Study of the Relative Mass and Width of the $Z^0 \rightarrow \mu^+ + \mu^-$ Decay, as a Function of Centrality, in Pb+Pb Collisions with CMS

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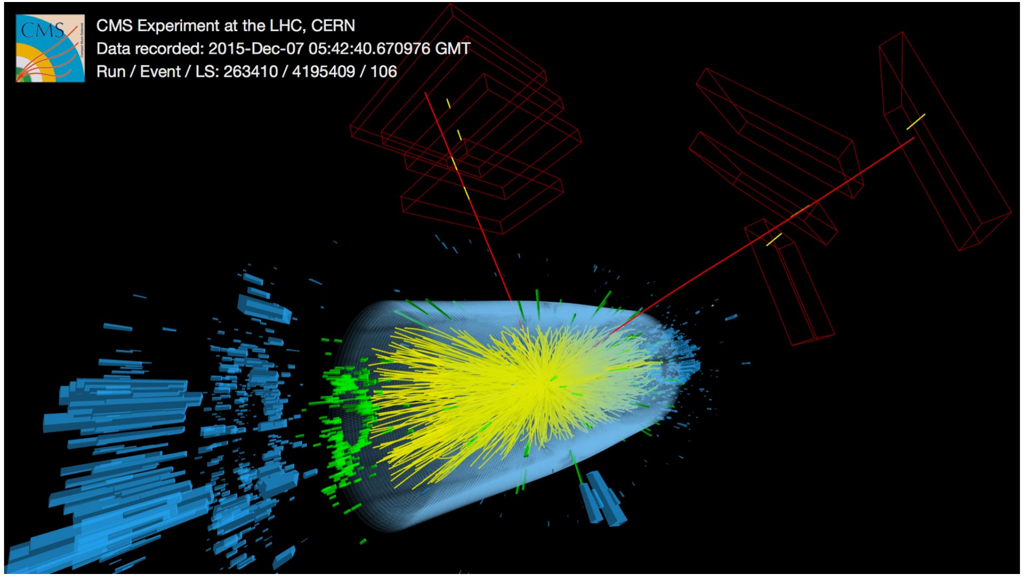
Outline

- **Introduction**
  - Physics Motivation
- **Analysis Methodology**
  - Kinematic Cuts
  - Techniques
  - Quarkonia Check
- **Systematic Checks**
- **Summary**



Can we Study Electromagnetic Fields in HIC via Z^0-Bosons?

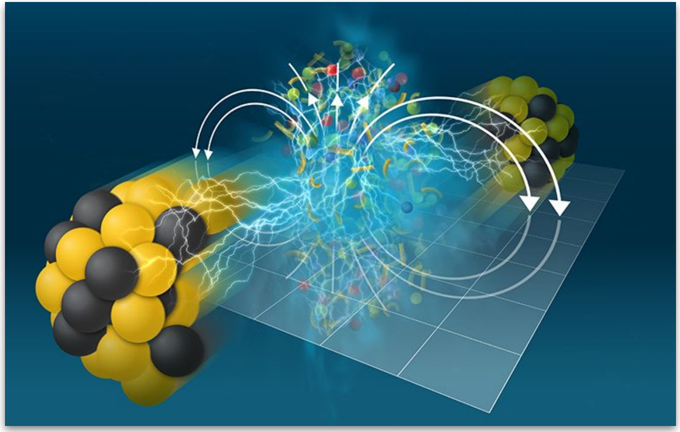
Theory: after collision, electric charges from relativistic nuclei could lead to *gargantuan* EM field.

- ➢ B-field: *strongest* in nature.
  - Magnitude: [PLB 816 (2021) 136271, PLB 827 (2022) 136962]

$$\boxed{|eB| \sim (15 - 73)\ m_\pi^2 \sim 10^{15}\ \mathrm{T}}$$

  - Depends on collision energy.
  - Time dependent, rapidly decaying ($c\tau$ ~ 0.05 – 0.4 fm).
  - Can affect particles that go through it.
- ➢ Magnitude and time-evolution is not well constrained.

Motivation for the study: *search for evidence of these EM fields.*

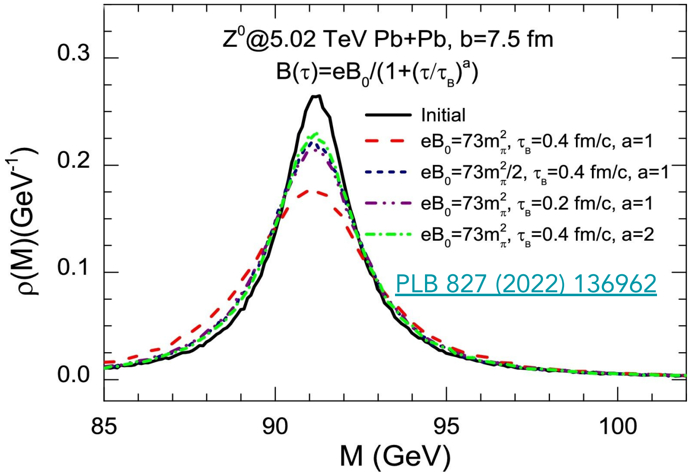


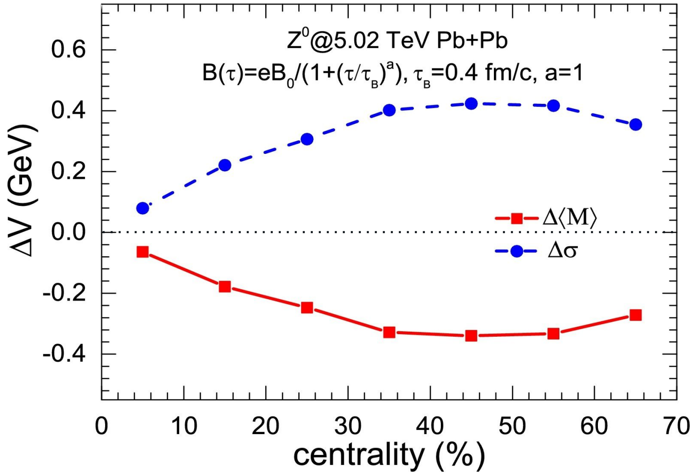
Tiffany Bowman & Jen Abramowitz, Brookhaven National Laboratory

Probing the EM Field via Leptonic Decay of the Z^0

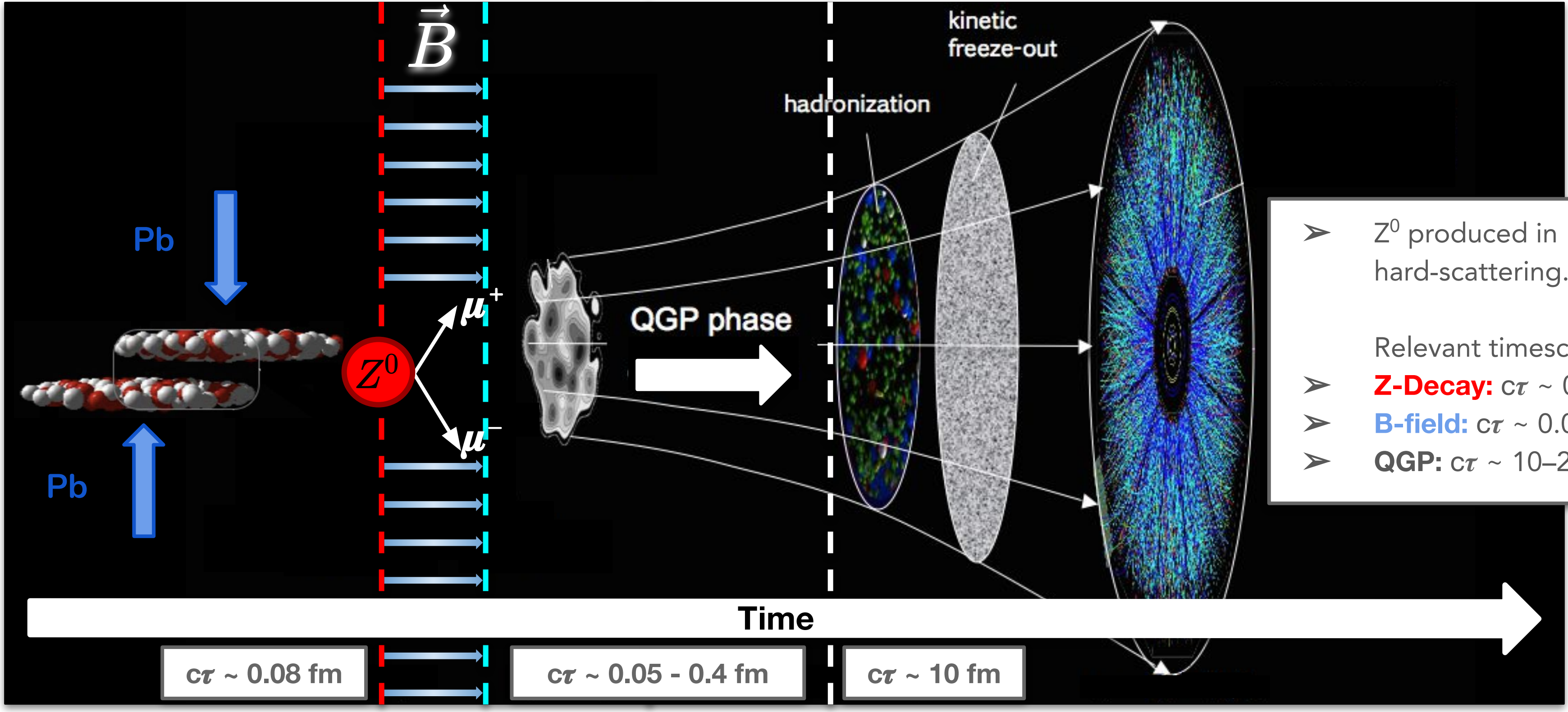
Prediction: large EM field can leave *imprints* in charged leptons from Z^0 decay. [PLB 827 (2022) 136962]

- **Potential avenue of study:** modification of invariant mass of Z^0.
  - EM field produces Lorentz force on decaying leptons, modifying their momenta.
    - **Shift in mass** + **increase in width**.
    - *Predicted shift on the order of ~400 MeV*, for strongest field.
- Strength of modification is dependent on centrality.
  - Maximal for semi-central collisions.





Time Scale of EM Field and Z^0-Boson Decay

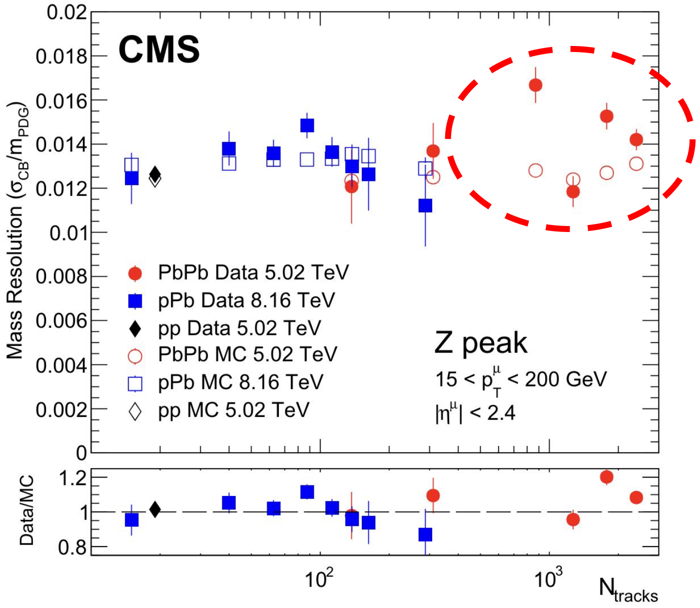


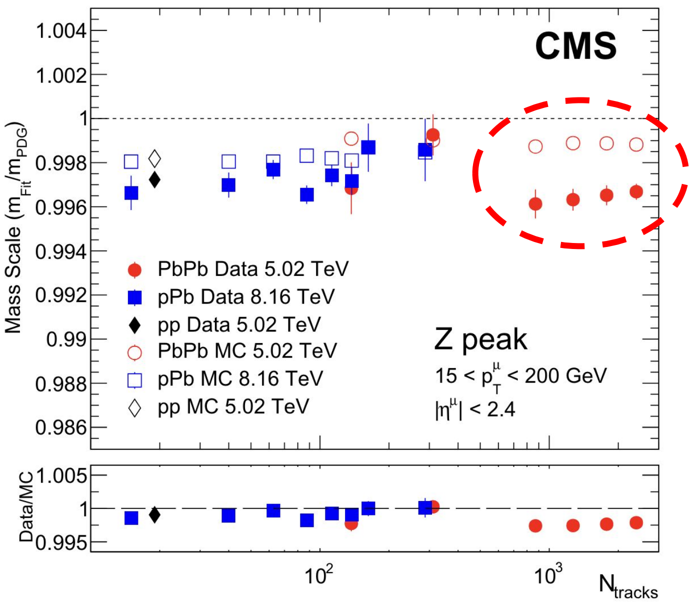
- Z^0 produced in hard-scattering.

Relevant timescales:

- **Z-Decay:** $c\tau$ ~ 0.08 fm.
- **B-field:** $c\tau$ ~ 0.05–0.4 fm.
- **QGP:** $c\tau$ ~ 10–20 fm.

Observations in Muon Performance Paper [JINST 19 (2024) P09012]





- Studies of mass resolution and scale of Z^0 performed across p+p, p+Pb and Pb+Pb data/MC.
- Observed possible effect.

Analysis Goal: Characterizing Z^0 Mass and Width

- ➢ Constrain magnitude of the EM field in HI collisions using Pb+Pb and p+p data.
- ➢ **Key question:** Is there a difference in the inv. mass distribution of the Z^0 in Pb+Pb compared to p+p?

  - Three methods to characterize the inv. mass distribution: Each method relies on different assumptions.
    - Window counting: calculate mean and std. dev from mass spectrum histogram.
    - Fit PDF: fit mass distribution with signal + bkgd PDF.
    - Template fit (not included here): generate MC template, re-weight to obtain large family of curves, compare each to data for goodness-of-fit.
- ➢ **Key idea:**
  - Each technique is implemented in the *same* manner for both Pb+Pb and p+p data.
  - Calibrations, resolution and natural width appear in both data sets; EM effect appears *only* in Pb+Pb.
  - Calculate the differences PbPb – pp: $\Delta M = M_{\mathrm{PbPb}} - M_{\mathrm{pp}}$ $\Delta\sigma = \sigma_{\mathrm{PbPb}} - \sigma_{\mathrm{pp}}$
- ➢ **Advantage:** focusing on differences in Pb+Pb to p+p results in large cancellation of systematics.

Methodologies

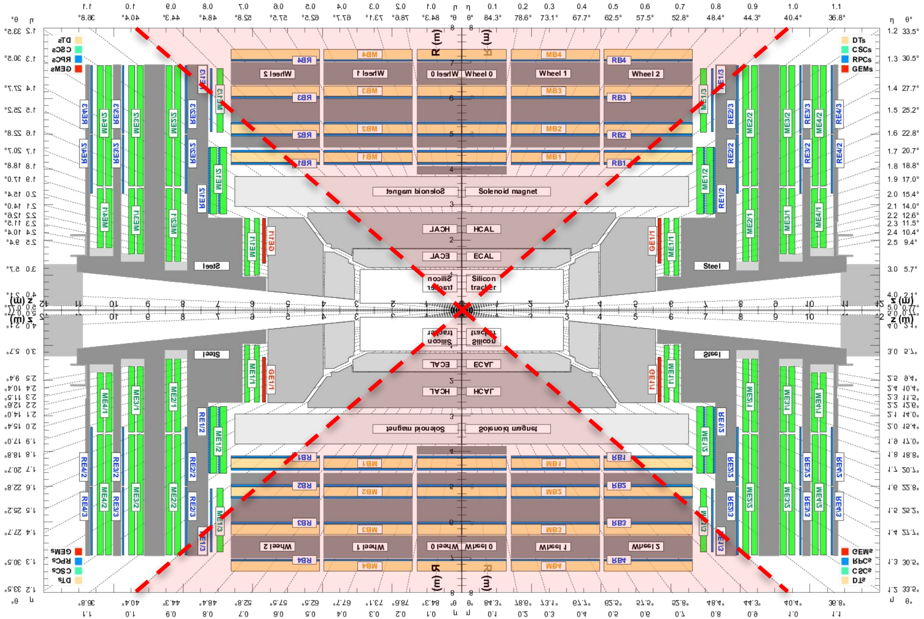
Cut Selections

➢ Analysis uses p+p (13 TeV) and Pb+Pb (5.02 TeV) $L = 1.8\ nb^{-1}$, 2018 data.

➢ Muon selections to gather Z^0-boson:

- $|\eta| < 2.4$, $p_T > 20$ GeV.
- Opposite-charge pairs.
- $60 < m_{\mu\mu} < 120$ GeV.

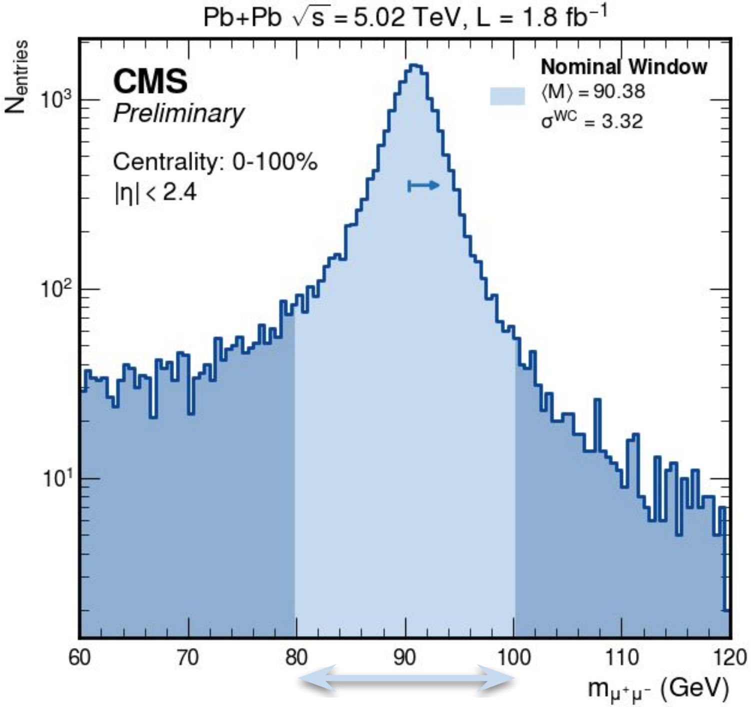
➢ Centrality: 0-10%, 10-20%, 20-30%, 30-100%, 0-100%.



“Window Counting” Method

Window counting: simplest method.

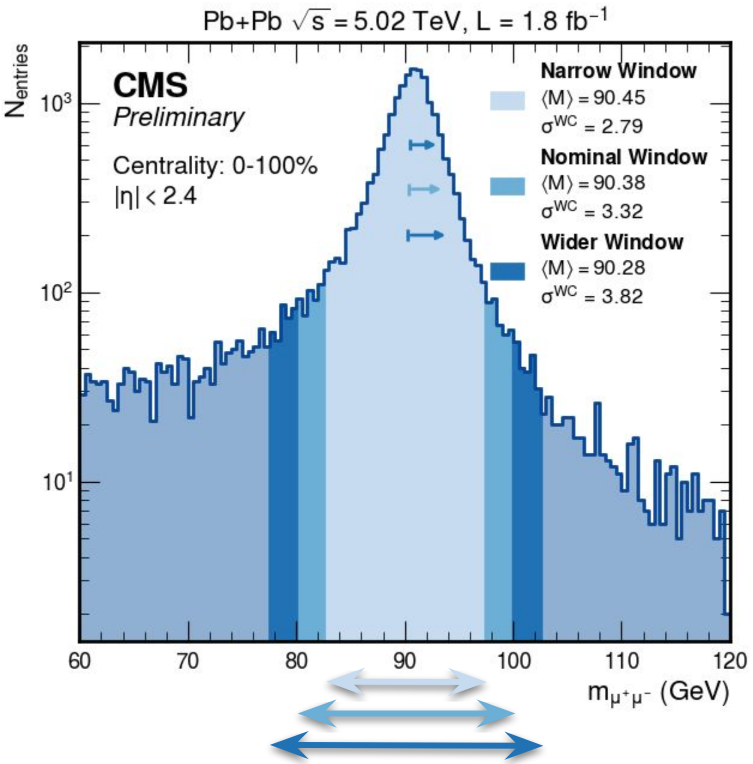
- ➢ Characterize Z^0 inv. mass using mean and std. dev.
  - Approach taken by theory paper. [PLB 827 (2022) 136962]
- ➢ Define “window range” for calculation of mean and std. dev.
  - Breit-Wigner has long tails, its std. dev. is ill-defined.
  - Calculation is well-defined when using a window.
    - Result depends on window size.



