Status of tracker alignment

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September 24th, 2024

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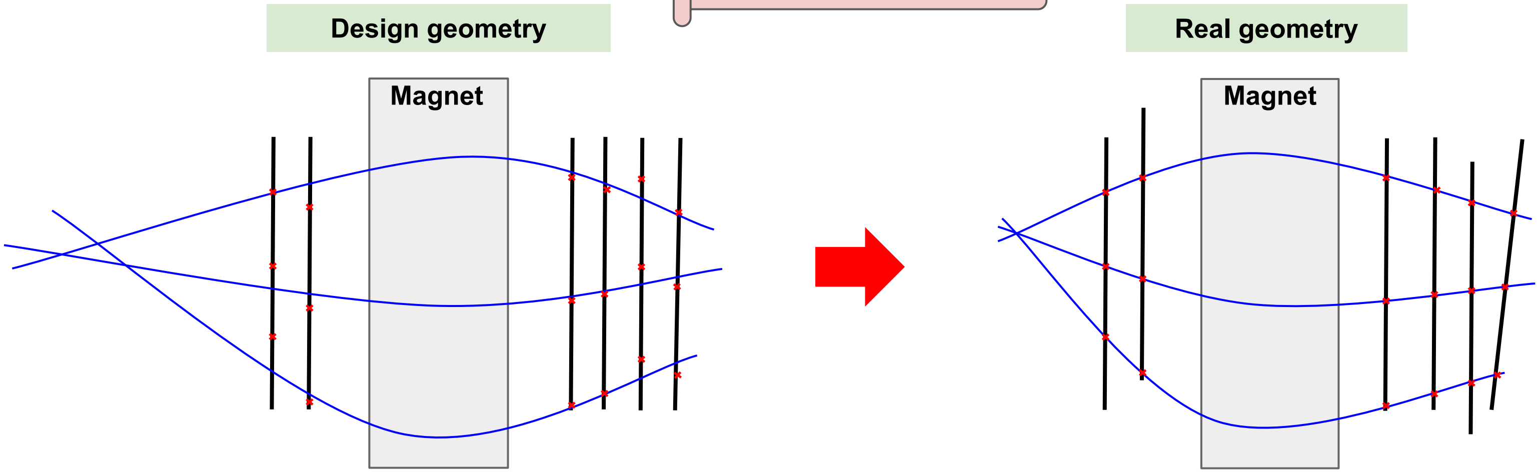
IMPRS
for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

Why do we need alignment?

Exaggerated for visualization purposes!



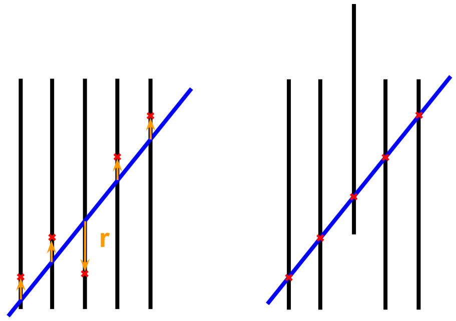
Worse **track and vertex χ^2** and degraded **momentum and mass resolution**

Improved mass resolution and better **track and vertex χ^2**

Even small O(10-100 μm) misalignments can have an impact for physics precision measurements

Track-based alignment in short

Employ **reconstructed tracks to extract information about the detector geometry** and determine the position and orientation of the detector elements



The basic transformations on the detector components are called **alignment constants**. We find their optimal values by minimizing the **global track χ^2** :

$$\chi^2(\mathbf{x}_1, ..., \mathbf{x}_{n_{tracks}}, \alpha) = \sum_i^{n_{tracks}} \chi_i^2(\mathbf{x}_i, \alpha)$$

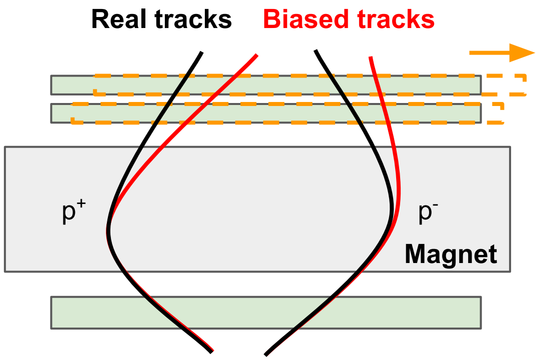
$$\chi_i^2(\mathbf{x}_i, \alpha) = \mathbf{r}(\mathbf{x}_i, \alpha)^T V^{-1} \mathbf{r}(\mathbf{x}_i, \alpha)$$

$\mathbf{x}_i$: vector of track parameters for track i

α: set of alignment constants

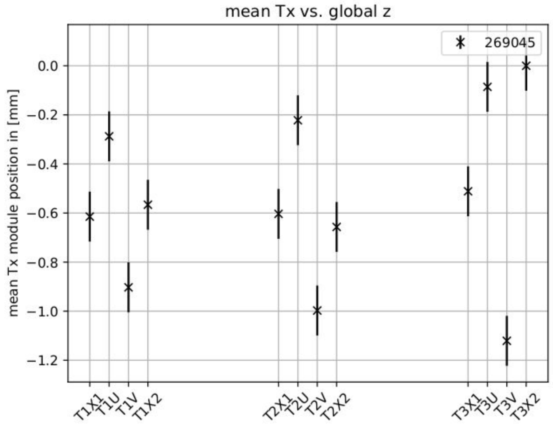
V: covariance matrix of the track residuals

- Tracks need to **cover the full detector acceptance and have good quality**
  - **VELO:** VELO tracks covering the full VELO acceptance
  - **UT and SciFi:** long tracks
- We use **mass and vertex constraints** to improve the alignment quality and remove **weak modes**
  - Weak modes are misaligned configurations with no impact on the track residuals
  - The new update combines D^0 and J/ψ mass constraints
- **Survey constraints and lagrange constraints** guide the algorithm to find the right minimum (survey) and avoid unphysical configurations (lagrange)

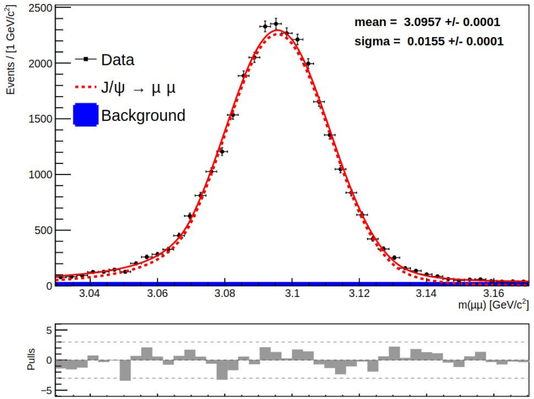


Tracker alignment at the start of 2024

- Followed strategy from 2022 ➝ **Sub-detectors aligned independently and on top of each other**
- **Mat-end contraction calibration** successfully applied to improve SciFi residuals
- **Automatic alignment of the VELO right-half almost** completely mitigated the impact of the drift
- Observed a global translation of the **SciFi in x and a "zig-zag" pattern** between stereo-layers

