Υ(nS) cross section measurement in pp collisions @ 13TeV

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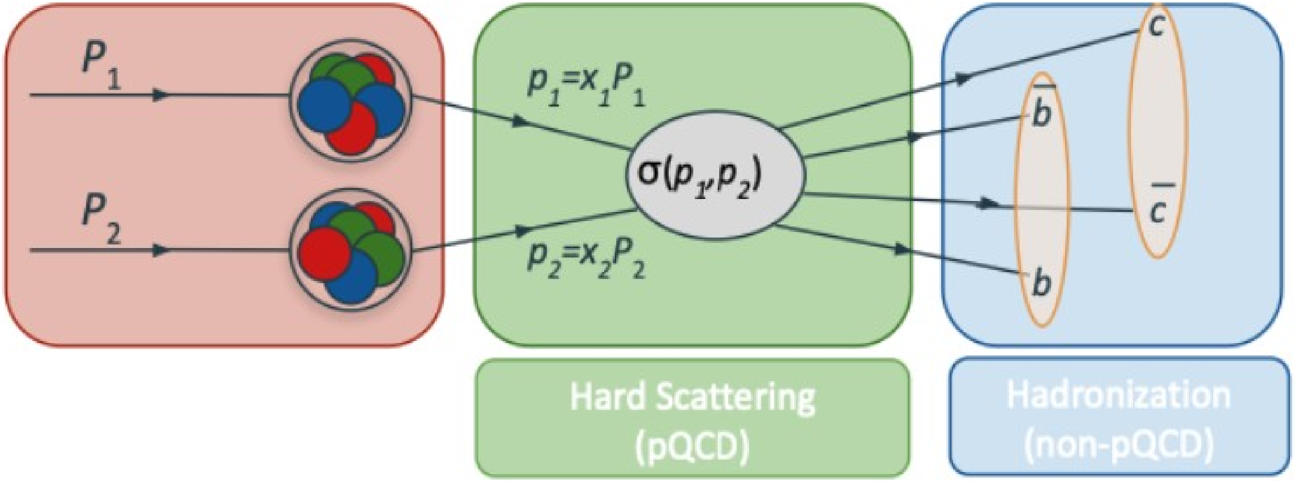
Introduction



- ➢ Charmonia: **J/ψ, ψ(2S)**
- ➢ Bottomonia : **ϒ(nS)**

Quarkonium production in pp collisions:
→ Initial heavy quark production (sensitive to pQCD)
→ Formation of bound quarkonium states (non perturbative QCD)
→ Constrain model calculations (CO/CS mechanism)
→ Reference measurement for heavy-ion system

Motivation and Analysis Details

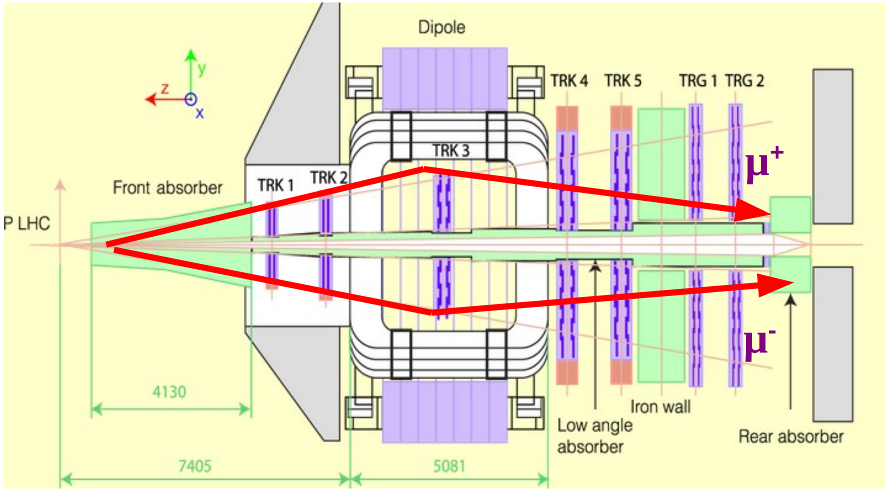
Physics motivation of this analysis:

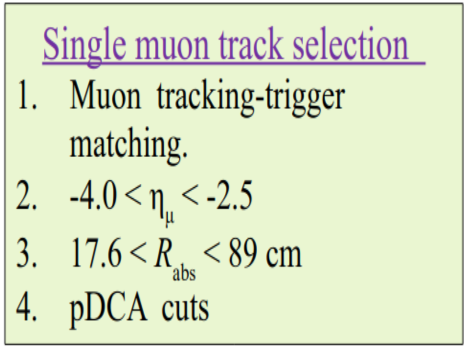
- ➢ Benefit from highest statistics Run 2 data to do precise measurements ϒ(nS) cross-sections in finner p_T and y bins
- ➢ Extend to ϒ(3S) in ALICE
- ➢ Facilitate more stringent test QCD
- ➢ Benchmark for RUN3 analyses and complementary to LHCb

Trigger selection : CMUL7-NOPF-MUFAST

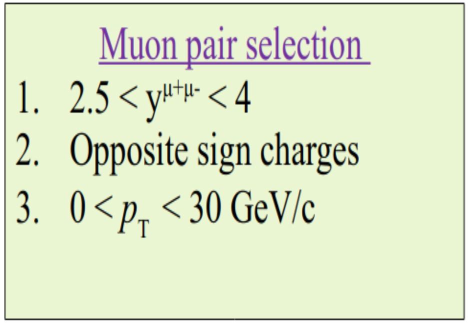
Physics selection : kMuonUnlikePt7 (LHC17 and LHC18) or kMUU7 (LHC16)

Total Analysed Events: ~ 647 M




Single muon track selection

1. Muon tracking-trigger matching.
2. $-4.0 < \eta_\mu < -2.5$
3. $17.6 < R_{abs} < 89$ cm
4. pDCA cuts


Muon pair selection

1. $2.5 < y^{\mu+\mu-} < 4$
2. Opposite sign charges
3. $0 < p_T < 30$ GeV/c

Signal Extraction

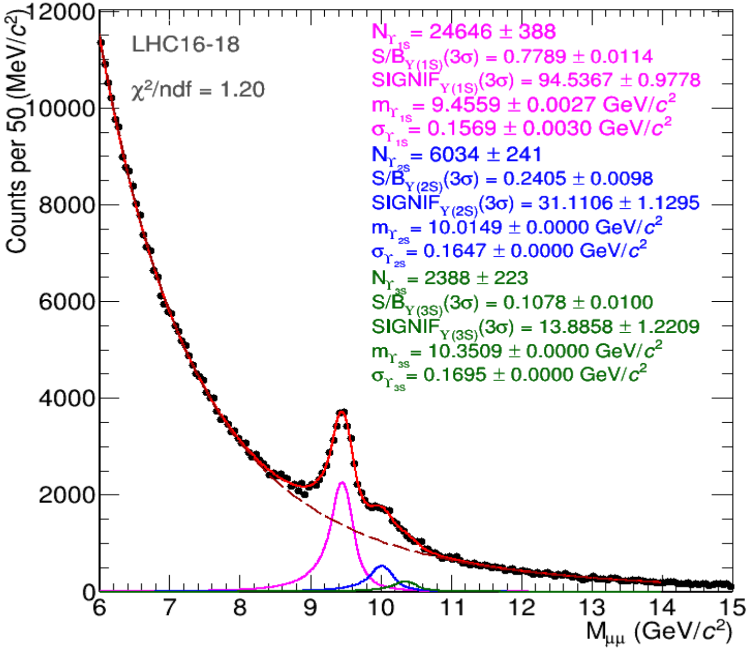
1. Obtain di-muon invariant mass spectra
2. Fit mass spectra with a combination of signal+ background function
   - → **Signal: Crystal Ball (An exponetial tail + Gaussian core)**
   - → **Background: DE, DP, VWG (Pl. See back up)**
3. Determine tail parameters
4. Refit invariant mass spectra keeping tail parameters fixed

Parameter initialization and constrains:

→ **Mass of $\Upsilon(1S)$ is kept free**

→ **Sigma of $\Upsilon(1S)$ is kept free**

$$m_{\Upsilon(nS)} = m_{\Upsilon(1S)} + \left(m^{\mathrm{PDG}}_{\Upsilon(nS)} - m^{\mathrm{PDG}}_{\Upsilon(1S)}\right), \quad \sigma_{\Upsilon(nS)} = \sigma_{\Upsilon(1S)} \times \frac{\sigma^{\mathrm{MC}}_{\Upsilon(nS)}}{\sigma^{\mathrm{MC}}_{\Upsilon(1S)}}$$



