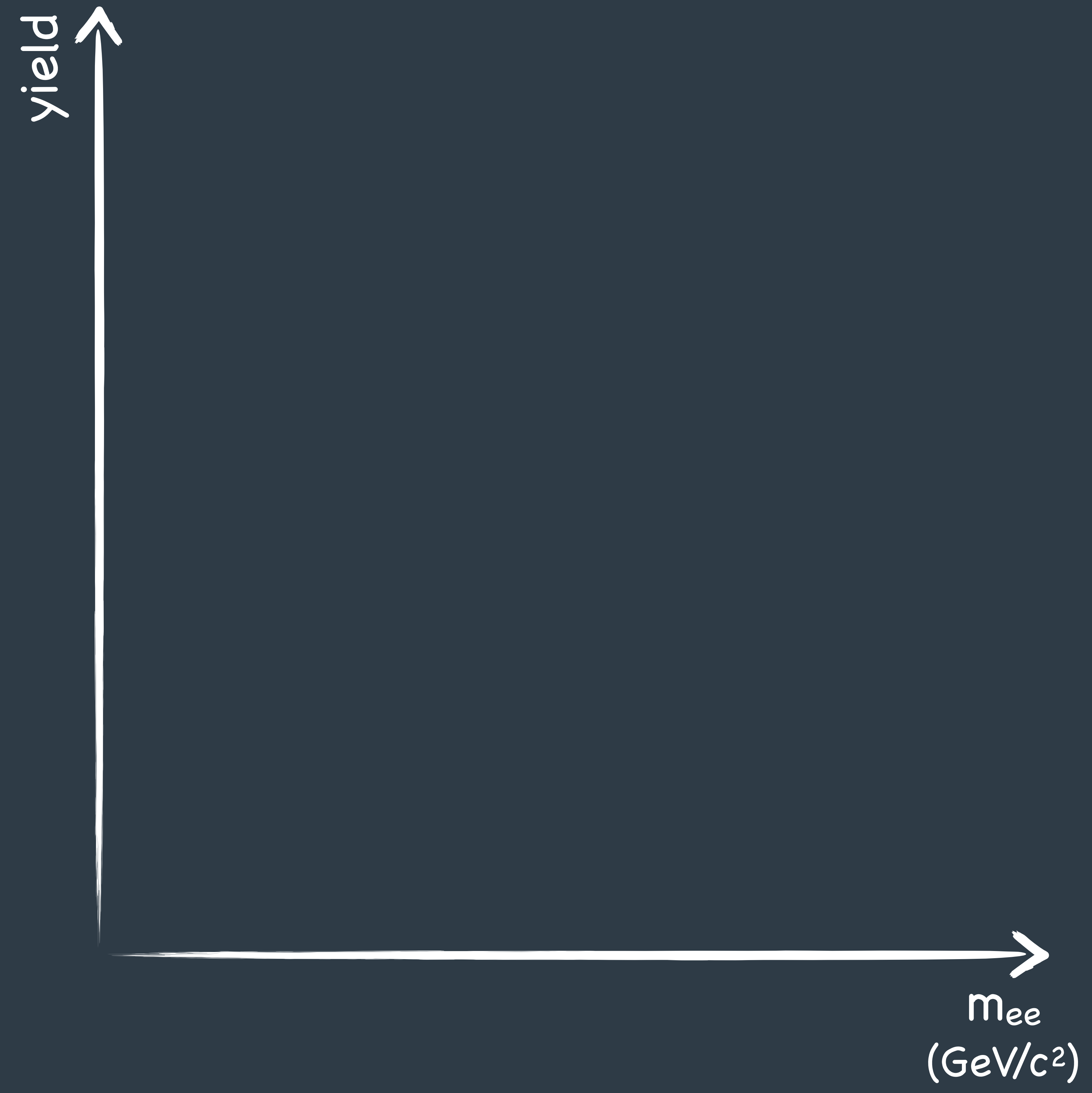
proton-proton (pp) collisions:

- Vacuum baseline for Pb–Pb studies (heavy-flavor, direct photons, Drell-Yan)
- Establish analysis techniques & search for new physics (onset of thermal radiation)

Motivation

Dielectrons in Heavy-Ion Collisions

Composition of the dielectron spectrum:

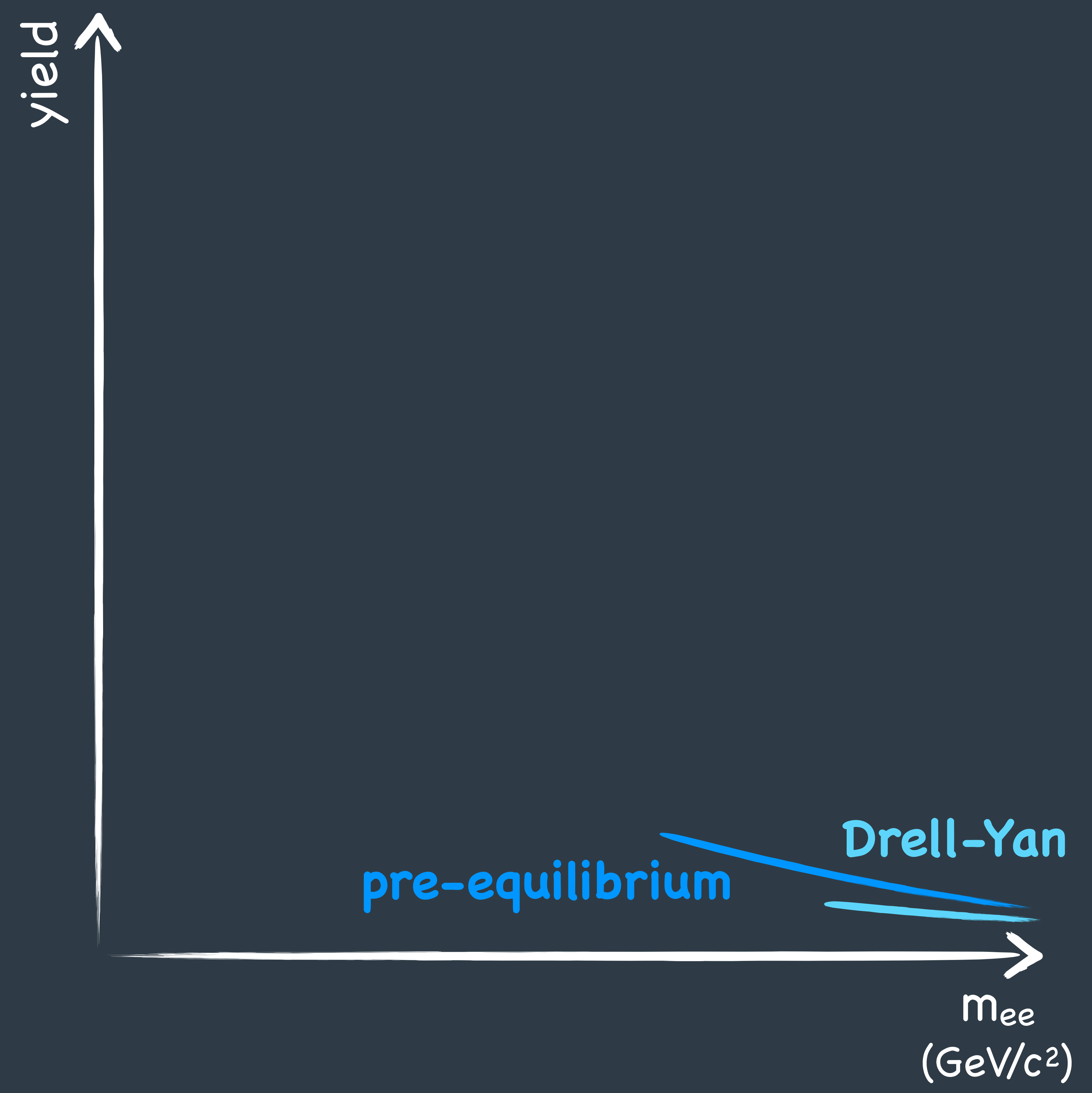


Motivation

Dielectrons in Heavy-Ion Collisions

Composition of the dielectron spectrum:

- Initial stage of the collision:
  Drell-Yan and hard scatterings
  pre-equilibrium contributions



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Composition of the dielectron spectrum:

- Initial stage of the collision:
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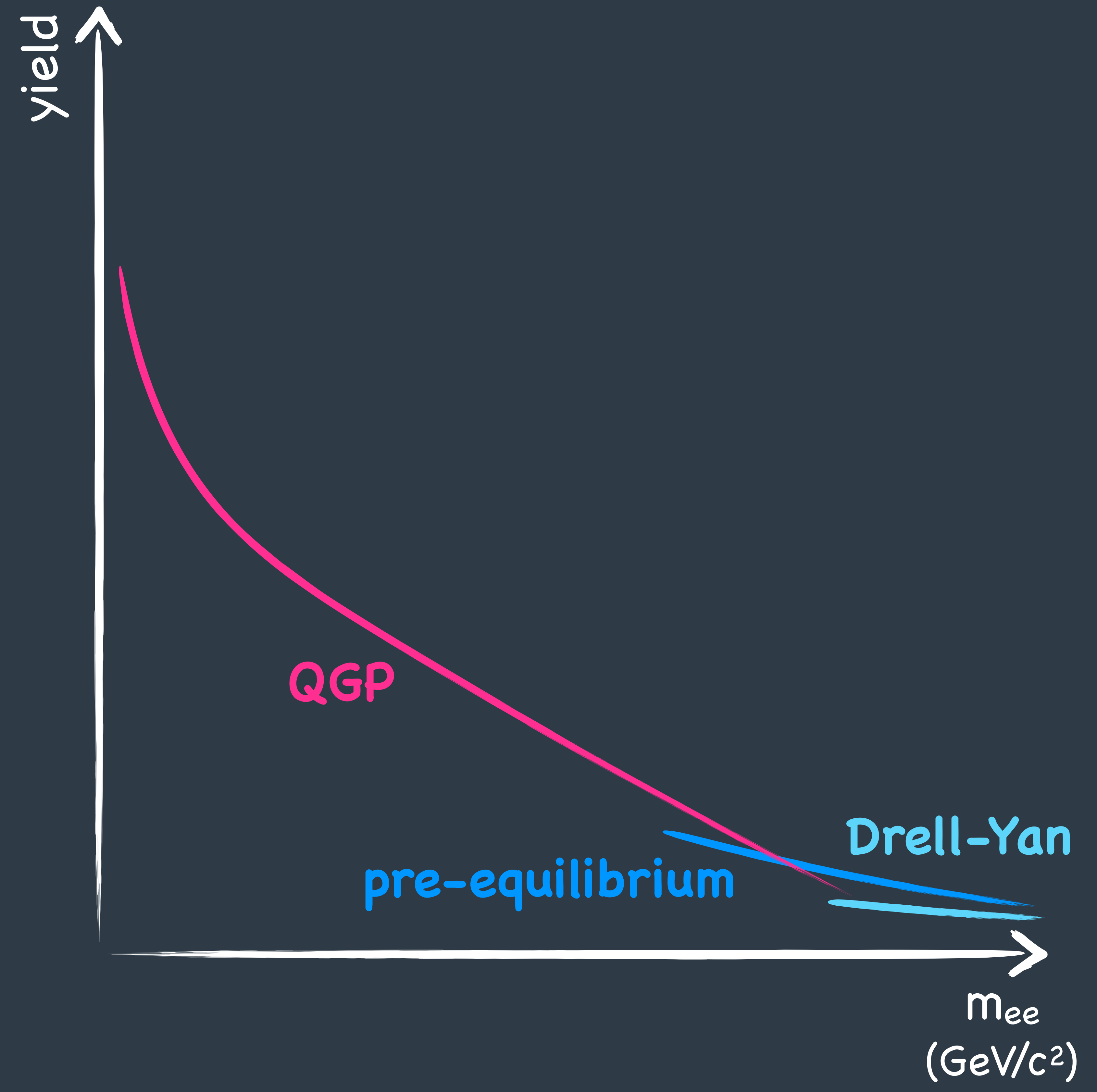

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Dielectrons in Heavy-Ion Collisions

ALICE

Composition of the dielectron spectrum:

- Initial stage of the collision:
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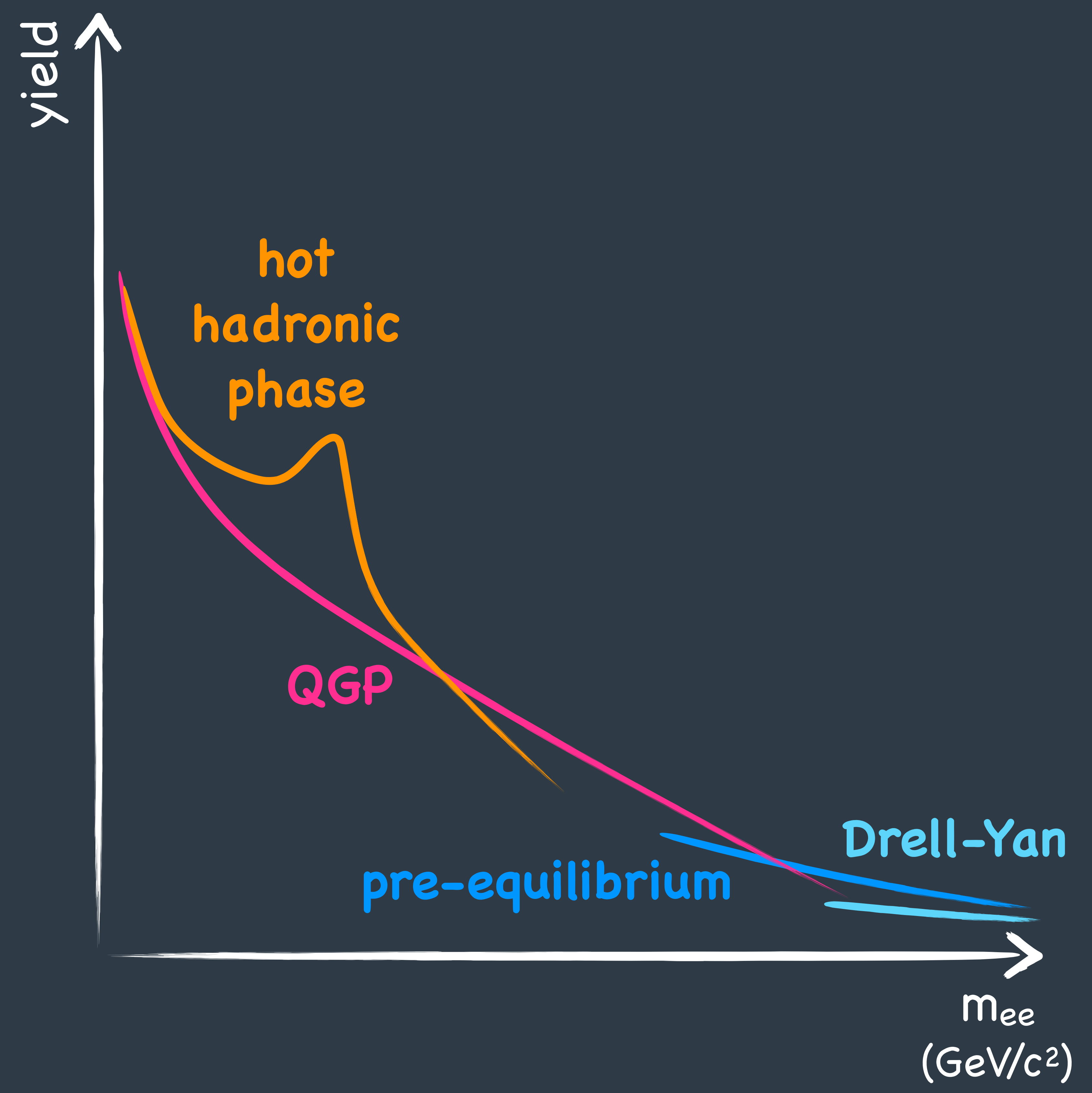