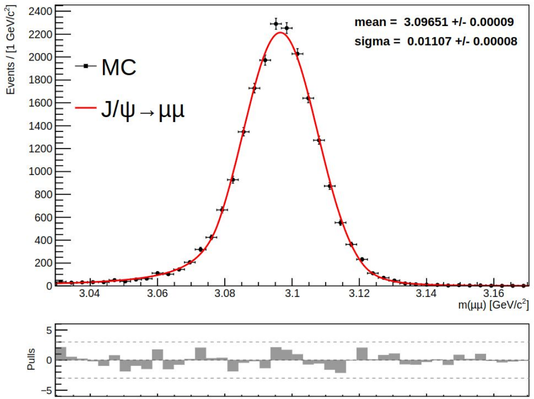


June post-TS alignment



σ [MeV] = 15.6

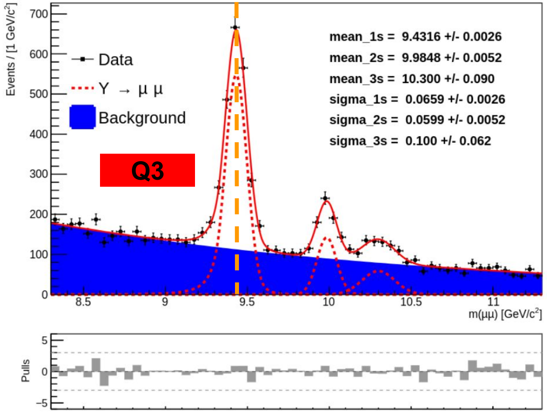
Realistic-2024 simulation

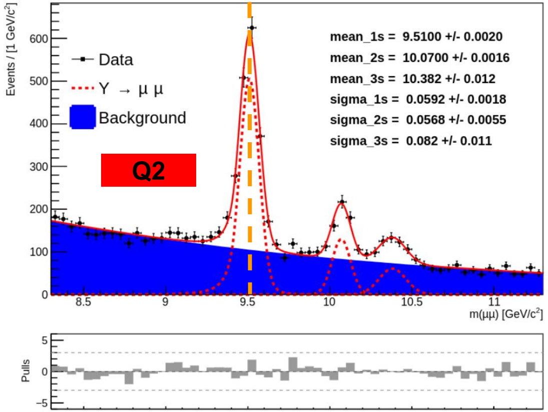


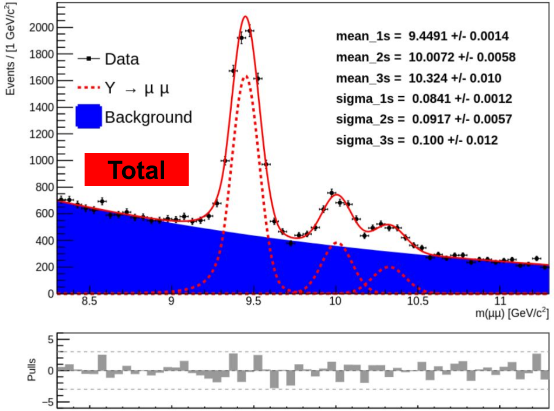
σ [MeV] = 11.1

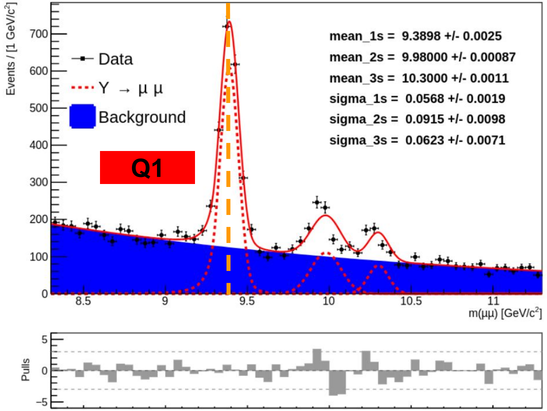
- **Mass resolution** steadily improving with alignment updates but still worse than in simulation
- **New magnetic field map deployed** to reduce mass shifts wrt their PDG values ➝ Slides from A. Venkateswaran
- Residual **mass asymmetry** between positively and negatively charged particles

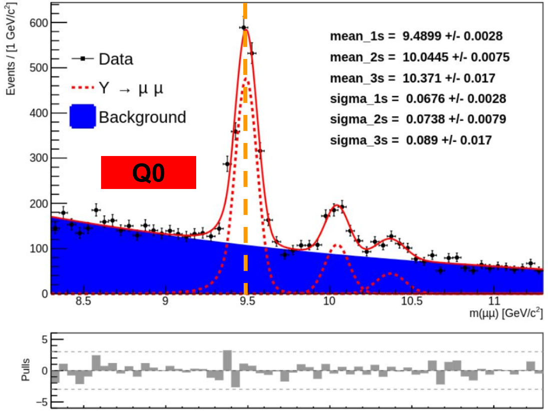
Key finding: mass splitting between quadrants











The position of the Υ(1S) mass peak varied by 70-120 MeV between detector quadrants!

Integrated mass was a sum of distributions peaking at different values

New global alignment in August 2024

New major alignment update deployed on 06.08.2024 and picked up online from fill 9982

Align the full tracker with magnet-off data

To separate alignment effects and imperfections in the magnetic field description

→

Re-evaluate the Global VELO rotations on magnet-on data taken after the belt replacement

Change in VELO global position after incident

See slides from S. Borghi

→

Align UT and SciFi half-layers on Tz

Employ magnet-on data with D^0 and J/ψ mass constraints to correct the scale of the tracker in z

↓

Realign SciFi modules on Tx and Rz

To improve SciFi rack residuals and χ^2 distribution of long tracks

←

Update UT internal alignment + SciFi half-modules alignment

Final adjustments to improve track residuals in UT and SciFi

←

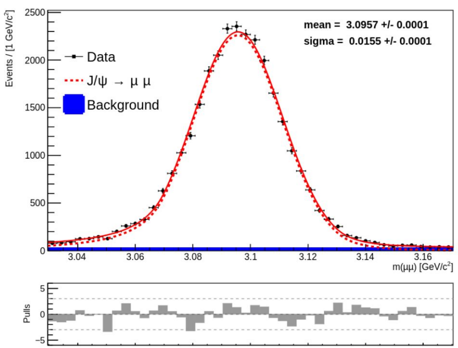
Scale the magnetic field map to bring masses closer to their PDG values

B field map scaled by a factor of 0.9993 determined from the ratio between the mean of the reconstructed J/ψ and $\Upsilon(1S)$ mass peaks and their PDG values

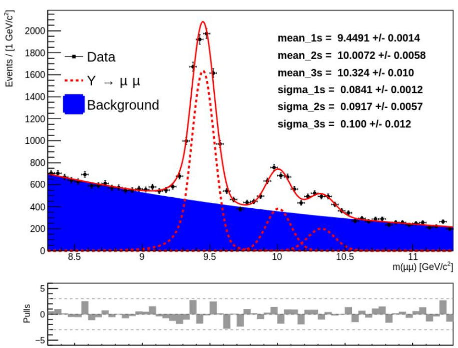
More details and dof in Biljana's presentation

