

PUERTO
VALLARTA



Dilepton measurements with the ALICE
experiment at the LHC

Elisa Meninno on behalf of the ALICE Collaboration

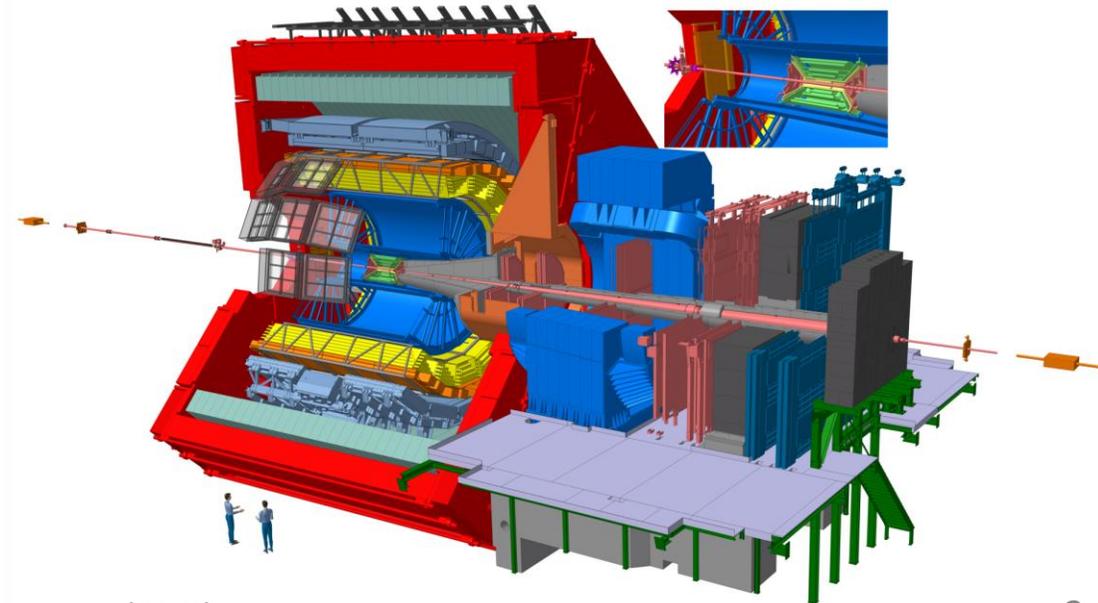
Stefan Meyer Institute for Subatomic Physics, Vienna



Der Wissenschaftsfonds.

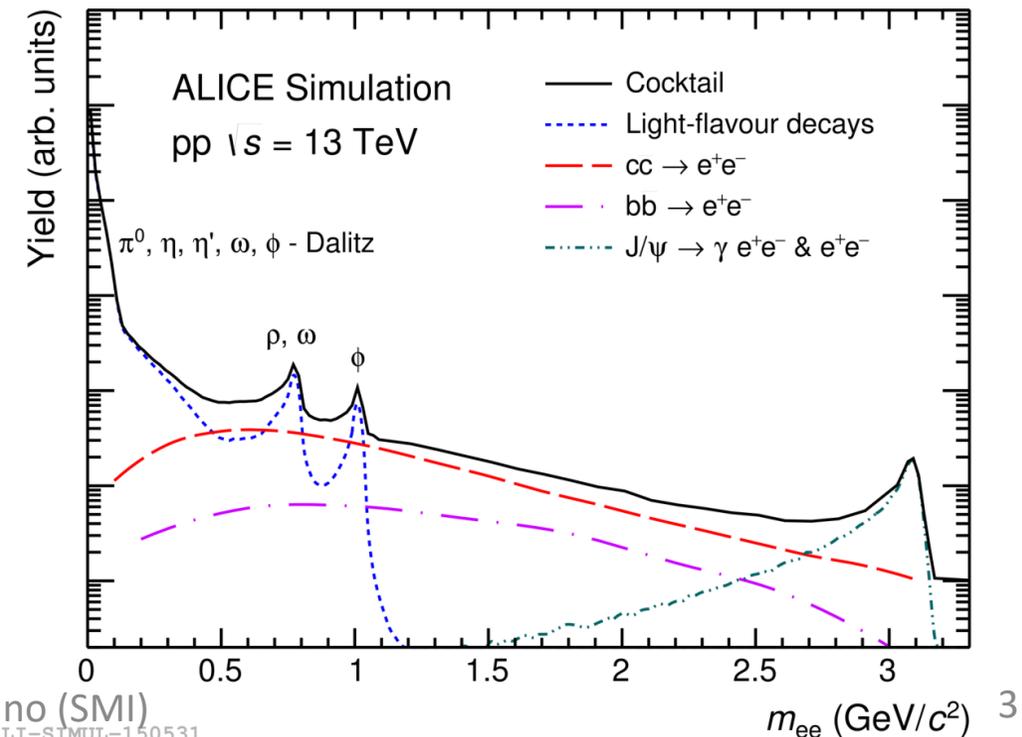
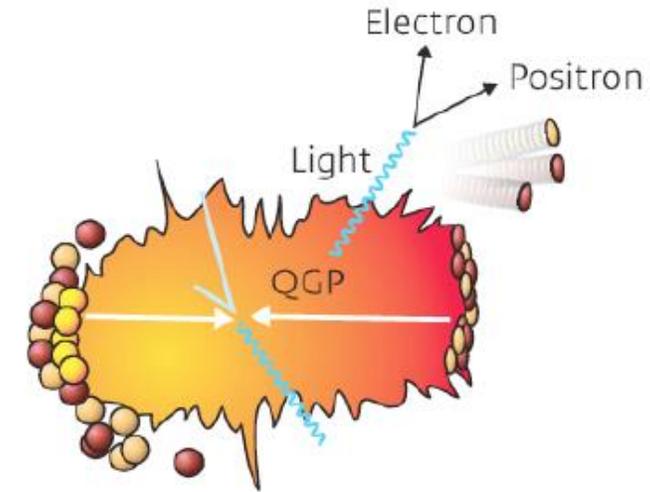
- Physics motivation
- The ALICE experiment
- Low mass dielectron analyses in ALICE
 - Studies in pp, p–Pb and Pb–Pb collisions
- Low mass dimuon analyses in ALICE
 - Results in pp and Pb–Pb collisions
- Outlook

**–Focus on recent results with Run 2 data
pp@5TeV and @13TeV, p–Pb, Pb–Pb @5TeV**



Electromagnetic probes

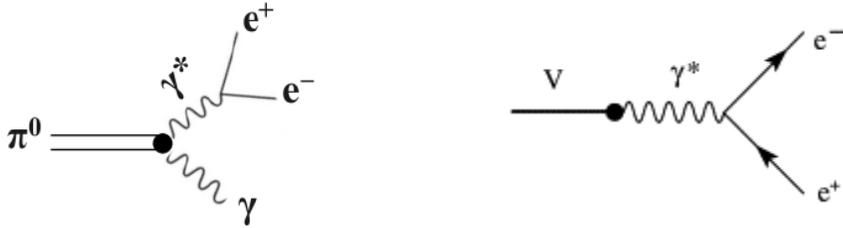
- Leptons and photons and experience no strong interactions, can therefore directly probe the full extension in space of collisions
 - **Transparent probes**
- Dileptons emitted from many sources during all stages of the collisions
 - **Investigate the whole history of the medium**
- Small systems used as reference measurements
 - **pp and p-Pb collisions**



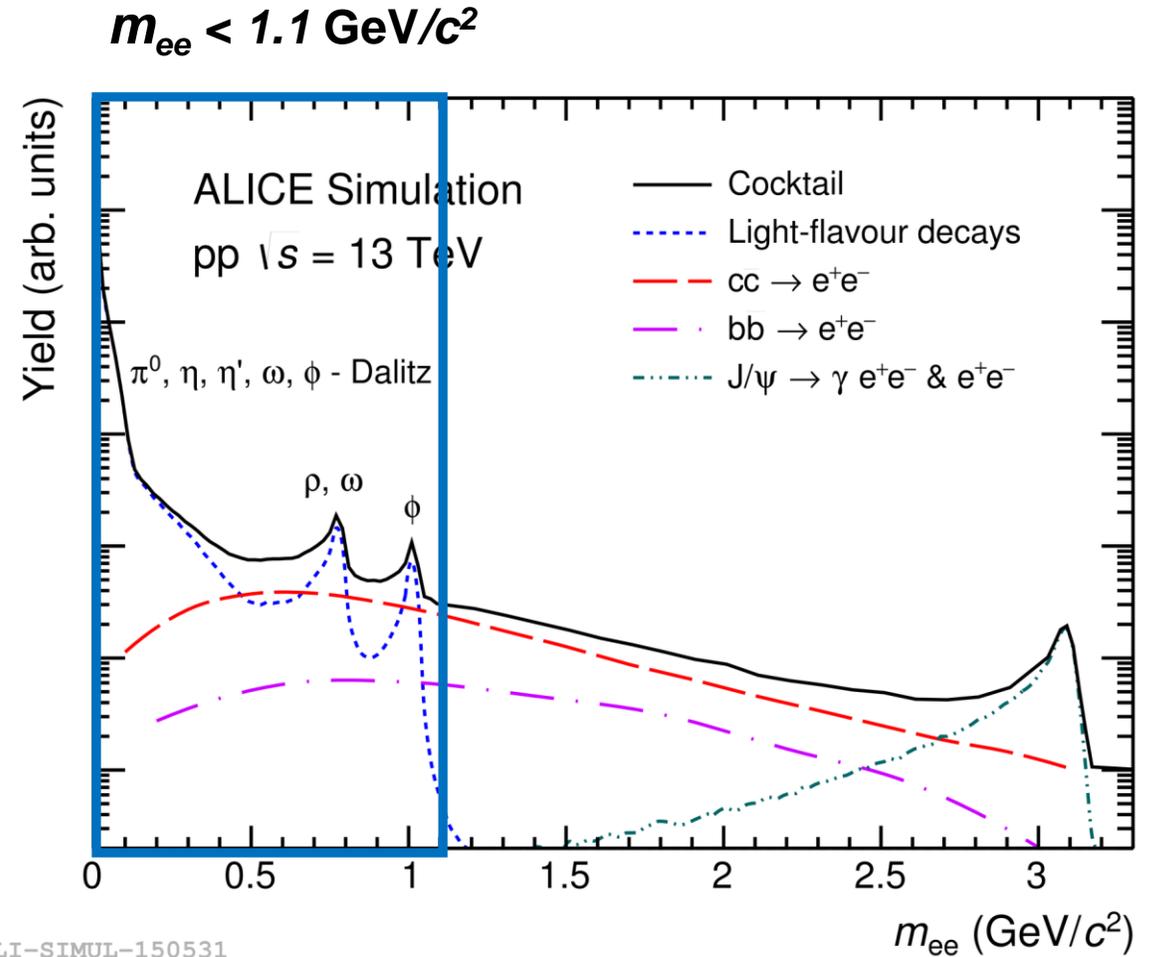
Dilepton mass spectrum

Different sources

- Dalitz decays ($\pi^0, \eta, \omega, \eta', \Phi$) and 2-body decays (ρ, ω, Φ) of light-flavour mesons



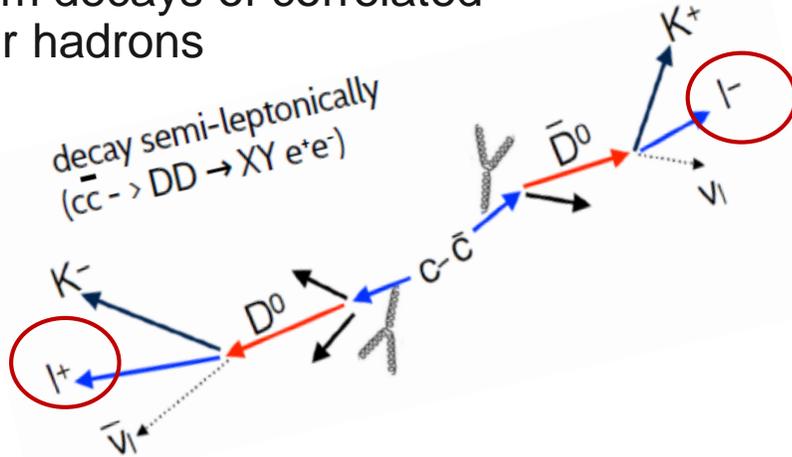
- $\Phi \rightarrow e^+e^-$ allows to study strangeness production
- ρ :
- Sensitive to chiral symmetry restoration
- Study thermal production of ρ and modification of ρ spectral function



Dilepton mass spectrum

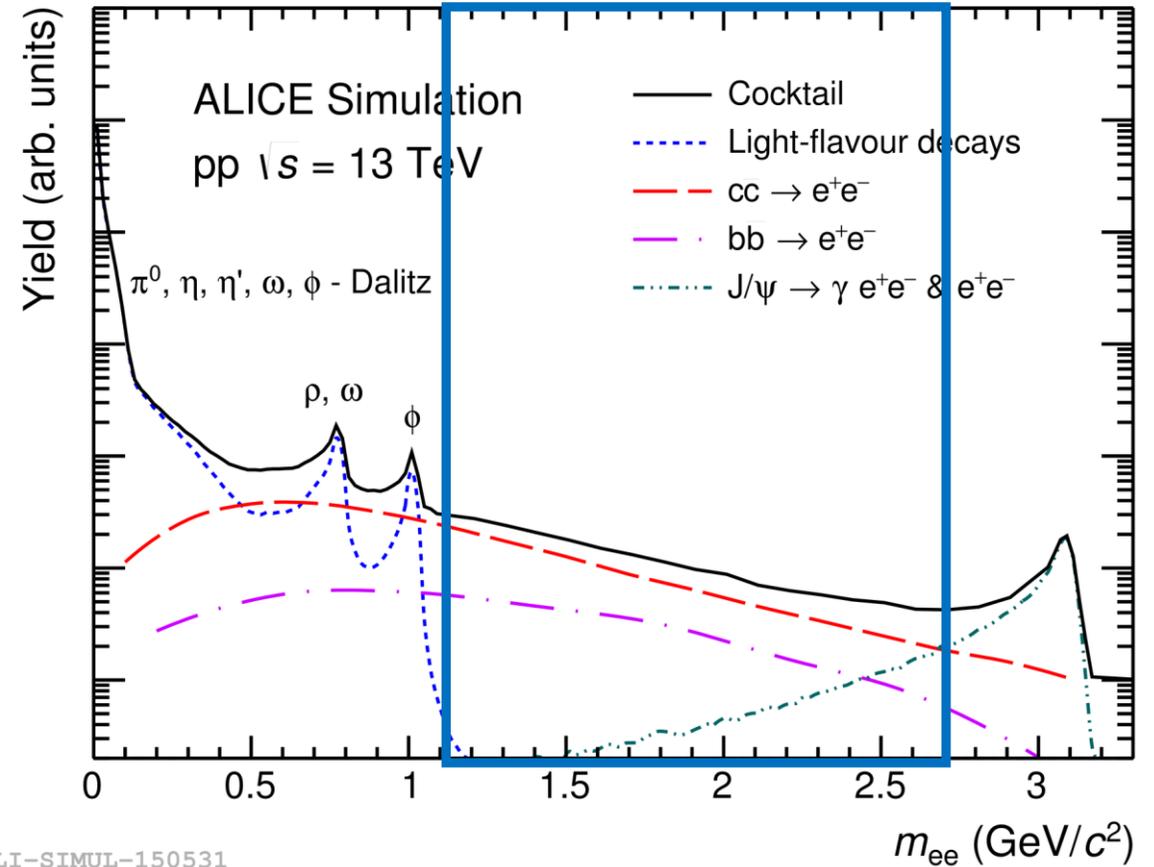
Different sources

- Dileptons from decays of correlated heavy-flavour hadrons



- $\sigma_{b\bar{b}}$ and $\sigma_{c\bar{c}}$ complementary to direct heavy-flavour hadron measurements
- Nuclear Parton Distribution Functions (nPDFs) in p-Pb and Pb-Pb collisions
- Energy loss, partial thermalization of correlated charm and beauty quarks

$$1.1 < m_{ee} < 2.7 \text{ GeV}/c^2$$



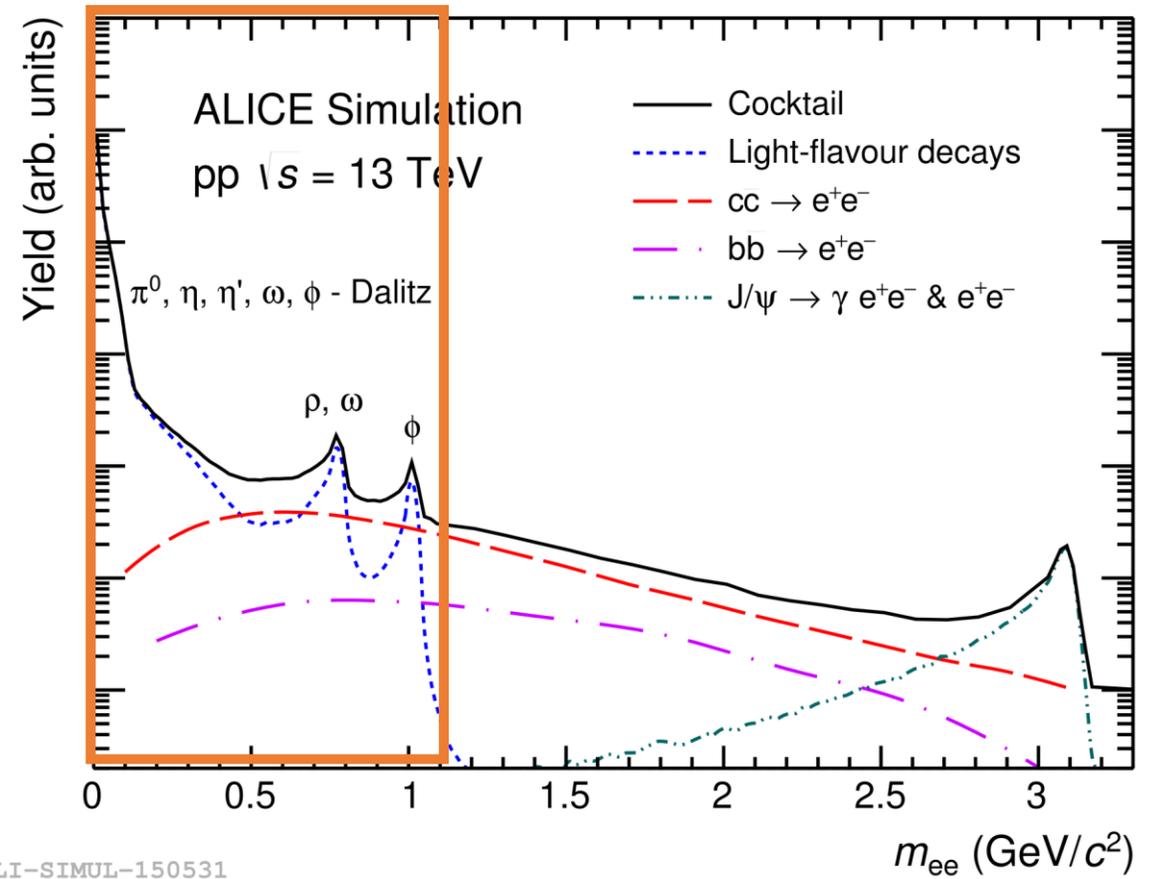
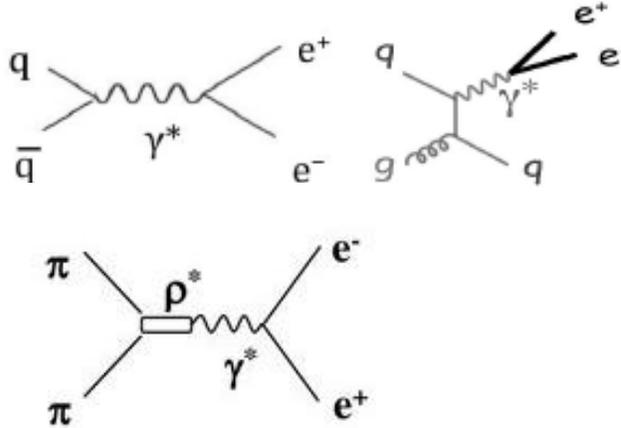
Dilepton mass spectrum



Different sources

Thermal radiation

- Quark-gluon plasma
- Hadronic gas

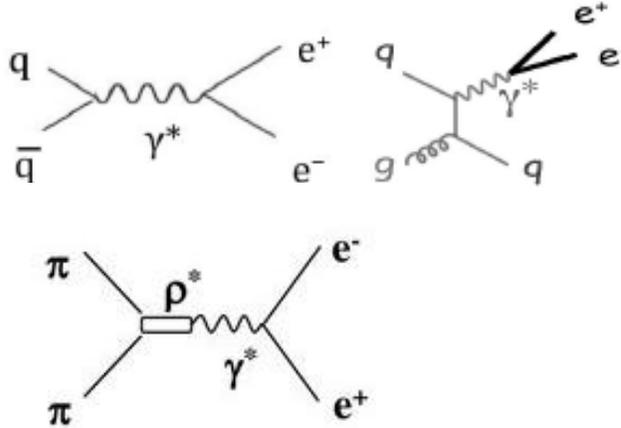


Dilepton mass spectrum

Different sources

Thermal radiation

- Quark-gluon plasma
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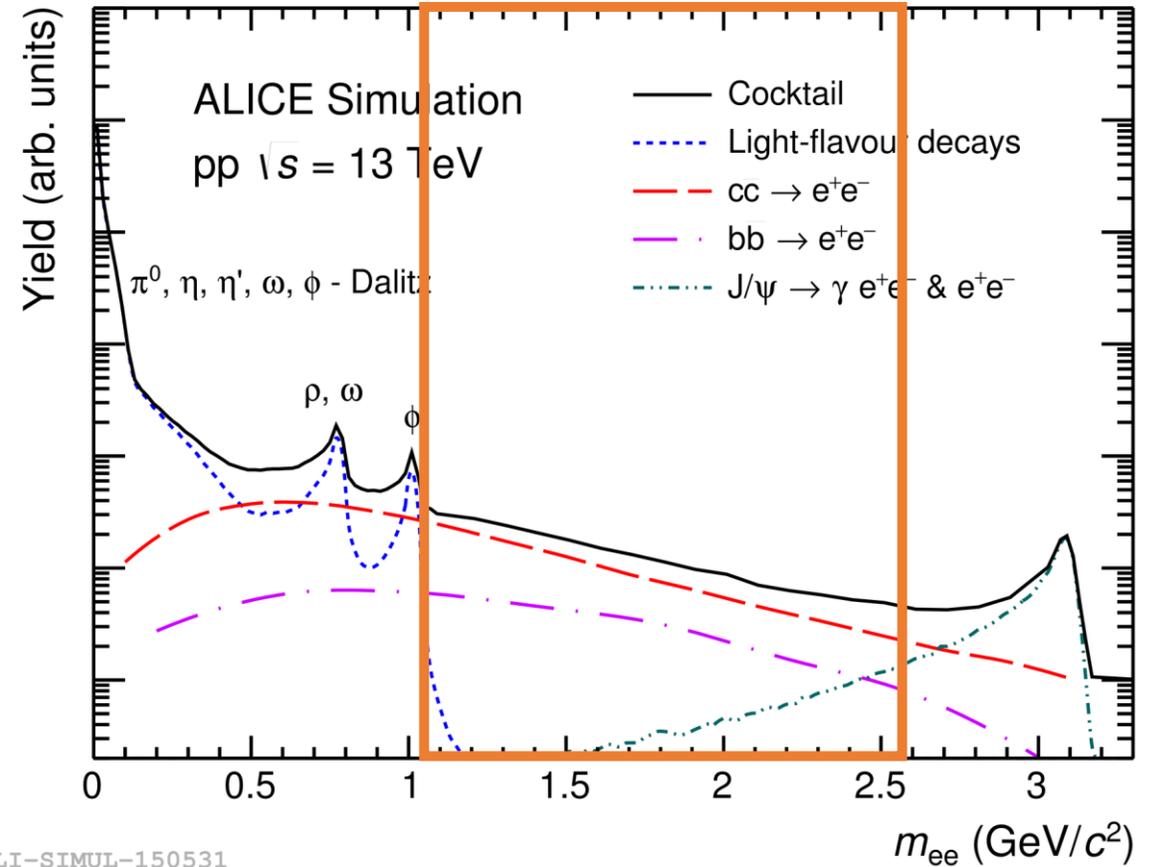


In the intermediate mass region (IMR)

- Thermal radiation from the partonic phase

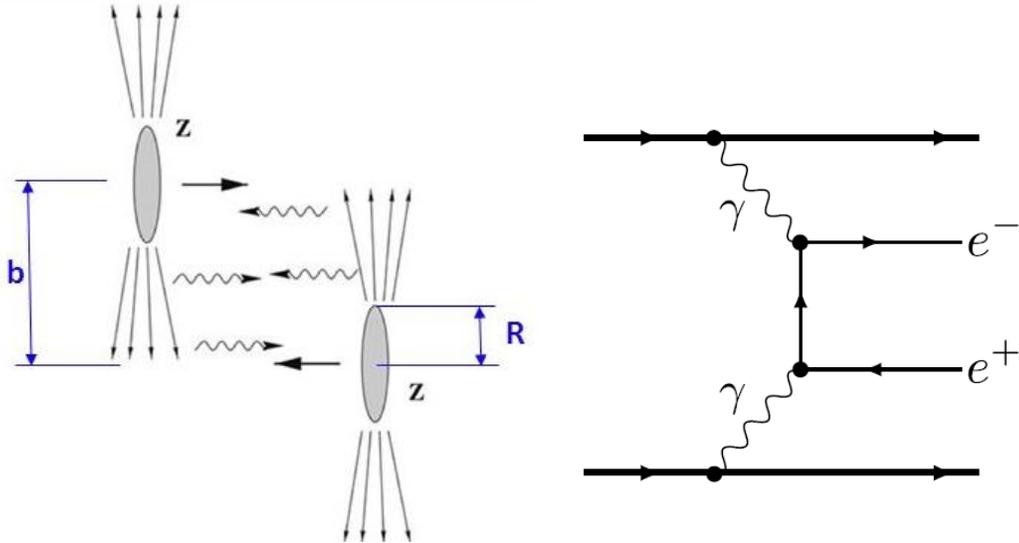
$$\frac{dN_{ee}}{dm_{ee}} \sim m^{3/2} e^{-m_{ee}/T}$$

