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

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Production and Decay Rates of Heavy Quarkonia

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 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, $Mv << \Lambda_{QCD} << M$)
- Could explain hadroproduction at Tevatron

Further models on the market:

- k_T factorization approach
- Color Evaporation Model
- ...

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.

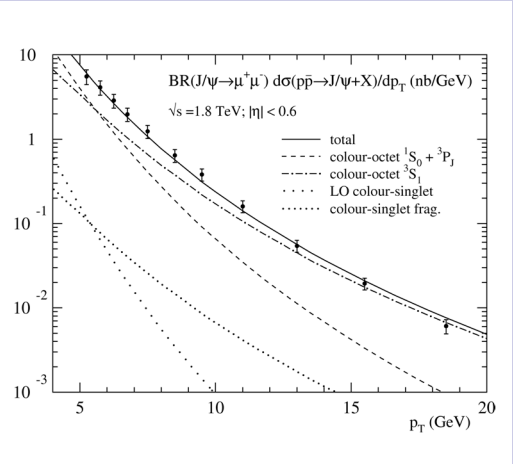
Scaling rules: LDMEs scale with definite power of v ($v^2 \approx 0.2$):

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

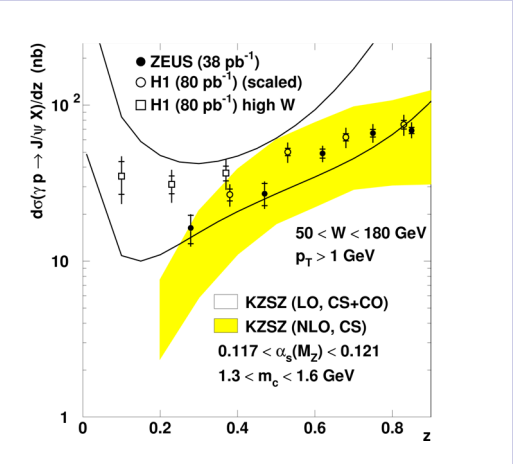
- **Double expansion** in v and α_s
- Leading term in v ($n = {}^3S_1^{[1]}$) equals **color-singlet model**.

J/ψ Production with NRQCD: Knowledge until 2005

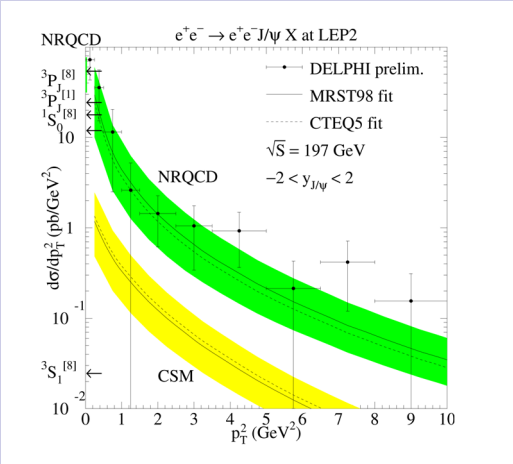
Hadroproduction at Tevatron:



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 → 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!)

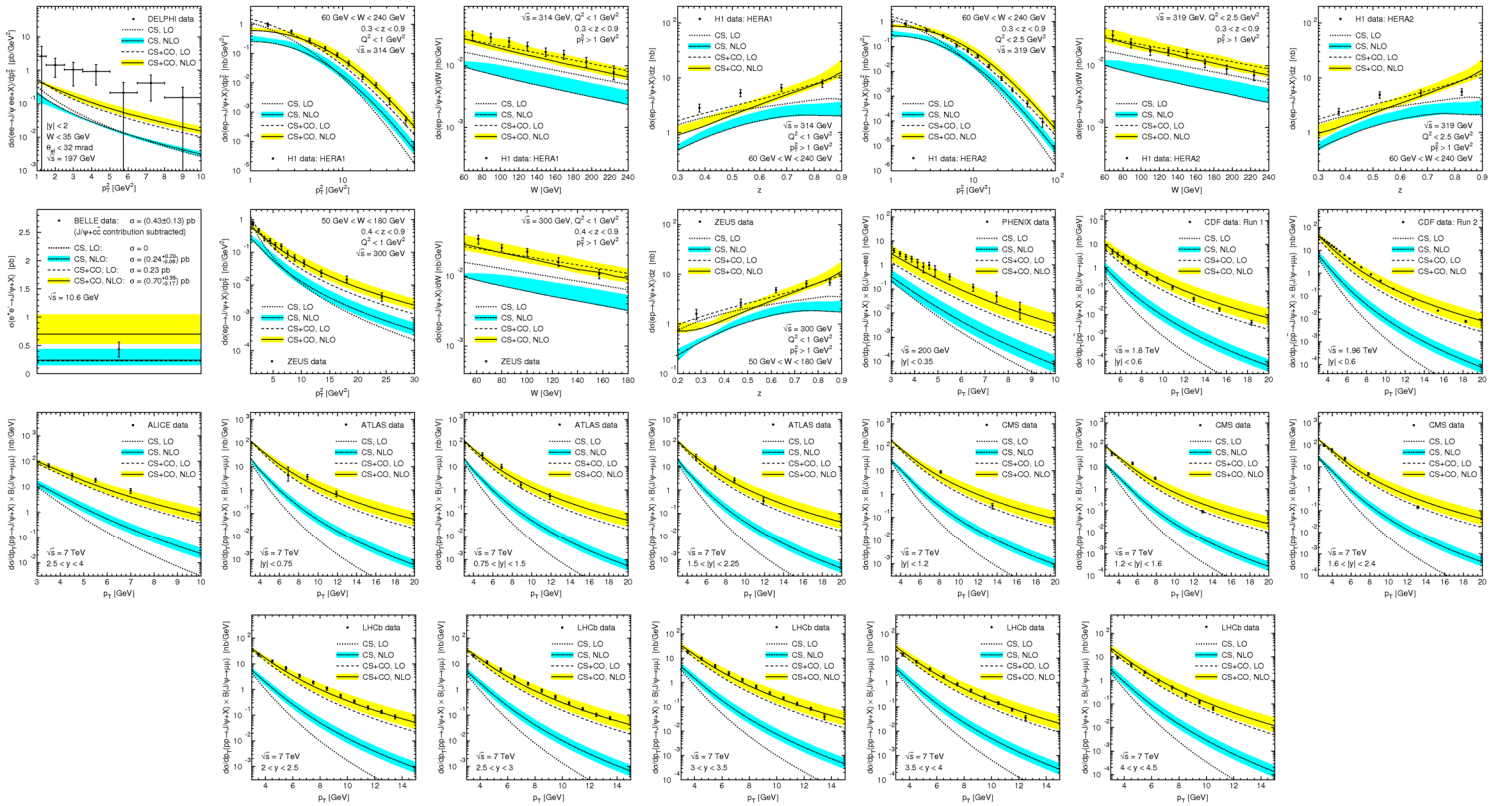
- CO LDMEs: **Global fit** to unpolarized data (194 points).
- **Polarization predictions** for photoproduction.

