Resummation in Heavy Particle Production

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Berkeley Workshop on Early LHC Physics, 5/7/09

Outline

- quarkonium production near kinematic endpoints

  color-octet mechanism in photoproduction, $e^+e^- \to J/\psi + X$

  S.Fleming, A. Leibovich, TM, PRD68:094011(2003),PRD74:114004(2003)

- threshold effects in $t\,\bar{t}$ pair production

  threshold resummation tt production

  Y. Kiyo, et.al. Eur.Phys. J. C60:375(2009)

  resummed cross sections for NP particles

  A. Idilbi, C. Kim, & T.M., arXiv:0903.3668[hep-ph]

  A. Kulesza and L. Motyka, arXiv:0807.2405[hep-ph]

  U. Langenfeld and S.O. Moch, arXiv:0901.0802[hep-ph]

Quarkonium Production Near Kinematic Endpoints

Review of NRQCD

- EFT for nonrelativistic $Q\overline{Q}$ $(J/\psi,\ \Upsilon,\ B_c)$
- Factorization Theorem for cross sections, decay rates:

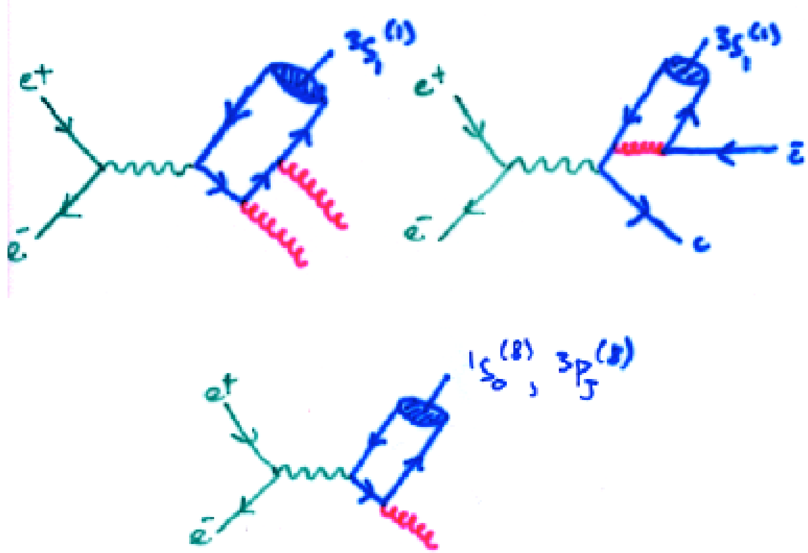
(Bodwin, Braaten and Lepage)

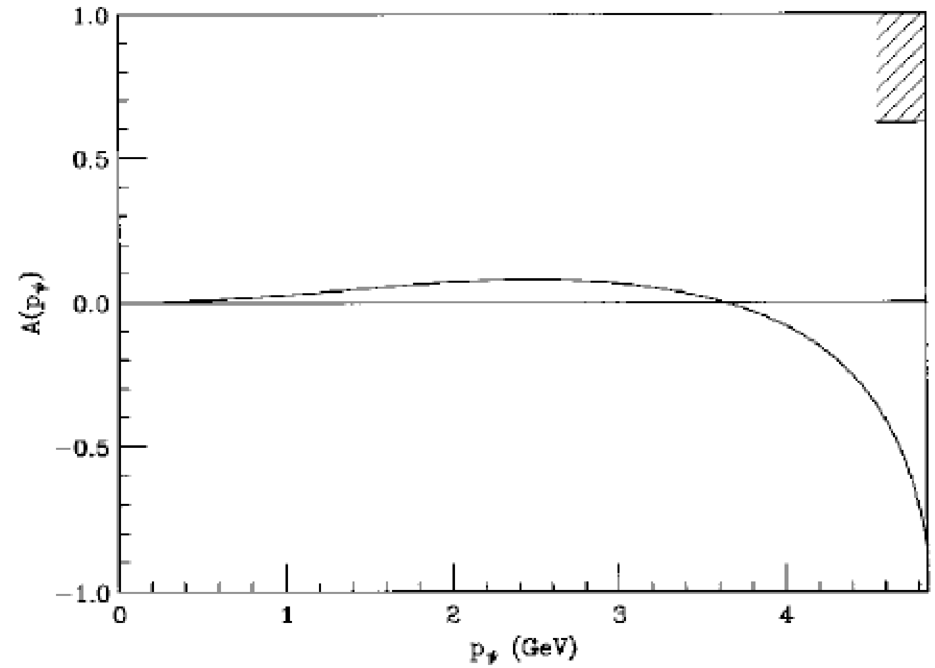
$$d\sigma = \sum_n c_n(\alpha_s)\langle O_n\rangle, \qquad \langle O_n\rangle \sim v^n$$

- double expansion in α_s, v
- color-singlet model (J/ψ) lowest order in v expansion
- color-octet mechanisms v suppressed but often important

Quarkonium Production Near Kinematic Endpoints

- Color-Octet Signal in $e^+e^- \to J/\psi + X$ (Braaten, Chen)





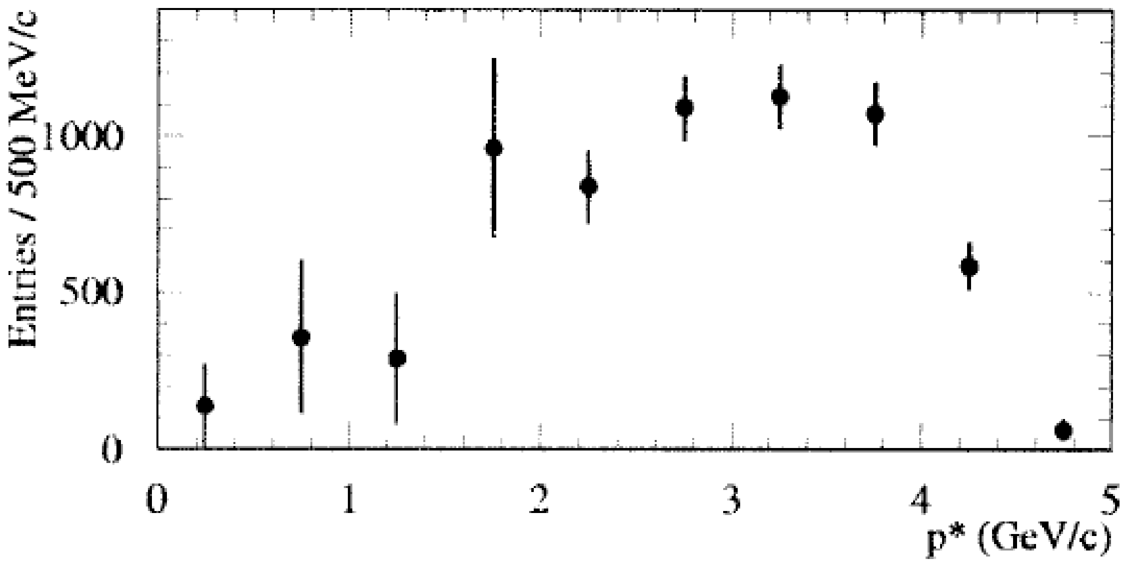
$$\sigma^{\rm LO}[e^+e^- \to J/\psi c\bar{c}] \sim 0.1\,\sigma^{\rm LO}[e^+e^- \to J/\psi gg]$$

- Large (~1 pb) CO contribution near endpoint (total CS 0.4-0.9 pb)

- angular distribution $(\cos\,\theta\ -\ \text{angle between } J/\psi \text{ and beam})$

$$\frac{d\sigma}{dp\,d\cos\theta} = S(p)(1 + A(p)\cos^2\theta)$$

- BaBar (J/ψ cross section)



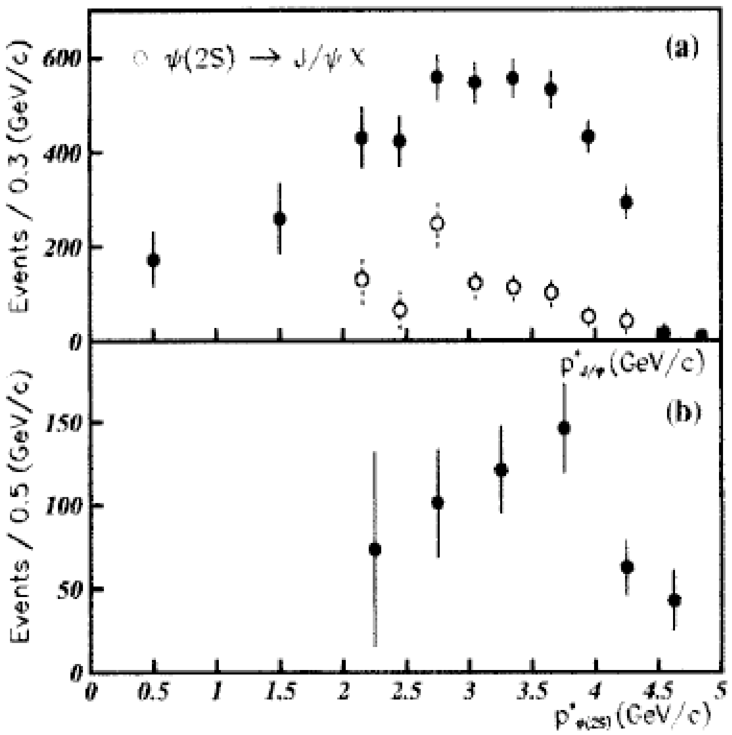
- $\sigma_{\text{tot}} = 2.52 \pm 0.21 \pm 0.21\,\text{pb}$

$$A(p) = \begin{cases} 0.05 \pm 0.22 & p < 3.5\,\text{GeV} \\ 1.5 \pm 0.6 & p > 3.5\,\text{GeV} \end{cases}$$

- Total cross section in excess of CSM, A(p)~1 for large p

- Where is color-octet contribution at endpoint?

