Production of muons from heavy-flavour hadron decays in heavy-ion collisions with ALICE

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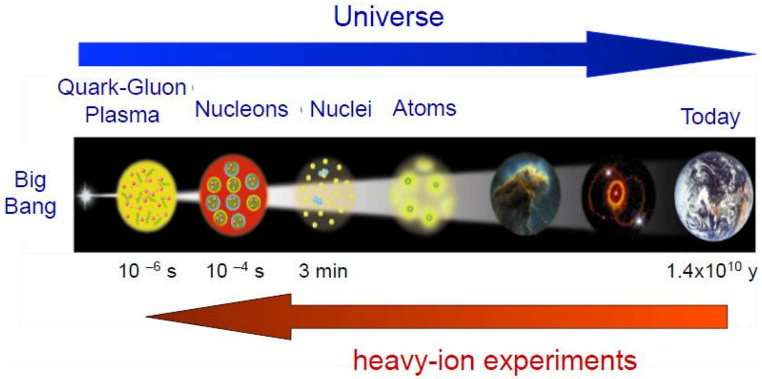
Outline

- Physics motivation
- Open heavy-flavour measurements with the ALICE muon spectrometer
- Analysis procedure
- Results
- Summary and outlook

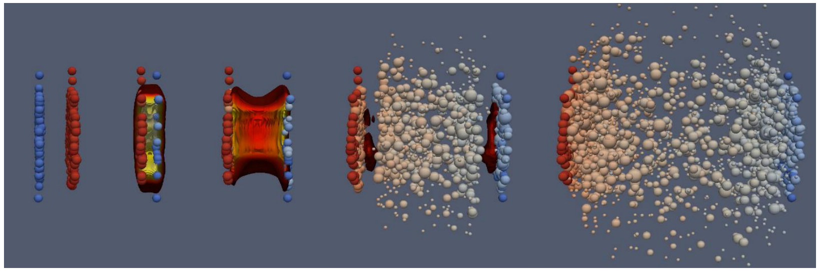
FCPPL2018, 22-25 May 2018, Marseille, France

Physics motivations (1/2)

- Quantum chromodynamics (QCD) predicts a phase transition from hadronic matter to a deconfined partonic medium, the Quark-Gluon Plasma (QGP), at high temperature
- QGP similar to early Universe (~ first few μs)
- QGP can be produced and studied in the lab by means of heavy-ion collisions



time-evolution of heavy-ion collisions



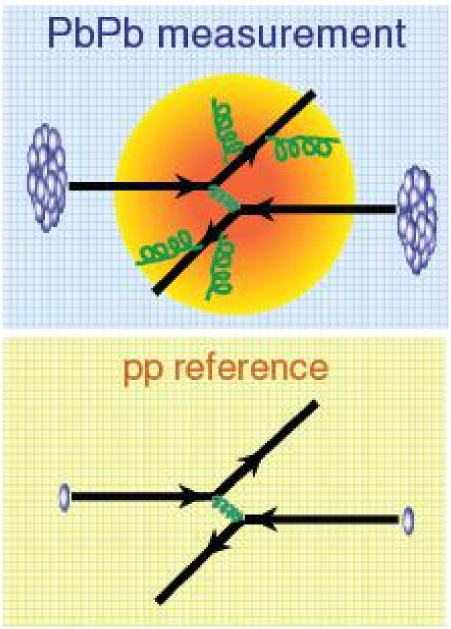
- First QGP signals from Super Proton Synchrotron (SPS, CERN, Switzerland)
- First QGP properties from Relativistic Heavy Ion Collider (RHIC, USA)
- Large Hadron Collider (LHC, CERN, Switzerland): precision measurements thanks to higher beam energy (x 30 RHIC)
  - ✓ hotter, bigger and longer-living system
  - ✓ larger cross section of hard probes (heavy quarks)

Physics motivations (2/2)

Charm and beauty quarks: sensitive probes of the medium properties

Open heavy flavours in nucleus-nucleus (A-A) collisions probe

- In-medium parton energy loss: gluon radiation and elastic collisions
- Heavy-quark participation in the collective expansion



Also needed:

- proton-proton (pp) collisions
  reference, tests of pQCD-based predictions
- p-A collisions
  reference, cold nuclear matter effects

Observable

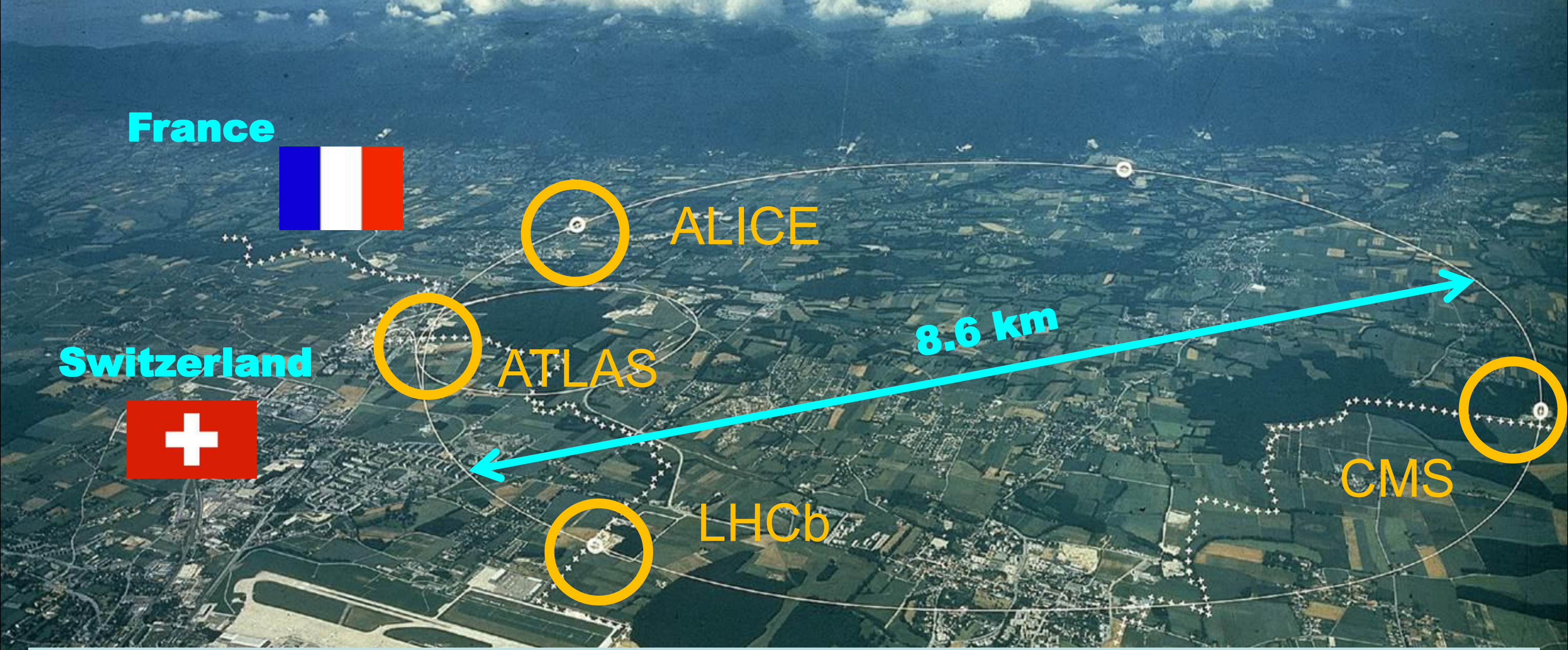
✓ The nuclear modification factor, R_{AA}, sensitive to the medium effects

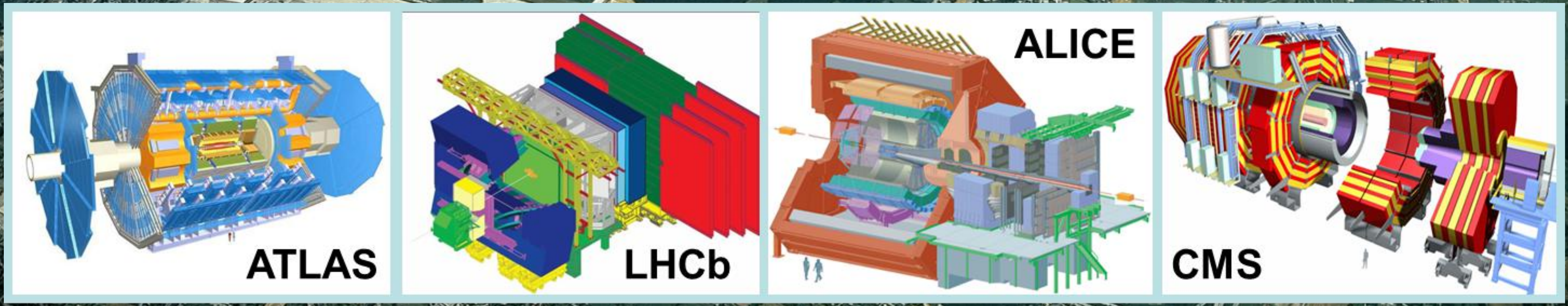
$$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{QCD\ \text{Medium}}{QCD\ \text{Vacuum}}$$

✓ If no nuclear effects: R_{AA} = 1

✓ Effects of the hot and dense medium produced in the collision breakup binary scaling: RAA ≠ 1

