Investigating Higgs self-interaction through di-Higgs plus jet production at 100TeV hadron collider

Based on arXiv:2210.14929[hep-ph]
in collaboration with Kangyu Chai and Jiang-Hao Yu

Hao Zhang

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Outlook

- Motivation
- The method: a parton-level (pre-)analysis
- A detector-level analysis for 100TeV hadron collider
- Conclusion and discussion

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WARNING

This is a hep-ph work by theorists, NOT hep-ex!

Motivation

- One of the most successful physics model in history: the (particle physics electroweak) standard model (SM).

- Motivations for new physics (NP) beyond the SM:

  - *Quantization of gravity;*
  - *Nature of dark matter and dark energy;*
  - *Matter anti-matter asymmetry;*
  - *Neutrino mass;*
  - *Fine-tuning problems;*
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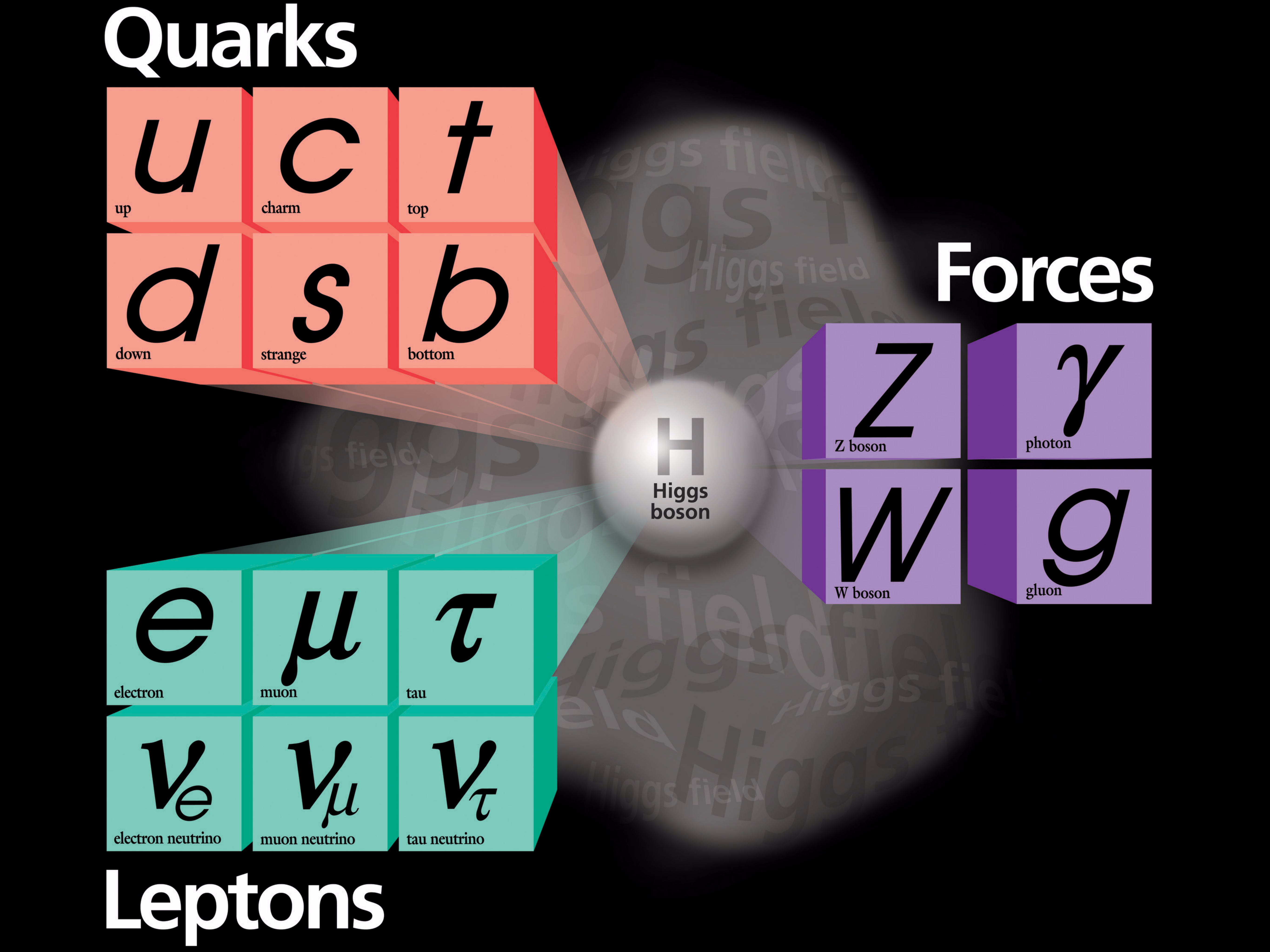
Quarks
u
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t
top
d
down
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strange
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Forces
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Z boson
γ
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W
W boson
g
gluon
H
Higgs
boson
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e
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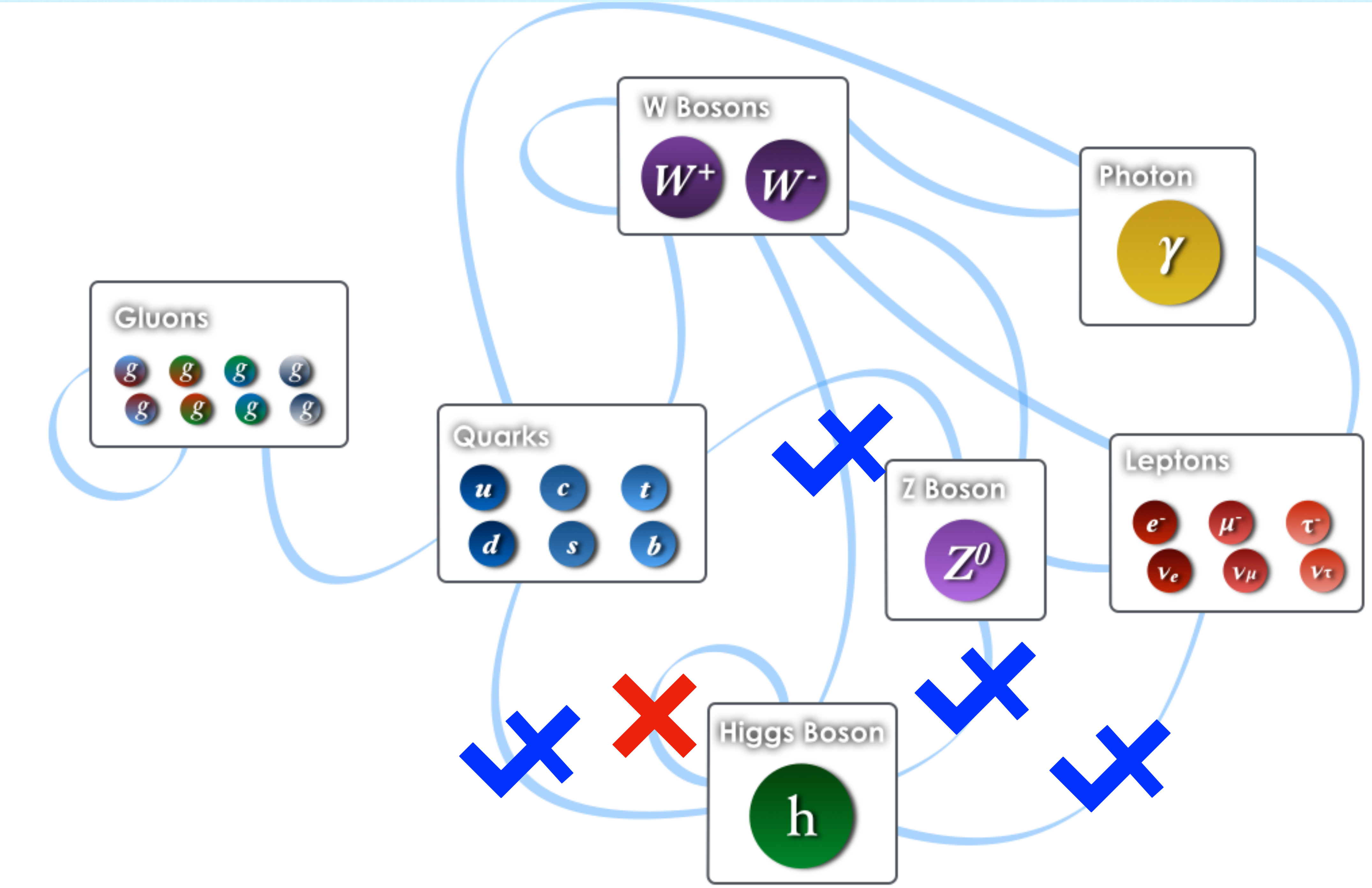
- What we do not know about the SM?



Motivation

- What we do not know about the SM?
  - *Higgs boson self-interactions:* H^3, H^4*;*
  - *Gauge interactions:* $H^2 W^{+\mu} W^-_\mu$, $H^2 Z^\mu Z_\mu$*;*
  - *Yukawa interactions (especially for light fermions):* $H\bar{f}f$*.*
- And others?
  - *In what sense can we "measure" the "vev" of the Higgs field?*
  - *The (center of the) symmetry group of the SM?*
  - *Other non-perturbative problems…*
  - *…*

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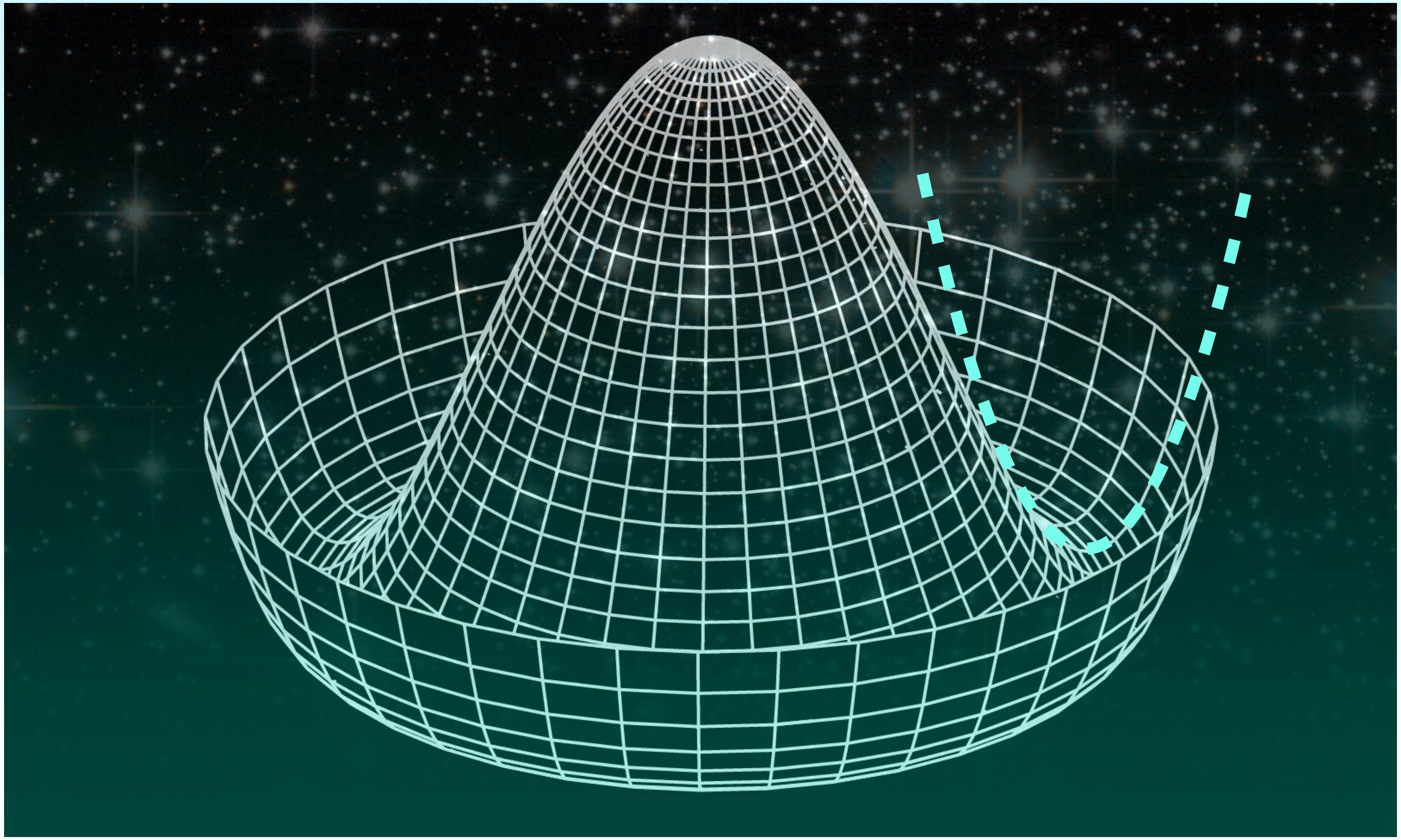
- The most hopeful one via collider experiment?
- Higgs self-interaction



