Séminaire de Physique Théorique – LPSC Grenoble

J/Ψ PRODUCTION IN $\vec{\gamma}\vec{\gamma}$, $\vec{\gamma}\vec{p}$, AND $\vec{p}\vec{p}$ COLLISIONS

Michael Klasen*

LPSC Grenoble

December 2, 2003

Contents:

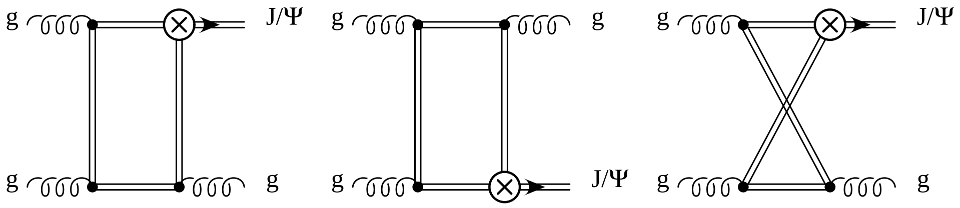
- Motivation
- Non-Relativistic QCD and Projector Formalism
- Complete Helicity Amplitudes for $\vec{\gamma}\vec{\gamma}, \vec{\gamma}\vec{p}, \vec{p}\vec{p} \to \mathcal{Q}, \mathcal{Q}X$
- Implementation of NRQCD processes in PYTHIA 6.2
- NLO corrections in α_s
- Numerical results for LEP, LC, SLAC E161, and RHIC
- Conclusion

---

*with B.A. Kniehl, L. Mihaila, M. Steinhauser:
Nucl. Phys. B 609 (2001) 518,
Phys. Rev. Lett. 89 (2002) 032001, and
Phys. Rev. D 68 (2003) 034017.

Motivation

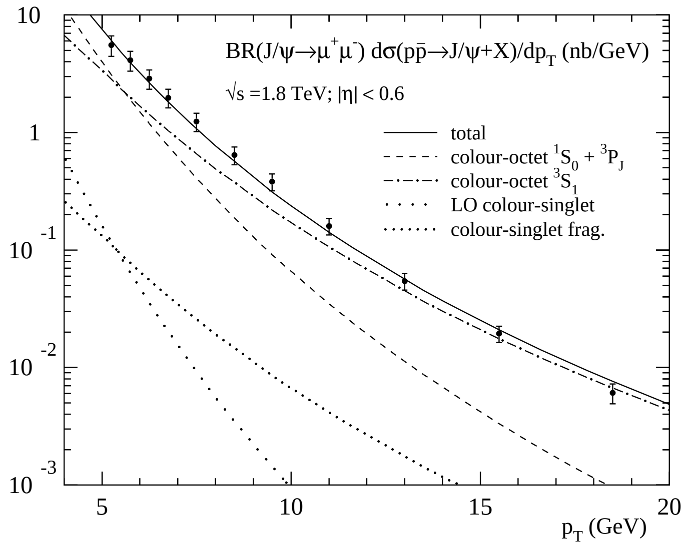
- The two sides of QCD:
  - Quarks and gluons: Asymptot. free, perturbative, carry color
  - Hadrons: Confined, non-perturbative, color-singlets
  - Simplest laboratory: Quarkonia, $J/\Psi = (c\bar{c}), \Upsilon = (b\bar{b})$, ...
- Color Evaporation Model: [Fritzsch; Halzen; Glück, Reya; 1977/8]
  - CS restored by soft gluon exchange with underlying event
  - CS+CO cross sections related to open heavy quark production
- Hard Comover Scattering: [Hoyer, Marchal, Peigné; 1999/2000]
  - CS restored by hard gluon exchange with classical color field
  - isotropic field generated by bremsstrahlung of the IS partons
  - explains ratio of $\chi_{c,1}$ and $\chi_{c,2}$ hadroproduction cross sections
  - explains observed non-polarization of hadroproduced $J/\psi, \psi'$
- Color Singlet Model: [Berger, Jones; Baier, Rückl, 1981]
  - $Q\bar{Q}$ state must already be in CS (wave function at origin)
  - Strong selection rules for production and decay processes:



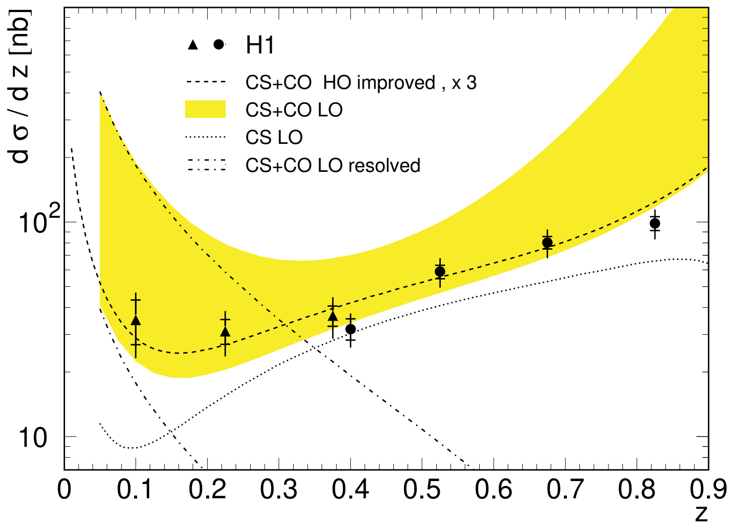
  - But: Discrepancy with CDF and D0 data for $J/\Psi, \Psi', \Upsilon, \ldots$
  - Uncanceled IR divergencies in P-wave decays

Motivation

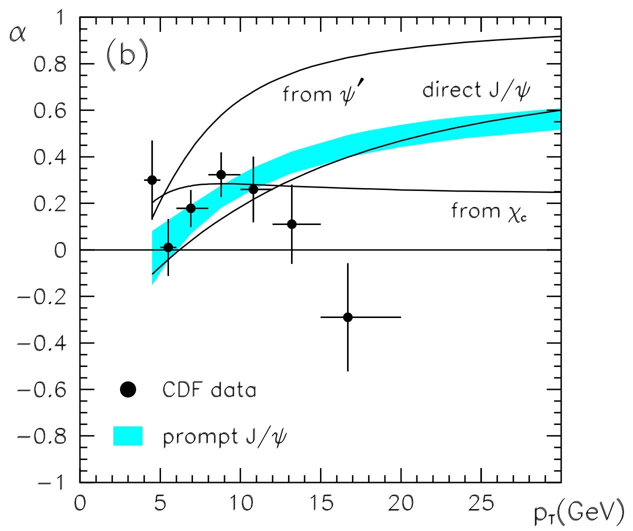
- $p\bar{p} \to J/\Psi X$ at Tevatron: [Braaten, 1995; Cho, Leibovich, 1996]



- $ep \to J/\Psi X$ at HERA: [Cacciari, Krämer, 1996]



- J/Ψ polarization at Tevatron: [Braaten, Kniehl, Lee, 1999]



Non-Relativistic QCD

- Separation of mass scales ($v_c^2 = 0.3, v_b^2 = 0.1$):
  - $m_c \quad = 1.5$ GeV (annihilation and production threshold)
  - $m_c v_c = 0.9$ GeV (size of bound state)
  - $m_c v_c^2 = 0.5$ GeV (splitting between resonances)
  - Double expansion in α_s and v (perturb. and relat. corrections)
- Lagrangian: [Caswell, Lepage, 1986]

$$\mathcal{L}_{\rm NRQCD} = \psi^\dagger \left(iD_0 + \frac{\vec{D}^2}{2m} \right) \psi + \chi^\dagger \left(iD_0 - \frac{\vec{D}^2}{2m} \right) \chi + \mathcal{L}_{\rm light} + \delta\mathcal{L},$$

  - ψ and χ are two-component heavy (anti)-quark spinors
  - $\delta\mathcal{L}$ reproduces $\mathcal{L}_{\rm QCD}$, contains bilinear and quartic terms:

$$\delta\mathcal{L}_{4-\rm fermion} = \sum_i \frac{d_i}{m^2} (\psi^\dagger \mathcal{K}_i \chi)(\chi^\dagger \mathcal{K}_i' \psi)$$

  - Annihilation and creation of $Q\bar{Q}$ pairs in different states
- Factorization: [Bodwin, Braaten, Lepage, 1995]

$$d\sigma(H + X) = \sum_n d\hat{\sigma}(Q\overline{Q}[n] + X) \langle \mathcal{O}^H [n] \rangle$$