Improvement on mass resolutions

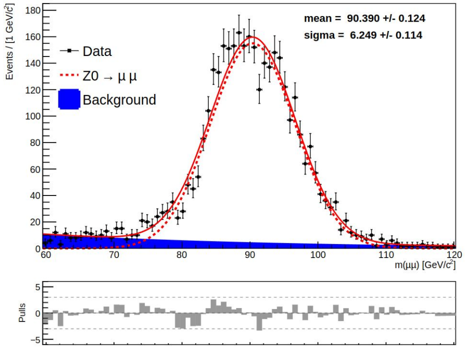
June post-TS alignment



σ [MeV] = 15.6

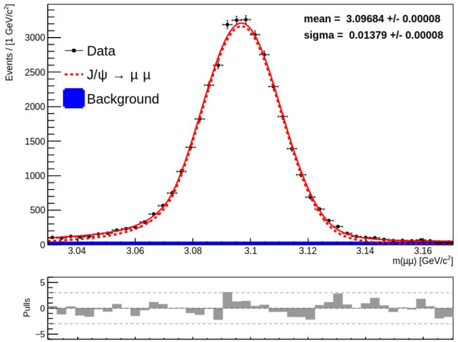


σ (Y(1S)) [MeV] = 84.1

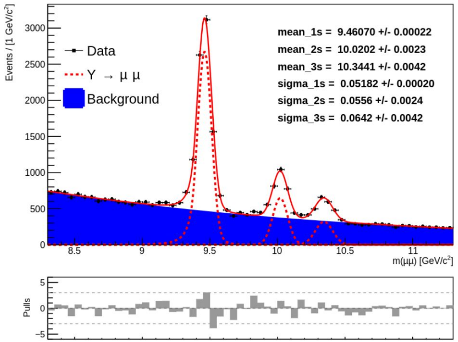


σ [GeV] = 6.2

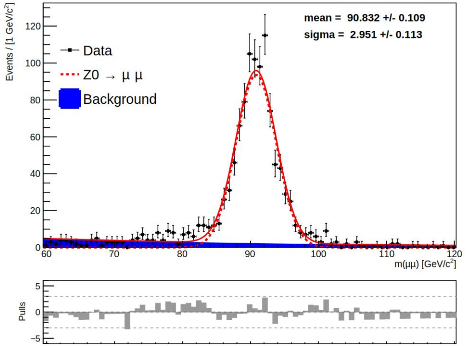
August 2024 alignment



σ [MeV] = 13.8



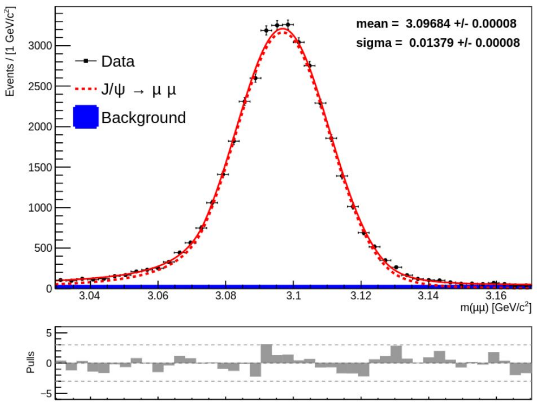
σ (Y(1S)) [MeV] = 51.8



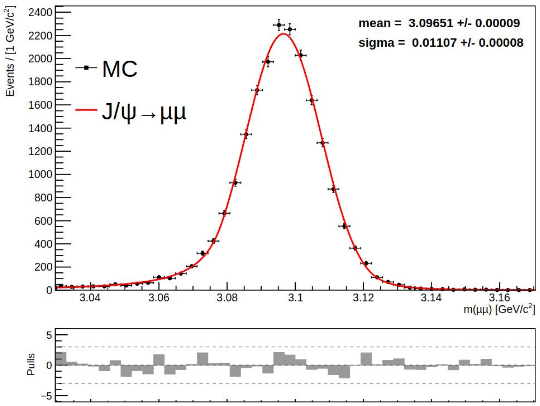
σ [GeV] = 3.0

Comparison with simulation and Run 1/2

Data with new alignment



Realistic-2024 simulation



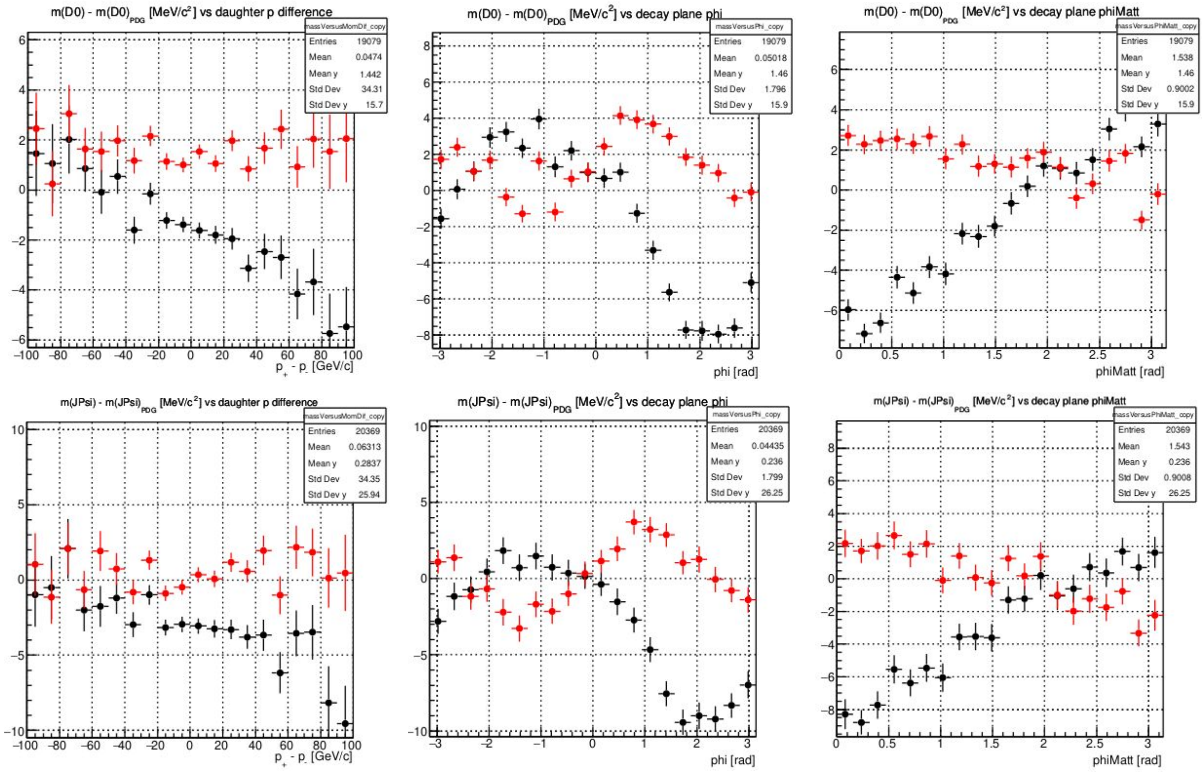
- Different **simulation conditions** depending on availability:
  - **Realistic 2024:** D^0, J/ψ, and Z^0
  - **Expected 2024:** Y(1S)
- **Compatible with simulation for D^0** candidates but some discrepancy is still observed for high masses
- **Simulation might be too optimistic** ➝ Study of the hit resolution and DetDesc vs DD4Hep on-going
- Already **close to Run 2 performance** ➝ Expected improvements from momentum scale calibration

	$\sigma(D^0)$ [MeV]	$\sigma(J/\psi)$ [MeV]	$\sigma(J/\psi)$ [MeV] 2015	σ(Y(1S)) [MeV]	σ(Y(1S)) [MeV] 2018	$\sigma(Z^0)$ [GeV]	$\sigma(Z^0)$ [GeV] 2010
Data	7.23	13.8	14.4	51.8	44.6	3.0	3.0
Simulation	7.37	11.1	13.3	33.9	39.1	1.6	-

***Run 1 and run 2 selections and fit models are different**

Mass profiles

	Daughter momentum difference	Decay plane Φ	Decay plane angle wrt magnetic field
D^0			
J/ψ			



Trends in mass profiles reduced after the alignment update

⬇

More **symmetric performance** across the phase space reduces the mass splitting and improves the resolution

