Υ(nS) polarization measurement at LHCb

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Introduction: *investigate the production mechanism in pp*

The understanding of the production mechanism of quarkonium states improved greatly in the last few years, also thanks to the input of the LHC.

Golden approach: NRQCD models $d\sigma_{pp\to\mathcal{Q}+X} = \sum_n d\hat{\sigma}_{pp\to Q\bar{Q}[n]+X}\langle\mathcal{O}^{\mathcal{Q}}(n)\rangle.$

A complete theoretical picture of quarkonium production should explain:

- ➪ production cross-section measurements
  - ✓ see for example Liupan's talk on central exclusive production
- ➪ associative production measurements
  - ✓ see for example the talk by Jia-Jia Qin on J/ψ + jet
- ➪ polarization of the quarkonium states

Adding measurements can challenge theoretical predictions, and help extending the prediction to low p_T regions.

The LHCb experiment: *designed for heavy flavours*

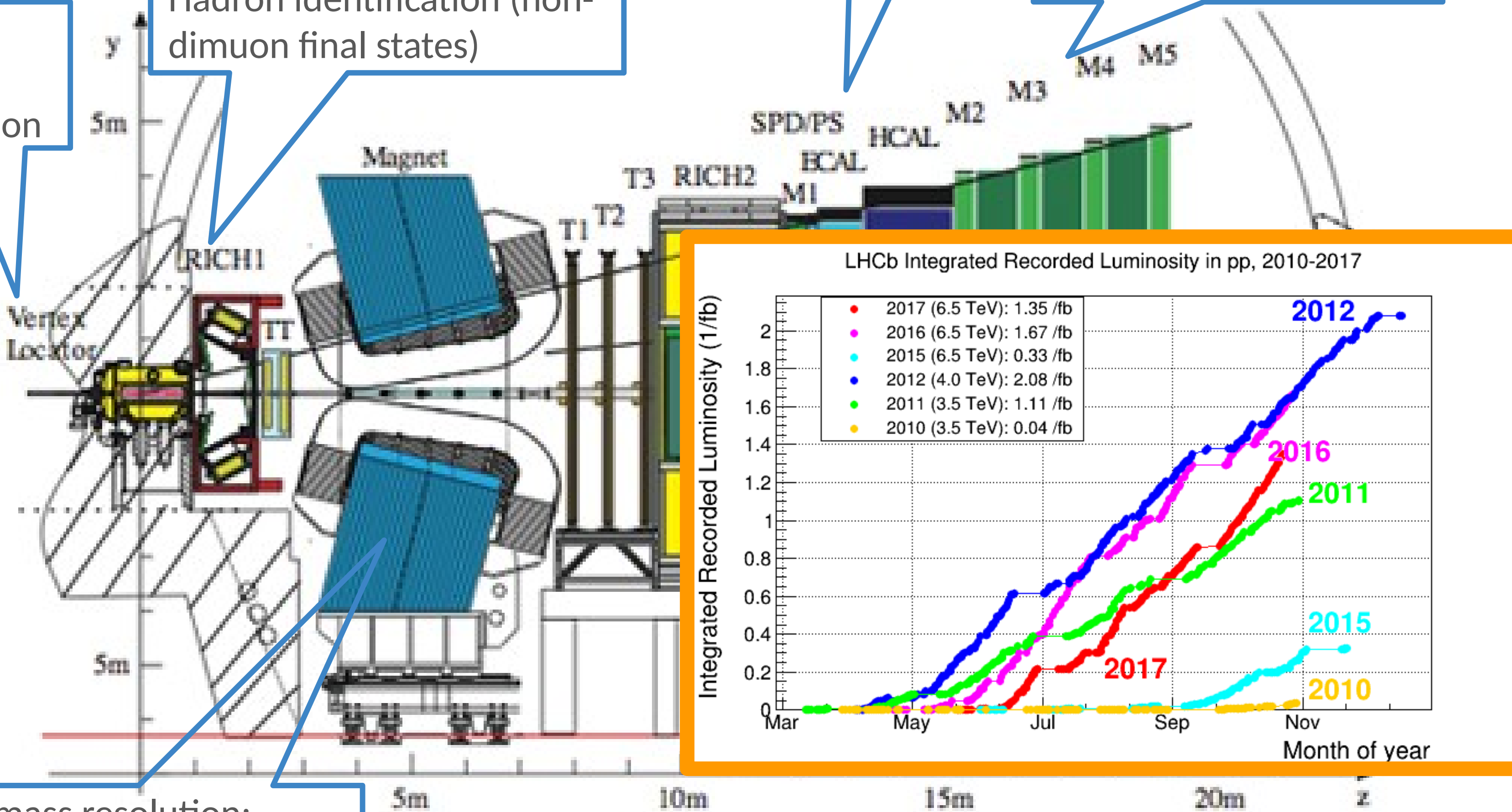
pp collisions at the LHC
A fully instrumented detector in the forward region

Photon detection
Electron identification

Muon identification

Prompt to detached discrimination

Hadron identification (non-dimuon final states)



Excellent mass resolution: better combinatorial rejection

Dataset: *data-taking conditions and kinematic range*

Analysis performed on **2011** and **2012** data collected in ***pp* collisions** at $\sqrt{s}$ = **7 TeV** [1 fb^{-1}] and $\sqrt{s}$ = **8 TeV** [2 fb^{-1}].

Unique momentum and rapidity acceptance

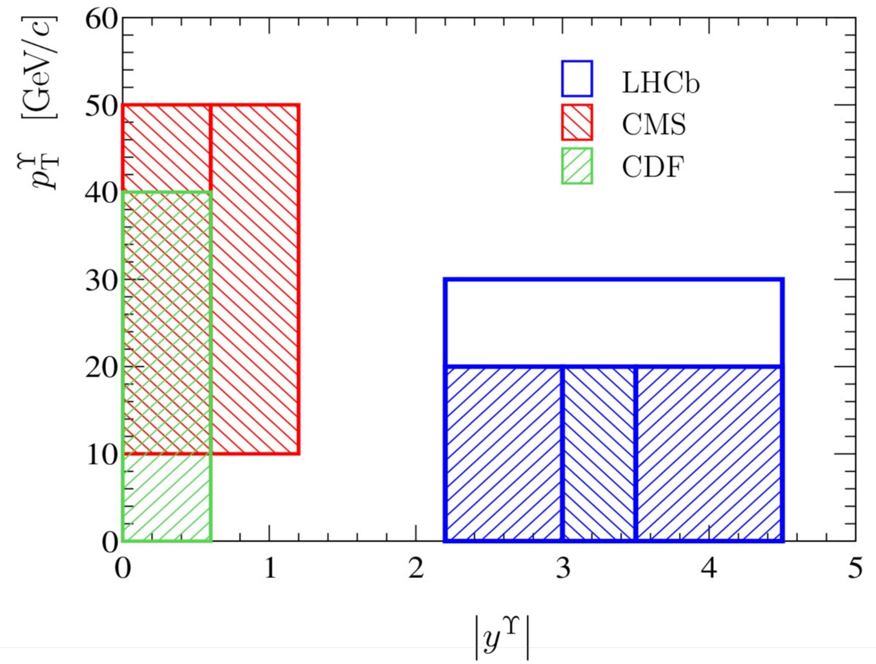
$2.2 < y(\Upsilon) < 4.5 \quad p_T(\Upsilon) < 30$ GeV/*c*

The analysis is performed also in three rapidity bins (but statistics become insufficient for p_T larger than 20 GeV/*c*).