- Challenging due to the dominant contribution from charm and beauty hadrons

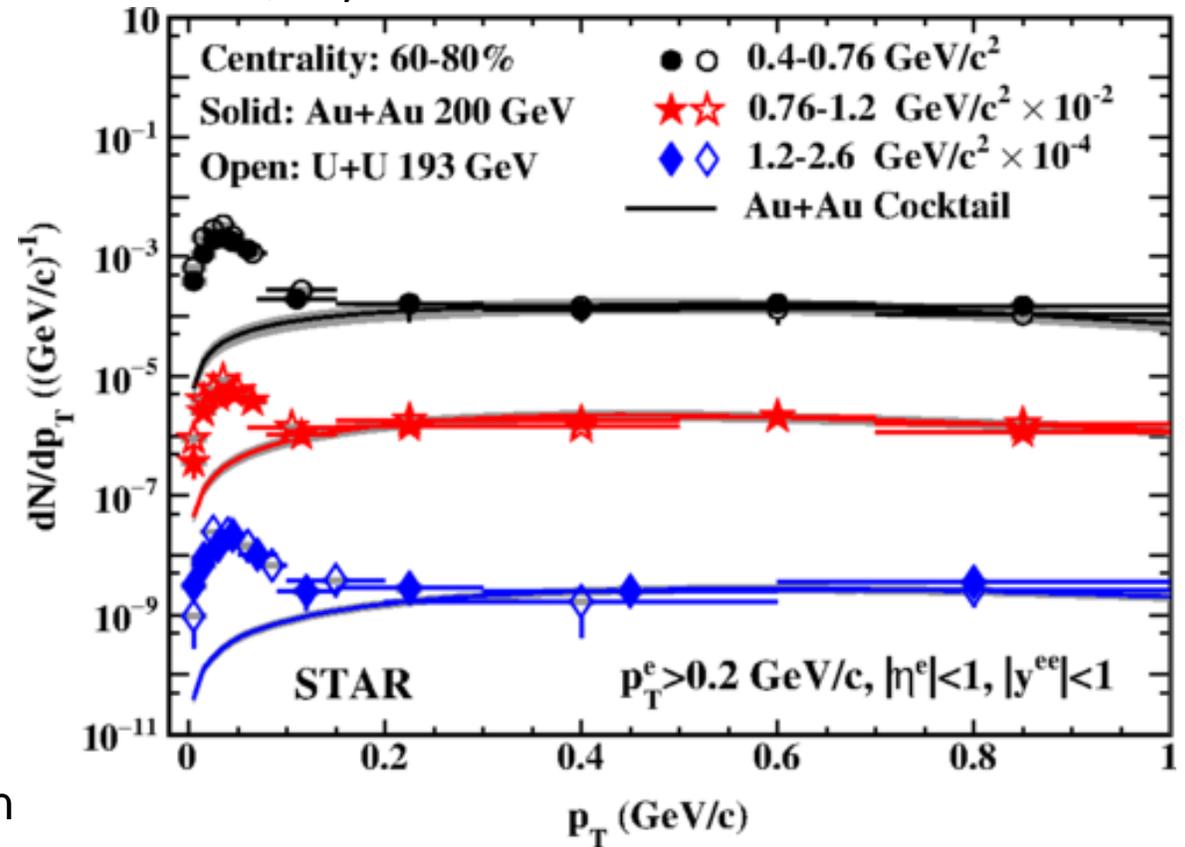


Dilepton photo production

- Photo-Production



STAR, Phys. Rev. Lett. 121. 132301

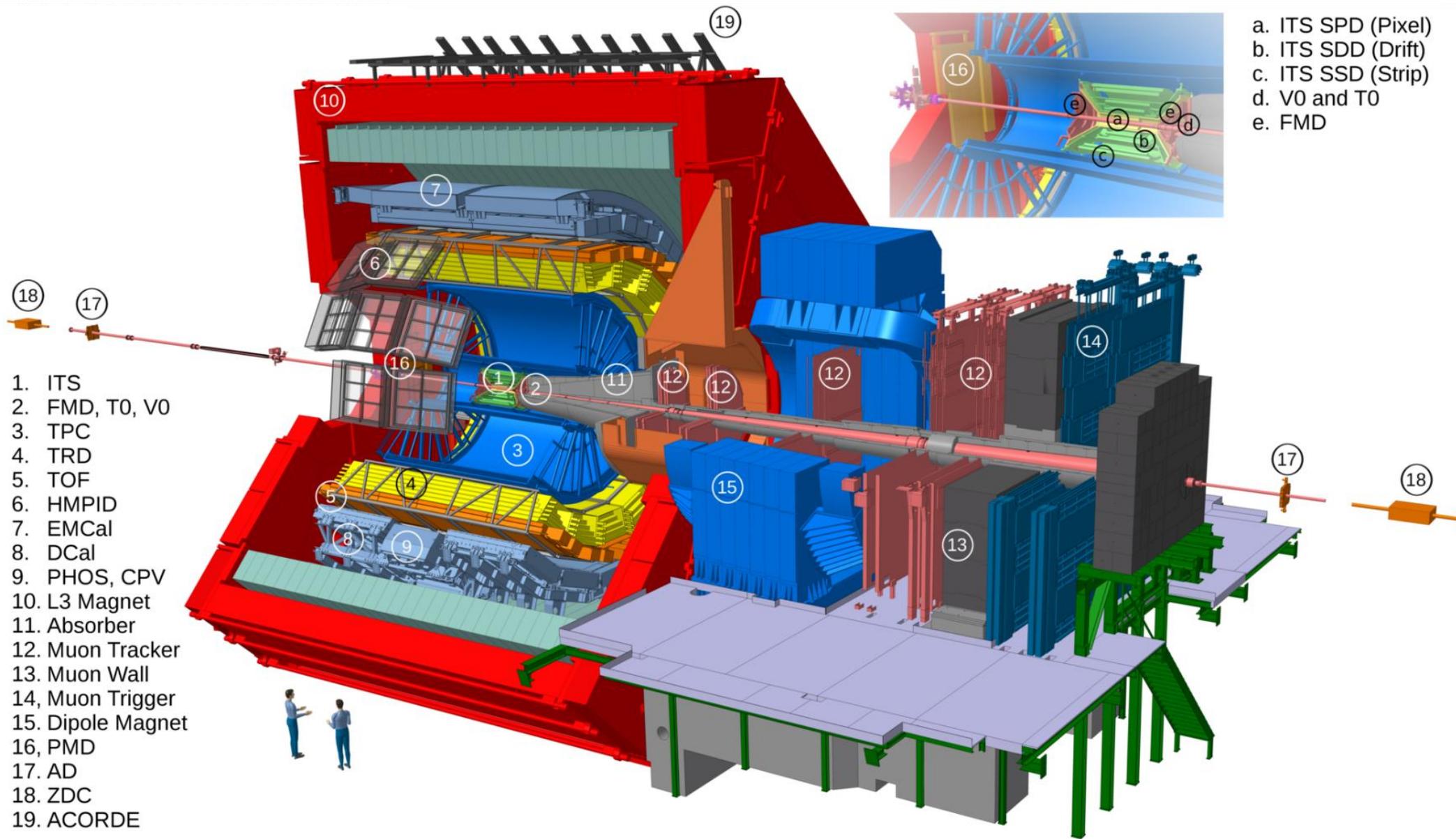


- Excess with respect to hadronic and thermal sources in peripheral collisions
 - Compatible with calculations for dielectron production from coherent photon-photon interactions

The ALICE apparatus



ALICE



The ALICE apparatus



ALICE

a. ITS SPD (Pixel)

b. TPC (Drift)

c. V0 (Strip)

d. TOF

V0

Trigger and centrality determination

$-3.8 < \eta < -1.7$ (V0C)

$2.8 < \eta < 5.1$ (V0A)

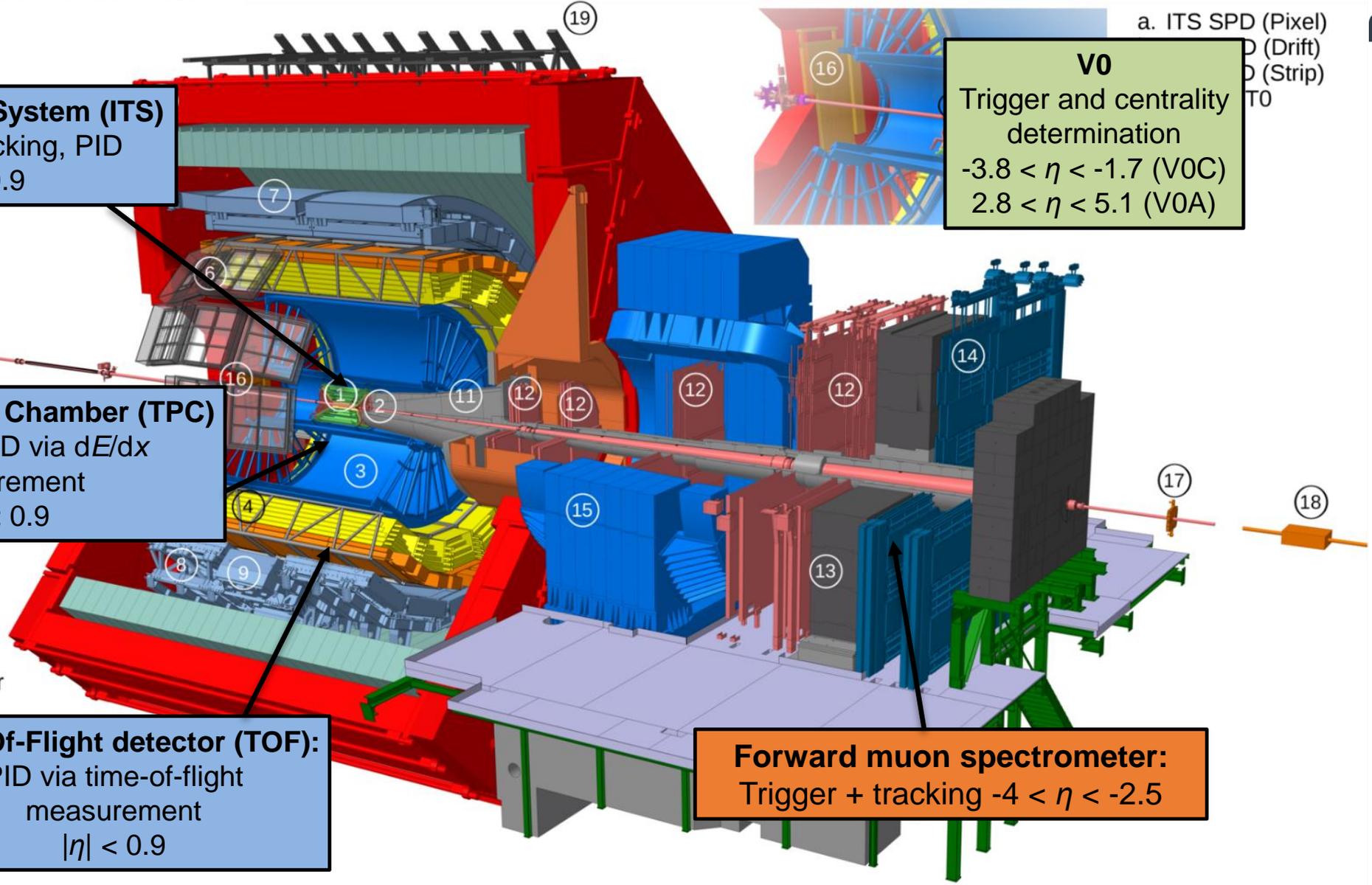
Inner Tracking System (ITS)
vertexing, tracking, PID
 $|\eta| < 0.9$

Time Projection Chamber (TPC)
Tracking, PID via dE/dx measurement
 $|\eta| < 0.9$

Time-Of-Flight detector (TOF):
PID via time-of-flight measurement
 $|\eta| < 0.9$

Forward muon spectrometer:
Trigger + tracking $-4 < \eta < -2.5$

- 7. EMCal
- 8. DCal
- 9. PHOS, CPV
- 10. L3 Magnet
- 11. Absorber
- 12. Muon Tracker
- 13. Muon Wall
- 14. Muon Filter
- 15. Dipole Magnet
- 16. PMT
- 17. AD
- 18. ZDC
- 19. AC



The ALICE apparatus



ALICE

a. ITS SPD (Pixel)
 b. TPC (Drift)
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Inner Tracking System (ITS)
 vertexing, tracking, PID
 $|\eta| < 0.9$

V0
 Trigger and centrality determination
 $-3.8 < \eta < -1.7$ (V0C)
 $2.8 < \eta < 5.1$ (V0A)

Time Projection Chamber (TPC)
 Tracking, PID via dE/dx measurement
 $|\eta| < 0.9$

Data samples used here:

pp collisions:

- Run 1 $\sqrt{s} = 7$ TeV (2009 - 2013), $\sqrt{s} = 8$ TeV (2012)
- Run 2 $\sqrt{s} = 5.02$ TeV (2015, 2017) and $\sqrt{s} = 13$ TeV (2015 - 2018)

p-Pb collisions:

- Run 1 $\sqrt{s_{NN}} = 5.02$ TeV (2013)
- Run 2 $\sqrt{s_{NN}} = 5.02$ TeV (2016)

Pb-Pb collisions

- Run 1 $\sqrt{s_{NN}} = 2.76$ TeV (2010, 2011)
- Run 2 $\sqrt{s_{NN}} = 5.02$ TeV (2015, 2018)

- 7. EMCal
- 8. DCal
- 9. PHOS, CPV
- 10. L3 Magnet
- 11. Absorber
- 12. Muon Tracker
- 13. Muon Wall
- 14. Muon Filter
- 15. Dipole Magnet
- 16. PM
- 17. AD
- 18. ZD
- 19. AC

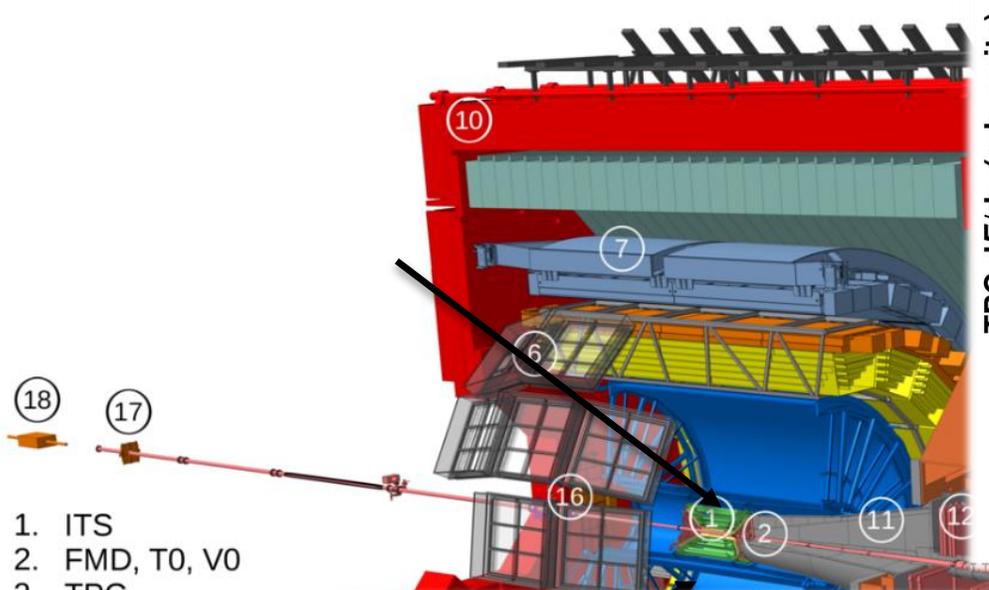
Time-Of-Flight detector (TOF):
 PID via time-of-flight measurement
 $|\eta| < 0.9$

Forward muon spectrometer:
 Trigger + tracking
 $-4 < \eta < -2.5$

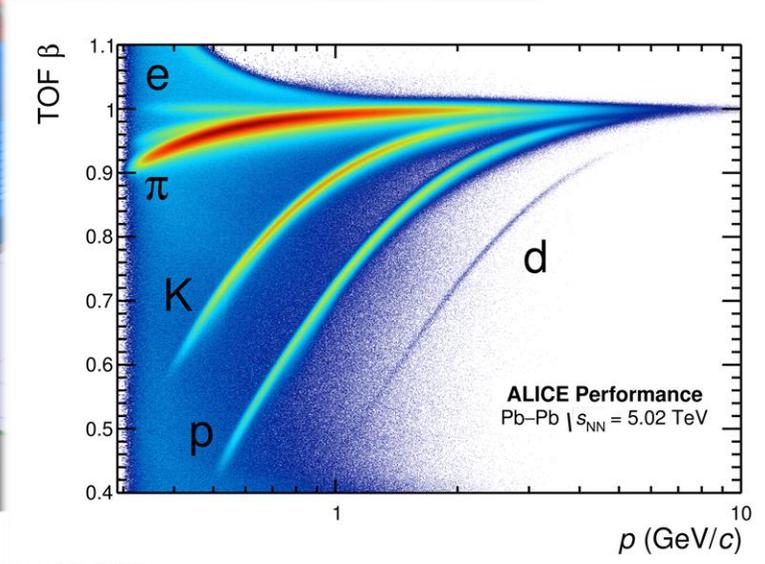
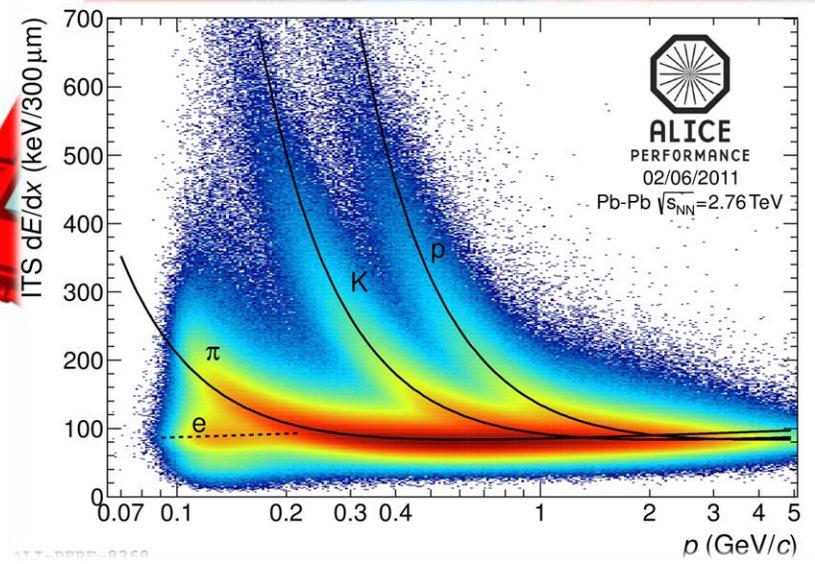
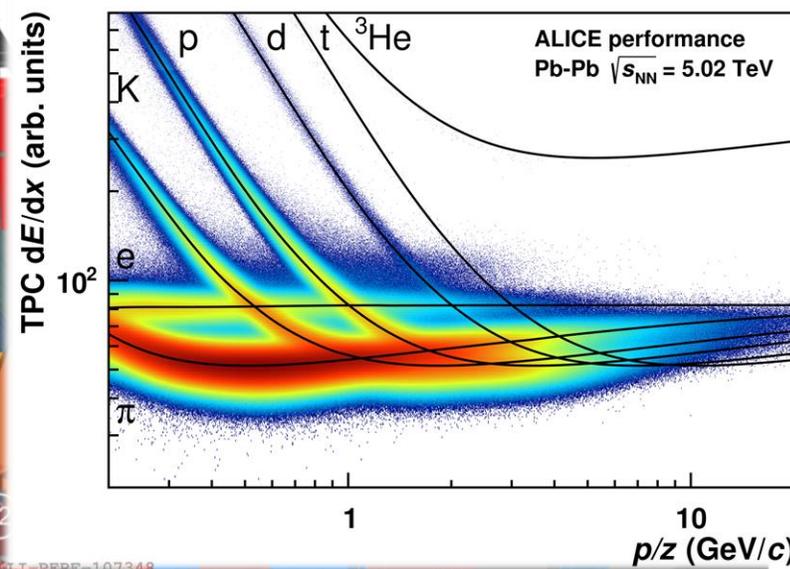
Electron identification



ALICE



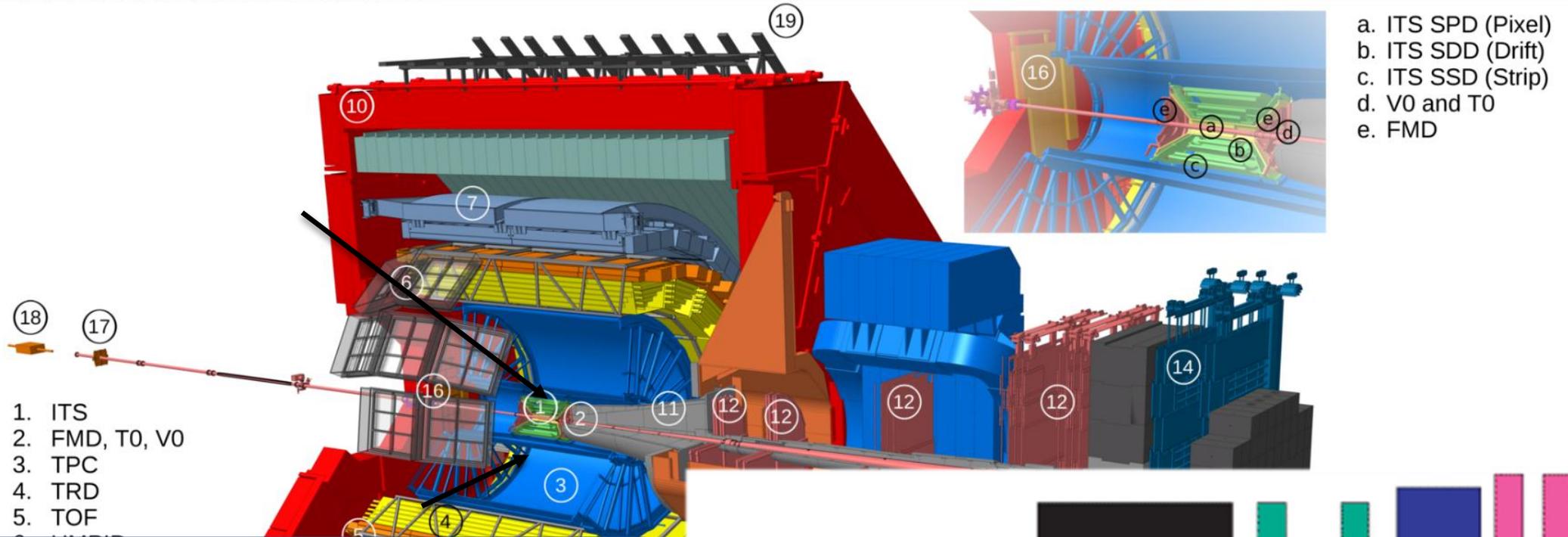
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE



The ALICE apparatus

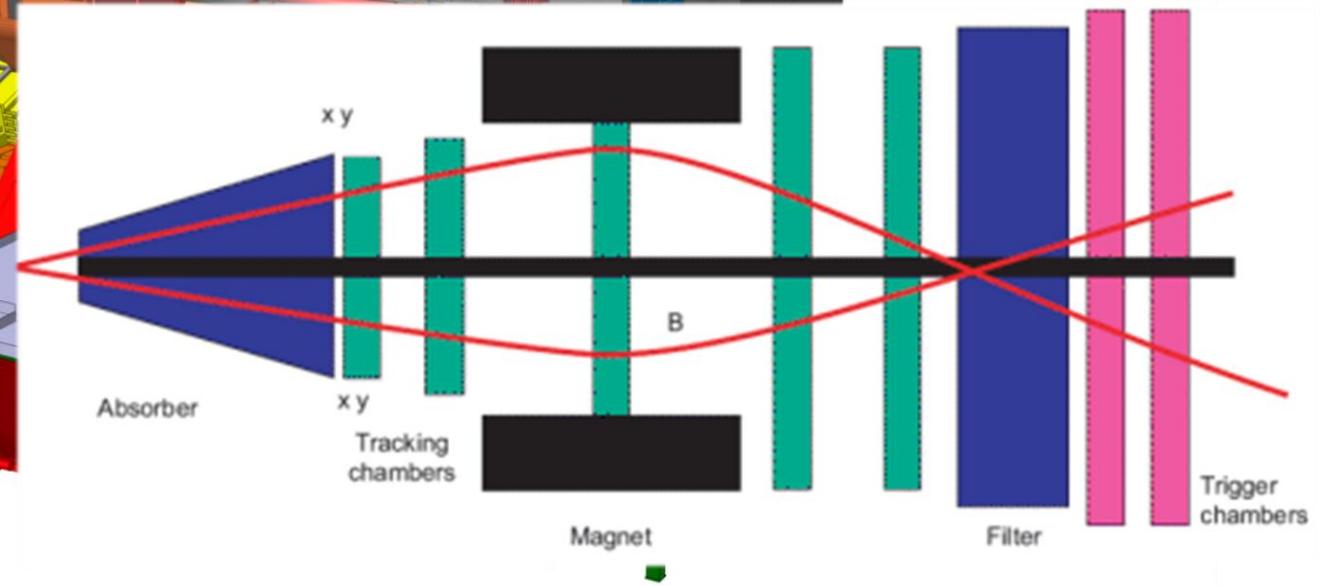


ALICE



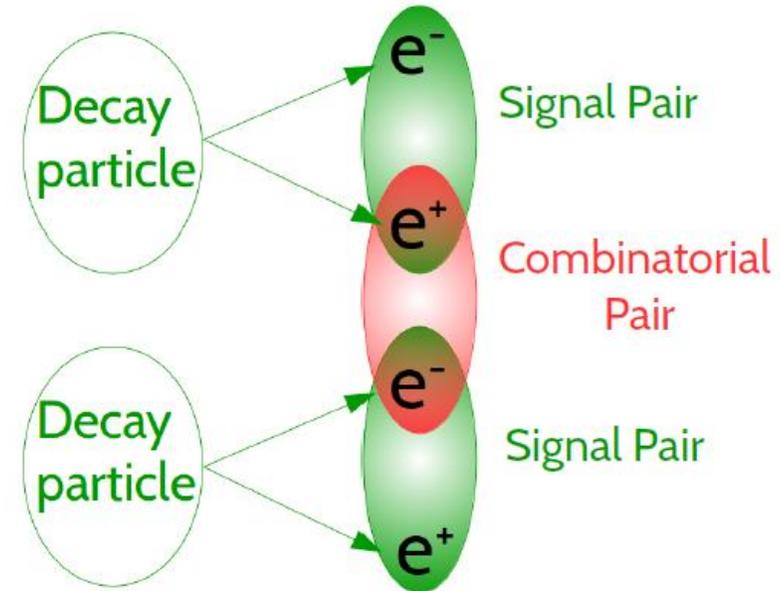
Muon spectrometer:

- Composed of absorber, tracking stations, dipole magnet, iron wall and trigger stations
- Absorber to remove hadrons
- Iron wall absorbs residual secondary hadrons



Obtaining the dilepton spectrum

- Track quality cuts applied to ensure only “good” quality tracks are used
- Particle identification performed
- Photon conversion into dileptons needs to be removed
- Obtain spectrum via like-sign subtraction for dielectrons:



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

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

Additional factor to account for different acceptances between ++ and -- tracks

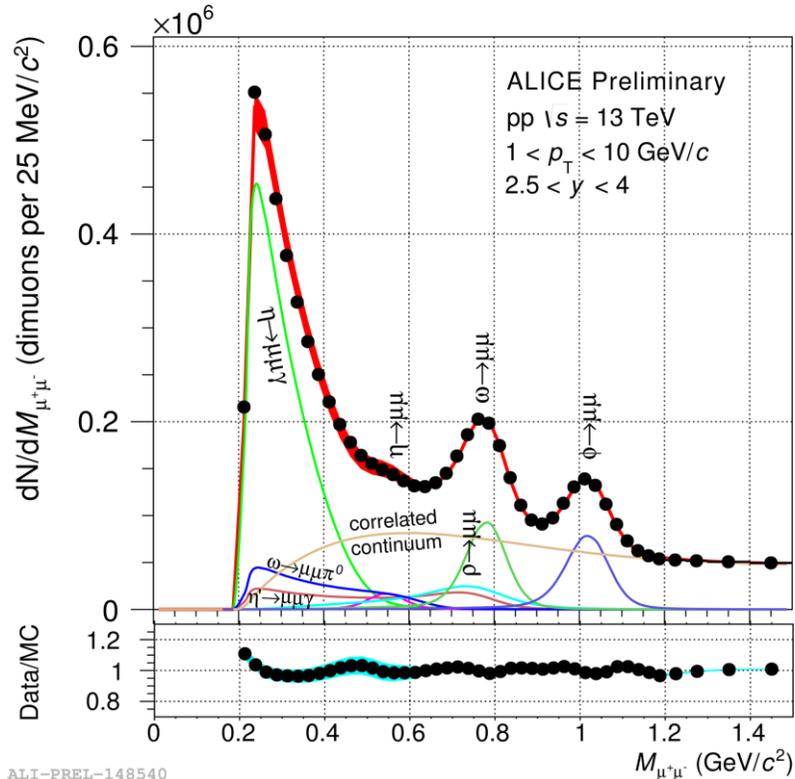
- Background evaluated with event mixing technique for dimuon analysis

Dimuon production

pp

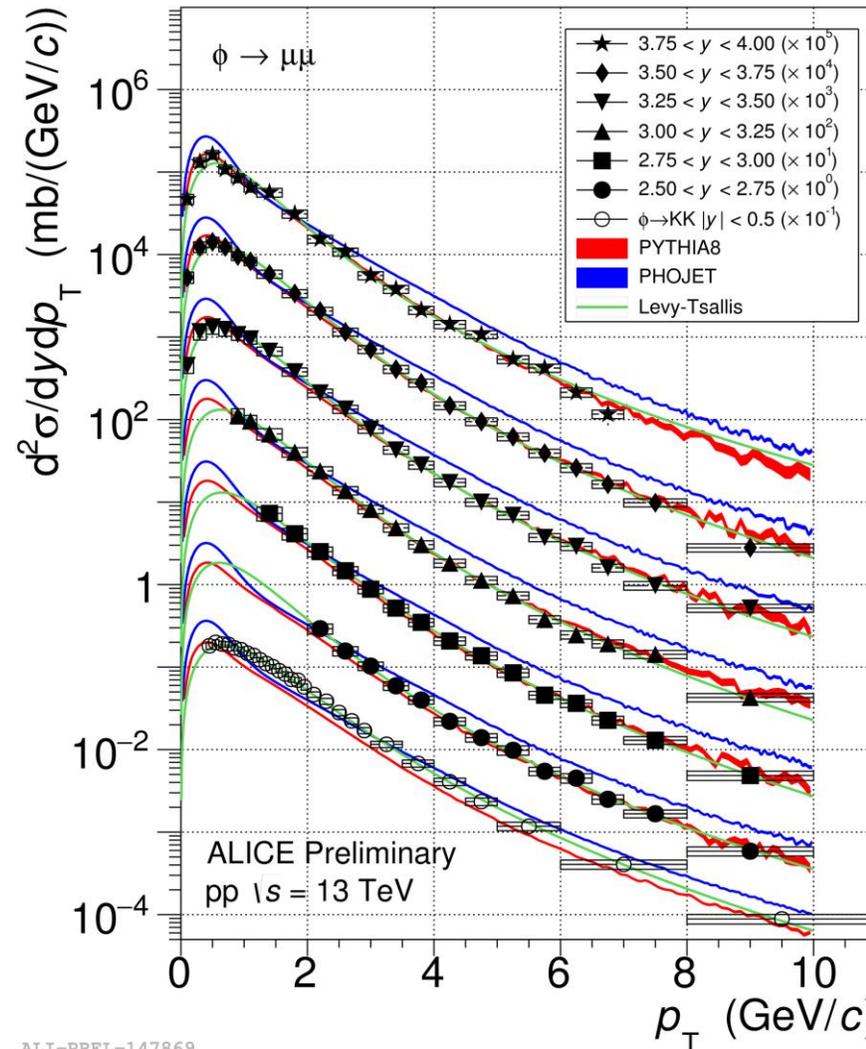


ALICE



Dimuon invariant mass spectrum for a p_T - and rapidity-integrated data sample

- Double-differential study of ϕ meson production vs p_T and rapidity:



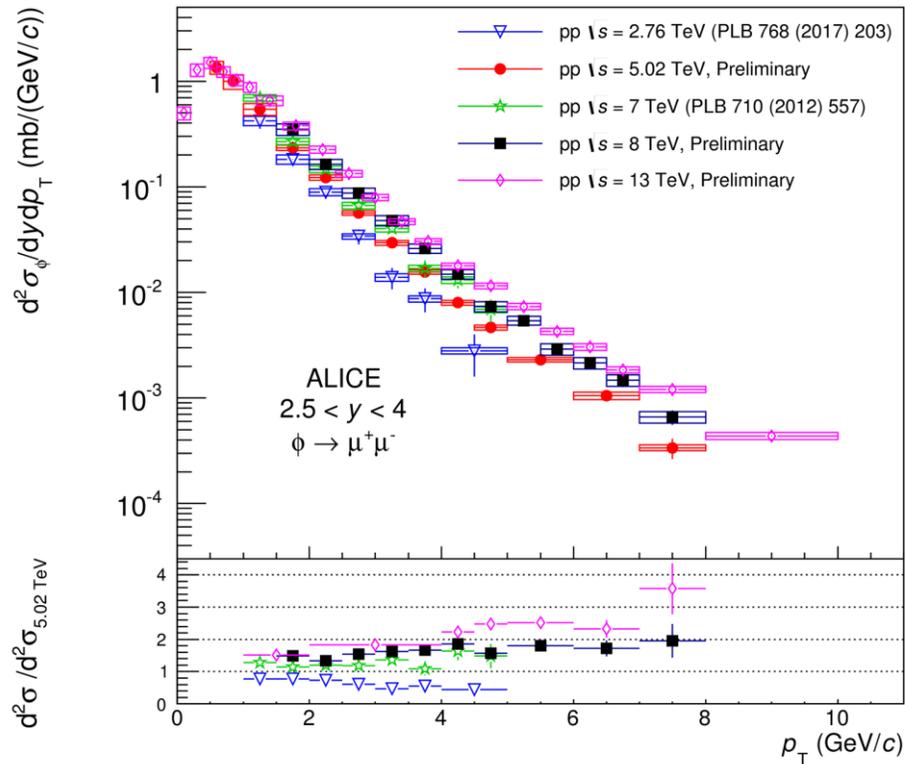
- Softer p_T spectra while increasing rapidity
- PYTHIA8 provides fair description of the p_T distributions
- PHOJET describes data only for $1 < p_T < 2$ GeV/c

PYTHIA8: Eur.286Phys. J.C74no. 8, (2014) 3024

PHOJET: Z. Phys.C66(1995) 203–214

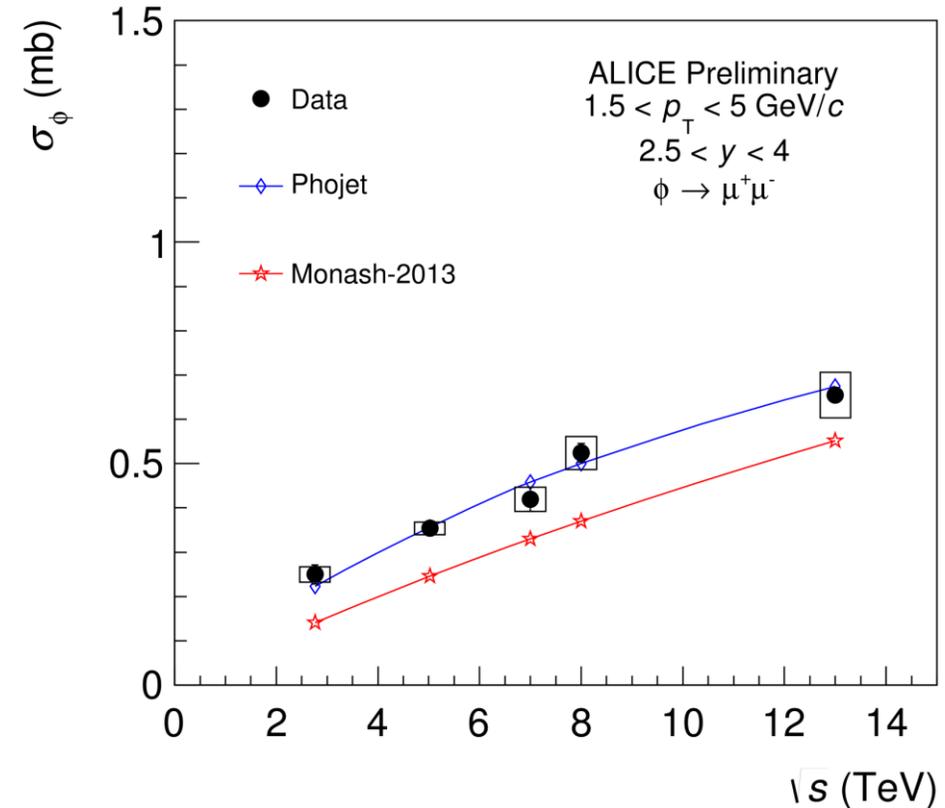
Dimuon production

pp



ALI-PREL-308099

- ϕ -meson production cross section vs p_T at various energies
 - hardening of the p_T spectra with increasing energy observed



ALI-PREL-308081

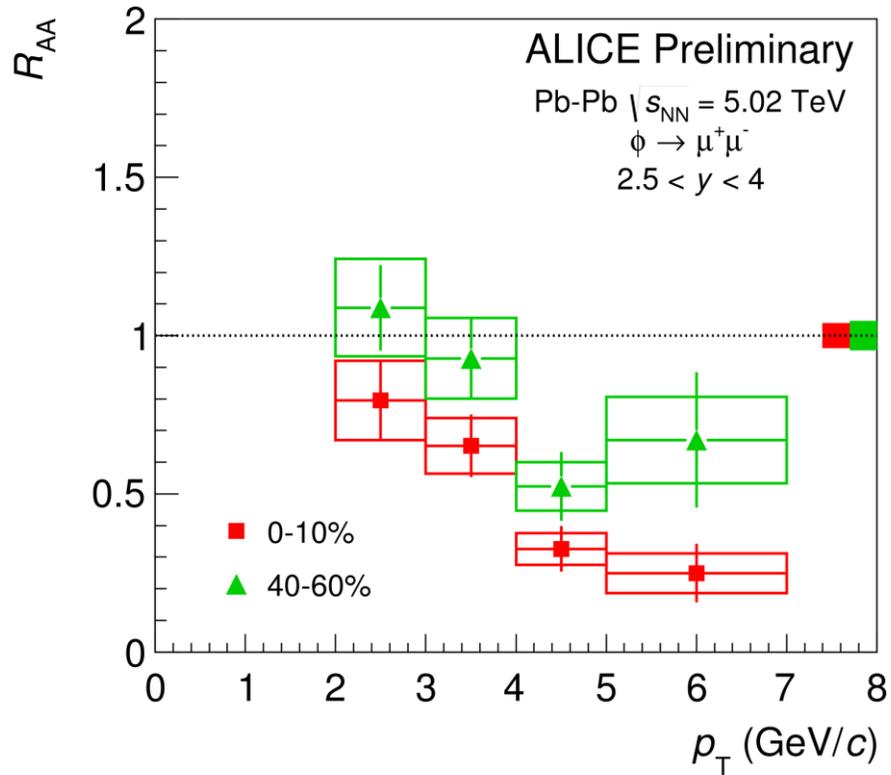
- Increase of the production with the energy
 - well described by PHOJET
 - underestimated by PYTHIA8 (Monash tune), although the trend of data is reproduced

PYTHIA8: Eur.286Phys. J.C74no. 8, (2014) 3024

PHOJET: Z. Phys.C66(1995) 203–214

Dimuon production

Pb-Pb

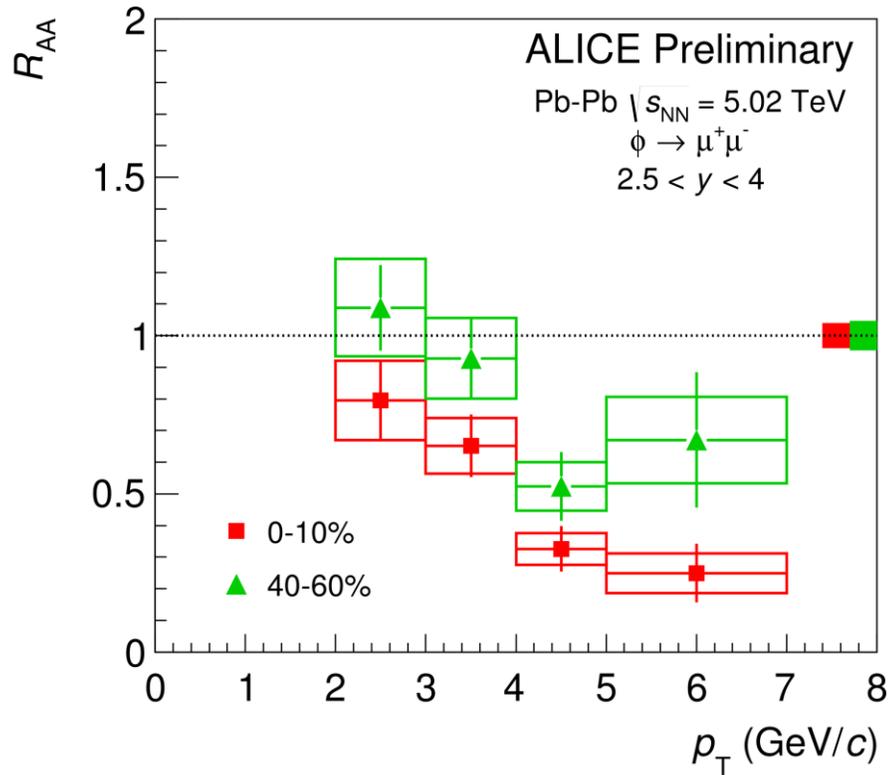


ALI-PREL-131956

- R_{AA} measured in central and semi-peripheral collisions
- Clear decrease observed in the R_{AA} for $p_T > 4$ GeV/c in central collisions
- Less pronounced decrease for semi-peripheral collisions

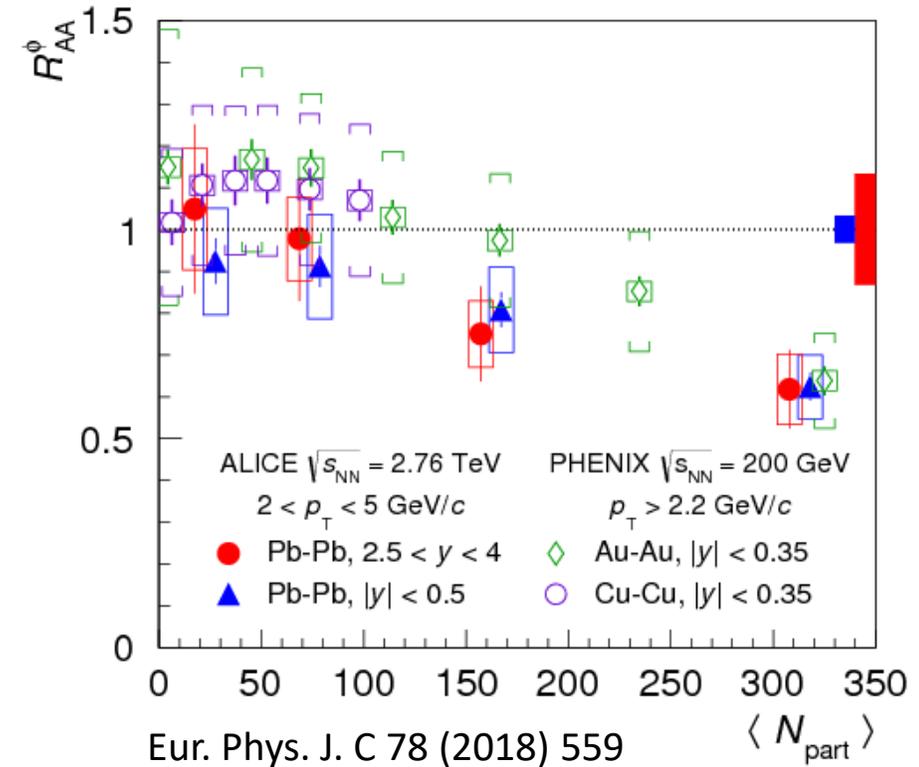
Dimuon production

Pb-Pb



ALI-PREL-131956

- R_{AA} measured in central and semi-peripheral collisions
- Clear decrease observed in the R_{AA} for $p_T > 4$ GeV/c in central collisions
- Less pronounced decrease for semi-peripheral collisions

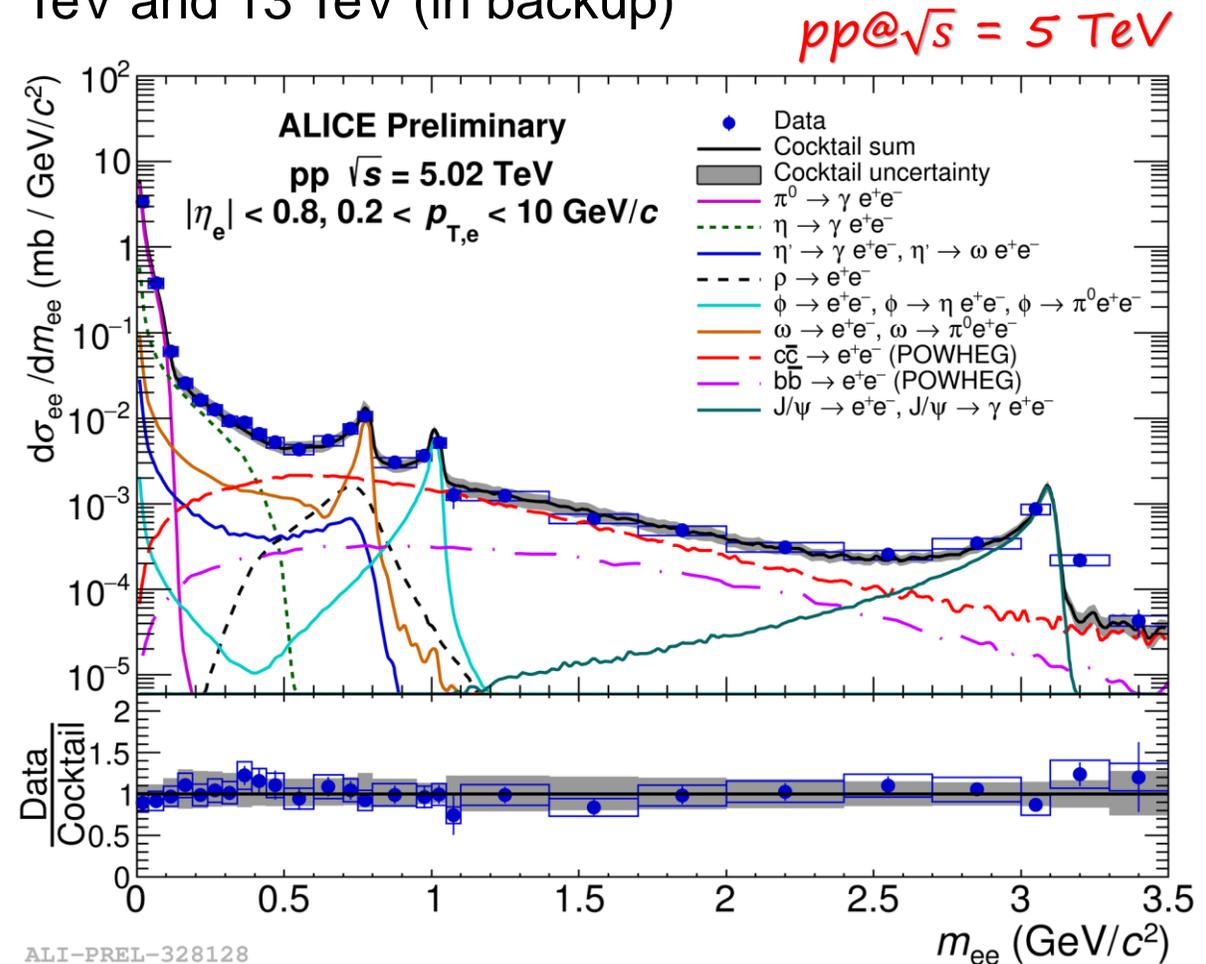


- ϕ - R_{AA} at forward rapidity reduced to ~ 0.65 at central collisions
- Results at forward and mid-rapidity compatible within uncertainties
 - Hint for similar mechanisms of interaction with the medium

Dielectron measurements in pp collisions

- Spectrum compared with cocktail of known hadronic sources
 - **Data well described by cocktail within uncertainties**
 - Similar results in pp collisions at $\sqrt{s} = 7$ TeV and 13 TeV (in backup)

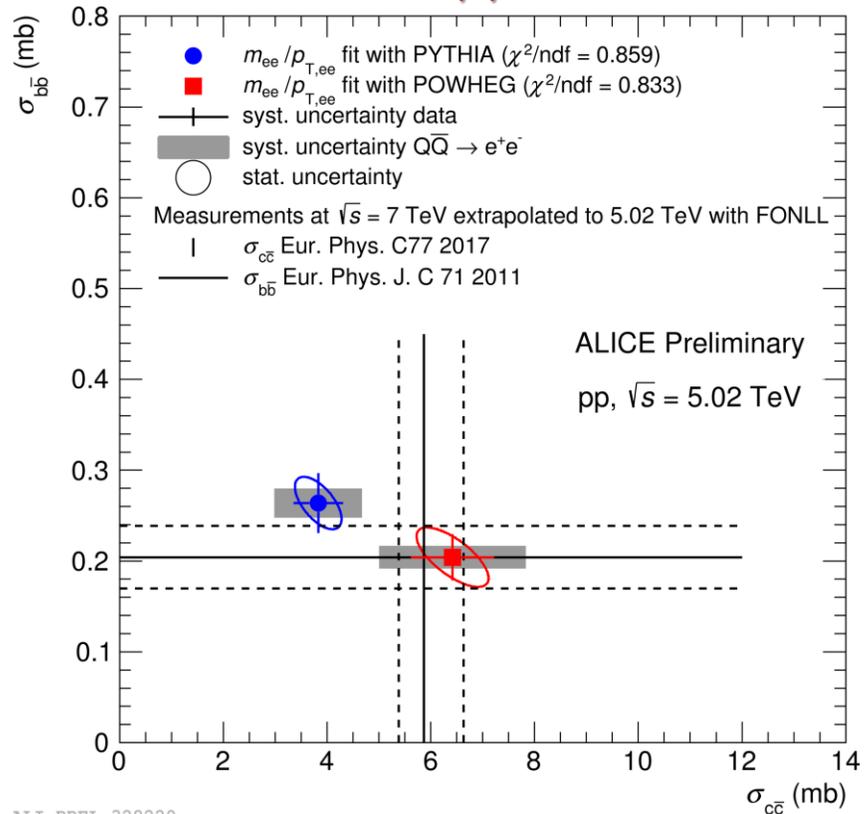
- Light flavour from parametrized measurements and particle ratios
- Heavy flavour from POWHEG or PYTHIA, normalized to measured σ_{bb} and σ_{cc} at 7 TeV, extrapolated to 5 TeV with FONLL



Dielectron measurements in pp collisions

- HF cross section extracted with a 2D m_{ee} $p_{T,ee}$ fit (pp@5,7,13 TeV)