- Belle



$$\sigma_{\rm tot} = 1.47 \pm 0.10 \pm 0.13\,{\rm pb}$$

$$A(p) = \begin{cases} 0.3^{+0.5}_{-0.4} & 2.0 < p < 2.6\,{\rm GeV} \\ 1.1^{+0.4}_{-0.3} & 2.6 < p < 3.4\,{\rm GeV} \\ 1.1^{+0.4}_{-0.3} & 3.4 < p < 4.9\,{\rm GeV} \end{cases}$$

- Other Puzzles: $\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12$ (2002)

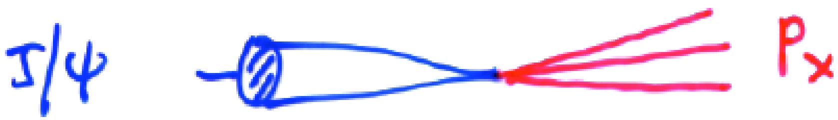
Recent Data

BELLE, arXiv:0901.2775 [hep-ex]

$$\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = 0.74 \pm 0.08^{+0.09}_{-0.08}\,{\rm pb}$$

$$\sigma[e^+e^- \to J/\psi + X({\rm non}{-}c\bar{c})] = 0.43 \pm 0.09 \pm 0.09$$

- Near endpoint c$\bar{c}$ recoiling against low mass energetic jet



$$P_X^2 \simeq s\left(1-\frac{M^2}{s}\right)(1-x)$$
$$\simeq s\left(1+\frac{M^2}{s}\right)(1-z)$$

$$x = \frac{E+p_z}{\sqrt{s}} \qquad\qquad z = E^{\psi}/E^{\psi}_{\rm max}$$

- Large perturbative, nonperturbative corrections

(Beneke, Rothstein, and Wise)

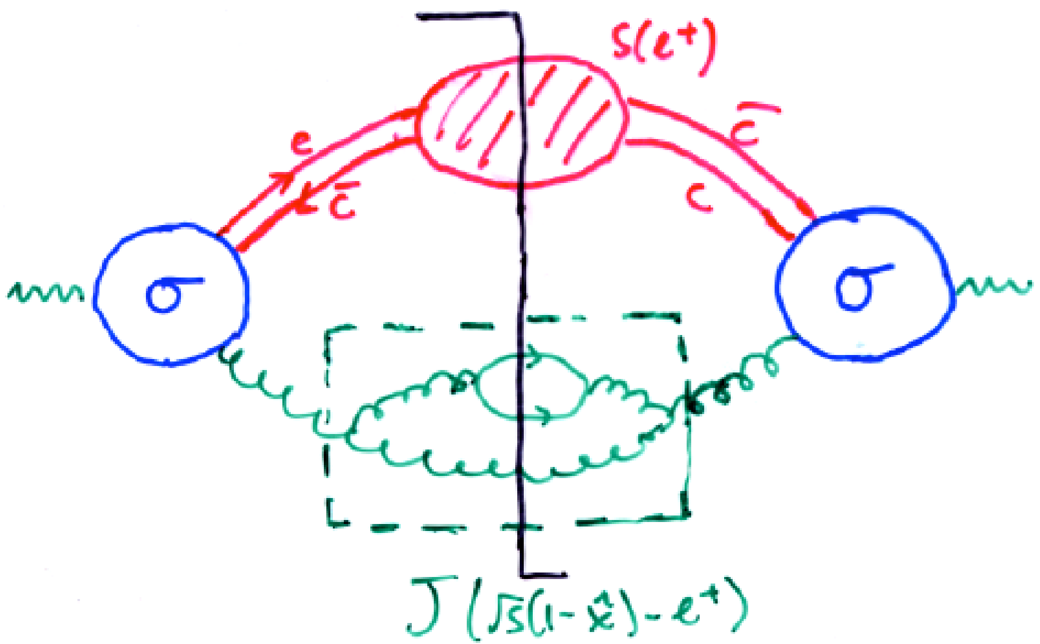
$$\alpha_s \frac{\ln(1-x)}{1-x} \qquad\qquad \frac{v^2}{1-x}$$

- $1-\hat{x} \sim \Lambda_{\rm QCD}/M \longrightarrow p_\psi \approx 3 \text{ GeV}$ $\qquad (p_\psi)_{\rm max} \approx 4.8 \text{ GeV}$

- as $x \to 1$ need a new factorization theorem

(Fleming, Leibovich, T.M.)

$$\frac{d\sigma}{dx} = \sigma(\mu) \int d\ell^+ S(\ell^+) J(\sqrt{s}(1-\hat{x}) - \ell^+)$$



- resum large logs using RGE's for $S(\ell^+)$, $J(\sqrt{s}(1-\hat{x}) - \ell^+)$
- nonperturbative corrections incorporated in shape function $S(\ell^+)$

Soft Collinear Effective Theory

(Bauer, Fleming, Luke, Pirjol, Stewart)

- Inclusive process   Hard Scale ~ Q

- Degrees of Freedom

$$n^\mu = (1,0,0,1),\ \bar{n}^\mu = (1,0,0,-1)$$

collinear $(\bar{n}\cdot p, n\cdot p, p_\perp) \sim Q(1,\lambda^2,\lambda)$

usoft $(\bar{n}\cdot p, n\cdot p, p_\perp) \sim Q(\lambda^2,\lambda^2,\lambda^2)$

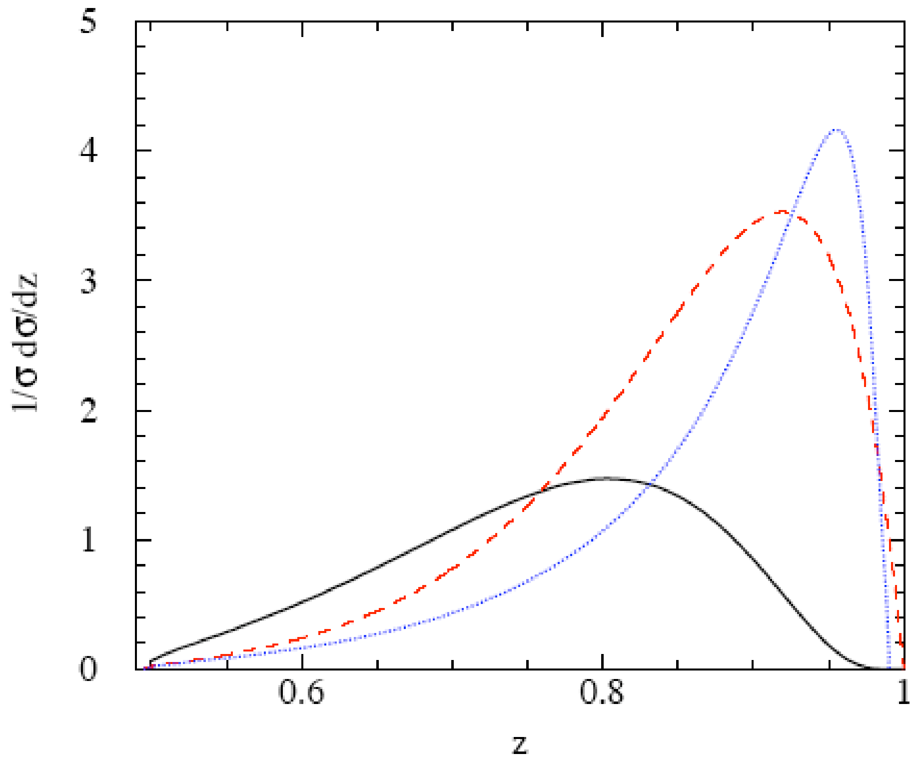
- $e^+e^- \to J/\psi + X$ $Q \sim \sqrt{s} \sim 2m_c$ $\lambda \sim \sqrt{\Lambda_{\mathrm{QCD}}/Q} \sim \sqrt{1-x}$

collinear gluons $J(\sqrt{s}(1-\hat{x}) - \ell^+)$

usoft gluons, heavy quarks $S(\ell^+)$

- Not Predictive - depends on unknown universal $S(\ell^+)$

  test universality in photo-, electroproduction ?



