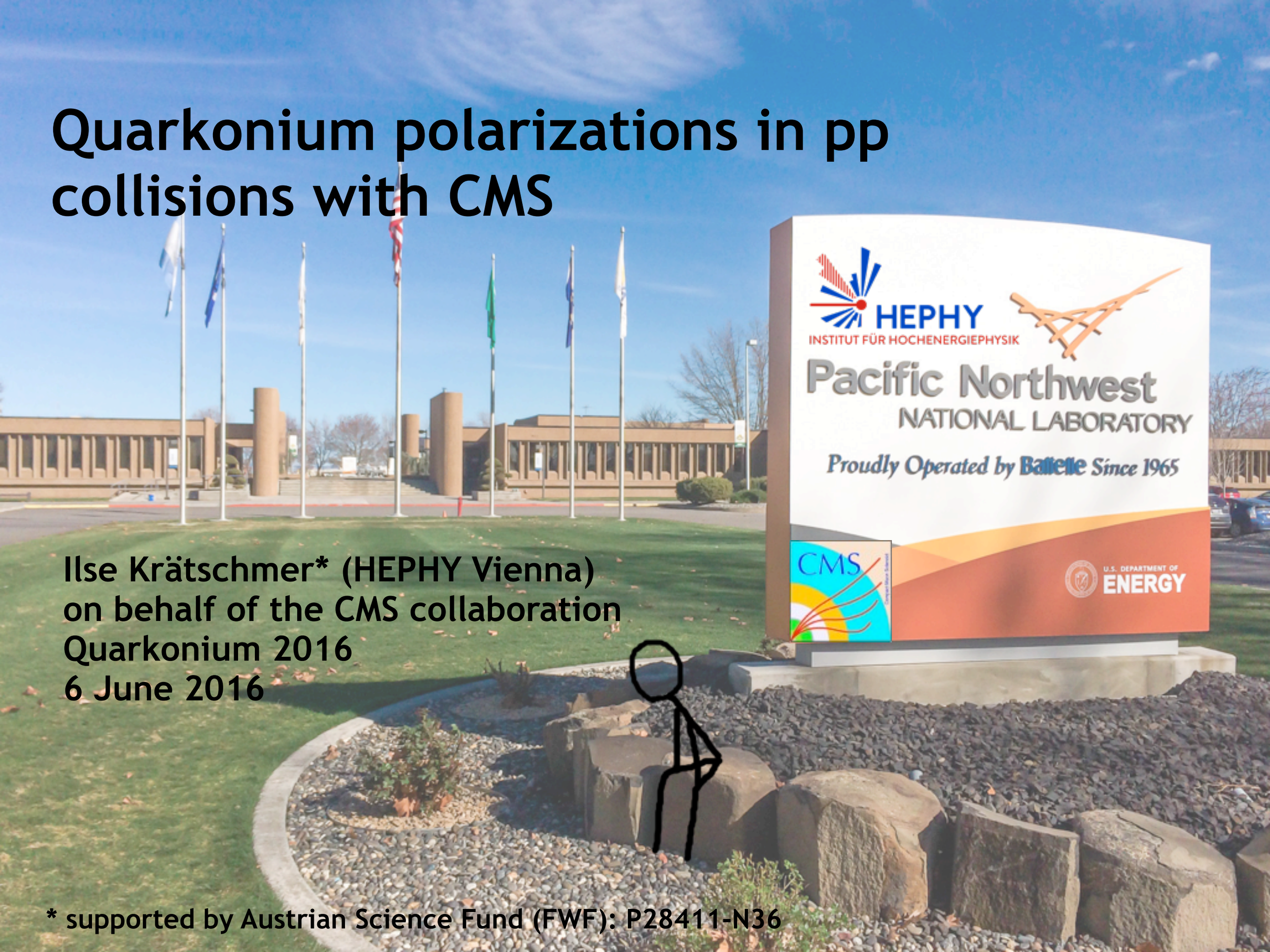
Quarkonium polarizations in pp collisions with CMS



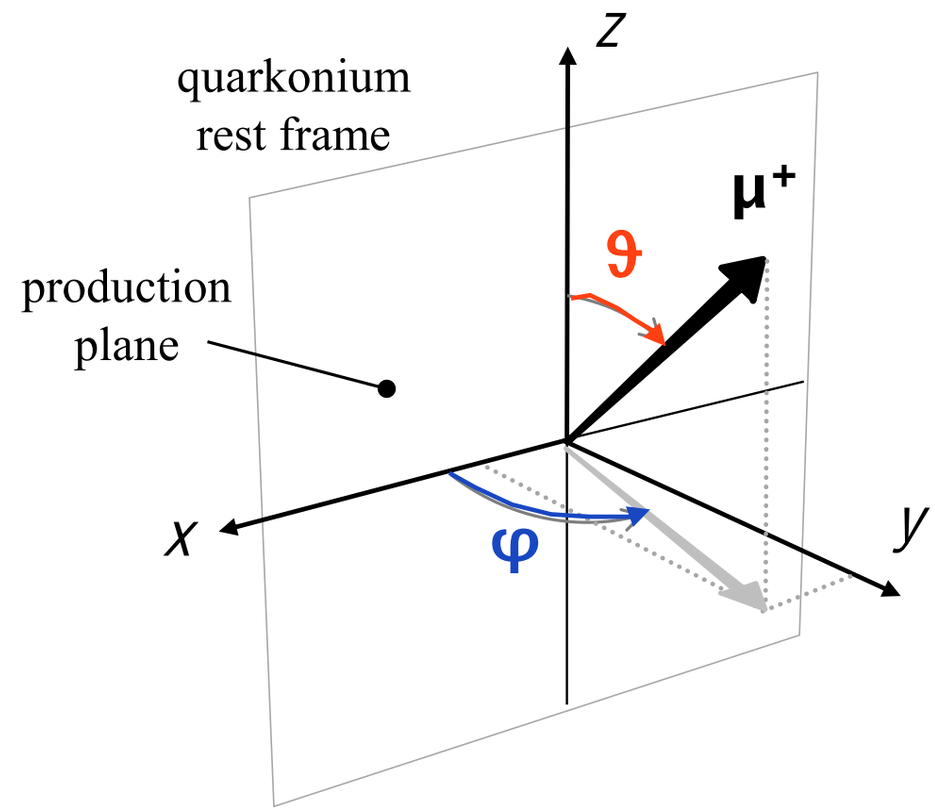
Ilse Krätschmer* (HEPHY Vienna)
on behalf of the CMS collaboration
Quarkonium 2016
6 June 2016

* supported by Austrian Science Fund (FWF): P28411-N36

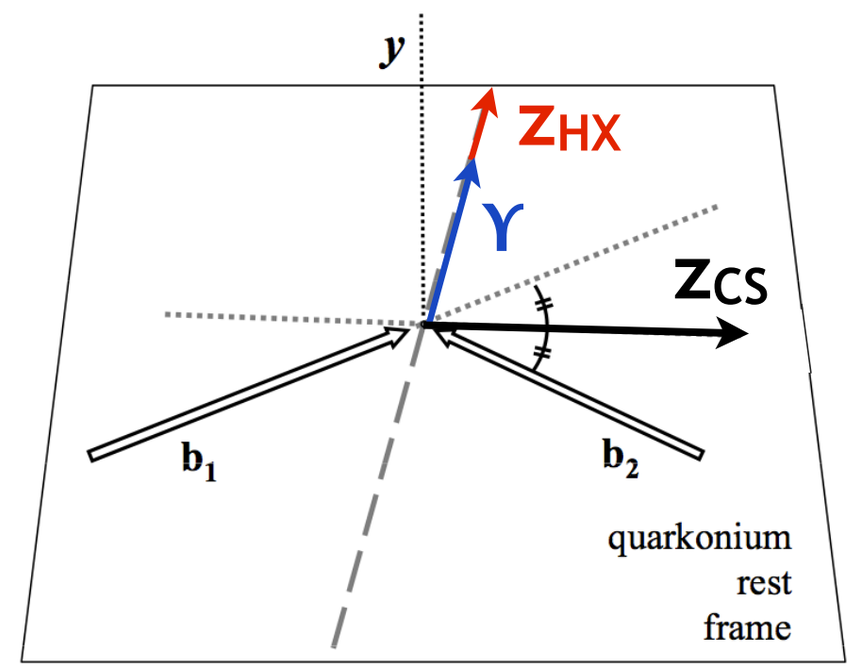
Quarkonium polarization

- Polarization is measured through the angular decay distribution

$$\frac{dN}{d\cos\vartheta d\varphi} \propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$



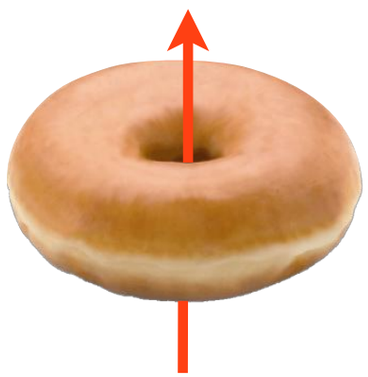
- Study of angular momentum requires quantization axis z
- Possible frames are
  - Center-of-mass helicity HX: $z_{HX} \approx$ direction of quarkonium momentum
  - Collins-Soper CS: $z_{CS} \approx$ direction of relative velocity of colliding particles
  - Perpendicular helicity PX: $z_{PX} \perp z_{CS}$



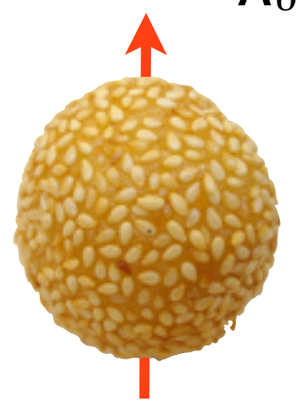
Polarization parameters

Longitudinal polarization
λ_ϑ = -1

$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$



Unpolarized
λ_ϑ = 0



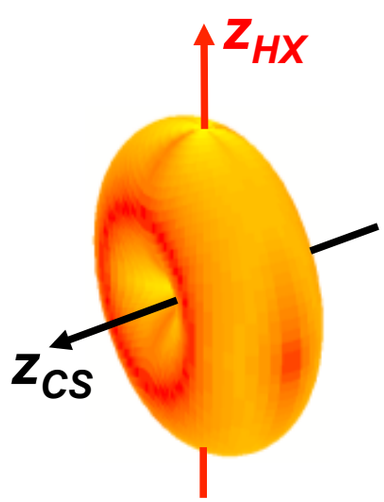
$\lambda_\vartheta = 0$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

Transverse polarization
λ_ϑ = +1

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

- Observed λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$ polarization parameters depend on the frame
- If only λ_ϑ parameter is measured, two very different physical cases are indistinguishable

CS ⊥ HX for
high p_T / mid-y



$\lambda_\vartheta = +1$
$\lambda_\varphi = -1$

$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$

$\lambda_\vartheta = +1$
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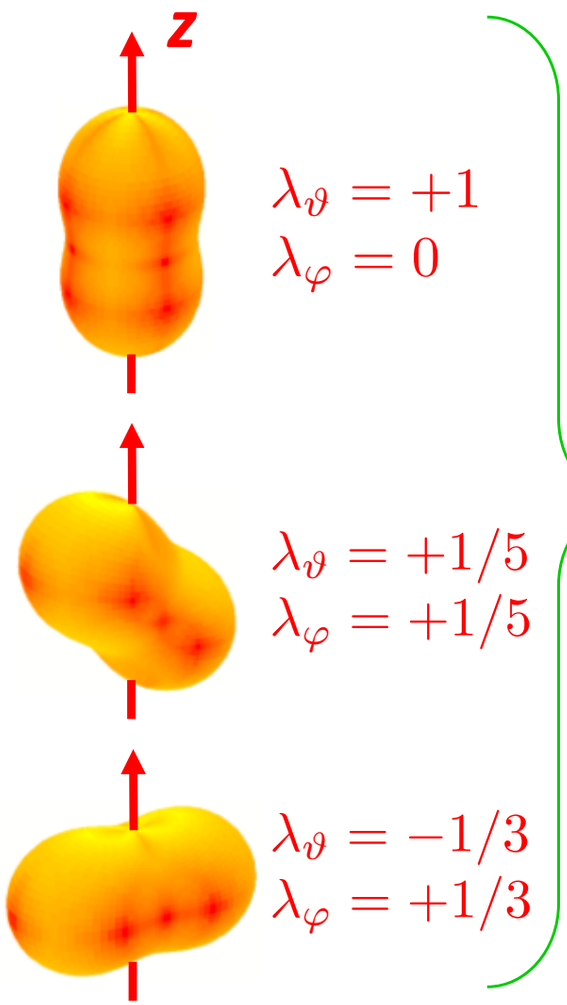
Frame-independent parameter

