Multi-Scalar production & self-coupling measurements at hadron colliders

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Nikhef

Max Planck Institute, Munich,
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introduction

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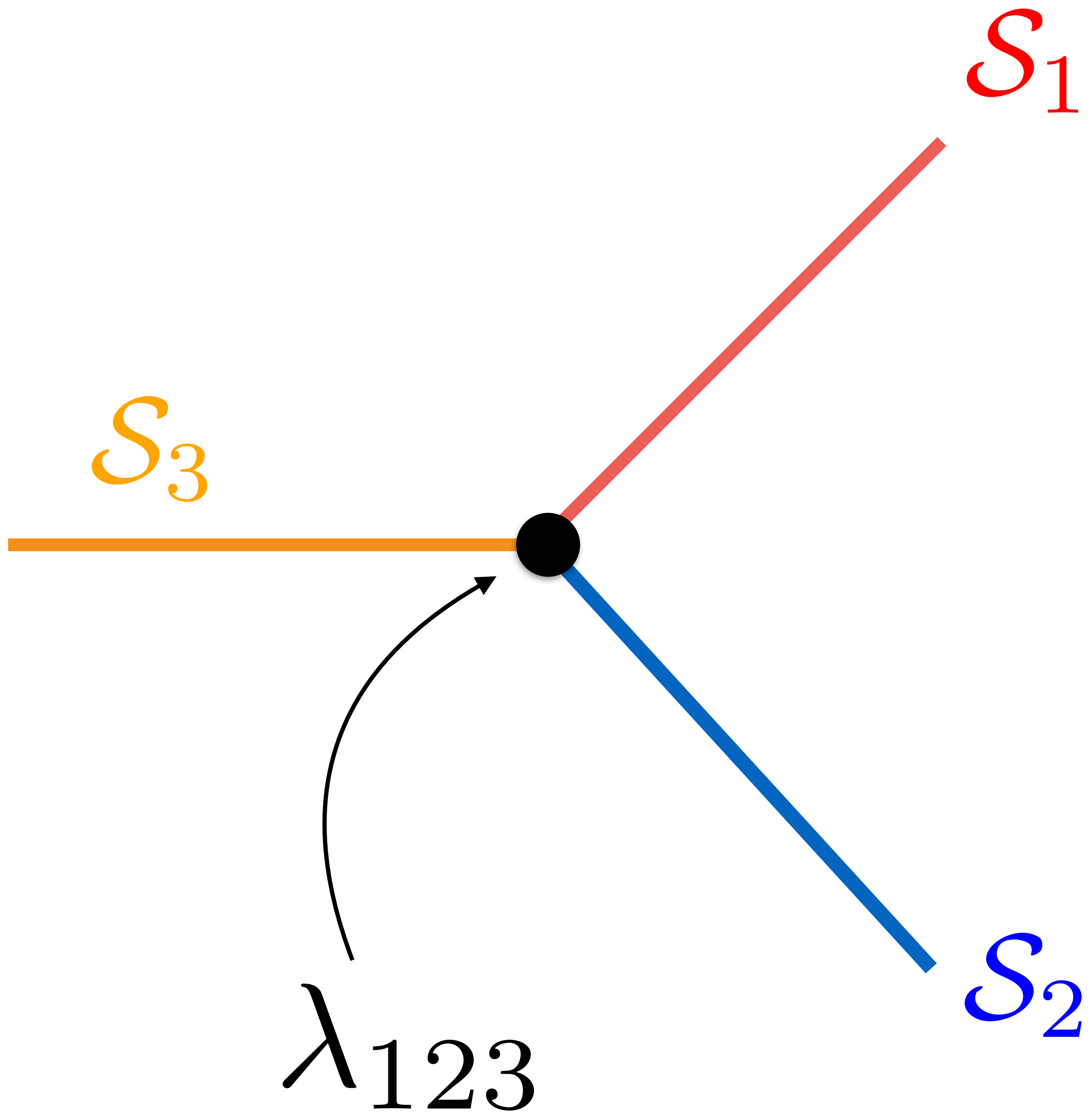

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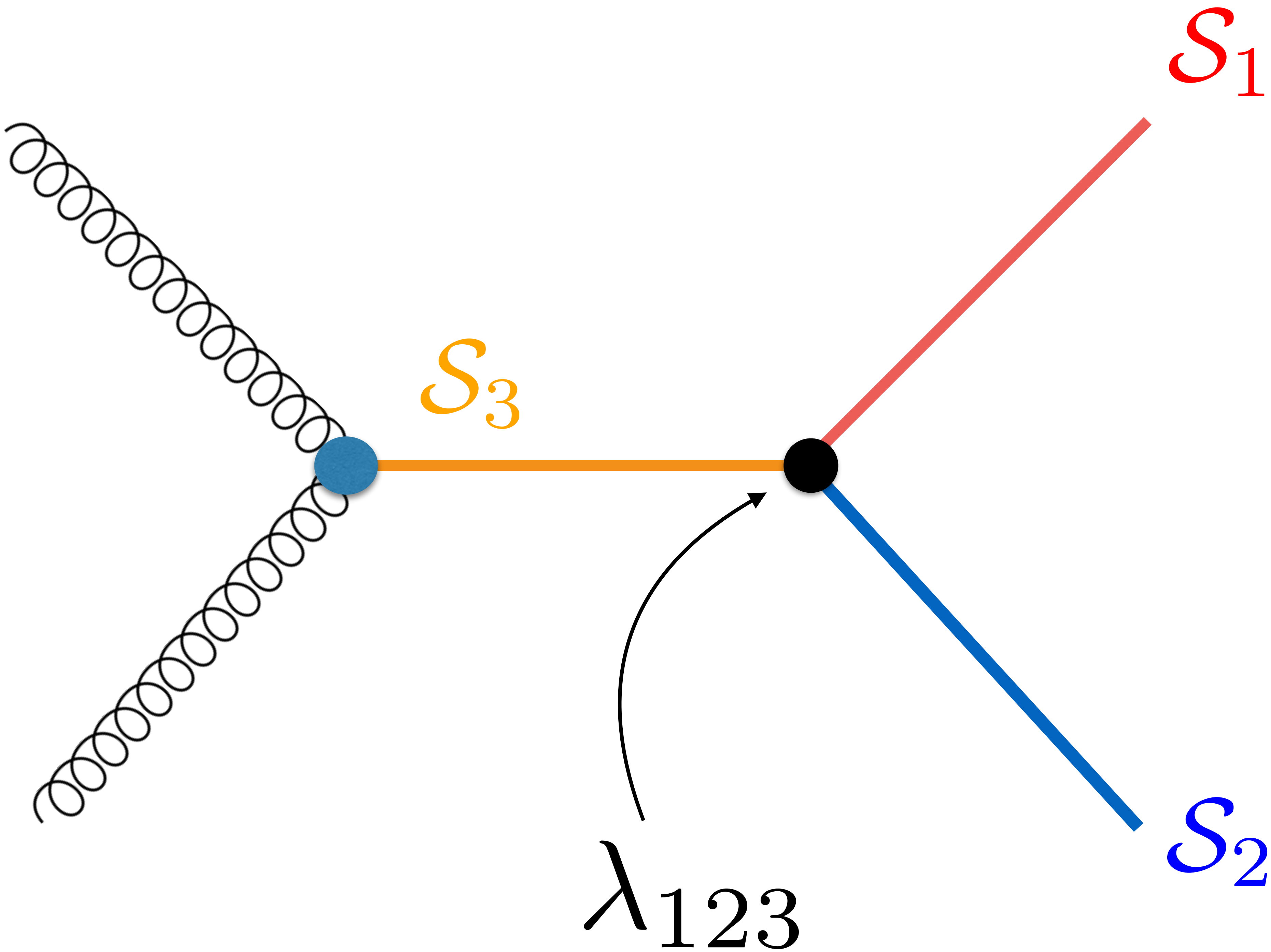
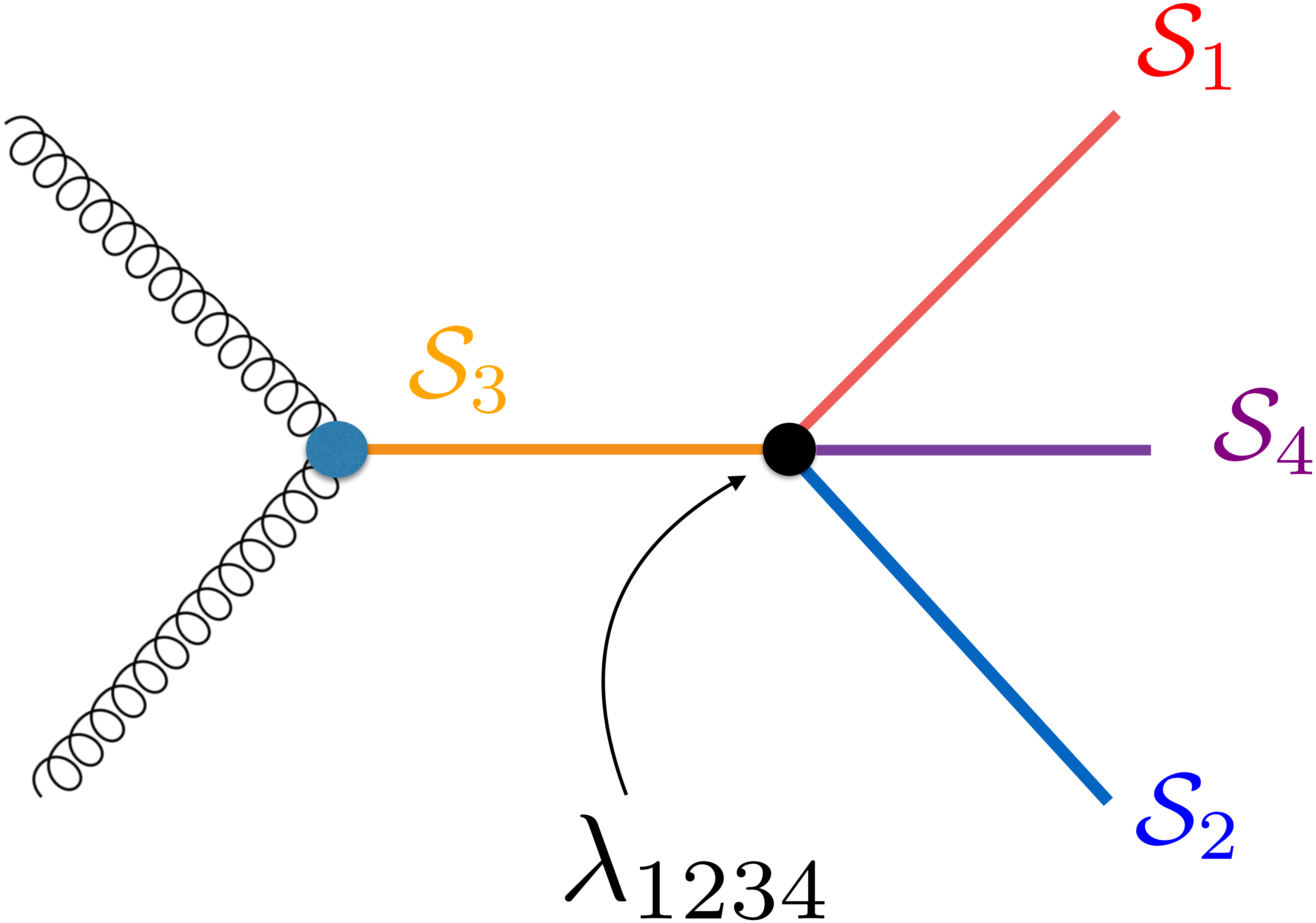
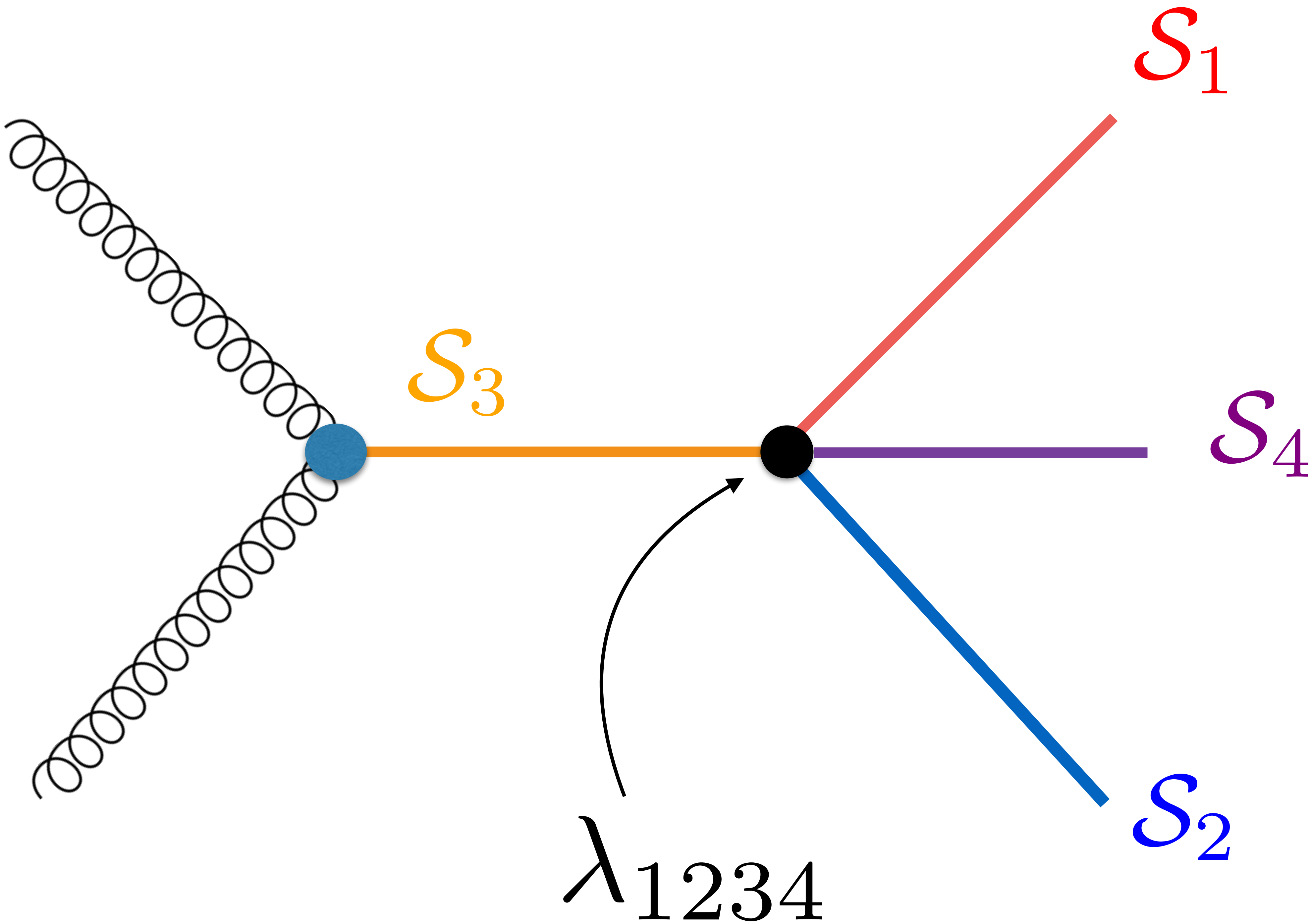
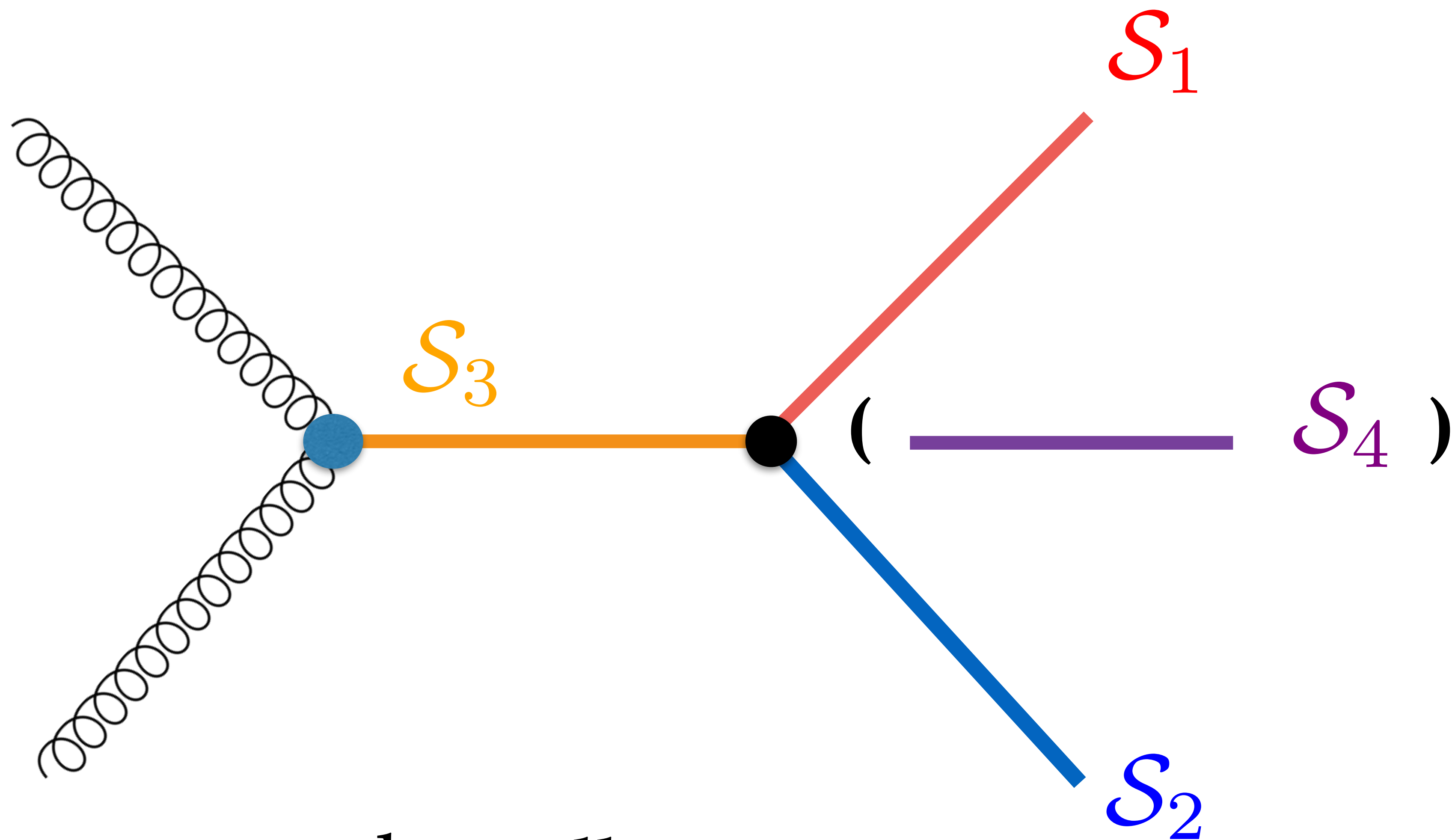

S_1
S_3
S_2
λ_{123}



$\mathcal{S}_1$
$\mathcal{S}_3$
$\mathcal{S}_4$
λ_{1234}
$\mathcal{S}_2$



$$\mathcal{L} \supset \lambda_{123}\Lambda\mathcal{S}_1\mathcal{S}_2\mathcal{S}_3 + \lambda_{1234}\mathcal{S}_1\mathcal{S}_2\mathcal{S}_3\mathcal{S}_4$$



- direct production, in this talk:

$\mathcal{S}_1 = \mathcal{S}_2 = \mathcal{S}_3 = h$ $\rightarrow$ Higgs **pair** production. $\rightarrow$ λ_3

$\mathcal{S}_1 = \mathcal{S}_2 = \mathcal{S}_3 = \mathcal{S}_4 = h$ $\rightarrow$ Higgs **triple** production. $\rightarrow$ λ_4

$\mathcal{S}_1 = h,\ \mathcal{S}_2 = S,\ \mathcal{S}_3 = \{S, h\}$ $\rightarrow$ Higgs-**New Scalar** production. $\rightarrow$ λ_{HS}

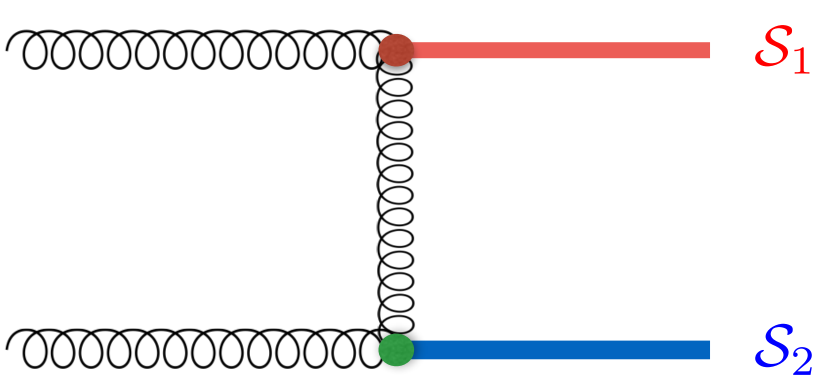
"portal coupling"

comments (I):

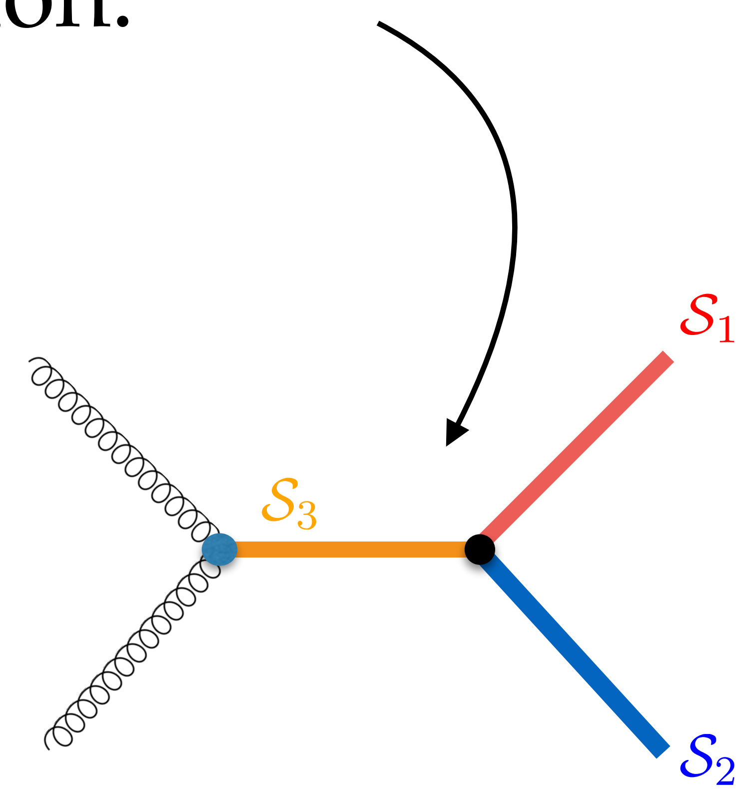
- "self-coupling" diagrams *not the only* diagrams contributing to the multi-Scalar final states.

- in fact, could be *suppressed* with respect to other diagrams: e.g. propagator suppression.

e.g.