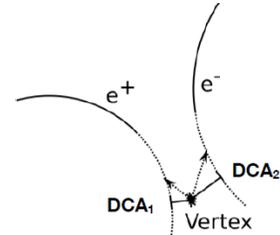
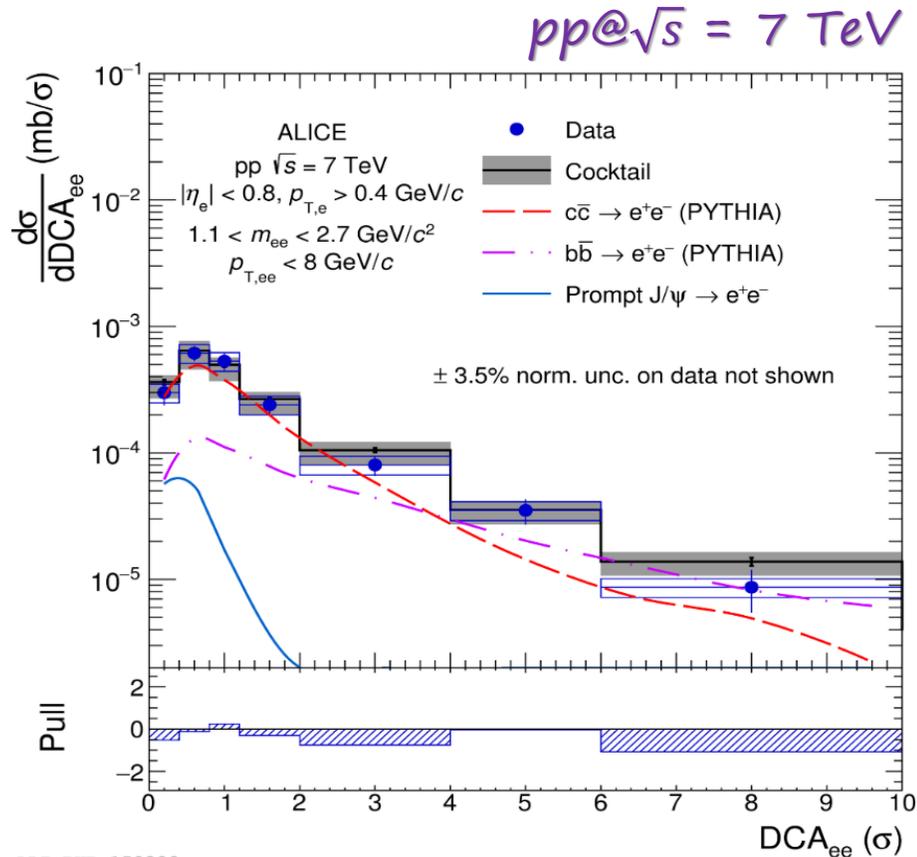
$pp@√s = 5 \text{ TeV}$



ALI-PREL-328220

- Model dependence observed in all available energies
- Charm and beauty cross sections compatible with previous measurements of HF hadron decays

- DCA dielectron spectra in IMR used to extract charm and beauty cross section



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

- Heavy-flavour hadrons have a delayed decay
- D-meson $c\tau = 150\text{-}300 \mu\text{m}$, B-meson $c\tau = 450 \mu\text{m}$

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

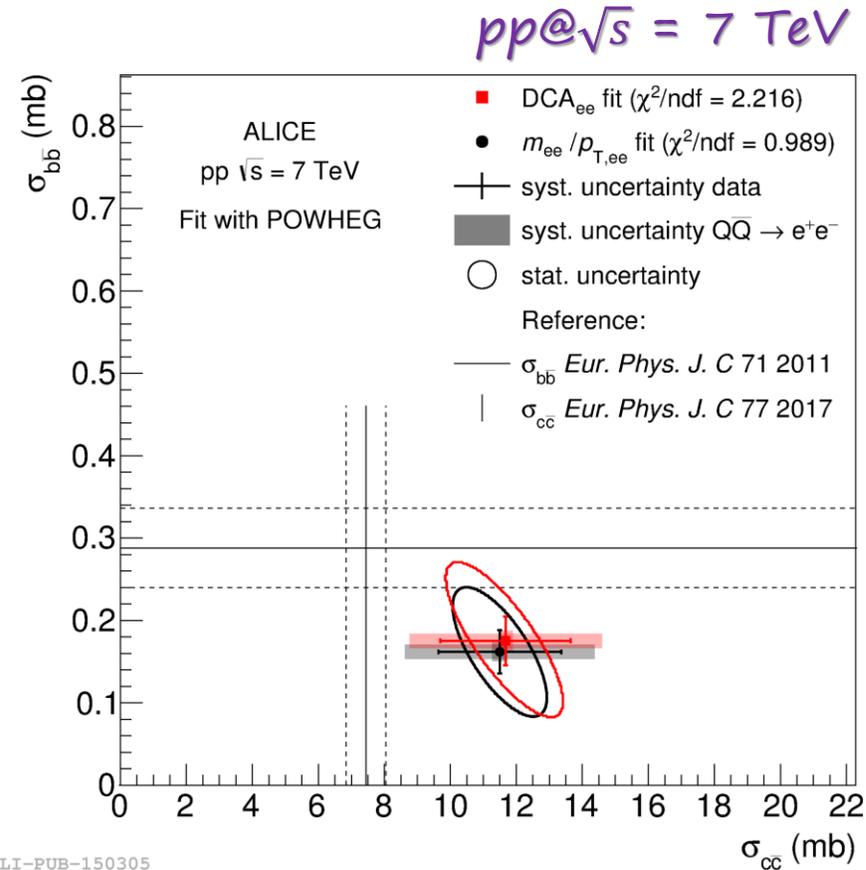
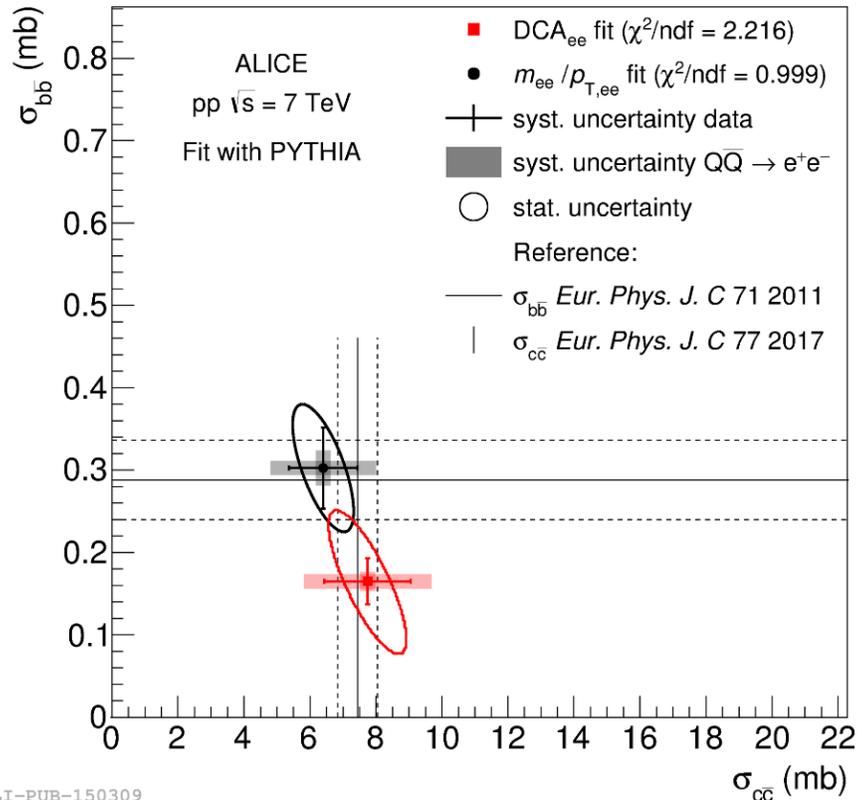


DCA useful variable to discriminate charm and beauty hadron decay electrons

- Additional fit with DCA (in pp collisions at $\sqrt{s} = 7$ TeV)

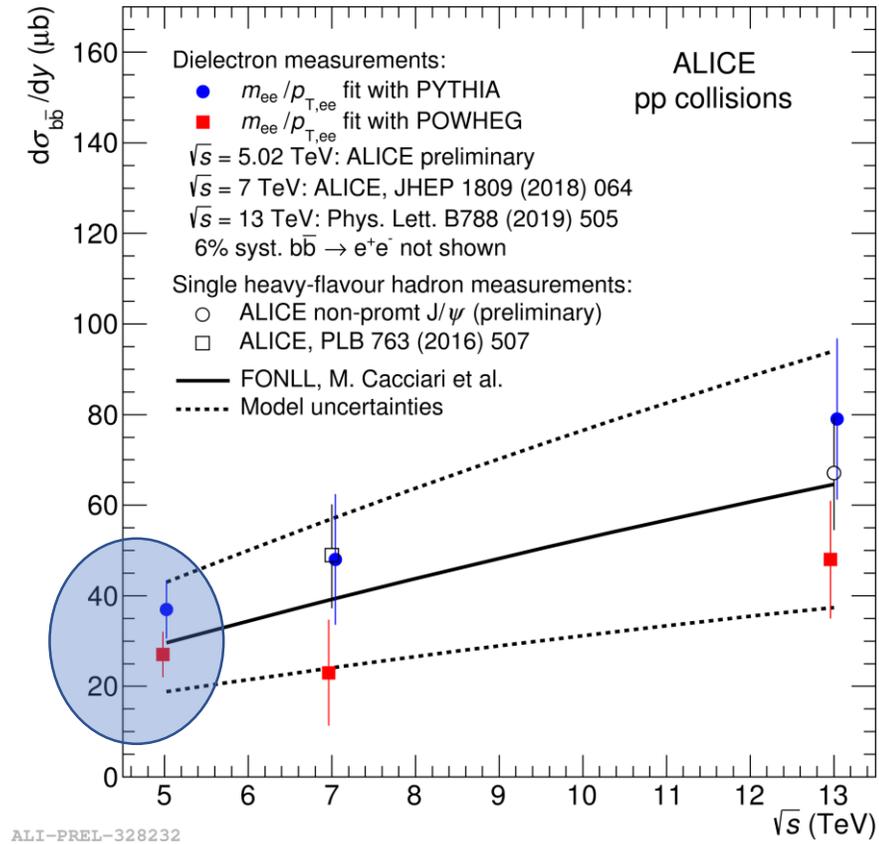
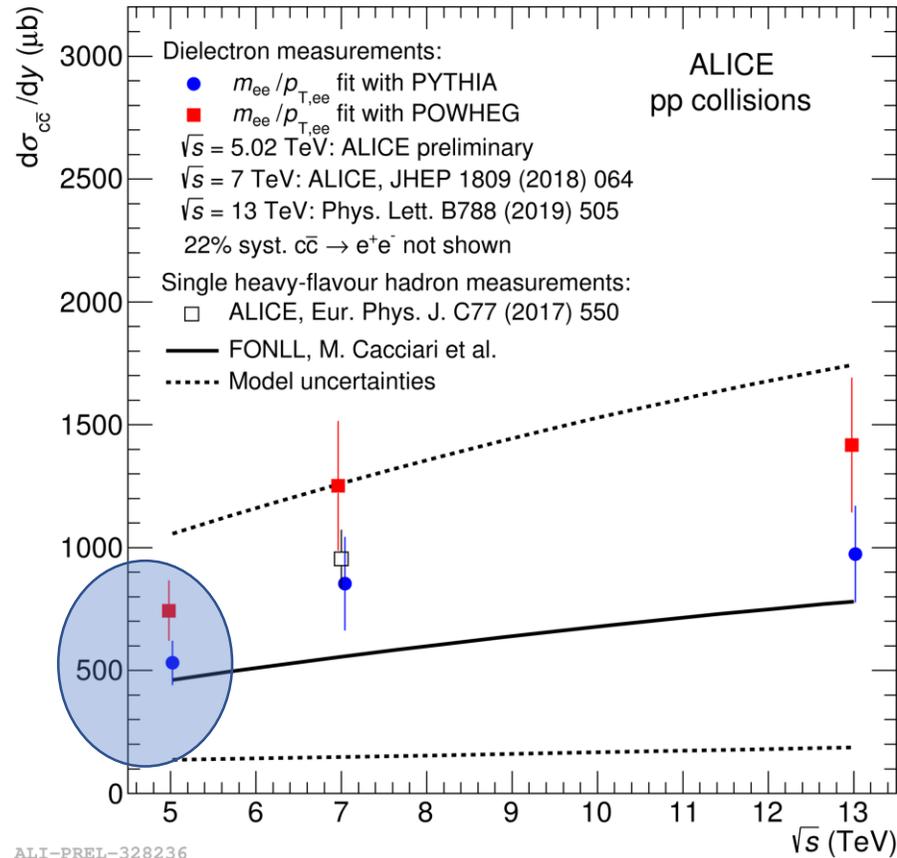
Dielectron measurements in pp collisions

- HF cross section extracted with a 2D m_{ee} $p_{T,ee}$ fit (pp@5,7,13 TeV) and DCA fit (pp@7TeV)



- Model dependence observed in all available energies
- Charm and beauty cross sections compatible with previous measurements of HF hadron decays
- Fit results of $(m_{ee}, p_{T,ee})$ and DCA_{ee} spectra in agreement within uncertainties

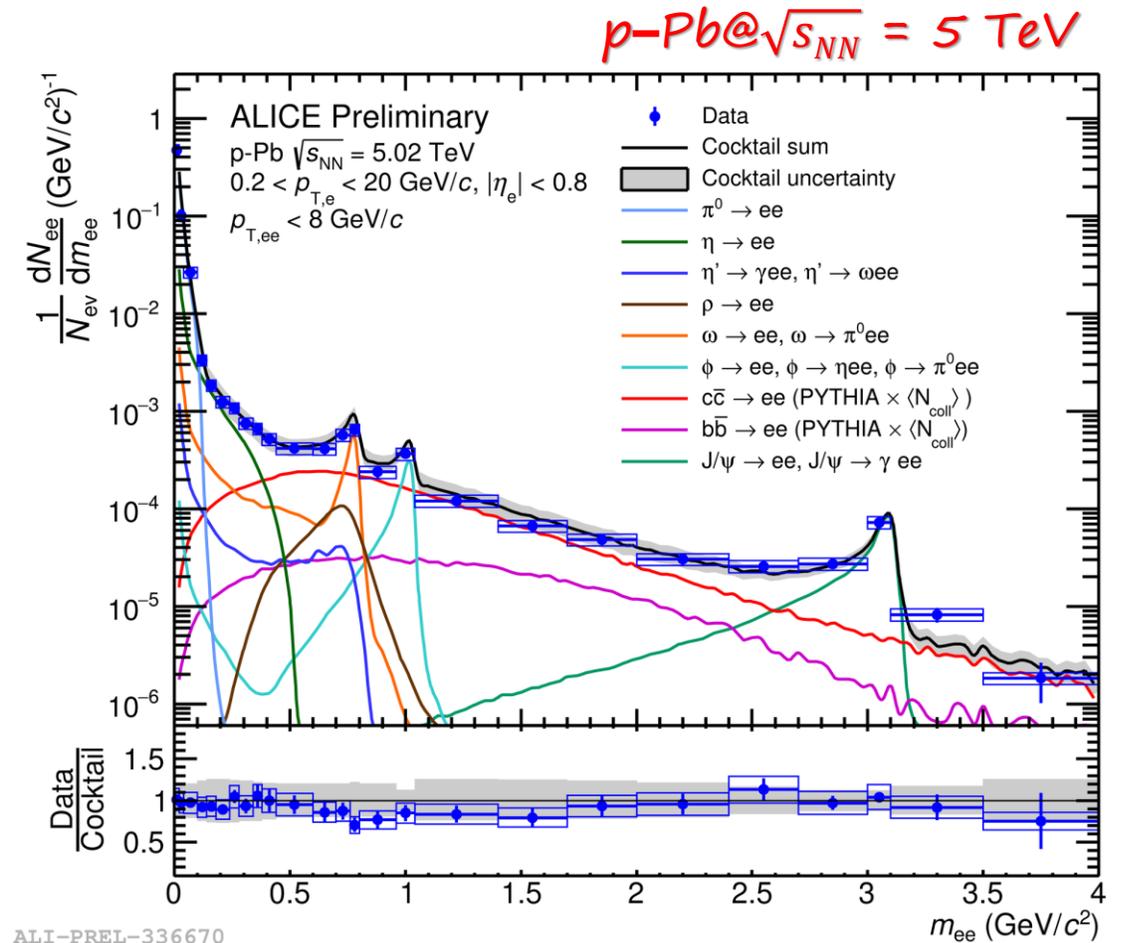
Dielectron measurements in pp collisions



- First measurement of $d\sigma_{c\bar{c}}/dy$ and $d\sigma_{b\bar{b}}/dy$ in pp at $\sqrt{s} = 5.02$ TeV

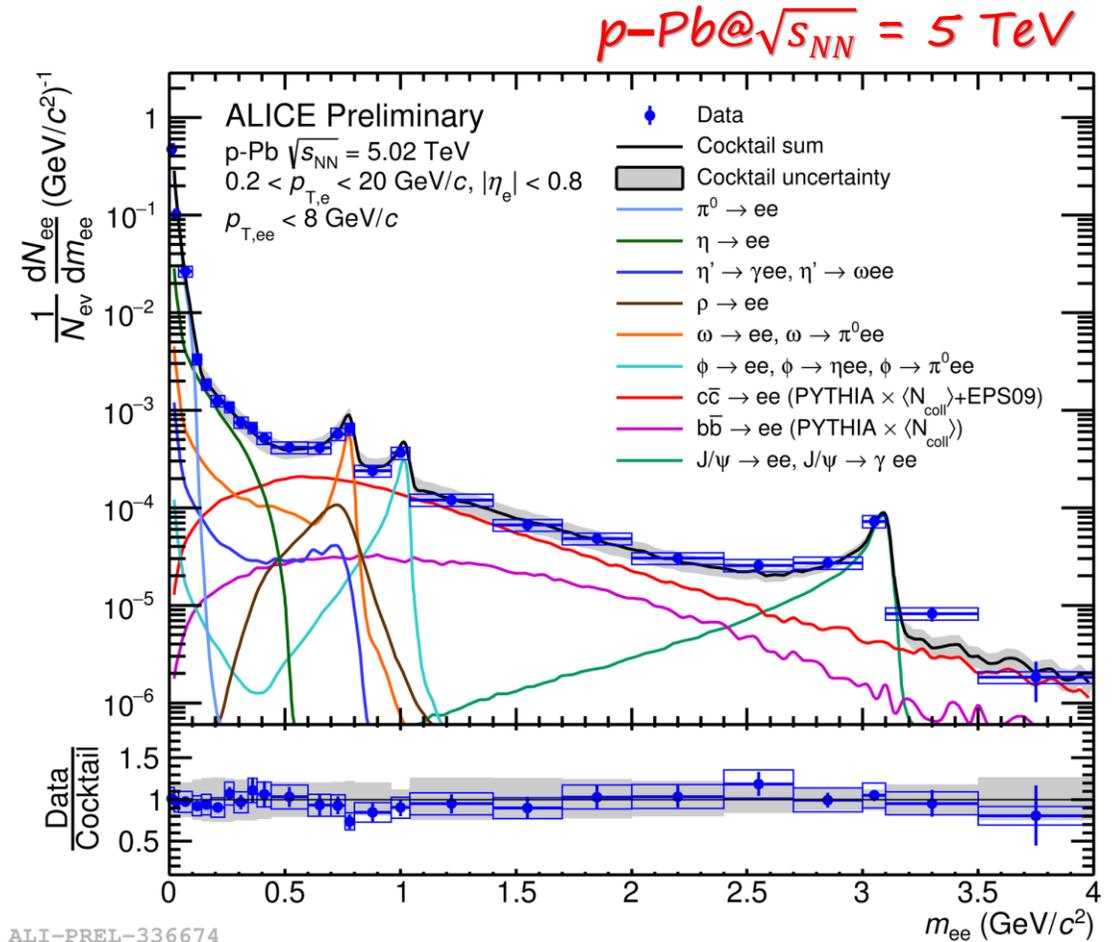
Measurements in p -Pb collisions

- Spectrum in good agreement with cocktail of known hadronic sources
 - Heavy flavour from PYTHIA or POWHEG (backup) based on N_{coll} scaled measured σ_{bb} and σ_{cc} at 7 TeV



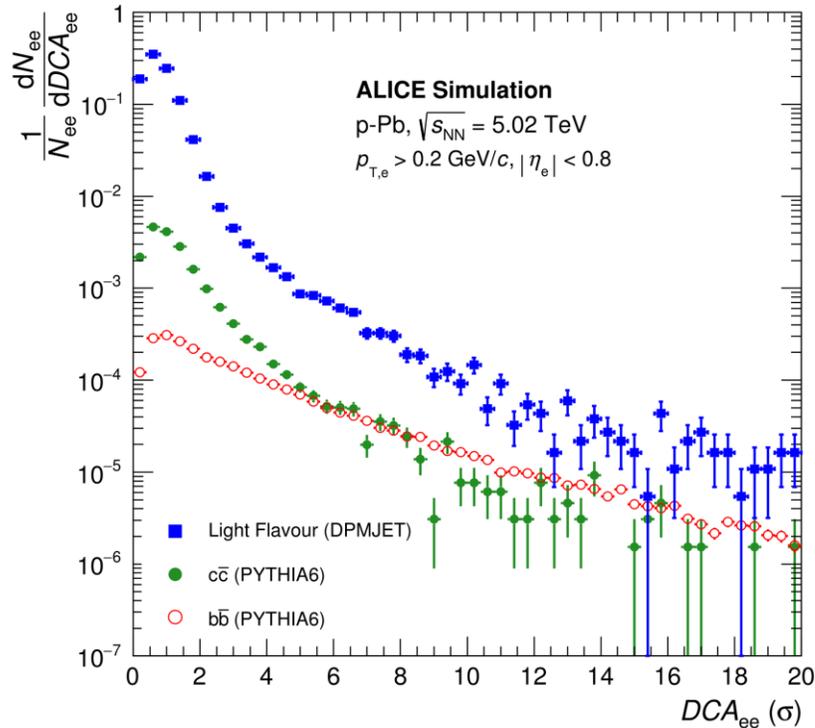
Measurements in p-Pb collisions

- Spectrum in good agreement with cocktail of known hadronic sources
 - Heavy flavour from PYTHIA or POWHEG (backup) based on N_{coll} scaled measured σ_{bb} and σ_{cc} at 7 TeV
- Current precision doesn't allow for conclusions on potential cold nuclear matter effects (PYTHIA+EPS09)



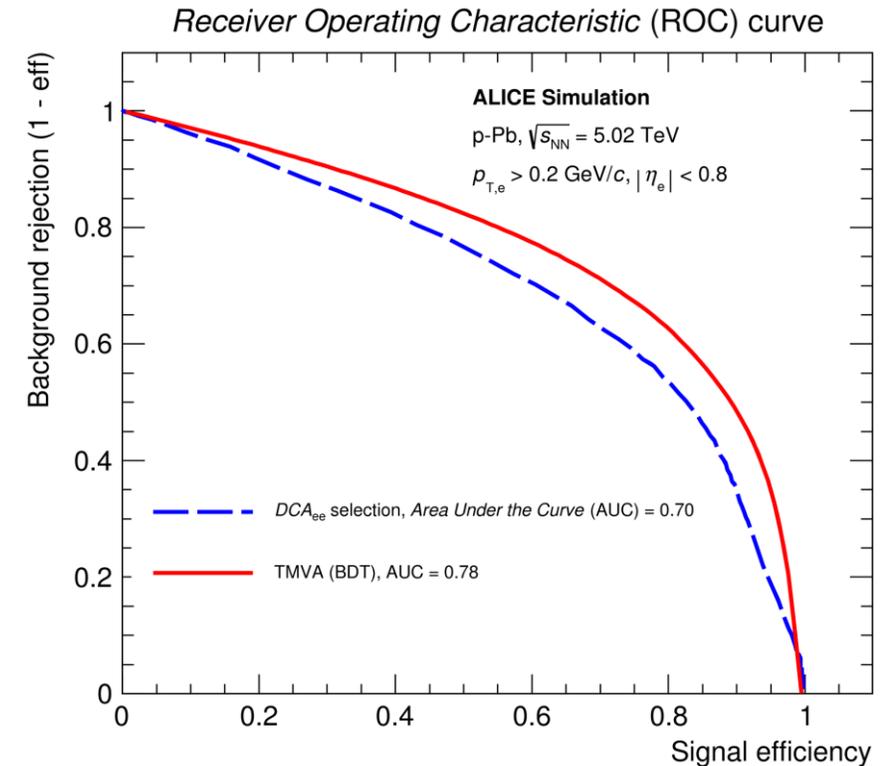
DCA_{ee} (distance of closest approach)

useful variable to discriminate charm and beauty hadron decay electrons from prompt sources (thermal radiation).



ALI-SIMUL-329863

Machine learning approach provides better separation than simple DCA selection

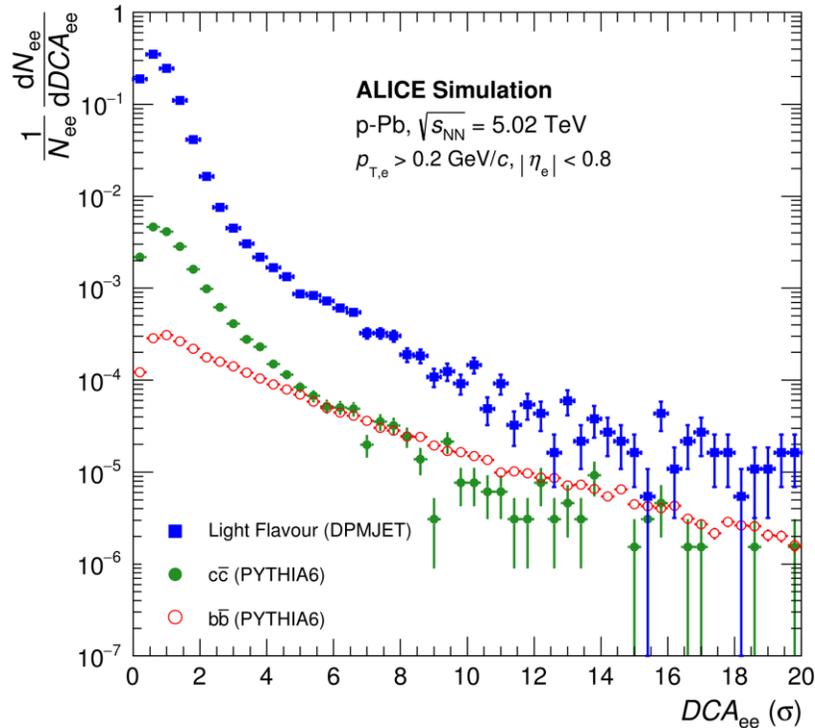


ALI-SIMUL-329874

DCA studies

DCA_{ee} (distance of closest approach)

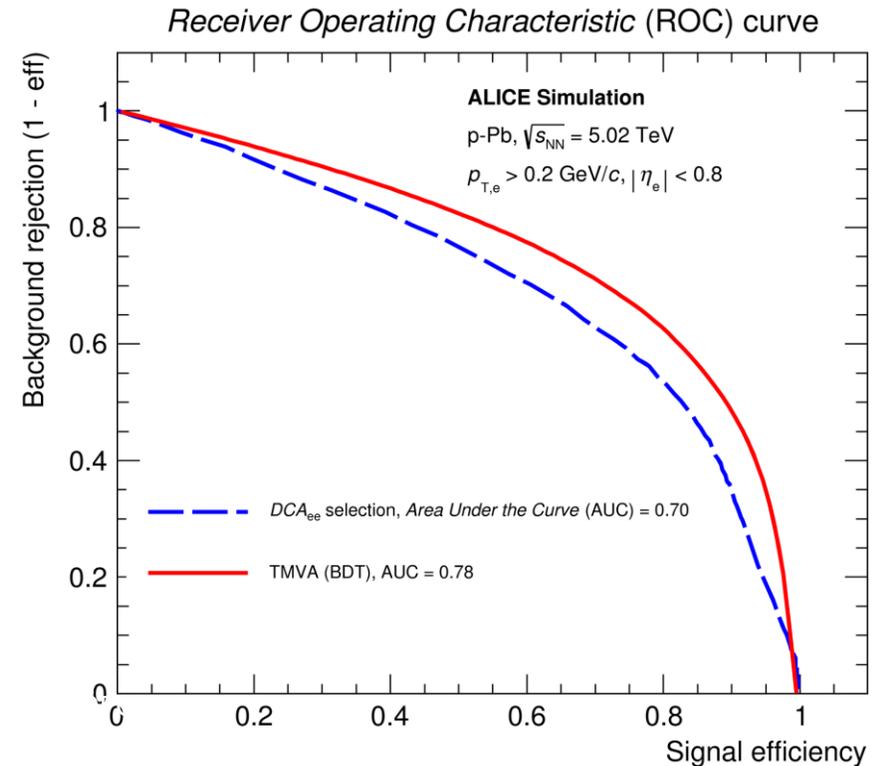
useful variable to discriminate charm and beauty hadron decay electrons from prompt sources (thermal radiation).



