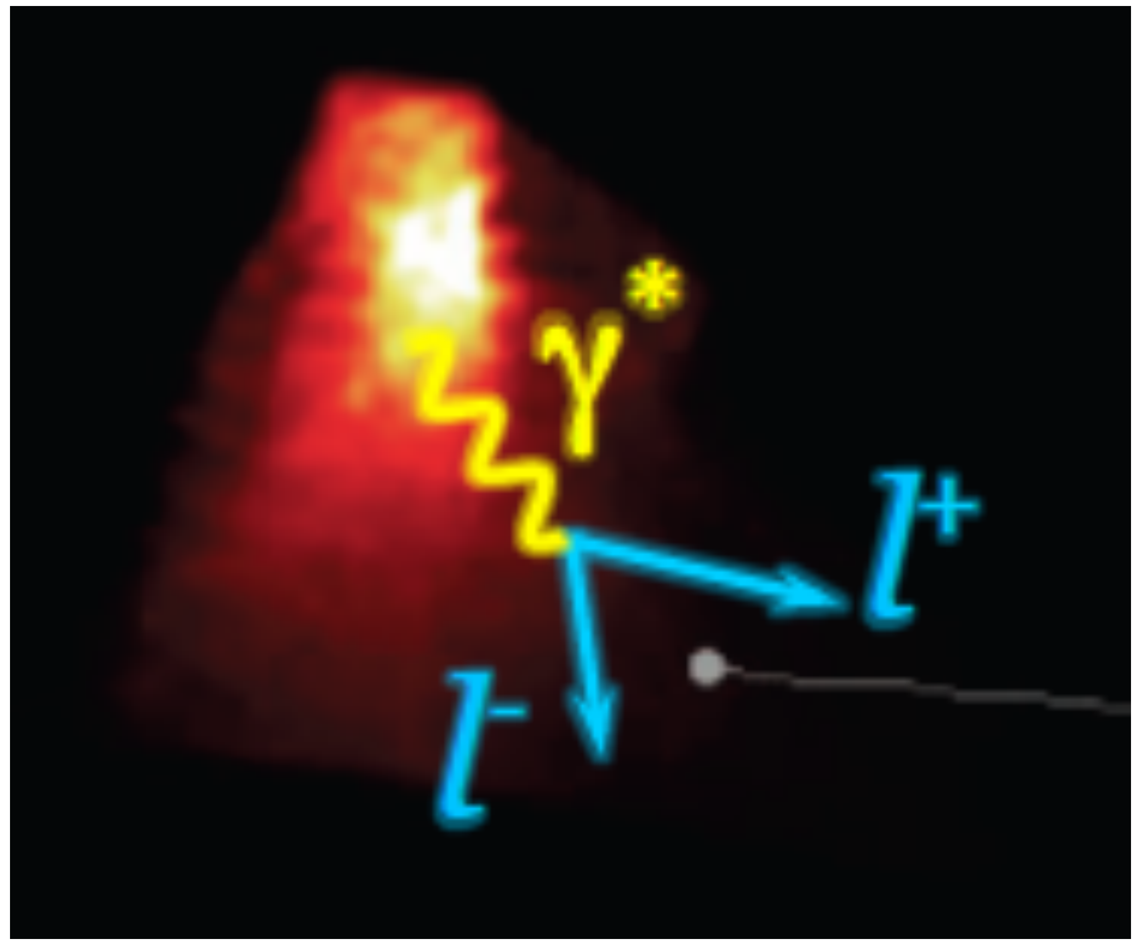


ALICE | FSP ALICE Erforschung von Universum und Materie

Probing nuclear matter under extreme conditions with dileptons in heavy-ion collisions

Raphaelle Bailhache

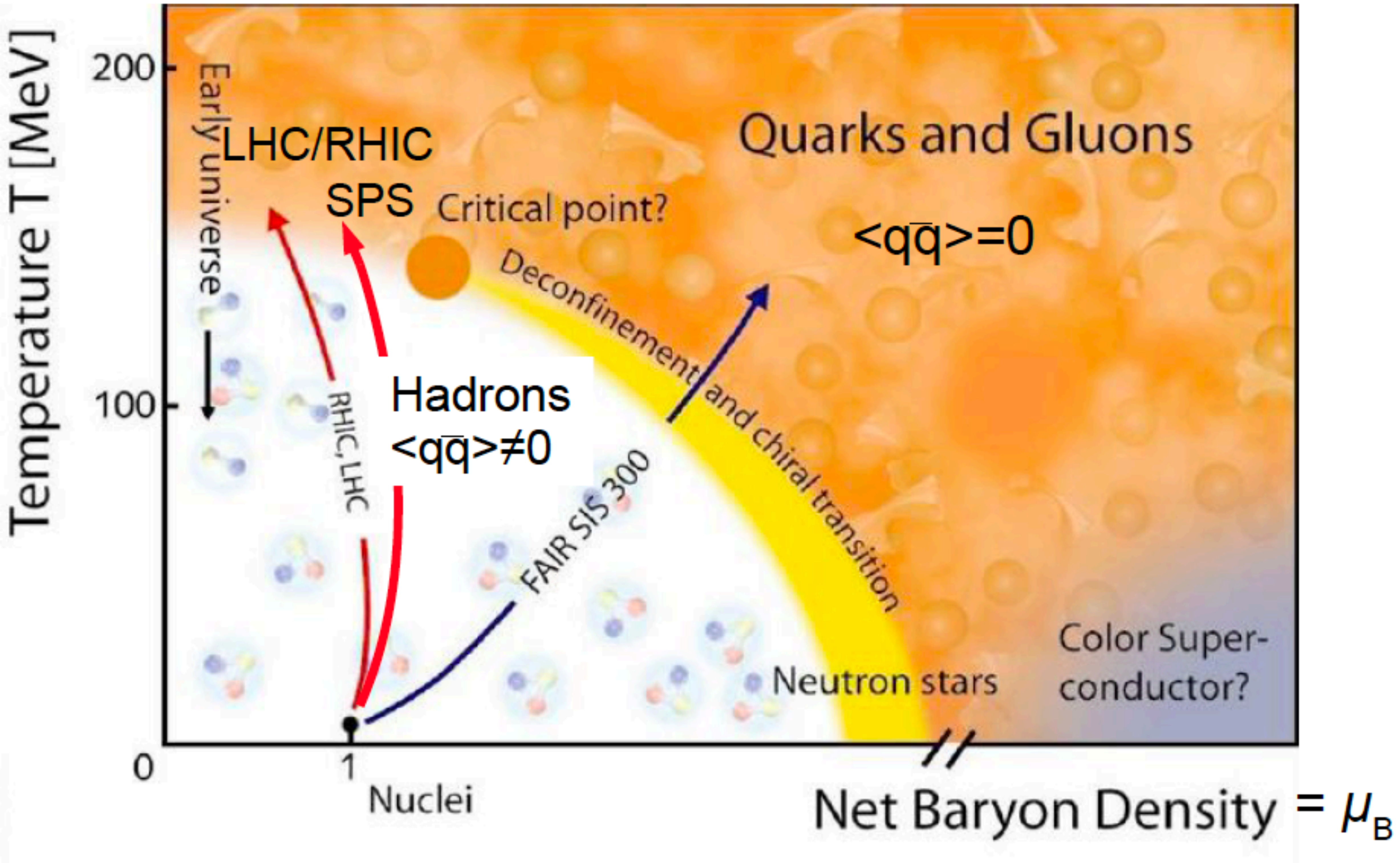
Goethe-Universitaet Frankfurt am Main, Germany

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Half an EMMI Day on 2-2-22

ALICE

Nuclear matter in the universe

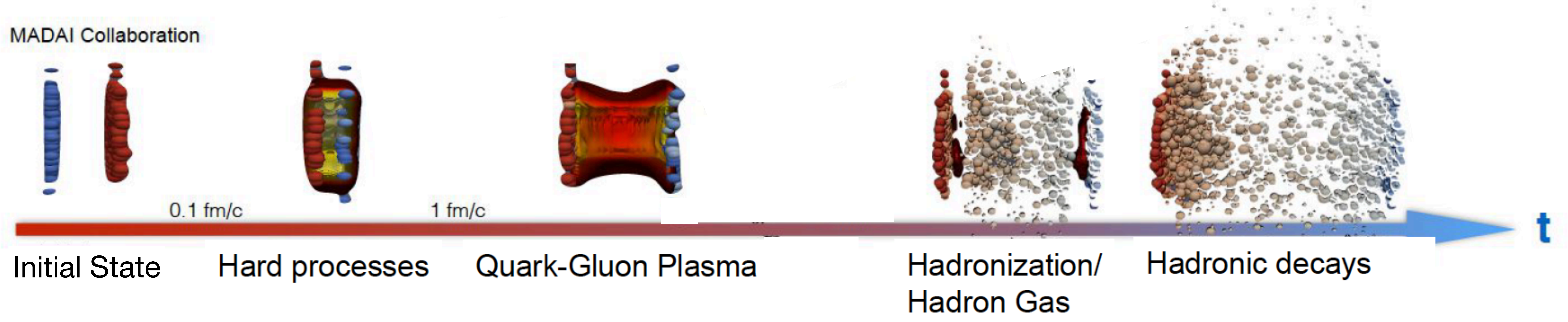


At high *T*, μ_B:

- **Deconfinement phase transition:** quark-gluon plasma (QGP)
  Predicted at $T_c \approx$ 160 MeV for μ_B=0 → QGP 100 000 times hotter than the center of the sun
- **Chiral phase transition** ($< q\bar{q} >$ = 0)

Accessible through heavy-ion collisions: high *T* and μ_B = 0 at the LHC

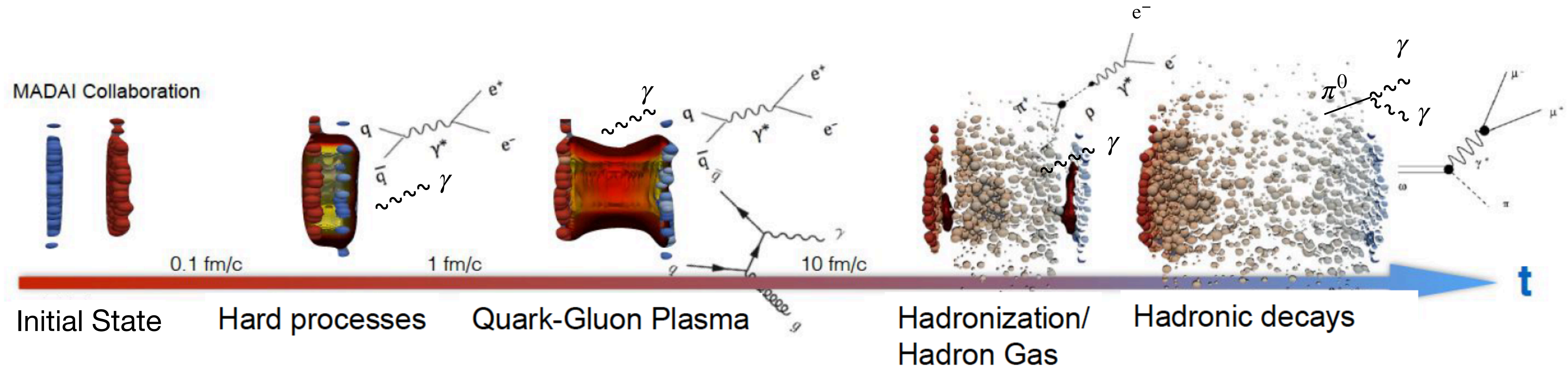
Heavy-ion collisions



Heavy-ion collisions at the LHC:

- Little Big Bang in the laboratory: high T and $\mu_{\mathrm{B}} = 0$ regime accessible by lattice QCD
- Highest-temperature, longest-lived experimentally accessible QGP

Electromagnetic probes



Real and virtual photons produced at all stages of the heavy-ion collision with negligible final-state interactions

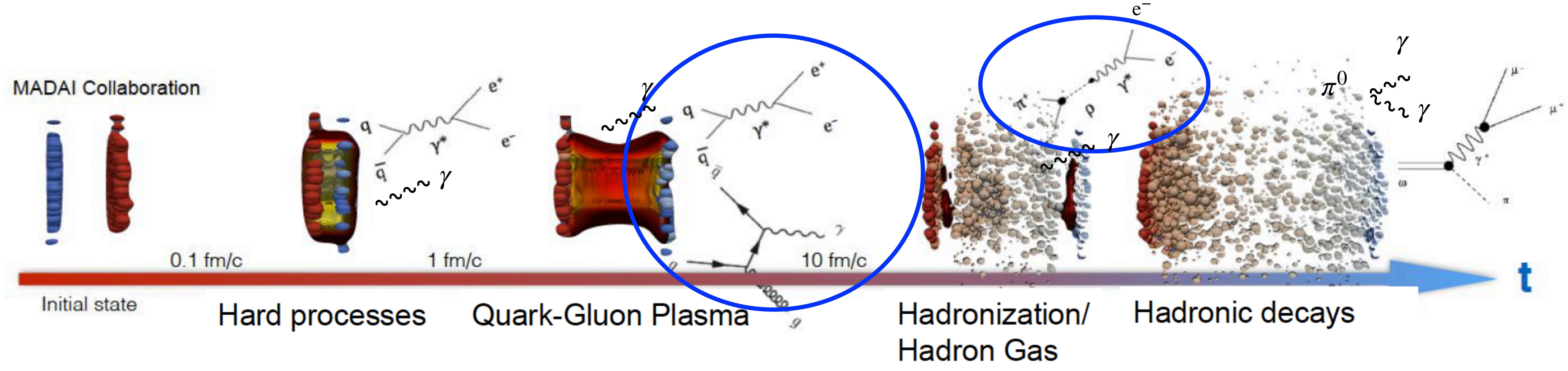
→ **Probe the *interior* of the heavy-ion collisions**

→ **Carry information from the whole space-time evolution of the system**

Real photons: larger cross sections

Virtual photons: additional invariant mass m_{ee} variable → disentangle contributions in time

Electromagnetic probes



Can study with thermal radiation:

- From the quark-gluon plasma ($q\bar{q} \rightarrow e^+e^-...$): **Deconfinement**
- From the hot hadron gas ($\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-...$): **Chiral symmetry restoration**

Chiral symmetry

Chirality = helicity for massless particles

- Chiral symmetry property of Quantum-ChromoDynamics:

- **In vacuum:**
  - **Chiral symmetry broken**
  - Order parameter of chiral symmetry $< q\bar{q} > \neq 0$
  - Origin of mass:
    - Naked quark masses: Higgs mechanisms
      $<$ 2% of visible mass
    - Constituent quark masses: chiral symmetry breaking
      $>$ 98% of visible mass

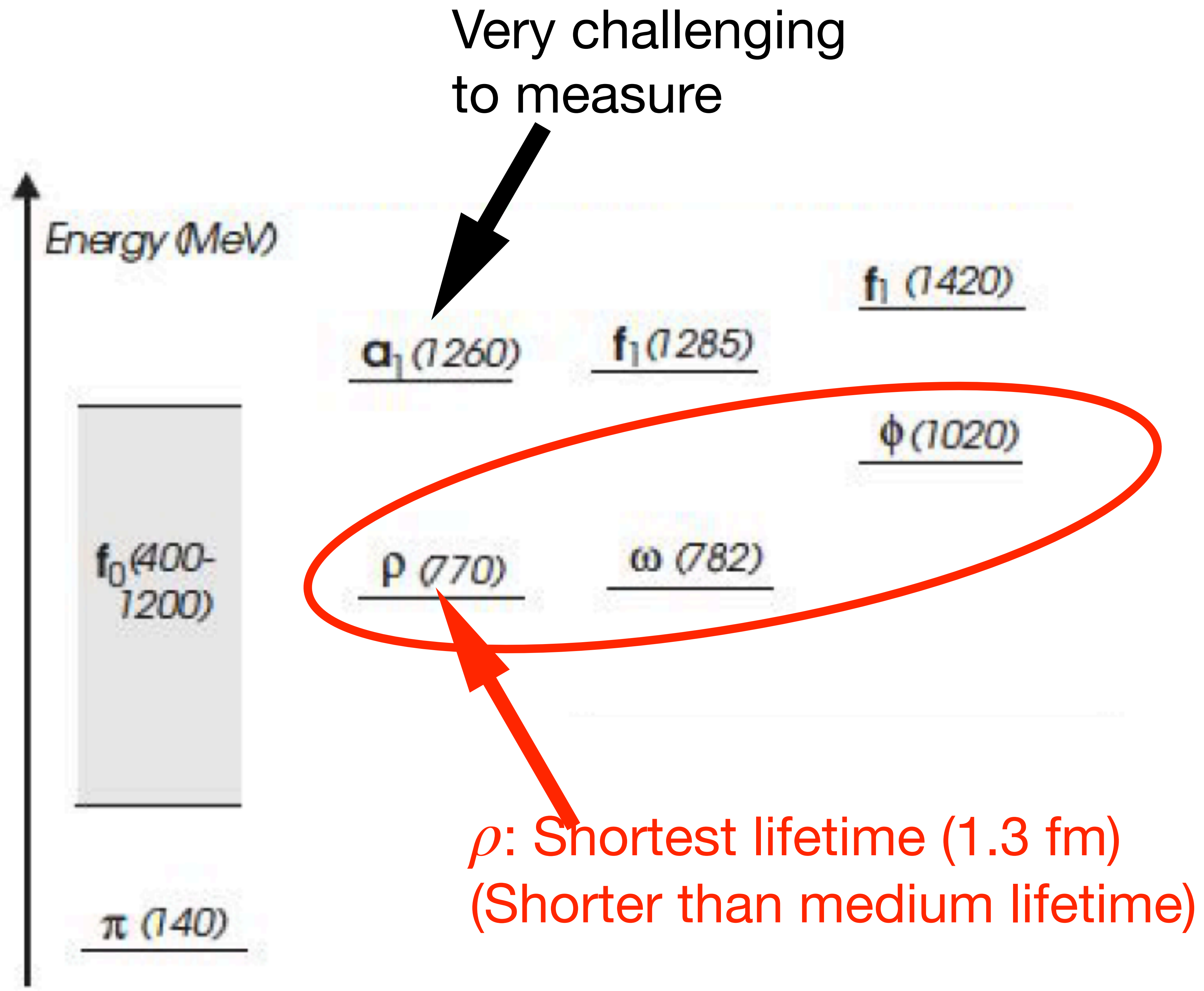
Chiral symmetry

Chirality = helicity for massless particles

- Chiral symmetry property of Quantum-ChromoDynamics:

- **In vacuum:**
  - **Chiral symmetry broken**
  - Order parameter of chiral symmetry $< q\bar{q} > \neq 0$
  - **Chiral partners have $\neq$ mass**
    Hadrons with same spin but opposite parity

Chiral partner splitting in vacuum
(Pseudo-scalar/scalar and vector/axialvector)



Vector mesons decay into $e^{+}e^{-}/\mu^{+}\mu^{-}$

Chiral symmetry

Chirality = helicity for massless particles

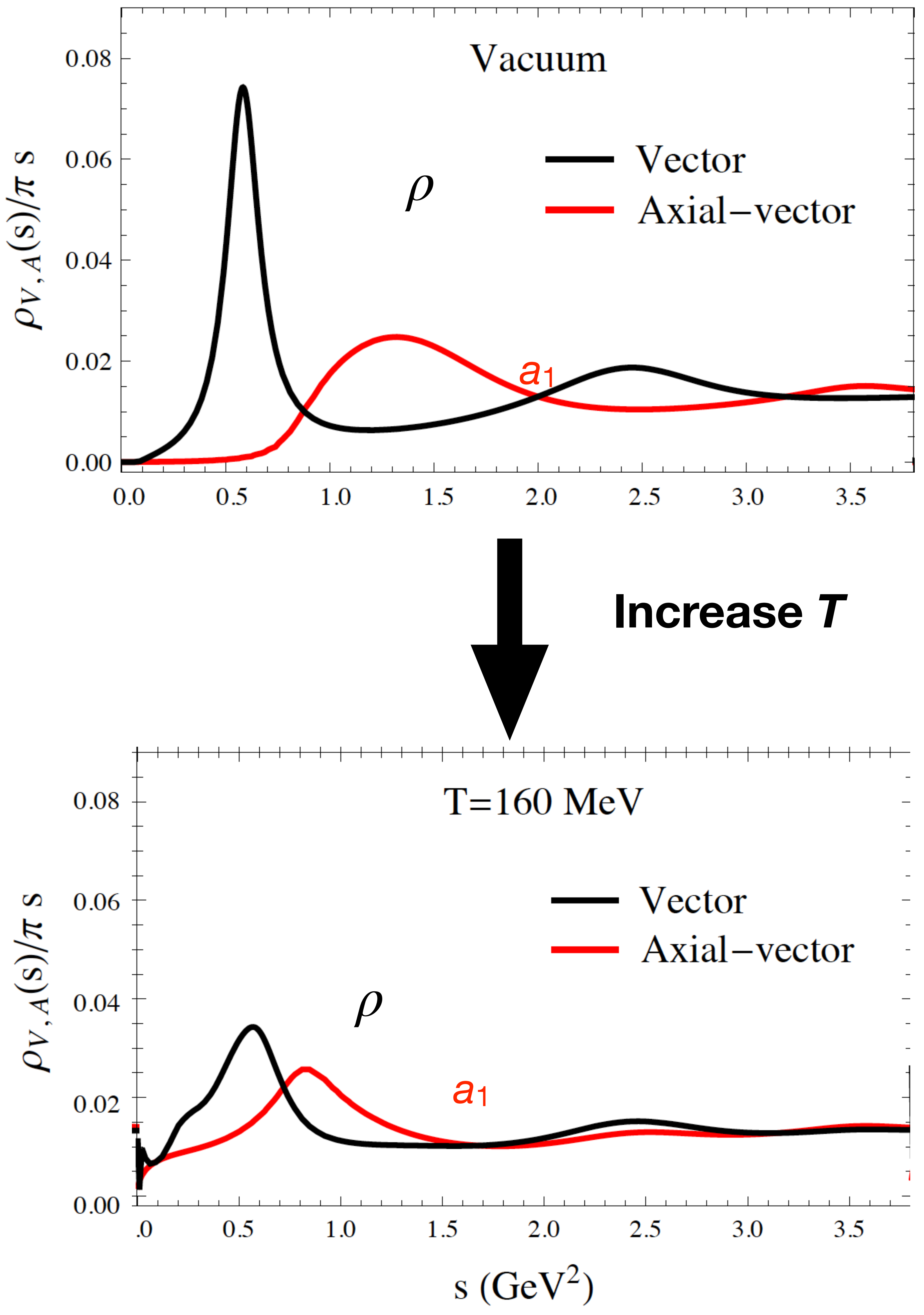
- Chiral symmetry property of Quantum-ChromoDynamics

- **At high *T*:**
  - **Chiral symmetry restored:** $< q\bar{q} >$ = 0
    Lattice QCD calculations: partially restored in confined phase
  - **Chiral partners have = mass and mix:**
    Medium modifications of vector/axialvector spectral functions

- **In heavy-ion collisions:**
  - Modifications ρ spectral function in the hot medium
  - Thermal production of ρ

Observed first at SPS energies CERES/NA45, PRL 91 (2003) 042301, NA60 PRL 96 (2006) 162302

Spectral functions

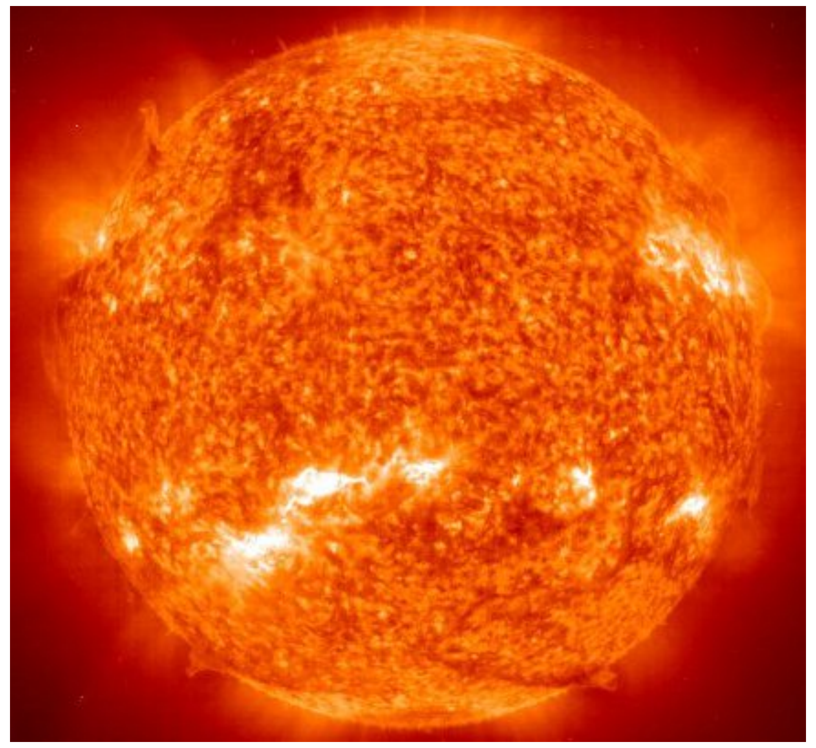


P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103

Deconfinement: temperature of QGP

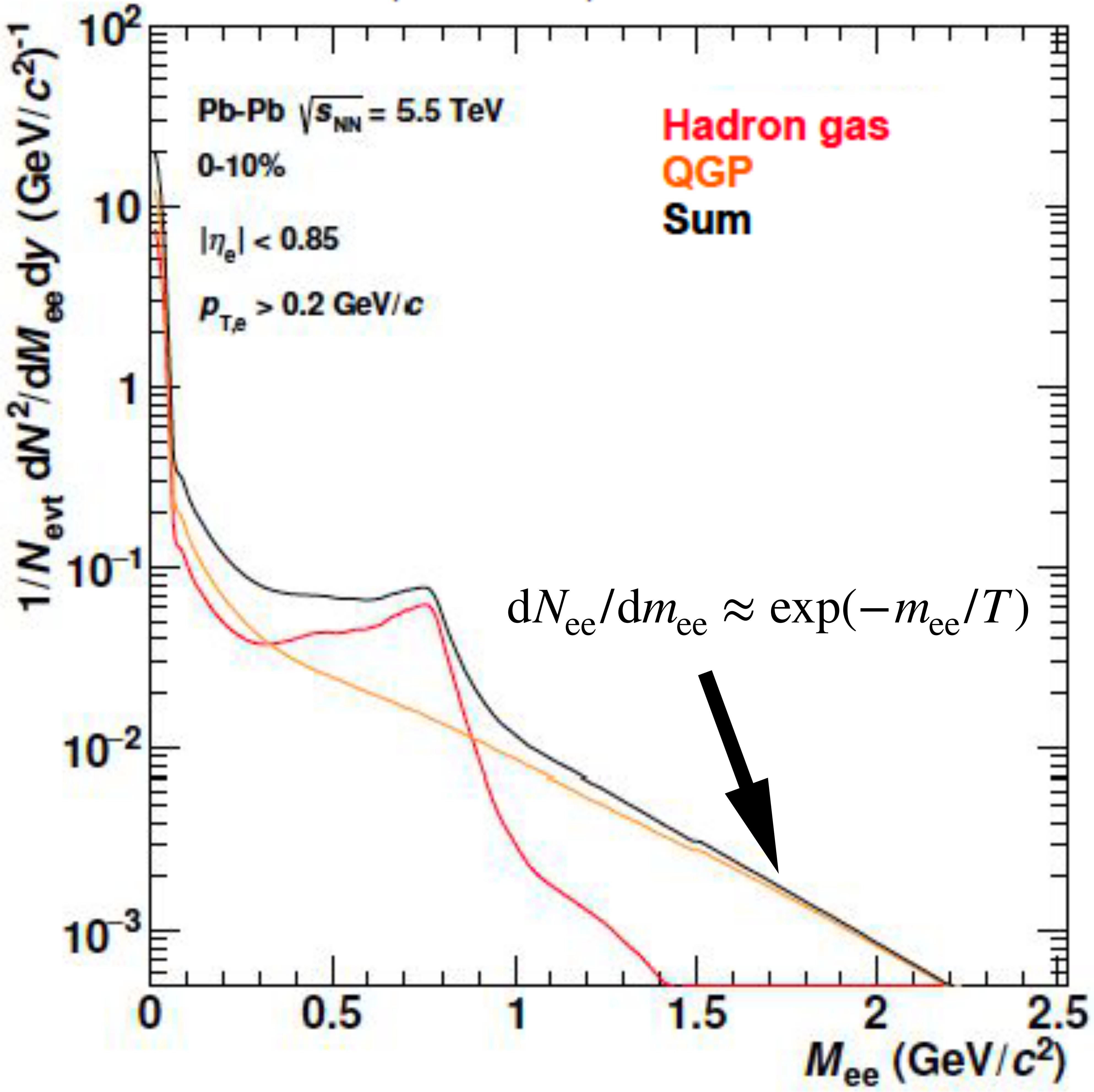
- **Invariant mass (M_{ee})** use to disentangle:
  - **Thermal e^+e^- from hot hadron gas**
  - **And thermal e^+e^- from QGP**

- **At intermediate invariant mass:**
  Black-body radiation from static source $\approx e^{-E/T}$



Here from the QGP integrated over space-time
→ Access to early QGP temperature

Thermal e^+e^- spectrum at LHC energies



R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
R. Rapp private communication

Deconfinement: temperature of QGP

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

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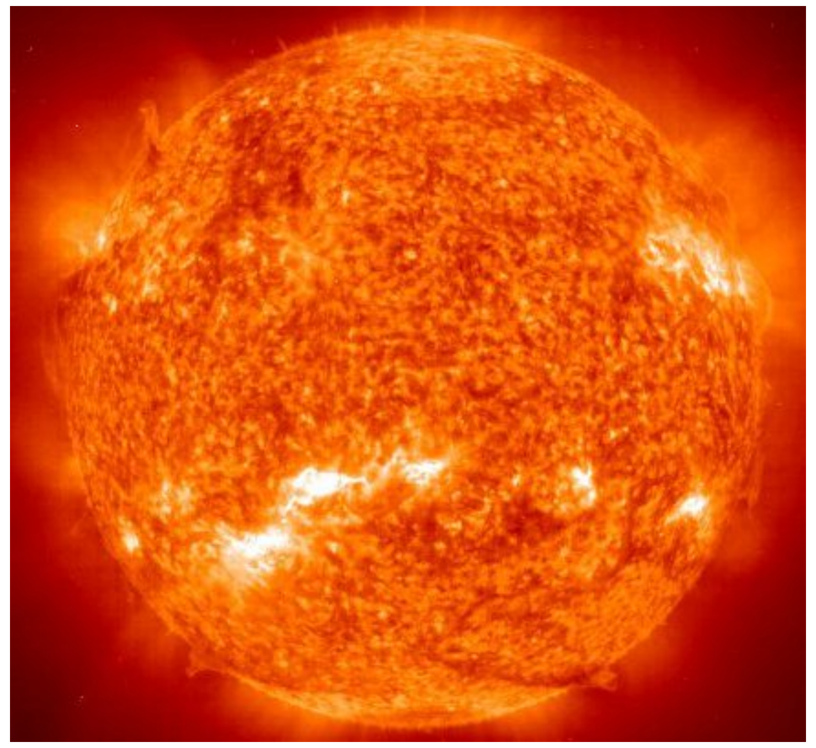
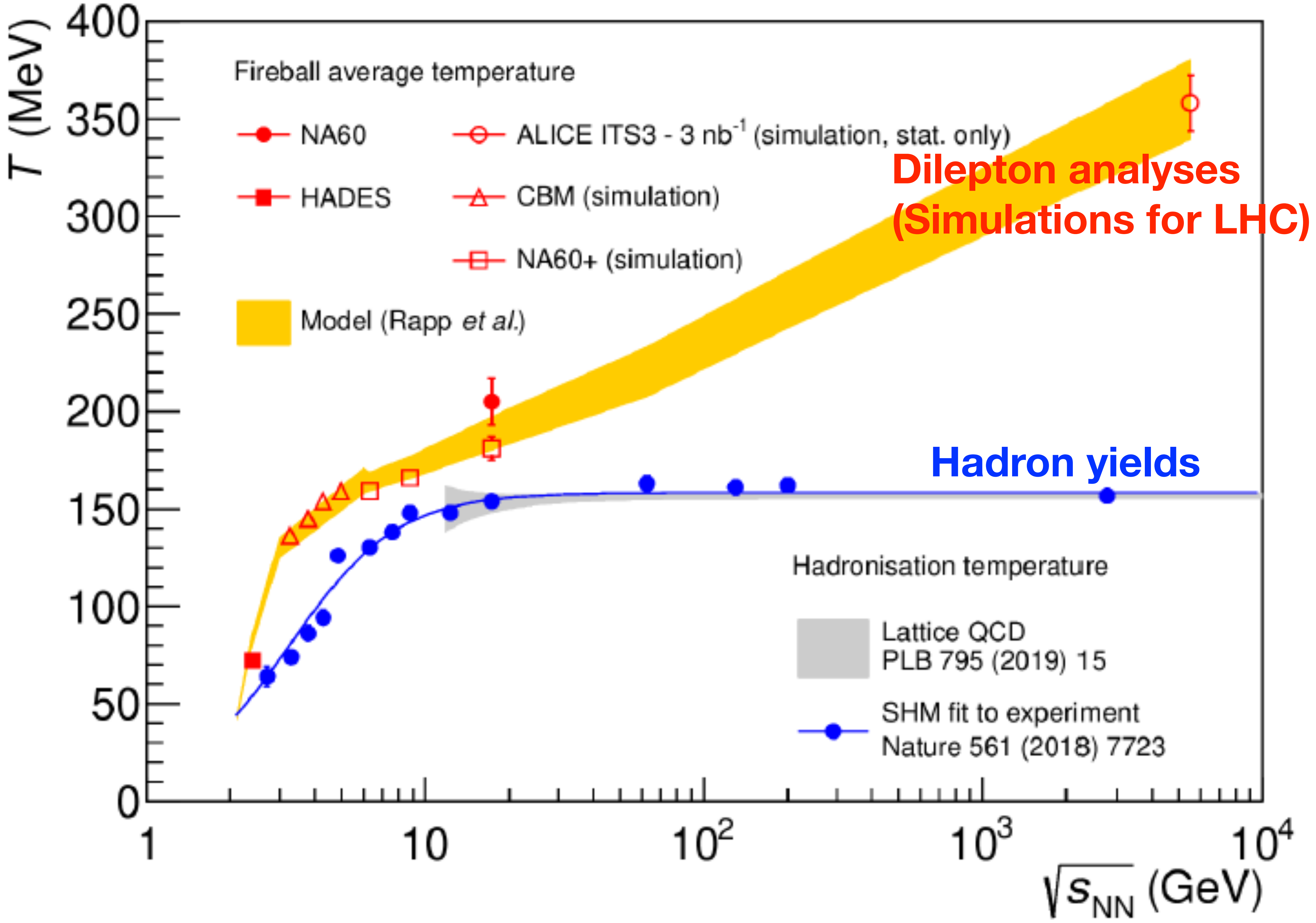


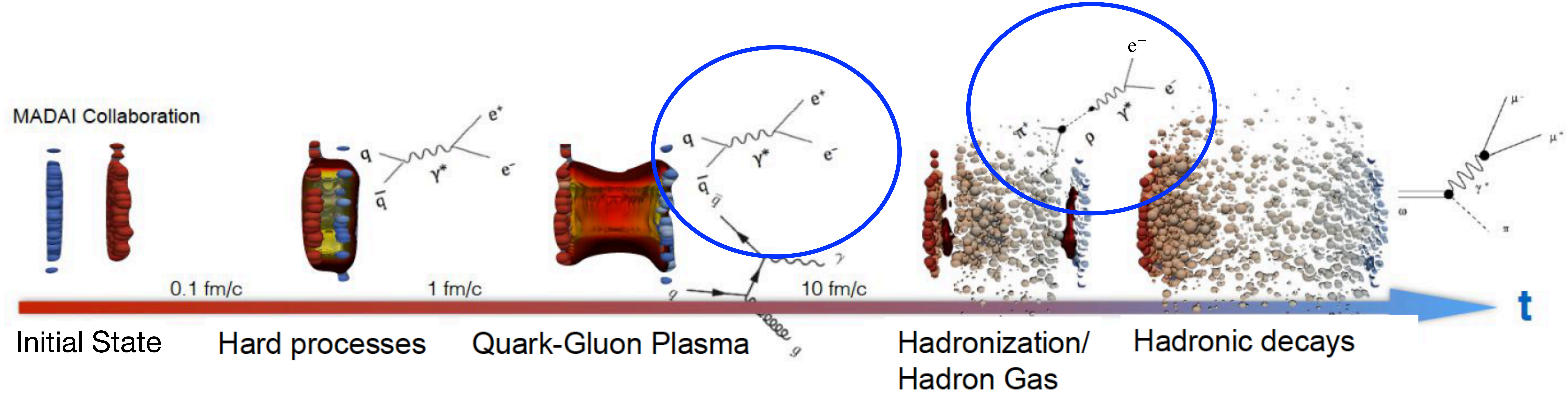
Here from the QGP integrated over space-time
→ Access to early QGP temperature

Temperatures in heavy-ion collisions



Early temperature no accessible **with hadrons**
→ **Temperature at chemical freeze-out**

Other sources of dielectrons



Thermal radiation from the medium are not the only source of $e^{+}e^{-}$!

