Inclusive h_c production at B factories

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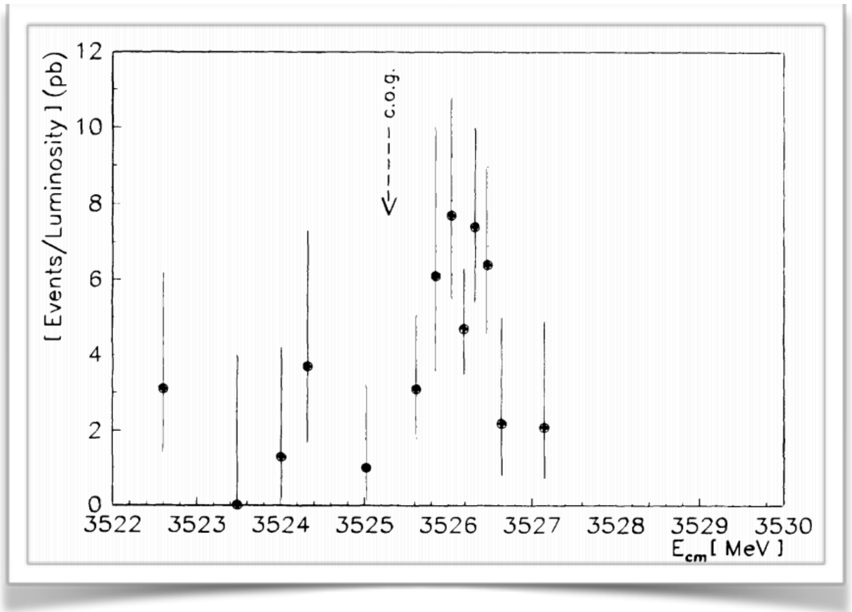
Sun, Jia, XL, Zhu, 2018

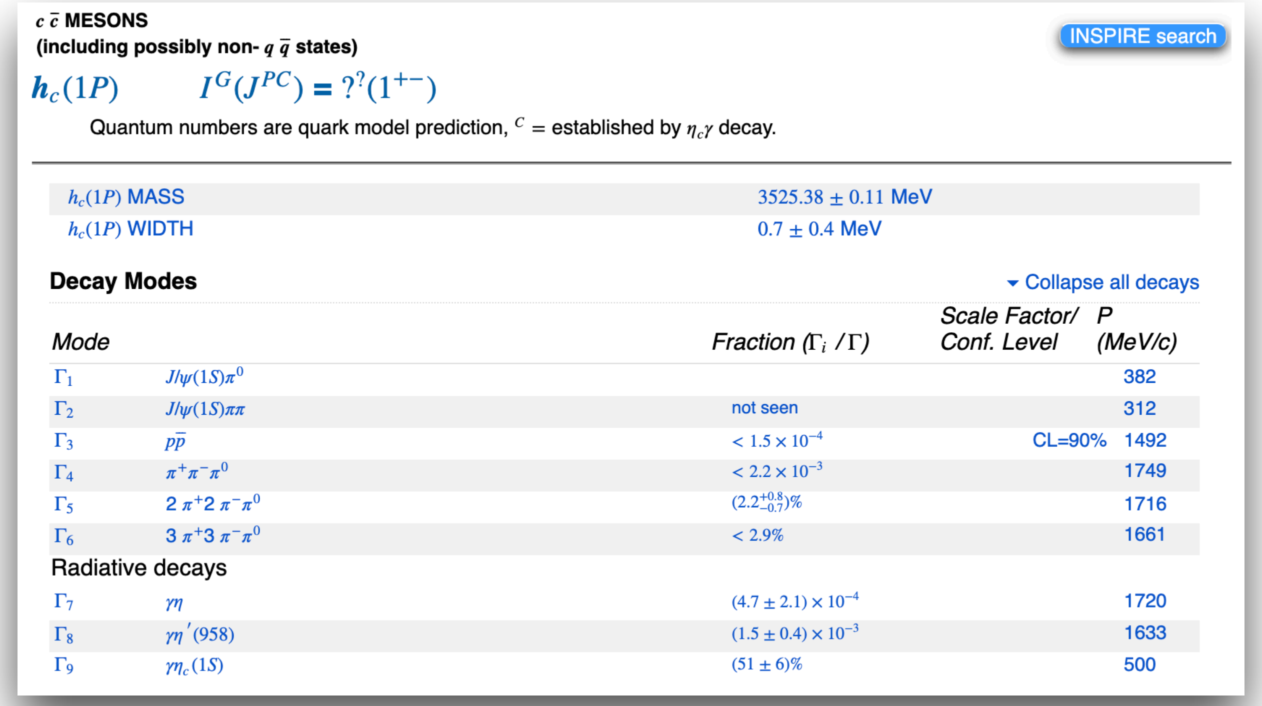
Outlines

- Current status of the h_c studies
- h_c production in e^+e^- annihilation
    - NLO + res. color octet, inclusive and energy spectrum
- Conclusions

Introduction

- $h_c(1P)$ experiments
  - The last member found below open charm threshold
  - First hint in 1992, established in 2005
  - Now we know more ···




$c\bar{c}$ **MESONS**
(including possibly non- $q\bar{q}$ **states)**

INSPIRE search

$\boldsymbol{h_c(1P)}$ $I^G(J^{PC}) = ?^?(1^{+-})$

Quantum numbers are quark model prediction, ^{C} = established by $\eta_c\gamma$ decay.