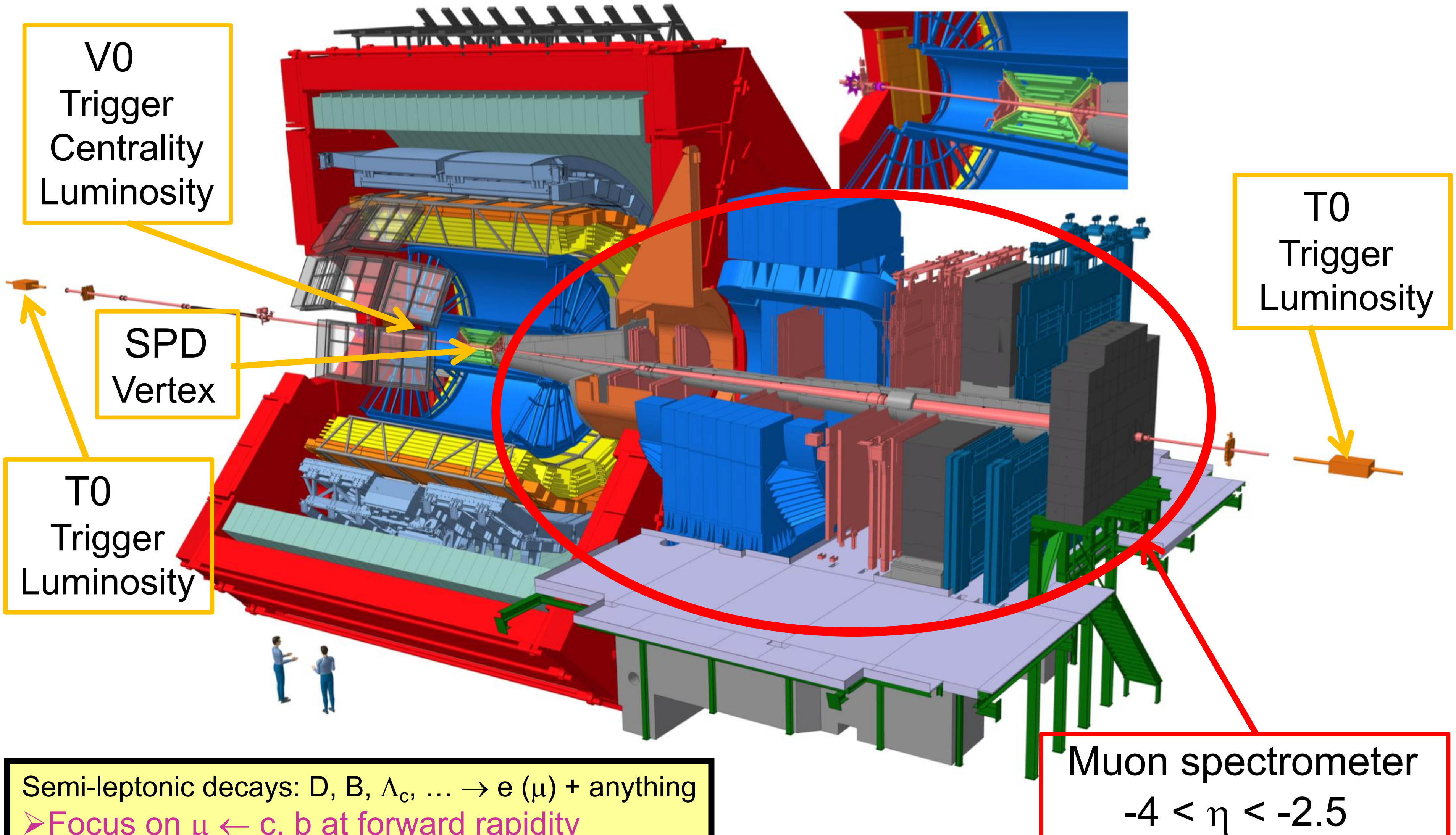
The LHC (Large Hadron Collider) @ CERN (European Organization for Nuclear Research)





Heavy-ion experiments: **ALICE**, ATLAS, CMS, LHCb

ALICE Run-2 setup



Semi-leptonic decays: D, B, Λ_c, … → e (μ) + anything

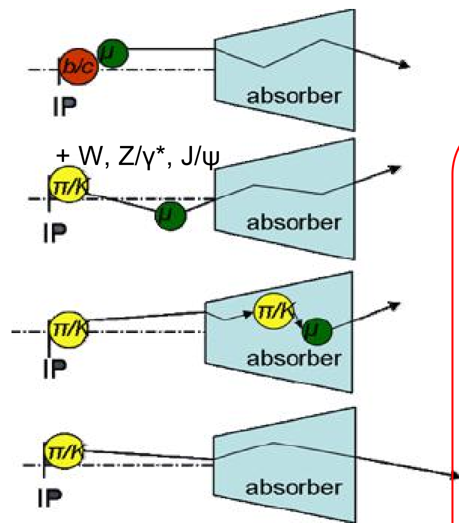
➢Focus on $\mu \leftarrow$ c, b at forward rapidity

Data samples and muon selections

	pp collisions at √s = 5.02 TeV	Xe-Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV
Data samples	LHC15n, collected in 2015	LHC17n, collected in 2017
Triggers	MSL (MSH): p_T threshold ~ 0.5 (4.2) GeV/c	MSL: p_T threshold ~ 1 GeV/c
L_{int}	MSL(MSH): ≈ 53.7 (104.4) nb^{-1}	MSL: ≈ 0.34 μb^{-1}

Muon track selection

- **Acceptance & geometrical cuts**
  select tracks in the spectrometer acceptance
- **p_T cut at 2 GeV/c**
  reject μ from secondary π, K
- **Muon tracking tracks matched with muon trigger tracks**
  reject hadrons crossing the front absorber
- **$p \times$DCA (Dist. of Closest Approach) in 6σ**
  reject beam-gas interactions & particles produced in the absorber



μ from heavy flavours

μ from primary π, K, W,Z/γ*, J/ψ

μ from secondary π, K

punch through hadrons

background ⟺

$\mu^{\pm} \leftarrow$ b, c studies

- **Remaining background**
  $\mu \leftarrow$ primary π, K decays (main contribution at low p_T)
  $\mu \leftarrow$ W, Z/γ* decays (main contribution at high p_T)
  $\mu \leftarrow$ J/ψ decays (main contribution at p_T ~ 5 GeV/c)

Analysis procedure in pp collisions

ALICE

$$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \cdot \frac{dN_{AA}^{\text{inclusive } \mu}/dp_T - dN_{AA}^{\text{bkg}}/dp_T}{d\sigma_{pp}^{\mu<-HF}/dp_T}$$

- Get inclusive muons with muon-triggered data, after muon event and track selection. Then **normalize inclusive muons to minimum-bias events** and **apply acceptance x efficiency correction**
- **Background: μ←π/K (dominates at low p_T, max. ~40% at 2 GeV/*c*)**
  - ✓ Inputs: π/K spectra at mid-rapidity at 5.02 TeV, extrapolated to higher p_T via power-law fit
  - ✓ Then, get π/K spectra in 4π with p_T-dependent rapidity shape in Monte-Carlo via:

$$\frac{1}{N_{ev}}\frac{d^2N_{pp}^{K/\pi}}{dp_T dy} = \frac{1}{N_{ev}}\frac{dN_{pp}^{K/\pi}}{dp_T}\Big|_{|y|<0.8} \times F(p_T, y)$$

  - ✓ Produce the π/K decay muon background in Monte-Carlo with fast simulation with parametrized muon front absorber response
- **Background: μ←W, Z/γ* (dominates at high p_T, max. ~13% in [18,20] GeV/*c*)**
  - ✓ Obtained from pp collisions by (POWHEG) simulation with CT10 PDF
- **Background: μ←J/ψ (dominates at p_T ~ 5 GeV/*c*, small compared to μ←π/K)**
  - ✓ Use J/ψ extrapolated p_T and *y* distributions as inputs, convert J/ψ spectra to muons with fast simulation, max. ~4% contribution at p_T ~ 5 GeV/*c*

Analysis procedure in Xe-Xe collisions

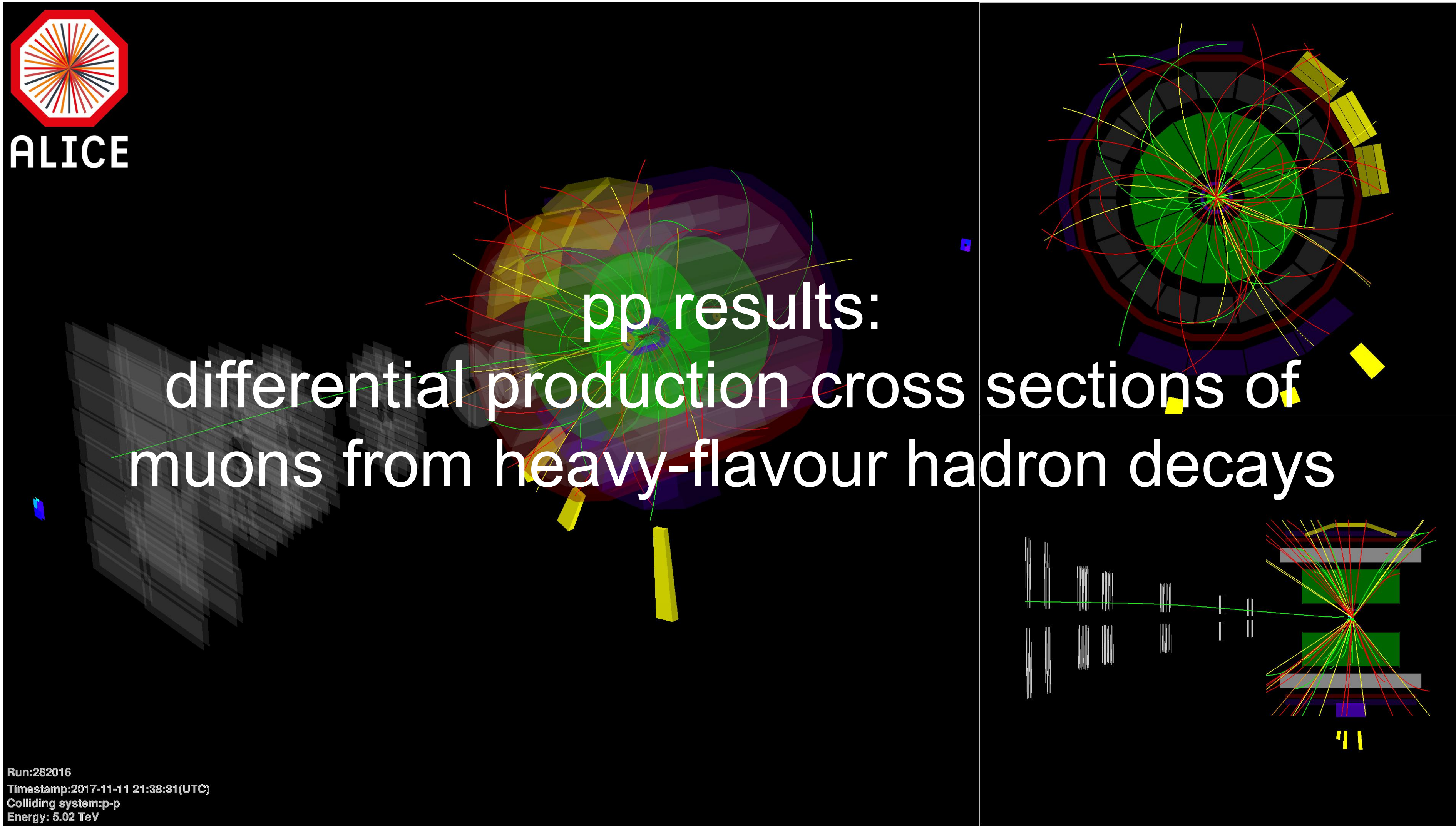
$$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \cdot \frac{dN_{AA}^{inclusive\ \mu}/dp_T - dN_{AA}^{bkg}/dp_T}{d\sigma_{pp}^{\mu<-HF}/dp_T}$$

