Low Mass Dielectrons in pp, p-Pb and Pb-Pb Collisions with ALICE

Aaron Capon, on behalf of ALICE
Stefan Meyer Institute for Subatomic Physics, Vienna

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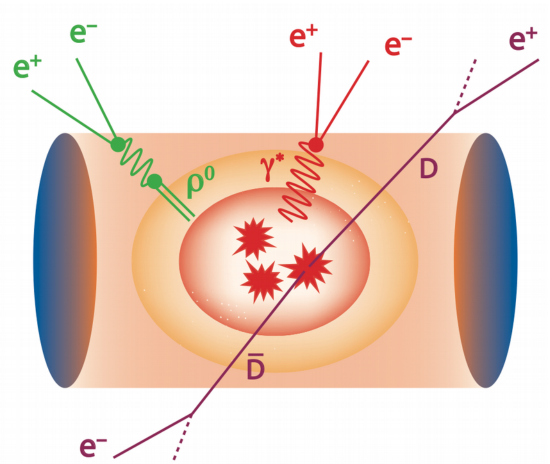
Dielectrons as Probes of the QGP

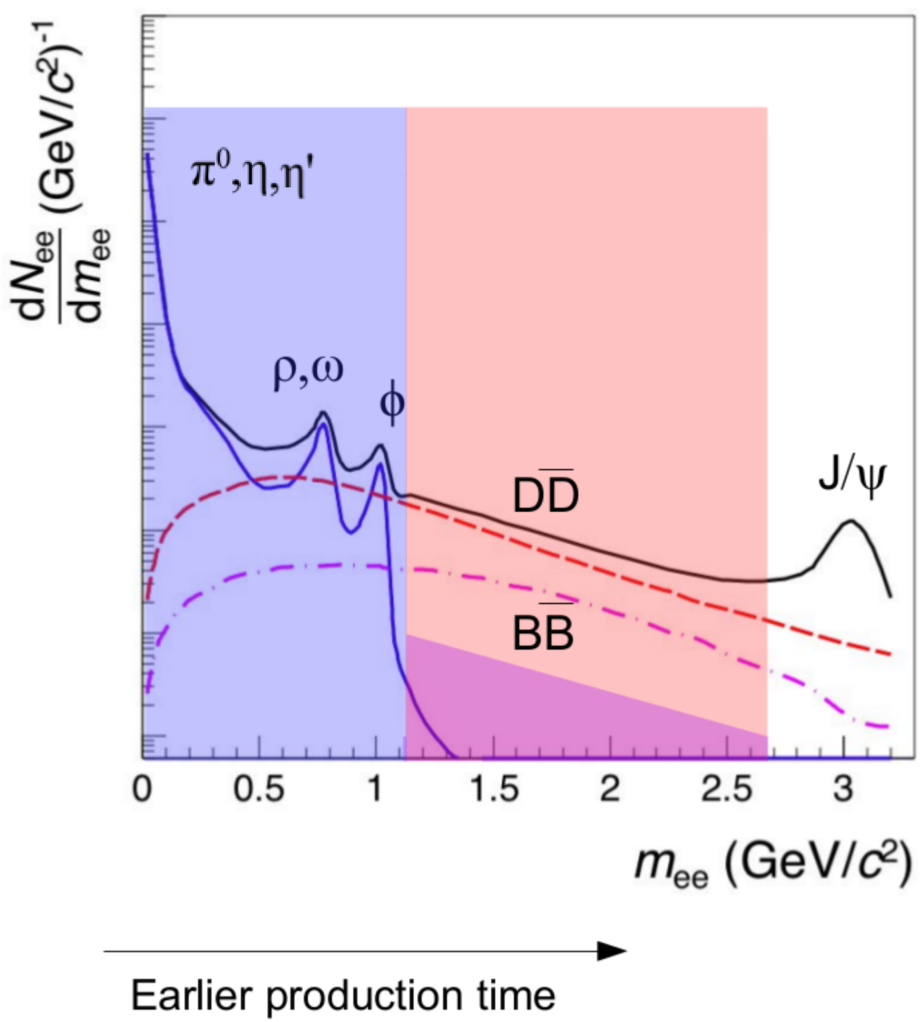
- Many sources of dielectrons created during the course of the collision

  → dielectron spectrum contains the whole "history" of the collision

- Photons and leptons experience no strong interactions and can therefore probe the inner regions of collisions unperturbed

  → medium is transparent to dielectrons

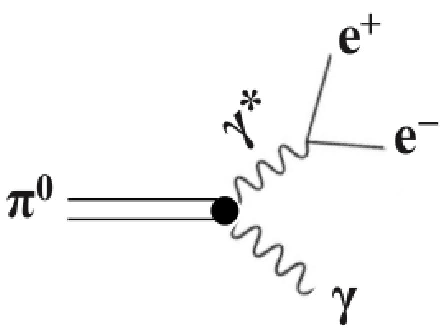




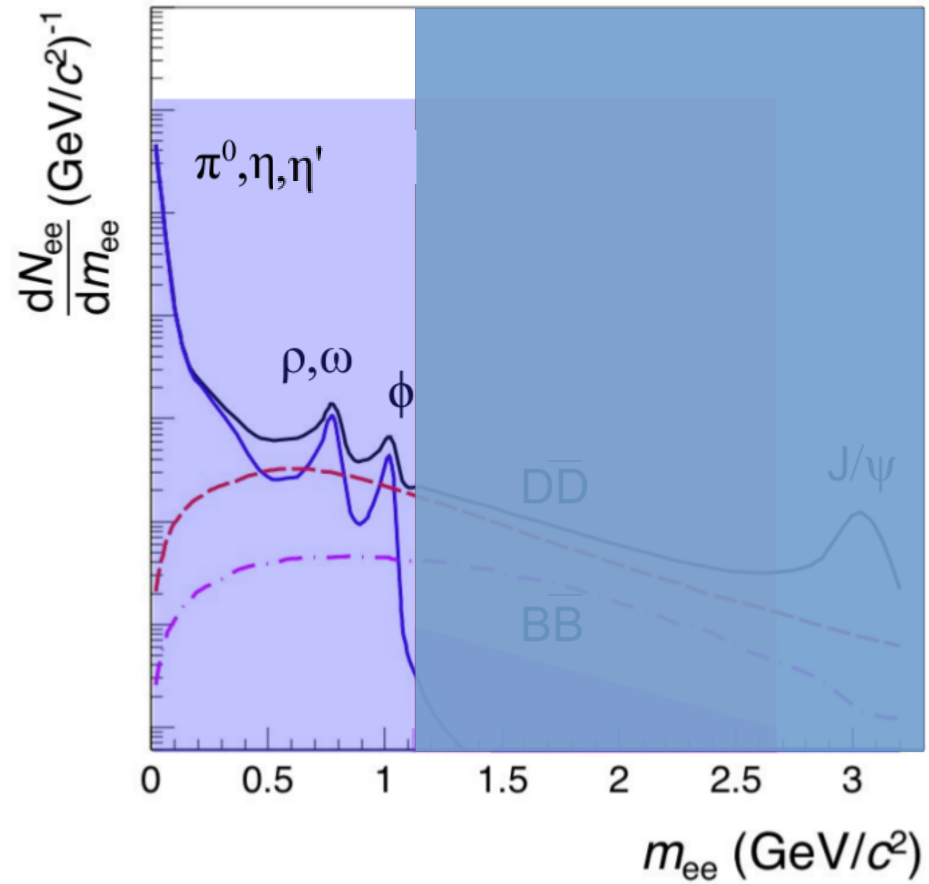
Dielectron Mass Spectrum

Low Mass Region

- m_{ee} < 1.1 GeV/c^2
- Populated with light neutral mesons
  - π^0, η, η', ρ, ω and ϕ
- Decaying via Dalitz, or two body decays



- Potentially sensitive to chiral symmetry restoration which is predicted at the high temperatures reached in heavy ion collisions
  - broadening of ρ observed at SPS and RHIC → measure at LHC: μ_B=0
- Thermal radiation via measurement of quasi-real photons



Earlier production time

Dielectron Mass Spectrum

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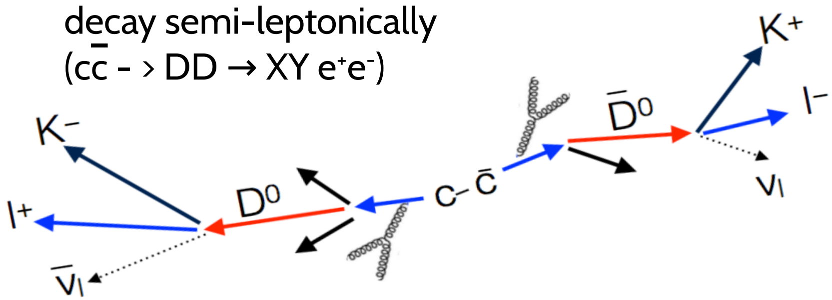
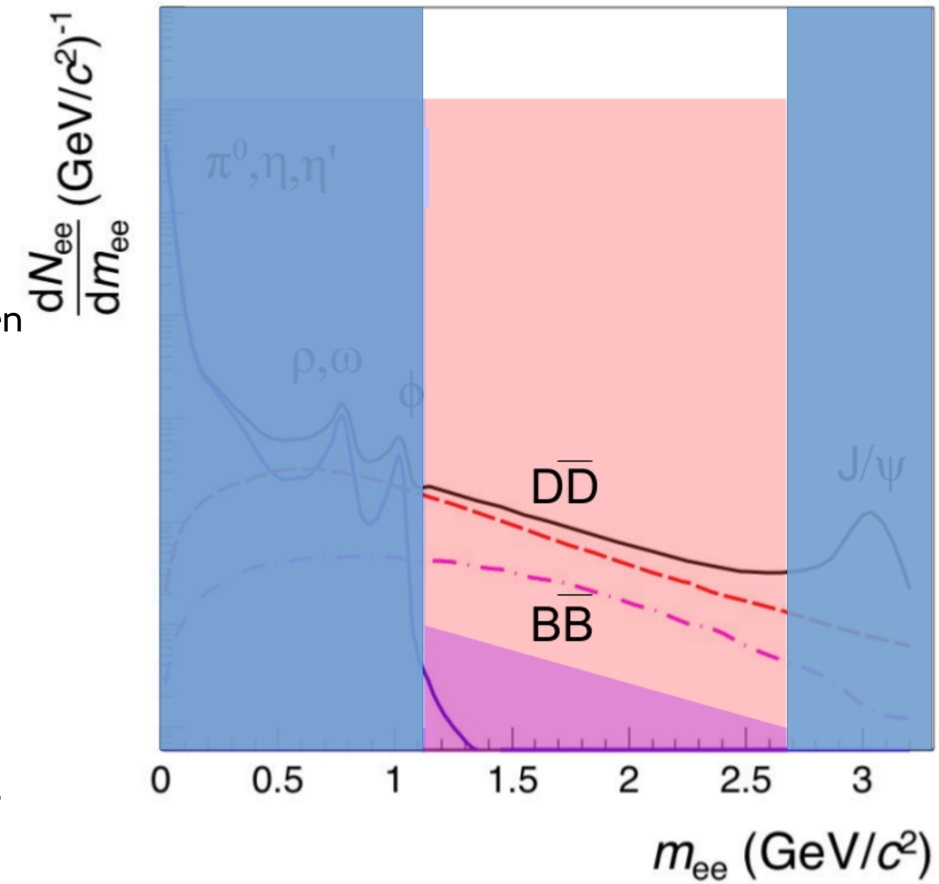
Intermediate Mass Region (IMR)

- $1.1 < m_{ee} < 2.5$ GeV/c^2
- Dominated by decays of correlated "open heavy flavour"
- $c\bar{c}$ and $b\bar{b}$ pairs created during the collision can form a bound state with a lighter quark and then decay semi-leptonically ($c\bar{c}$ - > D$\bar{D}$ → XY e^+e^-)



- Measure/investigate:
  - $\sigma_{c\bar{c},b\bar{b}}$
  - Nuclear parton distribution functions (PDF's) in p-Pb and Pb-Pb
  - Sensitive to production mechanisms in pp
  - Thermal radiation from the partonic phase
  - Photo-production: $\gamma\gamma \rightarrow e^+e^-$



Earlier production time

ALICE's Results Overview

pp

Run 1

- $\sqrt{s}$ = 7 TeV
  JHEP 1809 (2018) 064

Run 2

- $\sqrt{s}$ = 13 TeV
  PLB 788 (2019) 505
- $\sqrt{s}$ = 13 TeV (B = 0.2T)
  preliminary result
- $\sqrt{s}$ = 5.02TeV
  analysis ongoing

Pb-Pb

Run 1

- $\sqrt{s_{NN}}$ = 2.76 TeV (0-10% centrality)
  Phys. Rev. C 99, (2019) 024002

Run 2

- $\sqrt{s_{NN}}$ = 5.02 TeV
  preliminary (2015 data)
  ~10× more statistics from 2018 (0-10% centrality)

