Quarkonium production in *pp* collisions with the CMS detector

Alexis Pompili (on behalf of the CMS Collaboration)

UNIVERSITA' DEGLI STUDI DI BARI "ALDO MORO" & I.N.F.N. SEZIONE DI BARI

Introduction & Motivation

Quarkonia are bound states of an heavy quark and an heavy antiquark ($c\bar{c}$, $b\bar{b}$) and exist in "families" of several states (colorless, neutral mesons)

Quarkonium spectra & decays are well understood below open charm & beauty thresholds

Quarkonium production is still an active field of research;
production rates @ LHC are rather high ⇨ LHC is a "quarkonium factory"

Quarkonium production occurs through :

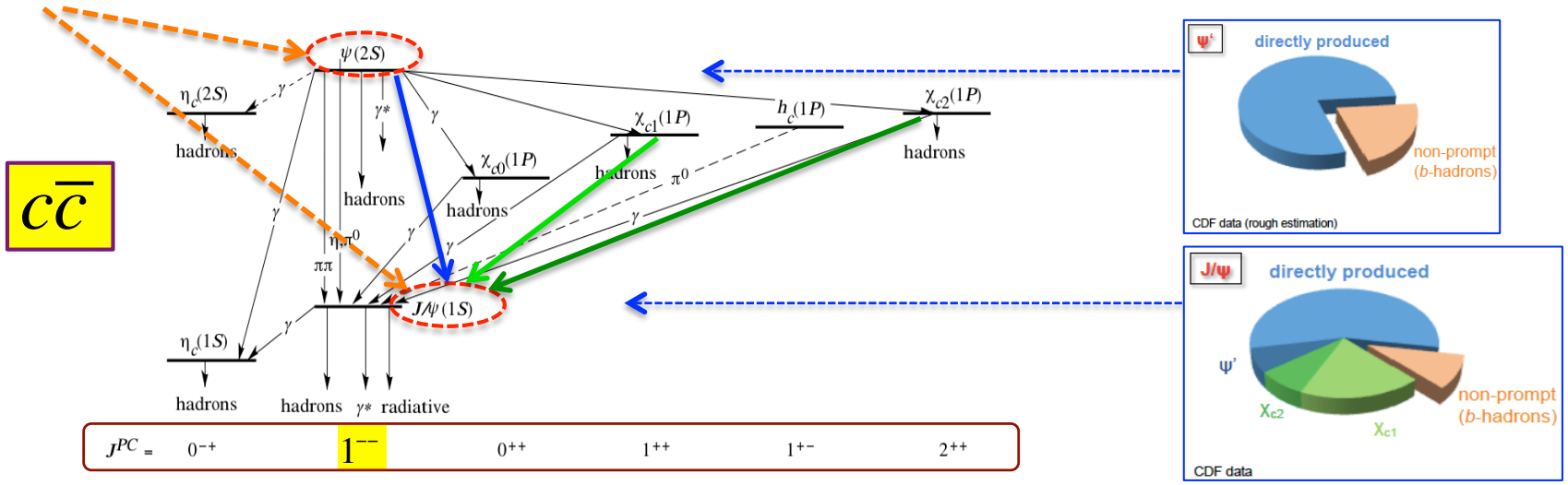
a) Prompt production: direct production or feed-down from higher quarkonium states
b) Non-prompt production : from B decays (charmonia only)

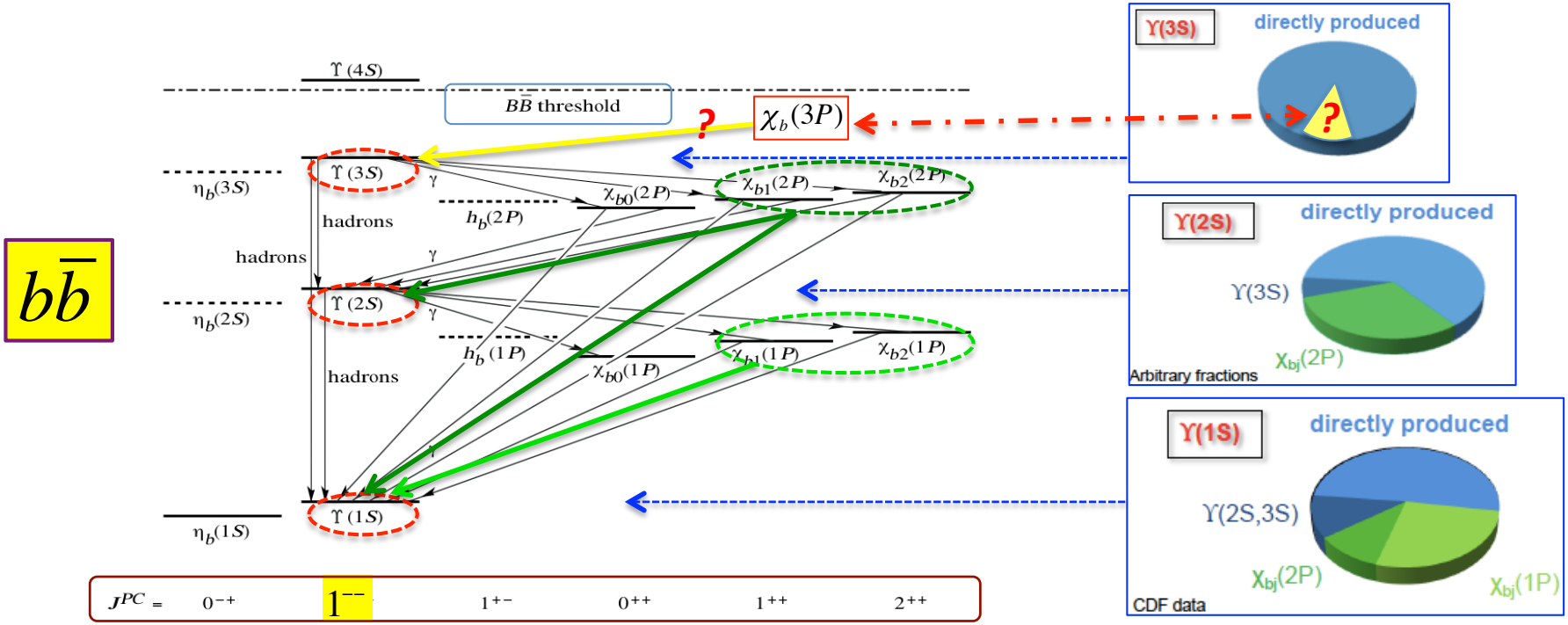
The study of quarkonium prompt production is suited to understand how quarks combine into a bound state (hadron) [not easy: it is part of the non-perturbative QCD sector]

Properties of QCD can be probed (by LHC experiments, in different new kinematic regions) through several quarkonium production measurements including :

- **production cross sections**
- **polarizations**

Quarkonium spectra & overview of feed-down into *spin-triplet S-wave* states





Quarkonium Production

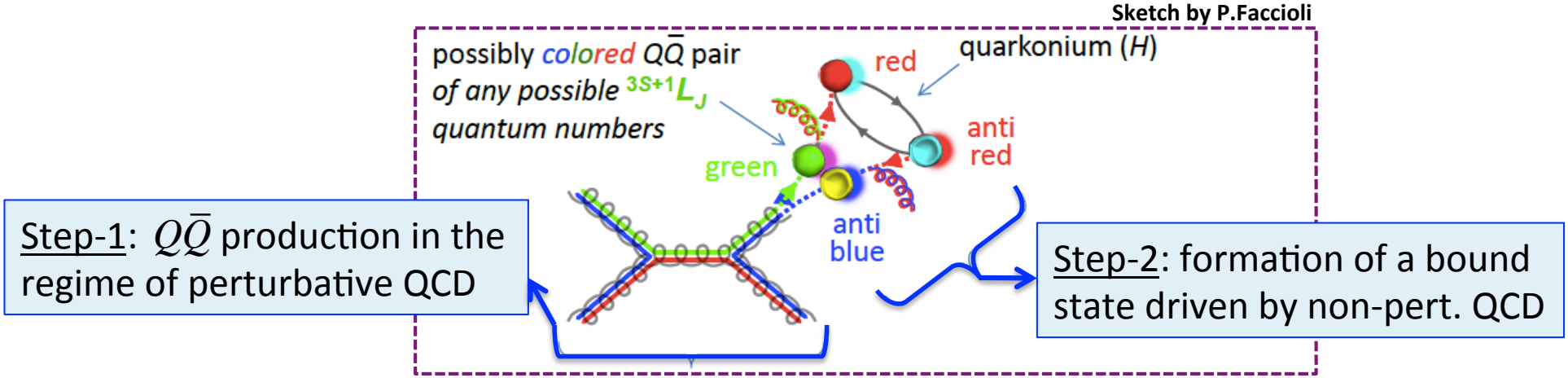
NRQCD Factorization conjecture

- In the $Q\bar{Q}$ center-of-mass frame quarks are not relativistic ($v = \upsilon/c << 1$; better approx. for $b\bar{b}$ than $c\bar{c}$)

  NRQCD : effective field theory that treats heavy quarkonia as non-relativistic systems

- The heavy-Q mass $m_Q >> \Lambda_{QCD}$ (that provides a natural boundary between short- and long-distance QCD) ⇨ the inclusive quarkonium production can be factorized in two distinct steps:

Sketch by P.Faccioli



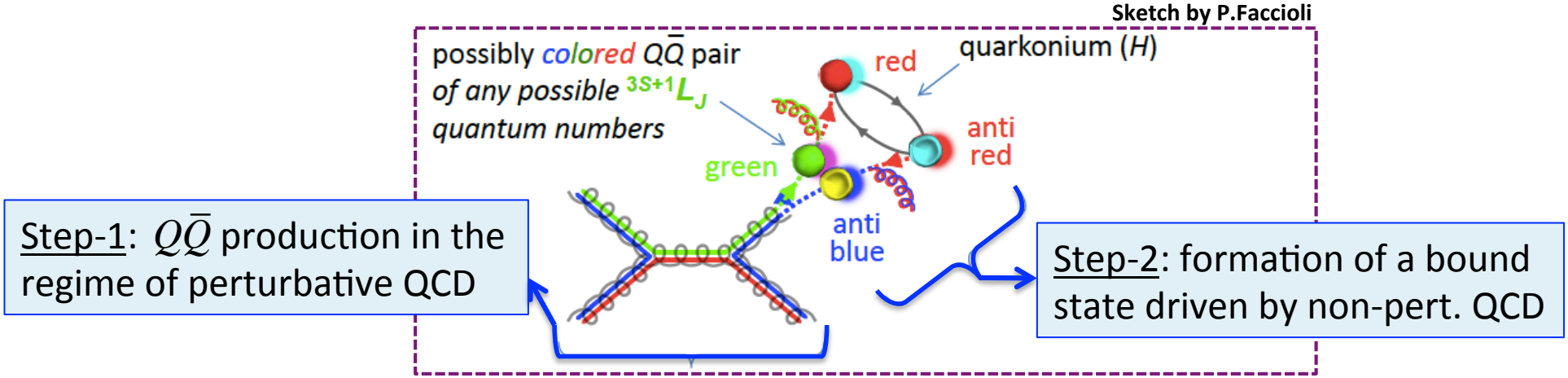
NRQCD Factorization conjecture

- In the $Q\bar{Q}$ center-of-mass frame quarks are not relativistic ($v = \upsilon/c << 1$; better approx. for $b\bar{b}$ than $c\bar{c}$)

  NRQCD : effective field theory that treats heavy quarkonia as non-relativistic systems

- The heavy-Q mass $m_Q >> \Lambda_{QCD}$ (that provides a natural boundary between short- and long-distance QCD) ⇨ the inclusive quarkonium production can be factorized in two distinct steps:

Sketch by P.Faccioli



- Inclusive xsection for producing quarkonium (***H***) with enough large momentum transfer p_T :

$$\sigma\left(A+B \to H+X\right) = \sum_n \sigma\left(A+B \to \left[Q\bar{Q}\right]_n + X\right) \cdot P\left(\left[Q\bar{Q}\right]_n \to H\right) \quad , \quad n = {}^{2S+1}L_J^{[C]}$$

$Q\bar{Q}$ can be, at short distances, produced in a state ***n*** with definite: spin ***S***, angular momentum ***L***, and color ***C*** = 1,..,8.

Short-distance coefficients (SDCs)

Long-distance matrix elements (LDMEs)

NRQCD : color-singlet & color-octet terms

Short-distance coefficients (SDCs)	**Long-distance matrix elements** (LDMEs)
Inclusive pQCD xsection of partonic processes to form $Q\bar{Q}$ in state n (convoluted with PDFs)	Probability of $Q\bar{Q}$ in state n to evolve into the quarkonium final state *H*
process-dependent **functions** of kinematics	universal **constants** (independent of kinematics)
calculated perturbatively as expansions in α_S	**determined by fits** to exp. data
	relative relevance given by v **- scaling rules**

NRQCD : color-singlet & color-octet terms

Short-distance coefficients (SDCs)	**Long-distance matrix elements** (LDMEs)
Inclusive pQCD xsection of partonic processes to form $Q\bar{Q}$ in state n (convoluted with PDFs)	Probability of $Q\bar{Q}$ in state n to evolve into the quarkonium final state *H*
process-dependent **functions** of kinematics	universal **constants** (independent of kinematics)
calculated perturbatively as expansions in α_S	**determined by fits** to exp. data
	relative relevance given by v **- scaling rules**

- Theoretical predictions are organized as double expansions in α_S and v.
  Truncation of v-expansion for *S-wave* states in NRQCD includes 4 terms:
  - the Color Singlet (CS) term: $^3S_1^{[1]}$
  - 3 Color Octet (CO) terms: $^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_{J=0,1,2}^{[8]}$ (of relative order $O(v^4)$ w.r.t. CS)

The CS term is characterized by a suppression of powers of α_S thus making important the CO channels despite of their suppression by powers of v !

NRQCD : color-singlet & color-octet terms

Short-distance coefficients (SDCs)	Long-distance matrix elements (LDMEs)
Inclusive pQCD xsection of partonic processes to form $Q\bar{Q}$ in state n (convoluted with PDFs)	Probability of $Q\bar{Q}$ in state n to evolve into the quarkonium final state *H*
process-dependent **functions** of kinematics	universal **constants** (independent of kinematics)
calculated perturbatively as expansions in α_S	**determined by fits** to exp. data
	relative relevance given by v **- scaling rules**

- Theoretical predictions are organized as double expansions in α_S and v.
  Truncation of v-expansion for *S-wave* states in NRQCD includes 4 terms:
  - the Color Singlet (CS) term: $^3S_1^{[1]}$
  - 3 Color Octet (CO) terms: $^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_{J=0,1,2}^{[8]}$ (of relative order $O(v^4)$ w.r.t. CS)

The CS term is characterized by a suppression of powers of α_S thus making important the CO channels despite of their suppression by powers of v !

- Color singlet assumption: initial $Q\bar{Q}$ & final ***H*** ($^3S_1$) have <u>same</u> quantum numbers!

NRQCD predicts the existence of intermediate CO states in nature, that subsequently evolve into physical color-singlet quarkonia by non-perturbative emission of soft gluons.

