Hadrons as Probes of the Primordial Plasma

Measurement of Upsilon Suppression in PbPb Collisions

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Objectives

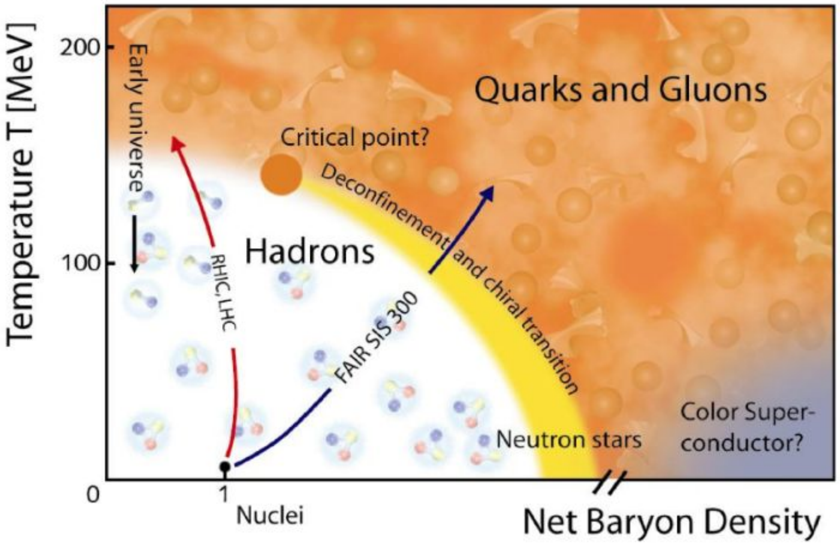
This summer internship had the following goals:

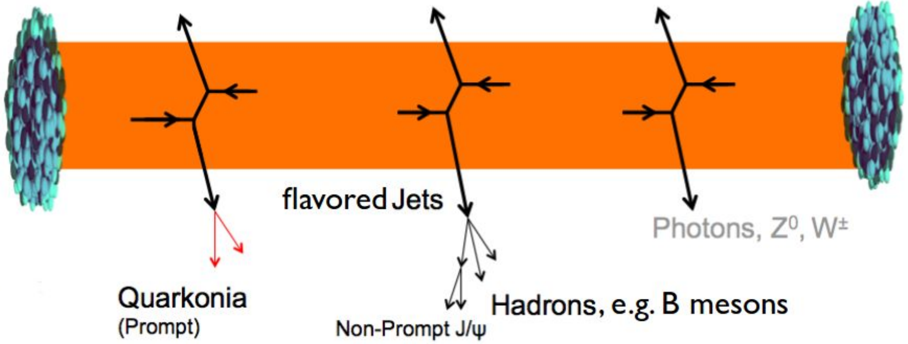
- Analyse heavy ion collisions with data collected by CMS using heavy flavor probes.
- Study the phenomenon of quarkonium suppression as a signature of the quark-gluon plasma (QGP).
- Measure Upsilon sequential suppression. Main reference for the study is the bottamonium review paper by N. Leonardo et al [1].

Introduction

Quark Gluon Plasma

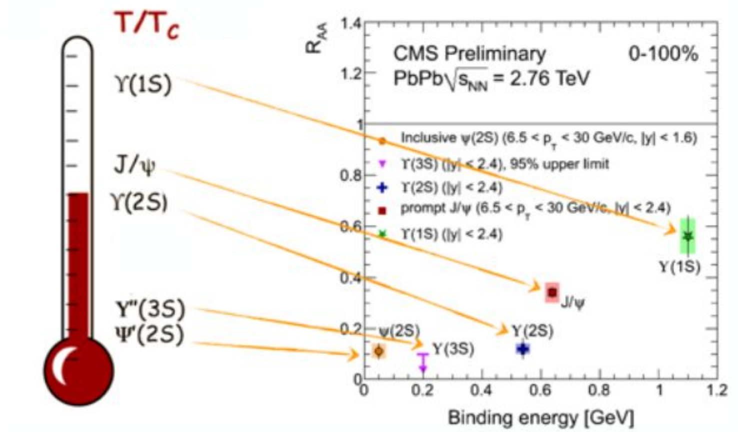
- State of matter formed by quarks and gluons deconfined, predicted by QCD, that occured in the early universe.
- Could be recreated in the lab through high energy heavy-ion collisions.



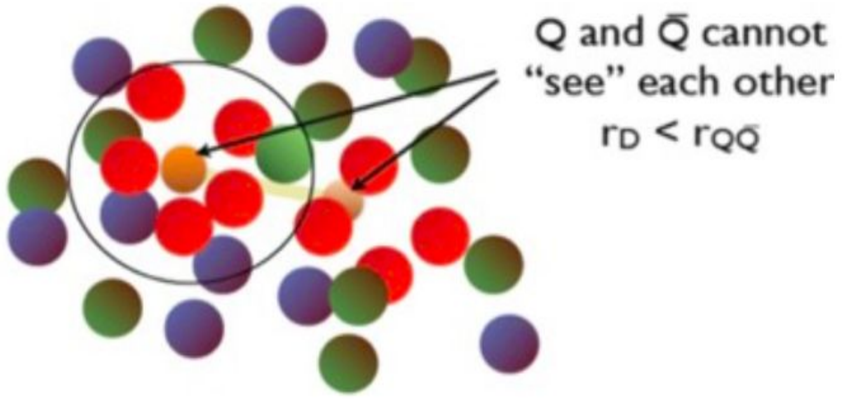


Quarkonium suppression

- Melting of quark-antiquark bound states (quarkonia) is a main signature of QGP.
- From the observed suppression pattern we can obtain the plasma temperature ([2]) because this is a sequential suppression, bigger for states with less binding energies.

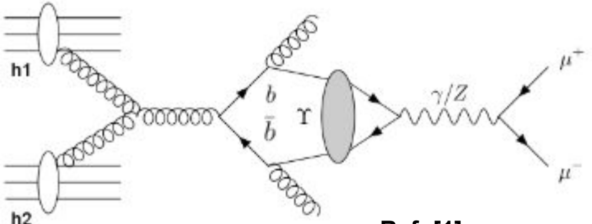


Ref: [3]



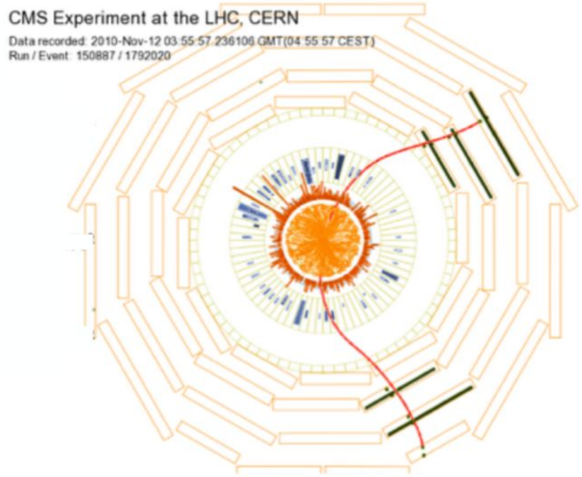
Ref: [4]

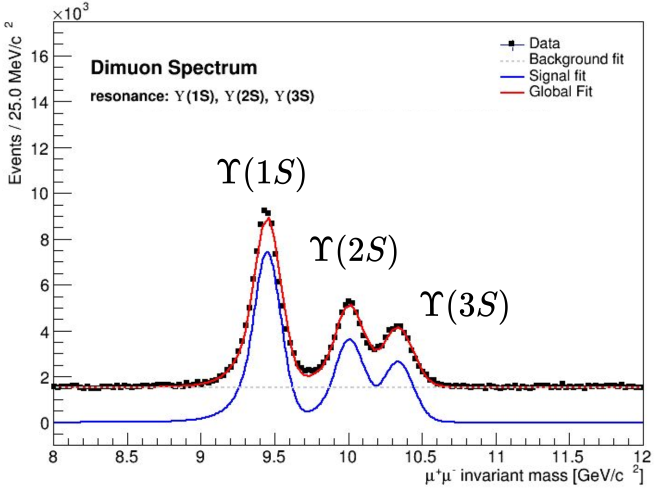
Upsilon



Ref: [1]

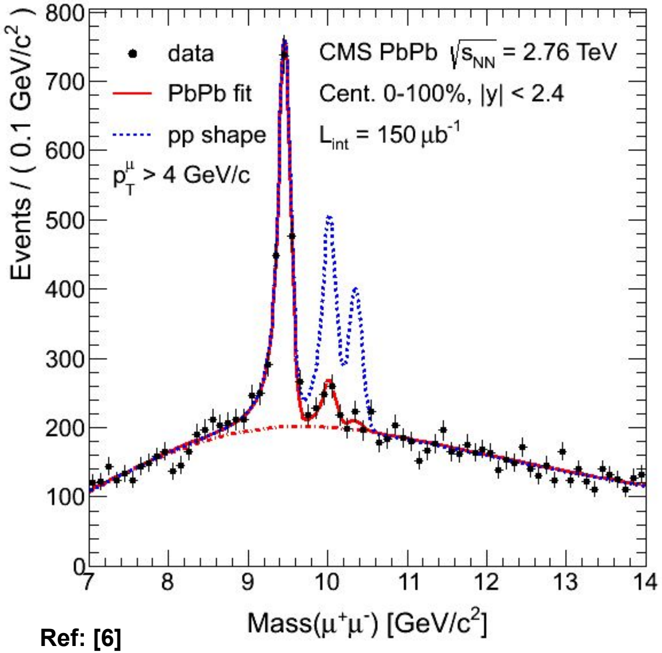
- Bound state of bottom-antibottom $b\bar{b}$.
- Decays to two muons, through a photon or Z.
- From the reconstructed muon momenta the dimuon invariant mass spectrum is obtained.





