Measurements of the $\boldsymbol{\Upsilon(1S, 2S, 3S)}$ Cross Sections at $\sqrt{s} = 13.6\ \mathbf{TeV}$ with **CMS** 2022 Data

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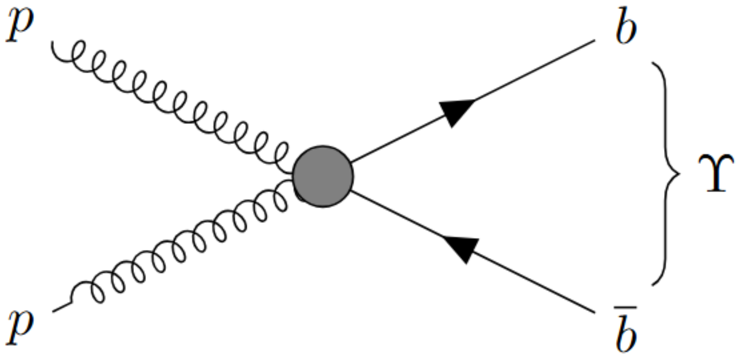
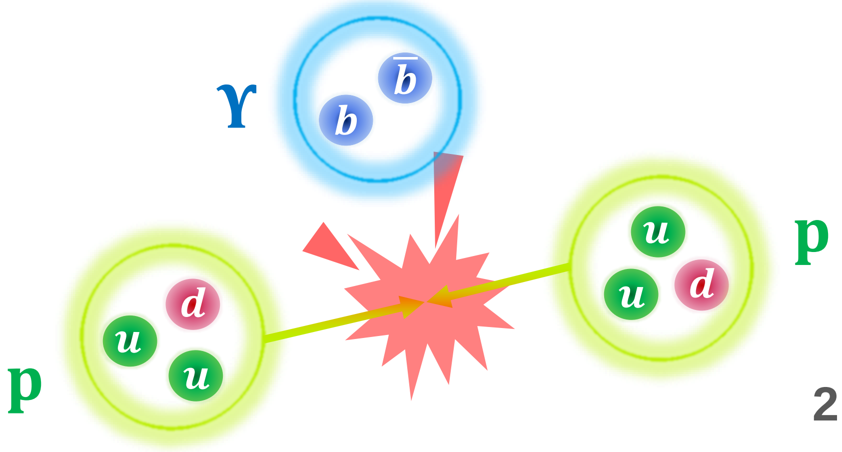
Introduction and Motivation

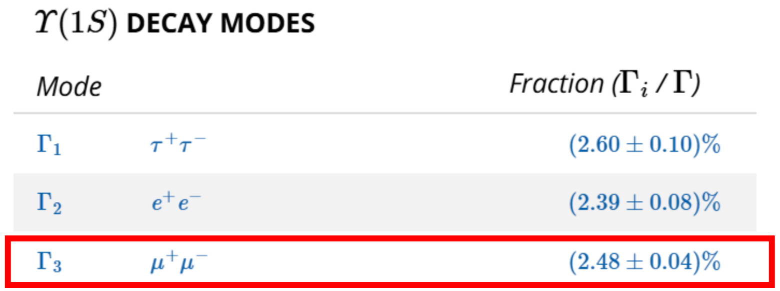
- Quarkonium production helps to study the interplay of perturbative and non-perturbative QCD.
- Quarkonium production mechanism is still unclear. Several contradictions exist in theoretical calculations:
    - The Color Singlet Model(CSM) underestimates cross sections.
    - Non-relativistic QCD (CSM + COM-Color Octet Mechanism) gives better prediction on cross sections but fails to describe the polarization effects.





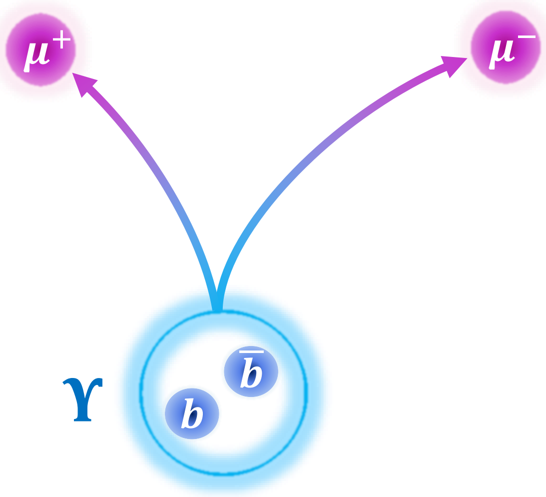
Introduction and Motivation

- An early analysis of 13.6 TeV will help to check Run-3 performance and understand the mechanisms of quarkonium production better.
- Our goal is to measure the cross sections at 13.6 TeV in a larger kinematic region and compare them with theory and those at 13 TeV.
  - $10\ \mathrm{GeV} < p_T < 200\ \mathrm{GeV}, |y| < 1.2$
  - Integrated luminosity of $37.4\ \mathrm{fb}^{-1}$.
- We choose Υ decay to two μ channel:
  - This physics process is cleaner.
  - CMS has the best technology to identity μ.



$\Upsilon(1S)$ **DECAY MODES**

Mode		Fraction (Γ_i/Γ)
Γ_1	$\tau^+\tau^-$	$(2.60 \pm 0.10)\%$
Γ_2	e^+e^-	$(2.39 \pm 0.08)\%$
Γ_3	$\mu^+\mu^-$	$(2.48 \pm 0.04)\%$



Previous Results

Collision Type	$\sqrt{s}$ [TeV]	Integrated Luminosity $[\mathrm{fb}^{-1}]$	Experiment	Kinematic Region for Differential Cross Section
pp	2.76	0.00023	CMS	
	5.02	0.028	CMS	p_T $0-30$ GeV, $\|y\| < 1.93$
	7	0.0031	CMS	p_T $0-30$ GeV, $\|y\| < 2$
	7	0.0358	CMS	p_T $0-50$ GeV, $\|y\| < 2.4$
	7	4.9	CMS	p_T $0-100$ GeV, $\|y\| < 1.2$
	7	1.8	ATLAS	p_T $0-70$ GeV, $\|y\| < 2$
	7	0.025	LHCb	p_T $0-15$ GeV, $2 < \|y\| < 4.5$
	7	0.0000056	ALICE	
	13	2.7	CMS	p_T $10-100$ GeV, $\|y\| < 1.2$
This Analysis	**13.6**	**37.4**	**CMS**	**p_T $10-200$ GeV, $\|y\| < 1.2$**
PbPb	2.76	0.00000000728	CMS	
	2.76	0.00000015	CMS	
pPb	5.02	0.0000356	CMS	p_T $0-30$ GeV, $\|y\| < 1.93$

- Differential cross sections of $\Upsilon(1S, 2S, 3S)$ as functions of transverse momentum (p_T) and rapidity (y).
- Results have shown discrepancies with theoretical predictions, highlighting the need for further research.
- Our analysis also focus on p_T and y differential cross sections but has largest kinematic region and statistic.

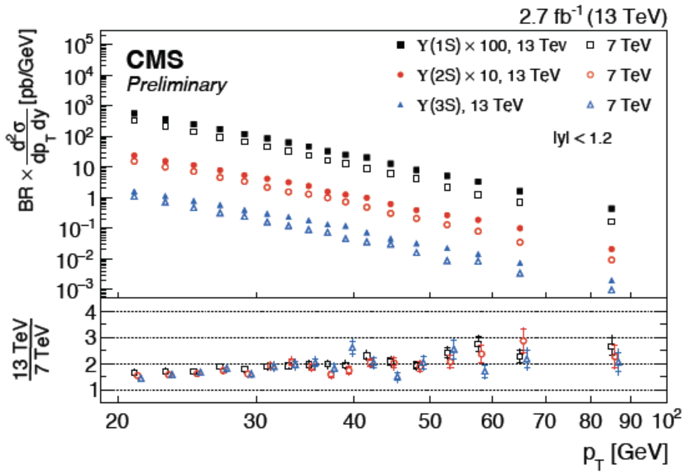
Previous Results: CMS 13 TeV BPH-15-005

- Differential cross sections:

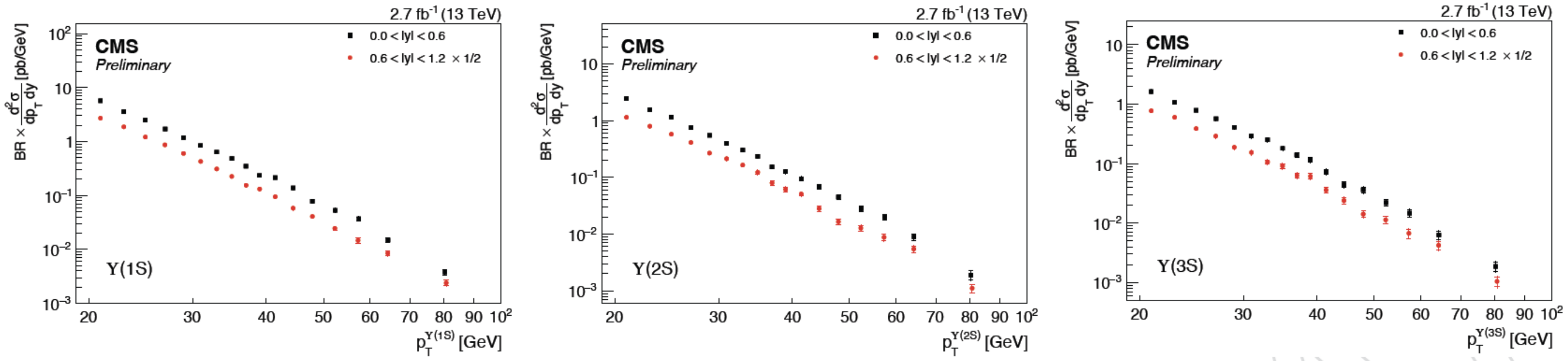
$$BR(\Upsilon \to \mu^+\mu^-) \times \frac{d^2\sigma}{dp_T dy} = \frac{N^{\Upsilon}(p_T,y)}{L\Delta y \Delta p_T} \cdot \langle \frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)} \rangle$$

$\left\langle \frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)} \right\rangle$: average weight over the corresponding (p_T, y) bin

- $N^{\Upsilon}(p_T,y)$: yields obtained from an Extended Maximum Likelihood
- L: integrated luminosity
- $\mathcal{A}(p_T,y)$: the geometrical acceptance obtained from MC (particle gun)
- $\epsilon(p_T,y)$: efficiency obtained from Tag&Probe and compared with MC (pythia)
- We use similar strategy to measure differential cross section at 13.6 TeV.



Cross Sections at 13 TeV for Υ(1S, 2S, 3S) in Two Rapidity Ranges



Comparison of Run-1 (7 TeV) and Run-2 (13 TeV) Cross Sections

Analysis Overview

Processed Run-3 2022 data and official ϒ MC

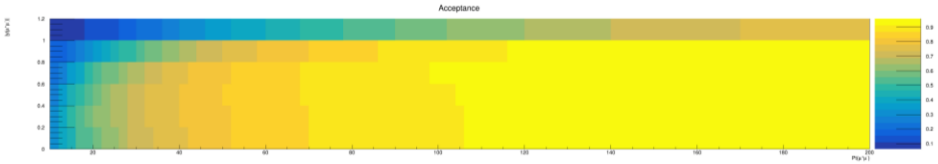
Calculated acceptance maps from MC, efficiency from data using Tag&Probe

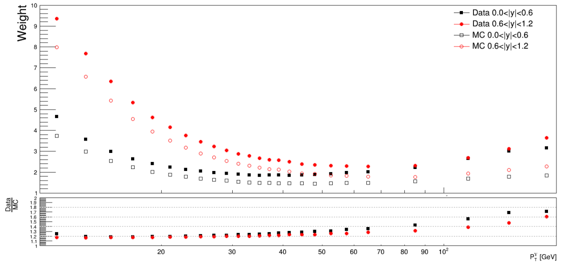
Calculated weight for each (p_T, y) bin

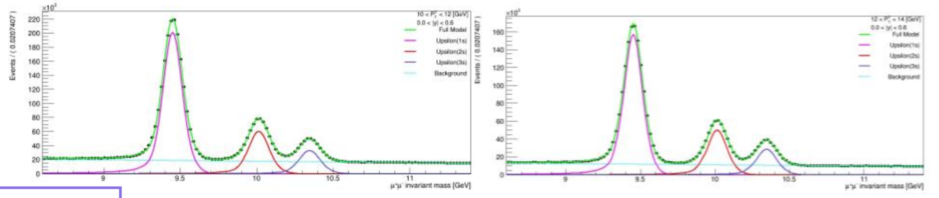
Performed raw fit to datasets, extracted the yields and got statistical uncertainty.

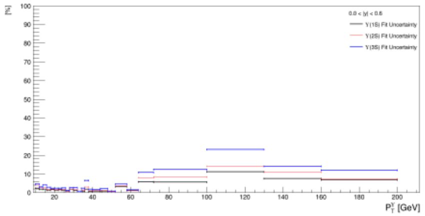
Calculated systematic uncertainties, including those on the yield, acc & eff and the luminosity

Measured differential cross sections









Datasets

- 2022 PromptReco **ParkingDoubleMuonLowMass**

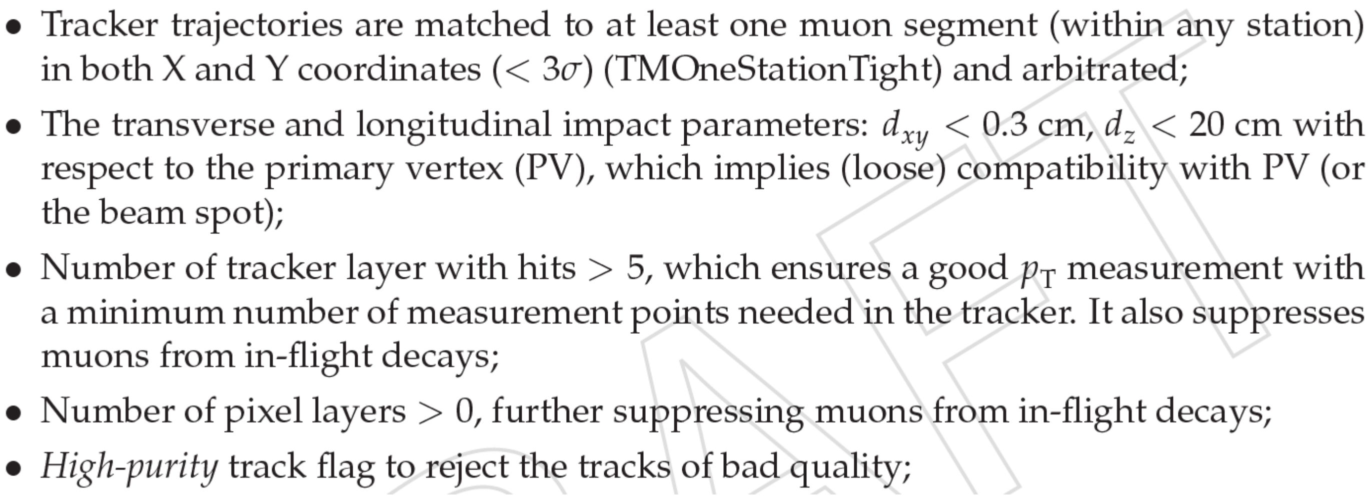
Dataset	Run Range	Integrated Luminosity
/Run2022C-PromptReco-v1/MINIAOD	355862-357482	9.6 fb^{-1}
/Run2022D-PromptReco-v1/MINIAOD	357538-357733	
/Run2022D-PromptReco-v2/MINIAOD	357734-357900	
/Run2022E-PromptReco-v1/MINIAOD	359356-360327	27.8 fb^{-1}
/Run2022F-PromptReco-v1/MINIAOD	360390-362167	
/Run2022G-PromptReco-v1/MINIAOD	362433-362760	

- Data quality as in Cert_Collisions2022_355100_362760_Muon.json
- Trigger Dimuon10_Upsilon_y1p4_v*
- MC samples

Upsilonto2Mu_UpsilonFilter_2MuFilter_TuneCP5_13p6TeV_pythia8	MC Efficiency
private gen-only Particle-gun MC with flat-p_T and no Gen filter	Acceptance
Private full-chain Pythia8 MC without Gen filter	Closure test

Pre-selection and Υ Reconstruction

- Traditional **Onia2MuMu** package with
  - Soft Muon ID
  - M($\mu^+\mu^-$) > 2 GeV
  - |dz1 - dz2| < 25 cm
- Muon quality based on standard POG recommended Soft ID



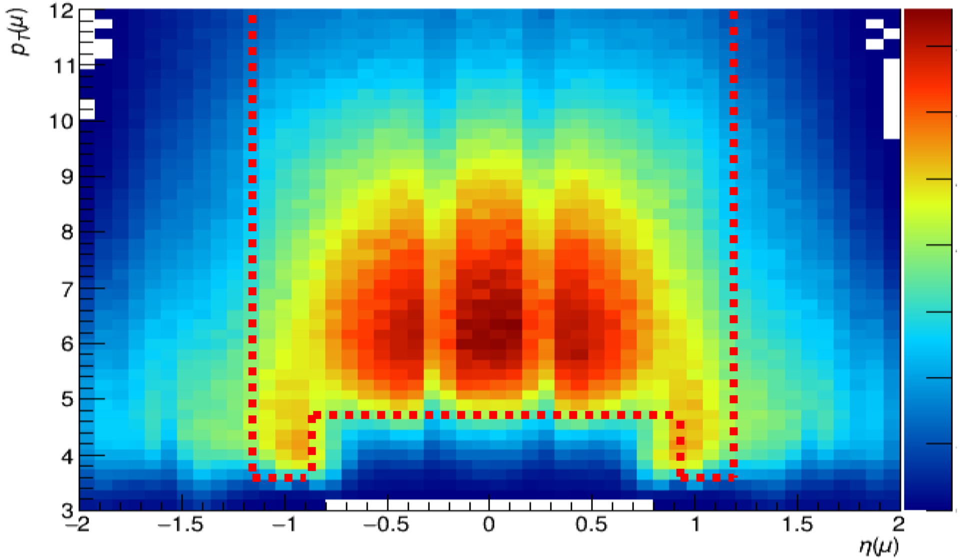
- Tracker trajectories are matched to at least one muon segment (within any station) in both X and Y coordinates ($< 3\sigma$) (TMOneStationTight) and arbitrated;
- The transverse and longitudinal impact parameters: $d_{xy} < 0.3$ cm, $d_z < 20$ cm with respect to the primary vertex (PV), which implies (loose) compatibility with PV (or the beam spot);
- Number of tracker layer with hits > 5, which ensures a good p_{T} measurement with a minimum number of measurement points needed in the tracker. It also suppresses muons from in-flight decays;
- Number of pixel layers > 0, further suppressing muons from in-flight decays;
- *High-purity* track flag to reject the tracks of bad quality;

- Datasets production are processed in CMSSW_12_4_11_patch1

Acceptance

- Using GEN-only Particle-gun MC with flat p_T
  - $p_T \in (0,200)\ \mathrm{GeV}, \eta \in (-3,3), \phi \in (-\pi,\pi)$
- Definition $\mathcal{A} = \frac{N_{GEN,\,pass}(p_T,y)}{N_{GEN}(p_T,y)}$
  - $N_{GEN,\,pass}(p_T,y)$: Number of generated events that pass the acceptance criteria
  - $N_{GEN}(p_T,y)$: Total number of generated events
- Acceptance criteria Same strategy as 13TeV
  - $p_T(\mu^+\mu^-) > 10\ \mathrm{GeV}$
  - $|y(\mu^+\mu^-)| < 1.2$
  - $p_T(\mu) > 4.6\ \mathrm{GeV}\ \text{ if }\ 0.0 < |\eta(\mu)| < 0.9$
  - $p_T(\mu) > 3.6\ \mathrm{GeV}\ \text{ if }\ 0.9 < |\eta(\mu)| < 1.2$

Acceptance Criteria



Single Muon Efficiency

$$\varepsilon^{\mu}(p_T,\eta) = 0.99\ \varepsilon_{\text{RECO\_ID}}\ \varepsilon_{\text{Trigger}}$$

Track efficiency =0.99

Reco&ID efficiency

Trigger efficiency

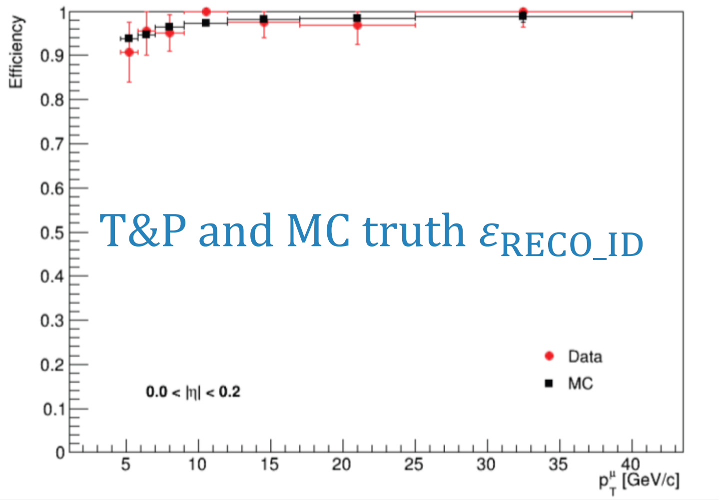
Tag and Probe

from Data

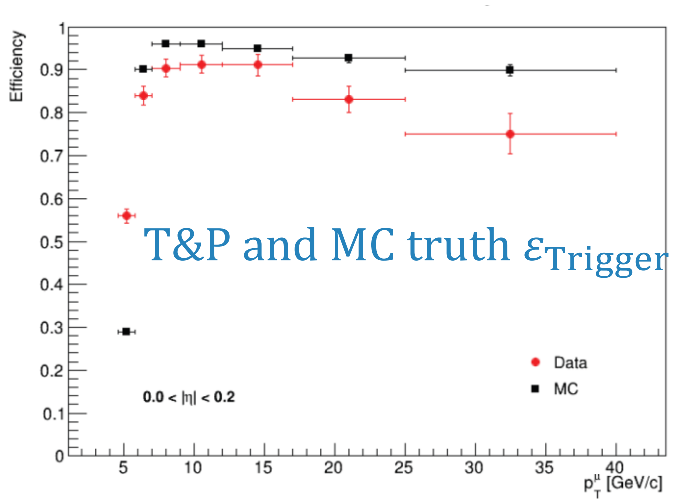
$$\epsilon = \frac{\text{Fit peak area of (tag, passing probe) pair mass}}{\text{Fit peak area of (tag, previous passing probe) pair mass}}$$

Results use T&P single muon efficiency measured from data.