VS

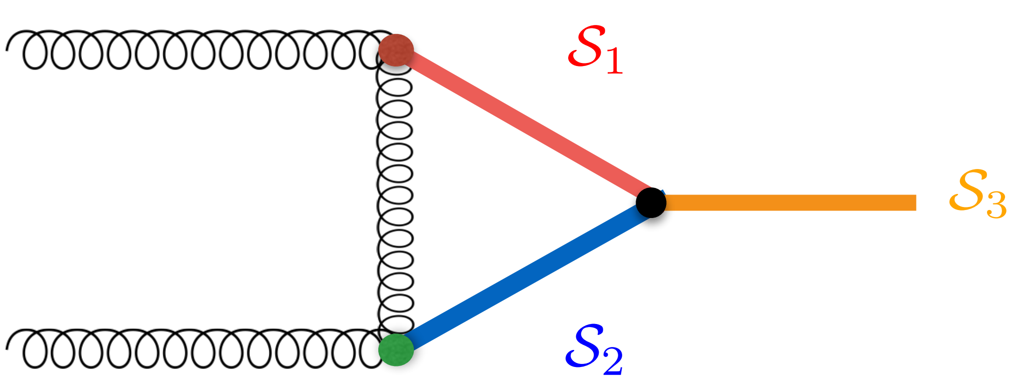


comments (II):

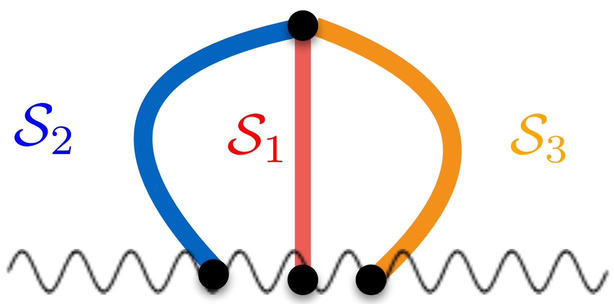
- the scalar "self-couplings" can appear in loop diagrams.

- "precision" measurements could probe them.

e.g.



or



contents:

- multi-Higgs (***hh*, *hhh***) production,
- indirect constraints on Higgs self-couplings,
- Higgs-Heavy Scalar (***hS***) associated production,
- conclusions.

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multi-Higgs production

motivation

- "standard" electroweak recipe in Standard Model:
- ingredients:

$SU(2) \times U(1)$ gauge symmetry,

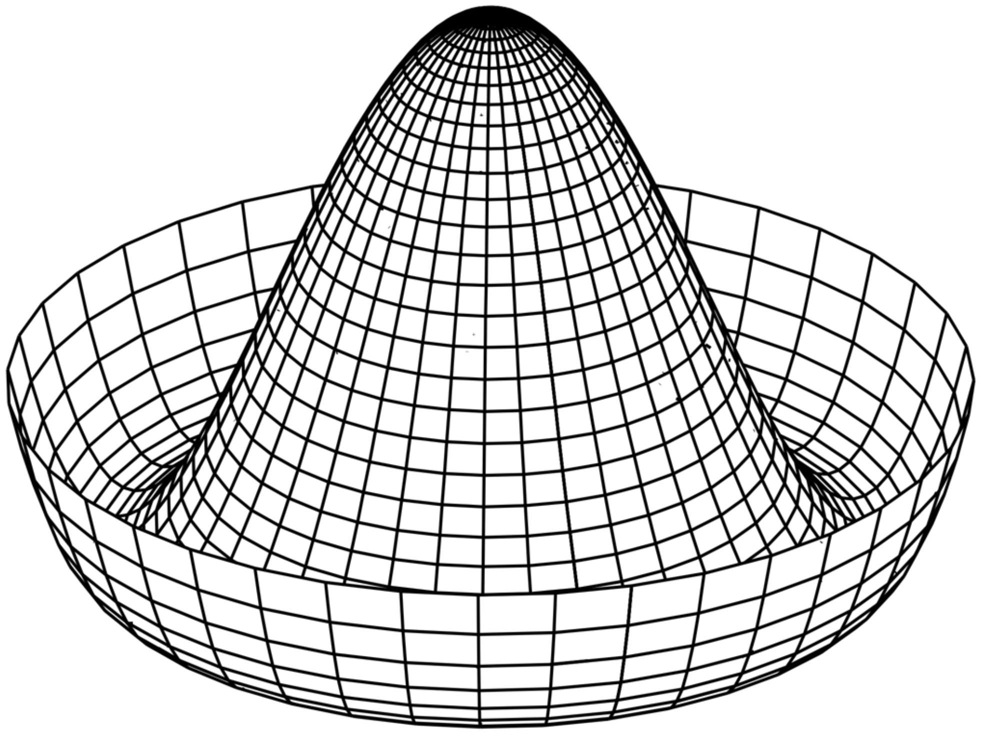
+ complex doublet scalar, H,

+ potential for H: $\mathcal{V}(H^\dagger H)$.

motivation

- instructions:
  - choose minimum in particular direction, keep U(1) invariance $\hookrightarrow$ **electroweak symmetry breaking**.
  - fluctuations of scalar field about minimum.
  - gauge transformation: absorb Goldstone modes into the gauge bosons.

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



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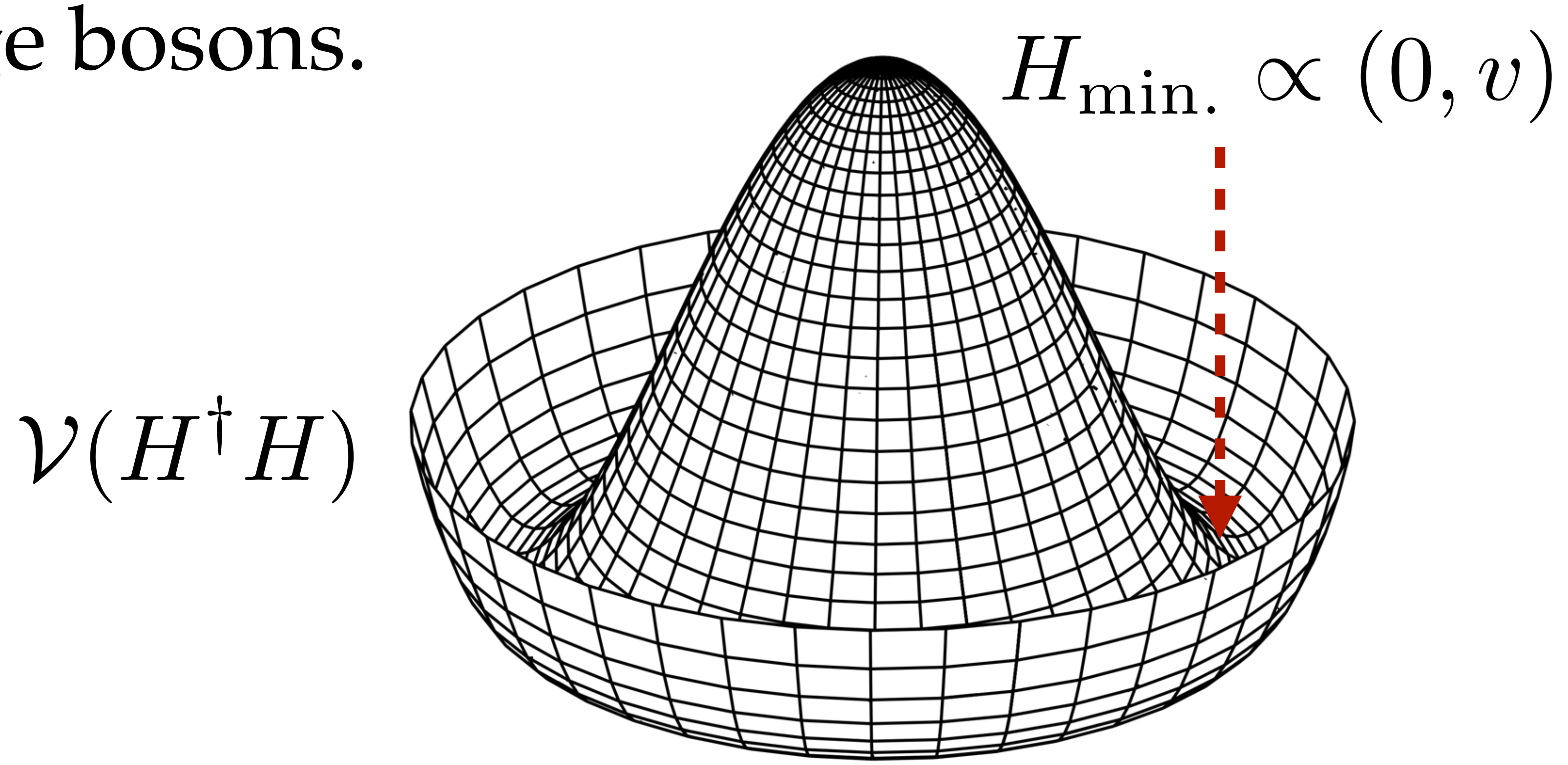

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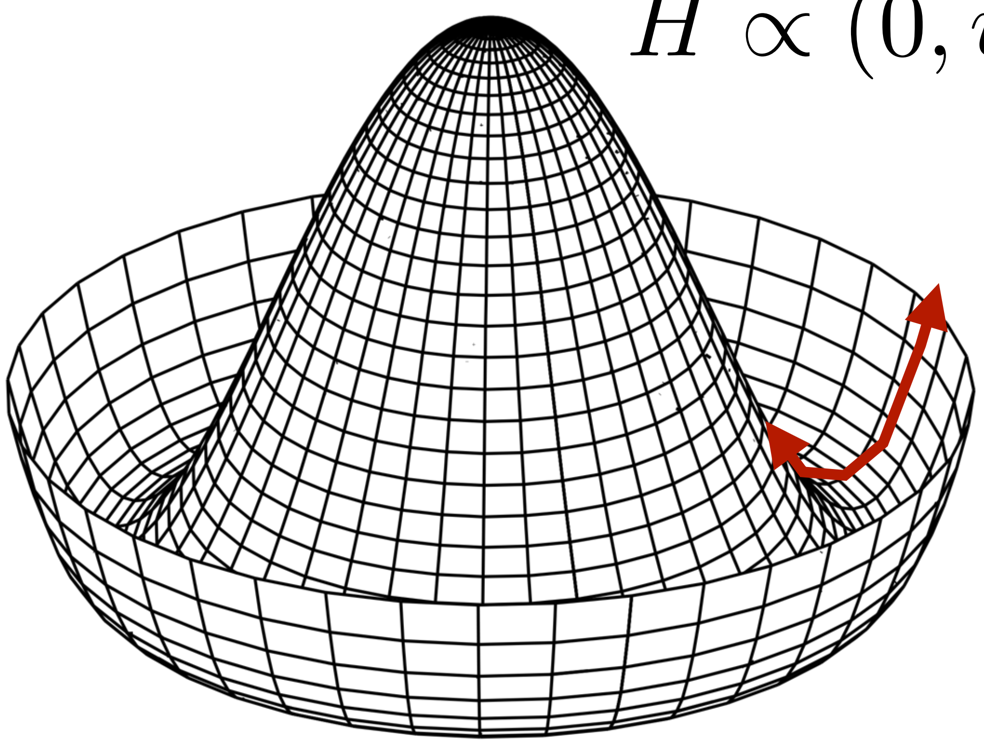
$H \propto (0, v+h)$

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



motivation

- the potential for the physical scalar Higgs boson, ***h*:**

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

- v=246 GeV [through four-fermion interactions via the Fermi constant.] and Higgs boson mass, $m_h \sim 125$ GeV.

- can predict all coefficients of h^n, within SM.

- consistency with SM a probe for new physics (c_3, d_4).

motivation

- the potential for the physical scalar Higgs boson, ***h*:**

$$\mathcal{L} \supset -\frac{1}{2} m_h^2 h^2 - \frac{m_h^2}{2v} (\overbrace{1 + c_3}^{\lambda_3}) h^3 - \frac{m_h^2}{8v^2} (1 + d_4) h^4$$

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multi-Higgs cross sections

- cross sections small for > one Higgs boson:

process	pp@14 TeV	pp@100 TeV
single Higgs	~50 000 fb	~800 000 fb
double Higgs	~50 fb	~1800 fb
triple Higgs	~0.1 fb	~5 fb

$\times\mathcal{O}(10^{-3})$

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[see, e.g., LHCHXSWG YR4: 1610.07922 and FCC-hh Higgs report: 1606.09408.]

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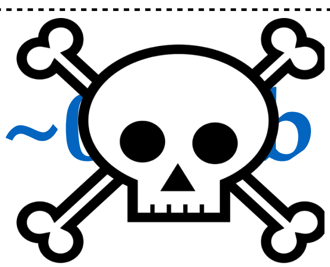
triple Higgs		**~5 fb**

single → double Higgs: $\times\mathcal{O}(10^{-3})$

double → triple Higgs: $\times\mathcal{O}(10^{-3})$

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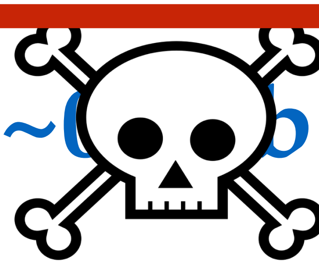
triple Higgs	~0[illegible]b 	~5 fb

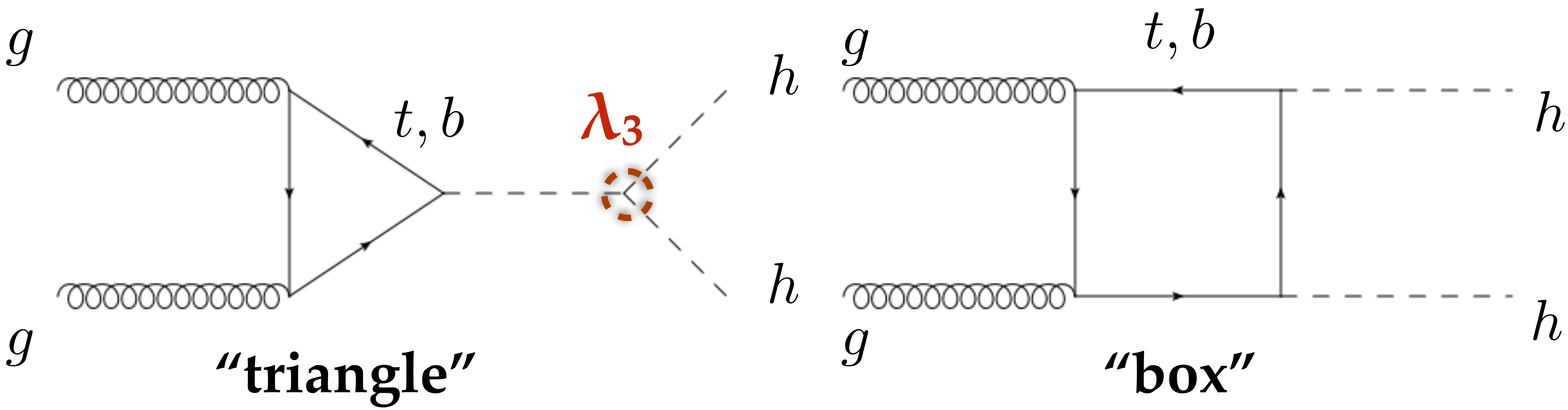
$\times\mathcal{O}(10^{-3})$ (single → double Higgs)

$\times\mathcal{O}(10^{-3})$ (double → triple Higgs)

[see, e.g., LHCHXSWG YR4: 1610.07922 and FCC-hh Higgs report: 1606.09408.]

Higgs boson pair production

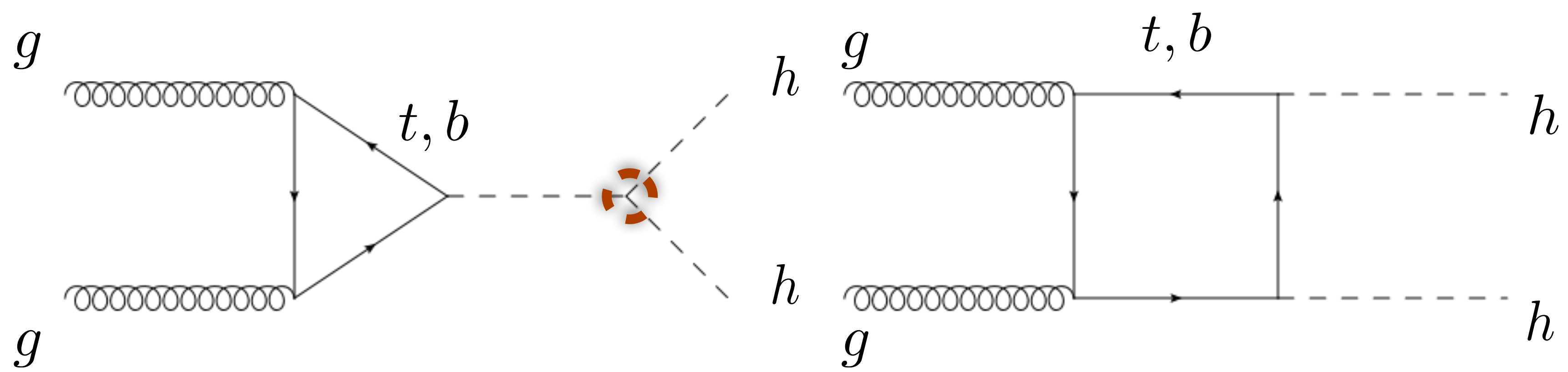
- dominant piece of ***hh*:** gluon fusion, via heavy quark loops,
  [for VBF *hh* study: Bishara, Contino, Rojo, 1611.03860]
- at leading order:



- cannot use heavy top mass approximation (Higgs Effective Field Theory = **HEFT**) to "shrink" loops, since:

$$Q^2 \geq 4m_h^2 > m_t^2$$

LO hh: anatomy



$$\mathcal{M} = \mathcal{M}_{\triangle} + \mathcal{M}_{\square}$$

with $\mathcal{M}_{\triangle} = \alpha_{\triangle} A_{1\mu\nu}$ and $\mathcal{M}_{\square} = \alpha_{\square} A_{1\mu\nu} + \beta_{\square} A_{2\mu\nu}$

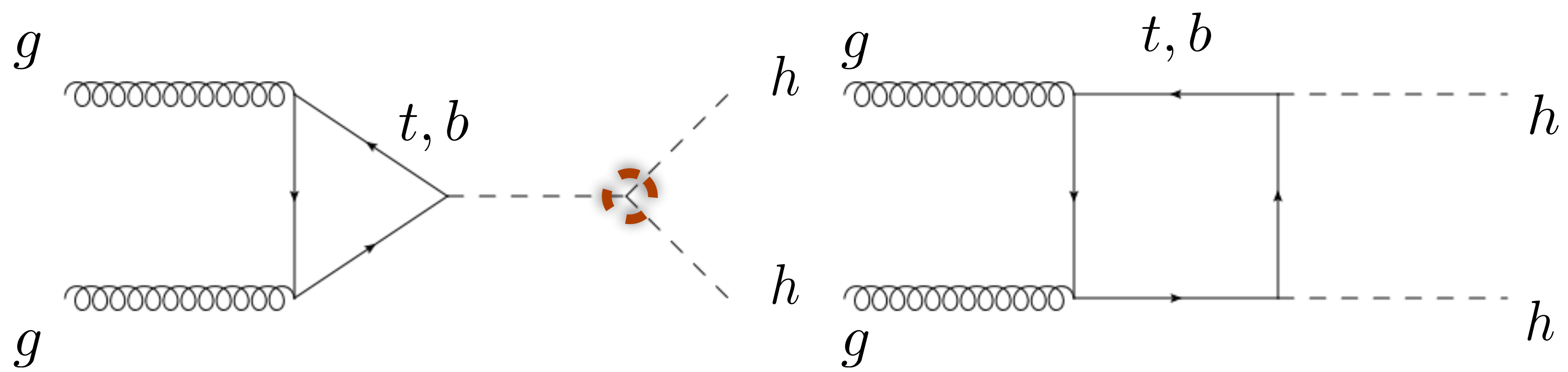
tensors: $A_1 \cdot A_2 = 0$ and $A_1 \cdot A_1 = A_2 \cdot A_2 = 2$

correspond to spin configurations for the gluons:

$$A_1 : \; S_z = 0 \qquad\qquad A_2 : \; S_z = 2$$

[Plehn, Spira, Zerwas, hep-ph/9603205, Binoth, Karg, Kauer, Rückl, hep-ph/0608057]

LO *hh*: anatomy



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with $\mathcal{M}_{\triangle} = \alpha_{\triangle} A_{1\mu\nu}$ and $\mathcal{M}_{\square} = \alpha_{\square} A_{1\mu\nu} + \beta_{\square} A_{2\mu\nu}$

$$\Rightarrow |\mathcal{M}|^2 \propto |\alpha_{\triangle}|^2 + 2\mathrm{Re}\{\alpha_{\triangle}\alpha_{\square}\} + |\alpha_{\square}|^2 + |\beta_{\square}|^2$$

$$\sigma_{hh}^{\mathrm{LO}}(14\ \mathrm{TeV}) = \left[5.22 \left(\frac{\lambda_3}{\lambda_{3,\mathrm{SM}}}\right)^2 - 25.1 \left(\frac{\lambda_3}{\lambda_{3,\mathrm{SM}}}\right) + 37.3\right]\ \mathrm{fb}$$

[Goertz, **AP**, Yang, Zurita, 1301.3492]

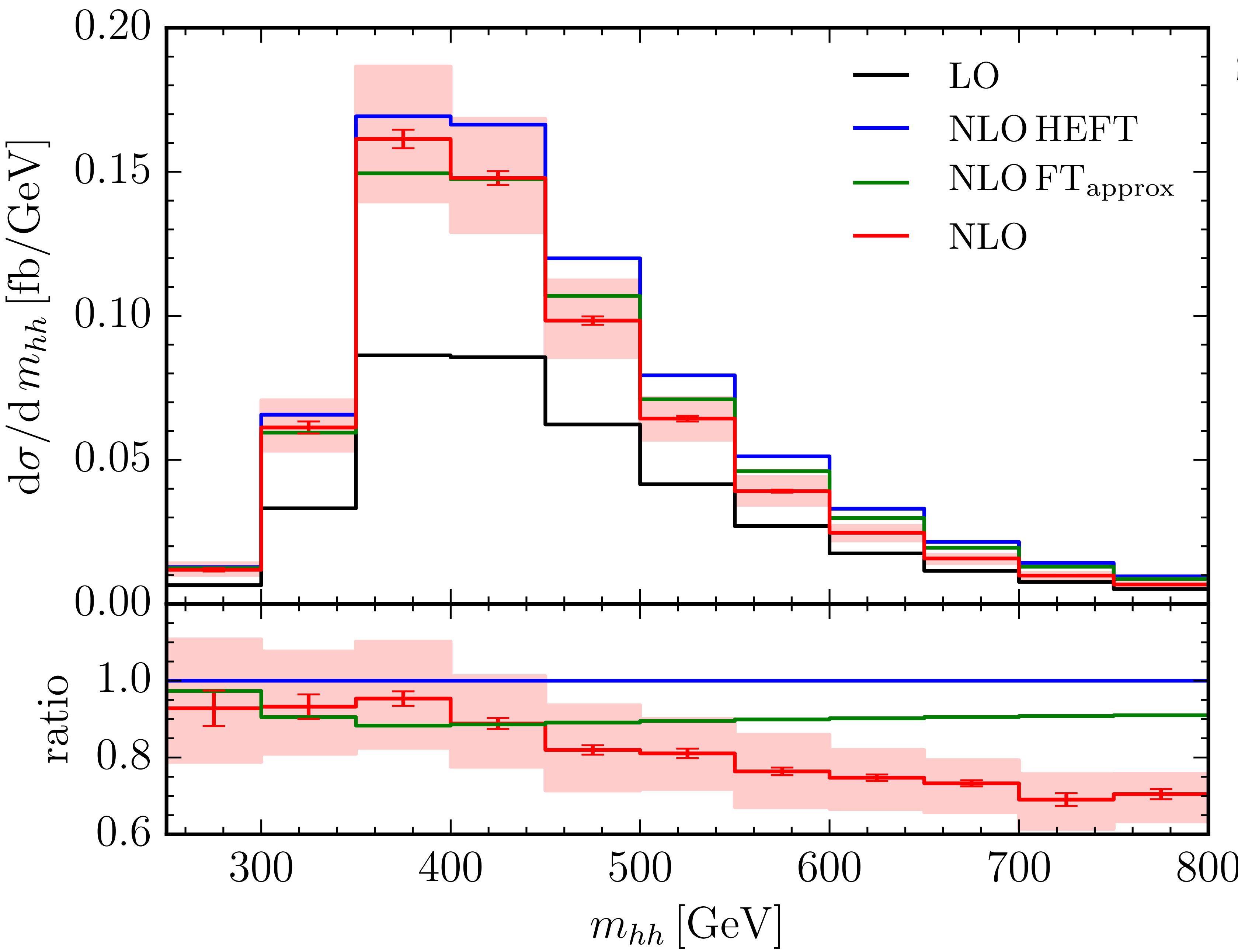
NLO *hh*

- **full NLO** (two-loop) calculation became available in **2016.**

[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zicke, 1604.06447]