Upsilon excited states suppression

- The run I observation [5]:



Ref: [6]

$$n = 2, 3$$

Single ratios

$$\Upsilon(nS)/\Upsilon(1S)|_{pp} = \frac{N_{ns,\,pp}}{N_{1S,\,pp}}$$

$$\Upsilon(nS)/\Upsilon(1S)|_{PbPb} = \frac{N_{ns,\,PbPb}}{N_{1S,\,PbPb}}$$

Double ratio

$$DR(nS/1S) = \frac{\Upsilon(nS)/\Upsilon(1S)|_{PbPb}}{\Upsilon(nS)/\Upsilon(1S)|_{pp}} = \frac{N_{nS,\,PbPb}/N_{1S,\,PbPb}}{N_{nS,\,pp}/N_{1S,\,pp}}$$

$$= \frac{R_{AA}(\Upsilon(nS))}{R_{AA}(\Upsilon(1S))}$$

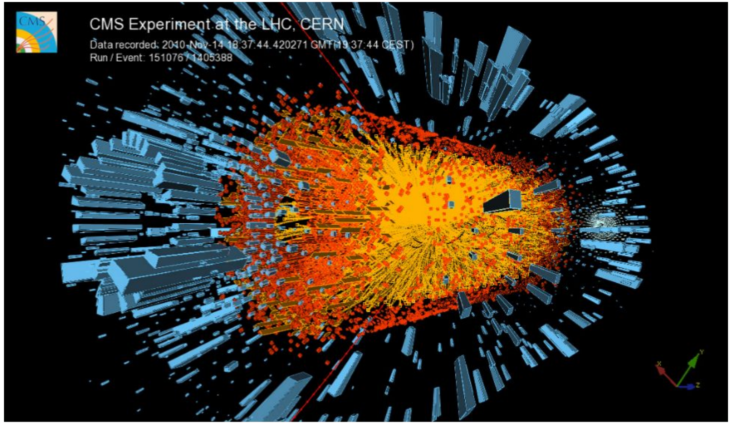
(Suppression when double ratio < 1)

$$DR(2S/1S) = 0.21 \pm 0.07(stat) \pm 0.02(syst)$$

$$DR(3S/1S) = 0.06 \pm 0.06(stat) \pm 0.06(syst)$$

Ref: [5]

Data



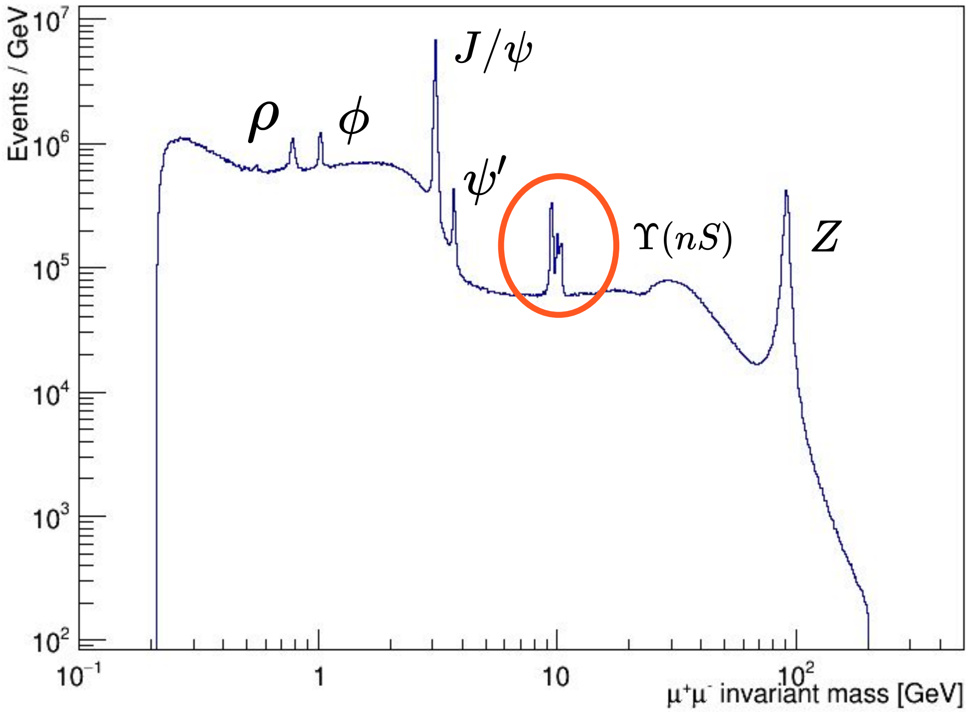
Collected by the CMS experiment

- **proton-proton (pp)**
  - 2015 - 13 Tev - for Resolution and Kinematic Studies.
  - 2015 - 5 TeV - as reference for the PbPb data.
- **heavy-ions (PbPb)**
  - 2015 - 5 TeV.

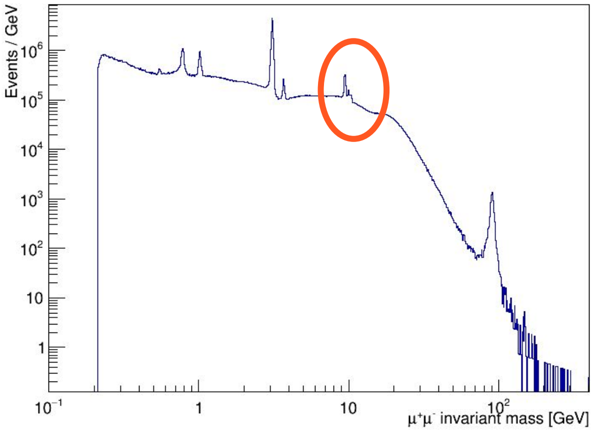
These data sets were obtained using a **dimuon trigger**

that selects in real time events with two muons.

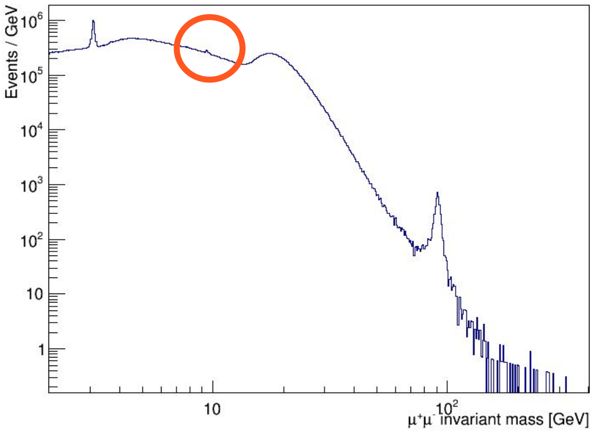
pp - 13 TeV



pp - 5 TeV

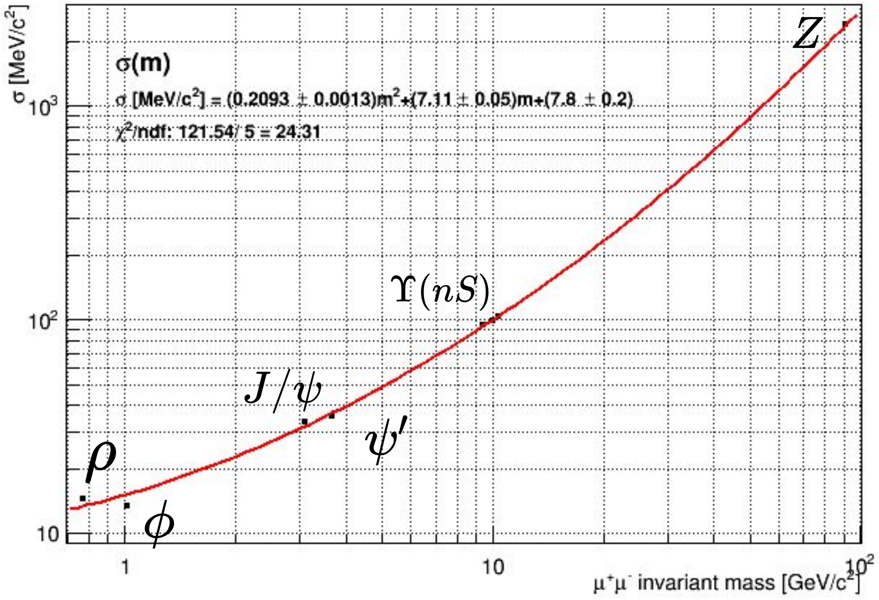


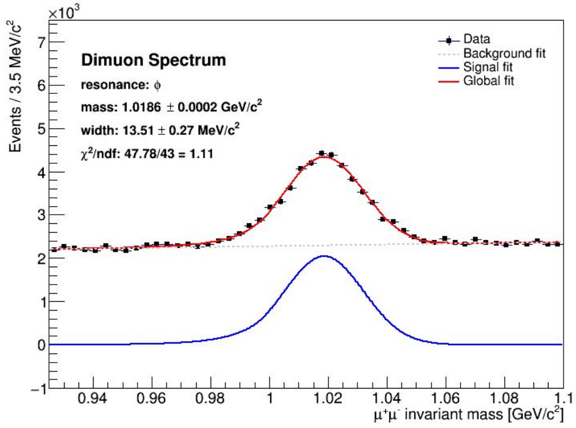
PbPb - 5 TeV



Detector Studies

Mass Resolution

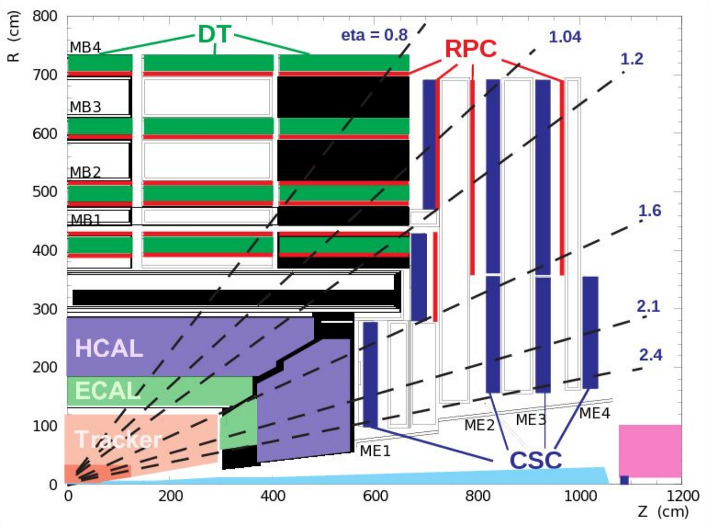


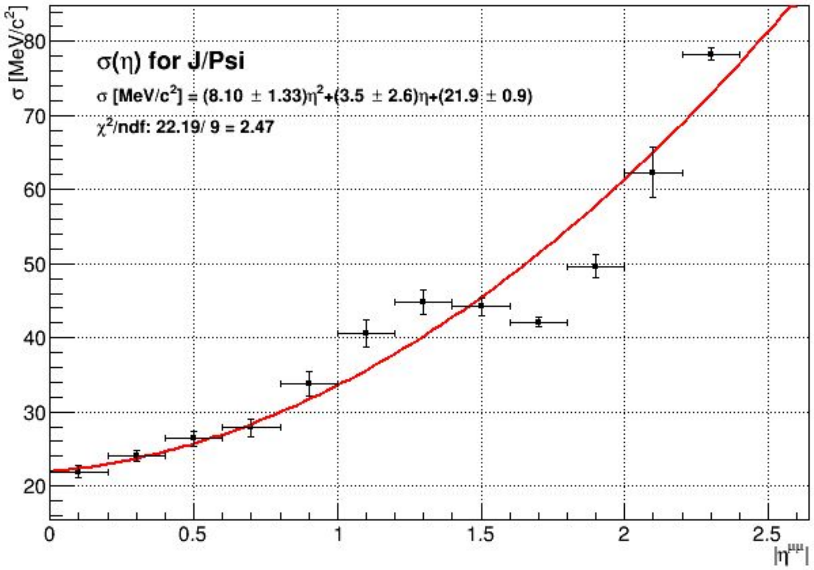


- Resolution worsens with mass.
- Z has a natural width not negligible, so the observed width isn't only due to detector resolution. Same for lower mass particles.