➡ Test LDME universality.

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 $\langle O[^3S_1^{[1]}]\rangle = 1.32\ \mathrm{GeV}^3$.
- 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!

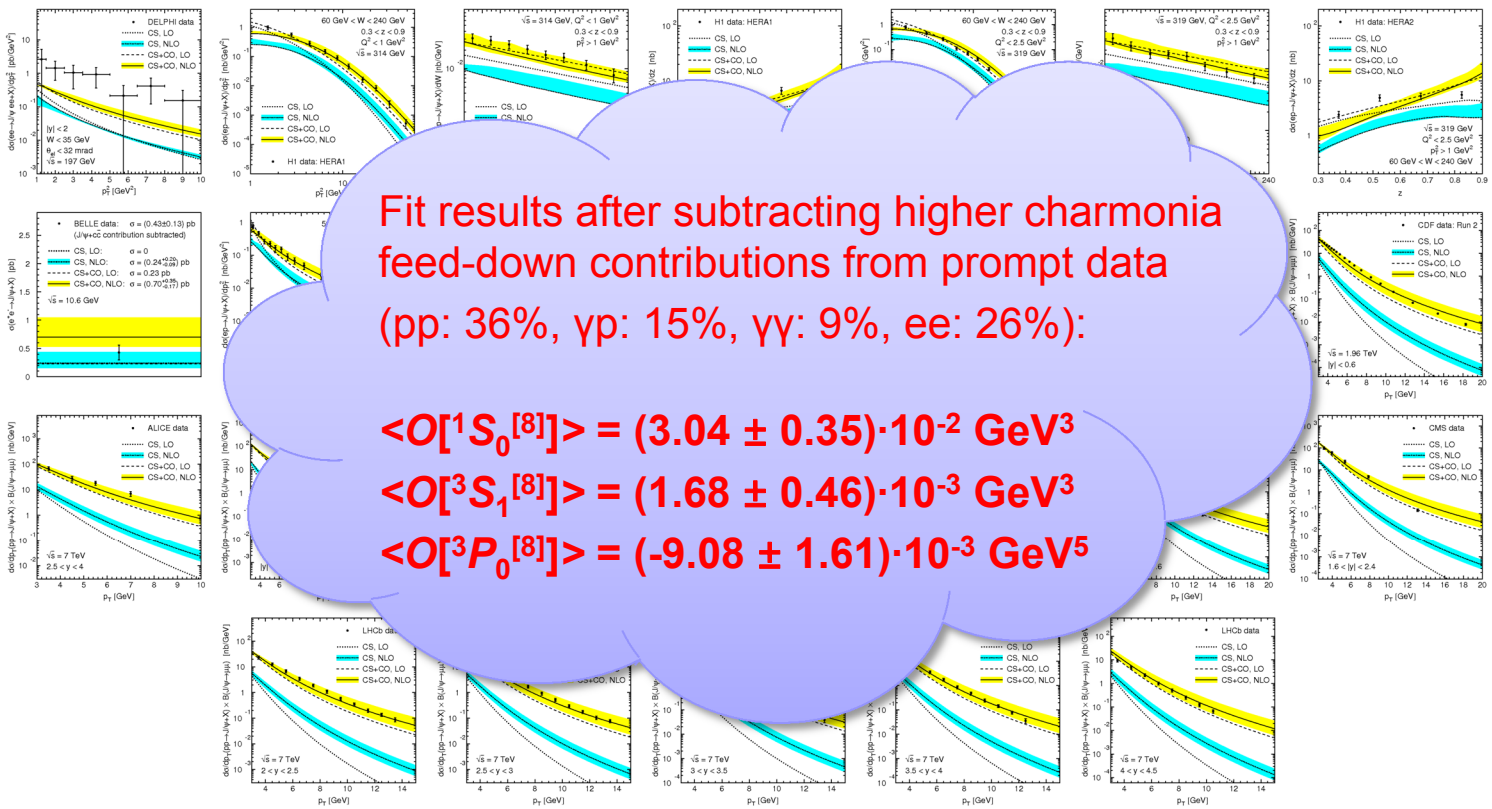
Global Fit Result



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

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

Global Fit Result



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

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

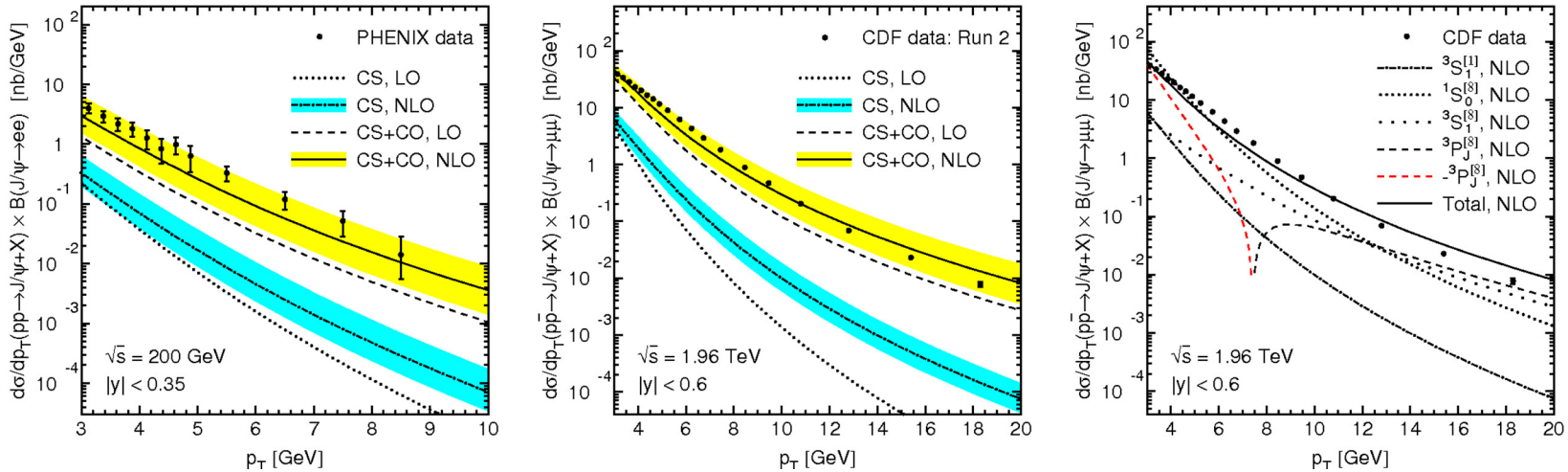
$\langle O[^3S_1^{[8]}]\rangle = (1.68 \pm 0.46)\cdot 10^{-3}\ \mathrm{GeV}^3$

