RADIATIVE HIGGS DECAYS TO QUARKONIUM

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Based on
Geoffrey Bodwin (ANL), HSC (TUM), June-Haak Ee, Jungil Lee (KU), PRD95 (2017) 054018, PRD96 (2017) 116014
Nora Brambilla, HSC, Wai Kin Lai (TUM), Vladyslav Shtabovenko (Zhejiang), Antonio Vairo (TUM), in preparation

The 13th International Workshop on Heavy Quarkonium
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OUTLINE

- Higgs-heavy quark coupling from Higgs radiative decays to quarkonium
- $H \to J/\psi + \gamma$ in NRQCD to relative order v^4
- Fixed-order and resummation calculation using **FeynOnium**
- Prospects at LHC

HIGGS–CHARM COUPLING

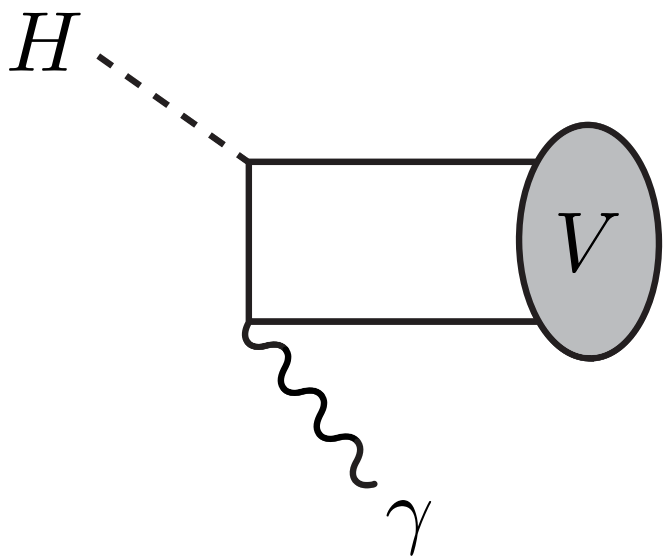
- The 125 GeV particle is *produced in colliders like a SM Higgs*, and *decays like a SM Higgs*, and is *compatible with* J^{PC}*=0*$^{++}$ *like a SM Higgs*.
- The Yukawa couplings for first- and second-generation fermions are still poorly constrained.
- Indirect constraint from global fit yields $\boldsymbol{\kappa_c = y_c/y_c^{\rm SM} < 6.2}$
  Perez, Soreq, Stamou, Tobioka, PRD92 (2015) 033016
- The Higgs-charm coupling may be probed directly from Higgs decays to $c\bar{c}$, or from the ***Higgs radiative decays to charmonium***.

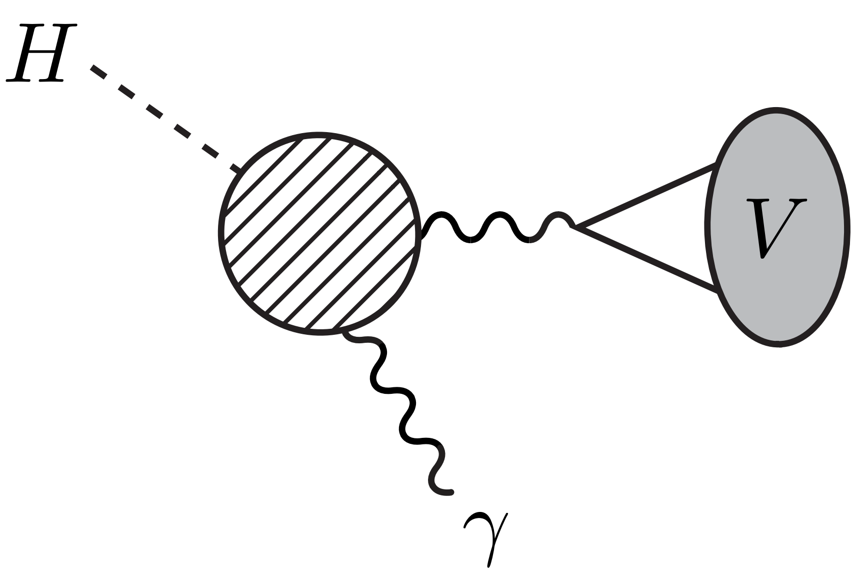
HIGGS DECAYS TO QUARKONIUM + PHOTON

- $H \to J/\psi + \gamma$ can be a good probe for the $Hc\bar{c}$ coupling :
  - Clean final states through J/ψ leptonic decay
  - Occurs through two distinct subprocesses that combine at the amplitude level, decay rate sensitive to both the size and the sign of the coupling.
  - ***direct amplitude*** is proportional to the $Hc\bar{c}$ coupling
  - ***indirect amplitude*** is almost independent of the Hcc coupling, and is an order of magnitude larger than the direct amplitude.