[note also asymptotic expansion: Degrassi, Giardino, Gröber, 1607.04251]

NLO K-factor ~ 2.



scale variation uncertainty: O(10%)

[c.f. PDF uncertainty: O(10%)]

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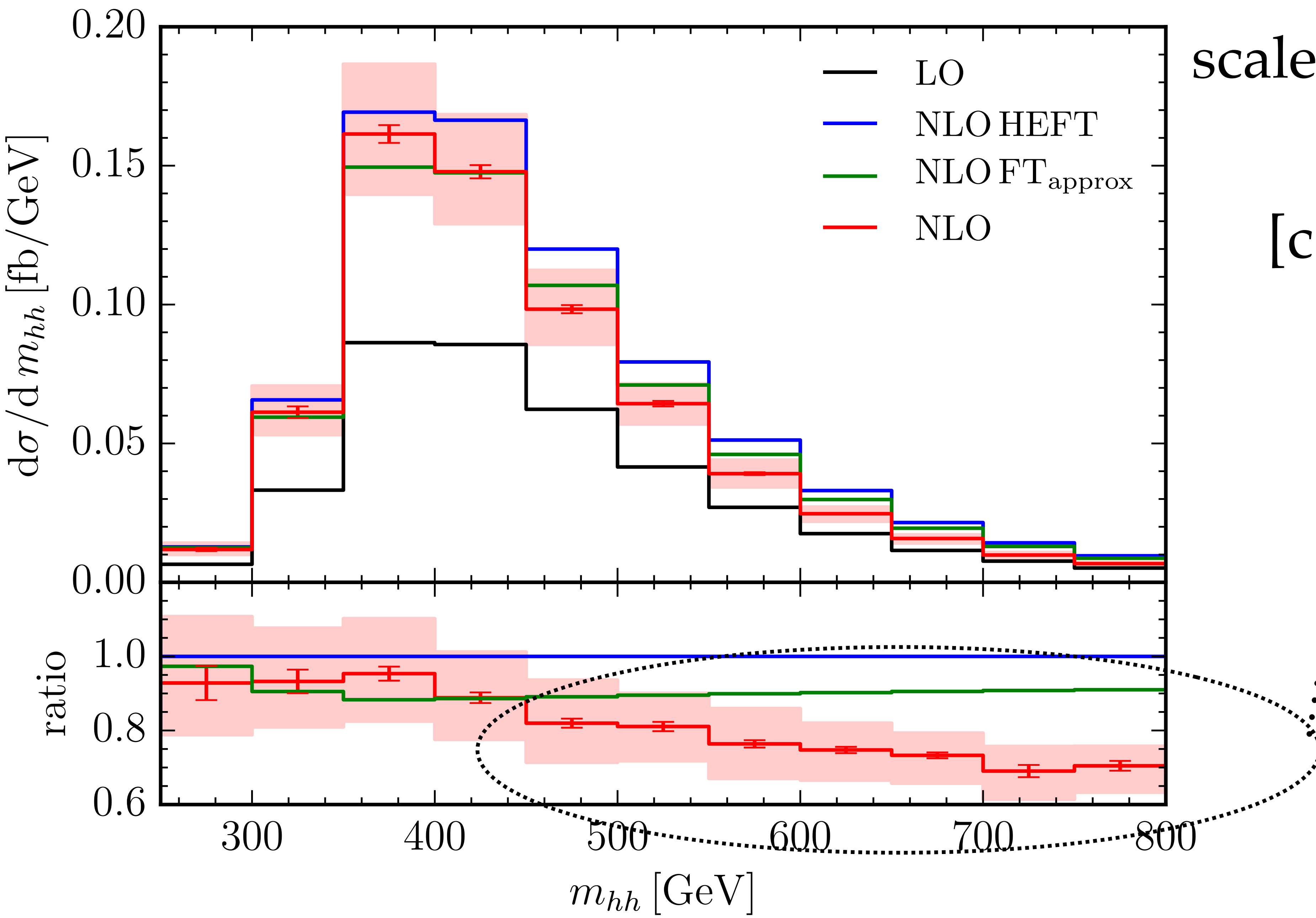

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calculation **important.**

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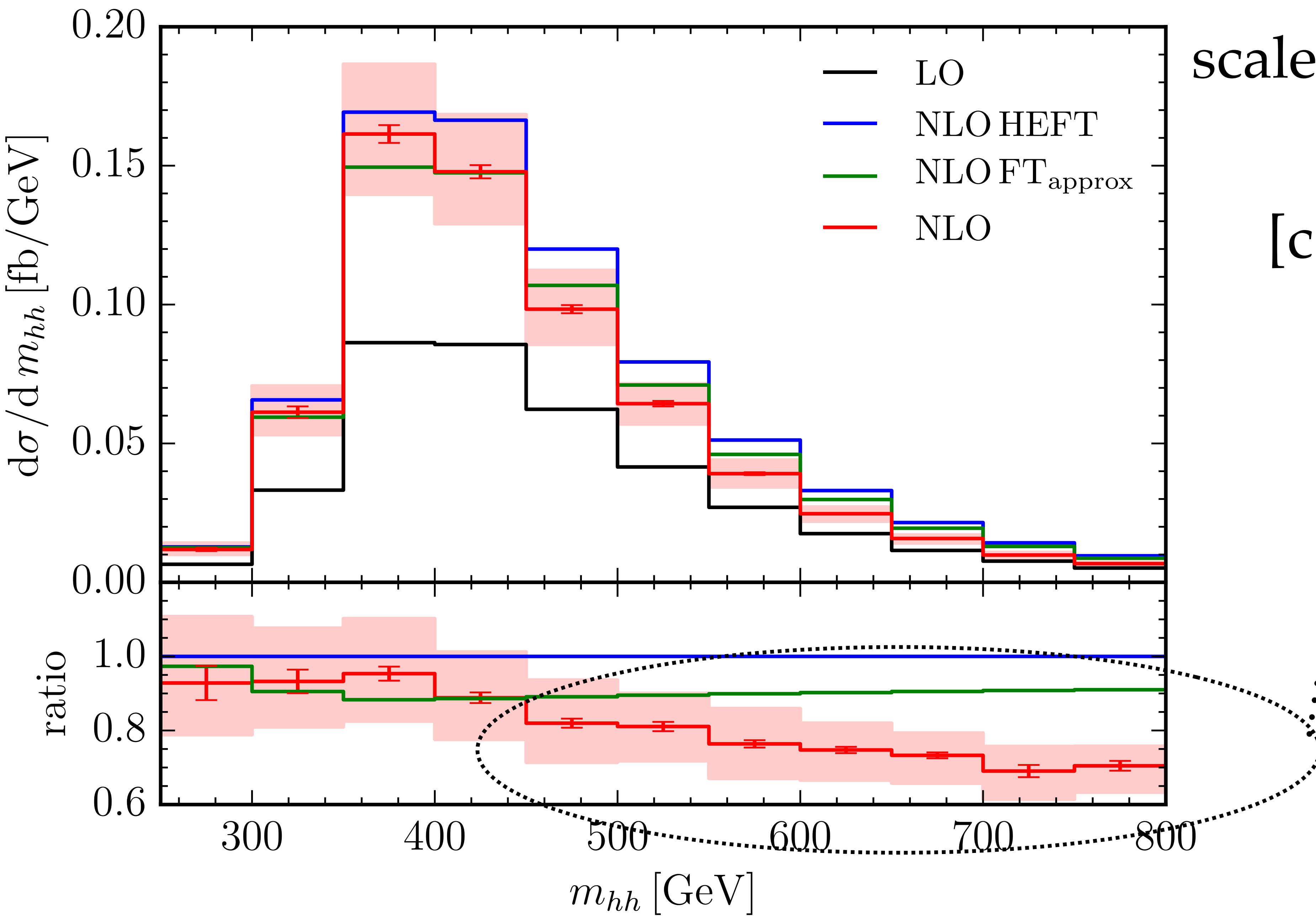

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[c.f. PDF uncertainty: O(10%)]

calculation **important.**

$\Rightarrow$

Next step: match to a parton shower!

[even] higher orders for *hh*

- NNLO HEFT: cross section increase wrt. NLO: **~20%.** [de Florian, Mazzitelli, 1309.6594]
- threshold resummation to NNLL matched to NLO HEFT. [Shao, Li, Li Wang, 1301.1245]
- NNLL matched to NNLO HEFT. [de Florian, Mazzitelli, 1505.07122]
- NLL + full NLO q_T resummation. [Ferrera, Pires, 1609.01691]

hh / *hhh* Monte Carlos

- up to recently: mostly private implementations, based on LO.
- **MG5_aMC@NLO:** [Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro,1401.7340, Maltoni, Vryonidou, Zaro, 1408.6542]
    - ***hh* and *hhh*,** LO + real emission with full top mass dep. + HEFT virtuals, (matched),
- **HERWIG 7:** [Maierhöfer, **AP**, 1401.0007]
    - ***hh*,** LO, D=6 EFT, *hh*+0j and *hh*+1j merged to the parton shower.
- + looking forward to matched full NLO + parton shower.

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multi-Higgs searches at colliders

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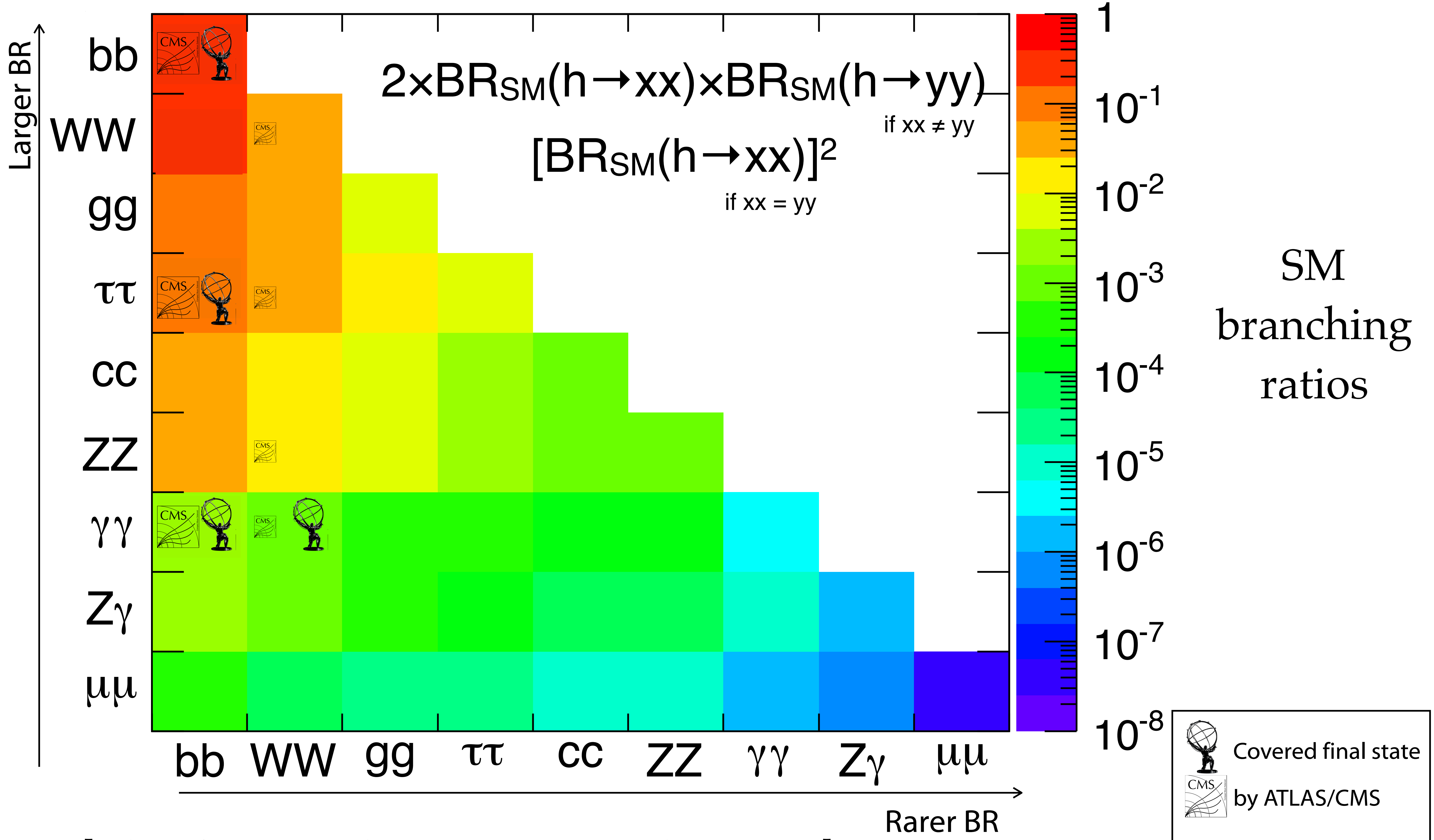
hh @ LHC



[taken from R. Salerno, Higgs Couplings 2015]

hh @ LHC

- not sensitive to SM Higgs pair production until ~ a few hundred inv. femtobarn.

- currently: limit is at ~50 times the SM cross section.

[e.g. ATLAS, 1509.04670]

$hh \to (b\bar{b})(b\bar{b})$	boosted or resolved analyses, **CMS**: limits on Radion, KK grav., **ATLAS**: heavy Higgs, non-resonant.
$hh \to (b\bar{b})(\tau^+\tau^-)$	**CMS**: 0, 1, 2 b-jets, $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, **ATLAS**: 1, 2+ b-jets, $e\tau_h$, $\mu\tau_h$,
$hh \to (b\bar{b})(\gamma\gamma)$	**CMS**: 0, 1, 2+ b-jets. **ATLAS**: 2 b-jets.

[+ multi-lepton/multi-photon final states.]

hh @ HL-LHC

- high-luminosity LHC (pp@14 TeV, 3000 fb^{-1}) **pessimistic**, e.g.:
  - CMS, all channels, 2σ observation of SM ***hh***,
  - ATLAS (@ 95% C.L.):
    - $(b\bar{b})(\gamma\gamma)$, $\lambda_3/\lambda_{3,SM}$ in [-1.3, 8.7],
    - $(b\bar{b})(\tau^+\tau^-)$, $\lambda_3/\lambda_{3,SM}$ in [-4, 12].

- experiments discussing combination of results.

[see, e.g., Goertz, **AP**, Yang, Zurita, 1301.3492]

- ***O(1)*** measurement after HL-LHC (**?**).

double Higgs production at 100 TeV

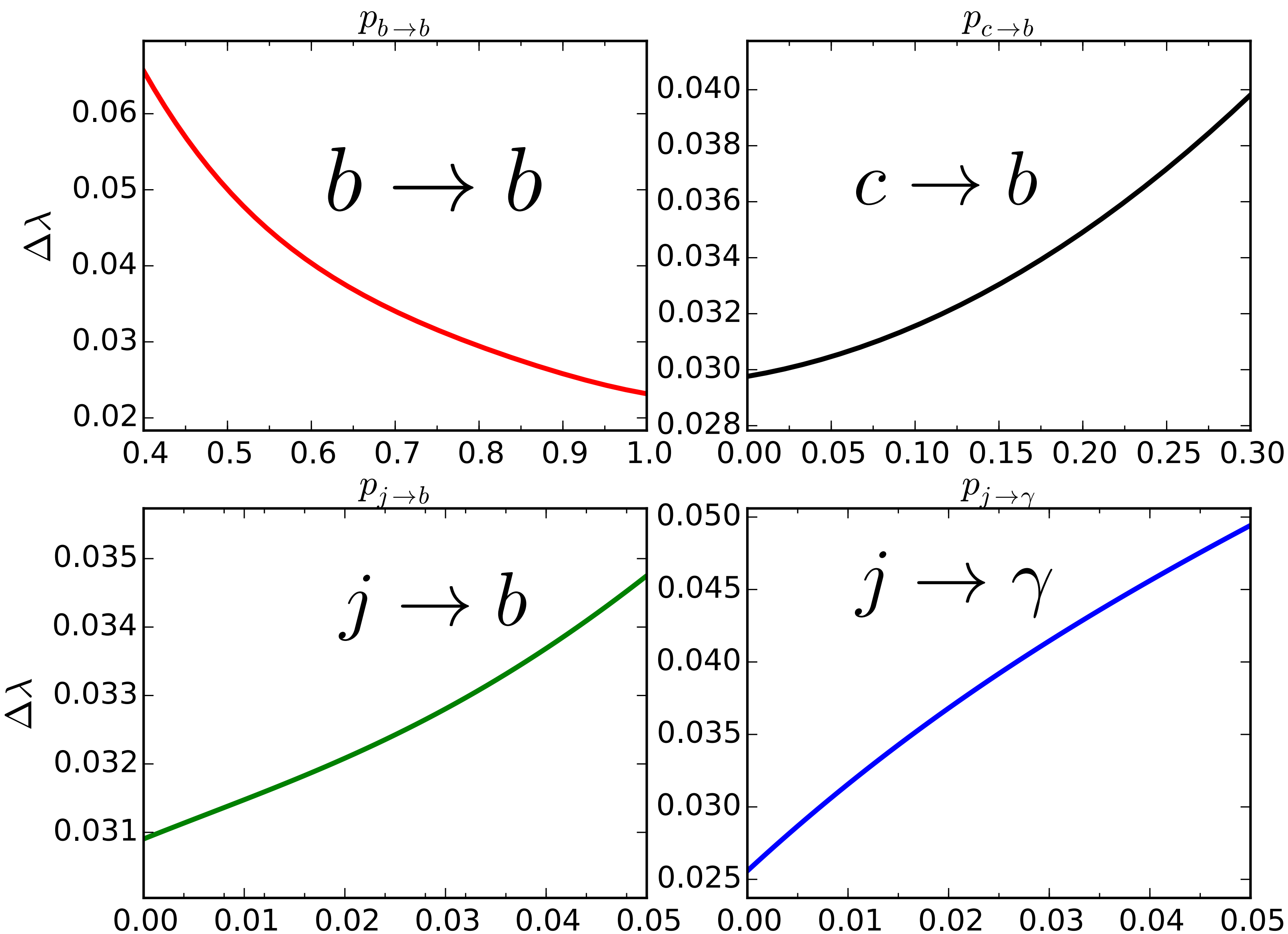
- cross section increases dramatically at **pp@100 TeV** (~1.8 pb),
- several pheno studies focus on $hh \to (b\bar{b})(\gamma\gamma)$.

[Azatov, Contino, Panico, Son, 1502.00539, Barr, Dolan, Englert, de Lima, Spannowsky, 1412.7154, He, Ren, Yao, 1506.03302]

- detailed dedicated study as part of the FCC-hh Higgs report [1606.09408].
- $\pm$ **3%** on λ_3 at 30 ab^{-1} of integrated luminosity.

e.g. variation of precision on λ_3 with tagging rates.

[FCC-hh Higgs, 1606.09408]



A. Papaefstathiou

double Higgs production at 100 TeV

- "new" final states can become accessible, e.g.:

$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$ (signal ~ a few, background ~ a few)

$$hh \to (b\bar{b})(W^+W^-)/(\tau^+\tau^-) \to (b\bar{b})(2\ell)$$ [**AP**, 1504.04621]

(signal ~ a few 10s, background ~ a few 100s)

$$hh \to (W^+W^-)(W^+W^-) \to 3\ell jj$$ [Li, Li, Yan, Zhao, 1503.07611]

BSM effects in *hh*?