Treat difference as MC inaccuracy.



T&P and MC truth $\varepsilon_{\text{RECO\_ID}}$



T&P and MC truth $\varepsilon_{\text{Trigger}}$

ϒ Efficiency

$$\epsilon(p_T,y) = \epsilon^{\mu^+}(p_T^{\mu^+},\eta^{\mu^+})\epsilon^{\mu^-}(p_T^{\mu^-},\eta^{\mu^-})\rho(p_T,y)$$

Single Muon Efficiency

T&P from Data

ρ factor

$$\rho(p_{\mathrm{T}}^{\Upsilon},y^{\Upsilon}) = \frac{\Upsilon\text{ efficiency measured from MC truth}}{\mu^+\times\mu^-\text{ efficiency measured from MC using T\&P}}$$

- Use Official MC sample
- Calculated in each ϒ kinetic bins same as cross sections

Weight of $\Upsilon(p_T,y)$ bin $\left\langle\frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)}\right\rangle_{\Upsilon\,(p_T,y)\text{ bin}}$

Differential Cross-section

$$BR(\Upsilon\to\mu^+\mu^-)\times\frac{d^2\sigma(p_T,y)}{dp_T dy} = \frac{N^{\Upsilon}(p_T,y)}{L\Delta y\Delta p_T}\cdot\left\langle\frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)}\right\rangle$$

Results

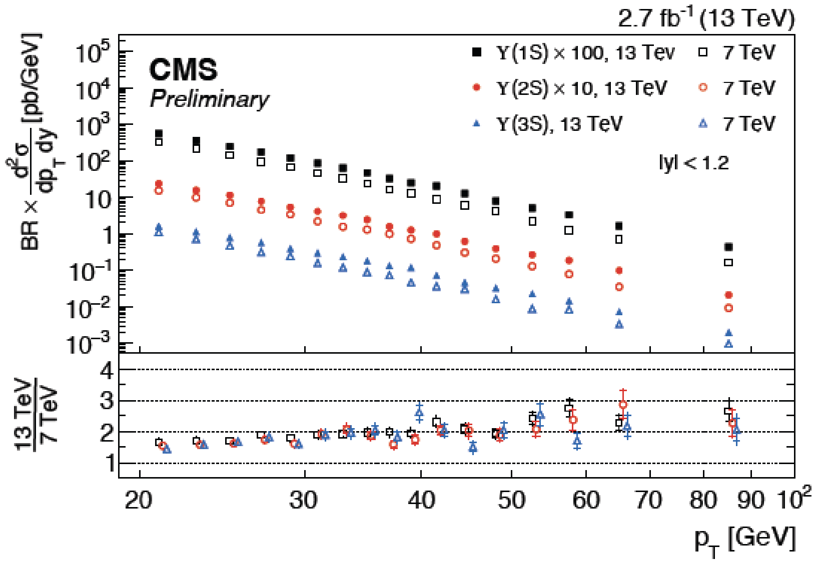
Double-differential Cross sections are calculated with the expression:

$$BR(\Upsilon \to \mu^+\mu^-) \times \frac{d^2\sigma(p_T,y)}{dp_T dy} = \frac{N^{\Upsilon}(p_T,y)}{L\Delta y\Delta p_T} \cdot \langle \frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)} \rangle$$

$\left\langle \frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)} \right\rangle$: weight of corresponding $\Upsilon(p_T,y)$ bin

- $\mathcal{A}$ from MC truth.
- ϵ from data using Tag&Probe method. (MC used for correlation factor calculation)

BPH-15-005 Measured double-differential cross sections times branching ratios for $\Upsilon(1S,2S,3S)$ at $\sqrt{s} = 13$ TeV

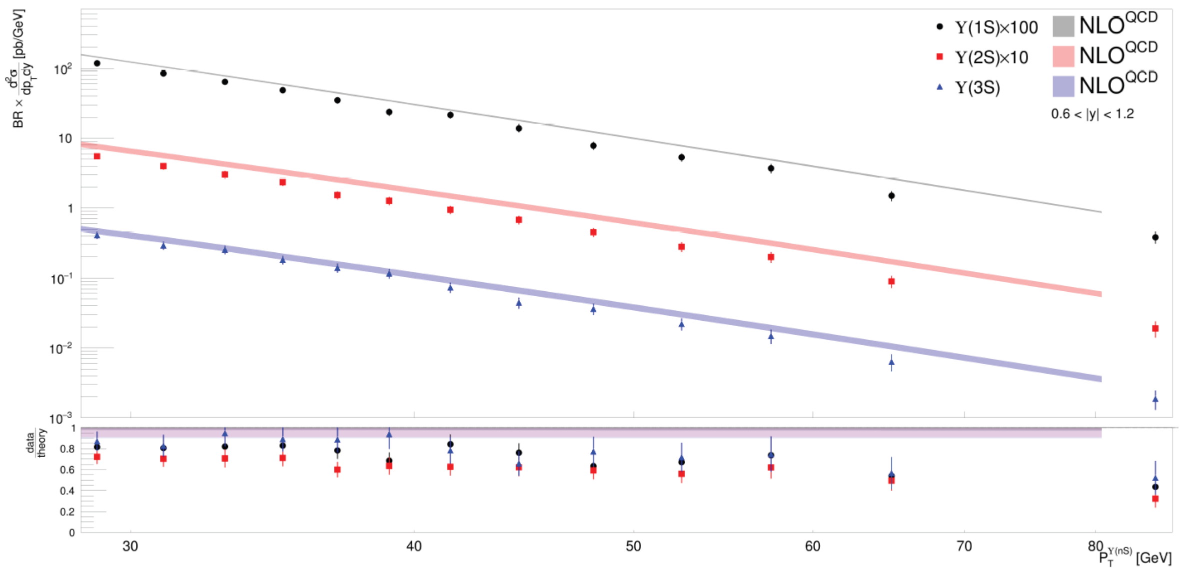


We measured similar results at $\sqrt{s} = 13.6$ TeV

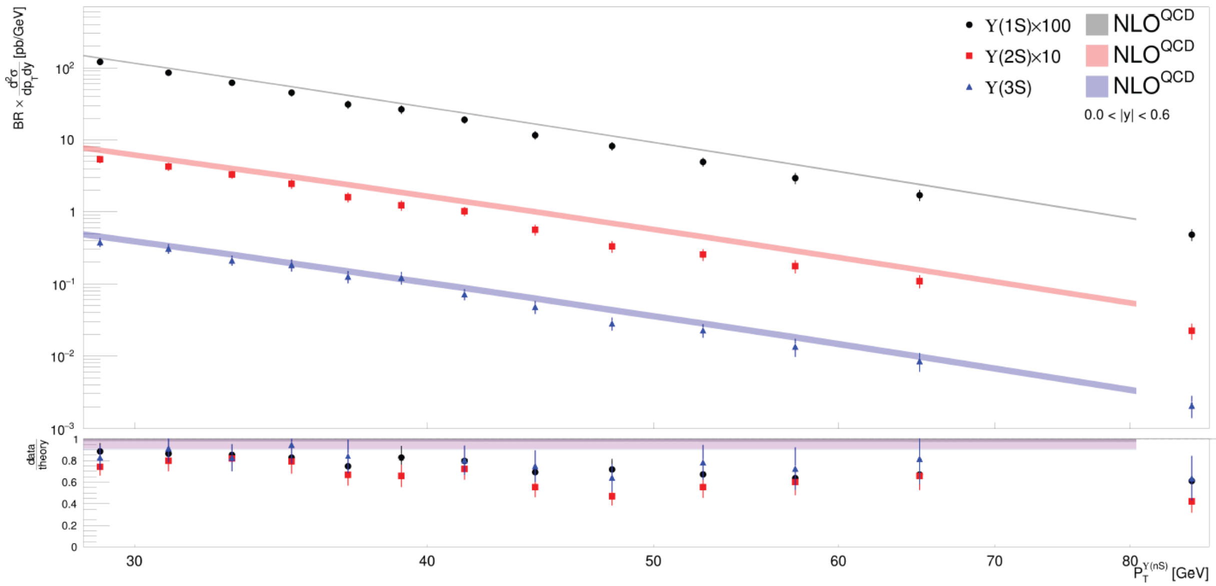
Awaiting approval

Comparison with Theory

- Measured differential cross sections at 13 TeV (BPH-15-005)
- Next-to-Leading Order QCD predictions are acquired through private communication with authors of Yu Feng *et al* 2021 *Chinese Phys. C* **45** 013117
- Uncertainty of theoretical calculations are estimated from LDMEs
- Branching ratios are according to the PDG



0.0 < |y| < 0.6



0.6 < |y| < 1.2

Measured results are slightly smaller relative to theoretical prediction.
We compared our results at $\sqrt{s} = 13.6\ \mathrm{TeV}$ with theory.

Summary and Outlook

- Measured $\Upsilon\,(1S, 2S, 3S)$ differential cross sections at 13.6 TeV. $10\ \mathrm{GeV} < p_T < 200\ \mathrm{GeV}, |y| < 1.2$
- Compared with previous 13 TeV results and theory.
- Wrote Analysis Note, paper draft and twiki page.
- Opened CMS CADI line **BPH-24-004**.
- Awaiting approval from CMS Collaboration.

Thanks for your attention!

Yiyang Zhao
Tsinghua University

BACKUP

Pervious Talks

P&P meeting

- 17th May 2023 https://indico.cern.ch/event/1281637/
- 13th December 2023 https://indico.cern.ch/event/1338471/
- 3rd   April 2024 https://indico.cern.ch/event/1400102/
- 10th July   2024 https://indico.cern.ch/event/1425425/

Muon POG meeting

- 29th July 2024 https://indico.cern.ch/event/1441994/

Open a **CADI line** **BPH-24-004**.

Run-3 2022 Datasets

- Data are stored in ParkingDoubleMuonLowMass primary data set.

Data Samples	**Run Range**	**Luminosity**
/Run2022C-PromptReco-v1/MINIAOD	355862-357482	$9.624 fb^{-1}$ (CD – preEE period)
/Run2022D-PromptReco-v1/MINIAOD	357538-357733	
/Run2022D-PromptReco-v2/MINIAOD	357734-357900	
/Run2022E-PromptReco-v1/MINIAOD	359356-360327	$27.787 fb^{-1}$ (EFG – postEE period)
/Run2022F-PromptReco-v1/MINIAOD	360390-362167	
/Run2022G-PromptReco-v1/MINIAOD	362433-362760	

- Data quality as in: Cert_Collisions2022_355100_362760_Muon.json
- Trigger: Dimuon10_Upsilon_y1p4_v*
- MC samples:

Upsilonto2Mu_UpsilonFilter_2MuFilter_TuneCP5_13p6TeV_pythia8	**official MC**
private gen-only particle-gun MC with flat-pT and no Gen filter	for acceptance
Private full-chain pythia MC without Gen filter	for closure test

MC samples

- Official 2022 MC:
  - For Run C D: /Upsilonto2Mu_UpsilonFilter_2MuFilter_TuneCP5_13p6TeV_pythia8/Run3Summer22MiniAODv3-124X_mcRun3_2022_realistic_v12-v2/MINIAODSIM
  - For Run E F G: /Upsilonto2Mu_UpsilonFilter_2MuFilter_TuneCP5_13p6TeV_pythia8/Run3Summer22EEMiniAODv3-124X_mcRun3_2022_realistic_postEE_v1-v2/MINIAODSIM

```
process.oniafilter = cms.EDFilter("PythiaFilter",
MaxRapidity = cms.untracked.double(1.3),
MinPt = cms.untracked.double(9.0),
MinRapidity = cms.untracked.double(-1.3),
ParticleID = cms.untracked.int32(553),
Status = cms.untracked.int32(2)
)
```

```
process.mumufilter = cms.EDFilter("PythiaDauVFilter",
ChargeConjugation = cms.untracked.bool(False),
DaughterIDs = cms.untracked.vint32(13, -13),
MaxEta = cms.untracked.vdouble(2.4, 2.4),
MinEta = cms.untracked.vdouble(-2.4, -2.4),
MinPt = cms.untracked.vdouble(3.0, 3.0),
MotherID = cms.untracked.int32(0),
NumberDaughters = cms.untracked.int32(2),
ParticleID = cms.untracked.int32(553) )
```

- Private gen-only particle-gun MC without Gen filter for acceptance
- Private full-chain pythia MC without Gen filter for closure test

Muon Pre-selection and Onia Reconstruction

- Use traditional Onia2MuMu package with:

  Soft Muon ID && M($\mu^+\mu^-$) > 2 GeV && |dz1 - dz2| < 25 cm

- Muon quality based on standard POG recommended “Soft ID”

```
process.selectedMuons.cut = cms.string('muonID(\"TMOneStationTight\")'
                     ' && abs(innerTrack.dxy) < 0.3'
                     ' && abs(innerTrack.dz)  < 20.'
                     ' && innerTrack.hitPattern.trackerLayersWithMeasurement > 5'
                     ' && innerTrack.hitPattern.pixelLayersWithMeasurement > 0'
                     ' && innerTrack.quality(\"highPurity\")'
                     ' && (abs(eta) <= 2.4 && pt > 3.)'
                     )
```

- ROOT trees are produced with CMSSW_12_4_11_patch1
- Finished jobs(full 2022) are stored in

  root://cms-xrd-global.cern.ch//store/user/yuxiao/Upsilon

  root://cms-xrd-global.cern.ch//store/user/yiyangz/Research/CMS_Run3_Upsilon

Acceptance Criteria

The acceptance in the (p_T, y) bin is defined as

$$\mathcal{A} = \frac{N_{GEN,\,pass}(p_T, y)}{N_{GEN}(p_T, y)}$$

- $N_{GEN,\,pass}(p_T, y)$: number of generated events that pass the acceptance criteria
- $N_{GEN}(p_T, y)$: total number of simulated events

Calculated using GEN-only Particle Gun MC with flat p_T

- $p_T \in (0{,}200)$ GeV, $\eta \in (-3{,}3)$, $\phi \in (-\pi, \pi)$

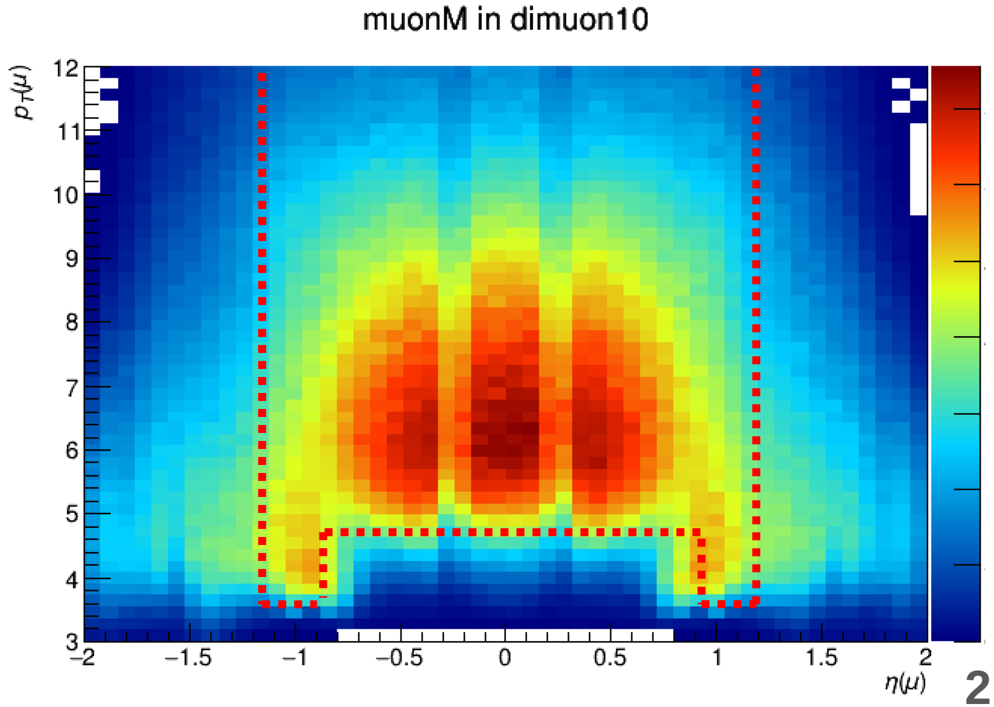
Our acceptance criteria:

- $p_T(\mu^+\mu^-) > 10$ GeV
- $0.0 < |y(\mu^+\mu^-)| < 1.2$
- $p_T(\mu) > 4.6$ GeV if $0.0 < |\eta(\mu)| < 0.9$
- $p_T(\mu) > 3.6$ GeV if $0.9 < |\eta(\mu)| < 1.2$

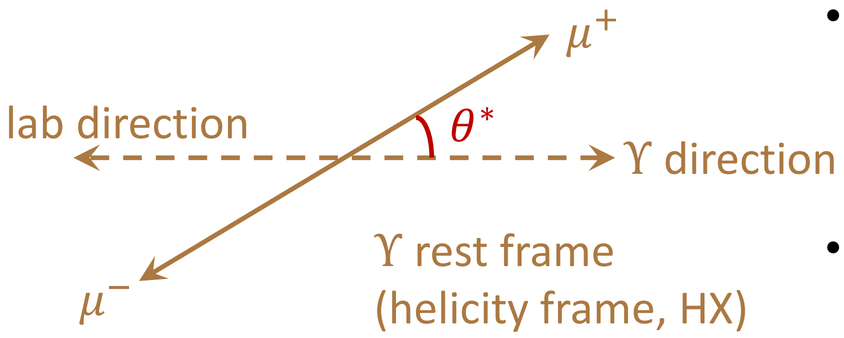
Slightly different than the 13 TeV analysis:

- $p_T(\mu^+\mu^-) > 20$ GeV
- $0 < |y(\mu^+\mu^-)| < 1.2$
- $p_T(\mu) > 4.5$ GeV if $0.0 < |\eta(\mu)| < 0.3$
- $p_T(\mu) > 4.0$ GeV if $0.3 < |\eta(\mu)| < 1.4$

- very loose GEN filter



Polarization Effects on Acceptance



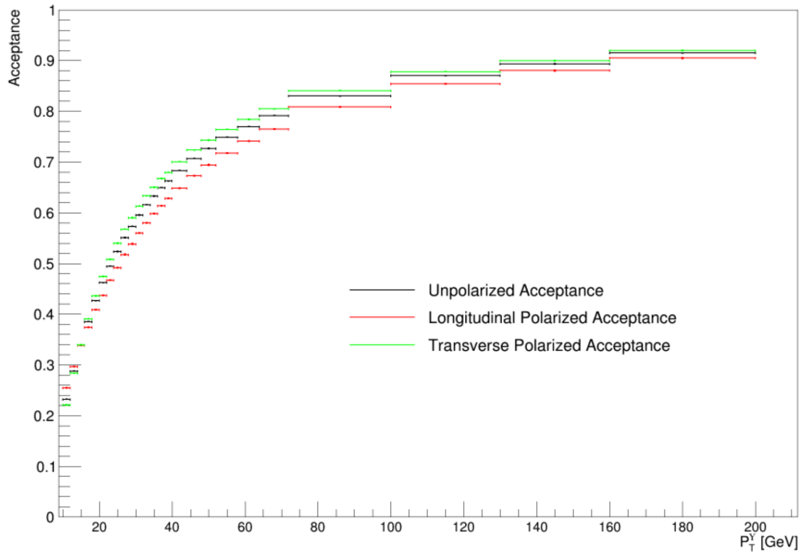
Υ rest frame
(helicity frame, HX)

