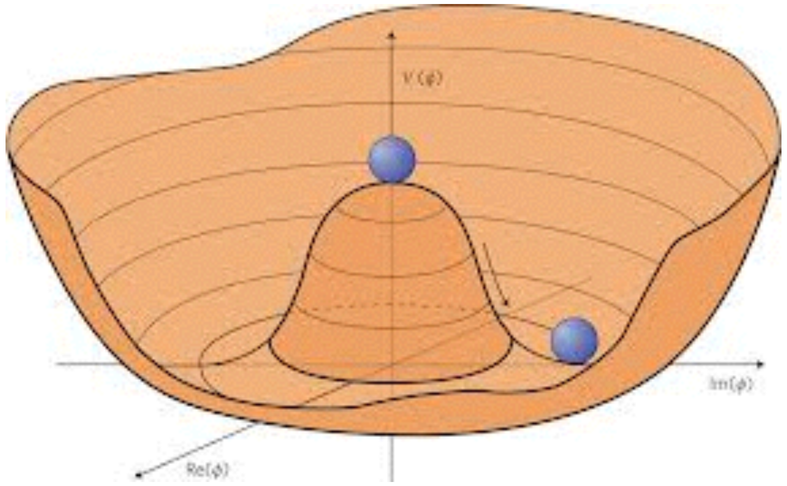
di-Higgs at the LHC

Michael Spannowsky

IPPP, Durham University

- We have the remnant of elw. symmetry breaking



- Now we want to finally study the mechanism/potential

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi) \qquad V\left(\Phi^\dagger \Phi\right) = \mu^2\, \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

- Studying quartic impossible at envisioned FCs
- One of best reasons for phase 2 upgrade: if ILC does not go to 1 TeV might not outperform LHC
- Jose talked about HH in Higgs portal context
- To contrast BSM measurement SM needs to be understood first. This talk SM HH and non-HP BSM

Higgs self-coupling measurements in the Standard Model

$$= \lambda_{\mathrm{SM}} = \mathrm{g}^2 m_h^2 / m_{\mathrm{W}}^2$$

$$
\begin{aligned}
-\mathcal{L} \supset \quad & \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4 \\
& - g m_V V^2 h - \frac{m_f}{v} \bar{f} f h \\
& - \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)
\end{aligned}
$$

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→ Potential needs at least dihiggs production!

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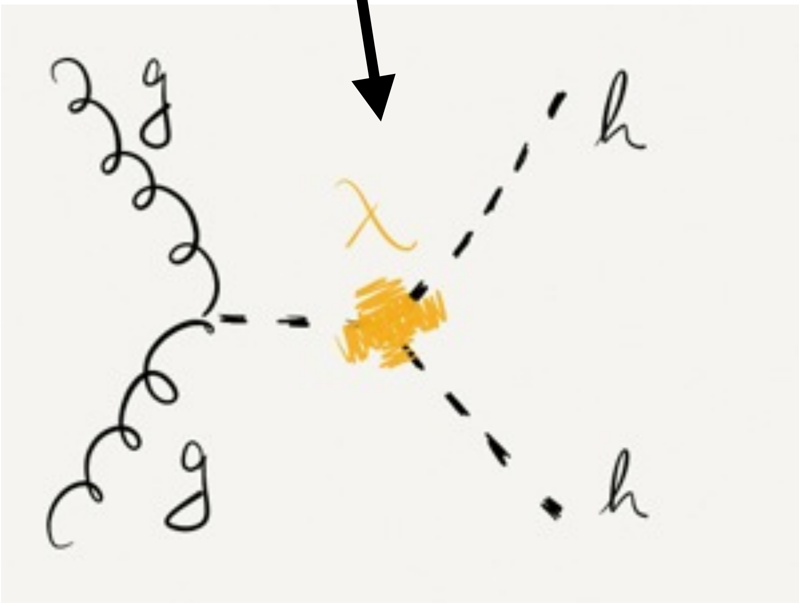

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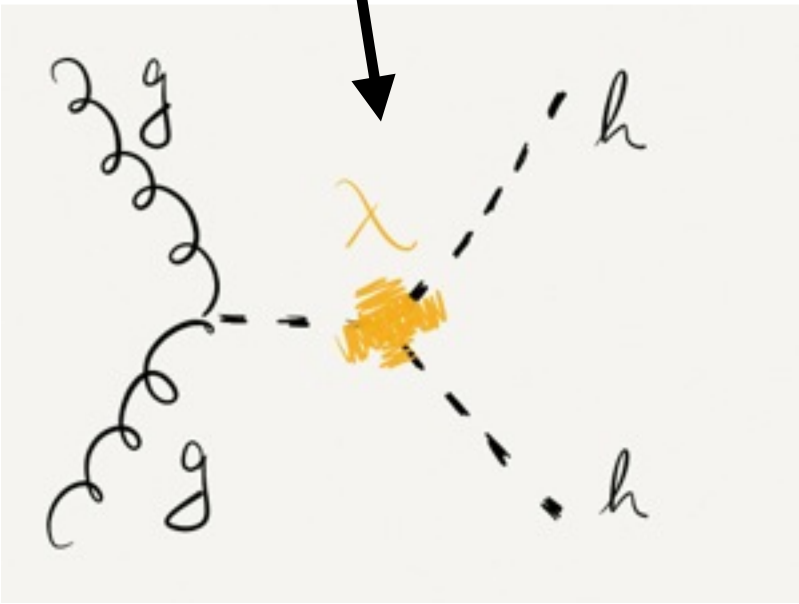

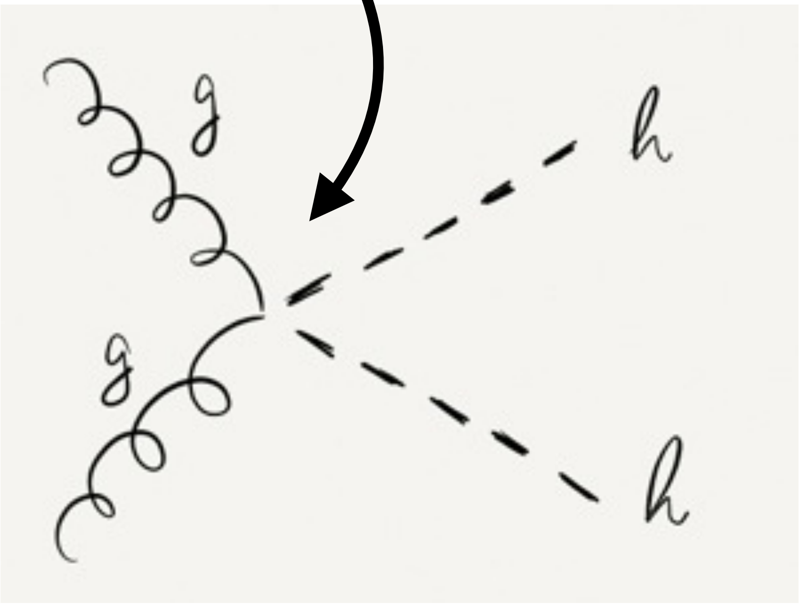

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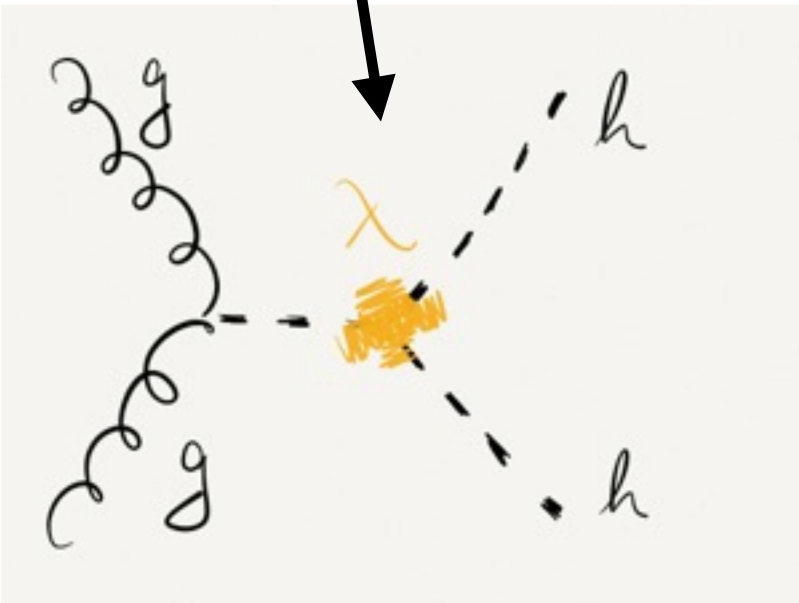

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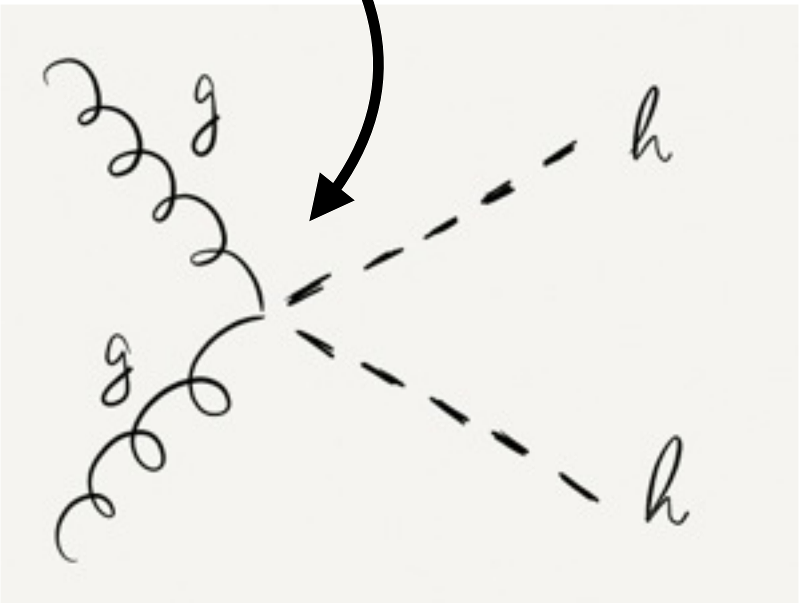
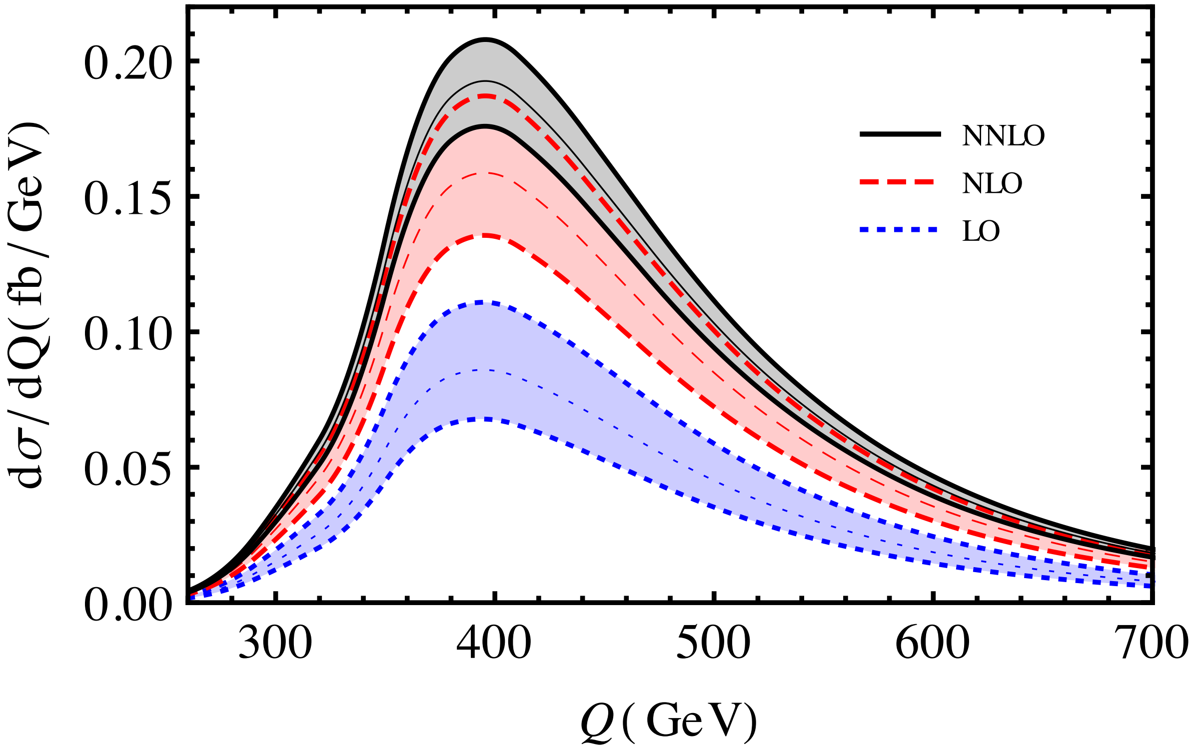


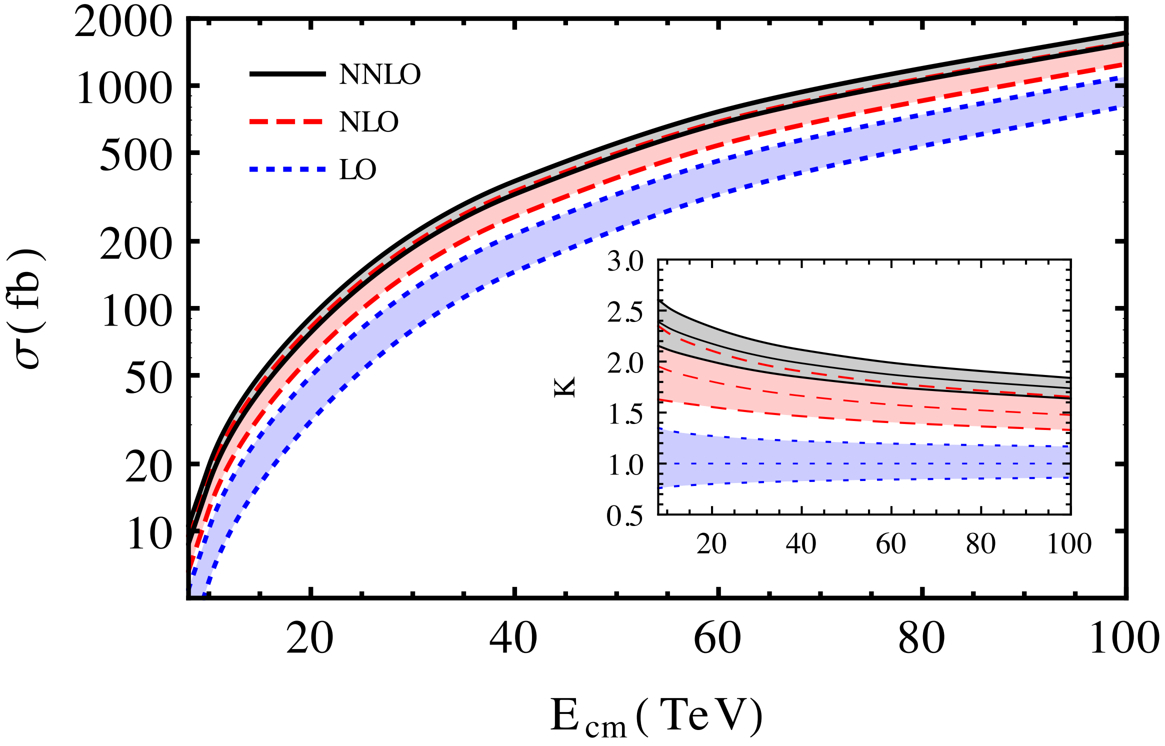
Recent progress in HH cross section calculations