$h_c(1P)$ MASS	3525.38 ± 0.11 MeV
$h_c(1P)$ WIDTH	0.7 ± 0.4 MeV

Decay Modes

Collapse all decays

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	$J/\psi(1S)\pi^0$			382
Γ_2	$J/\psi(1S)\pi\pi$	not seen		312
Γ_3	$p\bar{p}$	$< 1.5 \times 10^{-4}$	CL=90%	1492
Γ_4	$\pi^+\pi^-\pi^0$	$< 2.2 \times 10^{-3}$		1749
Γ_5	$2\pi^+2\pi^-\pi^0$	$(2.2^{+0.8}_{-0.7})\%$		1716
Γ_6	$3\pi^+3\pi^-\pi^0$	$< 2.9\%$		1661
Radiative decays				
Γ_7	$\gamma\eta$	$(4.7 \pm 2.1) \times 10^{-4}$		1720
Γ_8	$\gamma\eta'(958)$	$(1.5 \pm 0.4) \times 10^{-3}$		1633
Γ_9	$\gamma\eta_c(1S)$	$(51 \pm 6)\%$		500

Introduction

- $h_c(1P)$ theory
    - decay: quark potential models, NRQCD
    - Production (in NRQCD)
        - LHC: large rate but severe background contamination in the major decay channels

          Sridhar, Qiao et.al., Wang and Zhang
        - B factory: lower rate @ LO, but cleaner signals expected, color octet dominant

          Jia et.al,, Wang and Zhang

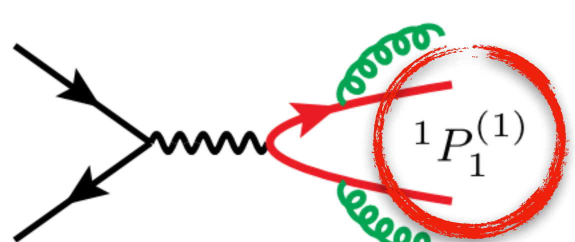
h_c production at B factory

- NRQCD   Caswell and Lepage, Bodwin, Braaten and Lepage

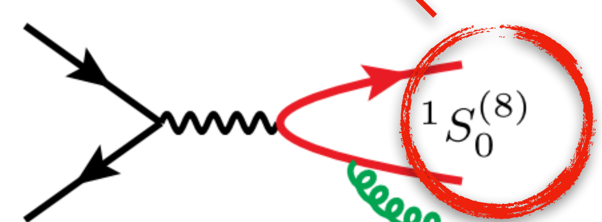
$$d\sigma[e^+e^- \to h_c + X] = \frac{dF_1(\mu_\Lambda)}{m_c^4}\boxed{\langle \mathcal{O}_1^{h_c}(^1P_1)\rangle} + \frac{dF_8}{m_c^2}\boxed{\langle \mathcal{O}_8^{h_c}(^1S_0)(\mu_\Lambda)\rangle} + \cdots$$

LO in the v expansion

Non-perturbative Long distance Matrix elements ~ O(Lambda$_{QCD}$), hadronization



CS (LO)



CO (LO)

$$\mathcal{O}_1^{h_c}(^1P_1) = \chi^\dagger\left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}\right)\psi\sum_X |h_c + X\rangle \cdot \langle h_c + X|\psi^\dagger\left(-\frac{i}{2}\overleftrightarrow{\mathbf{D}}\right)\chi,$$

$$\mathcal{O}_8^{h_c}(^1S_0) = \chi^\dagger T^a\psi\sum_X |h_c + X\rangle \cdot \langle h_c + X|\,\psi^\dagger T^a\chi,$$

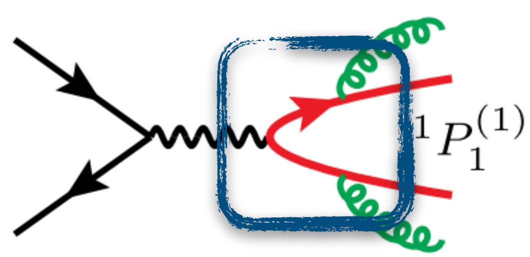
h_c production at B factory

- NRQCD   Caswell and Lepage, Bodwin, Braaten and Lepage

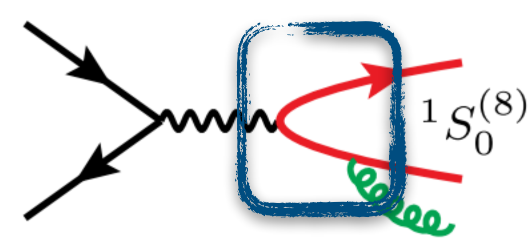
$$d\sigma[e^+e^- \to h_c + X] = \boxed{\frac{dF_1(\mu_\Lambda)}{m_c^4}}\langle \mathcal{O}_1^{h_c}(^1P_1)\rangle + \boxed{\frac{dF_8}{m_c^2}}\langle \mathcal{O}_8^{h_c}(^1S_0)(\mu_\Lambda)\rangle + \cdots$$

LO in the v expansion

Short distance coefficients ~ $O(m_c)$, perturbative, producing ccbar pair
could contain additional large logs (enough room for scale evolution, operator mixing $\cdots$)



CS (LO)



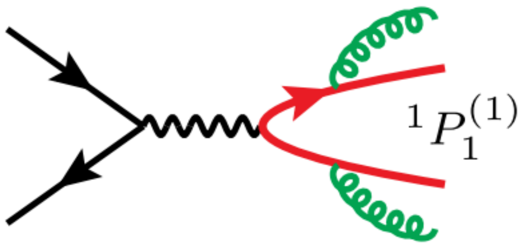
CO (LO)

example:
polarization attempts by Kang, Ma, Qiu, Sterman, Zhang

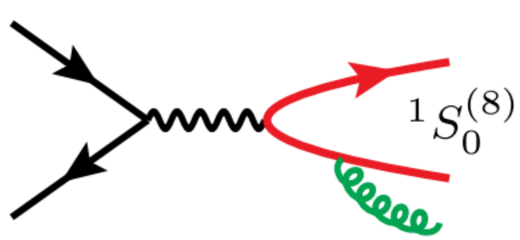
h_c production at B factory

- LO already known for both color singlet and octet

$$d\sigma[e^+e^- \to h_c + X] = \frac{dF_1(\mu_\Lambda)}{m_c^4}\langle \mathcal{O}_1^{h_c}({}^1P_1)\rangle + \frac{dF_8}{m_c^2}\langle \mathcal{O}_8^{h_c}({}^1S_0)(\mu_\Lambda)\rangle + \cdots$$