- **Data with new alignment**
- **Data with old alignment**

Summary and outlook

- After a summer of intensive work we managed to **identify and fix the main issues with the alignment of the LHCb tracker**

- We performed for the first time in Run 3 an **alignment job combining dof from all the trackers**

- We are getting close to expectations from simulation in terms of **mass resolution**
  - Already compatible for D^0 candidates and much closer for higher mass particles
  - A perfect agreement will require work from both sides

- **Mass profiles** as a function of kinematic variables are much flatter and **phase space dependencies** on the mass distributions have been reduced

- Next steps:
  - Perform a **detailed study** to understand what caused the mass splitting and asymmetries in previous alignment versions
  - Understand the **correlation between the new alignment and the magnetic field description**
    - This is still an effective alignment ➝ Imperfections on the magnetic field description are absorbed in the alignment constants

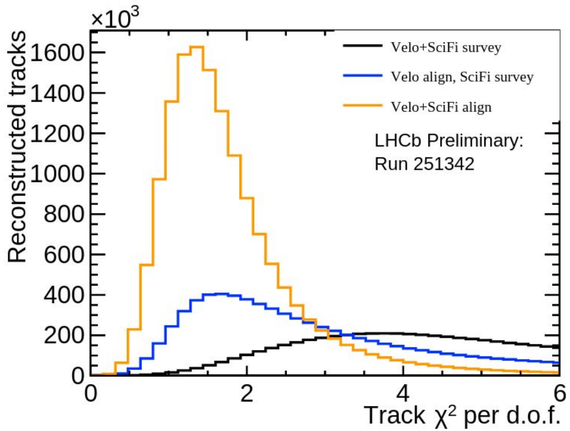
  - Establish a strategy to **automatize the alignment of UT and SciFi in 2025** to run them online together with the VELO alignment
    - We need to compute the thresholds to trigger alignment updates ➝ Study in MC on-going

Thank you!

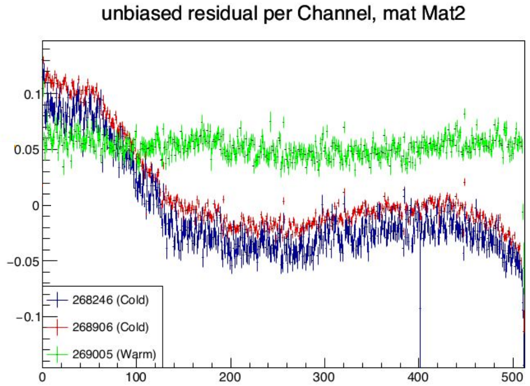
Backup

Alignment in Run 3

- Alignment algorithm heavily relies on the **software developed and applied during Run 2** (gitlab)
  - Some work needed to make the code compatible with the new DD4Hep geometry
- First **alignment results on 2022** demonstrated the impact on data quality
- **Alignment in 2023 was challenging** ➝ limited geometrical acceptance of long tracks due to open VELO
  - Time to polish the strategy and learn about the new detector
  - Found that SciFi alignment was sensitive to temperature changes ➝ **Mat-end contraction calibration** tested and deployed
- Alignment scenario at the **start of 2024:**
  - **VELO module + sensor alignment and RICH mirror alignment** from 2022
  - **SciFi alignment** starting from design geometry and running cold
    - CFrames had been opened and closed and there were known biases in 2022 alignment
  - **UT** started to run in global during some fills
    - Needed to develop a procedure to align it
  - **VELO reinstalled** ➝ Possible change in global position and orientation
  - **Drift of the VELO right half** during fills ➝ Noticed a the start of data taking (slides from S.Borghi and F.Reiss)



LHCB-FIGURE-2022-018



Link to slides from I. Sanderswood

Further remarks on the new alignment

- The **starting point** were the alignment conditions employed online before this update:
  - SciFi v20 computed following the same strategy as in the post-TS alignment but employing the new magnetic field map
  - UT Layers v4, Staves v4, and Modules v5 computed on top of SciFi v20

- During the **magnet-off alignment** the last SciFi layer was fixed in z with a lagrange constraint
  - If tracks are straight and no momentum information is available a global Tz of the whole tracker becomes a weak mode

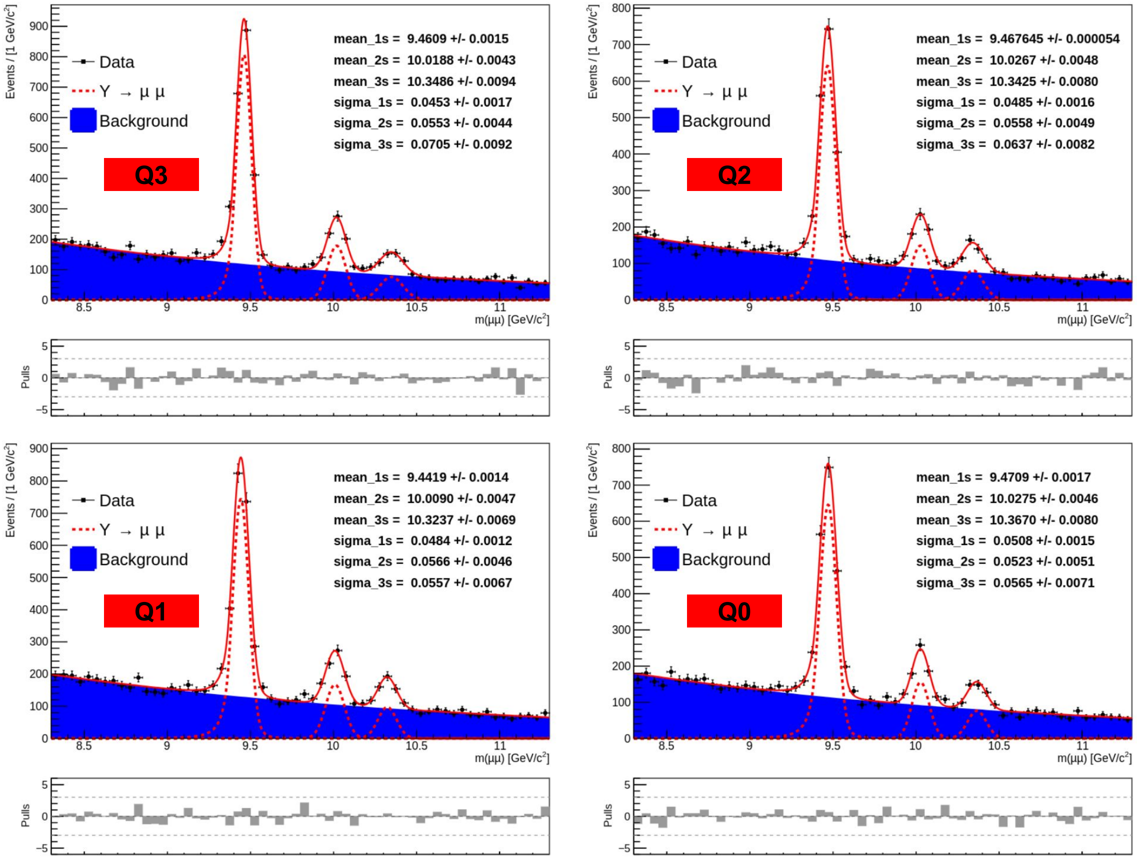
- The main purpose of the **Tz alignment of UT and SciFi layers employing magnet-on data** is to improve the track residuals and matching distributions
  - The weak mode affecting Tz is removed with the help of the mass constraints

- The **scale factor** in the magnetic field map was computed by requiring the reconstructed J/ψ mass to agree with the PDG value
  - Residual shifts for higher mass particles are small and can be fixed after a momentum scale calibration (see later)