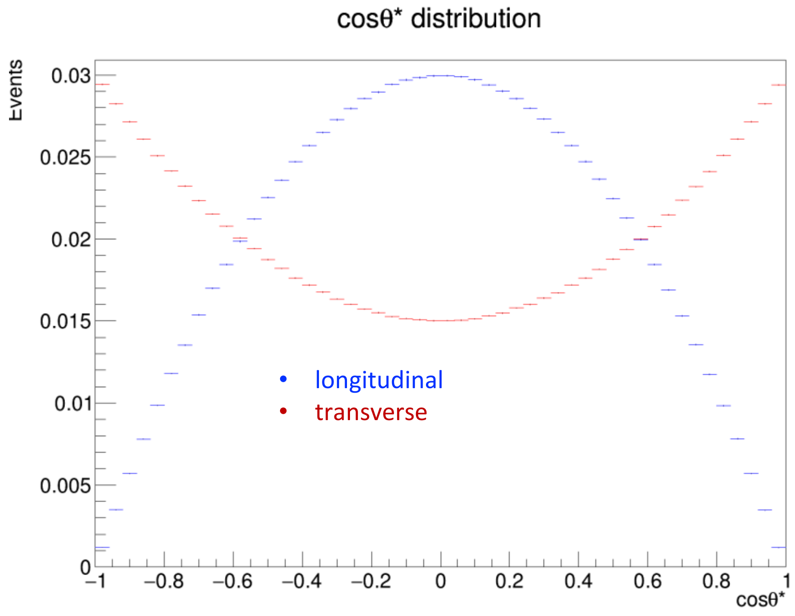
- $I(cos\theta^*) = \frac{d\sigma}{dcos\theta^*} \propto (1 + \lambda \cos^2 \theta^*)$

  $\sigma_{(L/T)}$: (longitudinal / transverse component of) the cross section

  λ: the polarization parameter. $\lambda = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$

  θ^*: the polar angle
- transverse polarization:
  - $I_T(cos\theta^*) = \frac{3}{8}(1 + \cos^2 \theta^*),\ \lambda = 1$
- longitudinal polarization:
  - $I_T(cos\theta^*) = \frac{3}{4}(1 - \cos^2 \theta^*),\ \lambda = -1$

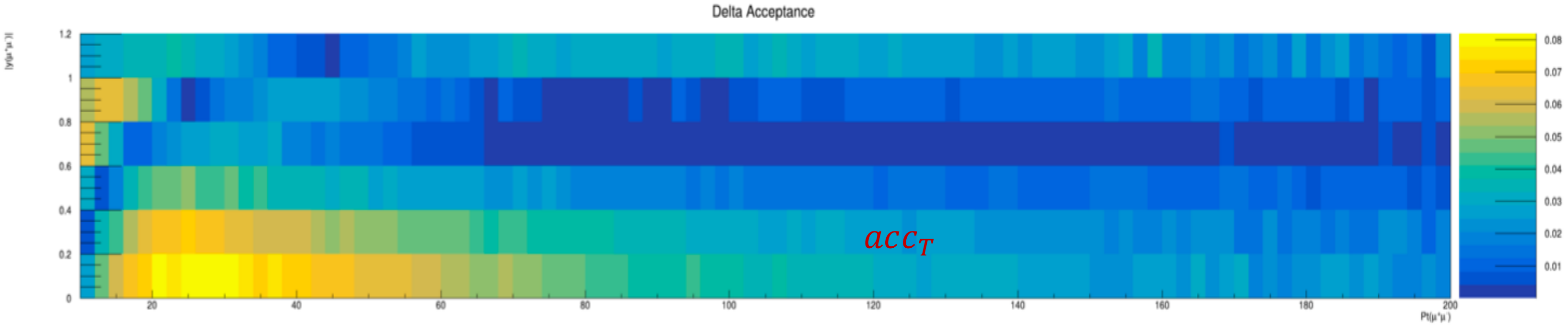


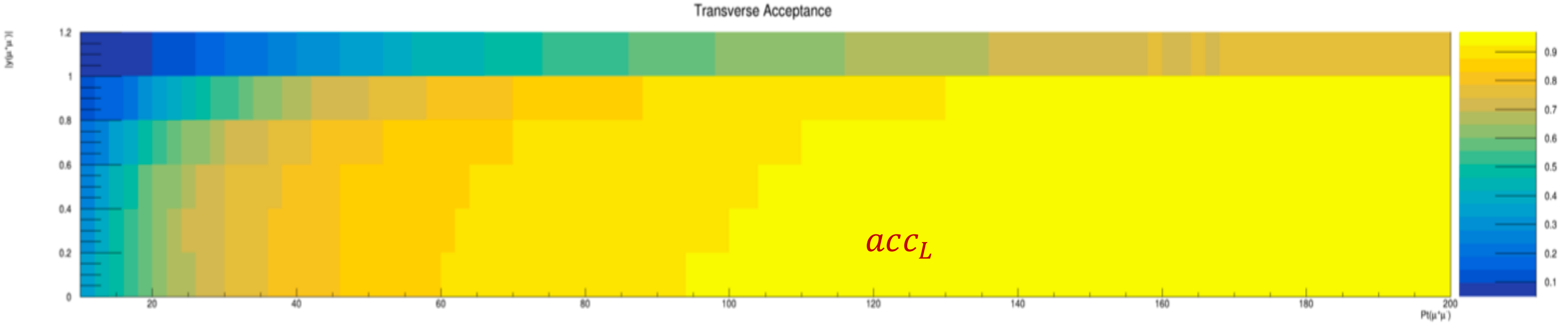


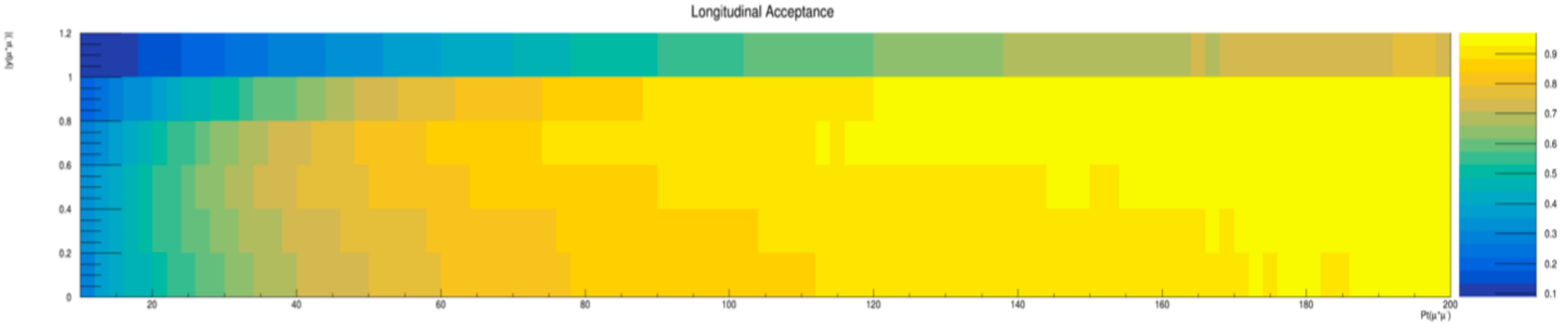
normalized

Polarization Effects on Acceptance

$|acc_T - acc_L|$







Provided as acceptance correction factor for each bins table in the AN.

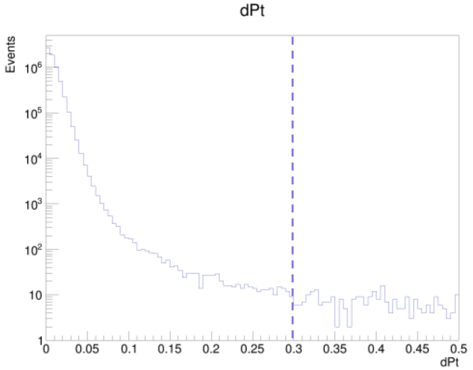
Efficiencies

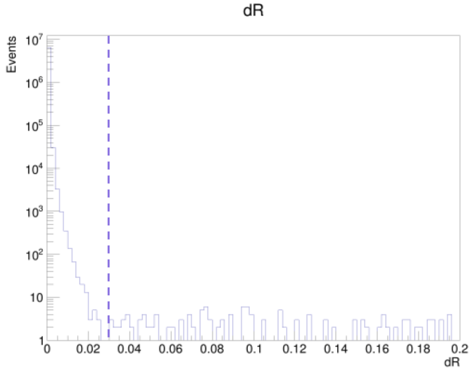
$\epsilon(p_T, y) = \epsilon_{RECO}(p_T, y)\epsilon_{SEL}(p_T, y)$

Efficiencies are calculated using the official Monte Carlo sample

- Reconstruction efficiency $\epsilon_{RECO}(p_T, y) = \dfrac{N_{RECO}(p_T, y)}{N_{GEN,pass}(p_T, y)}$

- $N_{RECO}(p_T, y)$: number of events that:
  - pass the acceptance criteria
  - pass the pre-selection
  - matched to GEN: $(\Delta p_{\mathrm{T}}(\Upsilon_{RECO}, \Upsilon_{\mathrm{GEN}}), \Delta R(\Upsilon_{RECO}, \Upsilon_{\mathrm{GEN}})) < (0.3, 0.03)$
- $N_{GEN,\,pass}(p_T, y)$: number of generated events that pass the acceptance criteria





- Selection efficiency $\epsilon_{SEL}(p_T, y) = \dfrac{N_{SEL}(p_T, y)}{N_{RECO}(p_T, y)}$

- $N_{SEL}(p_T, y)$: number of the reconstructed events that
  - vertex probability > 0.1
  - pass the high-level trigger HLT_dimuon10_y1p4_v

Efficiencies

- The acc & eff work together as a correction factor on the signal yields:

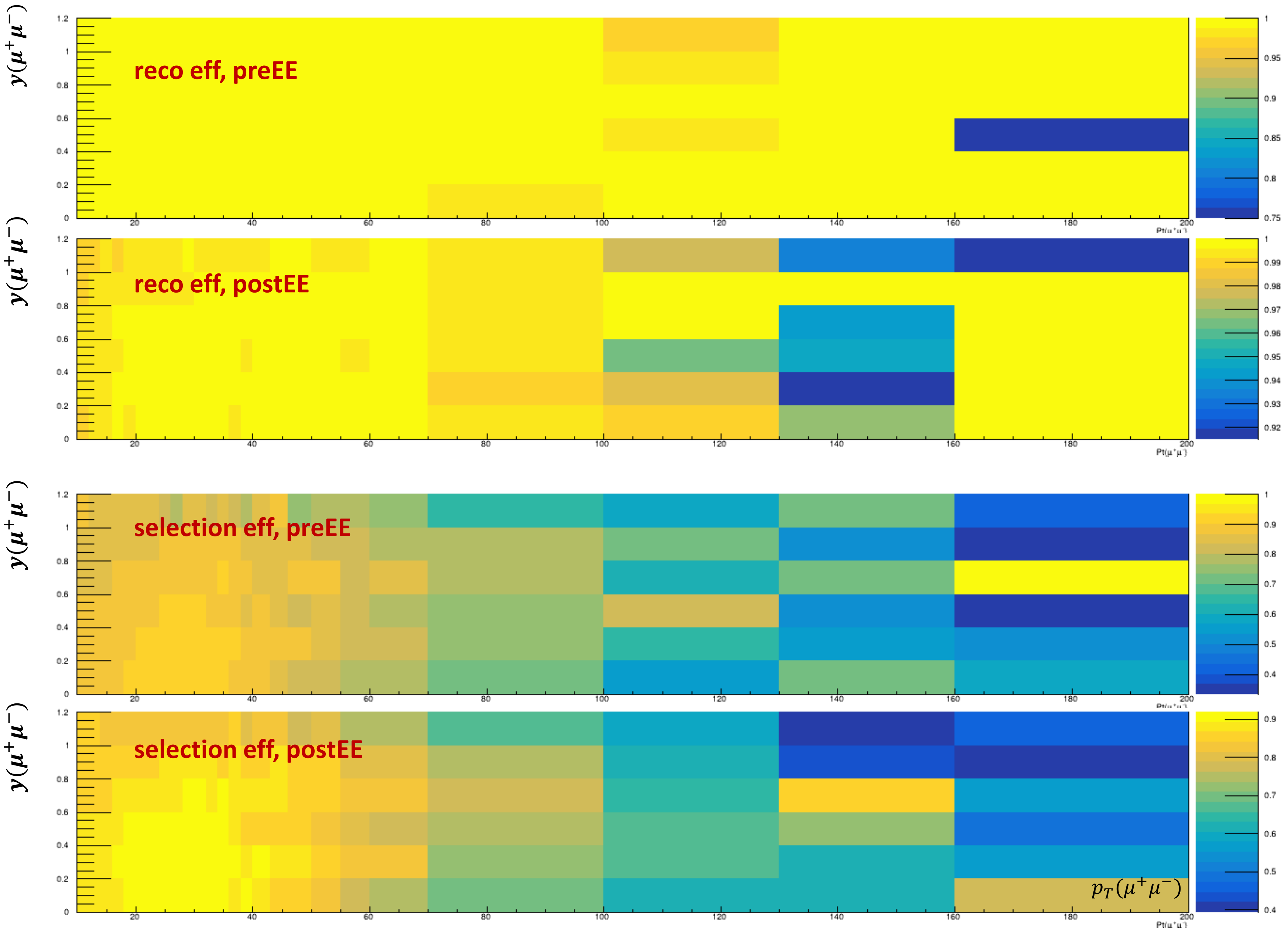
$$BR(\Upsilon \rightarrow \mu^+\mu^-) \times \frac{d^2\sigma(p_T, y)}{dp_T dy} = \frac{N^{\Upsilon}_{corrected}(p_T, y)}{L\Delta y \Delta p_T}$$

$$= \frac{N^{\Upsilon}(p_T, y) \cdot \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)}}{L\Delta y \Delta p_T}$$

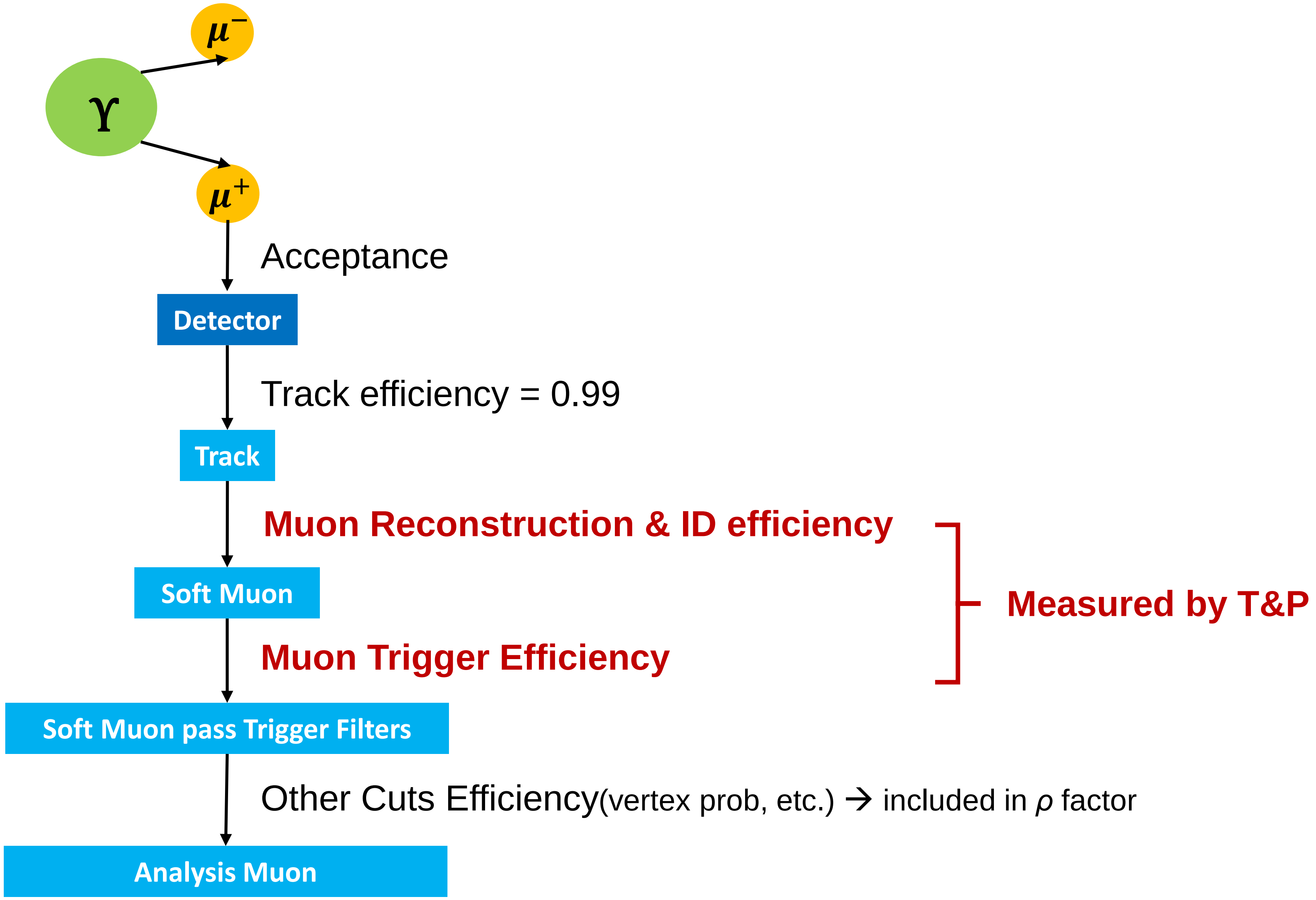
$$= \frac{N^{\Upsilon}(p_T, y) \cdot \frac{1}{\epsilon_{reco}(p_T, y)\epsilon_{cuts}(p_T, y)\mathcal{A}(p_T, y)}}{L\Delta y \Delta p_T}$$

- Data are split into 50 bins in total:
  - y bins: $0 < |y| < 0.6$ and $0.6 < |y| < 1.2$
  - p_T bins: 15 bins of 2 GeV in 10-40 GeV
    10 bins of 40-43, 43-46, 46-50, 50-55, 55-60,
    60-70, 70-100, 100-130, 130-160, 160-200 GeV
    Same as 13 TeV in the shared range — easy to compare

Efficiencies



Tag and Probe — Single Muon Efficiency



Υ

μ^-

μ^+

Acceptance

Detector

Track efficiency = 0.99

Track

Muon Reconstruction & ID efficiency

Soft Muon

Muon Trigger Efficiency

Measured by T&P

Soft Muon pass Trigger Filters

Other Cuts Efficiency(vertex prob, etc.) → included in ρ factor

Analysis Muon

Tag and Probe — Single Muon Efficiency

- Track efficiency = 0.99
- Reconstruction & ID efficiency
- Trigger Efficiency

$$\varepsilon_{\mu}\ (p_T, \eta) = 0.99\ \varepsilon_{RECO\_ID}\ \varepsilon_{Trigger}$$

For each step: $\epsilon = \frac{\text{fit peak area of passing probe}}{\text{fit peak area of previous passing probe}}$

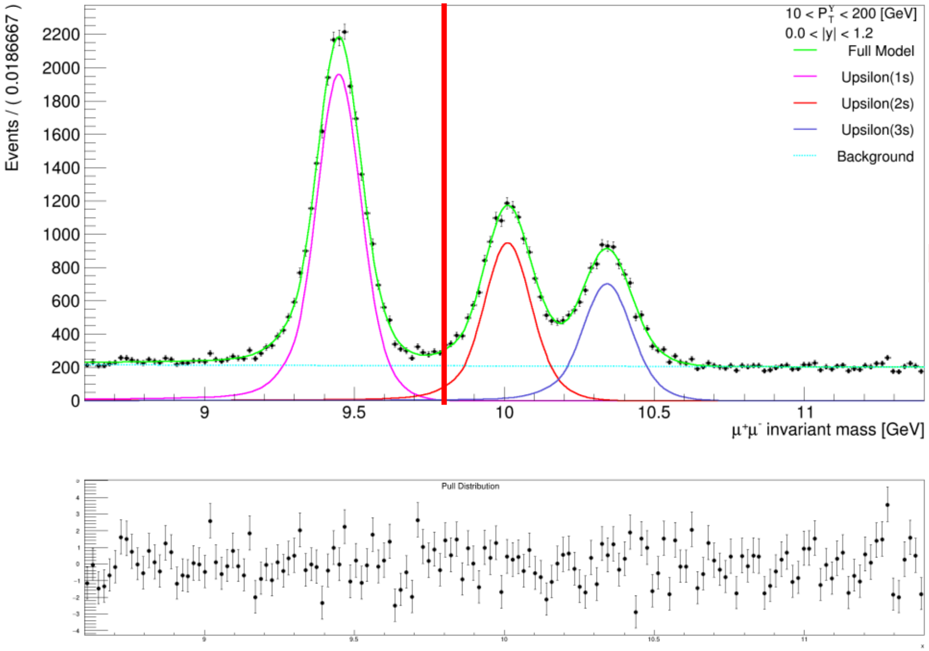
Use Run-3 2022 Muon datasets

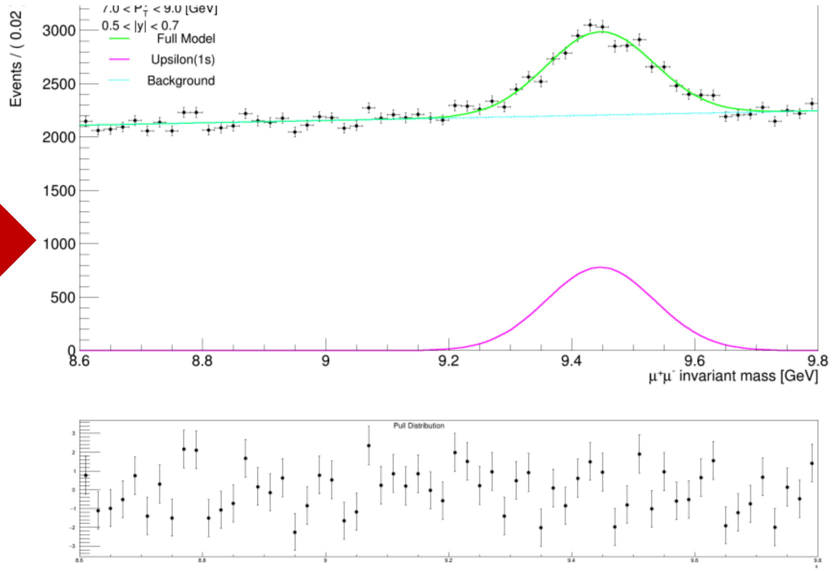
Data Samples	**Run Range**	**Integral Luminosity**
/Muon/Run2022C-22Sep2023-v1/MINIAOD	357538-357733	$8.08\ fb^{-1}$ (CD – preEE period)
/Muon/Run2022D-22Sep2023-v1/MINIAOD	357734-357900	
/Muon/Run2022E-22Sep2023-v1/MINIAOD	359356-360327	$27.09 fb^{-1}$ (EFG – postEE period)
/Muon/Run2022F-PromptReco-v1/MINIAOD	360390-362167	
/Muon/Run2022G-PromptReco-v1/MINIAOD	362433-362760	