CS (LO)



CO (LO)

LO in v expansion

Jia et.al,, Wang and Zhang

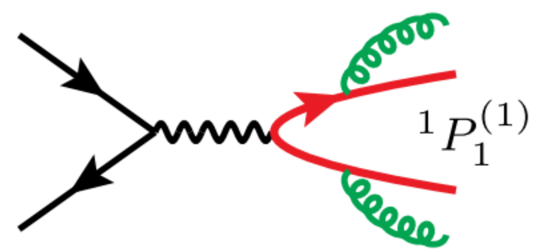
- But NLO corrections for charmonium could be large

Our Goal: NLO color octet

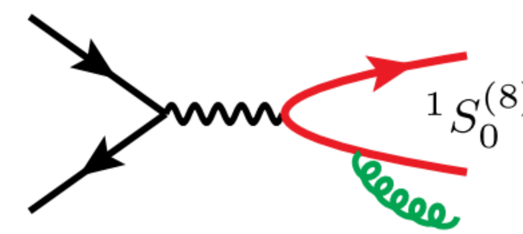
h_c production at B factory

- LO already known for both color singlet and octet

$$d\sigma[e^+e^- \to h_c + X] = \frac{dF_1(\mu_\Lambda)}{m_c^4}\langle \mathcal{O}_1^{h_c}({}^1P_1)\rangle + \frac{dF_8}{m_c^2}\langle \mathcal{O}_8^{h_c}({}^1S_0)(\mu_\Lambda)\rangle + \cdots$$



CS (LO)



CO (LO)

$$\frac{dF_8^{\rm LH}}{dz} = \frac{32\pi^2 e_c^2\alpha^2\alpha_s m_c}{3s^2}(1-r)\,\delta(1+r-z)$$

Sharp peak at the threshold, will be modified dramatically at higher orders. FO is not reliable!

Soft !

$$\left.\frac{dF_1^{\rm LH}(\mu)}{dz}\right|_{\overline{\rm MS}} = \frac{64\pi e_c^2\alpha^2 C_F\alpha_s^2 m_c}{9N_c s^2}\left\{\left(-\ln\frac{\mu^2}{4m_c^2} + 2\ln\frac{1-\sqrt{r}}{1+\sqrt{r}} + \frac{1}{3}\right)\times (1-r)\delta(1+r-z) + \left[\frac{1}{1+r-z}\right]_+\left(\frac{z^2-4r}{z-2r} + \sqrt{z^2-4r}\right) + \frac{2z}{z-2r} - \frac{2-z-\sqrt{z^2-4r}}{1+r-z}\right\} + \frac{m_c^3}{6N_c}\frac{d\hat{\sigma}_{\rm fin}}{dz},$$

$$r \equiv \frac{4m_c^2}{s}, \qquad z \equiv \frac{2P^0}{\sqrt{s}};$$

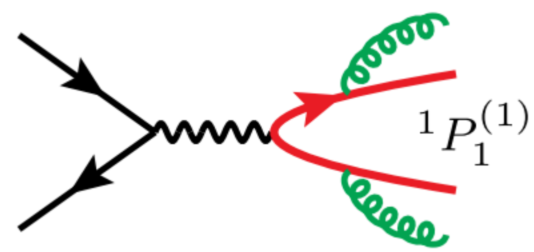
Color singlet mixed with color octet

Color octet channel is crucial to absorb all poles

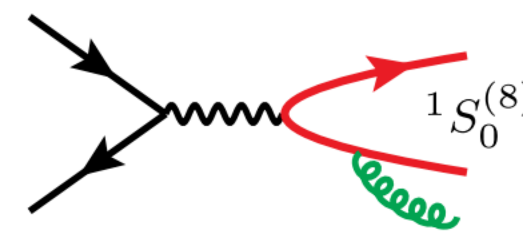
h_c production at B factory

- LO already known for both color singlet and octet

$$d\sigma[e^+e^- \to h_c + X] = \frac{dF_1(\mu_\Lambda)}{m_c^4}\langle \mathcal{O}_1^{h_c}(^1P_1)\rangle + \frac{dF_8}{m_c^2}\langle \mathcal{O}_8^{h_c}(^1S_0)(\mu_\Lambda)\rangle + \cdots$$



CS (LO)



CO (LO)

$$F_1^{\rm LH}(\mu)_{\overline{\rm MS}} = \frac{64\pi e_c^2\alpha^2 C_F\alpha_s^2 m_c}{9N_c s^2}(1-r)\Bigg[-\ln\frac{\mu^2}{4m_c^2} + 2\ln(1-r) - \frac{65-84r}{12(1-r)} \boxed{+\frac{7+7r-9r^2}{6(1-r)^2}\ln r} + \frac{r(5-7r)\ln^2\frac{1+\sqrt{1-r}}{1-\sqrt{1-r}}}{16(1-r)^2} + \frac{(14-15r)\ln\frac{1+\sqrt{1-r}}{1-\sqrt{1-r}}}{8(1-r)^{3/2}}\Bigg],$$

$$F_8^{\rm LH} = \frac{32\pi^2 e_c^2\alpha^2\alpha_s m_c}{3s^2}(1-r).$$

Collinear!