Mass Resolution and Pseudorapidity

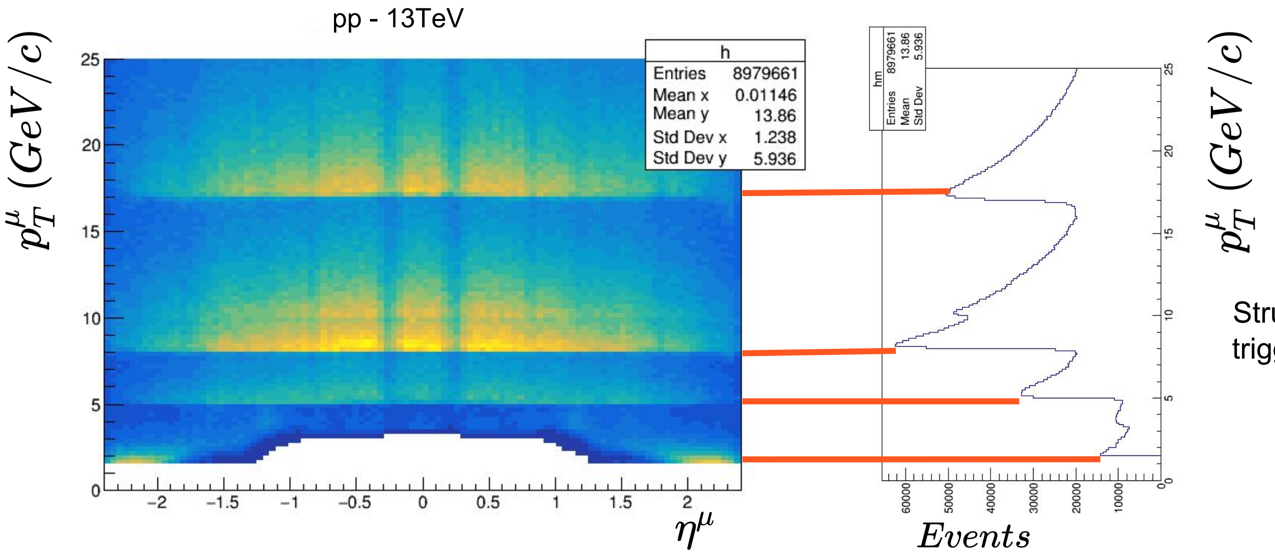
- The muon track is less precise for larger pseudorapidity.





Kinematic Studies

- CMS does not detect particles with p_T^μ < 3.5GeV/c at small pseudorapidity: particles with lower momentum and pseudorapidity will curl and not arrive at the muon chambers.

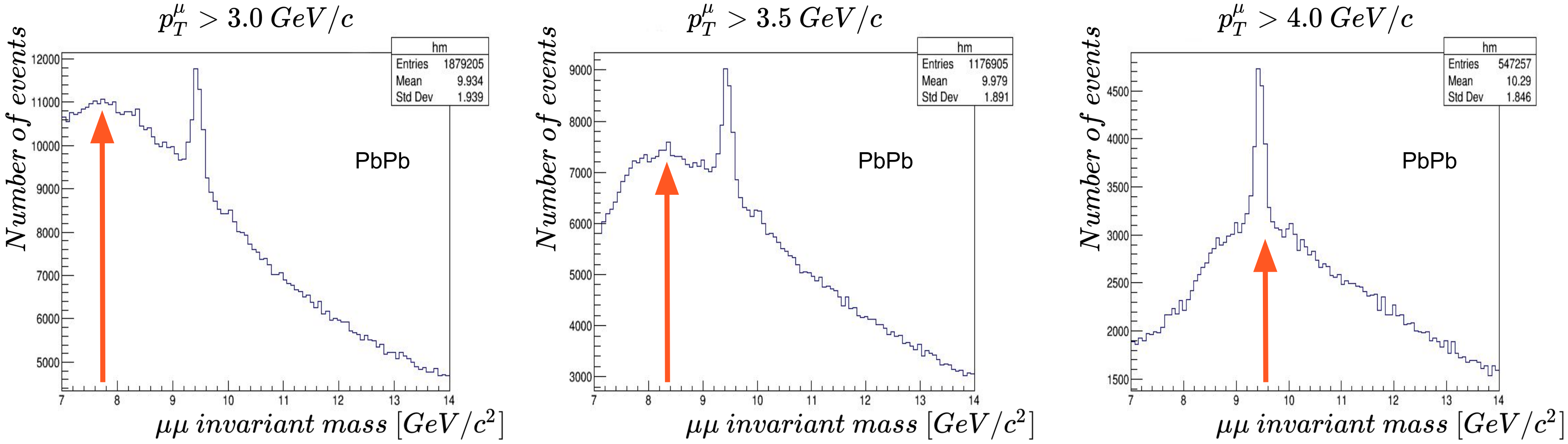


Structure due to different triggers used during data taking

Upsilon Analysis

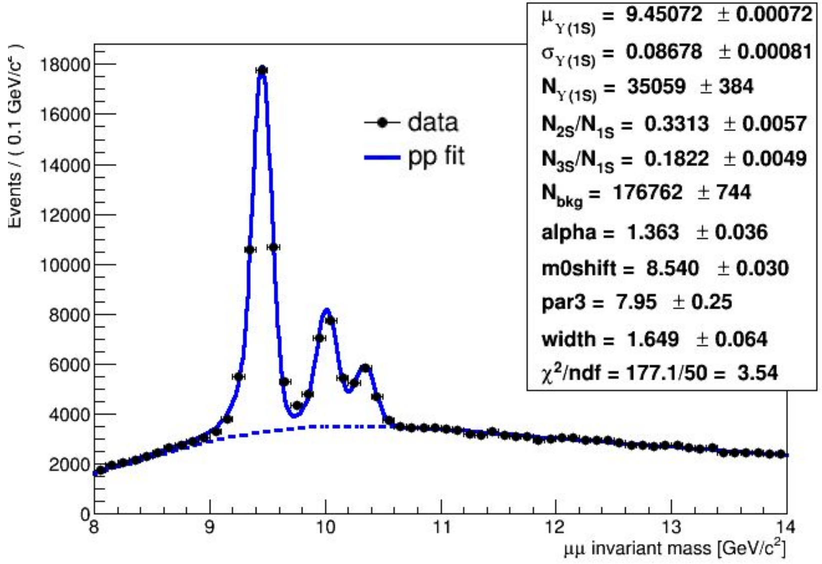
Selection

- Studied effect on background and signal yield, from applying different p_T^μ thresholds. These cuts induce a turn-on.



- There is no other optimization done: analysis is fully based on data, no Monte Carlo simulation used.

Fit to the data - pp

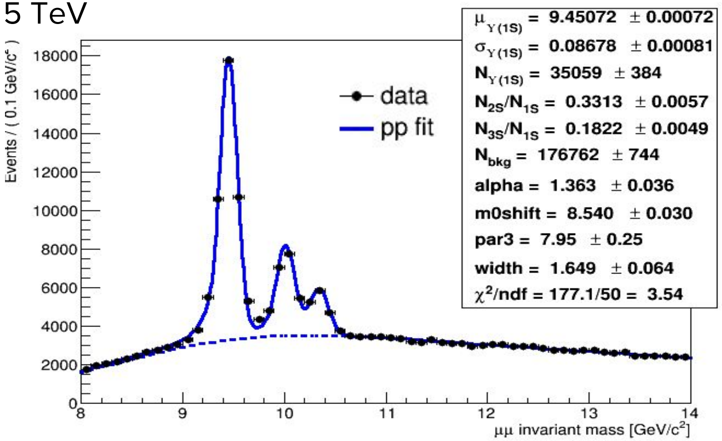


$$\Upsilon(2S)/\Upsilon(1S)|_{pp} = 0.3314 \pm 0.0057(stat)$$
$$\Upsilon(3S)/\Upsilon(1S)|_{pp} = 0.1822 \pm 0.0049(stat)$$

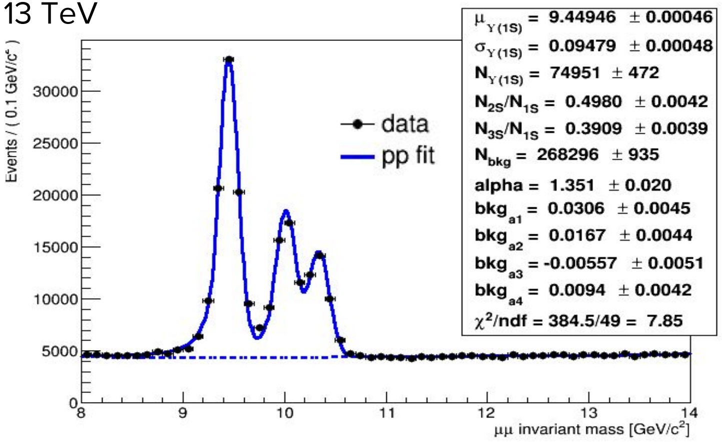
- Data fitted with unbinned maximum likelihood method (RooFit).
- Signal model:
  - 1 CrystalBall per peak
- Background (bckg) model:
  - Exponential (background distribution without cuts) x Error function (to describe cut and turn-on)

Suppression in pp?

pp - 5 TeV



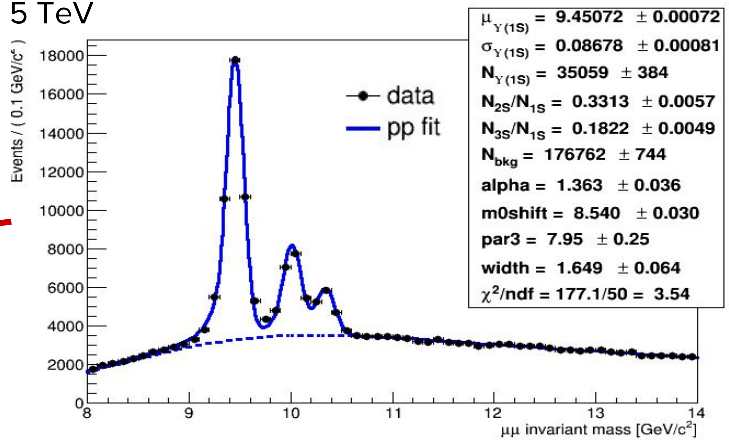
pp - 13 TeV



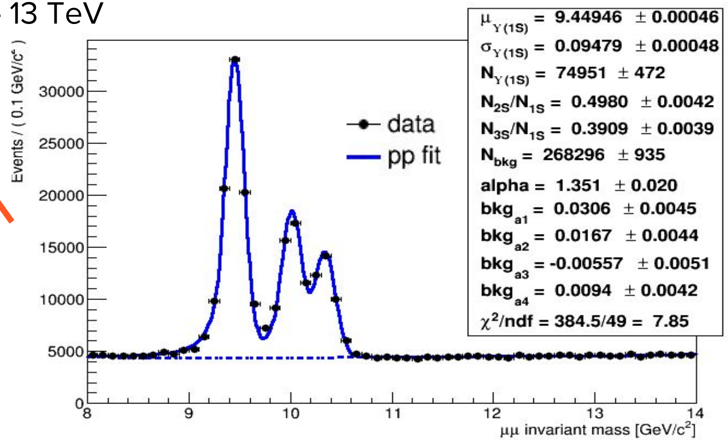
Suppression in pp?

