PERSPECTIVES ON HIGGS PHYSICS

CHRISTOPH ENGLERT

PPT Seminar
Edinburgh, 24.10.2012

OUTLINE

- A tell-tale story of Higgs physics
- Higgs boson couplings
- Higgs boson spin & CP
- Higgs boson self-interactions

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- Higgs boson self-interactions

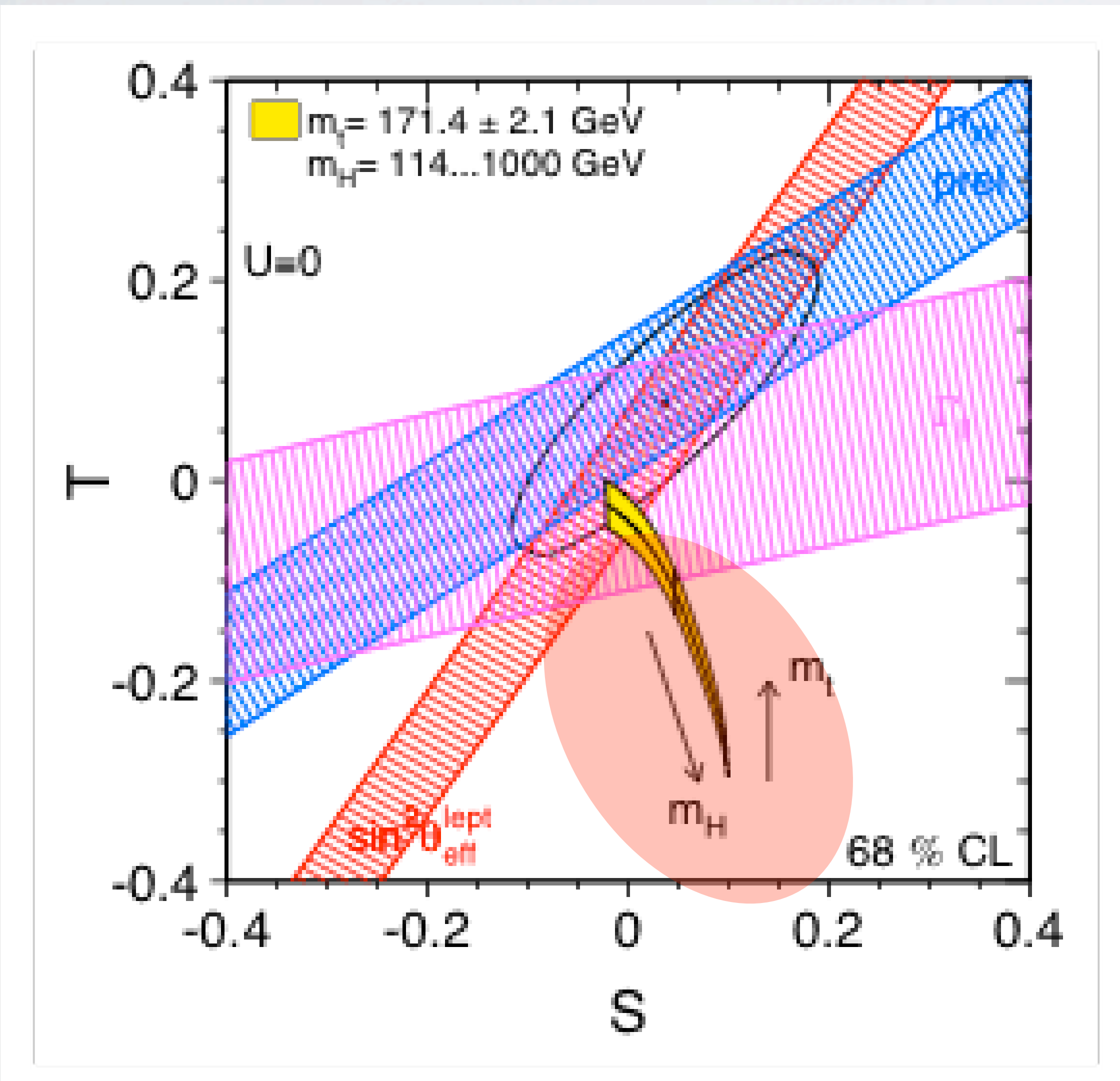
A tell-tale story of the light Higgs boson

- well-defined massive gauge bosons $\Longleftrightarrow$ spontaneous symmetry breaking

[Heisenberg `28]
⋮
[Higgs `64] [Brout, Englert `64]
[Guralnik, Hagen, Kibble `64]
[Cornwall, Levin, Tiktopoulos `75]

- LEP/Tevatron upshot (electroweak precision)

[LEP Tevatron Higgs WG `06]



$\Lambda \sim m_W$:

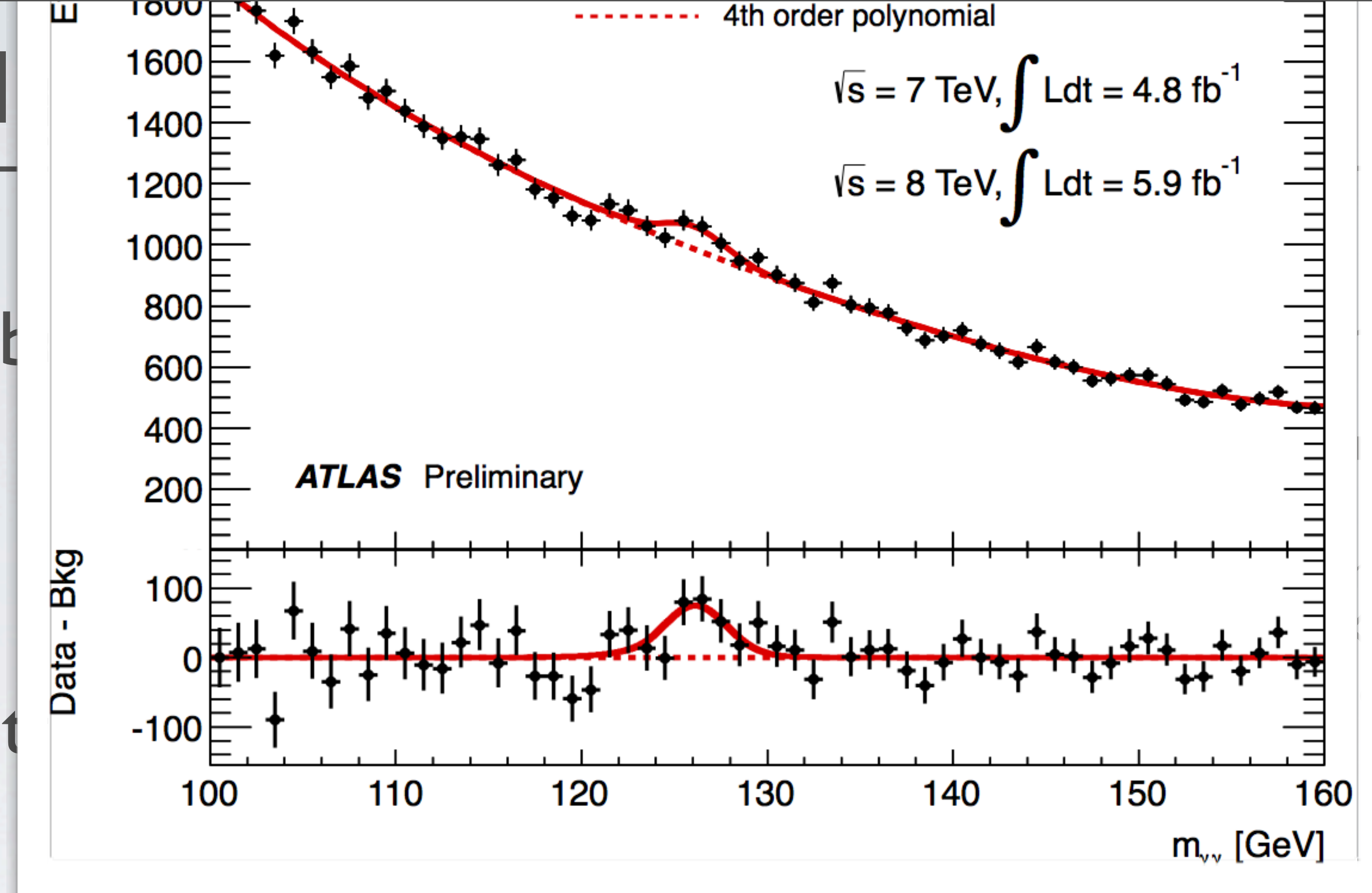
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\xrightarrow{?} SU(3)_C \times U(1)_Q$$

$$W_L^{\pm}, Z_L \sim [SU(2)_L \times U(1)_Y]/U(1)_Q$$

$+$ light scalar

- SM Higgs field ~ $(1,2)_{1/2}$ implements EWSB in the most economic way

A tell-tale story of the l



- well-defined massive gauge b ... g

berg `28]

glert `64]

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- LEP/Tevatron upshot (elect

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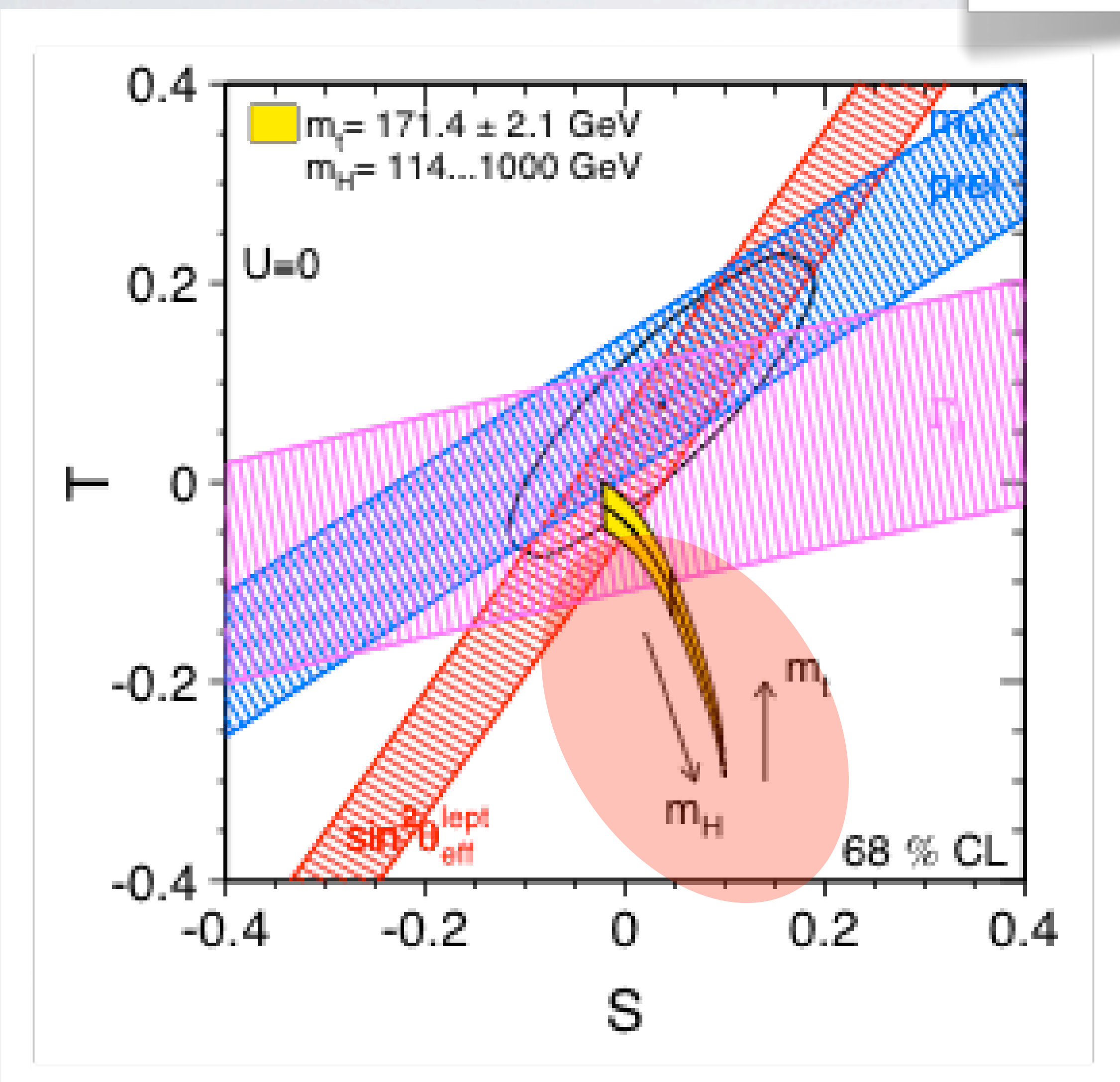