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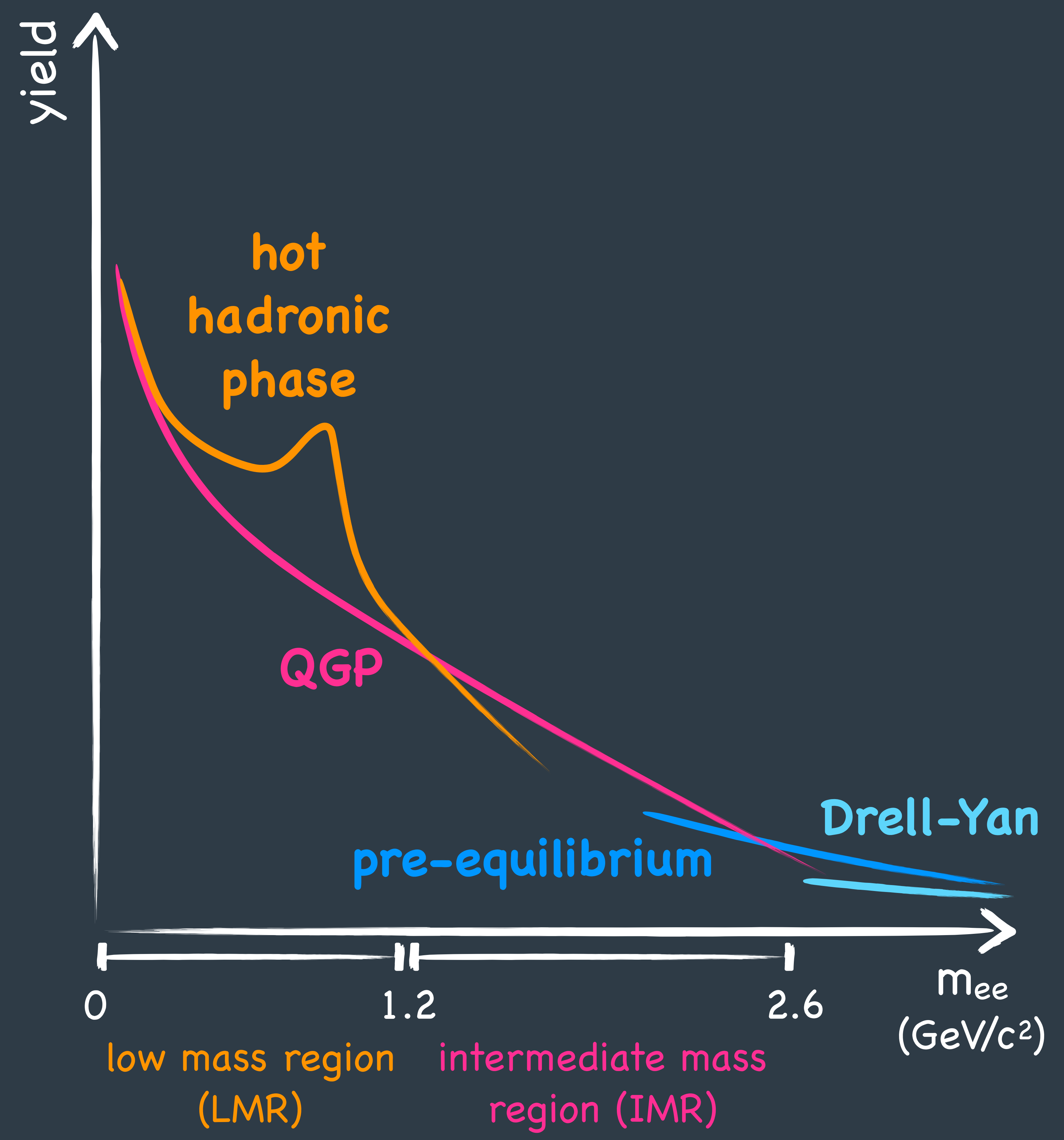
→ separation of collision stages via **invariant mass (m_{ee})**



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Dielectrons in Heavy-Ion Collisions

ALICE

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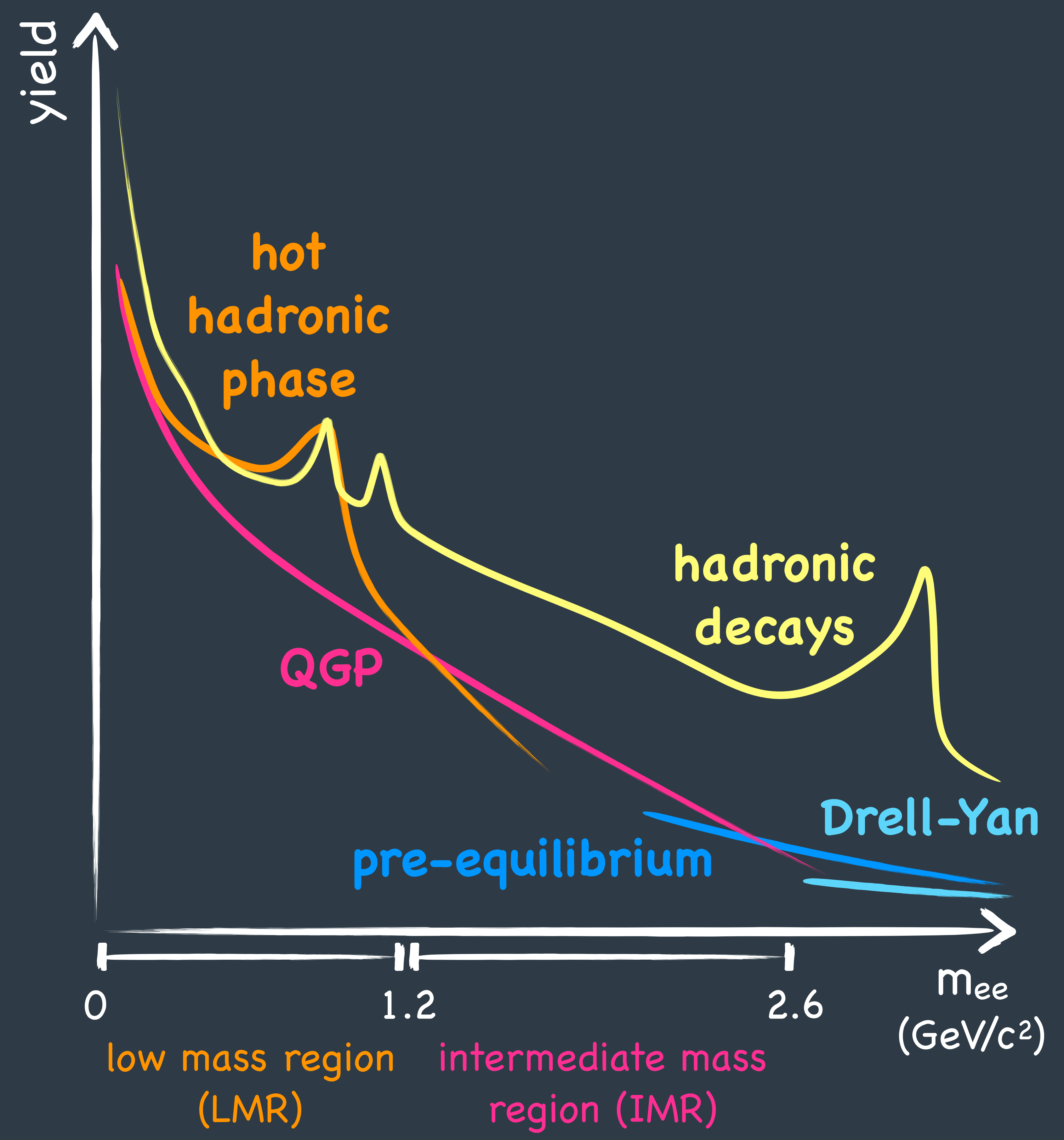
  hot hadronic phase

→ separation of collision stages via **invariant mass ($\boldsymbol{m_{ee}}$)**

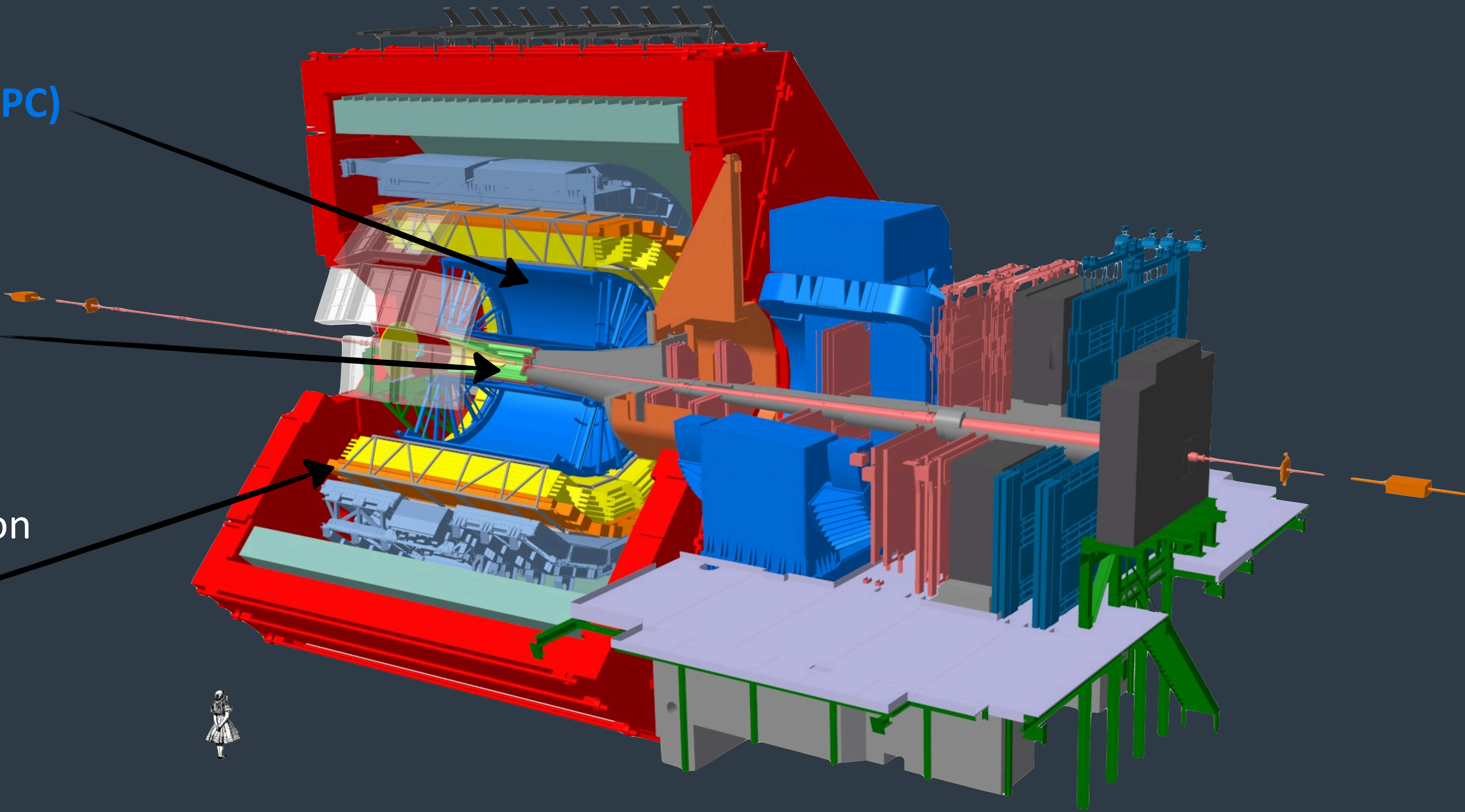
- Large combinatorial & physical backgrounds: **hadronic decays**
  - Light-flavor (LF) mesons and quarkonia (π^0, η, ρ, ω, ϕ, J/ψ)
  - Semi-leptonic decays of correlated heavy-flavor (HF) hadrons



ALICE

Relevant Detectors for Dielectron Analysis

- Time Projection Chamber (TPC)
  - Tracking
  - Electron identification
- Inner Tracking System (ITS)
  - Tracking
  - DCA measurement
  - Photon conversion rejection
- Time of Flight (TOF)
  - Hadron rejection



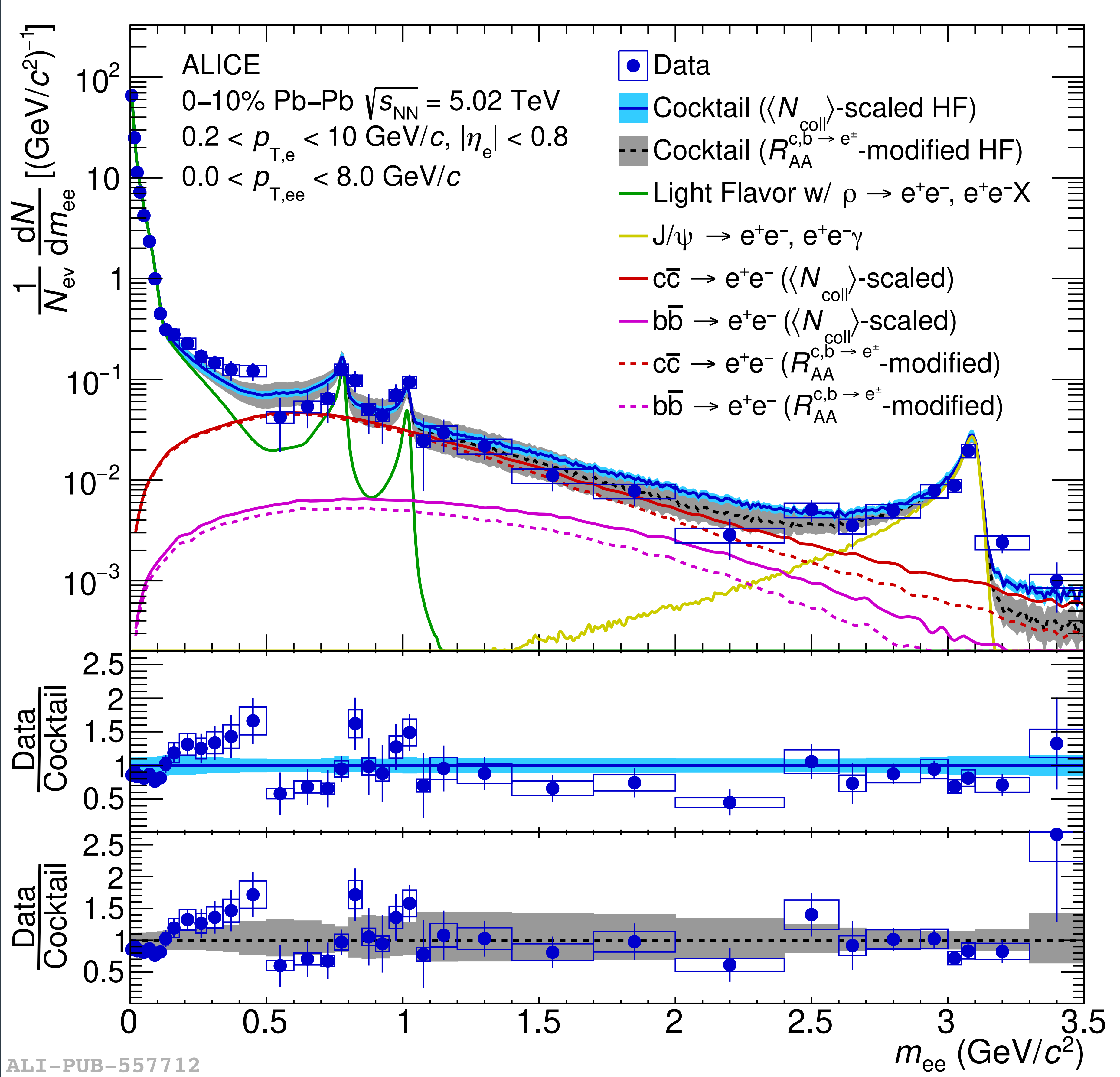
Run 2 central Pb–Pb

Invariant Mass Spectrum

ALICE, arXiv:2308.16704

Expectations from known hadronic sources (cocktail):

- **Cocktail 1:** N_{coll}-scaled HF measured in pp at $\sqrt{s}$ = 5.02 TeV
  → vacuum baseline
  - Good description of π^0-Dalitz and J/ψ decays
  - Indication of HF suppression compared to pp
    → expected due to cold- and hot-nuclear matter effects
- **Cocktail 2:** include measured R_{AA} of c/b→e$^{\pm}$
  → modified-HF contribution
  - Overall improved description of the data including HF suppression



Run 2 central Pb–Pb

Excess Spectrum

Subtraction of known hadronic sources without ρ

- Comparison to theoretical models (R. Rapp):
  - in-medium ρ from hot hadronic matter
  - thermal radiation from QGP