Bodwin, Petriello, Stoynev, Velasco, PRD88 (2013) 053003

HIGGS DECAYS TO QUARKONIUM + PHOTON



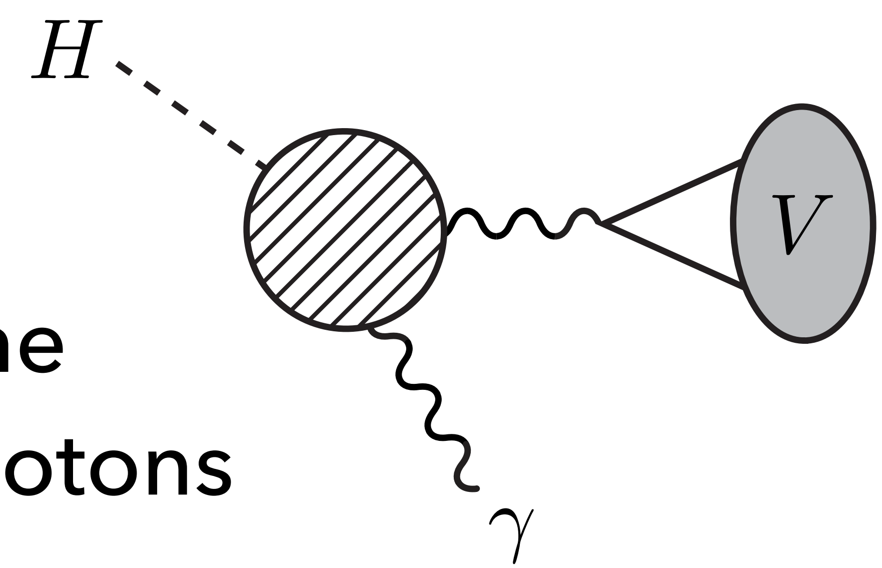


- ***Direct amplitude*** : $c\bar{c}$ is produced through the Yukawa interaction, which produces a J/ψ after radiating a photon.
- ***Indirect amplitude*** : Higgs decays to two photons, one photon subsequently evolves into a J/ψ through the J/ψ EM current.

Bodwin, Petriello, Stoynev, Velasco, PRD88 (2013) 053003

$$\Gamma(H \to J/\psi + \gamma) = |\mathcal{A}_{\rm dir} + \mathcal{A}_{\rm ind}|^2$$

INDIRECT AMPLITUDE



- Indirect amplitude factorizes into the Higgs decay amplitude into two photons and the J/ψ EM current.
- Higgs two-photon decay rate has been computed with estimated uncertainty of 1%.

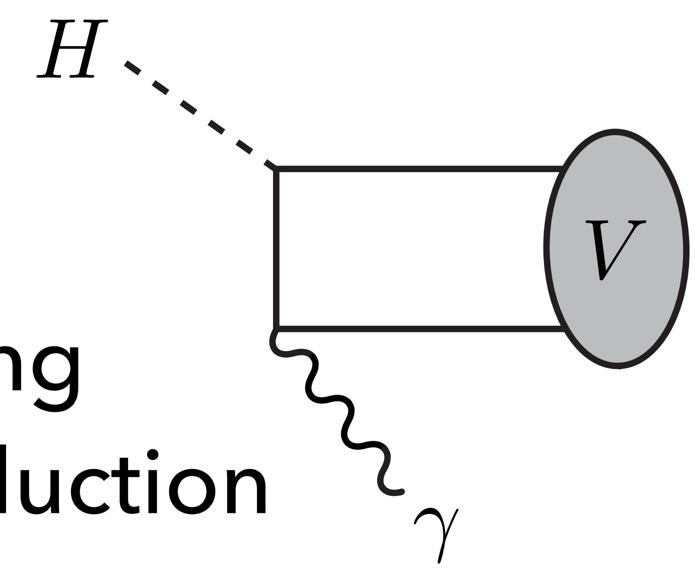
Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables arXiv:1101.0593 [hep-ph]

- The J/ψ EM current can be obtained from the leptonic decay rate of J/ψ, which has been measured precisely.

M. Tanabashi et al. (Particle Data Group), PRD98 (2018) 030001

- $\mathcal{A}_{\rm ind}$ can be computed with precision better than 2%.

DIRECT AMPLITUDE



- The direct amplitude can be computed using NRQCD factorization for exclusive EM production processes.

$$\mathcal{A}_{\rm dir} = \sum_n \frac{c_n}{m^{d_n-3}} \langle J/\psi | \mathcal{O}_n | 0 \rangle$$

- Order-α_s correction and LL resummation : **Shifman and Vysotsky, NPB 186, 475 (1981)**
- LO in v, LL resummation: **Bodwin, Petriello, Stoynev, Velasco, PRD88 (2013) 053003**
- Order-v^2 correction, NLL resummation : **Bodwin, HSC, Ee, Lee, Petriello, PRD90 (2014) 113010**
  Bodwin, HSC, Ee, Lee, PRD95 (2017) 054018, PRD96 (2017) 116014
- Order-v^4 correction including NLL resummation : **Brambilla, HSC, Lai, Shtabovenko, Vairo, in preparation**

DIRECT AMPLITUDE TO RELATIVE ORDER v^4

Using conservative power counting from Brambilla, Mereghetti, Vairo, JHEP 0608, 039 (2006), PRD79 (2009) 074002

- Nonperturbative LDMEs :

LO in v : $\langle J/\psi|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\lambda)\chi|0\rangle$

Relative order v^2 : $\langle J/\psi|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\lambda)(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\chi|0\rangle$

Relative order v^3 : $\langle J/\psi|\psi^\dagger g_s \boldsymbol{B}\cdot\boldsymbol{\epsilon}(\lambda)\chi|0\rangle$

Relative order v^4 : $\langle J/\psi|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\lambda)(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})^4\chi|0\rangle$

$$\langle J/\psi|\psi^\dagger \epsilon^i(\lambda)\sigma^j(-\tfrac{i}{2})^2\overleftrightarrow{\boldsymbol{D}}^{(i}\overleftrightarrow{\boldsymbol{D}}^{j)}\chi|0\rangle$$

$$\langle J/\psi|\psi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\lambda)\tfrac{1}{3}(\overleftrightarrow{\boldsymbol{D}}\cdot g_s\boldsymbol{E}+g_s\boldsymbol{E}\cdot\overleftrightarrow{\boldsymbol{D}})\chi|0\rangle$$

$$\langle J/\psi|\psi^\dagger \boldsymbol{\epsilon}(\lambda)\cdot\tfrac{1}{2}[\boldsymbol{\sigma}\times(\overleftrightarrow{\boldsymbol{D}}\times g_s\boldsymbol{E}-g_s\boldsymbol{E}\times\overleftrightarrow{\boldsymbol{D}})]\chi|0\rangle$$

