HIGGS POTENTIAL 2024

HIGGS POTENTIAL AND BSM OPPORTUNITIES

Outlining the Shape of the Higgs Potential

Based on
Phys. Rev. D 96 (2017) 095031 in collaboration with Qing-Hong Cao, Gang Li, Bin Yan, and Dong-Ming Zhang,
Phys. Rev. D 107 (2023) 055031 in collaboration with Kangyu Chai and Jiang-Hao Yu,
Phys. Rev. D 107 (2023) 055040 in collaboration with Qing-Hong Cao, Kun Cheng, Yandong Liu, Xin-Kai Wen, and Changlong Xu

Hao Zhang

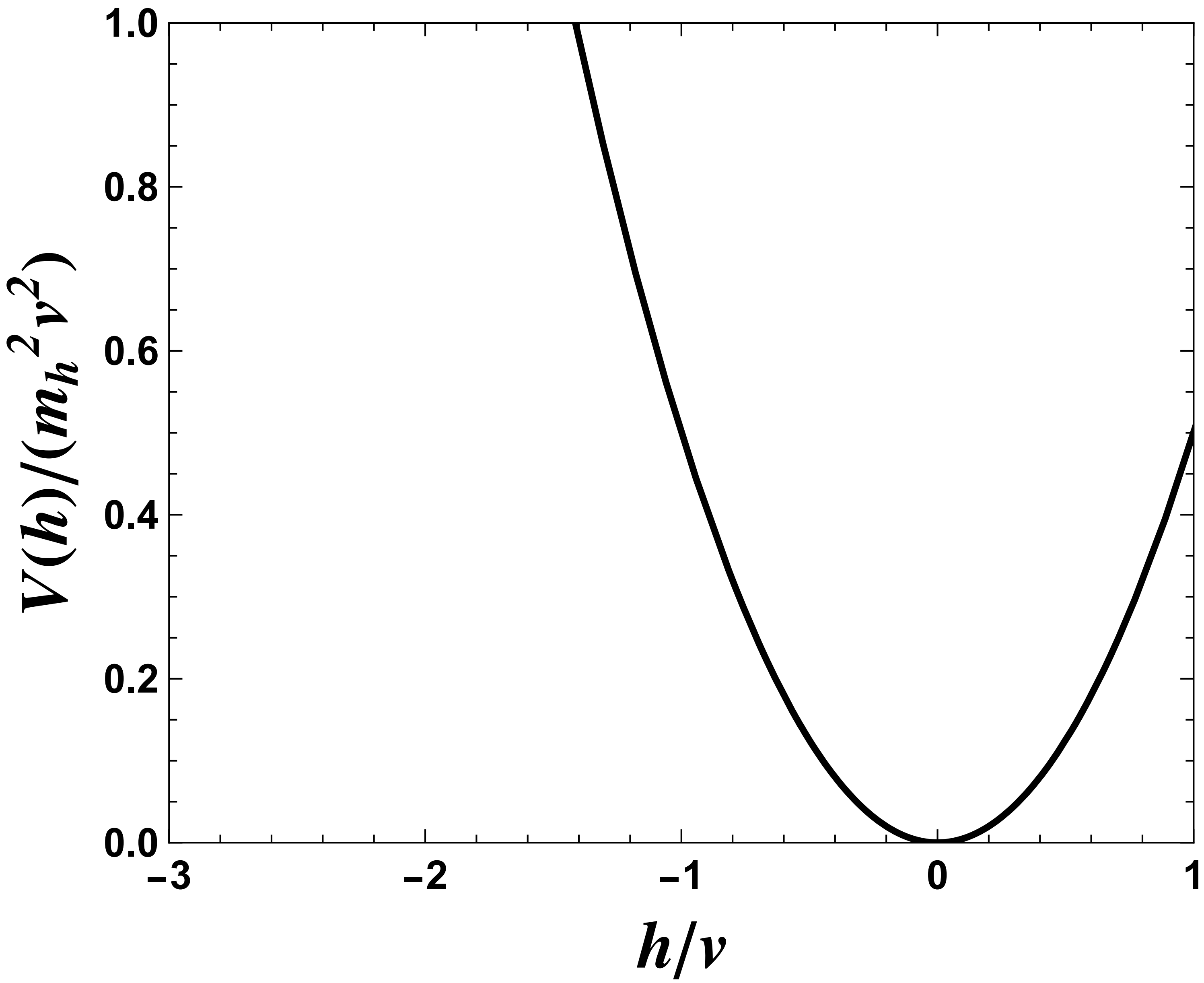
Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences
For "HIGGS POTENTIAL 2024", Dec 21st 2024

The Potential

The Potential

- A free scalar field whose mass is 125GeV.

$$V(h) = \frac{1}{2} m_h^2 h^2$$

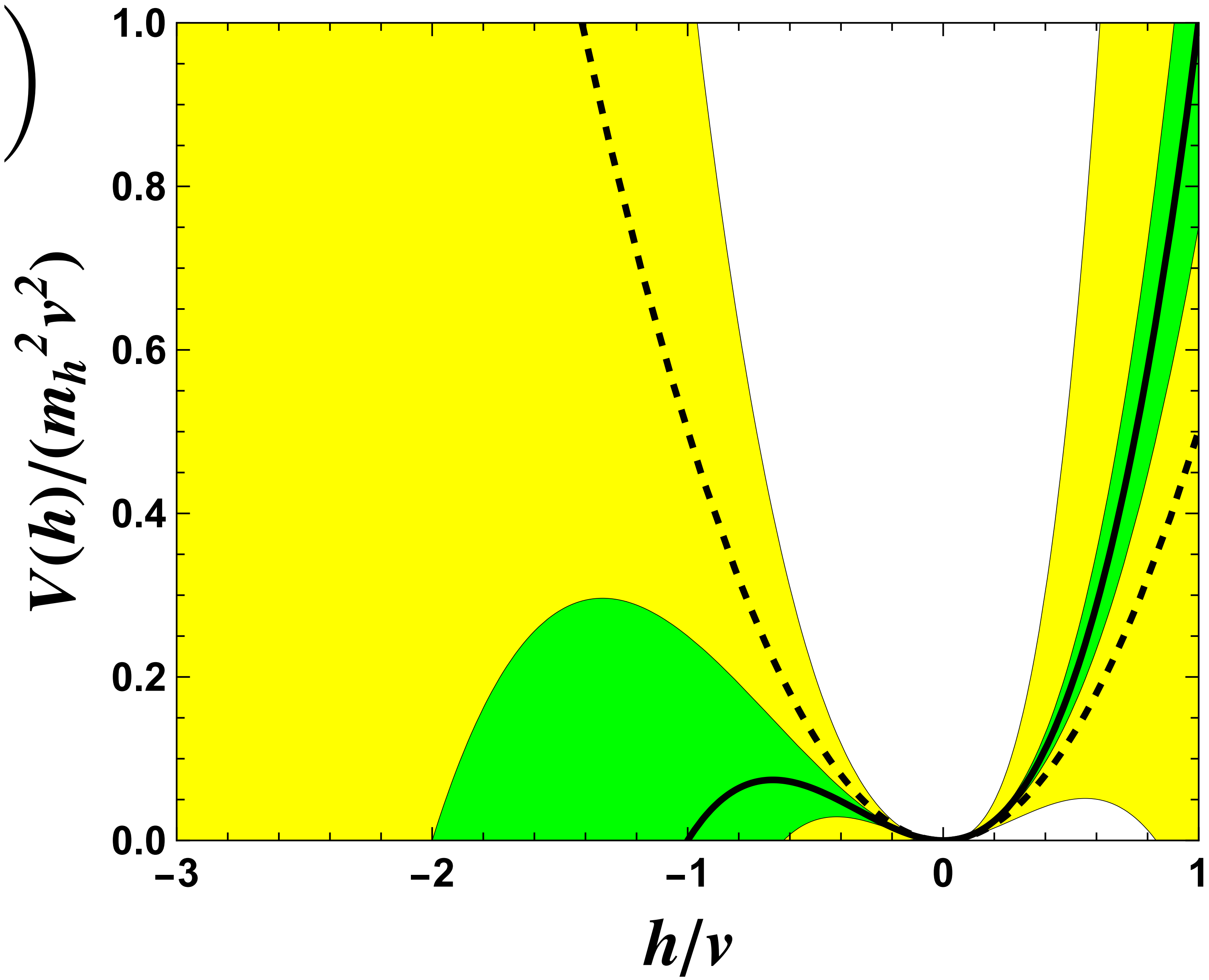


The Potential

- Allowed region of the cubic potential by current Higgs pair data.

$$V(h) = \frac{1}{2}m_h^2\left(h^2 + \frac{\kappa_\lambda}{v}h^3\right)$$

$$\kappa_\lambda \in [-1.2,\ 7.02]$$



ATLAS Collaboration, Phys. Rev. Lett. 133 (2024) 101801;
CMS Collaboration, CMS PAS HIG-20-011.

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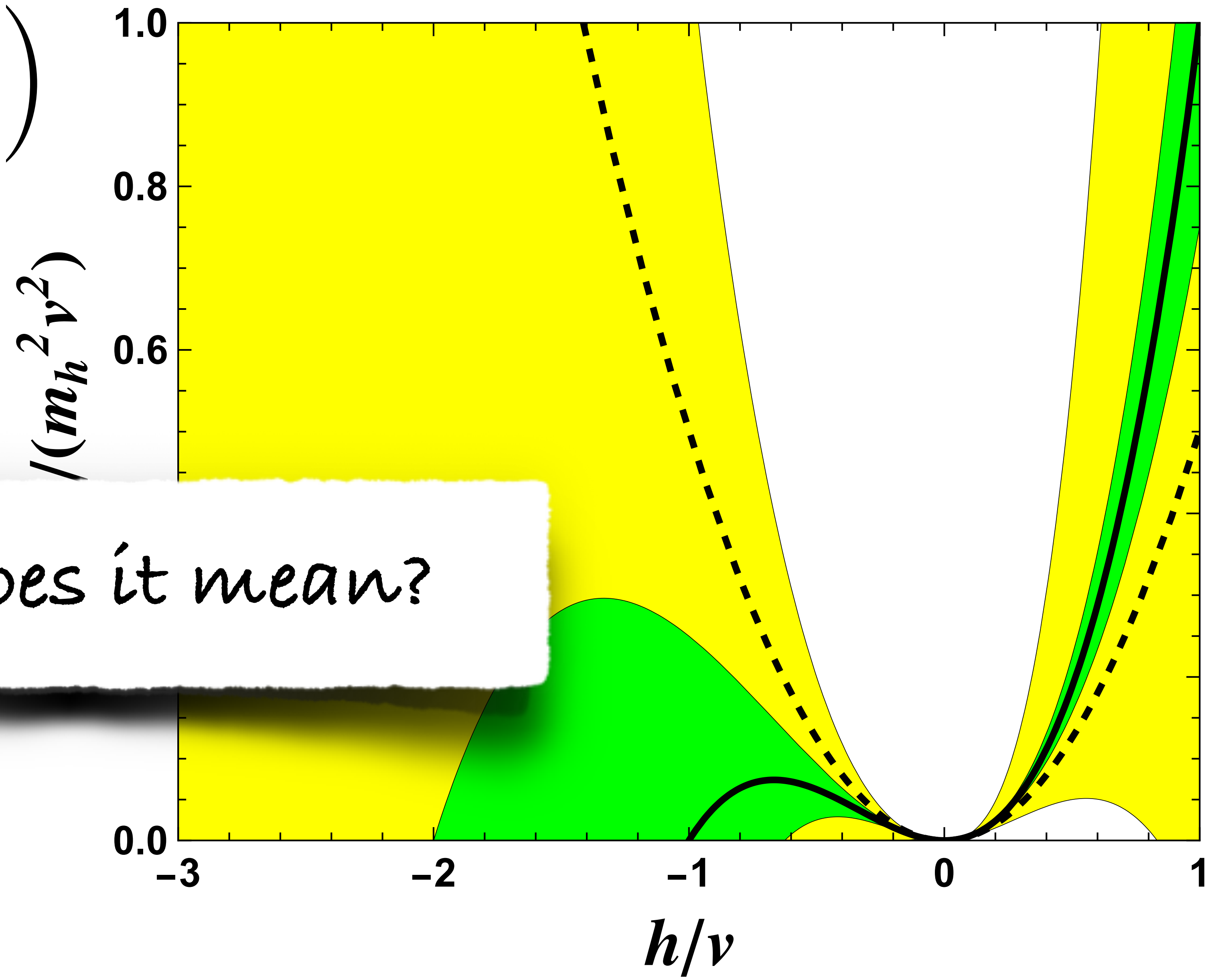

What does it mean?

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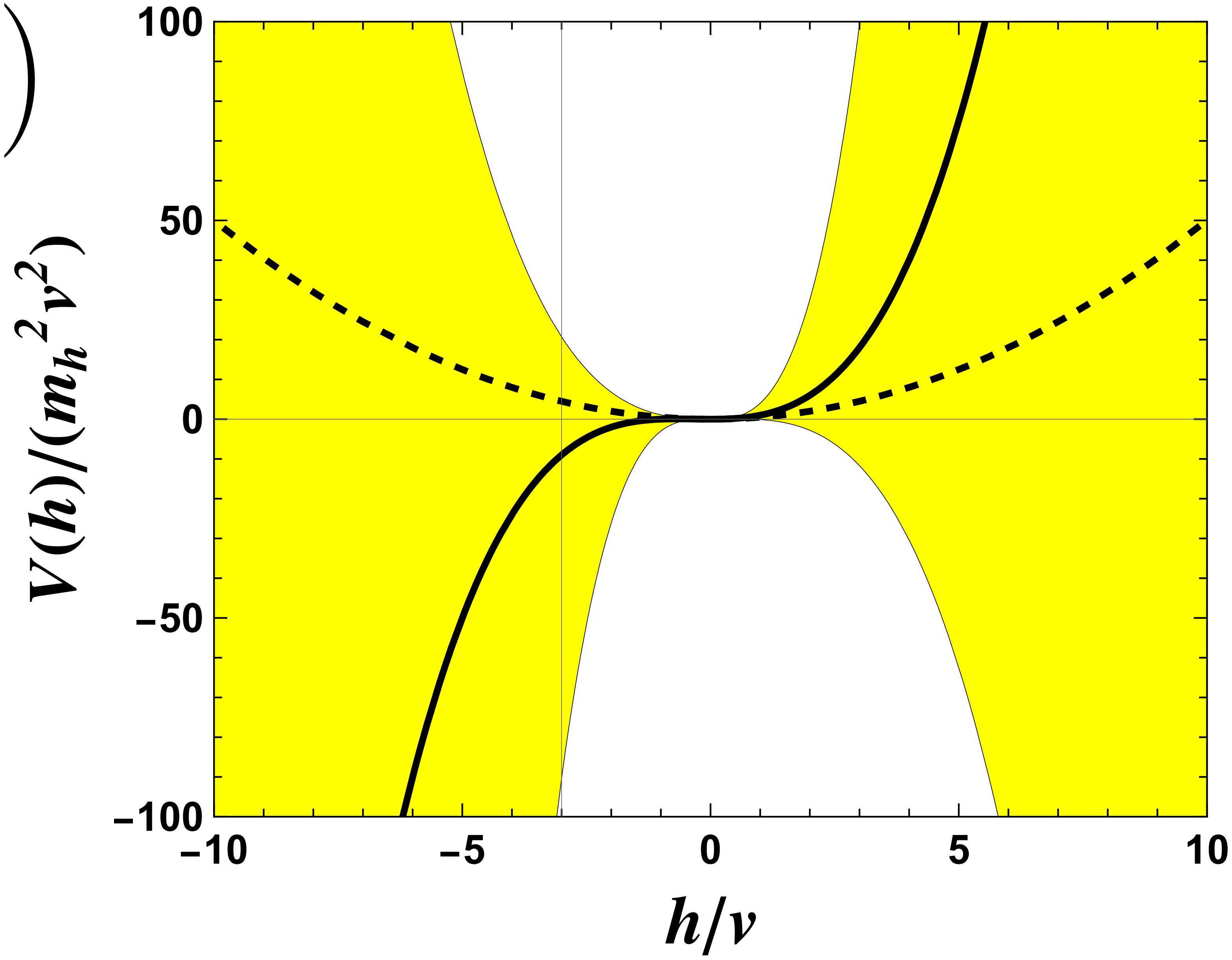