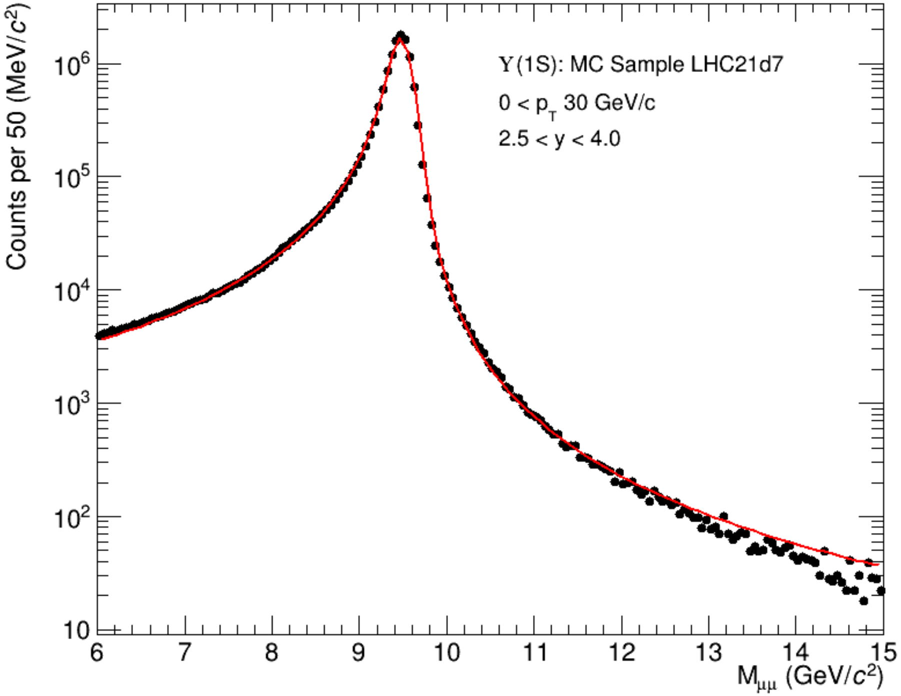
Tail Extraction from Monte Carlo

-Invarient mass distribution is fitted with CB2

-No background

-p_T and rapidity inclusive

α_L	1.016
n_L	2.035
α_R	2.063
n_R	2.247



Data driven tail extraction

Steps of extraction

1. A bkg function is fitted excluding at least $\pm 5\sigma$ around $\Upsilon(1S)$ mass peak

2. Bkg+Gaus is fitted excluding $\Upsilon(2S)$ and $\Upsilon(3S)$

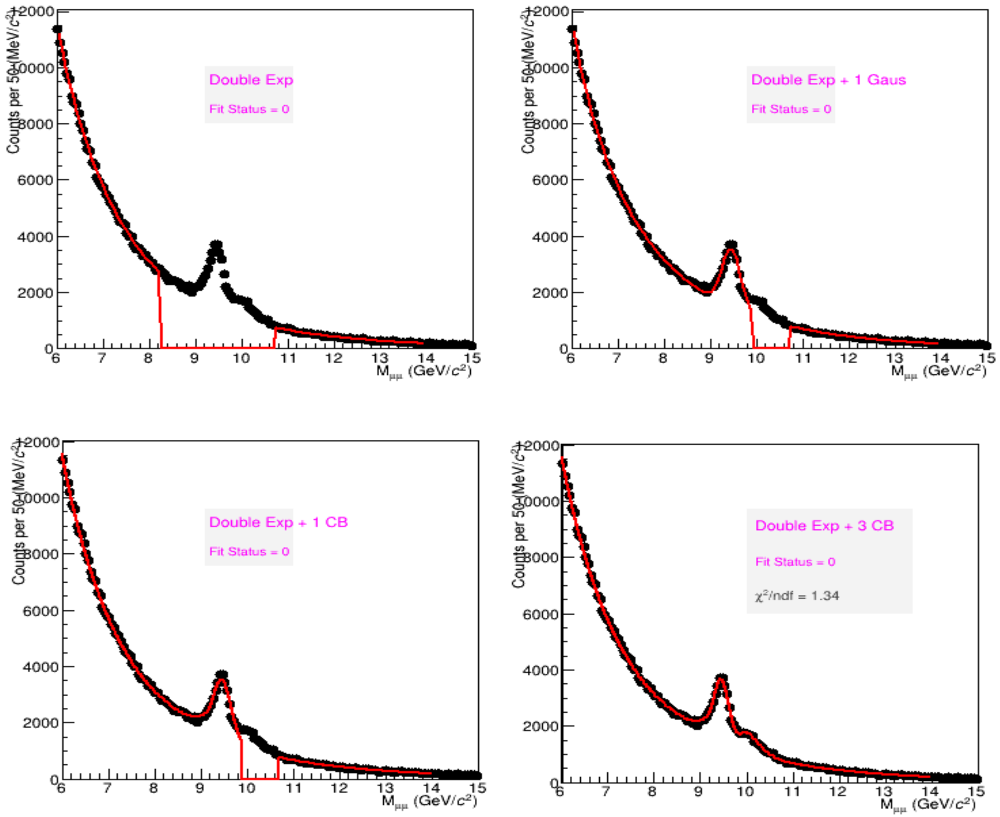
3. Bkg+1CB2 taking mass and σ of 1S from step2, excluding 2s and 3s, and bkg params are fixed

4. Bkg + 2CB2 excluding 3s, bkg params fixed

5. Bkg + 3CB2, bkg params fixed

6. Mass and sigma of $\Upsilon(1S)$ and, tail parameters are always kept free

Graphical demonstration



Data driven tail extraction

Steps of Extraction

1.A bkg function is fitted excluding at least ±5σ around Υ_{1s} mass peak

2.Bkg+Gaus is fitted excluding Υ_{2S} and Υ_{3S}

3.Bkg+1CB2 taking mass and σ of 1s from step2, excluding 2s and 3s, and bkg params are fixed

4.Bkg + 2CB2 excluding 3s, bkg params fixed

5. Bkg + 3CB2, bkg params fixed

6. Mass and sigma of Υ_{1s} and, tail parameters are always kept free

Systematics are done repeating 1-5 for following conditions

Bkg Functions	1. Double Exponential 2. Sum of two power law 3. Variable Width Gaussian
Fit ranges	6-13, 7-14, 5-12
Exclusion region around Υ(1S) mass peak	±5σ, ±6σ, ±8σ

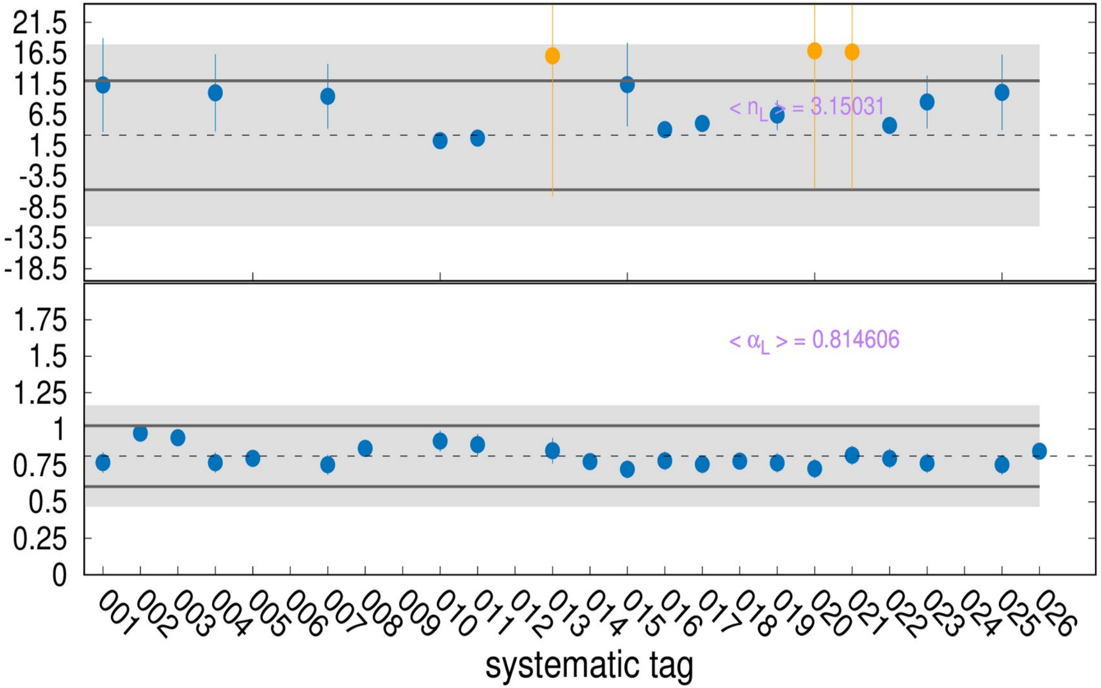
Left Tail Parameters (α_L and n_L)

Gray band ±5σ around global mean

Black solid lines ±3σ around global mean

Orange markers, data points ±3σ away from global mean

Blue markers, data points within ±3σ of global mean



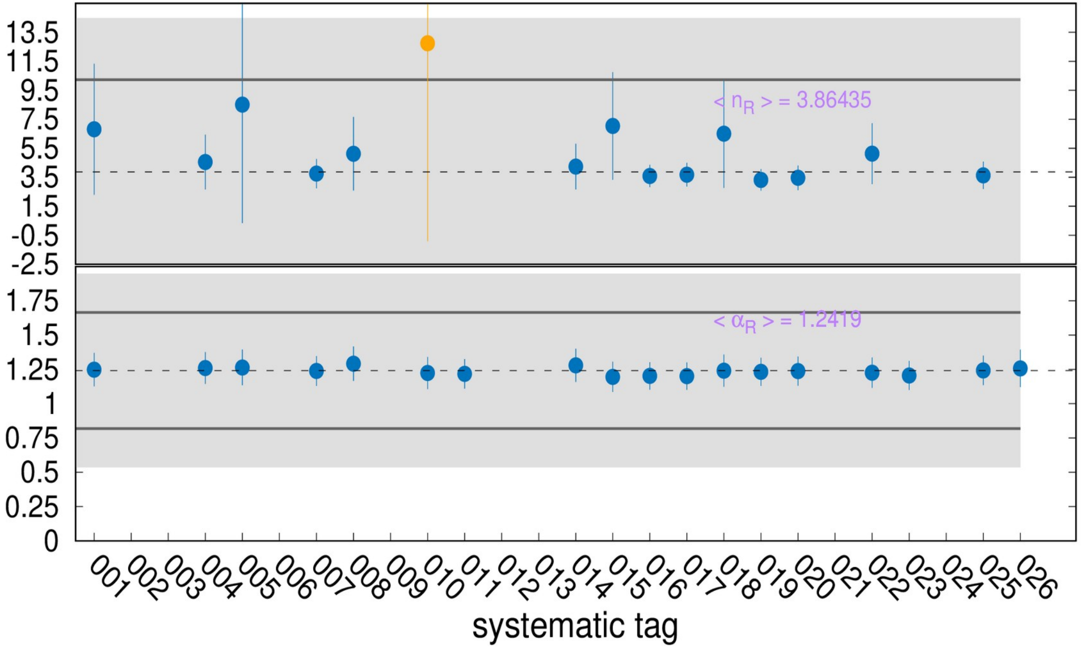
Right Tail Parameters (α_R and n_R)

Gray band ±5σ around global mean

Black solid lines ±3σ around global mean

Orange markers, data points ±3σ away from global mean

Blue markers, data points within ±3σ of global mean

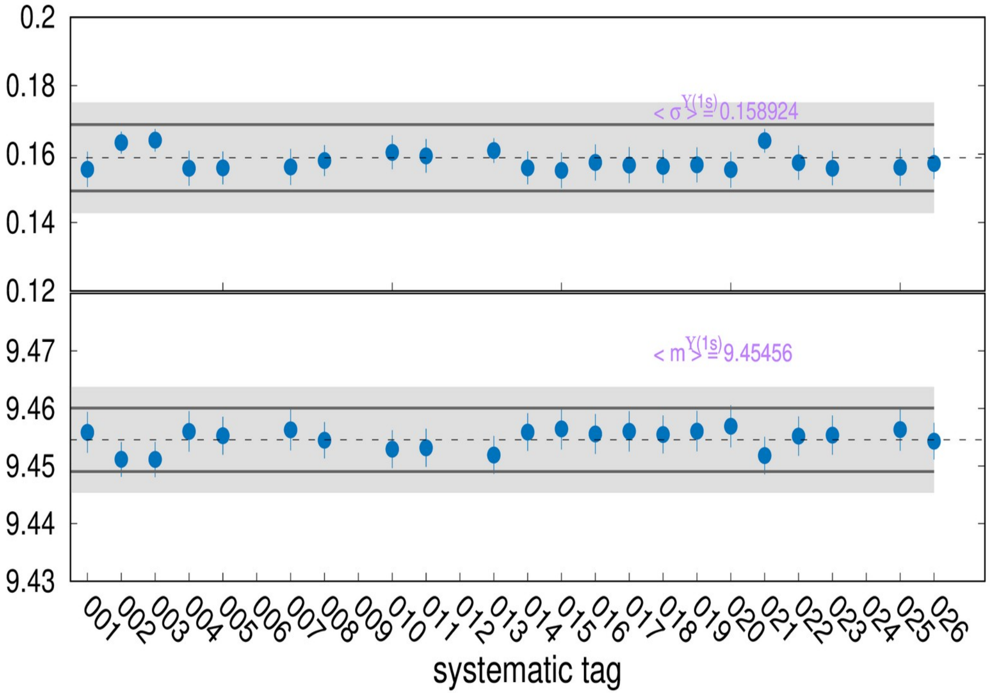


Final Tail Parameters (data)

