Charm and beauty production in hadronic collisions via muon measurements at forward rapidity with ALICE

Maolin Zhang on behalf of the ALICE Collaboration
Laboratoire de Physique Clermont Auvergne, IN2P3-CNRS, UCA, France
Institute Of Particle Physics, CCNU-Wuhan, China

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Outline

- Motivations
- The ALICE detector
- Latest measurements
- Run 3 perspectives

Physics motivations

Heavy (charm and beauty) quarks: sensitive probes of the quark-gluon plasma (QGP)

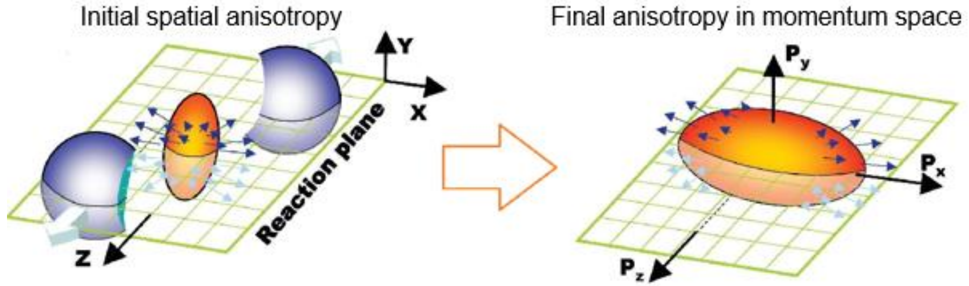
- $\tau_{c/b}$ ~ 0.01-0.1 (fm/*c*) < τ_{QGP} ~0.3 (fm/*c*) [PRC 89 (2014) 034906]
- Experience the whole collision evolution

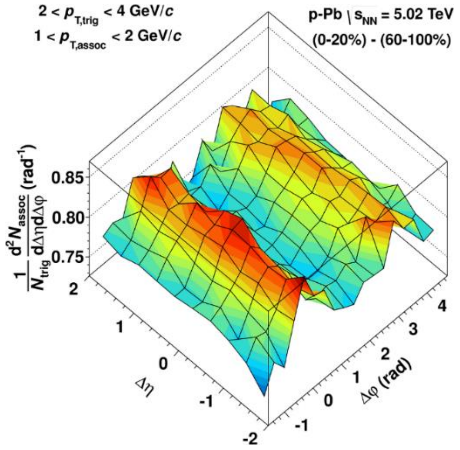
❖ Key observable: azimuthal anisotropy quantified by means of a Fourier expansion of azimuthal distributions of produced particles

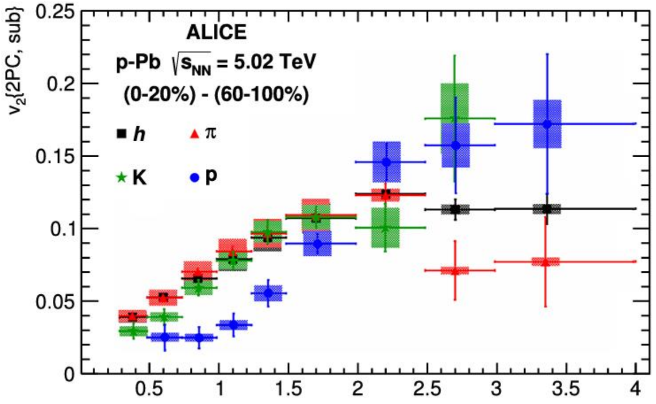
$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$

$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

$$n = 2, \text{elliptic flow}$$







PLB 726 (2013) 164–177

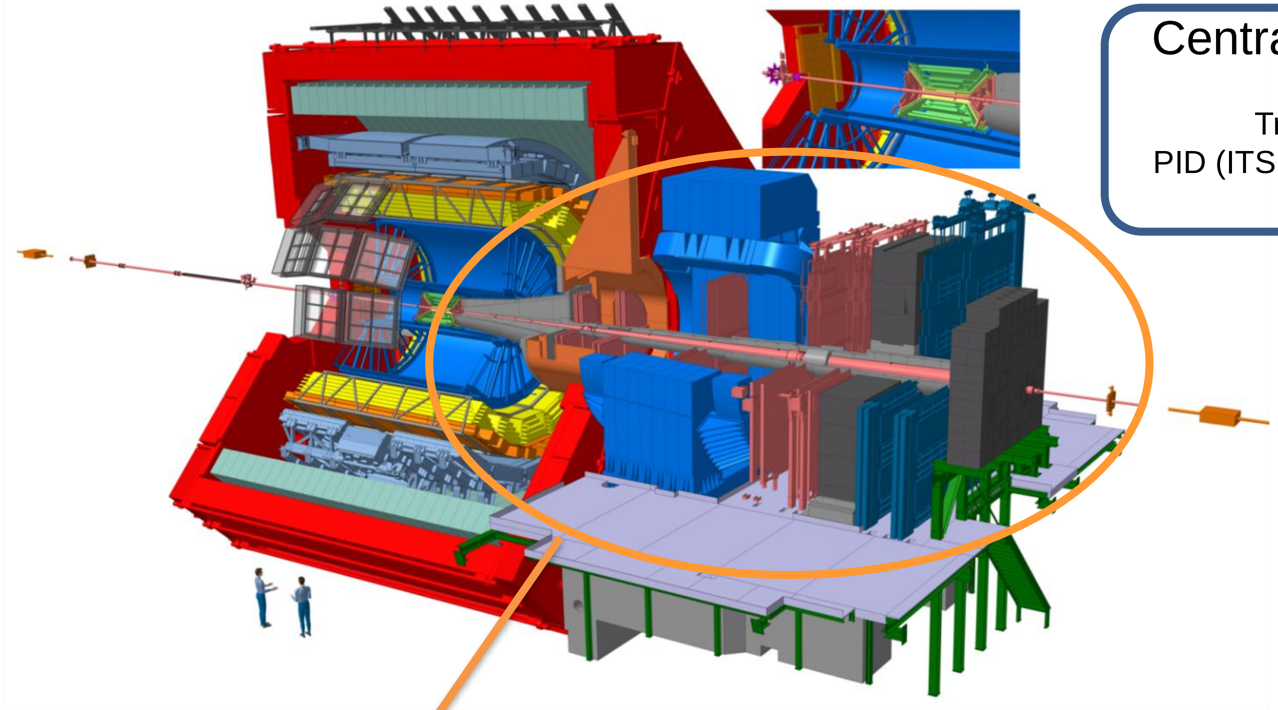
Small collision systems (pp & p–Pb collisions):

- ❖ Baseline for heavy-ion collisions
- ❖ pp collisions: test pQCD-based calculations and production mechanisms
- ❖ p–Pb collisions: cold nuclear matter effects and study of nuclear parton distribution functions

No (or very tiny) QGP effect is expected

❖ Long-range angular correlations and clear mass ordering observed in p–Pb collisions at high multiplicity, as in Pb–Pb collisions

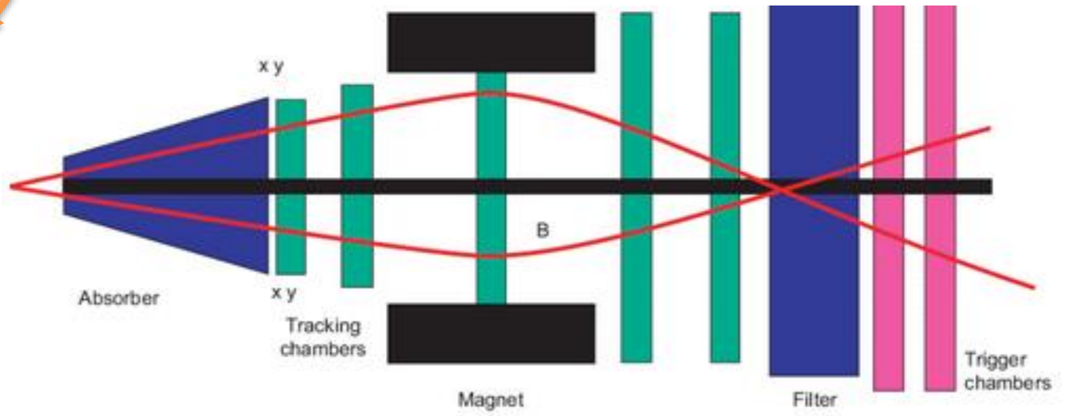
The ALICE detector (Run 2 layout)



Central Barrel, $|\eta| < 0.9$
Vertexing (ITS),
Tracking (ITS, TPC),
PID (ITS, TPC, TOF, TRD, HMPID, Calorimeters)

Forward/ Backward detectors (V0, T0, ZDC):
Trigger,
Timing,
Multiplicity/ Centrality,
Event plane

Muon spectrometer
$-4 < \eta < -2.5$
Tracking,
Triggering,
μ identification



Int. J. Mod. Phys. A29 (2014) 1430044

Hadronic decays (|*y*| < 0.8)

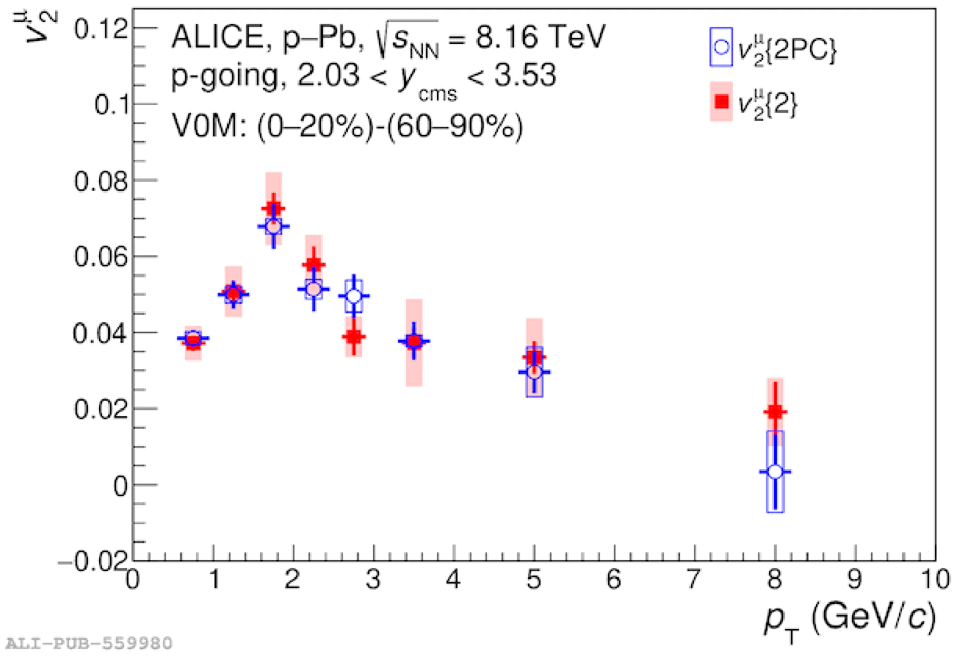
- $D^0 \to K^-\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D^{*+} \to D^0 (\to K^-\pi^+)\ \pi^+$
- $D^+_s \to \phi\ (\to K^-K^+)\pi^+$
- $D_{s1}^+ \to D^{*+}\ K^0_s$
- $D_{s2}^{*+} \to D^+\ K^0_s$
- $\Lambda_c^+ \to pK^0_s,\ \Lambda_c^+ \to pK^-\pi^+$
- $\Lambda_c^+ \to e^+\Lambda\nu_e$
- $\Xi_c^0 \to e^+\Xi^-\nu_e,\ \Xi_c^0 \to \pi^+\Xi^-$
- $\Xi_c^+ \to \pi^+\pi^+\Xi^-$
- $\Omega_c^0 \to \Omega^-\pi^+$
- $\Sigma_c^{0,++}(2455) \to \Lambda_c^+\pi^{-,+}$
- $\Sigma_c^{0,++}(2520) \to \Lambda_c^+\pi^{-,+}$