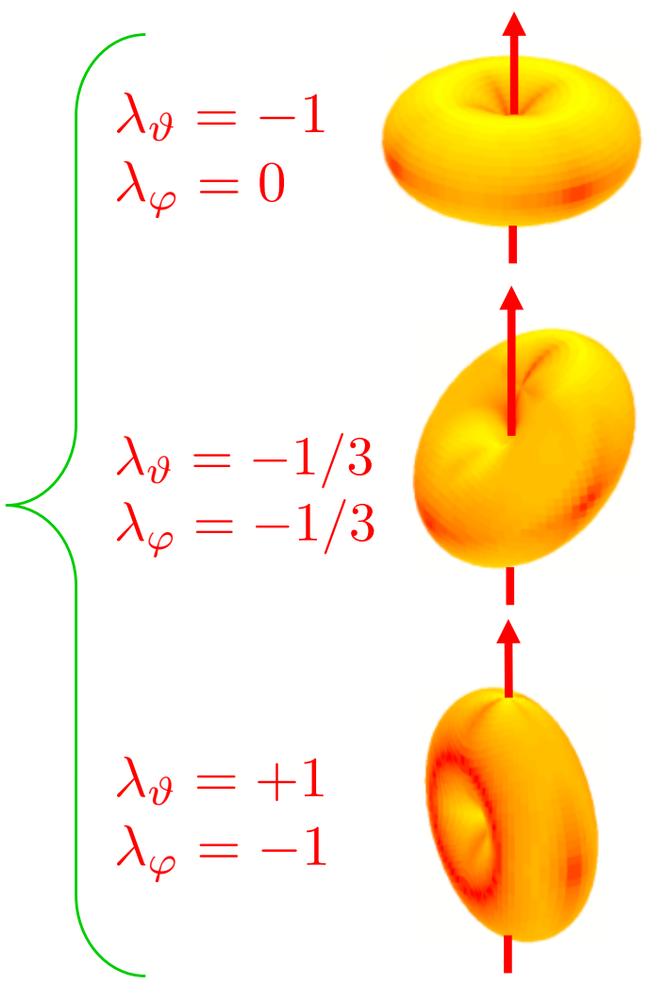
- The shape of angular distribution is frame-invariant and can be characterized as

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$



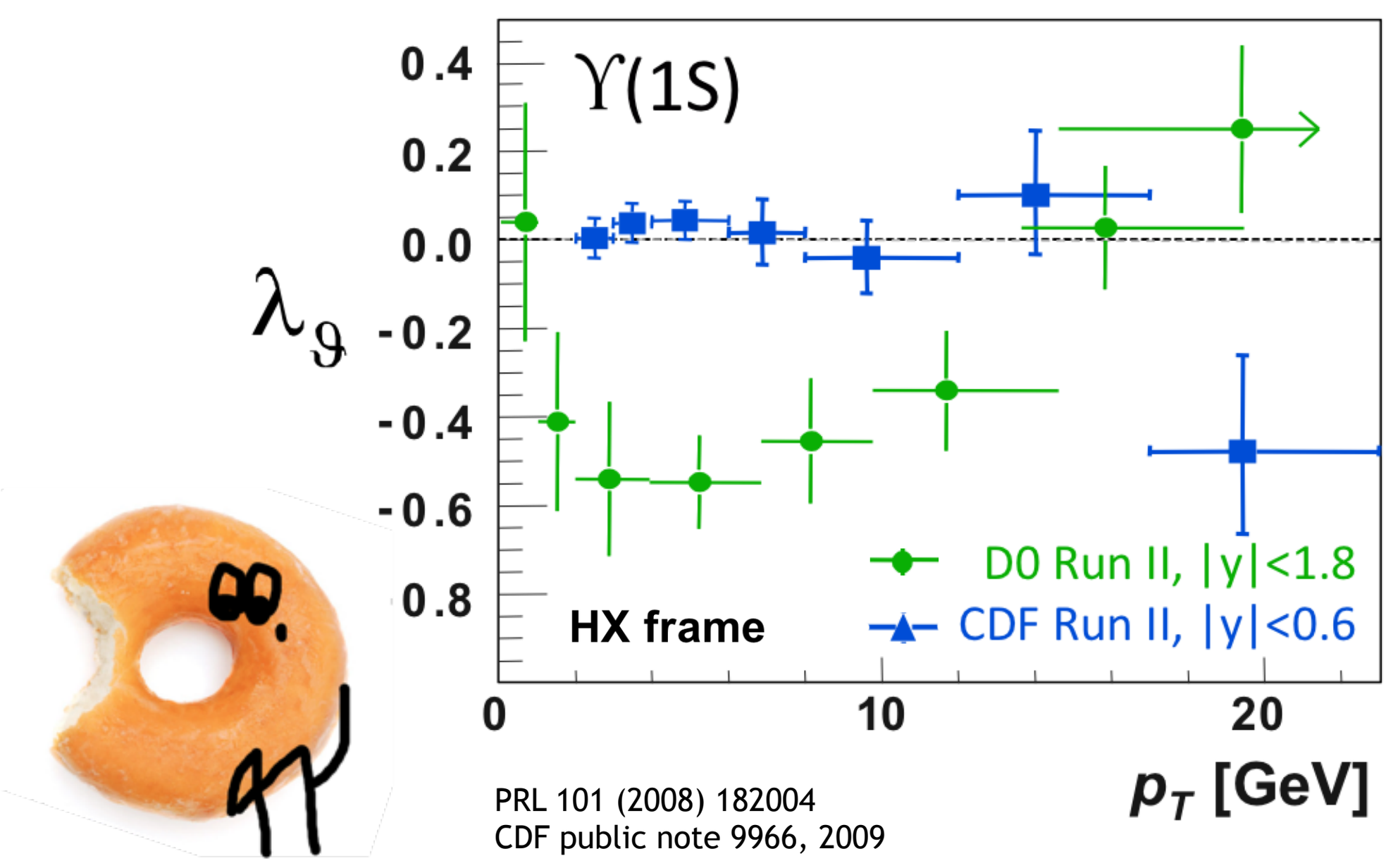
$\tilde{\lambda} = +1$ $\tilde{\lambda} = -1$

EPJC 69 (2010) 657



Experimental status before the LHC

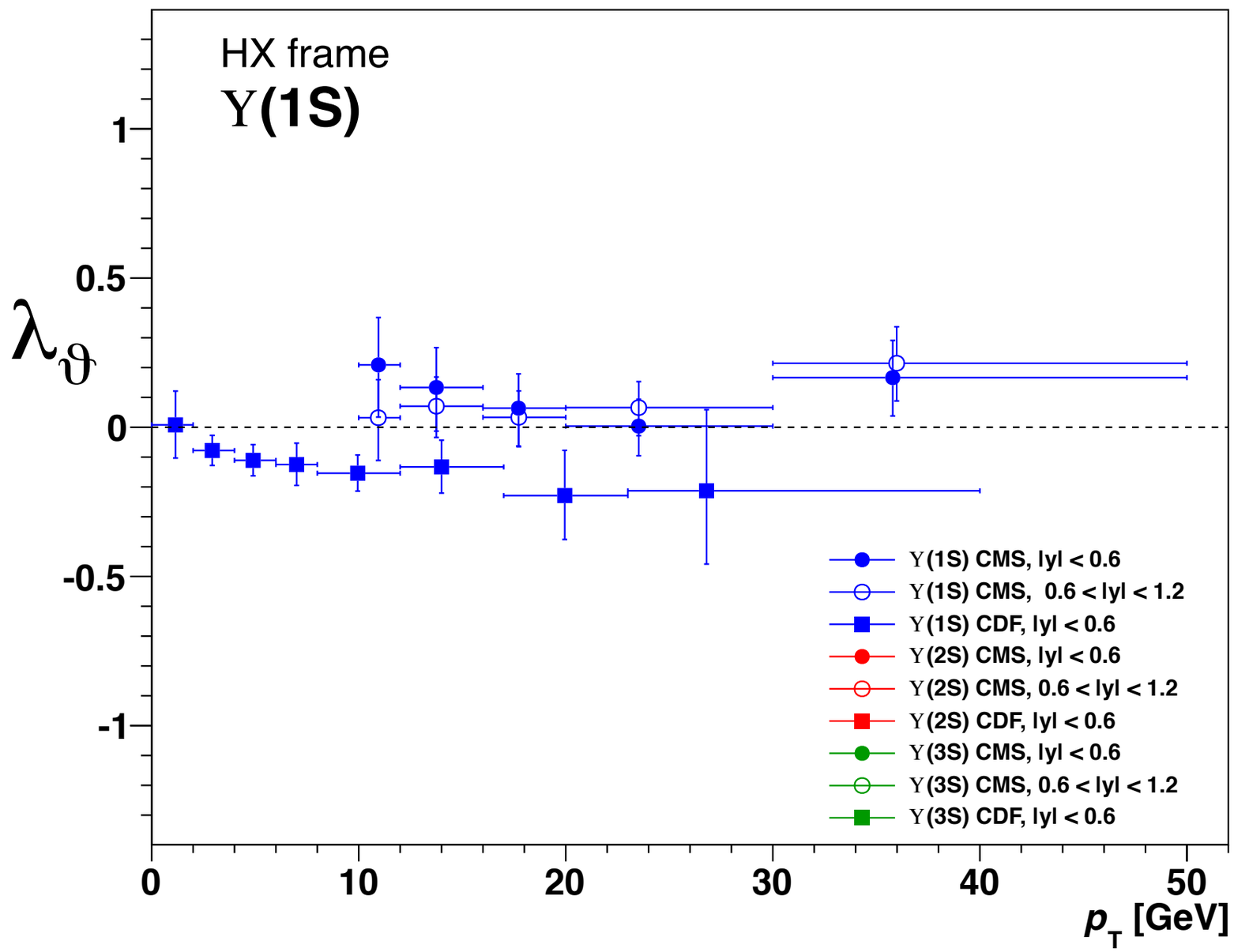
- Experimental results are inconsistent and incomplete: only λ_ϑ was measured in one reference frame



PRL 101 (2008) 182004
CDF public note 9966, 2009

Current experimental status

- All measurements cluster around 0
- Results from different experiments are consistent



PRL 110 (2013) 081802
PRL 108 (2012) 151802

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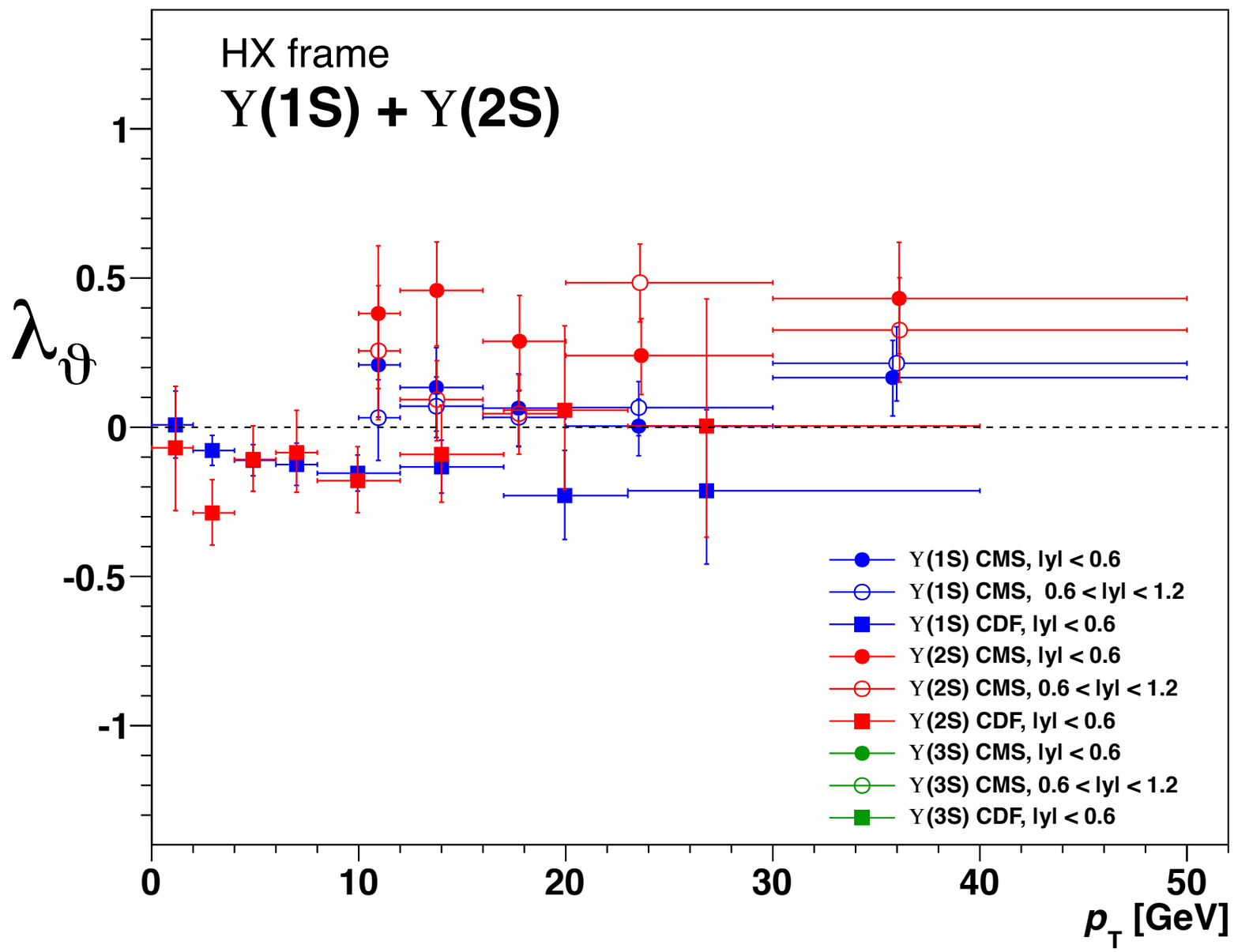