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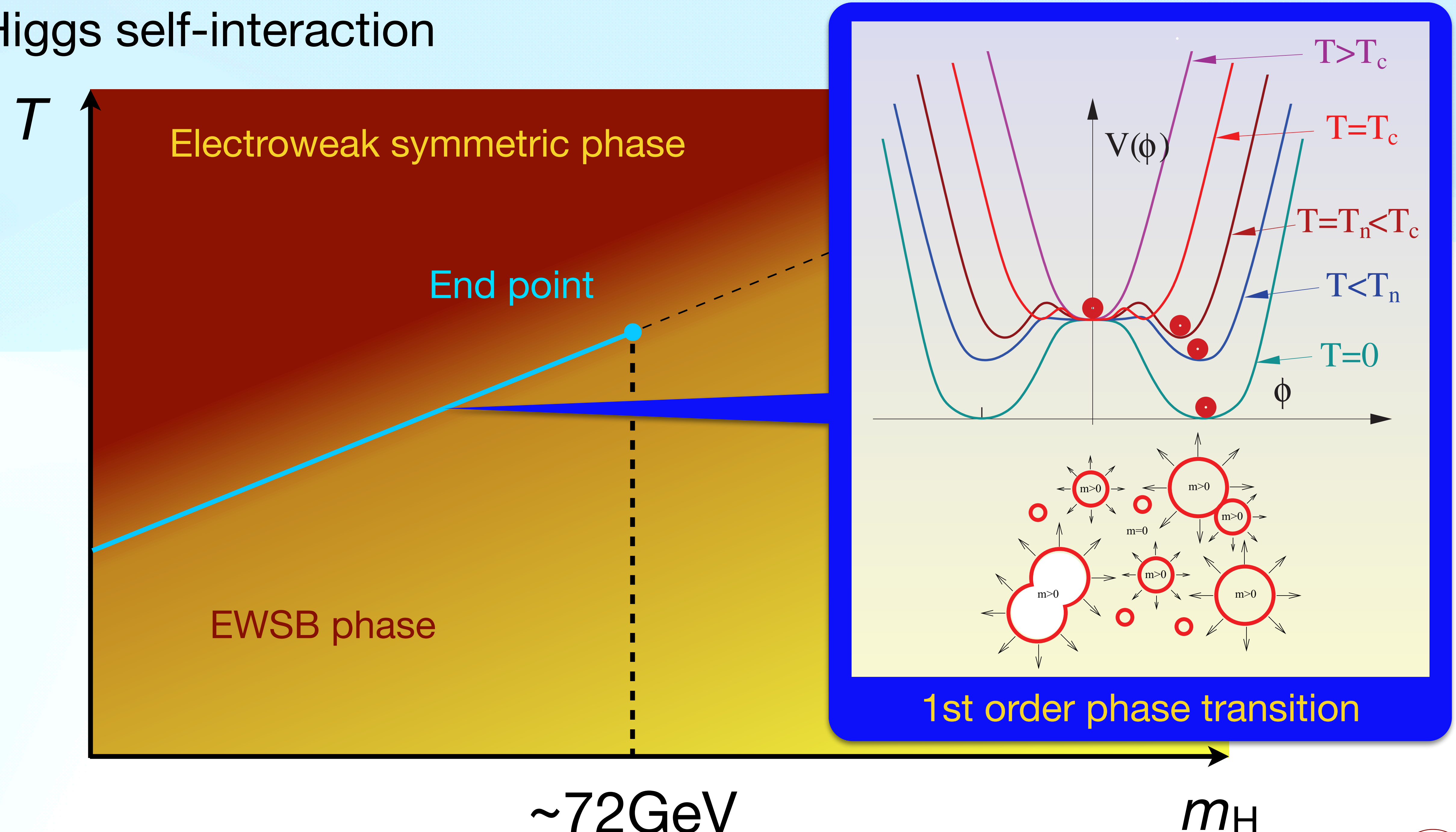

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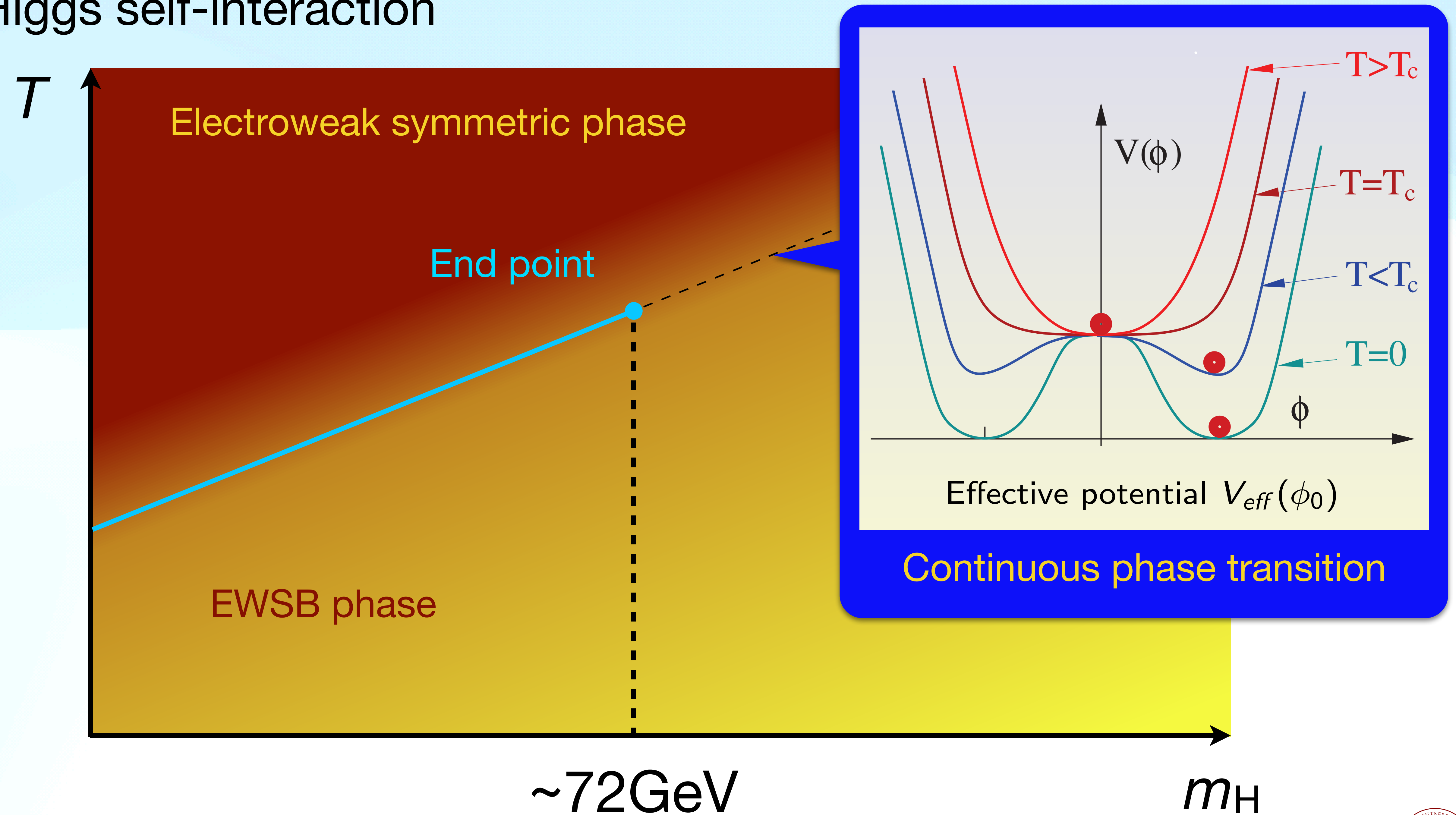

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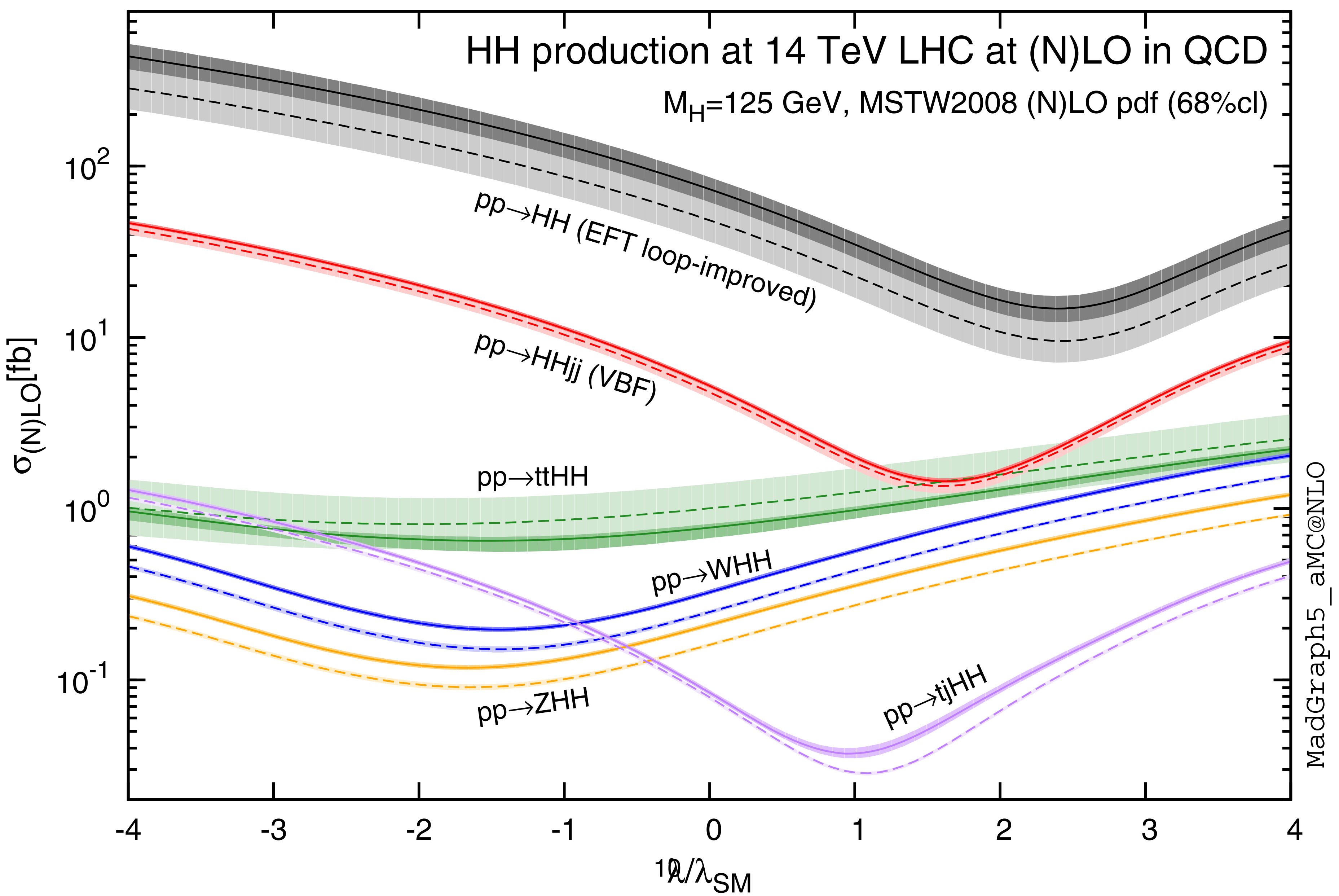

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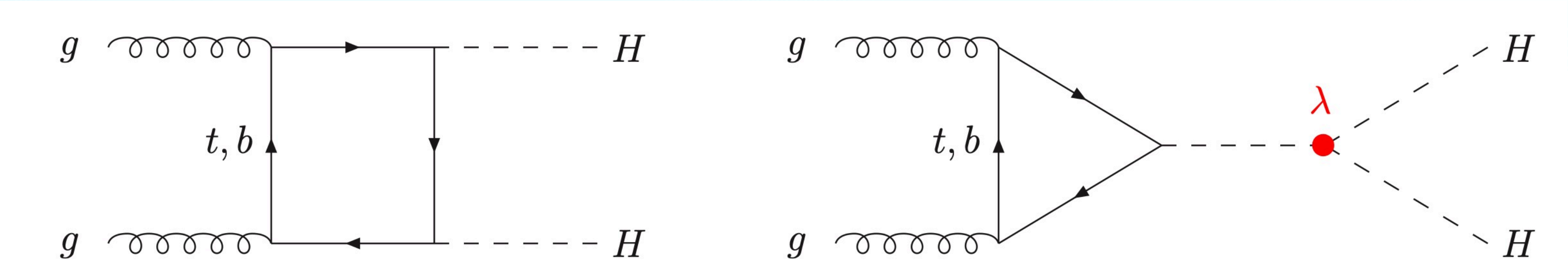