HH	LO full mt	[Plehn, Spira, Zerwas Nucl. Phys. B479, hep-ph 9603205] and now many others...
	NLO eff. mt	[Dawson, Dittmaier, Spira PRD 58 1998] implemented in HPair http://people.web.psi.ch/spira/hpair/
	NLO full mt	[Grigo, Hoff, Melnikov, Steinhauser 1311.7425]
	NNLO eff. mt	[De Florian, Mazzitelli PRL 111, 1309.6594]
HHj	LO full mt	[Dolan, Englert, MS JHEP 1210, 1206.5001] [Li, Yan, Zhao 1312.3830] [Maierhoefer, Papaefstathiou 1401.0007]
HHjj	LO full mt (reweighted)	[Dolan, Englert, Greiner, MS 1310.1084]

Higgs selfcoupling in HH+X

[De Florian, Mazzitelli PRL 111, 1309.6594]

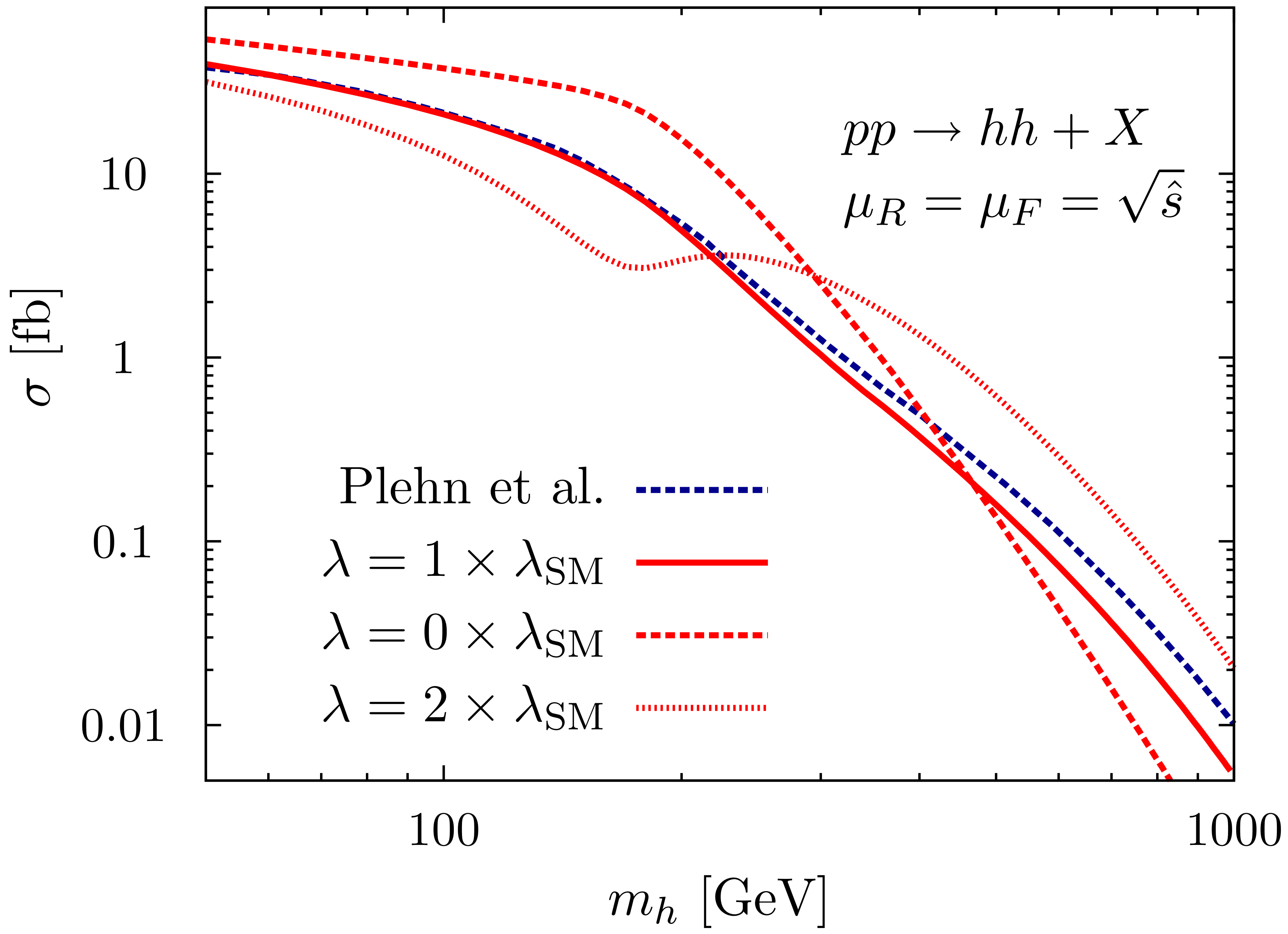




E_{cm}	8 TeV	14 TeV	33 TeV	100 TeV
σ_{NNLO}	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$	$+7.0-7.4$	$+5.9-5.8$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.5-2.6$	$+2.3-2.6$
PDF+α_S [%]	$+9.3-8.8$	$+7.2-7.1$	$+6.0-6.0$	$+5.8-6.0$

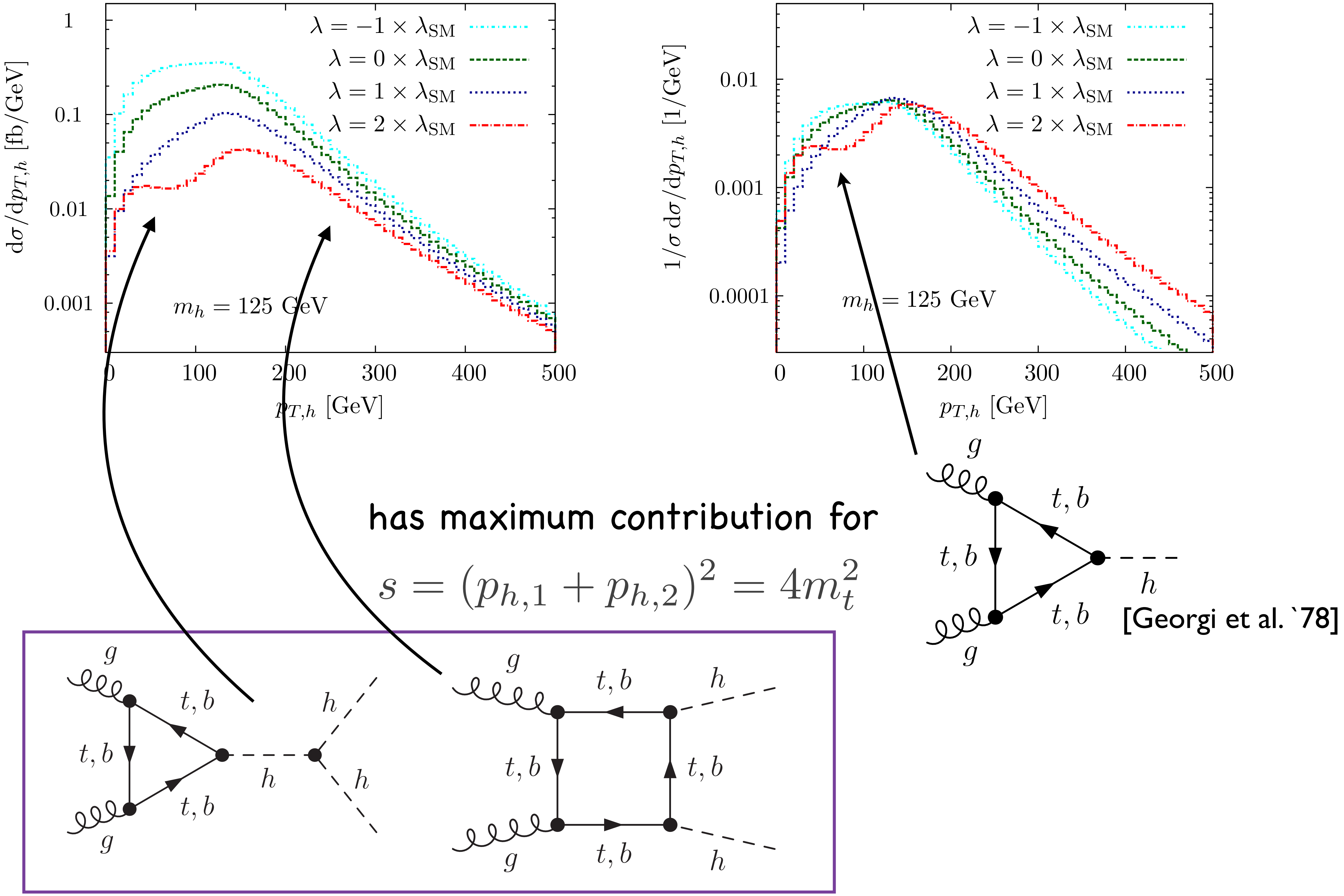
- NNLO in effective ggH
- Very large k-factors

Higgs selfcoupling in HH+X



A priori good sensitivity for $m_h = 125$ GeV

Higgs selfcoupling in HH+X



has maximum contribution for

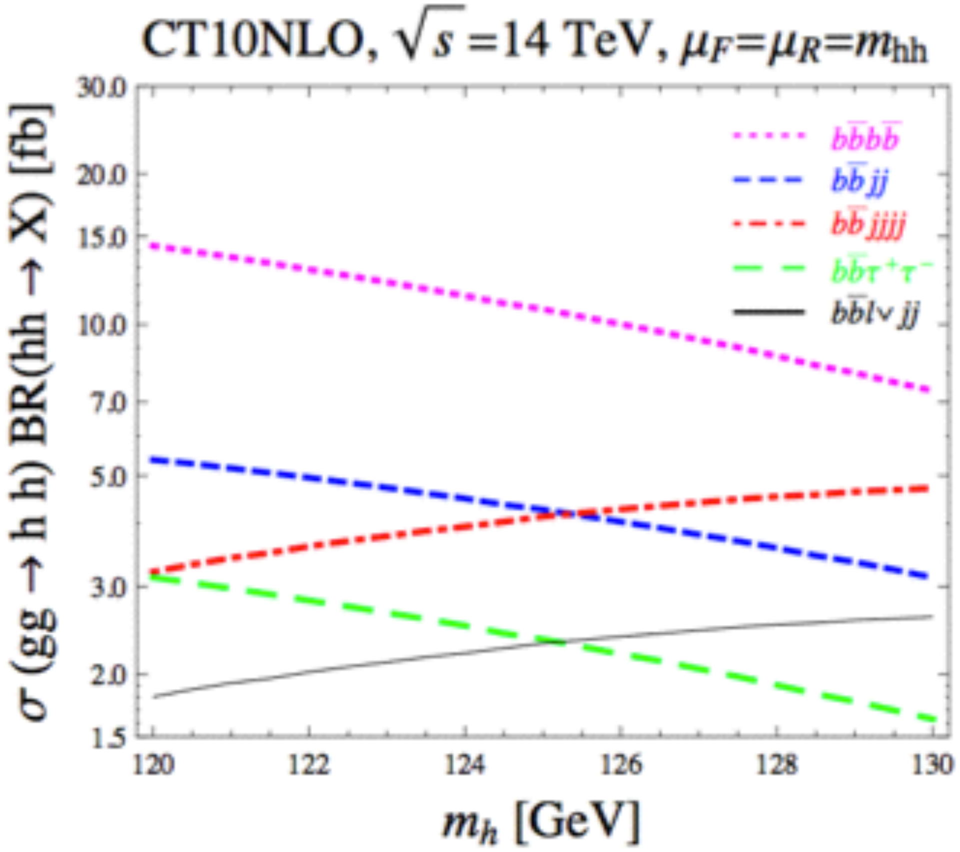
$$s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$$

[Georgi et al. `78]

Where is sensitivity located?

Measuring this small cross section in an inclusive search is very challenging at the HL-LHC: compromise between branching ratio and cleanliness of the signal

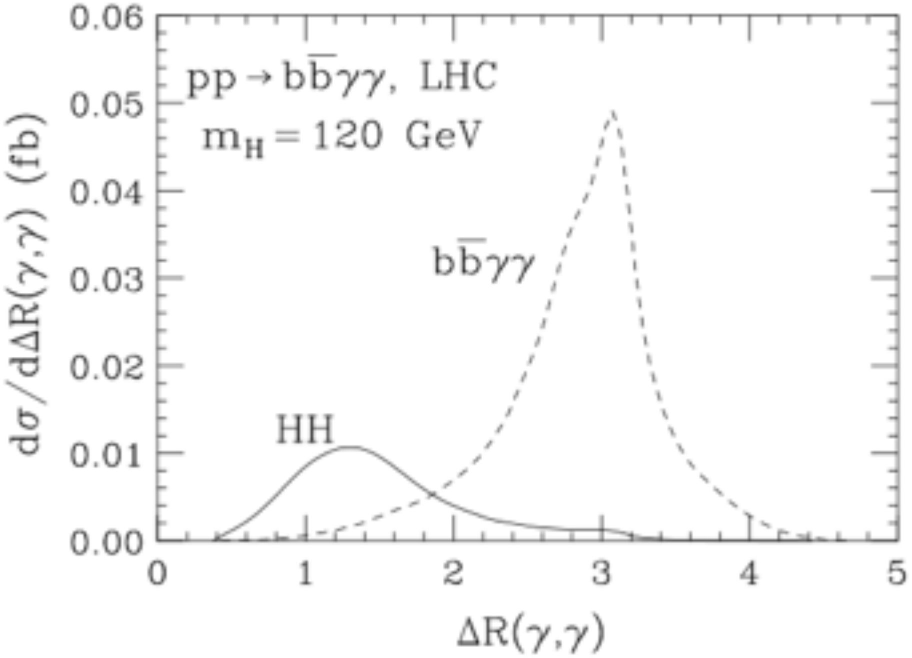
Channel	BR (%)	Events/3 ab
bbWW	24.7	30000
$bb\tau\tau$	7.3	9000
WWWW	4.3	5200
$bb\gamma\gamma$	0.27	330
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015	19
$\gamma\gamma\gamma\gamma$	0.00052	1



Several channels are currently under study by the collaborations

Possible final states:

$\bar{b}b\gamma\gamma$:



- Early on considered most sensitive
- Problem, difficult to simulate backgrounds:

  large reducible backgrounds (jets->photons)