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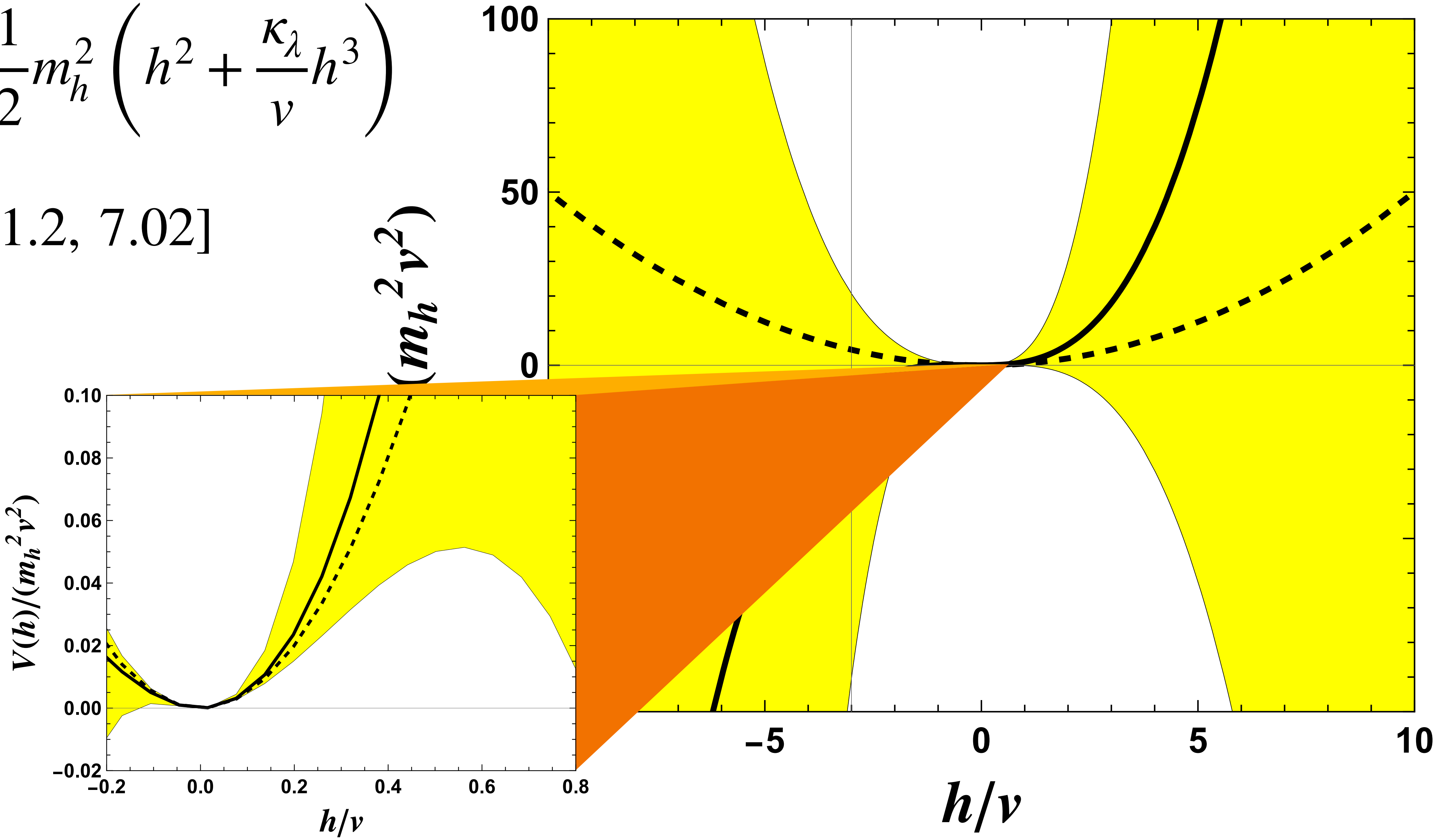

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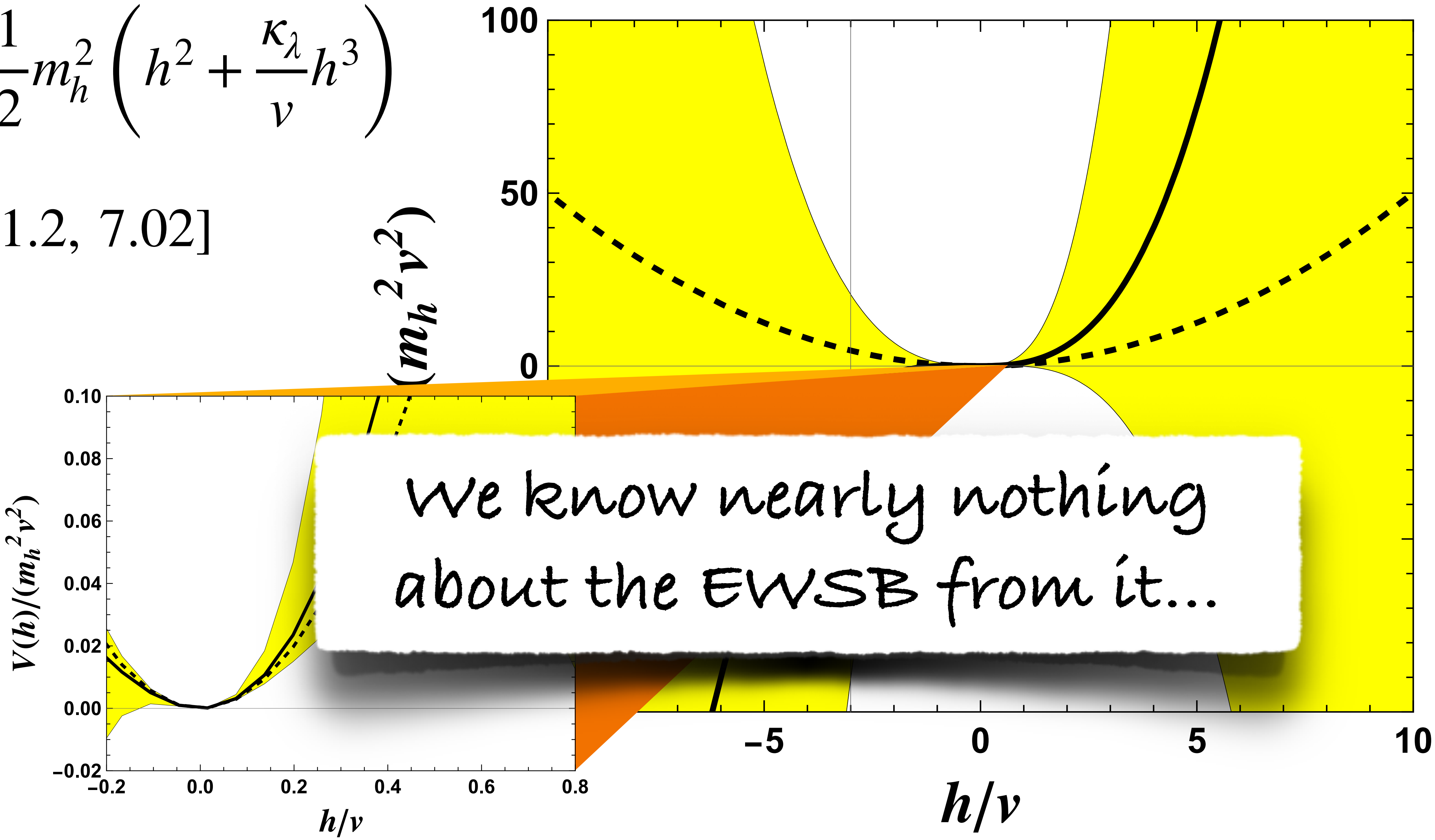

ATLAS Collaboration, Phys. Rev. Lett. 133 (2024) 101801;
CMS Collaboration, CMS PAS HIG-20-011.

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- (Expected) Allowed region of the cubic potential by HL-LHC.

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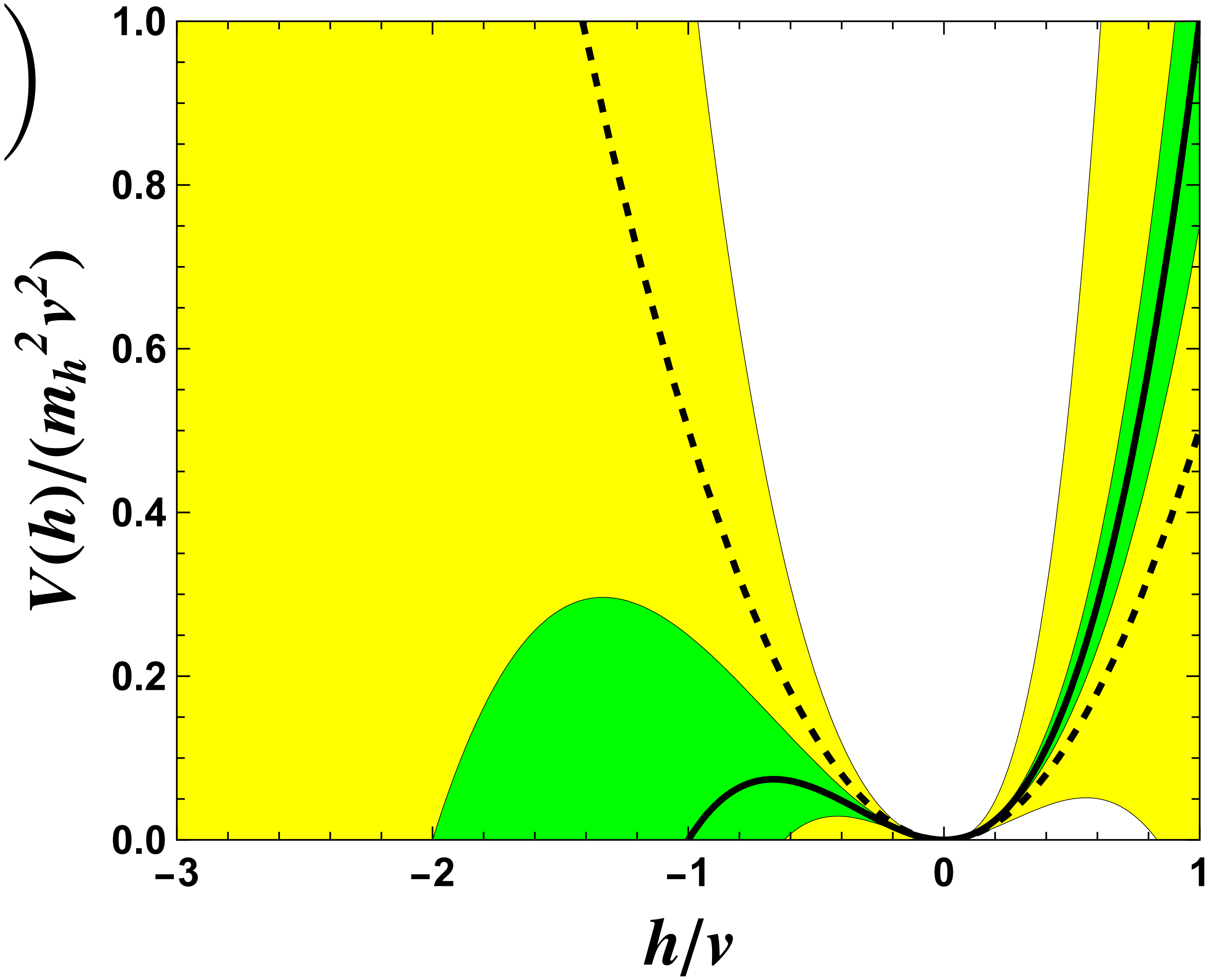


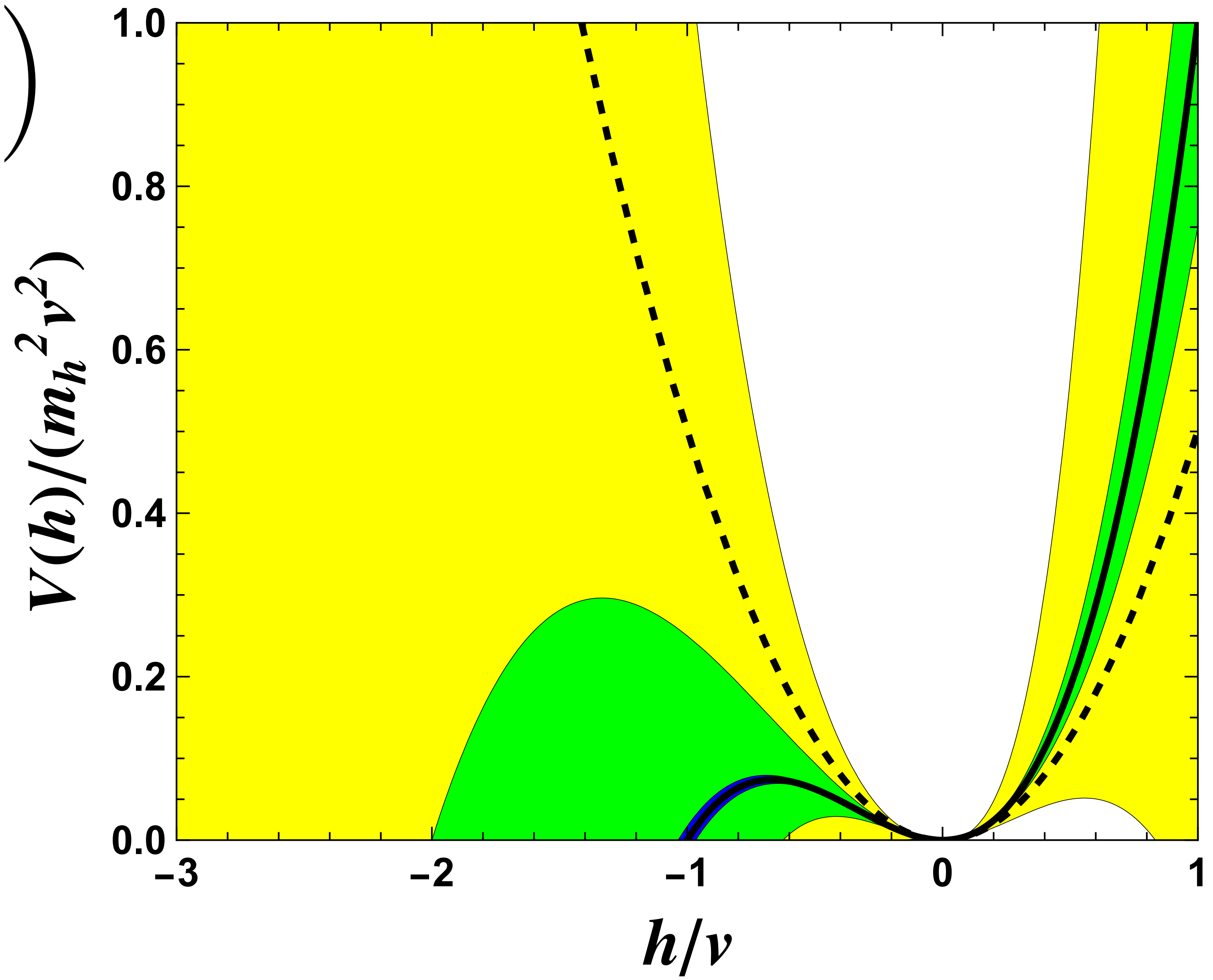
M. Mlynarikova, on behalf of the ATLAS and CMS collaborations, arXiv:2307.07772[hep-ex].