$[80, 100]\,\mathrm{GeV} \longrightarrow \pm 4\Gamma$

“Window Counting” Method

➢ Example of window-size dependence.
  - Mean and std. dev. depend on window size
➢ Studied as part of the systematic uncertainties.

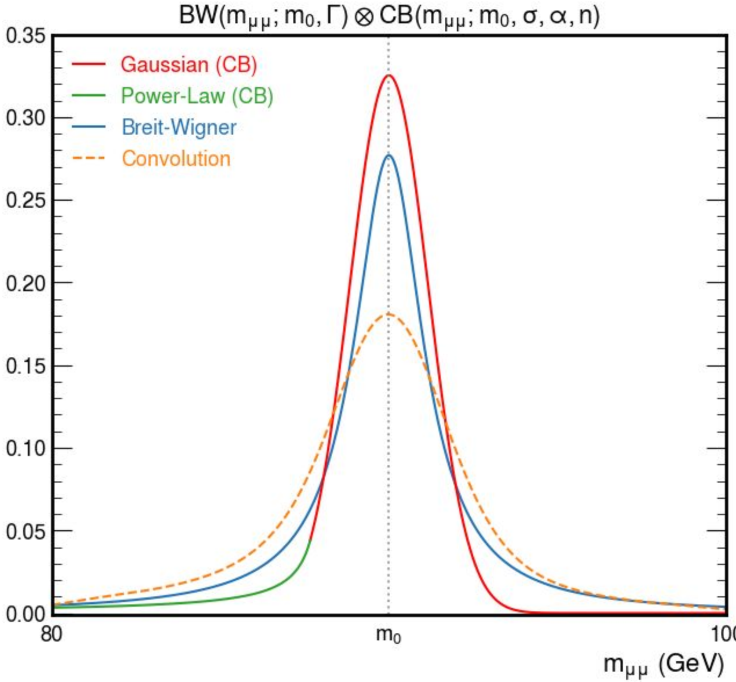


Likelihood Fit Method

Fit approach: characterize distribution by fitting inv. mass spectra w/ a signal and bkgd PDF (F = S + B).

Signal description:

- ➢ Z^0 distribution described by underlying BW.
- ➢ Resolution/Radiation effects modeled by Double-Sided Crystal Ball (DSCB) shape.
- ➢ Signal PDF: BW convolved with DSCB.



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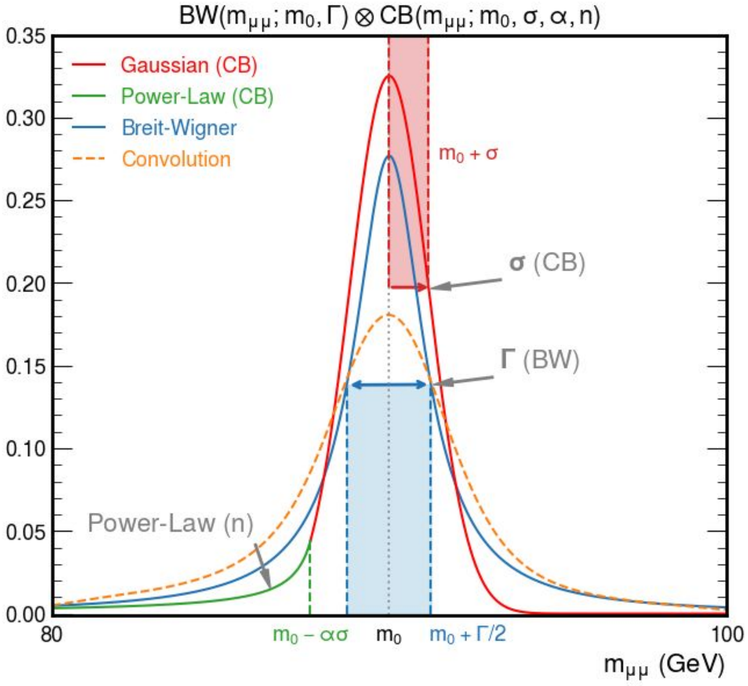
Fit approach: characterize distribution by fitting inv. mass spectra w/ a signal and bkgd PDF (F = S + B).

Signal description:

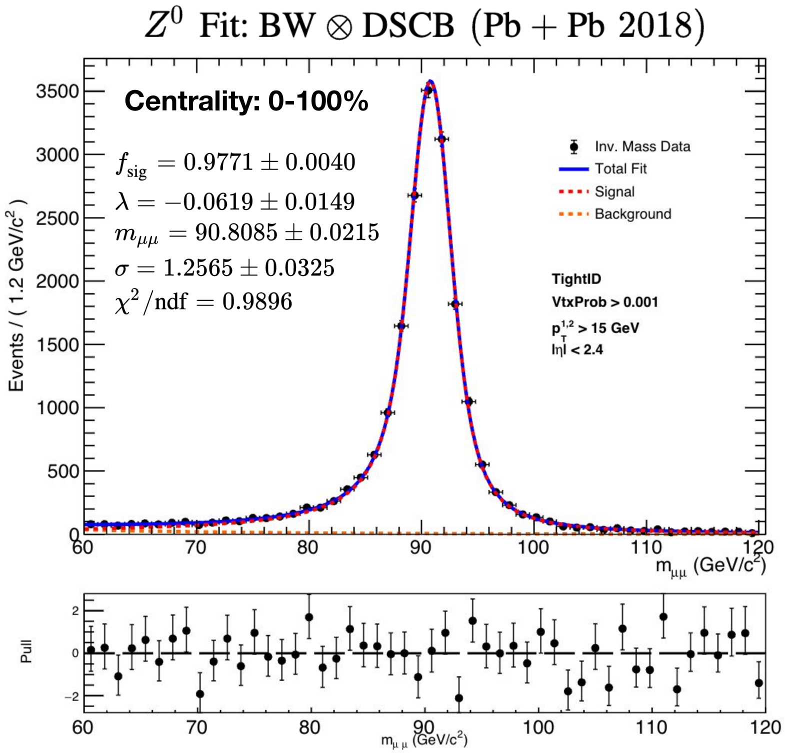
- ➢ Z^0 distribution described by underlying BW.
- ➢ Resolution/Radiation effects modeled by Double-Sided Crystal Ball (DSCB) shape.
- ➢ Signal PDF: BW convolved with DSCB.
  - Two signal parameters describe width: $\boldsymbol{\Gamma}$ (BW) and $\boldsymbol{\sigma}$ (DSCB).
  - Fixed $\boldsymbol{\Gamma}$ parameter from p+p data binned in rapidity.
- ➢ Bkgd PDF: single exponential.



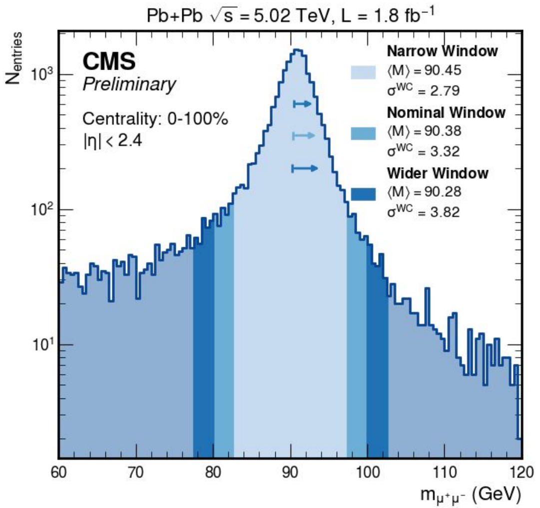
Likelihood Fit Method

- Example fit for Pb+Pb data.
  - Unbinned log-likelihood fit.
  - Background level is small.

- The only free parameters are:
  - Signal fraction.
  - Pole mass (m_0).
  - Std. dev. of Gaussian core ($\boldsymbol{\sigma}_{fit}$).

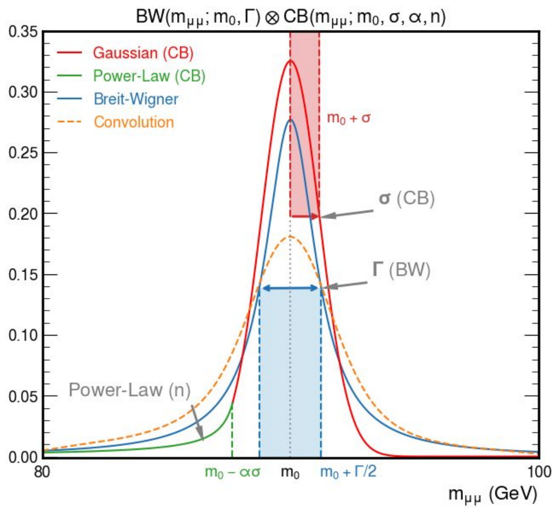


Methodologies: An Overview



$$\Delta\langle M\rangle = \langle M\rangle_{\text{PbPb}} - \langle M\rangle_{\text{pp}}$$
$$\Delta\sigma^{\text{WC}} = \sigma^{\text{WC}}_{\text{PbPb}} - \sigma^{\text{WC}}_{\text{pp}}$$

Window: mass and width estimated directly from mean and std. dev of inv. mass. Most general way to quantify broadening with as few assumptions as possible.



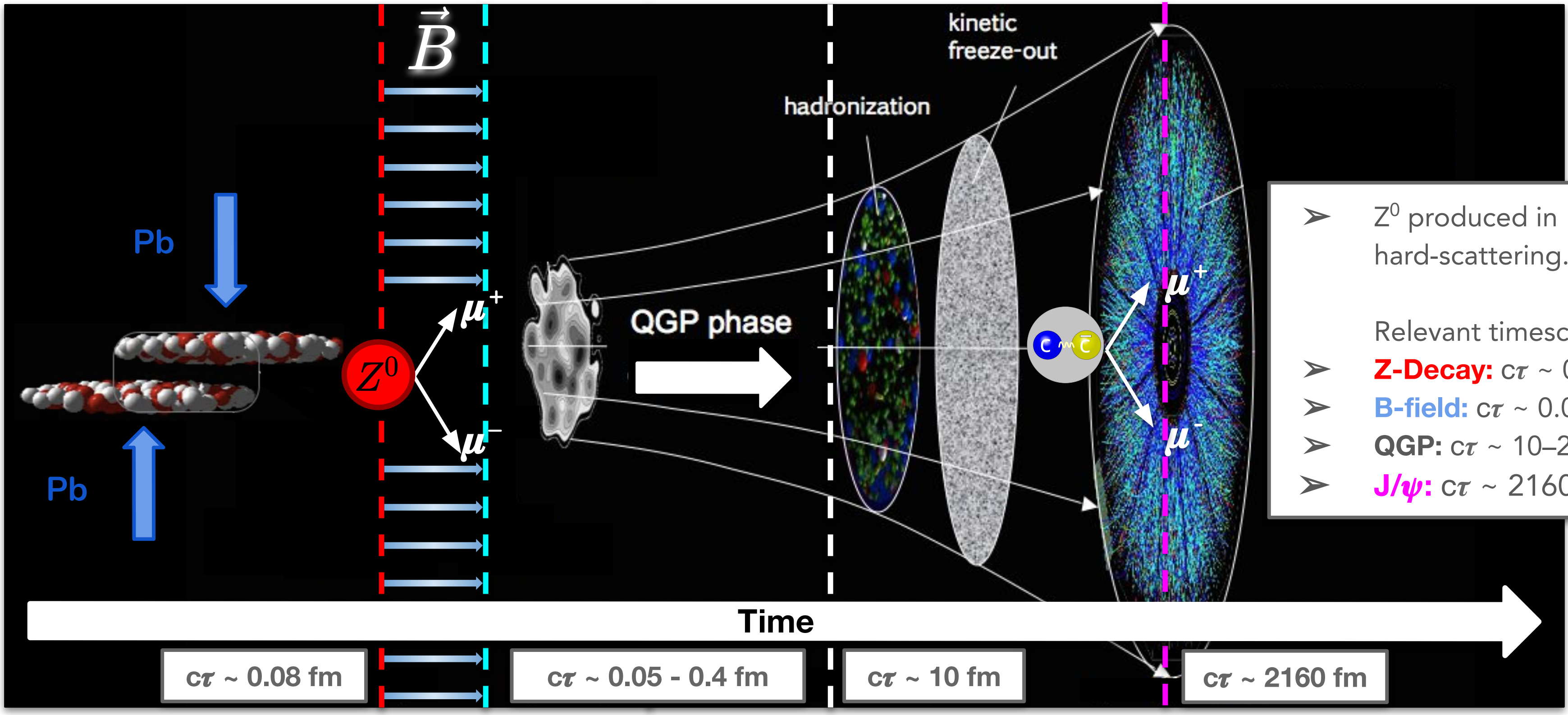
$$\Delta m_0^{\text{fit}} = m_{0,\,\text{PbPb}} - m_{0,\,\text{pp}}$$
$$\Delta\sigma^{\text{fit}} = \sigma^{\text{fit}}_{\text{PbPb}} - \sigma^{\text{fit}}_{\text{pp}}$$

Fit: from fit; mass is m_0 is BW mean, width characterized by Gaussian-core of DSCB.

NOTE: This is a statistics dominated analysis. All systematic uncertainties small compared to statistical uncertainties.

Quarkonia Stability Check

Time Scale Comparison: Quarkonia vs Z^0-Boson

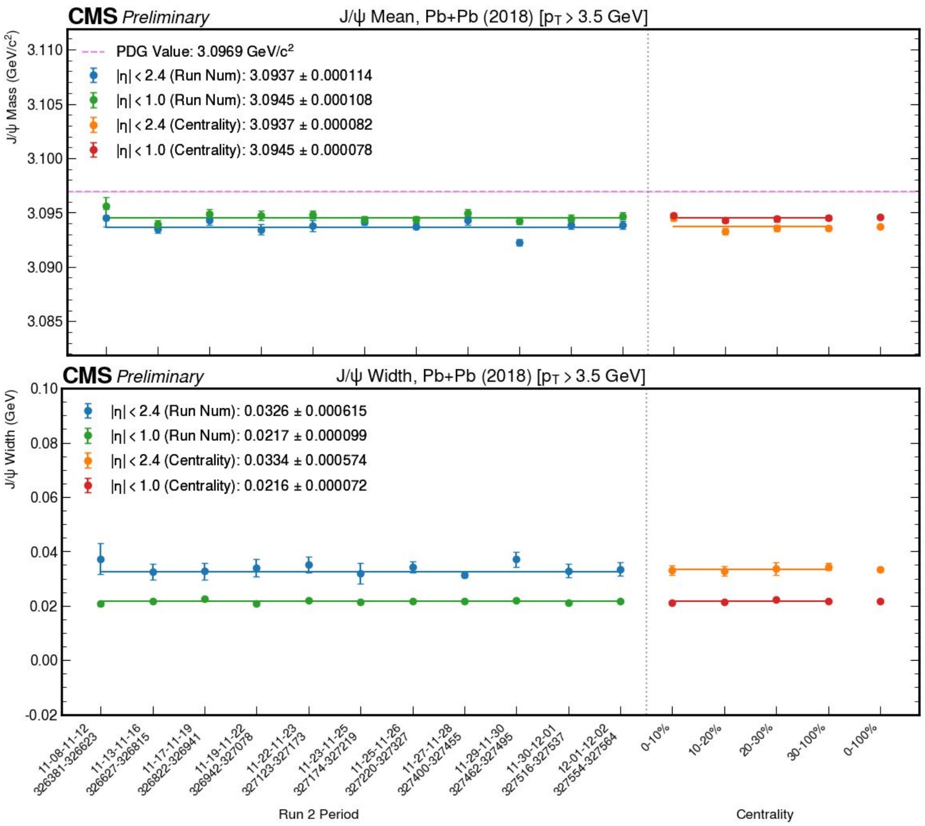


- Z^0 produced in hard-scattering.

Relevant timescales:

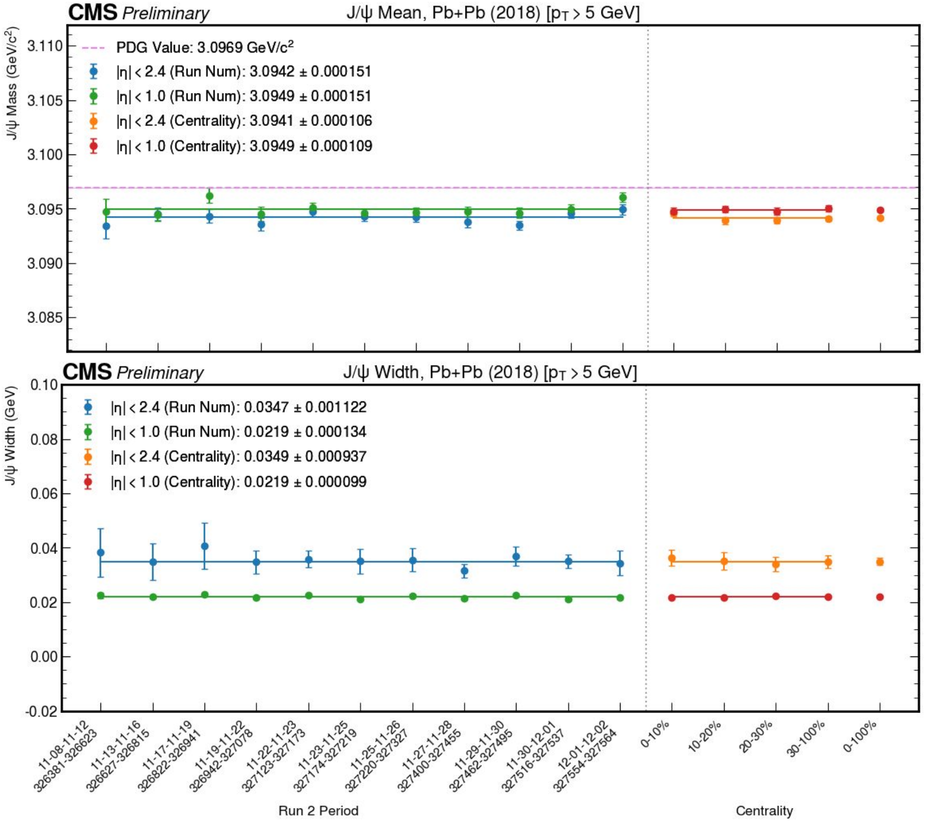
- **Z-Decay:** $c\tau$ ~ 0.08 fm.
- **B-field:** $c\tau$ ~ 0.05–0.4 fm.
- **QGP:** $c\tau$ ~ 10–20 fm.
- **J/ψ:** $c\tau$ ~ 2160 fm.

Pb+Pb J/ψ Stability per Run-Period/Centrality [p_T > 3.5 GeV]



- 2018 Pb+Pb data used to study stability in quarkonia.
  - Dimuon candidates: 2 < $m_{\mu\mu}$ < 4 GeV (J/ψ).
- Stability of mean and width as a function of time constant; no centrality dependence.
  - Calibration does not depend on multiplicity, neither does resolution.
- Width driven by detector resolution
  - Estimate on how large a shift in mean/width can be accounted for by resolution.

