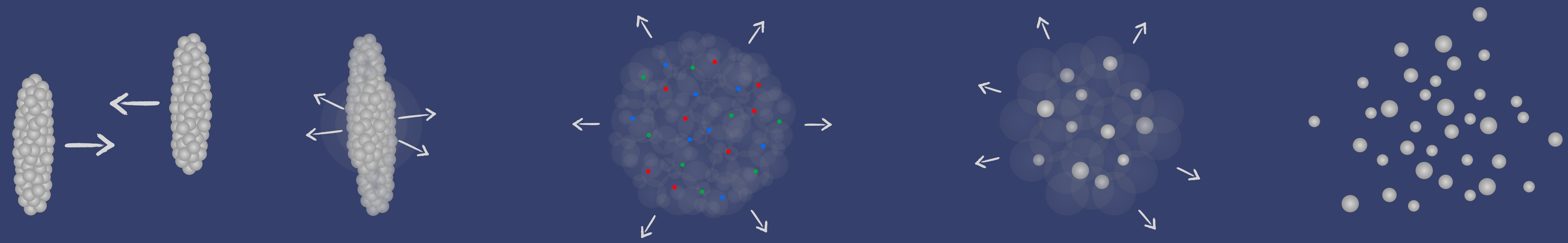
Dielectron production in pp and Pb–Pb collisions with ALICE in Run 3

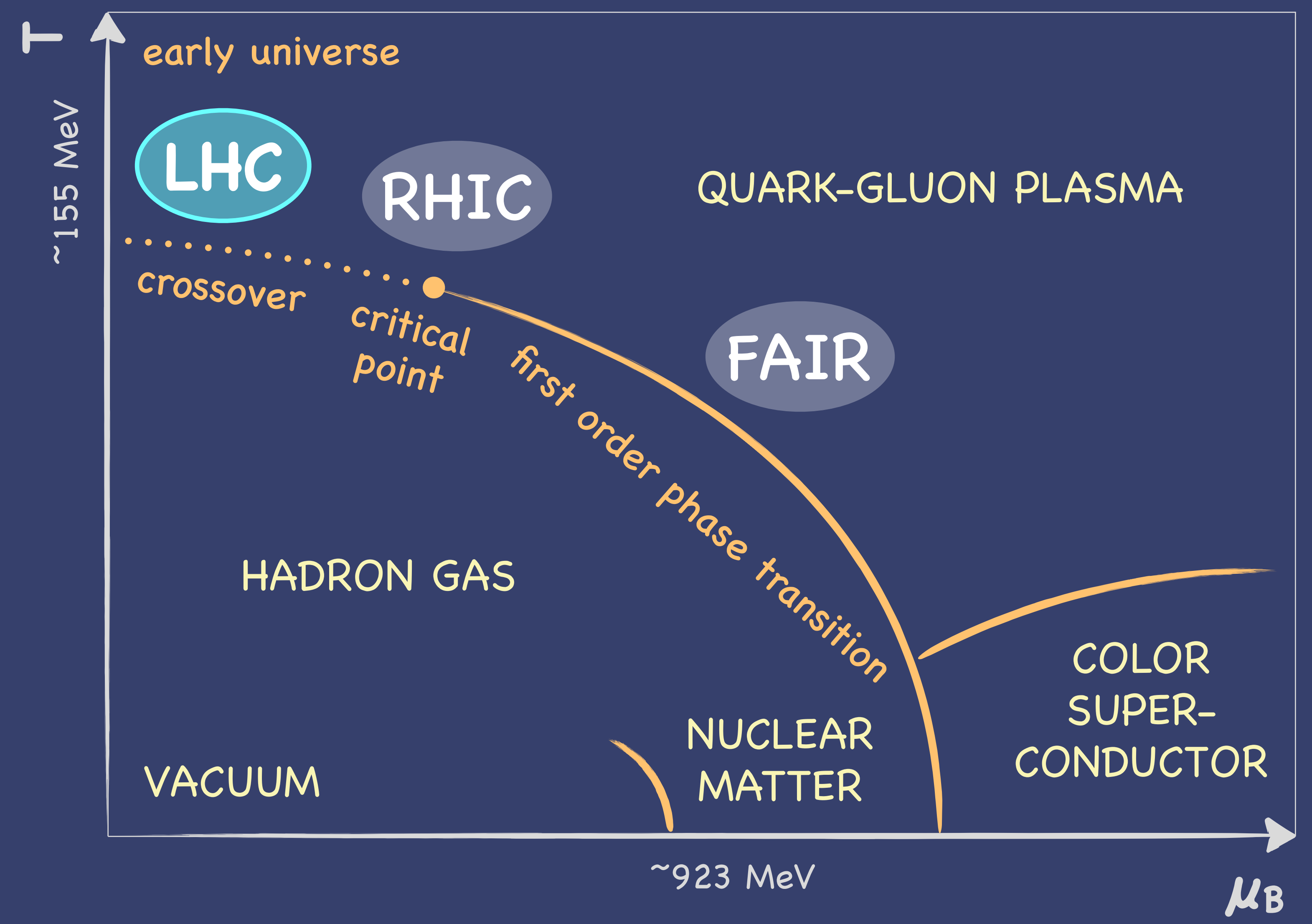
Emma Ege
for the ALICE Collaboration

European Physical Society Conference on High Energy Physics 2025

Motivation

Heavy-Ion Collisions



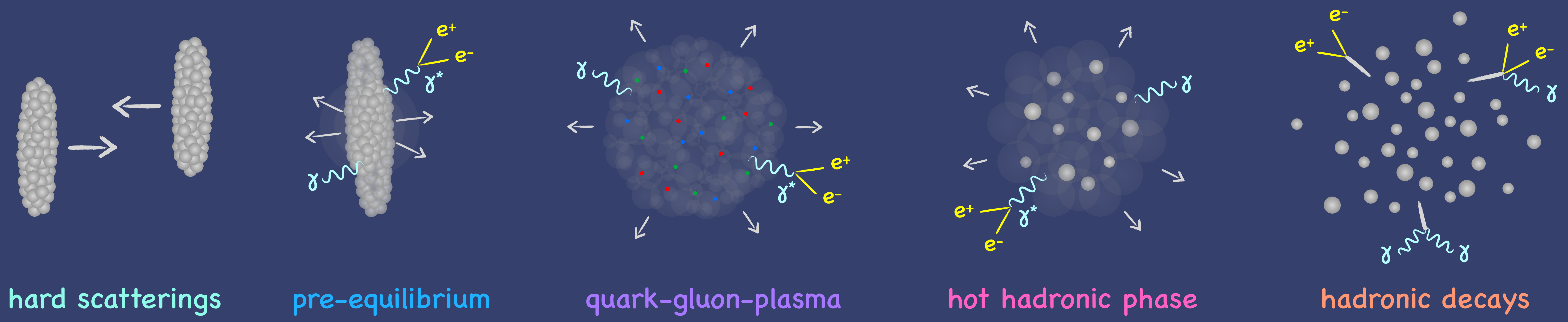


QCD phase diagram of strongly-interacting matter:
temperature T vs baryochemical potential μ_B

- Ordinary matter confined at low temperatures
- Phase transition to quasi-free state of matter, quark-gluon plasma
  - → similar state expected in early universe
  - → experimentally such high energy densities can be reached in heavy-ion collisions → **LHC**: high T & low μ_B

Motivation

Dielectrons in Heavy-Ion Collisions



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

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

- Created in all stages of the collision
- Do not interact strongly (no final-state interactions)
- Keep information about the medium at the time of their production

Motivation

Dielectrons in Heavy-Ion Collisions

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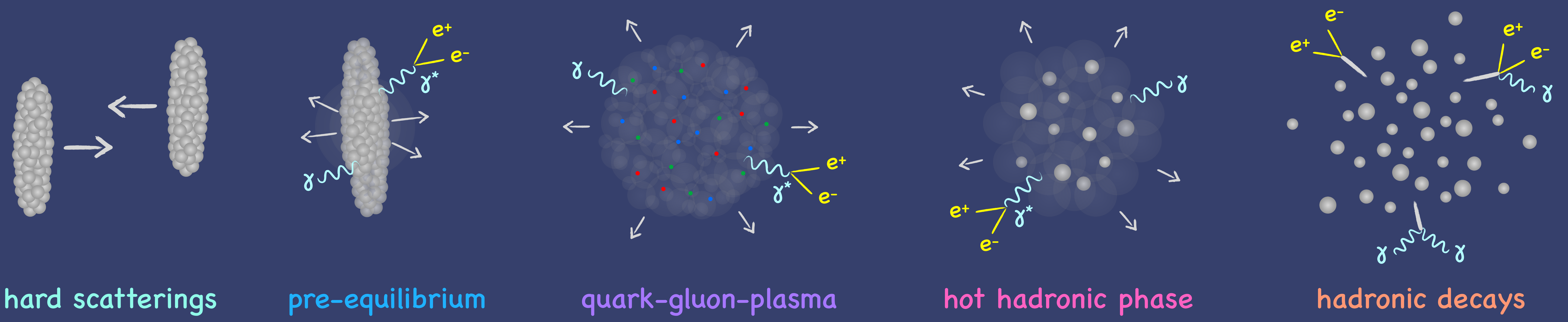


Heavy-ion (Pb–Pb) collisions:

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

proton–proton (pp) collisions:

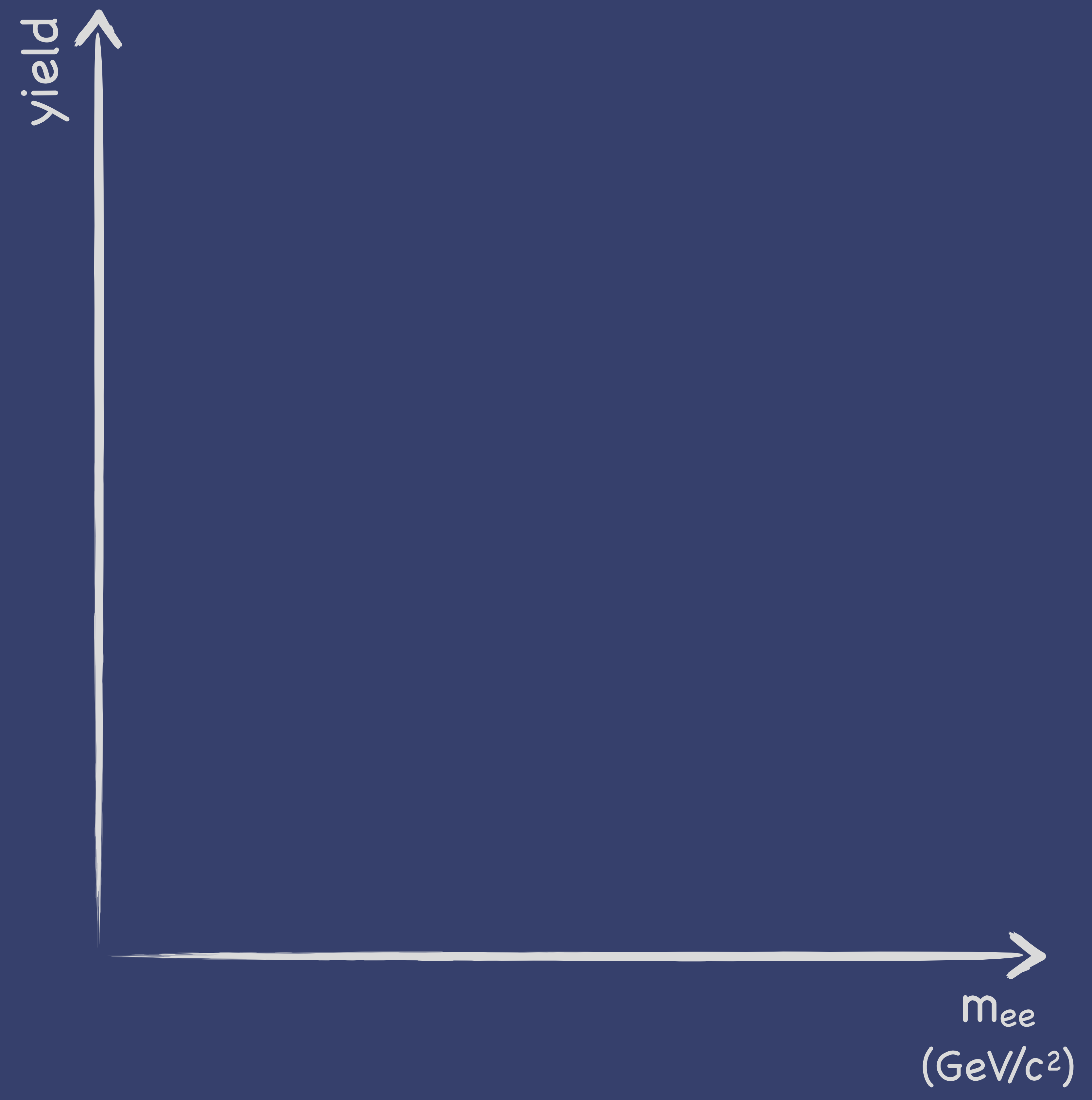
- Vacuum baseline for Pb–Pb studies (heavy flavor, direct photons, Drell–Yan)
- Establish analysis techniques & search for new physics (onset of thermal radiation?)

Motivation

Dielectron Spectrum in Heavy-Ion Collisions

ALICE

Composition of the dielectron spectrum:



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Dielectron Spectrum in Heavy-Ion Collisions

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Composition of the dielectron spectrum:

- Initial stage of the collision:
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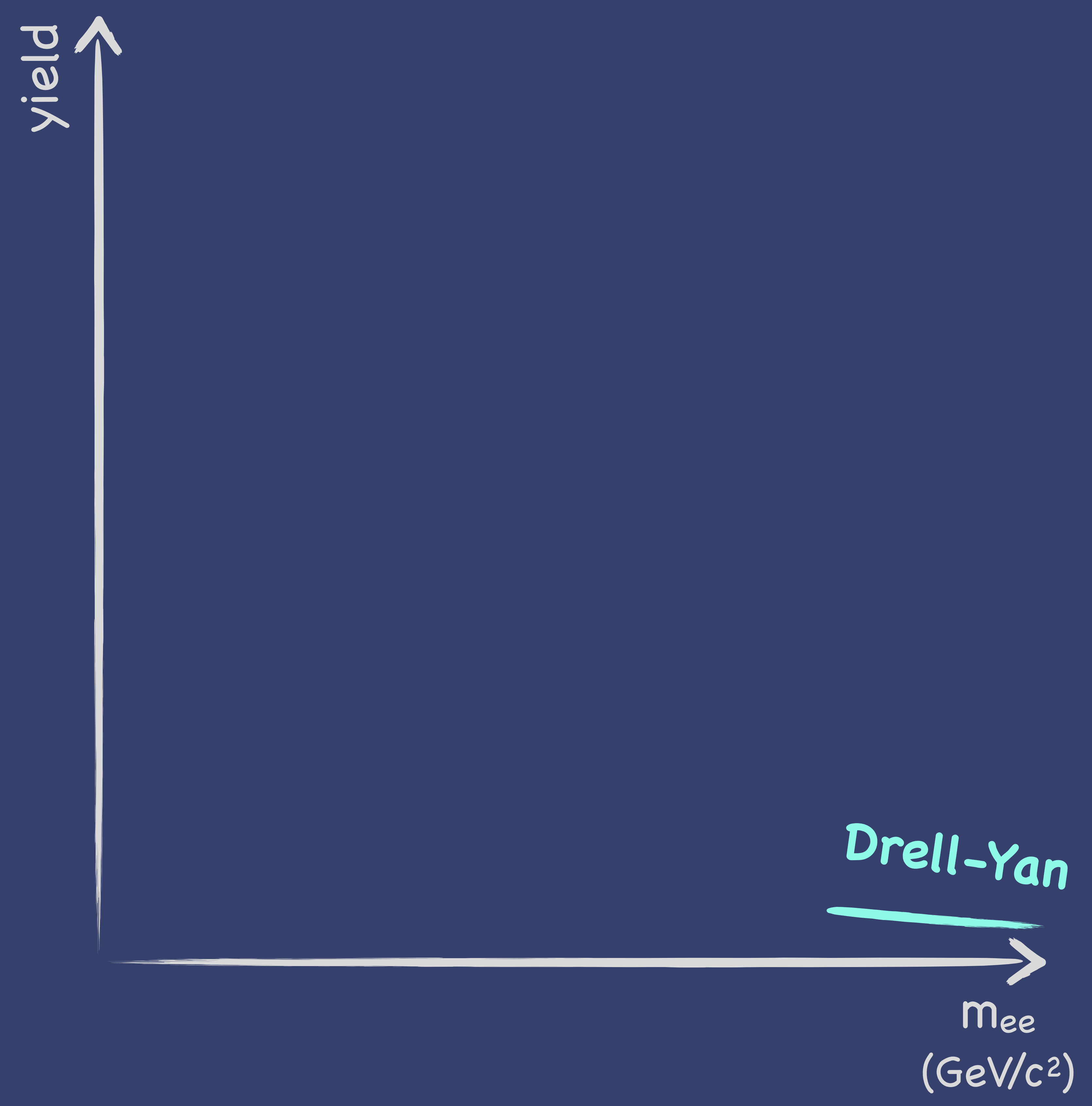

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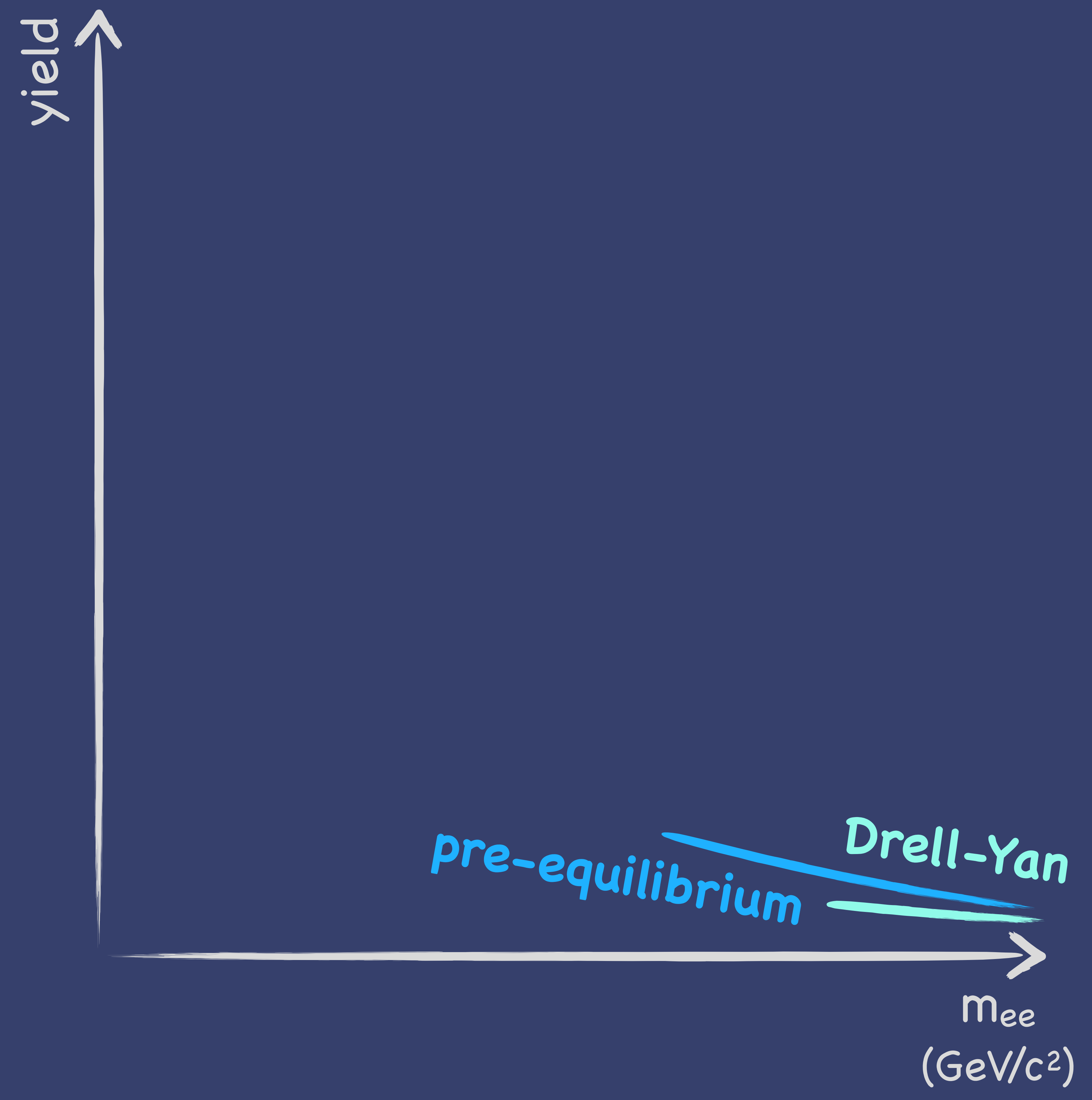