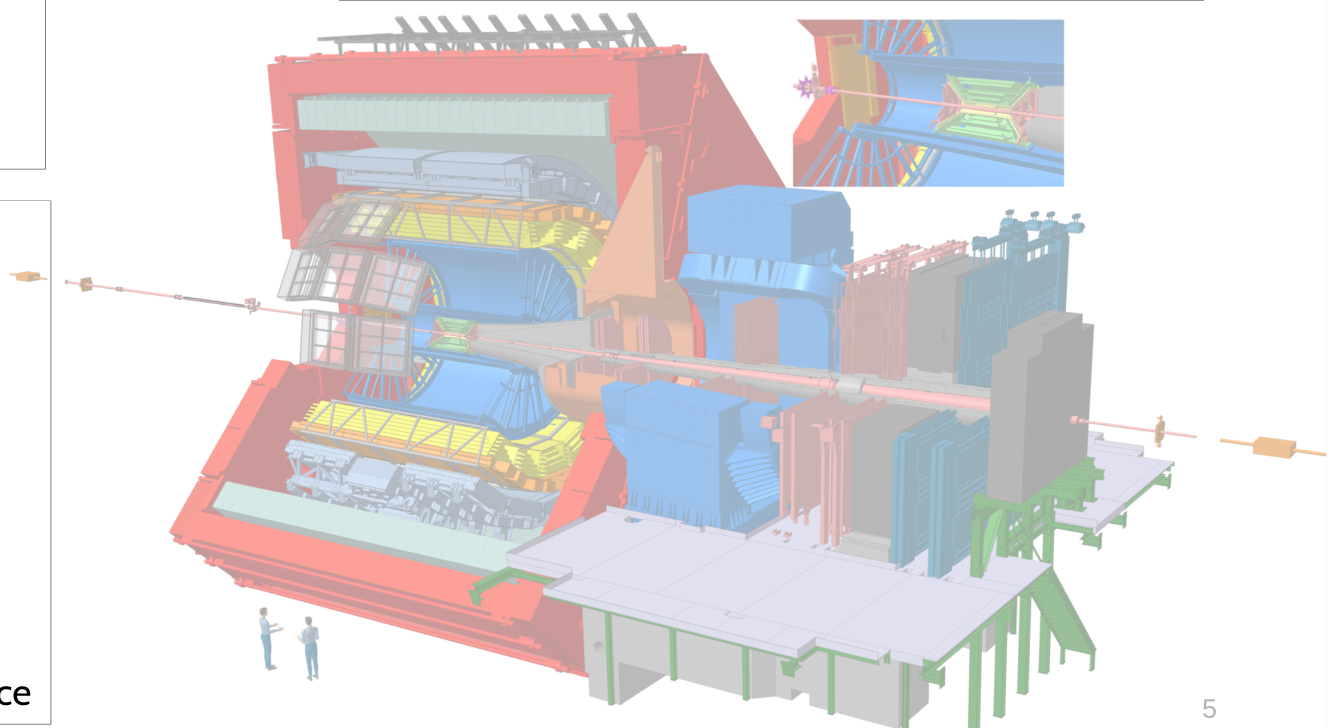
p-Pb

Run 1

- $\sqrt{s_{NN}}$ = 5.02 TeV
  preliminary

Run 2

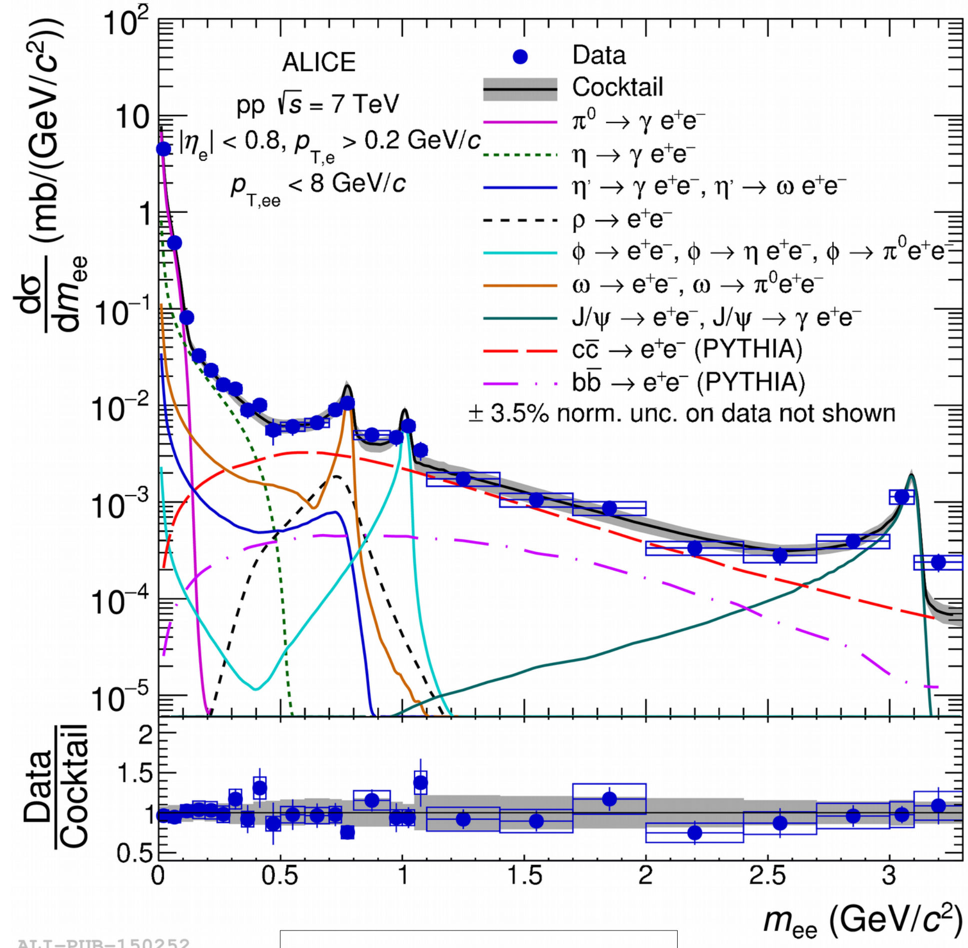
- $\sqrt{s_{NN}}$ = 5.02 TeV
  ~5× more statistics
  ongoing work
    DCA studies
    multiplicity dependence



Dielectron Invariant Mass in pp

$\sqrt{s}$ = 7 TeV

- Dielectron mass spectra in pp act as baseline for measurements in p-Pb and Pb-Pb
- Compare spectrum to cocktail of known hadronic sources
- Cocktail at $\sqrt{s}$ = 7 TeV comprised of:
  - $\pi^{\pm}$(for π^0), η, ϕ, J/ψ: measurements used for input
  - η': m_T scaling
  - ω & ρ: $\omega/\pi^{\pm}$ and $\rho/\pi^{\pm}$ ratios from PYTHIA 8 Monash 2013 tune and measurements in pp at $\sqrt{s}$ = 7 TeV
  - $c\bar{c}$ and $b\bar{b}$: PYTHIA 6 Perguia 2011 tune scaled to measured $\sigma_{c\bar{c},b\bar{b}}$
- Data well described by cocktail within uncertainties
  → baseline measurement well understood

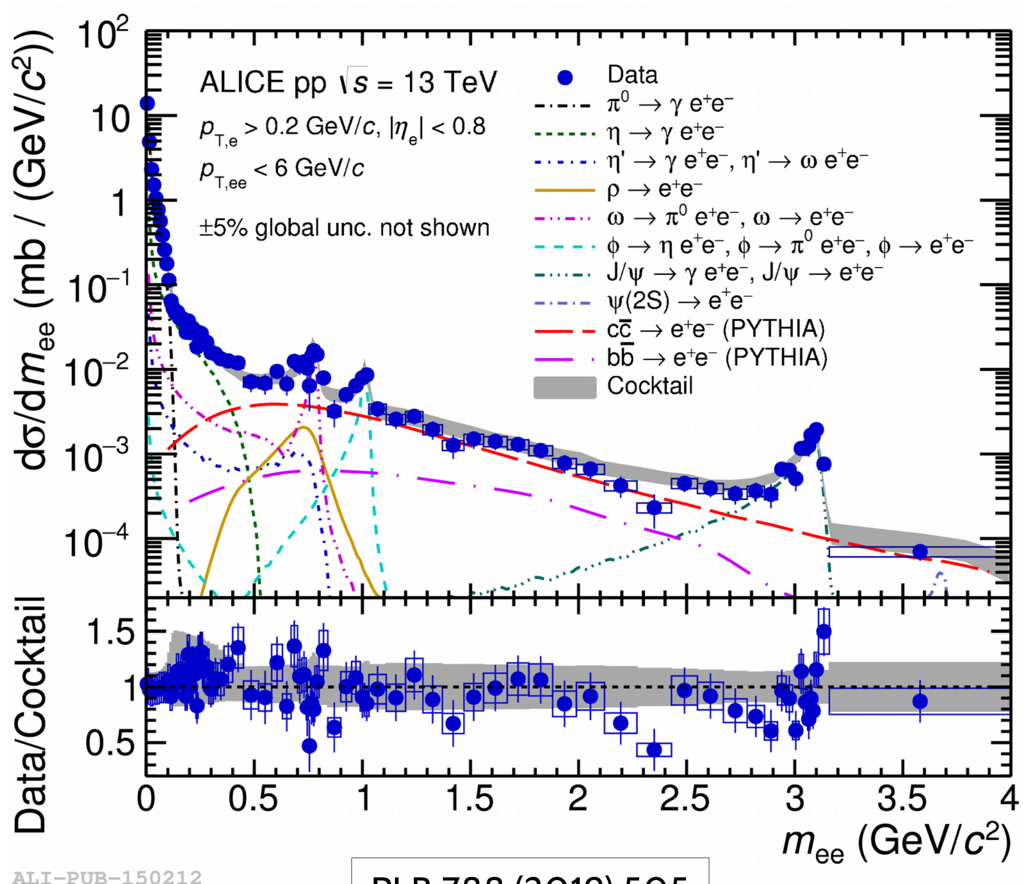


JHEP 1809 (2018) 064

Dielectron Invariant Mass in pp

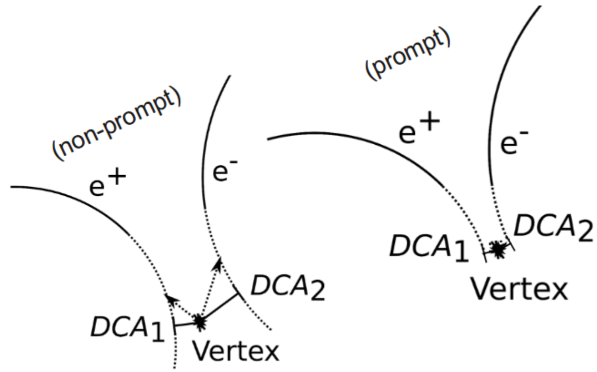
$\sqrt{s}$ = 13 TeV

- Dielectron mass spectra in pp act as baseline for measurements in p-Pb and Pb-Pb
- Compare spectrum to cocktail of known hadronic sources
- Cocktail at $\sqrt{s}$ = 13 TeV comprised of:
  - $\pi^{\pm}$(for π^0): via scaling by the $\pi^{\pm}$/hadrons$^{\pm}$ ratio from measurement at $\sqrt{s}$ = 7 TeV
  - η: measured η/π^0 ratio at 7 TeV
  - η' & ϕ : m_T scaling
  - ω & ρ: $\omega/\pi^{\pm}$ and $\rho/\pi^{\pm}$ ratios from PYTHIA 8 Monash 2013 tune
  - $c\bar{c}$ and $b\bar{b}$: PYTHIA 6 Perguia 2011 tune scaled to $d\sigma_{c\bar{c},b\bar{b}}/dy|_{y=0}$ scaled with FONLL from $\sqrt{s}$ = 7 TeV measurement
- Data well described by cocktail within uncertainties
  → baseline measurement well understood



PLB 788 (2019) 505

DCA Studies in pp

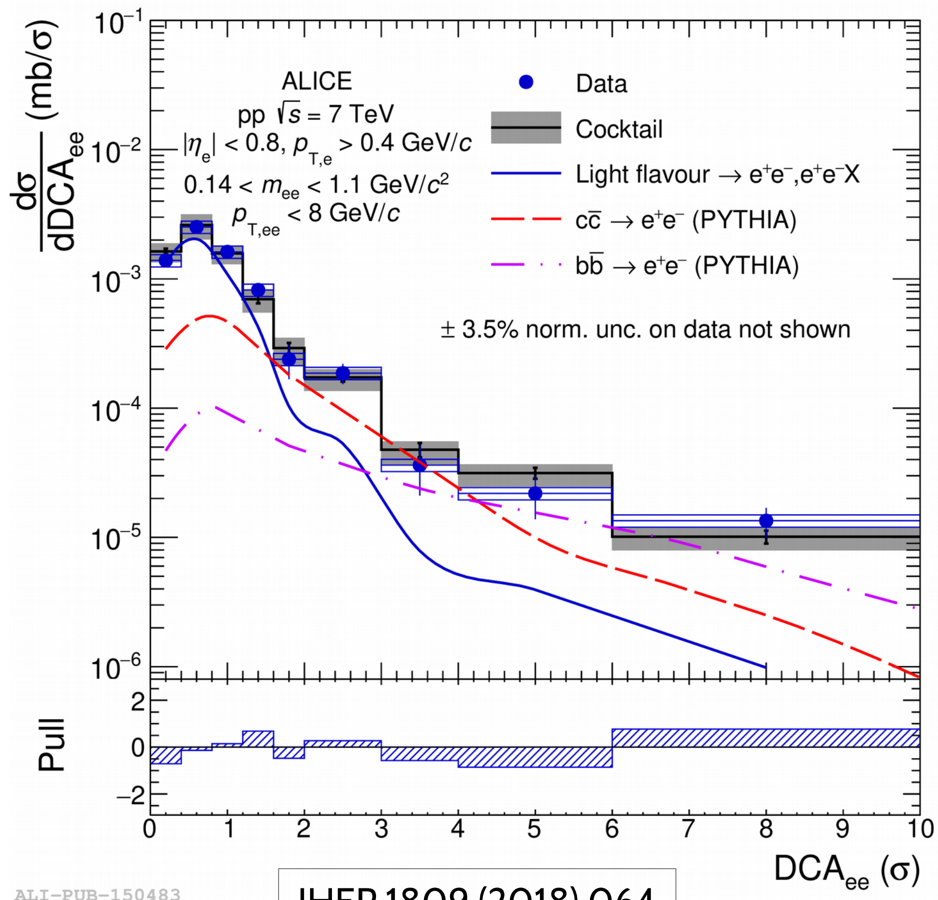


$$\mathrm{DCA_{ee}} = \sqrt{0.5\left(\left(\frac{\mathrm{DCA}_1}{\sigma_1}\right)^2 + \left(\frac{\mathrm{DCA}_2}{\sigma_2}\right)^2\right)}$$

- Observable → DCA = Distance of Closest Approach - normalised to track resolution

- Useful variable to separate prompt from non-prompt dielectron sources

$\mathrm{DCA_{ee}}$(**prompt**) < $\mathrm{DCA_{ee}}$(**charm**) < $\mathrm{DCA_{ee}}$(**beauty**)



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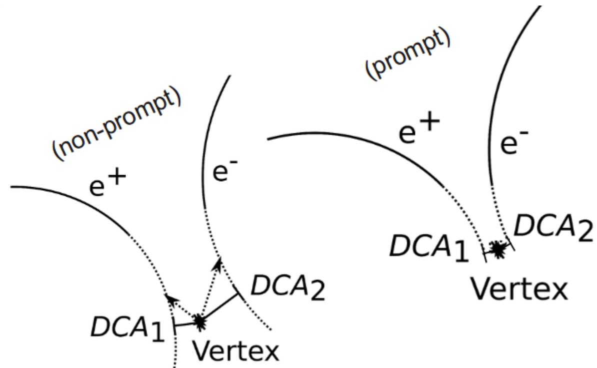