Pb+Pb J/ψ Stability per Run-Period/Centrality [p_T > 5 GeV]



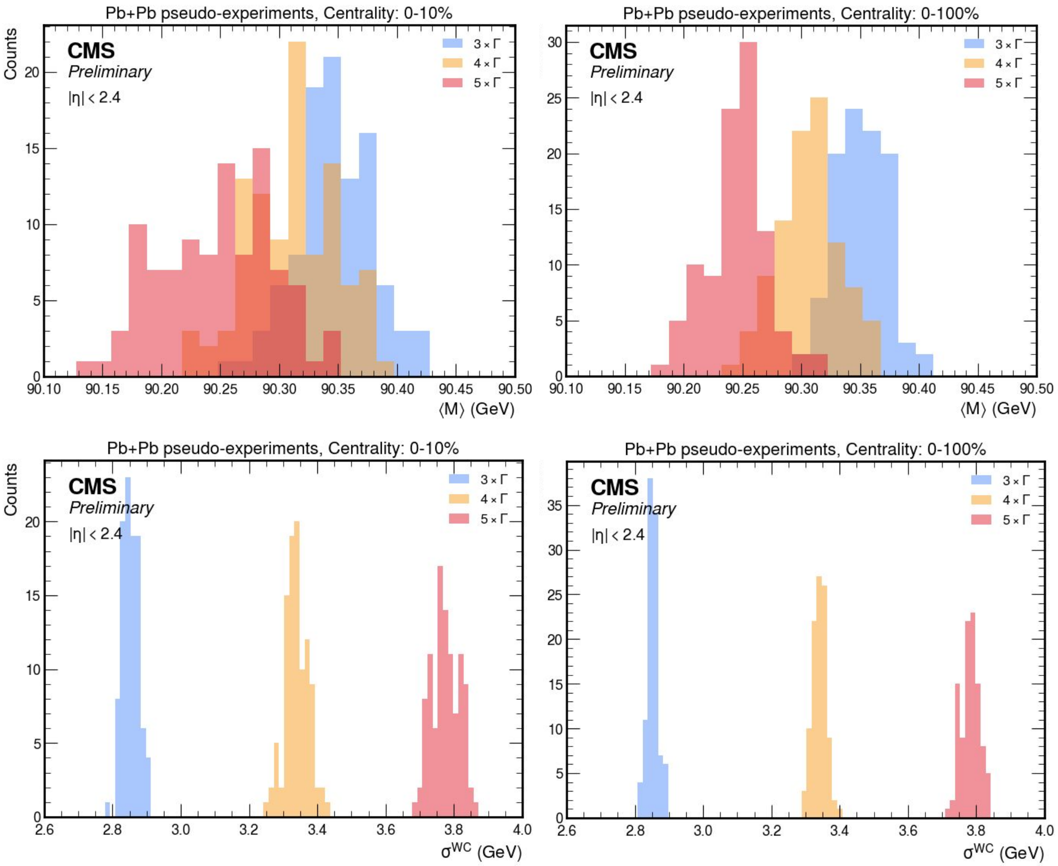
- ➢ J/ψ with p_T > 5 GeV presents same trend as lower p_T: stability, no centrality dependence.

- ➢ CMS resolution scales linearly w/ p_T up to 100 GeV.
- ➢ J/ψ width error ~3 MeV, can accommodate error of ~15 MeV for muons from Z^0 decay.

- ➢ This shift is *smaller than* the EM-field effect we seek.

Systematics

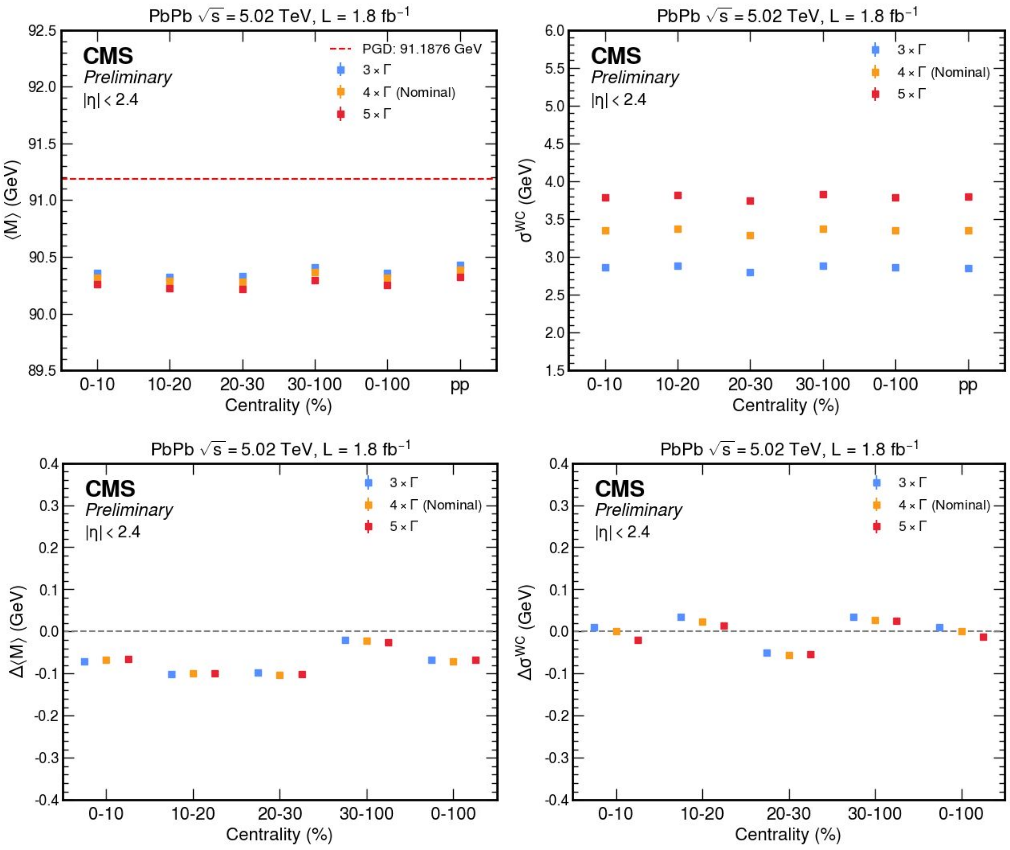
Window Counting Method: Pseudo-Experiments



➢ Window counting: main systematic arises from window width.
- **Narrow: [82.5, 97.5] GeV.**
- **Nominal: [80, 100] GeV.**
- **Wider: [77.5, 102.5] GeV.**

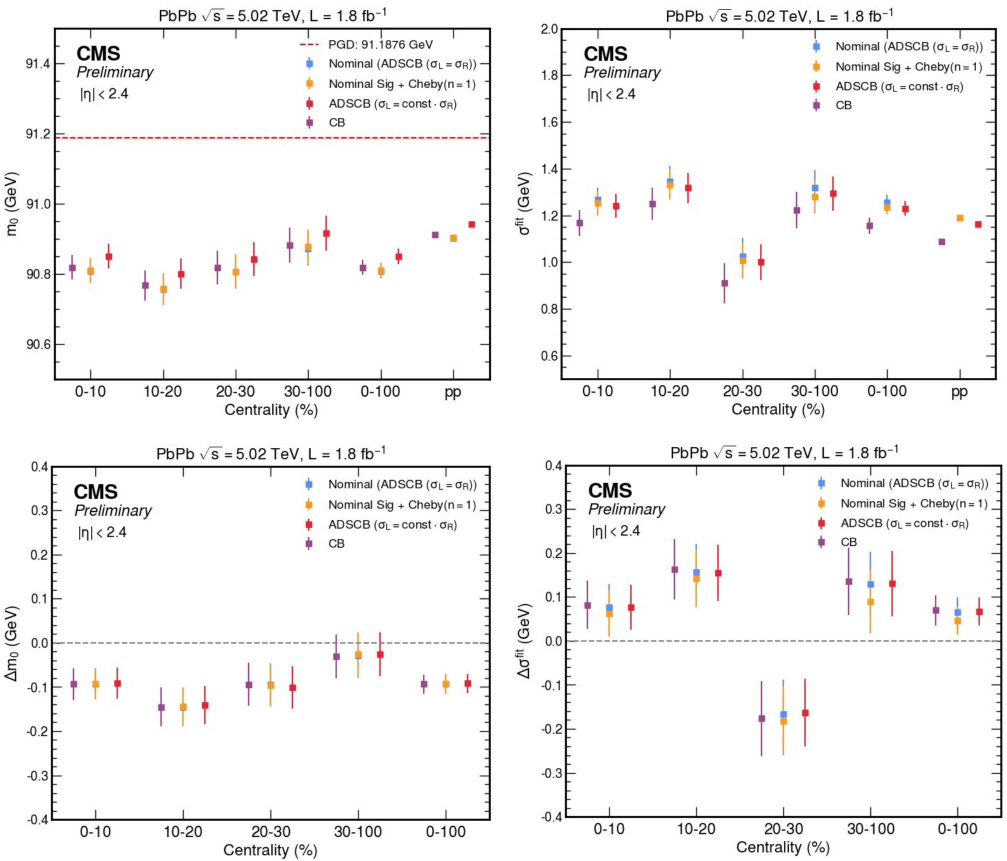
➢ Procedure:
- Estimate systematic change in mean and std. dev. using pseudo-experiments.

Window Counting Method: Window Size



- Values (Top). Increasing window size:
  - Smaller mass.
  - Larger std. dev.
- Differences (Bottom):
  - Diff. in mean roughly constant.
  - Slight variation in width.
- All variations in the differences are smaller than the statistical uncertainties.

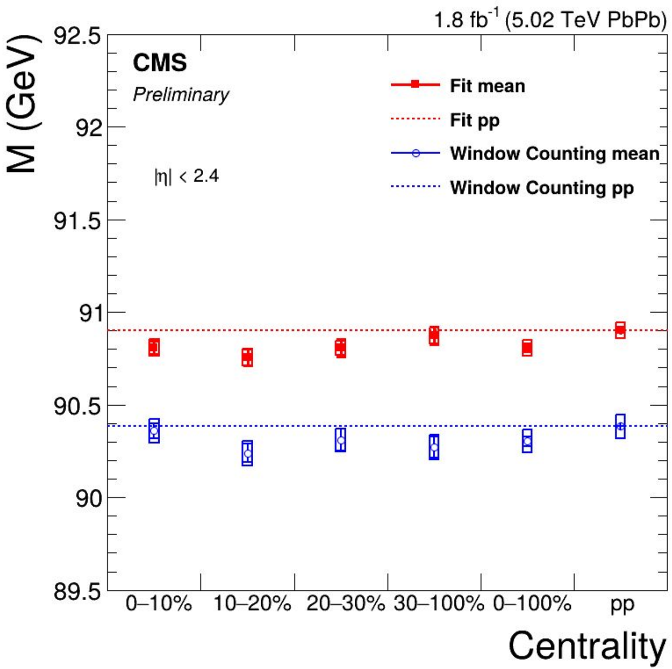
Likelihood Fit: Exploring Alternative PDFs

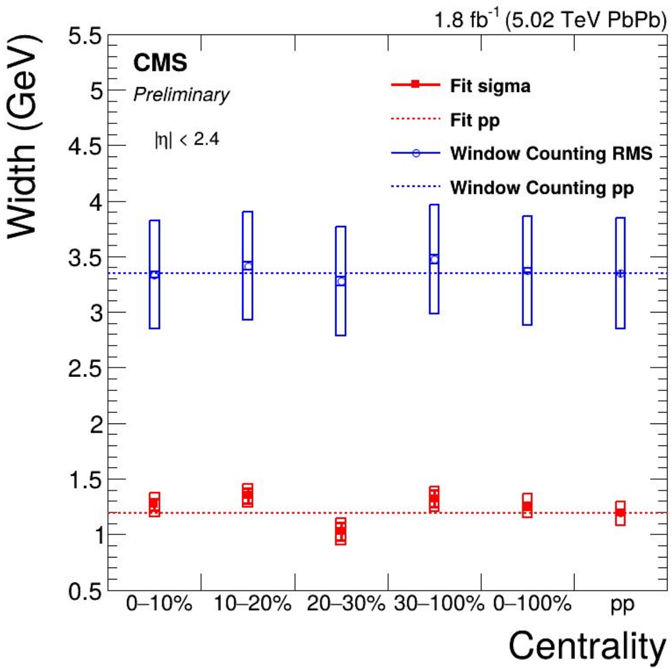


- ➢ Considered different choices for signal and bkgd PDFs for model.
  - **Nominal: DSCB.**
  - **ADSCB: fixed tail parameters.**
  - **Single CB: one width parameter.**
  - **Nominal signal + 1st-order Chebyshev.**
  - All signal variations convolved with BW.
- ➢ Values (Top):
  - The systematic uncertainty is as large (or larger) than the statistical uncertainty.
- ➢ Differences (Bottom):
  - Uncertainties correlated: largely cancel in Pb+Pb – p+p.
- ➢ Variations in signal & bkgd PDFs smaller than stat. uncertainties.

Results

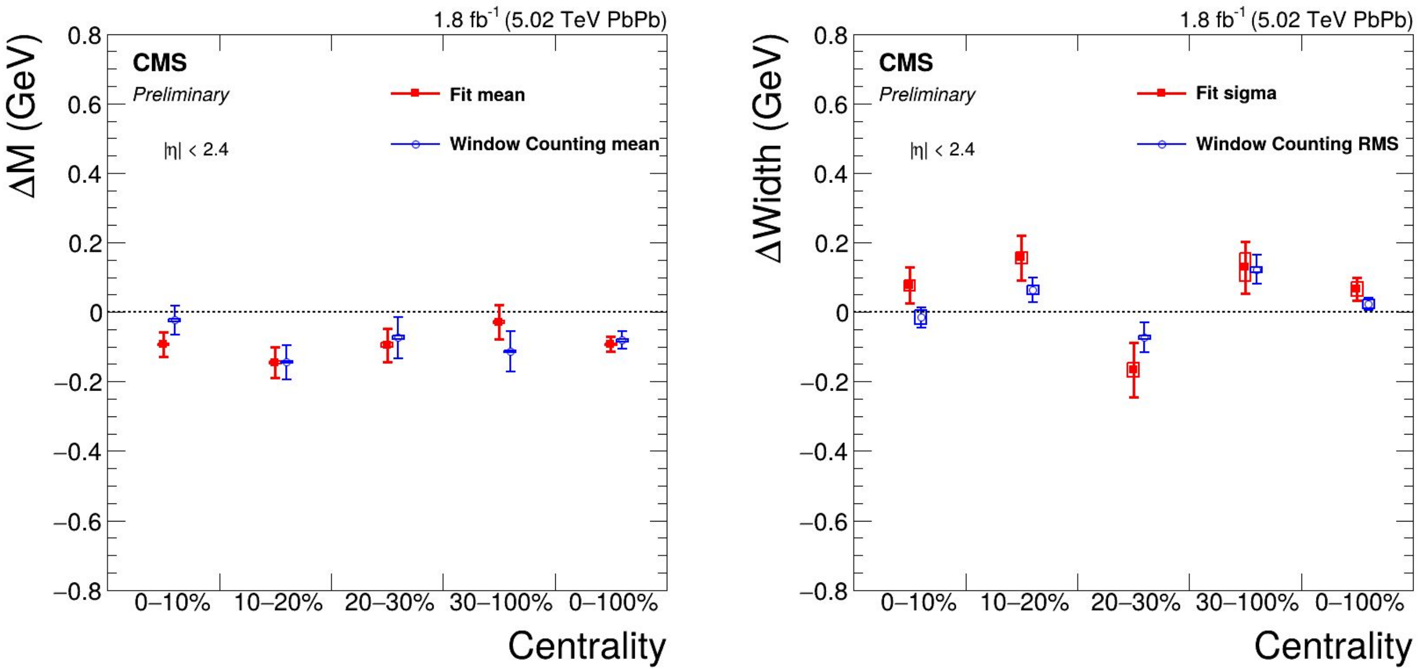
Current Analysis Status: Mass and Width Values ($|\eta| < 2.4$)





- We report two observables: mass and width *values*, and *difference* in Pb+Pb and p+p.
  - Each method results in quantitatively different value of mass/width to characterize inv. mass distribution.
  - We don’t expect results from all methods to have same values.

Current Analysis Status: Mass and Width Differences ($|\eta| < 2.4$)



- Once each mass/width value from each method is compared to corresponding p+p, *a **consistent** picture emerges.*
  - Data in full acceptance rule out large shifts (> 400 MeV) mass/width.
  - All methods agree on mass shift toward low masses, ~100 MeV for int. cent.
  - Remaining item: Take into account p_T difference between Pb+Pb and p+p. Stay tuned!

Summary

We presented a study comparing inv. mass and width of Z^0 in p+p and Pb+Pb.

➢ Quantified changes in mass/width of Z^0 via two methods.

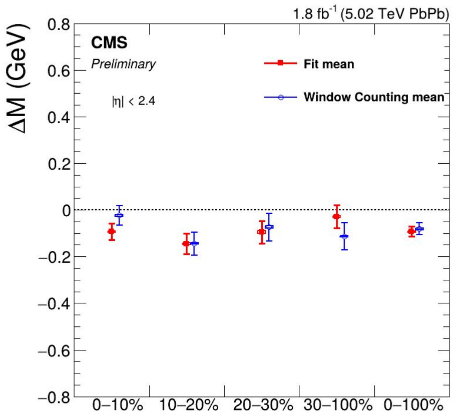
- WC: obtain mean and std. dev. of inv. mass.
- Likelihood Fit: fit inv. mass with signal/bkgd PDF, account for detector resolution, natural width.

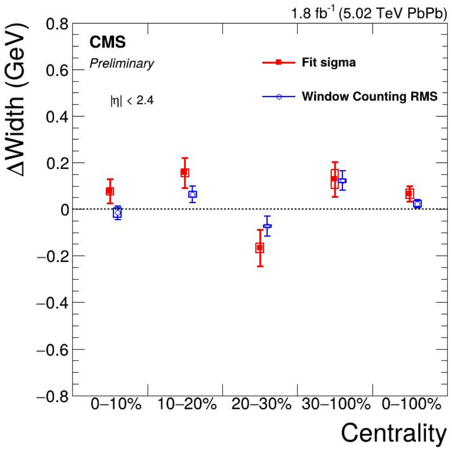
➢ By taking the *difference*, systematics largely cancel.

➢ Regardless of method, we see a *consistent trend.*

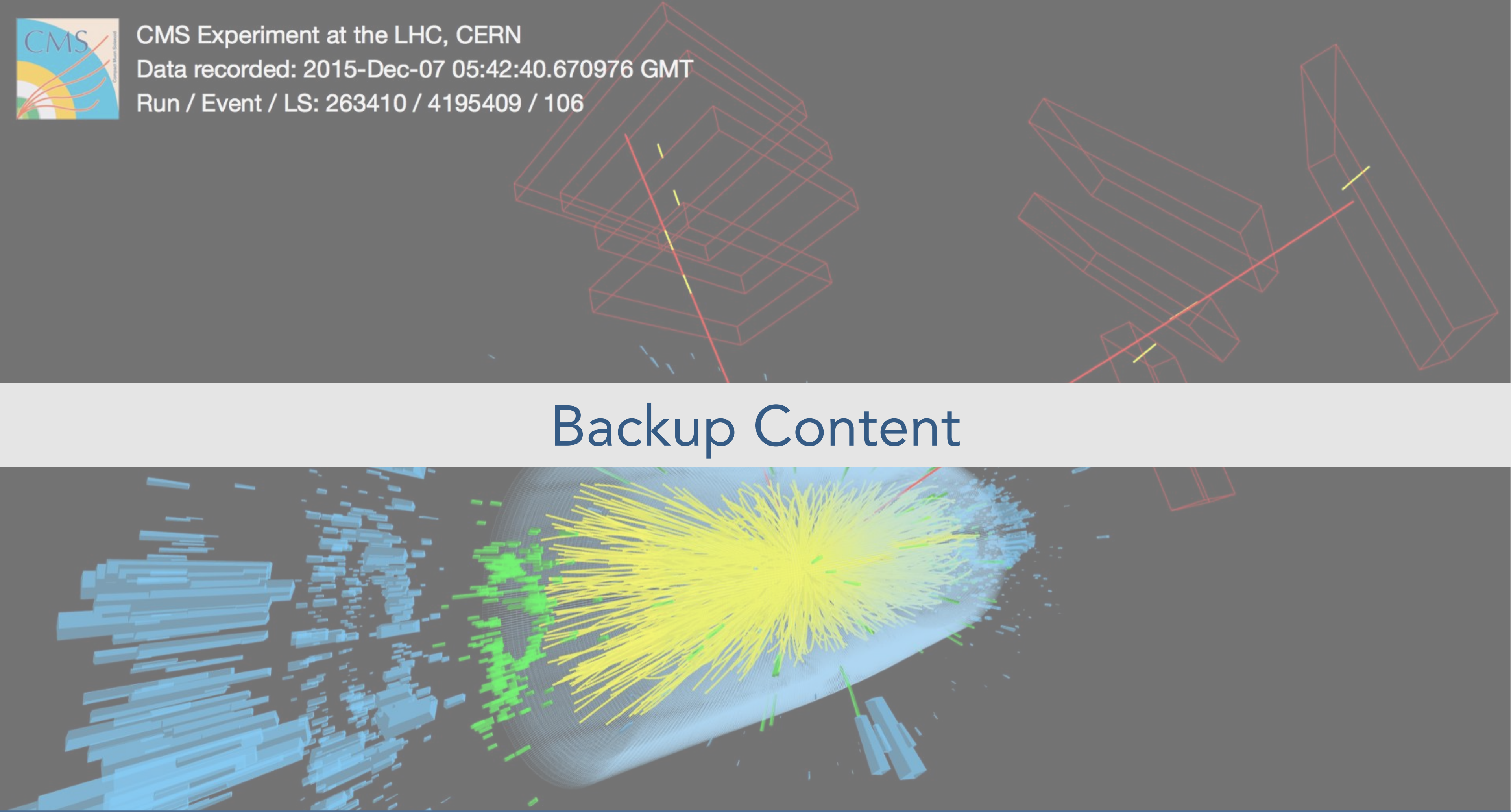
- All methods *agree* on whether shift is positive/negative.
- This is the current status of the analysis.
- To do: address p_T dependence in p+p spectrum to match Pb+Pb.