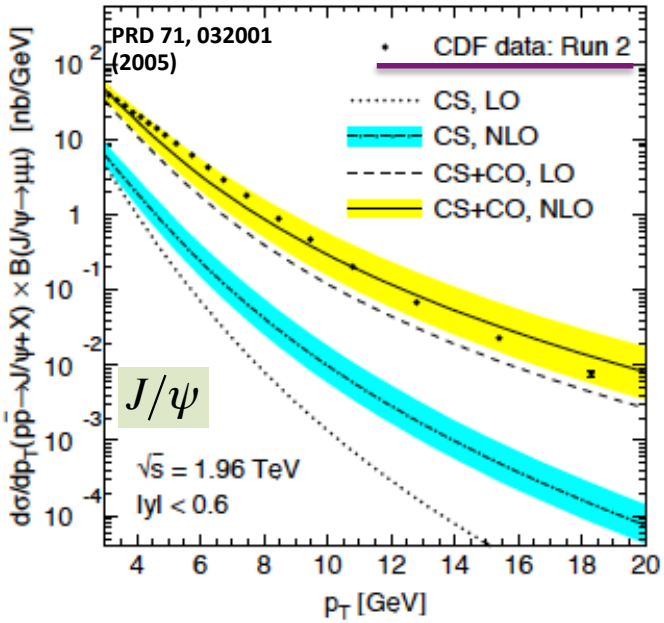
NRQCD in action: differential xsections

CO & NLO corrections in α_S

good consistency in the fit of the differential xsections vs. p_T

Fit function : superposition of CS and CO SDCs
- CS contribution is fixed
- CO terms have fixed shape but floating normalizations (the LDMEs)

M.Butenschoen & B.Kniehl, PRD84, 051501 (2011)

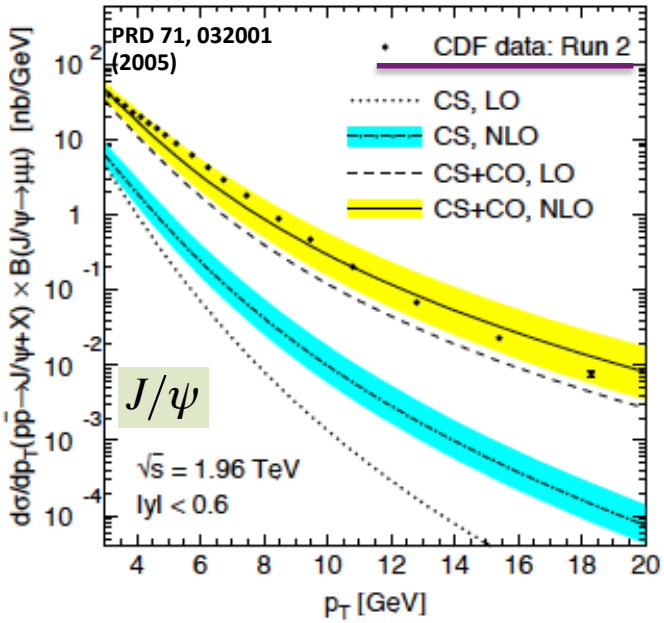


NRQCD in action: differential xsections

CO & NLO corrections in α_S

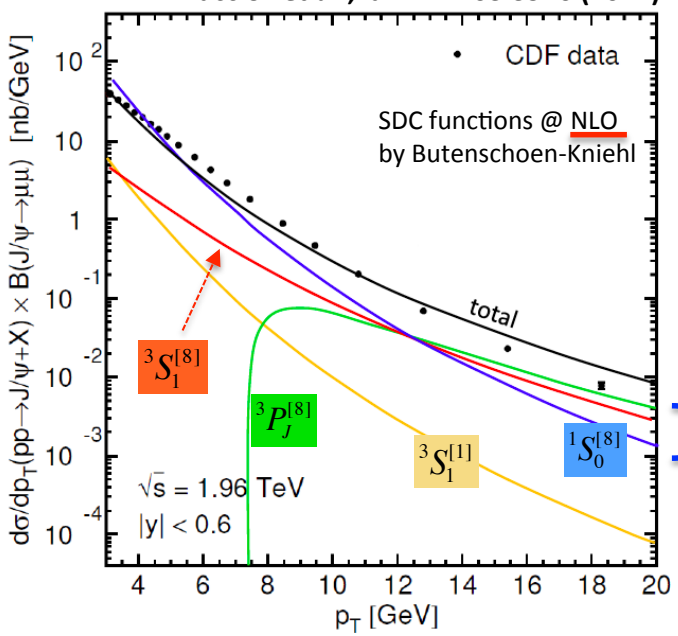
good consistency in the fit of the differential xsections vs. p_T

M.Butenschoen & B.Kniehl, PRD84, 051501 (2011)



Fit function : superposition of CS and CO SDCs
- CS contribution is fixed
- CO terms have fixed shape but floating normalizations (the LDMEs)

P.Faccioli *et al.*, arXiv:1403.3970 (2014)



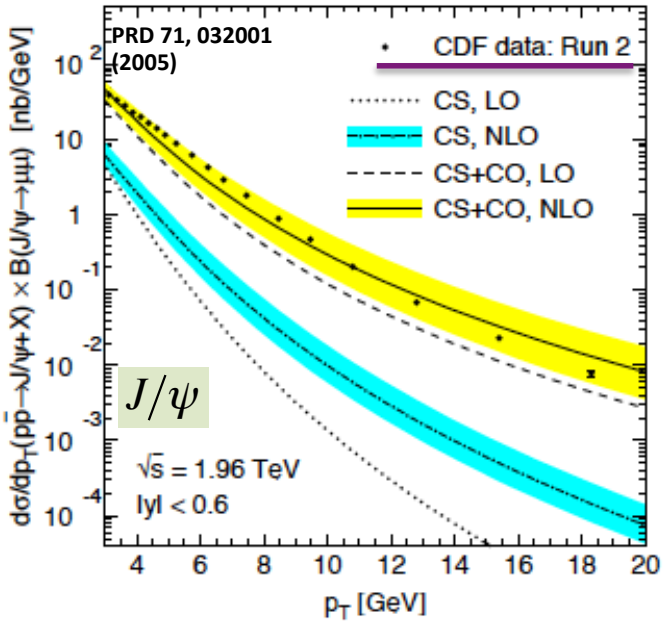
Fit starts @ lowest-p_T : $^3S_1^{[8]}$ & $^3P_J^{[8]}$ dominate.
However… **IF** …
… fit starts @ $p_T \geq 10 GeV$: $^1S_0^{[8]}$ would dominate!

NRQCD in action: differential xsections

CO & NLO corrections in α_S

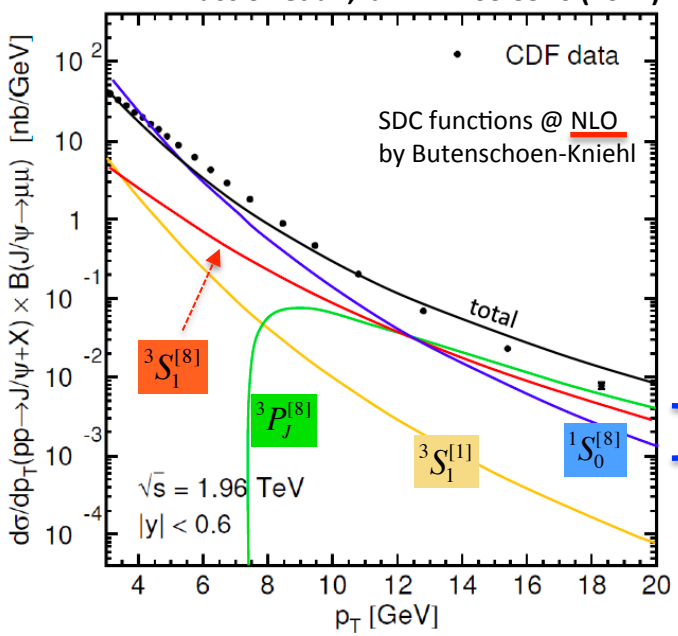
good consistency in the fit of the differential xsections vs. p_T

M.Butenschoen & B.Kniehl, PRD84, 051501 (2011)



Fit function : superposition of CS and CO SDCs
- CS contribution is fixed
- CO terms have fixed shape but floating normalizations (the LDMEs)

P.Faccioli *et al.*, arXiv:1403.3970 (2014)



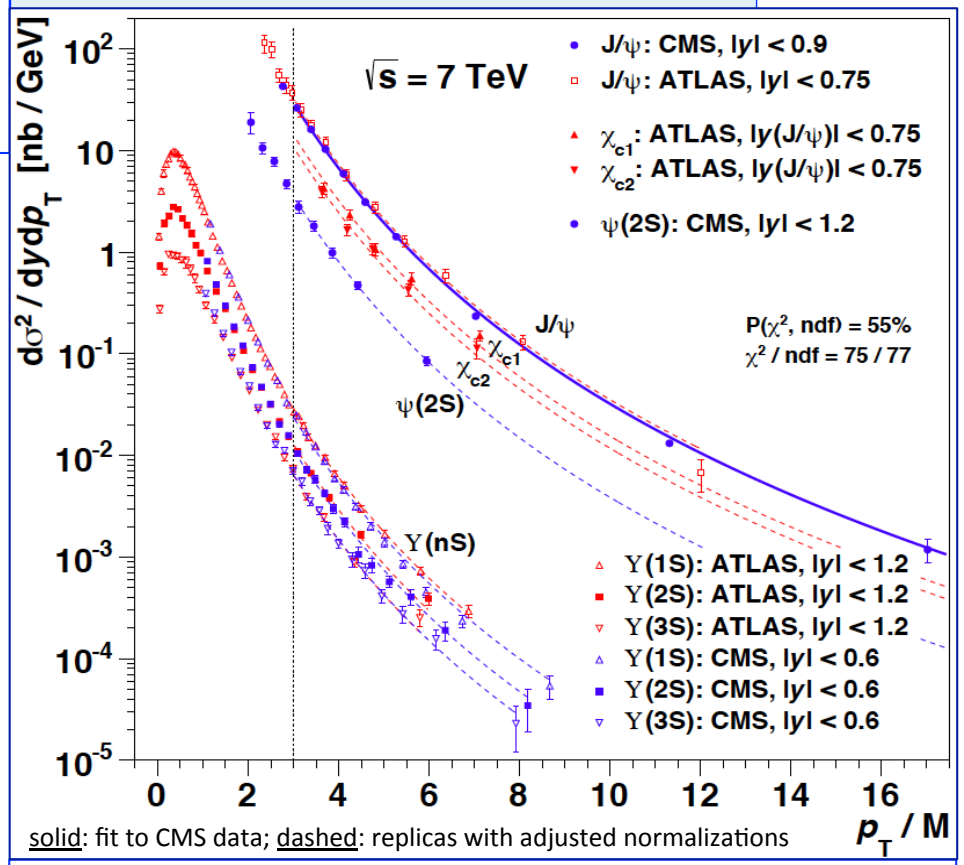
This approach brought the calculations of "p_T spectra" to agree almost well with the data. BUT… as discussed later… the same calculations are not able to reproduce satisfactorily the polarization results ("polarization puzzle")!

Fit starts @ lowest-p_T : $^3S_1^{[8]}$ & $^3P_J^{[8]}$ dominate.
However… **IF** …
… fit starts @ $p_T \geq 10 GeV$: $^1S_0^{[8]}$ would dominate!

LHC data for quarkonium production

Mid-rapidity double differential cross sections for the production of 7 different quarkonia as a function of p_T/M (*)

Compilation by P.Faccioli *et al.*, arXiv:1403.3970 (2014)



solid: fit to CMS data; dashed: replicas with adjusted normalizations

(*) p_T is mass-rescaled to equalize the kinematics effects of different average parton momenta and phase spaces

ATLAS, CONF-2013-095; arXiv:1404.7035 (submitted to JHEP)
ATLAS, NPB 850, 387 (2011)
ATLAS, PRD 87, 052004 (2013)
CMS, PLB 727, 101 (2013)
CMS, JHEP 02, 011 (2012)

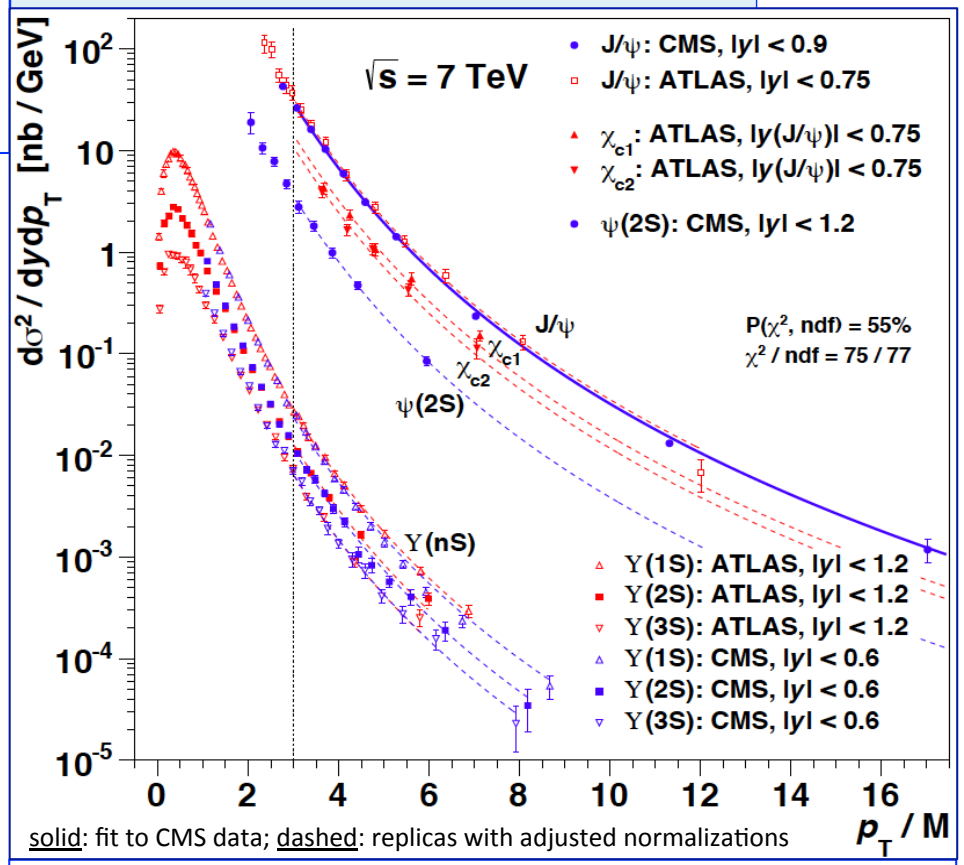
few plots in backup slides

LHC data for quarkonium production

Mid-rapidity double differential cross sections for the production of 7 different quarkonia as a function of p_T/M (*)

Shapes are well described by a single empirical power-law for $p_T/M > 3$.
This p_T/M **scaling behaviour** …
… common to 5 *S-wave* & 2 *P-wave* states
with different feed-down contaminations ,
suggests a simple composition of processes dominated by 1 single mechanism.

Compilation by P.Faccioli *et al.*, arXiv:1403.3970 (2014)



solid: fit to CMS data; dashed: replicas with adjusted normalizations

(*) p_T is mass-rescaled to equalize the kinematics effects of different average parton momenta and phase spaces

ATLAS, CONF-2013-095; arXiv:1404.7035 (submitted to JHEP)
ATLAS, NPB 850, 387 (2011)
ATLAS, PRD 87, 052004 (2013)
CMS, PLB 727, 101 (2013)
CMS, JHEP 02, 011 (2012)

few plots in backup slides

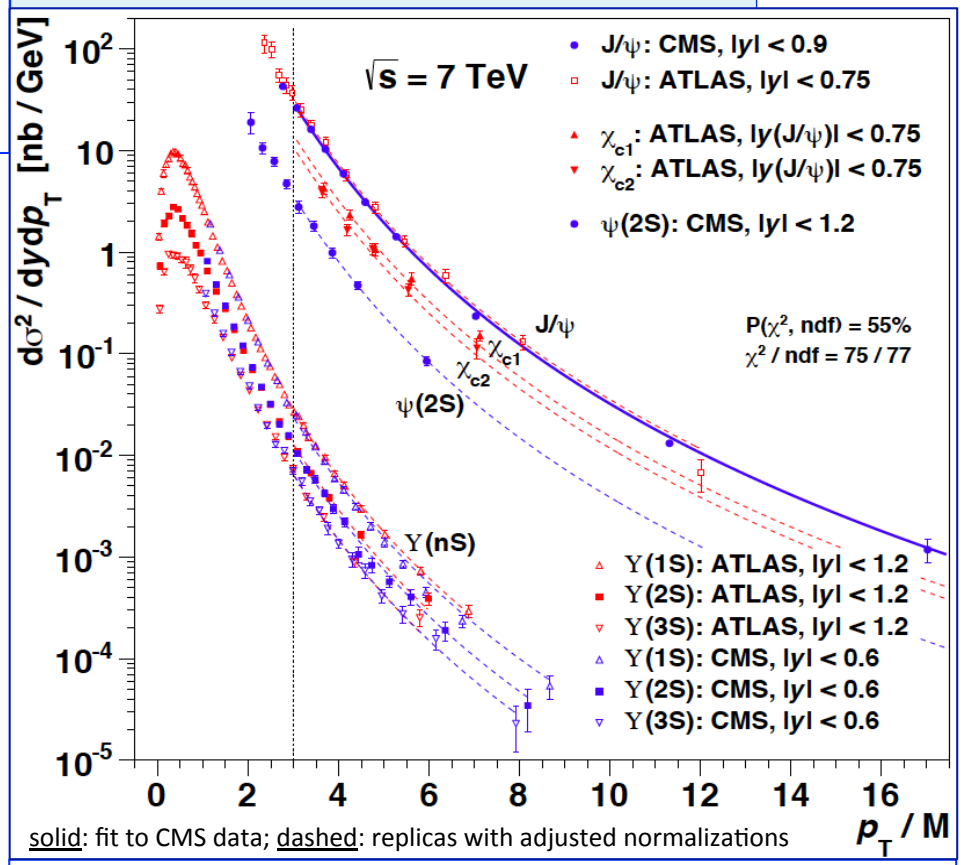
LHC data for quarkonium production

Mid-rapidity double differential cross sections for the production of 7 different quarkonia as a function of p_T/M (*)

Shapes are well described by a single empirical power-law for $p_T/M > 3$.
This p_T/M **scaling behaviour** …
… common to 5 *S-wave* & 2 *P-wave* states with different feed-down contaminations, suggests a simple composition of processes dominated by 1 single mechanism.