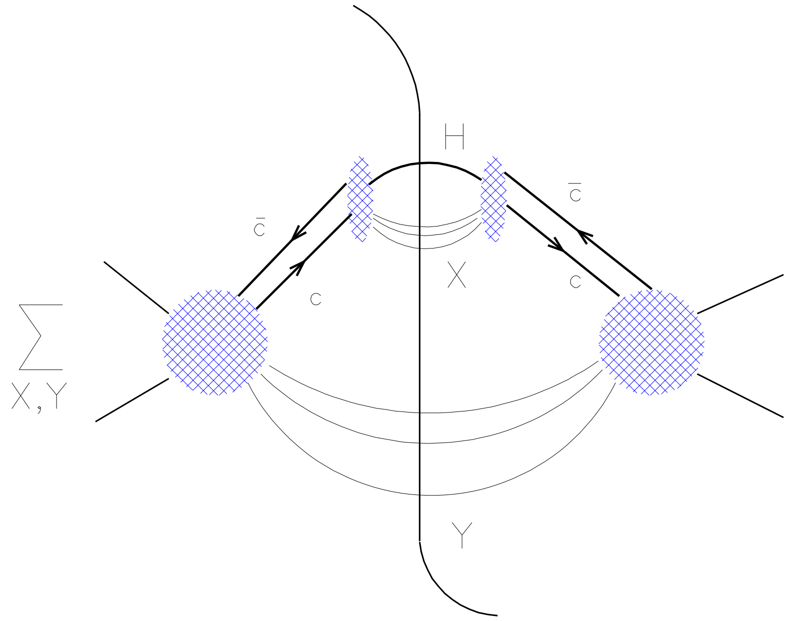
  - Sum over all color and angular momentum states
  - Transition $Q\bar{Q} \to H$ by soft gluon emission, probability:

$$\langle \mathcal{O}^H [n] \rangle \equiv \sum_{X,\lambda} \langle 0 | \chi^\dagger \mathcal{K}_n \psi | H(\lambda) + X \rangle \langle H(\lambda) + X | \psi^\dagger \mathcal{K}_n' \chi | 0 \rangle$$

  - Velocity scaling rules for Fock states and operators
  - Matrix elements: Non-perturbative calculations or fits to data
  - Soft gluons between quarkonium and remnants should cancel
  - Proven for decays, related to production by vacuum saturation

PROJECTOR FORMALISM

- Exploits factorization at the amplitude level:



$$
\begin{aligned}
\mathcal{A} &= T_{ij}(Q\bar{Q}+Y)\langle H X|\bar{\psi}_i \psi_j|0\rangle \\
&= \sum_n \langle H X|Q\bar{Q}[n]\rangle\langle Q\bar{Q}[n]|\bar{\psi}_i\psi_j|0\rangle T_{ij} \\
&= \sum_n \langle H X|Q\bar{Q}[n]\rangle \mathrm{Tr}\left[T\Pi^{(n)}\right]
\end{aligned}
$$

- Spin projectors for $S=0$ and 1: [Kühn *et al.*, 1979]

$$
\begin{aligned}
\Pi_0 &= \frac{1}{\sqrt{8m^3}}\left(\frac{\not{P}}{2}-\not{q}-m\right)\gamma_5\left(\frac{\not{P}}{2}+\not{q}+m\right) \\
\Pi_1^\alpha &= \frac{1}{\sqrt{8m^3}}\left(\frac{\not{P}}{2}-\not{q}-m\right)\gamma^\alpha\left(\frac{\not{P}}{2}+\not{q}+m\right)
\end{aligned}
$$

  - Momenta: $Q=P/2+q$ and $\bar{Q}=P/2-q$
  - Beyond $D=4$ not only spin 0 and 1, but infinite set of states
  - No spin flip for $m\to\infty$. Finite m: Sufficiently low order in v
  - Are at least of $\mathcal{O}(\epsilon)$, have no soft/collinear $1/\epsilon$ poles

Projector Formalism

- Orbital angular momentum projectors for $L = 0$ and 1:

$$
\begin{aligned}
\mathcal{A}_{S=0,\,L=0} &= \mathrm{Tr}\,[C\Pi_0\,\mathcal{A}]\;|_{q=0} \\
\mathcal{A}_{S=1,\,L=0} &= \epsilon_\alpha\,\mathrm{Tr}\left[C\Pi_1^\alpha\,\mathcal{A}\right]\;|_{q=0} \\
\mathcal{A}_{S=0,\,L=1} &= \epsilon_\beta\,\frac{\mathrm{d}}{\mathrm{d}q_\beta}\mathrm{Tr}\,[C\Pi_0\,\mathcal{A}]\;|_{q=0} \\
\mathcal{A}_{S=1,\,L=1} &= \mathcal{E}_{\alpha\beta}\,\frac{\mathrm{d}}{\mathrm{d}q_\beta}\mathrm{Tr}\left[C\Pi_1^\alpha\,\mathcal{A}\right]\;|_{q=0}
\end{aligned}
$$

- Total angular momentum projectors for $J = 0,\ 1,$ and 2:

$$
\begin{aligned}
{}^3S_1\ (\mathrm{vector}) &: \quad \sum_{J_z}\epsilon_\alpha\,\epsilon^*_{\alpha'} = \Pi_{\alpha\alpha'} = -g_{\alpha\alpha'} + \frac{P_\alpha P_{\alpha'}}{4m^2} \\
{}^3P_0\ (\mathrm{scalar}) &: \quad \mathcal{E}^{(0)}_{\alpha\beta}\,\mathcal{E}^{(0)*}_{\alpha'\beta'} = \frac{1}{D-1}\Pi_{\alpha\beta}\Pi_{\alpha'\beta'} \\
{}^3P_1\ (\mathrm{tensor}) &: \quad \sum_{J_z}\mathcal{E}^{(1)}_{\alpha\beta}\,\mathcal{E}^{(1)*}_{\alpha'\beta'} = \frac{1}{2}\left[\Pi_{\alpha\alpha'}\Pi_{\beta\beta'} - \Pi_{\alpha\beta'}\Pi_{\alpha'\beta}\right] \\
{}^3P_2\ (\mathrm{tensor}) &: \quad \sum_{J_z}\mathcal{E}^{(2)}_{\alpha\beta}\,\mathcal{E}^{(2)*}_{\alpha'\beta'} = \frac{1}{2}\left[\Pi_{\alpha\alpha'}\Pi_{\beta\beta'} + \Pi_{\alpha\beta'}\Pi_{\alpha'\beta}\right] \\
&\qquad\qquad - \frac{1}{D-1}\Pi_{\alpha\beta}\Pi_{\alpha'\beta'}
\end{aligned}
$$

- Color projectors for $\underline{a} = \underline{1}$ and $\underline{8}$:

$$
\begin{aligned}
C_1 &= \frac{\delta_{ij}}{\sqrt{N_C}} \\
C_8 &= \sqrt{2}T^c_{ij}
\end{aligned}
$$

Complete Helicity Amplitudes for $\vec{p}\vec{p}, \vec{\gamma}\vec{p}, \vec{\gamma}\vec{\gamma} \to \mathcal{Q}, \mathcal{Q}X$

- Helicity projection operators: [Craigie *et al.*, Phys. Rep. 99 (1983) 69]

$$
\begin{aligned}
u(p,h)\bar{u}(p,h) &= \frac{1}{2}(\not{p}+m)(1-h\gamma_5) \\
v(p,h)\bar{v}(p,h) &= \frac{1}{2}(\not{p}-m)(1+h\gamma_5) \\
\varepsilon^{\mu}(p,h)\varepsilon^{*\nu}(p,h) &= \frac{1}{2}\left[-g^{\mu\nu}+\frac{p^{\mu}\eta^{\nu}+p^{\nu}\eta^{\mu}}{p.\eta}+ih\varepsilon^{\mu\nu\rho\sigma}\frac{p_{\rho}\eta_{\sigma}}{p.\eta}\right]
\end{aligned}
$$

  - Computer algebra does not distinguish upper/lower indices
  - Unconventional definition of $\varepsilon_{\mu\nu\rho\sigma}$ in FORM:

$$
\begin{aligned}
\mathrm{TRACER:}\quad \mathrm{Tr}[\gamma_5\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma] &= 4\,i\,\varepsilon_{\mu\nu\rho\sigma} \\
\mathrm{FORM:}\quad \mathrm{Tr}[\gamma_5\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma] &= 4\;\varepsilon_{\mu\nu\rho\sigma}
\end{aligned}
$$

  - Cf. muon anomalous magnetic moment [Hayakawa, Kinoshita, hep-ph/0112102]
  - Caution: Correct sign for boson-fermion scattering?

- Hadron collisions:
  - $\vec{p}\vec{p} \to \mathcal{Q}$: [CSM: Doncheski, Robinett, PLB 248 (1990) 188; Batunin, Slabospitsky, PLB 188 (1987) 269] [NRQCD: Gupta, Mathews, PRD 55 (1997) 7144]
  - $\vec{p}\vec{p} \to \mathcal{Q}X$: [CSM: Gastmans, Troost, Wu, NPB 291 (1987) 731; Robinett, PRD 43 (1991) 113] no analytical results! [NRQCD: Tkabladze, Teryaev, PRD 56 (1997) 7331]
  - $\vec{p}\vec{p} \to \mathcal{Q}\gamma$: no analytical results!

