J/ψ production with NRQCD: A global data analysis.

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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.

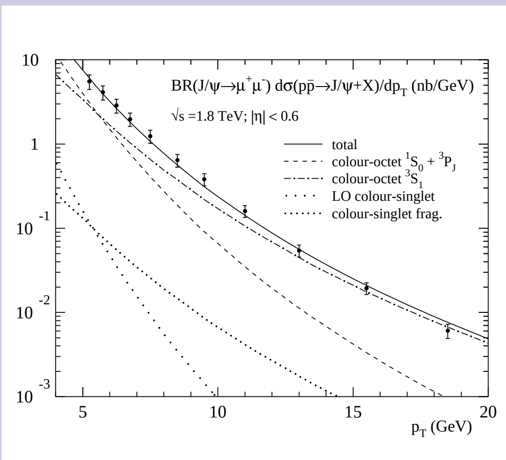
Scaling rules: LDMEs scale with definite power of v ($v^2 \approx 0.2$):

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

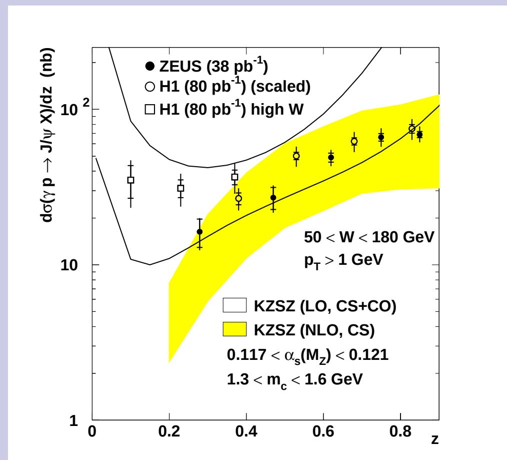
- **Double expansion** in v and α_s
- Leading term in v (n = $^3S_1^{[1]}$) equals **color-singlet model**.

J/ψ Production with NRQCD: Knowledge until 2005

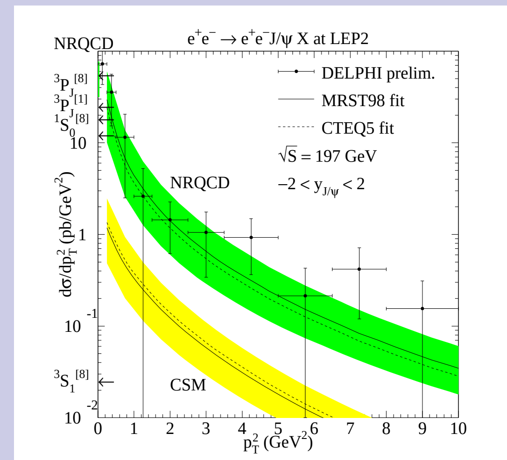
Hadroproduction at Tevatron:



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

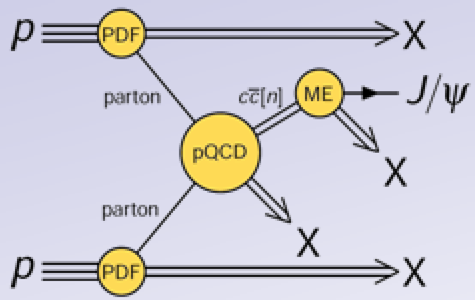
- Klasen, Kniehl, Mihaila, Steinhauser (2005):
  γγ scattering at LEP (neglecting resolved photons)
- Butenschön, Kniehl (2009):
  Photoproduction at HERA (neglecting resolved photons)
- Zhang, Ma, Wang, Chao (2009):
  e^+e^- scattering at *B* factories
- Ma, Wang, Chao (2010):
  Hadroproduction (including feed-down contributions)
- Butenschön, Kniehl (2010):
  Hadroproduction (combined HERA-Tevatron fit)

So far missing: A rigorous global data analysis!