Semi-leptonic decays

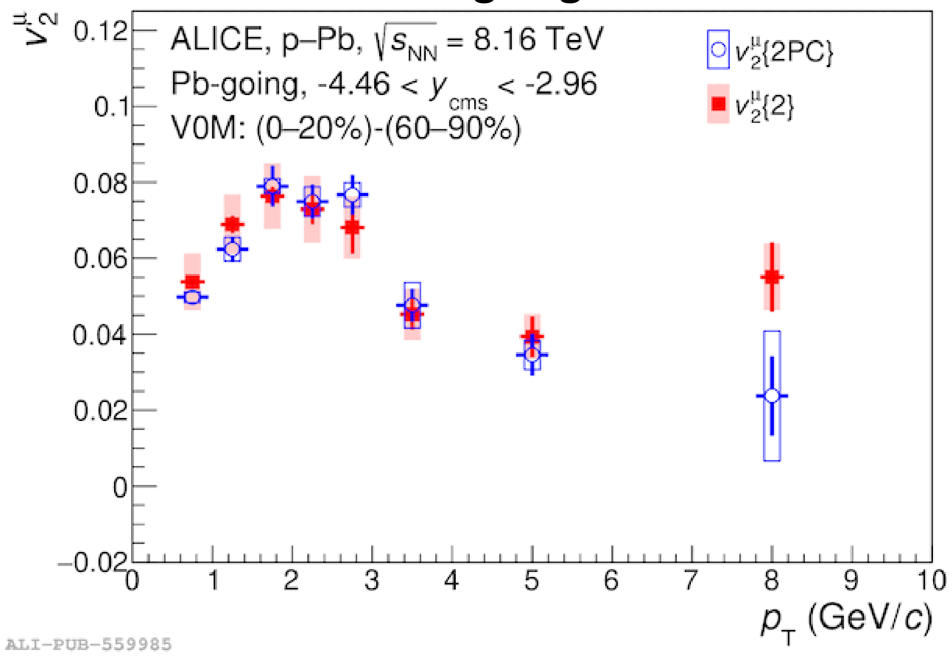
- **c, b $\to \mu^\pm$ ($2.5 < y < 4.0$)**
- c, b $\to e^\pm$ ($|y| < 0.8$ or 0.6

Heavy-flavour hadron decay muon v_2 in p–Pb collisions

p-going



Pb-going



HF-μ dominate at p_T > 2 GeV/*c*

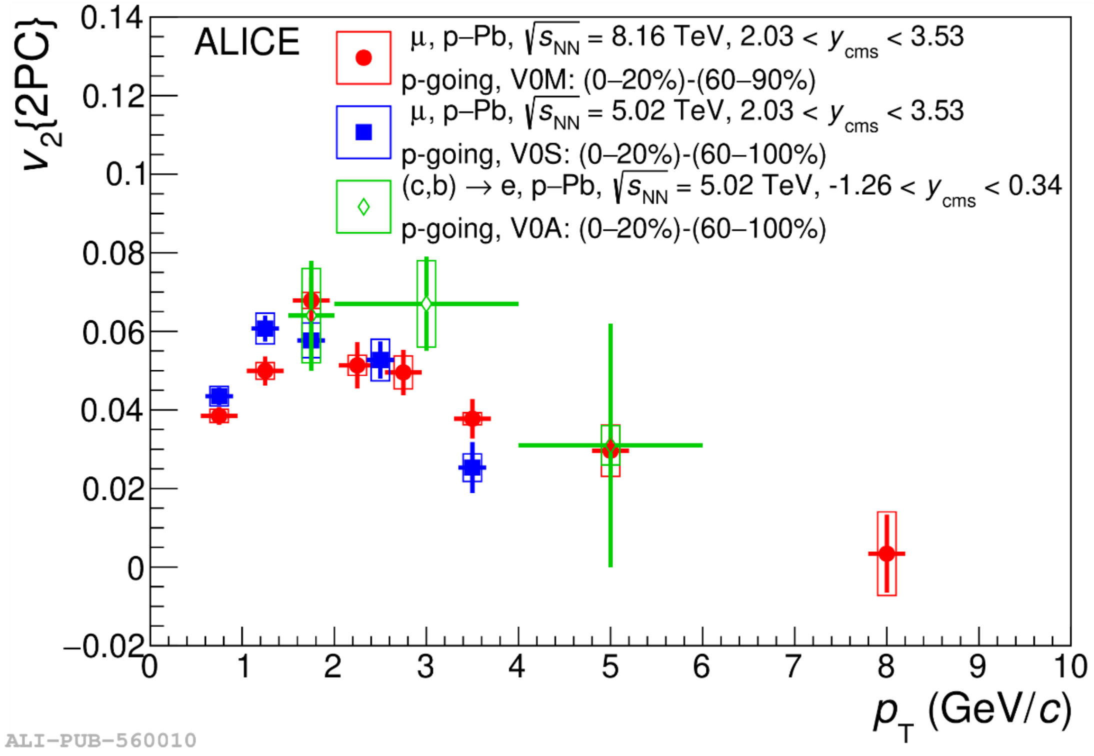
PLB 846 (2023) 137782

- Two different techniques: forward-central two-particle correlations and two-particle cumulants

- Positive muon v_2 measured for the first time over a wide p_T interval at both forward and backward rapidities with a significance of 4.7σ and 7.6σ for 2 < p_T < 6 GeV/*c*, respectively
- Consistent v_2 values with two-particle correlations and two-particle cumulants
- Hint for a smaller v_2 at forward than backward rapidity: consequence of decorrelation effects of flow vectors in different rapidity regions

Comparison with other published measurement

p-going



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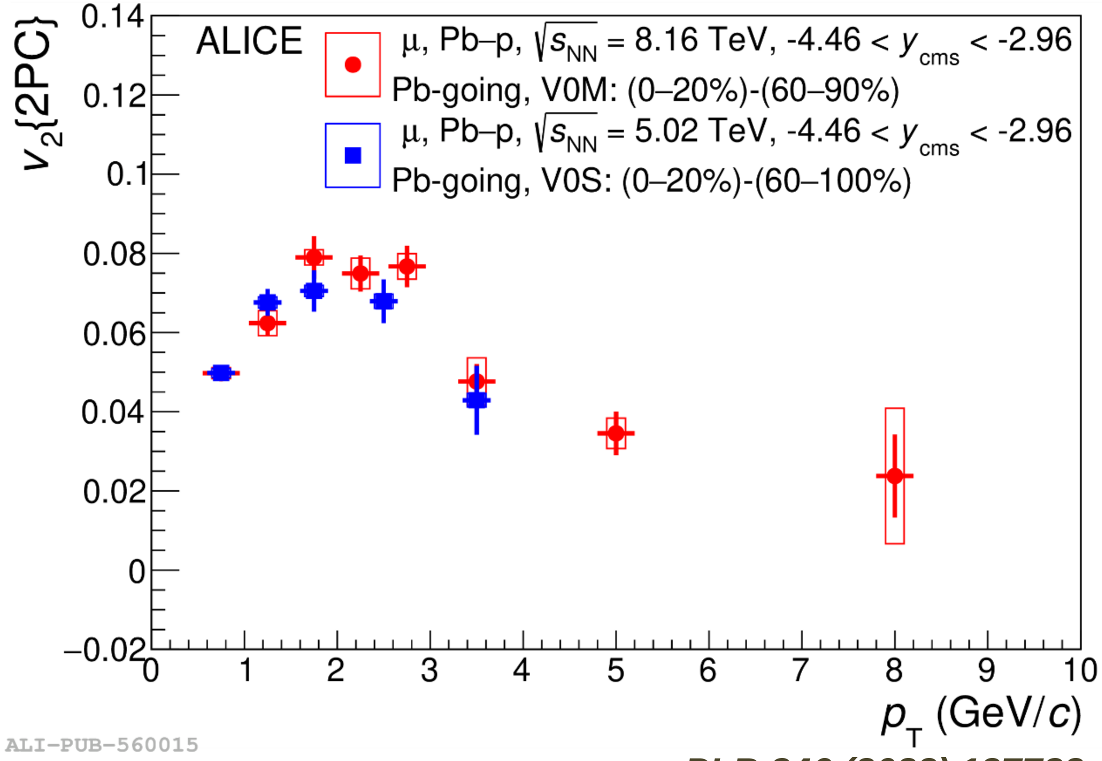
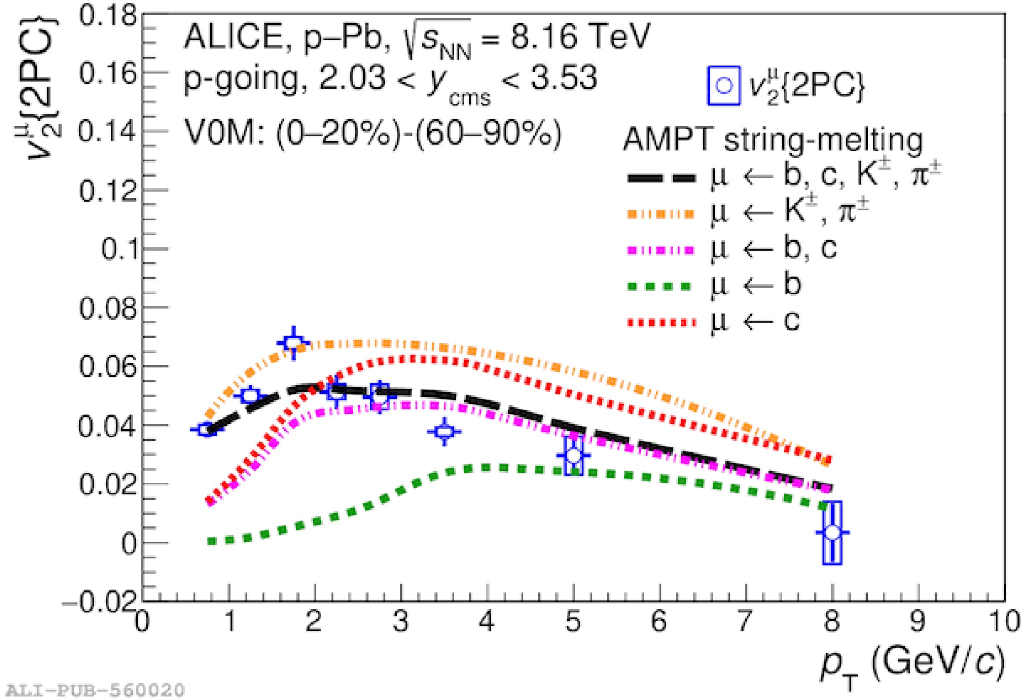


