Feed-down contributions to quarkonium production at the LHC

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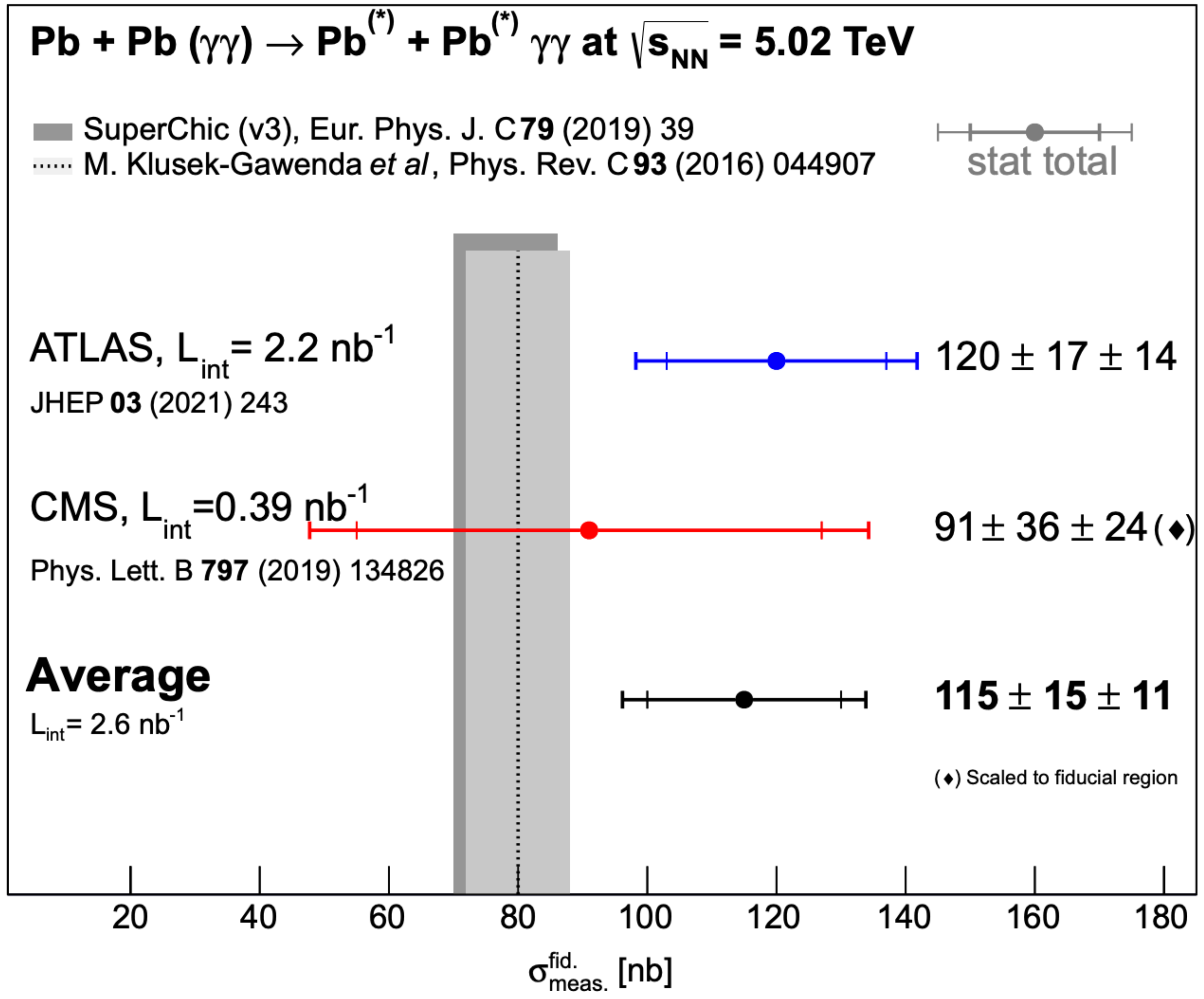
STRONG-2020 annual meeting – 17 October 2022

The HonexComb initiative

JRA1-LHC-Combine: *Inter-experiment combination of heavy-ion measurements at the LHC* (WP19)

- cross-experiment combination of measurements
  - rare processes: light-by-light scattering ☛
  - over a large phase space: total charm cross section, **quarkonium feed-downs**
- identification (and resolution?) of tensions (e.g., Λ_c / D^0 yield ratios)
- comparison and definition of observables

Combination of ATLAS and CMS measurements of $\gamma\gamma \to \gamma\gamma$ cross sections [arXiv:2204.02845]



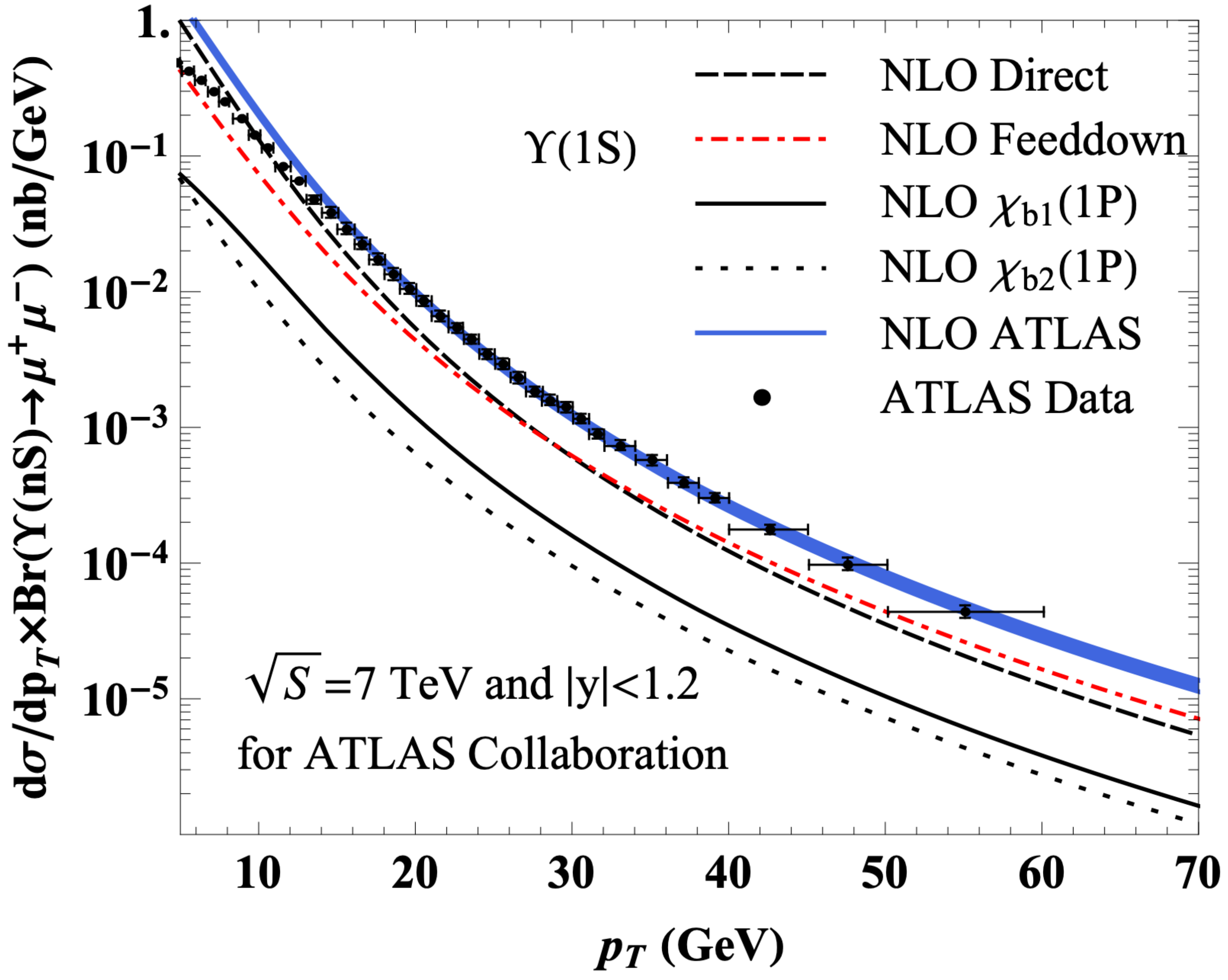
More details in Raphael's report (Wednesday, 11:40)

Feed-downs, feed-downs everywhere!

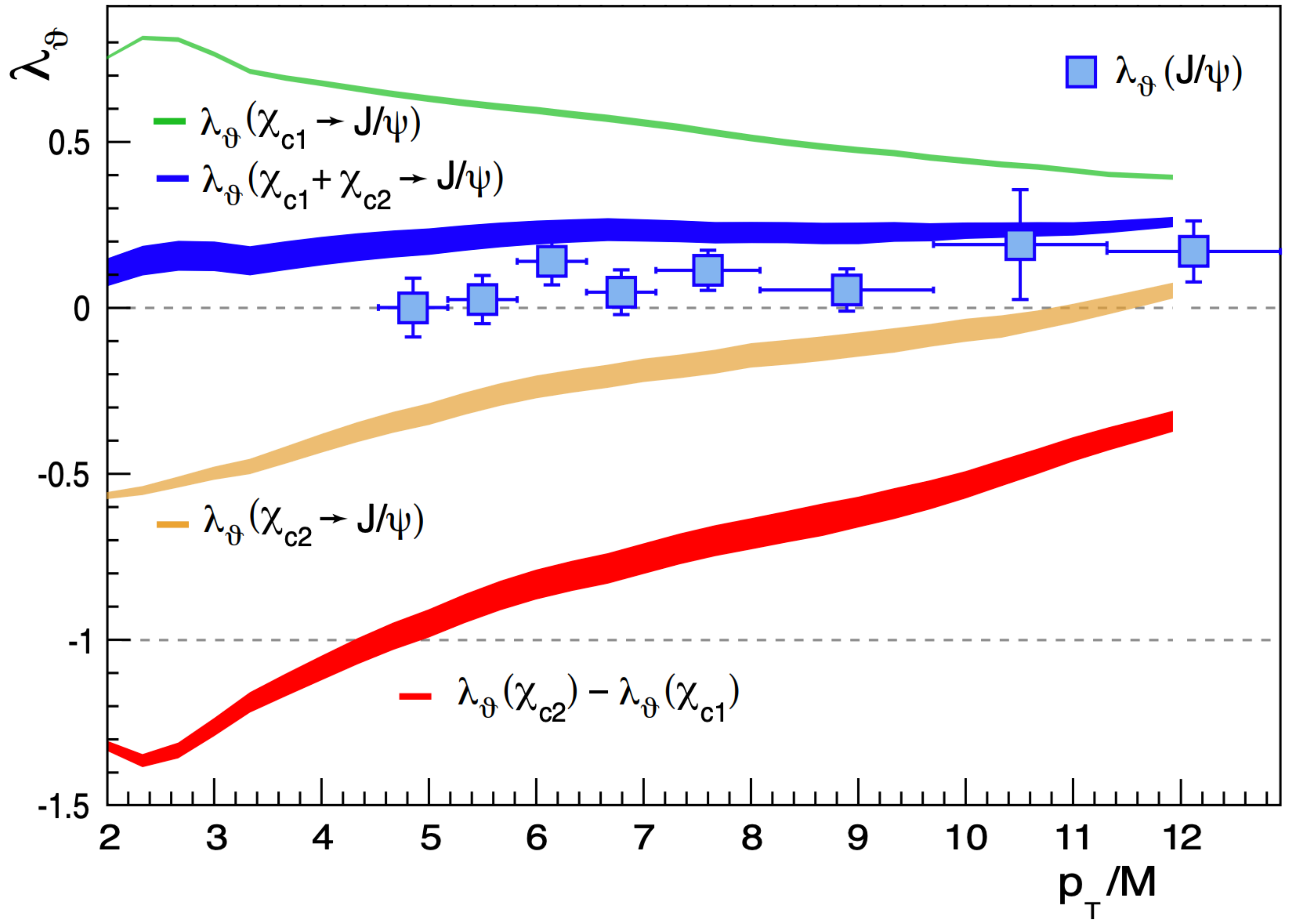
Transitions from a given quarkonium state to a lighter one of the same family

☛ *contaminate* the production measured (prompt yield = direct production + feed-down sources)

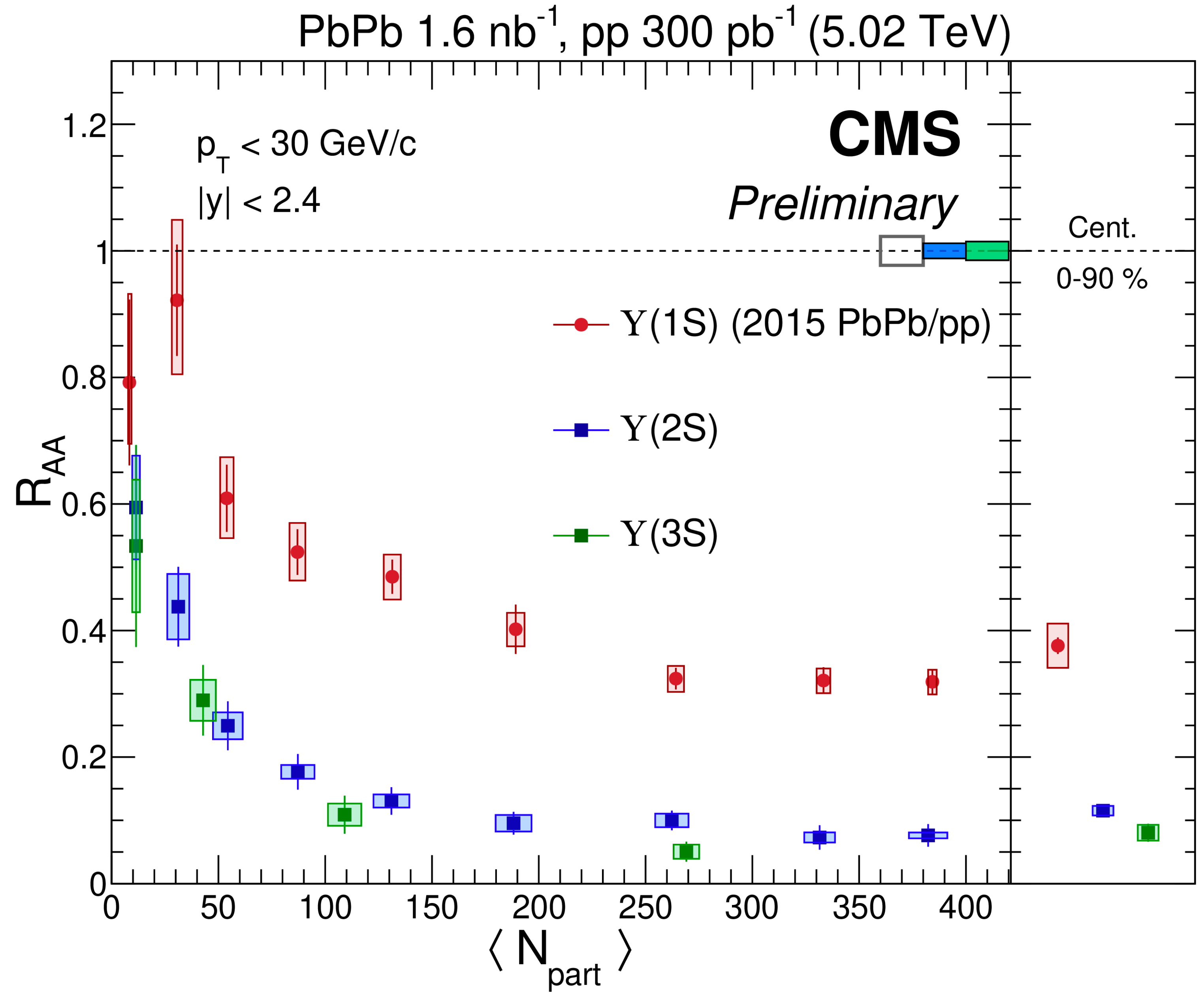
p_T spectrum of Υ(1S) production [Han et al., [PRD 94 (2016) 014028](#)]



null J/ψ polarization from the *cancellation of χ_c feed-downs* [Faccioli et al., [EPJC 78 (2018) 268](#)]



relative suppression of Υ states in AA collisions [[CMS-HIN-21-007](#)]



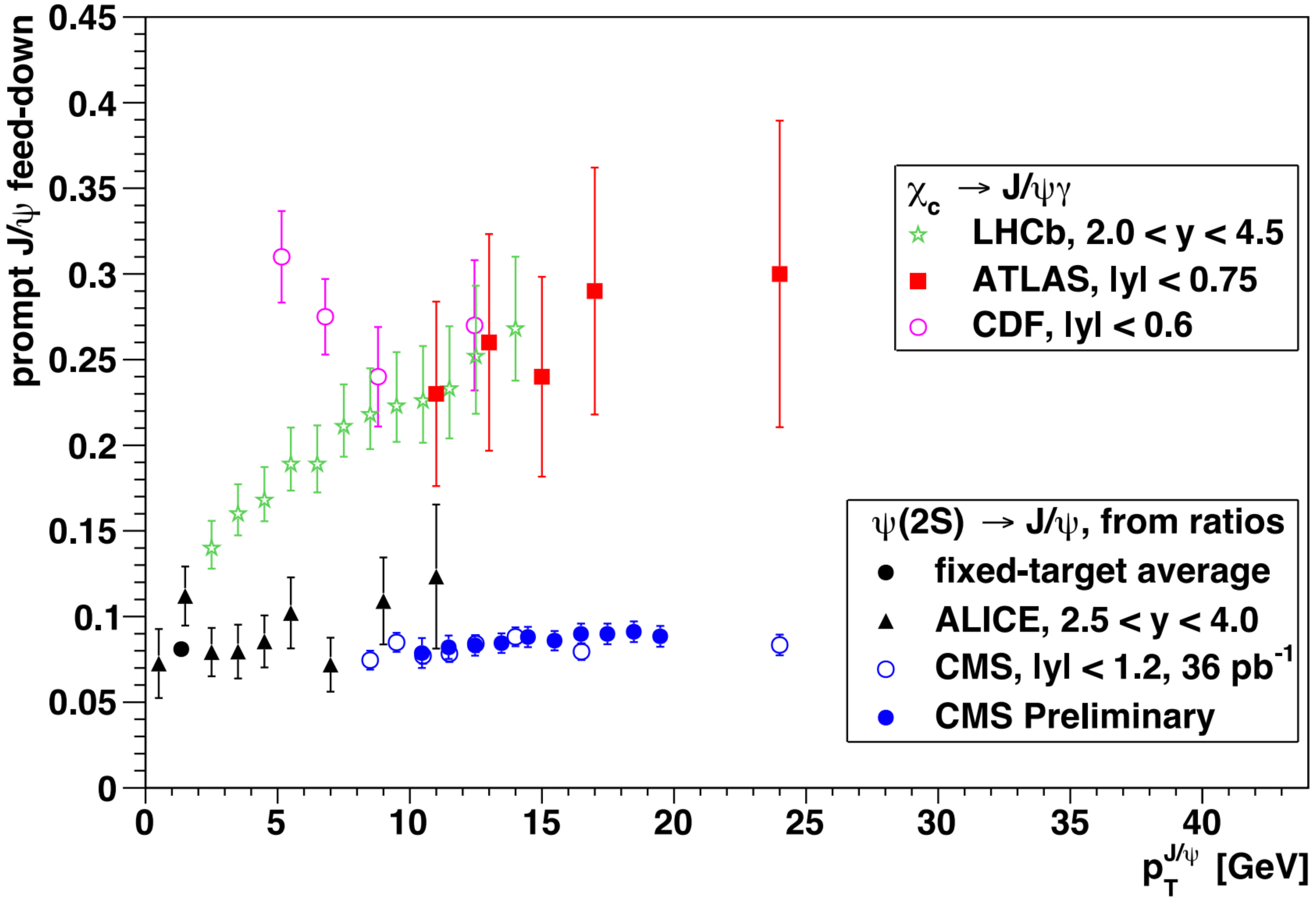
Motivations

Feed-down fraction: relative fraction of $\mathcal{Q}(ml)$ production originating from the decay of $\mathcal{Q}'(nl')$

$$\mathcal{F}^{\mathcal{Q}'(nl')}_{\mathcal{Q}(ml)} \equiv \frac{\sigma(\mathcal{Q}'(nl'))}{\sigma(\mathcal{Q}(ml))} \times \mathcal{B}(\mathcal{Q}'(nl') \to \mathcal{Q}(ml) + X) \text{ with } n \geq m$$

