Measuring the Higgs-charm couplings in $H \to J/\psi + \gamma$

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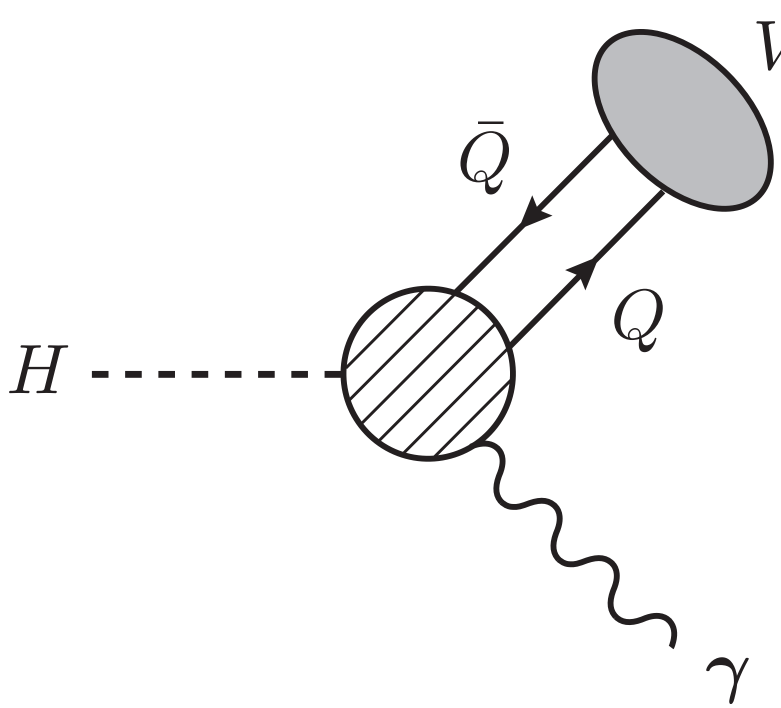
Outline

- Introduction: $H \to V + \gamma$ decay
- Review of PRD **88**, 053003 (2013), Bodwin et al.
- Relativistic corrections to $H \to V + \gamma$ decay
- Summary

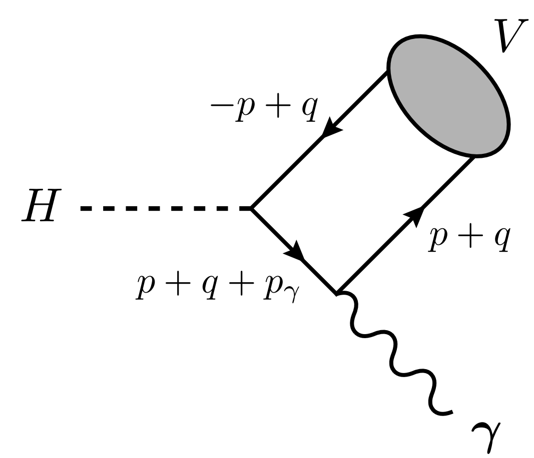
Introduction: Higgs decays to quarkonia

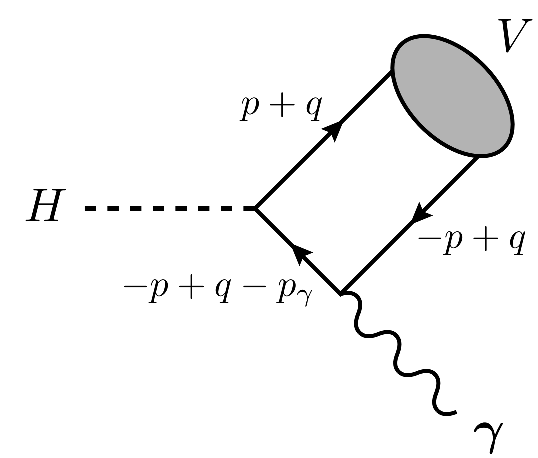
Introduction

- Exclusive mode of Higgs decays to a quarkonium and a photon



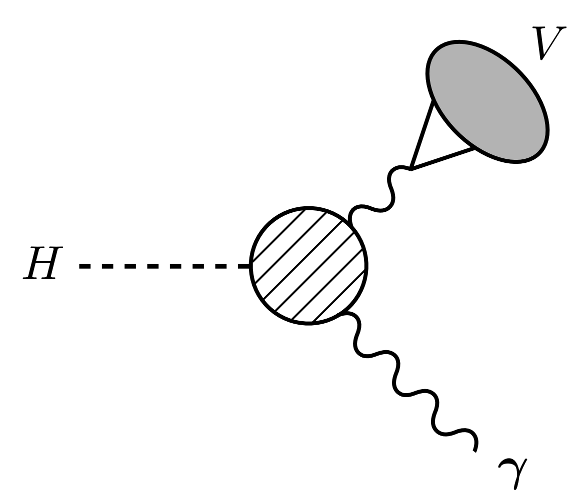
  - Direct process:
    quarks directly couples to Higgs.





