J/ψ production with NRQCD: Unpolarized global analysis. Polarized photoproduction.

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Production and decay rates of Heavy Quarkonia

Heavy Quarkonia: Bound states of heavy quark and antiquark.

- Charmonia ($c\bar{c}$) and Bottomonia ($b\bar{b}$)
- Top decays to fast for bound state.

The classic approach: Color-singlet model

- Calculate cross section for heavy quark pair in physical **color singlet** (=color neutral) state. In case of J/ψ: $c\bar{c}[^3S_1^{[1]}]$
- Multiply by quarkonium wave function (or its derivative) at origin
- Mid 90's: Strong disagreement with Tevatron data apparent

Nonrelativistic QCD (NRQCD):

- Rigorous effective field theory: Bodwin, Braaten, Lepage (1995)
- Based on **factorization of soft and hard scales** (Scale hierarchy: Mv^2, $Mv \ll \Lambda_{QCD} \ll M$)
- Could explain hadroproduction at Tevatron

J/ψ Production with NRQCD

Factorization theorem: $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \cdot \langle O^{J/\psi}[n] \rangle$

- ***n***: Every possible Fock state, including **color-octet** states.
- $\boldsymbol{\sigma_{c\bar{c}[n]}}$: Production rate of $c\bar{c}[n]$, calculated in perturbative QCD
- $\boldsymbol{\langle O^{J/\psi}[n] \rangle}$: Long distance matrix elements (LDMEs): describe $c\bar{c}[n] \rightarrow J/\psi$, universal, extracted from experiment.

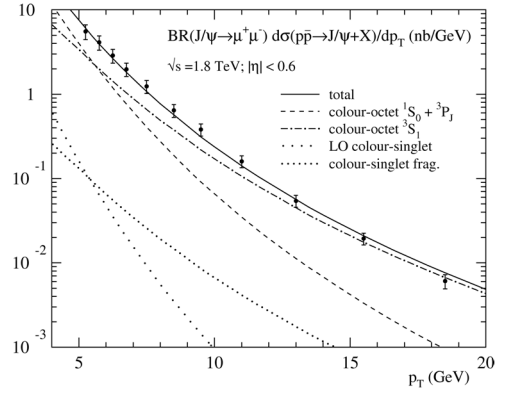
Scaling rules: LDMEs scale with definite power of v ($v^2 \approx 0.2$):

scaling	v^3	v^7	v^{11}
n	$^3S_1^{[1]}$	$^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$	...

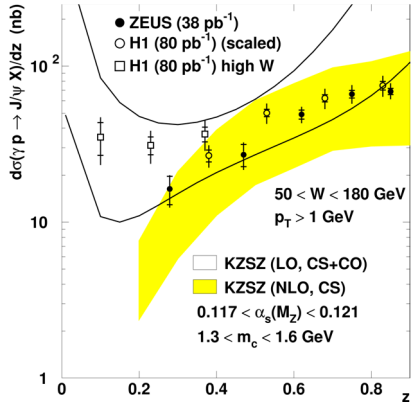
- **Double expansion** in v and α_s
- Leading term in v ($n = {}^3S_1^{[1]}$) equals **color-singlet model**.

J/ψ Production with NRQCD: Knowledge until 2005

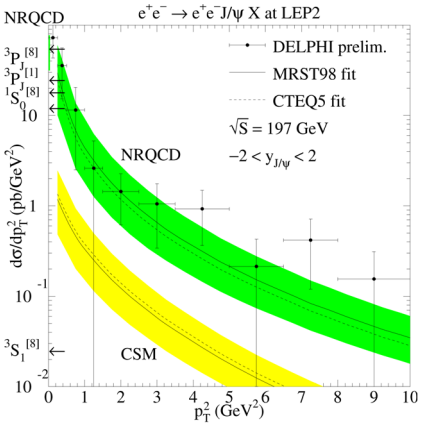
Hadroproduction at Tevatron:



Photoproduction at HERA:



γγ Scattering at LEP:



- CO LDMEs extracted from **Born fit to Tevatron** (one linear combination). Used for predictions at HERA and LEP.
- No **NLO** calculations for color-octet (CO) contributions yet!
- **Universality** of CO LDMEs open question.

NLO Corrections to Color Octet Contributions

- Petrelli, Cacciari, Greco, Maltoni, Mangano (1998):
  Photo- and hadroproduction (only $2 \to 1$ processes)
- Klasen, Kniehl, Mihaila, Steinhauser (2005):
  γγ scattering at LEP (neglecting resolved photons)
- M.B., Kniehl (2009):
  Photoproduction at HERA (neglecting resolved photons)
- Zhang, Ma, Wang, Chao (2009):
  e^+e^- scattering at *B* factories
- Ma, Wang, Chao (2010):
  Hadroproduction (including feed-down contributions)
- M.B., Kniehl (2010):
  Hadroproduction (combined HERA-Tevatron fit)

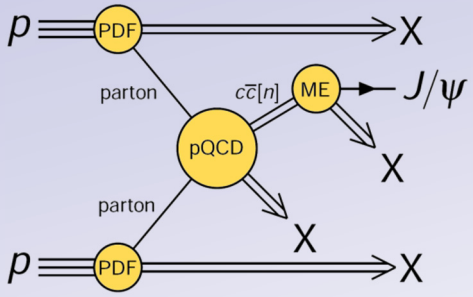
Our 2011 work:
(This talk!)

- CO LDMEs: **Global fit** to unpolarized data (194 points).
- **Polarization predictions** for photoproduction.

➡ Test LDME universality.

Calculate Inclusive J/ψ Production within NRQCD

Factorization formulas (here hadroproduction):



- Convolute partonic cross section with **proton PDFs:**

$$\sigma_{\text{hadr}} = \sum_{i,j} \int dx\, dy\, f_{i/p}(x)\, f_{j/p}(y) \cdot \sigma_{\text{part,i,j}}$$

- **NRQCD factorization:**

$$\sigma_{\text{part,i,j}} = \sum_{n} \sigma(ij \to c\bar{c}[n] + X) \cdot \langle O^{J/\psi}[n] \rangle$$