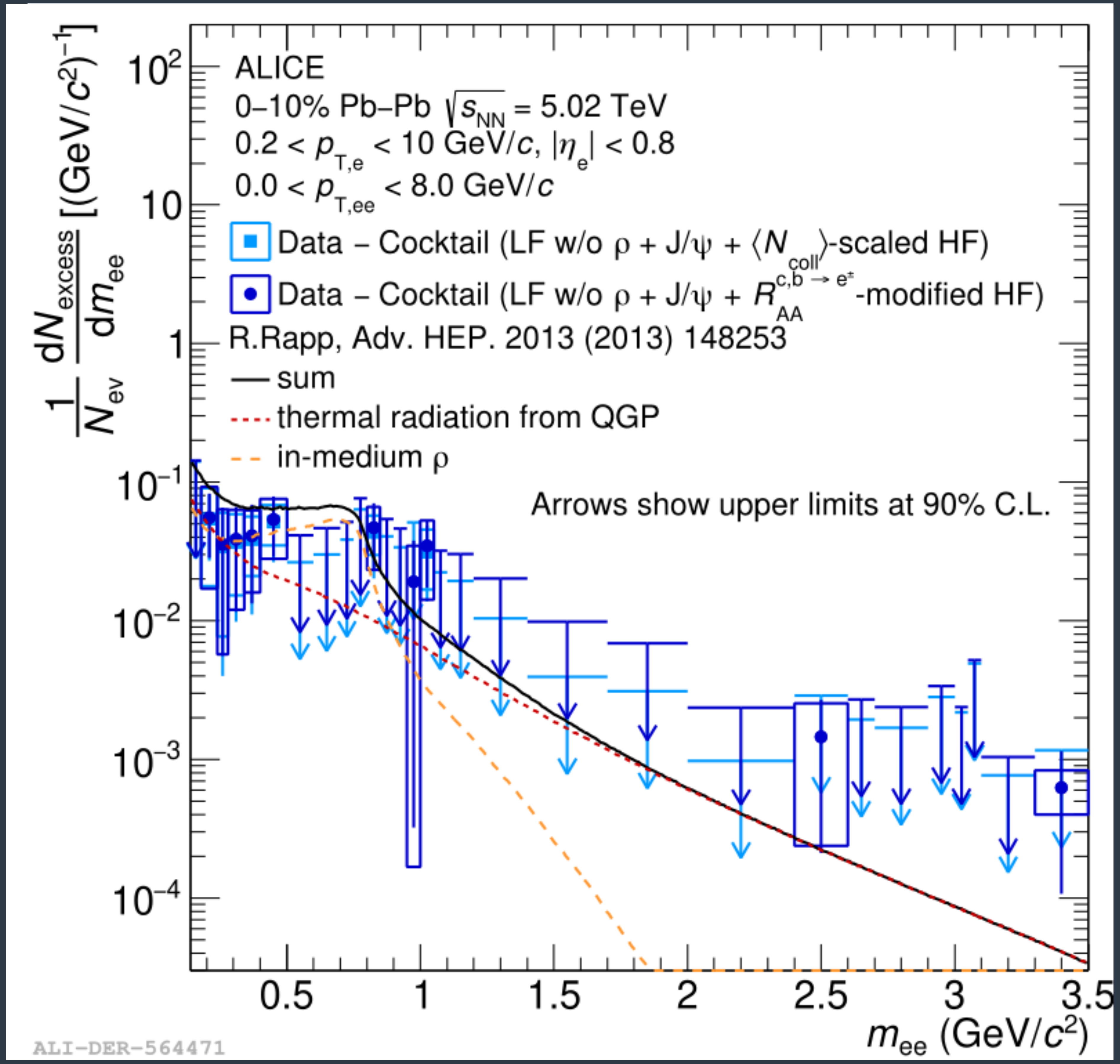
LMR:

- Excess compatible with model prediction
- Some tension in $0.5 < m_{ee} < 0.7$ GeV/c^2
  → more data needed to confirm

IMR:

- Large uncertainties after cocktail subtraction
  → cocktail-independent approach needed to access QGP

ALICE, arXiv:2308.16704



Topological Separation

Definition

Separation of prompt and non-prompt sources based on their decay topology:

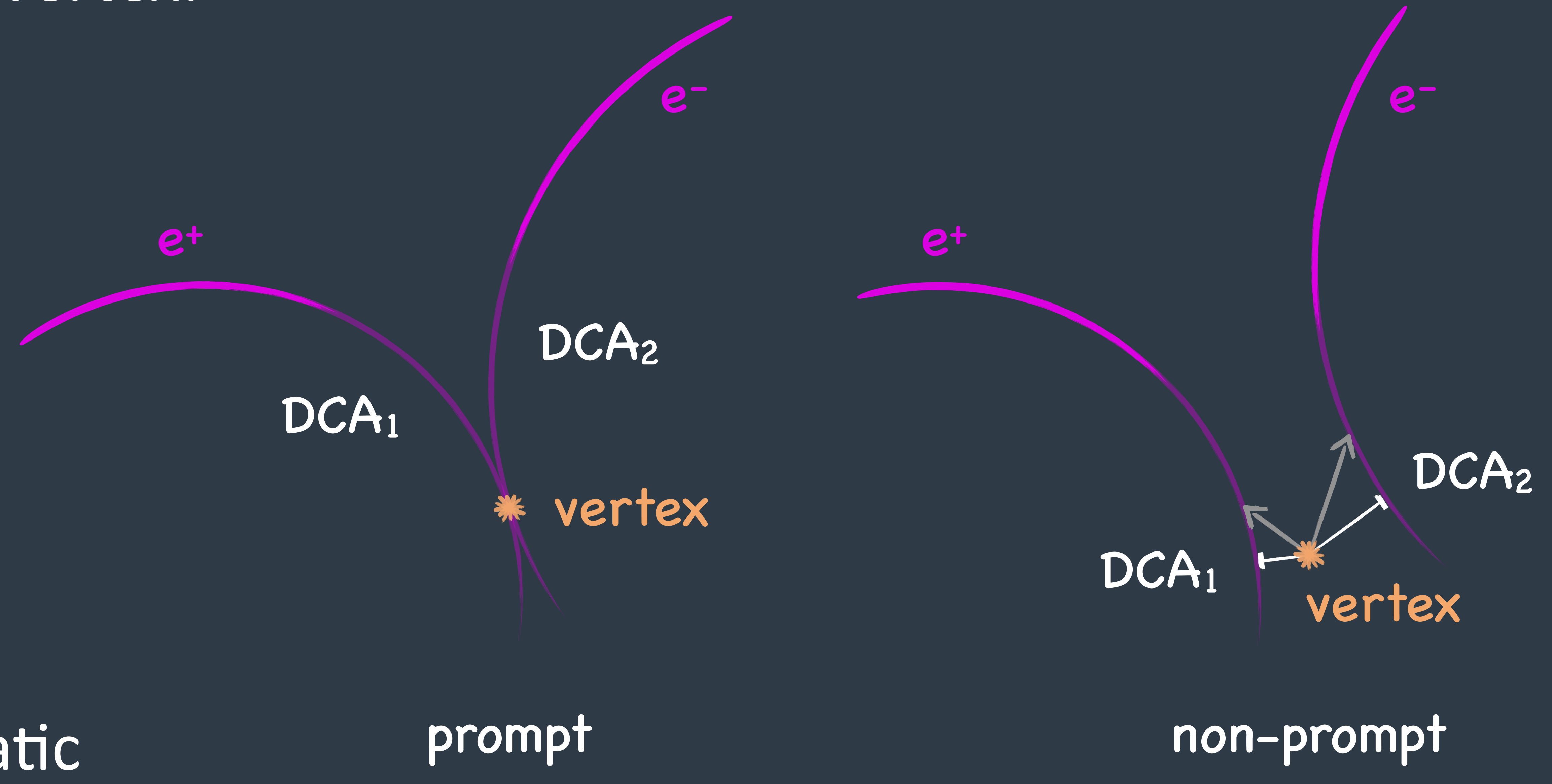
→ distance-of-closest approach (DCA) to the primary vertex:

- Tracks of prompt decays (LF) → small DCA
- Tracks of late decay time (HF) → large DCA

- DCA of the pair: $DCA_{ee} = \sqrt{\frac{(DCA_1/\sigma_1)^2 + (DCA_2/\sigma_2)^2}{2}}$

- Method only relies on the well-known decay kinematic
  → independent of cocktail and theory input

- Requires high-resolution vertex detector



ALICE

Upgrades for LHC Run 3

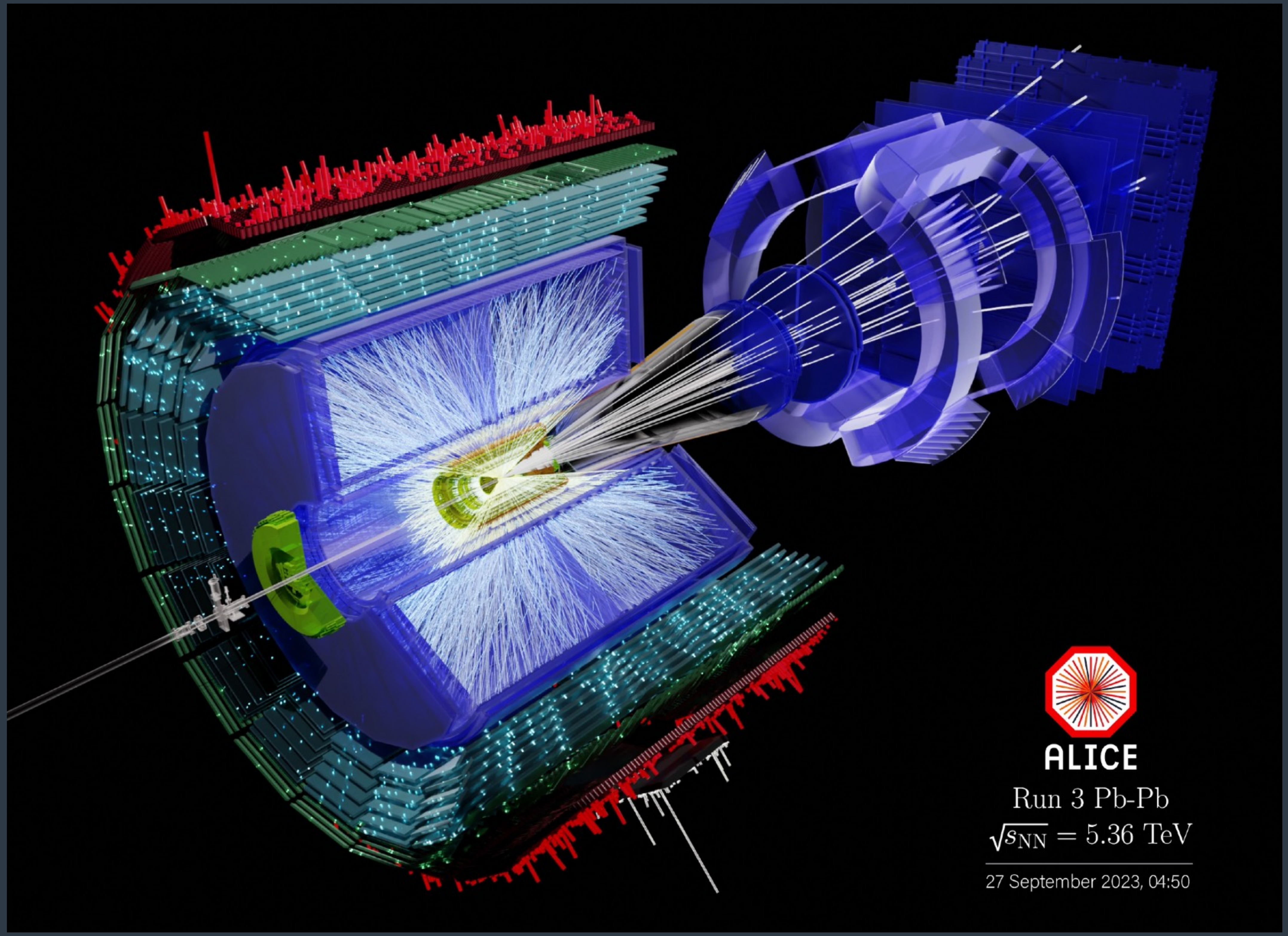
- New ITS CMOS MAPS technology

  → improved pointing resolution and faster readout

- New TPC GEM-based readout chambers

  → higher data acquisition rate due to continuous readout (up to 50 kHz in Pb–Pb & 1 MHz in pp)

2023&2024: factor ~20 more Pb–Pb and ~1000 more pp events than in Run 1&2



Run 3 pp
Dielectron Spectra

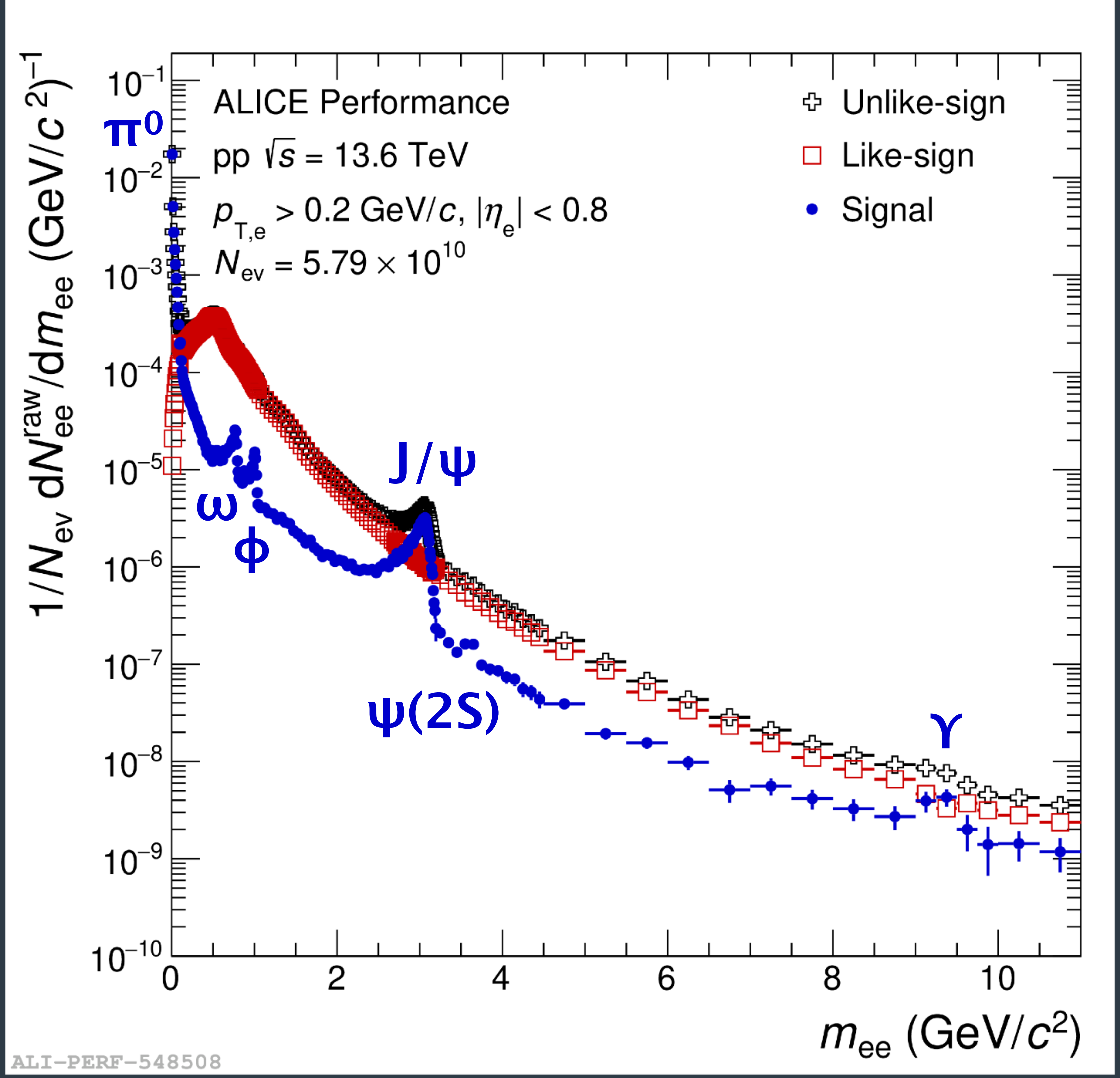
2022 data

First dielectron analysis with pp data from 2022:

- High statistical precision due to upgraded ALICE detector
- Much further in mass
  compared to published Run 2 results
  Phys. Lett. B 788 (2019) 505 & arXiv:2411.14366

→ enables search for prompt sources in pp
(Drell-Yan & onset of thermal radiation)

→ topological separation (DCA_{ee})
of prompt & non-prompt sources crucial



Run 3 pp

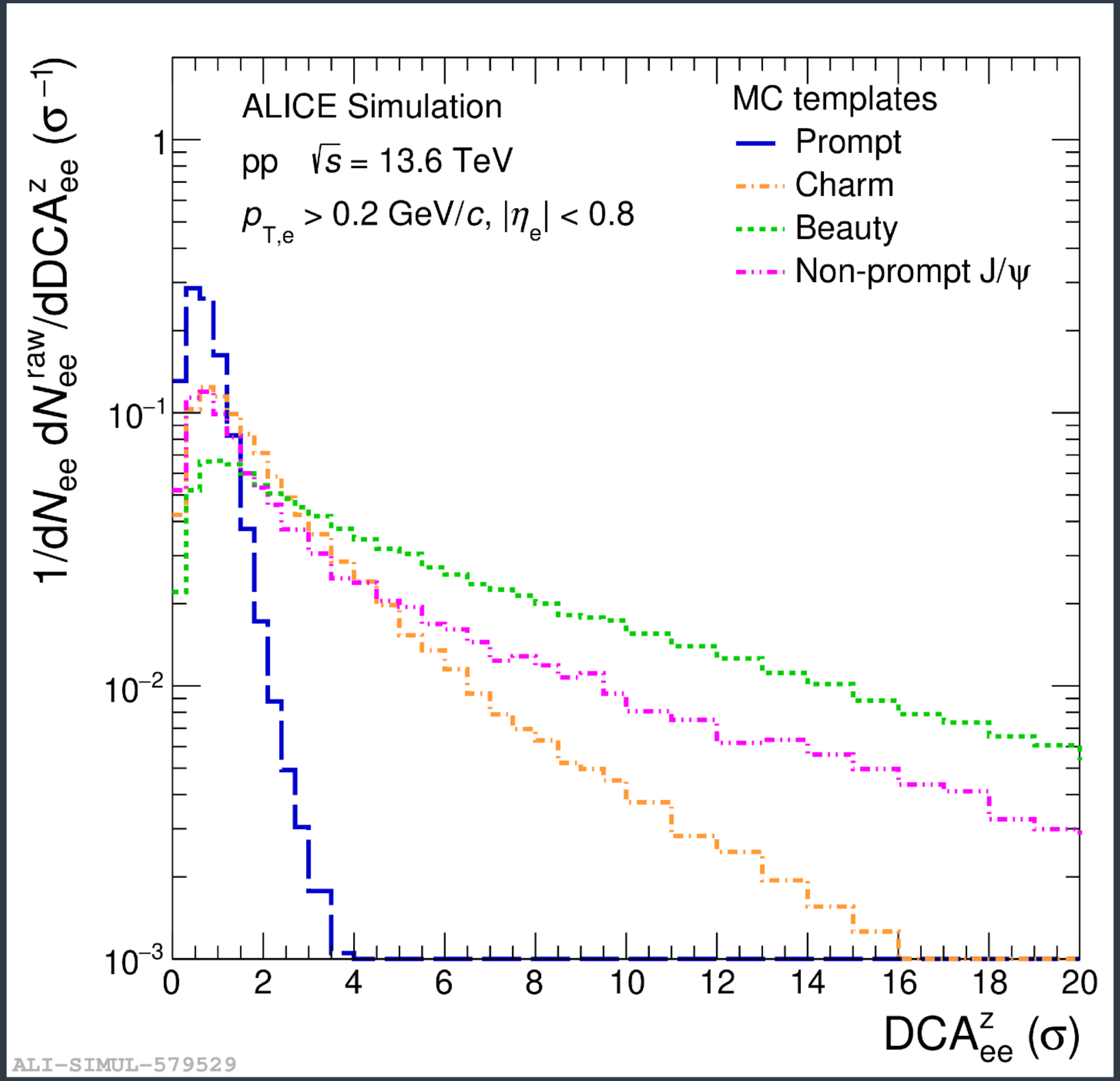
Topological Separation with MC Templates

ALICE

2022 data

Extract DCA_{ee} templates from full MC simulation
→ separate prompt and non-prompt dielectrons

- **Prompt**: LF & J/ψ decays
- **Charm**: D^0, $D^\pm$, D_s & Λ_c decays
- **Beauty**: different decay channels of b-hadrons
- **Non-prompt J/ψ**: constrained from Run 2 measurement



Run 3 pp

Topological Separation with MC Templates

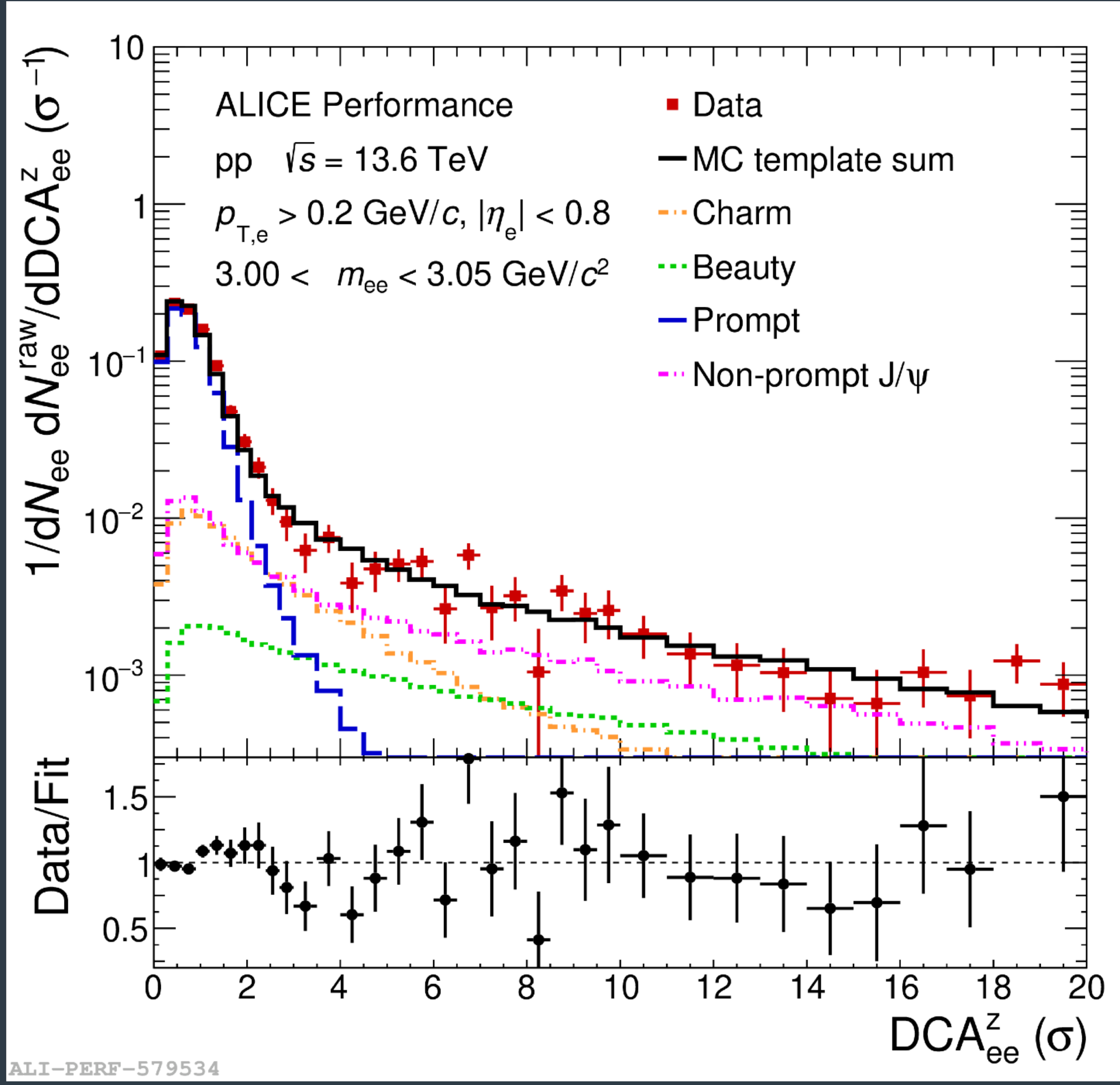
Template fits are performed directly to raw spectra in different mass intervals:

- J/ψ region as control region with dominant prompt signal

→ data well described by sum of all templates
→ validating DCA resolution in MC simulations

J/ψ region

2022 data



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Topological Separation with MC Templates

Template fits are performed directly to raw spectra in different mass intervals:

- J/ψ region as control region with dominant prompt signal

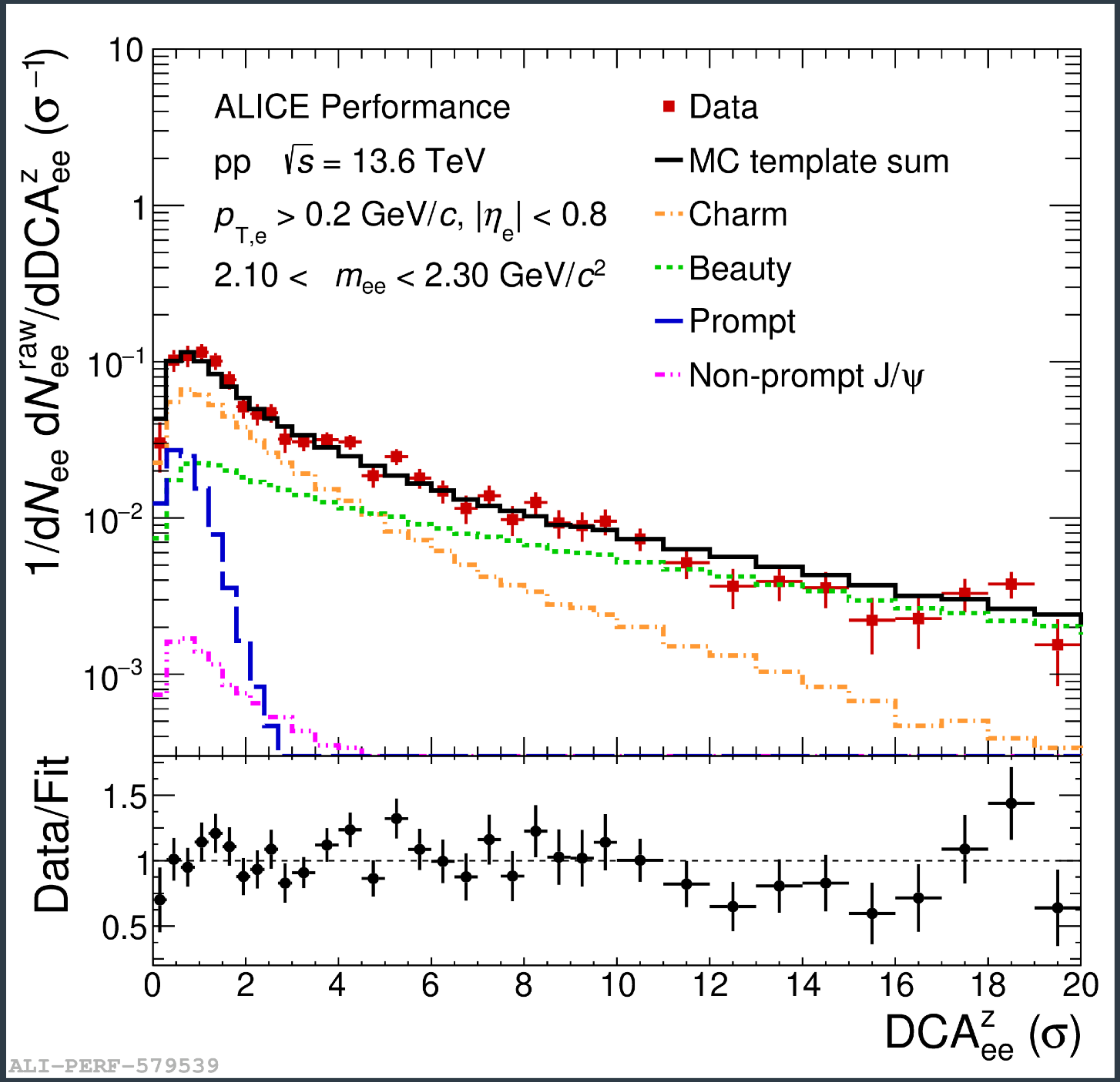
  → data well described by sum of all templates
  → validating DCA resolution in MC simulations

- IMR as region of interest
  → search for additional prompt signal

  → data at high DCA_{ee} fully described by HF templates
  → additional prompt contribution at small DCA_{ee} preferred by data

IMR region

2022 data



Run 3 pp

Topological Separation with MC Templates

ALICE

2022 data

Goal: unfold mass spectrum via DCA fits
→ separate sources independently from hadronic cocktail

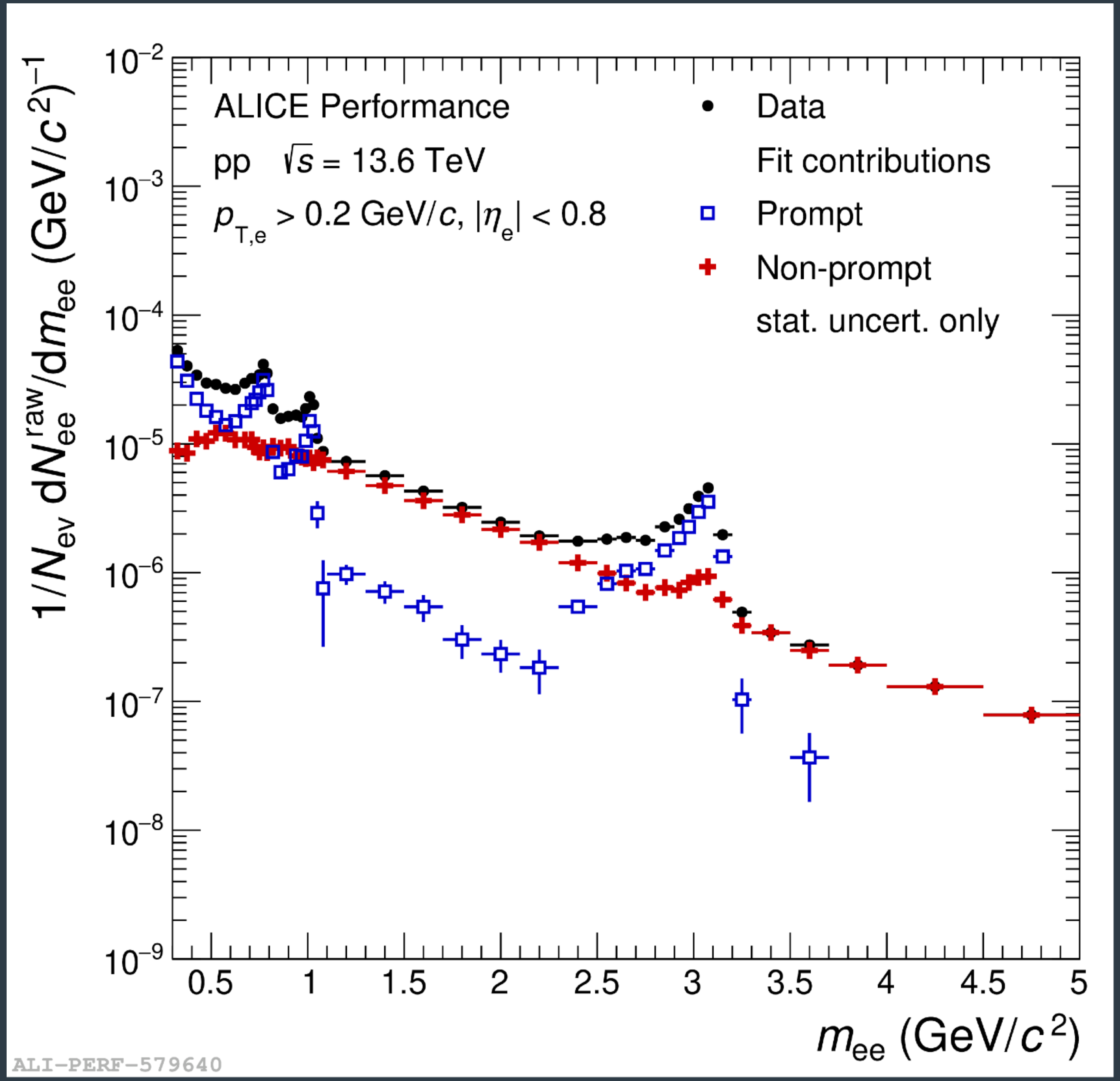
DCA$_{ee}$ template fits performed in slices of m_{ee}:

- LF peaks described by prompt contribution
- Non-prompt HF contribution describes continuum

→ Indication for prompt contribution in IMR

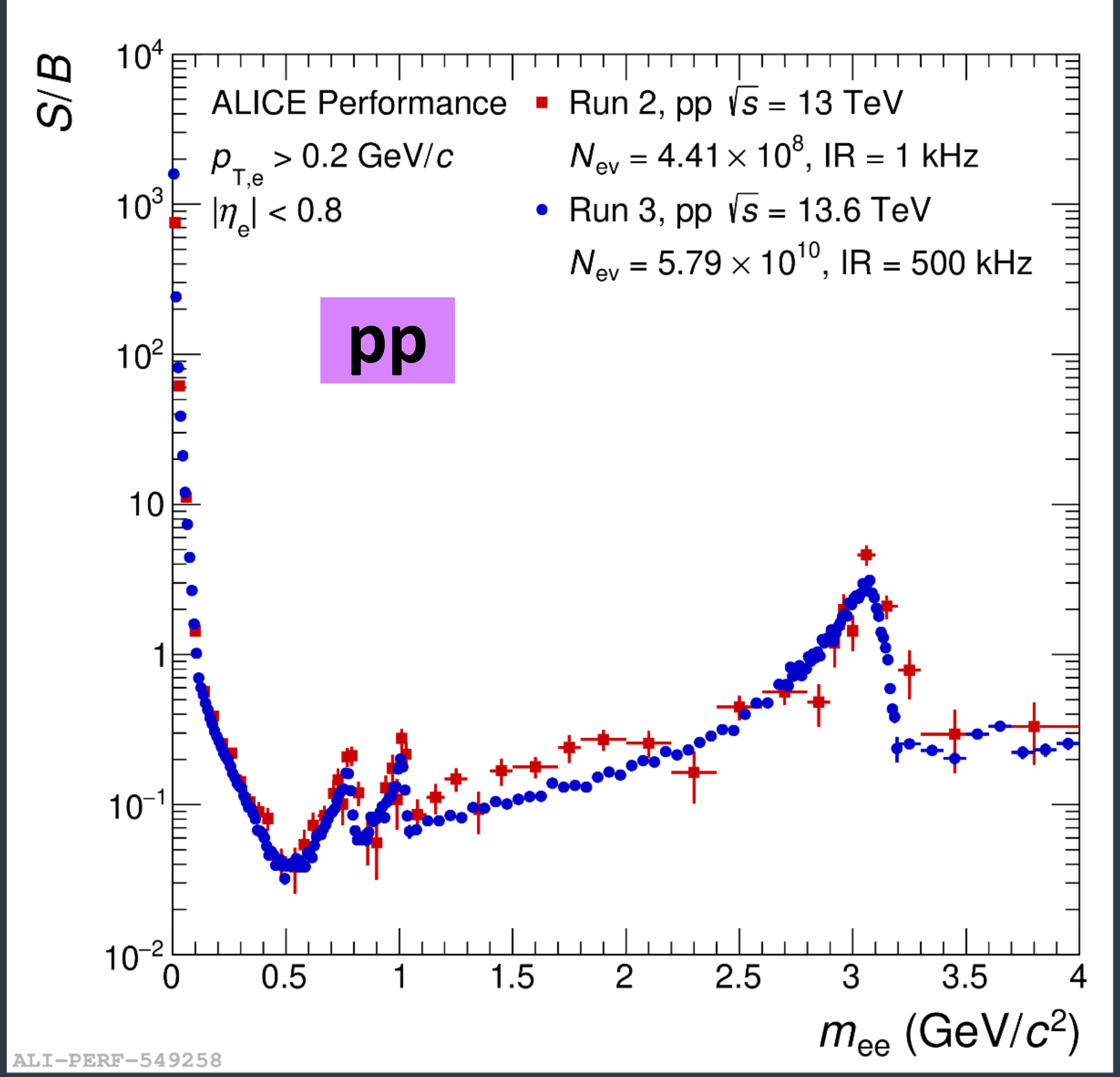
Next steps:

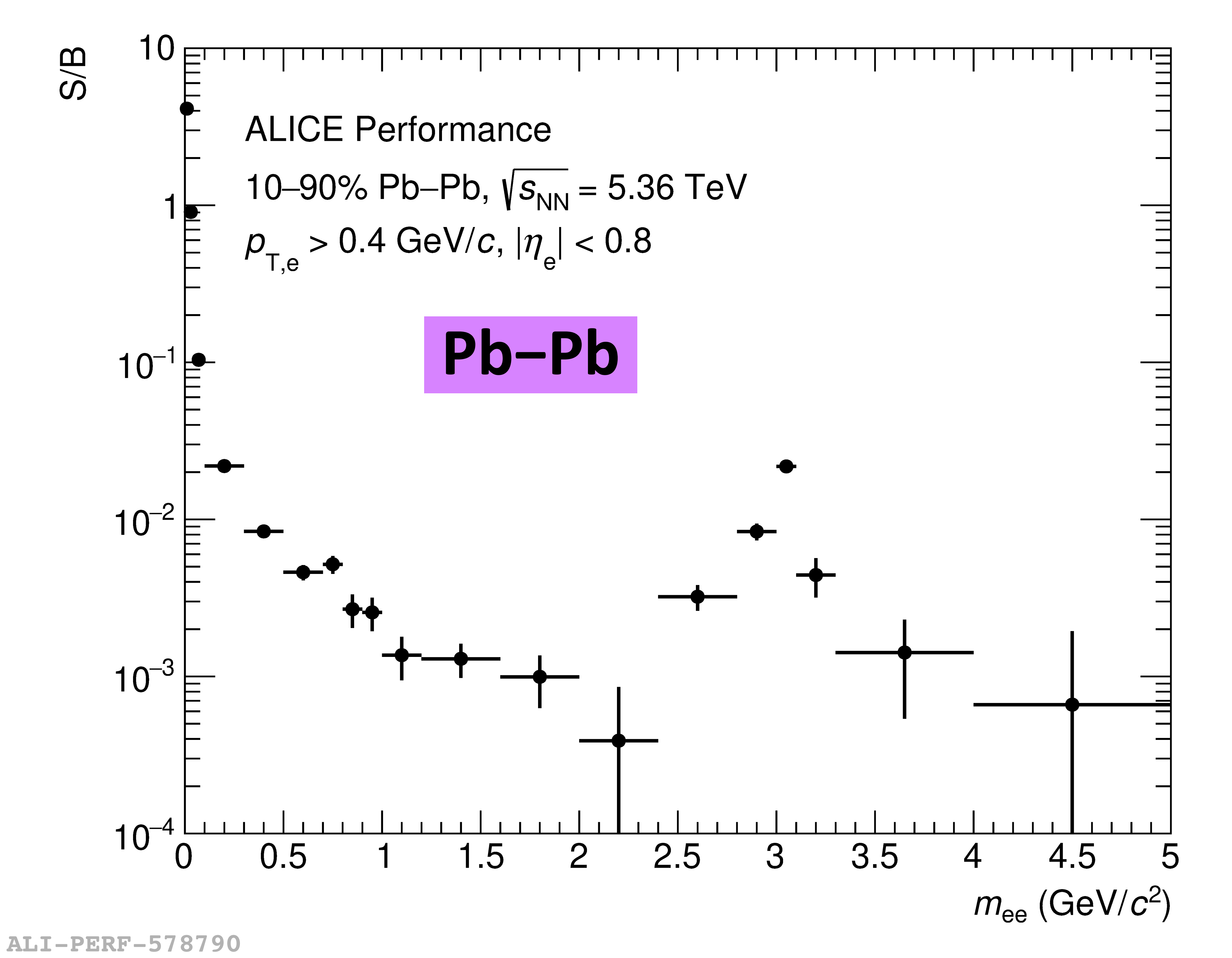
- Final correction
- Comparison to hadronic cocktail sources



Run 3 Pb–Pb

Signal-over-Background





- Analysis much more challenging than in pp collisions
- S/B decreases by factor of 100 → much higher precision of background required

Run 3 Pb–Pb

Raw Dielectron Spectra

First look at dielectron signal in Pb–Pb collisions in Run 3:

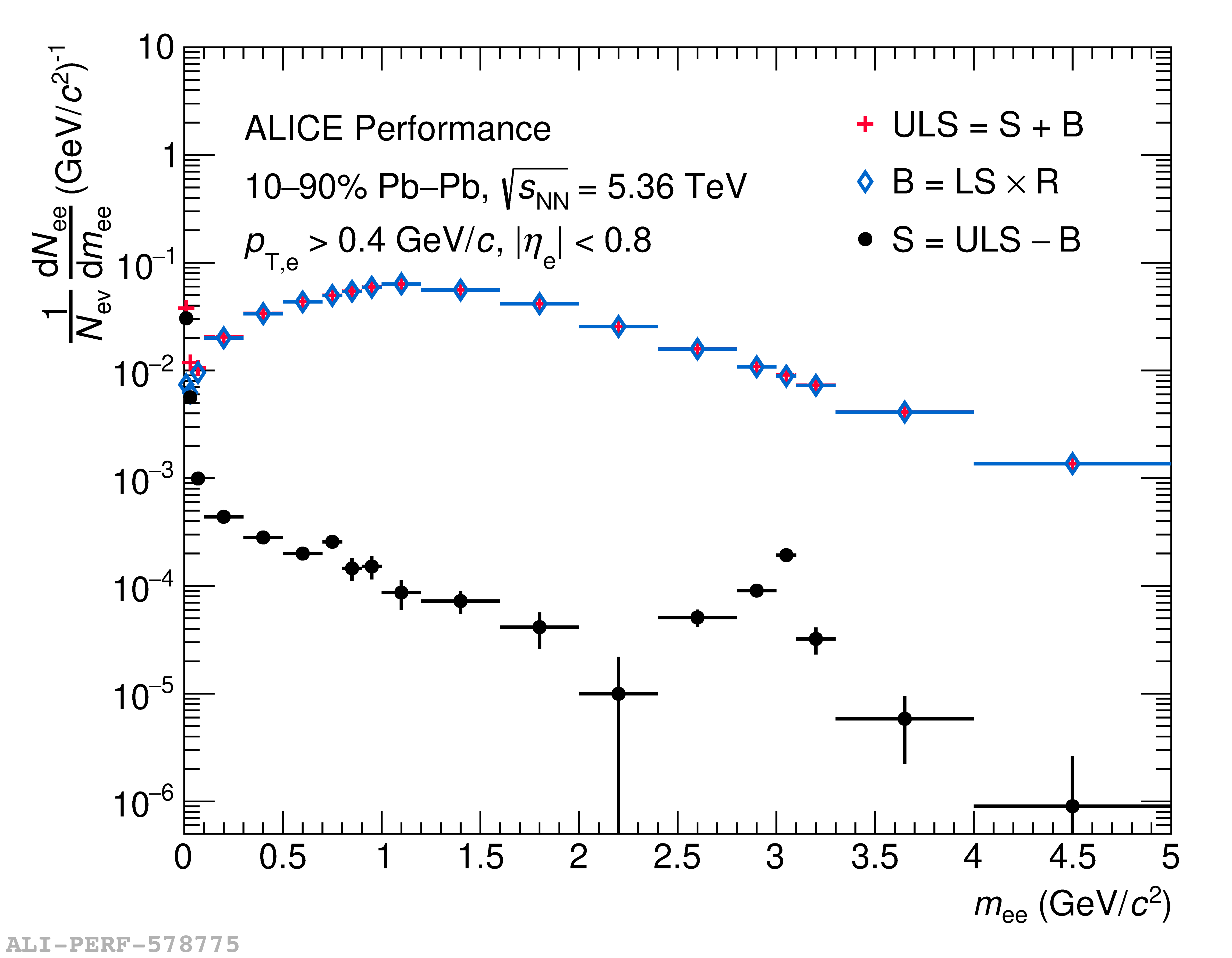
- Effective interaction rates between 6 and 43 kHz, continuous readout (Run 2 trigger rate < 1 kHz)
- 900 million events in 10-90% centrality (only subset of 2023 Pb–Pb data of 1.5 nb^{-1})
- About same amount of data recorded in 2024

→ characteristic features (π^0 and J/ψ peaks) clearly visible

Next steps:

- Analysis of full statistics
- DCA analysis

extracted raw dielectron signal



Summary & Outlook

ALICE

Dielectrons are the ideal probes to study properties of strongly-interacting matter in heavy-ion collisions

Run 2 Pb–Pb: Excess in LMR visible & compatible with theory
However, statistical limitation to extract thermal signal in the IMR

Run 3 pp: High statistical precision due to upgraded ALICE detector
→ unfolding mass spectrum with topological separation possible

Run 3 Pb–Pb: Initial performance studies completed
→ further studies to improve signal extraction ongoing
→ perform DCA template analysis of raw signal

→ more data to be recorded in Run 3 & 4

Backup

Run 2 central Pb–Pb

Invariant Mass Spectrum

Expectations from known hadronic sources (Cocktail):

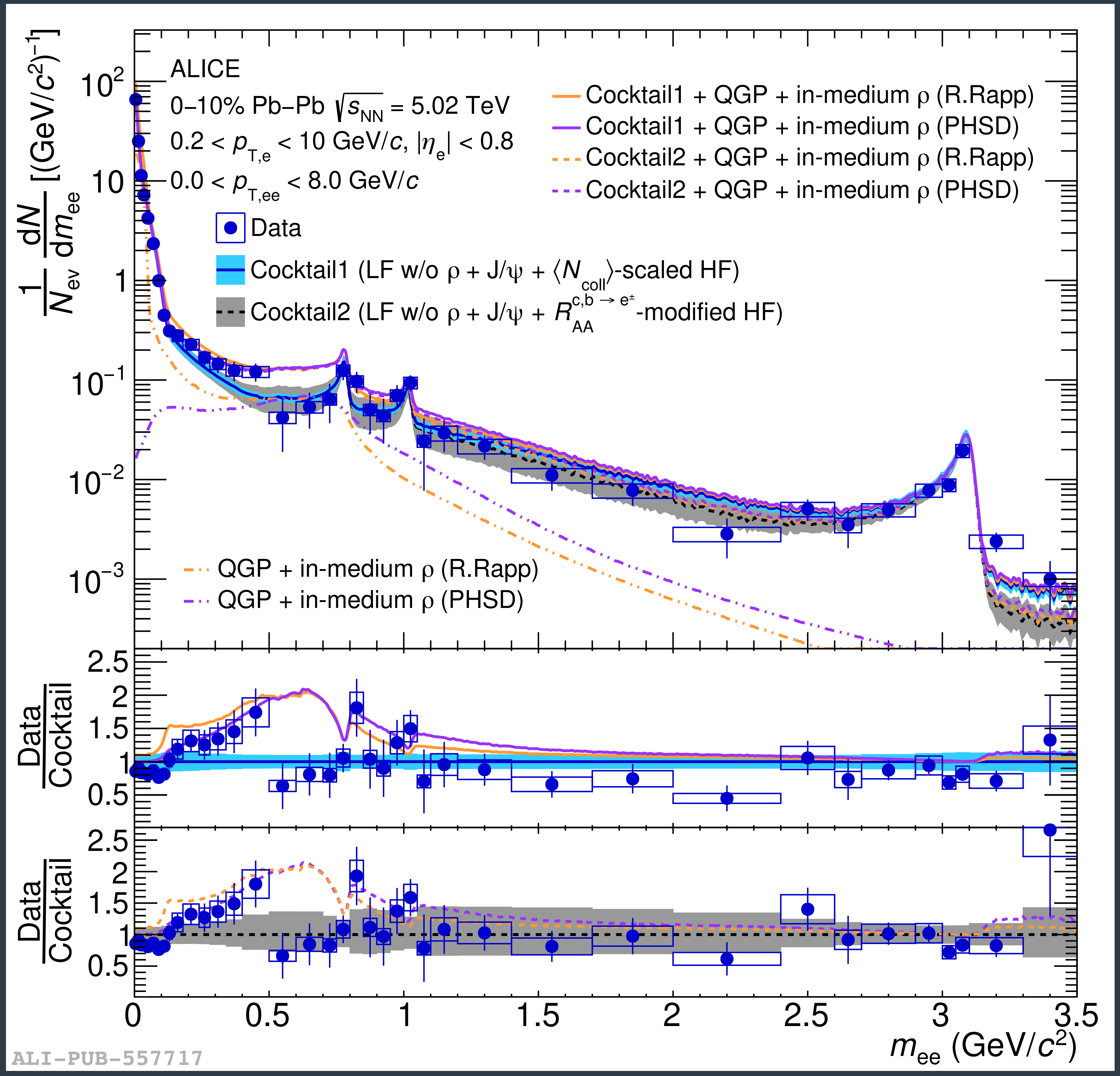
ALICE, arXiv:2308.16704

- **Cocktail 1:** N_{coll}-scaled HF measured in pp at $\sqrt{s}$ = 5.02 TeV
  → vacuum baseline
- **Cocktail 2:** include measured R_{AA} of c/b→e$^{\pm}$
  → modified-HF cocktail