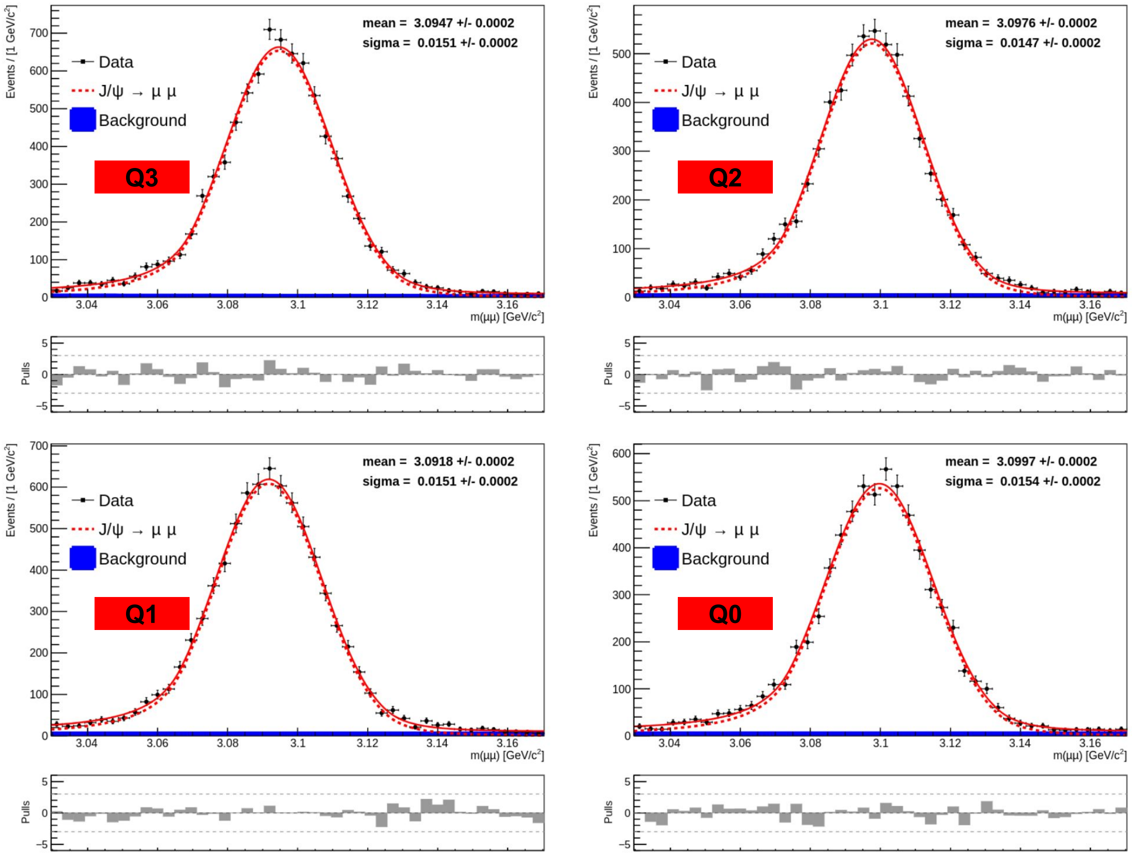
- The **RICH alignment and calibration** has been computed on top of the new constants and the performance is compatible with the previous one

- See logbook entry for more details

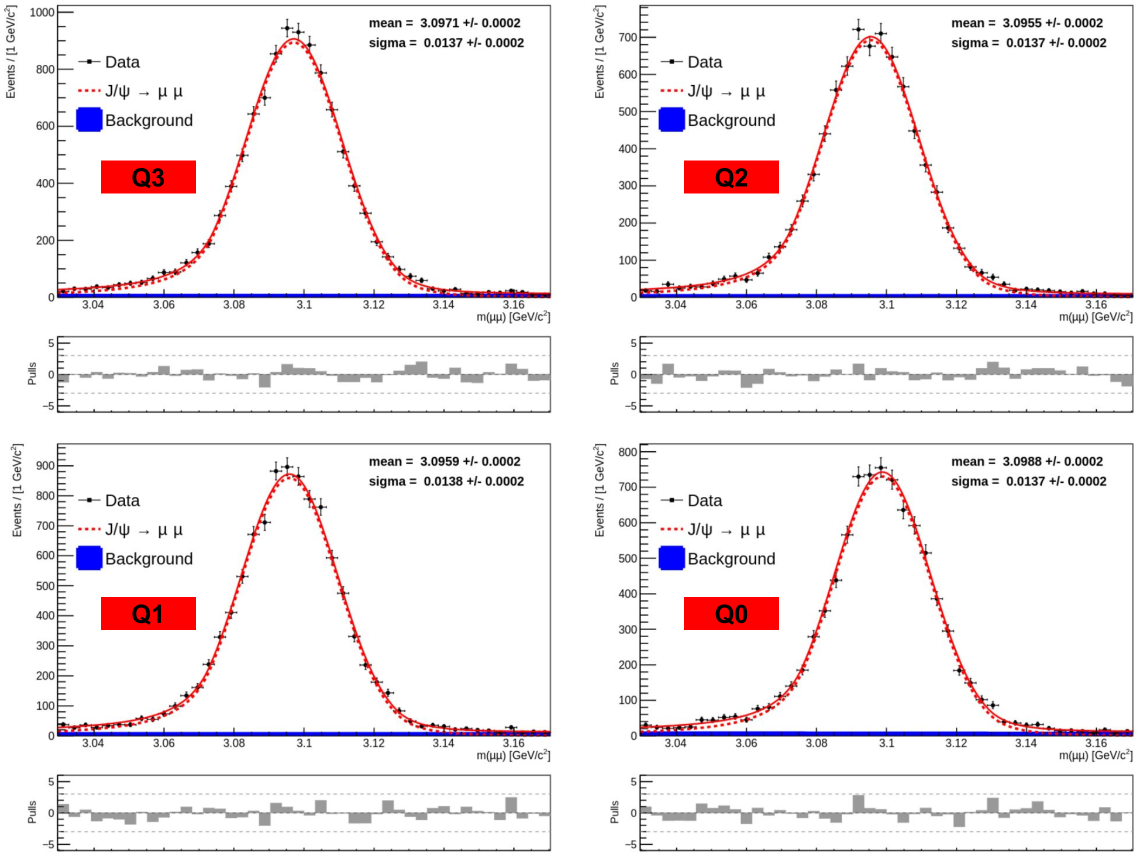
Mass splitting between quadrants with new alignment: Y