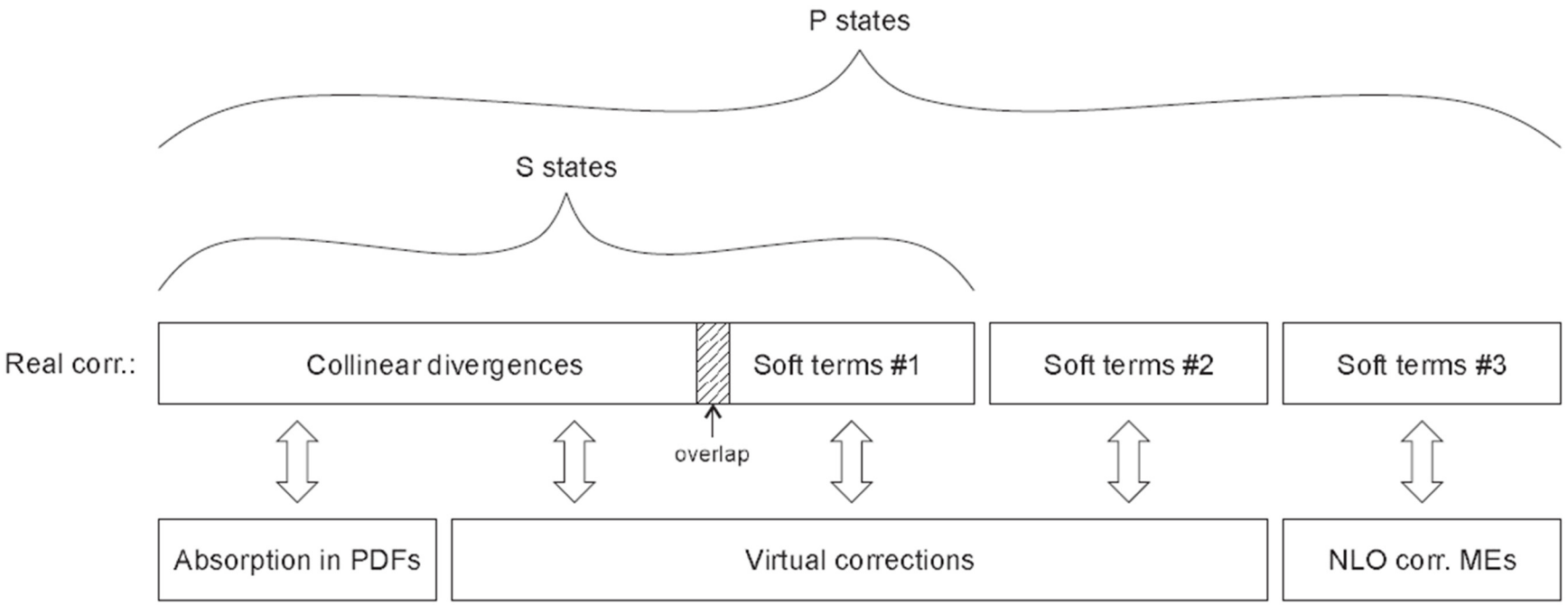
Amplitudes for $c\bar{c}[n]$ production by projector application, e.g.:

$$A_{c\bar{c}[^3S_1^{[1/8]}]} = \varepsilon_\alpha(m_s)\,\mathrm{Tr}\,[C\,\Pi^\alpha\,A_{c\bar{c}}]\,|_{q=0}$$

$$A_{c\bar{c}[^3P_J^{[8]}]} = \varepsilon_\alpha(m_s)\,\varepsilon_\beta(m_l)\,\frac{d}{dq_\beta}\,\mathrm{Tr}\,[C\,\Pi^\alpha\,A_{c\bar{c}}]\,|_{q=0}$$

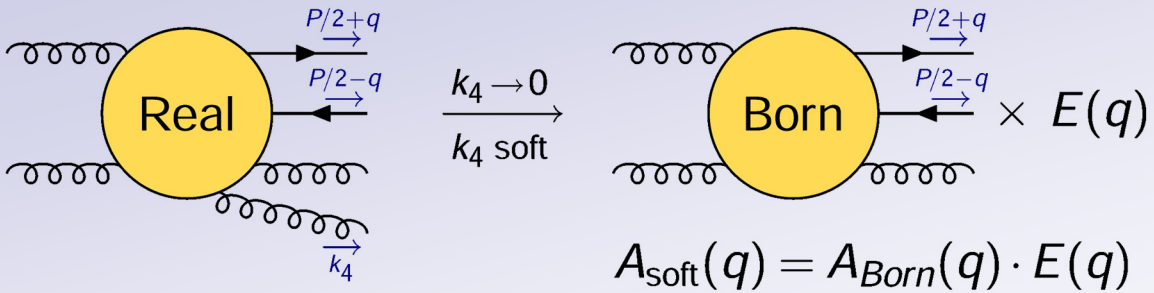
- $A_{c\bar{c}}$: Amputated pQCD amplitude for open $c\bar{c}$ production.
- q: Relative momentum between c and $\bar{c}$. ε: Polarization vectors.

Overview of IR Singularity Structure



Structure of Soft Singularities

Soft limits of the real corrections:



$$A_{\text{soft}}(q) = A_{Born}(q) \cdot E(q)$$

S and P states: Soft #1 + Soft #2 + Soft #3 terms:

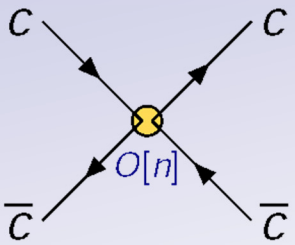
$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

$$|A_{\text{soft,s}}|^2 = |A_{\text{Born,s}}|^2 \cdot E(0)^2$$
$$|A_{\text{soft,p}}|^2 = |A_{\text{Born,p}}|^2 \cdot E(0)^2 + 2\,\text{Re}\, A^*_{\text{Born,s}} A_{\text{Born,p}} \cdot E(0)E'(0) + |A_{\text{Born,s}}|^2 \cdot E'(0)^2$$

Radiative Corrections to LDMEs

In NRQCD: Long distance MEs = $c\bar{c}$ scattering amplitudes:

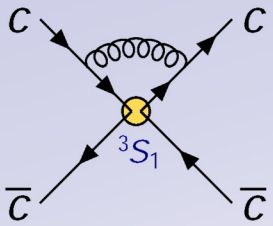
$$\langle O^{J/\psi}[n] \rangle =$$



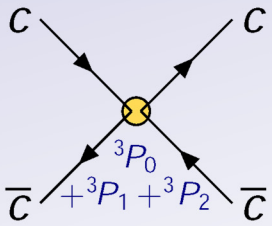
$O[n]$ = 4-fermion operators

$(n = {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}, \ldots)$

Corrections to $\langle O^{J/\psi}[{}^3S_1^{[1/8]}] \rangle$ with NRQCD Feynman rules:



$+$ similar diagrams $\propto \frac{4\alpha_s}{3\pi m_c^2}\left(\frac{1}{\varepsilon_{\text{UV}}} - \frac{1}{\varepsilon_{\text{IR}}}\right) \cdot$

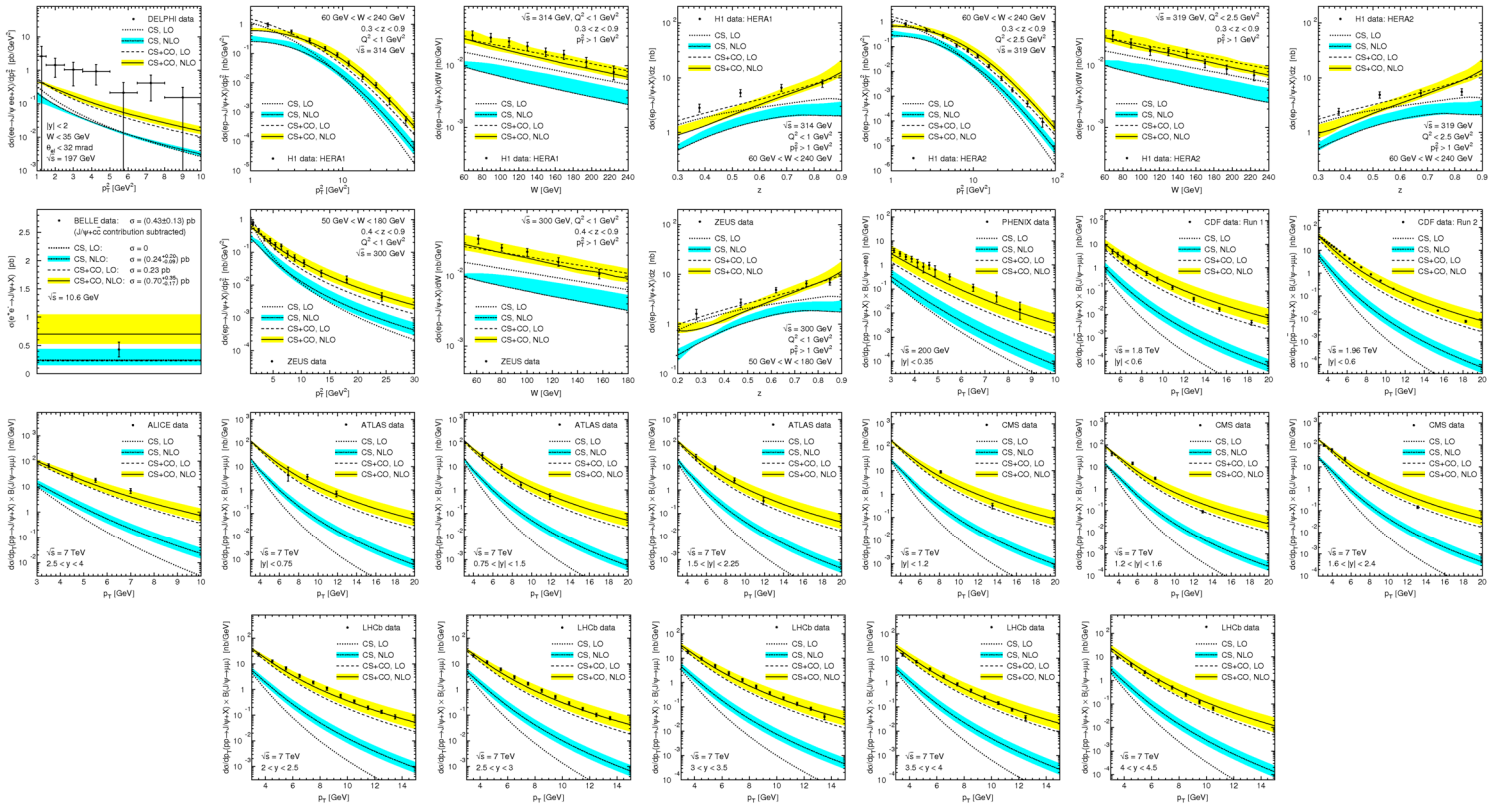


- **UV singularity** cancelled by renormalization of 4-fermion operator.
- **IR singularity** cancels soft #3 terms of *P* states.

CO LDMEs: Global Fit to unpolarized data

- We perform a fit to **194 data points** from 26 data sets from 10 experiments: ALICE, ATLAS, BELLE, CDF, CMS, DELPHI, H1, LHCb, PHENIX, ZEUS.
- Here: Consider **inclusive unpolarized J/ψ production** yield.
- Partonic Born cross sections: Parton + Parton → J/ψ + Parton
  (Parton means gluon or u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$ quark.)
- Partonic real correction cross sections: Parton + Parton → J/ψ + 2 Partons
- Set color singlet LDME to $\langle O[^3S_1^{[1]}] \rangle = 1.32\ \text{GeV}^3$.
- Fit **color octet LDMEs** $\langle O[^1S_0^{[8]}] \rangle$, $\langle O[^3S_1^{[8]}] \rangle$ and $\langle O[^3P_0^{[8]}] \rangle$.
- Ignore feed-downs in calculation, but effect estimated later on.
- Low p_T hadroproduction cannot be described due to nonperturbative effects
  ➡ Exclude data points with $p_T < 3$ GeV.
- Photoproduction at HERA and $\gamma\gamma$ scattering at LEP:
  For the first time including **resolved photon** contributions!