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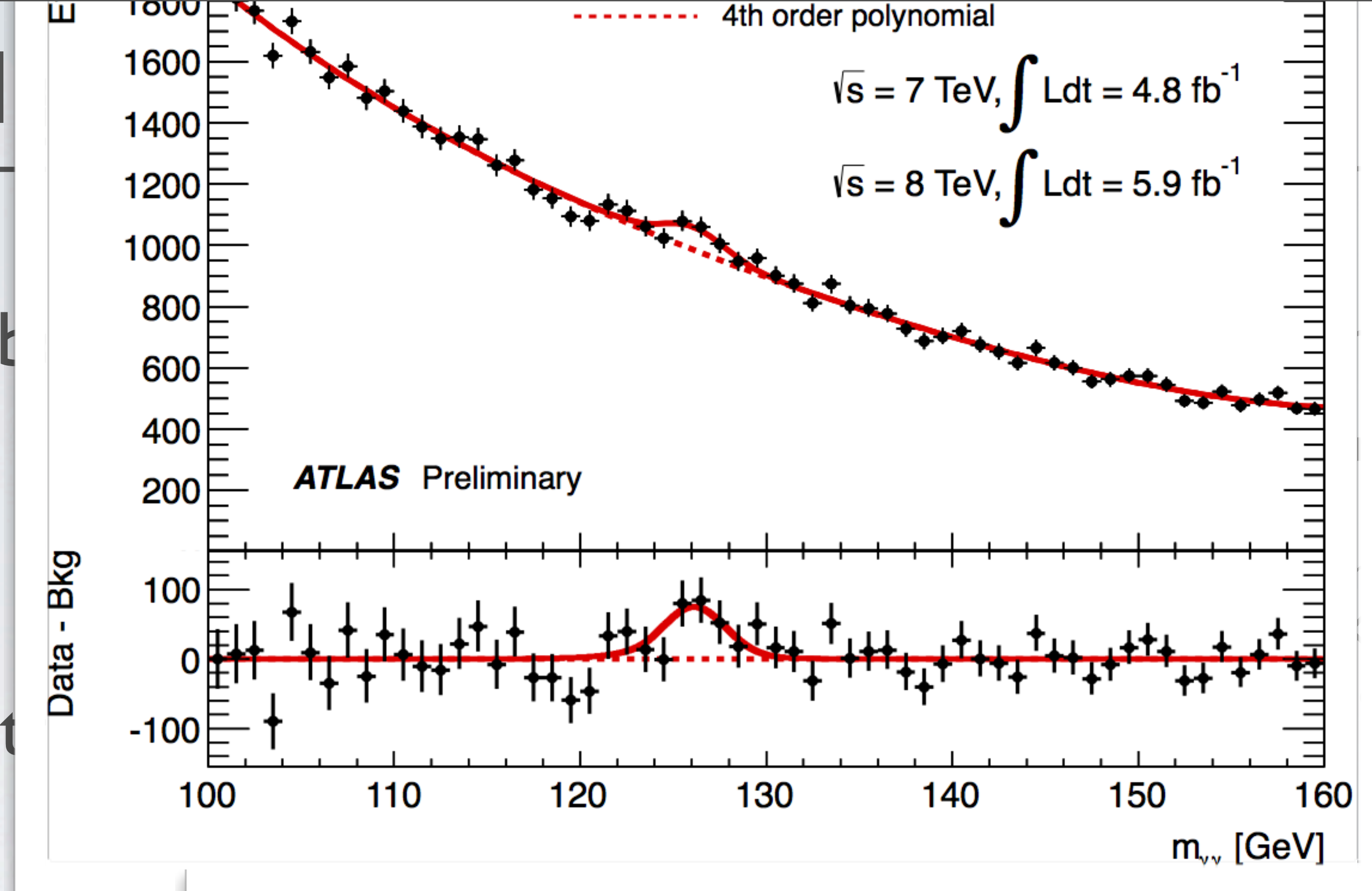