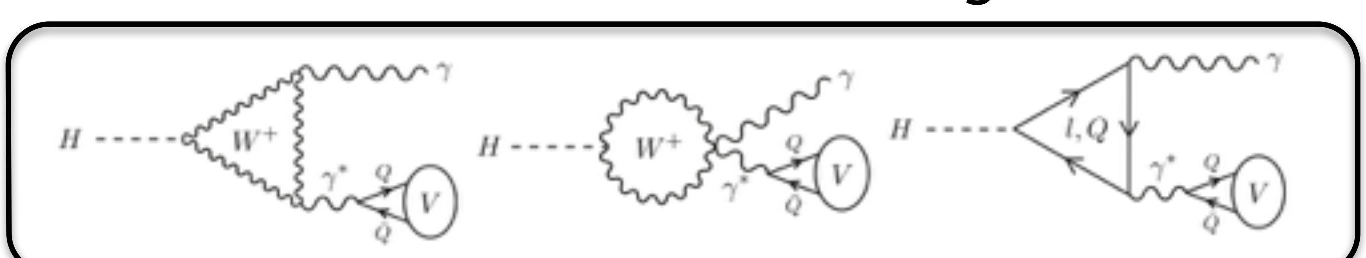
interference!

  - Indirect process



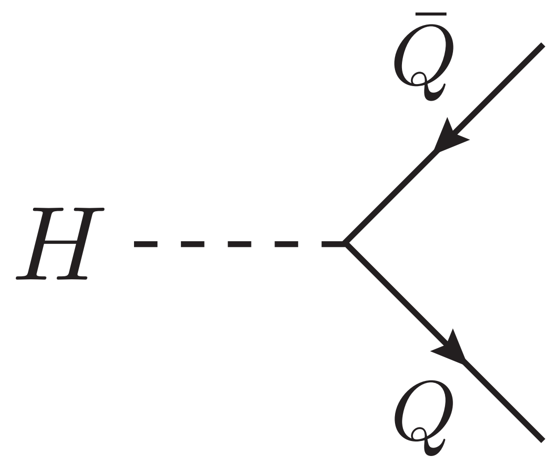
Virtual photon couples to heavy quark-antiquark pair to create an 1^{--} quarkonium

Lowest order indirect diagrams



Higgs Yukawa Coupling

- Higgs Yukawa coupling is given by



:

quark mass

$$i\mathcal{M}_{HQ\bar{Q}} = -ig\frac{m_Q}{2m_W} \times \kappa_Q$$

In SM, $\kappa_Q = 1$

- Until now, the only measured Higgs Yukawa couplings are for tau and bottom. That for top is implicitly measured from loop contributions.
- In HL-LHC, we can make use of this process to probe the Higgs-charm coupling that appears in the interference contribution.

Review of PRD 88, 053003 (2013), Bodwin et al.

NRQCD Matrix Elements

- NRQCD factorization formula

$$\mathcal{M} = \sum_n c_n \langle \boldsymbol{q}^{2n} \rangle \langle \mathcal{O}_1 \rangle^{1/2}$$

- Matrix elements at leading order in the heavy-quark velocity v

$$\langle \mathcal{O}_1 \rangle_V = \left| \langle V(\boldsymbol{\epsilon}) | \psi^\dagger \boldsymbol{\sigma} \cdot \boldsymbol{\epsilon} \chi | 0 \rangle \right|^2 \longrightarrow \phi_0(V) = \frac{1}{\sqrt{2N_c}} (\langle \mathcal{O}_1 \rangle_V)^{1/2}$$

- Ratios of matrix elements of higher orders in v to the leading-order matrix elements

$$\langle \boldsymbol{q}^{2n} \rangle_V = m_Q^{2n} \langle v^{2n} \rangle_V = \frac{\langle V(\boldsymbol{\epsilon}) | \psi^\dagger (-\frac{i}{2} \overleftrightarrow{\boldsymbol{D}})^{2n} \boldsymbol{\sigma} \cdot \boldsymbol{\epsilon} \chi | 0 \rangle}{\langle V(\boldsymbol{\epsilon}) | \psi^\dagger \boldsymbol{\sigma} \cdot \boldsymbol{\epsilon} \chi | 0 \rangle} \Rightarrow$$

Relativistic Corrections

NRQCD Matrix Elements

Hard scattering amplitude

$$\mathcal{M} = \sum_n \underbrace{\left[\frac{1}{n!}\left(\frac{\partial}{\partial v^2}\right)^n H(v^2)\right]\Bigg|_{v^2=0}}_{\text{Short distance coefficients}} \langle v^{2n}\rangle_V \langle \mathcal{O}_1\rangle_V^{1/2}$$

