Measurements of the $\Upsilon(1S, 2S, 3S)$ Cross Sections in Proton-Proton Collisions at $\sqrt{s} = 13.6$ TeV

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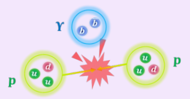
Introduction & Motivation

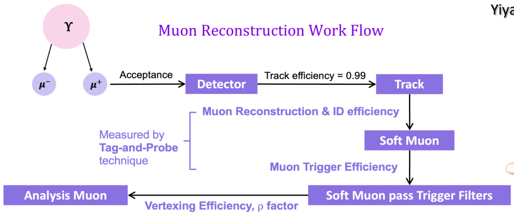
Quarkonium production tests fundamental QCD, but the mechanism remains uncertain despite decades of experimental and theoretical effort.

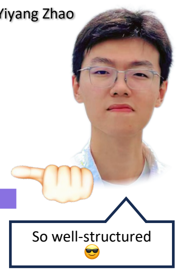
Key Questions:
❖ How do heavy quark pairs hadronize into bound states?
❖ What are the roles of color-singlet vs color-octet production?
❖ Can NRQCD provide a unified description of rates AND polarization?

This Measurement:
✓ First Υ cross sections at √s = 13.6 TeV (Run-3 data)
✓ Extended to pT = 200 GeV (2× previous range)
✓ 14× improved statistics → precision tests of theory
✓ Direct constraints on NRQCD long-distance matrix elements



Methodology

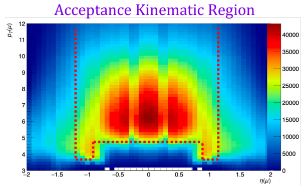




Data Collection
❖ Dataset: ParkingDoubleMuonLowMass (2022)
❖ Luminosity: 37.4 fb^{-1} at √s = 13.6 TeV
❖ Trigger: HLT_Dimuon10_Upsilon_y1p4

Event Selection
- Soft Muon ID quality
- M($\mu^+\mu^-$) > 2 GeV
- |dz1 - dz2| < 25 cm
- $p_T(\mu^+\mu^-) > 10$ GeV
- $|y(\mu^+\mu^-)| < 1.2$
- $p_T(\mu) > 4.6$ GeV if $0.0 < |\eta(\mu)| < 0.9$
- $p_T(\mu) > 3.6$ GeV if $0.9 < |\eta(\mu)| < 1.2$

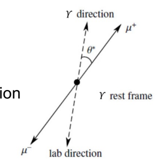
Acceptance Kinematic Region



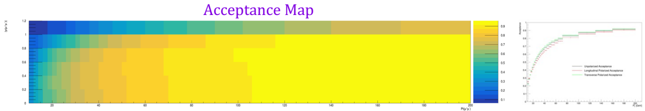
Polarization Effects on Acceptance

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

- λ: the polarization parameter. $\lambda = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$
- $\sigma_{(L/T)}$: (longitudinal / transverse component of) the cross section
- θ^*: the polar angle
- transverse polarization: $I_T(\cos\theta^*) = \frac{3}{8}(1 + \cos^2\theta^*),\ \lambda = 1$
- longitudinal polarization: $I_T(\cos\theta^*) = \frac{3}{4}(1 - \cos^2\theta^*),\ \lambda = -1$



Acceptance Map



Efficiency Calculation – Tag-and-Probe (TnP) Technique

All probe: tracks passing pre-selection   Passing probe: Soft ID probe

$$\epsilon_{\mathrm{reco\&ID}} = \frac{\text{fit peak area of PassingProbe}}{\text{fit peak area of AllProbe}}$$

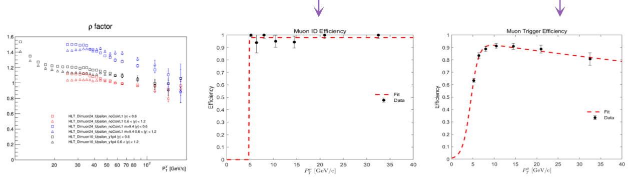
$$\epsilon^{\mu}(p_T, \eta) = \epsilon_{track} \times \epsilon_{\mathrm{RECO\_ID}} \times \epsilon_{\mathrm{Trigger}}$$

Track efficiency = 0.99 from Muon POG

Reco&ID efficiency

Trigger efficiency

From the *data-driven* **Tag-and-Probe** Technique (TnP)



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

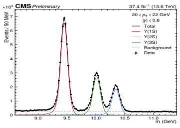
Results

Double-differential Cross sections are calculated with the expression:

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

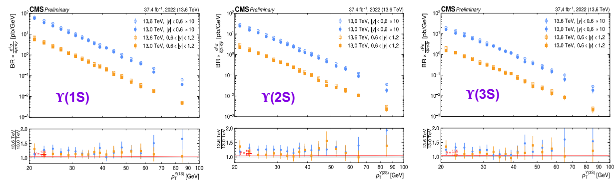
$\left\langle \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)} \right\rangle$: weight of corresponding $\Upsilon(p_T, y)$ bin

- $\mathcal{A}$ from MC truth.
- ϵ from data using Tag&Probe method. (MC used for Υ efficiency ρ factor calculation)
- $N^{\Upsilon}(p_T, y)$ from Υ(1S, 2S, 3S) mass fit →

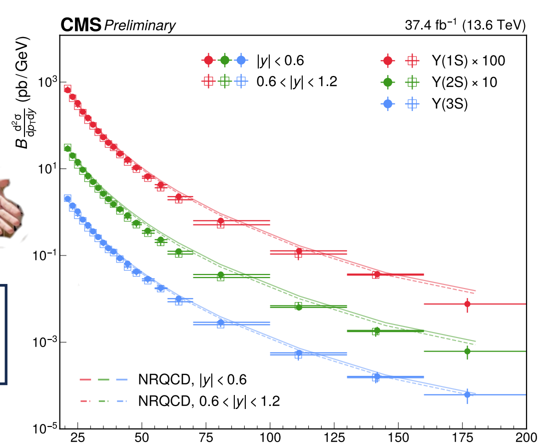


Split into **50 kinetic bins** in total:
- $|\eta^{\Upsilon}| \in [0, 0.6, 1.2]$
- $p_T^{\Upsilon} \in$ [10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 43, 46, 50, 55, 60, 70, 100, 130]

Comparison with the 13 TeV Υ(1S, 2S, 3S) Cross Section Measurements



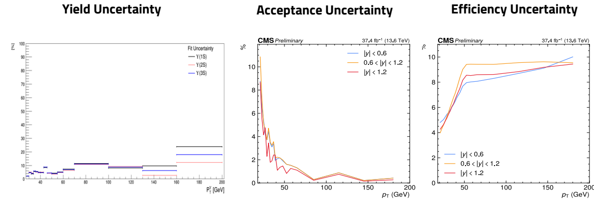
Comparison with NRQCD theory with one particular set of LDMEs



NRQCD ref: Feng Yu et al., doi: 10.1088/1674-1137/abc682

Systematic Uncertainty Evaluations

Yield Uncertainty **Acceptance Uncertainty** **Efficiency Uncertainty**



Uncertainty Source	Detailed Factors	Υ(1S) %	Υ(2S) %	Υ(3S) %
Fit	Signal PDF	1.12	2.13	1.65
	Background PDF	0.73	0.97	0.87
Weight	Acceptance	3.96	3.84	3.76
	Single Muon Efficiency	3.84	3.84	3.84
	Rho Factor	3.66	3.76	3.83
Luminosity		1.40	1.40	1.40
Total		6.99	7.27	7.12