Dotted - resummation only

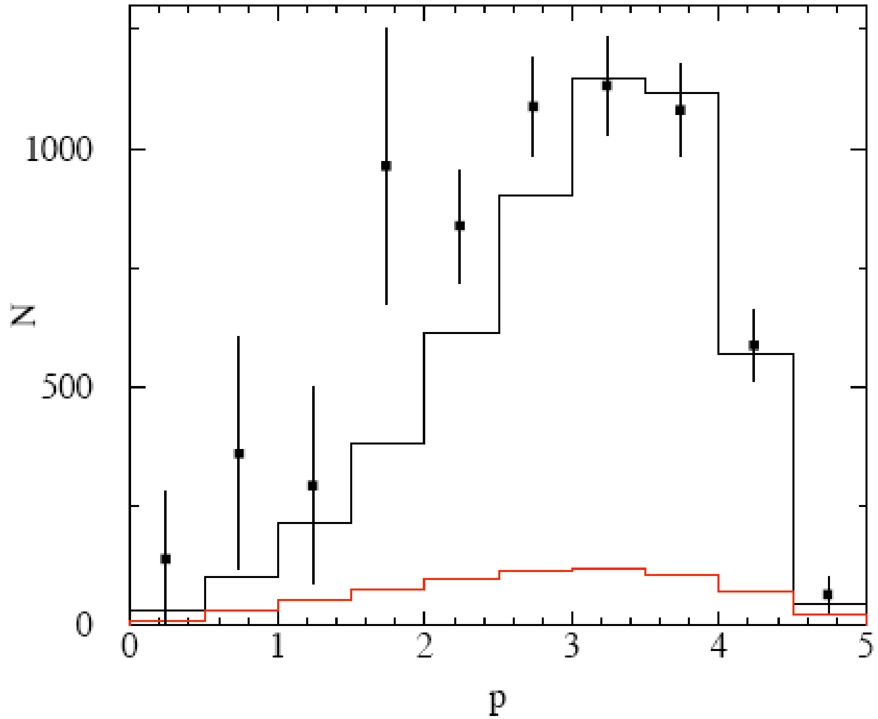
Dashed - shape function only

Solid - both

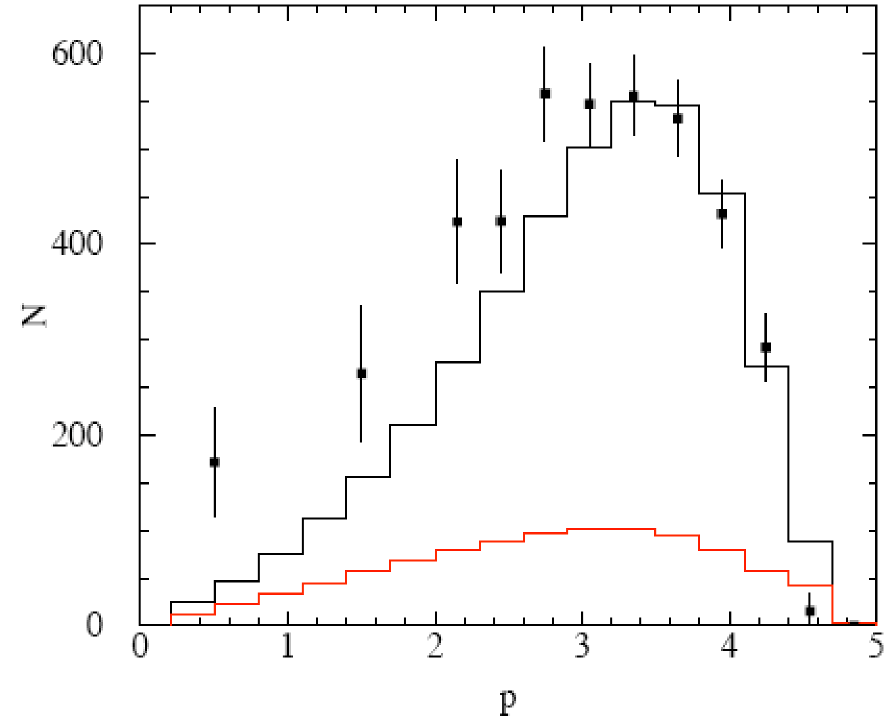
- NRQCD scaling rules:

$$S_N = \int d\hat{\ell}^+ (\hat{\ell}^+)^N \, S(\hat{\ell}^+) \sim (2m_c v^2)^N \sim \Lambda_{\rm QCD}^N ; \; N \geq 1$$

- Comparison with Data (Different normalization)



BaBar



Belle

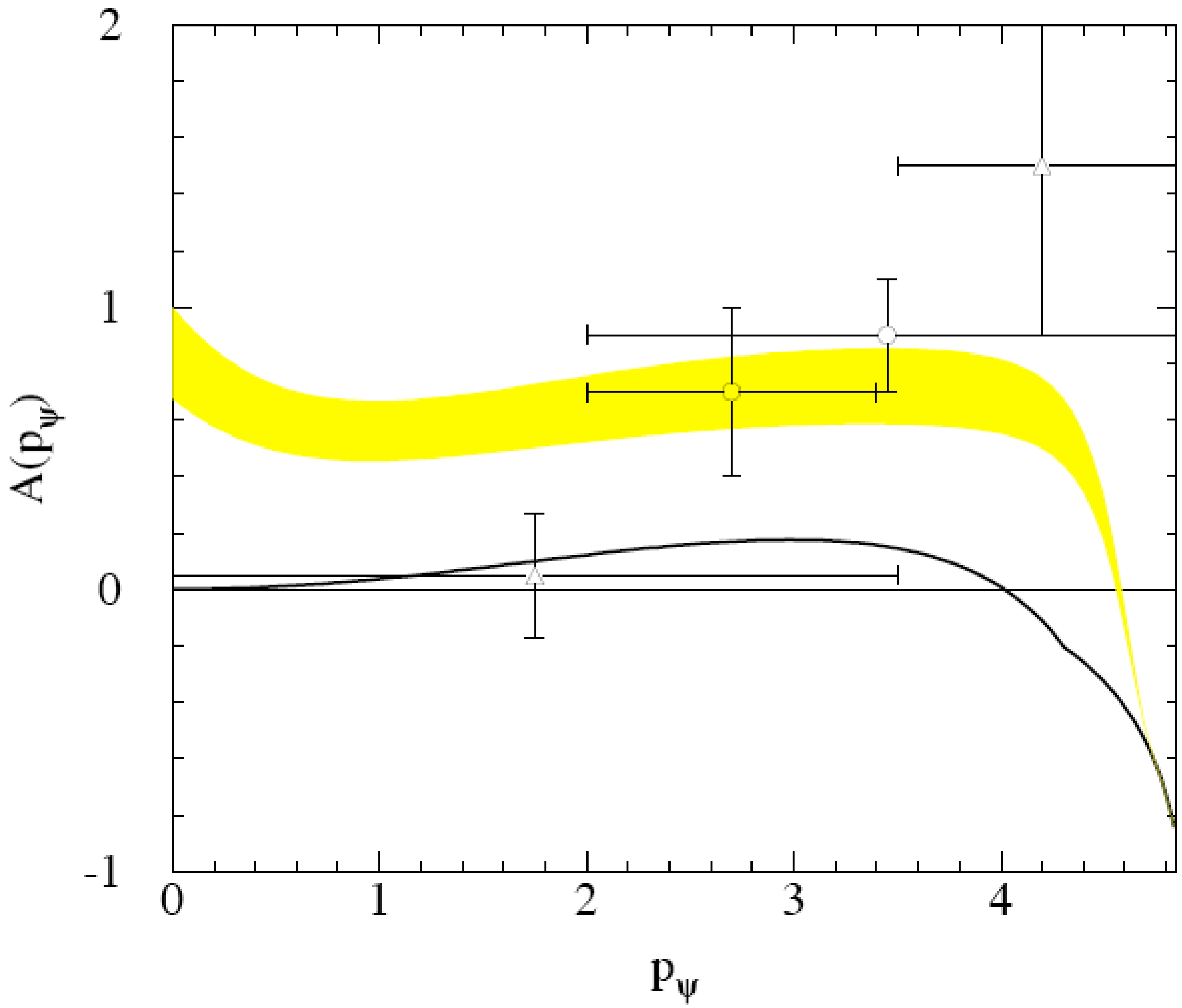
- Absence of color-octet peak near endpoint understood
- $\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)}$ still unexplained, NLO effects close gap slightly

$\sigma^{\mathrm{NLO}}[e^+e^- \to J/\psi c\bar{c}] \approx 1.8\, \sigma^{\mathrm{LO}}[e^+e^- \to J/\psi c\bar{c}]$ Y.-J. Zhang & K.-T. Chao, PRL 98:092003 (2007)

$\sigma^{\mathrm{NLO}}[e^+e^- \to J/\psi gg] \approx 1.2\, \sigma^{\mathrm{LO}}[e^+e^- \to J/\psi gg]$ B. Gong & J.-X. Wang, PRL 98:092003 (2007)

feeddown from ψ'

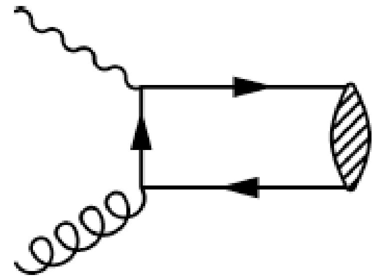
- Angular distribution

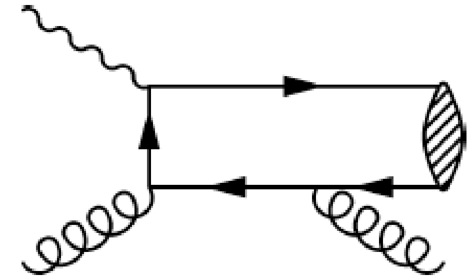


Solid line - Color-Singlet Model, Yellow Band - Resummed Color-Octet

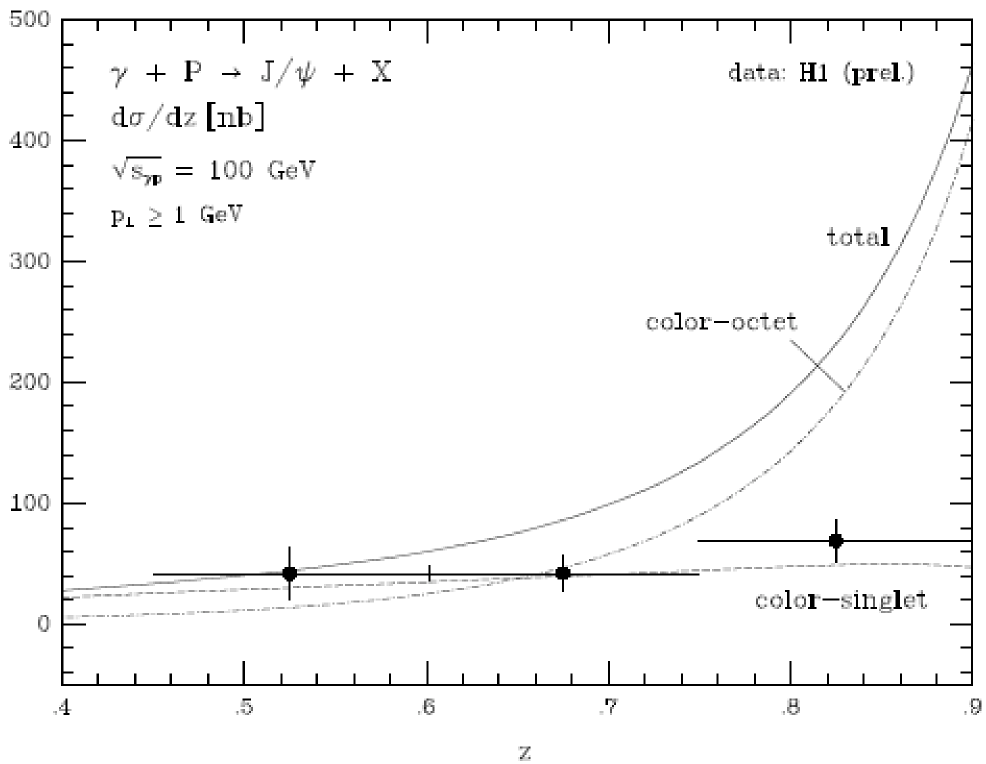
$A(p_\psi) \approx 1$ at large p_ψ (don't believe resummation at small p_ψ)