- The numerical values for NRQCD MEs for J/psi up to v^2

$$\phi_0^2(J/\psi) = 0.07285^{+0.0109}_{-0.0092}\ \mathrm{GeV}^3,$$

$$\langle v^2\rangle(J/\psi) = 0.201 \pm 0.064$$

Bodwin, Chung, Kang, Lee, Yu, PRD **77,** 094017 (2008)

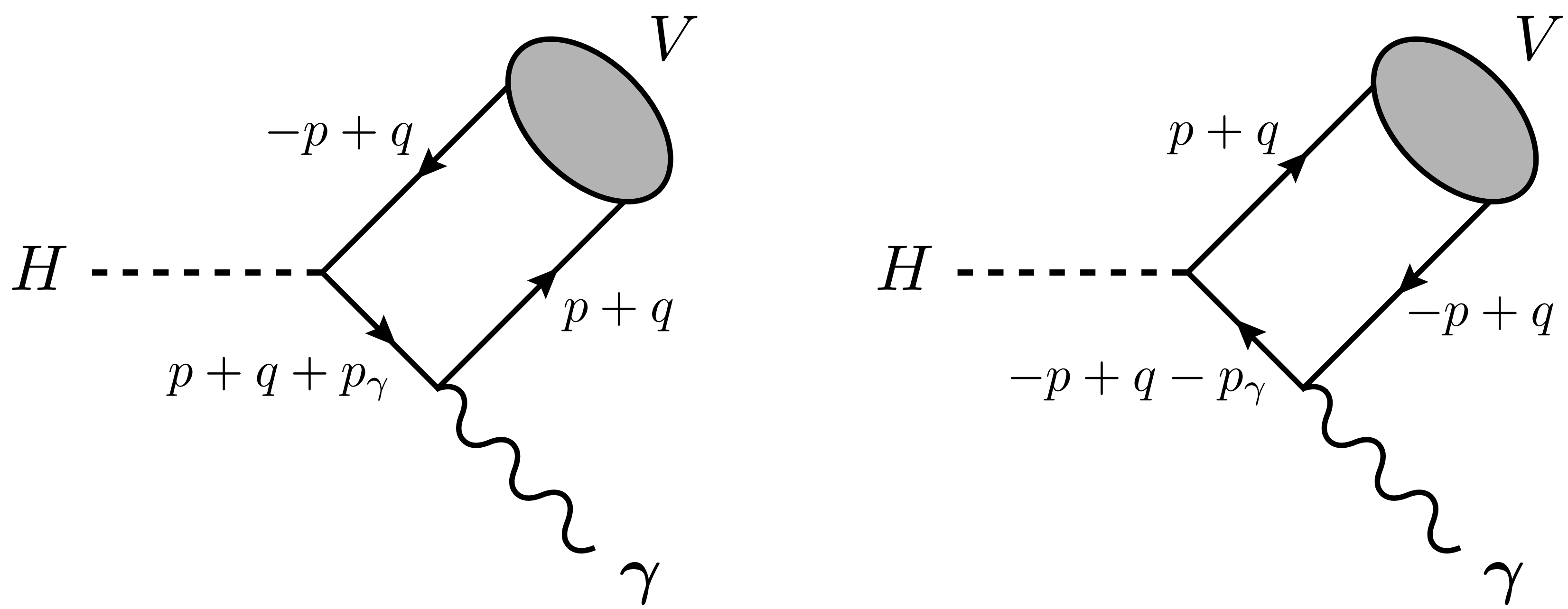
- The numerical values for NRQCD MEs for Upsilon up to v^2

$$\phi_0^2(\Upsilon) = 0.512^{+0.035}_{-0.032}\ \mathrm{GeV}^3$$

$$\langle v^2\rangle(\Upsilon) = -0.0092^{+0.0034}_{-0.0035}$$

Chung, Lee, Yu, PLB **697,** 48 (2008)

Direct Amplitude(v=0)



- First, let us assume the quarks in the meson are at rest. Then, from NRQCD matching, we obtain $i\mathcal{M}_{\rm dir}(H \to V + \gamma)$ by multiplying $i\mathcal{M}_{\rm dir}[H \to Q\bar{Q}({}^3S_1^{[1]}) + \gamma]\Big|_{v^2=0}$ by $\sqrt{2m_V}\phi_0(V)$.

(v is the velocity of a quark in a quarkonium rest frame.)