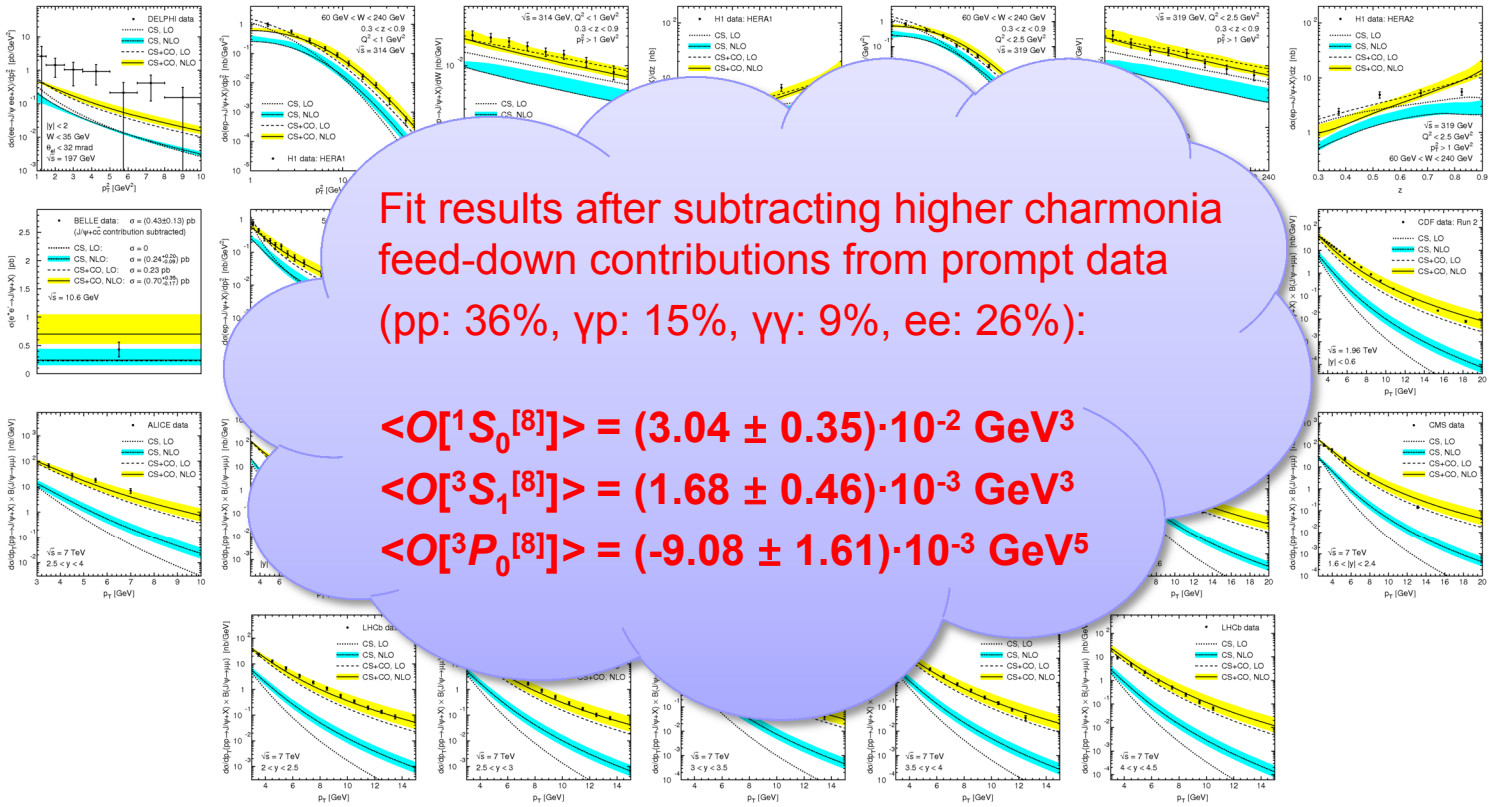
Global Fit Result



$\langle O[^1S_0^{[8]}] \rangle = (4.97 \pm 0.44) \cdot 10^{-2}$ GeV^3 $\quad \langle O[^3S_1^{[8]}] \rangle = (2.24 \pm 0.59) \cdot 10^{-3}$ GeV^3

$\langle O[^3P_0^{[8]}] \rangle = (-1.61 \pm 0.20) \cdot 10^{-2}$ GeV^5

Global Fit Result



Fit results after subtracting higher charmonia feed-down contributions from prompt data (pp: 36%, γp: 15%, γγ: 9%, ee: 26%):

$\langle O[^1S_0^{[8]}] \rangle = (3.04 \pm 0.35) \cdot 10^{-2}$ GeV^3

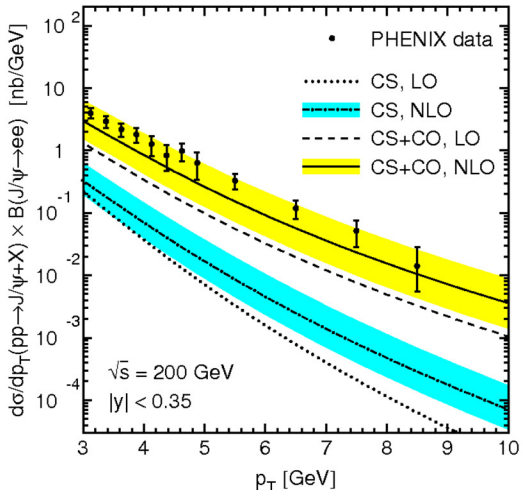
$\langle O[^3S_1^{[8]}] \rangle = (1.68 \pm 0.46) \cdot 10^{-3}$ GeV^3

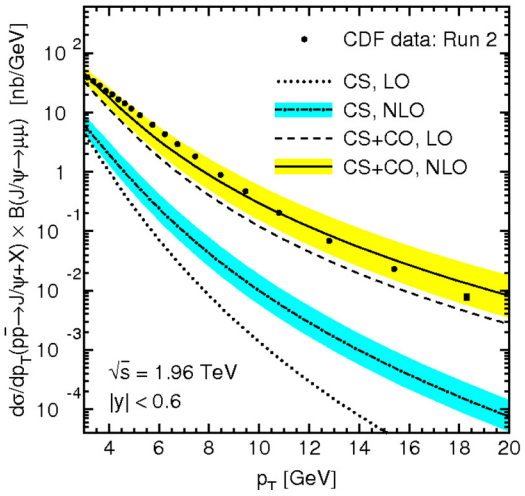
$\langle O[^3P_0^{[8]}] \rangle = (-9.08 \pm 1.61) \cdot 10^{-3}$ GeV^5

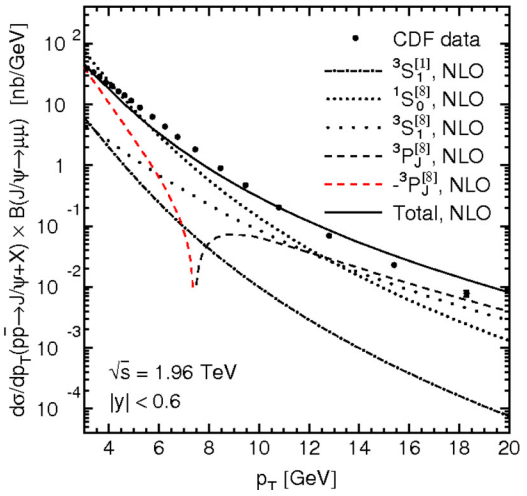
$\langle O[^1S_0^{[8]}] \rangle = (4.97 \pm 0.44) \cdot 10^{-2}$ GeV^3 $\quad$ $\langle O[^3S_1^{[8]}] \rangle = (2.24 \pm 0.59) \cdot 10^{-3}$ GeV^3

