A Large Ion Collider Experiment

Dielectrons with ALICE - Status and Perspectives

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on behalf of the ALICE Collaboration

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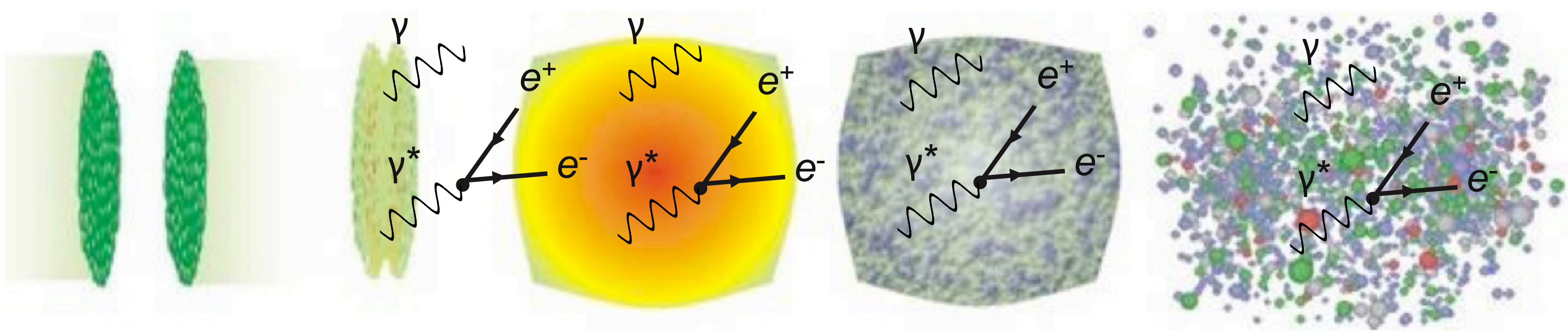
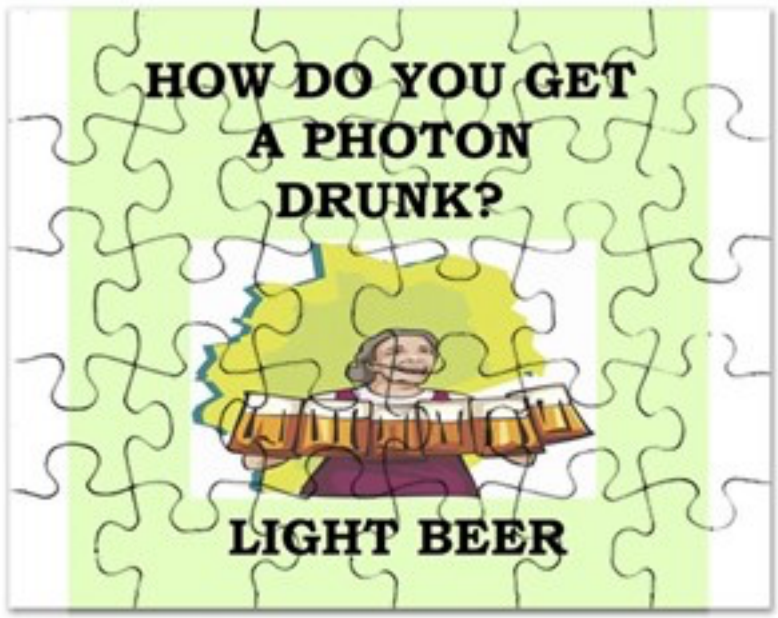
Photons and dileptons

- the EM thermal radiation spectrum of hot QCD matter
- are produced at all stages of the collison
- leave the system without FSI



hard photons thermal QGP thermal hadronic hadronic decays

Photon puzzle



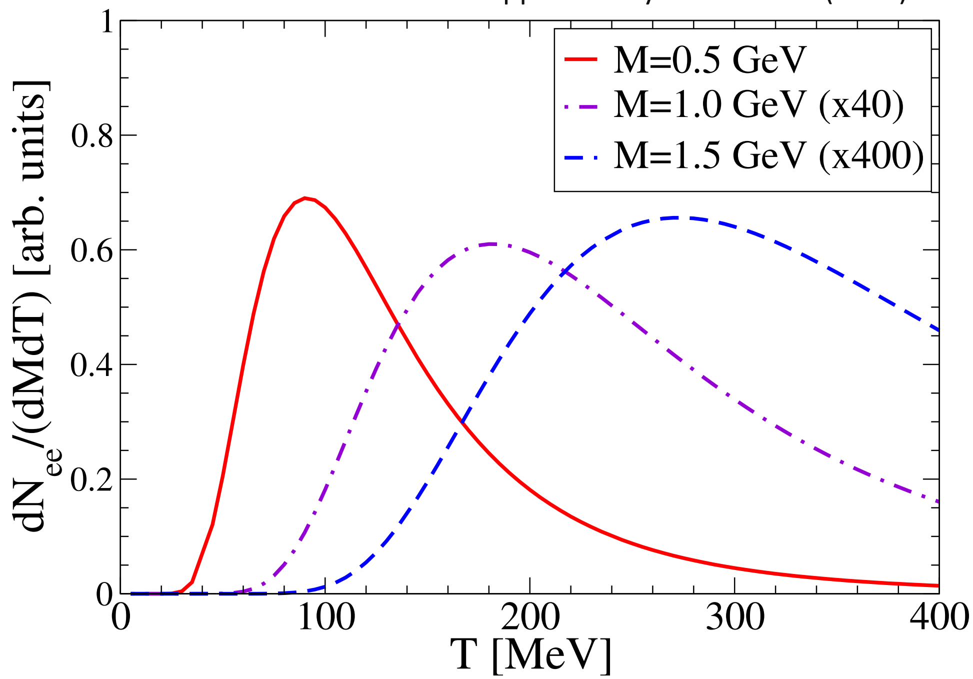
- Early and late emission times are not separable
- Worst case: QGP radiation could be outshined by late hadronic processes

Dileptons

- EM radiation spectrum: space-time integral over thermal emission rate:

$$\frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha^2}{\pi^3 M_{ee}^2} f^{BE}(q_0, T)\,\mathrm{Im}_{EM}(M_{ee}, q, \mu_B, T)$$

R. Rapp Acta Phys.Polon. B42 (2011)



- encodes microscopic properties (degrees of freedom, spectral functions) and bulk properties (EoS) of the medium
- continuous mass scale
- mass dependence allows separation of collision stages

Scientific objectives

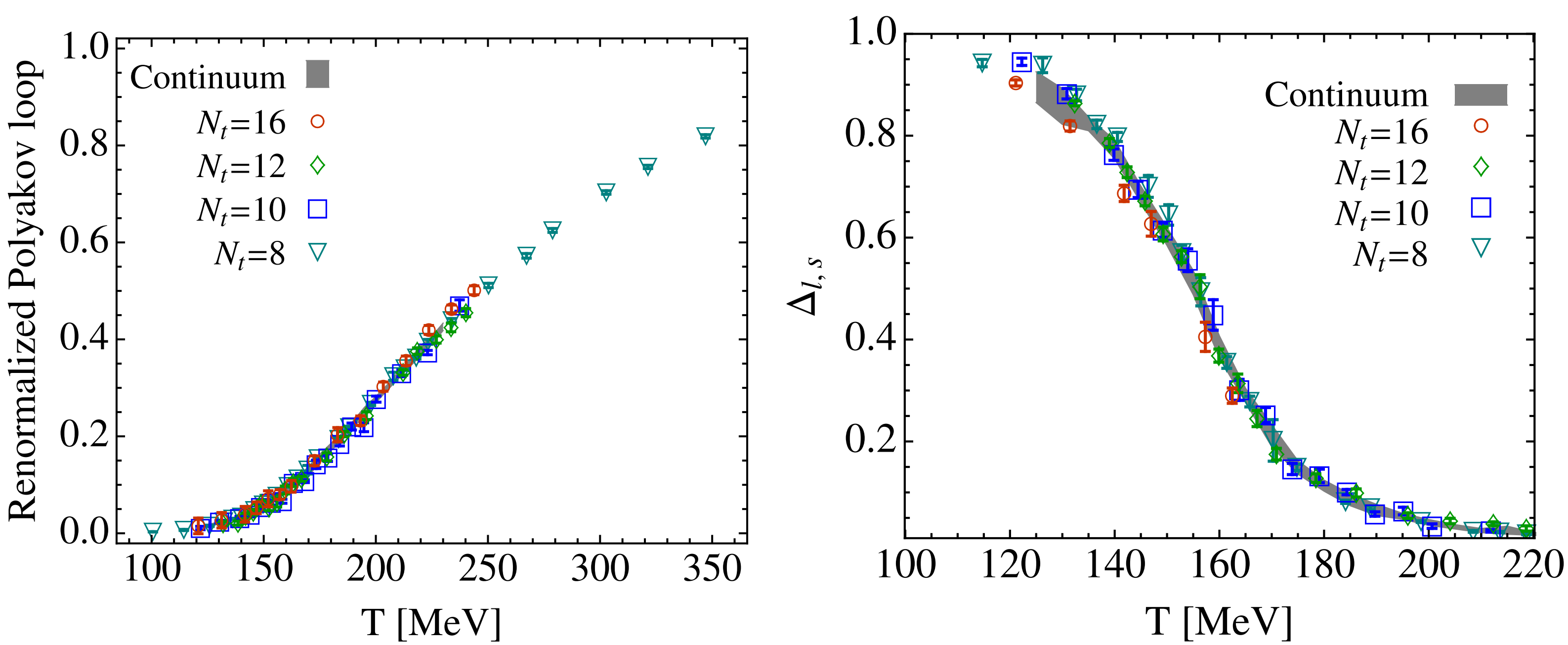
- Chiral symmetry restoration (m_{ee}<1 GeV/c^2)
- Early-temperature measurement (m_{ee} > 1 GeV/c^2)
- Space-time evolution, EoS:
  - hadronic (m_{ee}< 1 GeV/c^2) and partonic (m_{ee}> 1 GeV/c^2)

Chiral symmetry restoration

LQCD: chiral transition region (T = 130-170 MeV) in confined phase

→ observable via in-medium properties of hadrons

→ Thermal radiation in the low mass region (m_{ee} < 1 GeV/c^2)



J. Borsanyi et al., JHEP 1009 (2010)

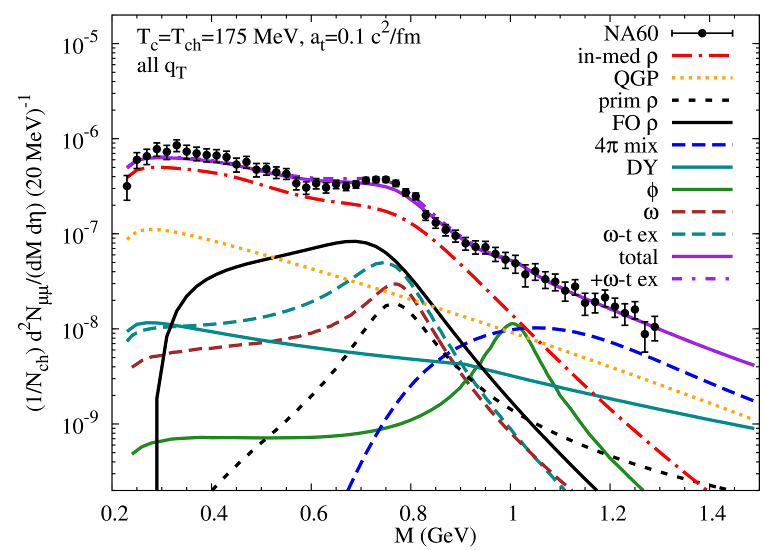
Chiral symmetry restoration

CSR ←→vector-axialvector degeneracy

Vector spectral function in medium: ρ – melting

→ mechanism confirmed by NA60

H. van Hees, R. Rapp, Nucl. Phys. A806 (2008)



Towards CSR:

Axial-vector experimentally inaccessible

Requires constraints from theory (LQCD, sum rules) → Possible at $\mu_B=0$

Requires experimental access to M_{ee}~$p_{T,ee}$-~T region

R. Rapp, Nucl.Phys. A870 (2013)

Chiral symmetry restoration

CSR ←→vector-axialvector degeneracy

Vector spectral function in medium: ρ – melting

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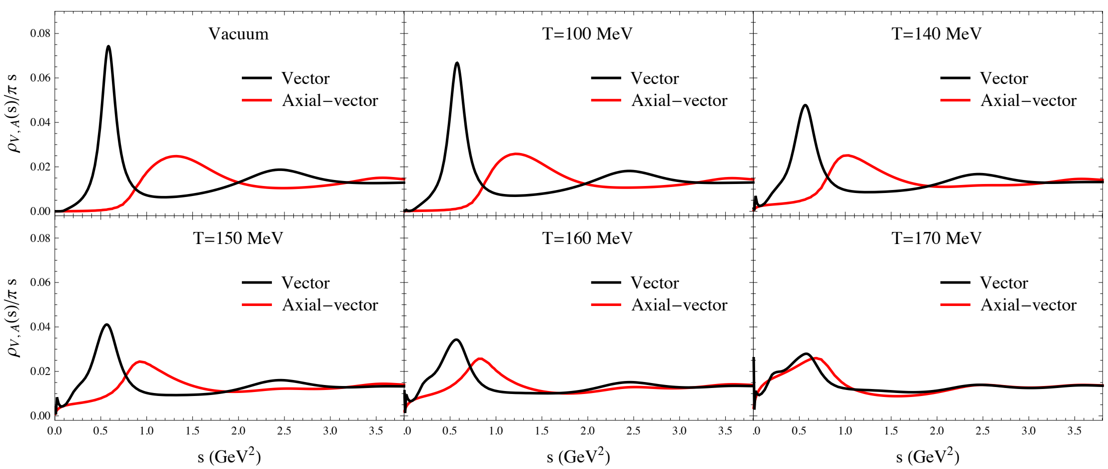
P. Hohler, R. Rapp, Phys. Lett. B731 (2014) 103



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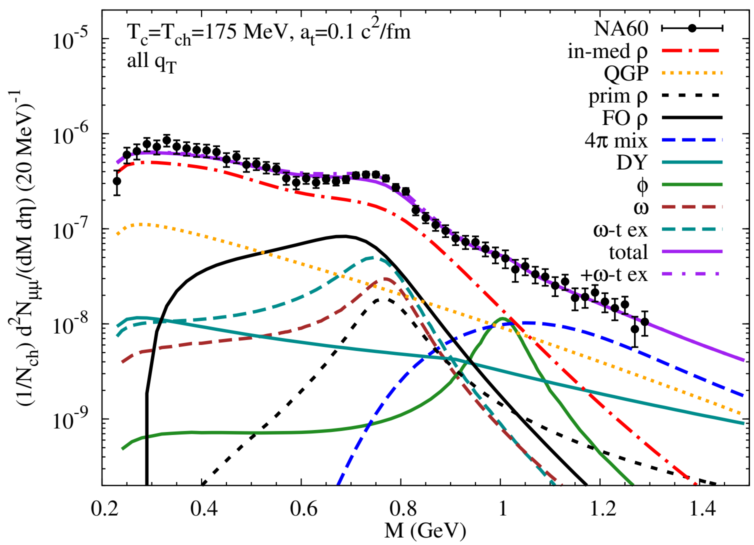

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- Axial-vector experimentally inaccessible
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Early temperature

In the low-mass region ($0.15 < m_{ee} < 0.3$ GeV/c^2) at $1 < p_{T,ee} < 5$ GeV/c:

- virtual photon yield allows extrapolation to real photons at relatively low p_T
- complementary to real photon measurements via calorimetry or conversions

In the intermediate mass range ($1.1 < m_{ee} < 3$ GeV/c^2):

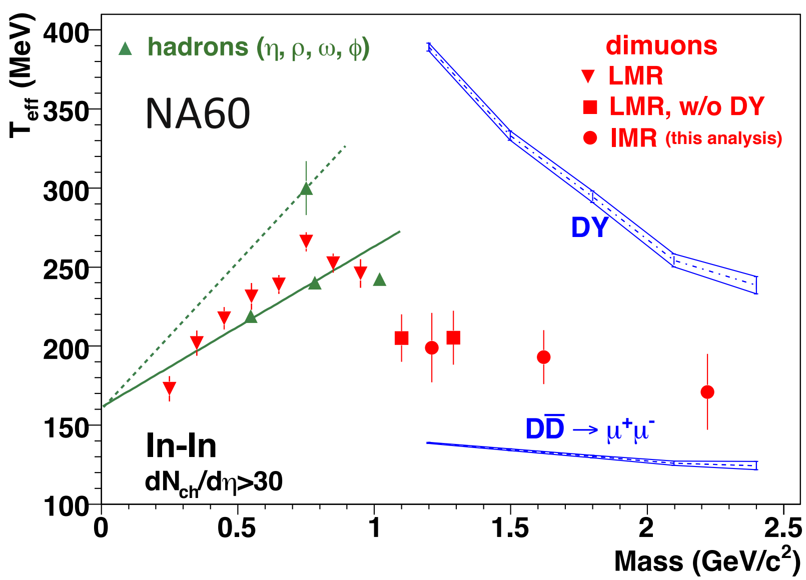
- structureless („dual“) spectral function allows most direct temperature determination from exponential in m_{ee}, no blue shift
- complicated by large physical background from charm

Space-time evolution

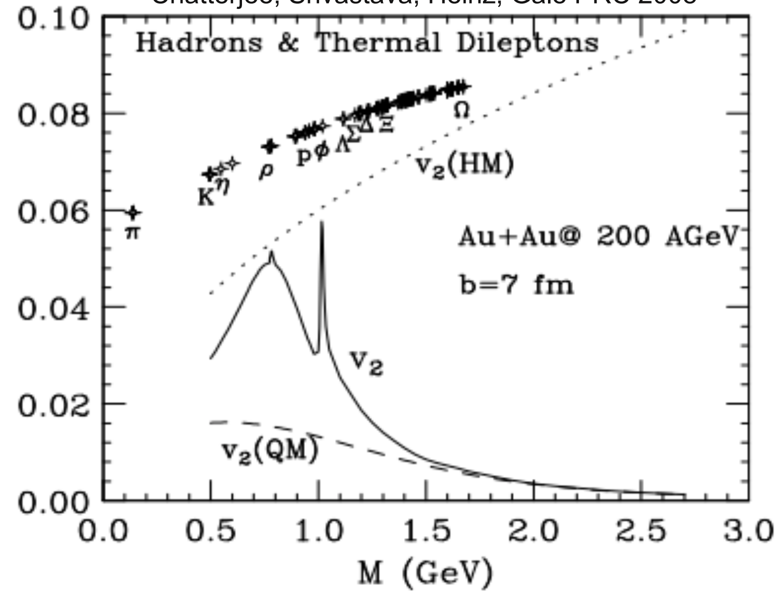
Transverse momentum spectra contain information on collective radial and elliptic flow (T_{eff} and v_2)