Could break down the perturbative expansion

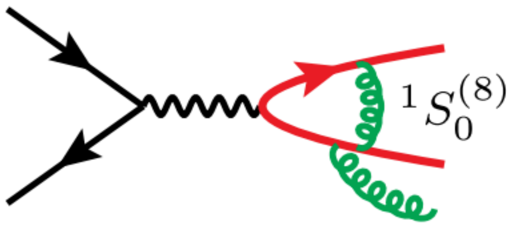
FO is NOT reliable!

Same feature happens for pT distribution in other charmonium productions

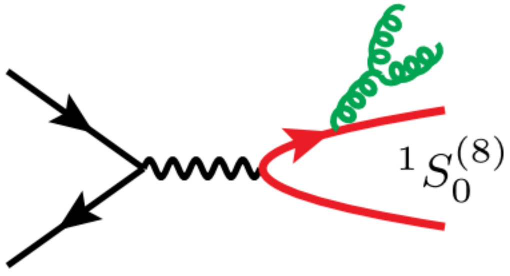
h_c production at B factory

- NLO for color octet

Virtual: FeynCalc, FeynArts, $Apart, IBP by FIRE, MI calculated analytically



CO (NLO Virtual)



CO (NLO Real)

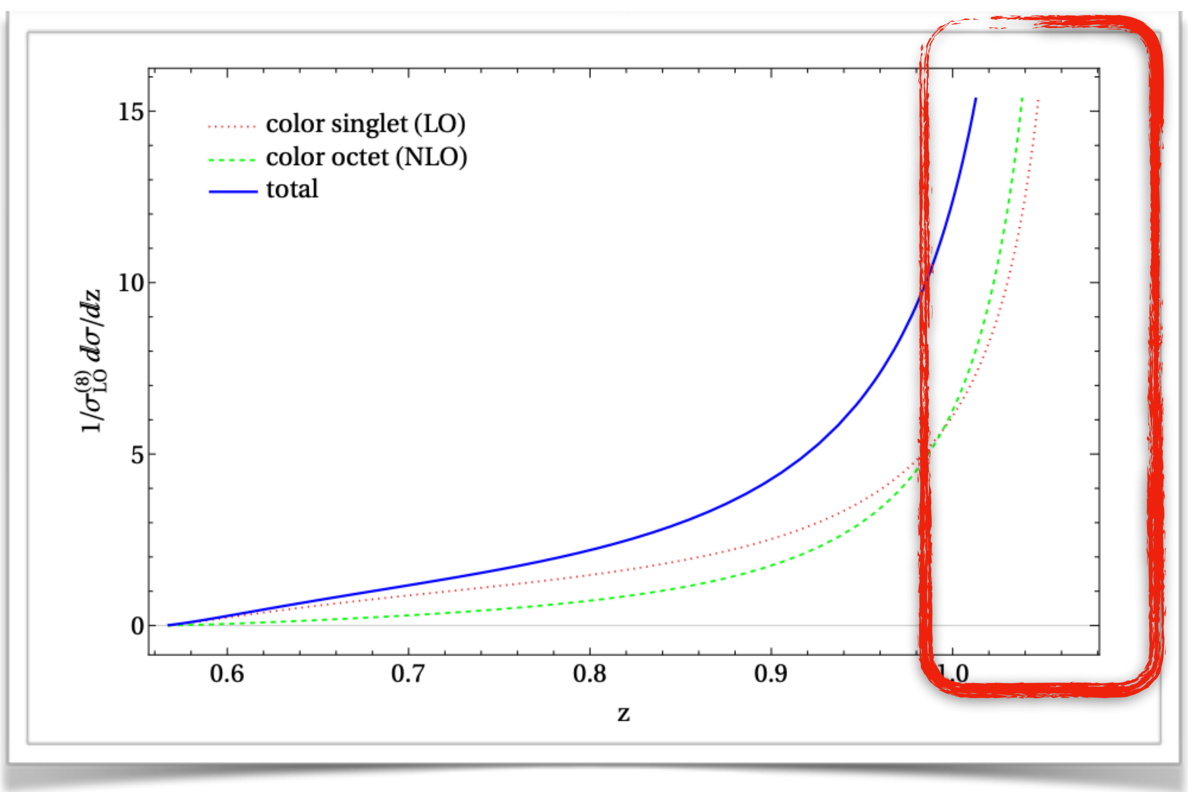
Numerically by Zhang, Ma, Wang, Chao

Real: Follow the strategy for color singlet for phase space integration, more diagrams though