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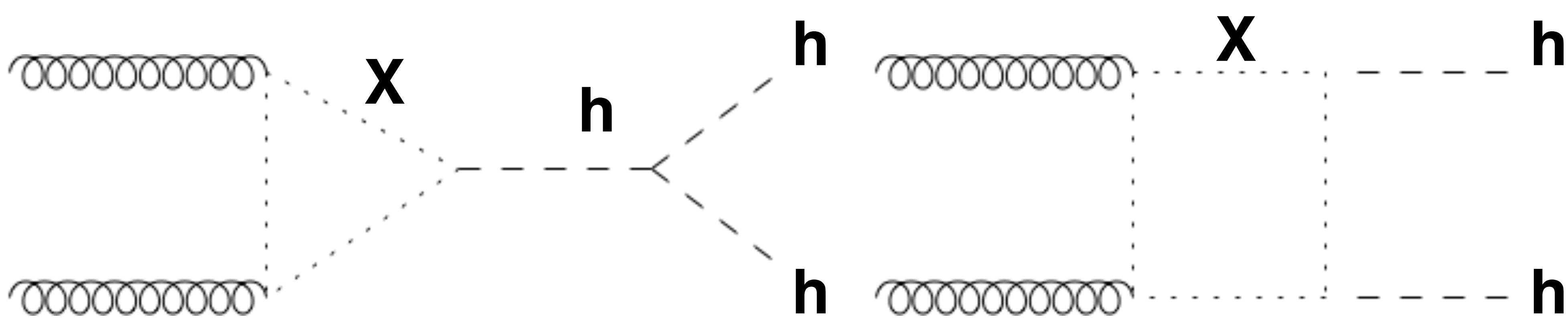
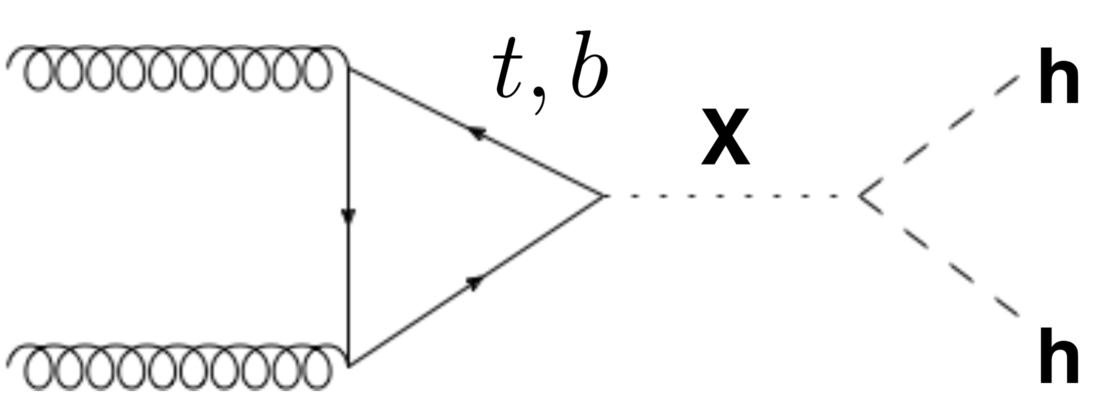
new particles

- ***hh*** can probe the presence of new particles:
- **(a)** e.g. in the loops:



- **(b)** e.g. in a propagator coupling to two Higgs bosons:



[*hh* resonances have already been searched for by ATLAS & CMS in Run 1: 1406.5053, CMS-PAS-HIG-13-032, 1503.04114]

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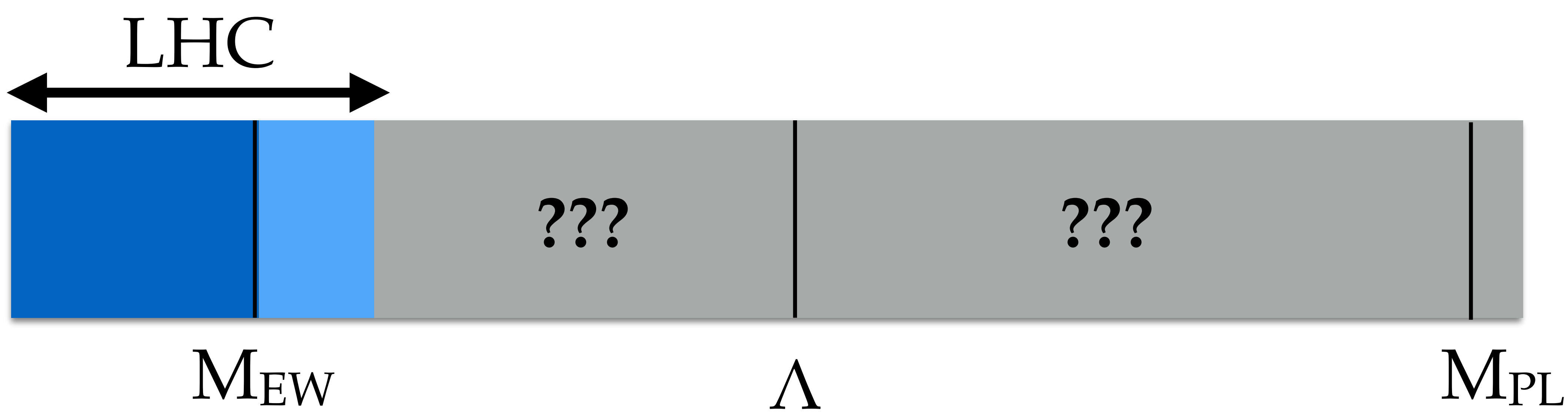
BSM through D=6 effective field theory



➡ construct D=6 operators made of SM fields:

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{D\leq 4} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{D=6}$$

e.g.:

$$\mathcal{O}_6 = -\lambda |H|^6$$

$$\mathcal{O}_t = -c_t |H|^2 \bar{Q}_L H^c t_R$$

operators built out of SM fields, respecting SM gauge symmetries $\equiv$ **New Physics**

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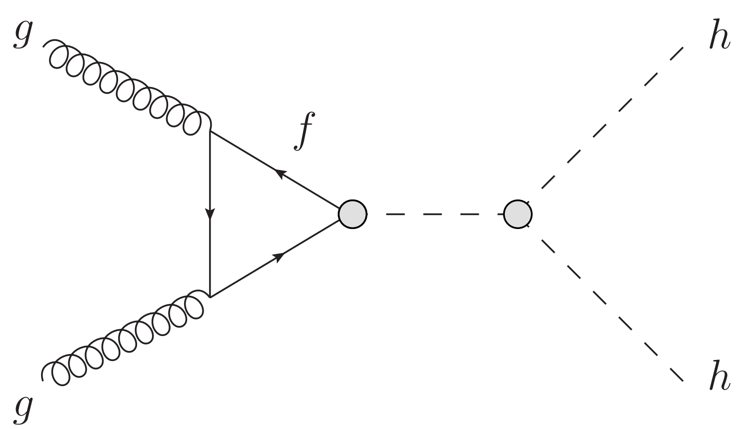
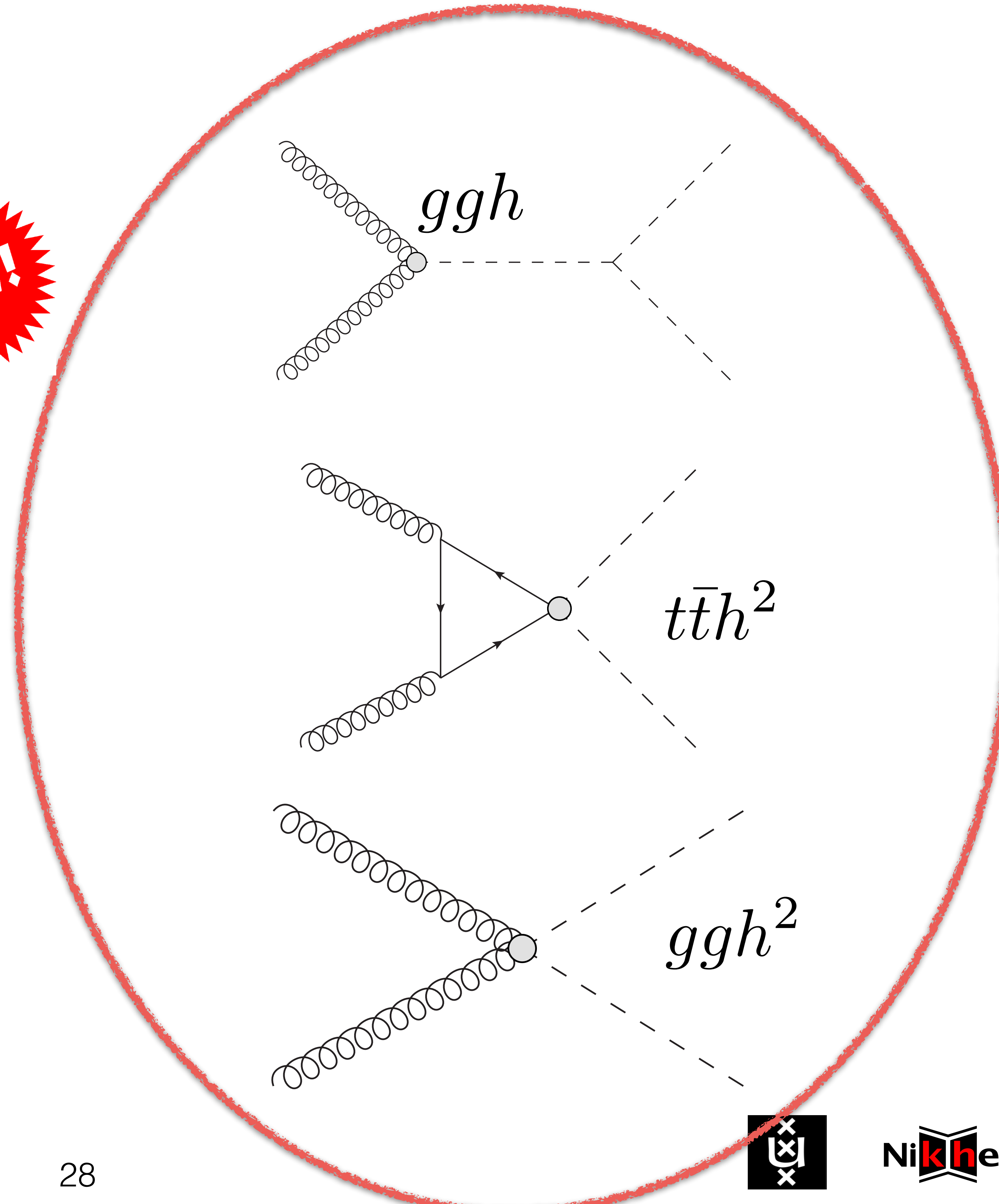
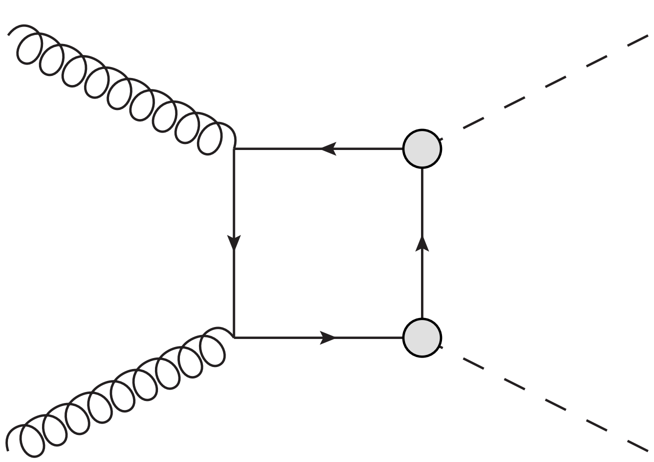
hh in D=6 EFT



NEW!

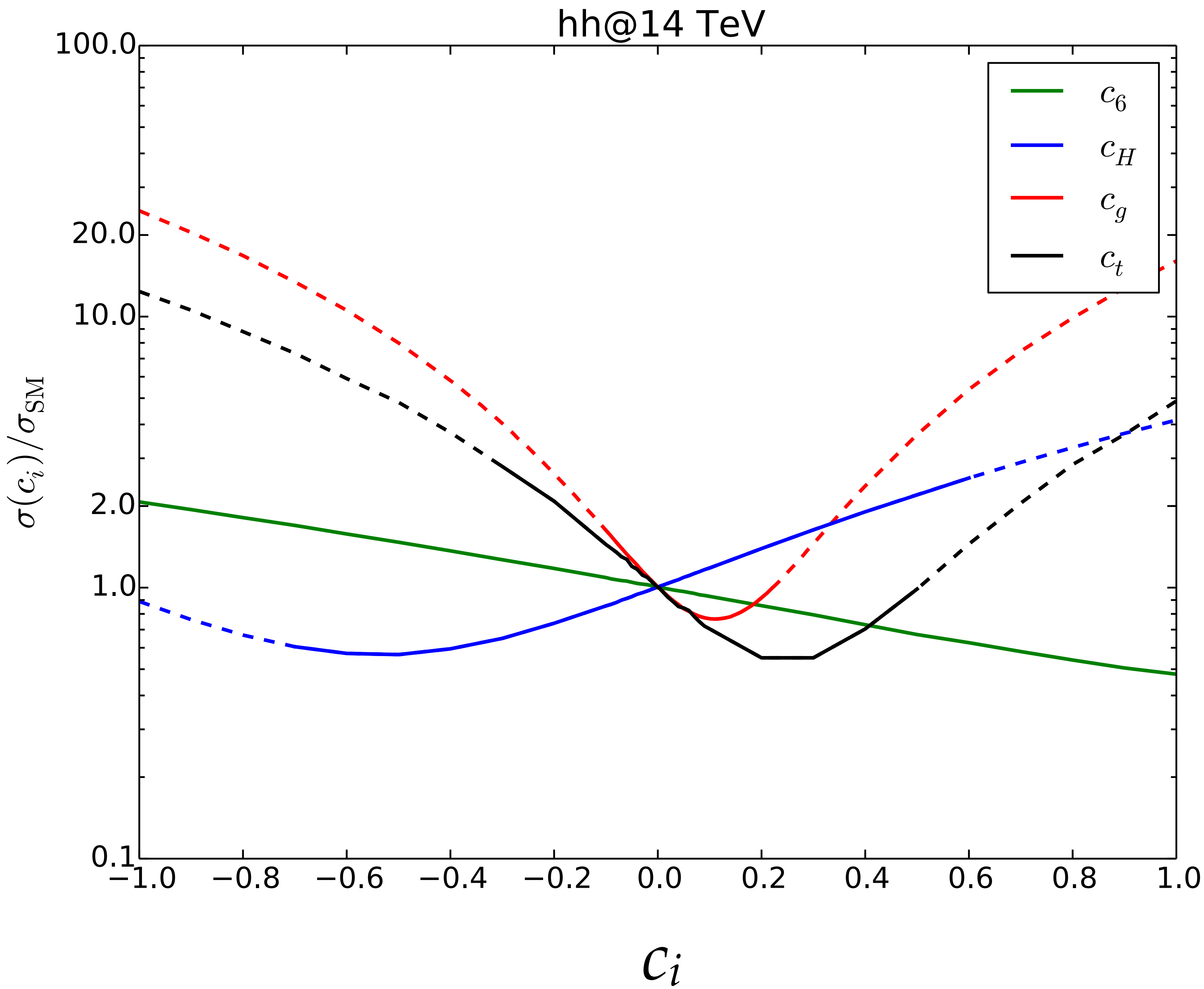


[Goertz, **AP**, Yang, Zurita, 1410.3471]



hh in D=6 EFT

- LHC and FCC-hh phenomenology, e.g.:



[Goertz, **AP**, Yang, Zurita, 1410.3471]

cross section variation with respect to coeffs.

[σ_{SM} (14 TeV) ~ 40 fb]

[also: Azatov, Contino, Panico, Son, 1502.00539]

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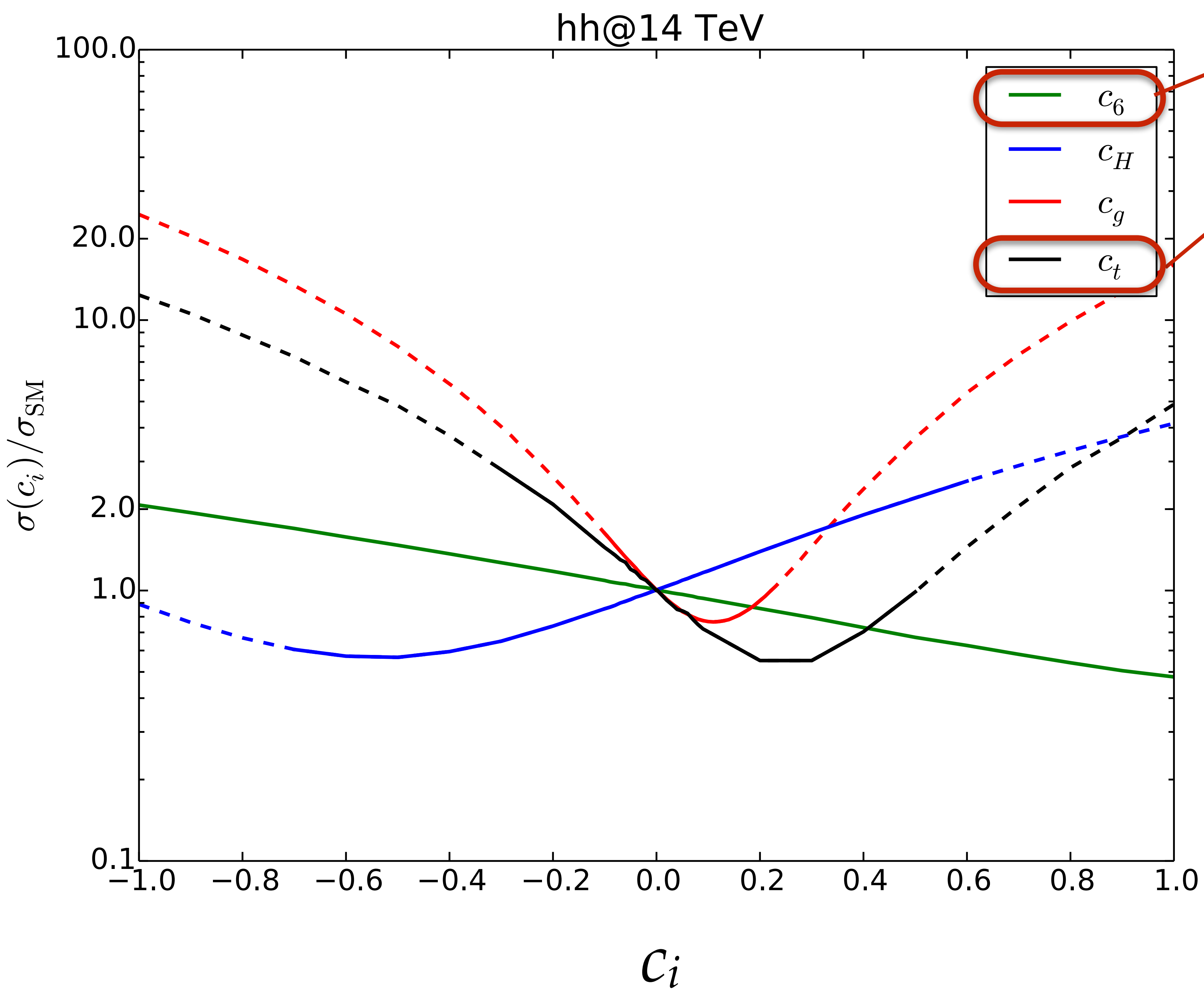

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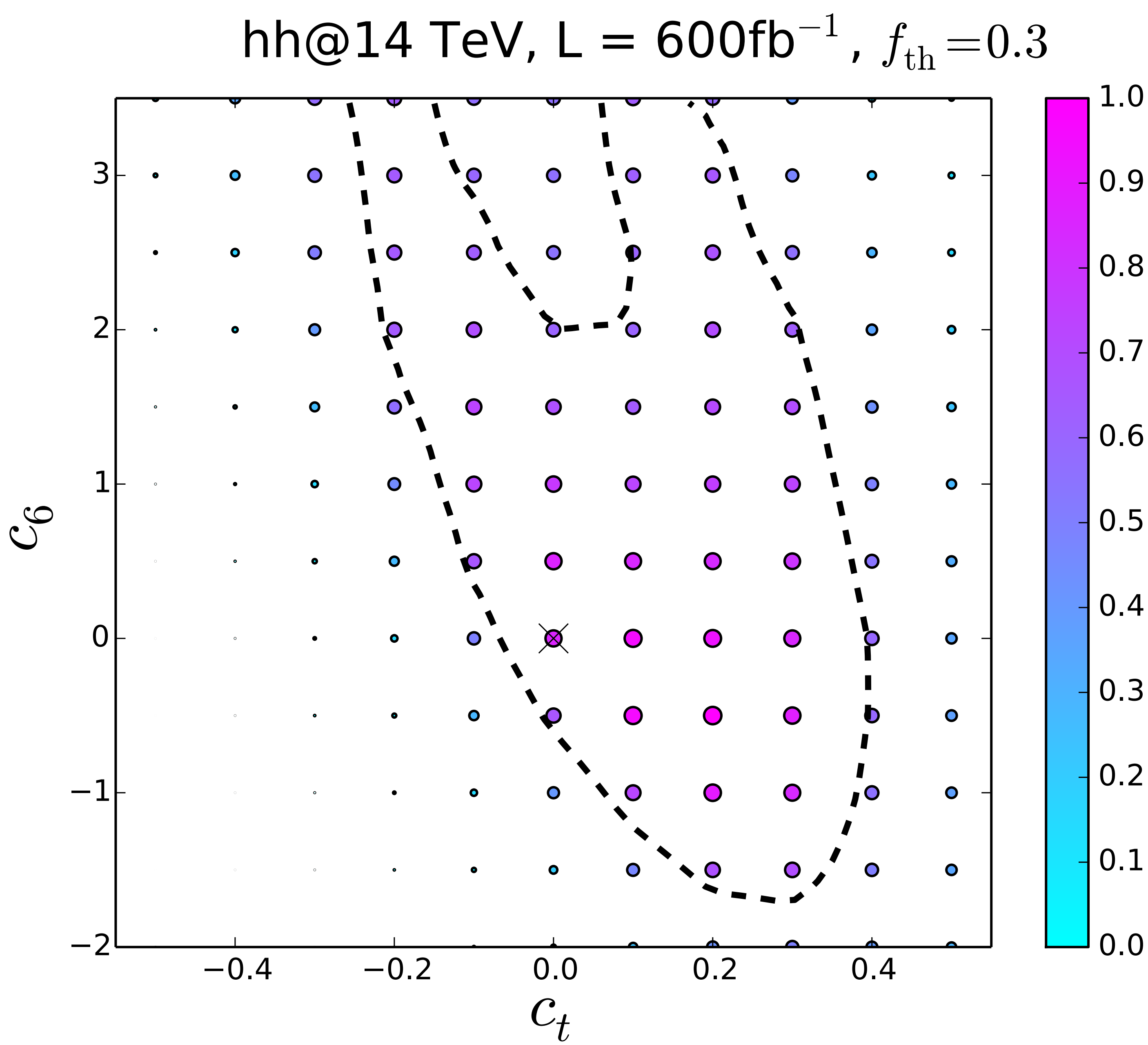


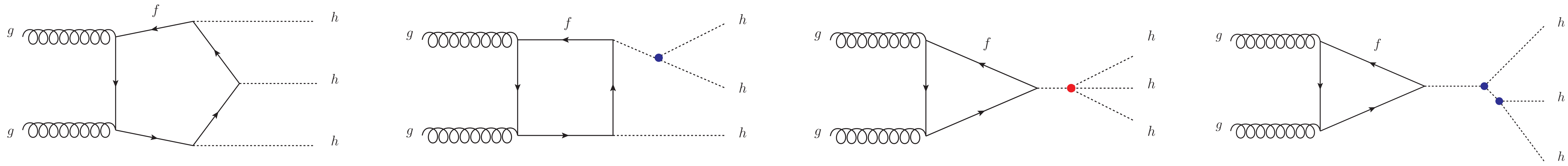
1σ **constraint, on the plane of two Wilson coefs.:**

c_t-c_6

(LHC14, 600 fb^{-1})

[see also: Azatov, Contino, Panico, Son, 1502.00539]

triple Higgs production at 100 TeV



- tiny cross section at LHC@14 TeV (~0.1 fb),

- still challenging at 100 TeV: SM σ ~ 5 fb!

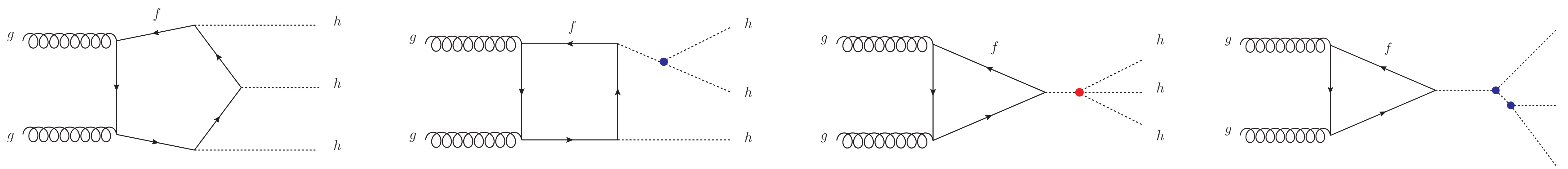
[Plehn, Rauch, hep-ph/0507321, Binoth, Karg, Kauer, Rückl, hep-ph/0608057, Maltoni, Vryonidou, Zaro, 1408.6542]

- ‘high-lumi’ 100 TeV machine <u>could</u> probe it (30 ab^{-1}).