In this Work: Fit CO LDMEs to 194 data points from 10 experiments.
⇒ 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:**

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

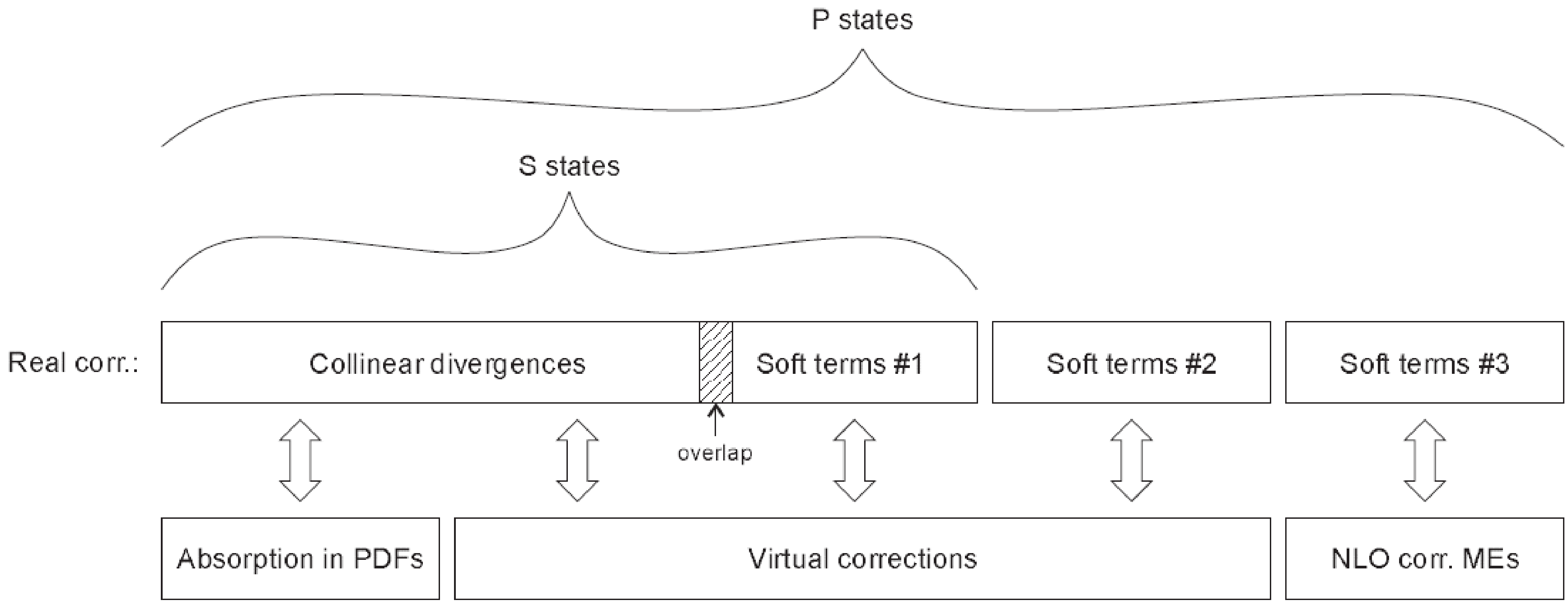
Amplitudes for $c\bar{c}[n]$ production by projector application, e.g.:

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

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

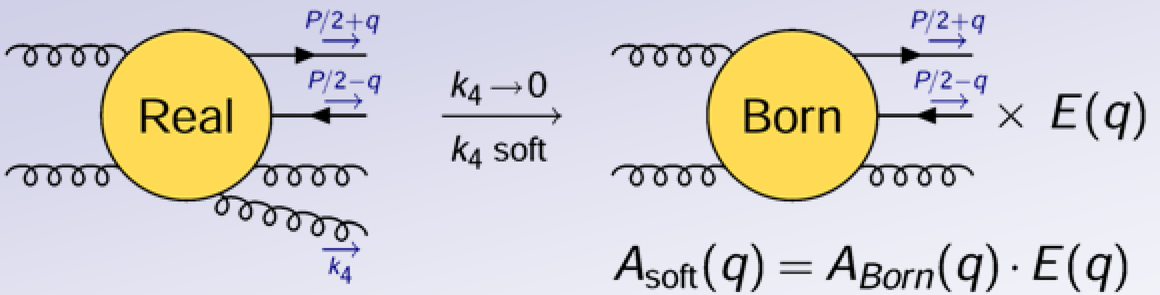
- $A_{c\bar{c}}$: Amputated pQCD amplitude for open $c\bar{c}$ production.
- q: Relative momentum between c and $\bar{c}$.