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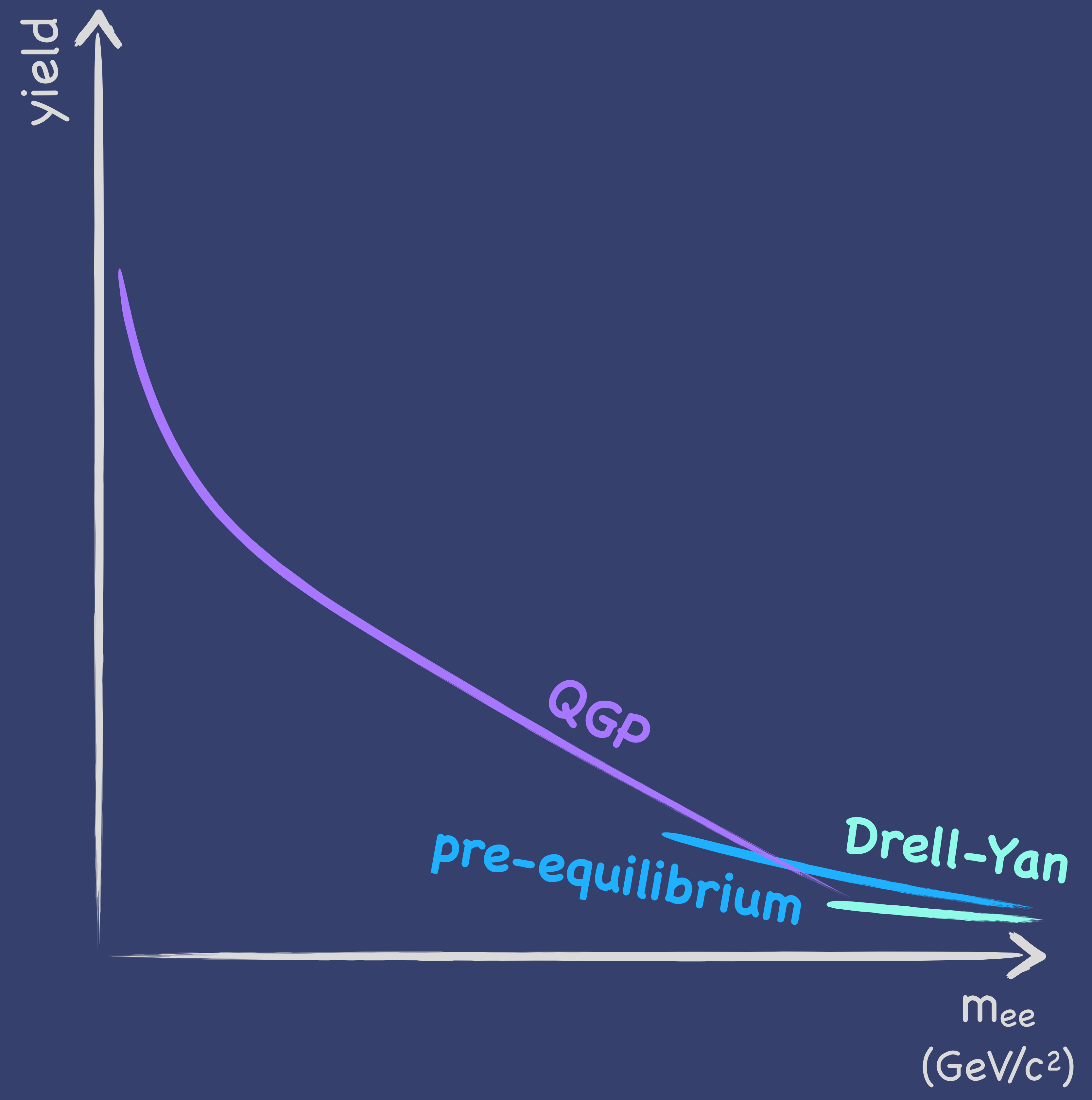

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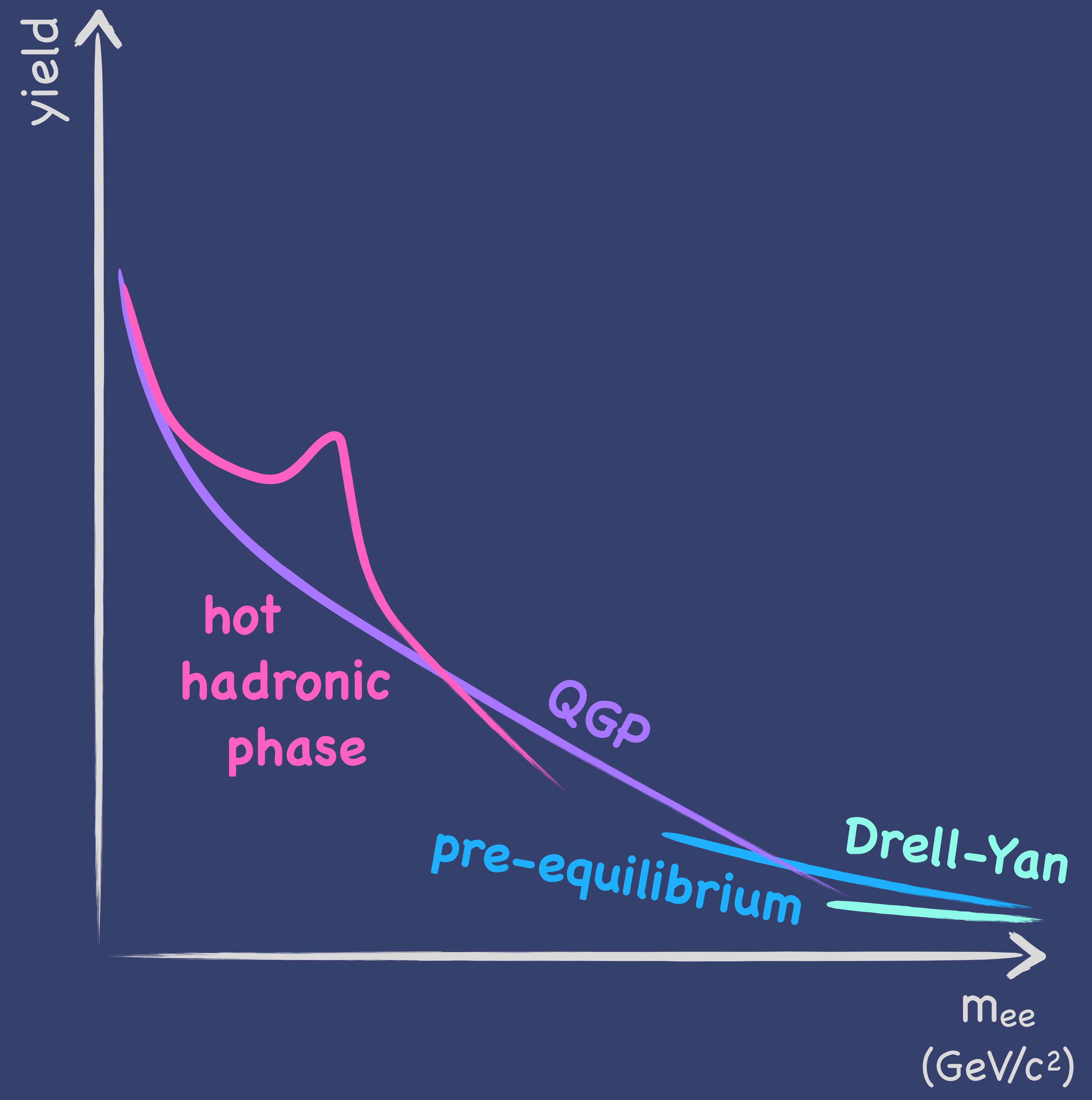

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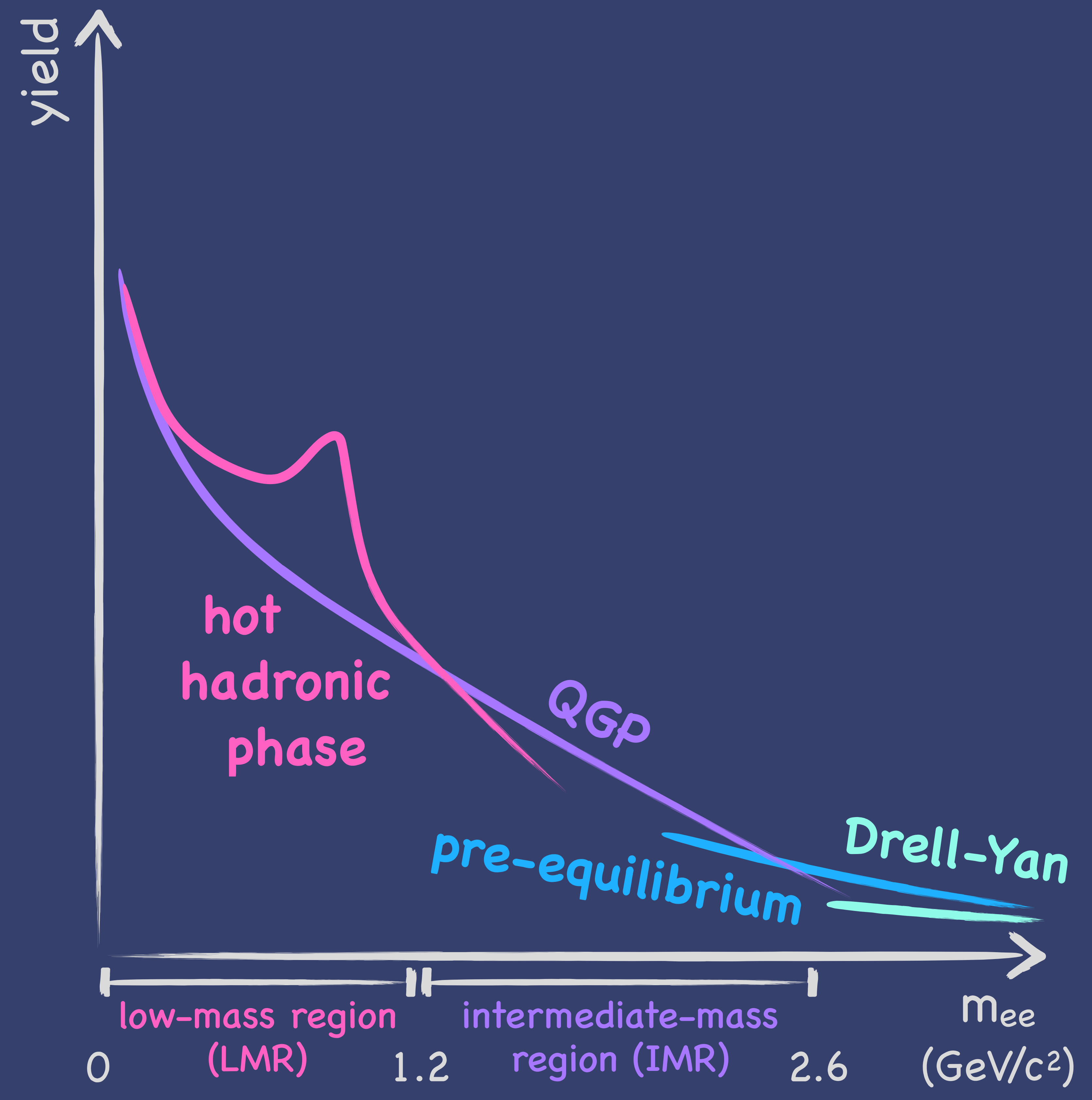
→ separation of collision stages via **invariant mass (m_{ee})**



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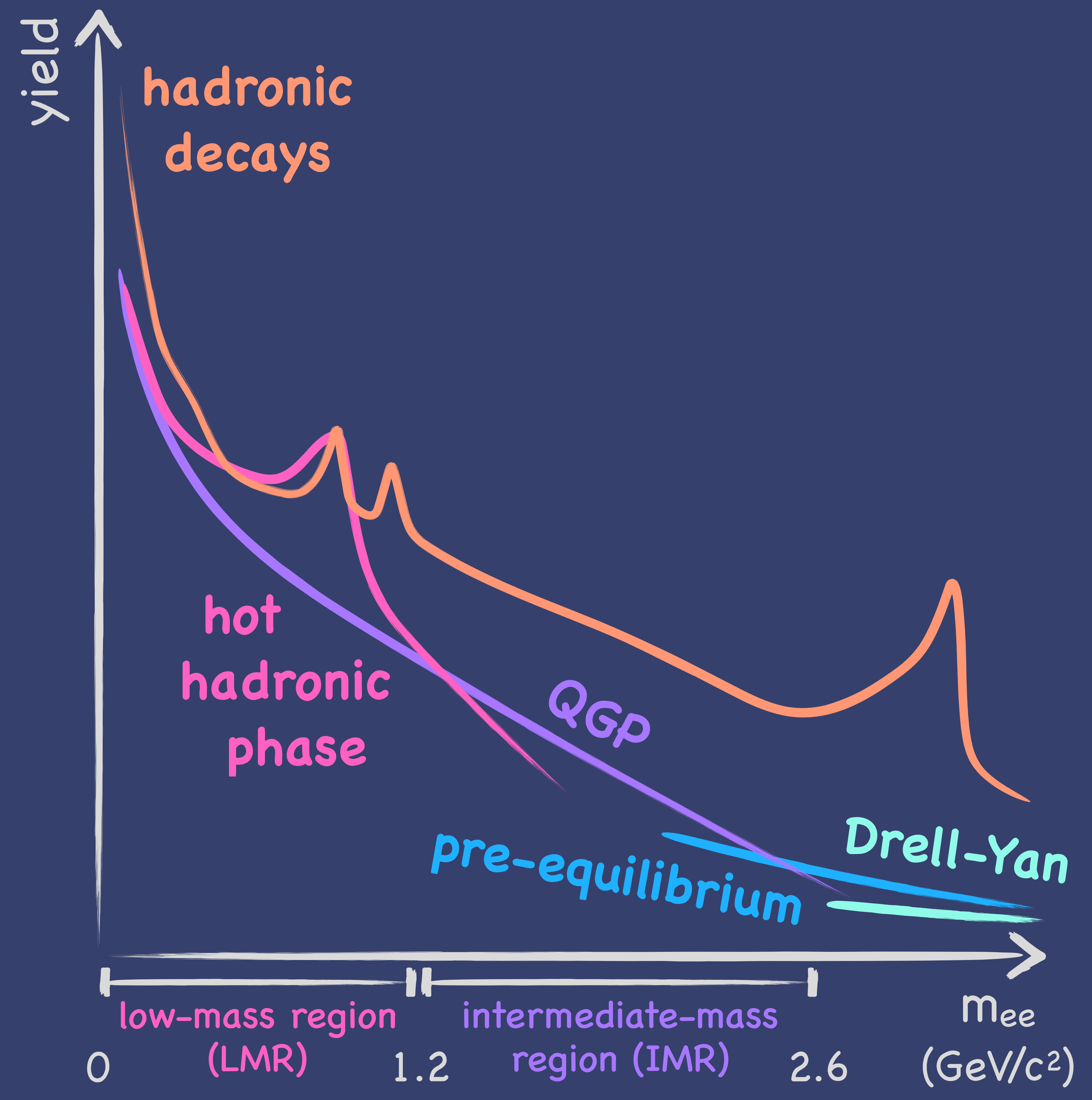
- Large combinatorial & physical backgrounds: **hadronic decays**



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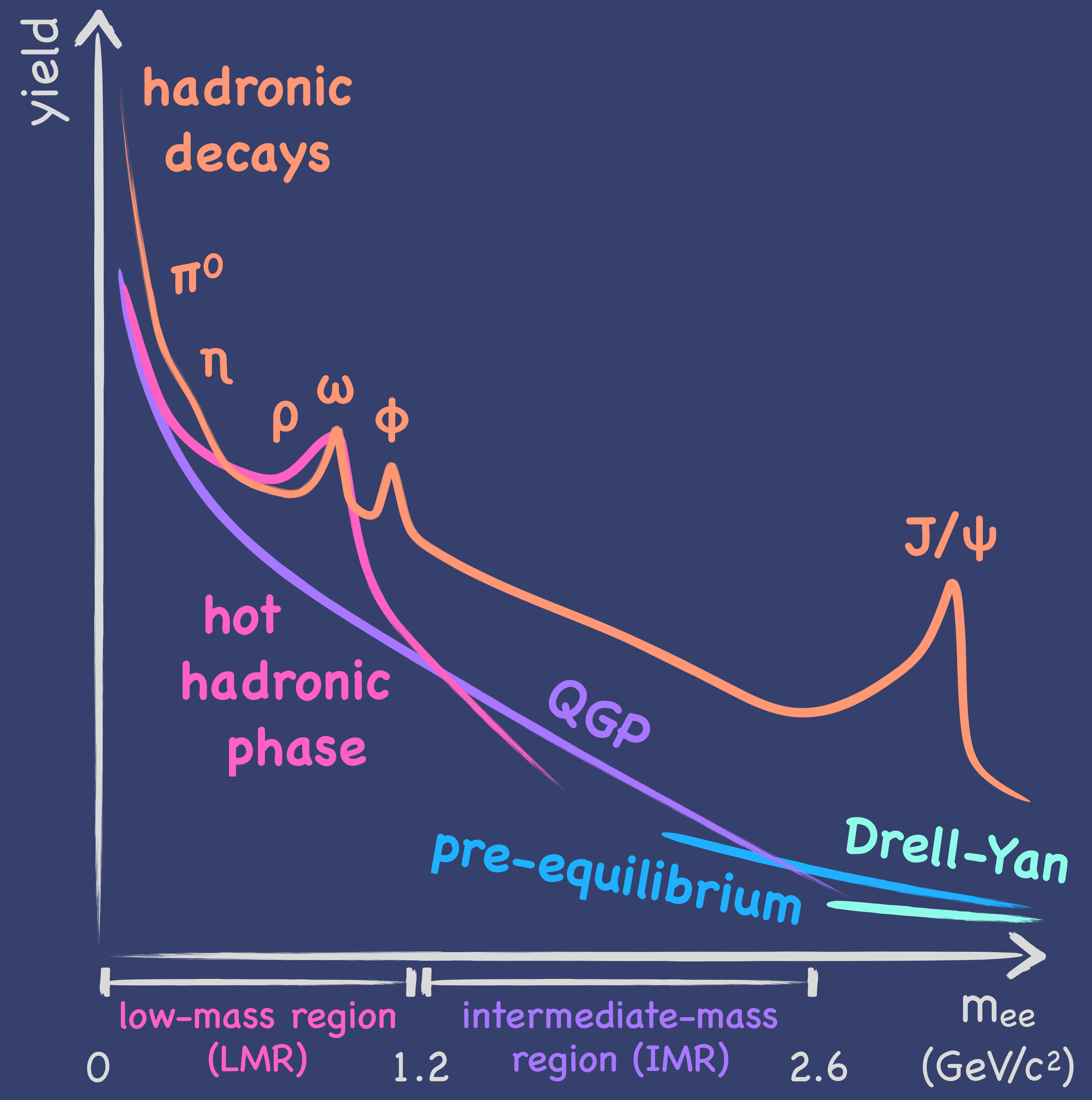