Mass dependence gives access to early times →

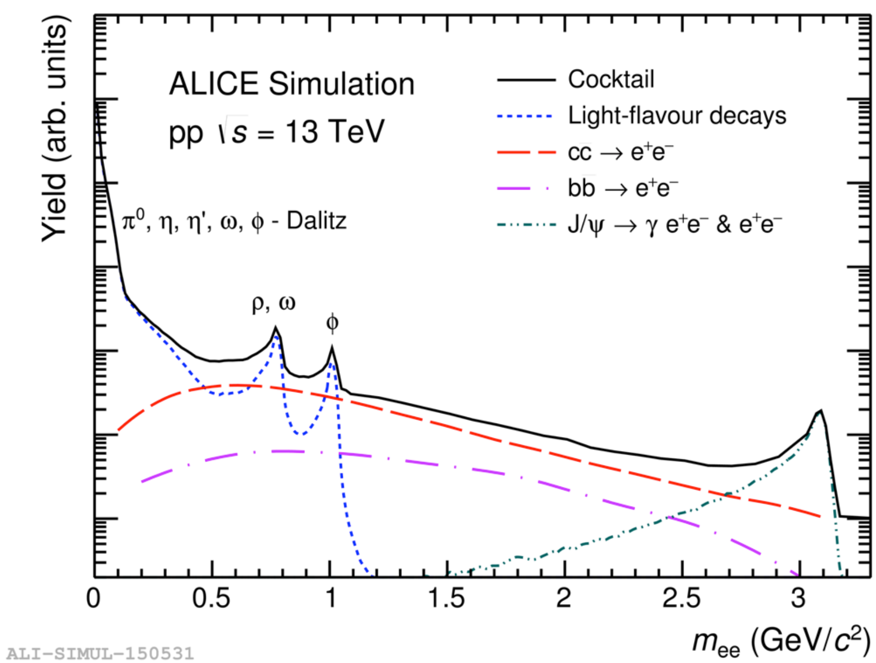
$$\frac{dN_{ee}}{dm_{ee}\,dp_{T,ee}\,d\Psi}$$



Chatterjee, Srivastava, Heinz, Gale PRC 2008



Dielectrons with ALICE at the LHC



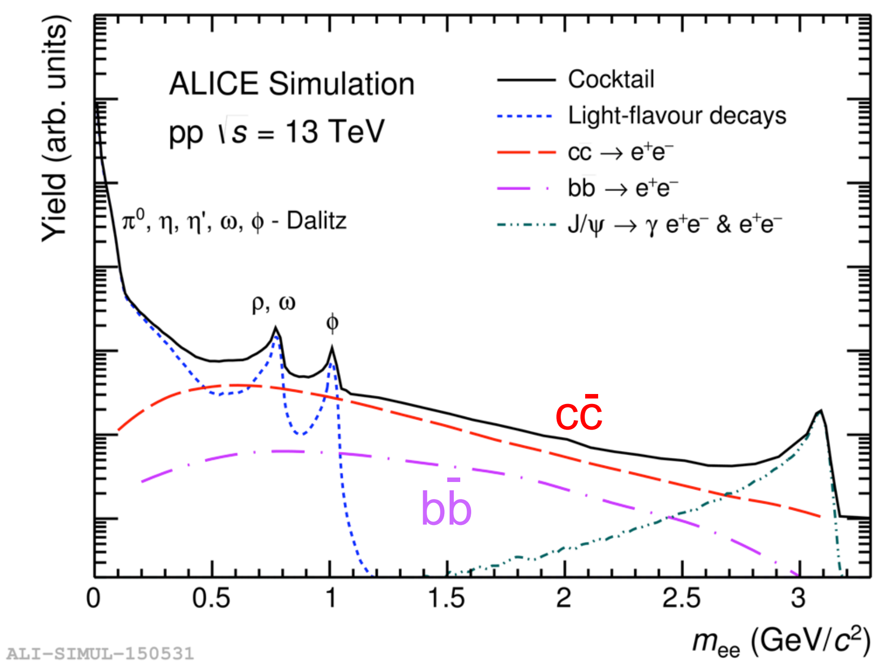
pp:
- Vacuum baseline for p-Pb and Pb-Pb
- Heavy-flavour and direct-photon production
- Possible new (and old) phenomena

p-Pb:
- Cold nuclear matter effects
- Thermal radiation

Pb-Pb:
- Chiral symmetry restoration
- QGP radiation – early T, β, v_2

→ Pb-Pb at the LHC *is* the **largest, hottest, and longest-lived system**!

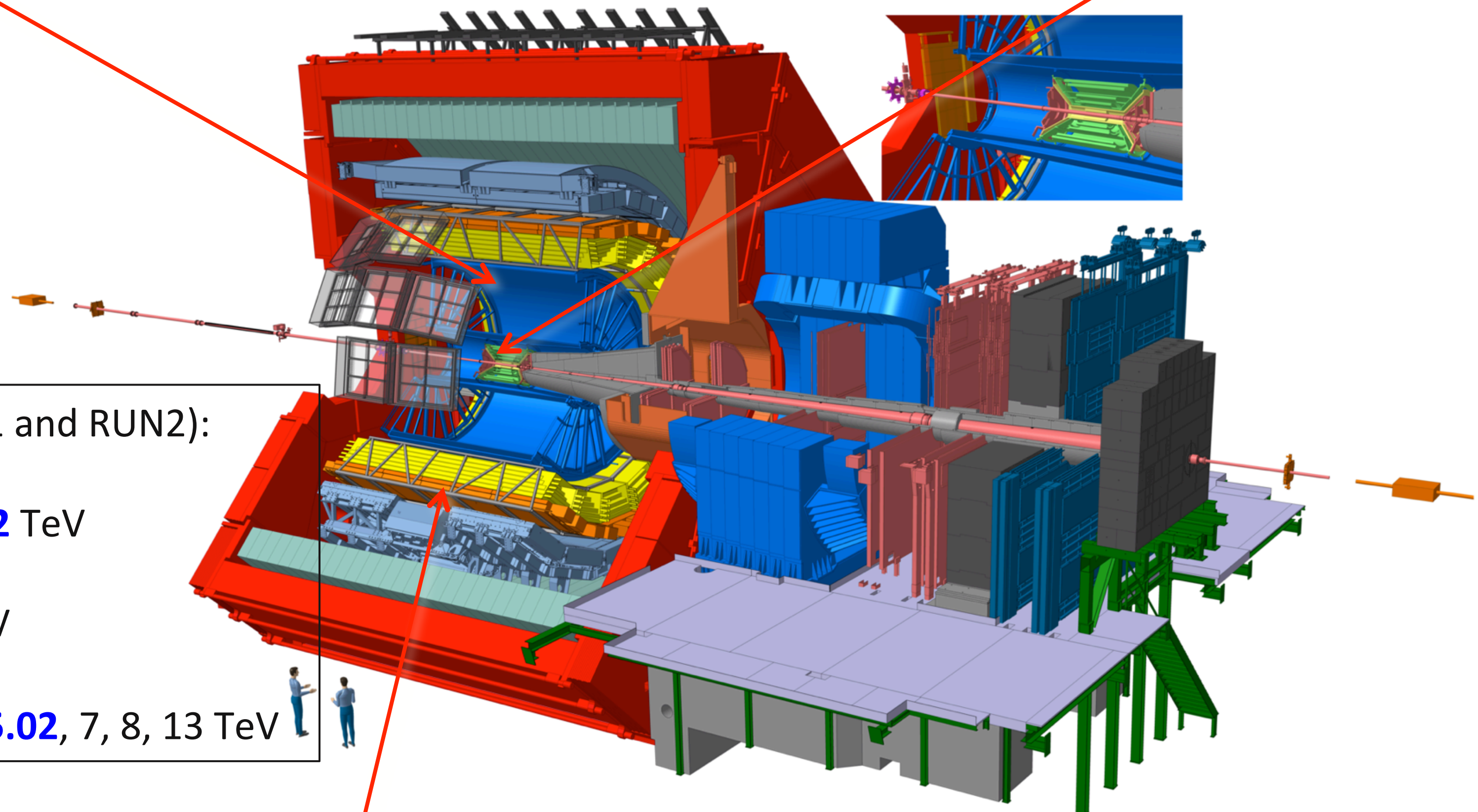
The boon and bane of heavy quarks



- HF production dominates the dielectron spectrum at the LHC over a wide range in mass
- Standard cocktail techniques are not sufficiently precise to isolate thermal contributions
- Additional experimental means are needed to separate HF dielectrons from prompt sources

→ Dielectrons turn into a **complementary probe** to study HF physics at the LHC

ALICE detector at the LHC



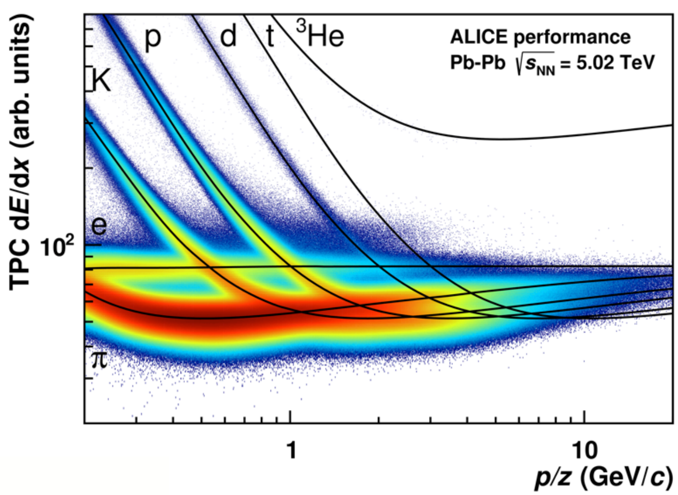
Since 2009 (LHC RUN1 and RUN2):

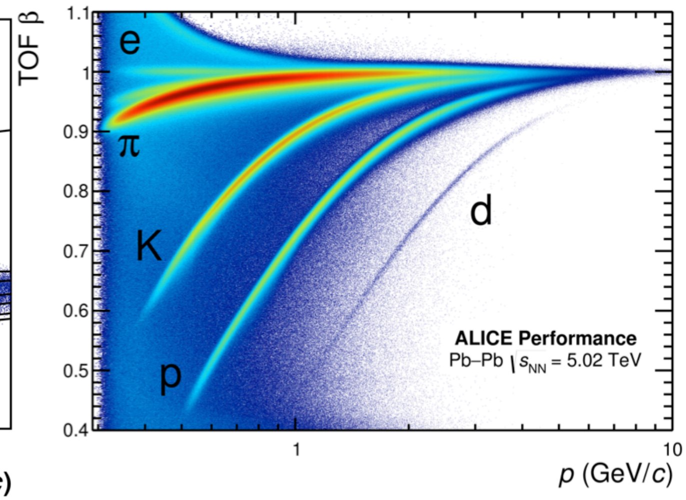
Pb-Pb at 2.76 and **5.02** TeV

p-Pb at **5.02** and 8 TeV

pp at 0.9, 2.36, 2.76, **5.02**, 7, 8, 13 TeV

Dielectron analysis





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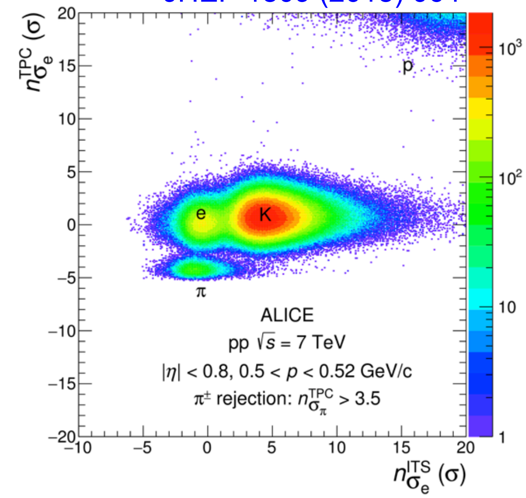
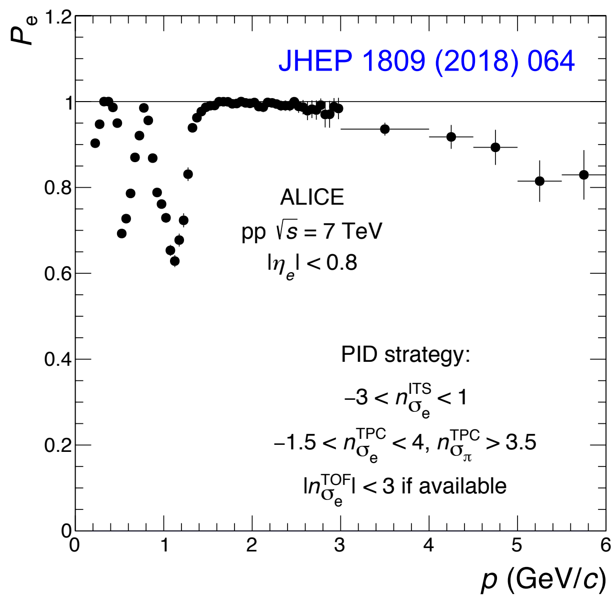
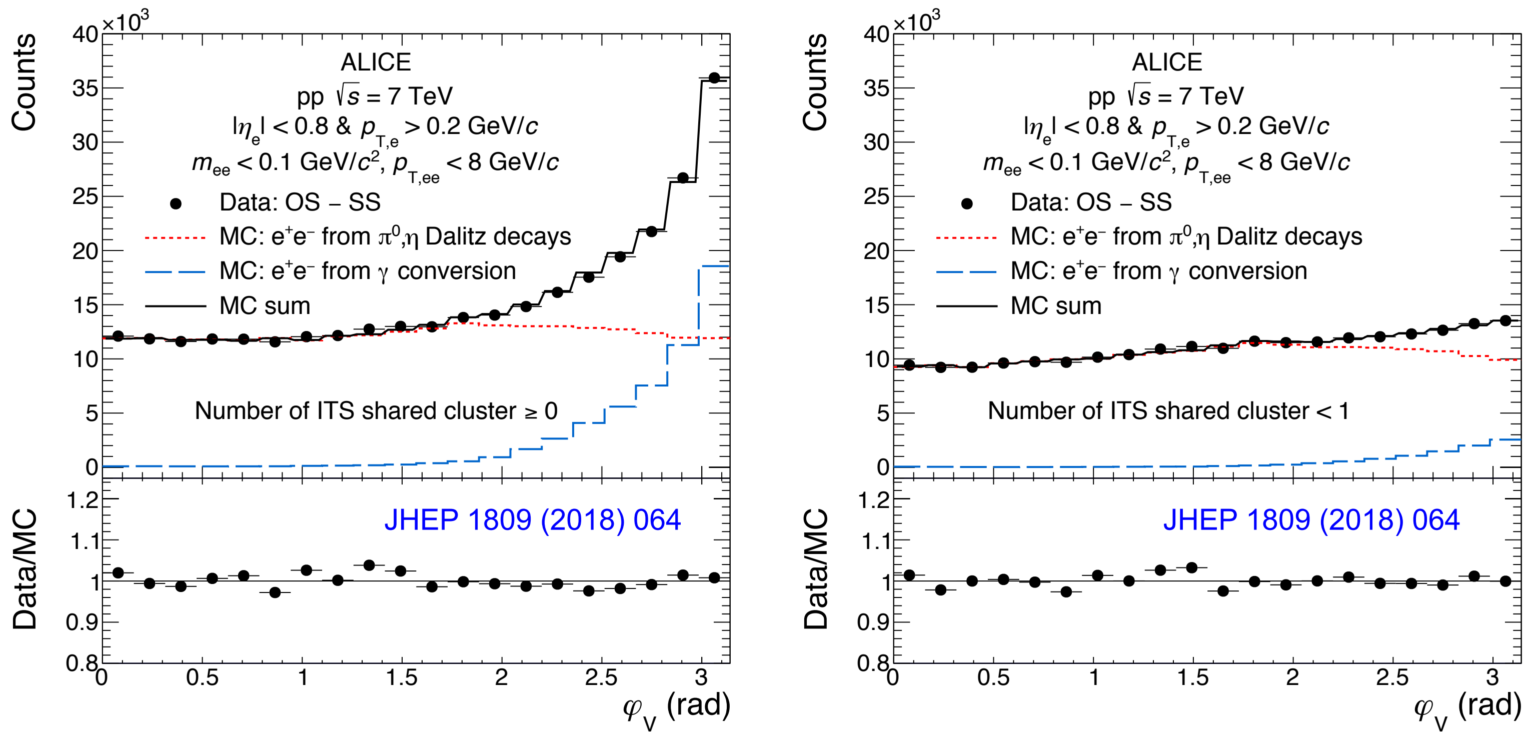




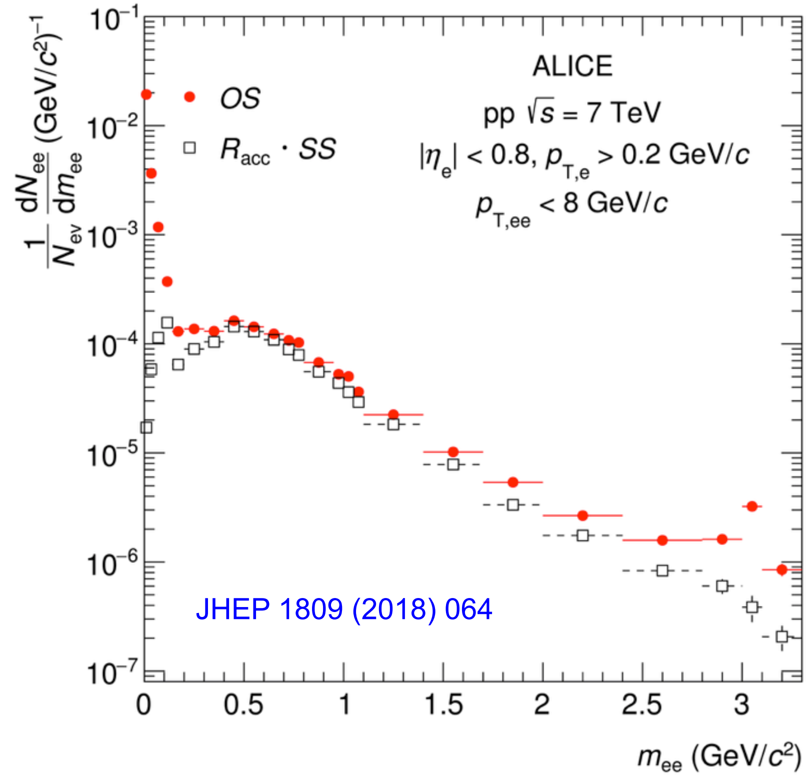
Electron selection based on TPC d*E*/dx, TOF, and ITS d*E*/dx in $|\eta_e|$<0.8