- Then, the direct amplitude is

$$\begin{pmatrix} 2p \to p_V \\ \epsilon_{Q\bar{Q}} \to \epsilon_V \end{pmatrix}$$

$$\boxed{\mathcal{M}_{\rm dir} = 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) \left(-\epsilon_\gamma^* \cdot \epsilon_V^* + \frac{p_\gamma \cdot \epsilon_V^* p_V \cdot \epsilon_\gamma^*}{p_\gamma \cdot p_V}\right)}$$

Corrections to direct process

- We include the full NLO correction in α_s and the all-order resummations of the leading logarithms of the form $\alpha_s \log(m_H^2/m_Q^2) \approx 0.9$.

- Let us denote the correction factor of order-v^0 as g_{SV}.

(M. A. Shifman and M. I. Vysotsky, Nucl. Phys. B **186**, 475)

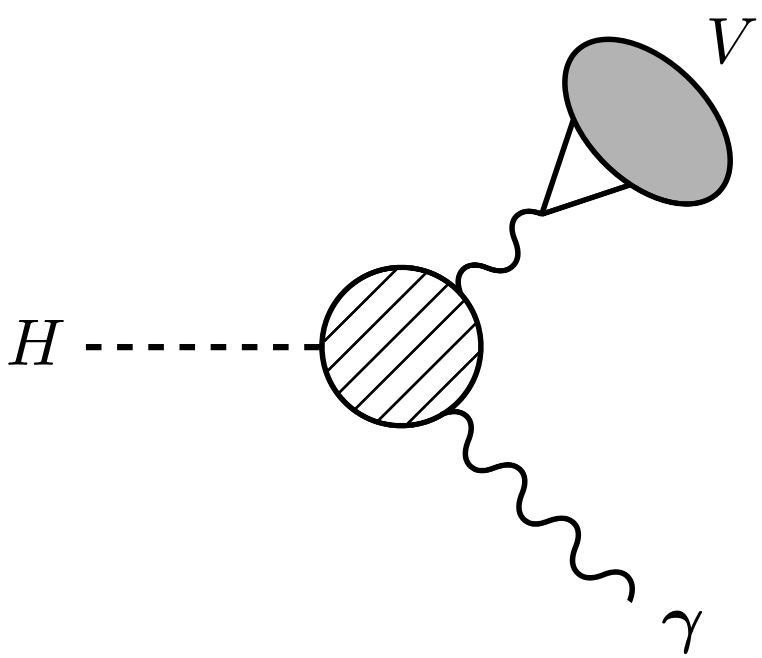
- g_{SV}: full NLO QCD correction + $HQ\bar{Q}$ coupling evolution
  + all order resummations of the leading logarithms

- Then, the direct amplitude becomes

(0.597 for J/psi)
(0.689 for Upsilon)

$$\boxed{\mathcal{M}_{\rm dir} = 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) g_{SV} \left(-\epsilon_\gamma^* \cdot \epsilon_V^* + \frac{p_\gamma \cdot \epsilon_V^* p_V \cdot \epsilon_\gamma^*}{p_\gamma \cdot p_V} \right)}$$

Indirect Amplitude



- Higgs decays to two photons, and one of them fragments to V.
- Indirect amplitude is factorized as

$$i\mathcal{M}_{\mathrm{ind}} = i\mathcal{M}(H \to \gamma\gamma^*) \cdot \frac{-i}{m_V^2} \cdot i\mathcal{M}(\gamma^* \to V)$$

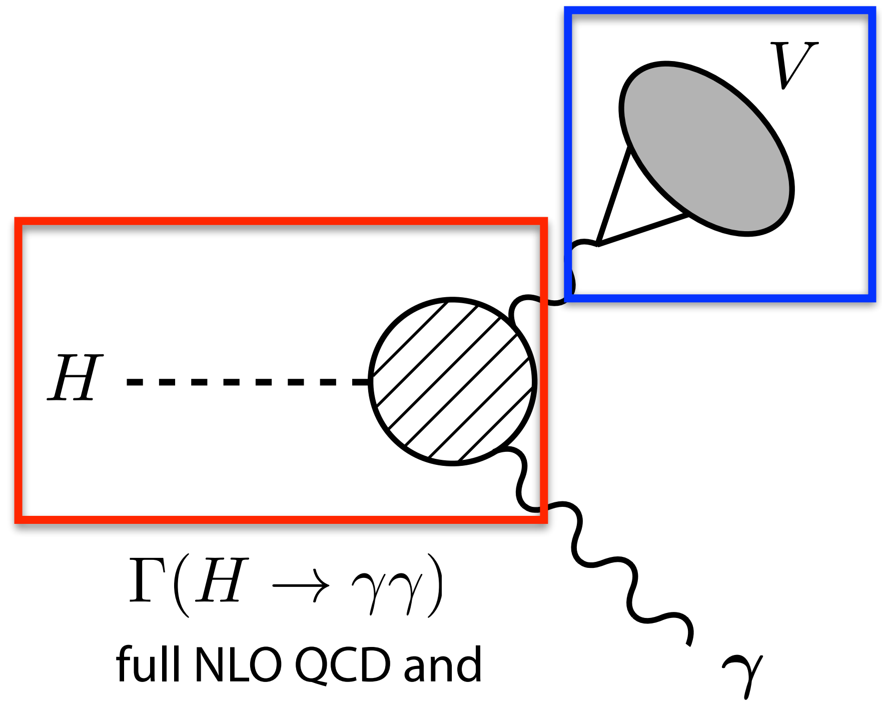
- $i\mathcal{M}(H \to \gamma\gamma^*) = i\mathcal{M}(H \to \gamma\gamma) + \mathcal{O}(m_V^2/m_H^2)$