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

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

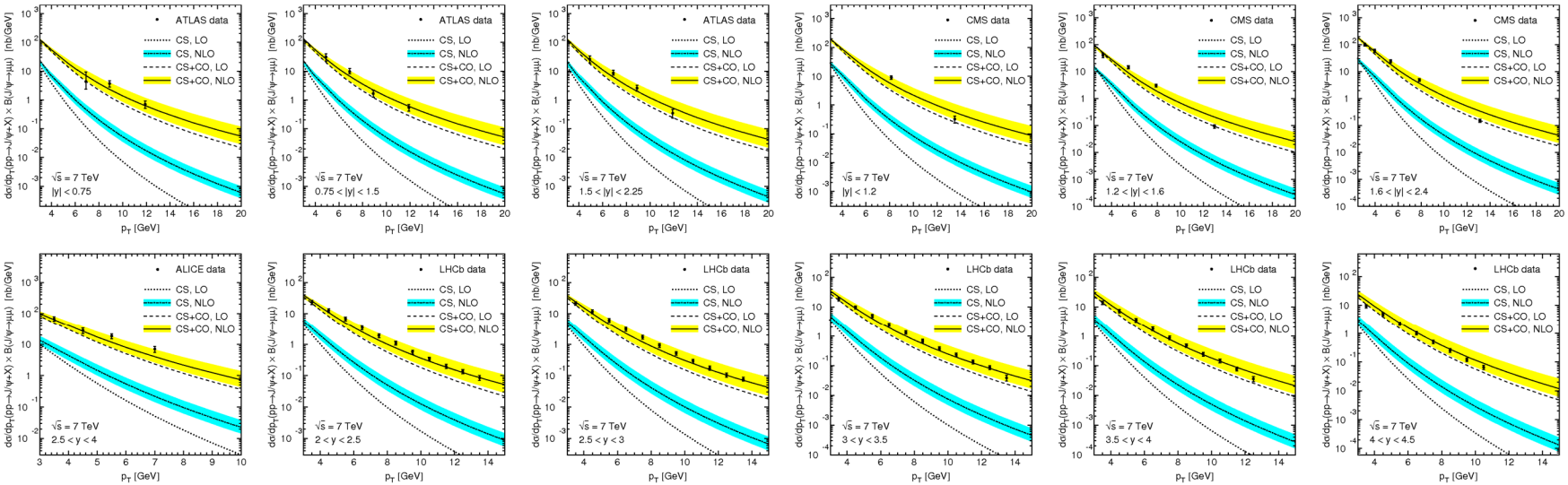
$\langle O[^3P_0^{[8]}]\rangle$ = $(-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$

In Detail: Hadroproduction (RHIC, Tevatron)



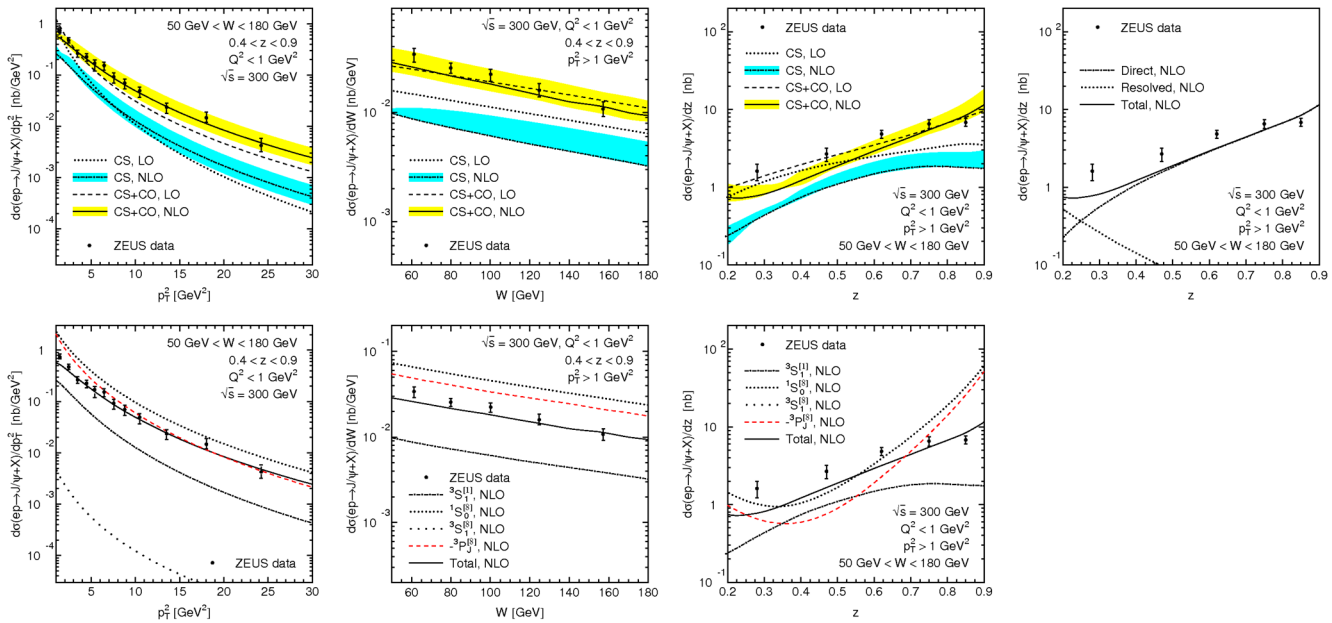
- Color singlet model **not enough** to describe data (although increase from Born to NLO)
- **CS+CO** can describe data.
- ${}^3P_J^{[8]}$ short distance cross section **negative** at $p_T > 7$ GeV.
- But: Short distance cross sections and LDMEs **unphysical**
  ➡ No problem!