➢ Results help place constraints on magnitude and evolution of EM field in HI.





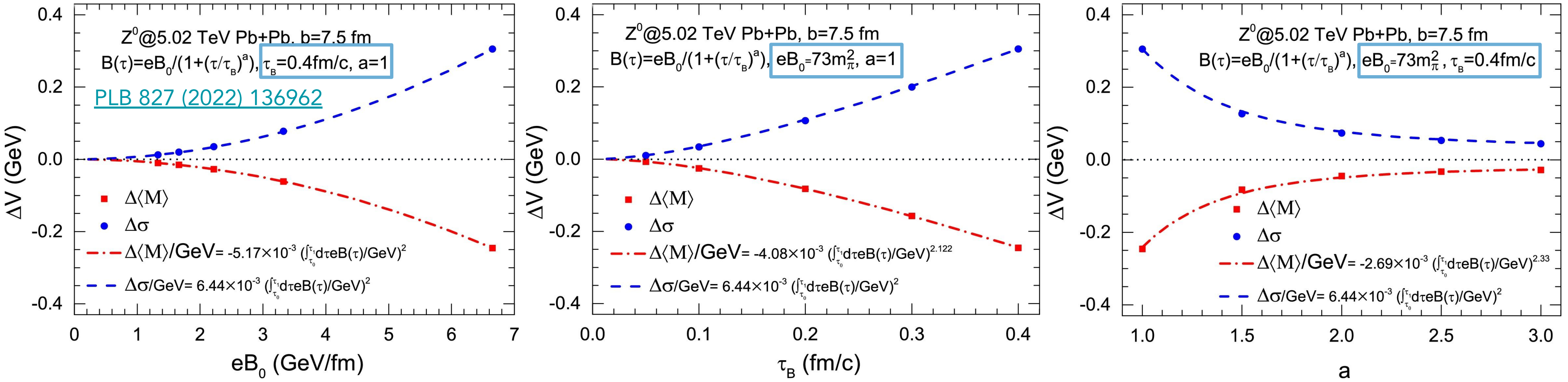
Thank you all so much for your attention! 🙂



Backup Content

Extra Material

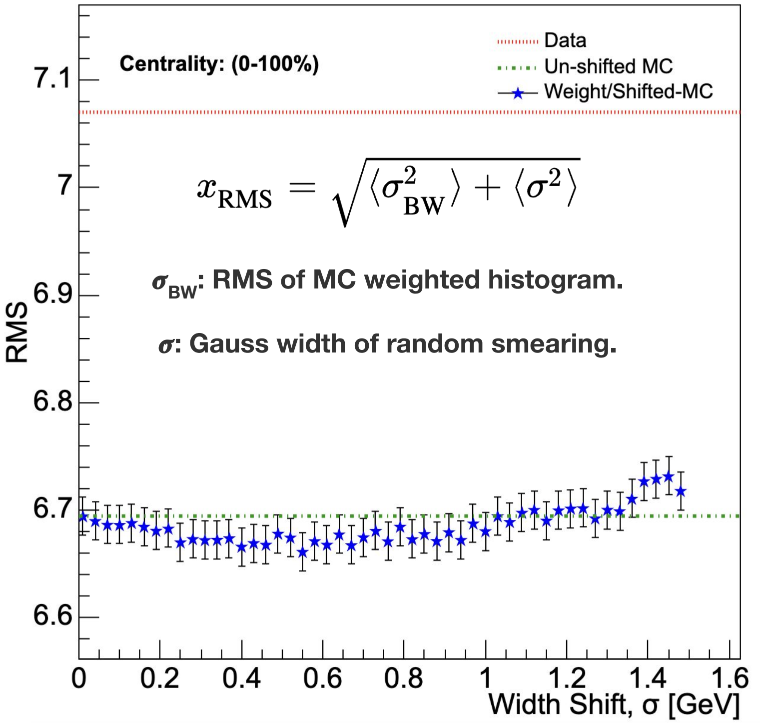
Magnetic Field Time-Evolution

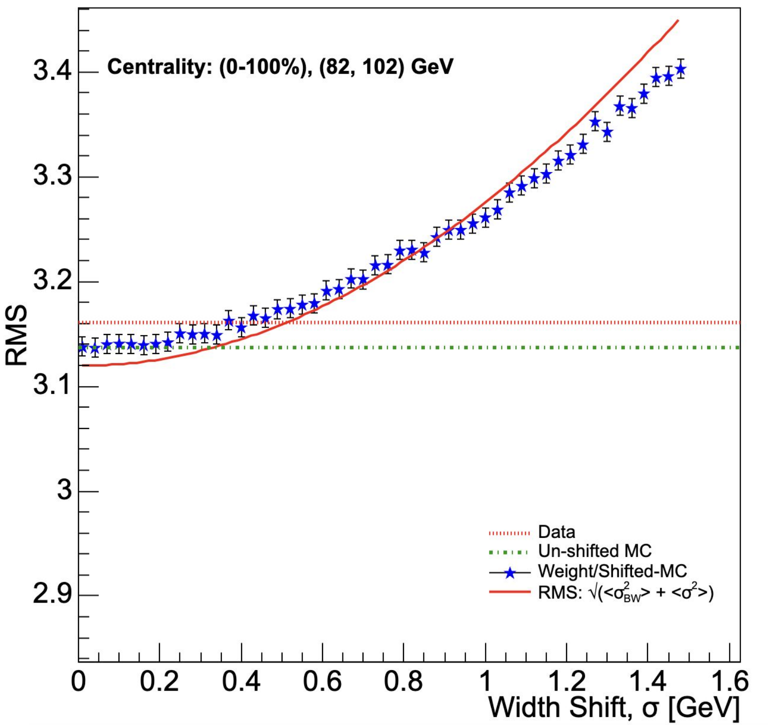


$$B(\tau) = eB_0 / \left(1 + \left(\frac{\tau}{\tau_B}\right)^a\right)$$

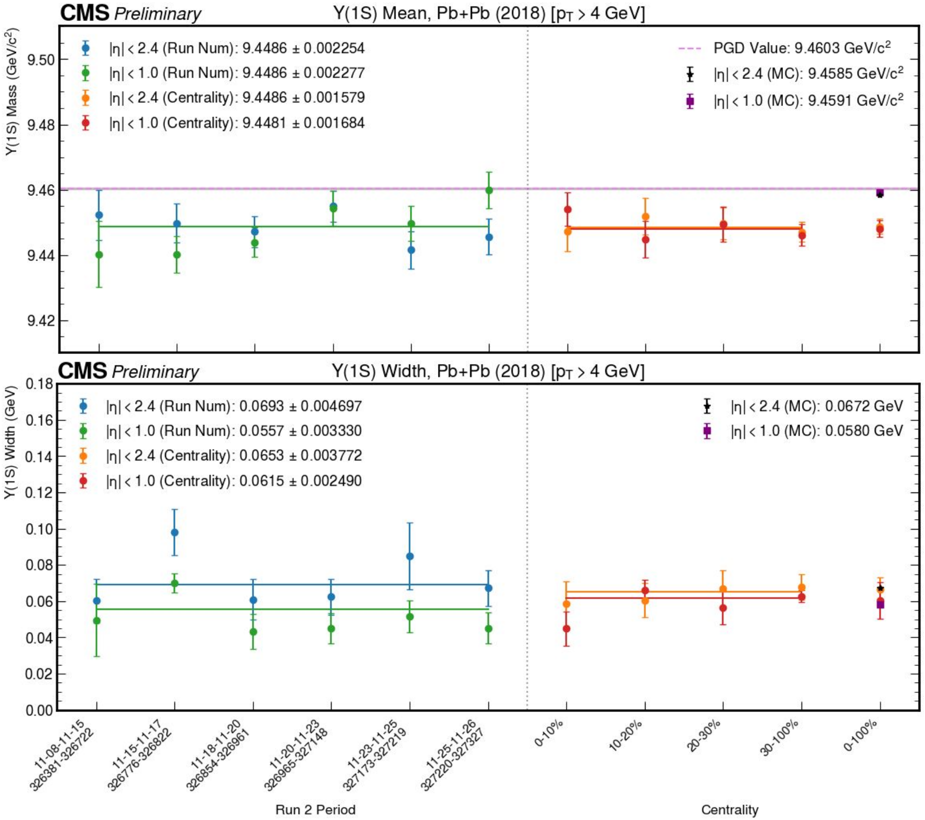
- B-field decays with time; power-law parameter (a) controls rate of decay.
- Expect E-field along x-direction (in-plane), Faraday's law.
- Study varied magnitude, lifetime & power-law to find pattern of strength and time-dependence of EM field.
  - Magnitude: Z^0-boson change in mean/width in mid-rapidity, for fixed lifetime/power-law
  - Lifetime: dependence extended from 0.05 – 0.4 fm/c.
  - Power-Law: varied by factor of 3 in B-field parametrization; corresponds to large change in time-dependence.

Monte Carlo Smearing: Implementing a Mass Window





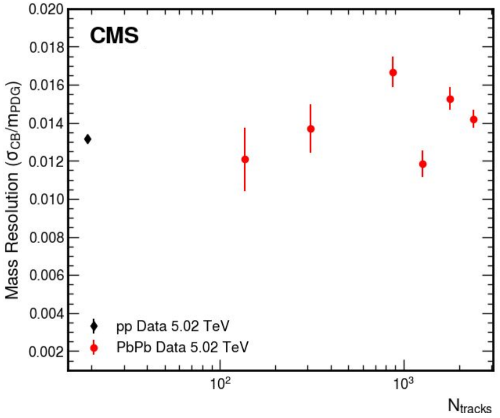
Pb+Pb Υ(1S) Stability per Run-Period/Centrality [p_T > 4 GeV]

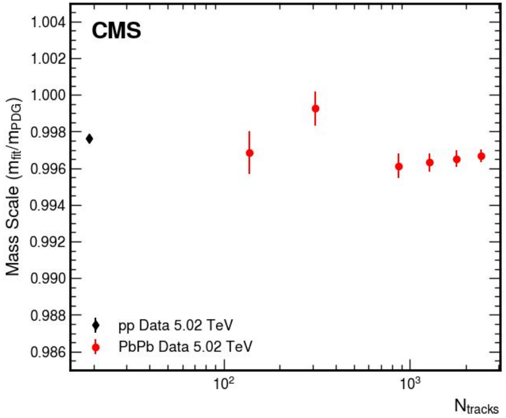


- Conclusion holds for Υ as well, but larger error bars.
  - Dimuon candidates: $6 < m_{\mu\mu} < 14$ GeV (Υ).
  - We do not see anything that would mimic effect we seek.
  - Constrain placed by J/ψ w/ p_T > 5 GeV muons.
- Fit inv. mass with DCB, fixing tail parameters from MC, for all acceptance regions.

Muon Reconstruction Check

Muon Reconstruction Performance: N_{tracks} to Centrality





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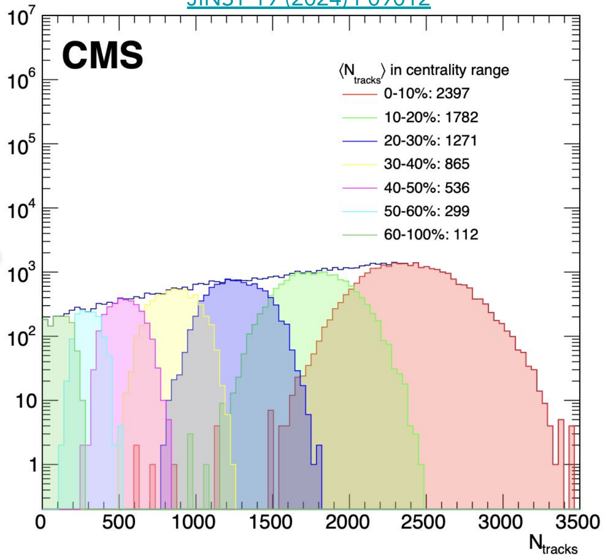
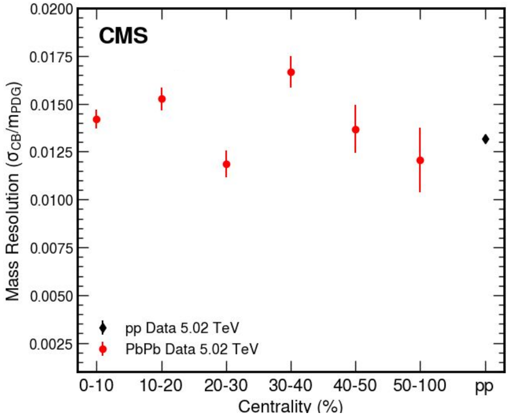
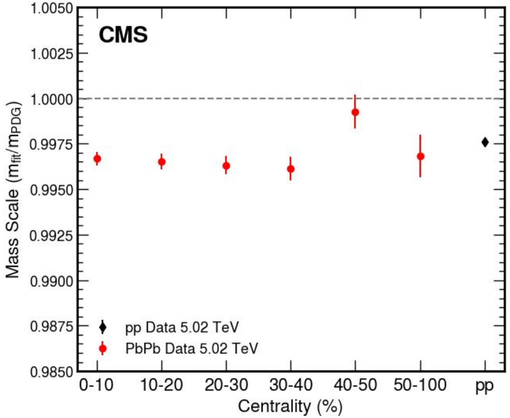


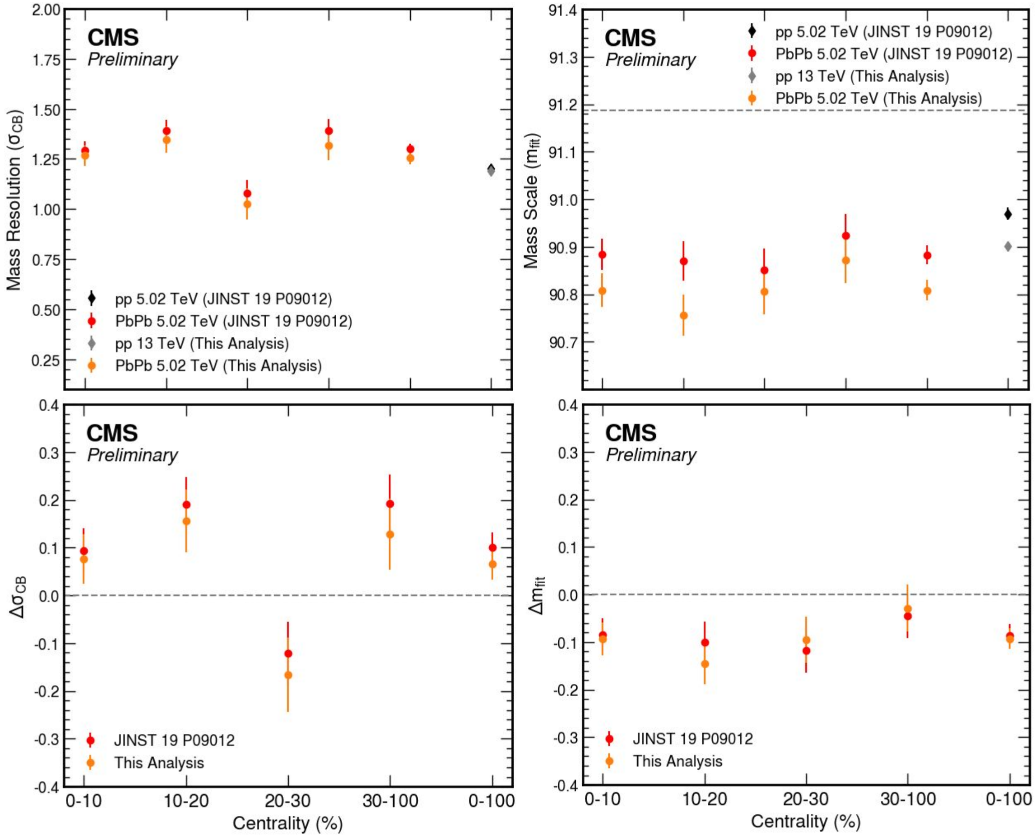
➢ Checked consistency using muon performance study results.

➢ Converted N_{tracks} to centrality, and calculated difference w/ p+p baseline.





Muon Reconstruction Performance: Difference = Pb+Pb – p+p

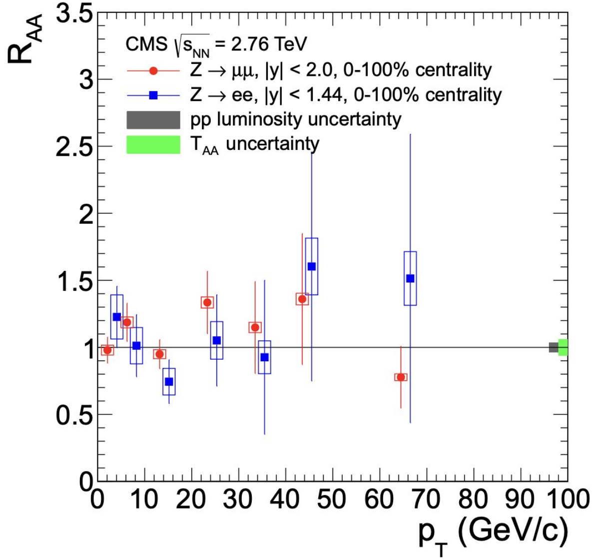


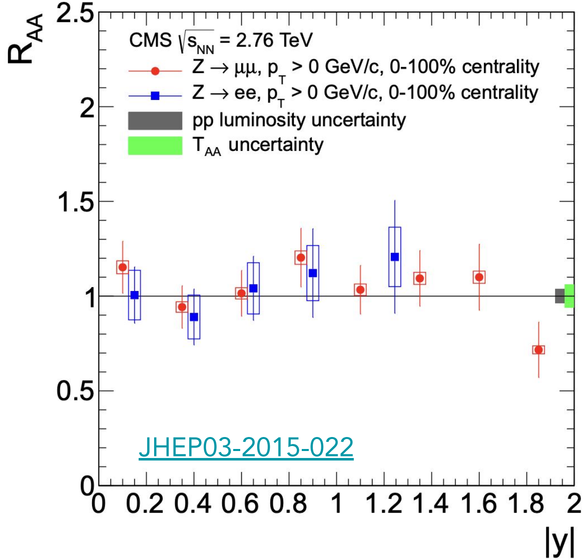
- ➢ Scaled mass resolution/scale to PDG scale.
- ➢ Translated muon performance paper centrality bins to ours.
- ➢ Muon study convolved BW with CB.
- ➢ Analysis convolved with DSCB.
- ➢ Both fix BW Gamma width.

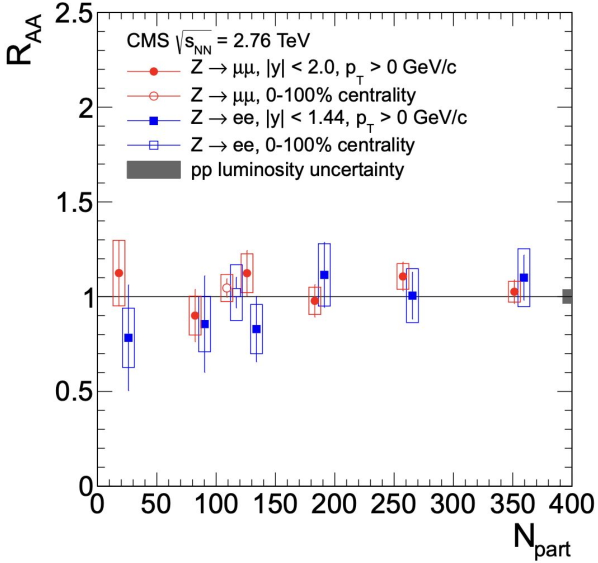
- ➢ Values (Top), Differences (Bottom):
  - Vals/Diff consistent with analysis.