The Potential

- (Expected) Allowed region of the cubic potential by FCC-hh.

$$V(h) = \frac{1}{2}m_h^2\left(h^2 + \frac{\kappa_\lambda}{v}h^3\right)$$

$$\kappa_\lambda \in [0.966,\ 1.034]$$



A. Abada, et. al., FCC-hh: The Hadron Collider, Eur. Phys. J. Special Topics 228 (2019) 755.

The Potential

- (Expected) Allowed region of the cubic potential by FCC-hh.

When?

The tentative timeline is:

- **2025**: Completion of the FCC Feasibility Study
- **2027–2028**: Decision by the CERN Member States and international partners
- **2030s**: Start of construction
- **Mid-2040s**: **FCC-ee** begins operation and runs for approximately 15 years
- **2070s**: **FCC-hh** begins operation and runs for approximately 25 years

https://home.cern/science/accelerators/future-circular-collider

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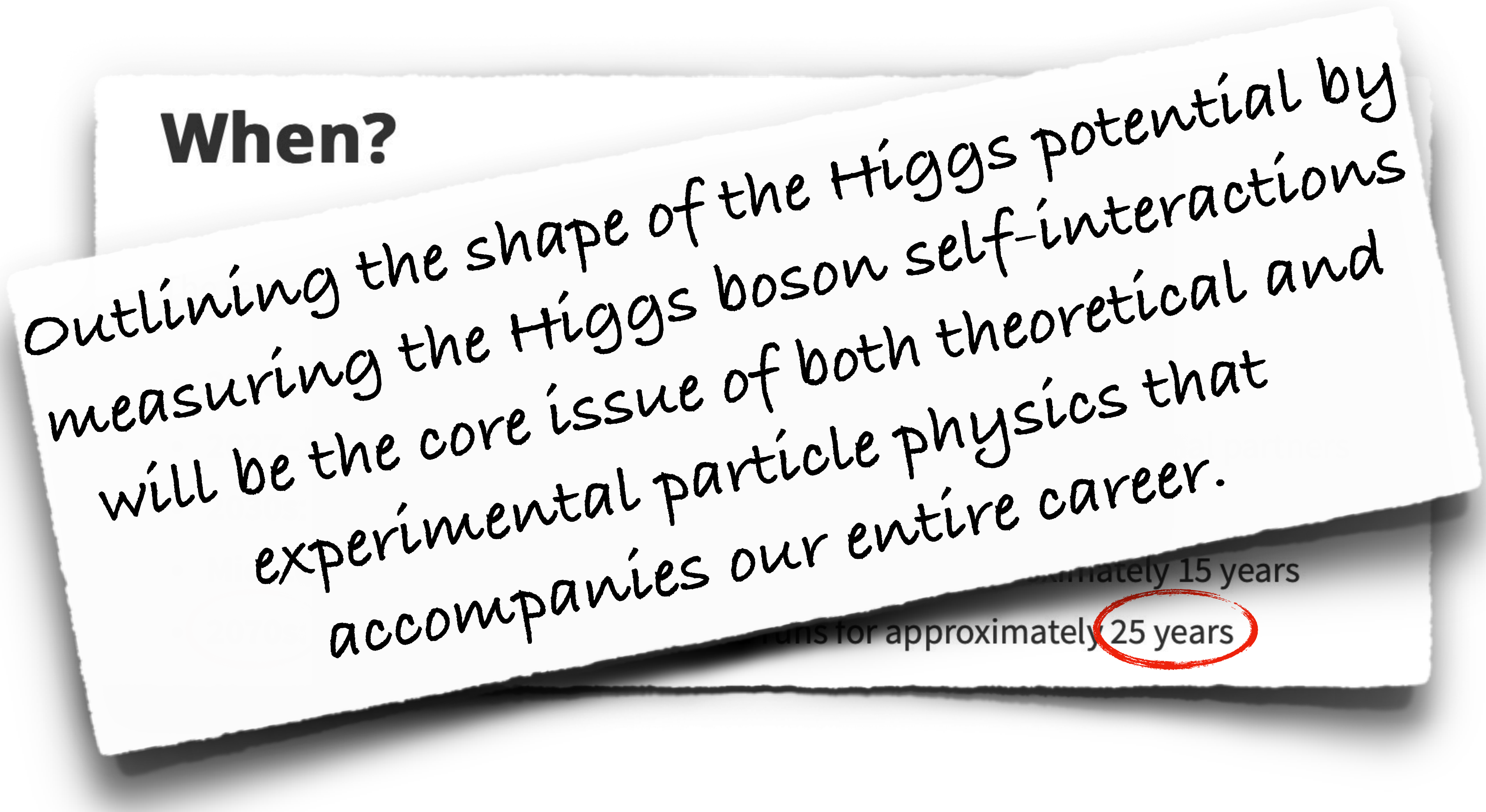

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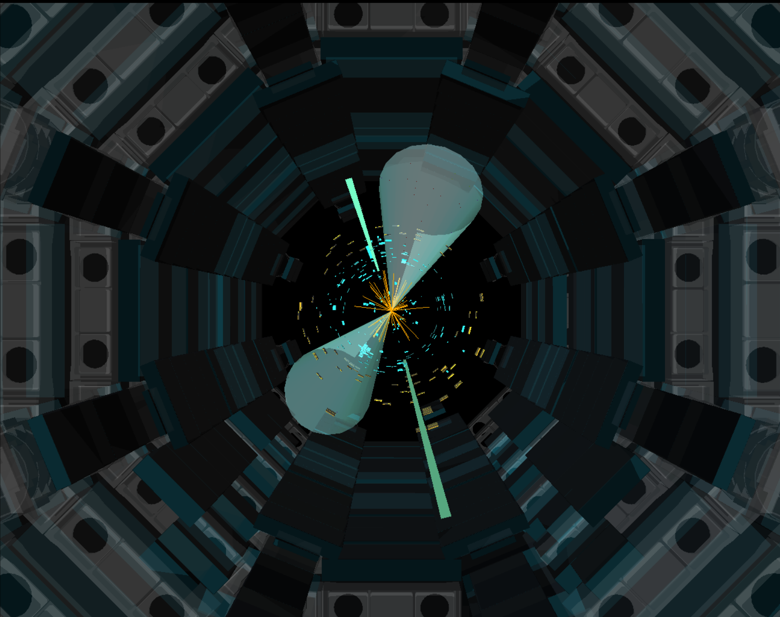
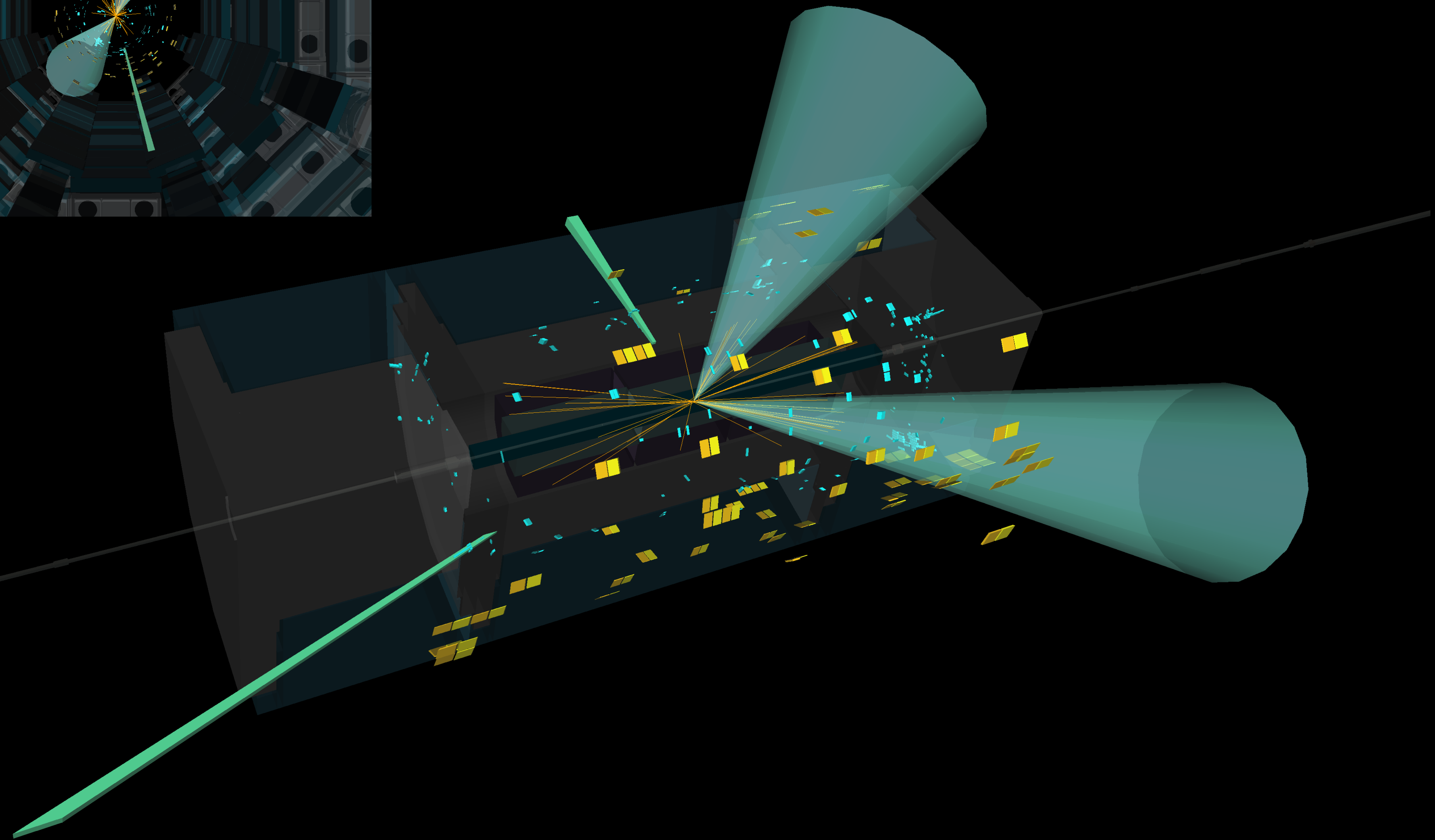
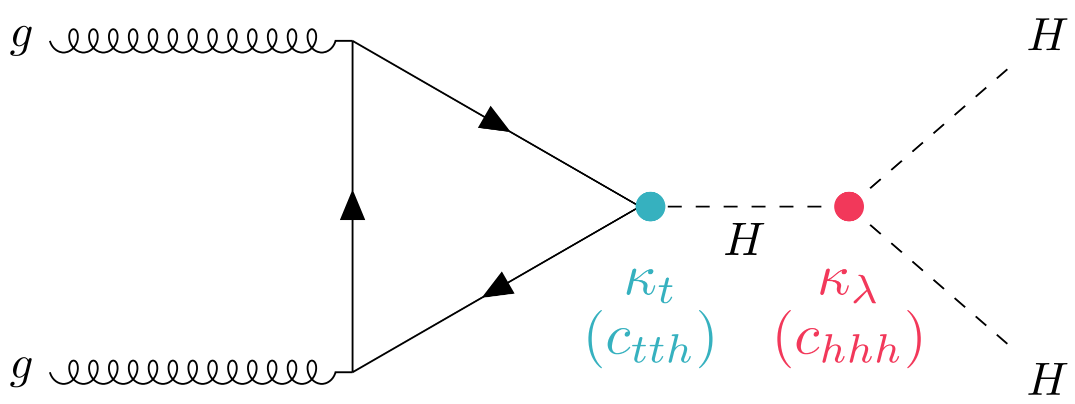


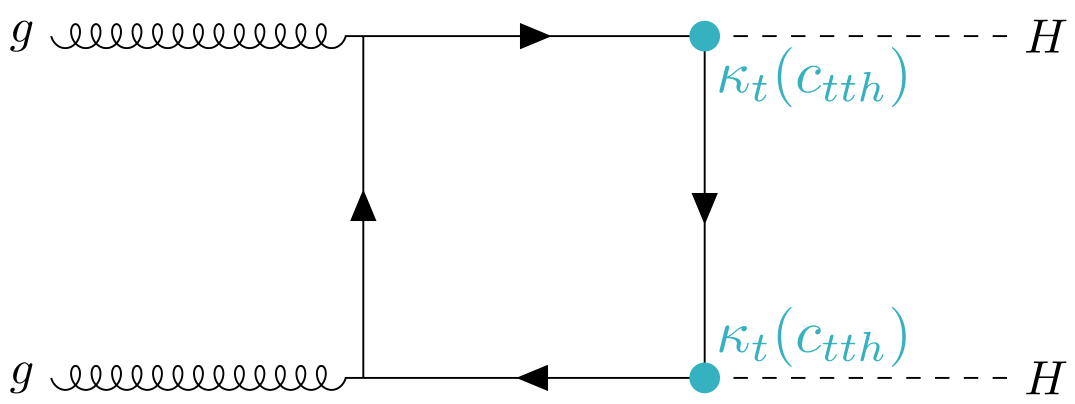


The Shape for the Shape

The Motivation

- The direct method to study the Higgs self-interaction: di-Higgs processes at colliders.
- Higgs self-interaction measurement at (hadron) colliders
- Gluon fusion channel: important and not easy.