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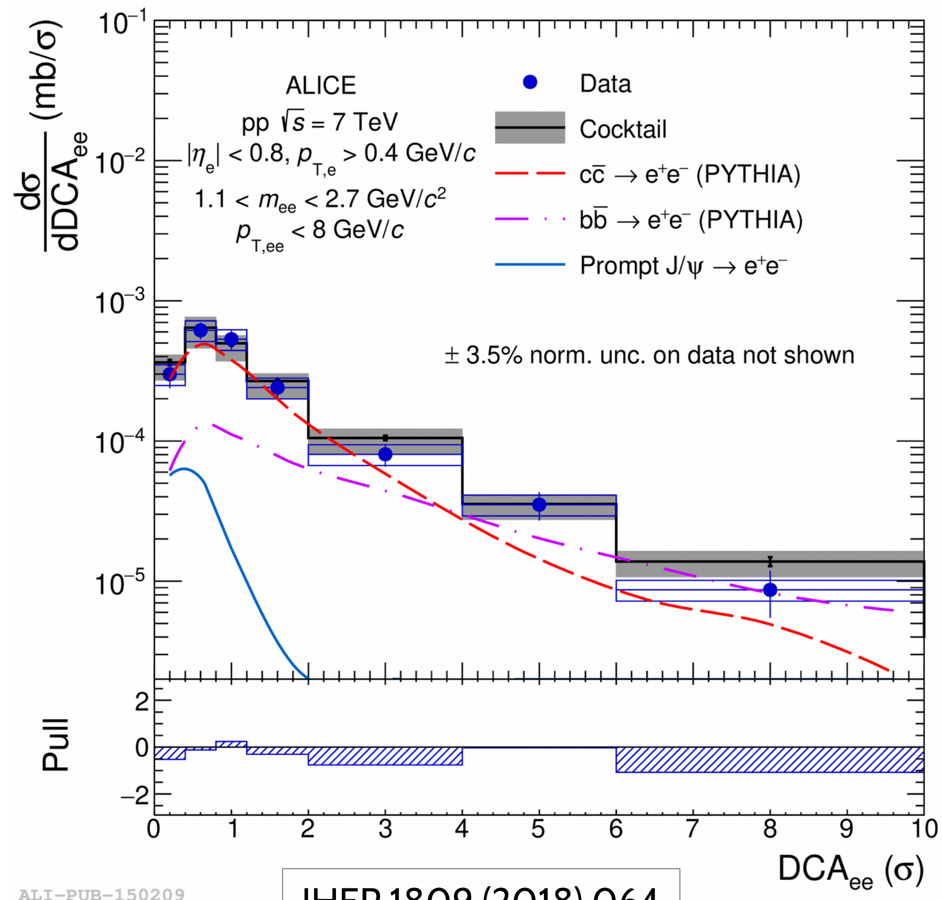

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- Observable → DCA = Distance of Closest Approach
  - normalised to track resolution
- Useful variable to separate prompt from non-prompt dielectron sources

  $\mathrm{DCA_{ee}}$(**prompt**) < $\mathrm{DCA_{ee}}$(**charm**) < $\mathrm{DCA_{ee}}$(**beauty**)

- No evidence of prompt sources in pp
  - as expected in IMR

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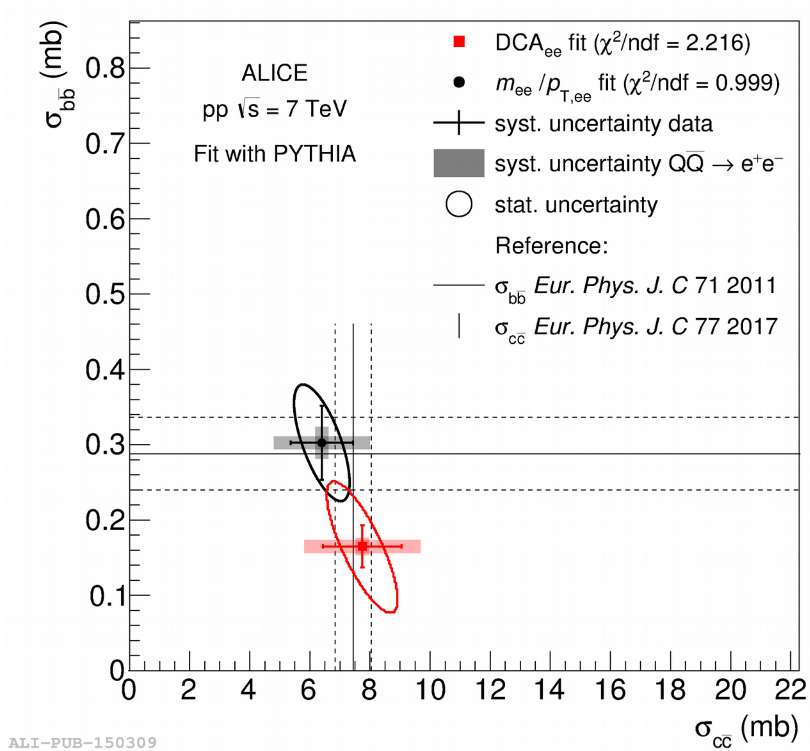
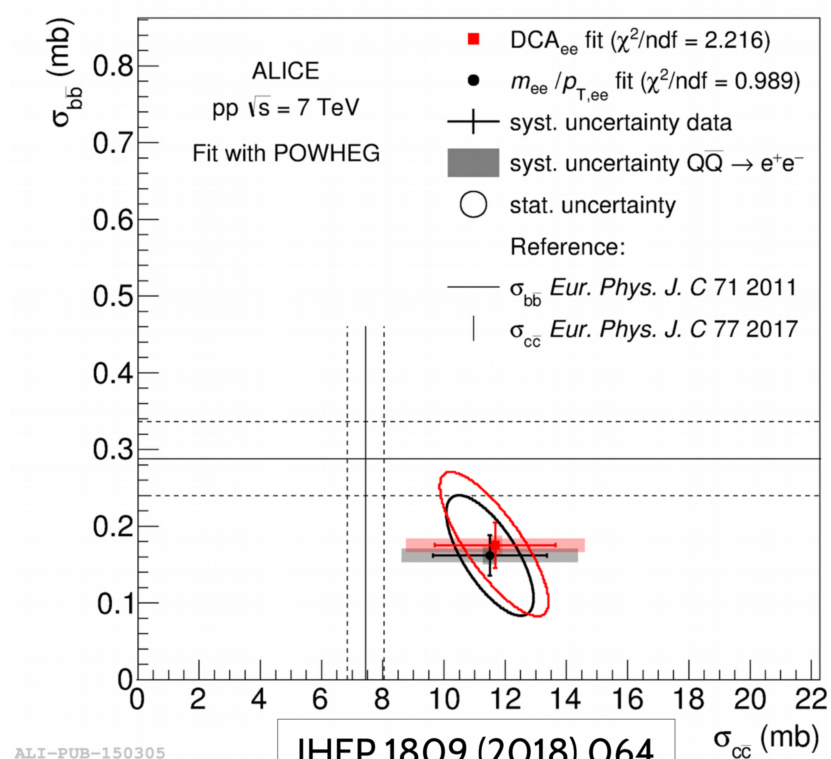
HF Cross Sections in pp





JHEP 1809 (2018) 064

- Both DCA$_{ee}$ and m$_{ee}$/p$_{T,ee}$ fit methods in agreement
- Dominant systematic uncertainty coming from $c\bar{c} \rightarrow$ ee branching ratio (±22%)
- PYTHIA fits in agreement with independent measurements using single HF hadrons
- Discrepancy between PYTHIA and POWHEG $c\bar{c}$ and $b\bar{b}$ results
  → Sensitive to production mechanisms from Monte Carlo generators

Dielectron Invariant Mass in PbPb

- Run 2 data from 2015
  - Higher collision energy than Run 1
    → Phys. Rev. C 99, (2019) 024002
  - Acceptance increase due to lowered p_T cut
    0.4 GeV/c → 0.2 GeV/c
- Data consistent with an enhancement in the low mass region (0.14 < m_{ee} < 0.7 GeV/c^2)
  - Statistics too low to address spectral shape changes
  - Awaiting analysis of 2018 data
    → ~10× more events (0-10% centrality)

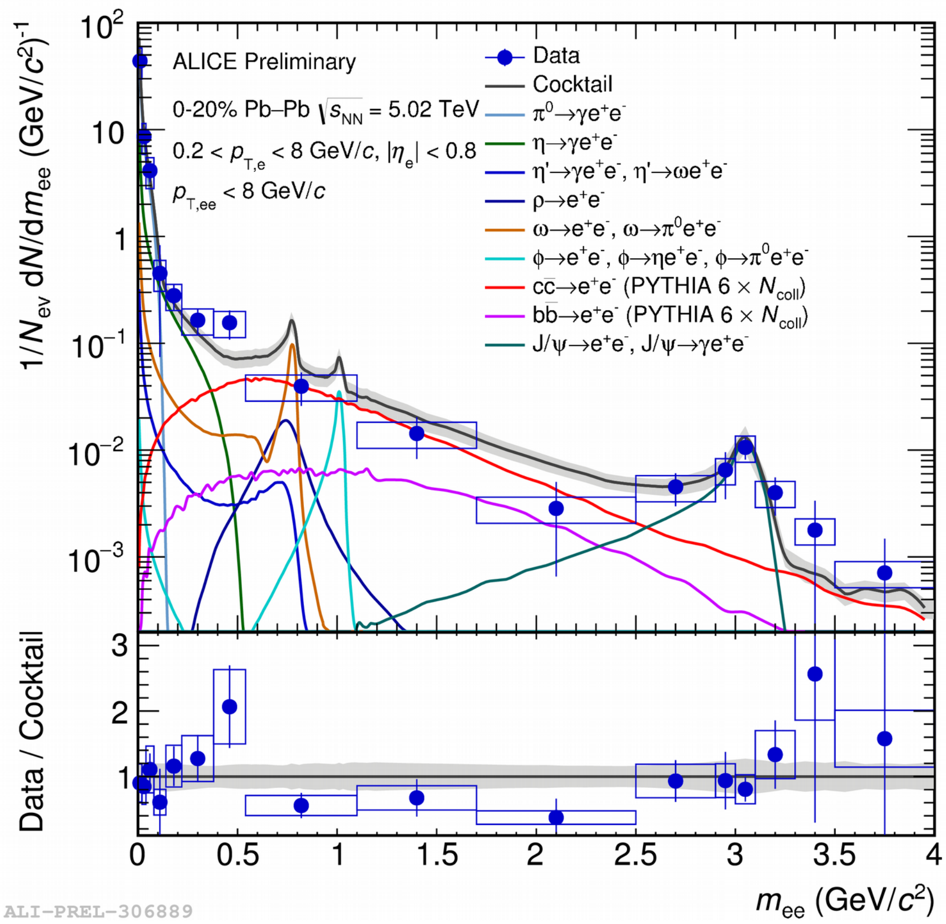
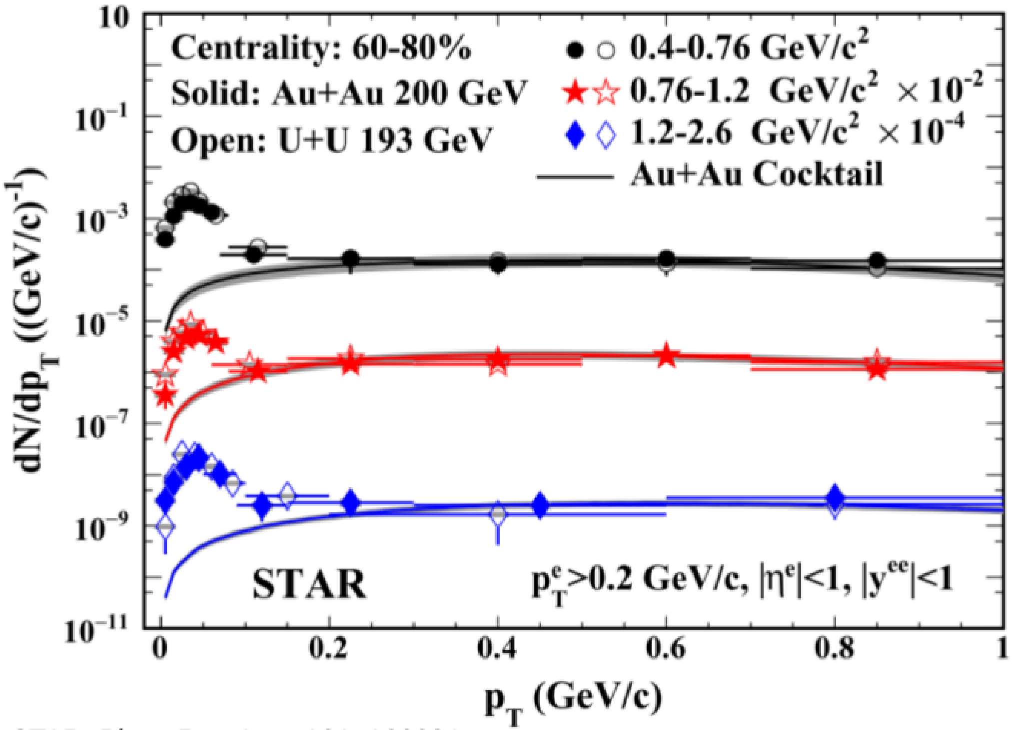


Photo-Production in Hadronic AA

$$\gamma\gamma \rightarrow e^{+}e^{-}$$

- Photo-production scales with Z^4
- Coherent scattering → peak at low-$p_{T,ee}$
- Relative contributions from photo-production expected to be smaller in central collisions compared to peripheral collisions
- Recently photo-production in peripheral collisions measured by STAR



STAR, Phys. Rev. Lett. 121, 132301

Photo-Production in Hadronic AA

- Run 2 data from 2015
- $1.1 < m_{ee} < 2.7$ GeV/c^2 → HF dominated region
- MVA employed to suppress combinatorial background from electrons originating from photon conversions
- No significant discrepancy in 0 – 40% centrality