R_{AA} Studies: Z^0-Boson

R_{AA} Distribution for the Z^0-Boson (CMS)

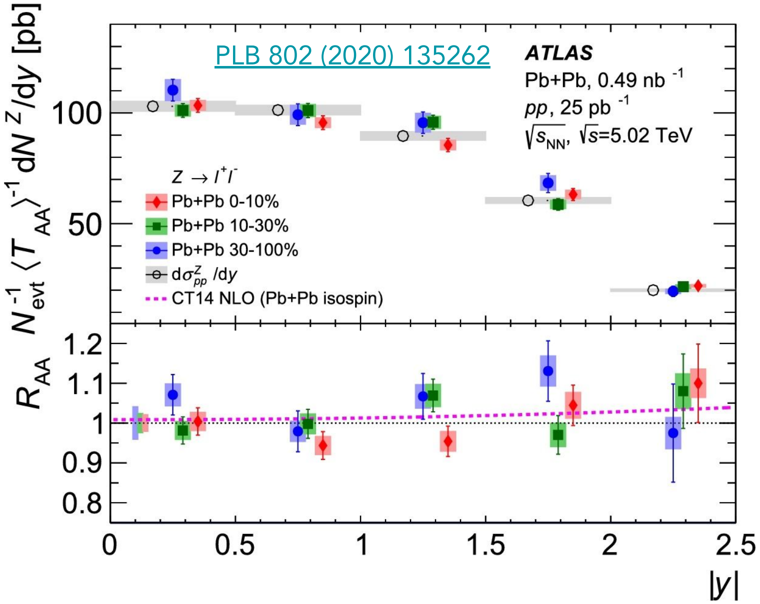


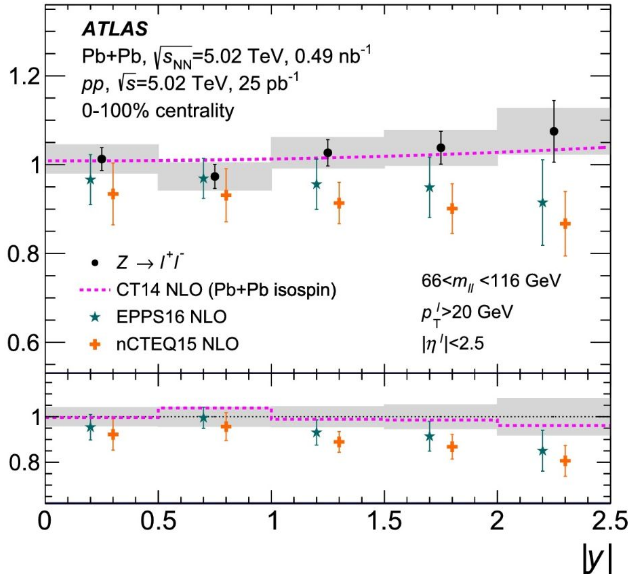




- ➢ R_{AA} distribution of the Z^0-boson, as a function of p_T, |y| and N_{part}, for the dimuon and dielectron channels.
  - Study shows that R_{AA} displays no dependence on p_T, y and centrality for both muons and electrons.
  - R_{AA} ~ 1: no variation in nuclear effects. Thus, distribution of Z-bosons is flat in p+p and Pb+Pb, as a function of kinematic variables.

R_{AA} Distribution for the Z^0-Boson (ATLAS)

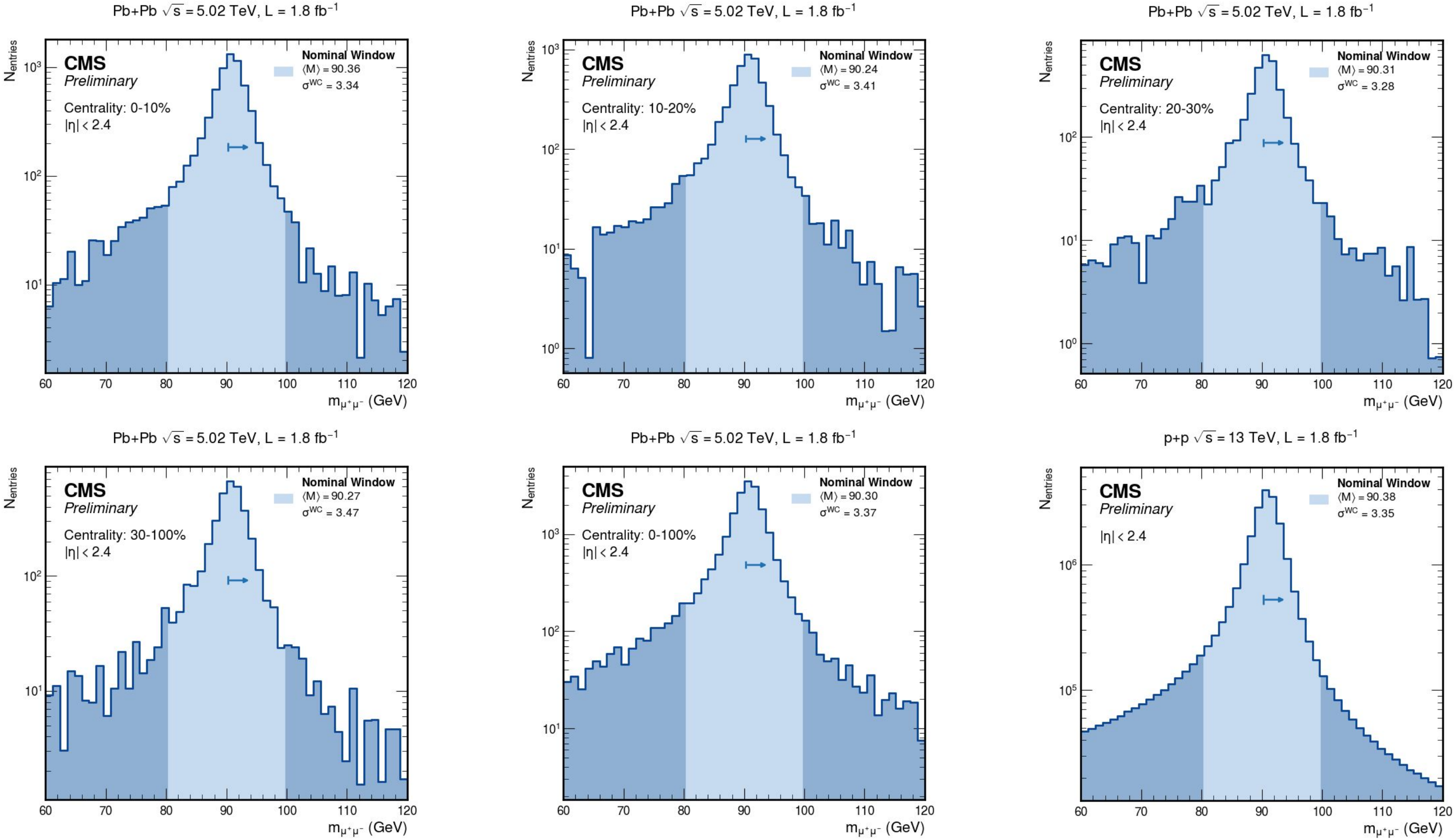




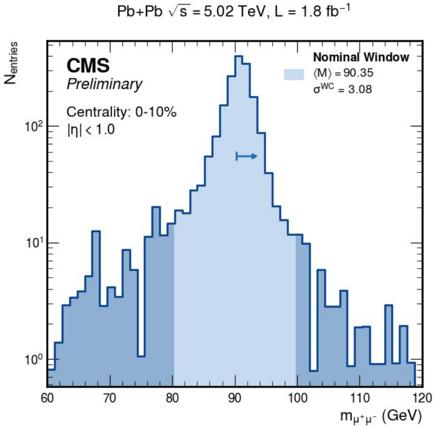
- Measurements from ALICE place production yield of Z^0 in Pb+Pb with R_{AA} ~ 1, across all centrality intervals.
  - LHS: Normalized Z yield as a function of rapidity, for 3 cent intervals. Results consistent within their statistical uncertainties.
  - RHS: Data consistent with R_{AA} ~ 1, and with isospin effect only.

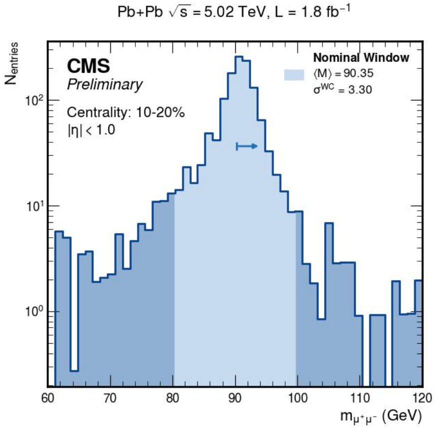
Window Counting w/ Bkgd Subtraction

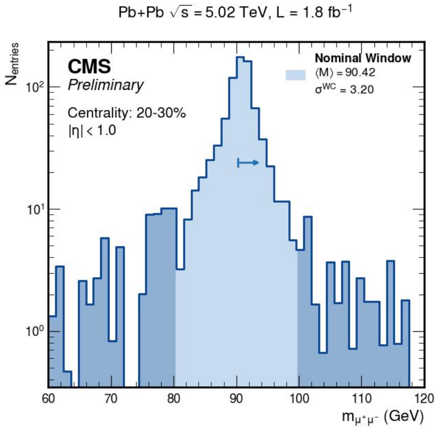
Window Counting: Background Subtracted Inv. Masses (|η| < 2.4)

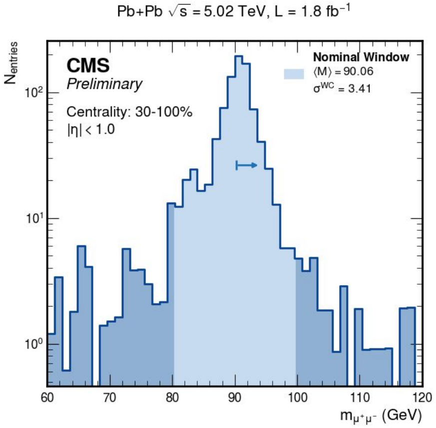


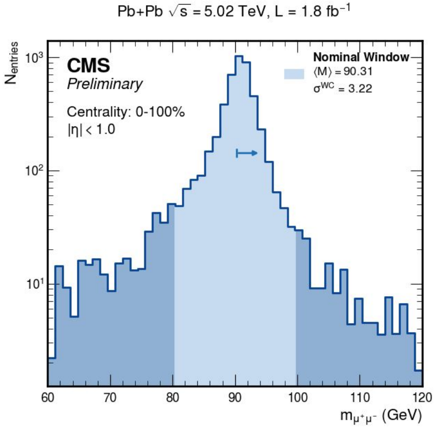
Window Counting: Background Subtracted Inv. Masses (|η| < 1.0)

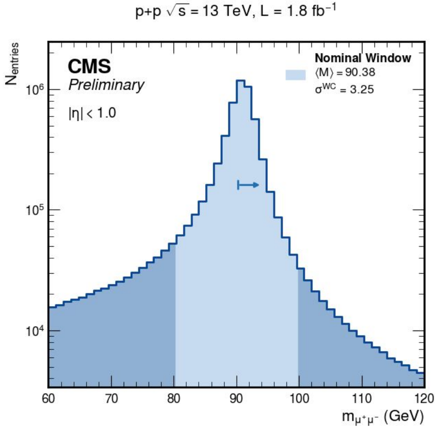








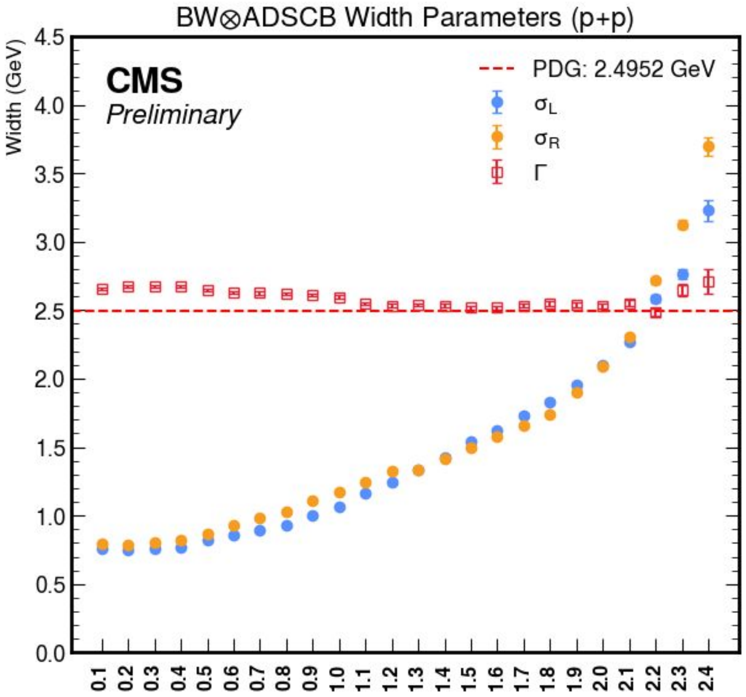




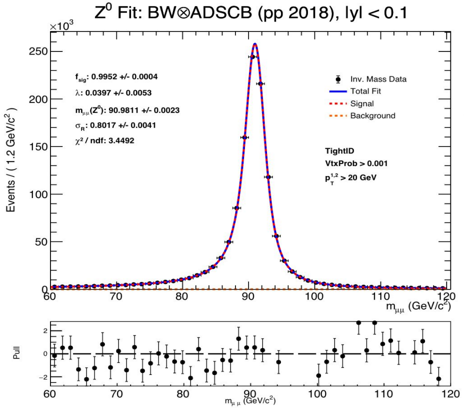
p+p Fits Binned in Rapidity (|y|)

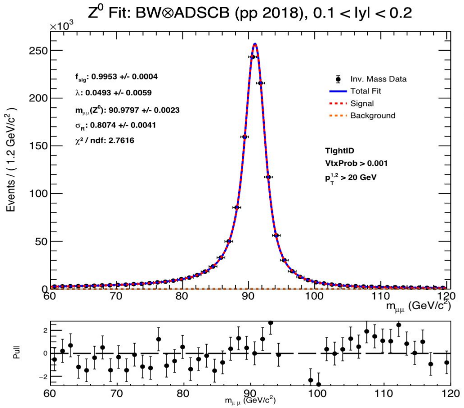
Likelihood Fit Method

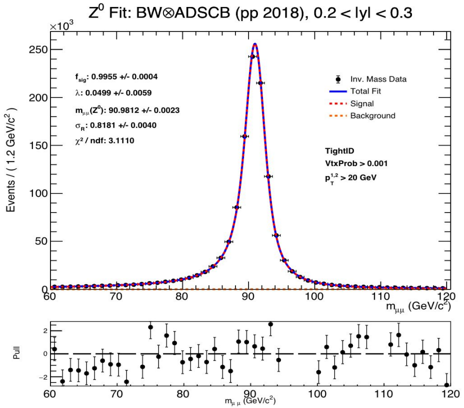
- ➢ Narrowed down parameter space by fixing ~constant parameters.
- ➢ Expectation: resolution depends on rapidity.
  - Width $\boldsymbol{\sigma}$ captures this behavior.
  - $\boldsymbol{\Gamma}$ stays constant near PDG value.
  - Enabled to fix BW $\boldsymbol{\Gamma}$ parameter, and use a single width $\boldsymbol{\sigma}$.