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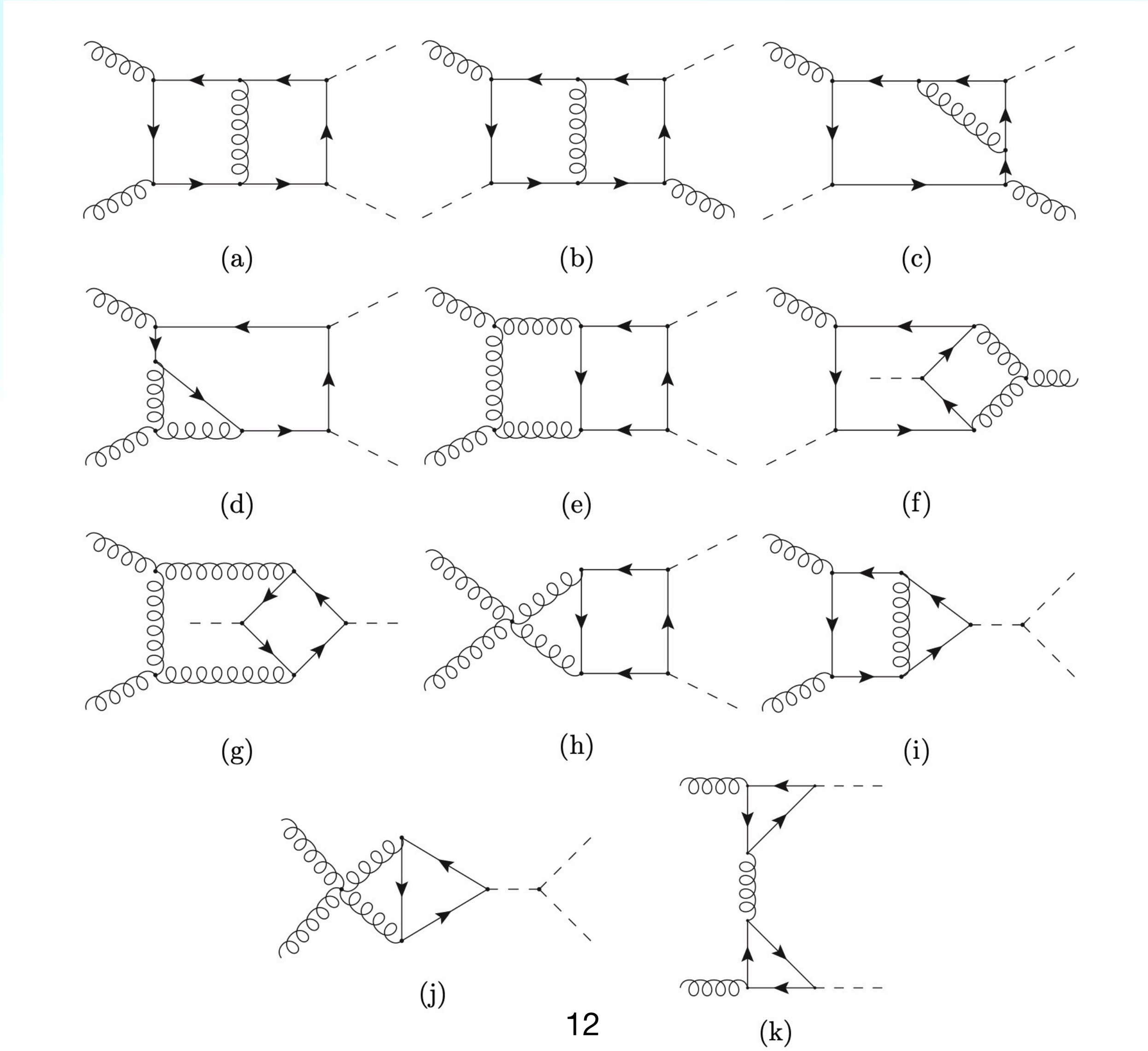

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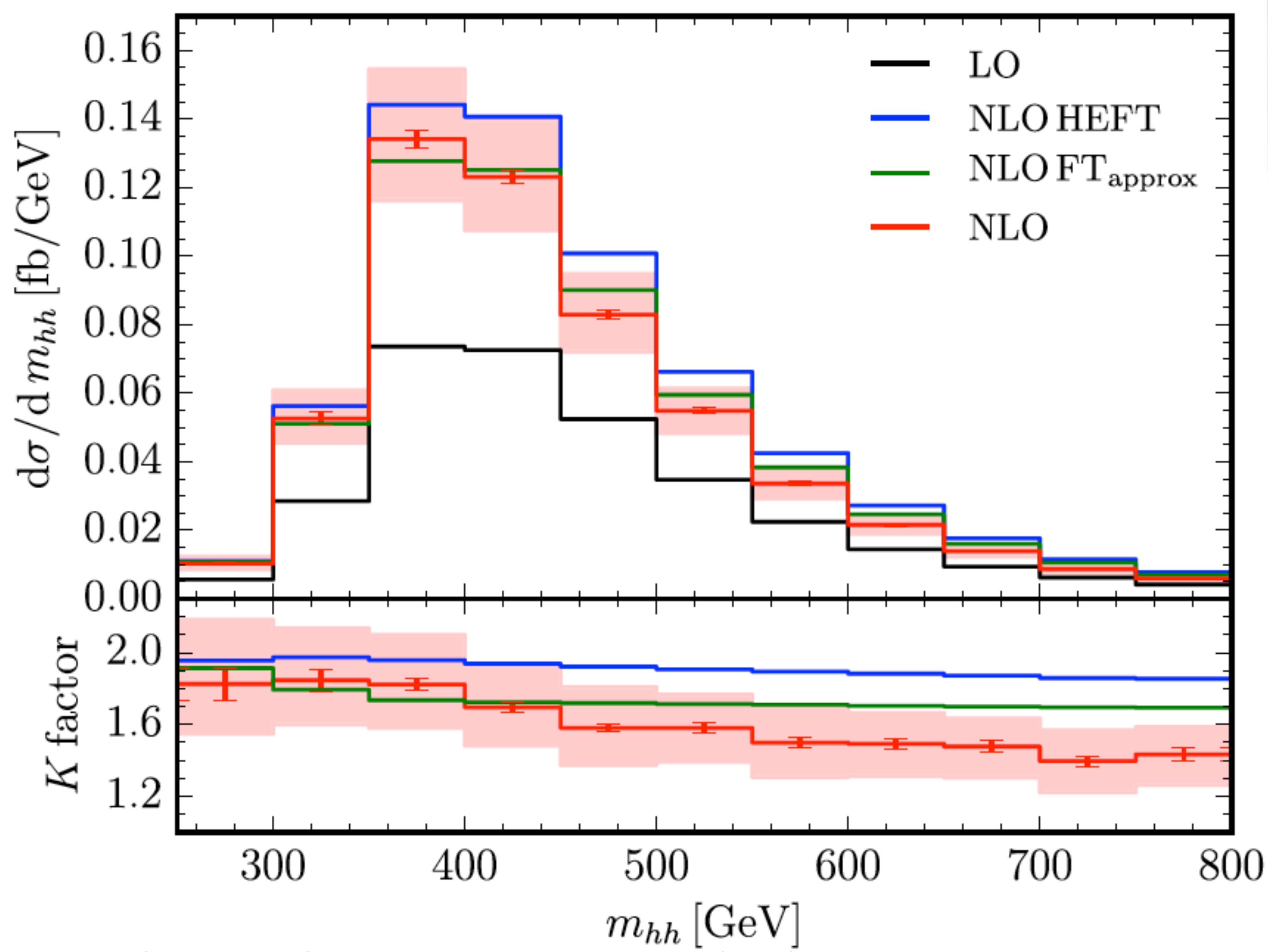

S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, and T. Zirke, PRL117(2016)079901.

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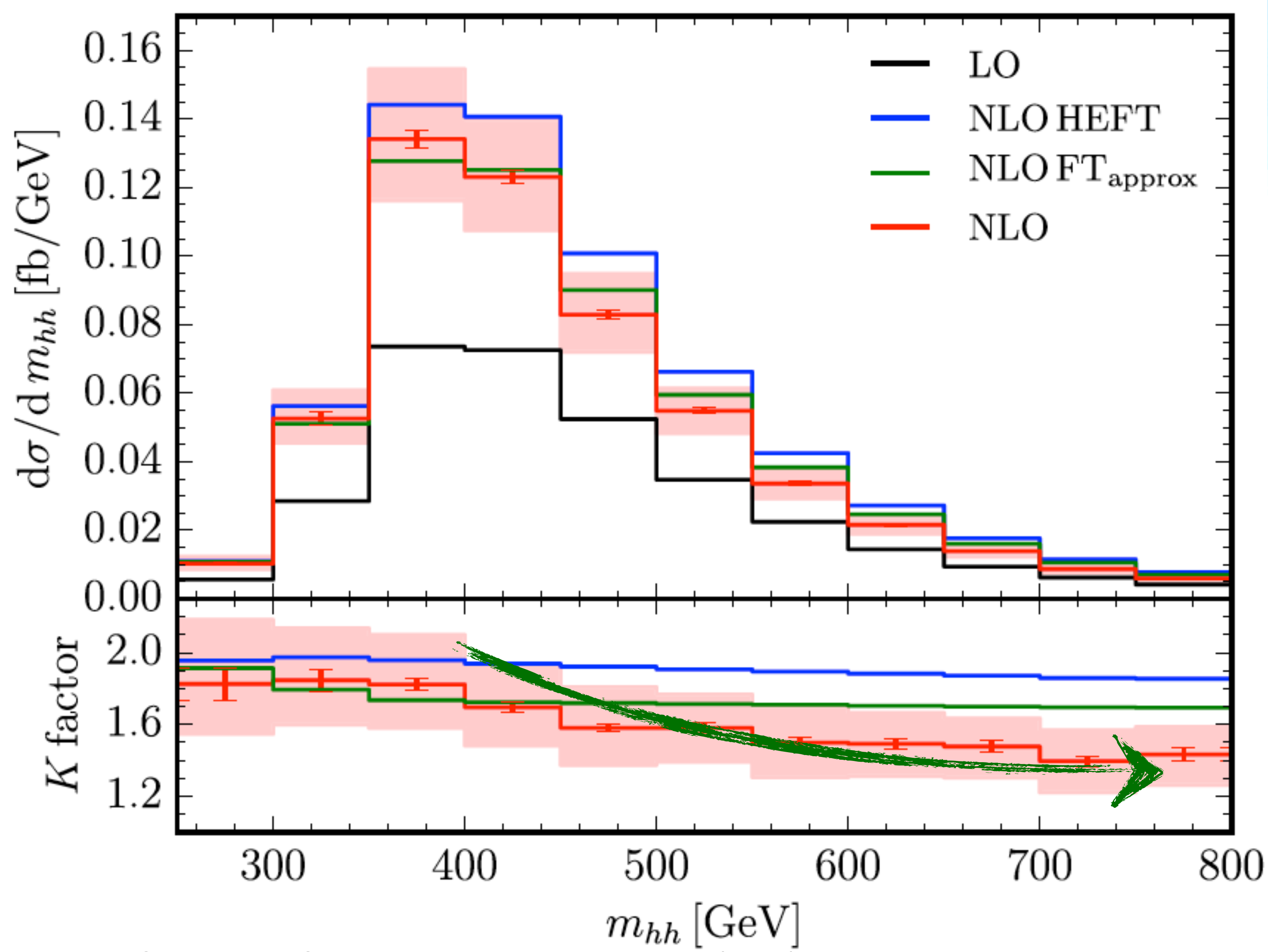

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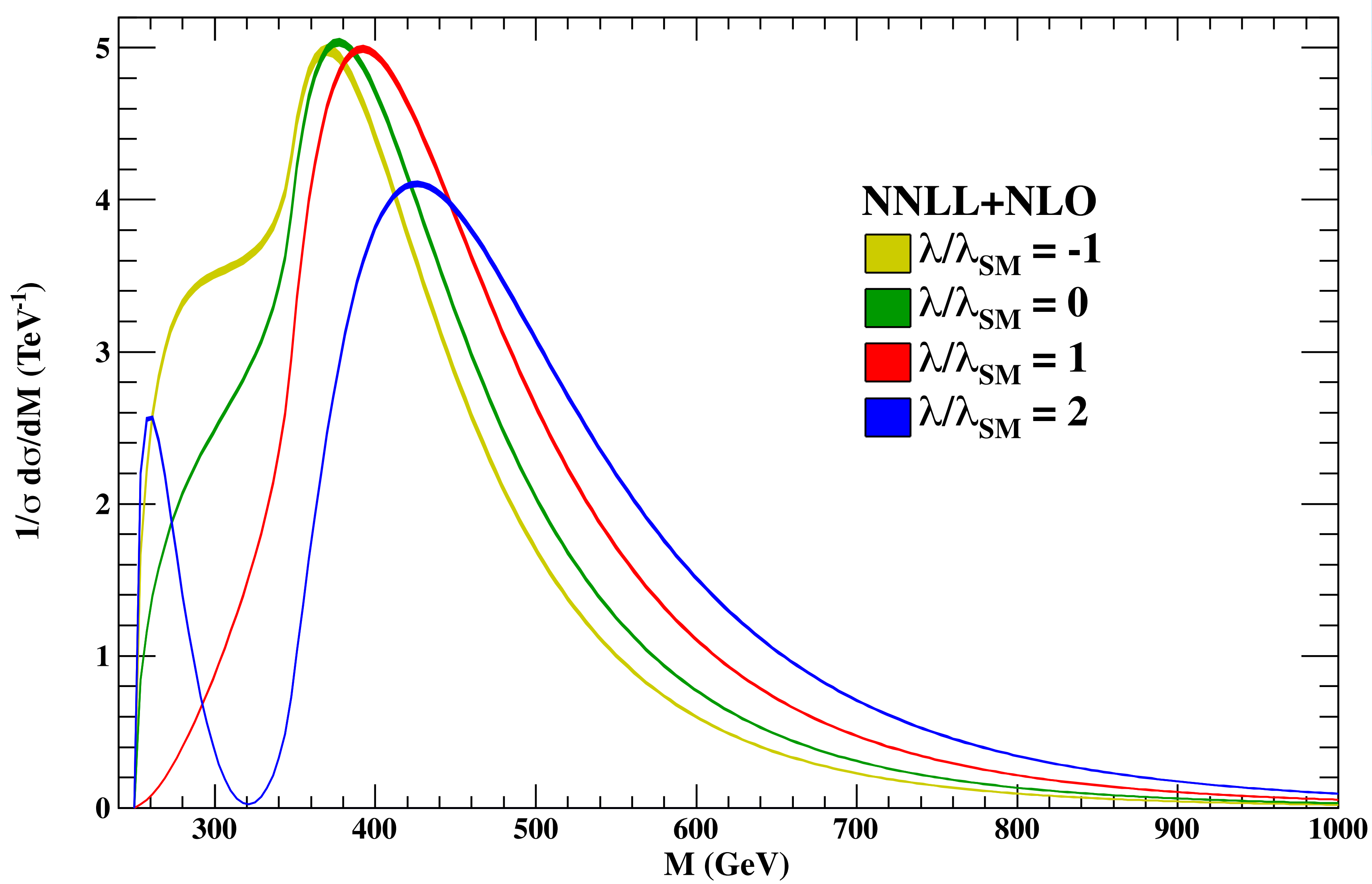