$2.2 < y(\Upsilon) < 3.0 \quad p_T(\Upsilon) < 20$ GeV/*c*

$3.0 < y(\Upsilon) < 3.5 \quad p_T(\Upsilon) < 20$ GeV/*c*

$3.5 < y(\Upsilon) < 4.5 \quad p_T(\Upsilon) < 20$ GeV/*c*



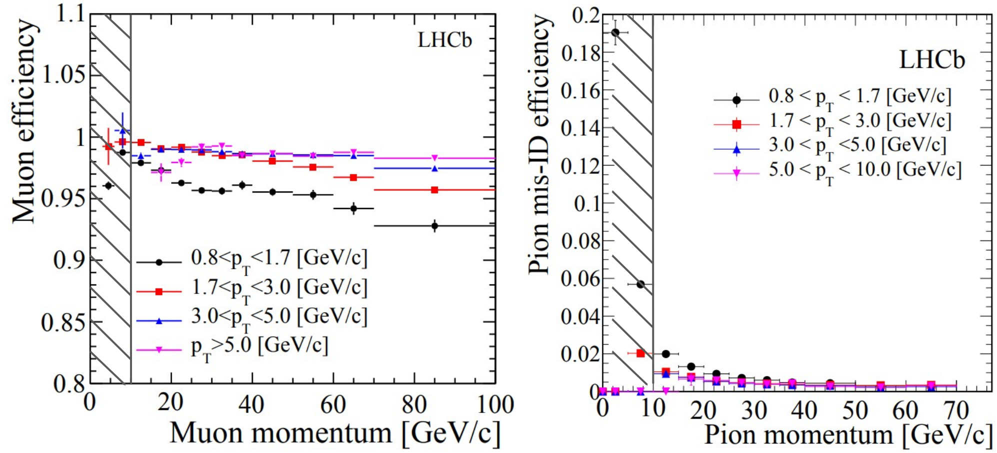
No overlap between CMS/CDF and LHCb kinematic regions,

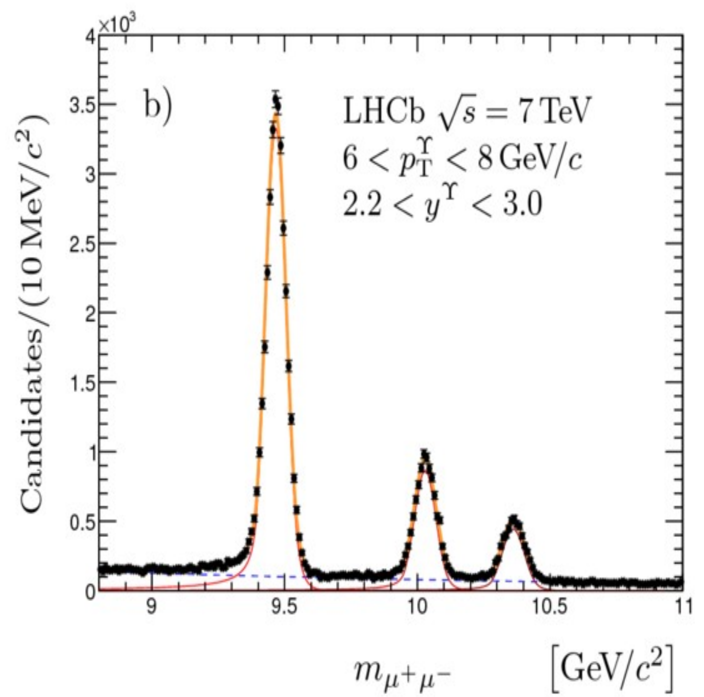
but mild dependence on y is expected, allowing for the comparison of results.

Signal selection: *clean dimuon final state*

High-momentum muons (p > 10 GeV/c) from $\Upsilon \to \mu\,\mu$ decay can be selected with great purity and high efficiency **already at trigger level**.

Excellent momentum resolution allows to get **narrow peaks** despite the large energy release in the decay.





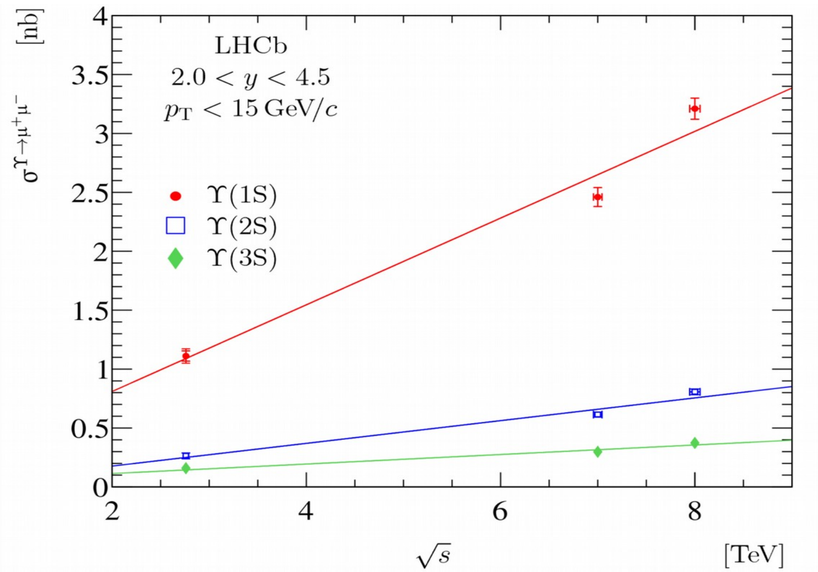
__Fit__: 3 *Crystal Ball Functions* (peaks) + exponential background.