- Photoproduction:
  - $\vec{\gamma}\vec{p} \to \mathcal{Q}$: [CSM: Duke, Owens, PRD 24 (1981) 1403] no analytical results! [NRQCD: Sudoh, Morii, PRD 62 (2000) 057501]
  - $\vec{\gamma}\vec{p} \to \mathcal{Q}X$: [CSM: Duke, Owens, PRD 24 (1981) 1403] [NRQCD: Yuan *et al.*, PRD 61, 114013; Japaridze, Nowak, Tkabladze, PRD 62, 034022]
  - $\vec{\gamma}\vec{p} \to \mathcal{Q}\gamma$: no results!

- Photon collisions:
  - $\vec{\gamma}\vec{\gamma} \to \mathcal{Q}$: no results!
  - $\vec{\gamma}\vec{\gamma} \to \mathcal{Q}X$: no results!
  - $\vec{\gamma}\vec{\gamma} \to \mathcal{Q}\gamma$: no results!

IMPLEMENTATION OF NRQCD PROCESSES IN PYTHIA 6.2

- Default PYTHIA 6.2:
  - CSM: $gg \to J/\Psi(\gamma, g), \gamma g \to J/\Psi g, \gamma\gamma \to J/\Psi\gamma$
  - VDM + elastic scattering: $\gamma p \to J/\Psi p, \gamma\gamma \to J/\Psi\rho$
- Problems:
  - Large normalization uncertainty, bad efficiencies
  - Combination of diffractive/non-diffractive processes
- Hadron collisions: [Cano-Coloma, Sanchis-Lozano, NPB 508 (1997) 753)]
  - $gg \to \mathcal{Q}g$: modification of $gg \to J/\Psi g$ subprocess
  - $gq \to \mathcal{Q}q$: approximated by scaling factor
- Implementation of NRQCD in PYTHIA 6.2:
  - All quark initiated processes, have correct parton densities
  - All color octet processes, can be selected independently
  - $2 \to 1$ and $2 \to 2$ processes, can be selected independently
  - User has access to operator matrix elements
- Applications:
  - Extraction of approximate higher order matrix elements
  - $\gamma\gamma \to J/\Psi X$ at LEP (ALEPH, DELPHI, L3, OPAL)

NLO CORRECTIONS TO $\gamma\gamma \to J/\Psi X$

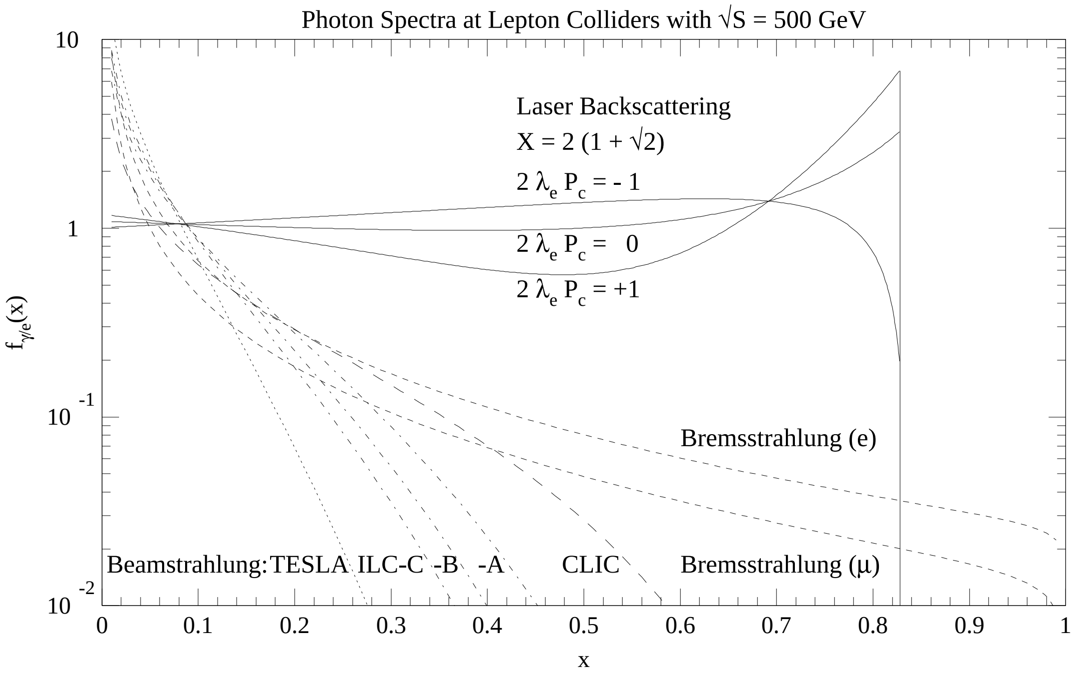
- J/Ψ production with finite p_T $(e^+e^- \to e^+e^- J/\Psi + X)$:

$$\frac{d^3\sigma}{dp_T^2\, dy\, dy_1} = x_+ f_{a/e}(x_+) x_- f_{b/e}(x_-) \sum_n \sum_{\substack{a,b,d= \\ \gamma,q,g}} \frac{d\sigma}{dt}(ab \to c\bar{c}(n)d)$$

- Parton densities:

$$f_{a,b/e}(x_\pm) = \int_{x_\pm}^{1} \frac{dy}{y} f_{\gamma/e}\left(\frac{x_\pm}{y}\right) f_{a,b/\gamma}(y)$$

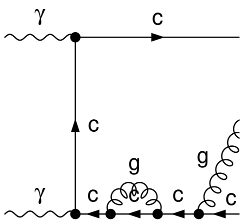
- Photon spectra:



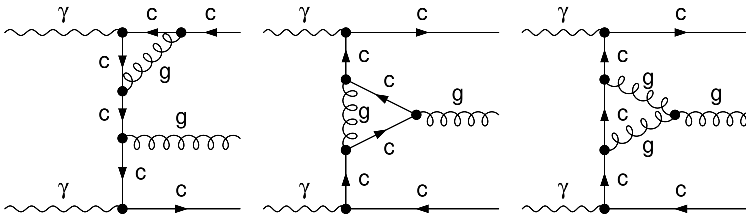
- Partonic processes: [Godbole, Indumathi, Krämer, 2001]
  - Direct (large p_T):
    - $\gamma\gamma \to (c\bar{c})\gamma$ (CS)
    - $\gamma\gamma \to (c\bar{c})g$ (CO)
  - 1-resolved (low p_T):
    - $\gamma g \to (c\bar{c})g$ (CS, CO)
    - $\gamma q \to (c\bar{c})q$ (CO)
  - 2-resolved:
    - $gg \to (c\bar{c})g$ (CS, CO)
    - $gq \to (c\bar{c})g$ (CO)
    - $q\bar{q} \to (c\bar{c})g$ (CO)

NLO CORRECTIONS TO $\gamma\gamma \to J/\Psi X$

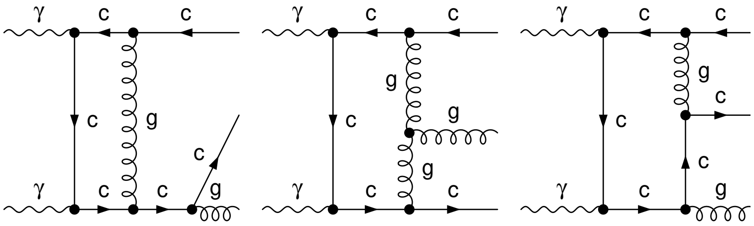
- Virtual corrections $(X = g/\gamma)$:
  - Self-energies (12/12):



  - Vertex corrections (38/30):



  - Four- and five-point box diagrams (30/24):



  - Dimensional regularization: $d = 4 - 2\varepsilon$ dimensions
  - Reduction of tensor integrals [Passarino and Veltman, 1979]
  - Analytic results for scalar integrals in D dimensions
  - Alternative: Numerical evaluation of tensor loop integrals
    $\to$ LoopTools, FF [Oldenborgh, Vermaseren, 1990; Hahn,2000]
  - Non-trivial for five-point functions, P-waves
  - UV-singularities in self-energies and vertex corrections
  - IR-singularities in box diagrams
  - Longitudinal gluon exchange $\to$ Coulomb singularity π^2/v

NLO CORRECTIONS TO $\gamma\gamma \to J/\Psi X$

- Renormalization and singularity cancellation:

  - On-shell renormalization of masses and wave functions:

$$
\begin{aligned}
m_0 &= Z_m^{\mathrm{OS}} m_R \quad [\mu - \text{dependence only in } \alpha_s] \\
\psi_0 &= \sqrt{Z_2^{\mathrm{OS}}}\,\psi_R \; [\text{no additional LSZ} - \text{terms}]
\end{aligned}
$$