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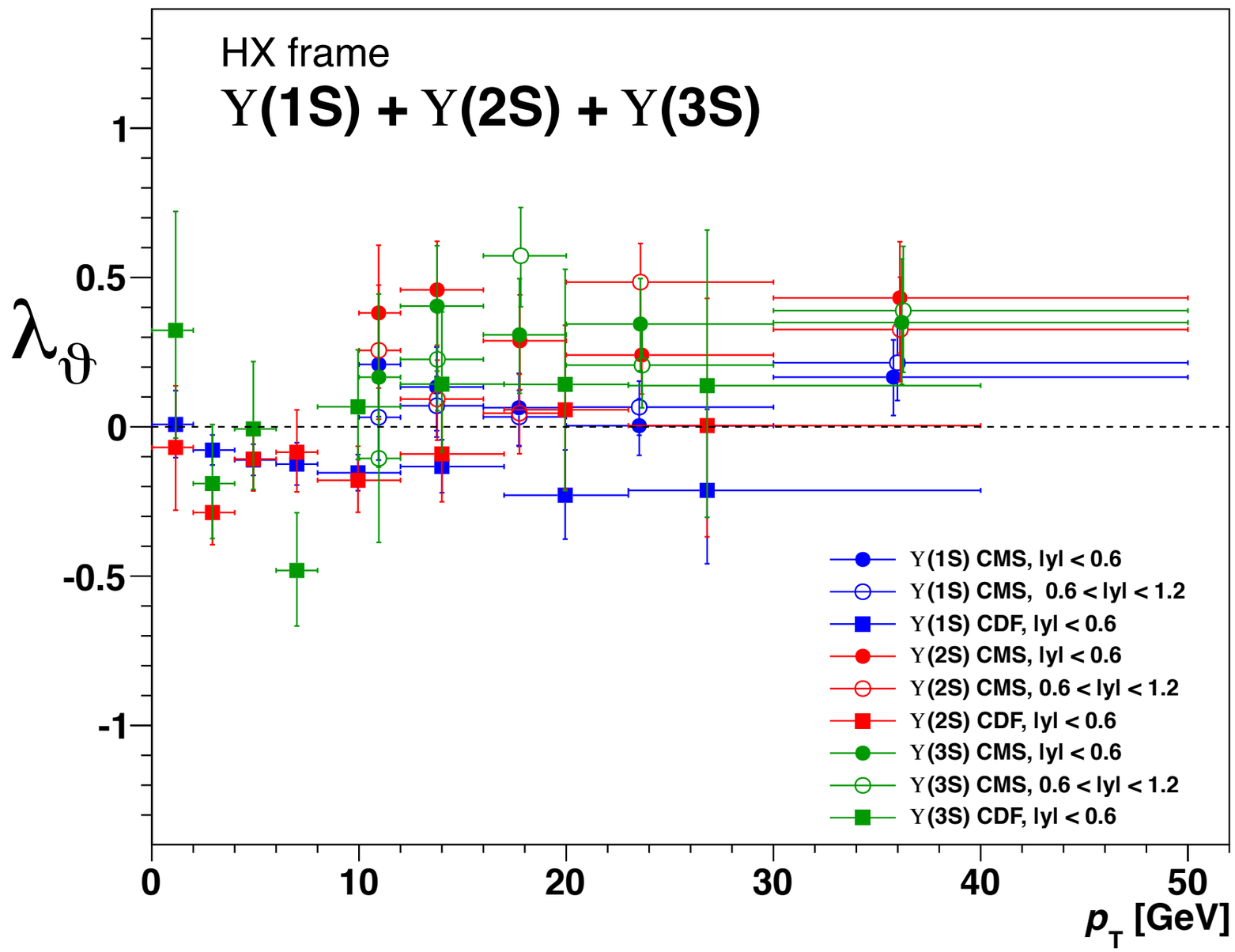

PRL 110 (2013) 081802
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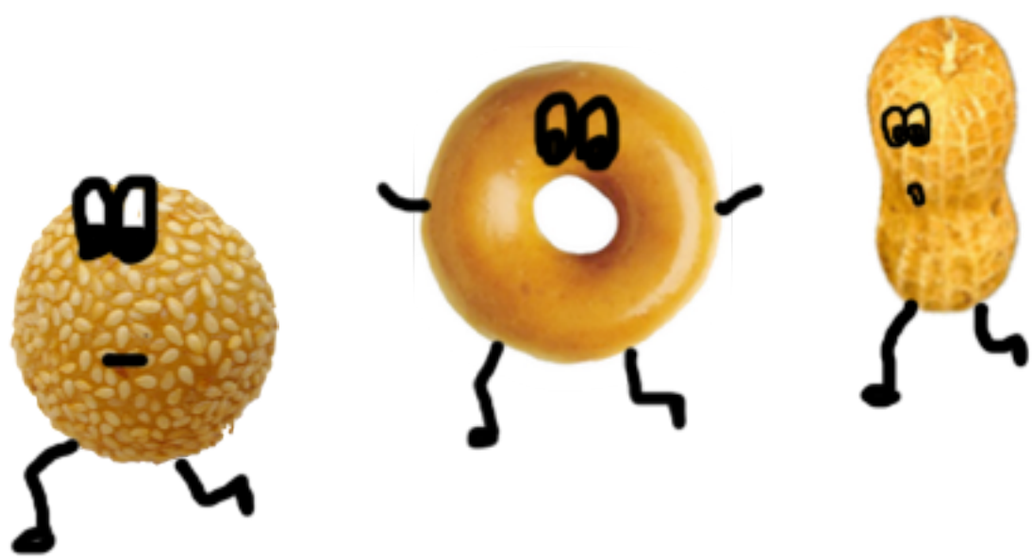
Available measurements of quarkonium polarizations at CMS

- Υ(nS) polarizations as function of transverse momentum, p_T, in bins of |y|: PRL 110 (2013) 081802
- ψ(nS) polarizations as function of p_T in bins of rapidity, |y|: PLB 727 (2013) 381
- Υ(nS) polarizations as function of charged particle multiplicity N_{ch} in bins of p_T: arXiv:1603.02913, to appear in PLB



Υ(nS) polarization as function of N_{ch}

- NRQCD factorizes quarkonium production in two steps

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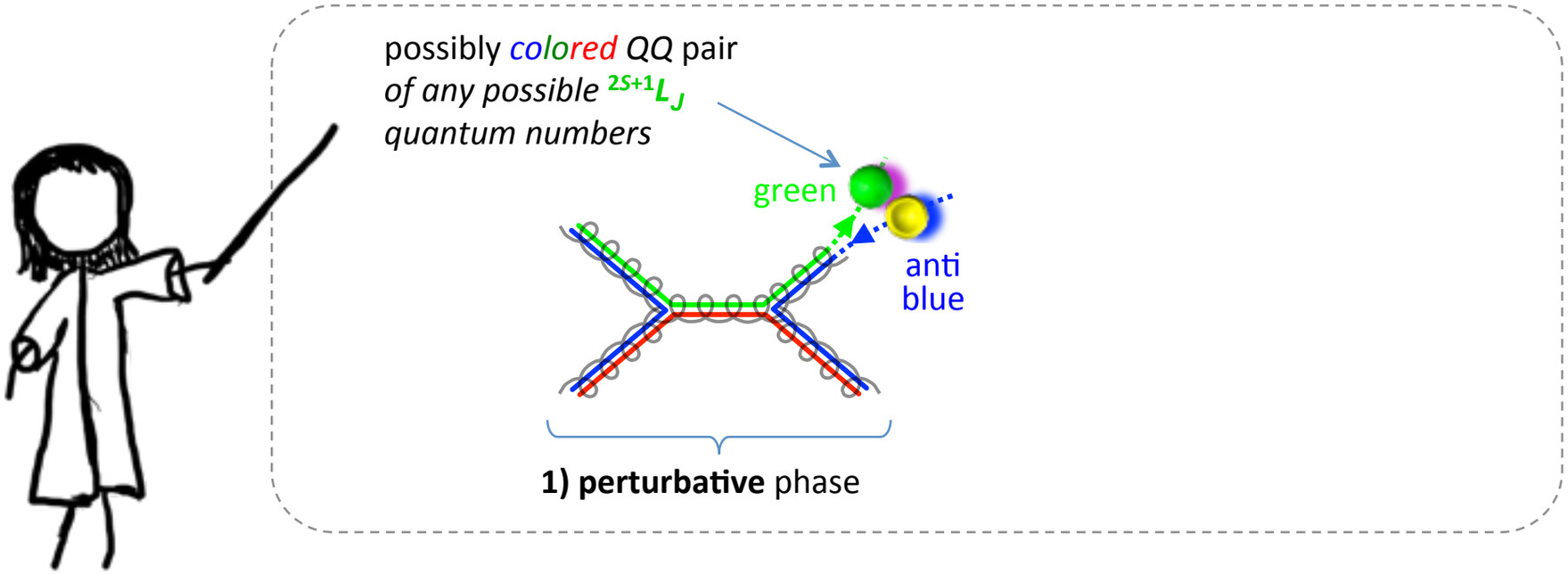
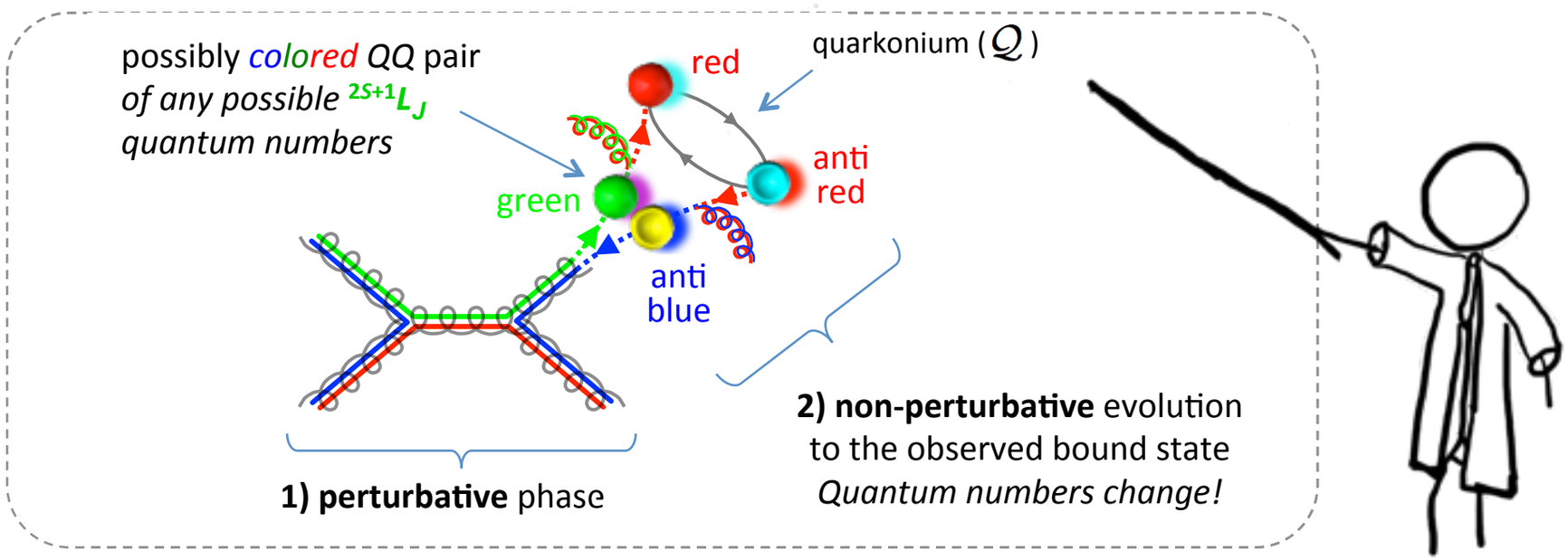
1. Production of the initial quark-antiquark pair (perturbative QCD)



Υ(nS) polarization as function of N_{ch}

- NRQCD factorizes quarkonium production in two steps
  1. Production of the initial quark-antiquark pair (perturbative QCD)
  2. Hadronization of the initial pair into a bound state (non-perturbative QCD)



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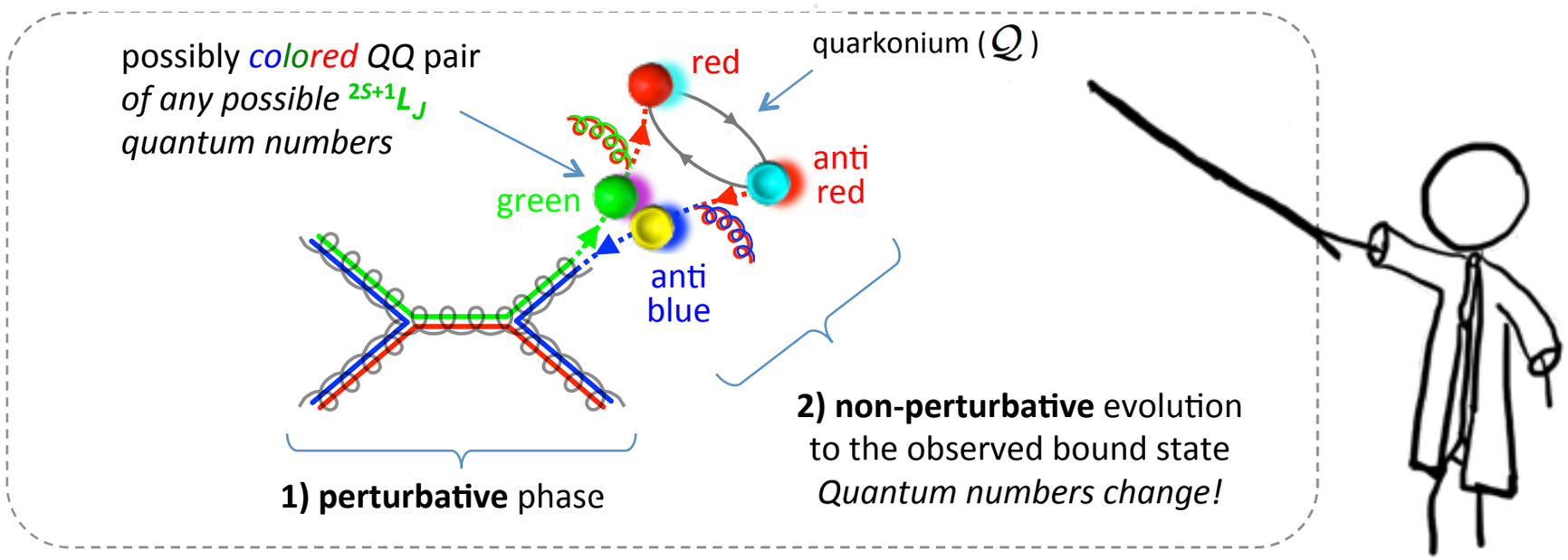


