The Higgs boson as a probe at hadron colliders

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Nikhef

[The Future of Particle Physics: A Quest for Guiding Principles, Karlsruhe, 01-02/10/18]

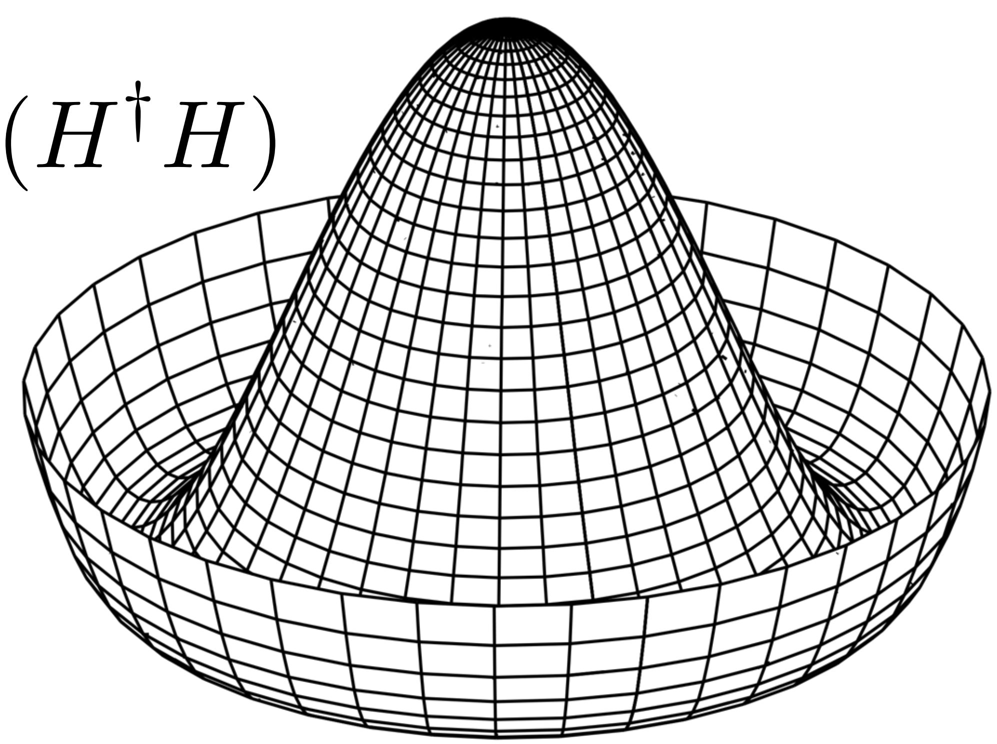
electro-weak symmetry breaking

- amongst the main goals of High Energy Physics:

  to understand electro-weak symmetry breaking (EWSB).

➡ study the central protagonist, the Higgs boson:

$\mathcal{V}(H^\dagger H)$



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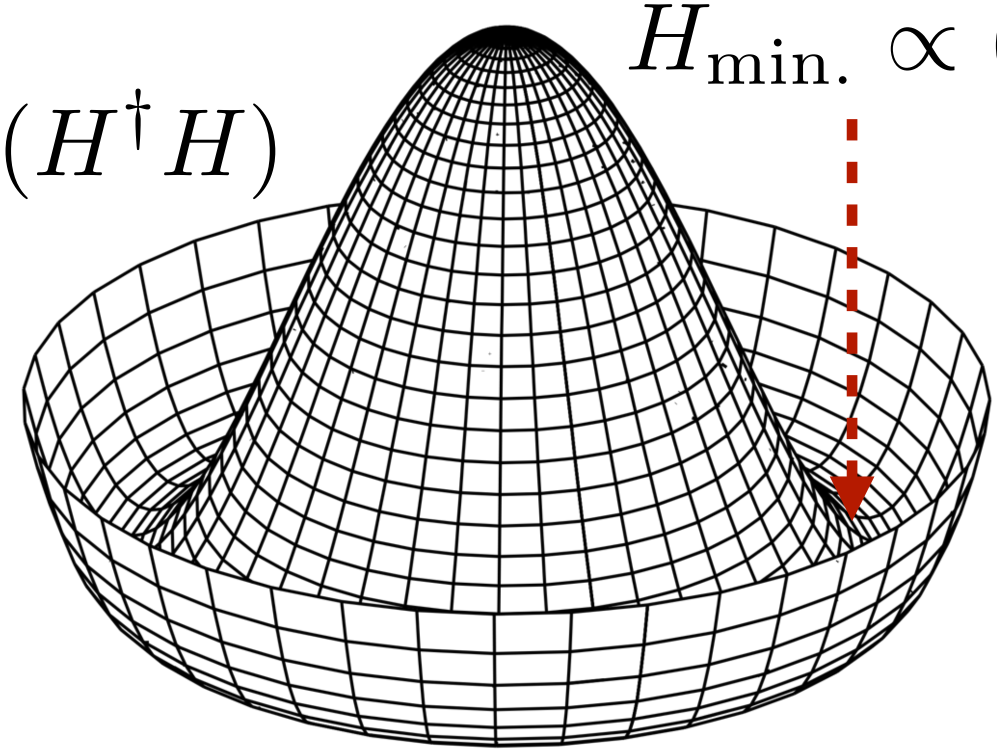

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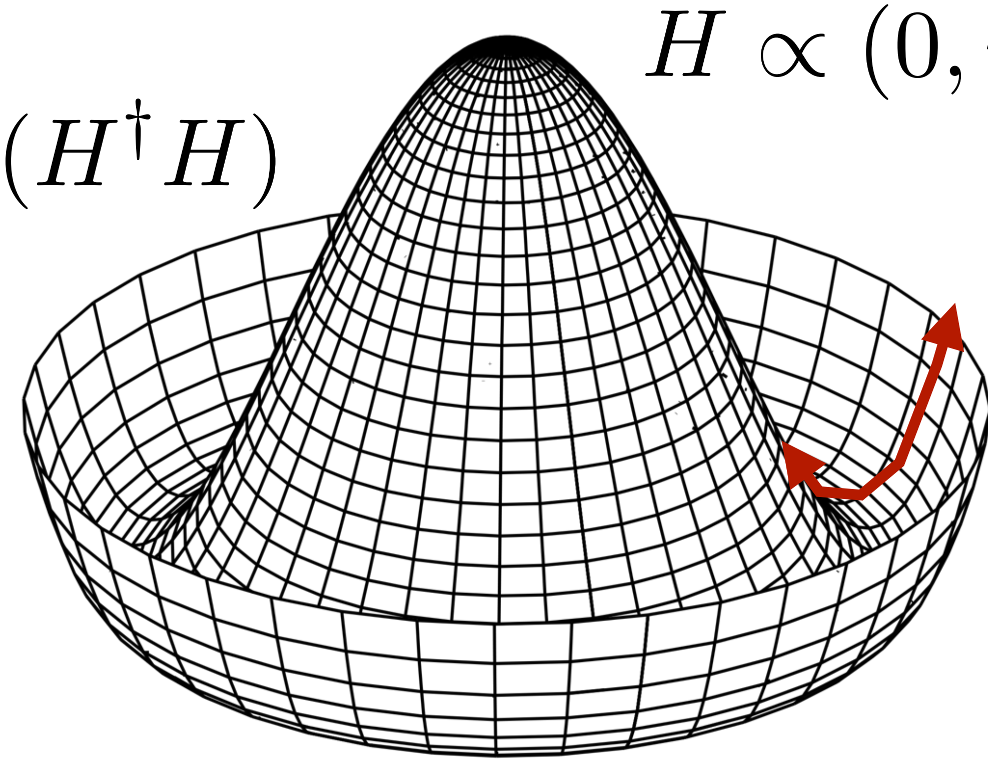

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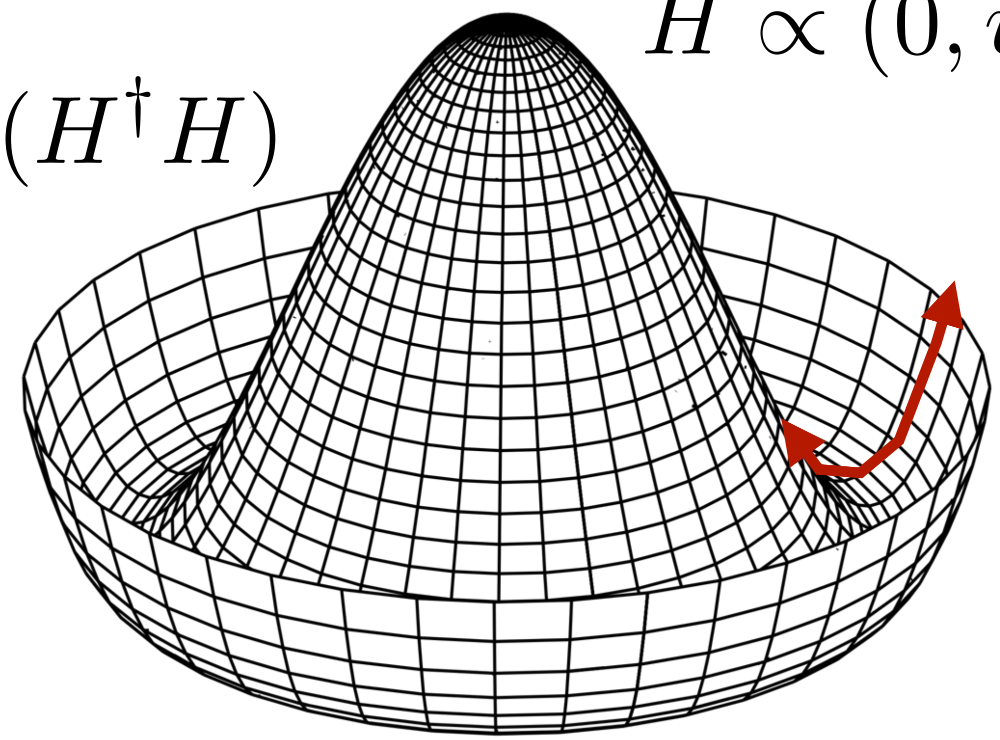

$H \propto (0, v + h)$

$\Rightarrow$

e.g. fermion masses & interactions:

$$\mathcal{L} \supset - m_f \bar{f}_L f_R - \frac{m_f}{v} h \bar{f}_L f_R + \text{h.c.}$$

electro-weak symmetry breaking

e.g. gauge boson masses and interactions:

$$\Longrightarrow \mathcal{L} \supset [m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu] \left(1 + \frac{h}{v}\right)^2$$

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e.g. Higgs mass and self-interactions:

$$\Longrightarrow \mathcal{L} \supset -\frac{1}{2} m_h^2 h^2 - \frac{m_h^2}{2v} h^3 - \frac{m_h^2}{8v^2} h^4$$

electro-weak symmetry breaking

also: effective interactions of Higgs bosons and gluons/photons:

$$\Rightarrow \quad \mathcal{L} \supset \frac{\alpha_S}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{h}{v} + \frac{\alpha_{\mathrm{em}}}{2\pi} F^{\mu\nu} F_{\mu\nu} \frac{h}{v} \left(N_c \frac{e_t^2}{3} - \frac{7}{4} \right)$$

[see, e.g. B. Kniehl, M. Spira, hep-ph/9505225]

EWSB & new scalars

- Higgs doublet bilinear $H^\dagger H$:

  only <u>gauge</u> & <u>Lorentz invariant</u> ***D*=2** SM operator.

➡ e.g. could couple to new <u>singlet scalar</u> ***S***:

$$\mathcal{L} \supset -\frac{\lambda_{HS}}{2} H^\dagger H S^2$$

Extra BONUS!

EWSB & new scalars

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only <u>gauge</u> & <u>Lorentz invariant</u> ***D*=2** SM operator.

➡ e.g. could couple to new <u>singlet scalar</u> ***S***:

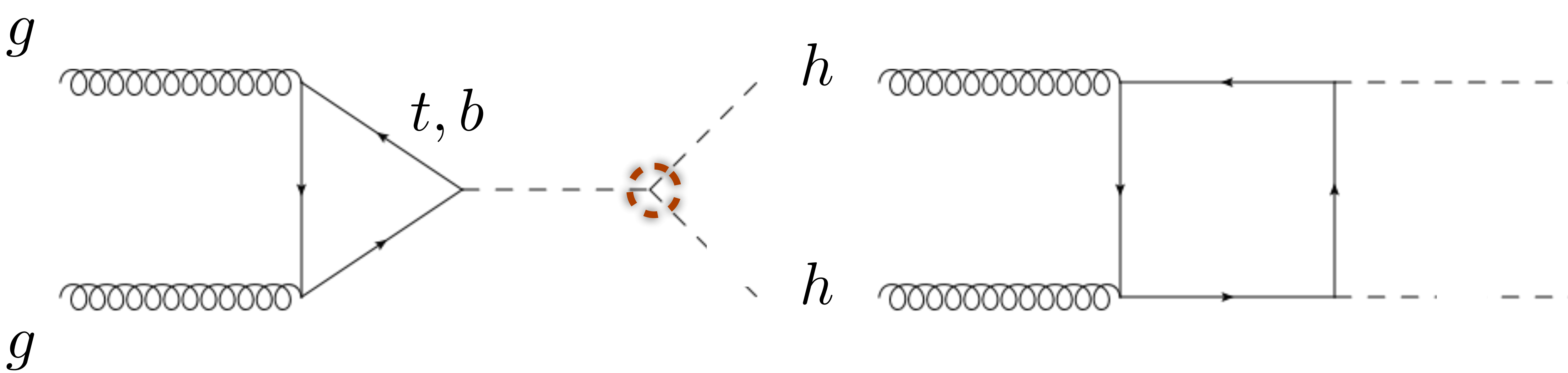
EWSB: $H \propto (0, v + h)$

$$\mathcal{L} \supset -\frac{\lambda_{HS}}{2} H^\dagger H S^2 \implies \mathcal{L} \supset -\lambda_{HS} v h S^2$$

➡ the Higgs boson can be used **to study the SM**, e.g. the self-couplings via:

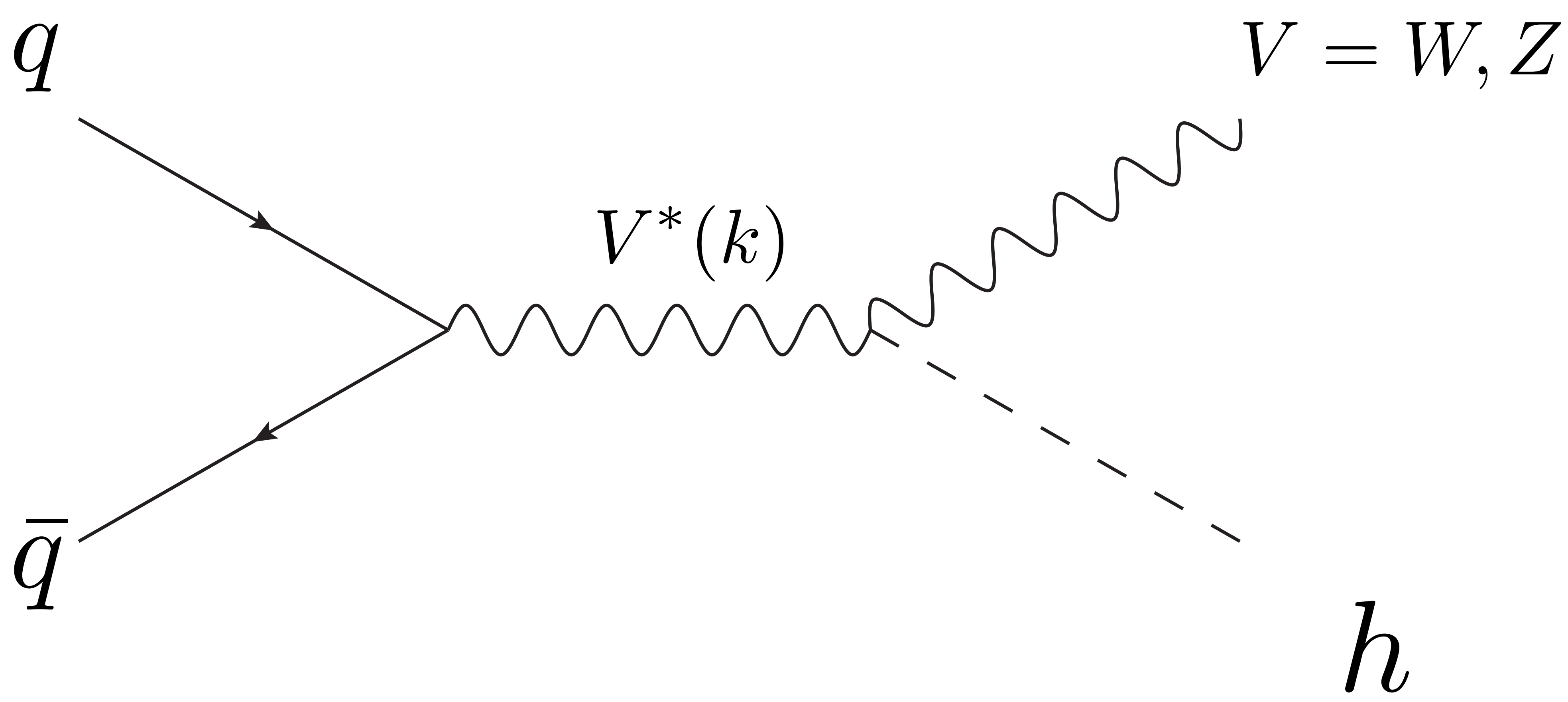
$$pp \to hh$$ **(also:** $pp \to hhh$**)**

[see talk by J. Baglio]



or via associated production with vector bosons:

$$pp \to hV$$ **(and:** $pp \to hhV$**)**



[this talk!]

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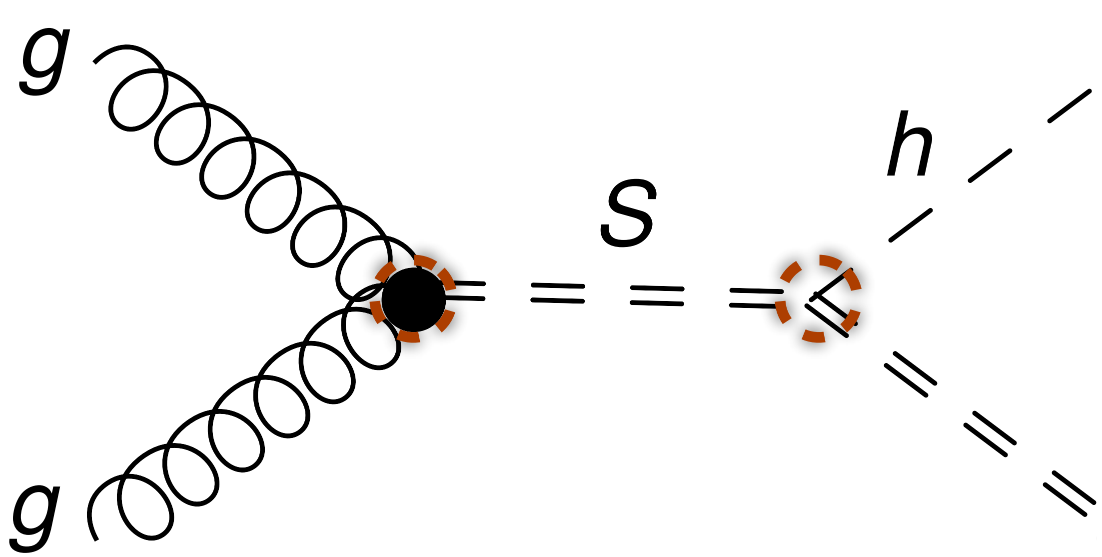
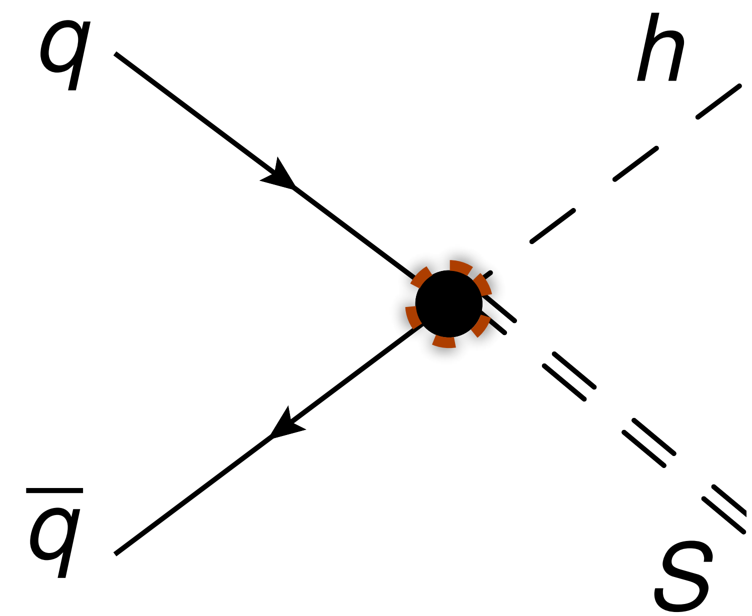
or by relating new particles to EWSB:

$$pp \to hS$$

[Carmona, Goertz, **AP**, 1606.02716]



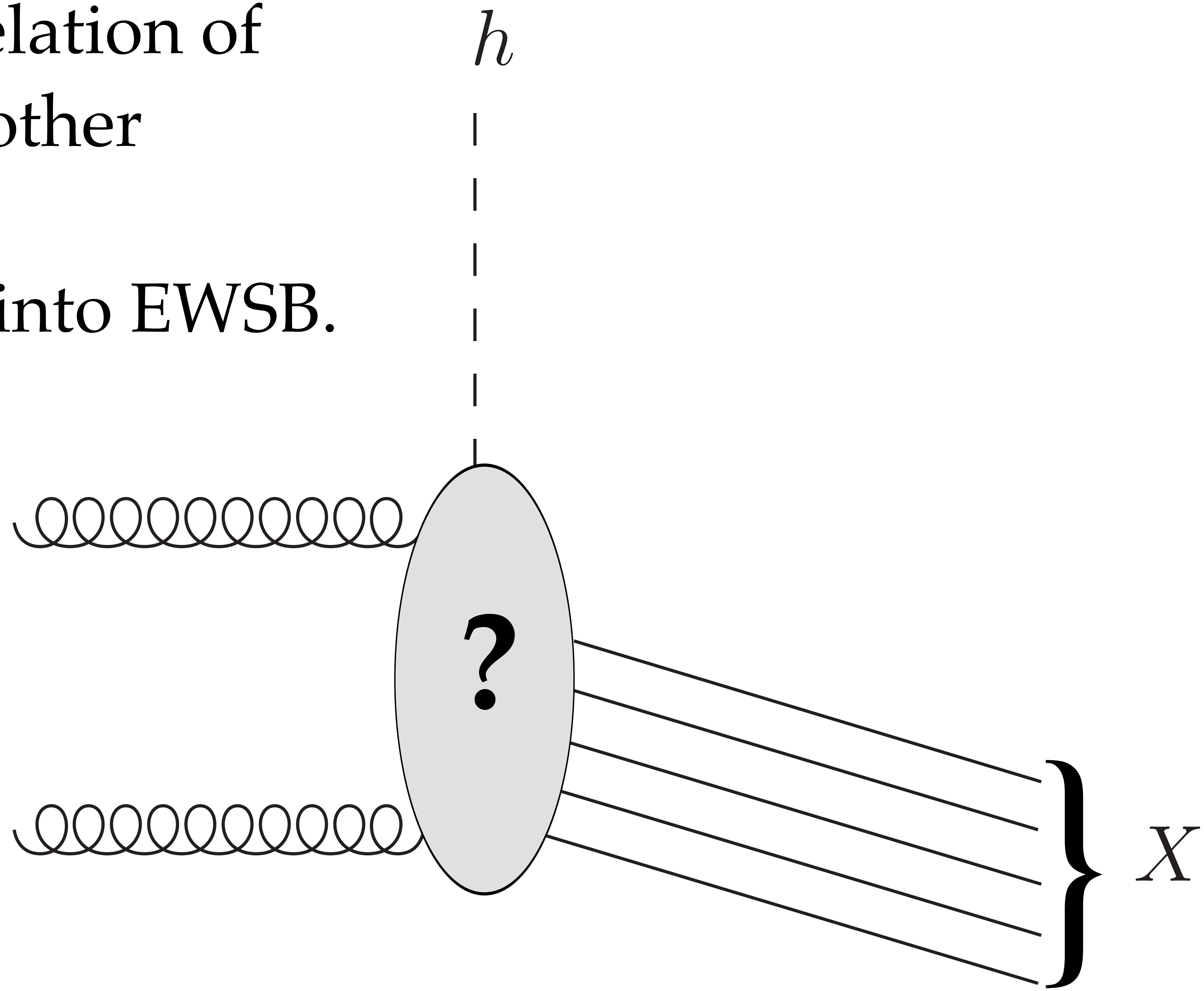


[not this talk, but see appendices]

➡ the Higgs boson will be used as a probe at the LHC and future colliders:

→ learn about relation of Higgs boson to other particles,

→ gain insights into EWSB.