- ☐ Get inclusive muons with muon-triggered data, after muon event and track selection. Then **normalize inclusive muons to minimum-bias events** and **apply acceptance x efficiency correction**
- ☐ **Background: μ←π/K (dominates at low p_T)**
  - ✓ Inputs: π/K spectra at mid-rapidity at 5.44 TeV, extrapolated to higher p_T
  - ✓ Then, get π/K spectra in 4π with p_T-dependent rapidity shape in Monte-Carlo via:

$$\frac{d^2N_{AA}^{K/\pi}}{dp_T dy} = n_y \times R_{AA} \times F(p_T, y) \times \frac{dN_{pp}^{K/\pi}}{dp_T}\Big|_{|y|<0.8} = n_y \times F(p_T, y) \times \frac{dN_{AA}^{K/\pi}}{dp_T}\Big|_{|y|<0.8}$$

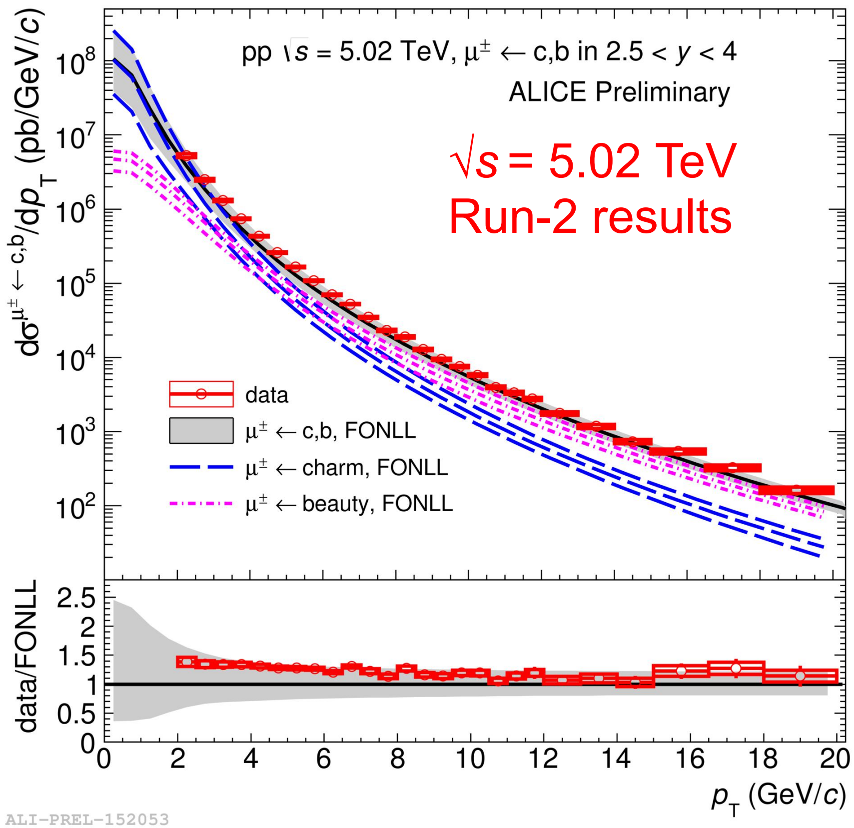
n_y (= 1): quenching factor, systematic uncertainty varying n_y within 0.5-1.5
$F(p_T, y)$: p_T-dependent y extrapolation factor, from pp simulations with Monte-Carlo event generators

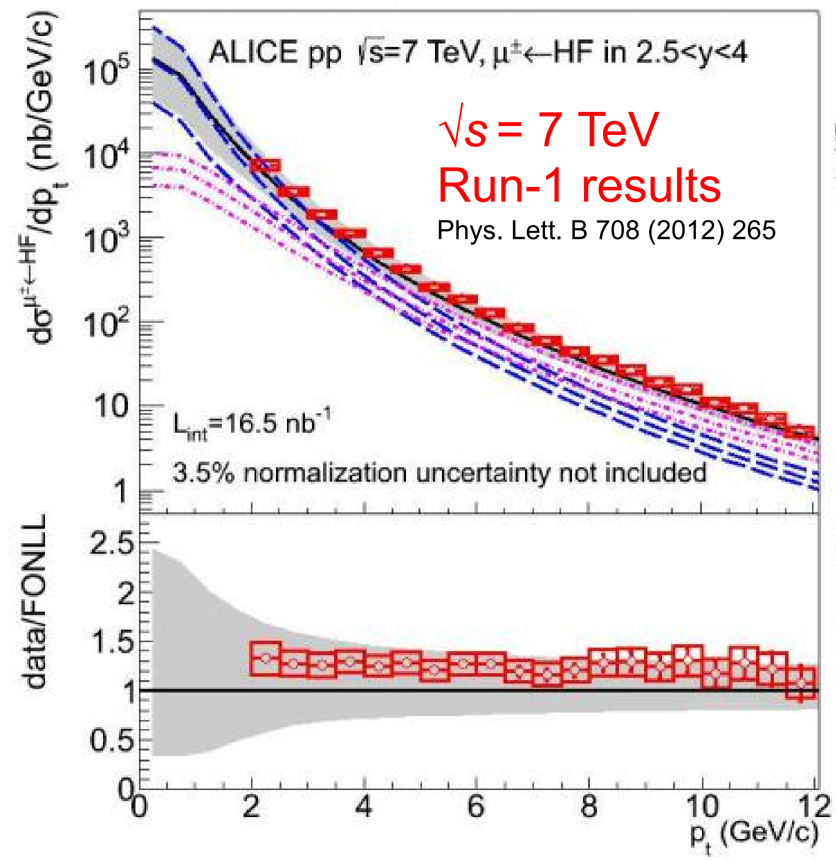
  - ✓ Produce the π/K decay muon background in Monte-Carlo with fast simulation with parametrized muon front absorber response
- ☐ **Background: μ←J/ψ (dominates at p_T ~ 5 GeV/c, small compared to μ←π/K)**
  - ✓ Use J/ψ extrapolated p_T and y distributions as inputs, convert J/ψ spectra to muons with fast simulation, max. ~4% contribution at p_T ~ 5 GeV/c



pp results: differential production cross sections of muons from heavy-flavour hadron decays

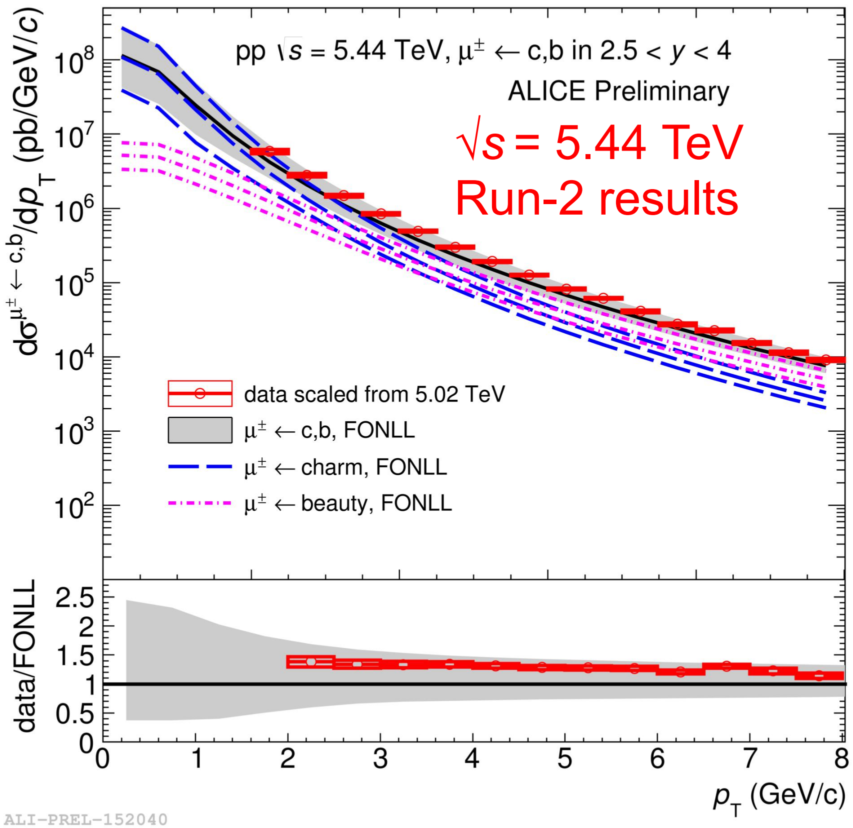
p_T-differential production cross section (1/2)