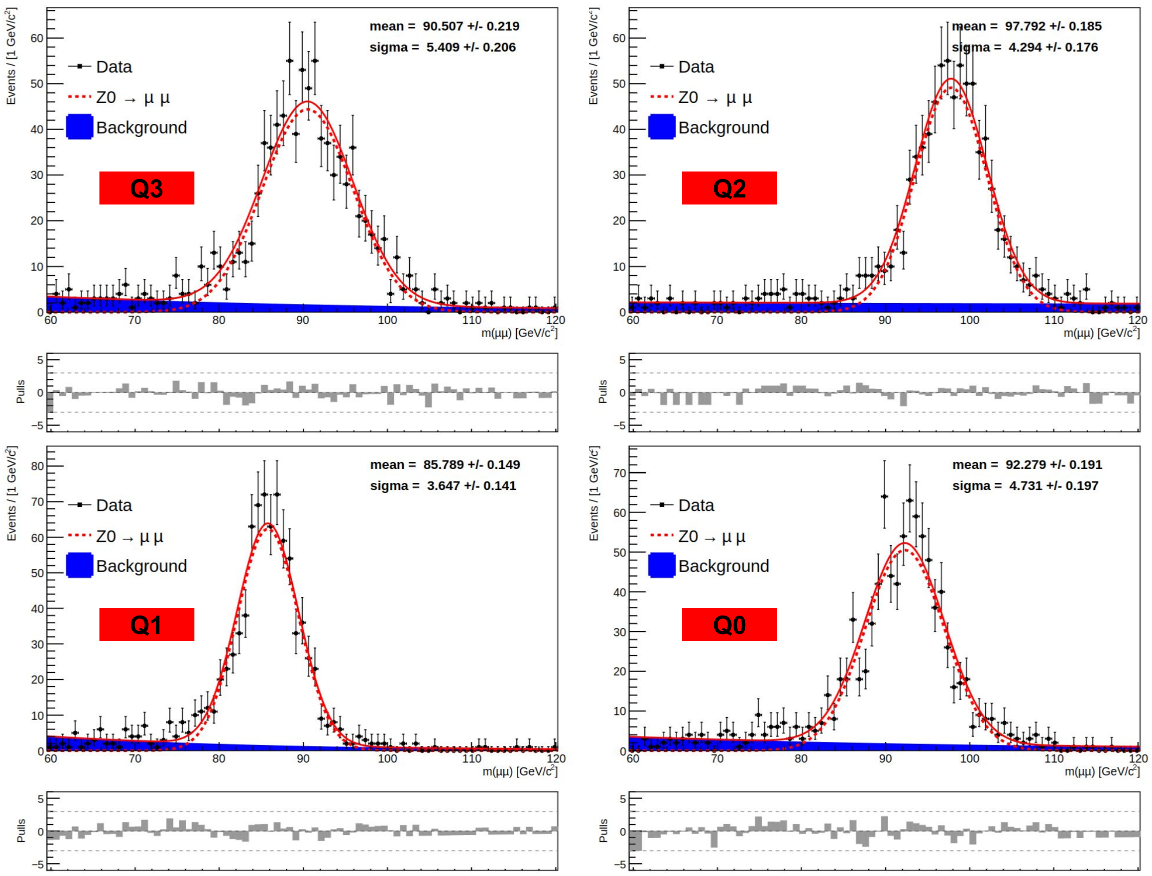
Mass splitting between quadrants before August: J/ψ



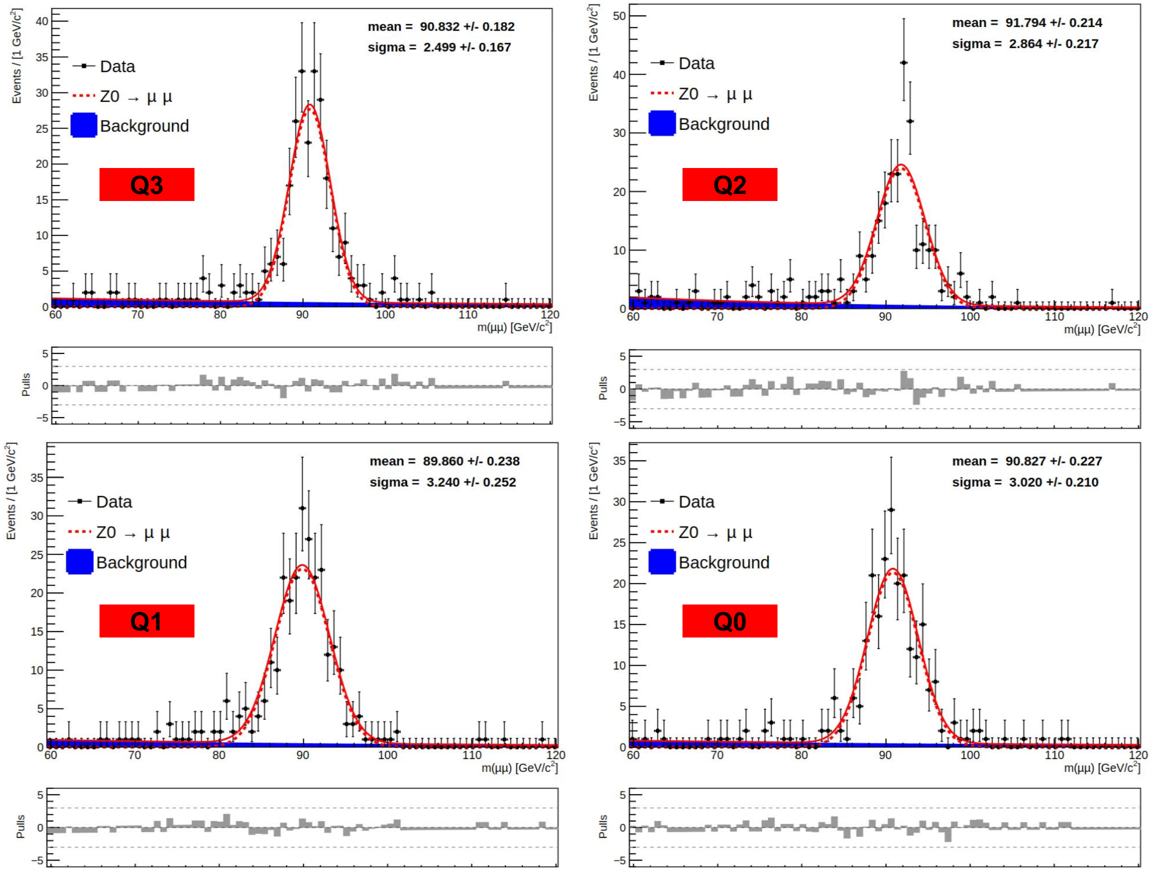
Mass splitting between quadrants with new alignment: J/ψ