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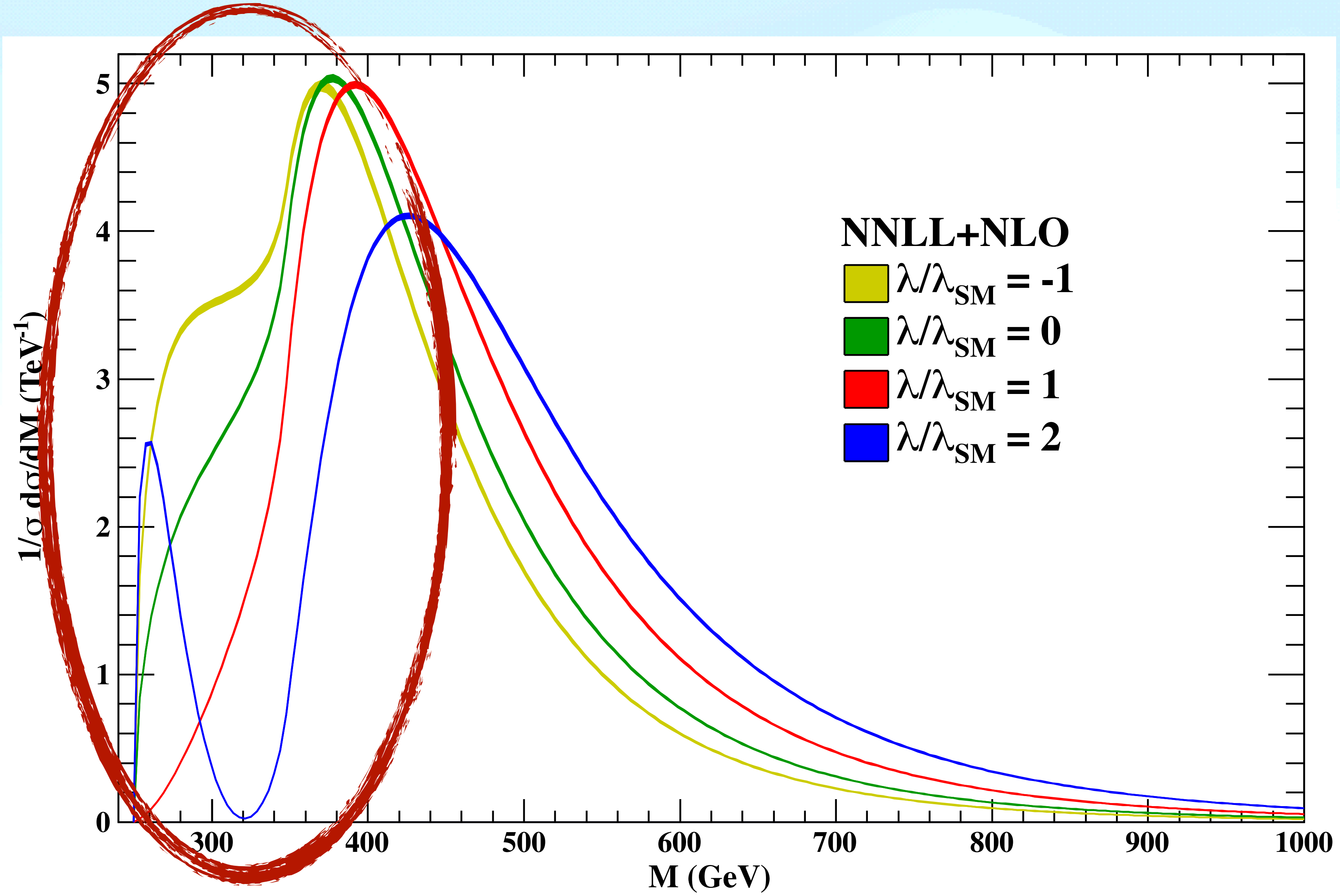

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Motivation

- Unfortunately, we have the SM backgrounds!
- Usually, a transverse momentum cut of the Higgs bosons is necessary.

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

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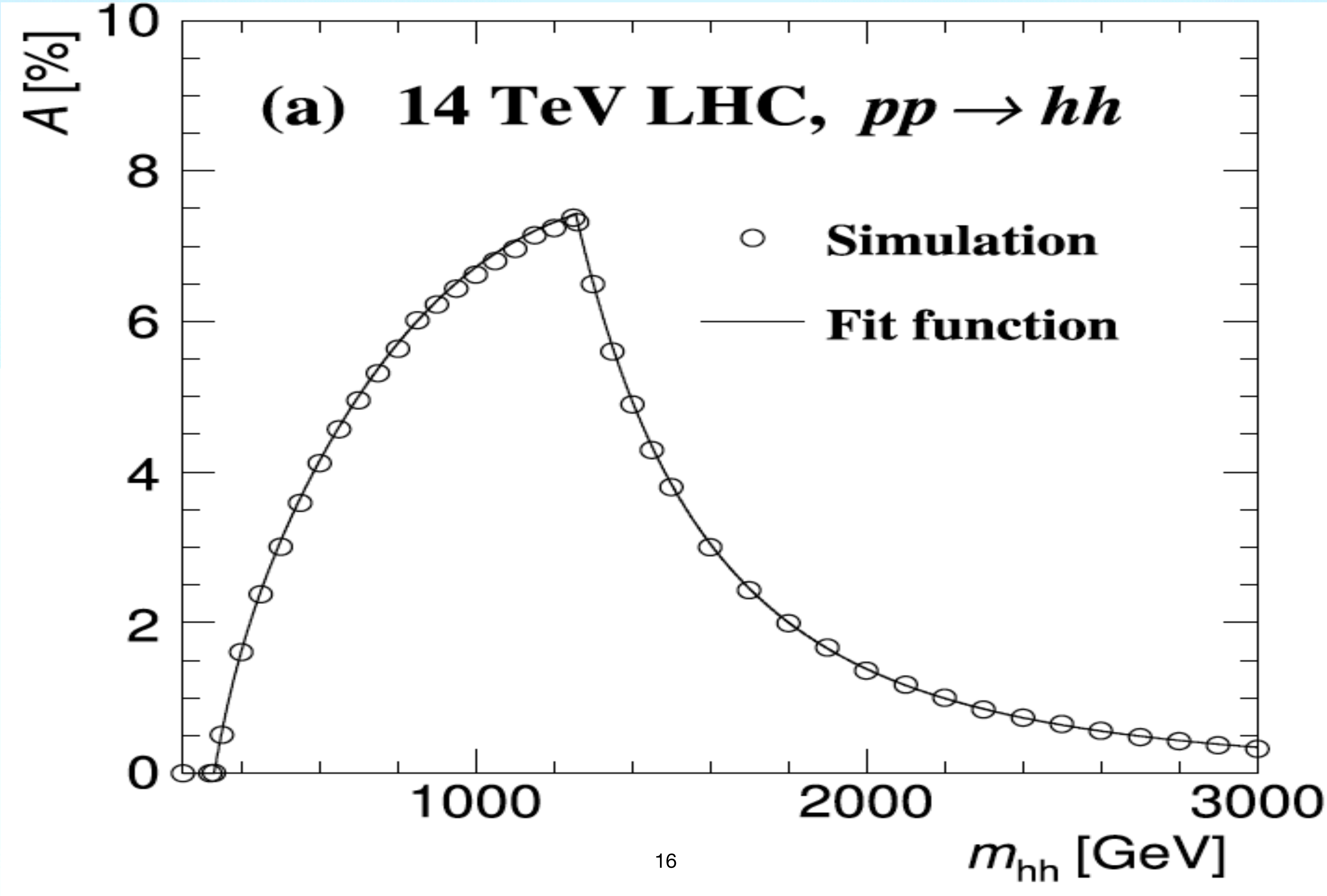

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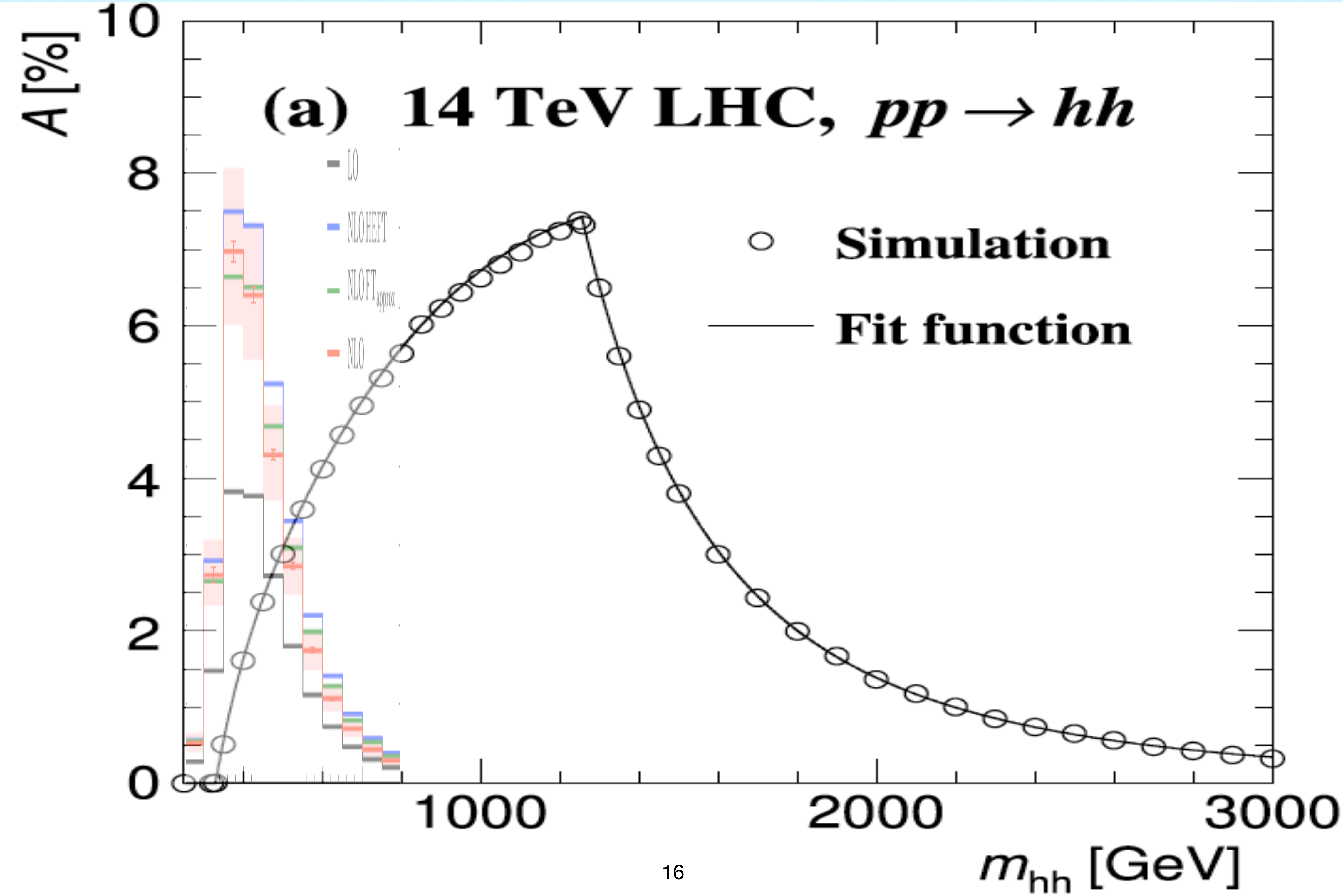