CS processes must be negligible!
A single CO term dominates production!
It could be $^1S_0^{[8]}$ **IF** the NRQCD fit would start @ 10-15*GeV* **[arXiv:1403.3970]**

Compilation by P.Faccioli *et al.*, arXiv:1403.3970 (2014)



solid: fit to CMS data; dashed: replicas with adjusted normalizations

(*) p_T is mass-rescaled to equalize the kinematics effects of different average parton momenta and phase spaces

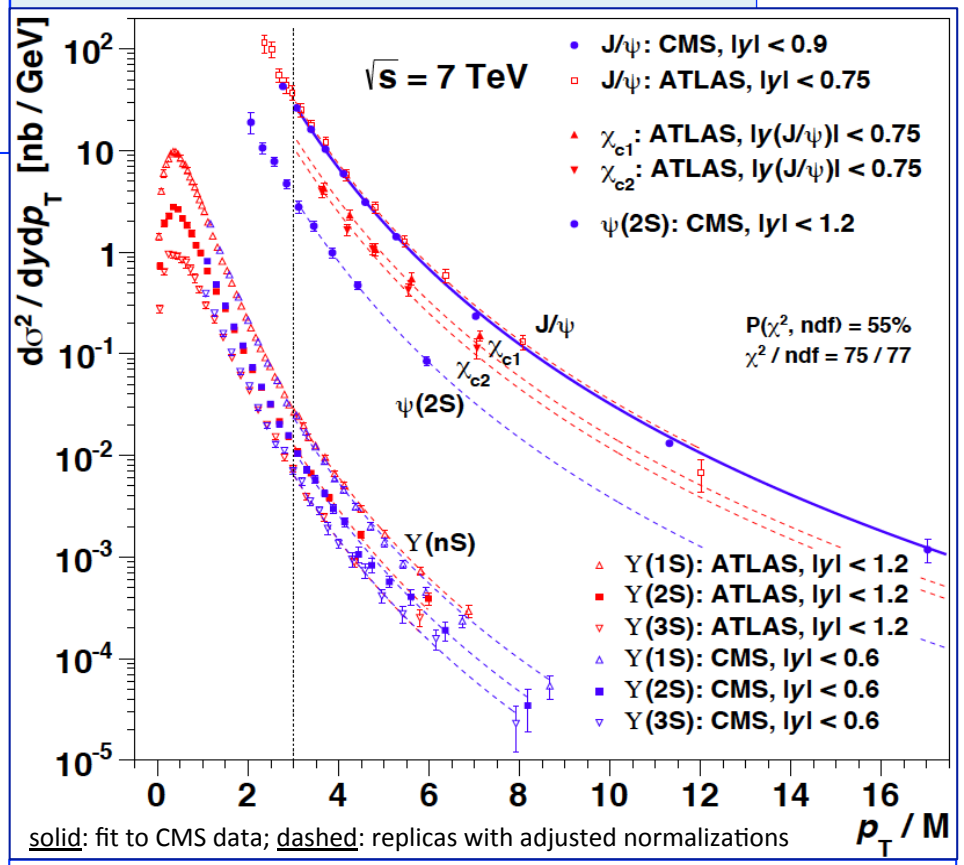
ATLAS, CONF-2013-095; arXiv:1404.7035 (submitted to JHEP)
ATLAS, NPB 850, 387 (2011)
ATLAS, PRD 87, 052004 (2013)
CMS, PLB 727, 101 (2013)
CMS, JHEP 02, 011 (2012)

few plots in backup slides

LHC data for quarkonium production

Mid-rapidity double differential cross sections for the production of 7 different quarkonia as a function of p_T/M (*)

Compilation by P.Faccioli *et al.*, arXiv:1403.3970 (2014)



solid: fit to CMS data; dashed: replicas with adjusted normalizations

(*) p_T is mass-rescaled to equalize the kinematics effects of different average parton momenta and phase spaces

Shapes are well described by a single empirical power-law for $p_T/M > 3$.
This p_T/M **scaling behaviour** ...
... common to 5 *S-wave* & 2 *P-wave* states with different feed-down contaminations, suggests a simple composition of processes dominated by 1 single mechanism.

CS processes must be negligible!
A single CO term dominates production!
It could be $^1S_0^{[8]}$ **IF** the NRQCD fit would start @ 10-15*GeV* **[arXiv:1403.3970]**

Scaling behaviour must be confirmed with:
- more accurate data up to higher p_T
- polarization data

ATLAS, CONF-2013-095; arXiv:1404.7035 (submitted to JHEP)
ATLAS, NPB 850, 387 (2011)
ATLAS, PRD 87, 052004 (2013)
CMS, PLB 727, 101 (2013)
CMS, JHEP 02, 011 (2012)

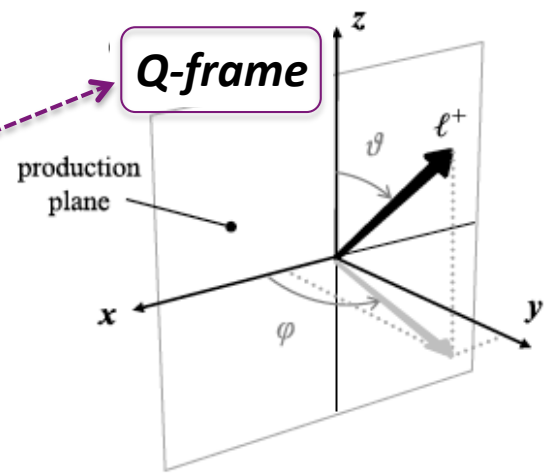
few plots in backup slides

Quarkonium Polarization

Polarization is sensitive to the hadroproduction mechanism and therefore important for the theoretical understanding

Polarization frames

- The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions, specified in terms of spherical angles θ & ϕ for $\vec{p}(\ell^+)$ in the **meson rest frame**



- To define these angles a *polarization frame* must be chosen:

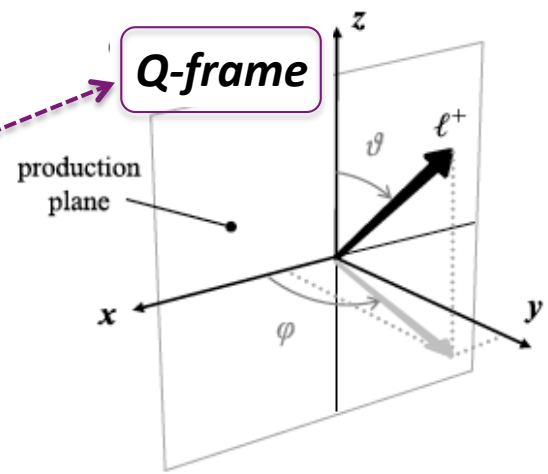
  θ : polar angle w.r.t. the spin-quantization axis (***z***)

  ϕ : azimuthal angle w.r.t. the ***x***-axis that lies, together with ***z***-axis, in the *collision plane* defined by the momenta of the colliding hadrons boosted in the *Q-frame*

- Not unique choice of polarization ***z***-axis

Polarization frames

- The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions, specified in terms of spherical angles θ & ϕ for $\vec{p}(\ell^+)$ in the **meson rest frame**



- To define these angles a *polarization frame* must be chosen:

  θ : polar angle w.r.t. the spin-quantization axis (***z***)

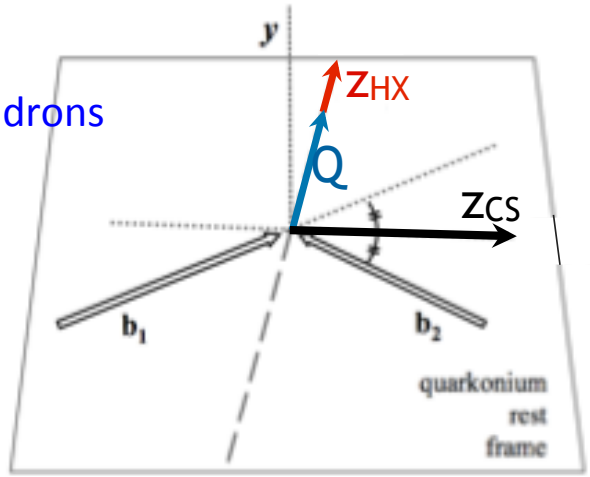
  ϕ : azimuthal angle w.r.t. the ***x***-axis that lies, together with ***z***-axis, in the *collision plane* defined by the momenta of the colliding hadrons boosted in the *Q-frame*

- Not unique choice of polarization ***z***-axis ⇨ 3 conventional reference frames:

  - ***center-of-mass helicity*** axis (**HX**): z_{HX}
    flight direction of the quarkonium in the c.m. frame of colliding hadrons

  - ***Collins-Soper*** axis (**CS**): z_{CS}
    direction of the vectorial difference between the velocity vectors of colliding hadrons in the *Q-frame*

  - ***perpendicular helicity*** axis (**PX**): z_{PX}
    direction of the vectorial sum of the velocity vectors of colliding hadrons in the *Q-frame*

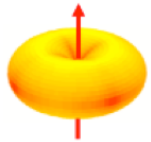


Angular decay distribution

- The most general 2D angular distribution ***W*** for the dileptons from the decay of vector mesons is specified by 3 polarization parameters $\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}$:

$$W \equiv \frac{d^2\mathrm{N}}{d(\cos\theta)d\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$

- Two extreme angular decay distributions:

Transverse Polarization	$J_z=\pm 1$	2 transverse states	$\lambda_\theta=+1$ $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$	⇨ $W \propto \frac{1}{4}\left(1+\cos^2\theta\right)$	
Longitudinal Polarization	$J_z=0$	1 longitudinal state	$\lambda_\theta=-1$ $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$	⇨ $W \propto \frac{1}{2}\left(1-\cos^2\theta\right)$	

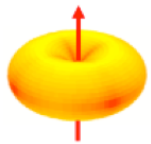
"Natural" polarization axis (for instance z_{HX}):
- azimuthal angle distribution is symmetric : $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$
- λ_θ is maximal

Angular decay distribution

- The most general 2D angular distribution ***W*** for the dileptons from the decay of vector mesons is specified by 3 polarization parameters $\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}$:

$$W \equiv \frac{d^2\mathrm{N}}{d(\cos\theta)d\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$

- Two extreme angular decay distributions:

Transverse Polarization	$J_z=\pm 1$	2 transverse states	$\lambda_\theta=+1$ $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$	⇨ $W \propto \frac{1}{4}\left(1+\cos^2\theta\right)$	
Longitudinal Polarization	$J_z=0$	1 longitudinal state	$\lambda_\theta=-1$ $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$	⇨ $W \propto \frac{1}{2}\left(1-\cos^2\theta\right)$	

"Natural" polarization axis (for instance z_{HX}):
- azimuthal angle distribution is symmetric : $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$
- λ_θ is maximal

- λ_θ measures the degree of polarization w.r.t. the spin-quantization axis; theoretically … $\lambda_\theta=\dfrac{\sigma_T-2\sigma_L}{\sigma_T+2\sigma_L}$ where σ_T/σ_L are the xsections for the 2 transverse states /1 longitudinal state).

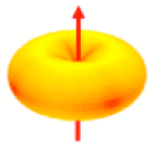
Each CS and CO term has a specific polarization :

Angular decay distribution

- The most general 2D angular distribution ***W*** for the dileptons from the decay of vector mesons is specified by 3 polarization parameters $\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}$:

$$W \equiv \frac{d^2\mathrm{N}}{d(\cos\theta)d\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$

- Two extreme angular decay distributions:

Transverse Polarization	$J_z=\pm 1$	2 transverse states	$\lambda_\theta=+1$ $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$	⇨ $W \propto \frac{1}{4}\left(1+\cos^2\theta\right)$	
Longitudinal Polarization	$J_z=0$	1 longitudinal state	$\lambda_\theta=-1$ $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$	⇨ $W \propto \frac{1}{2}\left(1-\cos^2\theta\right)$	

"Natural" polarization axis (for instance z_{HX}):
- azimuthal angle distribution is symmetric : $\lambda_\phi=0,\ \lambda_{\theta\phi}=0$
- λ_θ is maximal

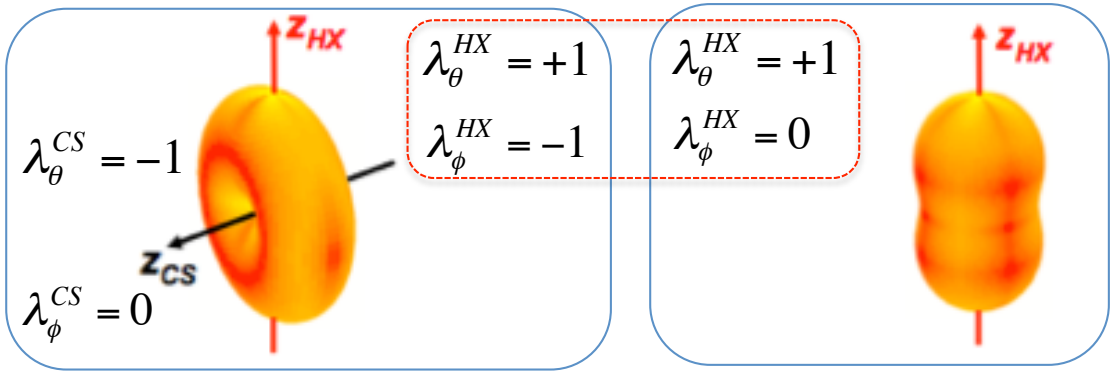
- λ_θ measures the degree of polarization w.r.t. the spin-quantization axis; theoretically … $\lambda_\theta=\dfrac{\sigma_T-2\sigma_L}{\sigma_T+2\sigma_L}$ where σ_T/σ_L are the xsections for the 2 transverse states /1 longitudinal state).

Each CS and CO term has a specific polarization :
- $CS\ \ {}^3S_1^{[1]}:\ \lambda_\theta=+1$ @ LO & $\lambda_\theta=-1$ @ NLO [longitudinal]
- $CO\ \ {}^1S_0^{[8]}:\ \lambda_\theta=0$ @ LO, NLO, etc. [isotropic]
- $CO\ \ {}^3S_1^{[8]}:\ \lambda_\theta=+1$ @ LO, NLO, etc. (@ high p_T) [transverse]
- $CO\ \ {}^3P_J^{[8]}:\ \lambda_\theta=0$ @ LO & $\lambda_\theta\geq+1$ @ NLO & high p_T ["hyper-transverse"]

Frame (in)dependence

- Different choices for the polarization frame can be obtained by a relative ***y***-rotation of the collision plane (in the *Q-frame*). The angular distribution has the same form but with different polarization parameters, i.e. the observed polarization depends on the frame ! **[Faccioli *et al.*, EPJ C 69, 657 (2010)]**

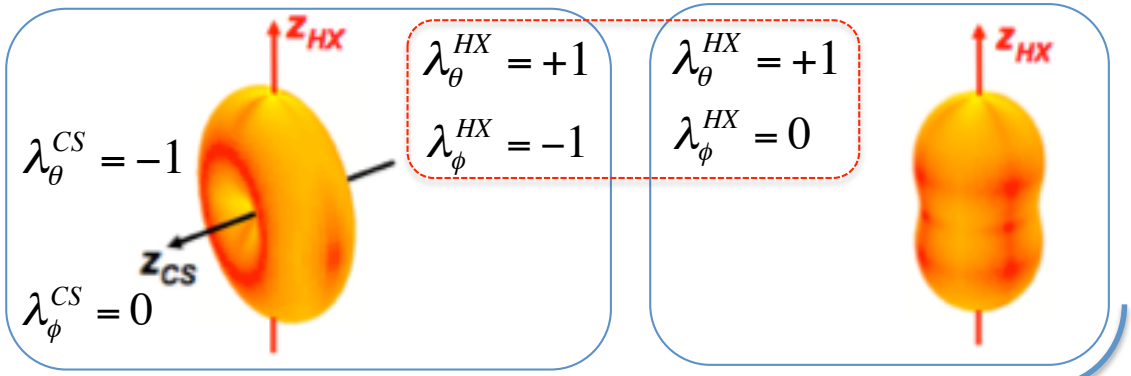
For instance, after a 90° rotation …
… 2 very different physical cases are indistinguishable if only λ_θ is measured (both have $\lambda_\theta = +1$) while λ_ϕ is integrated over!



Frame (in)dependence

- Different choices for the polarization frame can be obtained by a relative ***y***-rotation of the collision plane (in the *Q-frame*). The angular distribution has the same form but with different polarization parameters, i.e. the observed polarization depends on the frame ! [Faccioli *et al.*, EPJ C 69, 657 (2010)]

For instance, after a 90° rotation …
… 2 very different physical cases are indistinguishable if only λ_θ is measured (both have $\lambda_\theta = +1$) while λ_ϕ is integrated over!



Polarization can be fully determined when …
… both the polar and azimuthal components of angular distributions are known, or …
… a single polarization parameter is measured in at least 2 complementary polarization frames

On the other hand …

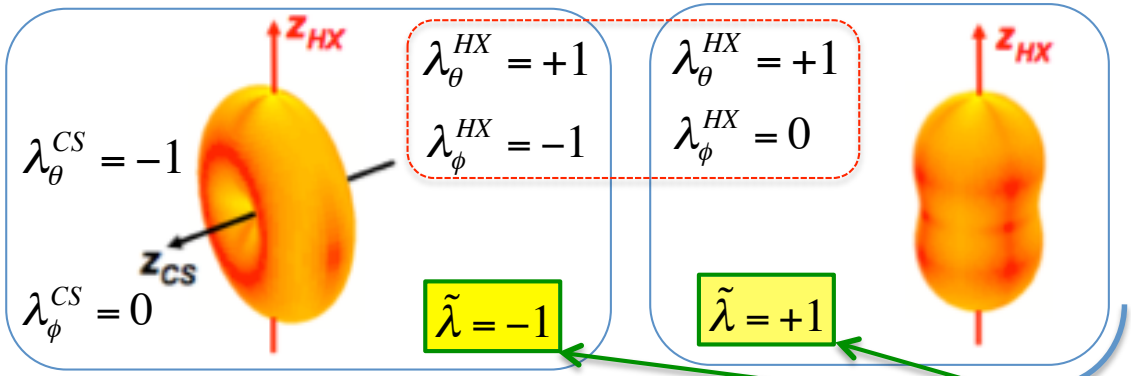
… being the shape of the angular distribution frame-independent, it can be characterized by a frame-invariant combination of the parameters such as…

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

Frame (in)dependence

- Different choices for the polarization frame can be obtained by a relative ***y***-rotation of the collision plane (in the *Q-frame*). The angular distribution has the same form but with different polarization parameters, i.e. the observed polarization depends on the frame ! [Faccioli *et al.*, EPJ C 69, 657 (2010)]

For instance, after a 90° rotation …
… 2 very different physical cases are indistinguishable if only λ_θ is measured (both have $\lambda_\theta = +1$) while λ_ϕ is integrated over!



