Recent results and upgrade of the ALICE muon spectrometer

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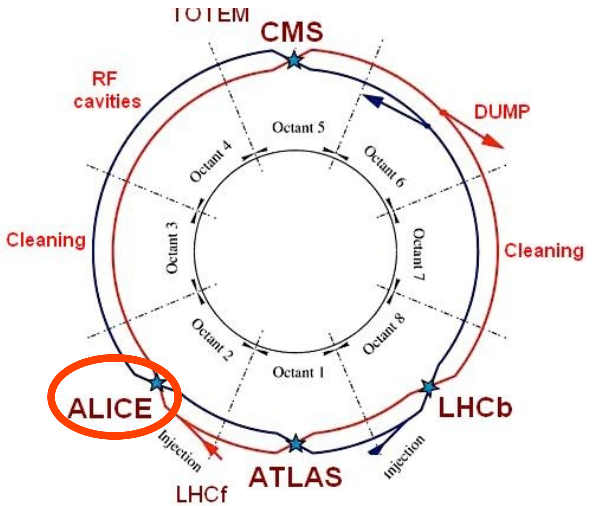
Overview

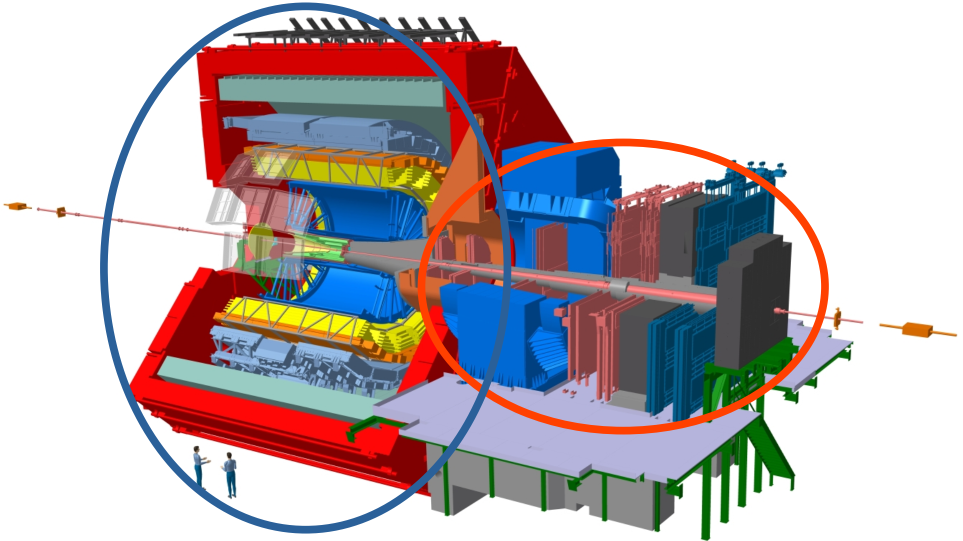
- ALICE and its Muon Spectrometer (MS) in LHC Run 1 and 2
- Some results from the MS in Run 2
- The upgraded MS for Run 3 onward
- Physics performance in Run 3
- Conclusions

The ALICE detector at CERN

- A Large Ion Collider Experiment (ALICE) is one of the four experiments located at the CERN Large Hadron Collider (LHC)
- Multi-purpose detector, taking data in all colliding systems: pp, Pb-Pb and p-Pb
- Mainly focused on the study of Quark-Gluon plasma (QGP) in heavy-ion collisions



Scheme of the LHC ring, taken from Evans, L. and Bryant, P. (2008)


Rendering of the ALICE detector

- Two spatially distinct detection regions
- Central barrel |y| < 0.9
  - Particle tracking & identification
- Muon spectrometer (MS) -4 < y < 2.5
  - Located at forward rapidity
  - Muon identification and tracking down to $p_T = 0$

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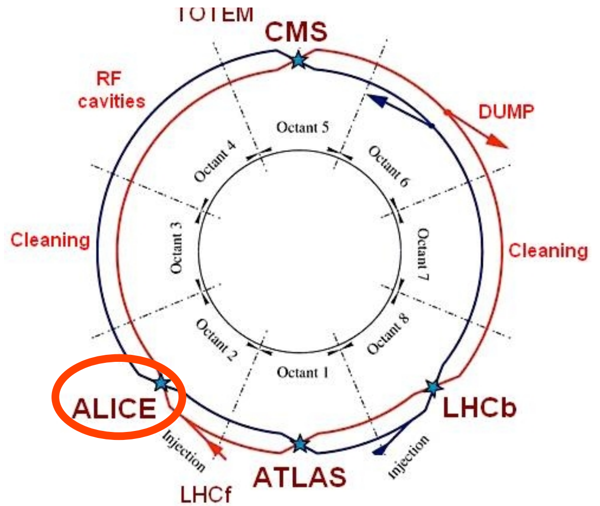

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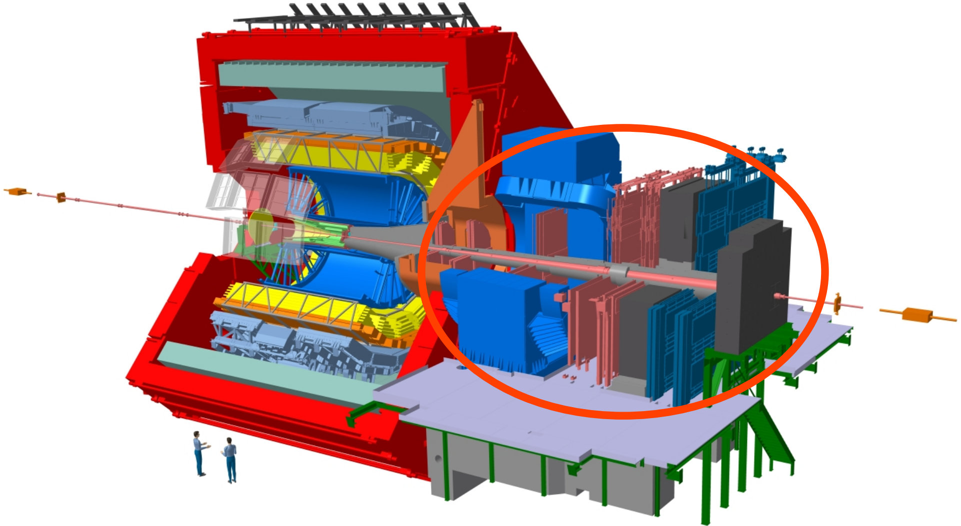
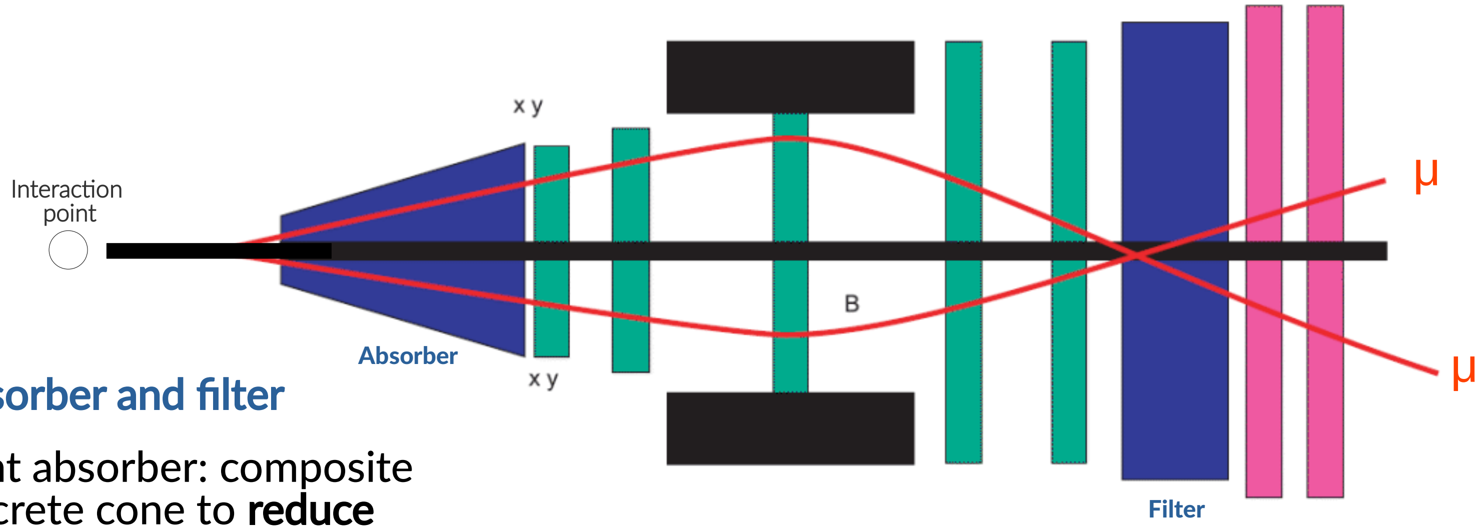


Rendering of the ALICE detector

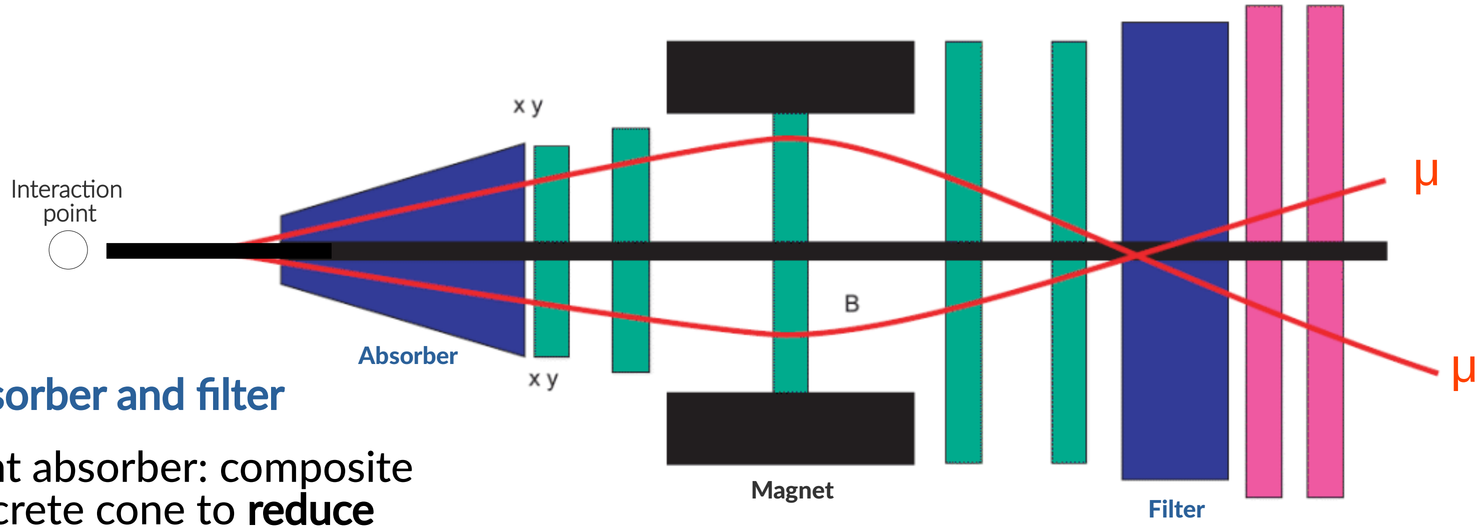
The ALICE Muon Spectrometer in Run 1/2



Front absorber and filter

- Front absorber: composite concrete cone to **reduce hadron contamination**
- Filter: iron wall to **stop residual hadrons**