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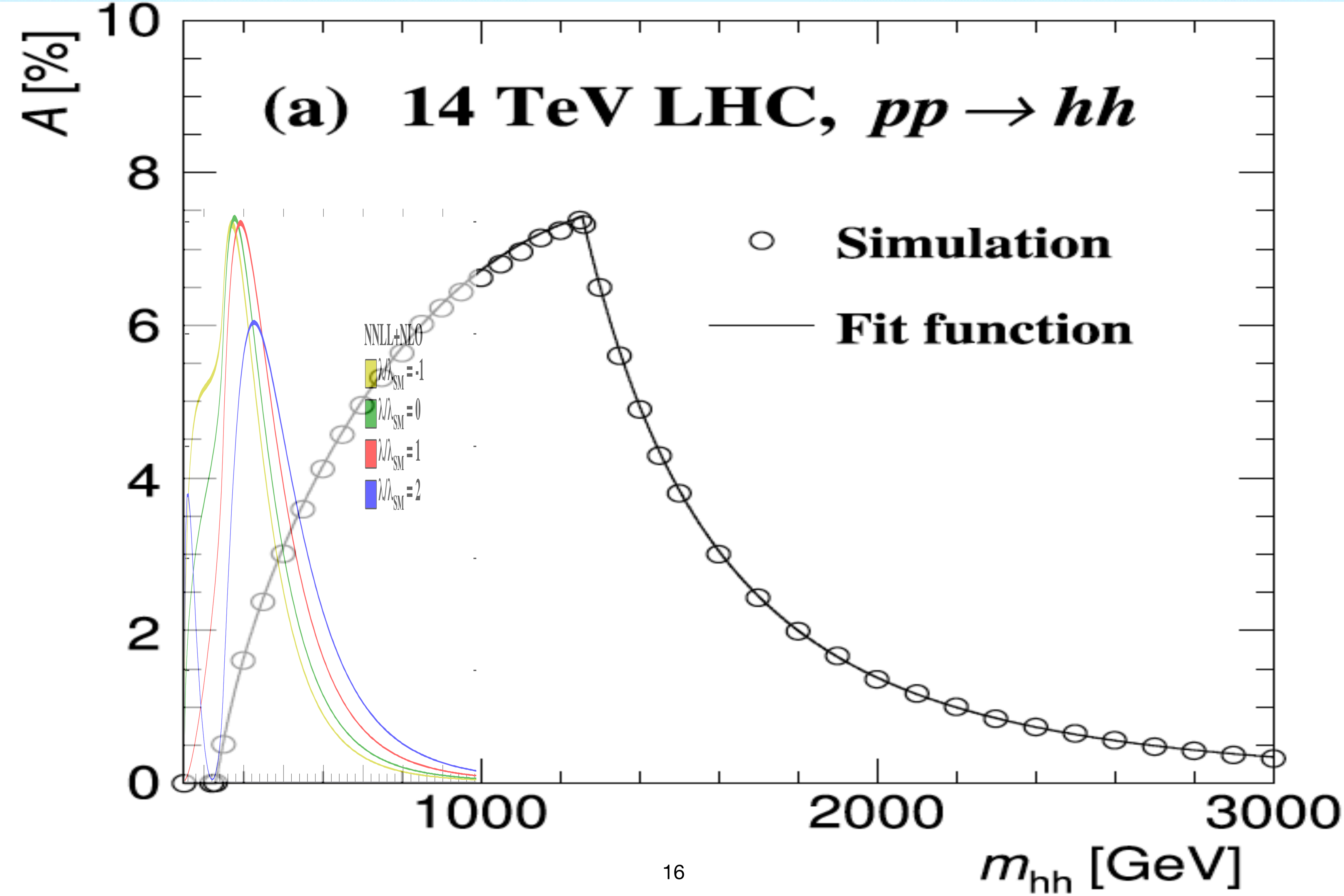
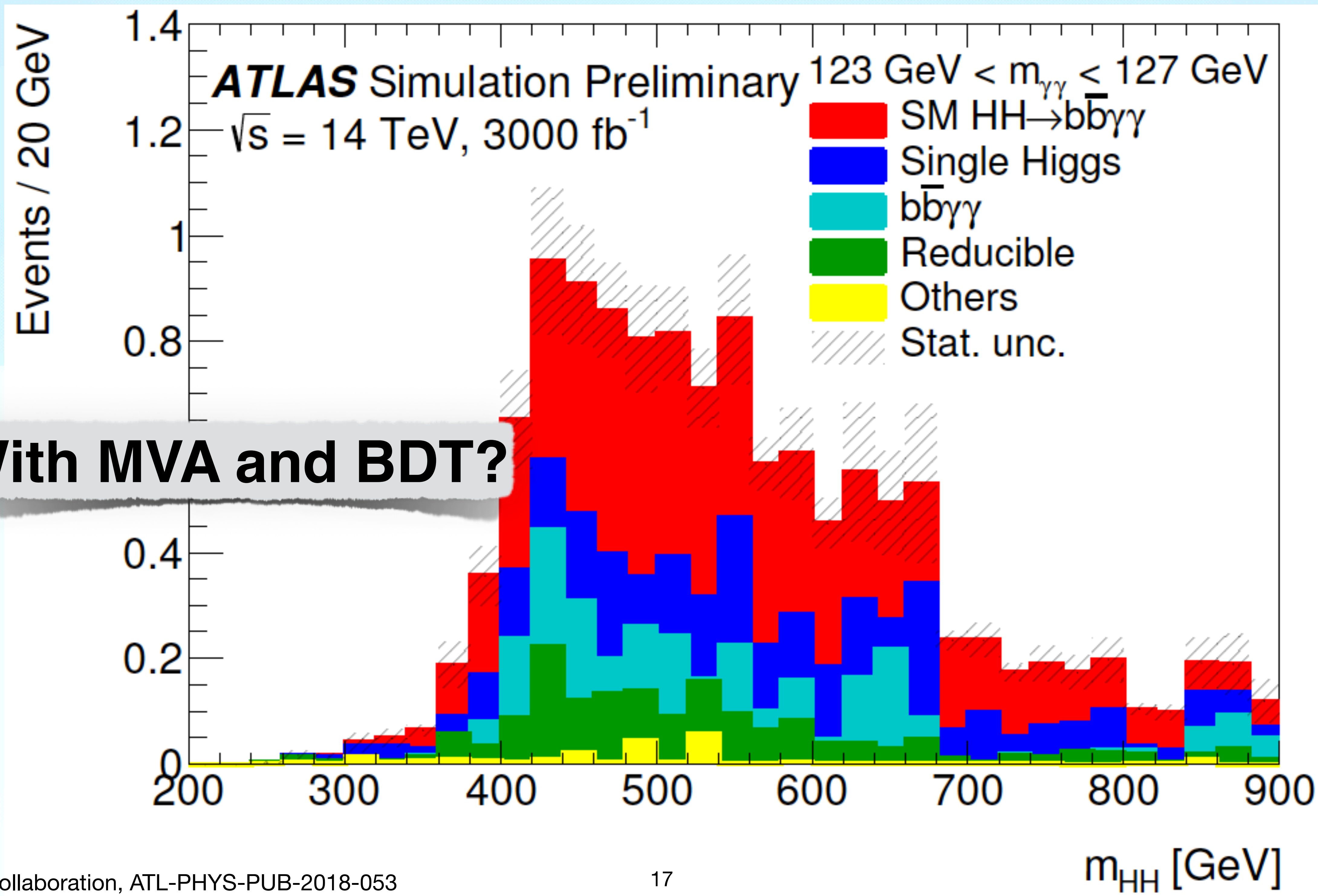


Motivation

- Even with ***smart machine***



With MVA and BDT?

ATLAS Collaboration, ATL-PHYS-PUB-2018-053

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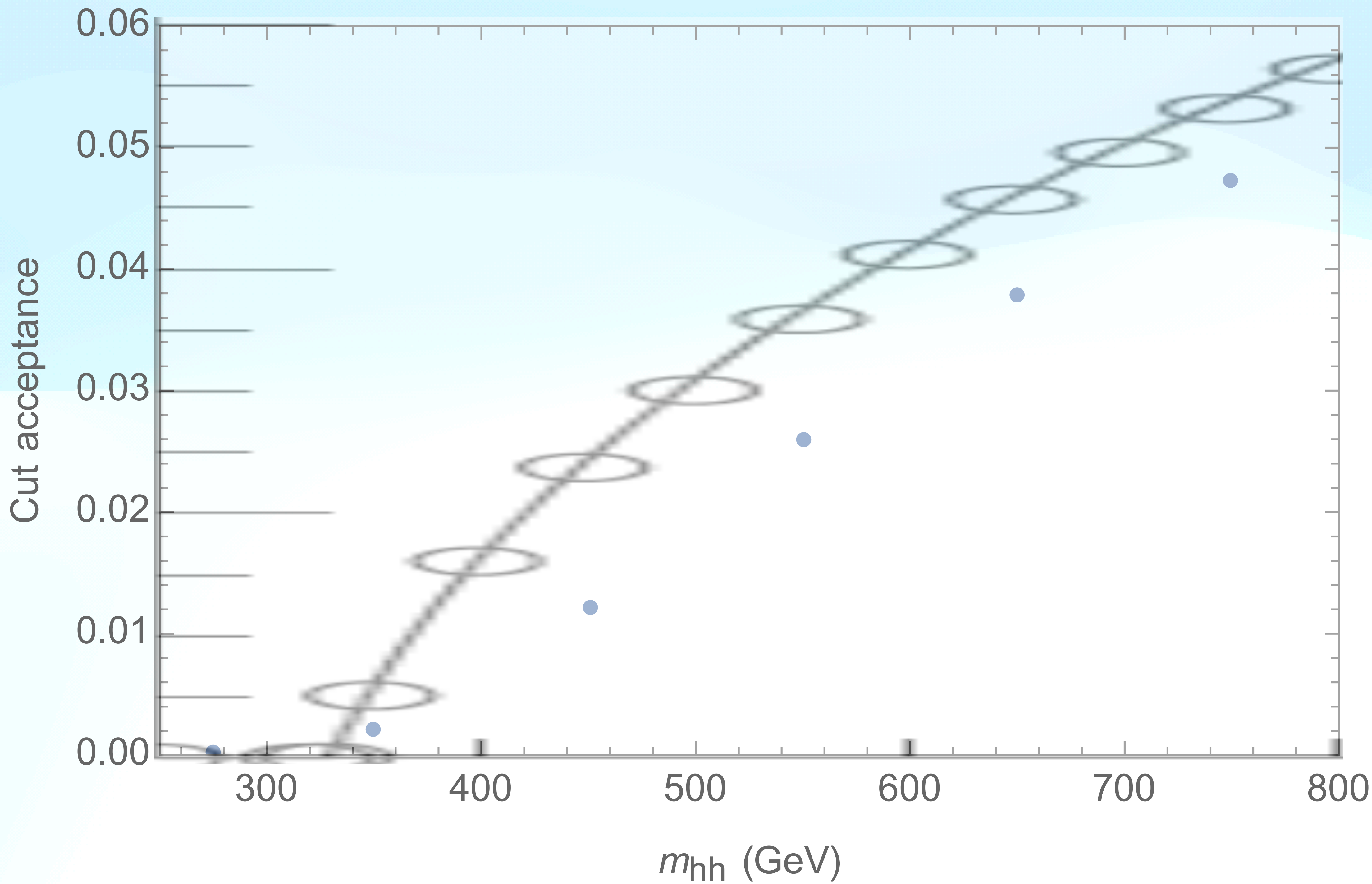

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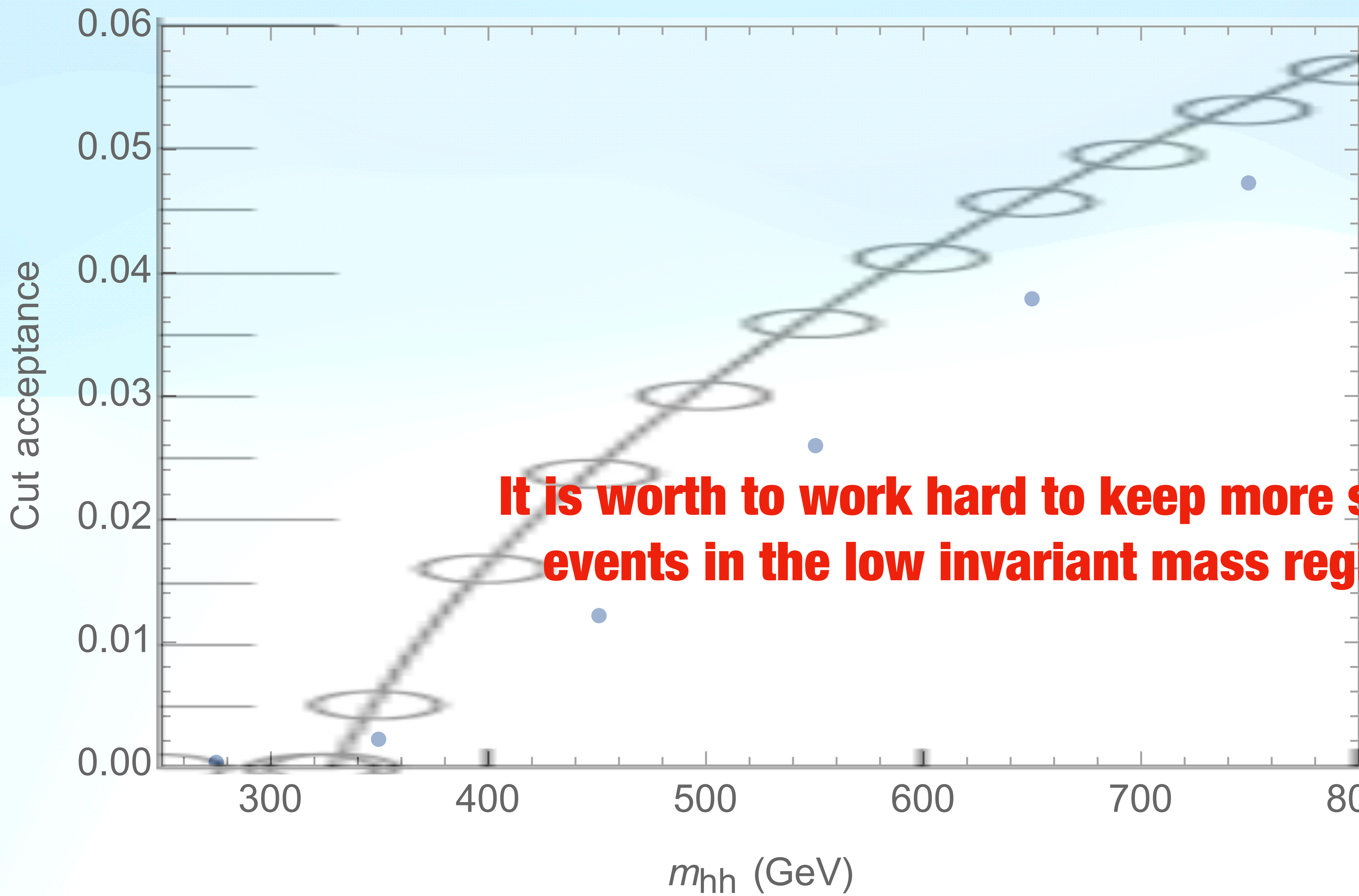