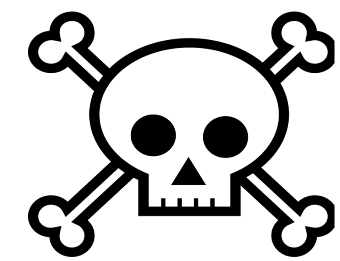
- e.g. in $hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$. [**<u>AP</u>**, Sakurai, 1508.06524]

- also:
  $hhh \to (b\bar{b})(b\bar{b})(\tau^+\tau^-), (b\bar{b})(\tau^+\tau^-)(\tau^+\tau^-)$ [Fuks, Kim, Lee, 1510.07697]
  $hhh \to (b\bar{b})(W^+W^-)(W^+W^-)$ [Kilian, Sun, Yan, Zhao, Zhao 1702.03554]
  $hhh \to (b\bar{b})(b\bar{b})(b\bar{b})$ [Bishara, Hartland, **<u>AP</u>**, Rojo, Tillim, to appear]

triple Higgs production at 100 TeV



- tiny cross section at LHC@14 TeV (~0.1 fb),



- still challenging at 100 TeV: SM σ ~ 5 fb!

[Plehn, Rauch, hep-ph/0507321, Binoth, Karg, Kauer, Rückl, hep-ph/0608057, Maltoni, Vryonidou, Zaro, 1408.6542]

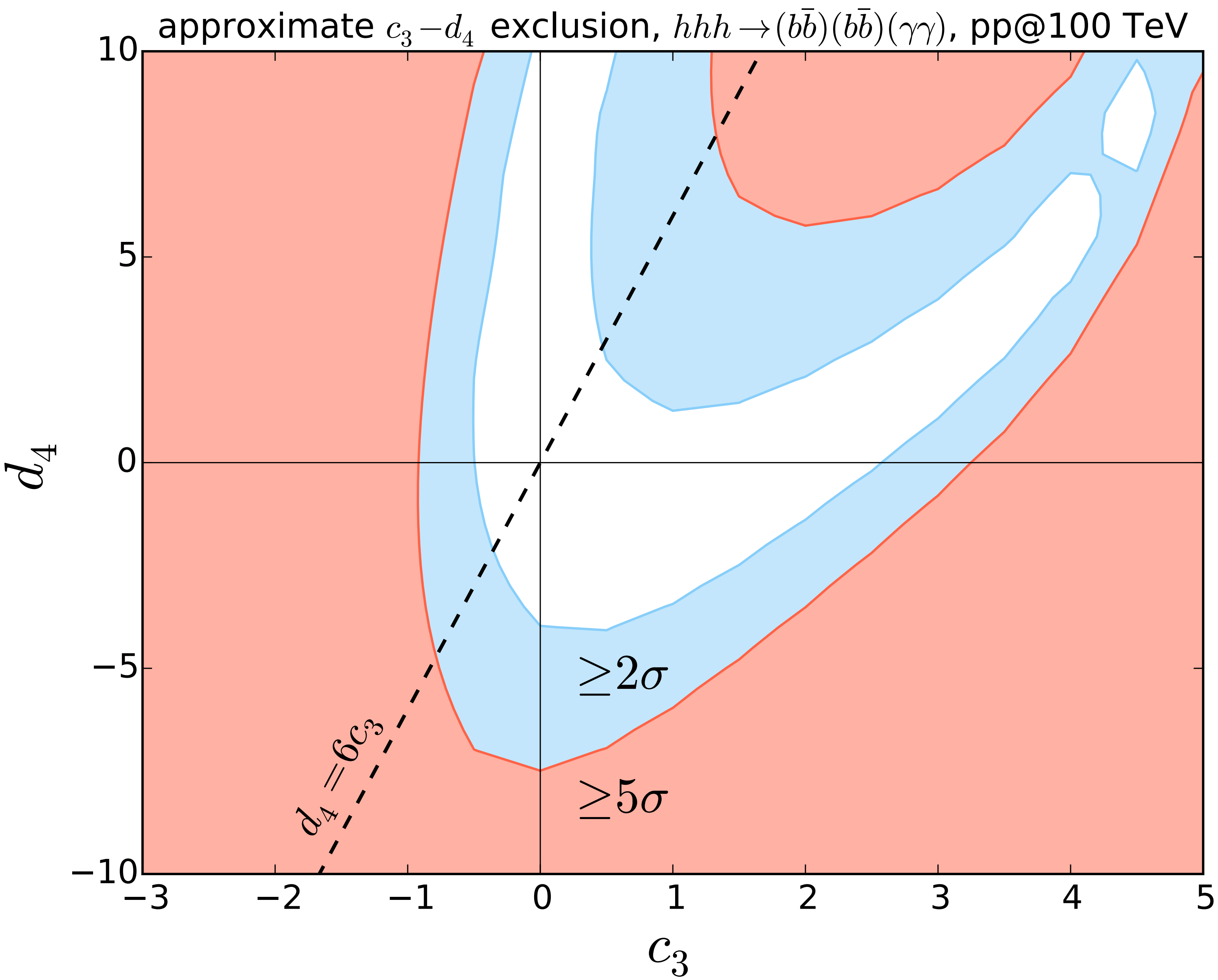
- ‘high-lumi’ 100 TeV machine <u>could</u> probe it (30 ab^{-1}).

- e.g. in $hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$. [**AP**, Sakurai, 1508.06524]

- also:
  $hhh \to (b\bar{b})(b\bar{b})(\tau^+\tau^-), (b\bar{b})(\tau^+\tau^-)(\tau^+\tau^-)$ [Fuks, Kim, Lee, 1510.07697]
  $hhh \to (b\bar{b})(W^+W^-)(W^+W^-)$ [Kilian, Sun, Yan, Zhao, Zhao 1702.03554]
  $hhh \to (b\bar{b})(b\bar{b})(b\bar{b})$ [Bishara, Hartland, **AP**, Rojo, Tillim, to appear]

triple Higgs production at 100 TeV

[**AP**, Sakurai, 1508.06524]



$$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$$

(30 ab-1)

$$\lambda_4/\lambda_{4,\mathrm{SM}} = 1 + d_4$$

$$\lambda_3/\lambda_{3,\mathrm{SM}} = 1 + c_3$$

for $\lambda_3 = \lambda_{3,\mathrm{SM}} \Rightarrow \lambda_4/\lambda_{4,\mathrm{SM}} \in [\sim -4, \sim +16]$ @95% C.L.

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left as an exercise

- **associated production modes:** e.g. $t\bar{t}hh$

  $\longrightarrow$ the leading channel if triple coupling > SM value.

  [Englert, Kraus, Spannowsky, Thompson, 1409.8074]

  [+ ***VBF*, *Whh*, *Zhh***]

- **e^+e^- colliders, e^-p colliders,** [1306.6352 (ILC), hep-ph/0106315 (TESLA)] [Kumar, Ruan, Islam, Cornell, Klein, Klein, Mellado, 1509.0401]

- more **BSM studies!**

multi-Higgs: summary

	HL-LHC (14 TeV, 3000 fb^{-1})	pp@100 TeV (30 ab^{-1})
λ_3	$\mathcal{O}(1)$	$\mathcal{O}(5\%)$
λ_4	☠	$\mathcal{O}(1) - \mathcal{O}(10)$

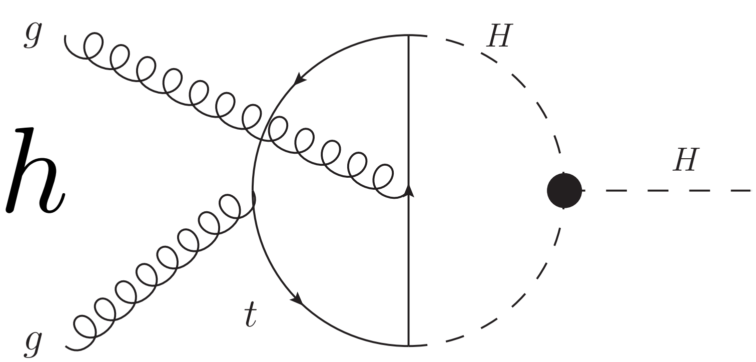
indirect constraints on Higgs self-couplings

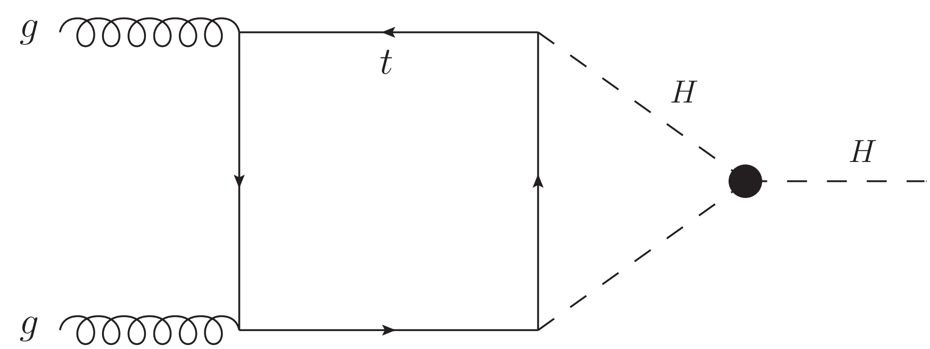
indirect constraints from single Higgs

- e.g. single Higgs boson production observables @ hadron colliders: [Gorbahn, Haisch, 1607.03773, Degrassi, Giardino, Maltoni, Pagani, 1607.04251, Bizoń, Gorbahn, Ulrich Haisch, Zanderighi, 1610.05771]

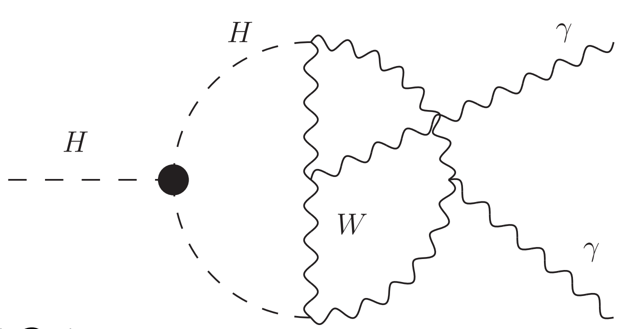
e.g.

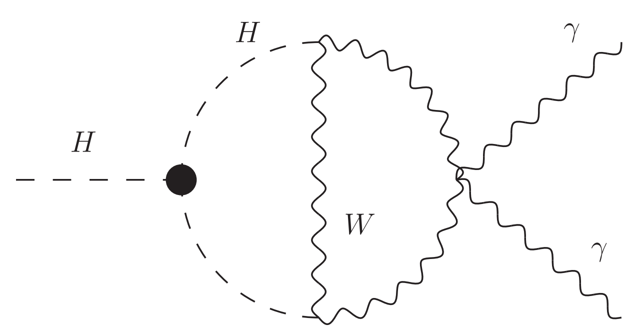
$gg \to h$

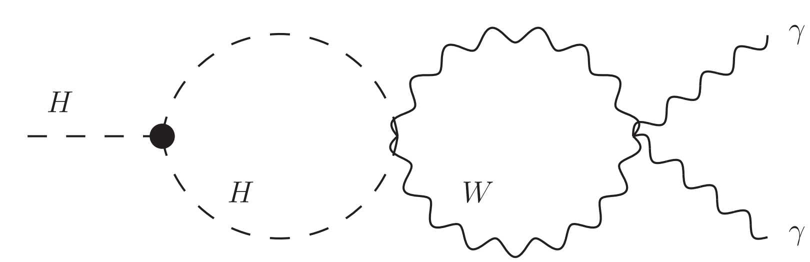


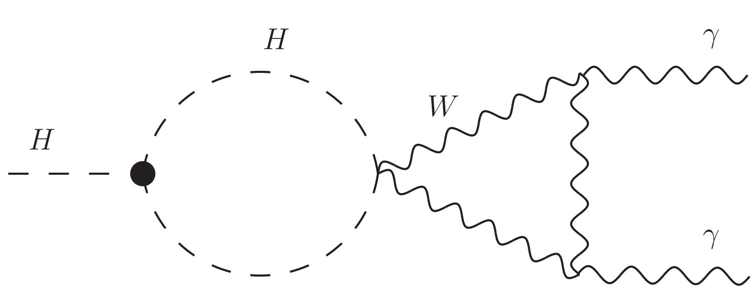


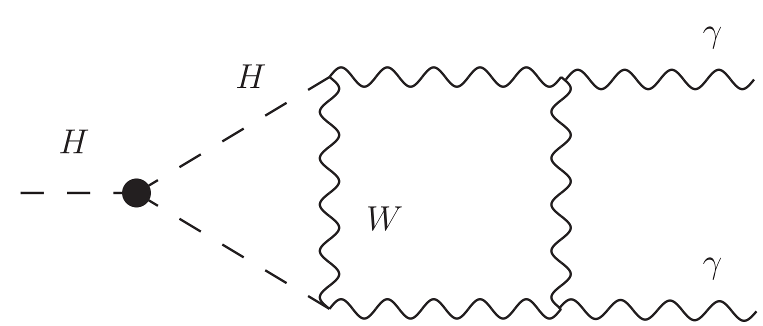
$h \to \gamma\gamma$











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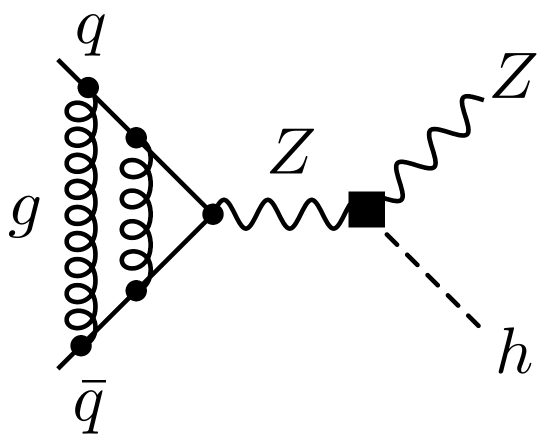
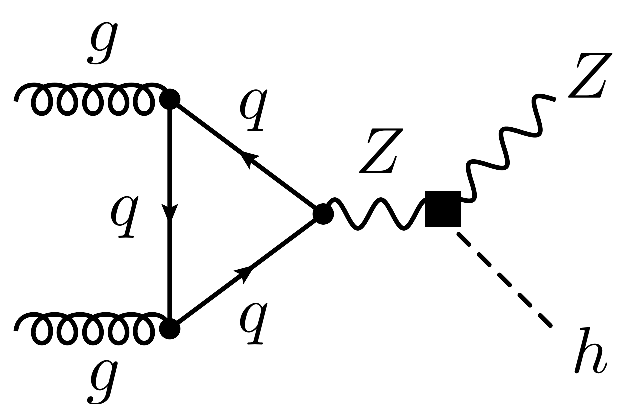
indirect constraints from single Higgs

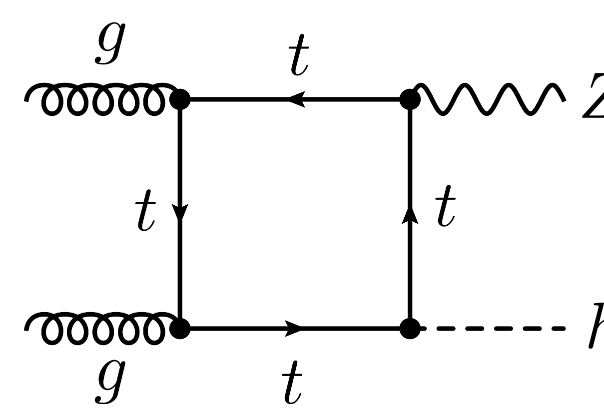
[Gorbahn, Haisch, 1607.03773, Degrassi, Giardino, Maltoni, Pagani, 1607.04251, Bizoń, Gorbahn, Ulrich Haisch, Zanderighi, 1610.05771]

e.g.

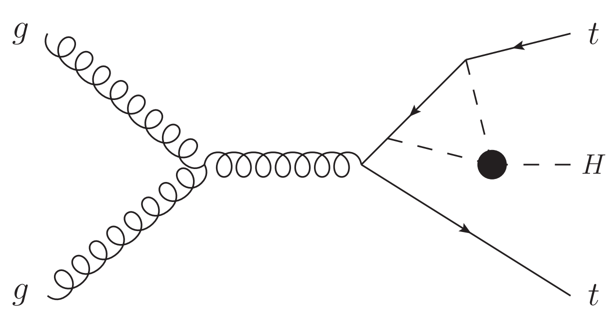
$pp \to hZ$

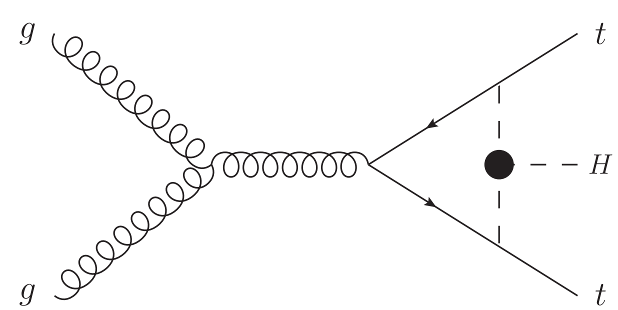


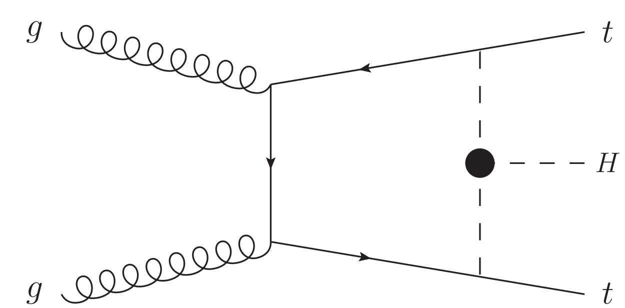




$pp \to t\bar{t}h$







- bounds competitive with those from Higgs boson pair production.

indirect constraints from precision observables

[Degrassi, Fedele, Giardino, 1702.01737, Kribs, Maier, Rzehak, Spannowsky, Waite, 1702.07678]

- two approaches based on "precision observables":
  - W mass & $\sin^2\theta_{\text{eff}}$, [Degrassi, Fedele, Giardino, 1702.01737]
  - S & T parameters. [Kribs, Maier, Rzehak, Spannowsky, Waite, 1702.07678]
- Higgs boson triple self-coupling modifications appear at **two-loops**.
- no quartic coupling contributions at this order!
- approach has been shown to be gauge invariant.
- again: results competitive to direct hh.

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(current) constraints summary

λ_3 allowed regions @ 95% C.L. (multiples of SM)

indirect

	"single Higgs":	EW precision (m_W & $\sin^2\theta_{\mathrm{eff}}$) + "single Higgs":
indirect	**[-9.4, 17.0]** [Degrassi, Giardino, Maltoni, Pagani, 1607.04251]	**[-8.2, 13.7]** [Degrassi, Fedele, Giardino, 1702.01737]
	Vh + VBF h:	**EW precision (S & T):**
	[-14.0, 16.3] [Bizoń, Gorbahn, Ulrich Haisch, Zanderighi, 1610.05771]	**[-14.0, 17.4]** [Kribs, Maier, Rzehak, Spannowsky, Waite, 1702.07678]
c.f. direct hh:	**[-14.5, 19.1]** [ATLAS, combination of channels, 1509.04670]	**[-8.4, 13.4]** [ATLAS, 4b, ATLAS-CONF-2016-049]

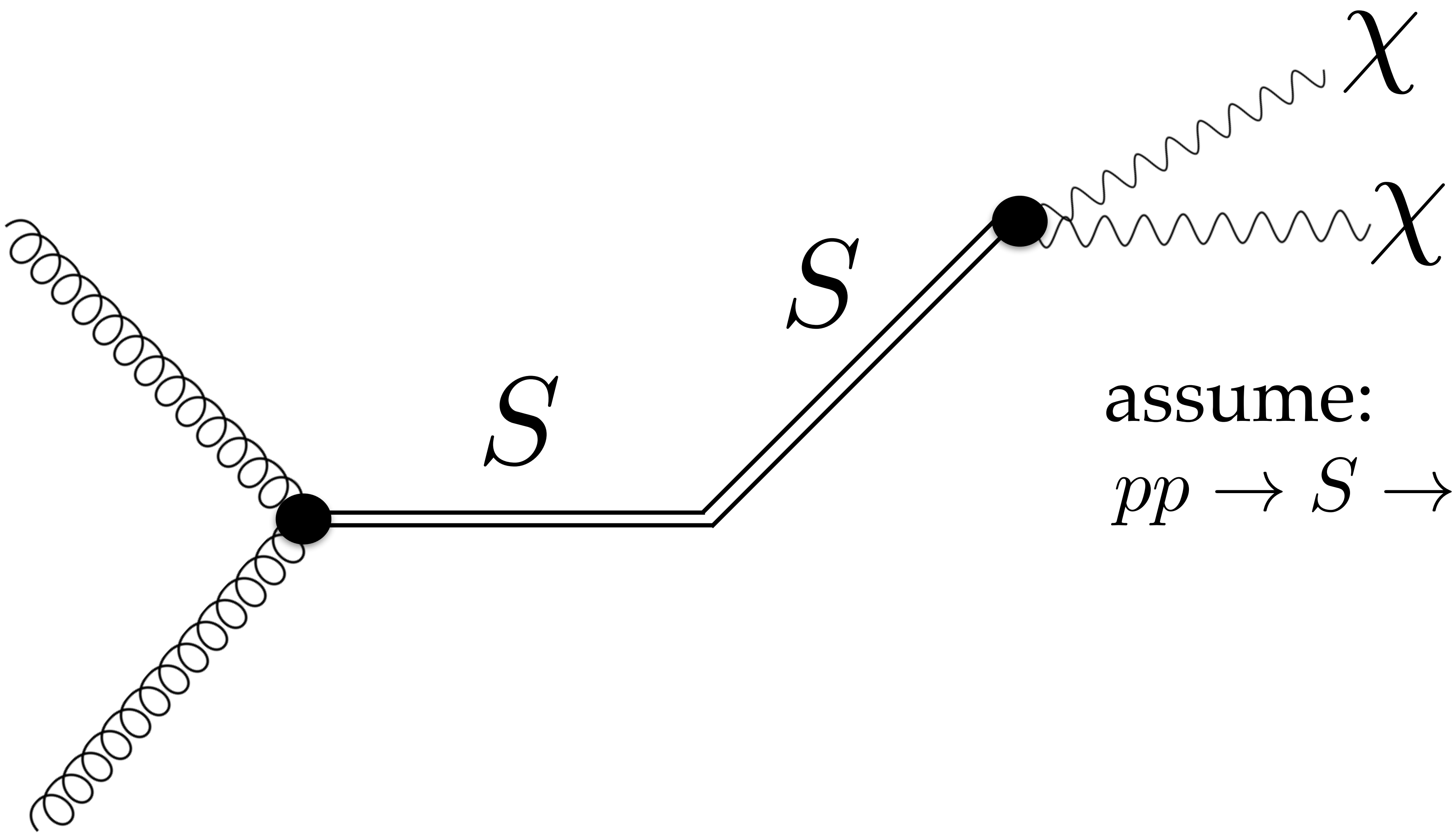
Higgs-New Scalar associated production

new scalar resonances

- the Higgs boson is the first (seemingly) fundamental scalar we know of: there may be more waiting to be discovered!
- if so: they could be **related** to the Higgs boson and EWSB.
- could we measure <u>**their couplings to the Higgs boson**</u>?