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→ learn about relation of Higgs boson to other particles,

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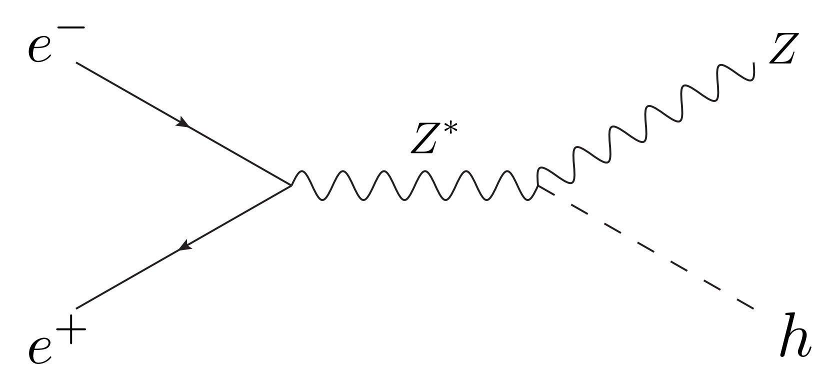
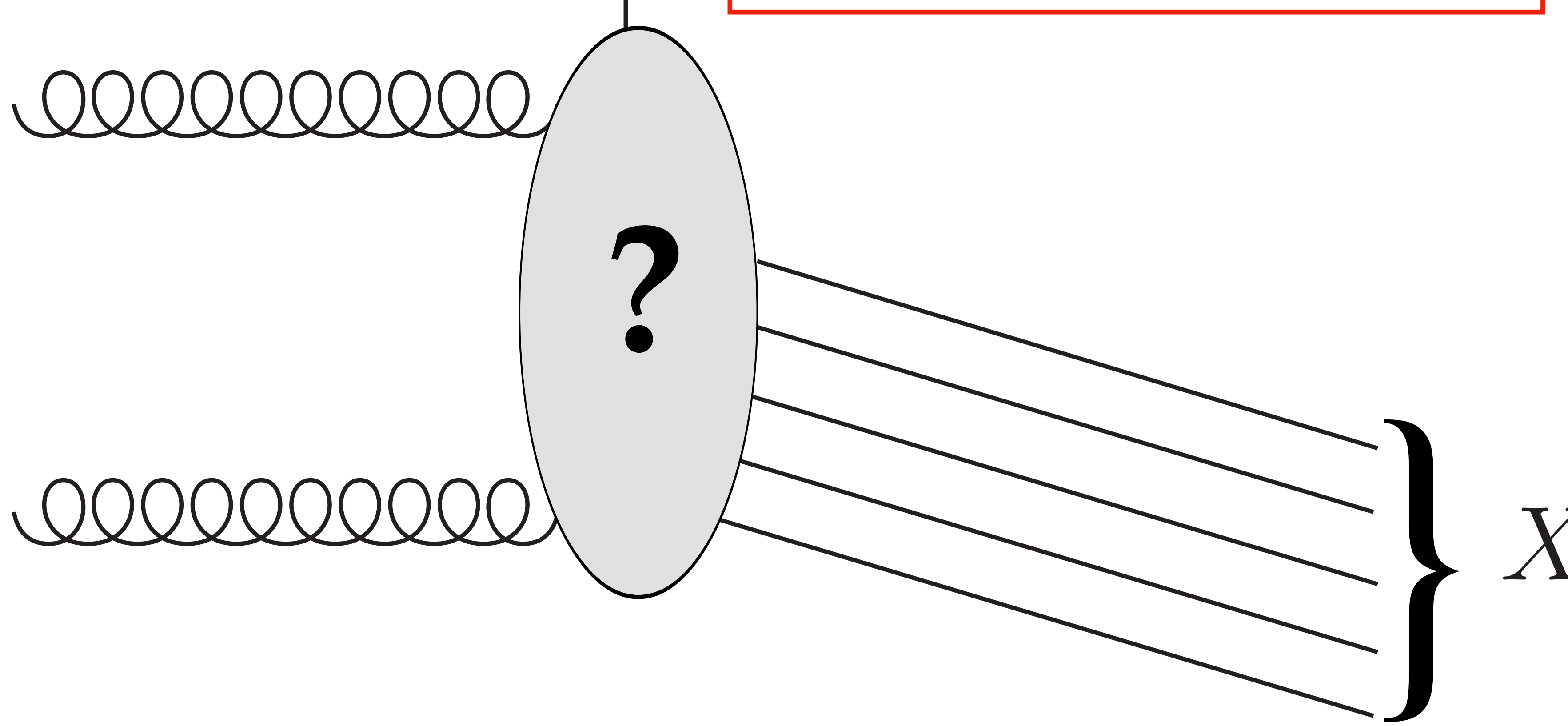
note: $\mathbf{e^+e^-}$ machines <u>primarily</u> through associated production!





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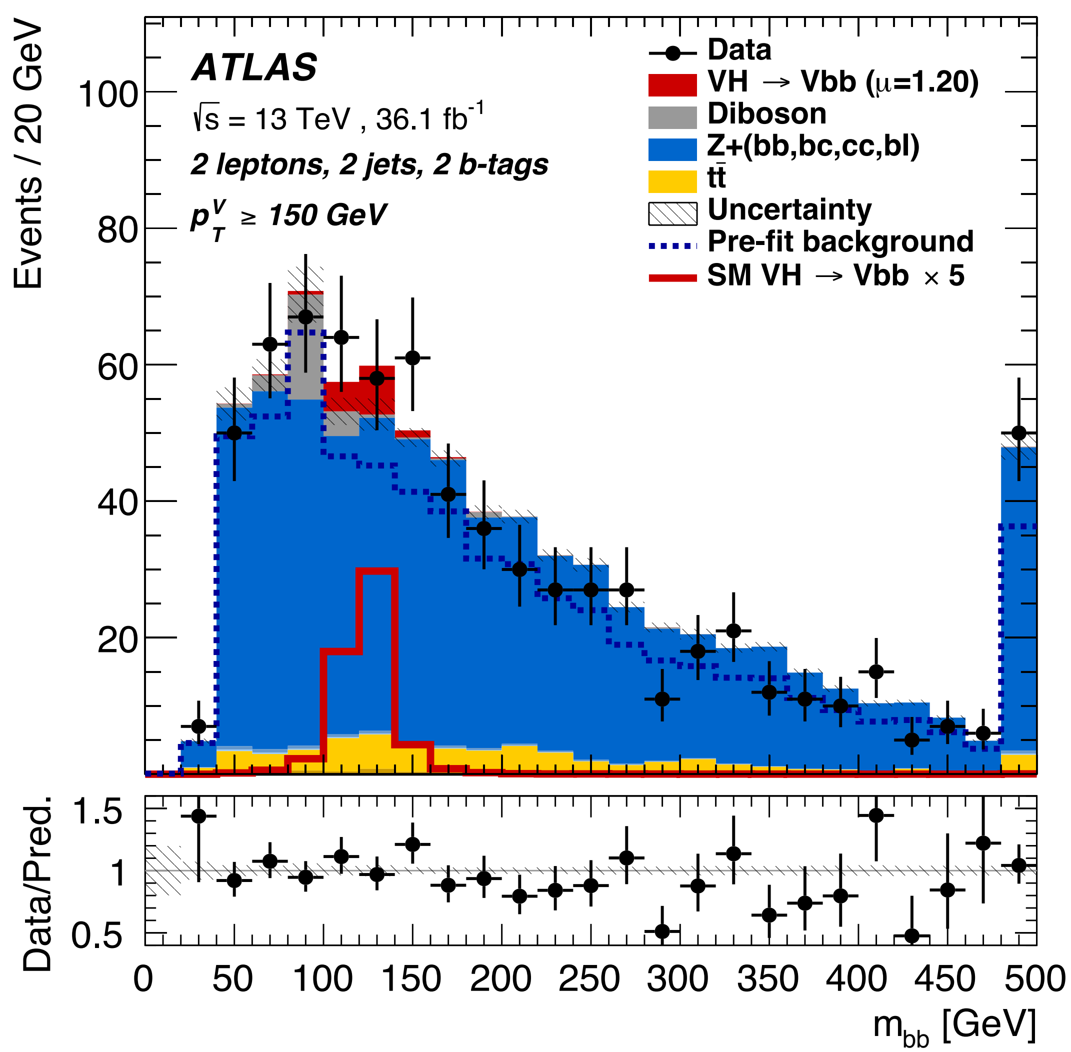
Higgs associated production:

- $pp \to hh$ [see talk by J. Baglio]
- $pp \to hV$ this talk!
- $pp \to hS$ [not this talk, but see appendices]
- $pp \to ht\bar{t},\ pp \to h + \text{jets},\ [\ldots]$ [not this talk, but extremely interesting!]

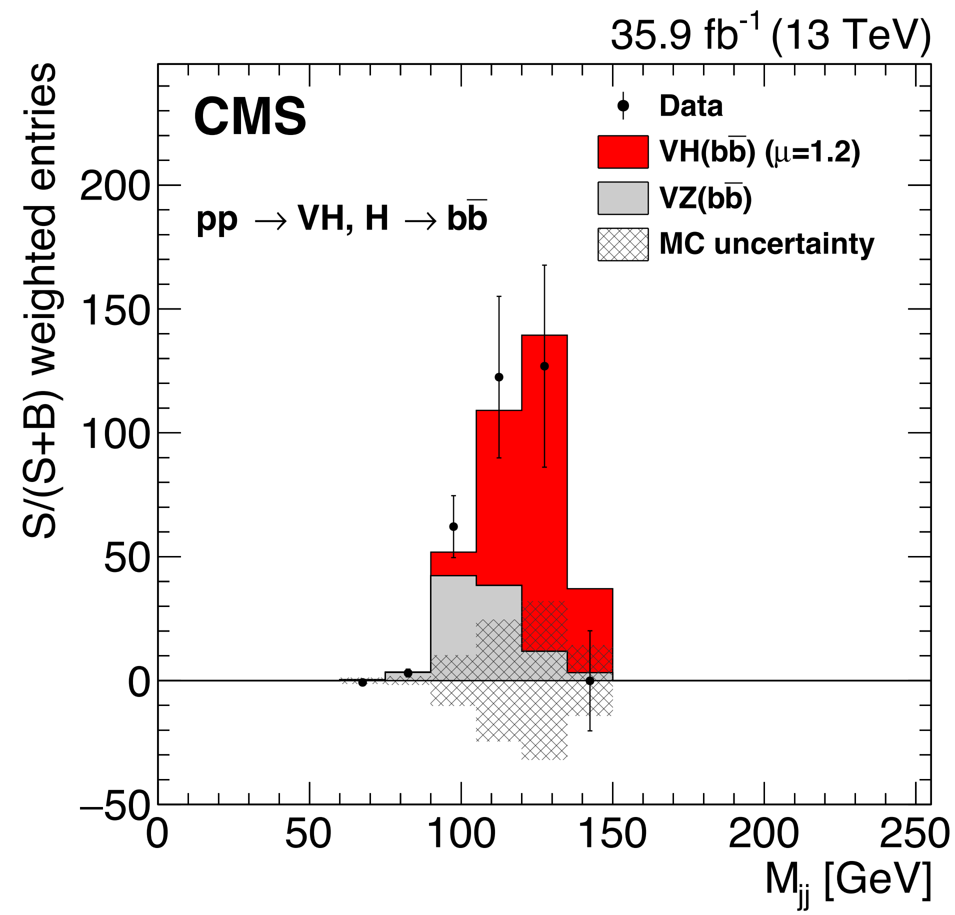
Higgs+Vector boson

→ observed in LHC Run II data: $Vh(\to b\bar{b})$

[ATLAS, 1708.03299, CMS 1709.07497]

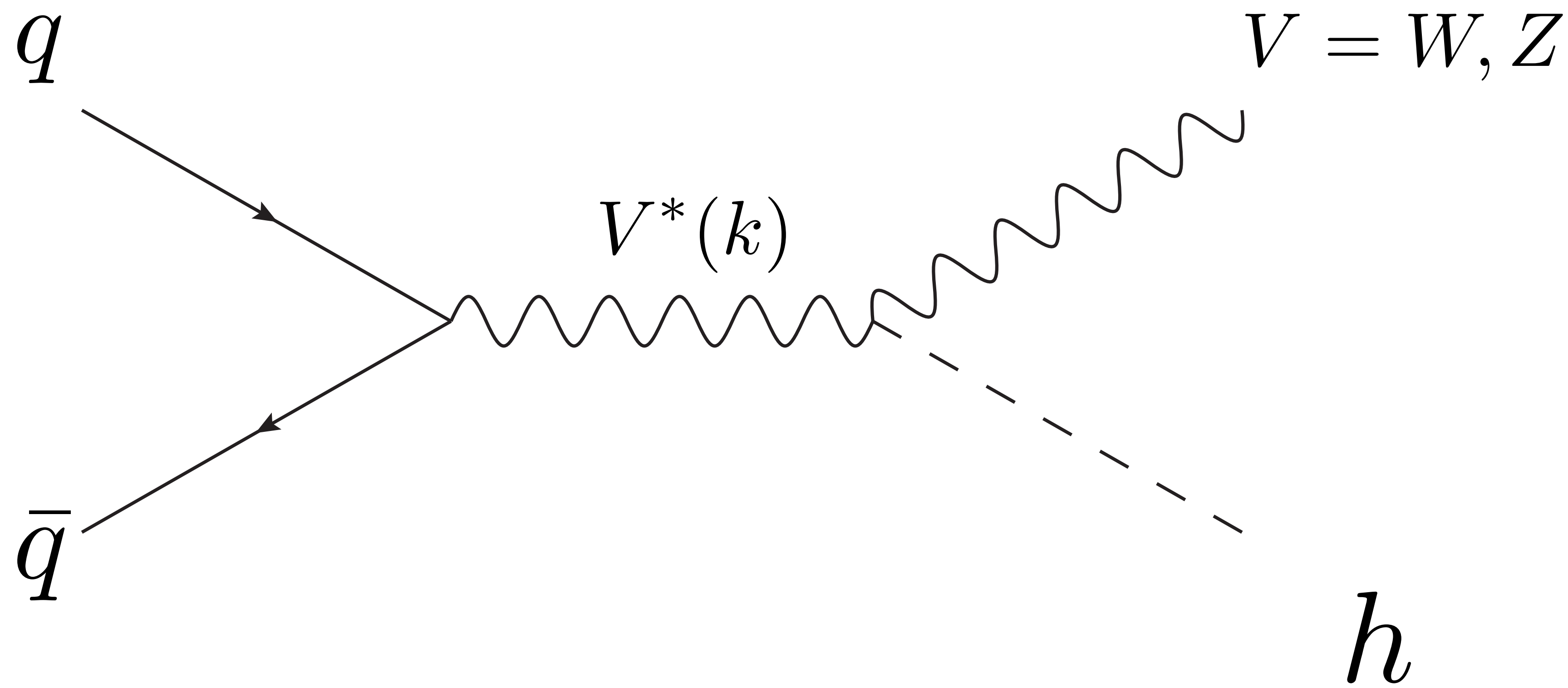


[The post-fit distributions for the bottom-anti-bottom invariant mass.]



[Weighted dijet invariant mass distribution for events in all channels combined. Shown are data and the VH and VZ processes with all other background processes subtracted.]

Drell-Yan-like **pp → *hV***

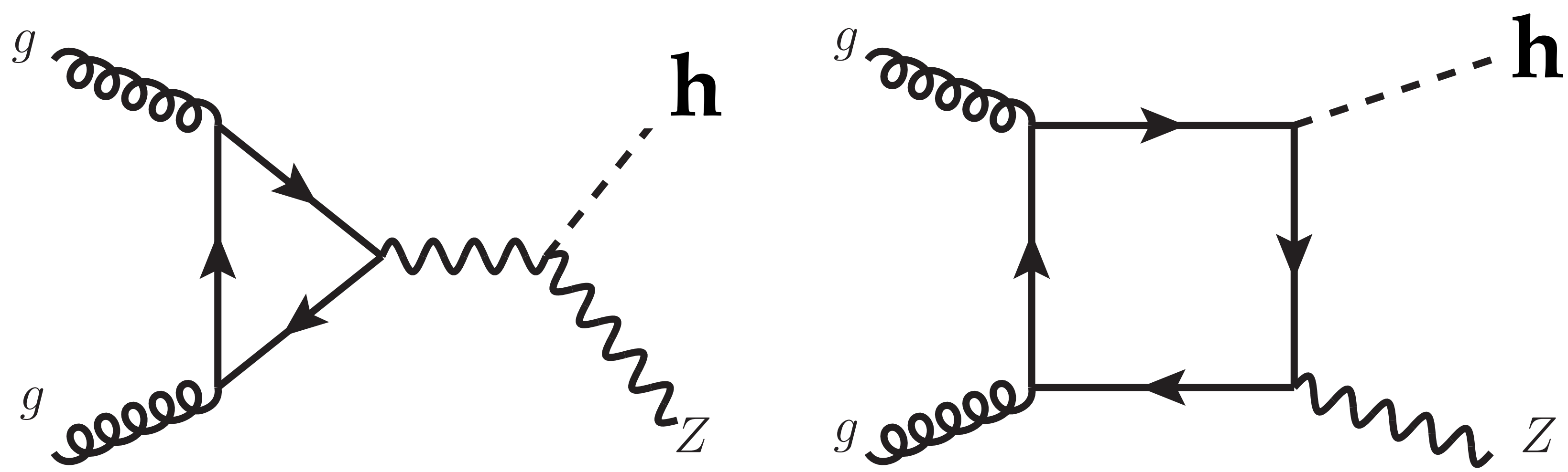


$$\sigma_{\mathrm{DY}}^{VH} \simeq \int \mathrm{d}k^2 \sigma^{V^*}(k^2) \frac{\mathrm{d}\Gamma_{V^* \to VH}}{\mathrm{d}k^2}$$

- known to NNLO in QCD. [e.g. Brein, Djouadi, Harlander, hep-ph/0307206]
- electro-weak corrections also known.

[Ciccolini, Dittmaier, Krämer hep-ph/0306234, Denner, Dittmaier, Kallweit, Mück 1112.5242]

gg → *hZ*



- formally: an NNLO QCD contribution to **pp** → ***hZ***.

- exact QCD corrections currently **not** available.

[Altenkamp, Dittmaier, Harlander, Rzehak, Zirke, 1211.5015, Harlander, Kulesza, Theeuwes, Zirke, 1410.0217, Hasselhuhn, Luthe, Steinhauser, 1611.05881]

- (and **no** estimates of EW corrections.)

- @LHC: ~7% of ***hZ*** **σ**, ~16% with $p_T(h) > 150$ GeV.

probing **gg** → ***hZ*** using ratios

[Harlander, Klappert, Pandini, **AP**, 1804.02299]

- The general idea:
  - Drell-Yan **pp** → ***hW*** and **pp** → ***hZ*** are similar.*
  - ratio of signal strengths of (**pp** → ***hZ***) and (**pp** → ***hW***):

    ➡ **cancel** some theoretical and experimental (systematic) uncertainties.
  - potential discovery of **SM gg** → ***hZ*** @ LHC (***L***=3000 fb^{-1}).