COLOR SINGLET LDMES AVAILABLE FROM POTENTIAL MODEL CALCULATIONS

COLOR OCTET LDMES SENSITIVE TO THE $|c\bar{c}g\rangle$ FOCK STATE

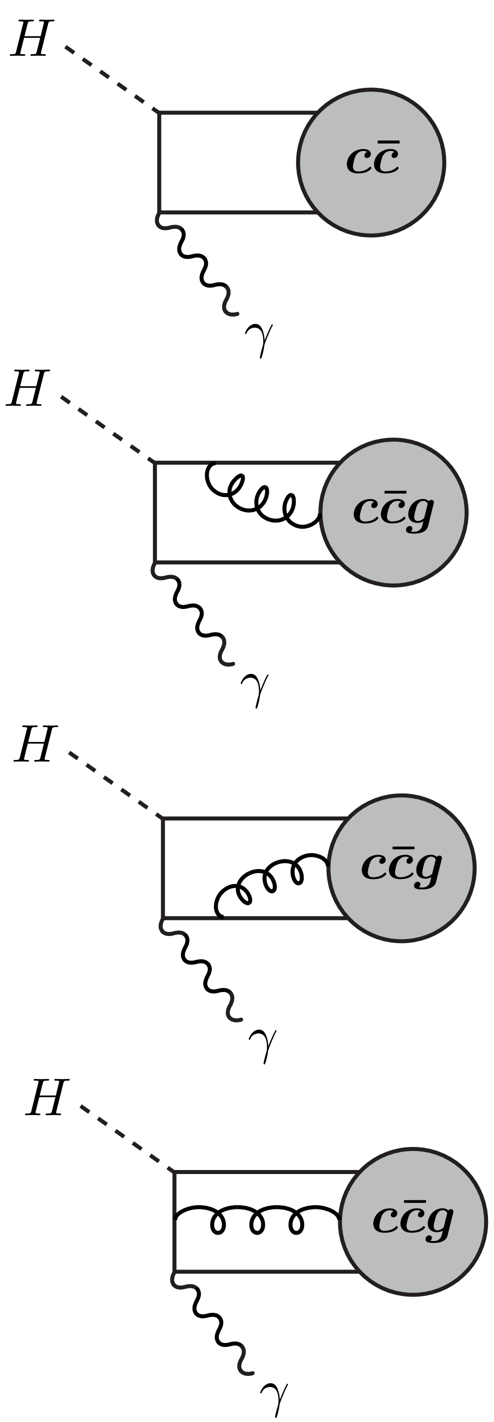
DIRECT AMPLITUDE TO RELATIVE ORDER v^4

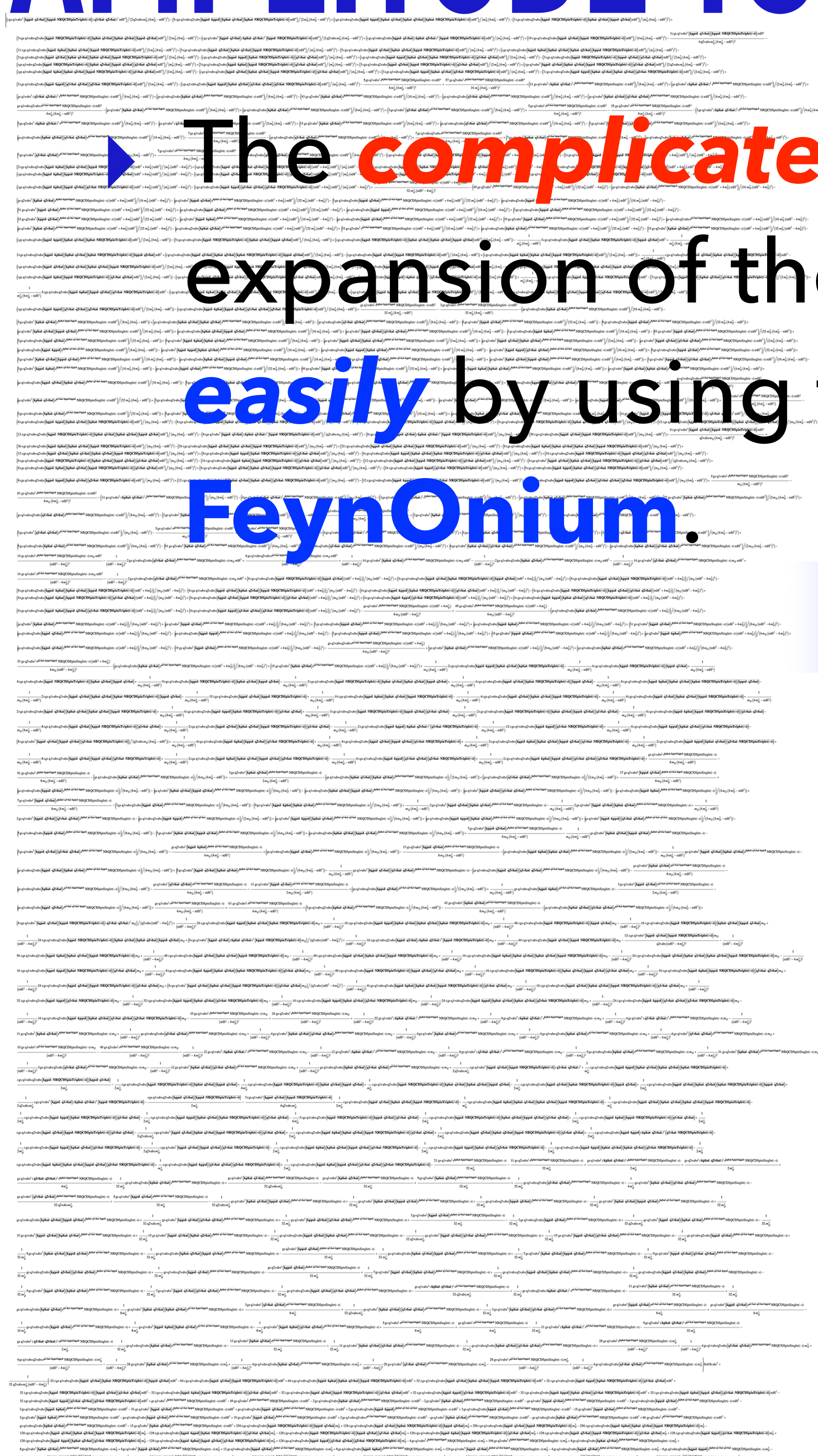
- Short-distance coefficients are computed by matching perturbative QCD and NRQCD amplitudes order by order in the velocity expansion.
- Computation of matching conditions to relative order v^4 requires calculation of $\boldsymbol{H \to c\bar{c}} + \gamma$ and $\boldsymbol{H \to c\bar{c}g} + \gamma$ amplitudes.

