Lightcone resummation in $H \to J/\psi + \gamma$ to $\mathcal{O}(v^4)$

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OUTLINE

- $H \to J/\psi + \gamma$ as a key channel to measure $Hc\bar{c}$ coupling

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- Summary and Outlook

Higgs boson in SM

- We found a candidate with $m_H = 125$ GeV
- $J^{PC} = 0^{++}$
- Unitarize transverse $WW \to WW$ scattering at high energies
- Gives masses to $W^{\pm}, Z$
- Gives masses to fermions via Yukawa coupling:

$$\mathcal{L}_{Yukawa} = g_u^{ij} \bar{u}_R^i H^T \epsilon Q_L^j - g_d^{ij} \bar{d}_R^i H^\dagger Q_L^j - g_e^{ij} \bar{e}_R^i H^\dagger L_L^j + h.c.$$

In terms of fermion mass eigenstates:

$$\mathcal{L}_{Yukawa} = \sum_i \left[-m_u^i \left(1 + \frac{h}{v}\right) \bar{u}^i u^i - m_d^i \left(1 + \frac{h}{v}\right) \bar{d}^i d^i - m_e^i \left(1 + \frac{h}{v}\right) \bar{e}^i e^i \right]$$

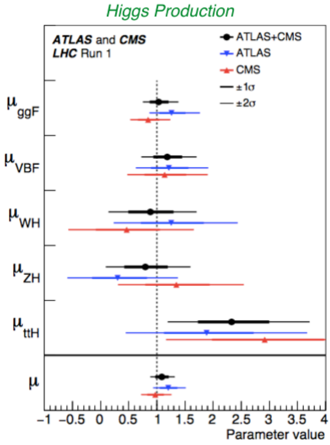
$$m_i = \frac{v y_i}{\sqrt{2}}$$

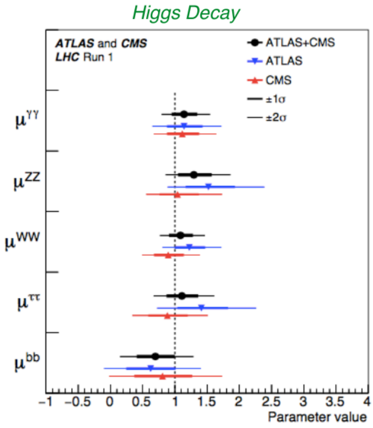
$y_c = 0.007, y_b = 0.024, y_t = 0.99$

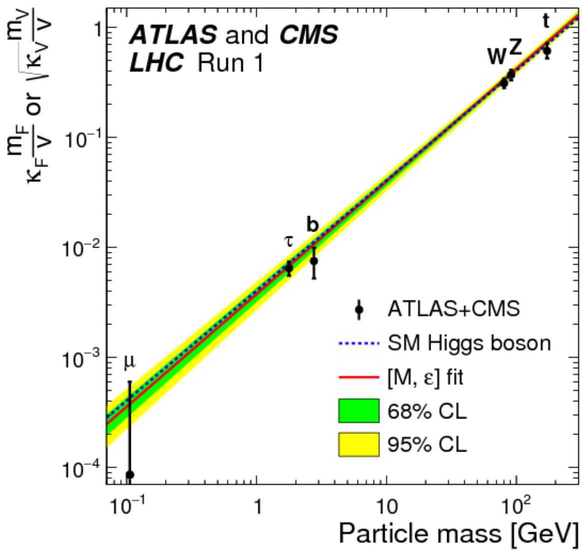
- Check Yukawa coupling, parametrize $Hf\bar{f}$ coupling by κ_i: $\mathcal{L}_{Hf\bar{f}} = -\sum_i \kappa_i \frac{m_i}{v} h \bar{\psi}_i \psi_i$

Results of LHC Run 1:

$$\mu_i = \frac{\sigma_i}{\sigma_{i\,SM}} \qquad \mu^i = \frac{\mathrm{Br}^i}{\mathrm{Br}^i_{SM}}$$