The ALICE Muon Spectrometer in Run 1/2



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- Dipole magnet to **bend** muon tracks
- Measure **momentum** and **charge**

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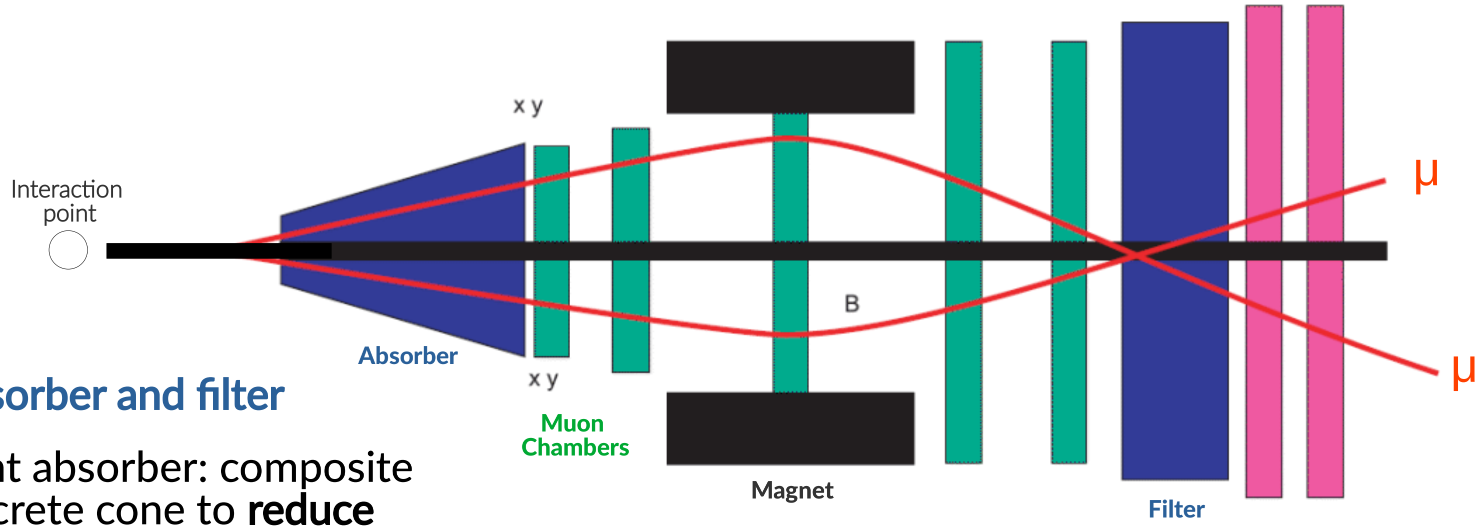

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Muon chambers (MCH)

- Five stations of **cathode pad/strip chambers**
- Provide **muon tracking**

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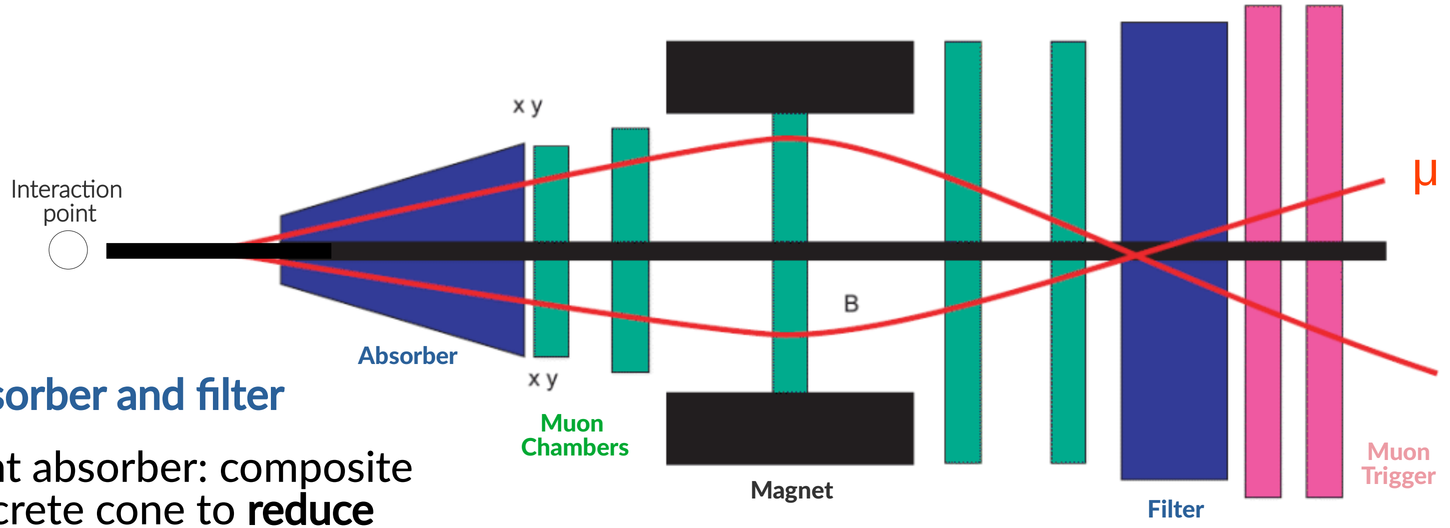


Front absorber and filter

- Front absorber: composite concrete cone to **reduce hadron contamination**
- Filter: iron wall to **stop residual hadrons**

Muon Trigger (MTR)

- Two stations of **Resistive Plate Chambers**
- Provides muon **triggering** for the MS

Magnet

- Dipole magnet to **bend** muon tracks
- Measure **momentum** and **charge**

Muon chambers (MCH)

- Five stations of **cathode pad/strip chambers**
- Provide **muon tracking**

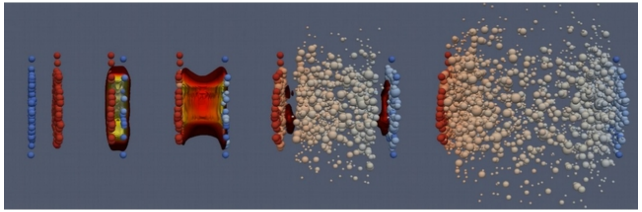
Physics goals of the MS

- Space-time evolution of ultra-relativistic heavy-ion collision

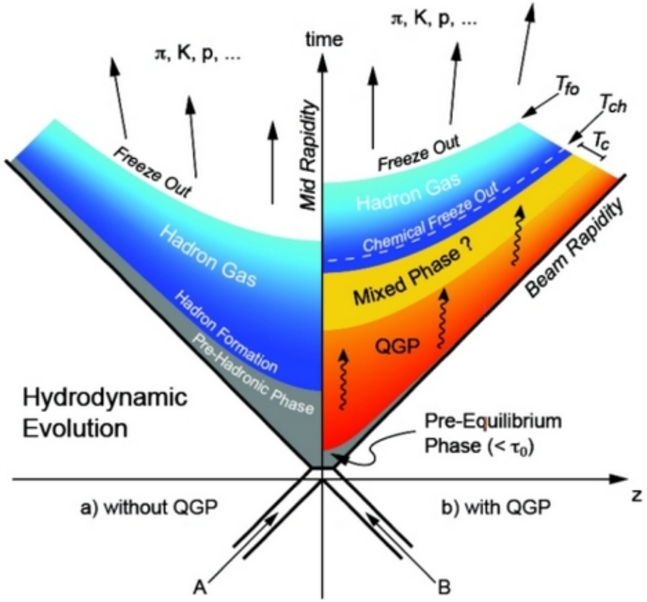
- If **critical temperature** and **energy density** is reached
  → Formation of **QGP**
  → State of nuclear matter where quarks and gluons are not confined and can move freely over distances larger than hadron size

- QGP is short-living (**~10 fm/c**)
  - Cannot be studied directly
  - Long-lived probes are needed

  - Few examples of interest in the MS discussed later
    - **Heavy-flavor production**
    - **J/Ψ elliptic flow**
    - **Quarkonium suppression**
    - …..



Simulation of heavy-ion collision evolution, taken from this website



Schematic space-time evolution of a heavy-ion collision, taken from this website

MS capabilities

- Exploit **muonic decays of quarkonia and heavy flavors** to study QGP
- Measure charmonium production down to $\mathbf{p_T = 0}$
    - Charmonium production is sensitive to QGP effects
- Cover a pseudorapidity range that completes the central barrel ($|\eta| < 0.9$) and the ATLAS/CMS coverage
- Disentangle the 3 ϒ resonances (ϒ(1S), ϒ(2S), ϒ(3S))
    - $\mathbf{\Delta M_{\Upsilon(3s)-\Upsilon(2s)} \sim 300\ MeV/c^2}$
    - **Mass resolution ~ 150 MeV/c^2 and ~70 MeV/c^2 in the ϒ and J/ψ mass regions**

Physics results: heavy-quark production

- Heavy quarks are **produced in the first stages of the Pb-Pb collisions**
  - They experience the full evolution of the system
  - They lose energy in the QGP via **radiative** and **collisional** energy loss
  - **Dead-cone effect**
    → Lighter quarks lose more energy while traversing QGP

- In-medium effects quantified by the nuclear modification factor (**R_{AA}**)

$$R_{AA}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \times \frac{d^2 N_{AA} / dp_T dy}{d^2 \sigma_{pp} / dp_T dy}$$

- **$\langle T_{AA} \rangle$** is the **average nuclear overlap function**, the numerator is the p_T and y-dependent particle yield in Pb-Pb collisions and the denominator is the production cross-section in pp collisions (at the **same center-of-mass energy as the Pb-Pb** ones)

Quarkonium suppression

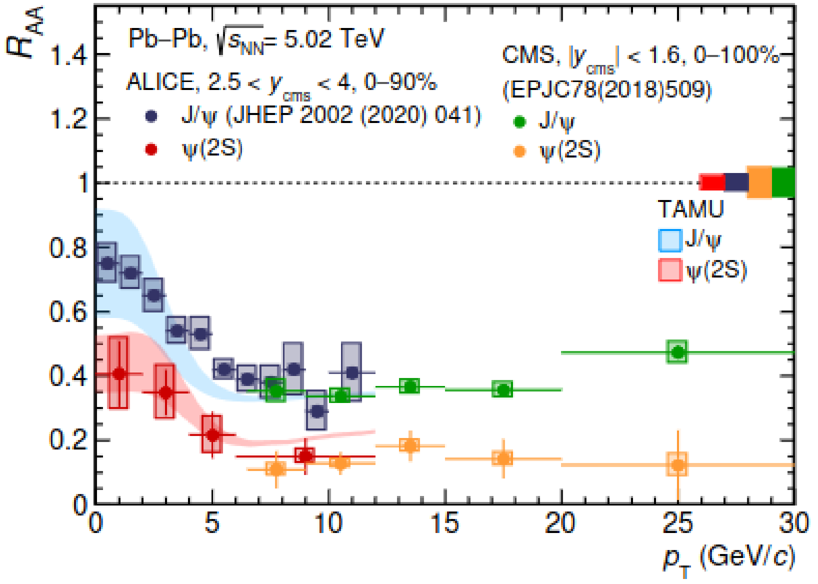
- Large density of free color charges in QGP
  → **Screening of quark-antiquark binding** and dissociation of quarkonia
  → Charmonia ($c\bar{c}$ pairs) exist in different states
  → **J/ψ and ψ(2s)** (excited state) with **different binding energy** (~640 vs ~50 MeV)
  → Dissociation of different states happens at different temperatures