Data driven tail parameters are extracted averaging over those fits that have converged

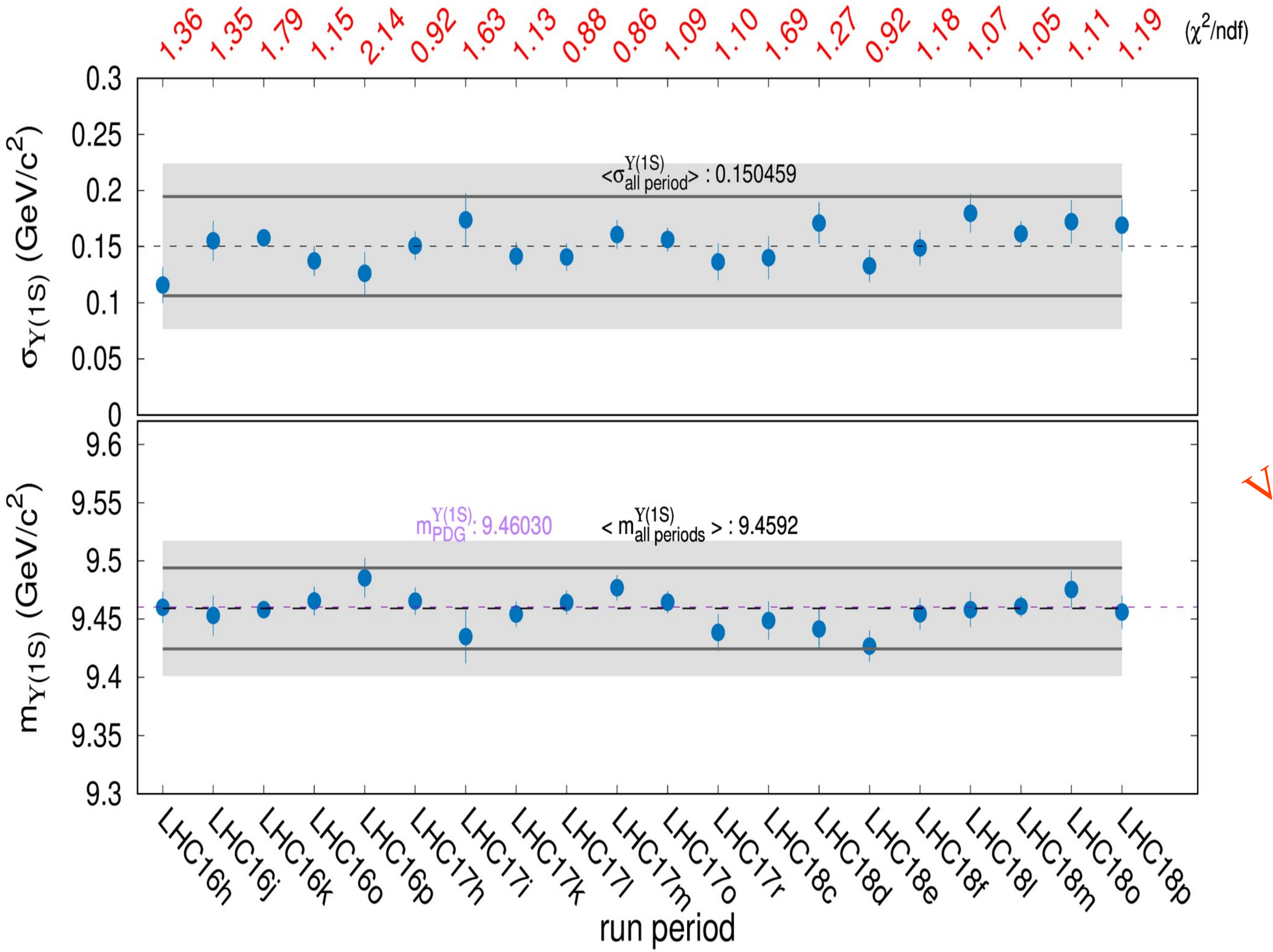
α_L	0.814
n_L	3.150
α_R	1.242
n_R	3.864

No explicit cut over χ^2/ndf is applied



Mass and σ of Υ(1S) of corresponding fits

Mass and Sigma of Υ(1S) across different run-periods with data-driven tail params

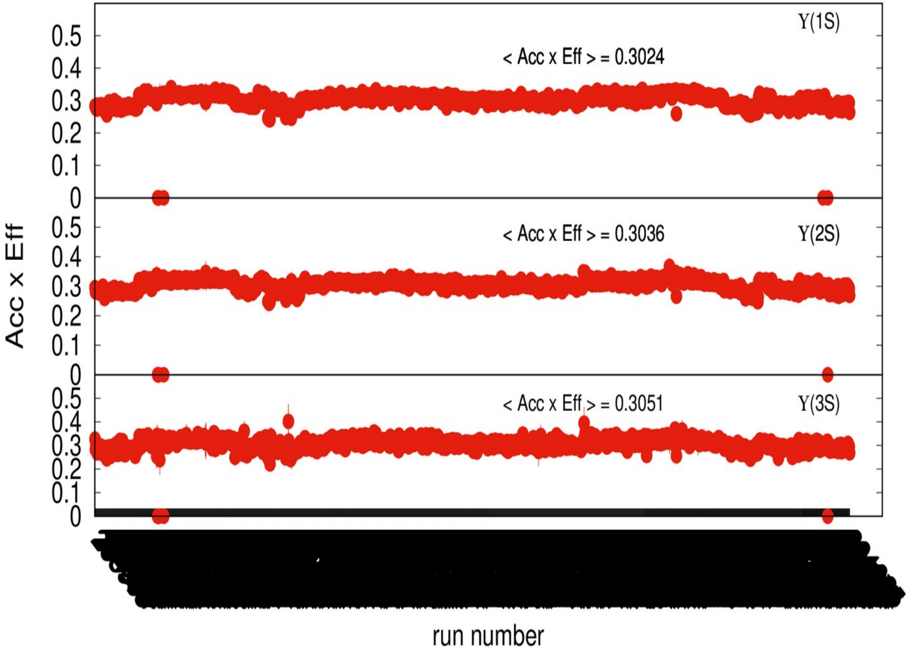


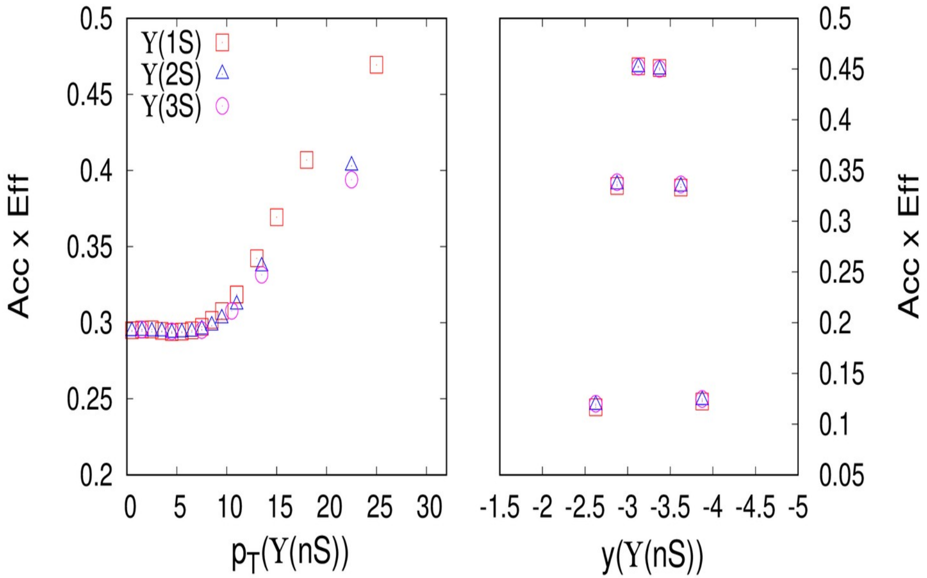
Variation across run-periods within 3σ

Acceptance and Efficiency corrections [Υ(nS)]

MC sample:
tuned on LHCb data @ 13TeV
LHC21d7
LHC22d4

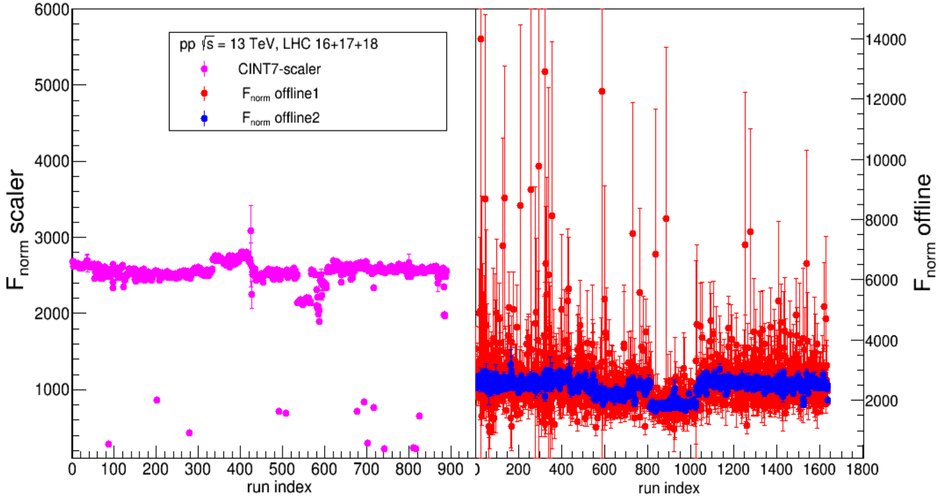
$$< A\varepsilon > = \frac{N_{\text{reconstructed}}}{N_{\text{generated}}}$$





Luminosity

For systematics two methods are used to determine F_{norm} : offline (direct & indirect)



F_{norm} offline1 (direct)   = 2467.04 +/- 13.36

F_{norm} offline2 (indirect) = 2400.25 +/- 1.34

ΔF_{norm} = 66.79 (2.78%) [syst]