For $X = \gamma$ no renormalization of couplings

  - Cancellation of UV- and IR-singularities:

$$
\begin{aligned}
2\mathrm{Re}\left[\mathcal{A}^*_{\mathrm{Born}}\left(\mathcal{A}_{\mathrm{self}} + \mathcal{A}_{\mathrm{vertex}} + \mathcal{A}_{\mathrm{wfct}} + \mathcal{A}_{\mathrm{massct}}\right)\right]_{\mathrm{UV}} &= 0 \\
2\mathrm{Re}\left[\mathcal{A}^*_{\mathrm{Born}}\left(\mathcal{A}_{\mathrm{box}} + \mathcal{A}_{\mathrm{wvct}}\right)\right]_{\mathrm{IR}} &= 0
\end{aligned}
$$

  - Cancellation of Coulomb singularities:

Quarkonium $(c\bar{c})$ production cross section:

$$
\frac{d\sigma^0}{dt} \propto 2\mathrm{Re}\left[\mathcal{A}^*_{\mathrm{Born}}\mathcal{A}_{\mathrm{box}}\right]_{\mathrm{Cb}} = \frac{\alpha_s}{\pi} C_F \frac{\pi^2}{v} \, |\mathcal{A}_{\mathrm{Born}}|^2
$$

NRQCD operator matrix element:

$$
\langle \mathcal{O}^H_R\,[n]\rangle = \langle \mathcal{O}^H_0\,[n]\rangle \left(1 + \frac{\alpha_s}{\pi} C_F \frac{\pi^2}{v}\right)
$$

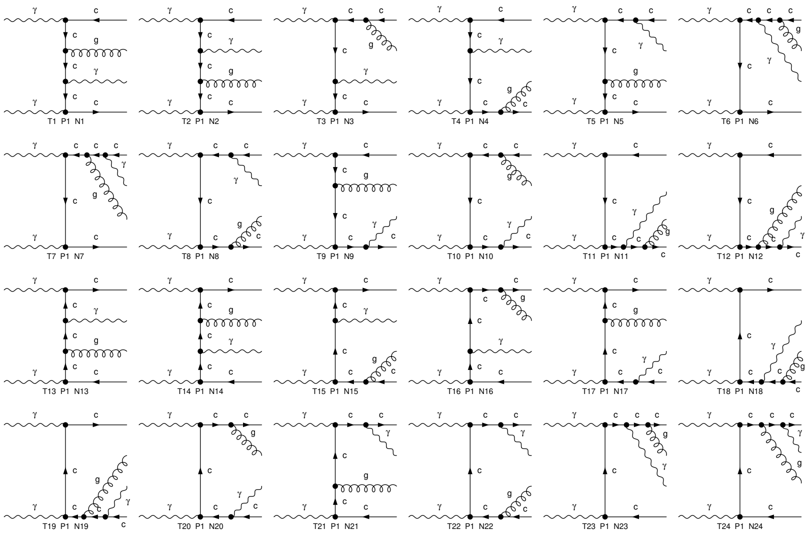
Hadron (H) production cross section:

$$
\begin{aligned}
\frac{d\sigma}{dt}(\gamma\gamma \to HX) &= \frac{d\sigma^0}{dt}(\gamma\gamma \to c\bar{c}X)\,\langle \mathcal{O}^H_0\,[n]\rangle \\
&= \frac{d\sigma^R}{dt}(\gamma\gamma \to c\bar{c}X)\,\langle \mathcal{O}^H_R\,[n]\rangle
\end{aligned}
$$

NLO corrections to $\gamma\gamma \to J/\Psi X$

- Real corrections ($X = \gamma$):

  - Gluon emission:



  - Quarkonium production cross sections:

$$\begin{aligned}
\sigma(\gamma\gamma \to c\bar{c}\left({}^{2S+1}L_J^{(1)}\right)\gamma g) &= 0 \\
\sigma(\gamma\gamma \to c\bar{c}\left({}^{3}S_1^{(8)},{}^{1}P_1^{(8)}\right)\gamma g) &= 0 \\
\sigma(\gamma\gamma \to c\bar{c}\left({}^{1}S_0^{(8)}\right)\gamma g) &= \mathrm{IR-finite} \\
\sigma(\gamma\gamma \to c\bar{c}\left({}^{3}P_J^{(8)}\right)\gamma g) &= \mathrm{IR-divergent}
\end{aligned}$$

  - Explicit form of the IR-singularity for $c\bar{c}\left({}^{3}P_J^{(8)}\right)$:

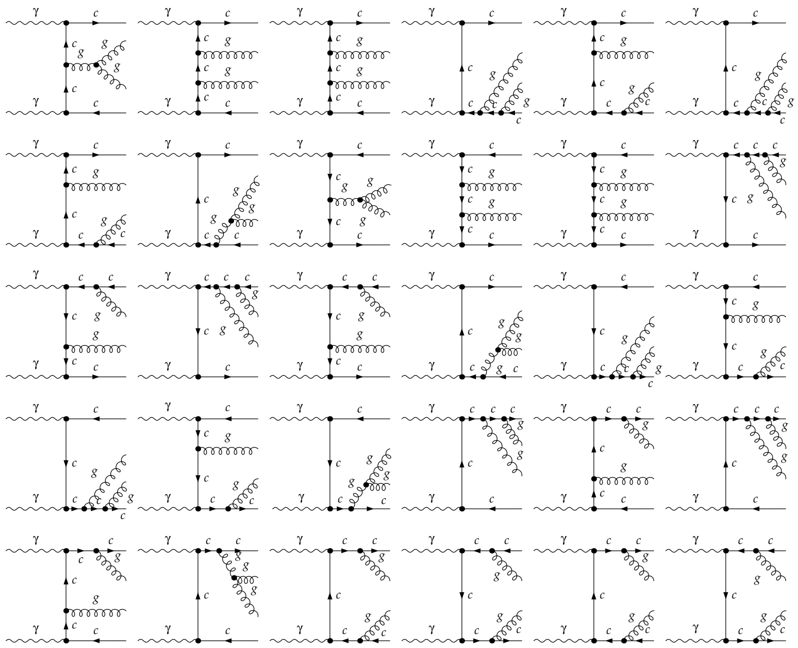
$$\left|\mathcal{A}_{\mathrm{real}}\left({}^{3}P_J^{(8)}\right)\right|^2 \propto \frac{\alpha_s}{(p_c . k_g)^2}\left|\mathcal{A}_{\mathrm{Born}}\left({}^{3}S_1^{(1)}\right)\right|^2$$

$$\int d\Omega_{d-1}\left|\mathcal{A}_{\mathrm{real}}\left({}^{3}P_J^{(8)}\right)\right|^2 \propto \frac{\alpha_s}{\pi}\,\frac{4}{3}\,\frac{C_F}{m^2}\,\frac{1}{\varepsilon}\left|\mathcal{A}_{\mathrm{Born}}\left({}^{3}S_1^{(1)}\right)\right|^2$$

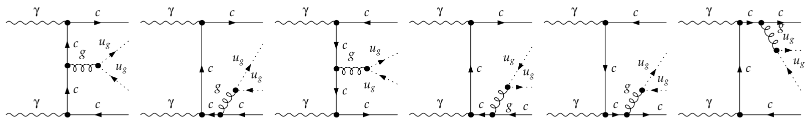
  - Renormalizes NRQCD operator matrix element $\langle\mathcal{O}^H\,[{}^3S_1^{(1)}]\rangle$

NLO corrections to $\gamma\gamma \to J/\Psi X$

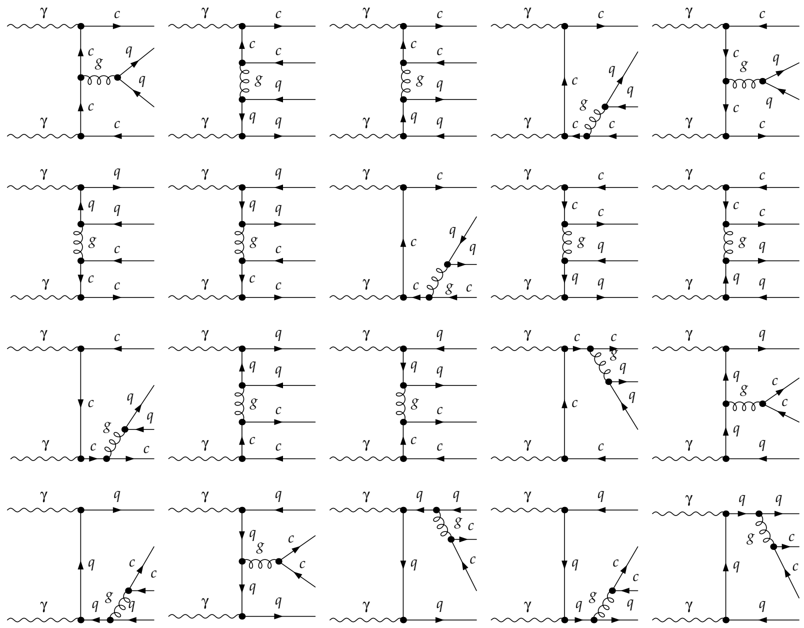
- Real corrections ($X = g$):
  - Gluon emission:



  - Ghost contributions:



  - Quark emission:



NLO CORRECTIONS TO $\gamma\gamma \to J/\Psi X$

- High degree of automatization (huge size of amplitudes):
  - Amplitude generation with FeynArts and Qgraf
  - Trace evaluation with FeynCalc and Form
  - Numerical integration with Fortran and VEGAS
- Dominant processes and matrix elements $\langle \mathcal{O}^H[n] \rangle$:

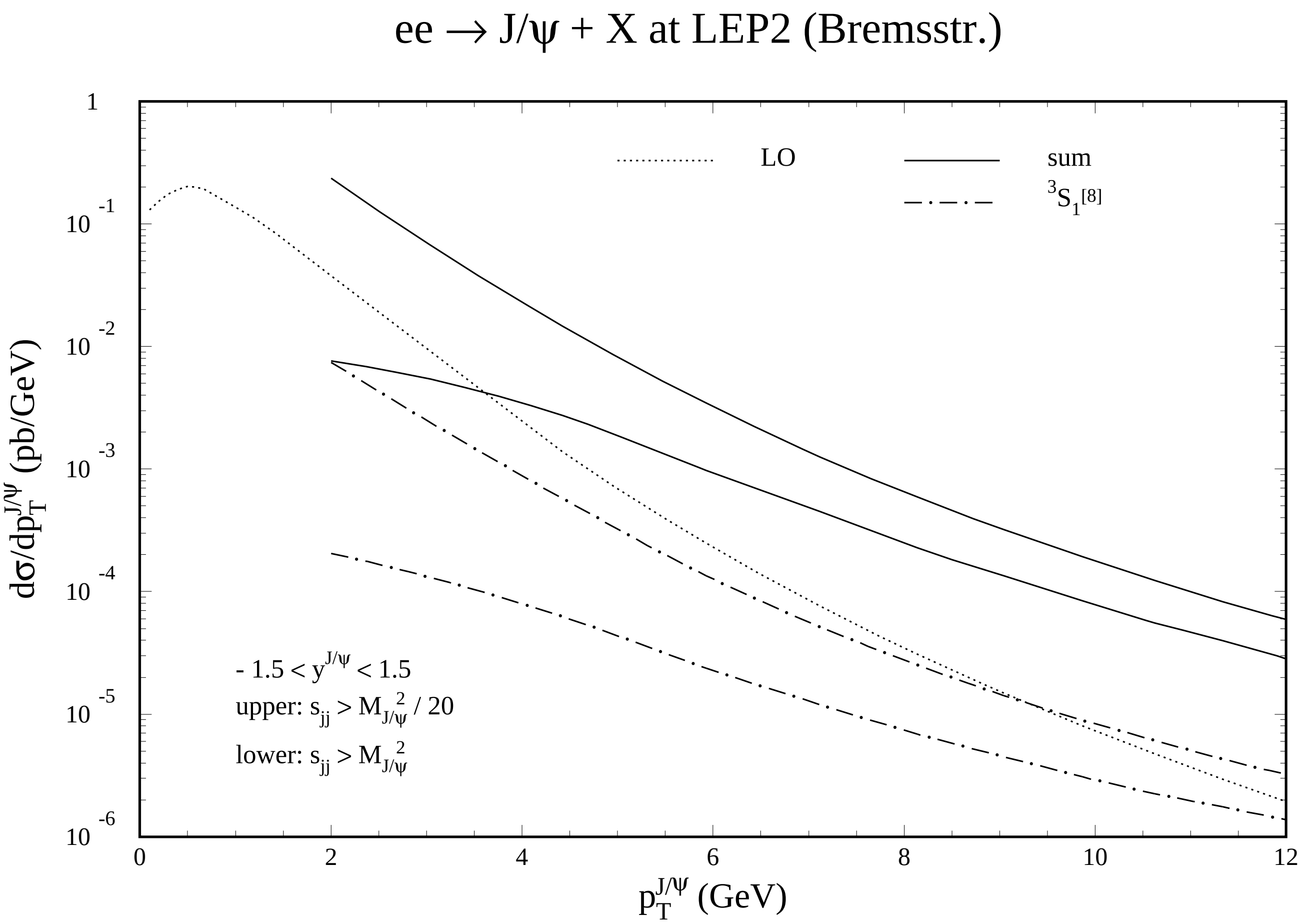
Diagram	Order	L=0		L=1	
$\gamma\gamma \to \mathrm{J}/\Psi\mathrm{g}$	$\alpha^2\alpha_s$	$^3S_1^{[8]}$:E_1^2	v^4	$^1P_1^{[8]}$:E_1M_1	v^8
$\gamma\gamma \to \mathrm{J}/\Psi\gamma$	α^3	$^3S_1^{[1]}$	v^0	$^1P_1^{[1]}$:M_1E_1	v^8
$\gamma\gamma \to \mathrm{J}/\Psi\mathrm{gg}$	$\alpha^2\alpha_s^2$	$^3S_1^{[8]}$:E_1^2	v^4	$^3P_J^{[8]}$:E_1	v^4
	$\alpha^2\alpha_s^2$	$^1S_0^{[8]}$:M_1	v^4	$^1P_1^{[8]}$:M_1E_1	v^8
$\gamma\gamma \to \mathrm{J}/\Psi\mathrm{q\bar{q}}$	$\alpha^2\alpha_s^2$	$^3S_1^{[8]}$:E_1^2	v^4	$^3P_J^{[8]}$:E_1	v^4
	$\alpha^2\alpha_s^2$	$^1S_0^{[8]}$:M_1	v^4	$^1P_1^{[8]}$:M_1E_1	v^8

- Numerical input (Tevatron p_T-dist.): [Braaten, Kniehl, Lee, 2000]

$\mathrm{O}(^1\mathrm{S}_0^{[8]})$	$\mathrm{O}(^3\mathrm{S}_1^{[8]})$	$\frac{\mathrm{O}(^3\mathrm{P}_0^{[8]})}{\mathrm{m}_c^2}$	$\frac{\mathrm{O}(^3\mathrm{P}_1^{[8]})}{\mathrm{m}_c^2}$	$\frac{\mathrm{O}(^3\mathrm{P}_2^{[8]})}{\mathrm{m}_c^2}$
4.3510^{-2}	4.410^{-3}	1.2810^{-2}	3.8410^{-2}	6.4010^{-2}

  - $m_c = (1.5 \pm 0.1)$ GeV
  - $\alpha_s^{\mathrm{LO},\, n_f=3}(\mu = \xi\sqrt{4m_c^2 + p_T^2}, \Lambda = 204$ MeV), $\xi \in [0.5; 2]$
  - p: GRV98, $\vec{p}$: GRStV00, γ: GRSc, $\vec{\gamma}$: GStV
  - Weizsäcker-Williams spectrum, $\theta_{\mathrm{max}} = 32$ mrad