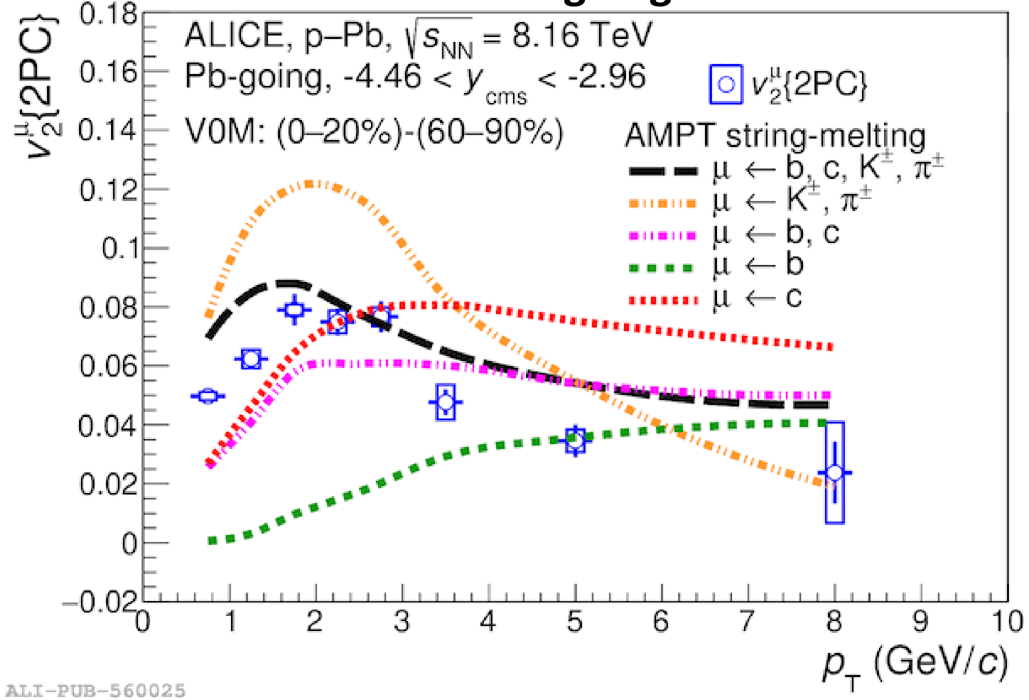
PLB 846 (2023) 137782

- No significant energy dependence on the muon v_2 values obtained at $\sqrt{s_{NN}}$ = 5.02 TeV and 8.16 TeV
- Results in good agreement within uncertainties at midrapidity with the heavy-flavour hadron decay electron v_2 at $\sqrt{s_{NN}}$ = 5.02 TeV

p-going



Pb-going



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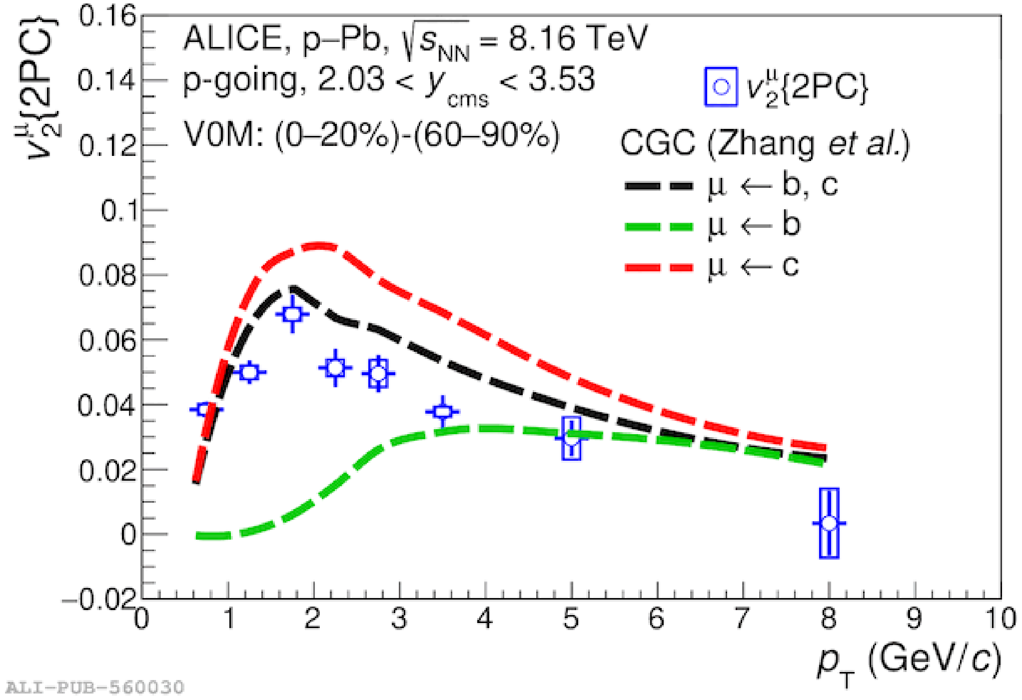
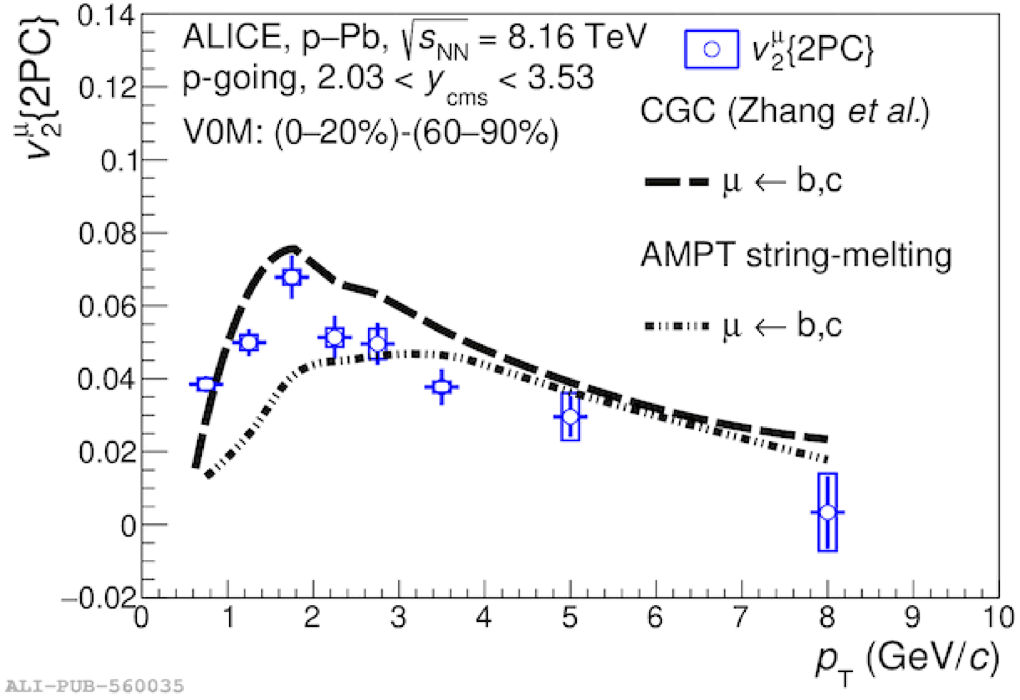
- AMPT calculations [Z. W. Lin, PRC 72 (2005) 064901]: non-equilibrium dynamics, microscopic evolution of parton interactions
  - Larger v_2 for muons from light-flavor hadron decays than for heavy-flavor hadron decay muons
  - Larger v_2 at backward rapidities: rapidity-dependent flow-vector fluctuations
- AMPT predictions in fair agreement with the measured v_2, although the model slightly overestimates the data at backward rapidities
  - Suggests that the v_2 could be due to the anisotropic parton escape mechanism