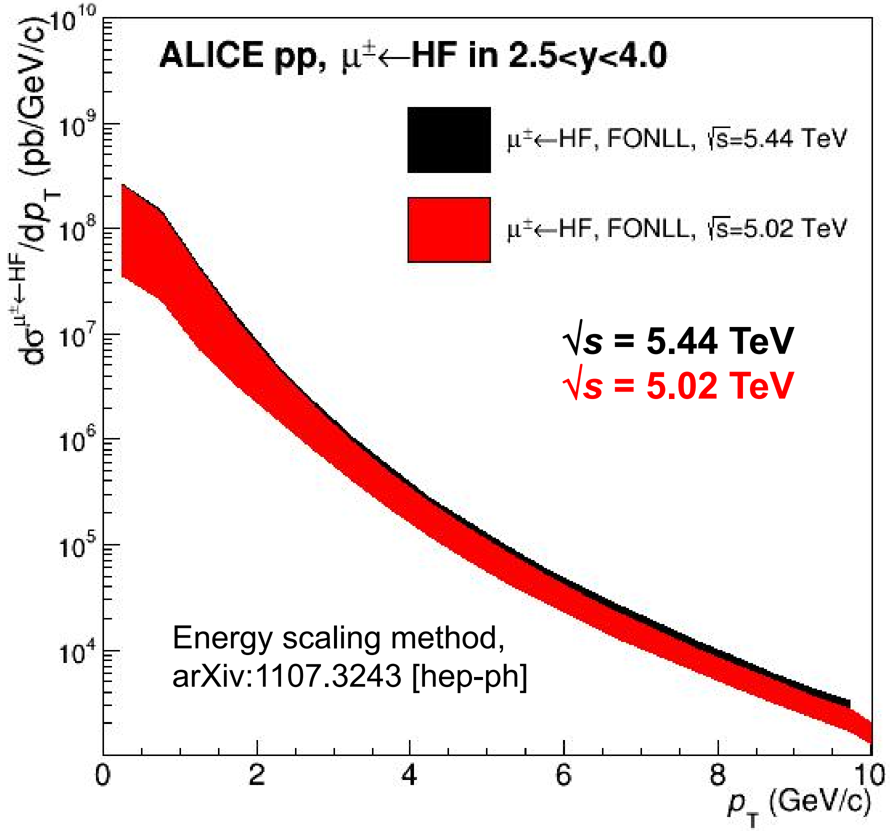




- Measurement over a wide p_T range: $2 < p_T < 20$ GeV/c in pp collisions at 5.02 TeV
- Data in agreement with FONL predictions within uncertainties although at the upper edge of FONLL predictions
- Quite precise measurement, strong constraints on pQCD-based calculations
- The reference for Pb-Pb measurements at $\sqrt{s_{NN}}$ = 5.02 TeV
- Systematic uncertainties reduced by about a factor two, compared to Run-1 results

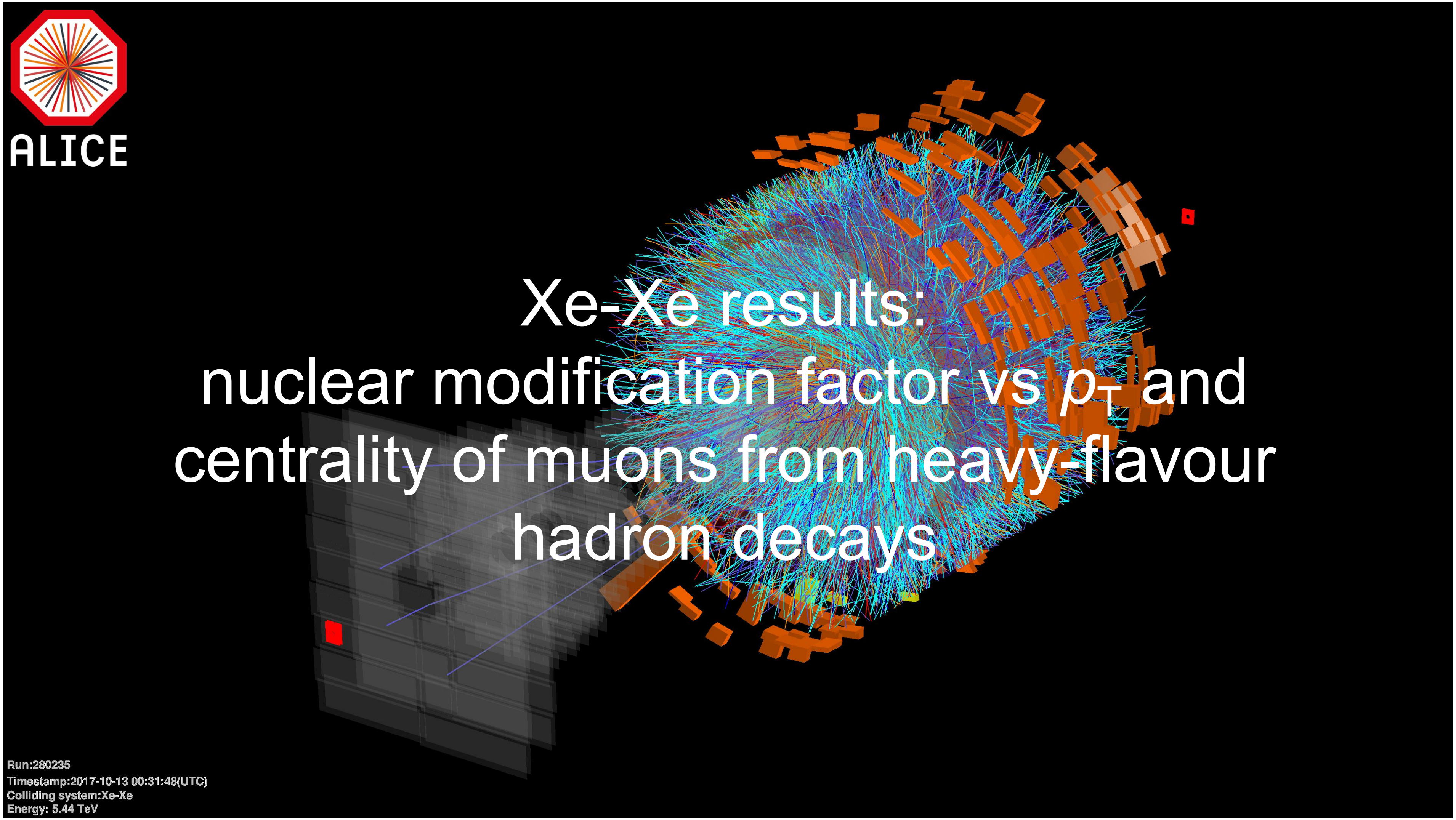
p_T-differential production cross section (2/2)



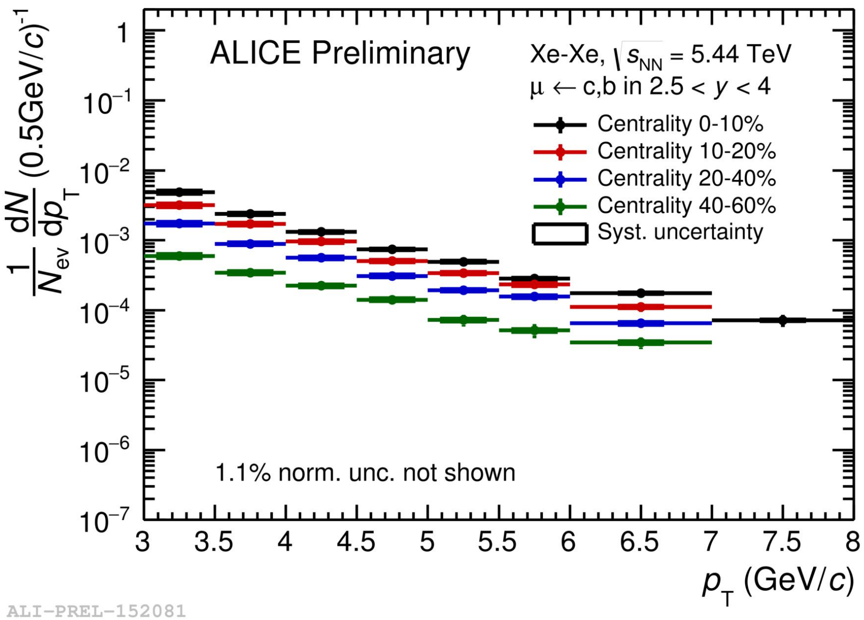


- $\sqrt{s}$ = 5.02 TeV measurement in 3 < p_T < 8 GeV/c scaled to $\sqrt{s}$ = 5.44 TeV with FONLL
- Data in agreement with FONL predictions, strong constraints on pQCD-based calculations
- The reference for Xe-Xe measurements at $\sqrt{s_{NN}}$ = 5.44 TeV

Xe-Xe results:
nuclear modification factor vs p_T and centrality of muons from heavy-flavour hadron decays