Sun, Jia, XL, Zhu, 2018

h_c production at B factory

- NLO for color octet



$$
\begin{aligned}
\frac{d\hat{\sigma}^{(8),gg}_{\rm Div}}{dz} =& \hat{\sigma}^{(8)}_{\rm LO}\frac{\alpha_s}{\pi}\frac{(1-r)^{-2\epsilon}r^{\epsilon}}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{s}\right)^{\epsilon} \\
&\times C_A\Bigg\{\left(\frac{1}{2\epsilon^2}+\frac{17}{12}\frac{1}{\epsilon}-2\ln^2\frac{\sqrt{r}}{1+\sqrt{r}}-\frac{23}{6}\ln\frac{\sqrt{r}}{1+\sqrt{r}}-\frac{\pi^2}{4}+\frac{67}{36}\right)\delta(1+r-z) \\
&+\left[\frac{1}{1+r-z}\right]_+\Bigg[2\ln\frac{2-z+\sqrt{z^2-4r}}{2}-\ln\frac{z-\sqrt{z^2-4r}}{z+\sqrt{z^2-4r}} \\
&-\frac{2\sqrt{z^2-4r}}{1-r}+\frac{\sqrt{z^2-4r}\,(6+2r-6z+z^2)}{12(1-r)^3}\Bigg]-\left[\frac{\ln(1+r-z)}{1+r-z}\right]_+\Bigg\},
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\hat{\sigma}^{(8),q\bar{q}}_{\rm R}}{dz} =& \hat{\sigma}^{(8)}_{\rm LO}\frac{\alpha_s}{\pi}\frac{(1-r)^{-2\epsilon}r^{\epsilon}}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{s}\right)^{\epsilon}\frac{n_f}{6}\Bigg\{\left[-\frac{1}{\epsilon}+2\ln\frac{\sqrt{r}}{1+\sqrt{r}}-\frac{5}{3}\right]\delta(1+r-z) \\
&+\left[\frac{1}{1+r-z}\right]_+\frac{\left(z^2-4r\right)^{3/2}}{(1-r)(2-z)^2}\Bigg\}.
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\hat{\sigma}^{(8)}_{\rm V}}{dz} =& \hat{\sigma}^{(8)}_{\rm LO}\frac{\alpha_s}{\pi}\frac{(1-r)^{-2\epsilon}r^{\epsilon}}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{s}\right)^{\epsilon}\Bigg\{-\frac{C_A}{2\epsilon^2}-\frac{2C_A+\beta_0}{4\epsilon}+\frac{\beta_0}{4}\ln\frac{\mu_r^2}{m_c^2} \\
&+\frac{C_A(2-r)-2C_F(2+r)}{8(1-r)}\ln^2\frac{1-\sqrt{1-r}}{1+\sqrt{1-r}}+\frac{3\,(C_A-2C_F)}{2\sqrt{1-r}}\ln\frac{1-\sqrt{1-r}}{1+\sqrt{1-r}} \\
&+\frac{C_A(1-r)+2C_F}{4(1-r)}\left(\ln^2\frac{r}{2-r}+2\mathrm{Li}_2\frac{r}{2-r}\right) \\
&+\frac{-2C_A(2-r)+4C_F(3-2r)+(2-r)^2\beta_0}{2(2-r)^2}\ln\frac{r}{2(1-r)}+\frac{C_A\left(9+4\pi^2\right)}{6} \\
&-\frac{C_F\left[\pi^2(2-r)+6(1-r)(9-5r)\right]}{6(2-r)(1-r)}\Bigg\}\delta(1+r-z),
\end{aligned}
$$

ALL poles cancel !

Check against known results

FO could be break down in the threshold, more severe than CS.