Polarization can be fully determined when …
… both the polar and azimuthal components of angular distributions are known, or …
… a single polarization parameter is measured in at least 2 complementary polarization frames

On the other hand …

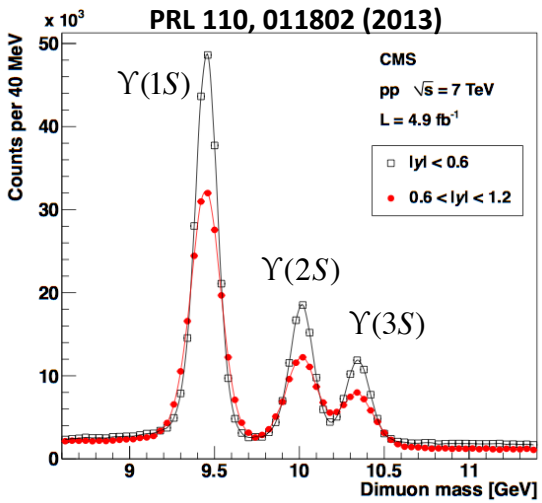
… being the shape of the angular distribution frame-independent, it can be characterized by a frame-invariant combination of the parameters such as…

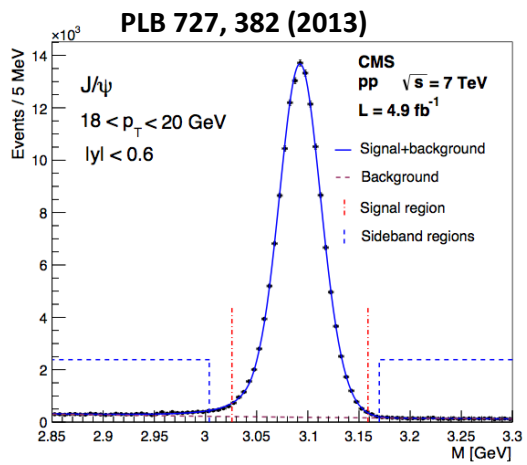
$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

Polarization measurements

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ and $\tilde{\lambda}$ are measured in 3 different frames (HX,CS,PX) for 5 *S-wave* states as a function of the transverse momentum p_T and rapidity y

- Only dimuon decays are considered :
  - they provide a particularly clean signature
  - they are easier to be reconstructed and triggered on



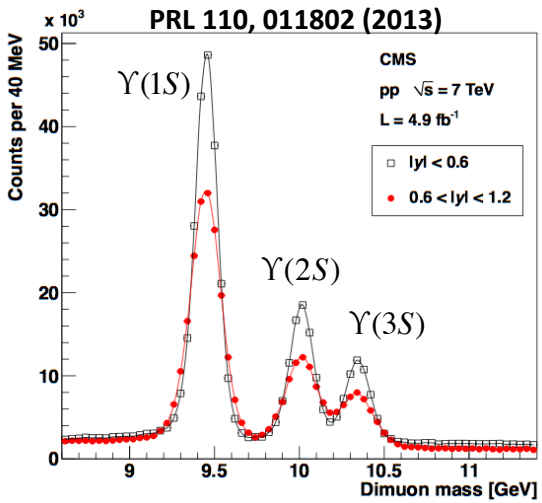


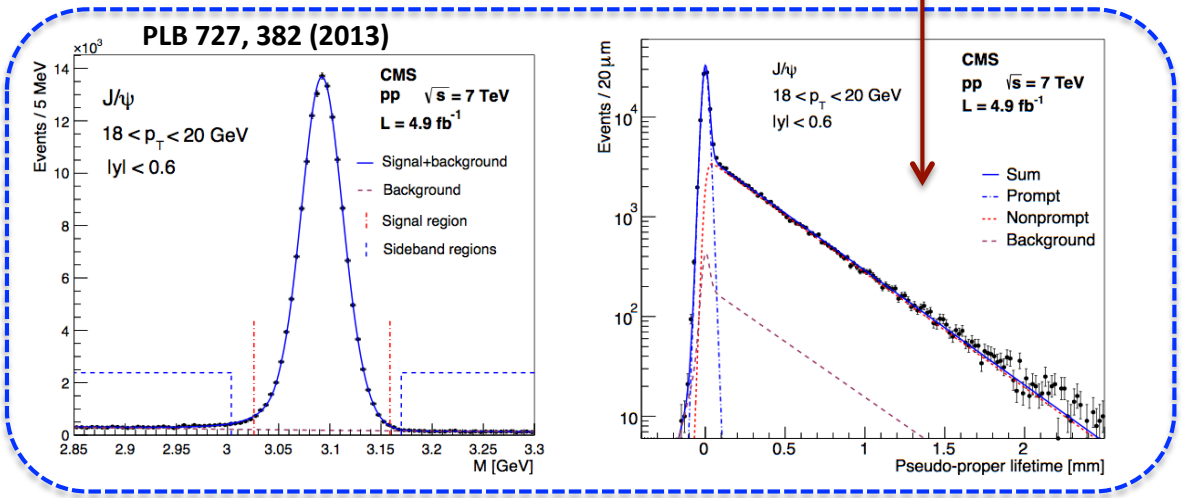
Polarization measurements

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ and $\tilde{\lambda}$ are measured in 3 different frames (HX,CS,PX) for 5 *S-wave* states as a function of the transverse momentum p_T and rapidity y

- Only dimuon decays are considered :
  - they provide a particularly clean signature
  - they are easier to be reconstructed and triggered on

An additional non prompt component (decays of *B hadrons* into J/ψ, $\psi(2S)$) is taken into account



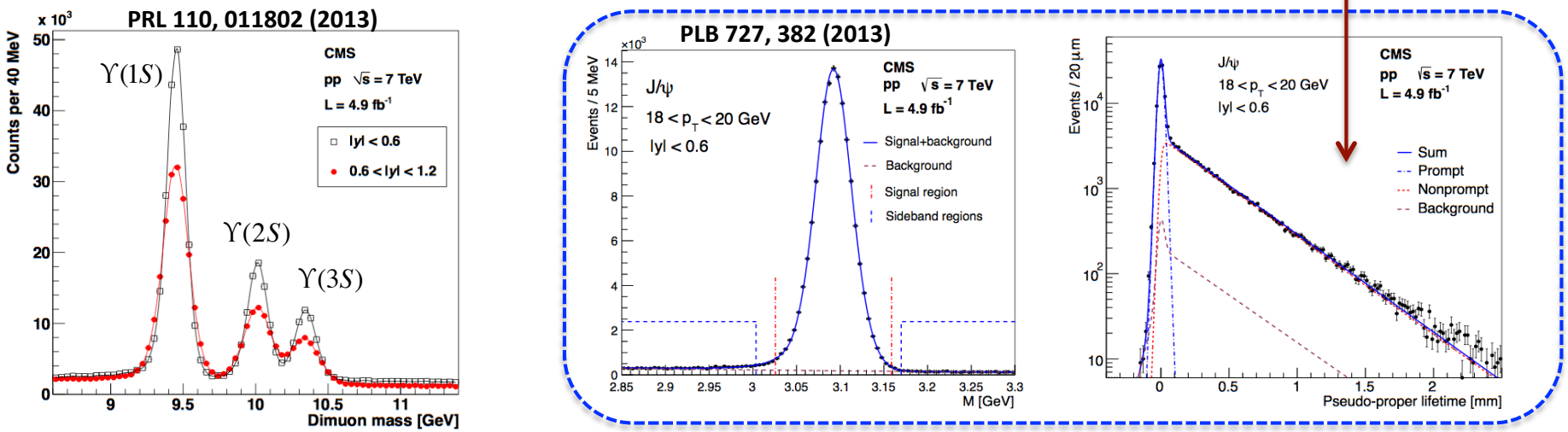


Polarization measurements

- $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ and $\tilde{\lambda}$ are measured in 3 different frames (HX,CS,PX) for 5 *S-wave* states as a function of the transverse momentum p_T and rapidity y

- Only dimuon decays are considered :
  - they provide a particularly clean signature
  - they are easier to be reconstructed and triggered on

An additional non prompt component (decays of *B hadrons* into J/ψ, $\psi(2S)$) is taken into account

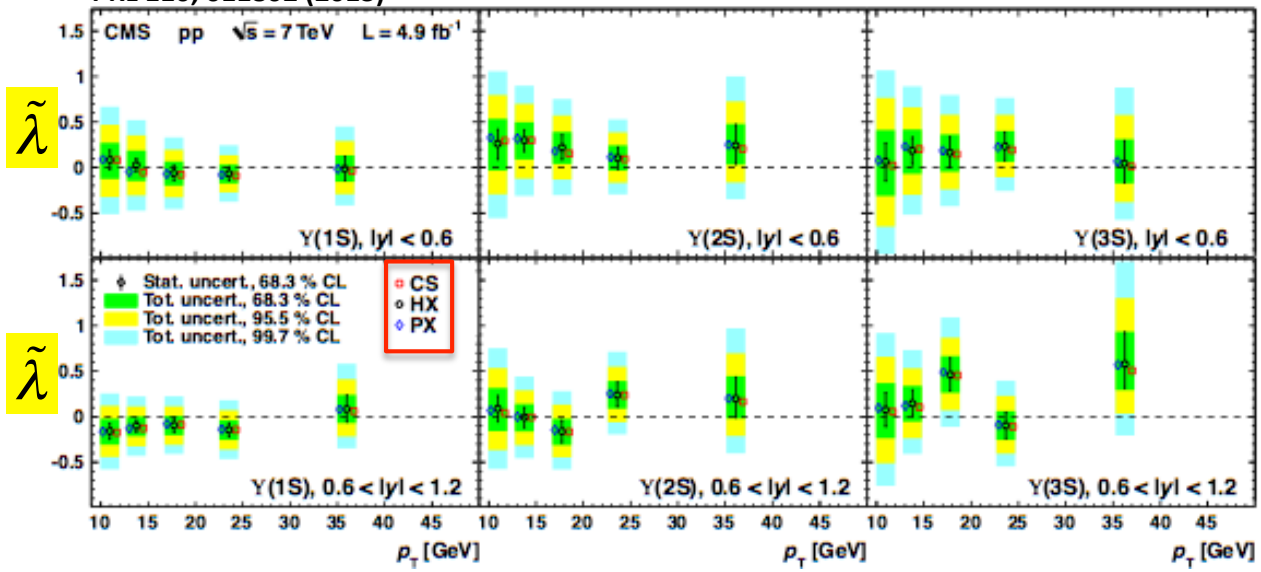


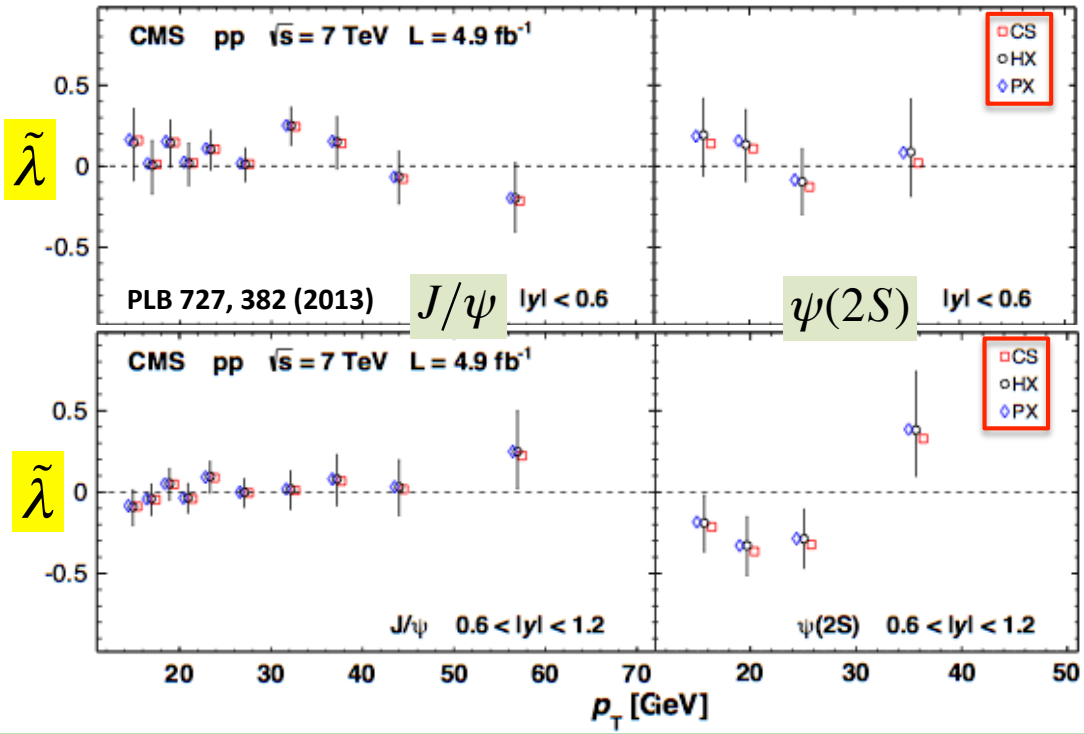
- Photons & pions from the feed-down transitions have low energy : difficult to be reconstructed and associated with the dimuon pair in order to separate feed-down and direct production

- Precise knowledge of efficiencies are needed to avoid introducing artifical polarization: they are data-driven and accounted on an event-by-event basis

$\tilde{\lambda}$ CMS measurement for *S-wave* states

PRL 110, 011802 (2013)



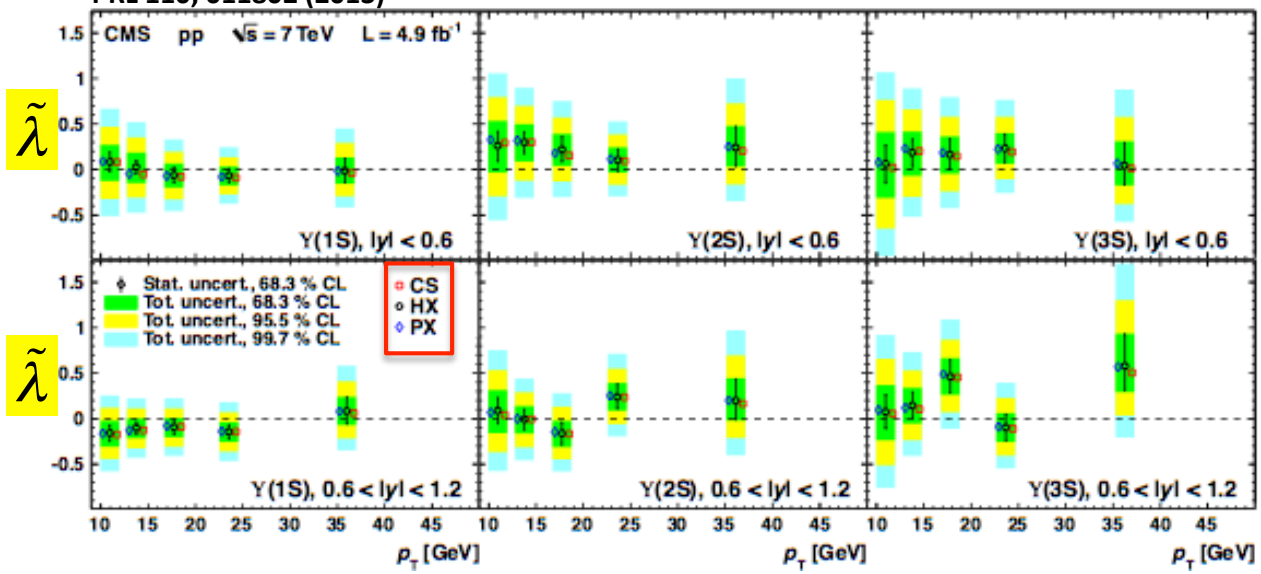


Total uncertainties are dominated by :

- systematics at low p_T
  (bkg model, μ efficiencies)
- low statistics at high p_T

$\tilde{\lambda}$ CMS measurement for *S-wave* states

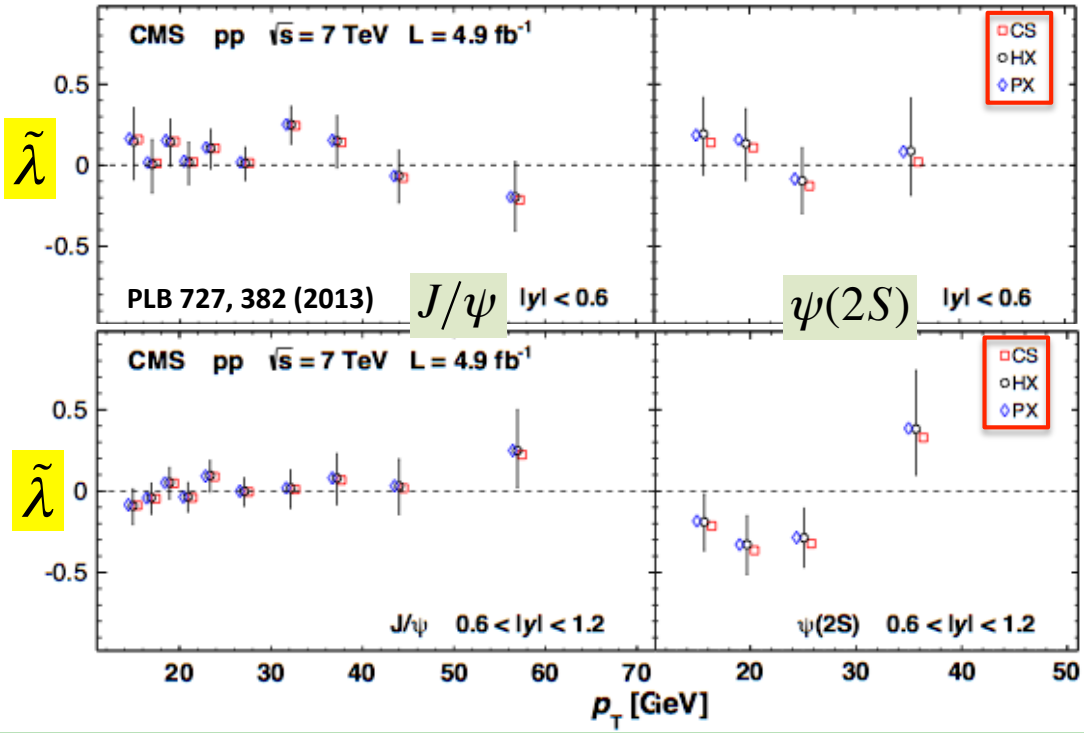
PRL 110, 011802 (2013)