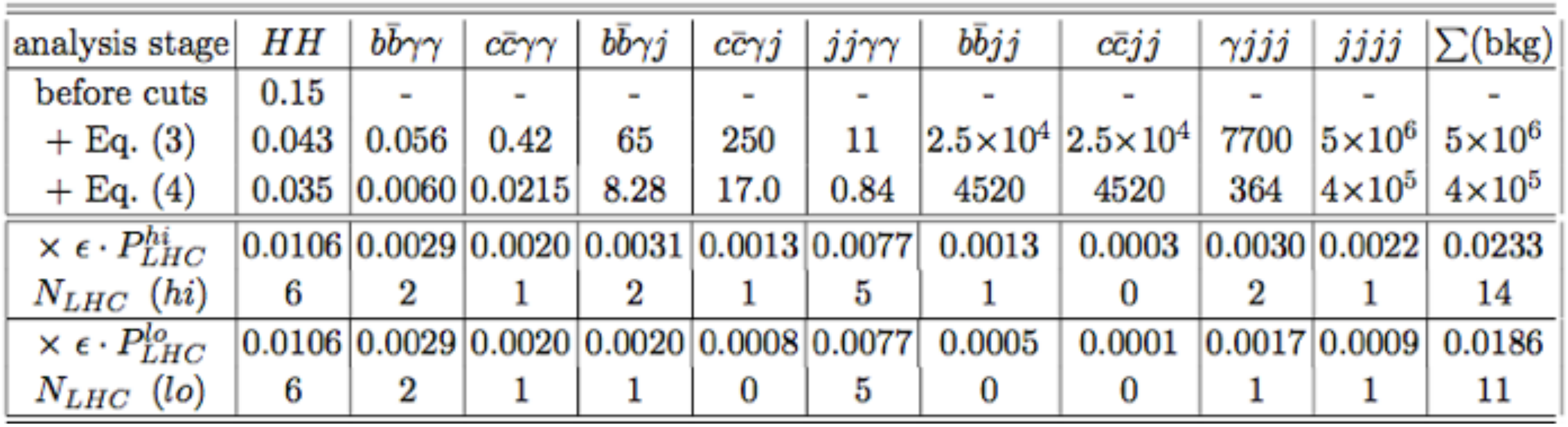
  multi-jets have not been included

cuts:

$$p_T(b) > 45\text{ GeV}\,, \qquad |\eta(b)| < 2.5\,, \qquad \Delta R(b,b) > 0.4\,,$$
$$m_H - 20\text{ GeV} < m_{b\bar{b}} < m_H + 20\text{ GeV}\,,$$
$$p_T(\gamma) > 20\text{ GeV}\,, \qquad |\eta(\gamma)| < 2.5\,, \qquad \Delta R(\gamma,\gamma) > 0.4\,,$$
$$m_H - 2.3\text{ GeV} < m_{\gamma\gamma} < m_H + 2.3\text{ GeV}\,,$$
$$\Delta R(\gamma,b) > 0.4\,,$$

- Possibly side-band analysis might help
- Still best analysis but parton level

[Baur, Pehn, Rainwater '03]

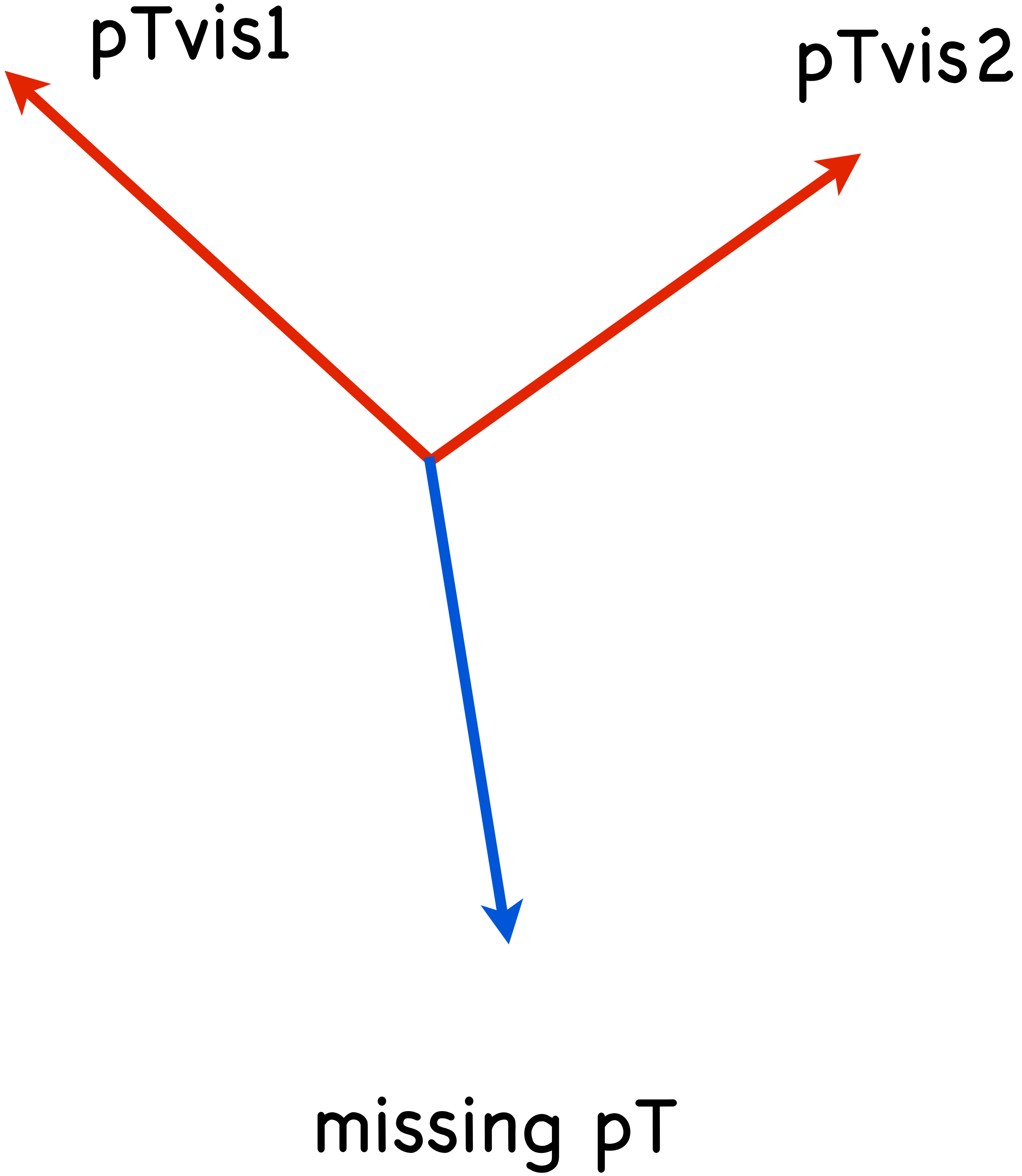


analysis stage	HH	$b\bar{b}\gamma\gamma$	$c\bar{c}\gamma\gamma$	$b\bar{b}\gamma j$	$c\bar{c}\gamma j$	$jj\gamma\gamma$	$b\bar{b}jj$	$c\bar{c}jj$	γjjj	$jjjj$	$\sum$(bkg)
before cuts	0.15	-	-	-	-	-	-	-	-	-	-
+ Eq. (3)	0.043	0.056	0.42	65	250	11	2.5×10^4	2.5×10^4	7700	5×10^6	5×10^6
+ Eq. (4)	0.035	0.0060	0.0215	8.28	17.0	0.84	4520	4520	364	4×10^5	4×10^5
$\times\,\epsilon\cdot P^{hi}_{LHC}$	0.0106	0.0029	0.0020	0.0031	0.0013	0.0077	0.0013	0.0003	0.0030	0.0022	0.0233
N_{LHC} (hi)	6	2	1	2	1	5	1	0	2	1	14
$\times\,\epsilon\cdot P^{lo}_{LHC}$	0.0106	0.0029	0.0020	0.0020	0.0008	0.0077	0.0005	0.0001	0.0017	0.0009	0.0186
N_{LHC} (lo)	6	2	1	1	0	5	0	0	1	1	11

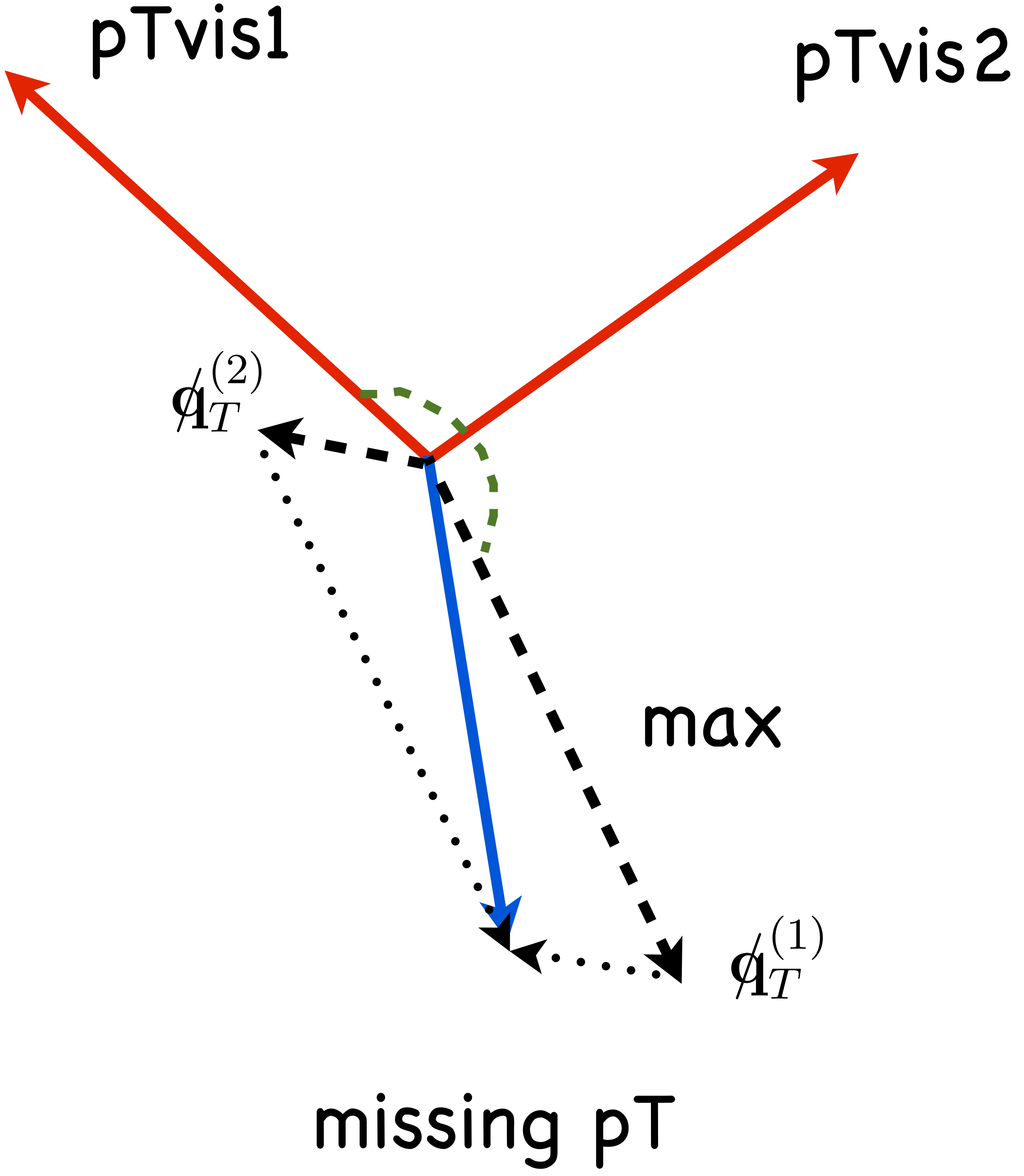
Possible final states:

$b\bar{b}\tau^+\tau^-$:

- Rate improvement
- Though reconstruction of taus difficult
- Plenty and sizable elw. backgrounds, e.g Zbb, HZ, WH, ttbar
- Best strategy:
  - require boost (fatjet) + jet substructure
  - reject ttbar with mT2



$$m_{T2}^2(\chi) \;\equiv\; \min_{\not{\mathbf{q}}_T^{(1)}+\not{\mathbf{q}}_T^{(2)}=\not{\mathbf{p}}_T} \left[\max\left\{m_T^2(\mathbf{p}_T^{\pi^{(1)}},\not{\mathbf{q}}_T^{(1)};\chi),\; m_T^2(\mathbf{p}_T^{\pi^{(2)}},\not{\mathbf{q}}_T^{(2)};\chi)\right\}\right]$$



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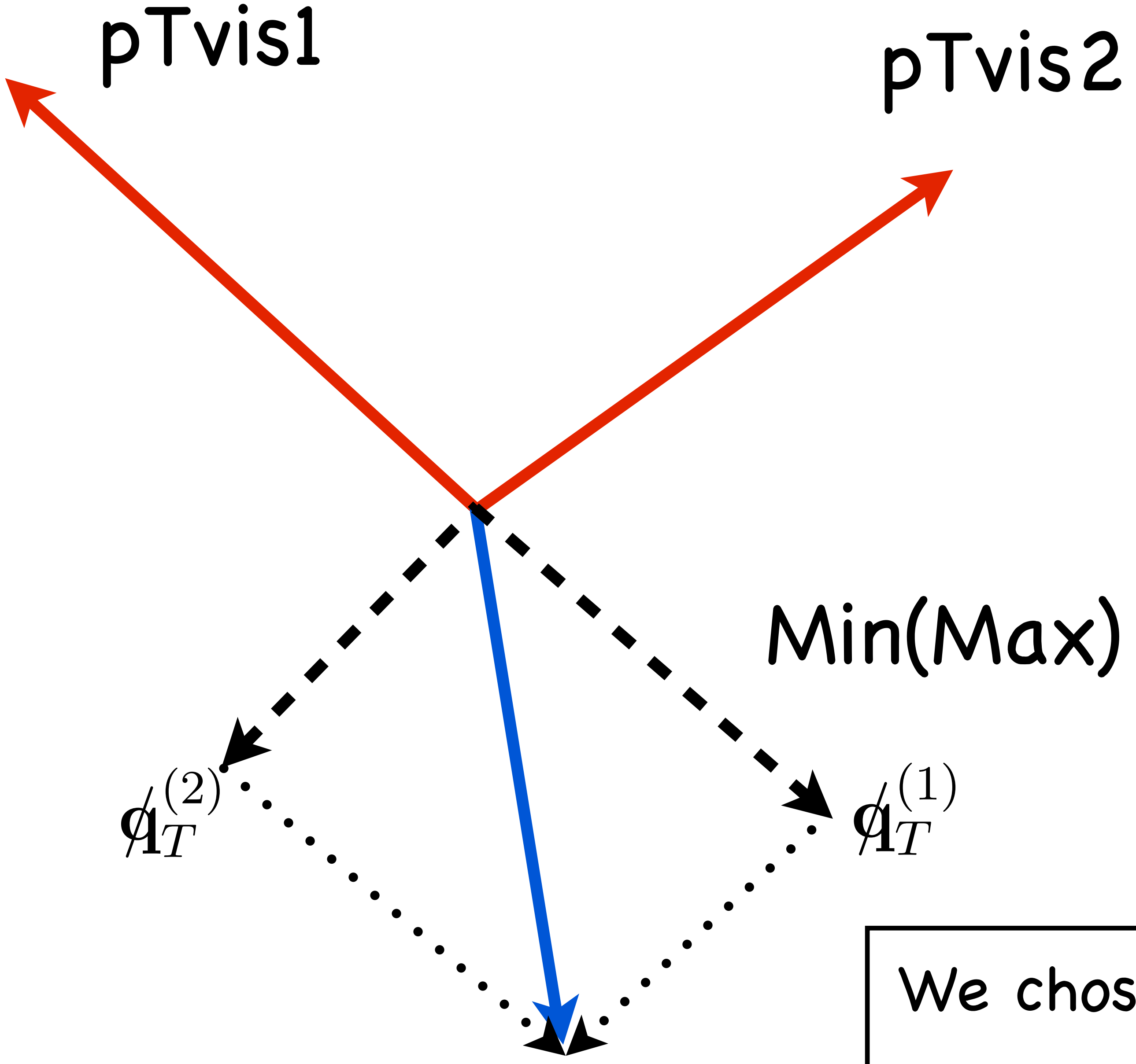

missing pT

We chose:

pTvis2=b1 and pTvis1=b2

→ vetos ttbar...
more prob. HZ, Zbb

$$m_{T2}^2(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{p}_T} \left[\max\left\{m_T^2(\mathbf{p}_T^{\pi^{(1)}}, \not{q}_T^{(1)};\chi),\ m_T^2(\mathbf{p}_T^{\pi^{(2)}}, \not{q}_T^{(2)};\chi)\right\}\right]$$