New Result

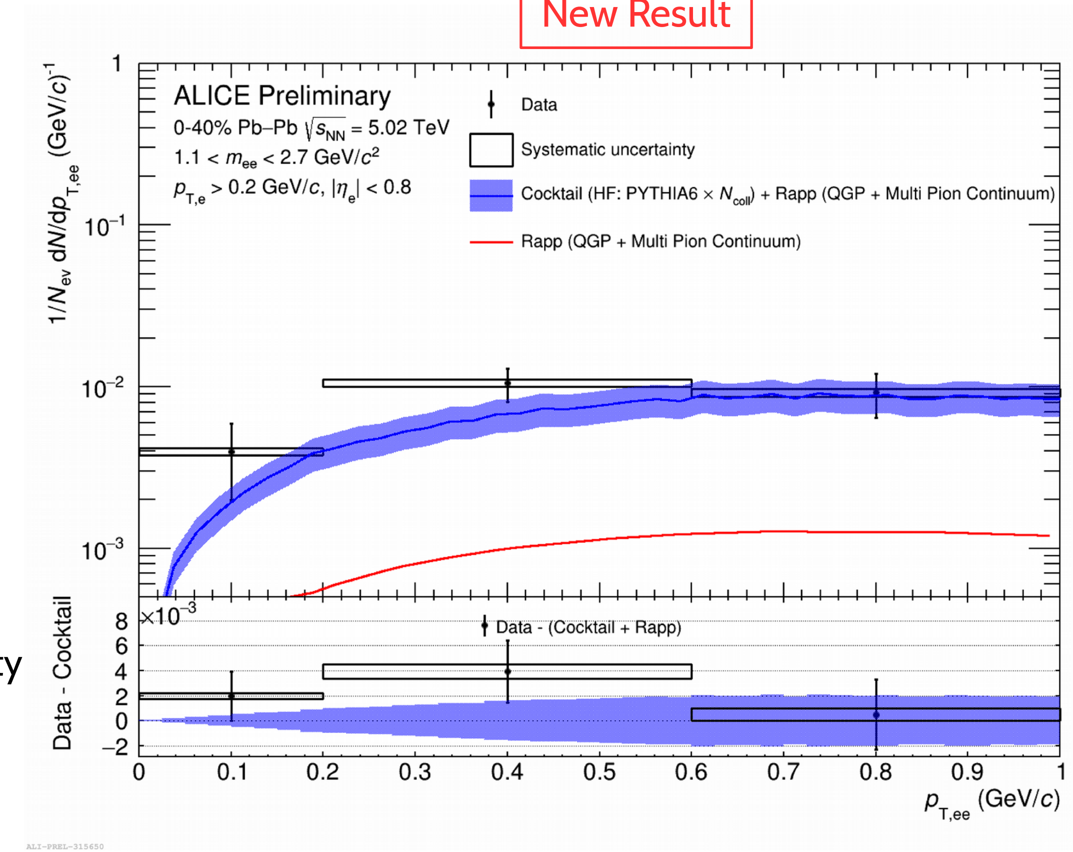


Photo-Production in Hadronic AA

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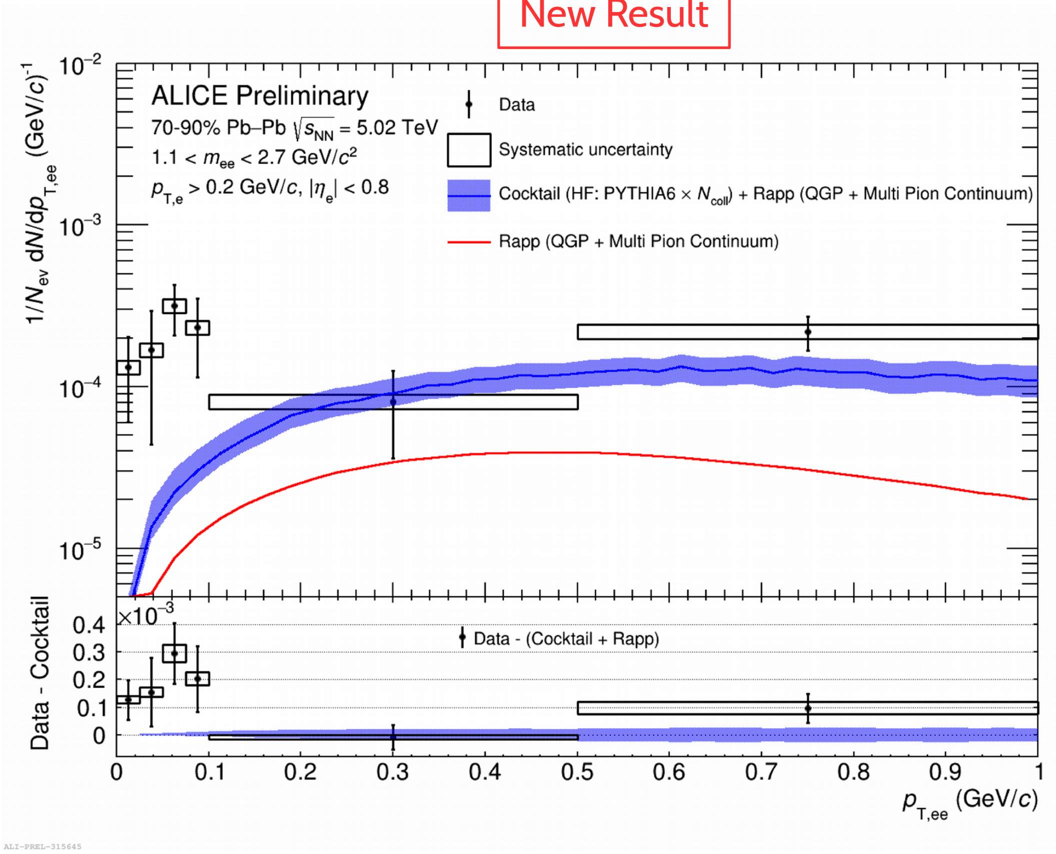
- Run 2 data from 2015
- $1.1 < m_{ee} < 2.7$ GeV/c^2 → HF dominated region
- MVA employed to suppress combinatorial background from electrons originating from photon conversions
- 3.6σ excess observed in 70 -90% centrality
  - Relative excess smaller than observed by STAR

New Result

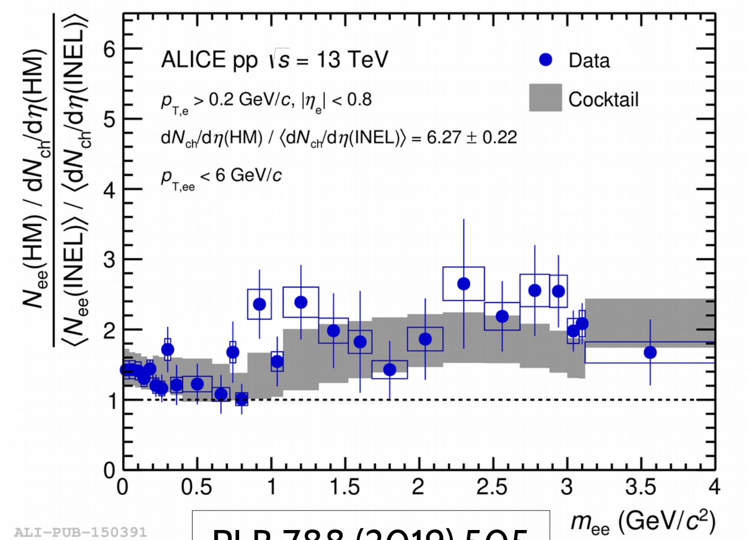


Dielectron Production in Small Systems

- Study heavy-ion like phenomena in high multiplicity pp and p-Pb collisions with dielectrons
  - Production of ρ, thermal radiation, etc…?
- Study with dielectrons

Observable: $\frac{N_{ee}(HM)/dN_{ch}/d\eta(HM)}{N_{ee}(INEL)/\langle dN_{ch}/d\eta(INEL)\rangle}$

  - High multiplicity (HM) trigger selected 0.036% of events in pp
  - Cocktail takes into account the following modifications:
    - Hardening of hadronic p_T spectrum
      → *assume same for LF hadrons at same m_T*
    - D and J/ψ scale faster than multiplicity
      → *assume same enhancement for open beauty as for open charm*
- No excess observed in ρ dominated region
- Beauty assumption confirmed in high p_T IMR



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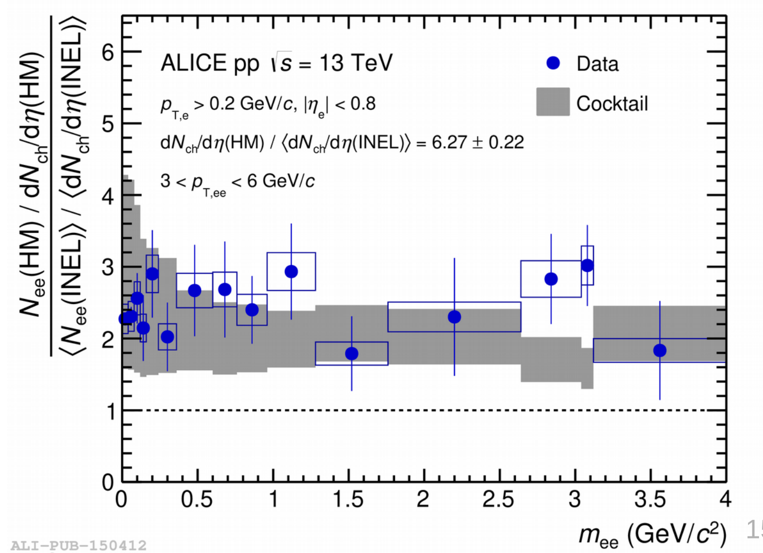


Summary and Outlook

pp: $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 13 TeV

- Baseline $m_{ee}/p_{T,ee}$ and DCA_{ee} measurements well understood
- Complementary measurements of $\sigma_{c\bar{c},b\bar{b}}$

p-Pb: $\sqrt{s_{NN}}$ = 5.02 TeV

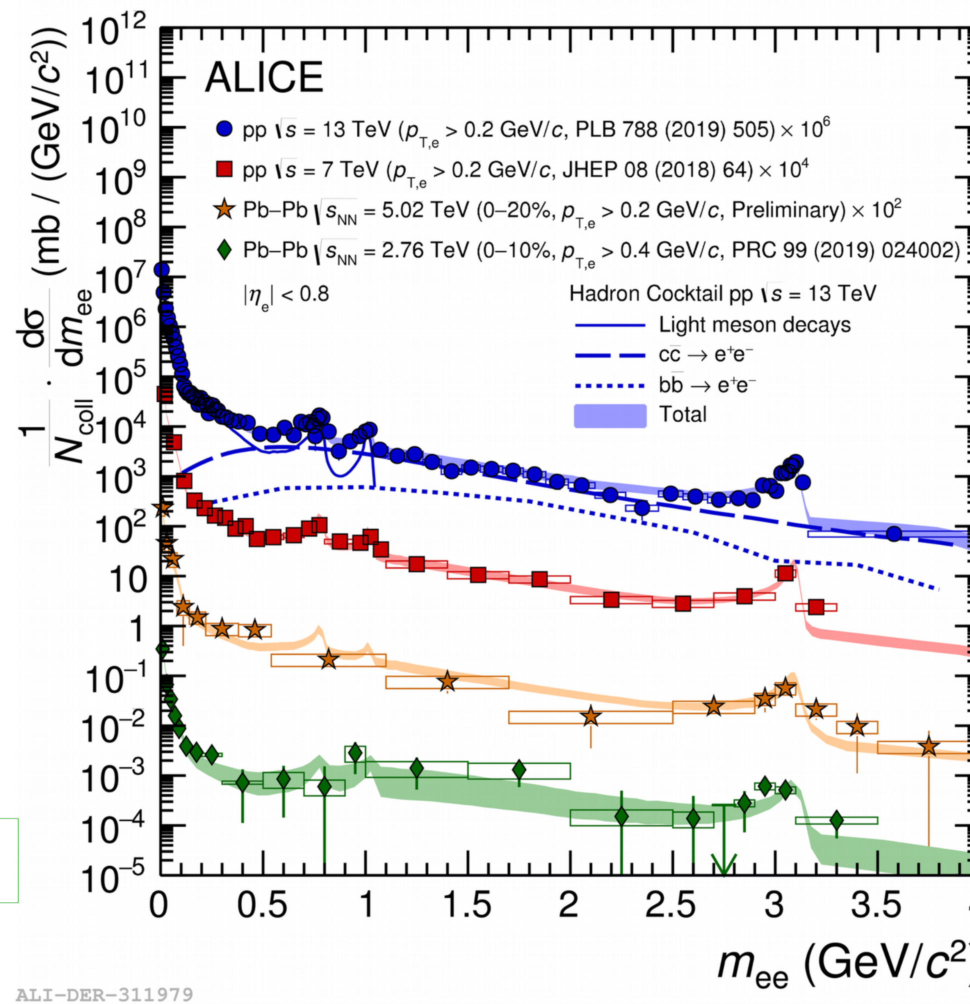
- Both DCA_{ee} and $m_{ee}/p_{T,e}$ multiplicity dependant analyses under way using run 2 data
  - Utilising MVA for ePID

Pb-Pb: $\sqrt{s_{NN}}$ = 2.76 TeV and $\sqrt{s_{NN}}$ = 5.02 TeV

- $m_{ee}/p_{T,ee}$ measurements statistics limited
  - ~10× more data obtained in 2018 (0-10% centrality)
  - Promising outlook for Run 3

→ Talk at SQM: "Physics with the detector upgrades at LHC" By M. Weber, Friday, 17:00

- Photo-production observed, 3.6σ, in 70-90% centrality



Backup slides

Dielectron Invariant *Mass* in PbPb

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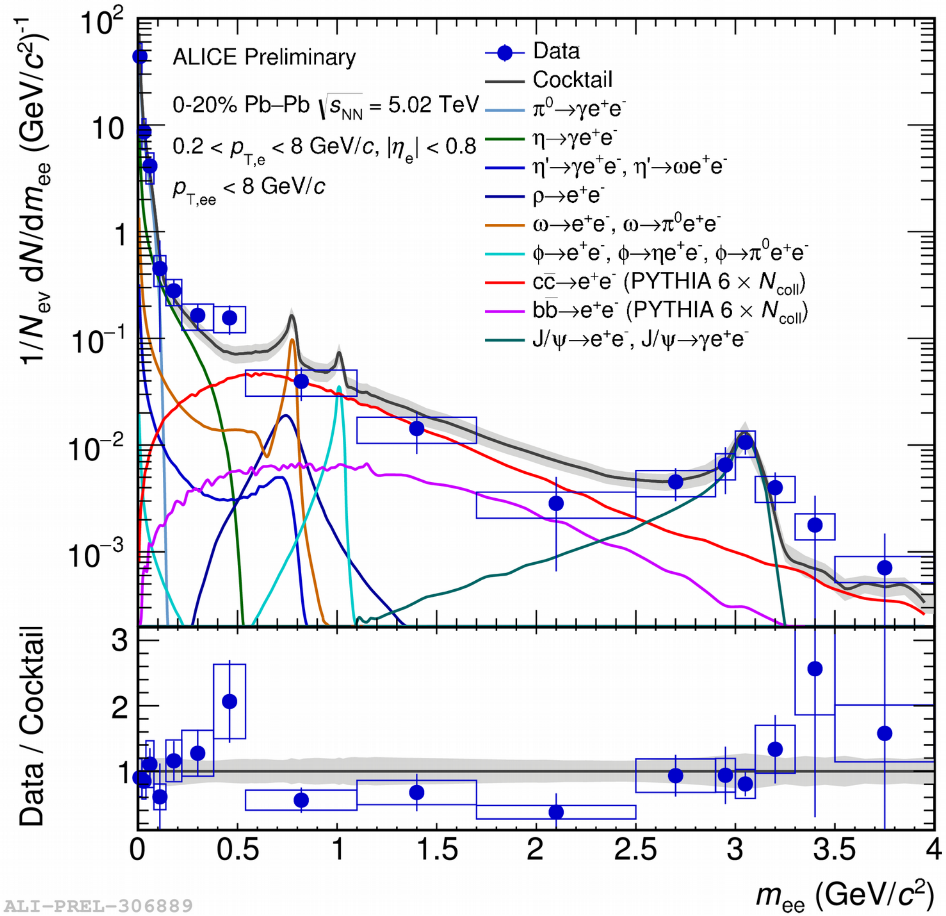
- Run 2 data from 2015
  - Higher collision energy than Run 1
    → Phys. Rev. C 99, (2019) 024002
  - Acceptance increase due to lowered p_T cut
    0.4 GeV/c → 0.2 GeV/c