$\Delta\sigma_{v0}$ = 2.0 %

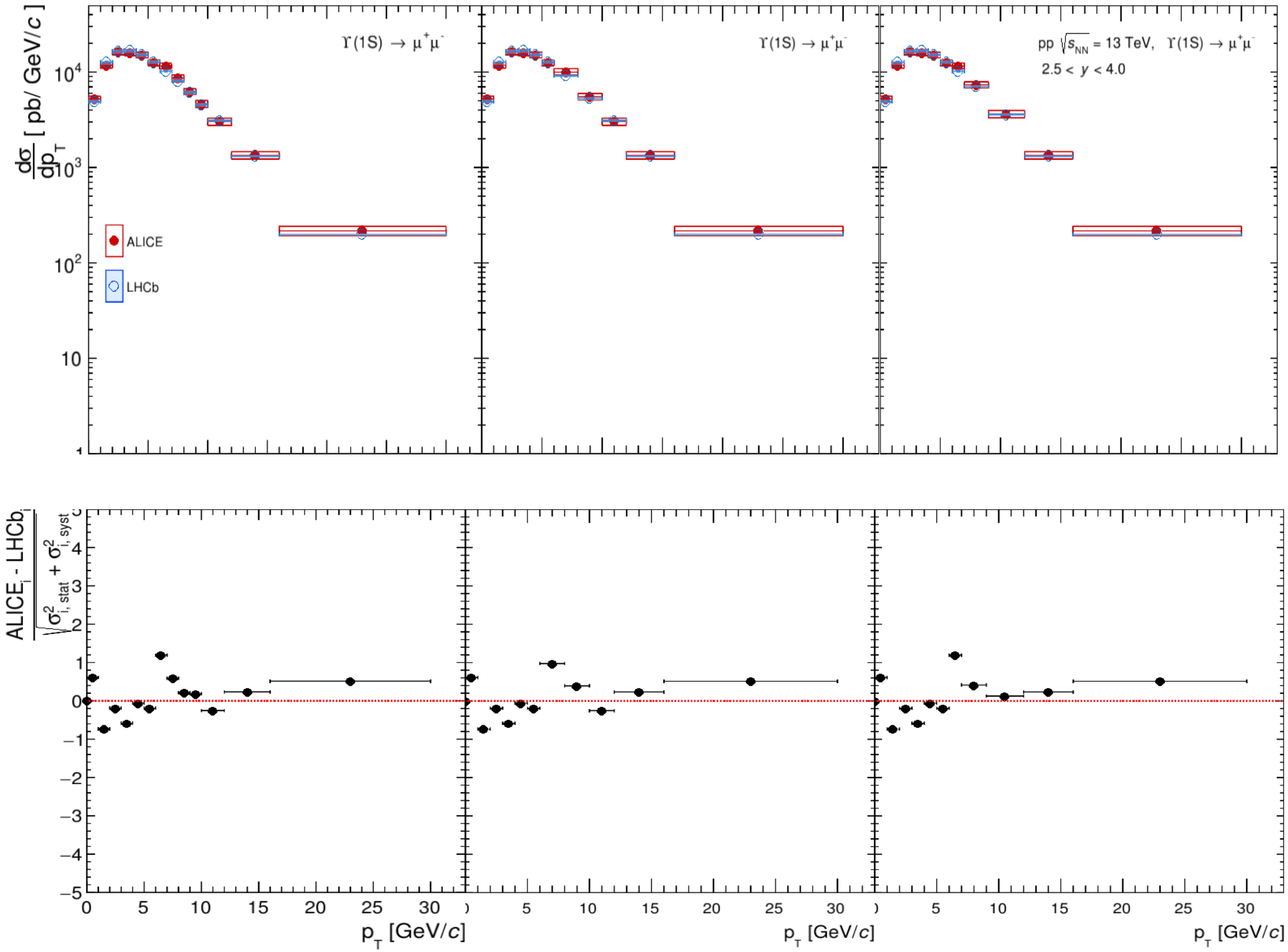
Total uncertainty = 3.46%

$$L_{int} = \frac{N_{CMUL7,PS} \times F_{norm}}{\sigma_{VdM}}$$

(57.8 +/-1.2 mb)

Taking F_{norm} offline2 as default choise, integrated lumnosity 26.87 +/- 0.037%(stat) +/- 3.46%(syst) pb^{-1}

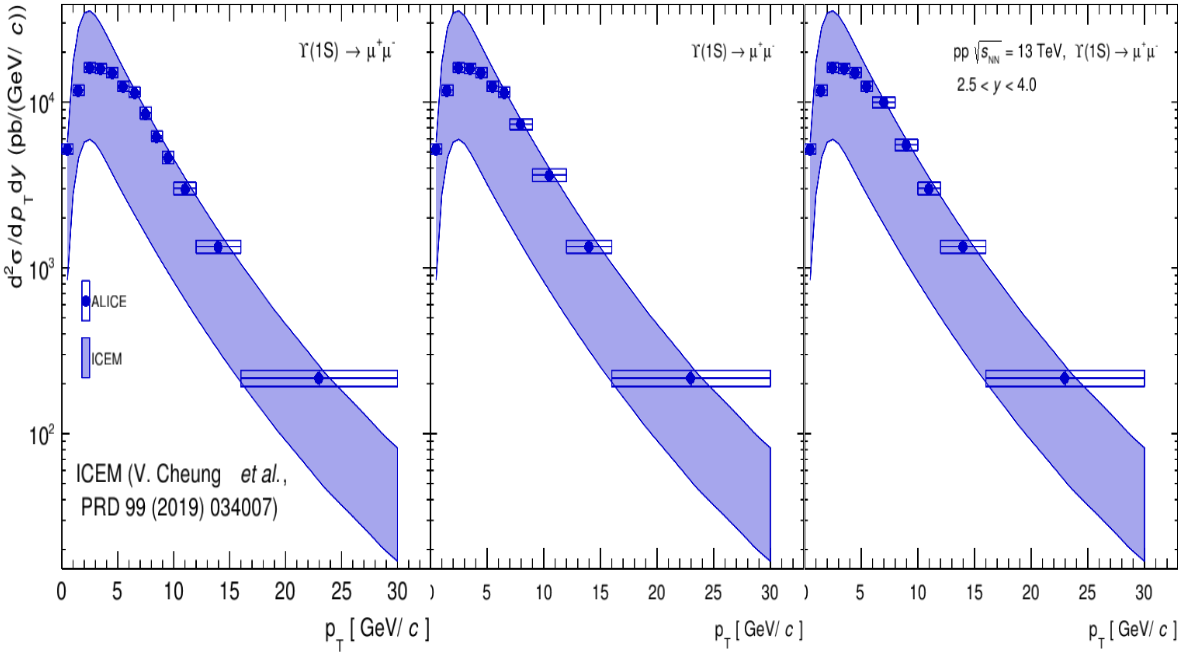
p_T differenential Υ(1S) cross sections



$$\frac{d^2\sigma_{\Upsilon(\mathrm{nS})}}{dy\,dp_T} = \frac{N_{\Upsilon(\mathrm{nS})}}{A \times \varepsilon}\,\frac{1}{BR_{\Upsilon(\mathrm{nS})\to\mu^+\mu^-}}\,\frac{1}{\mathscr{L}_{\mathrm{int}}}\,\frac{1}{\Delta y \Delta p_T}$$

Υ(1S) cross sections
are in good ageement
between ALICE & LHCb
➔Mostly within 1σ

p_T differenential $\Upsilon(1S)$ cross sections compared to ICEM



$$\frac{d\sigma_\psi(P)}{d^3P} = F_\psi \int_{2m_c}^{2M_D} dM \, \frac{d\sigma_{c\bar{c}}(M,P)}{dM\, d^3P}$$

Colour Evaporation model

➢ A fixed fraction of QQbar pairs form J/ψ or ϒ(nS), provided mass of QQbar pair < D/B-meson mass threshold

➢ CEM is in general successful in describing quarkonium production

➢ A flaw in the approach: ratios of two charmonium states are independent of kinematics.

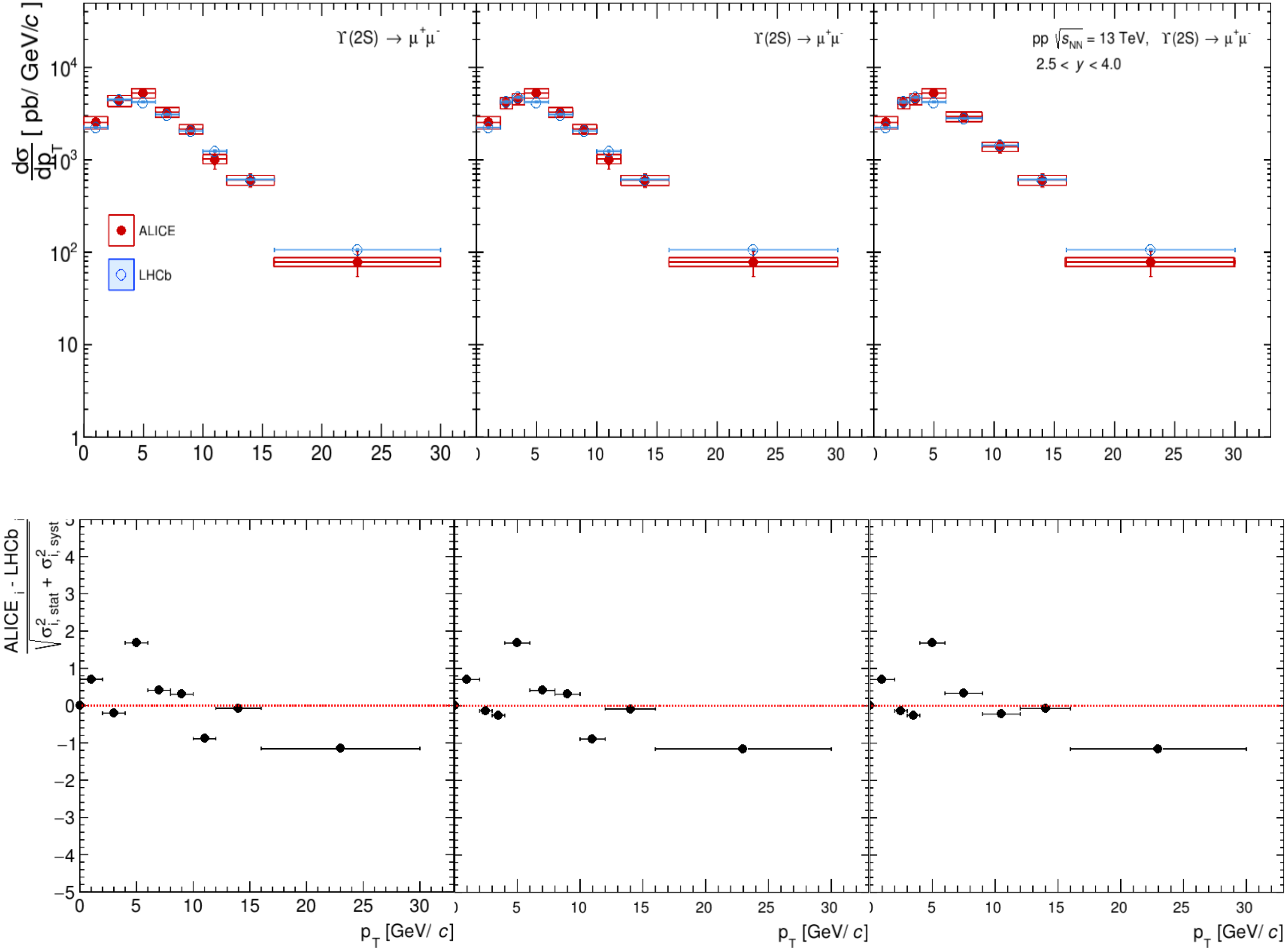
$$\frac{d\sigma_\psi(P)}{d^3P} = F_\psi \int_{M_\psi}^{2M_D} d^3P' dM \, \frac{d\sigma_{c\bar{c}}(M,P')}{dM\, d^3P'} \delta^3\left(P - \frac{M_\psi}{M} P'\right)$$

Improved Colour Evaporation Model:

➢Incorporates the kinematic dependence

In general good agreement within uncertainties

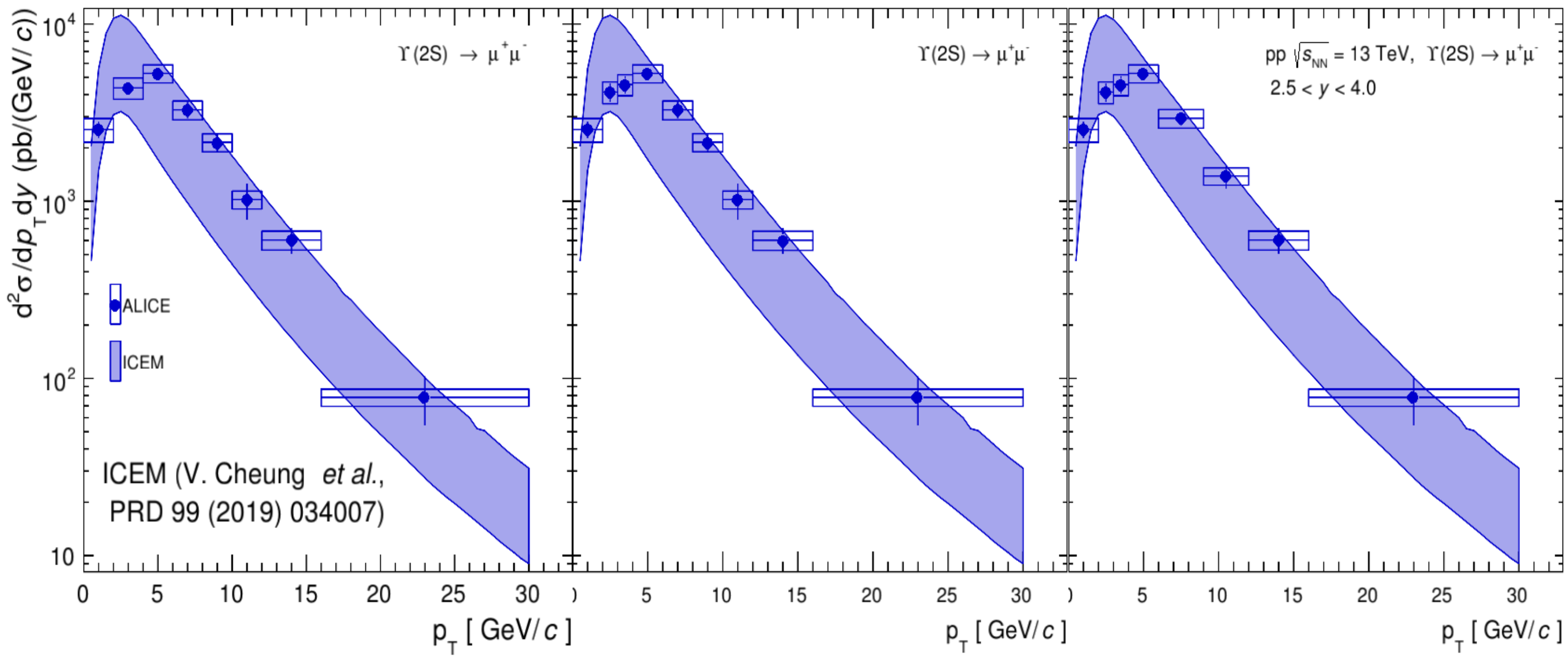
p_T differenential Υ(2S) cross sections



Υ(2S) cross sections are in good ageement between ALICE & LHCb

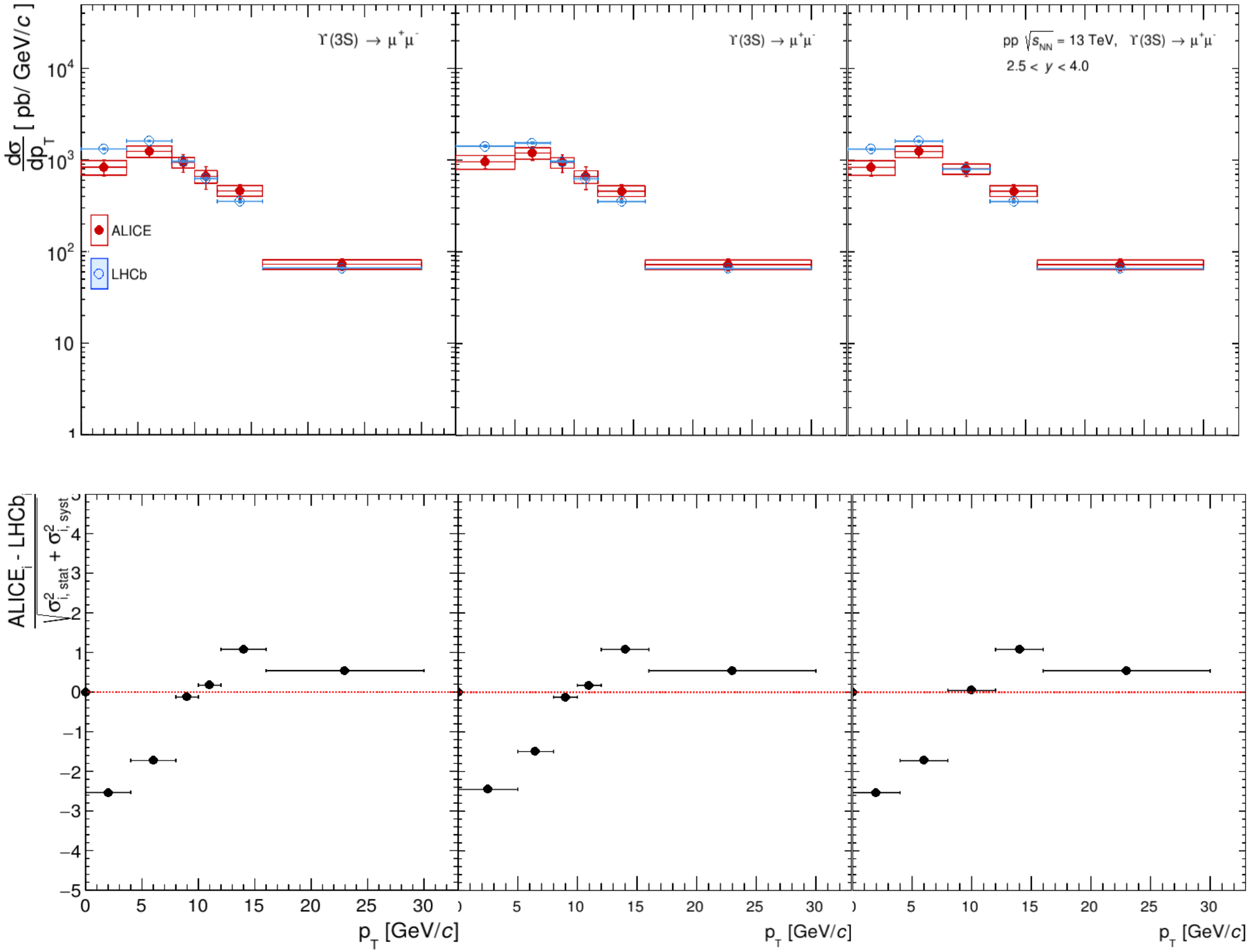
➔ Mostly within 1σ

p_T differenential Υ(2S) cross sections compared to ICEM



In general good agreement within uncertainties

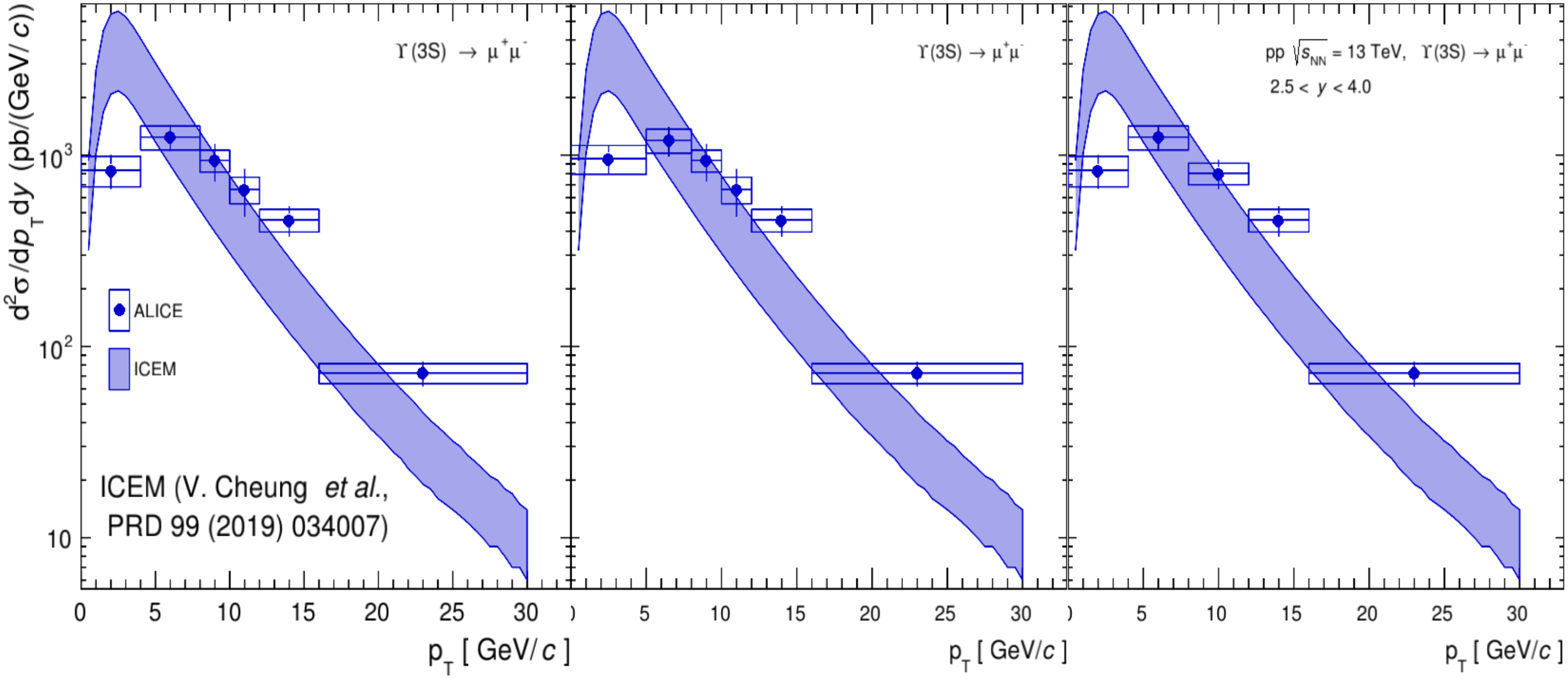
p_T differenential ϒ(3S) cross sections



ϒ(3S) cross sections are in low p_T bins have large disagreement between ALICE & LHCb