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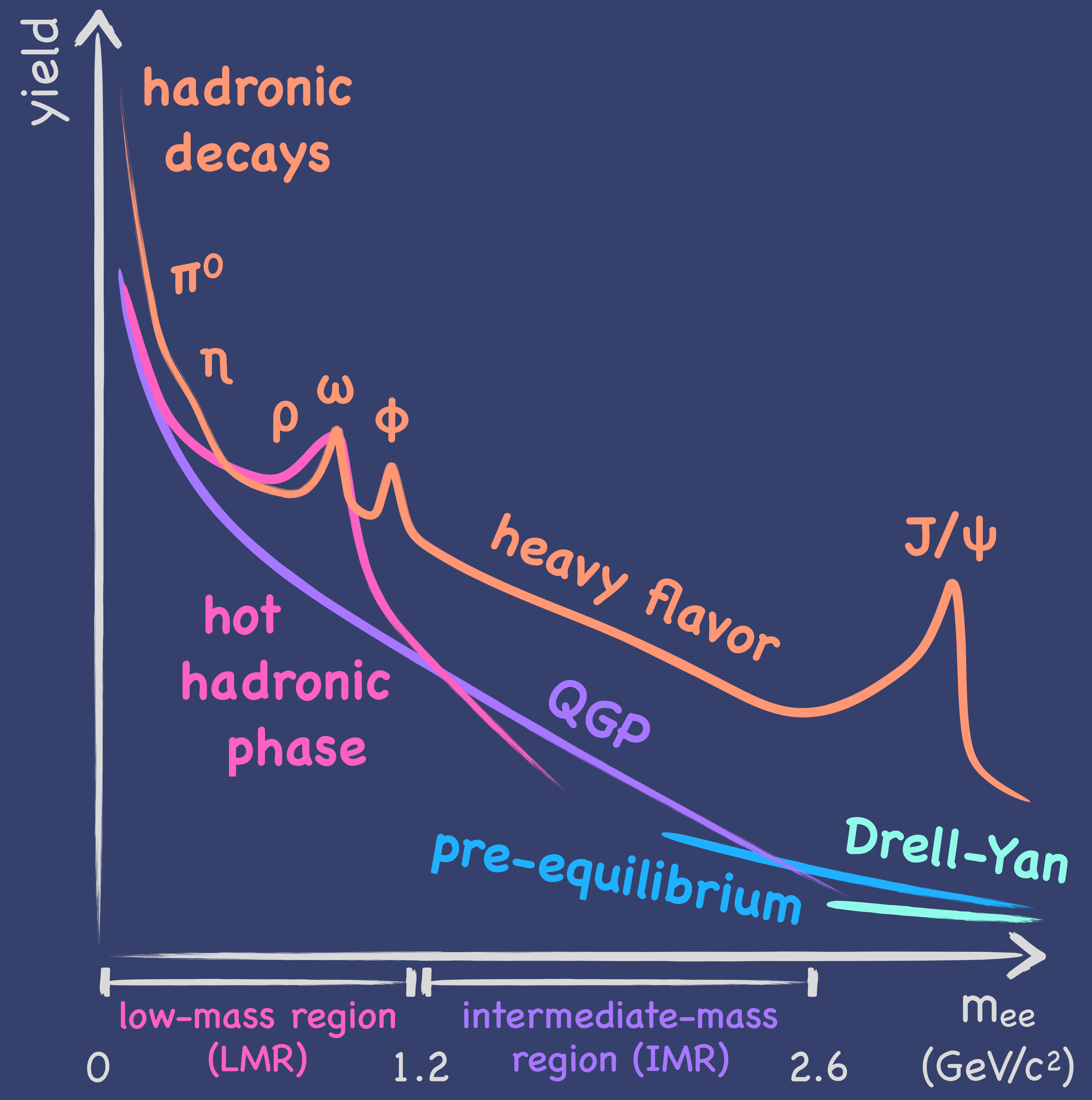

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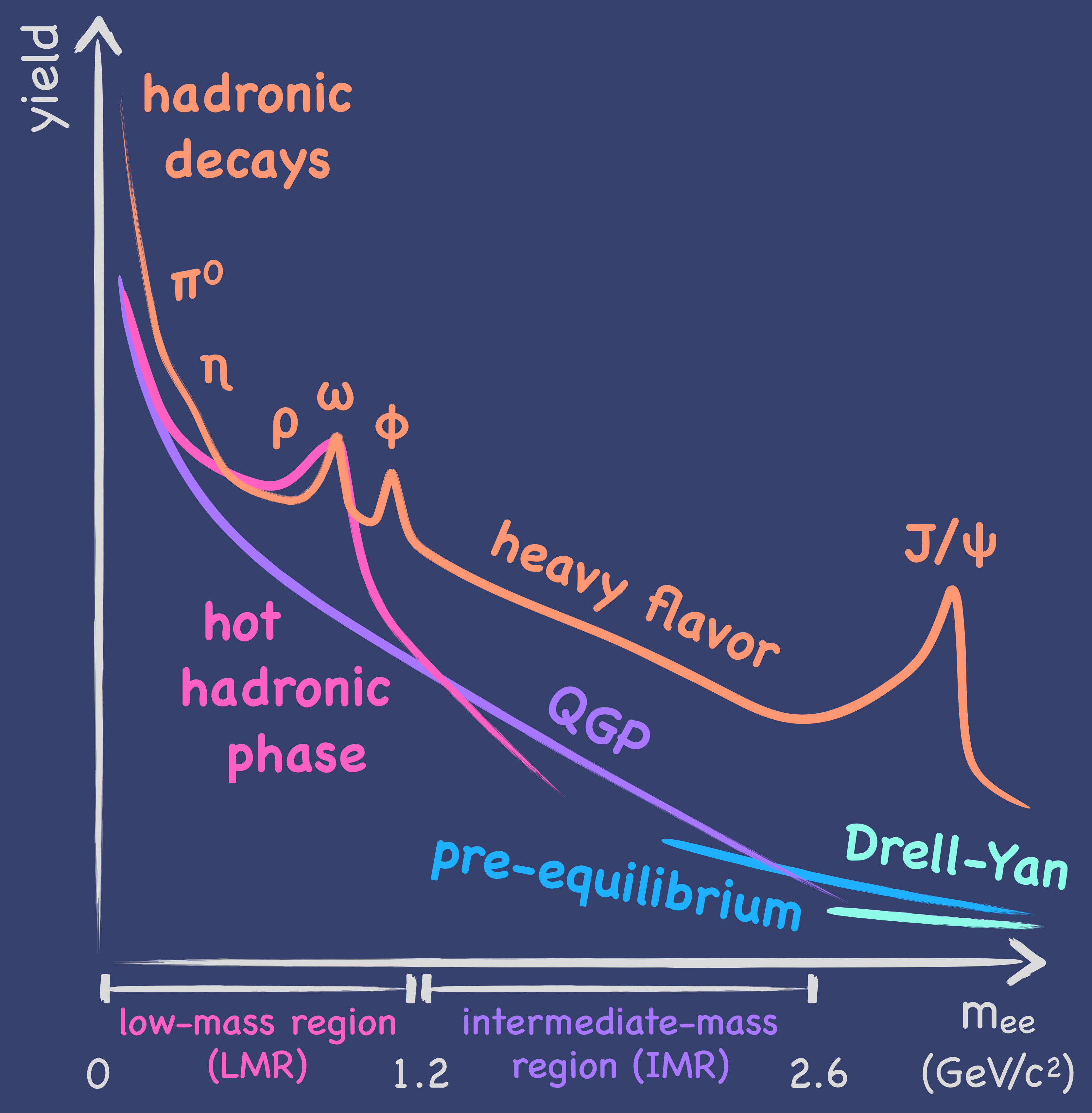
  → requires large statistics & good pointing resolution



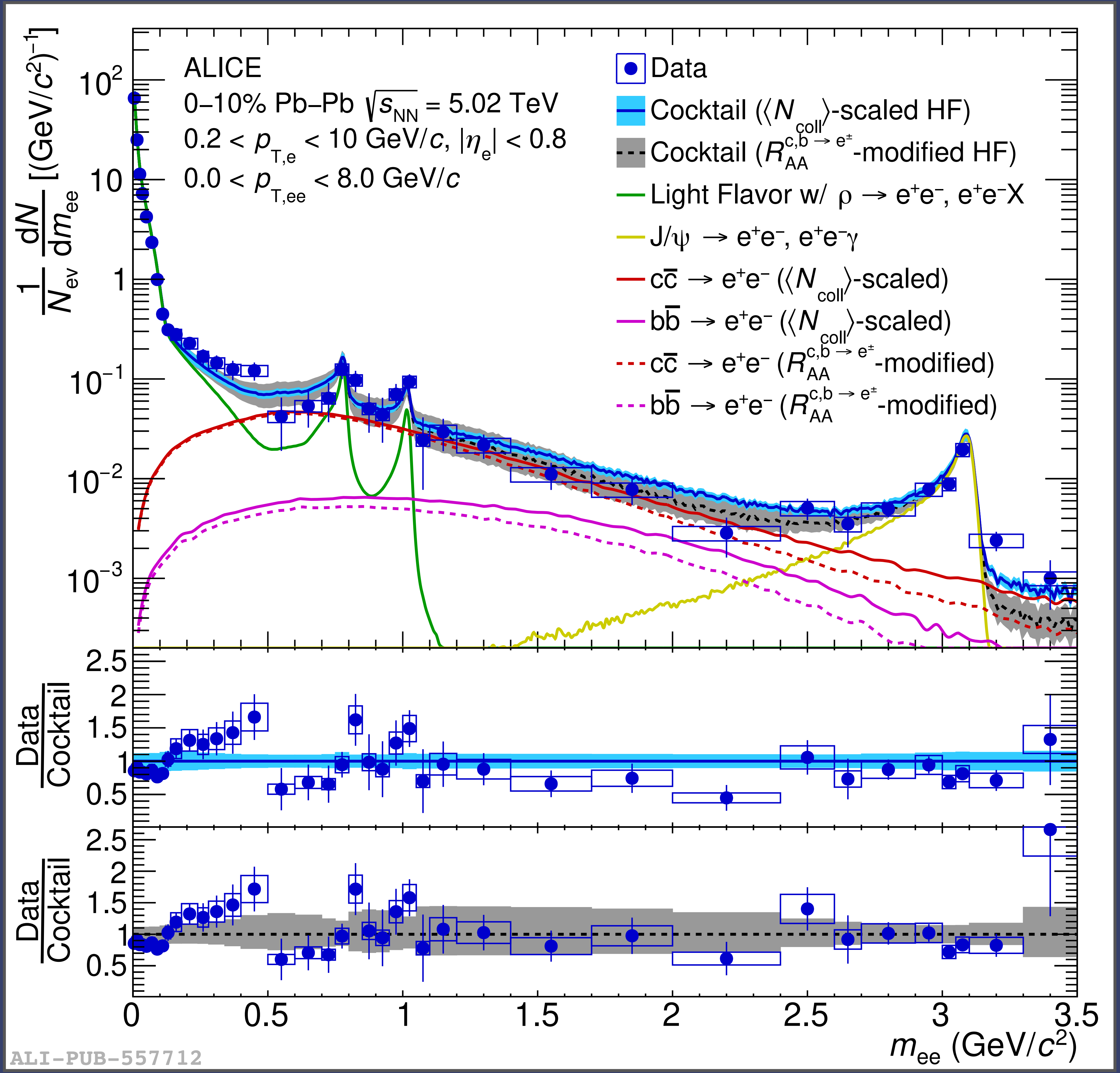
Status from Run 2

Dielectron Production in Pb–Pb collisions

Dielectron spectrum in Pb–Pb collisions in Run 2:

- Hint for modified spectrum, compared to vacuum expectations
- Necessary statistical precision in Run 2 not achieved

Poster „Thermal radiation from small to large systems via low-mass dielectrons with ALICE“ by Ivan Vorobyev



ALICE

Detectors for Dielectron Analysis

Time Projection Chamber (TPC)

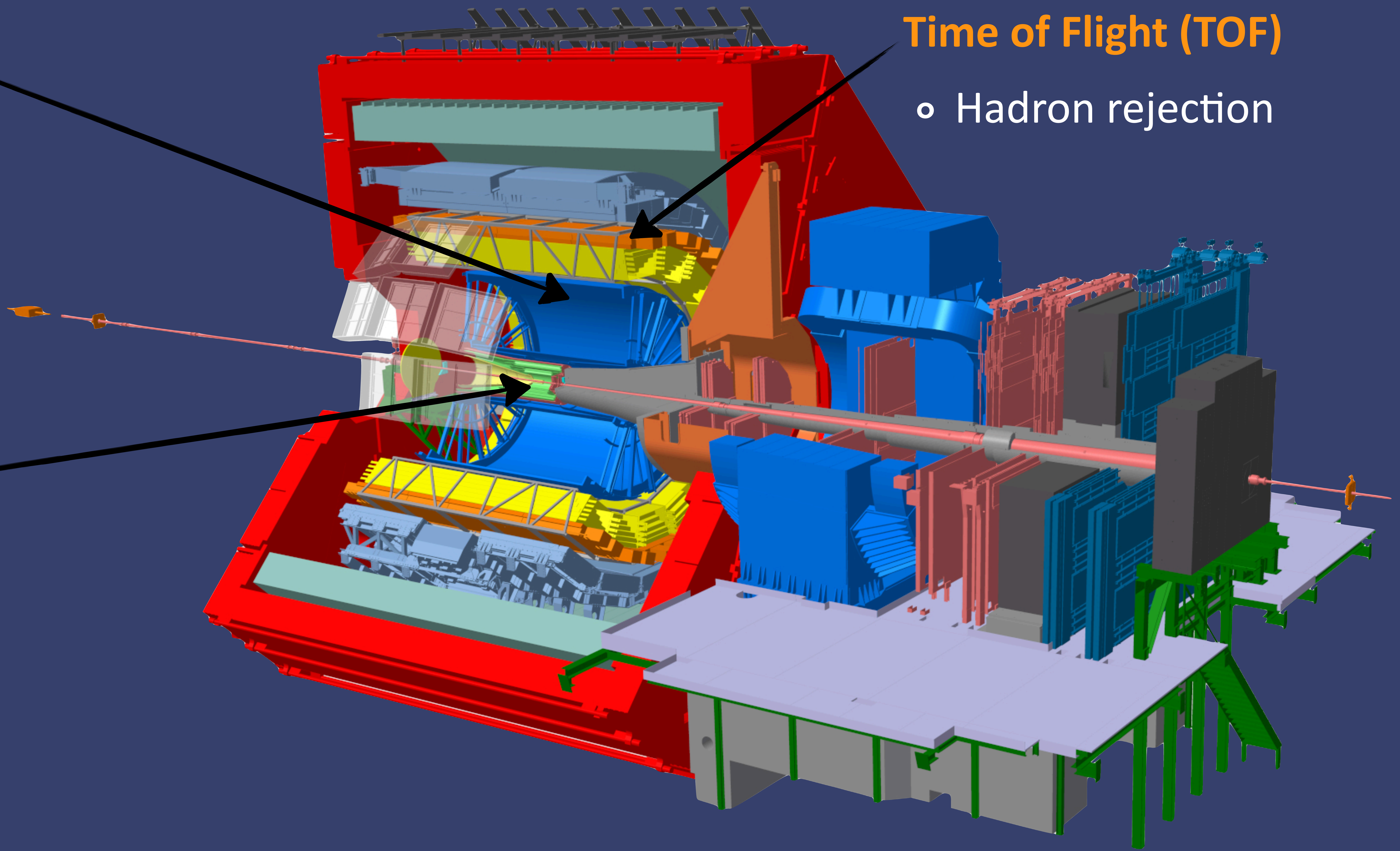
- Tracking & electron identification

Time of Flight (TOF)

- Hadron rejection

Inner Tracking System (ITS)

- Tracking, vertex determination & photon conversion rejection



ALICE

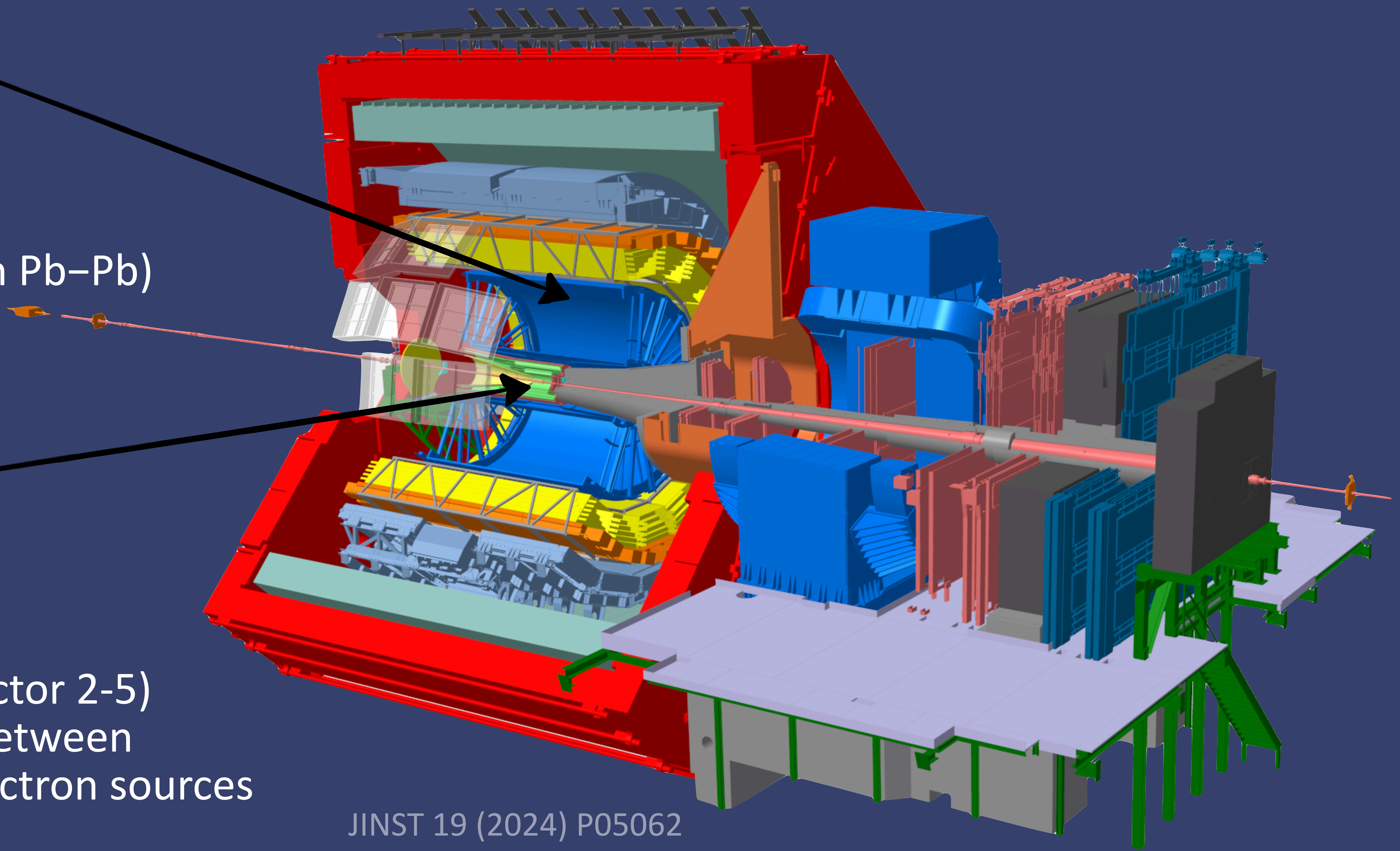
Upgrades for LHC Run 3

Time Projection Chamber (TPC)

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

Inner Tracking System (ITS2)