Mass splitting between quadrants before August: Z^0

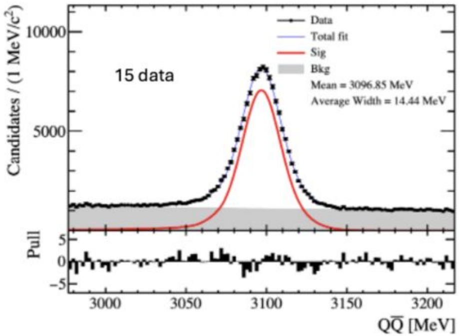


Mass splitting between quadrants with new alignment: Z^0



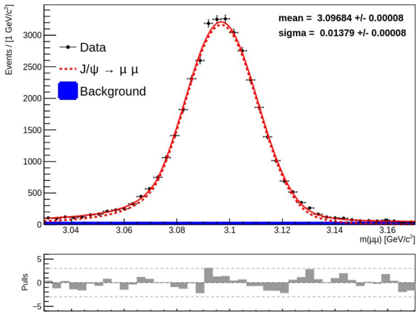
Comparison with Run 2

J/ψ in 2015

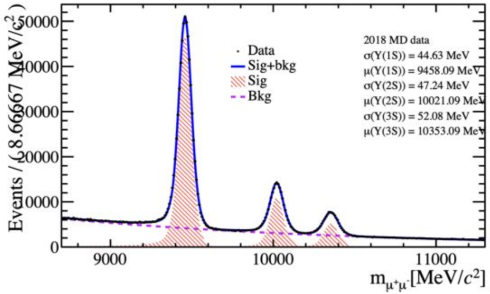


Plot by Zhihong Shen

J/ψ in 2024

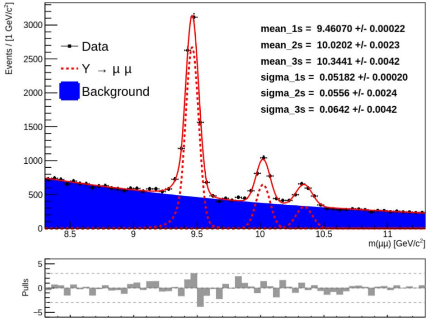


Υ in 2018

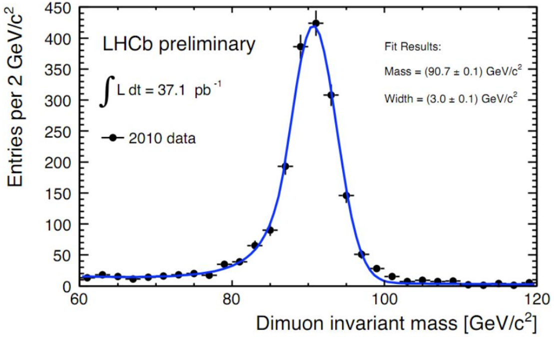


Selection from ANA-2023-056

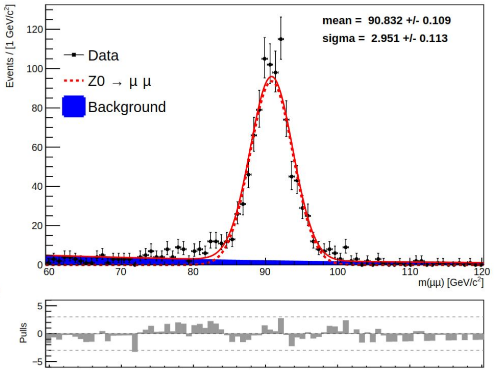
Υ in 2024



Z^0 in 2010

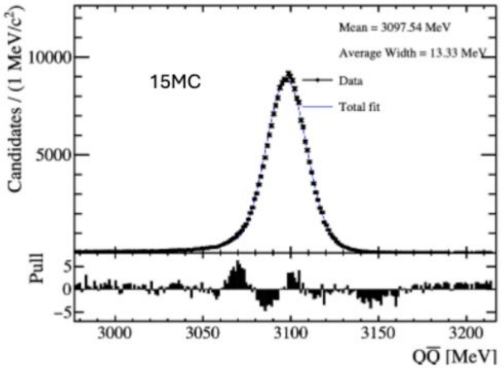


Z^0 in 2024



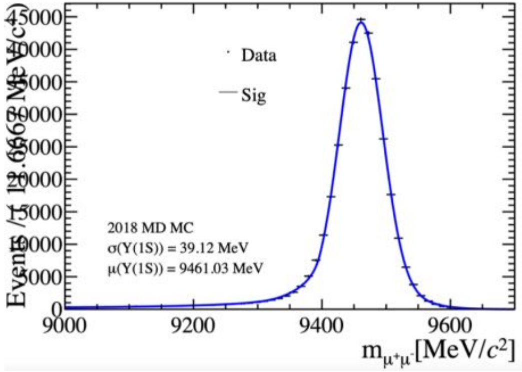
Mass distributions in MC: Run 2

J/ψ in 2015



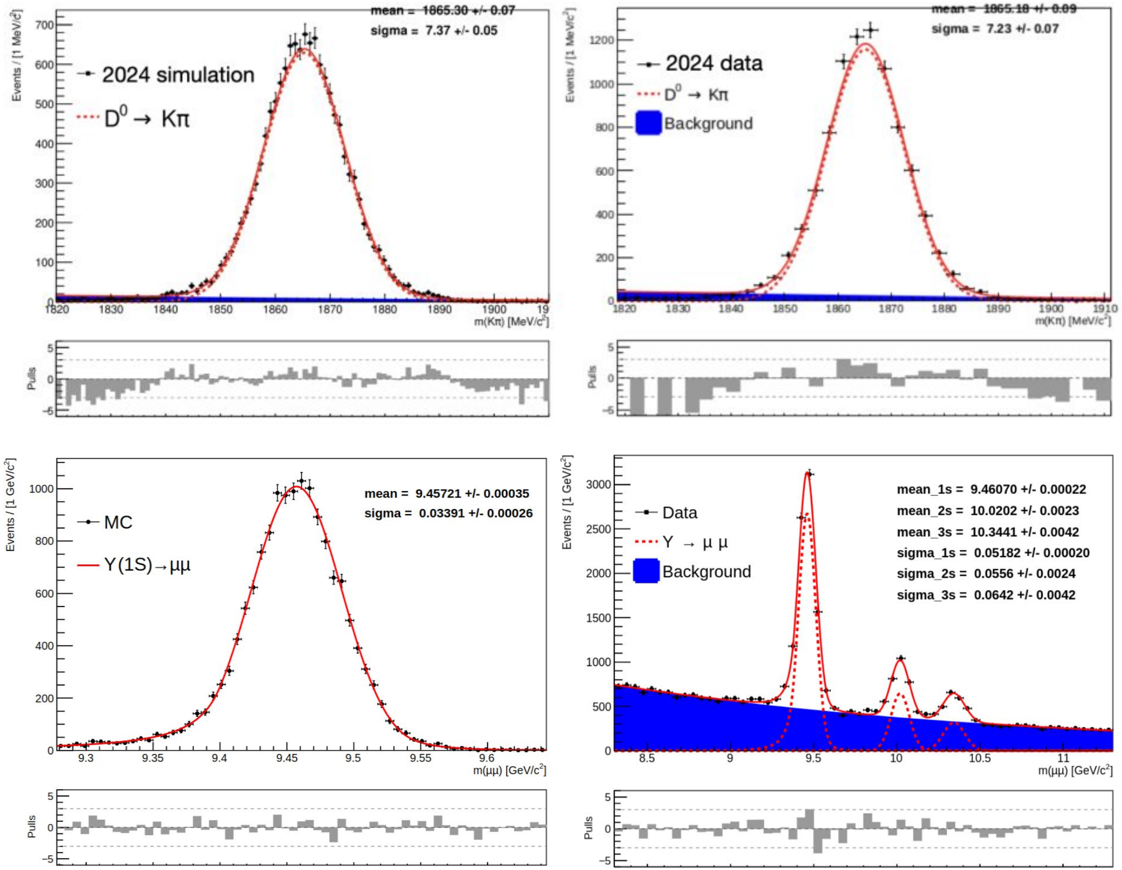
Plot by Zhihong Shen

Y(1S) in 2018

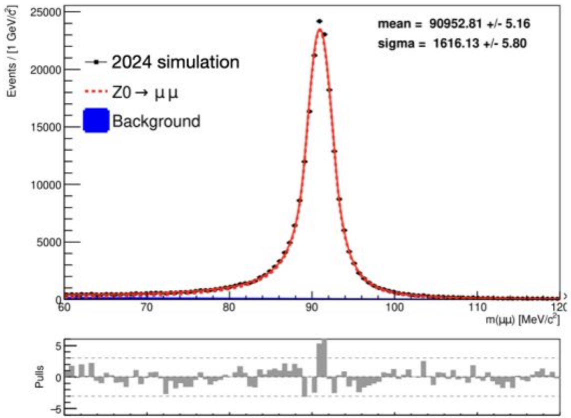


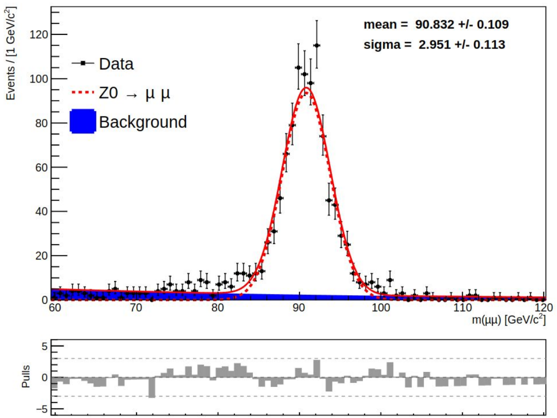
Selection from ANA-2023-056

D^0 and Υ vs simulation

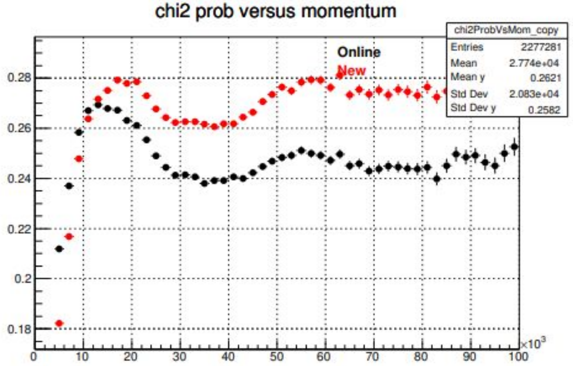


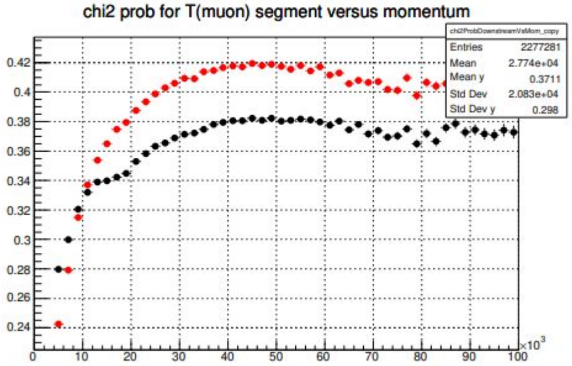
Z^0 vs simulation

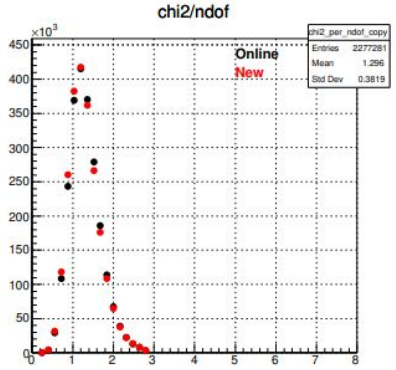




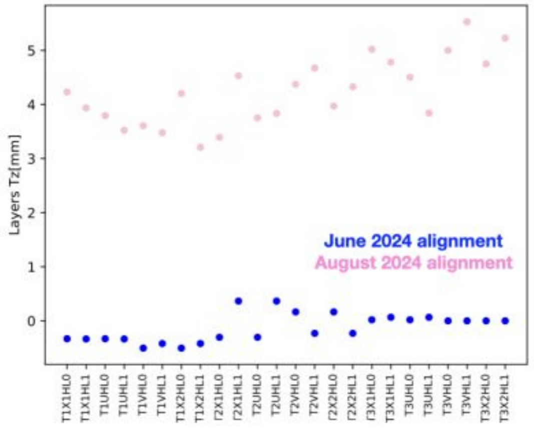
Tracking performance and detector geometry







- **Data with new alignment**
- **Data with old alignment**



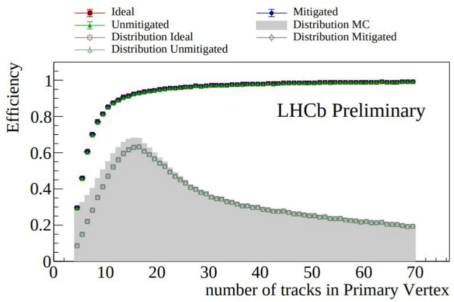
SciFi half-layers

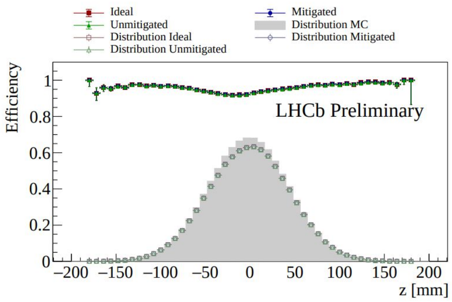
- Large **improvement in track quality at high momenta** but it **worsens at low momenta**
  - Overall tracking performance better with the new alignment