[* the symmetry between ***V*** = ***W*** and ***V*** = ***Z*** has been used before as a way to measure the W boson mass at hadron colliders, see Giele, Keller, hep-ph/9704419.]

probing $gg \to hZ$ using ratios

[Harlander, Klappert, Pandini, **AP**, 1804.02299]

- ratio of signal strengths of ($\mathbf{pp} \to hZ$) and ($\mathbf{pp} \to hW$):

$$\mu_{Vh} \equiv \frac{\sigma_{Vh}^{\text{measured}}}{\sigma_{Vh}^{\text{theory}}} \longrightarrow R = \frac{\mu_{Zh}}{\mu_{Wh}}$$

"double ratio of signal strengths"

- error propagation:

$$\left(\frac{\delta R}{R}\right)^2 = \left(\frac{\delta \mu_{Zh}}{\mu_{Zh}}\right)^2 + \left(\frac{\delta \mu_{Wh}}{\mu_{Wh}}\right)^2 - 2\,\rho(\mu_{Zh}, \mu_{Wh})\,\delta\mu_{Zh}\delta\mu_{Wh}$$

the correlation between the signal strengths. $\Rightarrow$ **quantifies how much systematics may cancel.**

[systematic uncertainties should be correlated]

probing gg → *hZ* using ratios

[Harlander, Klappert, Pandini, **AP**, 1804.02299]

$$R = \frac{\sigma_{Zh}^{\text{measured}}}{\sigma_{Wh}^{\text{measured}}} \times \frac{\sigma_{Wh}^{\text{theory}}}{\sigma_{Zh}^{\text{theory}}}$$

contains <u>data statistics uncertainty.</u>
[here: estimated via pheno Monte Carlo analysis.]

actually, "measure": $R' = \frac{\sigma_{Zh}^{\text{measured}}}{\sigma_{Wh}^{\text{measured}}} \times \frac{\sigma_{Wh}^{\text{theory}}}{\sigma_{Zh}^{\text{theory,DY}}}$ ↬

measuring: $R' > 1$
⇒ detect **non-DY** component of ***Zh***

- using ***R′*** instead of ***Zh*** rate directly: improved significance,

➡ provided high correlation between ***Zh*** and ***Wh*** systematics.

SM-like **gg** → ***hZ*** @ LHC

- using the **ATLAS** 36.1 fb^{-1} results, we performed a first estimate.

[Harlander, Klappert, Pandini, **AP**, 1804.02299]

- full correlation information currently not publicly available.

➡ symmetrise:

$$\mu_{Zh} = 1.12^{+0.34}_{-0.33}(\text{stat.})^{+0.37}_{-0.30}(\text{syst.})$$
$$\mu_{Wh} = 1.35^{+0.40}_{-0.38}(\text{stat.})^{+0.55}_{-0.45}(\text{syst.})$$

$$\left(\frac{\delta R'}{R'}\right)\Bigg|^{2}_{\text{syst.}} = \left(\frac{\delta\mu_{Zh}}{\mu_{Zh}}\right)^2 + \left(\frac{\delta\mu_{Wh}}{\mu_{Wh}}\right)^2 - 2\,\rho(\mu_{Zh},\mu_{Wh})\;\delta\mu_{Zh}\delta\mu_{Wh}$$

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$$\Rightarrow \left(\frac{\delta R'}{R'}\right)\Bigg|^2_{\text{syst.}} = 0.112 + 0.250 - 0.335\,\rho(\mu_{Zh},\mu_{Wh})$$

SM-like gg → *hZ* @ LHC

[Harlander, Klappert, Pandini, **AP**, 1804.02299]

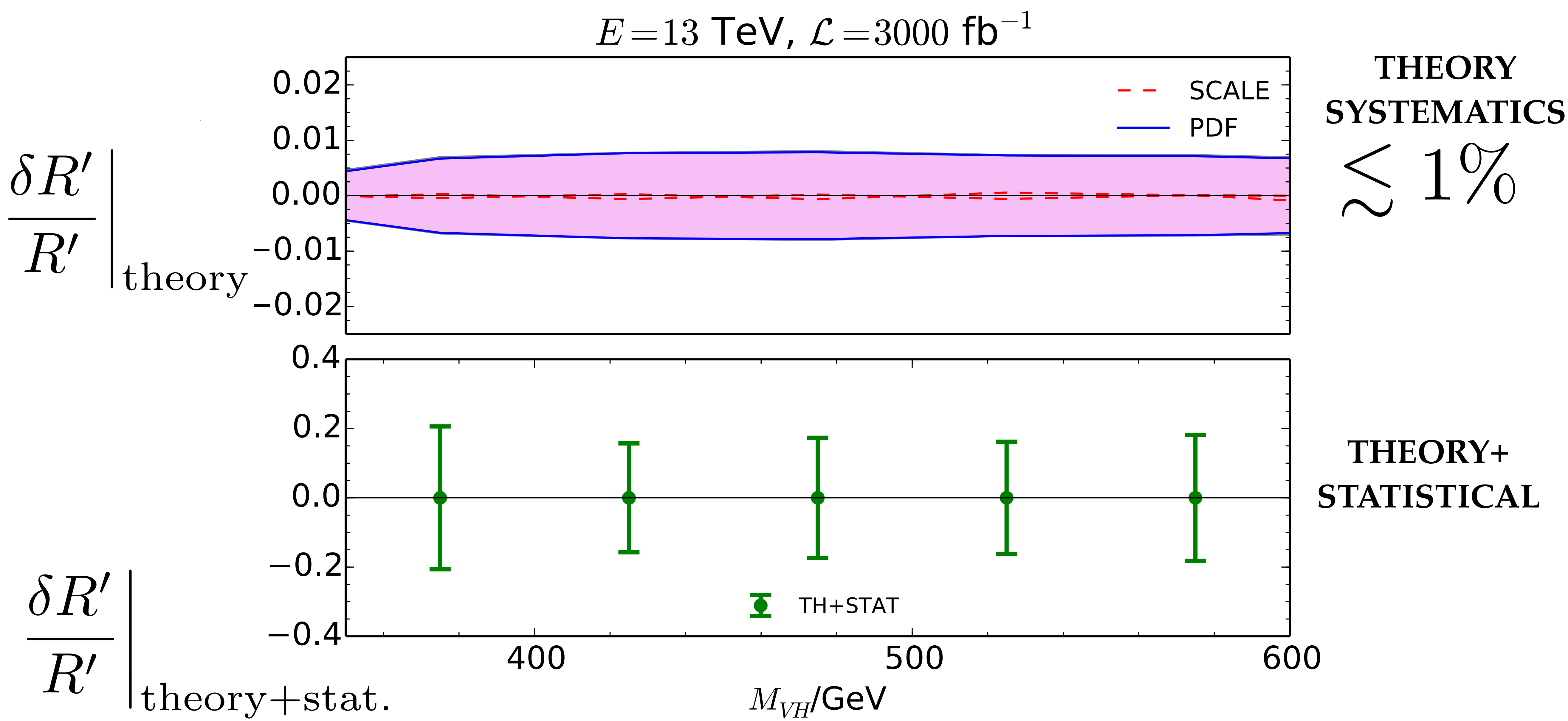
- extrapolate **current systematic ATLAS** uncertainties & assume fully-correlated ($\rho \sim 1$) [→ get $\delta R'$],
- & perform pheno analysis following **ATLAS [→** get value of ***R'*****].**

➡ SM **gg** → ***hZ*** observation only at ~**2σ**-level @ LHC 3000 fb^{-1}.

- with systematics **halved** ⇒ **~3.2σ @ 3000** fb^{-1} [1 + 2-lepton channels, 0-lepton channel **not** included].
- ratio method competitive with "direct" search of **gg** → ***hZ*** vs. total ***hZ*** production if correlation large: i.e. $\rho \gtrsim 0.75$.

SM-like $gg \to hZ$ @ LHC

- **but**: TH syst. uncertainties, already incl. in $\boldsymbol{\delta R}$, cancel significantly in double ratio: [Harlander, Klappert, Pandini, **AP**, 1804.02299]



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SM-like gg → hZ @ pp@100 TeV

fraction of gluon-fusion hZ in total:

pp Energy:	gg → hZ inclusively	gg → hZ $p_T(h) > 150$ GeV
13 TeV	~7%	~16%
100 TeV	~25%	~43%

- **13 → 100 TeV**: increase of **σ**: **gg: ~50×, DY: ~10×.**
- [the p_T spectrum gets only slightly harder.]

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gg → *hZ*: sensitivity to new phenomena.

consider the "theoretical" ratio:

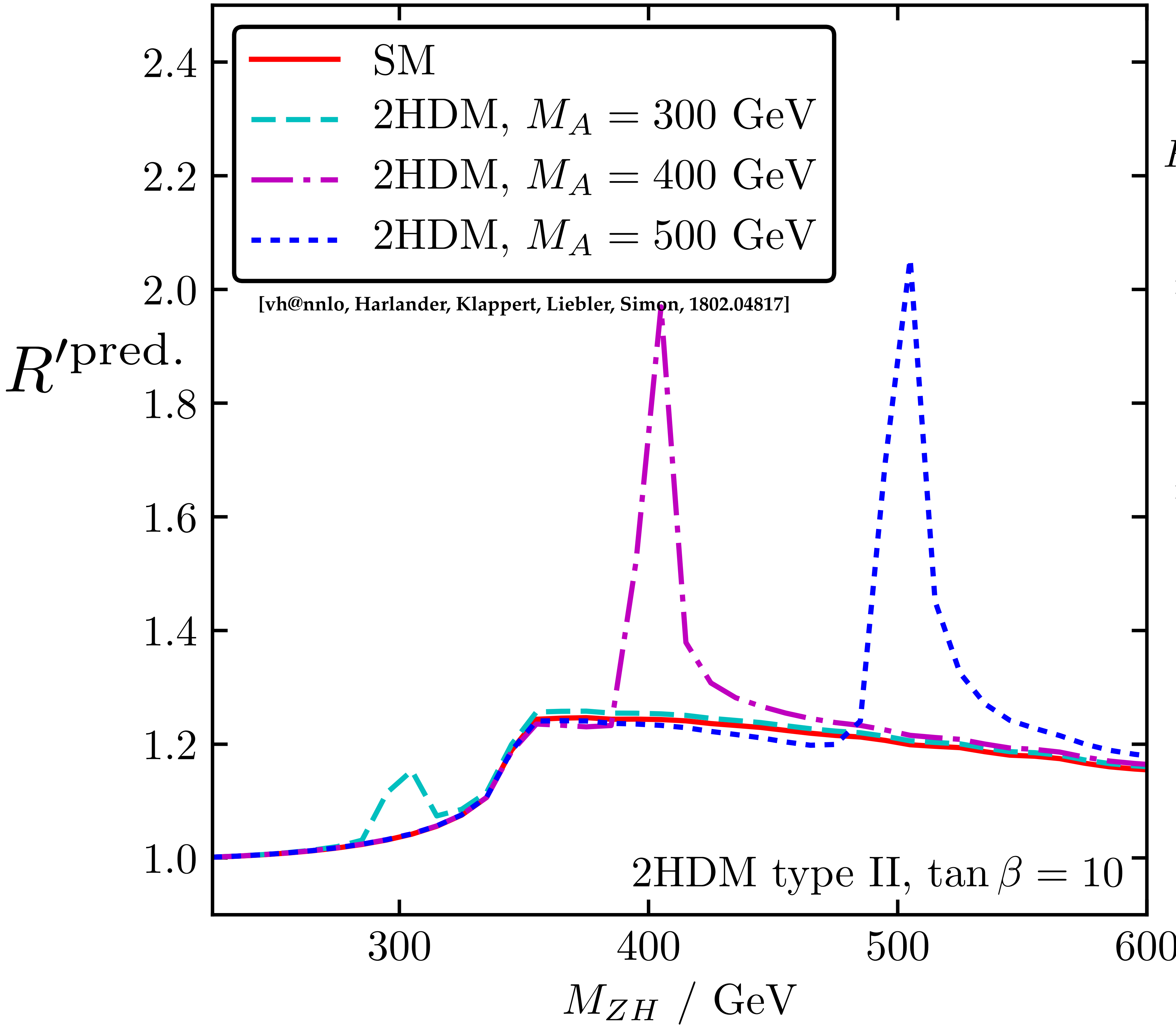
$$R'^{\mathrm{pred.}} = 1 + \frac{\sigma_{Zh}^{\mathrm{theory},non-DY}}{\sigma_{Zh}^{\mathrm{theory,DY}}}$$

➡ a <u>theoretical</u> prediction of **non-DY** ***Zh*** in total ***Zh***.

➡ compare this to ***R′*** (→ contains experimentally measured quantities),

➡ detect **non-DY** ***Zh***, i.e. ***R′* > *1*.**

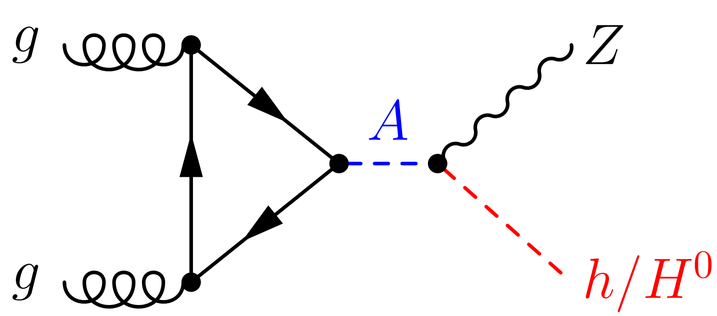
gg → hZ: sensitive to new phenomena.



$$R'^{\text{pred.}} = 1 + \frac{\sigma_{Zh}^{\text{theory},non-DY}}{\sigma_{Zh}^{\text{theory,DY}}}$$

measures the content of non-DY in total *Zh* production.

example: two-Higgs doublet model, A=pseudo-scalar Higgs



[Harlander, Klappert, Pandini, **AP**, 1804.02299]

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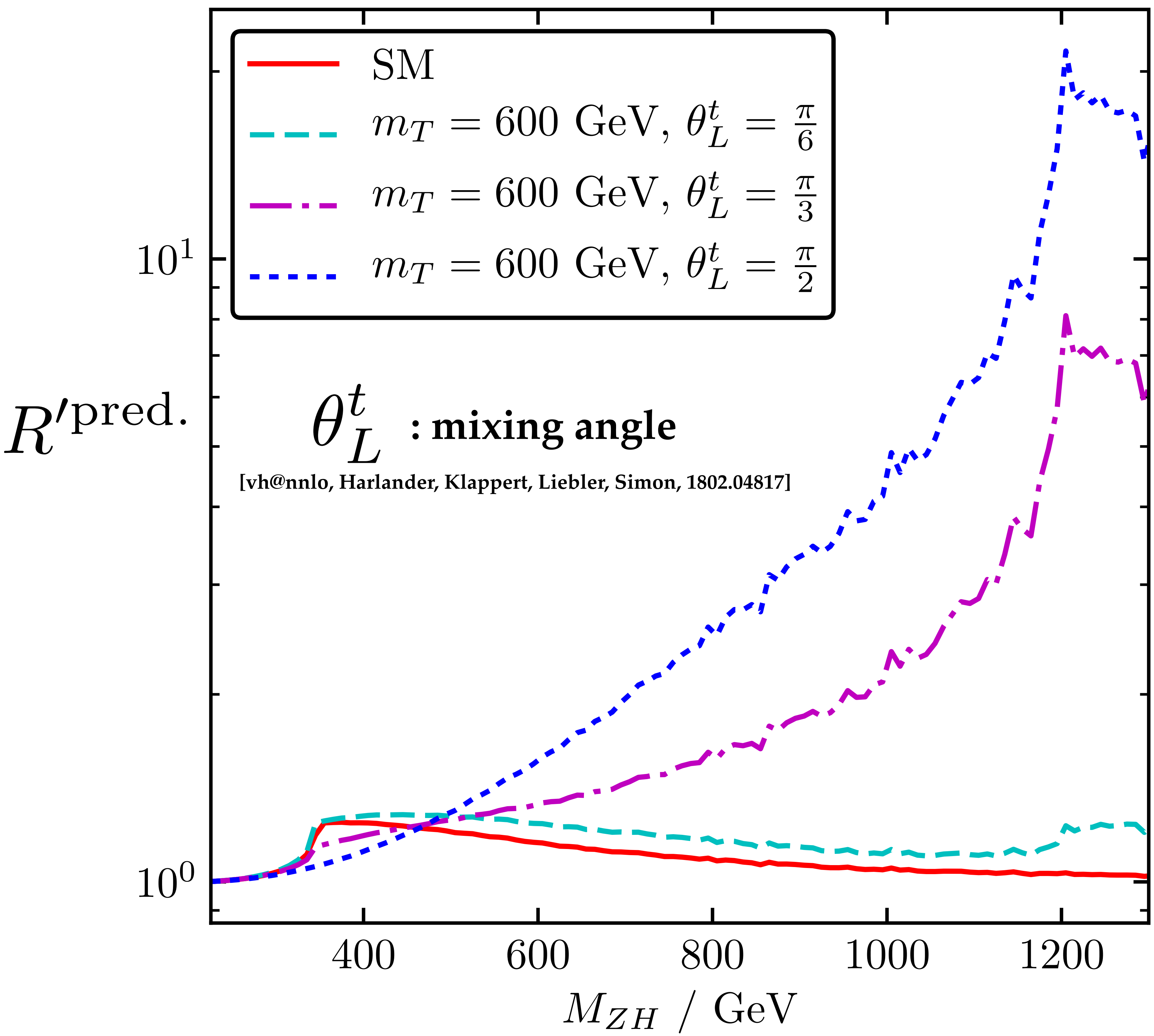
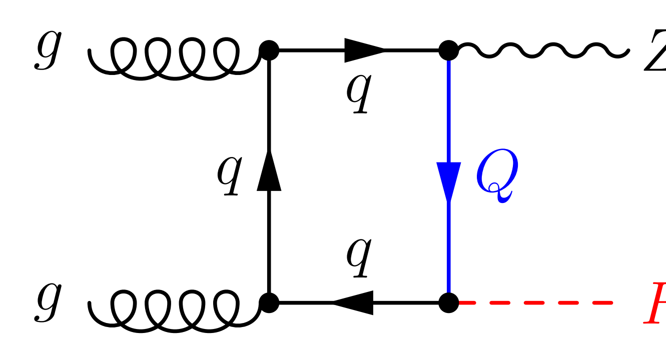


$$R'^{\text{pred.}} = 1 + \frac{\sigma_{Zh}^{\text{theory},non-DY}}{\sigma_{Zh}^{\text{theory,DY}}}$$

measures the content of non-DY in total *Zh* production.

example: T=vector-like quark running in loop.



[Harlander, Klappert, Pandini, **AP**, 1804.02299]

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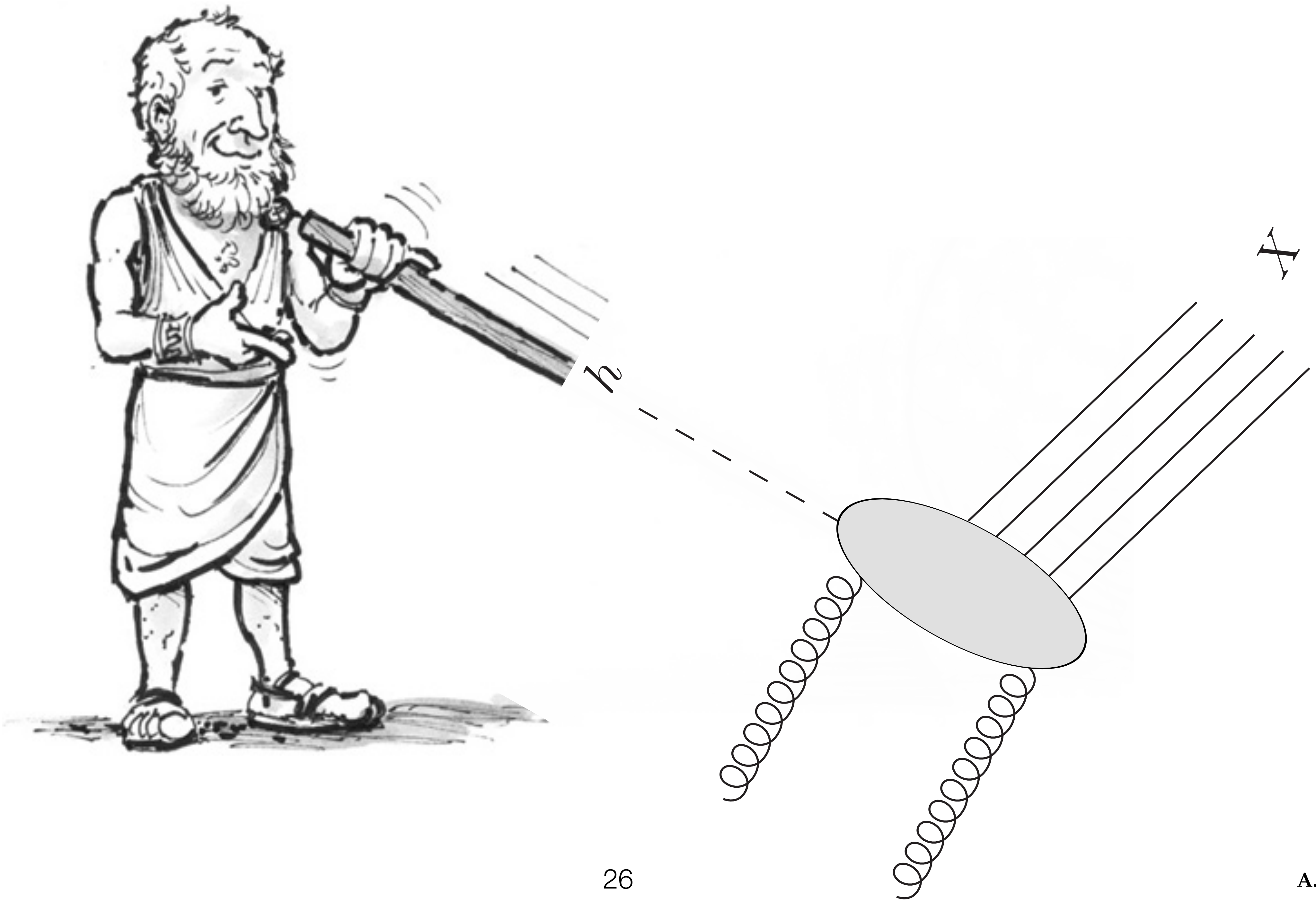
summary / conclusions

- the Higgs boson is the **central actor** of **EWSB**,
- can become a **"probe"** in several processes!
- important example: associated production with a vector boson, *Vh:* comes in two flavours, *V=W, Z*.
- separating out **gluon-fusion component** of *Zh:* **unravel** interesting new phenomena!
- ratio of *Wh* and *Vh* production can **eliminate systematics** & increase sensitivity.