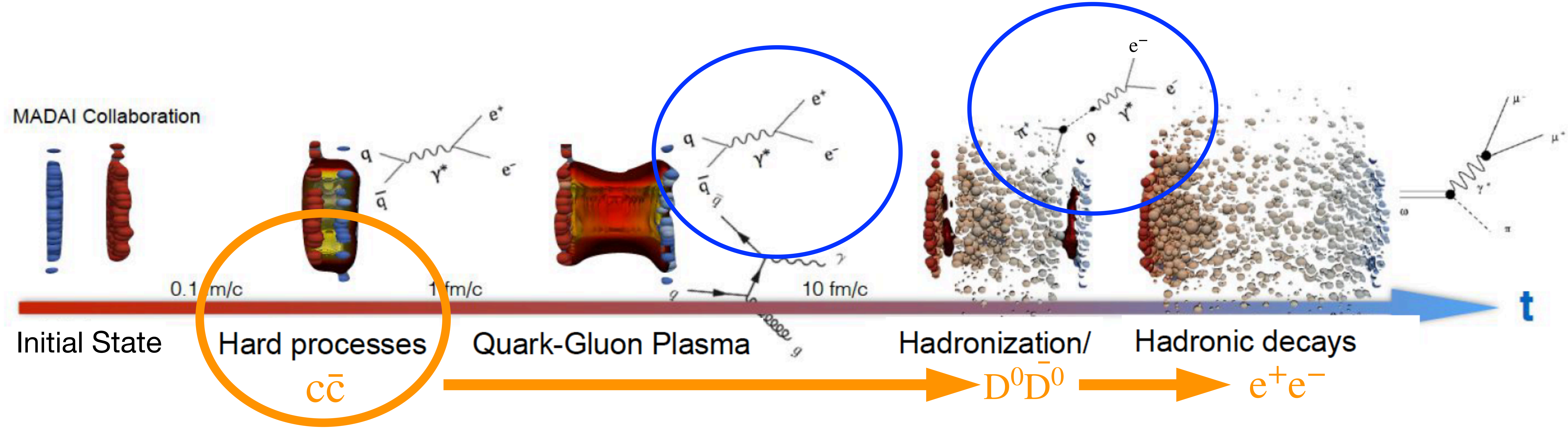
Other sources of dielectrons

Thermal radiation from the medium are not the only source of e^+e^- !

In addition:

- **Light-flavour hadron decays → Can be estimated from measured hadron spectra**
- Correlated heavy-flavour hadron decays
- Drell-Yan (negligible at LHC energies)

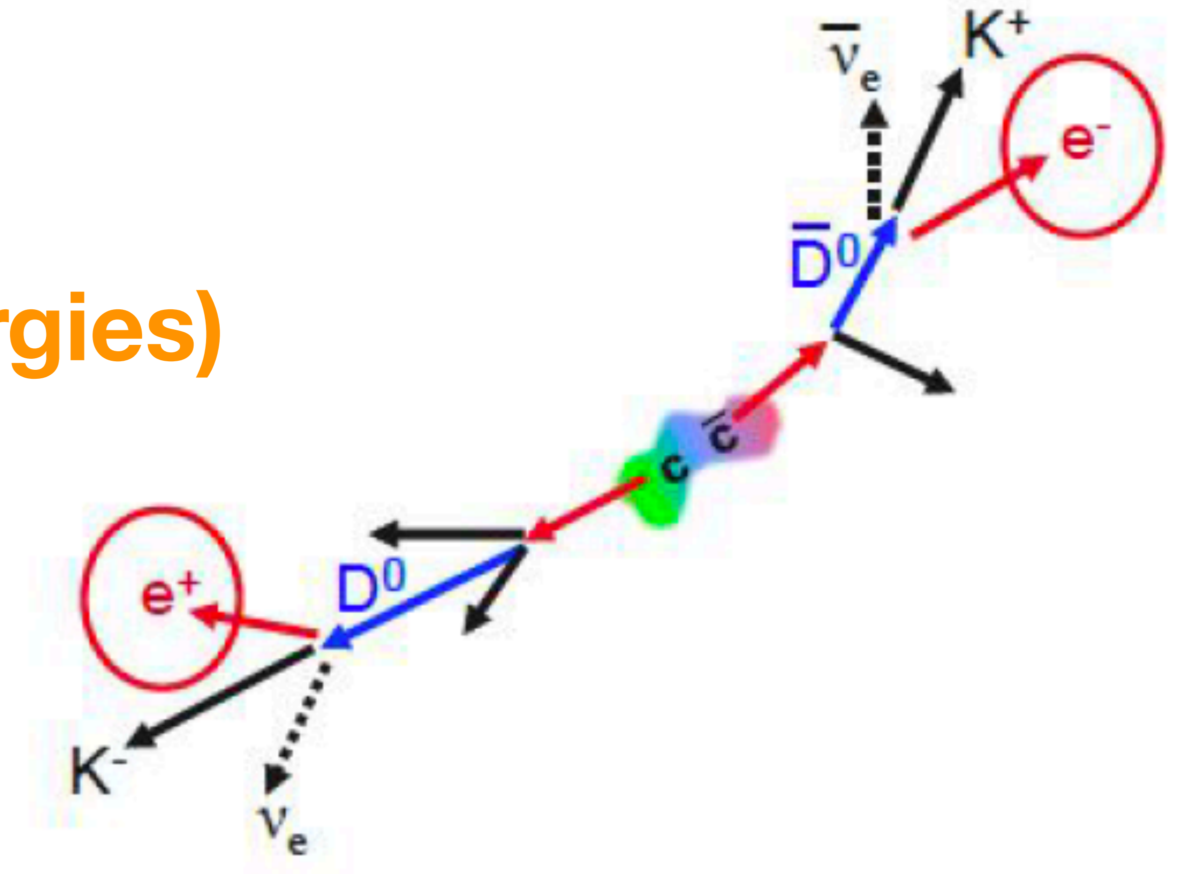
Other sources of dielectrons



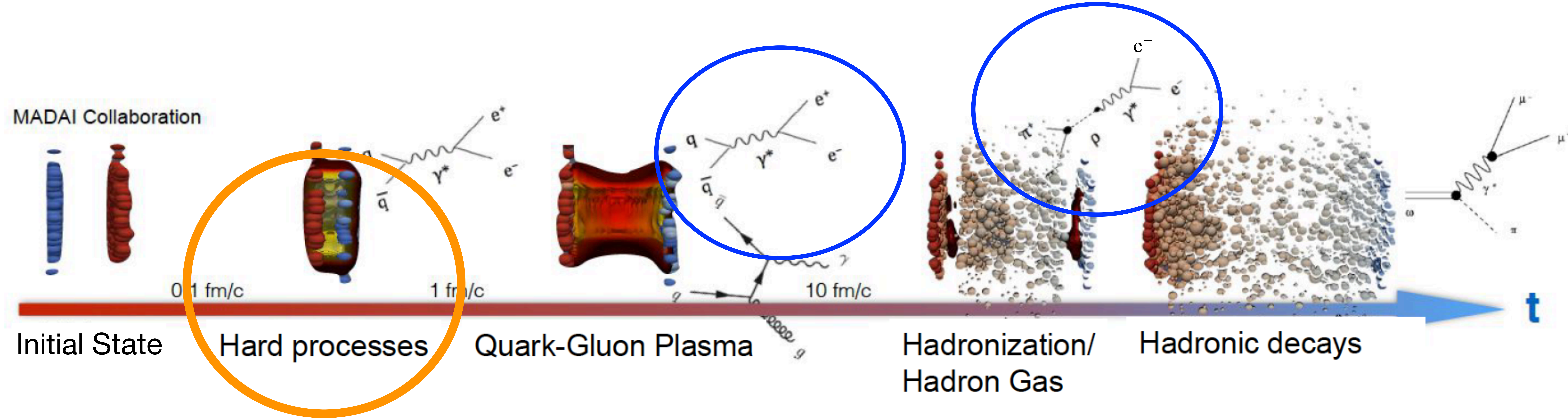
Thermal radiation from the medium are not the only source of e^+e^- !

In addition:

- Light-flavour hadron decays
- **Correlated heavy-flavour hadron decays (very large at LHC energies)**
  - **→ weak decays displaced from the interaction point**
- Drell-Yan (negligible at LHC energies)



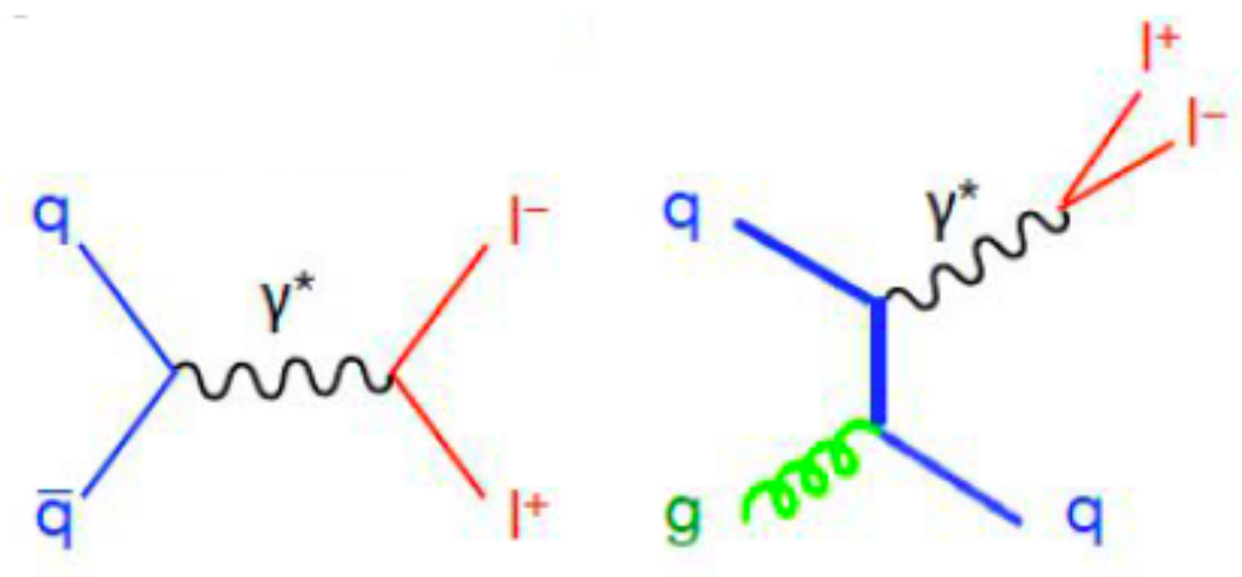
Other sources of dielectrons



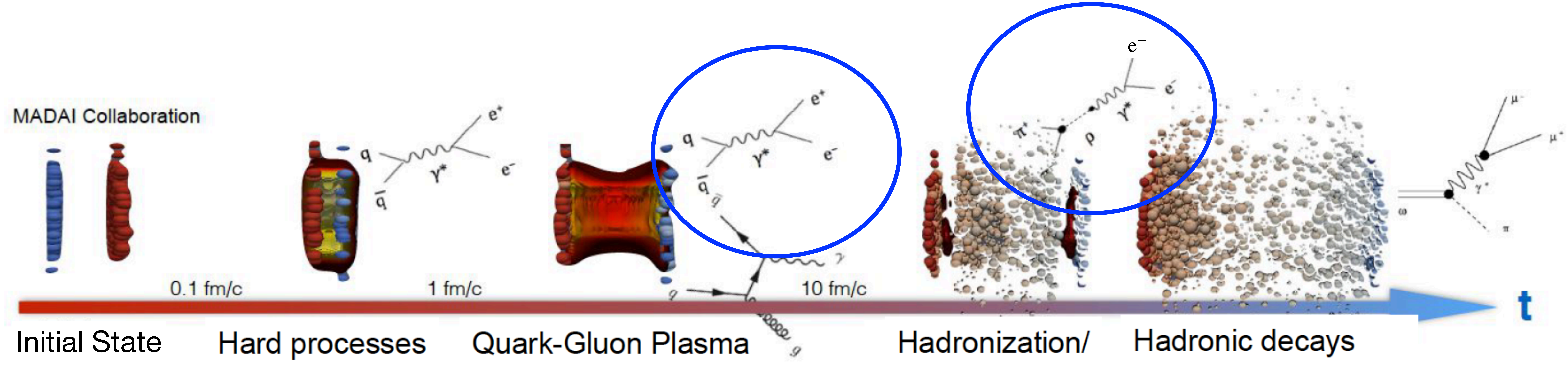
Thermal radiation from the medium are not the only source of e^+e^- !

In addition:

- Light-flavour hadron decays
- Correlated Heavy-flavour hadron decays
- **Drell-Yan → Negligible at LHC energies**



Other sources of dielectrons



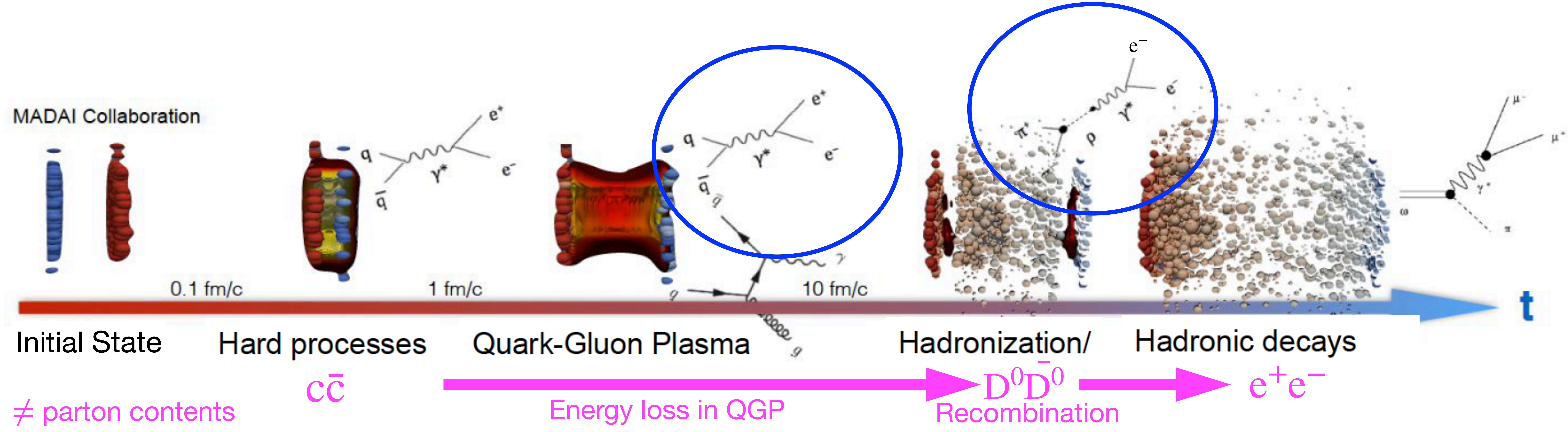
Thermal radiation from the medium are not the only source of e^+e^- !

In addition:

- Light-flavour hadron decays
- Heavy-flavour hadron decays
- Drell-Yan (negligible at LHC energies)

➡ **Main sources in proton-proton collisions (no thermal radiation)**

Other sources of dielectrons



Thermal radiation from the medium are not the only source of e^+e^- !

In addition:

- Light-flavour hadron decays
- Heavy-flavour hadron decays
- Drell-Yan (negligible at LHC energies)

→

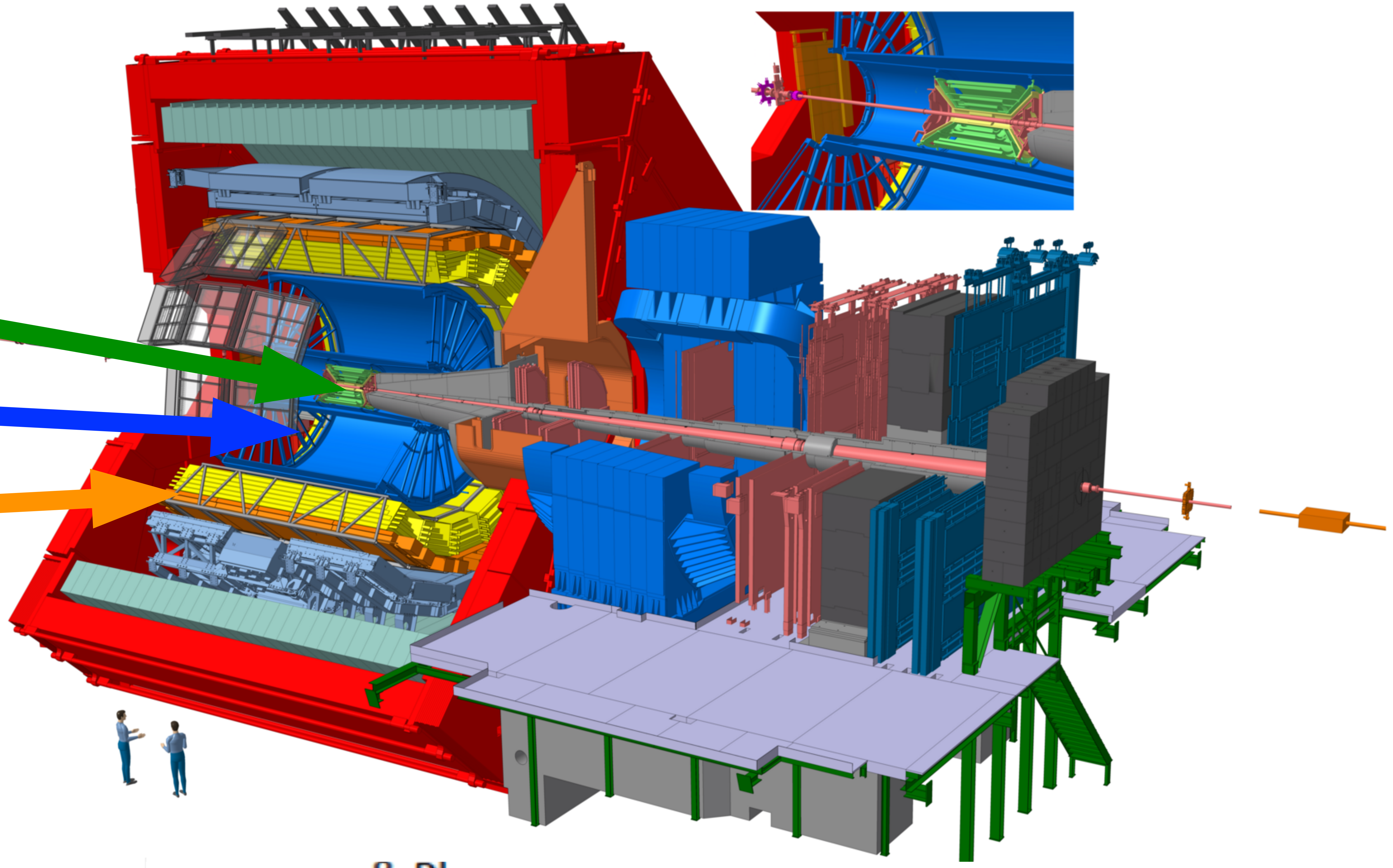
Main sources in proton-proton collisions (no thermal radiation)

Modified in p-Pb (cold-nuclear matter effect) and Pb—Pb (hot and cold-nuclear matter effect)

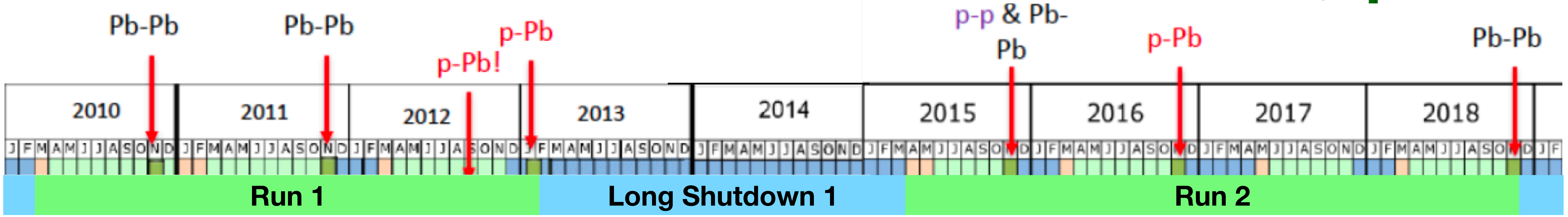
A Large Ion Collider Experiment

Dielectrons measured at midrapidity ($(|\eta_e| < 0.8)$)
in the central barrel

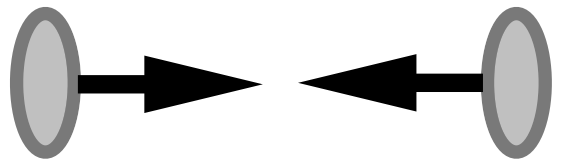
- **Inner Tracking System**
  Tracking, vertexing, particle identification
- **Time Projection Chamber**
  Tracking and particle identification
- **Time-Of-Flight**
  Particle identification



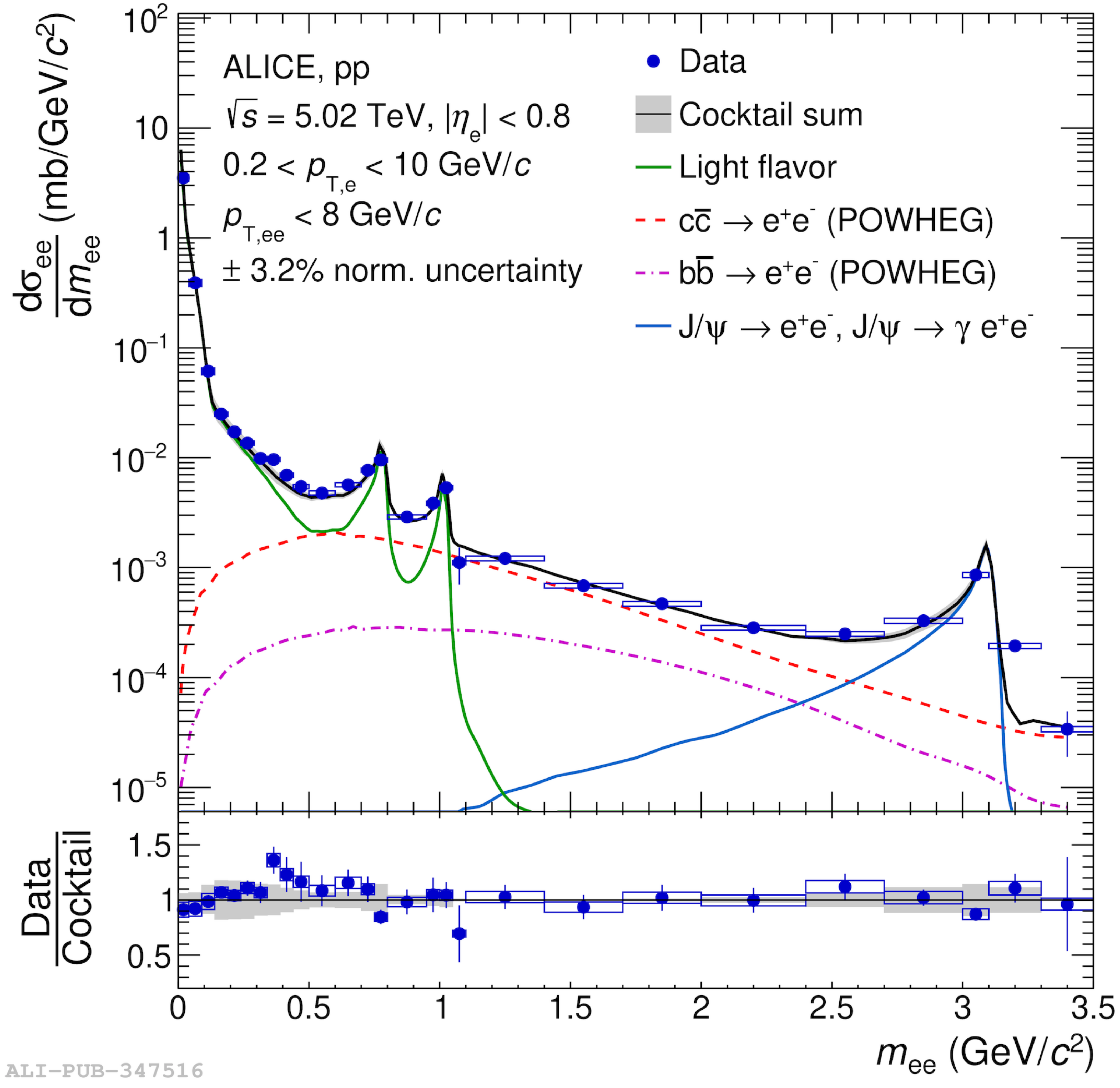
Results from Run 1 and Run 2 coming out



Baseline in proton-proton collisions

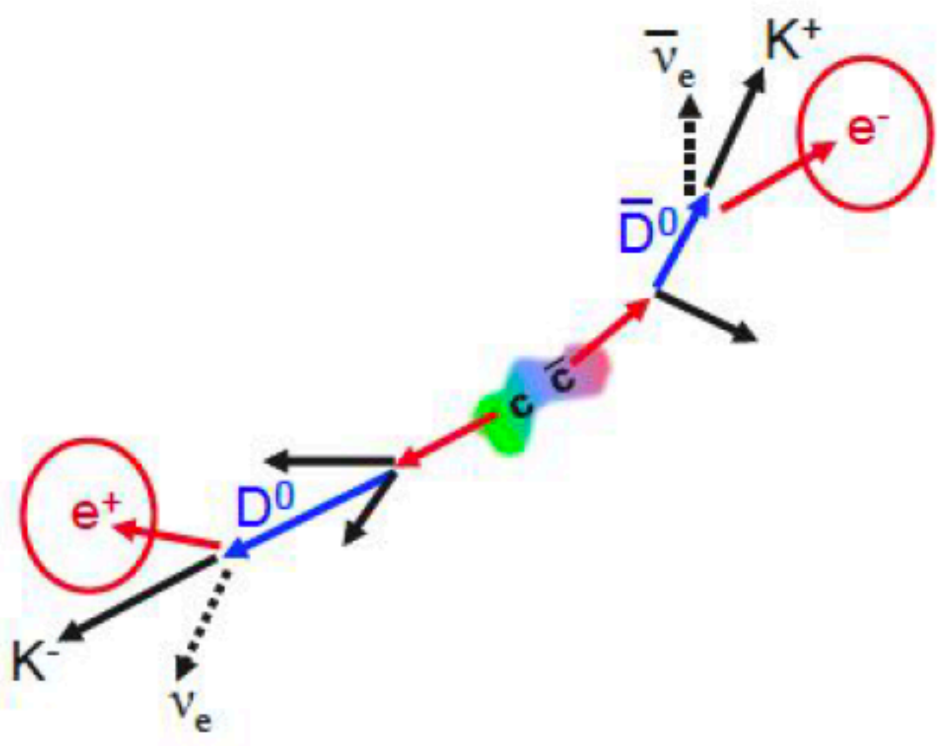


ALICE Phys. Rev. C102 (2020) 055204



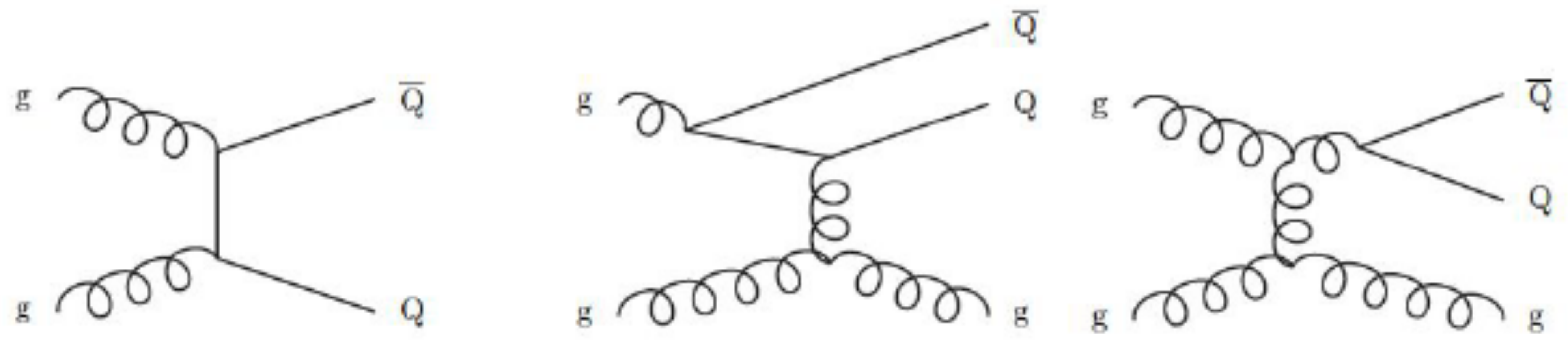
- pp collisions at the same $\sqrt{s}$ = 5.02 TeV
- Data ($p_{T,e} > 0.2$ GeV/c) fully described by hadronic sources
  - Light-flavour hadron decays
  - J/ψ decays
  - Correlated open-charm and open-beauty hadron decays

Baseline in proton-proton collisions



$c\bar{c}$ **and** $b\bar{b}$ **contributions** dominant for $1.1 < m_{ee} < 2.7$ GeV/c^2 and fitted to the data in m_{ee} and $p_{T,ee}$ in this range