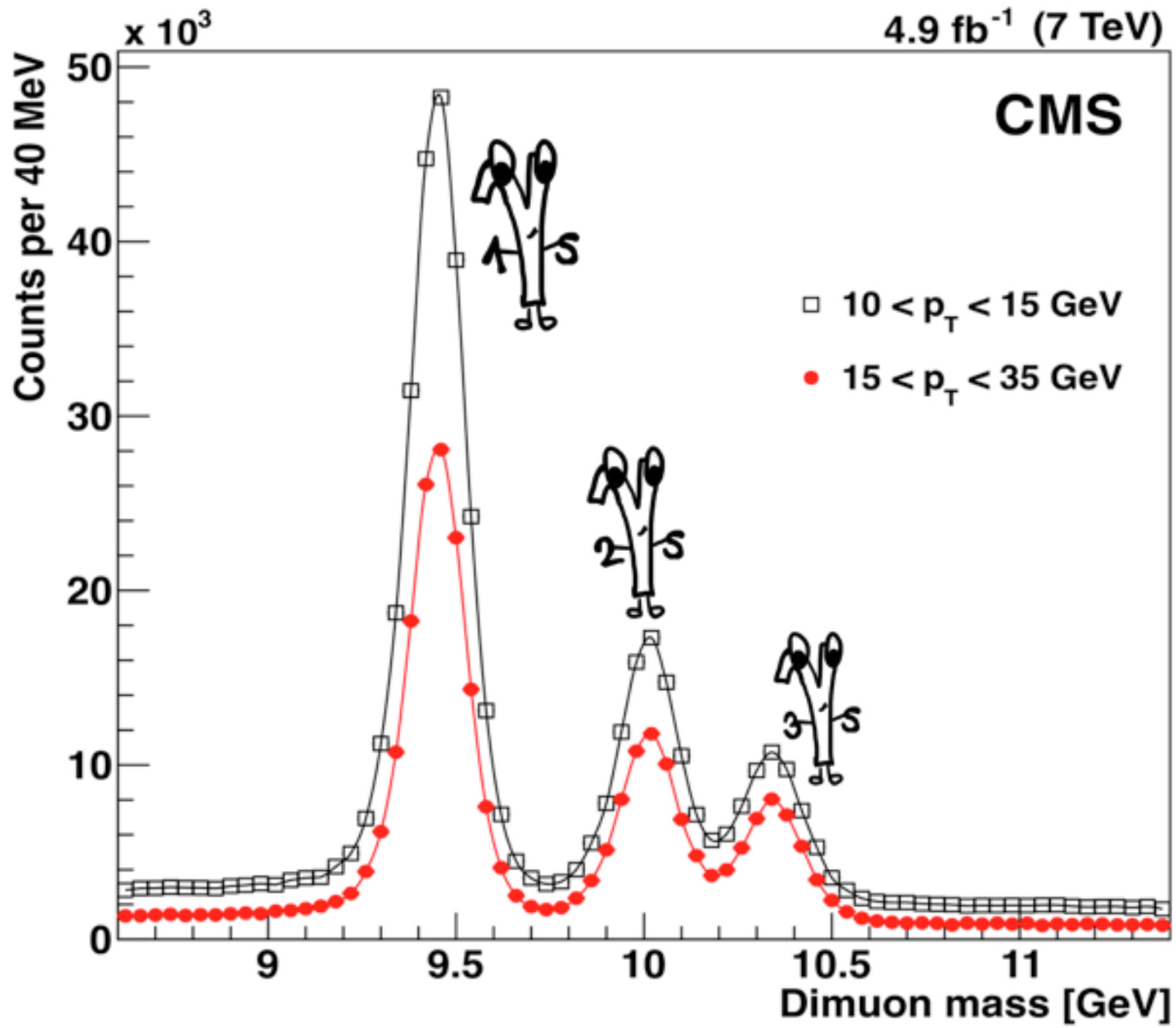
- $Q\bar{Q}$ pair must neutralize its color by absorbing or emitting gluons

➡ Study the influence of the surrounding medium on the quark-antiquark bound-state formation

- Extend studies to pPb and PbPb collisions to test assumed universality of the long distance matrix elements describing the non-perturbative part

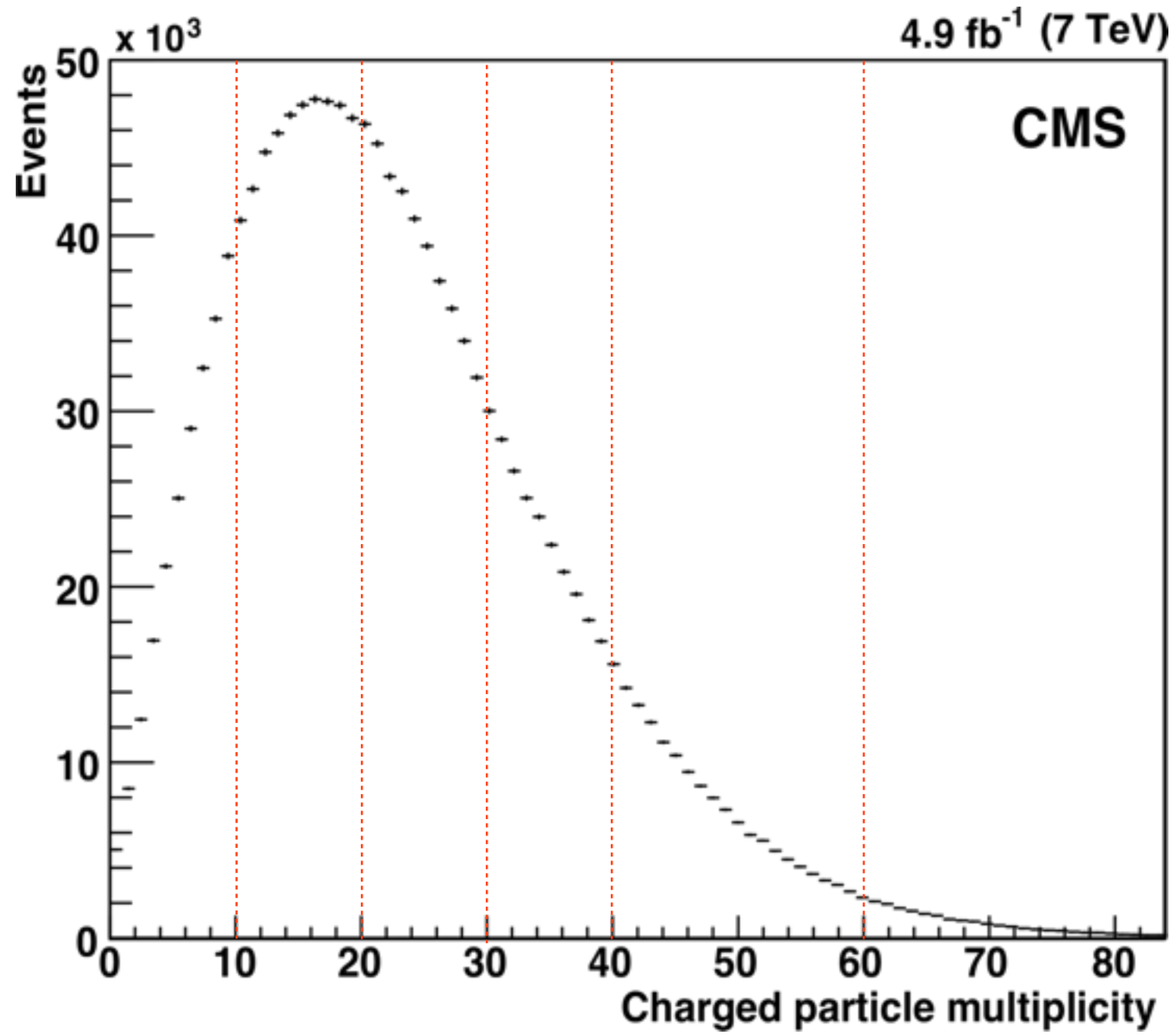
Dataset

- Data
  - Taken at $\sqrt{s}$ = 7 TeV in pp collisions with the CMS detector
  - Collected using a dimuon trigger in the Υ(nS) mass window
  - Corresponding to an integrated luminosity of 4.9 fb^{-1}
- No distinction between directly produced Υ(nS) and Υ(nS) coming from feed-down decays
- $|y(\mu\mu)| < 1.2$
- 2 p_T ranges: 10-15, 15-35 GeV



Definition of charged particle multiplicity

- N_{ch} is computed by counting high purity tracks with $|y| < 2.4$ and $p_T > 500$ MeV, excluding the two muons from the $\Upsilon(nS)$ decay
- Tracks are weighted by the likelihood that track belongs to the primary vertex
- Events with more than 16 vertices are rejected to reduce migration of events between N_{ch} bins
- 5 N_{ch} bins: 0, 10, 20, 30, 40, 60
- Last two bins at low p_T are merged for $\Upsilon(3S)$ to reduce the background-related systematic uncertainty



Obtaining polarization parameters

1. Definition of signal sample

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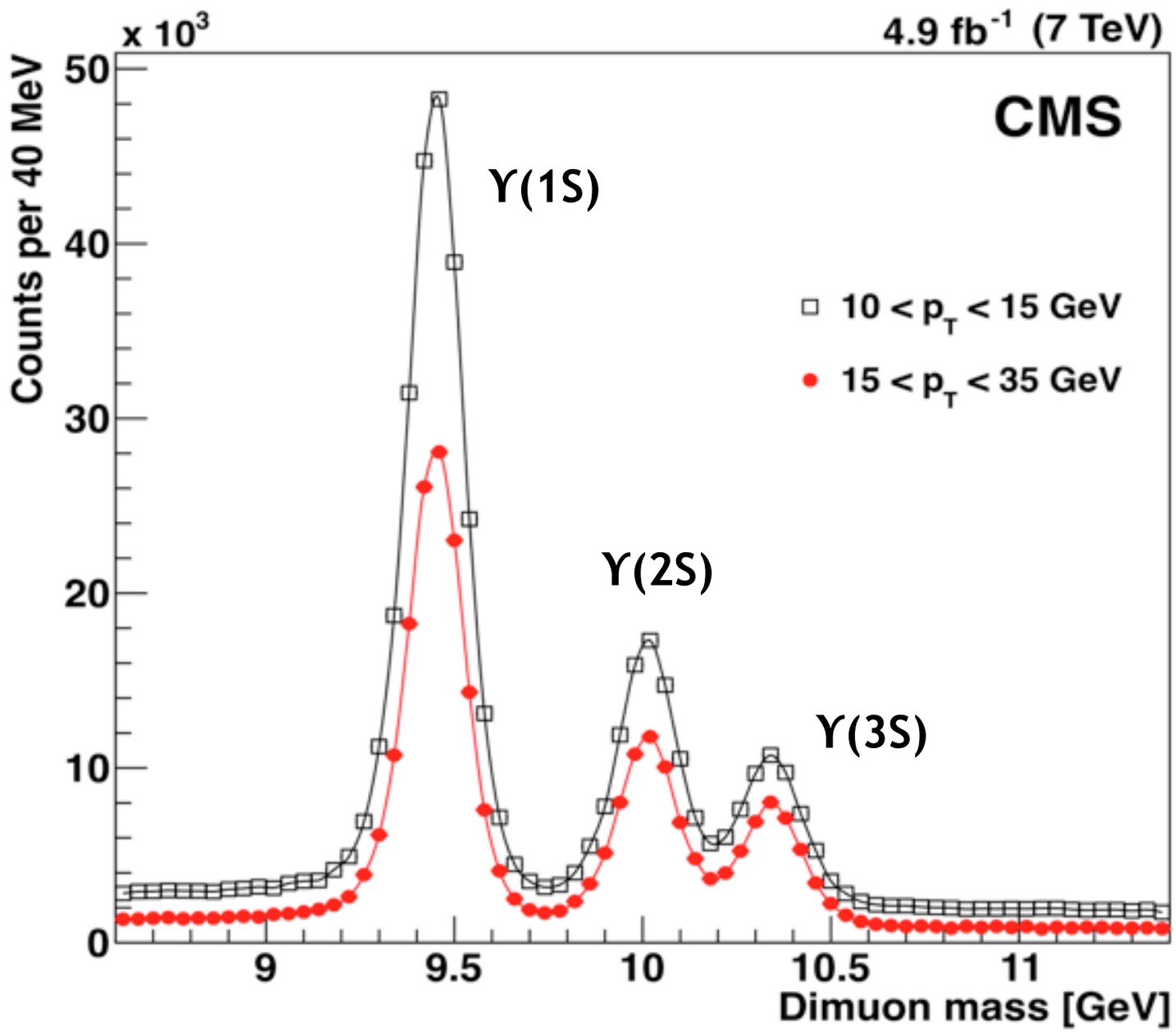

- Signal region is defined as ±1σ around mass peak
- Cross-feed between the Υ(nS) states is negligible
- Background fraction is determined by fits to the dimuon mass distribution
- Angular distribution of the background events is modeled as weighted sums of the distributions in the sidebands, left of Υ(1S) and right of Υ(3S) peak
- Dimuon mass resolution $\Delta m = 80$ MeV