- Clear **hierarchy** in J/ψ and ψ(2s) suppression across all p_T range

- **Larger suppression for ψ(2s)** but similar trend for the two states

- R_{AA} **increase at low p_T** explained by **recombination** of charm quarks/anti-quarks

- **CMS data** at higher p_T **in agreement with ALICE** results at lower p_T



ALICE collaboration, ψ(2S) *Suppression in Pb-Pb Collisions at the LHC*, Phys. Rev. Lett. 132 (2024)

J/Ψ flow in Pb-Pb collisions

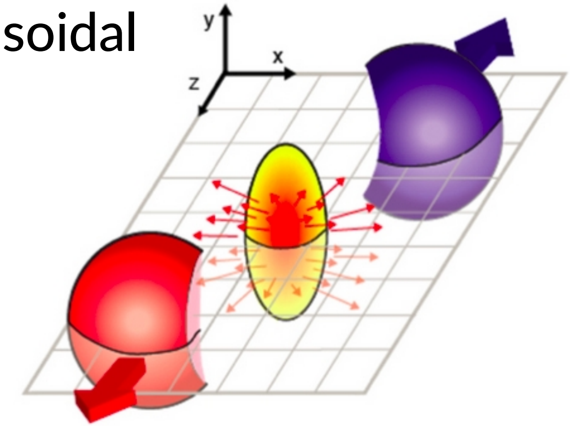
- **Azimuthal dependence of particle production in Pb-Pb collision**s
  - Quantified in terms of a Fourier expansion of the distribution of the difference of the azimuthal angle of the particles (φ) wrt the angle of the initial symmetry plane (Ψ_n)

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

  - **Initial state** spatial **anisotropy** of the collision overlap region is **transformed into** a **momentum anisotropy** of the produced particles

- Most dominant source of anisotropy is the ellipsoidal shape of the overlap region in peripheral Pb-Pb collisions
  - Second order harmonic (**v_2**)

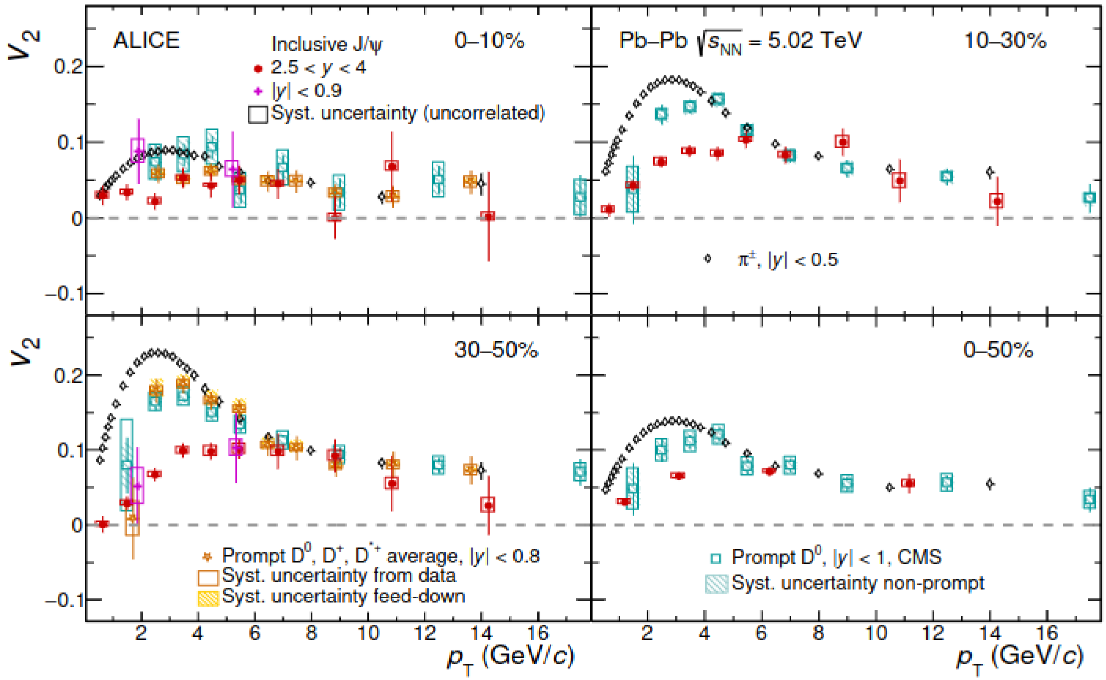
    → **Elliptic flow**



Sketch of peripheral Pb-Pb collision with ellipsoidal shape of overlap region. Figure taken from this website

J/Ψ flow in Pb-Pb collisions

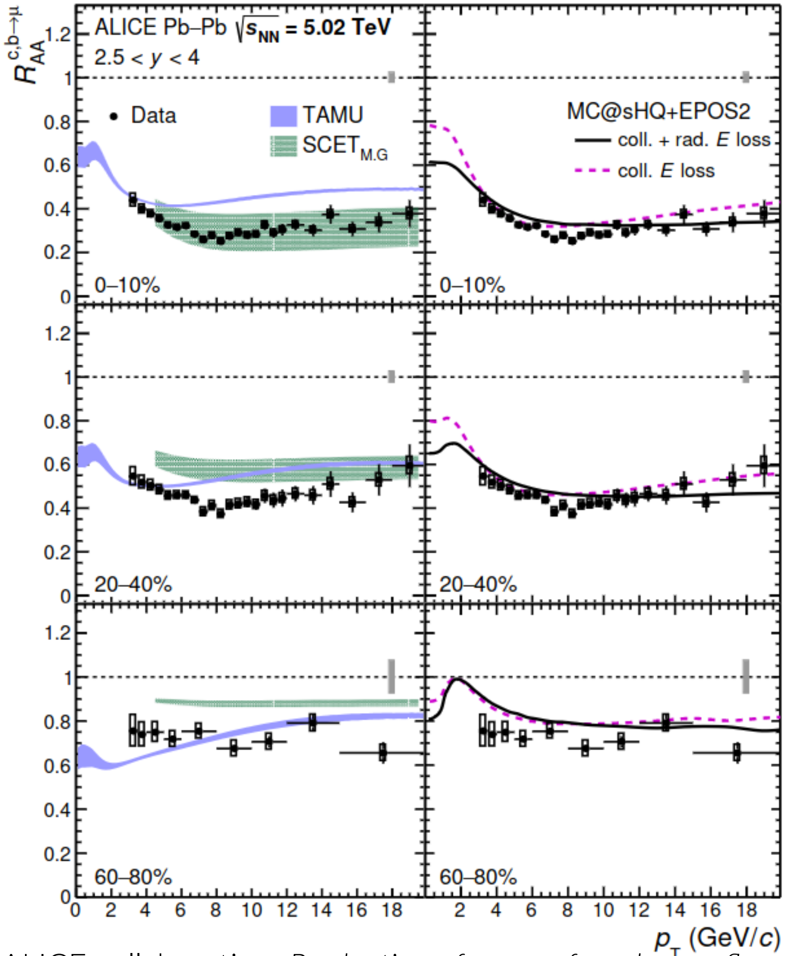
- **v_2** coefficient calculated using the **scalar product** technique
- v_2 **increases with p_T** with a maximum at intermediate p_T and it also increases in **more peripheral collision** wrt central ones
- v_2 values are **statistically compatible with results at mid-rapidity**
- v_2 mass ordering for p_T < 6 GeV/c while for p_T > 8 GeV/c it converges to similar values



ALICE collaboration, *J/ψ elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV*, J. High Energ. Phys., 141 (2020)

Heavy flavor production

- Inclusive heavy-quark (b and c) production studied in the MS
- **Larger suppression** (lower R_{AA}) **in more central collisions**, especially in the range $6 < p_T < 10$ GeV/c
- $\mathbf{R_{pPb}}$ ~ 1 (not shown here) in the same p_T range (QGP formation not expected in **pPb** collisions)
  → $R_{AA} < 1$ due to final state effects in Pb-Pb

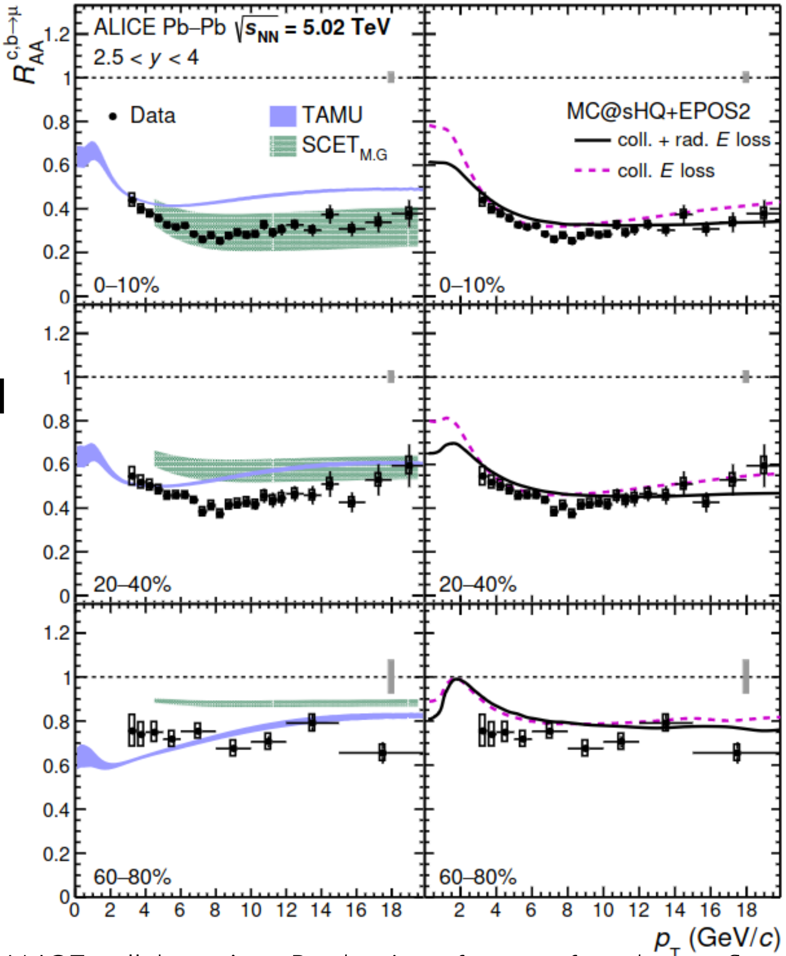


ALICE collaboration, *Production of muons from heavy-flavour hadron decays at high transverse momentum in Pb–Pb collisions at $\sqrt{s_{NN}}$=5.02 and 2.76 TeV*, Physics Letters B, 820 (2021)

Heavy flavor production

- Data compared to several models
- **TAMU** [*He, M. et al (2014)*]
  - Interactions described by **elastic collisions only**
- **SCET** [*Kang, Z.-B. Et al (2017)*]
  - pQCD-based model, it implements **medium-induced gluon radiation**
  - Modified splitting function and finite quark masses
- **MC@sHQ+EPOS2** [*Nahrgang, M. et al (2014)* and *Nahrgang, M. et al (2014)*] transport model:
  - **Hydrodynamic description of the medium**
  - Coupled with different parton energy losses

  → Describes the measured R_{AA} over the whole p_T range within uncertainties



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MS limitations

- Large **distance between tracking chambers and the interaction point + μ multiple scattering** in the absorber
  → No track constraint in the primary vertex region
  1) Limited possibilities to **reject μ from semi-leptonic decays of π and K**
  2) **Impossible** to disentangle **prompt/non-prompt J/Ψ**