$\langle O[^3P_0^{[8]}] \rangle = (-1.61 \pm 0.20) \cdot 10^{-2}$ GeV^5

In Detail: Hadroproduction (RHIC, Tevatron)

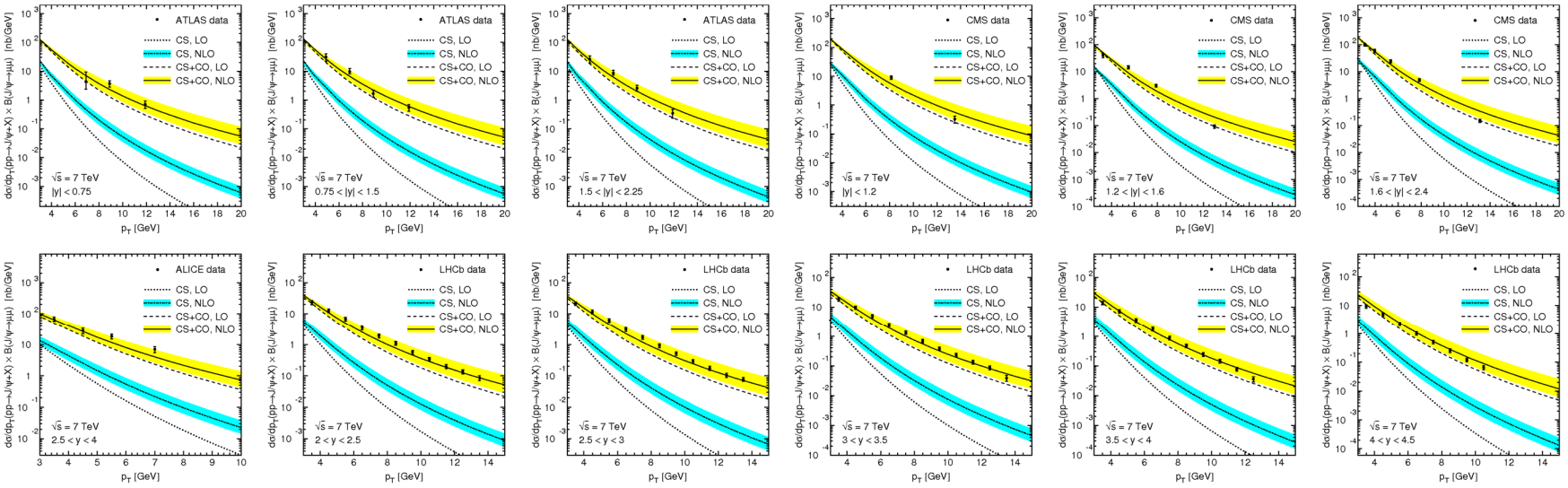






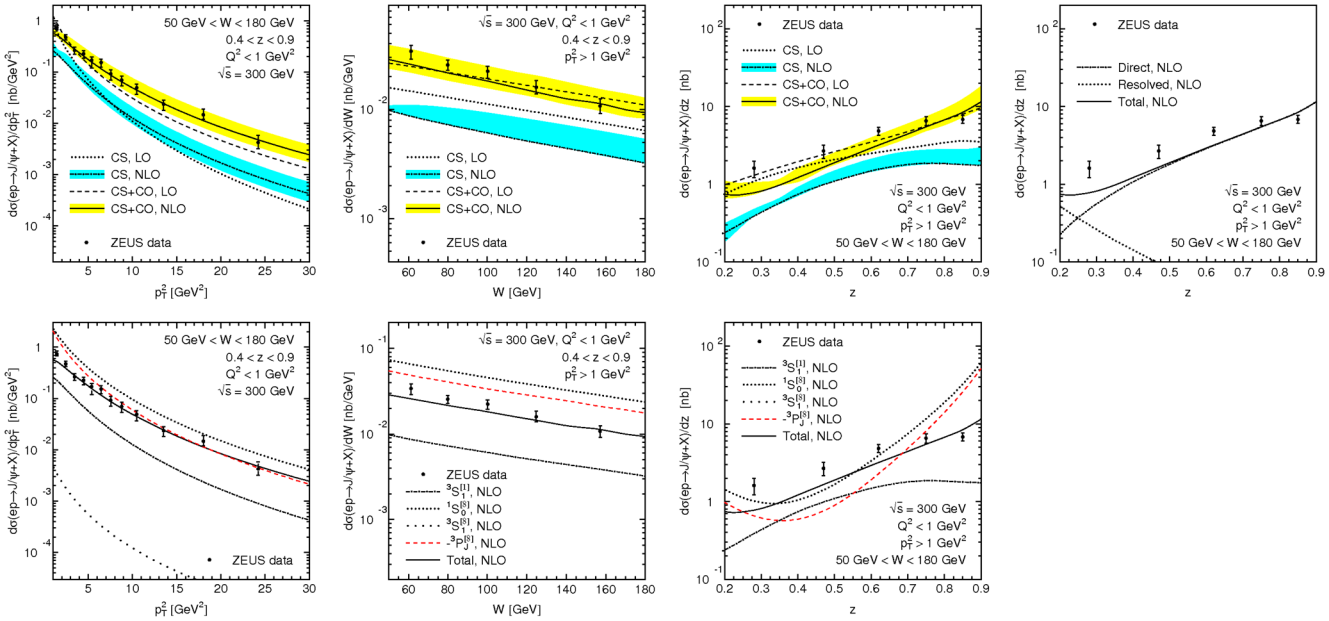
- Color singlet model **not enough** to describe data (although increase from Born to NLO)
- **CS+CO** can describe data.
- $^3P_J^{[8]}$ short distance cross section **negative** at $p_T > 7$ GeV.
- But: Short distance cross sections and LDMEs **unphysical**
  ➡ No problem!