Conversion rejection



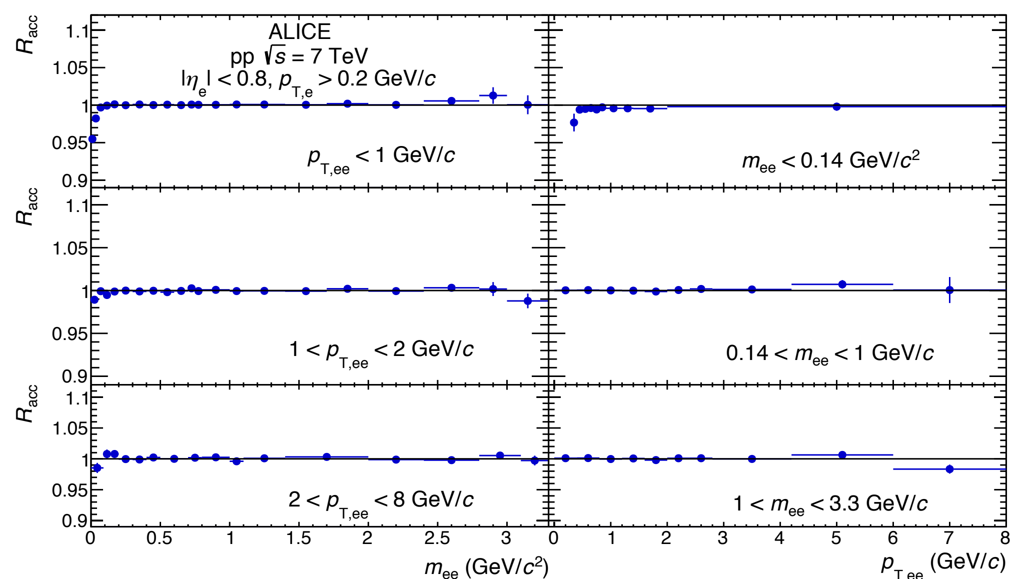
- Conversion pairs exhibit an apparent opening angle in the plane perpendicular to the magnetic field, characterized by φ_V (conversions are at $\varphi_V \approx \pi$)
- Conversion pairs are strongly suppressed by vicinity („shared-cluster") cuts in the ITS
- Distributions are well described by MC

Background and pair acceptance correction



- 2π azimuthal coverage allows powerful subtraction of combinatorial and correlated background pairs using same-sign combinations

$$S = OS - R_{acc} \cdot SS$$



pp collisions

Run 1:

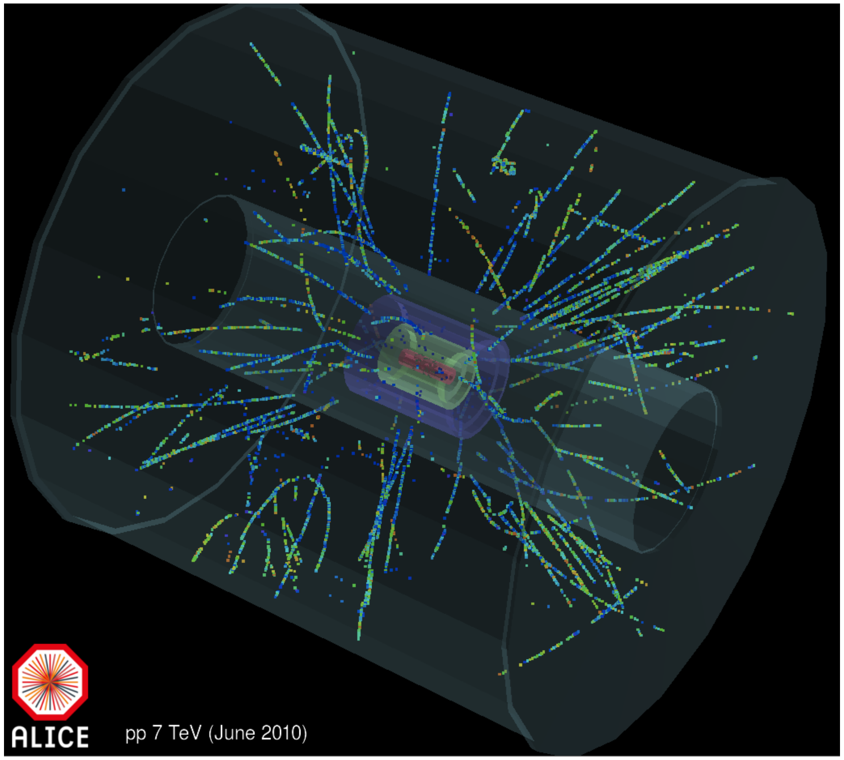
- pp at $\sqrt{s}$ = 7 TeV (min bias)
  ALICE Coll. JHEP 1809 (2018) 064

Run 2:

- pp at $\sqrt{s}$ = 13 TeV (min bias and HM)
  ALICE Coll. 1805.04407 (PLB acc.)

- pp at $\sqrt{s}$ = 13 TeV (B = 0.2 T)
  preliminary (status by Jerome Jung)

- pp at $\sqrt{s}$ = 5.02 TeV (min bias)
  analysis ongoing



pp mass spectra at √*s* = 7 and 13 TeV

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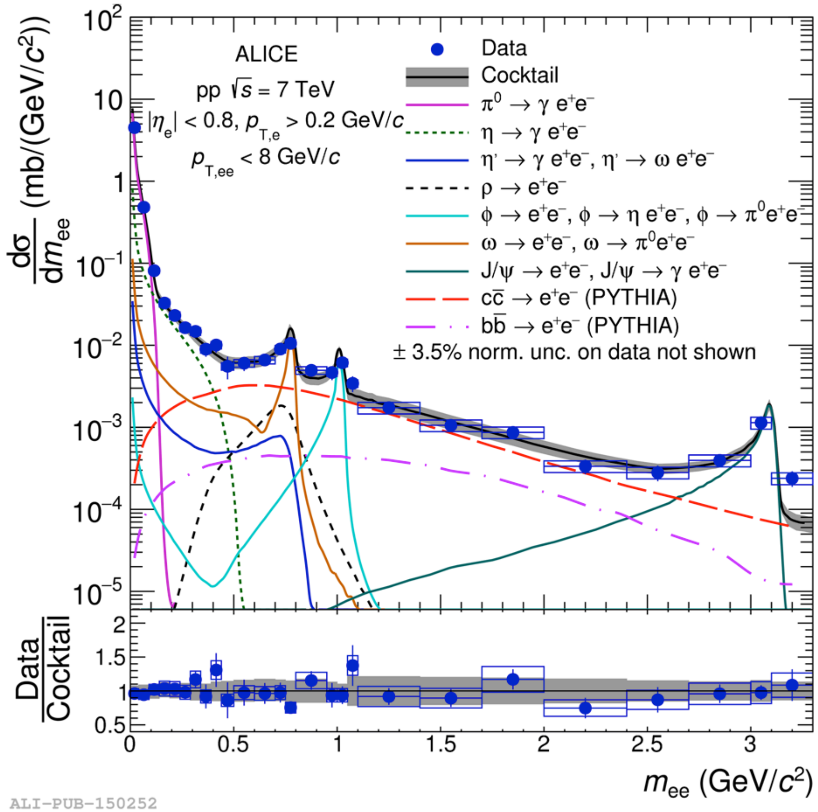
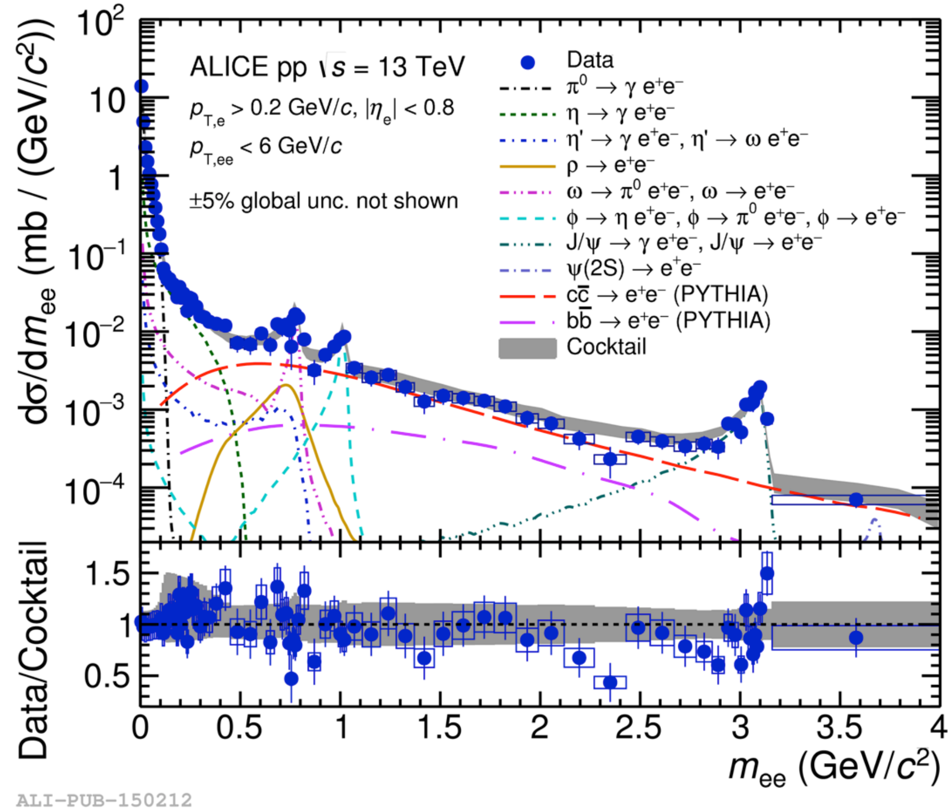
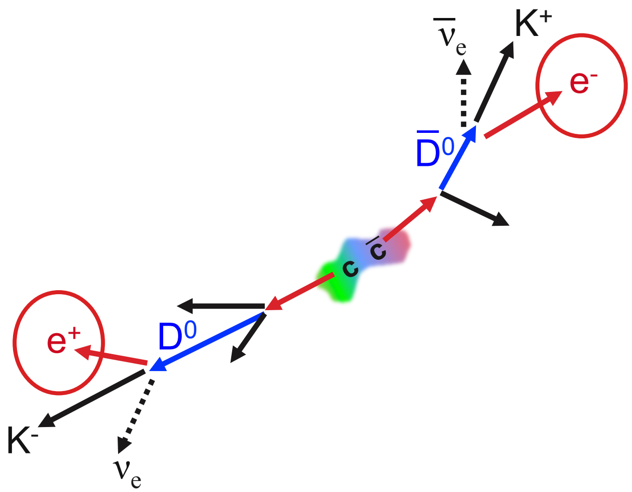


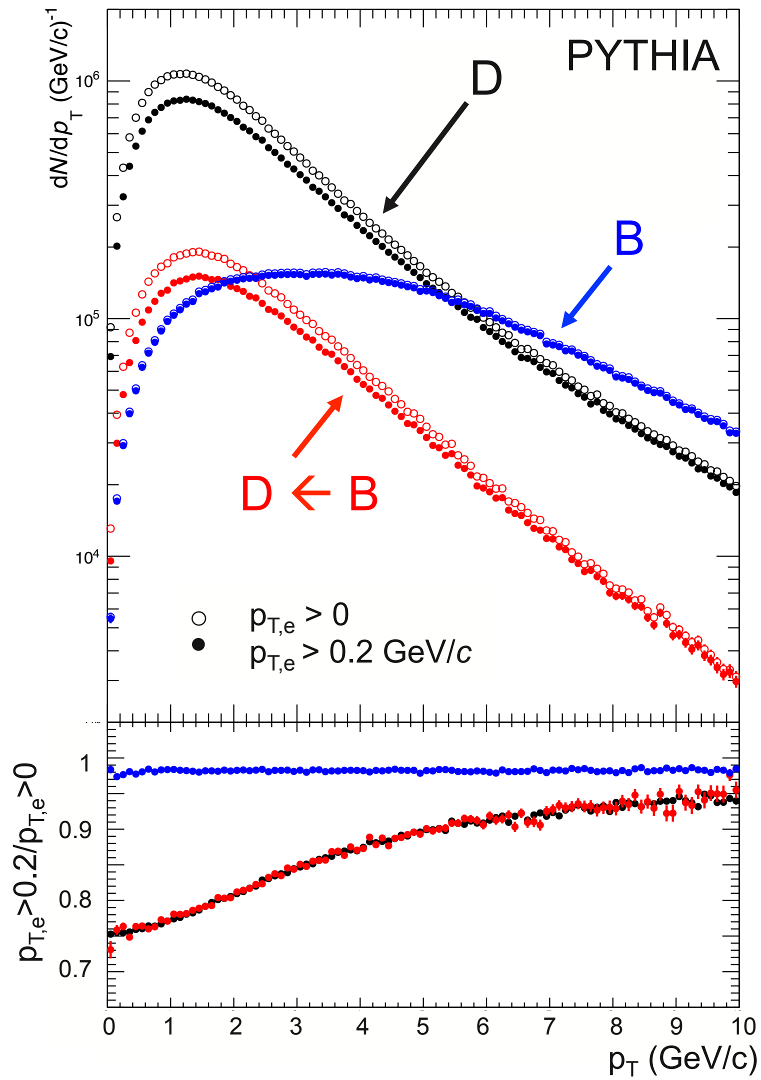
1805.04407 (acc. PLB)



- Dielectron production ($p_{T,e} > 0.2$ GeV/c) in min. bias pp is **well described by hadronic sources**
- Dominant contribution ($m_{ee} > 0.5$ GeV/c^2) is from **heavy-flavour decays**

Dielectrons from $c\bar{c}$ and $b\bar{b}$





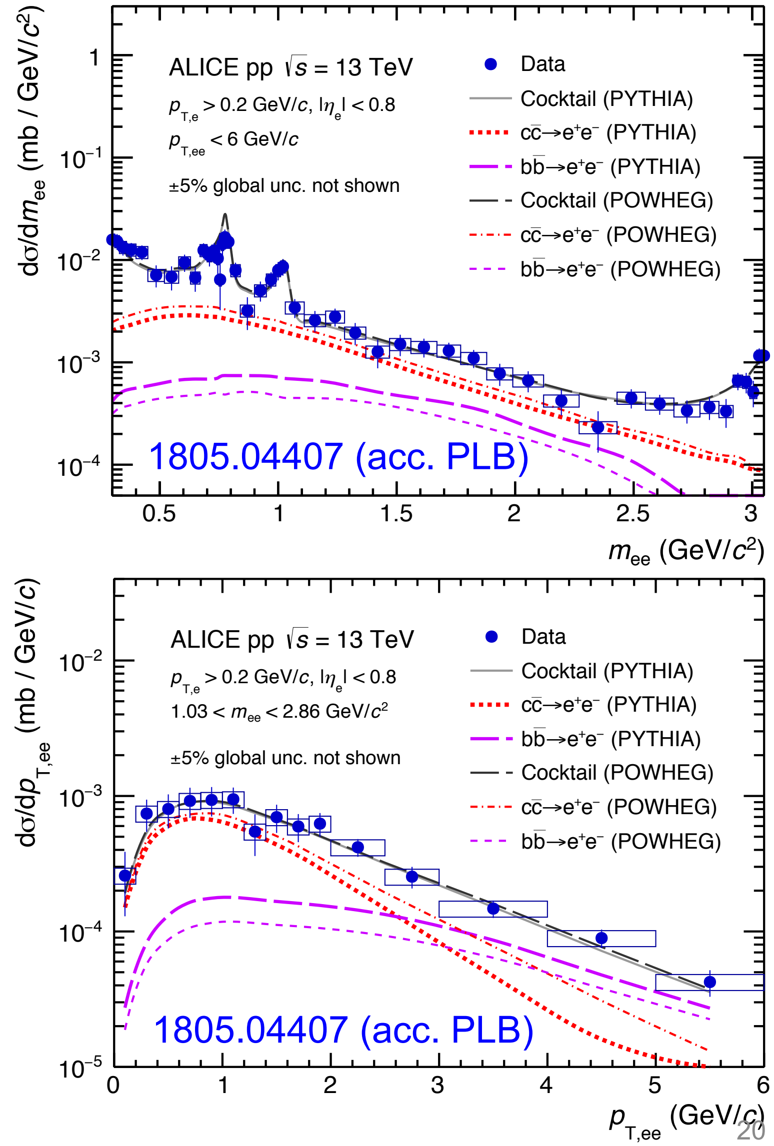
Typical single-electron low-$p_{T,e}$ cut preserves most of the heavy-flavour cross-section at mid-rapidity

$c\bar{c}$ and $b\bar{b}$ in pp at $\sqrt{s}$ = 13 TeV

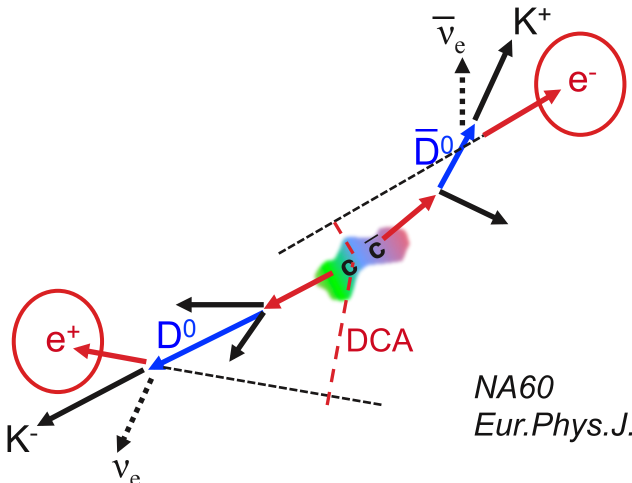
- Simultaneous fit to m_{ee} and p_{Tee} allows to **extract HF cross sections** and separate charm and beauty *(PHENIX Phys. Rev. C91 (2015))*

	Pythia	Powheg
$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y\|_{y=0}$	$974 \pm 138\,(\text{stat.}) \pm 140\,(\text{syst.})$ μb	$1417 \pm 184\,(\text{stat.}) \pm 204\,(\text{syst.})$ μb
$\mathrm{d}\sigma_{b\bar{b}}/\mathrm{d}y\|_{y=0}$	$79 \pm 14\,(\text{stat.}) \pm 11\,(\text{syst.})$ μb	$48 \pm 14\,(\text{stat.}) \pm 7\,(\text{syst.})$ μb
$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y\|_{y=0}^{\text{HM}}$	$4.14 \pm 0.67\,(\text{stat.}) \pm 0.66\,(\text{syst.})$ μb	$5.95 \pm 0.91\,(\text{stat.}) \pm 0.95\,(\text{syst.})$ μb
$\mathrm{d}\sigma_{b\bar{b}}/\mathrm{d}y\|_{y=0}^{\text{HM}}$	$0.29 \pm 0.07\,(\text{stat.}) \pm 0.05\,(\text{syst.})$ μb	$0.17 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$ μb