- # Photoproduction

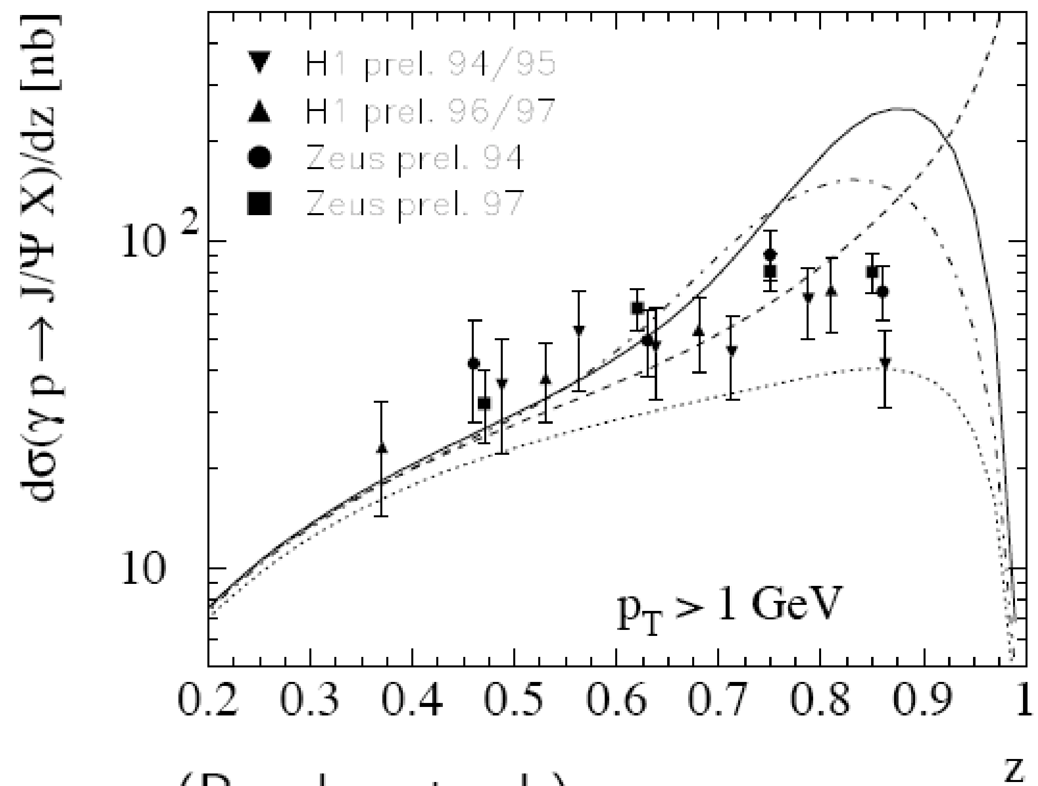




$$z = E^{\psi}/E^{\psi}_{\max} \qquad \sigma_0\delta(1-z) \qquad -\,\sigma_0\frac{C_A\alpha_s}{\pi}\frac{\ln(1-z)}{1-z}+\ldots$$



(Cacciari, Kramer)

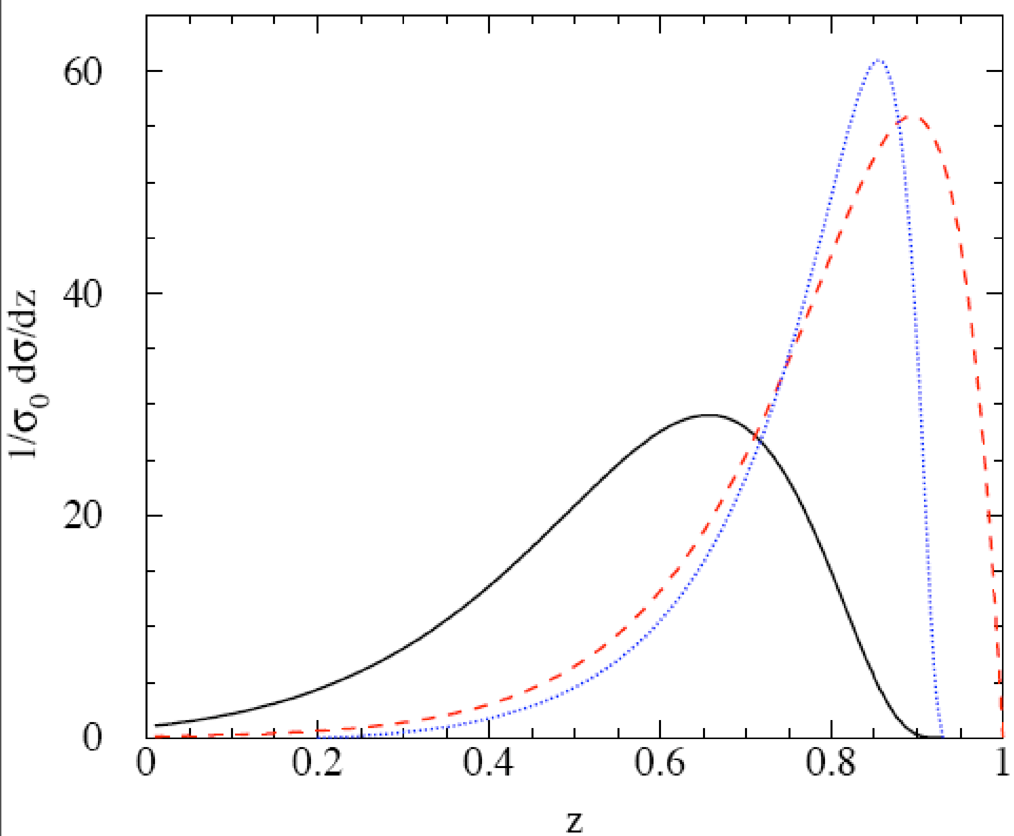


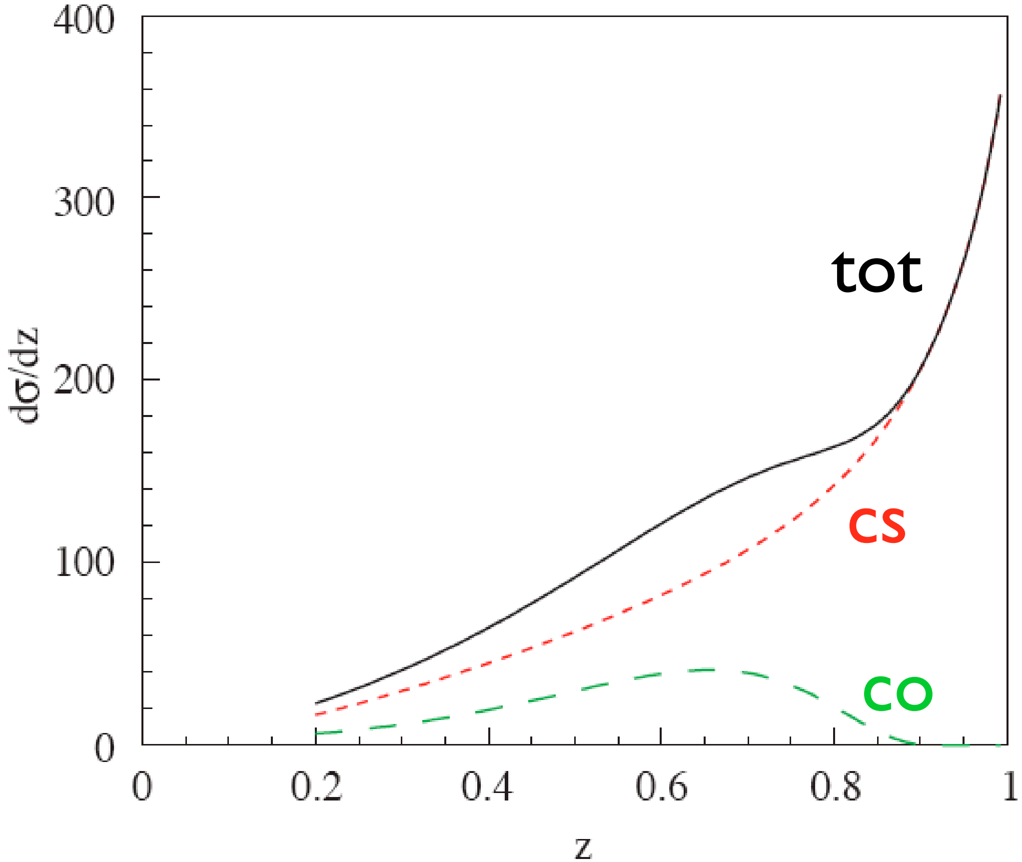
(Beneke, et. al.)

NLO CO

includes shape function, no resum.

- Resummed Cross Section



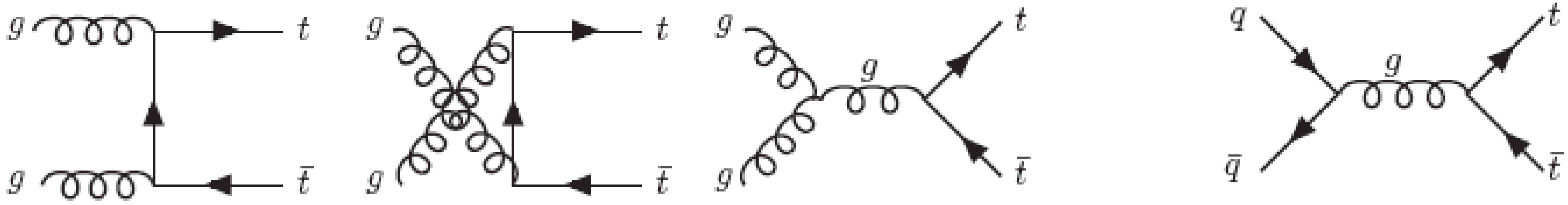


- Peak shifted from z ~ 0.9 to z ~ 0.7
- nonperturbative and perturbative resummation required
- CO matrix element is ~10 times smaller than Tevatron!