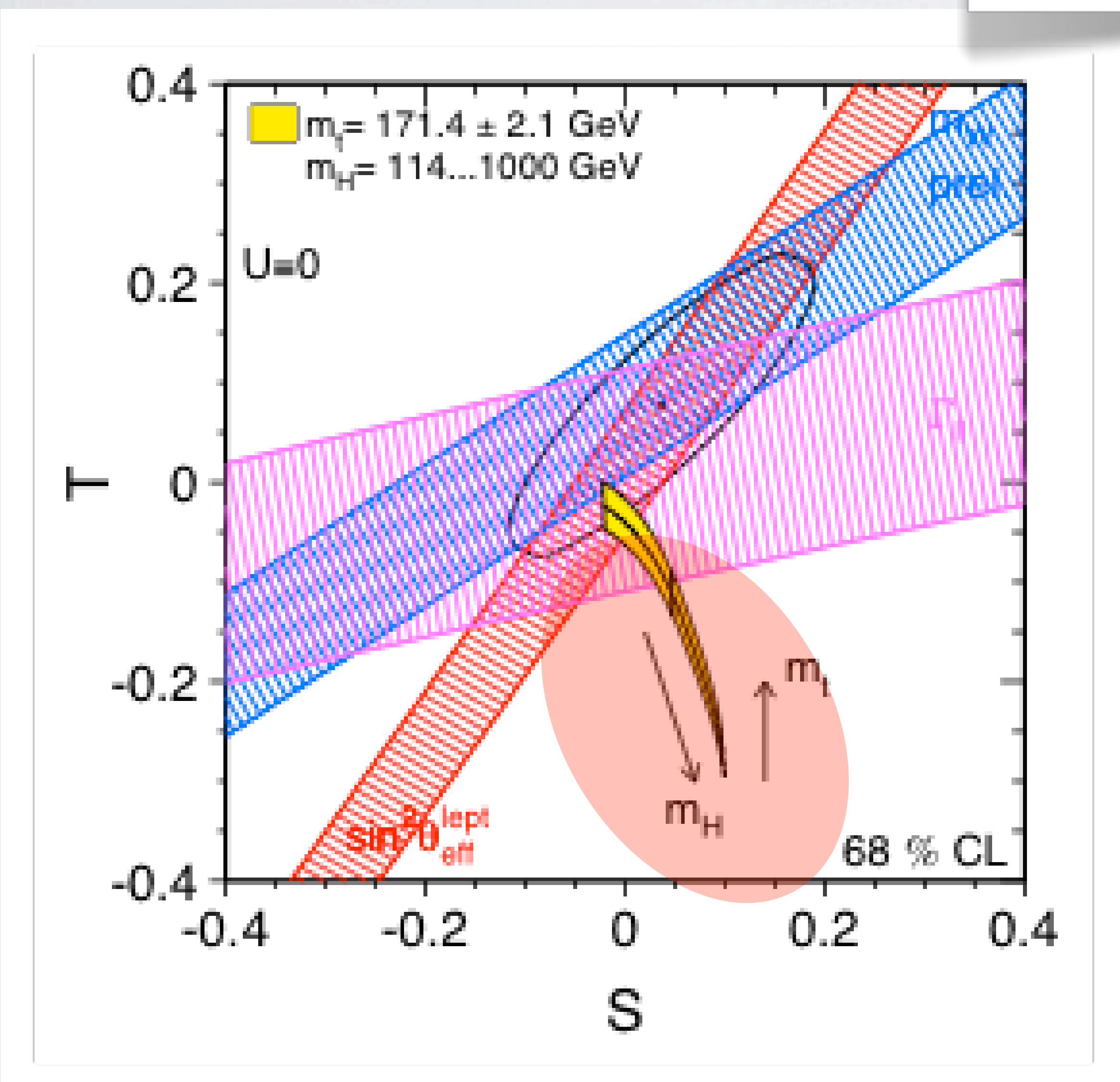

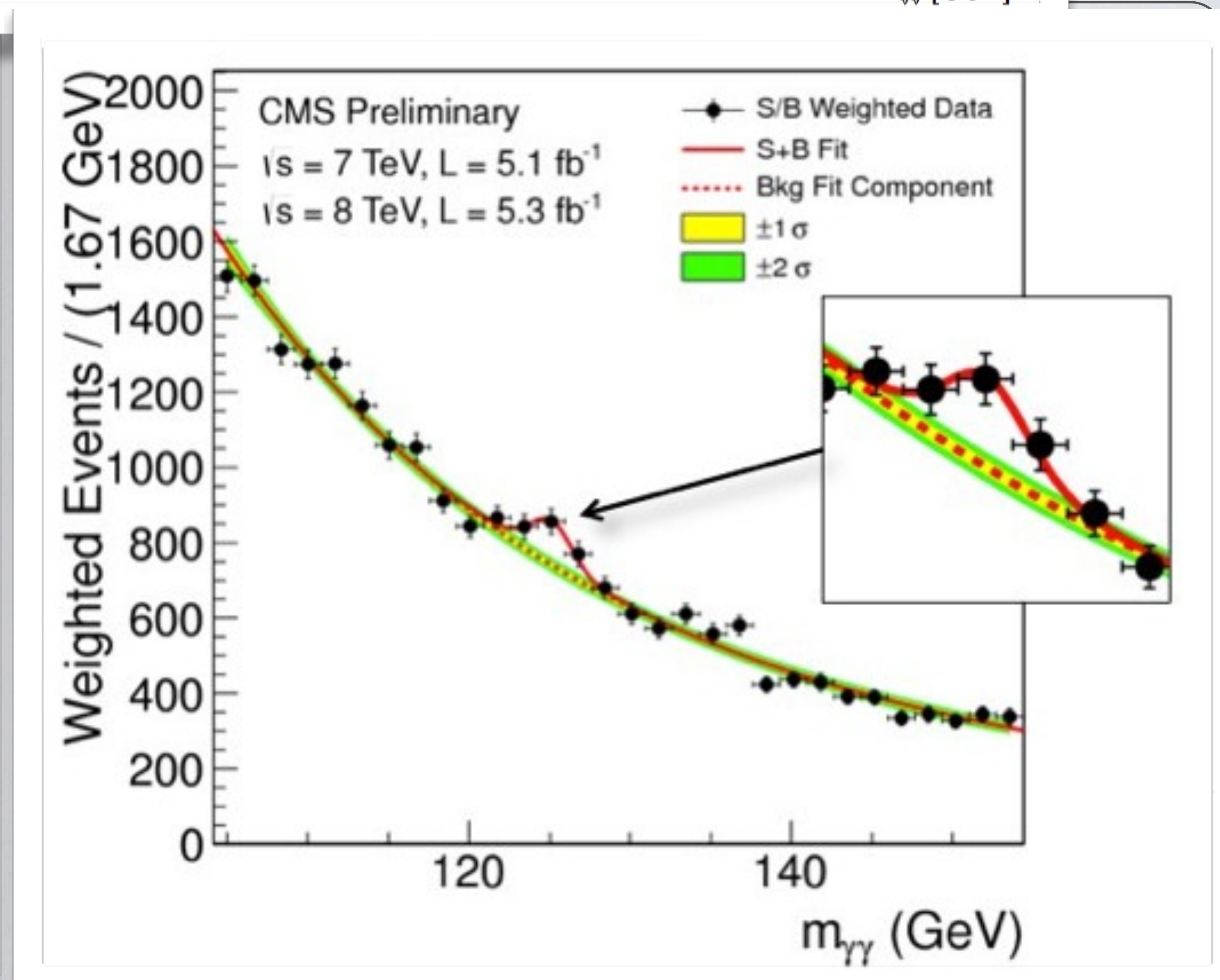

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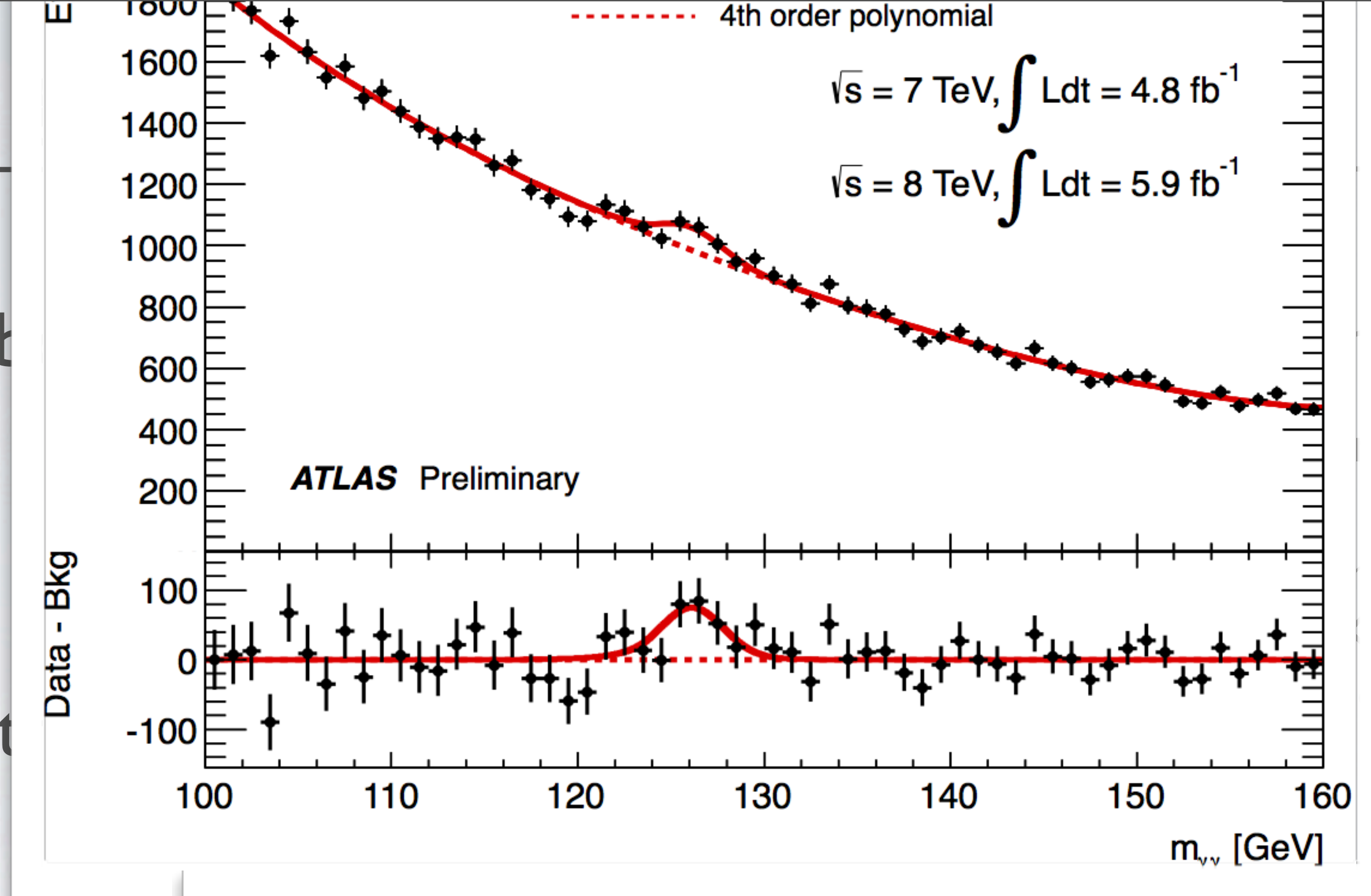
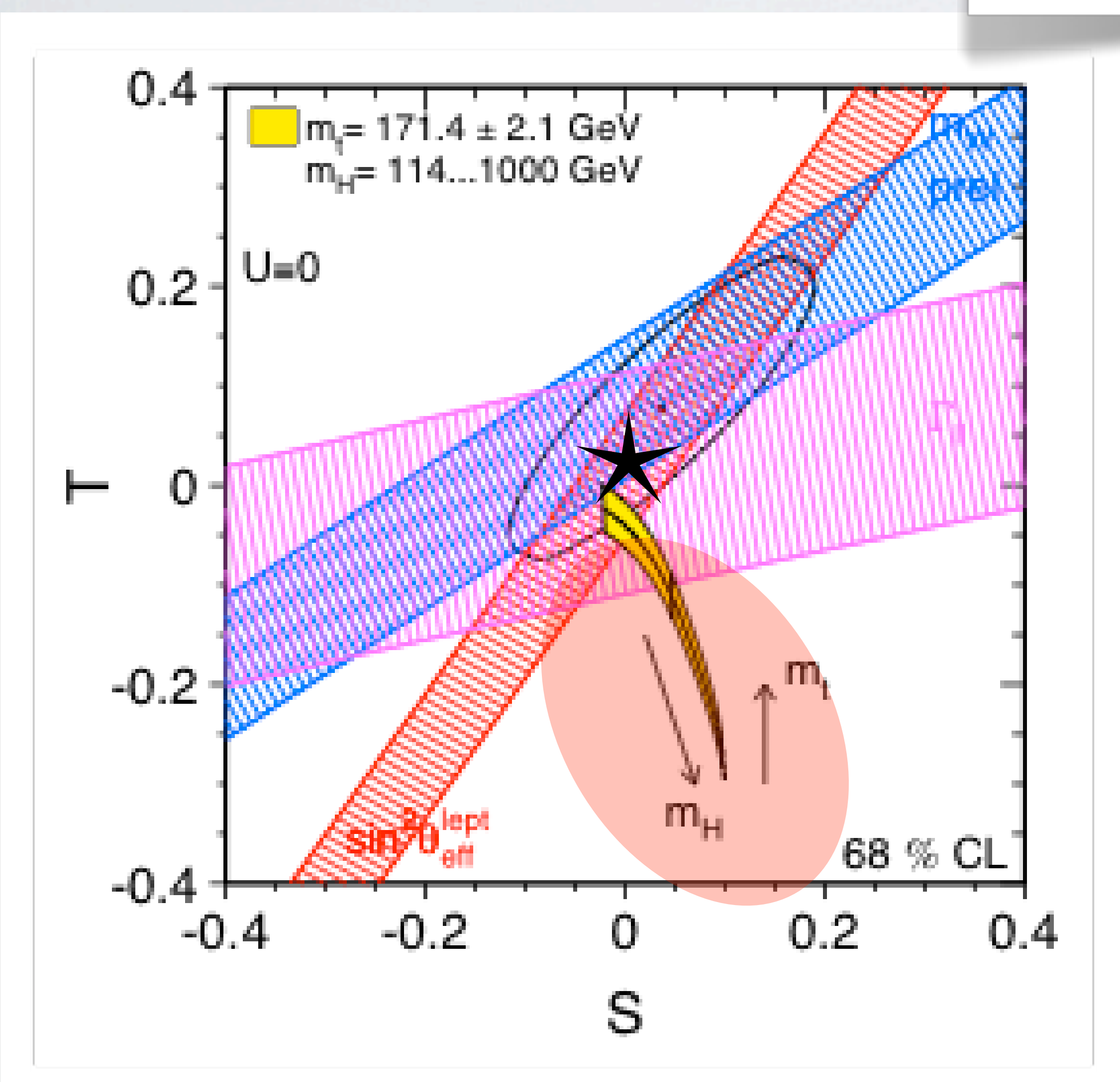
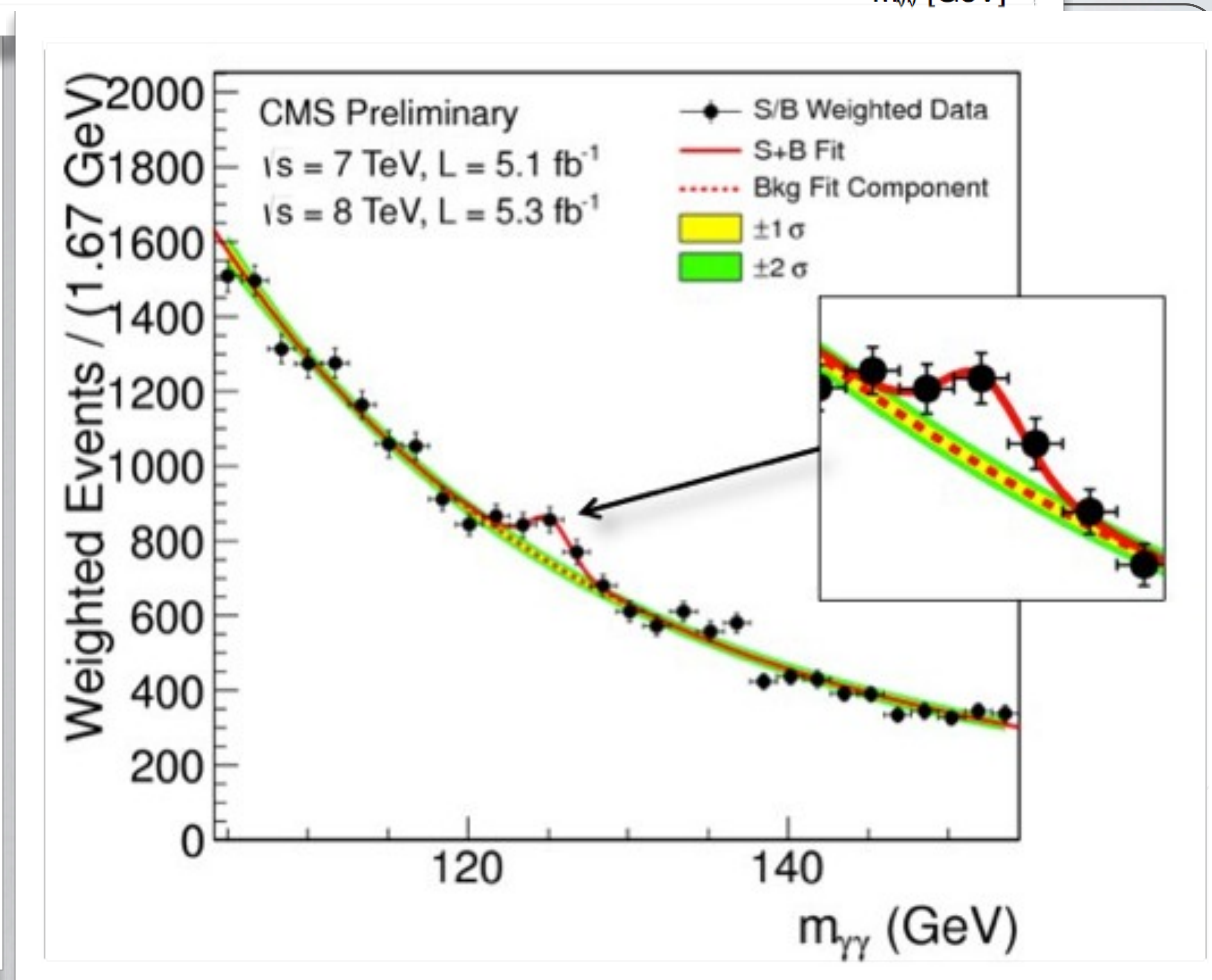






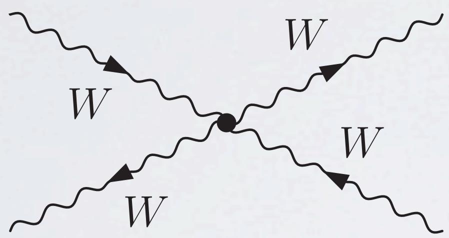
The role of the Higgs boson

$$a_\ell = \frac{1}{32\pi}\int_{-1}^{1} \mathrm{d}\cos\theta\, \mathcal{M}(\cos\theta) P_\ell(\cos\theta)\ , \quad |a_\ell| \leq 1$$

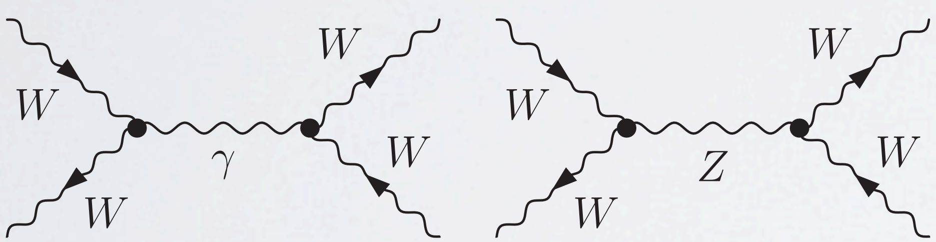
- unitarity in longitudinal gauge boson scattering

$\varepsilon_L^\mu = k^\mu/m_W + \mathcal{O}(m_W/E)$

$\mathcal{M} \sim$



$\sim E^4$



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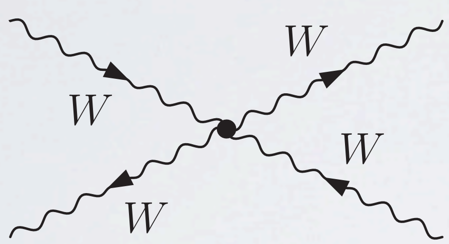

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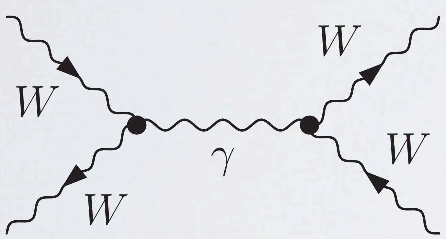