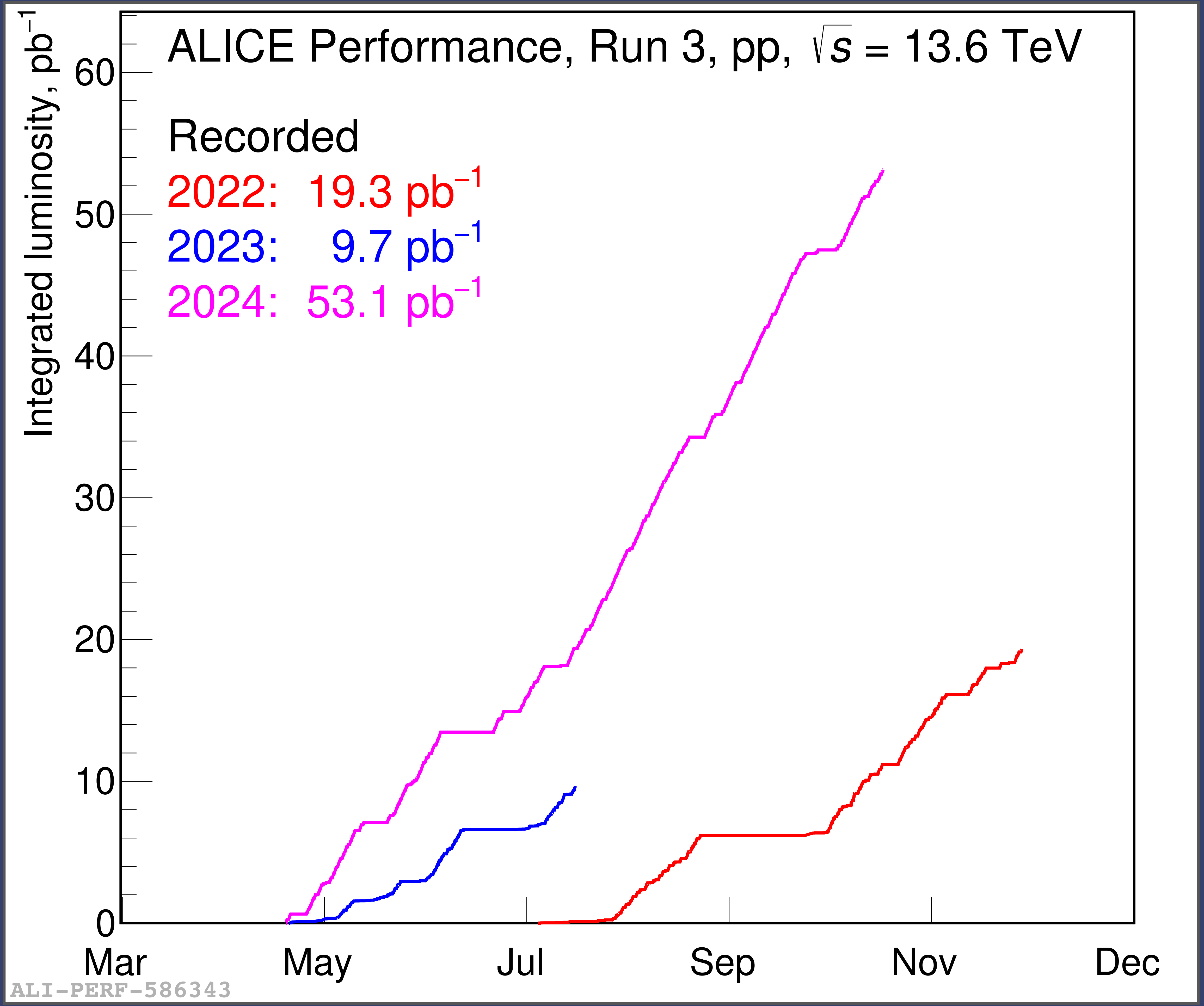
- New CMOS MAPS technology
  → faster readout and
  improved pointing resolution (factor 2-5)
    → improved separation power between
    prompt and non-prompt dielectron sources



JINST 19 (2024) P05062

Run 3 pp

Dataset



Run 3 ($\sqrt{s}$ = 13.6 TeV):

- 2022: $\mathcal{L}_{int}$ = 1 pb^{-1} analyzed luminosity
  → **58·10^{9} minimum-bias events**
- 2023: $\mathcal{L}_{int}$ = 4.17 pb^{-1} analyzed luminosity
  → **277·10^{9} minimum-bias events**

Run 2 ($\sqrt{s}$ = 13 TeV):

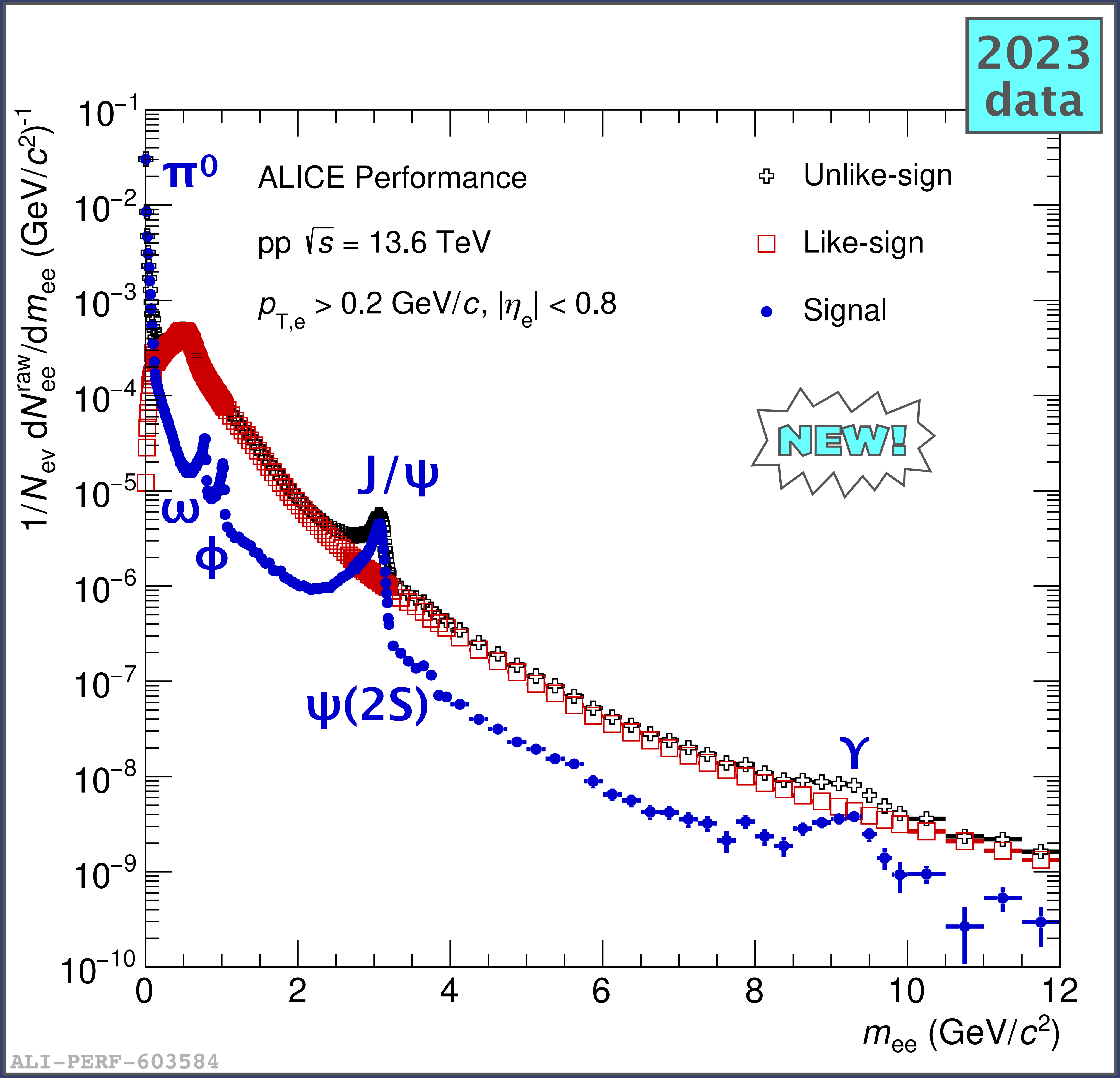
- $\mathcal{L}_{int}$ = 7.87 nb^{-1} analyzed luminosity
  → **455·10^{6} minimum-bias events**
  (Phys. Lett. B 788 (2019) 505 & Phys. Lett. B 868 (2025) 139645)

→ **factor ~600** more statistics analyzed

Run 3 pp

Raw Dielectron Yield

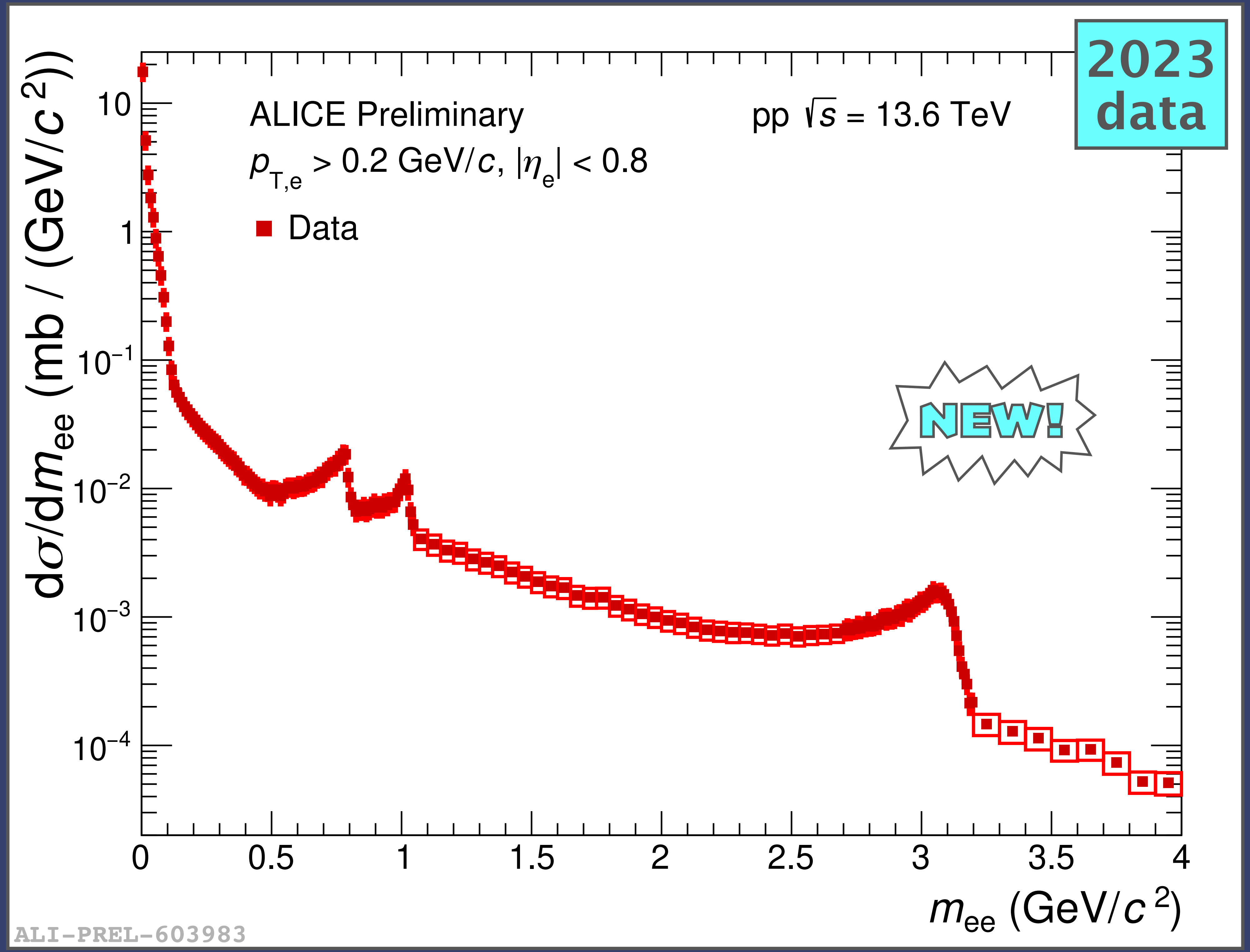
- Spectrum shows all key features of resonances
- Large statistics allows to extract dielectron signal up to Υ mass
- High statistical precision due to upgraded ALICE detector



Run 3 pp

Corrected Dielectron Spectrum

First corrected dielectron spectrum in Run 3



Run 3 pp

Corrected Dielectron Spectrum

ALICE

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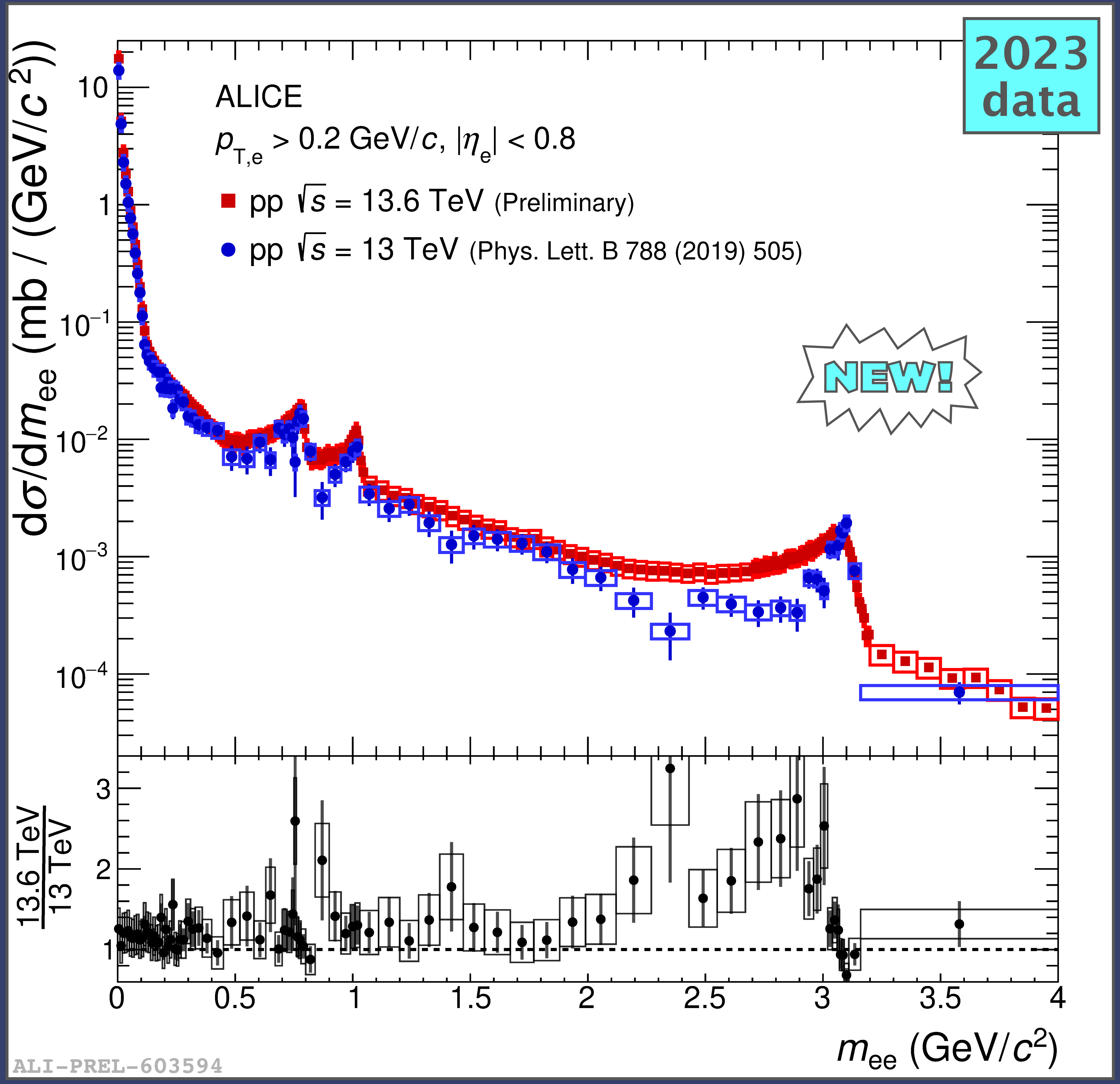
- Run 2 and Run 3 results in agreement within current uncertainties (for $m_{ee} < 2$ GeV/c^2)



Run 3 pp

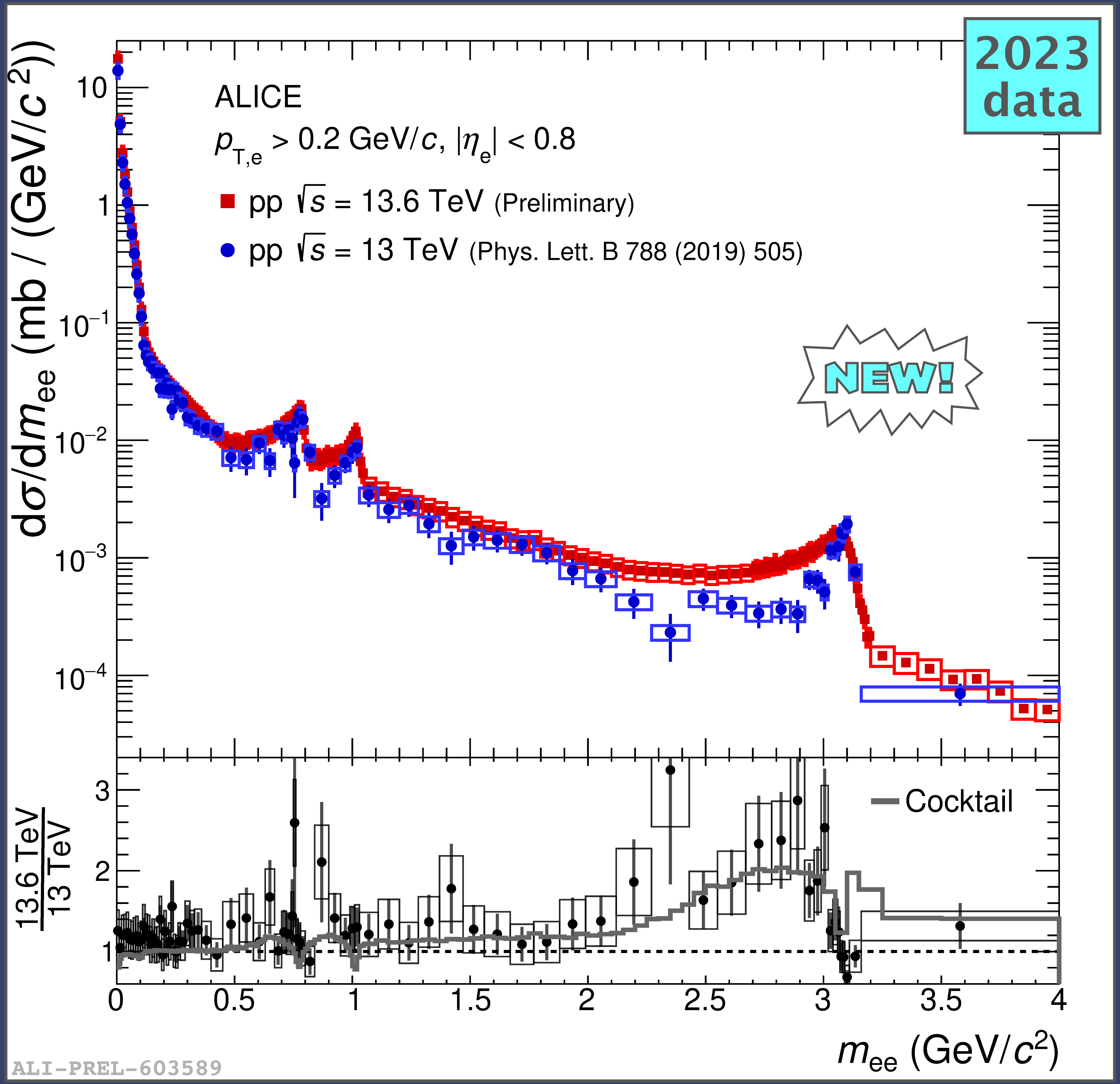
Corrected Dielectron Spectrum

ALICE

First corrected dielectron spectrum in Run 3

- Run 2 and Run 3 results in agreement within current uncertainties (for $m_{ee} < 2$ GeV/c^2)
- Different material budget due to upgraded detectors
  - Larger bremsstrahlung tails in Run 3 data

    → overall described by full simulation of hadronic decays (cocktail)