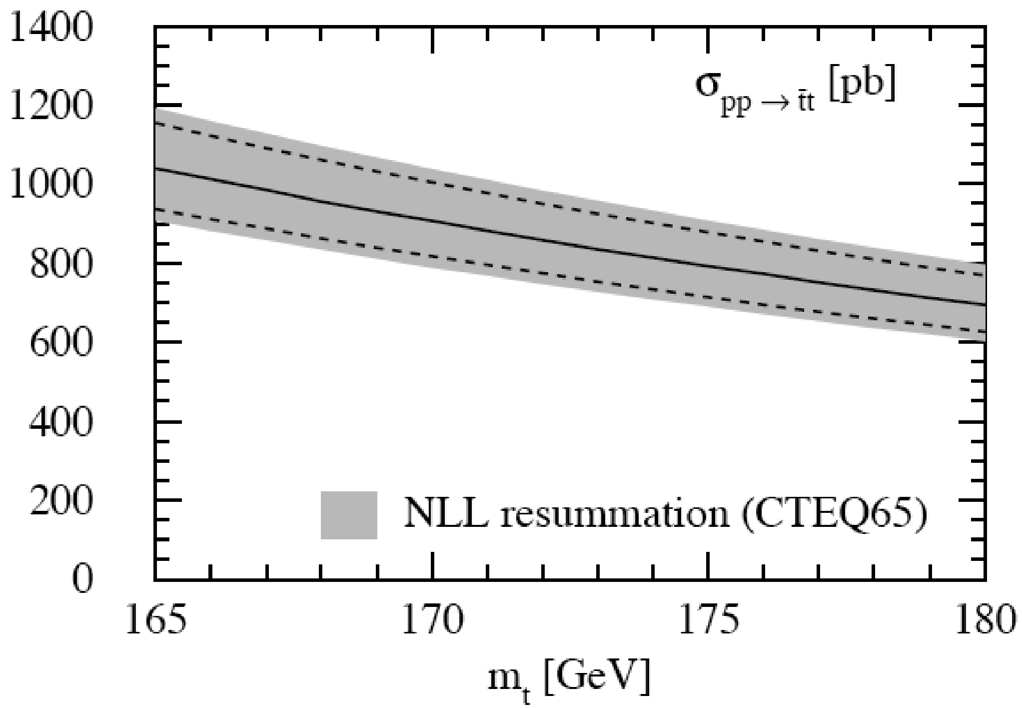
$t\,\bar{t}$ pair production

Top quark pair production

- dominant production mechanism - gluon-gluon fusion



- include NLO QCD correction, NLL resummation



S. Moch & P. Uwer, arXiv:0804.1476 [hep-ph]

$$\sigma_{\rm tot} \approx 900\,{\rm pb}\,,\sqrt{s} = 14\,{\rm TeV}$$
$$\approx 400\,{\rm pb}\,,\sqrt{s} = 10\,{\rm TeV}$$

Scale, pdf uncertainty ~10-15%

reduce to ~5% w/ full NNLO

only partial NNLO available now

Physics Goals

- measure m_t
- anomalous couplings

$$-\frac{g_W}{\sqrt{2}}\varepsilon^{*\mu}\bar{u}_b\left[(V_{tb}^* + f_L)\gamma_\mu P_L + f_R\gamma_\mu P_R + i\sigma_{\mu\nu}q^\nu\left(\frac{g_L}{m_W}P_L + \frac{g_R}{m_W}P_R\right)\right]u_t$$

indirect bounds from $B \to X_s\gamma$

B. Grzadkowski & M. Misiak, 0802.1413 [hep-ph]

$$\begin{array}{rcl} -0.13 < & f_L & < 0.03 \\ -7\,10^{-3} < & f_R & < 2.5\,10^{-3} \\ -1.5\,10^{-3} < & g_L & < 4\,10^{-4} \\ -0.15 < & g_R & < 0.57 \end{array}$$

- probe Higgs mechanism

top important source of longitudinal W bosons!

F_λ^W - fraction of W with helicity λ (assuming V-A coupling)

$$F_0^W \sim 0.7, \quad F_-^W \sim 0.3, \quad F_+^W \sim 0$$

measured through angular distribution in $W^+ \to \ell^+\nu_\ell$

- new physics, e.g. $t\bar{t}$ resonances

Threshold Resummation

- LHC: 80% of cross section $2m_t \leq \sqrt{\hat{s}} < 600\,\mathrm{GeV}$
- fixed order calculations exhibit large logs $M^2 = (p_t + p_{\bar{t}})^2$

$$\frac{d\sigma}{dM} = \sum_{ij} \tau \int_\tau^1 d\tau\, C_{ij}(M,z) F_{ij}(\tau/z) \qquad F_{ij}(y) = \int \frac{dx}{x} f_{i/p}(x) f_{j/p}(x/y)$$

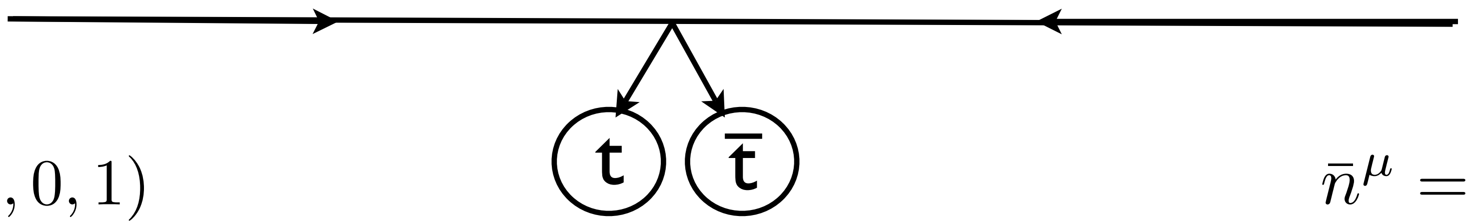
$$C_{ij}(M,z) \propto \alpha_s \left(\frac{\ln(1-z)}{1-z}\right)_+ , \alpha_s \left(\frac{1}{1-z}\right)_+ \ln\left(\frac{M^2}{\mu_f^2}\right) \qquad z = \frac{M^2}{\hat{s}}$$

- associated with soft-collinear radiation in threshold region
- fixed NLO, NLL resummation differ by ~5%

  resummation reduces scale uncertainty
- relevant to Drell-Yan, Higgs, heavy particle production

- kinematics in threshold region

$$\frac{\sqrt{\hat{s}}}{2} n^\mu \qquad \qquad \frac{\sqrt{\hat{s}}}{2} \bar{n}^\mu$$



$$n^\mu = (1,0,0,1) \qquad \qquad \bar{n}^\mu = (1,0,0,-1)$$

$$2m_t \, v^\mu$$

$$v^\mu = (1,0,0,0)$$

- soft radiation sees light-like (time-like) Wilson-line sources due to energetic (heavy) particles

- Factorization Theorem

$$\sigma(pp \to t\bar{t}X) = \tau H(M,\mu_f) \int_\tau^1 \frac{dz}{z} S(M(1-z),\mu_f) F(\tau/z,\mu_f)$$

- Parton densities (SCET collinear modes)

$$F(x,\mu_f) = \int_y^1 \frac{dy}{y} f_{g/P}(y,\mu_f) f_{g/p}(x/y,\mu_f)$$

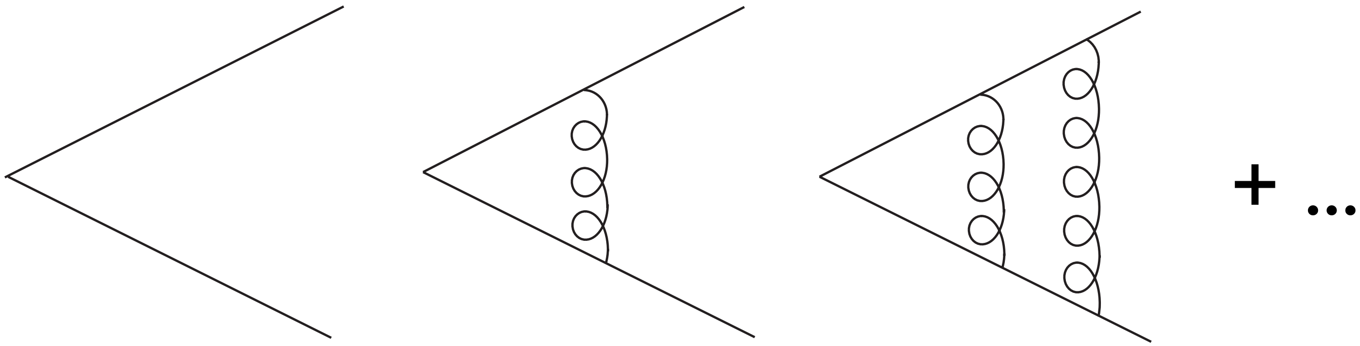
- Soft function (SCET soft modes) $S(M(1-z),\mu_f)$

- Hard function (SCET matching coefficient)

SCET RGE's for $S(M(1-z),\mu_f)$ $H(M,\mu_f)$ $F(x,\mu_f)$

resum large logarithms

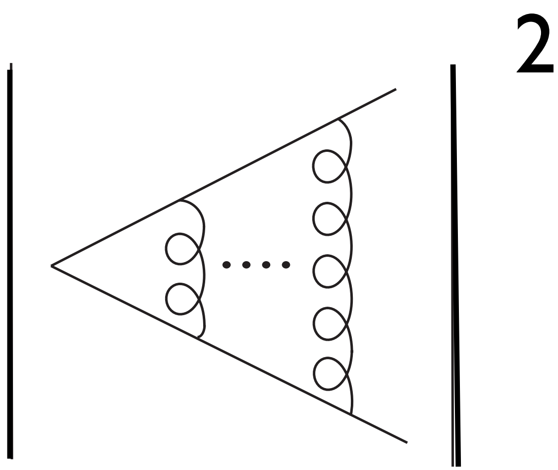
- v-enhanced corrections in threshold region



$O(1)$ $\qquad O(\alpha_s/v)$ $\qquad O(\alpha_s^2/v^2)$

- leading contribution comes from Coulomb gluons

when $v \sim \alpha_s$ sum to all orders using Schroedinger Eq.