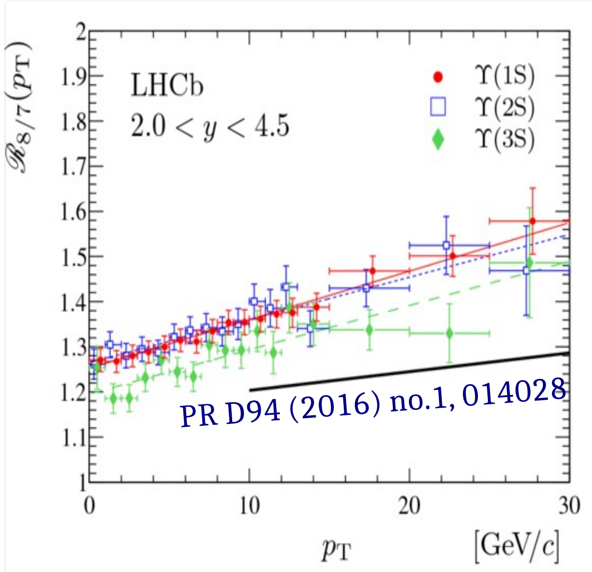
__Constraints__: $m_{\Upsilon(2S)} - m_{\Upsilon(1S)}$ [from PDG]
$m_{\Upsilon(3S)} - m_{\Upsilon(1S)}$ [from PDG]

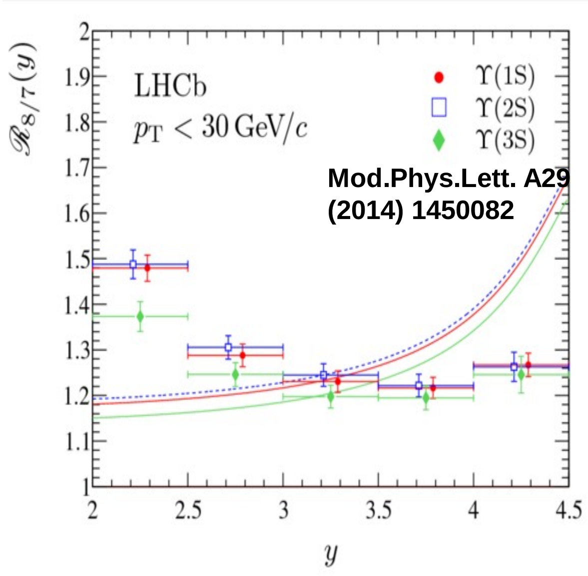
resolution scaling with the mass
shared "tail-shape parameters"

Production: *the cross-section measurement*

Production measurements performed on the same dataset found to **disagree** with (some) **theoretical predictions**, with an unexpectedly **large increase** in the production cross-section from 7 to 8 TeV in the c.m.s.







Polarization became an intriguing measurement.

Polarization: *anisotropic* $\Upsilon \to \mu\,\mu$ *decay*

The Υ (nS) mesons have quantum numbers $J^{PC} = 1^{--}$.

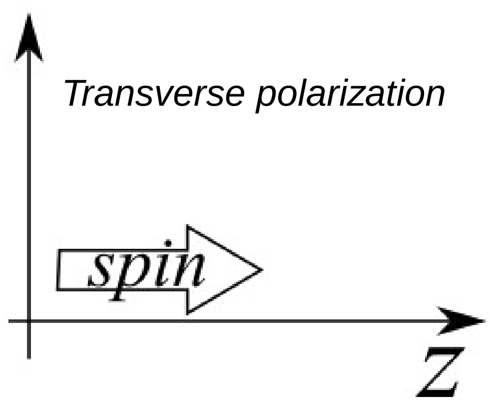
The Υ meson is **polarized** if is is **preferentially produced** in one of the spin states

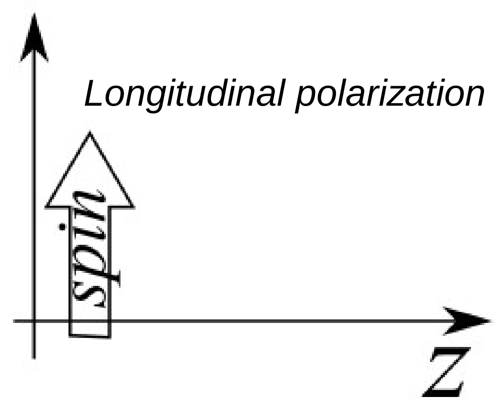
$$|J, J_z\rangle = |1, -1\rangle \quad \text{or} \quad |1, 0\rangle \quad \text{or} \quad |1, 1\rangle$$

and the **angular distribution of the produced muons** in the C.M.S. is not isotropic.

A *spin-independent* production mechanisms result into **unpolarized** Υ **mesons** and into an isotropic angular distribution for the muons.

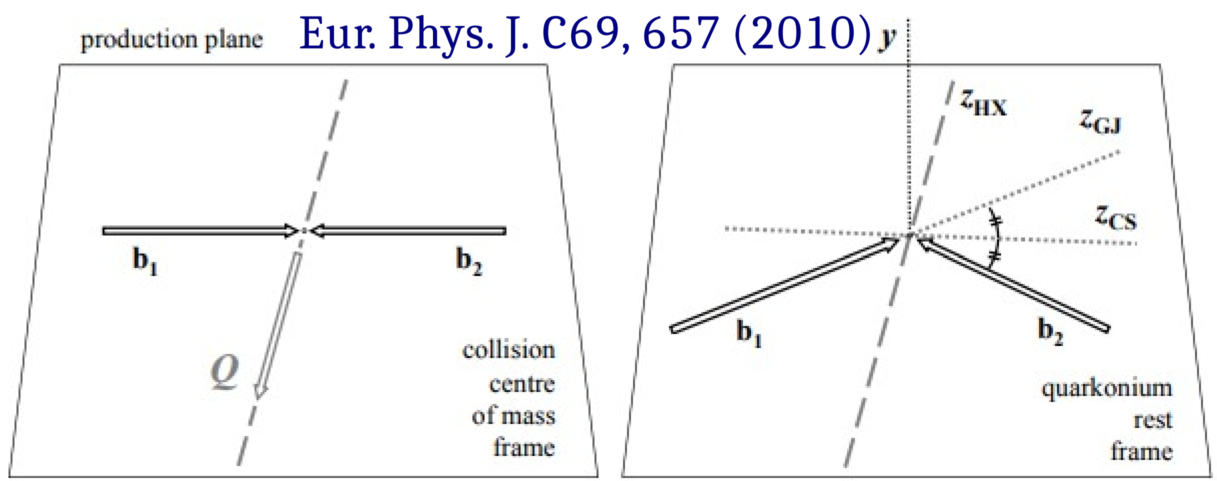
In analogy with electromagnetic radiation:





Polarization: *the arbitrary choice of the quantization axis*

Eur. Phys. J. C69, 657 (2010)

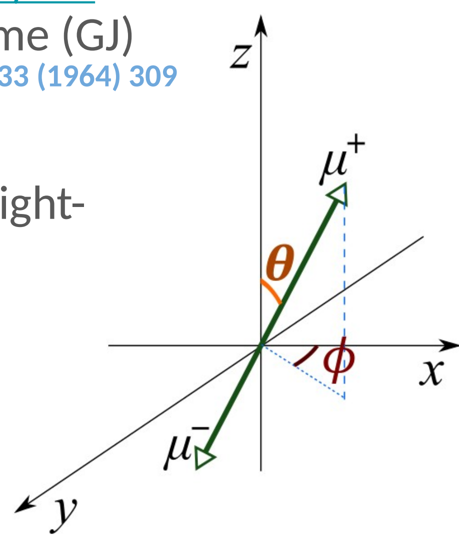


y-axis: normal to the production plane.

Three possible choices for the **z-axis**:

- ➪ Helicity frame (HX) Ann. Phys. 7 (1959) 404
- ➪ Collins-Soper frame (CS) PRD 16 (1977) 2219
- ➪ Gottfried-Jackson frame (GJ) Nuovo Cim. 33 (1964) 309

The **x-axis** completes the right-handed coordinate system



Angular distribution is parametrized through λ_ϕ, λ_θ and $\lambda_{\theta\phi}$.