- Sizeable model dependence can shed light on **HF production mechanisms**



Topological separation of dielectron sources



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

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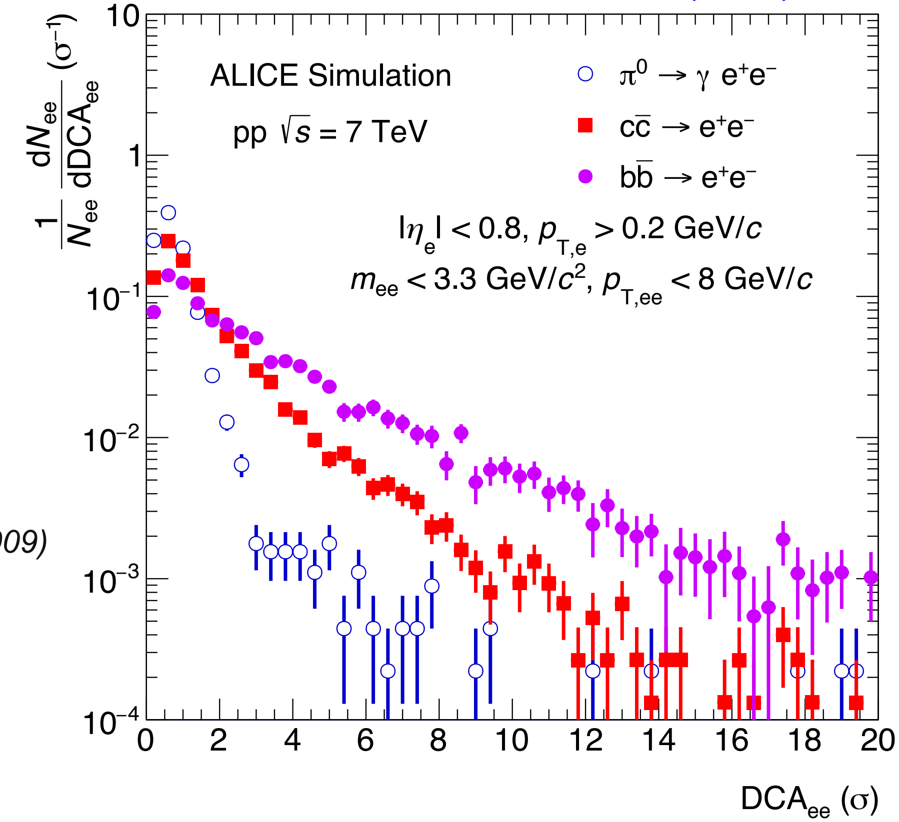
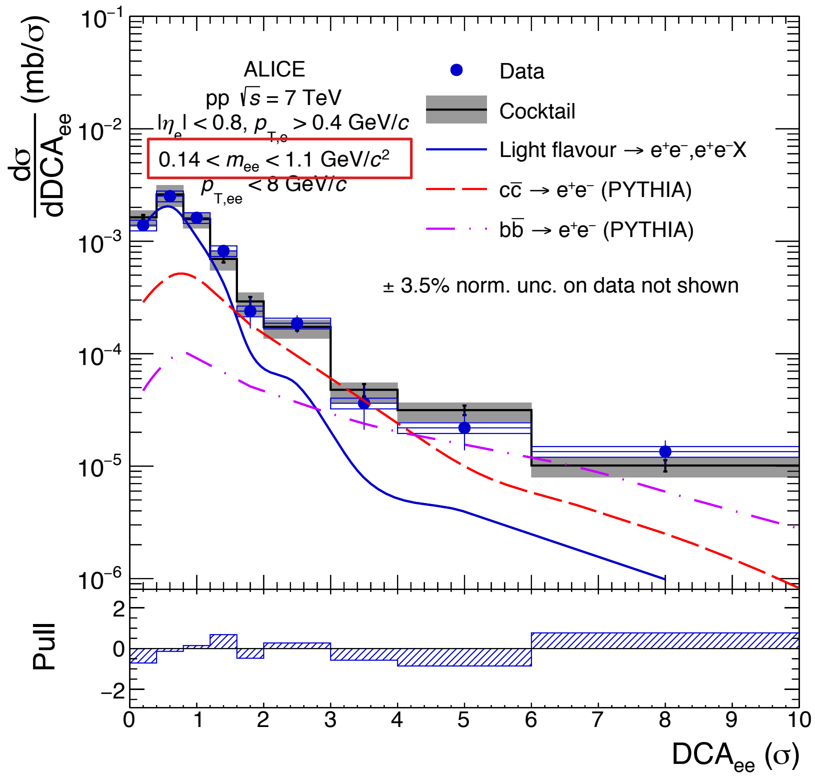


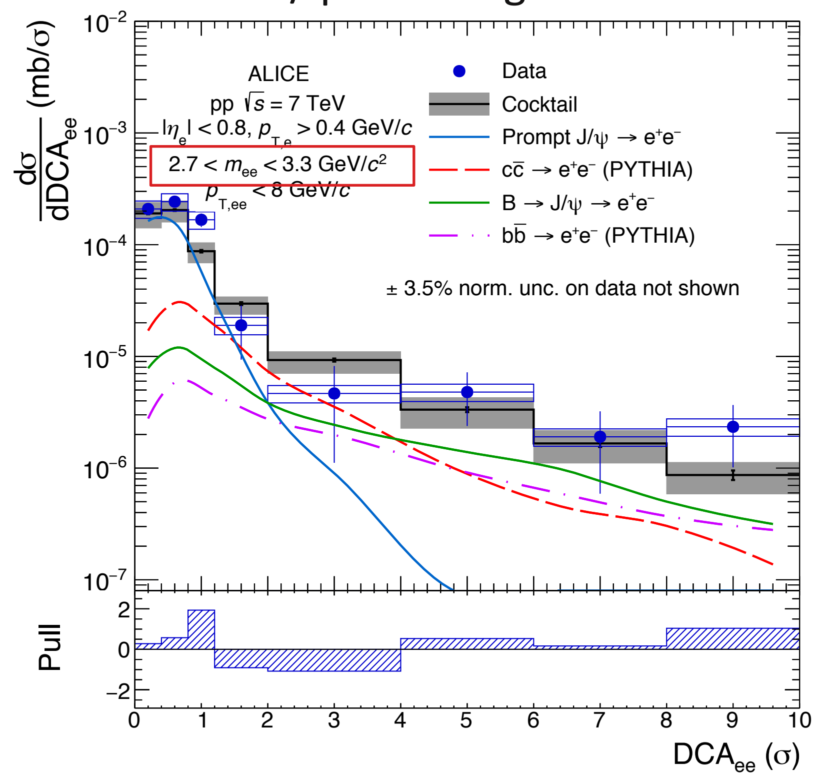
DCA_{ee} allows to **separate prompt from delayed dielectron sources**:

DCA_{ee}(prompt) < DCA_{ee}(charm) < DCA_{ee}(beauty)

Topological separation of dielectron sources

η,ρ,ω,φ mass region — JHEP 1809 (2018) 064 — J/ψ mass region



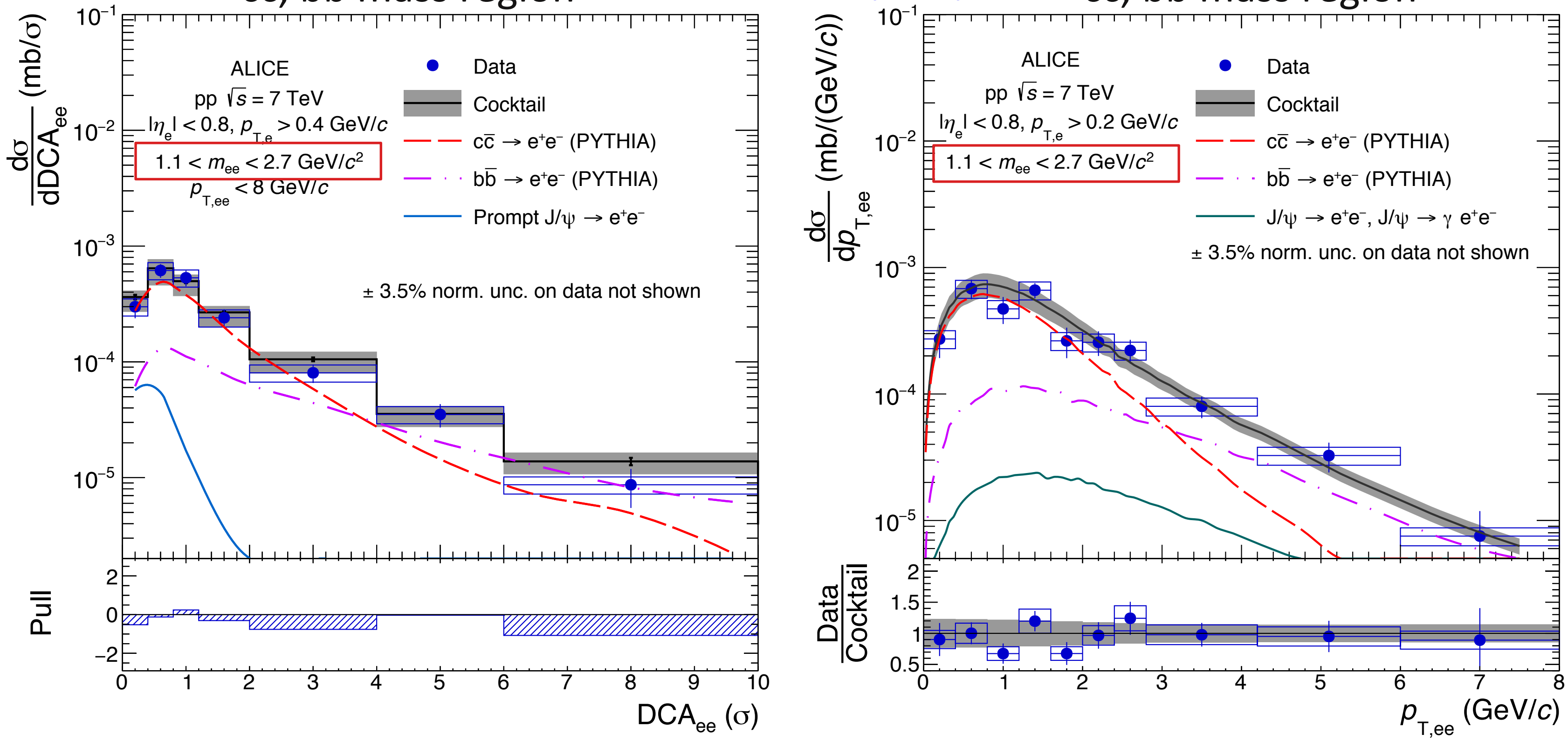


DCA_{ee} allows to **separate prompt from delayed dielectron sources:**

DCA_{ee}(prompt) < DCA_{ee}(charm) < DCA_{ee}(beauty)

$c\bar{c}$ and $b\bar{b}$ in pp at $\sqrt{s}$ = 7 TeV

$c\bar{c}$, $b\bar{b}$ mass region   JHEP 1809 (2018) 064 $c\bar{c}$, $b\bar{b}$ mass region



- No indication of **prompt source in IMR** – not expected in pp
- **Charm and beauty cross sections** from simultaneous fits of MC templates to DCA_{ee} and m_{ee}- p_{Tee} distributions in IMR

$c\bar{c}$ and $b\bar{b}$ cross sections pp at $\sqrt{s}$ = 7 TeV

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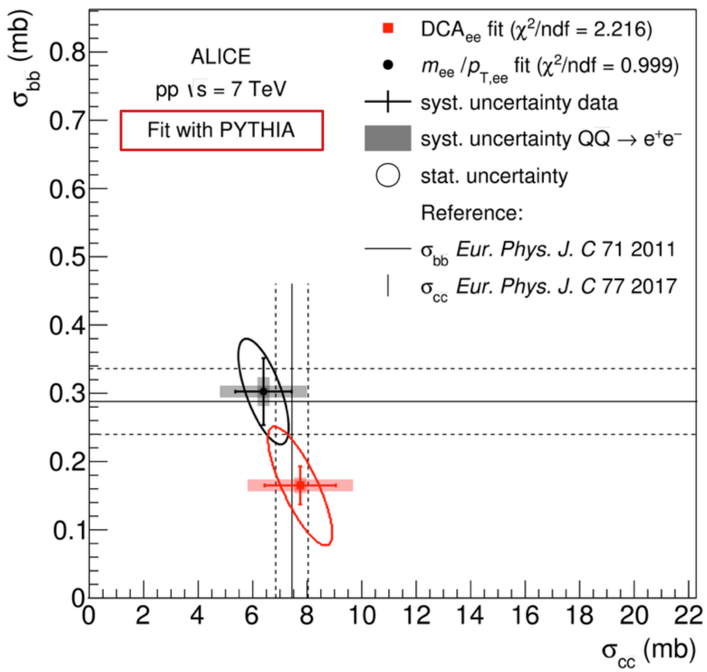

- DCA$_{ee}$ and m_{ee} - p_{Tee} fits agree well
- σ_{bb} and σ_{cc} agree with previous measurements using single-HF hadrons
- dominant systematic uncertainty from $c\bar{c} \rightarrow ee$ branching ratio (hadron composition)

$c\bar{c}$ and $b\bar{b}$ cross sections pp at $\sqrt{s}$ = 7 TeV

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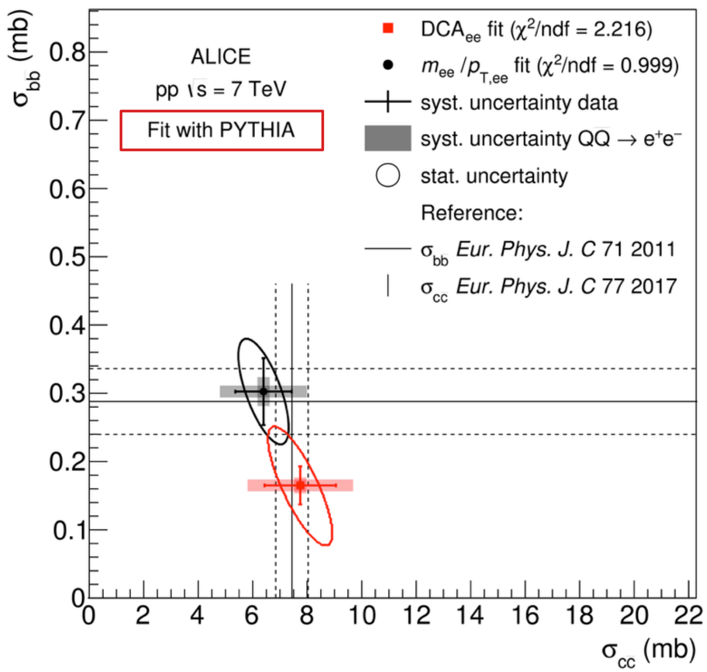

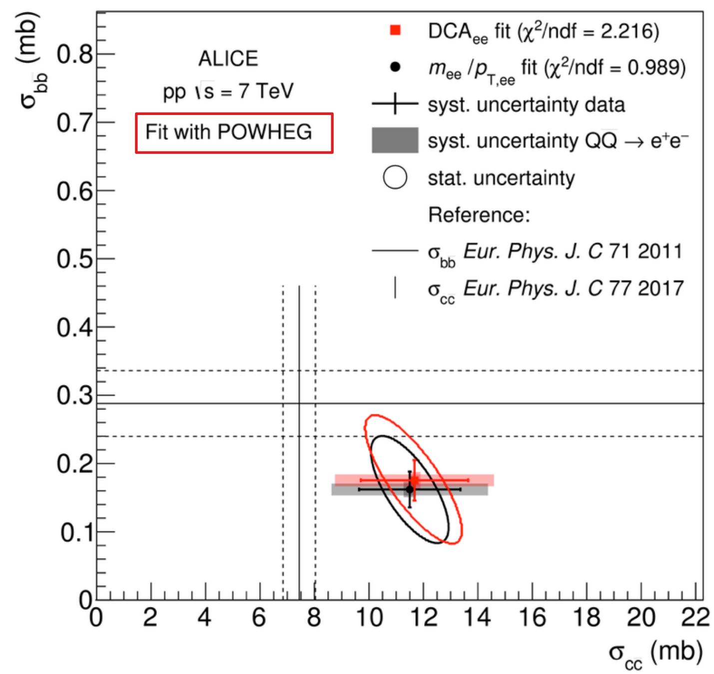

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- dominant systematic uncertainty from $c\bar{c}$→ee branching ratio (hadron composition)

- DCA$_{ee}$ and m_{ee} - p_{Tee} fits agree well
- σ_{bb} and σ_{cc} from POWHEG are different from PYTHIA fits
- Discriminate against different $Q\bar{Q}$ production mechanisms

High-multiplicity pp collisions

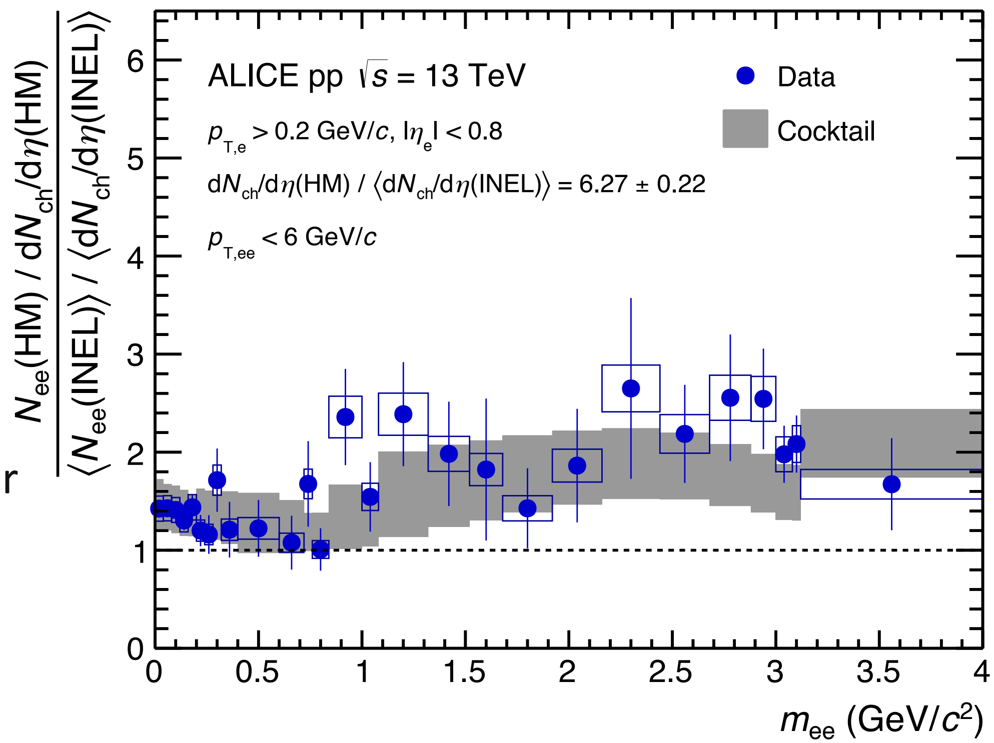
Medium effects in HM pp collisions?