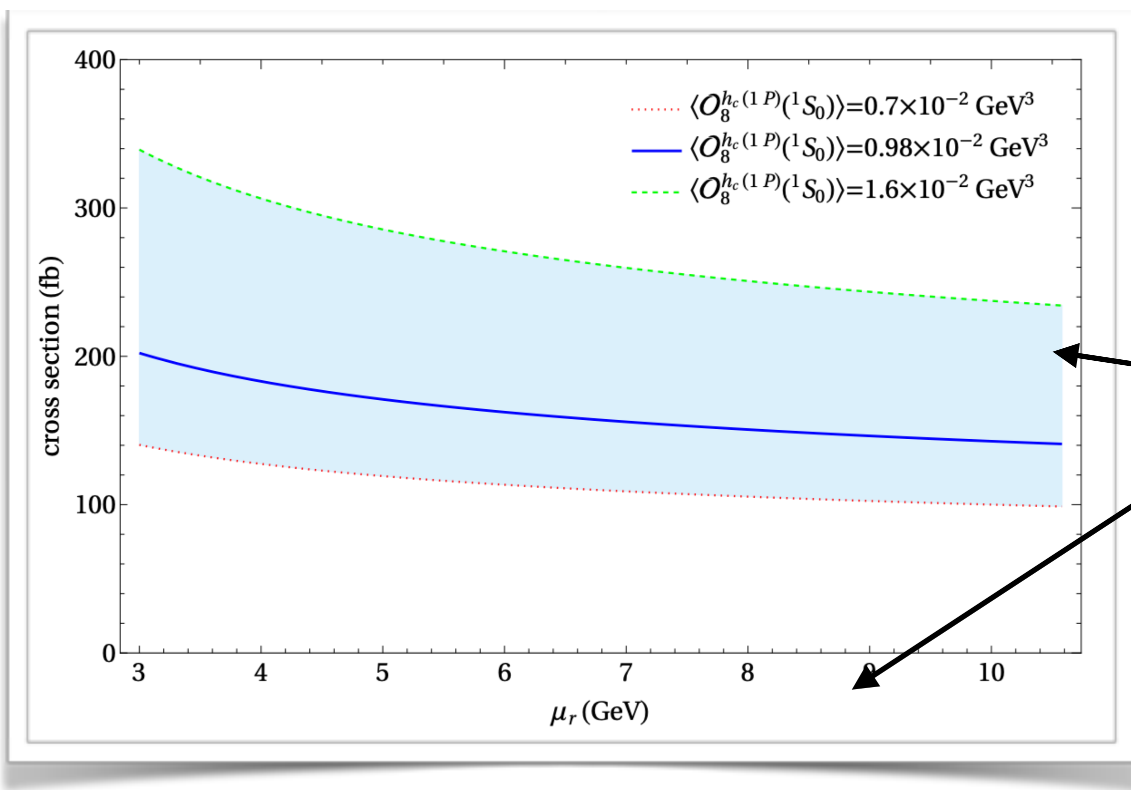
h_c production at B factory

- NLO for color octet

$$
\begin{aligned}
F_8^{\rm NLO} =& F_8^{\rm LO} + F_8^{\rm LO}\frac{\alpha_s}{\pi}\left\{\frac{\beta_0}{4}\ln\frac{\mu_r^2}{m_c^2} + \frac{C_A(6-5r)-4C_F(2+r)}{16(1-r)}\ln^2\frac{1-\sqrt{1-r}}{1+\sqrt{1-r}}\right.\\
&+\frac{C_A(28-27r)-36C_F(1-r)-4n_f}{12(1-r)^{3/2}}\ln\frac{1-\sqrt{1-r}}{1+\sqrt{1-r}} + C_A{\rm Li}_2\left(-\frac{1-r}{r}\right)\\
&+\frac{C_A(1-r)+2C_F}{4(1-r)}\left(\ln^2\frac{r}{2-r}+2{\rm Li}_2\frac{r}{2-r}\right)+\frac{C_A\,(1-6\ln r)}{6(1-r)}-\frac{n_f\,(20-8r-9\ln r)}{18(1-r)}\\
&+\frac{-2C_A(2-r)+4C_F(3-2r)+(2-r)^2\beta_0}{2(2-r)^2}\ln\frac{r}{2(1-r)}\\
&\left.-\frac{C_F\left[\pi^2(2-r)+6(1-r)(9-5r)\right]}{6(2-r)(1-r)}+\frac{C_A(289+9\pi^2)}{36}\right\}.
\end{aligned}
$$

Both double and single logs in r ->0, occur for CO.

Do harm to the FO predictions if r is too small

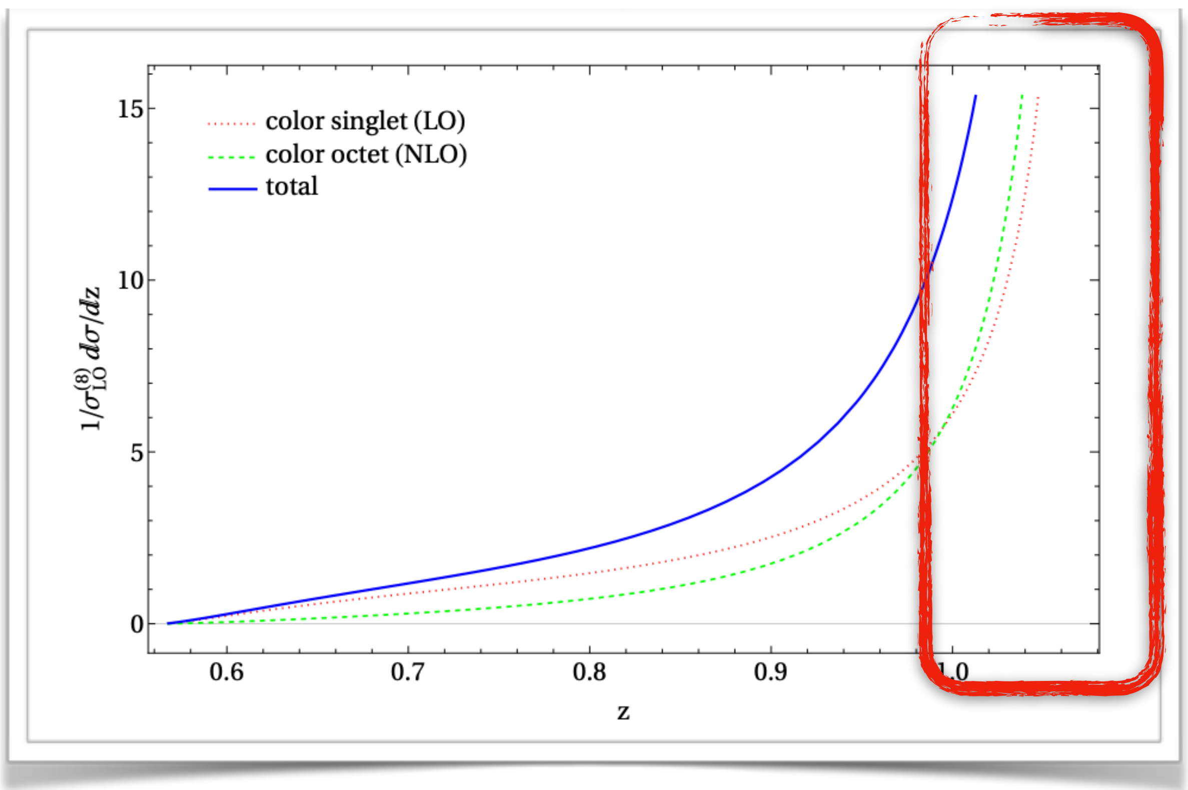


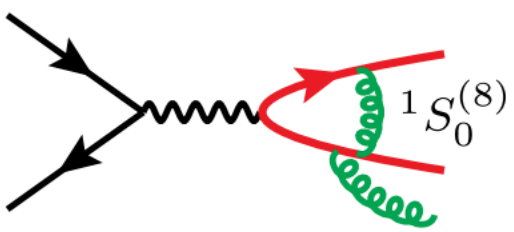
Scale uncertainties are relatively small.

Very sensitive to the CO matrix element. Future B factory could help (10^5 already produced, expected 10^6 if L ~ 50 ab^{-1})

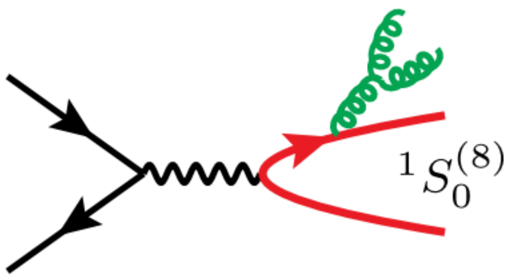
h_c production at B factory

- Deal with logs, z spectrum as an example





CO (NLO Virtual)



CO (NLO Real)