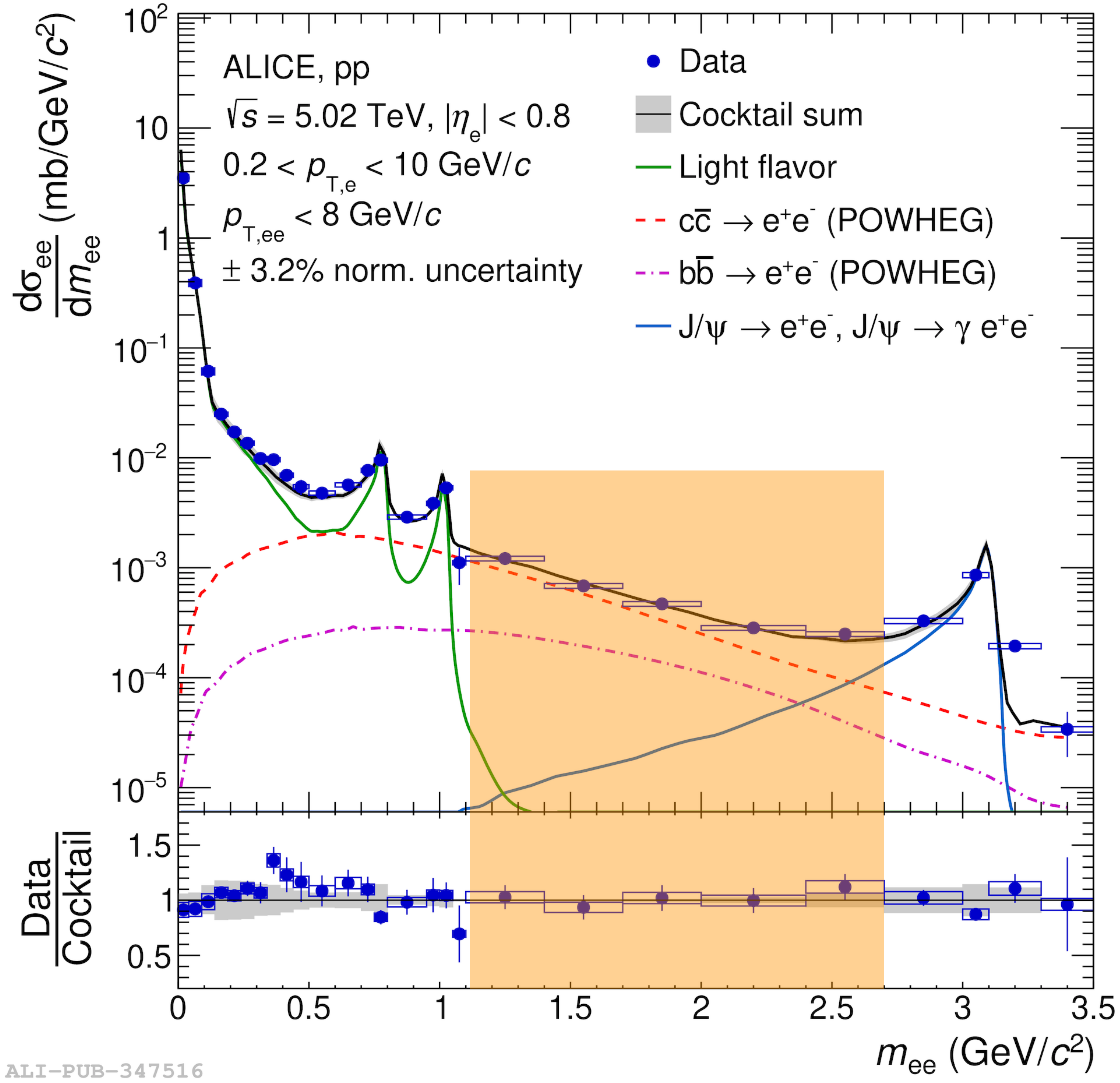
→ **Sensitive to kinematic correlation between** Q **and** $\bar{Q}$ linked to the $Q\bar{Q}$ production mechanisms



Leading order
Pair creation

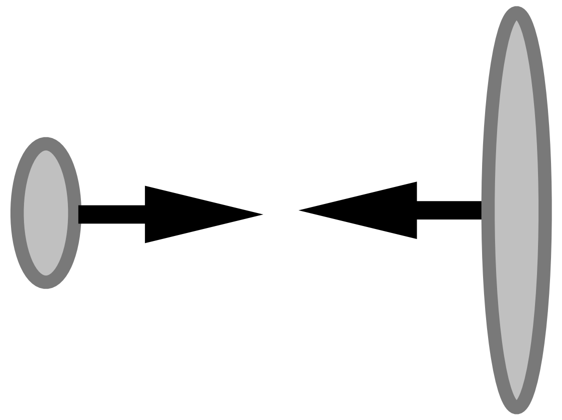
Next Leading order
Flavour excitation   Gluon splitting

ALICE Phys. Rev. C102 (2020) 055204



Dileptons complementary probe to study heavy-flavour physics at the LHC

Dielectrons in proton-lead collisions

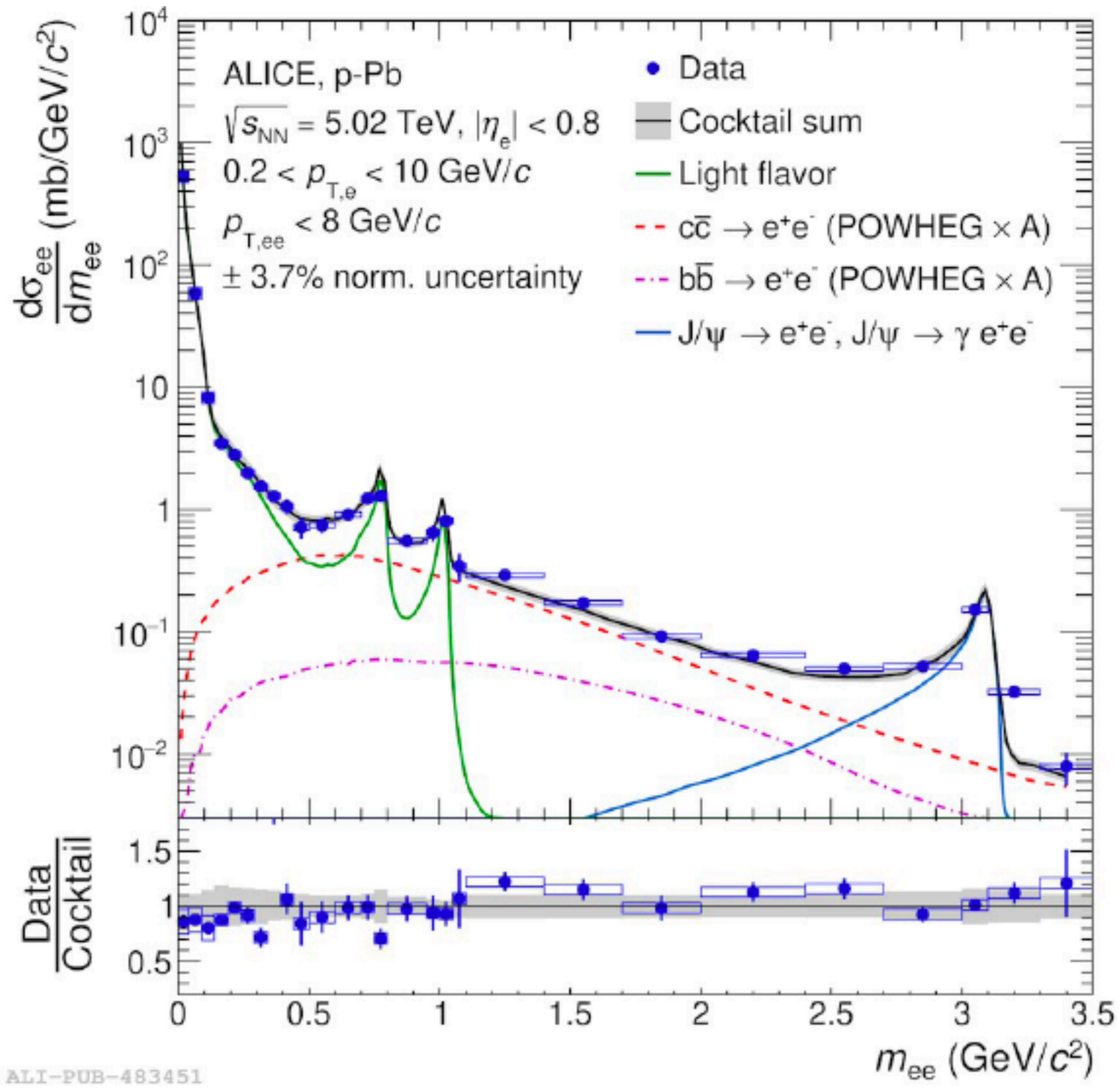


- p—Pb collisions at the same $\sqrt{s_{NN}}$ = 5.02 TeV

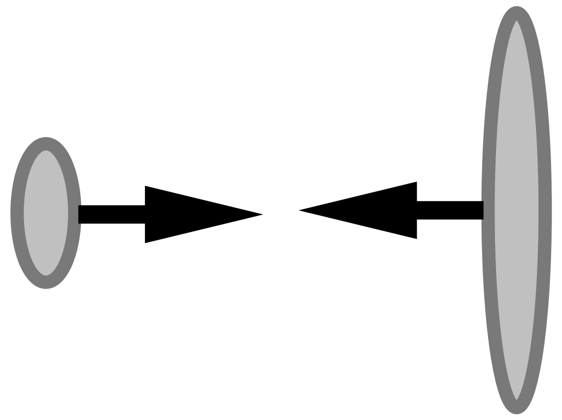
- Input from independent measurements for the light-flavour and J/ψ contributions

- Heavy-flavour cocktail assuming simple scaling with the number of binary nucleon-nucleon collisions from pp to p-Pb
  → Deviation from vacuum expectation seems to be below the sensitivity of the data

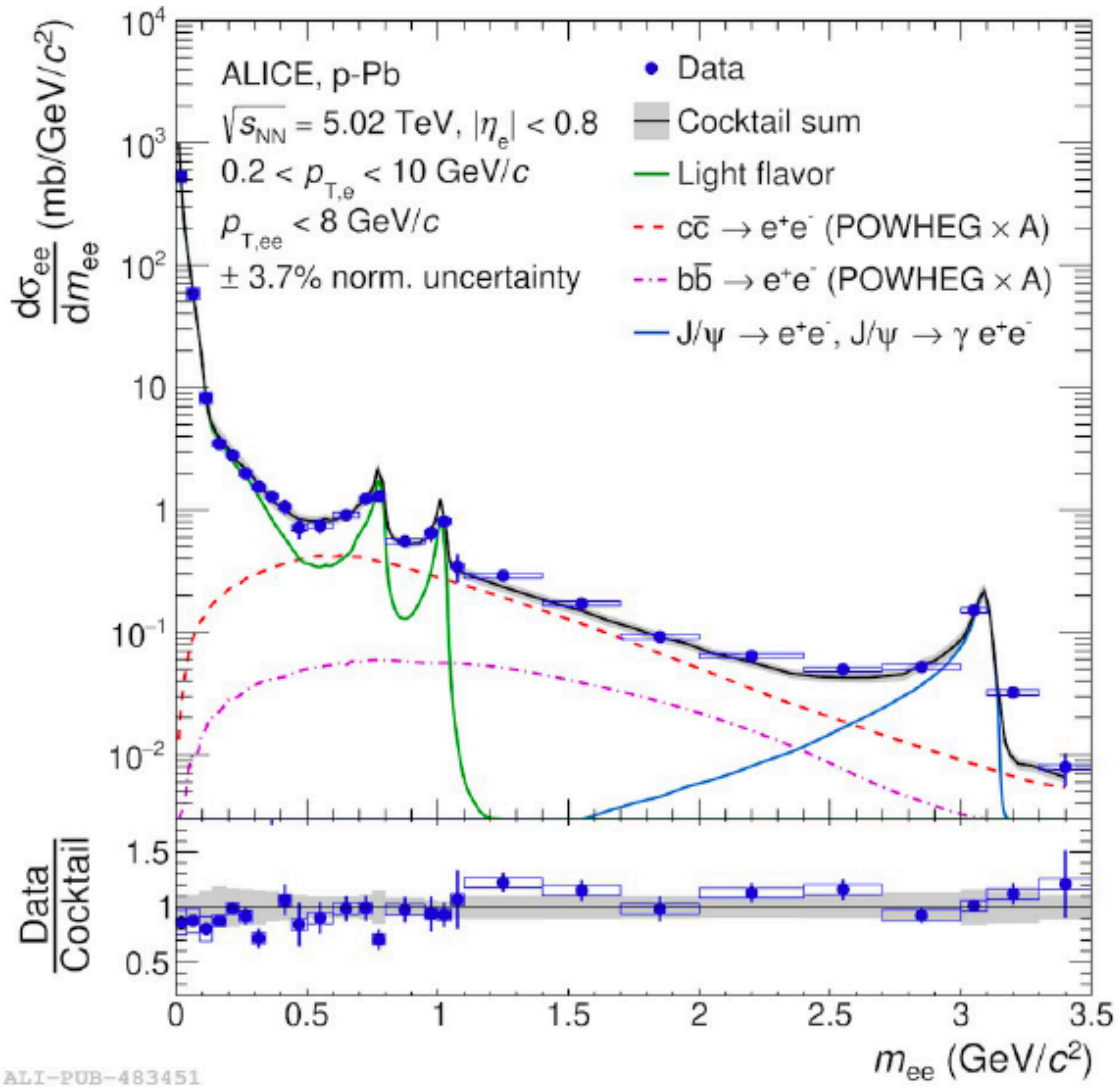
ALICE Phys. Rev. C102 (2020) 055204



Dielectrons in proton-lead collisions



ALICE Phys. Rev. C102 (2020) 055204



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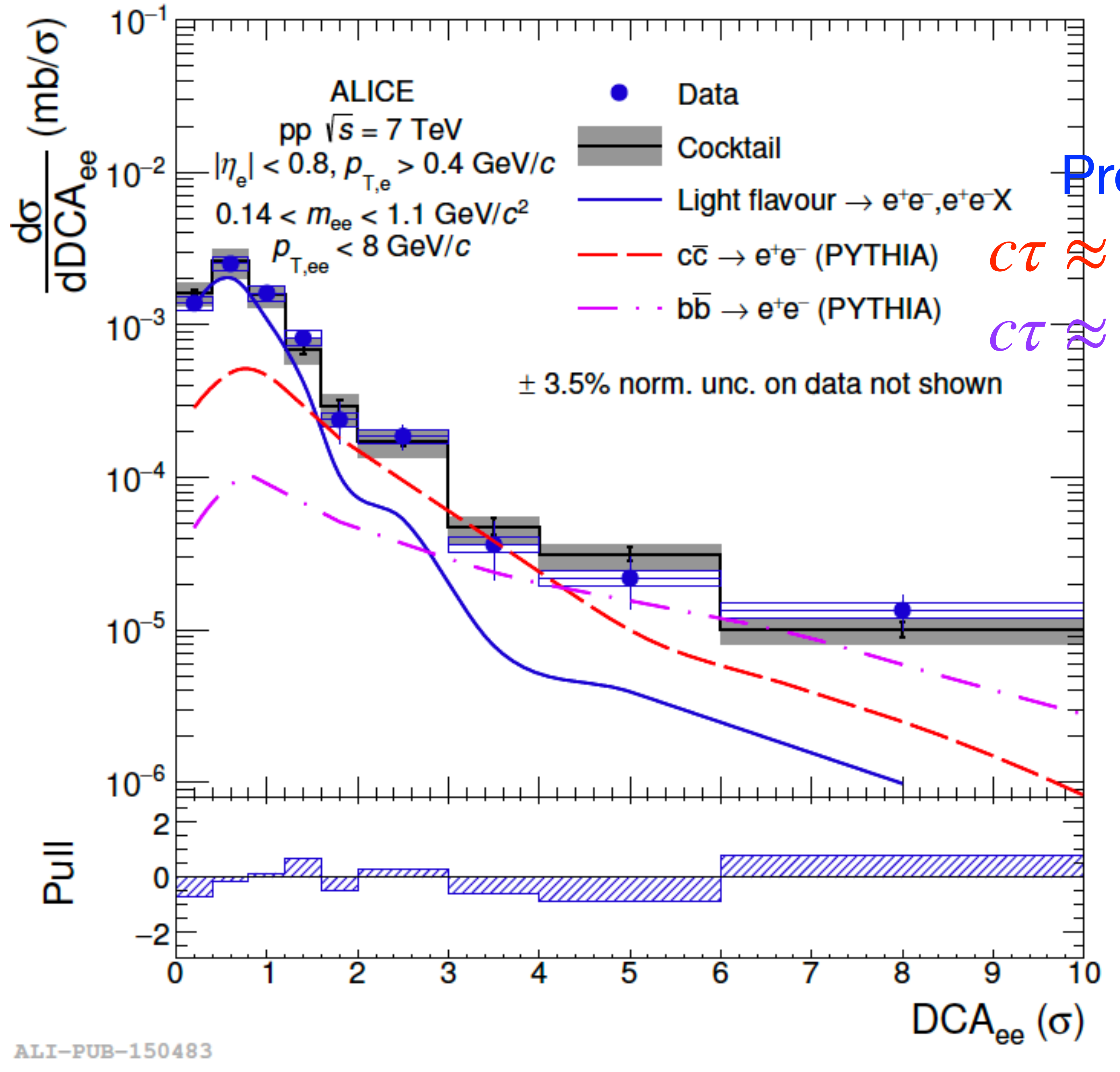
- Heavy-flavour cocktail assuming simple scaling with the number of binary nucleon-nucleon collisions from pp to p-Pb
  → Deviation from vacuum expectation seems to be below the sensitivity of the data

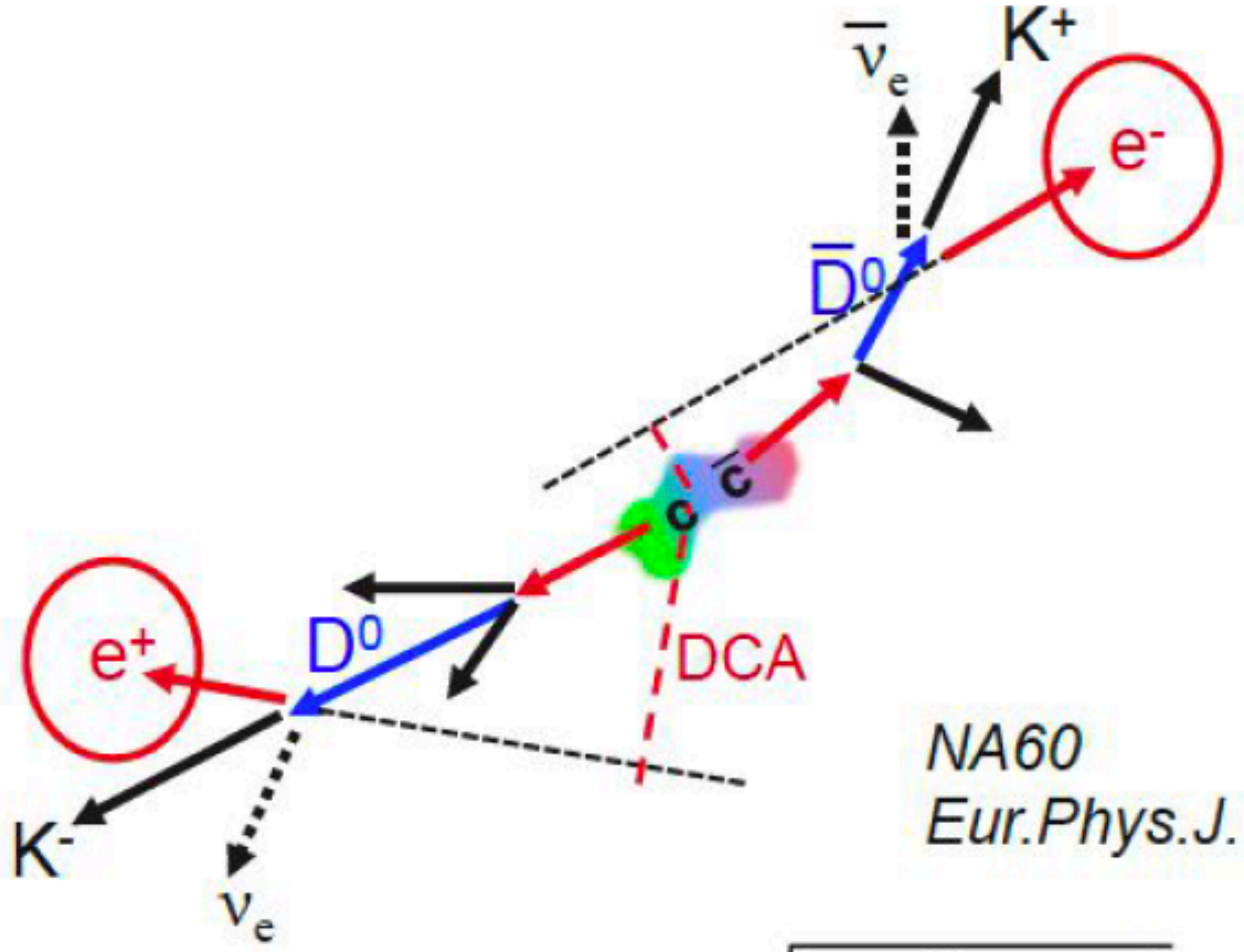
Possible small contributions from thermal radiation
→ Important to disentangle different e^+e^- sources

Topological separation

ALICE JHEP 1809 (2018) 064



Prompt
$c\tau \approx 150\mu m$
$c\tau \approx 470\mu m$



NA60
Eur.Phys.J. C59 (2009)

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

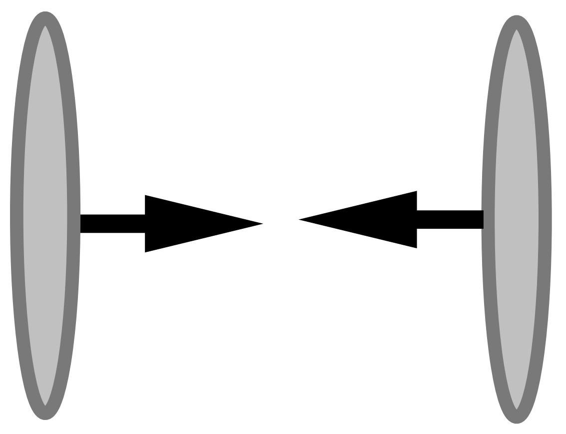
DCA$_{ee}$ (prompt) < DCA$_{ee}$(charm) < DCA$_{ee}$(beauty)

Separate thermal radiation from heavy-flavour background

Tested in pp collisions at $\sqrt{s}$ = 7 TeV (Run 1)

→ Expect better separation power in Run 3 and beyond

Central lead-lead collisions

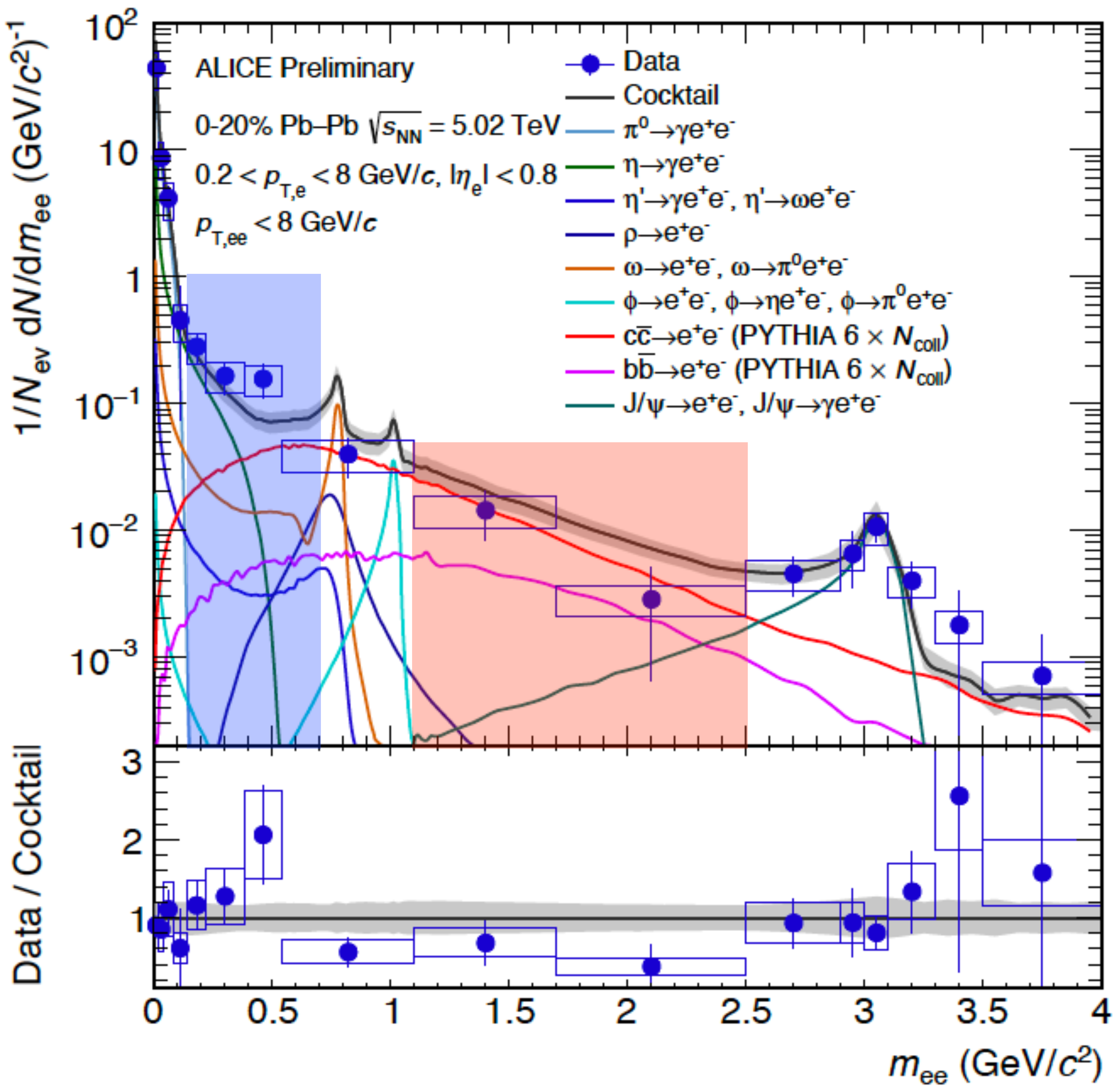


- Study on going in central Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV
  (Here: only 30% of the Run 2 data, no use of $\mathrm{DCA_{ee}}$)

- **Hint for a low-mass enhancement**
  Factor 1.15 ± 0.18 (stat.) ± 0.31 (syst.) ± 0.17 (cocktail) in $0.15 < m_{\mathrm{ee}} < 0.7$ GeV/c^2
  → Additional thermal radiations not in the cocktail

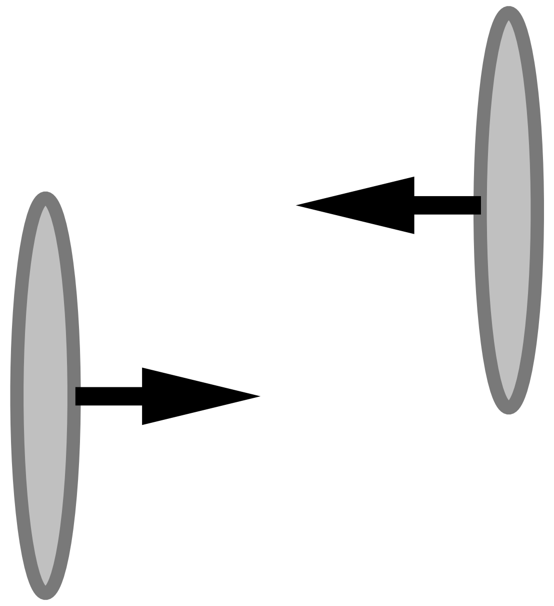
- **Indication for charm suppression**
  at intermediate mass ($1.1 < m_{\mathrm{ee}} < 2.5$ GeV/c^2)

**Mandatory to use $\mathrm{DCA_{ee}}$
to control heavy-flavour background**



See also ALICE Phys. Rev. C 99, 024002 (2019) for Run 1 data

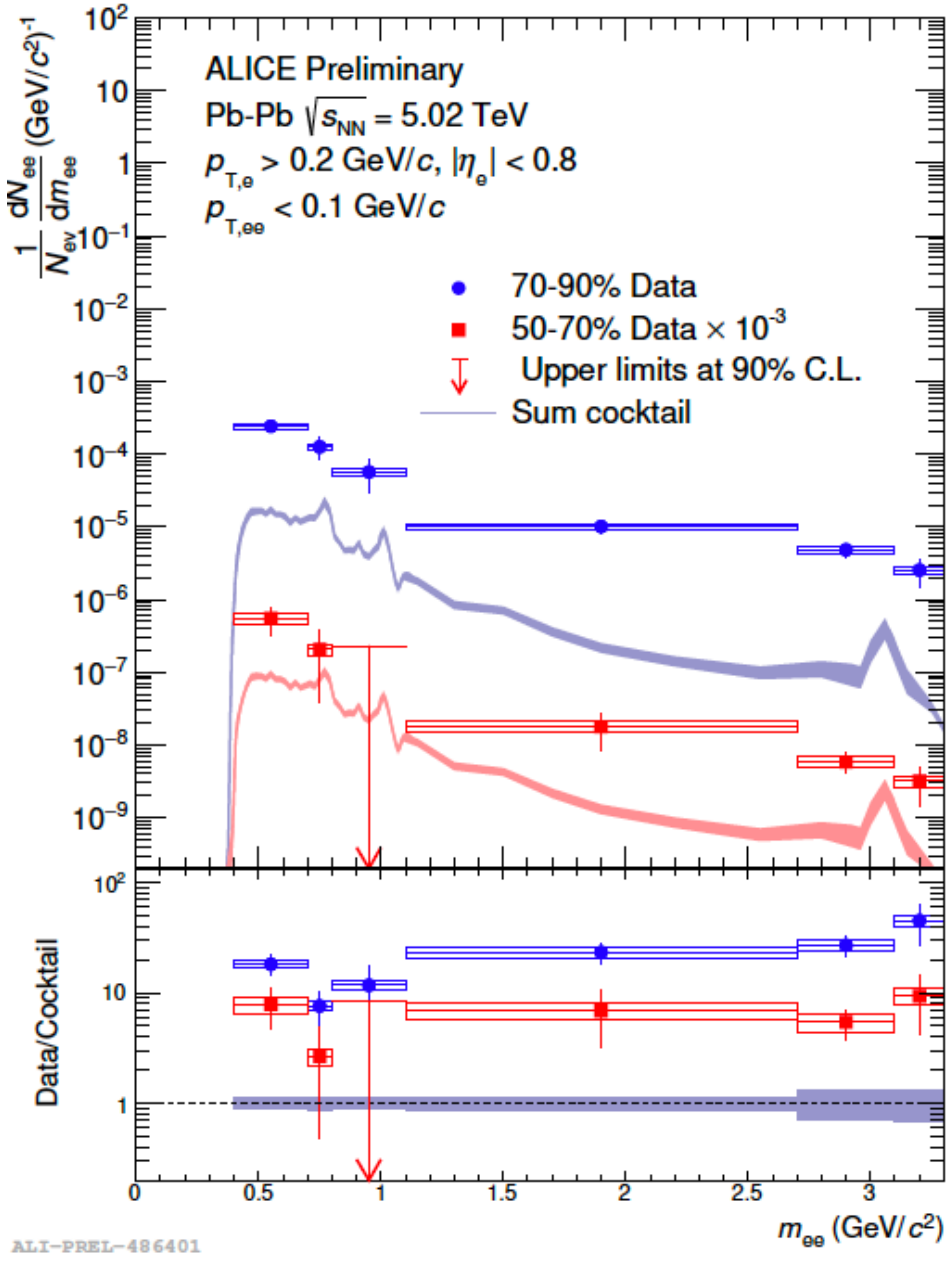
Peripheral lead-lead collisions



- e^+e^- **at very low pair momenta** in 50-70% and 70-90% most peripheral Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

  → **Clear excess over hadronic sources**

- Lorentz-contracted passing nuclei produce electromagnetic fields:
  - Strongest in the known universe
    (Up to 10^{15} Tesla, maximum electric field $\approx Ze\gamma_L/b^2$)
  - Acting over a very short timescale (10^{-25}s at LHC)



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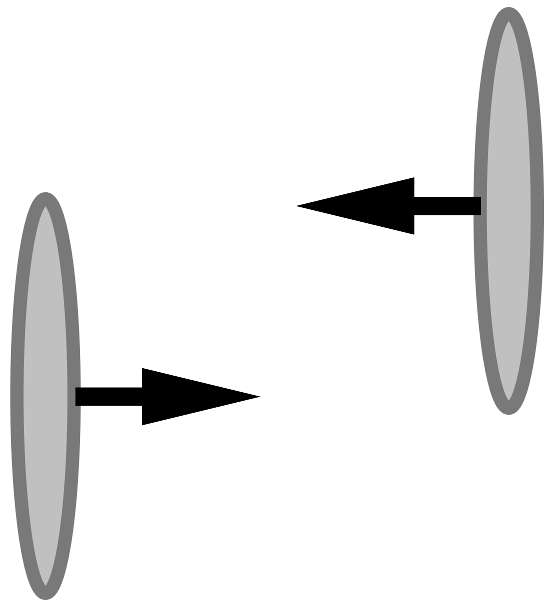