Normalized p_T-differential yields

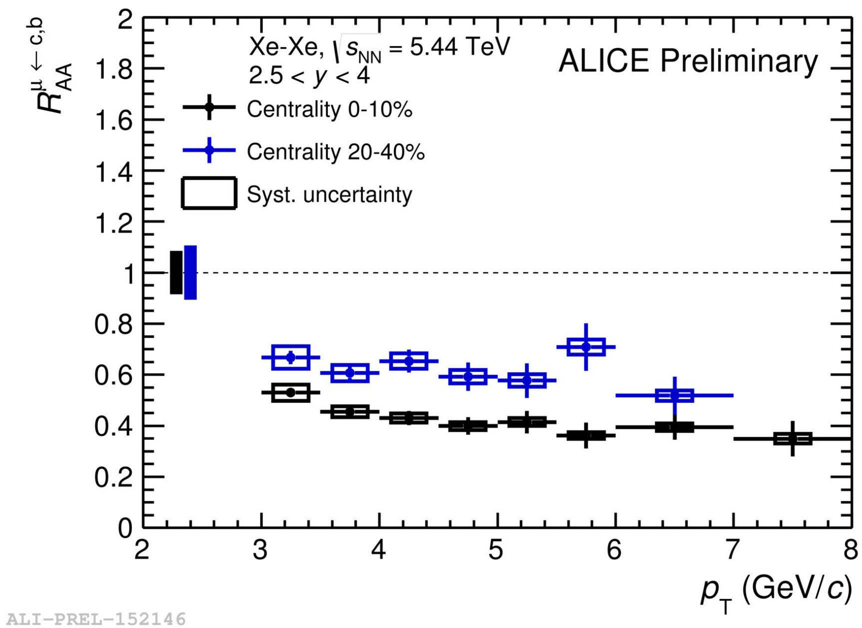


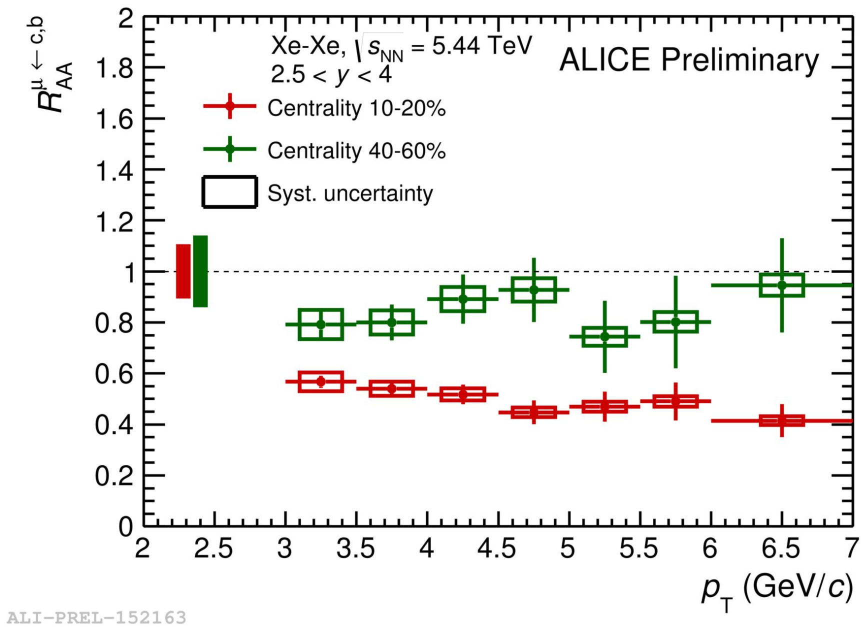
- Measurement in 3< p_T < 8 GeV/c for 10% most central collisions (3 < p_T < 7 GeV/c for 10-20%, 20-40%, 40-60%) with muon-triggered events
- Increasing normalized p_T-differential yields from peripheral to central collisions

p_T-differential R_{AA} of $\mu^{\pm} \leftarrow$ b, c

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$\langle T_{AA} \rangle$ values, see backup



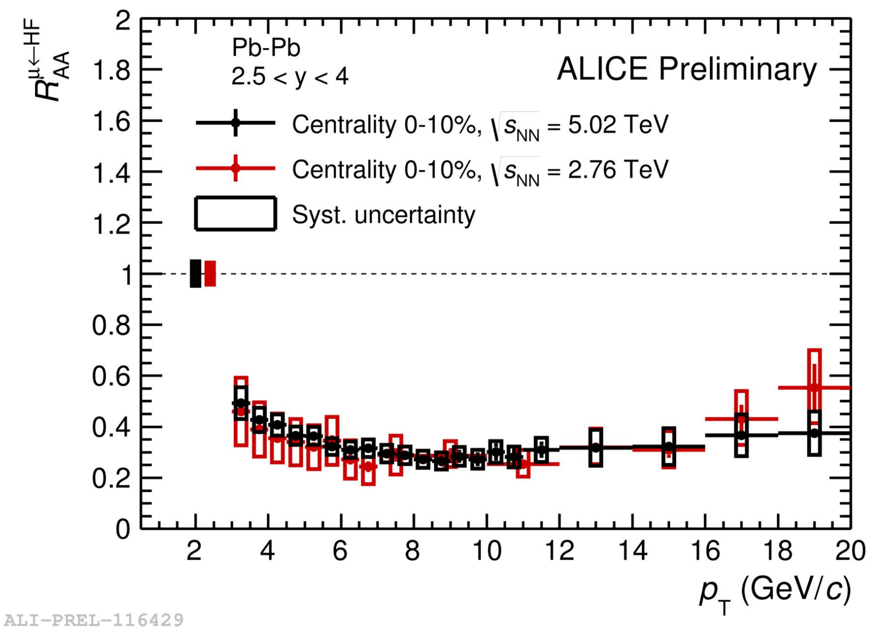


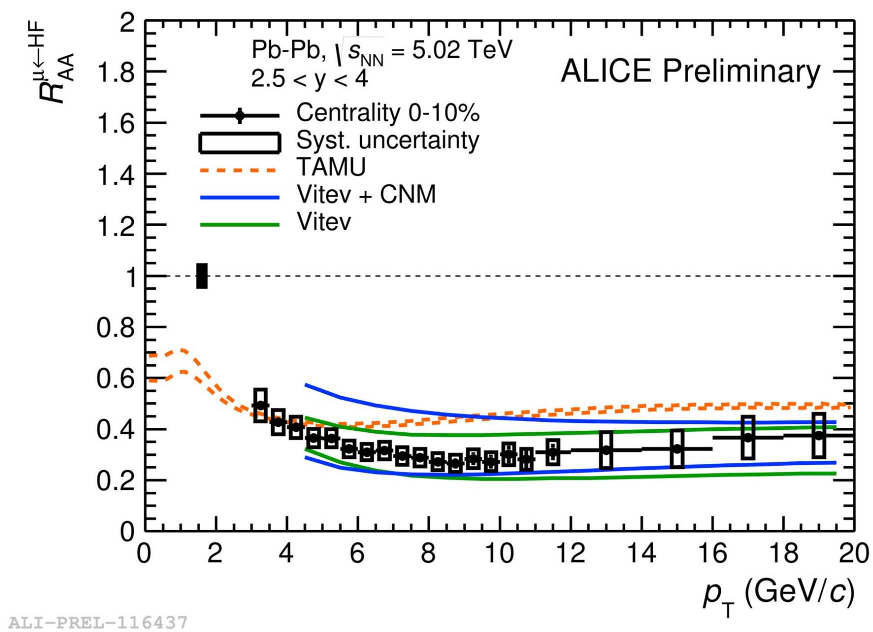
- p_T-differential R_{AA} of heavy-flavour decay muons in different centrality classes
- Increasing suppression from peripheral to central collisions

p_T-differential R_{AA} of $\mu^{\pm} \leftarrow$ b, c in Pb-Pb collisions

Centrality: 0-10%, 5.02 vs 2.76 TeV

Vitev: Phys. Rev. C 80 (2009) 054902
TAMU: Phys. Lett. B 735 (2014) 445

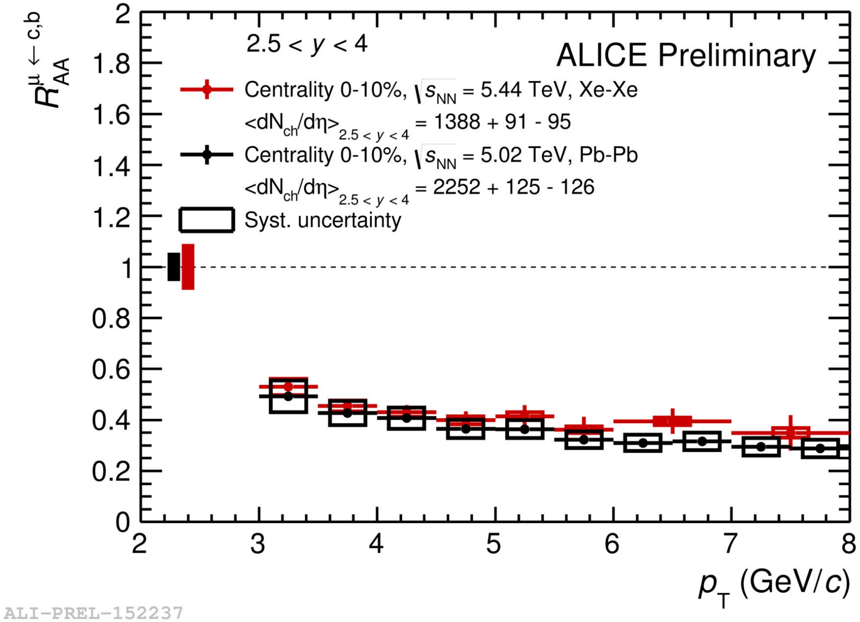




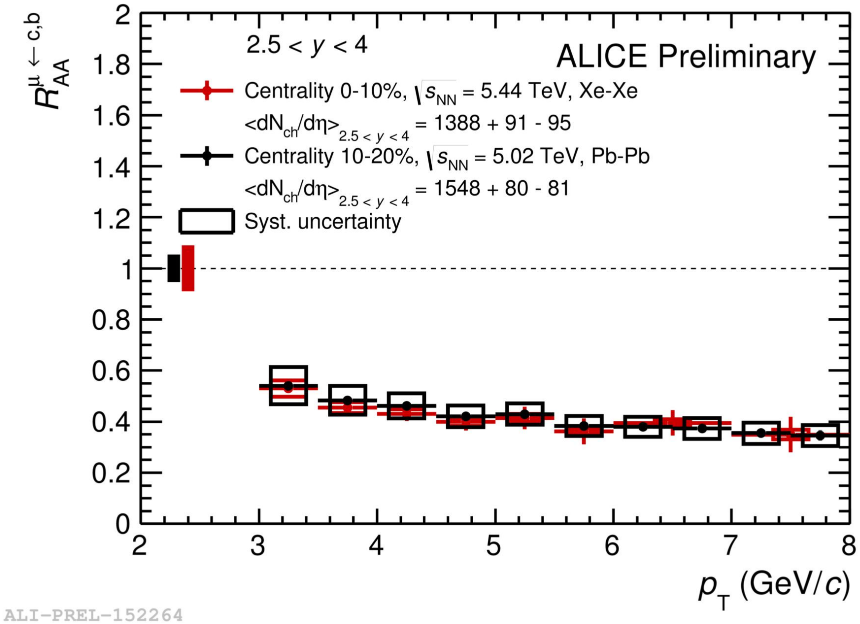
- Similar suppression at 5.02 TeV and at 2.76 TeV for central collisions within uncertainties
- Better precision in Run 2 ($\sqrt{s_{NN}}$ = 5.02 TeV)
- R_{AA} measurements at $\sqrt{s_{NN}}$ = 5.02 TeV provide new constraints on energy loss models

R_{AA}: $\sqrt{s_{NN}}$ = 5.44 TeV in Xe-Xe collisions vs $\sqrt{s_{NN}}$=5.02 TeV in Pb-Pb collisions