Hermine Wöhri @ QWG 2014

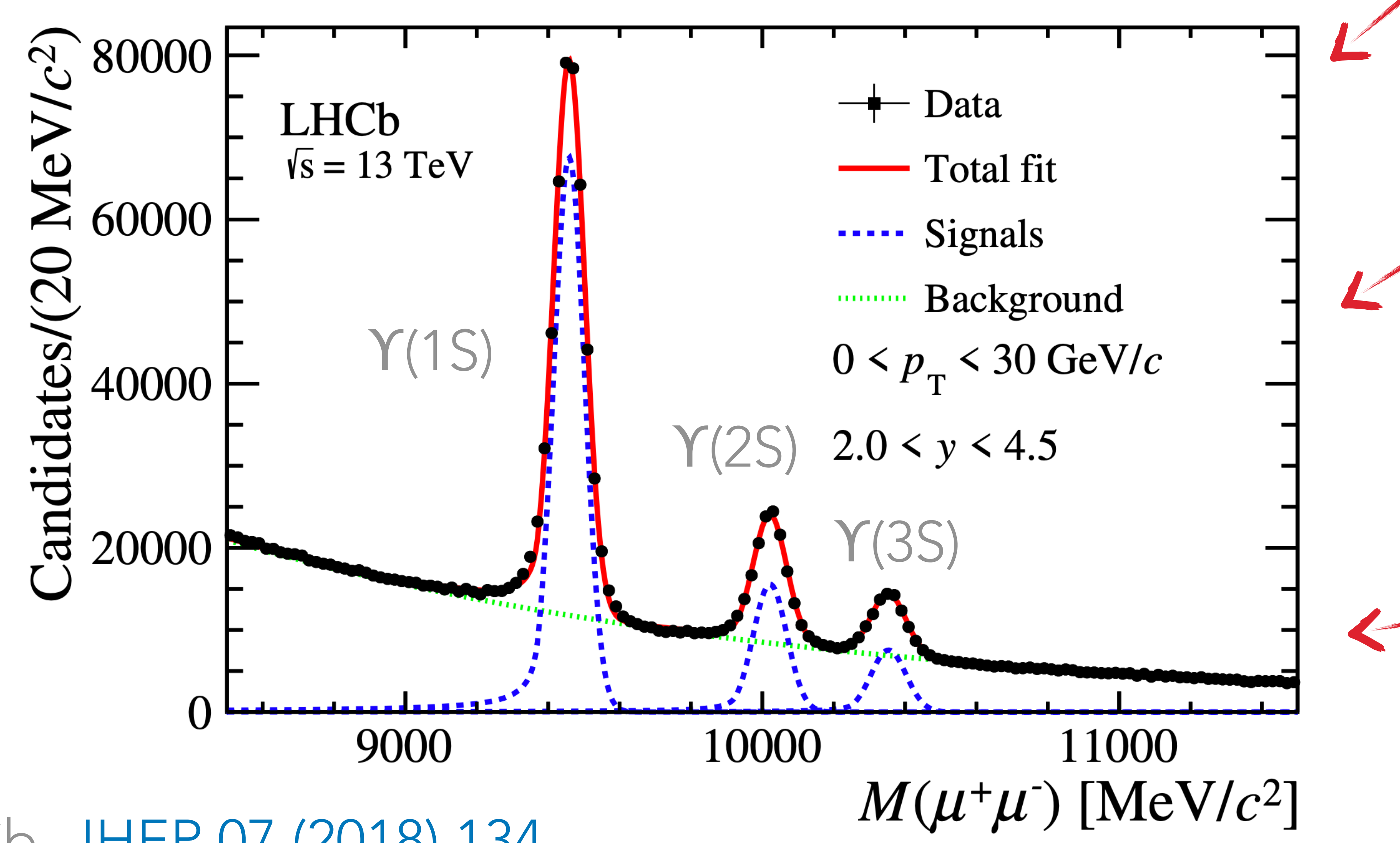
- derivation based on early Run 1 measurements ☛ never published!
- **review and exploitation of all available LHC measurements**
- ultimate achievement: assess long-standing questions ☛ *is the direct Υ(1S) production in AA collisions suppressed at the LHC?*



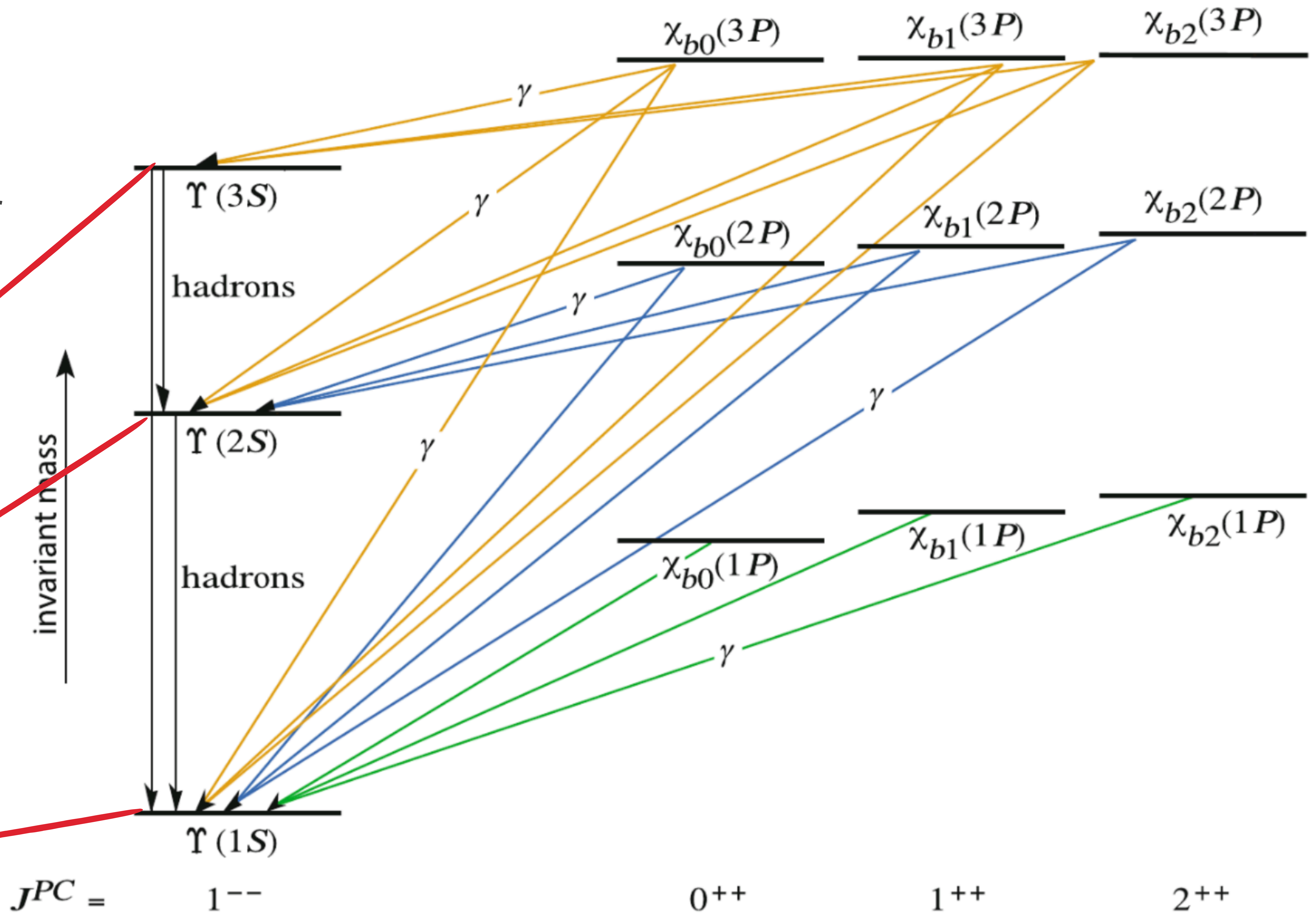
Bottomonia accessible at the LHC

ϒ(1,2,3S) measured down to p_T = 0 via the dimuon decay channel by all four experiments
☛ complementary rapidity acceptance!

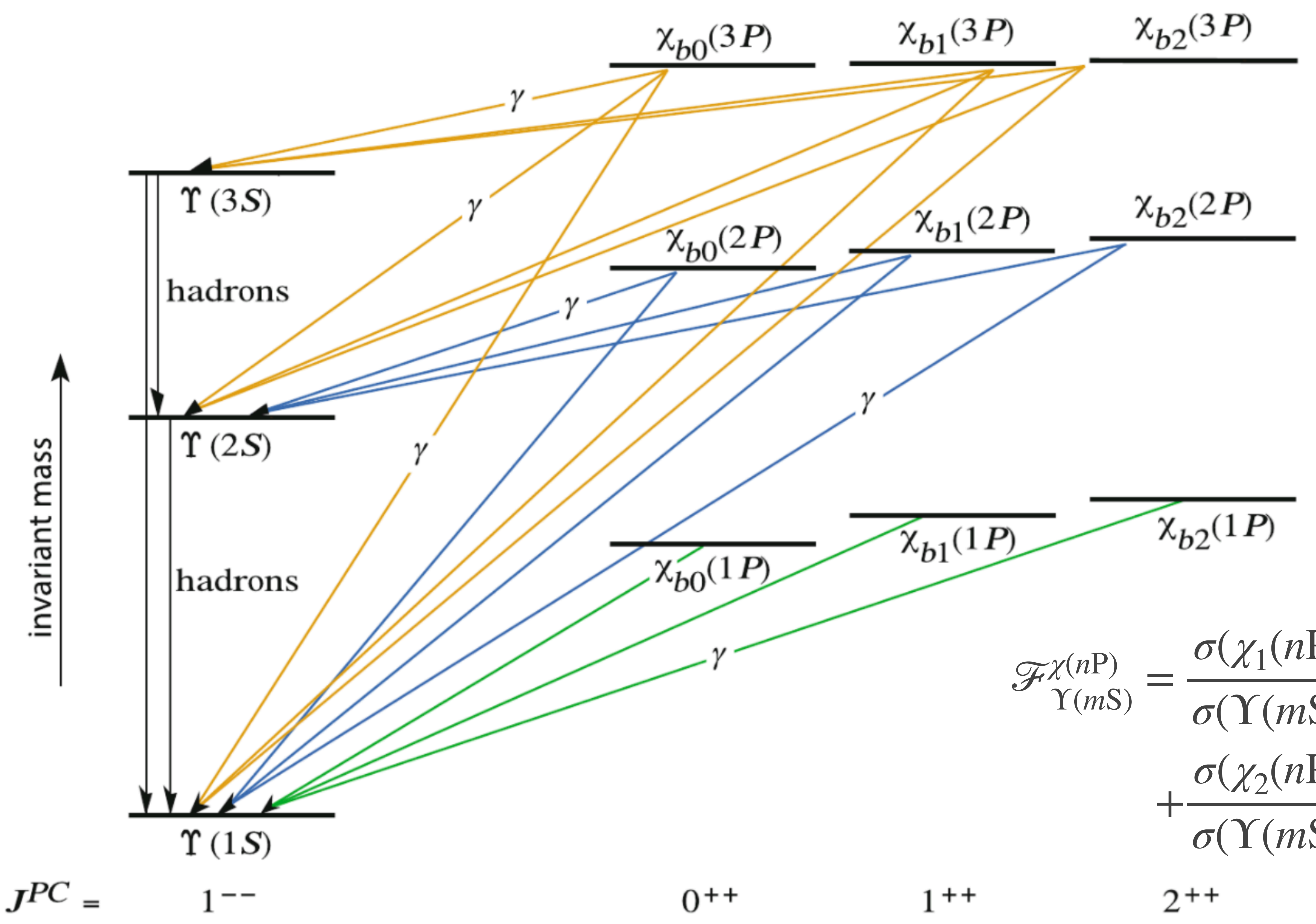
Inclusive cross section ratios to be corrected for **hadronic transitions**



LHCb, JHEP 07 (2018) 134



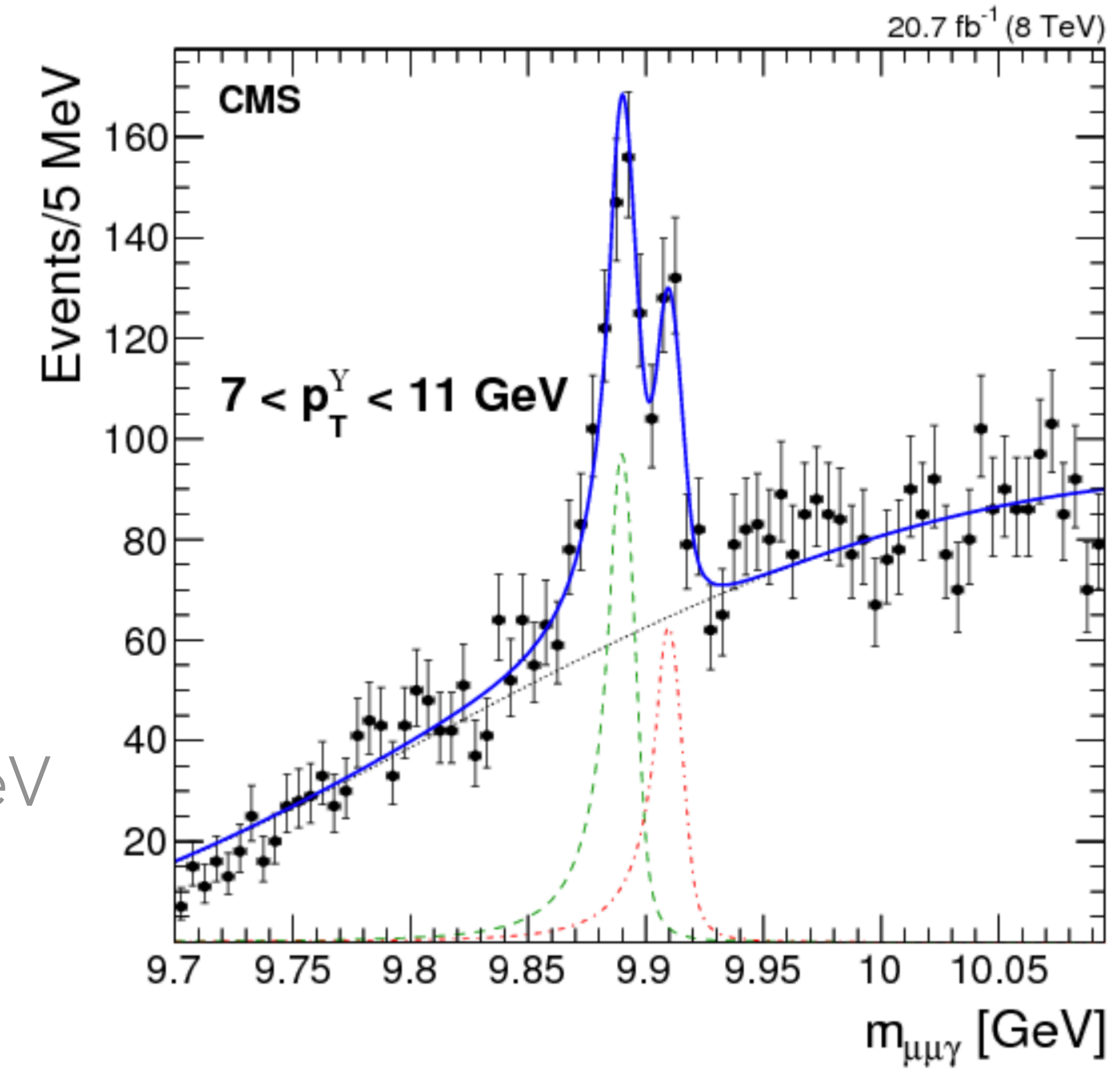
Bottomonia accessible at the LHC



Radiative decay of χ_b states to $\Upsilon(nS)$ with large branching ratios

- **direct measurement of the feed-down!**
- photon energy resolution of a few MeV to separate the multiplet mass peaks

$$\mathcal{F}^{\chi(nP)}_{\Upsilon(mS)} = \frac{\sigma(\chi_1(nP))}{\sigma(\Upsilon(mS))} \times \mathcal{B}(\chi_1(nP) \to \Upsilon(mS) + \gamma) + \frac{\sigma(\chi_2(nP))}{\sigma(\Upsilon(mS))} \times \mathcal{B}(\chi_2(nP) \to \Upsilon(mS) + \gamma)$$



CMS, PLB 743 (2015) 383

$M(\chi_{b2}(1P)) - M(\chi_{b1}(1P)) = 19$ MeV

caveat: will (have to) neglect any other feed-downs

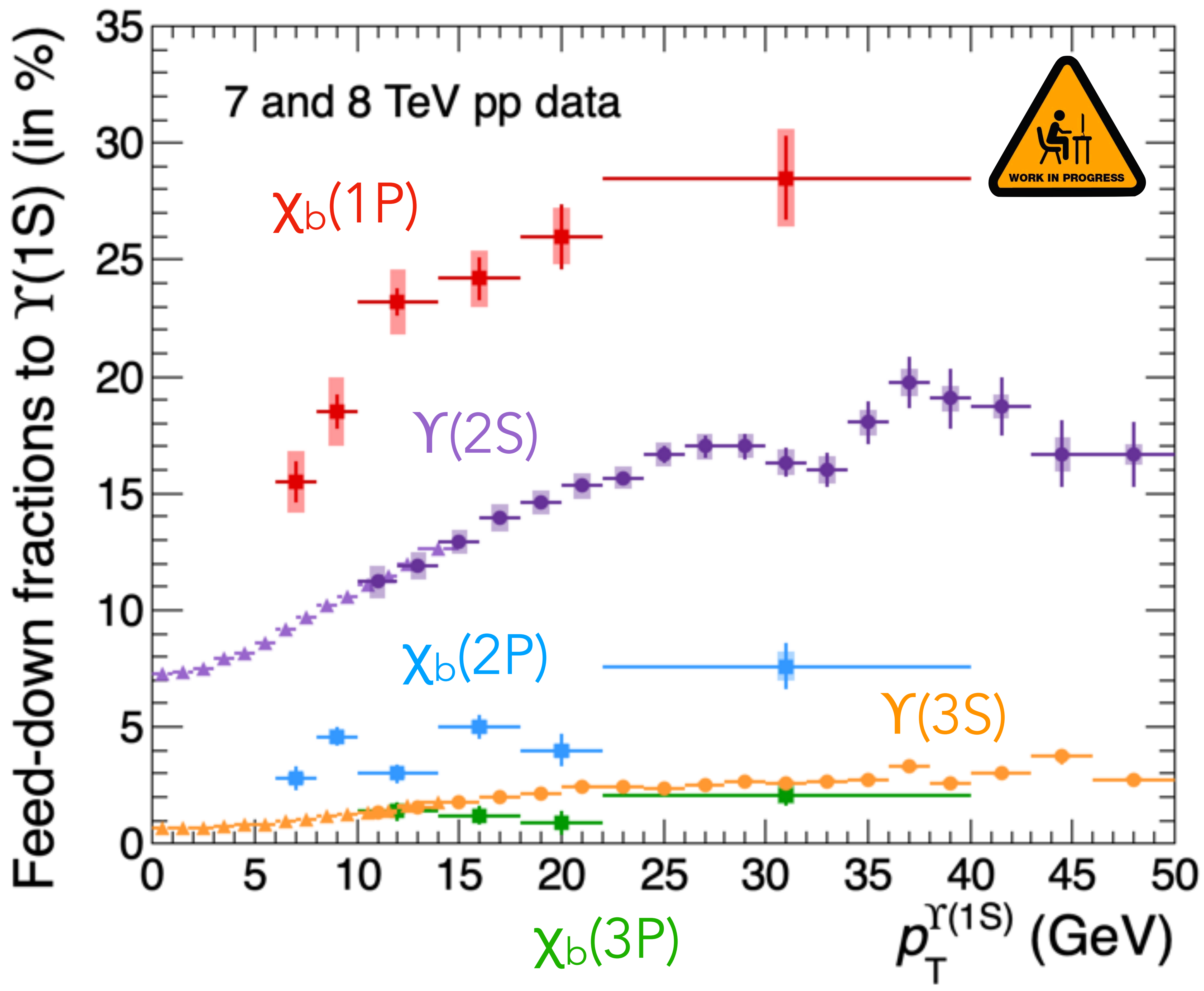
- χ_{b0} decays (not observed, small branching ratios)
- resonances above the B$\bar{\text{B}}$ mass threshold
- non-prompt production from tetraquark, EW and Higgs bosons decays

Snapshot – feed-downs to Υ(1S)

- Υ(*n*S) cross section ratios from 8 TeV LHCb (triangles) and 7 TeV CMS (circles) measurements
  ☛ Υ excited states well under control!