Comparisons with AMPT and CGC calculations





HF-μ dominate at p_T = 2 GeV/*c*

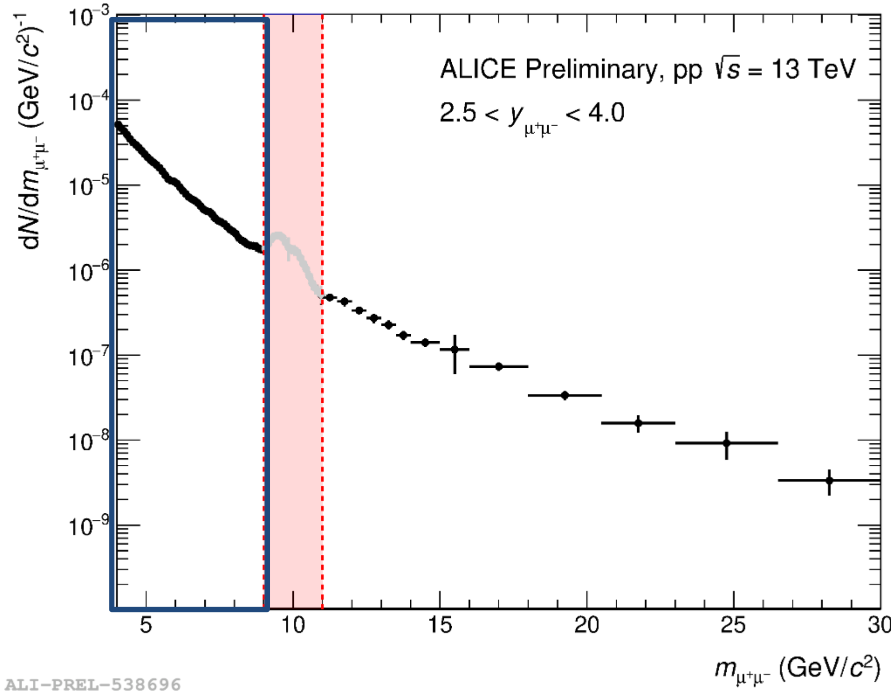
PLB 846 (2023) 137782

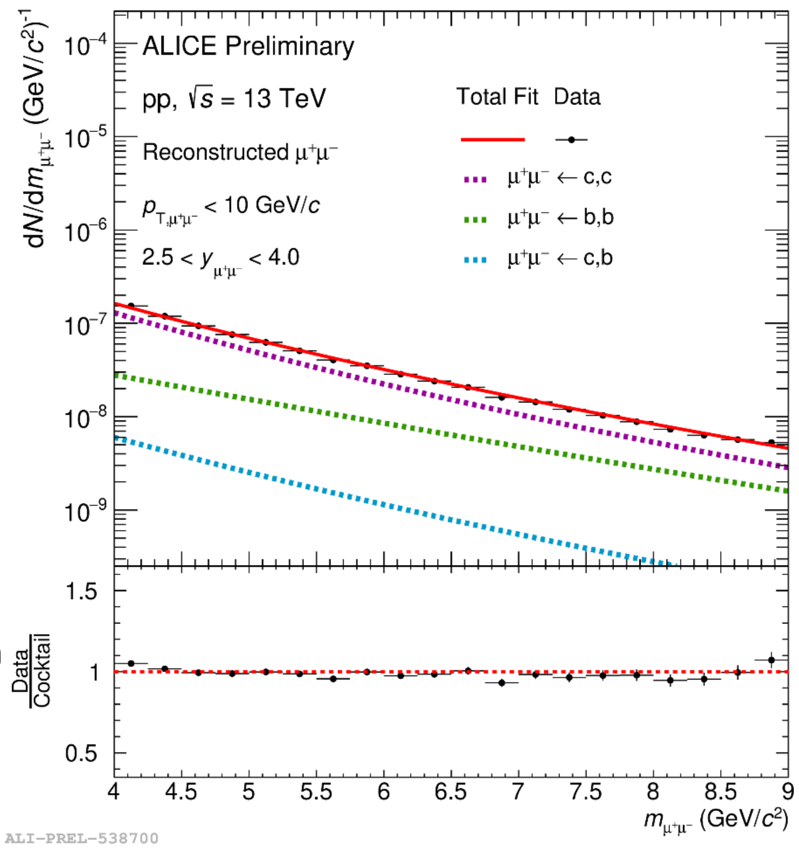
- CGC calculations [C. Zhang et al., PRL 122 (2019) 172303]: anisotropy generated from parton interactions in the early stage of collisions
  - Qualitative agreement with the measured v_2
  - Larger v_2 for heavy-flavour hadron decay muons at low p_T compared to AMPT
  - Compatible v_2 at high p_T with AMPT: heavy-flavour dominate
  - Possible contributions from initial-state effects not fully excluded

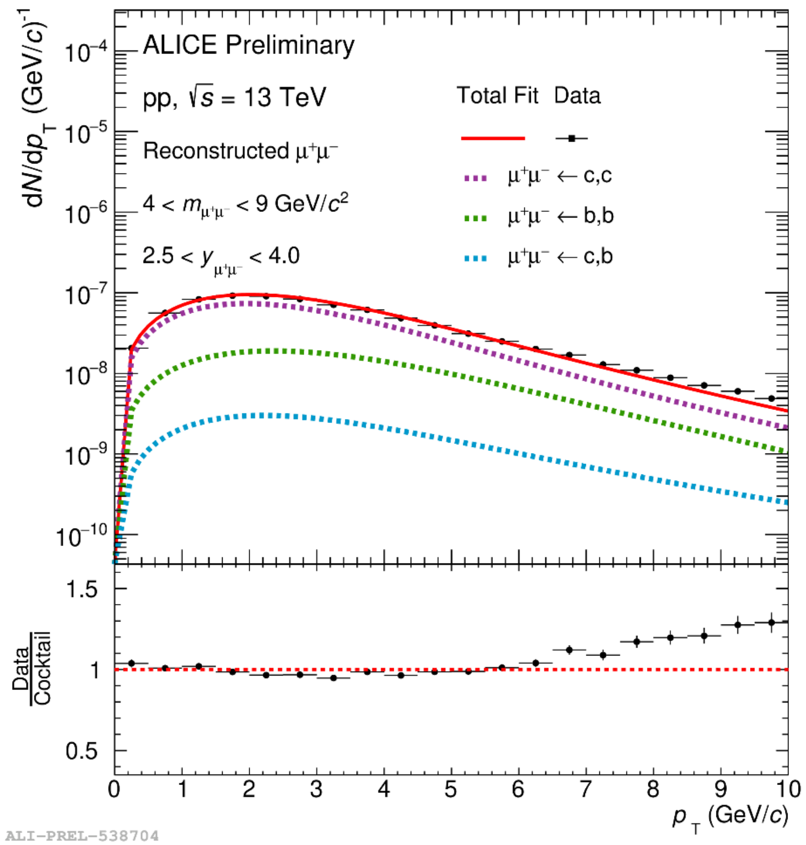
Heavy-flavour production in pp collisions at forward y via $\mu^+\mu^-$

- Charm and beauty production measured at $2.5 < y < 4.0$ in pp collisions at $\sqrt{s}$ = 13 TeV, exploiting the dimuon high-mass continuum dominated by the semimuonic decays of heavy-flavour hadrons
- Simultaneous fit to the mass and p_T distributions with a combined template of the main sources in the continuum
  - Templates extracted from the heavy-flavour enriched PYTHIA 8 simulations

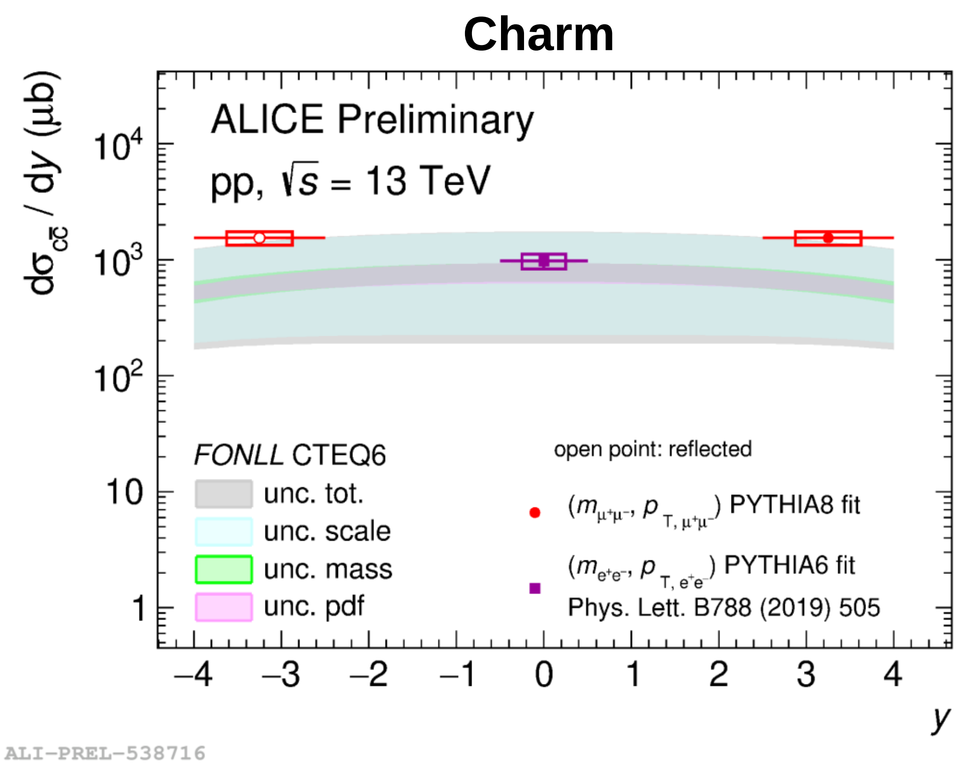
PYTHIA 8: Comput. Phys. Commun. 191 (2015) 159

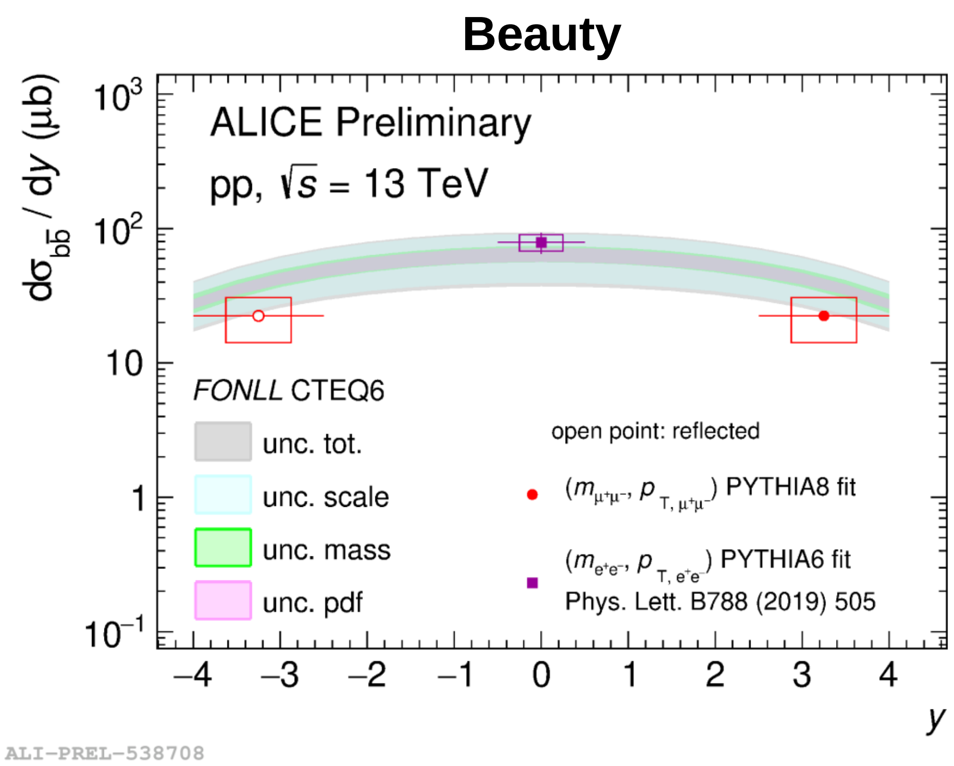






Charm and beauty production cross sections at forward y in pp collisions at $\sqrt{s}$ = 13 TeV