- Potential suppression in the intermediate mass region (1.1 < m_{ee} < 2.5 GeV/c^2)
  - 1.67σ effect
  - If including cold nuclear matter effects (EPPS16)
    - 0.41σ effect

Dielectron Invariant *Mass* in PbPb

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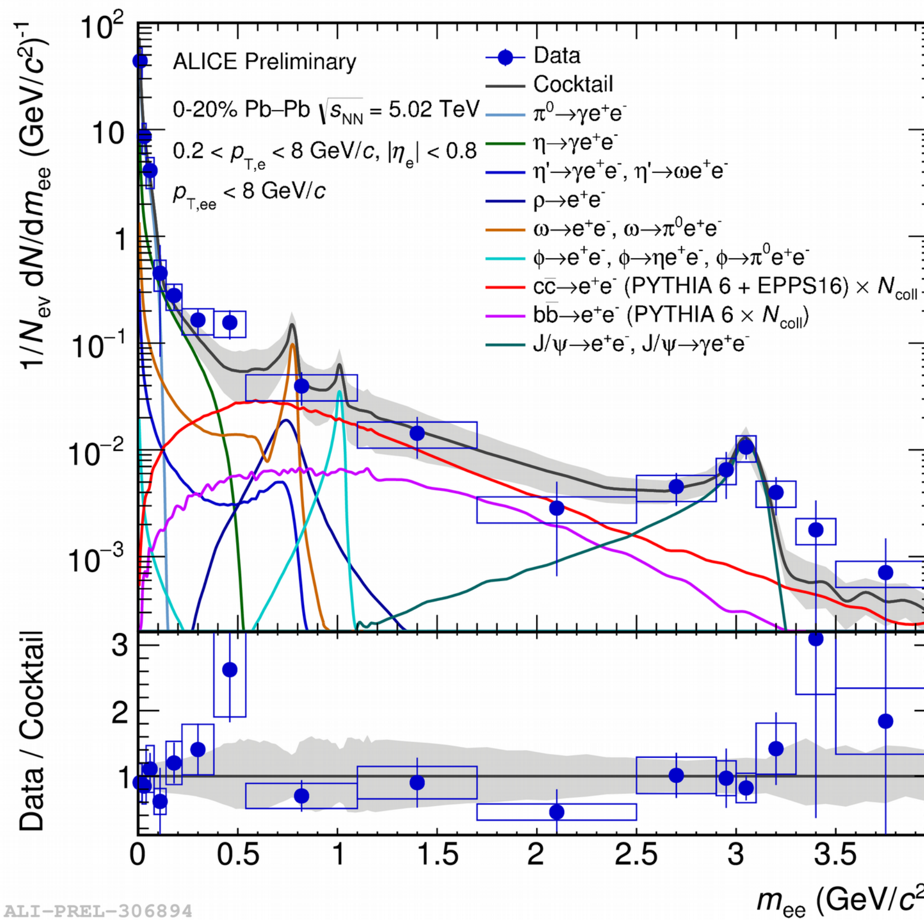

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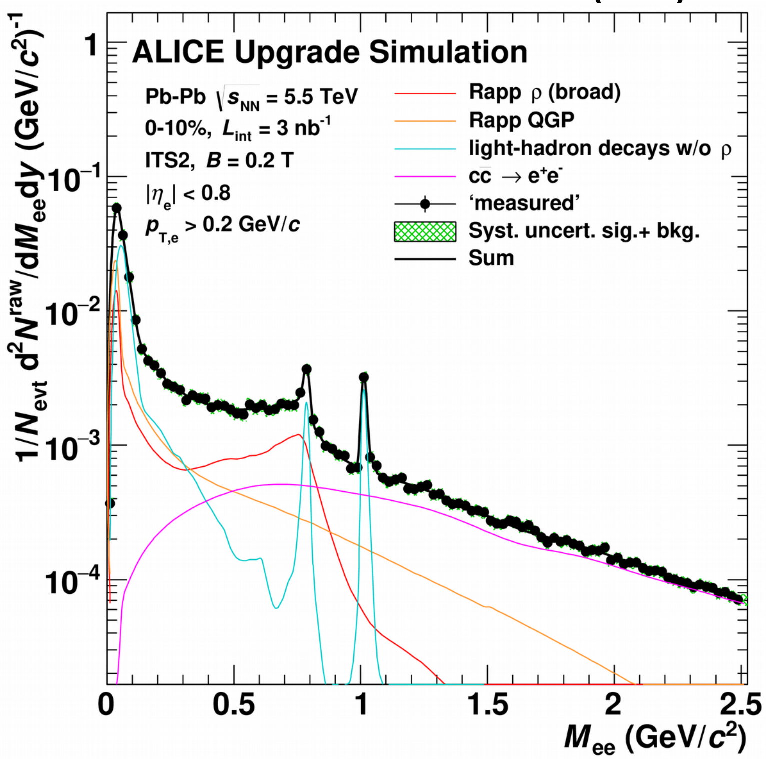
  - 1.67σ effect
  - If including cold nuclear matter effects (EPPS16)
    - 0.41σ effect

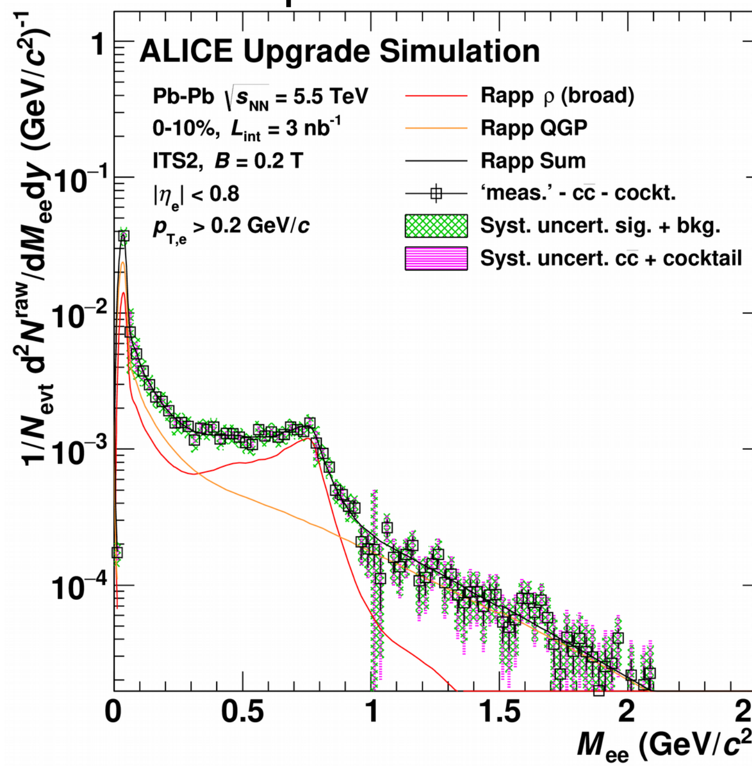
Run 3

- Major TPC and ITS upgrades
- **Dielectron Future**
  - Modified rho meson spectral function with uncertainty of ~15%
  - Extract temperature at m_{ee} > 1 GeV/c^2 with uncertainty of ~20%

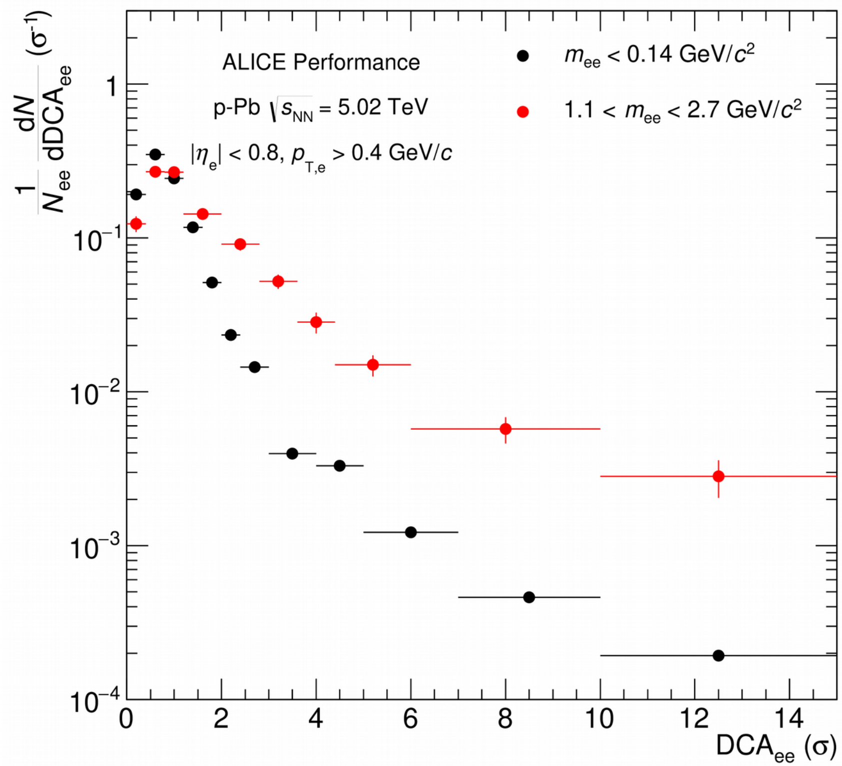
Dedicated low B-field run (0.2T)

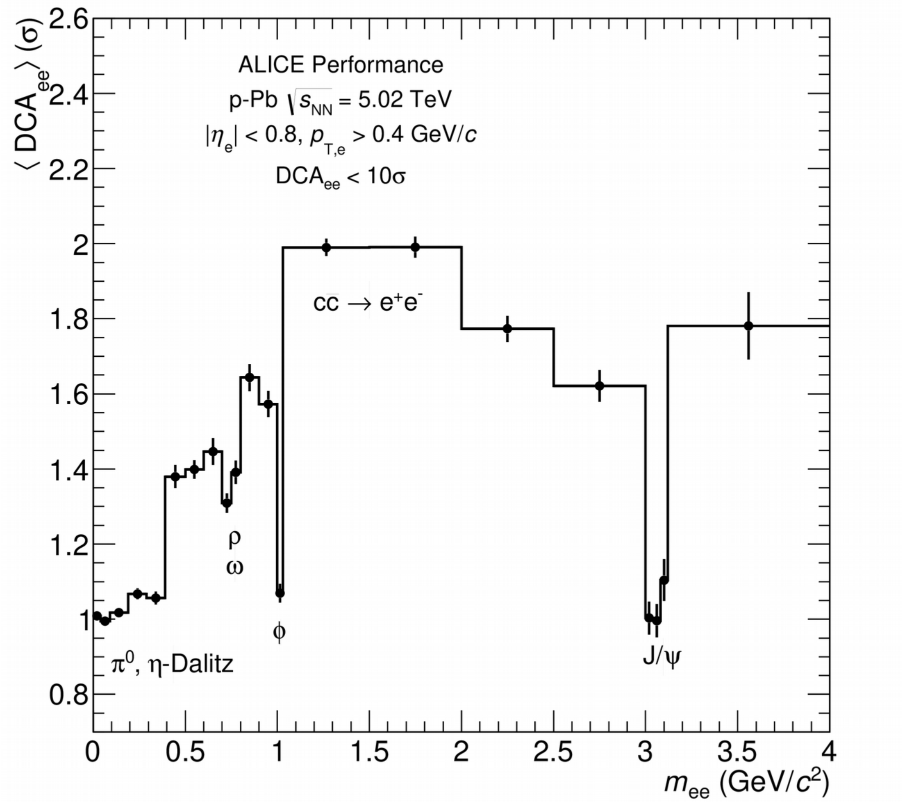


Excess in spectrum after one Pb-Pb run



DCA in p-Pb





- DCA studies also under way for Run 2 pPb data
- Investigate effects of cold nuclear matter on heavy flavour production

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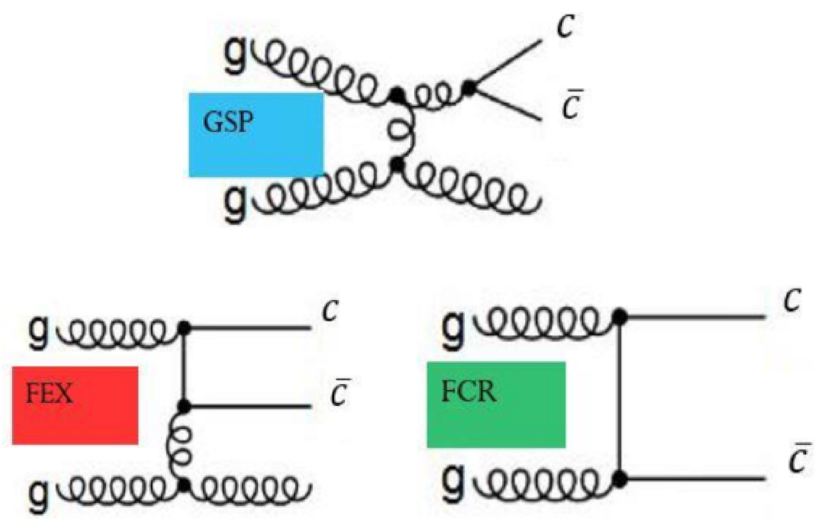
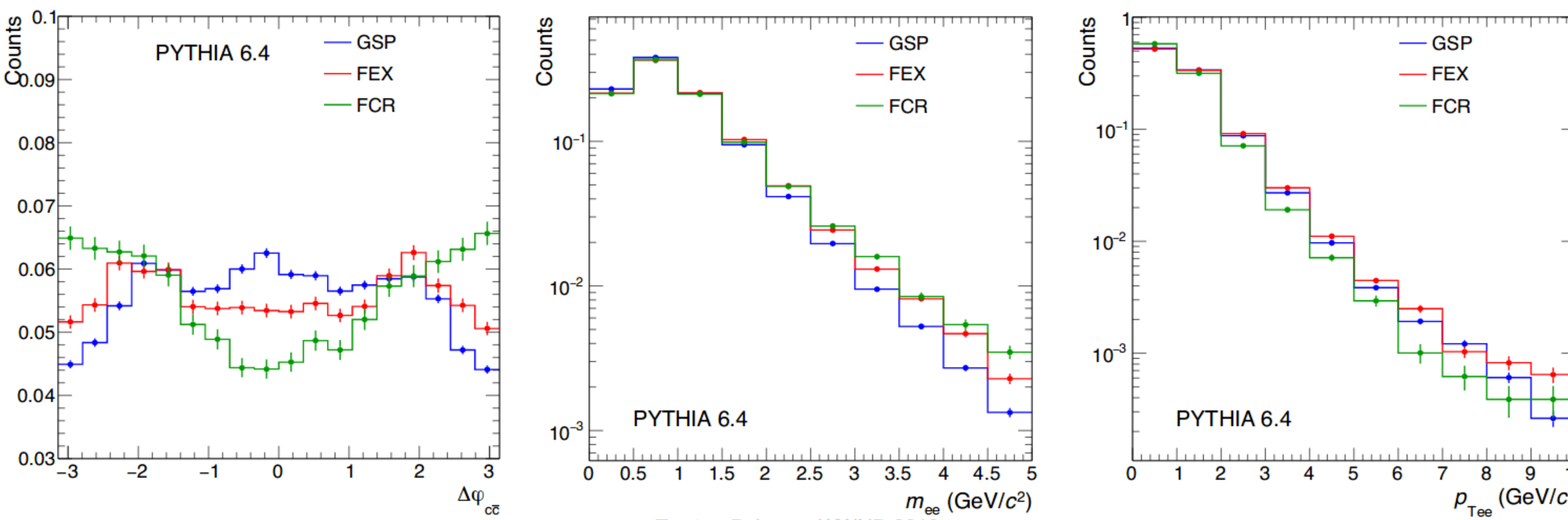
Heavy Flavour Production