Total uncertainties are dominated by :

- systematics at low p_T
  (bkg model, μ efficiencies)
- low statistics at high p_T

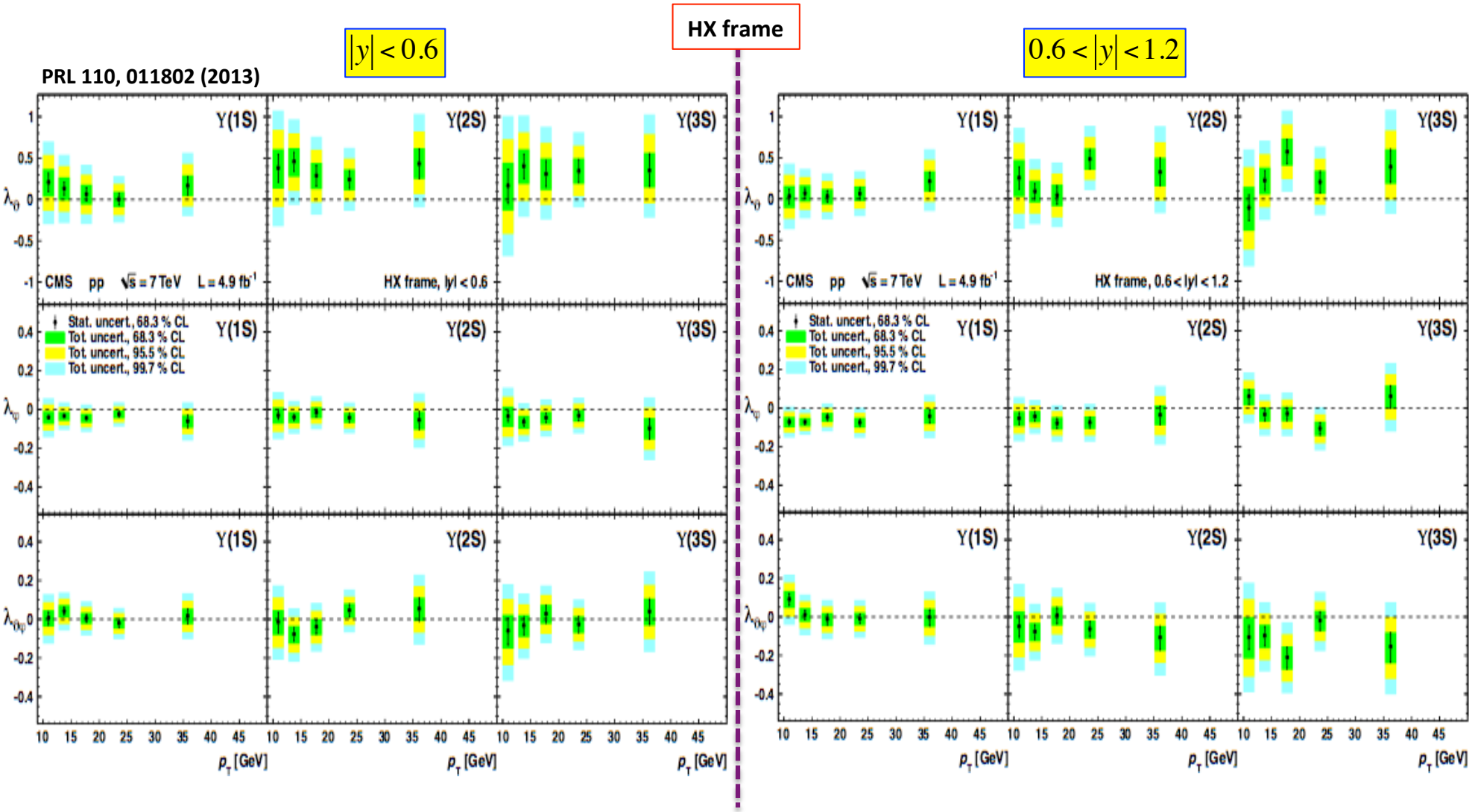
Good agreement among $\tilde{\lambda}$ values in the 3 ref. frames shows that the results are consistent (no hint for biases) !



No evidence of strong longitudinal or transverse polarizations has been observed for all the 5 S-wave states !

$\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$: CMS measurement for $\Upsilon(nS)$ states

PRL 110, 011802 (2013)

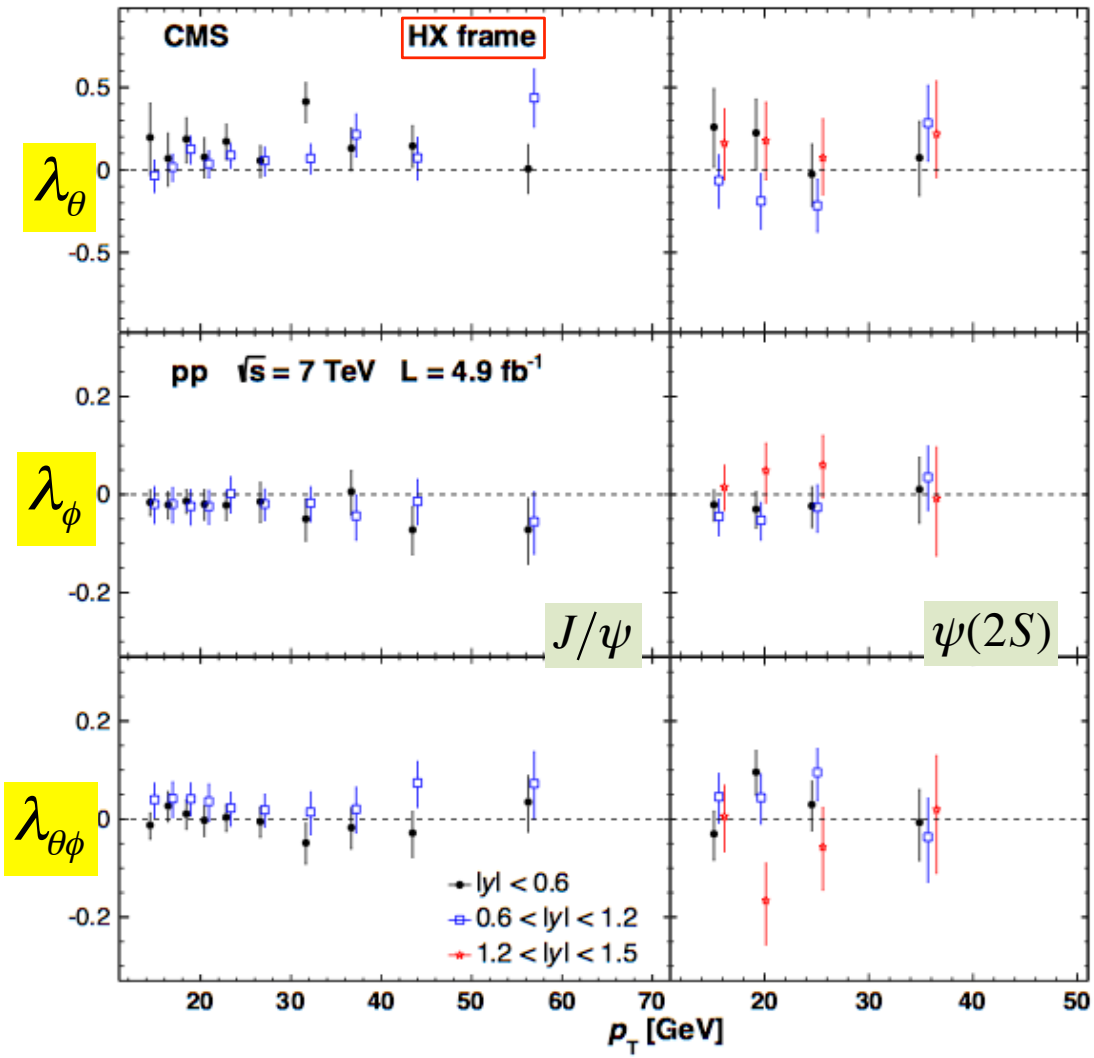


Plots of these 3 parameters in the other two polarization frames (CS,PX) can be found in backup slides

$\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$: CMS measurement for prompt $\psi(nS)$ states

PLB 727, 382 (2013)

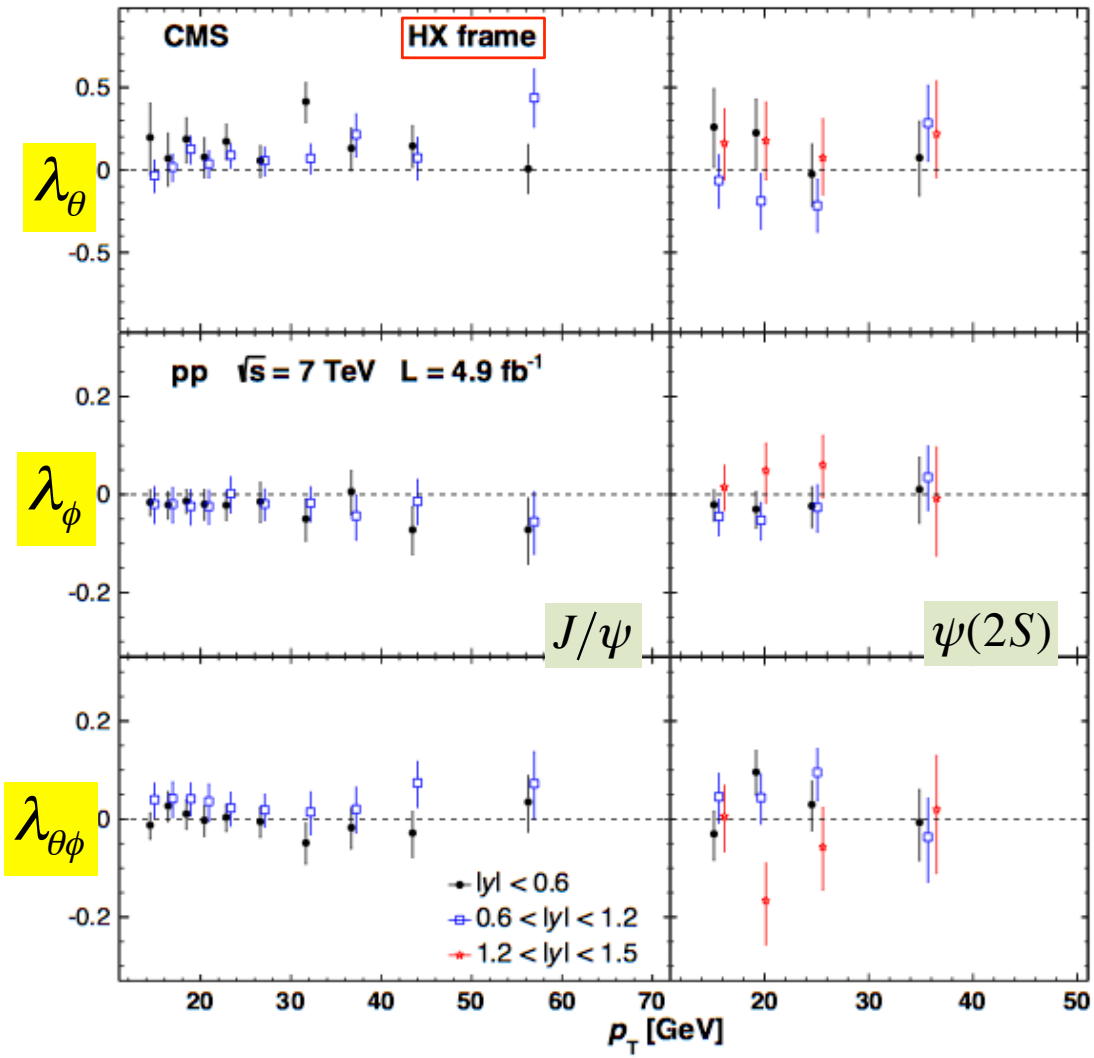
Error bars show total uncertainties @ 68.3% CL



$\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$: CMS measurement for prompt $\psi(nS)$ states

PLB 727, 382 (2013)

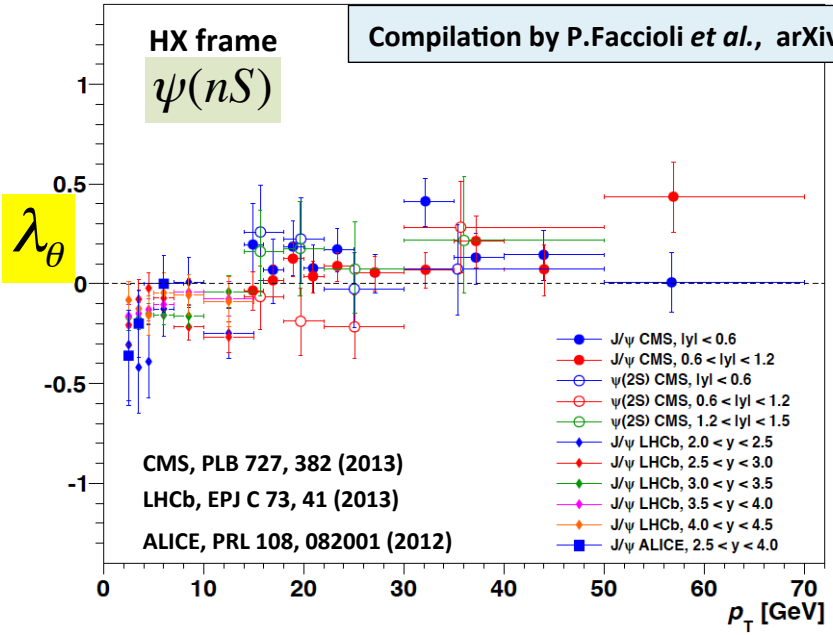
Error bars show total uncertainties @ 68.3% CL

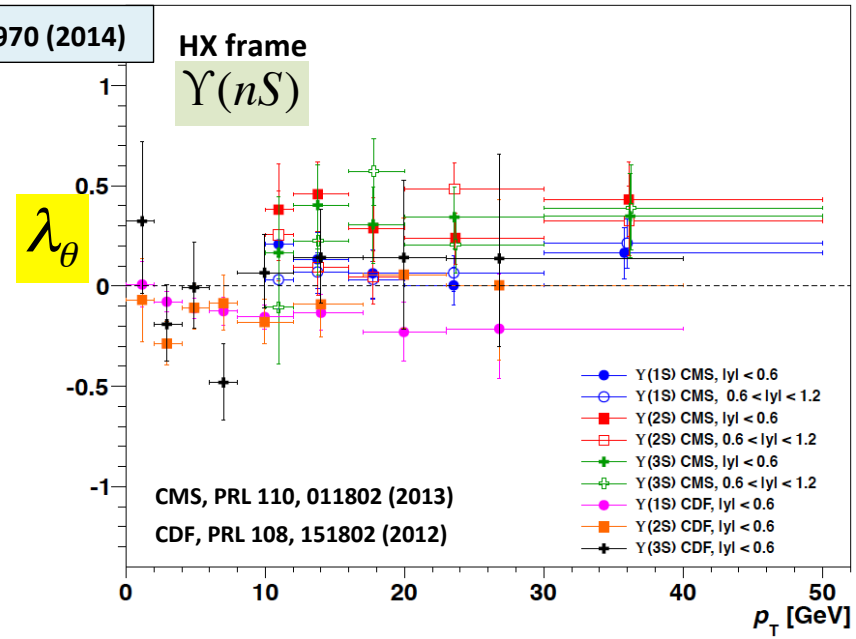


The 3 polarization parameters are measured to be small in the HX frame under study (and in the other two[*]), excluding transverse or longitudinal polarizations, also for the states that are less affected by feed-down contributions with unknown polarizations ($\psi(2S)$ here and $\Upsilon(3S)$ in previous slide)

[*] Results for the other two polarization frames (CS,PX) can be found in backup slides