1805.04407 (acc. PLB)

- High-multiplicity selection with

$$\frac{dN_{ch}/d\eta(HM)}{\langle dN_{ch}/d\eta(INEL)\rangle} = 6.27 \pm 0.22$$

i.e. 0.036% most-HM



- Cocktail reflects stronger-than-linear increase of HF production with charged-particle multiplicity and hardening of p_T spectra

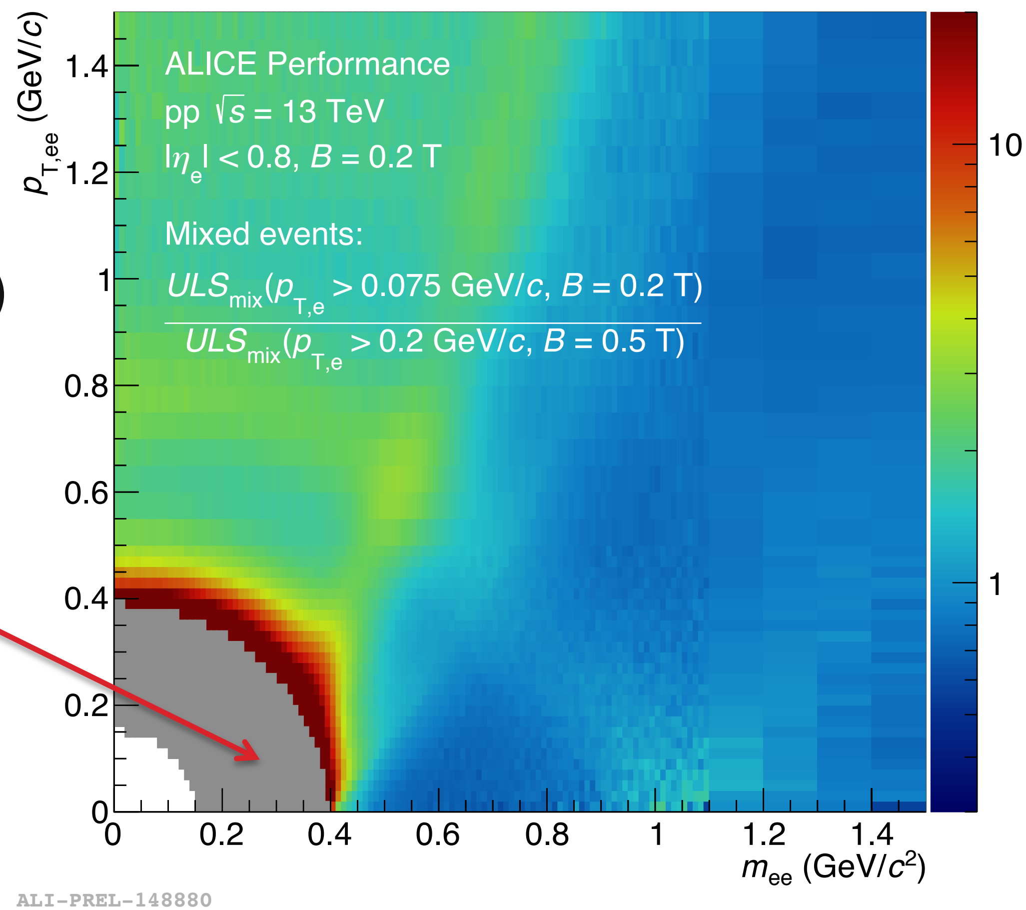
- at high $p_{T,ee}$, similar scaling in HM for beauty observed as for charm

- HM pp data show **no indication of medium radiation**

pp at √*s* = 13 TeV with low B-field

Dedicated campaigns in Run2 with **reduced solenoid field** (0.5 T → 0.2 T)

- Test case for Run3
- Allows dedicated studies of **very soft dileptons** at low mass in pp
- Talk by Jerome Jung



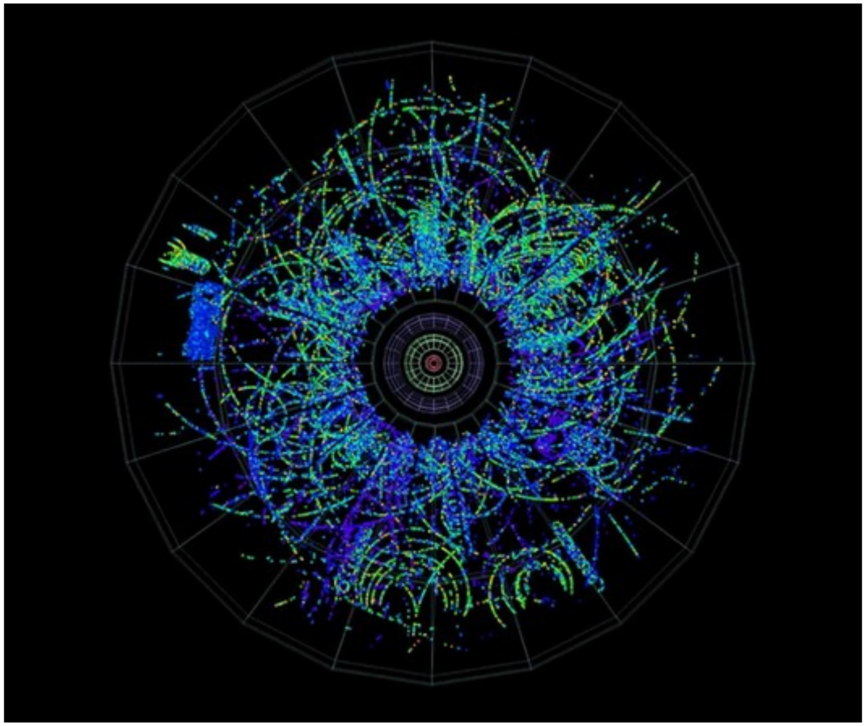
p-Pb collisions

Run 1:

- p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV (2013) preliminary

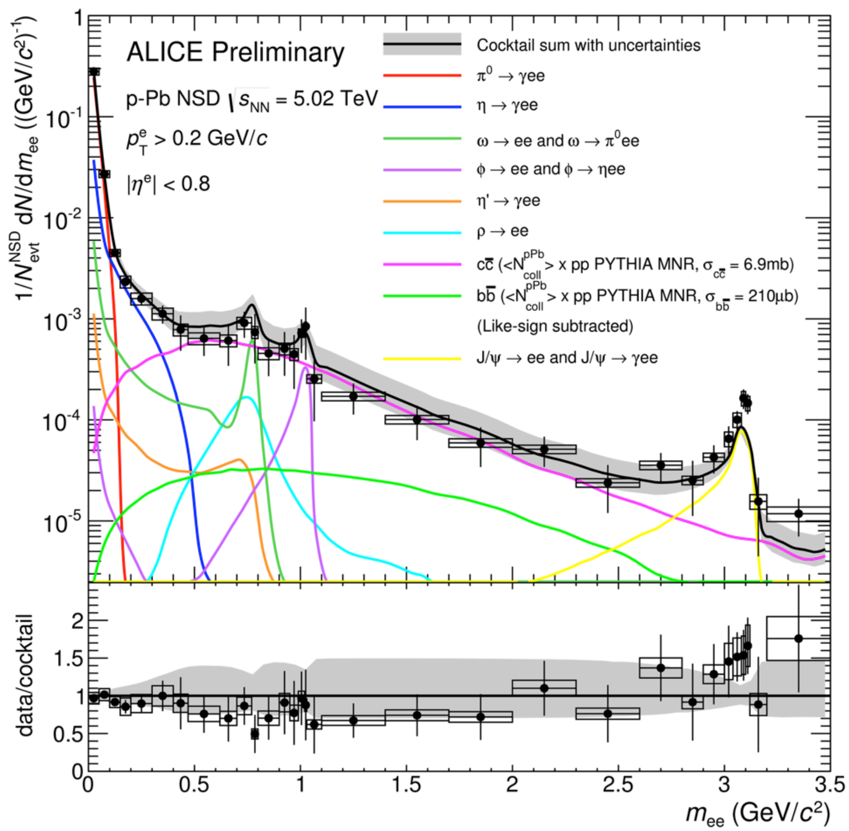
Run 2:

- p-Pb at $\sqrt{s_{NN}}$ = 5.02 and 8 TeV (2016) analysis ongoing



ALICE

p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV (2013)

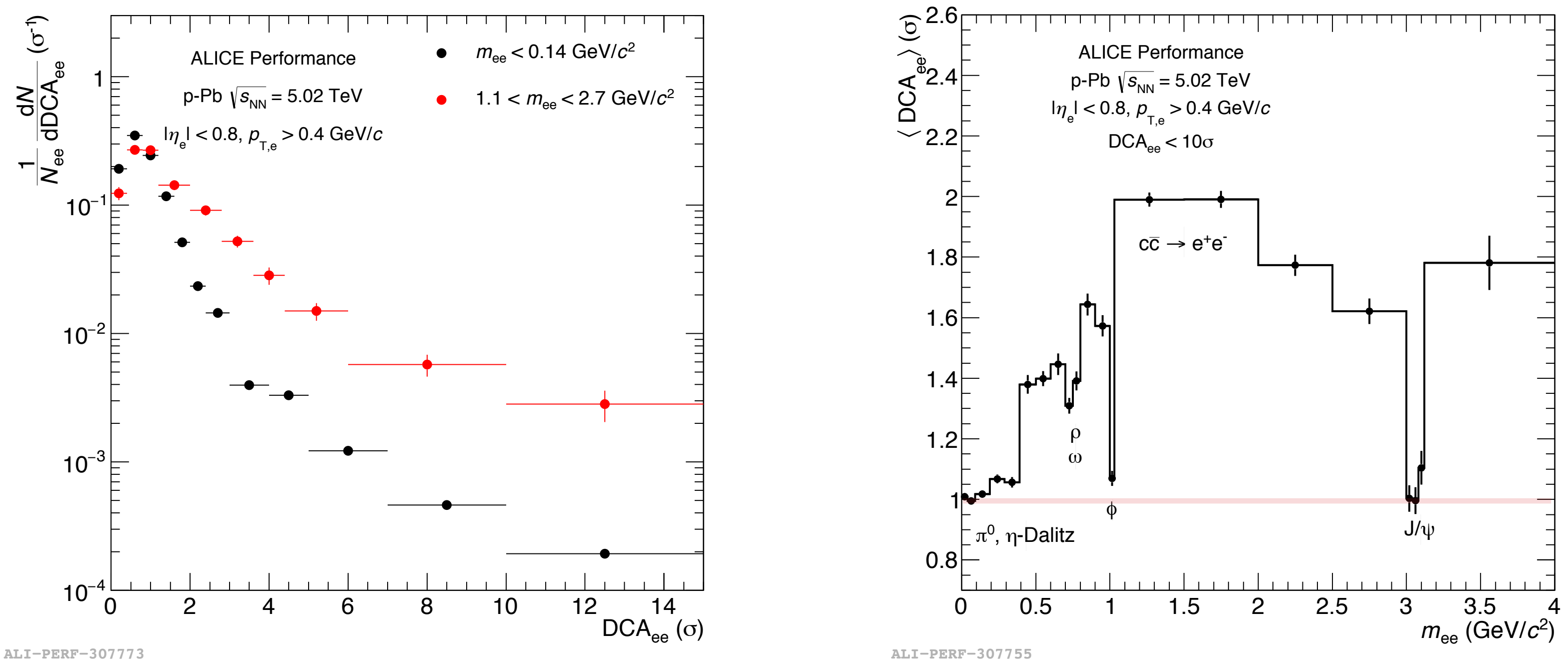


ALI-PREL-69715

- No indication for thermal radiation in min bias p-Pb
- Data are below N_{coll}-scaled HF cocktail indicative of CNM effects in p-Pb

→ p-Pb data set from 2016 has 5 times more statistics

p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV (2016)



High-statistics p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV data set allows study of

- CNM effects on HF production
- (onset of) thermal radiation in high-multiplicity p-Pb collisions

ALICE

Pb-Pb collisions

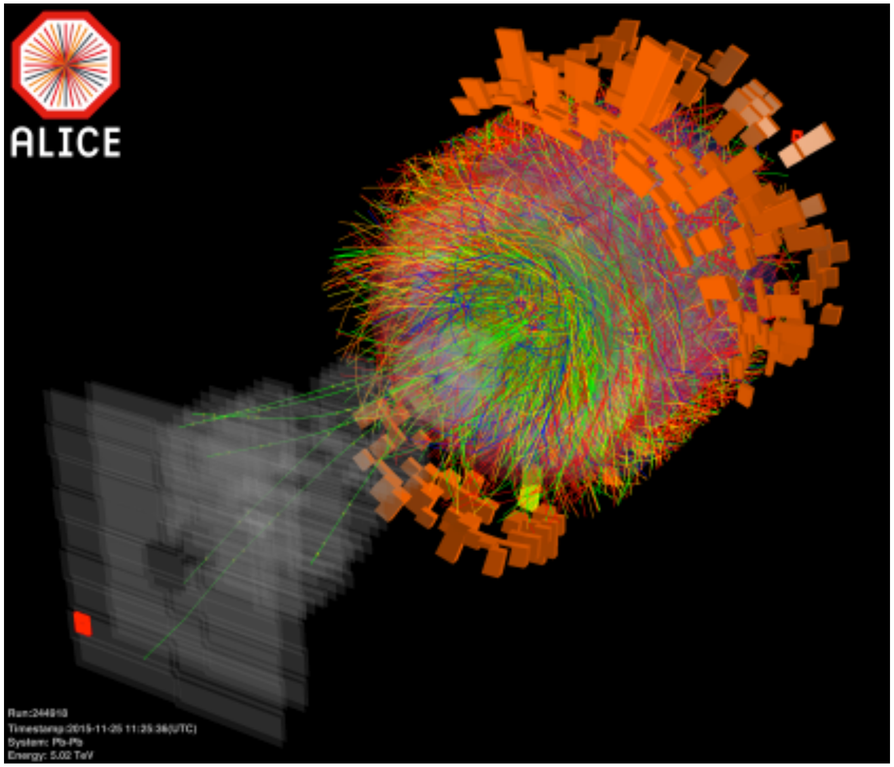
Run 1:

- Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
  ALICE Coll. 1807.00923 (PRC acc.)

Run 2:

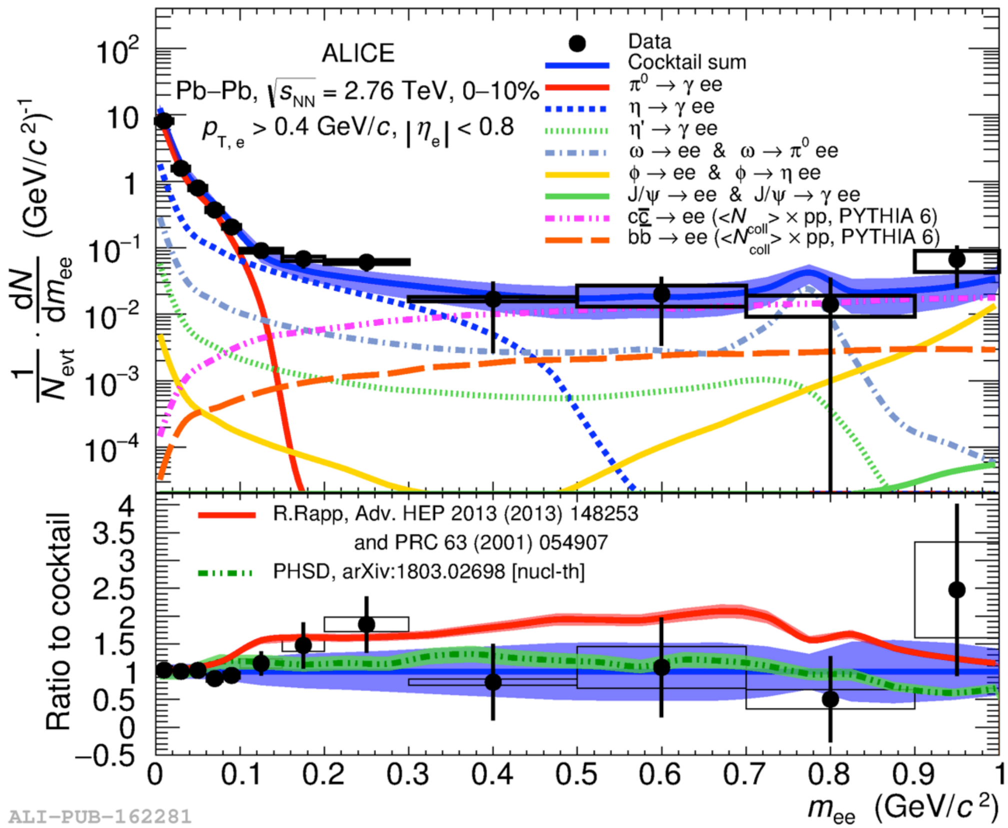
- Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV (2015)
  preliminary

- Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 (2018)
  high-statistics (central and mid-central),
  run ongoing (until Sunday 18:00)



Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

1807.00923 (PRC acc.)