Obtaining polarization parameters

1. Definition of signal sample
   Events distributed as in the background model are subtracted from the data sample until the previously determined background fraction is reached

p_T [GeV]	N_{ch}	Υ(1S)		Υ(2S)		Υ(3S)	
		N	f_{Bg}	N	f_{Bg}	N	f_{Bg}
10–15	0–10	26 900	3	10 200	7	6 500	10
	10–20	51 300	5	18 200	12	10 800	18
	20–30	39 200	7	13 000	18	7 500	26
	30–40	20 100	9	6 300	24	5 200	40
	40–60	11 300	12	3 400	31		
15–35	0–10	10 600	3	4 500	7	3 200	9
	10–20	27 900	4	12 100	9	8 200	12
	20–30	25 700	5	10 900	11	7 200	15
	30–40	15 100	6	6 300	14	3 800	20
	40–60	9 500	7	3 400	17	2 300	24

N...number of signal events
f_{Bg}...background fraction in %

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p_T [GeV]	N_{ch}	Υ(1S) N	Υ(1S) f_{Bg}	Υ(2S) N	Υ(2S) f_{Bg}	Υ(3S) N	Υ(3S) f_{Bg}
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highest f_{Bg}

N...number of signal events
f_{Bg}...background fraction in %

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p_T [GeV]	N_{ch}	Υ(1S) N	Υ(1S) f_{Bg}	Υ(2S) N	Υ(2S) f_{Bg}	Υ(3S) N	Υ(3S) f_{Bg}
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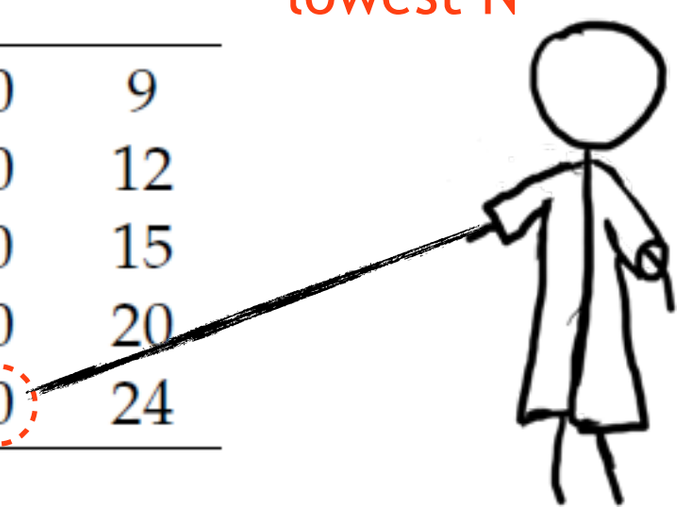
lowest N



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f_{Bg}...background fraction in %

Obtaining polarization parameters

1. Definition of signal sample
2. Definition of Posterior Probability Distribution (PPD) from signal-like events

Obtaining polarization parameters

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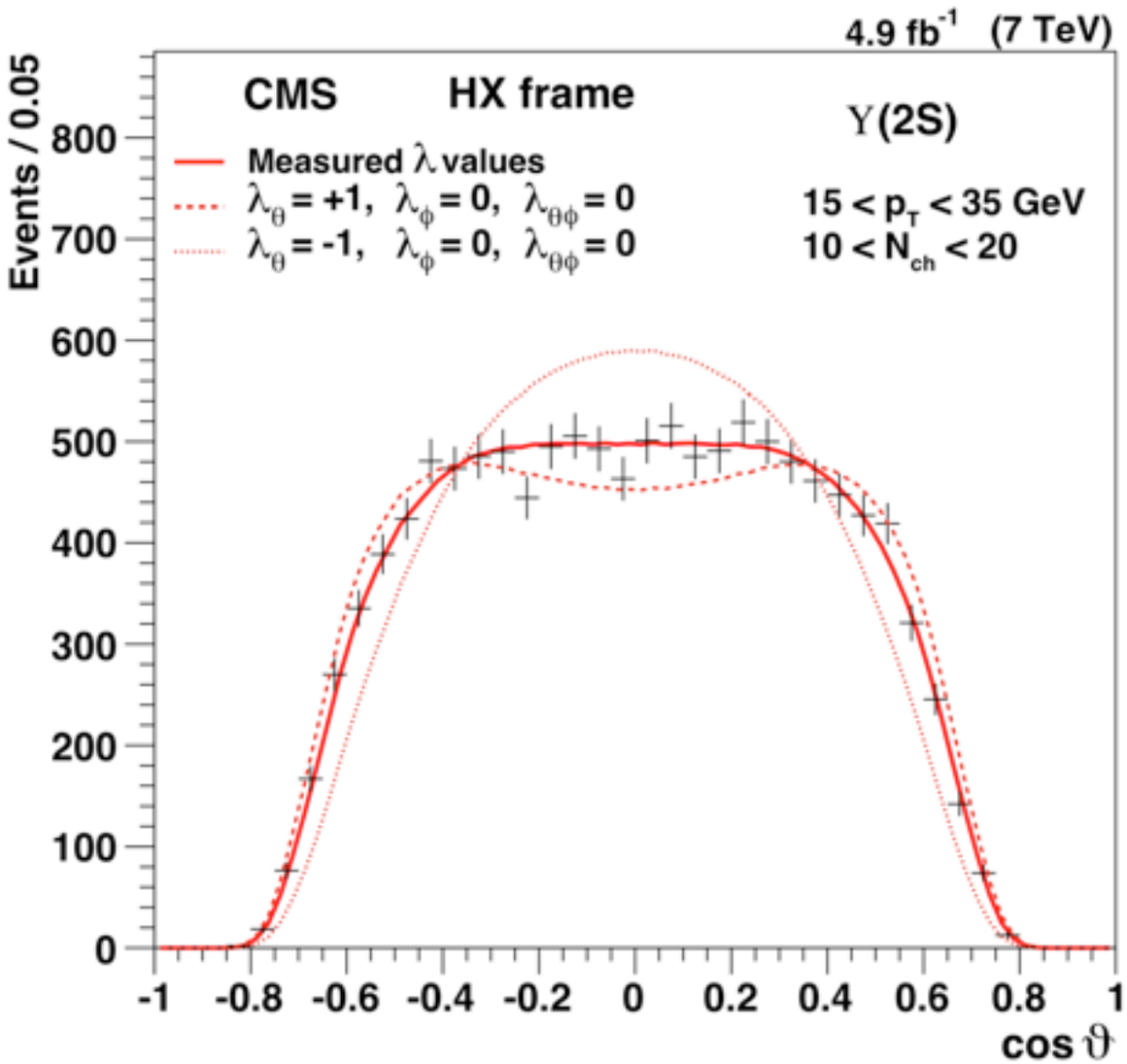
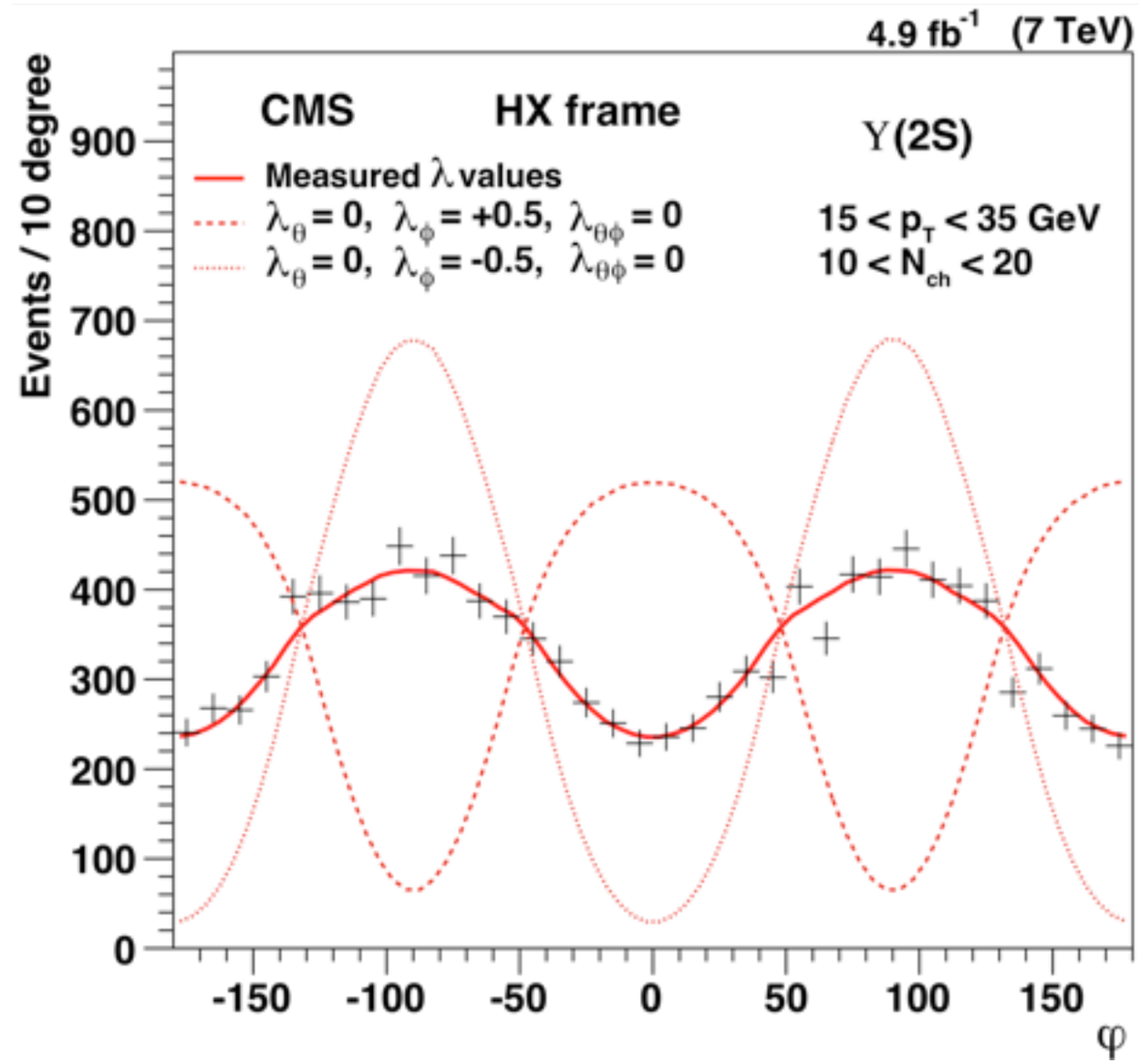
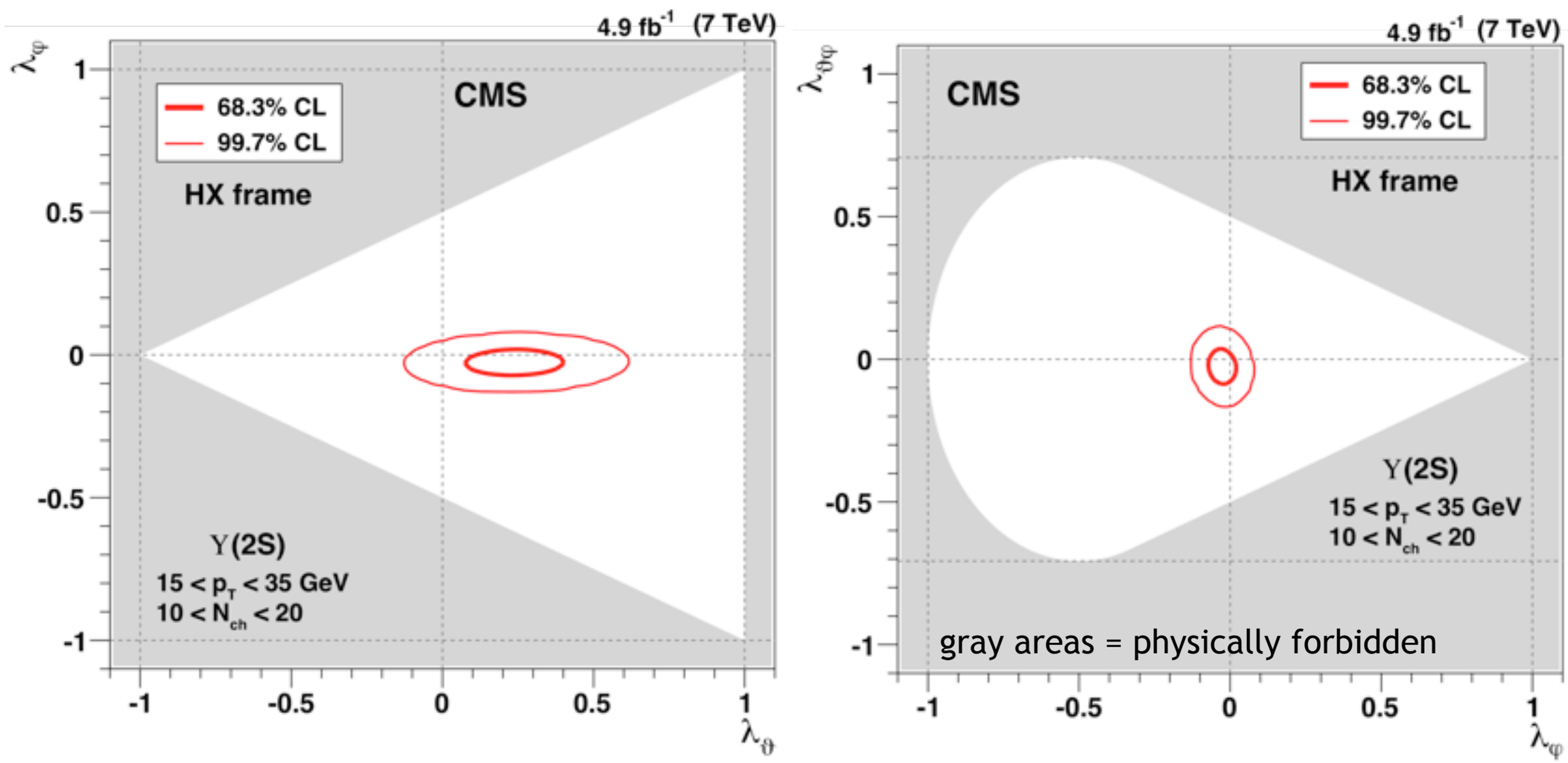
Measured cosϑ and φ distributions after background subtraction