Comparison to theoretical models: R. Rapp & PHSD

R. Rapp, Adv. HEP. 2013 (2013) 148253 & PHSD, PRC 97 (2018) 064907

→ excess in LMR expected from ρ mesons produced thermally in the medium



Run 2 central Pb–Pb

Topological Separation

ALICE, arXiv:2308.16704

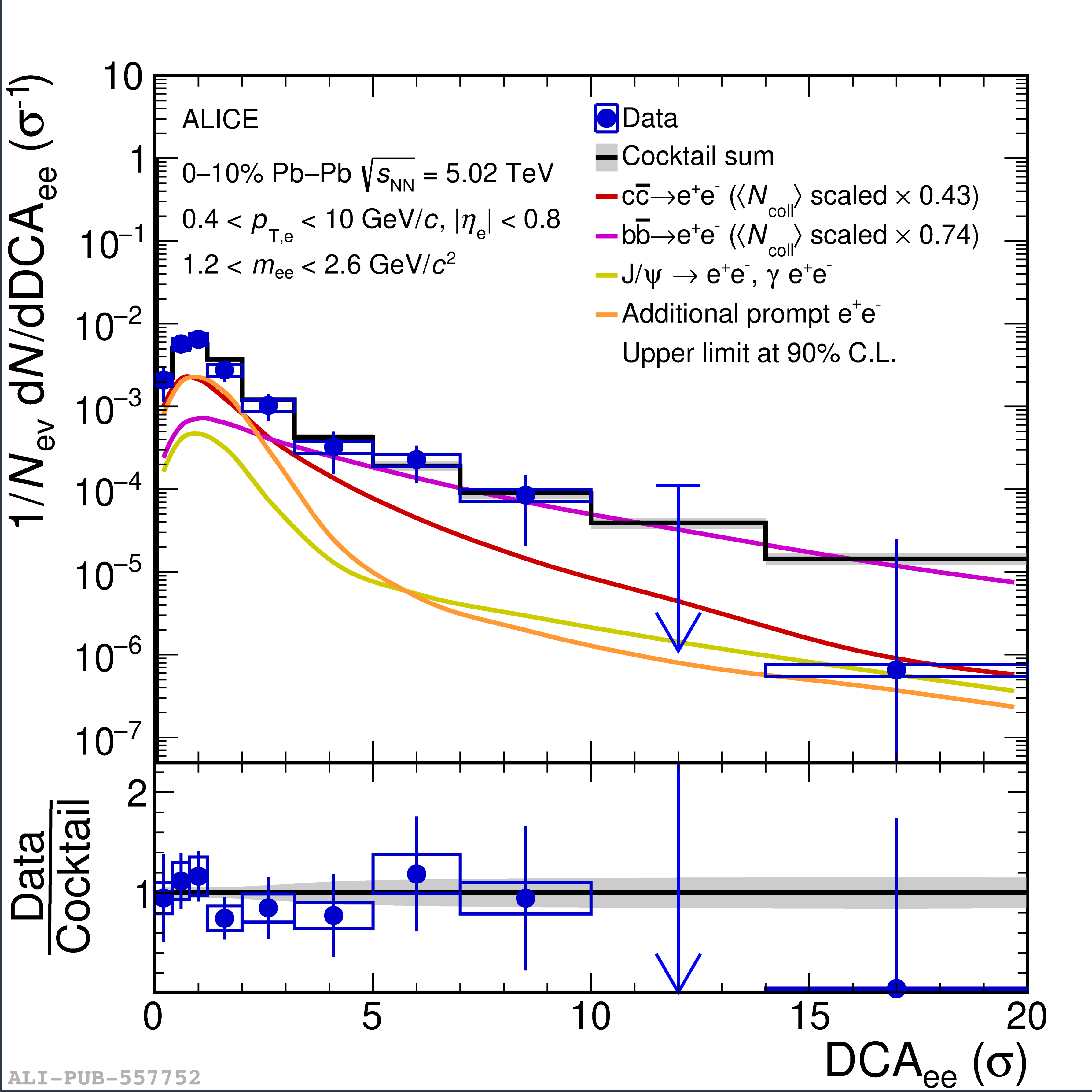
First DCA analysis in Pb–Pb at √s = 5.02 TeV

- Extraction of signals via template fits in the IMR:
  - **beauty** - 0.74 ± 0.24 (stat.) ± 0.12 (syst.) × N_{coll} scaling contribution fixed via separate fit at high $p_{\text{T,ee}}$
  - **charm** - 0.43 ± 0.40 (stat.) ± 0.22 (syst.) × N_{coll} scaling
  - **prompt** - 2.64 ± 3.18 (stat.) ± 0.29 (syst.) × Rapp

→ hint for (prompt) thermal dielectrons

→ small systematic uncertainties

However: statistical uncertainties too large to draw conclusions



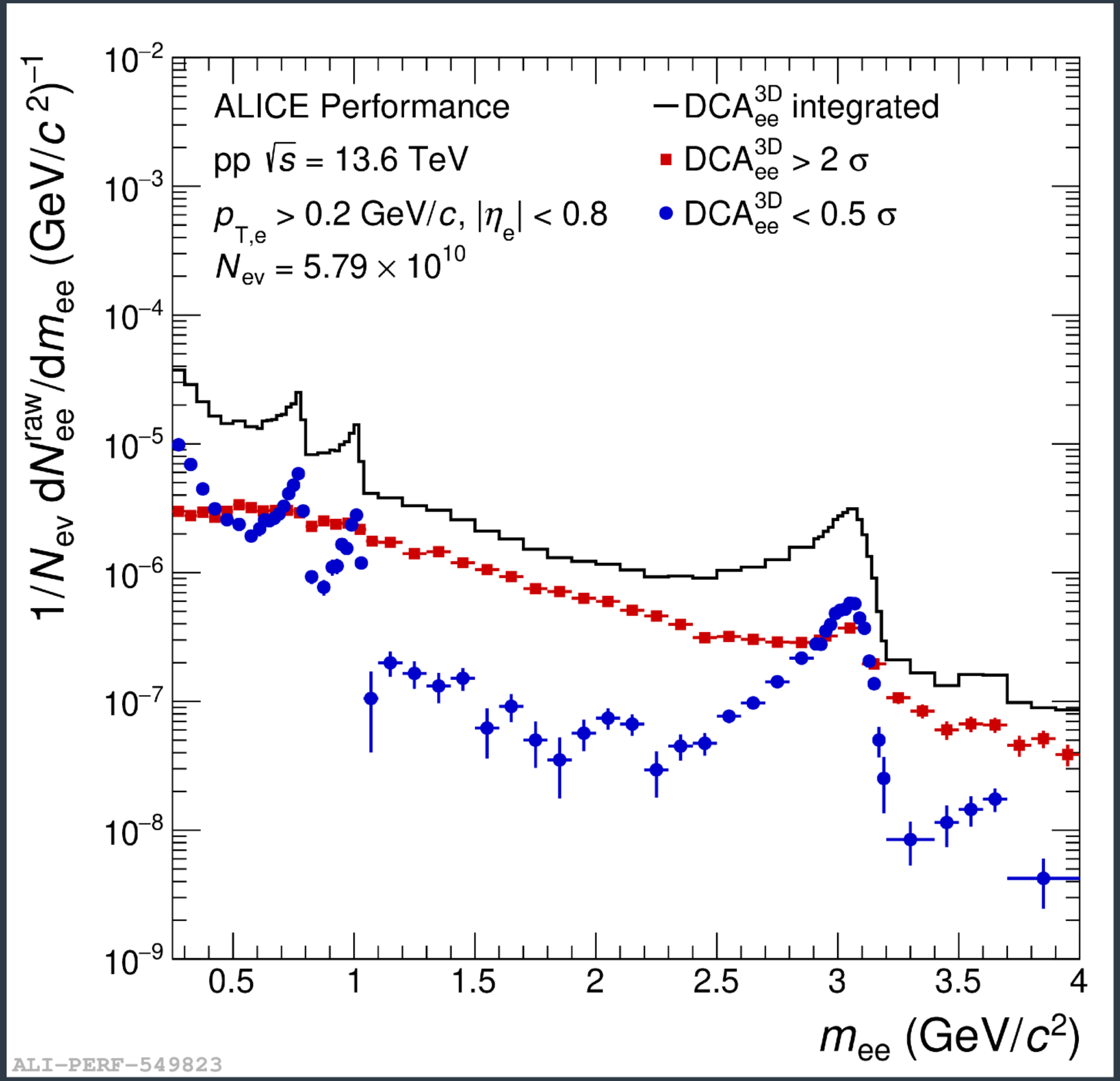
Run 3 pp

Topological Separation of Dielectron Sources

2022 data

Raw mass spectra with DCA_{ee} selections to separate prompt and non-prompt dielectron sources:

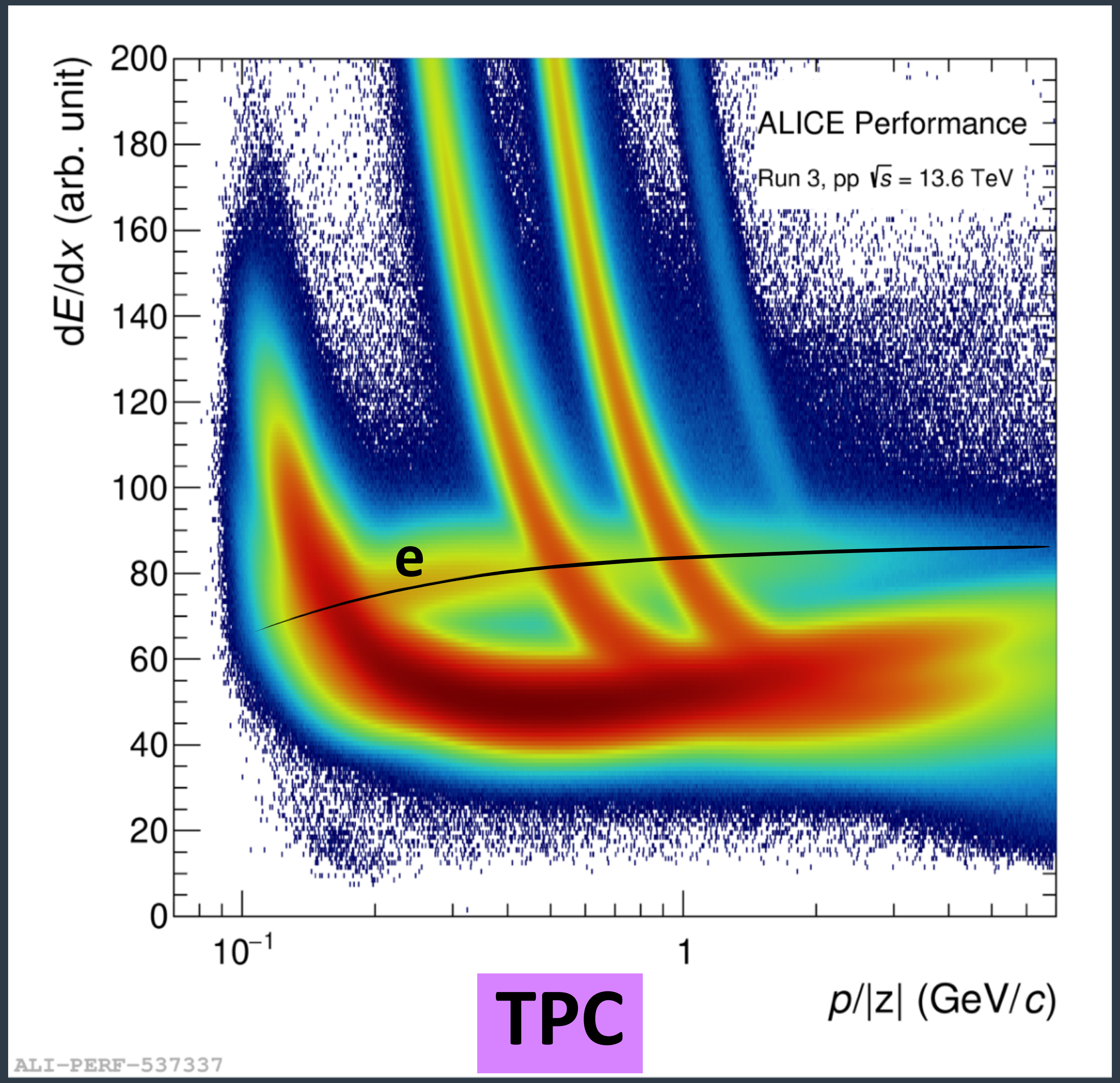
- LF peaks (prompt dielectrons) in low DCA_{ee} distribution included
- Shape of high DCA_{ee} distribution determined by HF decays (non-prompt dielectrons)
- Better pointing resolution of ITS improves separation power



Particle Identification (PID)

Electron Selection

- Identify electron and positron candidates with TPC dE/dx



Particle Identification (PID)

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- Identify electron and positron candidates with TPC dE/dx
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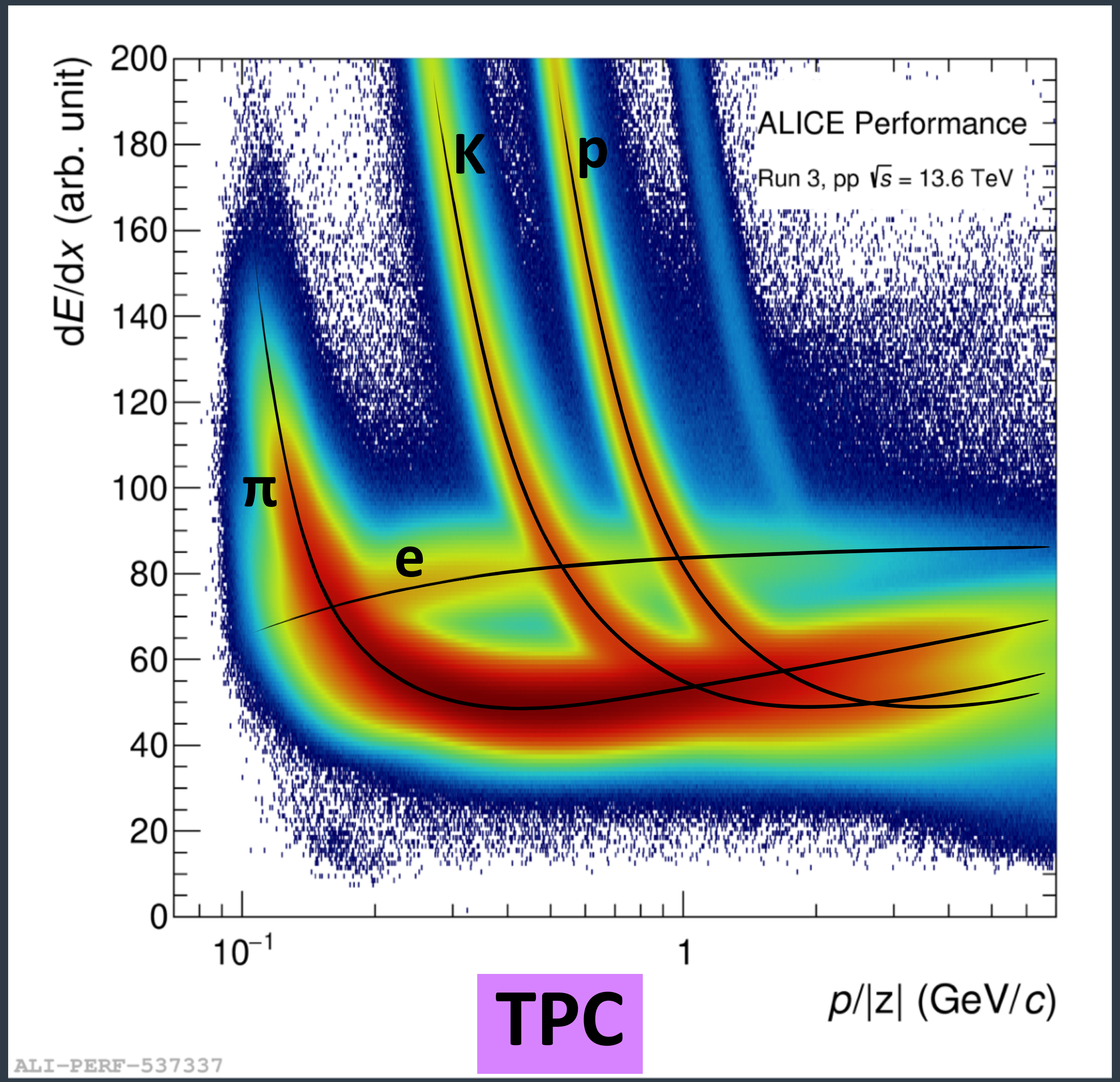