- Concept: investigate different charm production processes using PYTHIA6 simulations
- Default production fractions:
  - Gluon splitting (GSP): 55%
  - Flavour excitation (FEX): 20%
  - Flavour creation (FCR): 10 %

$$m_{\mathrm{ee}}^2 \approx 2p_{\mathrm{T},1}\, p_{\mathrm{T},2}(1 - \cos\Delta\varphi_{\mathrm{ee}})$$

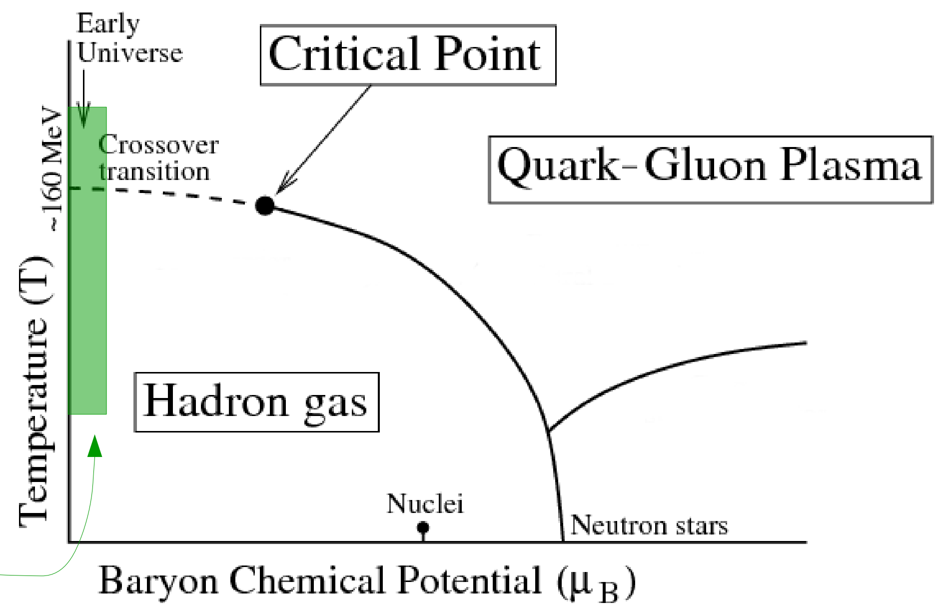




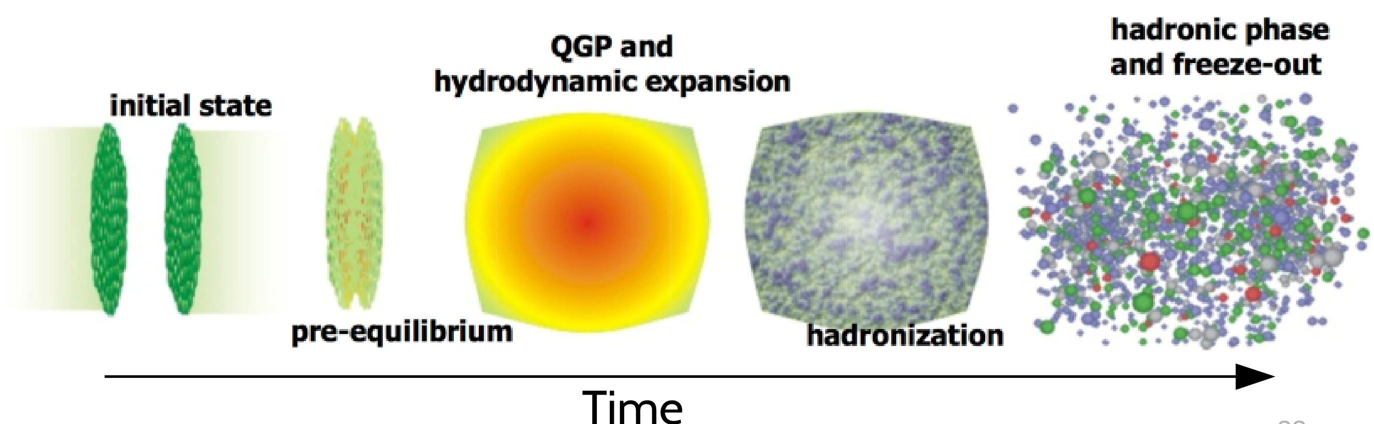
Torsten Dahms – WWND 2019

QCD & Heavy Ion Collisions

- QCD at high temperatures
  → "deconfinement"
- Quarks and gluons become relevant dof's
  → "Quark Gluon Plasma"
- Creation of hot, dense matter in lab
  → High-energy Heavy Ion collisions
  at the LHC and RHIC



Reference systems:
- Vacuum production
  → pp collisions
- Cold nuclear matter
  → pA collisions



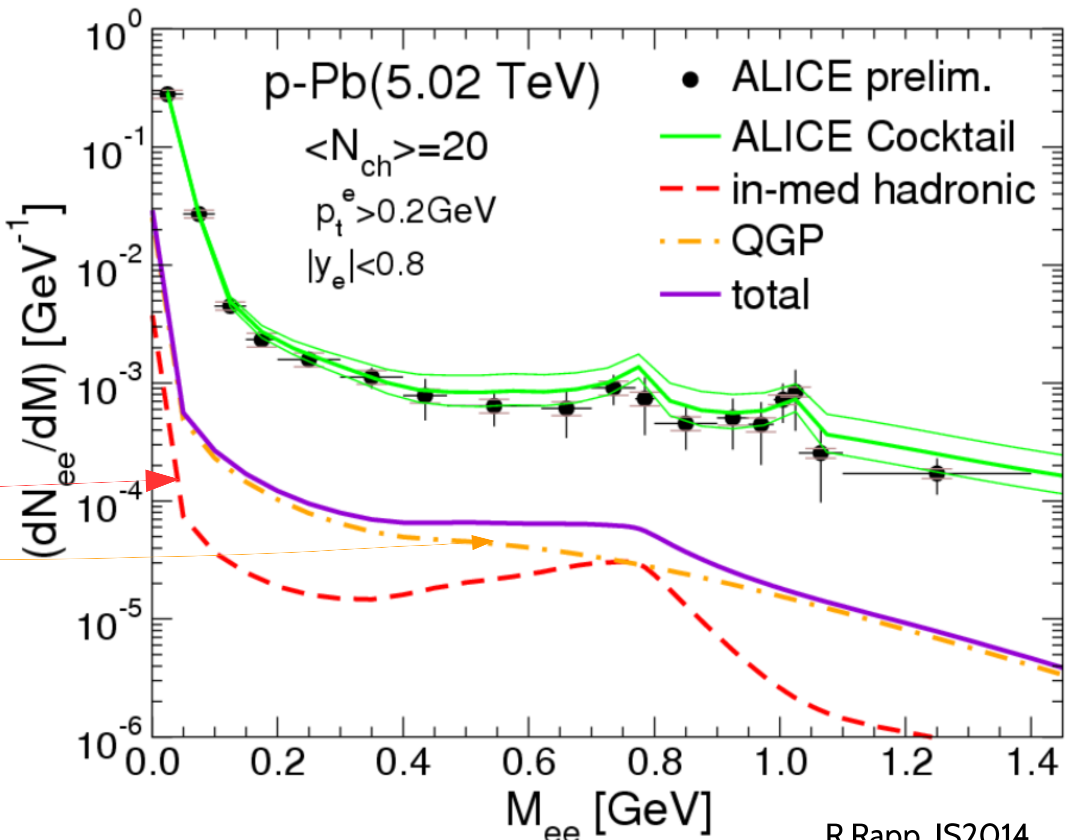
Small Systems

- Small systems used as reference measurements
  → pp and p-Pb collisions

- However, high multiplicity events in pp and p-Pb exhibit collective behaviour
  → Creation of Hot Dense Matter?

<u>What signals can we look for?</u>

- Final spectrum can be compared to "cocktail" of known hadronic sources*
  → in-medium meson modifications?
  → thermal photons?



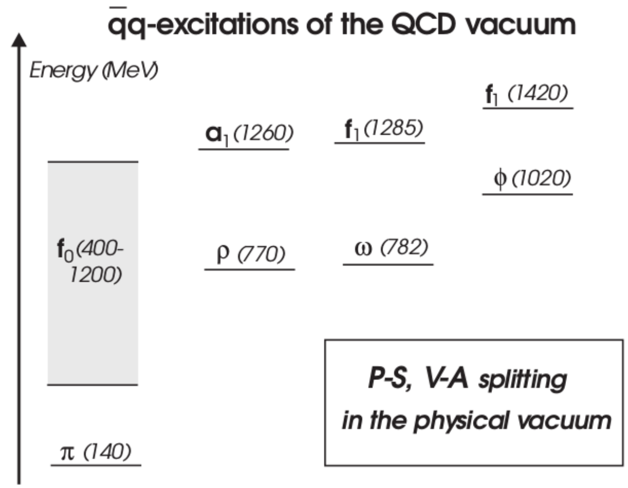
R.Rapp, IS2014

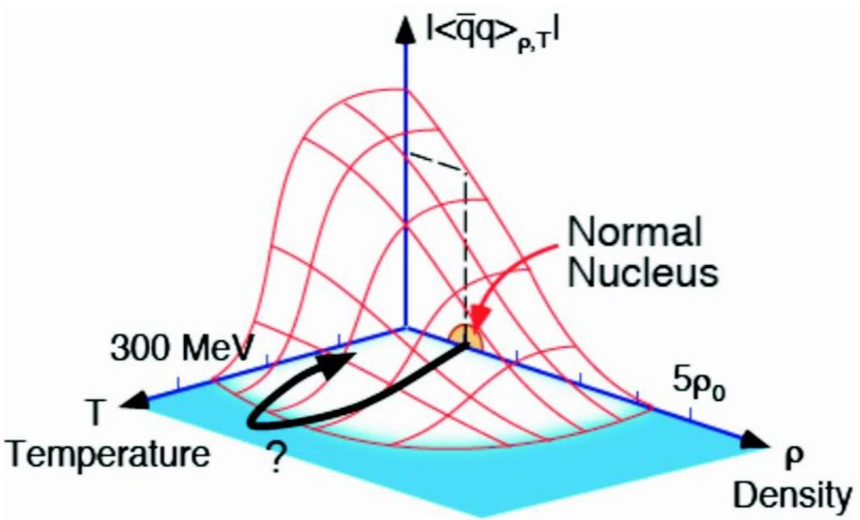
*Known sources, as measured in p-Pb, or from pp and up scaled by number of participants

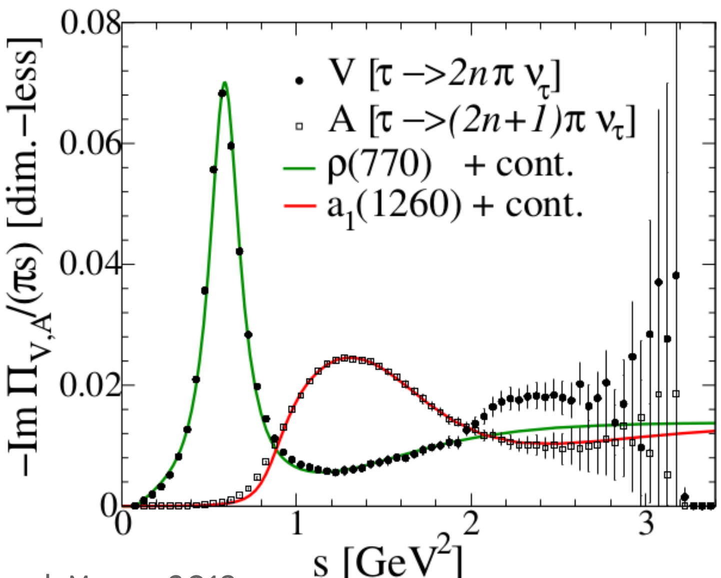
Chiral Symmetry

- In vacuum: <q^bar q> condensate != 0
  → mass splitting of chiral partners

- High enough temperatures/densities
  → restoration of chiral symmetry





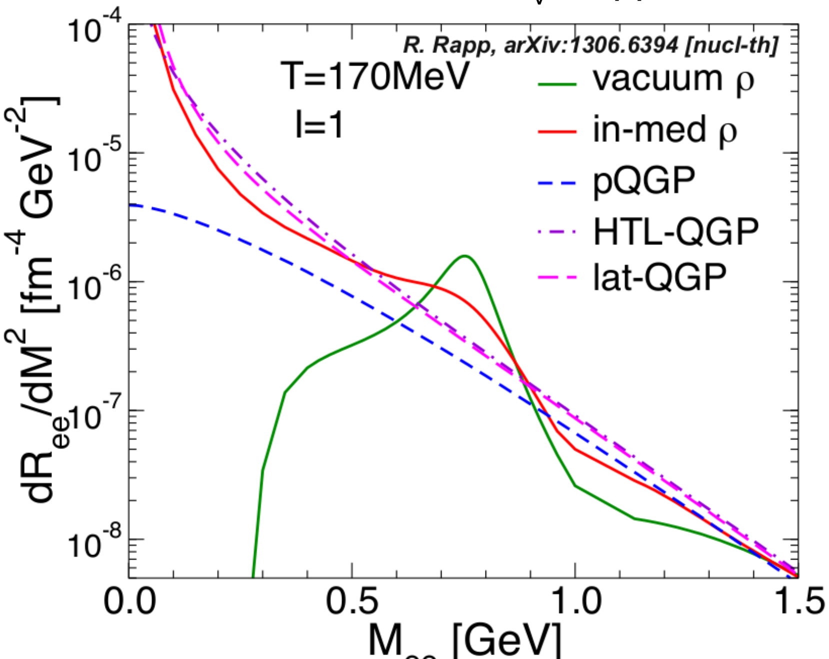


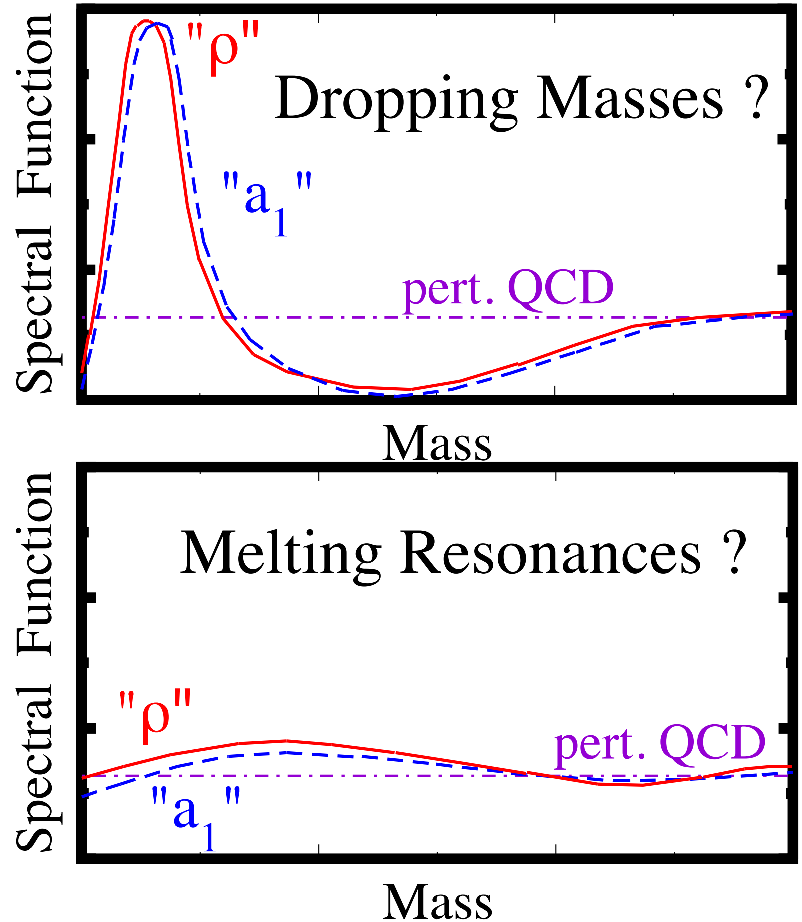
Chiral Symmetry Restoration

- Mechanism for restoration?