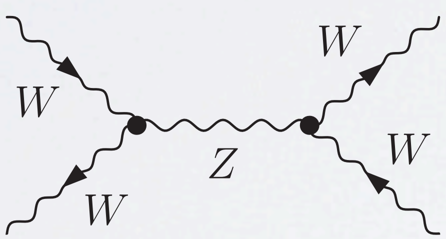

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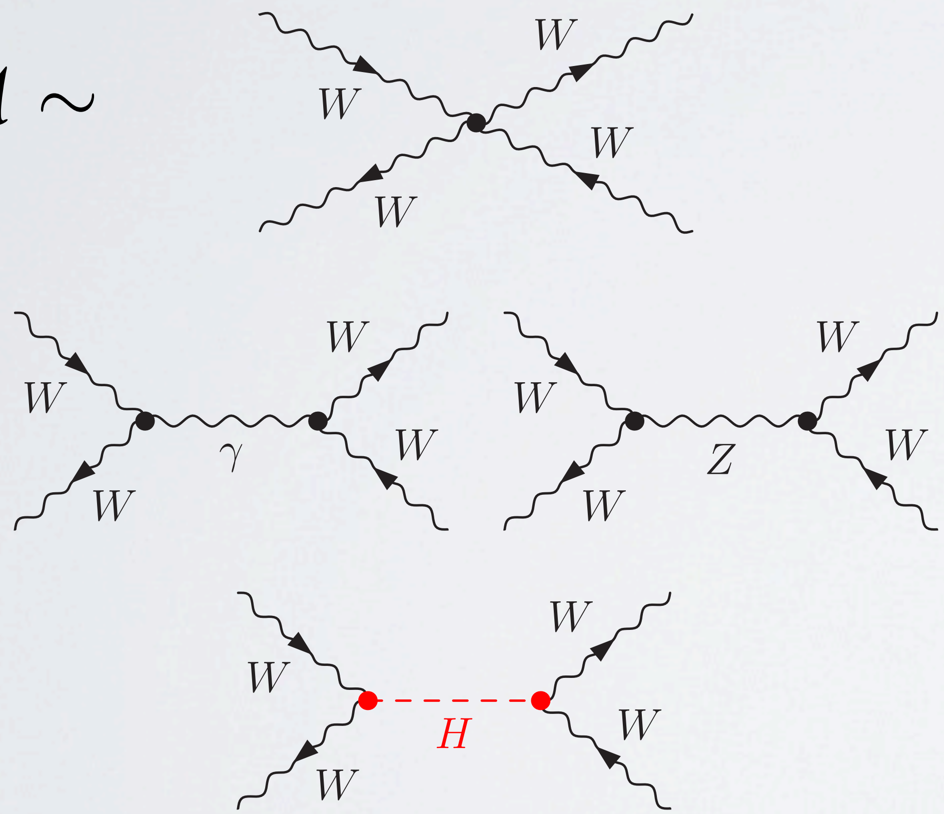

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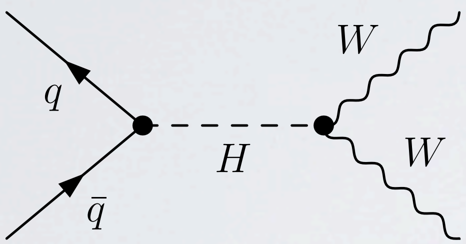
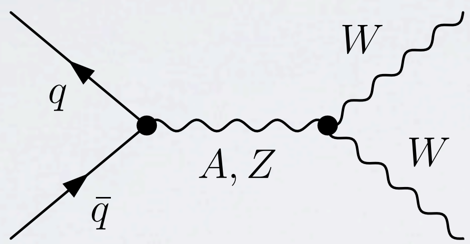
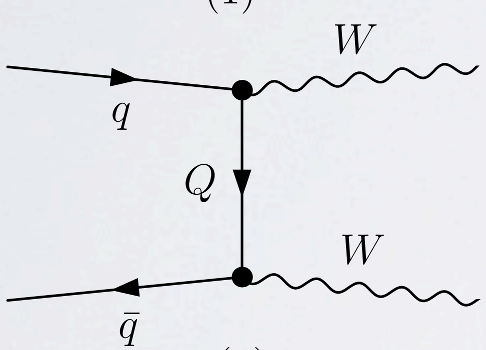


(1)



(2), (3)



(4)

$$\left.\begin{aligned} [1](s) - 2m_q\big([3]_L(s) + [3]_R(s)\big) &= 0 \\ [3]_R(s) + [3]_L(s) - [4]_L(t) &= 0 \\ [2](s) - [3]_R(s) &= 0 \end{aligned}\right\} \sim E^0$$

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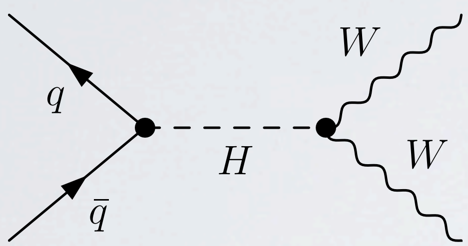

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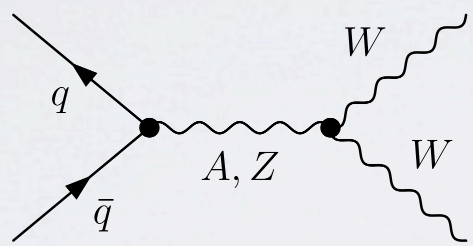

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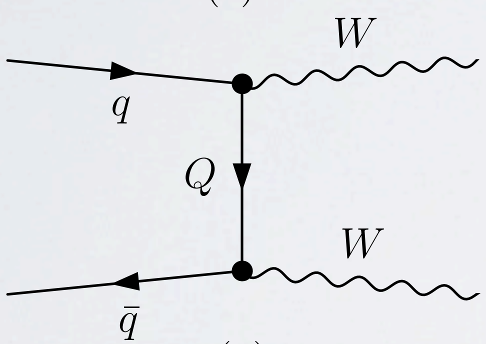

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$\sim E^0$

- constant terms constrained the Higgs boson to be lighter than ~ 1TeV

- unitarity determines Higgs boson couplings to quarks and gauge bosons

Higgs boson production at the LHC

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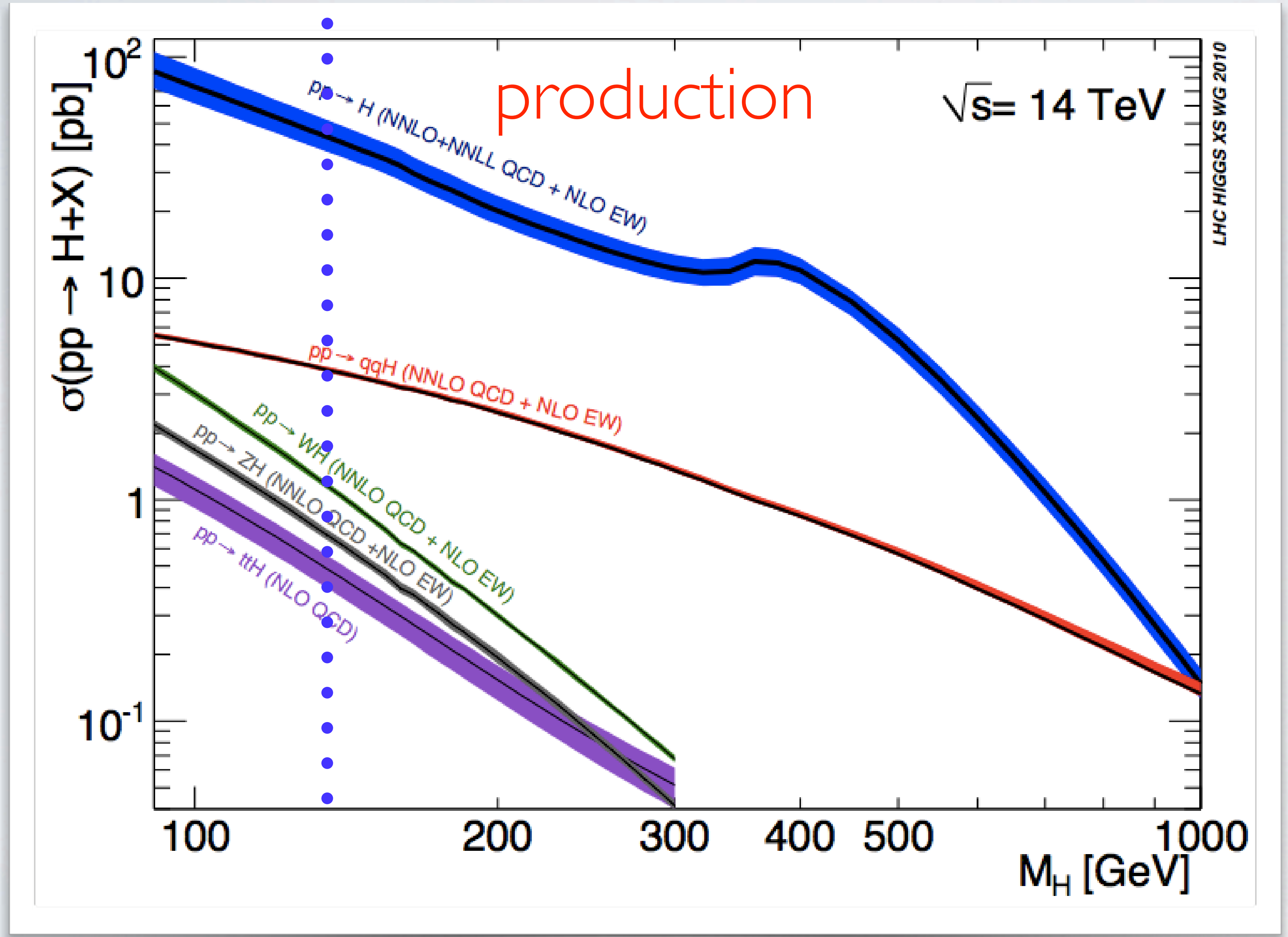
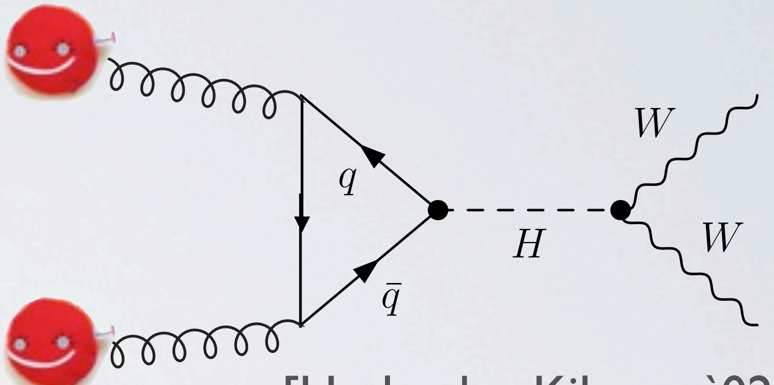
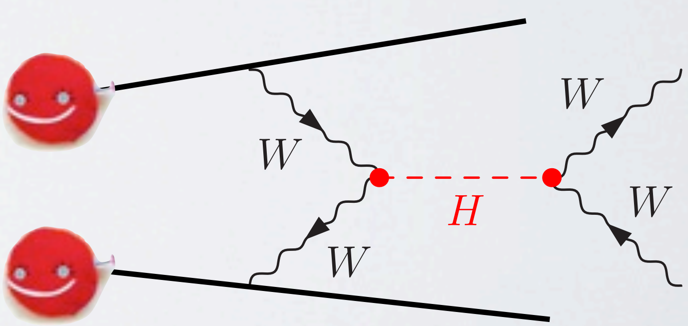


gluon fusion



[Harlander, Kilgore `02]
[Catani, de Florian, Grazzini, `03]
[Moch, Vogt `05]
[Ellis, Campbell, Williams `11]

weak boson fusion



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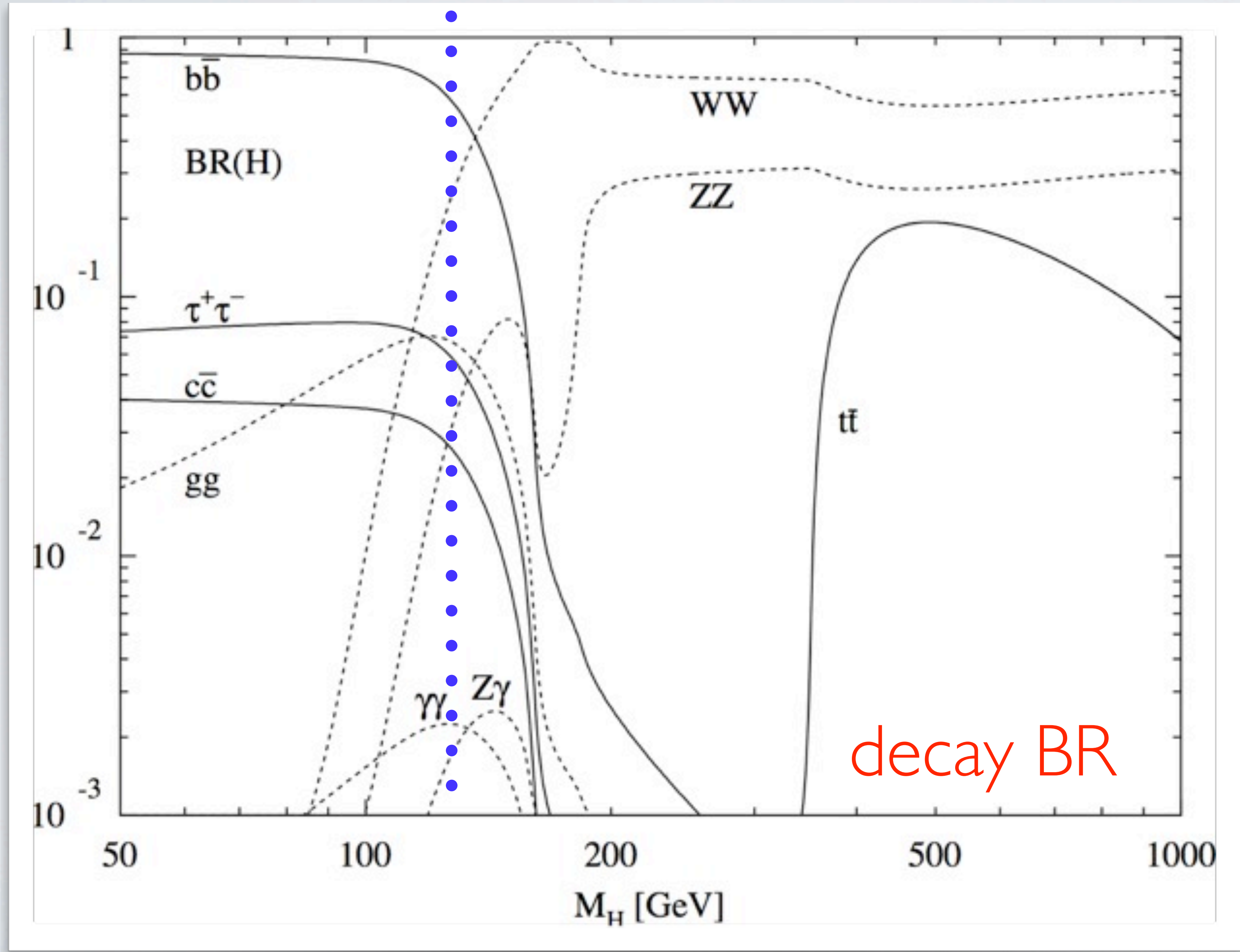