$$DR(2S/1S) = 0.665 \pm 0.013(stat)$$
$$DR(3S/1S) = 0.466 \pm 0.013(stat)$$

pp - 5 TeV



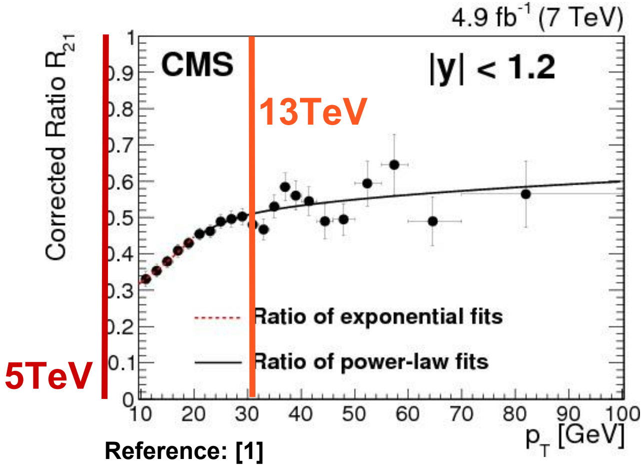
pp - 13 TeV



Suppression in pp?

$$DR(2S/1S) = 0.665 \pm 0.013(stat)$$
$$DR(3S/1S) = 0.466 \pm 0.013(stat)$$

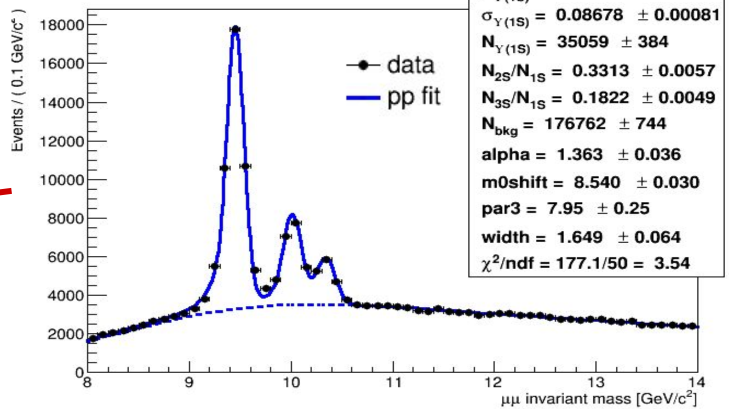
This fake suppression is a kinematic effect.



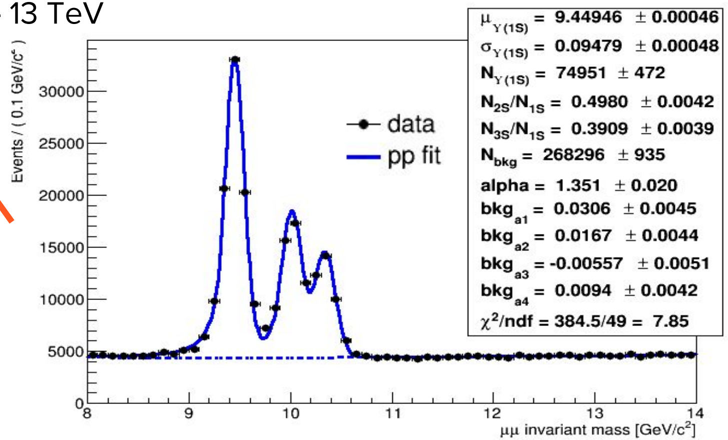
Reference: [1]

Relative 2S/1S yields

pp - 5 TeV

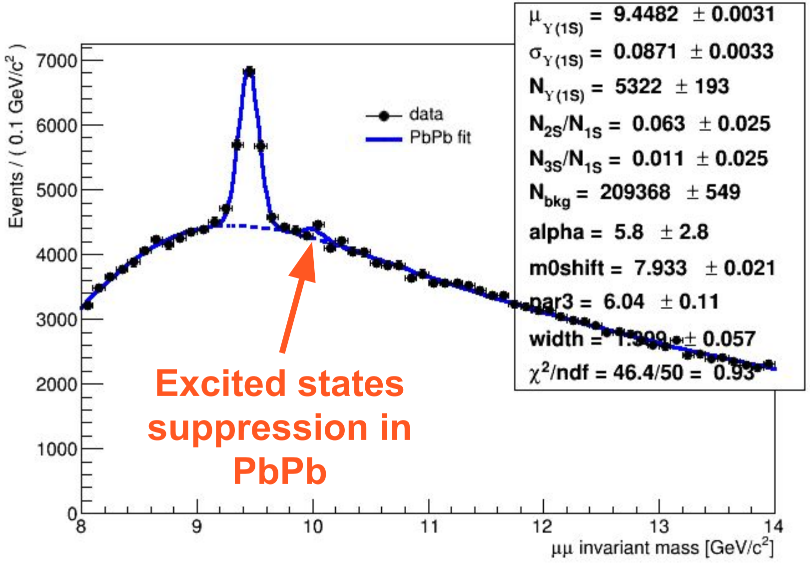


pp - 13 TeV



Yield varies with Upsilon p. Mean Upsilon p is different in pp collisions at 13TeV and 5TeV. We use pp and PbPb taken at same energy (5TeV) and with identical online and offline selections.

Fit to the data - PbPb



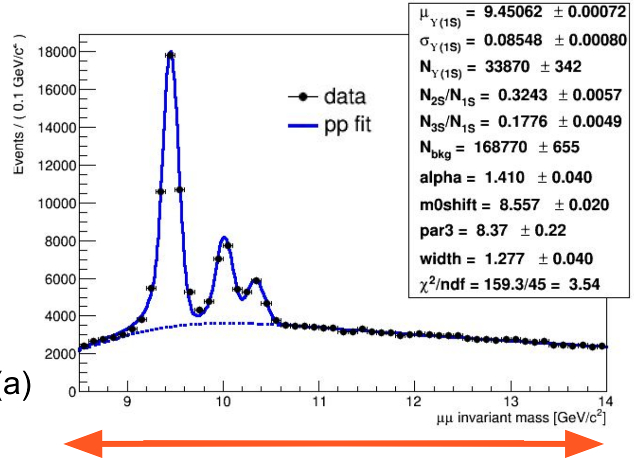
$$\Upsilon(2S)/\Upsilon(1S)|_{PbPb} = 0.063 \pm 0.025(stat)$$
$$\Upsilon(3S)/\Upsilon(1S)|_{PbPb} = 0.011 \pm 0.025(stat)$$

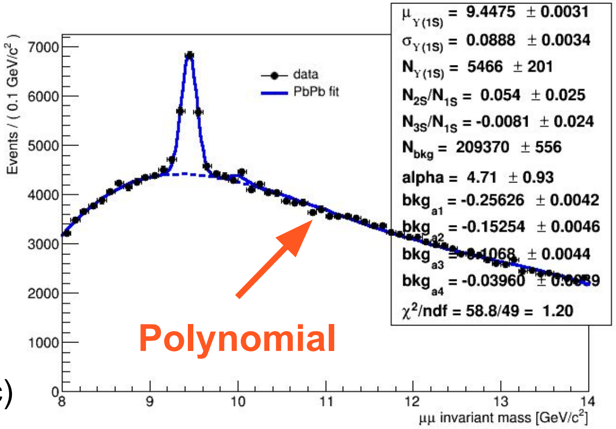
- Same fit model used.
- In PbPb collisions there are more particles produced so the background is higher.
- Clearly visible excited states suppression.

Systematic uncertainties

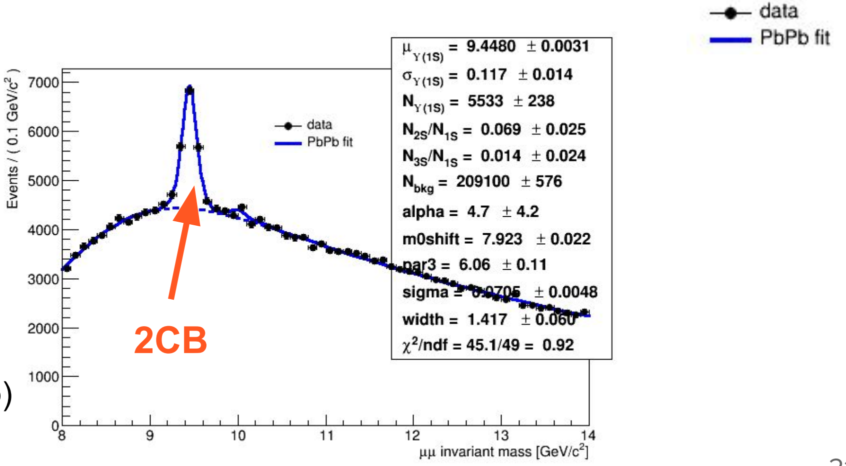
- Systematic uncertainties estimated varying (pp PbPb):
    - fit range (a) - 2-4 70-100 %
    - signal model: 1CB vs 2CB (b) - 1-5 9-27 %
    - bckg model: erf x exp vs polynomial (c) - 3-4 14-173 %

(a)



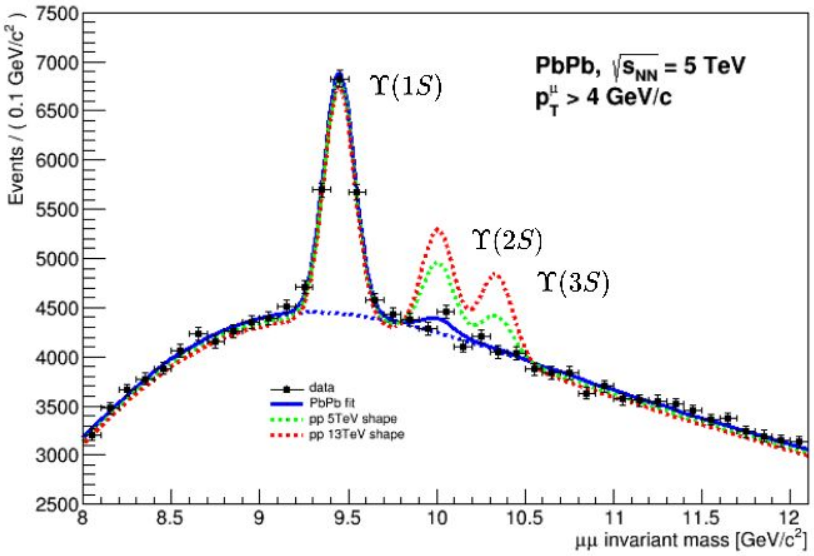


(c)



(b)

Final result



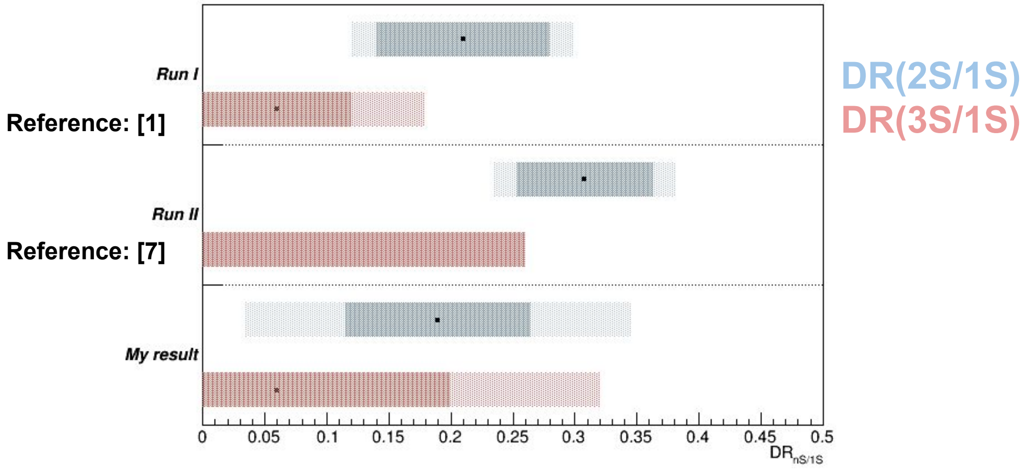
$$\Upsilon(2S)/\Upsilon(1S)|_{pp} = 0.331 \pm 0.006(stat) \pm 0.013(syst)$$
$$\Upsilon(3S)/\Upsilon(1S)|_{pp} = 0.182 \pm 0.005(stat) \pm 0.014(syst)$$
$$\Upsilon(2S)/\Upsilon(1S)|_{PbPb} = 0.068 \pm 0.025(stat) \pm 0.026(syst)$$
$$\Upsilon(3S)/\Upsilon(1S)|_{PbPb} = 0.011 \pm 0.025(stat) \pm 0.022(syst)$$

Observed suppression in PbPb data

$$DR(2S/1S) = 0.190 \pm 0.075(stat) \pm 0.080(syst)$$
$$DR(3S/1S) = 0.06 \pm 0.14(stat) \pm 0.12(syst)$$

Comparison with previous results

- Values compatible with published results.
- In comparison, uncertainties are larger.
- Selection optimization would be a natural next step.