  - Worsening at low momenta could stem from issues in **scattering corrections** or imperfections in the **magnetic field description** ➝ Under investigation
- The **whole detector is stretched by 4-5 mm** wrt its design geometry
  - Both UT and SciFi are displaced in z by 4-5 mm away from the VELO
  - Shift in z is incompatible with survey measurements for the SciFi
  - Large correlation between the z scale and the magnetic field map
- Still an **effective alignment** ➝ Imperfections in the magnetic field description absorbed on the alignment constants

Effect of the VELO drift on PV reconstruction

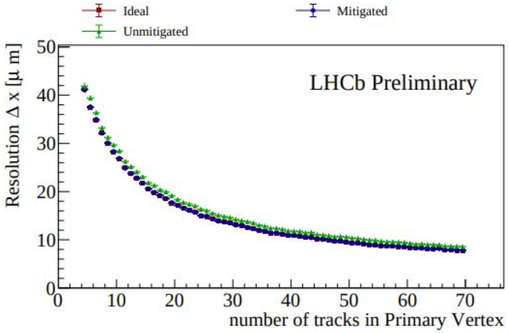
Results from a study of the **impact of the VELO drift on the PV reconstruction efficiency and resolution**

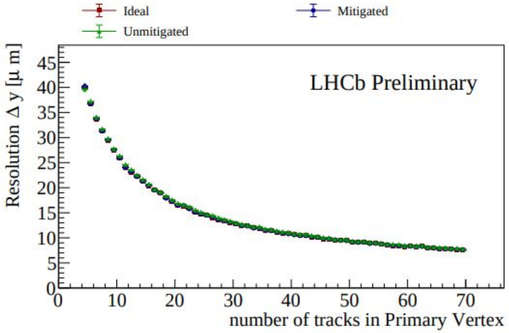
- Performed on **MC simulated data** with three different tags: **no drift, unmitigated drift, mitigated drift**
- **Efficiency** is almost unaffected by the drift
- Unmitigated sample has **up to 7% worse PV resolution → Recovered by the mitigation procedure**
- Results **shown for Allen** → Same conclusions for Moore TBLV and PatPV3DFuture
- VELO drift impact on **physics analyses** also found to be negligible after mitigation

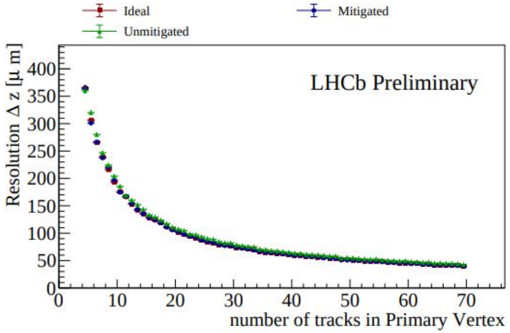




Category	Efficiency [%]	Fake rate [%]
Ideal	94.09	1.38
Unmitigated	93.93	1.46
Mitigated	94.09	1.38







More details in WP4 talk by Agnieszka