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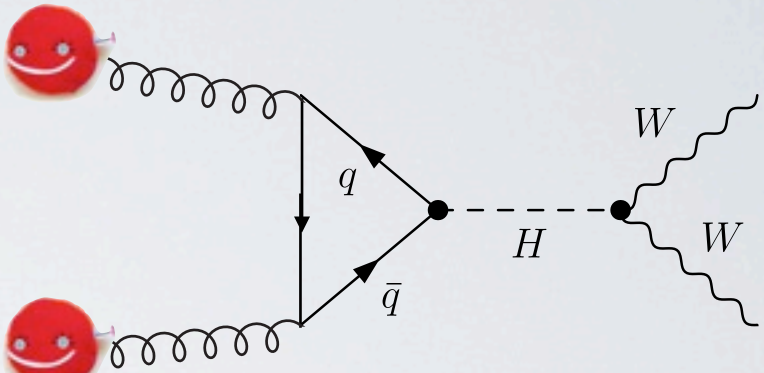

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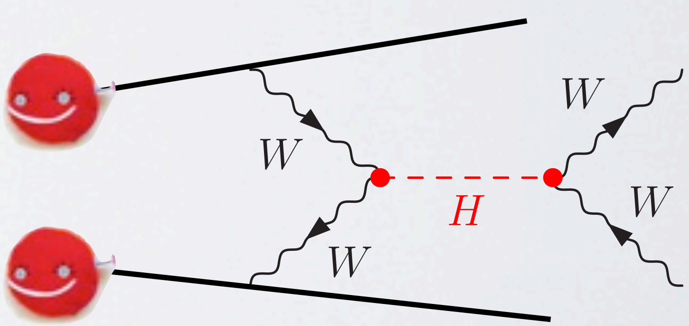

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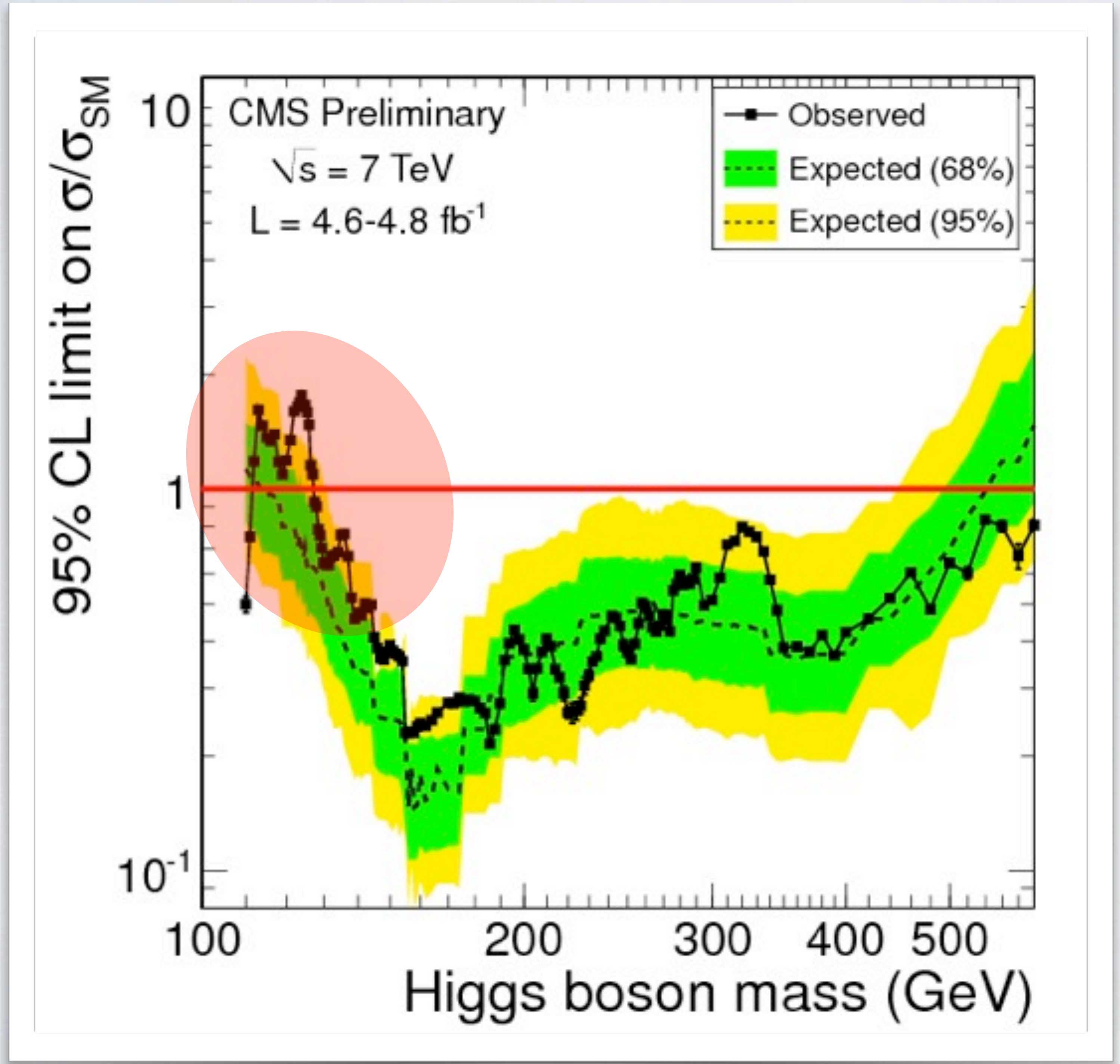

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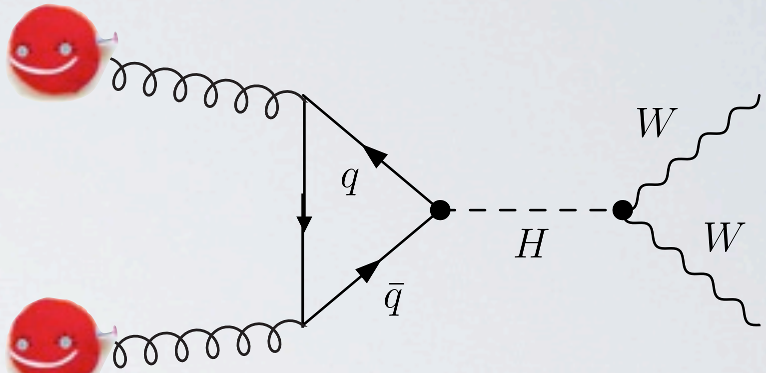

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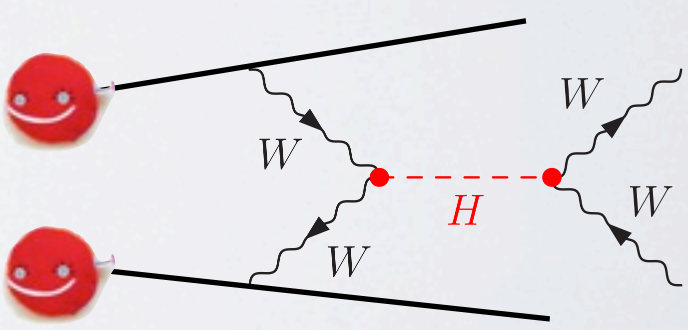

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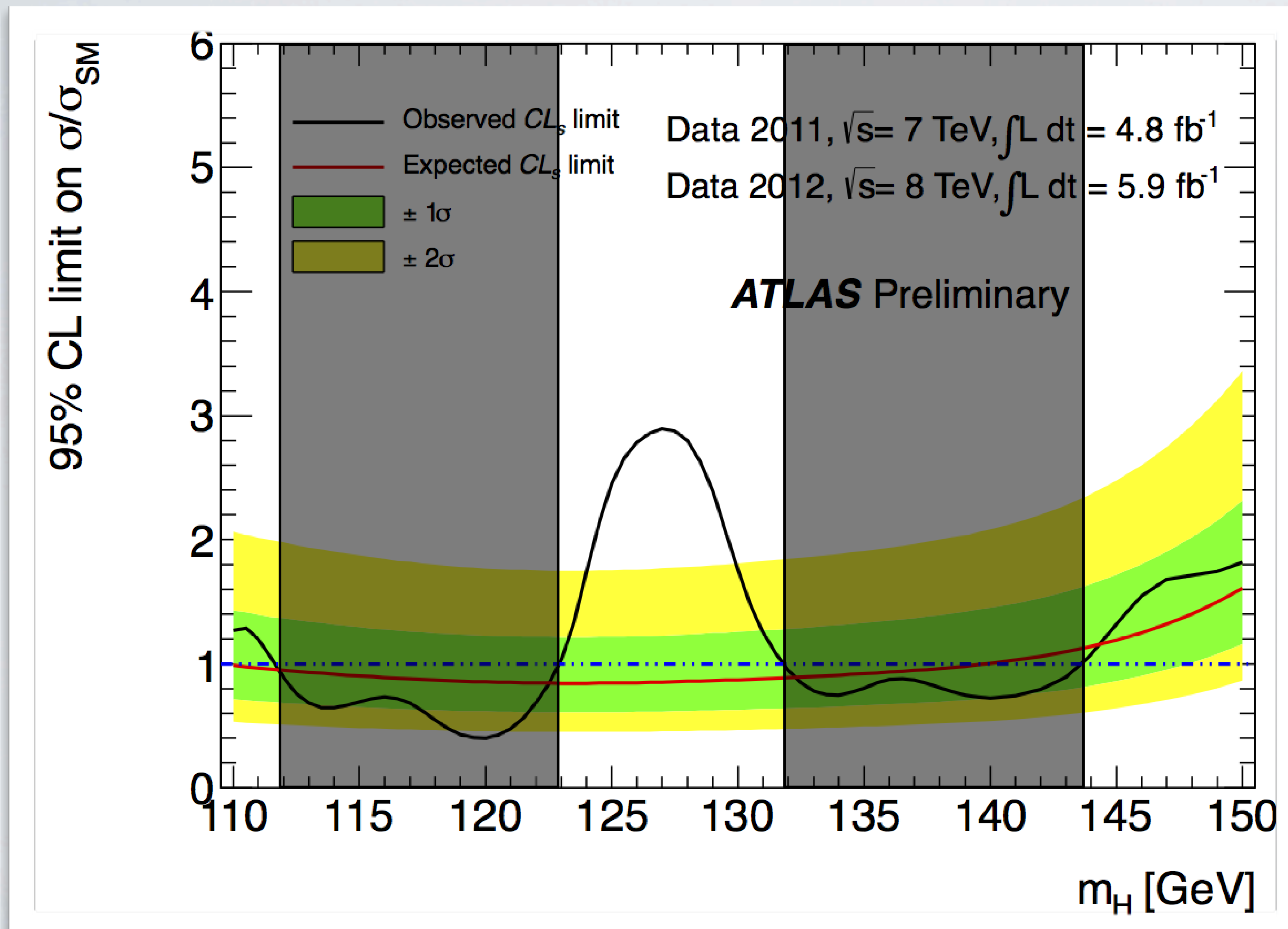

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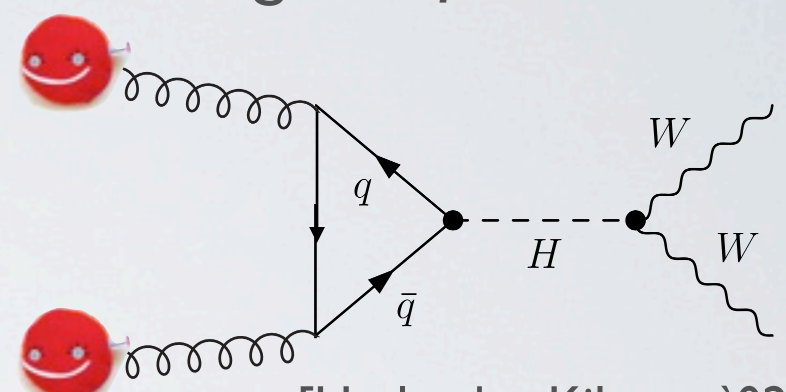