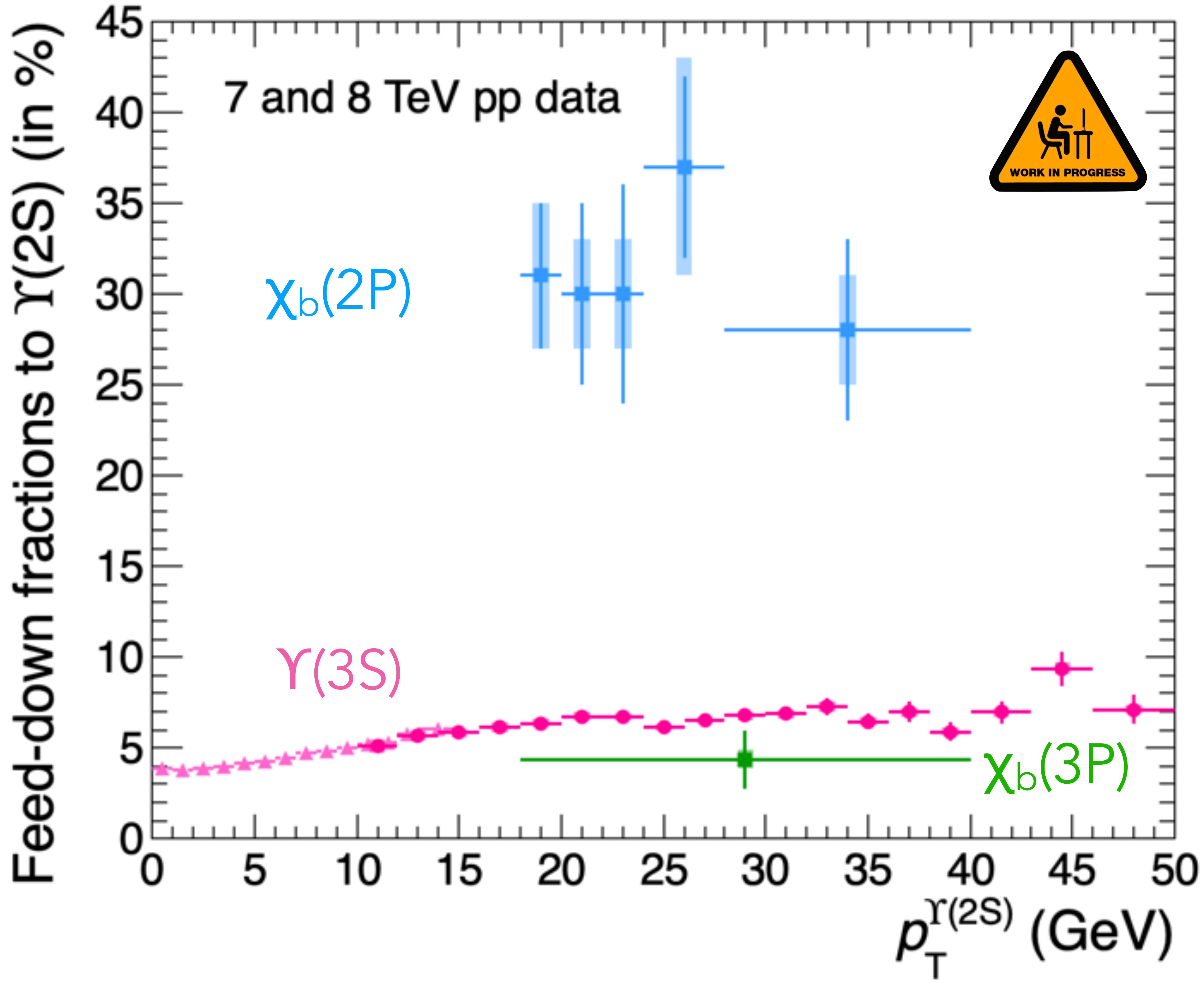
- **feed-down fractions from χ_b decays** directly taken from LHCb measurements at 8 TeV
  ☛ **how to extrapolate down to p_T = 0?**

- **branching ratio uncertainties not represented** (probably the dominant source of final systematics, partially correlated)



Snapshot – feed-downs to Υ(2S)

- Υ(3S)-over-Υ(2S) cross section ratios from 8 TeV LHCb (triangles) and 7 TeV CMS (circles) measurements
  ☛ Υ(3S) contribution well under control!
- **feed-down fractions from χ_b decays** directly taken from LHCb measurements at 8 TeV
  ☛ **how to extrapolate down to p_T = 0?**
- **branching ratio uncertainties not represented** (probably the dominant source of final systematics, partially correlated)



Extraplation of χ_b feed-down fractions

Do the feed-down fractions $\chi_b(nP) \to \Upsilon(2,3S)$ decrease with p_T as $\chi_b(1P) \to \Upsilon(1S)$?

In his review [Physics Reports 889 (2020) 1], J.P. Lansberg notes that

$$\frac{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(mS)} \cdot \mathcal{F}^{\Upsilon(mS)}_{\Upsilon(1S)}}{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(1S)}} = \frac{\mathcal{B}(\chi_b(nP) \to \Upsilon(\mathrm{mS})) \cdot \mathcal{B}(\Upsilon(\mathrm{mS}) \to \Upsilon(1S))}{\mathcal{B}(\chi_b(nP) \to \Upsilon(1S))}$$

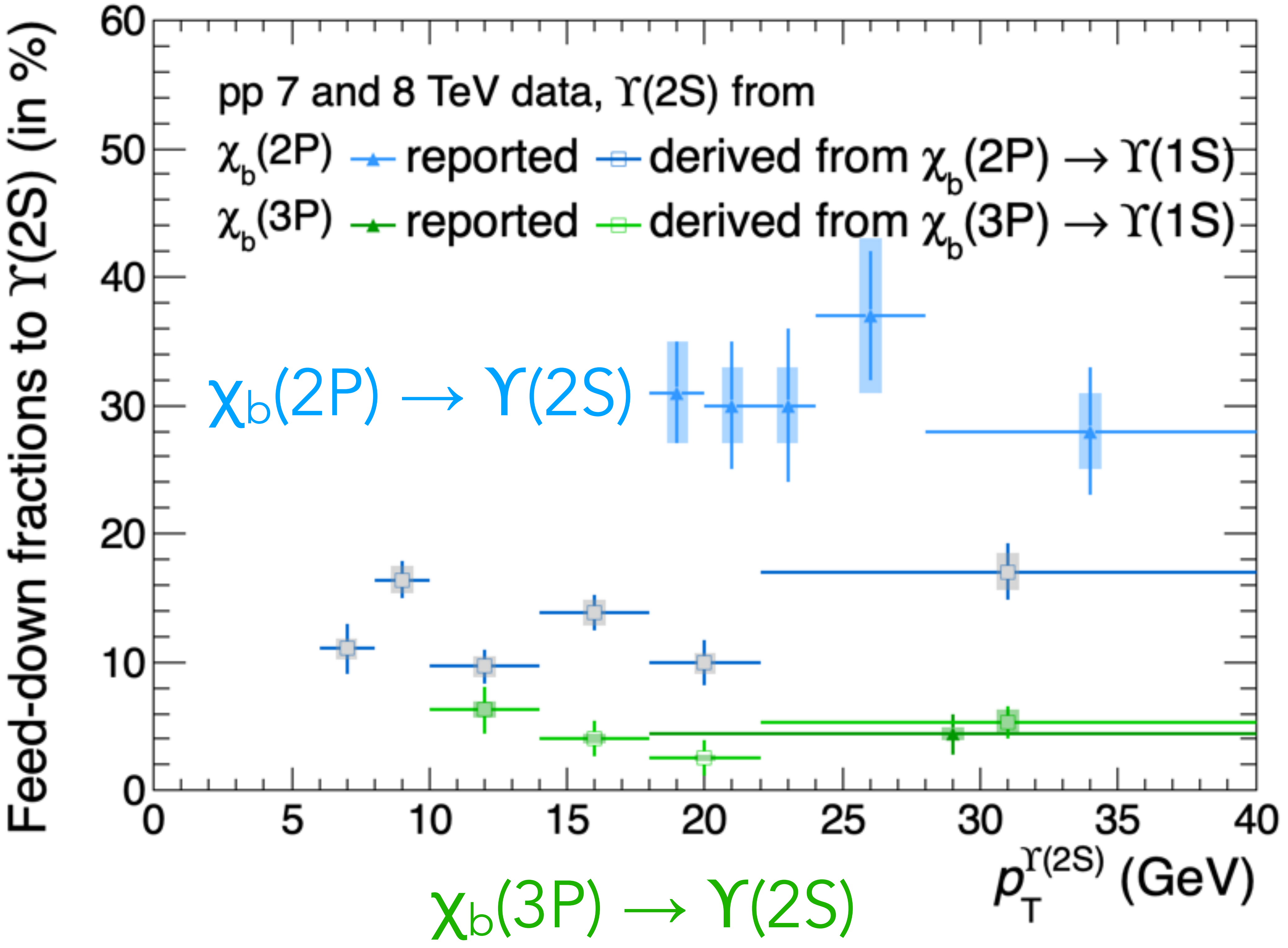
Isolating the term of interest, one get: $\mathcal{F}^{\chi_b(nP)}_{\Upsilon(mS)} = \frac{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(1S)}}{\frac{\sigma(\Upsilon(mS))}{\sigma(\Upsilon(1S))}} \times \frac{\mathcal{B}(\chi_b(nP) \to \Upsilon(\mathrm{mS}))}{\mathcal{B}(\chi_b(nP) \to \Upsilon(1S))}$

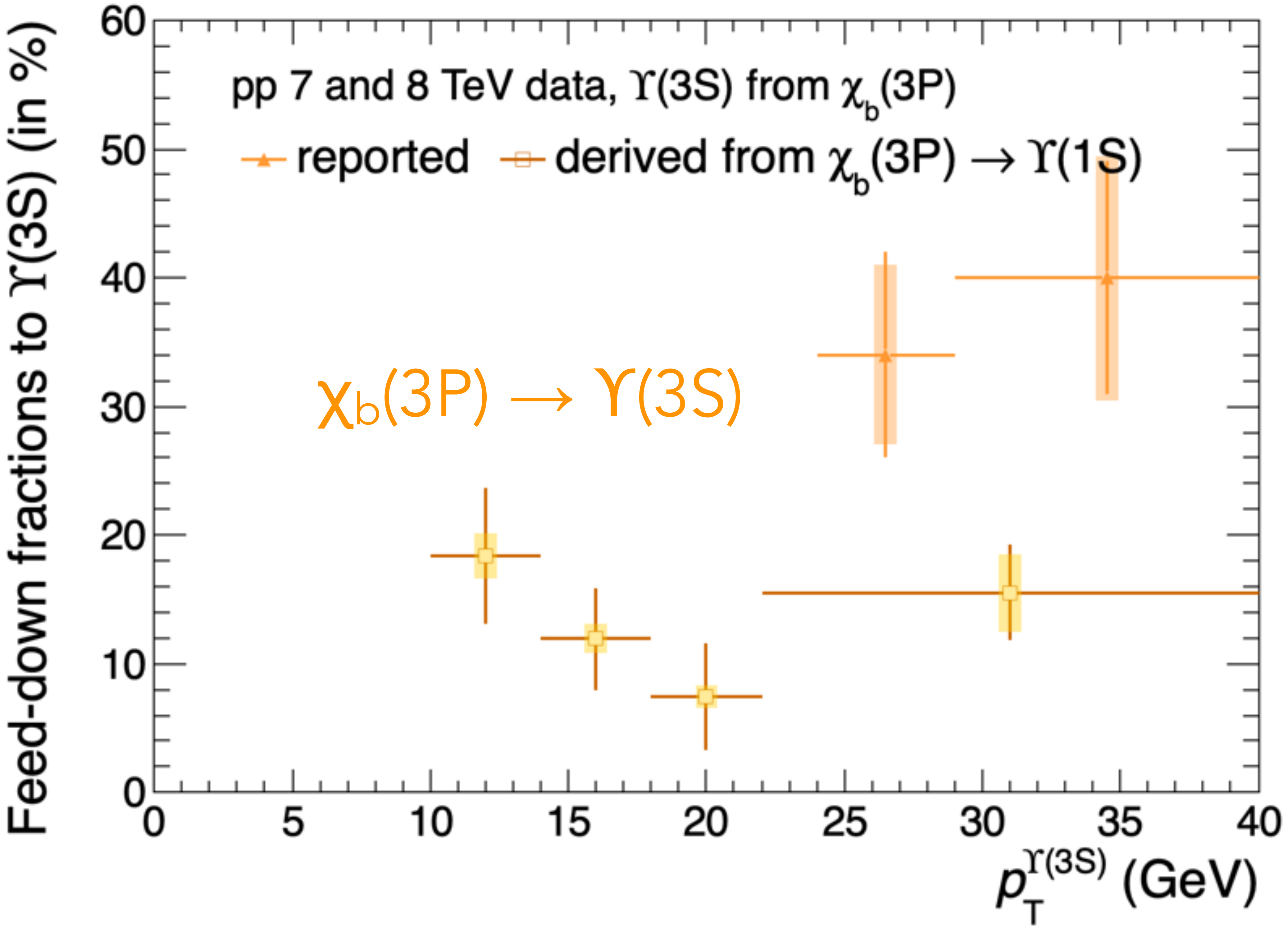
☛ **extension of χ_b feed-down fractions to Υ excited states** using the measured ones to $\Upsilon(1S)$

Lansberg's trick results

$$\mathscr{F}^{\chi_b(nP)}_{\Upsilon(mS)} = \frac{\mathscr{F}^{\chi_b(nP)}_{\Upsilon(1S)}}{\frac{\sigma(\Upsilon(mS))}{\sigma(\Upsilon(1S))}} \times \frac{\mathscr{B}(\chi_b(nP) \to \Upsilon(mS))}{\mathscr{B}(\chi_b(nP) \to \Upsilon(1S))} \text{ with } \mathscr{B}(\chi_b(nP) \to \Upsilon(mS)) = \sum_{J=0}^{2} \mathscr{B}(\chi_{b,J}(nP) \to \Upsilon(mS) + \gamma)$$

Branching ratios $\chi_{b,J}(3P) \to \Upsilon(mS) + \gamma$ unknown, taking NRQCD predictions [Han et al., PRD 94 (2016) 014028]





Separating the χ_b multiplet

If one neglects the J = 0 contribution (small radiative-decay branching ratio),

$$\mathcal{F}^{\chi(nP)}_{\Upsilon(mS)} = \frac{\sigma(\chi_1(nP))}{\sigma(\Upsilon(mS))} \times \mathcal{B}(\chi_1(nP) \to \Upsilon(mS) + \gamma) + \frac{\sigma(\chi_2(nP))}{\sigma(\Upsilon(mS))} \times \mathcal{B}(\chi_2(nP) \to \Upsilon(mS) + \gamma).$$

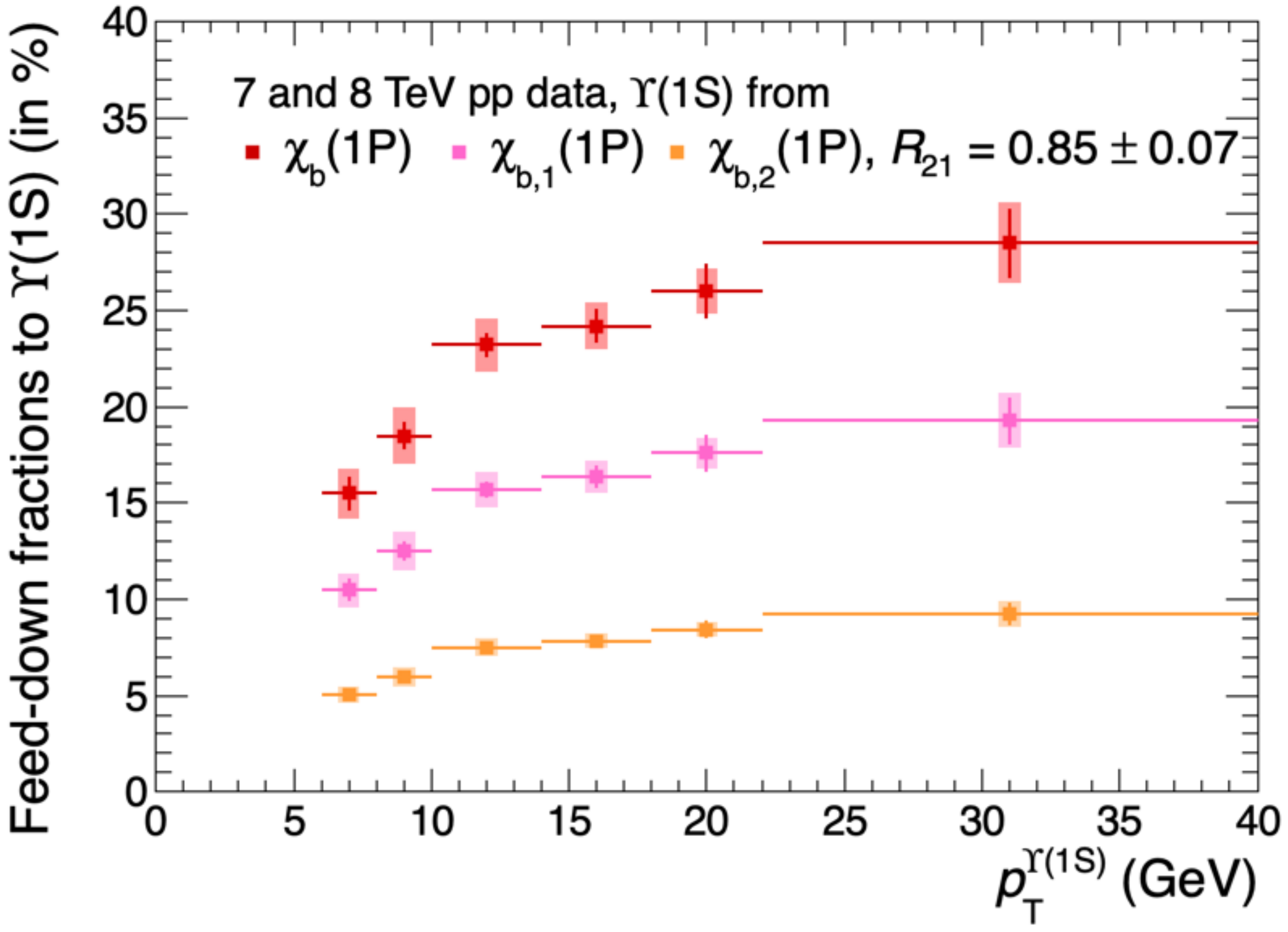
One can *separate* the feed-down fractions by introducing the cross section ratio $R_{21} = \frac{\sigma(\chi_2(nP))}{\sigma(\chi_1(nP))}$

using the χ_{b2}(1P) / χ_{b1}(1P) measurements.