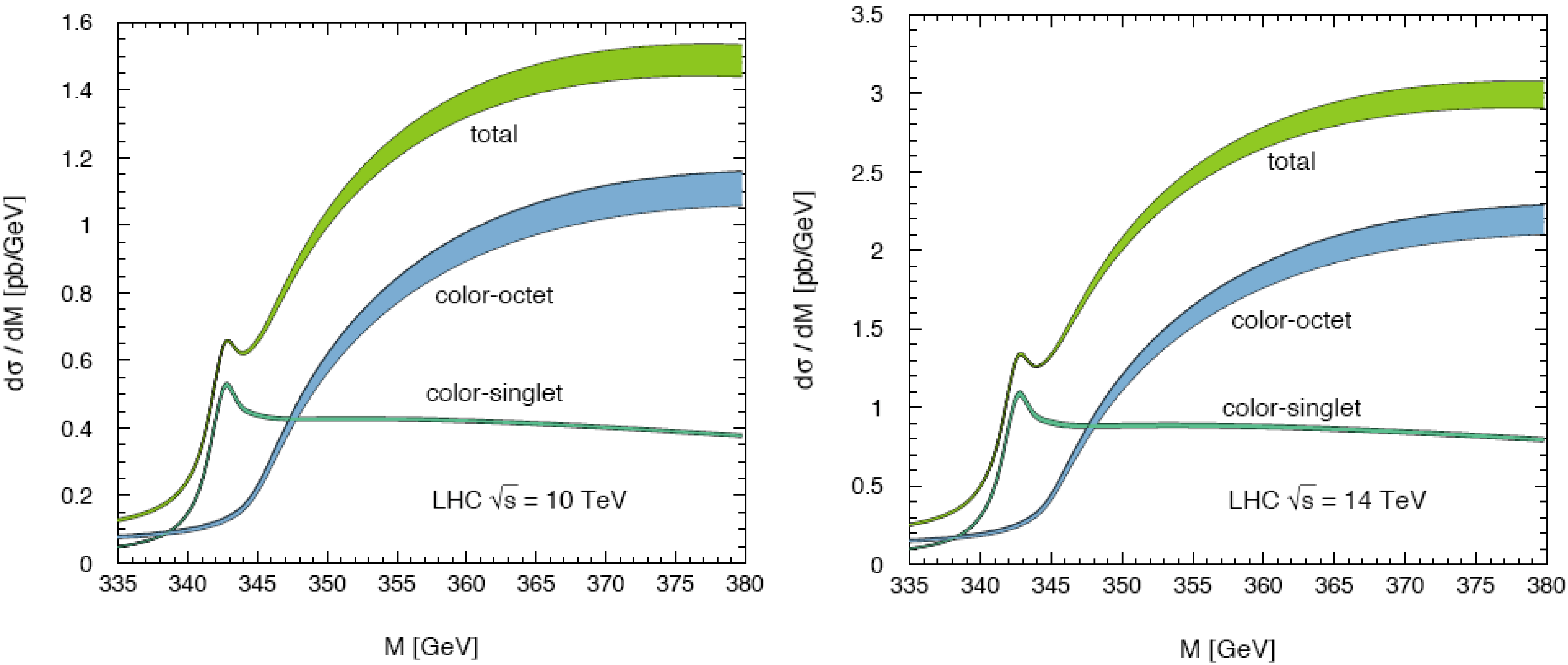


$\propto \mathrm{Im}\, G^{(1,8)}(\vec{0}; M + i\Gamma_t)$

$$\left\{ 2m_t + \left[\frac{(-i\nabla)^2}{m_t} + V_C^{[1,8]}(\vec{r}) \right] - (M + i\Gamma_t) \right\} G^{[1,8]}(\vec{r}; M + i\Gamma_t) \;=\; \delta^{(3)}(\vec{r})$$

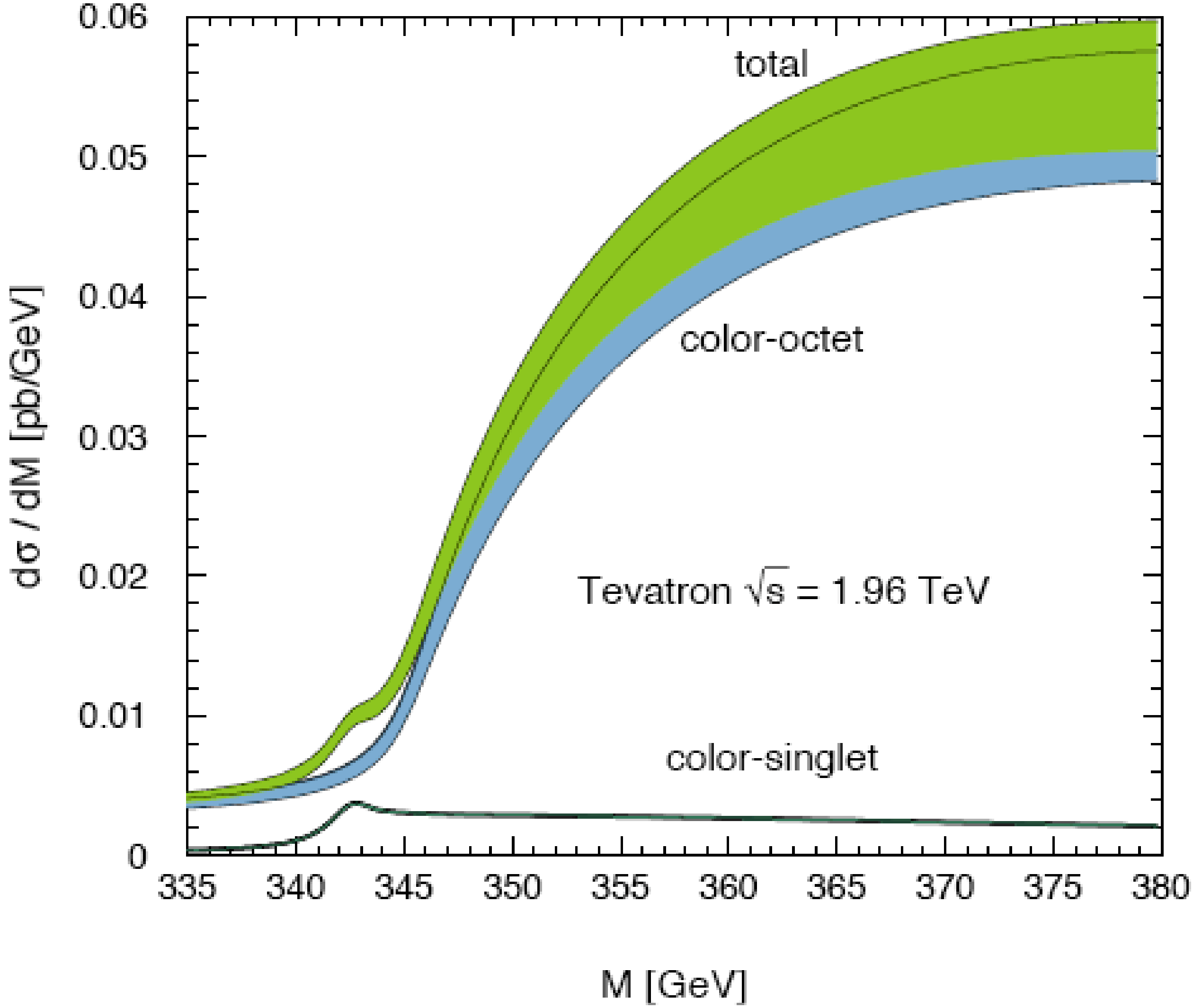
- including all threshold effects

(Y. Kiyo, et. al., Eur. Phys. J. C60:375 (2009))