Conclusions

- Analysed pp and PbPb data collected by CMS at the LHC.
- Observed Upsilon suppression in PbPb in Run II data:
  - 2S is suppressed with relation to 1S;
  - 3S is absent in the data (highest suppression).
- Results obtained are compatible with the original CMS observation.
- Precision may be improved using more data or optimizing selection (such study needs Monte Carlo simulation).
- More statistics of PbPb collisions would also be desirable to study centrality dependence.

Bibliography

[1] - Z. Hu, Nuno T. Leonardo, T. Liu, M. Haytmyradov, *Int. J. Mod. Phys. A* **32**, 1730015 (2017).

[2] - R.Vogt, *Physics* **5**, 123 (2012).

[3] - CMS Collab., https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/PhysicsResultsHIN12007.

[4] - T. Matsui, H. Satz, *Phys. Lett. B* **178**, 416-422 (1986).

[5] - CMS Collab., *Phys. Rev. Lett.* **109**, 222301 (2012)

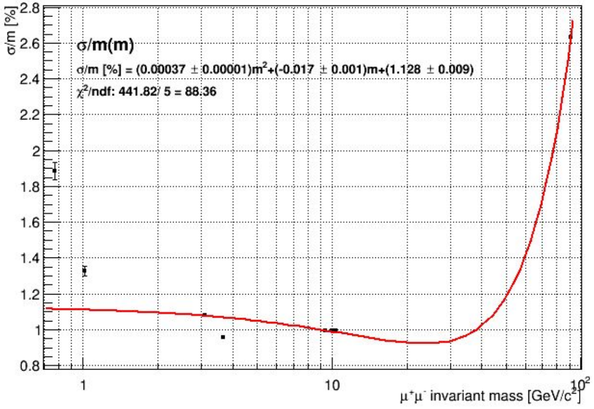
[6] - CMS Collab., https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011.

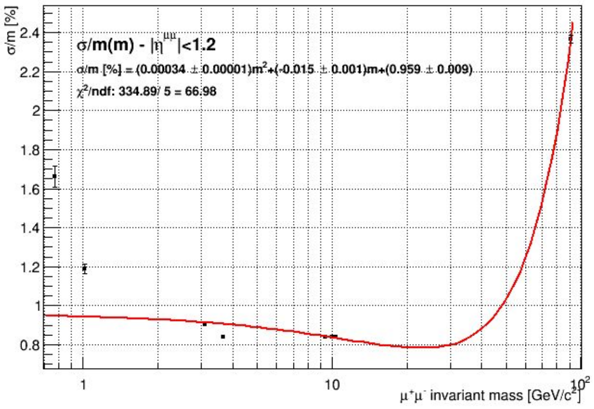
[7] - CMS Collab., *Phys. Rev. Lett.* **120**, 142301 (2018).

Backup

Resolution and Pseudorapidity II

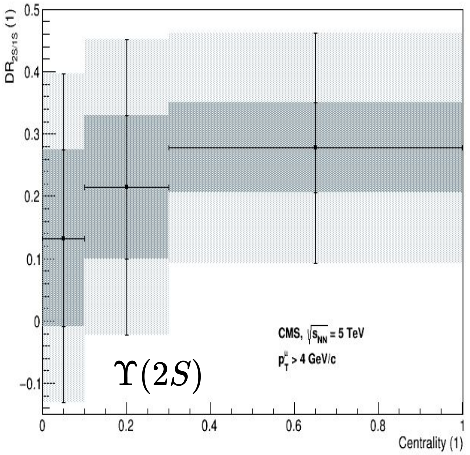
It was expected that the relative resolution would be constant; however, there are some deviations: for smaller masses these could be explained as being a pseudo rapidity related phenomenon, but these do not seem related to it but to the decay width of the resonance. To do a more complete study, the fits should be done with the convolution of a Breit-Wigner, with the width constrained (or fixed) to the PDG value, and a CB of free parameters, to try to separate the component only due to the detector resolution.

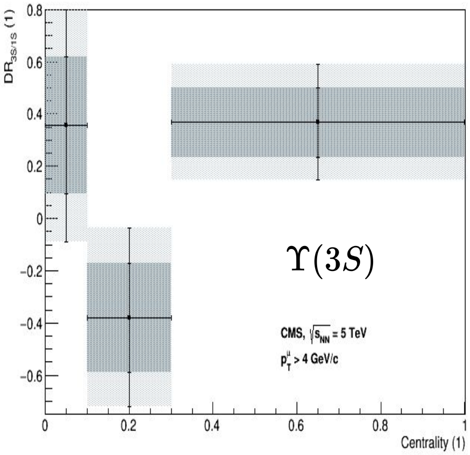


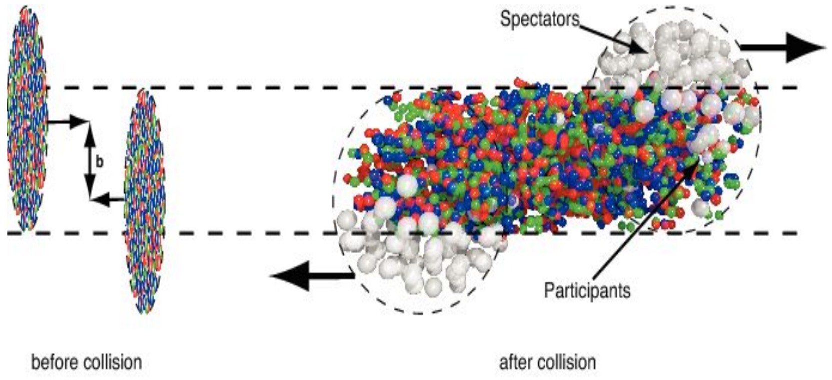


Centrality and Suppression

Centrality relates to the impact parameter of the collision. 0 means a central collision and 1 a peripheral one, which has less participants, (more like a pp collision) so it's expected a suppression decrease (DR increase) with centrality.





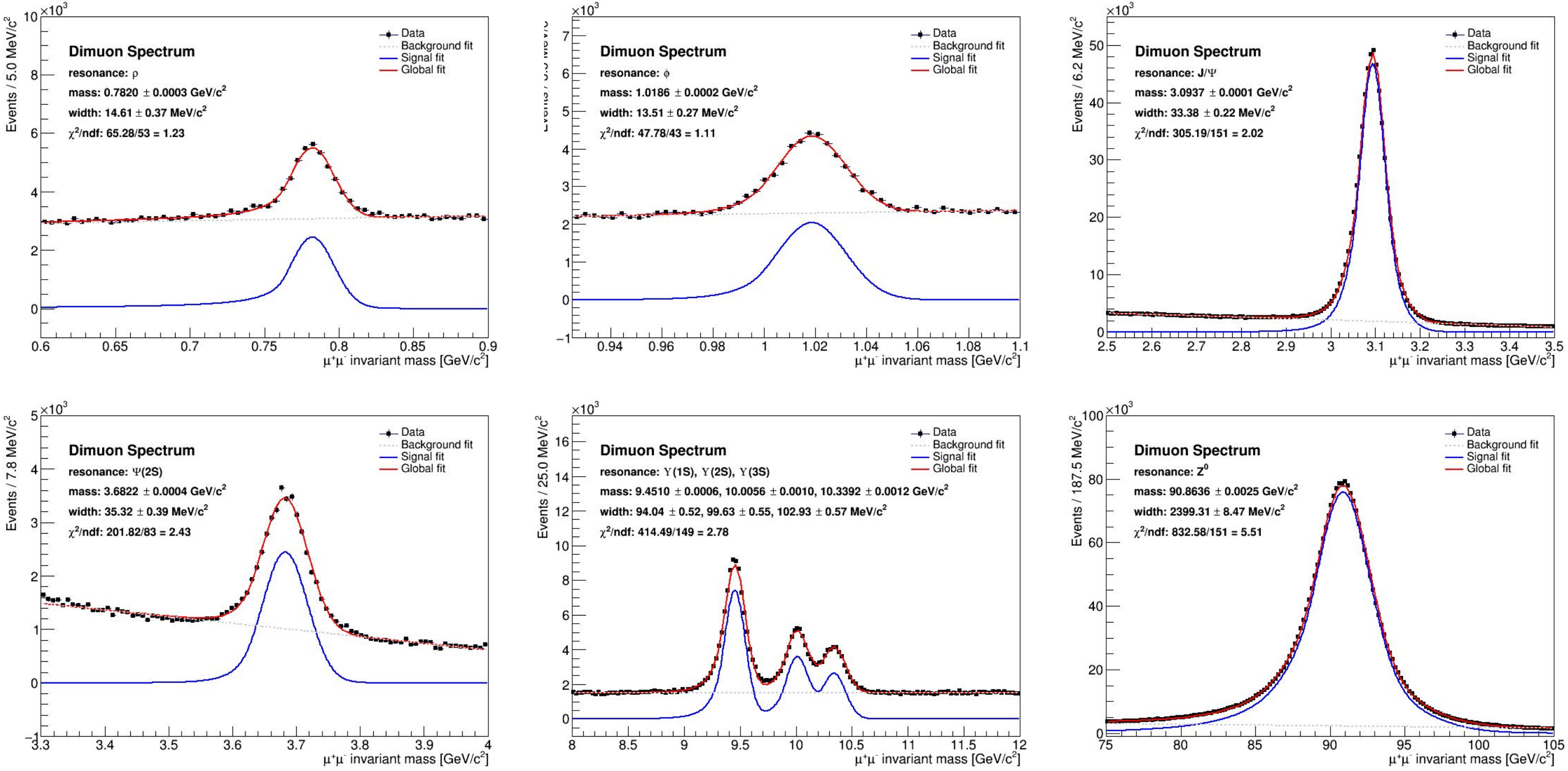


Statistics collected are not sufficient to make a more complete study, but general 2S behavior is as expected and 3S is almost compatible with zero.