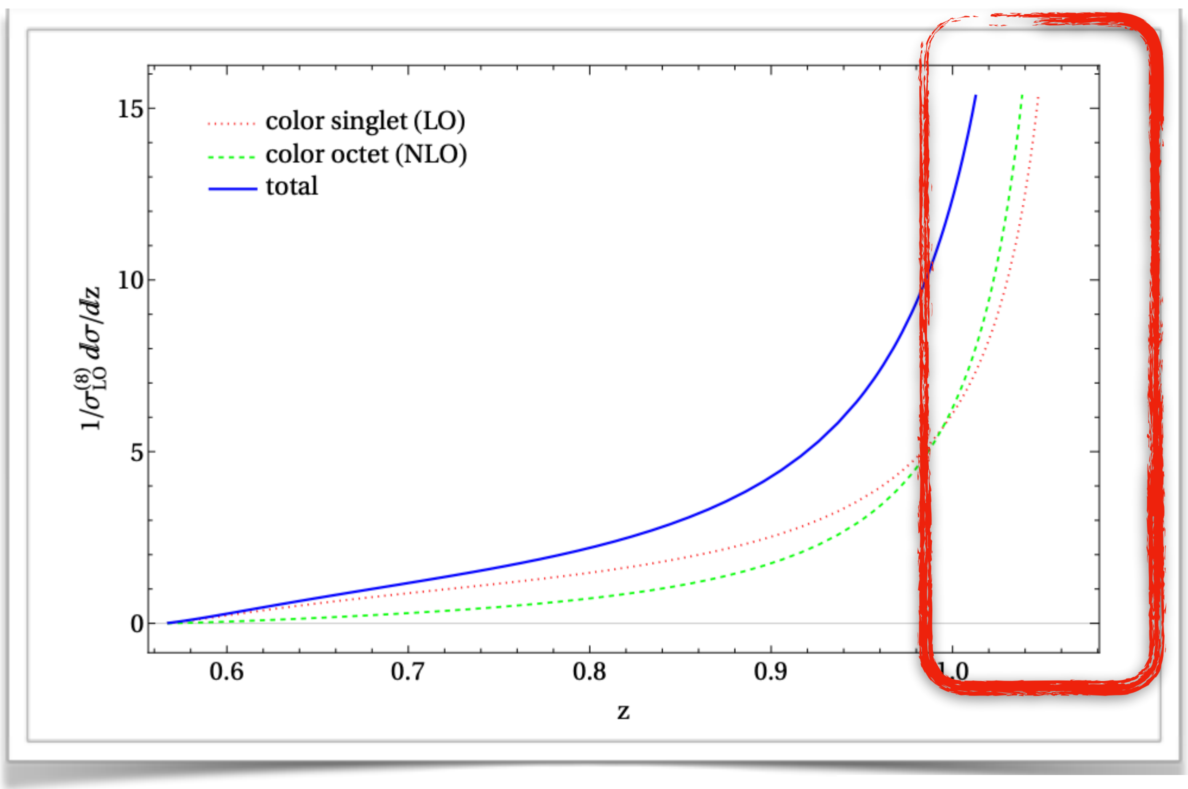
$$\frac{1}{1-z'-\hat{k}} \sim \frac{1}{1-z'} + \frac{1}{1-z'}\frac{\hat{k}}{1-z'} + \ldots$$

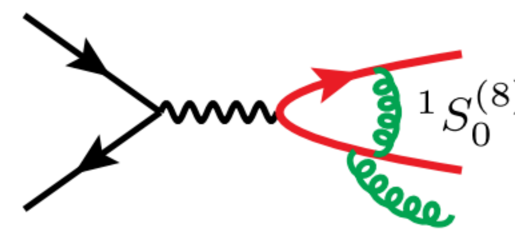
In NRQCD, z' ~ O(1) and 1- z' ~ O(1), and allow to truncate the khat series.

However when z' -> 1, this assumption will not hold

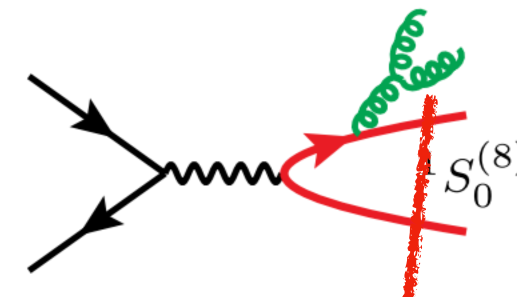
h_c production at B factory

- Deal with logs, z spectrum as an example





CO (NLO Virtual)



CO (NLO Real)

$$\frac{1}{1-z'-\hat{k}} \sim \frac{1}{1-z'} + \frac{1}{1-z'}\frac{\hat{k}}{1-z'} + \ldots$$