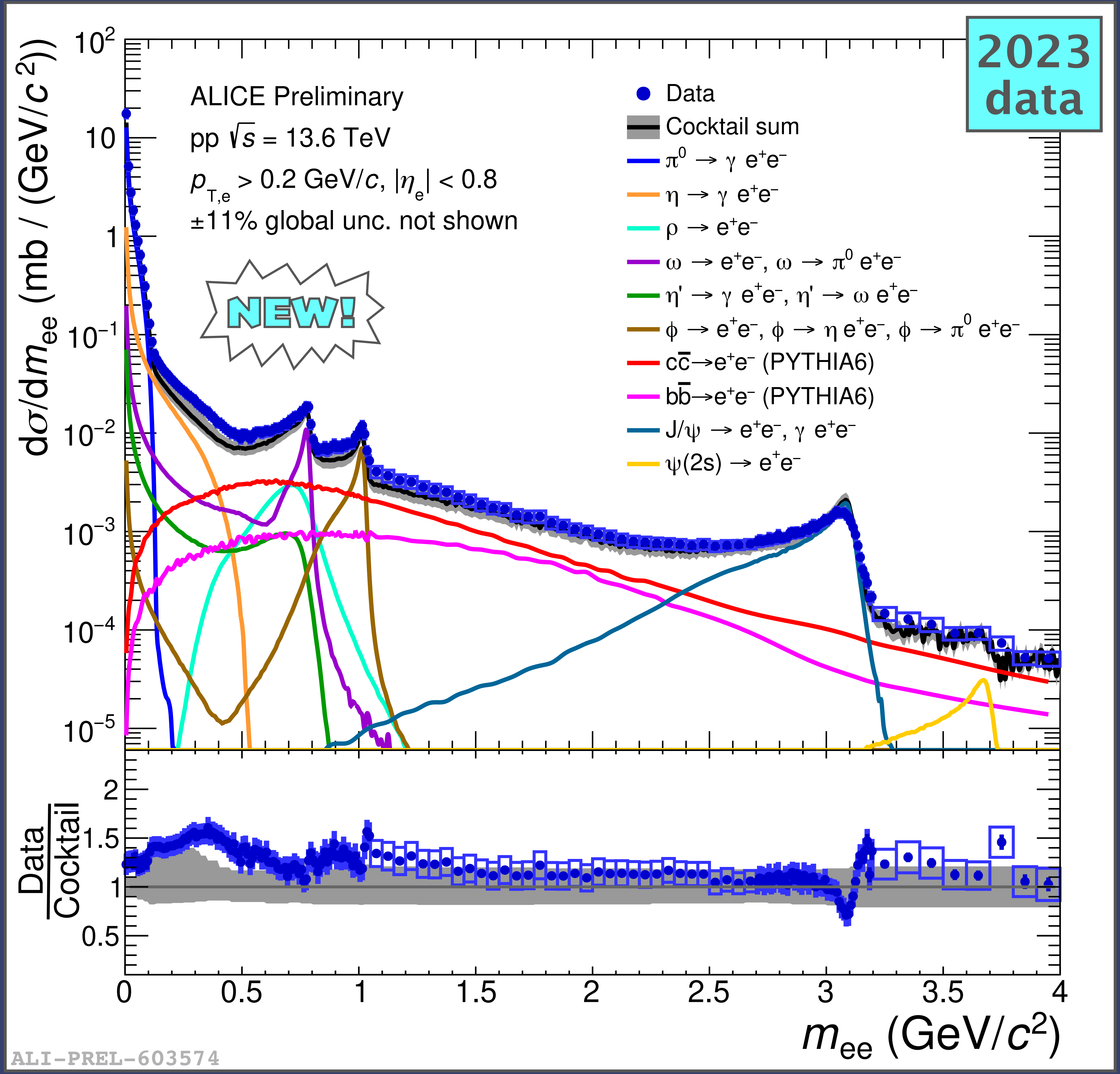
Run 3 pp
Dielectron Cross Section

First dielectron cross section in Run 3 with comparison to hadronic cocktail

Cocktail of expected dielectron sources:

- LF: measured hadron spectra from pp at 13 TeV
- HF: PYTHIA calculations fitted to dielectron results in pp at 13 TeV
  - Energy dependence estimated by FONLL calculations
- Applied detector resolution from Run 3

→ overall agreement between cocktail and data



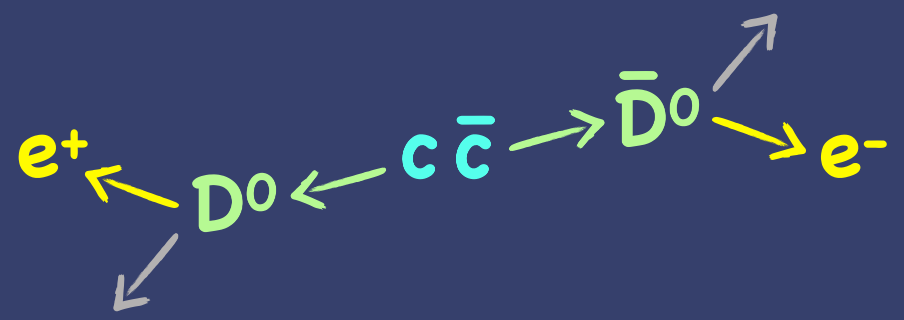
Run 3 pp

Dielectron Cross Section

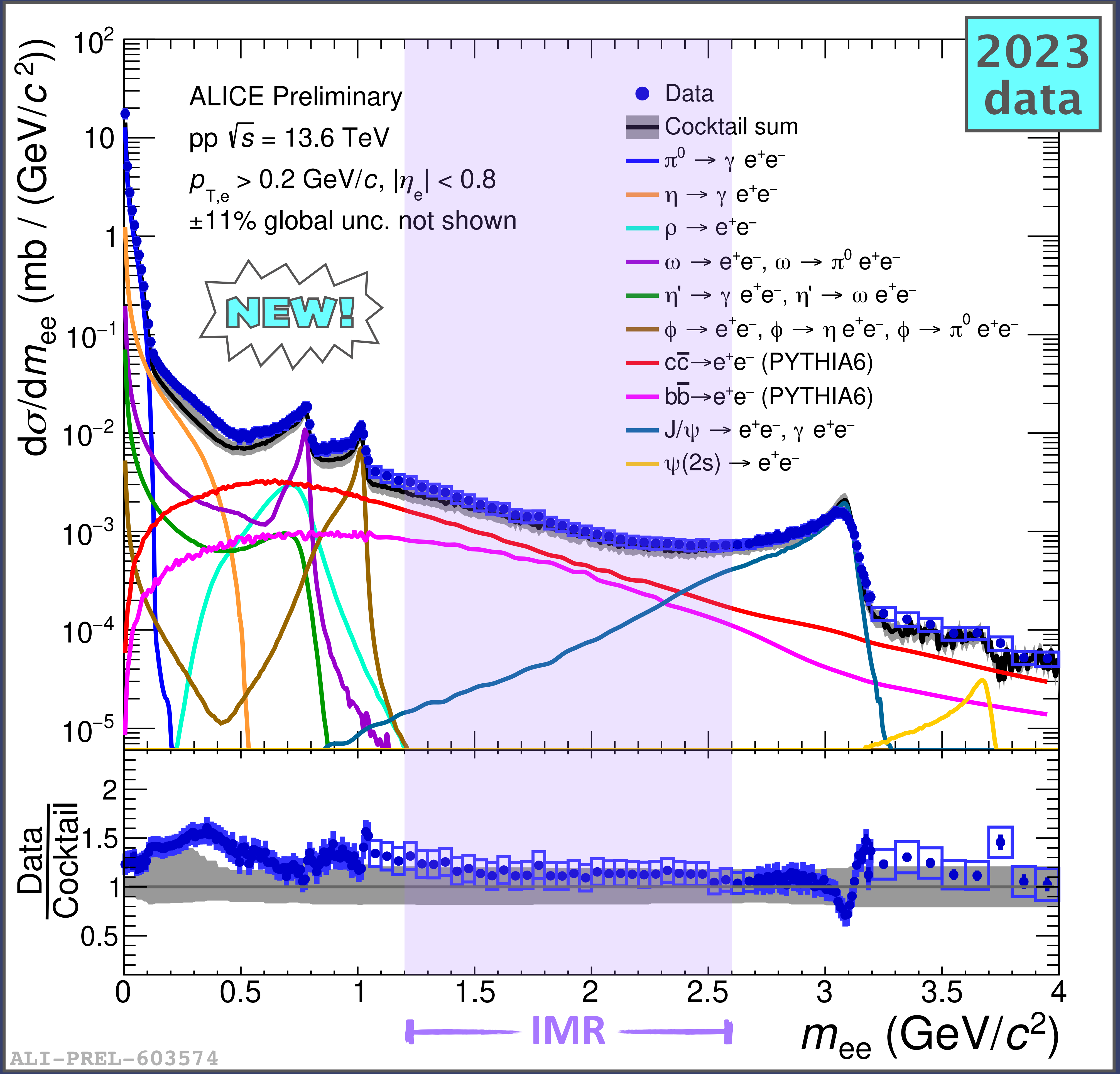
IMR dominated by open heavy-flavor decays

Measurement of prompt sources in the IMR:

- Drell–Yan & thermal radiation
  - Requires high precision of HF sources
    - → very challenging with cocktail method
- Exploit long lifetime of HF-mesons: $c\tau_D$ ~150 µm & $c\tau_B$ ~450 µm
  - → decay length of D and B mesons much larger than that of LF sources



→ unfold spectra through characteristic decay topologies



Topological Separation

Definition

ALICE

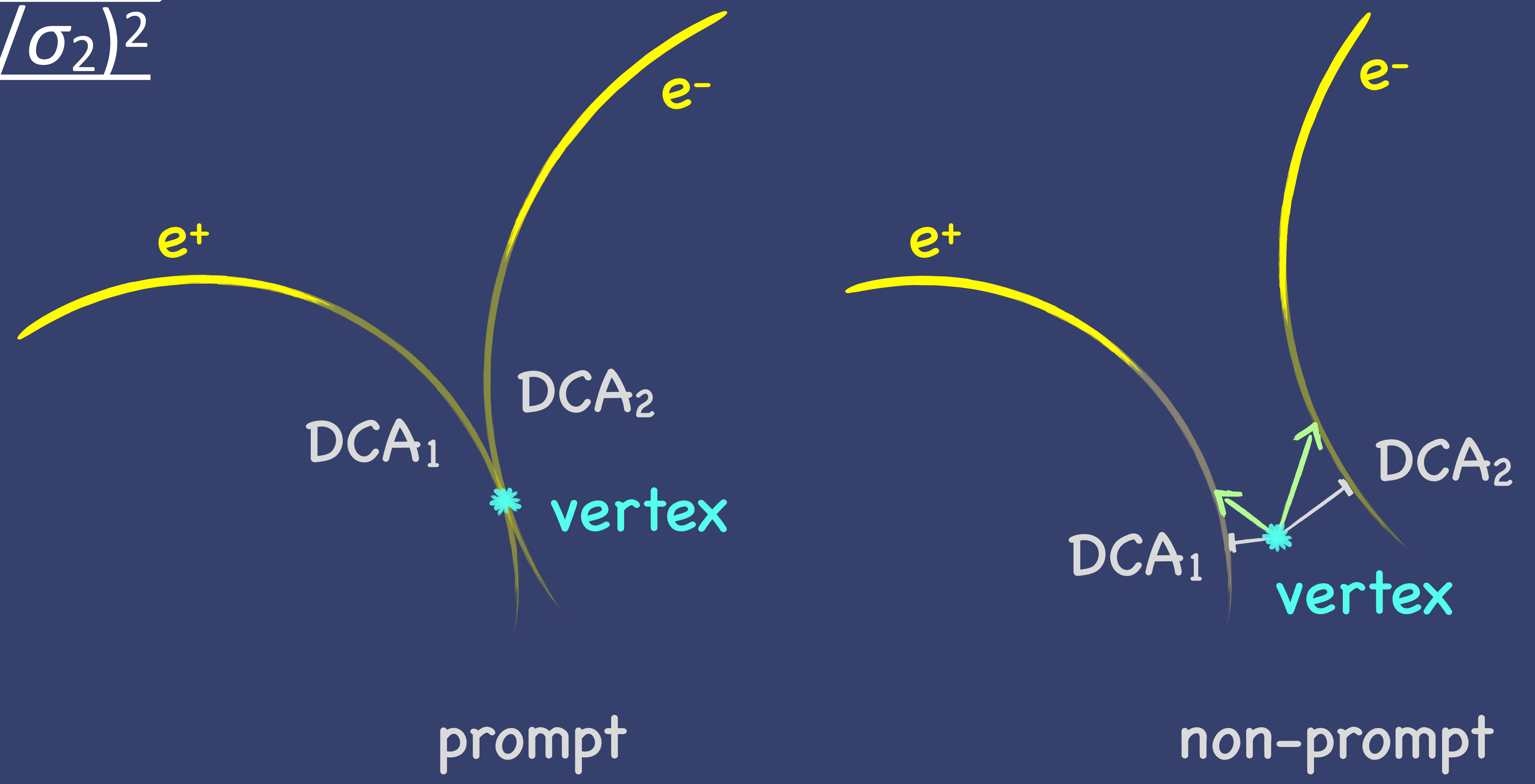
Separation of prompt and non-prompt sources based on their decay topology:

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

- Prompt sources (light flavor, quarkonia & thermal radiation) → small DCA
- Non-prompt decays (heavy flavor) → large DCA

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

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



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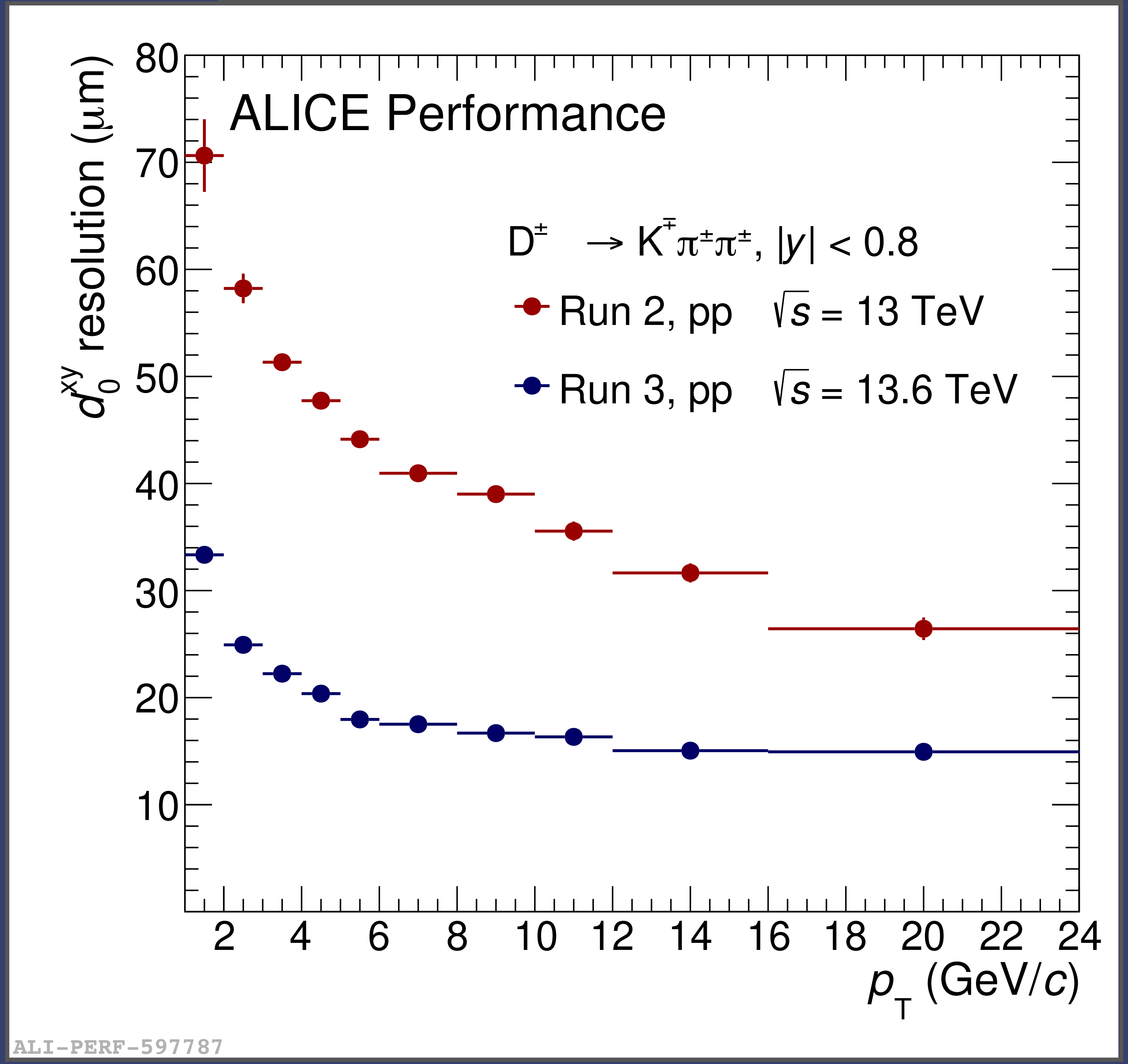
- Method only relies on the well-known decay kinematic → independent of cocktail and theory input
  - Requires high-resolution vertex detector → use improved pointing resolution of upgraded ITS2

d_0 resolution with ITS/ITS2



Run 3 pp

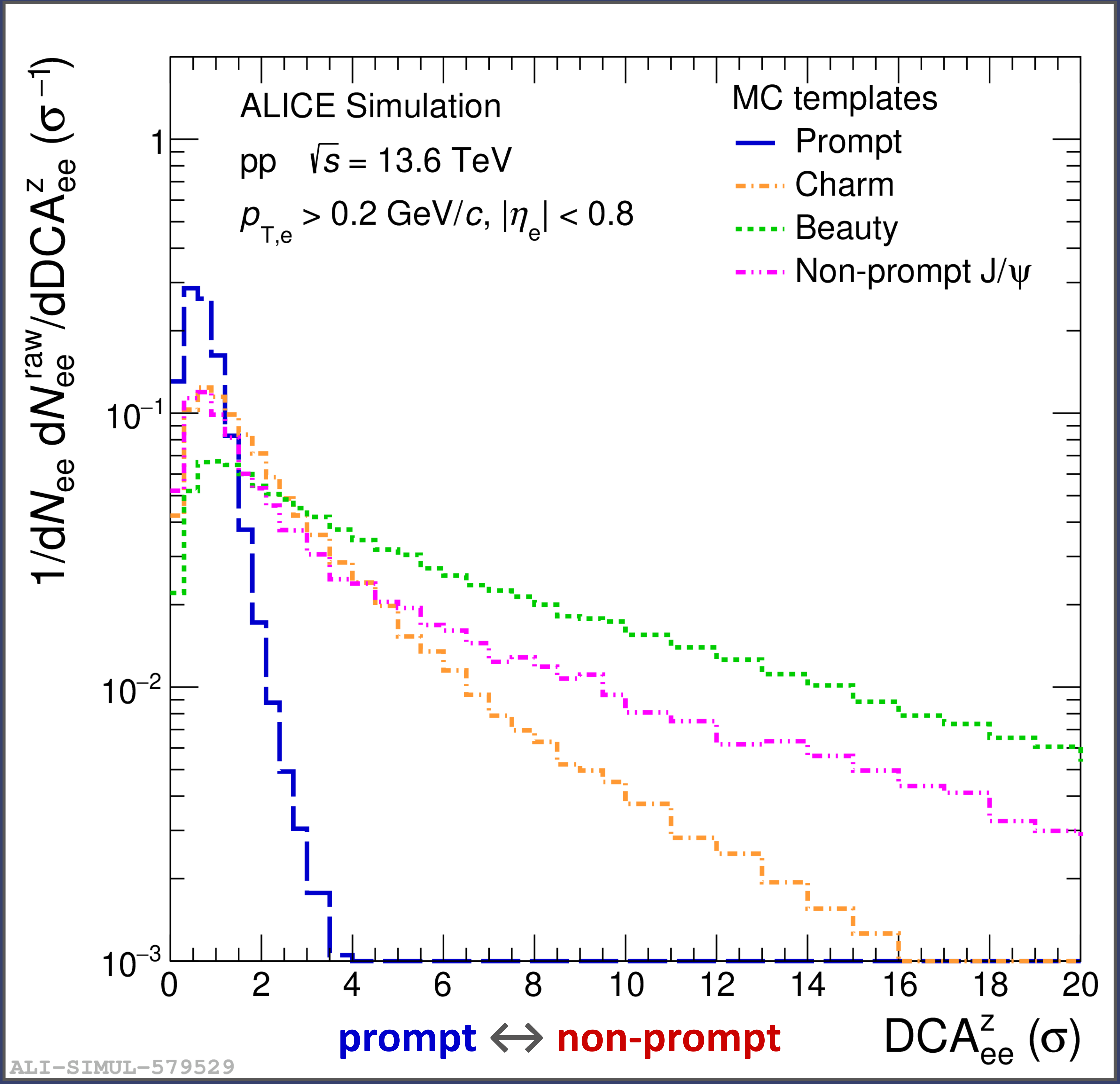
Topological Separation with MC Templates