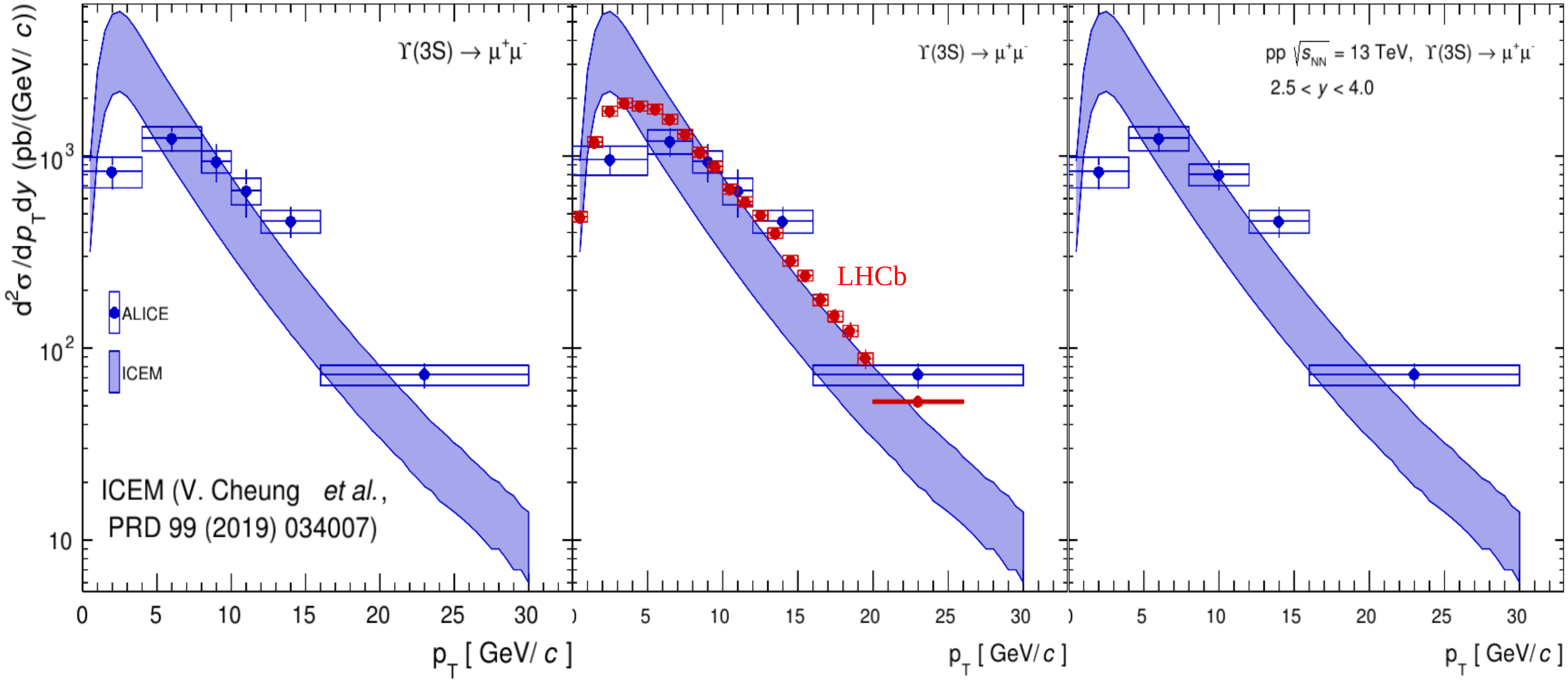
➔Agreement at high p_T is better

p_T differenential Υ(3S) cross sections compared to ICEM



ICEM calculations not in a good agreement even within uncertainties

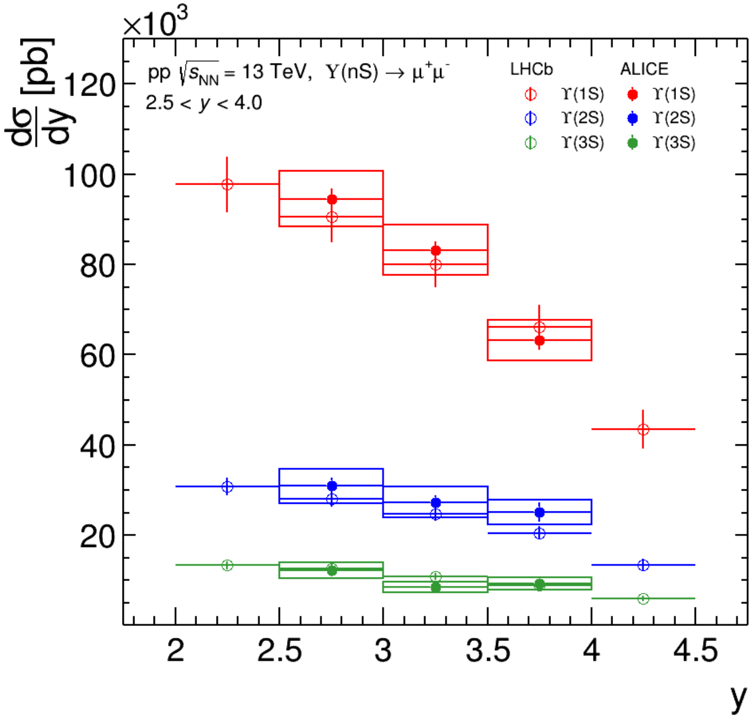
p_T differenential Υ(3S) cross section compared to ICEM

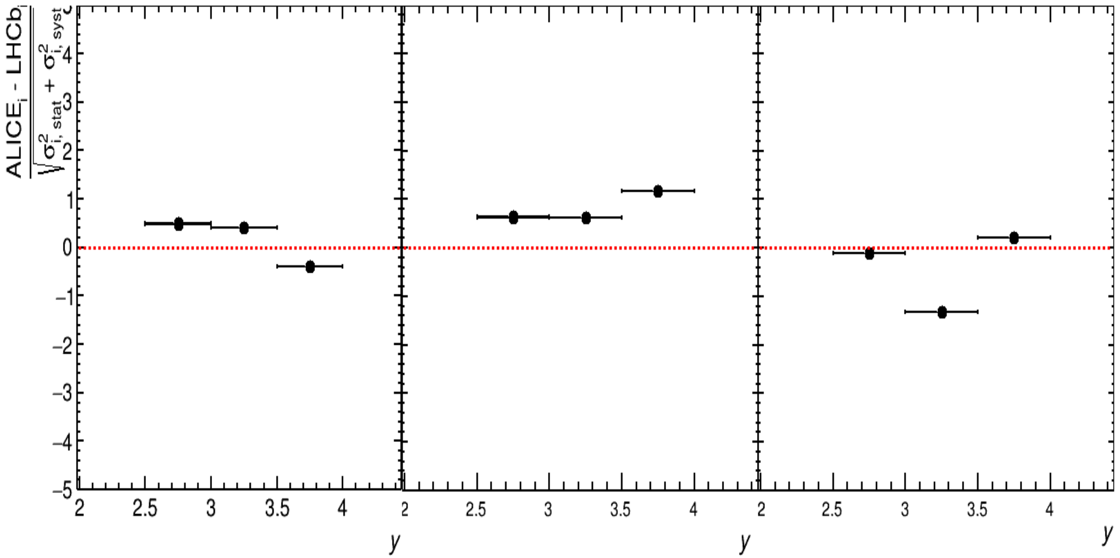


In general not a very good agreement even within uncertainties

y differenential Υ(nS) cross sections

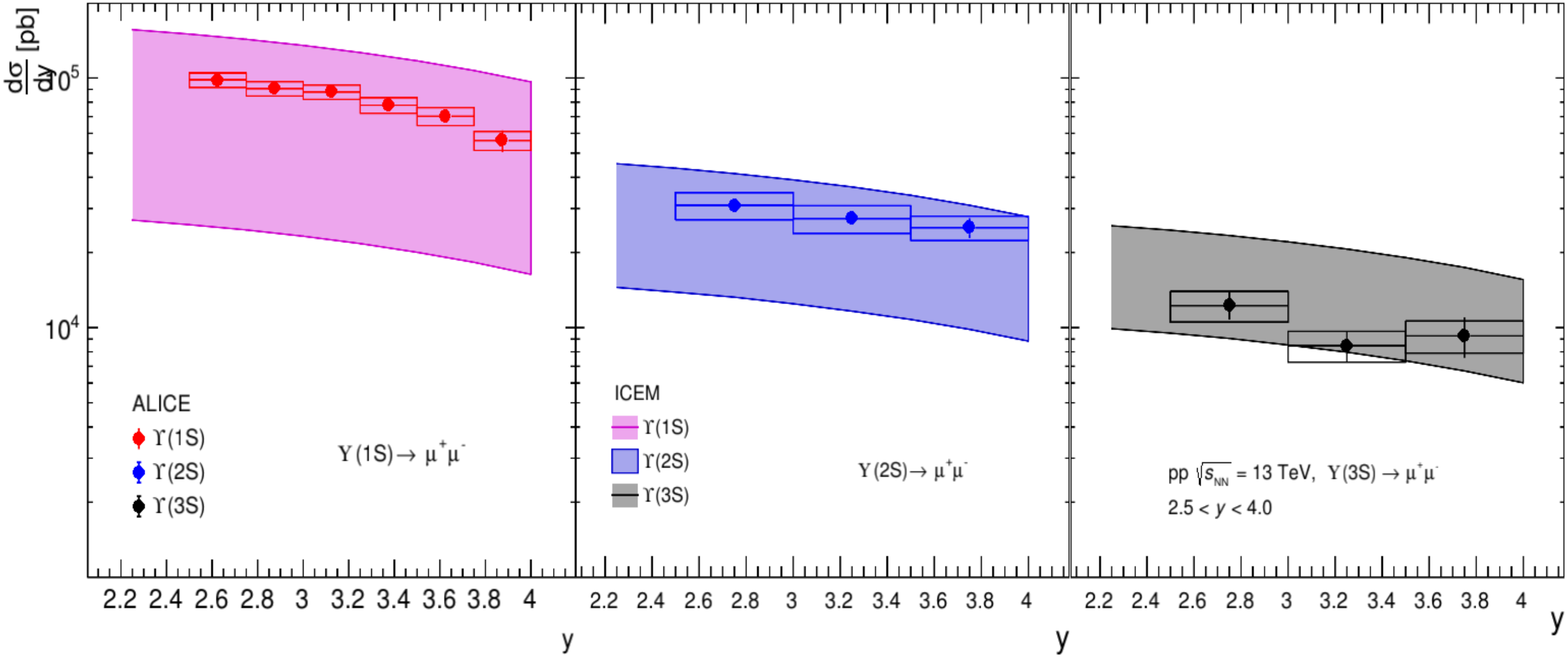
$$\frac{d\sigma_{\Upsilon(\mathrm{nS})}}{dy} = \frac{N_{\Upsilon(\mathrm{nS})}}{A\times\varepsilon}\frac{1}{BR_{\Upsilon(\mathrm{nS})\to\mu^+\mu^-}}\frac{1}{\mathscr{L}_{\mathrm{int}}}\frac{1}{\Delta y}$$