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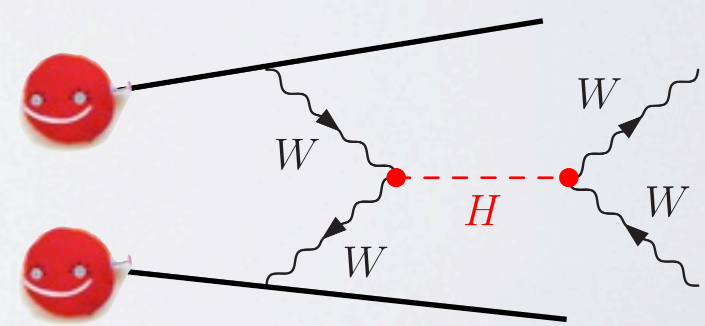

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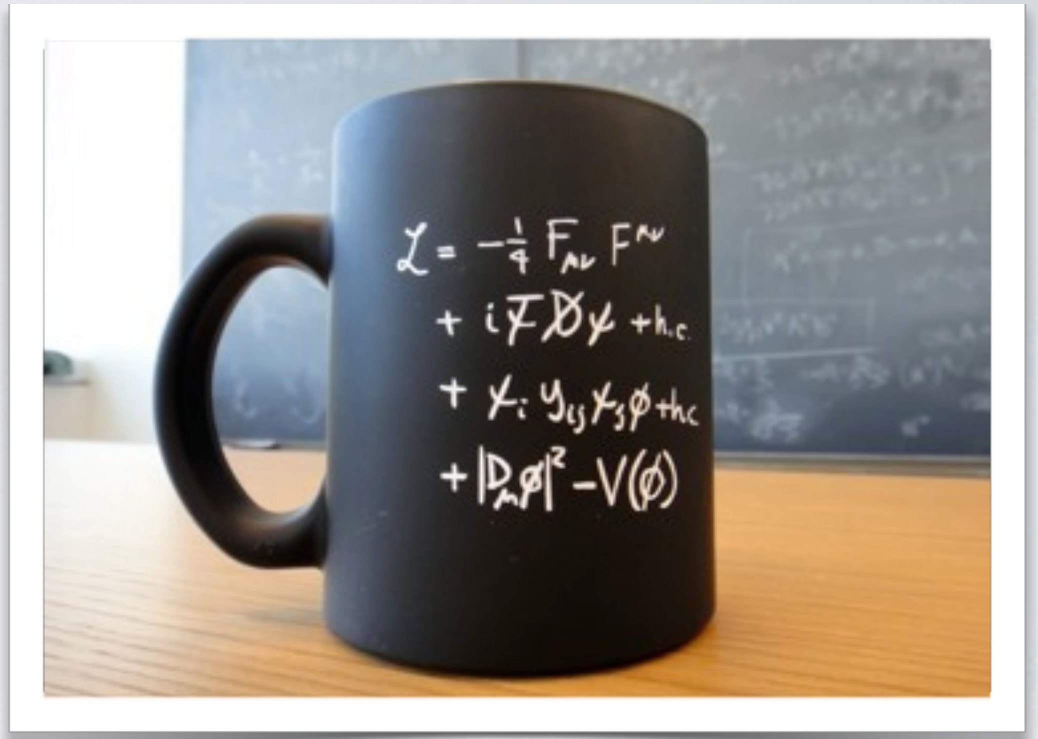
OUTLINE

- A tell-tale story of Higgs physics √
- Higgs couplings
- Higgs Spin & CP
- Higgs self-interactions

Reconstructing Higgs boson properties at the LHC

- Relevant interactions for Higgs pheno at the LHC (*the better CERN mug*®)

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



Reconstructing Higgs boson properties at the LHC

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← Higgs potential, symmetry breaking

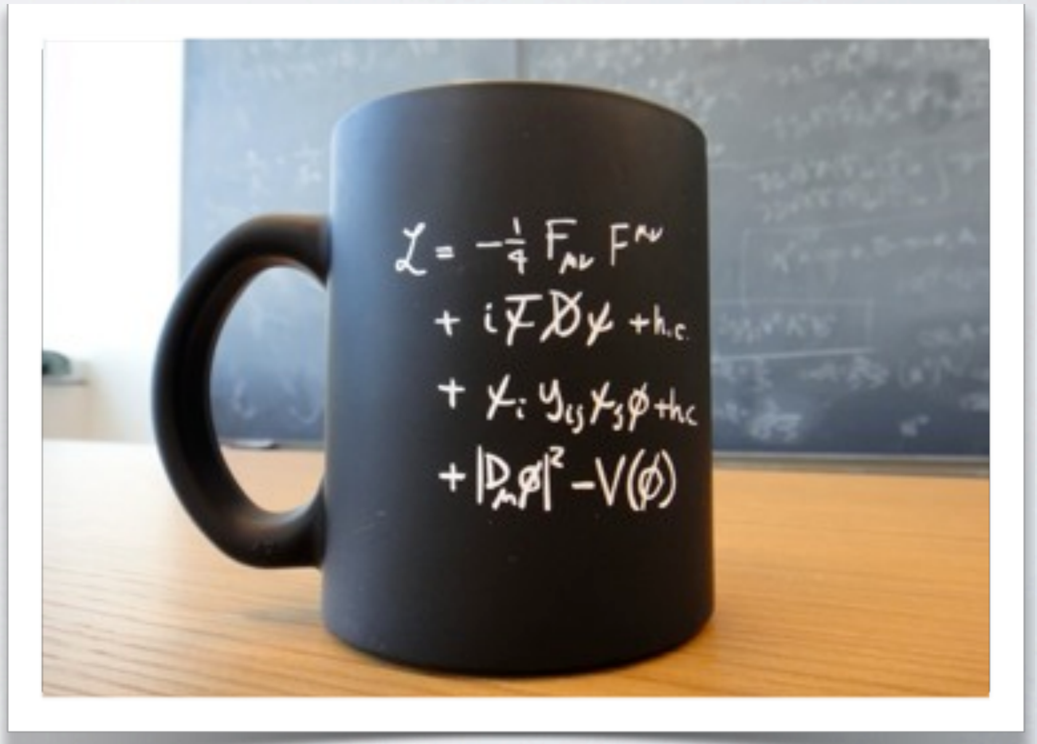
$$- g_v m_V V^2 h + \frac{m_f}{v} \bar{f} f h$$

← gauge boson and fermion masses, BRs, xsections

$$- \frac{1}{4} \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

← fancy way to include $gg \to h^n$, $h^n \to \gamma\gamma$

[Shifman et al. `79]



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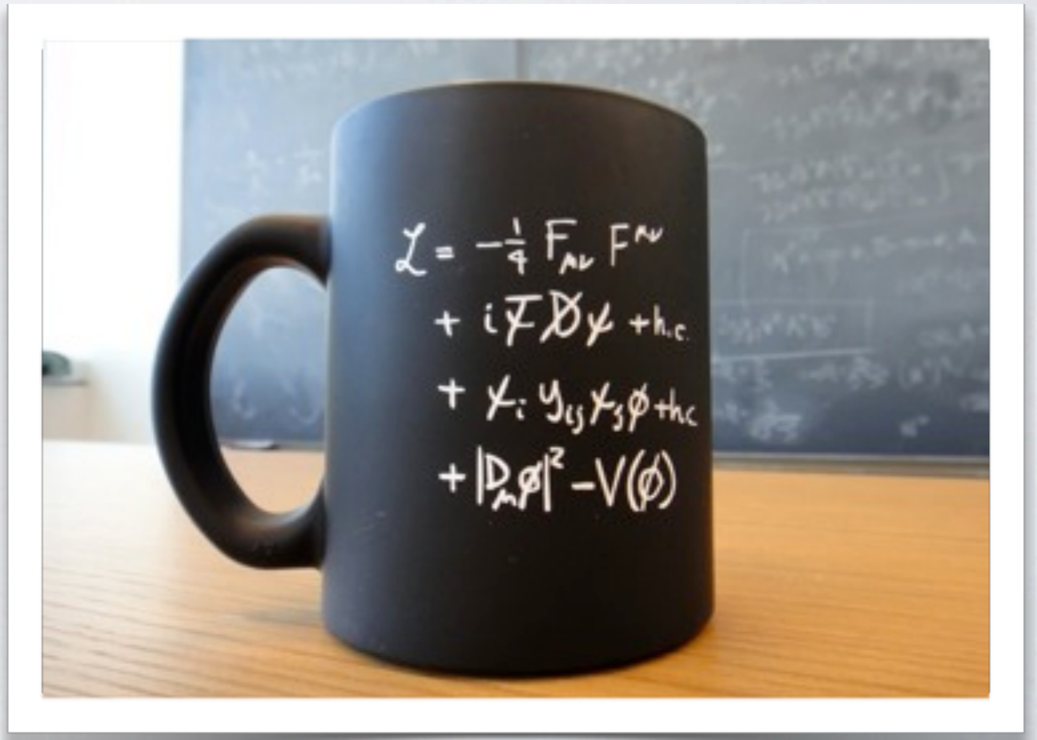
$$+ \text{ nothing else}$$



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Higgs potential, symmetry breaking

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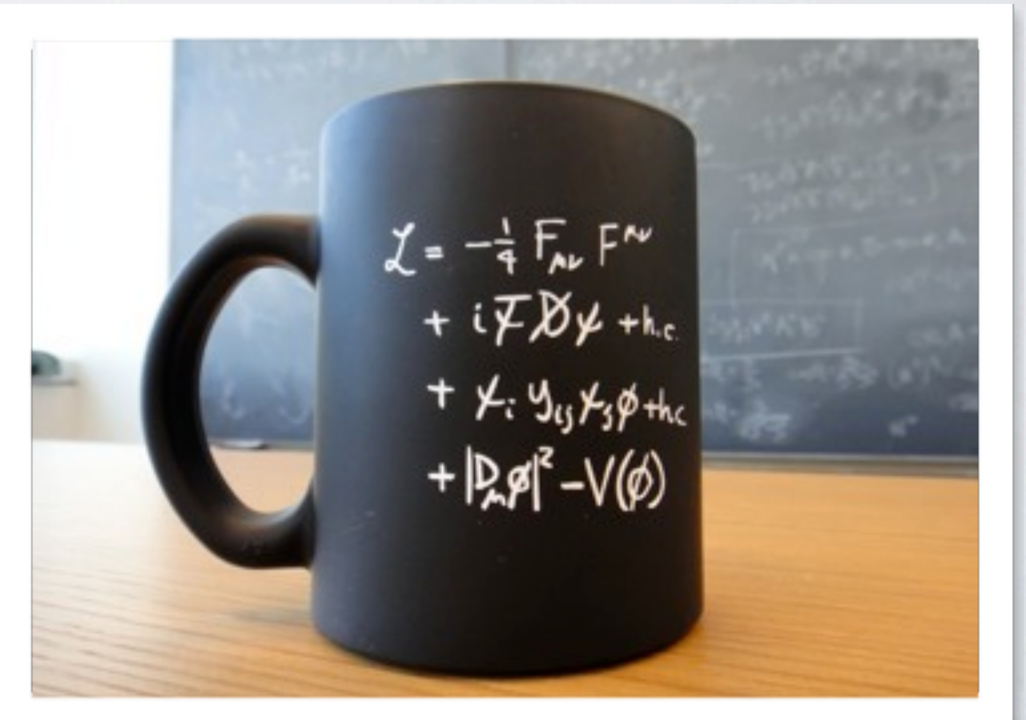
[Shifman et al. `79]

- the SM Higgs is a CP even scalar $\mathcal{L} \not\supset G\widetilde{G}h$ ...

- no exotic decays (well ... by definition)

- all couplings are predictions and need to be measured:

  deviations of xsections, BRs, ...