$$\mathcal{A}_{\rm QCD}[H \to c\bar{c}(g) + \gamma] - \mathcal{A}_{\rm NRQCD}[H \to c\bar{c}(g) + \gamma]$$
$$= \mathcal{A}_{\rm QCD}[H \to c\bar{c}(g) + \gamma] - \sum_n \frac{c_n}{m^{d_n - 3}} \langle c\bar{c}(g)|\mathcal{O}_n|0\rangle = 0$$

- Nonrelativistic expansion and rearrangement of the QCD amplitude in terms of J^{PC} involve a *huge amount* of algebra.

DIRECT AMPLITUDE TO RELATIVE ORDER v^4





- The ***complicated and tedious*** nonrelativistic expansion of the QCD amplitude can be done ***easily*** by using the FeynCalc package **FeynOnium**.

$$\left\{c0 \to -i,\ c2 \to \frac{i\,\mathrm{mH}^2}{2\left(\mathrm{mH}^2-4\,m_Q^2\right)} - \frac{14\,i\,m_Q^2}{3\left(\mathrm{mH}^2-4\,m_Q^2\right)},\ c2T \to -\frac{3\,i\,\mathrm{mH}^2}{10\left(\mathrm{mH}^2-4\,m_Q^2\right)} - \frac{34\,i\,m_Q^2}{5\left(\mathrm{mH}^2-4\,m_Q^2\right)},\right.$$

$$c4 \to \frac{11\,i\,\mathrm{mH}^2\,m_Q^2}{3\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} - \frac{98\,i\,m_Q^4}{5\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} - \frac{43\,i\,\mathrm{mH}^4}{120\left(\mathrm{mH}^2-4\,m_Q^2\right)^2},$$

$$c4T \to \frac{i\,\mathrm{mH}^2\,m_Q^2}{35\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} - \frac{258\,i\,m_Q^4}{7\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} + \frac{83\,i\,\mathrm{mH}^4}{280\left(\mathrm{mH}^2-4\,m_Q^2\right)^2},$$

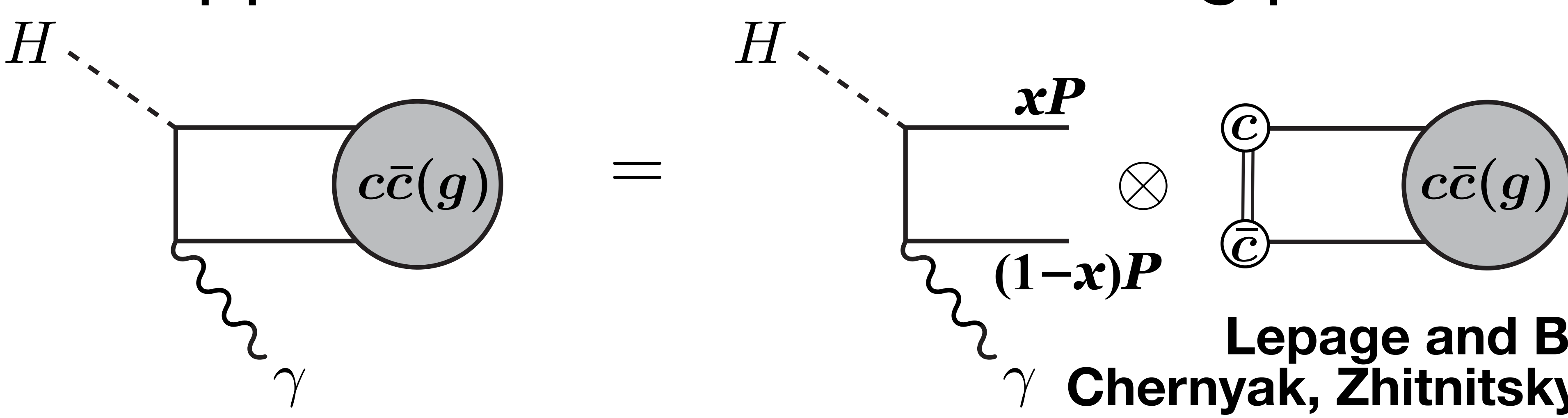
$$cB \to -i,\ cDE0 \to -\frac{6\,i\,\mathrm{mH}^2\,m_Q^2}{\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} + \frac{20\,i\,m_Q^4}{\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} + \frac{3\,i\,\mathrm{mH}^4}{4\left(\mathrm{mH}^2-4\,m_Q^2\right)^2},$$

$$cDE1 \to -\frac{2\,i\,\mathrm{mH}^2\,m_Q^2}{\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} + \frac{10\,i\,m_Q^4}{\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} + \frac{3\,i\,\mathrm{mH}^4}{8\left(\mathrm{mH}^2-4\,m_Q^2\right)^2},\ cDE1p \to \frac{5\,i\,\mathrm{mH}^2}{4\left(\mathrm{mH}^2-4\,m_Q^2\right)} - \frac{2\,i\,m_Q^2}{\mathrm{mH}^2-4\,m_Q^2},$$

$$\left.cDE2 \to -\frac{3\,i\,\mathrm{mH}^2\,m_Q^2}{5\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} + \frac{14\,i\,m_Q^4}{\left(\mathrm{mH}^2-4\,m_Q^2\right)^2} - \frac{9\,i\,\mathrm{mH}^4}{40\left(\mathrm{mH}^2-4\,m_Q^2\right)^2}\right\}$$

DIRECT AMPLITUDE : RESUMMATION

- In fixed-order perturbation theory, large logarithms of $m_{\rm Higgs}/m_c$ appear at higher orders in α_s.
- The logarithms can be resummed using the light-cone approach that is valid at leading power in $m_c/m_{\rm Higgs}$.