Obtaining polarization parameters

1. Definition of signal sample
2. Definition of Posterior Probability Distribution (PPD) from signal-like events
3. Numerical results and graphical representations are determined from 1D and 2D projections of the PPD



Challenges

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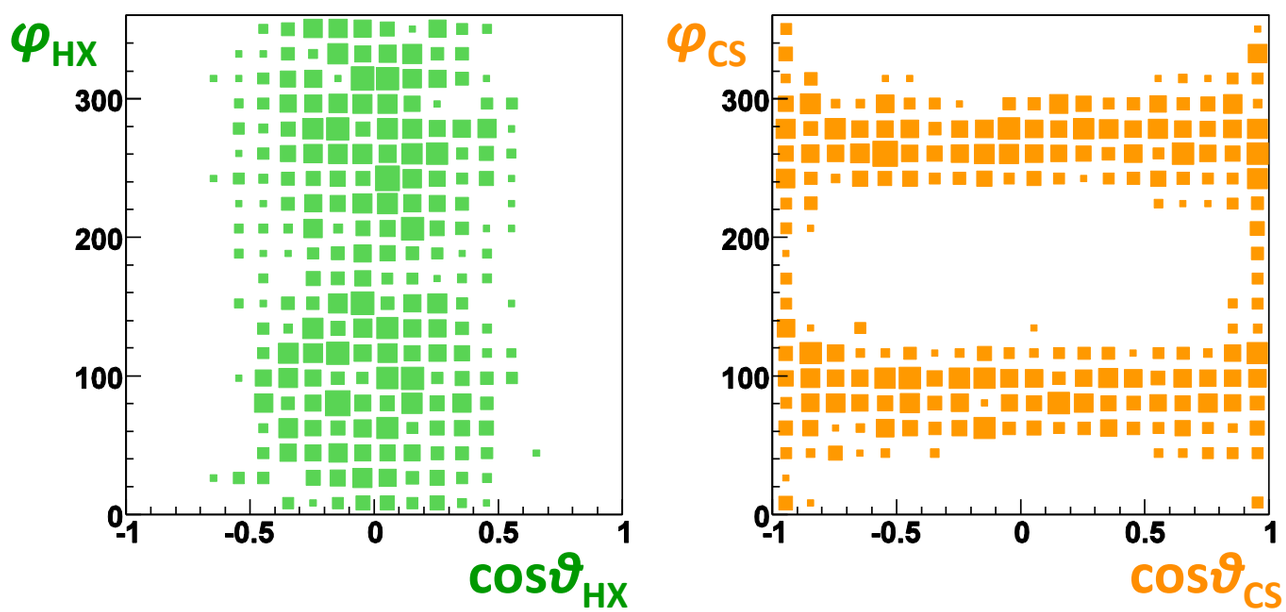
  - Large holes in acceptance reduce the precision of the extracted parameters



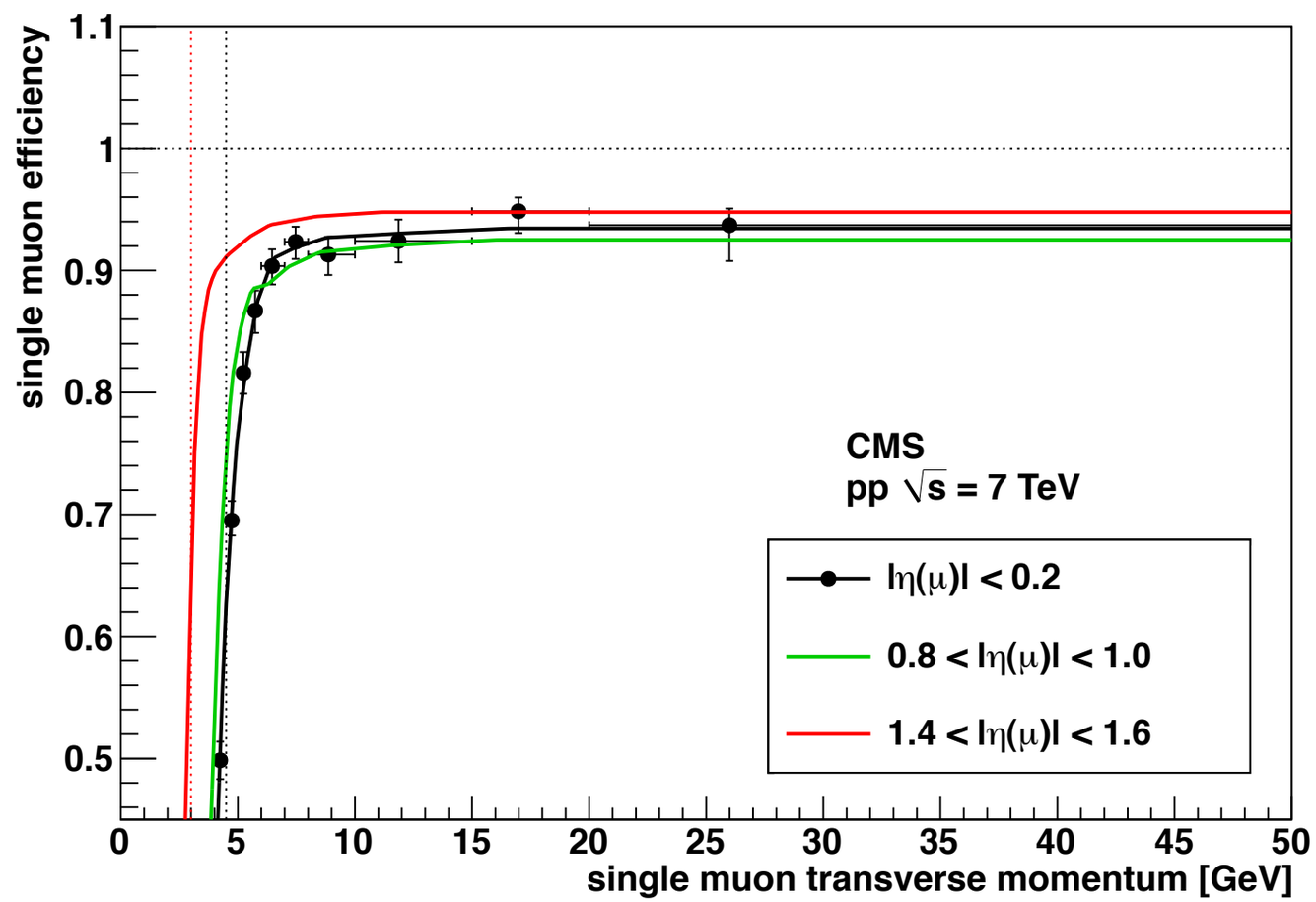
Toy MC
with $p_T(\mu) > 3$ GeV

Reconstructed, unpolarized $\Upsilon(1S)$
with $p_T(\Upsilon(1S)) > 10$ GeV,
$|y(\Upsilon(1S))| < 1$

Talk J. Seixas at ECT* workshop "New Observables in Quarkonium Production" in Trento, Mar. 2016

Challenges

- Reliable background modeling from data sidebands
- Limited angular phase space coverage due to cuts on single muons
  - Large holes in acceptance reduce the precision of the extracted parameters
- Precise mapping of single muon and dimuon efficiencies
  - Data-driven single muon efficiencies measured with the Tag&Probe method using dedicated triggers
  - Correlations between muons are calculated in detailed MC studies, but are negligible

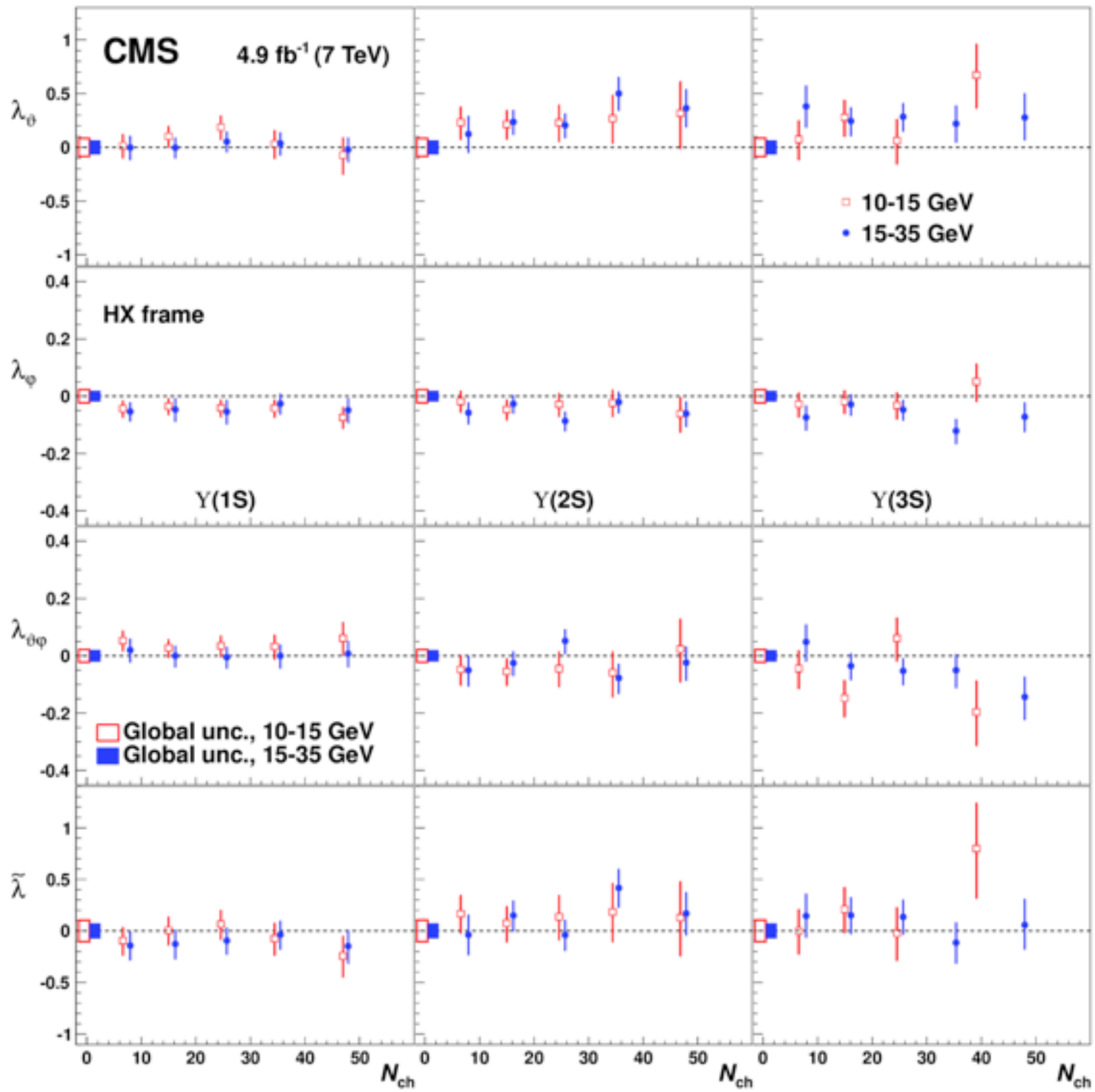


Systematic uncertainties

- Sources of systematic uncertainties
  - Extraction of polarization parameters / robustness of the framework
  - Background model
  - Single muon and dimuon efficiencies (N_{ch} independent uncertainty of 2-3%)
- N_{ch} dependent systematic uncertainties are propagated to the PPD
- Background model uncertainty dominates in highest N_{ch} bins and lowest p_T range
- Statistical uncertainties are dominant for $\Upsilon(2S)$ and $\Upsilon(3S)$

Results in the HX frame

No significant changes from low to high multiplicity pp collisions, but large uncertainties preclude definite statements for Υ(2S) and Υ(3S)