In Detail: Hadroproduction (LHC)



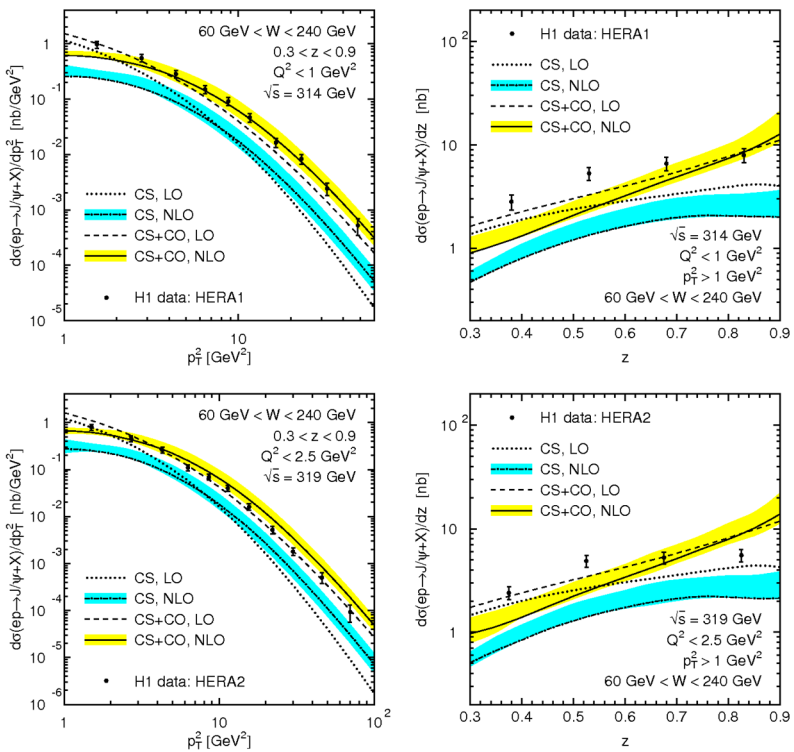
- Data from ALICE, ATLAS, CMS and LHCb.
- All data points assuming **unpolarized** *J/ψ.*
- Like at RHIC and Tevatron: CS far **below** data, **CS+CO** describes data well.
- Observation: Change *s* or rapidity *y* just **rescaling** of cross sections:
  CO LDMEs describing RHIC or Tevatron must also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

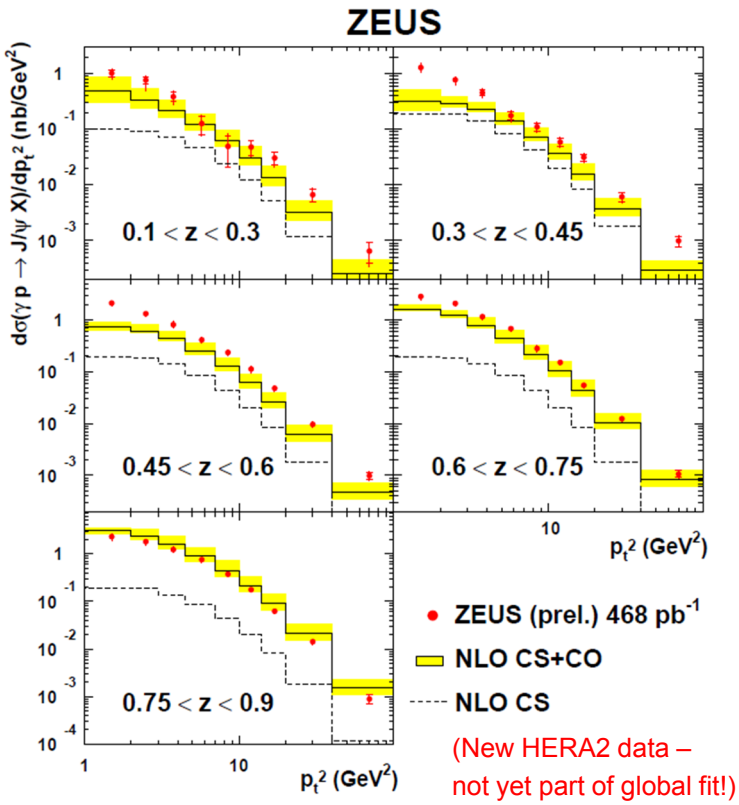
In Detail: Photoproduction (ZEUS HERA1)



- **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!