In Detail: Hadroproduction (LHC)



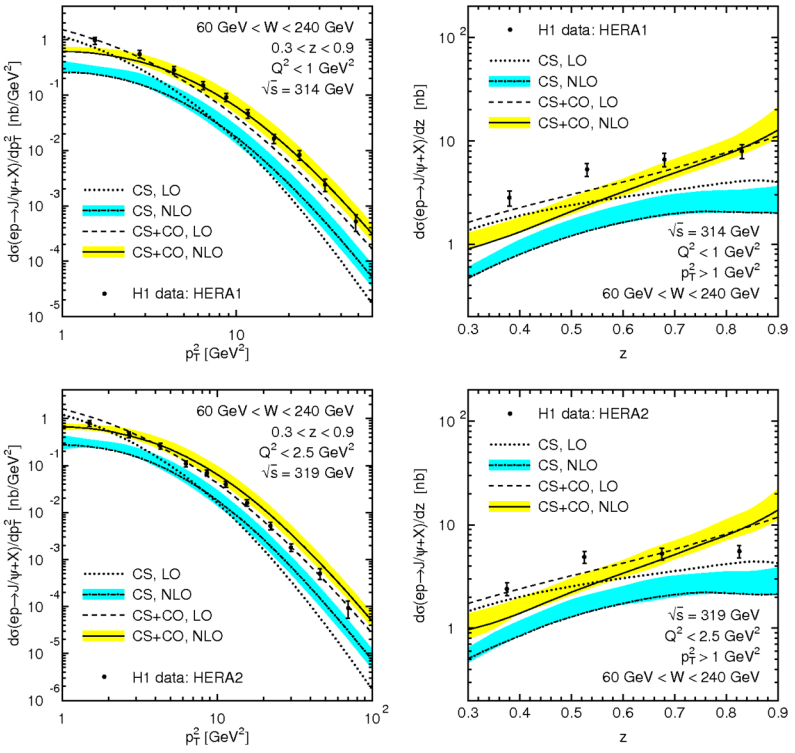
- Data from ALICE, ATLAS, CMS and LHCb.
- All data points assuming **unpolarized** *J/ψ.*
- Like at RHIC and Tevatron: CS far **below** data, **CS+CO** describes data well.
- Observation: Change *s* or rapidity *y* just **rescaling** of cross sections:
  CO LDMEs describing RHIC or Tevatron must also describe LHC!

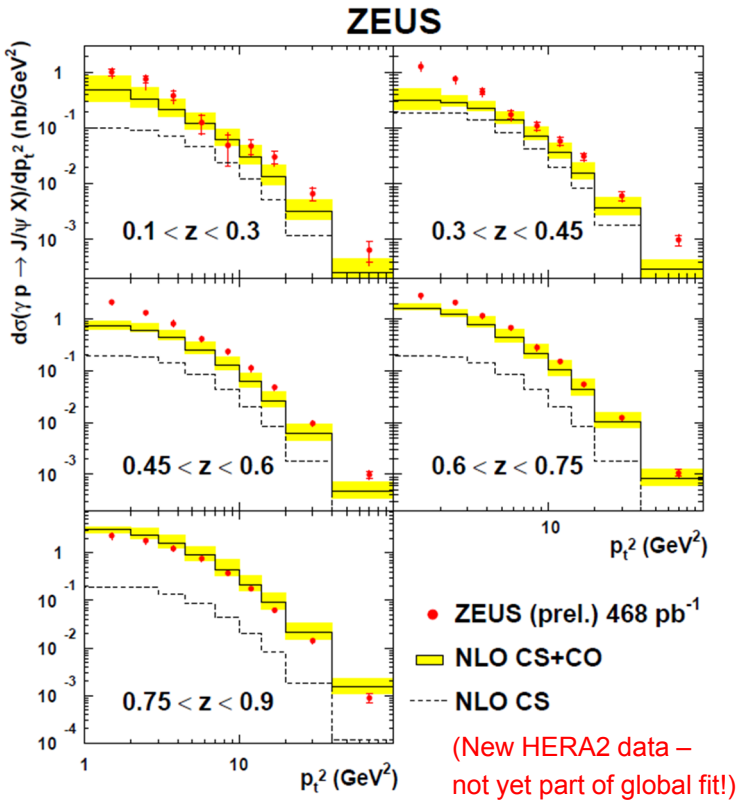
In Detail: Photoproduction (ZEUS HERA1)



- **Distributions:** Transverse momentum (p_T), photon-proton c.m. energy (W), and z = Fraction of photon energy going to J/ψ.
- Again: Color singlet alone **below** the data, **CS+CO** describes data well.
- Calculation includes **resolved** photon contributions: Important at low z.
- **Good description at high z:** No increase like in older Born analyses!

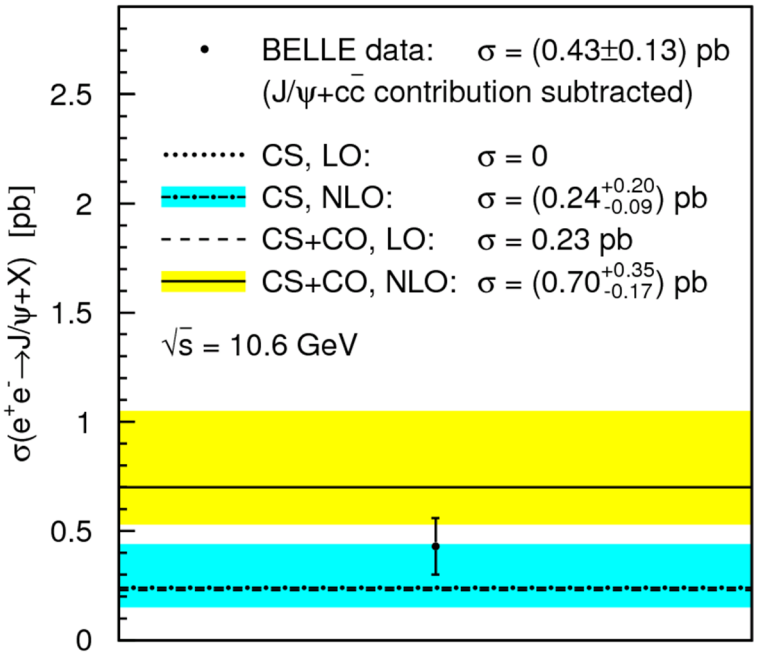
In Detail: More Photoproduction





- Again: CS alone **below** data; **CS+CO** good description, especially at high *z*.
- H1 HERA2 data systematically below H1 HERA1 and ZEUS HERA1 + 2.