ATLAS and CMS
LHC Run 1
ATLAS+CMS
SM Higgs boson
[M, ε] fit
68% CL
95% CL
μ
τ
b
W
Z
t
Particle mass [GeV]
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
10^2

Summary of results from LHC Run 1:

- Production well tested:
  ggF, VBF, VH observed, cross sections consistent with SM
- ttH not observed
- Decay well tested:
  $\gamma\gamma$, WW, ZZ, $\tau^+\tau^-$ (3.7σ) observed, branching ratio consistent with SM
- $H \to b\bar{b}$ not observed

Update from Run LHC 2:

- ttH (4.2σ) observed, cross section consistent with SM
- $H \to \tau^+\tau^-$ (5.9σ) confirmed
- $H \to b\bar{b}$ (3.8σ) observed, branching ratio consistent with SM

But how about $H \to c\bar{c}$? (Note that $\mathrm{Br}(H \to c\bar{c}) = 3\%$, $\mathrm{Br}(H \to b\bar{b}) = 58\%$)
So it's very hard to measure Higgs-charm coupling!

Two ways to measure $Hc\bar{c}$ coupling:

- Inclusive observable: $H \to c\bar{c} + X$, tag two c-jets
  Advantage: large rate
  Disadvantage: c-tagging challenging, signs of coupling degenerate

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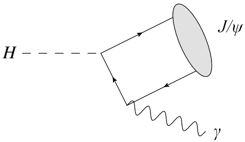
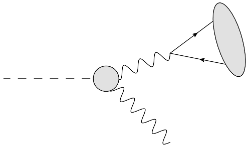
  Disadvantage: c-tagging challenging, signs of coupling degenerate
- Exclusive observable: $H \to J/\psi + \gamma$
  Advantage: clean signal ($J/\psi \to \mu^+\mu^-$), sensitive to both magnitude and sign of coupling
  Disadvantage: small rate



Direct amplitude



Indirect amplitude

- $A = A_{dir} + A_{indir}$, $\Gamma \sim |\alpha_V - \beta_V \kappa_Q|^2$. Γ sensitive to both magnitide and sign of κ_Q.
- Indirect amplitude determined to percent level.
- Direct amplitude has large uncertainty. State of the art: $\mathcal{O}(v^2)$ with light-cone resummation, and $\mathcal{O}(\alpha_s)$ fixed-order calculation at leading order in v. $\Delta\Gamma_{\alpha_s} \sim -60\%$ ($\ln^n(m_H/m_Q)$ needs resummation), $\Delta\Gamma_{resum} \sim -20\%$, $\Delta\Gamma_{v^2} \sim -10\%$.
- Aim of this project: $\mathcal{O}(v^4)$ corrections to the direct amplitude with light-cone resummation, matching LCDA with color-octet LDME's.

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$$\begin{aligned}\sigma &= H(\mu_h) \otimes LCDA(\mu_h) \\ &= H(\mu_h) \otimes U(\mu_h, \mu_s) \times LCDA(\mu_s) \\ &= H(\mu_h) \otimes U(\mu_h, \mu_s) \otimes C(\mu_s) \otimes LDME(\mu_s) \\ &\approx H(\mu_h) \otimes U(\mu_h, \mu_s) \otimes C(\mu_s) \otimes LDME(\mu_{us})\end{aligned} \tag{1}$$

$\mu_h \sim m_H$, $\mu_s \sim m_Q$, $\mu_{us} \sim m_Q v$

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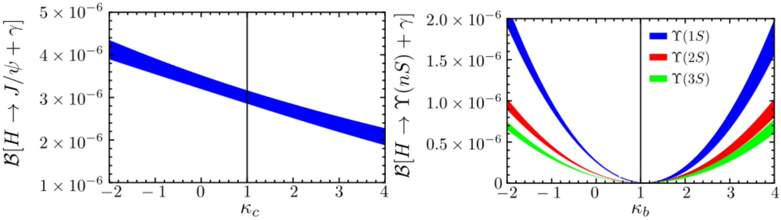
- $U(Q, m)$ resums $\ln^n(m_H/m_Q)$
- LDME's: nonperturbative matrix elements in NRQCD, appear in exclusive production cross sections of quarkonia
- Neglect running between $m_Q v$ and m_Q