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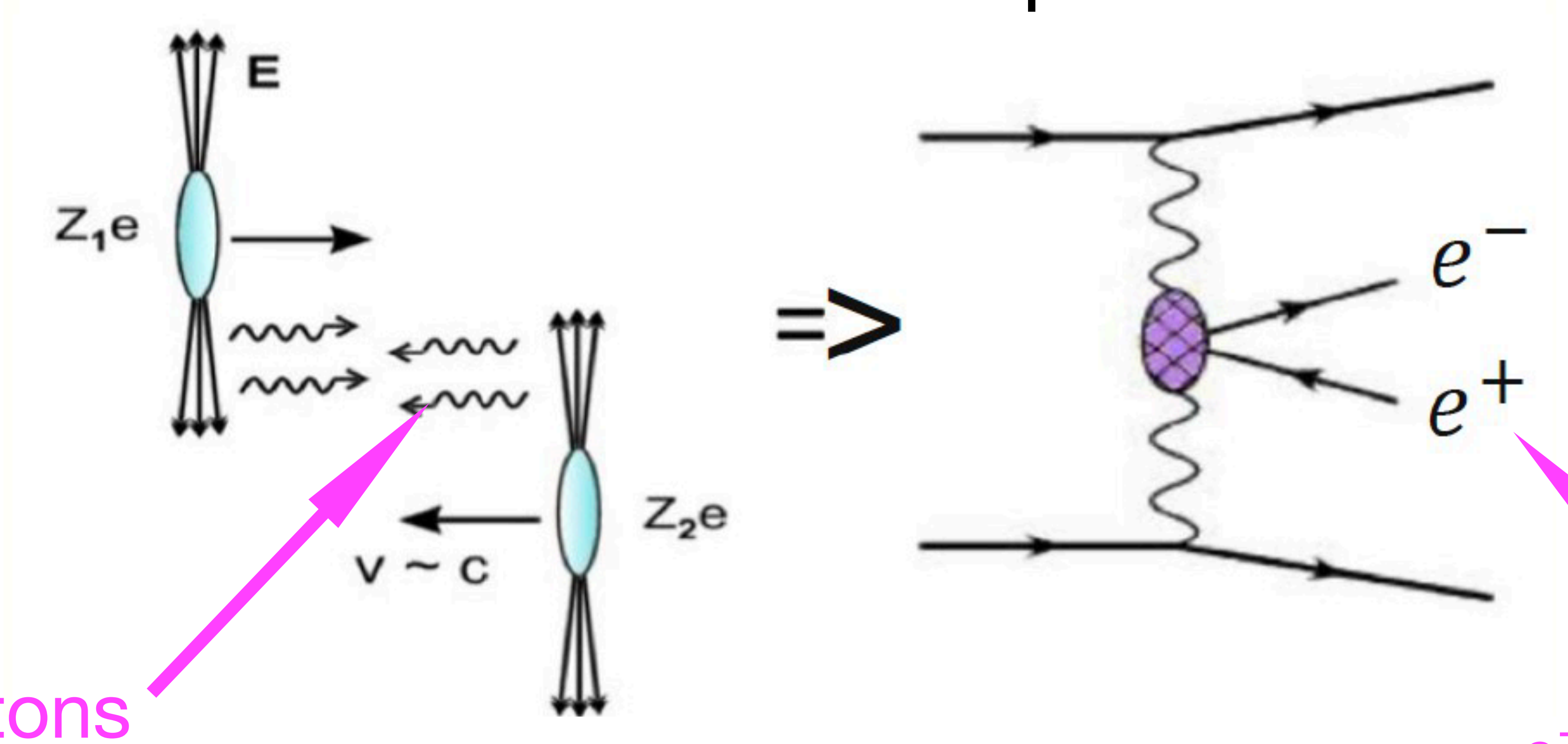
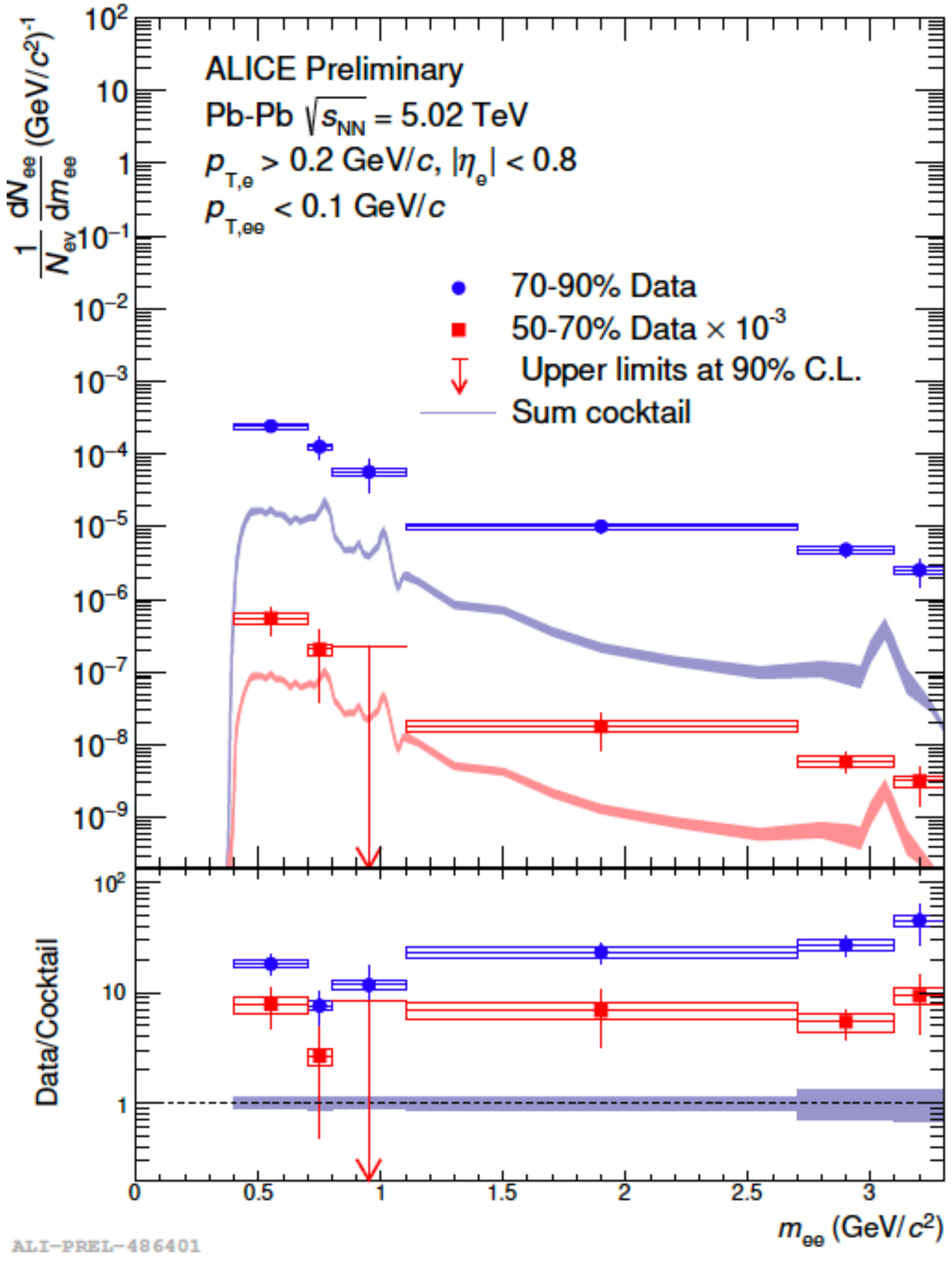
Breit-Wheeler process



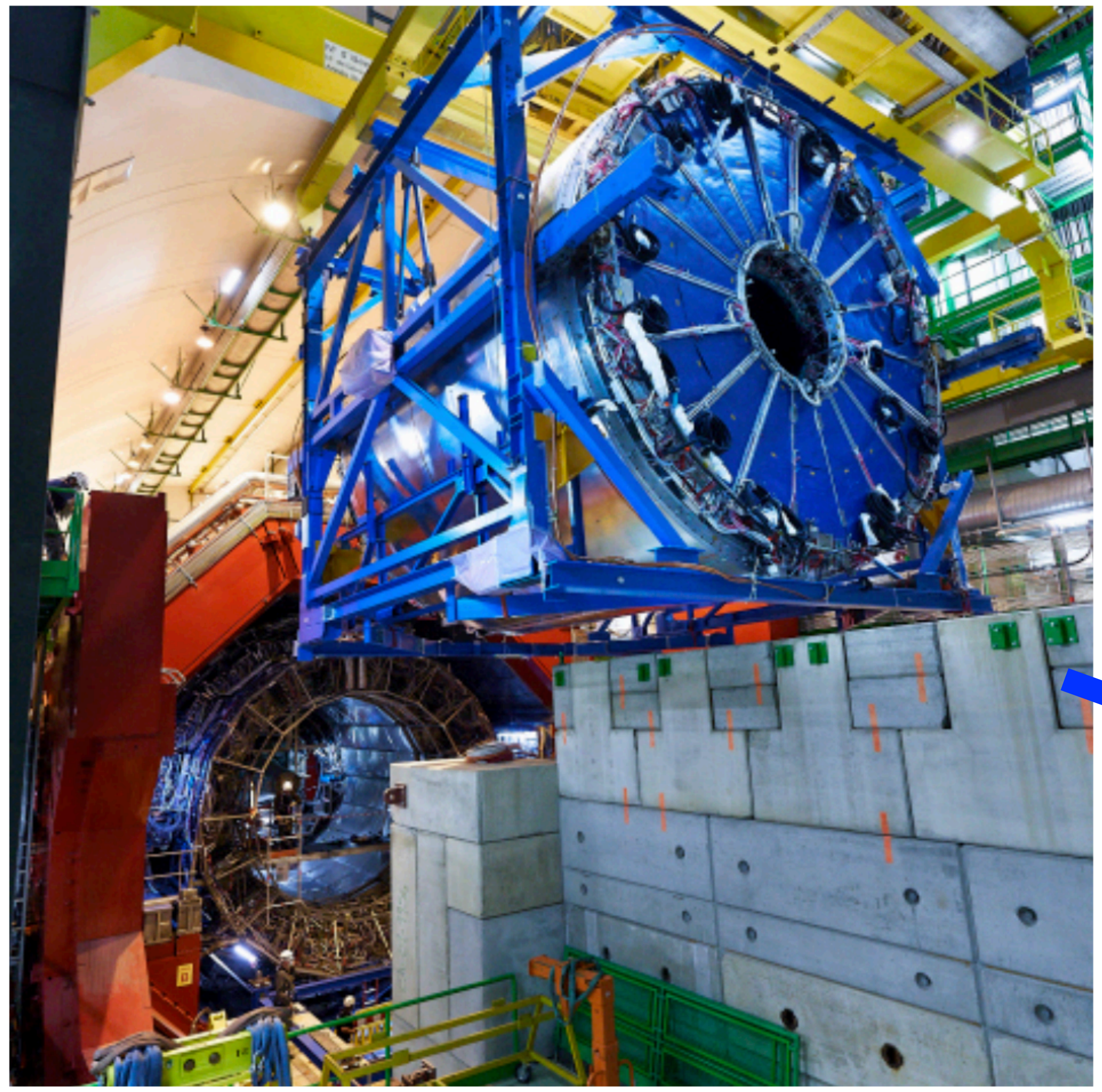
Quasi-real photons in beam direction

e^+e^- with very small $p_{T,ee}$



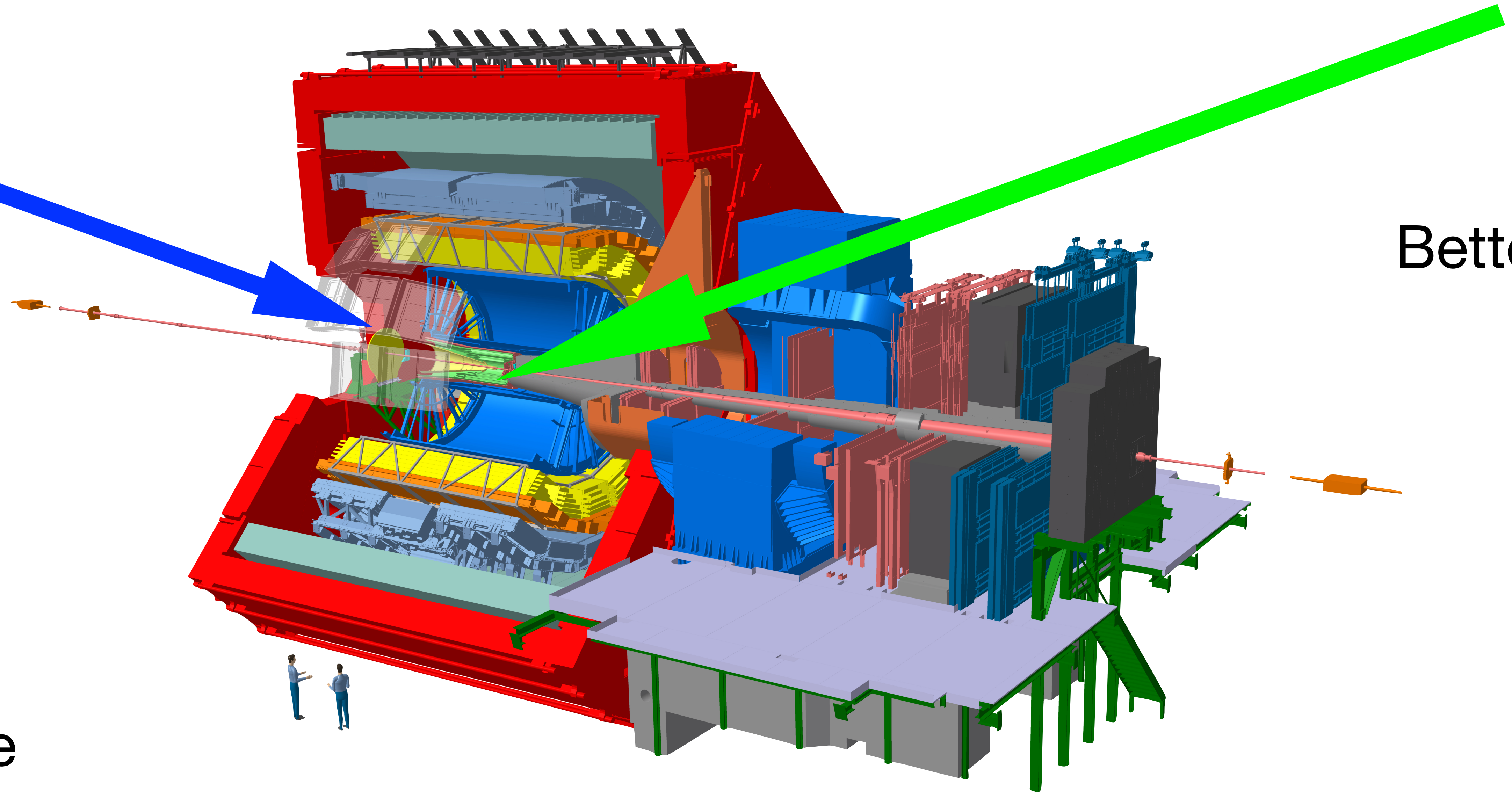
ALICE timeline

Long Shutdown 2 → ALICE 2



Time Projection Chamber
- GEM-based chambers
- New front-end electronics

→ Factor > 50 higher acquisition rate



New and upgraded central detectors

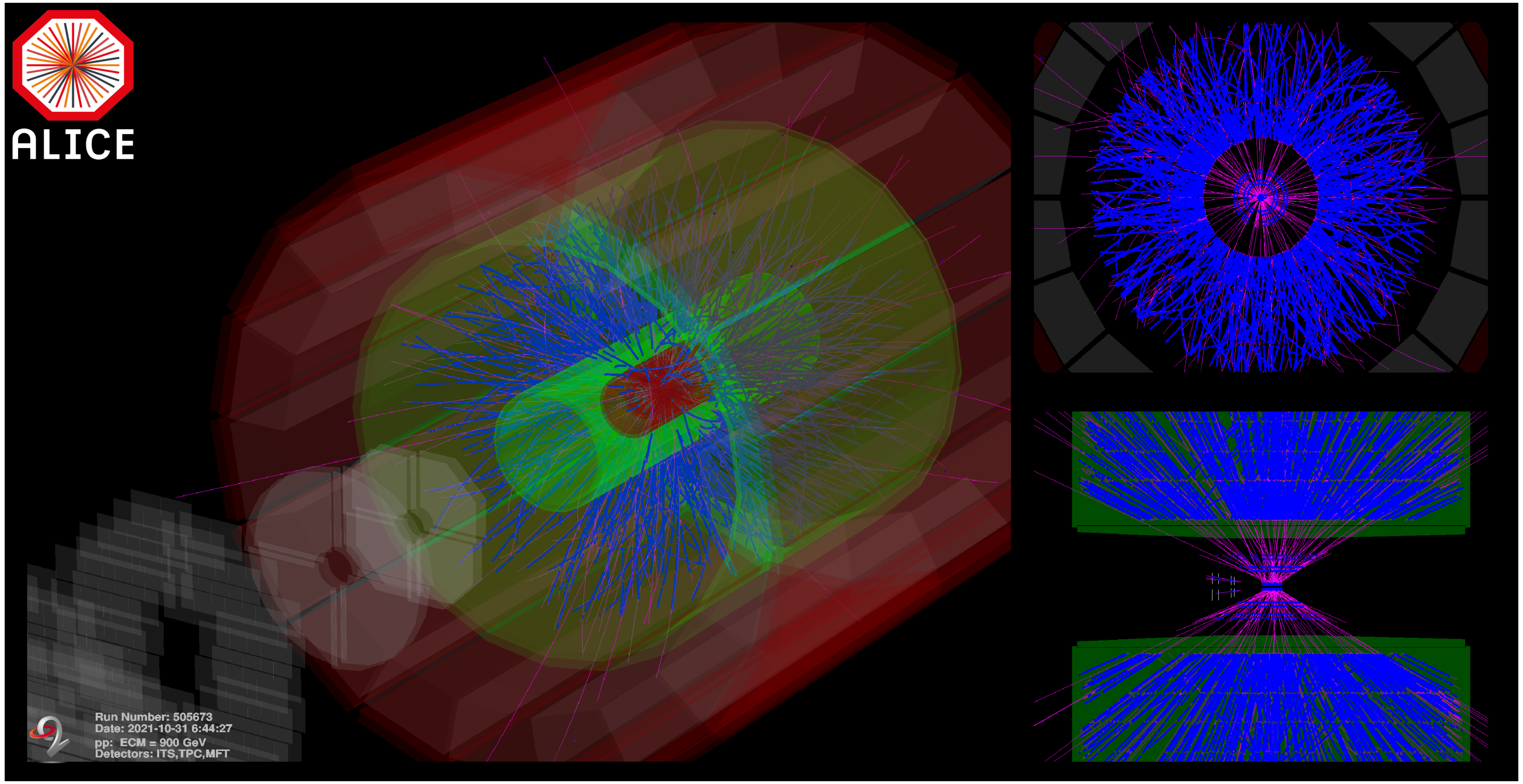
Continuous readout of Pb—Pb at 50 kHz

→13 nb^{-1} in Run 3 & 4

Inner Tracking System 2
Better pointing resolution (x3 in xy, x6 in z)

O2 Computing Farm
- Online Processing of all events
- Relevant for experiments at LHC, FAIR

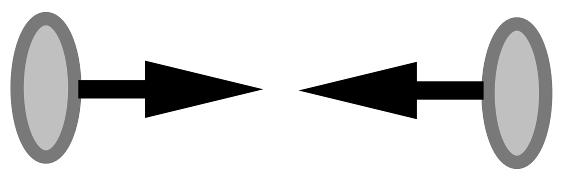
LHC pilot beam



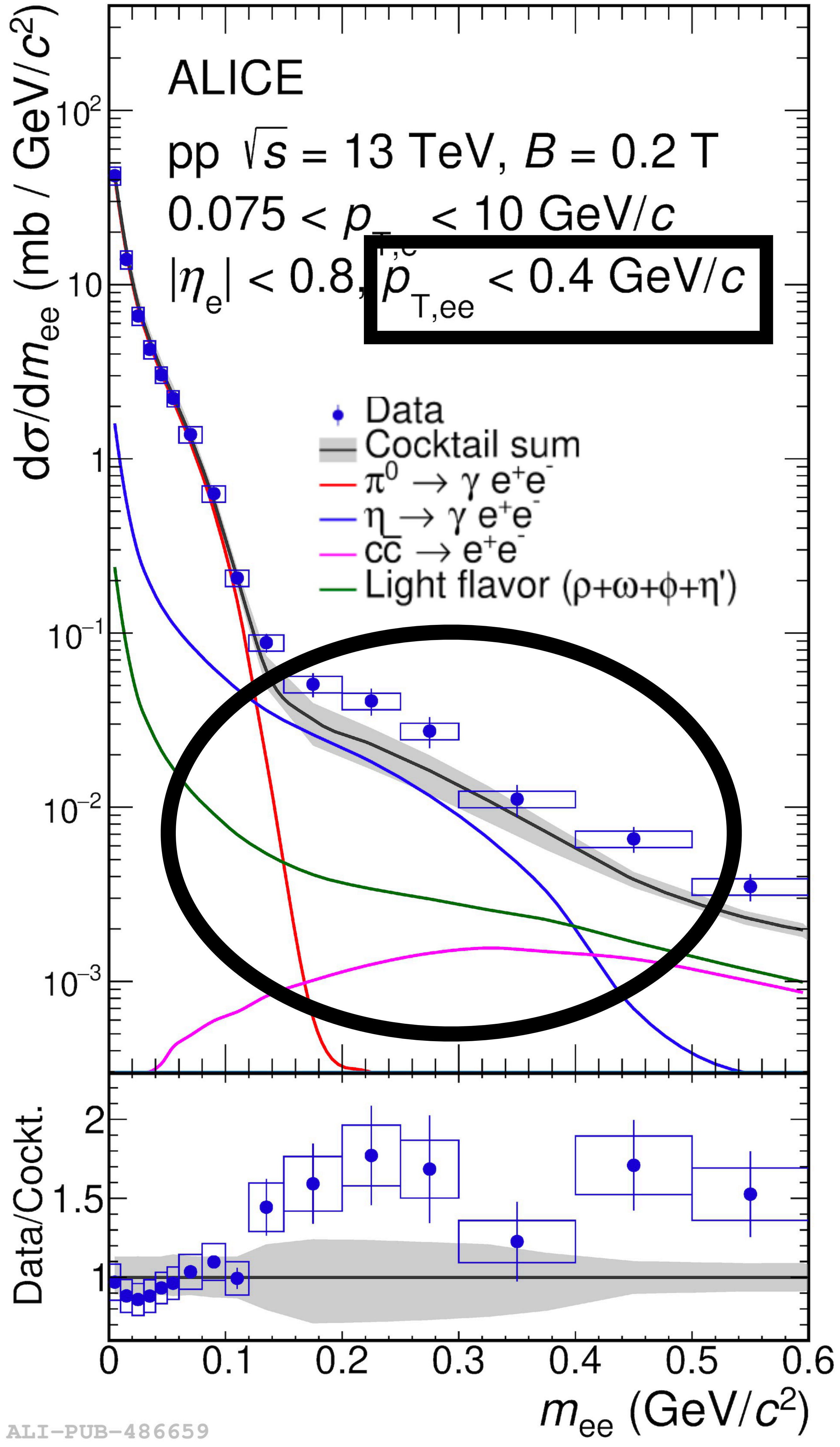
pp collisions in October 2021 at $\sqrt{s}$ = 900 GeV

- Upgrades completed and detector performance confirmed
- Continuous readout and synchronous reconstruction verified

Physics prospects Run 3&4



ALICE Phys. Rev. Lett. 127 (2021) 042302



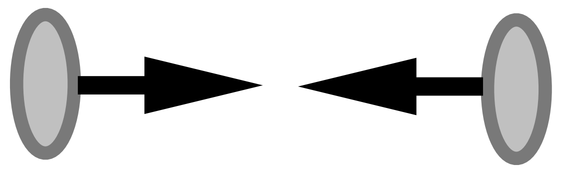
- Anomalous soft-photon and -dilepton excess in hadron-hadron collisions at lower energies reported by several experiments

- Data taken with a reduced ALICE solenoid magnetic field to 0.2 T
  → Unique sensitivity to soft e^+e^- production at the LHC

  First results from Run 2 low-*B* field data at LHC energies:
  → Data above the hadronic cocktail by a factor:
  1.61±0.13 (stat.)±0.17 (syst.)±0.34 (cocktail)
  in $0.14 < m_{ee} < 0.6$ GeV/c^2 & $p_{T,ee} < 0.4$ GeV/c

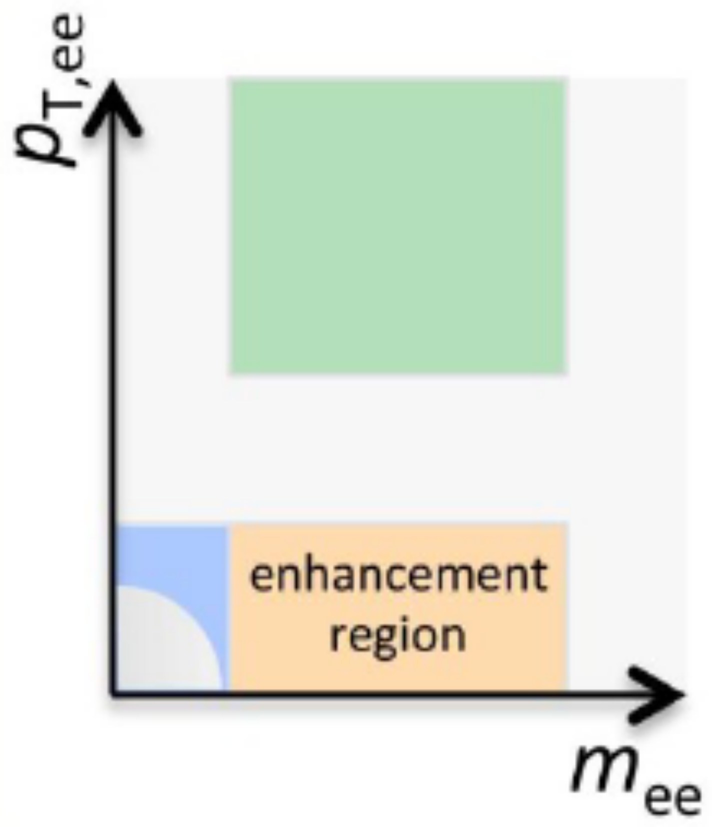
V. Hedberg PhD thesis, Lund (1987); DLS Collaboration, Phys. Rev. Lett. 61 (1988) 1069-1072; M.R.Adams *et al.* Phys, Rev. D27 (1983) 1977-1998; K.J. Anderson *et al.* Phys. Rev. Lett 37 (1976) 700-802; A.Belogianni *et al.* Phys.Lett. B548 no. 3 (2002) 122-128,129-130; J.Antos et al. Z. Phys. C59 (1993) 547-554

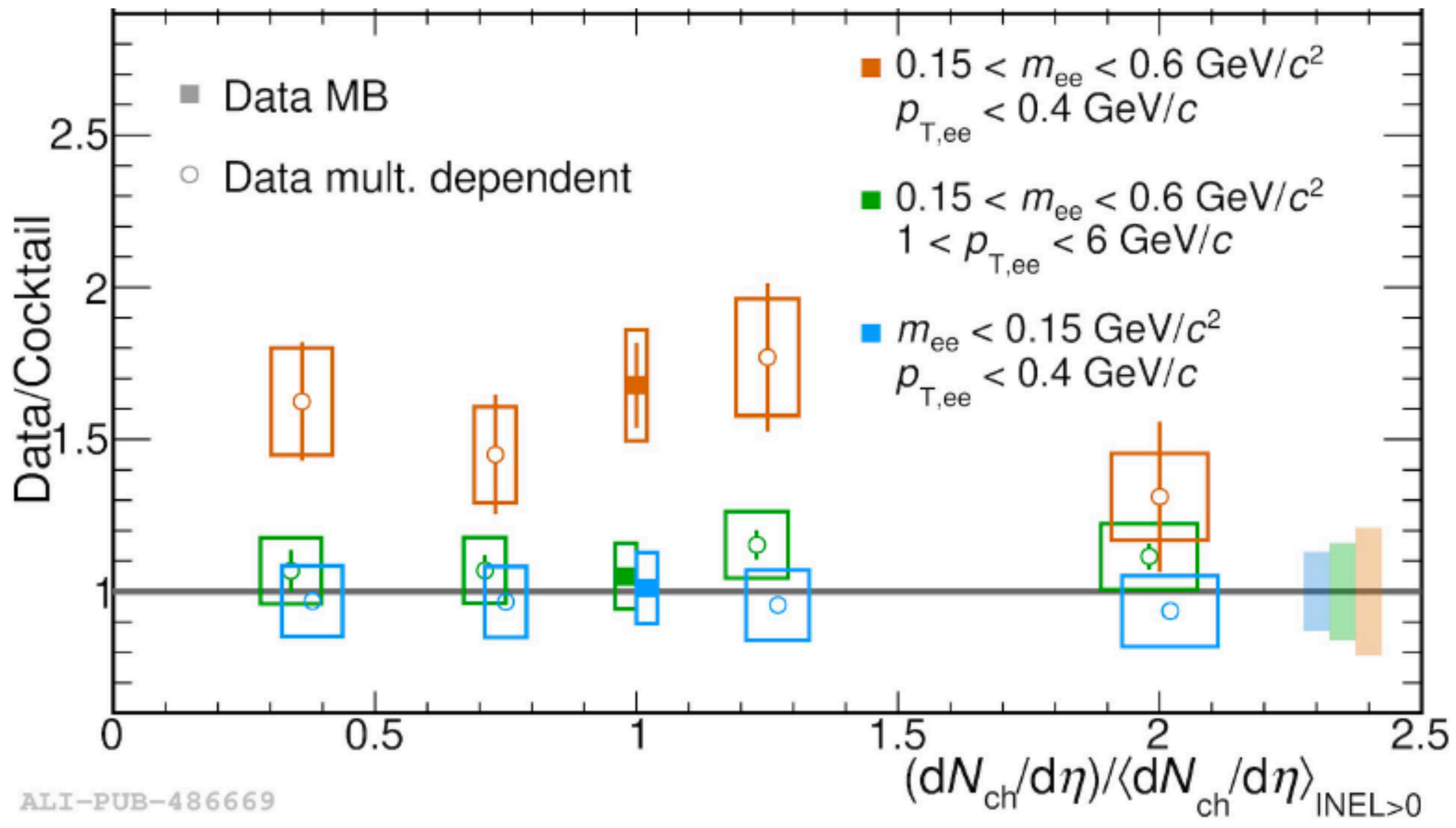
Physics prospects Run 3&4



ALICE Phys. Rev. Lett. 127 (2021) 042302

- Anomalous soft-photon and -dilepton excess in hadron-hadron collisions at lower energies reported by several experiments
- **First results from Run 2 low-*B* field data** at LHC energies:
  → Charged particle multiplicity dependence of the excess



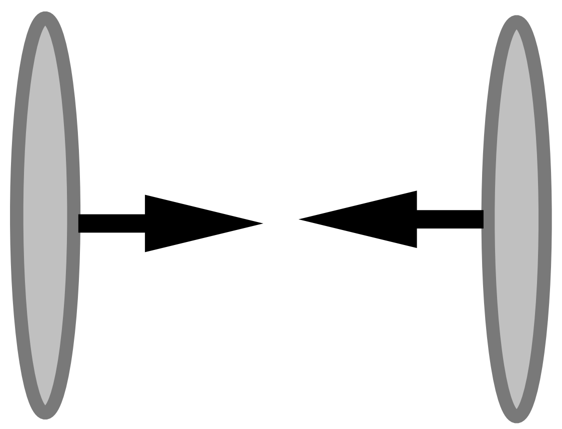


Low- → High-

multiplicity pp events

Increase statistics by a factor 400 in Run 3 & 4
→ Allows precise multi-differential analysis

Physics prospects Run 3&4



At the end of Run 4:

- Time-averaged QGP radiation
- Patterns indicative of chiral symmetry restoration

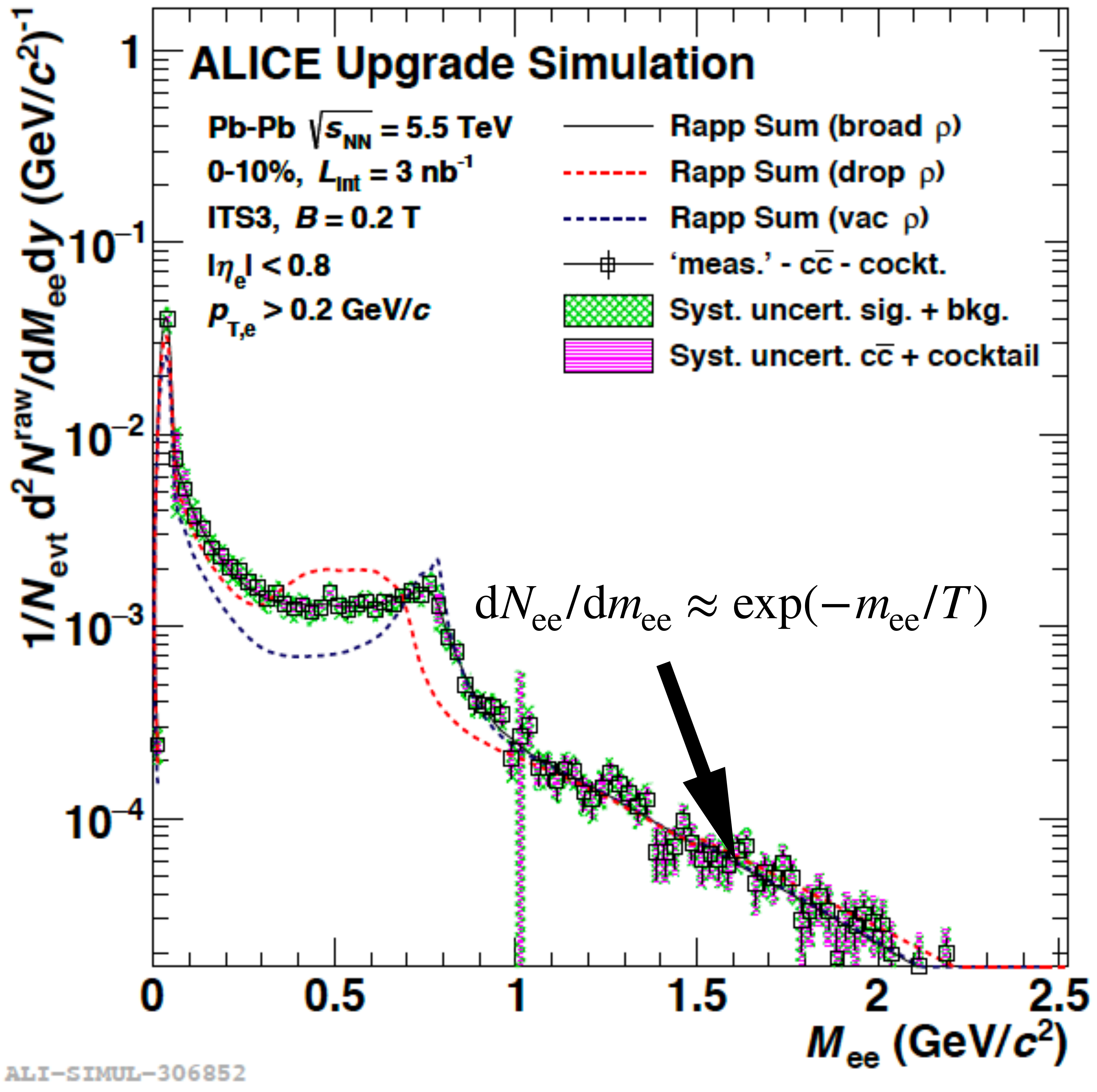
Fundamental questions will remain open, among them:

- Partonic equation of state and its temperature dependence
- Underlying dynamics of chiral symmetry restoration

→ **Call for a next-generation heavy-ion experiment**

Z. Citron et al CERN-LPCC-2018-07

Excess m_{ee} spectrum over cocktail in Run 4

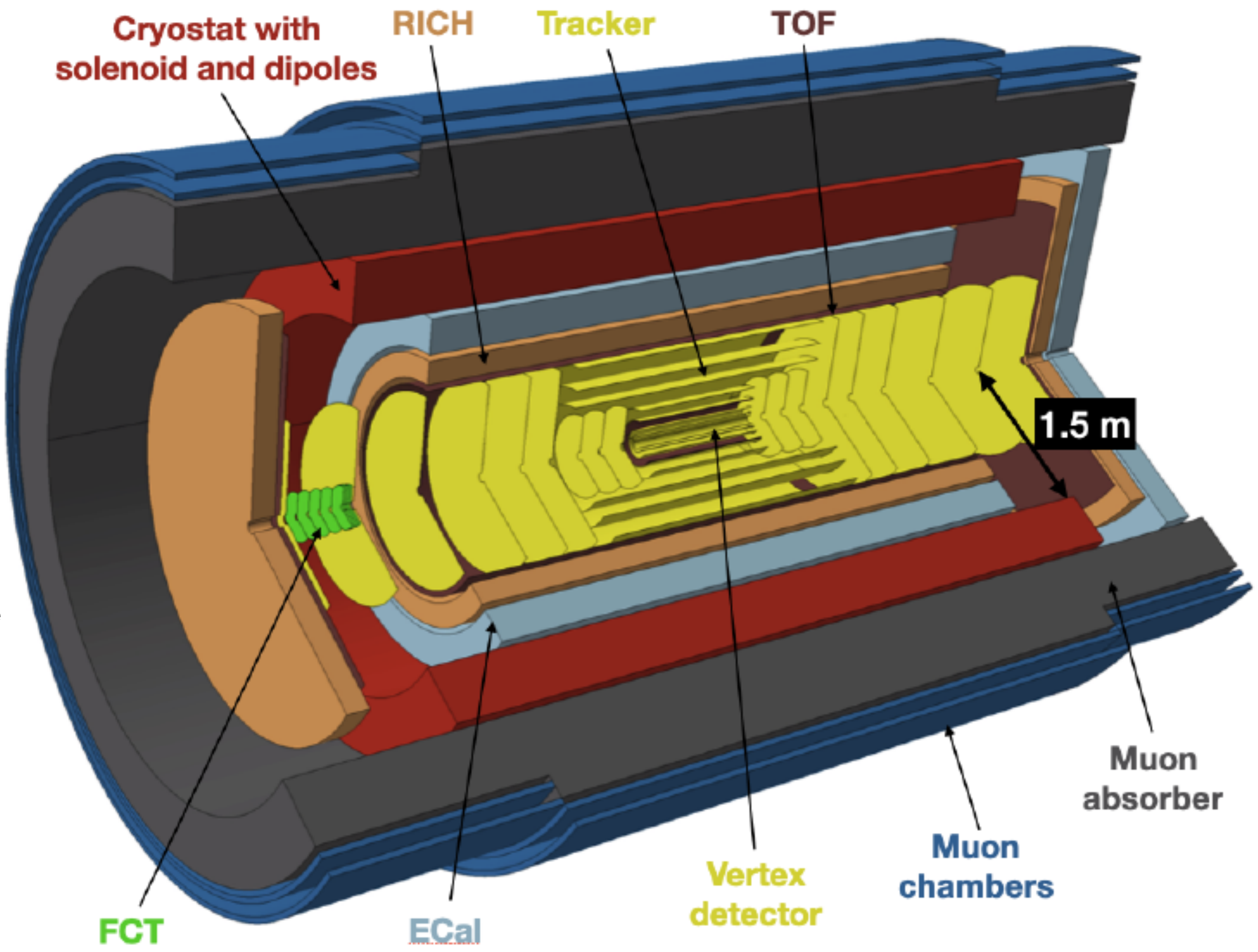


ALICE 3

- Compact all-silicon tracker
  in super-conducting magnets

- Particle identification for $-4 < \eta < 4$:
  TOF, RICH, Calorimeter, MUON

- Measure real and virtual photons at very low p_{T}/m_{ee}
  (Forward converter Tracker for very low p_T γ)



ALICE 3

- Compact **all-silicon tracker** in **super-conducting magnets**

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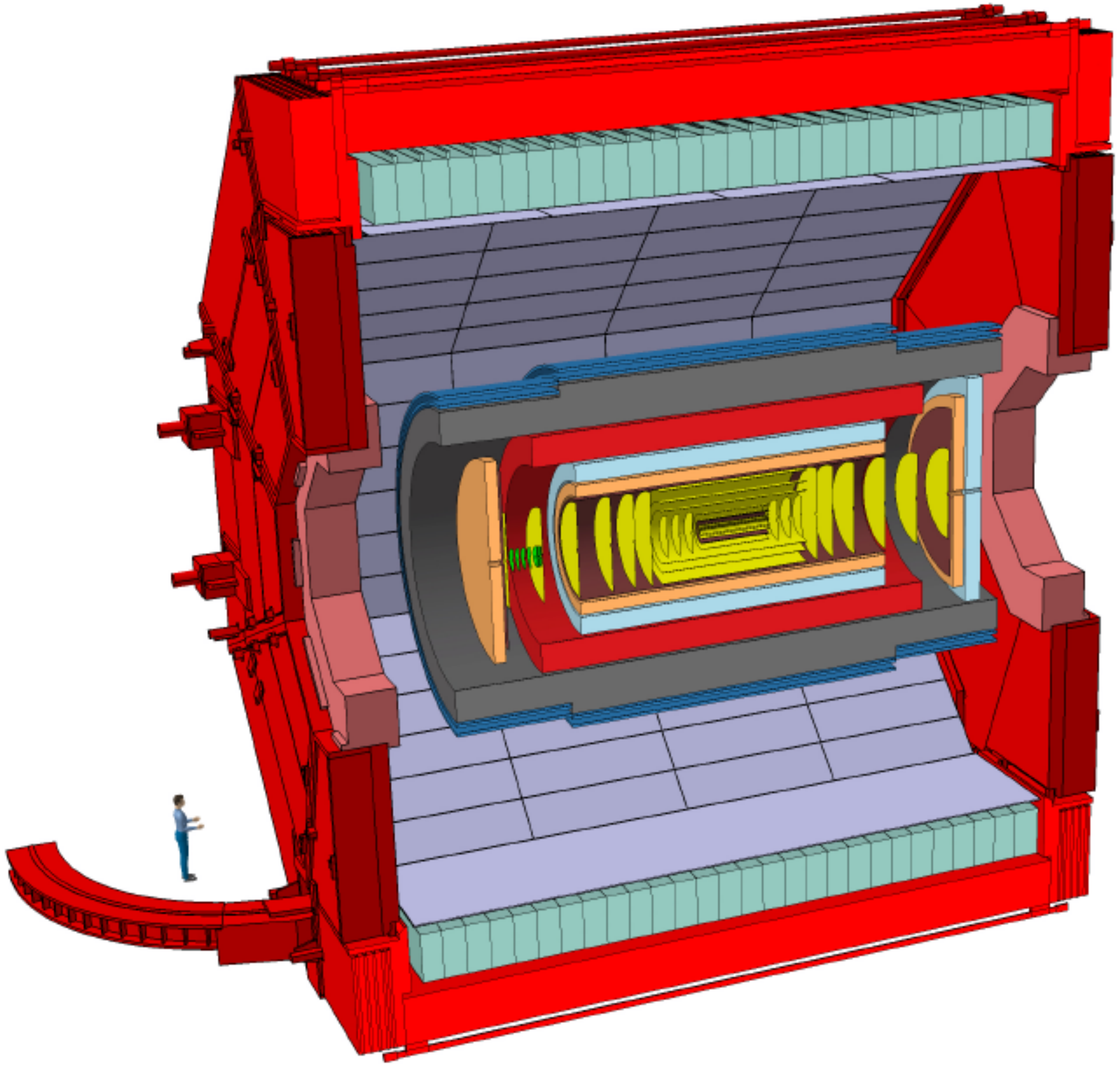
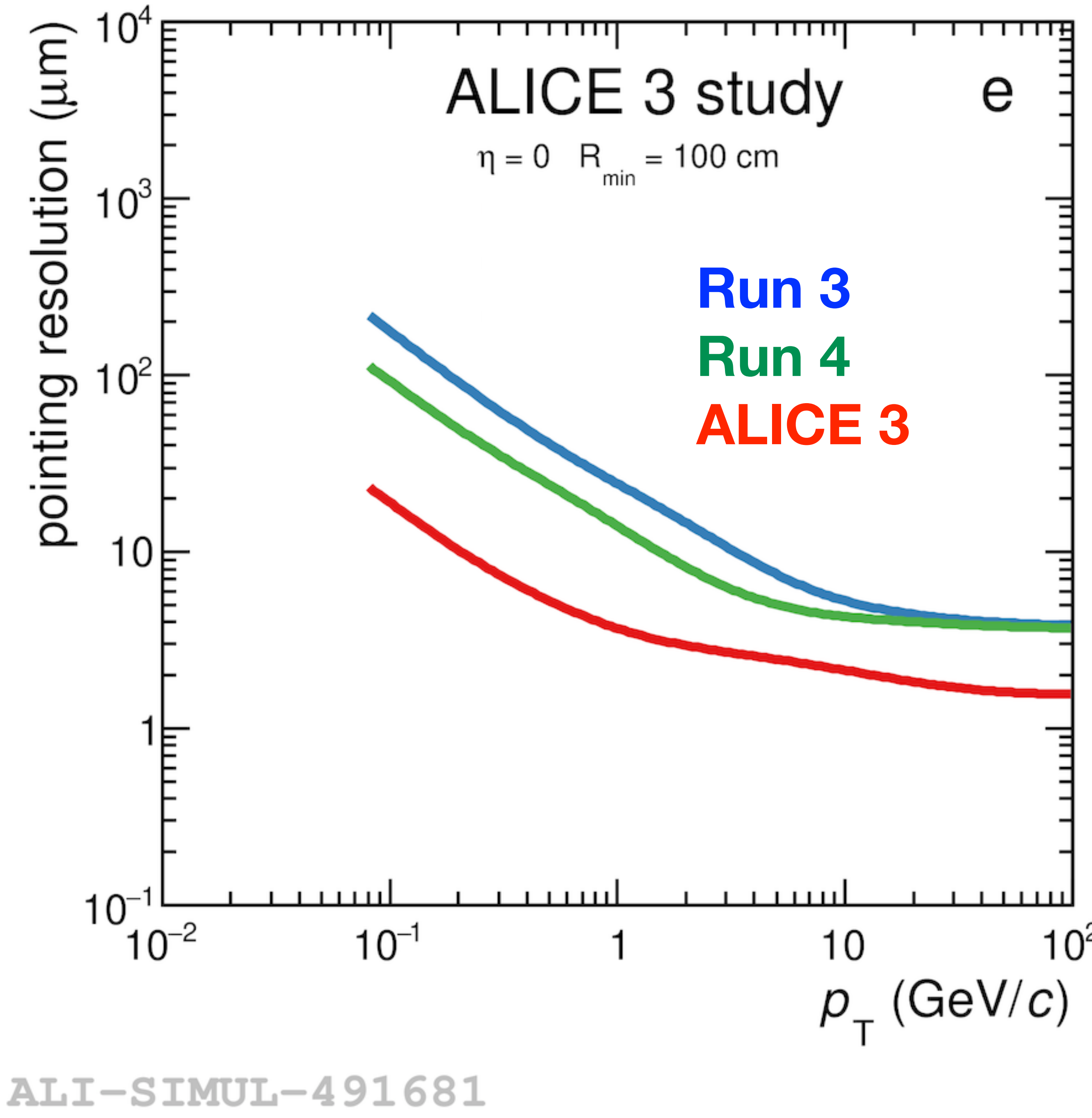


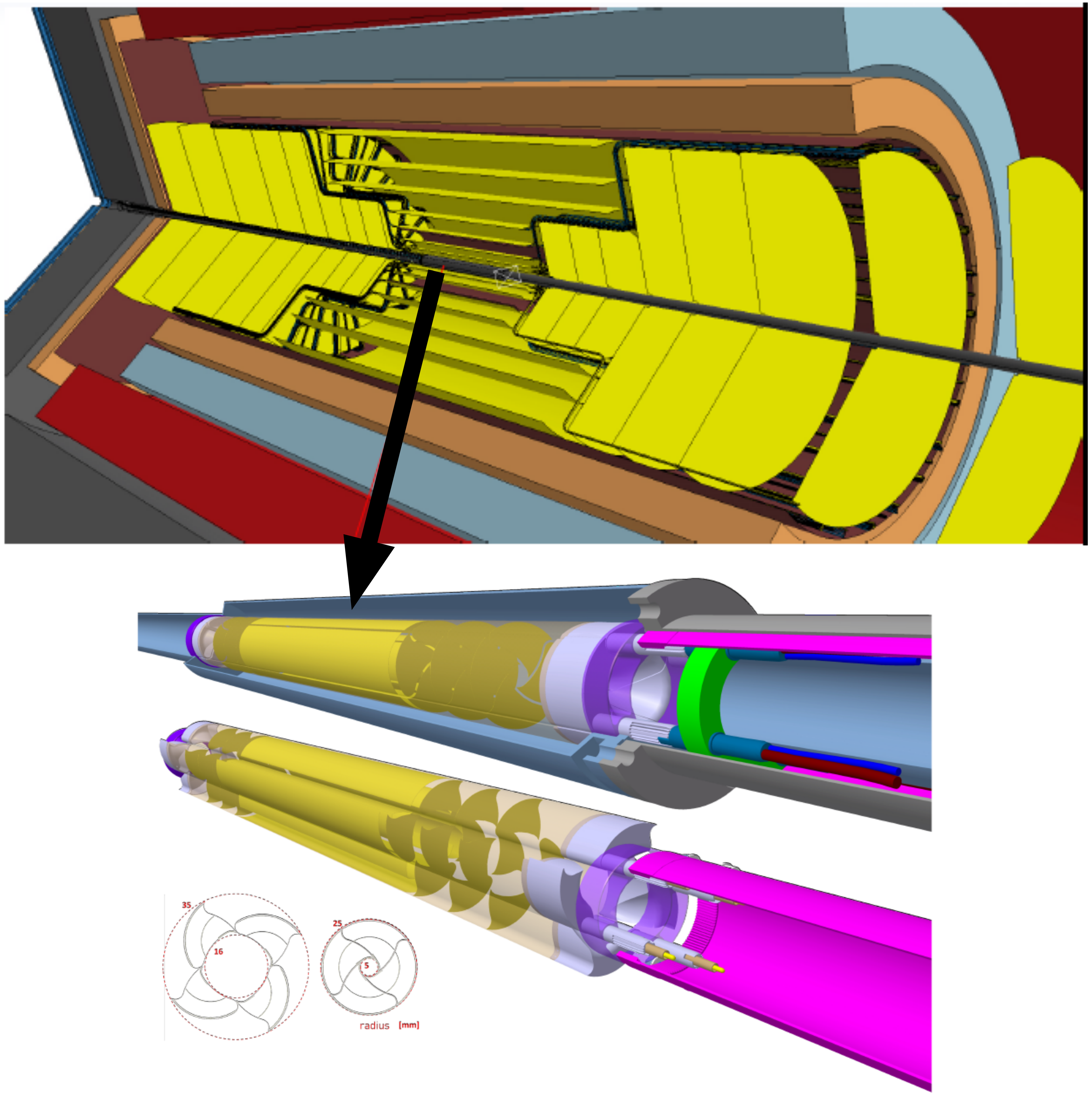
Could be installed in ALICE L3

Tracker

- Larger/longer MAPS-based tracker than ITS

- Retractable vertex detector
  - **Inside of the beam pipe** in secondary vacuum
  - **Position of the first layer** at mid-rapidity:
    - Closed: ***r* = 5 mm** (Run 4: 18mm)





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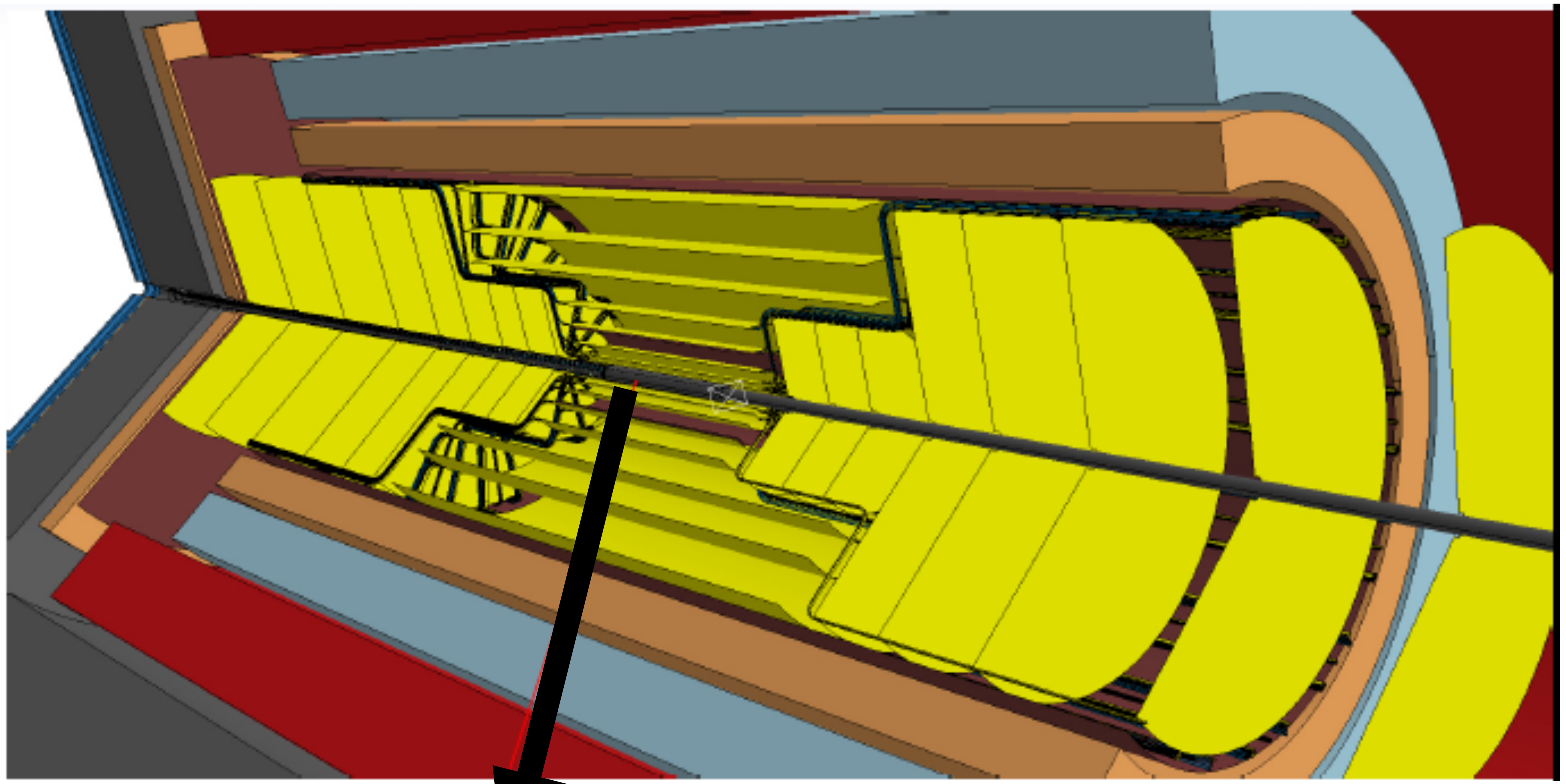
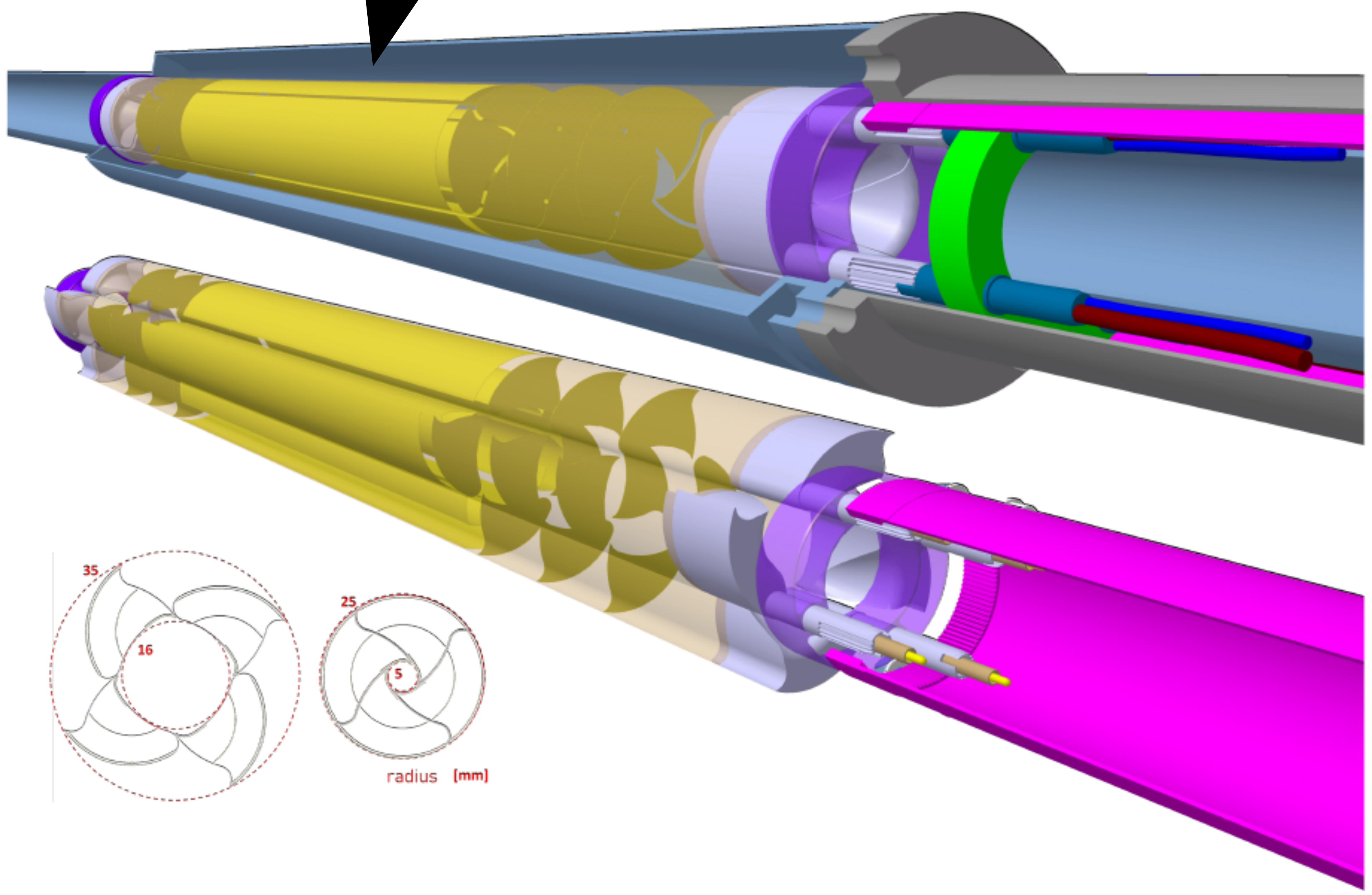
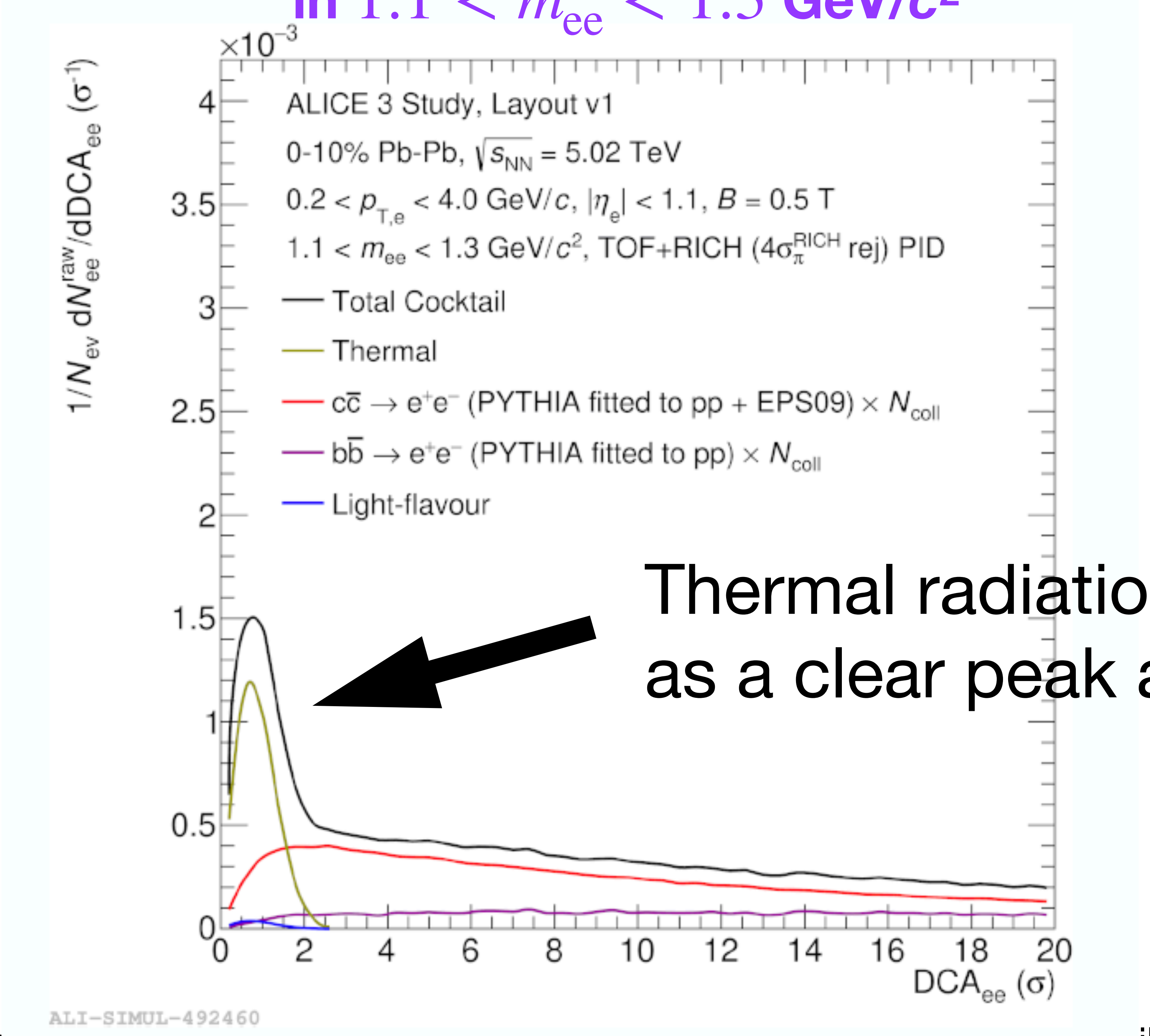


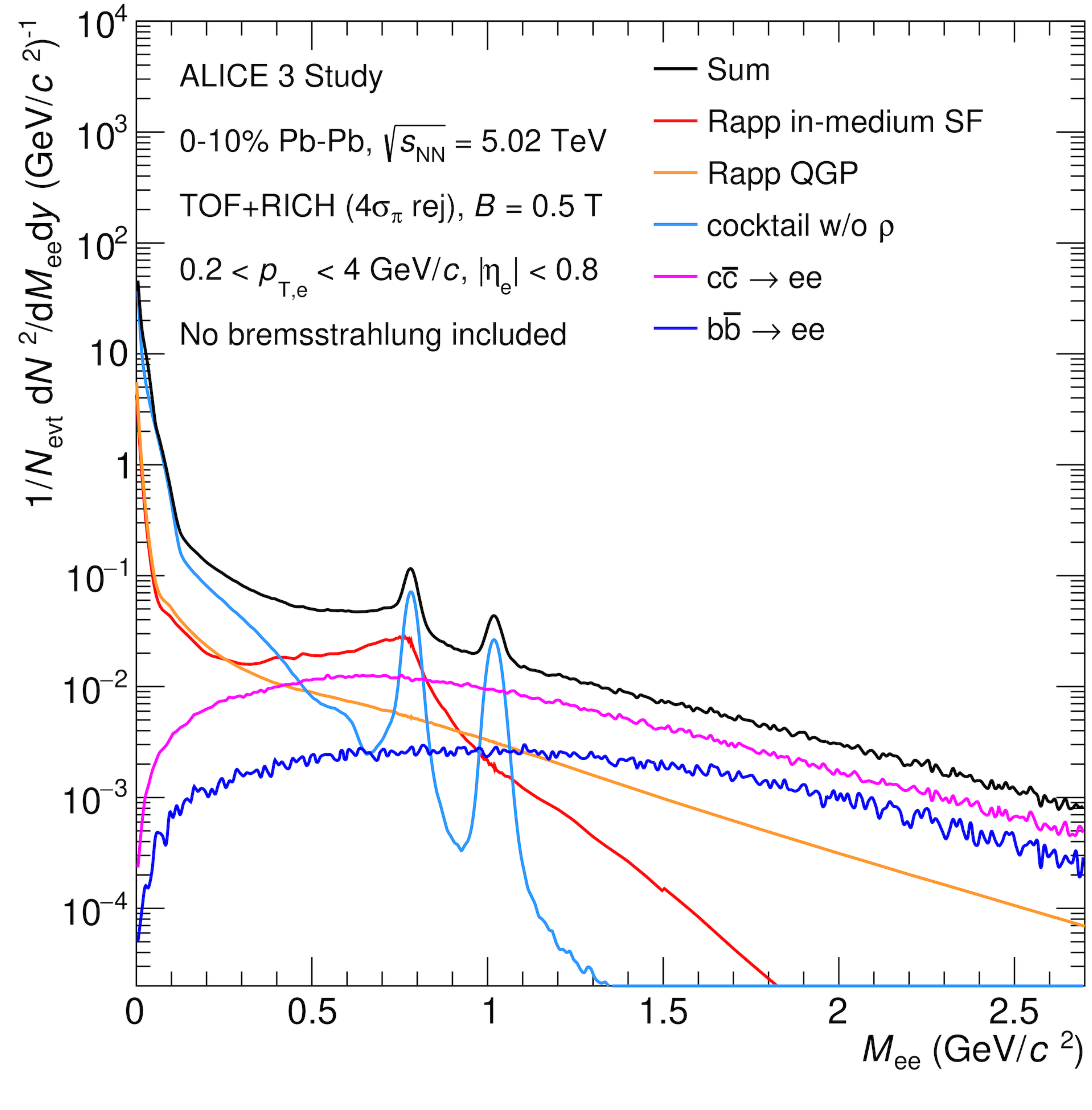


Expected DCA_{ee} distribution in central Pb—Pb collisions in $1.1 < m_{ee} < 1.3$ GeV/c^2



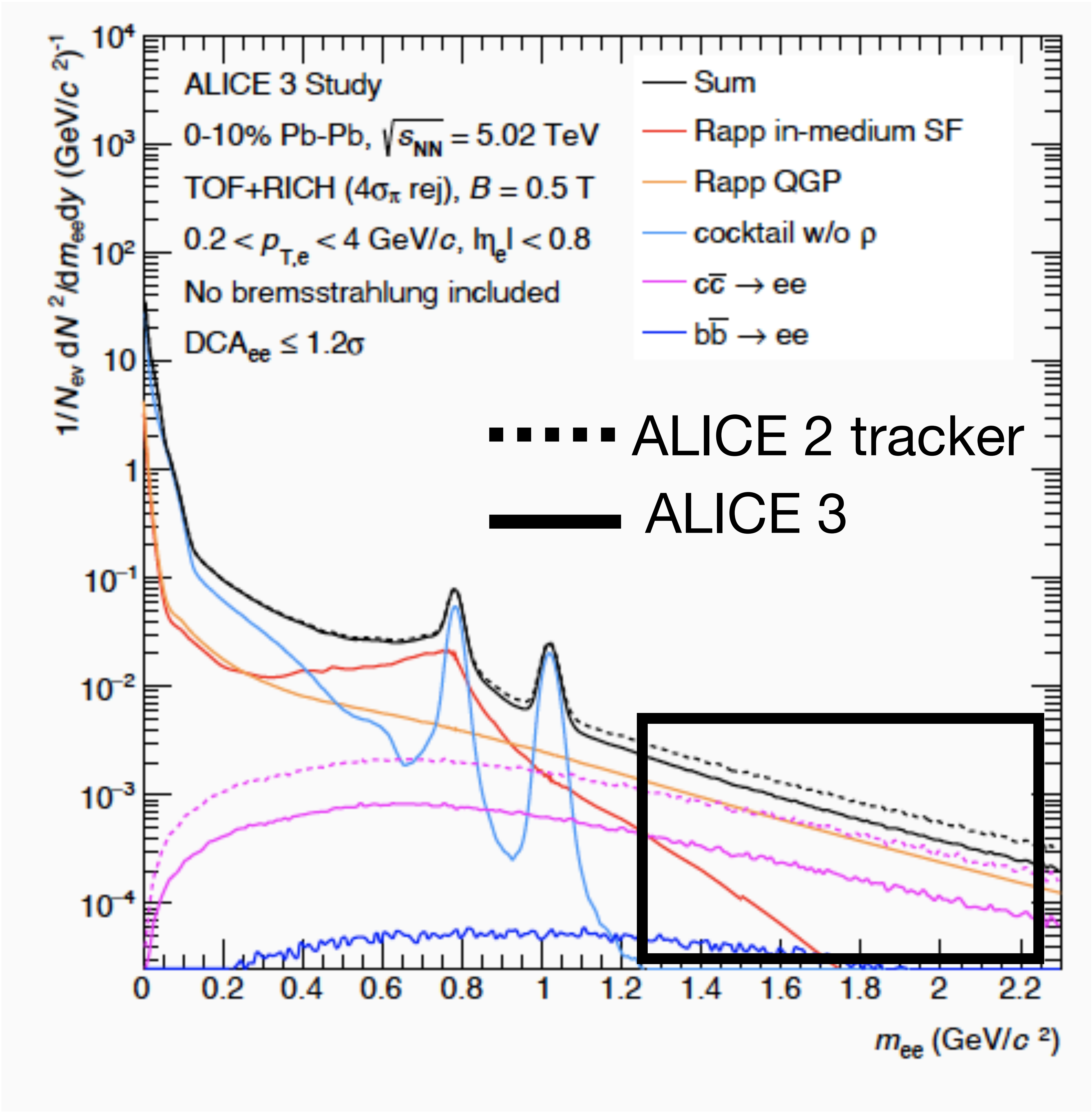
Thermal radiation seen as a clear peak at small DCA_{ee}