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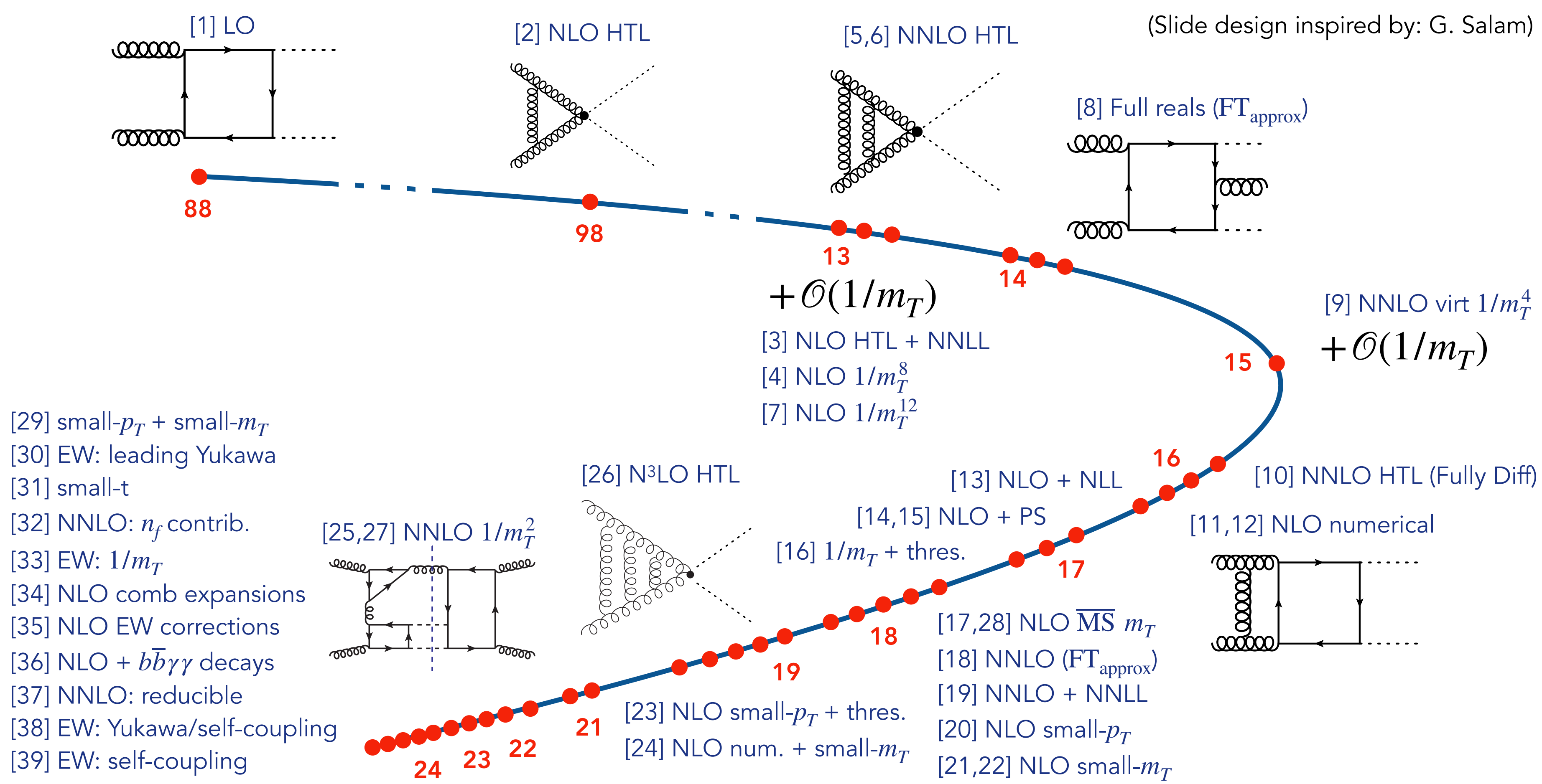

[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagnaschi, Degrassi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23 [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, SPJ, Kerner, Stone, Vestner [39] Li, Si, Wang, Zhang, Zhao 24

From S. Jones, "Higgs production: A theory overview", Higgs Hunting 2024.

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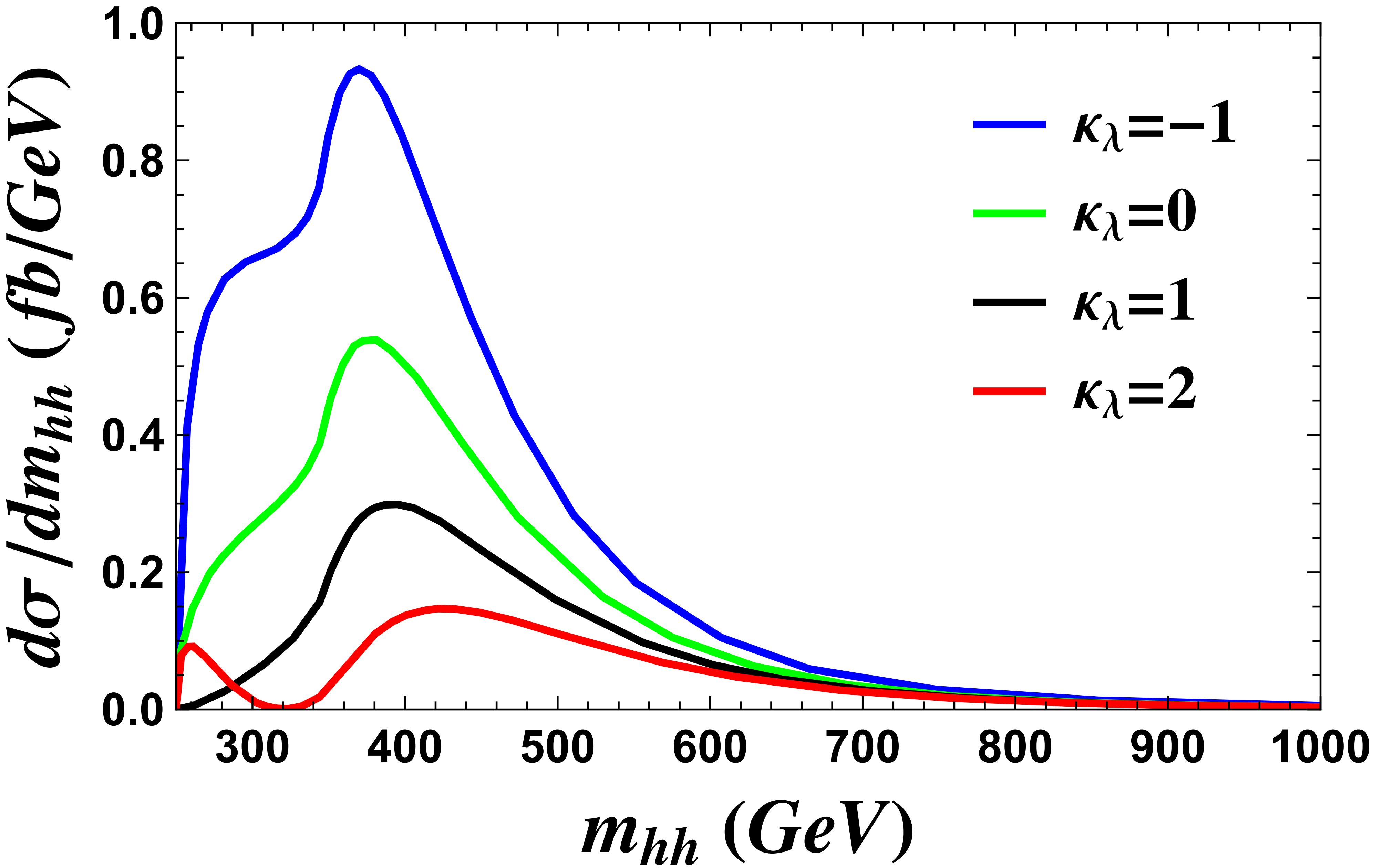
- The low mass ($m_{bb\gamma\gamma}$) region is important!



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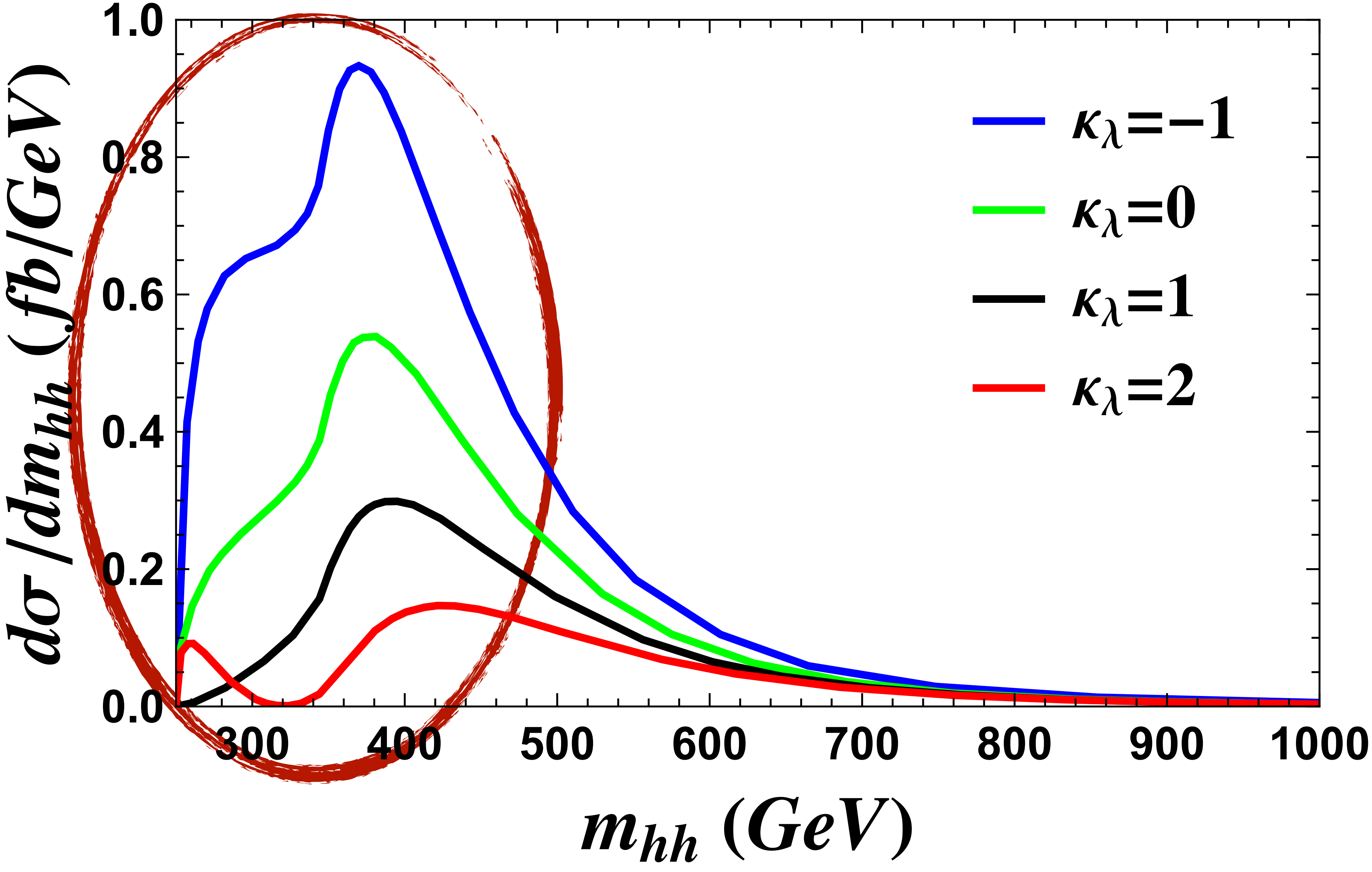

The Motivation

- Unfortunately, we have the SM backgrounds!
- In the traditional cut based analysis, a transverse momentum cut of the Higgs bosons is necessary.

$$
\begin{aligned}
m_{hh}^2 &= (p_1 + p_2)^2 \\
&= 2m_h^2 + 2p_1 \cdot p_2 = 2m_h^2 + 2(E_1E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2) \\
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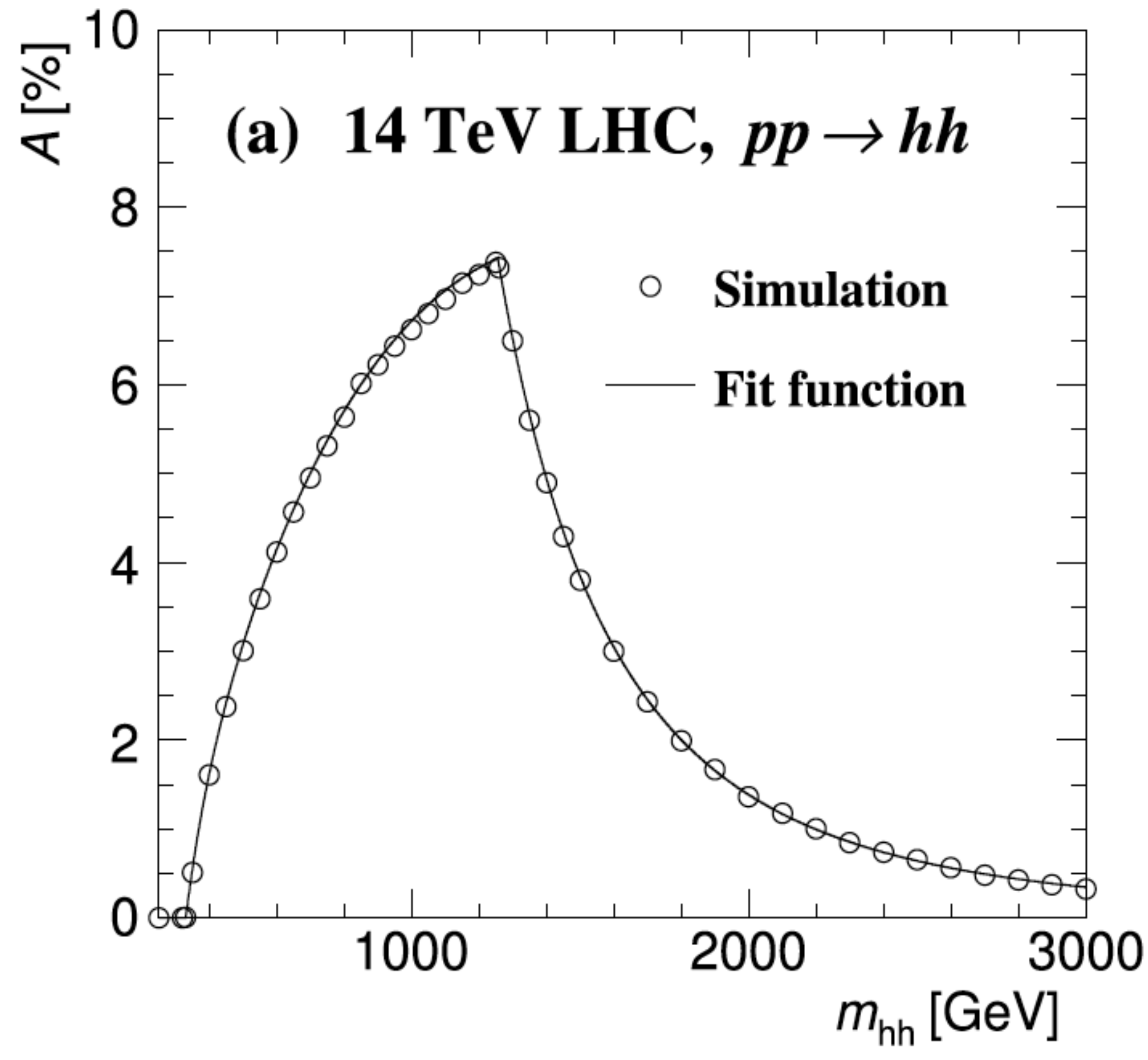
- For example, if we choose $p_{T,\mathtt{cut}} = 110\mathrm{GeV}$,

$$m_{hh} \geqslant 2\sqrt{125^2 + 110^2}\mathrm{GeV} = \mathbf{333GeV}$$

The Motivation

- The cut acceptance as a function of $m_{bb\gamma\gamma}$.