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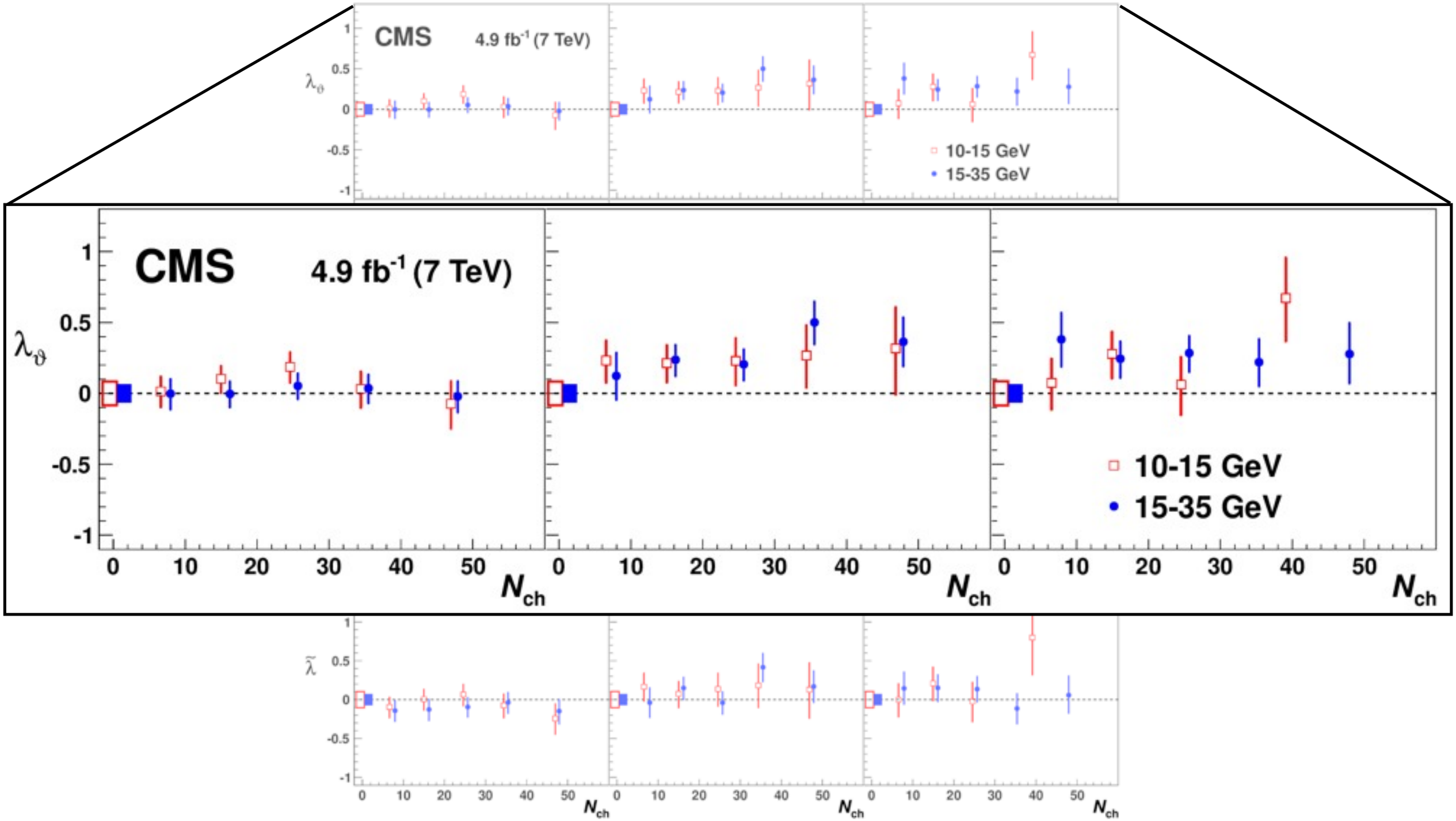

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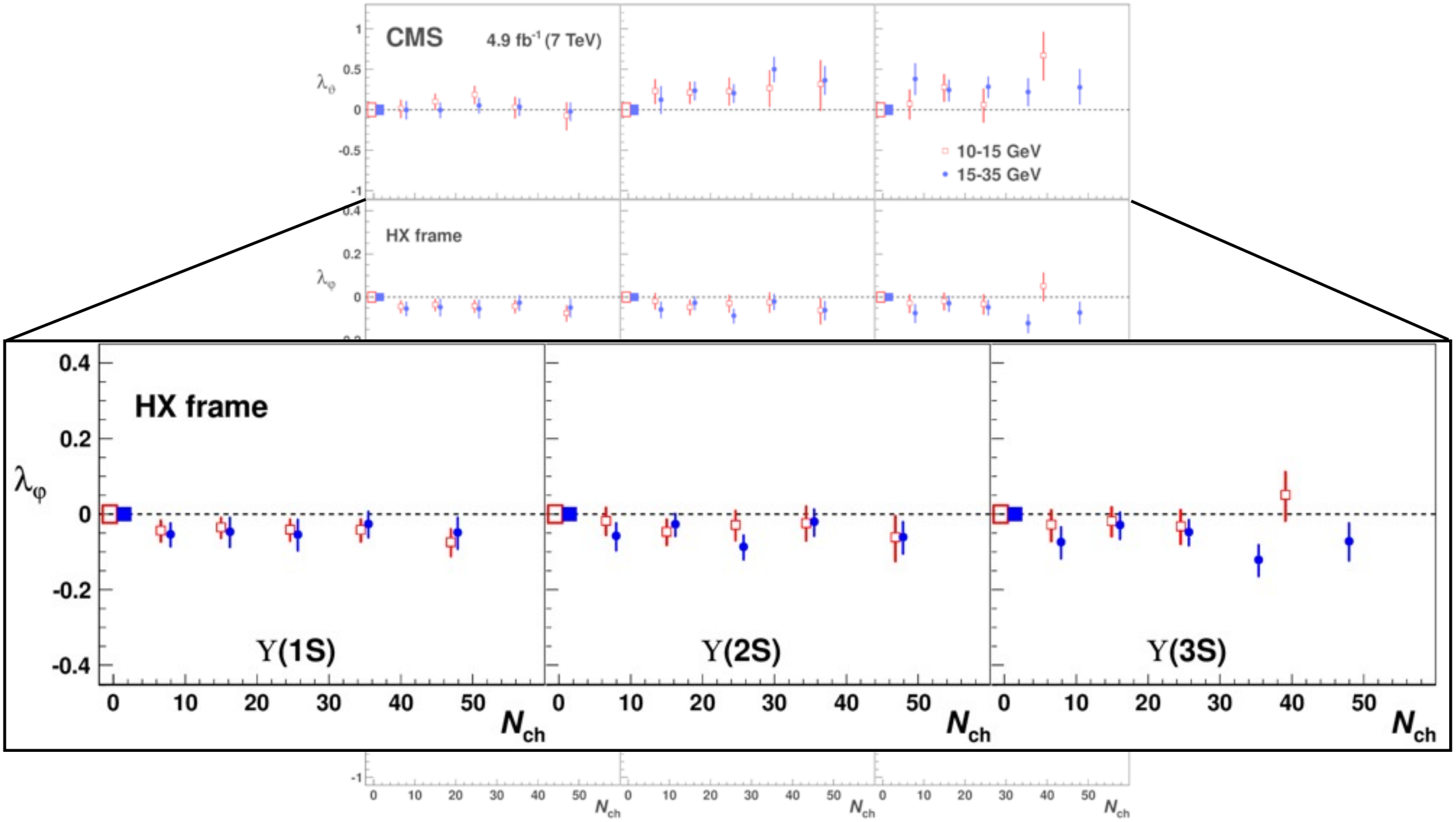

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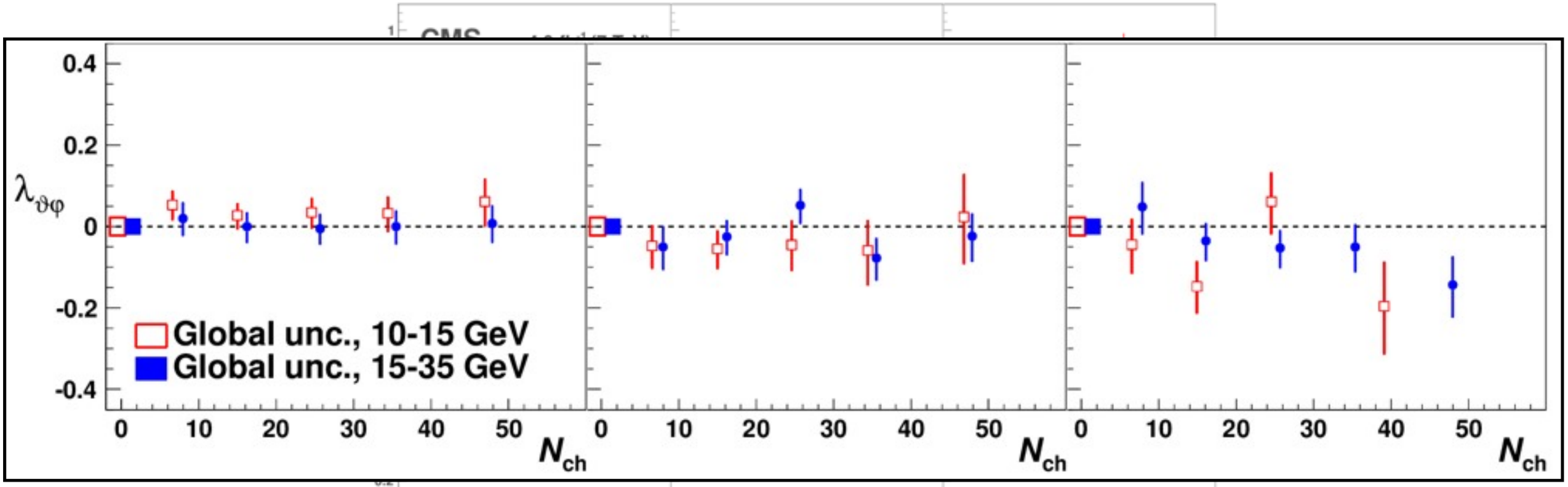