single production of a singlet scalar S

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

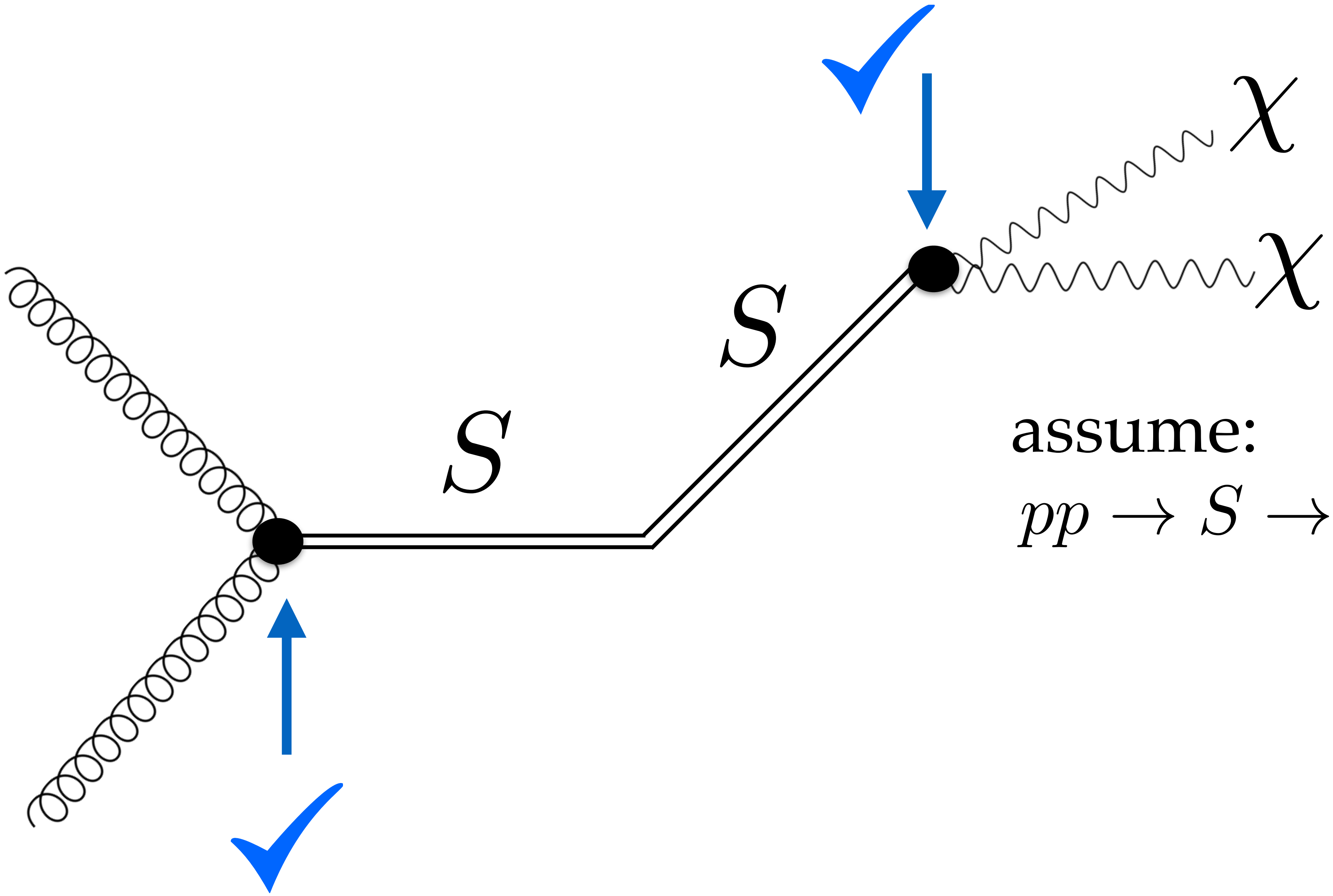


assume:

$pp \to S \to \chi\chi$ is observed

single production of a singlet scalar S

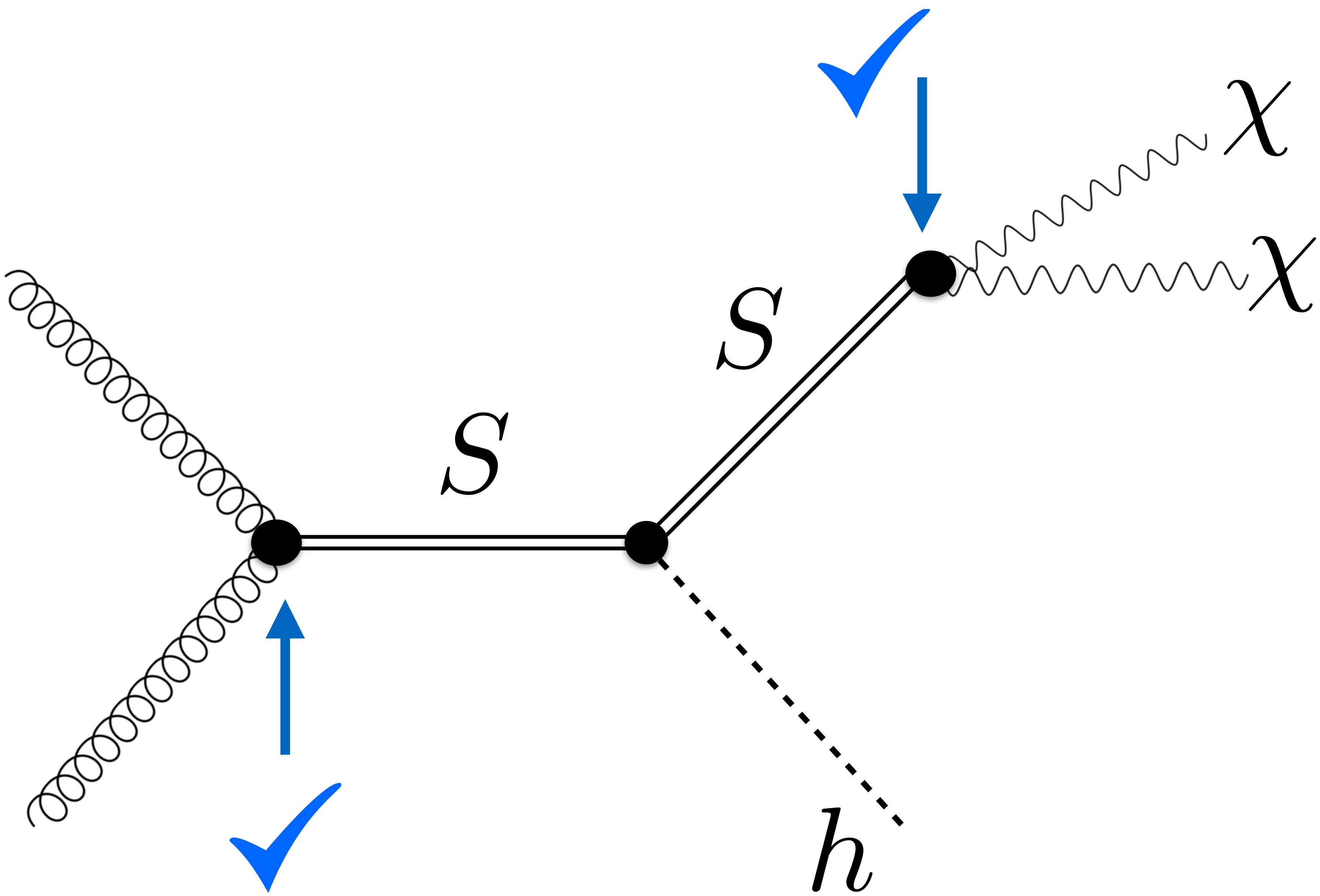
[Carmona, Goertz, **AP**, 1606.02716]



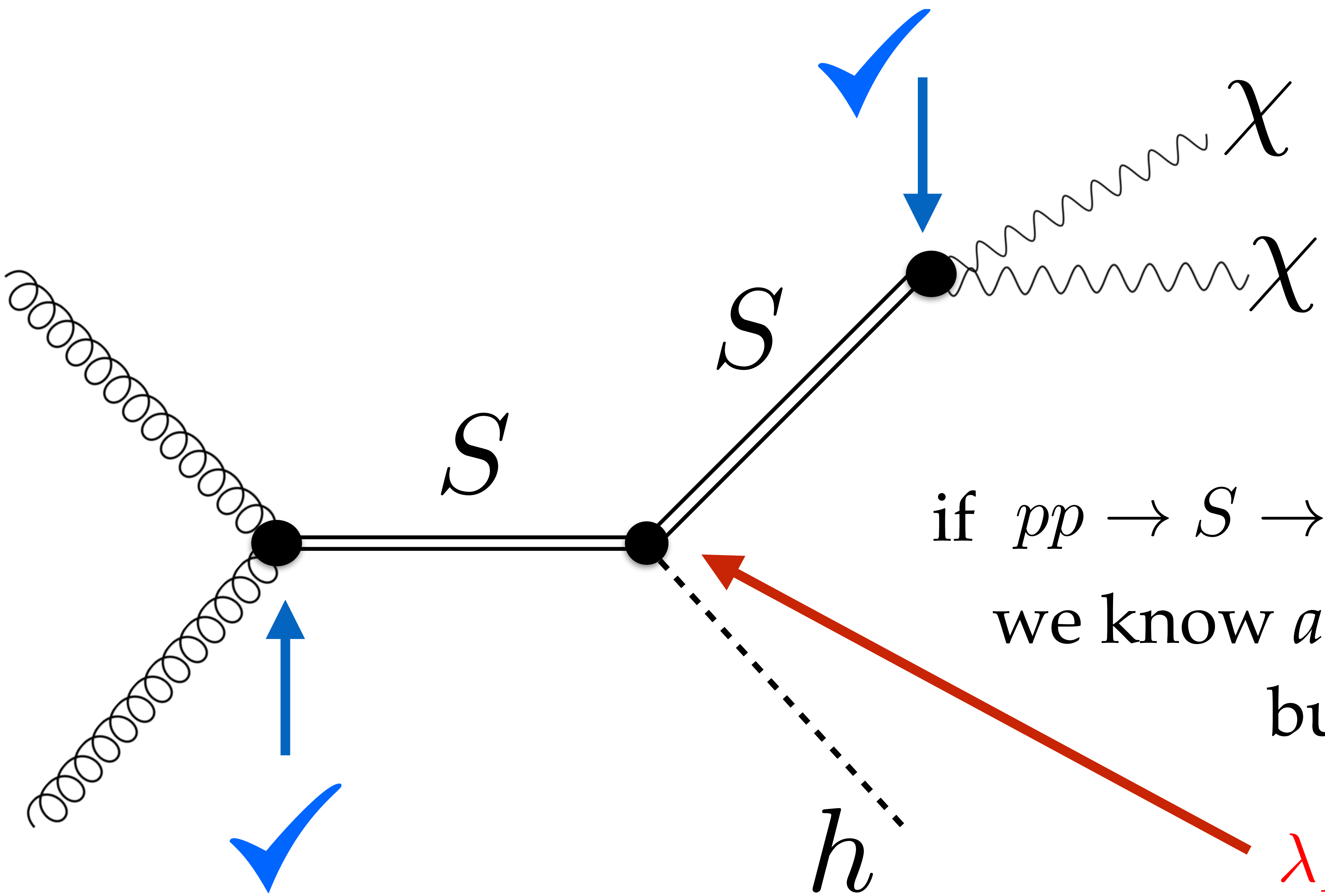
assume:

$pp \to S \to \chi\chi$ is observed

associated production with a Higgs boson



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"

e.g. from: $\lambda_{HS}|H|^2 S^2 \to \lambda_{HS}(v+h)^2 S^2$

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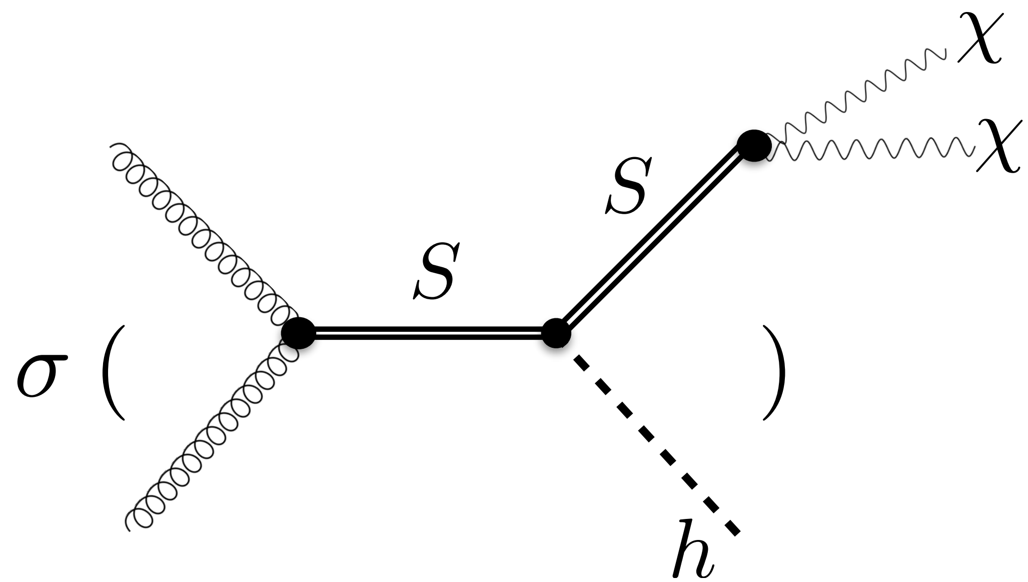
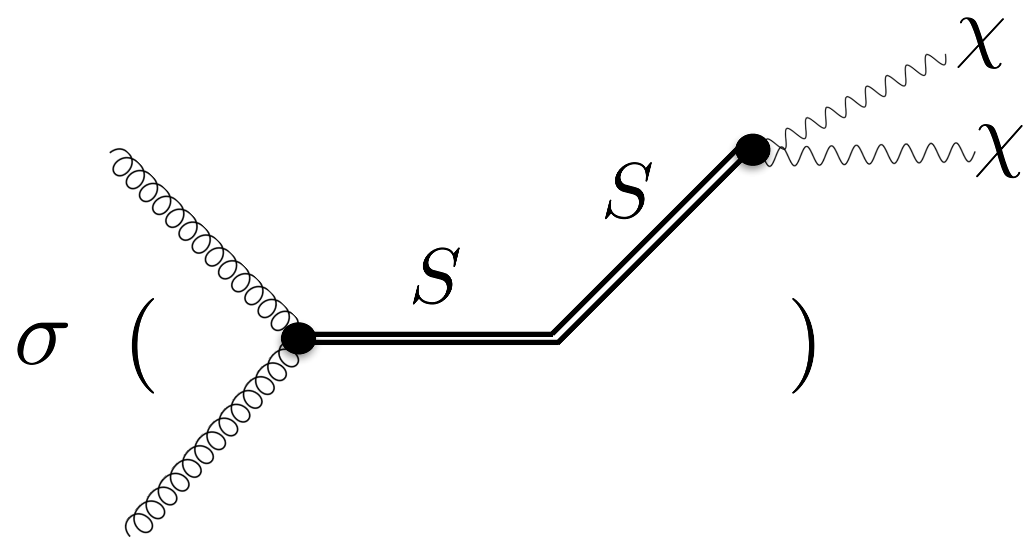
easy to calculate the cross section for associated production with *h*, if single production would be observed.

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





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.

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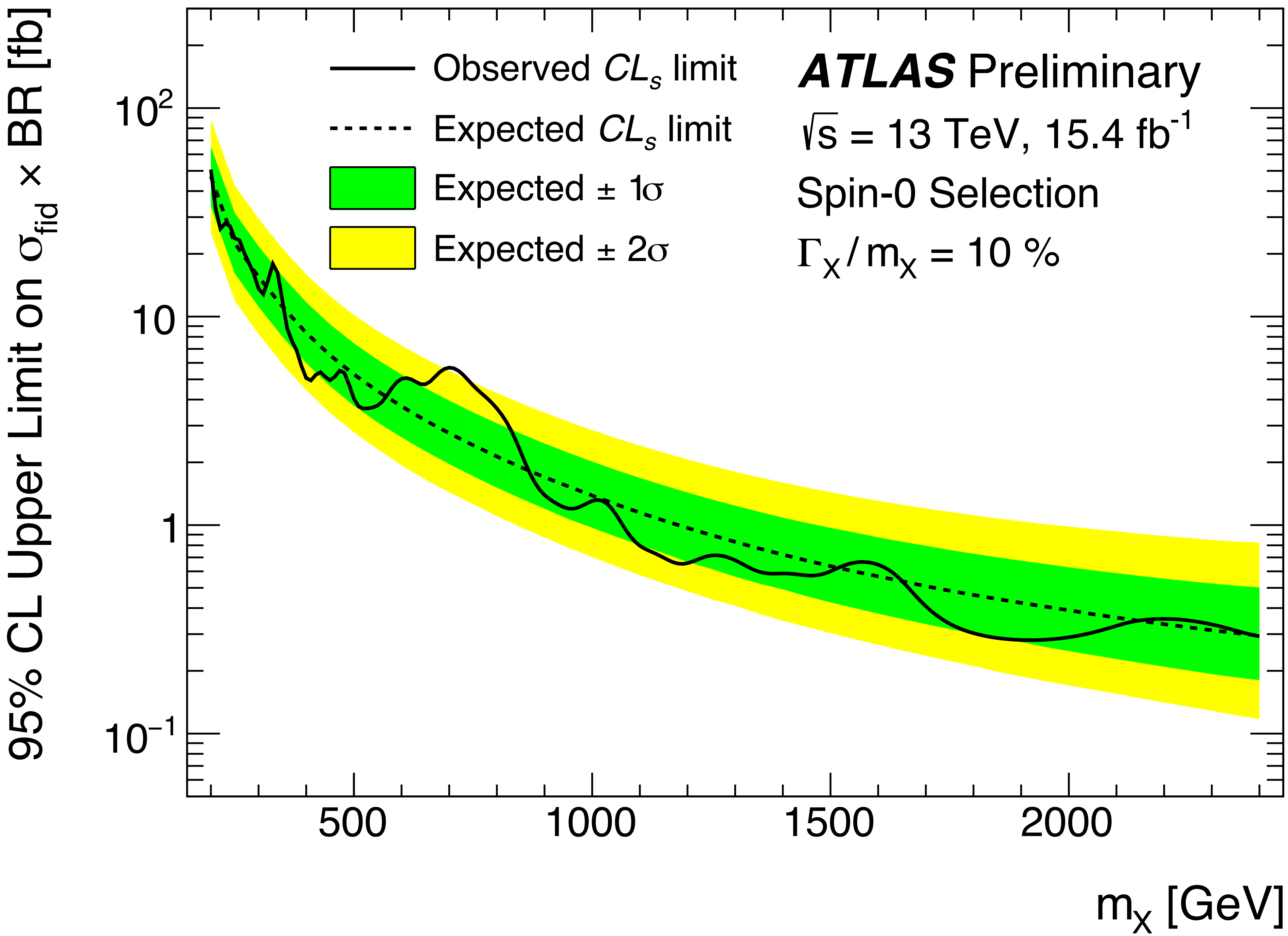
- the simplest scenario: χ = photon, i.e. di-photon resonance.
- current searches allow single production with reasonable cross section:



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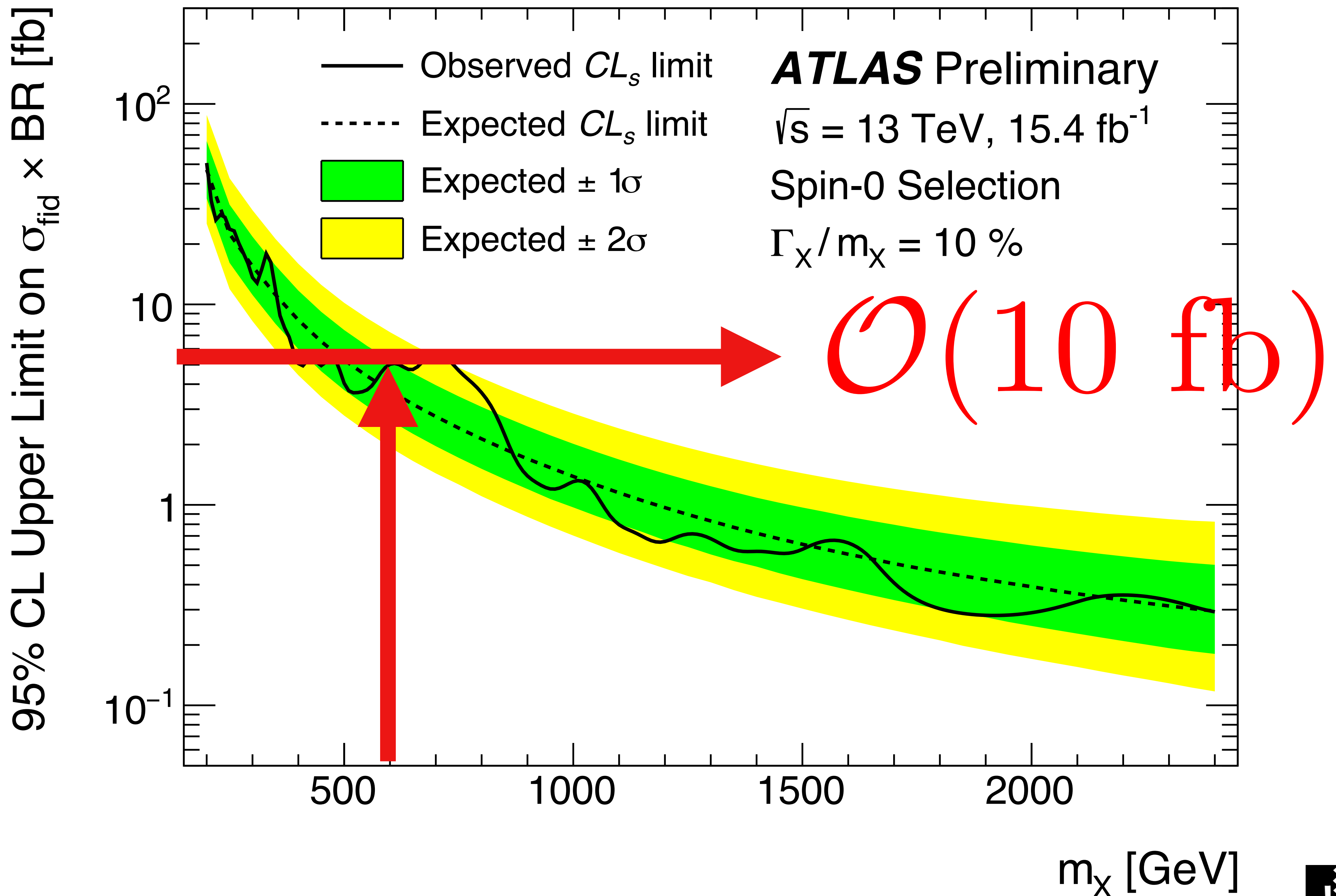

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$$\sigma(hS \to h\gamma\gamma) \sim 10 \text{ fb} \times \rho$$

single production allowed cross section, from ATLAS/CMS.

ratio, fitted from Monte Carlo.