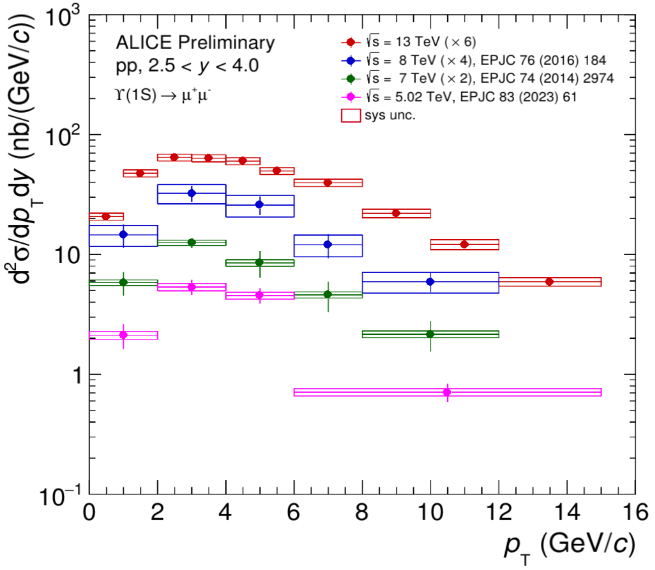
Υ(nS) cross sections in general have good agreement
→Mostly within 1σ

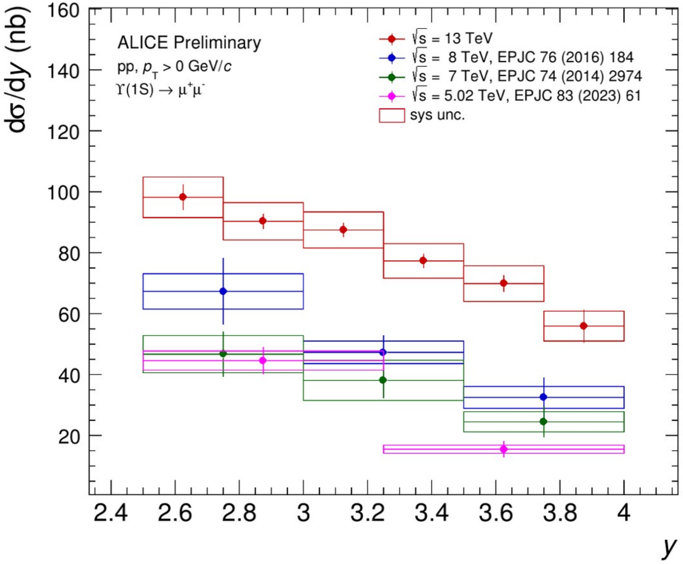
y differenential Υ(nS) cross sections compared to ICEM

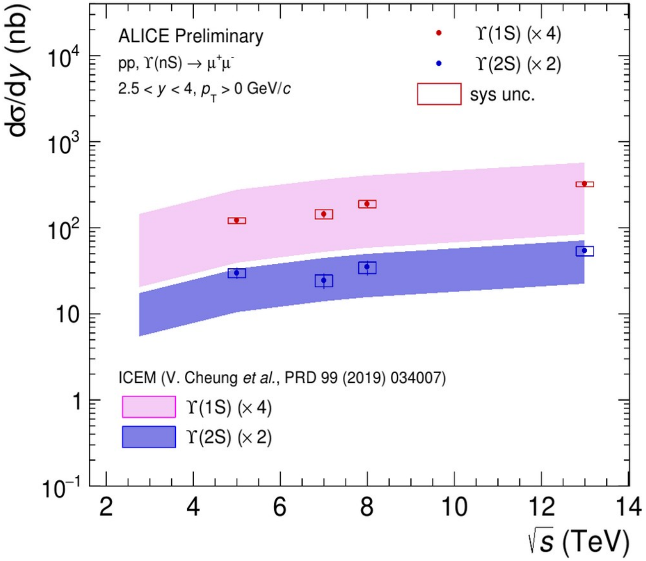


Good agreement within uncertainties

ϒ(1S & 2S) cross sections with √s



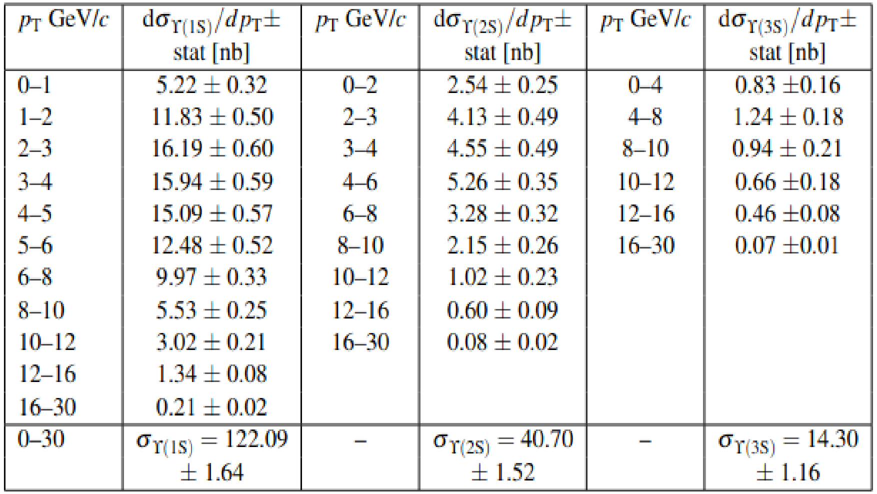




The cross sections of Υ(1S) at different collision energies are shown as functions of p_T and y.

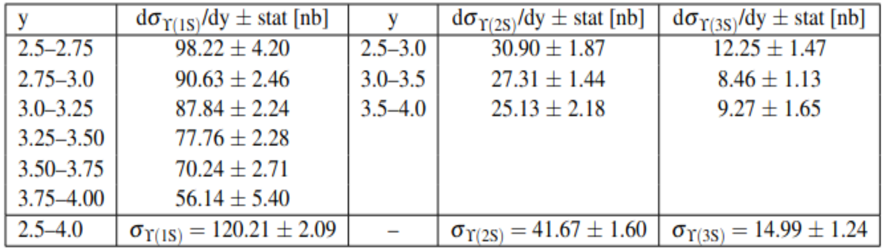
→ICEM model can describe the energy dependence of the production of ϒ(nS)

Integrated Υ(nS) cross section compared to ICEM



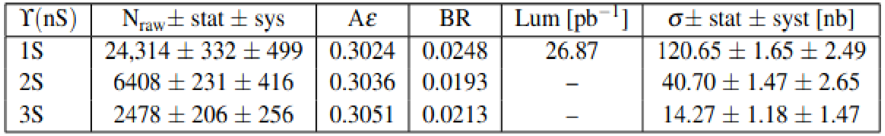
p_T GeV/c	$d\sigma_{\Upsilon(1S)}/dp_T \pm$ stat [nb]	p_T GeV/c	$d\sigma_{\Upsilon(2S)}/dp_T \pm$ stat [nb]	p_T GeV/c	$d\sigma_{\Upsilon(3S)}/dp_T \pm$ stat [nb]
0–1	5.22 ± 0.32	0–2	2.54 ± 0.25	0–4	0.83 ±0.16
1–2	11.83 ± 0.50	2–3	4.13 ± 0.49	4–8	1.24 ± 0.18
2–3	16.19 ± 0.60	3–4	4.55 ± 0.49	8–10	0.94 ± 0.21
3–4	15.94 ± 0.59	4–6	5.26 ± 0.35	10–12	0.66 ±0.18
4–5	15.09 ± 0.57	6–8	3.28 ± 0.32	12–16	0.46 ±0.08
5–6	12.48 ± 0.52	8–10	2.15 ± 0.26	16–30	0.07 ±0.01
6–8	9.97 ± 0.33	10–12	1.02 ± 0.23		
8–10	5.53 ± 0.25	12–16	0.60 ± 0.09		
10–12	3.02 ± 0.21	16–30	0.08 ± 0.02		
12–16	1.34 ± 0.08				
16–30	0.21 ± 0.02				
0–30	$\sigma_{\Upsilon(1S)}$ = 122.09 ± 1.64	–	$\sigma_{\Upsilon(2S)}$ = 40.70 ± 1.52	–	$\sigma_{\Upsilon(3S)}$ = 14.30 ± 1.16

Table 9: p_T-differential cross sections of $\Upsilon(nS)$, shown in Fig 17 are tabulated here.



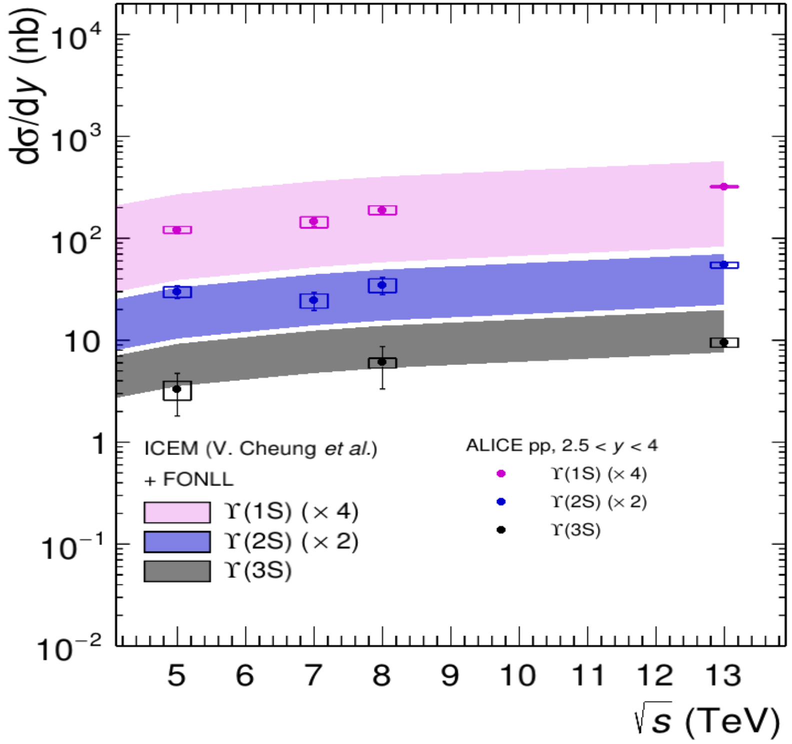
y	$d\sigma_{\Upsilon(1S)}$/dy ± stat [nb]	y	$d\sigma_{\Upsilon(2S)}$/dy ± stat [nb]	$d\sigma_{\Upsilon(3S)}$/dy ± stat [nb]
2.5–2.75	98.22 ± 4.20	2.5–3.0	30.90 ± 1.87	12.25 ± 1.47
2.75–3.0	90.63 ± 2.46	3.0–3.5	27.31 ± 1.44	8.46 ± 1.13
3.0–3.25	87.84 ± 2.24	3.5–4.0	25.13 ± 2.18	9.27 ± 1.65
3.25–3.50	77.76 ± 2.28			
3.50–3.75	70.24 ± 2.71			
3.75–4.00	56.14 ± 5.40			
2.5–4.0	$\sigma_{\Upsilon(1S)}$ = 120.21 ± 2.09	–	$\sigma_{\Upsilon(2S)}$ = 41.67 ± 1.60	$\sigma_{\Upsilon(3S)}$ = 14.99 ± 1.24

Table 10: Rapidity-differential cross sections of $\Upsilon(nS)$ as shown in left panel of Fig. 19



Υ(nS)	N_{raw} ± stat ± sys	$A\varepsilon$	BR	Lum [pb^{-1}]	σ± stat ± syst [nb]
1S	24,314 ± 332 ± 499	0.3024	0.0248	26.87	120.65 ± 1.65 ± 2.49
2S	6408 ± 231 ± 416	0.3036	0.0193	–	40.70 ± 1.47 ± 2.65
3S	2478 ± 206 ± 256	0.3051	0.0213	–	14.27 ± 1.18 ± 1.47

Table 11: Integrated cross sections obtained independently from the fit to inclusive mass spectra.