- Degradation of tracks angular resolution due to multiple scattering
  → Limited mass resolution of resonances (especially at low mass, e.g. ω and Φ)
  → From ~46 to 13 MeV/c^2 (without and with MFT) for ω
  → From ~50 to 15 MeV/c^2 for Φ

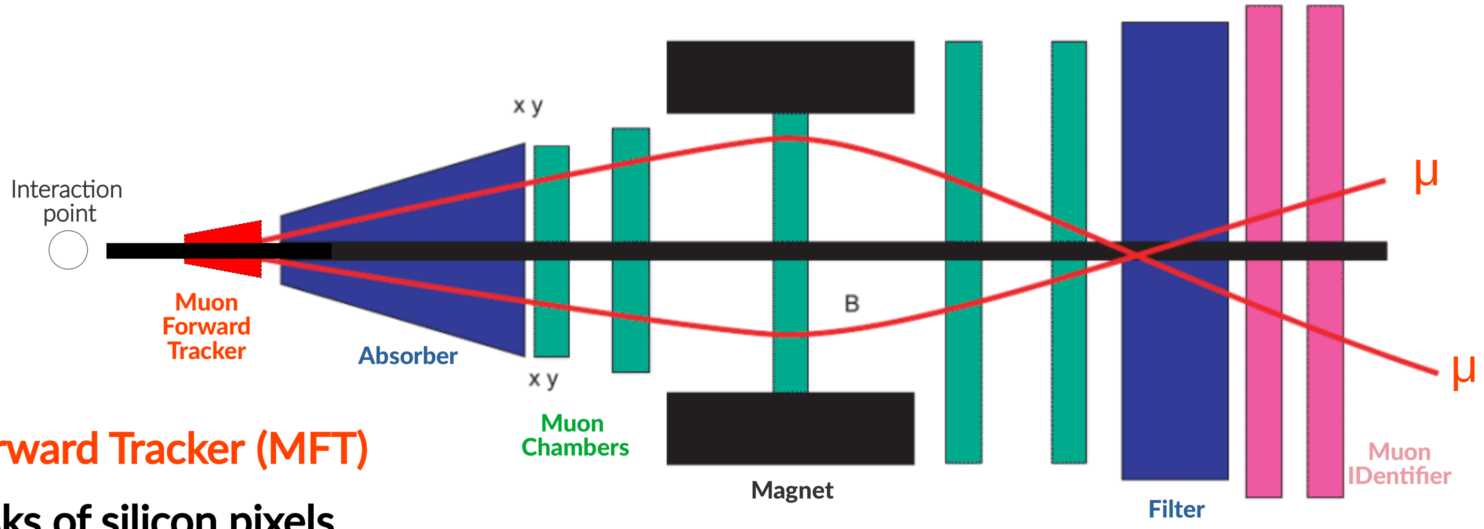
MS upgrade for Run 3/4

- Installation of silicon pixel vertex detector **upstream** of the hadron absorber
  - **M**uon **F**orward **T**racker (**MFT**)
  - Installed in ALICE during the LHC Long Shutdown 2 (2019-22)
  - It allows to match μ tracks *upstream* and *downstream* of the absorber, enabling vertex finding

- **Other MS upgrades**:
  - Higher luminosity in pp and Pb-Pb collisions
  - 50 kHz interaction rate in Pb-Pb
  - Need to run in continuous readout mode

- Goal of the upgrade for Run 3+4
  - Integrated luminosity of **13 nb^{-1}** in Pb-Pb, > **200 pb^{-1}** in pp and ~ **0.6 pb^{-1}** in p-Pb

The ALICE Muon Spectrometer upgrade



Muon Forward Tracker (MFT)

- **5 disks of silicon pixels**
- It covers the $-3.6 < \eta < -2.45$ range
- It **enables vertexing in the spectrometer**

Muon chambers upgrade

- New front-end electronics (**DUAL-SAMPA**)
- New DAQ chain to support **continuous** (trigger-less) **readout**

Muon Identifier (MID)

- **New front-end electronics** (FEERIC) with lower threshold (higher rate capability)
- Provide **muon identification** in new trigger-less mode

Beauty via non-prompt J/Ψ

- Measurement of **non-prompt J/Ψ**
  1) Originating from the decay of B-hadrons

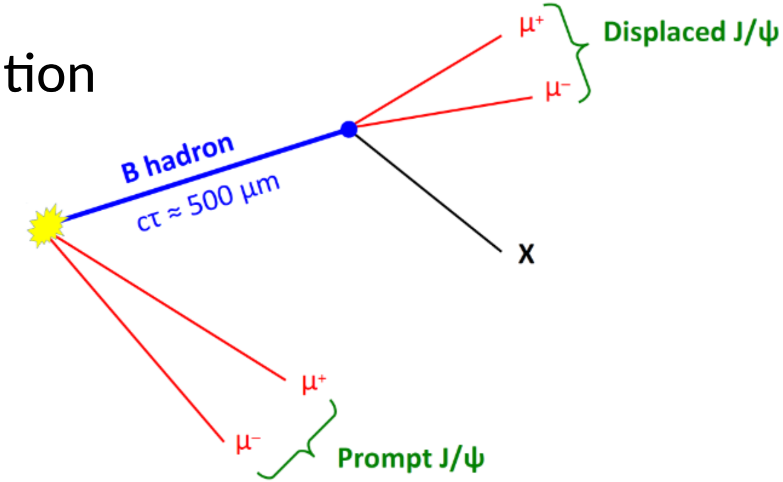
$$\mathbf{B \rightarrow J/\Psi + X}$$

  2) Based on the **measurement of the distance between primary** (collision) **and secondary** (decay of B-hadron) **vertices**

  3) B^0, B^+, B_s and Λ_b baryons give the largest contribution

- Distance of displaced vertex ≈ **cτ of B-hadron**
  - 420-490 nm

  - Need of precise vertex detector at forward rapidity → MFT



Example of displaced J/Ψ production.
Figure taken from: ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)

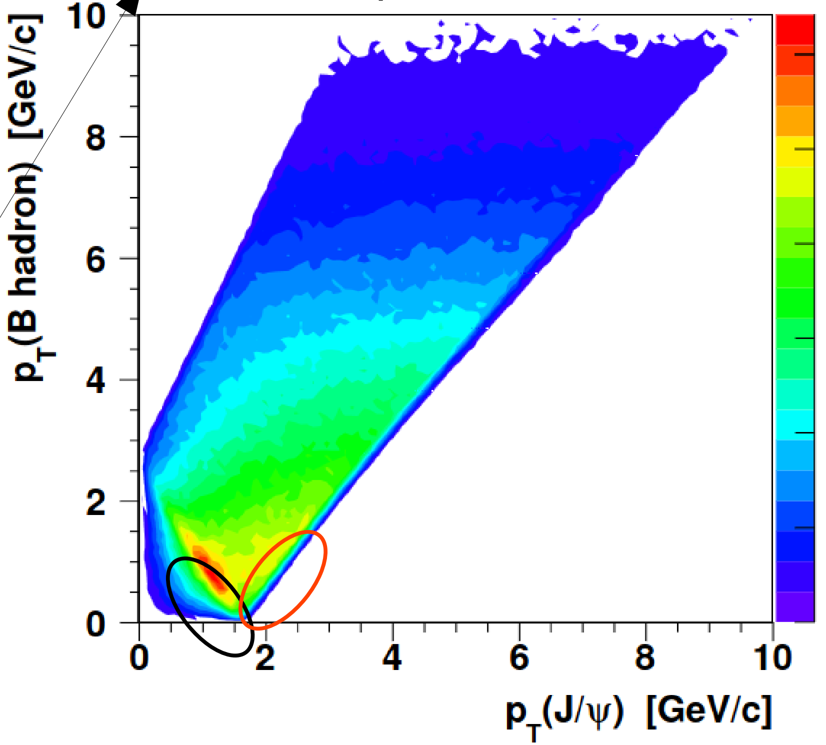
Beauty via non-prompt J/Ψ

- Interest in studying B-hadrons down to $p_T = 0$
- Possible thanks to peculiar kinematics correlation

p_T(J/Ψ) > 2 GeV/c
→ Loose correlation with p_T(B-hadron)

p_T(B-hadron) < 2 GeV/c
→ Anti-correlation with p_T (J/Ψ)
→ Minimum p_T (J/Ψ) ≈ 1.5 GeV
→ Well within MS capabilities

B-hadron with $p_T = 0$ decays into a J/Ψ with finite p_T due to the presence of other decay components (X)



Correlation between B-hadron and J/Ψ p_T. Figure taken from: ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)

Beauty via non-prompt J/Ψ

- Statistical separation between prompt and non-prompt J/Ψ according to the different distribution of their distance from the primary vertex (L)

- L/c (corrected by the γ factor of the B-hadron) = proper B-hadron decay time

- Assuming that $\gamma_{J/\Psi} \approx \gamma_{B\text{-hadron}}$
  → **pseudo-proper decay time** (t) of B-hadron introduced

Secondary vertex position

Primary vertex position

$$t = \frac{\left|\vec{r}_{J/\psi} - \vec{r}_{\mathrm{vtx}}\right| \cdot M_{J/\psi}}{p}$$

J/Ψ momentum

J/Ψ mass

$$t_{xy} = \frac{\sqrt{\left(x_{J/\psi} - x_{\mathrm{vtx}}\right)^2 + \left(y_{J/\psi} - y_{\mathrm{vtx}}\right)^2} \cdot M_{J/\psi}}{p_{\mathrm{T}}}$$

Transverse plane

Used in ALICE (better separation)

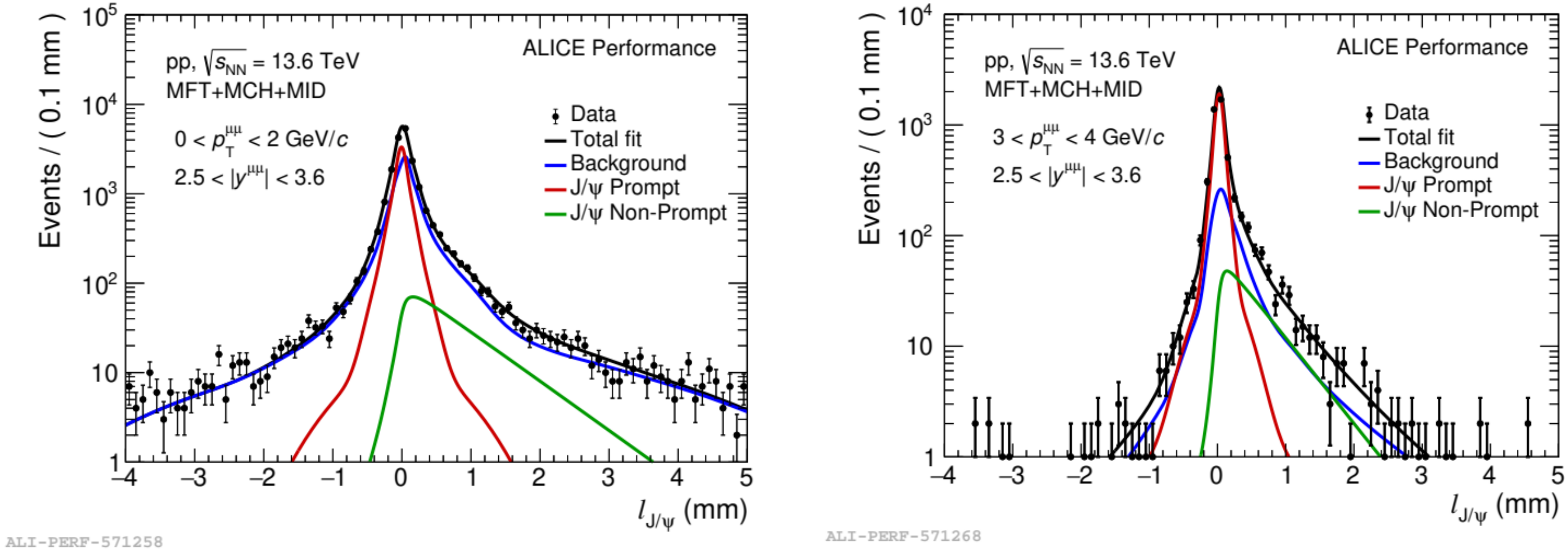
$$t_z = \frac{\left(z_{J/\psi} - z_{\mathrm{vtx}}\right) \cdot M_{J/\psi}}{p_z}$$