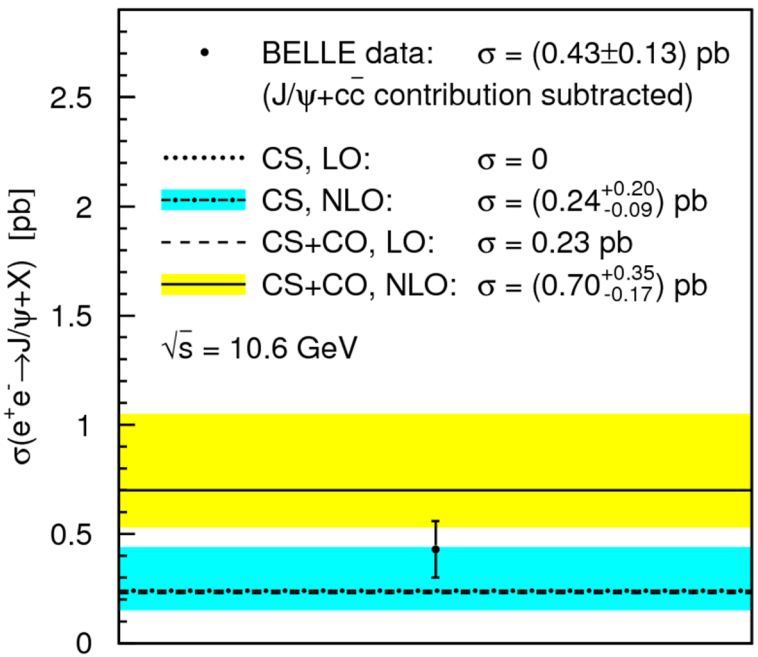
In Detail: More Photoproduction





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

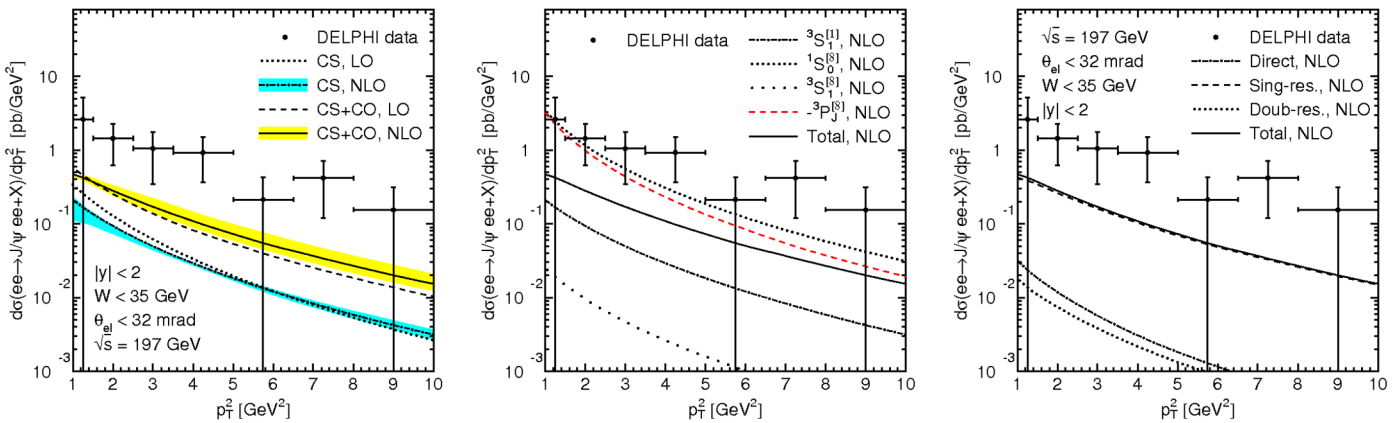
In Detail: Electron-Positron Scattering



- **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

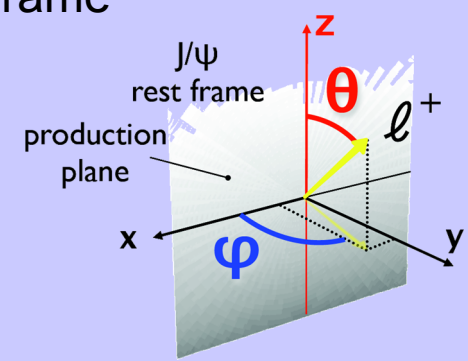


- **Photon-Photon** scattering measured by DELPHI at LEP.
- For the first time contribution of **resolved** photons included at NLO (direct + single resolved + double resolved). Single resolved dominates.
- CS below data, but also **CS+CO** prediction **too low**. Possible explanations:
  - Uncertainties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

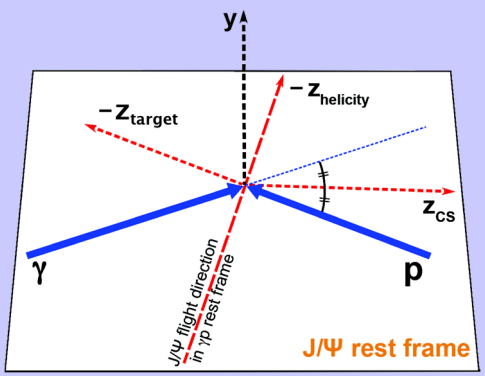
J/ψ Polarization in Photoproduction

- **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 $\parallel -(\vec{p}_\gamma + \vec{p}_p)$
  - Collins-Soper frame: z axis $\parallel \vec{p}_\gamma/|\vec{p}_\gamma| - \vec{p}_p/|\vec{p}_p|$
  - Target frame: z axis $\parallel -\vec{p}_p$