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

(depending on initial-state partons)

kinematic features of $h\gamma\gamma$

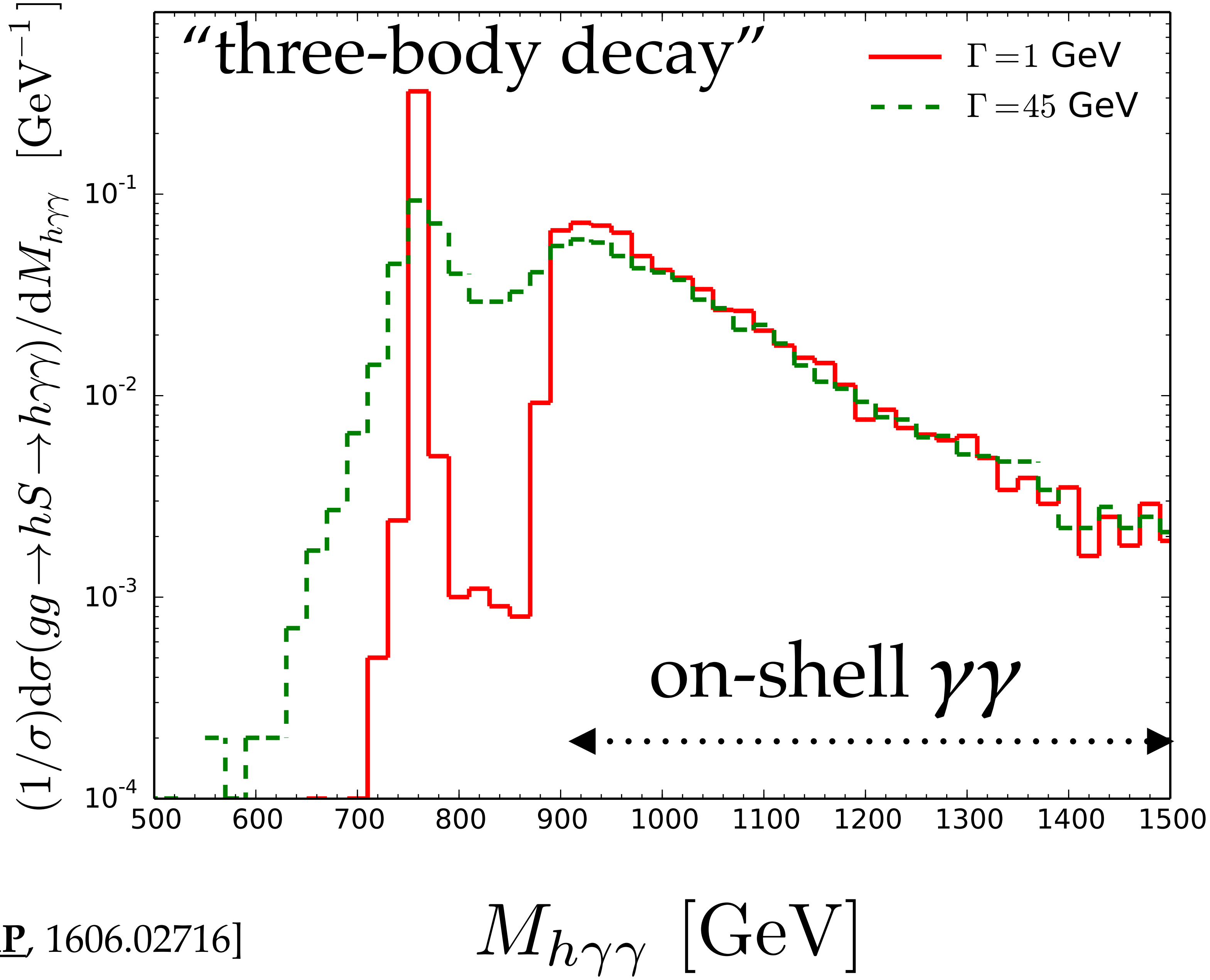
- S and Higgs boson at 13 TeV would be produced near threshold,
- photons from S would be energetic:

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

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

kinematic features of $h\gamma\gamma$

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



M= 750 GeV

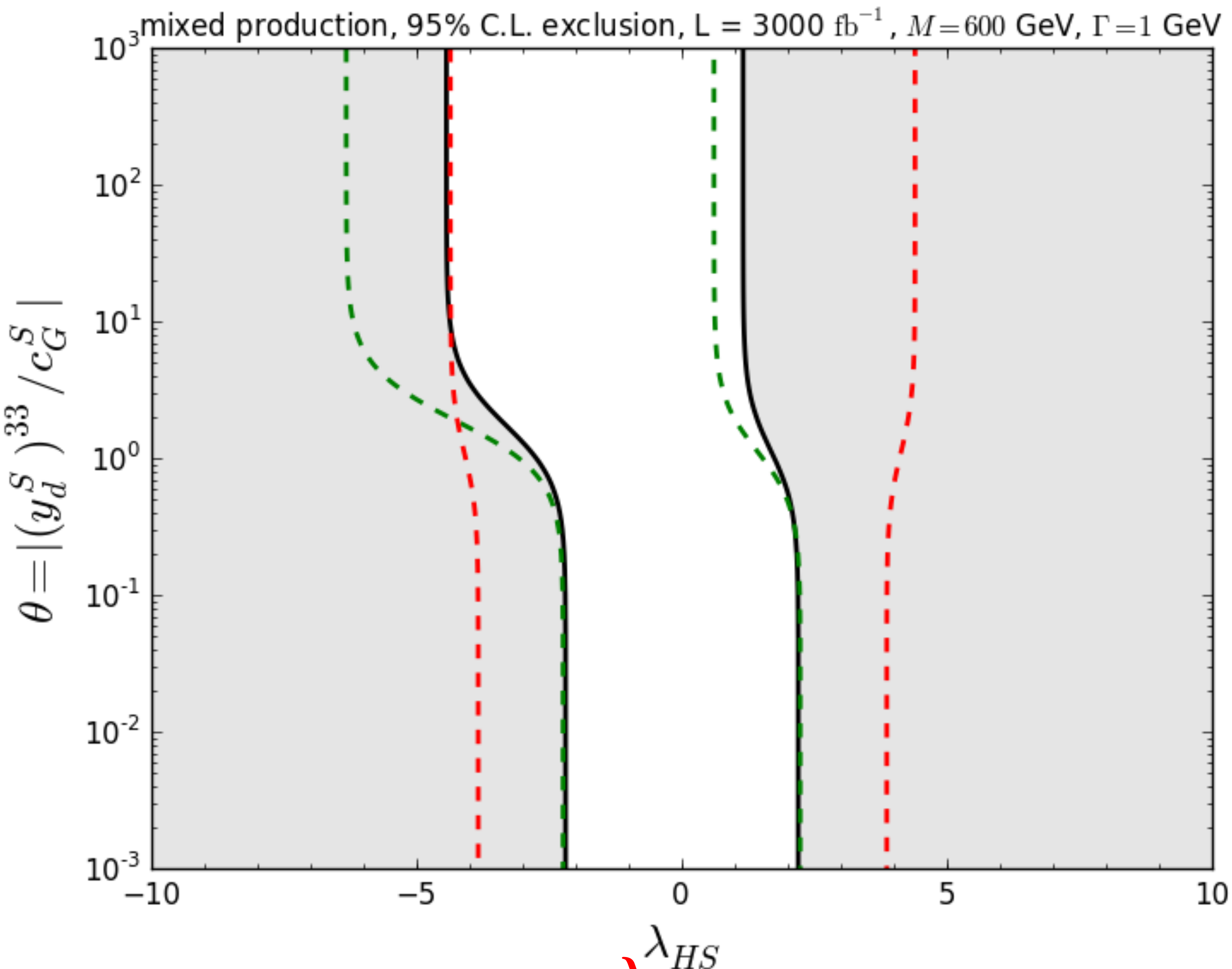
[Carmona, Goertz, **AP**, 1606.02716]

- construct two analysis "regions": "three-body decay", "on-shell $\gamma\gamma$".

- given assumption that "underlying" production is purely gluon fusion and λ_{HS}=1,
- calculate 95% C.L. exclusion for resonance produced in **mixture** of gluon fusion and ***b***-quark fusion:

(more ***b***-quark) ↑

y_b^S / c_G^S



λ_{HS}

M= 600 GeV, ***Γ*** = 1 GeV

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

red: "three-body decay"

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

conclusions

- **multi-Scalar final states** possess rich phenomenology allow us to probe couplings between scalars [+ other couplings].
- **Higgs boson multi-production** has received considerable attention since Higgs discovery:
  - higher-order corrections, BSM effects, experimental measurements + more.
- **indirect constraints** on the trilinear Higgs boson coupling will provide complementary information.
- **Higgs-New scalar associated production** has interesting kinematic features and would be necessary to consider if new states are discovered.

Thanks for your attention!

backup slides

branching ratios for *hh* and *hhh*

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branching ratios (m_h = 125 GeV)

$$BR[b\bar{b}b\bar{b}] = 33.3\%$$

$$BR[b\bar{b}WW] = 24.8\%$$

$$BR[b\bar{b}\tau\tau] = 7.29\%$$

$$BR[WWWW] = 4.62\%$$

$$BR[WW\tau\tau] = 2.71\%$$

$$BR[\tau\tau\tau\tau] = 0.399\%$$

$$BR[b\bar{b}ZZ] = 0.305\%$$

$$BR[b\bar{b}\gamma\gamma] = 0.263\%$$

$$BR[b\bar{b}Z\gamma] = 0.178\%$$

$$BR[b\bar{b}\mu\mu] = 0.025\%$$

<u>note</u>: each 1% corresponds to ~100 events per 300 fb^{-1} of luminosity @ LHC14.

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$BR[b\bar{b}ZZ] = 0.305\%$ ✗

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$BR[b\bar{b}b\bar{b}] = 33.3\%$ ✓

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$BR[b\bar{b}\mu\mu] = 0.025\%$ ✗

note: each 1% corresponds to ~100 events per 300 fb^{-1} of luminosity @ LHC14.

shown to be potentially viable (in the SM)

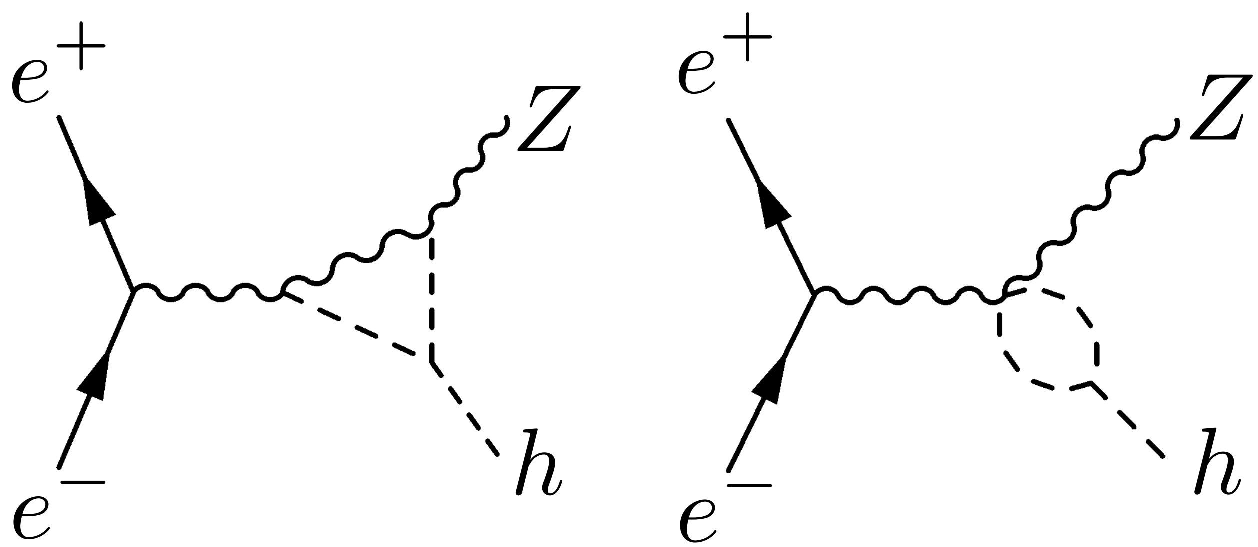
hhh branching ratios (m_h = 125 GeV)

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\mathrm{ab}^{-1}}$
$(bb)(bb)(bb)$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125
$(b\bar{b})(\gamma\gamma)(WW_{1\ell})$	0.057	3.291	98
$(b\bar{b})(\tau\bar{\tau})(\gamma\gamma)$	0.05	2.883	86
$(WW_{1\ell})(WW_{1\ell})(WW_{1\ell})$	0.038	2.169	65
$(\tau\bar{\tau})(WW_{2\ell})(WW_{1\ell})$	0.027	1.545	46
$(\tau\bar{\tau})(\tau\bar{\tau})(\tau\bar{\tau})$	0.025	1.459	43
$(b\bar{b})(WW_{2\ell})(WW_{2\ell})$	0.017	0.956	28
$(WW_{2\ell})(WW_{1\ell})(WW_{1\ell})$	0.015	0.882	26
$(b\bar{b})(b\bar{b})(ZZ_{4\ell})$	0.012	0.69	20
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{2\ell})$	0.012	0.677	20
$(b\bar{b})(ZZ_{2\ell})(WW_{2\ell})$	0.011	0.648	19
$(\tau\bar{\tau})(ZZ_{2\ell})(WW_{1\ell})$	0.009	0.524	15
$(b\bar{b})(\gamma\gamma)(WW_{2\ell})$	0.008	0.446	13
$(\tau\bar{\tau})(\gamma\gamma)(WW_{1\ell})$	0.006	0.36	10

indirect constraints in e+e-

- e.g. contributions to single Higgs observables through higher-order corrections.

- e.g. e^+e^- @ 240 GeV:



[M. McCullough, 1312.3322]

FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h.

- may determine triple Higgs coupling within ~30% at 10/ab.

other production modes?

- several associated production modes exist:

	cross section@14 TeV
$qq \to qqHH$	~1.8 fb
$qq \to WHH$	~0.4 fb
$qq \to ZHH$	~0.3 fb

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [1212.5581]

- (note: behaviour w.r.t. λ is different for each channel.)
- with decays $HH \to b\bar{b}b\bar{b}$, could be looked into with sub-structure techniques, but initial cross section low.

the failure of HEFT in *hh*

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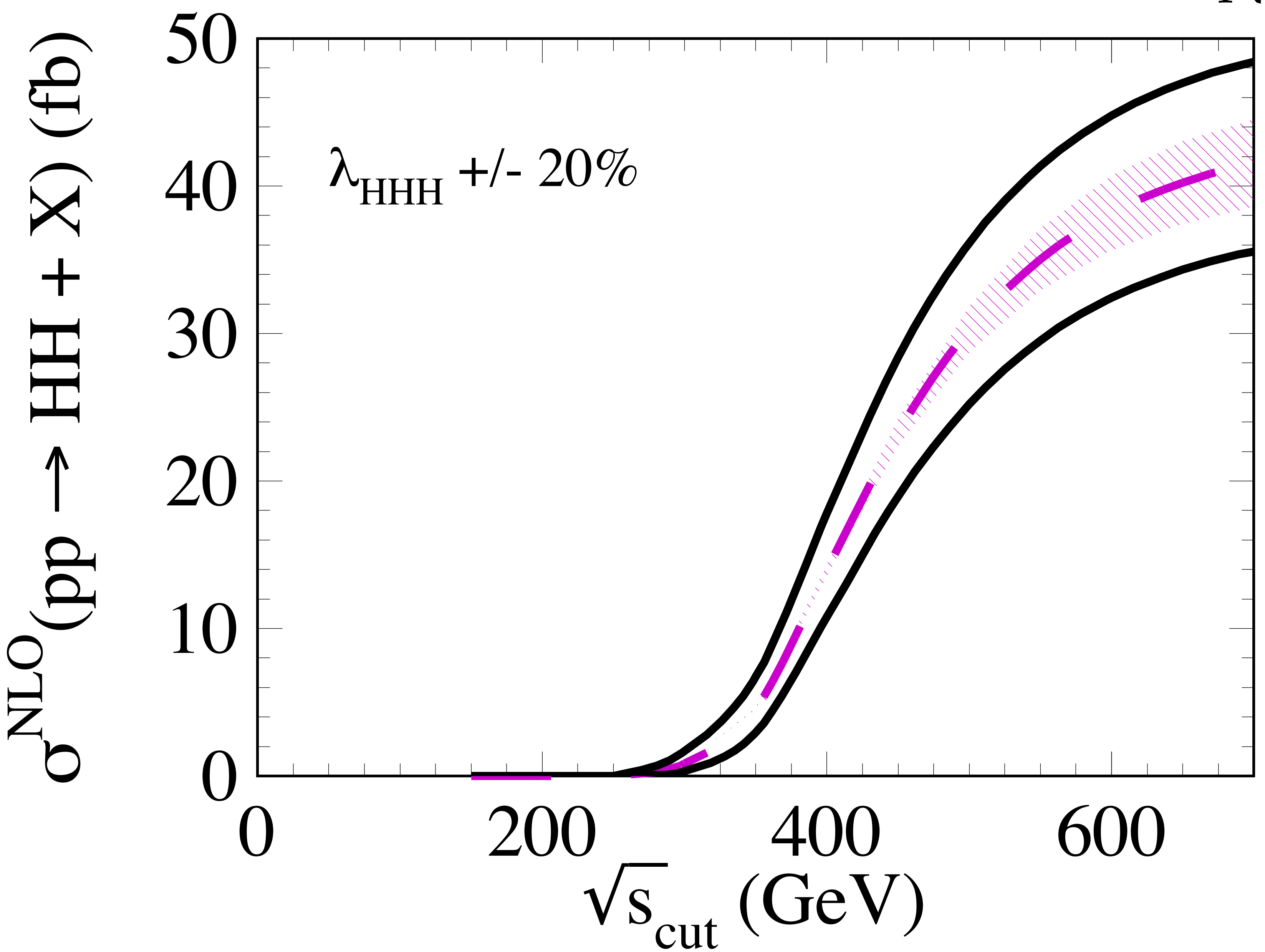
how good is the HT-EFT?

[Grigo, Hoff, Melnikov, Steinhauser, 1305.7340] $\longrightarrow$ corrections to NLO **σ** up to $\mathcal{O}(1/M_t^8)$



$\sqrt{s_{\text{cut}}}$: upper cut partonic c.o.m. energy.

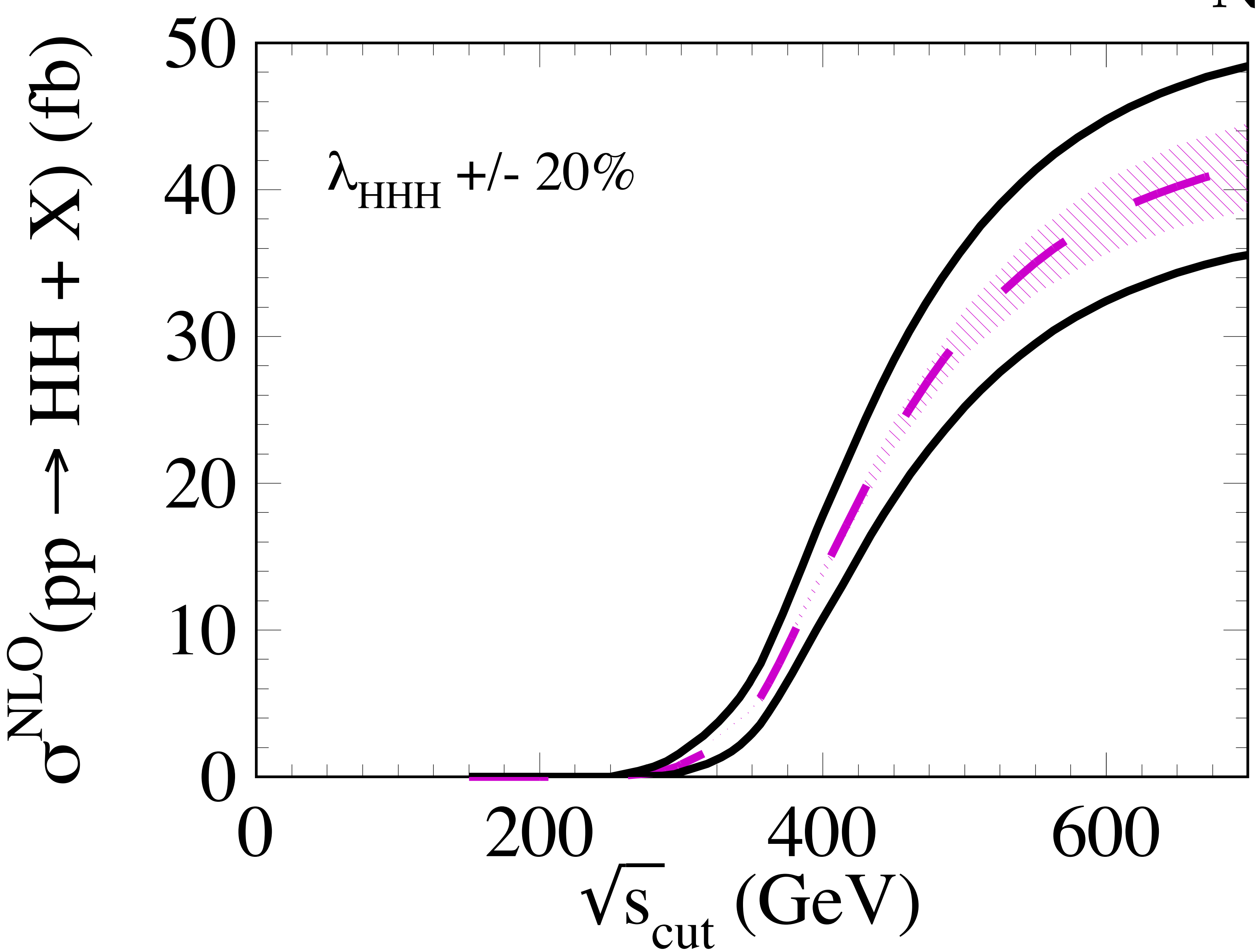
black: variations of the self-coupling by $\pm 20\%$.

violet: uncertainty due to un-calculated $1/M_t$ corrections.

$\longrightarrow \mathcal{O}(10\%)$

how bad is the HT-EFT?

[Grigo, Hoff, Melnikov, Steinhauser, 1305.7340] $\longrightarrow$ corrections to NLO **σ** up to $\mathcal{O}(1/M_t^8)$



$\sqrt{s_{\mathrm{cut}}}$: upper cut partonic c.o.m. energy.

black: variations of the self-coupling by $\pm 20\%$.