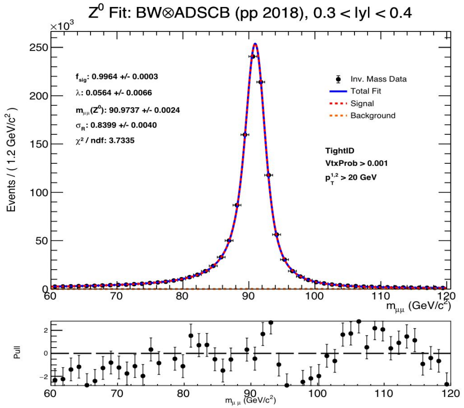


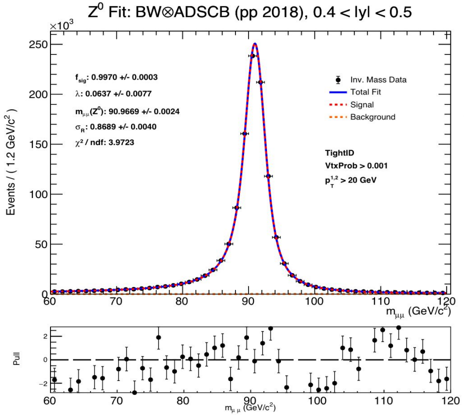
p+p Fits in Rapidity

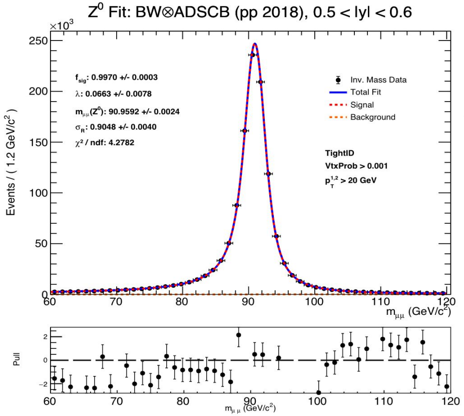


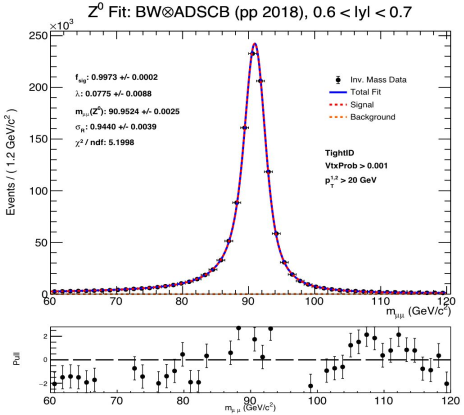


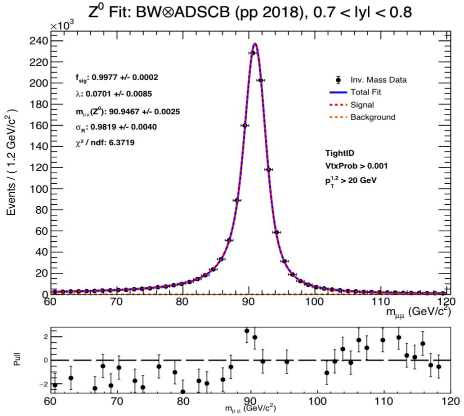




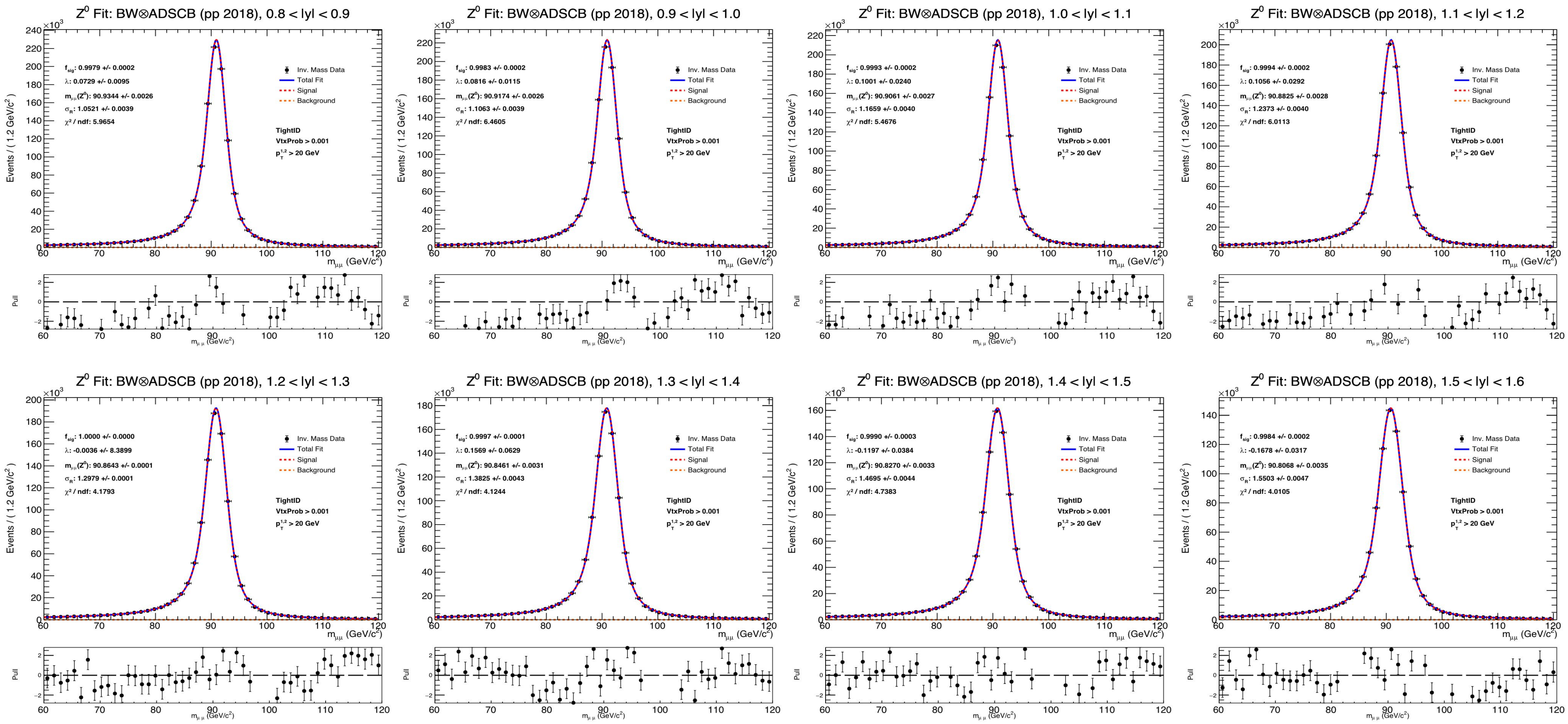




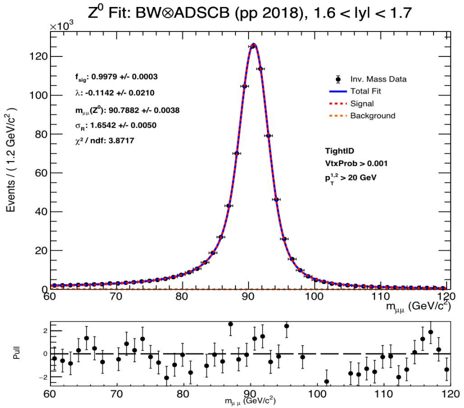


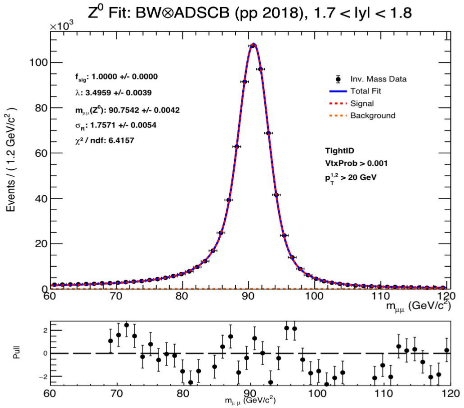


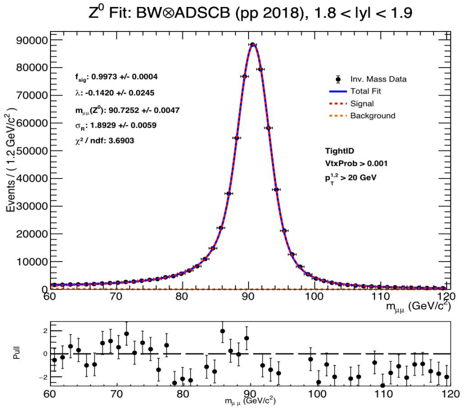
p+p Fits in Rapidity

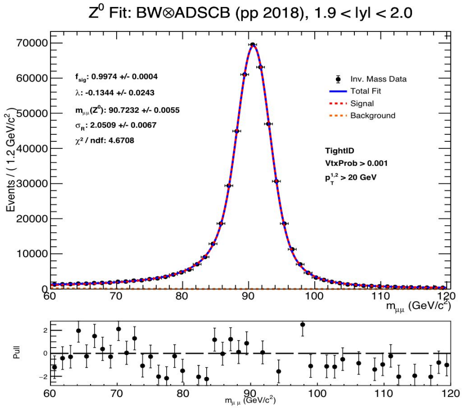


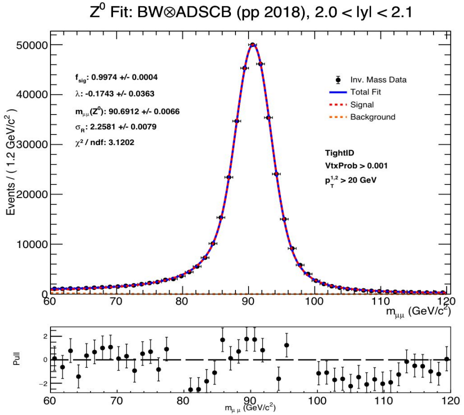
p+p Fits in Rapidity

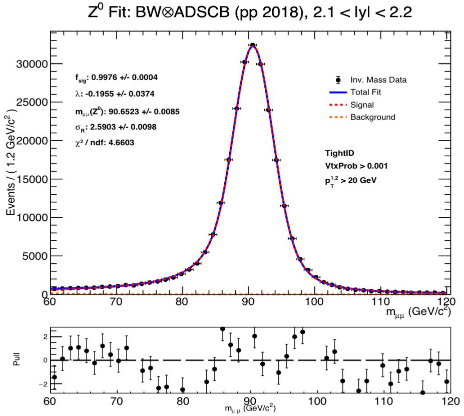


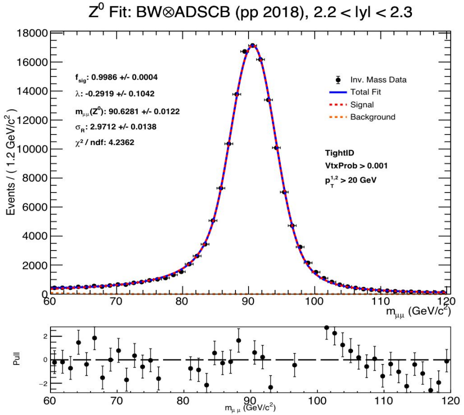


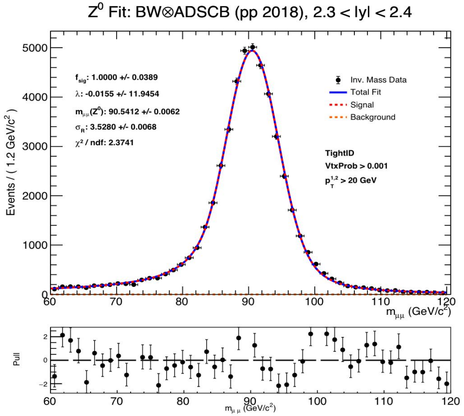








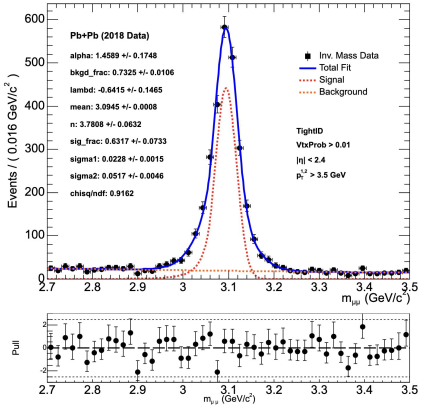




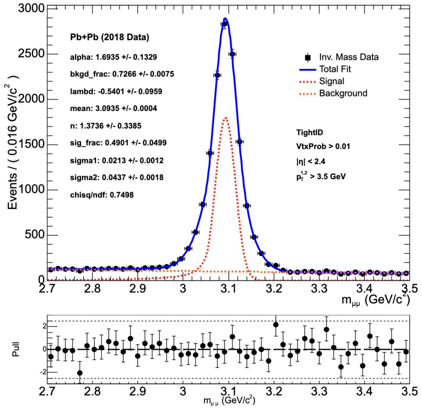
Quarkonia Fits (Run Number)

J/ψ Fits (p_T > 3.5 GeV) : Run Number (|η| < 2.4)

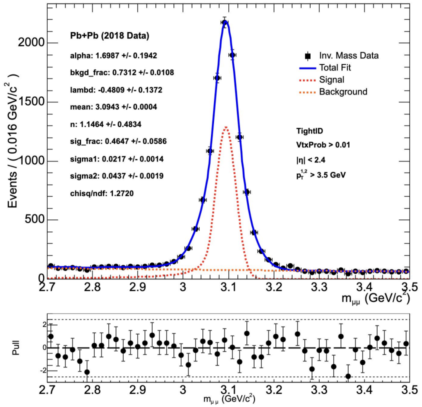
J/ψ Fit (Run: 326381 - 326623)



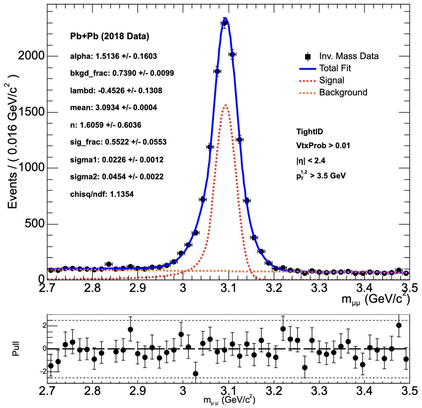
J/ψ Fit (Run: 326627 - 326815)



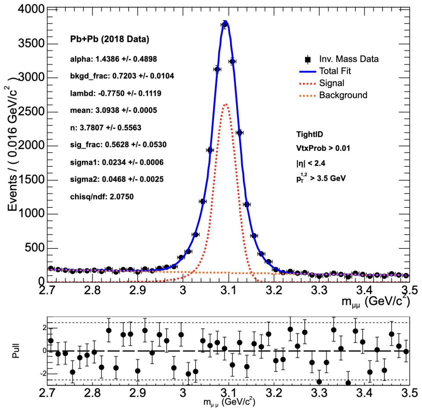
J/ψ Fit (Run: 326822 - 326941)



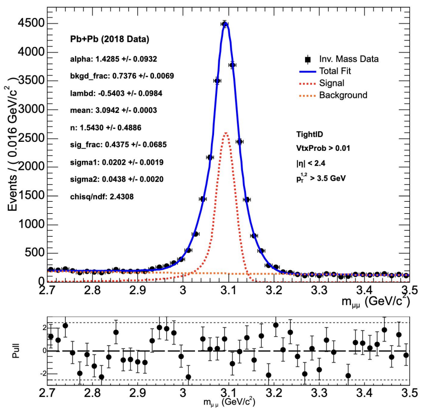
J/ψ Fit (Run: 326942 - 327078)



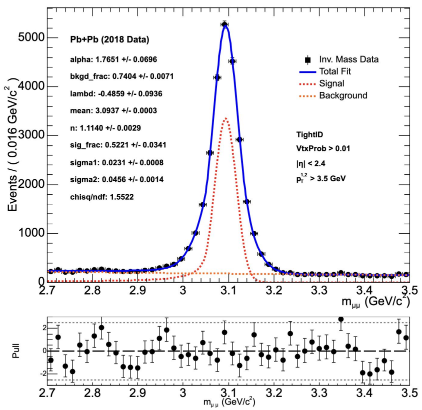
J/ψ Fit (Run: 327123 - 327173)



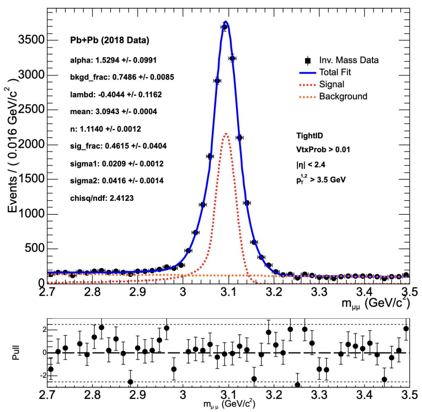
J/ψ Fit (Run: 327174 - 327219)



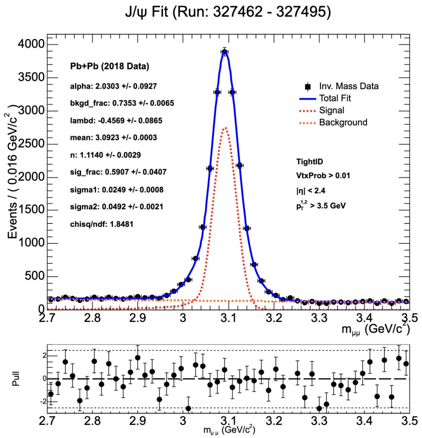
J/ψ Fit (Run: 327220 - 327327)

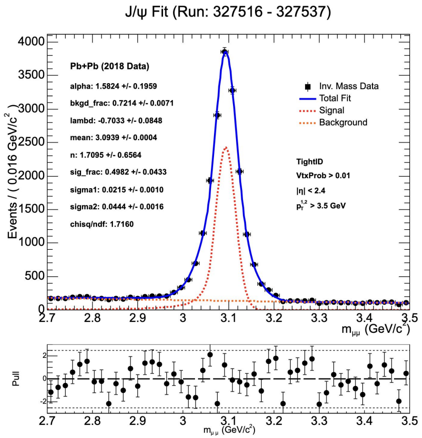


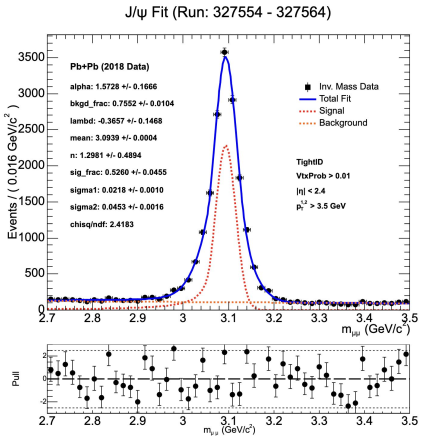
J/ψ Fit (Run: 327400 - 327455)



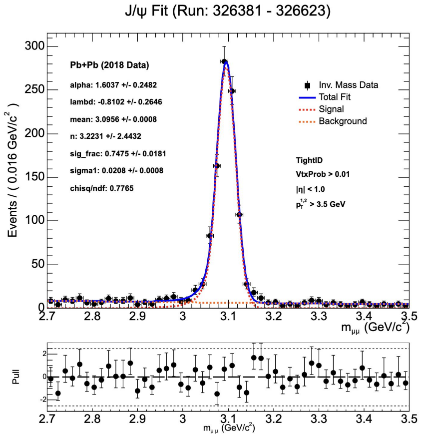
J/ψ Fits (p_T > 3.5 GeV) : Run Number ($|\eta|$ < 2.4)

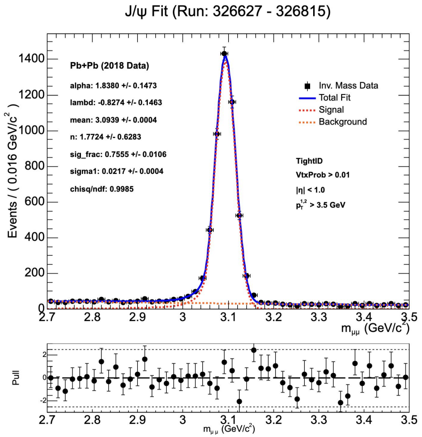


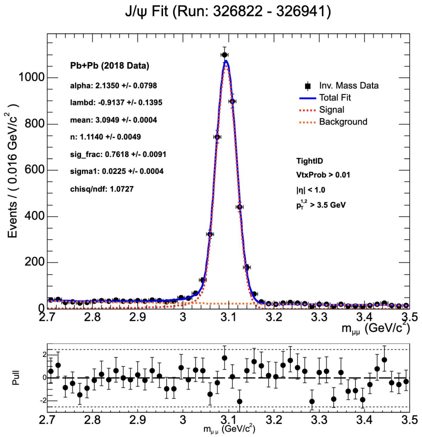


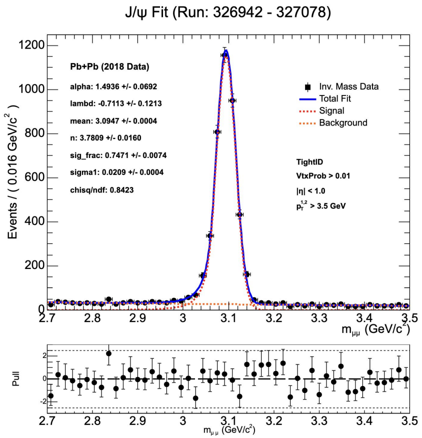


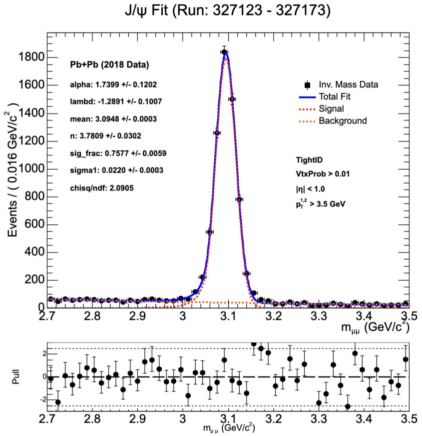
J/ψ Fits (p_T > 3.5 GeV) : Run Number ($|\eta|$ < 1.0)

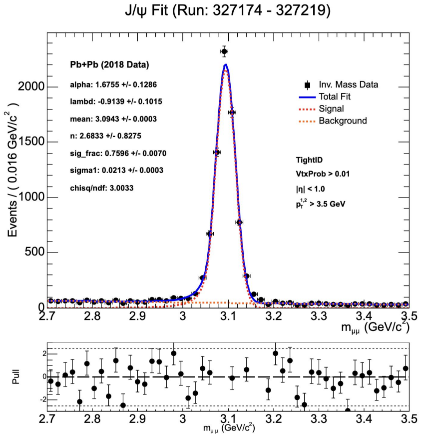


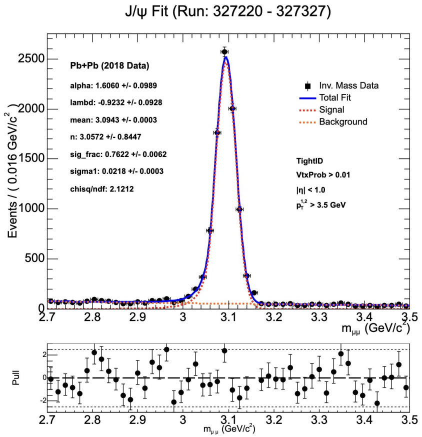


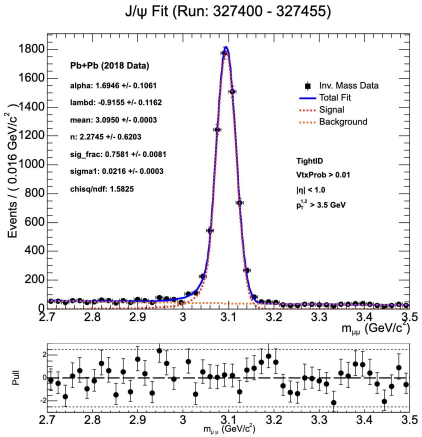




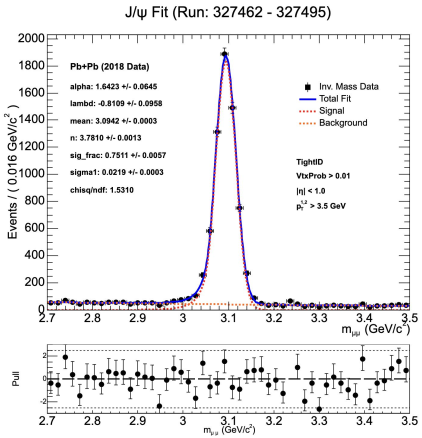


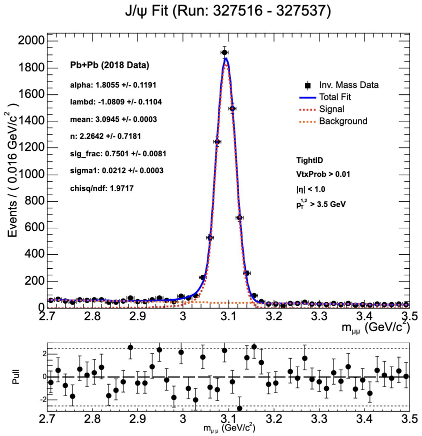


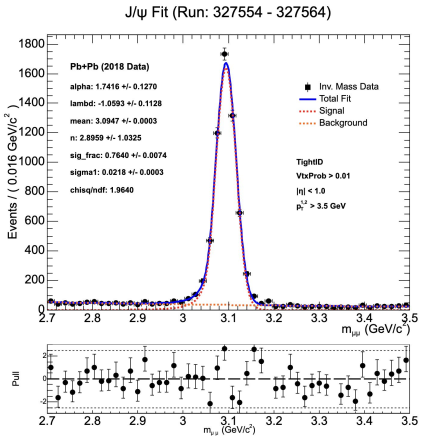




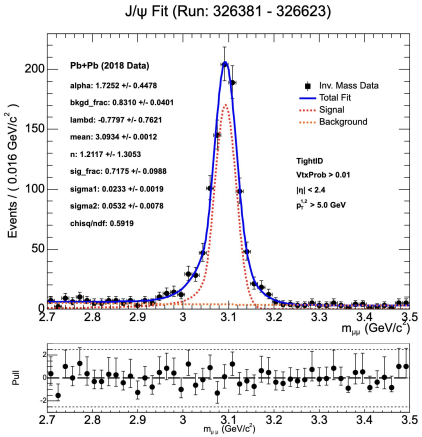
J/ψ Fits (p_T > 3.5 GeV) : Run Number ($|\eta|$ < 1.0)