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:

$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$

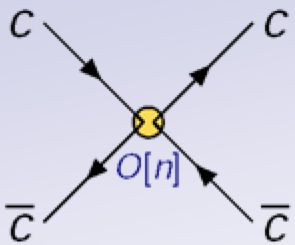
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

$$|A_{\text{soft,s}}|^2 = |A_{\text{Born,s}}|^2 \cdot E(0)^2$$

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

Radiative Corrections to LDMEs

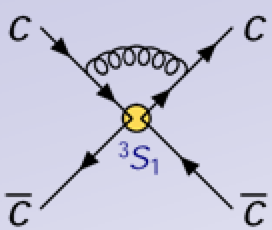
In NRQCD: Long distance MEs = $c\bar{c}$ scattering amplitudes:

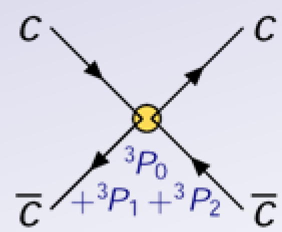
$\langle O^{J/\psi}[n] \rangle =$ 

$O[n]$ = 4-fermion operators

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

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



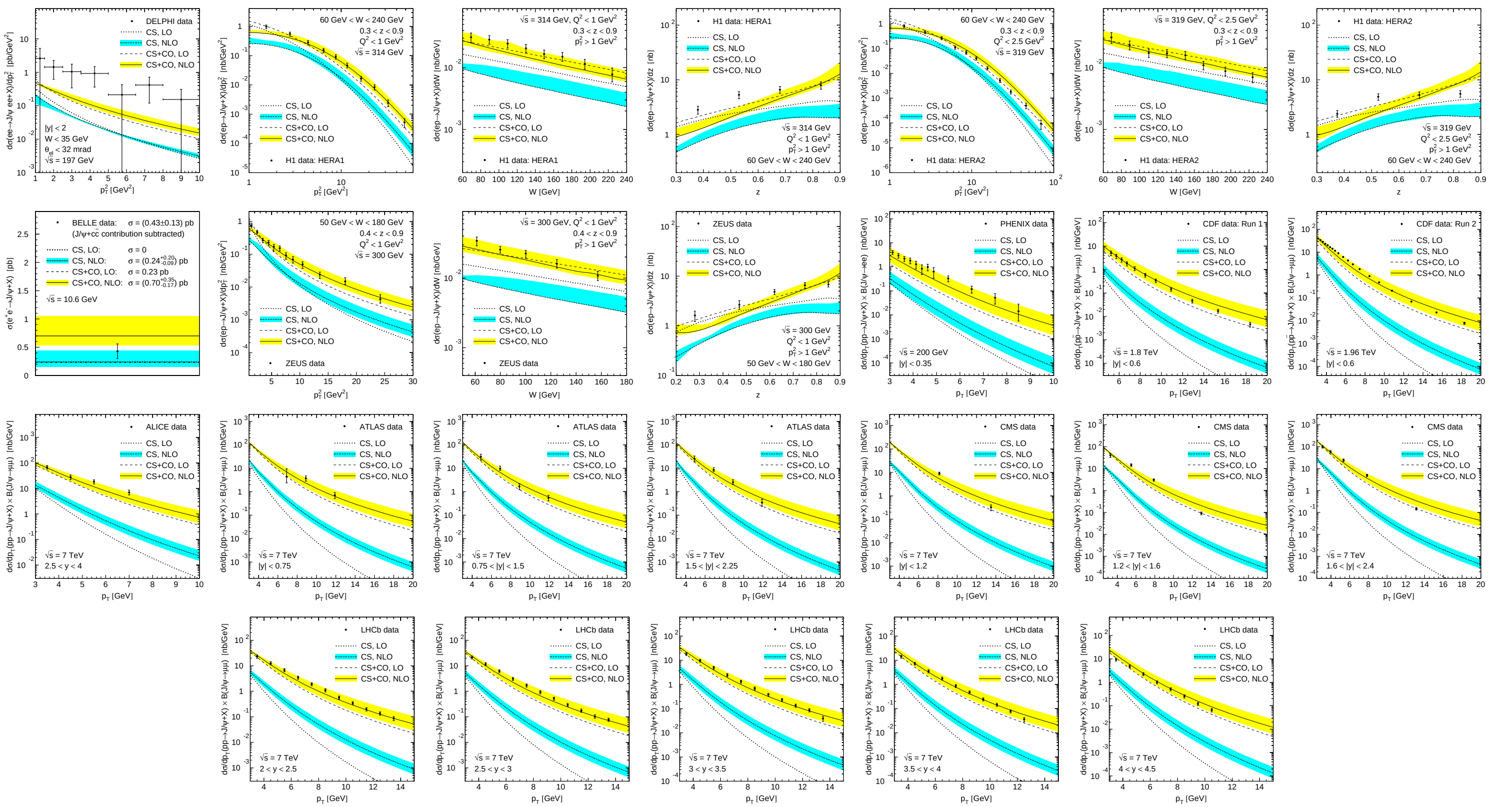
$+$ similar diagrams $\propto \frac{4\alpha_s}{3\pi m_c^2}\left(\frac{1}{\varepsilon_{UV}} - \frac{1}{\varepsilon_{IR}}\right) \cdot$ 

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

Our Fit

- 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.
- We consider the **inclusive J/ψ production** yield.
- Our partonic Born cross section: 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!