Fits

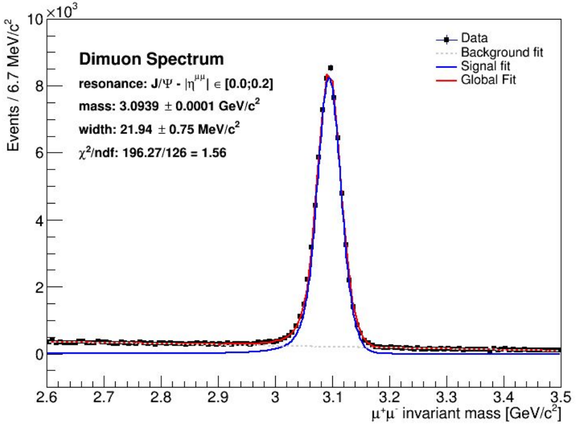
Fits for Mass Resolution

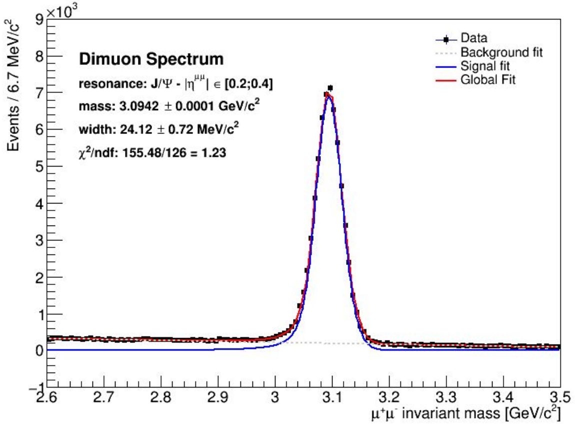
Bckg - linear
Signal - 1CB (rho, phi, psi, Upsilons)
2CB (J/psi, Z)

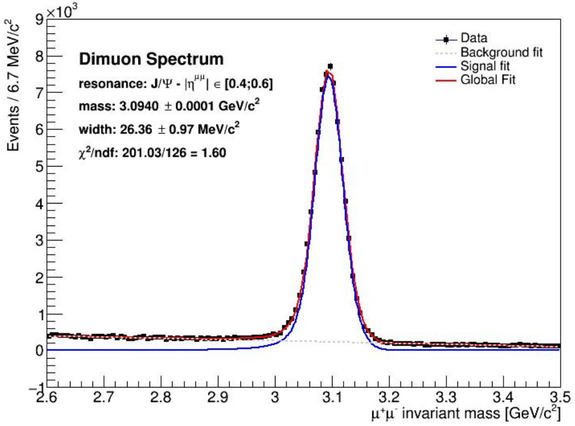


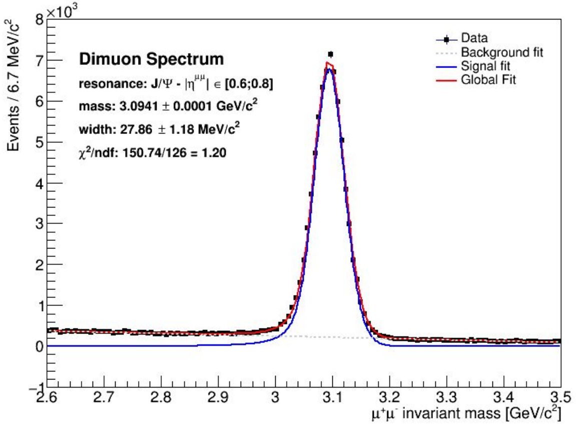
Fits for Resolution and Pseudorapidity

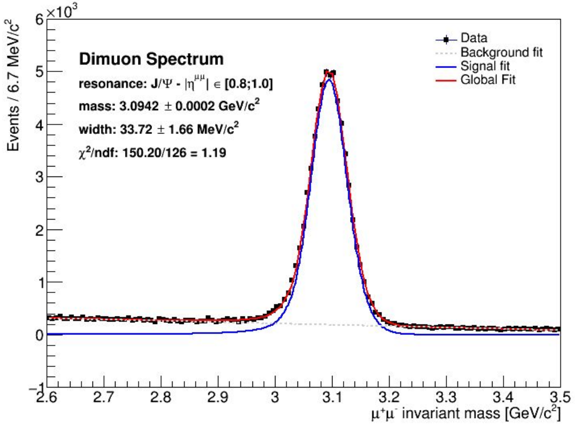
Bckg - linear
Signal - 2CB

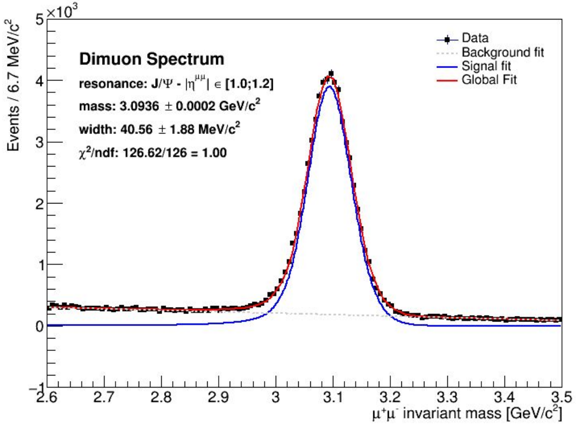




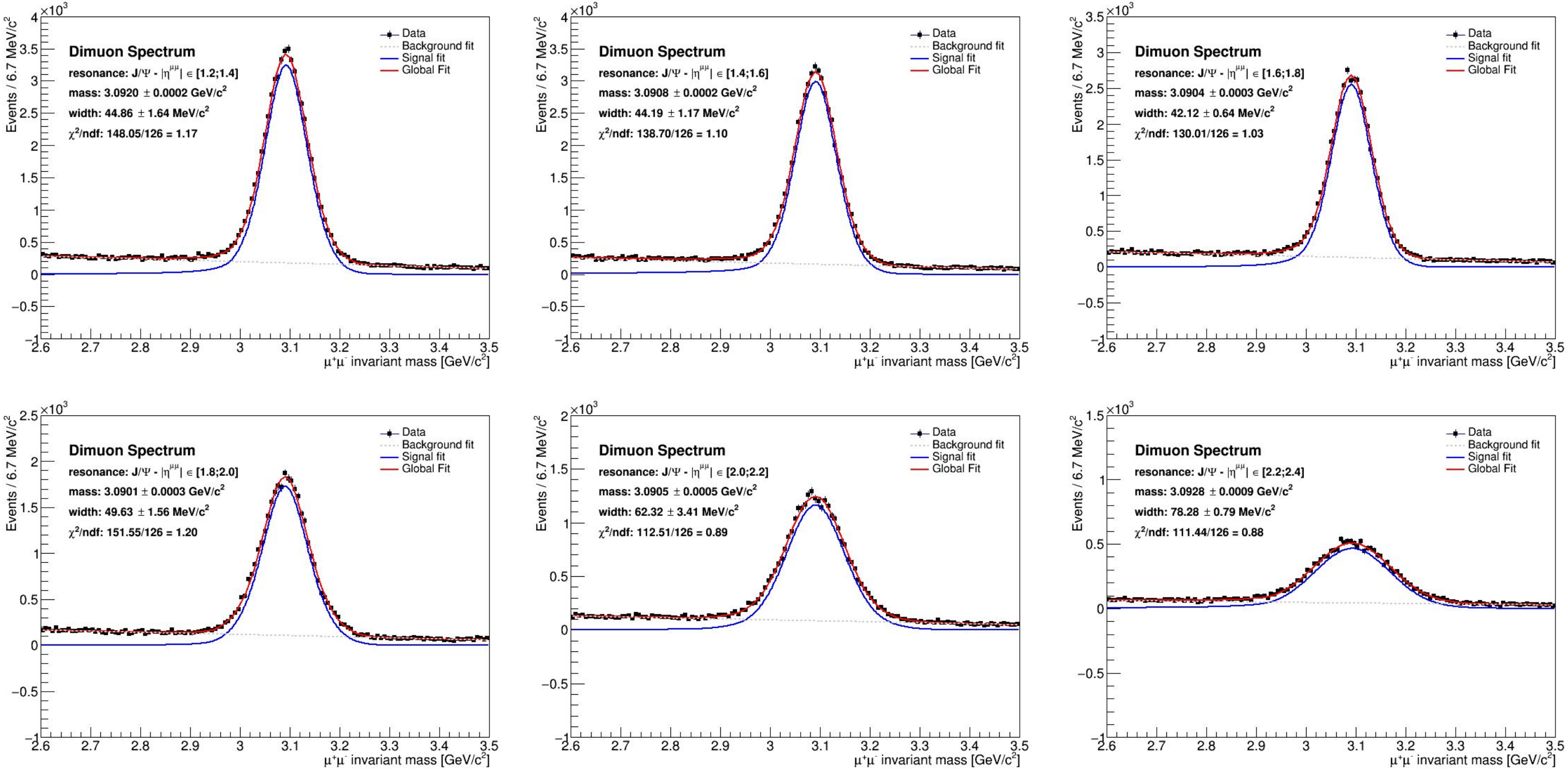




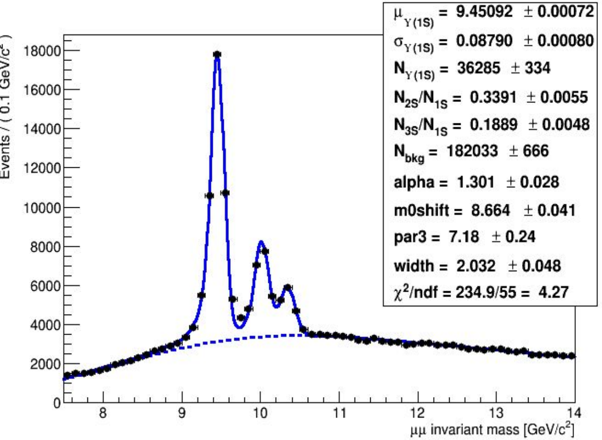


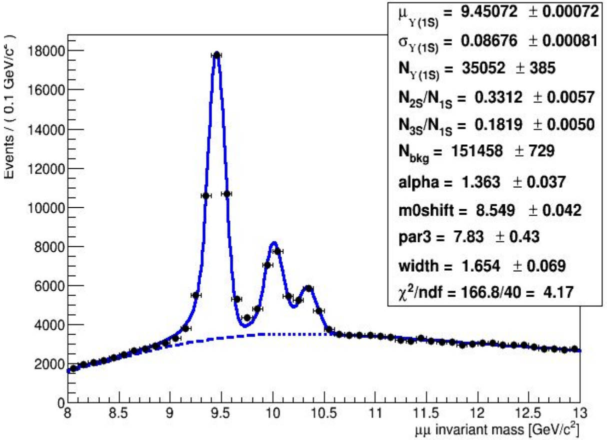


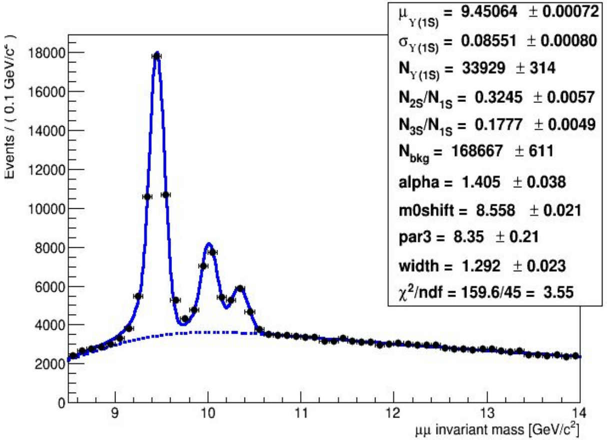
Fits for Resolution and Pseudorapidity (cont.)