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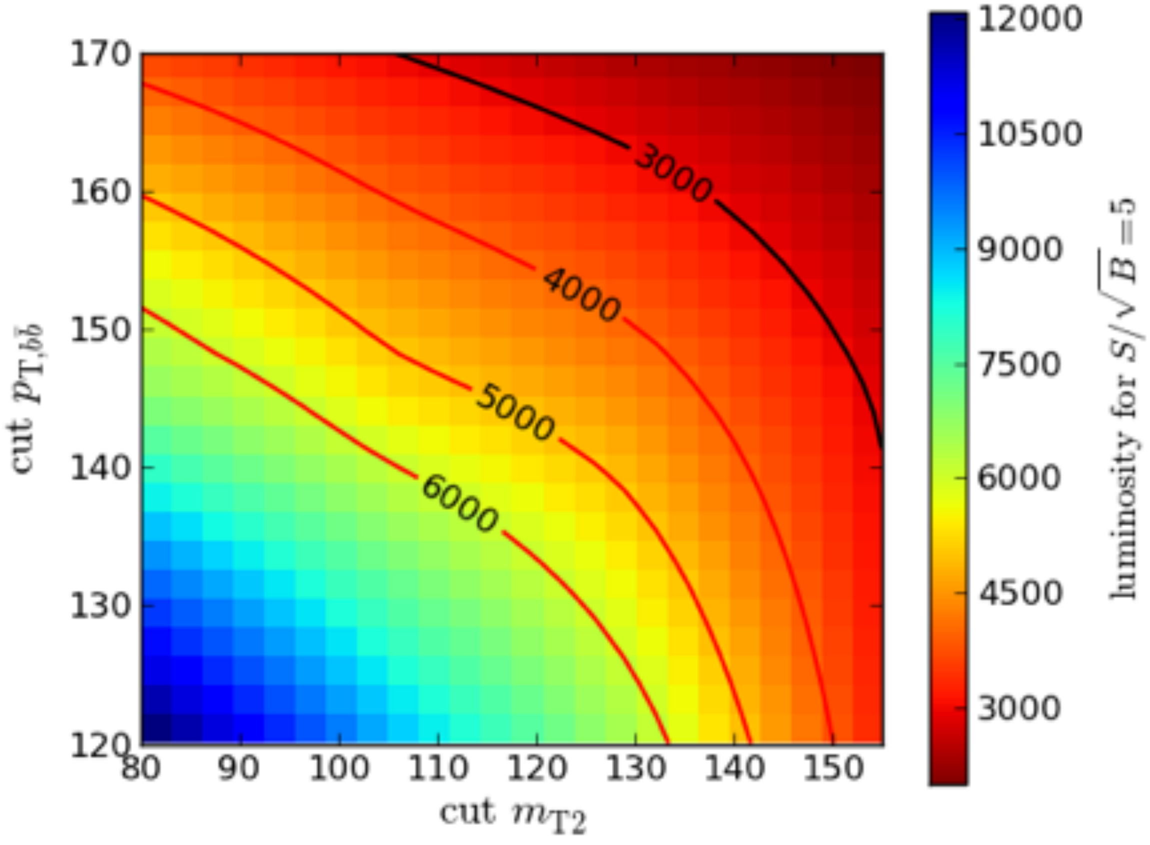
‘straightforward’
(without jet substructure)
to obtain S/B ~ 1/5

Exclusion at 95% CL:

$$\lambda > \lambda^{3000/\text{fb}}_{95\% \text{ CL}} \simeq 3.0 \times \lambda_{\text{SM}}$$

[Dolan, Englert, MS]

[Barr, Dolan, Englert, MS]



Possible final states:

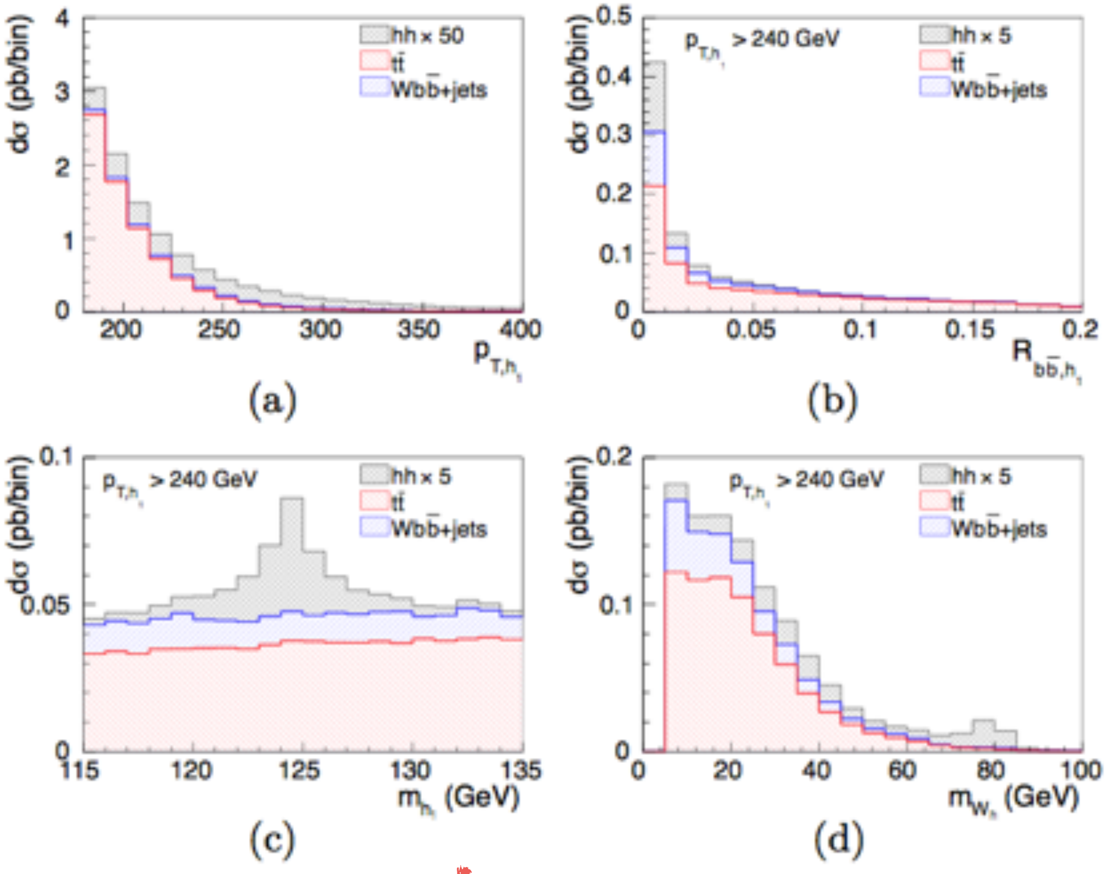
[Papaefstathiou, Yang, Zurita]

$\bar{b}bW^+W^-$:

$$hh \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}\ell\nu jj$$

- Fully reconstructable final state
- Triggering easy due to lepton
- But looks like ttbar...

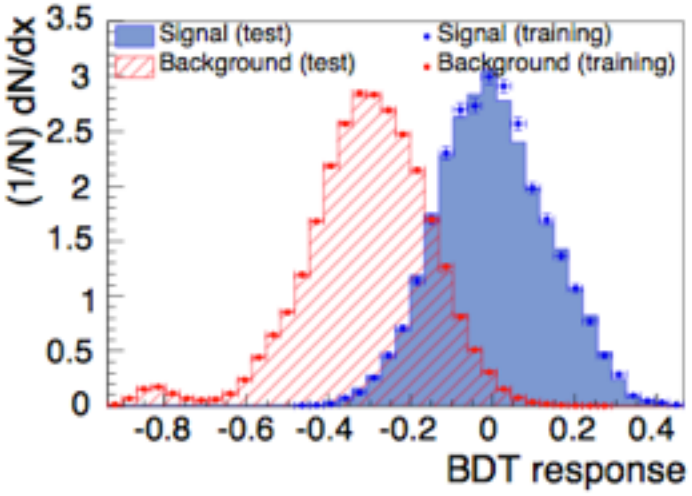
Process	σ_{initial} (fb)	σ_{basic} (fb)
$hh \to b\bar{b}\ell\nu jj$	2.34	0.134
$t\bar{t} \to b\bar{b}\ell\nu jj$	240×10^3	15.5
$W(\to \ell\nu)b\bar{b}$+jets	2.17×10^3	0.97
$W(\to \ell\nu)$+jets	2.636×10^6	$\mathcal{O}(0.01)$
$h(\to \ell\nu jj)$+jets	36.11	$\mathcal{O}(0.0001)$
$h(\to \ell\nu jj)b\bar{b}$	6.22	$\mathcal{O}(0.001)$
$h(\to b\bar{b}) + WW(\to \ell\nu jj)$	0.0252	-



(a) (b)

(c) (d)

BDT



For SM coupling

$$S/\sqrt{S+B} \sim 2.4 \qquad 3.1\sigma$$

with S=9 and B=6   after 600 ifb

Possible final states:

[Baur, Plehn, Rainwater]
[Dolan, Englert, MS]
[Papaefstathiou, Ferreira, MS]

$\bar{b}b\bar{b}b$:

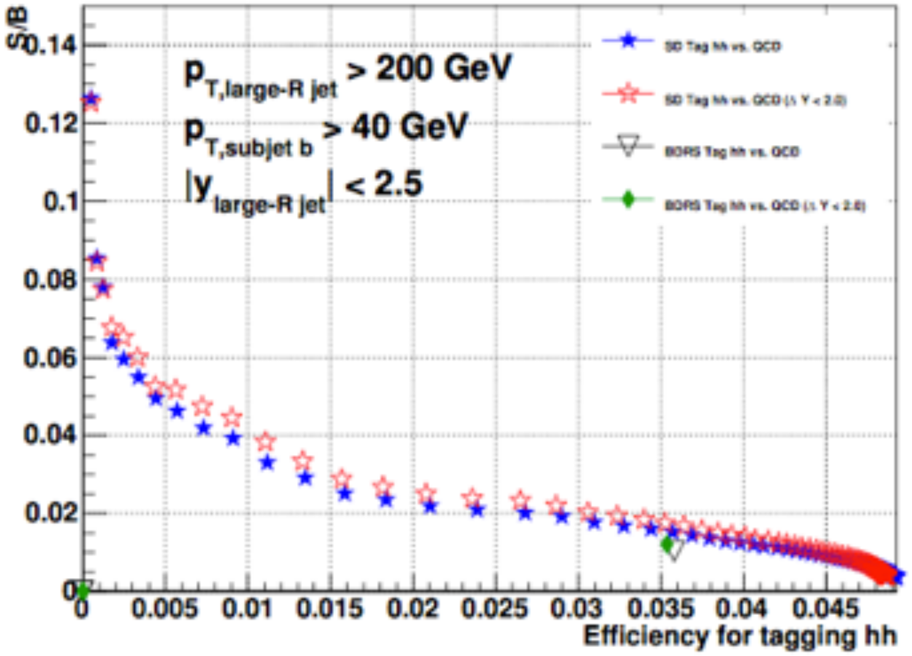
- Difficult to trigger (requires large pT cuts or fat jet)

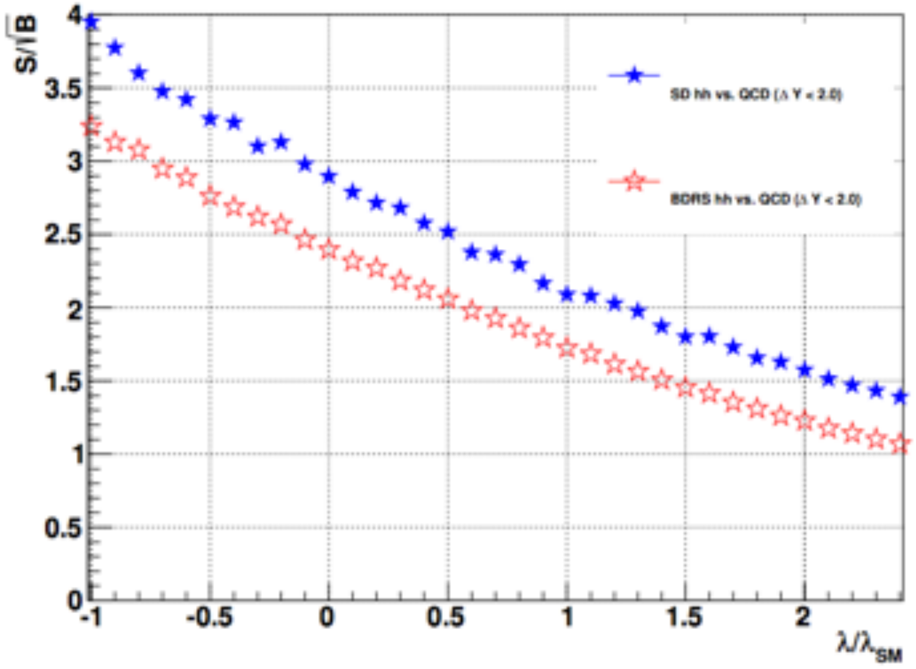
- Huge QCD backgrounds
- Can try to use jet substructure techniques to overcome large backgrounds

- Maybe sideband possible?