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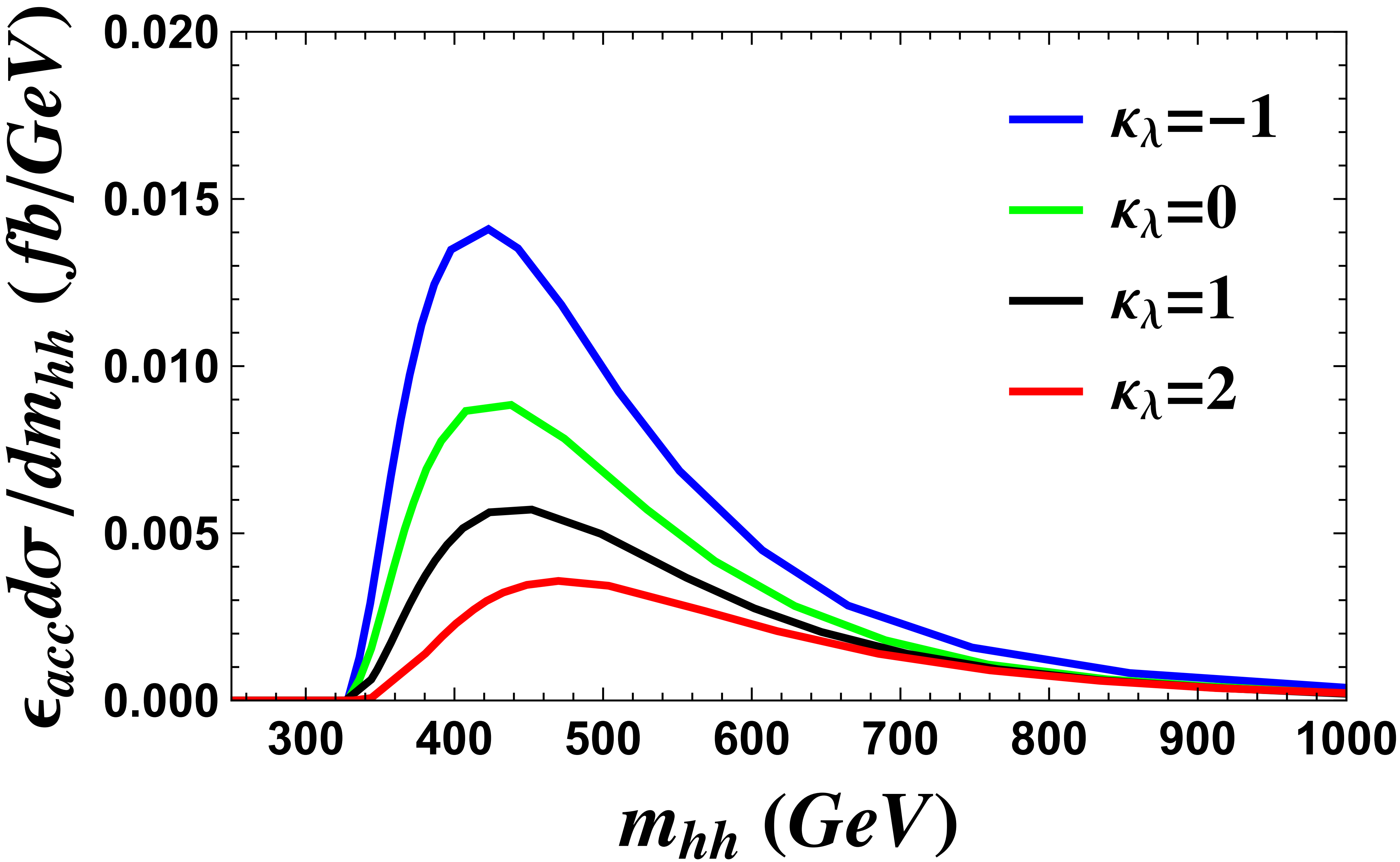

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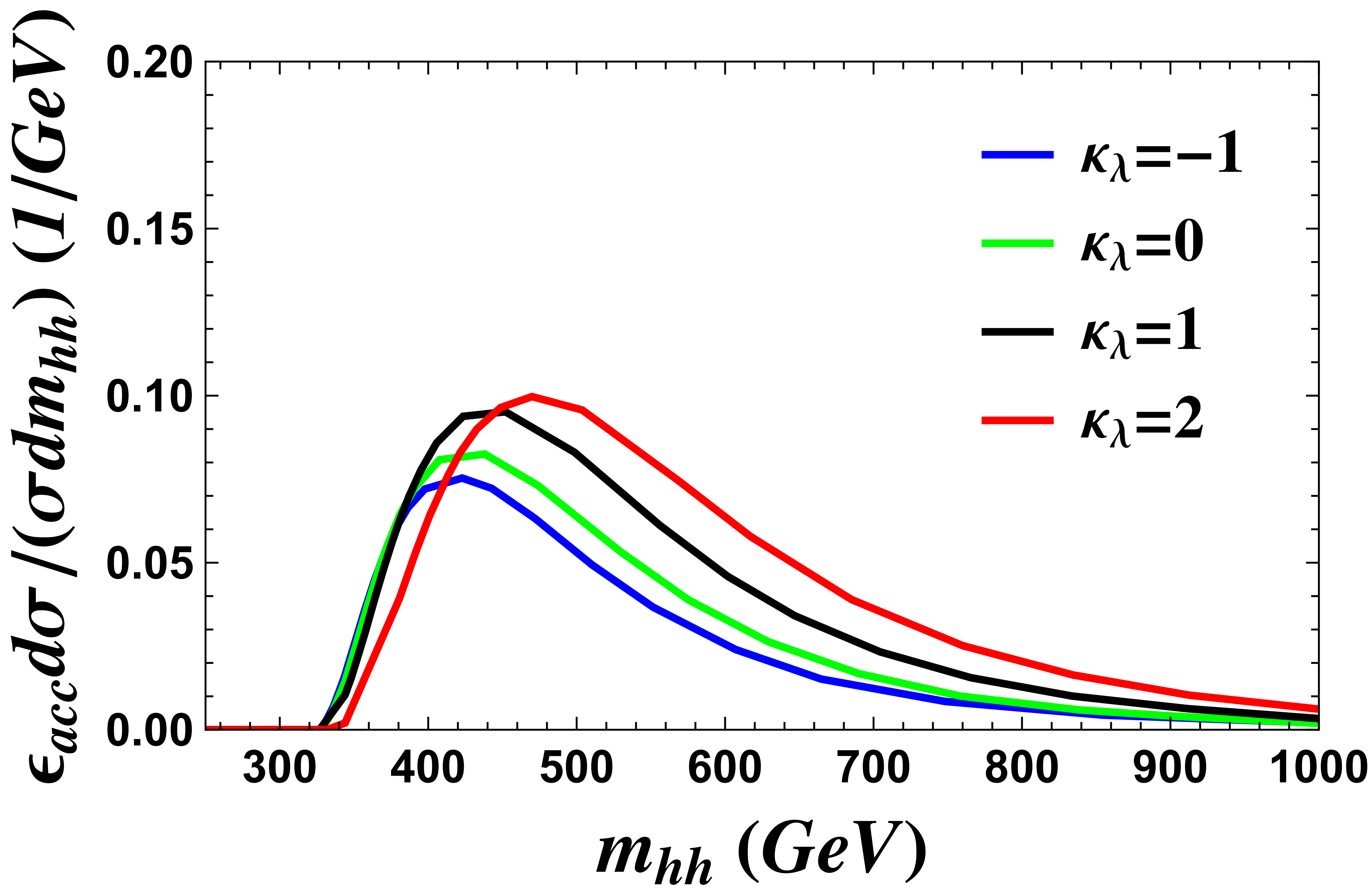
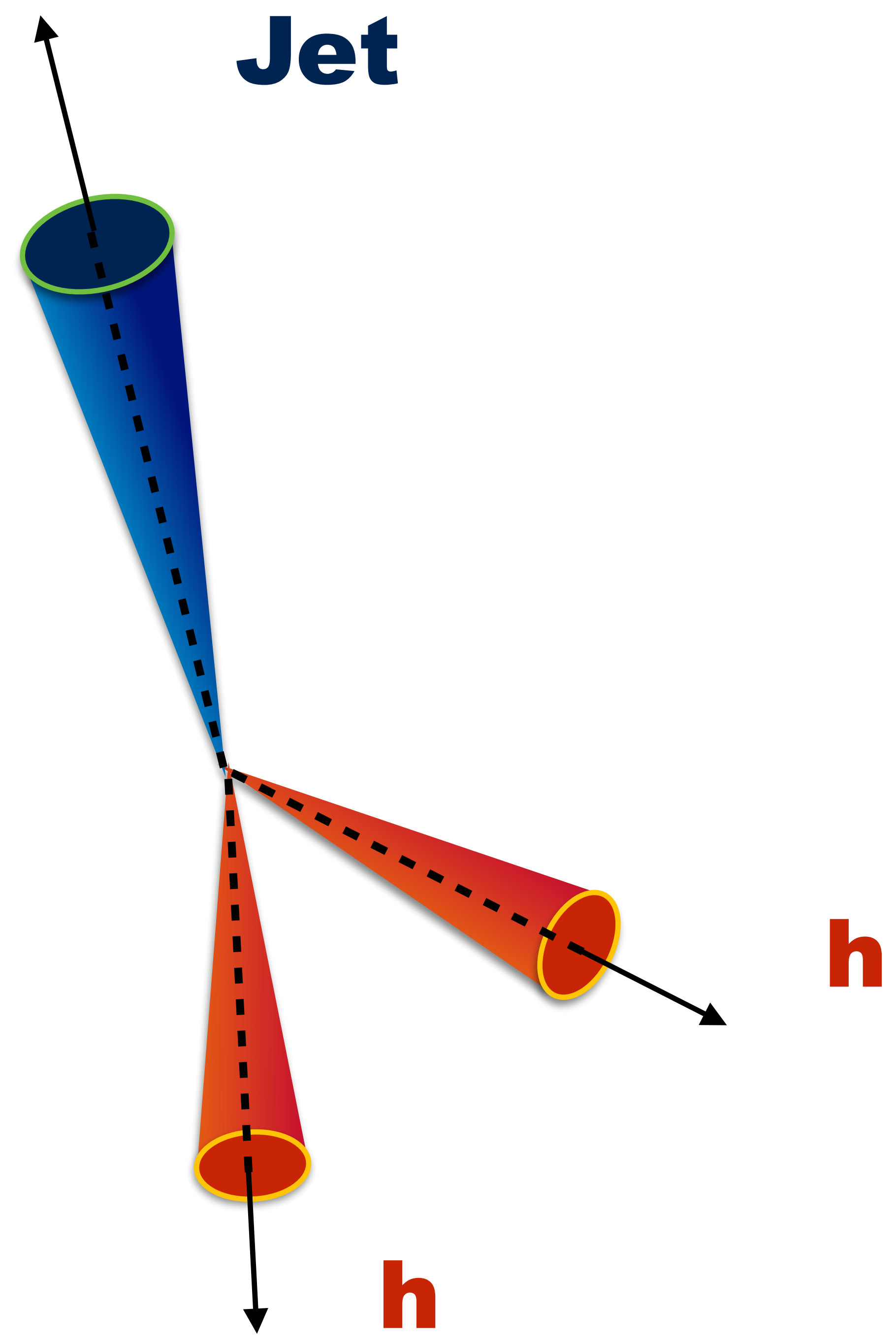


The Method

- Unfortunately, we have the SM backgrounds!
- It is worth to work hard to keep more signal events in the low invariant mass region.
- The result from MVA and BDT hints that it is essentially hard to avoid QCD backgrounds in the low invariant mass region.
- A possible method is considering the HHj events.



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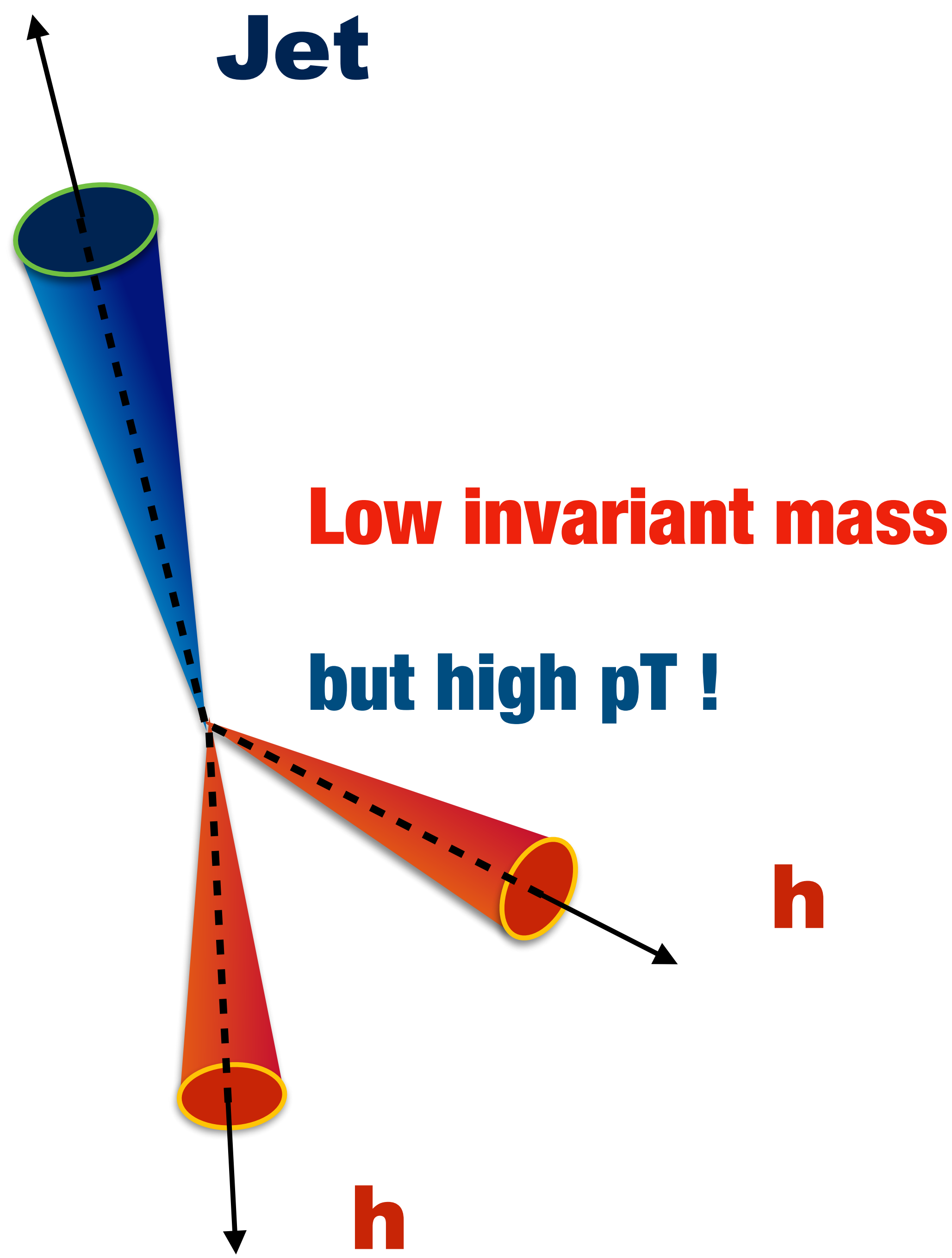
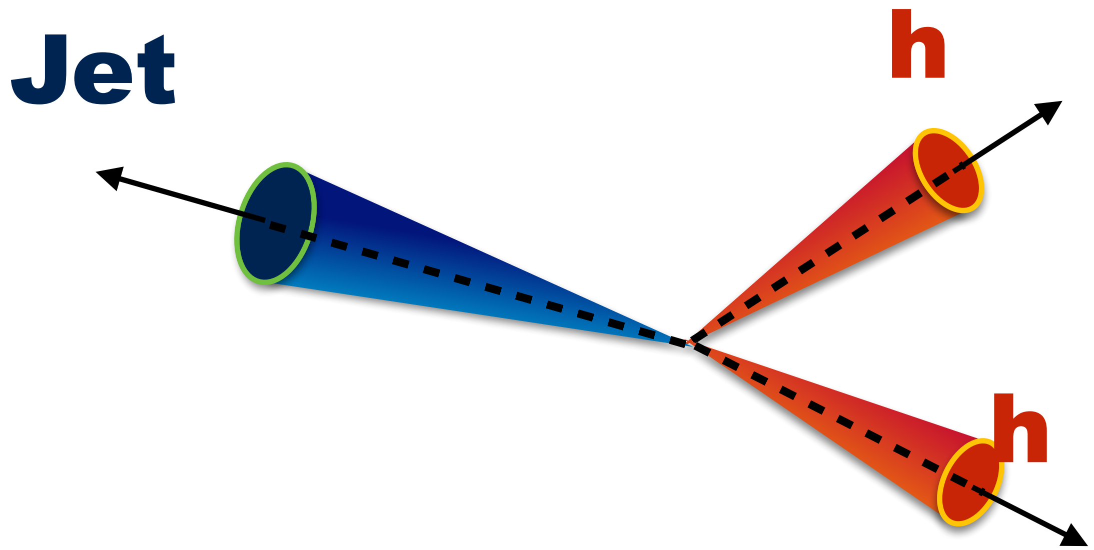
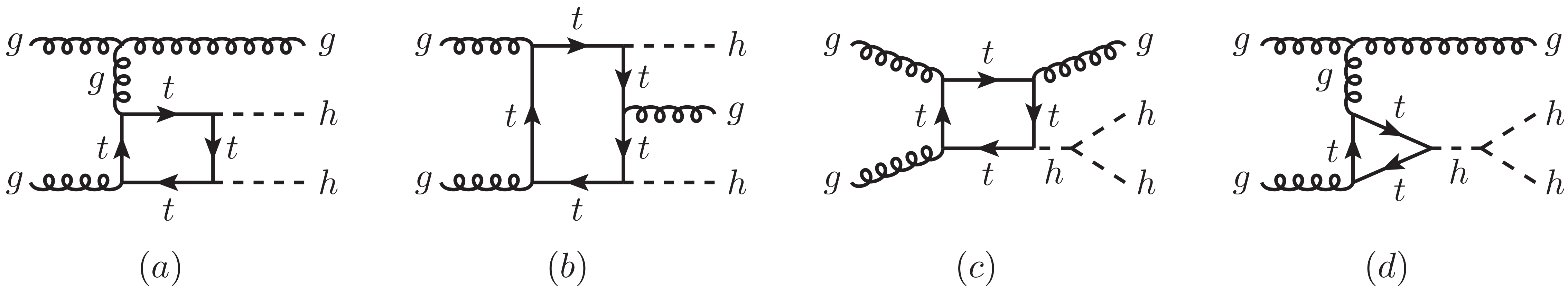