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{3+\lambda_\theta}\Big[1+\lambda_\theta\cos^2\theta + \lambda_{\theta\phi}\sin 2\theta\cos\phi + \lambda_\phi\sin^2\theta\cos 2\phi\Big]$$

Polarization: *frame-independent polarization*

The parameters λ_ϕ , λ_θ and $\lambda_{\theta\phi}$ depend on the choice of the frame.

A frame-independent parameter is defined

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

A deviation of $\tilde{\lambda}$ from 0 means **polarized Υ state.**

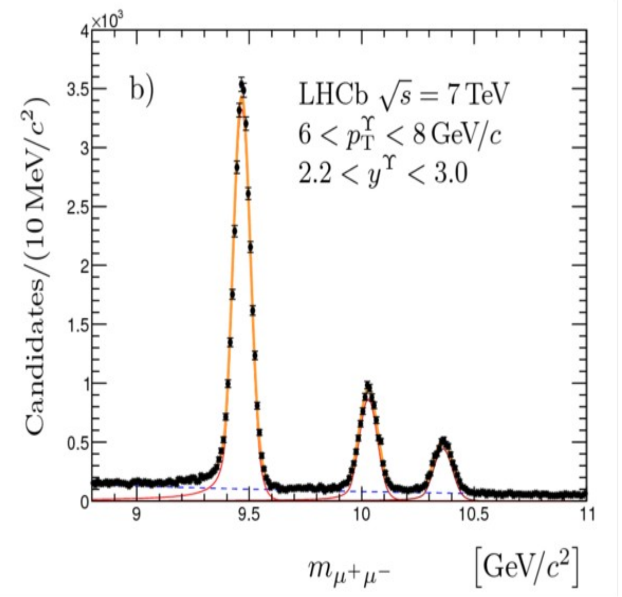
Statistical background subtraction: *sPlot technique*

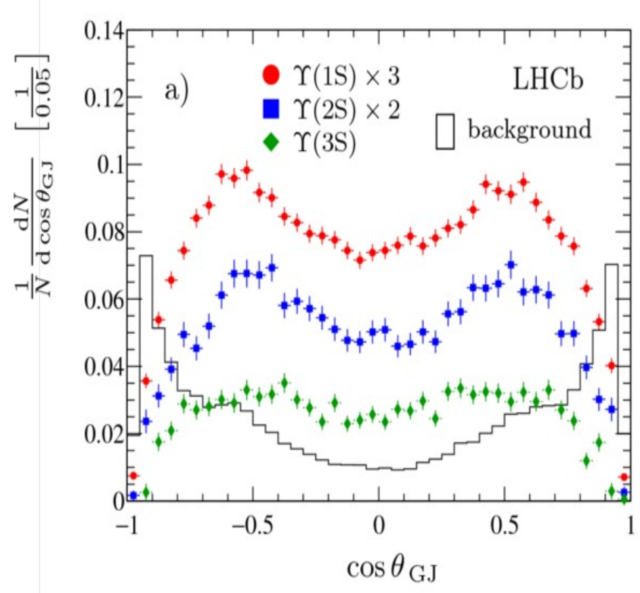
sPlot technique [1] used to statistically subtract the angular distributions of the **sidebands** from the sample, to obtain (and fit) signal distributions.

A weight $w_i^{\Upsilon} \in \mathbf{R}$ is assigned to each candidate, the weighted distributions are, by construction, background-subtracted.

Example of application: Studying the θ_{GJ} distribution, a peaking background structure was found, and rejected by the criterion

$$|\cos \theta_{GJ}| > 0.8$$





[1] Nucl.Instrum.Meth.A555:356-369,2005

Simulation: *validation and correction*

The polarization measurement relies on different angular distributions between a **simulated unpolarized** Υ dataset and the collected data.

The simulation of the angle-dependent efficiencies has to be accurate

Corrections

- ➪ **Geometrical acceptance**: simulated. Border-effects limited by fiducial volume.
- ➪ **Tracking efficiency**: simulated and corrected using abundant $J/\psi \to \mu\, \mu$ decays.
- ➪ **Trigger efficiency**: simulated and cross-checked with events triggered by single-μ
- ➪ **Muon identification efficiency**: taken from data (again $J/\psi \to \mu\, \mu$ decays).

Validation:

Background subtracted distributions of corrected simulation and real data are compared for fully reconstructed $B^+ \to J/\psi K^+$ decays (polarized J/ψ) to validate the procedure (though the kinematic range is a bit different)

The polarization fit: *the likelihood function*

Angular model:

$$\mathcal{P}(\Omega_i|\boldsymbol{\lambda}) \equiv 1 + \lambda_\theta \cos^2\theta_i + \lambda_{\theta\phi} \sin 2\theta_i \cos\phi_i + \lambda_\phi \sin^2\theta_i \cos 2\phi_i$$

Likelihood function:

Weight from the *s*Plot

$$\begin{aligned}\log \mathcal{L}^{\Upsilon}(\boldsymbol{\lambda}) &= s_w \sum_i w_i^{\Upsilon} \log\left[\frac{\mathcal{P}(\Omega_i|\boldsymbol{\lambda})\,\varepsilon(\Omega_i)}{\mathcal{N}(\boldsymbol{\lambda})}\right] \\ &= s_w \sum_i w_i^{\Upsilon} \log\left[\frac{\mathcal{P}(\Omega_i|\boldsymbol{\lambda})}{\mathcal{N}(\boldsymbol{\lambda})}\right] \\ &+ s_w \sum_i w_i^{\Upsilon} \log\left[\varepsilon(\Omega_i)\right] ,\end{aligned}$$

Constant, neglected term

Scale factor (sFit)

$$s_w \equiv \frac{\sum_i w_i^{\Upsilon}}{\sum_i (w_i^{\Upsilon})^2}$$

Normalization:

Efficiency correction

$$\mathcal{N}(\lambda) \equiv \int \mathrm{d}\Omega(\Omega|\lambda)\varepsilon(\Omega) \propto \sum_i \varepsilon^{\mu^+\mu^-} \mathcal{P}(\Omega_i|\lambda)$$

Efficiency

Sum over _selected_ simulated events

Systematic uncertainties: *overview*

- **Fit model**
  - ✓ signal parametrization taken from simulation
  - ✓ background parametrization fitted with exp($a \times m(\mu\mu)$) $\times$ polynomial (for systematics only)
  - ✓ In every bin, uncertainty due to the fit model < 10% of statistical uncertainty
- **Trigger Efficiency determination**
  - ✓ comparison of efficiency in data and MC shows discrepancy of order 2%

$$\varepsilon\left[\mathrm{Trig}(\mu\mu)\ \&\ \mathrm{Trig}(\mu)\middle|\mathrm{Trig}(\mu)\right]_{\mathrm{Data}} \qquad \varepsilon\left[\mathrm{Trig}(\mu\mu)\ \&\ \mathrm{Trig}(\mu)\middle|\mathrm{Trig}(\mu)\right]_{\mathrm{Simulation}}$$

- **Tracking and muon identification efficiency determination**
  - ✓ uncertainty propagated with toys from statistical uncertainty on the calibration samples.
- **Finite Simulated samples**
  - ✓ due to Υ simulated softer than produced, high-p_T bins are dominated by statistical uncertainty on MC

Systematic uncertainties: *results*

At low- and mid-p_T the measurement is **statistically limited**.