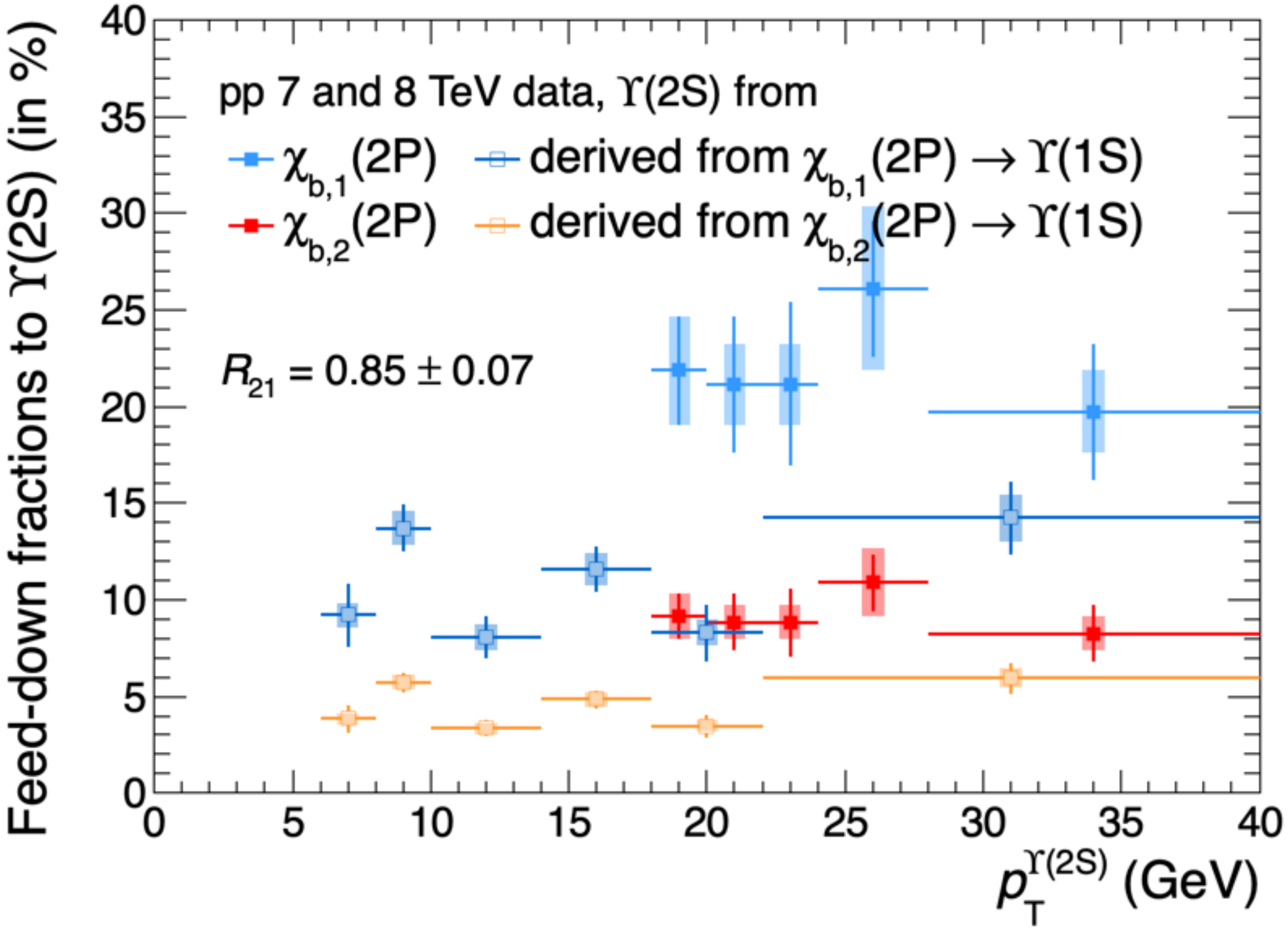
CMS average: R_{21} = 0.85 ± 0.07 [PLB 743 (2015) 383]

$$\mathcal{F}^{\chi_1(nP)}_{\Upsilon(mS)} = \mathcal{F}^{\chi(nP)}_{\Upsilon(mS)} \times \left[1 + R_{21} \times \frac{\mathcal{B}(\chi_2(nP) \to \Upsilon(mS) + \gamma)}{\mathcal{B}(\chi_1(nP) \to \Upsilon(mS) + \gamma)}\right]$$

$$\mathcal{F}^{\chi_2(nP)}_{\Upsilon(mS)} = \mathcal{F}^{\chi(nP)}_{\Upsilon(mS)} - \mathcal{F}^{\chi_1(nP)}_{\Upsilon(mS)}$$



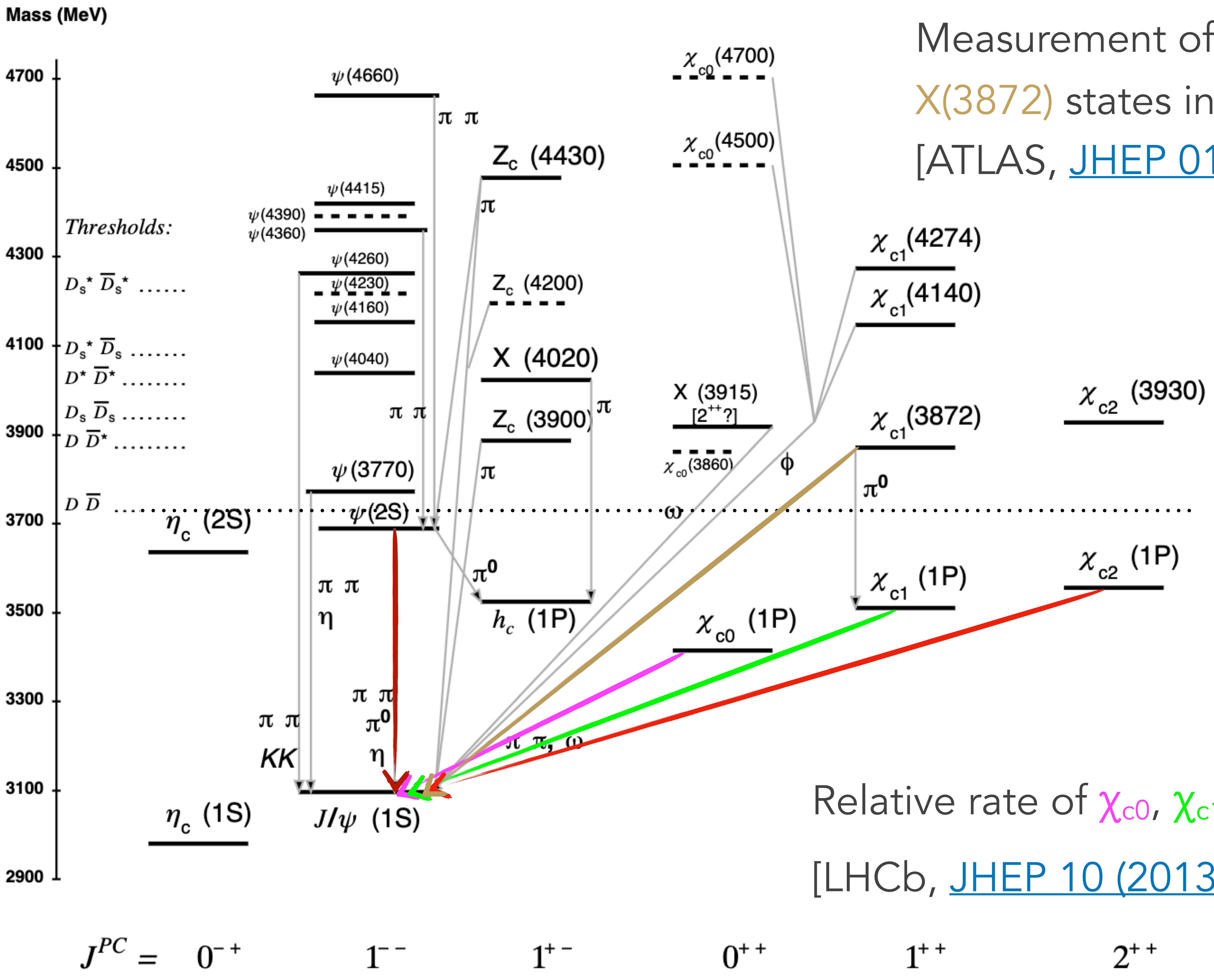
Lansberg's trick after multiplet separation



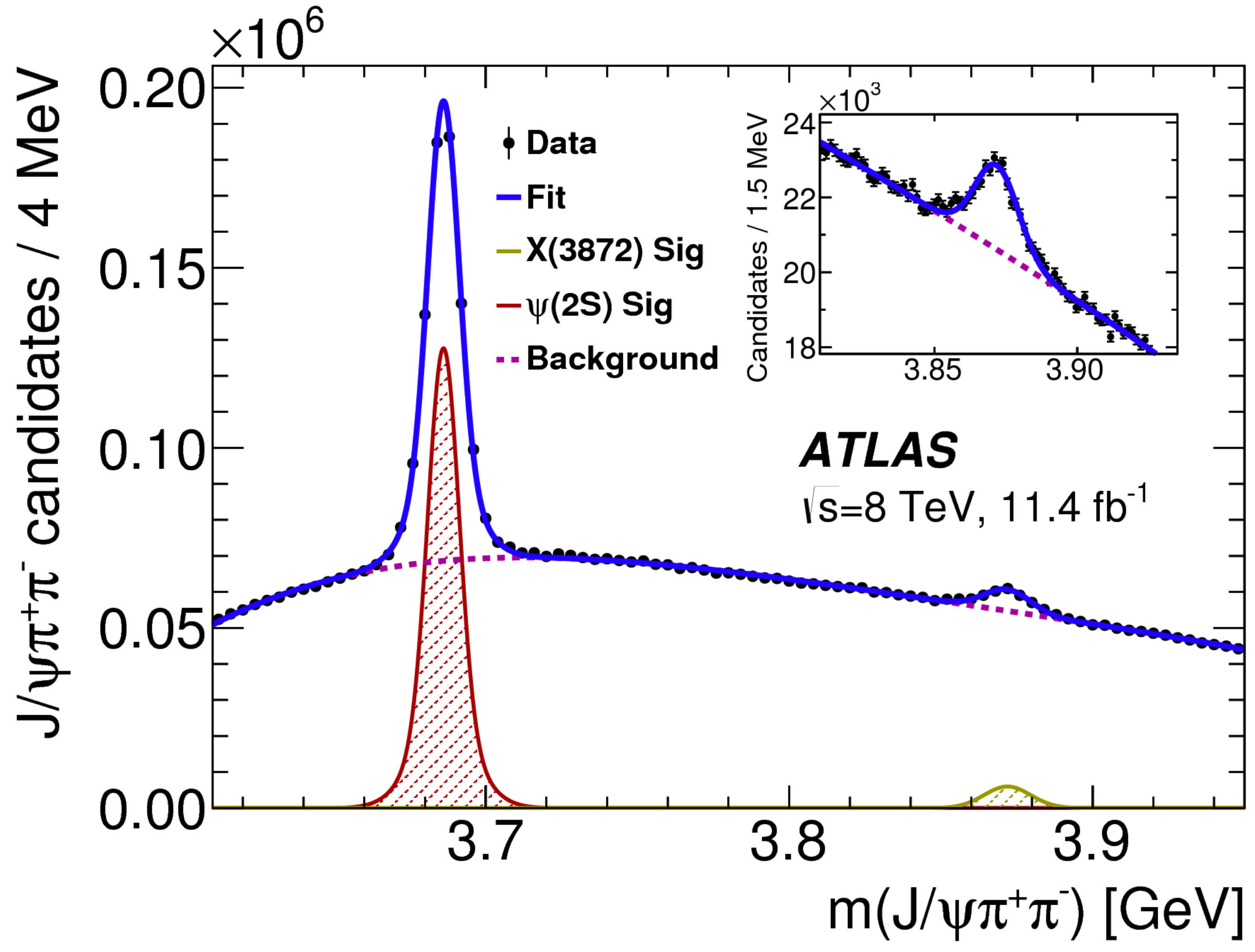
Extrapolation not conclusive so far…

☛ can we learn from the charmonium case?

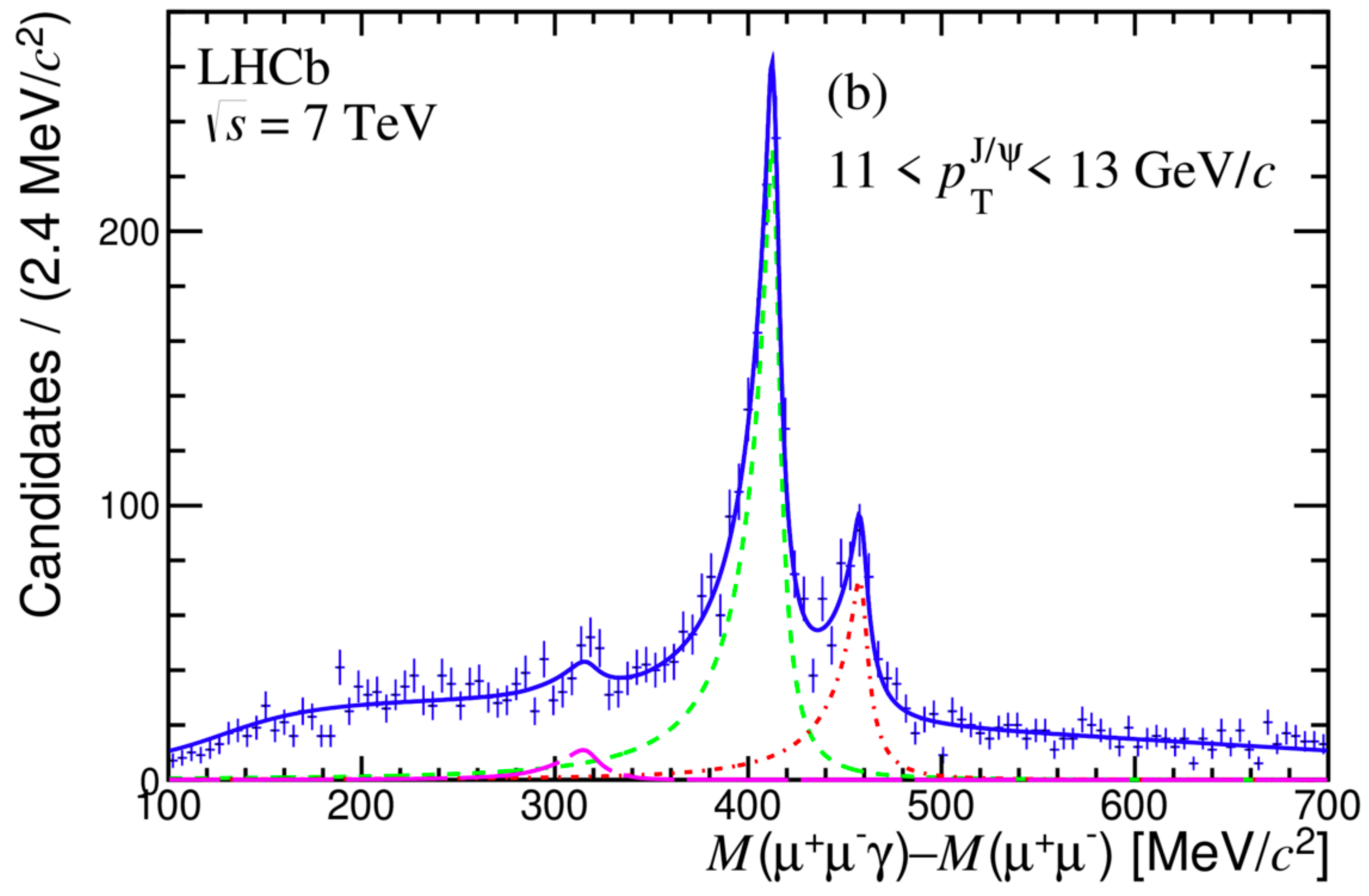
Charmonium production at the LHC



Measurement of $\psi(2S)$ and X(3872) states in $J/\psi\ \pi^+\pi^-$ [ATLAS, JHEP 01 (2017) 117]

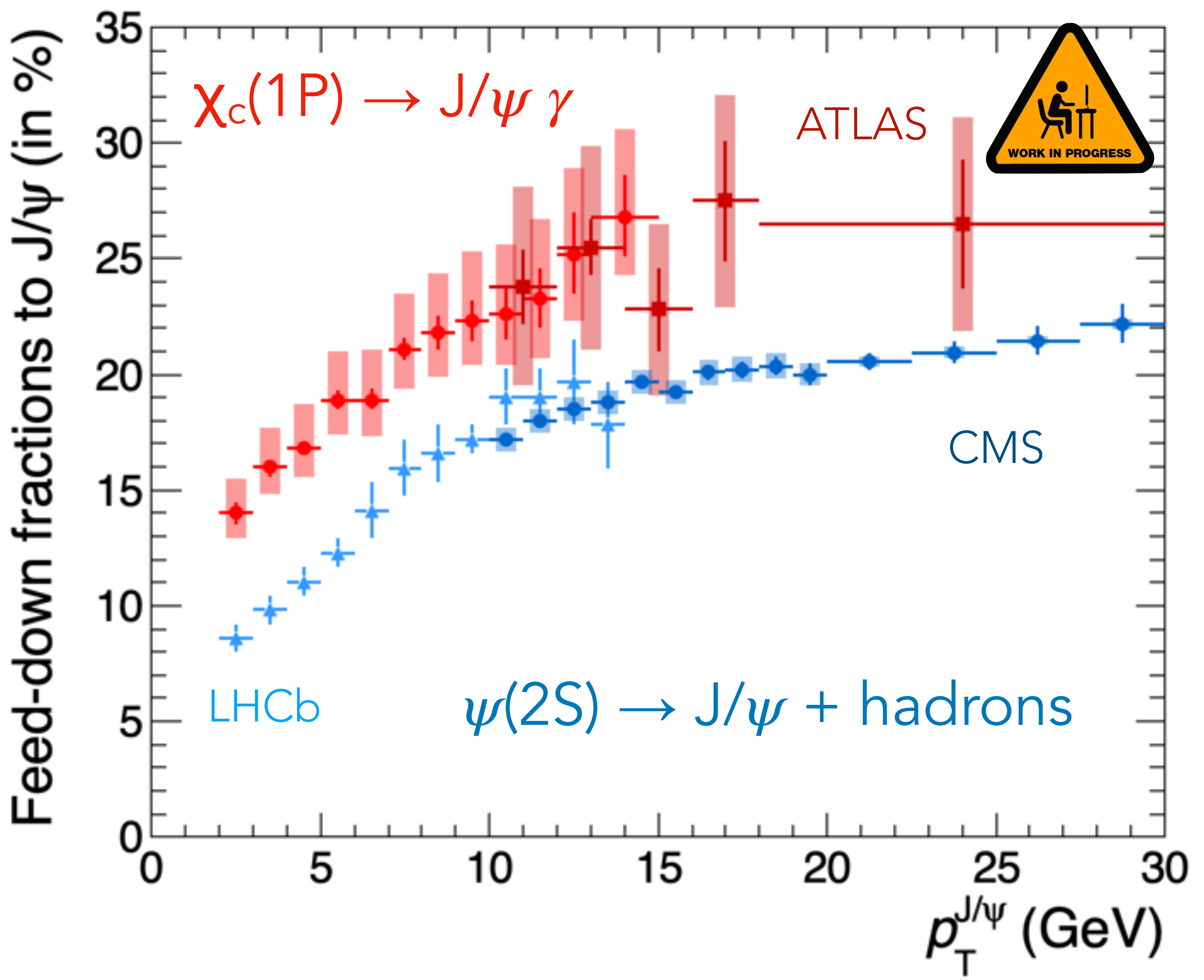


Relative rate of χ_{c0}, χ_{c1}, and χ_{c2} [LHCb, JHEP 10 (2013) 115]