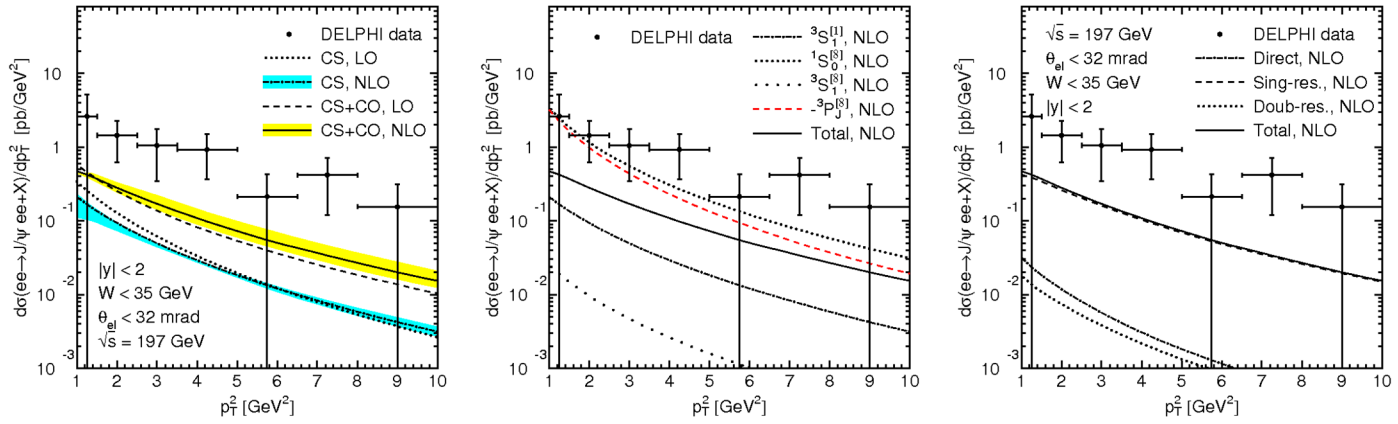
In Detail: Electron-Positron Scattering



- **Double charmonium** production cross section large (≈ 60%), but not included in our calculation. ➡ Use BELLE measurement with $J/\psi+c\bar{c}$ contribution **subtracted**.
- **CS:** Large overlap with data, **CS+CO:** Small overlap.
- Experimentally measurement of total cross section problematic, **discrapencies** between BELLE and BABAR (which is larger).

- For us, LO means J/ψ + parton, but in CMS, LO is J/ψ + 2 partons. In CMS, α_s corrections to J/ψ + 2 partons have been calculated, CS contribution increases. For consistency, not part of this analysis.

In Detail: Photon-Photon Scattering

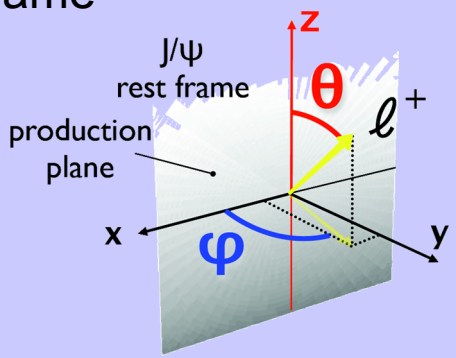


- **Photon-Photon** scattering measured by DELPHI at LEP.
- For the first time contribution of **resolved** photons included at NLO (direct + single resolved + double resolved). Single resolved dominates.
- CS below data, but also **CS+CO** prediction **too low**. Possible explanations:
  - Uncertainties in the measurement (just 16 events involved!)
  - Unknown higher order effects important at relatively low p_T.
  - Hint at problems with LDME universality.

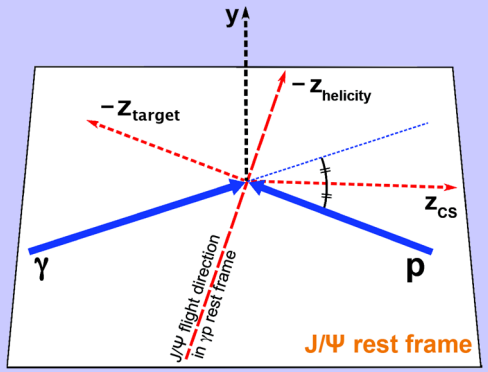
J/ψ Polarization in Photoproduction

- **Angular distribution** of decay lepton l^+ in J/ψ rest frame
  ➡ Polarization observables λ, μ, ν:

$$\frac{d\Gamma(J/\psi \to l^+ l^-)}{d\cos\theta\, d\phi} \propto 1 + \lambda\cos^2\theta + \mu\sin(2\theta)\cos\phi + \frac{\nu}{2}\sin^2\theta\cos(2\phi)$$



- Depends on choice of **coordinate system:**
  - Helicity frame: z axis $\| -(\vec{p}_\gamma + \vec{p}_p)$
  - Collins-Soper frame: z axis $\| \vec{p}_\gamma/|\vec{p}_\gamma| - \vec{p}_p/|\vec{p}_p|$
  - Target frame: z axis $\| -\vec{p}_p$