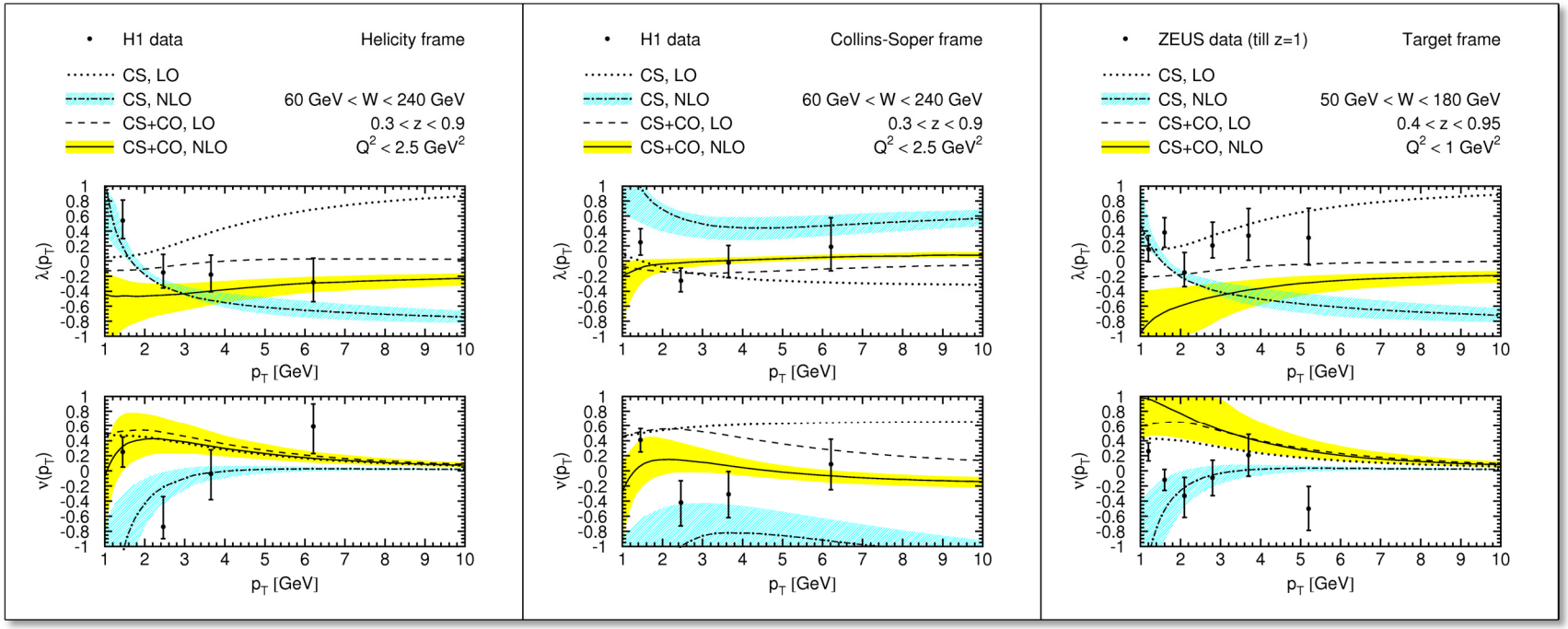


- **In Calculation:** Plug in explicit expressions for $c\bar{c}[n]$ spin polarization vectors according to

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

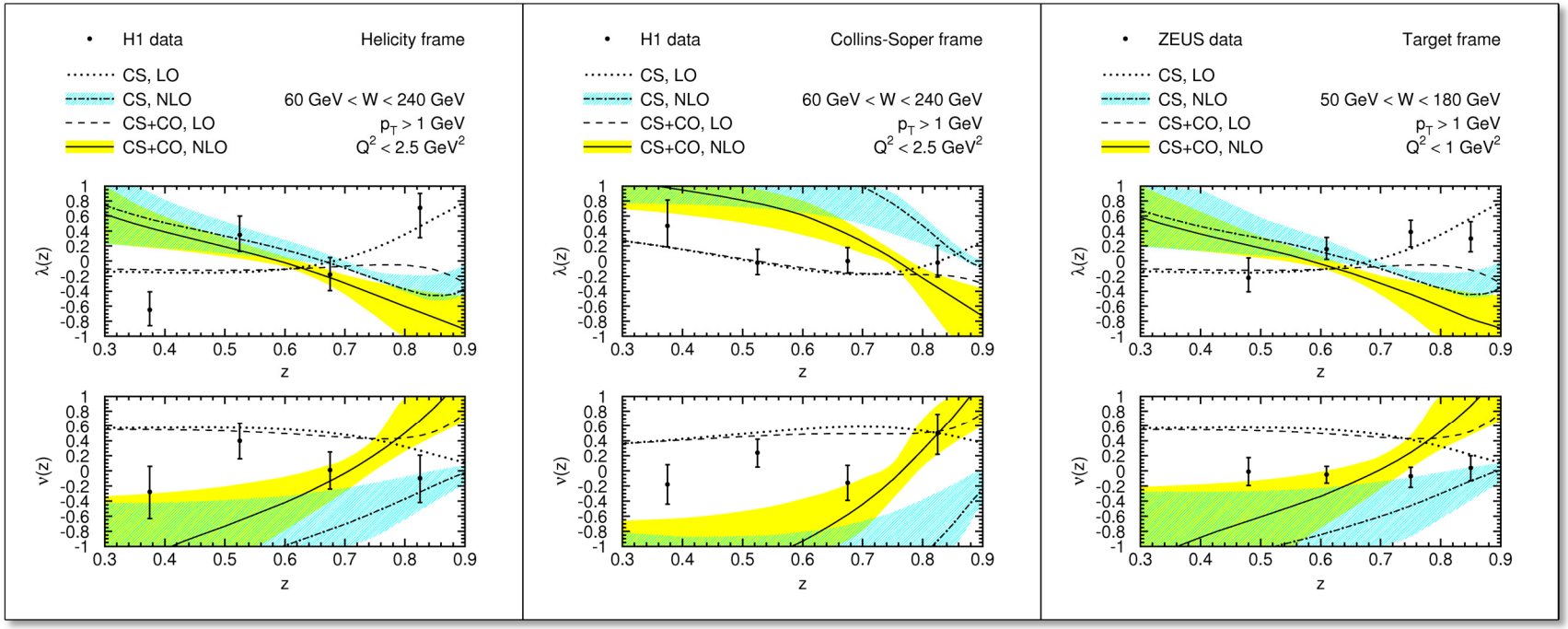
- Here: Direct photoproduction. CO LDME set with feed-downs subtracted.

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 $e^+e^- \to J/\psi + X$.
- Good agreement for **CS+CO** with data except perhaps for $\gamma\gamma \to J/\psi + X$.
- Extracted CO LDMEs in accordance with **velocity scaling rules**.

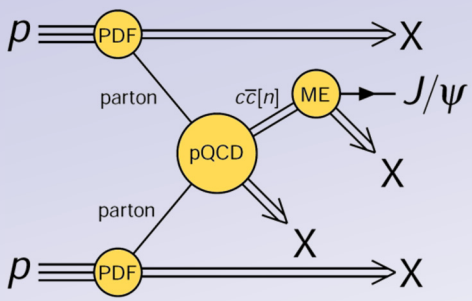
- First NLO calculation of **polarized** *J/ψ* cross section including CO states: Direct photoproduction at HERA.
- NRQCD predicts largely **unpolarized** *J/ψ*, CSM **longitudinally** polarized.
- H1 and ZEUS **data not precise** enough to discriminate CSM / NRQCD.