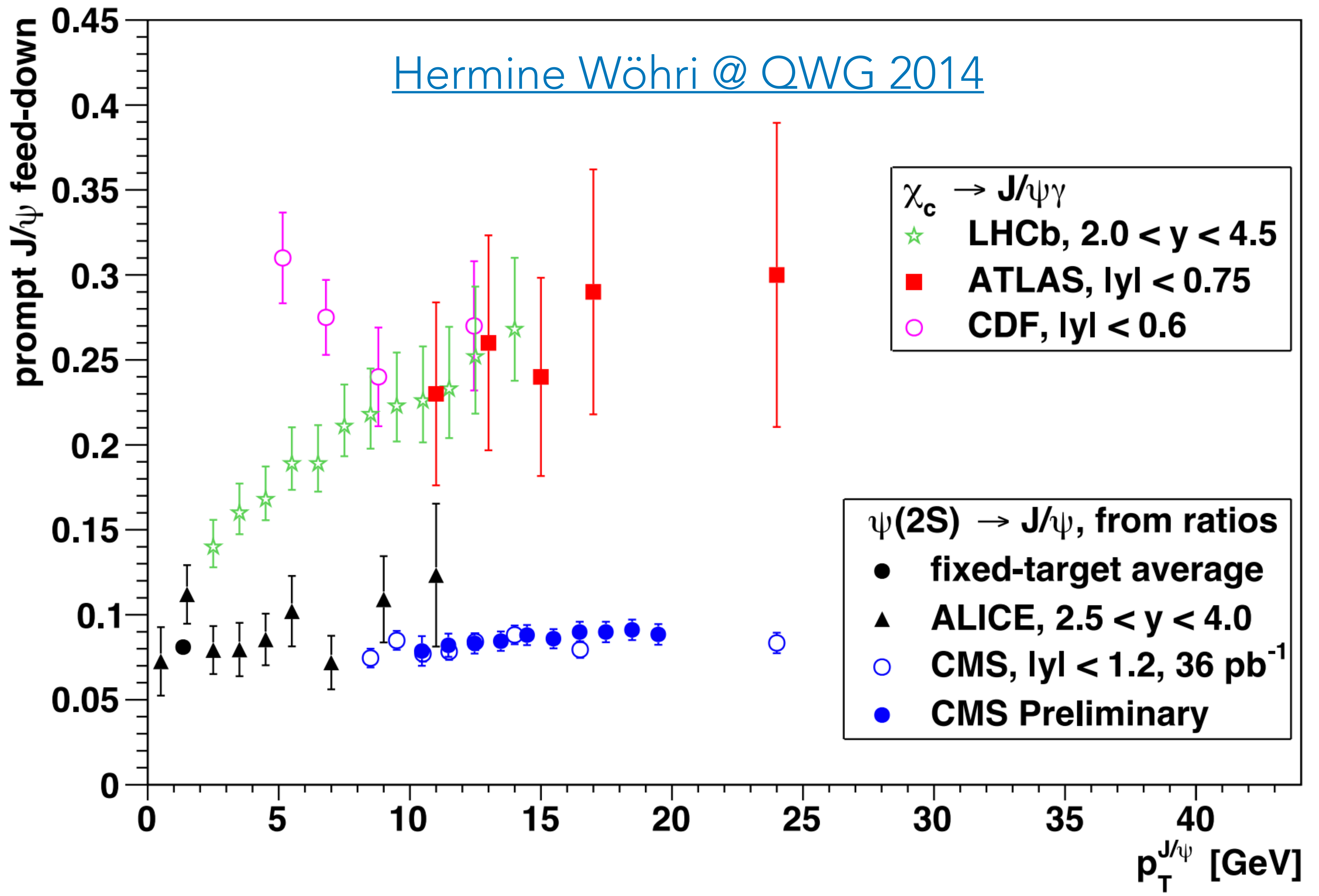
Feed-downs to prompt J/ψ

Trends similar to the Υ(1S) feed-down fractions (almost the scales too!)



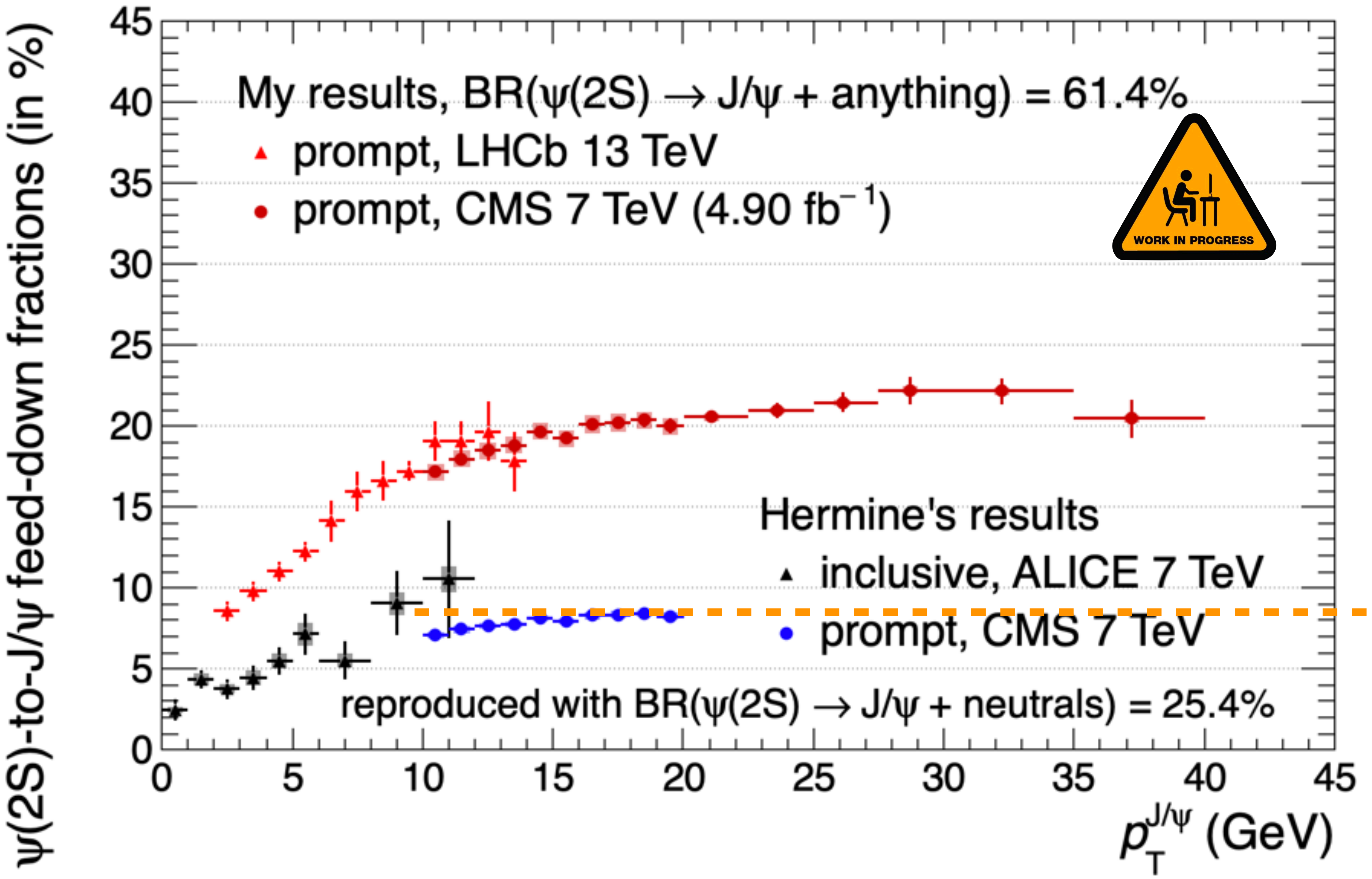
Odd **ψ(2S) results** in the previous derivation

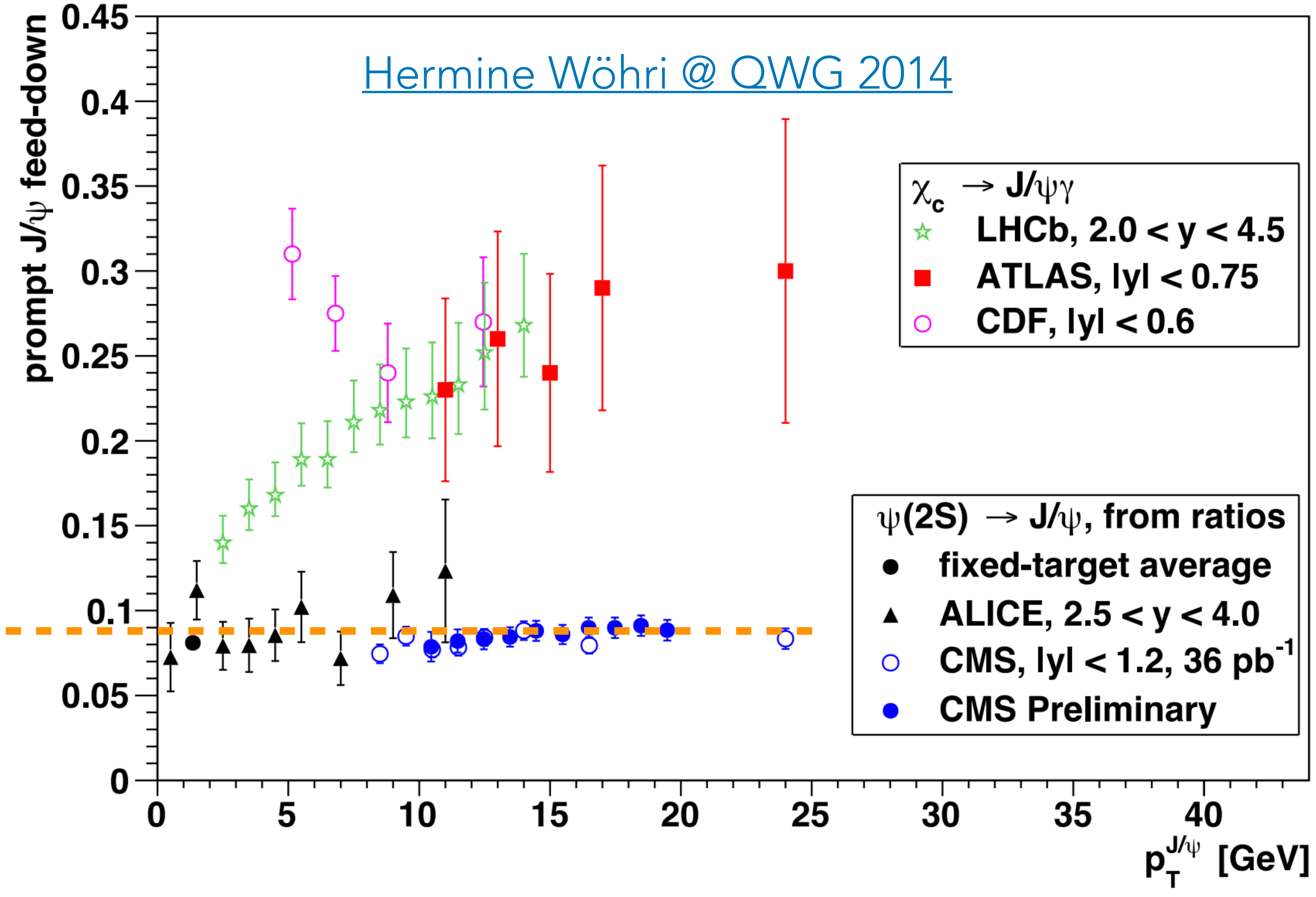
- no visible p_T dependence (must be here!!!)
- fractions from CMS data different by a factor 2



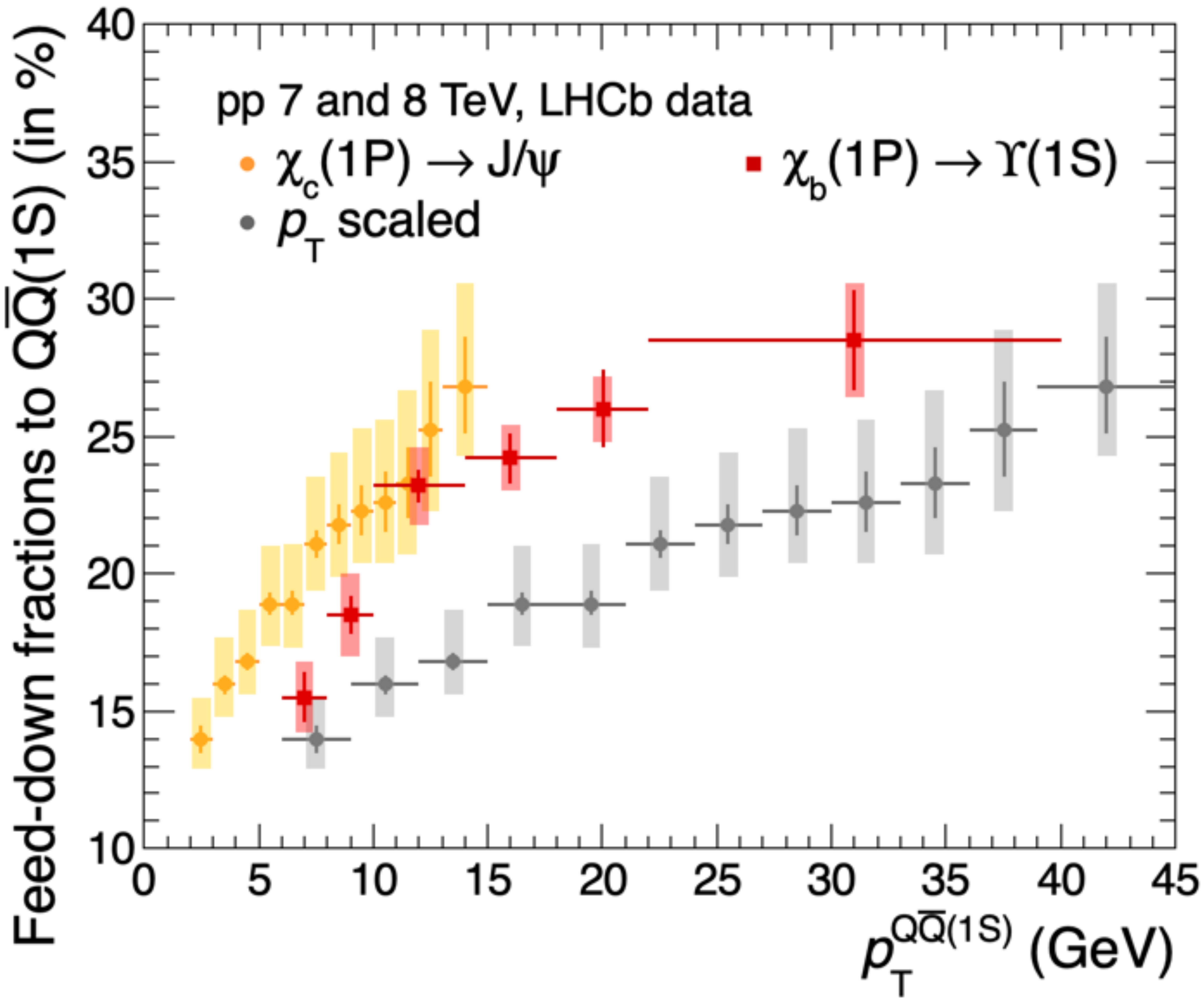
Reproduction of Hermine's results

- able to reproduce Hermine's results for $\psi(2S)$-to-J/ψ feed-down from 7 TeV CMS data by applying an ***incomplete* branching ratio** (more than a factor 2 difference!)
- **cannot explain the flatness of the ALICE points** (corrected for the non-prompt *b* fraction??)