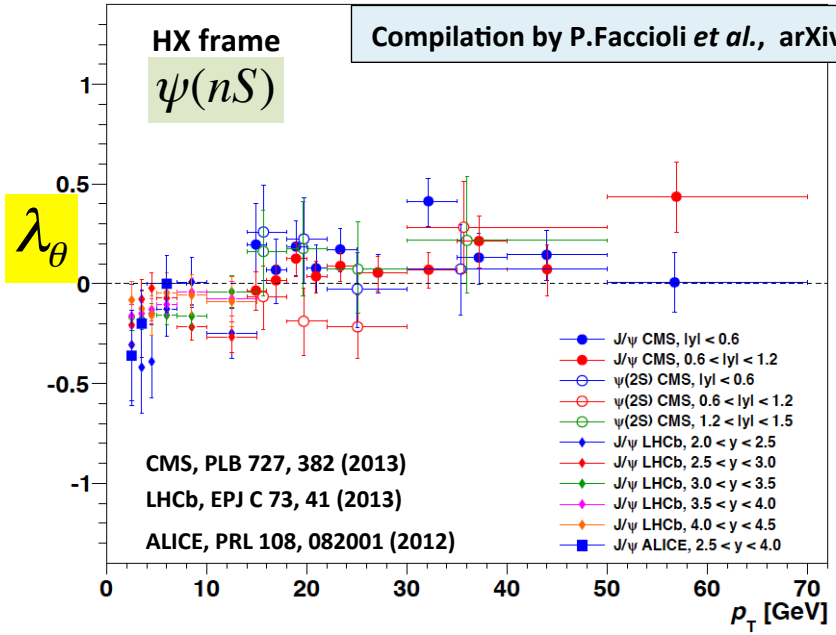
Comparison with other LHC experiments

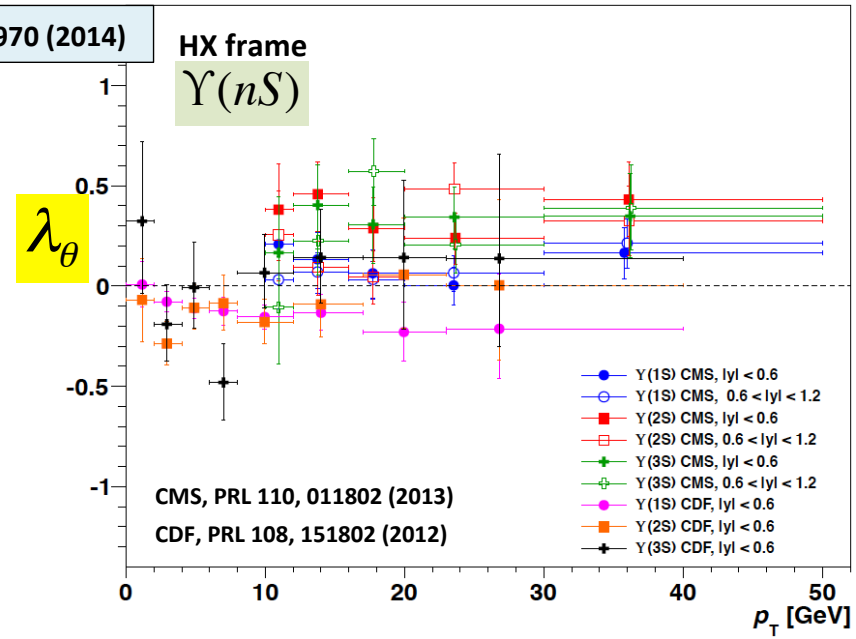




- All LHC results compatible with each other
- The polarizations cluster around the unpolarized limit ($\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0$) with …
  - no significance dependencies on p_T or y
  - no strong changes from full directly-produced states to those affected by *P-wave* feed-down decays
  - no evident differences between $c\bar{c}$ and $b\bar{b}$

Comparison with other LHC experiments

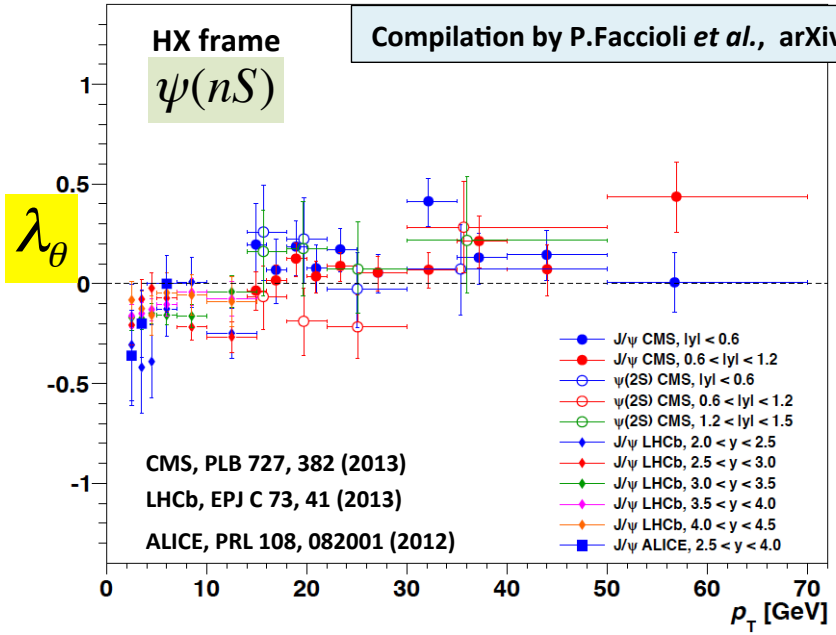


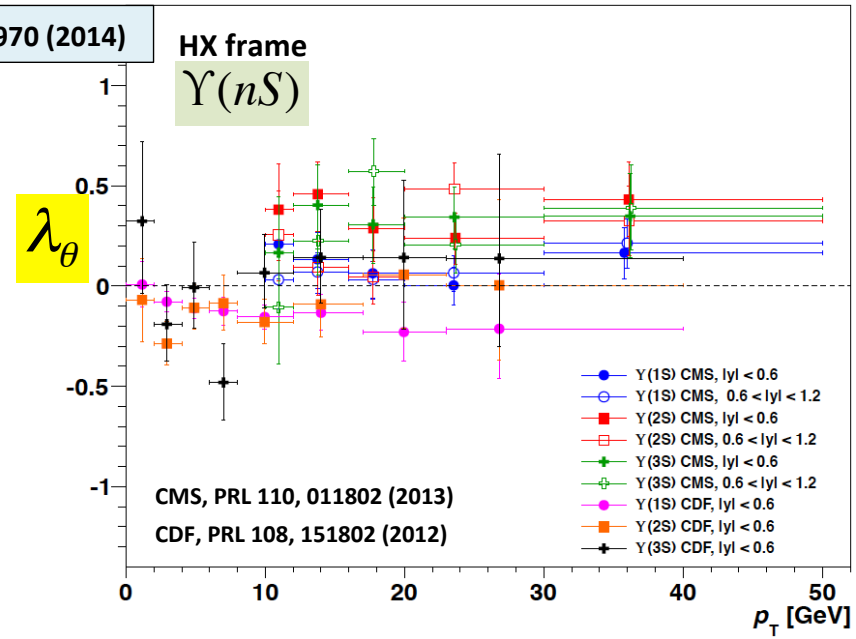


- All LHC results compatible with each other
- The polarizations cluster around the unpolarized limit ($\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0$) with …
  - no significance dependencies on p_T or y
  - no strong changes from full directly-produced states to those affected by *P-wave* feed-down decays
  - no evident differences between $c\bar{c}$ and $b\bar{b}$

suggest that …
- all quarkonia are dominantly produced by a single mechanism
- given the unpolarized result, the dominant contribution must be CO $^1S_0^{[8]}$

Comparison with other LHC experiments





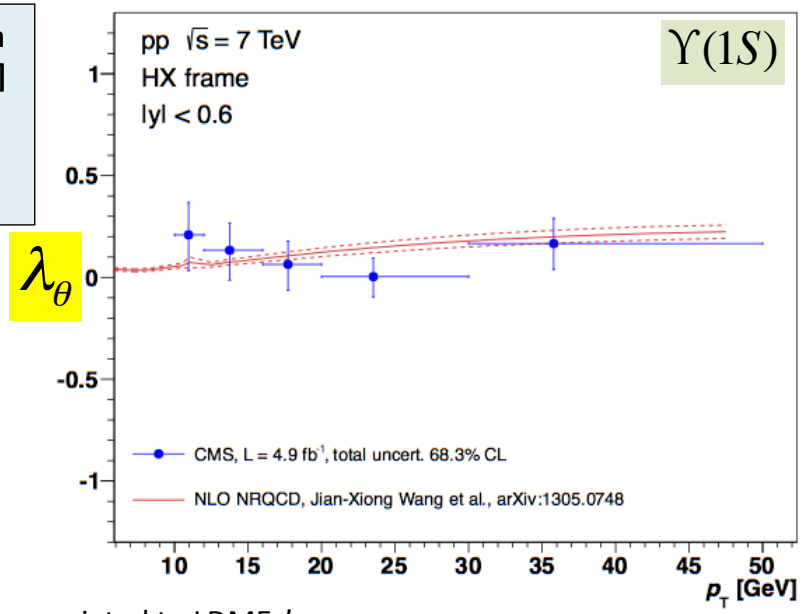
- All LHC results compatible with each other
- The polarizations cluster around the unpolarized limit ($\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0$) with …
  - no significance dependencies on p_T or y
  - no strong changes from full directly-produced states to those affected by *P-wave* feed-down decays
  - no evident differences between $c\bar{c}$ and $b\bar{b}$

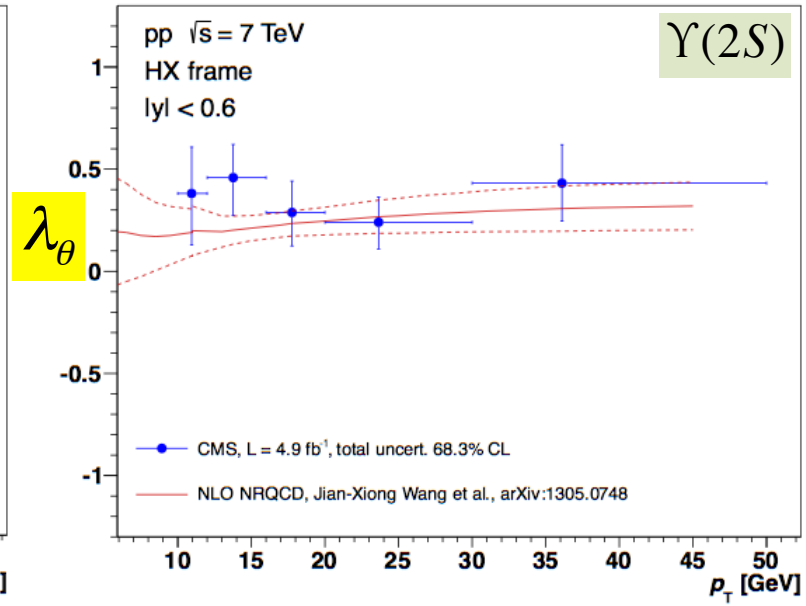
suggest that … all quarkonia are dominantly produced by a single mechanism
given the unpolarized result, the dominant contribution must be CO $^1S_0^{[8]}$

However… this is not the dominant term in the fit to the xsections …
… **unless** only the high-p_T behaviour is considered (NRQCD validity domain?)

Comparison with NLO NRQCD for $\Upsilon(nS)$ states

Comparison of CMS data [PRL 110, 011802 (2013)] with B.Gong *et al.*, PRL 112, 032001 (2014) [arXiv:1305.0748]



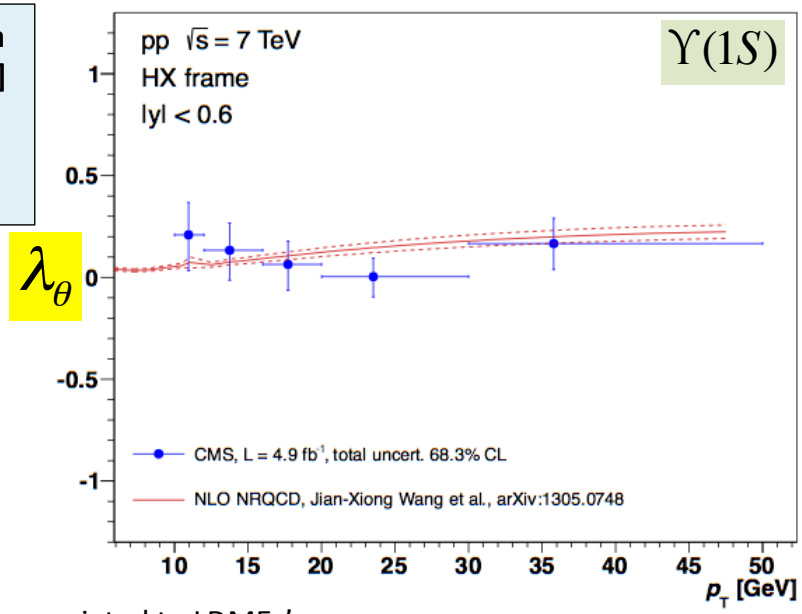


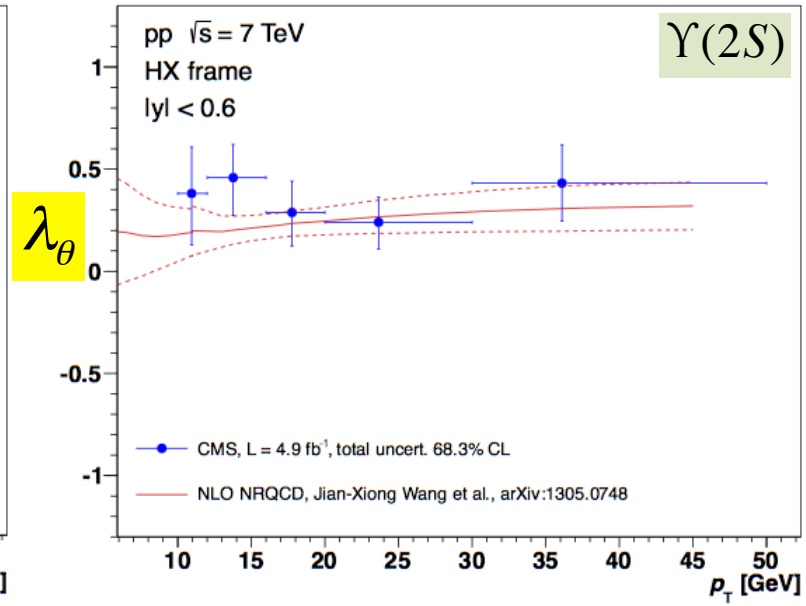
uncertainty bands associated to LDMEs' errors

CO LDMEs are fit to hadro-production data (CMS included) combining direct production and feed-down contributions to $\Upsilon(1S)$, $\Upsilon(2S)$. Extra adjustable fit parameters (LDMEs of $\chi_{bJ}(nP)$ states) help compatibility with data!

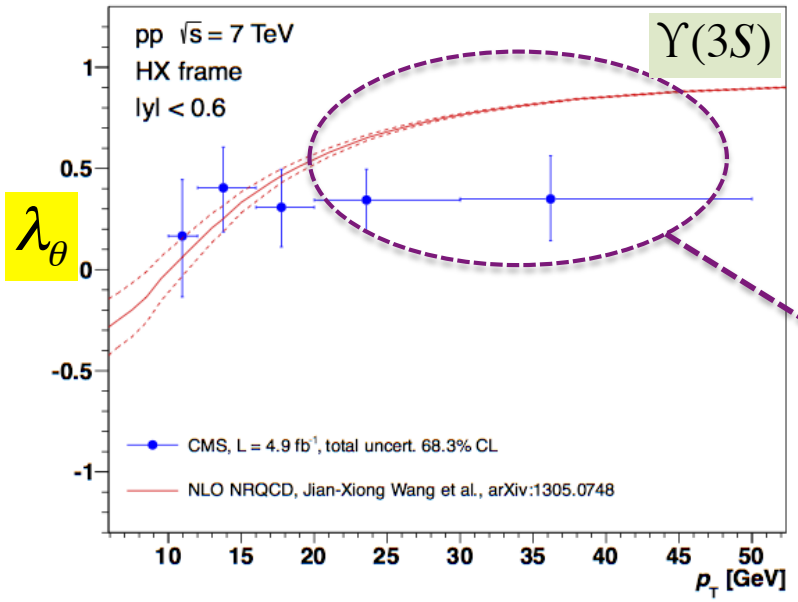
Comparison with NLO NRQCD for $\Upsilon(nS)$ states

Comparison of CMS data [PRL 110, 011802 (2013)] with B.Gong *et al.*, PRL 112, 032001 (2014) [arXiv:1305.0748]





uncertainty bands associated to LDMEs' errors

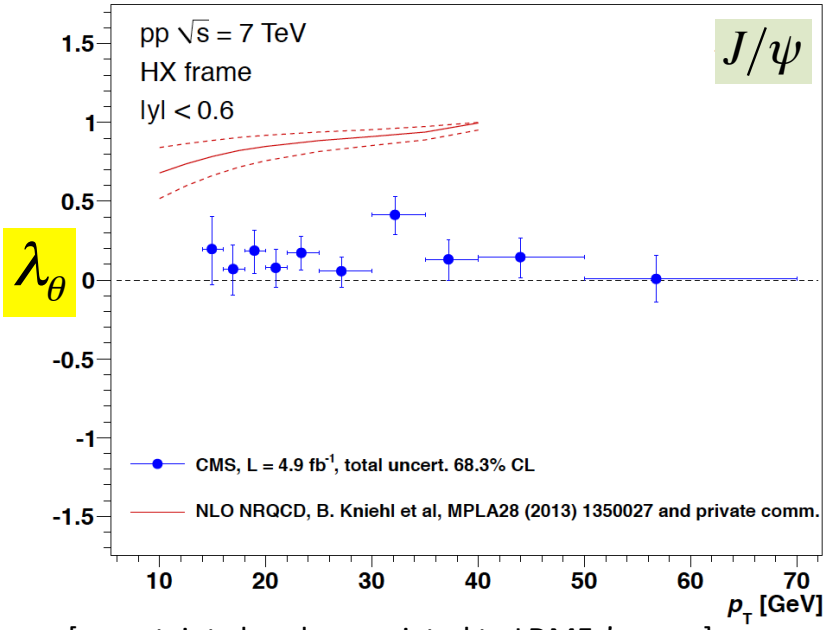


CO LDMEs are fit to hadro-production data (CMS included) combining direct production and feed-down contributions to $\Upsilon(1S)$, $\Upsilon(2S)$. Extra adjustable fit parameters (LDMEs of $\chi_{bJ}(nP)$ states) help compatibility with data!