ALI-SIMUL-329863

Outlook:
Better DCA_{ee} resolution expected in Run 3
→ better separation of prompt and non-prompt sources

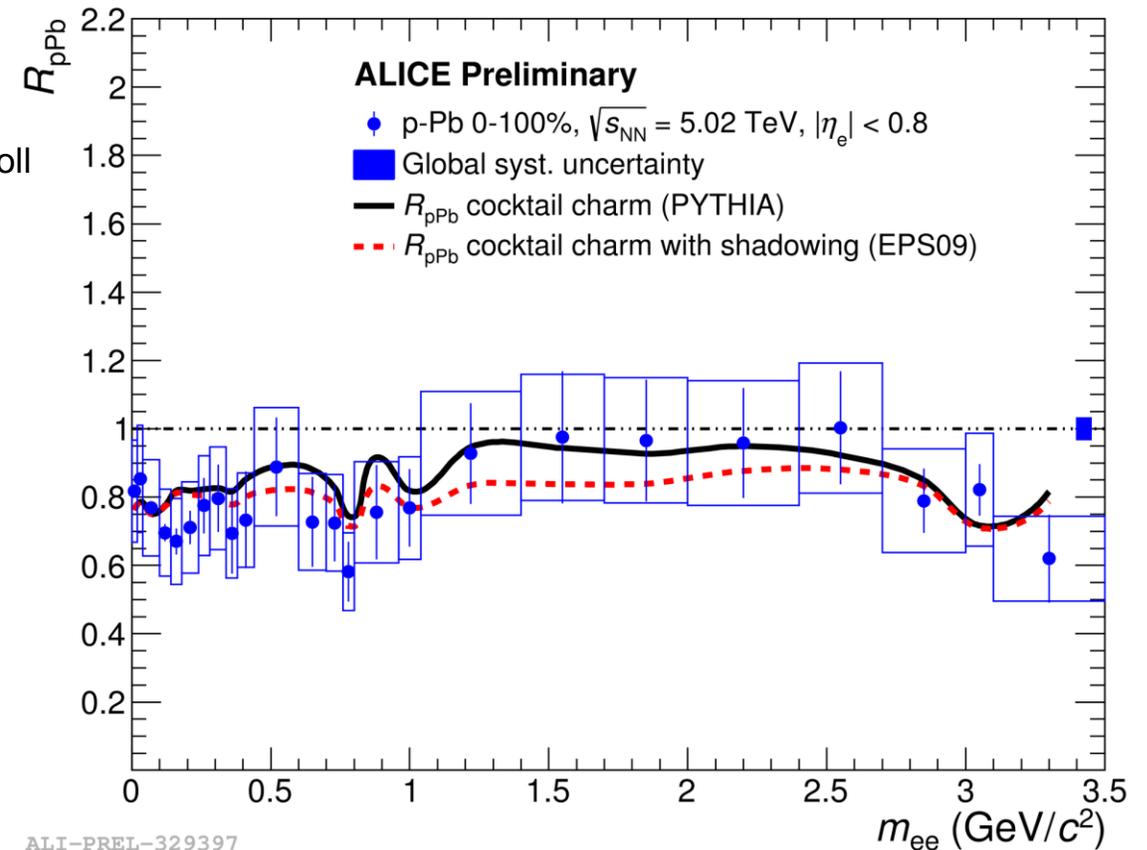
Machine learning approach provides better separation than simple DCA selection



ALI-SIMUL-329874

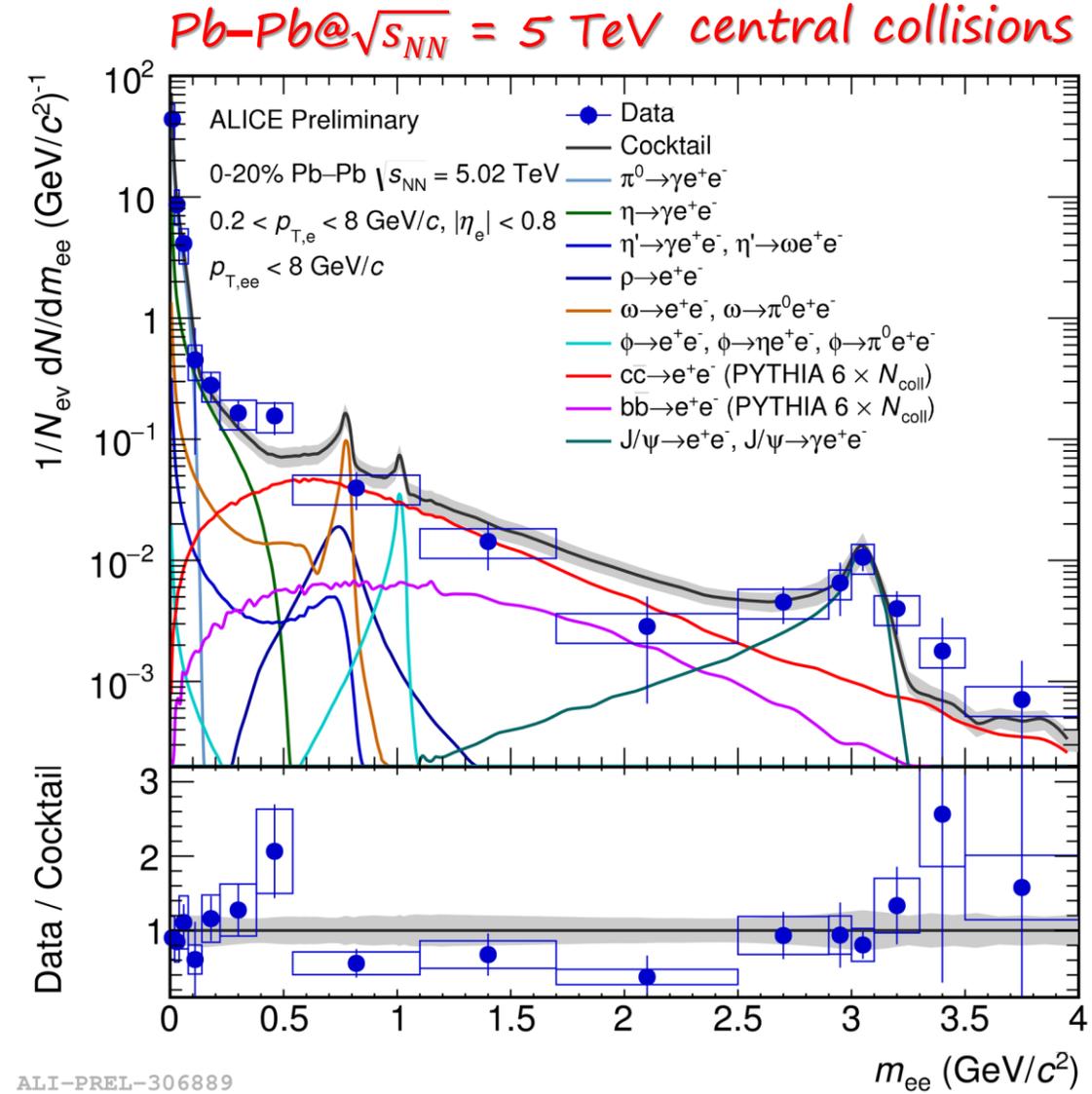
$$R_{pPb} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN/dm_{ee, pPb}}{dN/dm_{ee, pp}}$$

- Deviation from unity for $m_{ee} < 1 \text{ GeV}/c^2$
 - Expected since LF source don't scale with N_{coll}
- Compatible with unity in the IMR
 - Compatible with for D-meson R_{pPb}
- Comparison to models including only scaling effects or nuclear shadowing (EPS09)
 - Data compatible with both models within uncertainties
 - Data central points closer to EPS09 for $m_{ee} < 1 \text{ GeV}/c^2$



Measurements in Pb-Pb

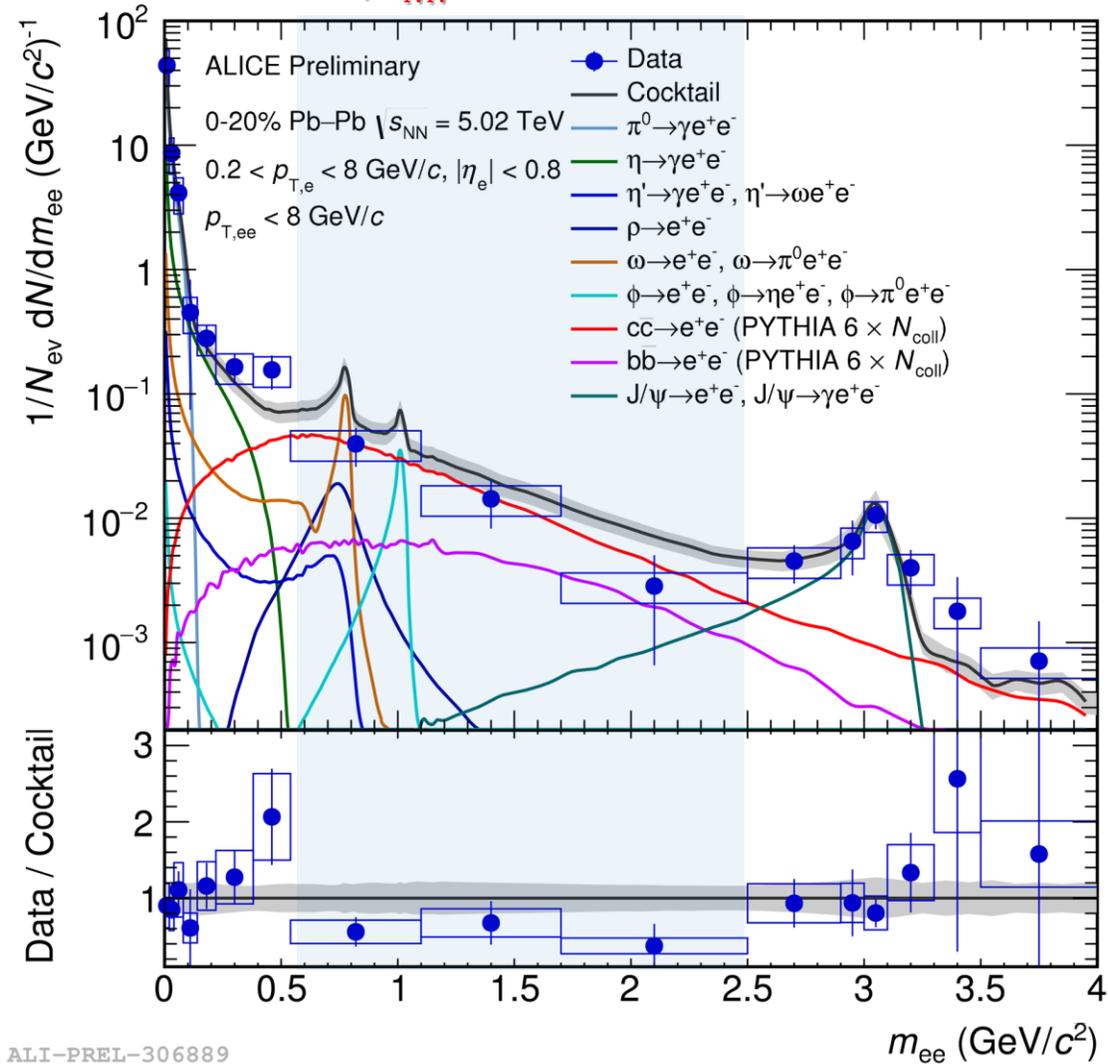
- HF: PYTHIA6 N_{coll} scaling



Measurements in Pb-Pb

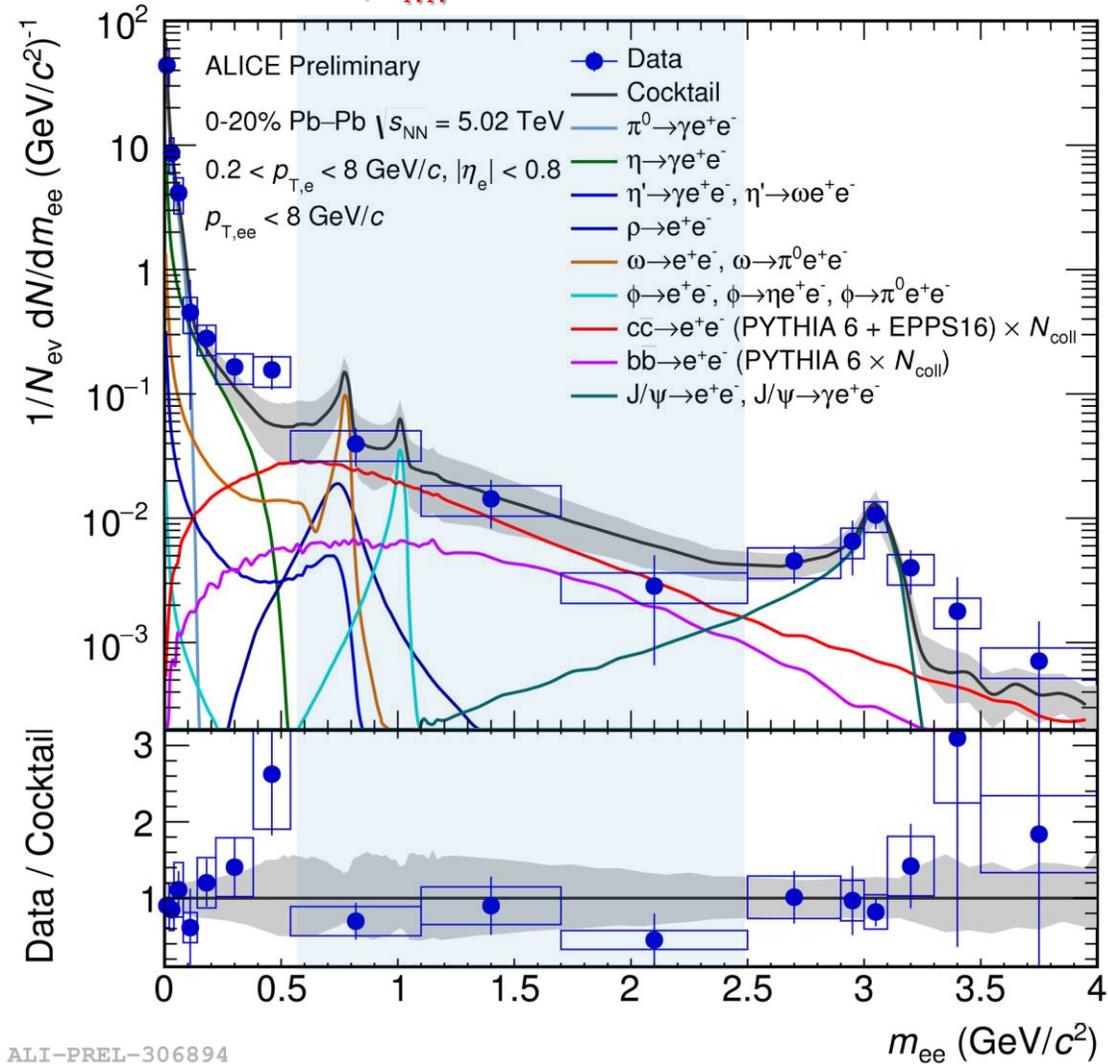
Pb-Pb@ $\sqrt{s_{NN}} = 5$ TeV central collisions

- HF: PYTHIA6 N_{coll} scaling
- Discrepancy with cocktail for m_{ee} in **0.5 – 2.5 GeV/c²**
 - Suppression observed in HF region



Pb-Pb@ $\sqrt{s_{NN}} = 5$ TeV central collisions

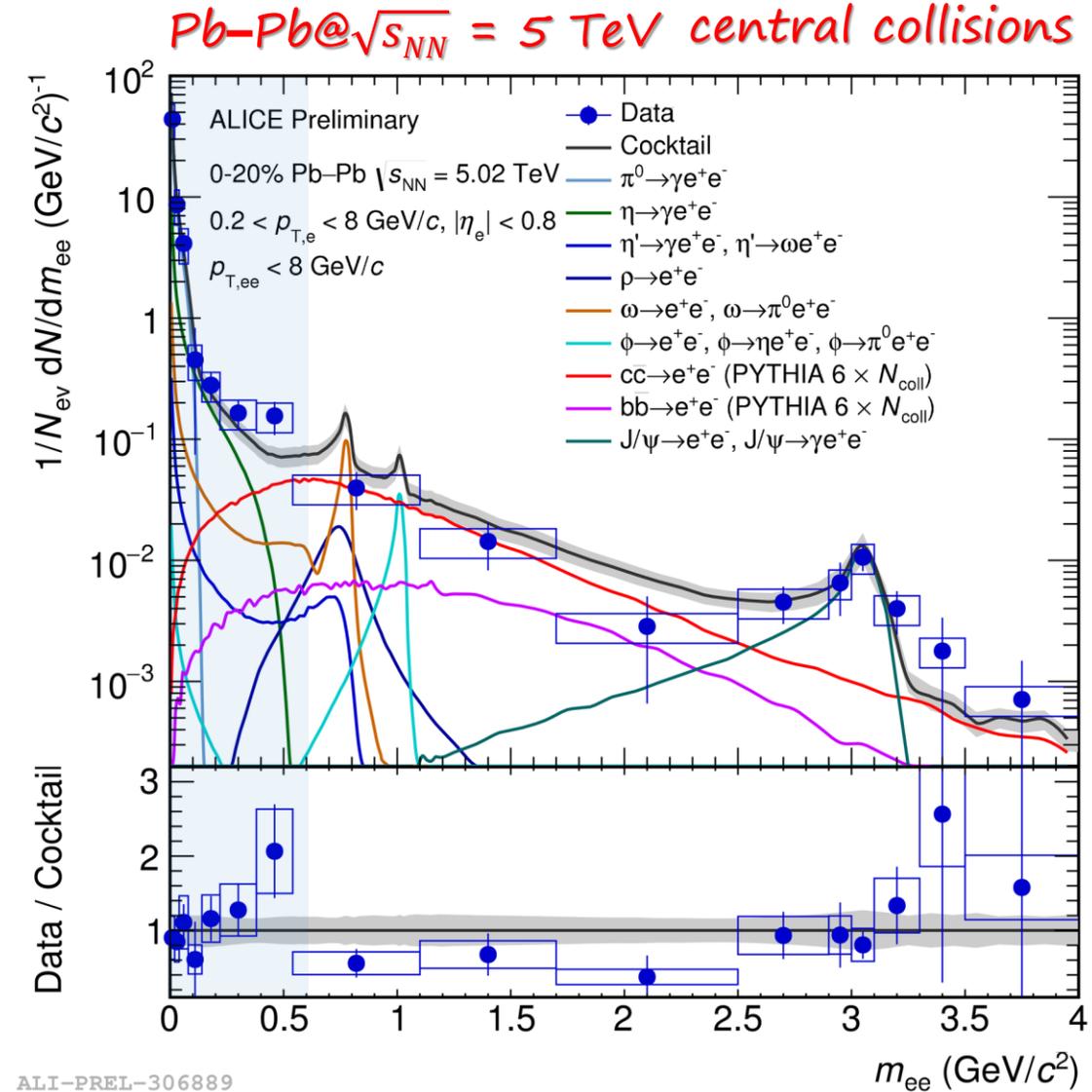
- HF: PYTHIA6 N_{coll} scaling
- Discrepancy with cocktail for m_{ee} in **0.5 – 2.5 GeV/c²**
 - Suppression observed in HF region
- Discrepancy reduced when nPDF included



ALI-PREL-306894

Measurements in Pb-Pb

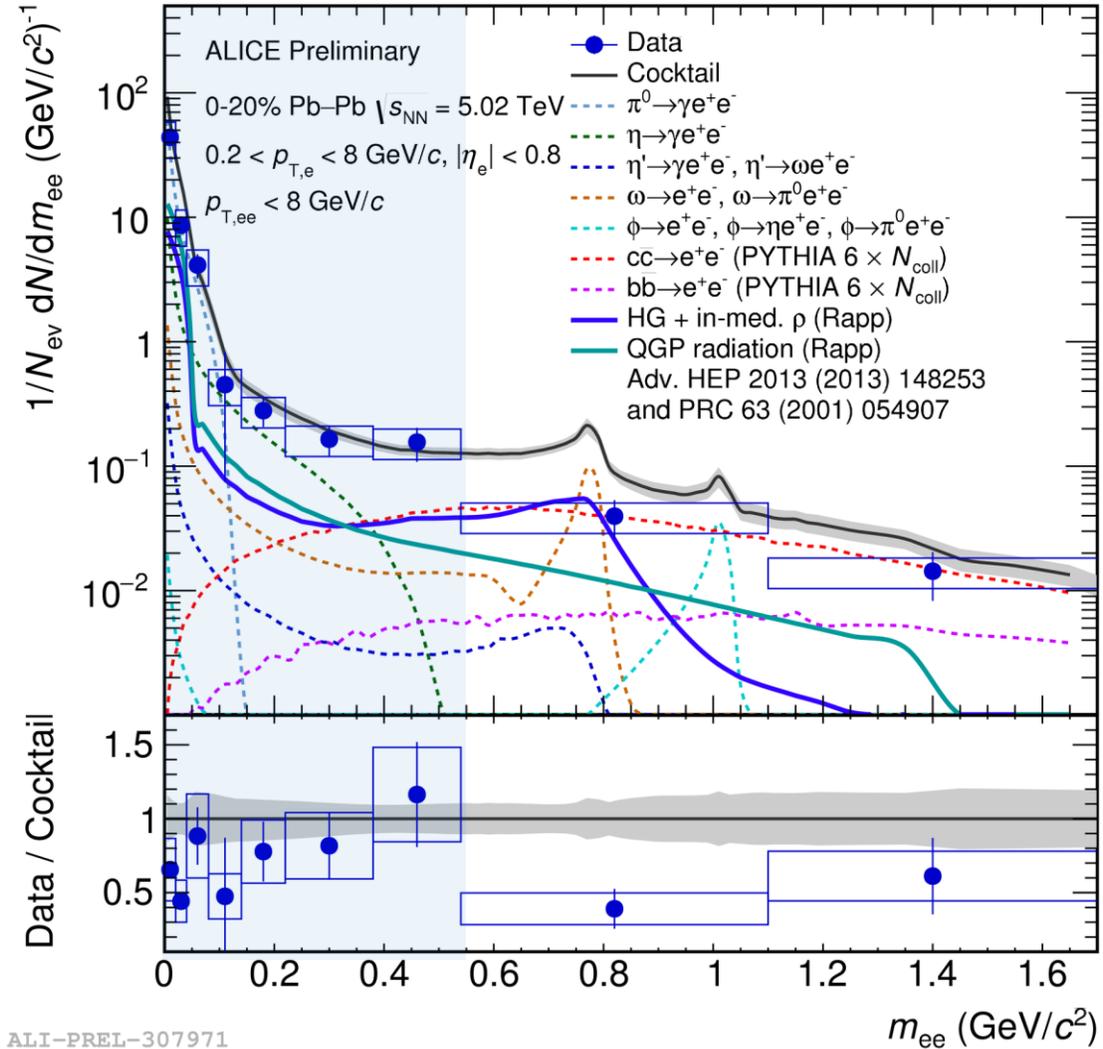
- HF: PYTHIA6 N_{coll} scaling
- Hint for enhancement at **low m_{ee}** ?