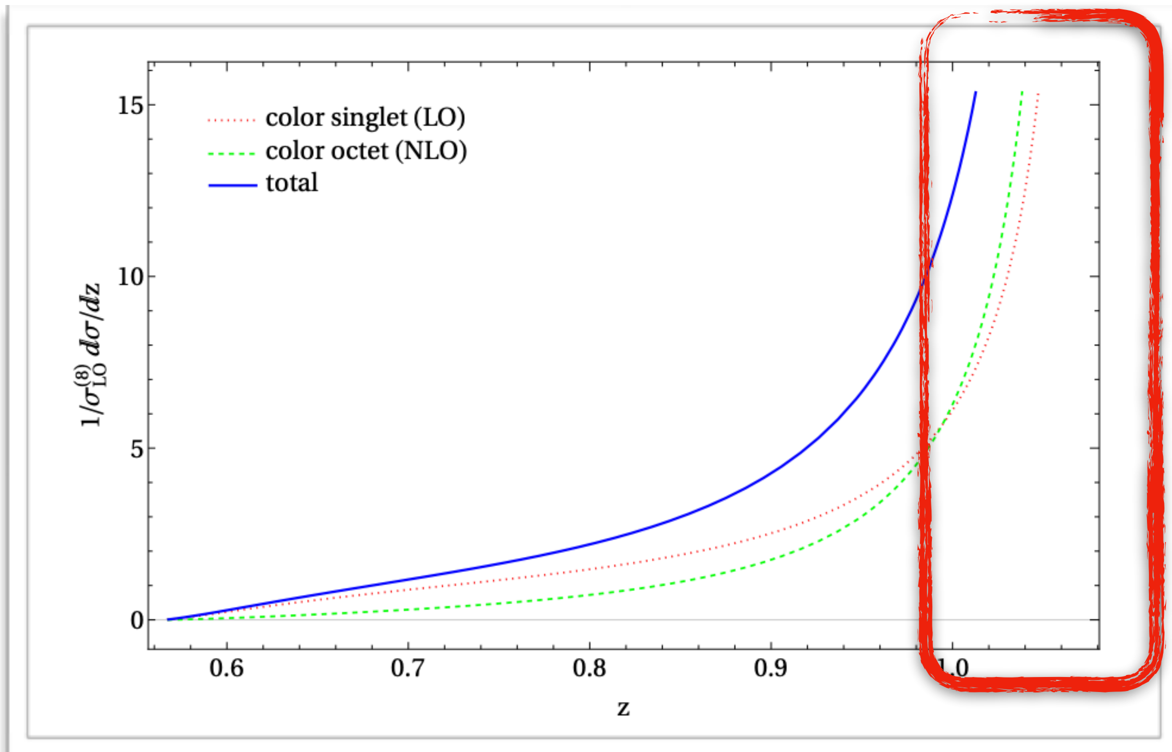
$$\frac{d\sigma}{dz'} = \hat{\sigma}_{\rm LO}^{(8)}\, H[\mu_H\,,\mu] \int_{z'}^{1} dx S[x,\mu_S\,,\mu_r] \times J\left[s(1+r)(x-z'),\mu_J\,,\mu_r\right]$$

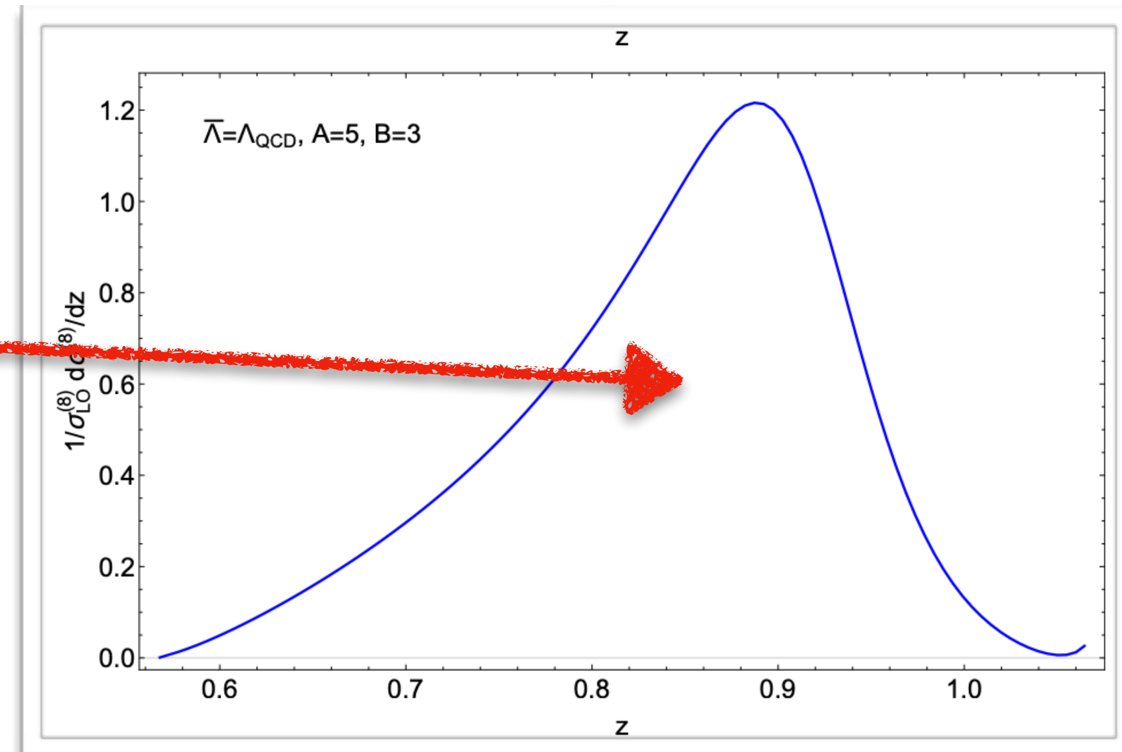
$$S(\ell^+) = \frac{\langle 0|\chi^\dagger T^a \psi\, a_{h_c}^\dagger a_{h_c} \delta(\ell^+ - in\cdot D)\psi^\dagger\, T^a \chi\,|0\rangle}{4m_c\,\langle \mathcal{O}_8^{h_c}\,(^1S_0)\rangle}$$

Not a constant anymore but sensitive to the soft activities

h_c production at B factory

- Deal with logs, z spectrum as an example





$$\frac{d\sigma}{dz'} = \hat{\sigma}^{(8)}_{\rm LO}\, H[\mu_H\,,\mu] \int_{z'}^{1} dx S[x,\mu_S\,,\mu_r] \times J\left[s(1+r)(x-z'),\mu_J\,,\mu_r\right]$$

Remove the divergence and shift the peak.

Conclusions

- NLO results for color octet h_c production at B factories
- See in several cases (threshold, large COM energy$\cdots$) that resummation is crucial to obtain reliable results
- Further investigation on color singlet production is interesting and demanded.

Thanks