NLO CORRECTIONS TO $\gamma\gamma \to J/\Psi X$



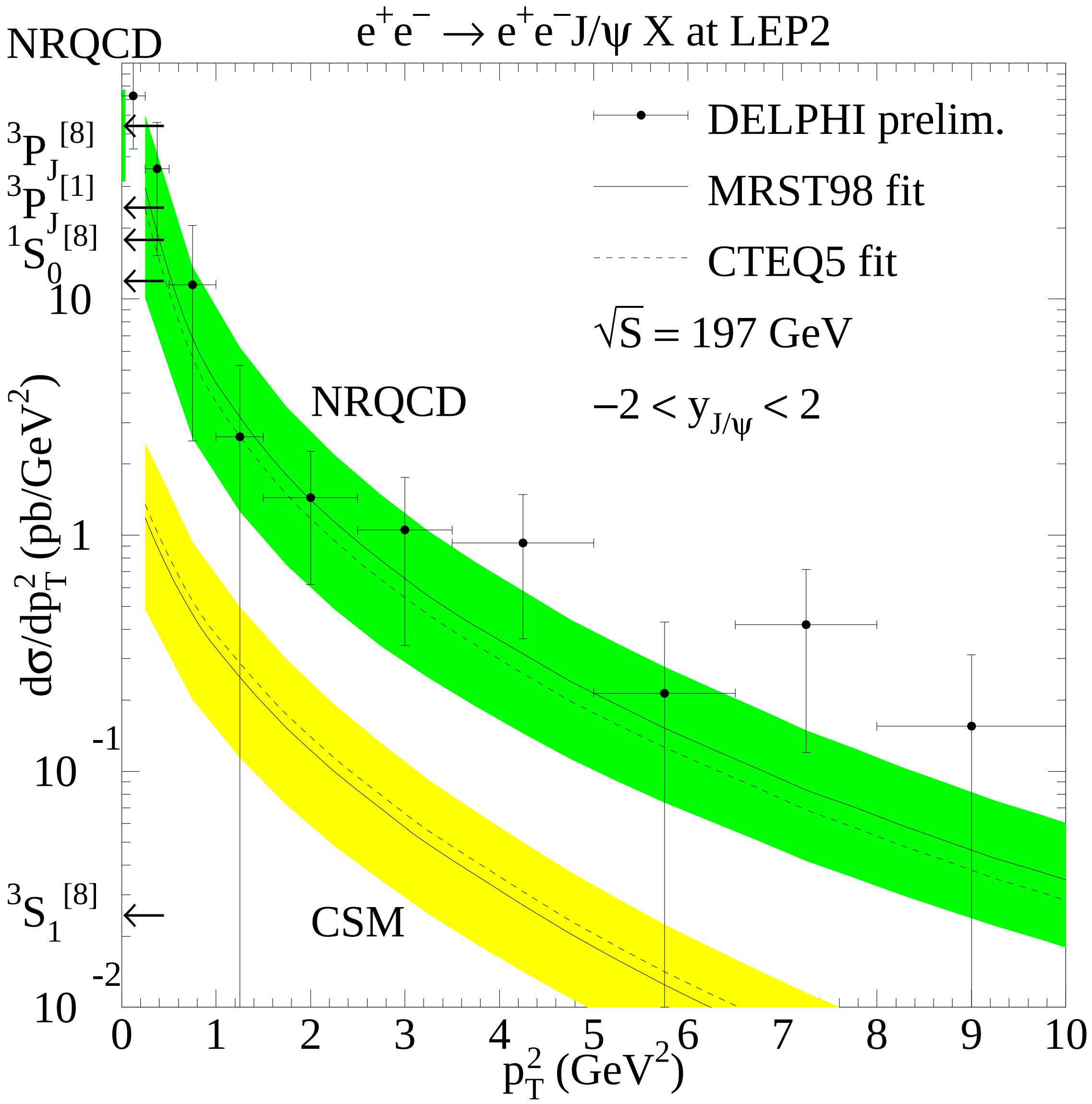
[Nucl. Phys. B 609 (2001) 518]

- Only real corrections included, regularized by

$$s_{jj} > M_{J/\Psi}^2/20,\ M_{J/\Psi}^2$$

- At large p_T:
  - Direct contribution dominates
  - Real corrections dominate, small cut-off dependence
  - NLO correction very large: $\sigma_{\rm NLO}/\sigma_{\rm LO} \gg 1$
- At small p_T:
  - Single-resolved contribution dominates
  - Cut-off dependence cancels against soft/virtual corrections
  - NLO correction small (cf. CSM) [Krämer, Znft, Steegborn, Zerwas, PLB 348 (1995) 657]

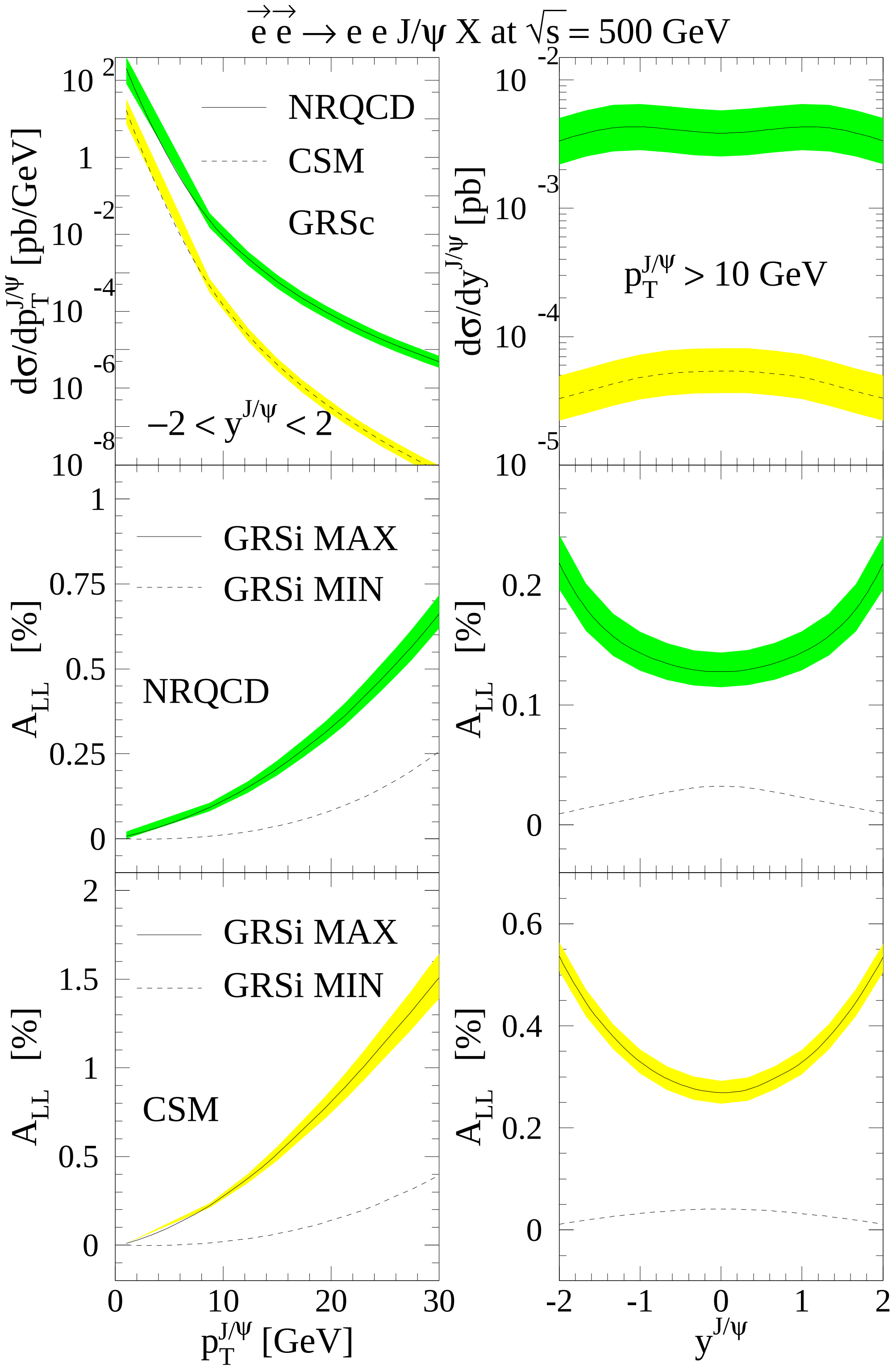
EVIDENCE FOR COLOR OCTET MECHANISM IN $\gamma\gamma \to J/\Psi X$



[Phys. Rev. Lett. 89 (2002) 032001]