Longitudinal plane

Run 3 data

Beauty via non-prompt J/Ψ

- Distribution of prompt J/Ψ pseudo-proper decay length is peaked at 0
- **Displaced J/Ψ has a positive $l_{J/\psi}$ tail that reflects B-hadron decay time** (also includes background)
- **Simultaneous fit** to invariant mass spectrum and $l_{J/\psi}$ distribution **Gaussian with variable width σ (~$M_{\mu\mu}^3$)**
  - Invariant mass fit to **fix the background normalization**
  - **$l_{J/\psi}$ decomposed in its components** (prompt/non-prompt J/ψ and background) and fitted with a variable width Gaussian
    → Inclusive J/ψ normalization and prompt/non-prompt ratio as free parameters (estimated with the fit)



Pseudo-proper decay length of muon pairs measured at forward rapidity using *global muon tracks* in two different p_T bins. ALICE performance figures

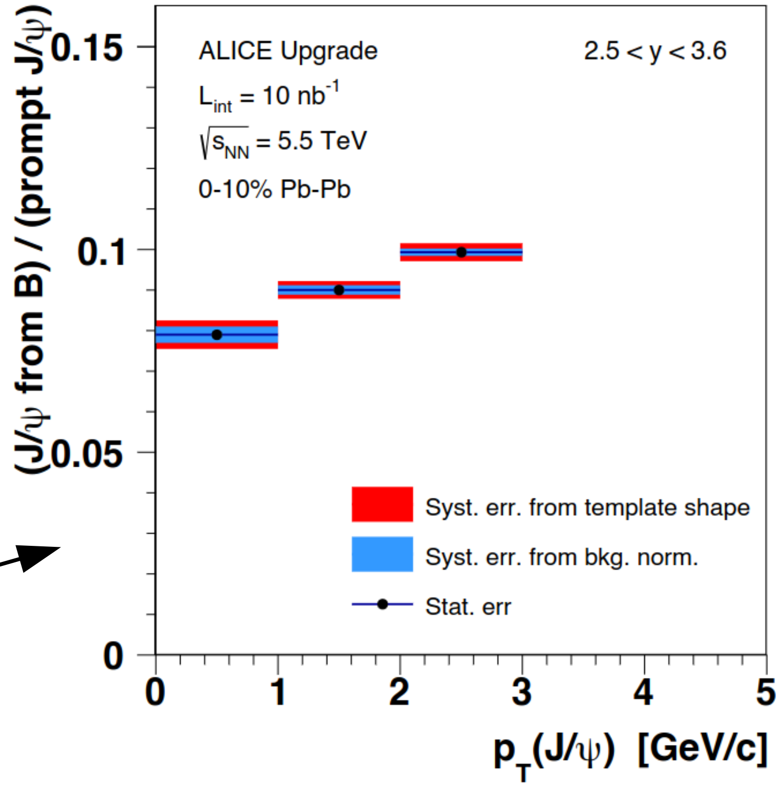
Beauty via non-prompt J/Ψ

- Statistical uncertainty: 0.8% to 1.6% in the range p_T < 3 GeV/c (obtained from the fit of the t_z distribution)

- **Two sources of systematic uncertainties**:
  1) 1% due to background normalization
     1a) Obtained by fitting the t_z distribution varying the background within 1%

  2)Uncertainty on the shape of t_z distributions
     2a) Experimental resolution on t_z varied by ±10% and re-fit of the distribution → Extremes taken as the error

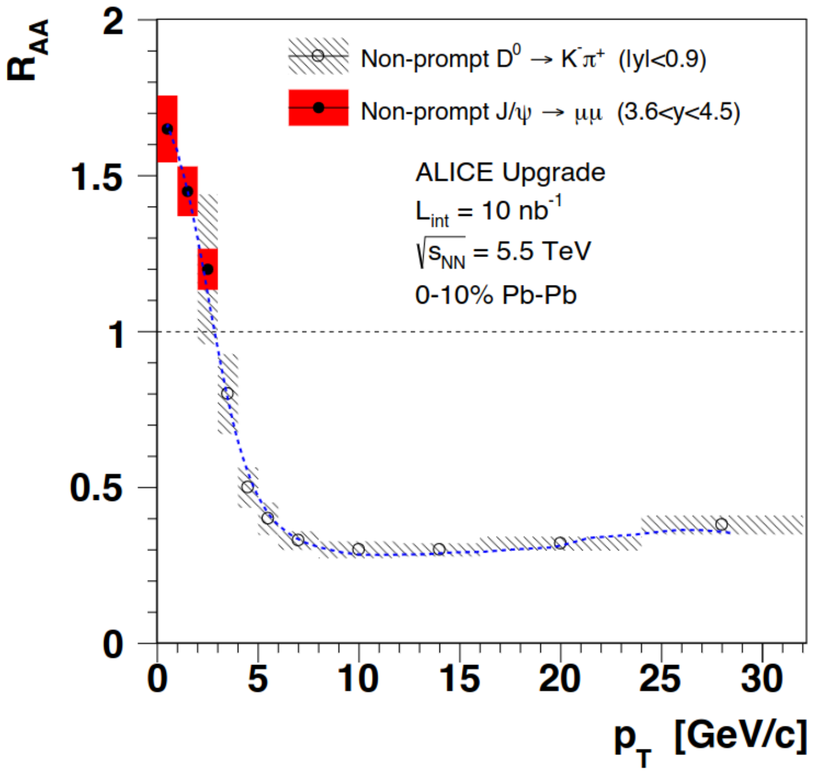
- In general **< 5% down to p_T = 0**



Uncertainties in the non prompt/prompt J/Ψ ratio as a function of p_T. Figure taken from: ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)

Non-prompt J/Ψ R_{AA}

- To calculate error on non-prompt J/ψ R_{AA}
  → Uncertainty coming from pp reference needed
  → Same √s as Pb-Pb (5.5 TeV)
- Signal obtained in Pb-Pb scaled to the expected L_{int} in pp reference
- Statistical uncertainty calculated by fitting the t_z distributions, in pp (perfect matching between MFT and MS due to lower background in pp)
- Systematic uncertainty assumed to be the same as for prompt/non-prompt J/Ψ
- 5% systematic uncertainty due to MS tracking efficiency
- **Possible down to p_T = 0**



R_{AA} of non-prompt J/Ψ at forward rapidity and of D^0 meson at central rapidity. Figure taken from: ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)

Open heavy-flavor in the single μ channel

- MFT will contribute to the study of open heavy flavors in the single muon and dimuon channels

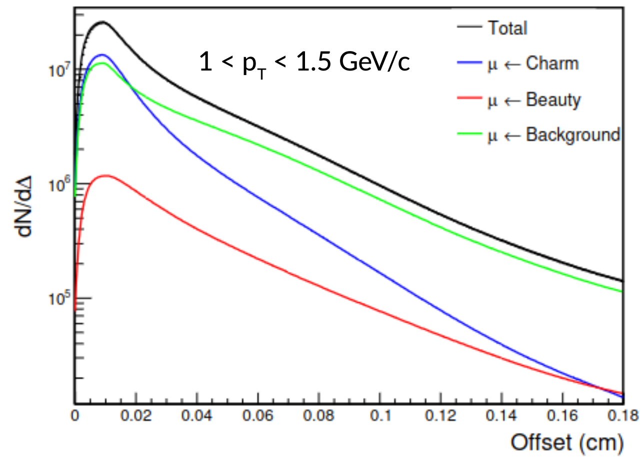
- Needed down to low p_T
  - To extract charm and beauty cross sections with least model dependence as possible (**charmonium regeneration**)

- **Separate study of charm and beauty**
  - Investigate different energy loss in QGP
  - Hierarchy of R_{AA}: $R_{AA}^{D} < R_{AA}^{B}$

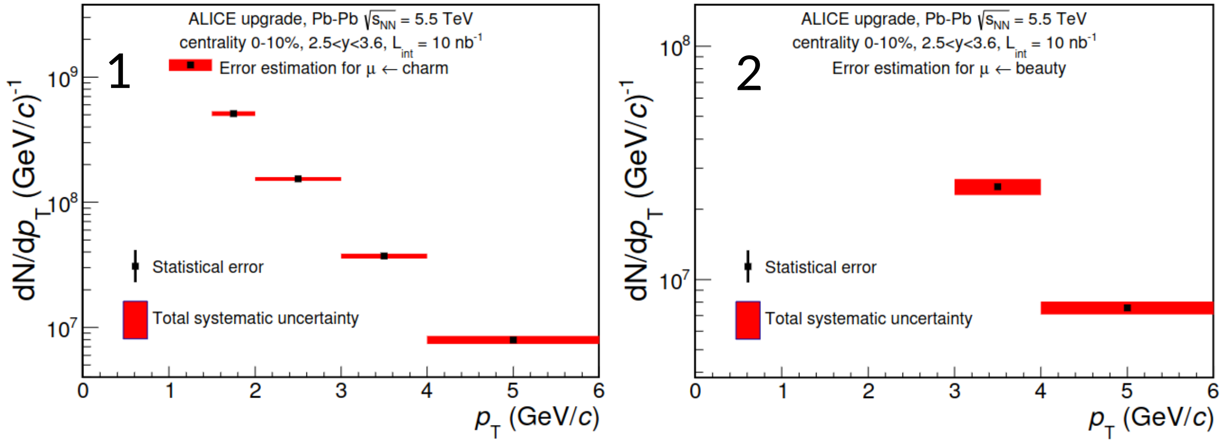
- Study done with MC simulation
  - **Signal**: b or c direct decays or *chain decays* $\mu \leftarrow D \leftarrow B$
  - **Background**: μ from decays of particles produced in the underlying event

Open heavy-flavor in the single μ channel

- **Yield study based on the offset (Δ) distribution**
  - Decay of b and c is displaced wrt primary interaction vertex
- Offset distribution for signal and background
  - Fitted in each p_T bin with a **vw Gaussian ($\sigma \sim \Delta^3$)**
- Total distribution re-fitted with normalization as free parameter to get the yield
- **Statistical error** in the single μ yield **< 0.5%**
- **4 sources of systematical** errors (see backup)



Single μ offset distribution in the 0-10% most central Pb-Pb collisions for L_{int} = 10 nb^{-1}. Figure taken from:ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)



P_T distribution of single muons from open charm (left) and beauty (right) in the 0-10% most central Pb-Pb collisions for L_{int} = 10 nb^{-1}. Figure taken from ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)