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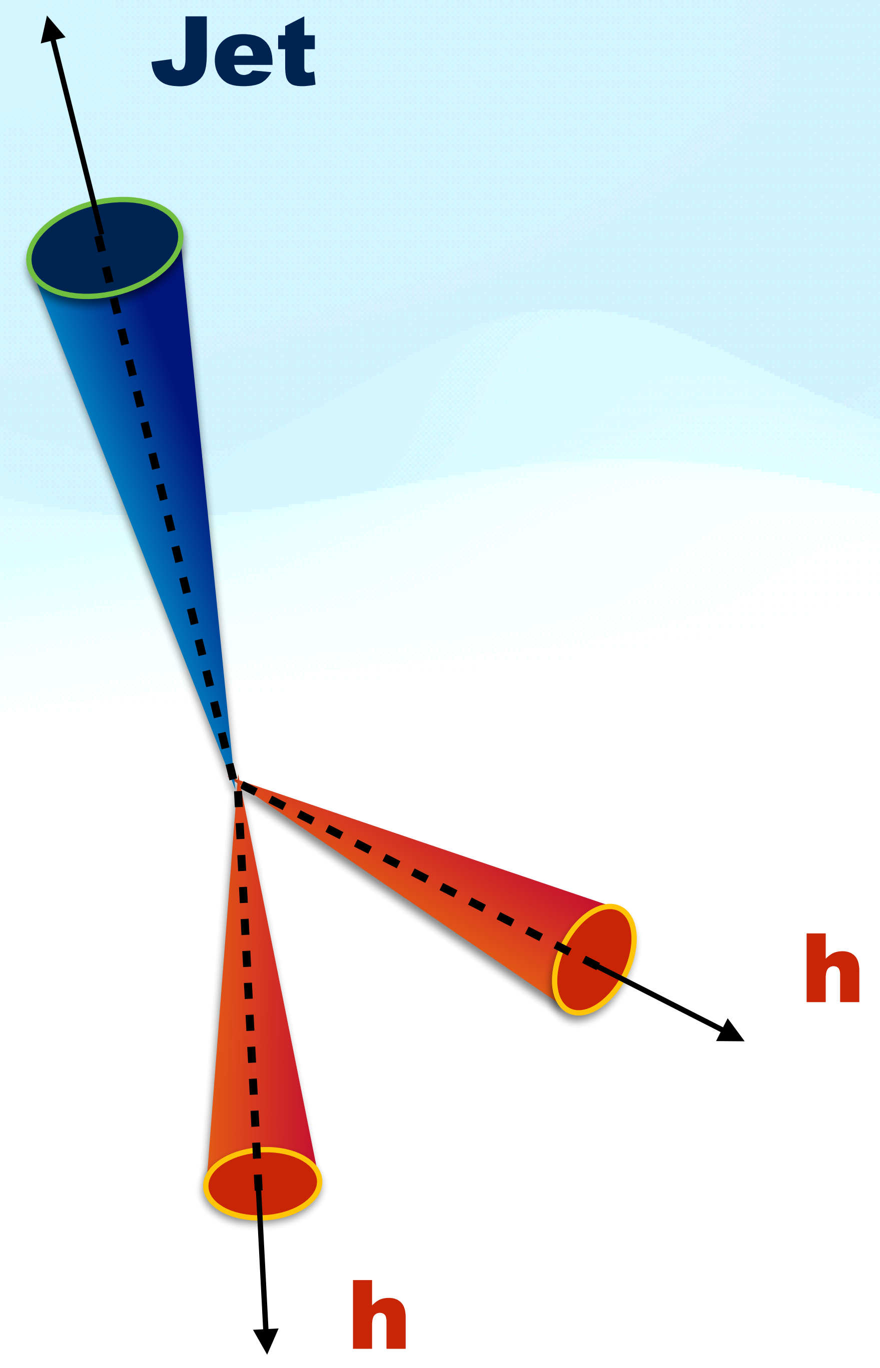
- A possible method is considering the HHj events.



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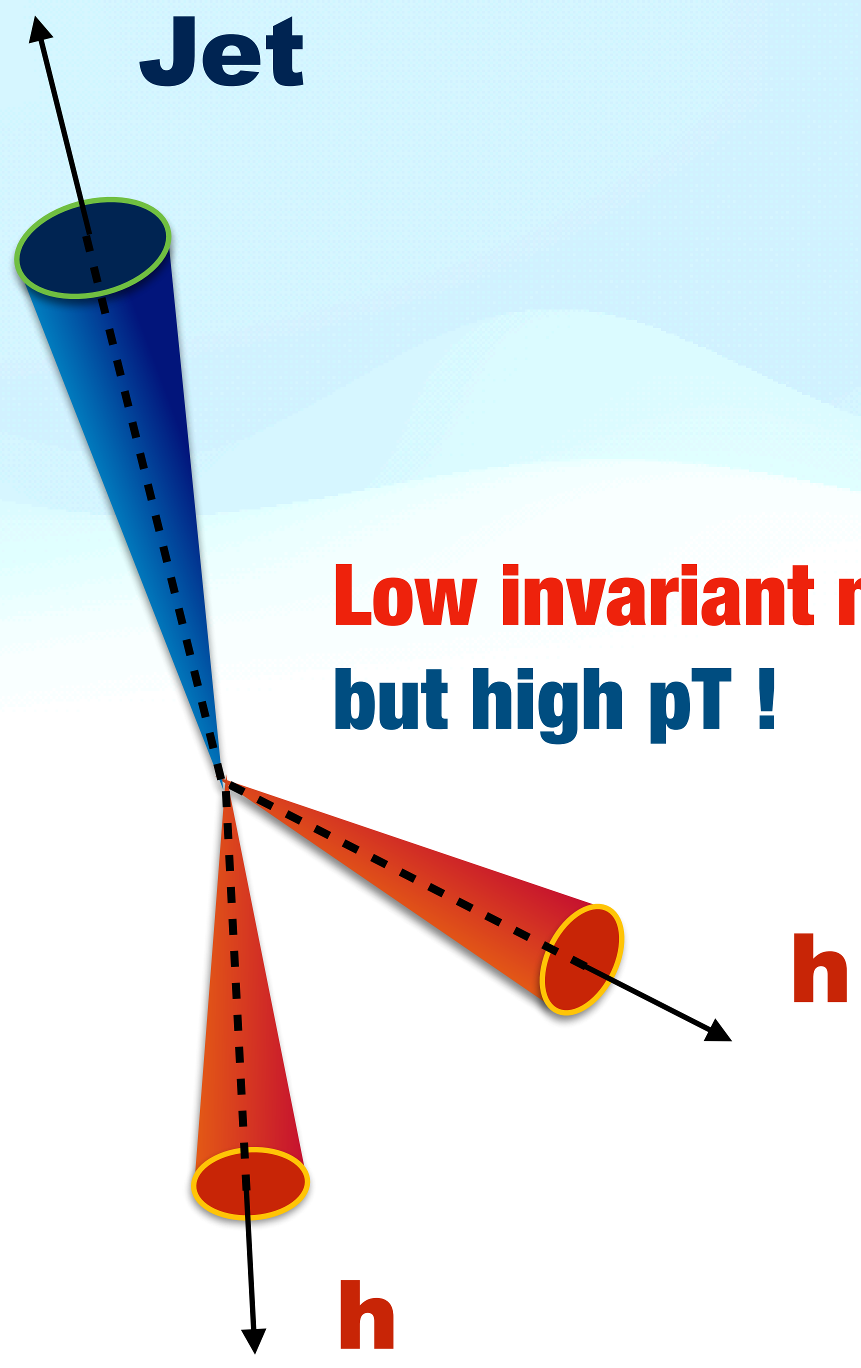
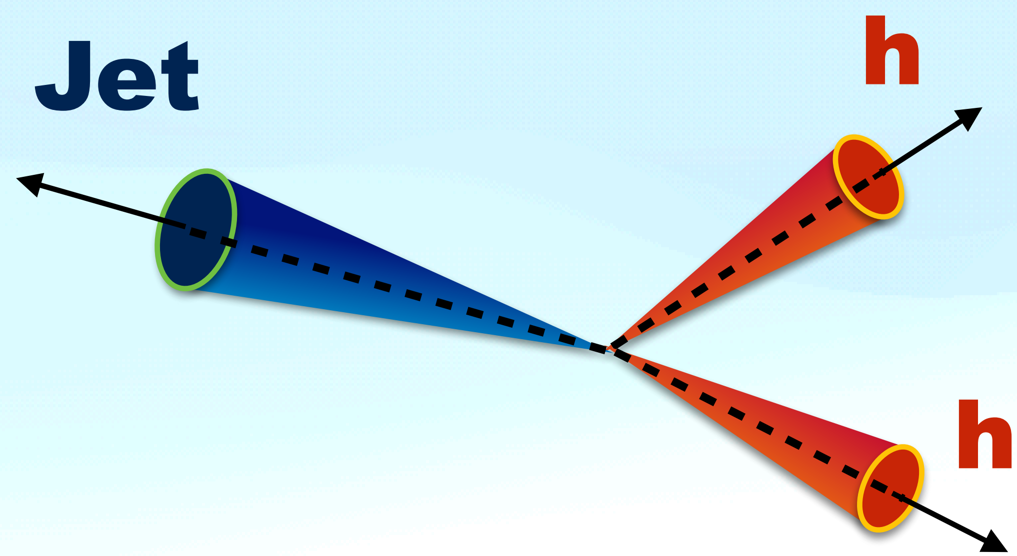
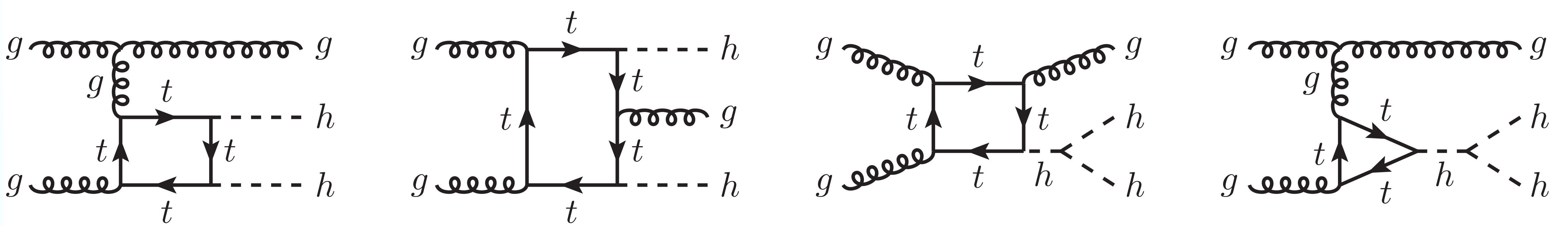


The Method

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

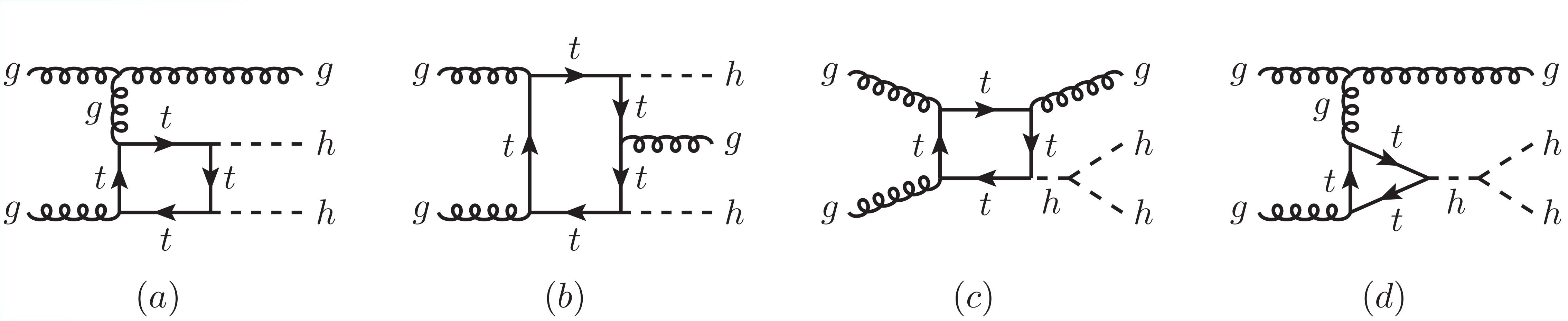




(a) (b) (c) (d)

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 Method

- A quick parton-level simulation ($bb\gamma\gamma$-channel)
- Main backgrounds:

$$pp \to t\bar{t}\,(h \to \gamma\gamma)$$
$$pp \to t\bar{t}\,(h \to \gamma\gamma)\,j$$
$$pp \to bb\gamma\gamma j$$
$$pp \to bb\gamma jj$$
$$pp \to bj\gamma\gamma j$$

- Kinematic cuts:

$$\Delta R_{bb,\gamma\gamma,b\gamma} < 0.4$$
$$p_{T,b} > 30\mathrm{GeV} \quad p_{T,\gamma} > 30\mathrm{GeV}$$
$$|\eta_b| < 2.5 \quad |\eta_\gamma| < 2.5$$
$$120\mathrm{GeV} < m_{\gamma\gamma} < 130\mathrm{GeV}$$
$$80\mathrm{GeV} < m_{bb} < 160\mathrm{GeV}$$
$$p_{T,j}^{\mathrm{leading}} > 150\mathrm{GeV}$$