Result with $\mathcal{O}(v^2)$ LDME's and light-cone resummation (courtesy H. S. Chung):



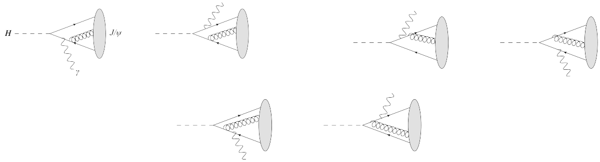
- Good sensitivty to κ_c, able to determine the sign
- Extremely low rate for $H \to \Upsilon + \gamma$ owing to destructive interference between the direct and indirect amplitudes

Light-cone distribution amplitude (LCDA) $\phi_V^{\perp}(x)$:

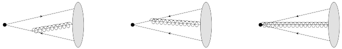
$$\frac{1}{2}\langle V|\bar{Q}(z)[\gamma^{\mu},\gamma^{\nu}][z,0]Q(0)|0\rangle = f_V(\epsilon_V^{*\mu} p_V^{\nu} - \epsilon_V^{*\nu} p_V^{\mu})\int_0^1 dx\, e^{ip_V^- zx}\phi_V^{\perp}(x) \tag{2}$$

where $[z,0] = \mathrm{P}\exp\left[ig\int_0^z dz' A^-(z'\bar{n})\right]$, $p_V = \frac{p^-}{2}n$, $n^2 = \bar{n}^2 = 0$, $\bar{n}\cdot n = 2$.

Explicit demonstration of QCD-LCDA factorization for $Q\bar{Q}g$ final state at leading order at α_s in the light-cone limit: QCD diagrams:



LCDA diagrams:



$$i\mathcal{M} = \frac{i}{2}ee_Q\kappa_Q m_Q(\sqrt{2}G_F)^{1/2} f_V\left(-\epsilon_V^*\cdot\epsilon_\gamma^* + \frac{\epsilon_V^*\cdot p_\gamma\,\epsilon_\gamma^*\cdot p_V}{p_\gamma\cdot p_V}\right)\int_0^1 dx\, T(x)\phi_V^{\perp}(x) \tag{3}$$

where $T(x) = \frac{1}{x(1-x)}$.

- Running of $\phi_V^\perp(x,\mu)$ governed by Brodsky-Lepage kernel:

$$\mu^2 \frac{\partial}{\partial \mu^2} \phi_V^\perp(x,\mu) = C_F \frac{\alpha_s(\mu)}{4\pi} \int_0^1 dy\, V_T(x,y) \phi_V^\perp(y,\mu) \tag{4}$$

- $\mathcal{M} = C_h f_V \int_0^1 dx\, T(x) \phi_V^\perp(x,\mu_h)$, $\mu_h \sim m_H$. Resum $\ln^n(m_H/m_Q)$ by running $\phi(x,\mu)$ from μ_s to μ_h, $\mu_s \sim m_Q$.
- Running is done by expansion in Gegenbauer polynomials.
  Need $\langle \xi^n \rangle \equiv \int_0^1 dx\, (2x-1)^n \phi_V^\perp(x,\mu_s)$ in terms of LDME's in NRQCD, which can be done by matching

$$\frac{1}{2} \langle V | \bar{Q}(0) [\gamma^\mu, \gamma^\nu] \left(\bar{n} \cdot \overleftrightarrow{D} \right)^n Q(0) | 0 \rangle = f_V (\epsilon_V^{*\mu} p_V^\nu - \epsilon_V^{*\nu} p_V^\mu)(\bar{n} \cdot p_V)^n \int_0^1 dx\, \xi^n \phi_V^\perp(x) \tag{5}$$

  in the rest frame of V.
- Matching to $\mathcal{O}(v^4)$ involves octet operators. Need matching with $Q\bar{Q}g$ final state.