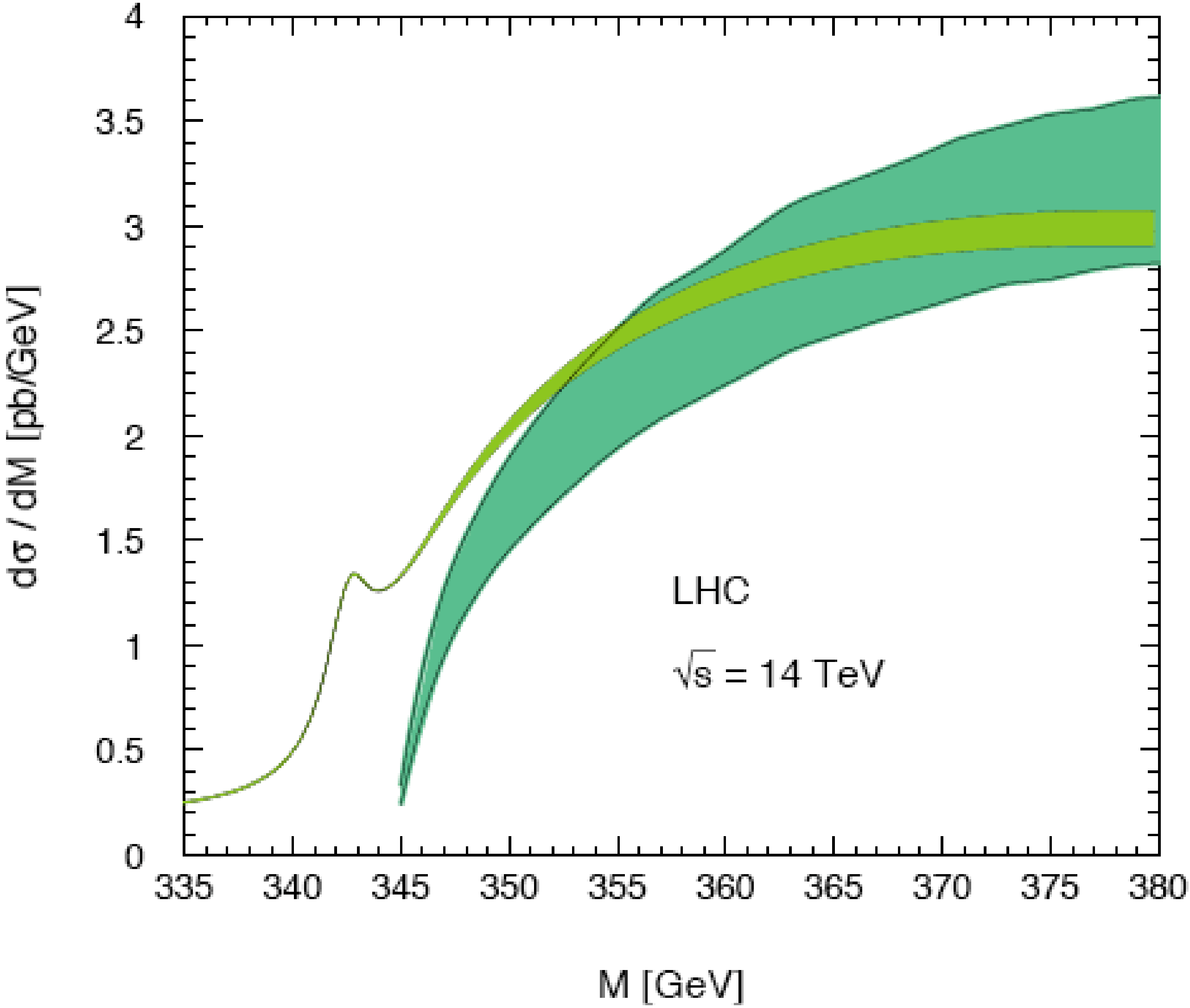


- Strong Coulombic attraction gives visible bump below threshold in color-singlet channel!

- contrast with $d\sigma/dM$ at Tevatron



- comparison w/ fixed order calculation



- bound state corrections large when $340\,\mathrm{GeV} < M < 360\,\mathrm{GeV}$
- interesting to consider relativistic corrections $0 < v^2 < 0.1$

fact. theorem: $\sigma(t\bar{t}) = \sigma^{\mathrm{resum}}(t\bar{t}) \times \mathrm{Im}\, G^C$ leading term as v → 0

Top Quark Mass

- current measurements of “m_t^{pole}” combine:

tree-level matrix elements
parton showers
hadronization models

} fit to invariant mass of decay products (jets and leptons)

errors 1-2 GeV (CDF, ATLAS, CMS)

- Ambiguities

color recombination with other particles in final state

renormalon pole ambiguity in definition of m_t^{pole}

- Prefer observable computed in terms of short-distance quantities

$$O^{\text{phys}}(\alpha_s(\overline{m}_t), \overline{m}_t(\overline{m}_t), \ldots)$$

where $\overline{m}_t(\mu_r)$ is MS or other short distance mass

$$O^{\text{phys}} : d\sigma/dM_{t\bar{t}}, \langle M_{t\bar{t}} \rangle, \ldots.?$$

Threshold Resummation for New Physics

$\sigma(gg \to S^A)$ color-octet scalars in Manohar-Wise model

A. Idilbi, C. Kim, & T.M., arXiv:0903.3668[hep-ph]

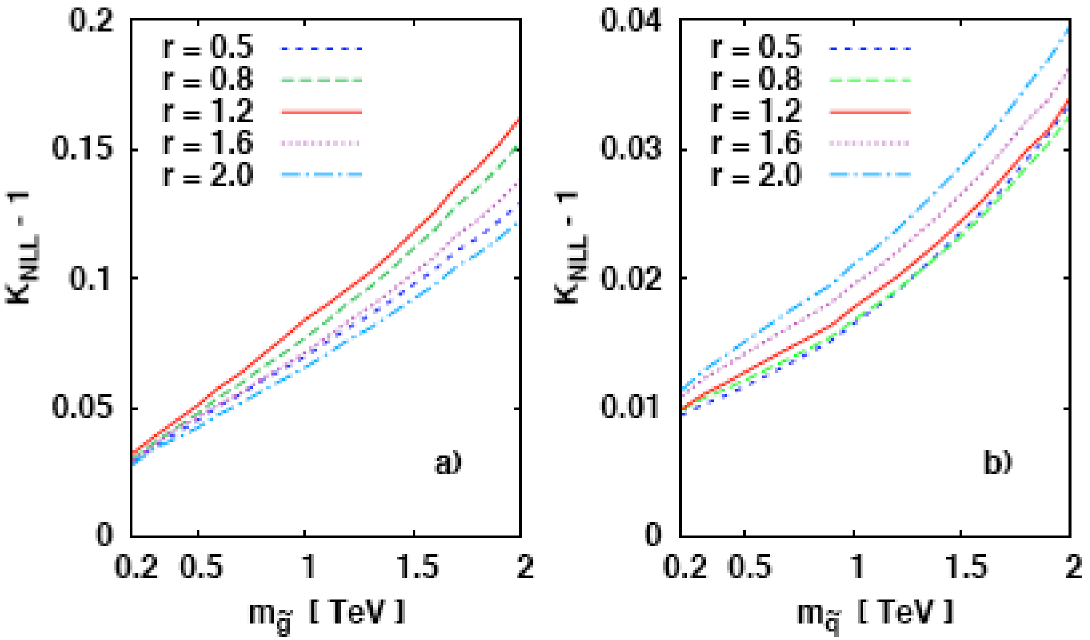
$\sigma(\tilde{g}\tilde{g}), \sigma(\tilde{q}\tilde{\bar{q}})$ in SUSY

A. Kulesza and L. Motyka, arXiv:0807.2405[hep-ph]

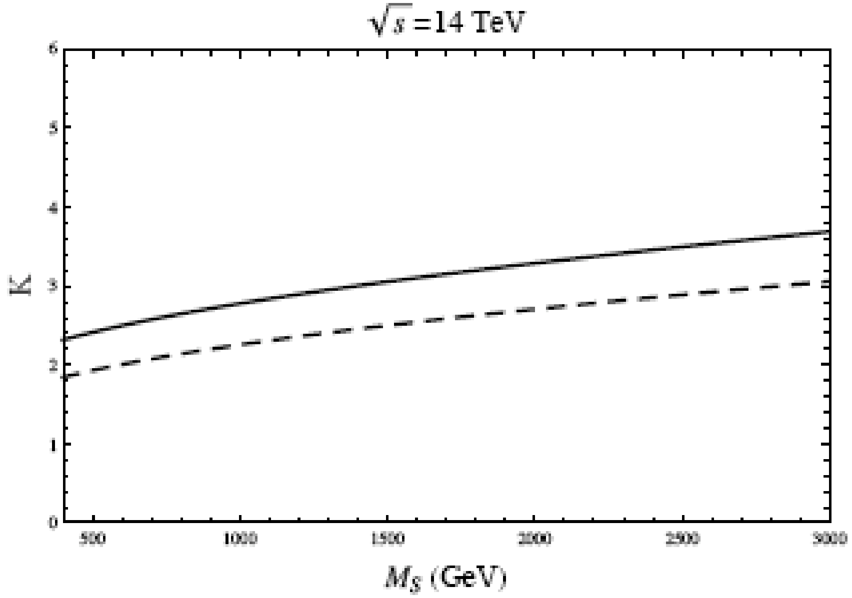
U. Langenfeld and S.O. Moch, arXiv:0901.0802[hep-ph]

- more important as masses get bigger!

$\sigma(\tilde{g}\tilde{g}), \sigma(\tilde{q}\tilde{\bar{q}})$



$\sigma(gg \to S^A)$



- bound state effects have not been considered!

Conclusion

- J/ψ photoproduction, $e^+e^- \to J/\psi + X$

  large logs, nonperturbative effects near kinematic endpoints

  qualitatively change expectations from fixed order CO calc.

  analysis resumed CO + NLO color singlet needed!

  most recent analysis of Belle data ignores $e^+e^- \to c\bar{c}(^3S_1^{(8)}) + g$!

  (B. Gong + J.-X. Wang, arXiv:0904.1103[hep-ph])

  Expectation: smaller values for COME relative to LO Tevatron fits

- t $\bar{\text{t}}$ production

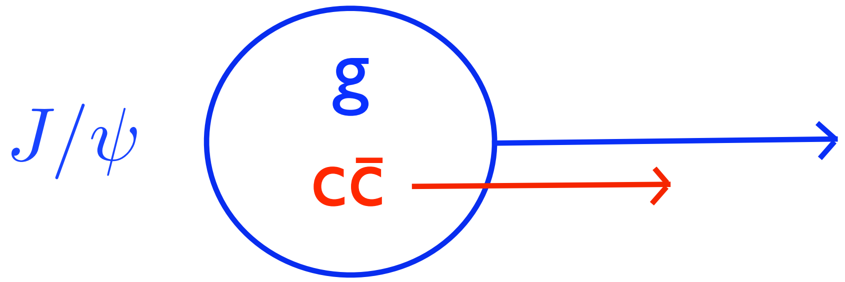
  resummation threshold effects, esp. Coulomb corrections to $d\sigma/dM$

  applications to new physics

Extra Slides

- **Kinematics** $n^\mu = (1,0,0,1) \qquad \bar{n}^\mu = (1,0,0,-1)$

$$p^\mu_\psi = M_\psi v^\mu \qquad v^\mu = \frac{M_\psi}{x\sqrt{s}}\frac{n^\mu}{2} + \frac{x\sqrt{s}}{M_\psi}\frac{\bar{n}^\mu}{2} \qquad p^\mu_{c\bar{c}} = 2m_c v^\mu + \ell^\mu \qquad \ell^\mu - \text{residual momentum}$$



$$\bar{n}\cdot\ell \sim \frac{M_\psi}{x\sqrt{s}}\Lambda_{QCD} \qquad n\cdot\ell \sim \frac{x\sqrt{s}}{M_\psi}\Lambda_{QCD} \qquad \ell^\mu_\perp \sim \Lambda_{\rm QCD}$$