Tag and Probe — Single Muon Efficiency

Only use $\Upsilon(1S)$ to calculate

- One peak of mass is easy to fit
- Accurate for our analysis





8.6 - 9.8 GeV

Tag and Probe — Single Muon Efficiency

- Split into 42 μ kinetic bins in total:

η^{μ} bins: $|\eta^{\mu}| \in [0, 0.2, 0.3, 0.5, 0.7, 0.9, 1.2]$

p_{T}^{μ} bins: $p_{\mathrm{T}}^{\mu} \in [3.6, 5.5, 7.5, 10, 14, 19, 25, 40]$

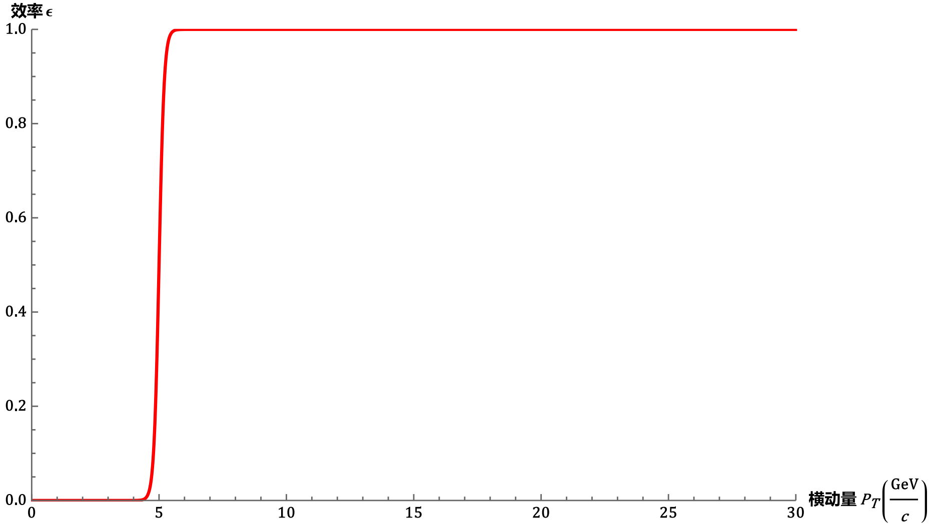
- Use (exp*) sigmoid function fit to get single muon efficiency for any p_T

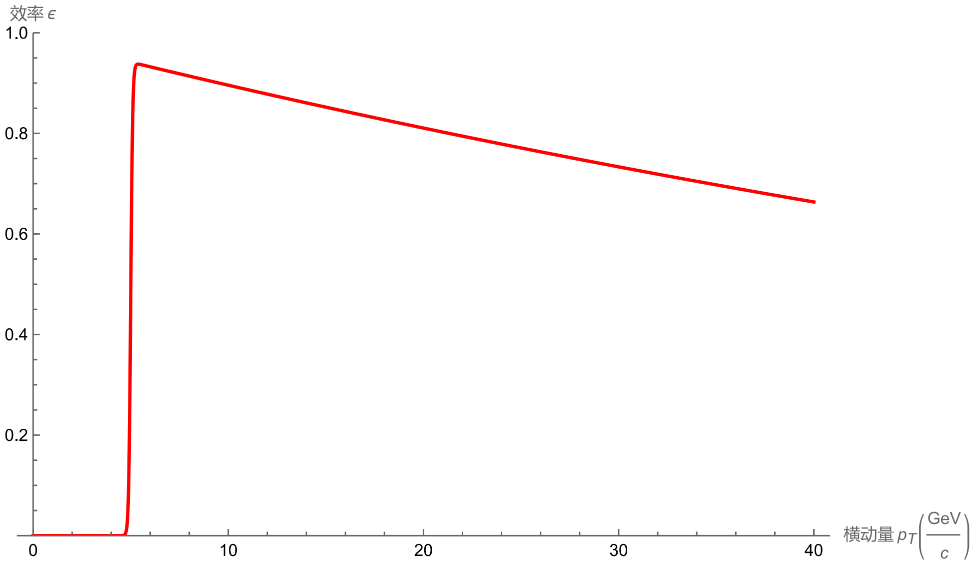
Sigmoid function

$$\varepsilon = \frac{\varepsilon_0}{1 + e^{-\alpha(p_T - p_{T0})}}$$

exp * Sigmoid function

$$\varepsilon = e^{-\frac{p_T}{\beta}} \frac{\varepsilon_0}{1 + e^{-\alpha(p_T - p_{T0})}}$$





If efficiency decreases in high p_T region.

Tag and Probe — Single Muon Efficiency

Pre-selection

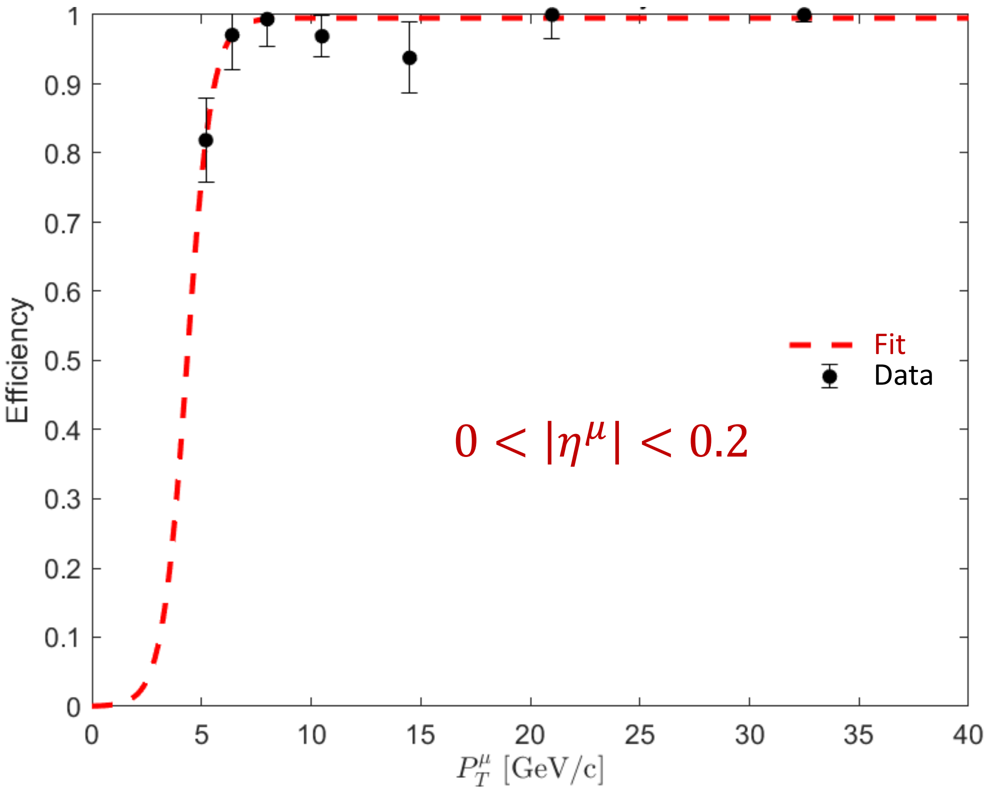
- Use MuonAnalyzer package for Tag&Probe ntuple:
  - Mass window: 8.6 GeV < m(Tag,Probe) < 11.4 GeV
  - Pair dz < 10.1 cm
  - Tag.vz-Probe.vz < 1 cm
  - Matched to track: [pt(mu)-pt(track)]/pt(track) < 1.0
  - Kills pair without vertex
- Tag selection
  - Global Muon
  - NumberOfMatched-Stations > 0
  - p_T > 8 GeV
  - Matched to muon in HLT_Mu8/15/17/19/20/27/50_v or HLT_IsoMu20/24_v
- Probe selection
  - p_T > 3 GeV
  - Dr / offline < 0.06
  - highPurity track

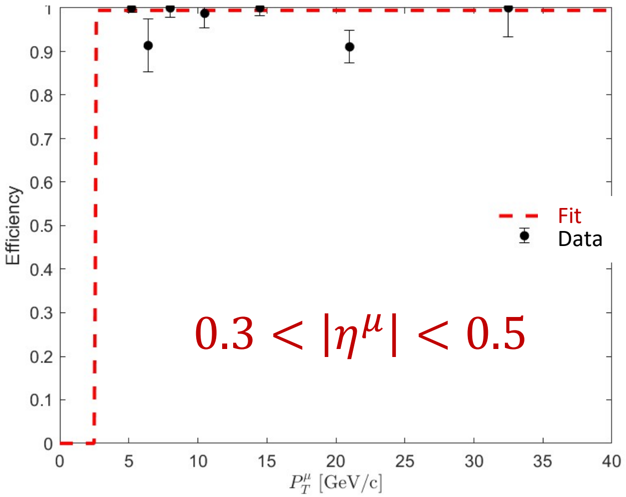
Tag and Probe — Single Muon Efficiency

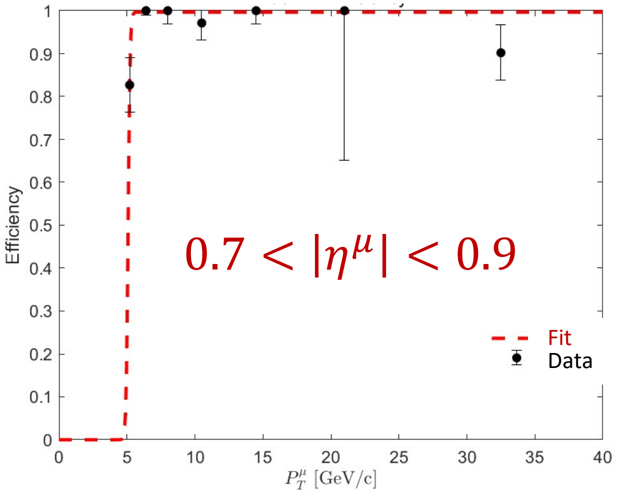
Muon Reconstruction & ID efficiency

- **All probe**: track passing pre-selection
- Passing probe： Soft ID probe
- Fit with sigmoid function

$$\epsilon_{\text{reco\&ID}} = \frac{\text{fit peak area of passing probe}}{\text{fit peak area of all probe}}$$







Tag and Probe — Single Muon Efficiency

Muon Trigger efficiency

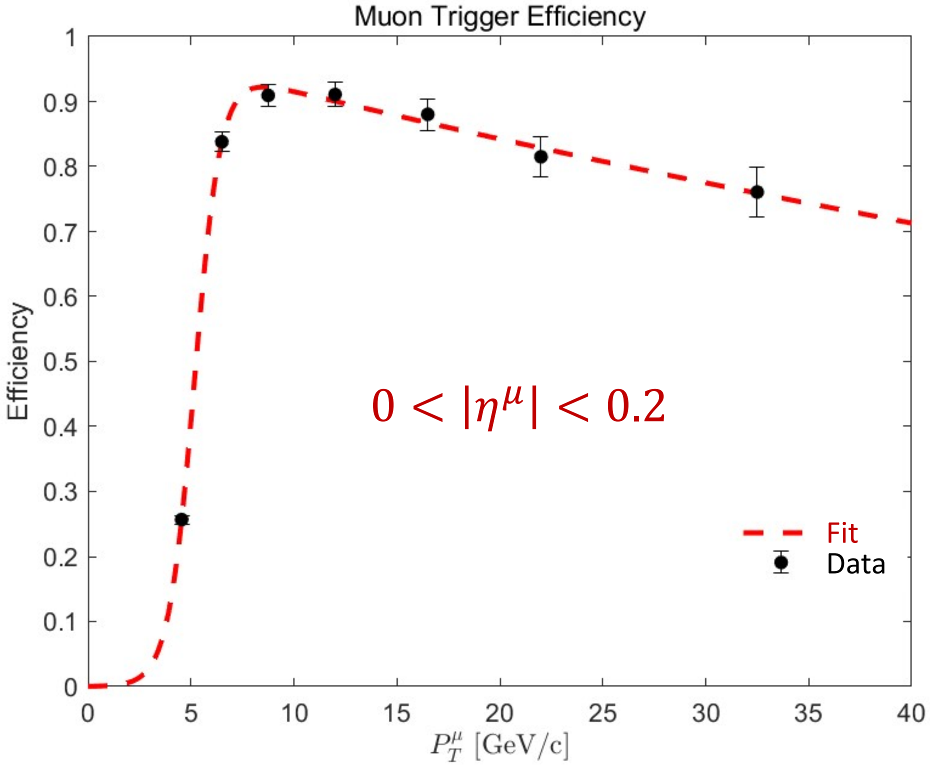
- **Passing probe**: Soft ID probe passing L1L2L3 filters of HLT_Dimuon10_Upsilon_y1p4_v

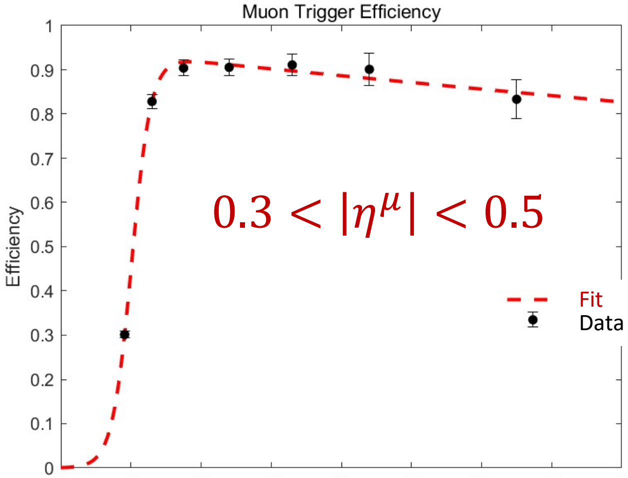
L1L2: hltL2fL1sL1s12DoubleMu4p5er2p0SQOSMass7to18L1f0L2v2PreFiltered0

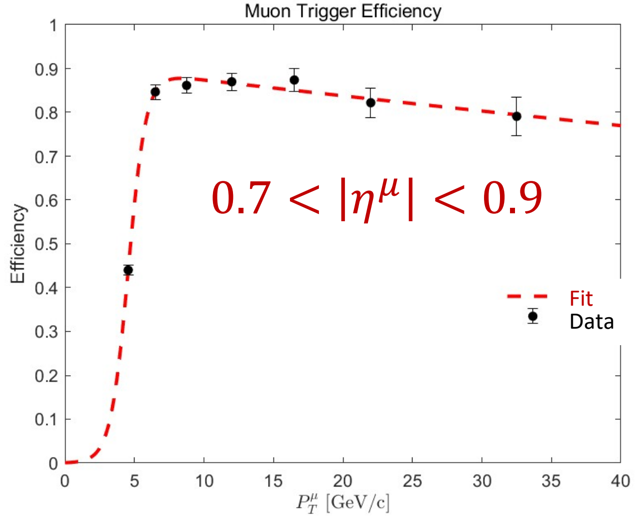
L3: hltL1fForIterL3L1fL1sL1s12DoubleMu4p5er2p0SQOSMass7to18L1v2Filtered0

- Fit with exp * sigmoid function

$$\epsilon_{\text{trigger}} = \frac{\text{fit peak area of passing probe}}{\text{fit peak area of Soft ID muon probe}}$$



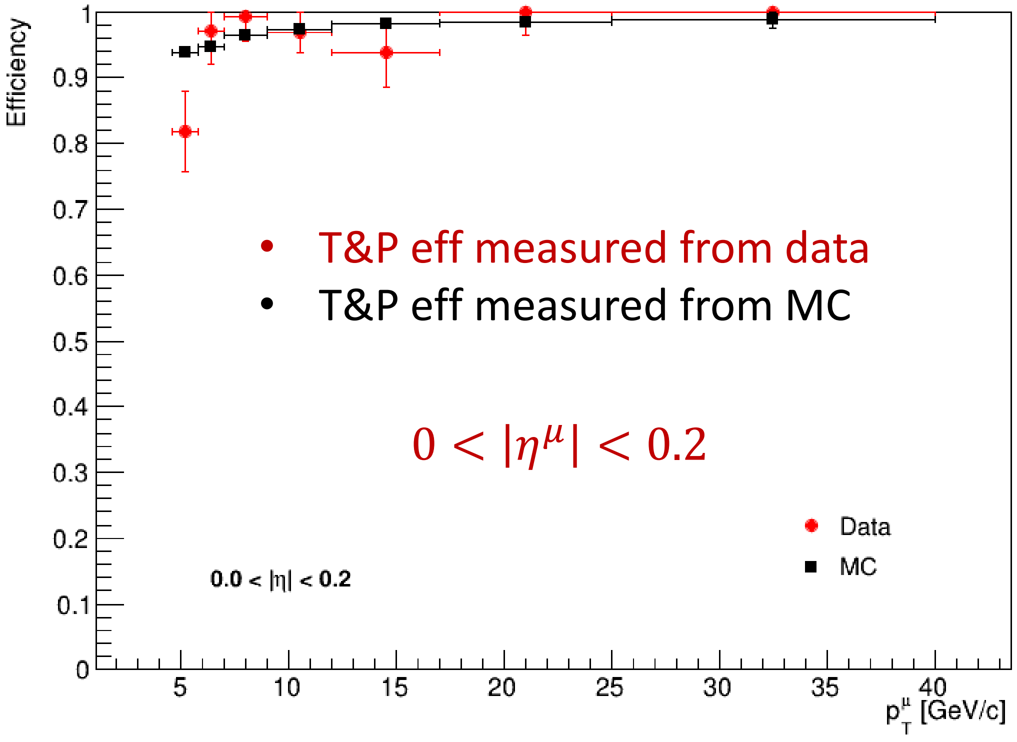




Comparison with MC Single Muon Efficiency

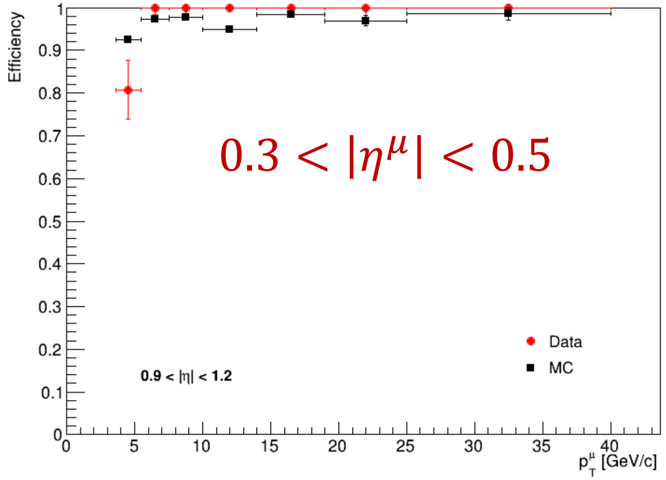
- Measured from official Monte Carlo sample using T&P
- Same selection and code with data single Muon Efficiency calculation

Muon Reconstruction & ID efficiency

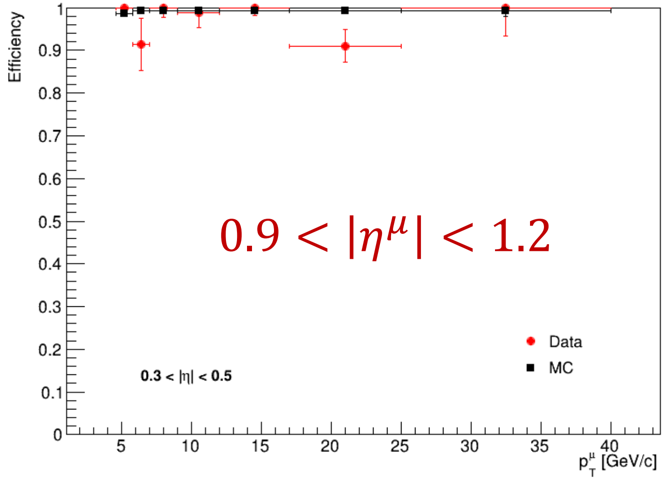


- T&P eff measured from data
- T&P eff measured from MC

$0 < |\eta^\mu| < 0.2$



$0.3 < |\eta^\mu| < 0.5$

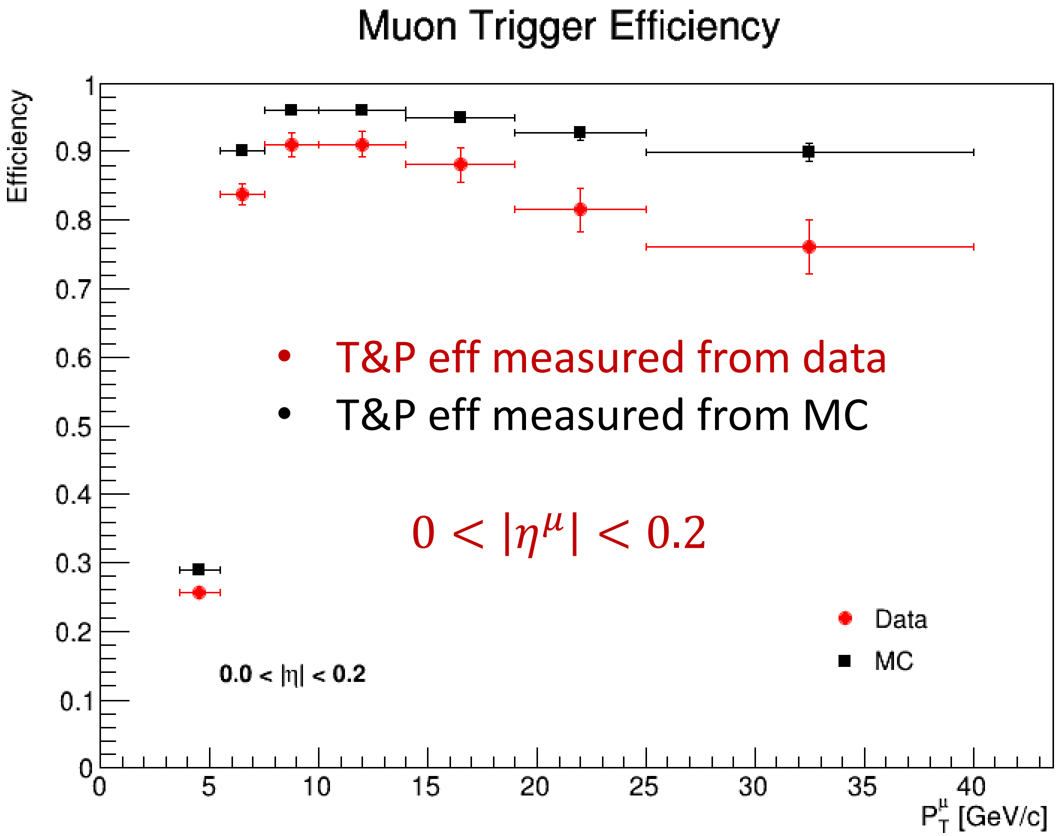


$0.9 < |\eta^\mu| < 1.2$

The differences are negligible for most bins.