With conservative power counting, to relatove order v^4 the following LDME's are included:

LDME (abbrev.)	LDME	relative order
ϕ_0	$\frac{1}{\sqrt{2N_c}}\langle V\|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi\|0\rangle$	1
$\langle v^2\rangle$	$\frac{1}{m_Q^2\sqrt{2N_c}\phi_0}\langle V\|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(-\frac{i}{2}\overleftrightarrow{\mathbf{D}})^2\chi\|0\rangle$	v^2
$\langle O_2\rangle$	$\frac{1}{m_Q^2\sqrt{2N_c}\phi_0}\langle V\|\psi^\dagger \sigma^i\epsilon^j(-\frac{i}{2})^2\overleftrightarrow{D}^{(i}\overleftrightarrow{D}^{j)}\chi\|0\rangle$	v^4
$\langle v^4\rangle$	$\frac{1}{m_Q^4\sqrt{2N_c}\phi_0}\langle V\|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(-\frac{i}{2}\overleftrightarrow{\mathbf{D}})^4\chi\|0\rangle$	v^4
$\langle O_B\rangle$	$\frac{1}{m_Q^2\sqrt{2N_c}\phi_0}\langle V\|\psi^\dagger g\mathbf{B}\cdot\boldsymbol{\epsilon}\chi\|0\rangle$	v^3
$\langle O_{E1}\rangle$	$\frac{1}{m_Q^3\sqrt{2N_c}\phi_0}\langle V\|\psi^\dagger(\boldsymbol{\sigma}\times(g\mathbf{E}\times\overleftrightarrow{\mathbf{D}}))\cdot\boldsymbol{\epsilon}\|0\rangle$	v^3
$\langle O_{E2}\rangle$	$\frac{1}{m_Q^3\sqrt{2N_c}\phi_0}\langle V\|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\overleftrightarrow{\mathbf{D}}\cdot g\mathbf{E}-g\mathbf{E}\cdot\overleftrightarrow{\mathbf{D}})\chi\|0\rangle$	v^3
$\langle O_{E3}\rangle$	$\frac{1}{m_Q^3\sqrt{N_c}\phi_0}\langle V\|\psi^\dagger(\boldsymbol{\sigma}\cdot g\mathbf{E})\boldsymbol{\epsilon}\cdot\overleftrightarrow{\mathbf{D}}\chi\|0\rangle$	v^3

Result:

$$f_V = \frac{\sqrt{N_c m_V}}{m_Q}\phi_0\left(1-\frac{5}{6}\langle v^2\rangle+\frac{19}{24}\langle v^4\rangle\right) \tag{6}$$

$$\langle\xi^2\rangle = \frac{1}{f_V}\left(-\frac{1}{2}\langle v^2\rangle+\frac{3}{10}\langle O_2\rangle-\langle O_B\rangle+\frac{3}{5}\langle O_{E1}\rangle+\frac{13}{40}\langle O_{E2}\rangle-\frac{9}{20}\langle O_{E3}\rangle\right) \tag{7}$$

$$\langle\xi^4\rangle = \frac{43}{120 f_V}\langle v^4\rangle \tag{8}$$

Among the 4 octet matrix elements, 3 combinations of them can be written in terms of $\langle v^2\rangle$, $\langle v^4\rangle$, $\langle O_2\rangle$ via the Gremm-Kapustin relations.

SUMMARY AND OUTLOOK

Summary:

- Explicit proof of QCD-LCDA factorization for $Q\bar{Q}g$ final state at leading order in α_s.
- Matching LCDA to LDME's to $\mathcal{O}(v^4)$ at leading order in α_s, including octet operators.

Outlook:

- Numerical estimate of uncertainties.
- Obtain relevant LDME's from data of other exclusive production channels.
- Propose ways to calculate the relavant LDME's on the lattice.
- Full $\mathcal{O}(\alpha_s v^2)$ calculation.
- Automate matching of LCDA's and LDME's.

Thank you.