LCDA $\phi(x, m_c, \mu)$

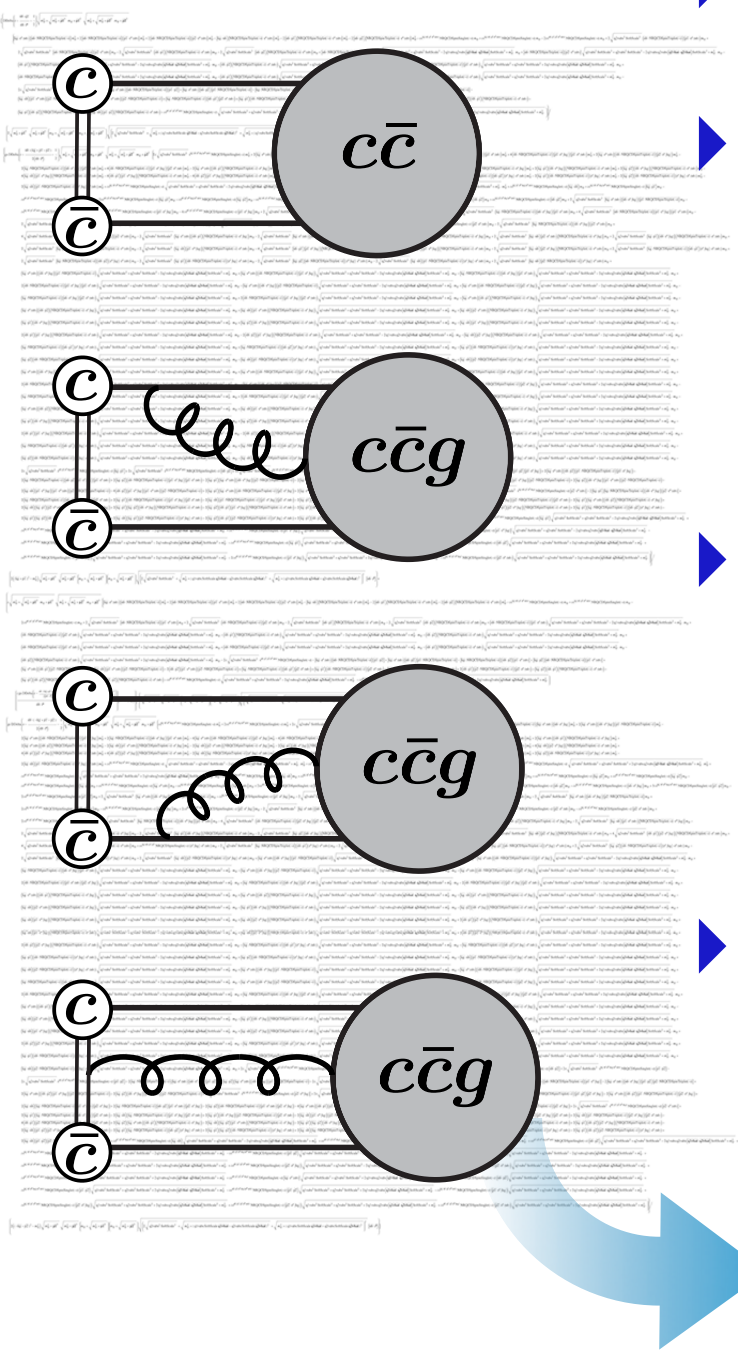
Lepage and Brodsky, PRD22, 2157 (1980)
Chernyak, Zhitnitsky, Phys.Rept.112, 173 (1984)

Hard part $T_H(x, m_{\rm Higgs}, \mu)$

- Resummation is achieved by solving the ERBL evolution equation for the LCDA.

Efremov and Radyushkin, PLB94, 245 (1980)
Lepage and Brodsky, PRD22, 2157 (1980)

DIRECT AMPLITUDE : RESUMMATION



- Hard part is available to NLO in α_s.
  X.-P. Wang, D. Yang, JHEP 1406 (2014) 121
- The J/ψ LCDA have been computed in NRQCD to relative order α_s and relative order v^2 accuracy.
  X.-P. Wang, D. Yang, JHEP 1406 (2014) 121
  Braguta, PRD75 (2007) 094016
  Bodwin, HSC, Ee, Lee, Petriello, PRD90 (2014) 113010
- To obtain order-v^4 corrections to LCDA we need ***light-cone*** calculations involving ***nonrelativistic*** $c\bar{c}$ and $c\bar{c}g$ final states.
- This requires the same ***complicated and tedious*** nonrelativistic expansion like the fixed-order calculation which again can be done ***easily*** using **FeynOnium**.

DIRECT AMPLITUDE TO RELATIVE ORDER v^4

- Without resummation, we find ***complete agreement*** between fixed-order and light-cone calculations at leading power in $m_c/m_{\rm Higgs}$.
- We include order-α_s, order-v^2, and the ***newly calculated order-v^4*** corrections. We resum logarithms to NLL accuracy.
- Color singlet LDMEs are available from potential models.