The Method

- Consider $pp \to hh + j + X$





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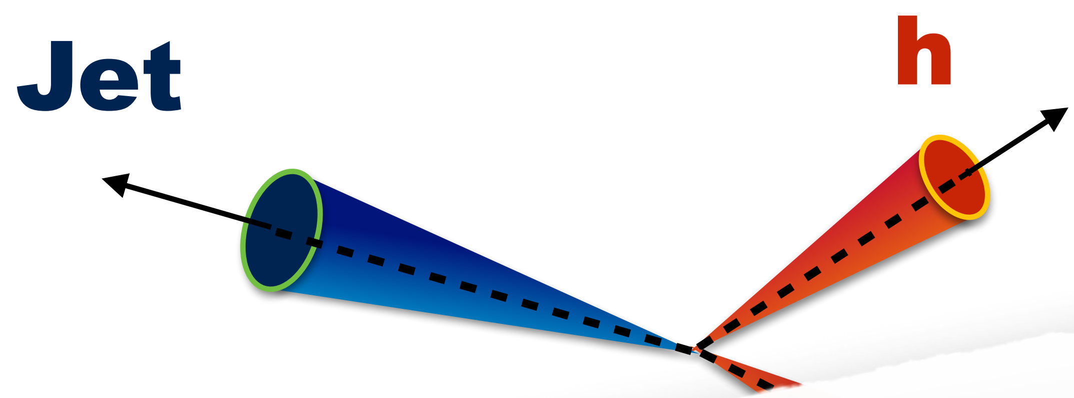
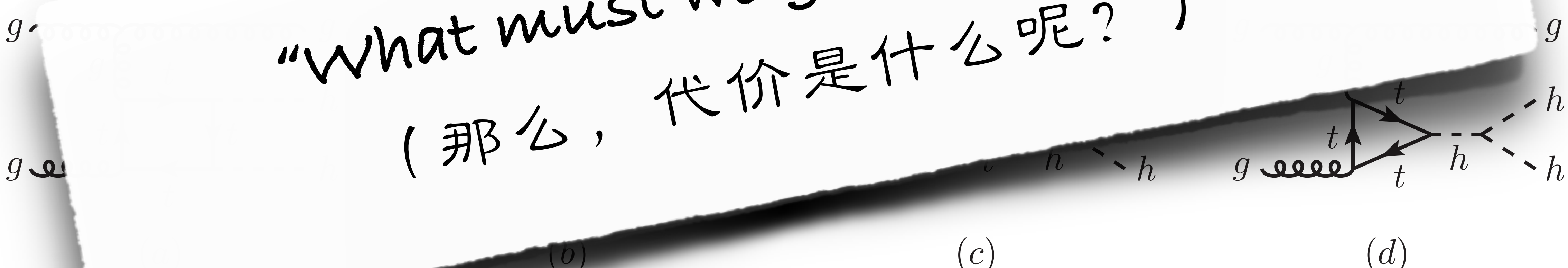
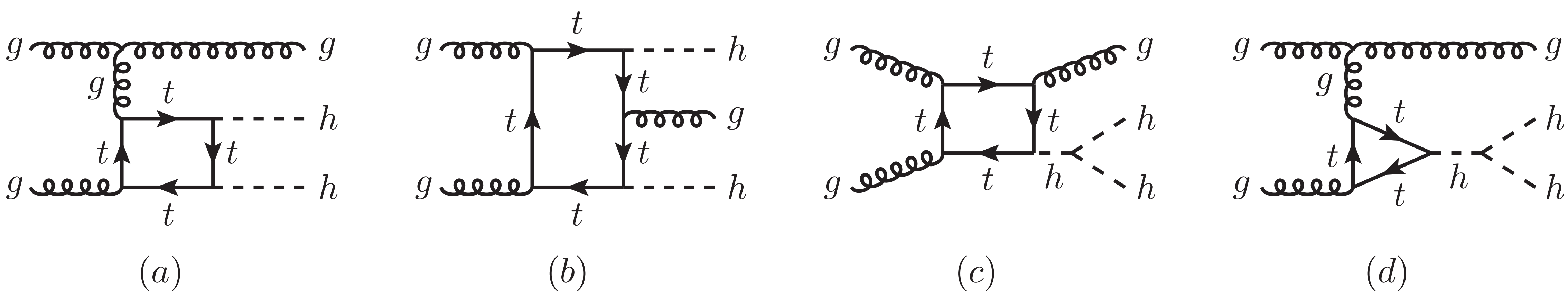


“What must we give in return?”
（那么，代价是什么呢？）



The Method

- Consider $pp \to hh + j + X$
- Benefits from the additional jet:
  - *suppressing the SM QCD background;*
  - *the invariant mass of the di-Higgs system could be small.*
- Costs from the additional jet:
  - *Less signal events;*
  - *Nearly no event left at HL-LHC.*



The Detector-Level Simulation

- MadGraph + PYTHIA8 + Delphes + *K*-factor;
- Anti-k_T jet algorithm with R=0.4;
- b-tagging efficiency: 80%; charm mistagging rate: 10%; light-jet mistagging rate: 1%; jet-fake-photon rate: 0.05%;
- 2 b-jets, 2 photons, at least 1 hard jet:

$$122\text{GeV} < m_{\gamma\gamma} < 128\text{GeV},$$
$$95\text{GeV} < m_{bb} < 155\text{GeV},$$
$$p_{T,j}^{\text{leading}} > 150\,\text{GeV}, \quad |\eta_j| < 4.5$$

The Detector-Level Simulation

- After these cuts, there are still sizable $t\bar{t}h$ and $t\bar{t}h + j$ backgrounds.

- So we try to reconstruct (at least one) top-quark in events and then reject those events.

  - ***Veto 1: with 1 or more isolated** $e^{\pm}(\mu^{\pm})$ **with** $p_{\mathrm{T}} > 25\mathrm{GeV}$ **and** $|\eta| < 2.5$**;***

  - ***Veto 2: with at least 4 additional jets (** j_1, j_2, j_3, j_4 **) and***

$$\chi^2 \equiv \min_{\sigma \in S_4} \left\{ \frac{\left(m_W - m_{j_{\sigma(1)}j_{\sigma(2)}}\right)^2}{\sigma_W^2} + \frac{\left(m_W - m_{j_{\sigma(3)}j_{\sigma(4)}}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m_{j_{\sigma(1)}j_{\sigma(2)}b_1}\right)^2}{\sigma_t^2} + \frac{\left(m_t - m_{j_{\sigma(3)}j_{\sigma(4)}b_2}\right)^2}{\sigma_t^2} \right\}$$

$$< 6$$

The Detector-Level Simulation

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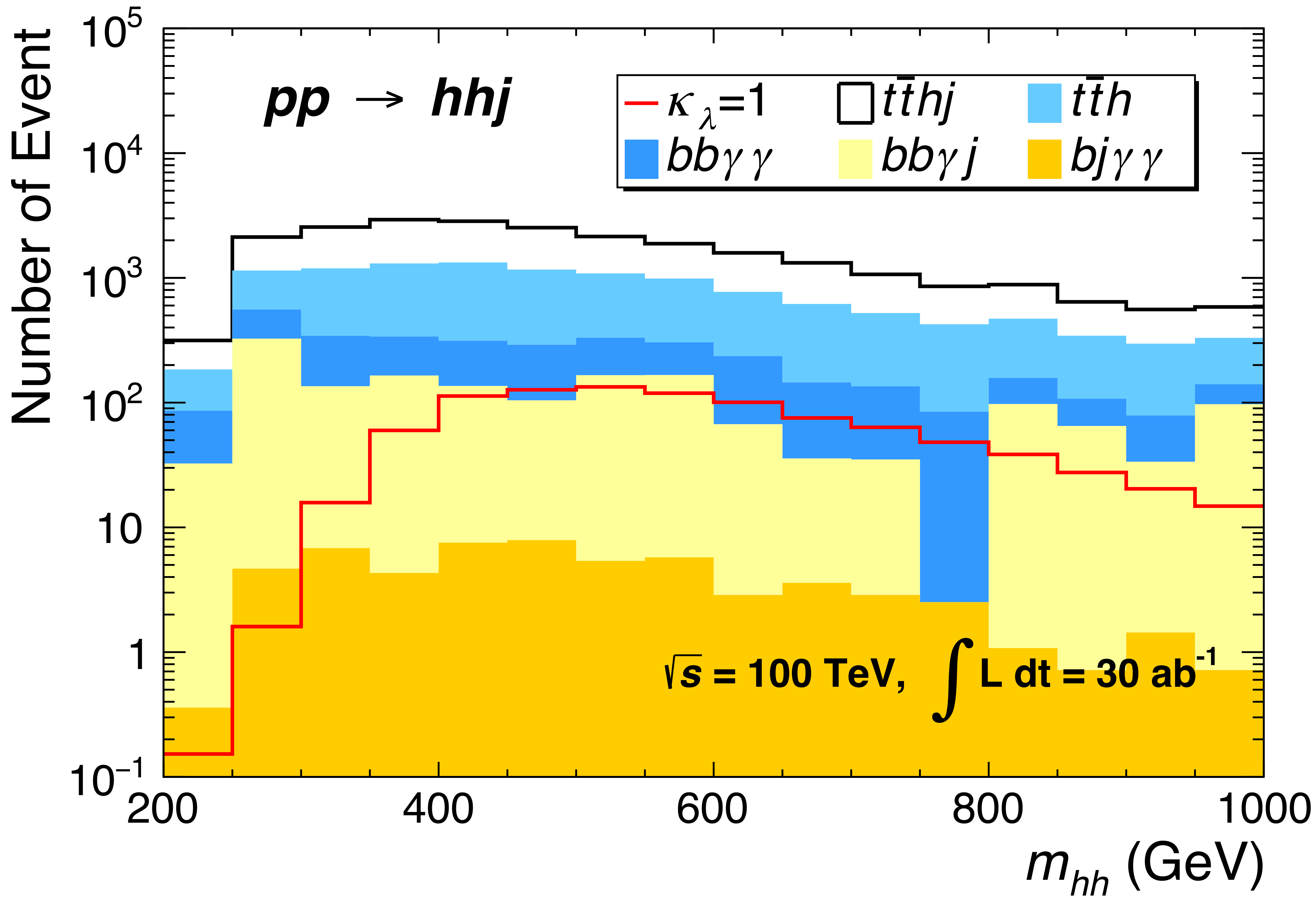