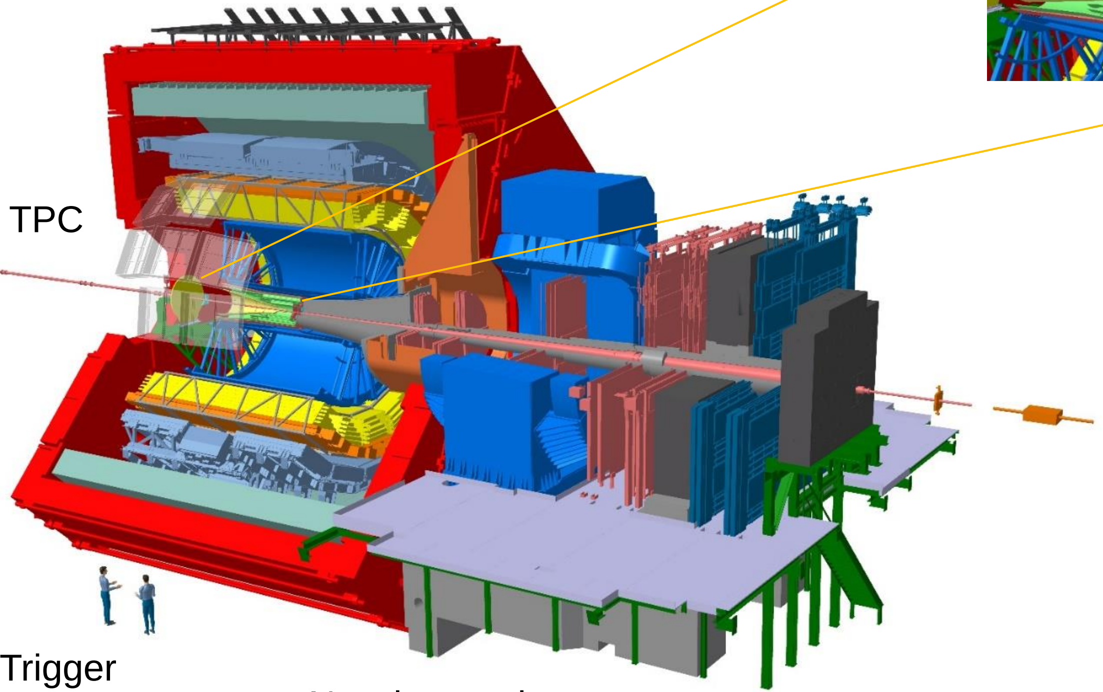
- Charm and beauty production cross sections measured separately at forward rapidity via the dimuon continuum
- Results in agreement with FONLL predictions within uncertainties, although they lie at the upper and lower limit of the calculations for charm and beauty production cross section, respectively
- Complement the previously published results at midrapidity in the dielectron channel

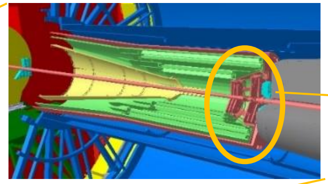
FONLL: JHEP 05 (1998) 007

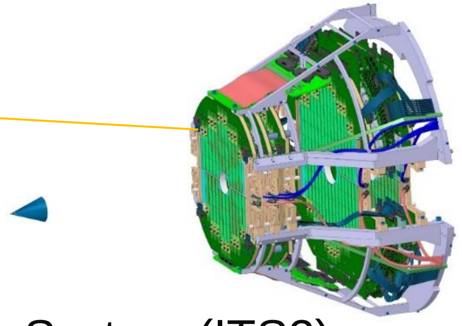
The ALICE detector: Run 3 setup

- ❖ Major upgrades installed in 2019-2021
- ❖ Data taking started at mid 2022

New GEM-based TPC

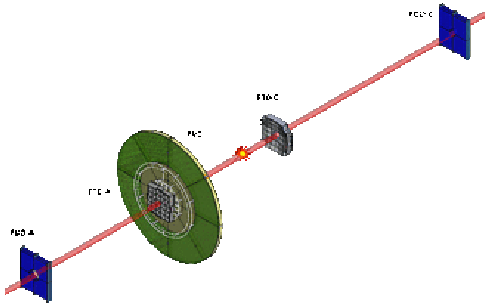




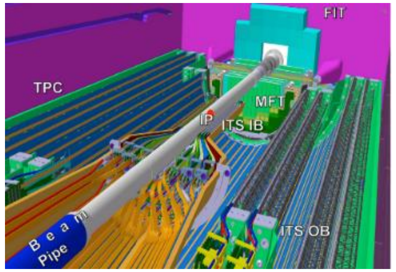


MFT

Fast Integration Trigger

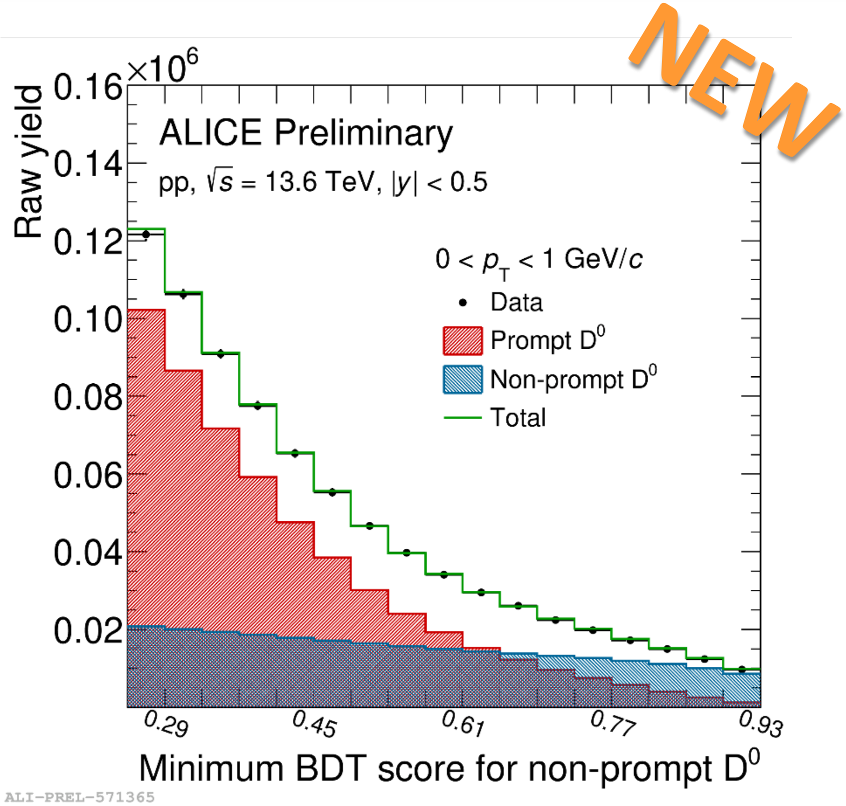


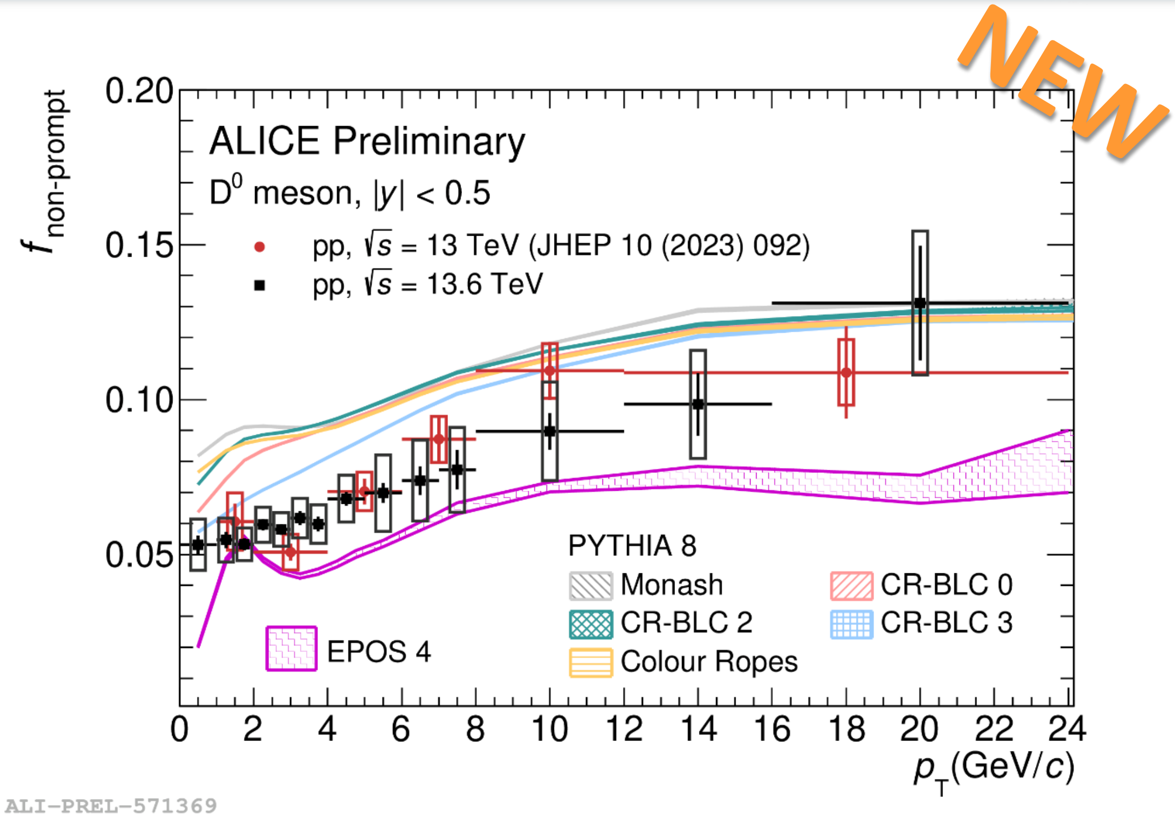
New beam pipe



- ❖ New Inner Tracking System (ITS2)
  - Better pointing resolution at midrapidity
- ❖ New Muon Forward Tracker (MFT)
  - Vertexing also at forward rapidity ($-3.6 < \eta < -2.5$)
  - Separation of charm and beauty components in the single muon channel at forward rapidity for the first time
- ❖ New readout system of most subdetectors
  - Continuous readout and increased luminosity
  - Multidifferential measurements of various muon sources down to lower p_T and up to higher p_T
- ❖ Extend heavy flavour measurements towards the forward rapidity region allowing for c/b separation

Midrapidity: non-prompt D^0-meson fraction in pp collisions at $\sqrt{s}$ =13.6 TeV