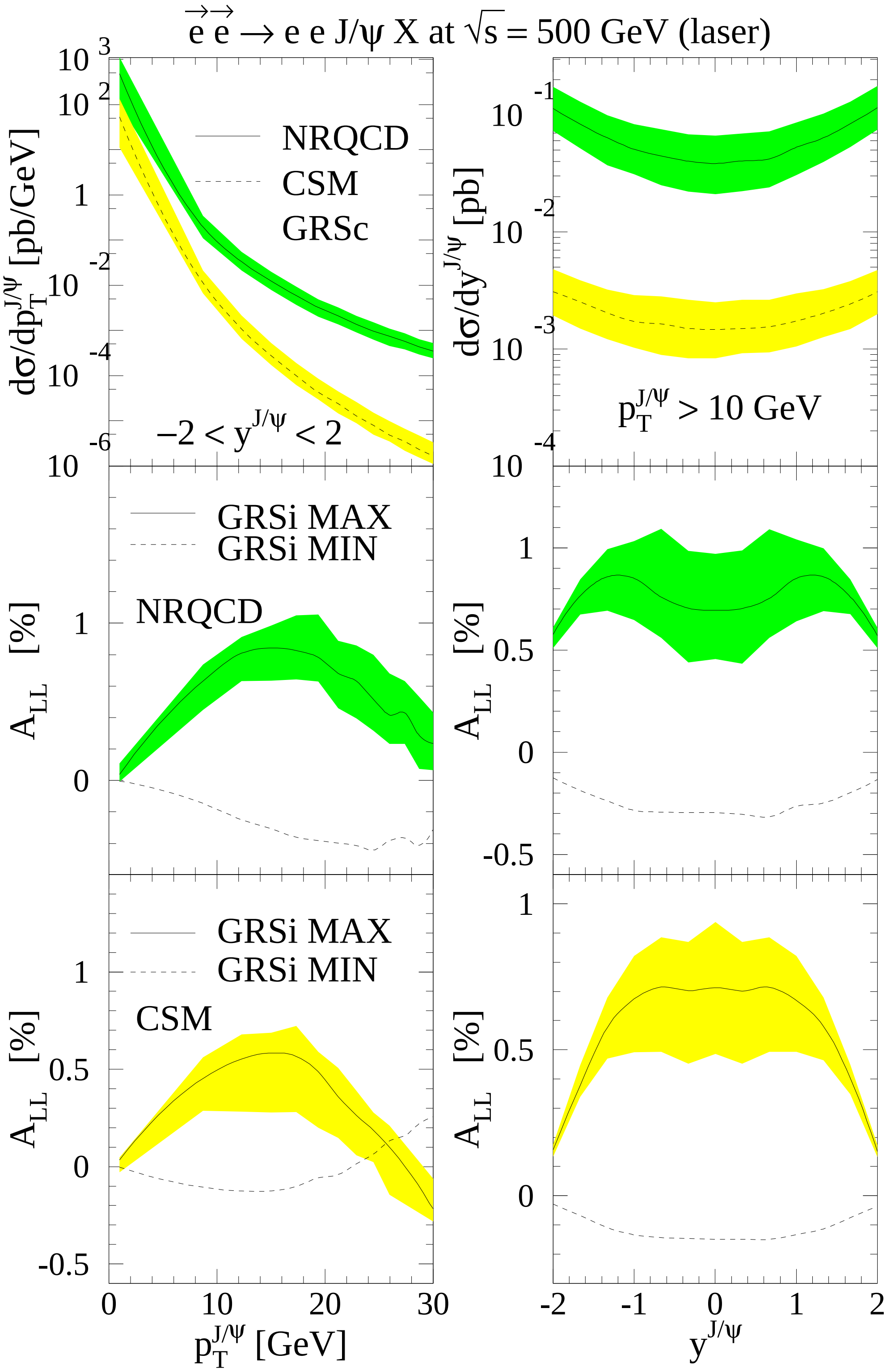
- LEP2 2000 data: $\sqrt{S} = 161 - 209$ GeV, $\theta_{\max} = 32$ mrad, $W < 35$ GeV, $-2 < y < 2$, 36 ± 7 events (limited statistics)
- CSM (CS) one order of magnitude too low
- NRQCD (CS+CO) prediction agrees very well with data
- Sizeable theoretical uncertainties from α_s, m_c, $\langle \mathcal{O}^H[n] \rangle$
- Single-resolved processes dominate (mostly $\gamma g \to J/\Psi g$)
- NRQCD(CSM): 91(77)% direct J/Ψ's, 9(23)% from χ_c decays

Determination of $\vec{g}_\gamma(x, Q^2)$ at Linear Colliders



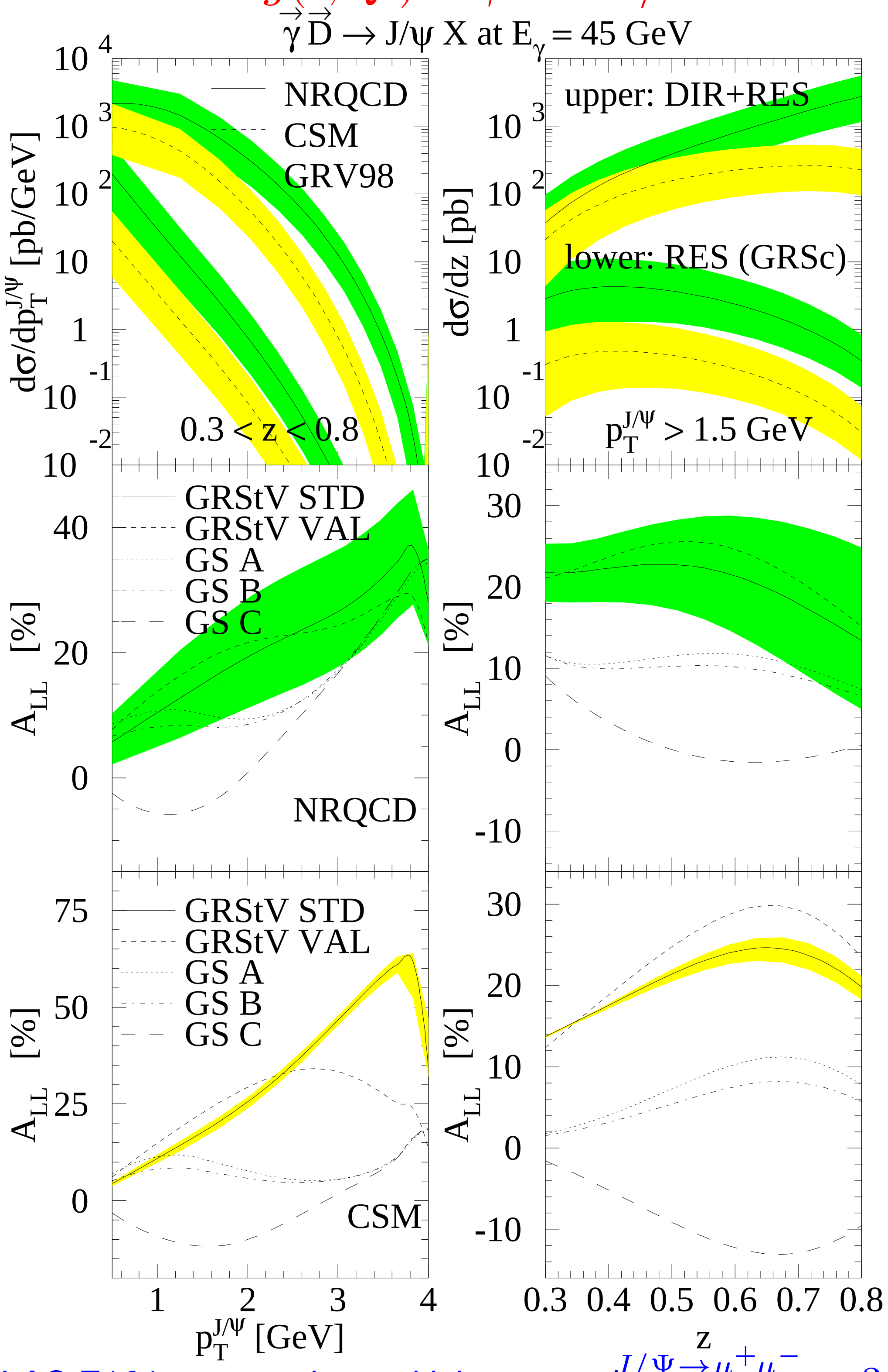
- Single-resolved photon contribution dominates
- $P(e^+) = 60\%$, $P(e^-) = 80\%$

Determination of $\vec{g}_\gamma(x, Q^2)$ at Photon Colliders



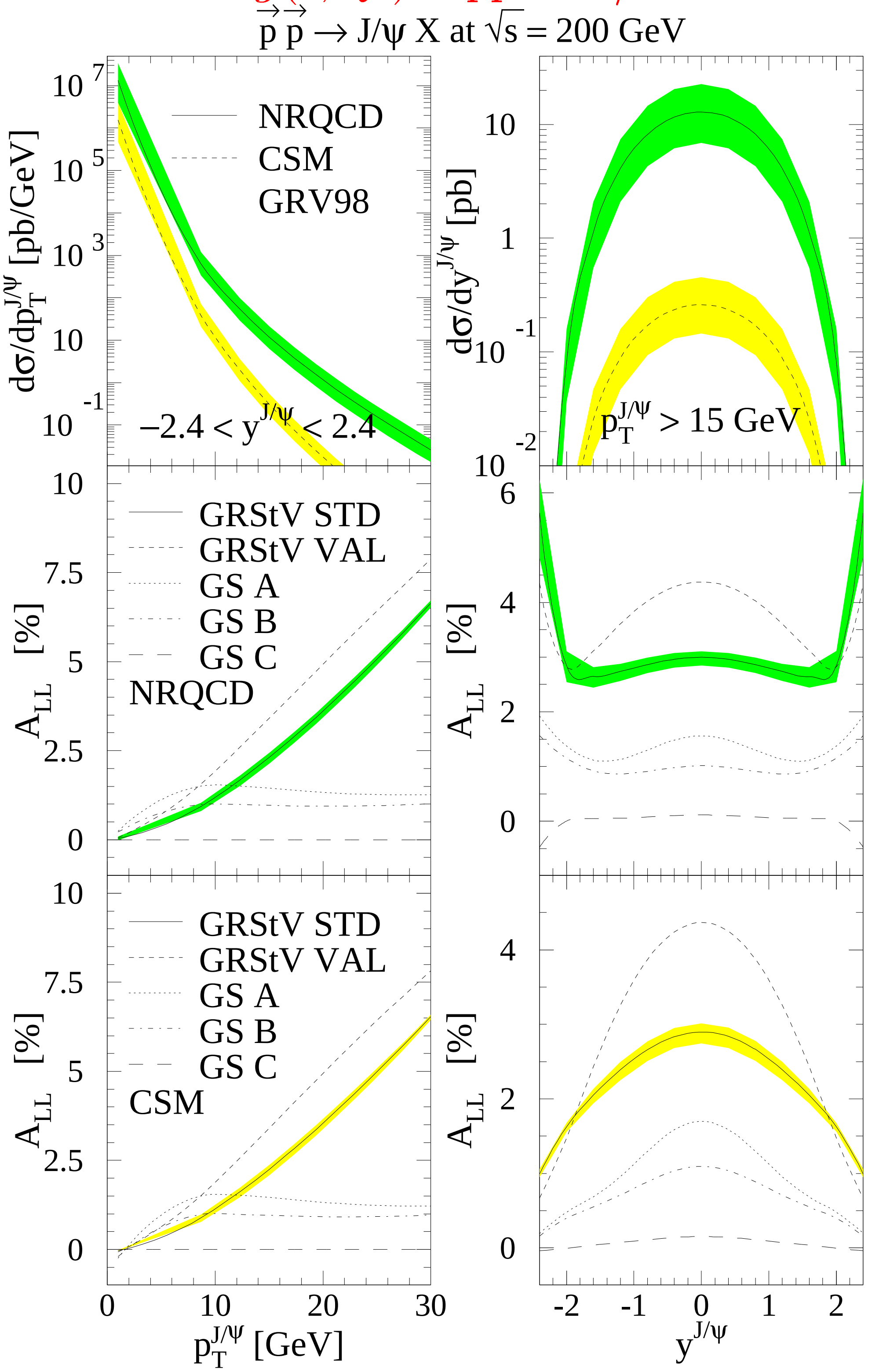
- $P(e^-) = 100\%$, $P(\text{laser}) = 100\%$