(correction due to our use of γ instead of γ^*)

- $\frac{-i}{m_V^2}$: photon propagator
- $i\mathcal{M}(\gamma^* \to V) = -ieg_{V\gamma}$: photon fragmentation ($V\gamma$ coupling) given by the measurement of $\Gamma(V \to l^+l^-)$:

$$\Gamma(V \to l^+l^-) = \frac{4\pi\alpha^2 g_{V\gamma}^2}{3m_V^3} \longrightarrow g_{V\gamma} = -\frac{e_Q}{|e_Q|}\left[\frac{3m_V^3\Gamma(V \to l^+l^-)}{4\pi\alpha^2}\right]^{1/2}$$

Corrections to Indirect Amplitude



$g_{V\gamma}$

determined by experiments

→ all order corrections

(QCD, EW, relativistic corrections)

$\Gamma(H \to \gamma\gamma)$

full NLO QCD and

full NLO EW corrections

→ theoretical uncertainty ~ 1%

- Since we can determine $g_{V\gamma}$ and $\Gamma(H \to \gamma\gamma)$ precisely, we can accurately predict the contribution from the indirect amplitude.

↓

Sensitive to direct amplitude through the interference!

Amplitudes

- Amplitudes

$$\mathcal{M}_{\rm dir} = \mathcal{A}_{\rm dir}\left(-\epsilon_\gamma^* \cdot \epsilon_V^* + \frac{p_\gamma \cdot \epsilon_V^* p_V \cdot \epsilon_\gamma^*}{p_\gamma \cdot p_V}\right)$$

$$\mathcal{M}_{\rm ind} = \mathcal{A}_{\rm ind}\left(-\epsilon_\gamma^* \cdot \epsilon_V^* + \frac{p_\gamma \cdot \epsilon_V^* p_V \cdot \epsilon_\gamma^*}{p_\gamma \cdot p_V}\right)$$

where

$$\boxed{\begin{aligned} \mathcal{A}_{\rm dir} &= 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) g_{SV} \\ \mathcal{A}_{\rm ind} &= \frac{e g_{V\gamma}\sqrt{m_H}}{m_V^2}\left[16\pi\Gamma(H\to\gamma\gamma)\right]^{1/2} \end{aligned}}$$

- Since $g_{V\gamma} \sim -e_Q$, the interference is always destructive.

$$\left(g_{V\gamma} = -\frac{e_Q}{|e_Q|}\left[\frac{3m_V^3\Gamma(V\to l^+l^-)}{4\pi\alpha^2}\right]^{1/2} \right)$$

Uncertainties of Amplitudes

- Uncertainties of the direct amplitude

$$\mathcal{A}_{\rm dir} = 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) g_{SV}$$

$\phi_0(V)$ uncertainties: 7.5% for J/ψ, 3.4% for $\Upsilon(1S)$

order-α_s^2 correction: 2%

order-v^2 correction: 30% for J/ψ and 10% for $\Upsilon(1S)$

- Uncertainties of the indirect amplitude

$$\mathcal{A}_{\rm ind} = \frac{e g_{V\gamma} \sqrt{m_H}}{m_V^2} [16\pi \Gamma(H \to \gamma\gamma)]^{1/2}$$

$\Gamma(H \to \gamma\gamma)$ theoretical uncertainties: 1%

m_t, m_W uncertainties: 0.022%, 0.024%

$g_{V\gamma}^2$ uncertainties: 2.5% for J/ψ, 1.3% for $\Upsilon(1S)$

Relativistic Corrections to Direct Amplitude

Factorization of Amplitude

- According to the NRQCD factorization,

$$\mathcal{M} \sim \sum_n \underbrace{c_n(Q,m)}_{\text{NRQCD matching coefficient}} \underbrace{\langle v^{2n}\rangle \langle \mathcal{O}_1 \rangle_V^{1/2}}_{\text{NRQCD matrix element}}$$

NRQCD matching coefficient (short distance, perturbative)

NRQCD matrix element (long distance, nonperturbative)

- Generally, c_n depends on two energy scales, where
  Q : typical kinematic scale such as CM energy,
  m : heavy quark mass $\quad (Q > m \gg \lambda_{\mathrm{QCD}})$
- If $Q \gg m$, there arises the ambiguity of setting the renormalization scale in α_s, whether to put it around m^2 or Q^2.
- Also, $[\alpha_s \log(Q^2/m^2)]^n$ in higher order corrections in c_n are not negligible.