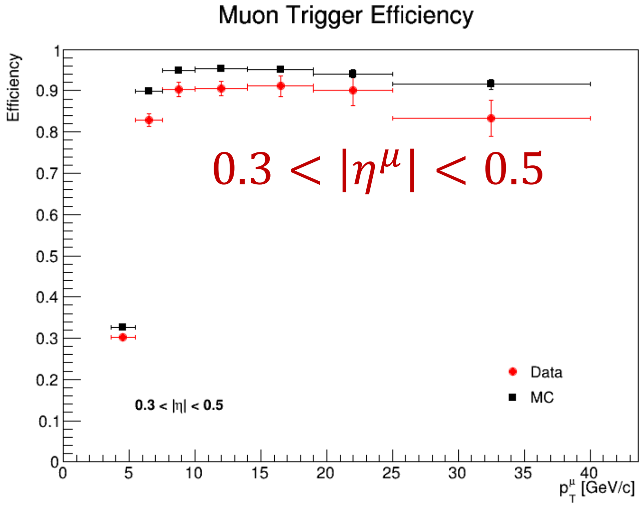
Data and MC Single Muon Efficiency Comparison

Muon Trigger efficiency

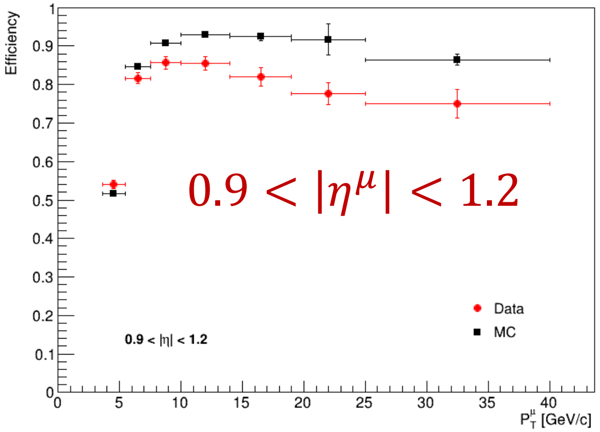


- T&P eff measured from data
- T&P eff measured from MC

$0 < |\eta^{\mu}| < 0.2$



$0.3 < |\eta^{\mu}| < 0.5$



$0.9 < |\eta^{\mu}| < 1.2$

Muon trigger efficiencies measured from MC are larger than those from data.

Cross section results now use MC truth efficiency.

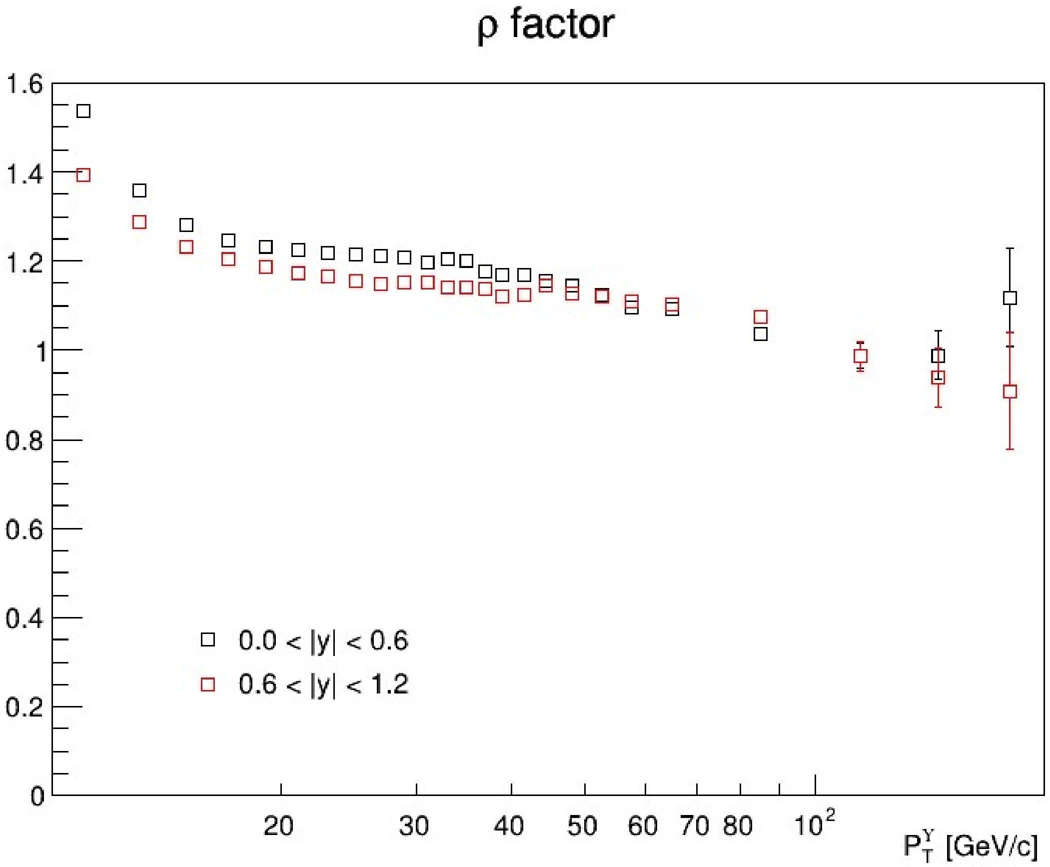
Final results will use T&P single muon efficiency measured from data.

ρ factor

$\Upsilon \rightarrow \mu^{+}\mu^{-}$

$$\rho(p_{\mathrm{T}}^{\Upsilon}, y^{\Upsilon}) = \frac{\Upsilon \text{ efficiency measured from MC truth}}{\mu^{+} \times \mu^{-} \text{ efficiency measured from MC using T\&P}}$$

- Use official Monte Carlo sample
- Split into 50 Υ kinetic bins (same as cross section results)



Negative correlation to the p_T^{Υ}

Weight

$\Upsilon(p_T, y) \rightarrow \mu^+\mu^-$ $\quad \epsilon(p_T, y) = \epsilon^{\mu^+}(p_T^{\mu^+}, \eta^{\mu^+})\epsilon^{\mu^-}(p_T^{\mu^-}, \eta^{\mu^-})\rho(p_T, y)$

- **Weighted Fit**

Weight of the $\Upsilon(p_T, y)$ event $\quad \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)}$

- **Fit-then-weight**

Weight of the $\Upsilon(p_T, y)$ bin $\quad \left\langle \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)} \right\rangle_{(p_T, y)\ \mathrm{bin}}$

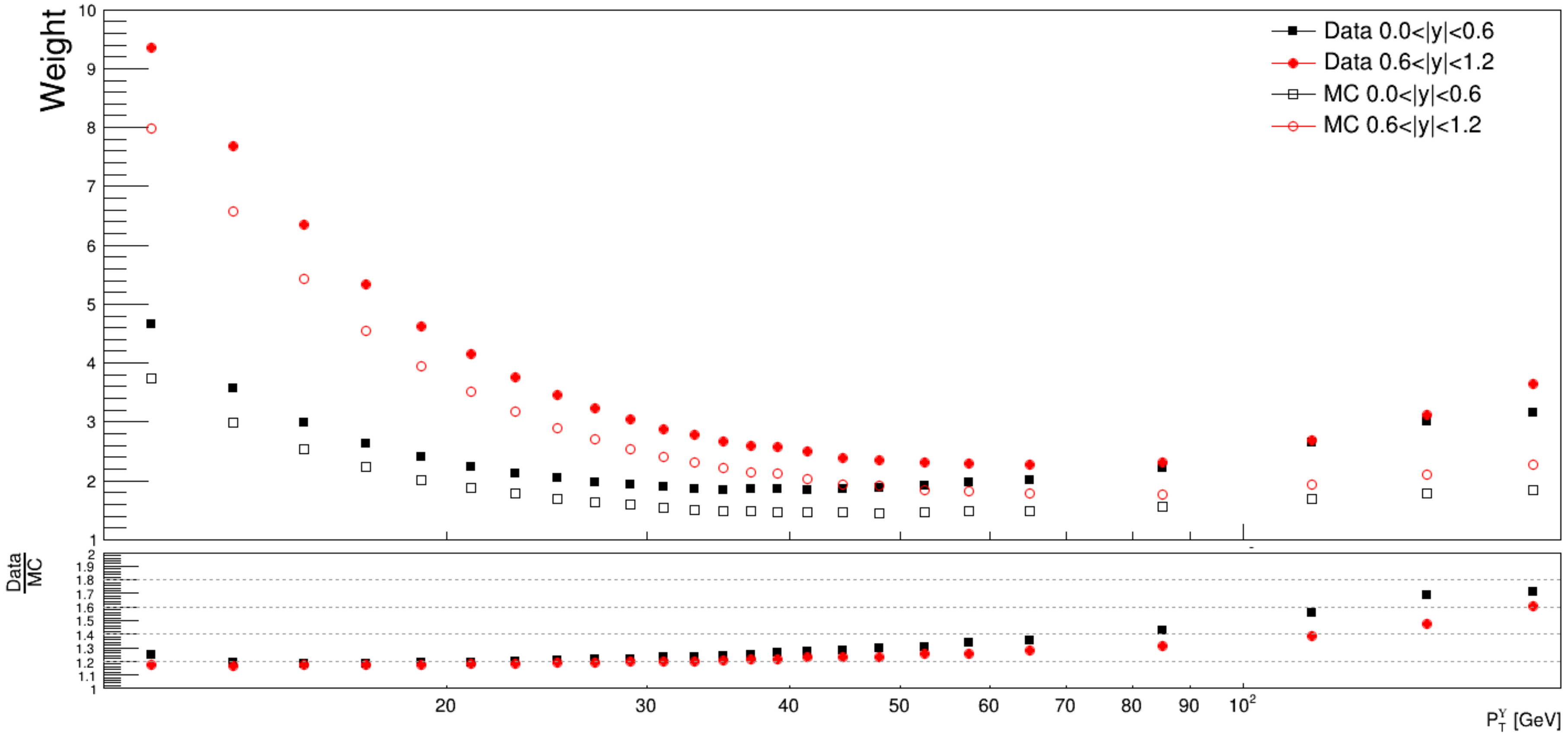
Results now use weighted fit method with efficiency from MC truth.

Final results will use fit-then-weight method with T&P data efficiency.

Comparison Between MC and Data Bin Weight

- Fit-then-weight

Weight of the $\Upsilon(p_T, y)$ bin $\left\langle \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)} \right\rangle_{(p_T,y)}$ bin



Signal Muon Efficiency Difference →

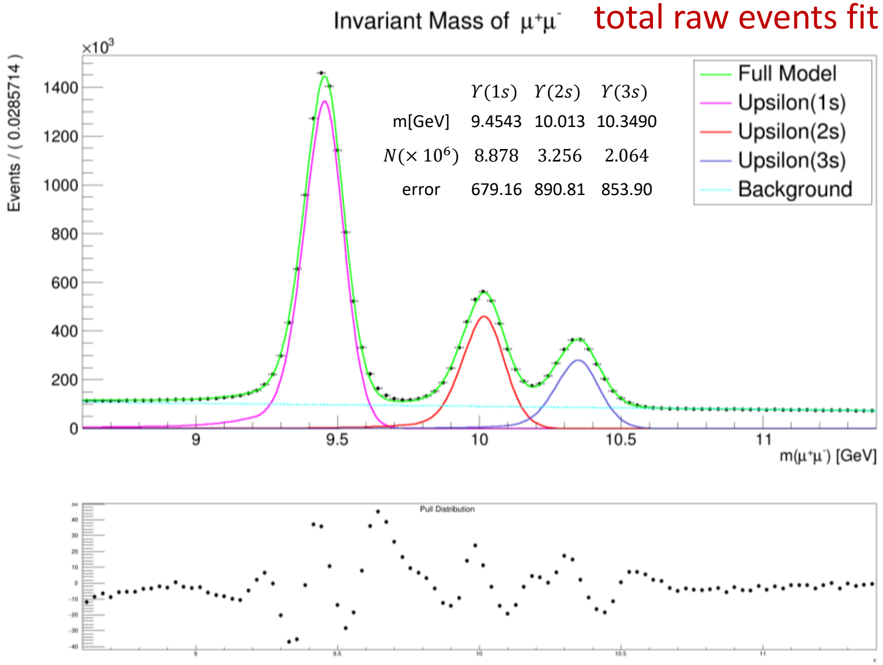
Bin weights measured from MC are smaller than those from data

Yield Extraction

$$BR(\Upsilon \to \mu^+\mu^-) \times \frac{d^2\sigma(p_T,y)}{dp_T dy} = \frac{N^{\Upsilon}_{corrected}(p_T,y)}{L\Delta y \Delta p_T} = \frac{N^{\Upsilon}(p_T,y)\cdot \frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)}}{L\Delta y\Delta p_T} = \frac{N^{\Upsilon}(p_T,y)\cdot \frac{1}{\epsilon_{reco}(p_T,y)\epsilon_{cuts}(p_T,y)\mathcal{A}(p_T,y)}}{L\Delta y\Delta p_T}$$

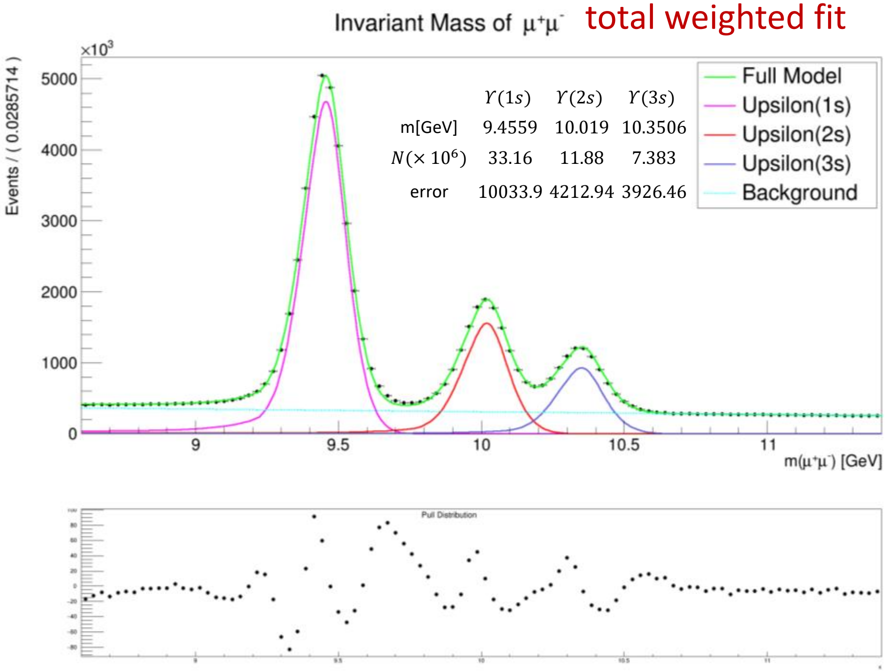
The weight of the **$\Upsilon(p_T, y)$ event**

- Signal PDF: Double Crystalball for each $\Upsilon(nS)$ peak. $n = 1,2,3$
  - Each di-CB shares the same $\alpha_{1,2}$ and $n_{1,2}$
    - $n_{1,2}$ fixed from a large data sample $p_T \in (20,40)$, $|y| \in (0,0.6)$
    - $\alpha_{1,2}$ float
  - Mass gaps $\Delta m\big(\Upsilon(1S), \Upsilon(2,3S)\big)$ are fixed according to PDG, and $m_{\Upsilon(1S)}$ floats
  - Widths of $\Upsilon(ns)$ are set to satisfy: $\frac{\sigma_{\Upsilon(ns)}}{m_{\Upsilon(ns)}} = constant\ (n = 1,2,3)$
- Background PDF: 1st order polynomial



total raw events fit

	$\Upsilon(1s)$	$\Upsilon(2s)$	$\Upsilon(3s)$
m[GeV]	9.4543	10.013	10.3490
$N(\times 10^6)$	8.878	3.256	2.064
error	679.16	890.81	853.90



total weighted fit

	$\Upsilon(1s)$	$\Upsilon(2s)$	$\Upsilon(3s)$
m[GeV]	9.4559	10.019	10.3506
$N(\times 10^6)$	33.16	11.88	7.383
error	10033.9	4212.94	3926.46

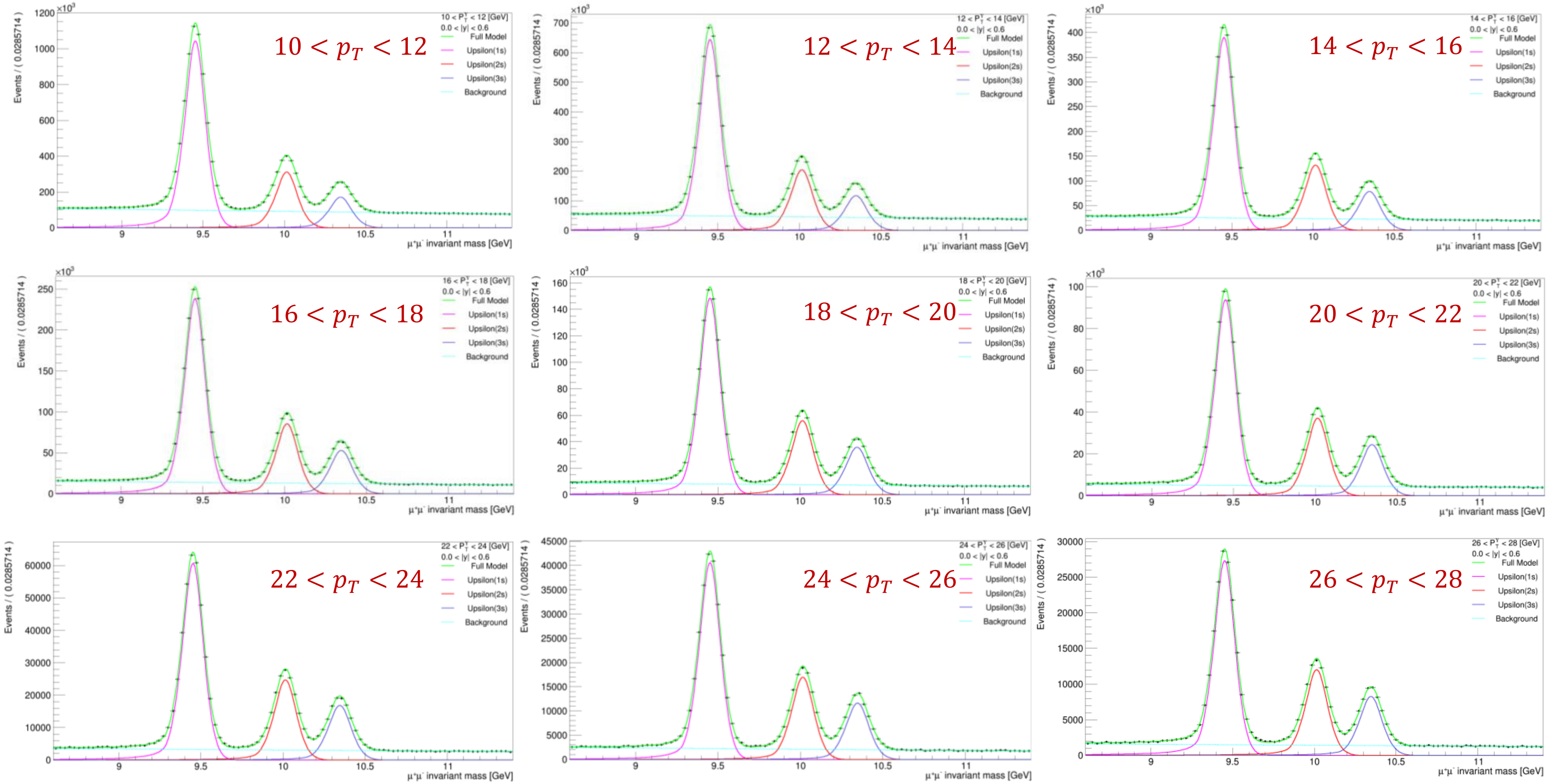
Weighted fit is performed on each (p_T, y) bin for the differential cross section measurements