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PRELIMINARY

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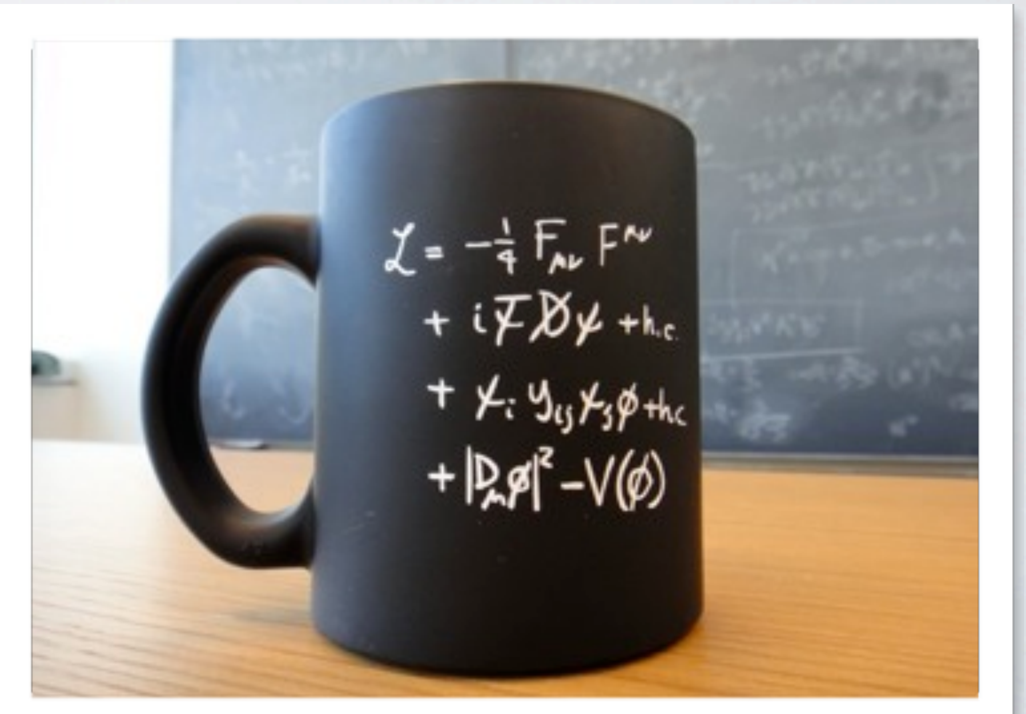

SM-like Higgs couplings

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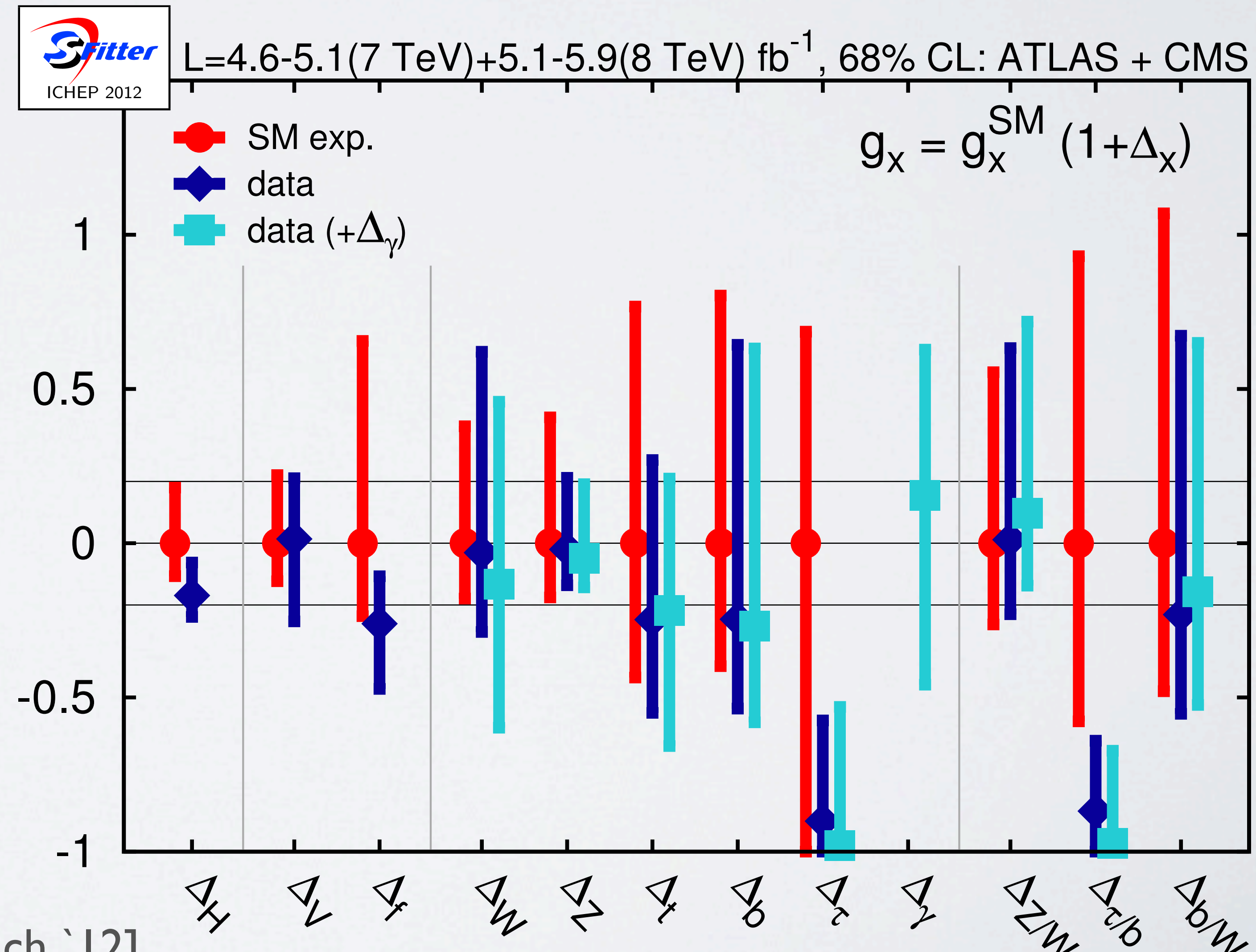
$$+ \text{ nothing else}$$

$$\sigma_p \times \mathrm{BR}_d \sim \frac{\Gamma_p \Gamma_q}{\Gamma_{\mathrm{tot}}}$$

$$\sim g_p^2 \, g_d^2 \Big/ \left(\sum_{\text{modes}} g_i^2 \right)$$



[Plehn, Rauch `12]

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$$+ \text{ nothing else}$$

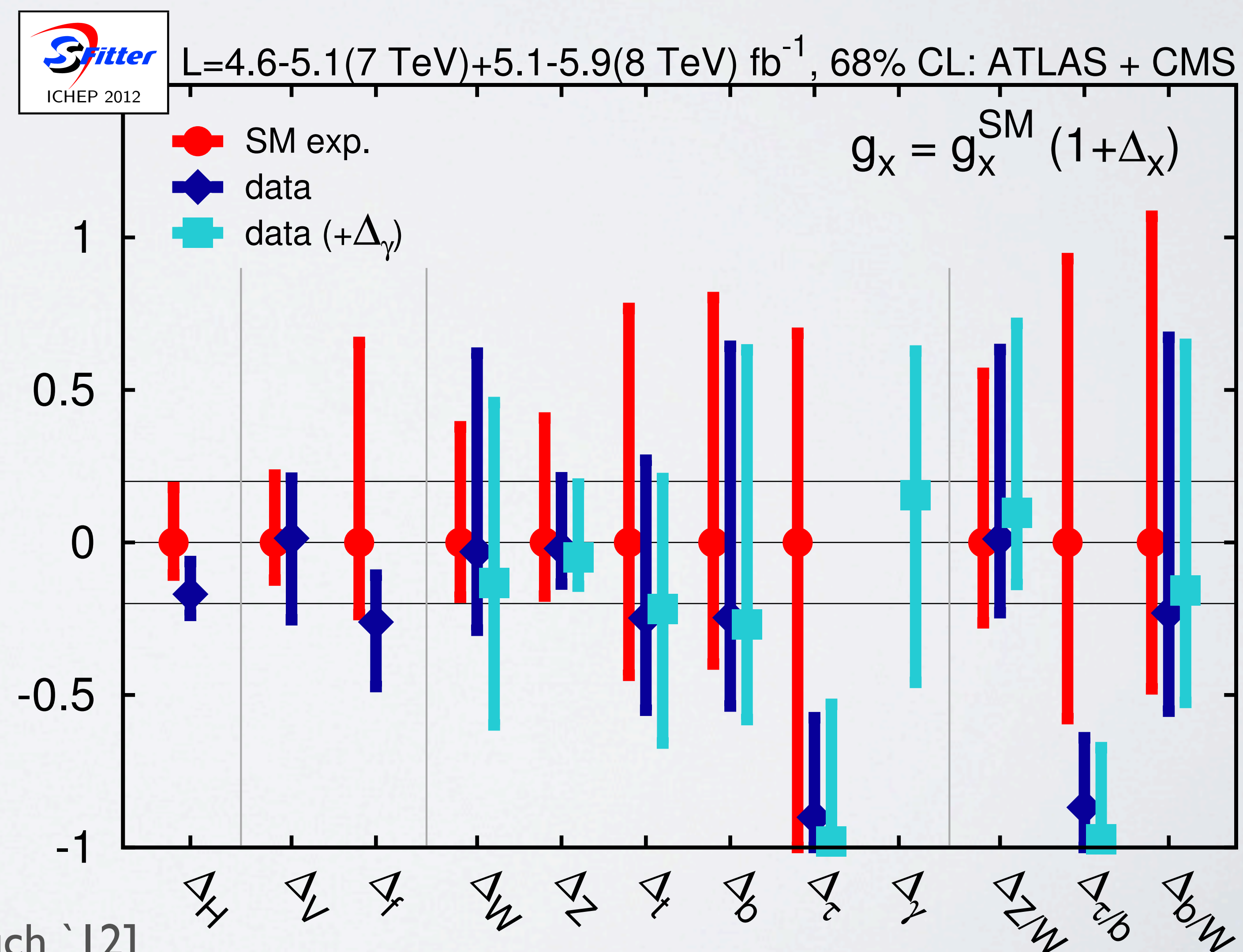
But what about non-standard decay modes?

Can we separate production modes?

→ impact on global fit!

$$\sigma_p \times \mathrm{BR}_d \sim \frac{\Gamma_p \Gamma_q}{\Gamma_{\rm tot}}$$

$$\sim g_p^2\, g_d^2 \Big/ \Big(\sum_{\rm modes} g_i^2 \Big)$$

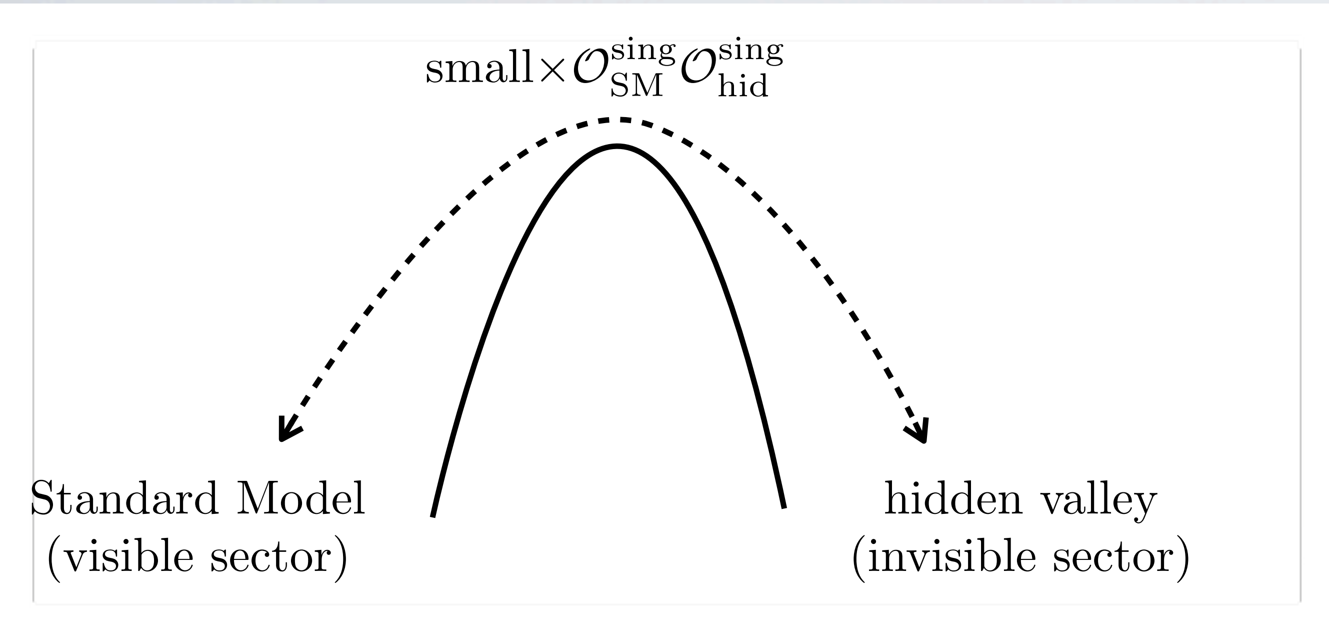


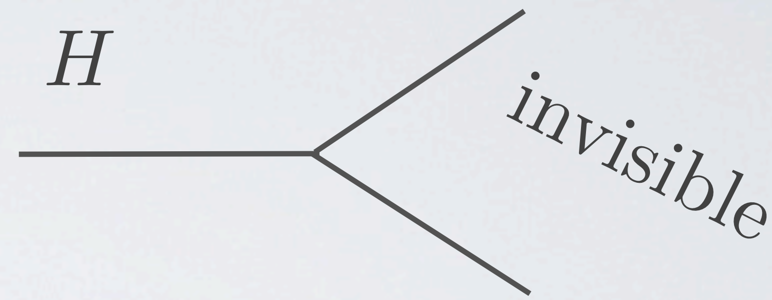
[Plehn, Rauch `12]