Pioneering study in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

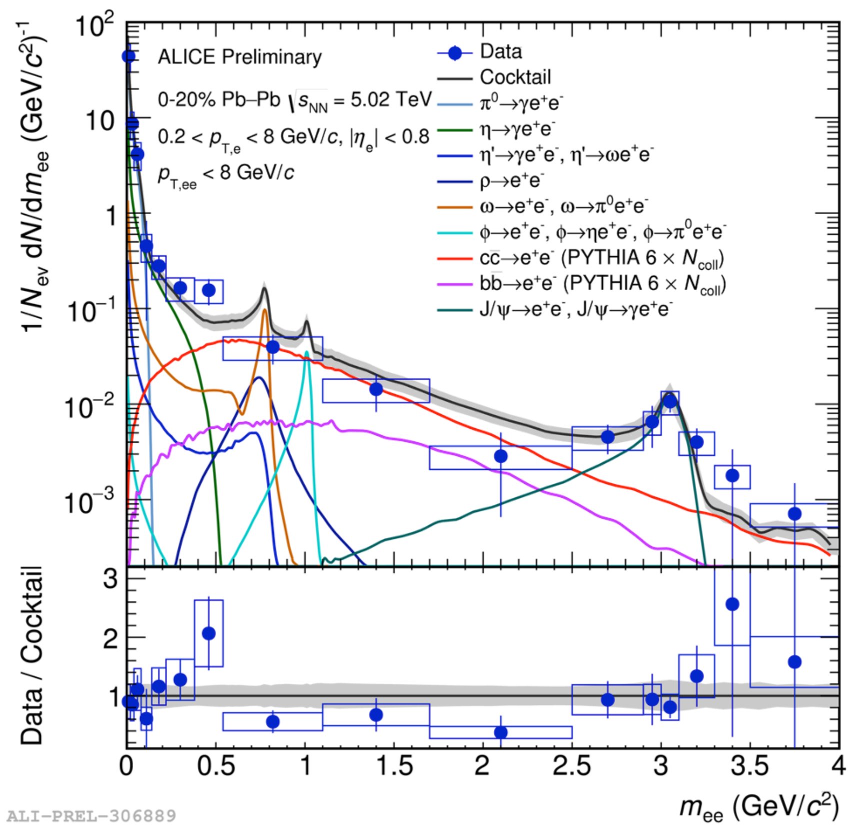
- Indication of **enhancement** over cocktail in $0.15 < m_{ee} < 0.7$ GeV/c^2:

$$1.40 \pm 0.28\ (stat.) \pm 0.08\ (syst.) \pm 0.27\ (cocktail)$$

- Compatible with models including **thermal dielectron production**

ALICE

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

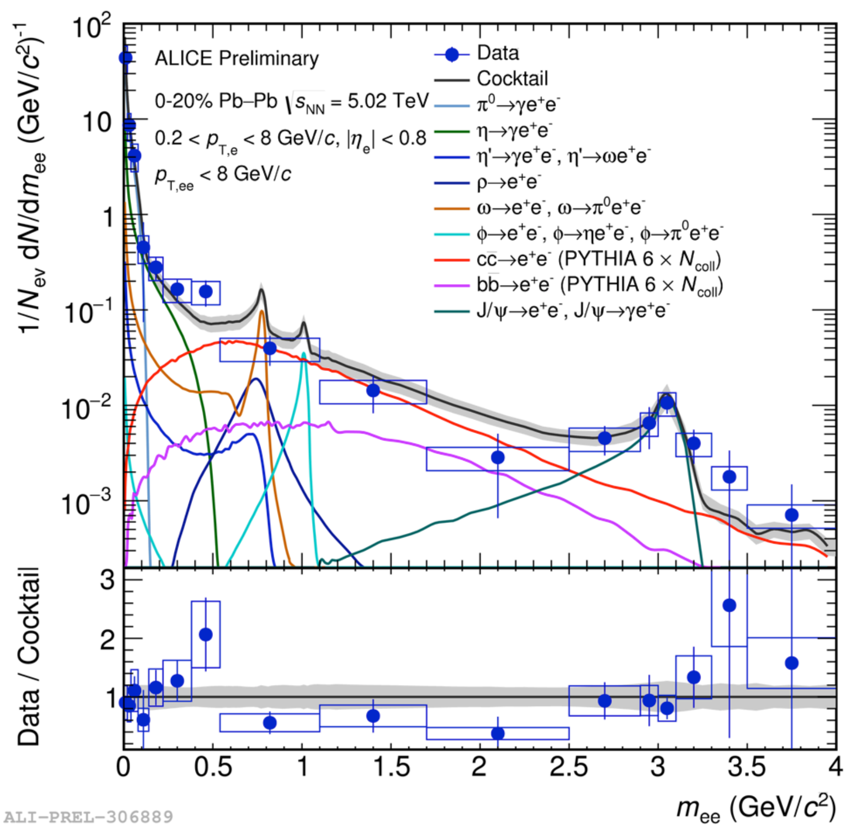


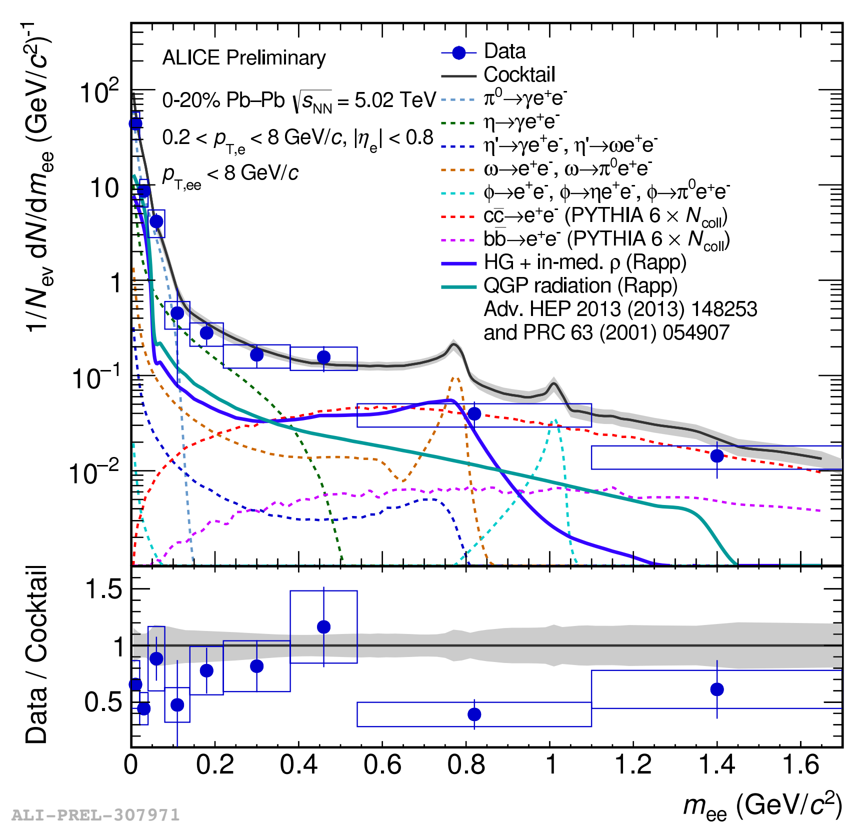
Run2 Pb-Pb data from 2016

- Higher collision energy
- Higher detector efficiency
- More powerful analysis cuts
- Acceptance gain by lowering p_{Te} cut:
  0.4 GeV/c → 0.2 GeV/c
- Ongoing developments:
  Machine Learning for PID

- Preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV are also compatible with low-mass enhancement

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

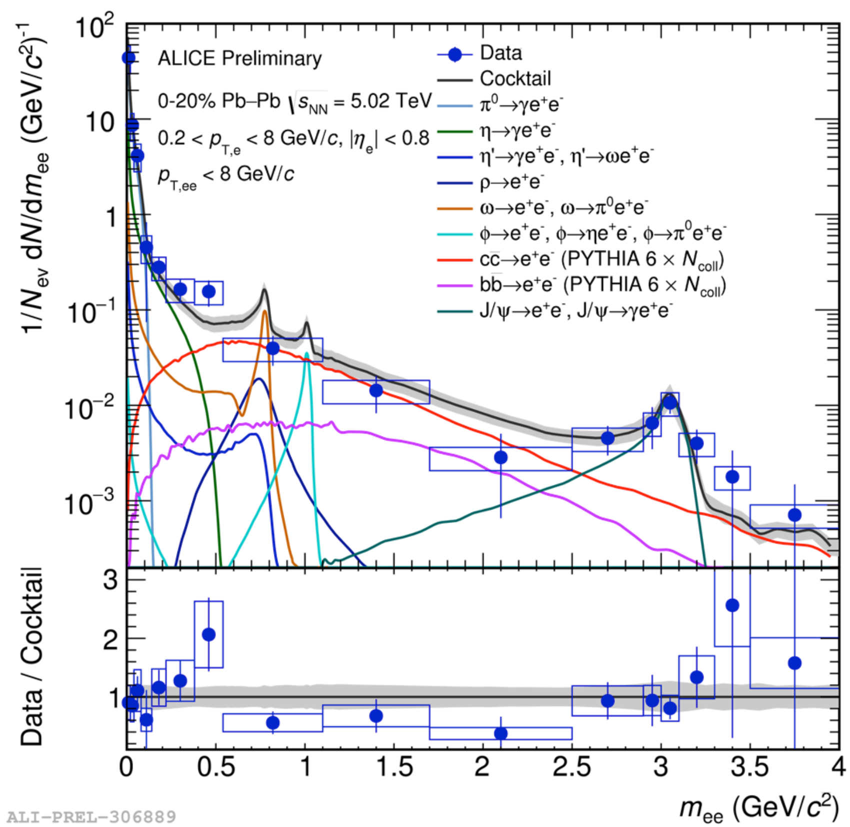




- Preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV are also compatible with low-mass enhancement
- Enhancement is compatible with thermal dielectron production

ALICE

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



- Cocktail including N_{coll} - scaled HF overshoots data in $1.1 < m_{ee} < 2.5$ GeV/c^2:

$$0.53 \pm 0.19\ (stat.) \pm 0.12\ (syst.) \pm 0.13\ (cocktail)$$

→ indication for **charm suppression** in Pb-Pb

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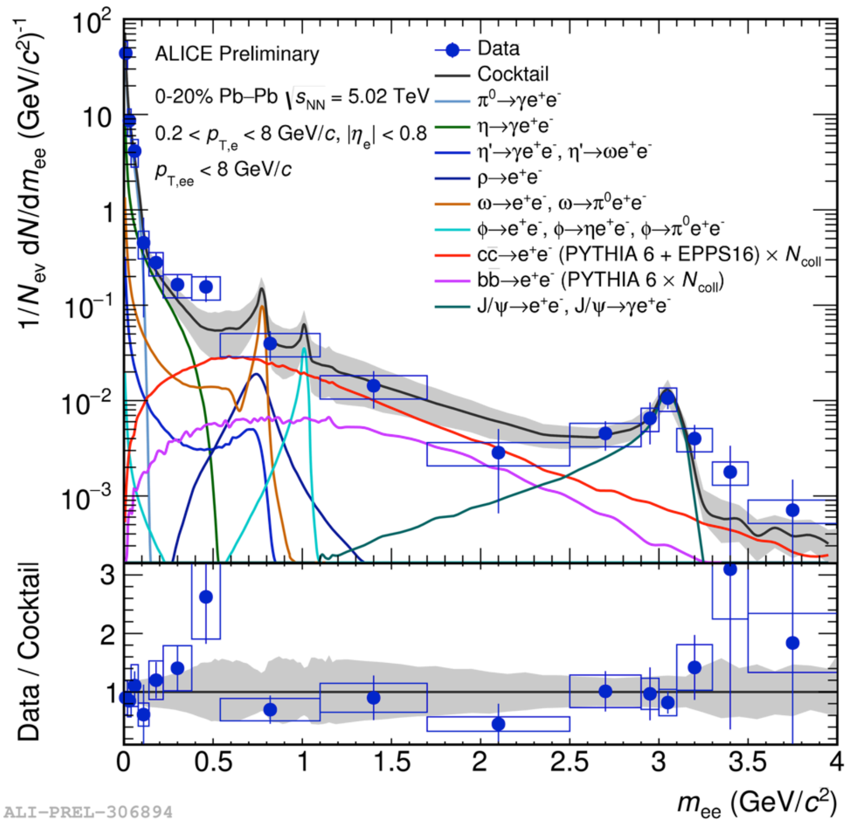

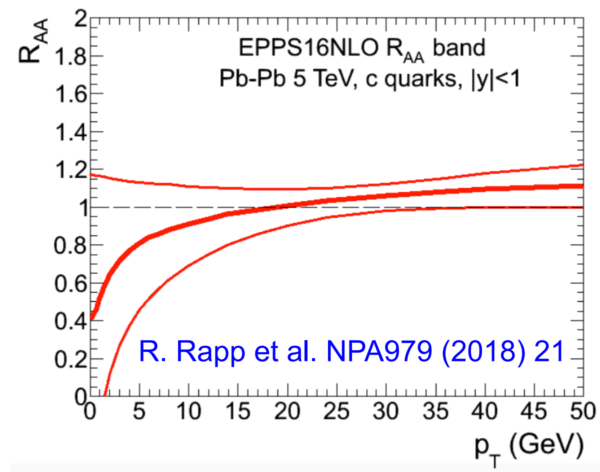

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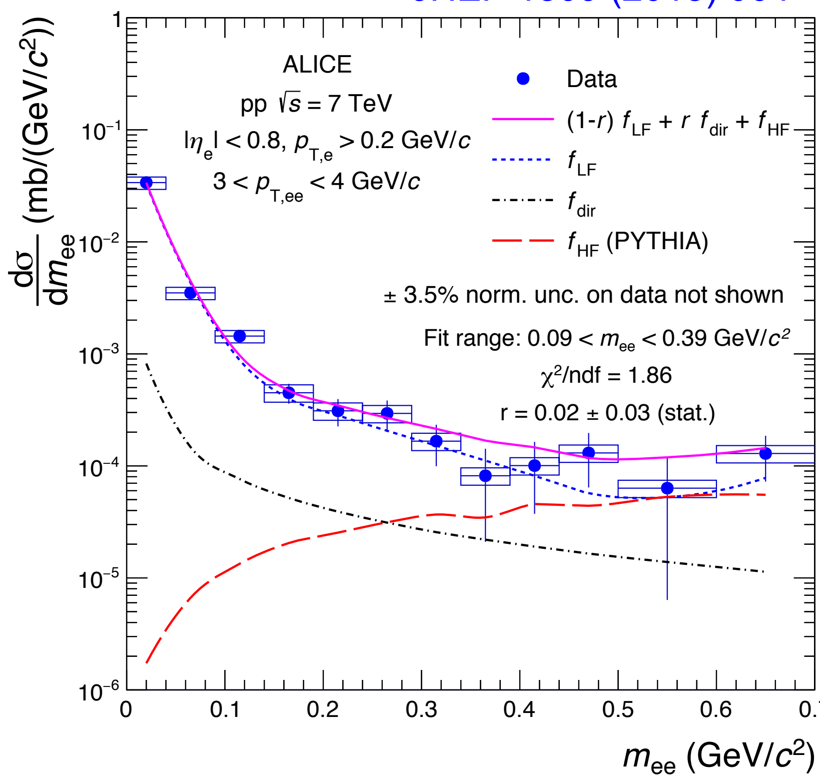
→ indication for **charm suppression** in Pb-Pb

→ Charm cocktail including **CNM effects** (EPPS16) is consistent with data

Virtual direct photons

JHEP 1809 (2018) 064

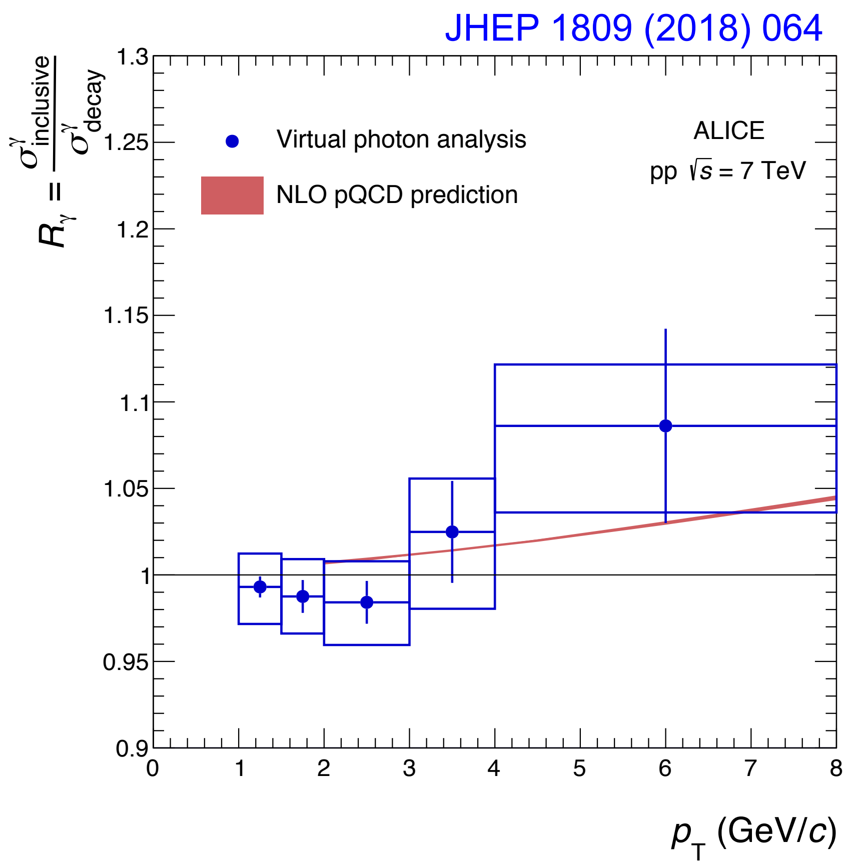


Real and virtual photons are connected by the Kroll-Wada equation (for $p_{T,ee}$):

$$\frac{d^2 N_{ee}}{dm_{ee}\, dp_{T,ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\cdot\frac{1}{m_{ee}}\frac{dN_\gamma}{dp_T}$$