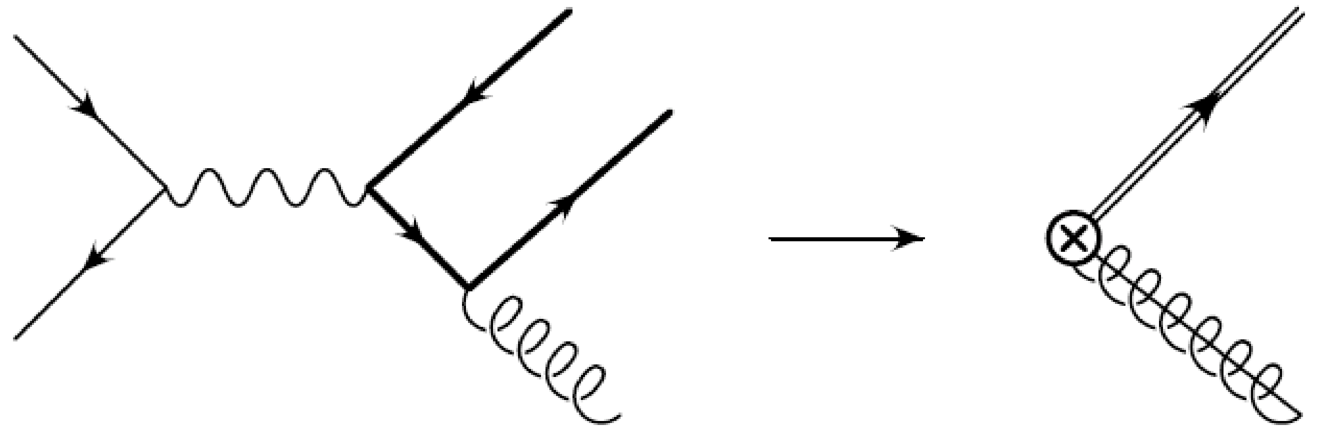
$$p^\mu_X = \frac{\sqrt{s}}{2}\left(1-\frac{r}{\hat{x}}\right)n^\mu + \frac{\sqrt{s}}{2}(1-\hat{x})\,\bar{n}^\mu - \ell^\mu \qquad r = \frac{M^2}{s} \quad \hat{x} = \frac{M}{M_\psi}x \quad M = 2m_c$$

- When $1-\hat{x} \sim \Lambda_{\rm QCD}/M$ cannot neglect $n.\ell$!

- $1-\hat{x} \sim \Lambda_{\rm QCD}/M \longrightarrow p_\psi \approx 3$ GeV $\qquad (p_\psi)_{\rm max} \approx 4.8$ GeV

Factorization for $e^+e^- \to J/\psi + X$ in SCET

- Matching current $({}^1S_0^{(8)})$



$+ \; crossed \; diagram$

$$J_\mu = \Gamma^8_{\alpha\mu}(-n\cdot v\bar{\mathcal{P}},\mu)\psi^\dagger_{-\mathbf{p}} B^\alpha_\perp \chi_{\mathbf{p}}$$

- Collinear: $B^\alpha_\perp = \frac{1}{g_s} W^\dagger(\mathcal{P}^\alpha_\perp + g_s A^\alpha_{n,q})W$ USoft: $\psi^\dagger_p, \chi_p$
- Reparametrization Invariance: $-n\cdot v\bar{\mathcal{P}}$ (Manohar, T.M., Pirjol, Stewart)

- Decoupling usoft fields from collinear fields

$$A^{\mu}_{n,q} \to Y_n A^{(0)}_{n,q} Y^{\dagger}_n \qquad B^{\alpha}_{\perp} \to Y_n B^{(0)\alpha}_{\perp} Y^{\dagger}_n$$

$$\boxed{in\cdot D_{us} \to in\cdot\partial}$$

- Factorization:

$$2E_{\psi}\frac{d\sigma}{d^3p_{\psi}} \propto L^{\mu\nu}\int d^4y\, e^{-iq\cdot y}\sum_X \langle 0|J^{\dagger}_{\nu}(y)|J/\psi+X\rangle\langle J/\psi+X|J_{\mu}(0)|0\rangle$$

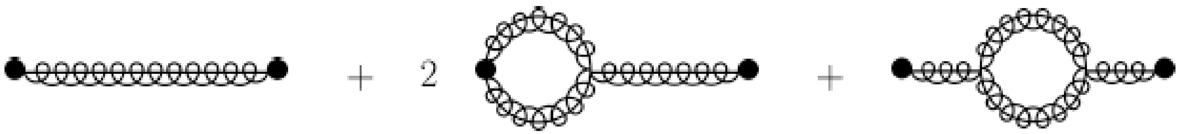
$$\langle J/\psi+X|J_{\mu}|0\rangle = 2\,\Gamma^{8}_{\alpha\mu}(s(1-r)/M,\mu)\;\langle J/\psi+X_{us}|\psi^{\dagger}_{-p}YT^aY^{\dagger}\chi_p|0\rangle\langle X_c|Tr[T^aB^{(0)\alpha}_{\perp}]|0\rangle$$

$$\boxed{\frac{d\sigma}{dx} = \sigma(\mu)\int d\ell^{+}S(\ell^{+})J(\sqrt{s}(1-\hat{x})-\ell^{+})}$$

$$J(k^{+}) \propto \mathrm{Im}\left[i\int d^4y\, e^{ik^{+}y^{-}/2}\,\langle 0|T\left(\mathrm{Tr}\left[T^BB^{(0)\beta}_{\perp}(y)\right]\mathrm{Tr}\left[T^BB^{(0)}_{\perp\,\beta}(0)\right]\right)|0\rangle\right]$$

$$S(\ell^{+}) = \frac{\langle 0|\chi^{\dagger}_{-\mathbf{p}}Y^{\dagger}_nT^BY_n\psi_{\mathbf{p}}a^{\dagger}_{\psi}a_{\psi}\delta(\ell^{+}-in\cdot\partial)\psi^{\dagger}_{\mathbf{p}}Y^{\dagger}_nT^BY^{\dagger}_n\chi_{-\mathbf{p}}|0\rangle}{4m_c\langle\mathcal{O}_8(^1S_0)\rangle}$$

- $J(\ell^+) : p_X^2 = s(1 - M^2/s)(1-x) \sim Q\Lambda_{\rm QCD}$ perturbative



Lowest order in perturbation theory: $J(\ell^+) \propto \delta(\ell^+)$

$$\frac{d\sigma}{dx} = \sigma(\mu)\int d\ell^+ S(\ell^+) J(\sqrt{s}(1-\hat{x}) - \ell^+)$$
$$\rightarrow \sigma_0 S(\sqrt{s}(1-\hat{x}))$$

- Far from endpoint $1-\hat{x} > v^2$ $in\cdot\partial \sim \frac{\sqrt{s}}{M} M v^2$

$$S(\ell^+) = \frac{\langle 0|\chi_{-\mathbf{p}}^\dagger Y_n^\dagger T^B Y_n \psi_{\mathbf{p}} a_\psi^\dagger a_\psi \delta(\sqrt{s}(1-\hat{x}) - in\cdot\partial)\psi_{\mathbf{p}}^\dagger Y_n T^B Y_n^\dagger \chi_{-\mathbf{p}}|0\rangle}{4m_c\langle \mathcal{O}_8({}^1S_0)\rangle}$$
$$\rightarrow \delta(1-\hat{x})$$

$$\boxed{\frac{d\sigma}{dx} = \sigma_0\,\delta(1-\hat{x})}$$

- Recover LO NRQCD differential cross section

- Usoft Wilson Lines in Color-Octet Operators

$$\langle \mathcal{O}_8({}^1S_0)\rangle = \frac{\langle 0|\chi^\dagger_{-\mathbf{p}} Y_n^\dagger T^B Y_n \psi_{\mathbf{p}} a^\dagger_\psi a_\psi \psi^\dagger_{\mathbf{p}} Y_n^\dagger T^B Y_n^\dagger \chi_{-\mathbf{p}}|0\rangle}{4m_c}$$

- required in pQCD analysis for factorization

(Nayak, Sterman, Qiu)

analyze gluon fragmentation function

$$D_{H/i}(z, m_c, \mu) = \sum_n d_{i\to c\bar{c}[n]}(z, \mu, m_c)\,\langle \mathcal{O}_n^H\rangle$$

at two loops, find IR divergent matching coefficients unless Wilson lines are included in the color-octet operators

- appear automatically in SCET formalism

- Resummation

Moments $\sigma_N = \int dx\, x^N \frac{d\sigma}{dx}$ $\sigma_N = \sigma_\mu J_N S_N$

$$\frac{\ln(1-x)}{1-x} \to \frac{1}{2}\ln^2 \bar{N} \qquad \frac{1}{1-x} \to -\ln \bar{N} \qquad \bar{N} = N e^{\gamma_E}$$

- RGE's from SCET

$$\mu \frac{d}{d\mu} J_N(\mu) = \left[\frac{2C_A\alpha_s}{\pi}\log\left(\frac{\mu^2 \bar{N}}{s(1-r)}\right) + \frac{2\alpha_s}{\pi}\left(\frac{11}{12}C_A - \frac{n_f}{6}\right)\right] J_N(\mu)$$

$$\mu \frac{d}{d\mu} S_N(\mu) = \left[-\frac{2C_A\alpha_s}{\pi}\log\left(\frac{\mu \bar{N}}{M}\right) + \frac{\alpha_s C_A}{\pi}\right] S_N(\mu)$$

- Resummed moments

$$\sigma_N = \sigma_0 S_N e^{\log(N) g_1(\chi) + g_2(\chi)} \qquad \chi = \log(N)\, \alpha_s(\mu_H)\beta_0/4\pi$$