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

BACKUP SLIDES

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:**

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

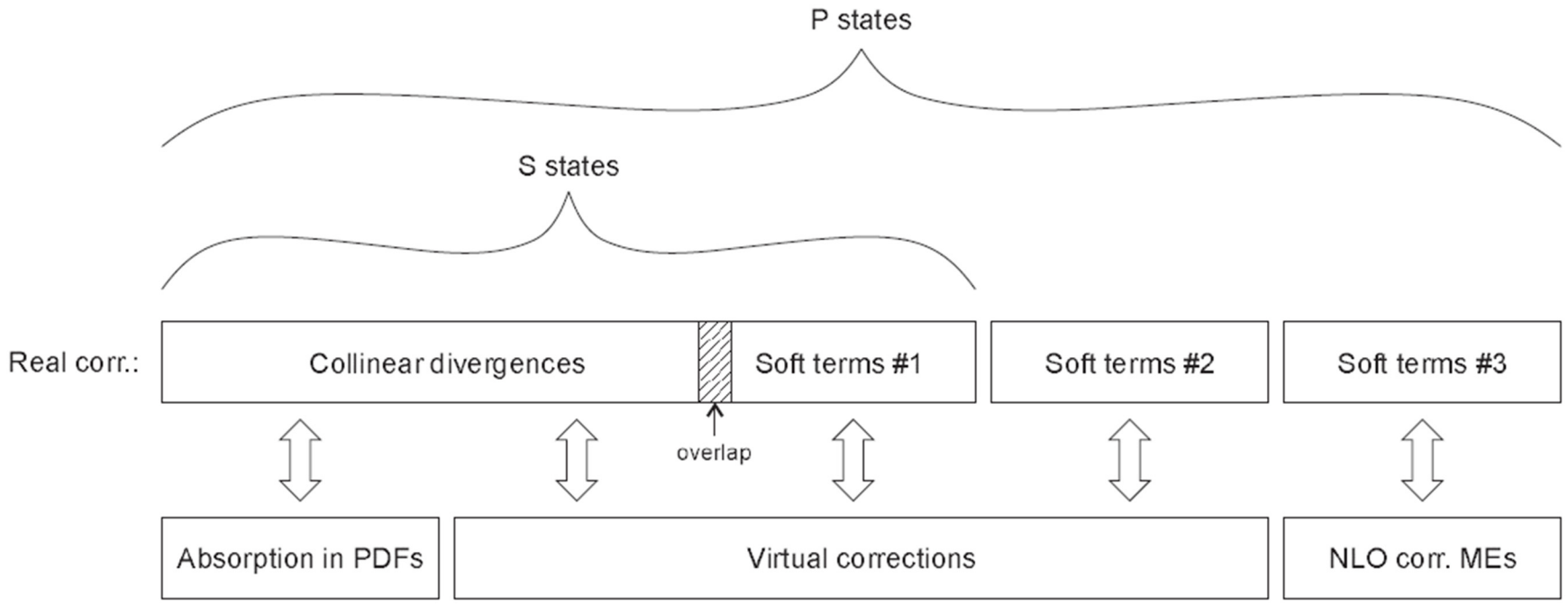
Amplitudes for $c\bar{c}[n]$ production by projector application, e.g.:

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

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

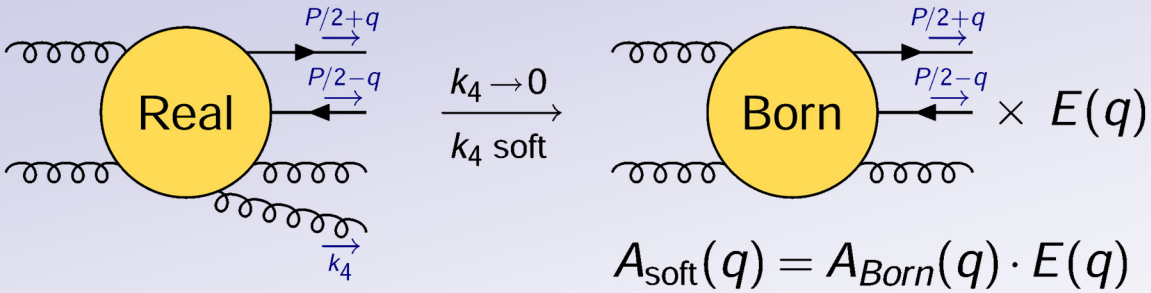
- $A_{c\bar{c}}$**:** Amputated pQCD amplitude for open $c\bar{c}$ production.
- q**:** Relative momentum between c and $\bar{c}$. ε**:** Polarization vectors.

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:

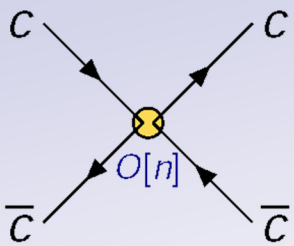
$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

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

Radiative Corrections to LDMEs

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

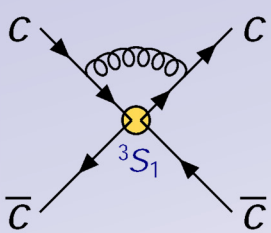
$$\langle O^{J/\psi}[n]\rangle =$$



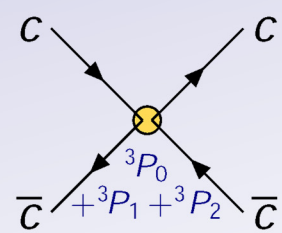
$O[n]$ = 4-fermion operators

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

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



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



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

Hadroproduction-only Fit

Global fit to hadroproduction data alone, vary low-p_T cut:

	p_T > 1 GeV	p_T > 2 GeV	p_T > 3 GeV	p_T > 5 GeV	p_T > 7 GeV
$\langle O[^1S_0^{[8]}]\rangle$ [10^{-2} GeV^3]	8.54 ± 0.52	16.85 ± 1.23	11.02 ± 1.67	1.68 ± 2.20	2.18 ± 2.56
$\langle O[^3S_1^{[8]}]\rangle$ [10^{-3} GeV^3]	-2.66 ± 0.69	-13.36 ± 1.60	-5.56 ± 2.19	8.75 ± 2.98	10.34 ± 3.55
$\langle O[^3P_0^{[8]}]\rangle$ [10^{-2} GeV^5]	-3.63 ± 0.23	-7.70 ± 0.61	-4.46 ± 0.87	2.20 ± 1.23	3.50 ± 1.50
M_0 [10^{-2} GeV^3]	**2.25 ± 0.12**	**3.51 ± 0.19**	**3.29 ± 0.20**	**5.50 ± 0.29**	**8.24 ± 0.58**
M_1 [10^{-3} GeV^3]	**6.37 ± 0.19**	**5.80 ± 0.19**	**5.54 ± 0.20**	**3.27 ± 0.29**	**1.63 ± 0.43**

- Fit **underconstrained.** Therefore give two linear combinations of Ma *et al.*:

$$M_0 = \langle O(^1S_0^{[8]})\rangle + 3.9\,\langle O(^3P_0^{[8]})\rangle/m_c^2 \qquad M_1 = \langle O(^3S_1^{[8]})\rangle - 0.56\,\langle O(^3P_0^{[8]})\rangle/m_c^2$$

- Fit results **depend strongly** on low-p_T cut.