Bodwin, HSC, Kang, Lee, Yu, PRD77 (2008) 094017

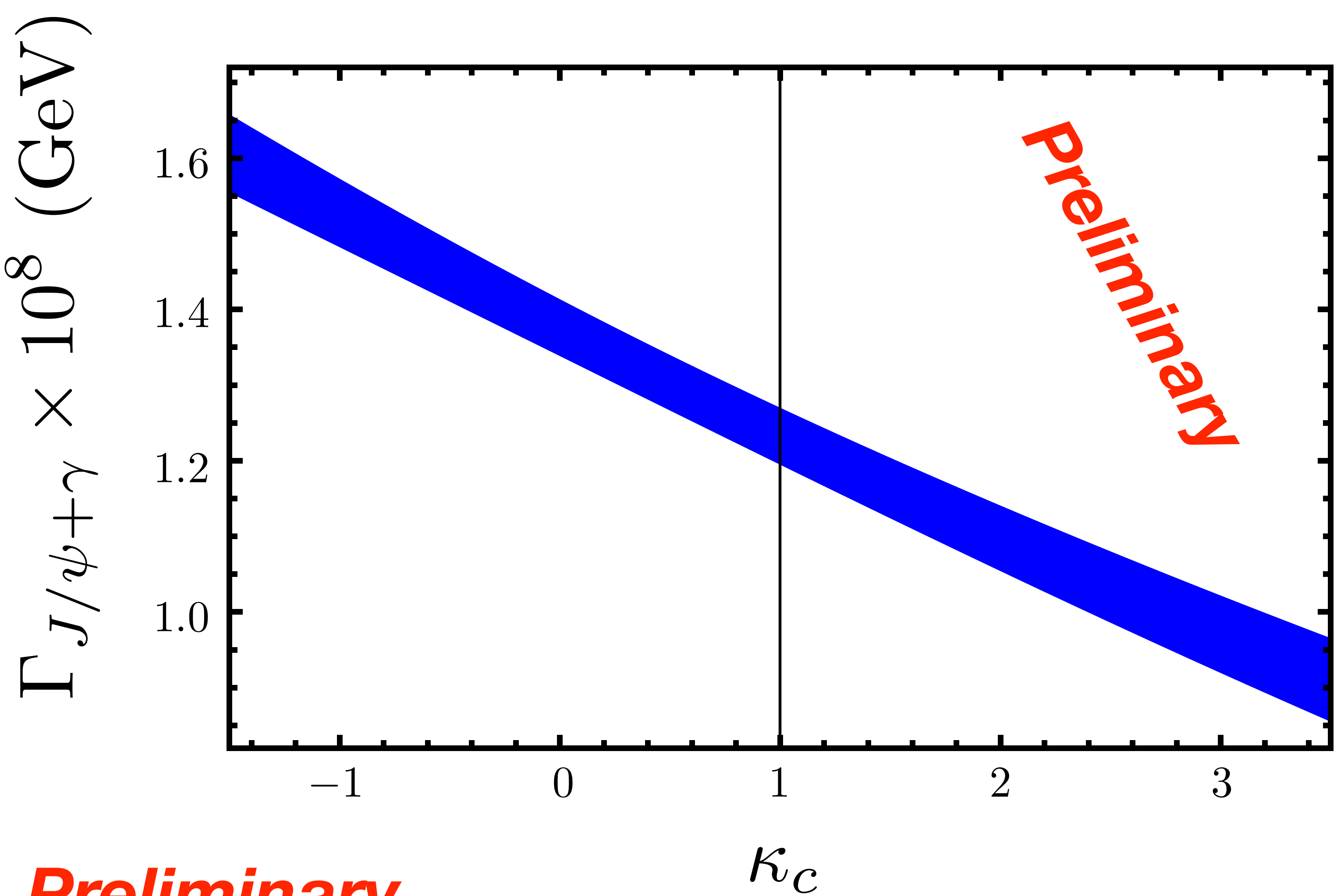
- Direct amplitude depends on two LDMEs yet to be determined : $\langle J/\psi|\psi^\dagger \epsilon^i(\lambda)\sigma^j(-\tfrac{i}{2})^2 \overleftrightarrow{\boldsymbol{D}}^{(i}\overleftrightarrow{\boldsymbol{D}}^{j)}\chi|0\rangle$

$$\langle J/\psi|\psi^\dagger \boldsymbol{\epsilon}(\lambda)\cdot\tfrac{1}{2}[\boldsymbol{\sigma}\times(\overleftrightarrow{\boldsymbol{D}}\times g_s\boldsymbol{E}-g_s\boldsymbol{E}\times\overleftrightarrow{\boldsymbol{D}})]\chi|0\rangle$$

DIRECT AMPLITUDE TO RELATIVE ORDER v^4

- Scale variations give uncertainty of about 9%.
- Uncertainty from the LDMEs is about 8% :
  - LDMEs computed using potential models contain uncertainties from potential-model parameters and experimental input. **Bodwin, HSC, Kang, Lee, Yu, PRD77 (2008) 094017**
  - Uncertainties from yet-to-be-computed LDMEs are estimated using their velocity-scaling rules.
- Uncertainty in the direct amplitude is about 13%.
- Order-α_s^2 and $\alpha_s v^2$ corrections may reduce scale uncertainty.