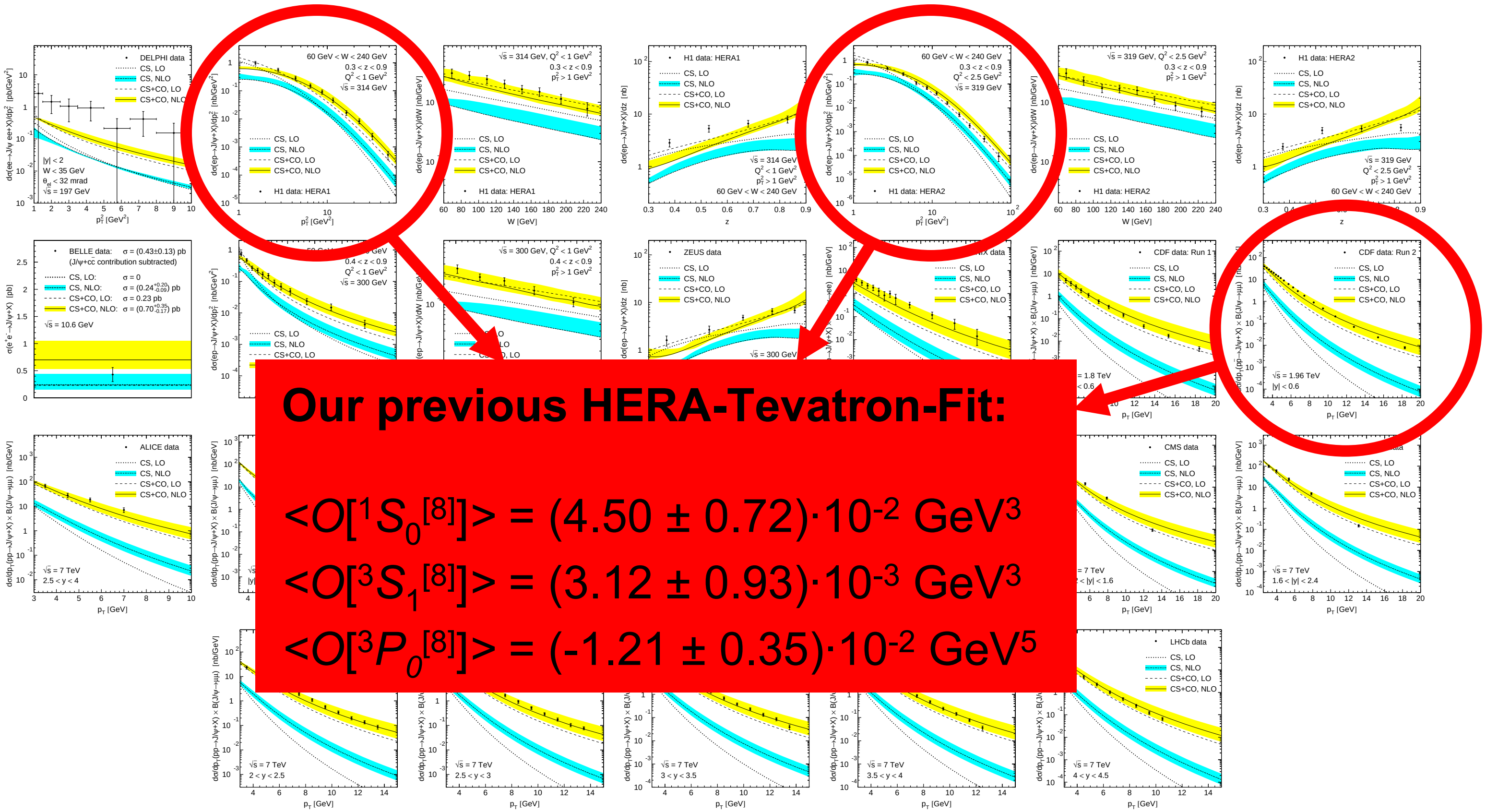
Our Fit Result



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

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

Our Fit Result



Our previous HERA-Tevatron-Fit:

$\langle O[^1S_0^{[8]}]\rangle = (4.50 \pm 0.72)\cdot 10^{-2}\ \mathrm{GeV}^3$

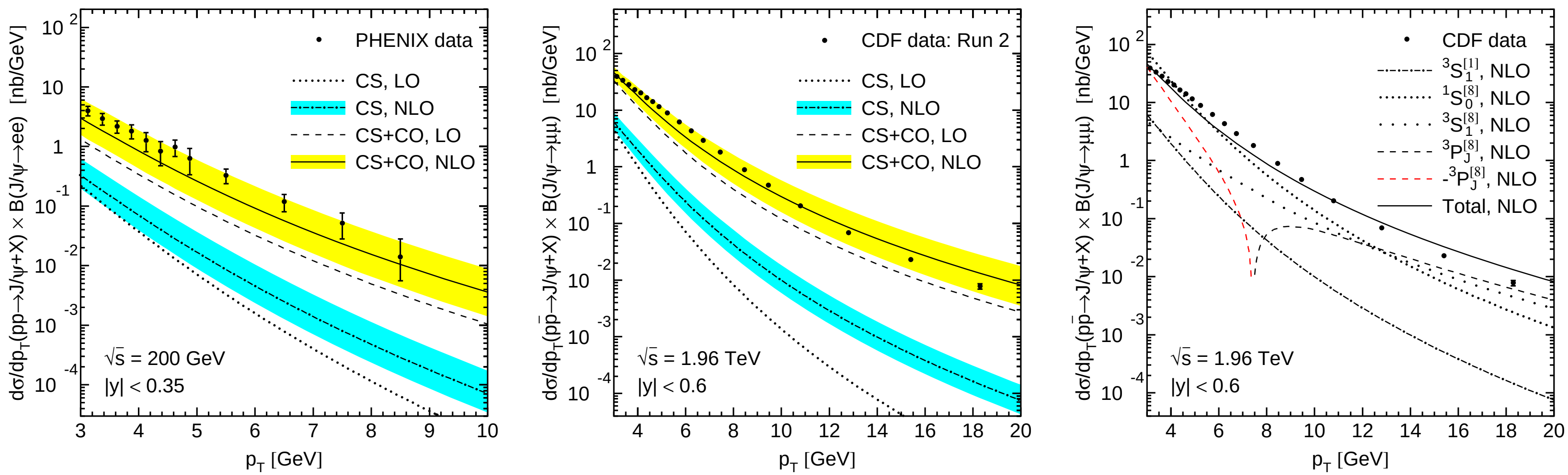
$\langle O[^3S_1^{[8]}]\rangle = (3.12 \pm 0.93)\cdot 10^{-3}\ \mathrm{GeV}^3$

$\langle O[^3P_0^{[8]}]\rangle = (-1.21 \pm 0.35)\cdot 10^{-2}\ \mathrm{GeV}^5$

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

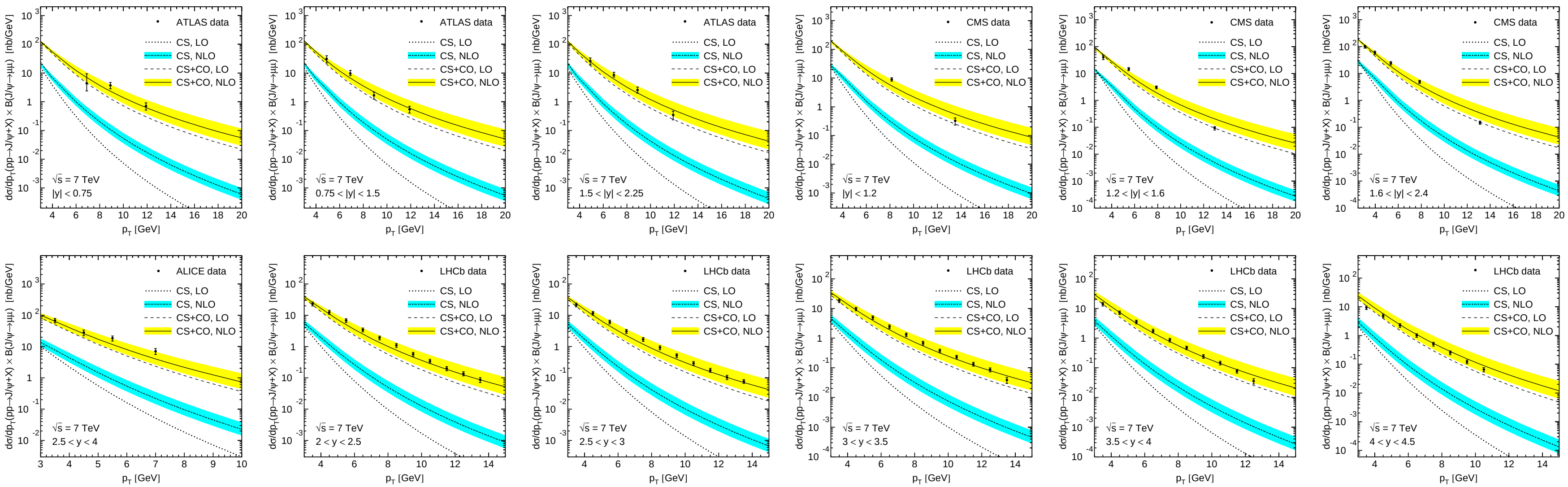
$\langle O[^3P_0^{[8]}]\rangle = (-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$