Measurements in Pb-Pb

- HF: PYTHIA6 N_{coll} scaling
- Hint for enhancement at **low m_{ee}** ?
 - Compatible with thermal radiation models

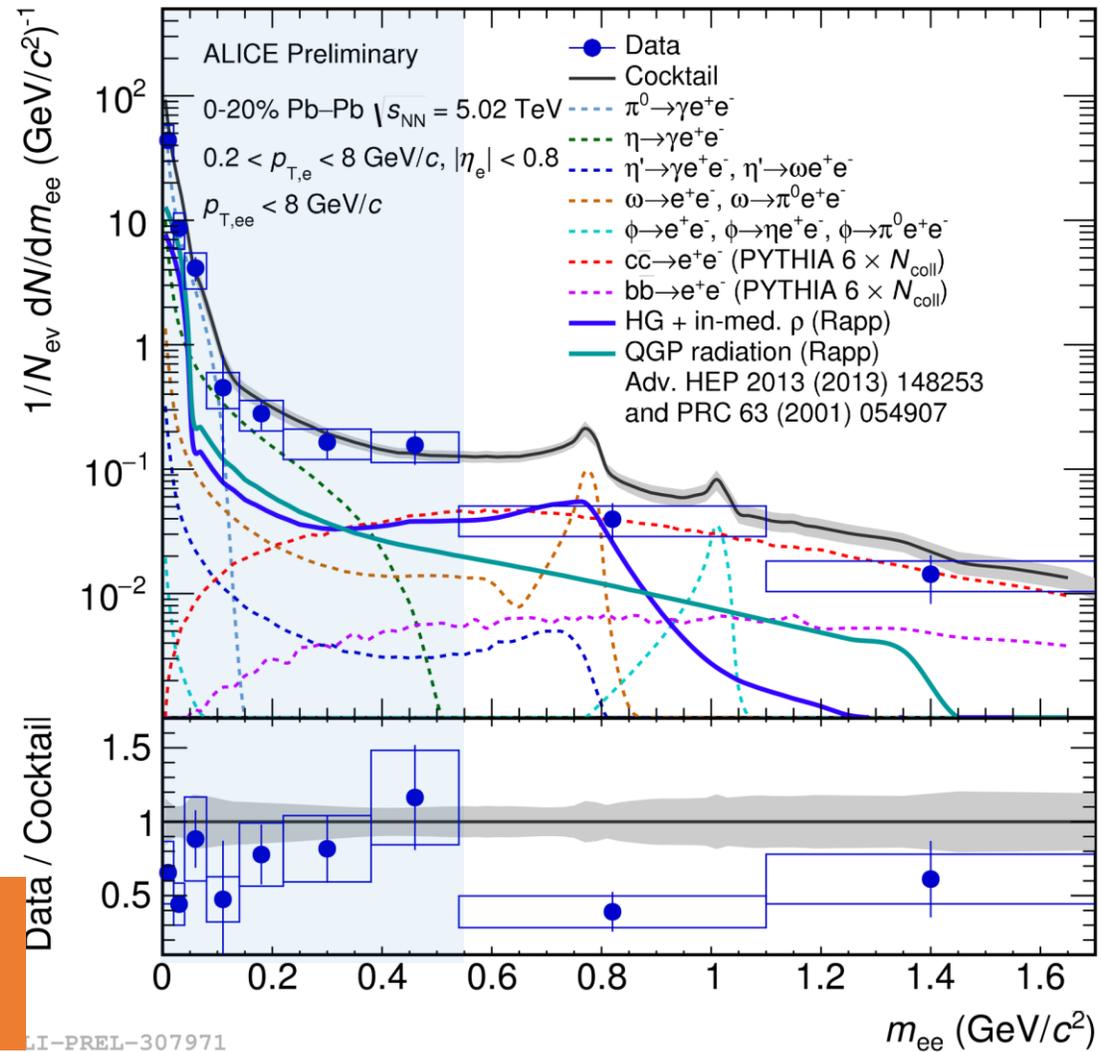
Pb-Pb@ $\sqrt{s_{NN}} = 5$ TeV central collisions



Measurements in Pb-Pb

- HF: PYTHIA6 N_{coll} scaling
- Hint for enhancement at **low m_{ee}** ?
 - Compatible with thermal radiation models

Pb-Pb@ $\sqrt{s_{NN}} = 5$ TeV central collisions



Outlook:
 Analysis of 2018 Pb-Pb data (**9 times more data in 0-10% centrality**) is ongoing!

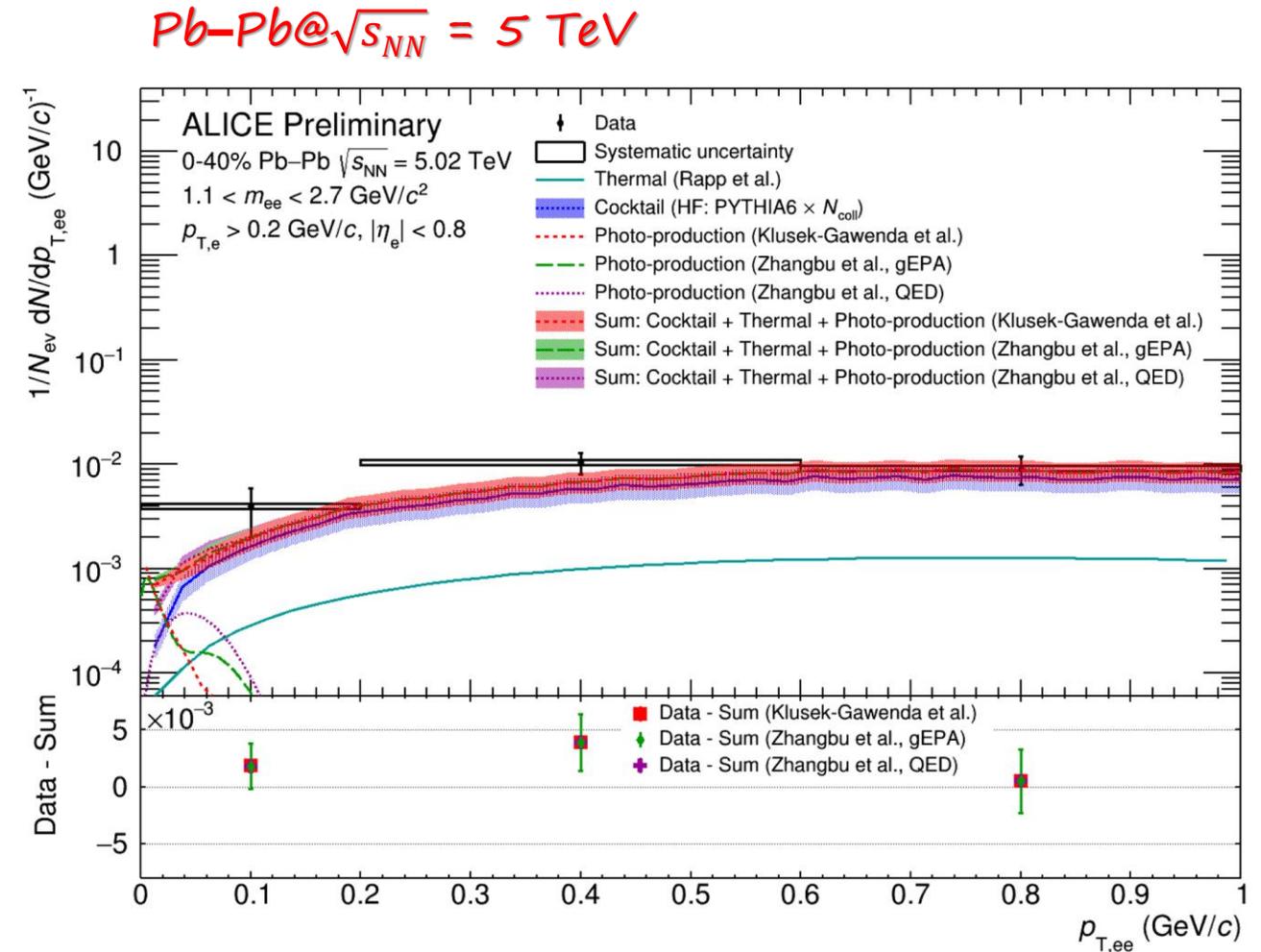
ALICE-PREL-307971

Low p_T analysis in Pb-Pb

Photo-Production in Pb-Pb

- Analysis performed in the mass range dominated by HF, $1.1 < m_{ee} < 2.7 \text{ GeV}/c^2$

- No significant discrepancy observed in **0-40% centrality**



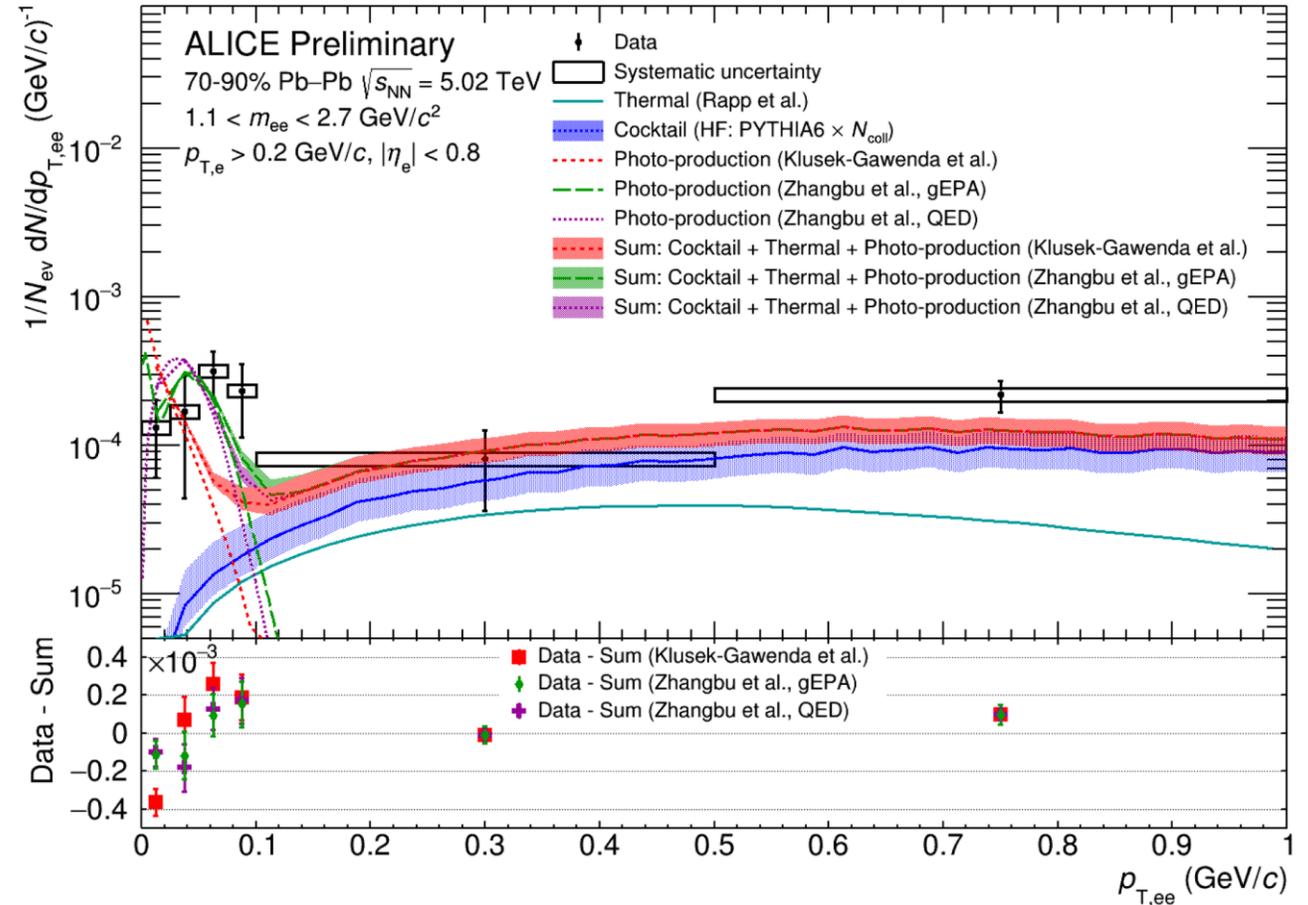
ALI-PREL-326038

Low p_T analysis in Pb-Pb

Photo-Production in Pb-Pb

- Analysis performed in the mass range dominated by HF, $1.1 < m_{ee} < 2.7 \text{ GeV}/c^2$
- Centrality **class 70-90%** more sensitive to the photo-production than 0-40%
 - Excess w.r.t. cocktail and thermal sources at $p_{T,ee} < 0.1 \text{ GeV}/c$
 - Compatible with photo-production models
 - Excess observed at the same $p_{T,ee}$ range as at STAR STAR, Phys. Rev. Lett. 121. 132301

Pb-Pb@ $\sqrt{s_{NN}} = 5 \text{ TeV}$



ALI-PREL-326033

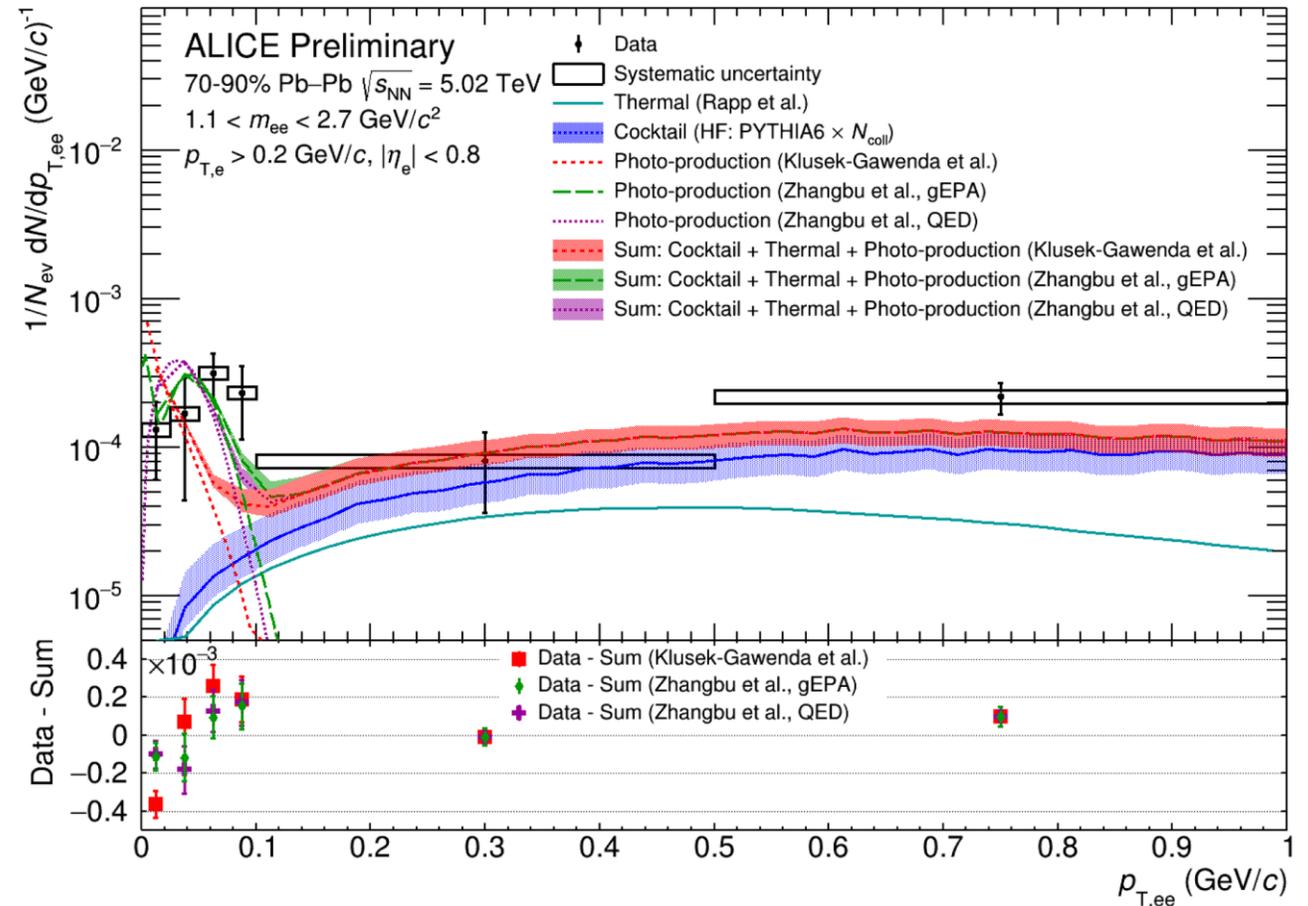
Low p_T analysis in Pb-Pb

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 - Compatible with photo-production models
 - Excess observed at the same $p_{T,ee}$ range as at STAR STAR, Phys. Rev. Lett. 121. 132301

Outlook:
2018 data: **2 times more statistics** in 70-90% centrality!

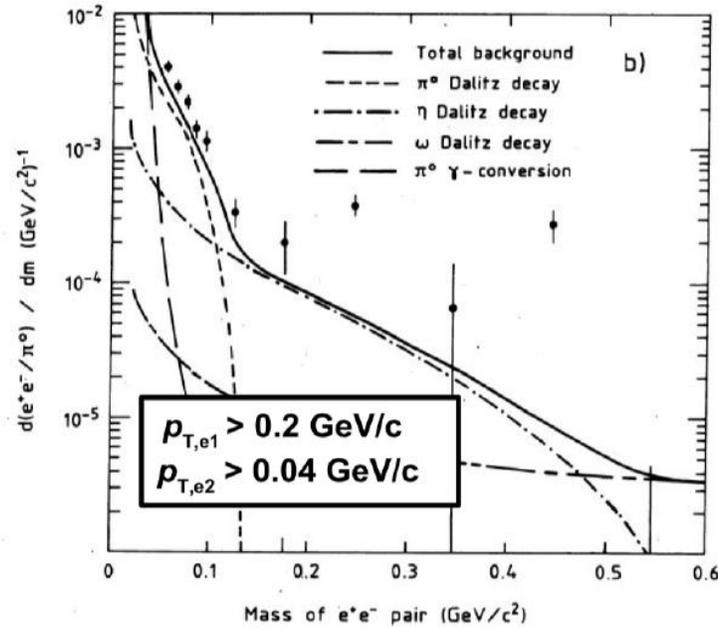
Pb-Pb@ $\sqrt{s_{NN}} = 5 \text{ TeV}$



ALI-PREL-326033

Soft dielectrons in in pp 13 TeV

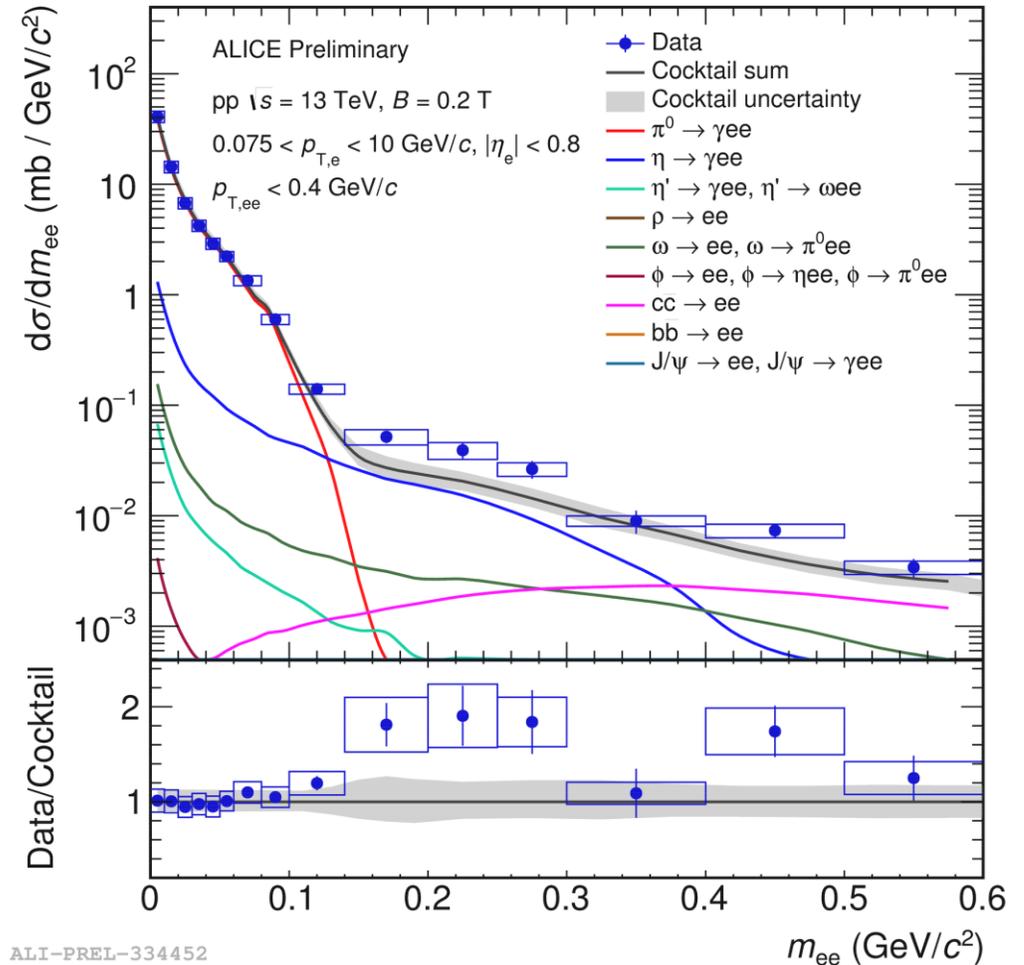
V. Hedberg, PhD Thesis, Lund University (1987)



- Low-mass region (LMR) excess:
- Not explainable with contribution of known hadronic decays

See talk by
H. Appelshaeuser

pp@ $\sqrt{s} = 13 \text{ TeV}$



ALI-PREL-334452

Future dilepton measurements

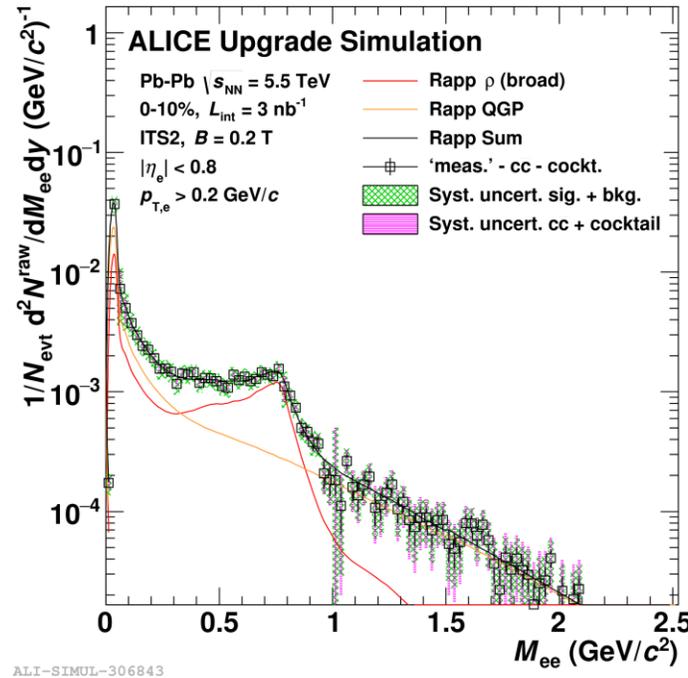


ALICE

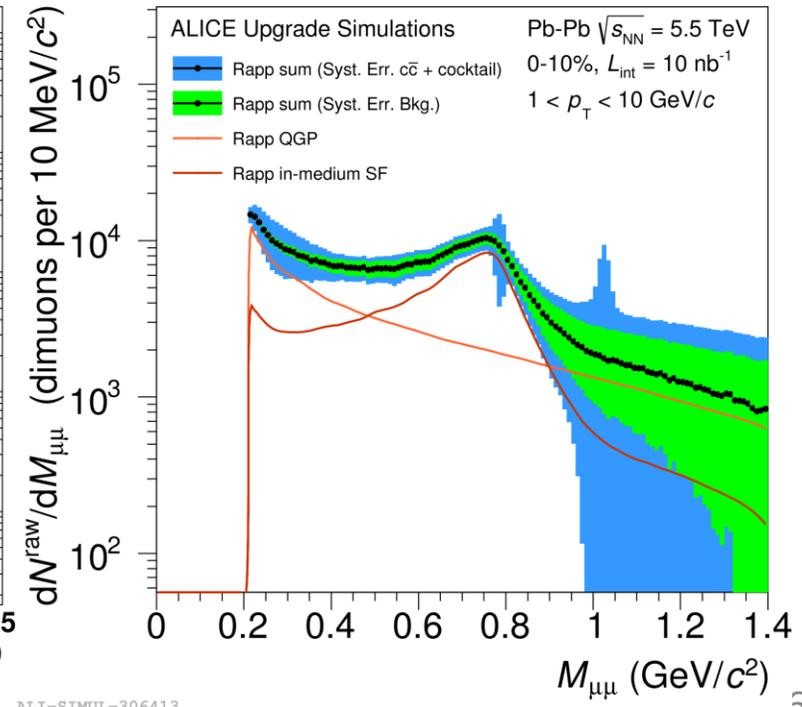
- Upgrade of ITS and TPC: improved vertex resolution, reduced material budget, higher acquisition rate, dedicated Pb-Pb run with low B field configuration
 - Better separation of prompt sources (thermal radiation) from HF electrons, via DCA studies
- New Muon Forward Tracker (MFT)
 - Adding vertexing capability to the ALICE muon spectrometer
 - Better dimuon mass resolution, reduced background
- Sensitivity to in-medium modified ρ spectral function

CERN-LPCC-2018-07 (arXiv:1812.06772)

See talk by
H. Appelshaeuser



ALI-SIMUL-306843



ALI-SIMUL-306413

Summary



Dielectron measurements in pp, p–Pb and Pb–Pb collisions

pp

- Model dependence of heavy-flavour production
- First measurement of charm and beauty cross section in pp collisions at $\sqrt{s} = 5.02$ TeV
- Low-mass region (LMR) excess in pp collisions at $\sqrt{s} = 13$ TeV

p–Pb

- No significant modification of heavy-flavour production in IMR
- Hint of $R_{pPb} < 1$ for smaller masses

Pb–Pb

- Possible excess from thermal radiation ~ 0.5 GeV/ c^2
- Suppression of heavy flavour from final state effects
- Centrality class 70-90% sensitive to photo-production

Summary



Dimuon measurements in pp, p–Pb and Pb–Pb collisions

- Double-differential study of ϕ meson production vs p_T and rapidity in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV:
 - Hardening of the p_T spectra with increasing energy observed
- Clear decrease observed in the ϕR_{AA} for $p_T > 4$ GeV/c in central collisions
- Less pronounced decrease for semi-peripheral collisions
- Results at forward and mid-rapidity compatible within uncertainties
 - Hint for similar mechanisms of interaction with the medium