ALICE

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:** feed-down from b-hadron decays

→ weighted with the measured branching ratios and fragmentation functions



Run 3 pp

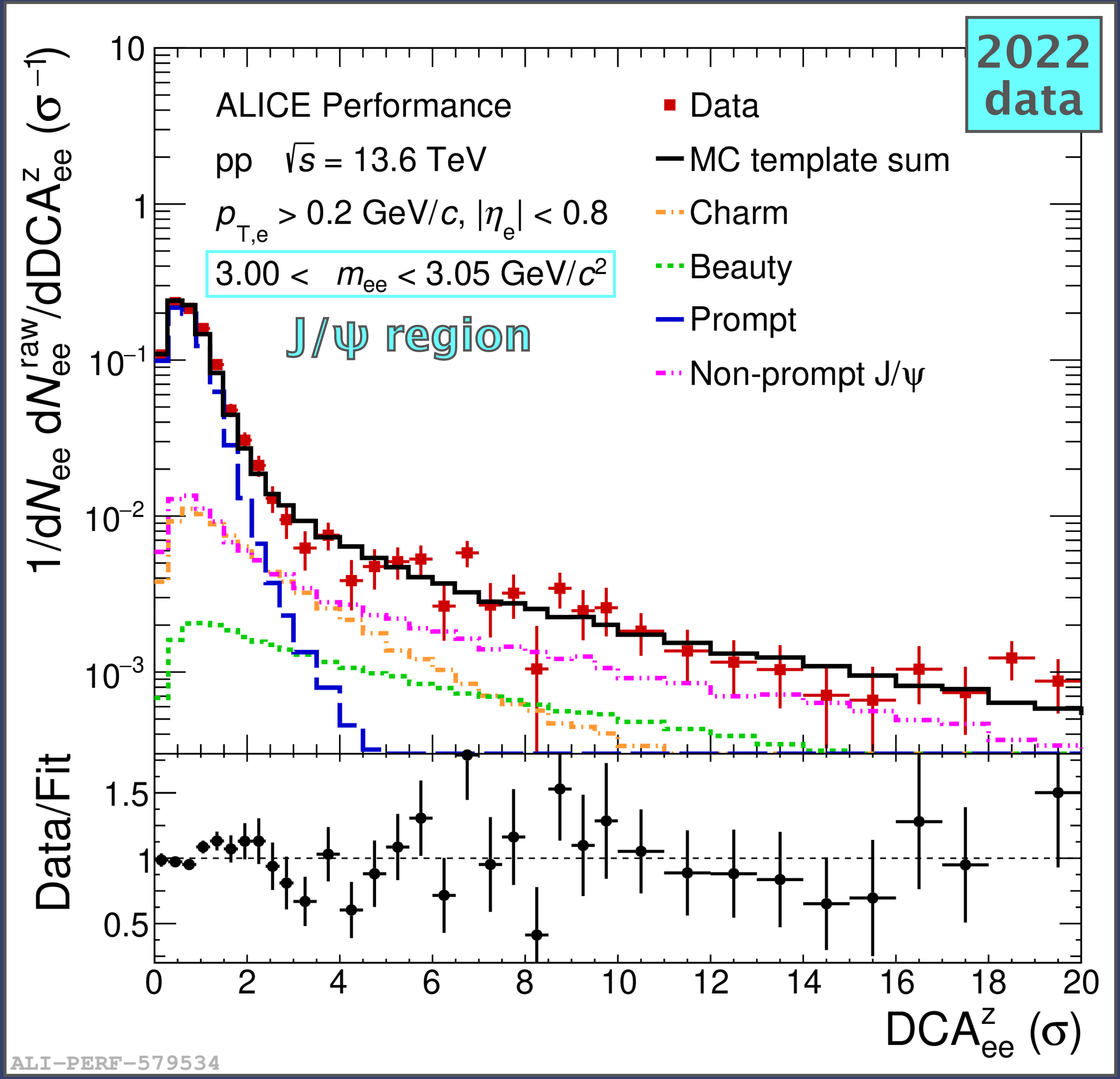
Topological Separation with MC Templates

ALICE

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

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

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



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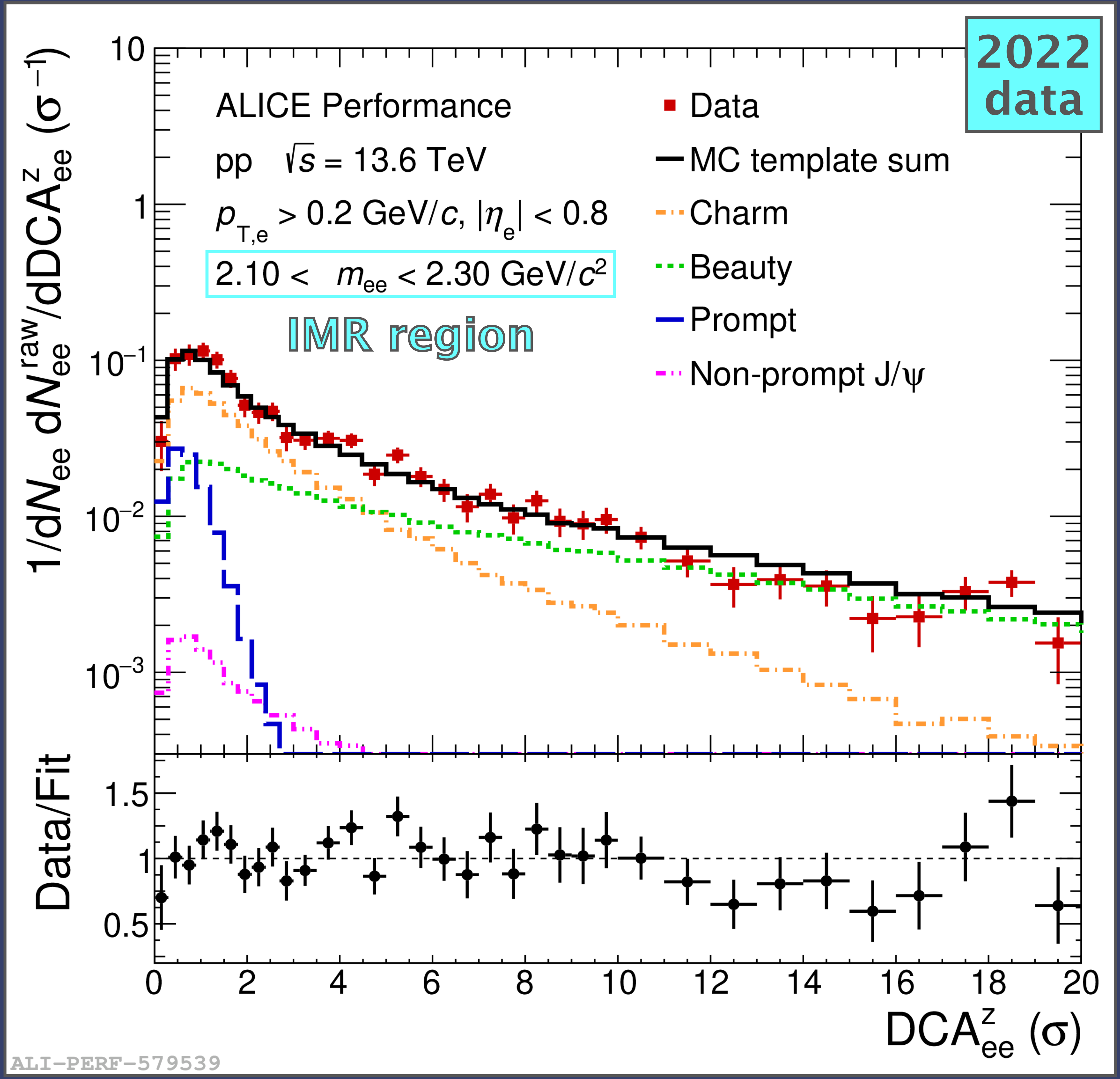
- **J/ψ** as control region with dominant prompt signal

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

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

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

Fit results describe data very well over wide DCA_{ee} range



Run 3 pp
Unfolded Raw Dielectron Spectrum

ALICE

First unfolded raw dielectron spectrum in Run 3

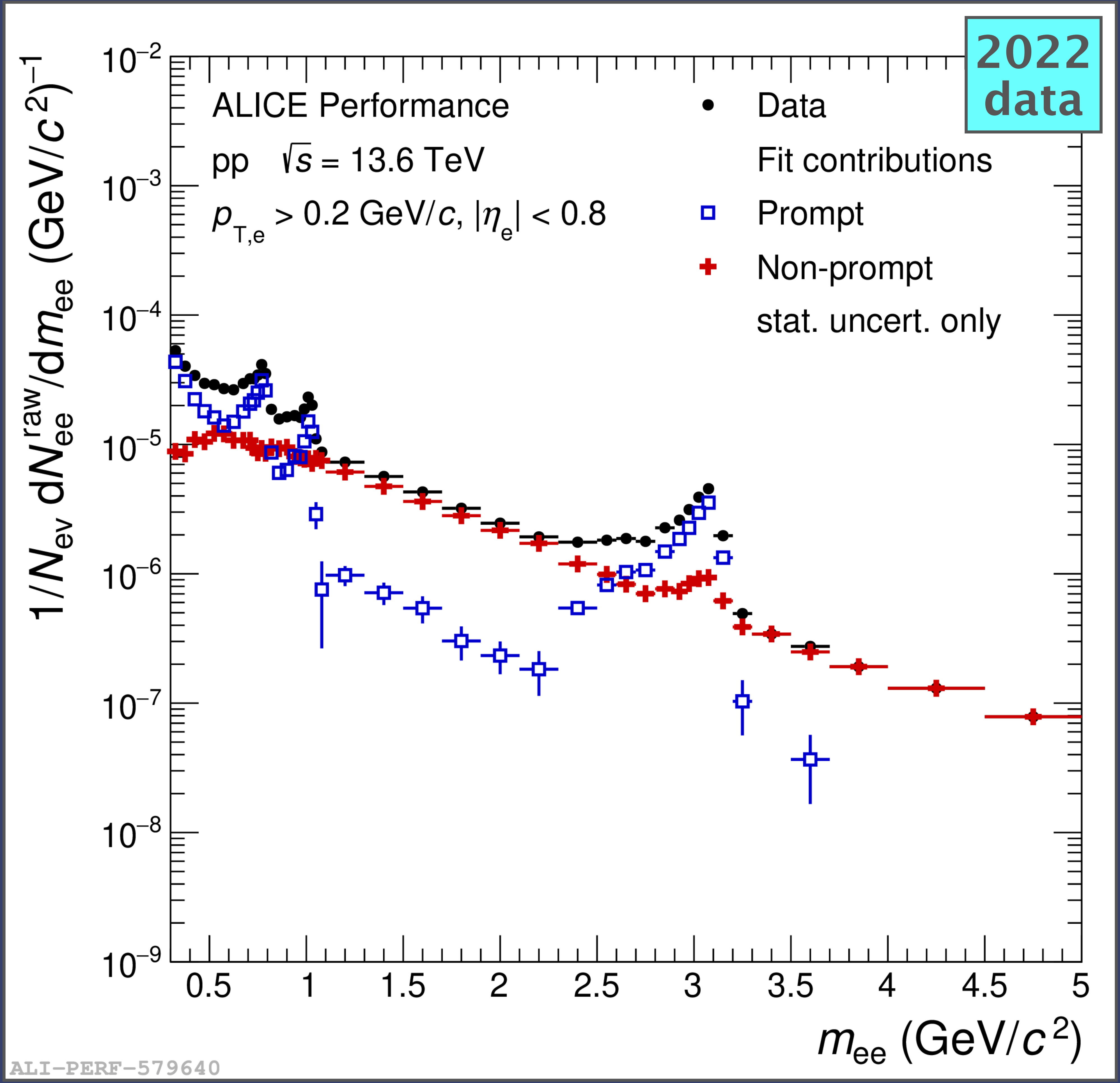
→ data-driven approach

- DCA_{ee} template fits performed in slices of m_{ee}:
  - Clear resonance structures of pseudo scalar and vector mesons described by prompt contribution
  - Non-prompt HF contribution describes continuum

  → indication for prompt contribution in IMR

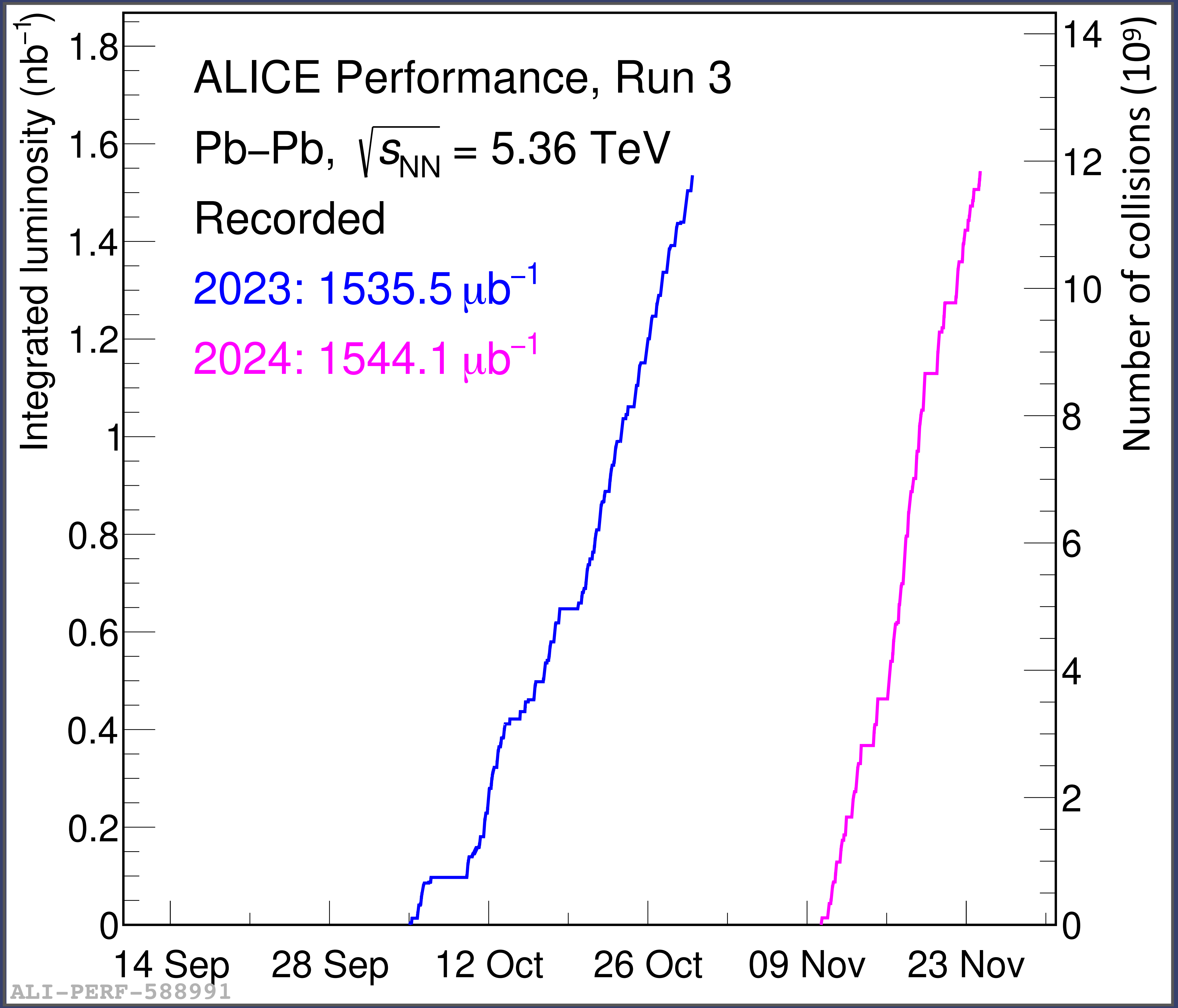
→ showcase of capabilities of detector upgrades and analysis techniques

→ important baseline for Pb–Pb measurements



Run 3 Pb–Pb

Dataset



Run 3 ($\sqrt{s_{NN}}$ = 5.36 TeV):

- 2023+2024: $\mathcal{L}_{int}$ = 0.5 nb^{-1} analyzed luminosity
  → **4·10^9 events in 10-90%**
- Effective interaction rates: 6-50 kHz (continuous readout)

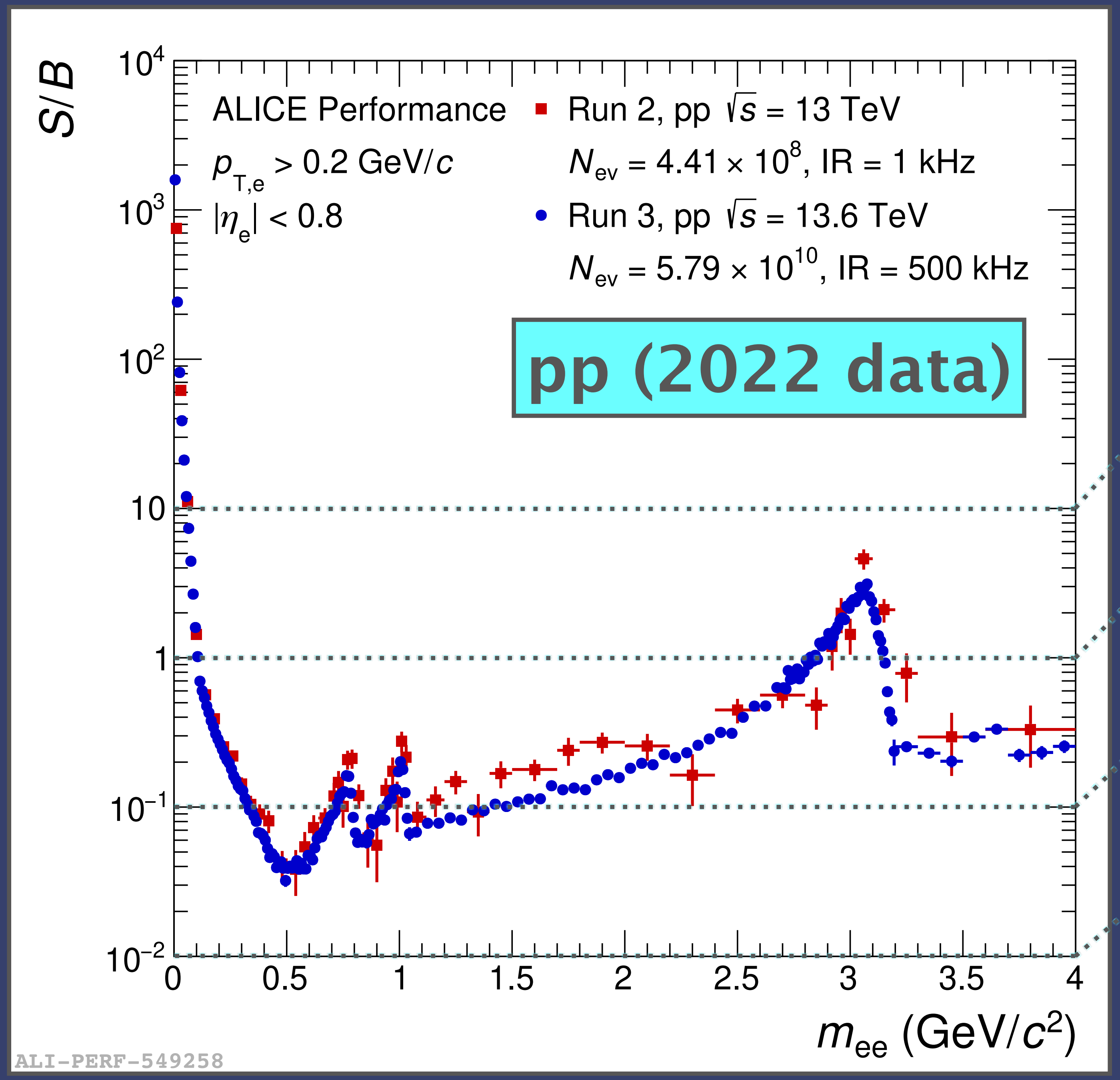
Run 2 ($\sqrt{s_{NN}}$ = 5.02 TeV):