Yield Extraction

$$BR(\Upsilon \rightarrow \mu^+\mu^-) \times \frac{d^2\sigma(p_T,y)}{dp_T dy} = \frac{N^{\Upsilon}_{corrected}(p_T,y)}{L\Delta y \Delta p_T} = \frac{N^{\Upsilon}(p_T,y)\frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)}}{L\Delta y \Delta p_T} = \frac{N^{\Upsilon}(p_T,y)\frac{1}{\epsilon_{reco}(p_T,y)\epsilon_{cuts}(p_T,y)\mathcal{A}(p_T,y)}}{L\Delta y \Delta p_T}$$

The weight of the $\boldsymbol{\Upsilon(p_T, y)}$ **event**

- Weighted fits results of 9 bins with $0 < |y| < 0.6$ (out of 50)

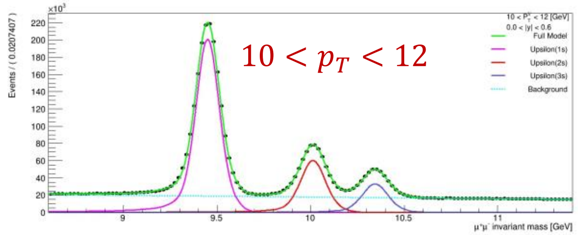


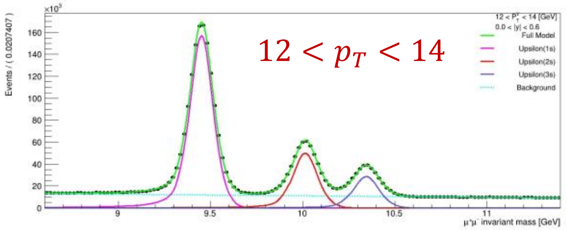
Yield Extraction

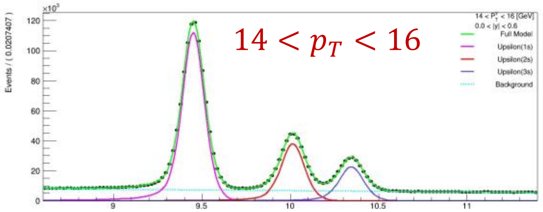
$$BR(\Upsilon \to \mu^+\mu^-) \times \frac{d^2\sigma(p_T,y)}{dp_T dy} = \frac{N^{\Upsilon}_{corrected}(p_T,y)}{L\Delta y \Delta p_T} = \frac{N^{\Upsilon}(p_T,y)\left\langle \frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)} \right\rangle}{L\Delta y \Delta p_T} = \frac{N^{\Upsilon}(p_T,y)\left\langle \frac{1}{\epsilon_{reco}(p_T,y)\epsilon_{cuts}(p_T,y)\mathcal{A}(p_T,y)} \right\rangle}{L\Delta y \Delta p_T}$$

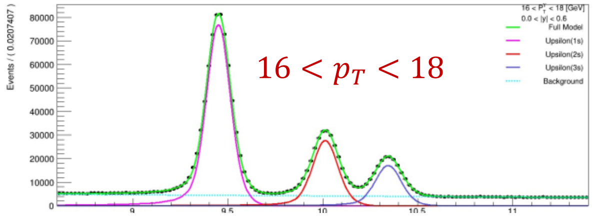
The weight of the $\boldsymbol{\Upsilon(p_T, y)}$ **bin**

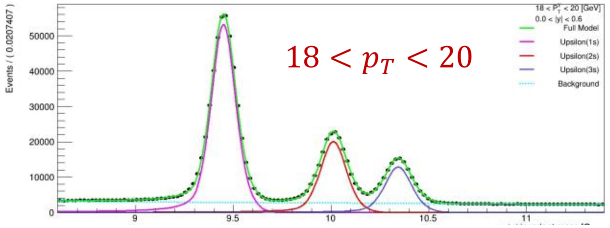
- Raw fits are also performed → Final results will use fit-then-weight method
- Raw fits results of 9 bins with $0 < |y| < 0.6$ (out of 50)

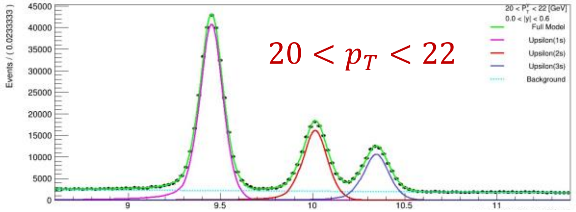


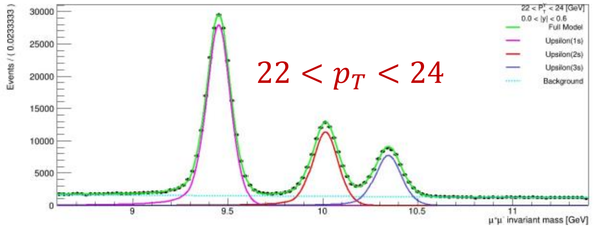


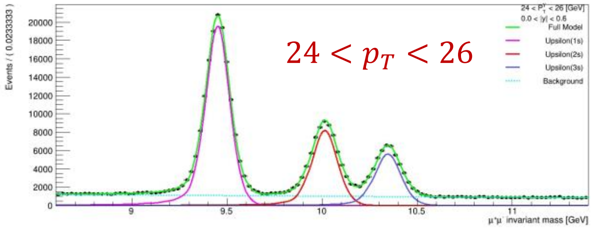


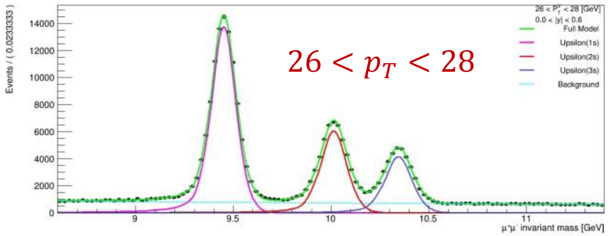












Systematic Uncertainties

$20 \text{ GeV} < p_T < 40 \text{ GeV}$
$|y| < 0.6$

- Uncertainties on Yield: vary pdf parameters one at a time
  - For the $\Upsilon(1S, 2S, 3S)$ signal, vary $n_{1,2}$ by $\pm 5\sigma_{n_1,n_2}$, fix $\alpha_{1,2}$ from data
  - Free $\mathrm{m}_{\Upsilon(1S)}$, $\mathrm{m}_{\Upsilon(2S)}$ and $\mathrm{m}_{\Upsilon(3S)}$ without any constraints among them
  - Replace the background PDF with an exponential shape
- Uncertainties on Acceptance and Efficiency
  - The cross section $\sigma(p_T, y)$ is proportional to $\frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)}$
  - Put the statistical uncertainties into the error propagation equation
  - Uncertainties on eff will be replaced by uncertainties of T&P once T&P study finished
- Uncertainty on Luminosity = 1.4%

Total Systematic Uncertainty = RMS of all uncertainties mentioned above

Uncertainties on the Integrated Rapidity Ranges: merge y bins altogether

- Syst. uncertainties on yields = Uncertainties on yield in Integrated Rapidity Ranges
- Other Syst. uncertainties = weighted average of those from individual y bins

Closure Test for Acceptances and Efficiencies

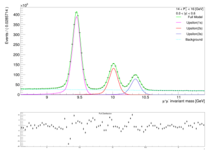
- Performed with a private full-chain Monte Carlo sample generated by Pythia 8
- Without selective GEN filter

Data	Map-calculated yield	After-selection yield	Differences
Original data	80935	80935	None
Data after acceptance	51066	51130	0.12%
Data after RECO matching	50746	51071	0.64%
Data after selection	44183	44836	**1.46%**

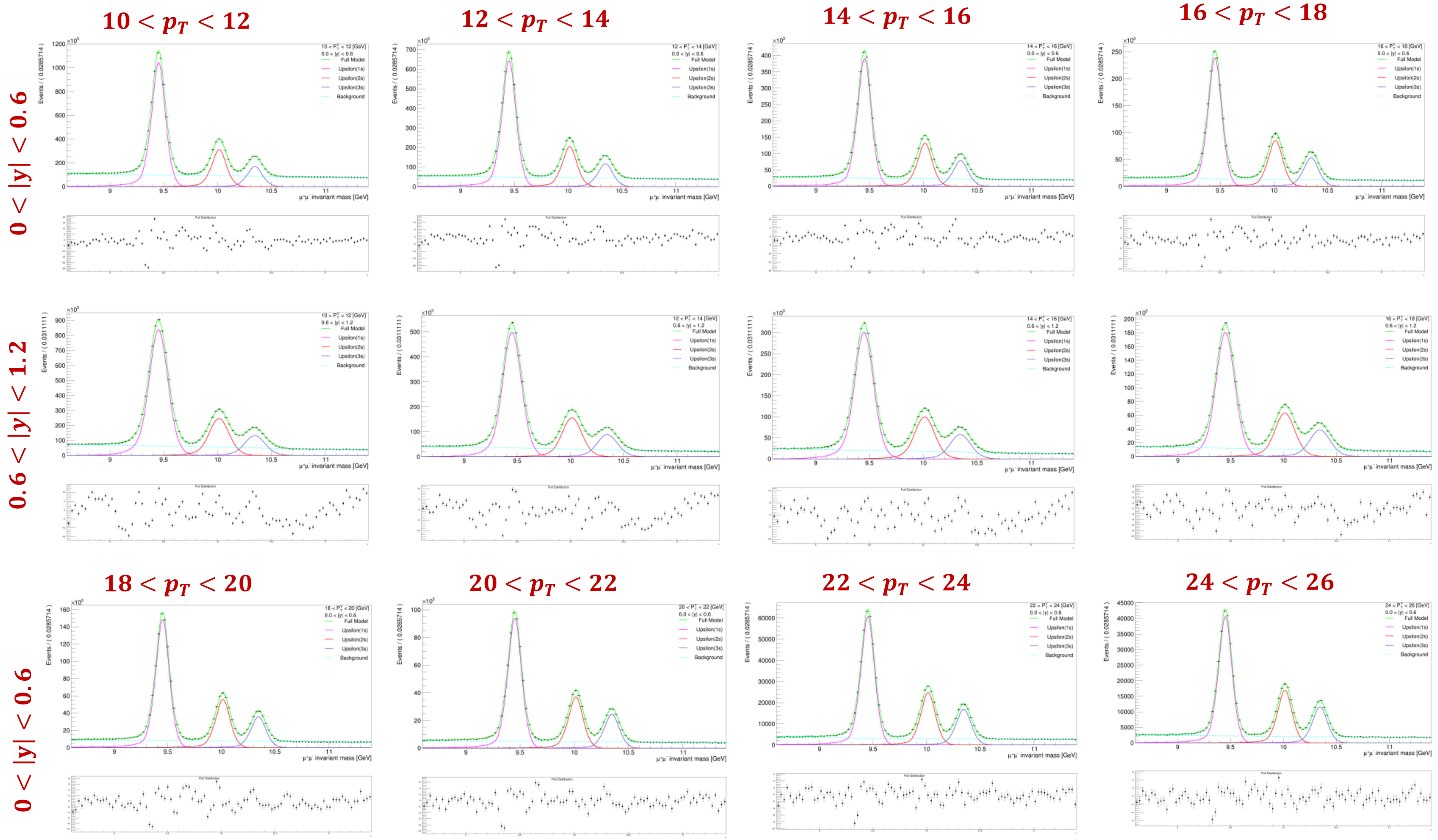
- Statistical uncertainty of acc and eff maps → already included
- Systematic uncertainty due to binning → test to be negligible

Test by using same MC sample for closure

test and acceptance&efficiency calculation



ned Weighted Fit



$10 < p_T < 12$ | $12 < p_T < 14$ | $14 < p_T < 16$ | $16 < p_T < 18$

$0 < |y| < 0.6$

$0.6 < |y| < 1.2$

$18 < p_T < 20$ | $20 < p_T < 22$ | $22 < p_T < 24$ | $24 < p_T < 26$

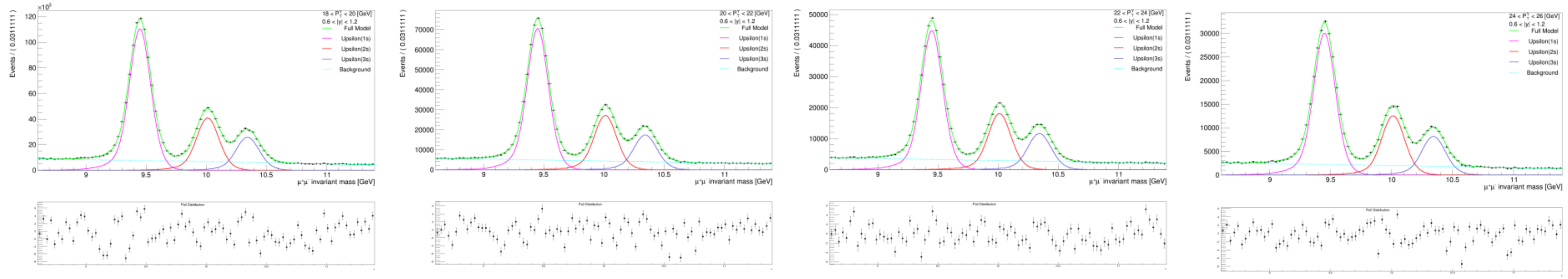
$0 < |y| < 0.6$

~20 times more data comparing with 13 TeV Run 2 analysis

Binned Weighted Fit

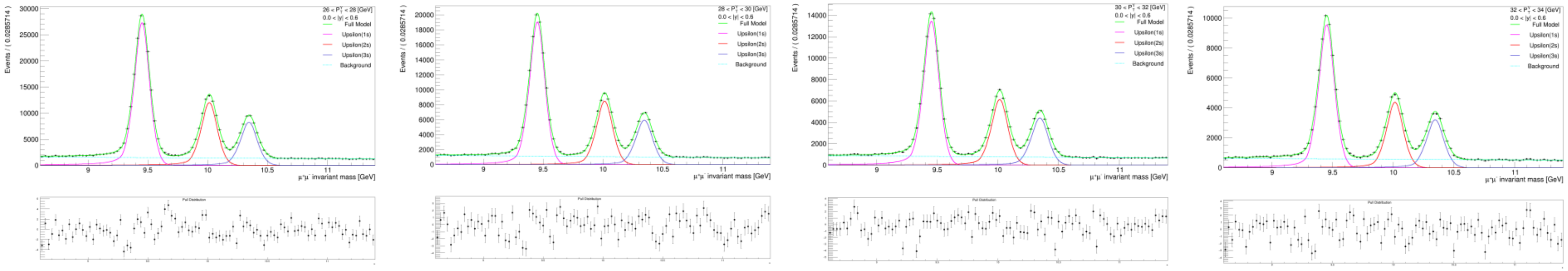
$18 < p_T < 20$ **$20 < p_T < 22$** **$22 < p_T < 24$** **$24 < p_T < 26$**