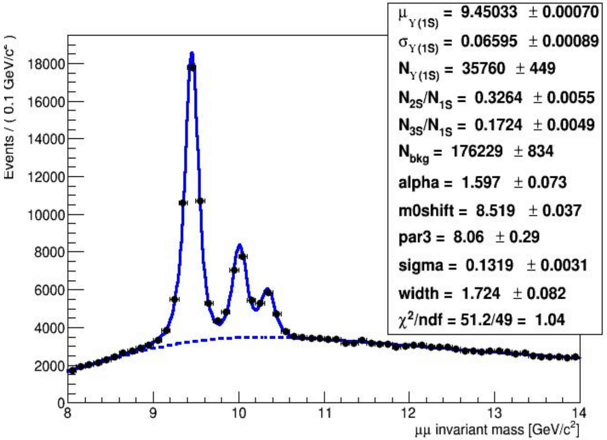


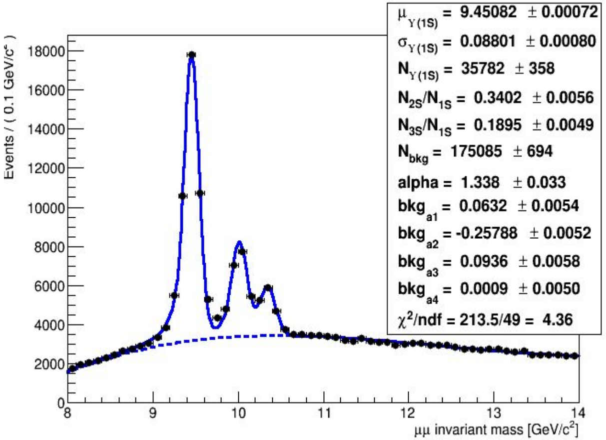
Fits for pp - systematic uncertainties



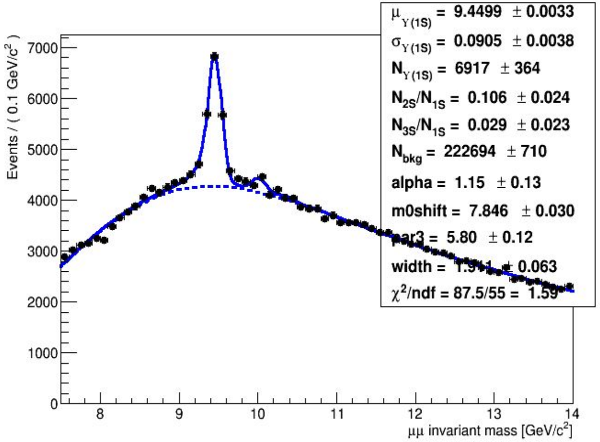


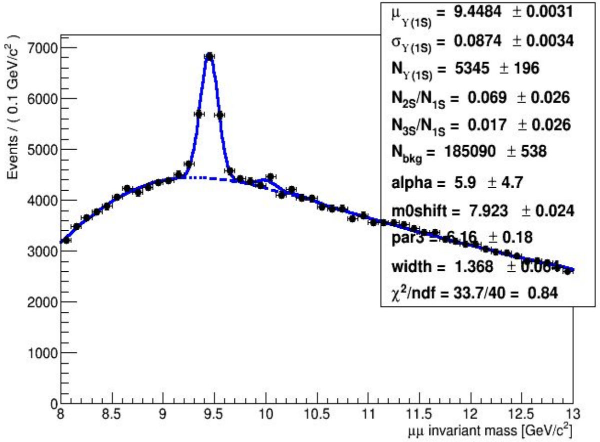


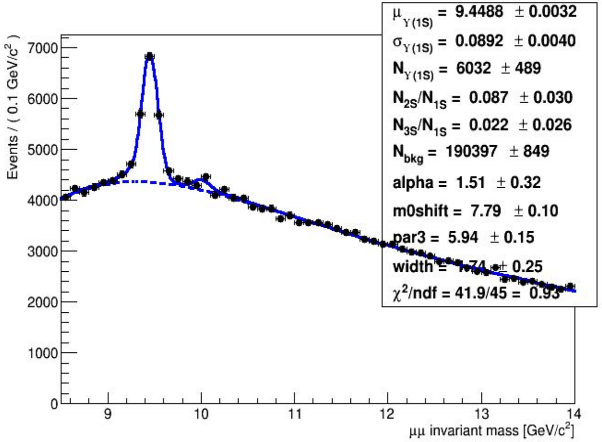


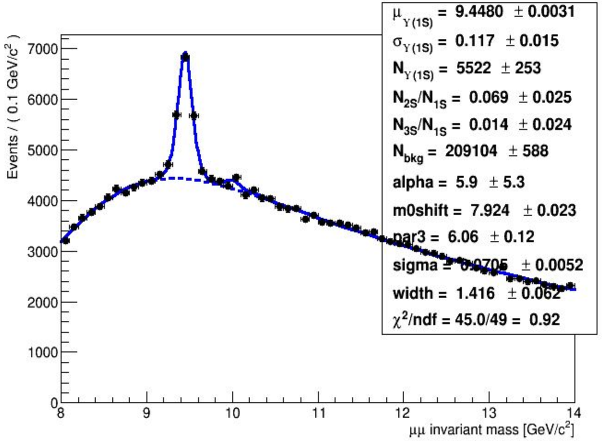


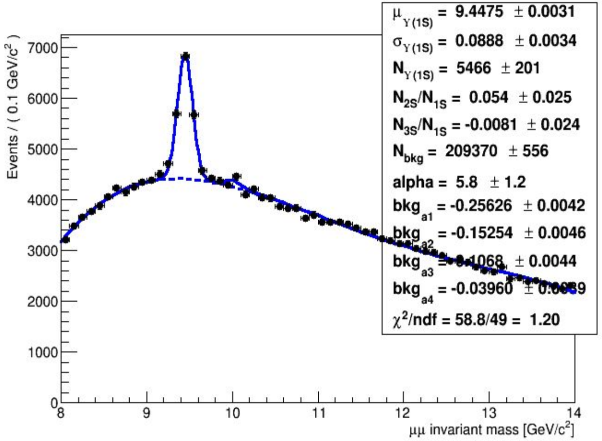
Fits for PbPb - systematic uncertainties