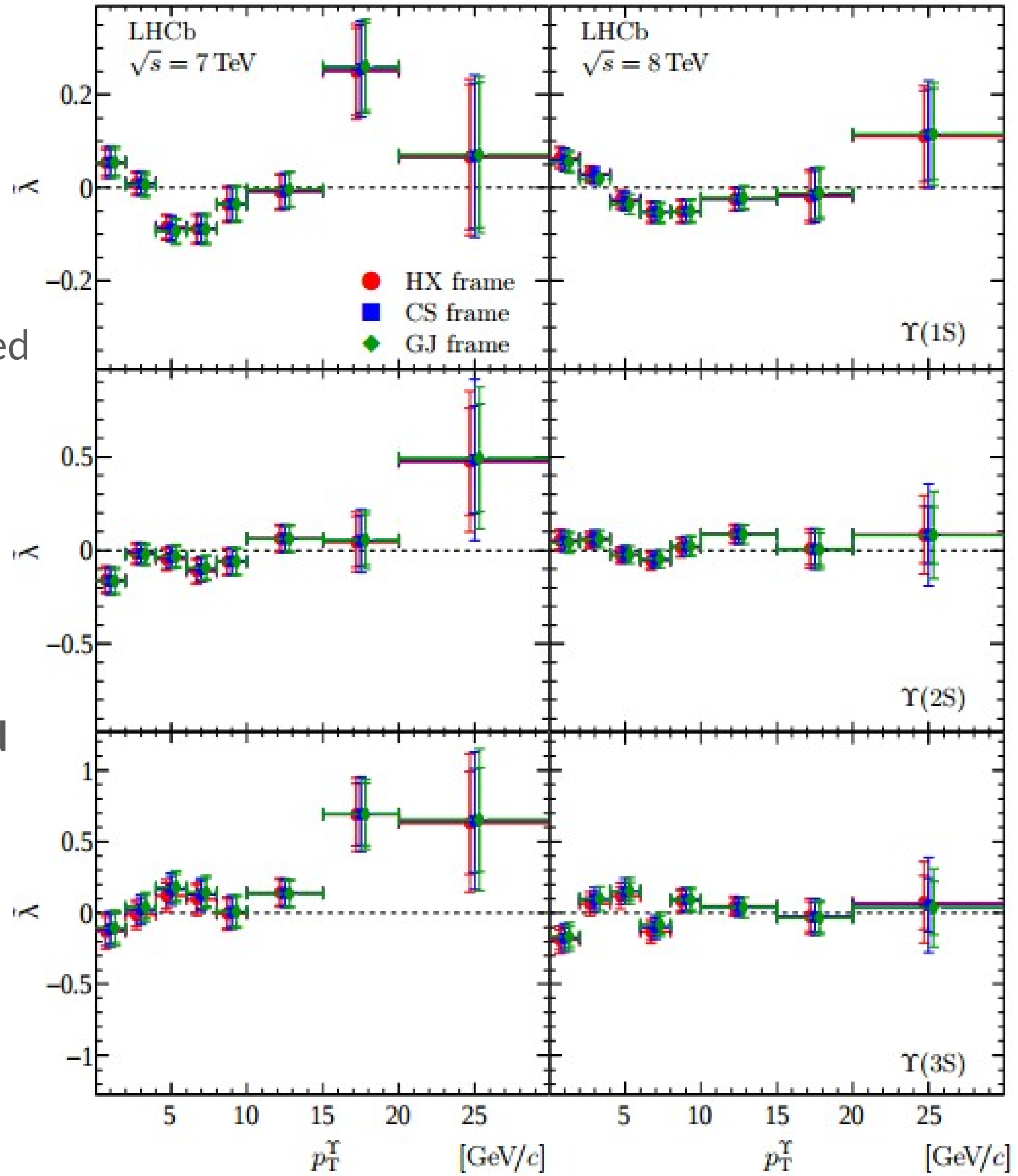
At high-p_T statistical and systematic uncertainties are competitive.

Source	σ_{λ_θ} $[10^{-3}]$	$\sigma_{\lambda_{\theta\phi}}$ $[10^{-3}]$	σ_{λ_ϕ} $[10^{-3}]$	$\sigma_{\tilde{\lambda}}$ $[10^{-3}]$
		$\Upsilon(1S)$		
Dimuon mass fit	1.0 – 12	0.2 – 10	0.1 – 7	1.8 – 20
Efficiency calculation				
muon identification	0.2 – 10	0.1 – 7	0.1 – 6	0.2 – 17
correction factors for $\varepsilon^{\mu^+\mu^-}$	0.7 – 12	0.4 – 5	0.1 – 4	2.1 – 14
trigger	0.1 – 18	0.1 – 8	0.1 – 5	0.3 – 19
Finite size of simulated samples	6.0 – 82	1.3 – 29	0.9 – 35	6.9 – 95
		$\Upsilon(2S)$		
Dimuon mass fit	0.6 – 37	0.2 – 19	0.3 – 16	4.6 – 53
Efficiency calculation				
muon identification	0.2 – 11	0.1 – 6	0.1 – 5	0.2 – 13
correction factors for $\varepsilon^{\mu^+\mu^-}$	0.7 – 12	0.3 – 5	0.1 – 5	2.1 – 13
trigger	0.1 – 17	0.1 – 7	0.1 – 5	0.3 – 18
Finite size of simulated samples	9.8 – 210	2.5 – 98	1.5 – 120	14 – 320
		$\Upsilon(3S)$		
Dimuon mass fit model	1.4 – 72	0.2 – 24	0.5 – 21	7.2 – 86
Efficiency calculation				
muon identification	0.2 – 12	0.1 – 7	0.1 – 5	0.3 – 22
correction factors for $\varepsilon^{\mu^+\mu^-}$	0.6 – 14	0.3 – 6	0.1 – 5	2.1 – 18
trigger	0.2 – 17	0.1 – 8	0.1 – 4	0.3 – 19
Finite size of simulated samples	12 – 280	3.5 – 100	2.1 – 110	16 – 350

Polarization fit: *results*

The results on the frame-independent parameter $\tilde{\lambda}$ are shown **as "sum-check"** as obtained from fits in the three frames:

+ Helicity frame (HX)
+ Collins-Soper frame (CS)
+ Gottfried-Jackson frame (GJ)



No large polarization effect observed (neither longitudinal nor transverse).