In Detail: Hadroproduction (RHIC, Tevatron)



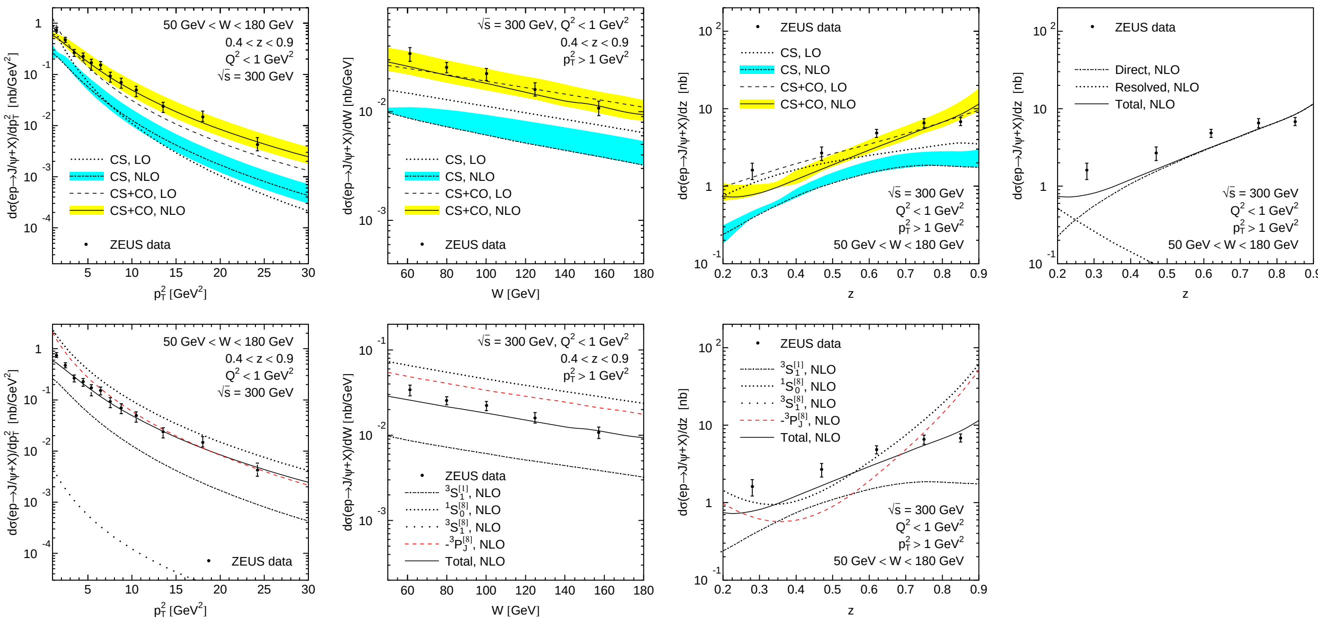
- Color singlet model **not enough** to describe data (although increase from Born to NLO)
- **CS+CO** can describe data.
- $^3P_J^{[8]}$ short distance cross section **negative** at $p_T > 7$ GeV.
- But: Short distance cross sections and LDMEs **unphysical**
  ➡ No problem!