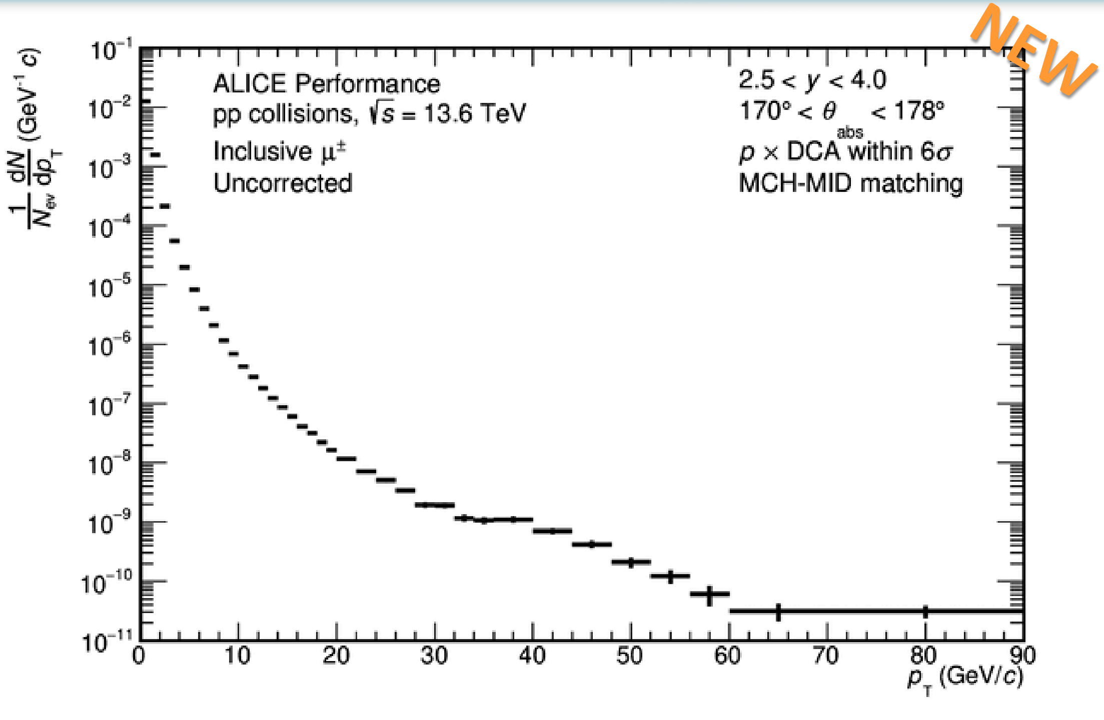




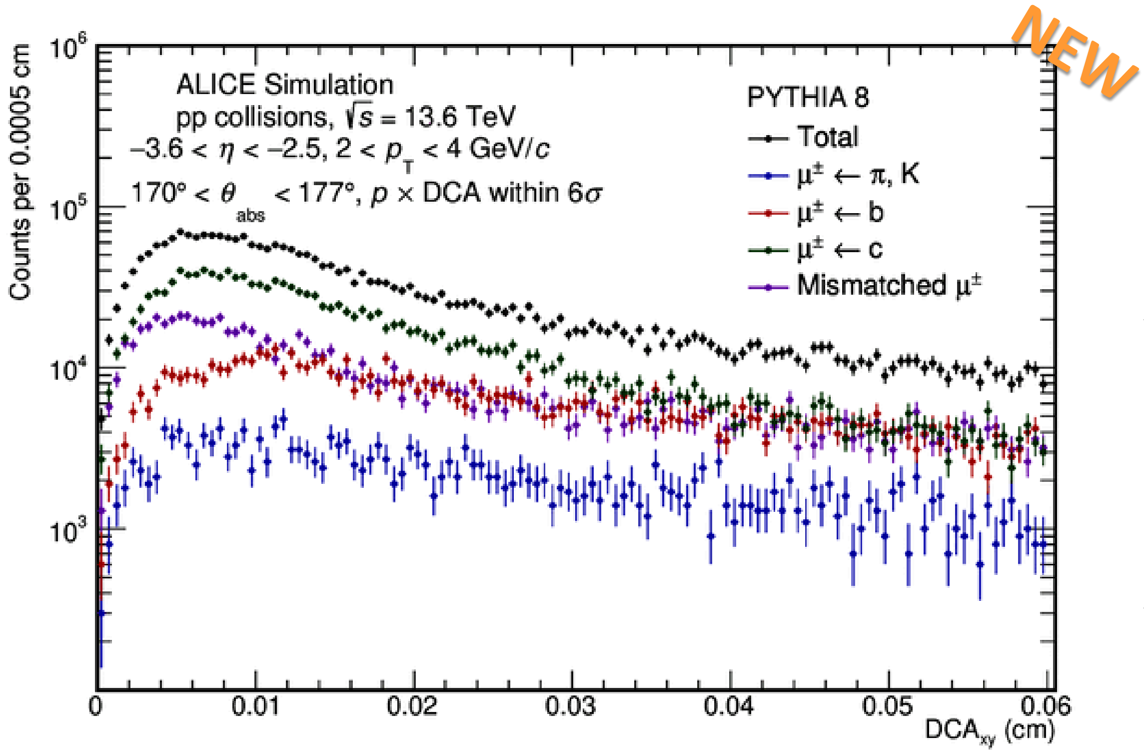
- First measurement of the non-prompt D^0-meson fraction down to $p_T = 0$ in Run 3
  - In agreement with the measurements in pp collisions $\sqrt{s}$ = 13 TeV
  - Increased granularity and extended p_T reach
  - Strong constraints on model calculations

Open heavy-flavour measurements via single muons in Run 3

- High p_T region measurements feasible even with a fraction of the 2022-2023 pp sample at $\sqrt{s}$ = 13.6 TeV
- Muons from W-boson decays clearly observed at p_T ~ 40 GeV/c
- Very promising to perform multidifferential measurements of open heavy flavours in the semimuonic channel with high precision, analysing the full pp sample



ALI-PERF-571756



ALI-SIMUL-571812

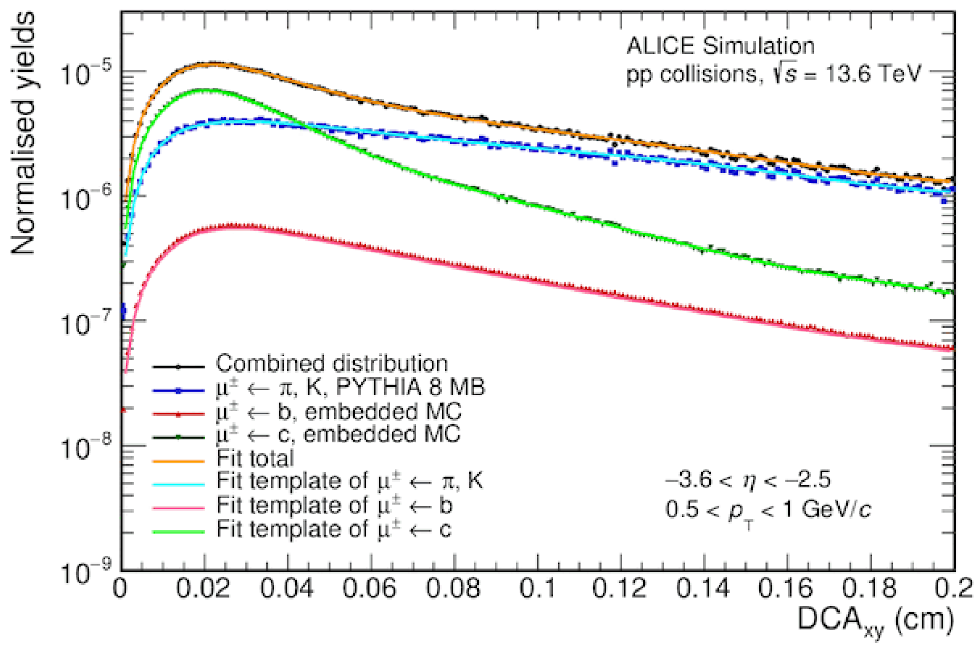
- Different decay length of charm and beauty hadrons
  - Observable: DCA_{xy} (Distance of Closest Approach to the primary vertex in the transverse plane) of heavy-flavour decay muons

- Distinct features of various sources: charm and beauty separation at forward rapidity can be achieved with the MFT

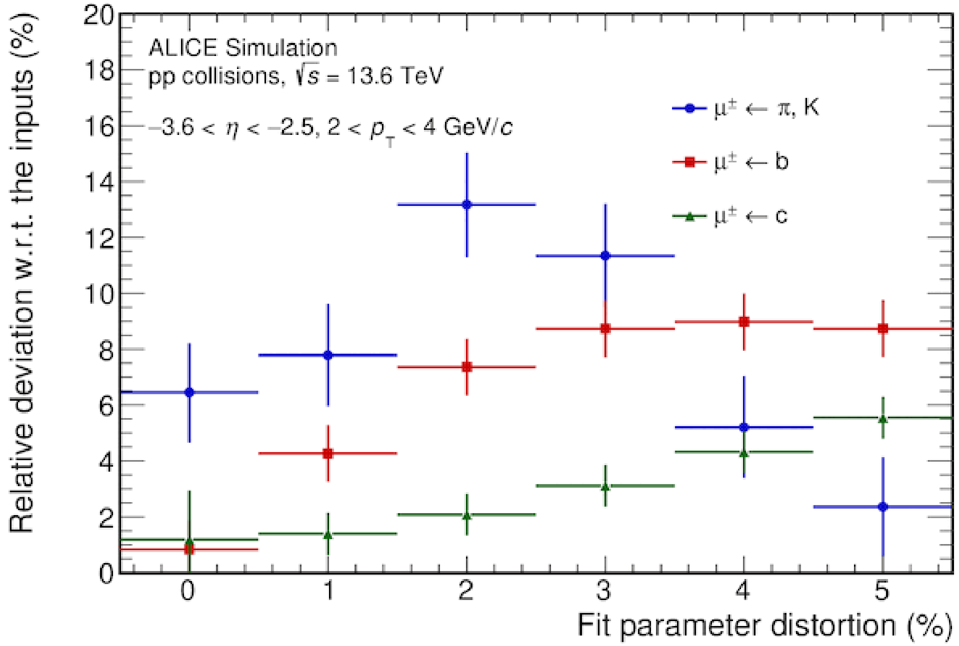
Strategy to separate charm- and beauty-decay muons

- Procedure based on Monte Carlo templates of DCA_{xy} for each source and in each p_T interval
  - Parametrized with a variable-width Gaussian function
  - Total DCA_{xy} distribution for each p_T interval fitted as a combination of the various templates
  - Closure test performed varying fit parameters to mimic detector effects

- Procedure validated with full realistic simulations



ALI-SIMUL-547324



ALI-SIMUL-547377

- $\mu \leftarrow c$ and $\mu \leftarrow b$ can be measured separately in the semimuonic channel at forward rapidity in pp collisions at $\sqrt{s}$ = 13.6 TeV with the MFT coupled with the muon spectrometer, **down to the low p_T region**

Conclusion

- Azimuthal anisotropies in small collision systems
  - Collective-like behaviour of heavy quarks in high-multiplicity p–Pb collisions at both forward and backward rapidities
  - New constraints in the interpretation of the collective-like behaviour in small collision systems and to the model calculations

- p_T -integrated production cross section of charm and beauty measured via dimuons in pp collisions at $\sqrt{s}$ = 13 TeV

- The Muon Forward Tracker allows us to inquire further physics channels
  - Multidifferential measurements of production of charm- and beauty-decay muons separately in the semimuonic channel down to low p_T
  - Template fit method tested and validated with full Monte Carlo simulations

Stay tuned: more to come soon in both pp and Pb–Pb collisions for the measurements in the semimuonic channel