- Two main ideas:
  → dropping masses
  Weinberg sum rules: $\rho_V - \rho_A \sim \langle qq \rangle$

  → Melting resonances
  QCD sum rules: $\rho_V \sim \langle qq \rangle$





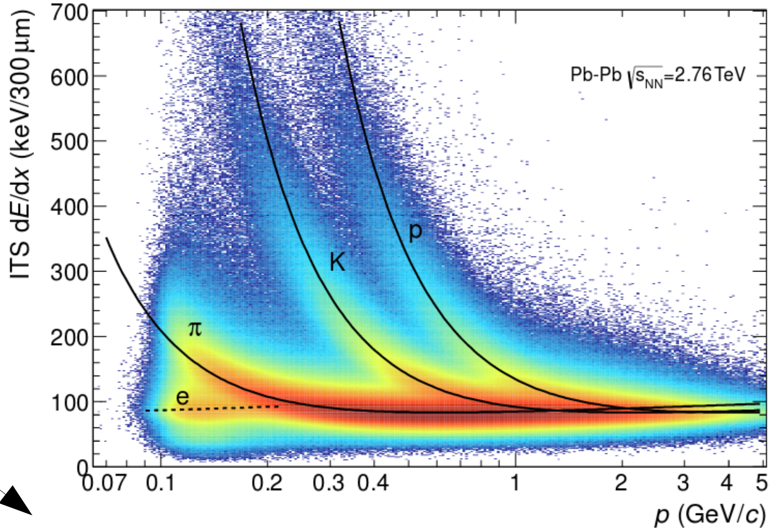
MVA ePID

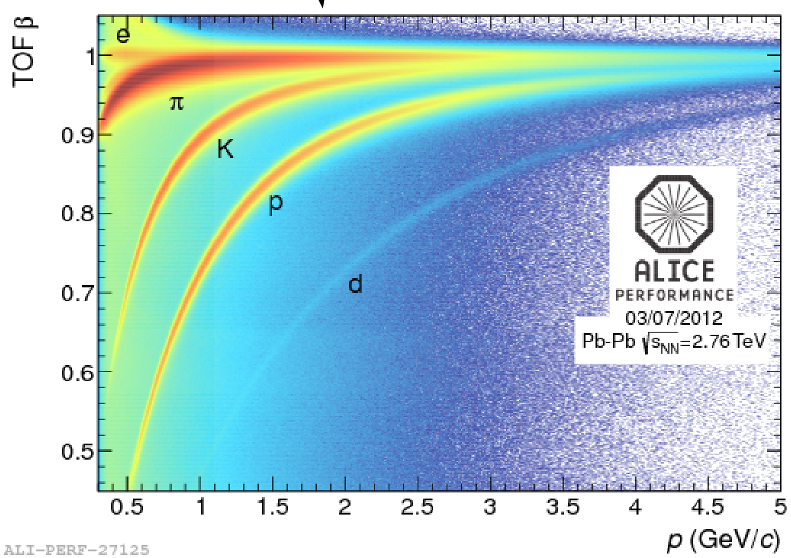
Particle Identification

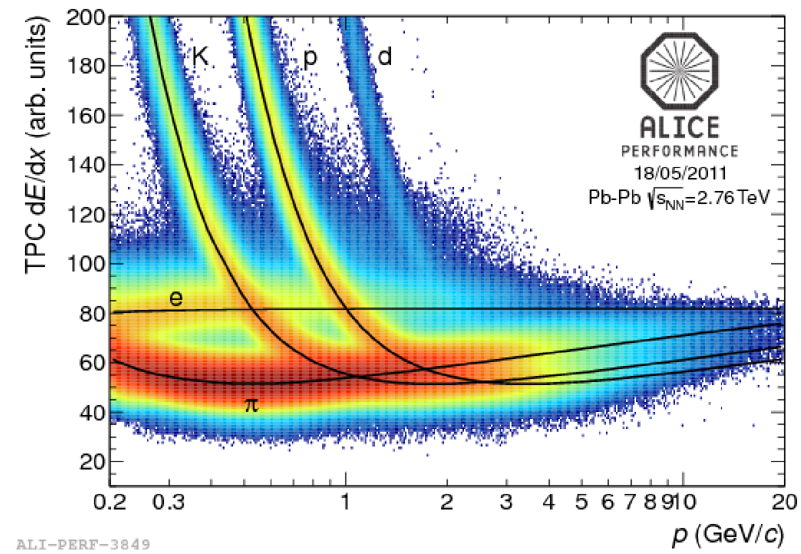
Inner Tracking System
- PID (dE/dx), vertex, and tracking

Time Projection Chamber
- PID (dE/dx), and tracking

Time of Flight
- PID (β)

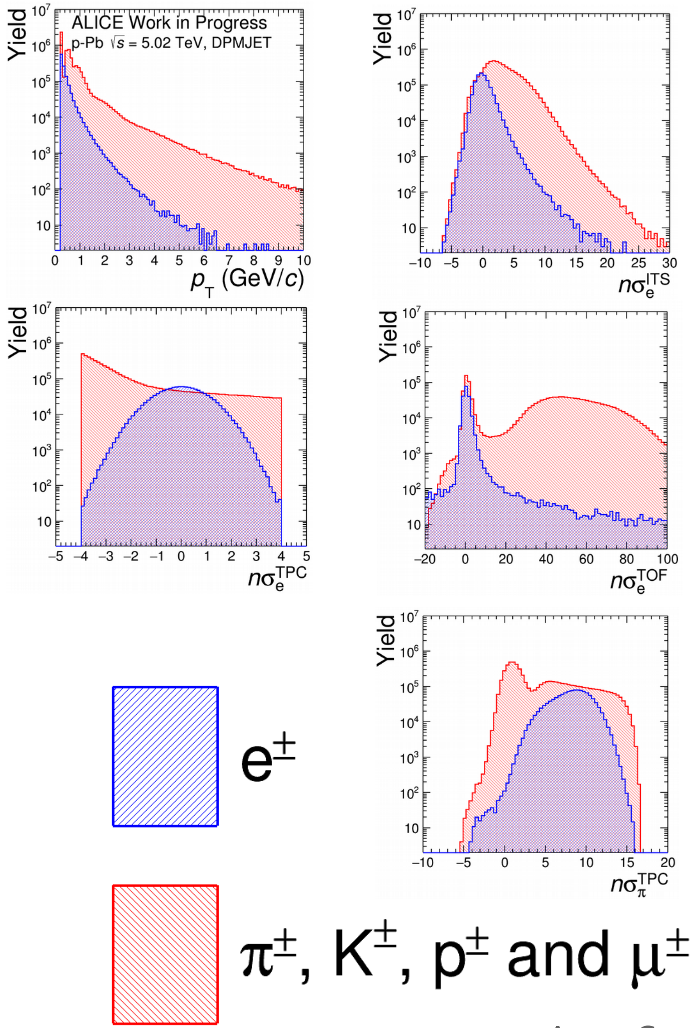


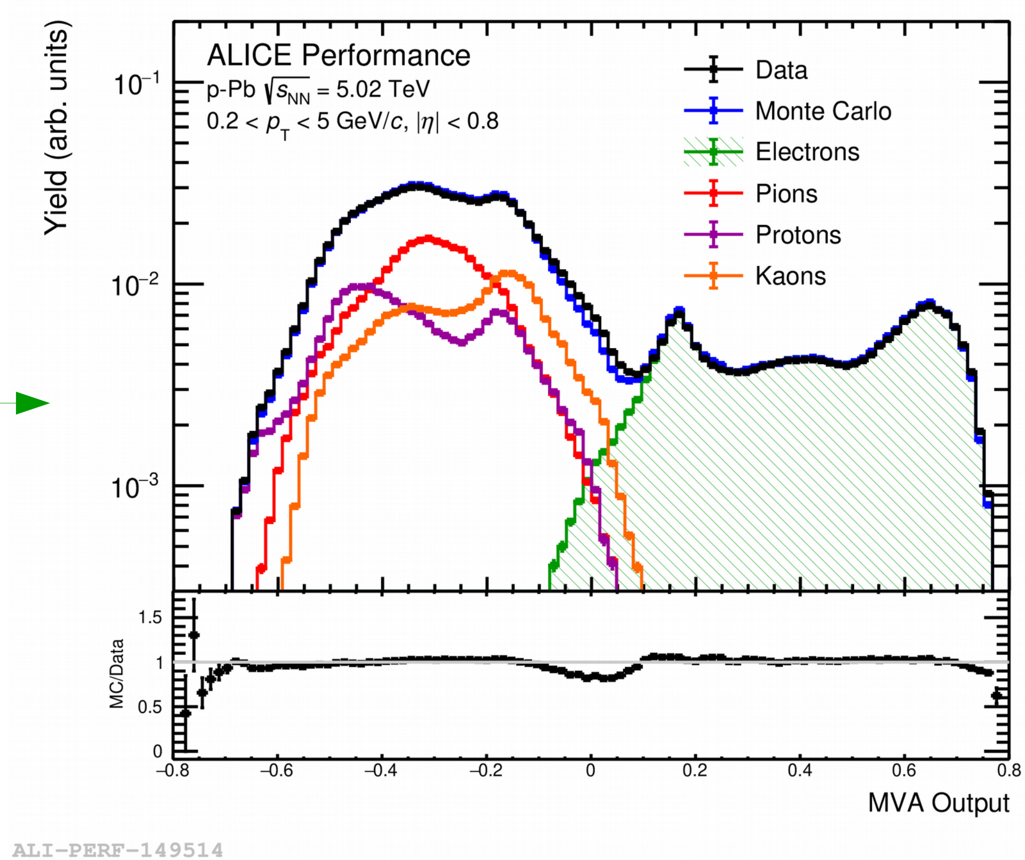




Classifier Training

- Input features shown to classifier

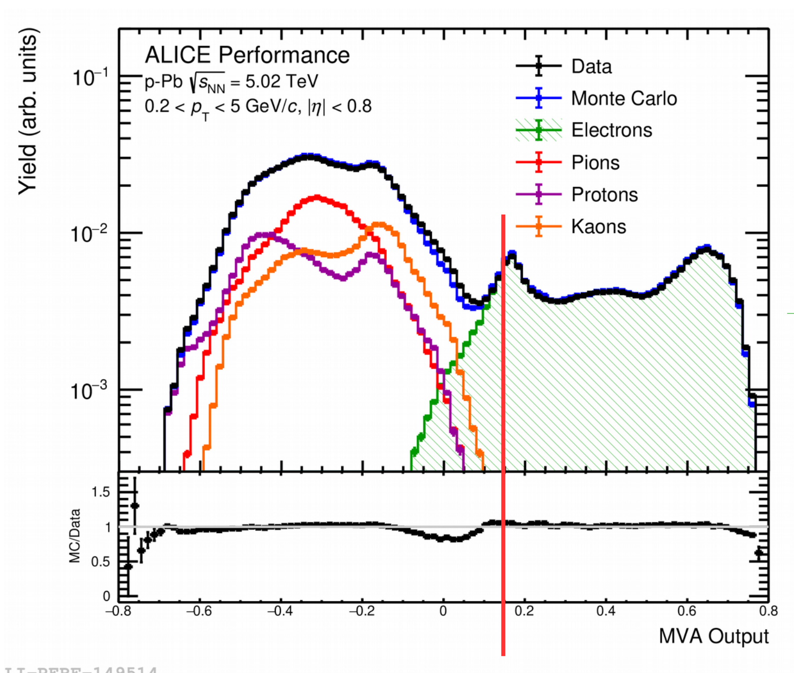




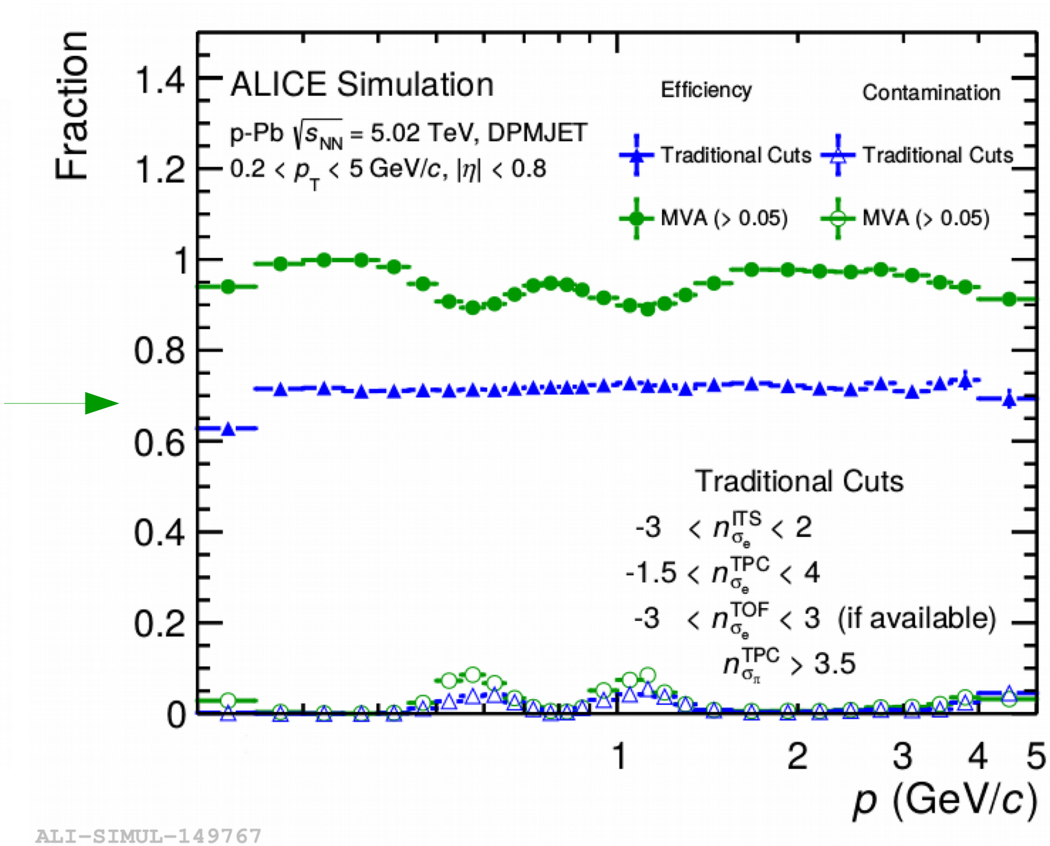
ePID Results

- Cut on classifier output via maximisation of → $significance(PID) = \frac{signal}{\sqrt{signal + background}}$