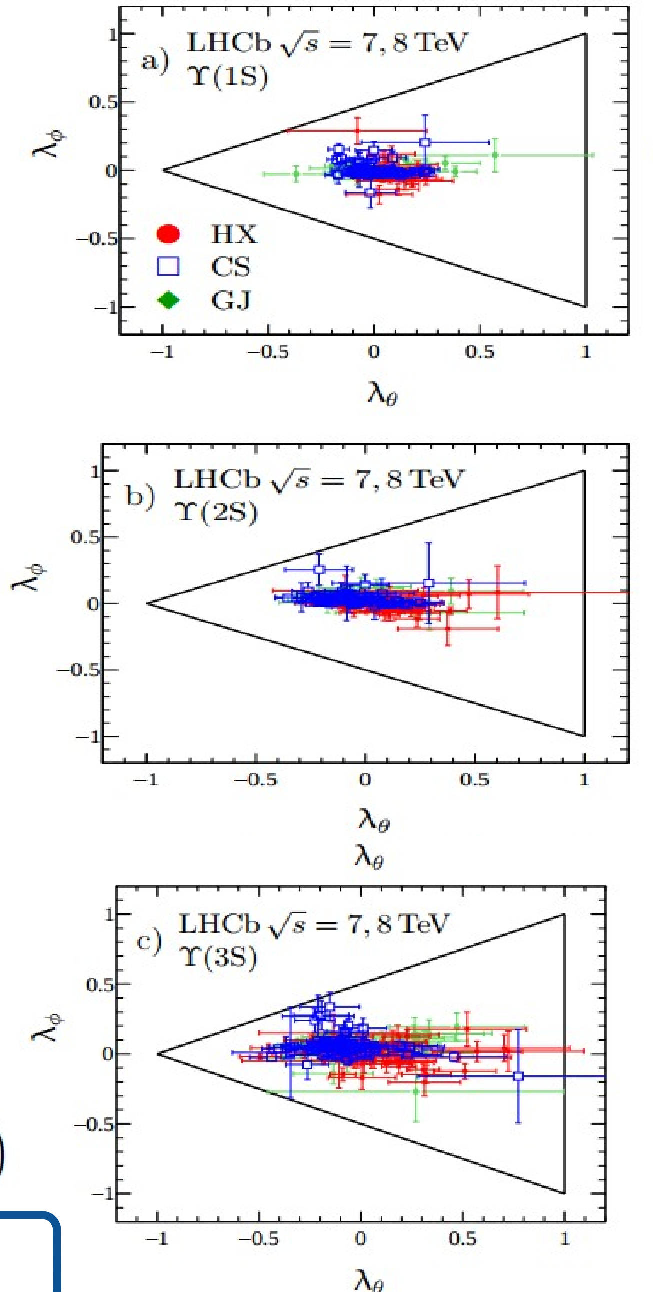
Positivity test: *spin-1 density matrix*

Density matrix of the Υ decay in the Υ rest frame:

$$\begin{pmatrix} \frac{1-\lambda_\theta}{2} & \lambda_{\theta\phi} & 0 \\ \lambda_{\theta\phi} & \frac{1+\lambda_\theta-2\lambda_\phi}{2} & 0 \\ 0 & 0 & \frac{1+\lambda_\theta+2\lambda_\phi}{2} \end{pmatrix}$$

The density matrix is positive by construction,
implying six constraints
(translated into admitted regions in the parameter space)

$$\begin{aligned}
0 &\leq \mathcal{C}_1 = 1 - |\lambda_\theta| \\
0 &\leq \mathcal{C}_2 = 1 + \lambda_\theta - 2\,|\lambda_\phi| \\
0 &\leq \mathcal{C}_3 = (1-\lambda_\theta)\,(1+\lambda_\theta-2\lambda_\phi) - 4\lambda_{\theta\phi}^2 \\
0 &\leq \mathcal{C}_4 = (1-\lambda_\theta)\,(1+\lambda_\theta+2\lambda_\phi) \\
0 &\leq \mathcal{C}_5 = (1+\lambda_\theta)^2 - 4\lambda_\phi^2 \\
0 &\leq \mathcal{C}_6 = (1+\lambda_\theta+2\lambda_\phi)\left((1-\lambda_\theta)\,(1+\lambda_\theta-2\lambda_\phi) - 4\lambda_{\theta\phi}^2\right)
\end{aligned}$$



All positivity constraints are satisfied in all kinematic bins

A word on theoretical predictions

Theoretical predictions are based on NRQCD with a factorization approach

$$d\sigma_{pp\to\mathcal{Q}+X} = \sum_n d\hat{\sigma}_{pp\to Q\bar{Q}[n]+X}\langle\mathcal{O}^{\mathcal{Q}}(n)\rangle.$$

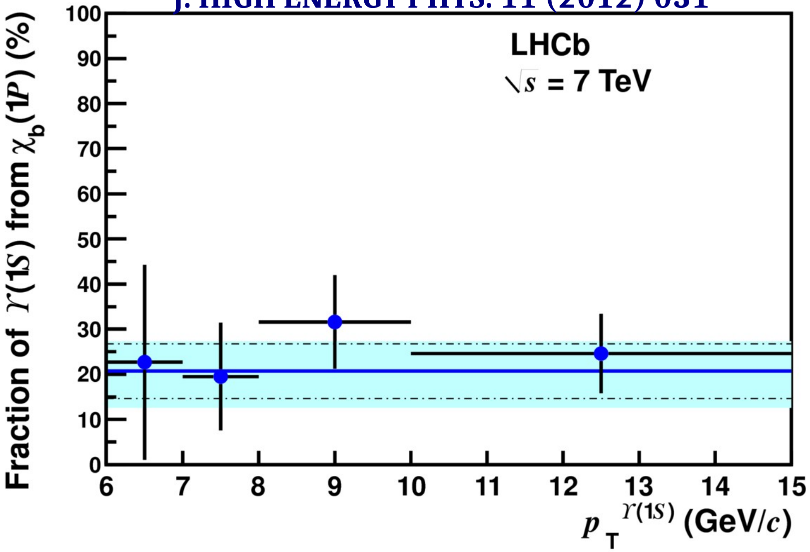
Perturbative part (QCD scattering)

Non perturbative Long Distance Matrix Elements (LDME) (from fit to data)

An important unknown in the computation comes from the contribution from $\chi_b \to \Upsilon\gamma$ feed-down.

It was measured for $\chi_b\,(1\mathrm{P})$ and assumed for the other states, leading to important uncertainties.