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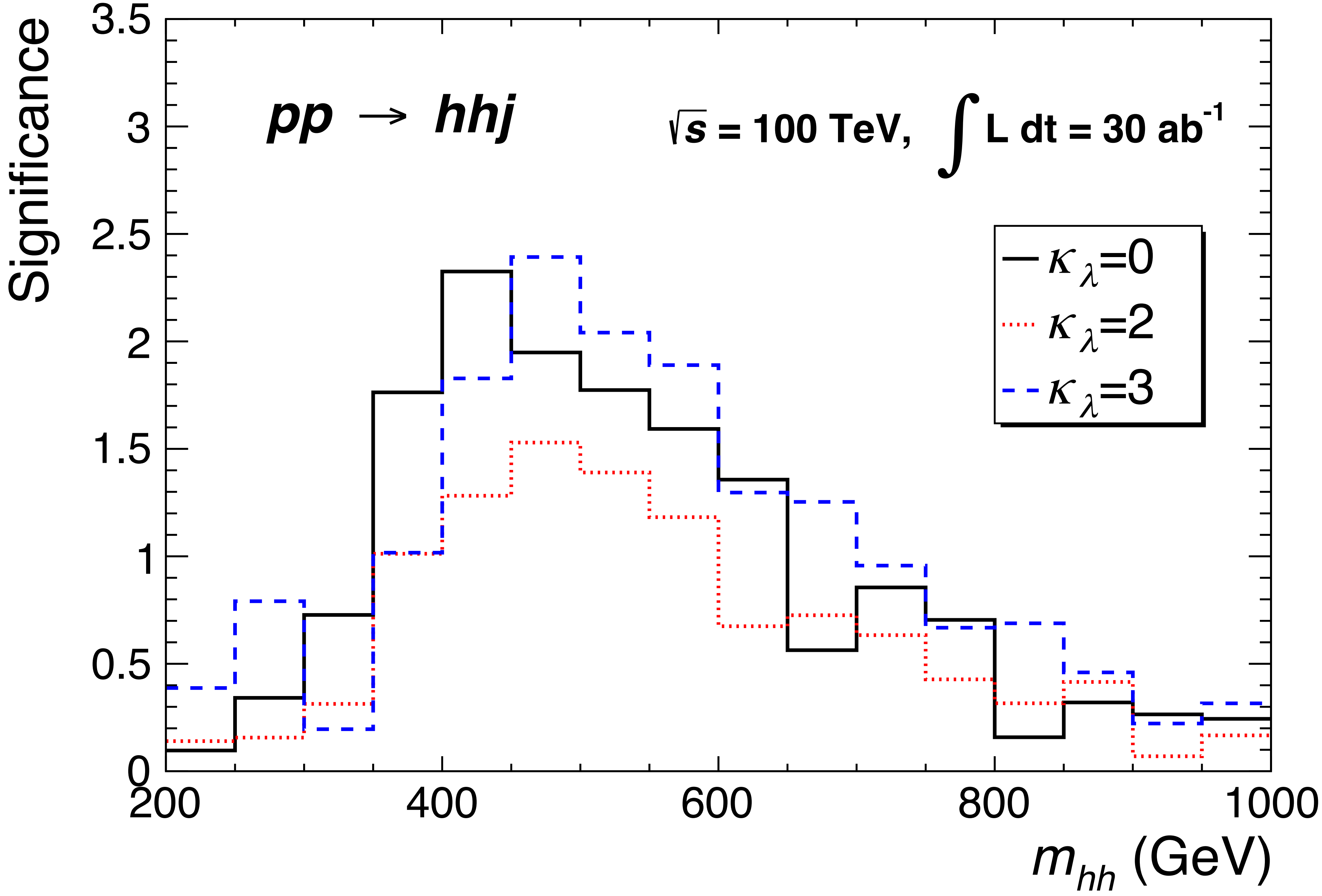

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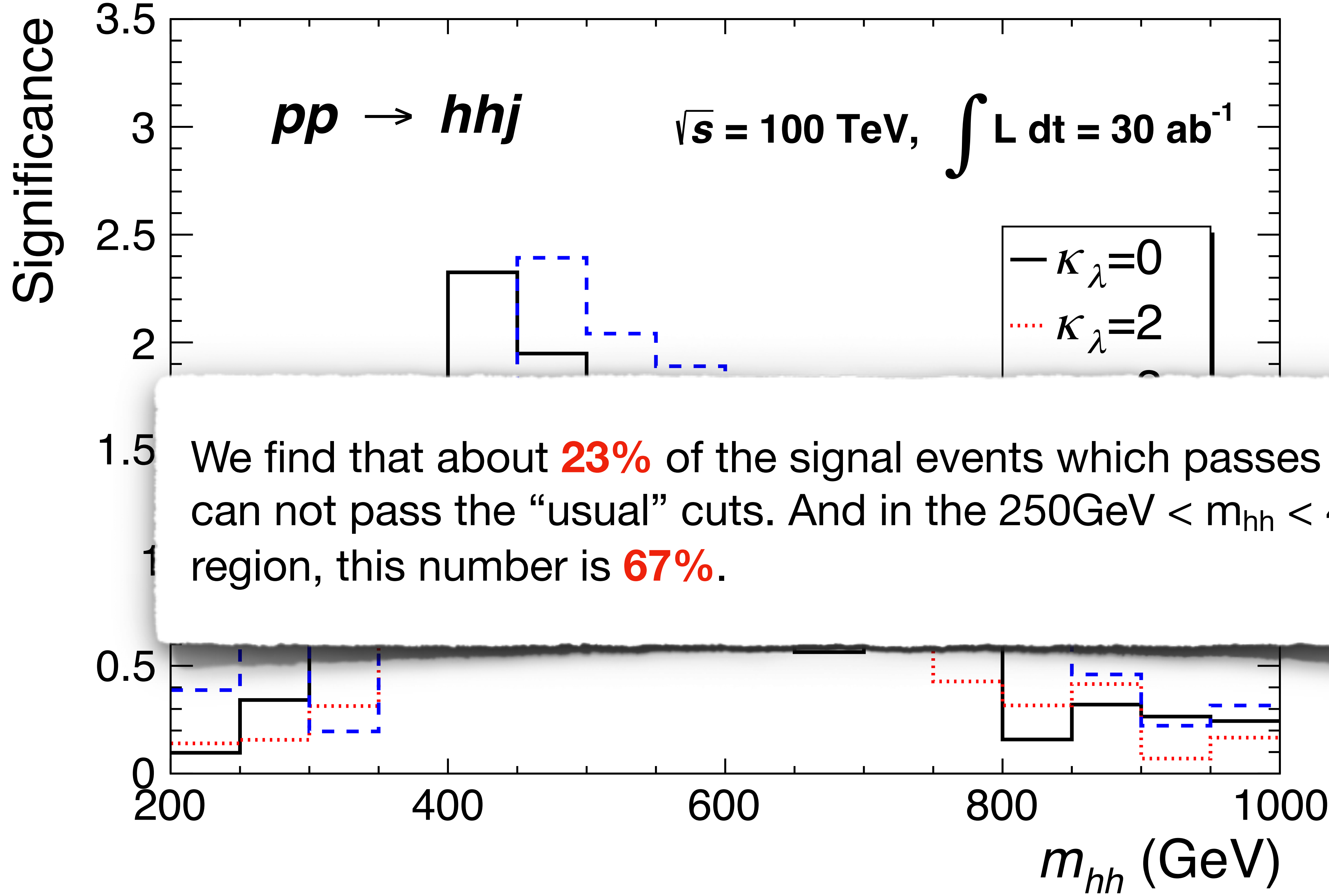

We find that about **23%** of the signal events which passes our cuts can not pass the "usual" cuts. And in the 250GeV < m_{hh} < 400GeV region, this number is **67%**.

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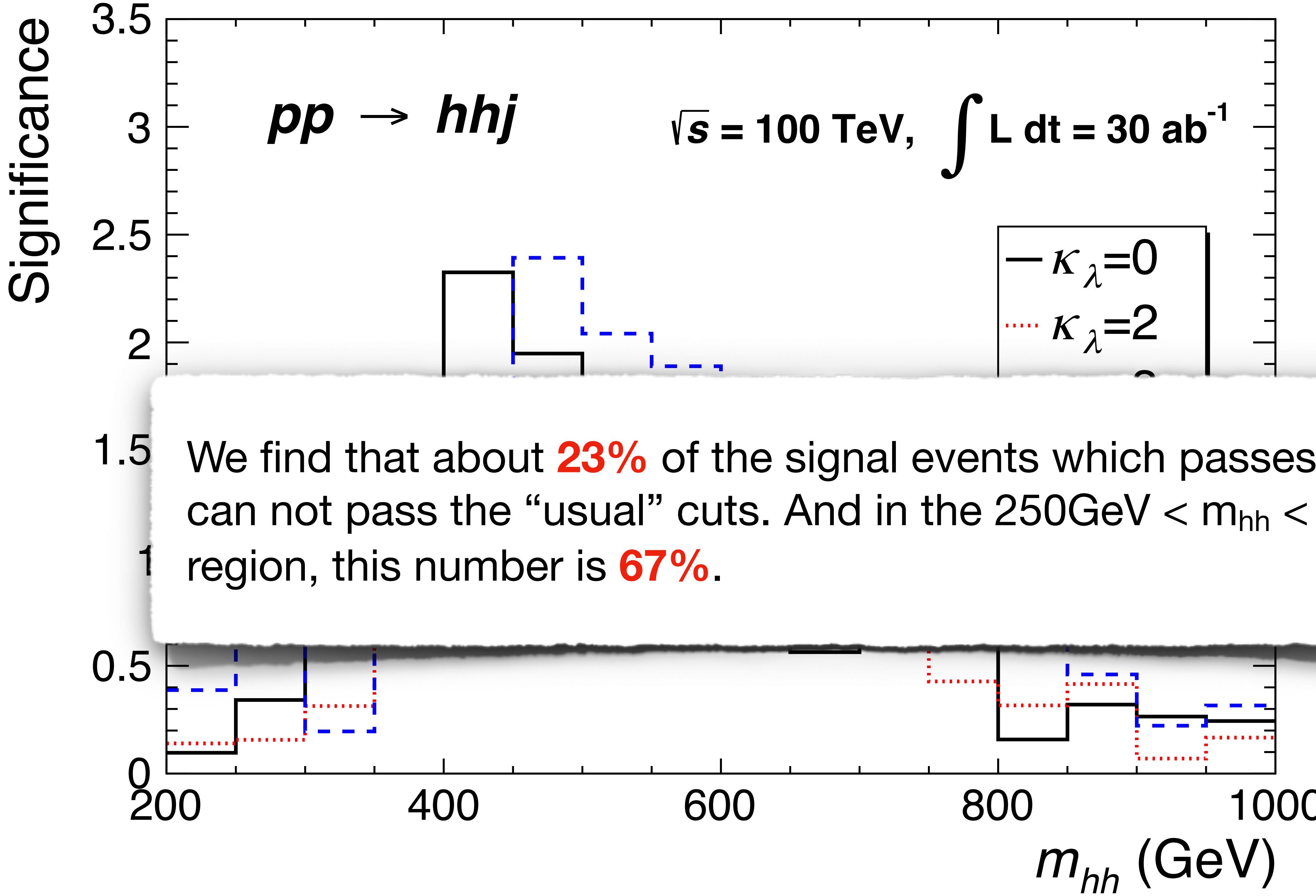

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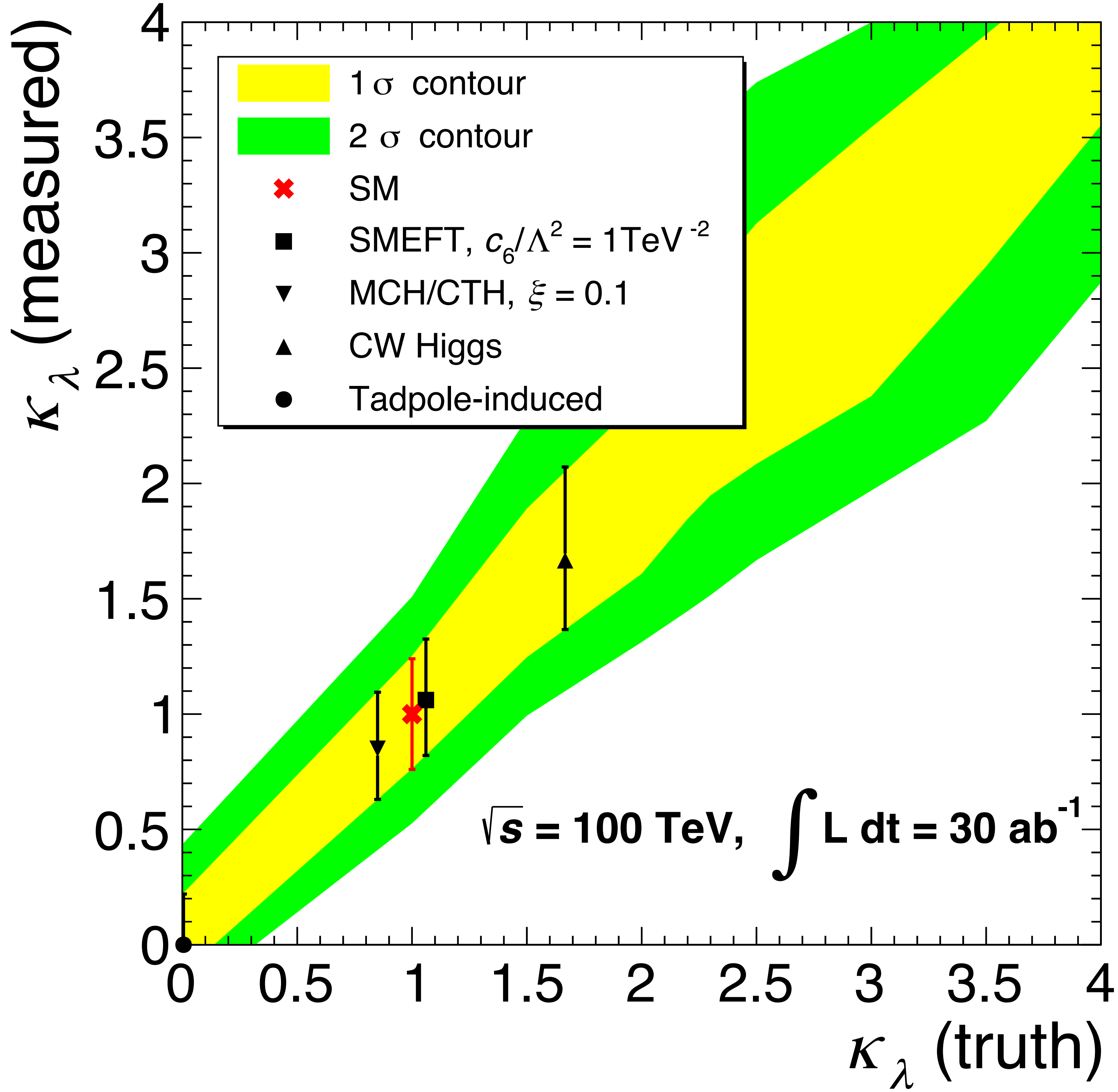
The word “usual” means the cuts in A. J. Barr, M. J. Dolan, C. Englert, D. E. Ferreira de Lima, and M. Spannowsky, “Higgs Self-Coupling Measurements at a 100 TeV Hadron Collider,” JHEP 02 (2015) 016, arXiv:1412.7154.

Conclusion and Discussion

- The ability of distinguishing NP with **this channel only**.



Conclusion and Discussion

- Our result is not as good as the result shown in current literatures. This is because we only use the di-Higgs plus one hard jet events since we focus on investigating the information carried by these signal events. These events are only small part of the signal events. A combination with regular signal events will highly increase the total event number and suppress the statistic uncertainty.