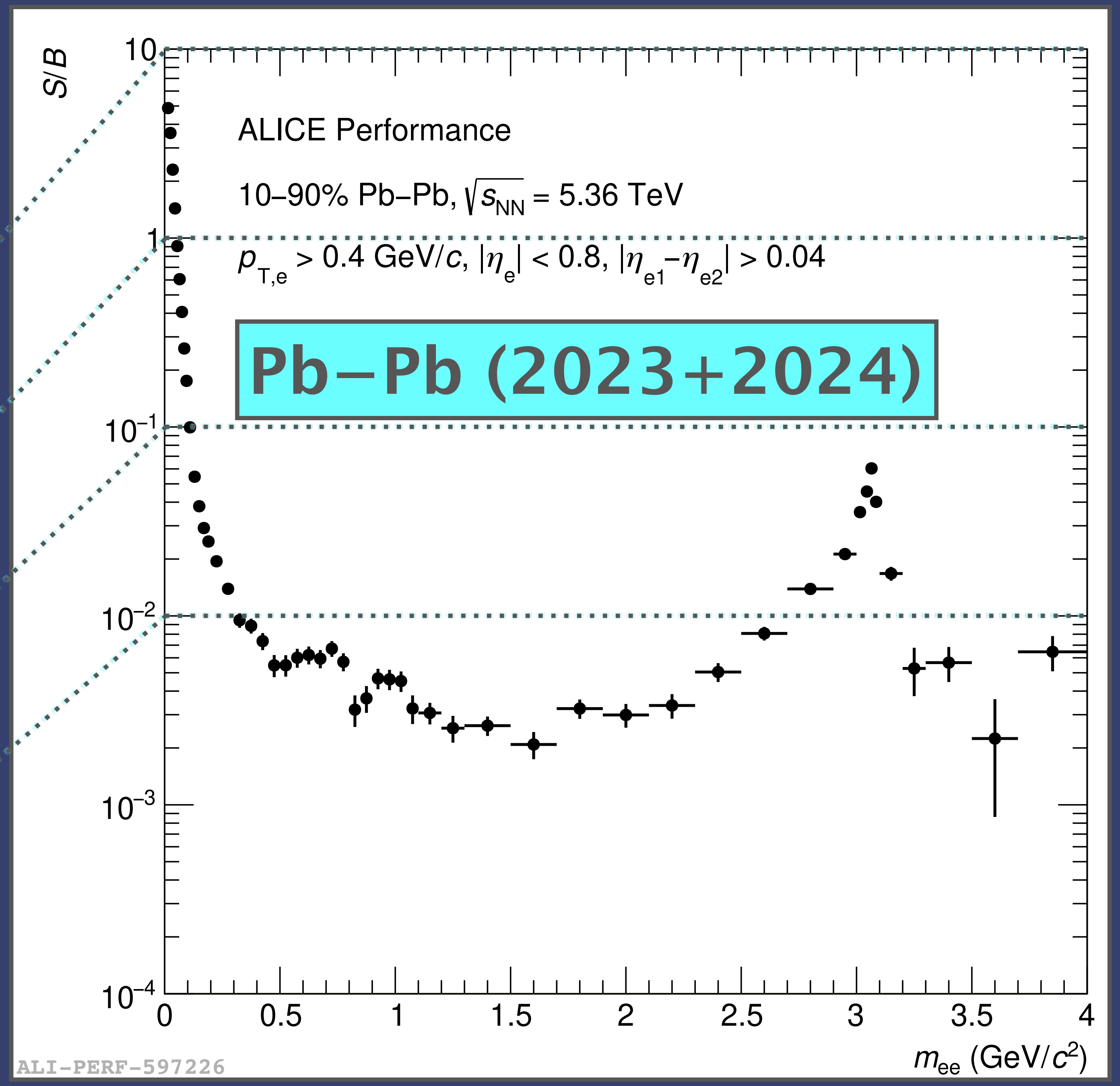
- 2018: $\mathcal{L}_{int}$ = 85 μb^{-1} analyzed luminosity
  → **65·10^6 events in 0-10%** (arXiv:2308.16704)
- Trigger rate ≈ 800 Hz

→ **factor ~60** more statistics analyzed

Run 3 Pb–Pb

Signal-over-Background Ratio





- Analysis much more challenging in Pb–Pb than in pp collisions
- High-multiplicity events → smaller signal-to-background ratio
- *S*/*B* decreases by factor of 10-100 → much higher precision of background description required

Run 3 Pb–Pb

Extracted Raw Dielectron Signal

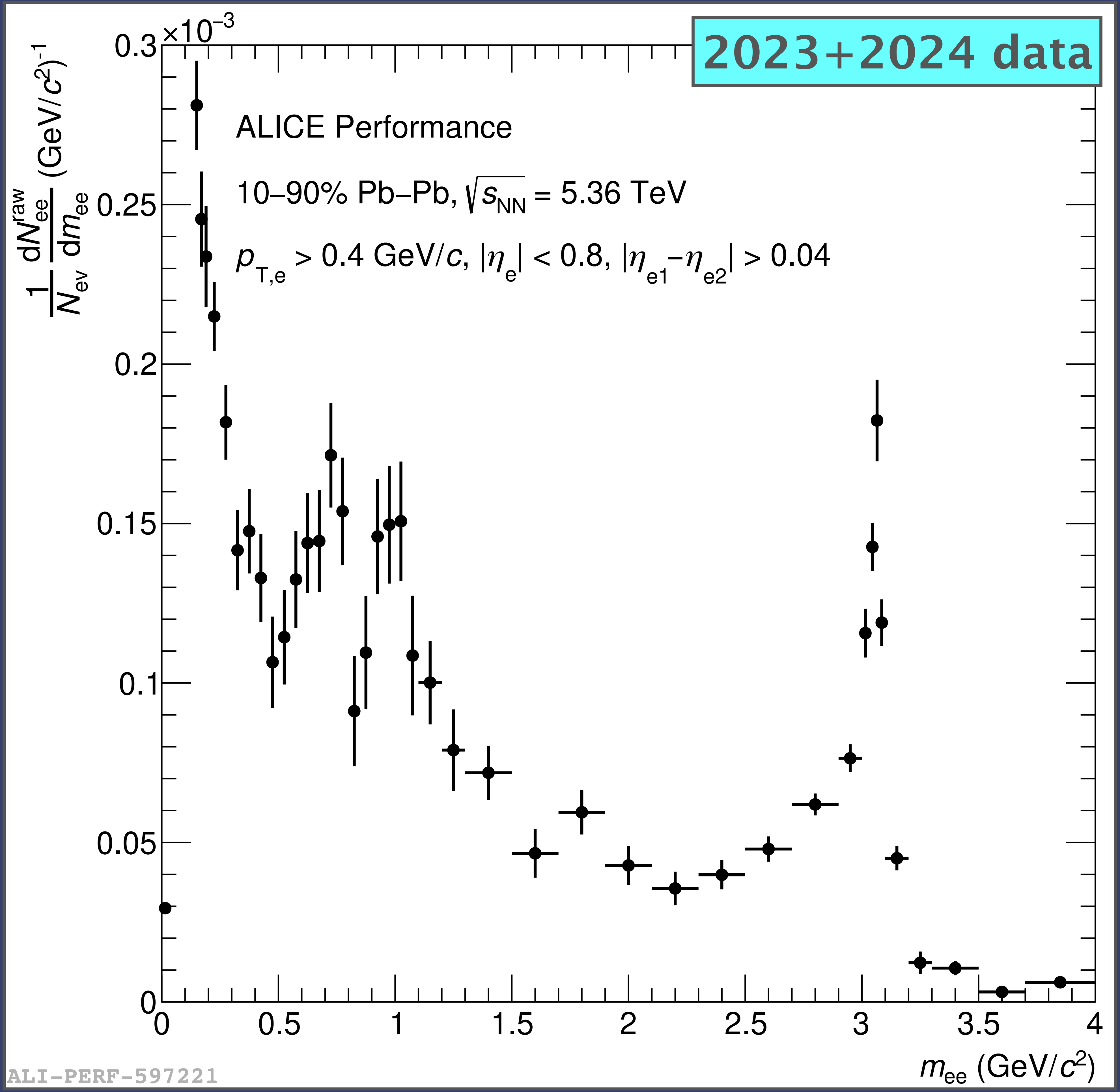
First raw dielectron signal in Pb–Pb collisions in Run 3

- Additional rejection of pairs with small opening angles with $|\eta_{e1}-\eta_{e2}| < 0.04$

  → reduce combinatorial background to improve *S/B*

- Characteristic features:
  - π^0 and J/ψ peaks clearly visible
  - ω and ϕ resonance structures

→ topological separation crucial to disentangle the medium modified non-prompt contribution



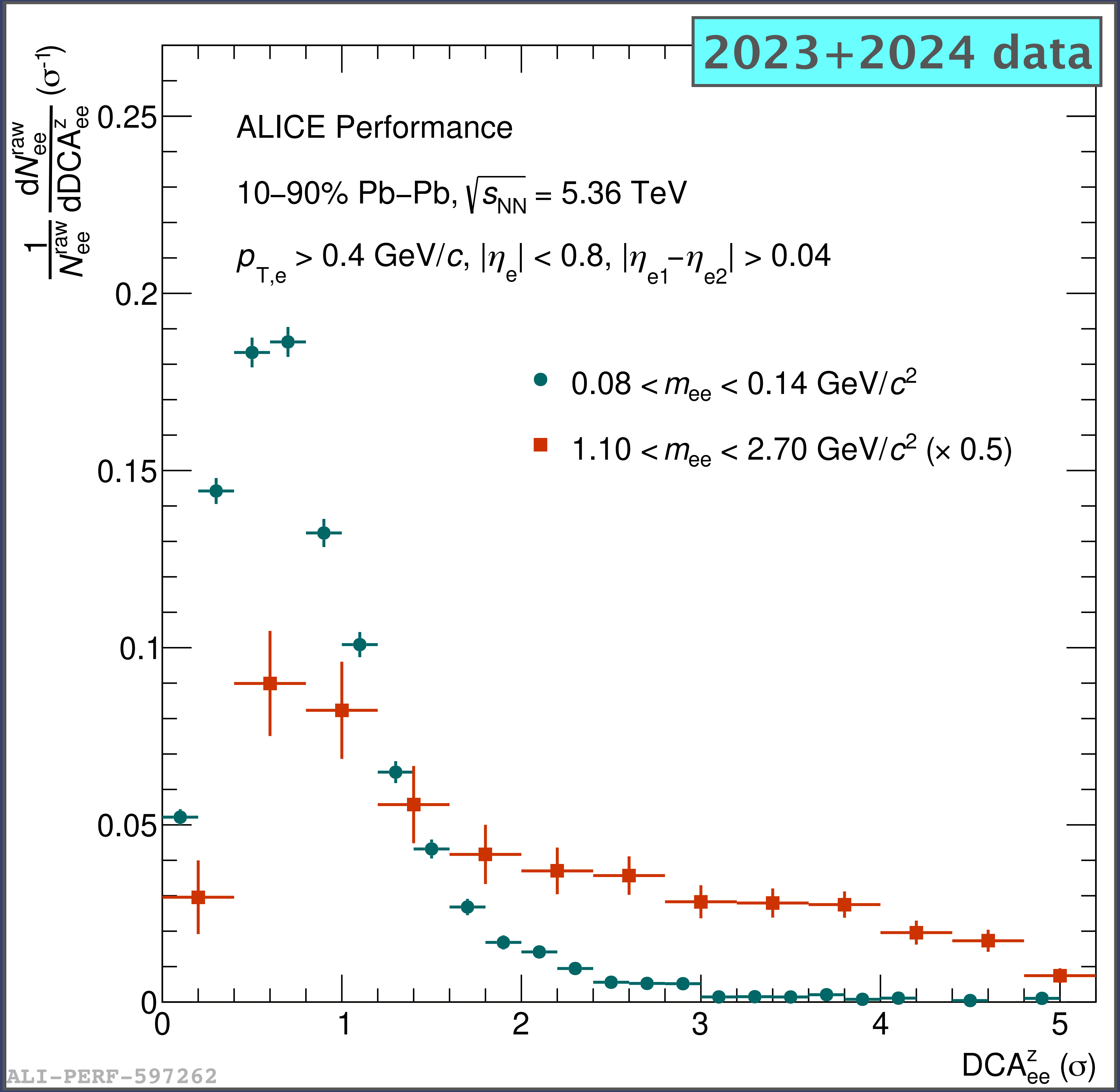
Run 3 Pb–Pb

Topological Separation

Separation of prompt and non-prompt dielectron sources with DCA_{ee} in Pb–Pb collisions in Run 3

- Two mass regions selected:
  - $0.08 < m_{ee} < 0.14$ GeV/c^2
    → dominated by prompt π^0 decays
  - $1.1 < m_{ee} < 2.7$ GeV/c^2
    → dominated by non-prompt HF decays

- Run 3 upgraded high-resolution vertex detector improves separation power compared to Run 2



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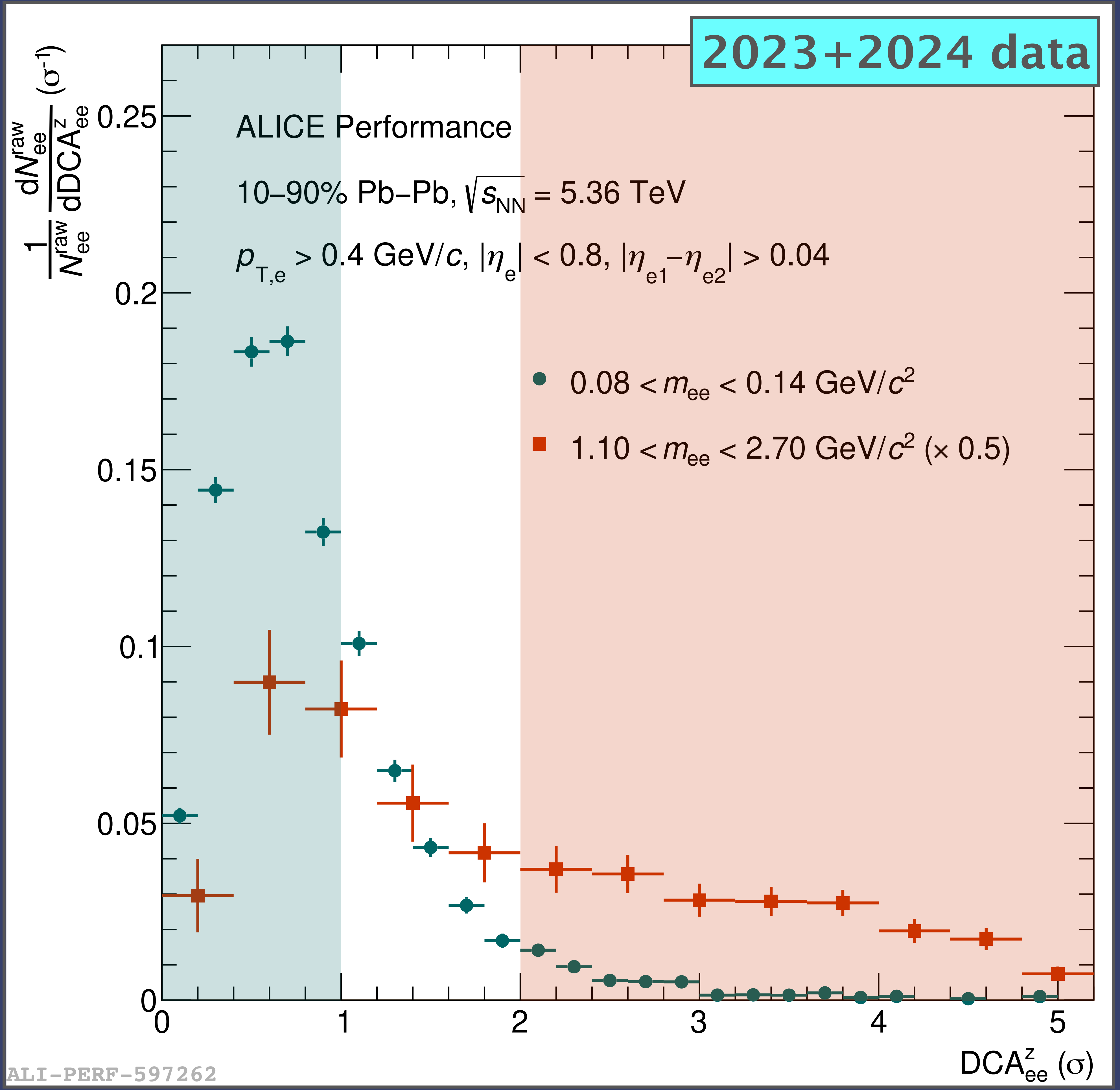


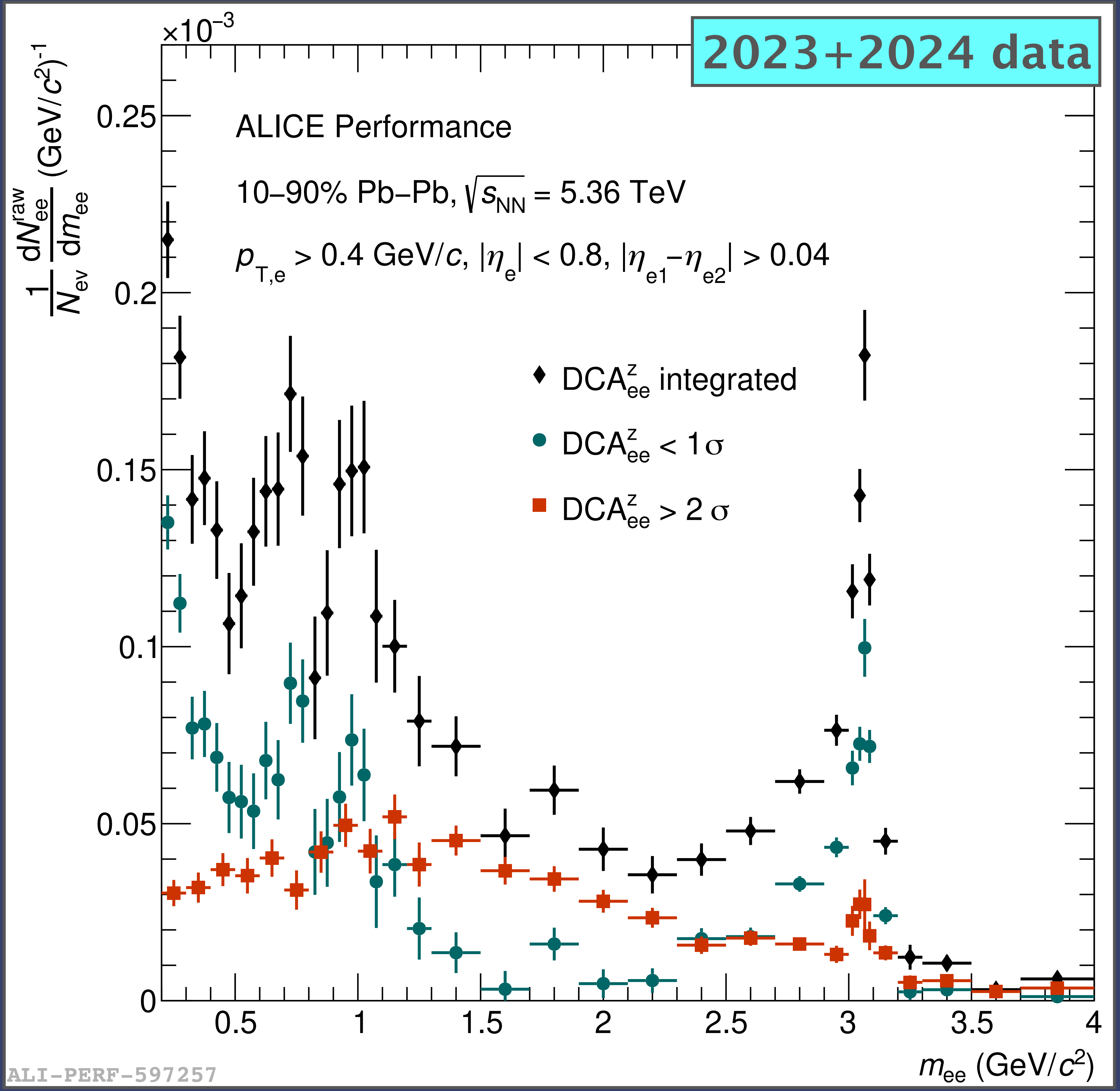
Run 3 Pb–Pb

Topological Separation

ALICE

First dielectron spectrum with DCA_{ee} selections in Pb–Pb collisions in Run 3

→ selection shows good separation of prompt and non-prompt contributions also in Pb–Pb collisions