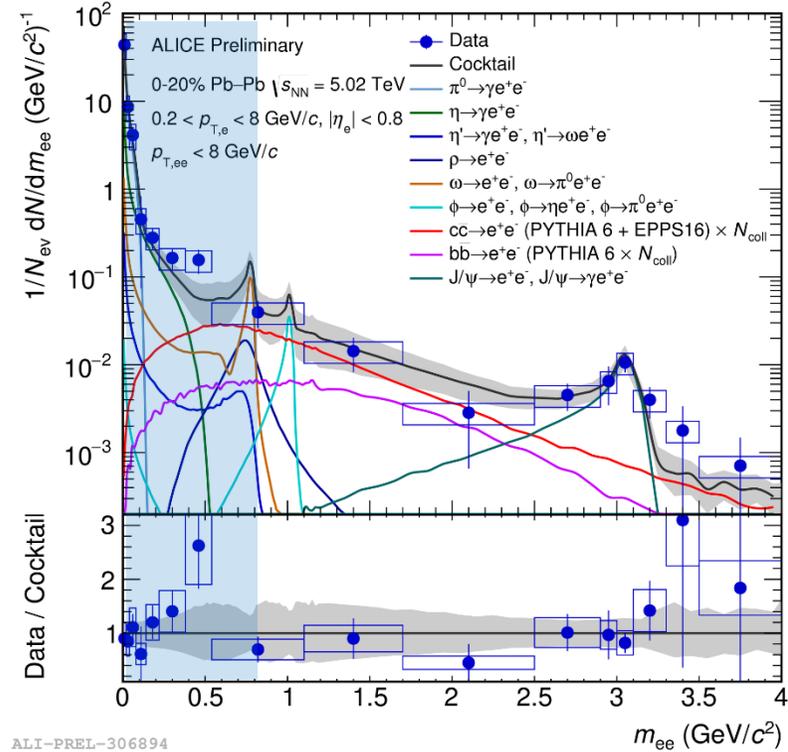
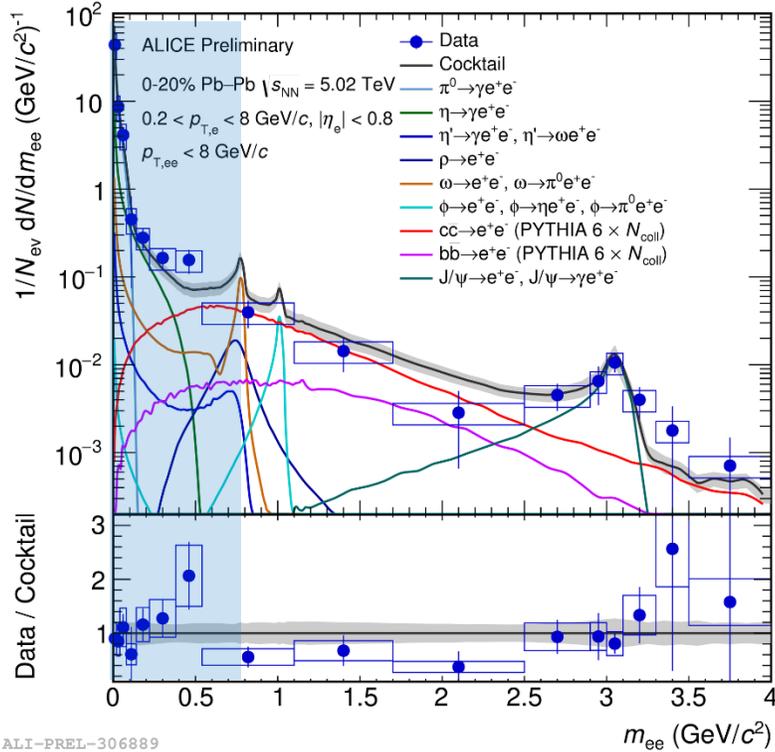
Backup

Measurements in Pb-Pb



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Pb-Pb @ 5.02 TeV



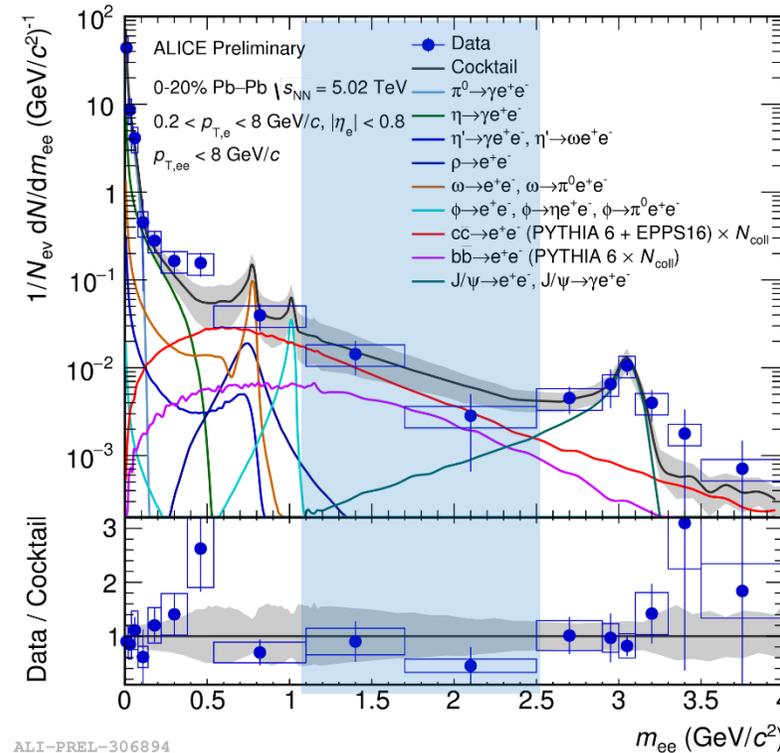
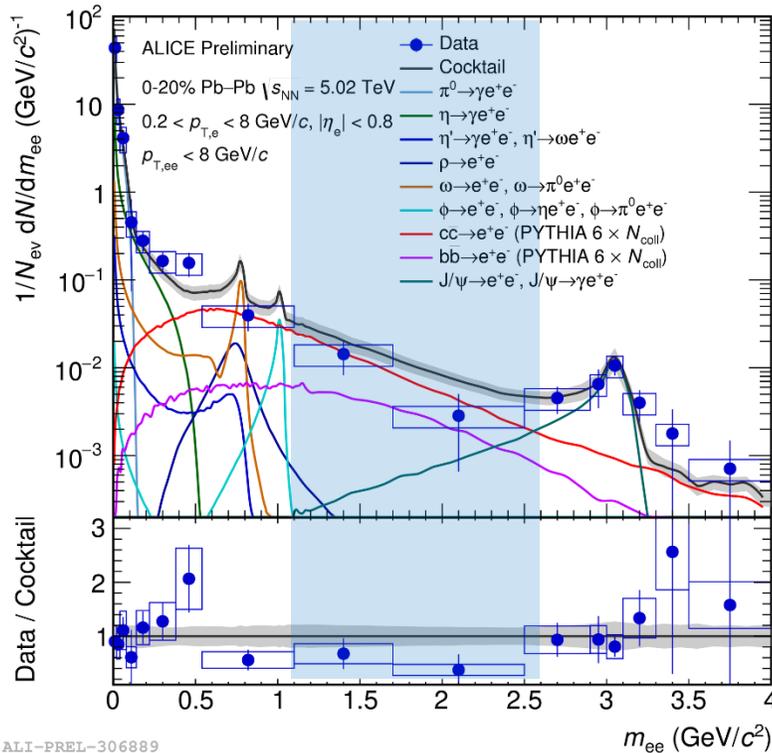
- Data consistent with low-mass enhancement (in $0.15 < m_{ee} < 0.7 \text{ GeV}/c^2$)

Measurements in Pb-Pb



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Pb-Pb @ 5.02 TeV



- Data consistent with low-mass enhancement (in $0.15 < m_{ee} < 0.7$ GeV/c²)
- Indication for **charm suppression** in intermediate mass range ($1.1 < m_{ee} < 2.5$ GeV/c²)
 → Better description if cold-nuclear matter effects are taken into account for charm (EPPS16 nPDF)

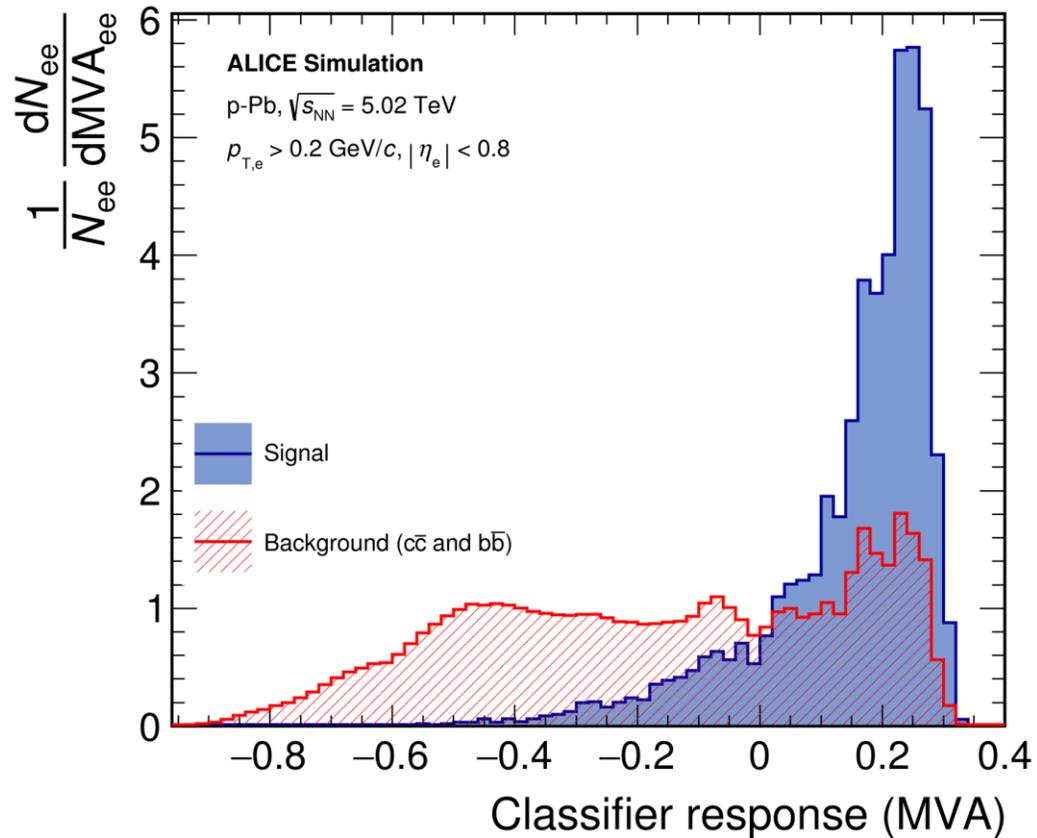
DCA studies in p-Pb collisions

Multivariate HF rejection

Signal → non-combinatorial pairs without conversions and without HF

Background → correlated heavy flavour pairs

Input variables:
 $DCA_{xy}[\sigma]$, $DCA_z[\sigma]$



ALI-SIMUL-329881

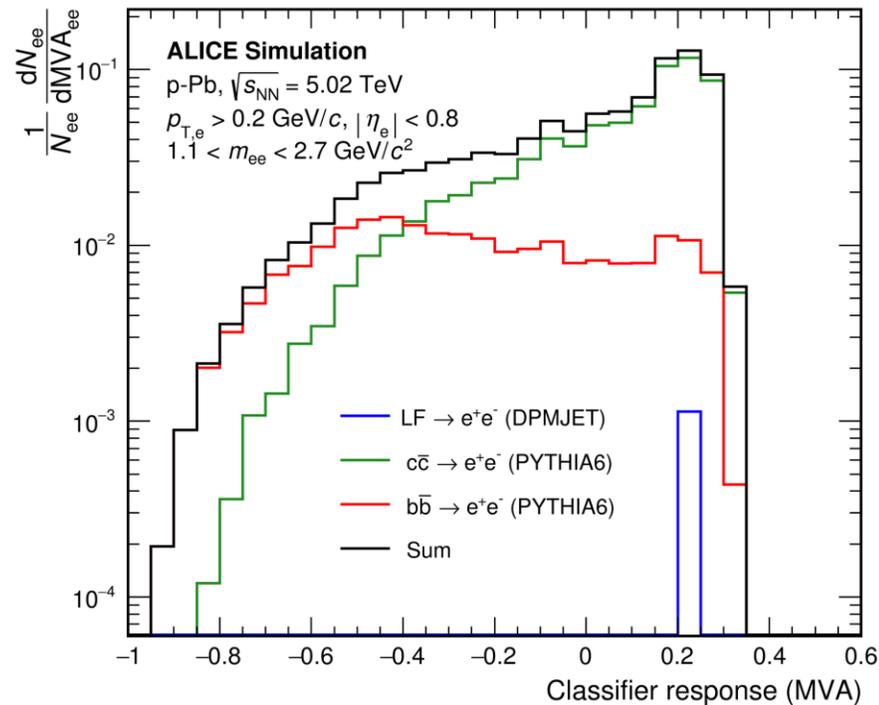
DCA studies in p-Pb collisions



Multivariate HF rejection

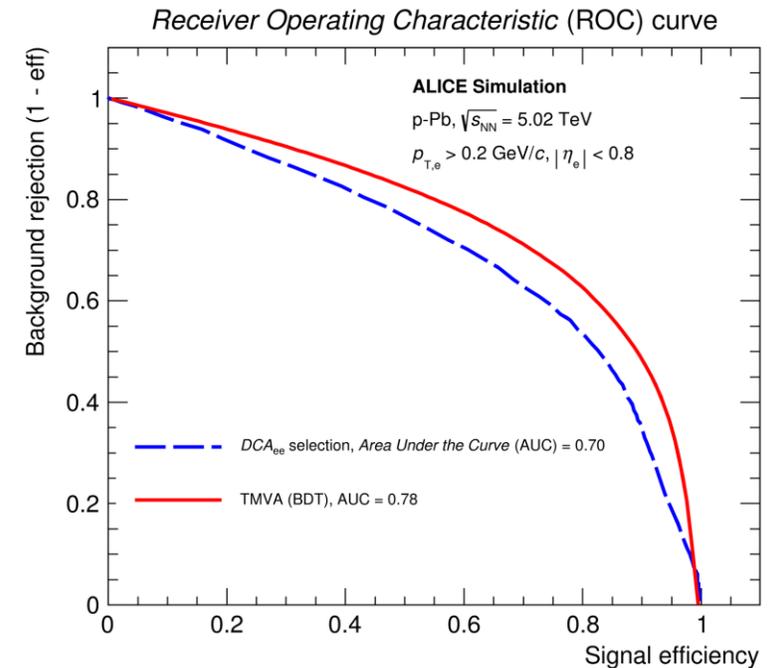
Signal \rightarrow non-combinatorial pairs without conversions and without HF

Bakground \rightarrow correlated heavy flavour pairs



ALI-SIMUL-329908

ROC curve

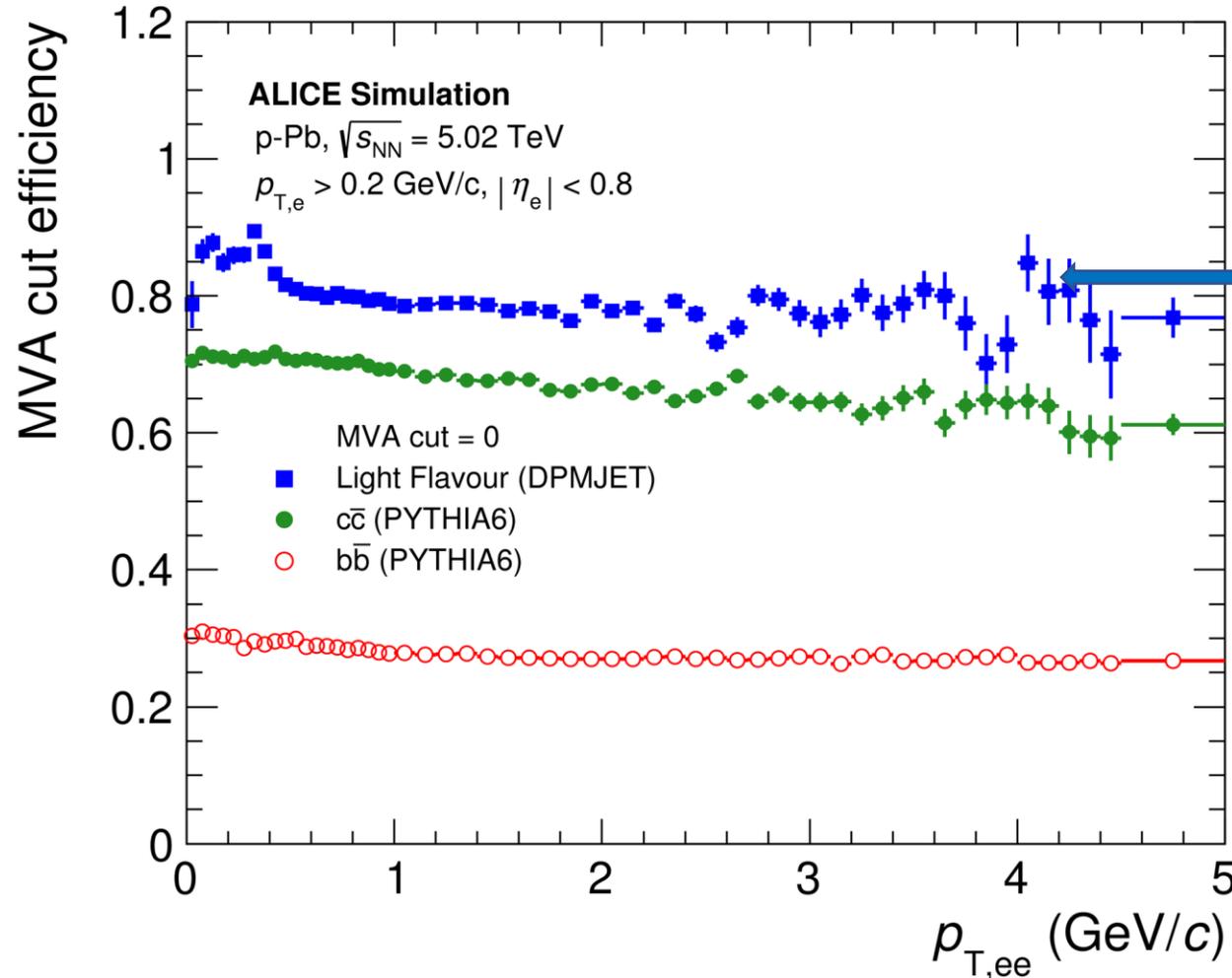


ALI-SIMUL-329874

Efficiencies



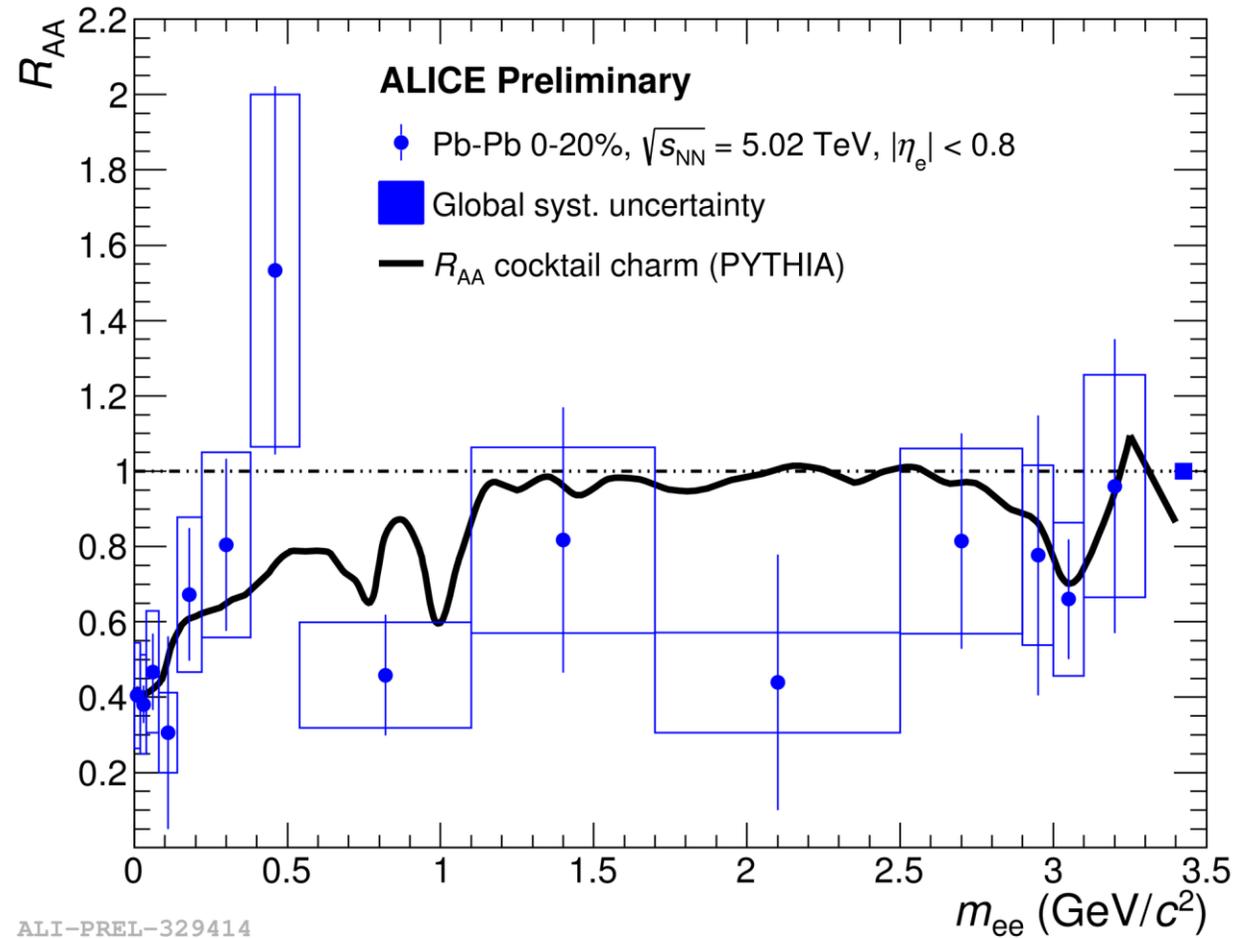
- Cut on classifier output via maximisation of $\text{significance} = \frac{\text{signal}}{\sqrt{\text{signal} + \text{background}}}$



Very flat signal efficiency!

ALI-SIMUL-329870

- Hint of suppression in the IMR, although very big uncertainties
 - possible final state effects?
 - medium effects not included in model calculations, compatible with unity
- Hint of enhancement in low mass region



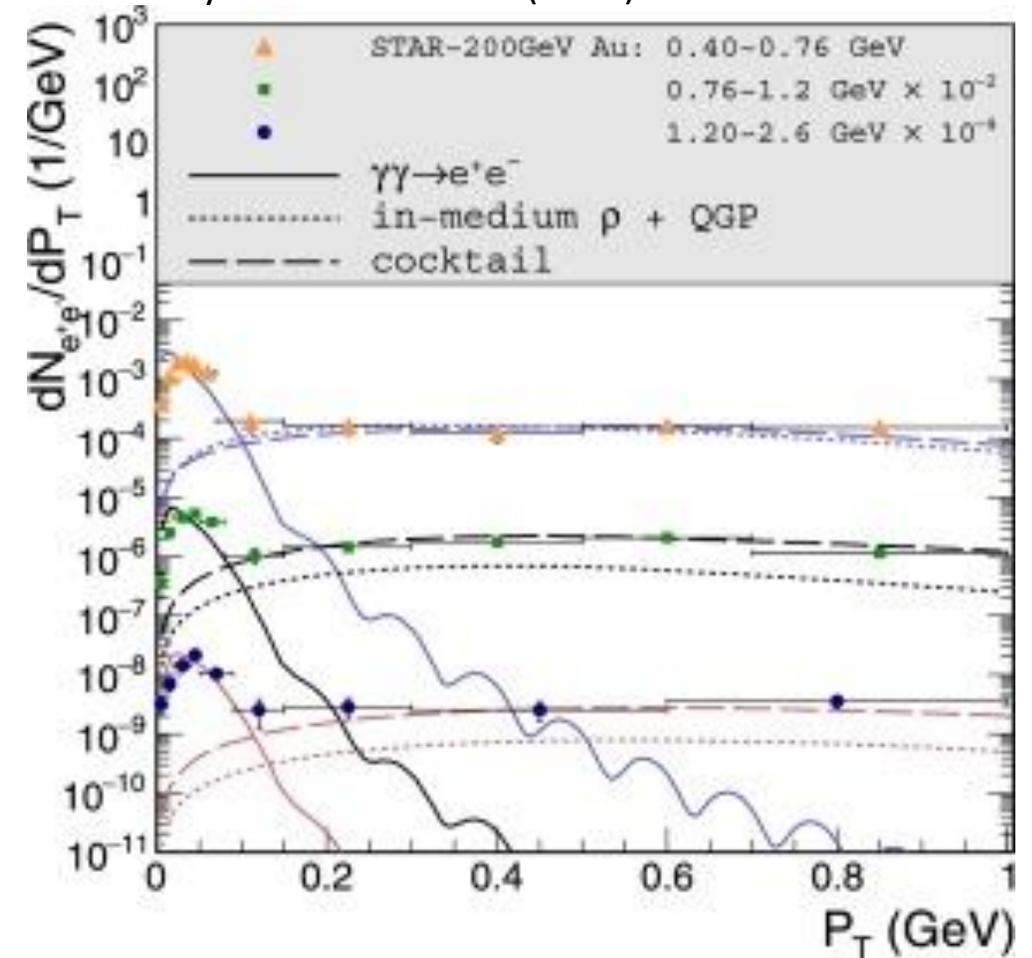
Dilepton mass spectrum



ALICE

- Dielectron p_T spectra measured by STAR in UPC in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- Compared with calculated pair- p_T spectra for coherent $\gamma\gamma$ interactions, thermal radiation and hadronic cocktail
 - **$\gamma\gamma$ fusion clearly dominates at very low p_T**