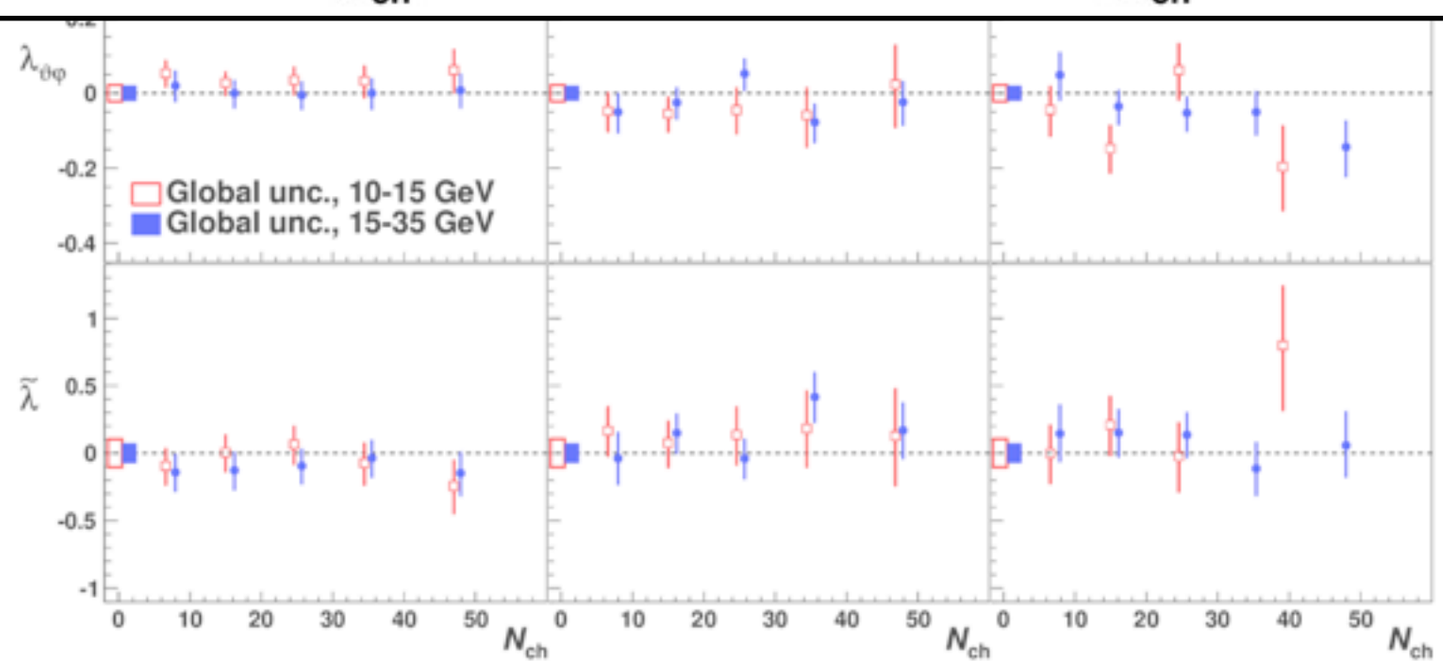

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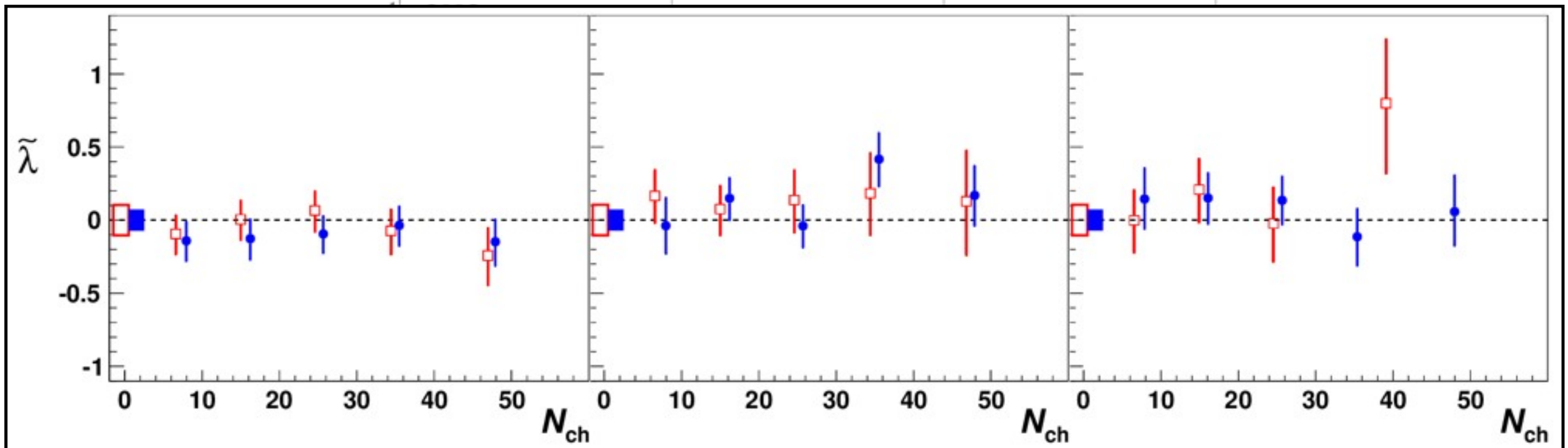
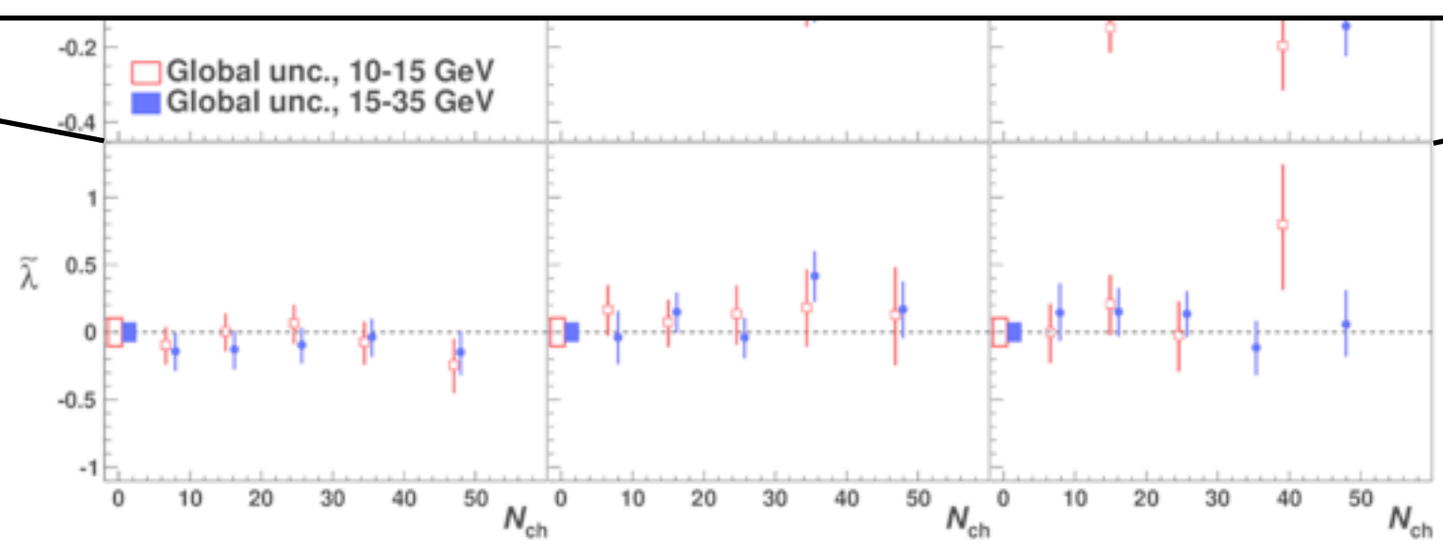


Frame-invariant parameters are consistent in all tested frames



Interpretation of results

- Polarization of a sample of quarkonium states produced through two different processes with polarizations λ_0 and λ_1

$$\lambda(f) = \left[\frac{(1-f)\lambda_0}{3+\lambda_0} + \frac{f\lambda_1}{3+\lambda_1}\right] \Big/ \left[\frac{(1-f)}{3+\lambda_0} + \frac{f}{3+\lambda_1}\right]$$

with f being the fraction of events with λ_1 linearly changing with N_{ch}

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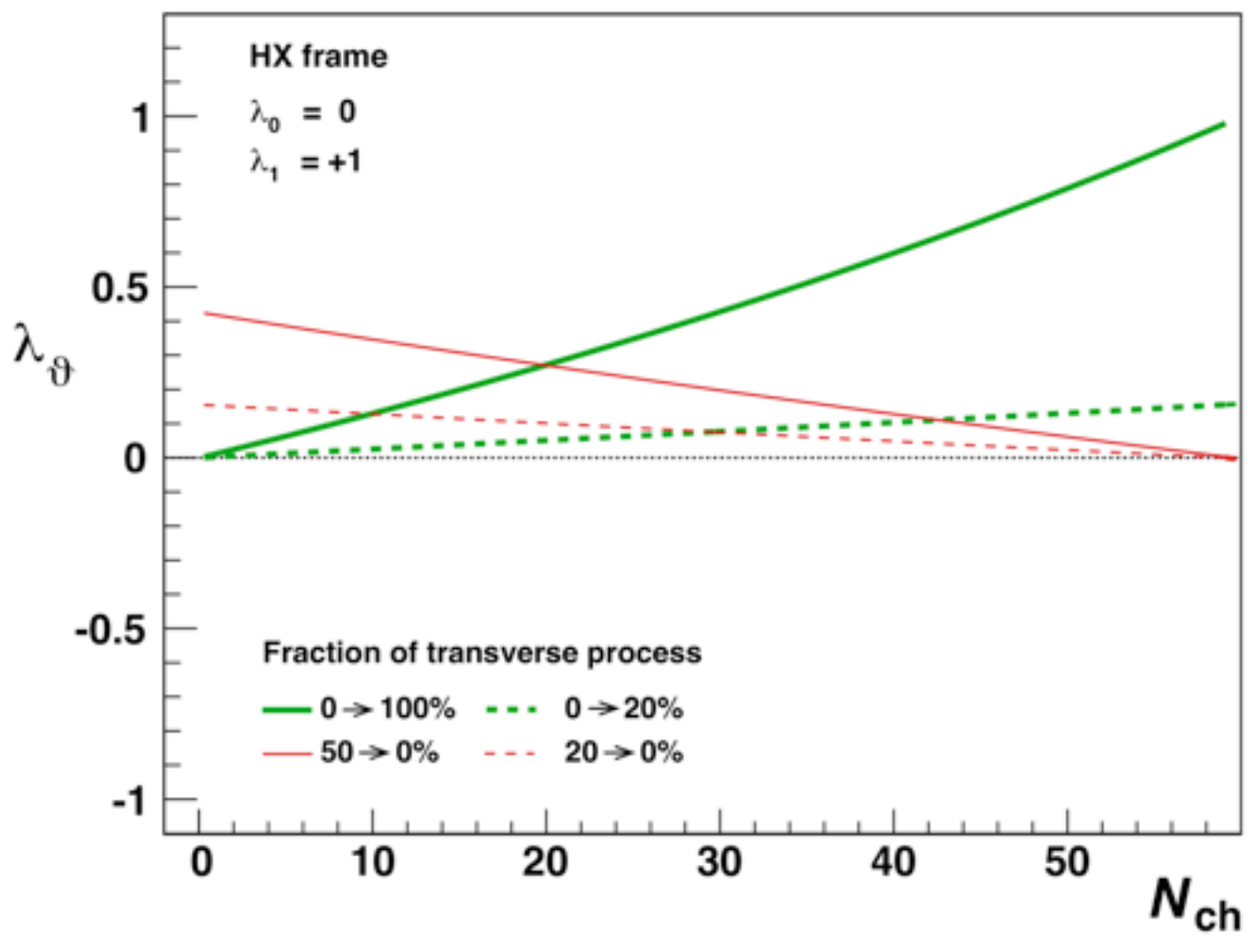

- Check the influence of a polarized contribution to the total process
- $\lambda_0 = 0$ (unpolarized process)
- $\lambda_1 = +1$ (fully transversely polarized process)
- Different values for fraction f

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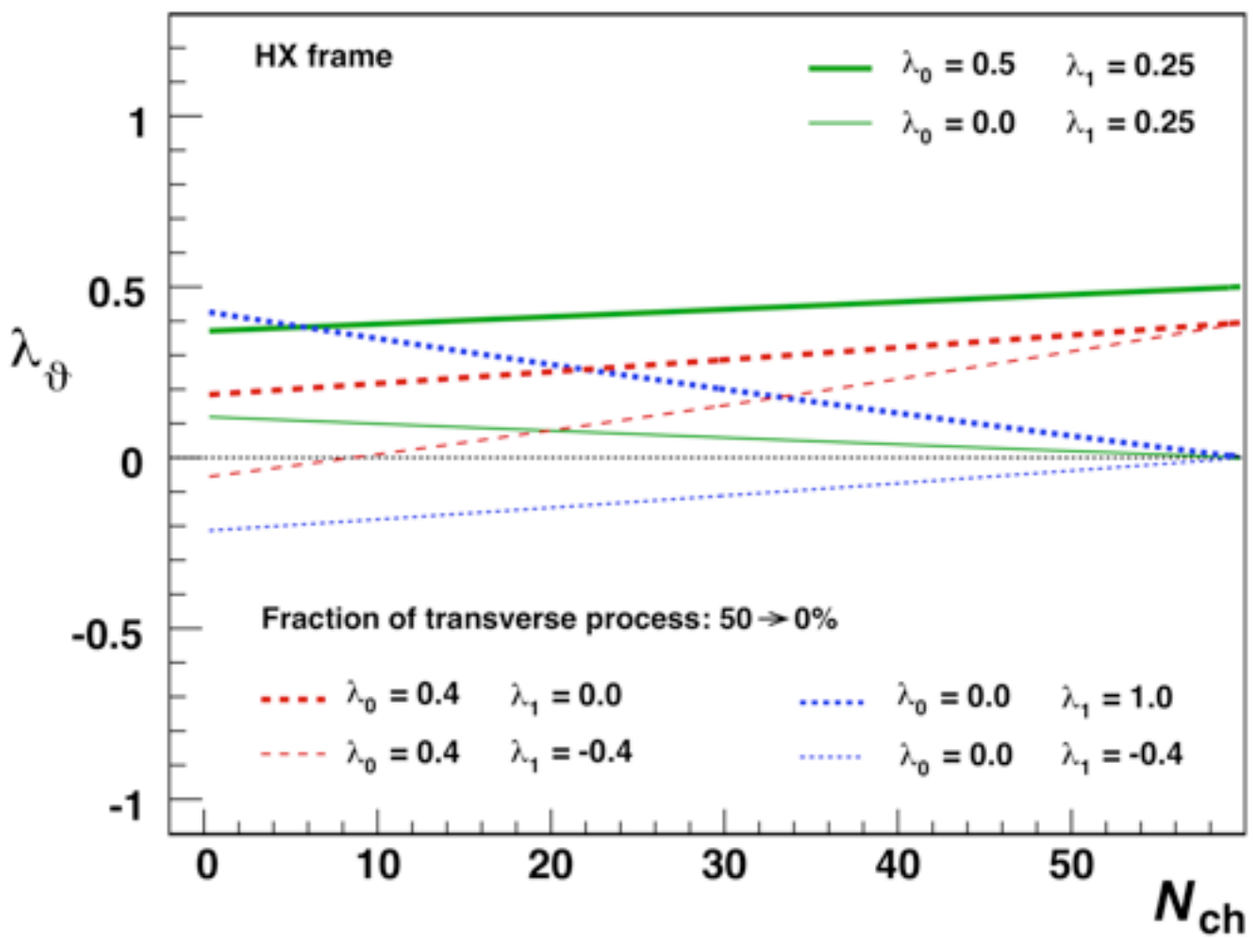
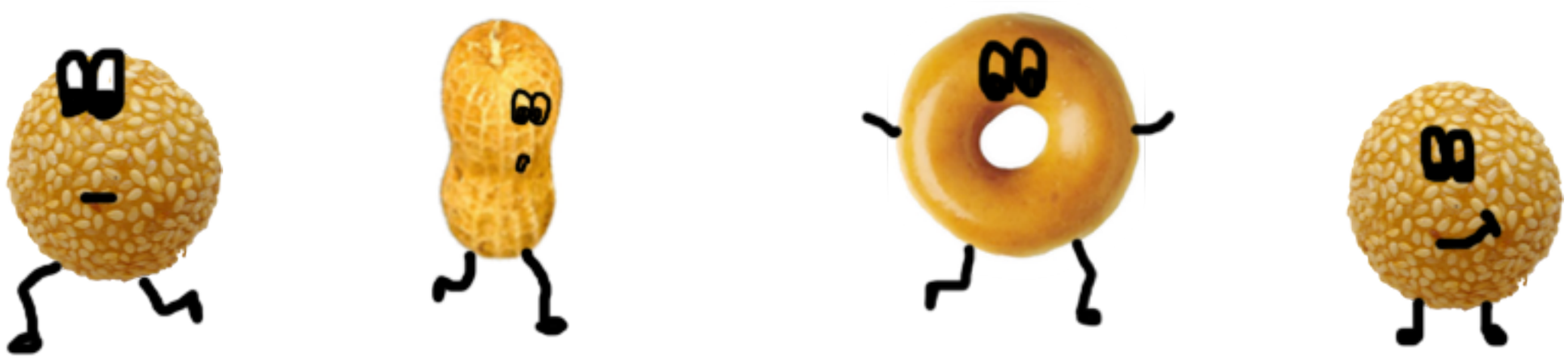


- Probe changes of the inclusive polarization caused by feed-down decays with fraction f and polarization λ_1
- Fraction f is linearly changing from 50 to 0%
- Different values for λ_0 and λ_1

Summary and conclusions

- Polarizations of the Υ(1S), Υ(2S) and Υ(3S) states in pp collisions at $\sqrt{s}$ = 7 TeV have been measured as function of charged particle multiplicity in ranges of p_T
- No significant changes from low to high multiplicity pp collisions, but large uncertainties preclude definite statements for Υ(2S) and Υ(3S)
- First step in a broader study
  - Extension to charmonium family, in particular ψ(2S) that is not affected by feed-down
  - Extension to pPb and PbPb collisions to study how the quark-antiquark bound-state formation is influenced by the surrounding medium