Assuming that the unknown $\chi_{bJ}(3P)$ feed-down is negligible … the polarization of $\Upsilon(3S)$ can't be explained.

Direct production measurements are needed!

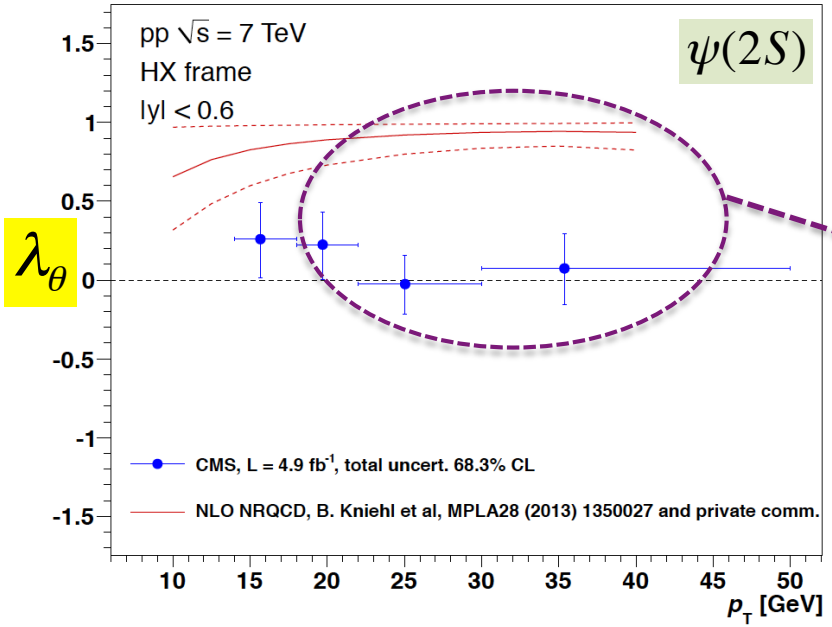
Comparison with NLO NRQCD for $\psi(nS)$ states



[uncertainty bands associated to LDMEs' errors]

Comparison of CMS data [PLB 727, 382 (2013)] with M.Butenschoen & B. Kniehl, PRL 108, 172002 (2012) + Priv. Comm. [later in MPLA28, 1350027 (2013)]

Calculations use global fit of CO LDMEs to photo- as well as hadro-production data (excluding polarization results); predictions only consider direct production



NLO NRQCD predictions fail to describe data for $\psi(2S)$ that shouldn't suffer from feed-down contributions !

Summary : puzzles & outlooks - I

- Strong theoretical preference for NRQCD at NLO !
  However… is this the correct theory (@what order in α_S, v)?
  Or … what is its validity domain?

- Xsections measurements @ Tevatron & LHC are dominated by color-octet production.
  The $Q\bar{Q}$ bound states are preferably formed by two heavy quarks of …
  - different colors (rather than in an already color neutral configuration)
  - smaller relative angular momentum and spin

- Measurements @ Tevatron & LHC show that no relevant longitudinal or transverse polarizations are found for S-wave states. Puzzle: disagree with NRQCD predictions.

- Discrepancy between theory and experiment w.r.t. polarization deserves further investigation both theoretically and experimentally.

  Theory-data comparison can be reconsidered including polarization data in global NRQCD analyses of production.

Summary : puzzles & outlooks - II

- It's essential to measure production xsections and polarization to the highest attainable p_T, thus testing the validity domain of NRQCD.
  Higher energy & luminosity increase [LHC Run2 (2015-16)/ 13*TeV* / 100fb^{-1}] will allow to extend the p_T -reach of quarkonium studies with very small uncertainties.

  CMS has not yet fully exploited the potential of the 2011 & 2012 datasets!
  Indeed there are new results with Run1 data foreseen within this year.

- It would be very useful for future measurements to separate the feed-down contributions from direct production contributions.

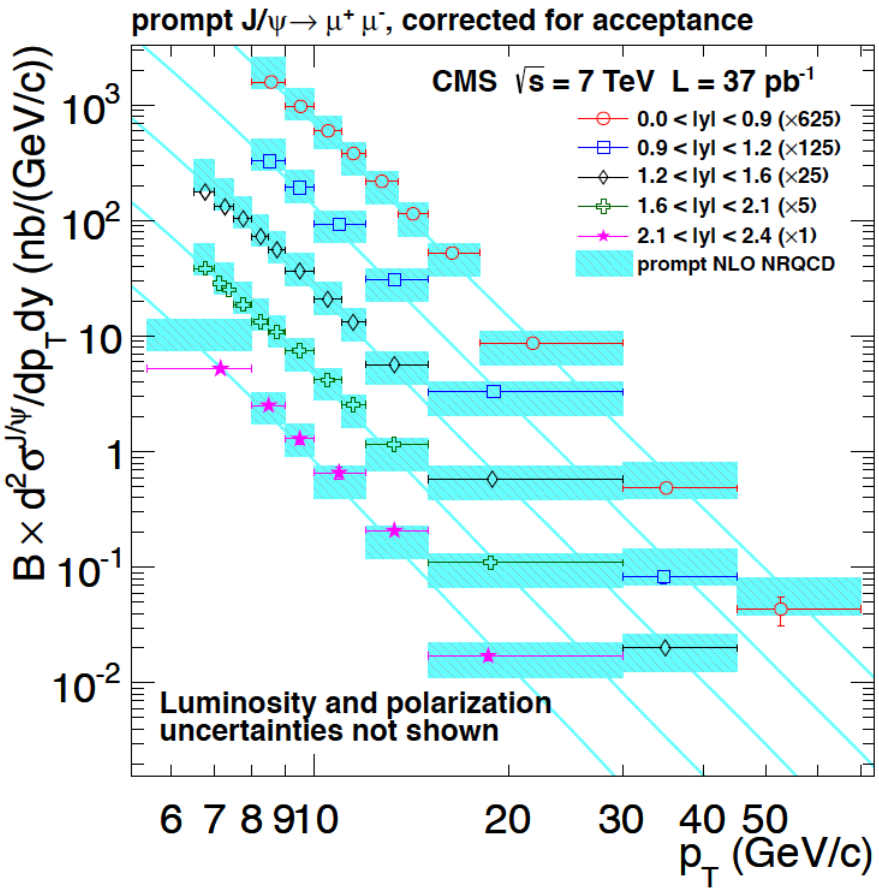
- Challenging measurements of production & polarization for the χ_{cJ} and χ_{bJ} *P-wave* states would provide valuable additional tests.

Backup slides/Additional material

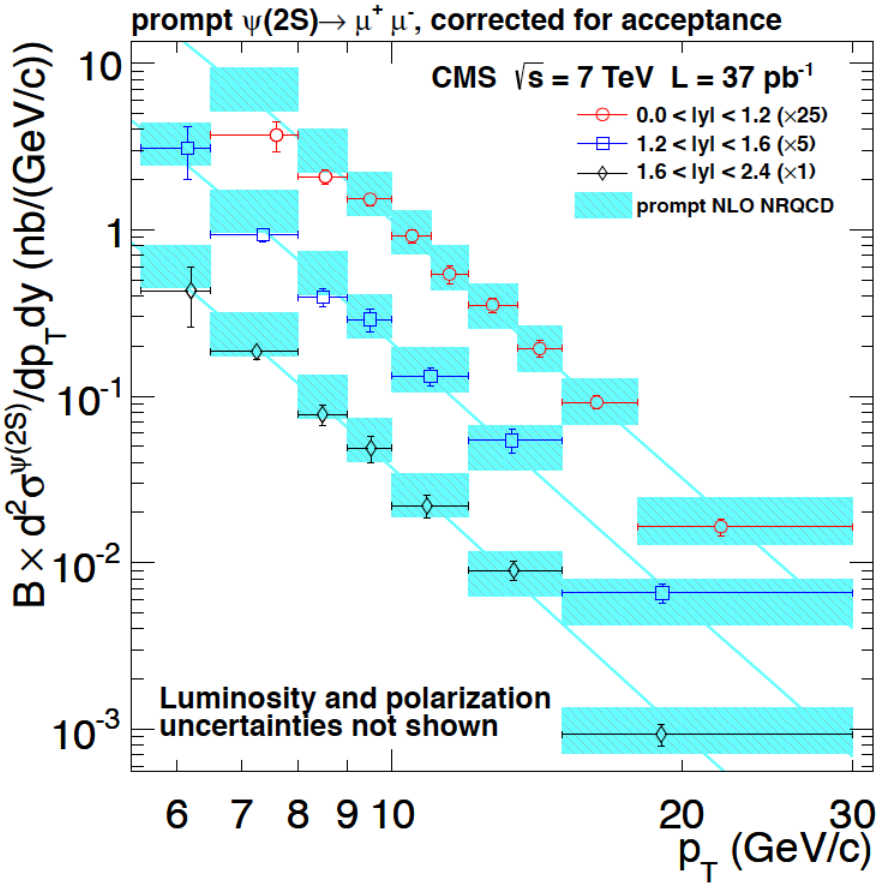
CMS diff. xsections measurement for prompt $\psi(nS)$

CMS, JHEP 02, 011 (2012)

$\psi(1S)$



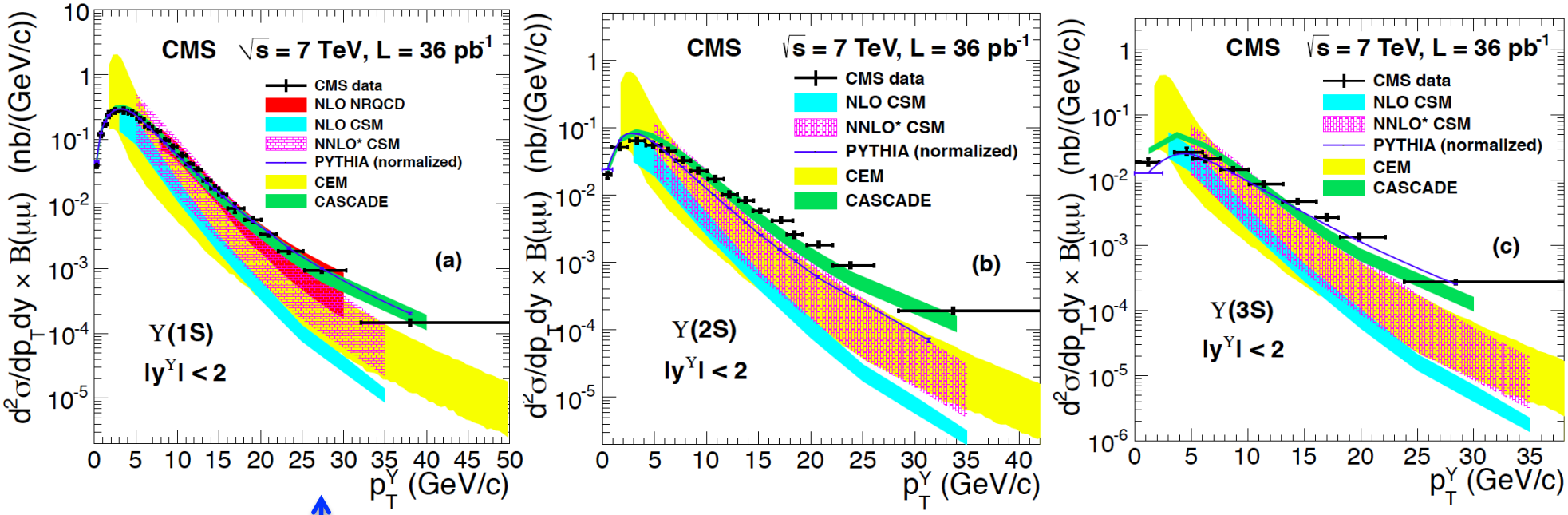
$\psi(2S)$



Reported values offset for better viewing. NRQCD predictions by Y.Q.Ma *et al.*, PRL 106, 042002 (2011)

CMS differential xsections measurement for $\Upsilon(nS)$

CMS, PLB 727, 101 (2013)

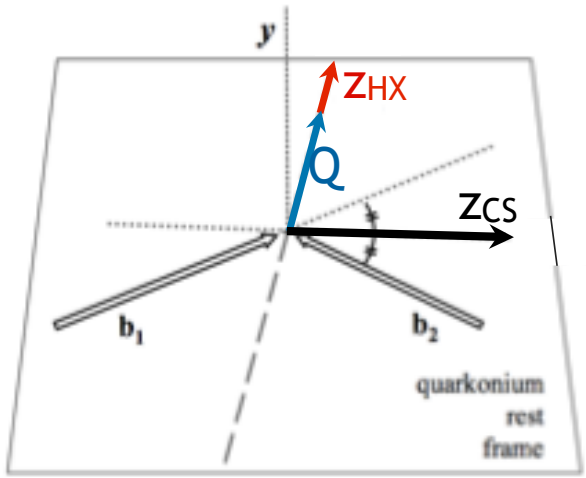


NLO NRQCD predictions by K.Wang *et al.*, PRD 85, 114003 (2012) + Priv. Comm.

Polarization frames details

Three of the different conventional reference frames are:

- ***center-of-mass helicity*** axis (**HX**): z_{HX}
  flight direction of the quarkonium in the center-of-mass frame of the colliding hadrons
  (= direction of the boost vector required to go from the *Q-frame* to the center-of-momentum frame of the colliding hadrons)



- ***Collins-Soper*** axis (**CS**): z_{CS}
  bisector of the angle between colliding beams (as in figure);
  (≈ direction of the vectorial difference between the velocity vectors of colliding hadrons in the *Q-frame*)

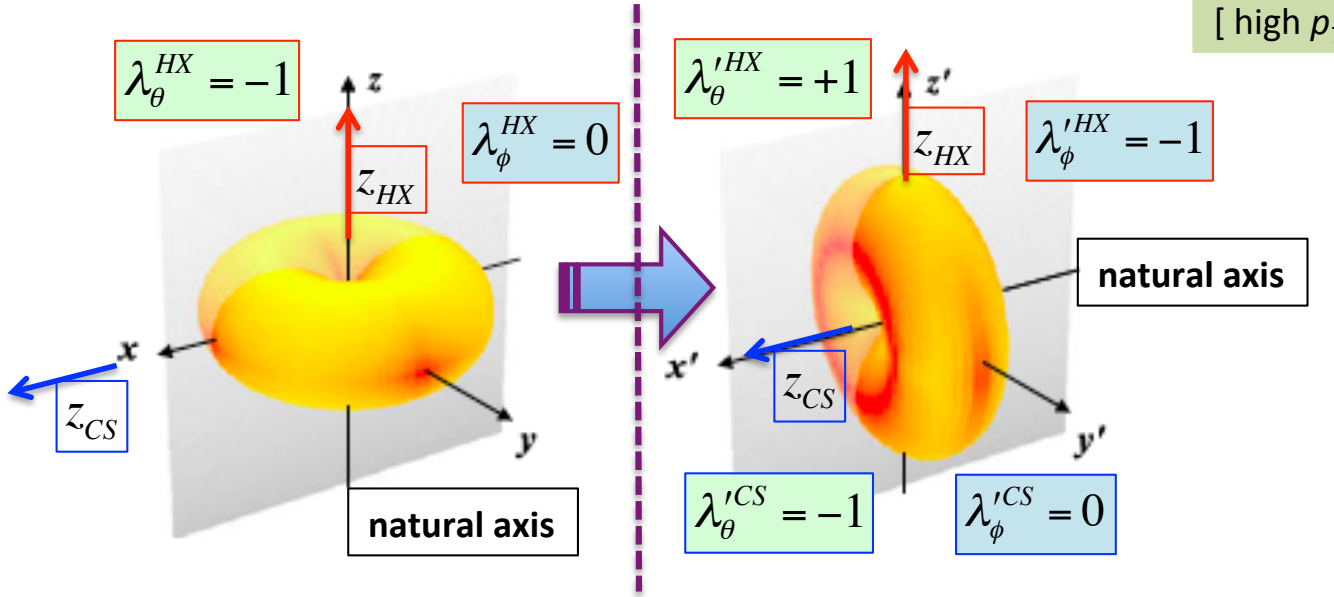
- ***perpendicular helicity*** axis (**PX**): z_{PX}
  direction of the vectorial sum of the velocity vectors of colliding hadrons
  (= direction of the boost required to go from the Q-frame to the frame in which the quarkonium momentum is perpendicular to the axis of the colliding beams)

Frame dependence

A different choice for the polarization frame can be obtained by a rotation (about the y-axis) of the collision plane (in the *Q-frame*) [or, alternatively, a relative polarization frame rotation]

Example (*) : consider a 90° rotation: it is of physical relevance since $z_{HX} \perp z_{CS}$ when $|p_L| << p_T$

[high p_T & mid *rapidity*]



A fully longitudinal natural polarization [$\lambda_\theta = -1$] translates, in a rotated polarization frame, into a fully transverse polarization [$\lambda'_\theta = +1$] with a maximal azimuthal anisotropy [$\lambda'_\phi = -1$].