In Detail: Hadroproduction (LHC)



- CMS and LHCb data: Preprints; ALICE and ATLAS data: Preliminary.
- 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)

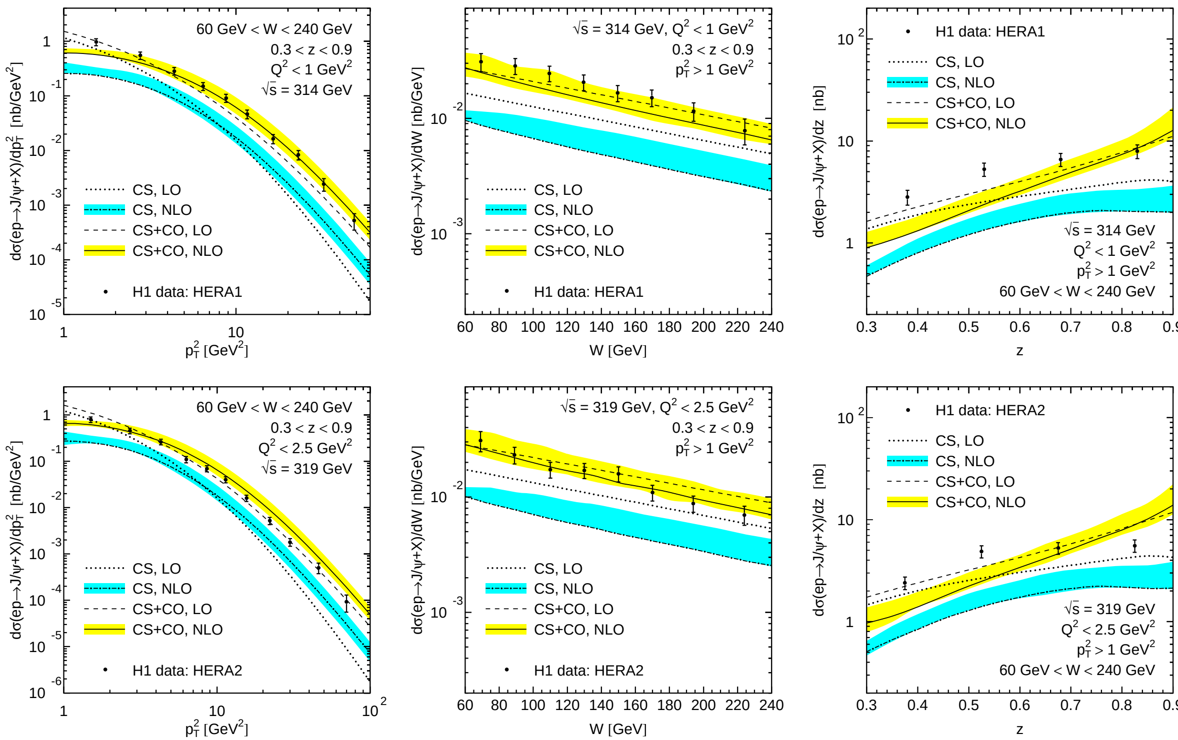


- **Photoproduction** = Photon-proton scattering in *ep* collider
- **Distributions:** Transverse momentum (p_T), photon-proton c.m. energy (W), and z = Fraction of photon energy going to J/ψ.
- Again: Color singlet alone **below** the data, **CS+CO** describes data well.
- Calculation includes **resolved** photon contributions: Important at low z.

In Detail: Photoproduction (H1)

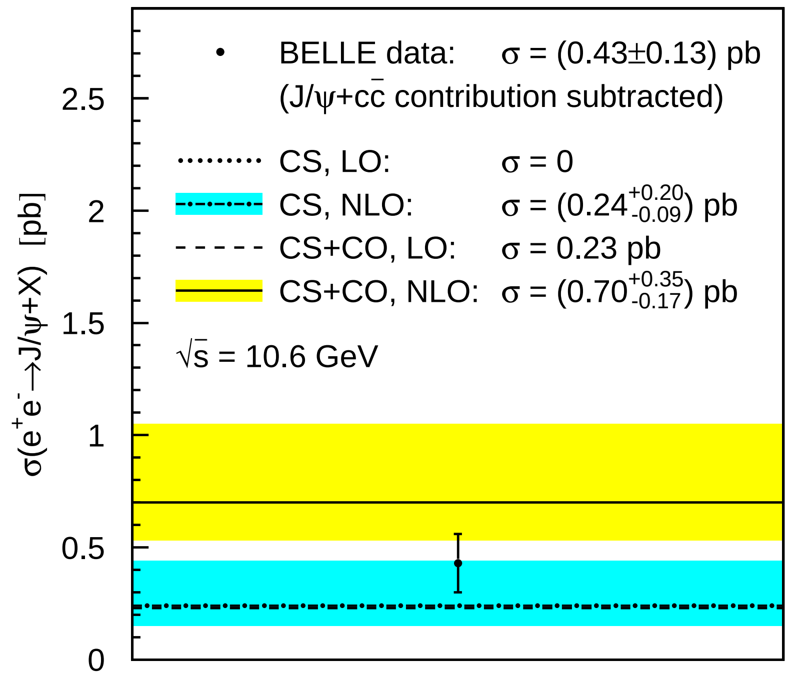
HERA 1 (1996 - 2000):