HIGGS DECAYS TO QUARKONIUM + PHOTON



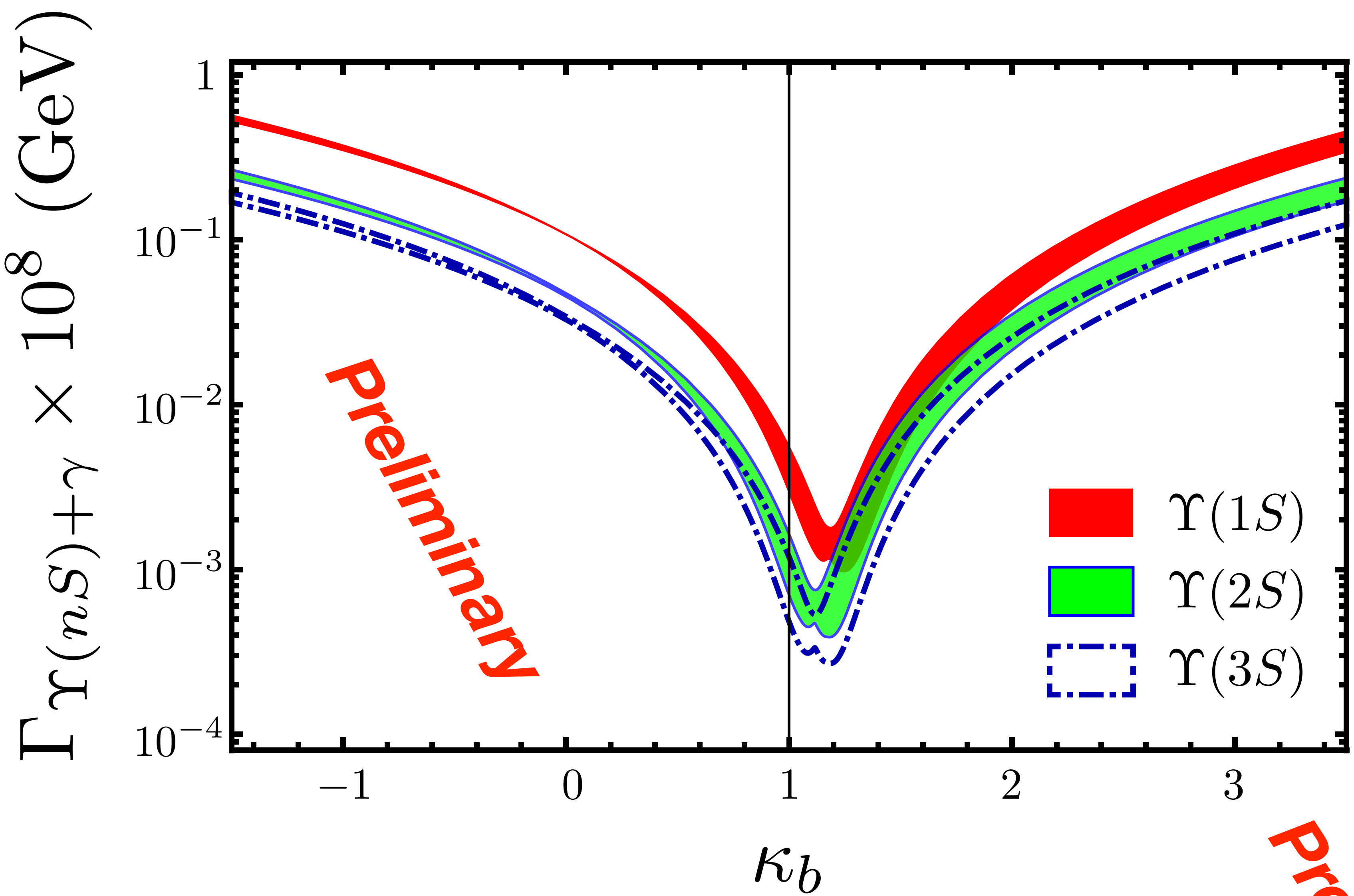
Preliminary

$$\Gamma(H \to J/\psi + \gamma)_{\rm SM} = 12.31^{+0.38}_{-0.37}\ \rm eV$$

$$\mathrm{Br}(H \to J/\psi + \gamma)_{\rm SM} = (3.01 \pm 0.15) \times 10^{-6}$$

- SM branching ratio is obtained with 5% uncertainty.
- Compatible with previous results but uncertainty is reduced.
- If κ_c=+6.2 (−6.2), branching ratio would be half (twice) the SM value.

HIGGS DECAYS TO QUARKONIUM + PHOTON



- If $\kappa_b \approx -1$, the branching fractions are 2 orders of magnitude larger than the SM values.

nS	$\mathrm{Br}(H \to \Upsilon(nS) + \gamma)$
$1S$	$(9.97^{+4.04}_{-3.03}) \times 10^{-9}$
$2S$	$(2.62^{+1.39}_{-0.91}) \times 10^{-9}$
$3S$	$(1.87^{+1.05}_{-0.69}) \times 10^{-9}$

Preliminary

- When $\kappa_b \approx 1$, direct and indirect amplitudes almost cancel.

PROSPECTS AT THE LHC

- Current upper limit for $H \to J/\psi + \gamma$ at the LHC is about *2 orders of magnitude* larger than expected SM value.

95%CL upper limits for Br[$H \to J/\psi+\gamma$]

ATLAS : $3.5\times10^{-4} \approx 110 \times \mathrm{Br}_{\mathrm{SM}}[H \to J/\psi+\gamma]$
PLB 786 (2018) 134

CMS : $7.6\times10^{-4} \approx 260 \times \mathrm{Br}_{\mathrm{SM}}[H \to J/\psi+\gamma]$
EPJC 79 (2019) 94

- At HL-LHC, 3000 fb^{-1} of data is expected to give 95% CL upper limit for $\mathrm{Br}[H \to J/\psi+\gamma]$ of about *15 times* the SM expectation.