Centrality: 0-10%, Xe-Xe vs 0-10%, Pb-Pb



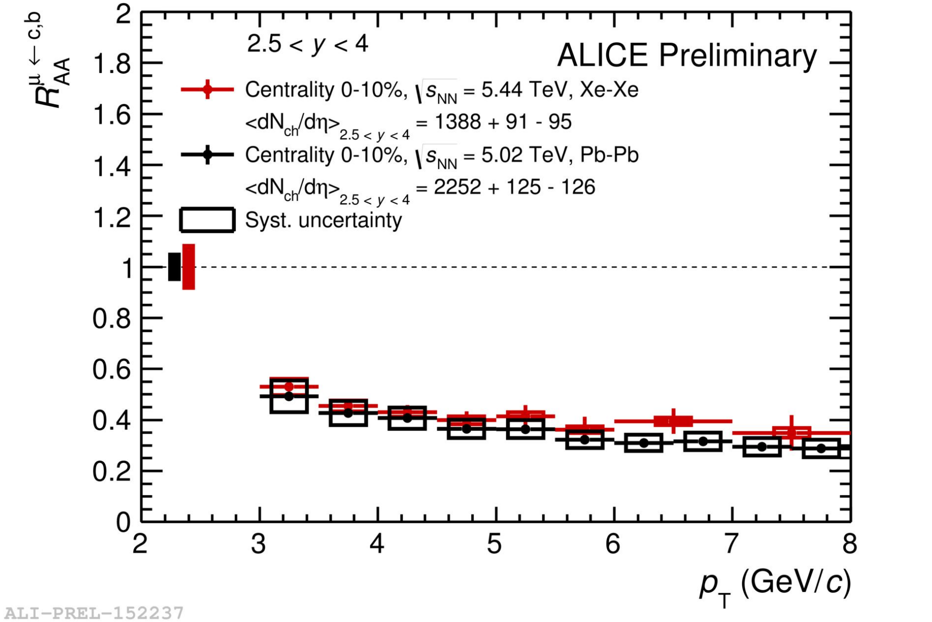
Centrality: 0-10%, Xe-Xe vs 10-20%, Pb-Pb



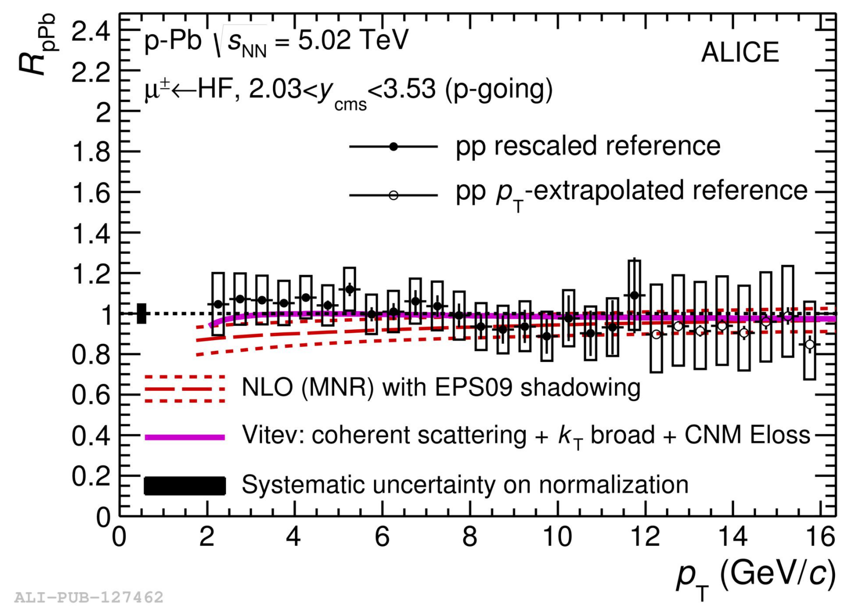
- Central values of R_{AA} at 5.44 TeV in Xe-Xe collisions are slightly higher than at 5.02 TeV in Pb-Pb collisions for central collisions (0-10%)
- In 2.5 < y < 4, $\langle dN_{ch}/d\eta \rangle$ value in 0-10% centrality class in Xe-Xe collisions is similar to $\langle dN_{ch}/d\eta \rangle$ value in 10-20% centrality class in Pb-Pb collisions
- Similar suppresssion as in 10-20% centrality class in Pb-Pb collisions

Comparison with p-Pb measurements

Centrality: 0-10%, Xe-Xe vs 0-10%, Pb-Pb



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



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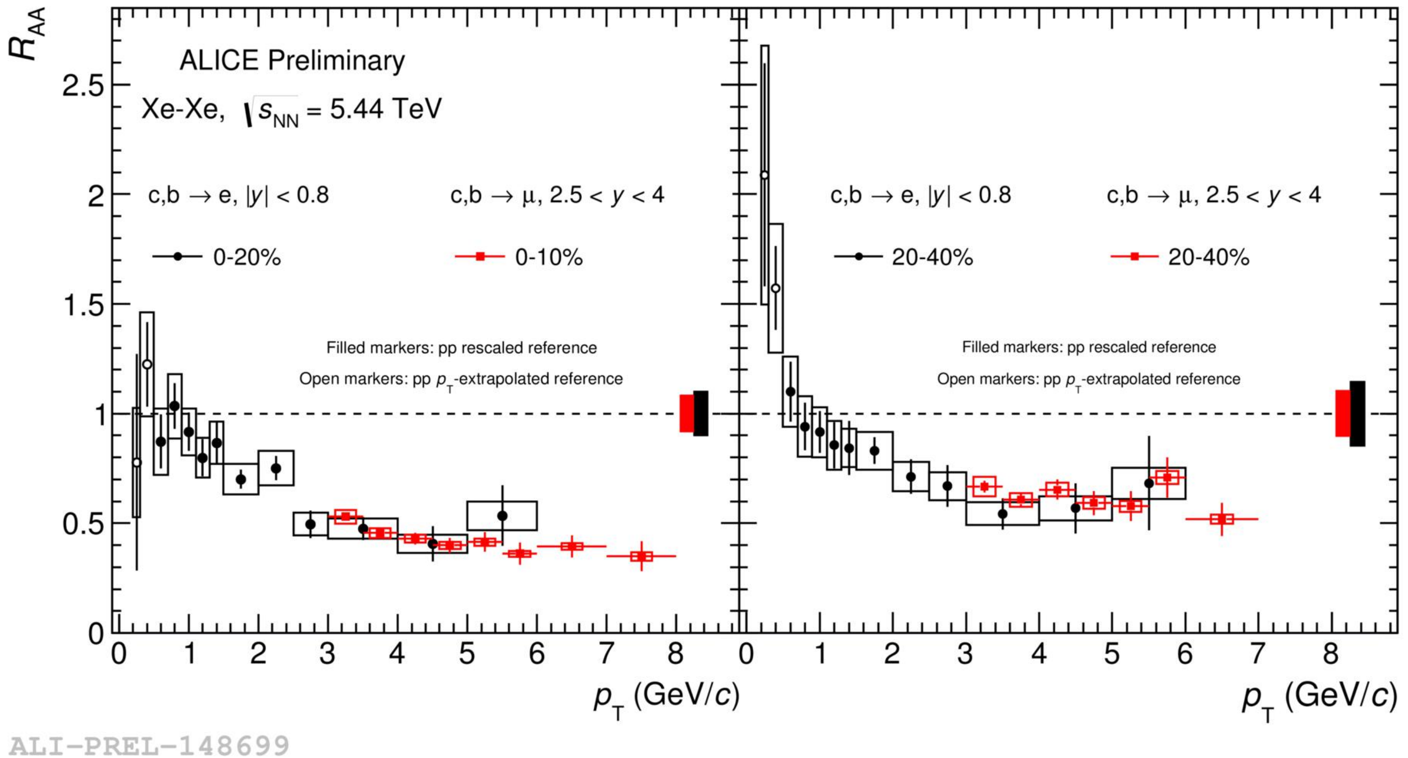
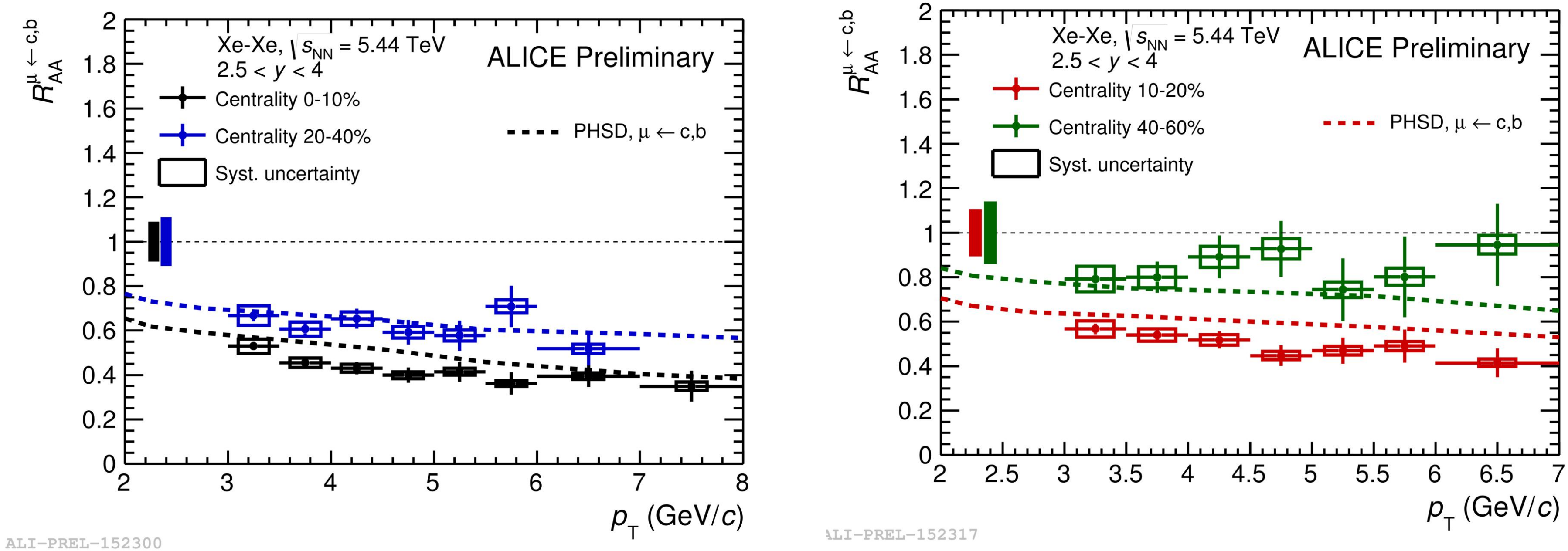
- R_{pPb}: consistent with unity within uncertainties over the whole p_T range
- The suppression observed at in central Xe-Xe and Pb-Pb collisions results from final-state effects related to parton energy loss