$0.6 < |y| < 1.2$

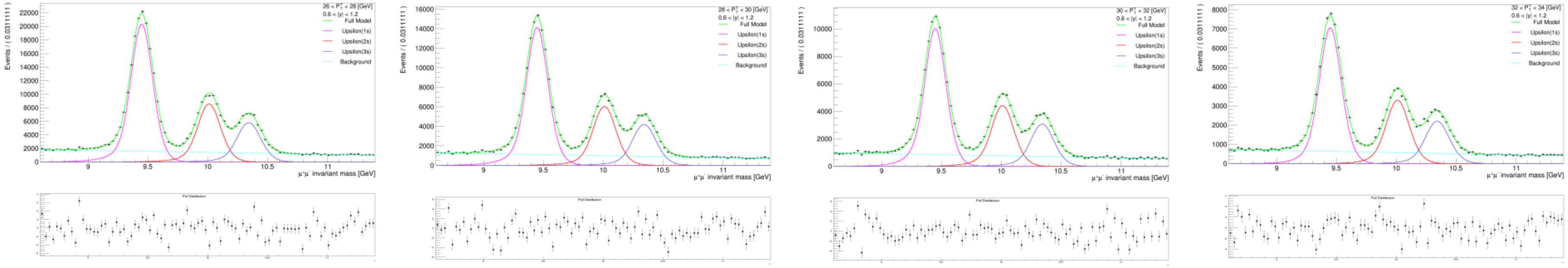


$26 < p_T < 28$ **$28 < p_T < 30$** **$30 < p_T < 32$** **$32 < p_T < 34$**

$0 < |y| < 0.6$



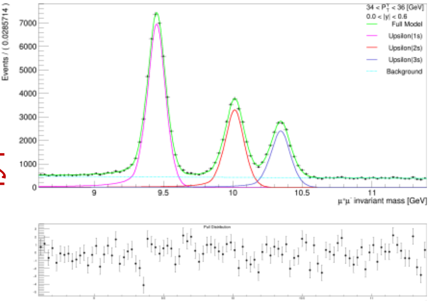
$0.6 < |y| < 1.2$



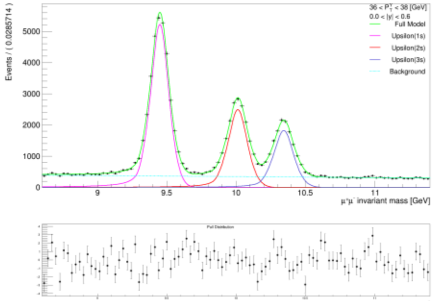
Binned Weighted Fit

$0 < |y| < 0.6$

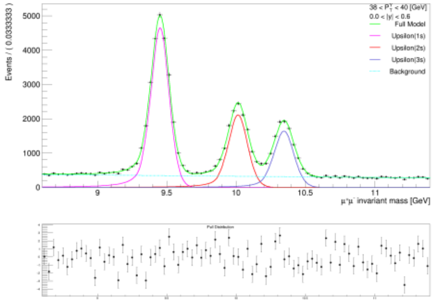
$34 < p_T < 36$



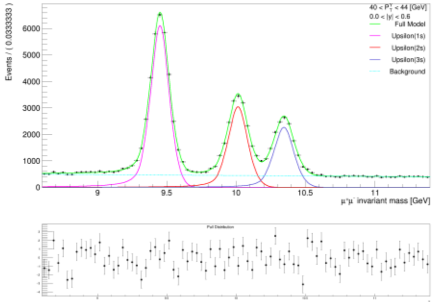
$36 < p_T < 38$



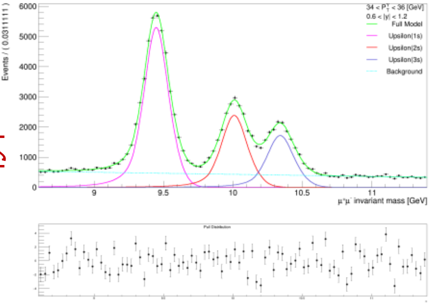
$38 < p_T < 40$

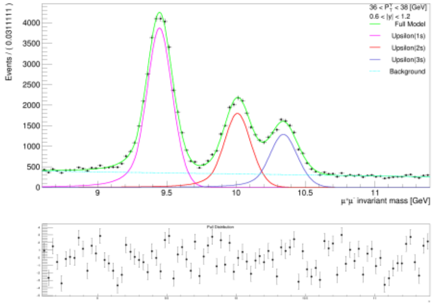


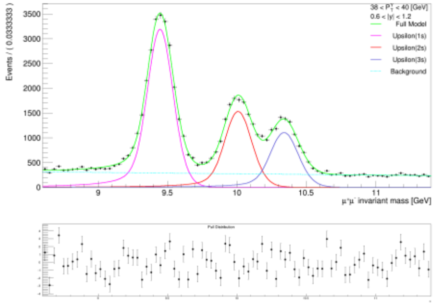
$40 < p_T < 44$

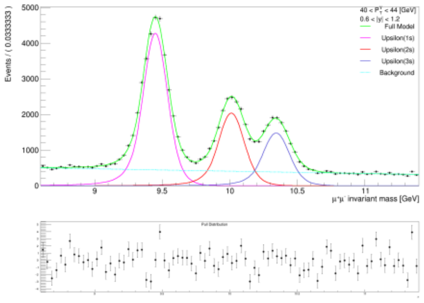


$0.6 < |y| < 1.2$



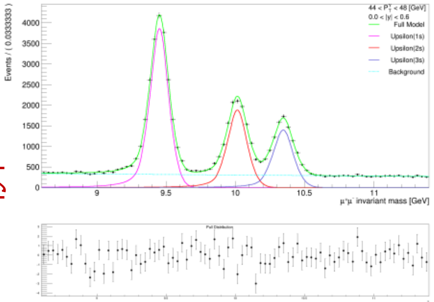




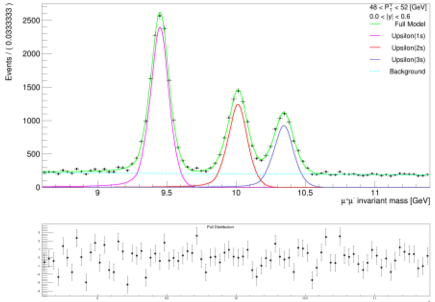


$0 < |y| < 0.6$

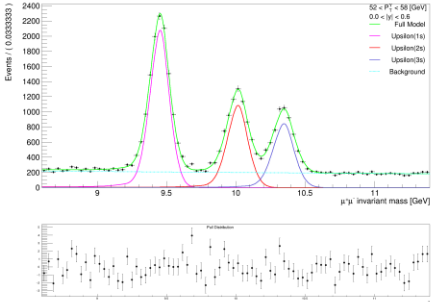
$44 < p_T < 48$



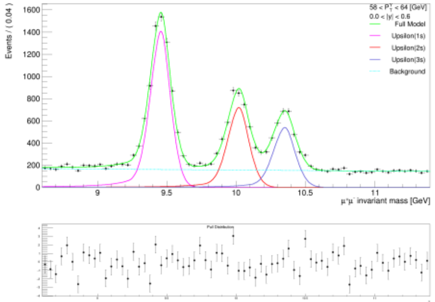
$48 < p_T < 52$



$52 < p_T < 58$



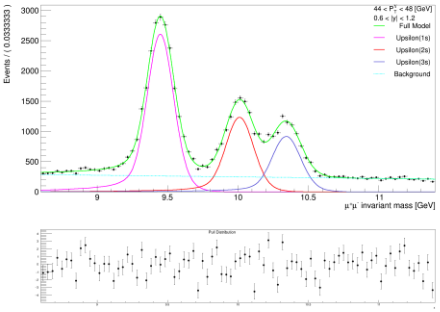
$58 < p_T < 64$



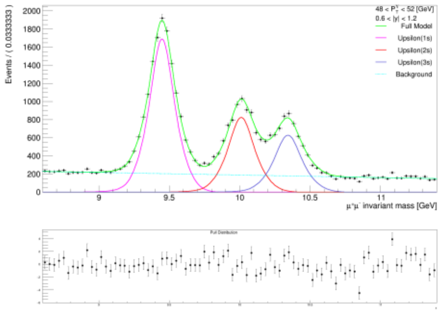
Binned Weighted Fit

$0.6 < |y| < 1.2$

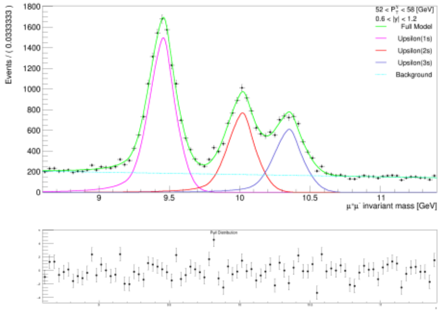
$44 < p_T < 48$



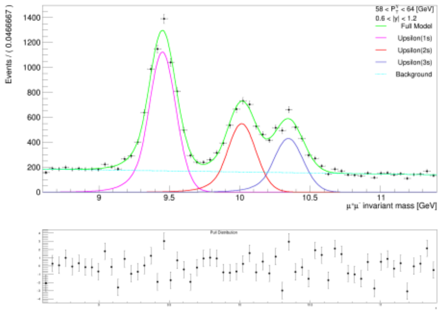
$48 < p_T < 52$



$52 < p_T < 58$

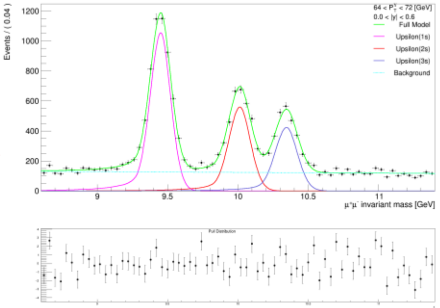


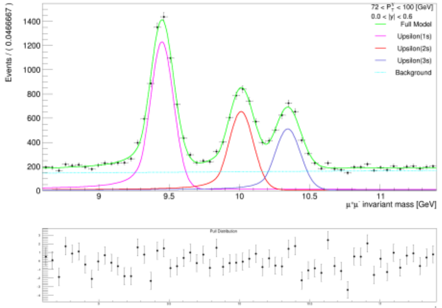
$58 < p_T < 64$

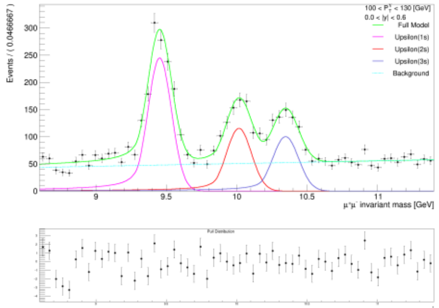


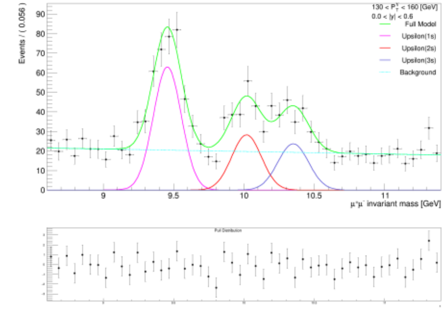
$64 < p_T < 72$ **$72 < p_T < 100$** **$100 < p_T < 130$** **$130 < p_T < 160$**

$0 < |y| < 0.6$

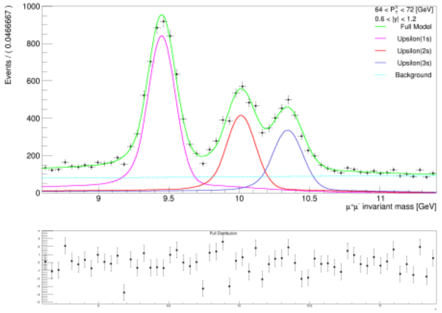


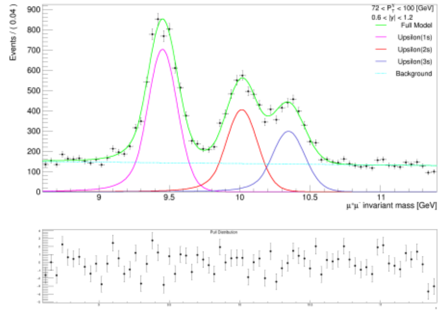


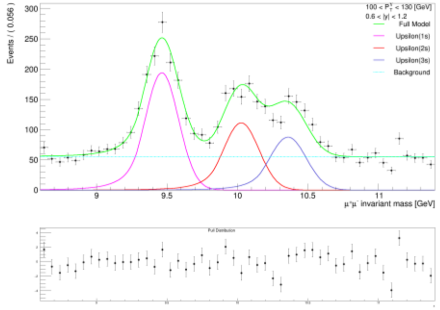


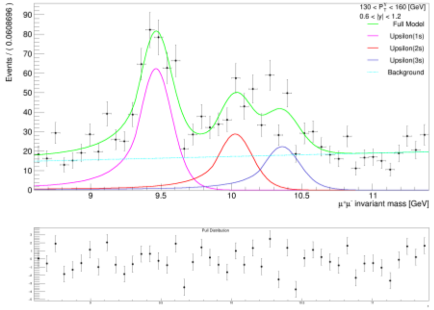


$0.6 < |y| < 1.2$





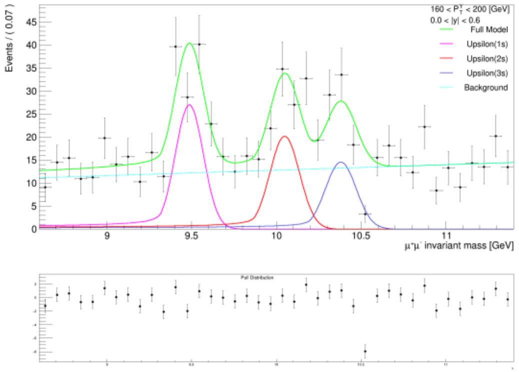




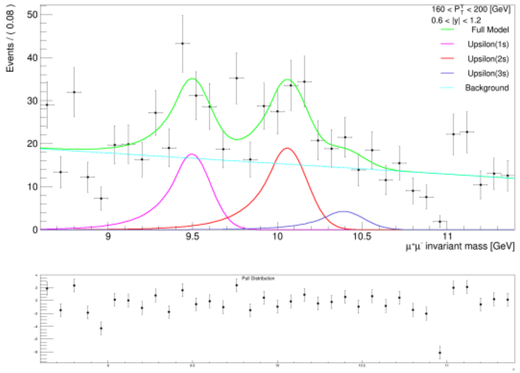
Binned Weighted Fit

$160 < p_T < 200$

$0 < |y| < 0.6$



$0.6 < |y| < 1.2$

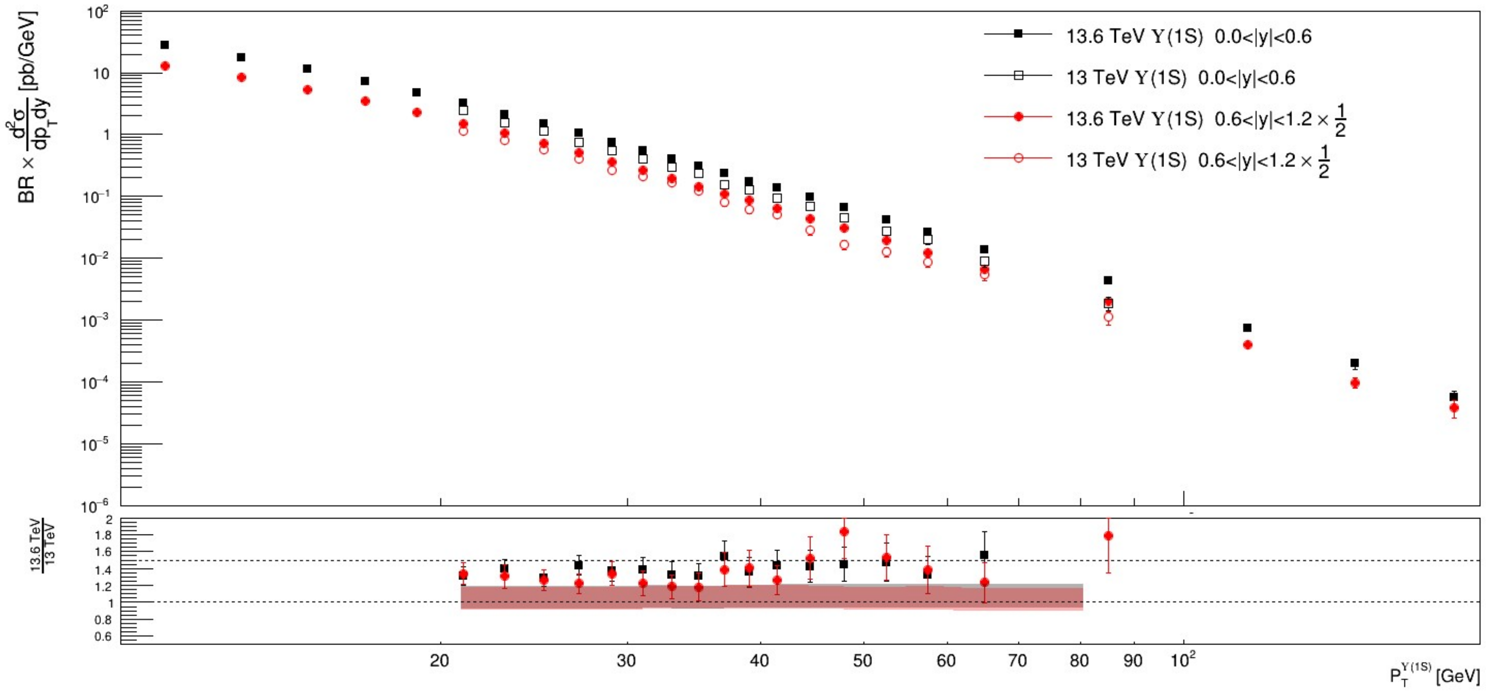


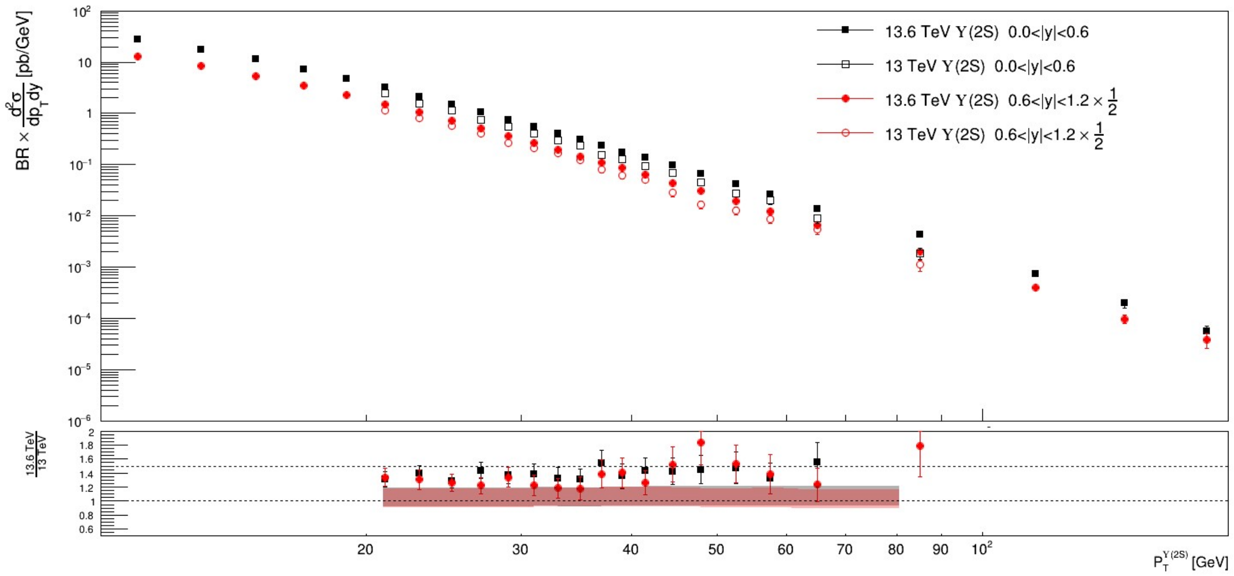
Total cross section

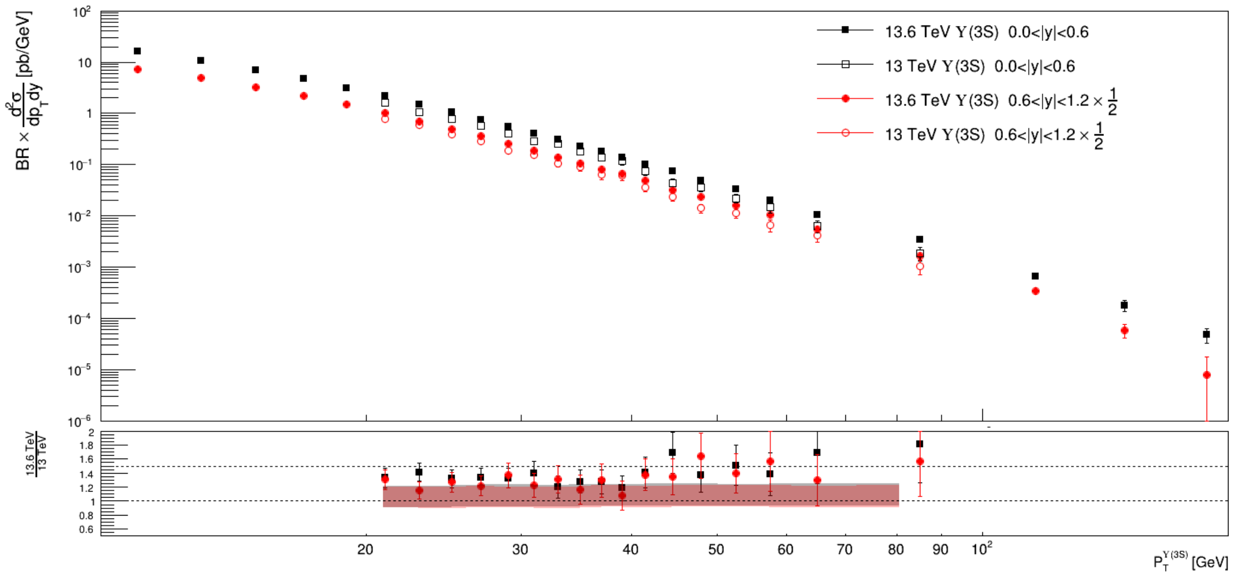
- We made a rough estimation of the total cross section of Y(1S) based on Pythia
- Total yield $N_{Y(1S)}$:
  - C D: 4.1026×10^5
  - E F G: 1.1845×10^6
- Luminosity L:
  - C D: $9.624 fb^{-1}$
  - E F G: $27.787 fb^{-1}$
- GEN filter efficiency ϵ_{filter}: $3.190\% \pm 0.176\%$
- RECO & cuts efficiency $\epsilon_{reco\&cuts} = \frac{N_{MCfit}}{N_{MCtotal}}$:
  - C D: ${}^{6.3806\times10^5}/_{2.1846\times10^7} = 2.9207\%$
  - E F G: ${}^{2.2180\times10^6}/_{7.5812\times10^7} = 2.9256\%$
- Estimated total cross section:

$$\sigma_{tot}(pp \to Y(nS)X) \times BR(Y(nS) \to \mu\mu) = \frac{N}{\epsilon_{filter} \cdot \epsilon_{reco\&cuts} \cdot L}$$

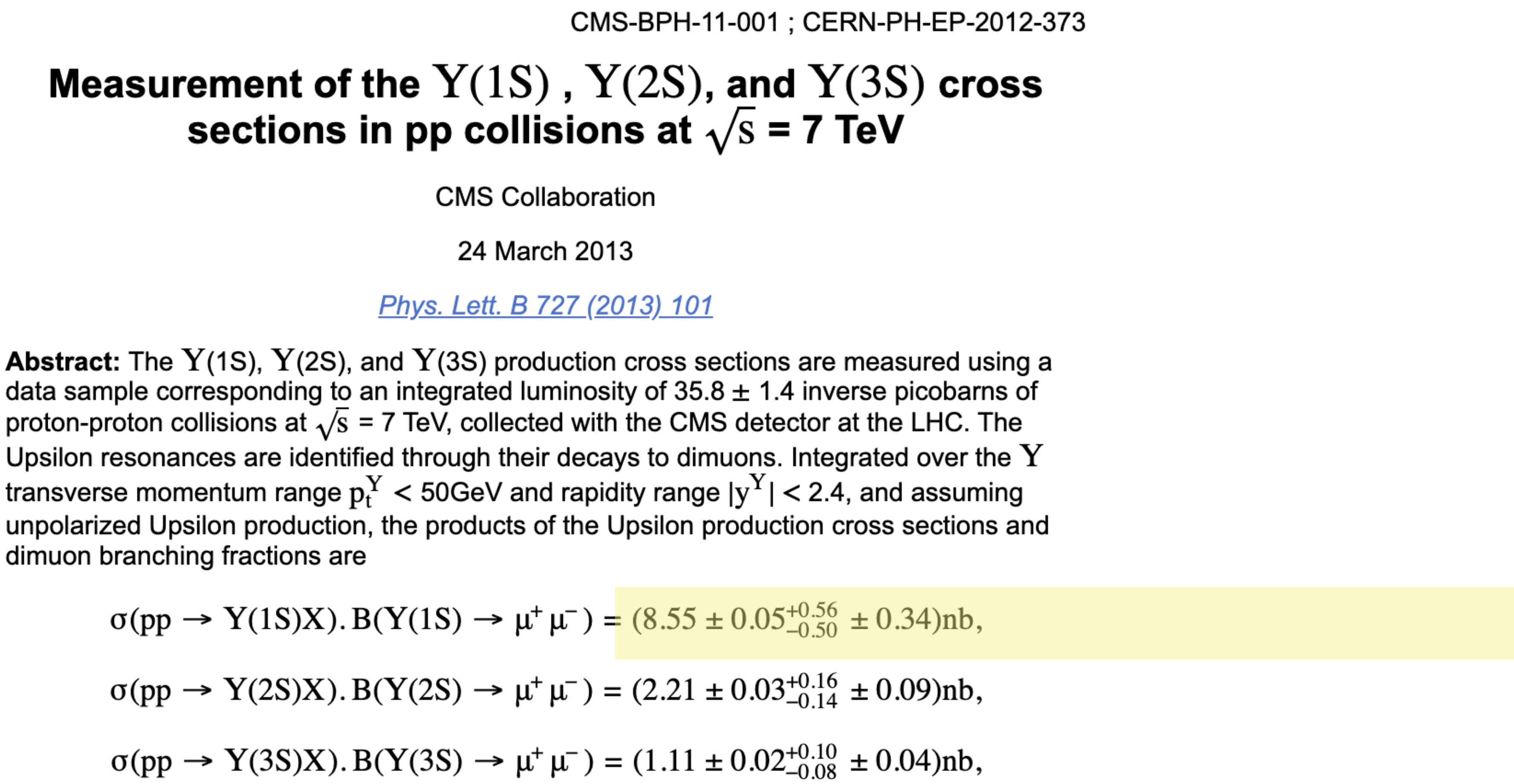
$$= 45.754nb$$


13.6 TeV ϒ(1S) 0.0<|y|<0.6
13 TeV ϒ(1S) 0.0<|y|<0.6
13.6 TeV ϒ(1S) 0.6<|y|<1.2 × 1/2
13 TeV ϒ(1S) 0.6<|y|<1.2 × 1/2
BR × d²σ/dp_T dy [pb/GeV]
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
13.6 TeV / 13 TeV
2
1.8
1.6
1.4
1.2
1
0.8
0.6
20
30
40
50
60
70
80
90
10²
P_T^ϒ(1S) [GeV]