Purity: 97%, Efficiency: 95%



ePID cut value



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Dielectron Analysis

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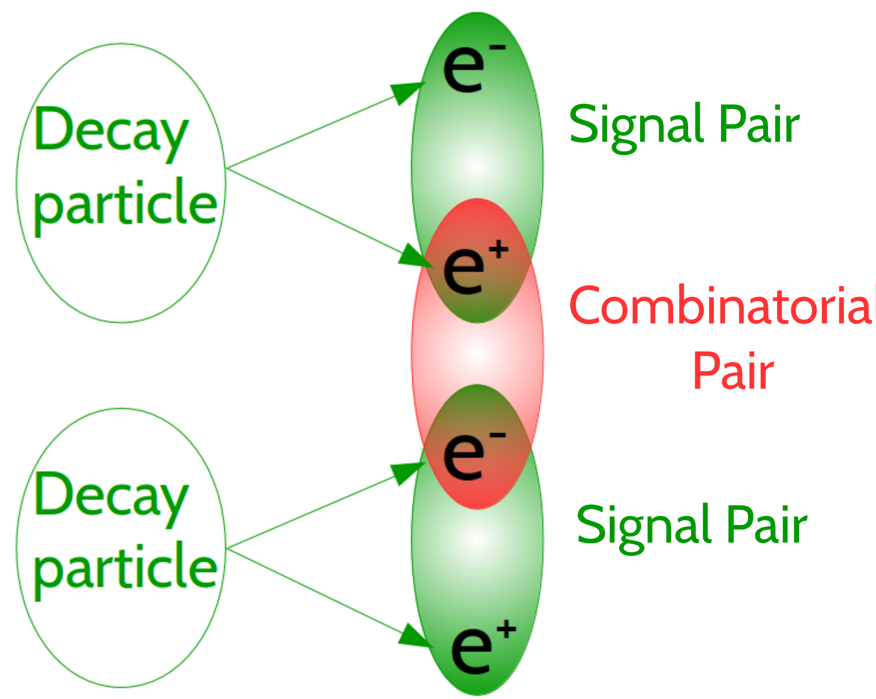
Obtaining the Spectrum

- Track quality cuts applied to ensure only “good” quality tracks are used
    - ->chi²/n.d.f in each detector etc
- Electron particle identification performed
- Real photons decaying into electrons need to be removed
    - → conversion rejection cuts
- Obtain spectrum via like-sign subtraction



$$LS_{all} = R \cdot \sqrt{N_{++} \cdot N_{--}}$$

$$US_{signal} = US_{all} - LS_{all}$$

Additional factor needed during like-sign subtraction to account for different acceptances between ++/-- and +- tracks. Currently not implemented.

Background Subtraction

ALICE

- For the final spectrum each positive and negative track, within each event, are paired together. These are labelled as the same event unlike-sign spectrum, N^{same}_{+-}, and contains not only the real dielectron pairs, but also many pairs which are merely combinatorial.

- The combinatorial background is calculated via the geometric mean (arithmetic if empty bins) of the like-sign pair spectra within the same event, B.

$$B = 2 \cdot \sqrt{N^{same}_{+-} \cdot N^{same}_{--}}$$

- The difference in acceptance between unlike and like-sign pairs is calculated with the acceptance factor, R, which uses event mixing to remove an correlations between pairs:

$$R = \frac{N^{mixed}_{+-}}{2 \cdot \sqrt{N^{mixed}_{++} \cdot N^{mixed}_{--}}}$$

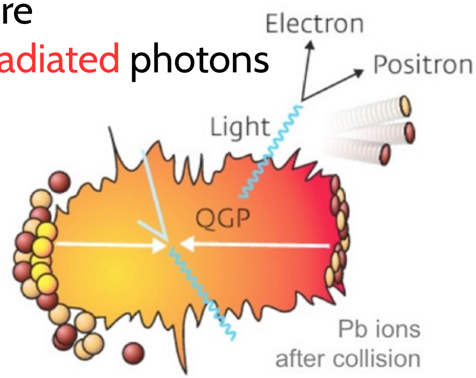
- The final raw spectrum is then determined with:

$$signal = N^{same}_{+-} - R \cdot B$$

Low-mass Thermal Radiation

Thermal Radiation

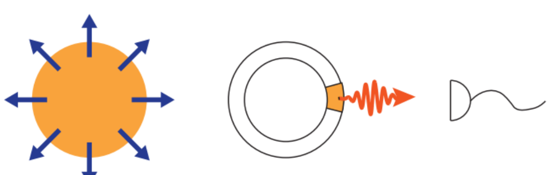
- Key QGP signature
  → thermally radiated photons

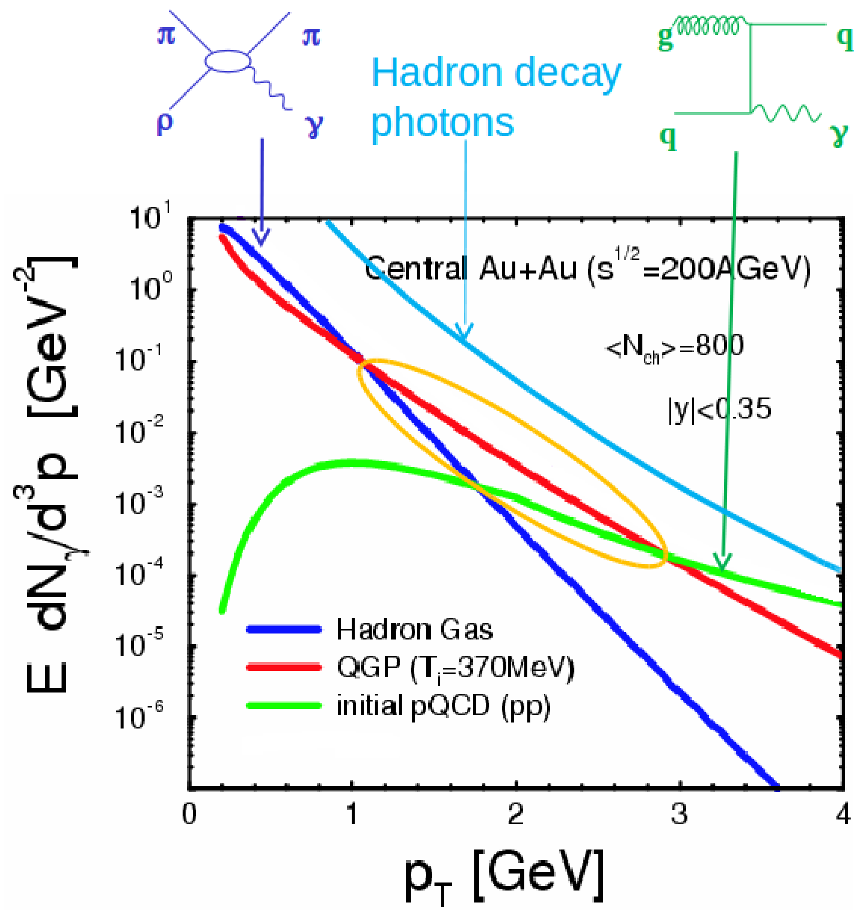


- Thermal radiation can be directly related to the temperature via

$$dN/dp_T \propto \exp\left(-\alpha \frac{p_T}{T}\right)$$

- However, photon measurements contain doppler and flow effects due to expanding medium





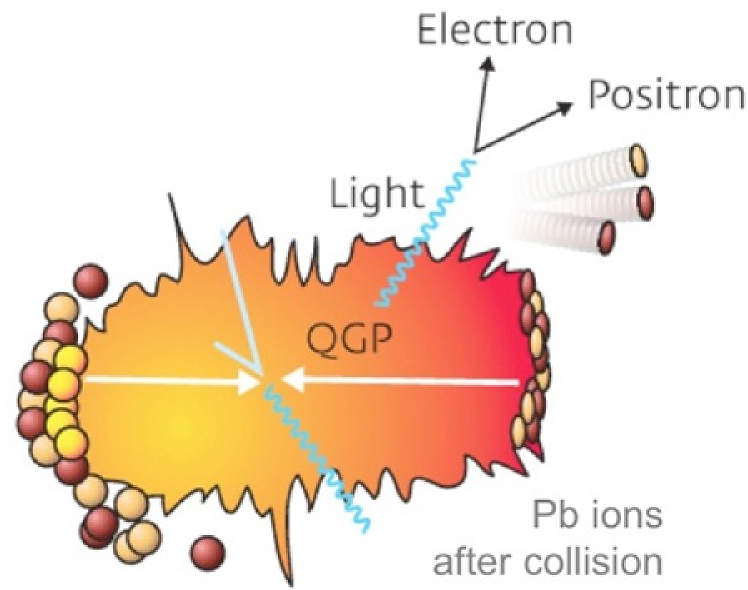
Direct Photon Measurement

ALICE

- Key QGP signature
  → thermally radiated photons

- Need to extract direct photons from inclusive photons
  direct: all photons not from hadron decays
  inclusive: all photons

- Relationship between yield of virtual photons and dielectron yield given by Kroll-Wada:



$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}\boxed{|F(m_{ee}^2)|^2\left(1-\frac{m_{ee}^2}{M^2}\right)^3}$$

Process dependent factor

Hadrons
S = 0 when $m_{ee} > M_{hadron}$

Direct photons*
If $p^2_T > M^2_{ee} \rightarrow S = 1$

Direct Photon Measurement

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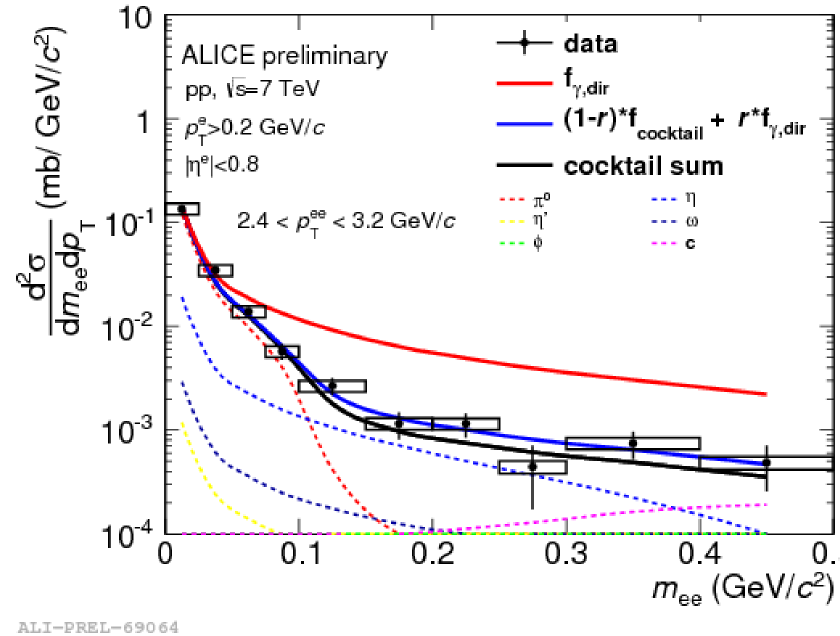

P. Reichelt, Nucl. Phys. A956 (2016)

Process dependent factor

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Direct photons*
If p_T^2 > M_{ee}^2 → S = 1

Extracting Direct Photons

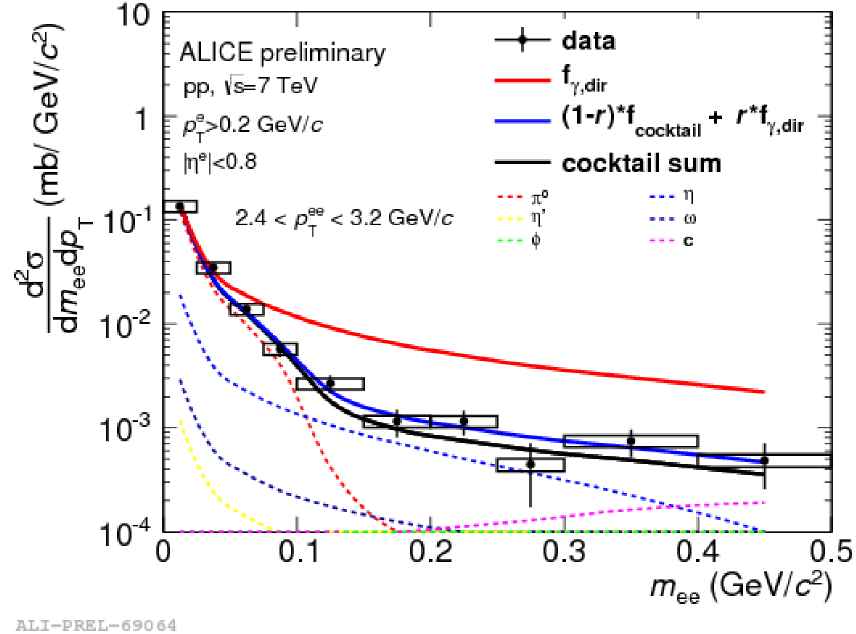
Fit the following function to the data

$$f(m_{ee}) = (1-r)\cdot f_{cocktail}(m_{ee}) + r\cdot f_{direct}(m_{ee})$$

Cocktail contributions

Photon input from Kroll-Wada

- r is the ratio of direct to inclusive photons
- Under the assumption that the ratio of direct to inclusive is the same as real to virtual
  → direct = r x inclusive (yields)
- Where the inclusive photon cross section is known via photon conversions[1]



P. Reichelt, Nucl. Phys. A956 (2016)

[1] M. Wilde (for the ALICE Collaboration), arXiv:1210.5958 [hep-ex] (2012)