Background rejection



Pb—Pb central

Reject heavy-flavour with DCA_{ee}

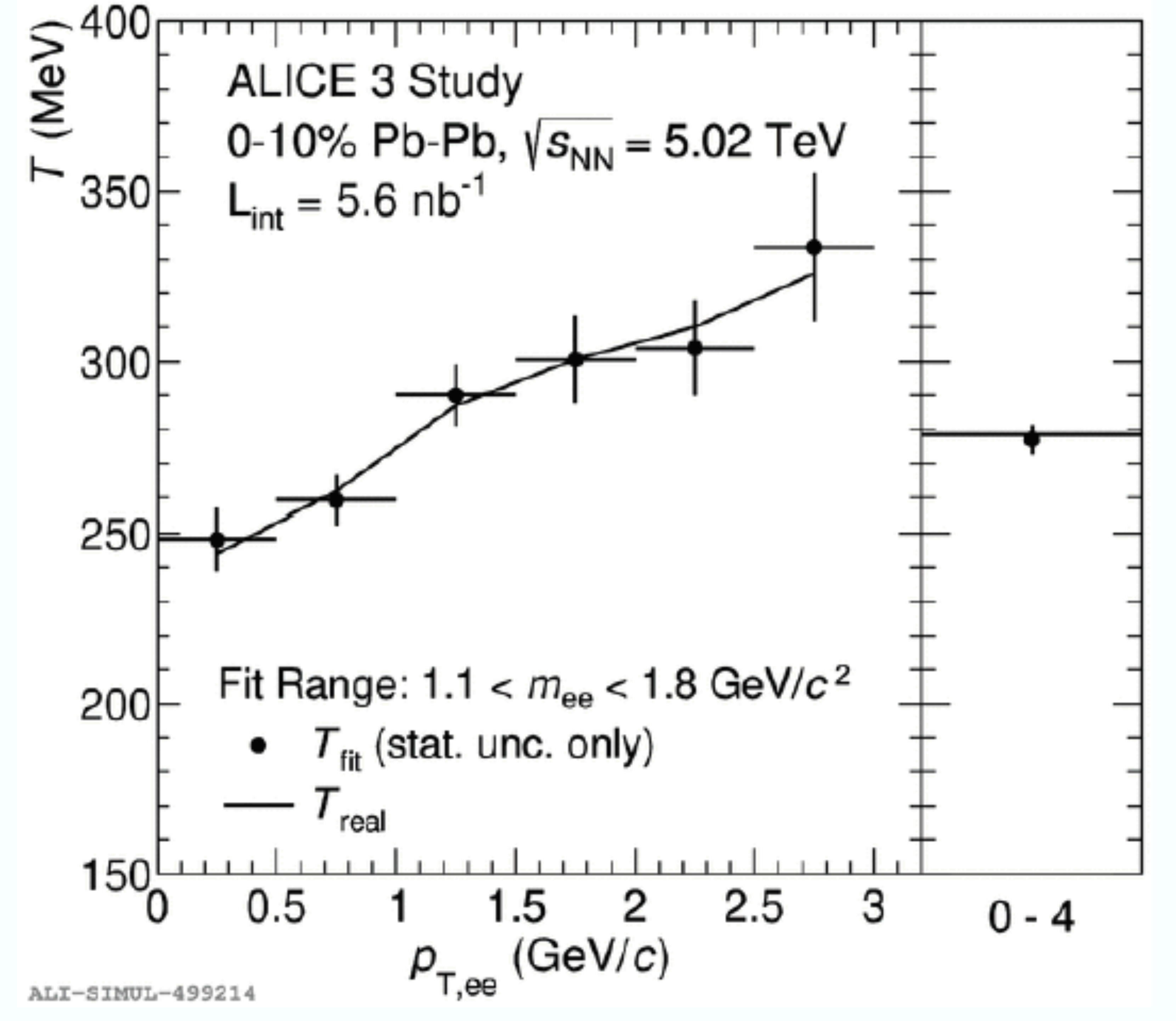


QGP thermal radiation and T measurements for $m_{ee} > 1.4$ GeV/c^2

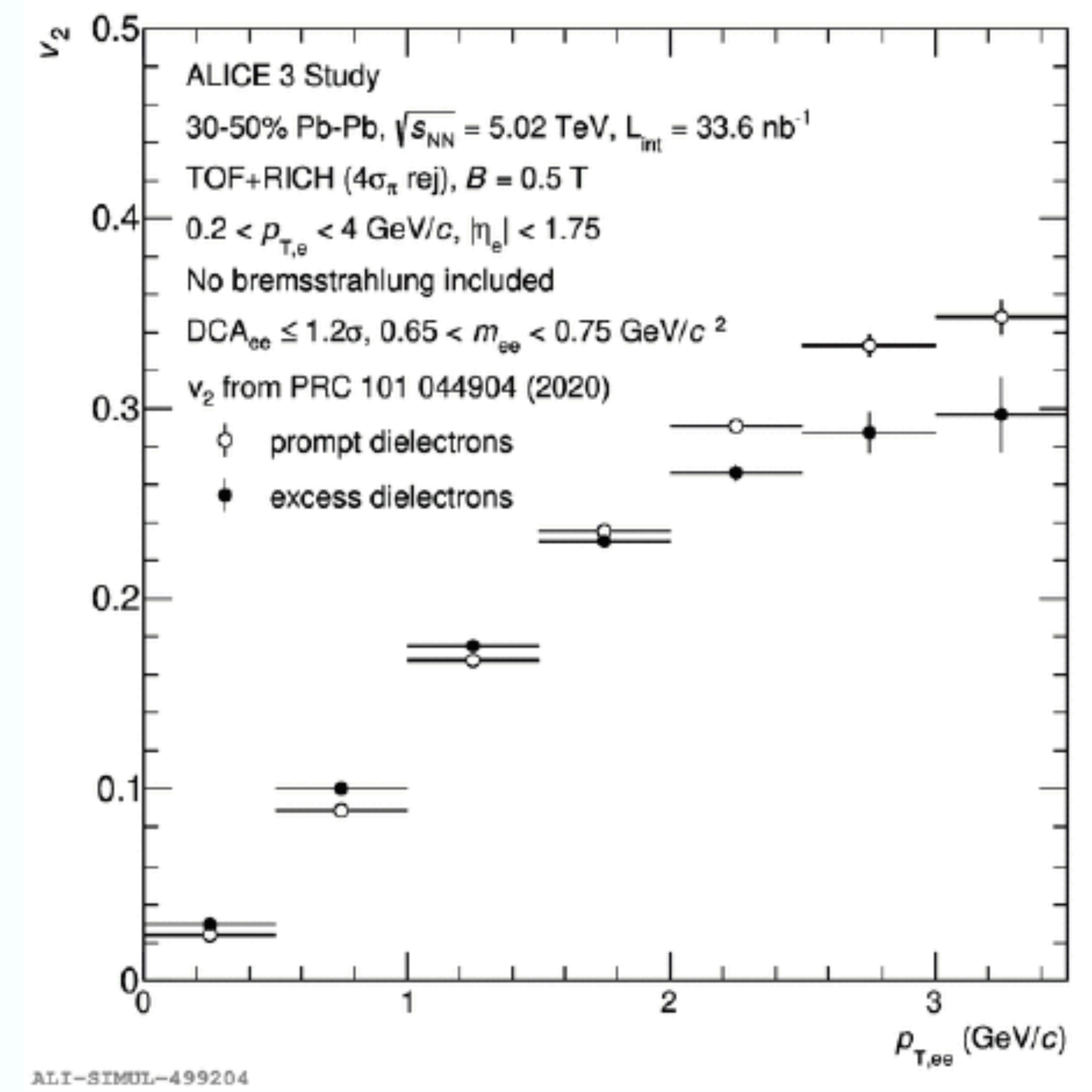
limited with ALICE 2 → significant improvement with ALICE 3

Physics performance studies ongoing

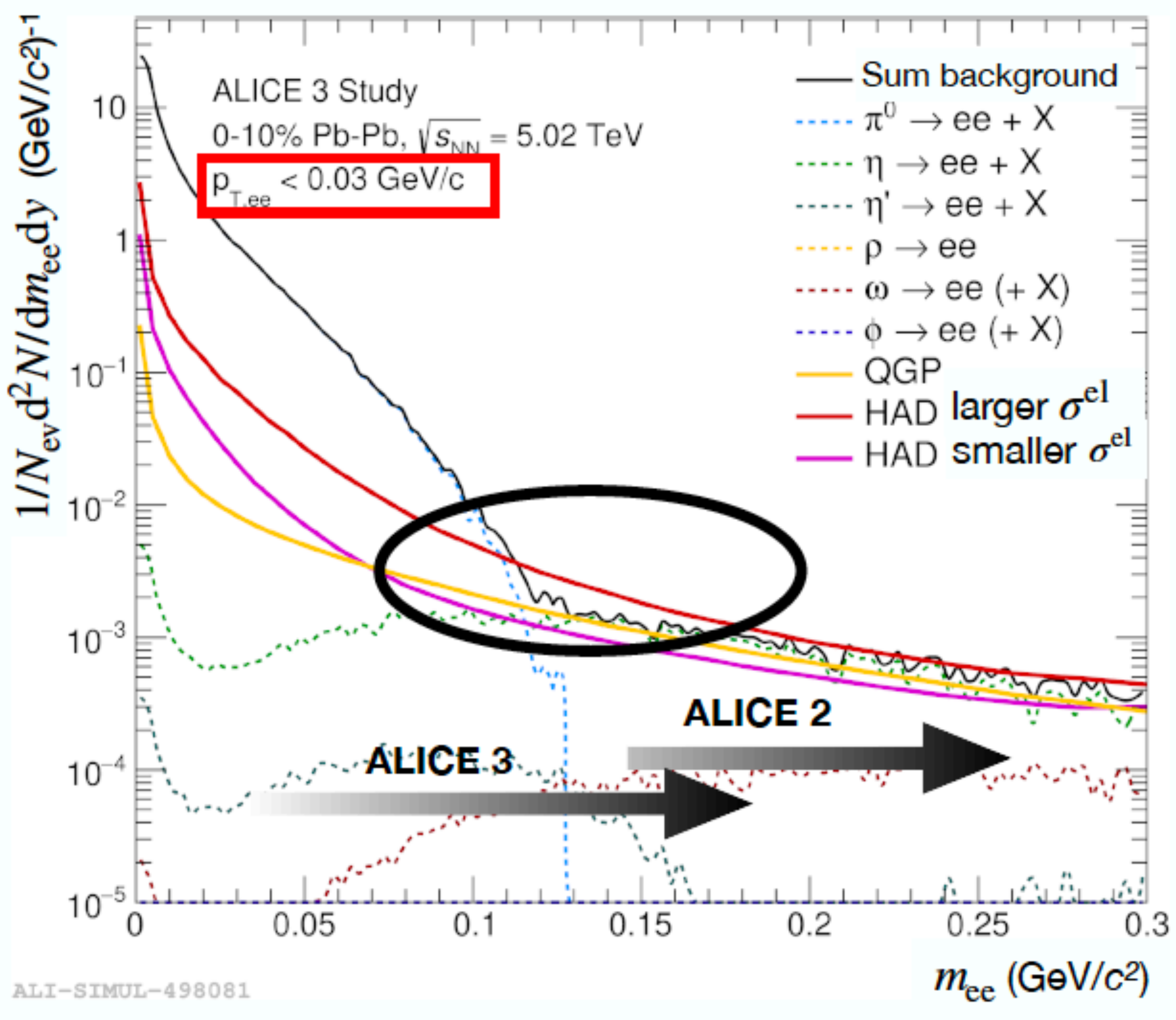
Differential early T measurements



Dielectron elliptic flow measurements



Electrical conductivity of the medium σ^{el} via e^+e^-at very low $p_{T,ee}$ and m_{ee}



ALICE 3 Letter-Of-Intent under LHCC review

(just endorsed by the ALICE Collaboration)

Non-dielectron physics topics not covered here…

ALICE 3 Workshop
https://indico.cern.ch/event/1063724/

Summary and Outlook

First dielectron results with ALICE Run 1 and Run 2 data…

… and a lot more to come with the next data-taking campaigns

Back-up

Central lead-lead collisions

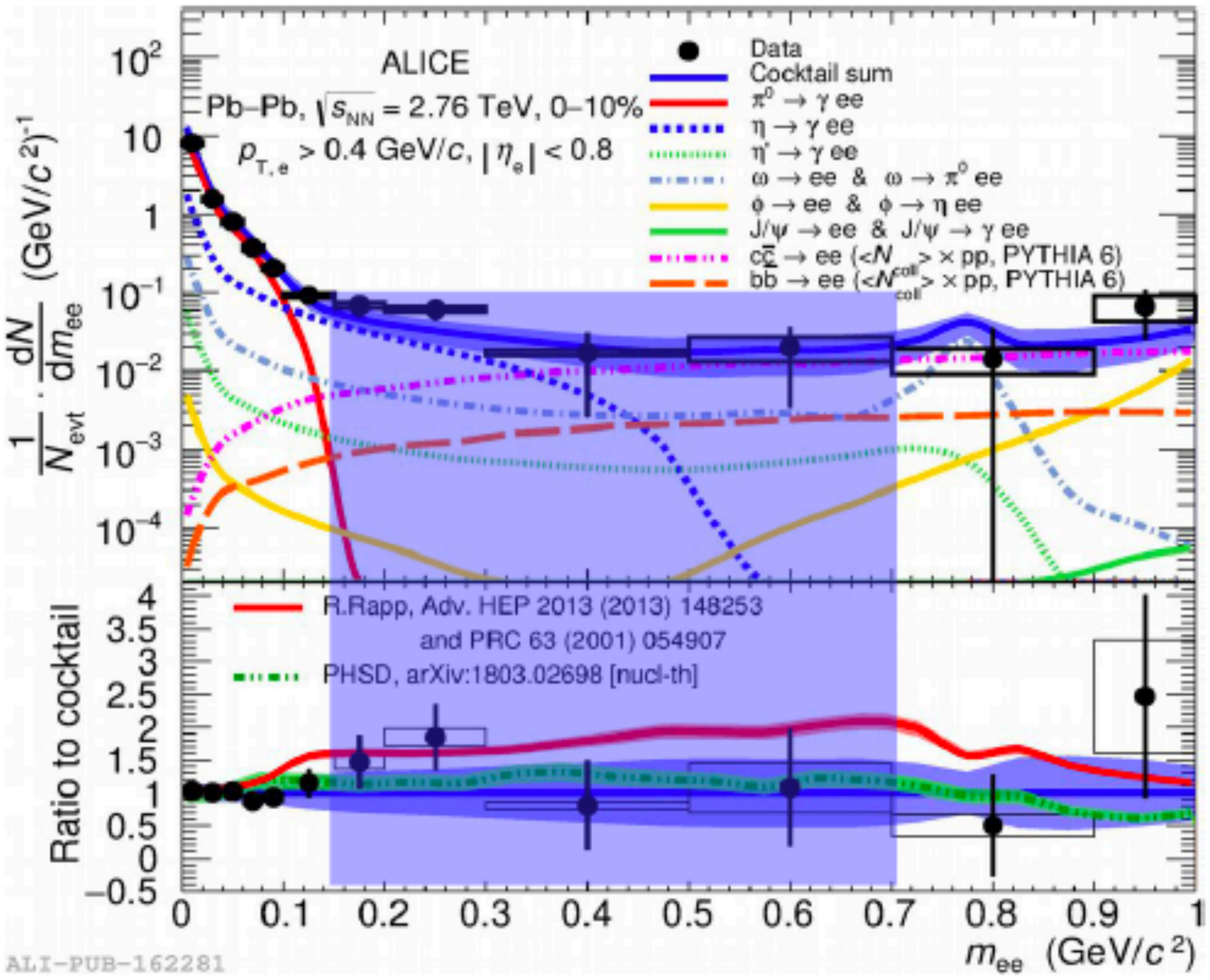
- Pioneering study in central Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV (Run 1 data, no use of DCA_{ee})

- **Hint for a low mass enhancement**
  Factor 1.38 ± 0.28 (stat.) ± 0.08 (syst.) ± 0.27 (cocktail) in $0.15 < m_{ee} < 0.7$ GeV/c^2

- Data compatible with:
  - Vacuum cocktail
  - But also models including thermal radiation

  No sensitivity yet

ALICE Phys. Rev. C 99, 024002



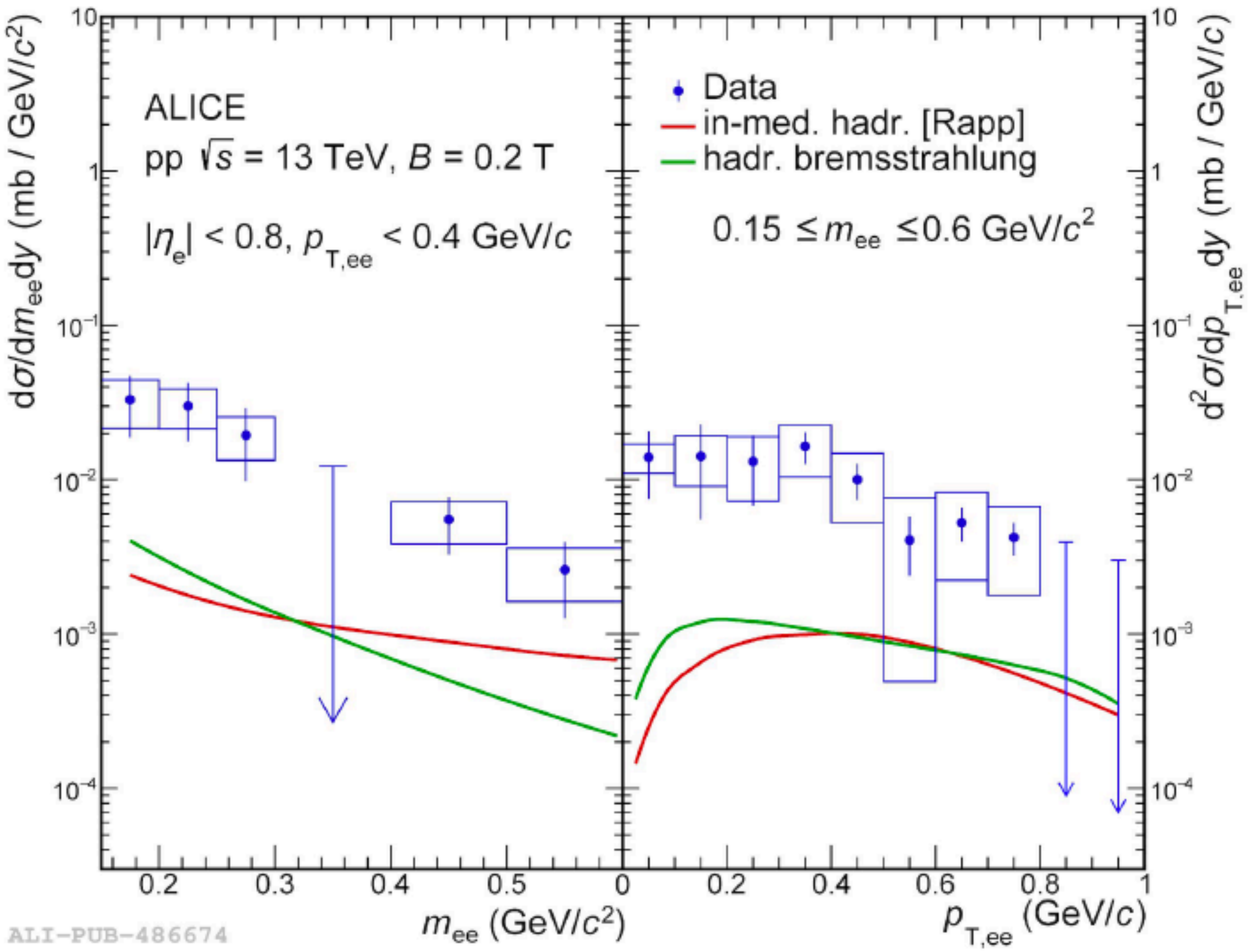
Soft dielectron production in pp at $\sqrt{s_{NN}}$ = 13 TeV

ALICE Phys. Rev. Lett. 127 (2021) 042302

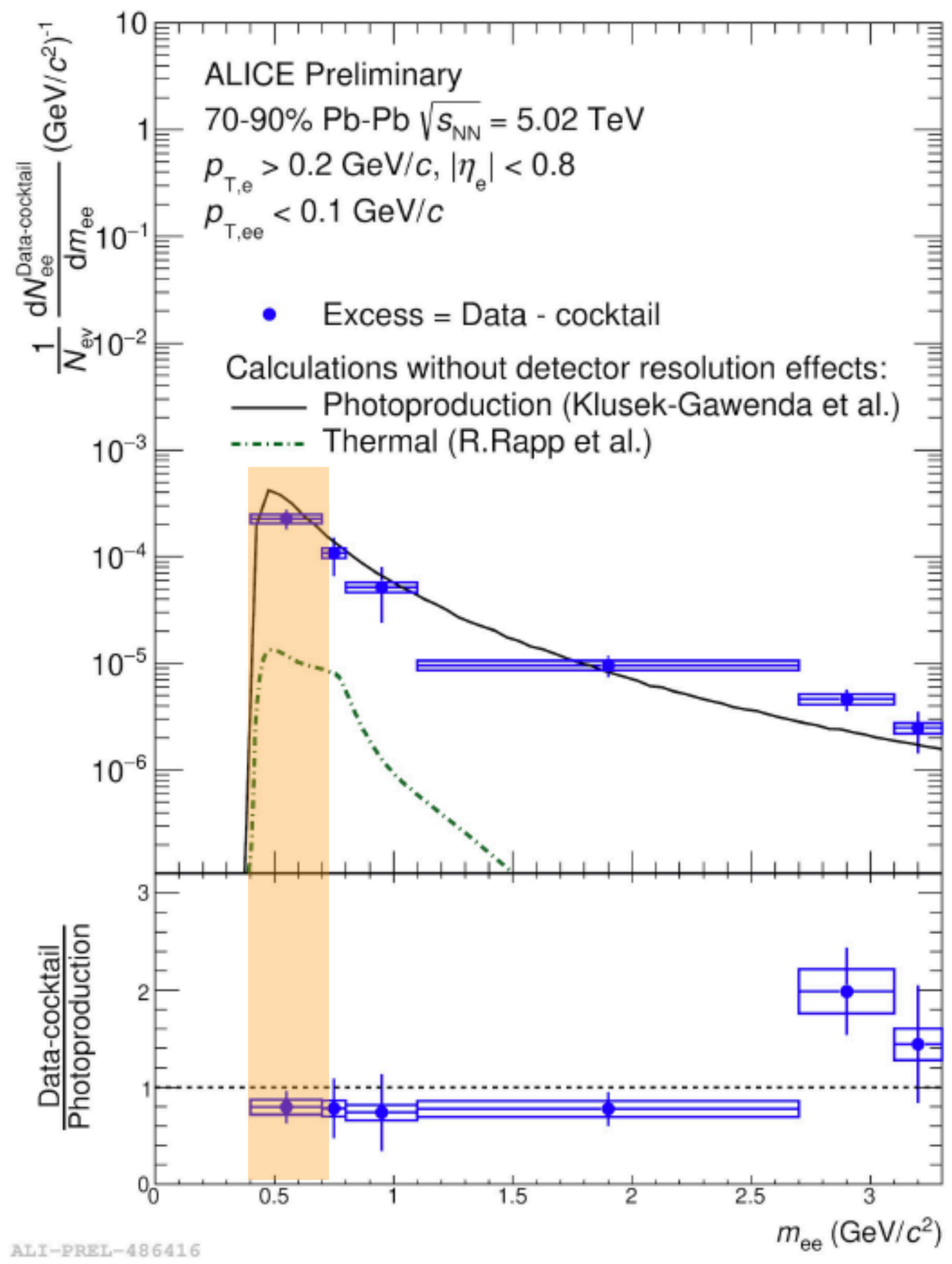
Acceptance corrected excess yield compared to theory predictions:

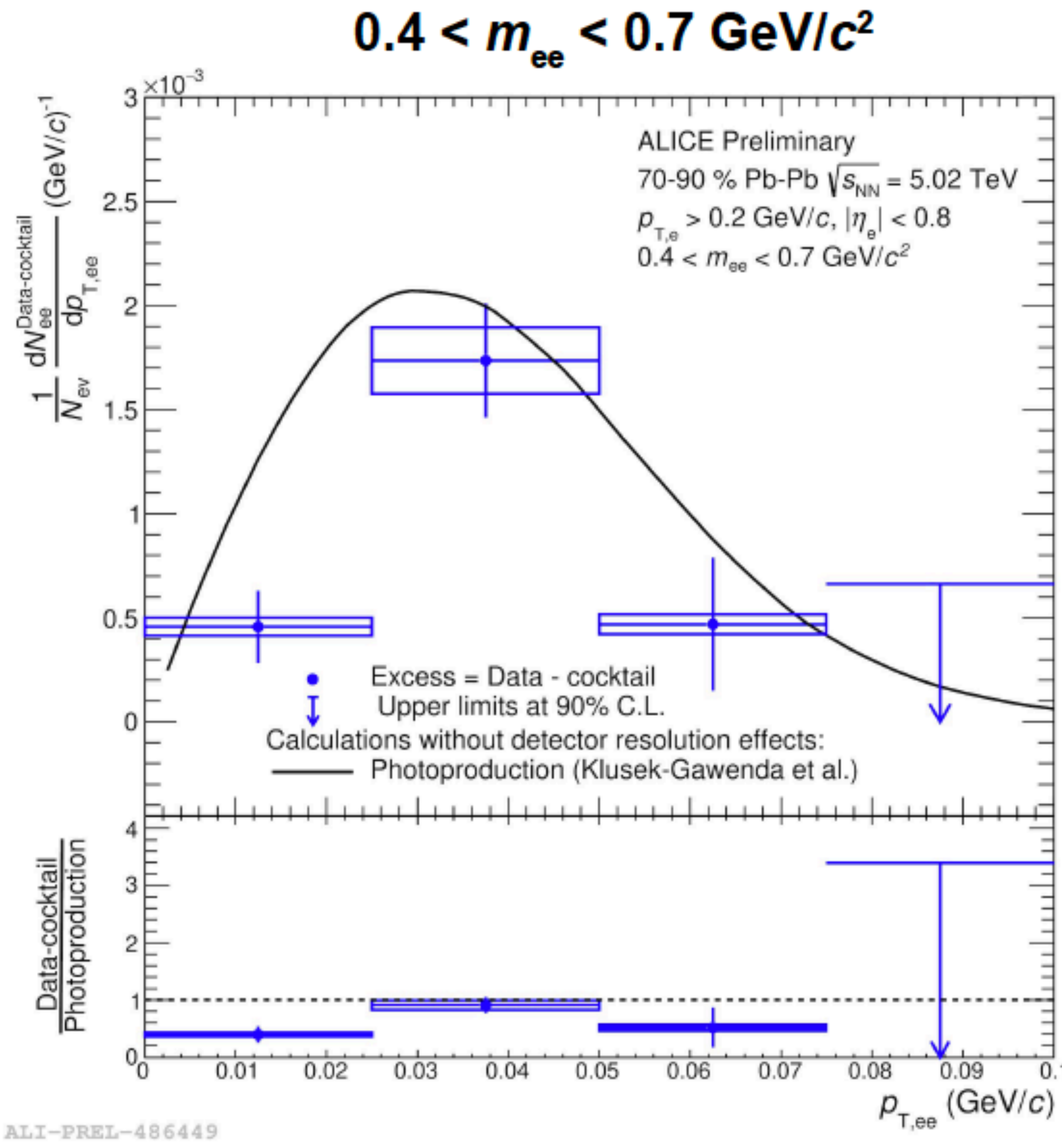
Data reproduced:

- Neither by calculations for bremsstrahlung from initial- and final-state hadrons
- Nor by predictions for thermal dielectron production



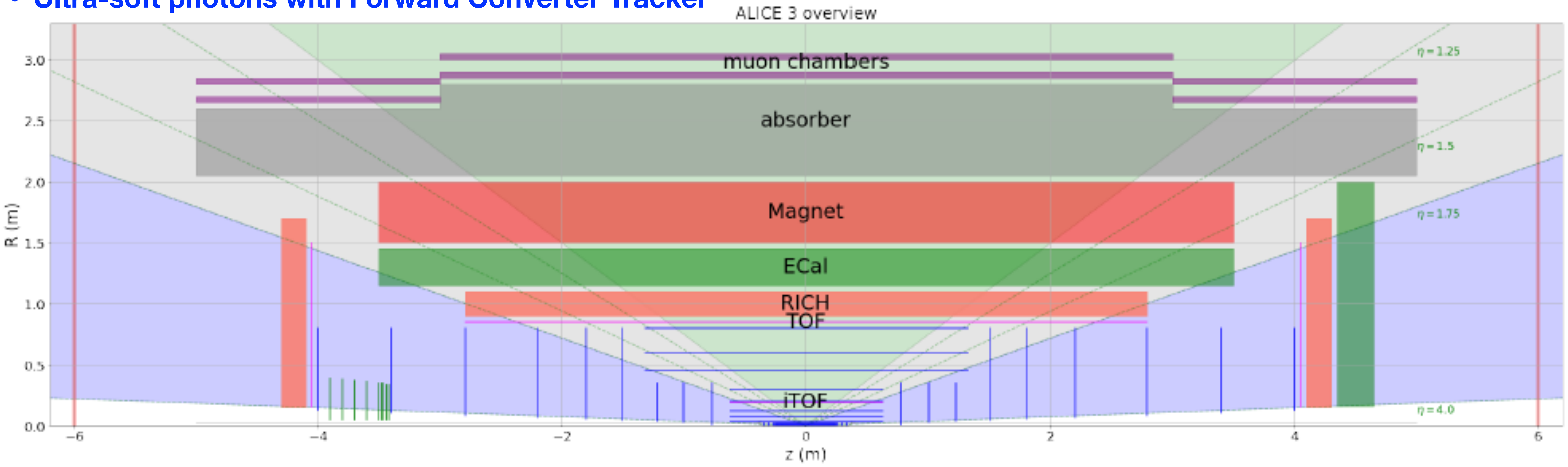
Peripheral Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





Detector overview

- **Cover -4 < η < 4 rapidity range**
- **Trackers**
  - At mid-rapidity: 11 layers with **first layer at 5mm** (ITS3: 18mm)
  - At forward- and backward-rapidity: 2x12 discs
- **Particle identification at mid-rapidity:**
  - Inner TOF at 20 cm: electron identification (eID) **down to p_T = 0.015 GeV/*c* for *B* = 0.5 T** (ALICE: 0.075 GeV/*c* for *B* = 0.2 T)
  - Outer TOF and RICH at about 1m: eID for *p* < 2 GeV/*c*, K and p up to 10 and 15 GeV/*c*
  - Pre-shower or ECAL detector: eID at larger *p*, photons
- **Ultra-soft photons with Forward Converter Tracker**