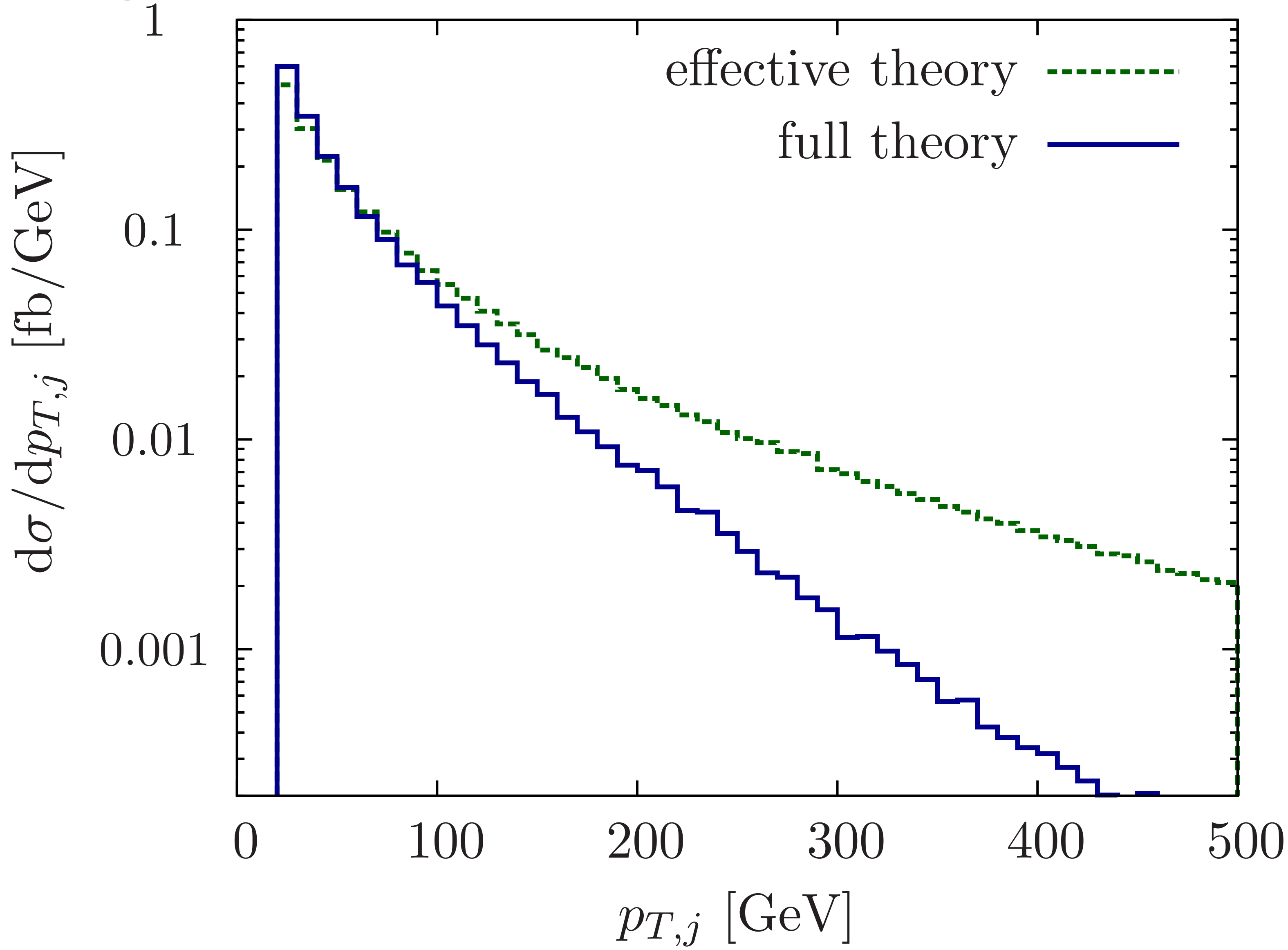
violet: uncertainty due to un-calculated $1/M_t$ corrections.
$\longrightarrow \mathcal{O}(10\%)$

HEFT gone wild

- differential quantities can be worse in certain regions of phase space, e.g.:

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

[Dolan, Englert, Spannowsky 1206.5001]



Merging and matching for *hh*

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merging via MLM

[Q. Li, Q. Yan, X. Zhao, 1312.3830]

[P. Maierhöfer, **AP**, 1401.0007]

- supplement the parton shower (PS) (soft/collinear QCD radiation) with exact matrix elements (MEs).
- use a merging scheme to put PS and MEs together, avoiding double-counting.
- MLM method "matches" jets to partons according to a "merging" scale and vetoes accordingly.

hh merging via MLM

[Li, Yan, Zhao, 1312.3830]
[P. Maierhöfer, **AP**, 1401.0007]

- implementation using MadGraph+Pythia, [Q. Li, Q. Yan, X. Zhao, 1312.3830]
- our implementation: using **OpenLoops** generator: evaluates one-loop MEs efficiently using numerical & tensor integral reduction. [F. Cascioli, P. Maierhöfer, S. Pozzorini, 1111.5206]
- kinematical description of the first jet at high-p_T: via exact ME for hh+1 parton.
- MLM merging performed in Herwig++.

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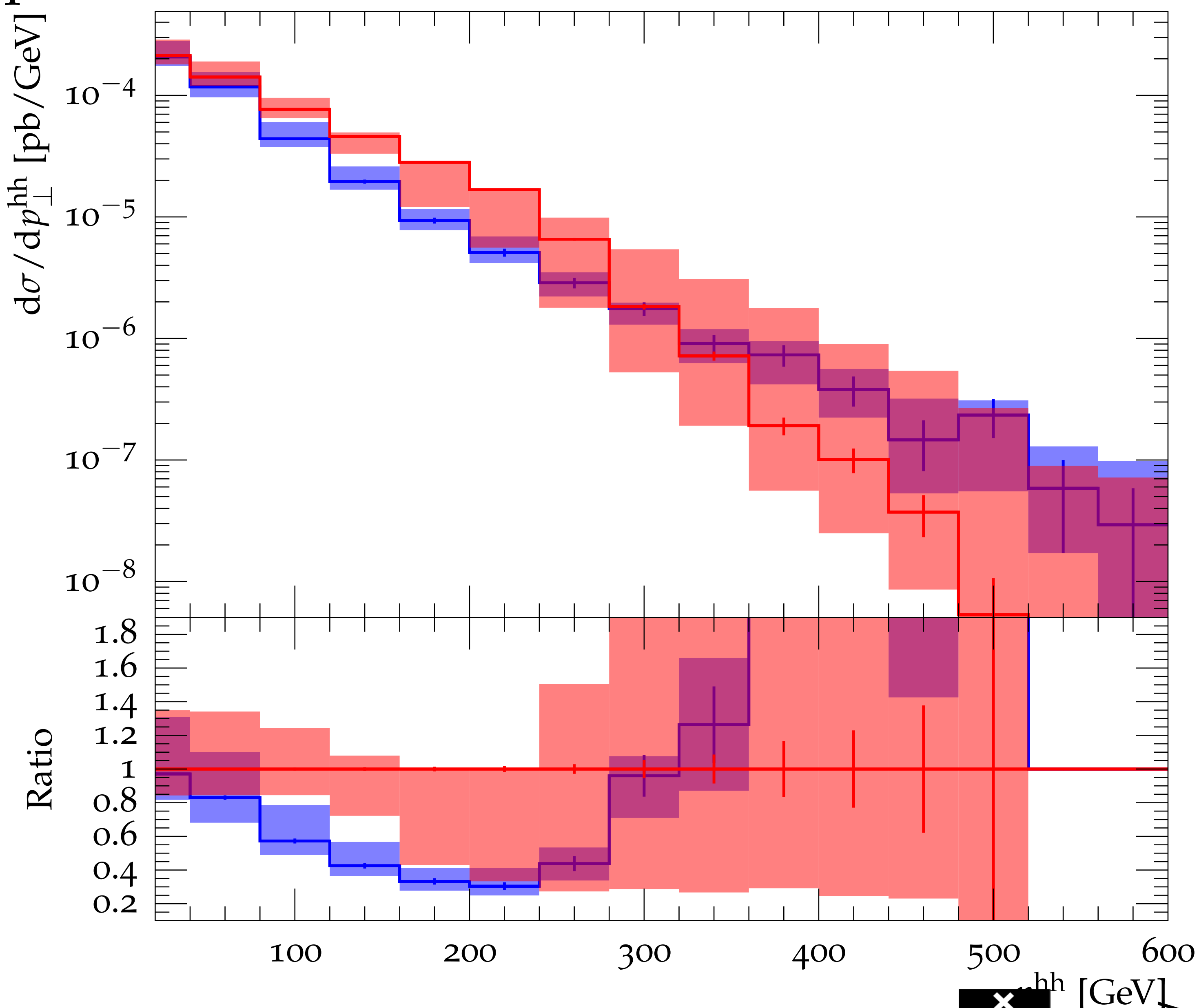
merging via MLM

[P. Maierhöfer, **AP**, 1401.0007]

- scale uncertainty reduction: from leading-log in PS to LO in ME for the first jet p_T.

- e.g. transverse momentum of Higgs boson pair.

- red: parton shower, blue: merged sample.



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matching using MC@NLO

[R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro, 1401.7340]

- use exact LO and real emission MEs (***hh***+1 parton) as was done with merging.

- use the "two-loop" virtual corrections as obtained using the low energy theorem ($M_t \to \infty$), reweight according to exact LO.

- match via MC@NLO method: removes the double-counting resulting from combination of hh+PS and hh+1 parton ME.

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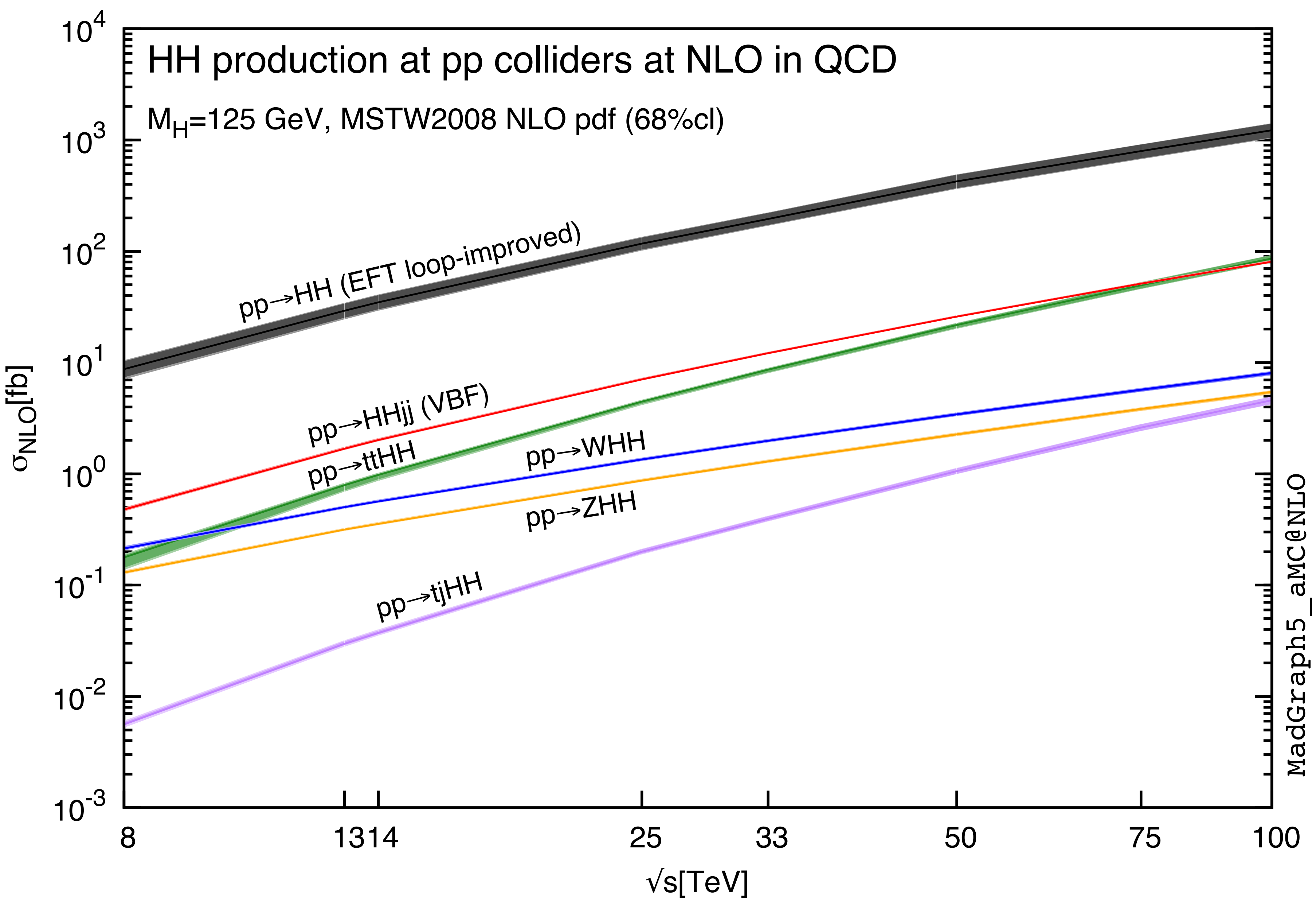
matching using MC@NLO

[R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro, 1401.7340]

- other *hh* production processes also included in the aMC@NLO framework:



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sensitivity to the triple coupling

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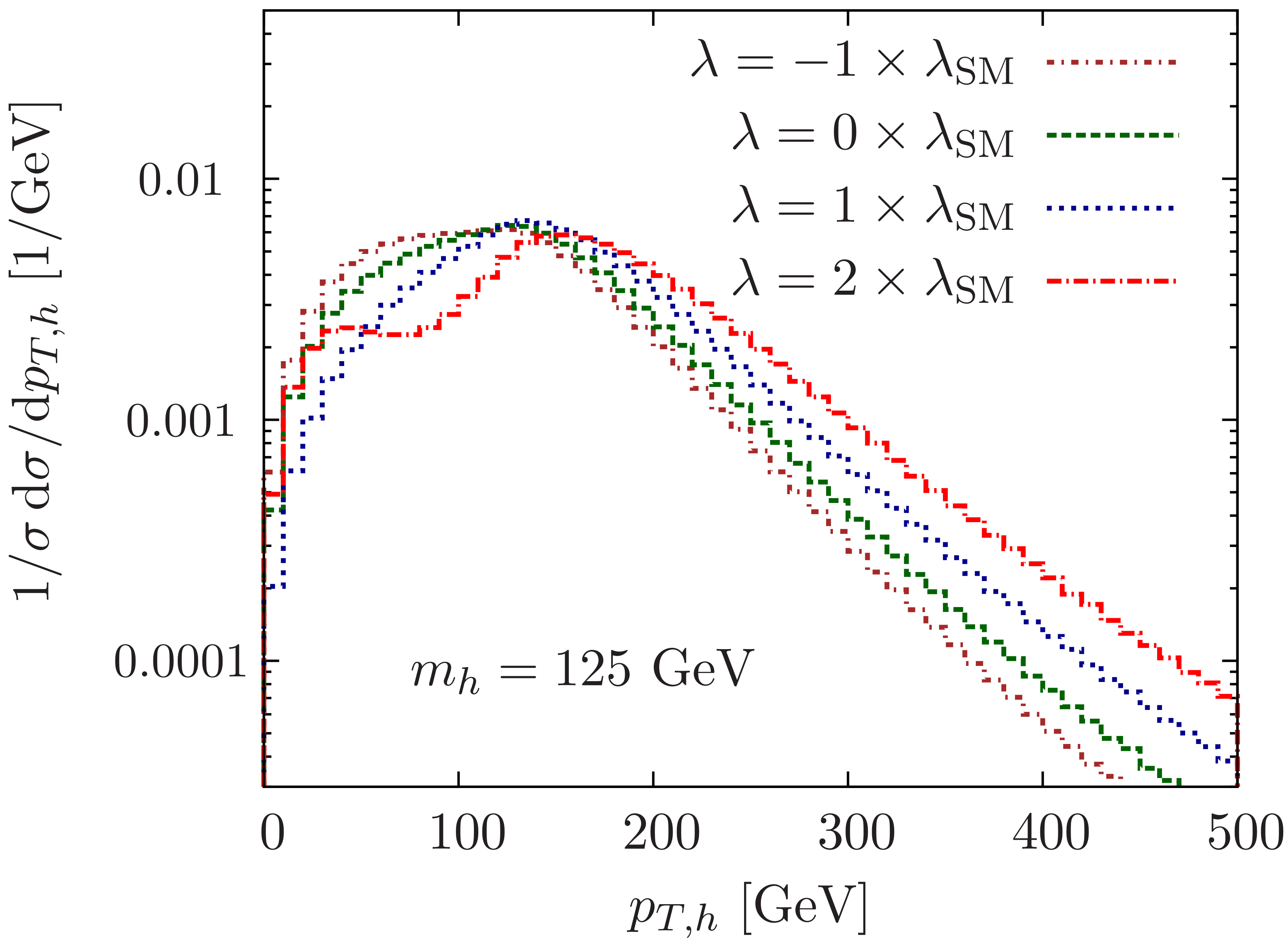
triple coupling sensitivity

[Dolan, Englert, Spannowsky, 1206.5001]



sensitivity lies in the low-p_T region.

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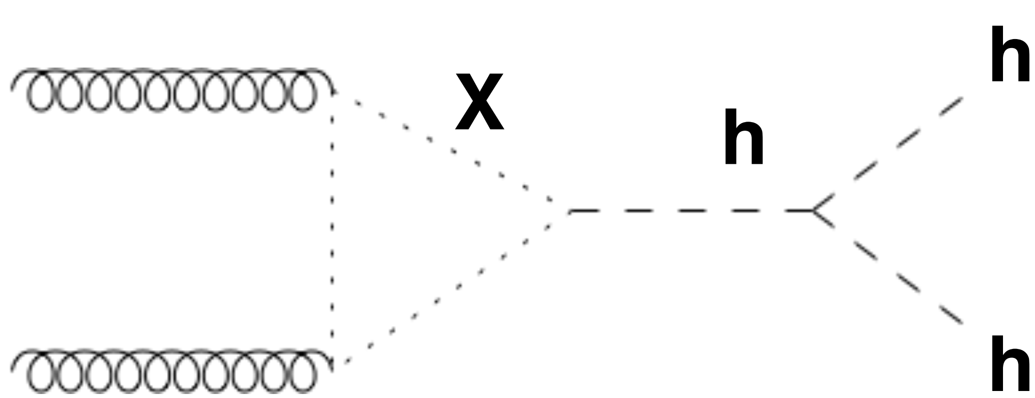
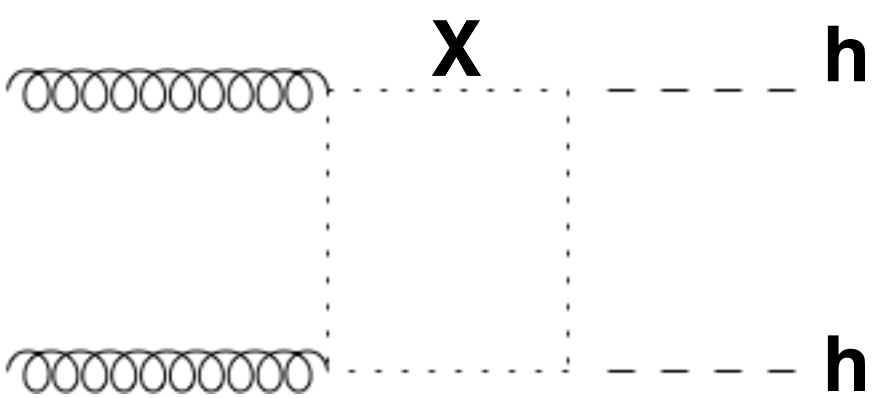
what about new physics effects in **hh**?

new particles

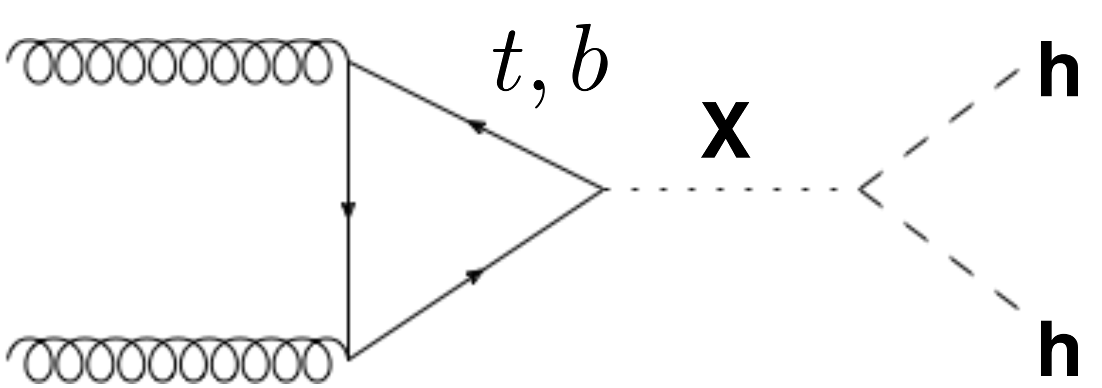
- *hh* can probe the presence of new particles:

- **(a)** e.g. in the loops:





- **(b)** e.g. in a propagator coupling to two Higgs bosons:



[*hh* resonances have already been searched for by ATLAS & CMS in Run 1: 1406.5053, CMS-PAS-HIG-13-032, 1503.04114]

(a): e.g. particles in loops

- **e.g. real scalar colour-octet**, coupling to the SM Higgs via:

$$S_a^2 \Phi^\dagger \Phi$$ [e.g. Kribs, Martin, 1207.4496]

- **e.g. top partners:** [e.g. Chen, Dawson, Lewis, 1406.3349]

SM third gen.:

$q_L = (t_L, b_L)$

$t_R, \ b_R$

heavy fermions:

$Q = (T, B)$ vector-like $SU(2)_L$ doublet

$U, \ D$ vector-like $SU(2)_L$ singlets

[left- and right- handed components have identical transformation properties under $SU(2)_L \times U(1)$]

(b): e.g. Higgs portal scenario

[e.g. (di-Higgs): Dolan, Englert, Spannowsky,1210.8166,
e.g. (general) Barbieri, Gregoire, Hall, hep-ph/0509242]

$$V = \mu_S^2 |\Phi_S|^2 + \lambda_S |\Phi_S|^4 + \mu_H^2 |\Phi_H|^2 + \lambda_H |\Phi_H|^4$$
$$+ \eta_\chi |\Phi_S|^2 |\Phi_H|^2 \quad [\text{“mirrored”}]$$

$|\Phi_S|$: SM Higgs doublet $\qquad$ $|\Phi_H|$: Hidden sector doublet

(b): e.g. Higgs portal scenario

[e.g. (di-Higgs): Dolan, Englert, Spannowsky,1210.8166,
e.g. (general) Barbieri, Gregoire, Hall, hep-ph/0509242]

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$|\Phi_S|$: SM Higgs doublet $\qquad$ $|\Phi_H|$: Hidden sector doublet

- after EWSB: $|\Phi_{S,H}| = v_{S,H}/\sqrt{2}$

  one gets **two** Higgs scalars: **h, H**.

  and couplings: hhh, HHH, hHH, hhH.

  $\Rightarrow$ get: $pp \to hh, \; hH, \; HH$

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(b): e.g. Higgs portal scenario

[Dolan, Englert, Spannowsky, 1210.8166]

- **example** parameter point:

$$v_S \simeq 246 \text{ GeV} \qquad m_h \simeq 125 \text{ GeV}$$
$$v_H \simeq 24 \text{ GeV} \qquad m_H \simeq 255 \text{ GeV}$$
$$\Gamma_H \simeq 24 \text{ GeV}$$

- leads to (LO):

$$pp \to hh + X \quad : \quad 44.4 \text{ fb}$$
$$pp \to Hh + X \quad : \quad 5.57 \text{ fb}$$
$$pp \to HH + X \quad : \quad 667 \text{ ab}$$

[NLO K-factor ~ 2]

- constrain the model by measuring the above.

- [note: phenomenology similar in the MSSM.]

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