→ Extract direct photon yield by extrapolation to $m_{ee} \to 0$

Virtual direct photons



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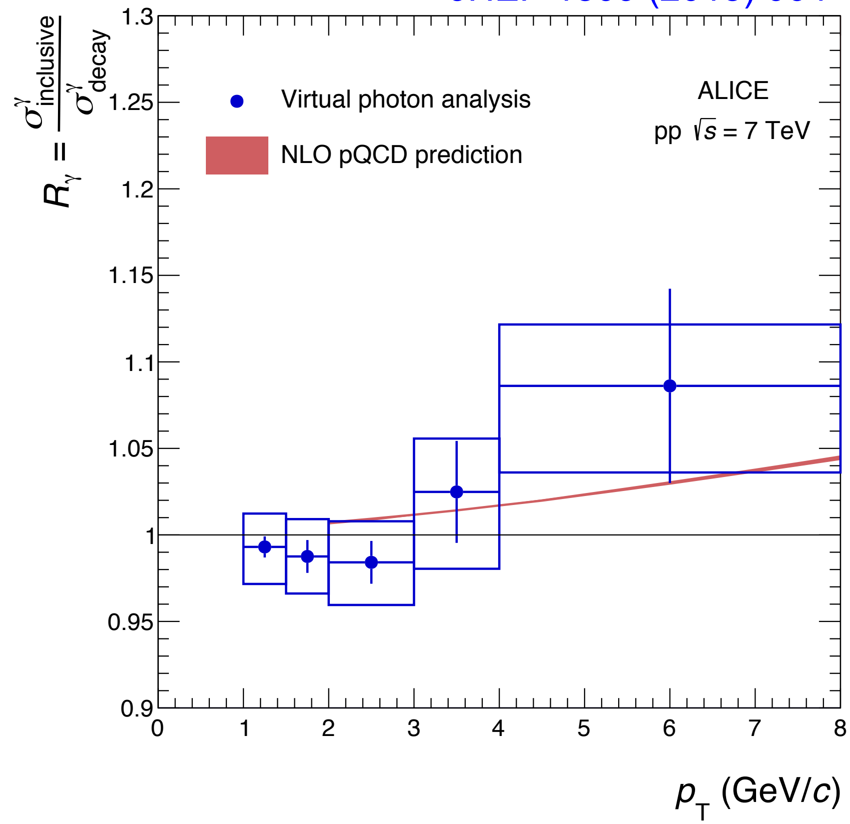
→ Extract direct photon yield by extrapolation to $m_{ee} \rightarrow 0$

- R_γ in pp at √s = 7 TeV from virtual analysis compatible with NLO pQCD

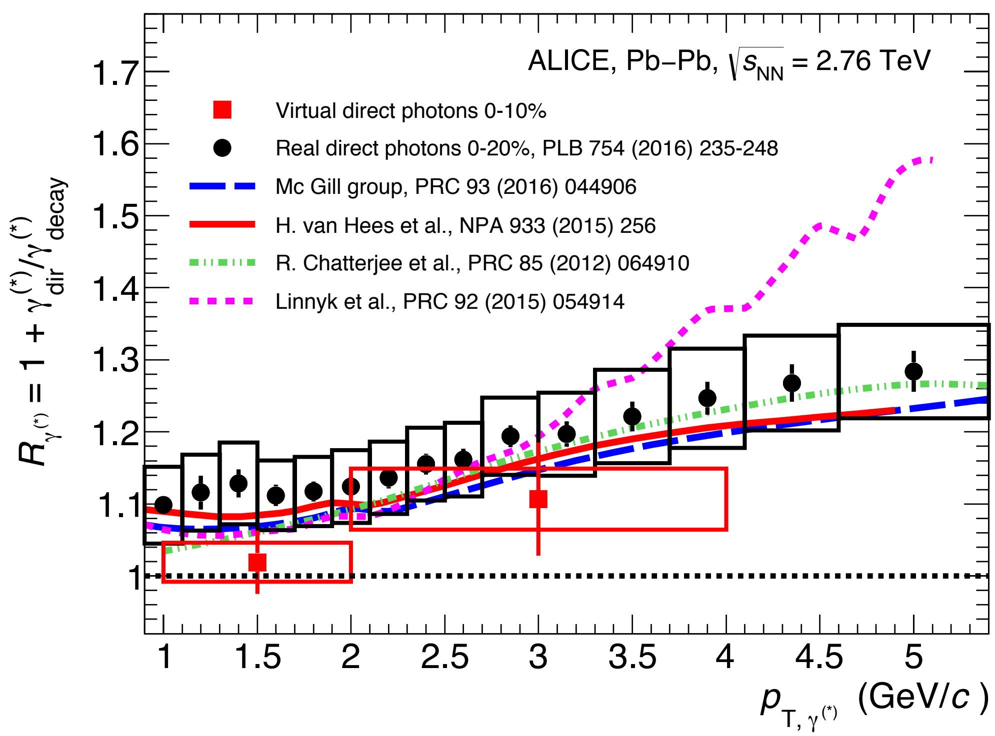
ALICE

Virtual direct photons

JHEP 1809 (2018) 064

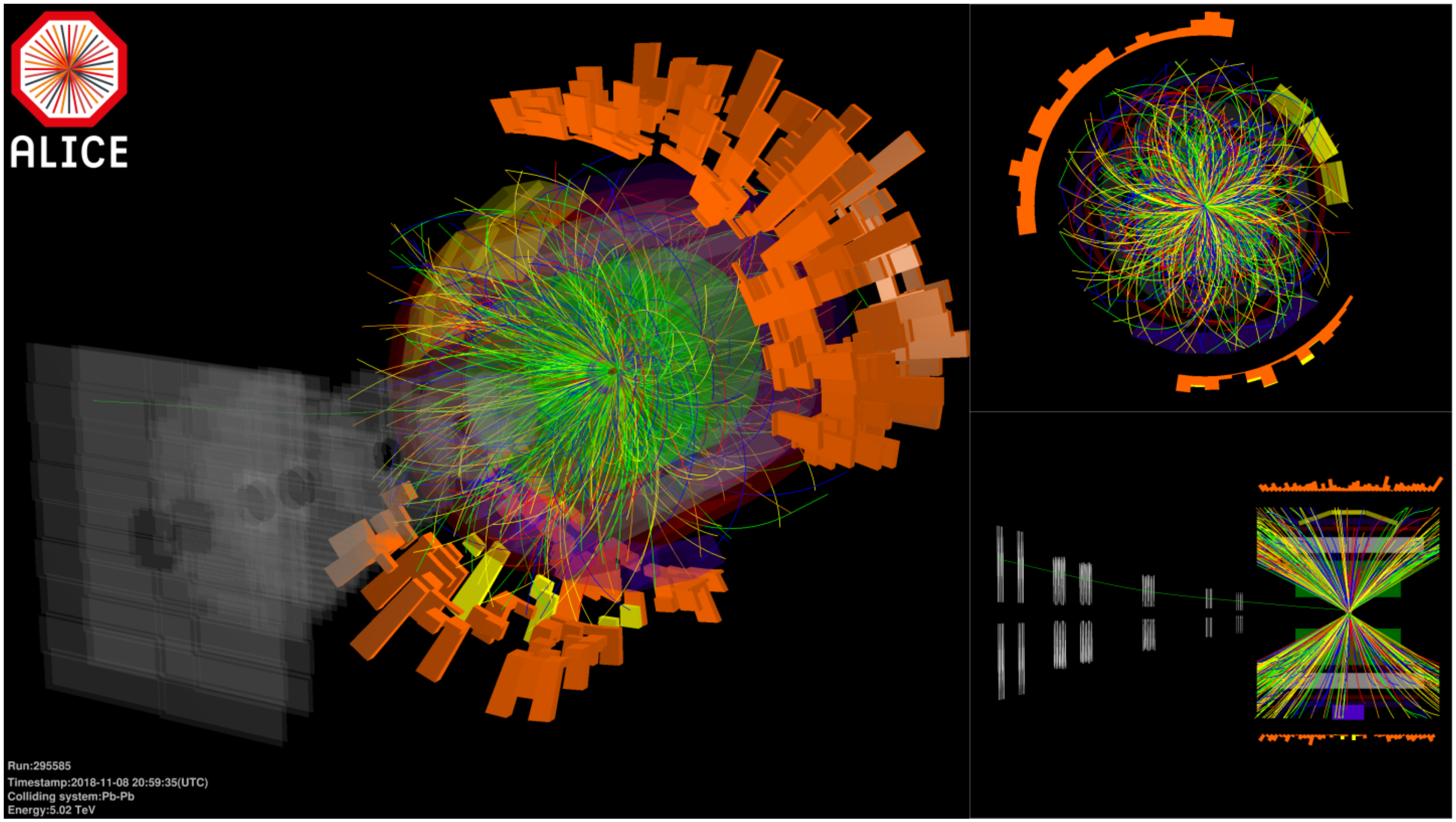


1807.00923 (PRC acc.)



- R_γ in pp at √s = 7 TeV from virtual analysis compatible with NLO pQCD
- R_γ in Pb-Pb compatible with real photon analysis

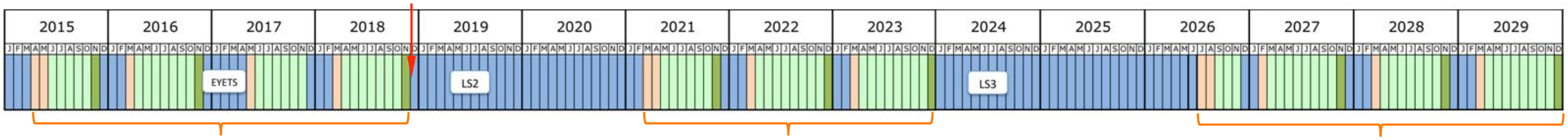
Pb-Pb in 2018



Pb-Pb run in November 2018 – 6-7 times more statistics in central collisions

ALICE

Heavy ions at the LHC in Run 3 and 4



Run 2: $\mathcal{L}_{\text{Pb-Pb}}$ = 1.0 nb^{-1} **Run 3:** $\mathcal{L}_{\text{Pb-Pb}}$ = 6.0 nb^{-1} **Run 4**: $\mathcal{L}_{\text{Pb-Pb}}$ = 7.0 nb^{-1}

ALICE strategy for Run 3 + Run 4:

- 50 kHz Pb-Pb interaction rate (now <10 kHz)
- Experiment upgrades (LS2)
- Collect $L_{\text{Pb-Pb}}$ = 13 nb^{-1} (3 nb^{-1} at B = 0.2 T)

ALICE physics goals

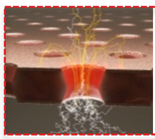
- Heavy-flavour mesons and baryons (down to very low p_T) → mechanism of quark-medium interaction and hadronization of heavy quarks
- Charmonium states → dissociation/regeneration as tool to study de-confinement and medium temperature
- **Di-leptons from QGP radiation and low-mass vector mesons** → χ symmetry restoration, initial temperature and EOS
- High-precision measurement of light and hyper-nuclei → production mechanism and degree of collectivity

→ **Need MB readout at highest possible rate no dedicated trigger possible**

ALICE in Run 3 and 4

New Inner Tracking System (ITS)
- Complementary Metal-Oxide-Semiconductor (CMOS) Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout

New Muon Forward Tracker (MFT)
- CMOS Pixels, MAPS technology
- Vertex tracker at forward rapidity



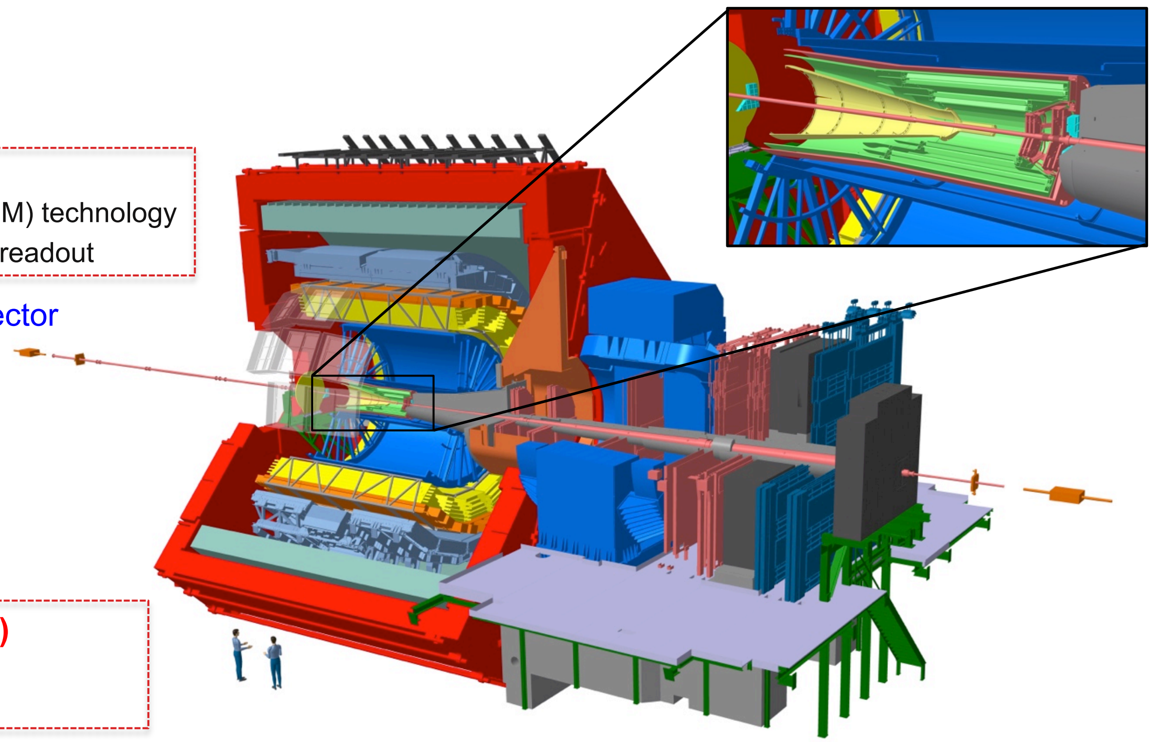
New TPC Readout System
- ROCs with Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

New Fast Interaction Trigger (FIT) Detector
- Centrality, event plane

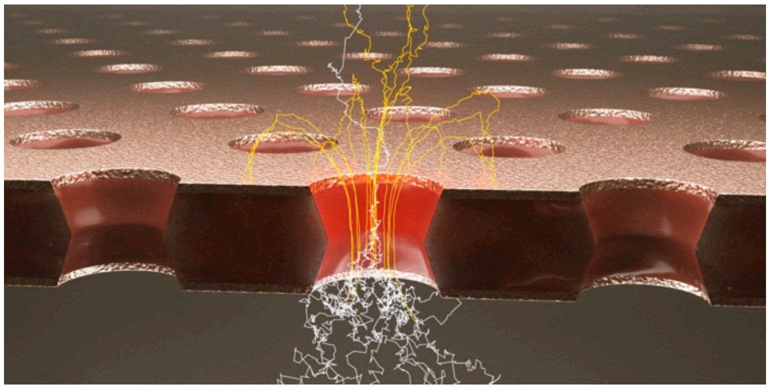
FoCal proposal (Run 4)
- Measure forward direct photons

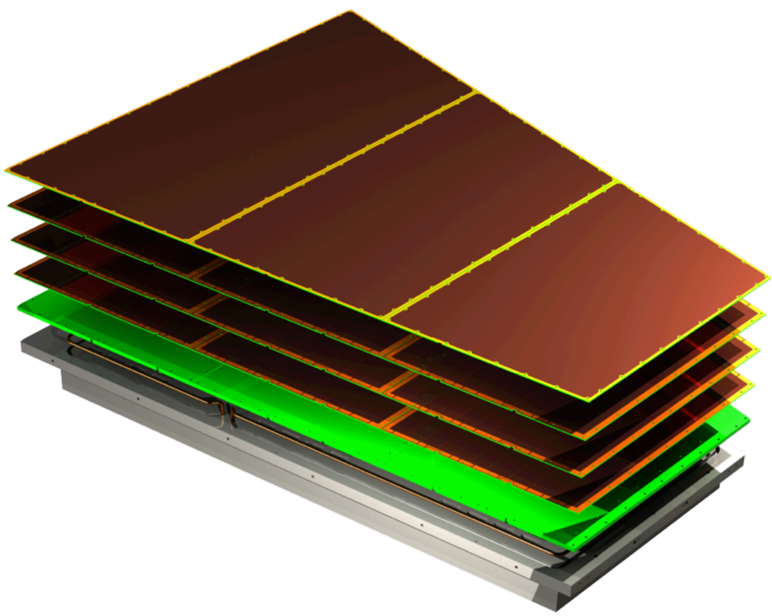
Readout upgrade
- TOF, TRD, MUON, ZDC, Calorimeters

Integrated Online-Offline system (O^2)
- Record MB Pb-Pb data at 50 kHz



ALICE TPC upgrade





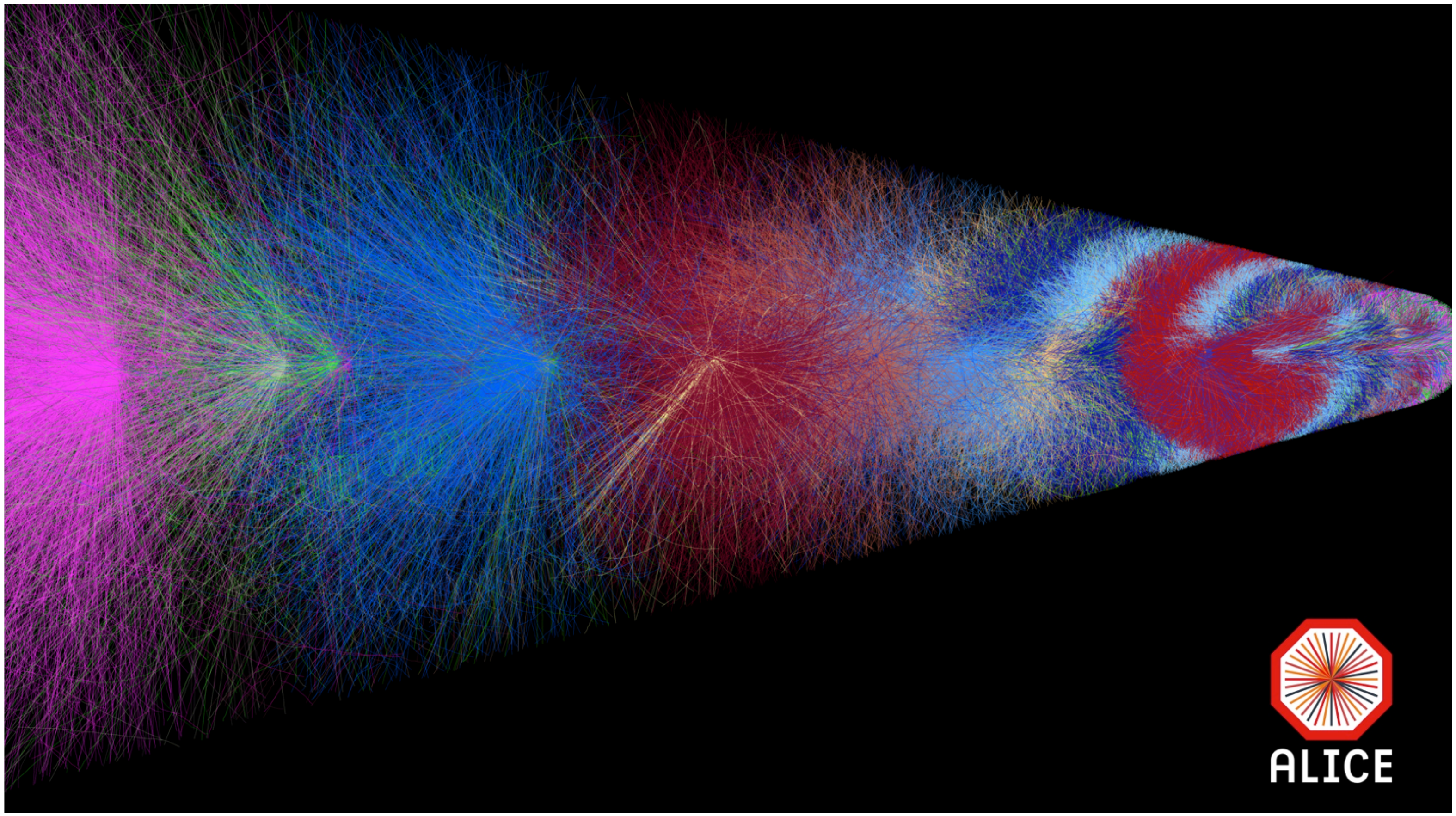
TPC Upgrade requirements

- Continuous readout at 50 kHz in Pb-Pb
- Stable operation under LHC Run 3 conditions
- Unprecedented challenges in terms of loads and performance