Factorization of c_n

- According to the standard collinear factorization theorem,

$$c_n(Q^2/m^2) \sim \underline{T(x,Q,\mu)} \otimes \underline{\phi(x,m,\mu)} + \mathcal{O}(m^2/Q^2)$$

hard-scattering part
involving massless quark
depends on Q not m

light cone distribution amplitude (LCDA)
depends on m not Q

- μ is an arbitrary scale separating Q and m.
- x is the minus light-cone momentum fraction of heavy quark to that of the quarkonium.
- Invariance of the physical $\mathcal{M}$ about the choice of μ leads to the RG equation, referred to Brodsky-Lepage equation, through which the large logarithms can be easily resummed:

$$\mu^2 \frac{\partial}{\partial \mu^2} \phi(x,m,\mu) = C_F \frac{\alpha_s(\mu^2)}{4\pi} \int_{-1}^{1} dy V_T(x,y) \phi(y,m,\mu)$$

Light-cone Amplitude

- The light-cone amplitude for the direct process at order α_s^0 and at leading order $1/m_H$ (leading twist) is

$$i\mathcal{M}_{\rm dir}^{\rm LC}[H \to V + \gamma] = \sqrt{2m_V}\phi_0 i\mathcal{M}_{\rm dir}^{(0)}[H \to V + \gamma]\left[1 - \frac{5}{6}\langle v^2\rangle + \mathcal{O}(\langle v^4\rangle)\right]$$

$$\times \boxed{\frac{1}{4}\int_{-1}^{1} dx T_0(x)\phi(x)} \rightarrow \boxed{1 + \langle x^2\rangle + \mathcal{O}(\langle x^4\rangle)}$$

where

Note that $\langle x^2\rangle = \frac{1}{3}\langle v^2\rangle$, [V. V. Braguta, PRD **75**, 094016 (2007)]

$$i\mathcal{M}_{\rm dir}^{(0)}[H \to V + \gamma] = iee_Q\kappa_Q(\sqrt{2}G_F)^{\frac{1}{2}}\sqrt{2N_c}\left(-\epsilon_V^* \cdot \epsilon_\gamma^* + \frac{\epsilon_V^* \cdot p_\gamma p_V \cdot \epsilon_\gamma^*}{p_\gamma \cdot p_V}\right)$$

$$\frac{T_0(x)}{4} = \frac{1}{1-x^2} = 1 + x^2 + \mathcal{O}(x^4)$$

$$\phi(x) = \sum_{k=0}^{\infty}\frac{(-1)^k\langle x^k\rangle}{k!}\delta^{(k)}(x)$$

Why LCDA?

- There are available **full 1-loop QCD correction results** at order $x^0 \to g_{SV}$ (M. A. Shifman and M. I. Vysotsky, Nucl. Phys. B **186**, 475)

- We can easily resum large logarithms $[\alpha_s \log(m_H^2/m_Q^2)]^n$ by using the known solution of BL equation.

$$i\mathcal{M}^{\rm LC}_{\rm dir}[H \to V + \gamma] = \sqrt{2m_V}\phi_0 i\mathcal{M}^{(0)}_{\rm dir}[H \to V + \gamma]\left[1 - \frac{5}{6}\langle v^2\rangle + \mathcal{O}(\langle v^4\rangle)\right]$$

$$\times\left[\boxed{1} + \boxed{\langle x^2\rangle} + \mathcal{O}(\langle x^4\rangle)\right]$$

evolution of x^0 terms in $\phi(x)$
+evolution of $HQ\bar{Q}$
+ full 1-loop QCD

$\to \boxed{g_{SV}}$

evolution of x^2 terms in $\phi(x)$
+evolution of $HQ\bar{Q}$
+ **no** QCD correction

$\to \boxed{\frac{1}{3}\langle v^2\rangle c_2(\mu) F_{HQ\bar{Q}}(\mu)}$

Relativistic Correction

- Direct amplitude at $v = 0$

$$\mathcal{A}_{\rm dir} = 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) g_{SV}$$

include $\langle v^2 \rangle$ correction

- Direct amplitude up to v^2

$$\mathcal{A}_{\rm dir} = 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) \boxed{\left[\left(1 - \frac{5}{6}\langle v^2 \rangle\right) g_{SV} + \frac{1}{3}\langle v^2 \rangle c_2(\mu) F_{HQ\bar{Q}}(\mu)\right]}$$