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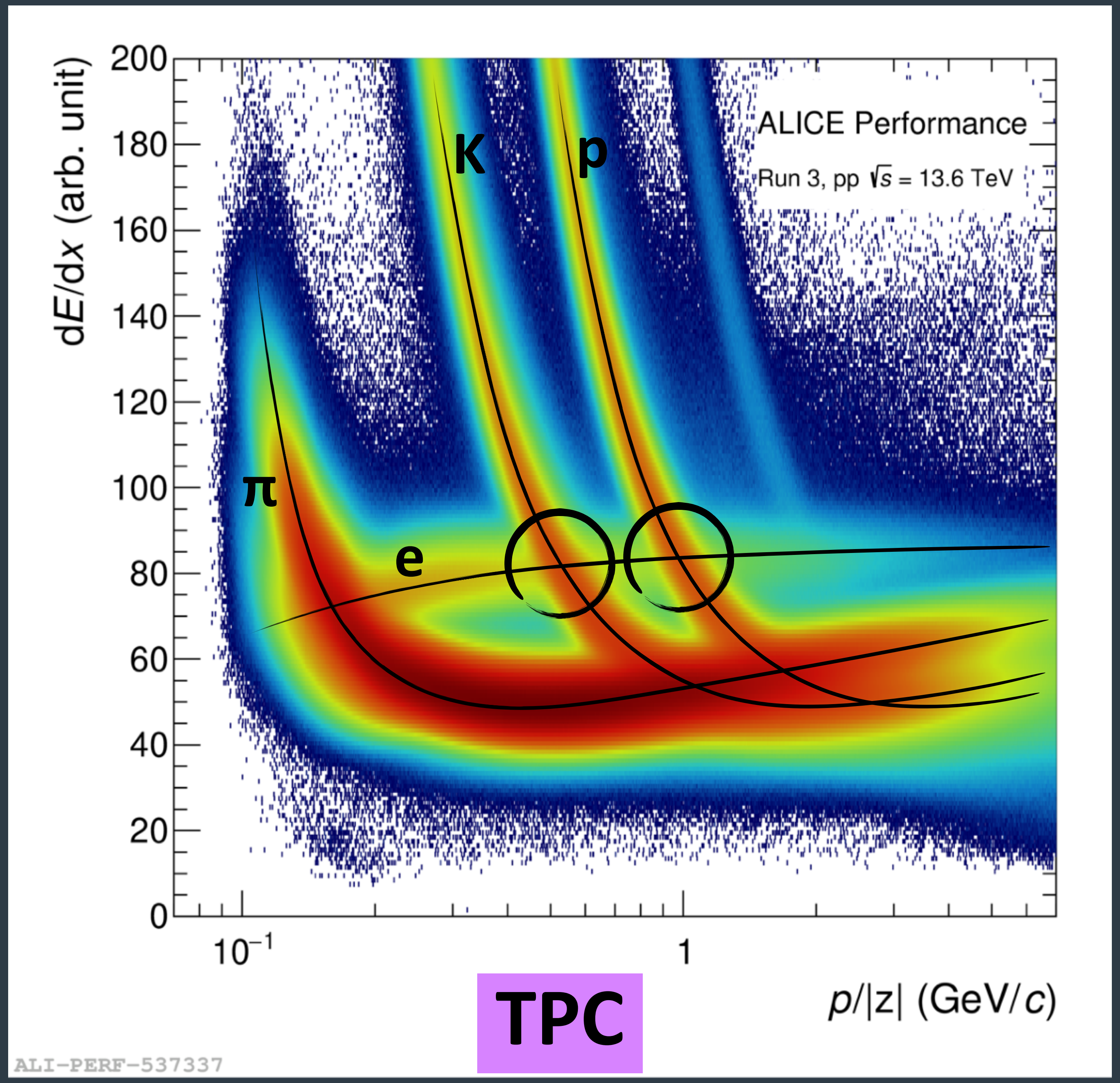
- However: crossing regions



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- Identify electron and positron candidates with TPC dE/dx
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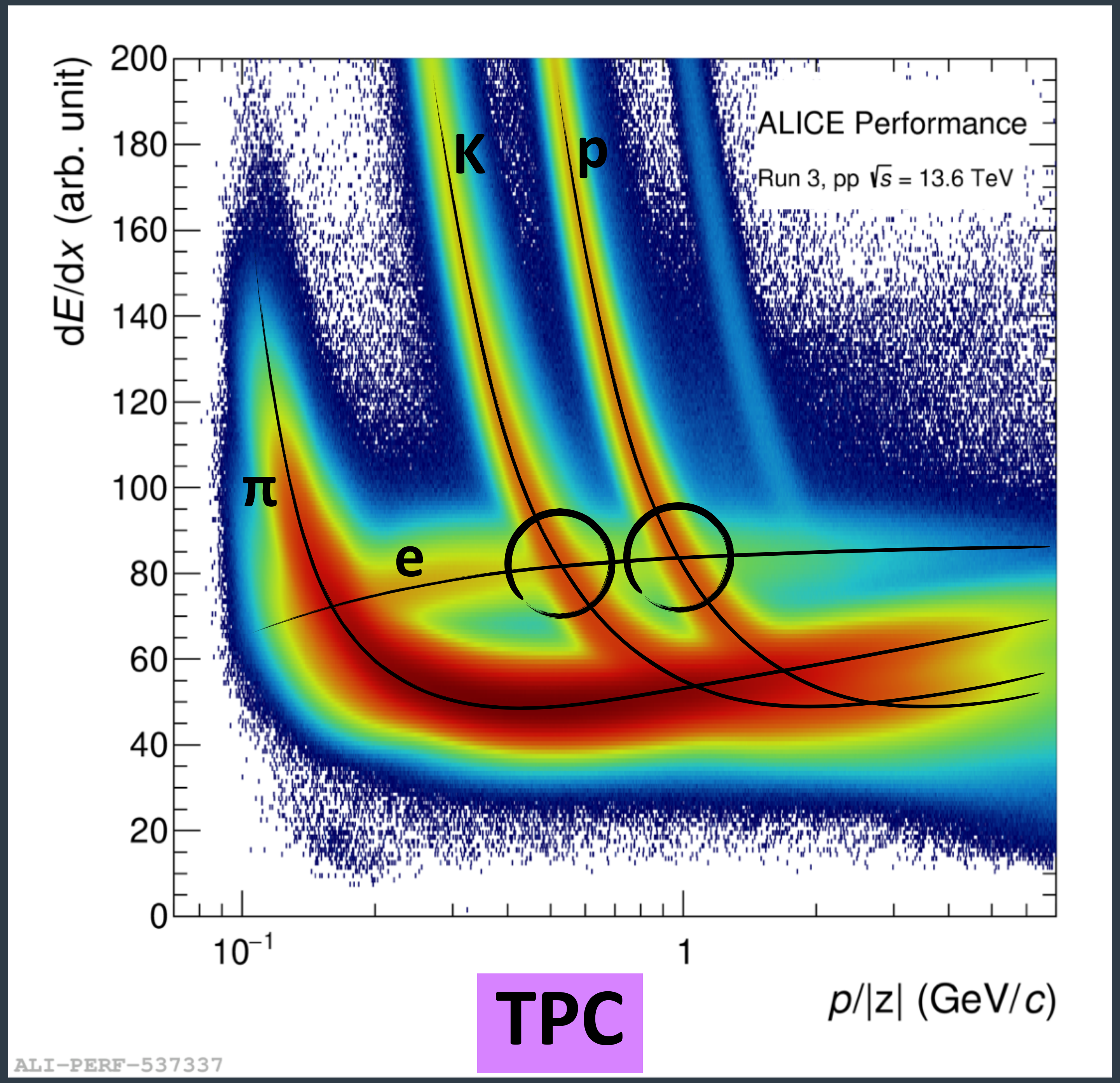
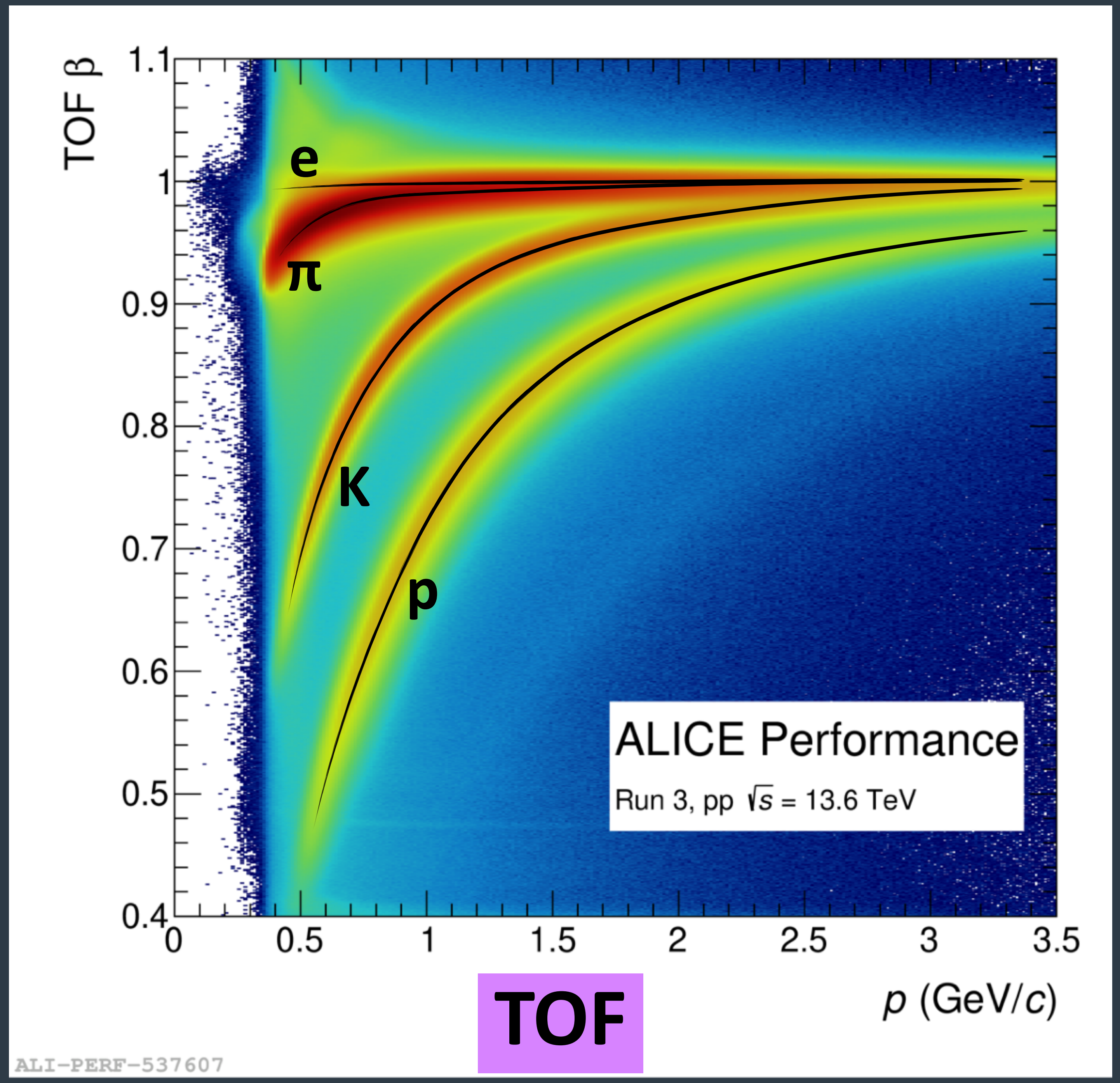
- However: crossing regions → recover well separated electrons and positrons with TOF β





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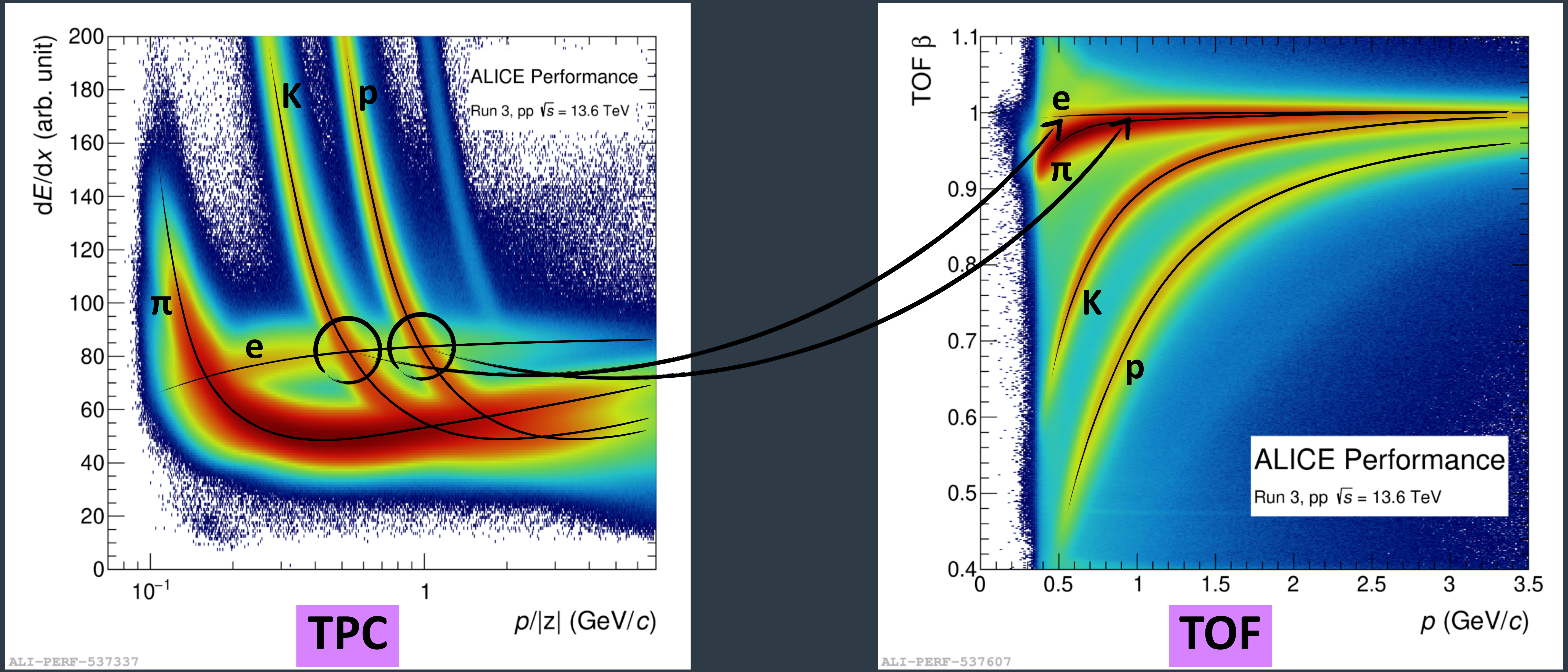

Signal Extraction

Definitions

Pairing of e^+ and e^- candidates to estimate **combinatorial background** and extract **raw dielectron signal**:

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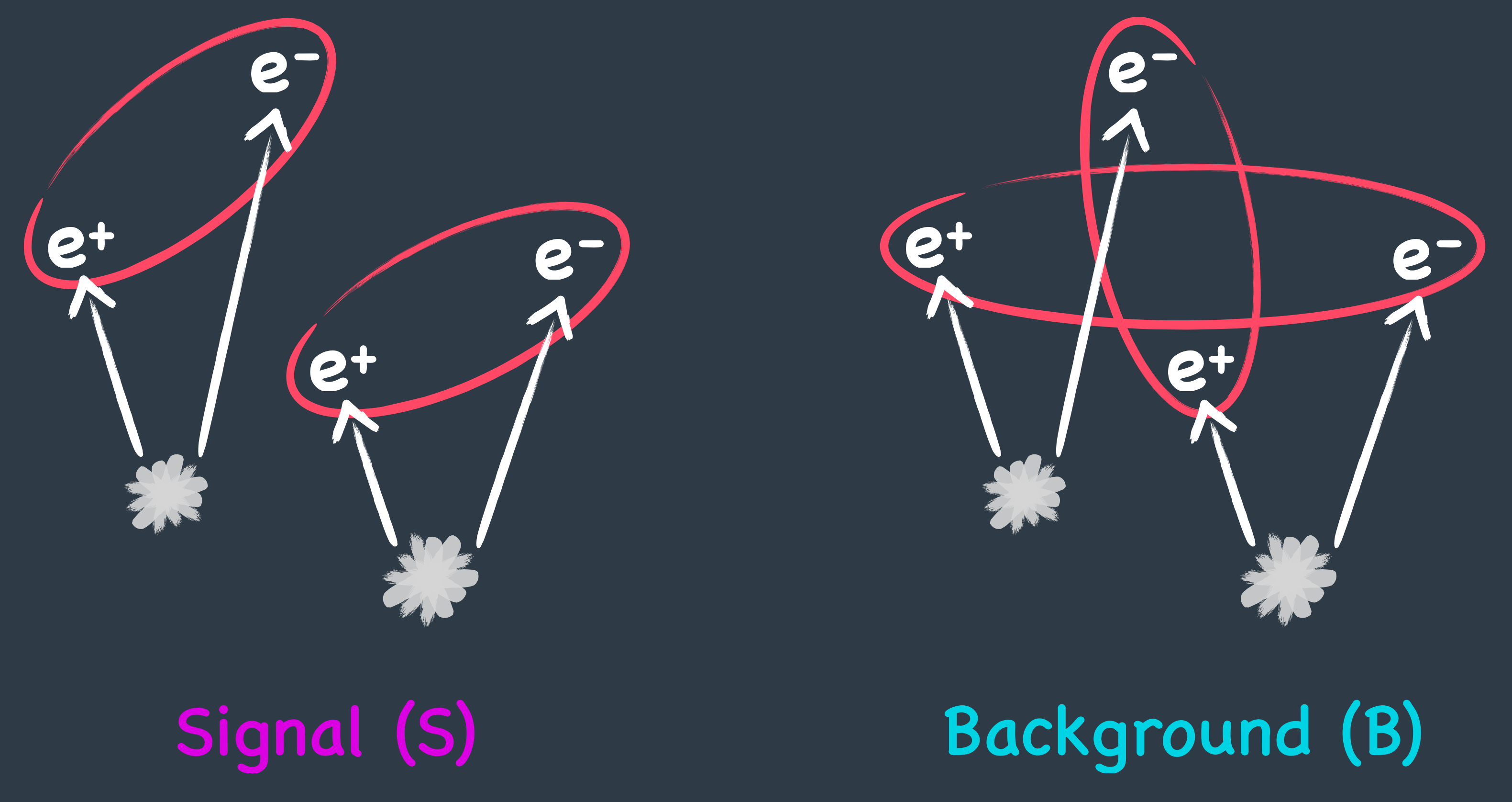
Pairing of e⁺ and e⁻ candidates to estimate **combinatorial background** and extract **raw dielectron signal**:



- **ULS**: unlike-sign pairs from same event N_{+-}^{same} → **ULS** = **S** + **B**

Signal Extraction

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ALICE

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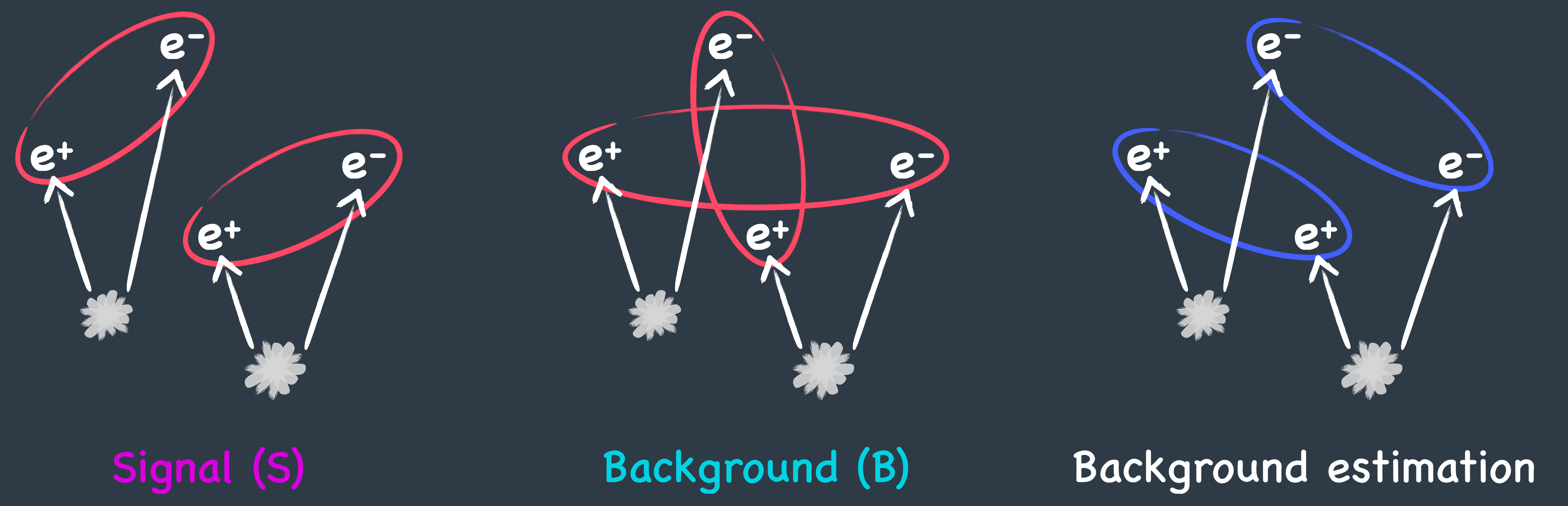

- **ULS**: unlike-sign pairs from same event N_{+-}^{same} → **ULS** = **S** + **B**
- **LS**: like-sign pairs from same event $N_{++,--} = 2 \cdot \sqrt{(N_{++}^{\text{same}} \cdot N_{--}^{\text{same}})}$

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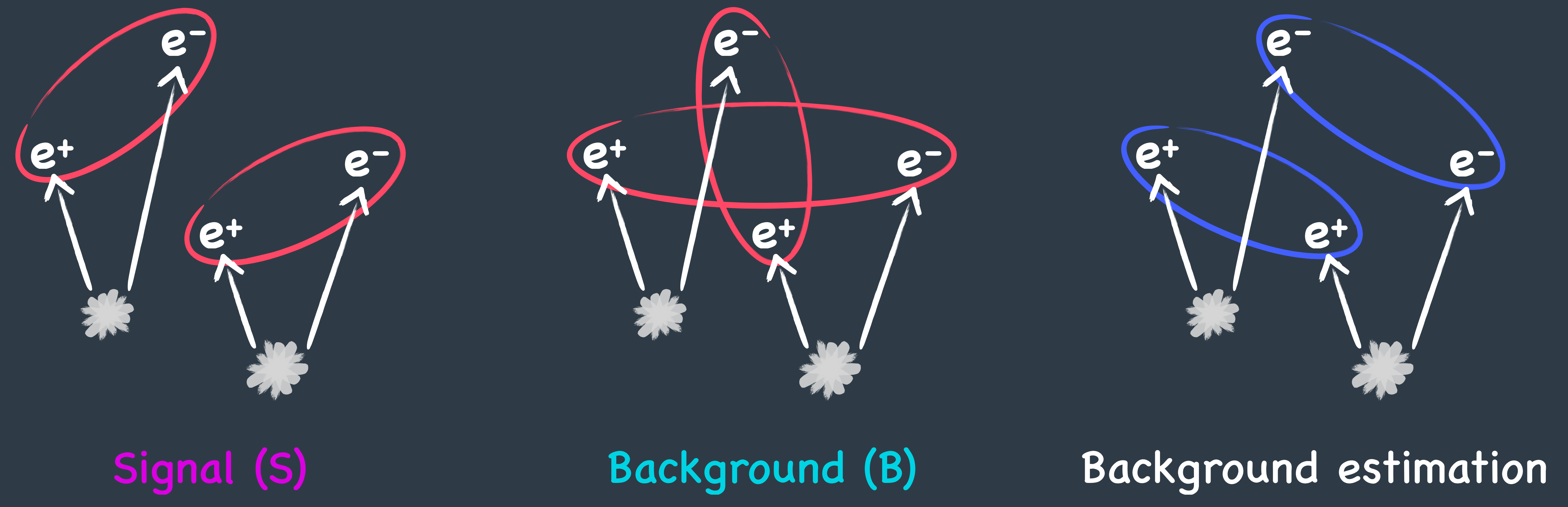

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- **LS**: like-sign pairs from same event $N_{++,--} = 2 \cdot \sqrt{(N_{++}^{\text{same}} \cdot N_{--}^{\text{same}})}$
- **R factor**: $R = N_{+-}^{\text{mix}} / 2 \cdot \sqrt{(N_{++}^{\text{mix}} \cdot N_{--}^{\text{mix}})}$
  Correction for different acceptance of ULS and LS pairs using mixed event ($R = 1 \pm 10^{-3}$) → **B** = **LS** × **R**

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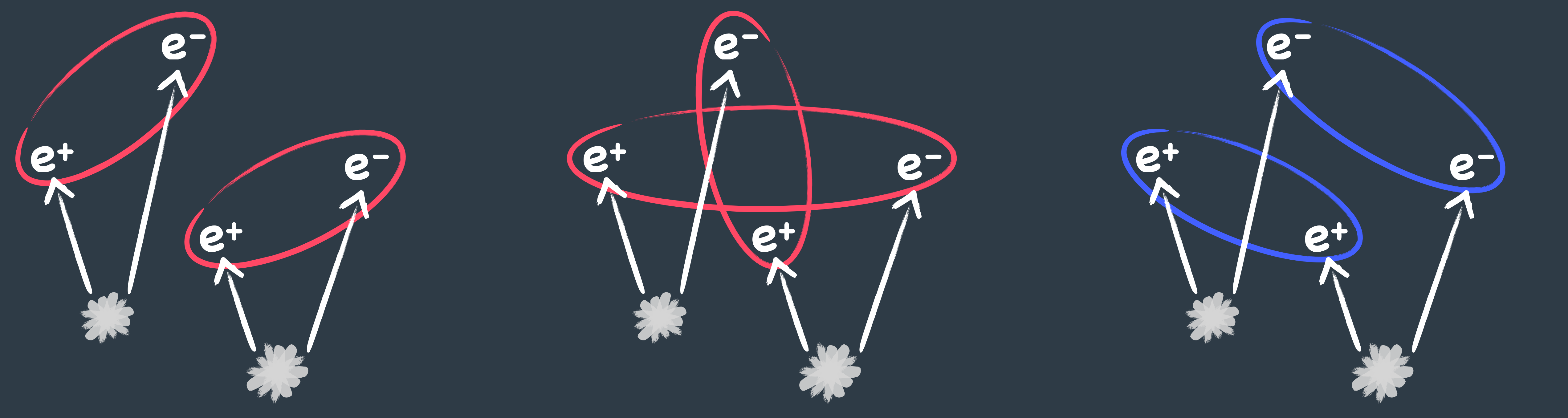

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  Correction for different acceptance of ULS and LS pairs using mixed event ($R = 1 \pm 10^{-3}$) → **B** = **LS** × **R**

→ **S** = **ULS** – **B**

ALICE

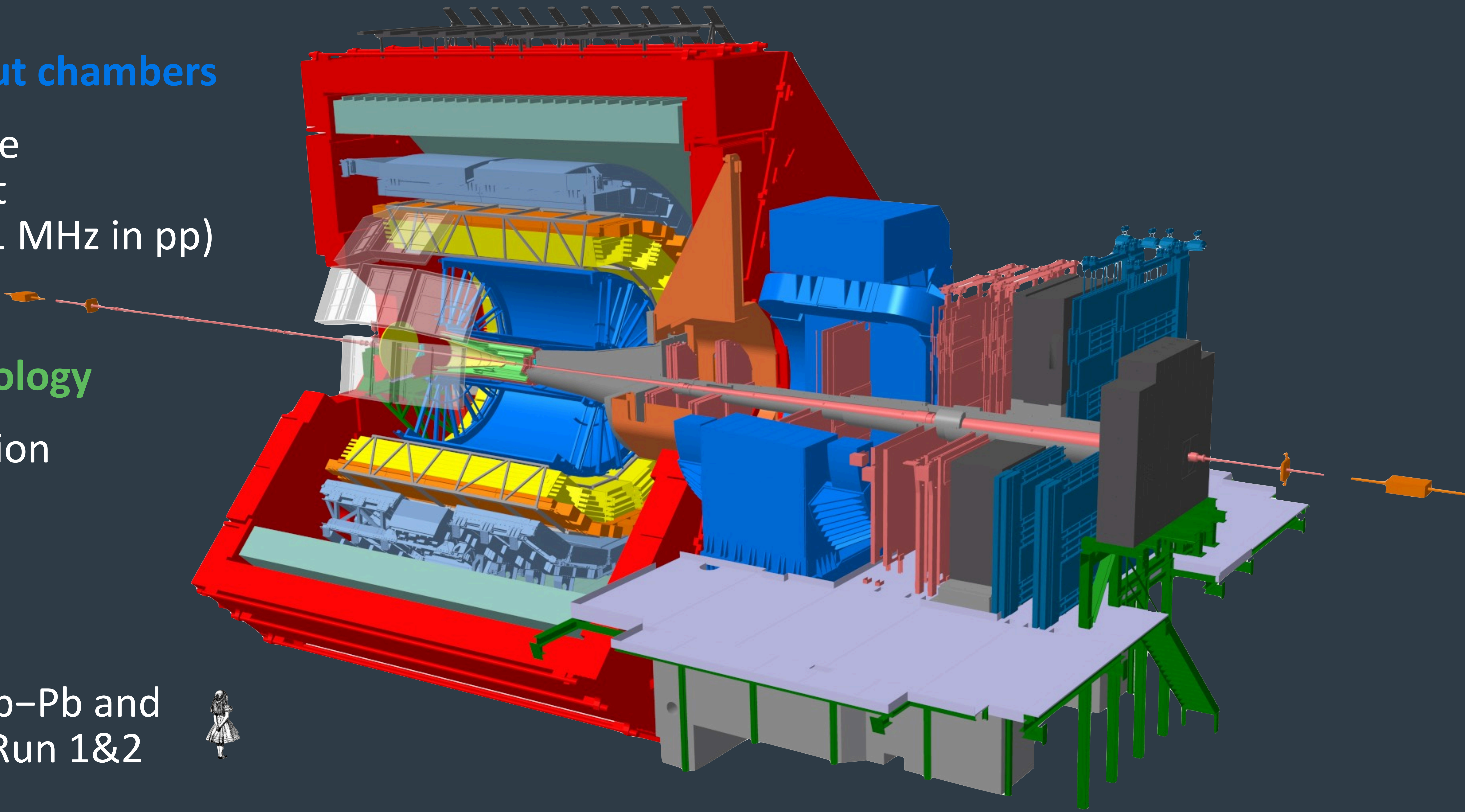
Upgrades for LHC Run 3

- New **TPC GEM-based readout chambers**

  → higher data acquisition rate
  due to continuous readout
  (up to 50 kHz in Pb–Pb & 1 MHz in pp)

- New **ITS CMOS MAPS technology**

  → improved pointing resolution
  and faster readout



2023&2024: factor ~20 more Pb–Pb and
~1000 more pp events than in Run 1&2