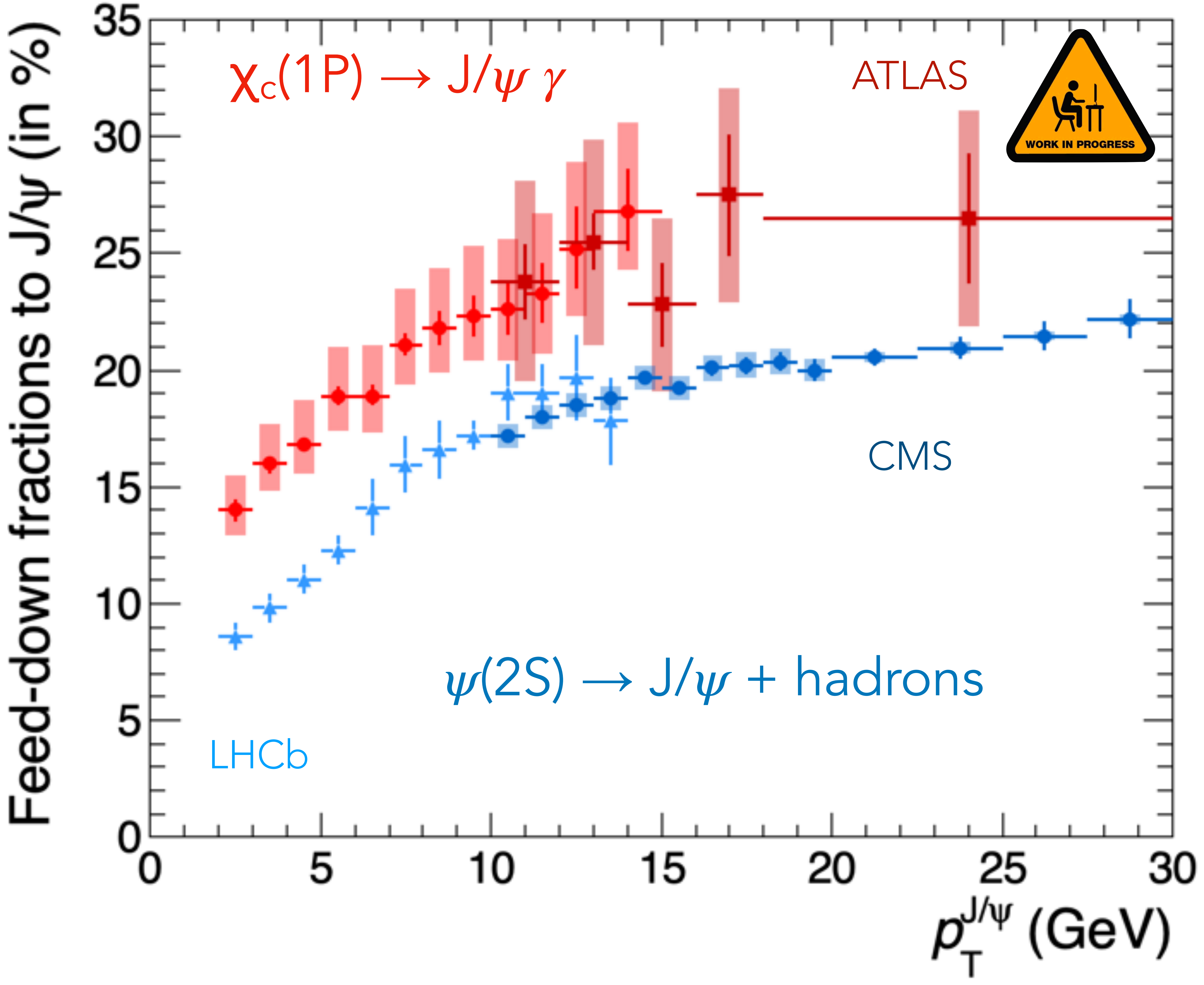
Comparison with $\chi_c(1P) \rightarrow J/\psi\,\gamma$

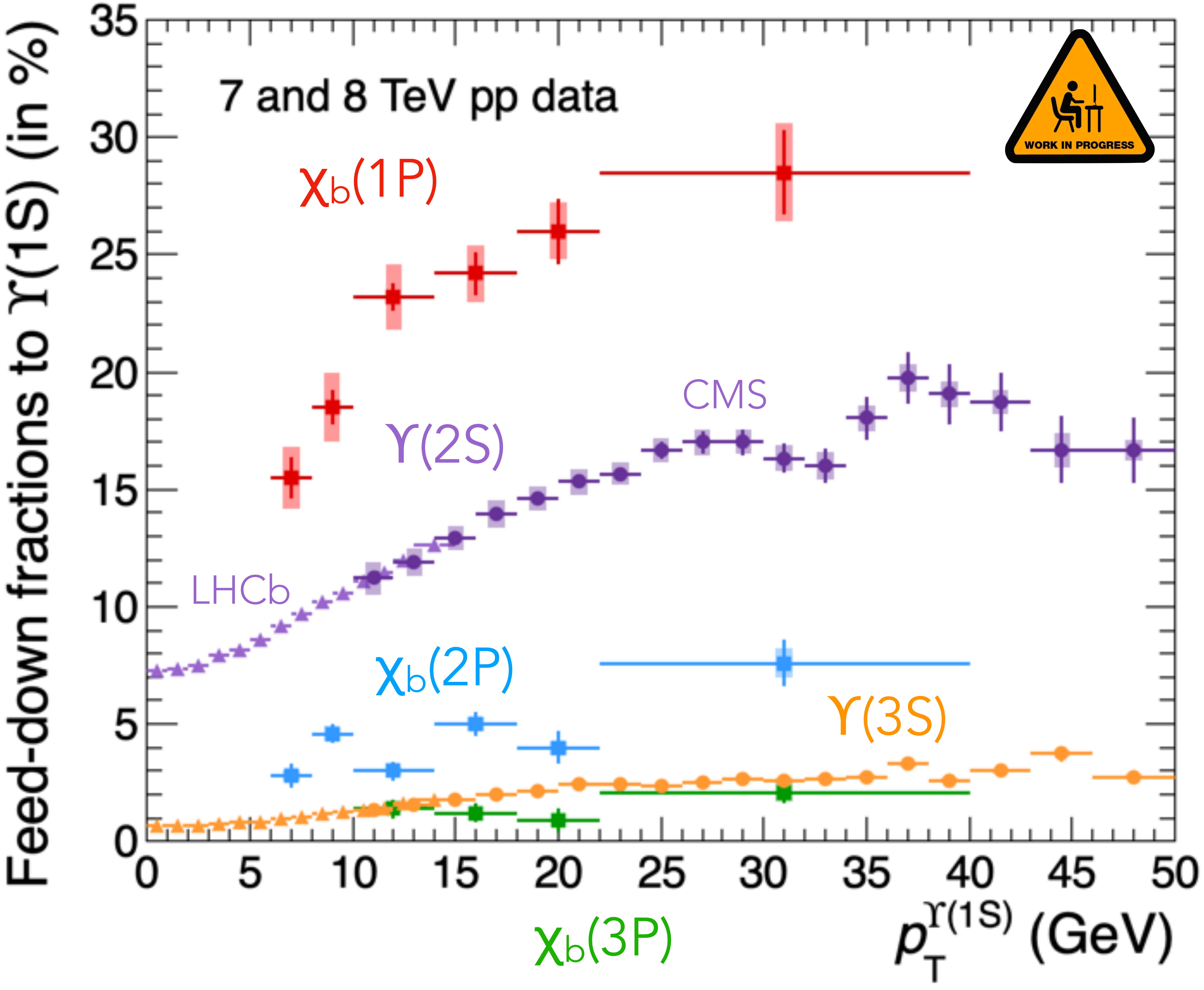


What can we learn from the charmonium case?

- similar trend between the $\chi_c(1P) \rightarrow J/\psi$ [PLB 718 (2012) 431] and $\chi_b(1P) \rightarrow \Upsilon(1S)$ feed-down fractions
- p_T of the χ_c results scaled by $m(\Upsilon) / m(J/\psi) \sim 3$ for a fair comparison

Current status





Summary

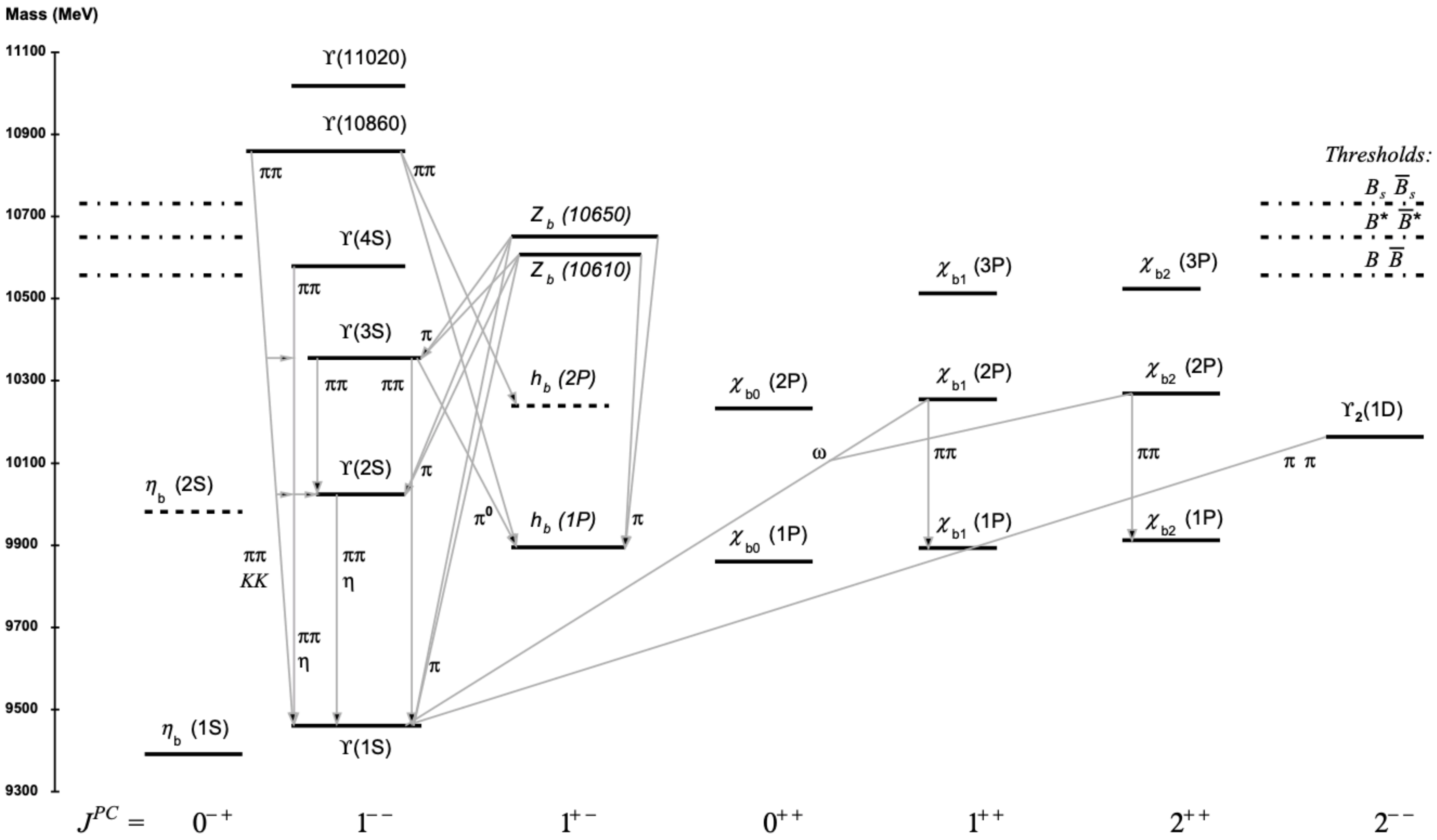
We aim to derive **feed-down fractions in quarkonium production** at the LHC by exploiting all available Run 1 and 2 measurements.

- contributions of **Υ excited states under control**
- feed-down fractions from **χ_b decays limited to LHCb measurements** [EPJC 74 (2014) 3092]
  - the derivation of $\chi_b(nP) \to \Upsilon(2,3S)$ thanks to $\chi_b(nP) \to \Upsilon(1S)$ data points is not conclusive
  - interesting similarities with $\chi_c(1P) \to J/\psi$, to be investigated further

Open questions

- **how to extrapolate down to p_T = 0?** Do they continue to drop? Do they saturate at some point? NRQCD formalism only applicable for $p_T \gg m_\Upsilon \sim 10$ GeV.
- what can we learn from the charmonium case?

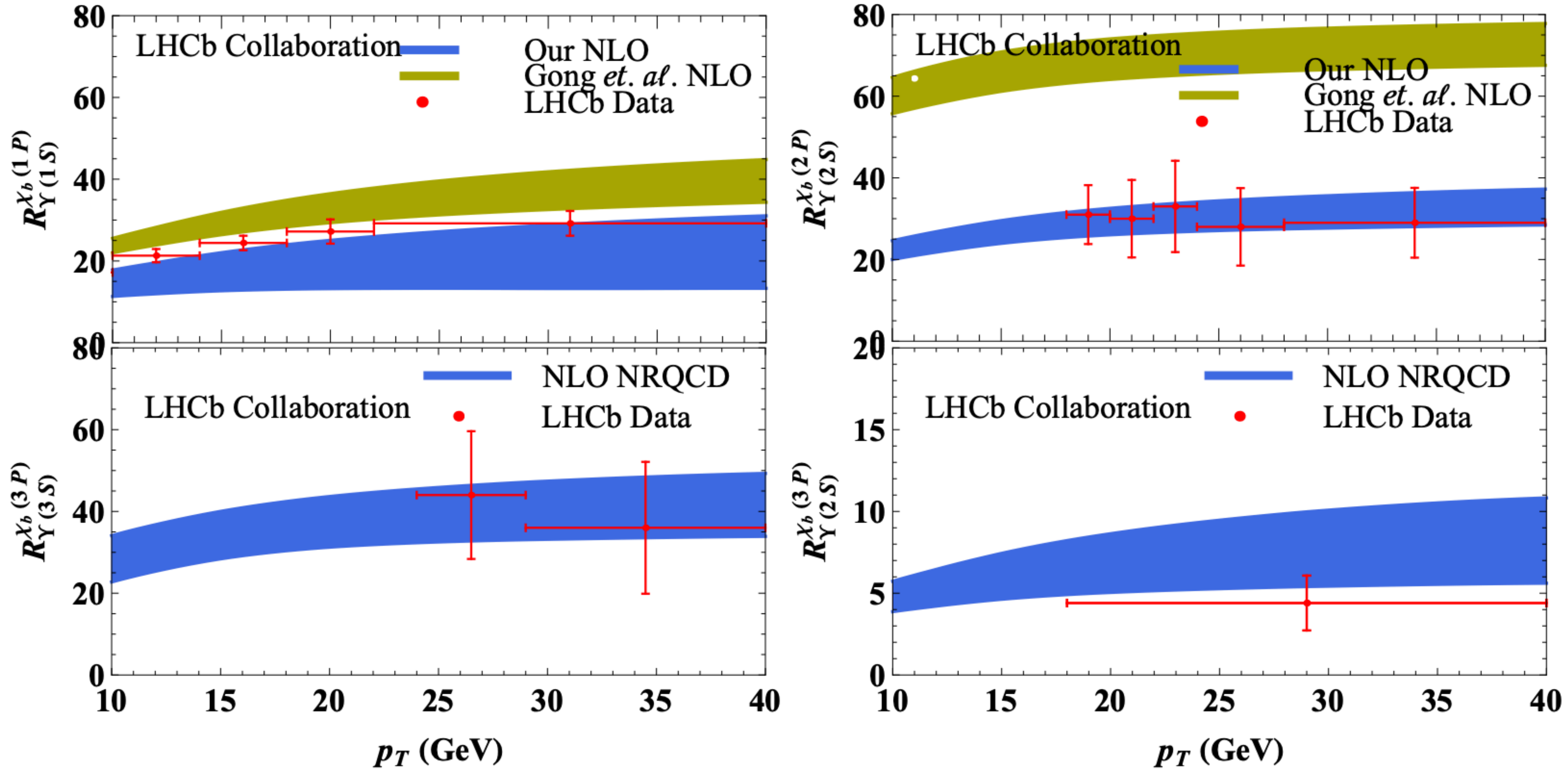
Bottomonium spectroscopy

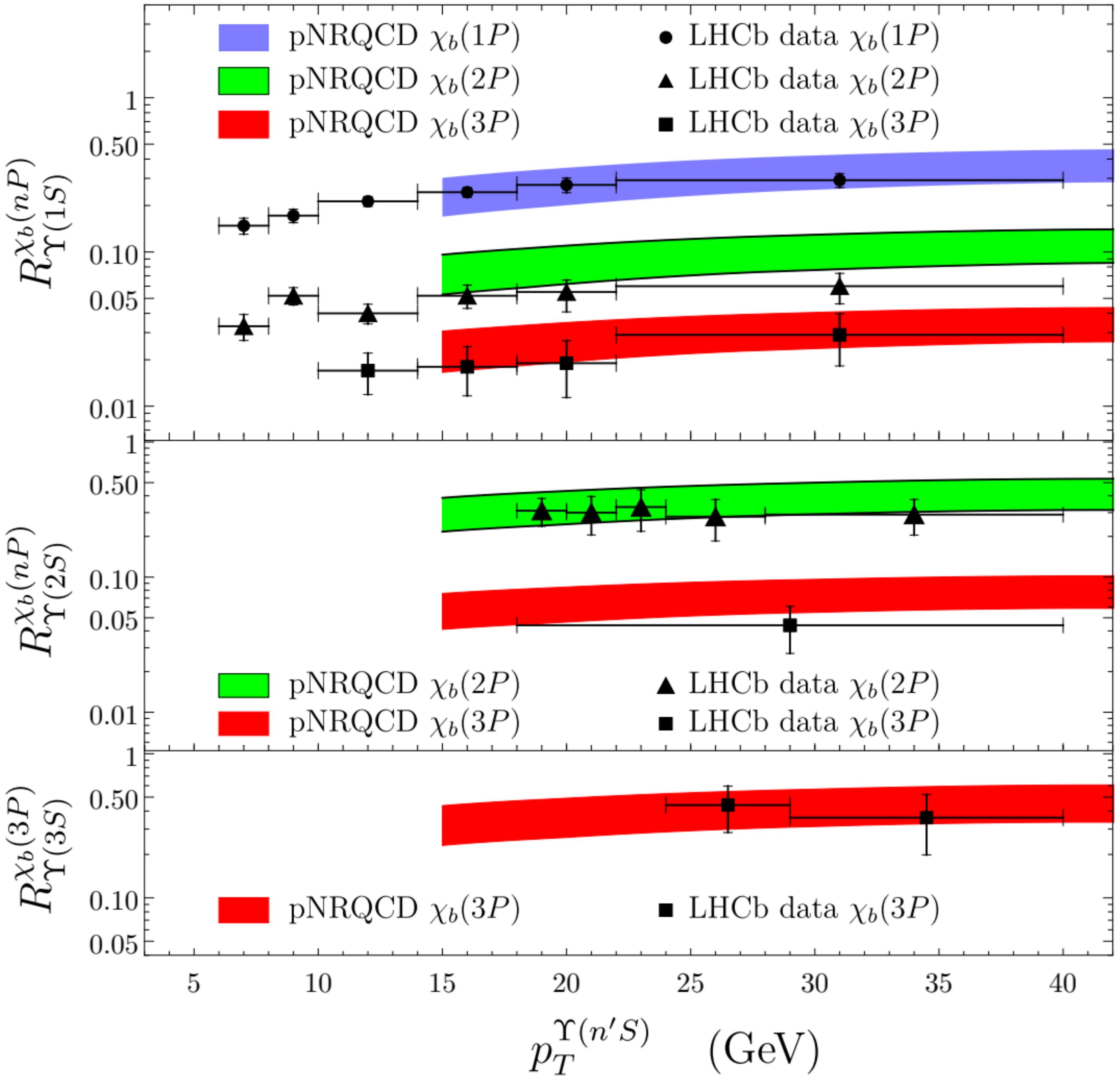


NRQCD predictions

NLO NRQCD [Han et al., PRD 94 (2016) 014028]

pNRQCD [Brambilla et al., JHEP 09 (2021) 032]