- After reconstruction and 3000 ifb:

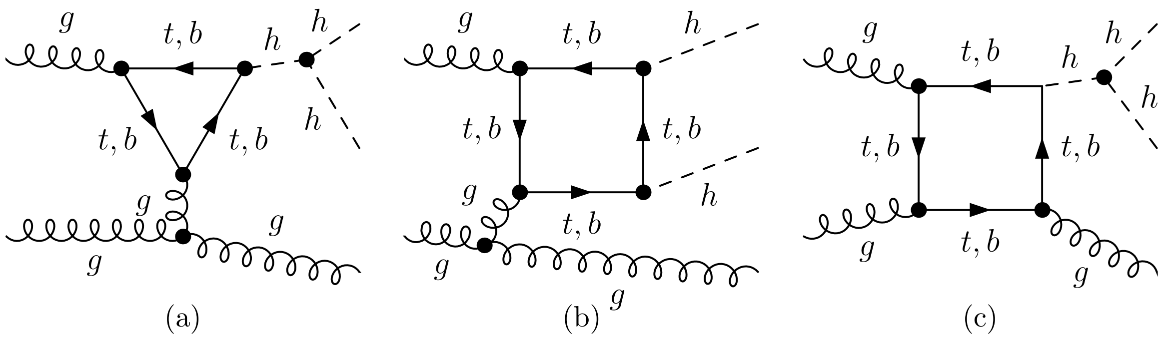
sample	σ_{initial} (fb)
$hh,\ h \to b\bar{b}$ (SM)	10.7
QCD $(b\bar{b})(b\bar{b})$	151.1×10^3
$Zb\bar{b},\ Z \to b\bar{b}$	8.8×10^3
$hZ,\ h \to b\bar{b},\ Z \to b\bar{b}$	70.0
$hW,\ h \to b\bar{b},\ W \to c\bar{b}(\bar{c}b)$	96.4

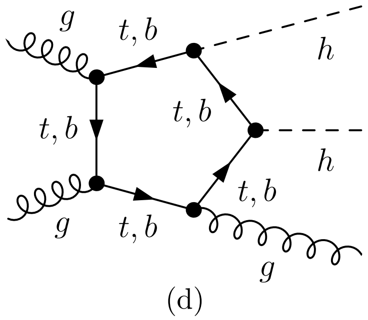




More jets more fun

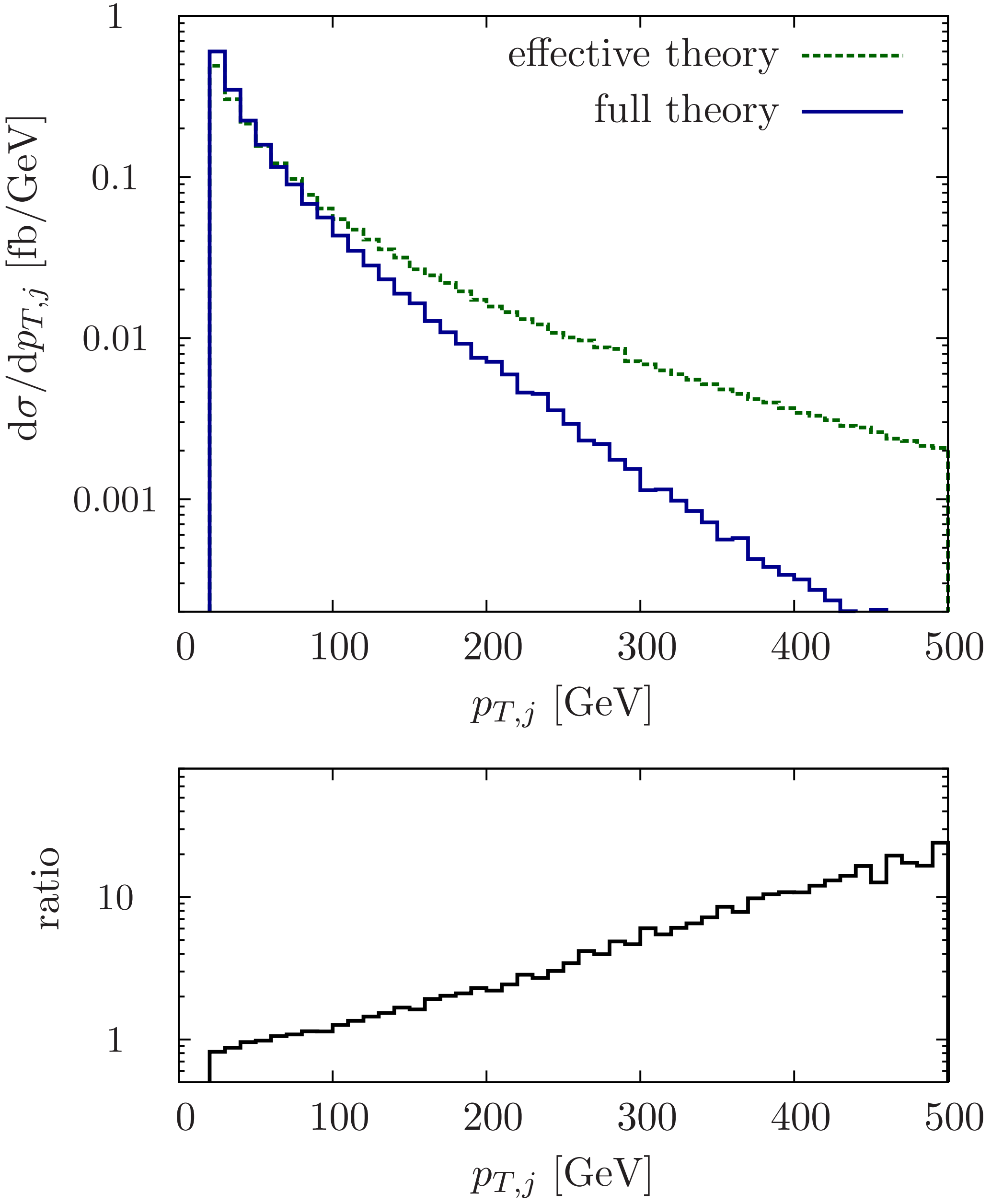
- need to work a little harder



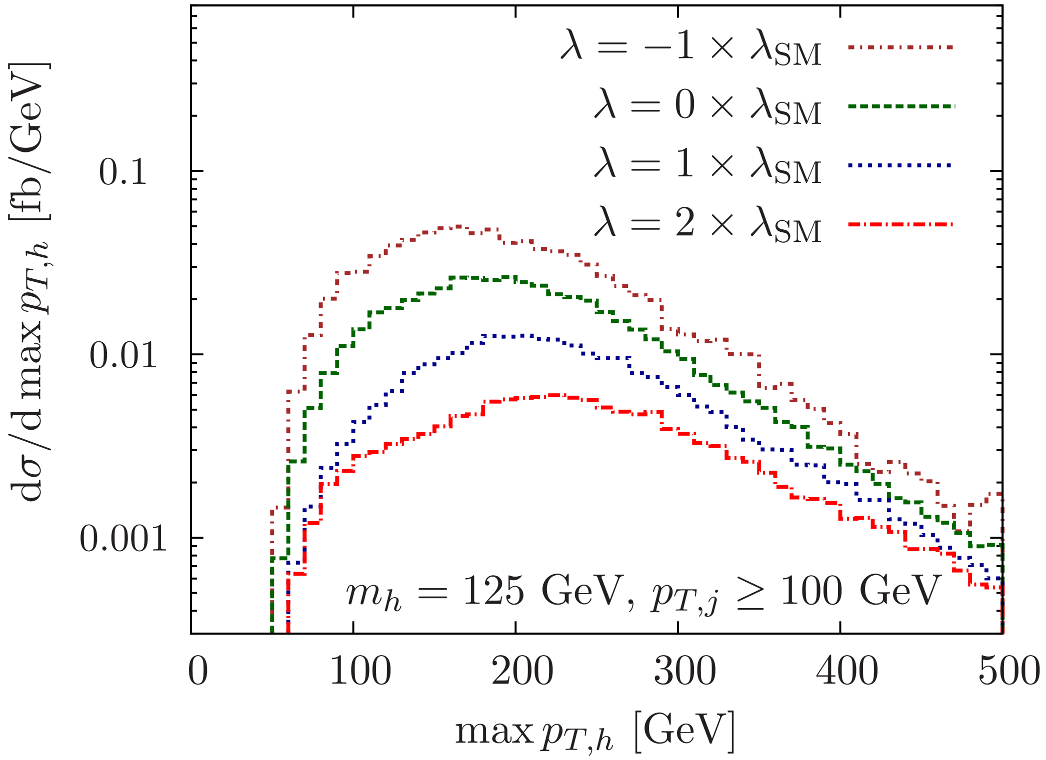


+ quark & gluon induced

Eff. theory breaks down quickly



retain sensitivity for boosted Higgs



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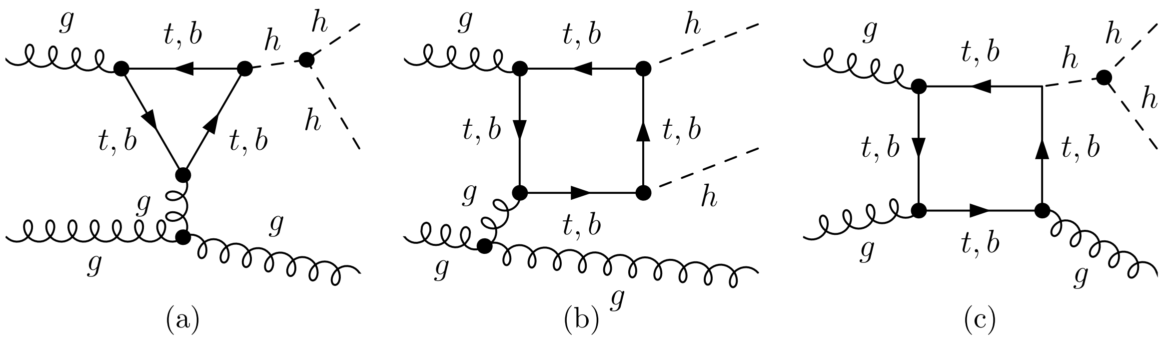

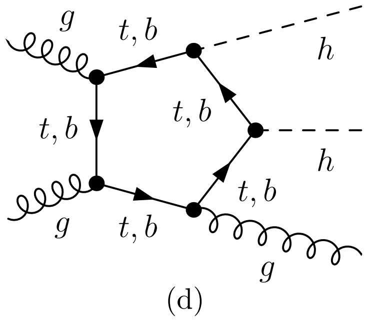

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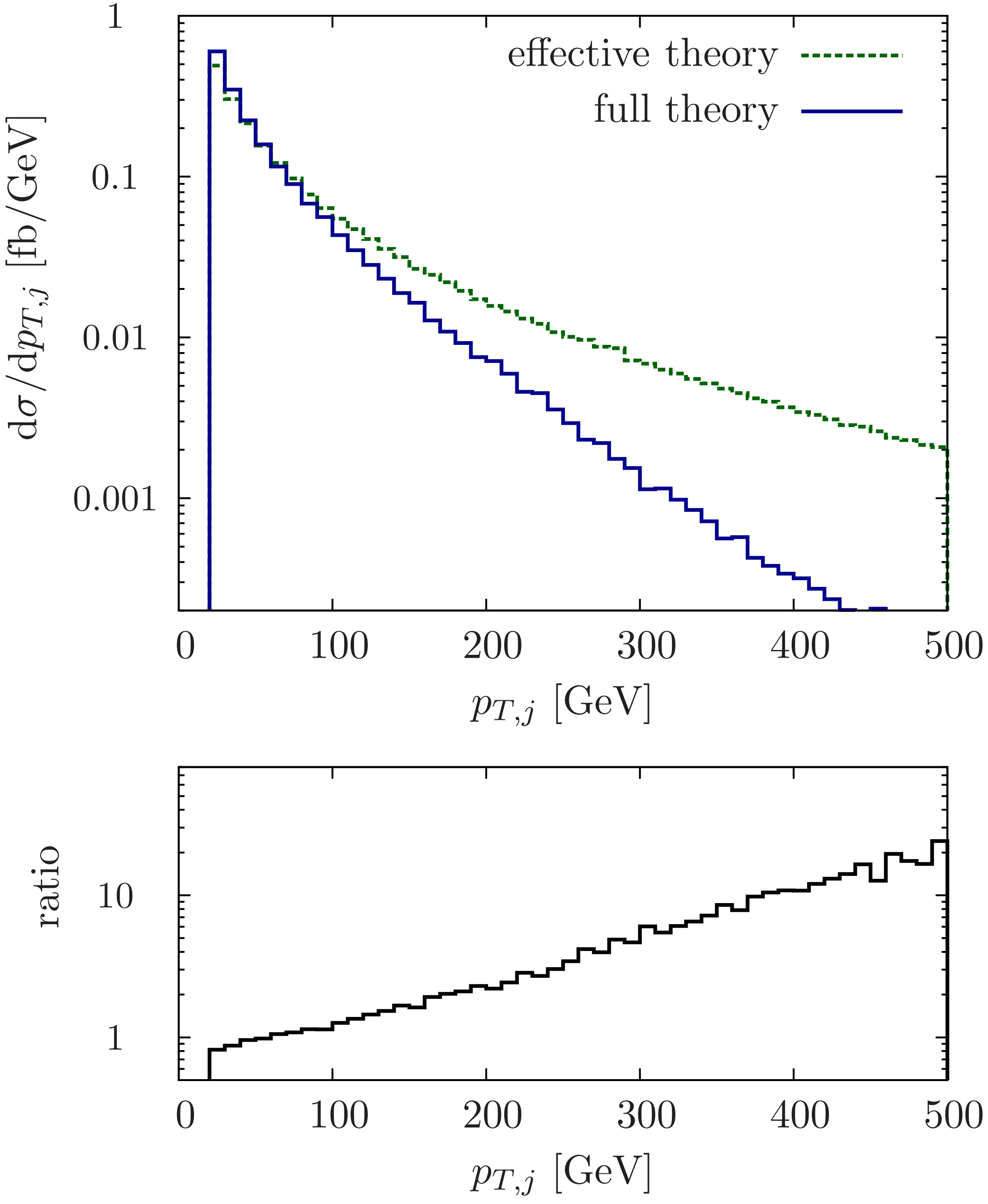

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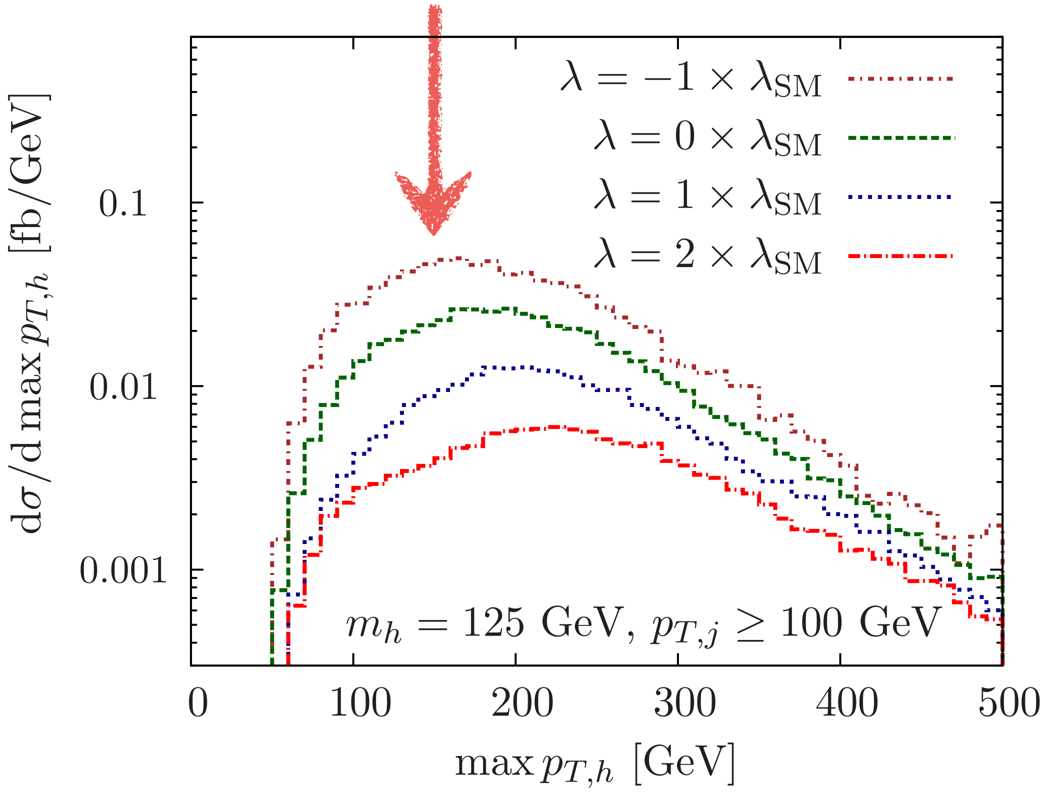


Higgs selfcoupling in HHj+X

- Additional jet ameliorates $1/m_{hh}^2$ suppression
- Jet adds handle to suppress backgrounds -> improvement S/B
- But cross section very small