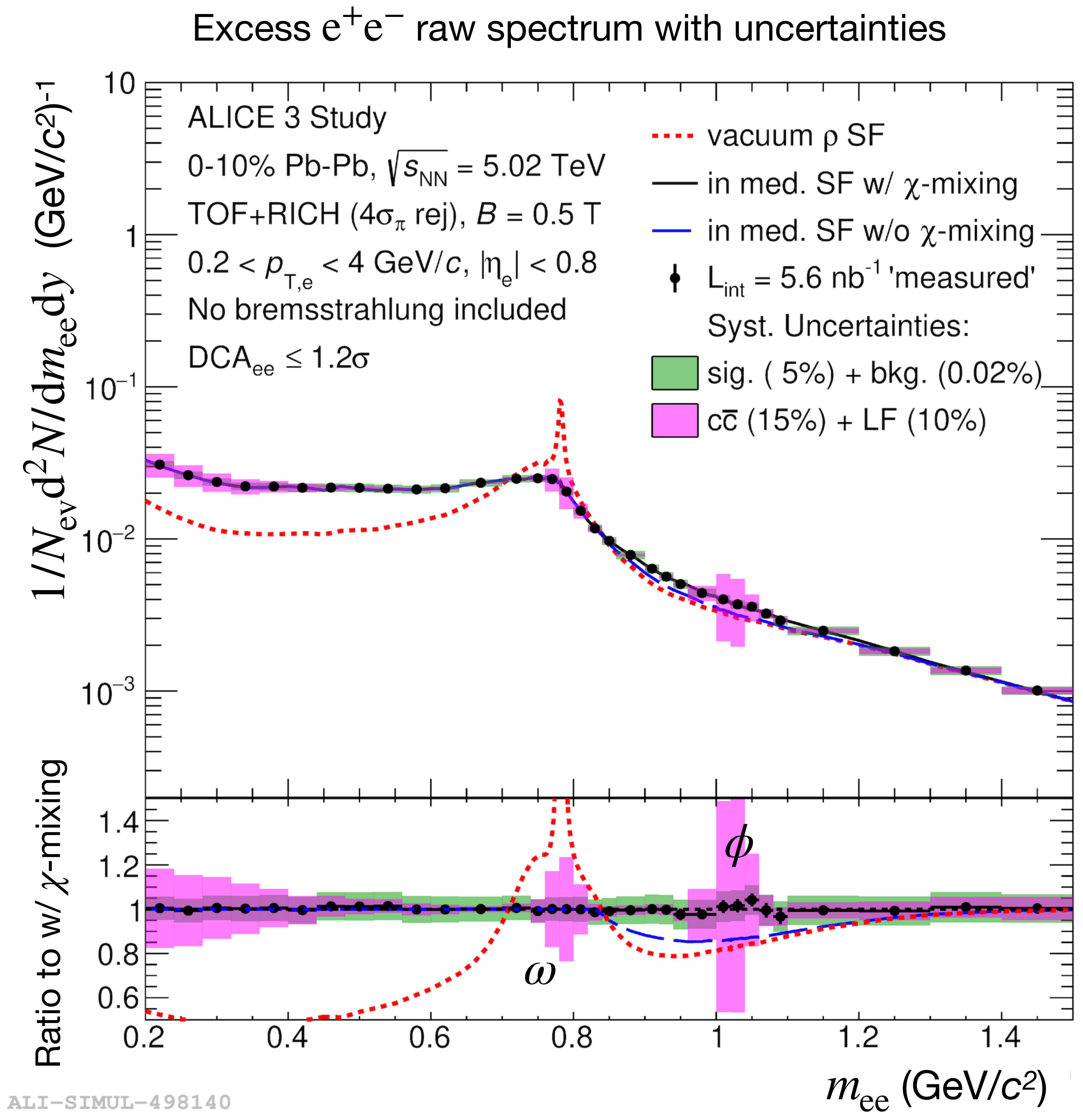


Dielectron excess

Chiral symmetry restoration

- Subtract hadronic light-flavour (LF) cocktail and residual heavy-flavour background
- **Additional source of uncertainties from the subtraction**
  Exact numbers under investigation
- Comparison with different ρ spectral functions:
  - **Vacuum ρ spectral function**
  - **In medium ρ spectral function w/o ρ-a_1 chiral mixing**
  - **In medium ρ spectral function w/ ρ-a_1 chiral mixing**

Expected to be sensitive
to details of the ρ spectral function up large m_{ee} with ALICE 3



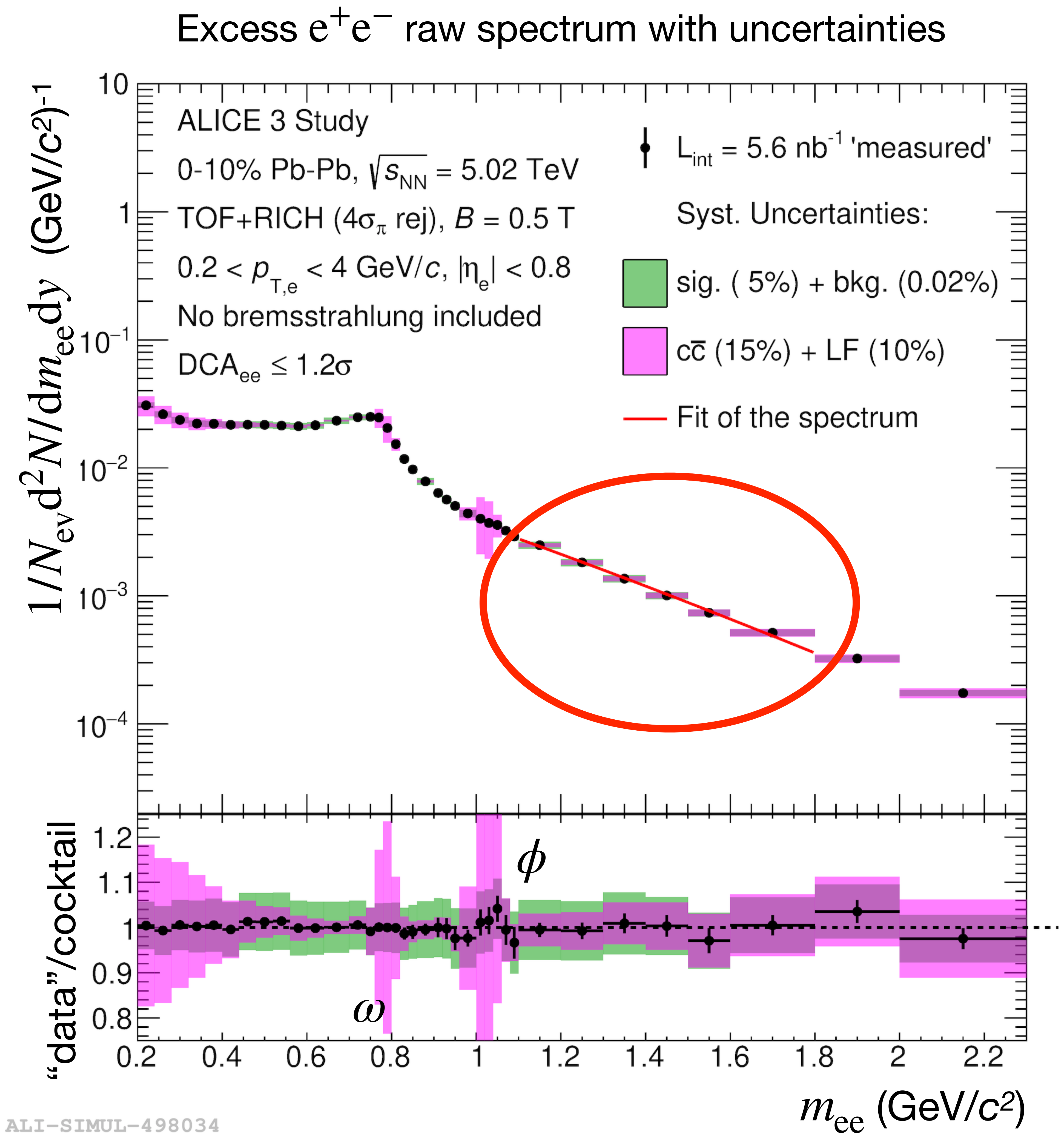
R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
R. Rapp private communication

Dielectron excess
Early-time temperature

- **Fit the m_{ee} spectrum to extract T**: $dN/dm_{ee} \sim \exp(-m_{ee}/T)$
- Extracted T:
  - **1.5% statistical uncertainty** **(4% from previous ITS 3 studies)**
  - 2% sys. unc. from charm assuming fully correlated sys. as a function of m_{ee}
    ($^{+4\%}_{-10\%}$ from previous ITS 3 studies)

Caveat: different hadronic cocktail as input in the feasibility studies

Statistics will allow more differential measurements of T with ALICE 3



R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
R. Rapp private communication

Dielectron elliptic flow

$$v_2^{\text{prompt}} = \frac{\pi}{4}\frac{1}{R_2}\frac{N^{\text{INP}} - N^{\text{OOP}}}{N^{\text{INP}} + N^{\text{OOP}}}$$

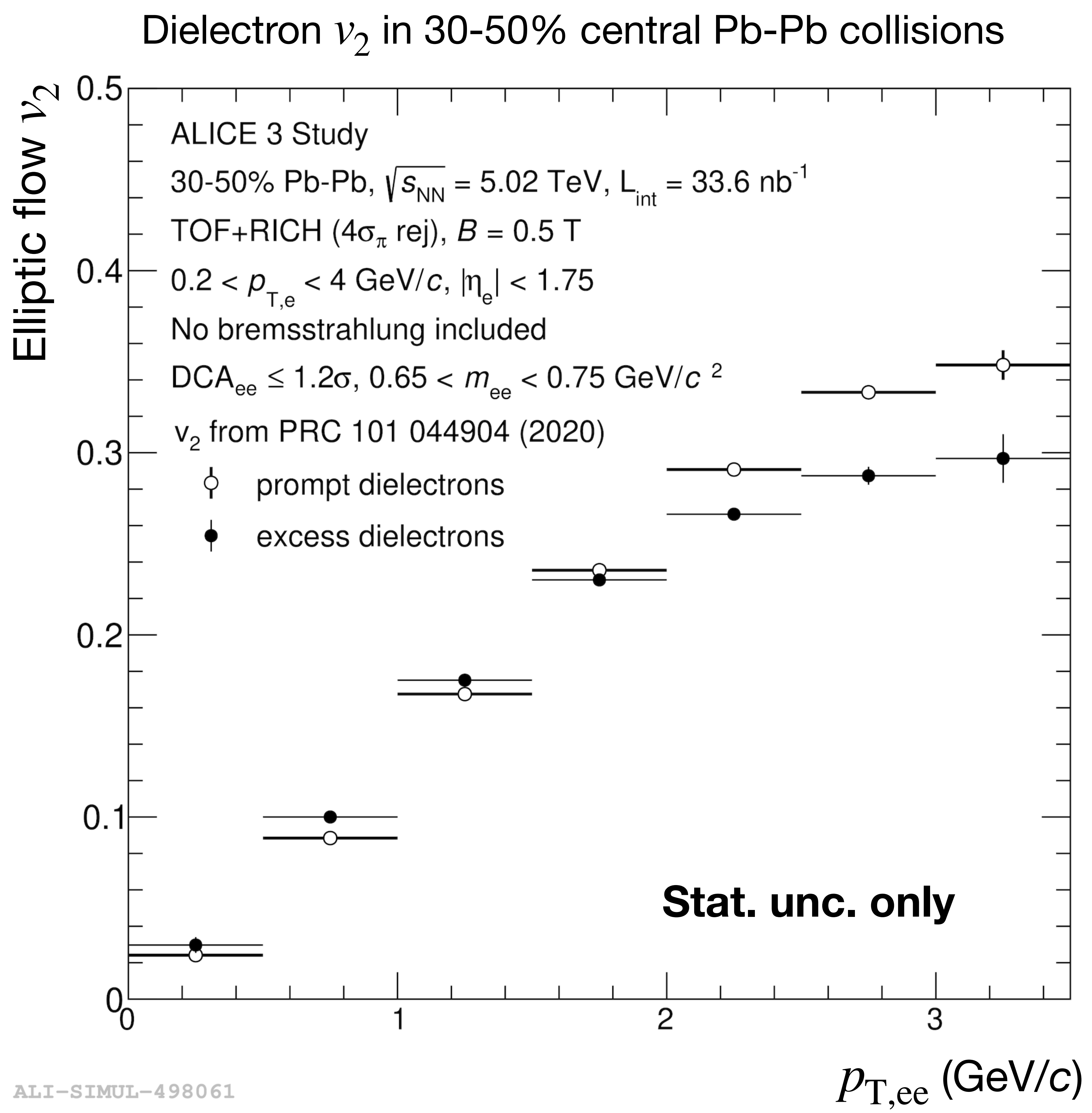
$N^{\text{INP}}, N^{\text{OOP}}$: prompt e^+e^- yields in- and out-of-plane
R_2 : resolution of the reconstructed event plane

Expected dielectron elliptic flow for all (prompt) and excess dielectrons in 30-50% Pb-Pb collisions

- v_2 values based on calculations by Gojko Vujanovic et al.
- **Statistical uncertainty** estimated for **6 years of data taking** (Absolute stat. unc. independent on v_2 for $N^{\text{INP}} \approx N^{\text{OOP}}$)

Statistics will allow
v_2 measurements as a function of m_{ee} and $p_{T,ee}$ with ALICE 3

$0.65 < m_{ee} < 0.75$ GeV/c^2



Pre-shower detector under study for higher in $p_{T,ee}/m_{ee}$
Access to pre-hydrodynamic phase

G. Vujanovic et al. PRC 101 (2020) 044904

Electric conductivity

$$\lim_{p_T \to 0} \frac{dN}{p_T\, dp_T} \propto \sigma^{\text{el}}$$

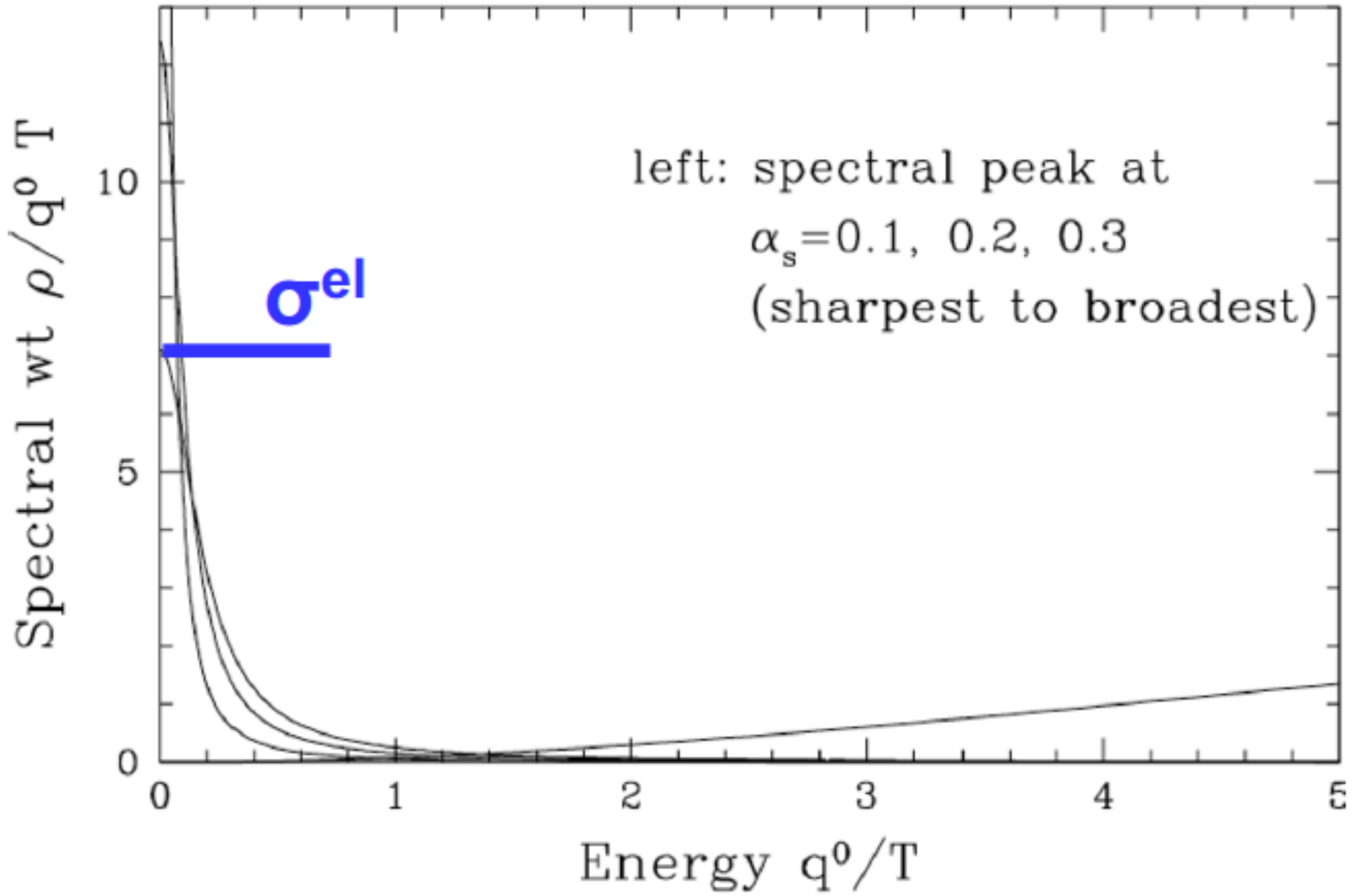
- **Thermal dielectron spectrum and low-p_T direct photon yield** connected to **electric conductivity** of the medium σ^{el} **at very low mass and p_T**

- **Wide spread of the predicted σ^{el}** values: $0.001 < \sigma^{\text{el}}/T < 0.1$
  Very poorly constrained by the current measurements

- Latest calculations by R. Rapp:
  Width of the thermal dielectron spectrum at low $p_{T,ee}$ as sensitive as the peak at $m_{ee} = 0$

- **Outside of ALICE 2 acceptance**

Example of spectral function with spectral peak



G. D. Moore and J.-M. Robert arXiv:hep-ph/0607172

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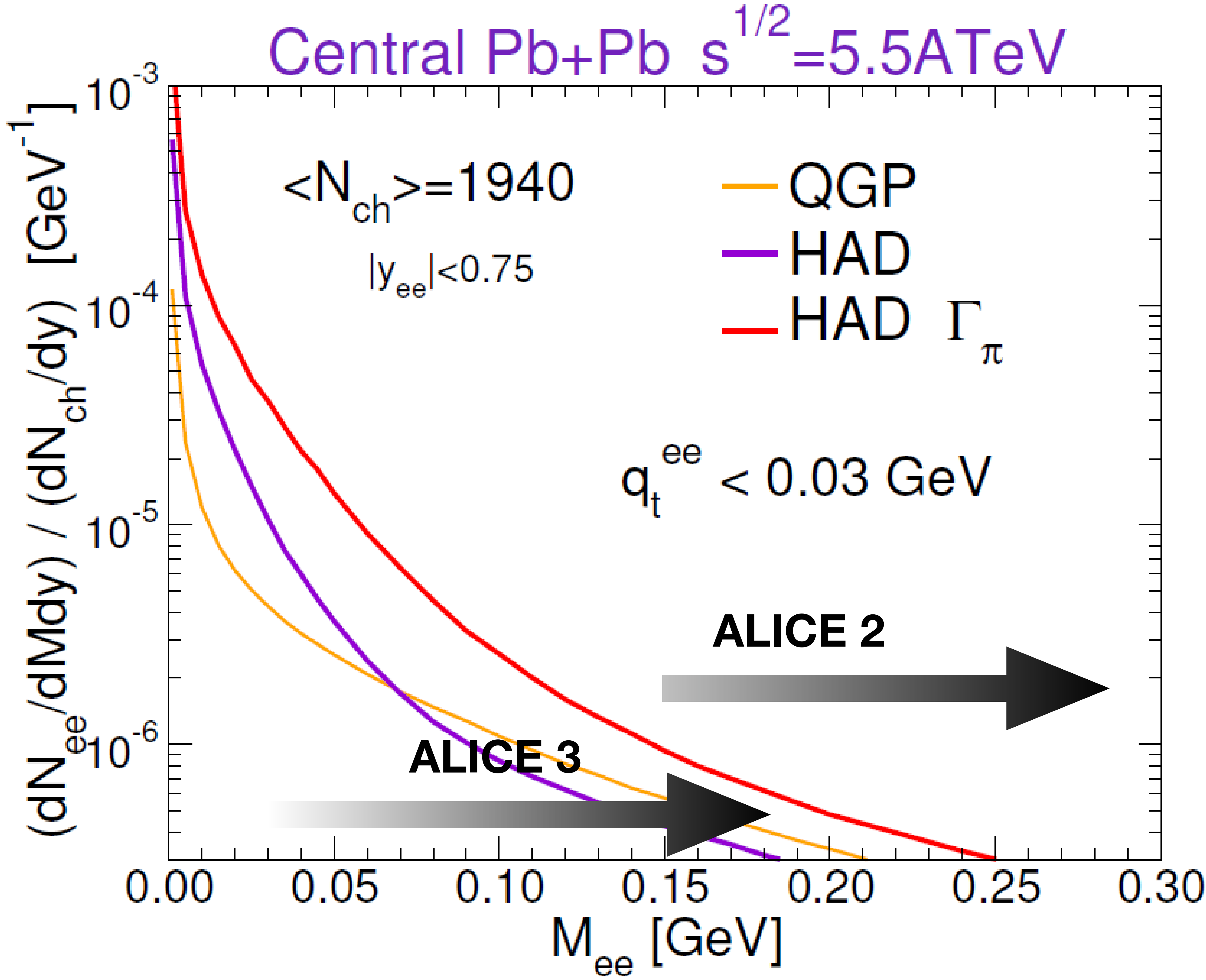
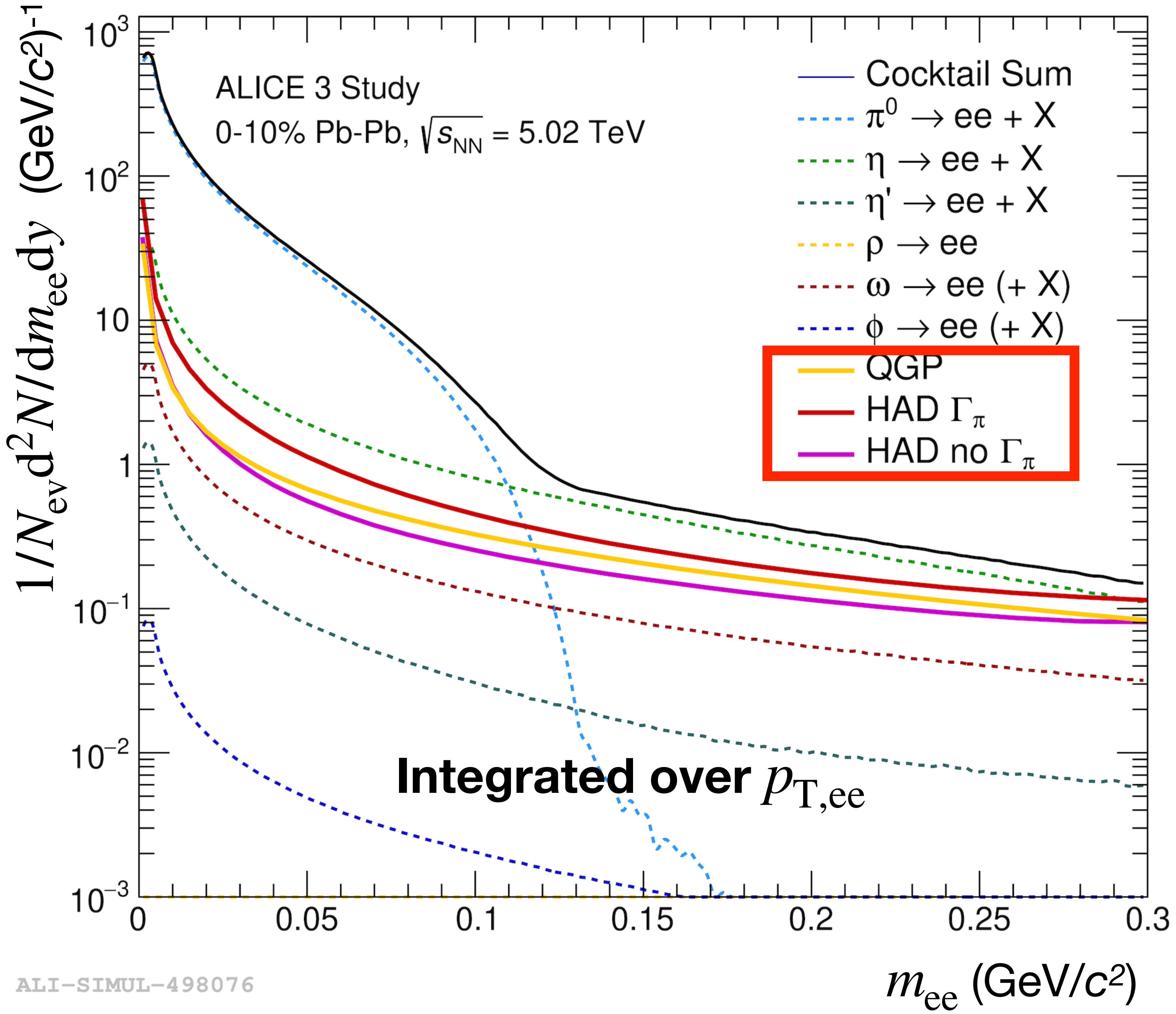


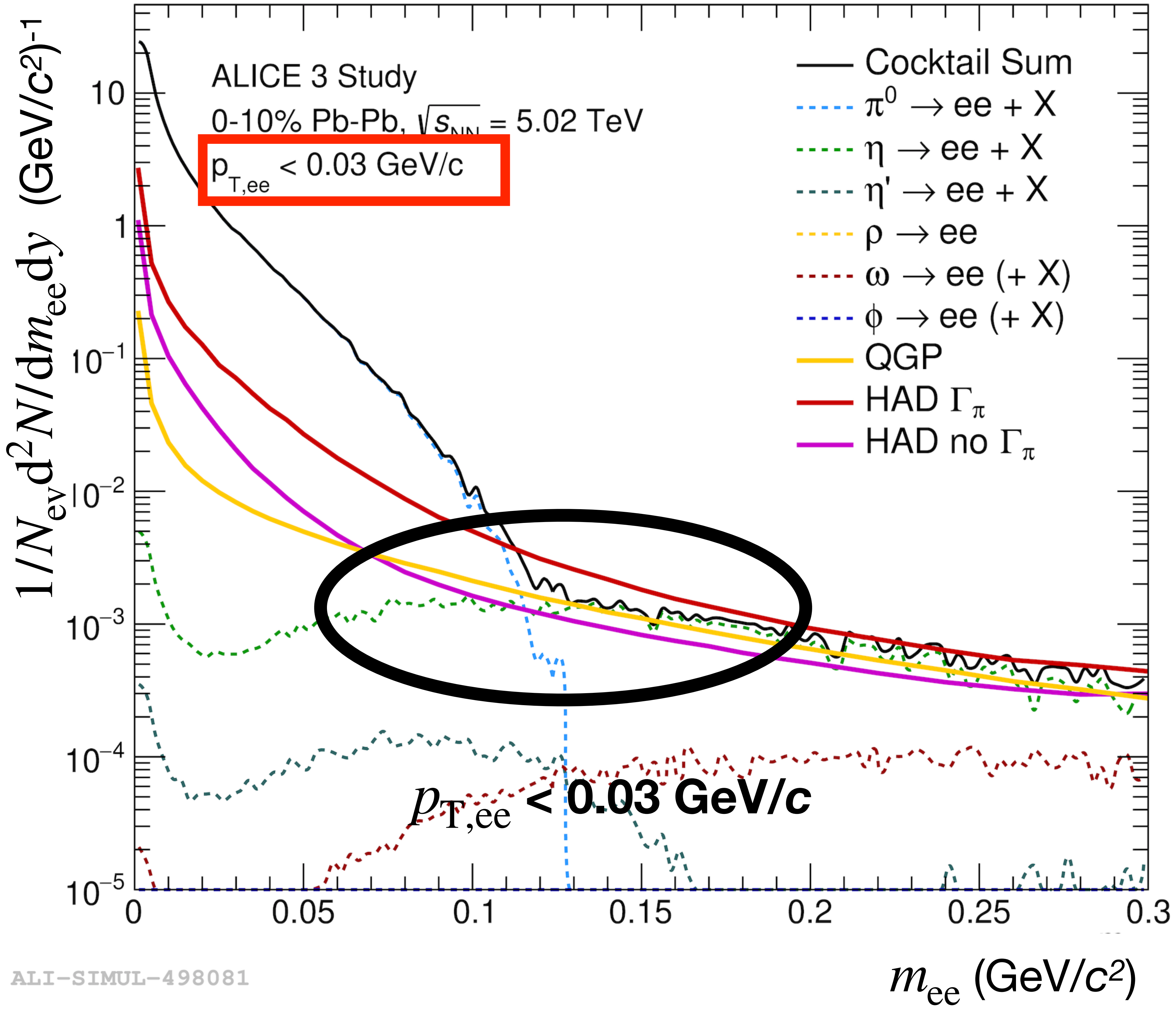
R. Rapp, EMMI Workshop 13.09.2021

Electric conductivity

Compare thermal dielectron yield at low m_{ee} with cocktail of light-flavour hadron decays
without single p_T cut on electrons



Going to very low $p_{T,ee}$



- Some room for possible measurements above m_{π^0} for $p_{T,ee} < 0.03$ GeV/c: **measurements of π^0, η mesons crucial at very low p_T**
- **Background from coherent photo-production of e^+e^- still under study**

Electric conductivity

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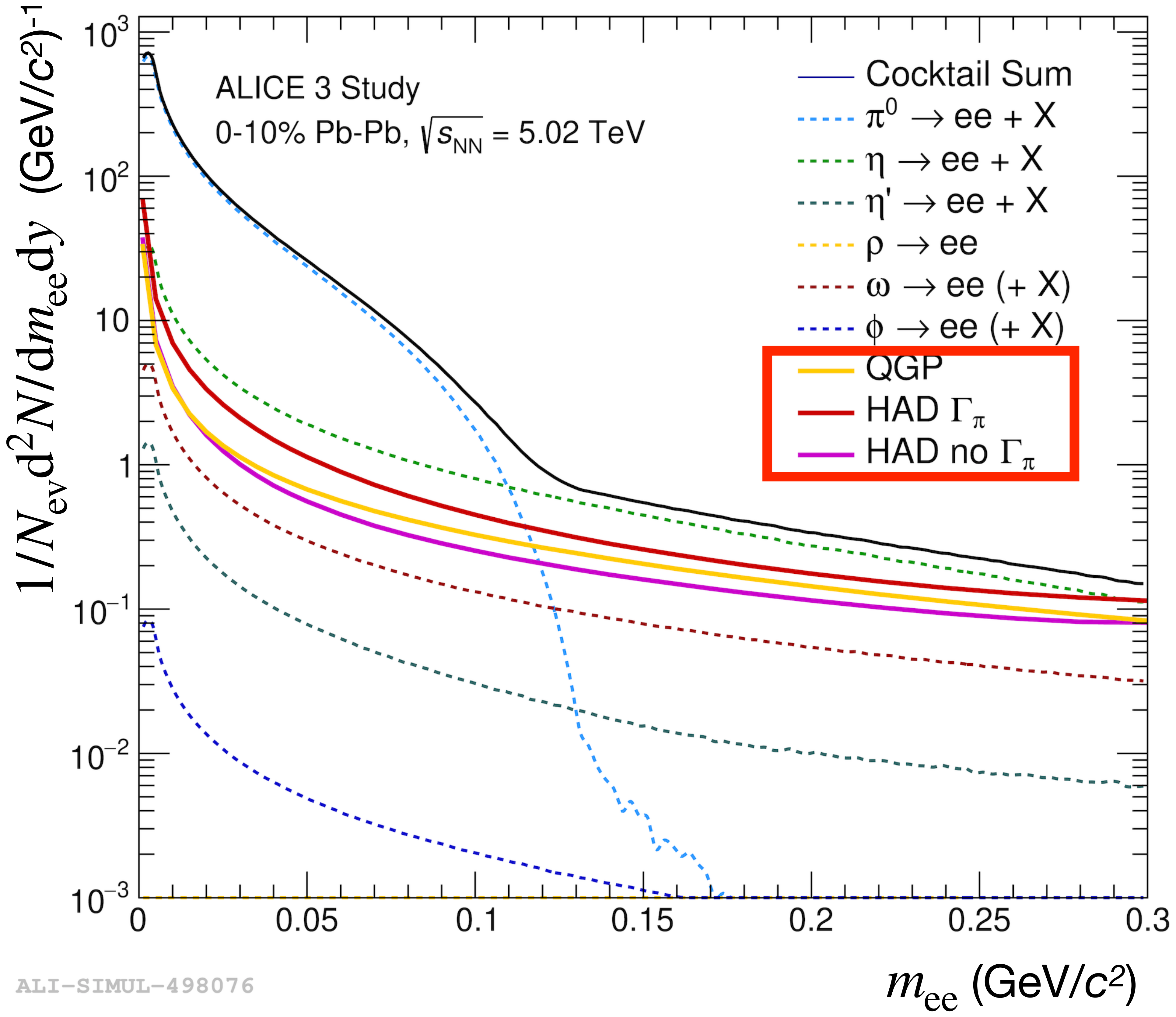