DETERMINATION OF $\vec{g}(x, Q^2)$ IN $\vec{\gamma}\vec{D} \to J/\Psi X$ AT SLAC E161



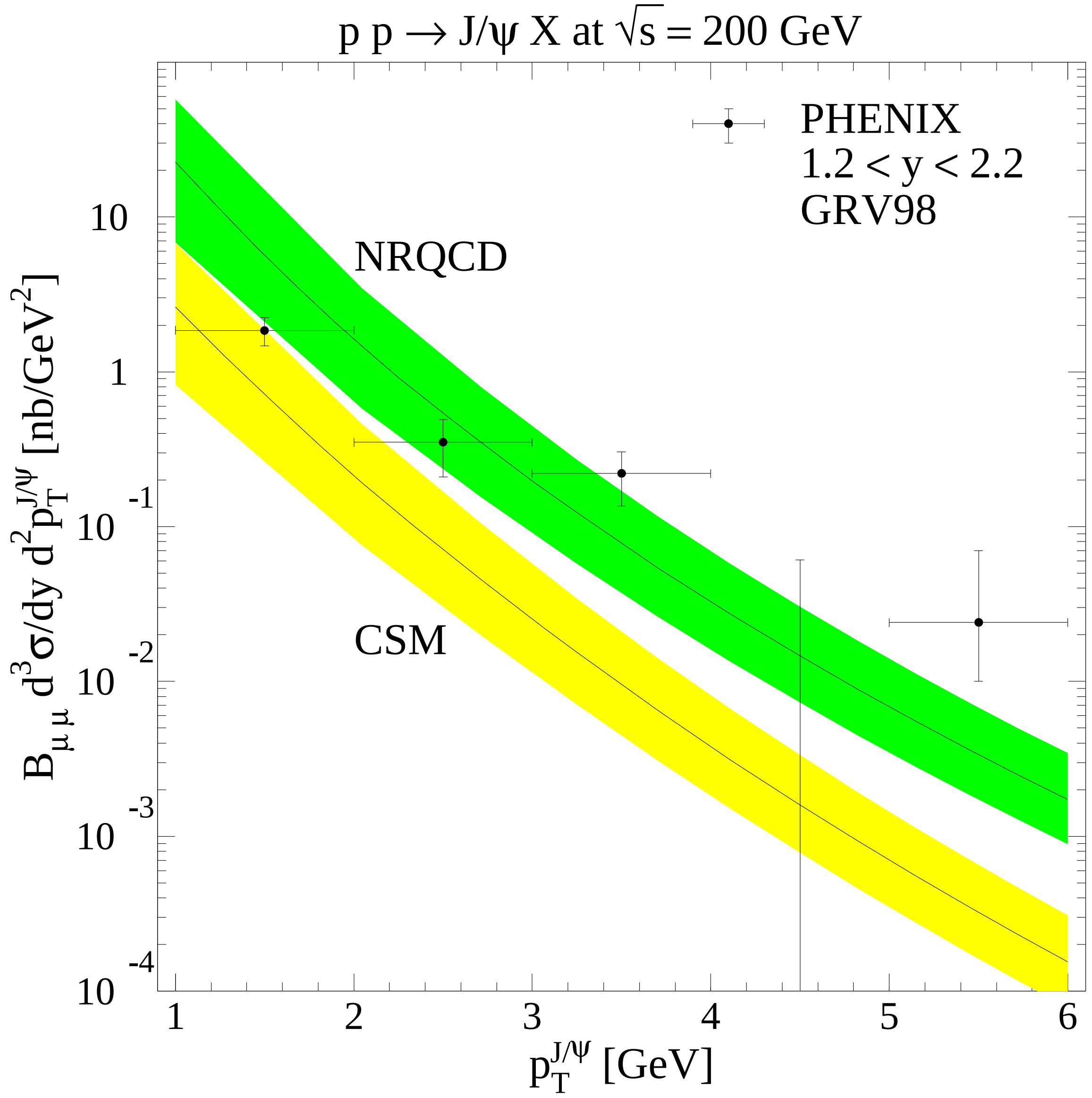
- SLAC E161 approved, sensitivity up to $p_T^{J/\Psi\to\mu^+\mu^-} \simeq 3$ GeV
- Resolved photon contribution to $\sigma < 10\%$, irrelevant for A_{LL}
- No uncertainties from photon PDF, α_s

Determination of $\vec{g}(x, Q^2)$ in $\vec{p}\vec{p} \to J/\Psi X$ at RHIC



- First data taken in Dec. 01, expected luminosity: $\mathcal{L} = 320$ pb^{-1}
- STAR: $|y^{J/\Psi \to e^+e^-}| < 1$, PHENIX: $|y^{J/\Psi \to \mu^+\mu^-}| \in [1.2; 2.4]$
- Similar results also for $\sqrt{s} = 50, 500$ GeV ($\mathcal{L} = 80, 800$ pb^{-1})

UNPOLARIZED CROSS SECTION $pp \to J/\Psi X$ AT RHIC



- S. Adler et al. [PHENIX Coll.] hep-ex/0307019, submitted to PRL
- $\mathcal{L}(J/\Psi \to \mu^+ \mu^-) = 67$ nb^{-1} in forward (not backward) region
- $\mathcal{L}(J/\Psi \to e^+ e^-) = 82$ nb^{-1} in central region (y< 0.35)
  $\to$ similar $p_T^{J/\Psi}$-spectrum
- $p_T^{J/\Psi} \in [0; 1]$ GeV suffers from IR/collinear singularities
- $p_T^{J/\Psi} > 5$ GeV need fragmentation contributions
- y-spectrum measured for $p_T^{J/\Psi} > 0$ GeV $\to$ no safe prediction

CONCLUSION

- Quarkonia simplest bound states, can study hadronization:
  - CSM: Very predictive, but fails at Tevatron. NLO corrections?
  - NRQCD: Describes Tevatron with fitted operators. Universality?
- Complete helicity amplitudes for $\vec{p}\vec{p}$, $\vec{\gamma}\vec{p}$, $\vec{\gamma}\vec{\gamma} \to \mathcal{Q}$, $\mathcal{Q}X$:
  - Caution: Correct sign of $\varepsilon_{\mu\nu\rho\sigma}$ in boson-fermion scattering?
  - Almost no results for NRQCD in the literature, mostly wrong
- Implementation of NRQCD processes in PYTHIA 6.2:
  - All $2 \to 1$ and $2 \to 2$ CS and CO processes
  - Important for experimental analyses
- NLO corrections to $\gamma\gamma \to J/\Psi X$:
  - Non-trivial five-point functions, P-wave integrals, in progress
  - Real corrections complete, important at large p_T
- Independent evidence for color octet mechanism from LEP:
  - CSM one order of magnitude below the DELPHI p_T^2 distribution
  - Limited statistics, more to come from ALEPH, L3, OPAL; TESLA
  - Sizeable theoretical uncertainties, consider ratio of χ_c decays
- Determination of the polarized gluon density:
  - Large asymmetries expected at approved SLAC E161
  - No uncertainties from photon PDF, α_s
  - Similar shapes in NRQCD and CSM
  - Good prospects also for RHIC