ATL-PHYS-PUB-2015-043

PROSPECTS AT THE LHC

- On the other hand, current limit for the yield $\sigma(pp \to ZH) \times \mathrm{Br}(H \to c\bar{c})$ through charm-jet tagging is about *110 times* the expected SM value.
  ATLAS, PRL120 (2018) 211802
- HL-LHC is expected to improve the limit to *6 times* the SM value.
  ATL-PHYS-PUB-2018-016
- 2×3000 fb^{-1} of data may provide an upper limit of $|\kappa_c| < 2.5 \sim 5.5$ at 95% CL.
  Perez, Soreq, Stamou, Tobioka, PRD93 (2016) 013001
- $pp \to Hc$ (through $gc \to Hc$) may also provide a comparable constraint of $|\kappa_c| < 2.6 \sim 3.9$ at 95% CL.
  Brivio, Goertz, Isidori, PRL115 (2015) 211801

SUMMARY AND OUTLOOK

- Higgs decay into $J/\psi+\gamma$ provides a way to probe the ***size*** and ***sign*** of the $Hc\bar{c}$ coupling.
- We computed relativistic corrections to this process up to relative order v^4 exploiting the capabilities of **FeynOnium**.
- Theoretical uncertainties seem to be under control.
- Prospect for a direct measurement of the $Hc\bar{c}$ coupling does not look so good even for HL-LHC
  — ***we need to produce more Higgs bosons.***

BACKUP

YUKAWA COUPLINGS

- Higgs decay into fermion pair is approximately proportional to the square of the Higgs-fermion coupling.
- Higgs decay into $J^{PC}=1^{--}$ quarkonium is sensitive to the ***size*** and ***sign*** of the Higgs-heavy quark coupling

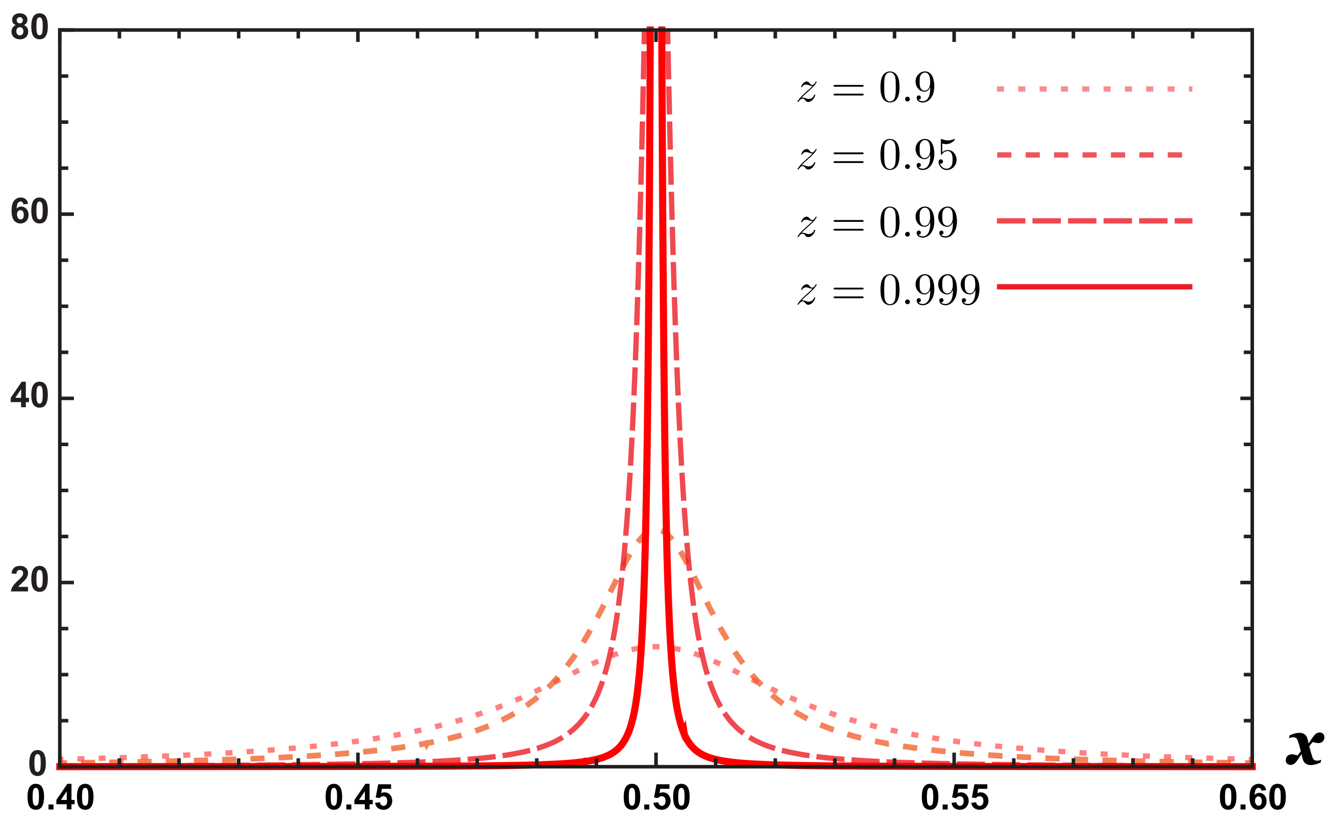
Process	Branching fraction
$H\to b\bar{b}$	0.58
$H\to\tau^+\tau^-$	6×10^{-2}
$H\to c\bar{c}$	3×10^{-2}
$H\to\mu^+\mu^-$	2×10^{-4}
$H\to J/\psi+\gamma$	$\sim3\times10^{-6}$
$H\to\Upsilon+\gamma$	$\sim10^{-8}$
$H\to h_c+\gamma$	$\sim10^{-9}$

Handbook of LHC Higgs Cross Sections: 3. Higgs Properties arXiv:1307.1347 [hep-ph]
Bodwin, Petriello, Stoynev, Velasco, PRD88 (2013) 053003
Mao, Guo-He, Gang, Yu, Jian-You, arXiv:1905.01589

RESUMMATION OF LOGARITHMS

- Resummation of logarithms is done by solving an evolution equation for LCDA. Formal solution to the evolution equation is found in terms of Gegenbauer polynomials.

$$\phi(x) = \sum_n \phi_n C_n^{(3/2)}(2x-1)$$



Gegenbauer expansion of δ(x-1/2) as z→1

- Expansion of sharply peaked distributions lead to divergent series. We define them as Abel sums.

$$\phi(x) = \lim_{z\to 1} \sum_n z^n \phi_n C_n^{(3/2)}(2x-1)$$

- Values of Abel sums can be computed efficiently using Padé approximants.

Bodwin, HSC, Ee, Lee, PRD95 (2017) 054018