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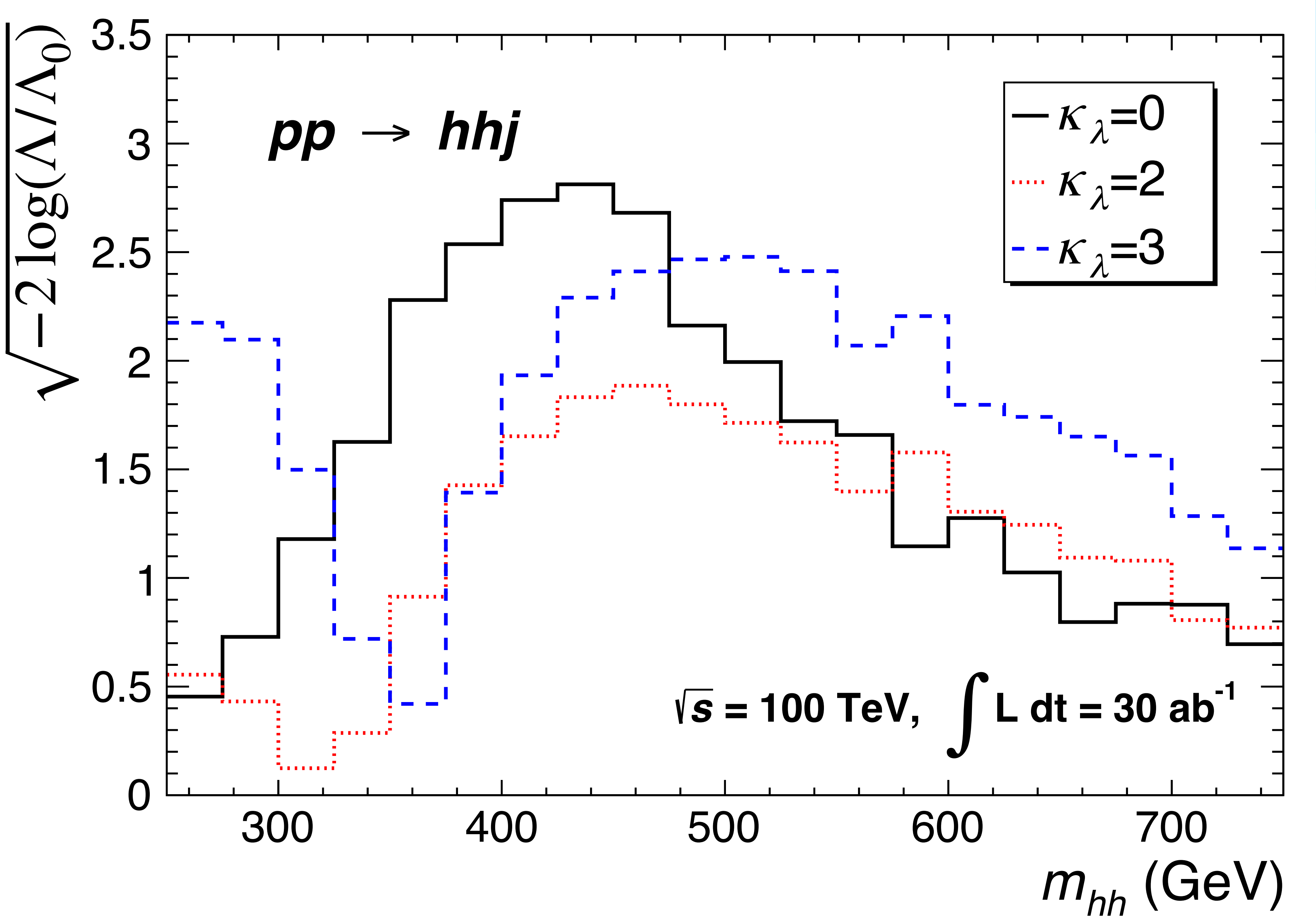

The Detector-Level Simulation

- 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*

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

$$< 6$$

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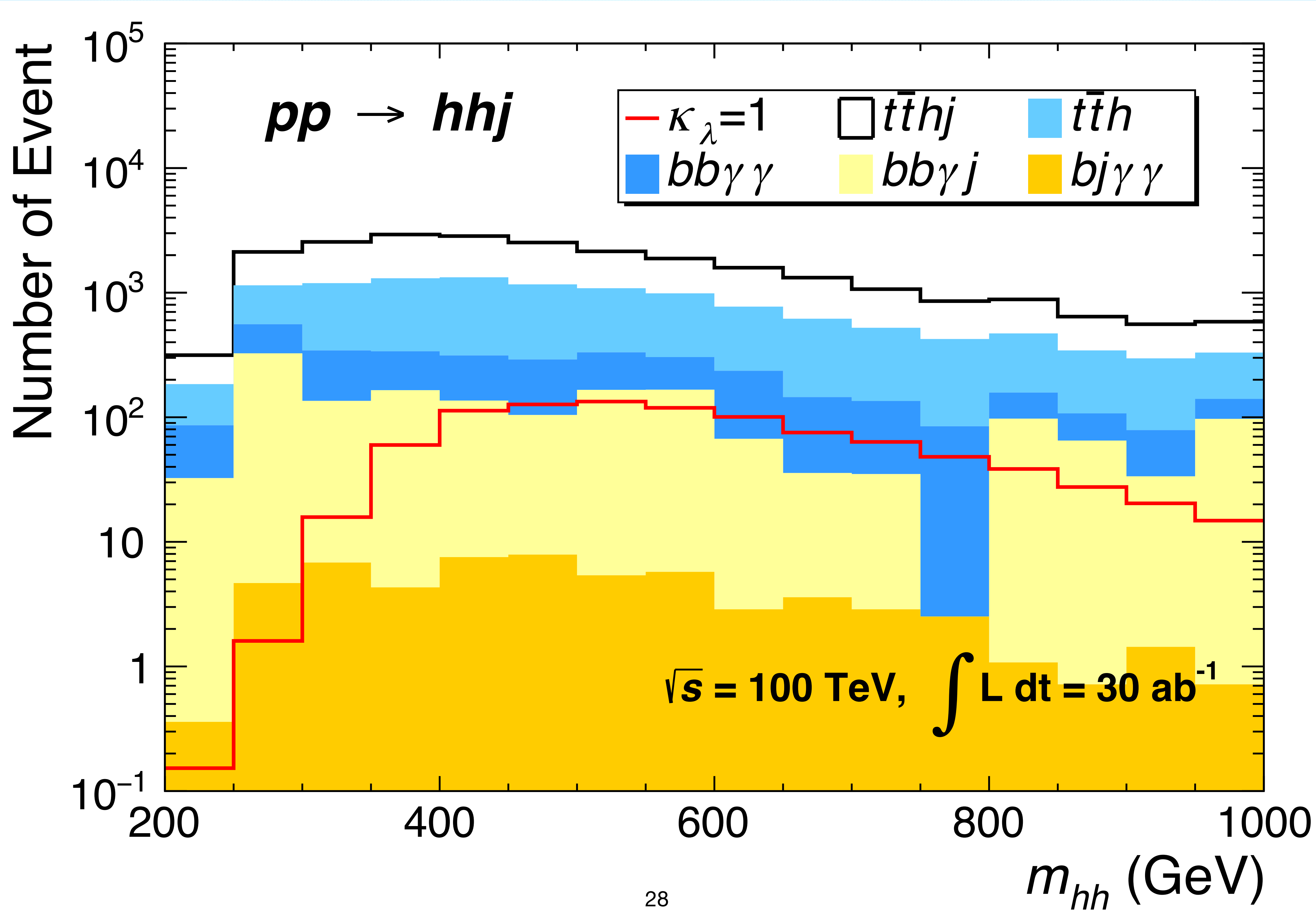

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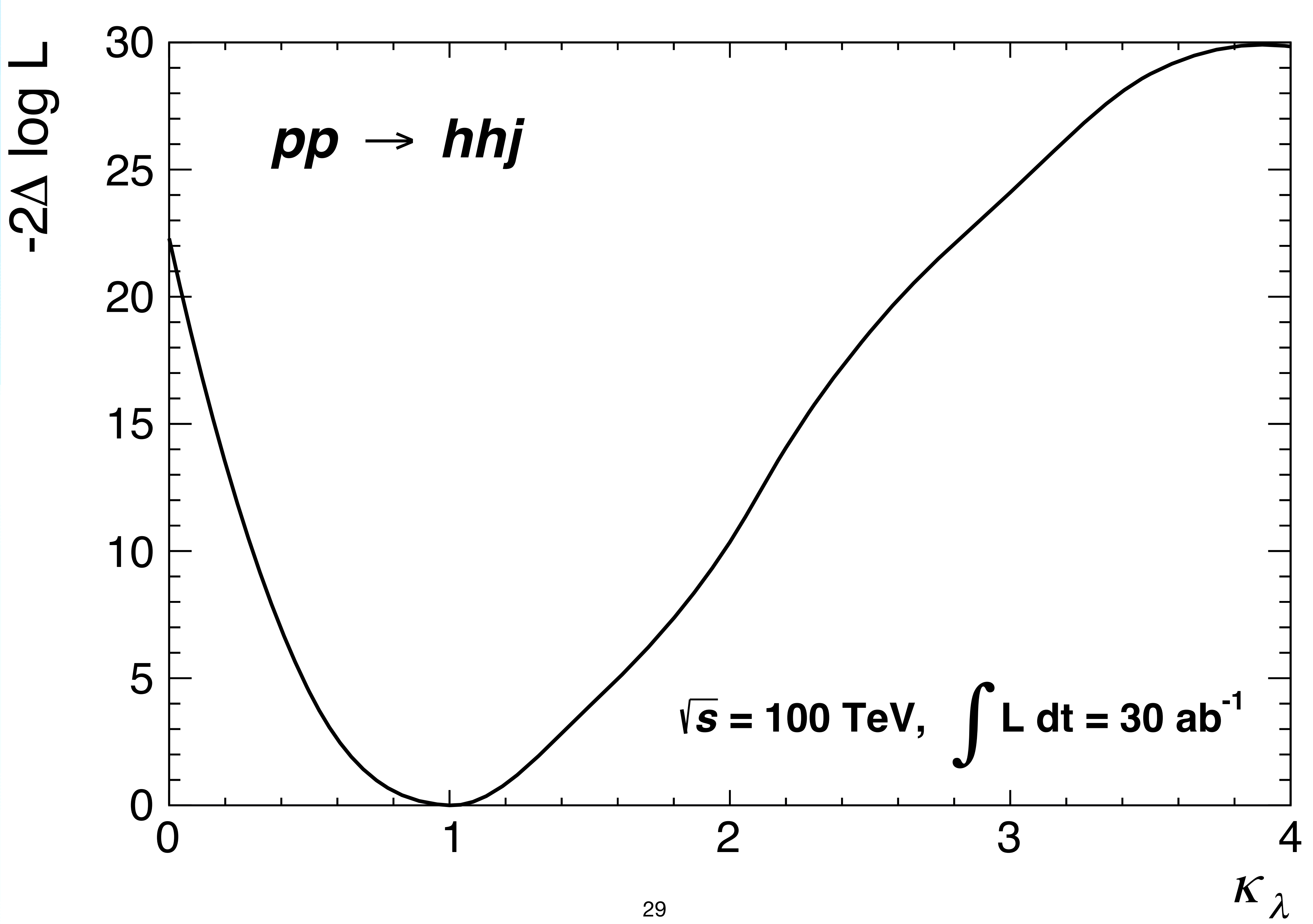

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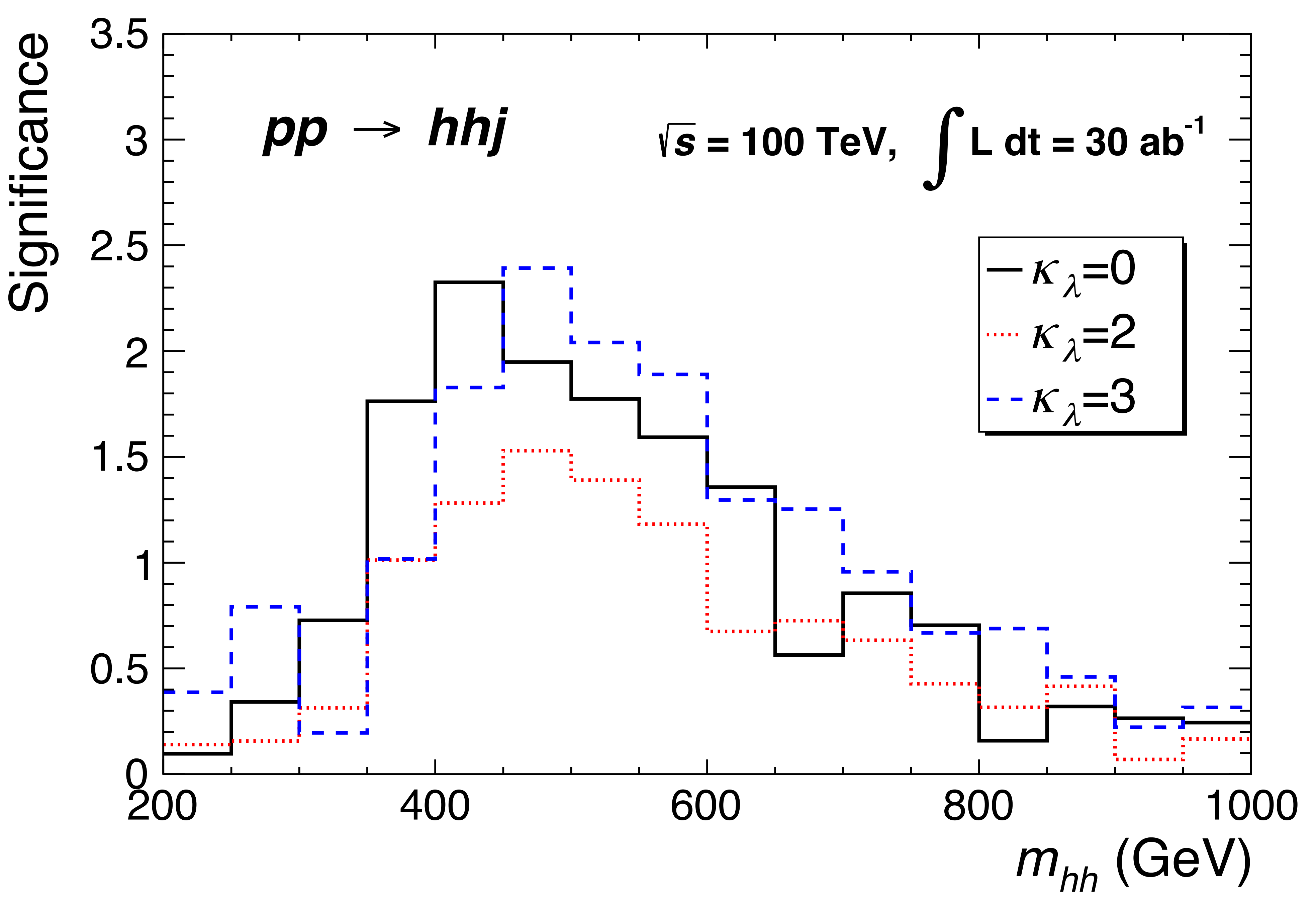