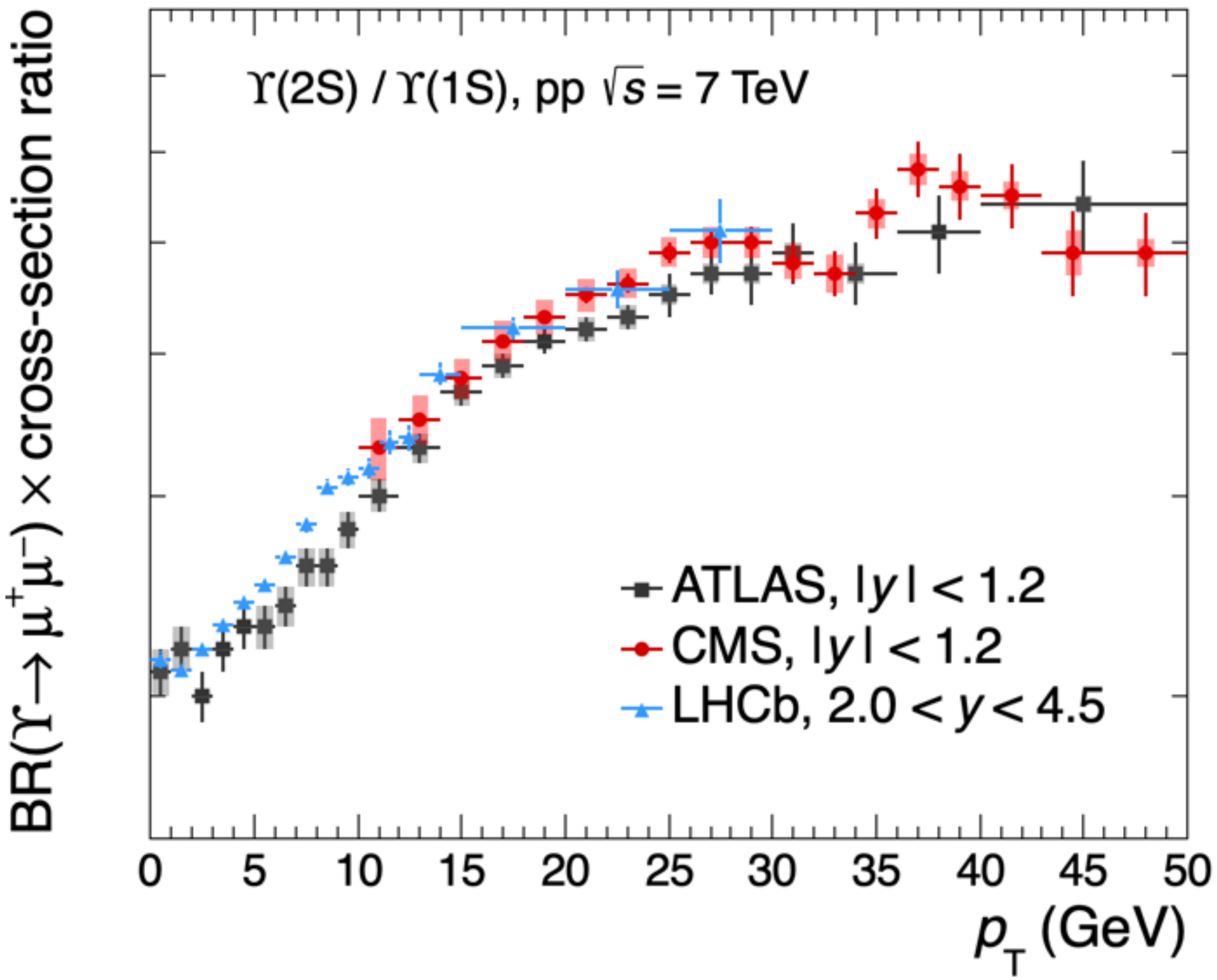
Overview of available data

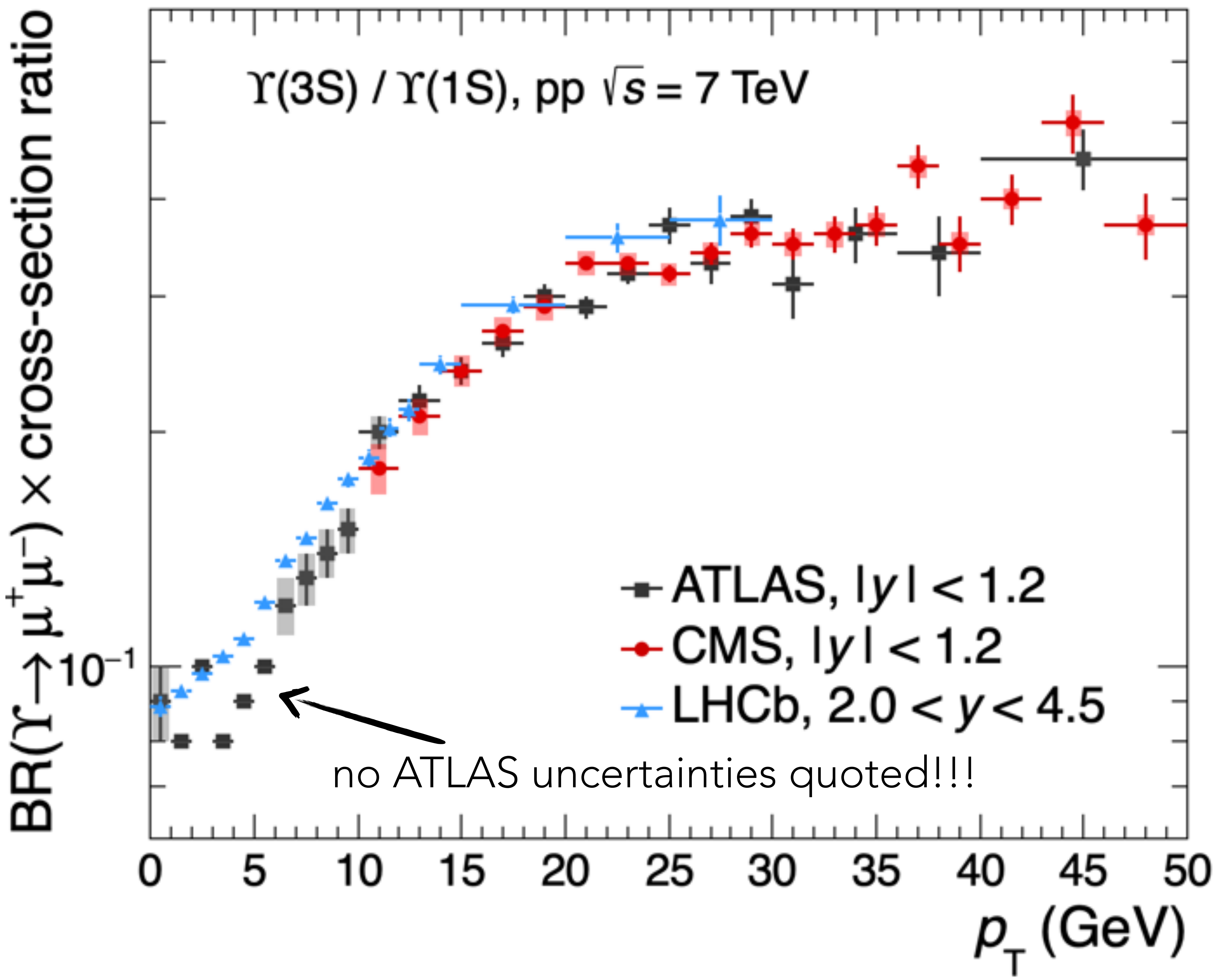
Centre-of-mass energy	Mid-rapidity		Forward rapidity	
	Υ(nS) cross-section ratio	χ_b measurement	Υ(nS) cross-section ratio	χ_b measurement
5 TeV	Only single-state cross sections are reported + binning matching pPb / PbPb measurements + no χ_b measurement		NONE!	
7 TeV	ATLAS: y-diff. and p_T-diff. up to 70 GeV CMS: p_T-diff. up to 40 GeV + **Υ(3S) / Υ(2S)** CMS: p_T-diff. from 10 to 100 GeV	ATLAS: first obervation of χ_b(3P)	LHCb: y-diff, p_T-diff, and double-diff up to 30 GeV + **Υ(3S) / Υ(2S)**	**LHCb: derivation of χ_b-to-Υ feed-down fractions** LHCb: χ_{b2}(1P) / χ_{b1}(1P)
8 TeV	None!	CMS: χ_{b2}(1P) / χ_{b1}(1P)		
13 TeV	CMS: p_T-diff. from 20 to 100 GeV + ratio to 7 TeV	CMS: observation of χ_{b1}(3P) and χ_{b2}(3P)	LHCb: y-diff, p_T-diff, and double-diff up to 30 GeV + ratio to 8 TeV	None

Which dataset(s) to use? – for ϒ(1S)

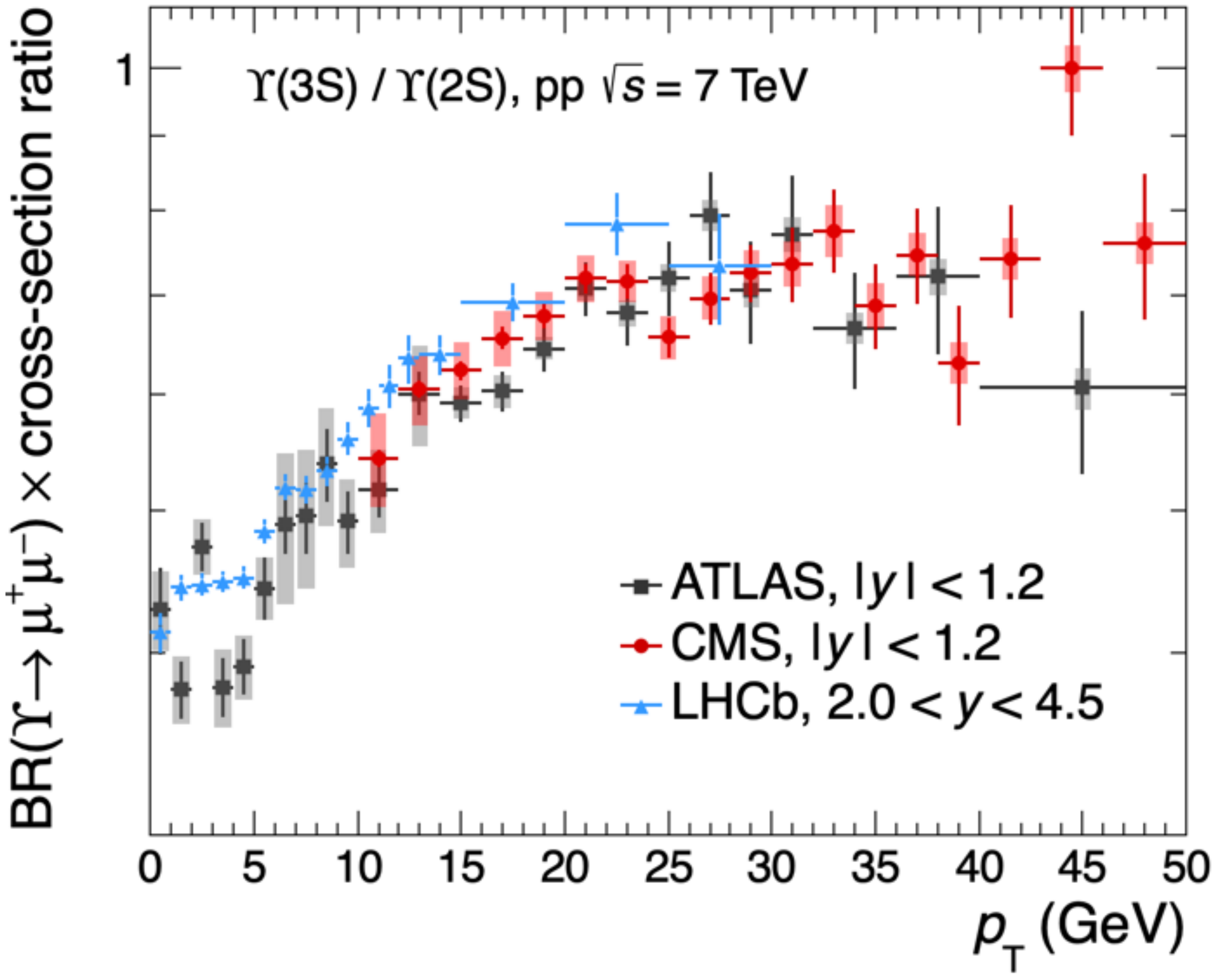
ATLAS, CMS and LHCb p_T-differential cross-section ratio measurements at 7 TeV (⚠ log scale)

- LHCb data more precise for $p_T \lesssim$ 15–20 GeV
- CMS data better for higher p_T (up to 100 GeV)





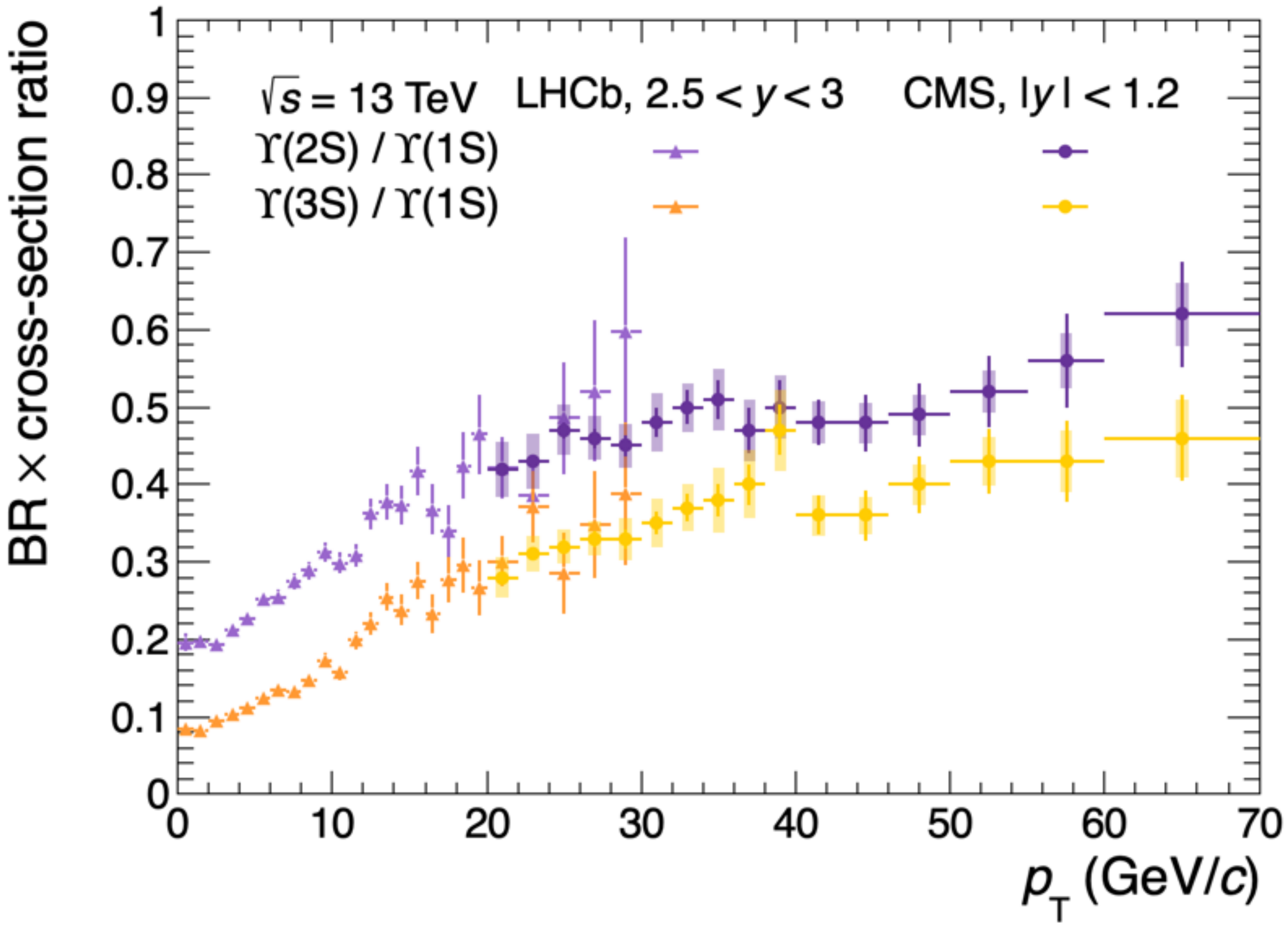
Which dataset(s) to use? – Υ(3S) / Υ(2S)



ATLAS, CMS and LHCb p_T-differential cross-section ratio measurements at 7 TeV (⚠ log scale)

- **computed by hand for ATLAS and CMS** data points (⚠ correlated systematic uncertainties)
- LHCb data more precise for $p_T \lesssim$ 15–20 GeV
- CMS data better for higher p_T (up to 100 GeV)

13 TeV datasets



p_T-differential measurements of ϒ(2S)-to-ϒ(1S) and ϒ(3S)-to-ϒ(1S) cross section ratios

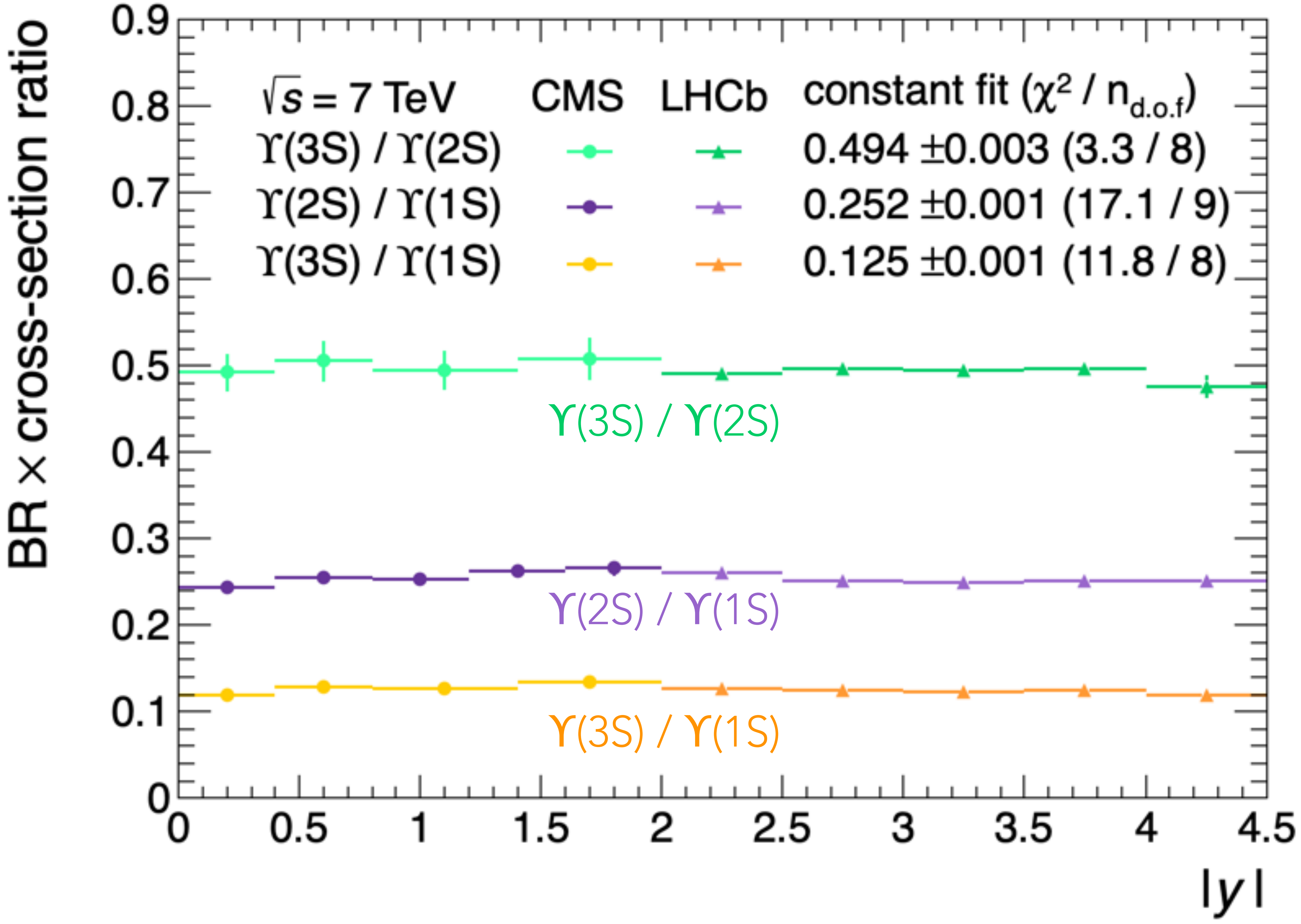
- LHCb data up to 30 GeV (⚠️ double-differential, **only up to 13 GeV for 2.0 < y < 4.5**)
- CMS data from 20 to 100 GeV