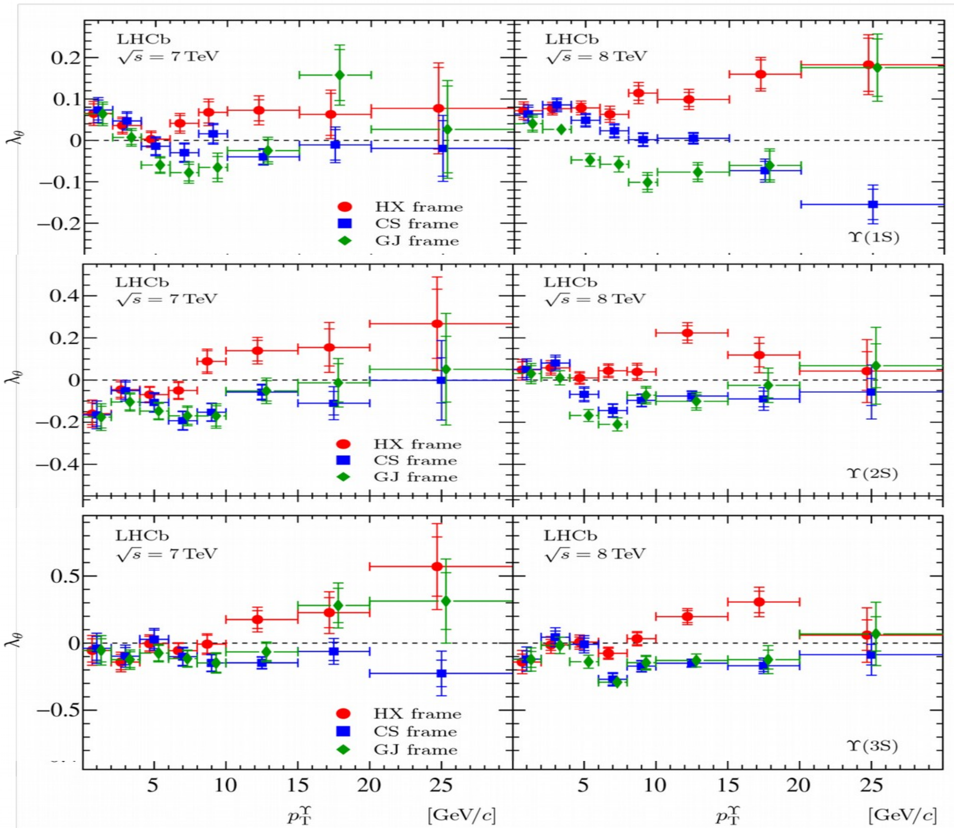
J. HIGH ENERGY PHYS. 11 (2012) 031



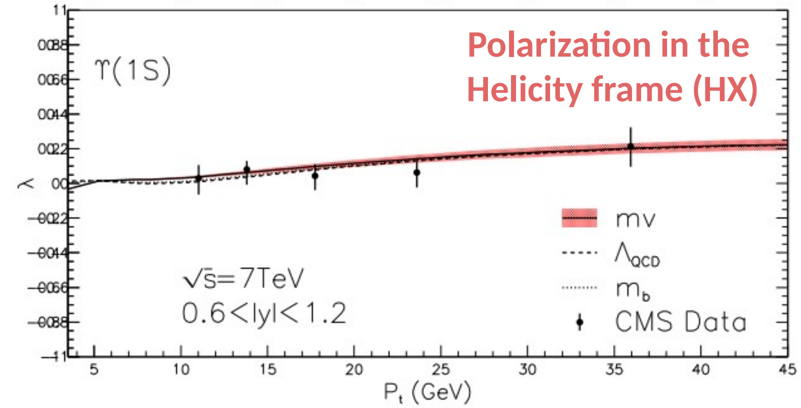
Predictions: PRL 112, 032001 (2014)

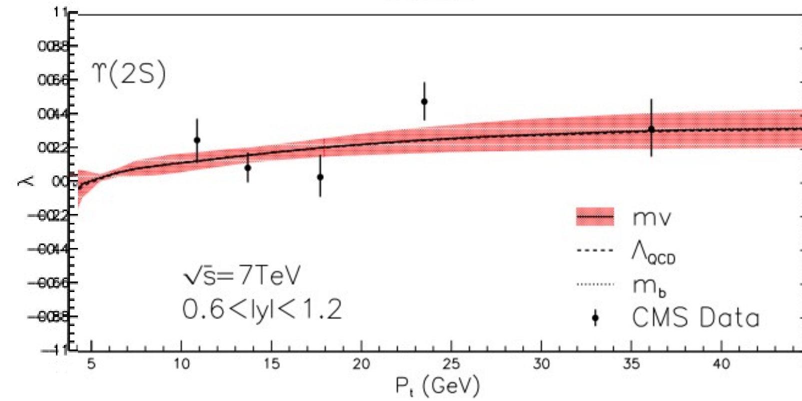
CMS data: PRL 110 081802 (2013)

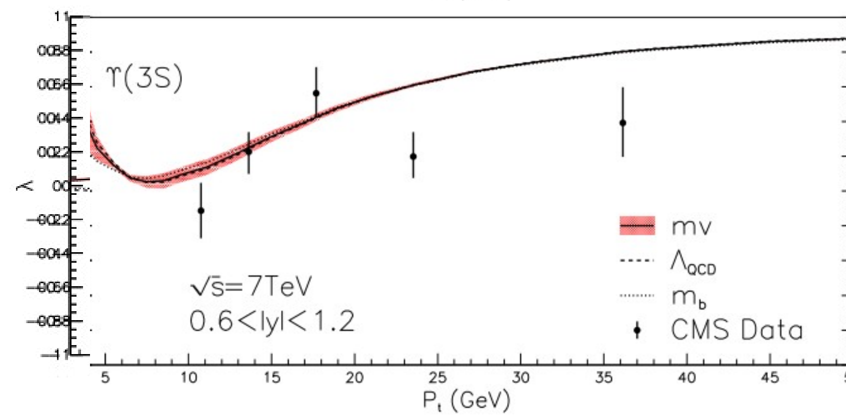
Comparison with NRQCD



Polarization in the Helicity frame (HX)