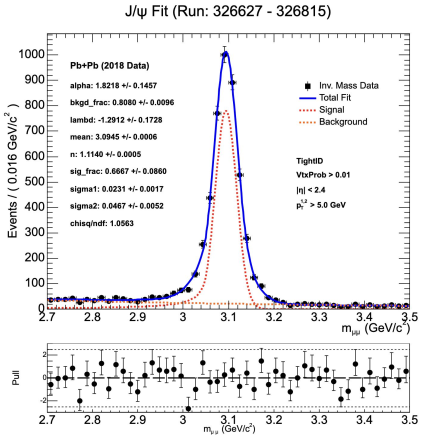


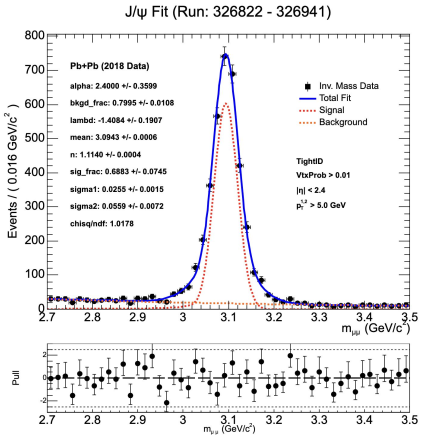


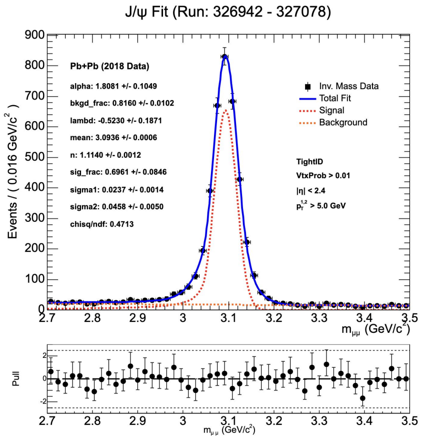


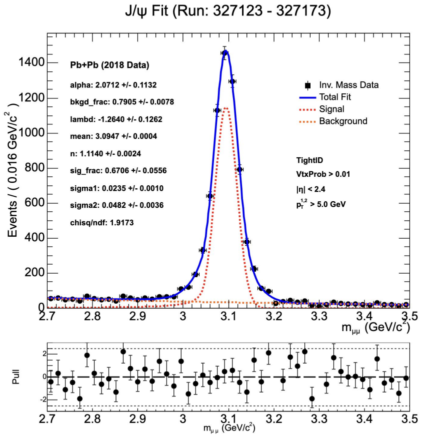
J/ψ Fits (p_T > 5 GeV) : Run Number ($|\eta|$ < 2.4)

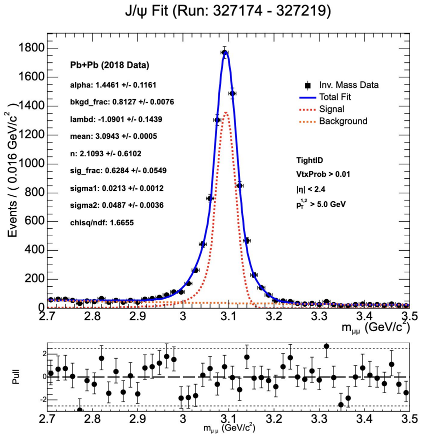


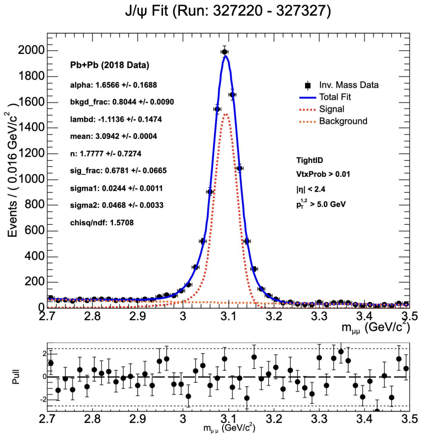


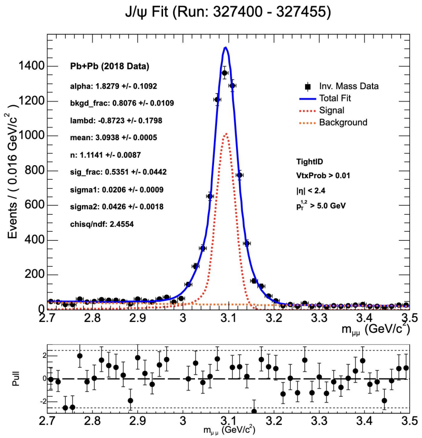




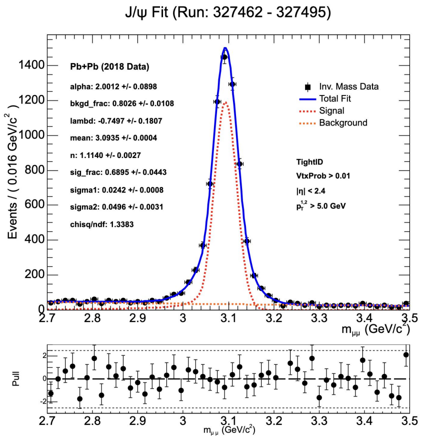


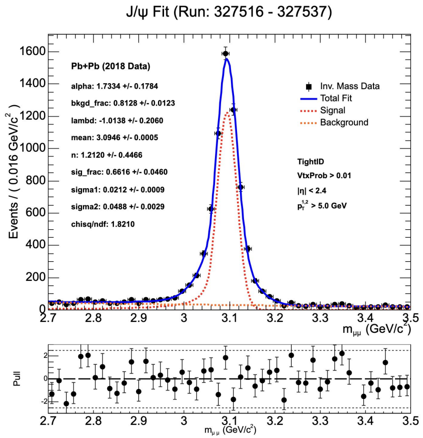


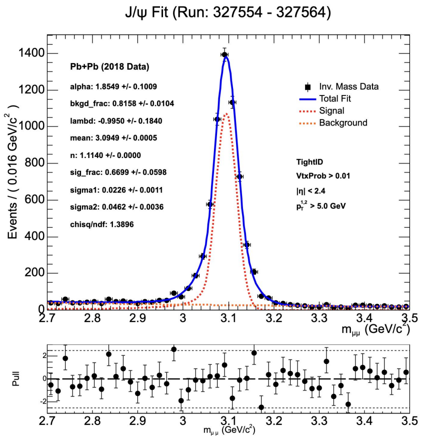




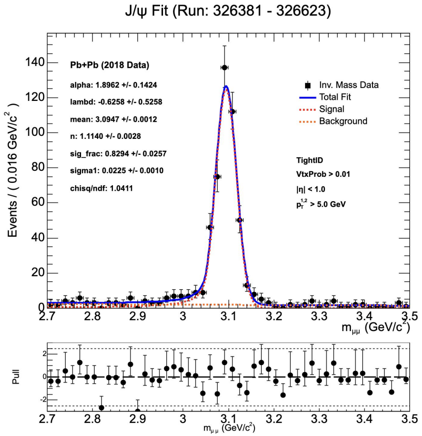
J/ψ Fits (p_T > 5 GeV) : Run Number (|η| < 2.4)

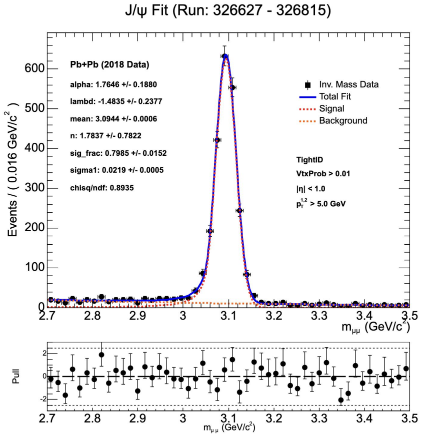


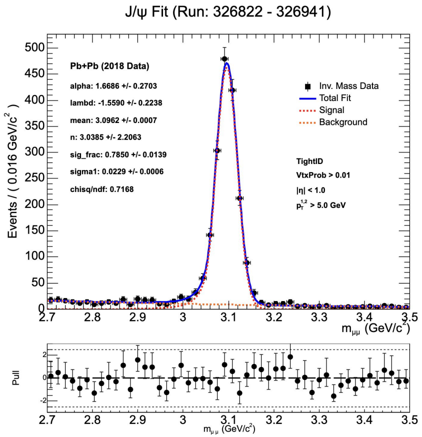


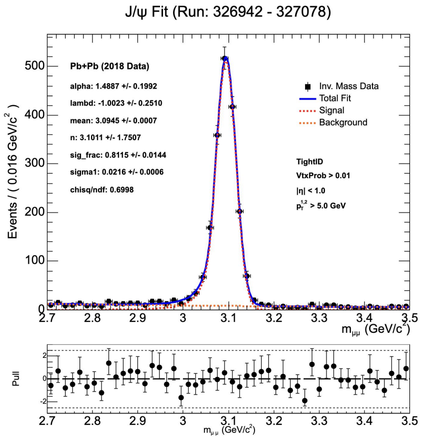


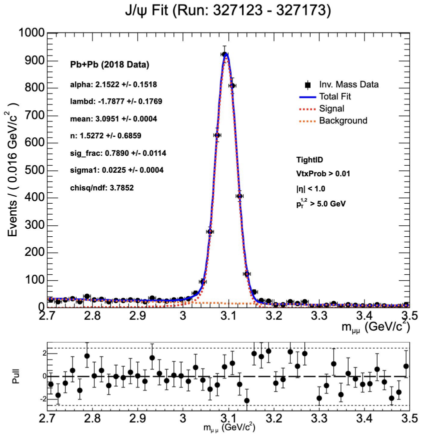
J/ψ Fits (p_T > 5 GeV) : Run Number ($|\eta|$ < 1.0)

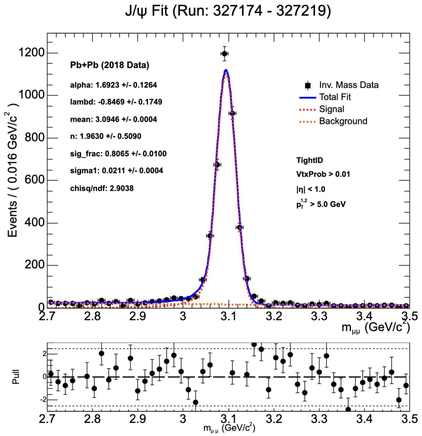


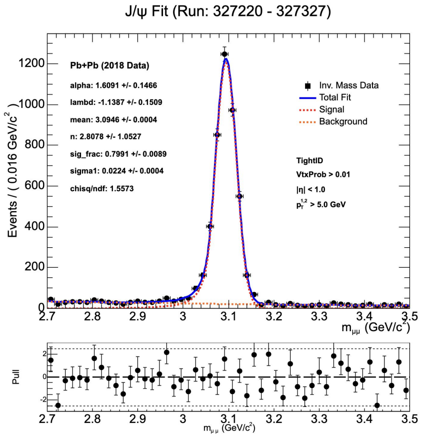


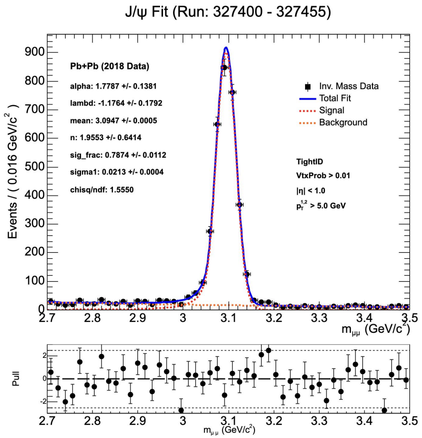




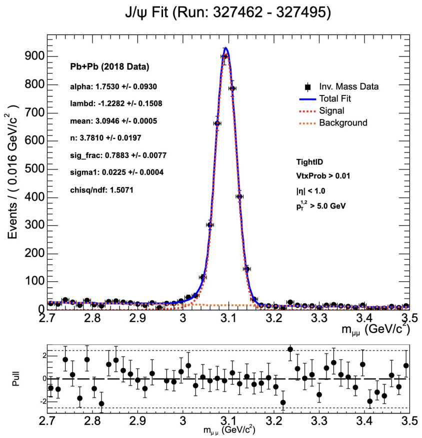


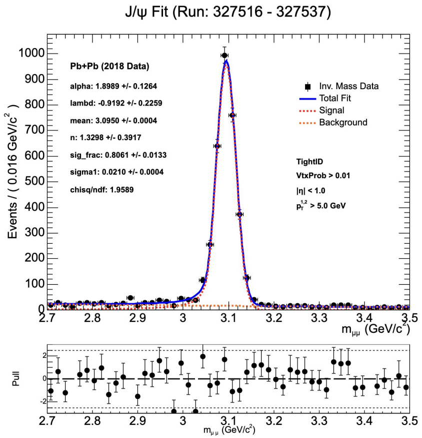


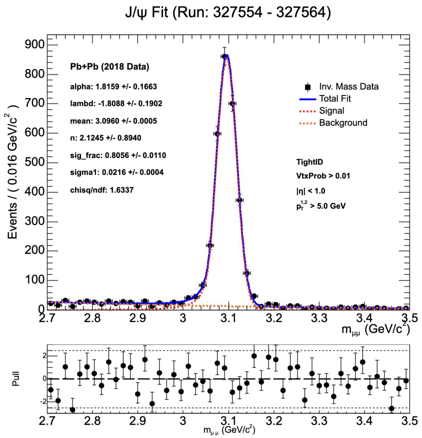




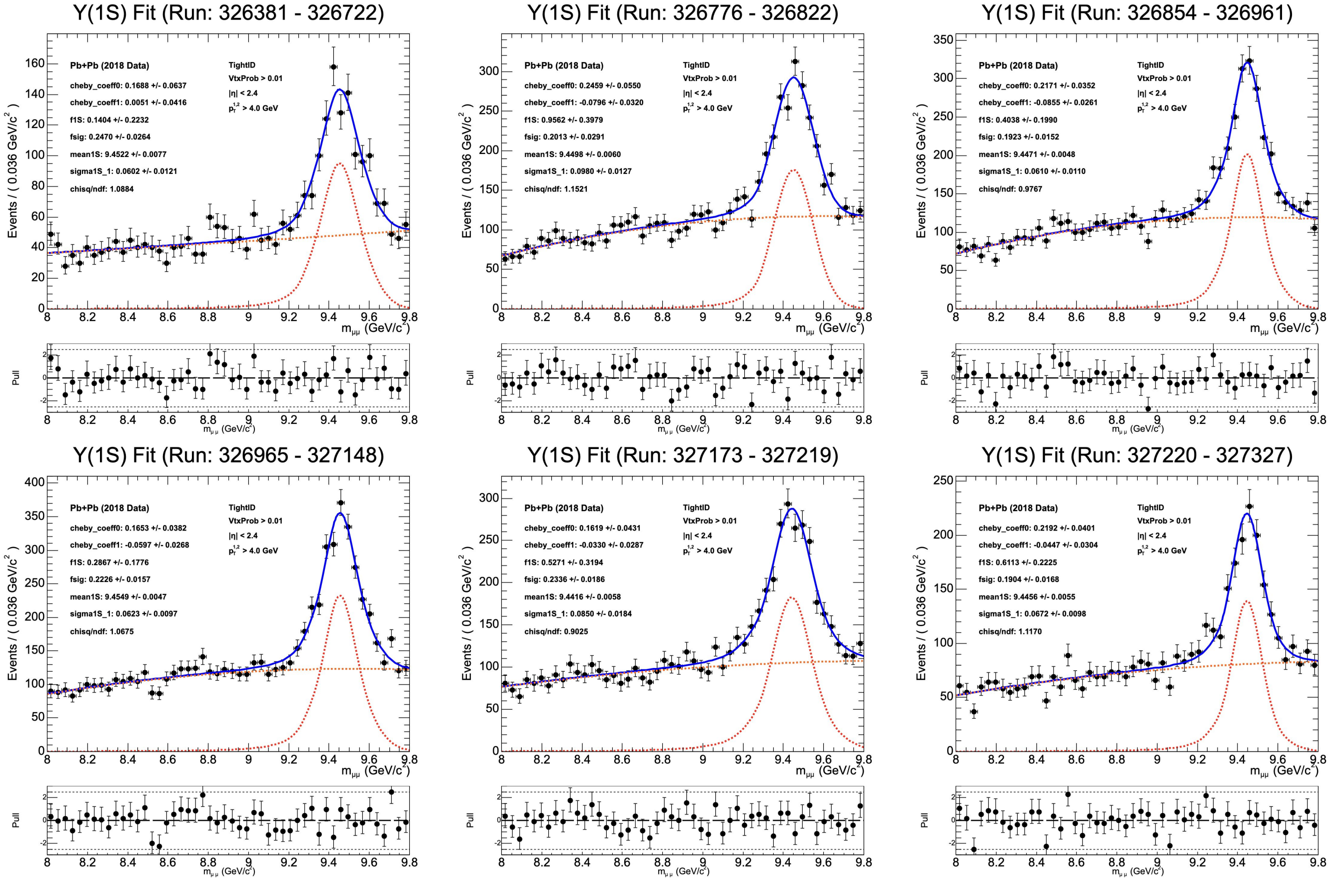
J/ψ Fits (p_T > 5 GeV) : Run Number (|η| < 1.0)





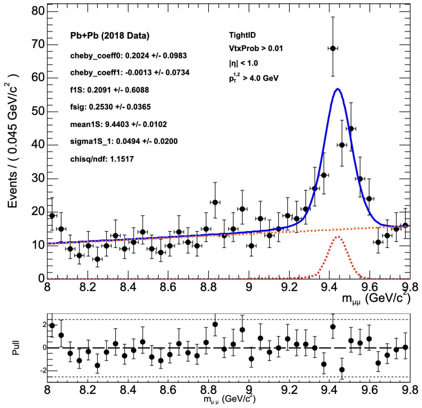


Υ(1S) Fits (p_T > 4 GeV) : Run Number ($|\eta|$ < 2.4)

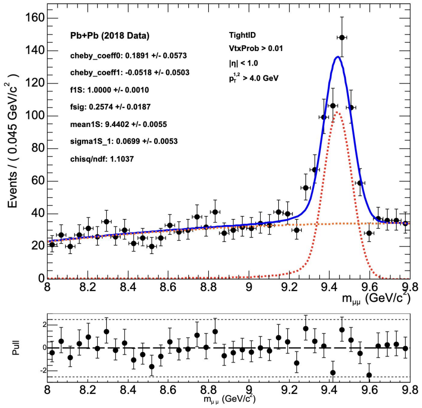


Υ(1S) Fits (p_T > 4 GeV) : Run Number (|η| < 1.0)

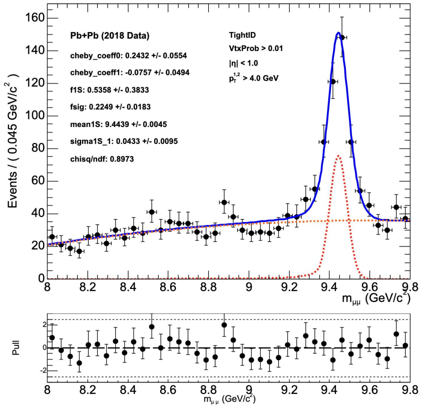
Y(1S) Fit (Run: 326381 - 326722)



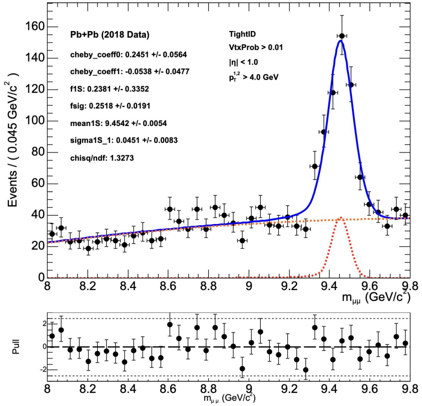
Y(1S) Fit (Run: 326776 - 326822)