1) For **open charm**
→ Total error < 10% at p_T = 1 GeV/c

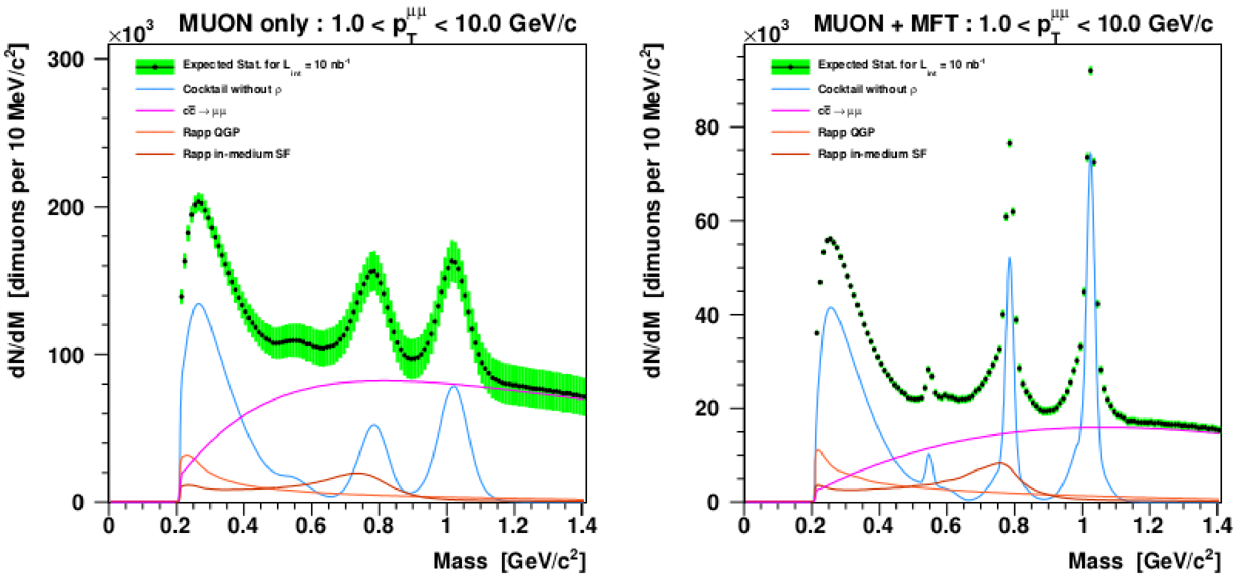
2) For **open beauty**
→ Robust measurements only for p_T > 3 GeV/c

Low-mass dimuons

- **Dimuon invariant mass depends on the momentum of both muons (p_1,p_2) and opening angle (θ)**

$$M_{\mu\mu} = \sqrt{2p_1p_2(1-\cos\theta)} \approx \sqrt{p_1p_2\theta^2}$$

- At low invariant mass measurements
  - **Multiple scattering in the absorber is the main source of error in $M_{\mu\mu}$ measurement**
- MFT will measure opening angle before the absorber, improving mass resolution and improving the S/B ratio

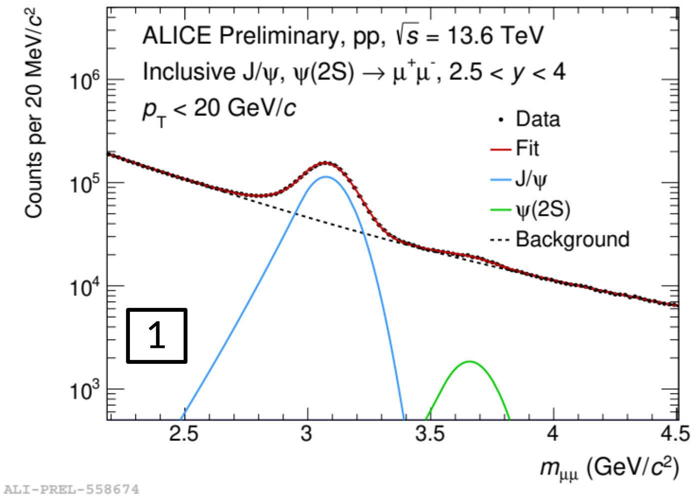


Improvement of low-mass dimuons invariant mass spectrum, with (right) and without (left) MFT. Figure taken from: ALICE collaboration, *Addendum of the Letter of Intent for the upgrade of the ALICE experiment : The Muon Forward Tracker*, CERN-LHCC-2013-014 (2013)

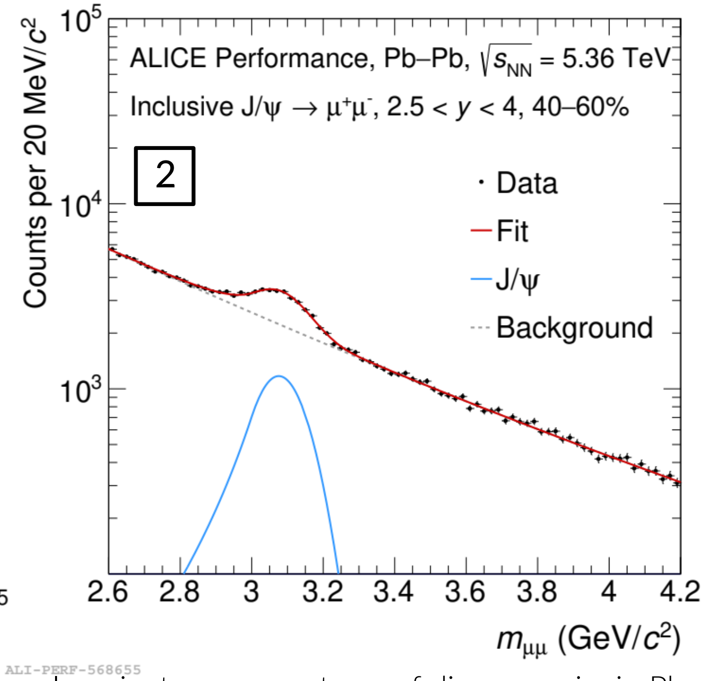
Run 3 data

Preliminary Run 3 results

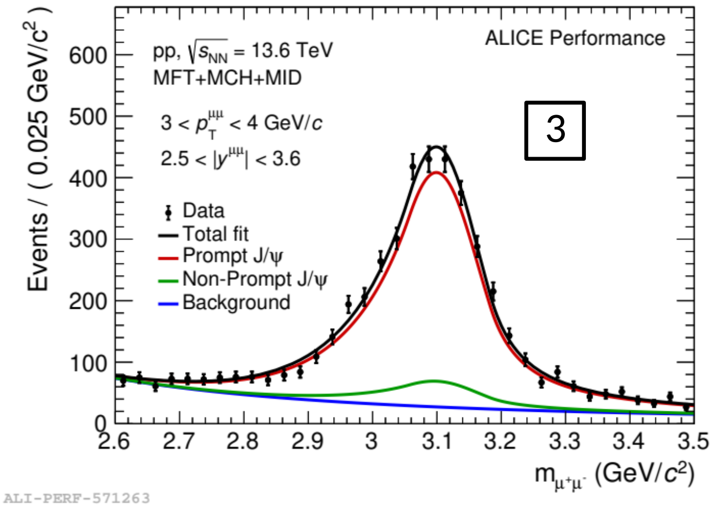
- **Analysis of Run 3** data has already produced preliminary and performance results of the upgraded MS
- Few results obtained in **pp and Pb-Pb** collisions ($\sqrt{s}$ = 13.6 and $\sqrt{s_{NN}}$ = 5.36 TeV) shown here
  → 1,2) **Inclusive J/ψ and ψ(2S) production** with the MS without MFT (in pp and Pb-Pb collisions)
  → 3) **Separation of prompt/non-prompt J/ψ** contributions to the dimuon invariant mass spectrum (with MFT)



Invariant mass spectrum of dimuon pairs in pp collisions at $\sqrt{s}$ = 13.6 TeV. Extraction of J/ψ and ψ(2s) signal



Invariant mass spectrum of dimuon pairs in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV, extraction of the J/ψ signal



Invariant mass distribution of dimuon pairs in pp collisions at $\sqrt{s}$ = 13.6 TeV. The contributions by prompt/non-prompt J/ψ and background are highlighted

Conclusion

- The ALICE **MS has performed well during Run 1 and 2**, leading to interesting physics results in the study of QGP
- The **detector upgrade during LS2** has allowed ALICE to run in continuous readout mode at higher interaction rate in Pb-Pb collision to reach higher integrated luminosity values
- The **installation of MFT** has unlocked new physics potential for the MS:
  1) Increase of S/B ratio for ψ and ψ(2s)

  2) Allow the study of prompt and non-prompt J/ψ at forward rapidity

  3) Study open heavy flavors separately (b and c quarks) in the single μ channel at forward rapidity

  4) Improve the S/B and mass resolution for low-mass dimuon pairs
- MFT has been fully integrated in ALICE and it is regularly taking data
- **Many interesting and exciting physics results to come!**

Thank you for your attention!

References

[1] ALICE collaboration, *Production of muons from heavy-flavour hadron decays at high transverse momentum in Pb–Pb collisions at* $\sqrt{s_{NN}}$*=5.02 and 2.76 TeV*, Physics Letters B 820, 136558 (2021)

[2] ALICE collaboration, *ψ(2s) Suppression in Pb-Pb Collisions at the LHC*, Phys. Rev. Lett. 132, 042301 (2024)

[3] ALICE collaboration, *J/ψ elliptic and triangular flow in Pb-Pb collisions at* $\sqrt{s_{NN}}$ *= 5.02 TeV*, J. High Energ. Phys., 141 (2020)

[4] ALICE collaboration, *Addendum of the Letter of Intent for the upgrade of the ALICE experiment : The Muon Forward Tracker*, CERN-LHCC-2013-014 (2013)

[5] ALICE collaboration, *Technical Design Report for the Muon Forward Tracker*, CERN-LHCC-2015-001 (2015)

Backup

Summary of physics performance

Table 1: *Comparison of physics reach for the two scenarios without and with the MFT (MUON only / MUON + MFT) assuming an integrated luminosity of 10 nb^{-1} in central Pb–Pb collisions. p_T^{min} gives the minimum accessible p_T for the different observables. The quoted uncertainties include both statistical and systematic uncertainties.*

Observable	MUON only		MUON + MFT	
	p_T^{min} (GeV/c)	uncertainty	p_T^{min} (GeV/c)	uncertainty
Inclusive J/ψ R_{AA}	0	5 % at 1 GeV/c	0	5 % at 1 GeV/c
ψ' R_{AA}	0	30 % at 1 GeV/c	0	10 % at 1 GeV/c
Prompt J/ψ R_{AA}		not accessible	0	10 % at 1 GeV/c
J/ψ from b-hadrons		not accessible	0	10 % at 1 GeV/c
Open charm in single μ			1	7 % at 1 GeV/c
Open beauty in single μ			2	10 % at 2 GeV/c
Open HF in single μ no c/b separation	4	30 % at 4 GeV/c		
Low mass spectral func. and QGP radiation		not accessible	1–2	20 % at 1 GeV/c