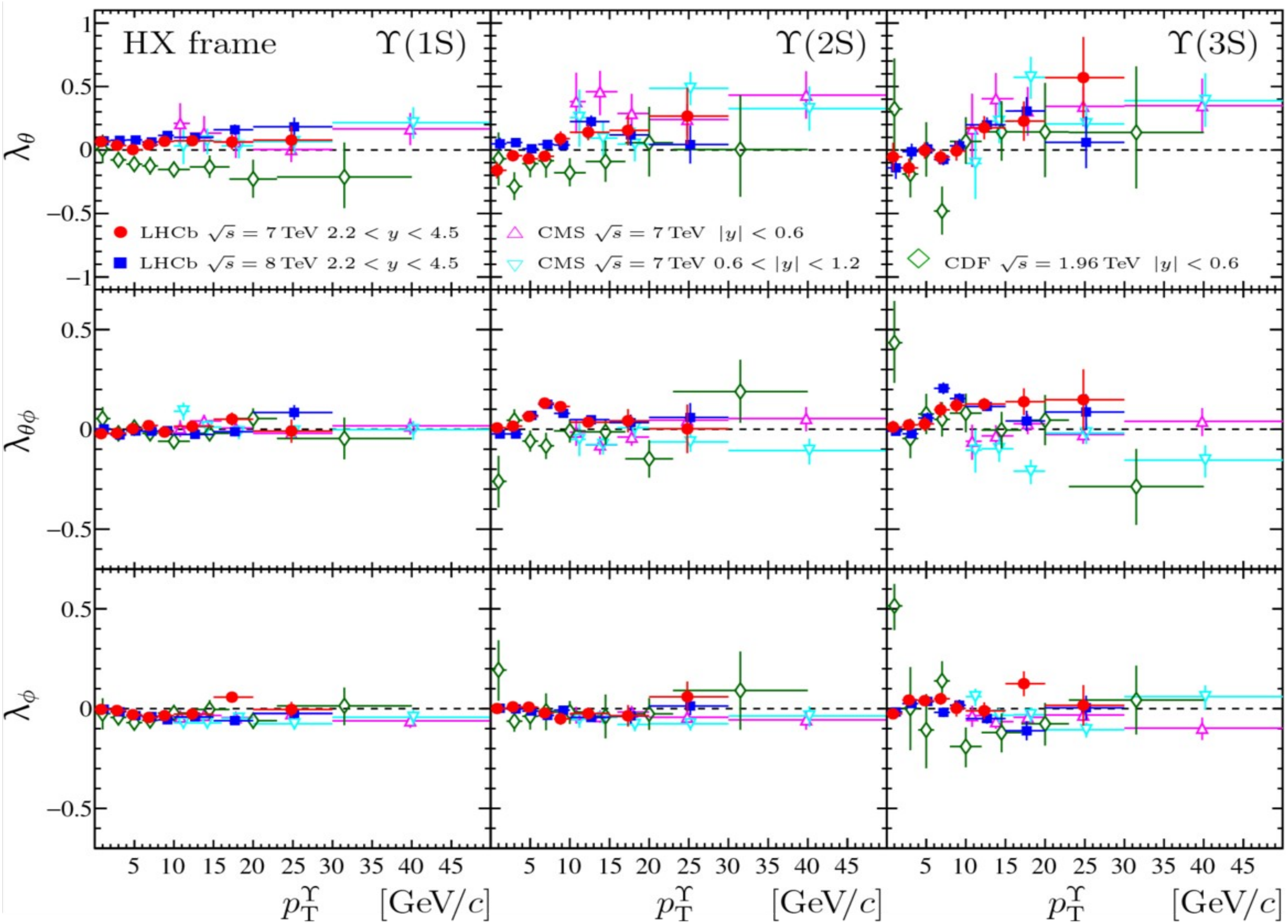






CMS data: PRL 110 081802 (2013)
CDF data: PRL 108, 151802 (2012)

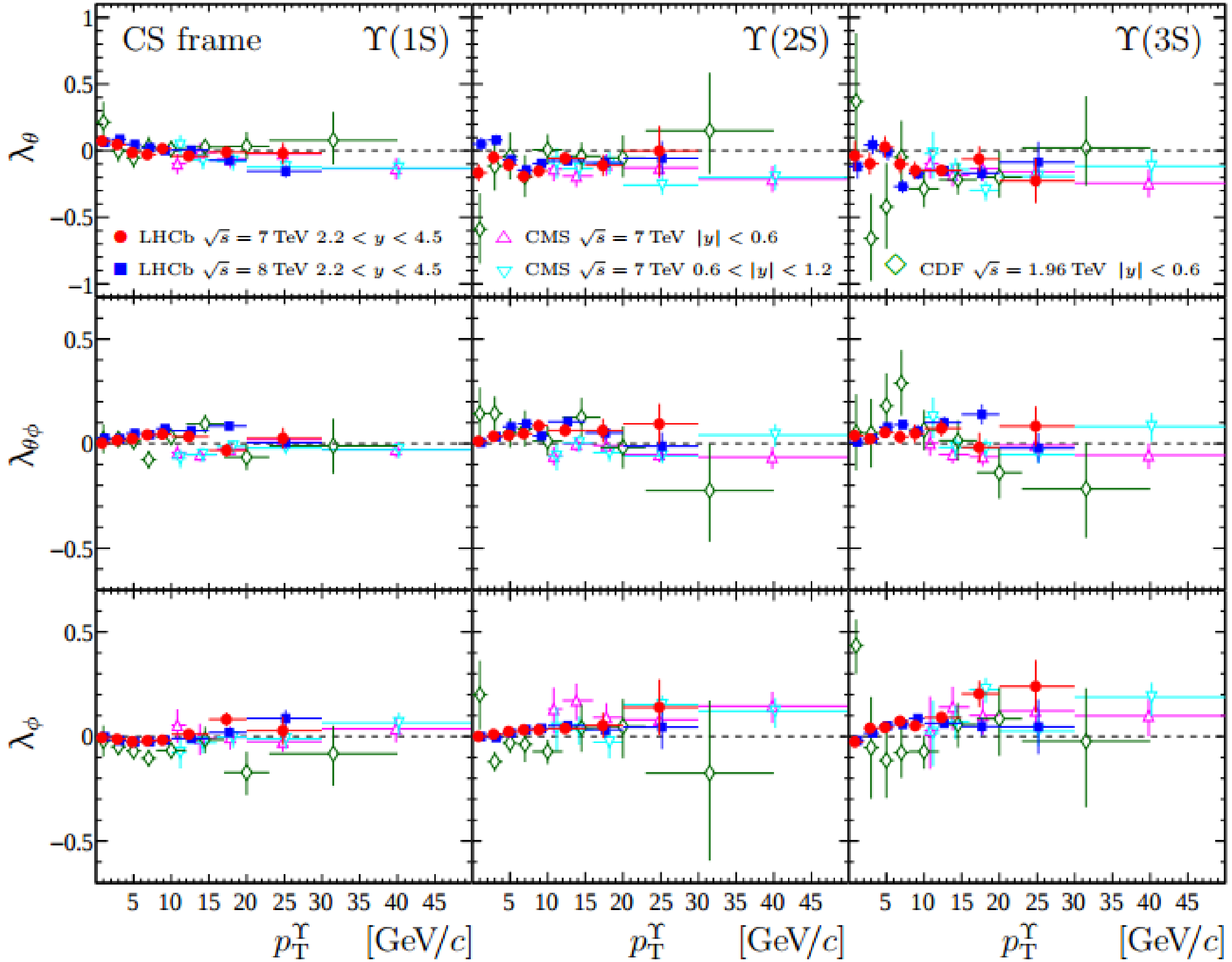
Comparisons with CMS and CDF data



Expecting small dependency of polarization on η, LHCb results (forward) are compared to CMS and CDF results. **In the HX frame, no good agreement with CMS.**

CMS data: PRL 110 081802 (2013)
CDF data: PRL 108, 151802 (2012)

Comparisons with CMS and CDF data



In Collins-Soper the agreement is good with both CMS and CDF.

Summary and outlook

LHCb measured the polarization of Y mesons through decays $Y \rightarrow \mu^+ \mu^-$.

Polarization parameters in different frames are measured in bins of $p_T(Y)$ and $\eta(Y)$.

No large longitudinal or transversal polarization is observed in the accessible space domain.

The polarization parameters for $\sqrt{s}$ = 7 and 8 TeV are in good agreement.

The results are in agreement with those of CMS and CDF.

LHCb will keep contributing to production and polarization measurements also thanks to the forthcoming upgrade that will allow higher efficiency on purely hadronic decays.