Comparison with measurements of e ←c,b (mid-rapidity)



- Compatible results within uncertainties for heavy-flavour decay electrons (|y| < 0.8) and heavy-flavour decay muons (2.5 < y < 4) R_{AA} in 0-10% centrality class
- Indication that heavy quarks suffer a strong interaction in a wide rapidity internal

Comparison with model calculations



- ☐ Centrality: 20-40%, models describe the measured R_{AA} within uncertainties; Centrality: 10-20%, models overestimate the measured R_{AA}
- ☐ R_{AA} measurements have the potential to constrain energy loss models

PHSD model: arXiv:1803.02698 and Phys.Rev. C96 (2017) no.1, 014905

Conclusion and outlooks

pp results: paper proposal approved by ALICE, to be submitted soon
Pb-Pb results: paper proposal approved by ALICE, to be submitted soon
Xe-Xe results: results approved by ALICE, results have been presented at QM2018

Conclusion

- Measurements in pp collisions, over a wider p_T range, extended to p_T = 20 GeV/c
  - Precise reference for the R_{AA} computation
  - Described by pQCD-based calculations (FONLL)

- Measurements in Xe-Xe collisions, new system size w.r.t Pb-Pb collisions
  - Strong suppression, a factor ~3 for $6 < p_T < 8$ GeV/c in 0-10% centrality class
  - The measured suppression is due to final-state effects ($R_{pPb} \sim 1$)
  - Results compatible within uncertainties with those obtained at $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions and with those at mid-rapidity with electrons
  - R_{AA} measurements have the potential to constrain energy loss models

More to come soon

- Elliptic flow, v_2, measurement in Run-2

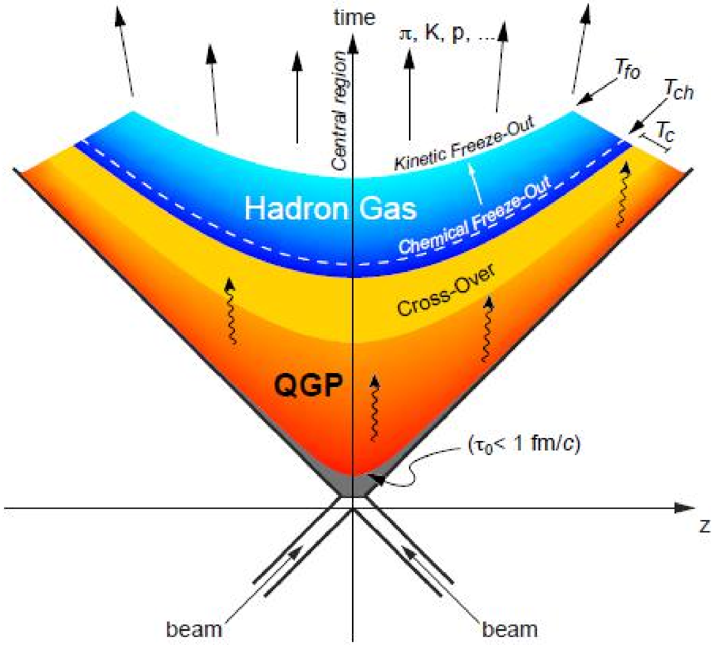
Thank you for your attention

Backup

Physics motivations (2/2)

Charm and beauty quarks: sensitive probes of the medium properties

Open heavy flavours in nucleus-nucleus (A-A) collisions probe
- ☐ In-medium parton energy loss
- ☐ Heavy-quark participation in the collective expansion



Also needed:
- ☐ proton-proton (pp) collisions
  reference, tests of pQCD-based predictions
- ☐ p-A collisions
  reference, cold nuclear matter effects

Observable
- ✓ The nuclear modification factor, R_{AA}, sensitive to the medium effects

$$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{QCD \text{ Medium}}{QCD \text{ Vacuum}}$$

- ✓ If no nuclear effects: R_{AA} = 1

Run-2 provides measurements of heavy-flavour hadron decay muons in a wide p_T range with improved precision which bring new constraints on in-medium energy loss

Comparison with models

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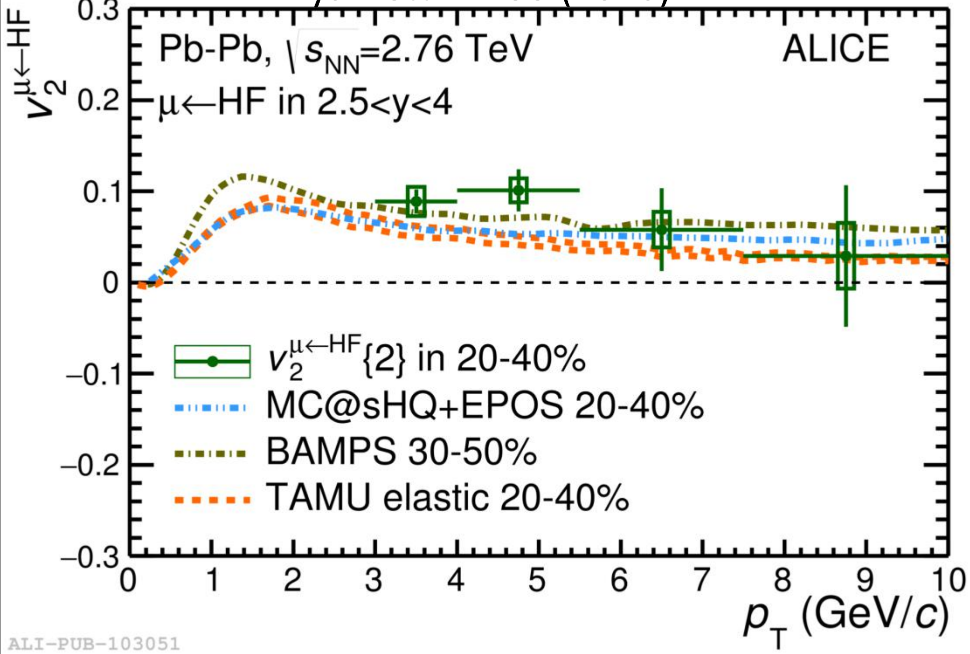
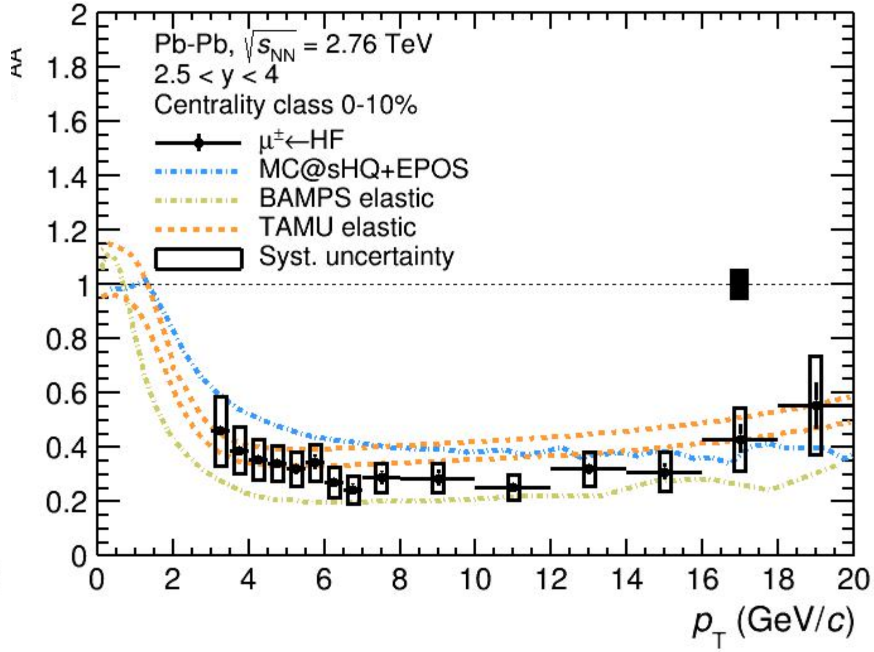


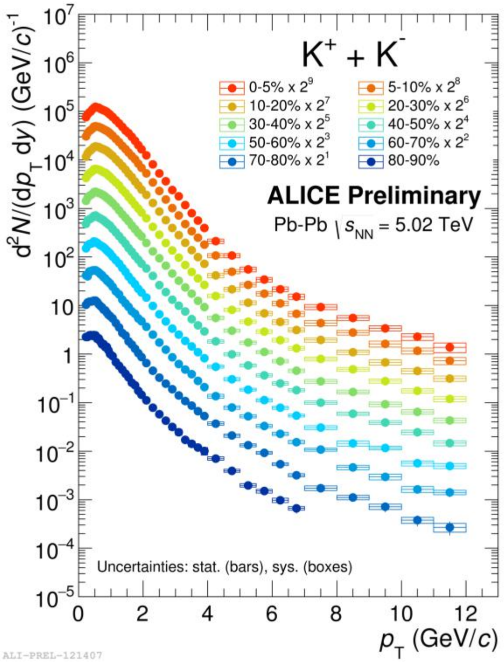


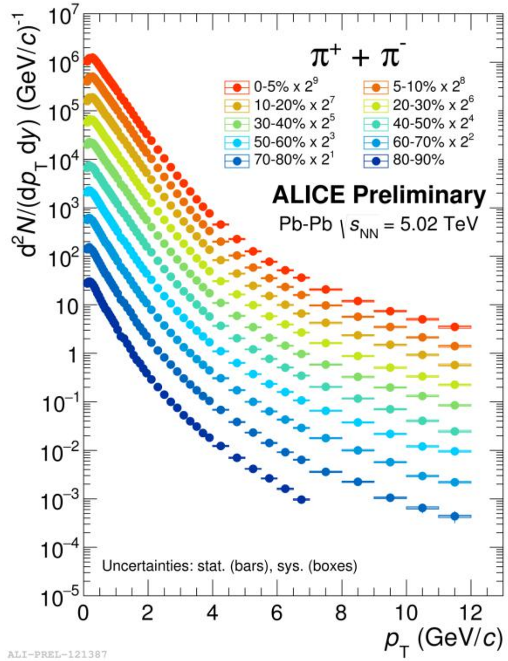
- Elliptic flow v_2: complementary measurement to R_{AA} sensitive to:
  - Low p_T: collective motion
  - High p_T: path-length dependence of parton energy loss
- Positive v_2 measured with a significance > 3σ for $3 < p_T < 5$ GeV/c in 20-40%
- Confirmation of significant interaction of heavy quarks with the medium