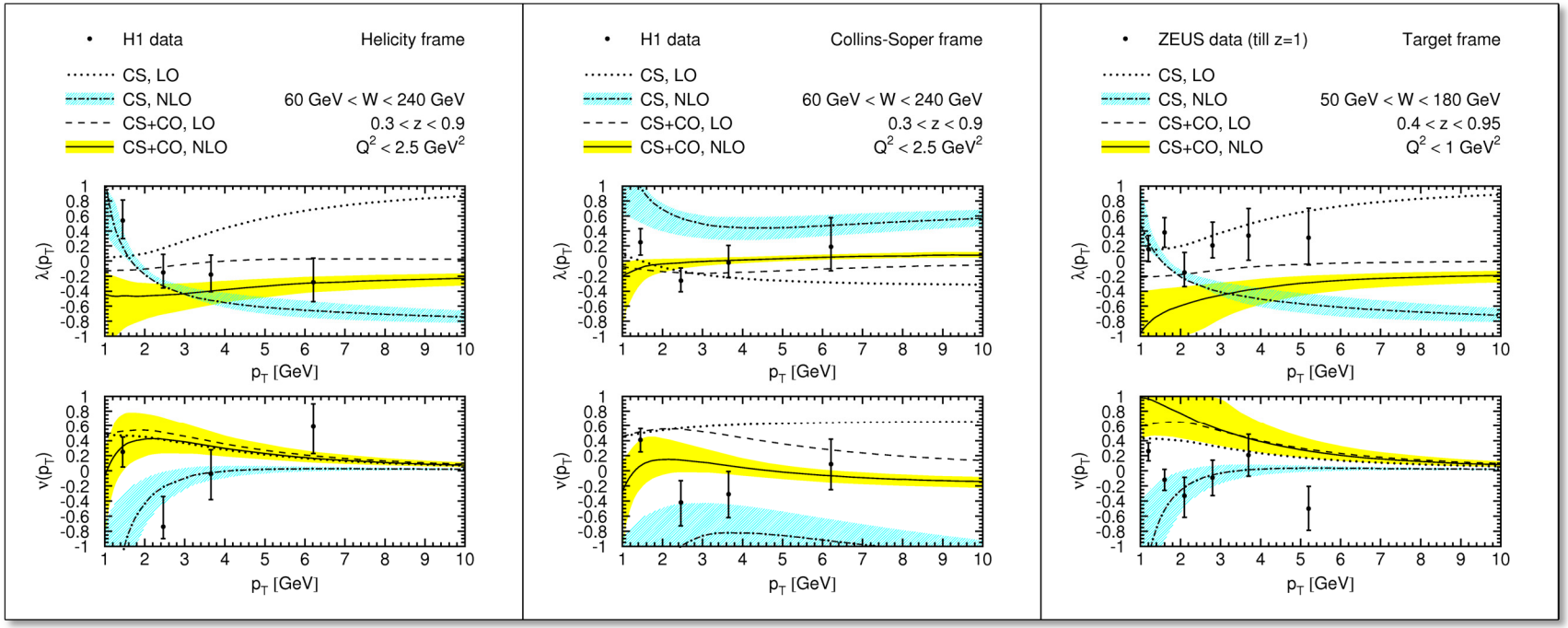


- **In Calculation:** Plug in explicit expressions for $c\bar{c}[n]$ spin polarization vectors according to

$$\lambda = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \quad \mu = \frac{\sqrt{2}\,\mathrm{Re}\, d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}}, \quad \nu = \frac{2d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}$$

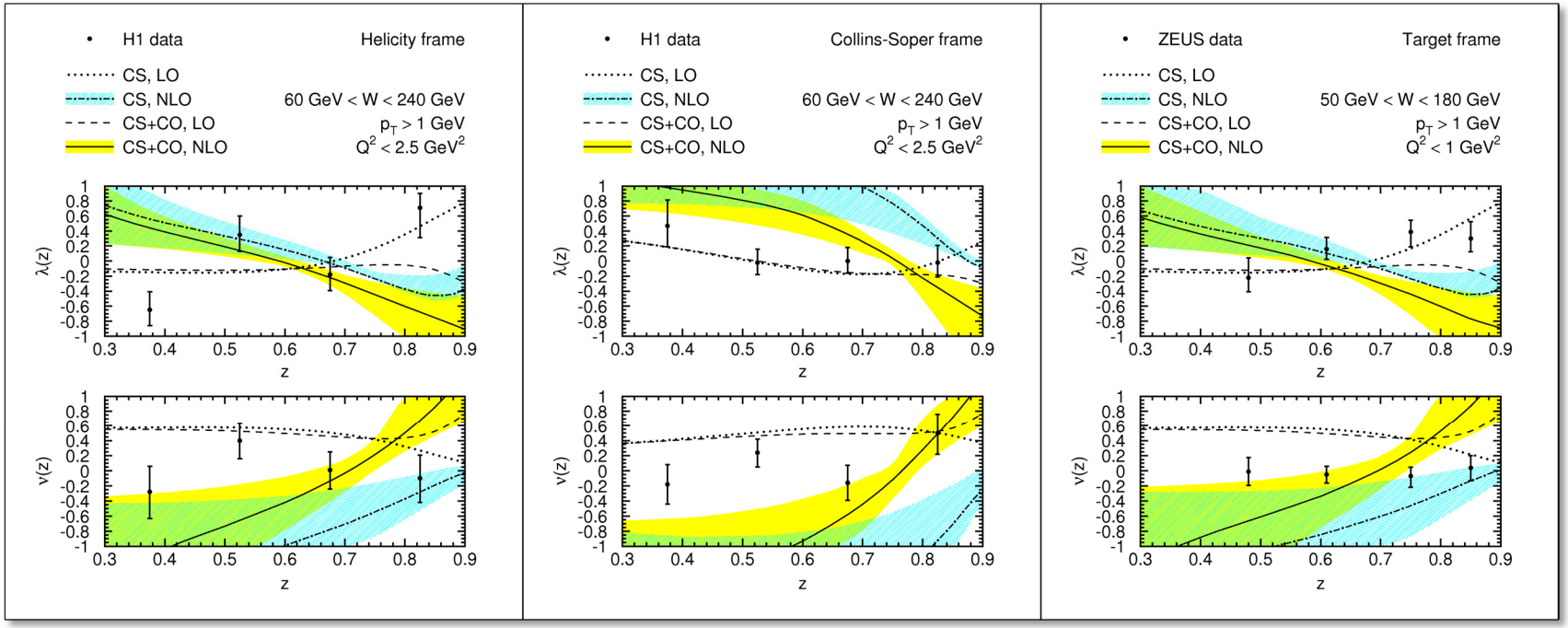
- Here: Direct photoproduction. CO LDME set with feed-downs subtracted.

J/ψ Polarization Results: p_T Distributions



- Bands: Uncertainties due to scale variation and CO LDMEs.
- **CSM** predicts **longitudinal** *J/ψ* at high p_T.
- **CS+CO:** largely **unpolarized** *J/ψ* at high p_T. α_s expansion converges better.
- H1 and ZEUS **data not precise** enough to discriminate CSM / NRQCD.

J/ψ Polarization Results: z Distribution



- Bands: Uncertainties due to scale variation and CO LDMEs.
- **Scale** uncertainties very large.
- **Error bands** of CSM and NRQCD largely **overlap**.

➡ p_T distribution better suited to discriminate production mechanisms than z.

Summary

- NRQCD provides rigorous **factorization theorem** for heavy quarkonium production. But: Need to proof **LDME universality**.

- **Combined NLO fit** of NRQCD LDMEs to inclusive *J/ψ* production data from ALICE, ATLAS, BELLE, CDF, CMS, DELPHI, H1, LHCb, PHENIX, ZEUS.
- **CSM** predictions fall **short of data** everywhere except for $e^+e^- \rightarrow J/\psi+X$.
- Good agreement for **CS+CO** with data except perhaps for $\gamma\gamma \rightarrow J/\psi+X$.

- First NLO calculation of **polarized** *J/ψ* cross section including CO states: Direct photoproduction at HERA.
- NRQCD predicts largely **unpolarized** *J/ψ*, CSM **longitudinally** polarized.
- H1 and ZEUS **data not precise** enough to discriminate CSM / NRQCD.

- **Outlook:** Polarization at Tevatron and LHC.