Thank you for your attention

Merci pour votre attention

感谢聆听

BACKUP SLIDES

Backup slides: AMPT(A multiphase transport) model

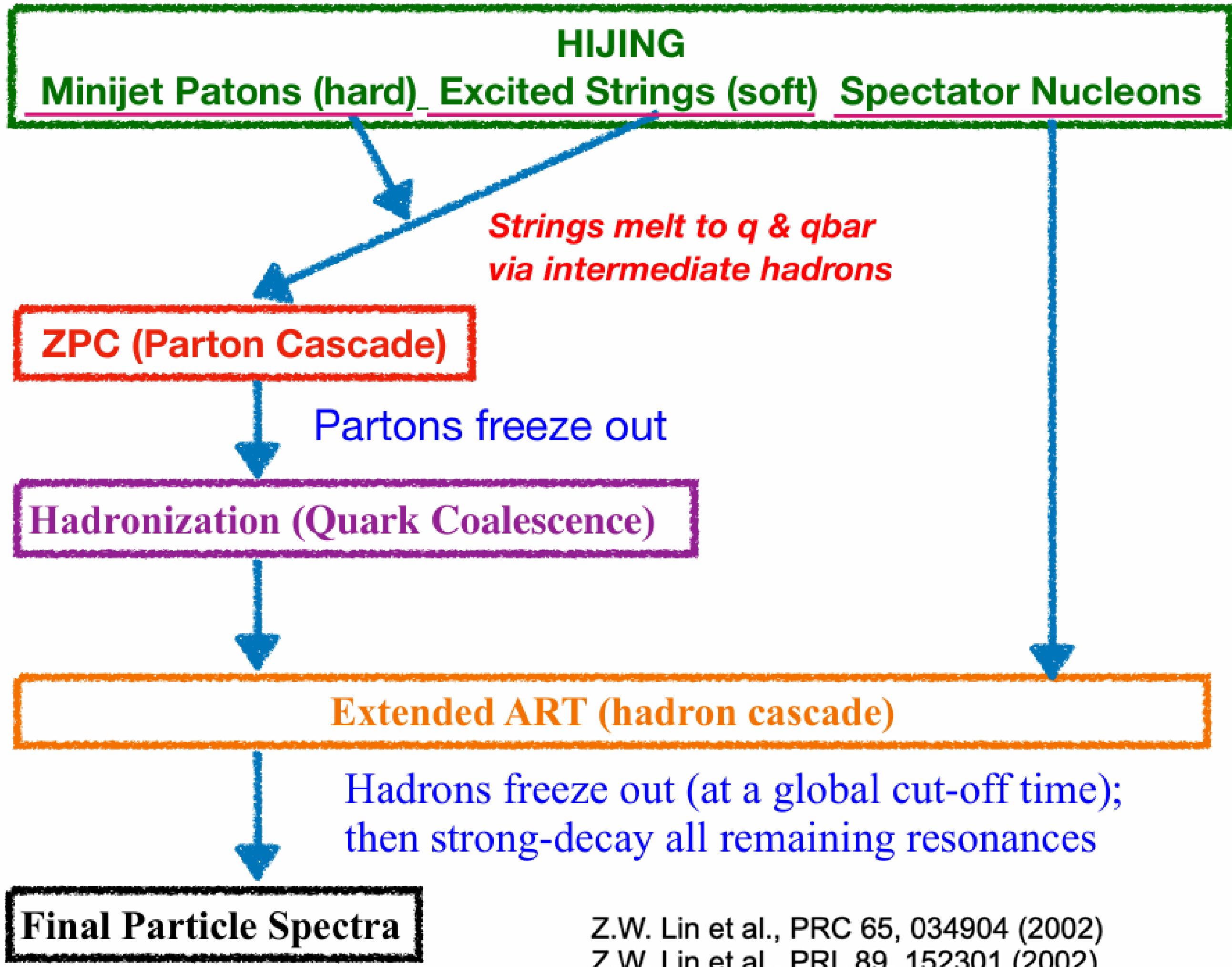
- **Initial conditions:** HIJING two-component model
- **String melting:** hadrons from string fragmentation are melted into primordial quarks and antiquarks
  - Quark formation time: $t_{\mathrm{f}} = E_{\mathrm{H}}/m^2_{\mathrm{T,H}}$
- **Parton cascade:** two-body elastic scattering described by ZPC model

Debye screening mass

$$\frac{d\sigma}{dt} = \frac{9\pi\alpha_s^2}{2}\left(1+\frac{\mu^2}{s}\right)\frac{1}{(t-\mu^2)^2}$$

- **Coalescence:** combine nearest quarks to meson/baryon
- **A R**elativistic **T**ransport (ART) to describe hadron scatterings

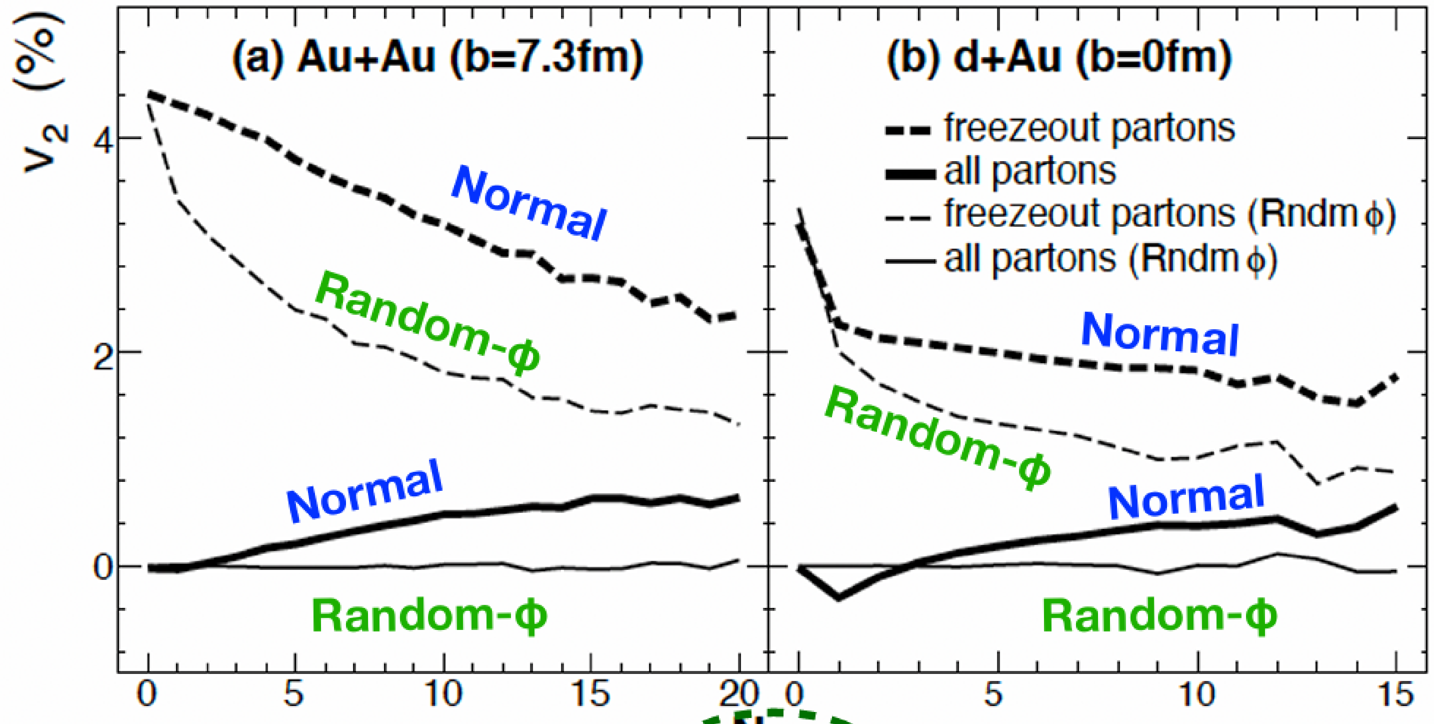
Structure of AMPT v2.xx (String Melting Version)



Z.W. Lin et al., PRC 65, 034904 (2002)
Z.W. Lin et al., PRL 89, 152301 (2002)

Backup slides: escape mechanisms

Zi-Wei Lin, IHEP2016



He et al. PLB753 (2016)

number of collisions suffered by a parton

Freeze out partons: freeze out after exactly N_{coll} collisions;

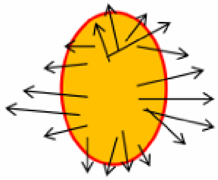
Active partons: will collide further, freeze out after > N_{coll};

All partons: sum of the above two partons

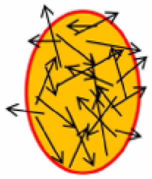
v_2	Normal v_2	Random-ϕ v_2
Au+Au	3.9%	2.7%
d+Au	2.7%	2.5%

	Fraction from pure escape	<N_{coll}> all partons
Au+Au	69%	4.6(modest)
d+Au	93%	1.2(low)

Normal:



Random:



- Few interactions are sufficient for anisotropy in AMPT
  - Partons more likely to escape in the short direction
  - Particle escape is the dominant mechanism for v_2 in small collision systems
  - The v_2 from pure escape decrease with increasing N_{coll} ➔ transport approach hydrodynamics

Backup slides: nonflow subtraction

- The nonflow contribution is estimated in low-multiplicity (60–90%) events, and subtracted for both differential and reference cumulants

$$v_2^{\mu}\{2\}(p_{\mathrm{T}}) = \frac{[d_2^{\mu}\{2\}(p_{\mathrm{T}})]_{(0\text{–}20\%)}}{\sqrt{[c_2\{2\}]_{(0\text{–}20\%)}}}$$

f : the ratio of mean SPD tracklet in low-multiplicity collisions to that in high-multiplicity collisions

subtraction of long-range jet correlation

$$v_2^{\mu}\{2\}(p_{\mathrm{T}}) = \frac{[d_2^{\mu}\{2\}(p_{\mathrm{T}})]_{(0\text{–}20\%)} - f\cdot[d_2^{\mu}\{2\}(p_{\mathrm{T}})]_{(60\text{–}90\%)}}{\sqrt{[c_2\{2\}]_{(0\text{–}20\%)} - f\cdot[c_2\{2\}]_{(60\text{–}90\%)}}}$$

f_{RP}, f' : the factors to remove the **remaining long-range jet correlations**, obtained from two-particle correlations

subtraction of remains long-range and short-range jet correlation

$$v_2^{\mu}\{2\}(p_{\mathrm{T}}) = \frac{[d_2^{\mu}\{2\}(p_{\mathrm{T}})]_{(0\text{–}20\%)} - f\cdot f'\cdot[d_2^{\mu}\{2\}(p_{\mathrm{T}})]_{(60\text{–}90\%)}}{f_{\mathrm{RP}}\cdot\sqrt{[c_2\{2\}]_{(0\text{–}20\%)} - f\cdot[c_2\{2\}]_{(60\text{–}90\%)}}}\cdot f_{\Delta\eta}$$