Give me a lever and I shall move the world. - Archimedes

Give us (plenty) of Higgs bosons and we shall move the world. - 21st-century Physicists



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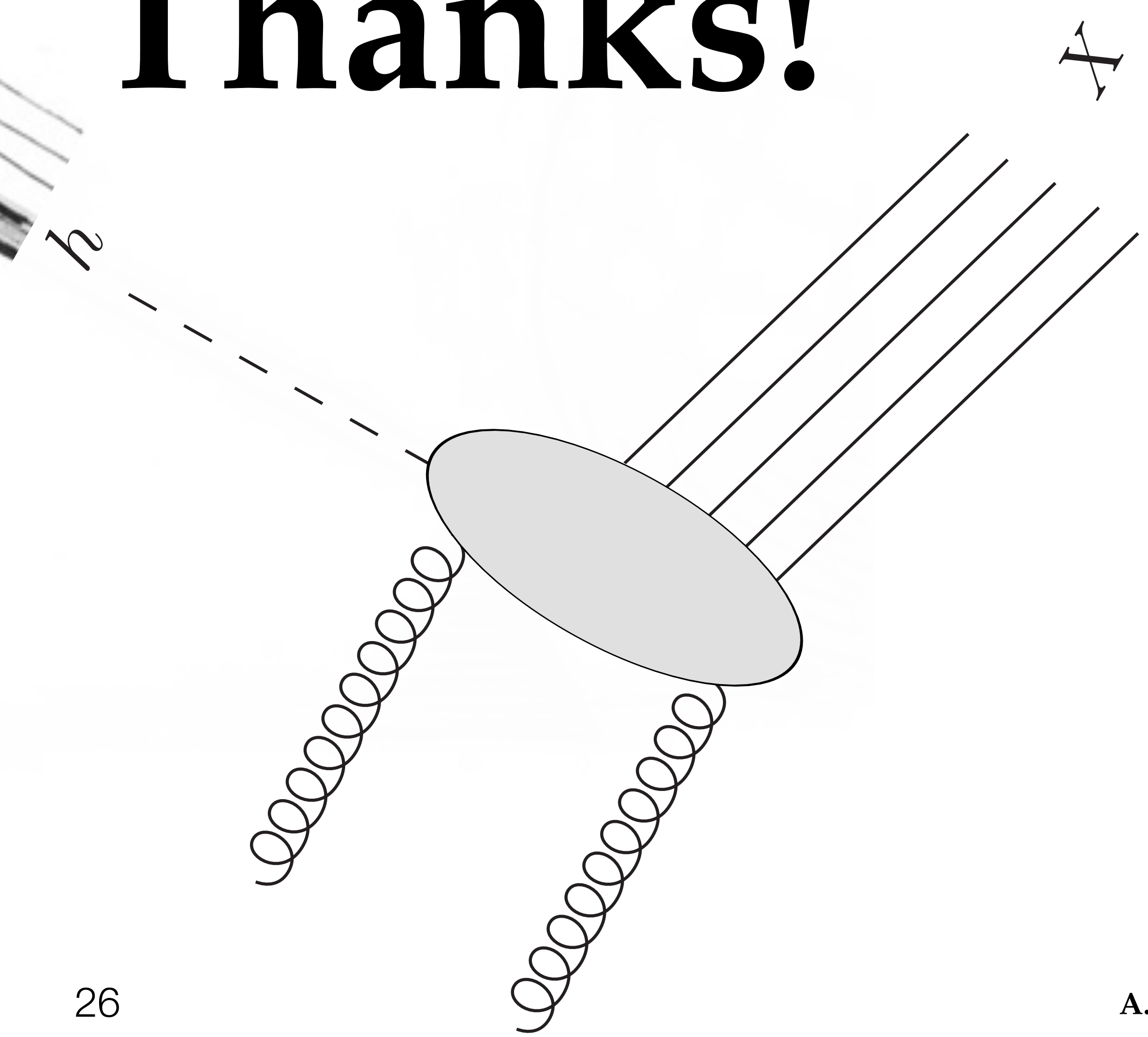
Thanks!



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appendix

gg → *hZ*: example SM-like measurement.

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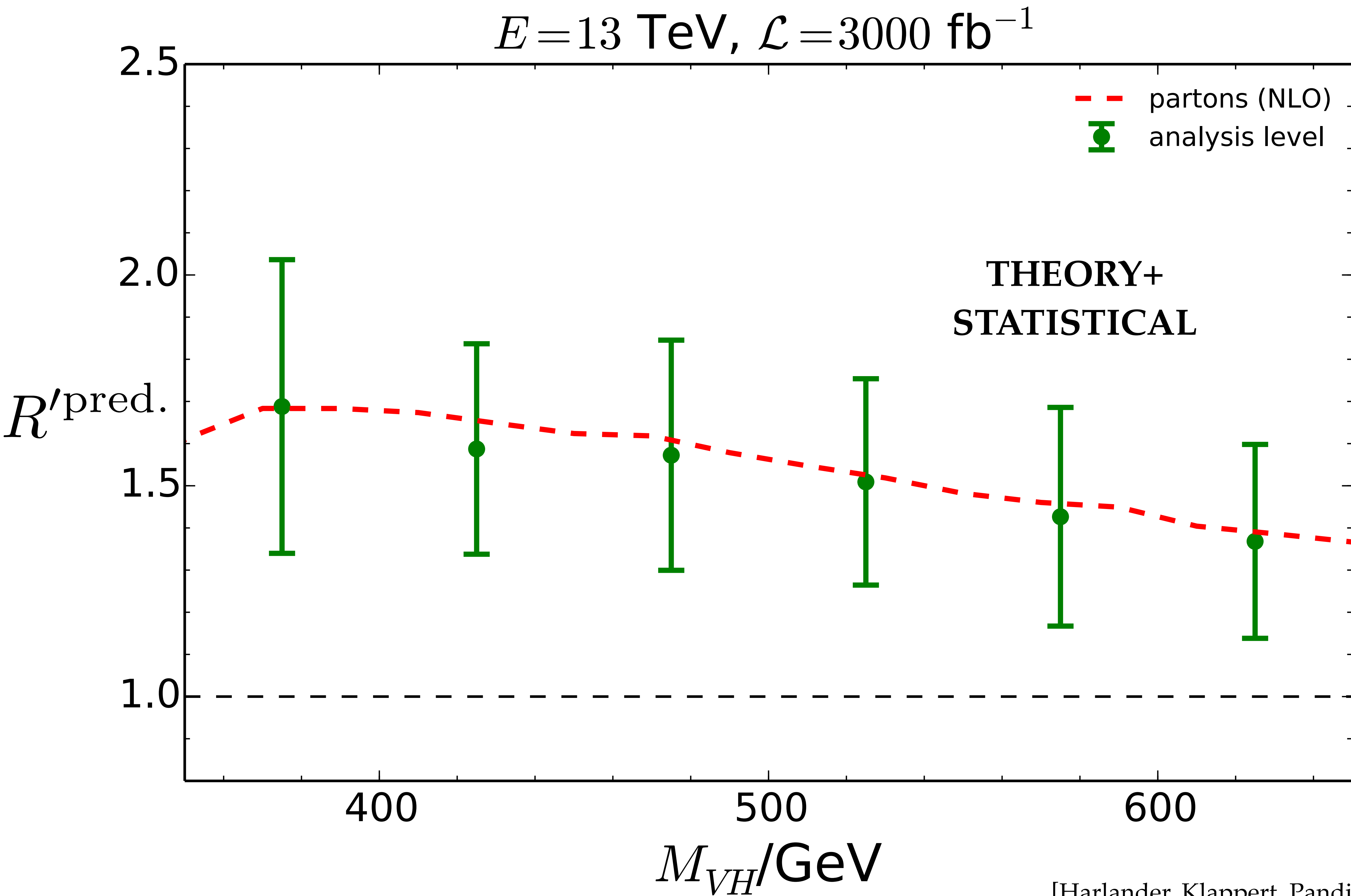
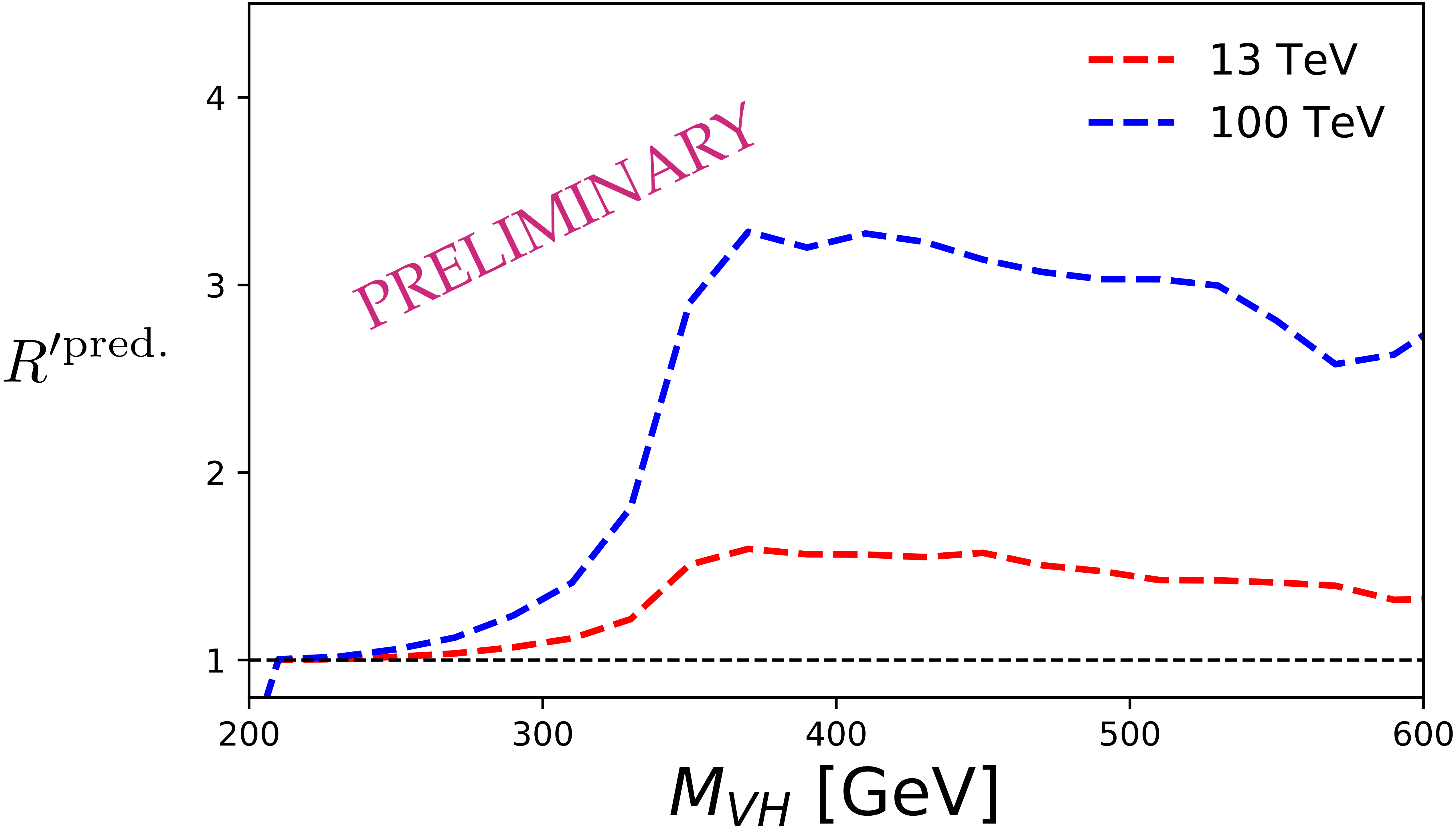
$gg \to hZ$: example SM-like measurement.



[Harlander, Klappert, Pandini, **AP**, 1804.02299]

gg → *hZ*: example SM-like measurement.



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Higgs+ **new** Scalar boson

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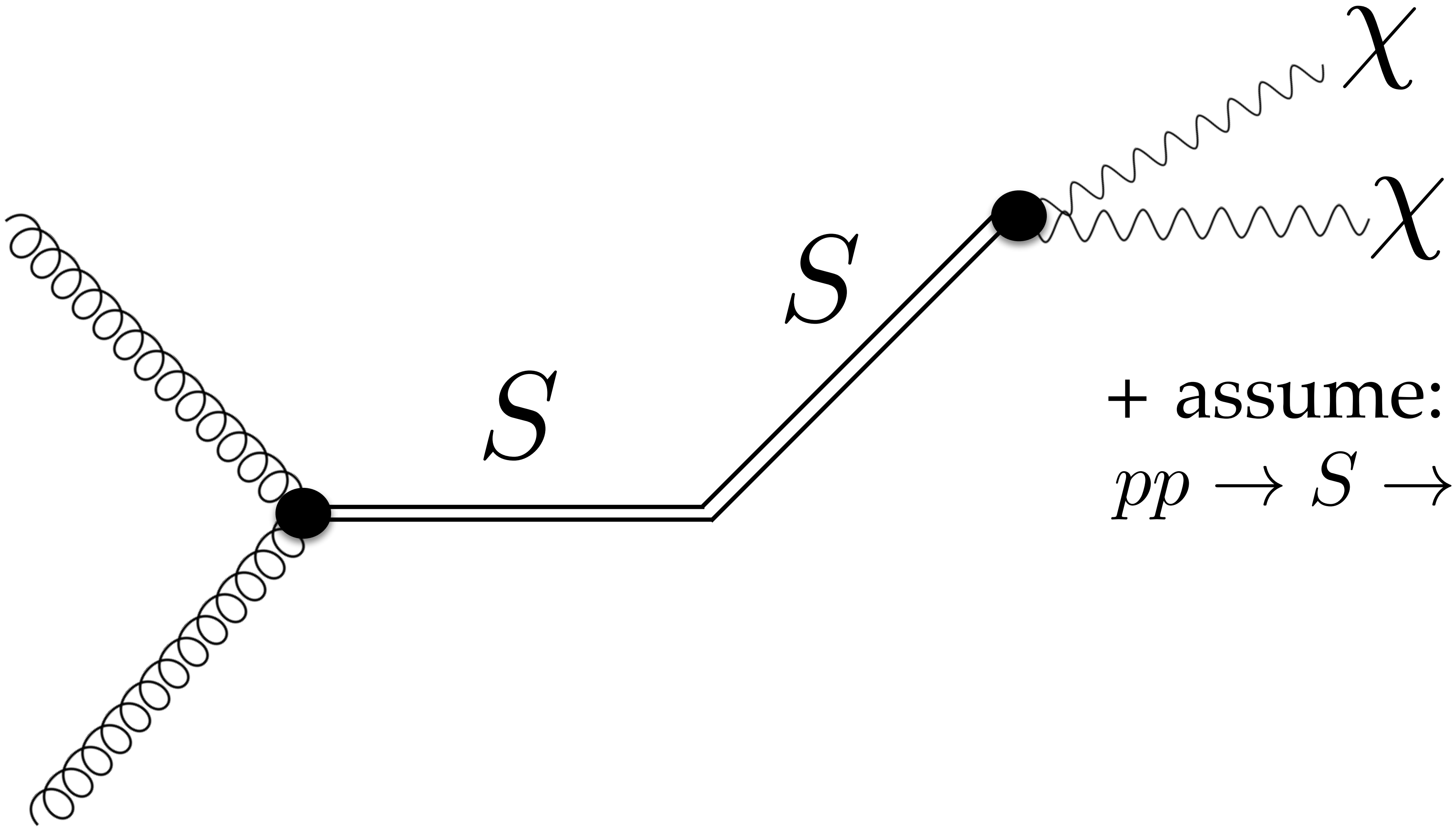
assume: single production of a singlet scalar S

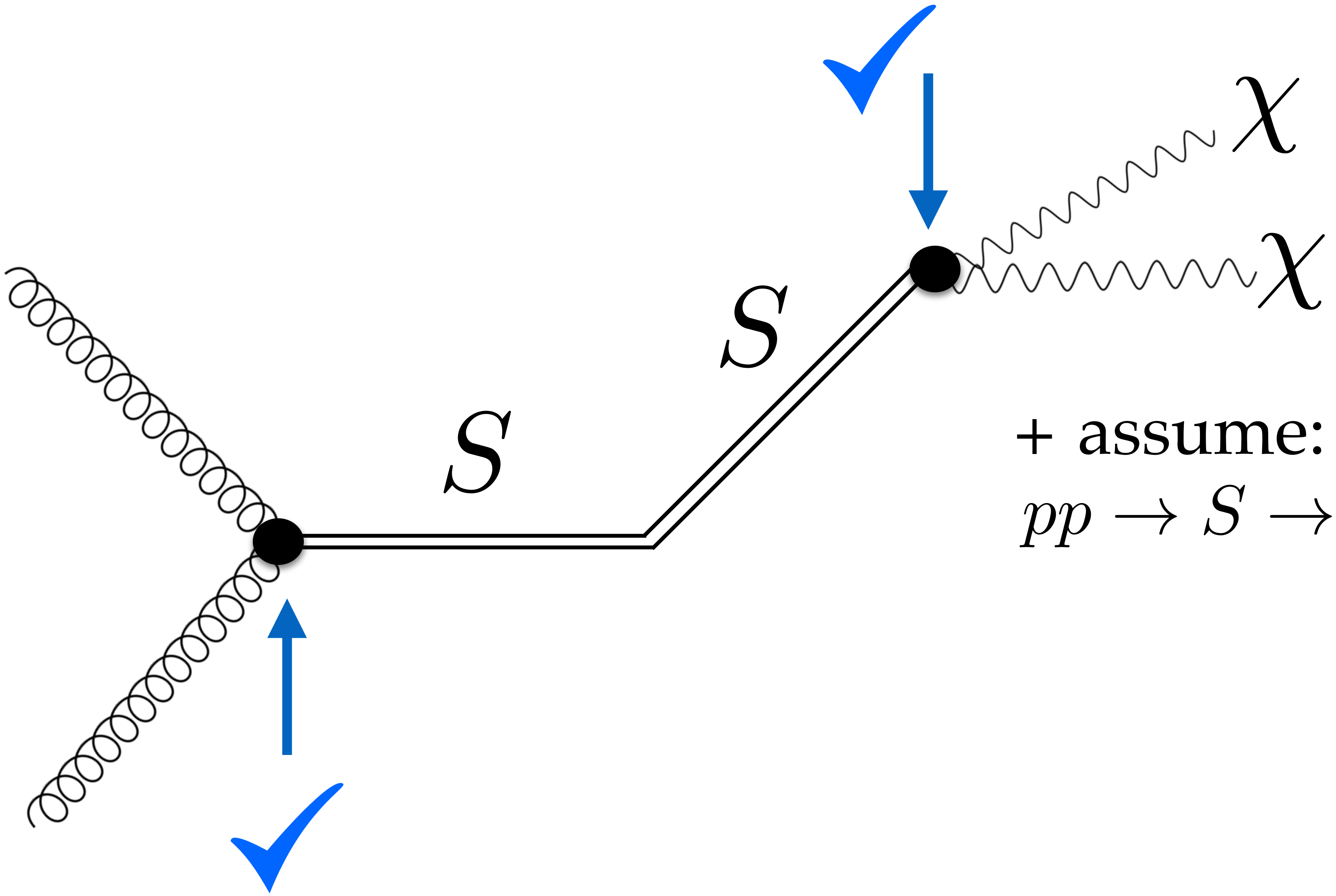
[Carmona, Goertz, **AP**, 1606.02716]



+ assume:
$pp \to S \to \chi\chi$ is observed

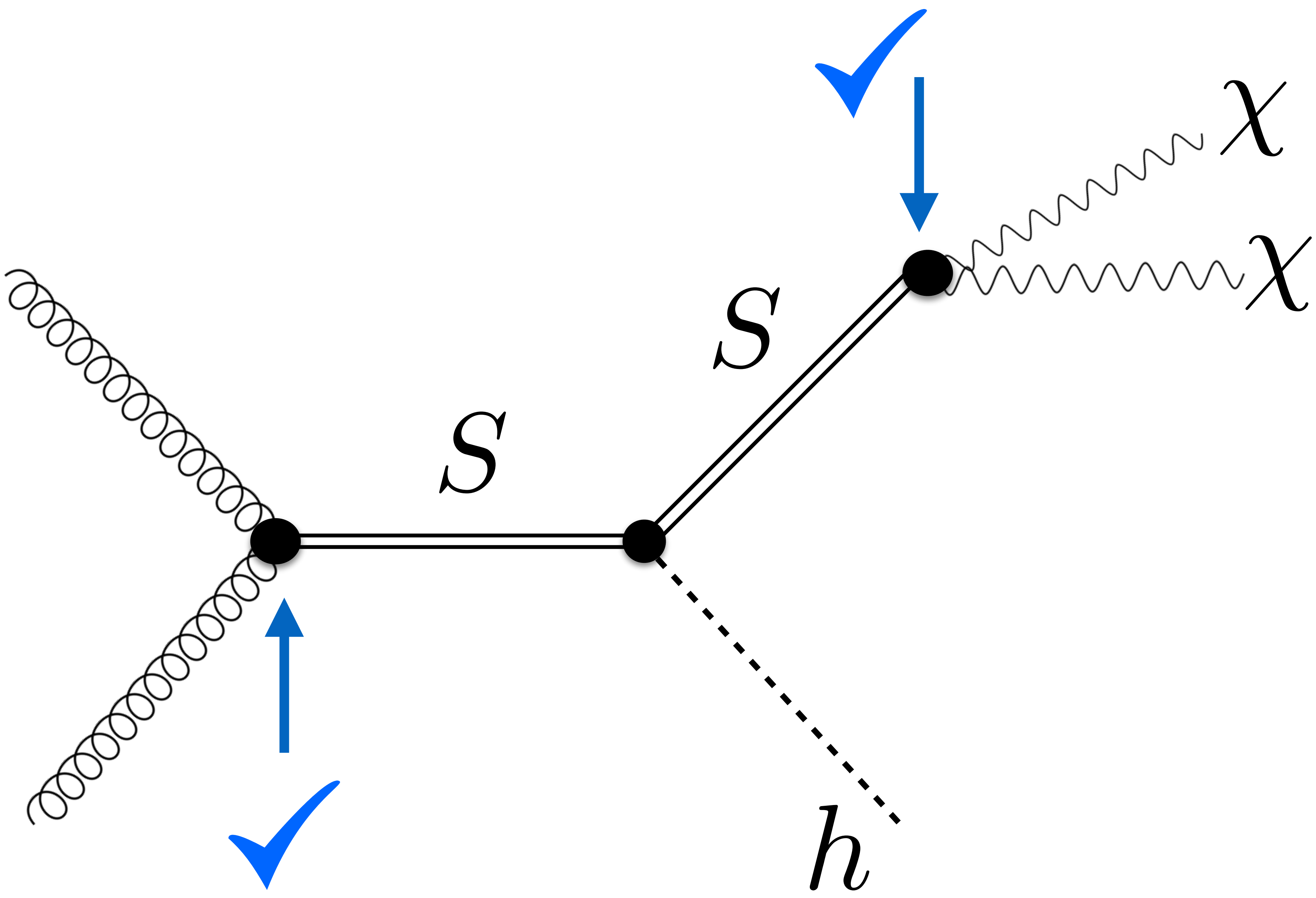
assume: single production of a <u>singlet scalar S</u>