Agreement with Ma *et al.*'s fit to Tevatron run II data with p_T > 7 GeV:

Default: Include feed-downs, directly fit M_0 and M_1:	**M_0 = (7.4 ± 1.9) 10^{-2} GeV^3**	**M_1 = (0.5 ± 0.2) 10^{-3} GeV^3**
Ignore feed-downs, directly fit M_0 and M_1:	**M_0 = (8.92 ± 0.39) 10^{-2} GeV^3**	**M_1 = (1.26 ± 0.23) 10^{-3} GeV^3**
Ignore feed-downs, M_0 and M_1 from 3-parameter fit:	**M_0 = (8.54 ± 1.02) 10^{-2} GeV^3**	**M_1 = (1.67 ± 1.05) 10^{-3} GeV^3**

[Ma, Wang, Chao: Table 1 of PRL 106, 042002 and equations (13) and (14) of arXiv:1012.1030]

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$$M_0 = \langle O(^1S_0^{[8]})\rangle + 3.9\,\langle O(^3P_0^{[8]})\rangle/m_c^2 \qquad M_1 = \langle O(^3S_1^{[8]})\rangle - 0.56\,\langle O(^3P_0^{[8]})\rangle/m_c^2$$

- Fit results **depend strongly** on low-p_T cut.

Agreement with Ma *et al.*'s fit to Tevatron run II data with p_T > 7 GeV:

Default: Include feed-downs, directly fit M_0 and M_1:	**M_0 = (7.4 ± 1.9) 10^{-2} GeV^3**	**M_1 = (0.5 ± 0.2) 10^{-3} GeV^3**
Ignore feed-downs, directly fit M_0 and M_1:	**M_0 = (8.92 ± 0.39) 10^{-2} GeV^3**	**M_1 = (1.26 ± 0.23) 10^{-3} GeV^3**
Ignore feed-downs, M_0 and M_1 from 3-parameter fit:	**M_0 = (8.54 ± 1.02) 10^{-2} GeV^3**	**M_1 = (1.67 ± 1.05) 10^{-3} GeV^3**

[Ma, Wang, Chao: Table 1 of PRL 106, 042002 and equations (13) and (14) of arXiv:1012.1030]

Global Fit: Dependence on Low-p_T Cuts (1)

Global fit: Vary low-p_T cut on hadroproduction data:

hadroproduction data left	$p_T > 1$ GeV 148 points	$p_T > 2$ GeV 134 points	$p_T > 3$ GeV 119 points	$p_T > 5$ GeV 86 points	$p_T > 7$ GeV 60 points
$\langle O[^1S_0^{[8]}]\rangle$ [10^{-2} GeV^3]	5.68 ± 0.37	4.25 ± 0.43	4.97 ± 0.44	4.92 ± 0.49	3.91 ± 0.51
$\langle O[^3S_1^{[8]}]\rangle$ [10^{-3} GeV^3]	0.90 ± 0.50	2.94 ± 0.58	2.24 ± 0.59	2.23 ± 0.62	2.96 ± 0.64
$\langle O[^3P_0^{[8]}]\rangle$ [10^{-2} GeV^5]	-2.23 ± 0.17	-1.38 ± 0.20	-1.61 ± 0.20	-1.59 ± 0.22	-1.16 ± 0.23
M_0 [10^{-2} GeV^3]	**1.81 ± 0.09**	**1.85 ± 0.09**	**2.18 ± 0.10**	**2.17 ± 0.12**	**1.89 ± 0.12**
M_1 [10^{-3} GeV^3]	**6.46 ± 0.17**	**6.37 ± 0.17**	**6.25 ± 0.17**	**6.18 ± 0.17**	**5.86 ± 0.18**

↑ **Our default fit**

- **Stabilizing** influence of **photoproduction** data.
- Fit **constrained** enough: Can now extract 3 CO LDMEs.
- Fit results now **almost independent** of low-p_T cut.
- Fit less stable with low-p_T cut below 2 GeV (nonperturbative effects).

Global Fit: Dependence on Low-p_T Cuts (2)

Global fit: Vary low-p_T cut on photoproduction (including γγ-scattering):

photoproduction data left	p_T > 1 GeV 74 points	p_T > 2 GeV 30 points	p_T > 3 GeV 15 points	p_T > 5 GeV 5 points	p_T > 7 GeV 1 point
$\langle O[^1S_0^{[8]}]\rangle$ [10^{-2} GeV^3]	4.97 ± 0.44	5.10 ± 0.92	4.05 ± 1.17	5.44 ± 1.27	9.56 ± 1.59
$\langle O[^3S_1^{[8]}]\rangle$ [10^{-3} GeV^3]	2.24 ± 0.59	2.11 ± 1.22	3.52 ± 1.56	1.73 ± 1.68	-3.66 ± 2.09
$\langle O[^3P_0^{[8]}]\rangle$ [10^{-2} GeV^5]	-1.61 ± 0.20	-1.58 ± 0.48	-0.97 ± 0.63	-1.63 ± 0.68	-3.73 ± 0.83
M_0 [10^{-2} GeV^3]	**2.18 ± 0.10**	**2.36 ± 0.12**	**2.37 ± 0.13**	**2.62 ± 0.15**	**3.10 ± 0.19**
M_1 [10^{-3} GeV^3]	**6.25 ± 0.17**	**6.05 ± 0.18**	**5.94 ± 0.19**	**5.78 ± 0.20**	**5.62 ± 0.20**

↑ **Our default fit**

- **Fit stable** against varying low-p_T cut in region 1 GeV ~ 3 GeV.
- Just 5 or 1 photoproduction against 119 hadroproduction points not enough to stabilize the fit. ➡ **Not stable** with low-p_T cut much larger than 3 GeV. (Would need more high-p_T photoproduction data.)