$f_{\Delta\eta}$: the factor to suppress the **short-range jet correlations**

Backup slides: non-prompt D^0-meson fraction

Define n sets of selections with different prompt and non-prompt D^0 contributions

For each selection set, the raw yield and the efficiencies are related to the corrected yields of prompt N_{prompt} and non-prompt $N_{non-prompt}$ D^0

$$\begin{cases} (\mathrm{Acc} \times \epsilon)_1^{prompt} \cdot N_{prompt} + (\mathrm{Acc} \times \epsilon)_1^{non-prompt} \cdot N_{non-prompt} = Y_1 \\ \dots \\ (\mathrm{Acc} \times \epsilon)_n^{prompt} \cdot N_{prompt} + (\mathrm{Acc} \times \epsilon)_n^{non-prompt} \cdot N_{non-prompt} = Y_n \end{cases}$$

The algebraic equations can be represented by:

$$\begin{pmatrix} \varepsilon_1^{\mathrm{p}} & \varepsilon_1^{\mathrm{np}} \\ \vdots & \vdots \\ \varepsilon_n^{\mathrm{p}} & \varepsilon_n^{\mathrm{np}} \end{pmatrix} \times \begin{pmatrix} N_{\mathrm{p}} \\ N_{\mathrm{np}} \end{pmatrix} - \begin{pmatrix} Y_1 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} \delta_2 \\ \vdots \\ \delta_n \end{pmatrix}$$

The χ^2 of the system is defined as:

$$\chi^2 = \delta^T C^{-1} \delta \,,$$

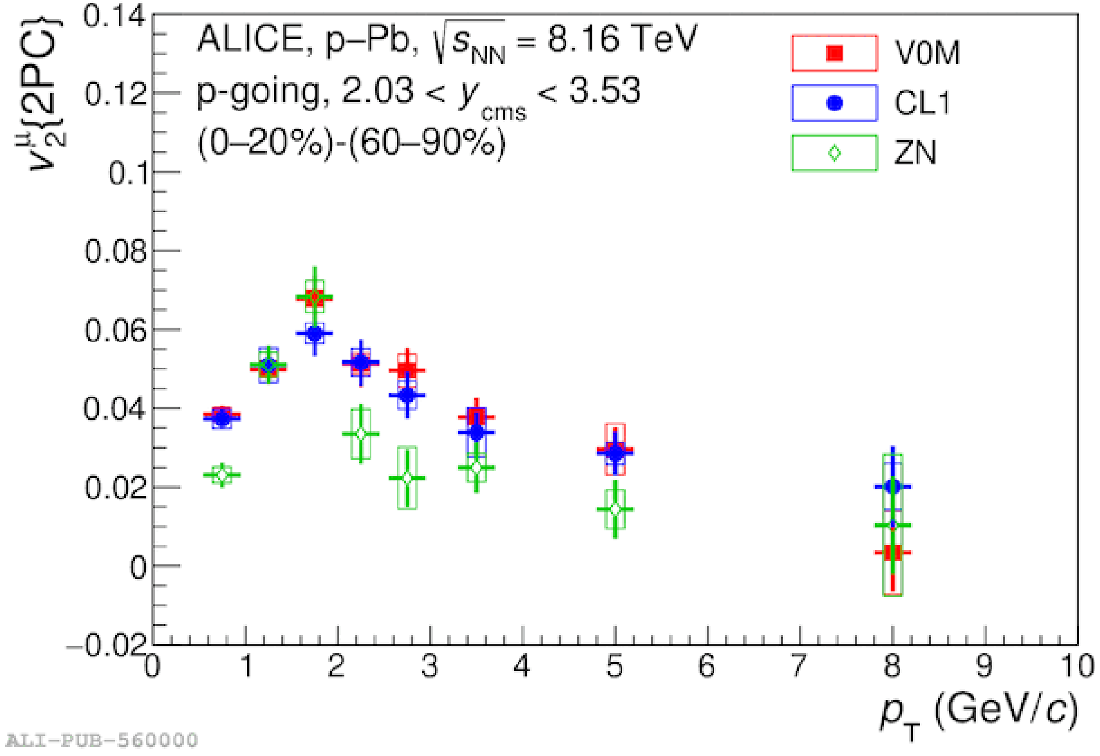
where C is the covariance matrix from the uncertainties

Corrected yields of prompt and non-prompt D^0 obtained from χ^2 minimization of the system

Non-prompt fraction $f_{non-prompt}$ evaluated for a given set of selections as

$$f^i_{non-prompt} = \frac{(\mathrm{Acc} \times \epsilon)_i^{non-prompt} \cdot N_{non-prompt}}{(\mathrm{Acc} \times \epsilon)_i^{non-prompt} \cdot N_{non-prompt} + (\mathrm{Acc} \times \epsilon)_i^{prompt} \cdot N_{prompt}}$$

Backup slides



❖ Compatible v_2 values with different multiplicity estimators within uncertainties with a hint for a smaller v_2 using the energy deposited in the neutron ZDC

Strategy to separate charm- and beauty-decay muons

- Procedure based on Monte Carlo templates of DCA_{xy} for each source and in each p_T interval
  - Parametrized with a variable-width Gaussian function, the width being a polynomial function of the DCA_{xy}

$$f(x) = Ae^{-(x-\mu)^2/2\sigma(x)^2}$$
$$\sigma(x) = \sigma_0^L + \sigma_1^L(\mu - x) + \ldots + \sigma_3^L(\mu - x)^3 \text{ for } x \leq \mu$$
$$\sigma(x) = \sigma_0^R + \sigma_1^R(x - \mu) + \ldots + \sigma_6^R(x - \mu)^6 \text{ for } x > \mu$$

  - Total DCA_{xy} distribution for each p_T interval fitted as a combination of the various templates

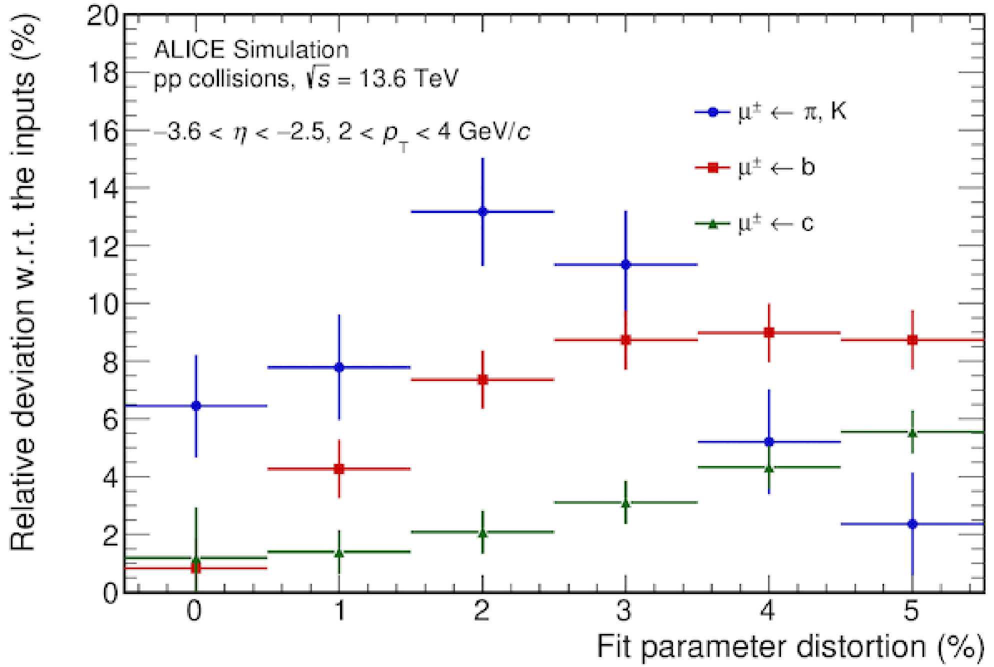
$$f(x) = B \cdot f_b(x) + C \cdot f_c(x) + D \cdot f_{bkg}(x)$$

  - Extraction of yields of $\mu \leftarrow c$ and $\mu \leftarrow b$

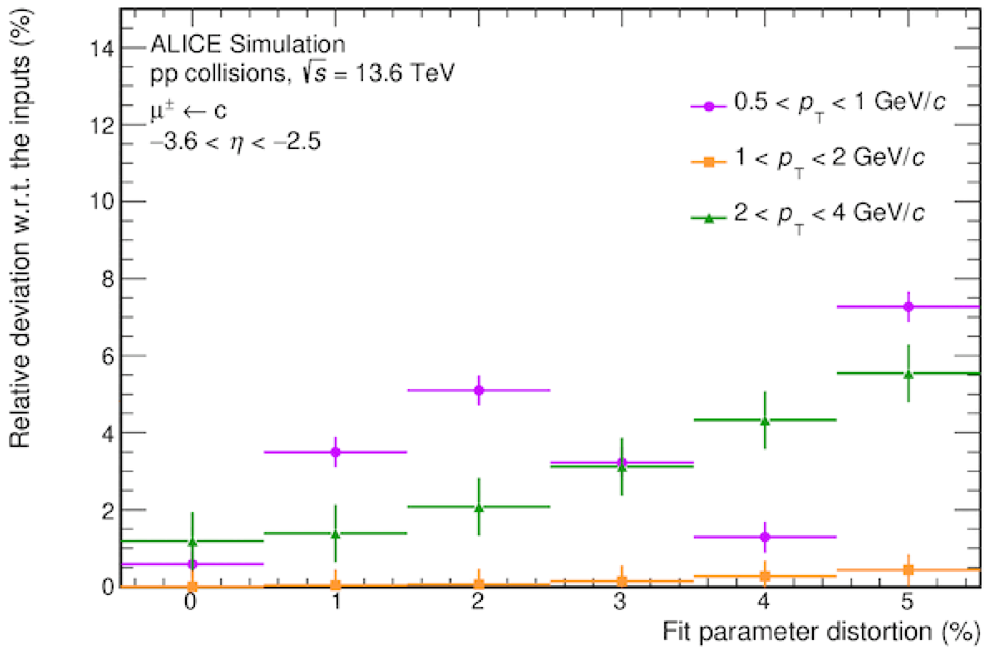
Strategy to separate charm- and beauty-decay muons

❖ Closure test: varying fit parameters to mimic detector effects

- Randomly vary width parameters by 1% to 5% to generate distorted templates
- Refit DCA_{xy} using these distorted templates and examine the sensitivity through their relative deviations



ALI-SIMUL-547377



ALI-SIMUL-547380

❖ μ ← c and μ ← b can be measured separately in the semimuonic channel at forward rapidity in pp collisions at √s = 13.6 TeV with the MFT coupled with the muon spectrometer, down to about 0.5 GeV/*c* and 2 GeV/*c* for charm and beauty, respectively