[Carmona, Goertz, **AP**, 1606.02716]



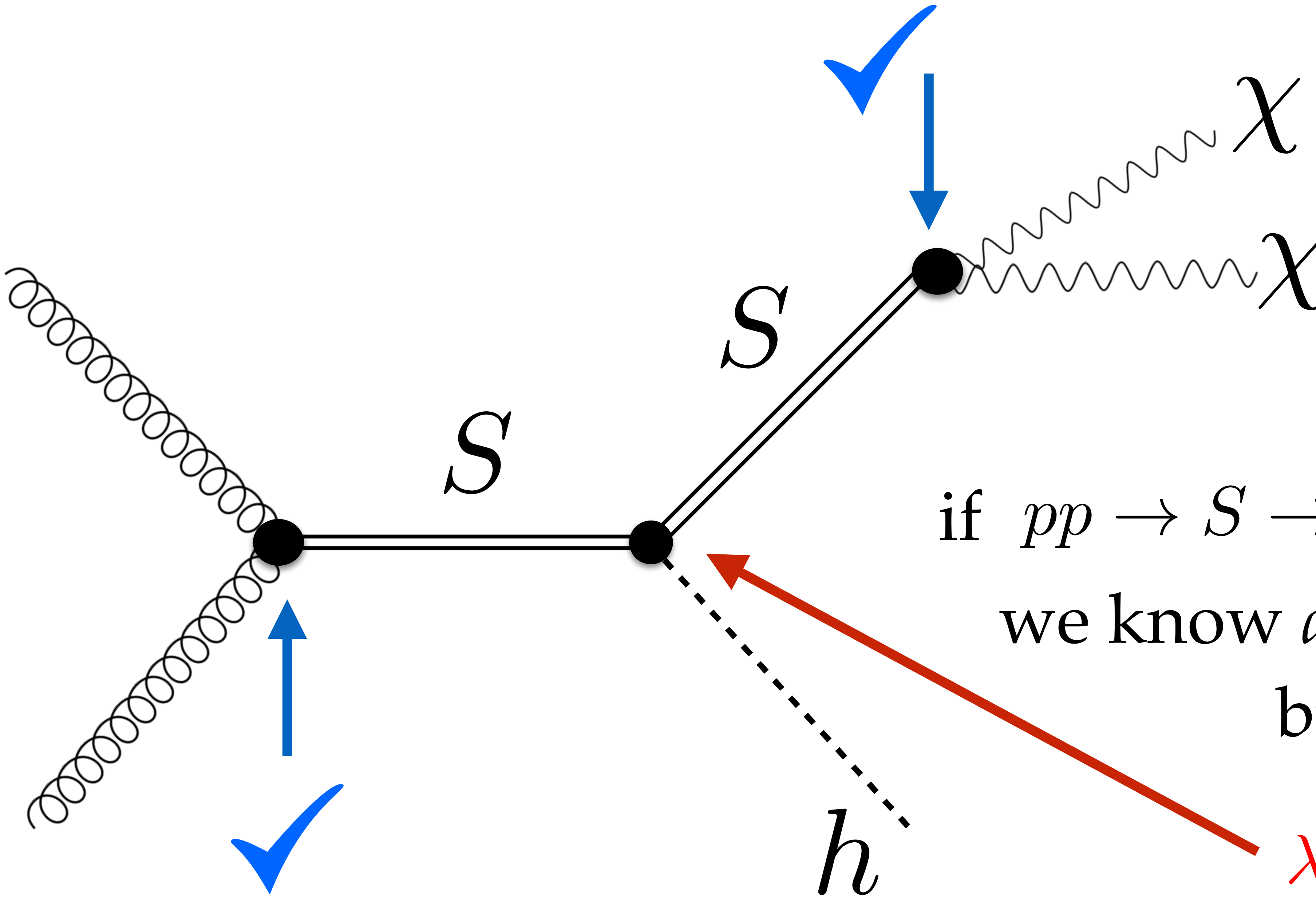
+ assume:
$pp \to S \to \chi\chi$ is observed

associated production with a Higgs boson



$$\lambda_{HS}|H|^2S^2 \rightarrow \lambda_{HS}(v+h)^2S^2$$

associated production with a Higgs boson



if $pp \to S \to \chi\chi$ is observed:
we know *all* the couplings
but one!

λ_{HS}
"portal coupling"

[from: $\lambda_{HS}|H|^2 S^2 \to \lambda_{HS}(v+h)^2 S^2$]

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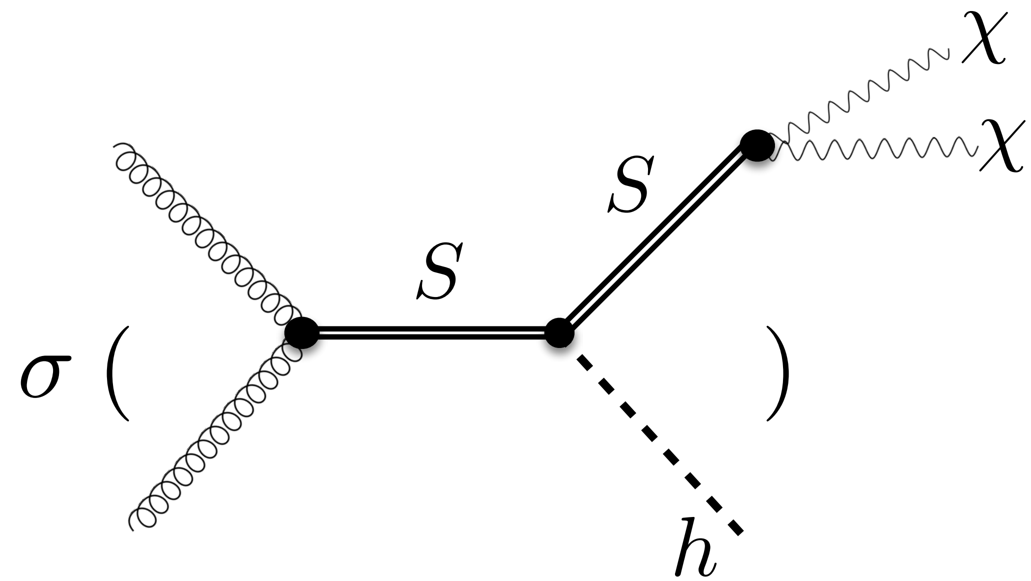
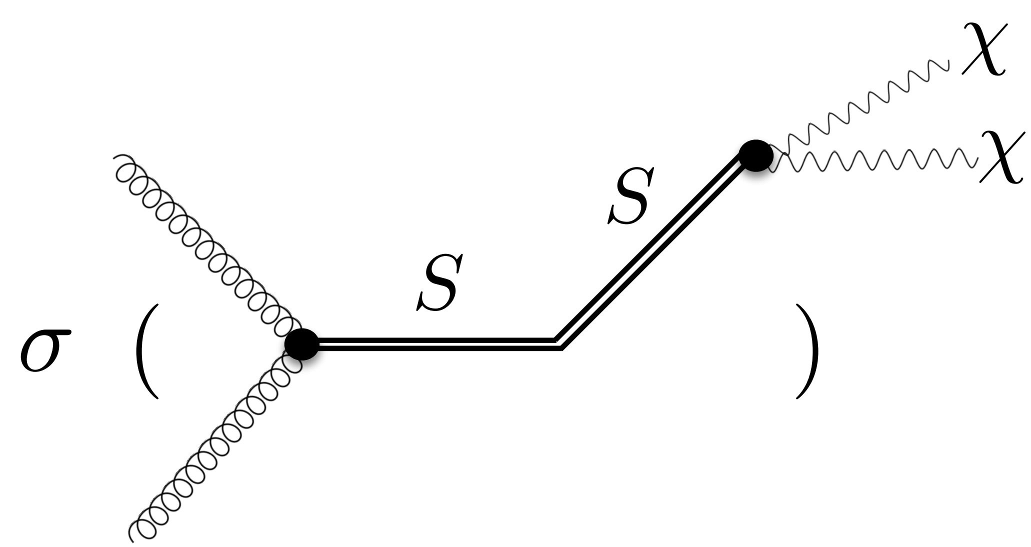
➡ for a given portal coupling and single production cross section: can predict associated production cross section!

$$\rho = \frac{\sigma(pp \to hS \to h\chi\chi)}{\sigma(pp \to S \to \chi\chi)} = \frac{\sigma(\text{diagram 1})}{\sigma(\text{diagram 2})} \propto \lambda_{HS}^2$$





truth is stranger than fiction…

- we won't know the initial-state partons.
- and, in general, there are other diagrams contributing:

$$\Rightarrow \rho = \frac{\sigma(pp \to hS \to h\chi\chi)}{\sigma(pp \to S \to \chi\chi)} = a\ \lambda_{HS}^2 + b\ \lambda_{HS} + c$$

a, b, c : obtained via Monte Carlo.

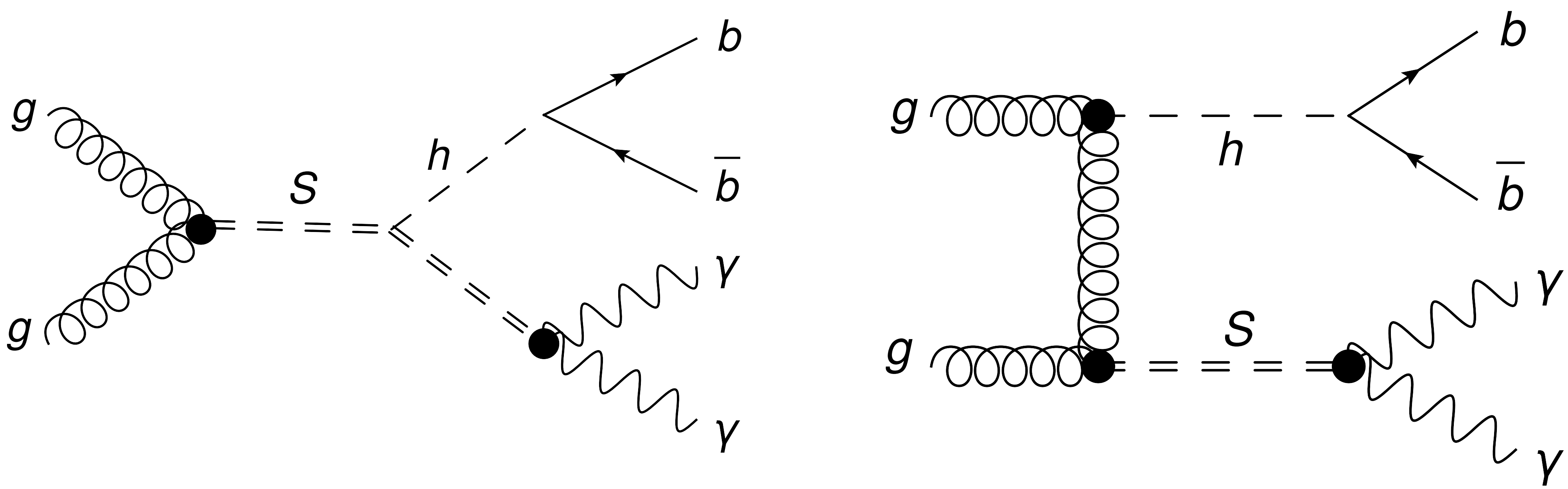
[for a given initial state, independently of the coupling values of S]

gluon-induced production

- gluon-induced production can arise from operator:

$$\frac{c_G^S}{\Lambda}\ \mathcal{S}G^{a\mu\nu}G^a_{\mu\nu}$$

- example diagrams:



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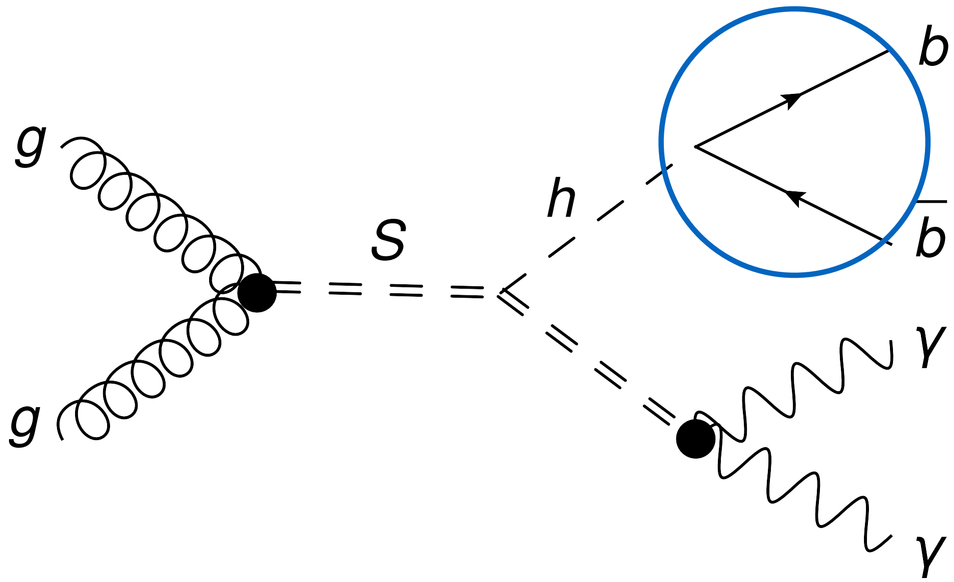
gluon-induced production

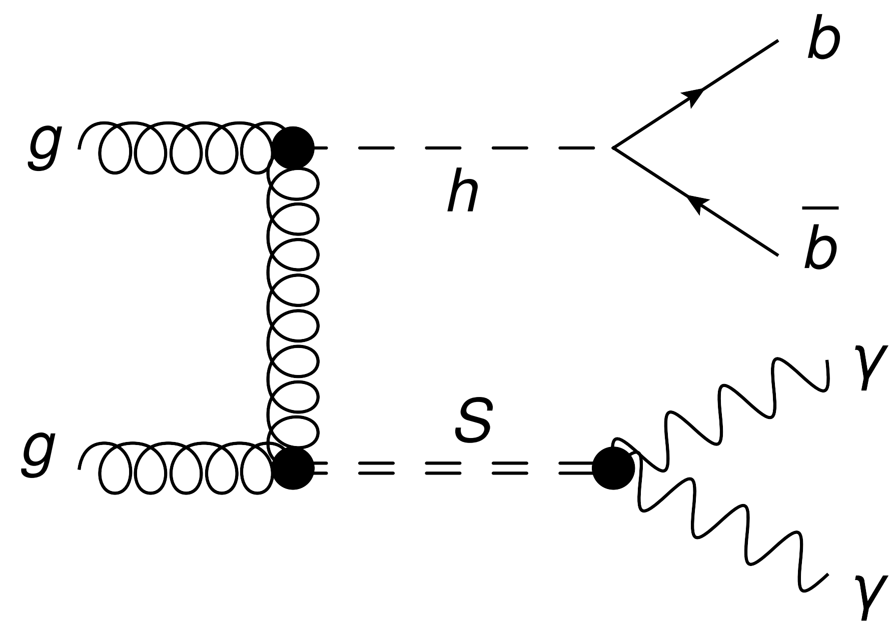
- gluon-induced production can arise from operator:

$$\frac{c_G^S}{\Lambda}\,\mathcal{S}G^{a\mu\nu}G^a_{\mu\nu}$$

- example diagrams:

$$\mathrm{BR}(h \to b\bar{b}) \sim 60\%$$





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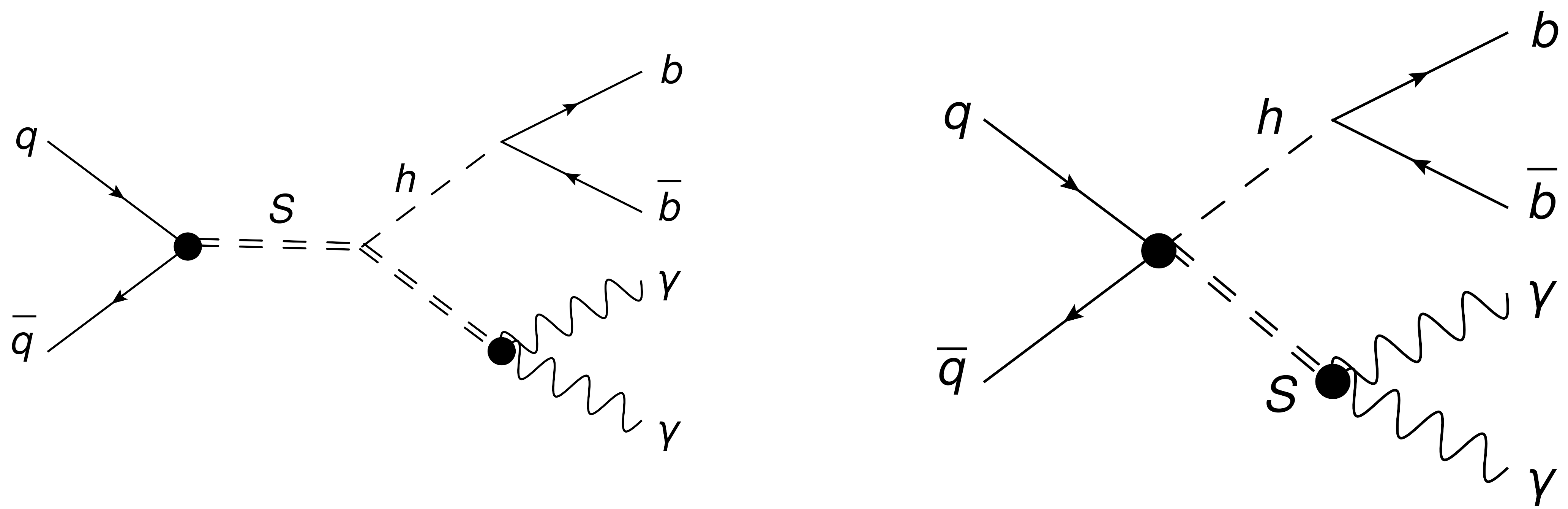
quark-induced production

- for the quark-induced case, assuming operator:

$$\frac{y_q^S}{\Lambda}\mathcal{S}\bar{Q}_L H Q_R \rightarrow \frac{y_q^S}{\Lambda}S\bar{Q}_L(h+v)Q_R$$

- additional **4-point** ***quark-quark-h-S*** interaction:



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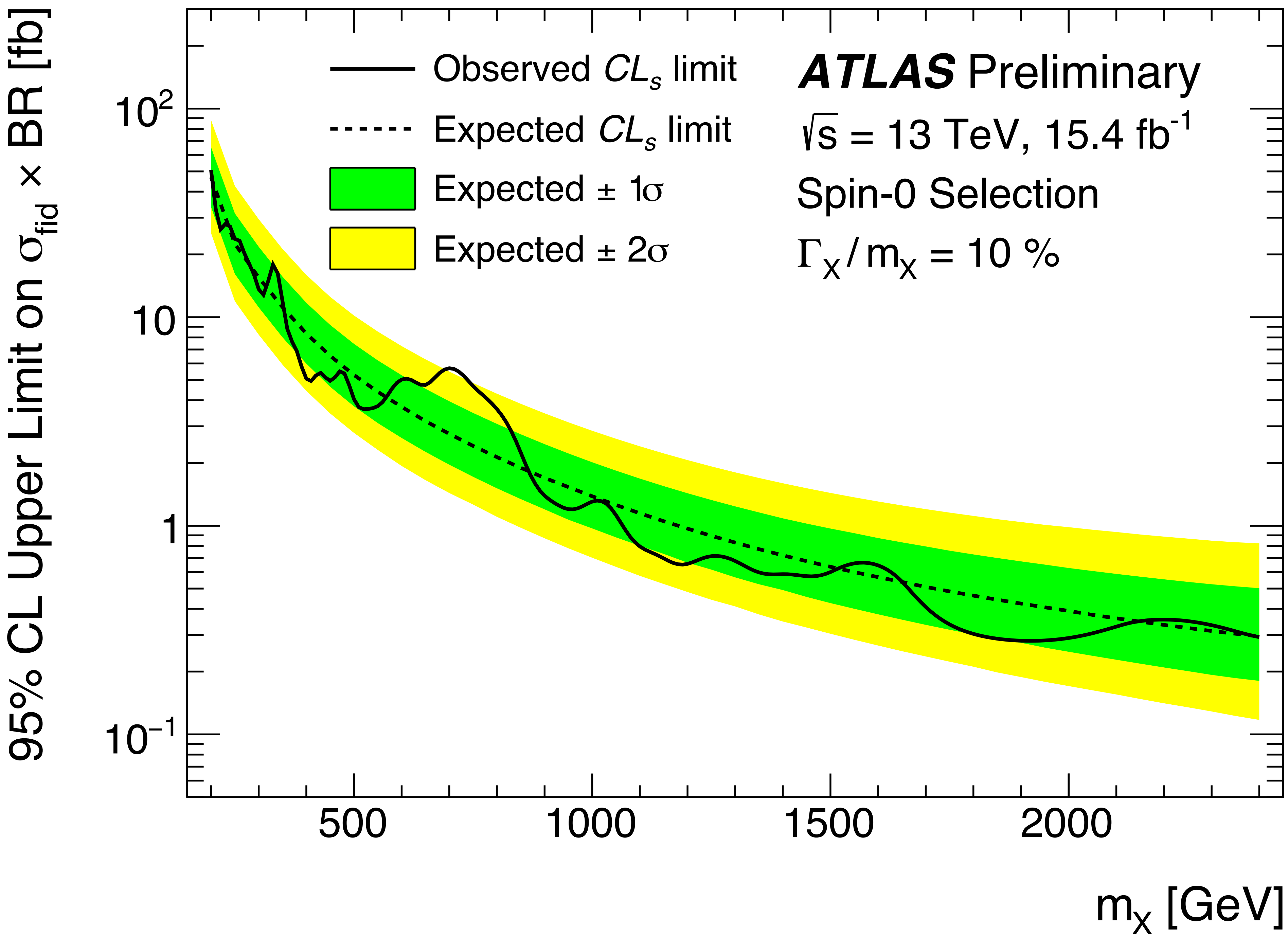
- a simple example: χ = photon, i.e. di-photon resonance.
- current searches allow single production with reasonable cross section:



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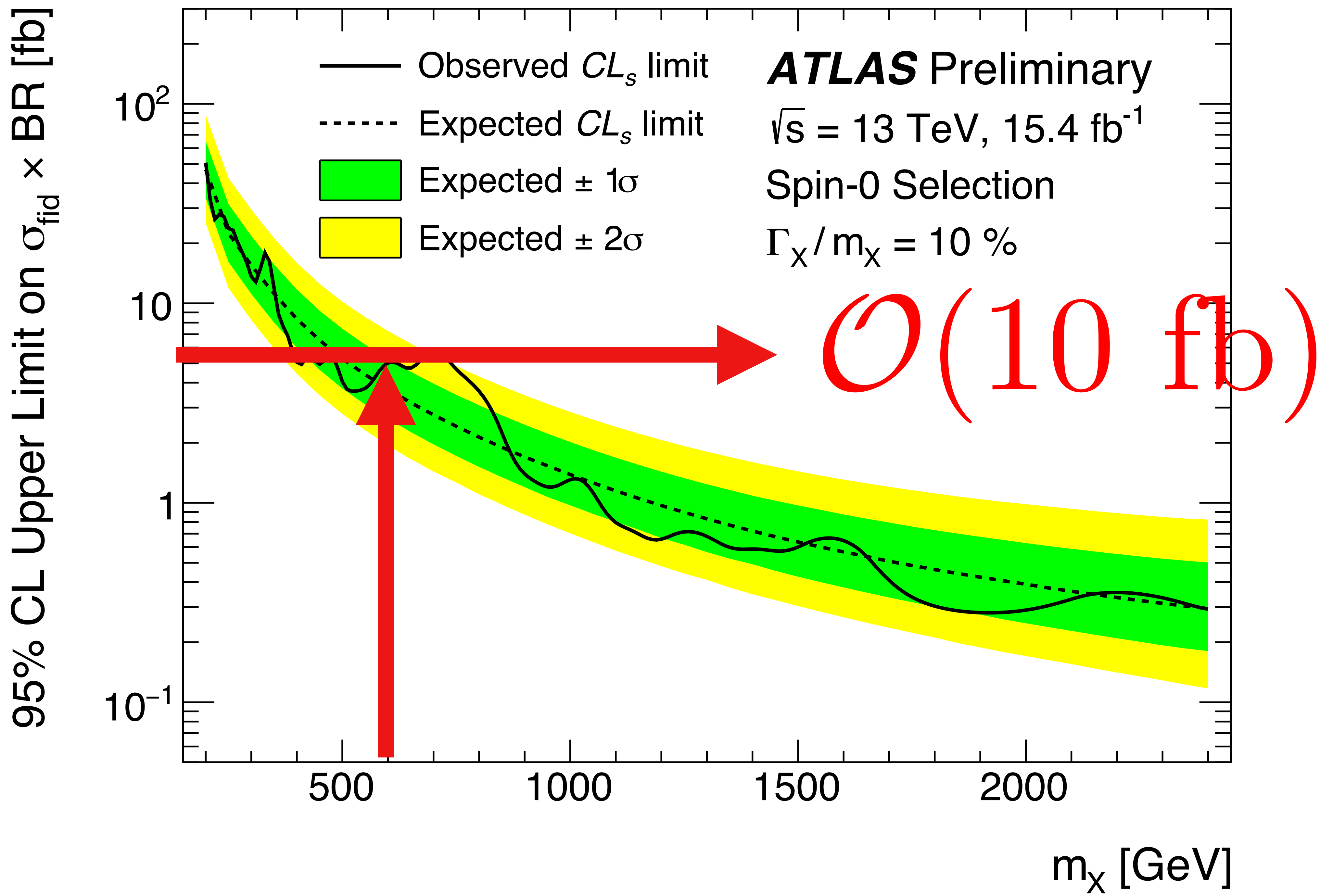

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$$\sigma(pp \to hS \to h\gamma\gamma) \sim 10 \text{ fb} \times \rho$$

single production allowed cross section, from ATLAS/CMS.

ratio, **fitted** from Monte Carlo.

$$\rho \sim 10^{-3} - 10^{-2}$$

(depending on initial-state partons)

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kinematic features of $h(b\bar{b})S(\gamma\gamma)$

- S and Higgs boson at 13 TeV would be produced near threshold,

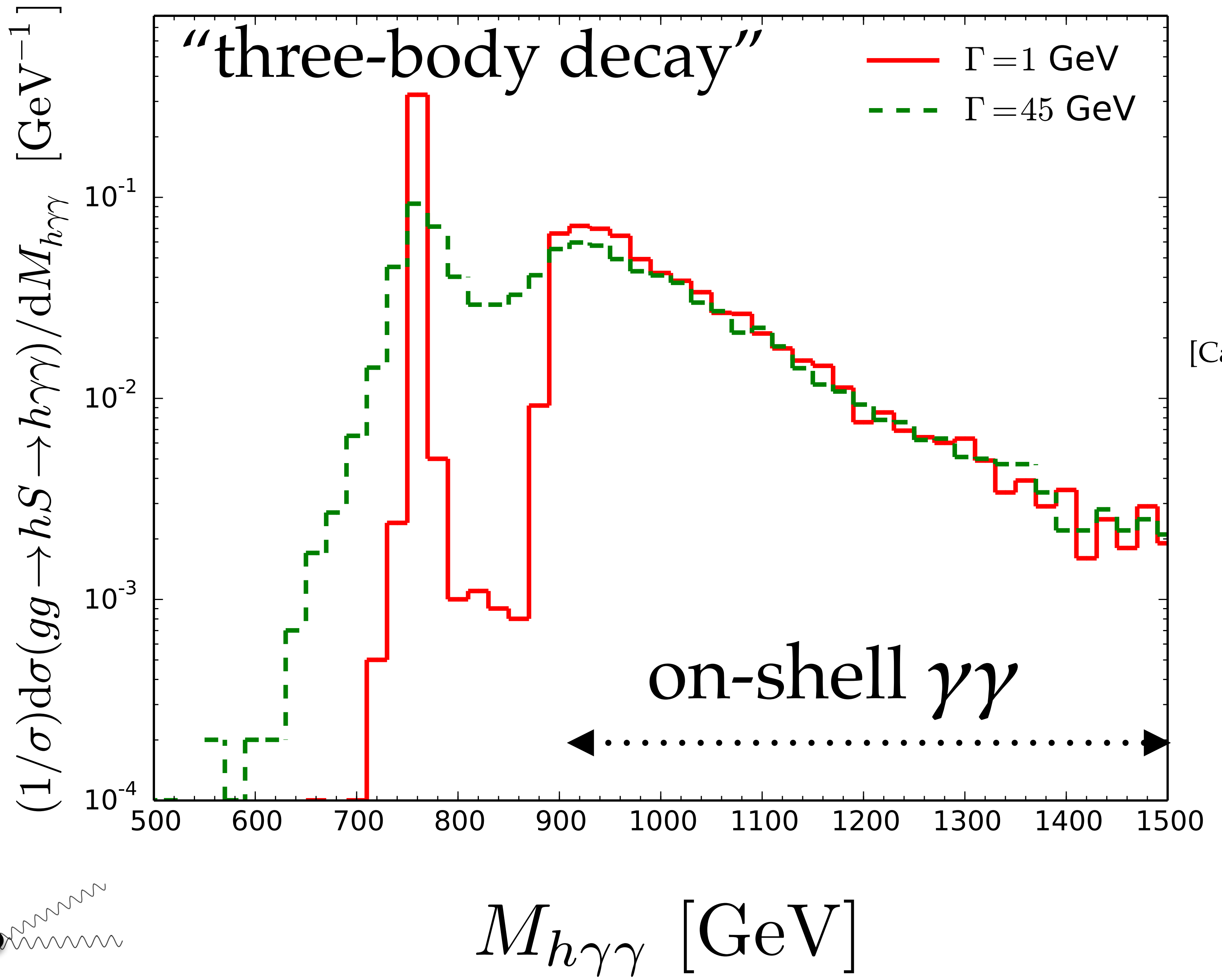
- photons from S would be energetic:

$$p_{T,peak} \sim M/2$$

- photons close to back-to-back, b-jets close to back-to-back ($\Delta R \sim \pi$).

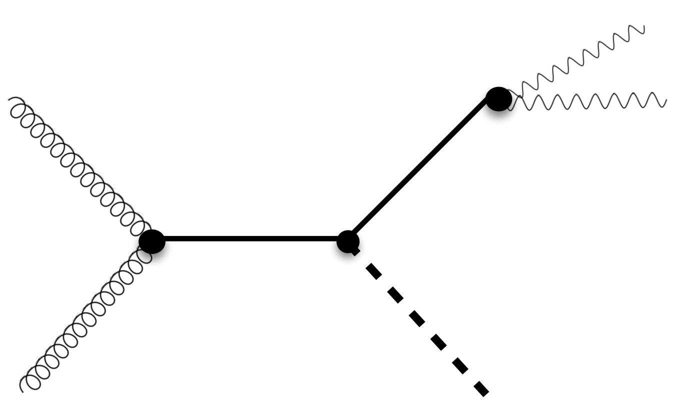
kinematic features of $h(b\bar{b})S(\gamma\gamma)$

- ***S*** can be resonant (i.e. near on-shell) *either* in ***s***-channel *or* decay:



M= 750 GeV

[Carmona, Goertz, AP, 1606.02716]



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kinematic features of $h(b\bar{b})S(\gamma\gamma)$

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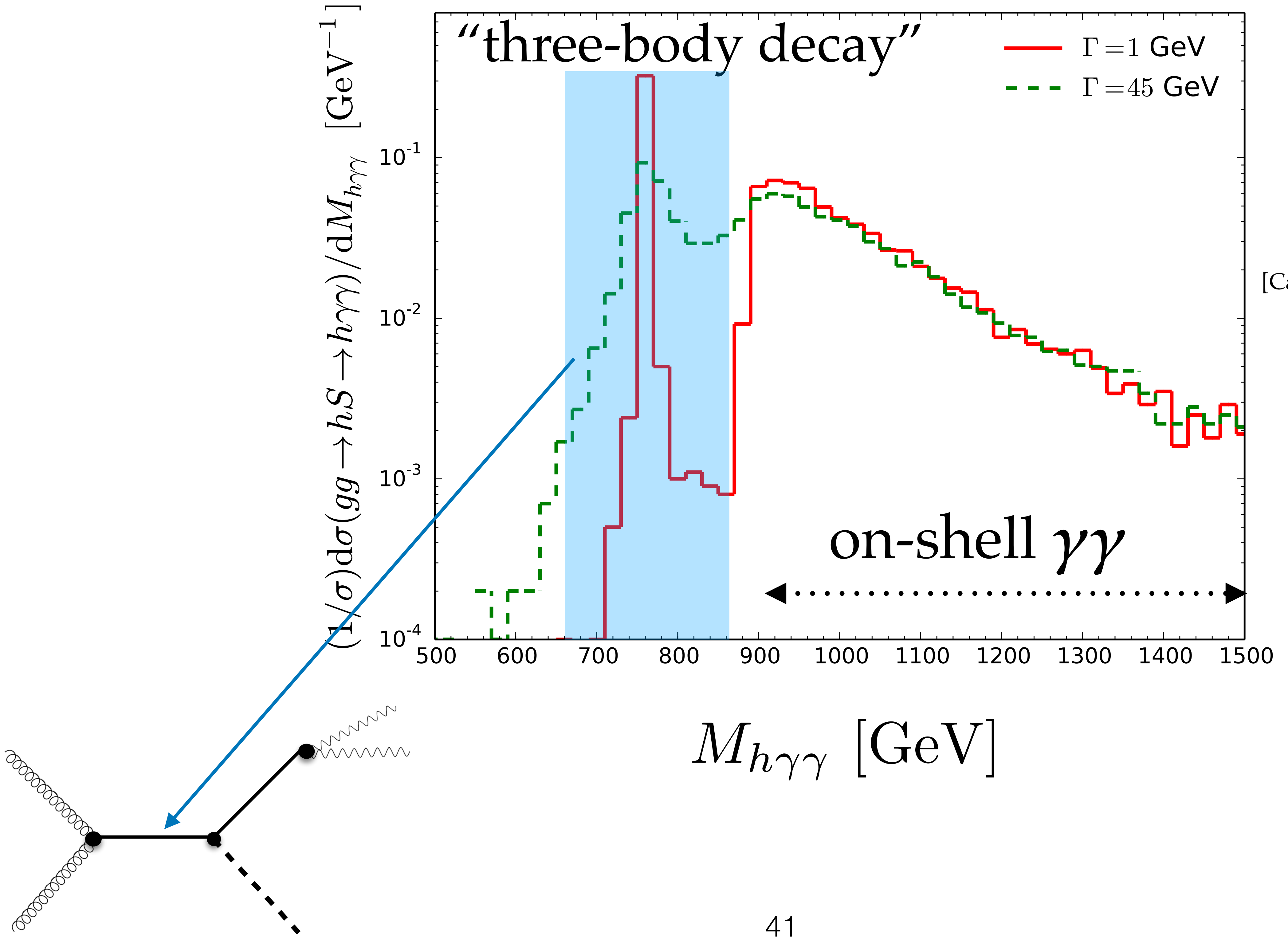

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kinematic features of $h(b\bar{b})S(\gamma\gamma)$

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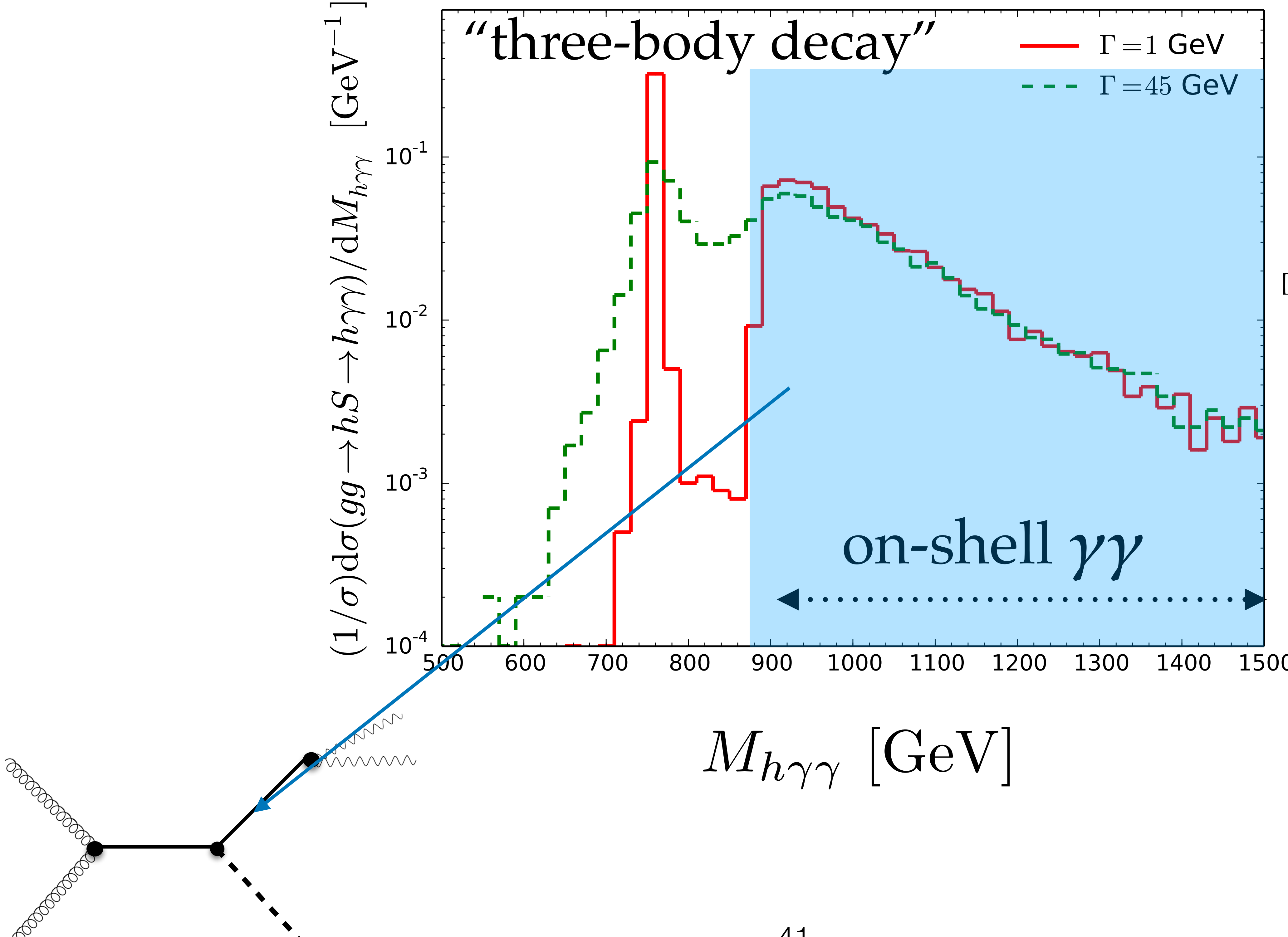

M= 750 GeV

[Carmona, Goertz, AP, 1606.02716]

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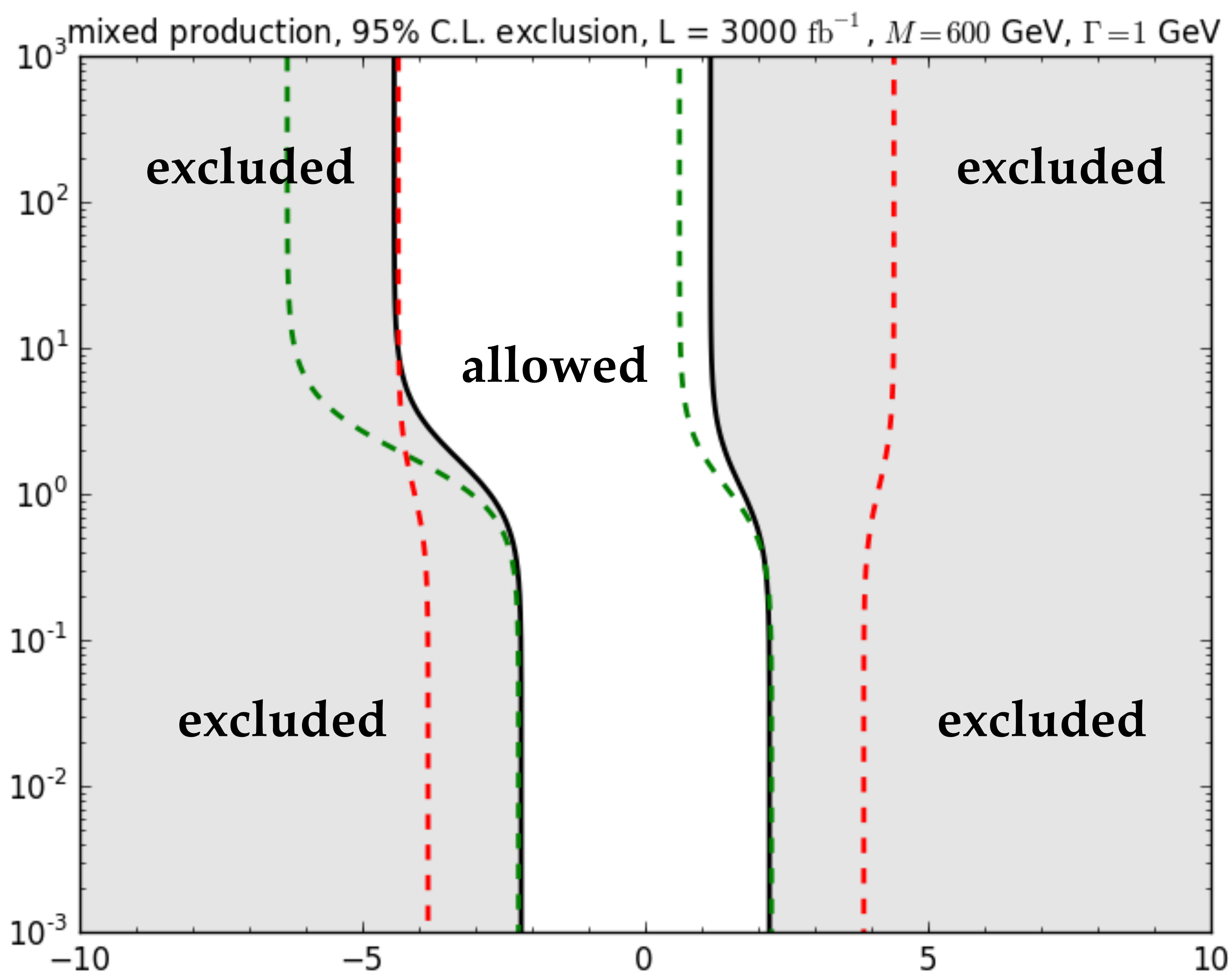
- calculate 95% C.L. exclusion for resonance produced in **mixture** of gluon fusion and ***b***-quark fusion:

[given assumption that "underlying" production is purely gluon fusion and λ_{HS}=1]

[more *b*-quark]

y_b^S / c_G^S

[more gluon]



λ_{HS}

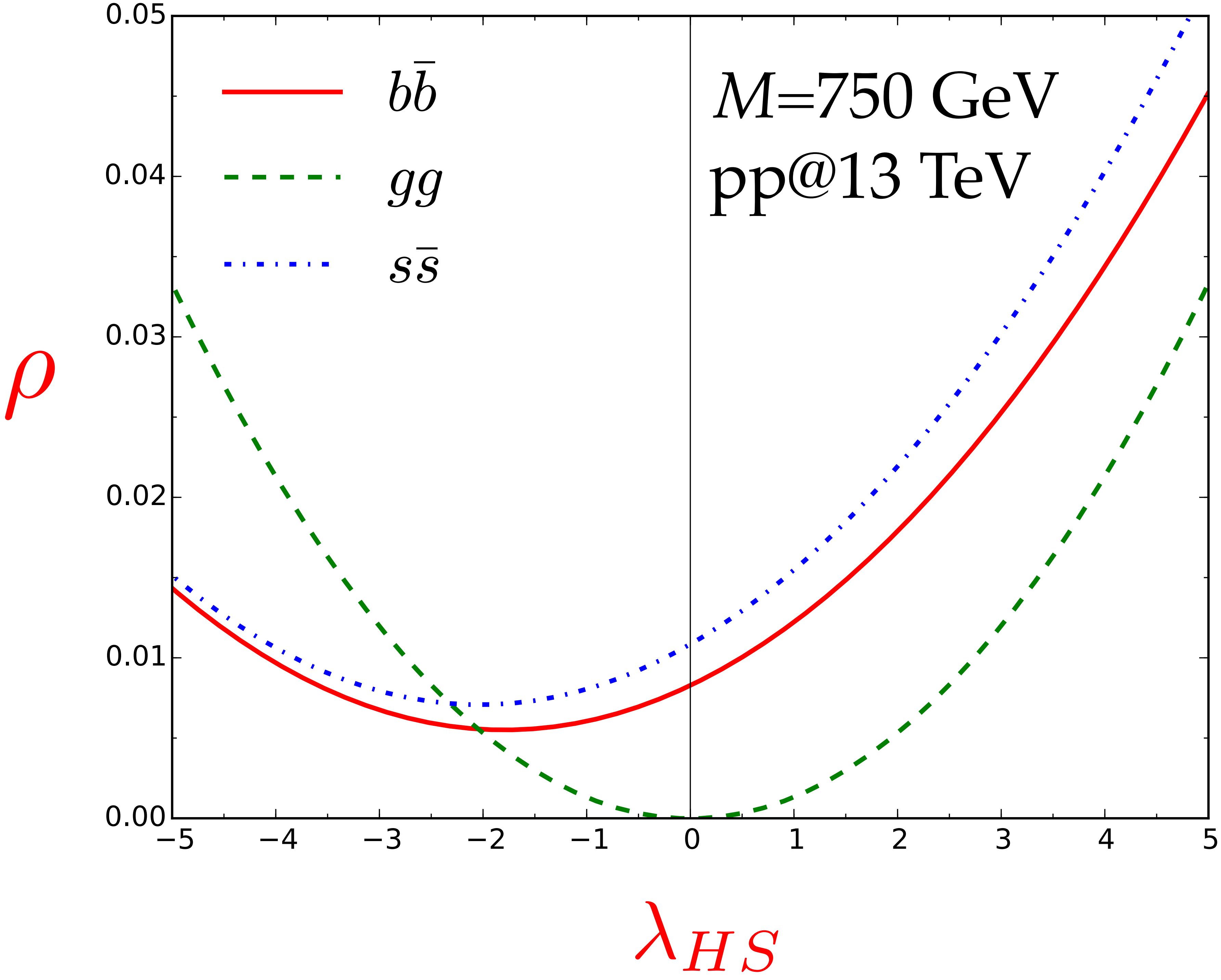
M= 600 GeV, ***Γ*** = 1 GeV

green: "on-shell $\gamma\gamma$"

red: "three-body decay"

[Carmona, Goertz, **AP**, 1606.02716]

$$\rho = \frac{\sigma(pp \to hS \to h\gamma\gamma)}{\sigma(pp \to S \to \gamma\gamma)} = a\ \lambda_{HS}^2 + b\ \lambda_{HS} + c$$



[Carmona, Goertz, **AP**, 1606.02716]

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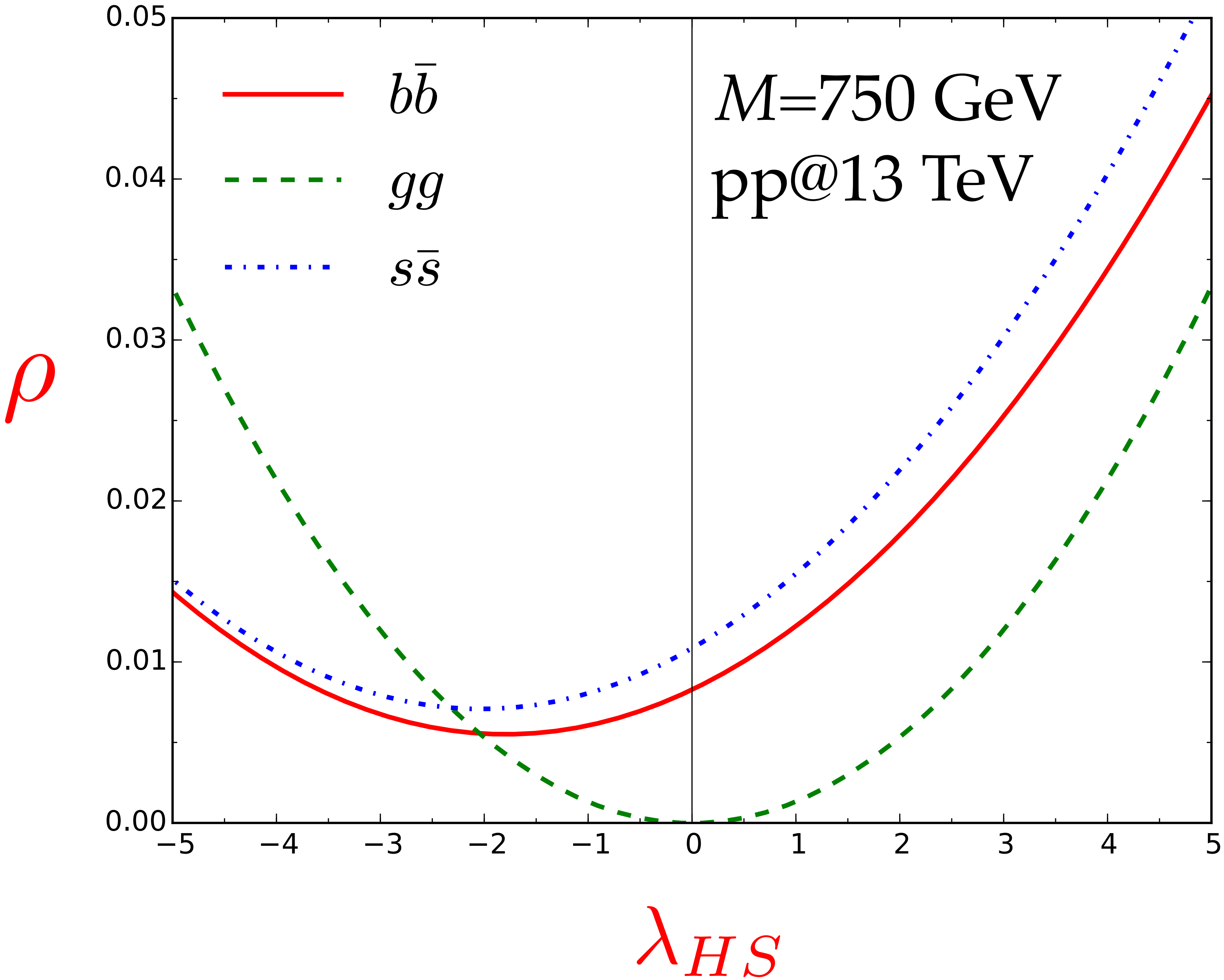


[Carmona, Goertz, **AP**, 1606.02716]

e.g., if (13 TeV):

$\sigma(pp \to S \to \gamma\gamma) = 10$ fb

$\lambda_{HS} = 1$

and purely gluon-induced:

$\sigma(gg \to hS \to h\gamma\gamma) =$

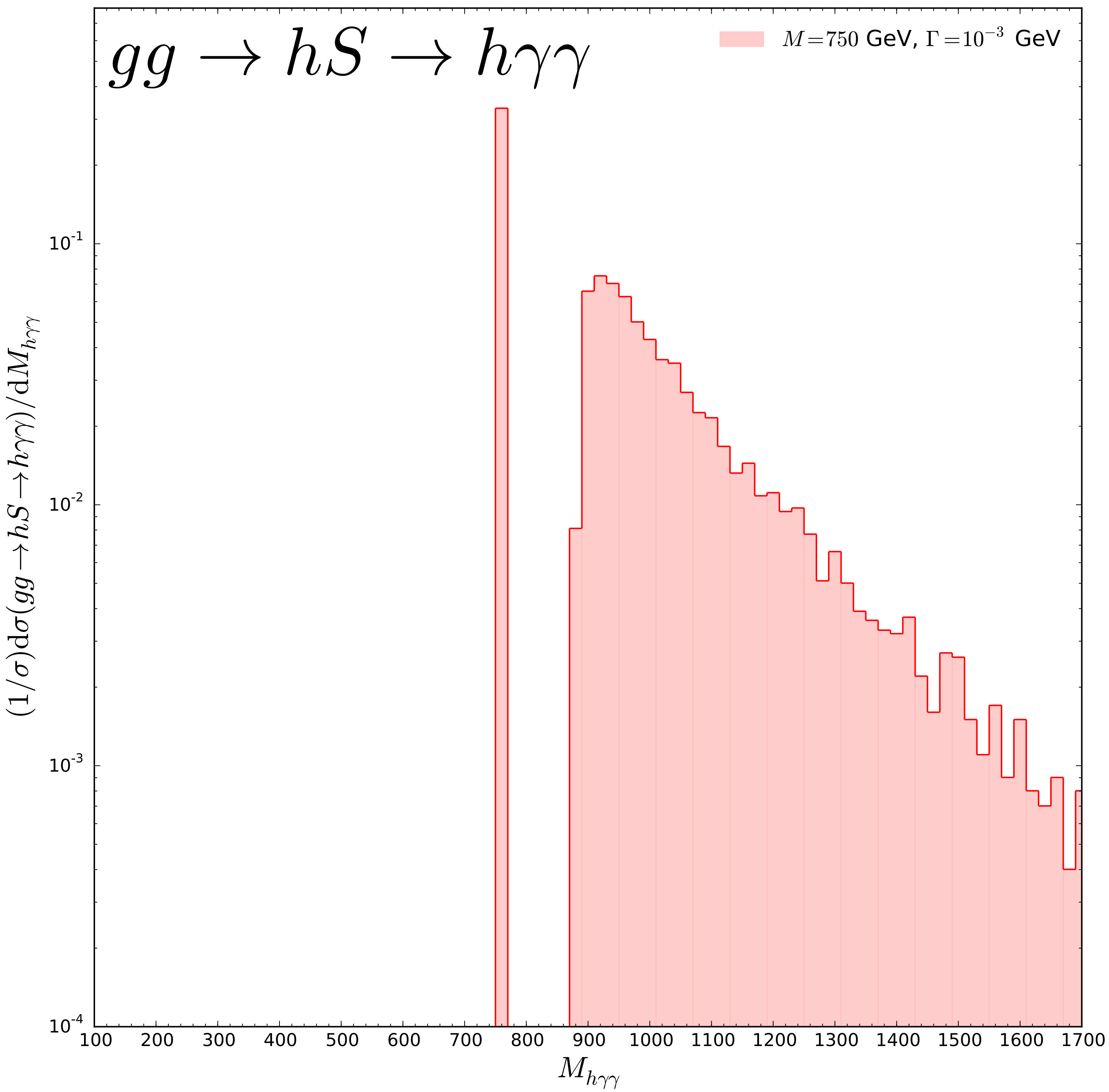
$\rho \times 10 \text{ fb} \sim 10^{-2} \text{ fb}$

or purely b-quark induced:

$\sigma(b\bar{b} \to hS \to h\gamma\gamma) =$

$\rho \times 10 \text{ fb} \sim 10^{-1} \text{ fb}$

kinematic features



$M_{h\gamma\gamma}$ [GeV]

M=750 GeV

$\Gamma = 10^{-3}$ GeV

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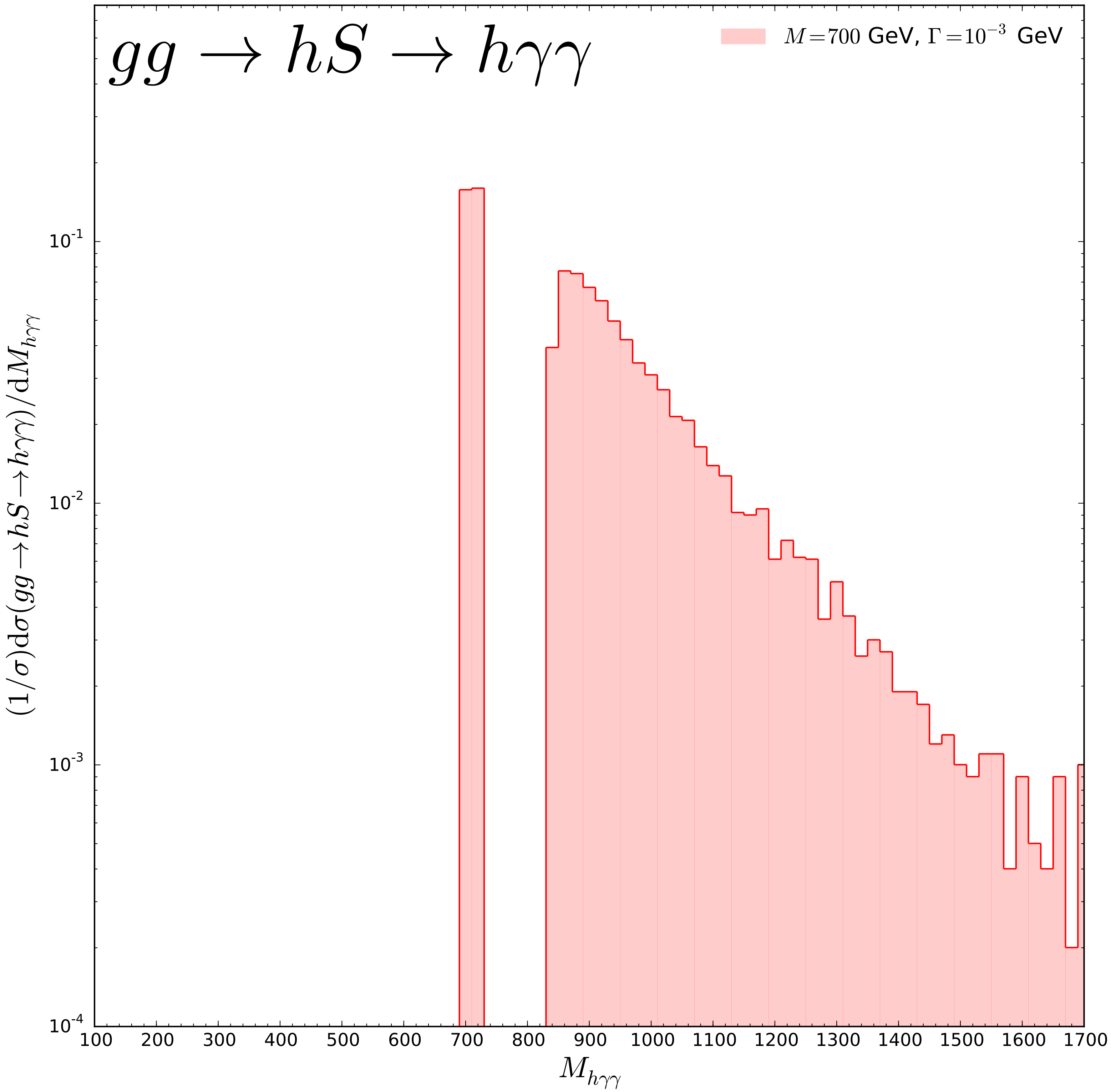
kinematic features



$M_{h\gamma\gamma}$ [GeV]

M=700 GeV

$\Gamma = 10^{-3}$ GeV

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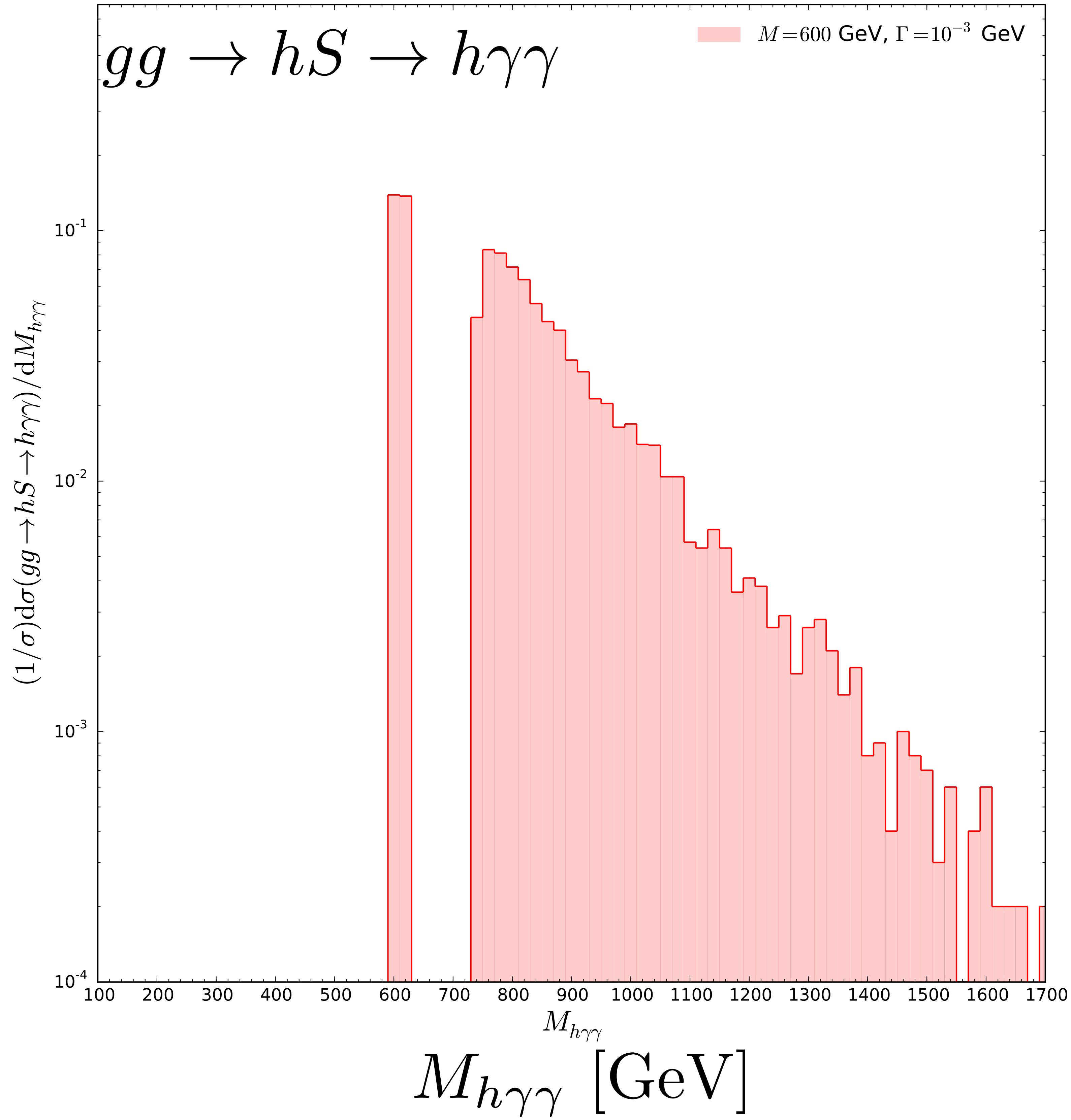
kinematic features