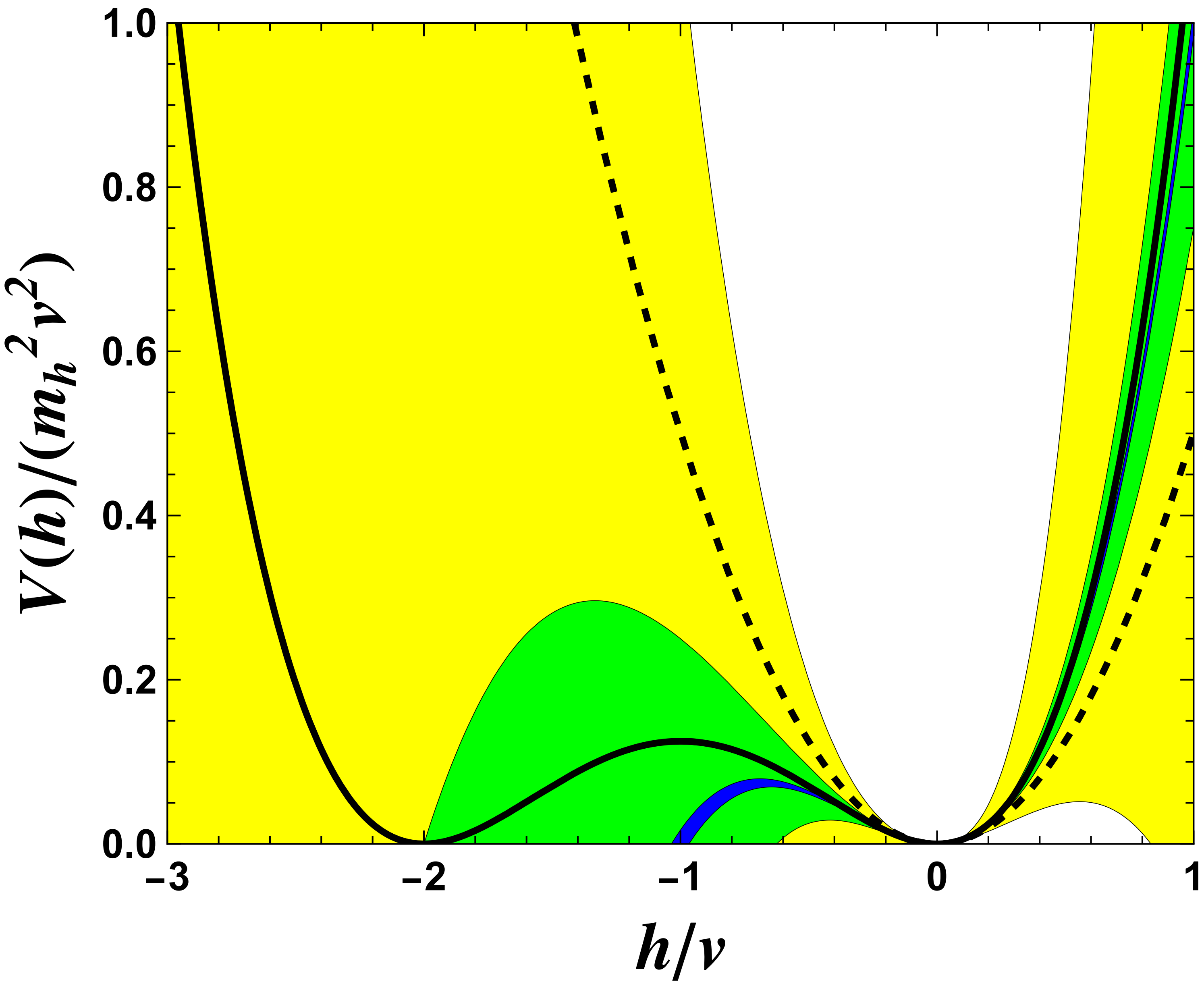
- However, we show that these signal events are helpful to study the low invariant mass region and thus the strength of the self-interaction of the Higgs boson, and a lot of them are missed in current analysis. We suggest our experimentalists colleagues consider to add them back to their signal events.

- Further efforts for keeping signal events in this region are needed.

Some Comments

- The SM Higgs potential.

$$V(h) = \frac{1}{2}m_h^2\left(h^2 + \frac{1}{v}h^3 + \frac{1}{4v^2}h^4\right)$$



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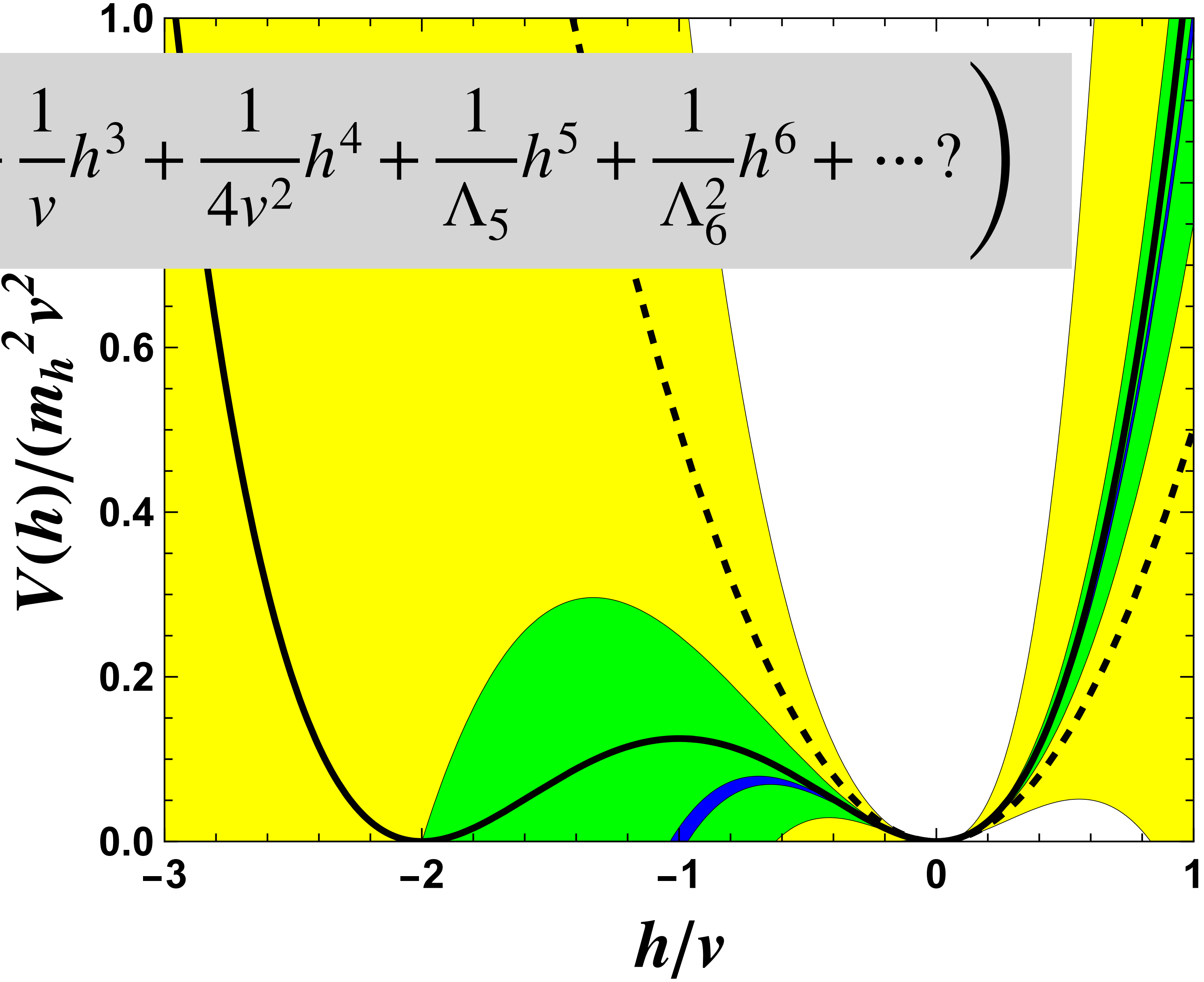
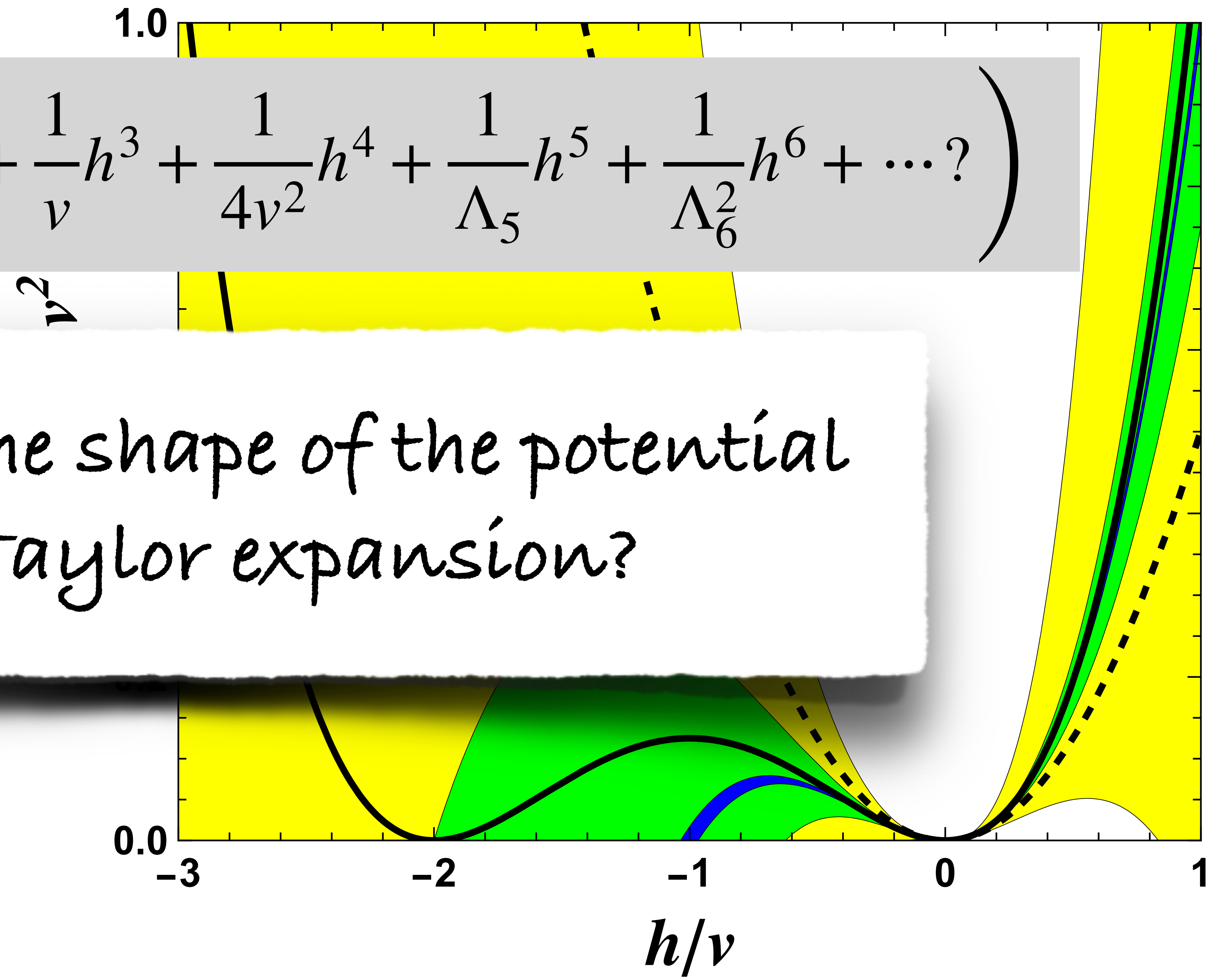
$$V(h) = \frac{1}{2} m_h^2 \left(h^2 + \frac{1}{v} h^3 + \frac{1}{4v^2} h^4 + \frac{1}{\Lambda_5} h^5 + \frac{1}{\Lambda_6^2} h^6 + \cdots ? \right)$$



Some Comments

- The potential.

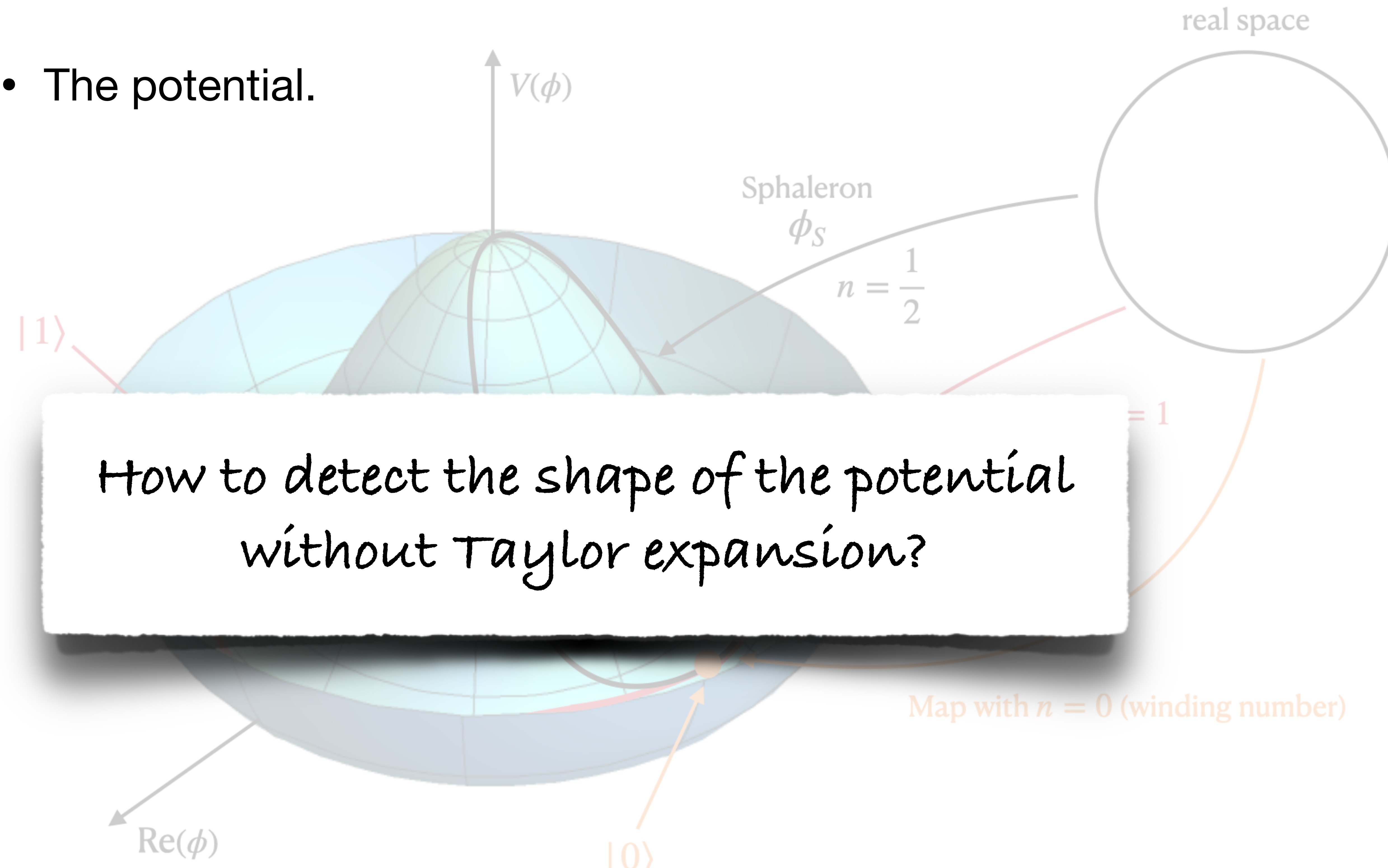
$$V(h) = \frac{1}{2}m_h^2\left(h^2 + \frac{1}{v}h^3 + \frac{1}{4v^2}h^4 + \frac{1}{\Lambda_5}h^5 + \frac{1}{\Lambda_6^2}h^6 + \cdots ?\right)$$



How to detect the shape of the potential without Taylor expansion?

Some Comments

- The potential.



How to detect the shape of the potential without Taylor expansion?

TO BE CONTINUED

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Thank you !