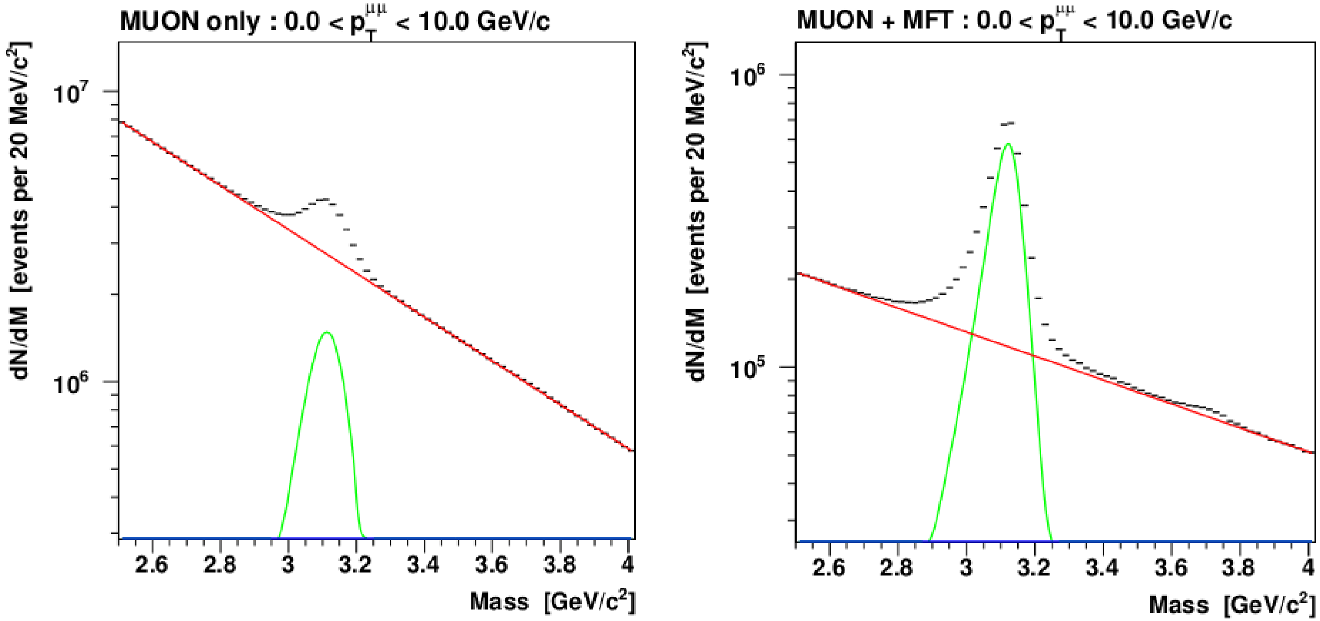
Table taken from the Muon Forward Tracker LoI

Inclusive charmonium production

- Comparison of the current MS layout and MS+MFT in inclusive quarkonium production

- Values computed for the 0-10% most central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV
  - Binary scaling (1600 binary collisions)
  - σ = 30 µb for J/Ψ production
  - σ = 60 mb inelastic pp
  - Ψ’ production = 0.14 J/Ψ production
  - R_{AA} (J/Ψ) = 0.7 and R_{AA} (Ψ’) = 0.3
  - Axε corrected

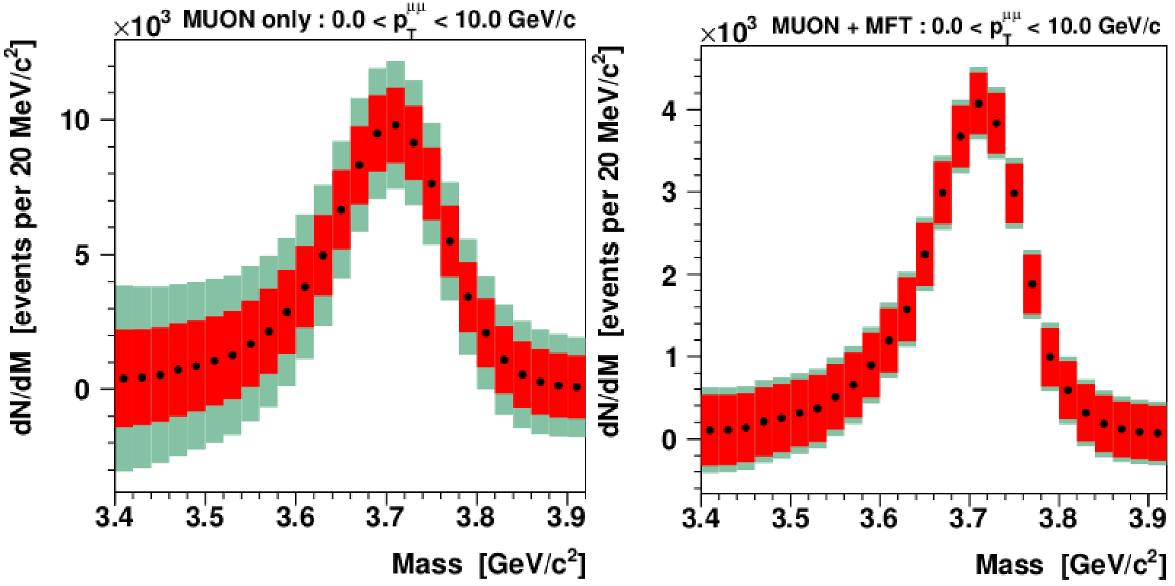
- Adding MFT
  - Global loss of statistics
  - Increase of S/B for both J/Ψ and Ψ’ (visible also without background subtraction)



Invariant mass spectra of dimuon pairs without (left) and with (right) the MFT.
Figure taken from ALICE collaboration (2013)

Inclusive charmonium production

- Example of Ψ’ signal extraction with and without the MFT
- Pure signal obtained by subtracting the background distribution (J/Ψ signal irrelevant due to no overlap)
- Statistical uncertainty
  - Combination of stat uncertainty of signal and background
- Systematic uncertainty
  - Shape and normalization of the background (~0.1% per bin)
  - Cuts and selections used to extract charmonium signals estimated ~4/5%



Signal shape for the Ψ’ with (right) and without (left) the MFT.
Figure taken from ALICE collaboration (2013)

Inclusive charmonium production

- Example of Ψ' signal extraction with and without the MFT
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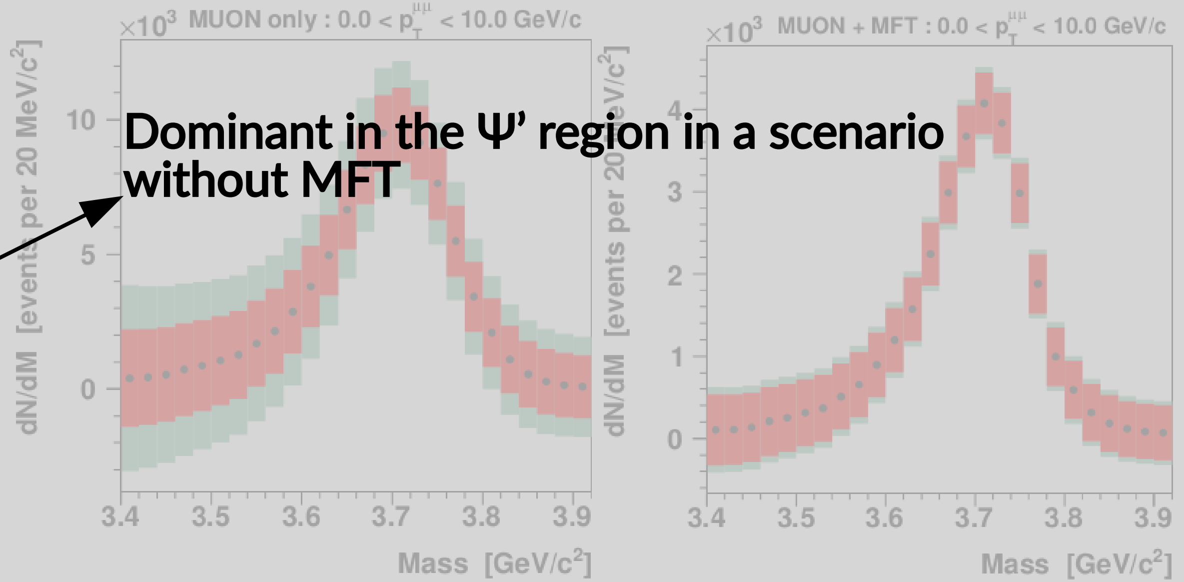
Dominant in the Ψ' region in a scenario without MFT



Signal shape for the Ψ' with (right) and without (left) the MFT.
Figure taken from ALICE collaboration (2013)

Inclusive charmonia production

Inclusive J/ψ $(2.80 < M_{\mu\mu} < 3.30$ GeV/$c^2)$: $R_{AA} = 0.7$, without the MFT					
p_T [GeV/c]	Signal [$\times 10^3$]	S/B	$S/\sqrt{S+B}$	Stat. Err. [%]	Sys. Err. [%]
$0-1$	1710	0.15	470	0.20	5
$1-2$	3320	0.14	650	0.14	5
$2-3$	2784	0.16	610	0.16	5
$3-4$	1750	0.16	490	0.19	5
$4-5$	1055	0.18	400	0.25	5
$0-10$	12040	0.15	1300	0.08	5

Inclusive J/Ψ production (S/B and significance) at forward rapidity without MFT, taken from the Muon Forward Tracker LoI

Inclusive J/ψ $(2.80 < M_{\mu\mu} < 3.30$ GeV/$c^2)$: $R_{AA} = 0.7$, with the MFT					
p_T [GeV/c]	Signal [$\times 10^3$]	S/B	$S/\sqrt{S+B}$	Stat. Err. [%]	Sys. Err. [%]
$0-1$	531.6	0.50	420	0.23	7
$1-2$	851.9	0.92	640	0.15	7
$2-3$	715.3	1.28	630	0.15	7
$3-4$	544.0	2.03	600	0.17	7
$4-5$	382.2	3.25	540	0.18	7
$0-10$	3664	1.15	1400	0.07	7

Inclusive J/Ψ production (S/B and significance) at forward rapidity with MFT, taken from the Muon Forward Tracker LoI

Inclusive ψ' $(3.40 < M_{\mu\mu} < 3.90$ GeV/$c^2)$: $R_{AA} = 0.3$, without the MFT					
p_T [GeV/c]	Signal [$\times 10^3$]	S/B	$S/\sqrt{S+B}$	Stat. Err. [%]	Sys. Err. [%]
$0-1$	12.8	0.0048	7.6	10.9	20.9
$1-2$	24.2	0.0039	9.7	9.5	26.5
$2-3$	20.4	0.0031	8.0	12.3	32.3
$3-4$	12.4	0.0026	5.6	17.7	39.0
$4-5$	6.9	0.0021	3.8	26.1	48.1
$0-10$	85.0	0.0030	16.1	6.0	33.3