M=600 GeV

$\Gamma = 10^{-3}$ GeV

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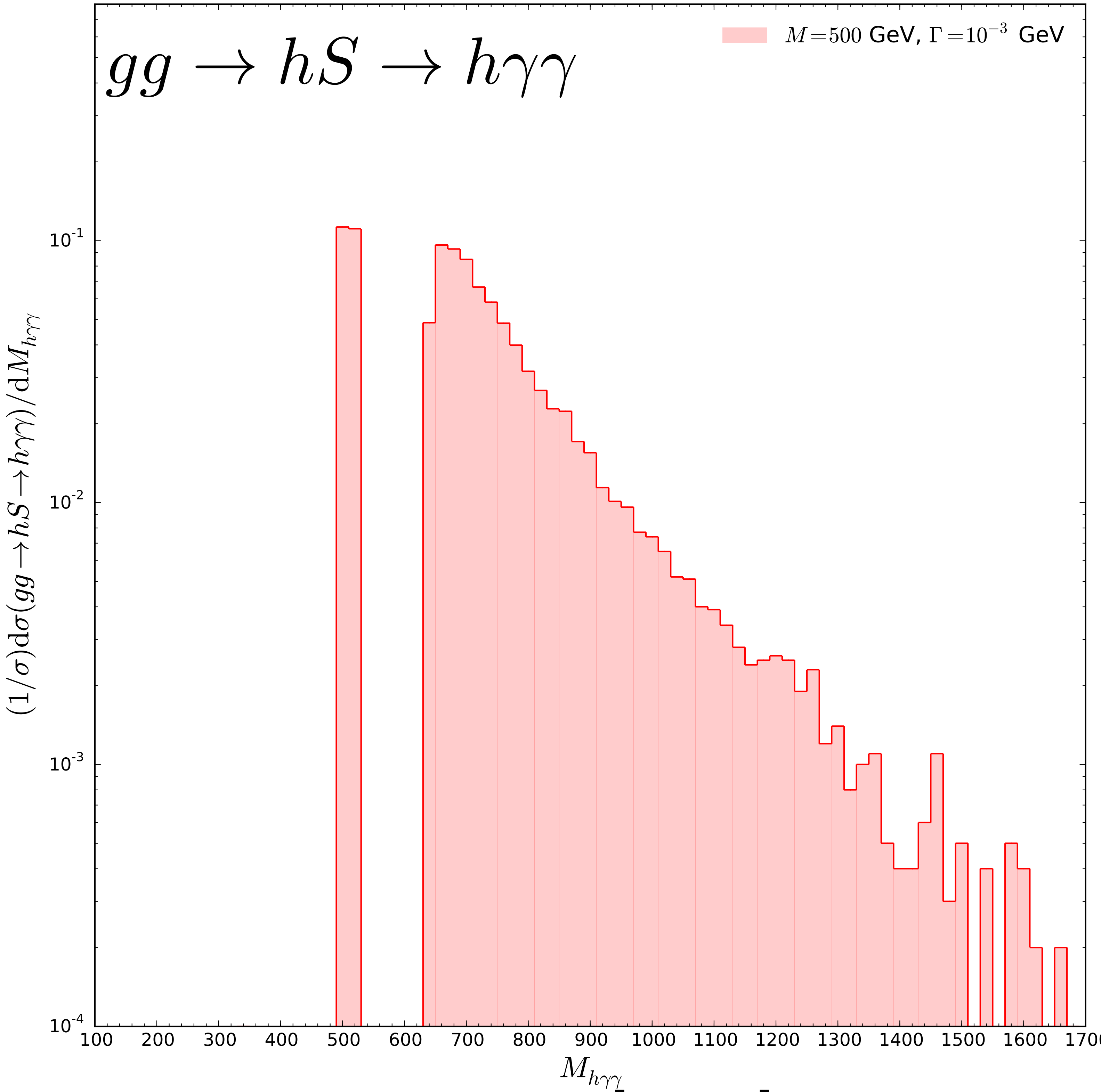
kinematic features



$M_{h\gamma\gamma}$ [GeV]

M=500 GeV

$\Gamma = 10^{-3}$ GeV

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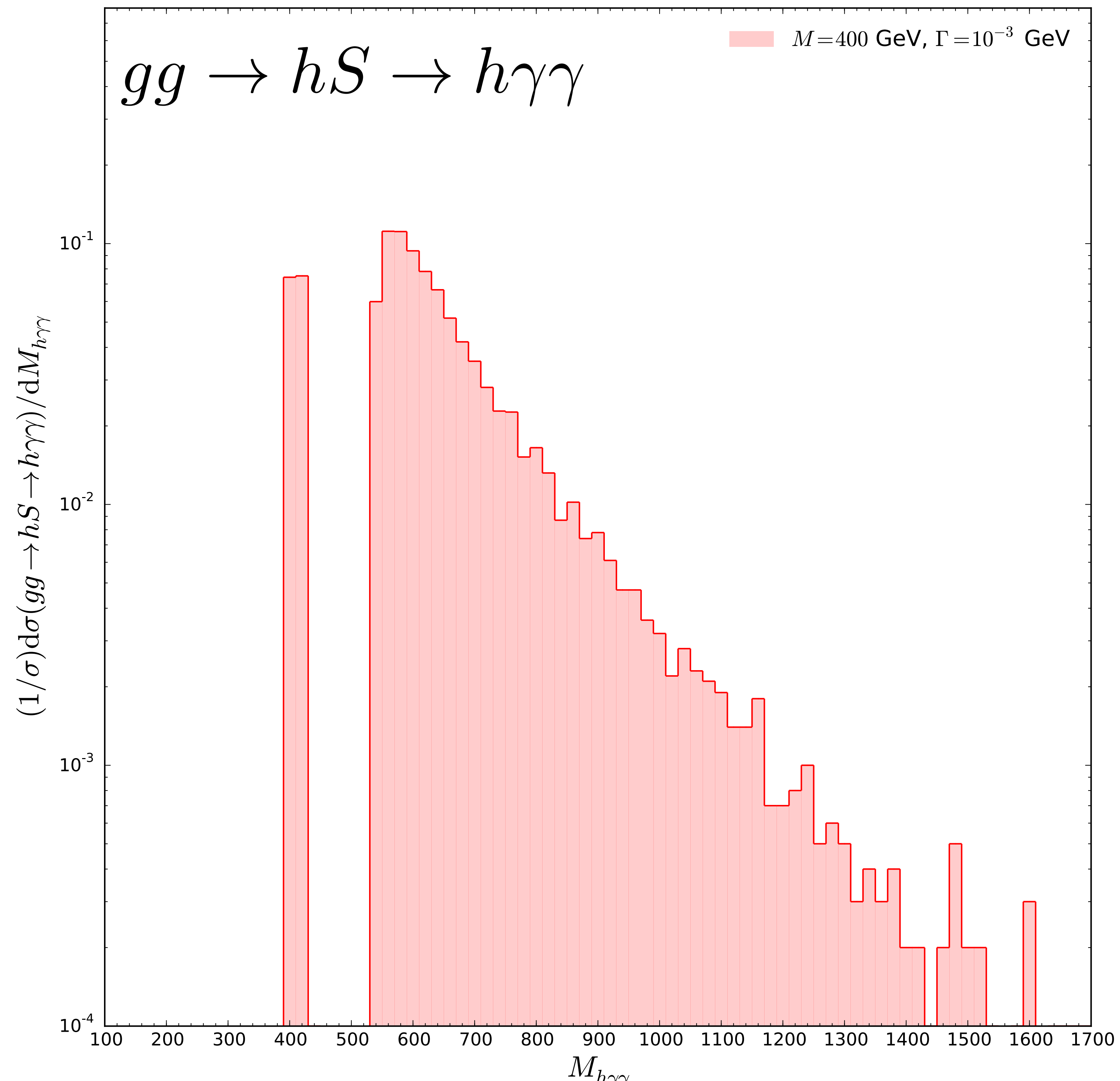
kinematic features



$M_{h\gamma\gamma}$ [GeV]

M=400 GeV

$\Gamma = 10^{-3}$ GeV

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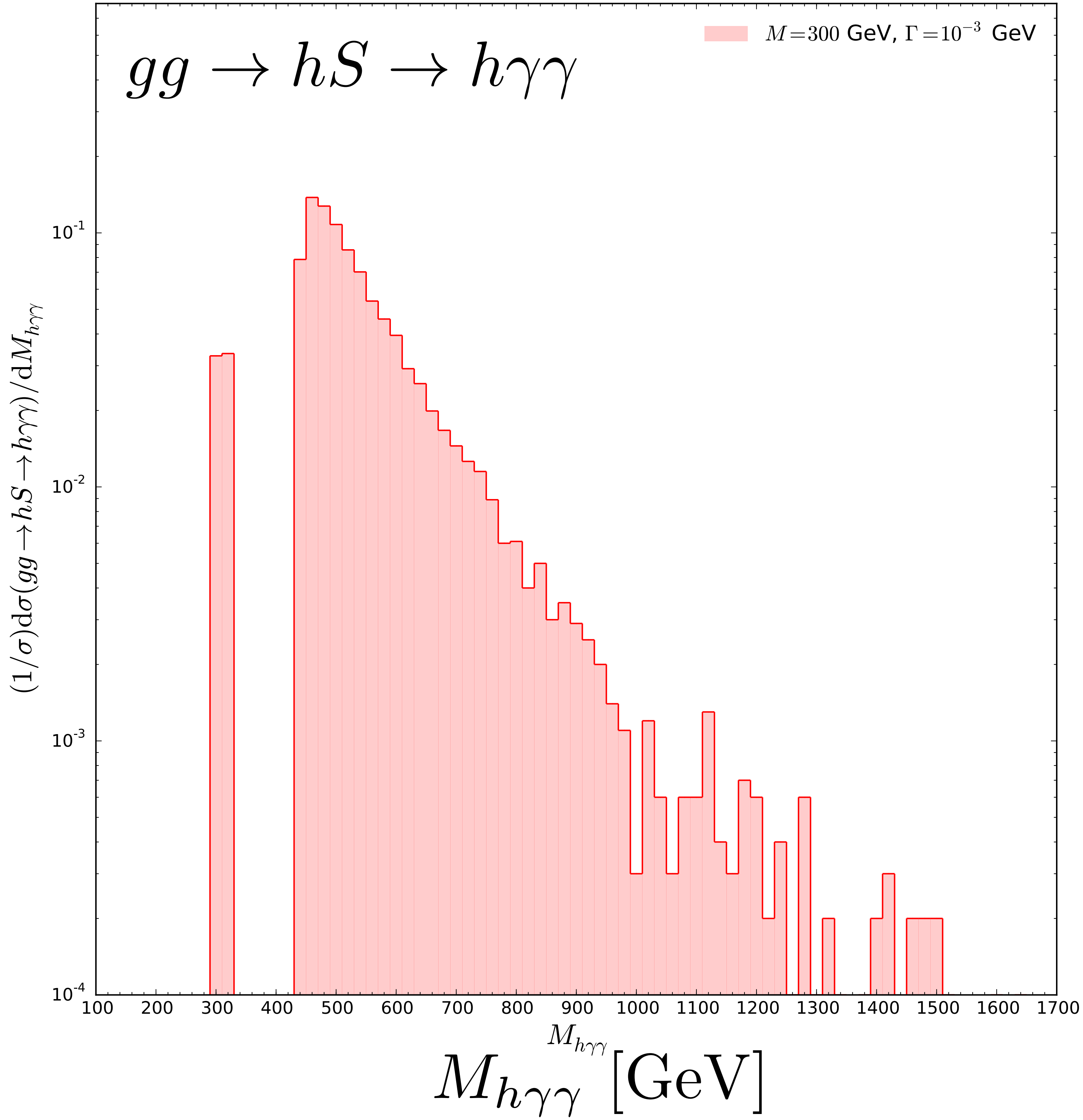
kinematic features



M=300 GeV

$\Gamma = 10^{-3}$ GeV

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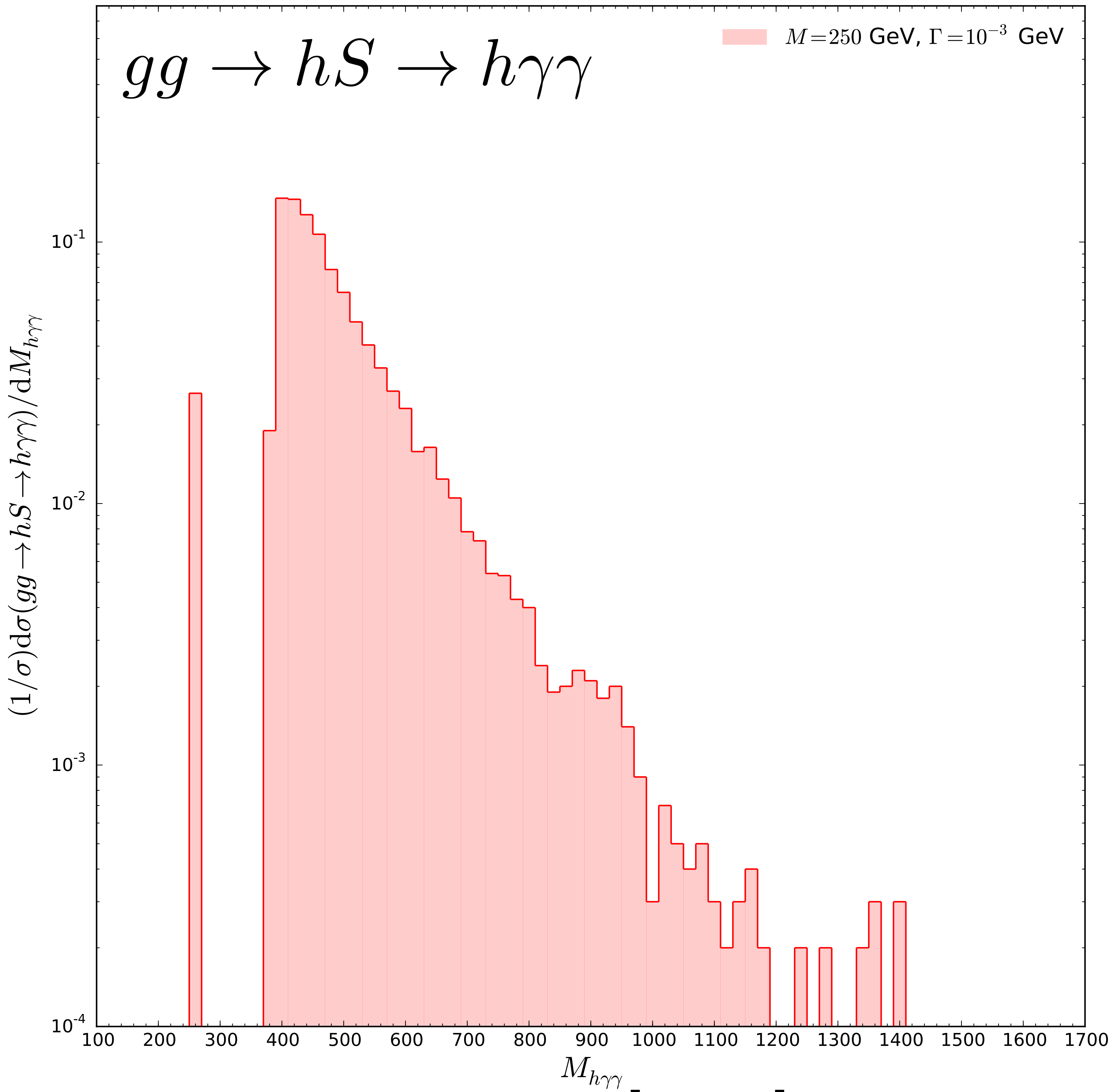
kinematic features



$M_{h\gamma\gamma}$ [GeV]

M=250 GeV

$\Gamma = 10^{-3}$ GeV

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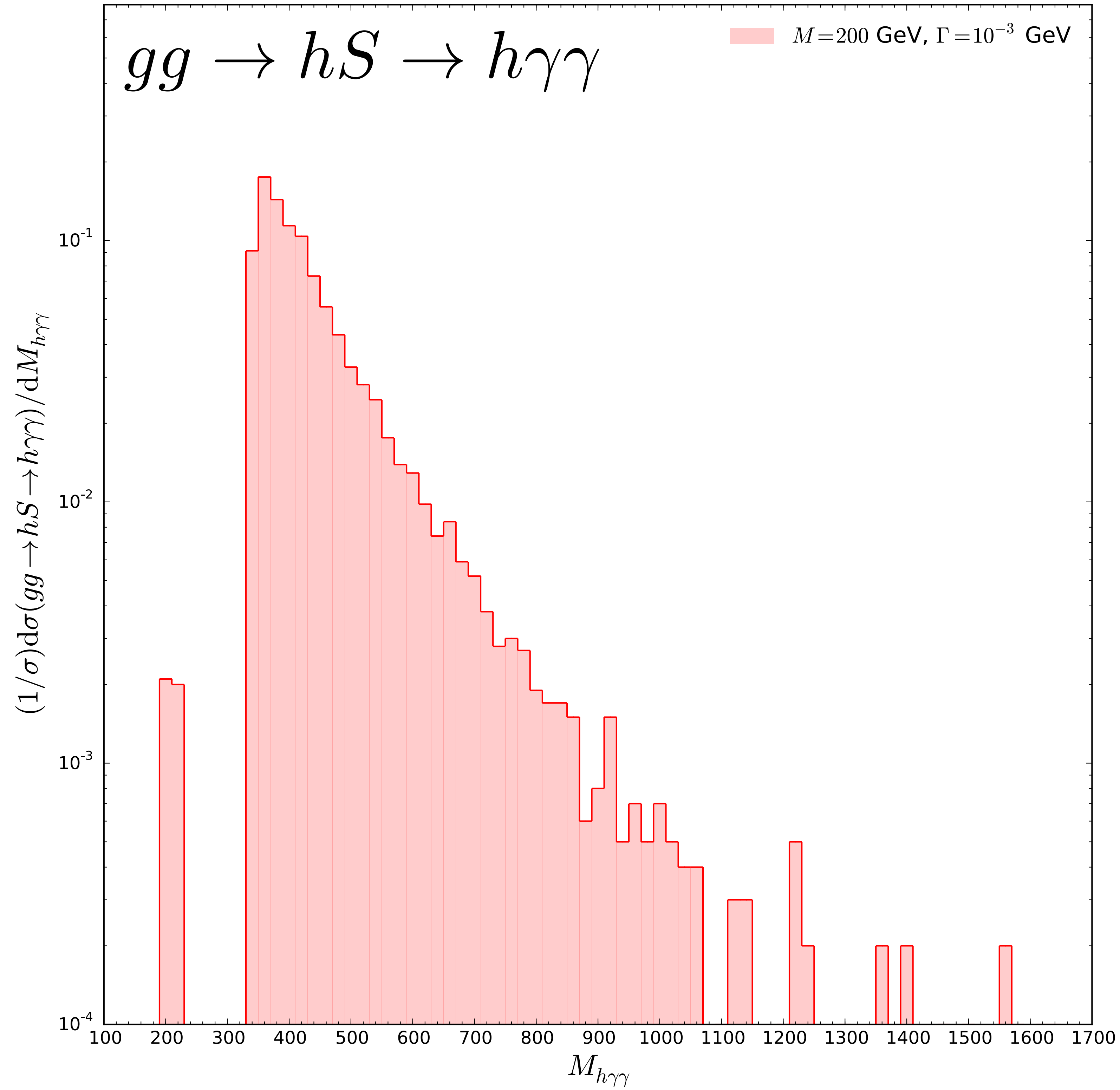
kinematic features

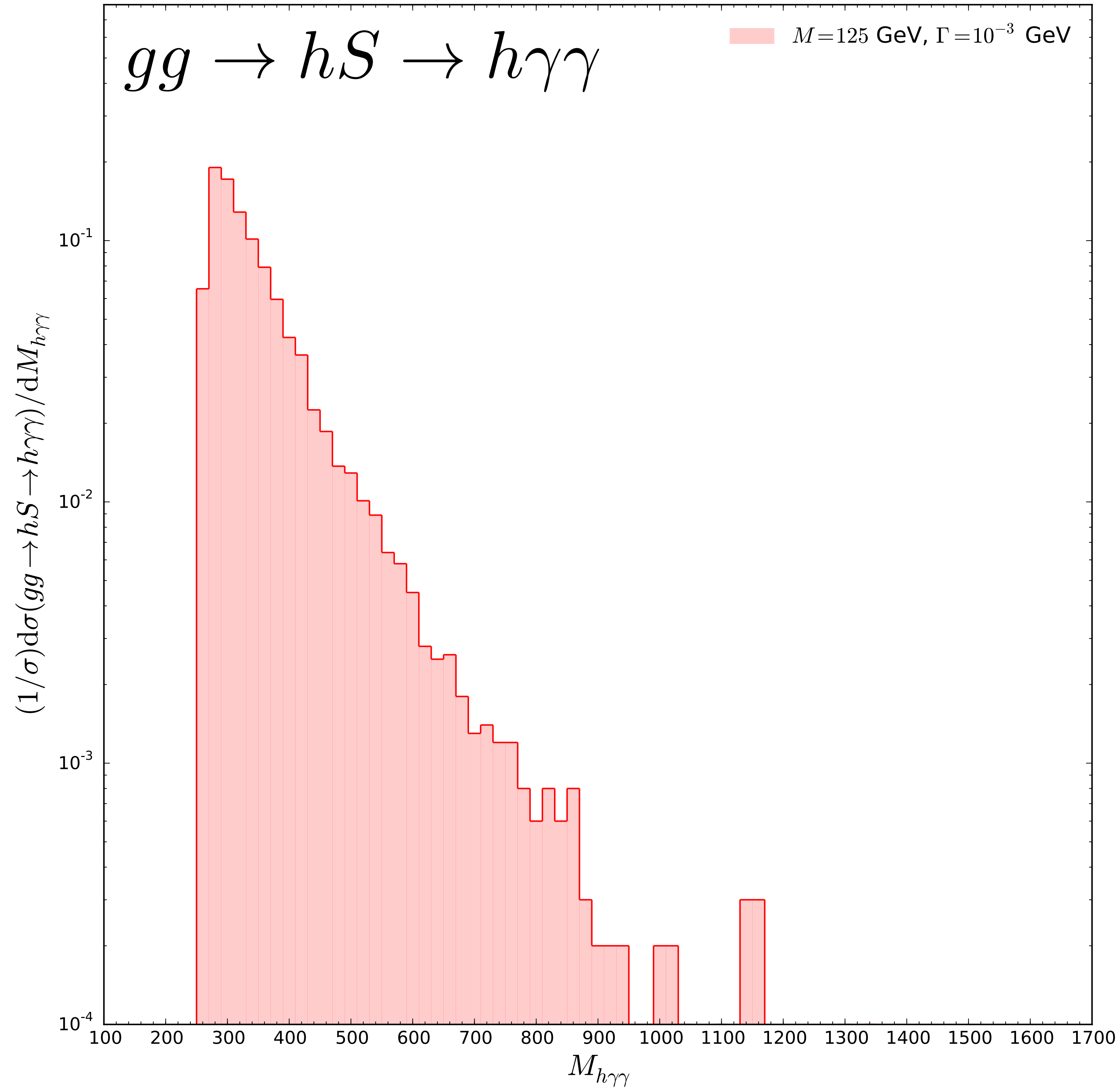


$M_{h\gamma\gamma}$ [GeV]

M=200 GeV

$\Gamma = 10^{-3}$ GeV

kinematic features



$M_{h\gamma\gamma}$ [GeV]

M=125 GeV

$\Gamma = 10^{-3}$ GeV

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