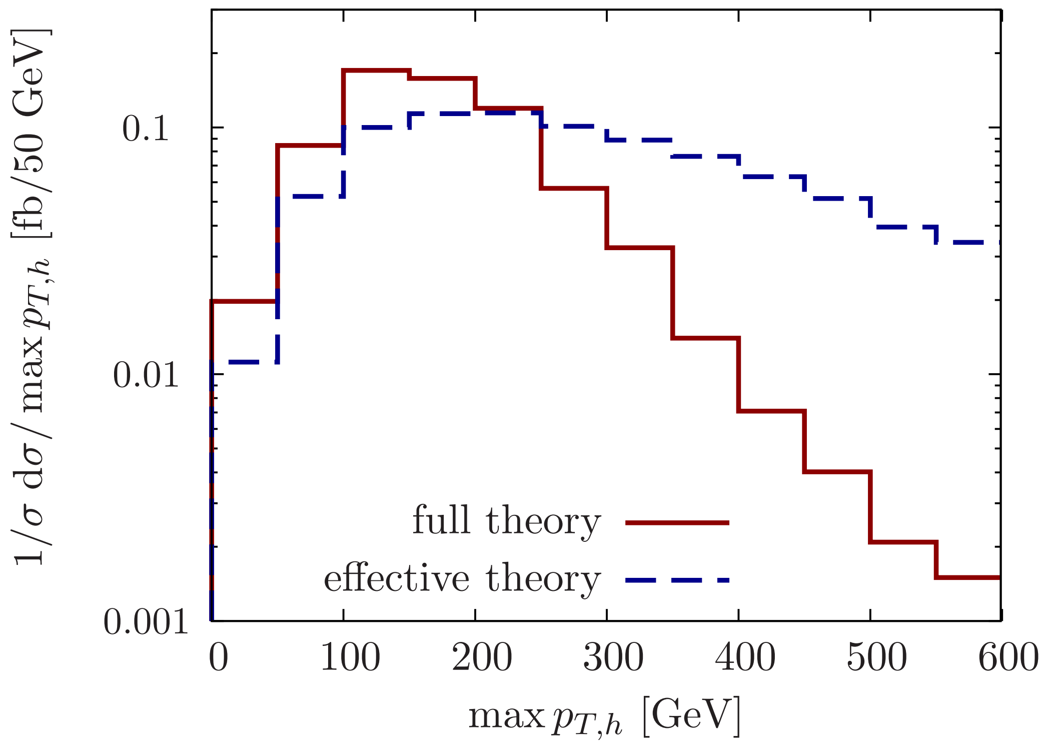
$b\bar{b}\tau^+\tau^-$ (assuming small tau fake rate)

	$\xi = 0$	$\xi = 1$	$\xi = 2$	$b\bar{b}\tau\tau$	$b\bar{b}\tau\tau$ [ELW]	$b\bar{b}W^+W^-$	ratio to $\xi = 1$
cross section before cuts	59.48	28.34	13.36	67.48	8.73	873000	$3.2 \cdot 10^{-5}$
reconstructed Higgs from τs	4.05	1.94	0.91	2.51	1.10	1507.99	$1.9 \cdot 10^{-3}$
fatjet cuts	2.27	1.09	0.65	1.29	0.84	223.21	$4.8 \cdot 10^{-3}$
kinematic Higgs reconstruction ($m_{b\bar{b}}$)	0.41	0.26	0.15	0.104	0.047	9.50	$2.3 \cdot 10^{-2}$
Higgs with double b-tag	0.148	0.095	0.053	0.028	0.020	0.15	0.48

$\bar{b}b\tau^+\tau^- j$ (assuming small tau fake rate)

	$\xi = 0$	$\xi = 1$	$\xi = 2$	$b\bar{b}\tau^+\tau^- j$	$b\bar{b}\tau^+\tau^- j$ [ELW]	$t\bar{t}j$	ratio to $\xi = 1$
cross section before cuts	6.45	3.24	1.81	66.0	1.67	106.7	$1.9 \cdot 10^{-2}$
2 τs	0.44	0.22	0.12	37.0	0.94	7.44	$4.8 \cdot 10^{-3}$
Higgs rec. from taus + fatjet cuts	0.29	0.16	0.10	2.00	0.150	0.947	$5.1 \cdot 10^{-2}$
kinematic Higgs rec.	0.07	0.04	0.02	0.042	0.018	0.093	0.26
$2b$ + hh invariant mass + $p_{T,j}$ cut	0.010	0.006	0.004	<0.0001	0.0022	0.0014	1.54

Higgs selfcoupling in HHjj+X



- Test for long. gauge boson scattering
- For kinematic distributions full loop recommended
- Gluon fusion dominating over WBF
- Analysis in $\bar{b}b\tau^+\tau^-$

So far very rudimentary analysis:

	Signal with $\xi \times \lambda$			Background		S/B
	$\xi = 0$	$\xi = 1$	$\xi = 2$	$t\bar{t}jj$	Other BG	ratio to $\xi = 1$
tau selection cuts	0.212	0.091	0.100	3101.0	57.06	0.026×10^{-3}
Higgs rec. from taus	0.212	0.091	0.100	683.5	31.92	0.115×10^{-3}
Higgs rec. from b jets	0.041	0.016	0.017	7.444	0.303	1.82×10^{-3}
2 tag jets	0.024	0.010	0.012	5.284	0.236	1.65×10^{-3}
incl. GF after cuts/re-weighting	0.181	0.099	0.067	5.284	0.236	1/61.76

Very bad S/B, but can be improved a lot...

New Physics in HH

Resonant enhancement

see also [Chen et al. 1312.7212]

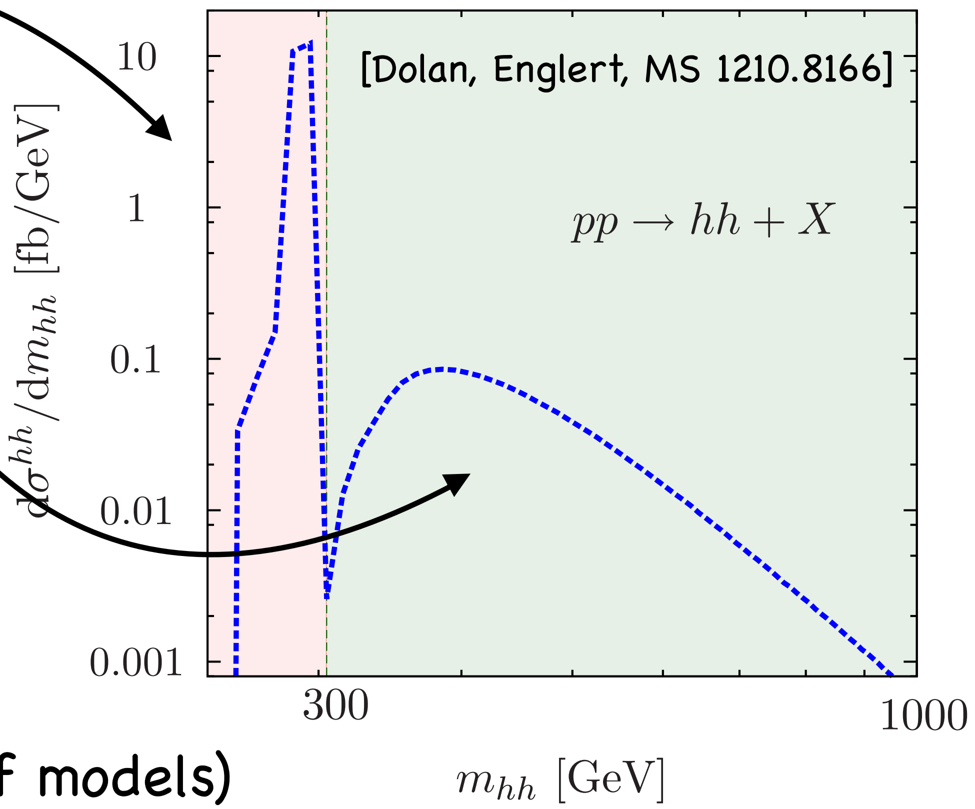
- SUSY, H -> hh

  Measurement of rel. CS Hhh and hhh translates directly to measurement of α and β

$$\lambda_{hhh} = 3\cos 2\alpha\,\sin(\beta+\alpha)$$
$$\lambda_{Hhh} = 2\sin 2\alpha\,\sin(\beta+\alpha) - \cos 2\alpha\,\cos(\beta+\alpha)$$
$$\lambda_{HHh} = -2\sin 2\alpha\,\cos(\beta+\alpha) - \cos 2\alpha\,\sin(\beta+\alpha)$$

(same in Higgs portal type of models)

Assuming decoupling limit such that MH > 2 Mh and BR(H->hh) = 45%

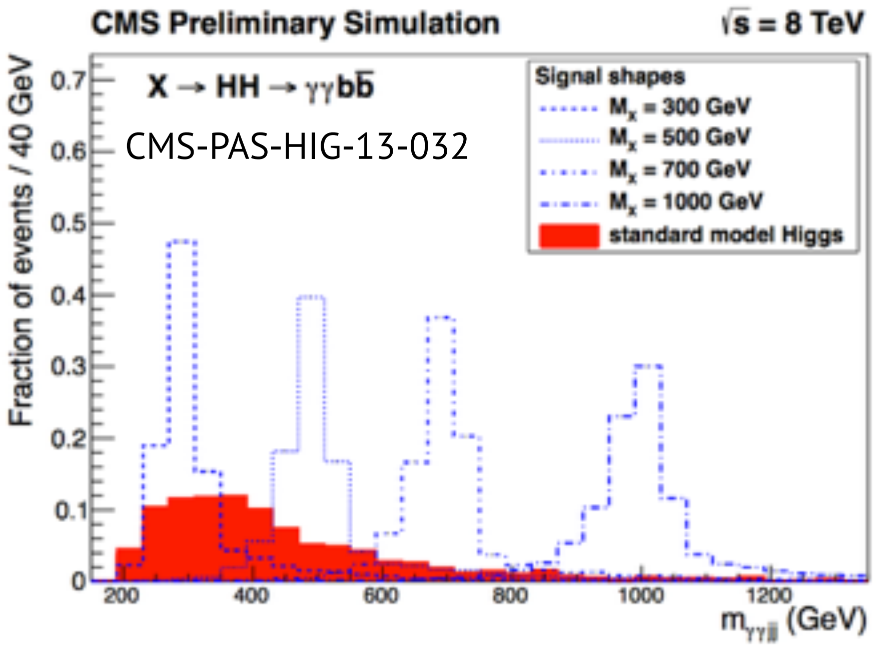

[Dolan, Englert, MS 1210.8166]

- E-dim, G -> hh -> 4b

  see [Gouzevitch et al. 1303.6636]

- Higgs portal

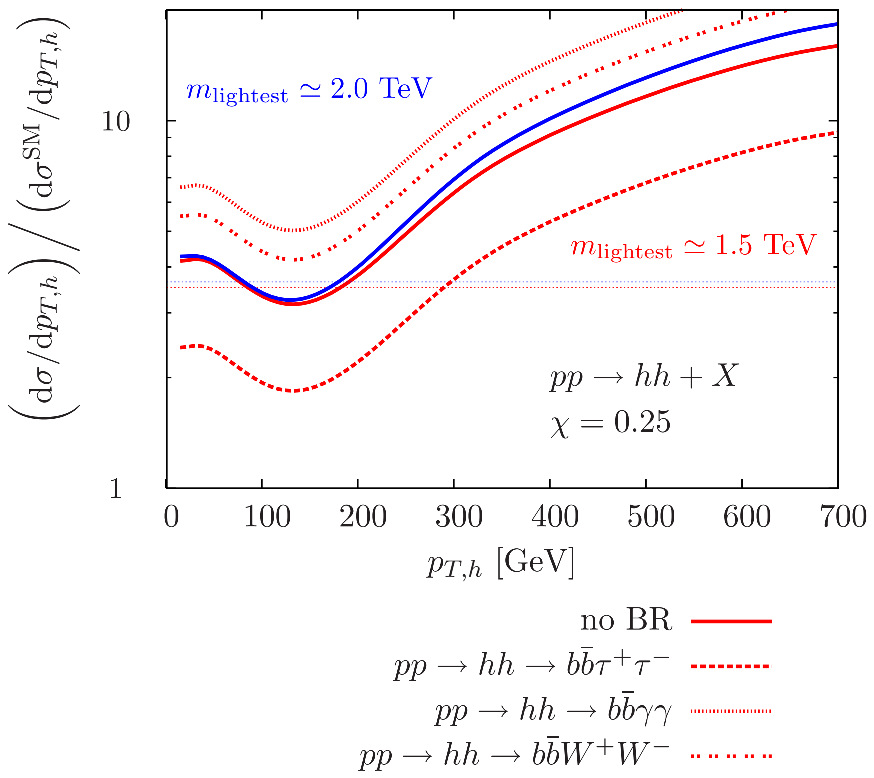
  see [No, Ramsey-Musolf 1310.6035]

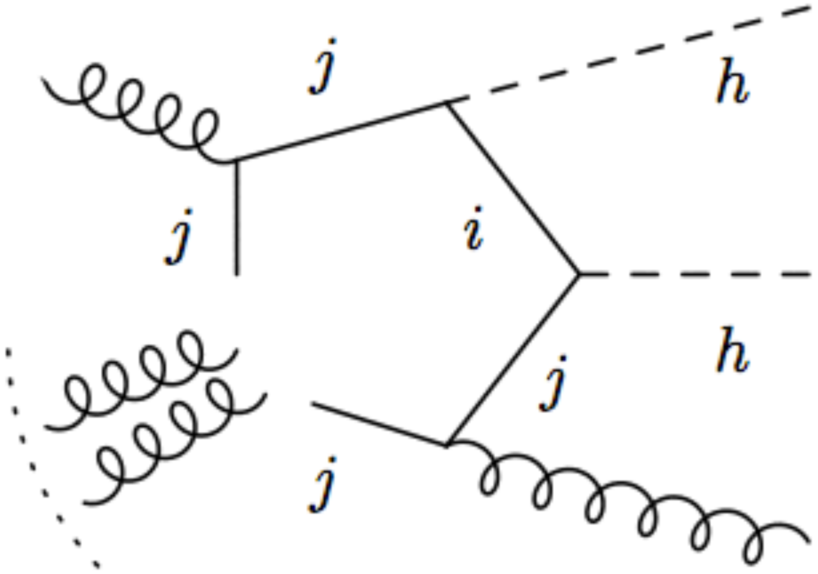

CMS-PAS-HIG-13-032

New Physics in HH

Continuous/Loop enhancement

- Composite Higgs
- 4th generation
  see [Kribs, Plehn, Tait, MS 0706.3718]
- Other theories modifying $hh\bar{t}_i t_j$ or $h\bar{t}_i t_j$



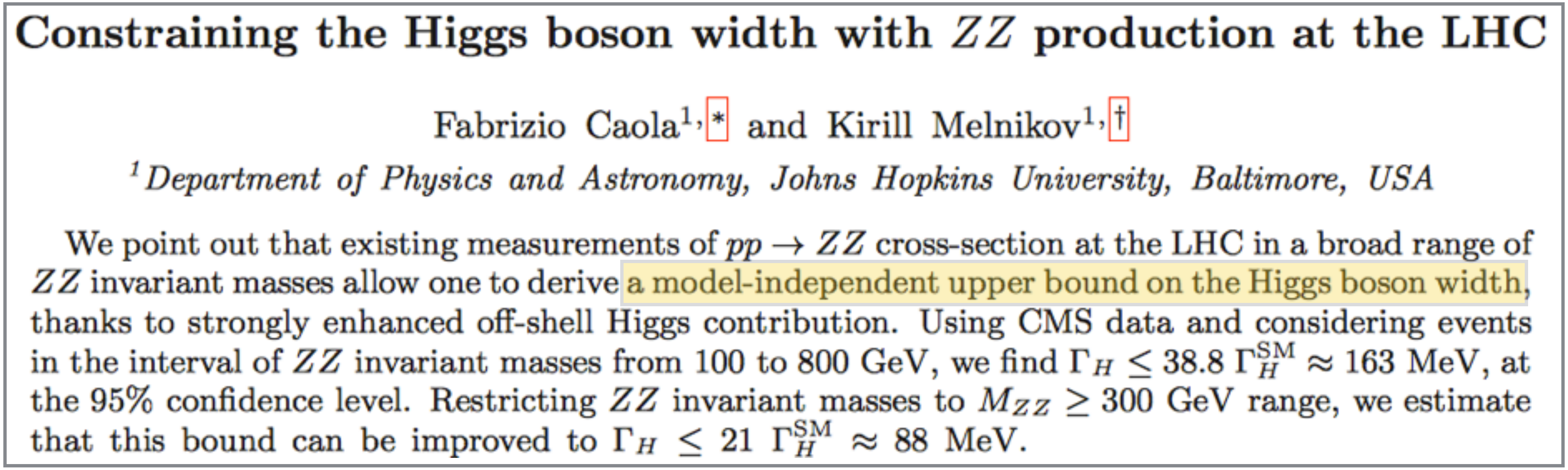


Usually high-pT region enhanced over SM

A portal to the Higgs width?