Integrated cross sections agree well with differential estimations

Summary

1. Υ(nS) cross sections are measured as a function of p_T (< 30 GeV) and y
2. Cross sections are compared to LHCb, agreement within 1σ in most bins
3. Compared with ICEM model calculations, Υ(1S and 2S) agrees well

Ongoing work:
Systematic error calculations related to track and trigger matching efficiency

Remaining task:
1. Comparison to other model calculations

Paper proposal:
1. Merged paper proposal of THIS analysis + Υ(1S) polarization anticipated soon

Thank you

Fit Functions

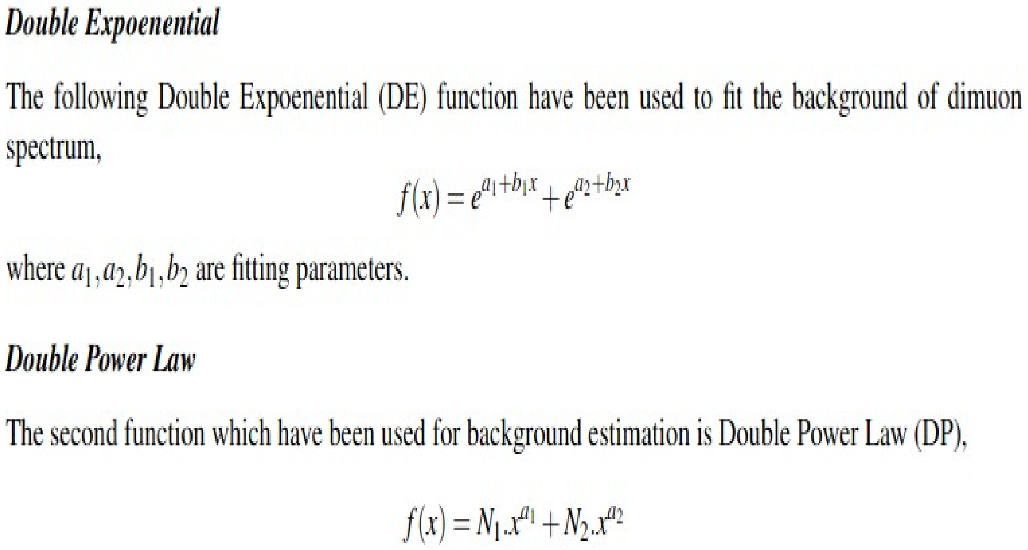
$$f(x;\mu,\sigma,\alpha_L,n_L,\alpha_R,n_R) = N.\begin{cases} \exp(-\frac{(x-\mu)^2}{2\sigma^2}) & \text{for } \alpha_R > \frac{x-\mu}{\sigma} > -\alpha_L \\ A.(B-\frac{x-\mu}{\sigma})^{-n_L} & \text{for } \frac{x-\mu}{\sigma} \leq -\alpha_L \\ C.(D+\frac{x-\mu}{\sigma})^{-n_R} & \text{for } \frac{x-\mu}{\sigma} \geq \alpha_R \end{cases}$$

$$A = \left(\frac{n_L}{|\alpha_L|}\right)^{n_L}.\exp\left(-\frac{|\alpha_\mathrm{L}|^2}{2}\right)$$

$$B = \frac{n_L}{|\alpha_L|} - |\alpha_L|$$

$$C = \left(\frac{n_R}{|\alpha_R|}\right)^{n_R}.\exp\left(-\frac{|\alpha_\mathrm{R}|^2}{2}\right)$$

$$B = \frac{n_R}{|\alpha_R|} - |\alpha_R|$$



Double Expoenential

The following Double Expoenential (DE) function have been used to fit the background of dimuon spectrum,

$$f(x) = e^{a_1+b_1x} + e^{a_2+b_2x}$$

where a_1, a_2, b_1, b_2 are fitting parameters.

Double Power Law

The second function which have been used for background estimation is Double Power Law (DP),

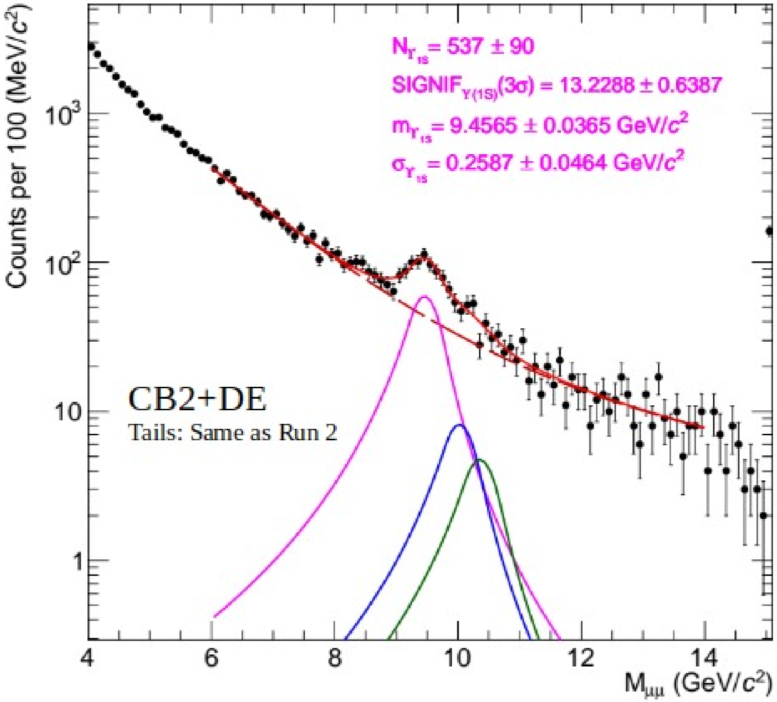
$$f(x) = N_1.x^{a_1} + N_2.x^{a_2}$$

Systematic tags

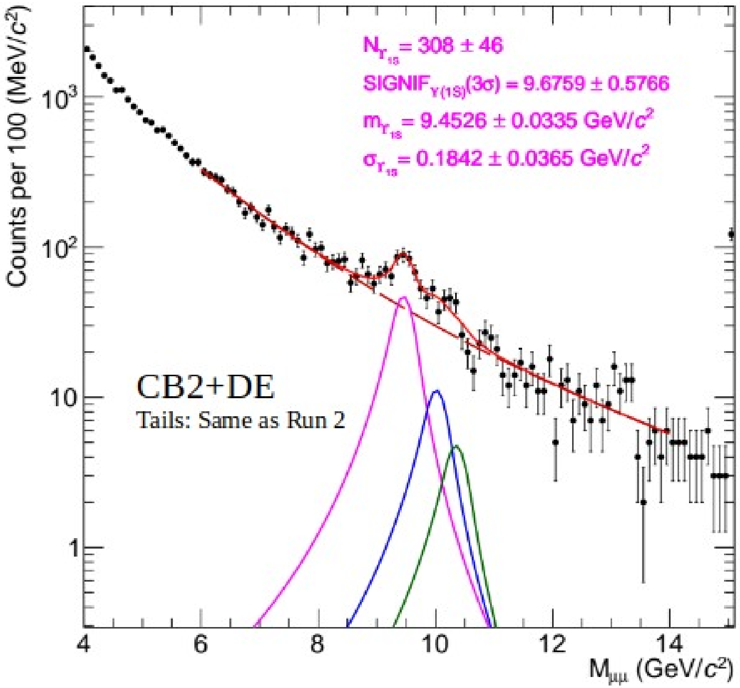
Bkg. Func	Fit Range	Tail type	Tag
DE	6-14	data	000
	7-12		001
	5-14		002
DP	6-14	data	003
	7-12		004
	5-14		005
VWG	6-14	data	006
	7-12		007
	5-14		008

Bkg. Func	Fit Range	Tail type	Tag
DE	6-14	MC	009
	7-12		010
	5-14		011
DP	6-14	MC	012
	7-12		013
	5-14		014
VWG	6-14	MC	015
	7-12		016
	5-14		017

Invariant mass distribution @ 13.6 TeV



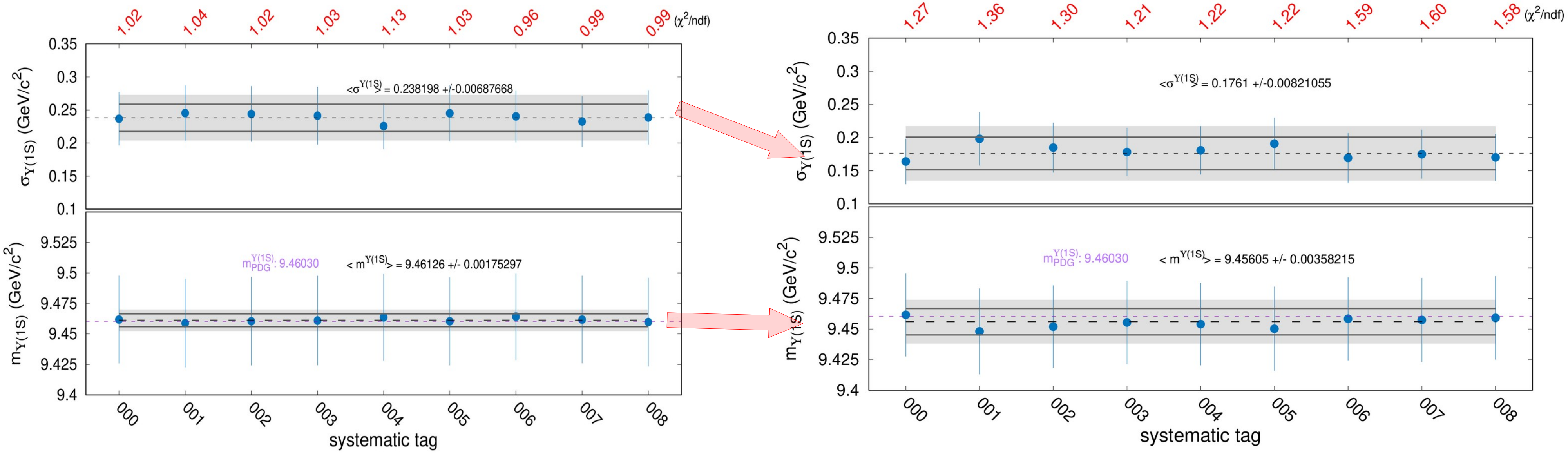
standard track association



time compatible track association (2σ)

- Improvement in mass resolution
- Mass position remains same

Systematics of mass position resolution



standard track association

time compatible track association (2σ)

- Improvement in mass resolution is apparent for all variations in fit
- Statistics is however, limited