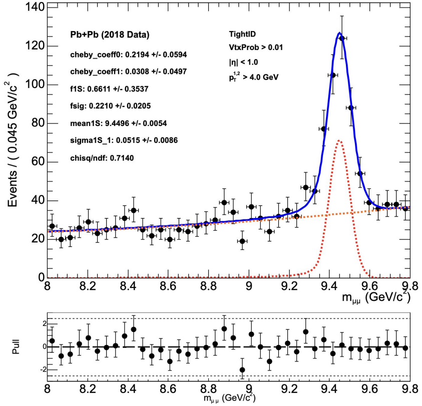
Y(1S) Fit (Run: 326854 - 326961)



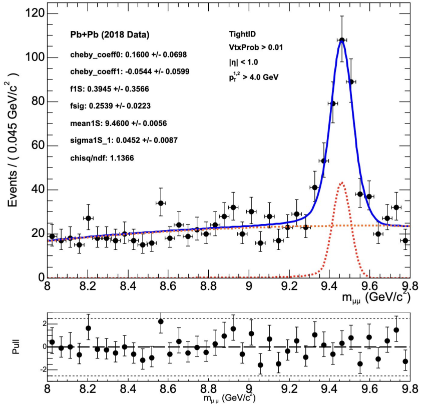
Y(1S) Fit (Run: 326965 - 327148)



Y(1S) Fit (Run: 327173 - 327219)

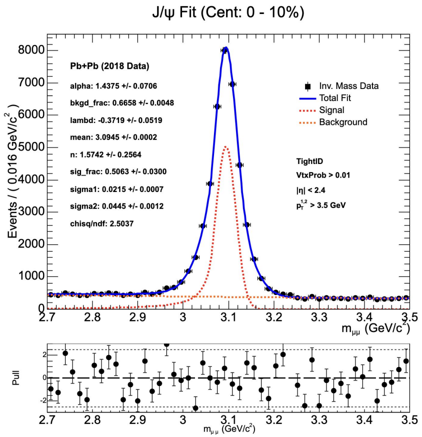


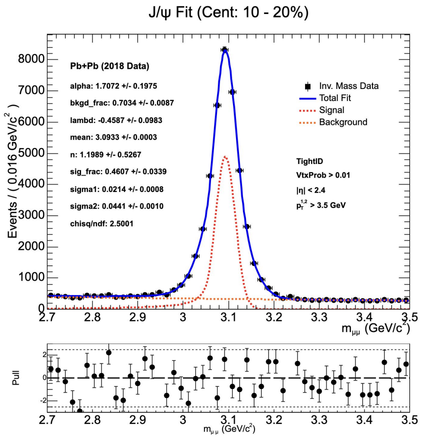
Y(1S) Fit (Run: 327220 - 327327)

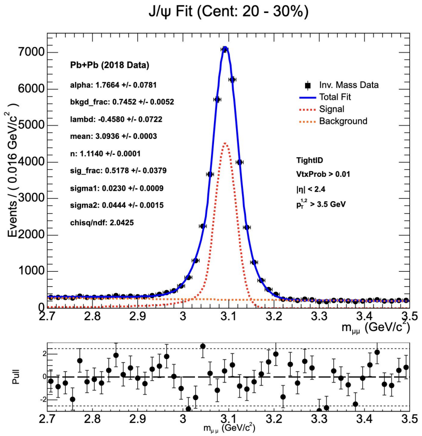


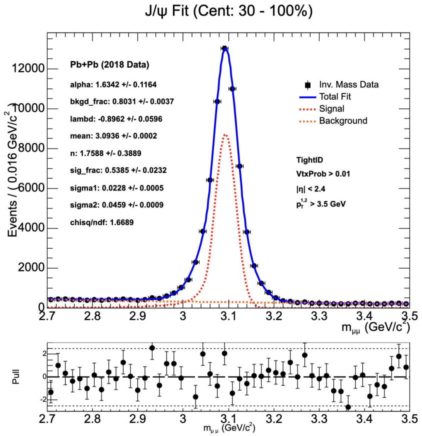
Quarkonia Fits (Centrality)

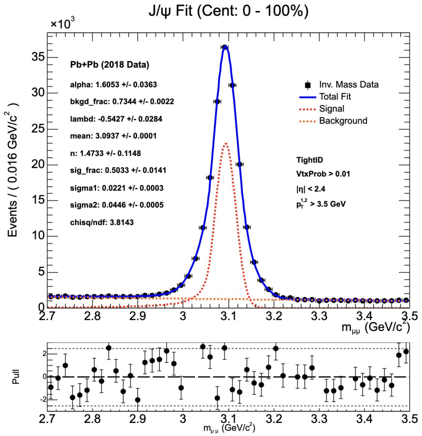
J/ψ Fits (p_T > 3.5 GeV) : Centrality ($|\eta|$ < 2.4)



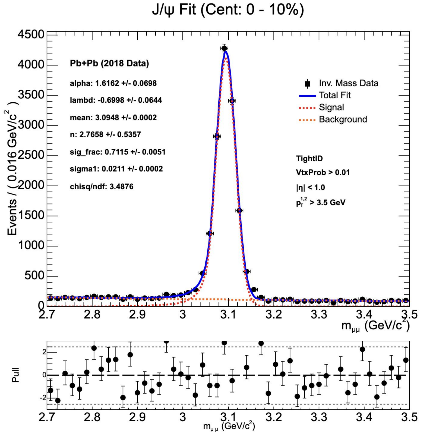


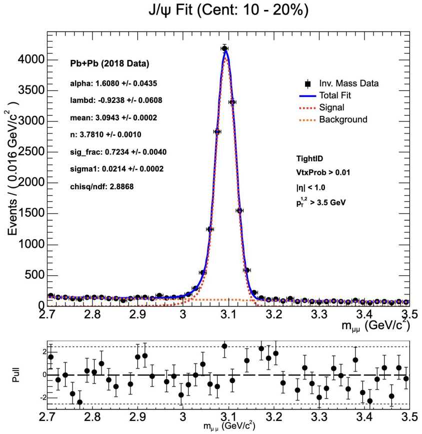


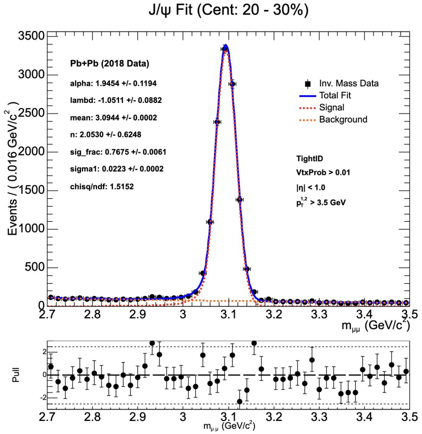


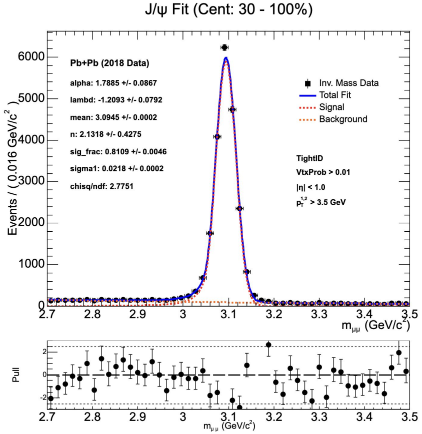


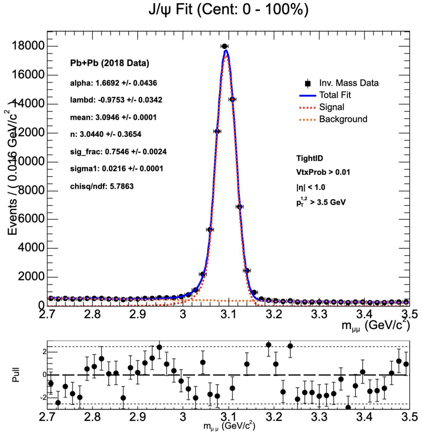
J/ψ Fits (p_T > 3.5 GeV) : Centrality (|η| < 1.0)





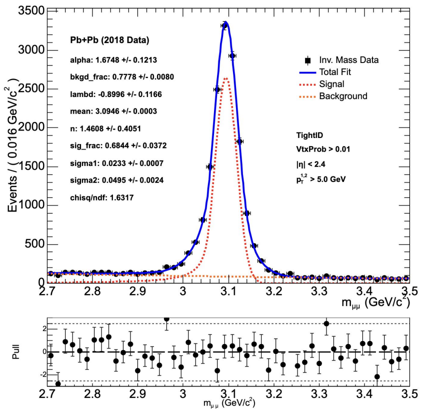




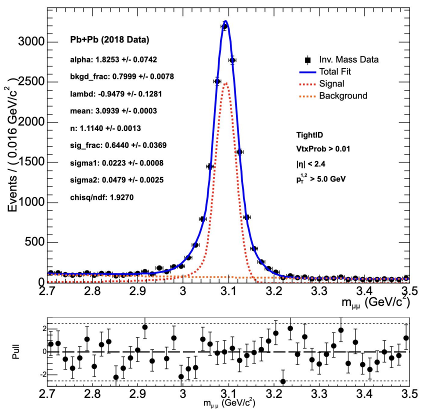


J/ψ Fits (p_T > 5 GeV) : Centrality (|η| < 2.4)

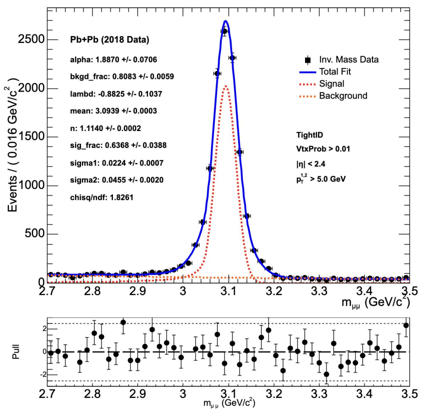
J/ψ Fit (Cent: 0 - 10%)



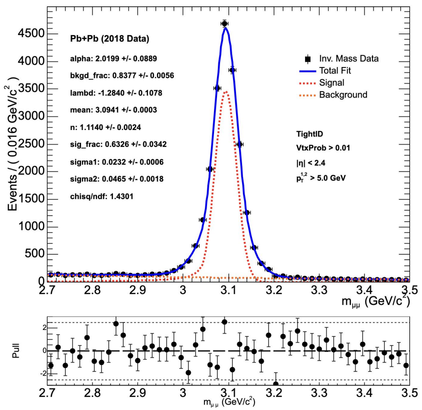
J/ψ Fit (Cent: 10 - 20%)



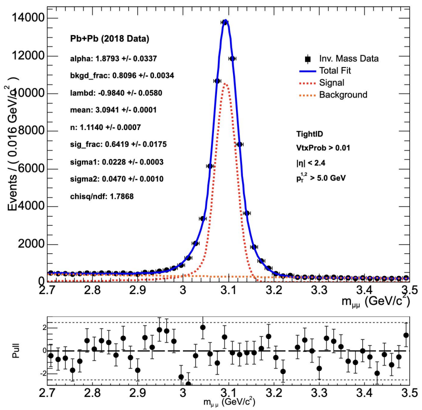
J/ψ Fit (Cent: 20 - 30%)



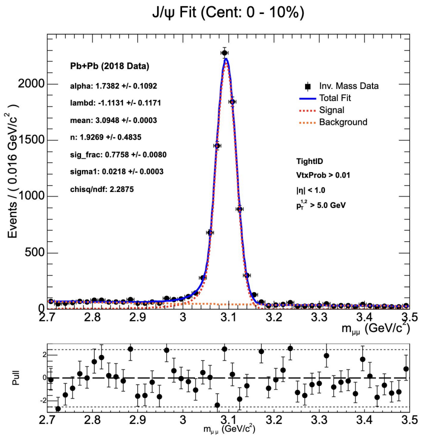
J/ψ Fit (Cent: 30 - 100%)

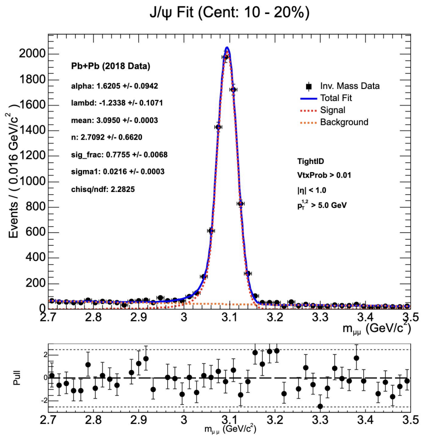


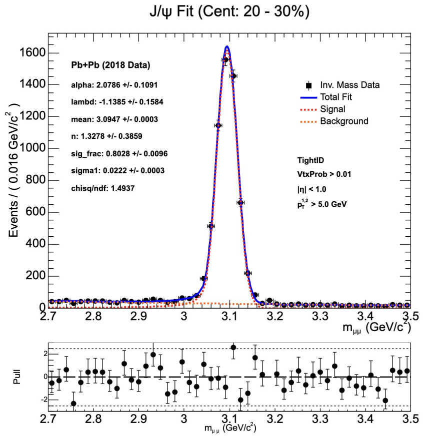
J/ψ Fit (Cent: 0 - 100%)

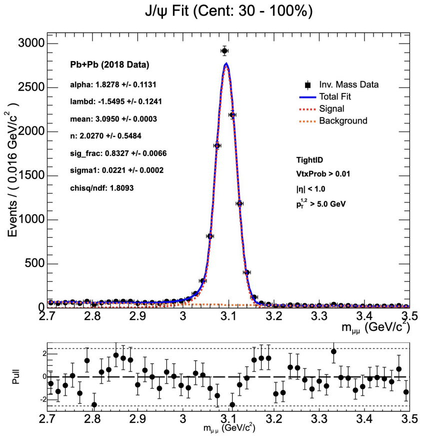


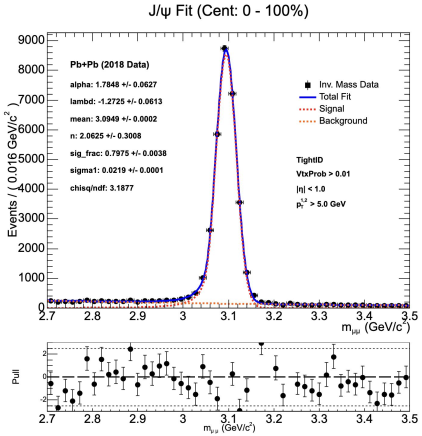
J/ψ Fits (p_T > 5 GeV) : Centrality ($|\eta|$ < 1.0)





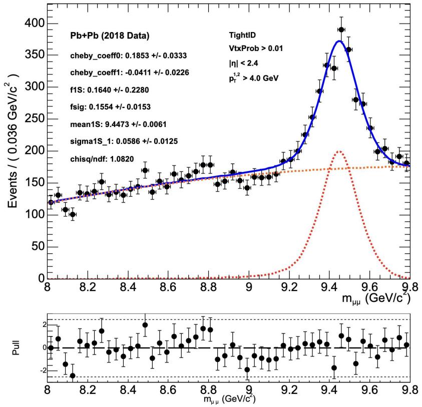




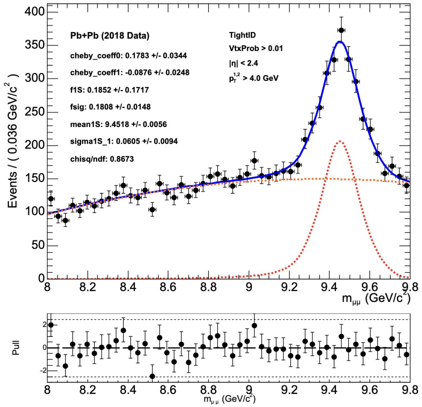


Υ(1S) Fits (p_T > 4 GeV) : Centrality ($|\eta|$ < 2.4)

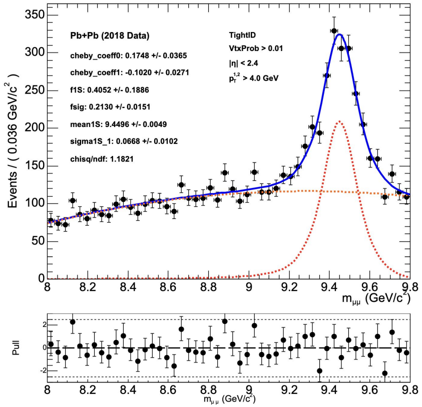
Y(1S) Fit (Cent: 0 - 10%)



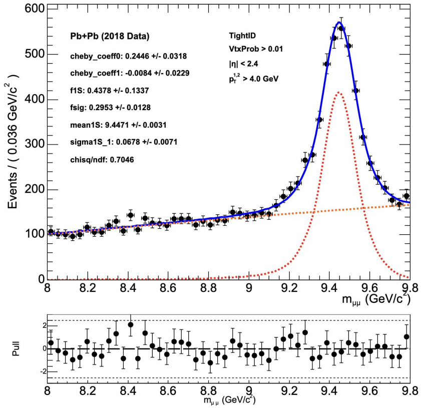
Y(1S) Fit (Cent: 10 - 20%)



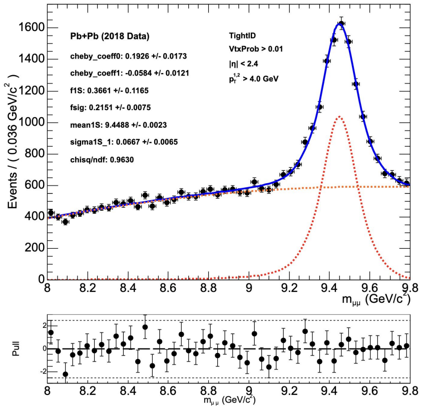
Y(1S) Fit (Cent: 20 - 30%)



Y(1S) Fit (Cent: 30 - 100%)

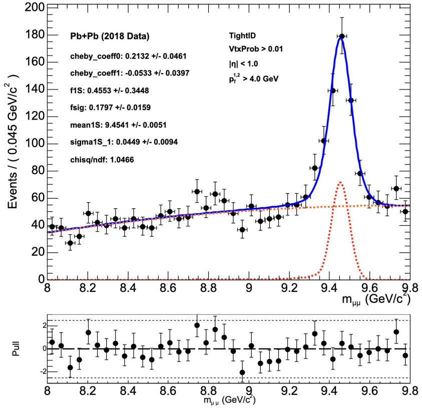


Y(1S) Fit (Cent: 0 - 100%)

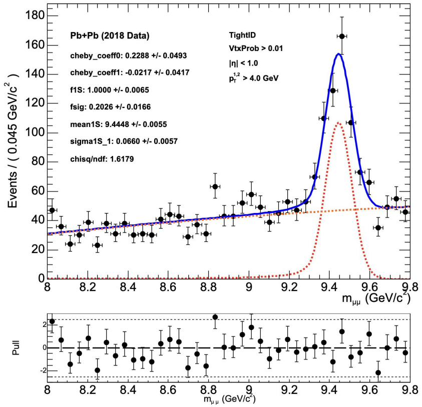


Υ(1S) Fits (p_T > 4 GeV) : Centrality ($|\eta|$ < 1.0)

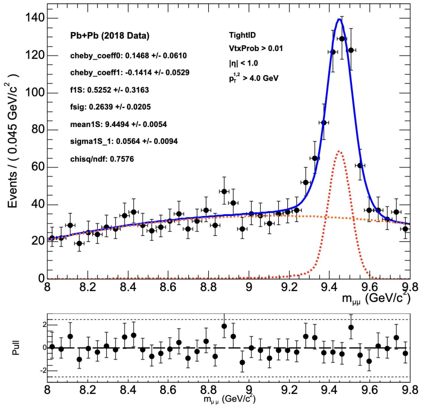
Y(1S) Fit (Cent: 0 - 10%)



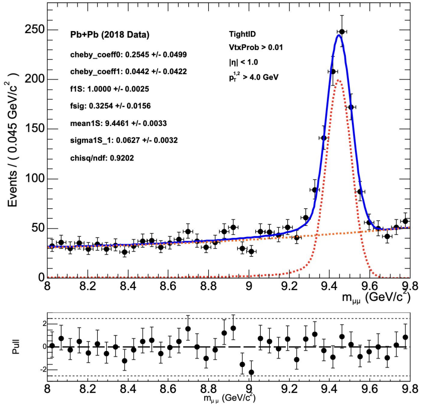
Y(1S) Fit (Cent: 10 - 20%)



Y(1S) Fit (Cent: 20 - 30%)



Y(1S) Fit (Cent: 30 - 100%)



Y(1S) Fit (Cent: 0 - 100%)