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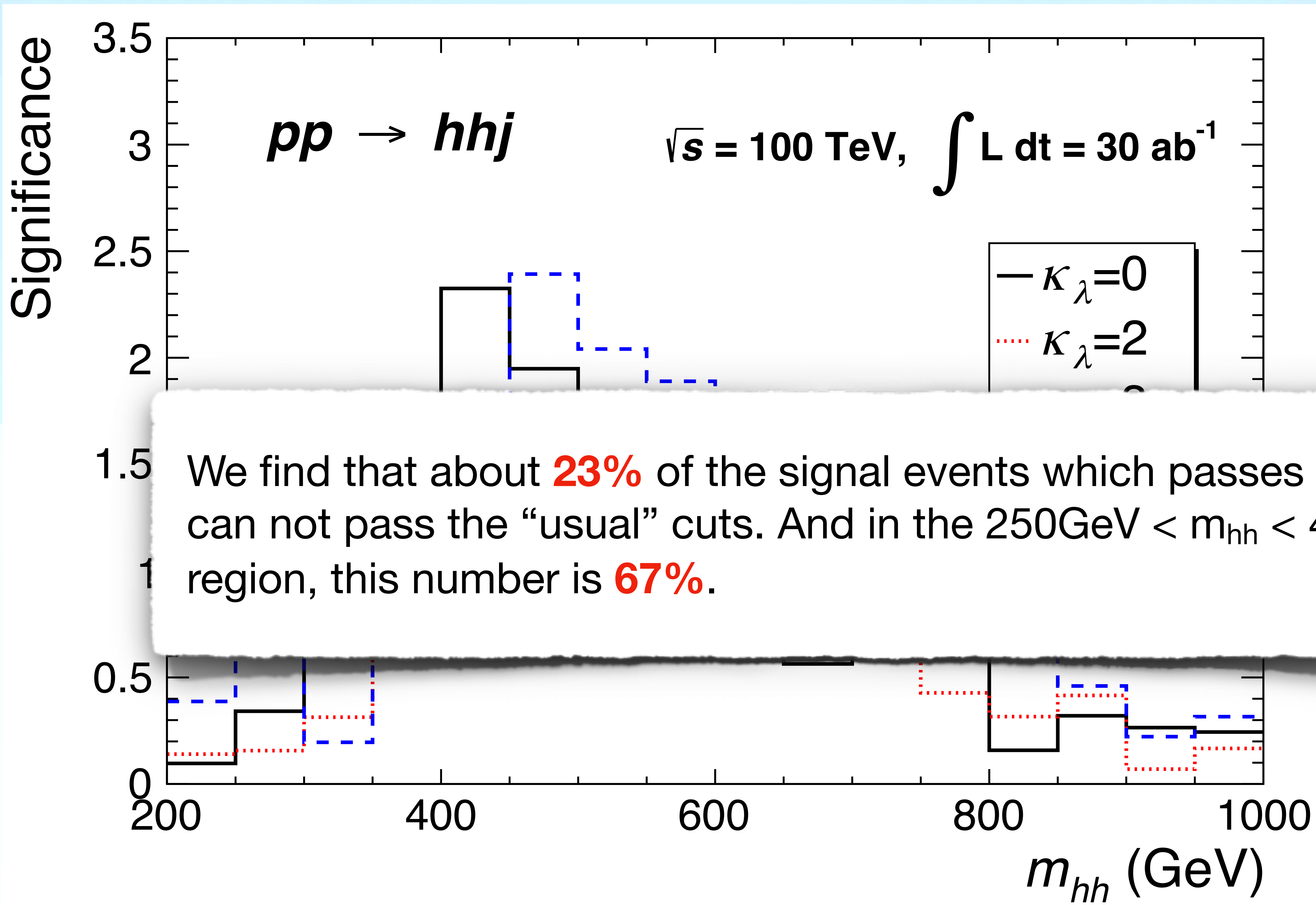

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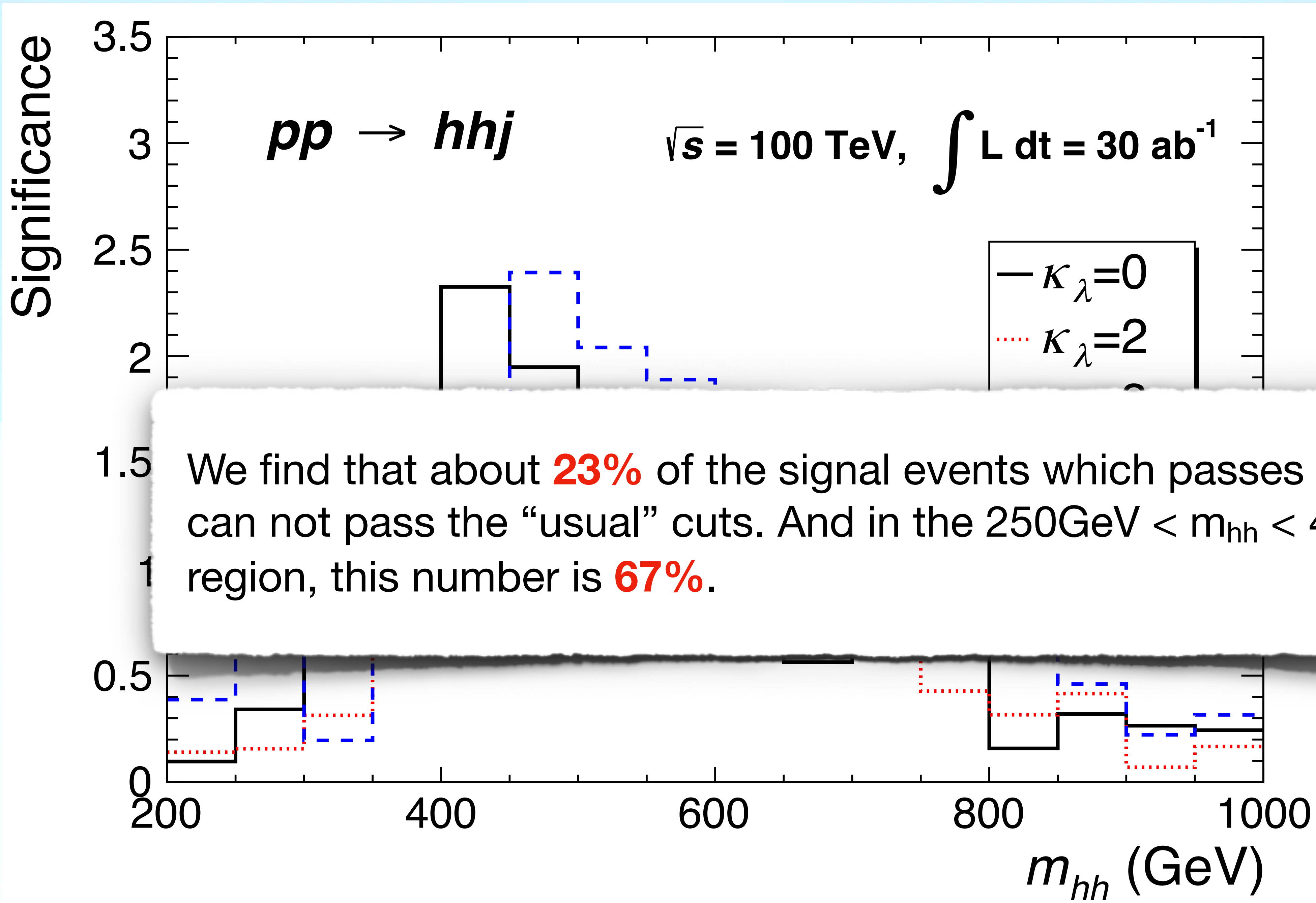

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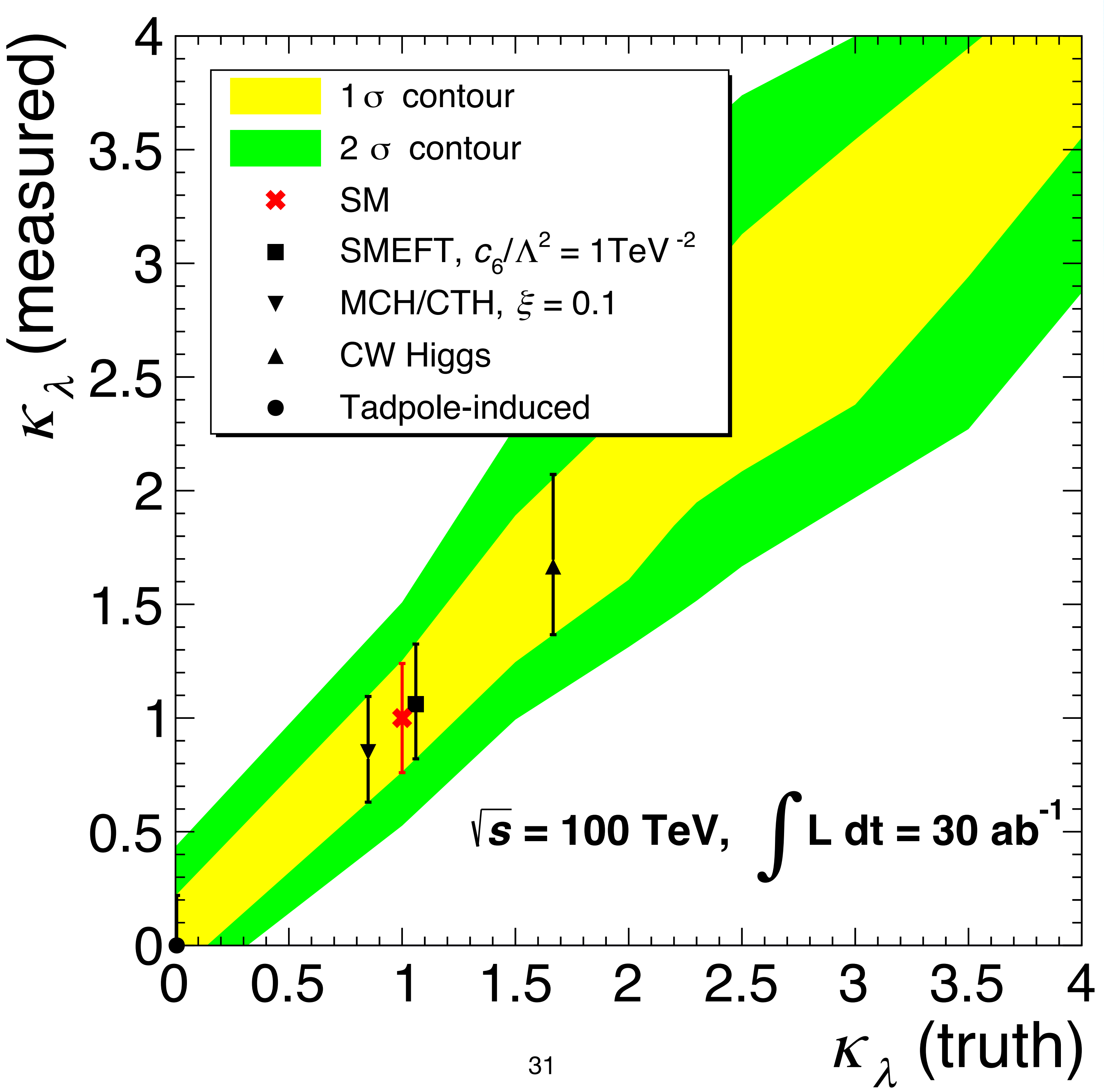
The word “usual” means the cuts in A. J. Barr, M. J. Dolan, C. Englert, D. E. Ferreira de Lima, and M. Spannowsky, “Higgs Self-Coupling Measurements at a 100 TeV Hadron Collider,” JHEP 02 (2015) 016, arXiv:1412.7154.

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.

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Thank you!