☛ complementarity / overlap between measurement points

However…

- ϒ(3S)-to-ϒ(2S) ratio to be made by hand
- **relative systematic uncertainties** (much) **larger than 8/7 TeV data** 🤷‍♂️

Checking the rapidity dependence



Independence always assumed but never demonstrated

- with ϒ(nS) cross-section ratios at 7 TeV measured by CMS (p_T < 50 GeV) and LHCb (p_T < 30 GeV)
- **best chi-square obtained with a constant fit**

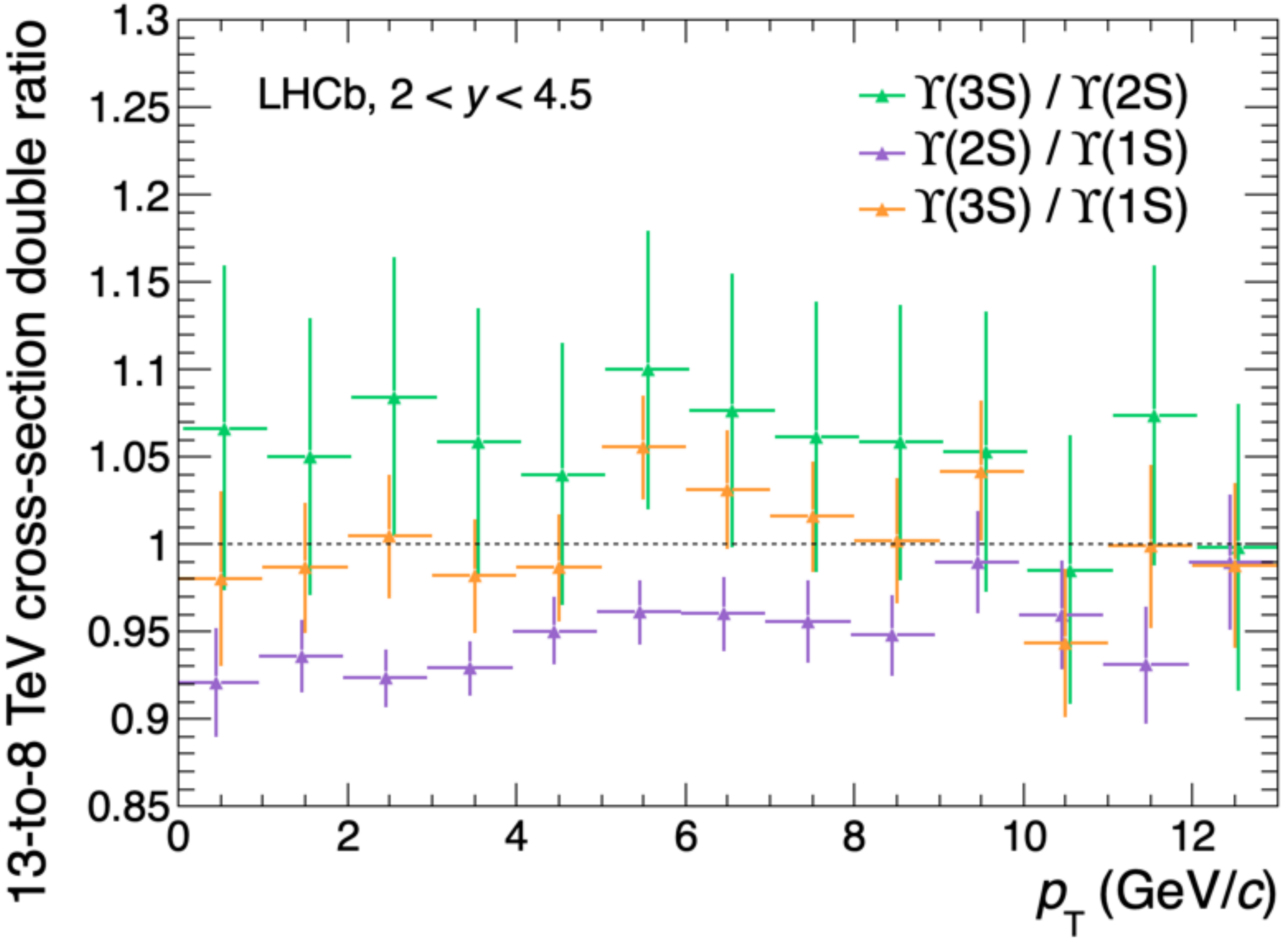
☛ can mix data measured for different rapidities without applying any correction

Checking the energy dependence

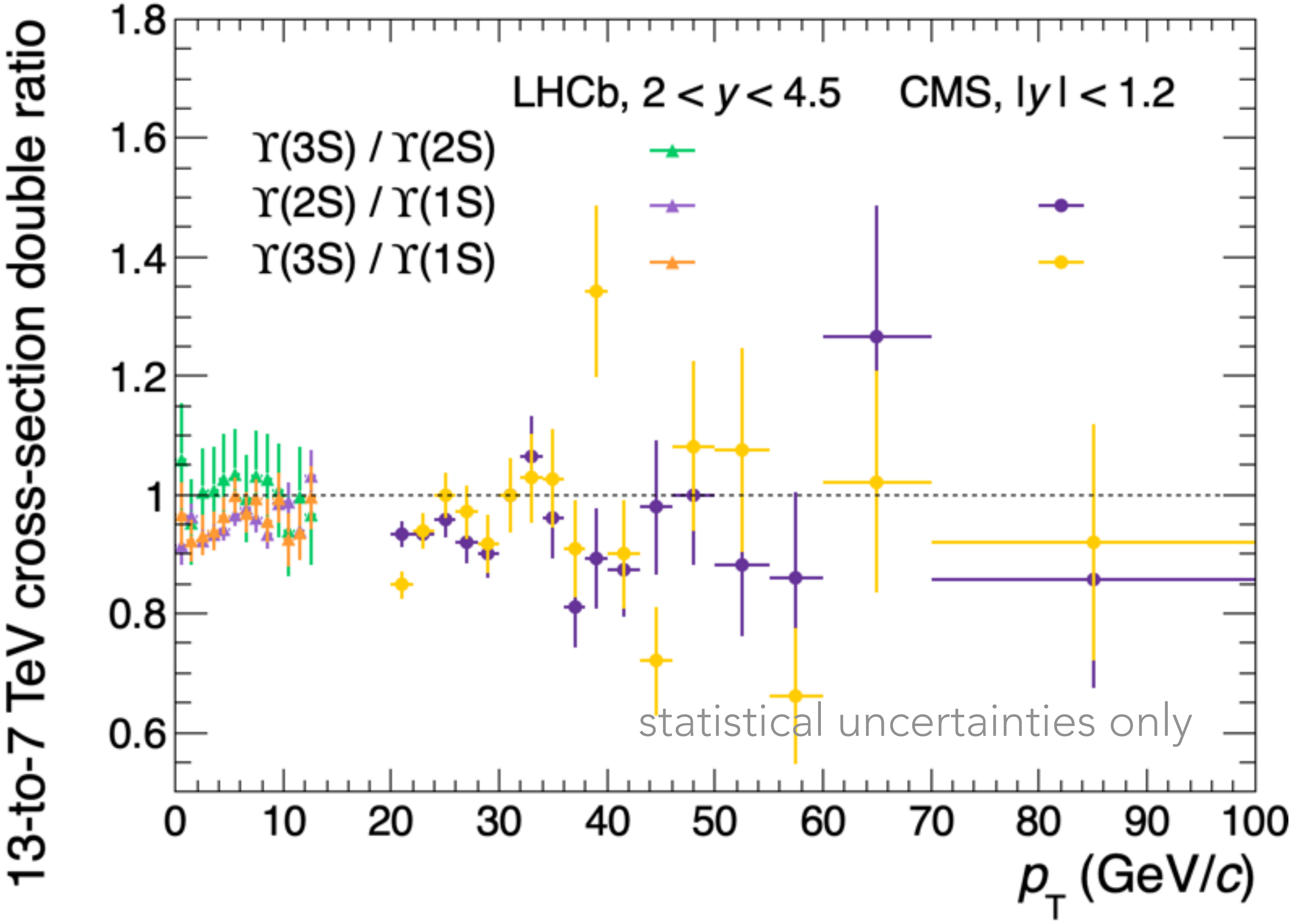
Investigation of the dependence of the cross-section ratios with the centre-of-mass energy

☛ can exploit measurements performed at different energies just by applying global scale factors

no p_T dependence + small energy dependence at low p_T



not clear for high p_T



2) Considering the χ_b multiplet

Reminder: if one neglects the $J = 0$ contribution (small radiative-decay branching ratio),

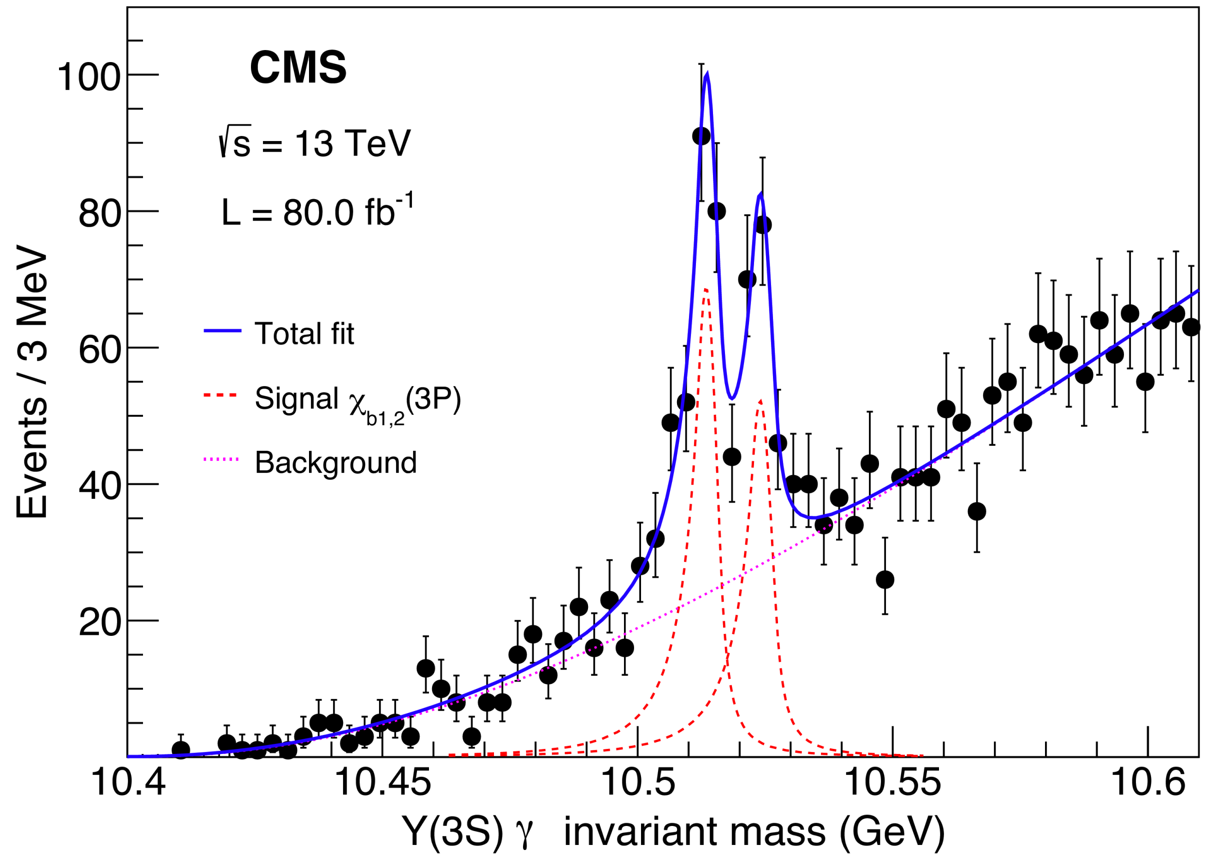
$$\mathcal{F}^{\chi(nP)}_{\Upsilon(mS)} = \frac{\sigma(\chi_1(nP))}{\sigma(\Upsilon(mS))} \times \mathcal{B}(\chi_1(nP) \to \Upsilon(\mathrm{mS}) + \gamma) + \frac{\sigma(\chi_2(\mathrm{nP}))}{\sigma(\Upsilon(\mathrm{mS}))} \times \mathcal{B}(\chi_2(\mathrm{nP}) \to \Upsilon(\mathrm{mS}) + \gamma)$$

Starting again from $\dfrac{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(mS)} \cdot \mathcal{F}^{\Upsilon(mS)}_{\Upsilon(1S)}}{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(1S)}}$ and after developments and factorisations, we get

$$\mathcal{F}^{\chi_b(nP)}_{\Upsilon(mS)} = \frac{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(1S)}}{\dfrac{\sigma(\Upsilon(mS))}{\sigma(\Upsilon(1S))}} \times \left[\frac{\mathcal{B}(\chi_1(nP) \to \Upsilon(\mathrm{mS}) + \gamma) + \boxed{\dfrac{\sigma(\chi_2(\mathrm{nP}))}{\sigma(\chi_1(\mathrm{nP}))}} \times \mathcal{B}(\chi_2(\mathrm{nP}) \to \Upsilon(\mathrm{mS}) + \gamma)}{\mathcal{B}(\chi_1(nP) \to \Upsilon(1\mathrm{S}) + \gamma) + \boxed{\dfrac{\sigma(\chi_2(\mathrm{nP}))}{\sigma(\chi_1(\mathrm{nP}))}} \times \mathcal{B}(\chi_2(\mathrm{nP}) \to \Upsilon(1\mathrm{S}) + \gamma)} \right]$$

Problem: cross section ratio $\chi_{b2}(nP)$ / $\chi_{b1}(nP)$ never been measured for $n > 1$

- PDG's average mass splitting: $m(\chi_{b,2}(2P)) - m(\chi_{b,1}(2P)) \approx 13$ MeV
- **first separation of the χ_b(3P) mass peaks** [PRL 121 (2018) 092002]
  measured mass splitting: $m(\chi_{b,2}(3P)) - m(\chi_{b,1}(3P)) \approx 10$ MeV



2) Considering the χ_b multiplet

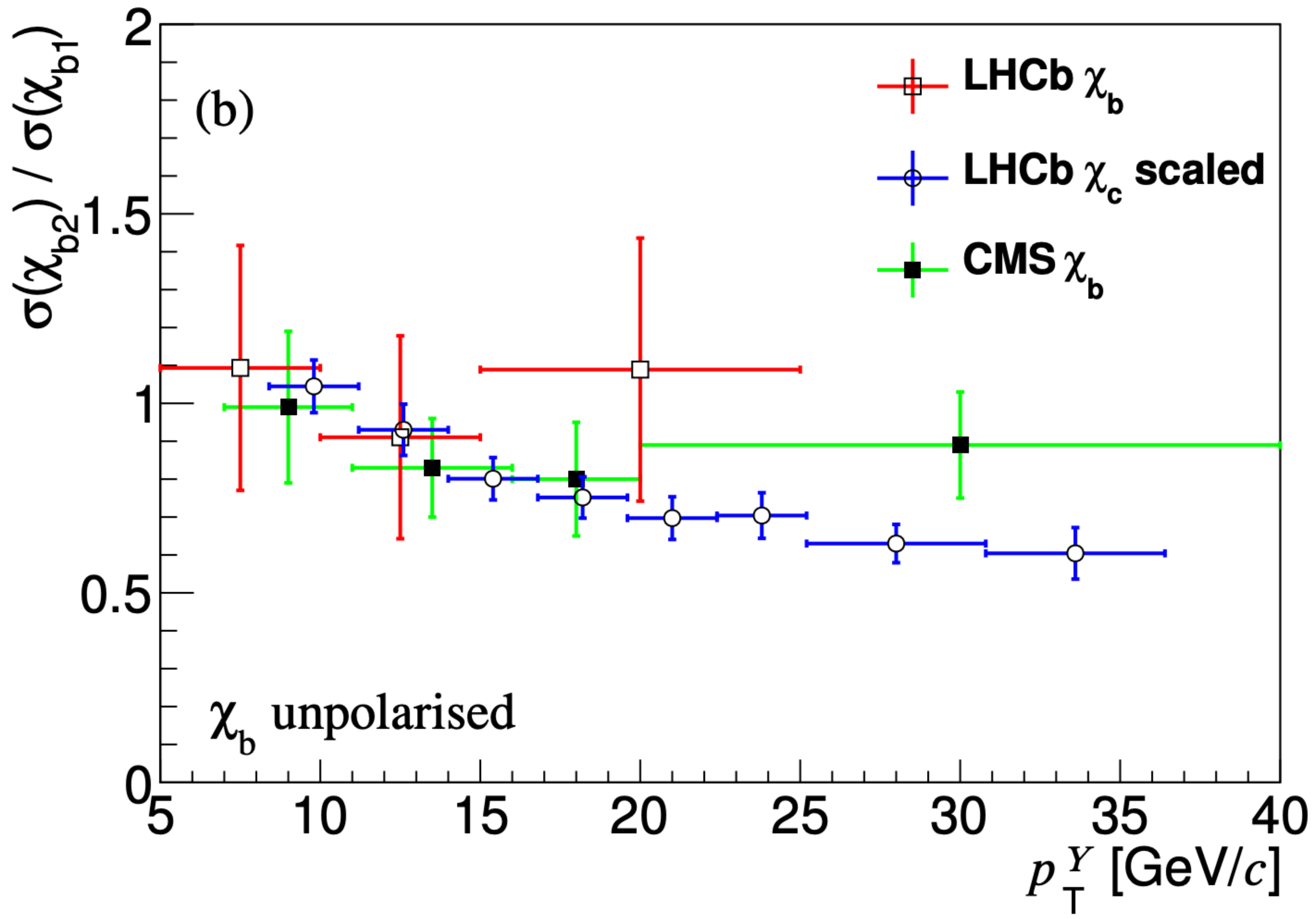
$$\mathcal{F}^{\chi_b(nP)}_{\Upsilon(mS)} = \frac{\mathcal{F}^{\chi_b(nP)}_{\Upsilon(1S)}}{\frac{\sigma(\Upsilon(mS))}{\sigma(\Upsilon(1S))}} \times \left[\frac{\mathcal{B}(\chi_1(nP) \to \Upsilon(mS)+\gamma) + \frac{\sigma(\chi_2(nP))}{\sigma(\chi_1(nP))} \times \mathcal{B}(\chi_2(nP) \to \Upsilon(mS)+\gamma)}{\mathcal{B}(\chi_1(nP) \to \Upsilon(1S)+\gamma) + \frac{\sigma(\chi_2(nP))}{\sigma(\chi_1(nP))} \times \mathcal{B}(\chi_2(nP) \to \Upsilon(1S)+\gamma)} \right]$$

Cross-section ratio $\chi_{b2}(nP)$ / $\chi_{b1}(nP)$ never been measured for $n > 1$

1) **use $\chi_{b2}(1P)$ / $\chi_{b1}(1P)$ measurements**
assuming the cross-section ratio does not depend of n
(supported by NRQCD calculations [JHEP 09 (2021) 032])

CMS average: $\sigma(\chi_{b2})$ / $\sigma(\chi_{b1})$ = 0.85 ± 0.07 [PLB 743 (2015) 383]
p_T dependence? binning slightly different

JHEP 10 (2014) 088



2) **take $\sigma(\chi_{c2})$ / $\sigma(\chi_{c1})$ measurements** and scale the χ_c p_T by $m(\chi_b)$ / $m(\chi_c)$ ~ 2.8
☛ good agreement, to be tested

Charmonium spectroscopy