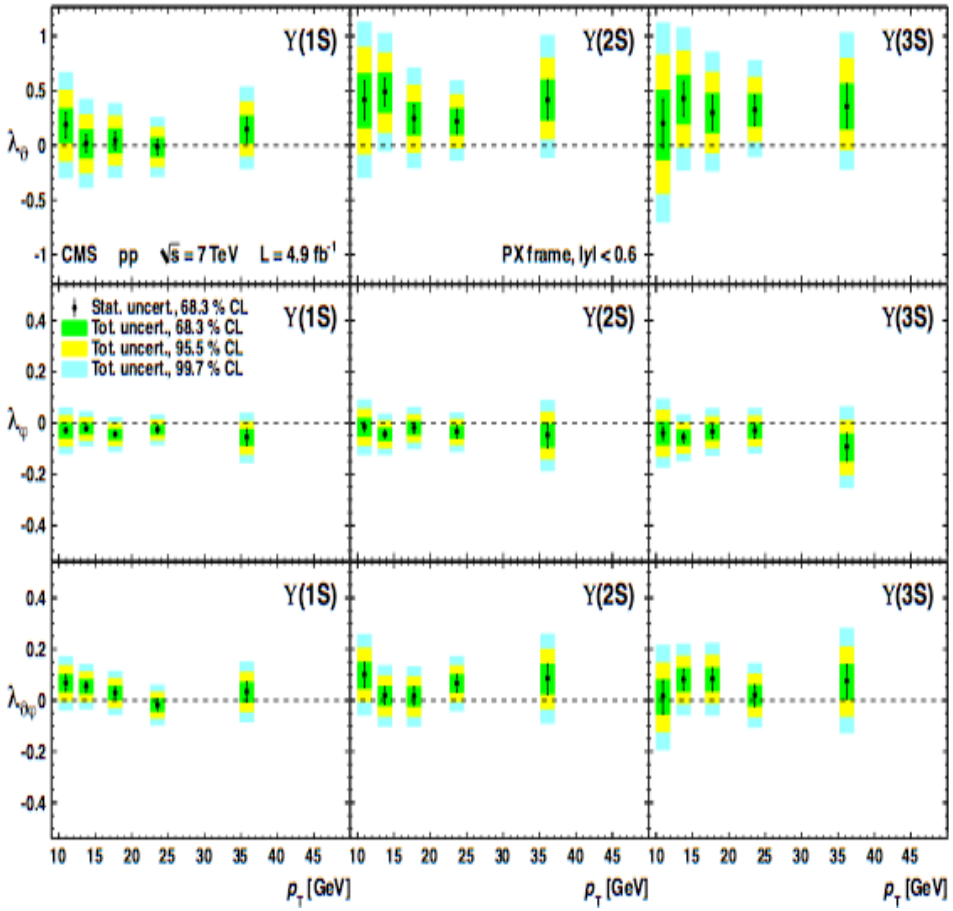
The angular distribution has the same form but with different polarization parameters, namely the observed polarization depends on the frame !

(*) Faccioli *et al.*, EPJ C (2010) 69

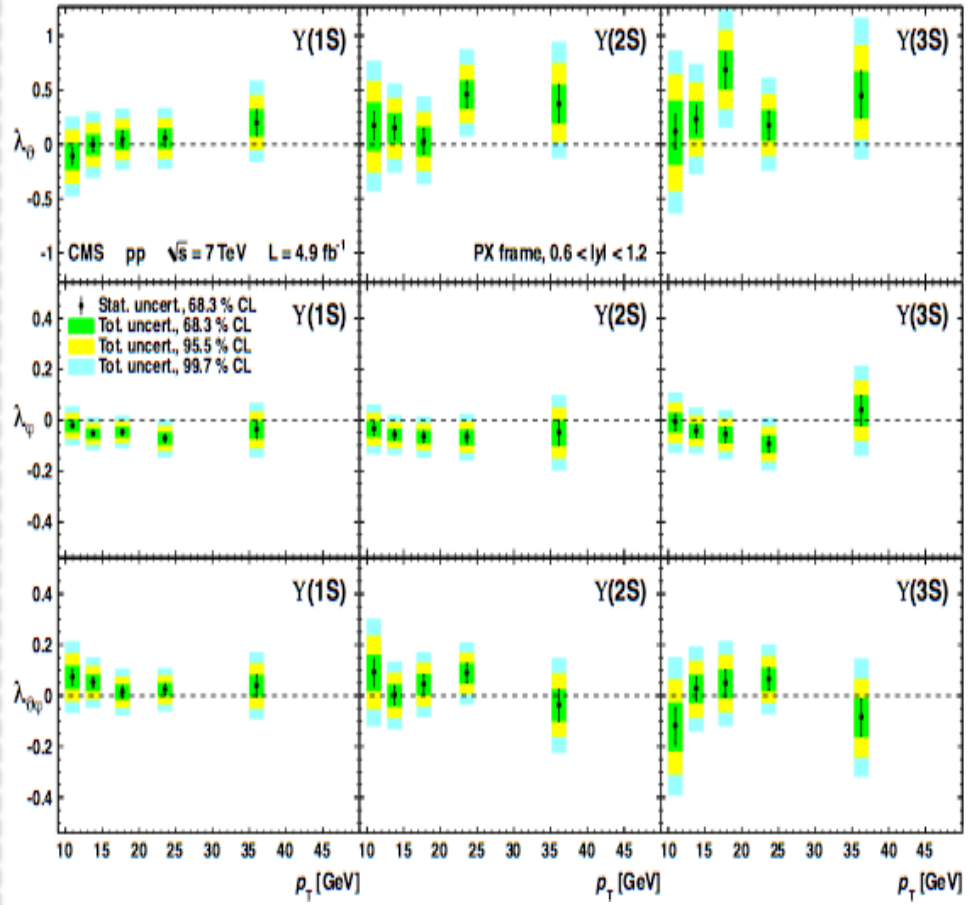
$\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ CMS measurement for $\Upsilon(nS)$ states in the PX frame

PRL 110, 011802 (2013)

$|y| < 0.6$



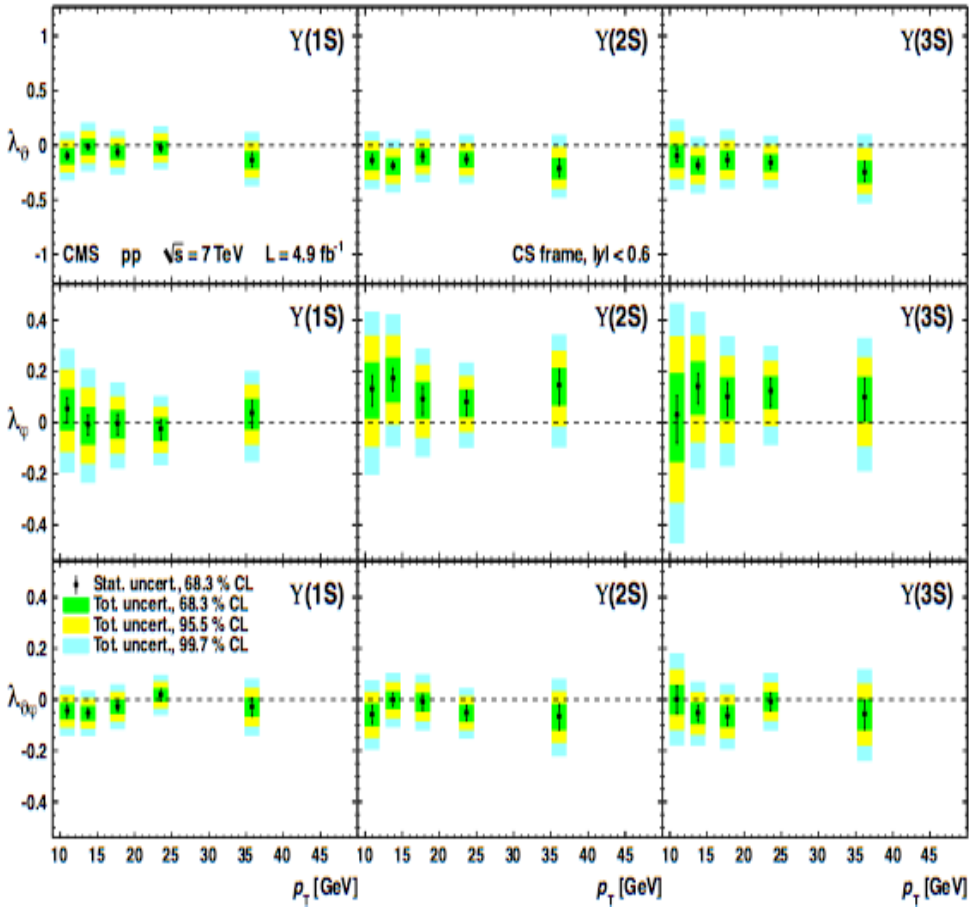
$0.6 < |y| < 1.2$



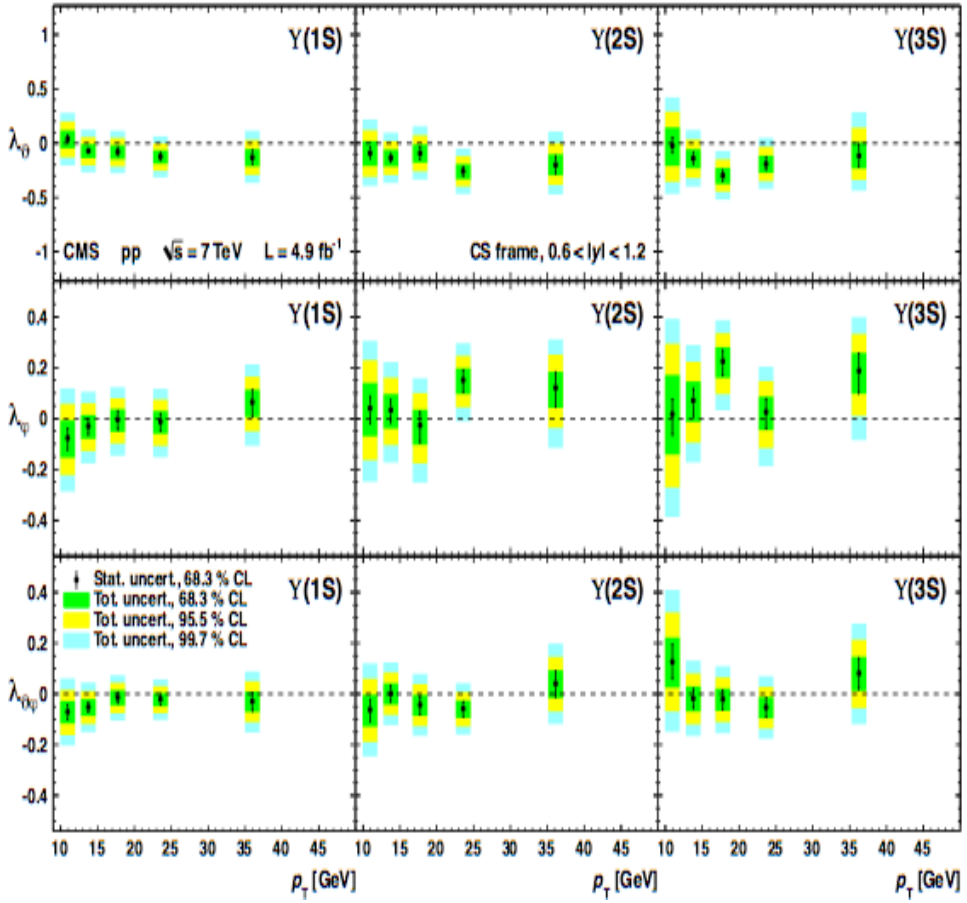
$\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ CMS measurement for $\Upsilon(nS)$ states in the CS frame

PRL 110, 011802 (2013)

$|y| < 0.6$



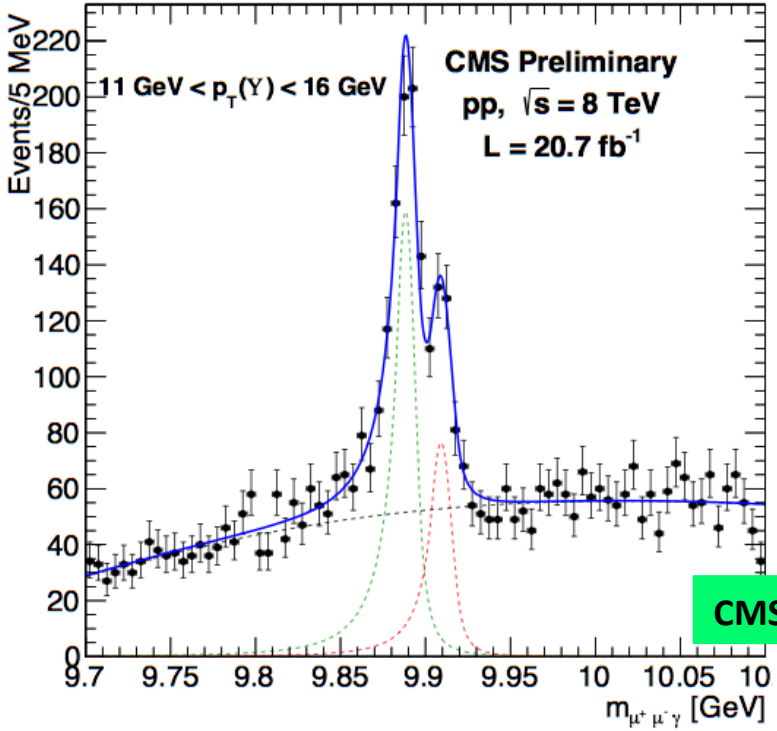
$0.6 < |y| < 1.2$

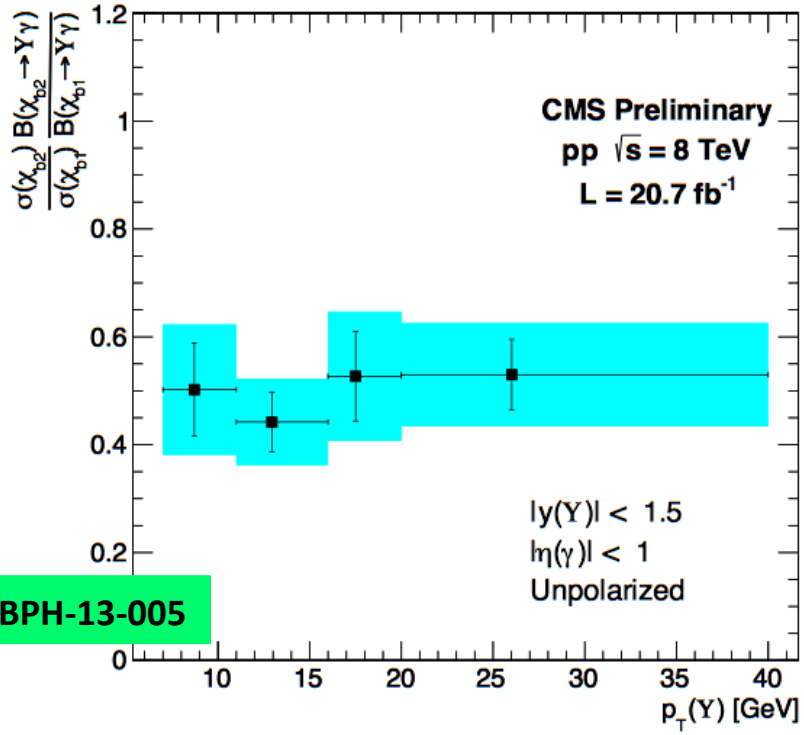


Relative production rate of $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$

- **First measurement @ hadron colliders of this production cross section ratio (corrected for the ratio of the branching fractions):**

$$\frac{\sigma\left(\chi_{b2}(1P)\right)}{\sigma\left(\chi_{b1}(1P)\right)} \cdot \frac{B\left(\chi_{b2}(1P) \to \Upsilon(1S)+\gamma\right)}{B\left(\chi_{b1}(1P) \to \Upsilon(1S)+\gamma\right)}$$





CMS-PAS-BPH-13-005

Photons reconstructed by conversions into electron-positron pairs, thus allowing enough mass resolution to resolve the two peaks (20*MeV* difference)

- **Ratios** $\frac{\sigma\left(\chi_{b2}(1P)\right)}{\sigma\left(\chi_{b1}(1P)\right)}$ **and** $\frac{\sigma\left(\chi_{c2}(1P)\right)}{\sigma\left(\chi_{c1}(1P)\right)}$ **[CMS, EPJ C72, 2251 (2012)] can be useful to fix the color-octet LDMEs**

- p_T is the momentum transfer in the A-B collision;

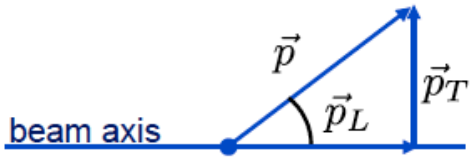
  when A and B are hadrons … p_T denotes the quarkonium transverse momentum

- Rapidity y

The rapidity y is a generalization of velocity $\beta_L = p_L/E$:

$$y := \operatorname{arctanh} \beta_L = \frac{1}{2} \ln \frac{1+\beta_L}{1-\beta_L} = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$$

$$p = \sqrt{p_L^2 + p_T^2}$$



- Pseudorapidity

$$y = \frac{1}{2} \ln \frac{E + p\cos\vartheta}{E - p\cos\vartheta} \overset{p \gg m}{\approx} \frac{1}{2} \ln \frac{1+\cos\vartheta}{1-\cos\vartheta} = \frac{1}{2} \ln \frac{2\cos^2\frac{\vartheta}{2}}{2\sin^2\frac{\vartheta}{2}} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

$$\cos(2\alpha) = 2\cos^2\alpha - 1 = 1 - 2\sin^2\alpha$$