<u>Next steps:</u>

- Improve reconstruction to include most central events
- DCA templates from MC to unfold dielectron spectra
- Estimate prompt contribution in IMR

Summary & Outlook

ALICE

ALICE Run 3 upgrades enable high-precision dielectron measurements

<u>Run 3 pp:</u>

- First corrected Run 3 dielectron spectrum → unprecedented precision at LHC energies
- First unfolded m_{ee} spectra by source topology → search for prompt sources & new physics in pp

→ specific studies possible with triggered data for high masses & reduced solenoid B-field data for low p_T

<u>Run 3 Pb–Pb:</u>

- First raw m_{ee} spectrum with DCA_{ee} selections → separation of prompt and non-prompt sources

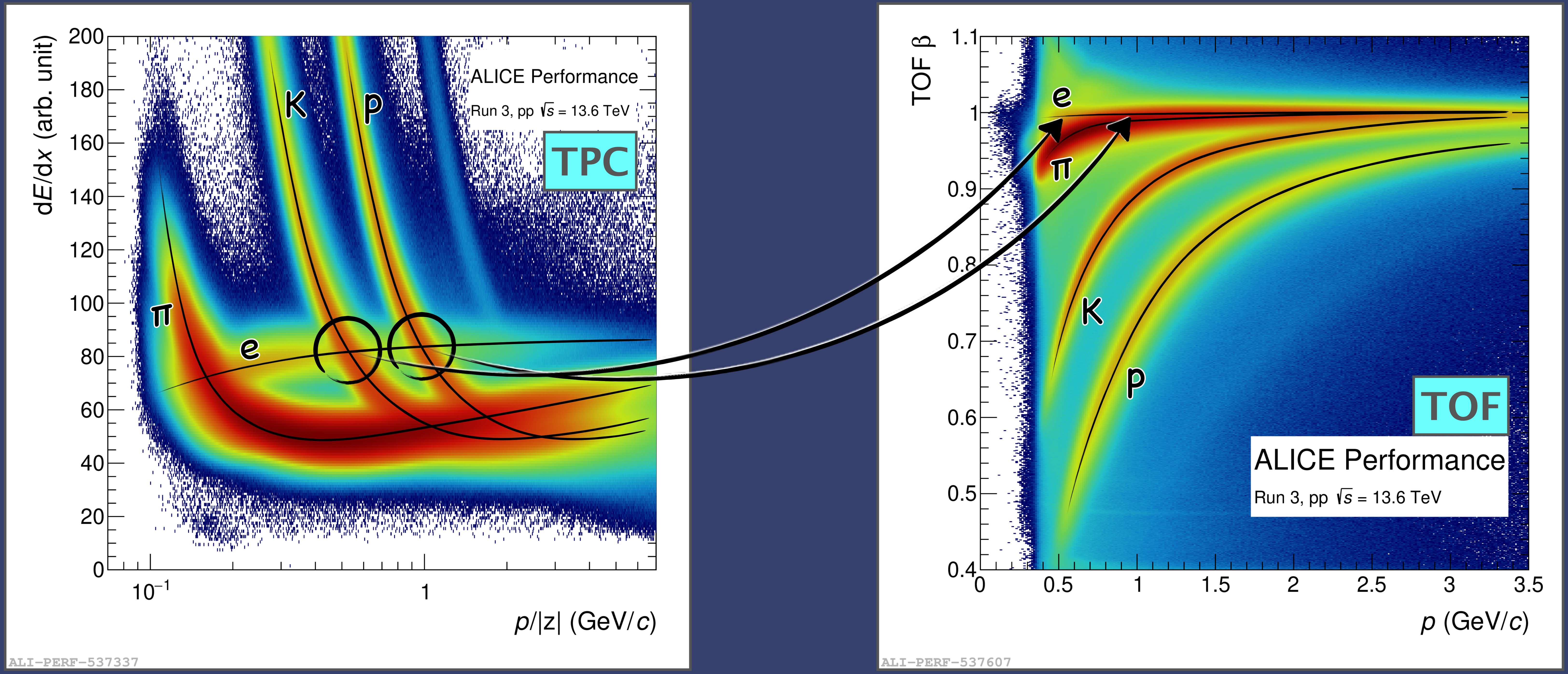
→ DCA template analysis & more data to be recorded

Backup

Particle Identification

Electron Selection

- Identify electron and positron candidates with TPC dE/dx
- Reject other charged particles (hadrons) with TPC dE/dx
- However: crossing regions → recover well separated electrons and positrons with TOF β

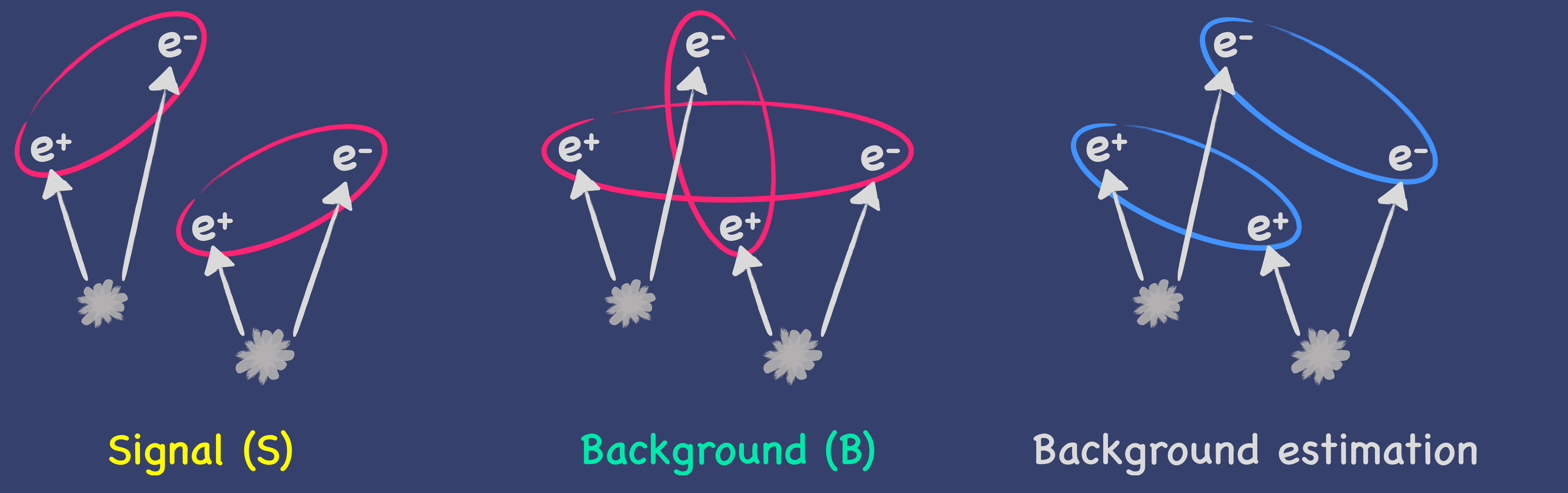


Signal Extraction

Definitions

ALICE

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

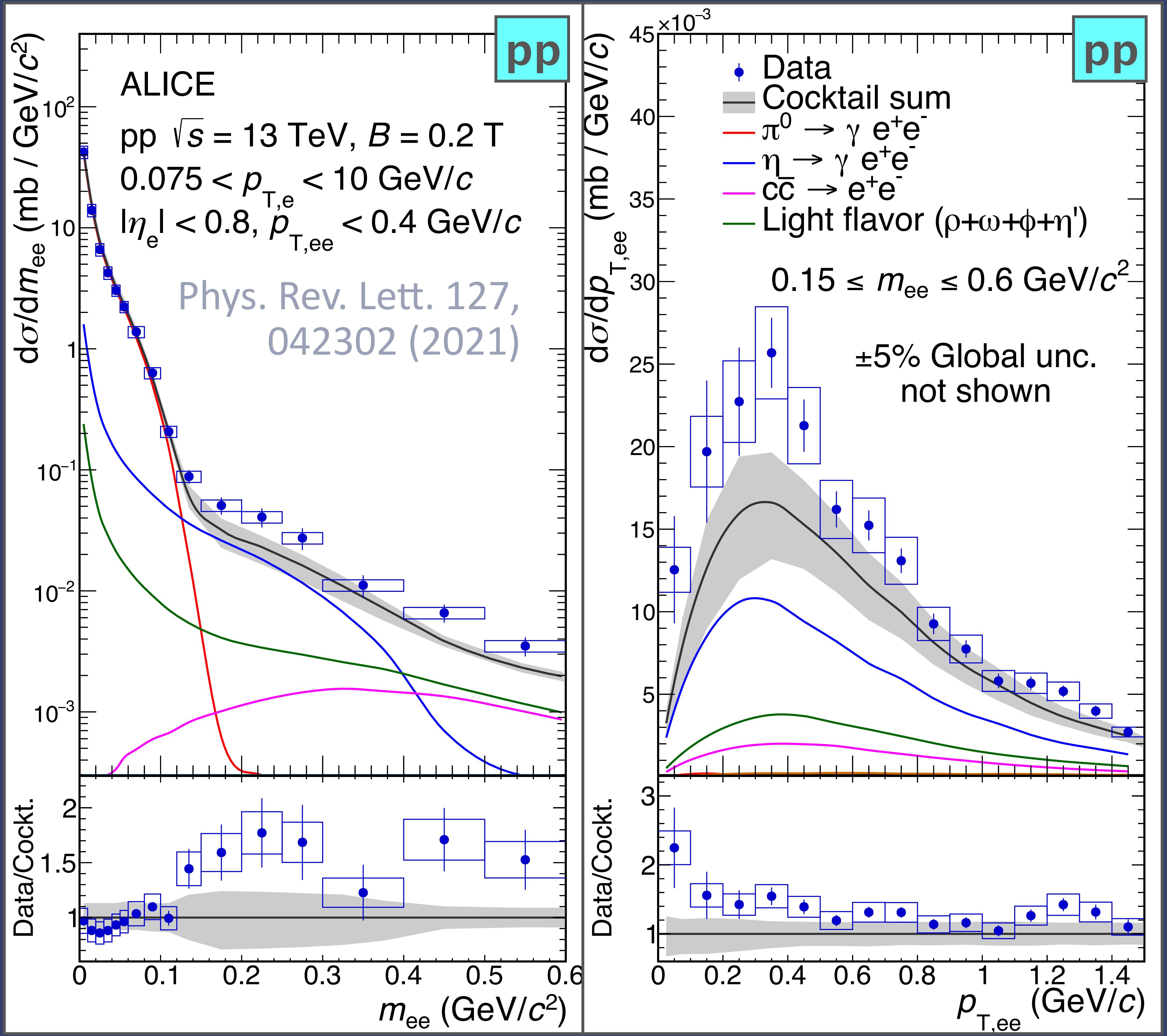


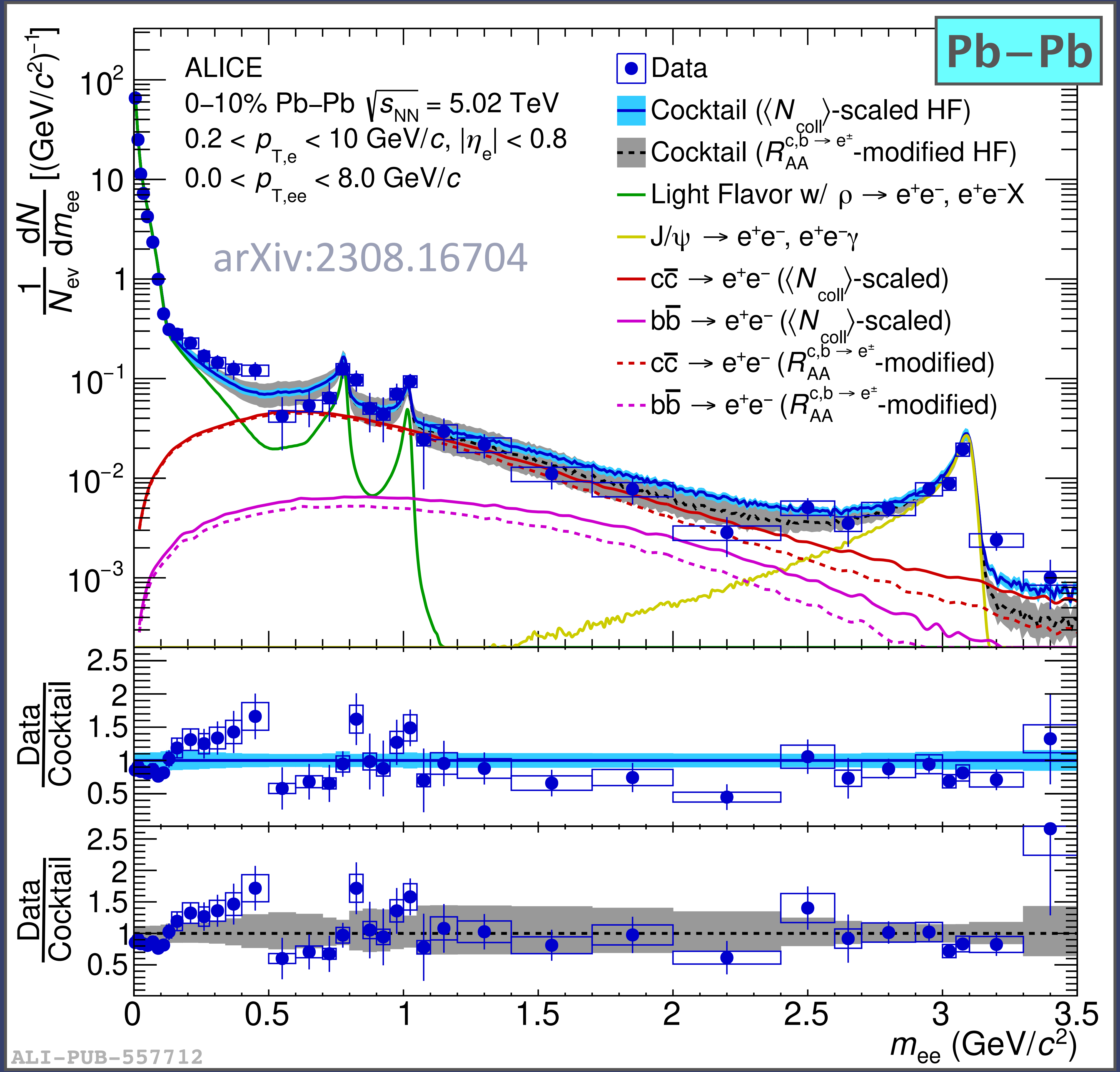
- **ULS**: unlike-sign pairs from same event N_{+-}^{same} → **ULS** = **S** + **B**
- **LS**: like-sign pairs from same event $N_{++,--} = 2 \cdot \sqrt{(N_{++}^{same} \cdot N_{--}^{same})}$
- **R factor**: $R = N_{+-}^{mix} / 2 \cdot \sqrt{(N_{++}^{mix} \cdot N_{--}^{mix})}$
  Correction for different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

→ **S** = **ULS** – **B**

Status

Dielectron Production in Run 2





Topological Separation

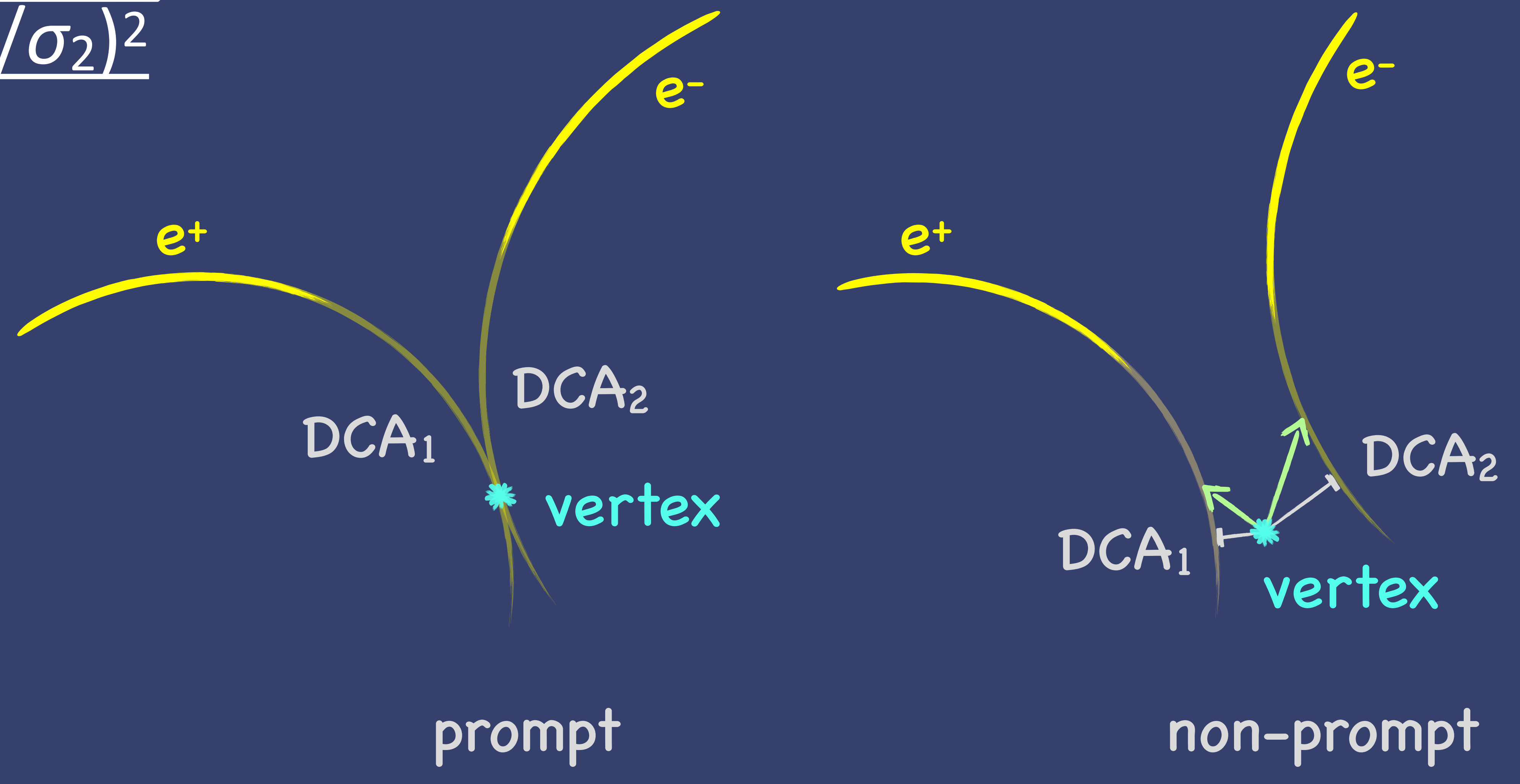
Definition

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

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

- Prompt sources (light flavor, quarkonia & thermal radiation) → small DCA
- Non-prompt decays (heavy flavor) → large DCA

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



- Method only relies on the well-known decay kinematic
  → independent of cocktail and theory input
  - Requires high-resolution vertex detector
    → use improved pointing resolution of upgraded ITS

Run 3 pp

Topological Separation of Dielectron Sources

ALICE

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