Physics Letters B 790 (2019) 339–344



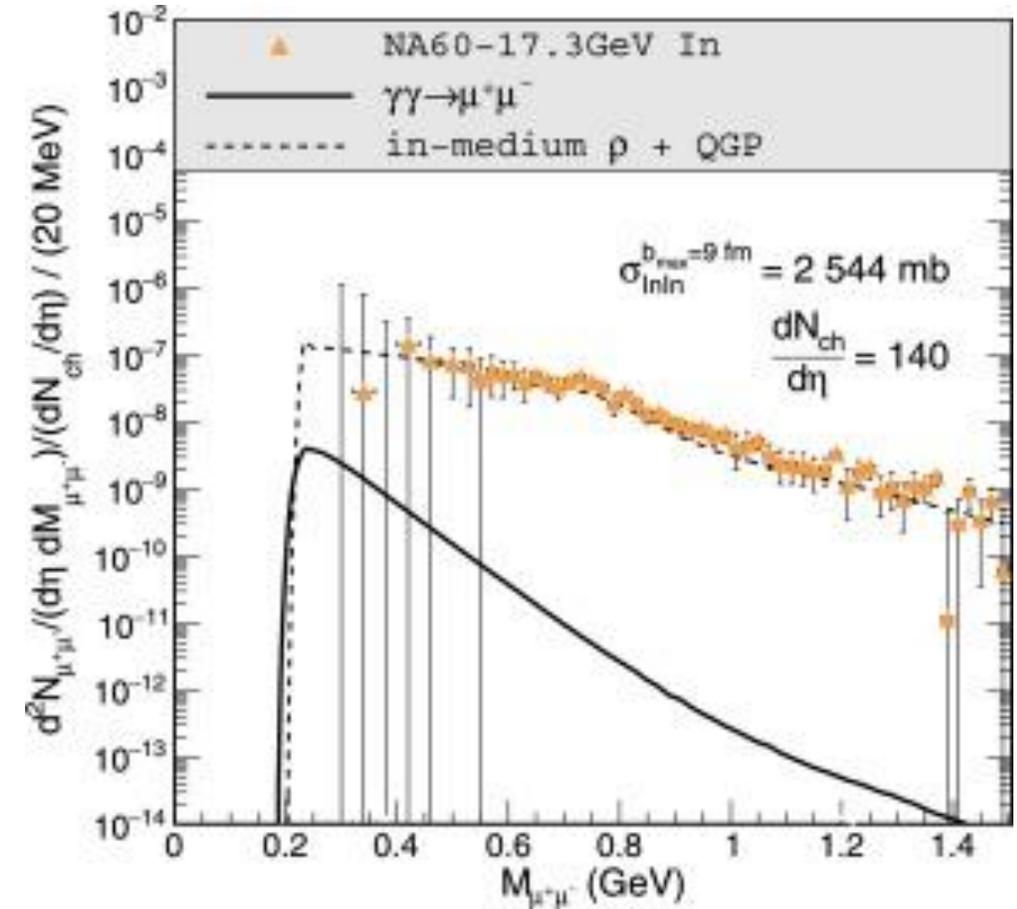
Dilepton mass spectrum



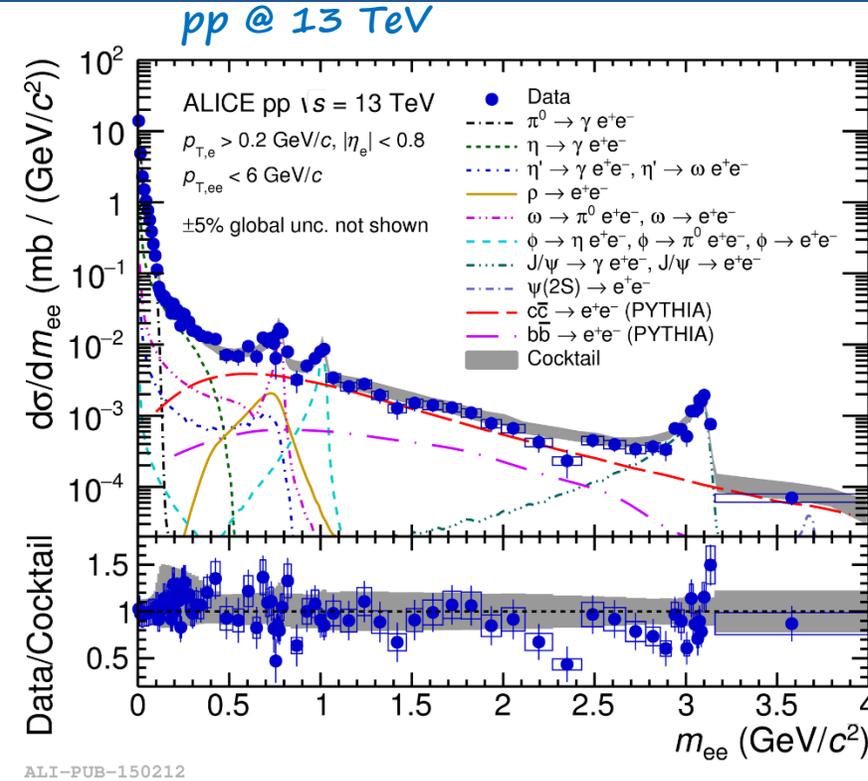
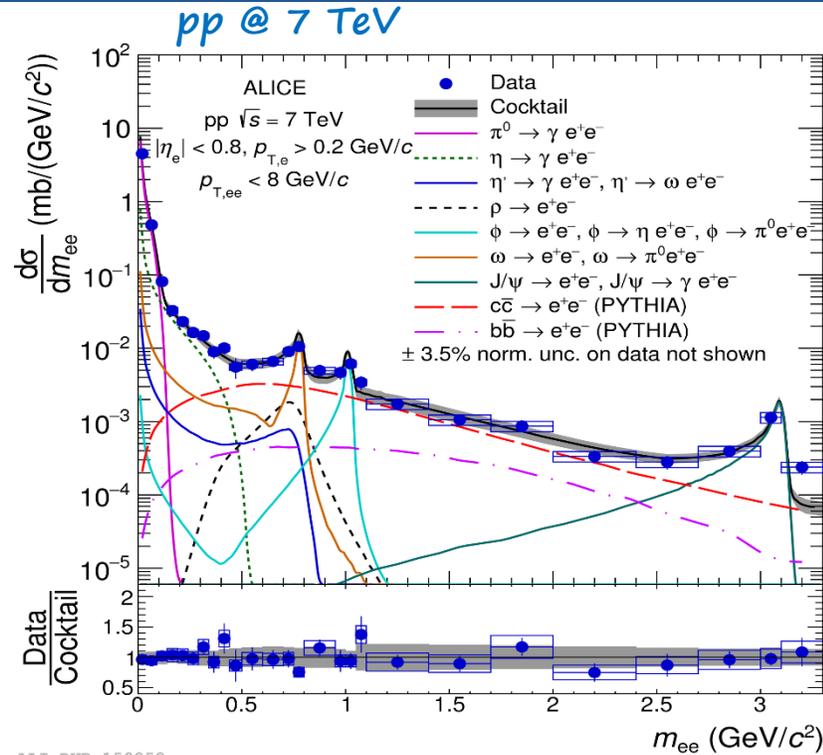
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Physics Letters B 790 (2019) 339–344

- Dimuon invariant mass spectra measured by NA60 experiment at SPS in In-In collisions at $\sqrt{s_{NN}} = 17.3$ GeV
- Compared with calculated pair- p_T spectra for coherent $\gamma\gamma$ interaction and thermal radiation and hadronic cocktail
 - Secondary role played by coherent photo production, at lower energies than STAR



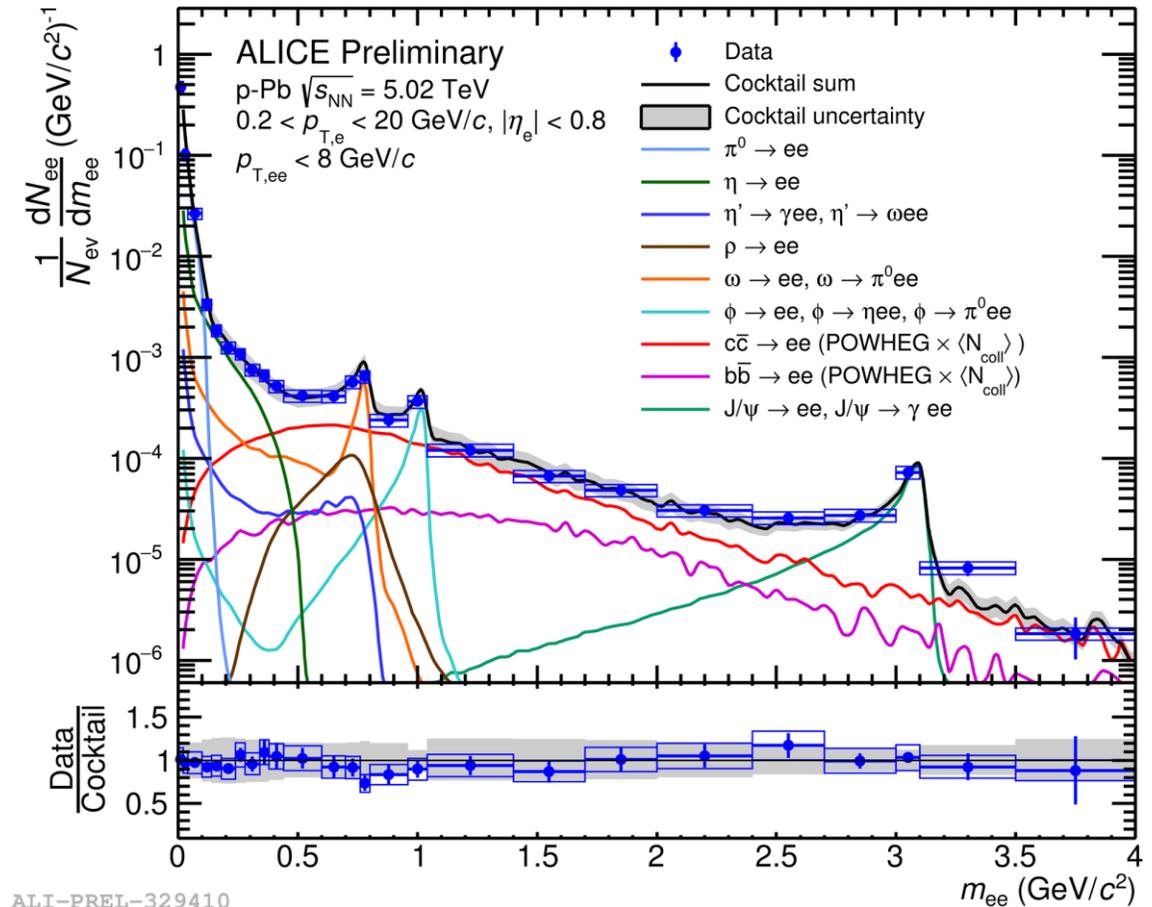
pp reference measurements @ $\sqrt{s} = 7$ TeV and 13 TeV



- Spectrum compared with cocktail of known hadronic sources
 - Data described by cocktail within uncertainties
- Dielectron production well understood for $p_{T,e} > 0.2$ GeV/c
- Heavy-flavour contributions dominate for $m_{ee} > 1.1$ GeV/c²
- Complementary (w.r.t. heavy-flavour hadron measurements) σ_{bb} and σ_{cc} measurements

Measurements in p -Pb collisions

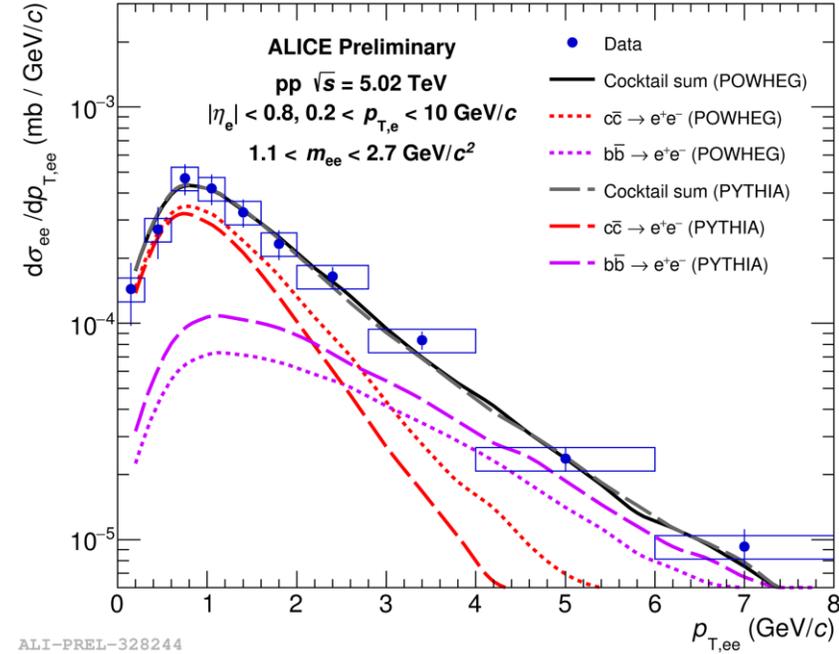
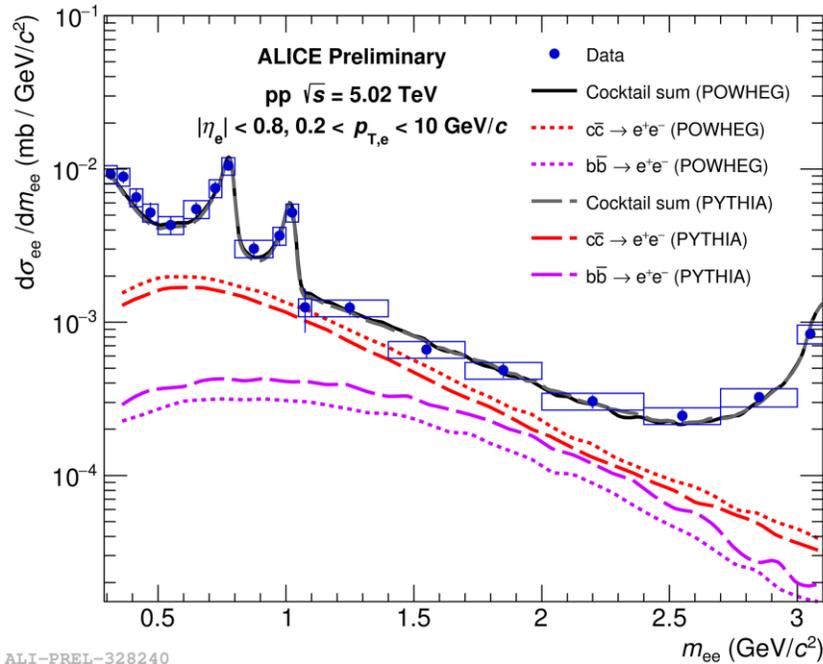
- Spectrum compared with cocktail of known hadronic sources
 - Light flavour from parametrized measurements and particle ratios from PYTHIA
 - Heavy flavor from POWHEG or PYTHIA, based on measured σ_{bb} and σ_{cc} at 7 TeV, extrapolated to 5 TeV with FONLL
 - Systematic uncertainties on cocktail limit the interpretation of results



ALI-PREL-329410

Dielectron measurements in pp collisions

- Distinct shape of charm and beauty in m_{ee} , $p_{T,ee}$, and DCA_{ee} can be used to fit cross sections



pp@√s = 5 TeV

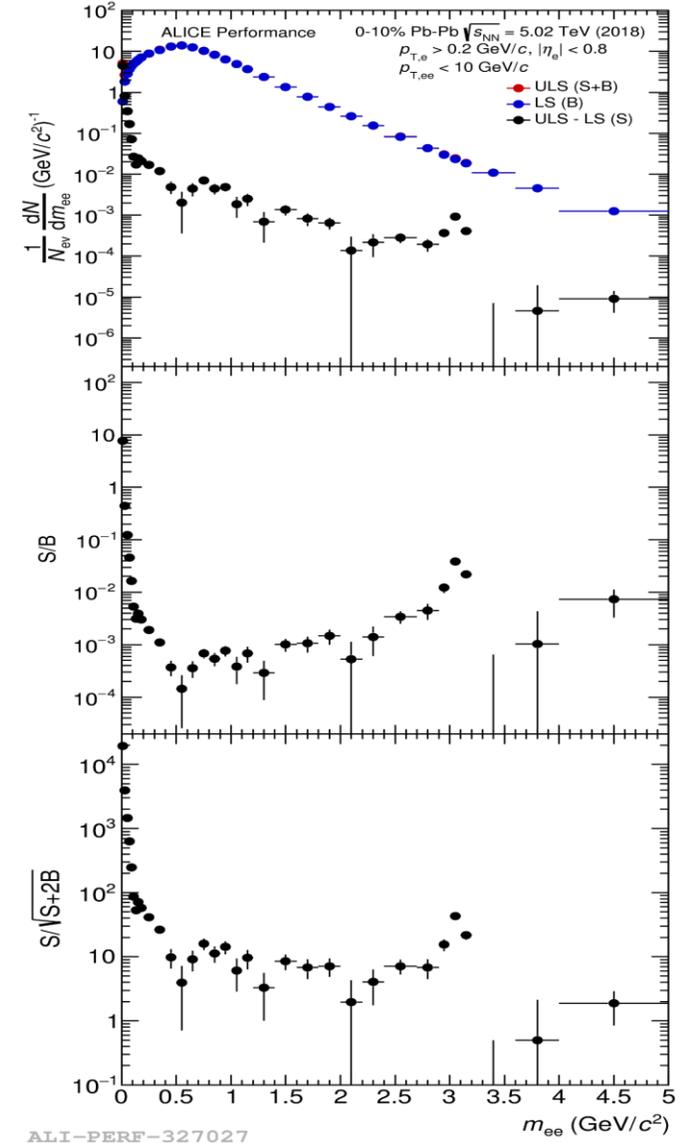
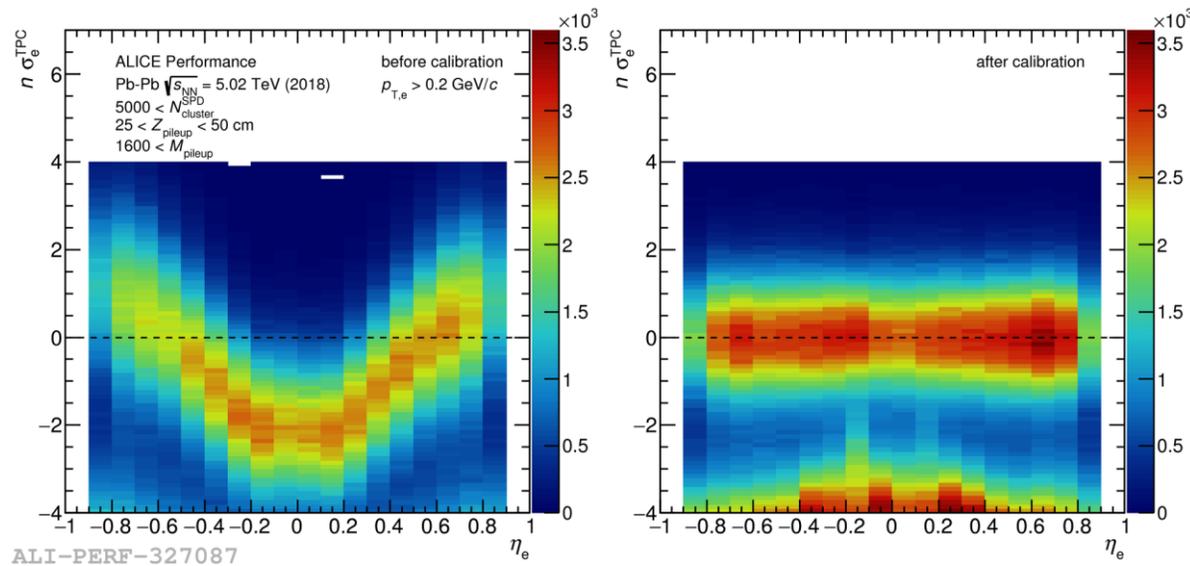
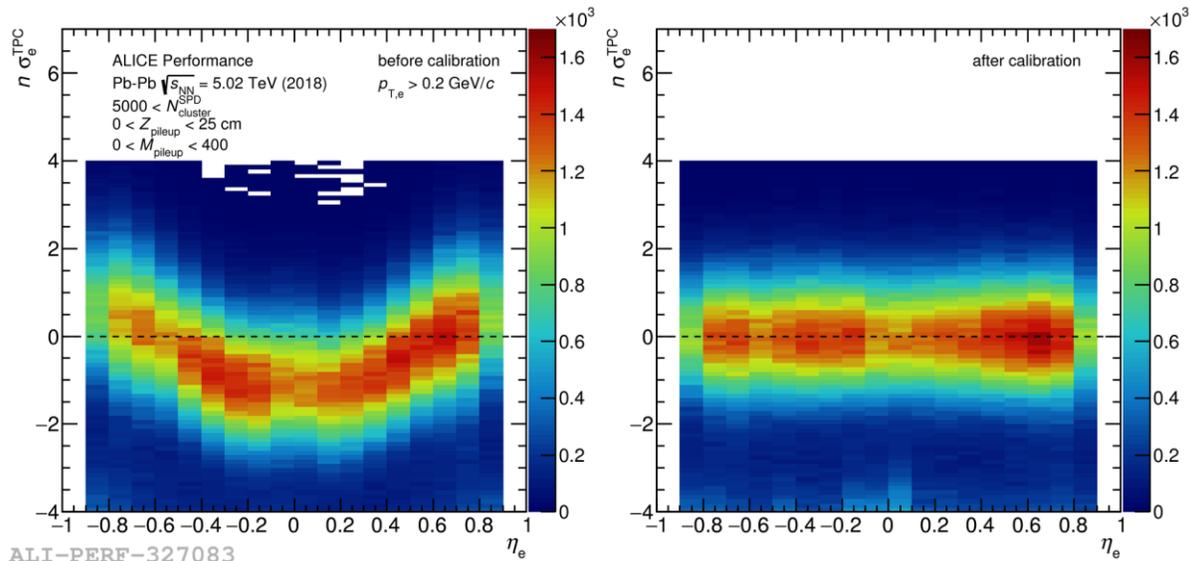
- Model dependence observed, similar to what observed in pp collisions at $\sqrt{s} = 7$ TeV and 13 TeV

	$d\sigma_{c\bar{c}}/dy$	$d\sigma_{b\bar{b}}/dy$
PYTHIA	0.531 ± 0.062 (stat.) ± 0.066 (syst.) mb	0.037 ± 0.004 (stat.) ± 0.005 (syst.) mb
POWHEG	0.743 ± 0.080 (stat.) ± 0.093 (syst.) mb	0.027 ± 0.004 (stat.) ± 0.003 (syst.) mb

Pb-Pb



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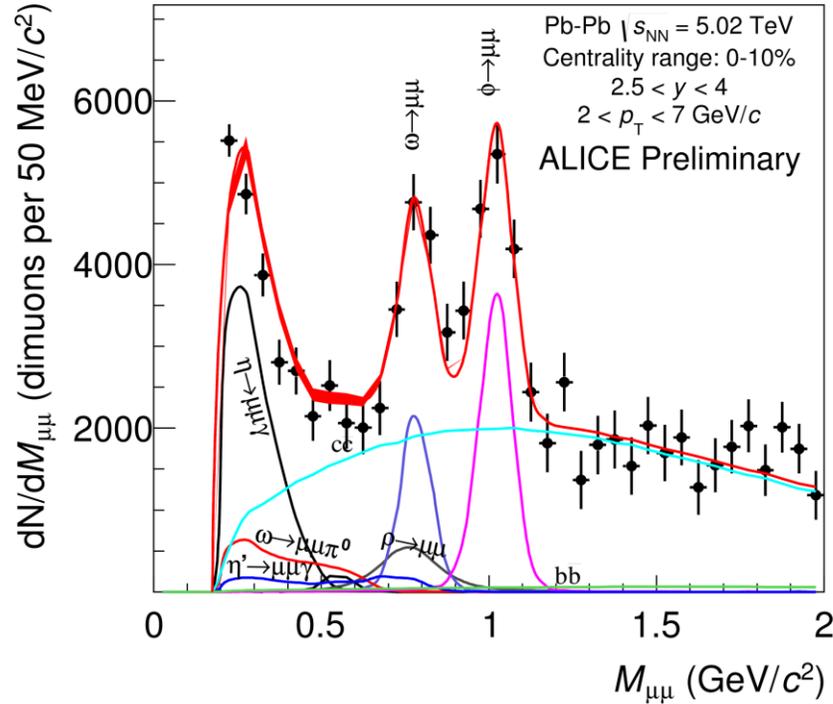
Dimuon production

Pb-Pb



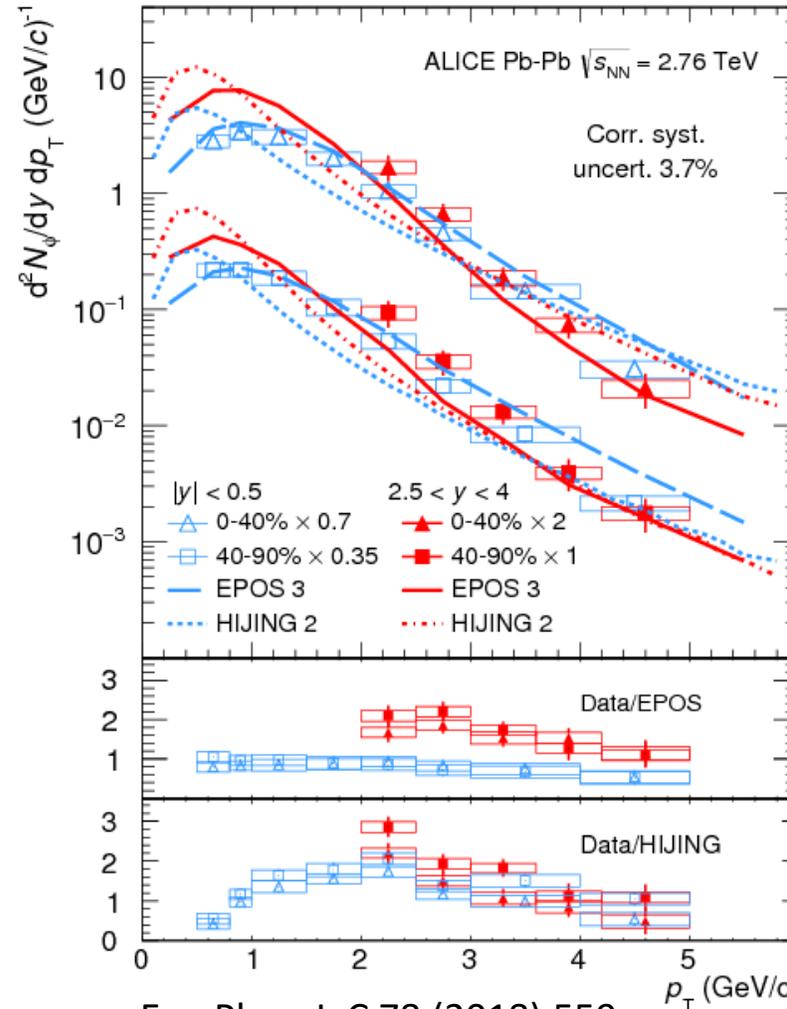
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Measurements at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV in $2 < p_T < 5$ GeV/c and $2 < p_T < 7$ GeV/c, respectively.



ALI-PREL-121162

- Invariant mass spectra extracted in different centrality classes



Eur. Phys. J. C 78 (2018) 559

- p_T spectra in different centralities compared with models:
- EPOS (hydrodynamic expansion) and HIJING (no hydrodynamic effects) underestimates data at forward rapidity.
- HIJING underestimates the data and shows harder p_T shape