13.6 TeV ϒ(2S) 0.0<|y|<0.6
13 TeV ϒ(2S) 0.0<|y|<0.6
13.6 TeV ϒ(2S) 0.6<|y|<1.2 × 1/2
13 TeV ϒ(2S) 0.6<|y|<1.2 × 1/2
BR × d²σ/dp_T dy [pb/GeV]
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
13.6 TeV / 13 TeV
2
1.8
1.6
1.4
1.2
1
0.8
0.6
20
30
40
50
60
70
80
90
10²
P_T^ϒ(2S) [GeV]


13.6 TeV ϒ(3S) 0.0<|y|<0.6
13 TeV ϒ(3S) 0.0<|y|<0.6
13.6 TeV ϒ(3S) 0.6<|y|<1.2 × 1/2
13 TeV ϒ(3S) 0.6<|y|<1.2 × 1/2
BR × d²σ/dp_T dy [pb/GeV]
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
13.6 TeV / 13 TeV
2
1.8
1.6
1.4
1.2
1
0.8
0.6
20
30
40
50
60
70
80
90
10²
P_T^ϒ(3S) [GeV]

Total Cross Sections Comparison with 7TeV



CMS-BPH-11-001 ; CERN-PH-EP-2012-373

Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ cross sections in pp collisions at $\sqrt{s}$ = 7 TeV

CMS Collaboration

24 March 2013

Phys. Lett. B 727 (2013) 101

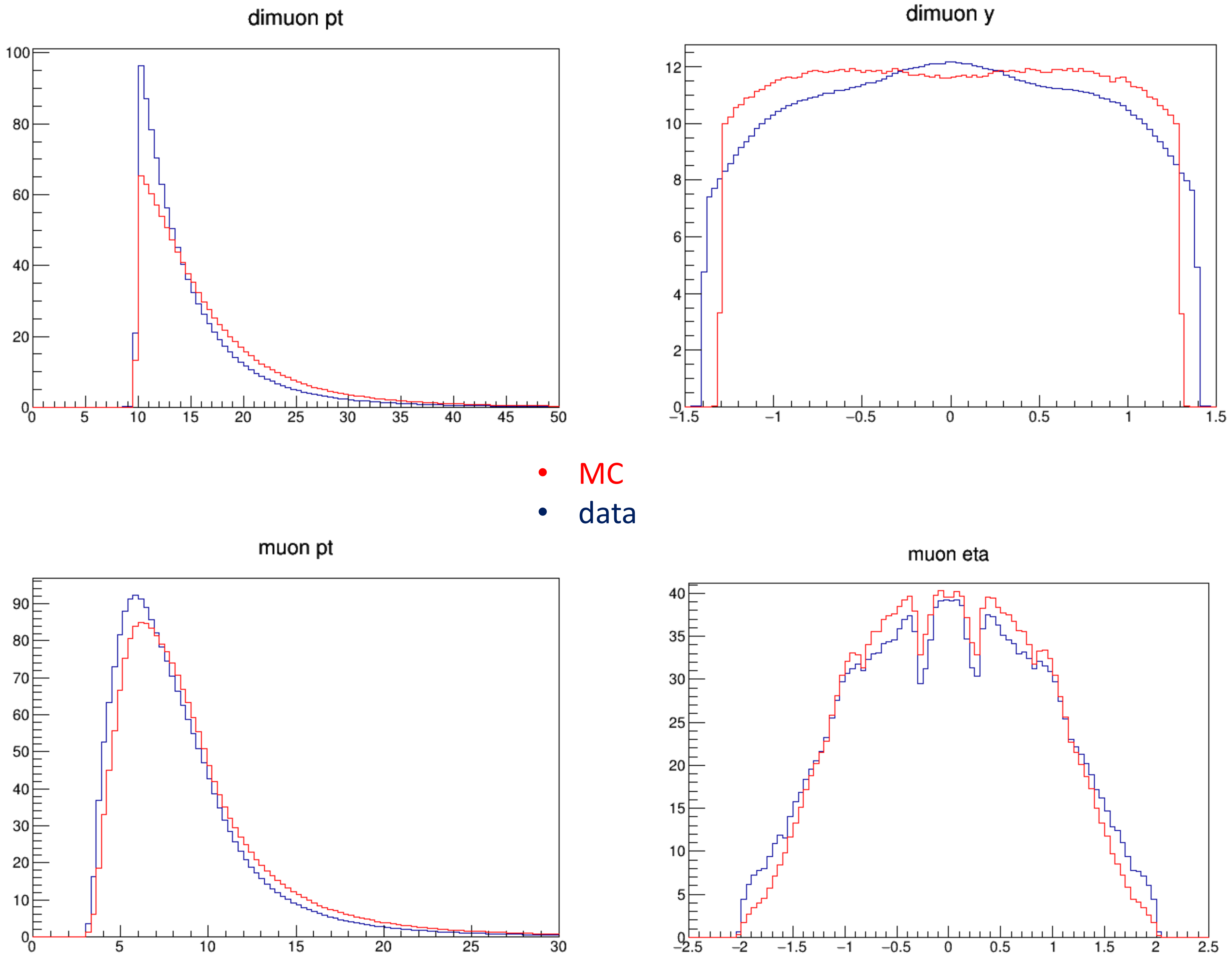
Abstract: The Υ(1S), Υ(2S), and Υ(3S) production cross sections are measured using a data sample corresponding to an integrated luminosity of 35.8 ± 1.4 inverse picobarns of proton-proton collisions at $\sqrt{s}$ = 7 TeV, collected with the CMS detector at the LHC. The Upsilon resonances are identified through their decays to dimuons. Integrated over the Υ transverse momentum range $p_t^{\Upsilon} < 50$GeV and rapidity range $|y^{\Upsilon}| < 2.4$, and assuming unpolarized Upsilon production, the products of the Upsilon production cross sections and dimuon branching fractions are

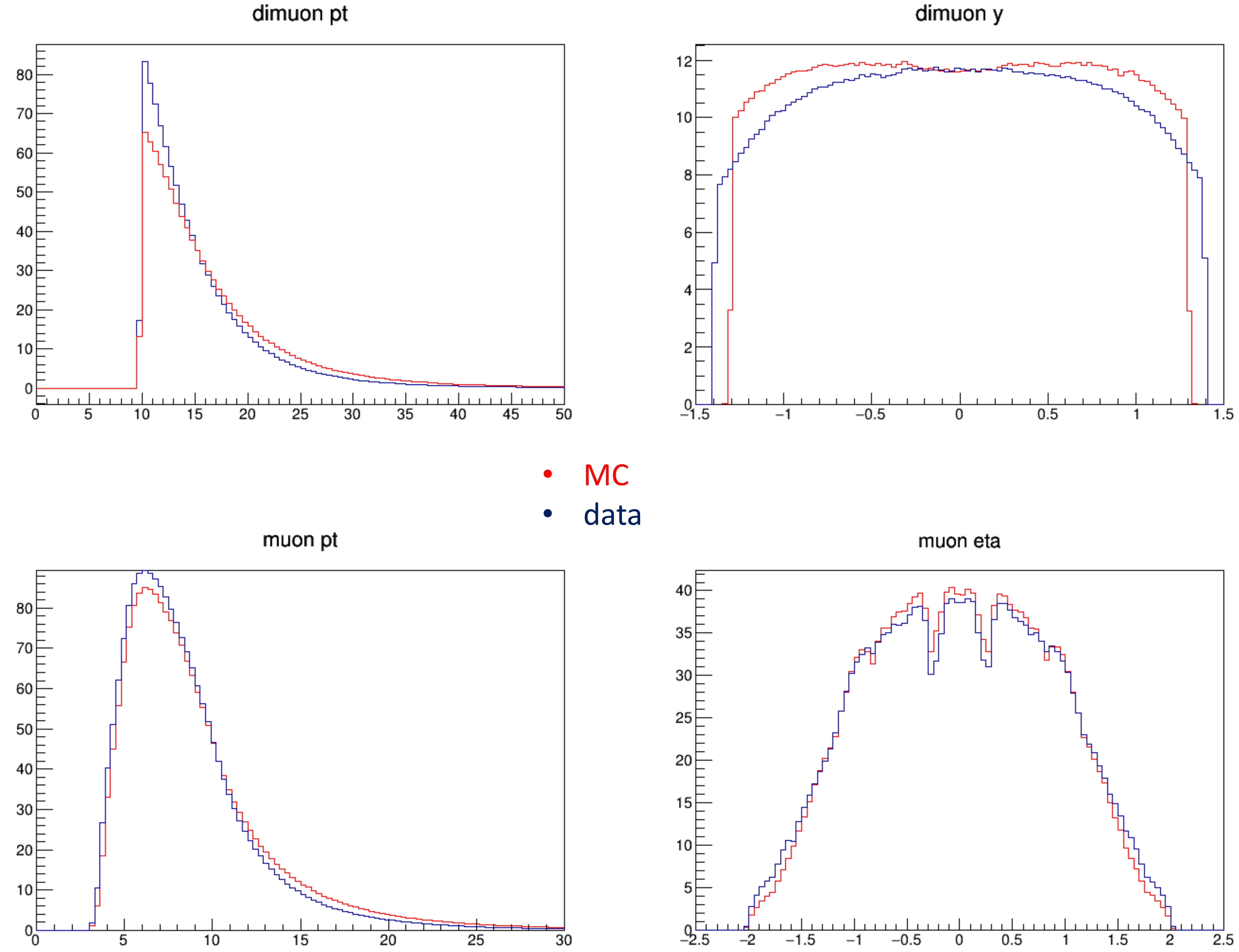
$$\sigma(pp \rightarrow \Upsilon(1S)X).B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (8.55 \pm 0.05^{+0.56}_{-0.50} \pm 0.34)\text{nb},$$

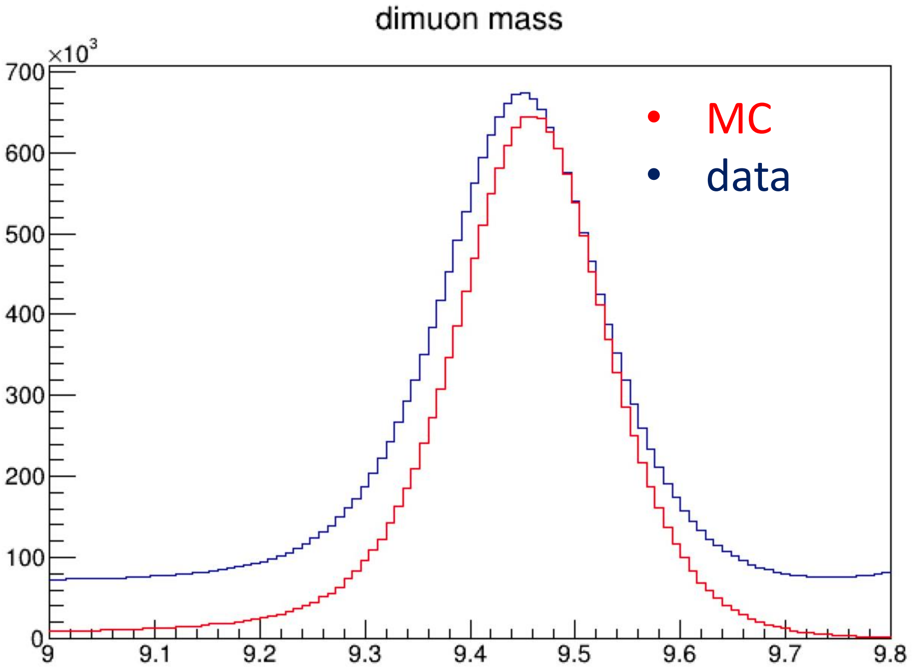
$$\sigma(pp \rightarrow \Upsilon(2S)X).B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (2.21 \pm 0.03^{+0.16}_{-0.14} \pm 0.09)\text{nb},$$

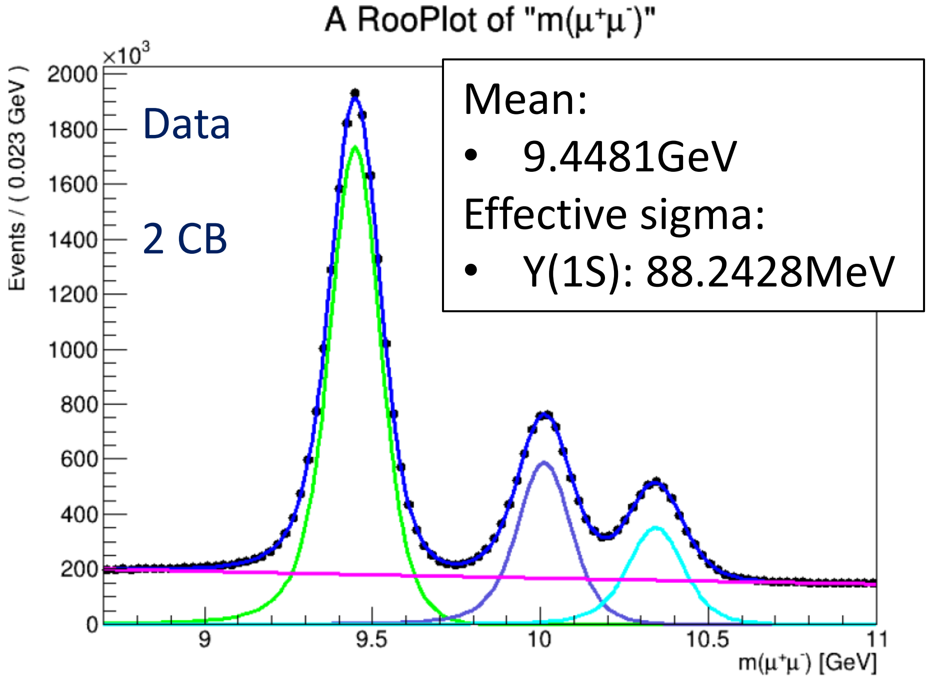
$$\sigma(pp \rightarrow \Upsilon(3S)X).B(\Upsilon(3S) \rightarrow \mu^+\mu^-) = (1.11 \pm 0.02^{+0.10}_{-0.08} \pm 0.04)\text{nb},$$

- GEN filter efficiency in similar kinematic region: $22.4\% \pm 1.32\%$
- A rough estimation of x-sec integrated over the Y pT< 40GeV and |y| < 2.4 @ 13.6 TeV : $45.754 \times 22.4\% = 10.259nb$


dimuon pt
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
50
dimuon y
12
10
8
6
4
2
0
−1.5
−1
−0.5
0
0.5
1
1.5
• MC
• data
muon pt
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
muon eta
40
35
30
25
20
15
10
5
0
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
2.5


dimuon pt
0
10
20
30
40
50
60
70
80
0 5 10 15 20 25 30 35 40 45 50
dimuon y
0
2
4
6
8
10
12
−1.5 −1 −0.5 0 0.5 1 1.5
● MC
● data
muon pt
0
10
20
30
40
50
60
70
80
0 5 10 15 20 25 30
muon eta
0
5
10
15
20
25
30
35
40
−2.5 −2 −1.5 −1 −0.5 0 0.5 1 1.5 2 2.5



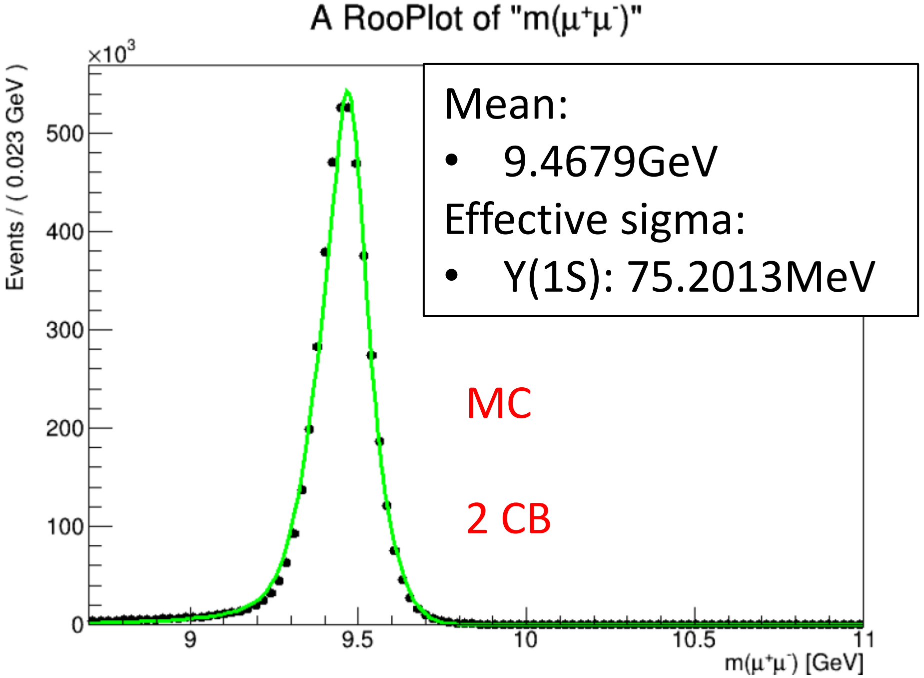


Data

2 CB

Mean:
- 9.4481GeV

Effective sigma:
- Y(1S): 88.2428MeV

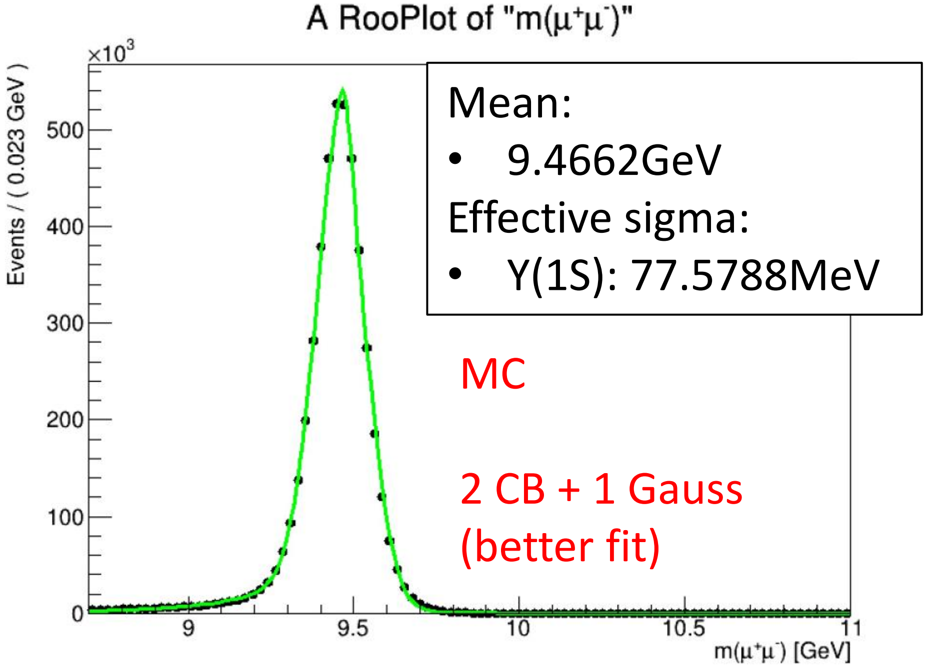


Mean:
- 9.4679GeV

Effective sigma:
- Y(1S): 75.2013MeV

MC

2 CB



Mean:
- 9.4662GeV

Effective sigma:
- Y(1S): 77.5788MeV

MC

2 CB + 1 Gauss
(better fit)