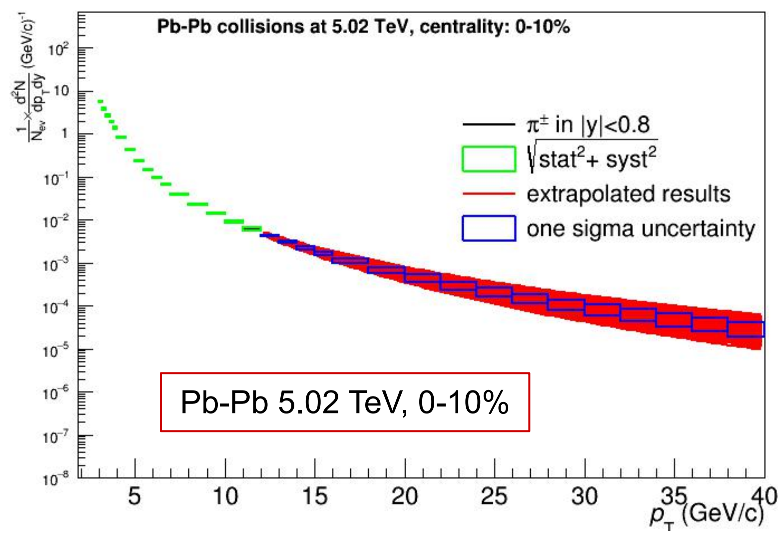
- Simultaneous description of R_{AA} in central collisions and v_2 in semi-central collsiions is challenging
- R_{AA} and v_2 measurements starts to provide constraints on energy loss models
- Similar picture for heavy-flavour decay electrons and D mesons

Analysis strategy in Pb-Pb collisions (2/5)
Muons from K/π decays

Inputs, from QM2017 approval







- Get K/π spectra at mid-rapidity in Pb-Pb collisions at 5.02 TeV and do p_T extapolation
  - ✓ p_T extrapolation with power-law fit

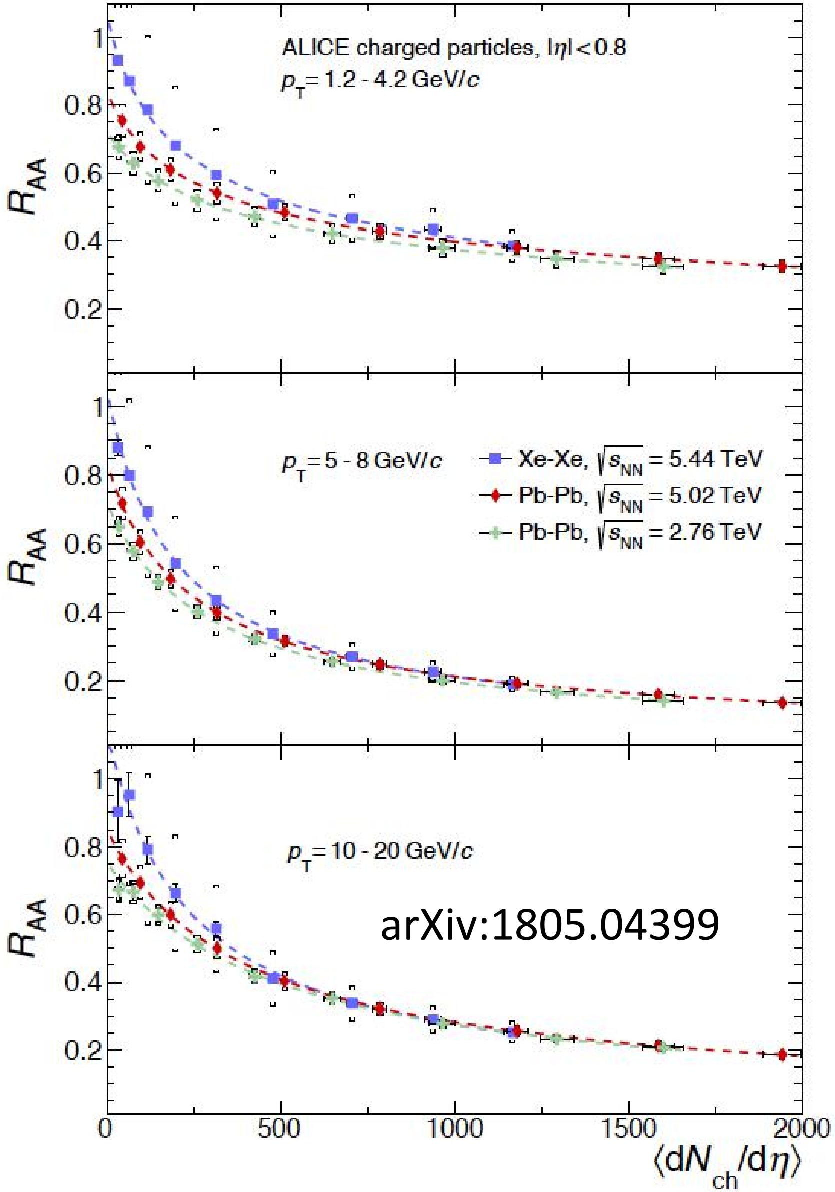
    (1) p_T < 12 GeV/c : Gaussian fit with gRandom->Gaus(μ,σ)

    μ: center value of K/π spectra; σ: stat. and syst. uncertainties of data

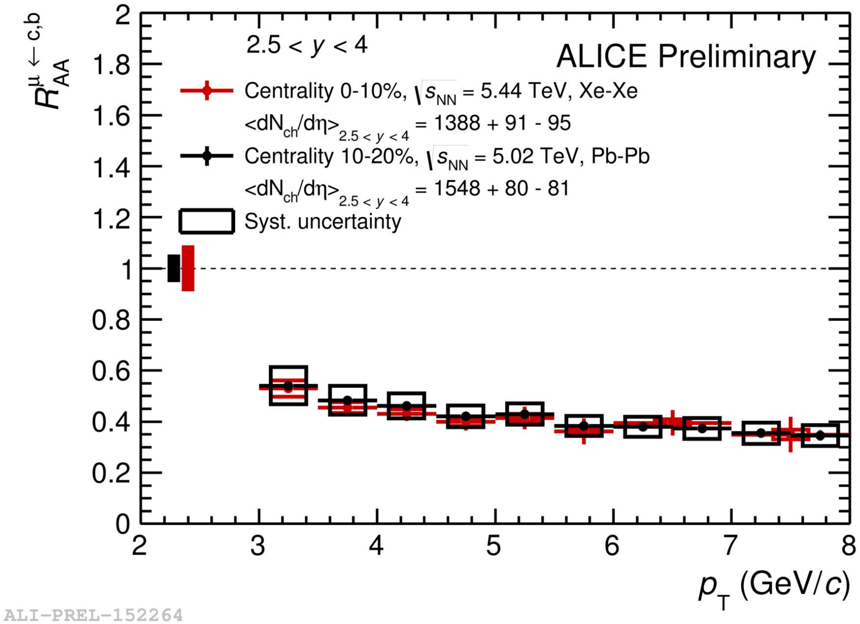
    (2) p_T > 12 GeV/c

    μ and σ from K/π spectra in p_T-extrapolated intervals

R_{AA} in Xe-Xe collisions at 5.44 TeV



arXiv:1805.04399



T_{AA} values in Xe-Xe and Pb-Pb collisions

ALICE

Xe-Xe

Cent (%)	Npart	RMS	Sys	Ncoll	RMS	Sys	TAA	RMS	Sys
0-10%	221.2	19	2.2	843.1	1.4e+02	70	12.33	2	1
10-20 %	164.8	18	2.8	510.6	86	51	7.465	1.3	0.74
20-30 %	118.4	14	3.8	302.8	58	40	4.426	0.85	0.59
30-40 %	82.21	11	3.9	171.3	38	27	2.505	0.56	0.4
40-50 %	54.56	8.8	3.6	91.81	24	16	1.342	0.35	0.24
50-60 %	34.06	6.5	3	46.04	14	8.8	0.6731	0.2	0.13
60-70 %	19.72	4.7	2.1	21.65	7.6	4.1	0.3166	0.11	0.061
70-80 %	10.5	3.1	1.1	9.515	3.9	1.6	0.1391	0.056	0.024
80-90 %	5.127	1.9	0.46	3.838	1.9	0.5	0.05611	0.028	0.0074
90-100 %	2.488	0.8	0.12	1.449	0.73	0.1	0.02118	0.011	0.0015

Pb-Pb

Cent	bmin [fm]	bmax [fm]	Npart	RMS	Sys	Ncoll	RMS	Sys	TAA	RMS	Sys
00 - 10 %	0.00	4.96	359	31.2	3.0	1636	246	170	23.4	3.51	0.78
10 - 20 %	4.96	7.01	263	27.1	3.6	1001	154	97	14.3	2.2	0.46
20 - 30 %	7.01	8.59	188	22.5	3.0	601	106	54	8.59	1.52	0.27
30 - 40 %	8.59	9.92	131	19.1	2.3	344	74.7	29	4.92	1.07	0.16
40 - 50 %	9.92	11.1	86.3	16.3	1.7	183	50.8	14	2.61	0.726	0.1
50 - 60 %	11.1	12.1	53.6	13.6	1.2	89.8	32.4	6	1.28	0.463	0.063
60 - 70 %	12.1	13.1	30.4	10.8	0.76	39.8	19.1	2.4	0.569	0.273	0.032
70 - 80 %	13.1	14.0	15.6	7.83	0.45	16.2	10.5	0.92	0.232	0.15	0.015
80 - 90 %	14.0	15.0	7.59	4.89	0.19	6.57	5.27	0.3	0.0923	0.0753	0.007
90 - 100 %	15.0	19.6	3.77	2.5	0.079	2.66	2.41	0.088	0.0378	0.0344	0.0033