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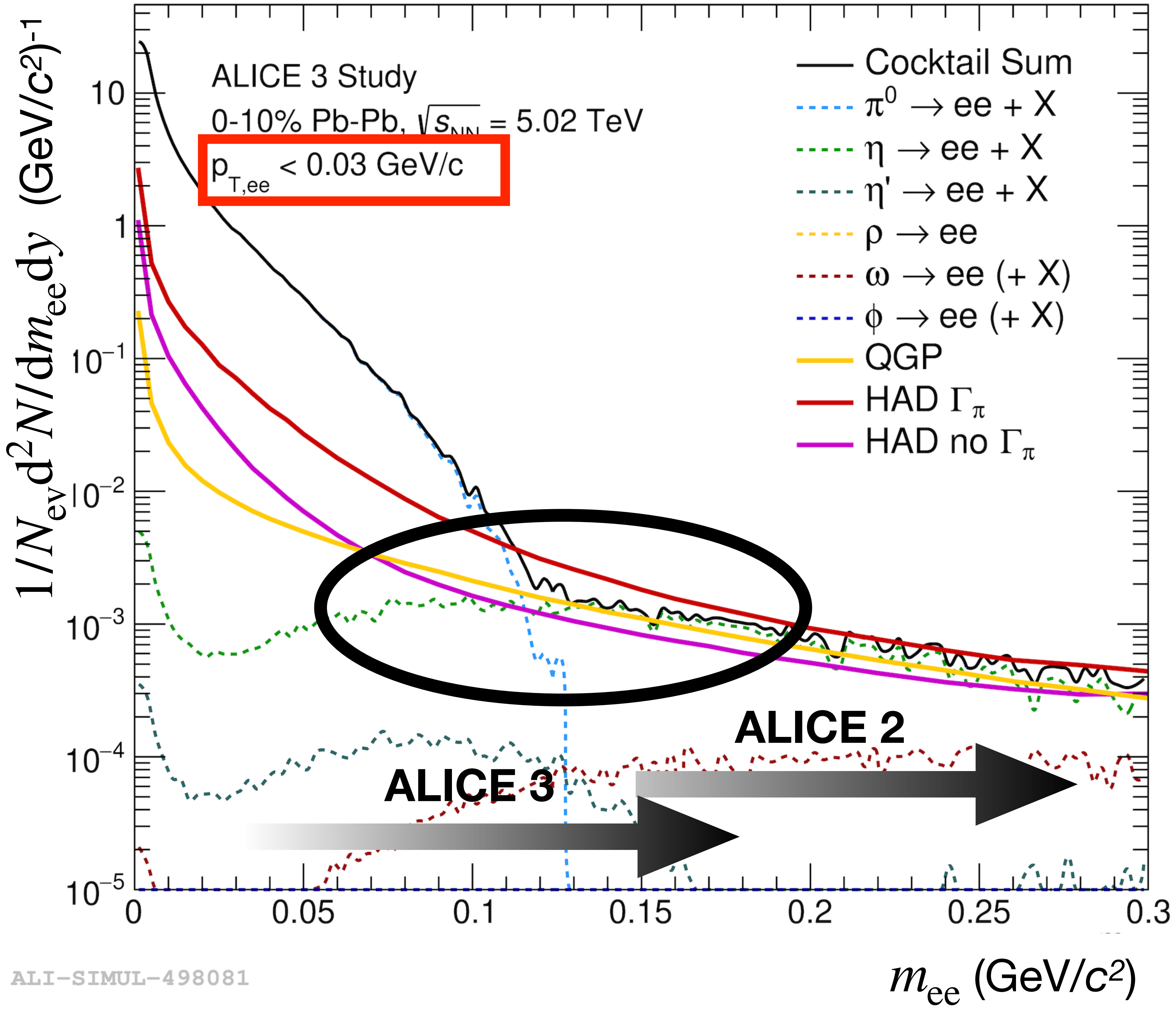
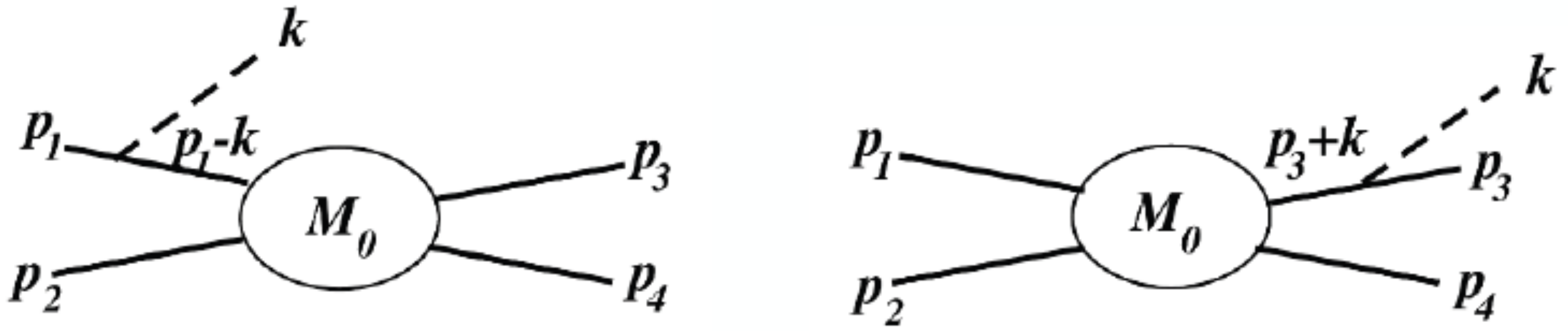


- Some room for possible measurements above m_{π^0} for $p_{T,ee} < 0.03$ GeV/c: **measurements of π^0, η mesons crucial at very low p_T**
- **Need to go lower in $p_{T,e}$ than ALICE 2**

Ultra-soft photons in pp collisions

- **At very low p_{T}, γ produced mainly via inner bremsstrahlung** = bremsstrahlung of initial and final hadronic states

$$p_1 + p_2 \rightarrow p_3 + p_4 + k.$$



- Cross-section **computable without model- and process-dependence (Low-theorem)** knowing the momenta of all incoming and outgoing charged particles (charge conservation)

  → **Related to infrared structure of quantum field theory**

  Francis E. Low., Phys.Rev.Lett. 110 (1958) 468

- Several **measurements** of soft photon production **performed previously** (BNL, AGS, CERN SPS, LEP) **observed excess** (factor ≈ 5) **in association with hadrons** compared to inner bremsstrahlung expectations

  → **Soft-photon puzzle**

  For an overview: see K. Reygers ALICE 3 Workshop 19.10.2021

ALICE 3 soft-photon strategy

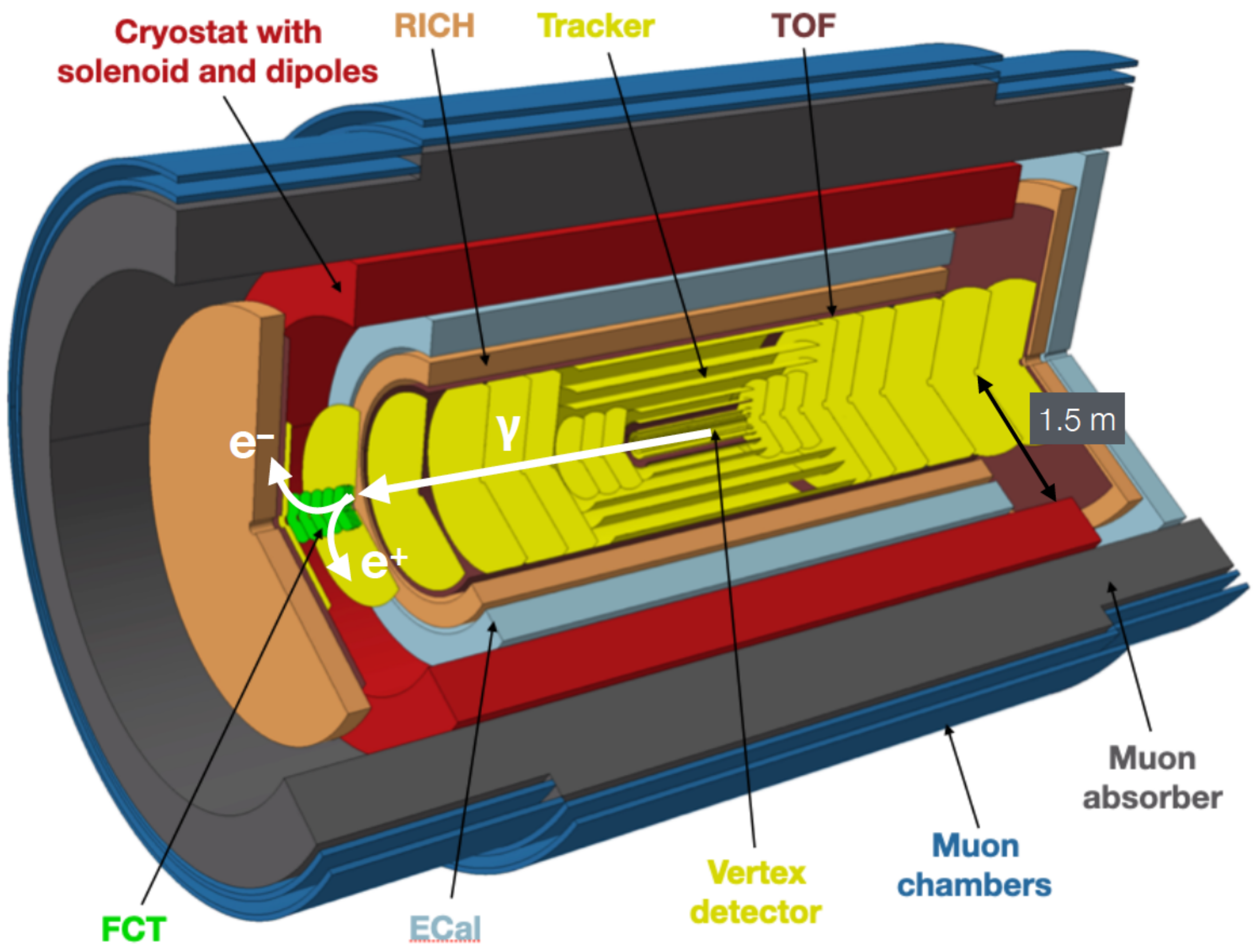
- **Reactions/Systems where to look:**
  - ***Clean* exclusive process** like $\mathrm{pp} \rightarrow \mathrm{pp}\pi^+\pi^-\gamma$
    - Precise calculations for $\mathrm{pp} \rightarrow \mathrm{pp}\pi^+\pi^-\gamma$ exist
  - **Inelastic (non-diffractive) pp collisions**
  - **Reactions/systems with higher charged particle multiplicities**

  → **Take advantage of the large rapidity coverage of ALICE 3:**
    - To select exclusive process
    - To measure charged particle multiplicity in more complicated reactions/systems

- **Rapidity where to measure:**
  - Need to measure γ with $p_{\mathrm{T}} \leq$ 5 MeV due to decay γ background n
  - Low E photon measurement possible down to $E \approx$ 50-100 MeV via conversion

  Gain a factor 10, 27 and 74 in p_{T} going to $\eta =$ 3, 4, 5 $(E/p_{\mathrm{T}} = cosh(\eta))$

  → **Forward Conversion Tracker covering $3 \leq \eta \leq$ 5**



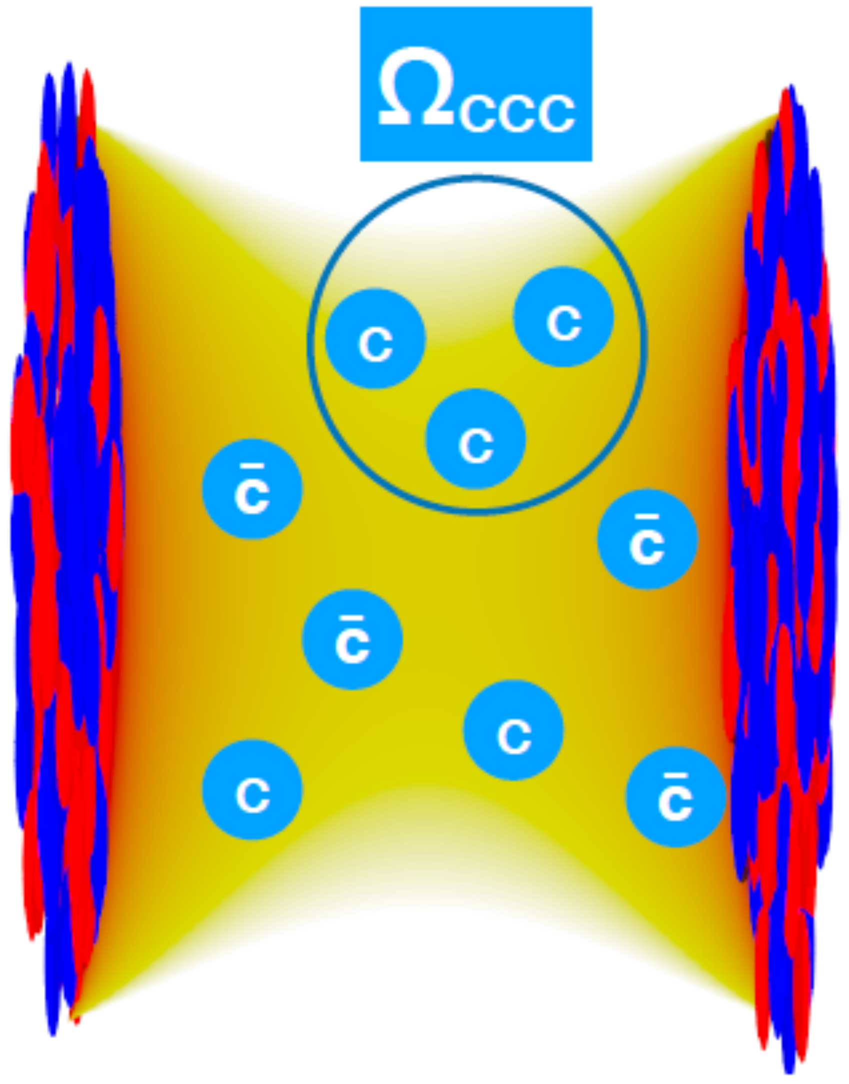
Deconfinement and hadronisation

- **In proton-proton:** hadronisation via string fragmentation
- **In QGP:** coalescence/thermal production contributions
- **Multi-charm baryons:**
    - Charm quark produced in initial hard scattering
    - Multi-charm baryons: produced mostly via coalescence

  → Large enhancement in AA (large $\sigma_{c\bar{c}}$)

  → Sensitive to the equilibrium properties of charm in the QGP

  ALICE: charmed baryons, ALICE 3: multi-charm baryons



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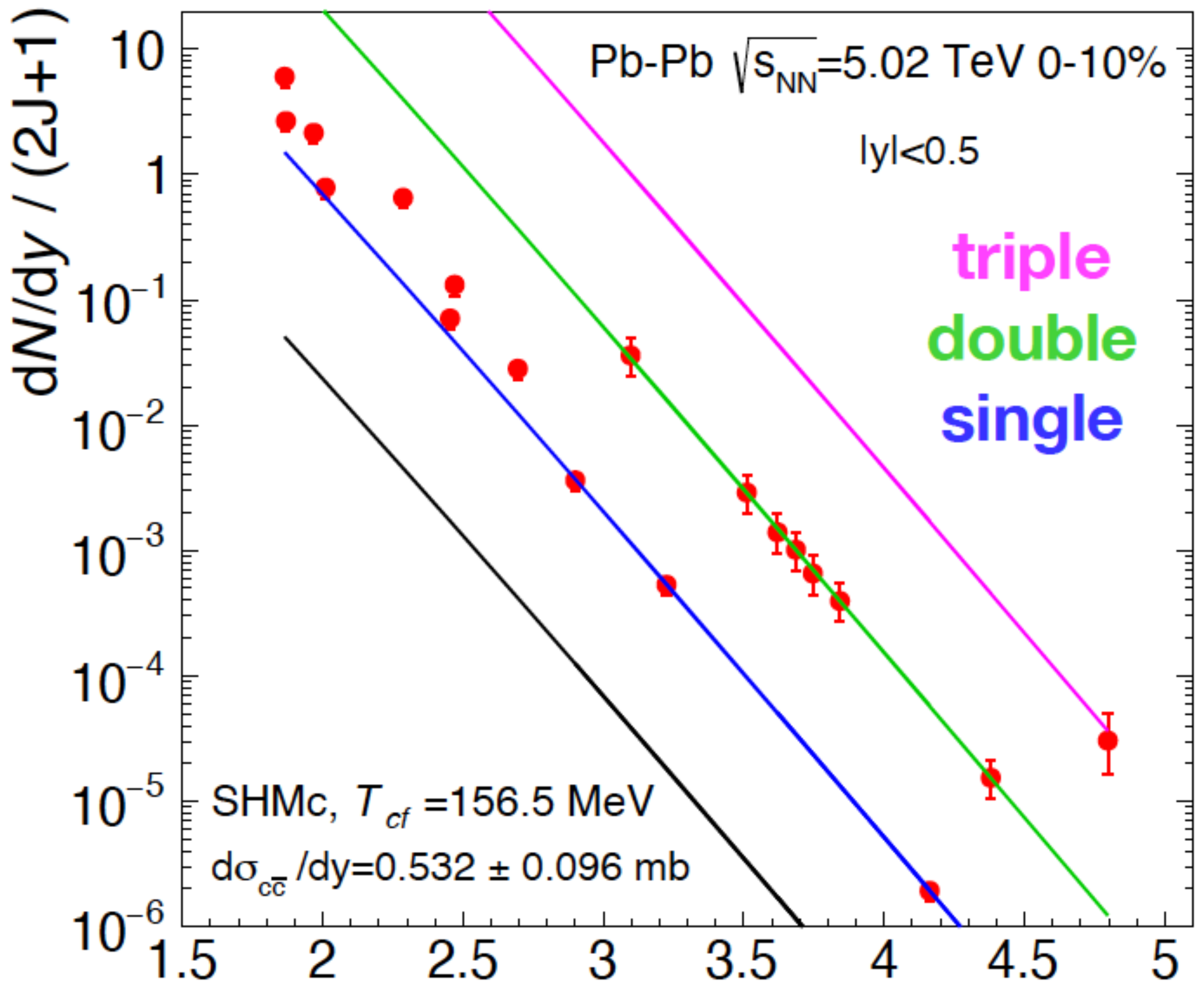
SHM predictions
u,d,s only particles in black
and (multi-)charm states in red



Andronic et al, arXiv:2104.12754

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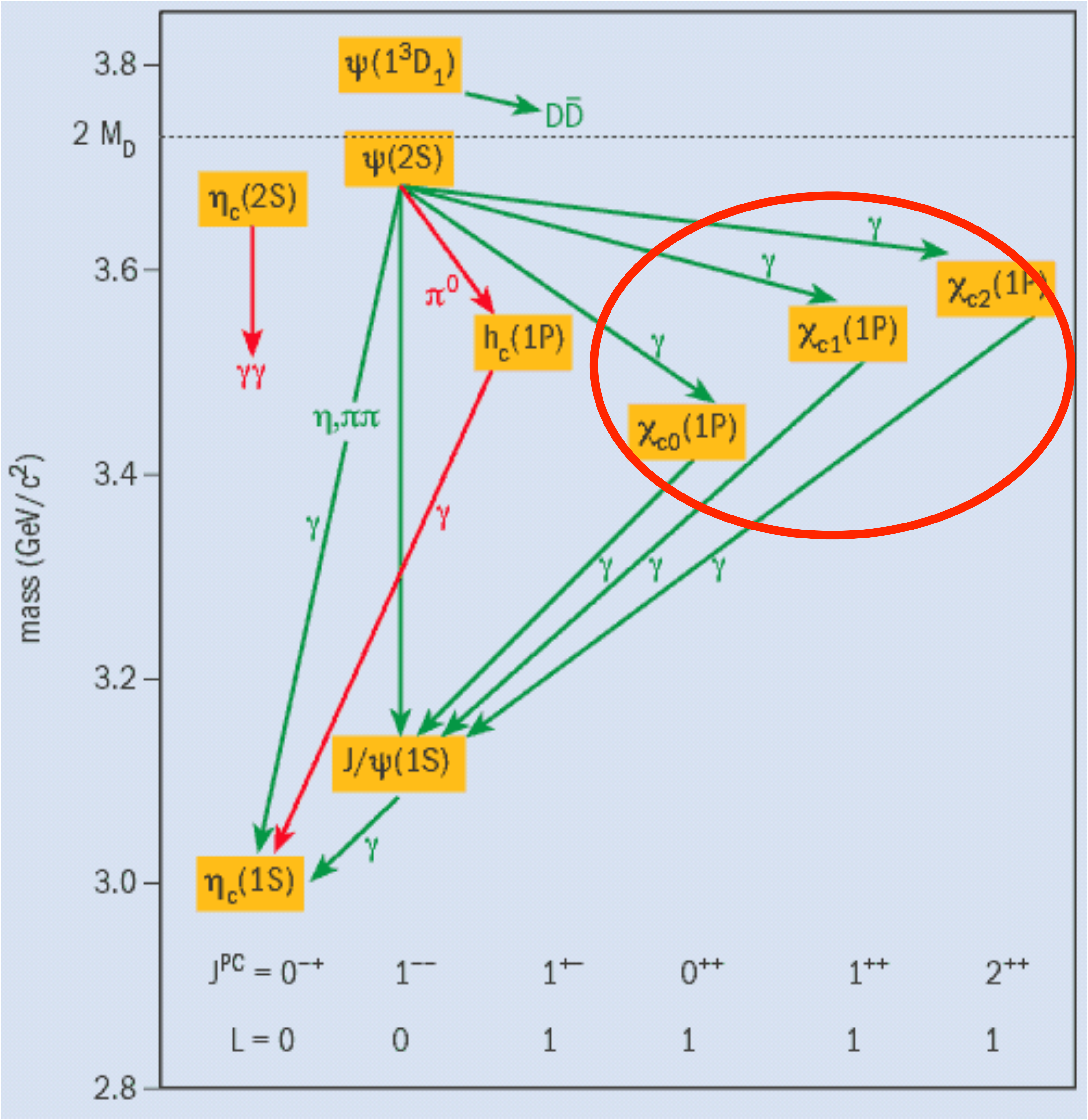
- **Quarkonium measurements beyond S-wave States:**
  - Measurements currently limited to S-wave states: $J/\Psi, \Psi(2S), \Upsilon(nS)$
  - χ_c, χ_b **states with ALICE 3 down to p_T = 0**

Charmonium states



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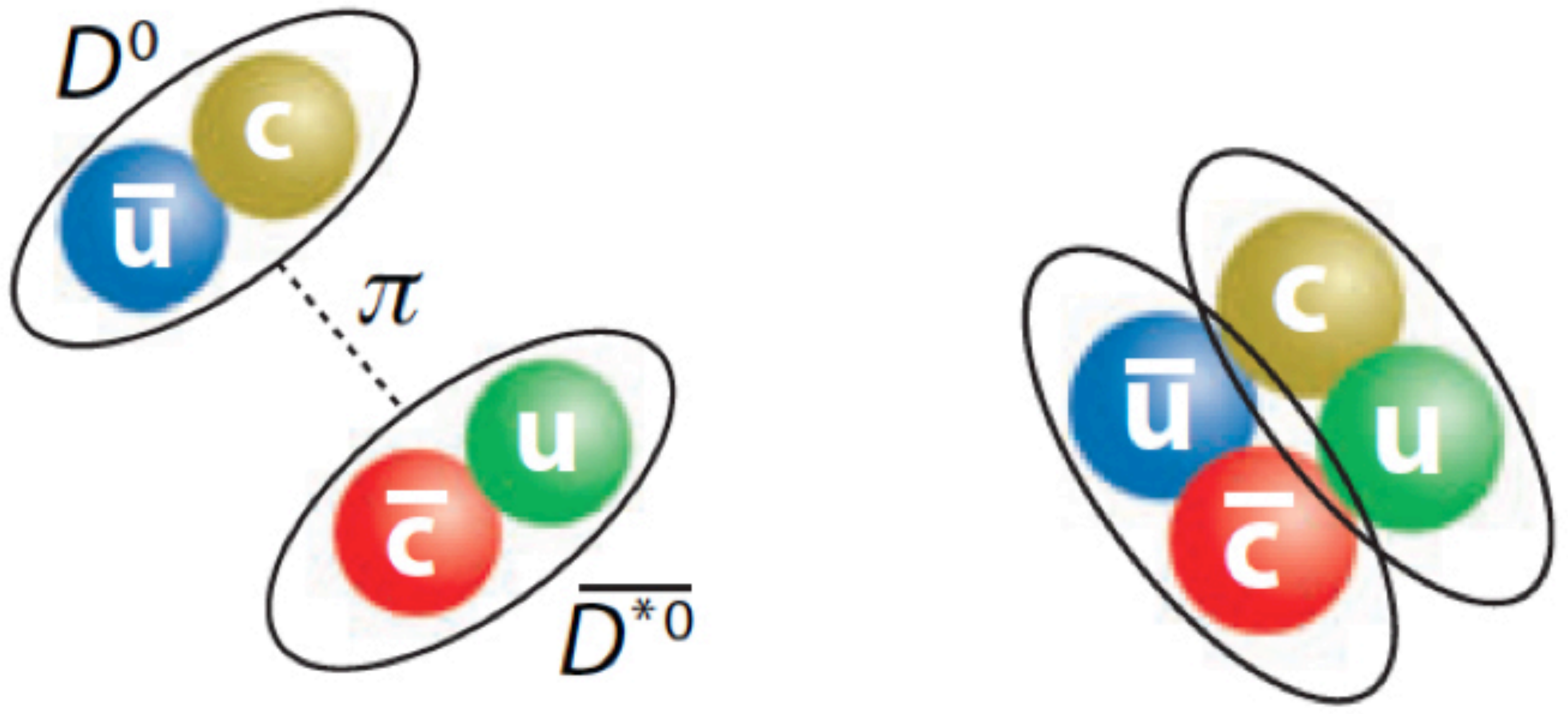
- **Heavy-flavour exotica:**
  - X(3872) discovered in 2003: nature not clear
    Measurement down to low-p_T with ALICE 3
  - **Many other states** expected but not yet discovered

Possible nature of X(3872) state



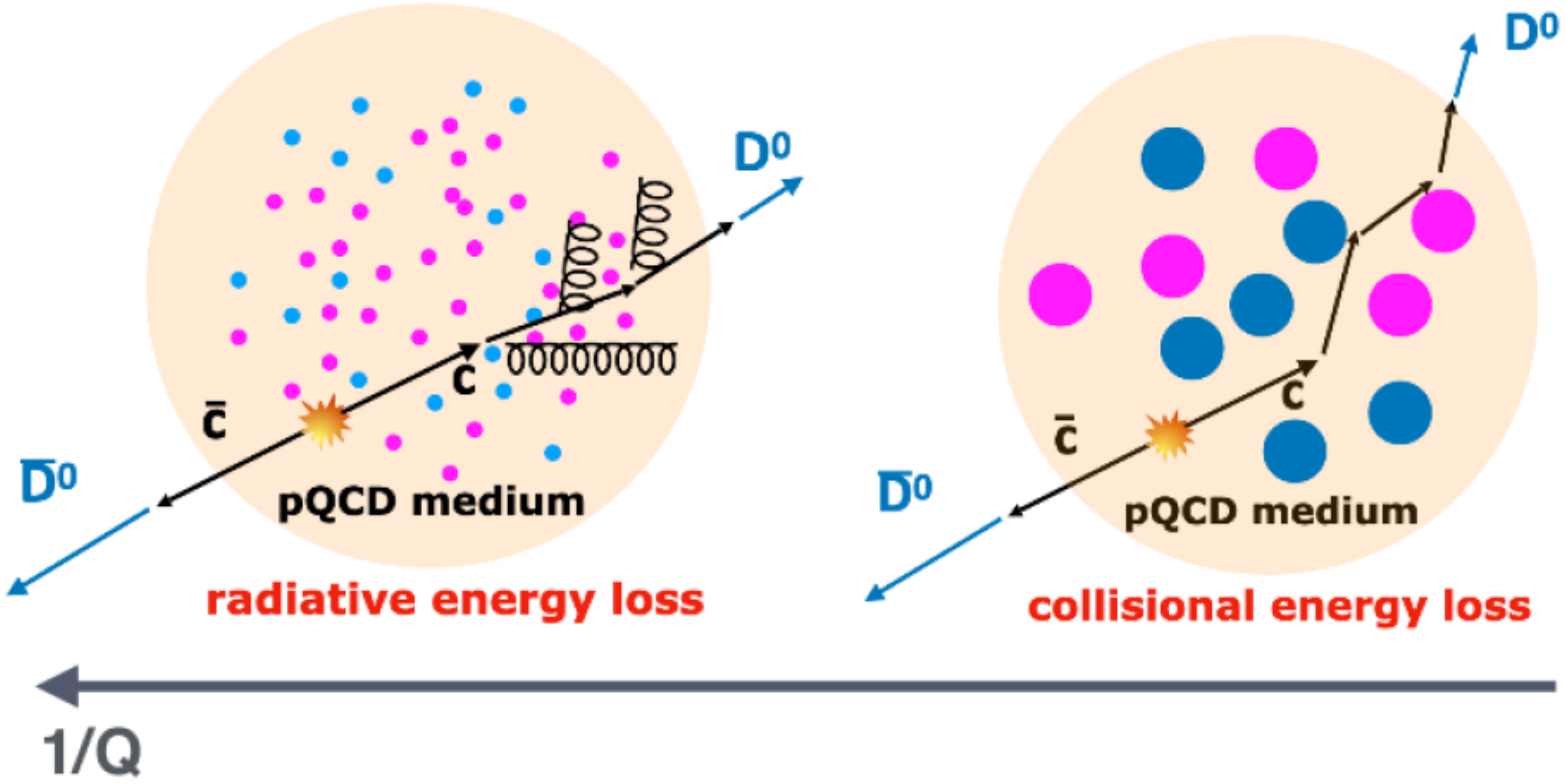
D^0–$\overline{D}^{*0}$ "molecule" Diquark–diantiquark

Heavy-flavour probes of the QGP

- **Parton-medium interactions via heavy-flavour correlations**
  - $\Delta\eta, \Delta\varphi$ correlation of heavy-quark pairs:
    - radiative energy loss (small broadening)
    - collisional energy loss (larger broadening)
    - “thermalization” (randomization)

  ALICE 3: $\mathrm{D\bar{D}}$ correlation over wide rapidity range

$D^0\bar{D}^0$ correlation



- **Energy loss and approach to thermalization:**
  - Photon-HF jet correlation:

    ALICE 3: down to low p_T over wide rapidity range
  - Heavy-flavour baryon flow (including beauty):

    ALICE 3: Λ_c, Λ_b v_2 down to low p_T
  - Heavy-flavour jet substructure….

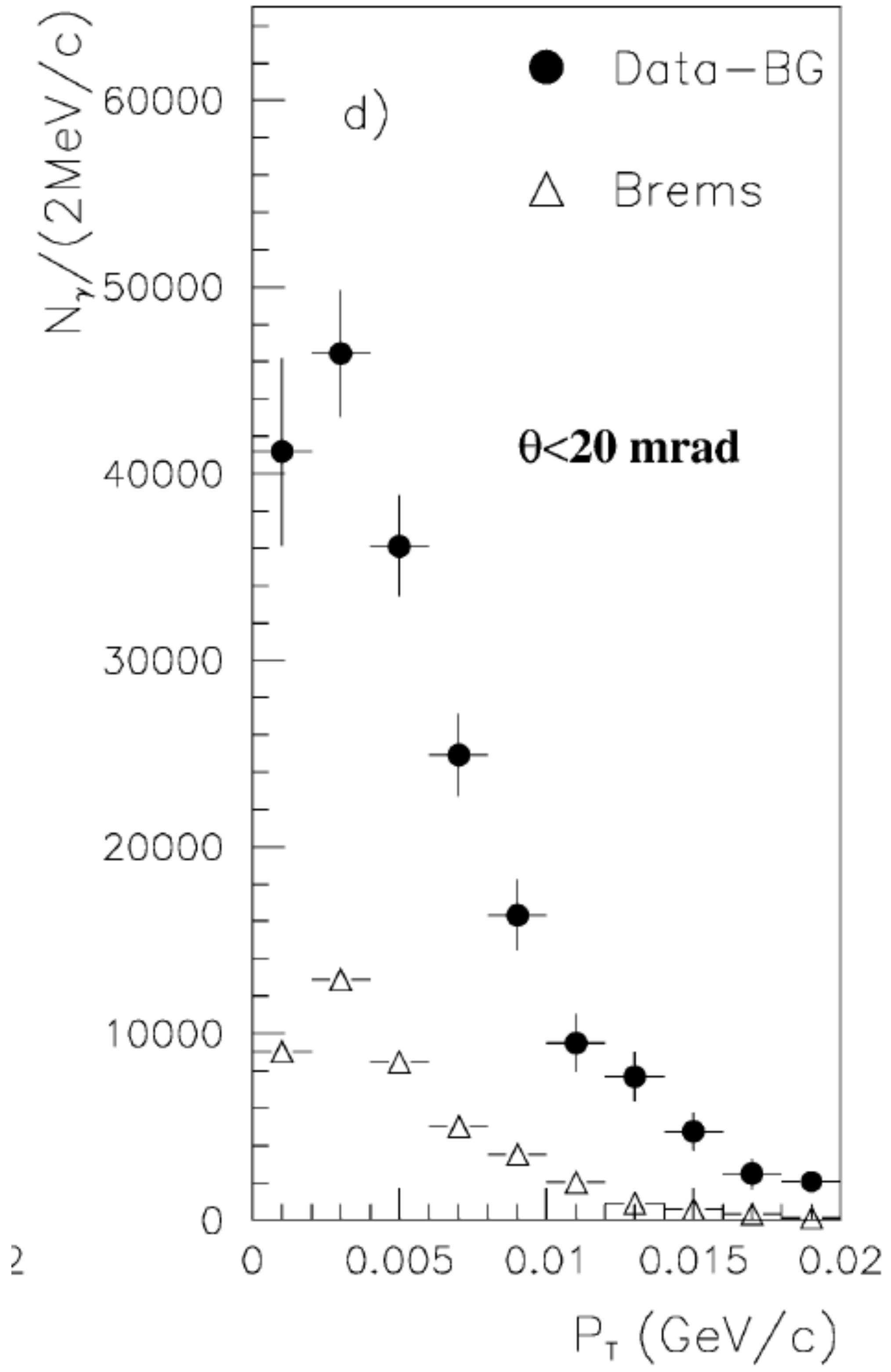
Non-QGP physics

- **Ultra-soft photons:**
  - At very low p_T, γ produced via inner bremsstrahlung
    → Cross section computable without model- and process-dependence (Low-theorem)
  - Very low p_T means: γ wavelength exceeds dimension of any hadronic or nuclear system
    → Easier to reach in small systems (pp collisions)
  - Previous measurements: excess of soft photon in association with hadrons

  ALICE 3: test Low-theorem in pp collisions

- **Others:**
  - Nuclei: search for super-nuclei (light-nuclei with c)….
  - Interaction potentials between charmed baryons and nucleons via femtoscopic correlation
  - Beyond Standard Model studies (axion-like particles…)

WA102 at CERN SPS: Photon production in pp collisions at 450 GeV/*c*



Belogianni et al., Phys. Lett. B548, 129 (2002)

Luminosity projections

- Ongoing discussions with machine groups to establish projections for 2030s
- Current assumptions for physics projections:

	levelling	limited by machine						
	pp	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$3.0 \cdot 10^{32}$	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$3.0 \cdot 10^{32}$	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathscr{L}_{AA}$ (nb^{-1} / month)	$5.1 \cdot 10^{5}$	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathscr{L}_{NN}$ (pb^{-1} / month)	505	409	550	500	510	512	434	242

- **Total luminosity increase 2-10 x wrt to Run 3 + 4**, depending on collision system
  (Larger increase for lighter collision system)
  Run 3 + 4: 13 nb^{-1} Pb-Pb, 200 pb^{-1} pp