- Indirect amplitude already includes the all-order relativistic corrections.

$$\mathcal{A}_{\rm ind} = \frac{e g_{V\gamma} \sqrt{m_H}}{m_V^2} \left[16\pi \Gamma(H \to \gamma\gamma)\right]^{1/2}$$

$$\mathcal{A}_{\rm ind} = \frac{g_{V\gamma} \sqrt{4\pi\alpha(m_V) m_H}}{m_V^2} \left[16\pi \frac{\alpha(m_V)}{\alpha(0)} \Gamma(H \to \gamma\gamma)\right]^{1/2}$$

Uncertainties of Amplitudes

- Uncertainties of the direct amplitude

$$\mathcal{A}_{\rm dir} = 2\sqrt{3} e_Q e \kappa_Q \left(\sqrt{2} G_F m_V\right)^{1/2} \phi_0(V) \left[\left(1 - \frac{5}{6}\langle v^2\rangle\right) g_{SV} + \frac{1}{3}\langle v^2\rangle c_2(\mu) F_{HQ\bar{Q}}(\mu)\right]$$

$\phi_0(V)$, $\langle v^2\rangle$ uncertainties
order-α_s^2 correction: 2%
order-$\alpha_s v^2$ correction: 5% for J/ψ, 1.5% for $\Upsilon(1S)$
order-v^4 correction: 9% for J/ψ, 1% for $\Upsilon(1S)$

- Uncertainties of the indirect amplitude

$$\mathcal{A}_{\rm ind} = \frac{g_{V\gamma}\sqrt{4\pi\alpha(m_V)} m_H}{m_V^2} \left[16\pi \frac{\alpha(m_V)}{\alpha(0)} \Gamma(H \to \gamma\gamma)\right]^{1/2}$$

$\Gamma(H \to \gamma\gamma)$ theoretical uncertainties: 1%
m_t, m_W uncertainties: 0.022%, 0.024%
$g_{V\gamma}^2$ uncertainties: 2.5% for J/ψ, 1.3% for $\Upsilon(1S)$

Decay Rates

Total decay rate: $\boxed{\Gamma(H \to V + \gamma) = \frac{m_H^2 - m_V^2}{8\pi m_H^3} \left|\mathcal{A}_{\rm dir} + \mathcal{A}_{\rm ind}\right|^2}$

$$\Gamma(H \to J/\psi + \gamma) = |(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c|^2 \times 10^{-10}\ \mathrm{GeV},$$

$$\Gamma(H \to \Upsilon + \gamma) = |(3.33 \pm 0.03) - (3.49 \pm 0.15)\kappa_b|^2 \times 10^{-10}\ \mathrm{GeV}$$

In SM, $\kappa_Q = 1$.

$$\Gamma_{\rm SM}(H \to J/\psi + \gamma) = 1.17^{+0.05}_{-0.05} \times 10^{-8}\ \mathrm{GeV},$$

$$\Gamma_{\rm SM}(H \to \Upsilon + \gamma) = 2.56^{+7.30}_{-2.56} \times 10^{-12}\ \mathrm{GeV}$$

With $\Gamma_H = 4.195^{+0.164}_{-0.159} \times 10^{-3}\ \mathrm{GeV}$, the branching fractions are (at $m_H = 125.9\ \mathrm{GeV}$)

$$\mathrm{BR}_{\rm SM}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6},$$

$$\mathrm{BR}_{\rm SM}(H \to \Upsilon + \gamma) = 6.11^{+17.41}_{-6.11} \times 10^{-10}$$

Expected Number of Events

- 3000 fb^{-1} of integrated luminosity at 14 TeV
- Higgs production cross section at 14 TeV LHC

$$\sigma(H) = 57.0283 \text{ pb} \quad \longrightarrow \quad 1.7 \times 10^8 \text{ Higgs will be produced}$$

- Detectable channels in LHC:

$$H \to J/\psi + \gamma \to l^+ l^- + \gamma$$

$$(l = e, \mu)$$

- $H \to J/\psi + \gamma$ branching fraction:

$$\mathrm{BR}_{\mathrm{SM}}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6}$$

- $J/\psi \to l^+ l^-$ branching fraction:

$$\mathrm{BR}_{\mathrm{SM}}(J/\psi \to l^+ l^-) = (5.97 \pm 0.03) \times 10^{-2}$$

Expected Number of Events

- Expected number of events

CMS and ATLAS

e^+e^- and $\mu^+\mu^-$

$$\boxed{\begin{aligned} N = 2 \times 2 \times \mathrm{BR}(H \to J/\psi + \gamma) \times \mathrm{BR}(J/\psi \to l^+l^-) \\ \times \mathcal{L} \times \sigma(H) \times \text{acceptance} \end{aligned}}$$

integrated luminosity

detector acceptance $\approx 50\%$

Higgs production cross section at 14 TeV

$$\boxed{N \approx 57}$$

- If $\kappa_Q = 0$, then the expected event number is $N \approx 69$.
- If $\kappa_Q = -1$, then the expected event number is $N \approx 81$.