New idea how to constrain Higgs width at hadron colliders:

[Caola, Melnikov PRD 88]



Constraining the Higgs boson width with ZZ production at the LHC

Fabrizio Caola[1,*] and Kirill Melnikov[1,†]

[1] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA*

We point out that existing measurements of $pp \to ZZ$ cross-section at the LHC in a broad range of ZZ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of ZZ invariant masses from 100 to 800 GeV, we find $\Gamma_H \leq 38.8\ \Gamma_H^{\rm SM} \approx 163$ MeV, at the 95% confidence level. Restricting ZZ invariant masses to $M_{ZZ} \geq 300$ GeV range, we estimate that this bound can be improved to $\Gamma_H \leq 21\ \Gamma_H^{\rm SM} \approx 88$ MeV.

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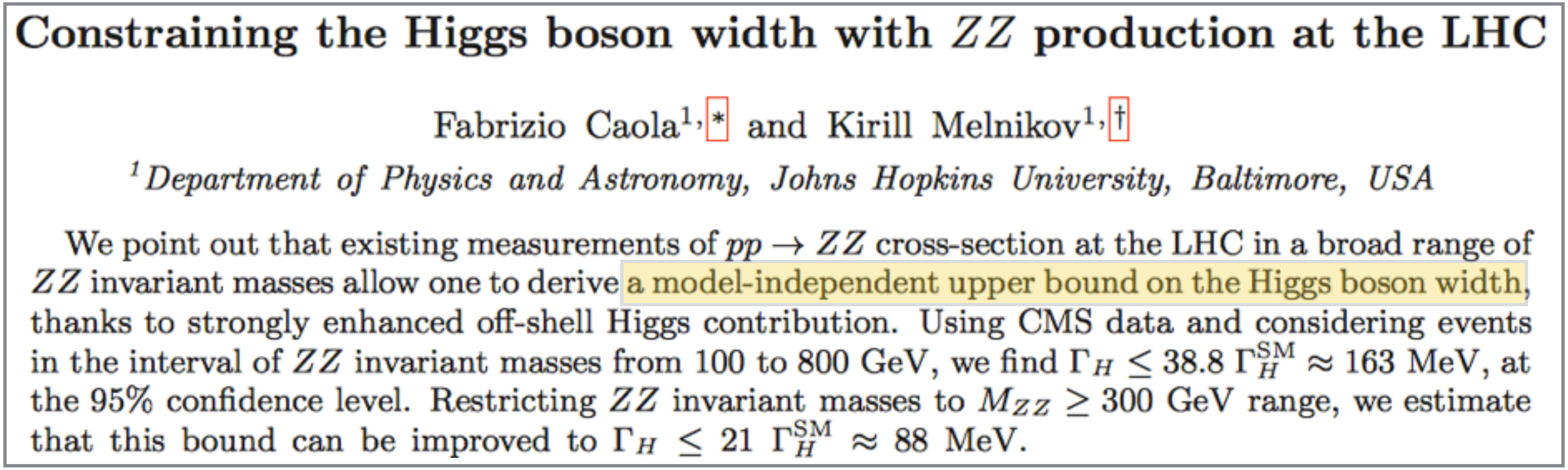

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Measurement done in CMS-PAS-HIG-14-002 and presented at Moriond ‘14
ATLAS is working to perform same measurement

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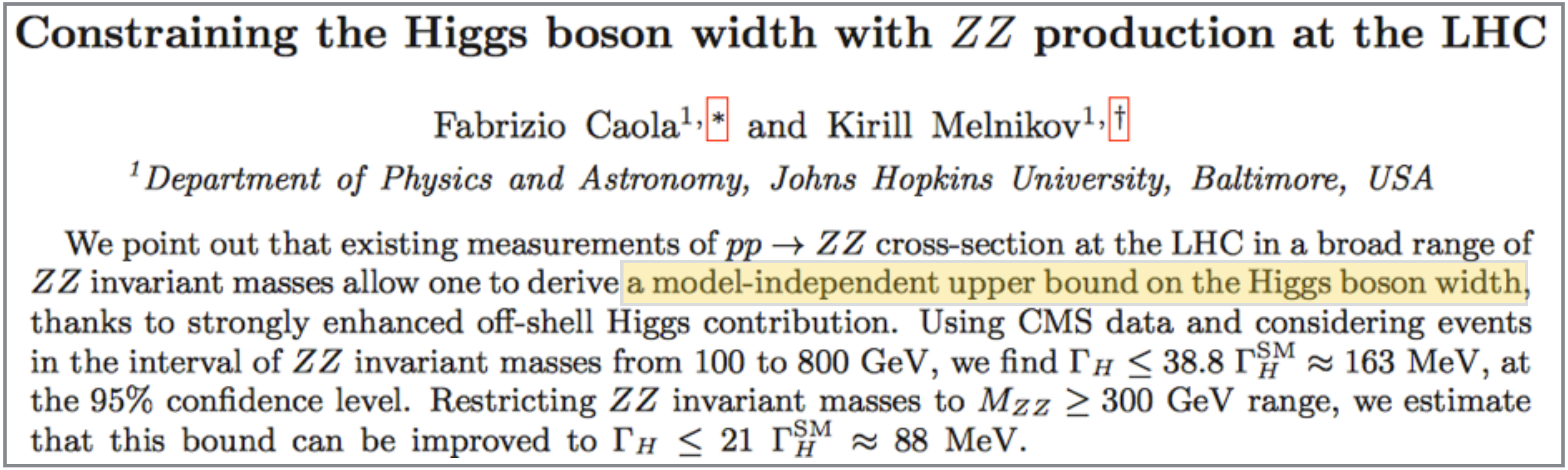

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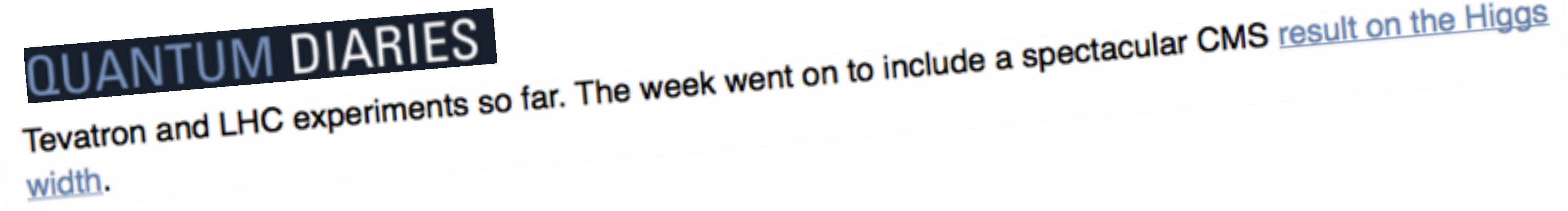

QUANTUM DIARIES

Tevatron and LHC experiments so far. The week went on to include a spectacular CMS result on the Higgs width.

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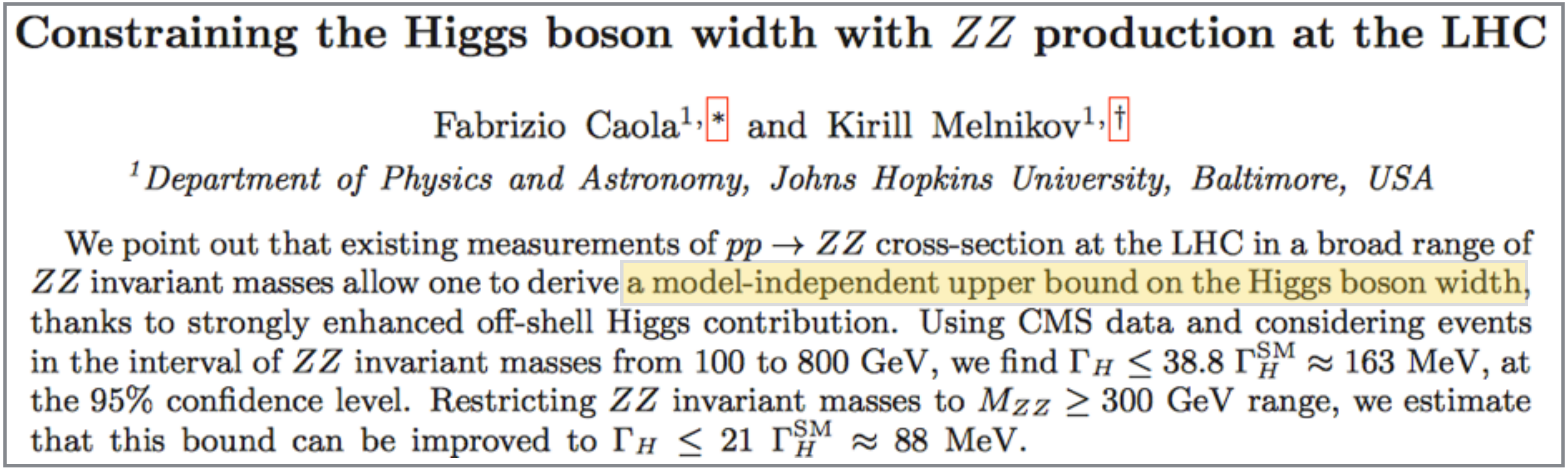

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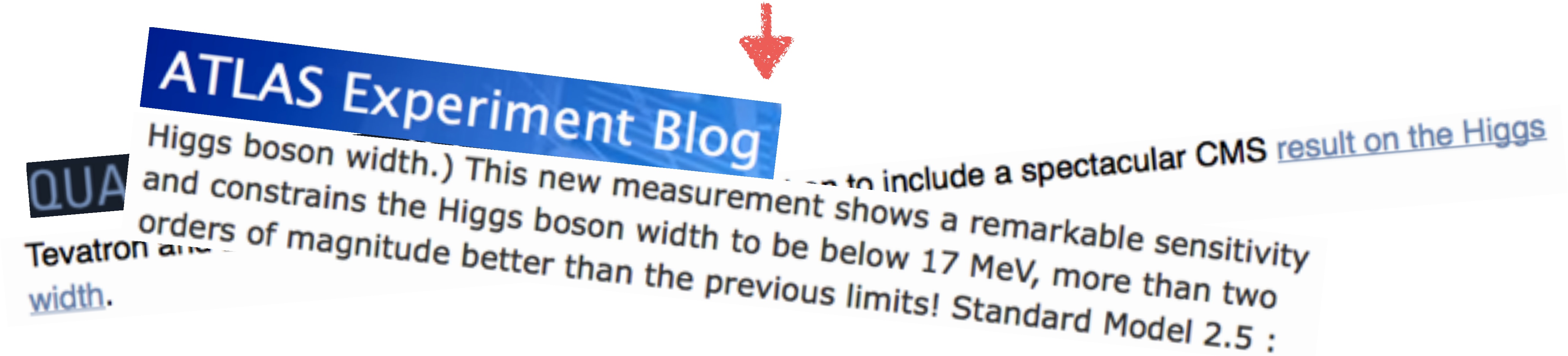

ATLAS Experiment Blog

Higgs boson width.) This new measurement shows a remarkable sensitivity and constrains the Higgs boson width to be below 17 MeV, more than two orders of magnitude better than the previous limits! Standard Model 2.5 :

QUA

to include a spectacular CMS result on the Higgs

Tevatron an

width.

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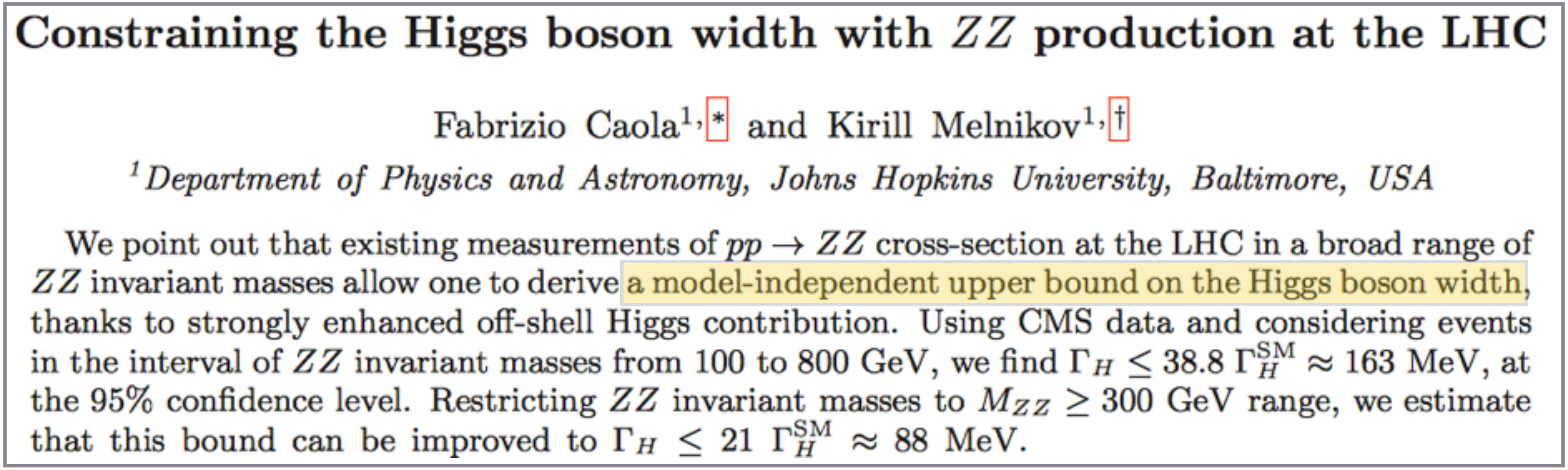