HERA 2 (2004 - 2007):



- Again: CS alone **below** data, **CS+CO** better.
- H1 data less well described than ZEUS data, especially *z* distribution and HERA2 data.

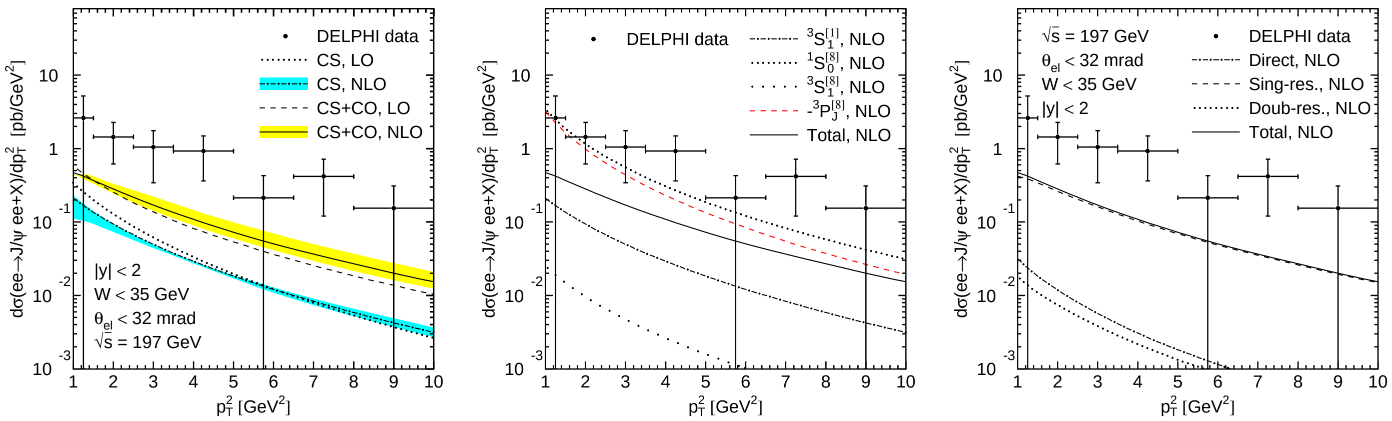
In Detail: Electron-Positron Scattering



- **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 difficult, discrepancies 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.

The 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.
- **Fit results:** $\langle O[^1S_0^{[8]}]\rangle = (4.97 \pm 0.44)\cdot 10^{-2}\ \mathrm{GeV}^3$
  $\langle O[^3S_1^{[8]}]\rangle = (2.24 \pm 0.59)\cdot 10^{-3}\ \mathrm{GeV}^3$
  $\langle O[^3P_0^{[8]}]\rangle = (-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$
- Negative unphysical quantities no problem.
- Most data prompt, but our cross sections direct. If we subtract estimated **feed-downs** (30% for pp, 15% for γp, 35% for e^+e^-, 10% for $\gamma\gamma$ scattering):
  Then fit results: $\langle O[^1S_0^{[8]}]\rangle = (3.33 \pm 0.36)\cdot 10^{-2}\ \mathrm{GeV}^3$
  $\langle O[^3S_1^{[8]}]\rangle = (1.83 \pm 0.47)\cdot 10^{-3}\ \mathrm{GeV}^3$
  $\langle O[^3P_0^{[8]}]\rangle = (-1.03 \pm 0.16)\cdot 10^{-2}\ \mathrm{GeV}^5$
- **CSM** predictions fall **short of data** everywhere except for $e^+e^- \to J/\psi+X$.
- Sufficient agreement for **CS+CO** with data except for $\gamma\gamma \to J/\psi+X$.

The Outlook

Still to be done:

- Include more “older” data in the fit and **further experiments** (DØ, STAR, UA1, fixed target experiments)
- More systematical treatment of **feed-down** contributions.
- Include further observables, like ***J/ψ* polarization**.
- **Higher order** corrections in v and α_s.