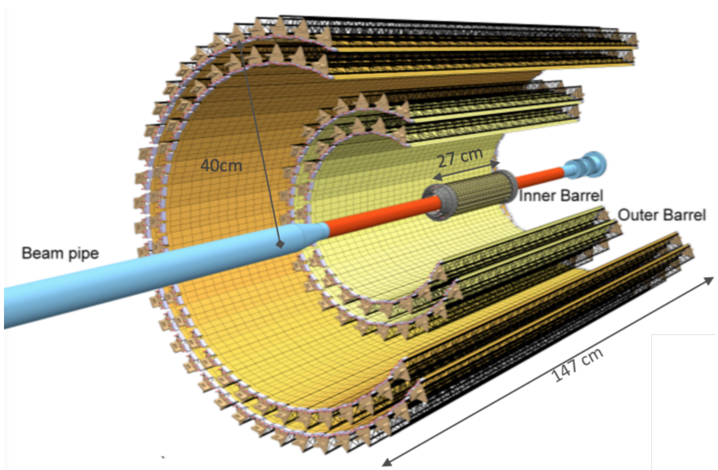
→ new Readout Chambers with GEMs

→ new Frontend Electronics

TPC operation at 50 kHz

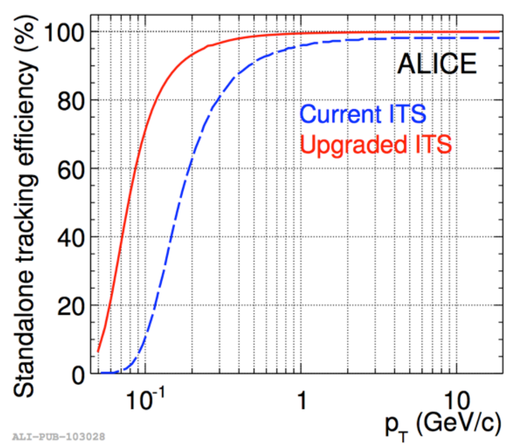


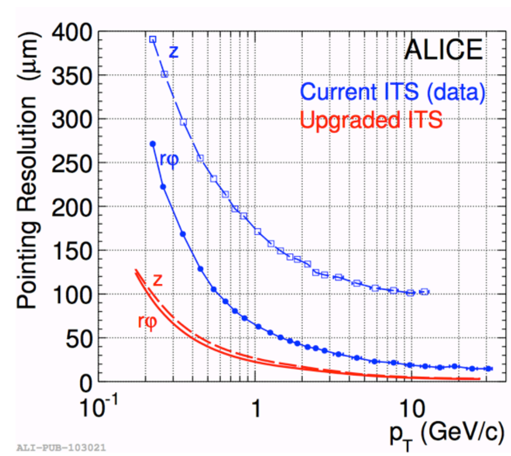
New ALICE ITS



10 m^2 active silicon area, 12.5×10^9 pixels

- Closer to IP: 39 mm ⟶ 22 mm
- Thinner (X_0 for innermost layers): ~1.14 % ⟶ ~0.30 %
- Smaller pixels: 50 × 425 μm^2 ⟶ 27 × 29 μm^2
- Granularity: 20 ch/cm^3 ⟶ 2000 pixels/cm^3
- Readout rate: 1 kHz ⟶ 100 kHz





New-ITS performance

- Improved tracking efficiency
- Improved tracking resolution
- Pointing resolution ×3 better in transverse plane (×6 along beam)
  → significant improvement in DCA_{ee}

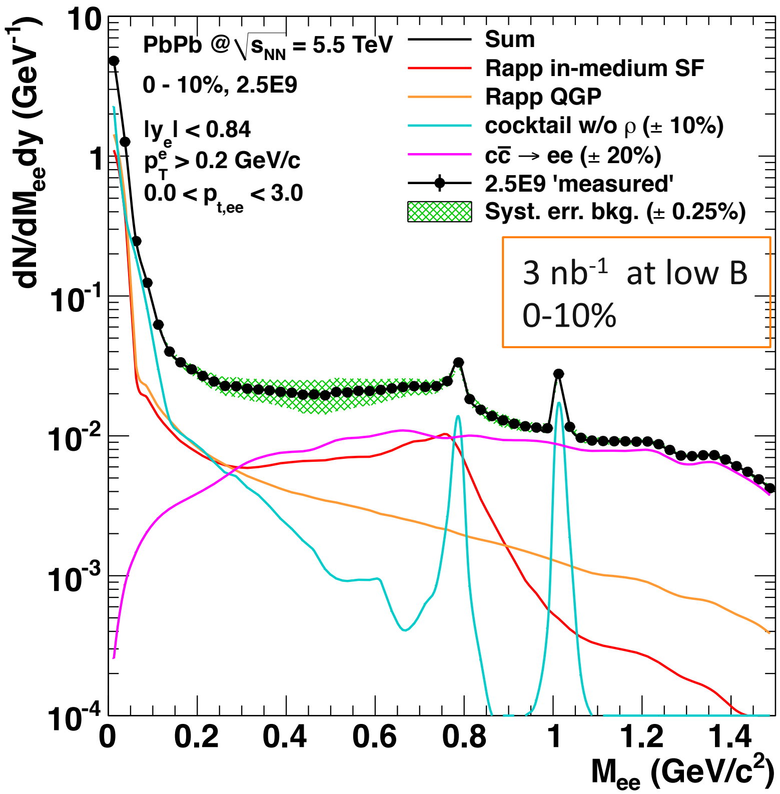
Low-mass dielectrons in Run 3 and 4

Pb-Pb running in Run3 and 4:

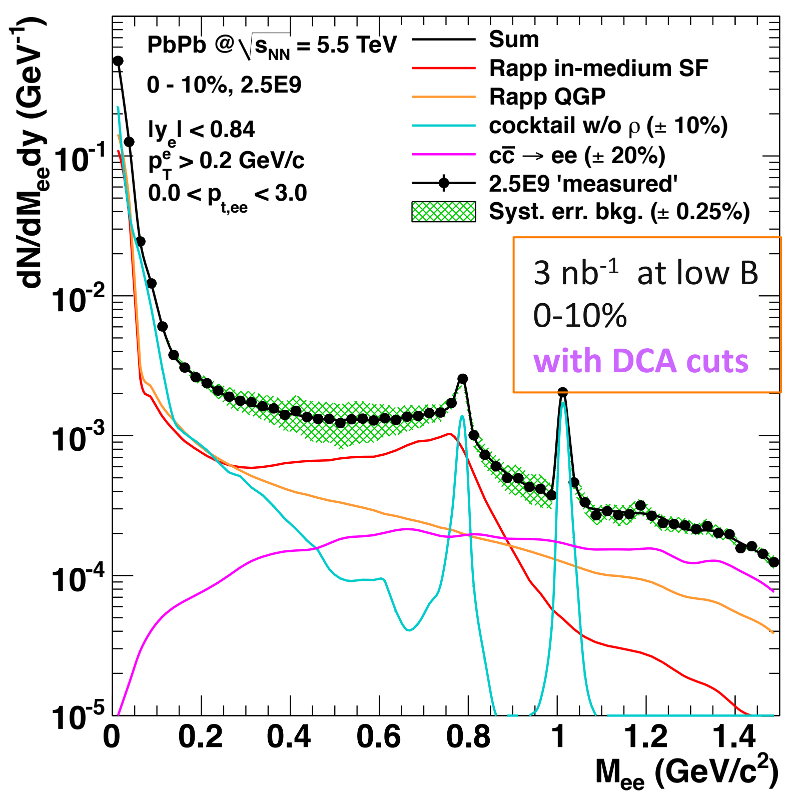
- 13 nb^{-1} (110 B minimum bias collisions) at B = 0.5 T
- 3 nb^{-1} (25 B minimum bias collisions) at B = 0.2 T
  dedicated for low-mass dielectron studies
  - Electron tracking and PID down to 75 MeV/*c*
    → Improve signal efficiency and background rejection
    → increase acceptance to low m_{ee} and $p_{T,ee}$
    → confirmed in low-B pp pilot runs in Run 2 (Jerome Jung's talk)
  - Separation of prompt dileptons from charm and beauty with new ITS
    → not yet fully implemented to Run 3 simulations

Inclusive mass spectrum in Run 3

ALICE LoI J. Phys. G41 (2014)



ALICE LoI J. Phys. G41 (2014)



Significant suppression of cc pairs by DCA cuts with the new ITS

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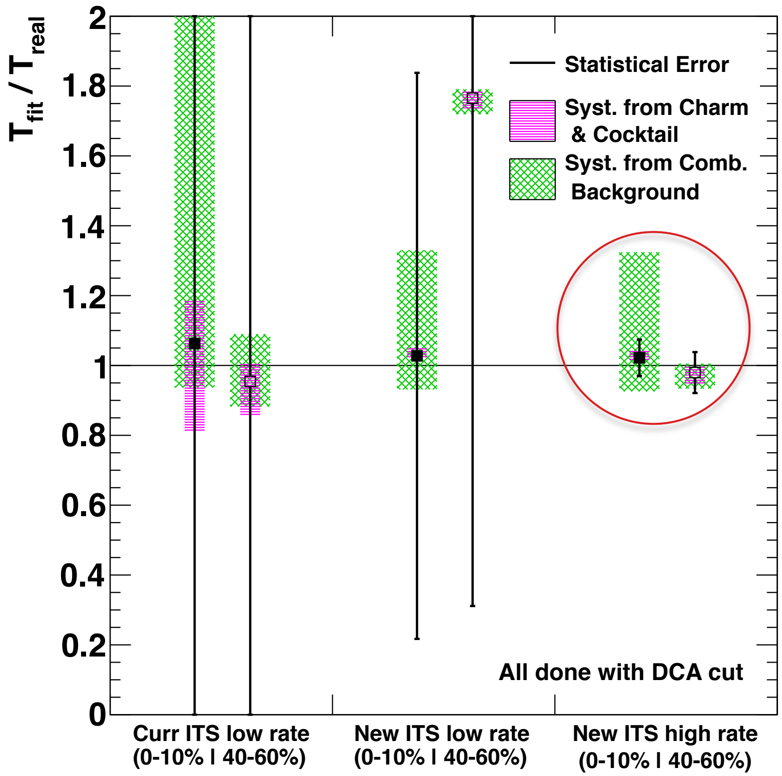
Excess mass spectrum and QGP temperature

ALICE LoI J. Phys. G41 (2014)



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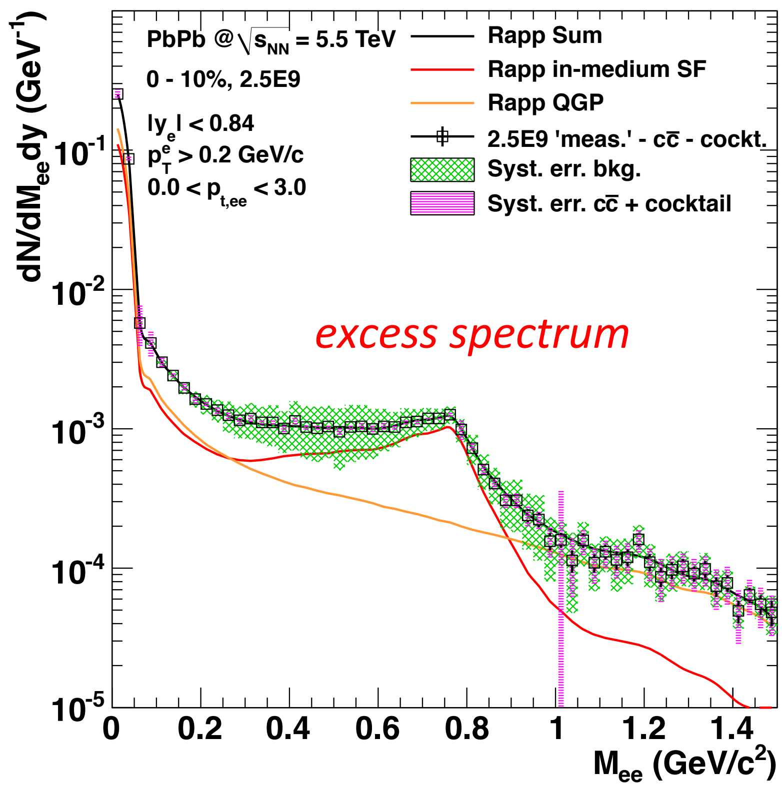
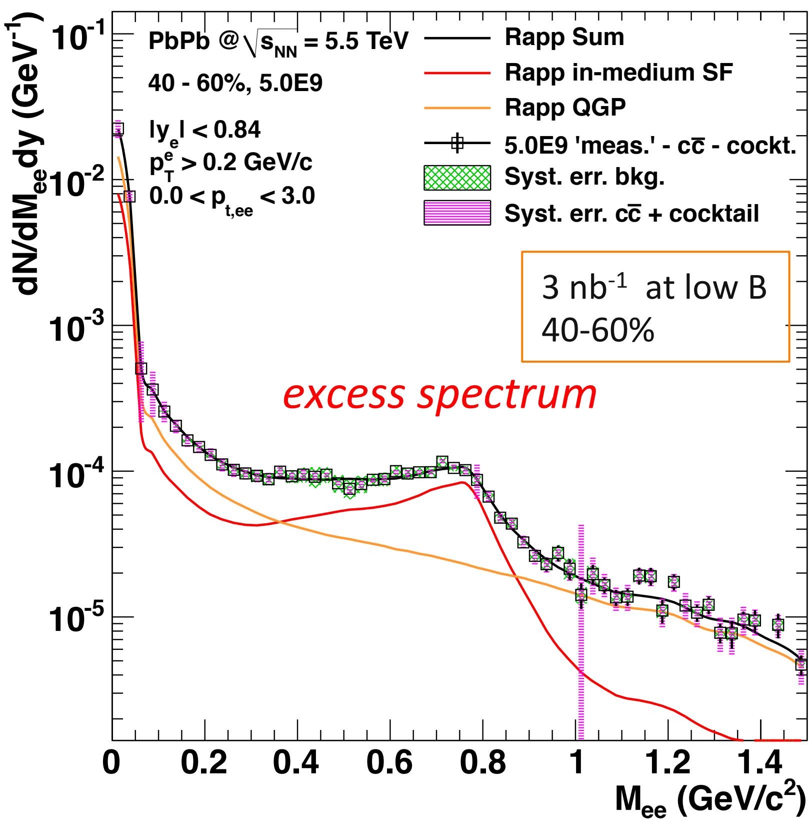


Fit to the IMR makes precise determination of T_{eff} possible

Flow of QGP radiation

ALICE LoI J. Phys. G41 (2014)



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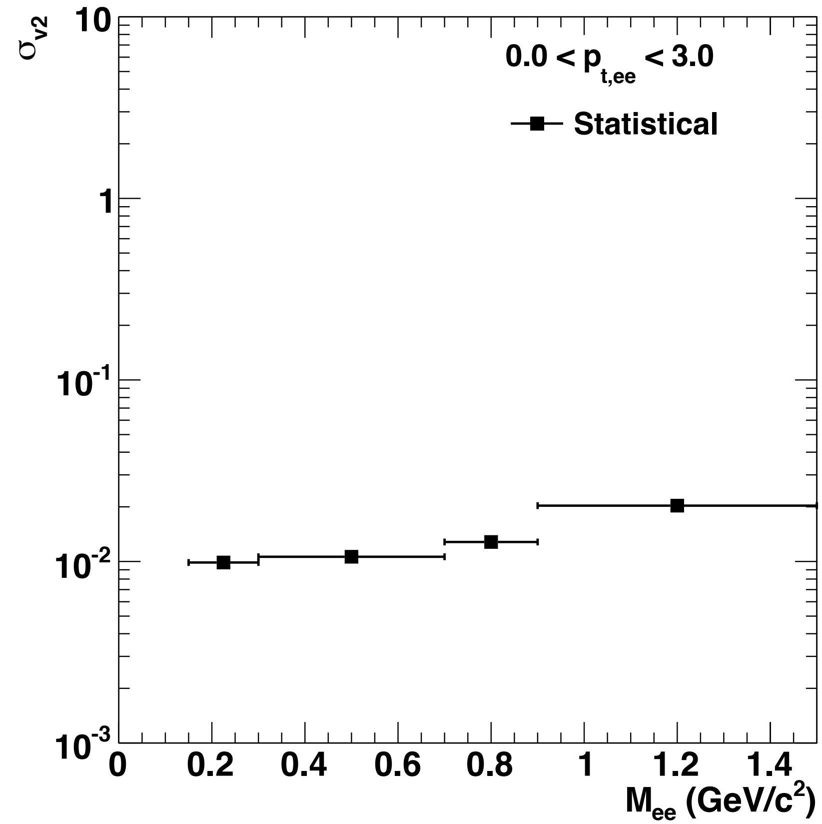

Statistical precision of v_2 measurement: 0.01-0.02

ALICE

New TPC readout chambers at P2

Run2 ends Sunday 18:00

Upgrade starts Monday 8:00

Summary

- Dielectron analysis in ALICE has reached cruising speed
- First results from Run1 and Run2 are available:

  Dielectron production in proton-proton collisions at √s=7 TeV
  ALICE Collaboration, JHEP 1809 (2018) 064
  Dielectron and heavy-quark production in inelastic and high-multiplicity proton-proton collisions at √s=13 TeV
  ALICE Collaboration, 1805.04407 (PLB acc.)
  Measurement of dielectron production in central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
  ALICE Collaboration 1807.00923 (PRC subm.)

- High-statistics data sets at 5.02 TeV are available in pp, p-Pb and Pb-Pb from Run 2
- ALICE upgrade for Run 3 and Run 4 will provide unique opportunities for precision measurements of thermal radiation in Pb-Pb at the LHC