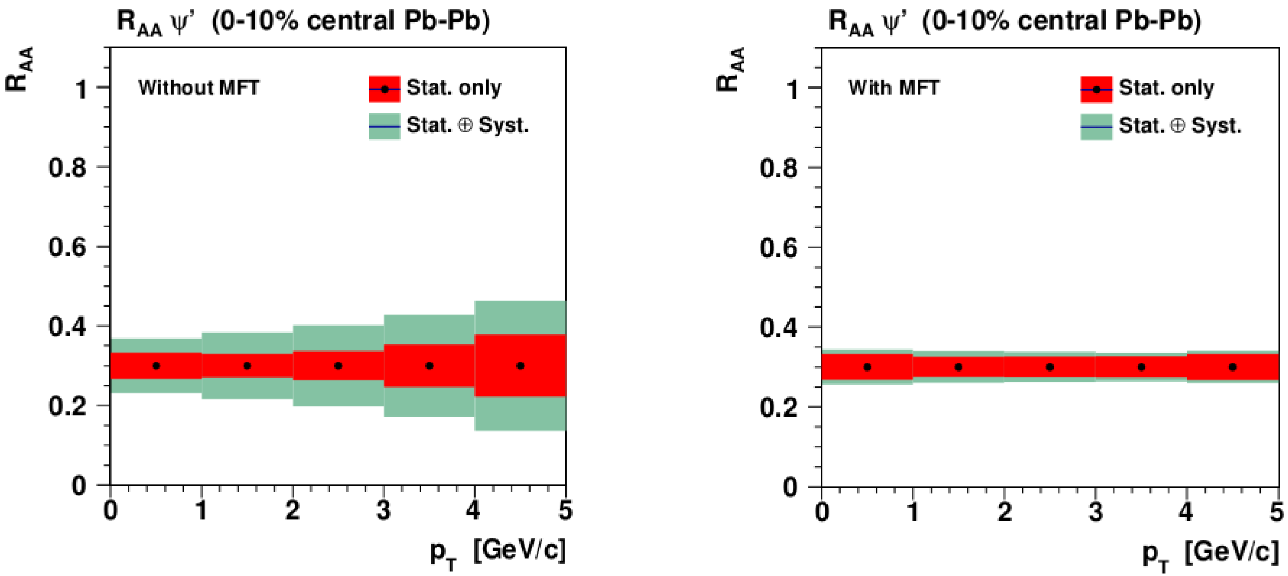
Inclusive Ψ' production (S/B and significance) at forward rapidity without MFT, taken from the Muon Forward Tracker LoI

Inclusive ψ' $(3.40 < M_{\mu\mu} < 3.90$ GeV/$c^2)$: $R_{AA} = 0.3$, with the MFT					
p_T [GeV/c]	Signal [$\times 10^3$]	S/B	$S/\sqrt{S+B}$	Stat. Err. [%]	Sys. Err. [%]
$0-1$	4.47	0.014	7.8	10.7	9.9
$1-2$	8.67	0.014	11	8.5	10.1
$2-3$	6.76	0.018	11	8.7	9.0
$3-4$	4.11	0.027	10	9.0	8.0
$4-5$	2.57	0.030	8.7	10.9	7.8
$0-10$	30.3	0.017	22	4.3	9.2

Inclusive Ψ' production (S/B and significance) at forward rapidity with MFT, taken from the Muon Forward Tracker LoI

Determination of Ψ' R_{AA}

- R_{AA} of Ψ' estimated at 0.3 (independent of p_T)
- Improvement of its estimation with the addition of MFT

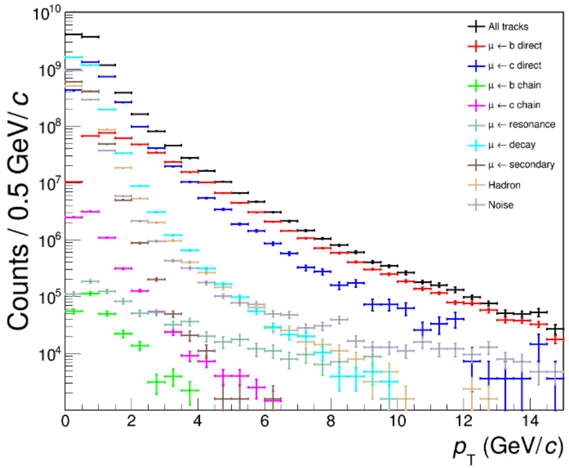


Estimation of the Ψ' R_{AA} with (right) and without (left) MFT

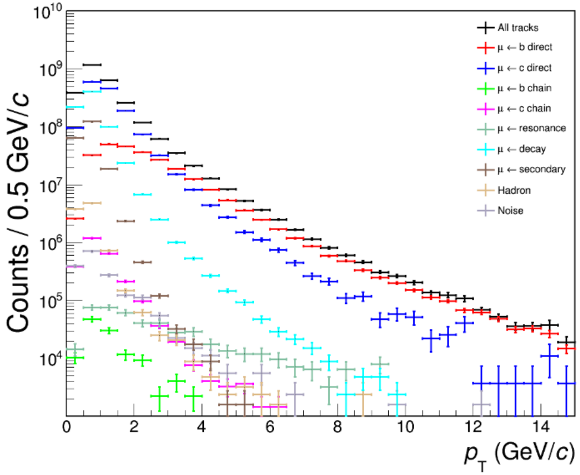
Heavy flavor analysis cuts

- Several cuts on the single muon track to reduce background contamination
  - Track must be within the acceptance of the MFT $-3.6 < \eta < -2.5$
  - All reconstructed tracks must match a *tracklet* in the MID (-96% hadron and -81% fakes) → match implies a p_T cut (-61% muons from light hadron decays)
  - Cut on the χ^2/ndf of the track: $\chi^2/\text{ndf} < 3$ (-99% of residual fake tracks, -66% of residual hadrons and only 8% signal loss)

- Lower p_T limit = 1 GeV/c (to improve MFT-MCH matching) and higher p_T limit = 6 GeV/c (lack of statistics in the background)



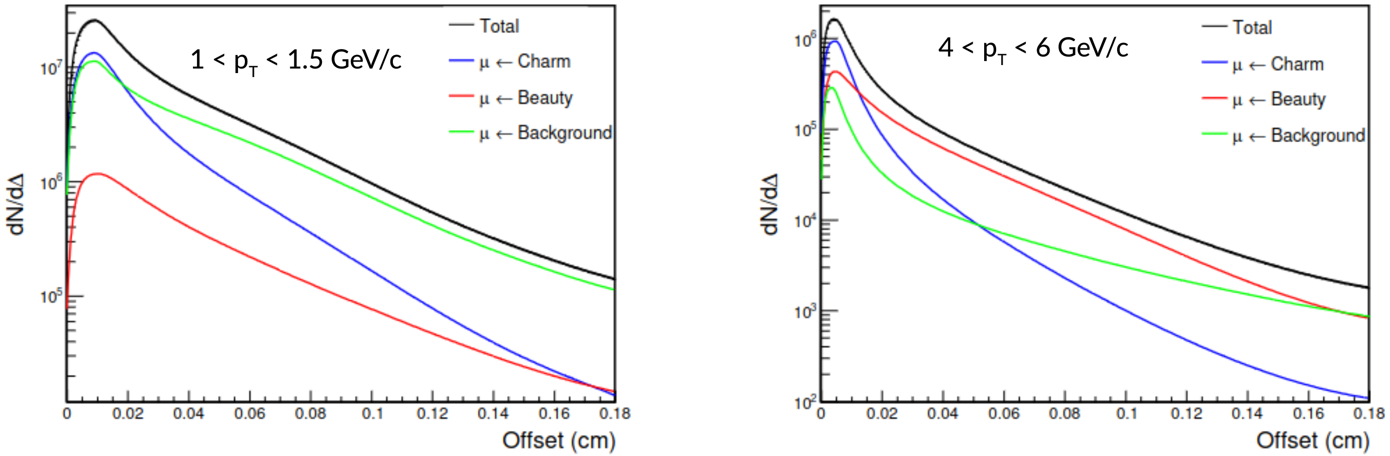
P_T distribution of single muons with no cuts as reported in the MFT TDR



P_T distribution of single muons with track cuts as reported in the MFT TDR

Open heavy-flavor in the single μ channel

- Yield study based on the offset distribution (Δ)
  - Decay of b and c is displaced wrt primary interaction vertex



Single μ offset distribution in the 0-10% most central Pb-Pb collisions for L_{int} = 10 nb^{-1}. Figure taken from ALICE collaboration (2015)

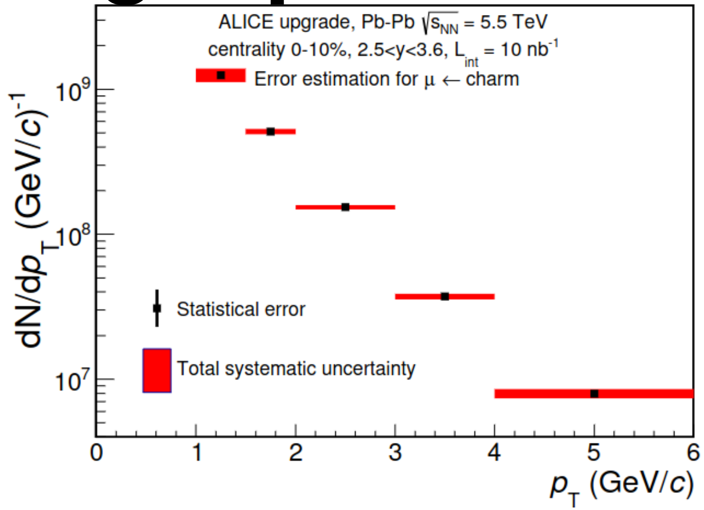
- Offset distribution for signal and background
  - Fitted in each p_T bin with a vw Gaussian ($\sigma \sim \Delta^3$) → MC template

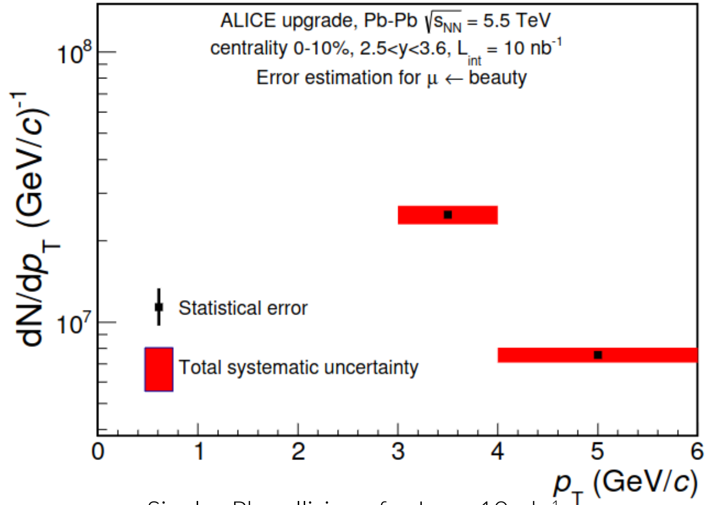
- Simulated data re-scaled to L_{int} = 10 nb^{-1}

- Total distribution fitted with $f(\Delta) = C \cdot f_c(\Delta) + B \cdot f_b(\Delta) + D \cdot f_d(\Delta)$
  - B,C,D = normalization = free parameters of the fit
  - $f_b(\Delta), f_c(\Delta), f_d(\Delta)$ = MC templates

MC Open heavy-flavor in the single μ channel

- Statistical error in the single μ yield < 0.5%
- 4 sources of systematical errors:
  1) Residual misalignment between ITS and MFT
     - ITS used to measure primary vertex
     - Primary vertex moved by ±10 μm and data re-fitted
  2) Weak dependence of the average offset value from the parent hadron p_T
     - Vary $R_{AA}(p_T)$ with models that describe ALICE data well
  3) Pointing resolution of the MFT
     - Gaussian smearing of the measured vertex
  4) MS tracking efficiency
     - Assumed to be ~ 2.5%
- Ratio between biased and reference offset represents the magnitude of the distortion
  → used to distort the nominal MC templates
- Deformed templates used to fit the nominal offset distributions
- For open charm, total error < 10% at p_T = 1 GeV/c
- For open beauty, robust measurements only for p_T > 3 GeV/c





Single -Pb collisions for L_{int} = 10 nb^{-1}.
Figure taken from ALICE collaboration (2015)