Summary

- The rare decay $H \to J/\psi + \gamma$ has a clean experimental signature and may be observable at a high-luminosity LHC.

- Through the interference between the direct and indirect amplitude, the rate is sensitive to the $HQ\bar{Q}$ coupling.

- In the recent work, we include the relativistic correction and reduce the uncertainties about a factor of 2-3.

$$\Gamma_{\rm SM}(H \to J/\psi + \gamma) = (1.00^{+0.10}_{-0.10}) \times 10^{-8}\ \text{GeV},$$
$$\Gamma_{\rm SM}(H \to \Upsilon + \gamma) = (6.01^{+8.45}_{-4.80}) \times 10^{-11}\ \text{GeV}$$

Order-v^0 result

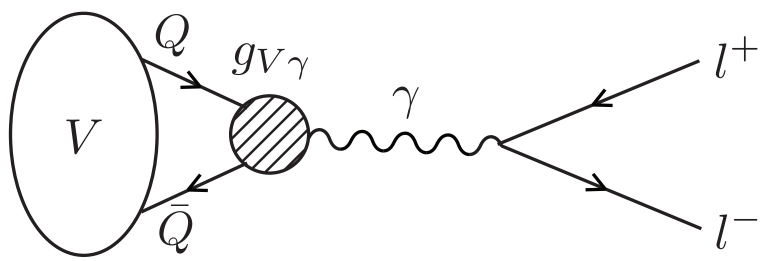
$\longrightarrow$

$$\Gamma_{\rm SM}(H \to J/\psi + \gamma) = 1.17^{+0.05}_{-0.05} \times 10^{-8}\ \text{GeV},$$
$$\Gamma_{\rm SM}(H \to \Upsilon + \gamma) = 3.52^{+8.07}_{-3.42} \times 10^{-12}\ \text{GeV}$$

Order-v^2 result

Thank you

Back Up Slides



Sign of $g_{V\gamma}$

$$\Gamma(V \to l^+ l^-) = \frac{4\pi\alpha^2 g_{V\gamma}^2}{3m_V^3} \quad \longrightarrow \quad g_{V\gamma} = -\frac{e_Q}{|e_Q|}\left[\frac{3m_V^3 \Gamma(V \to l^+ l^-)}{4\pi\alpha^2}\right]^{1/2}$$

- Note that the lepton-gamma vertex factor is

$$i\mathcal{M}(\gamma^* \to V) = -ie\langle V(\epsilon)|J_V^\mu(x=0)|0\rangle = -ieg_{V\gamma}\epsilon^{\mu *}$$

where ϵ^μ is the polarization vector of the quarkonium and J_V is the electomagnetic current $J_V^\mu(x) = \sum_q e_q \bar{q}(x)\gamma^\mu q(x)$

- Then, according to NRQCD factorization, at leading order in α_s and v, we have

$$\langle V(\epsilon)|J_V^\mu(x=0)|0\rangle = g_i^\mu e_Q \langle V(\epsilon)|\mathcal{O}^i({}^3S_1^{[1]})|0\rangle = -\sqrt{2N_c}\sqrt{2m_V}\phi_0 e_Q \epsilon^{*\mu}$$

and $g_{V\gamma} = -e_Q\sqrt{2N_c}\sqrt{2m_V}\phi_0 < 0$ (and higher order contributions are negligible.)

BL equation (RG evolution of LCDA)

$$\boxed{\mu^2 \frac{\partial}{\partial \mu^2} \phi(x, m, \mu) = C_F \frac{\alpha_s(\mu^2)}{4\pi} \int_{-1}^{1} dy V_T(x, y) \phi(y, m, \mu)}$$

$$V_T(x, y) = V_0(x, y) - \frac{1-x}{1-y}\theta(x-y) - \frac{1+x}{1+y}\theta(y-x)$$

$$V_0(x, y) = V_{\mathrm{BL}}(x, y) - \delta(x-y) \int_{-1}^{1} dz V_{\mathrm{BL}}(z, x)$$

$$V_{\mathrm{BL}}(x, y) = \frac{1-x}{1-y}\left(1 + \frac{2}{x-y}\right)\theta(x-y) + \frac{1+x}{1+y}\left(1 + \frac{2}{y-x}\right)\theta(y-x)$$