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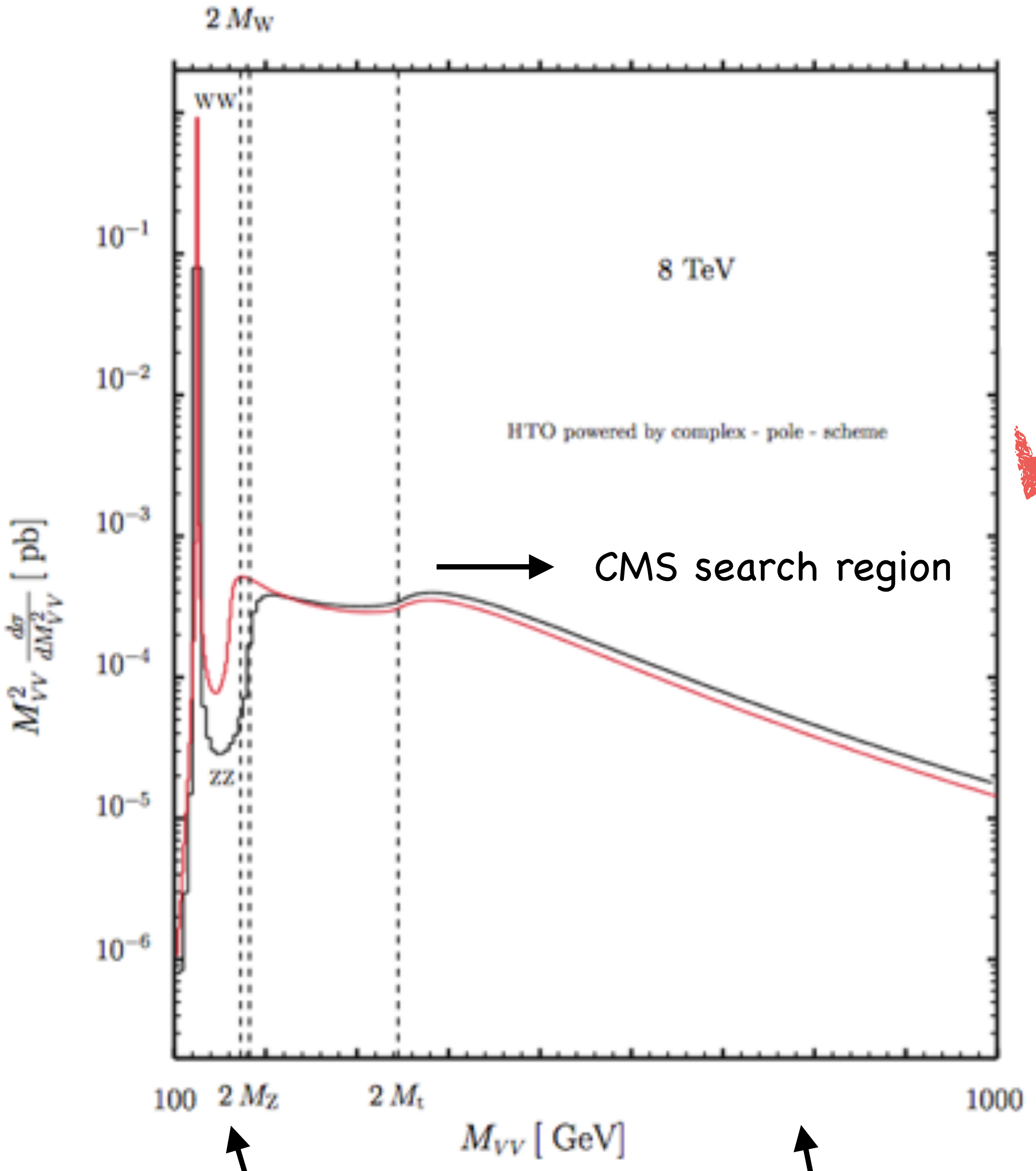
ATLAS is working to perform same measurement

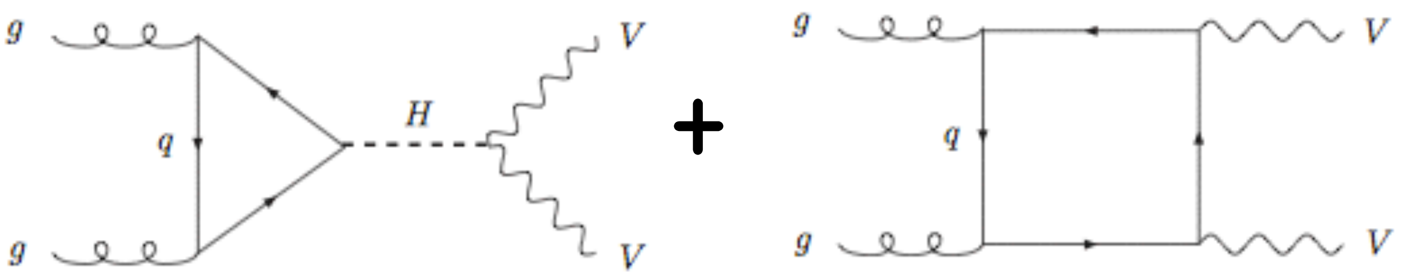
How wide is a Higgs?

In accord with Heisenberg's uncertainty principle, short-lived particles have uncertain mass. So the Higgs boson, which gives mass to other particles, is uncertain about its own mass. New results from the CMS experiment at the CERN LHC have started to tell us how uncertain

CMS Measurement



→ CMS search region



- measure $g^2_{ggH}g^2_{HZZ}$ off-peak using angular correlations of 4l decay products
- use in on-peak relation to measure width after fixing signal strength

$$\mu_{i,j} = \sigma_{h,i} \times \mathrm{BR}_j \sim \frac{\Gamma_i \Gamma_j}{\Gamma_h}$$

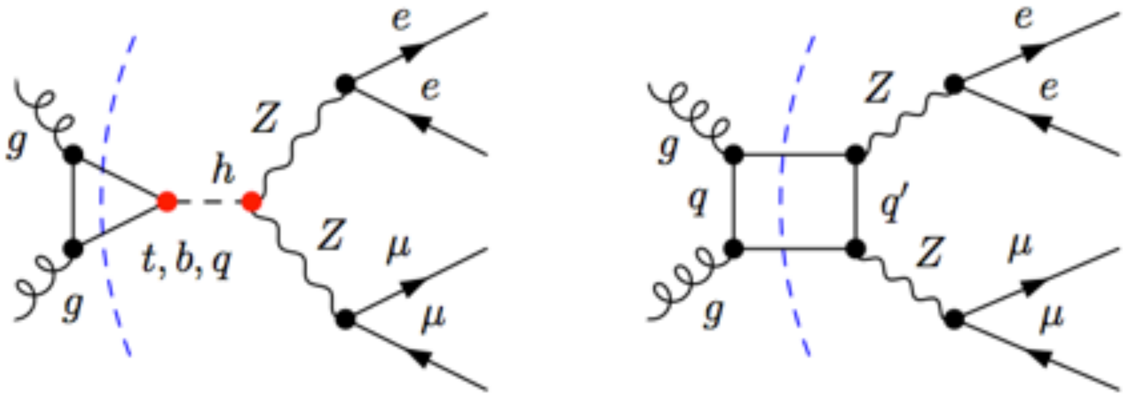
$$\sigma^{\mathrm{on-peak}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}$$

$$\sigma^{\mathrm{off-peak}}_{gg\to H\to ZZ} \sim g^2_{ggH}g^2_{HZZ}$$

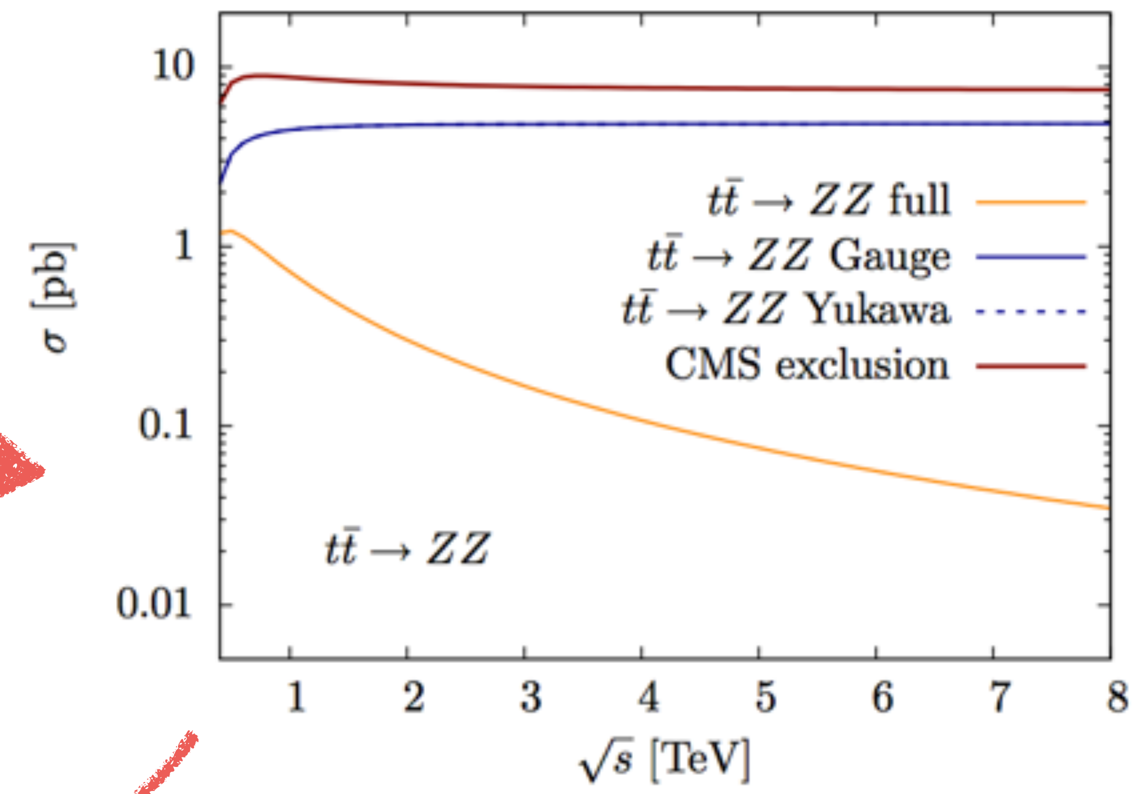
Obs.(exp.) @95% C.L:
$\Gamma_H <$ 4.2(8.5) Γ_H^{SM}
$\Gamma_H <$ 17.4 (35.3) MeV

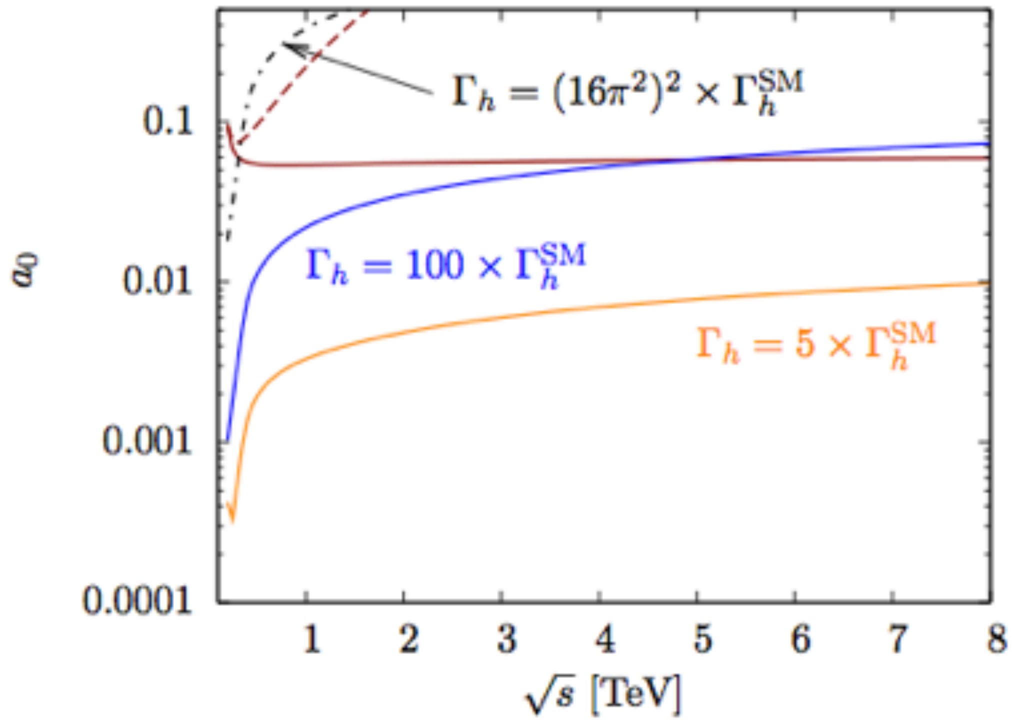
[Englert, MS] (submitted)

1. Is measurement well defined?



modifying couplings violates unitarity
of fermion-gauge interactions





while CMS test-hypotheses
certainly ill-defined
not killer at accessible energies

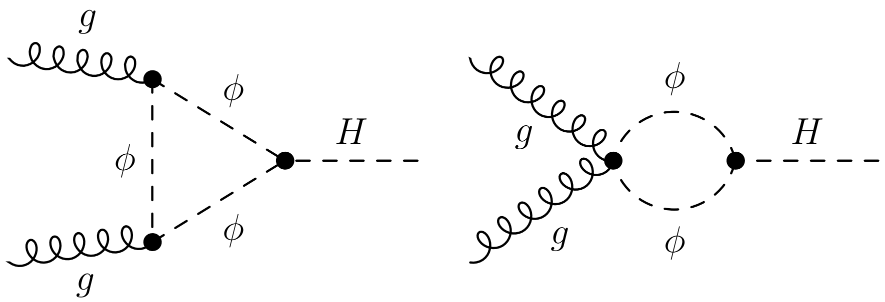
2. But how model independent is constraint? [Englert, MS] (submitted)

We have seen SM on-shell and off-shell region intimately related by unitarity requirements for fermion-gauge interactions

Direct correlation of on-shell $g_{ggh}^2\, g_{hZZ}^2$ and off-shell $g_{ggh}^2(\sqrt{s})\, g_{hZZ}^2(\sqrt{s})$

necessary ingredient for width measurement -> can be broken by BSM effects

Consider Higgs-portal (toy) model: $\mathcal{L}_\phi = |D_\mu\phi|^2 - \tilde{m}_\phi^2|\phi|^2 - \lambda|\phi|^2|H|^2 + \ldots\,.$



where ϕ scalar only charged under $\mathrm{SU}(3)_C$

$m_\phi^2 = \tilde{m}_\phi^2 + \lambda v^2$ free parameter

off-shell CS

m_ϕ	μ (h peak)	$\Gamma_h/\Gamma_h^{\mathrm{SM}}$	$\bar{\sigma}/\bar{\sigma}^{\mathrm{SM}}$ $[m(4\ell) \geq 330$ GeV$]^a$
70 GeV	$\simeq 1.0$	$\simeq 5$	-2%
170 GeV	$\simeq 1.0$	$\simeq 4.7$	$+80\%$
170 GeV	$\simeq 1.0$	$\simeq 1.7$	$+6\%$

[a] We impose the cut set used by CMS [17] without the Mela cut [34].

$g_{ggh}(m_h) > g_{ggh,\mathrm{SM}} \longrightarrow \Gamma > \Gamma_{\mathrm{SM}}$ for $\mu \sim 1$

Despite increased on-shell coupling (and Higgs width) negligible contribution in off-shell region

Note, shown here only simplest toy model

Summary

- Increasing interest and wide efforts in HH final state
- Might be possible to measure coupling at LHC 14 TeV
  -> a combination of all accessible final states will be necessary
- Still final states and reconstructions difficult to simulate:
  (ir)reducible backgrounds, taus, bs, photons

  Experimentalists → Need finally solid analyses
- Very few HH+(jets) samples: full loop, BSM

  Theorists → Need flexible MC

……

- Higgs width measurement extremely nice idea but not quite model independent (task for ILC)
- But off-shell measurement still important:
  - New Physics constraints
  - CP Higgs
  - ....