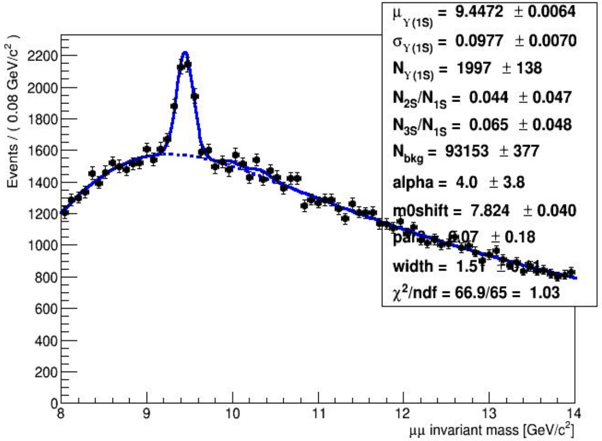




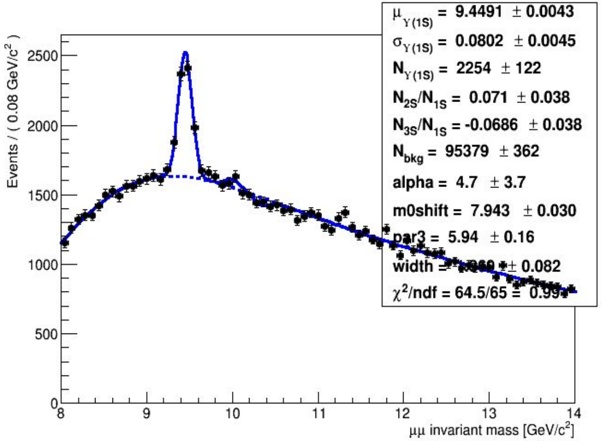


Fits for Peripheral

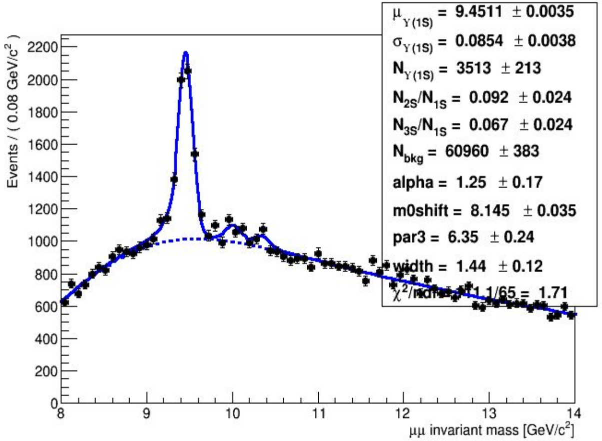
$Centrality \in [0; 0.1]$



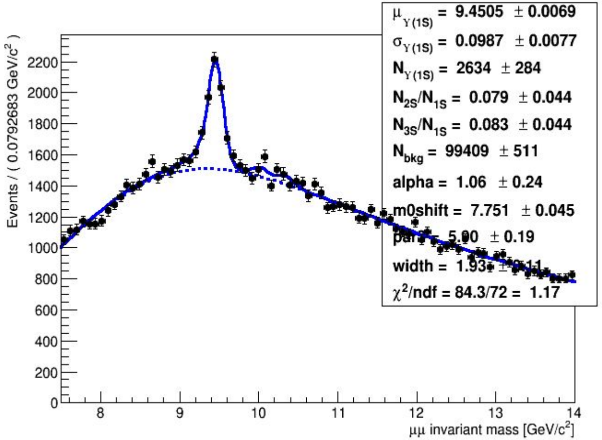
$Centrality \in [0.1; 0.3]$

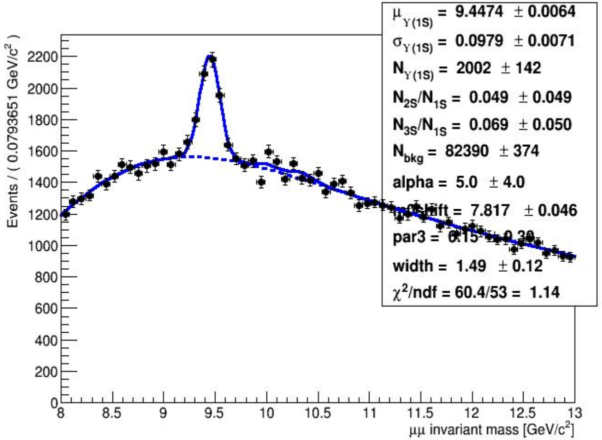


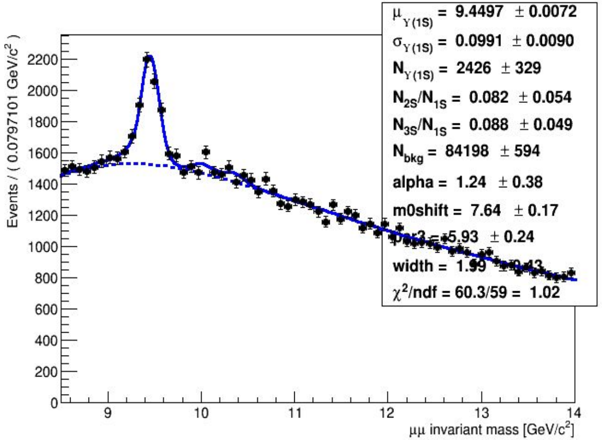
$Centrality \in [0.3; 1]$

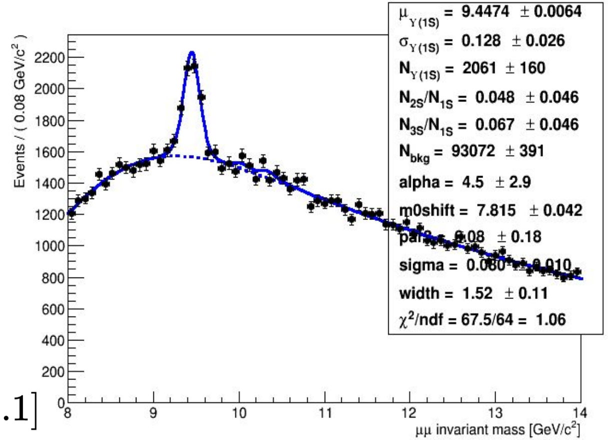


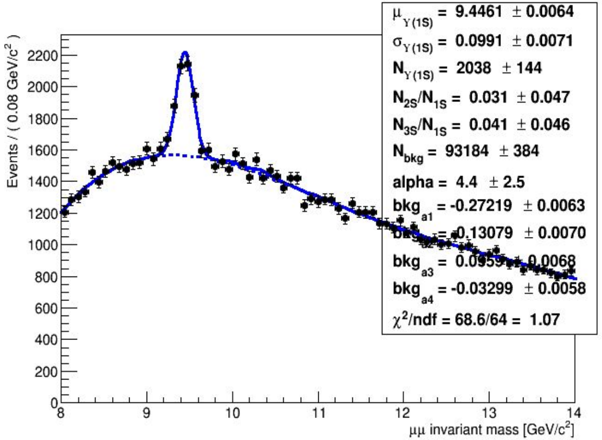
Fits for Peripheral - syst. uncertainties





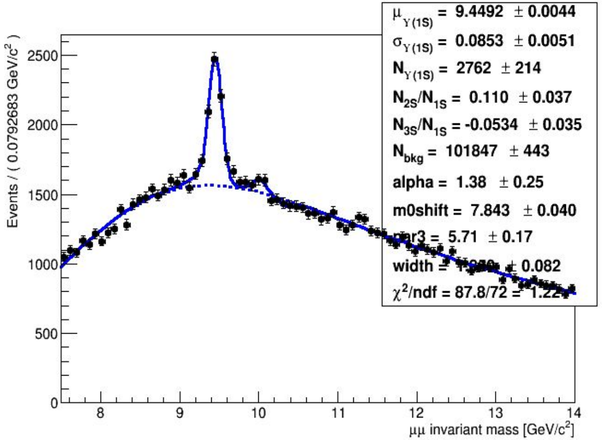


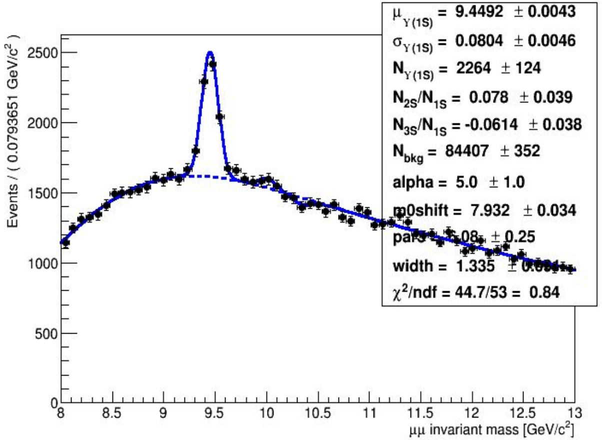


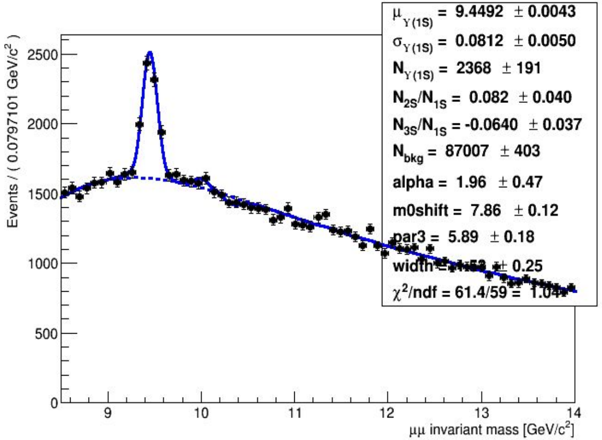


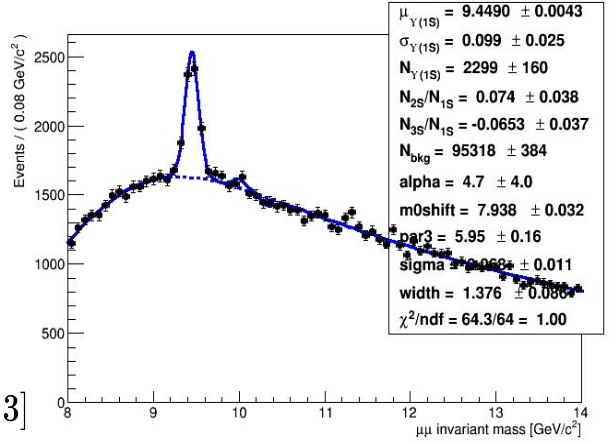
$Centrality \in [0; 0.1]$

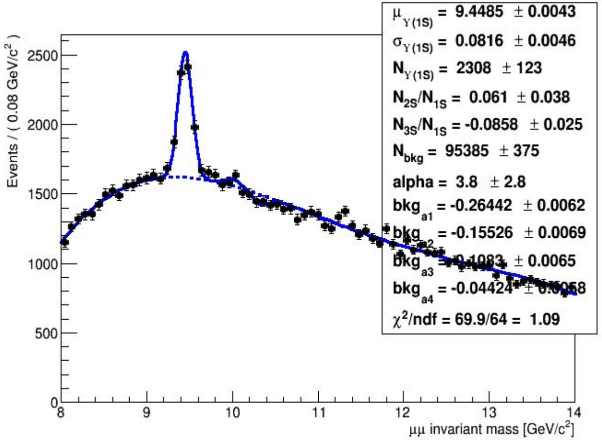
Fits for Peripheral - syst. uncertainties





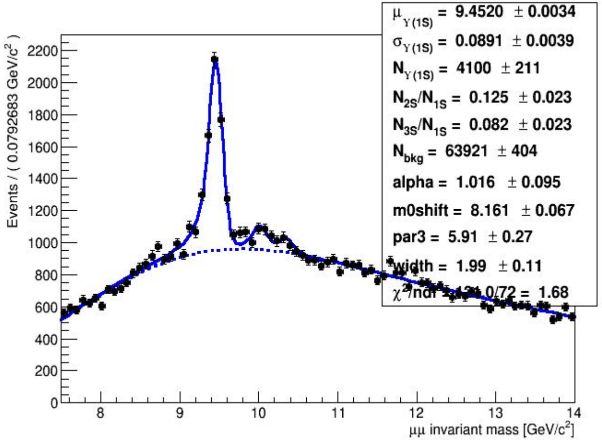


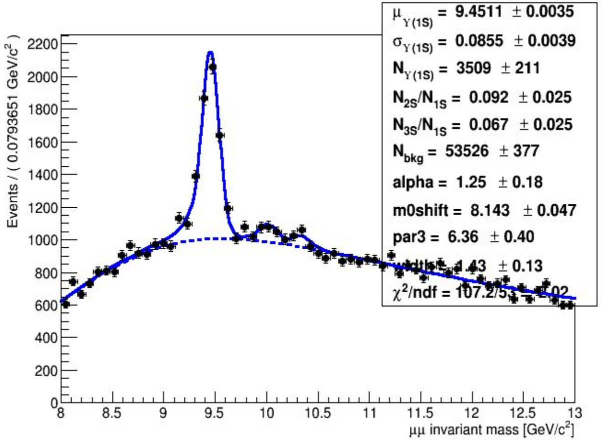


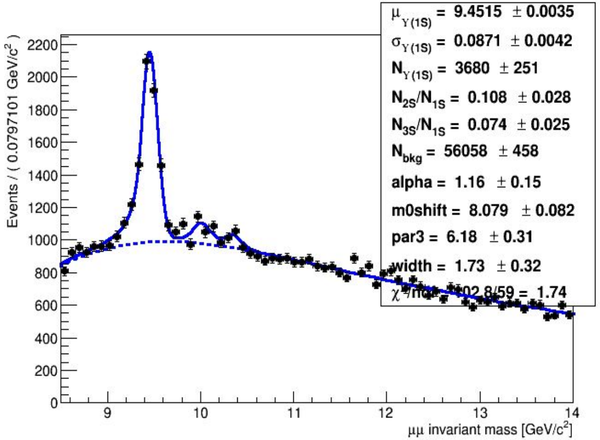


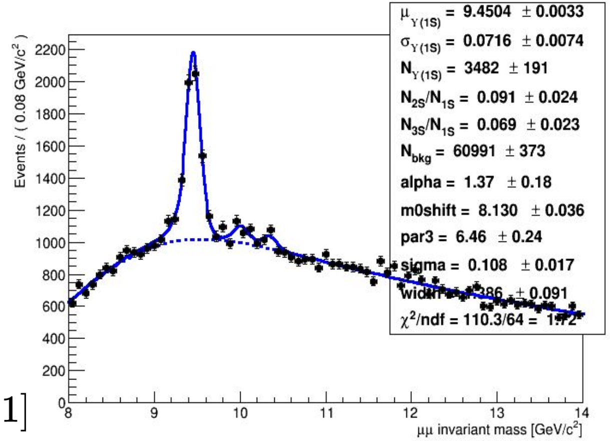
$Centrality \in [0.1; 0.3]$

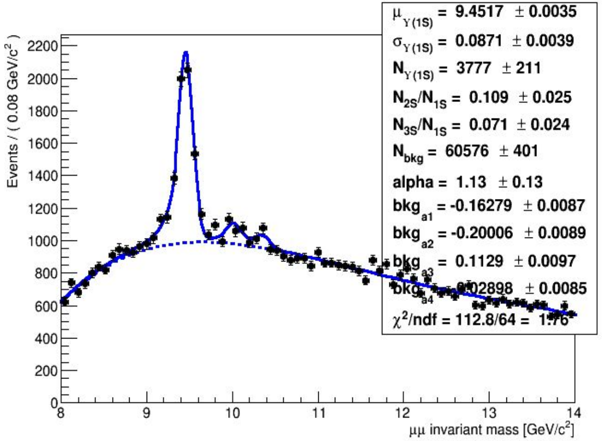
Fits for Peripheral - syst. uncertainties











$Centrality \in [0.3; 1]$