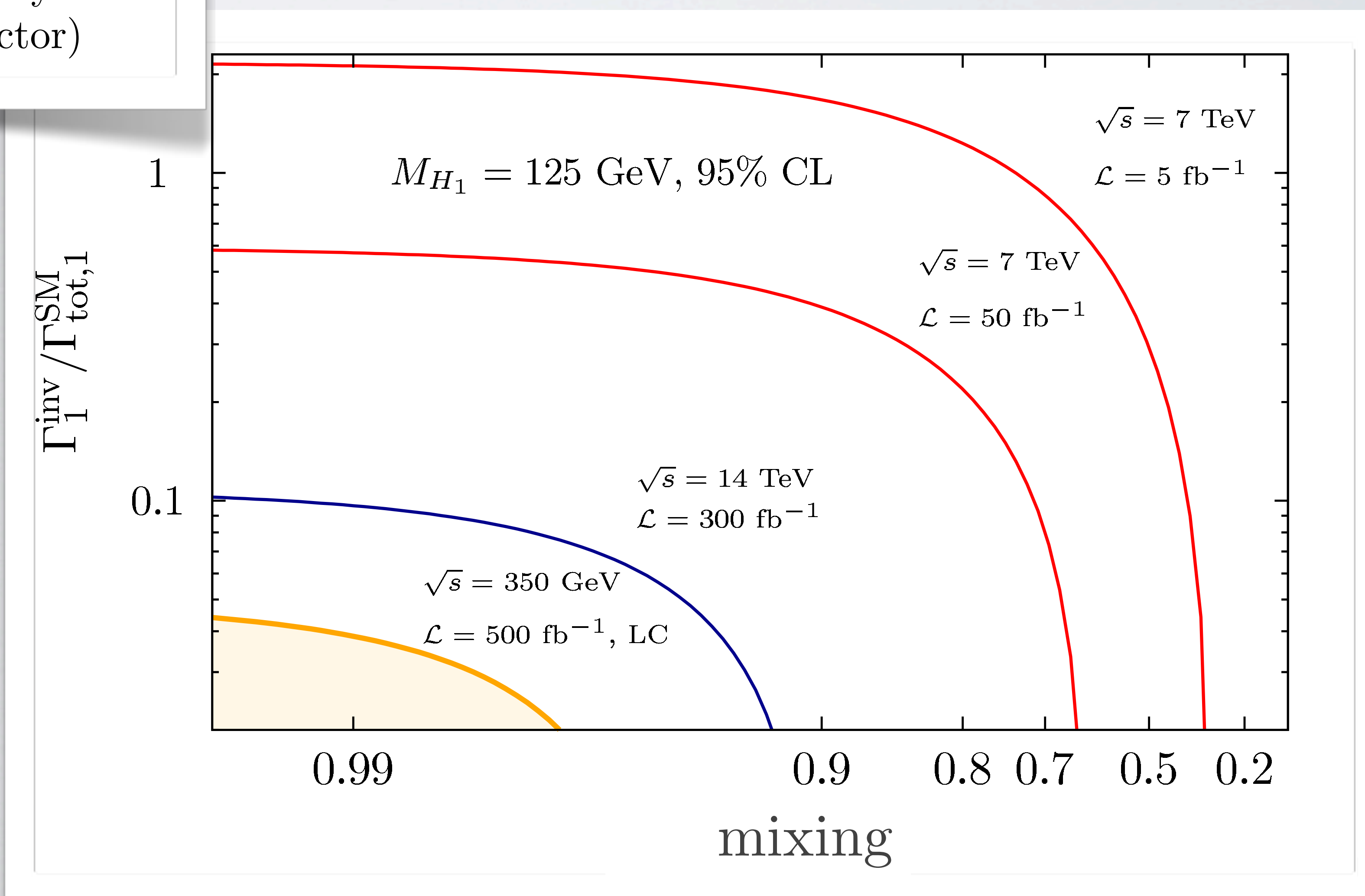
invisible branching ratios

$$\mathcal{L}_{\rm new} \overset{???}{\not\ni} \eta|\phi_{\rm SM}|^2|\phi_{\rm hid}|^2$$ (allowed by gauge invariance & renormalizability)

[Bowen, Cui, Wells `07] [Patt, Wilczek `06]....







[CE, Plehn, Zerwas, Zerwas `11]
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(in)visible non-standard branching ratios

[CE, Spannowsky, Wymant `12]

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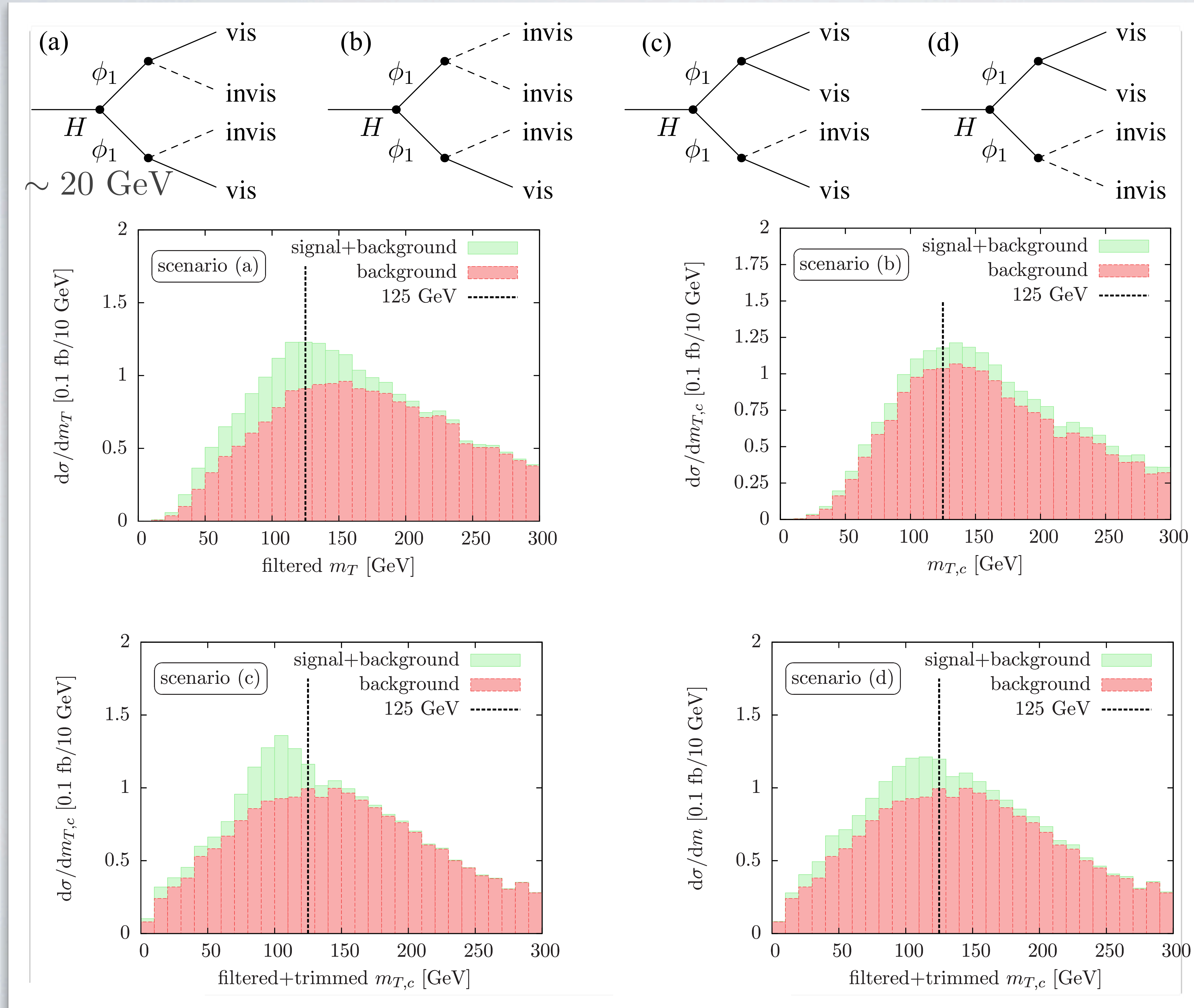

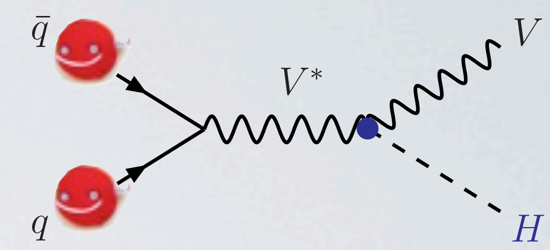

- boosted kinematics
- triggers $\surd$
- subjet algorithms
- b tagging
- "particle flow" $\not{E}_T$

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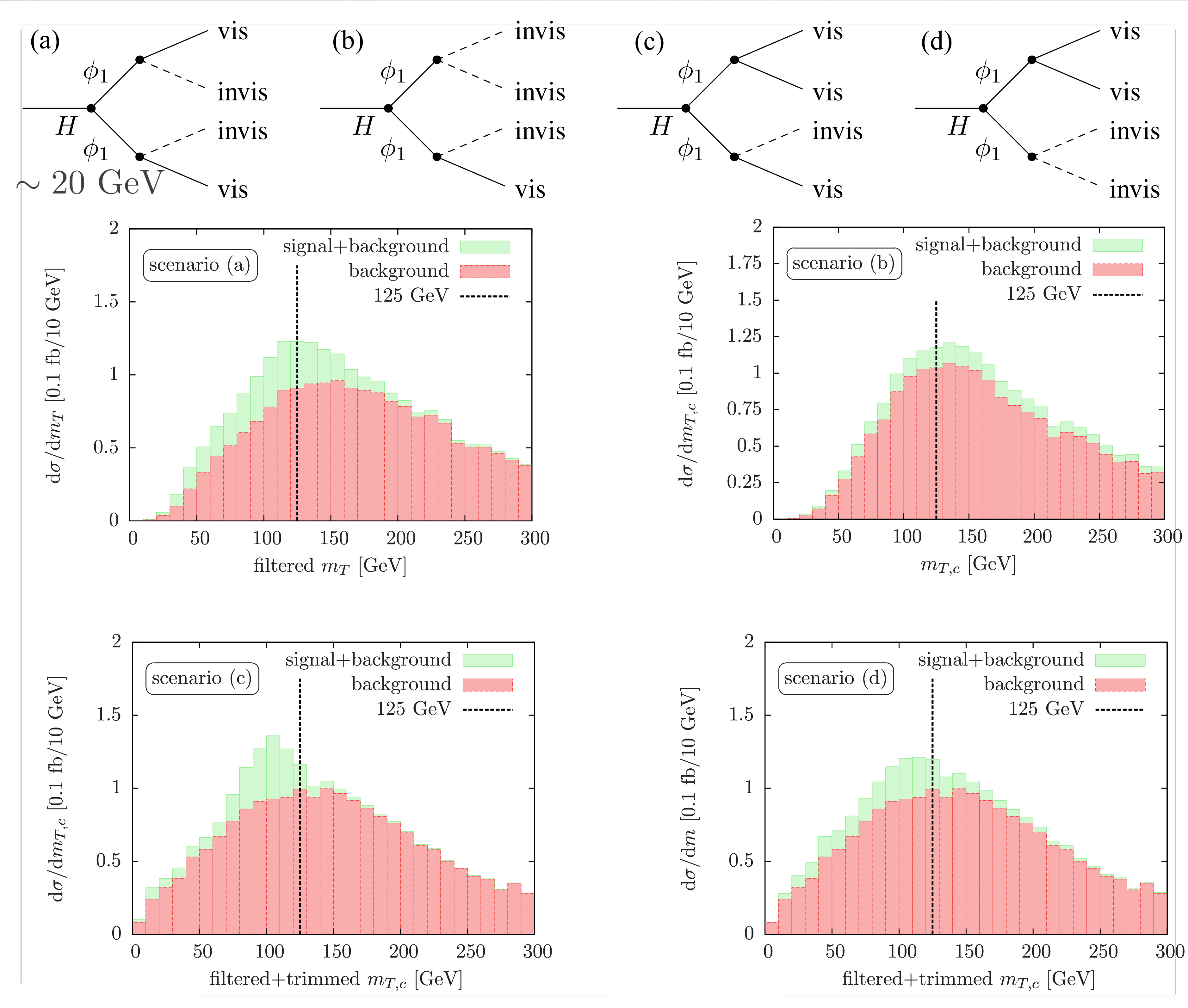

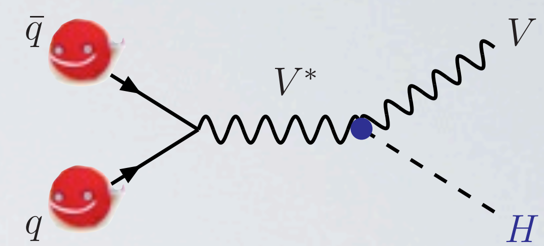

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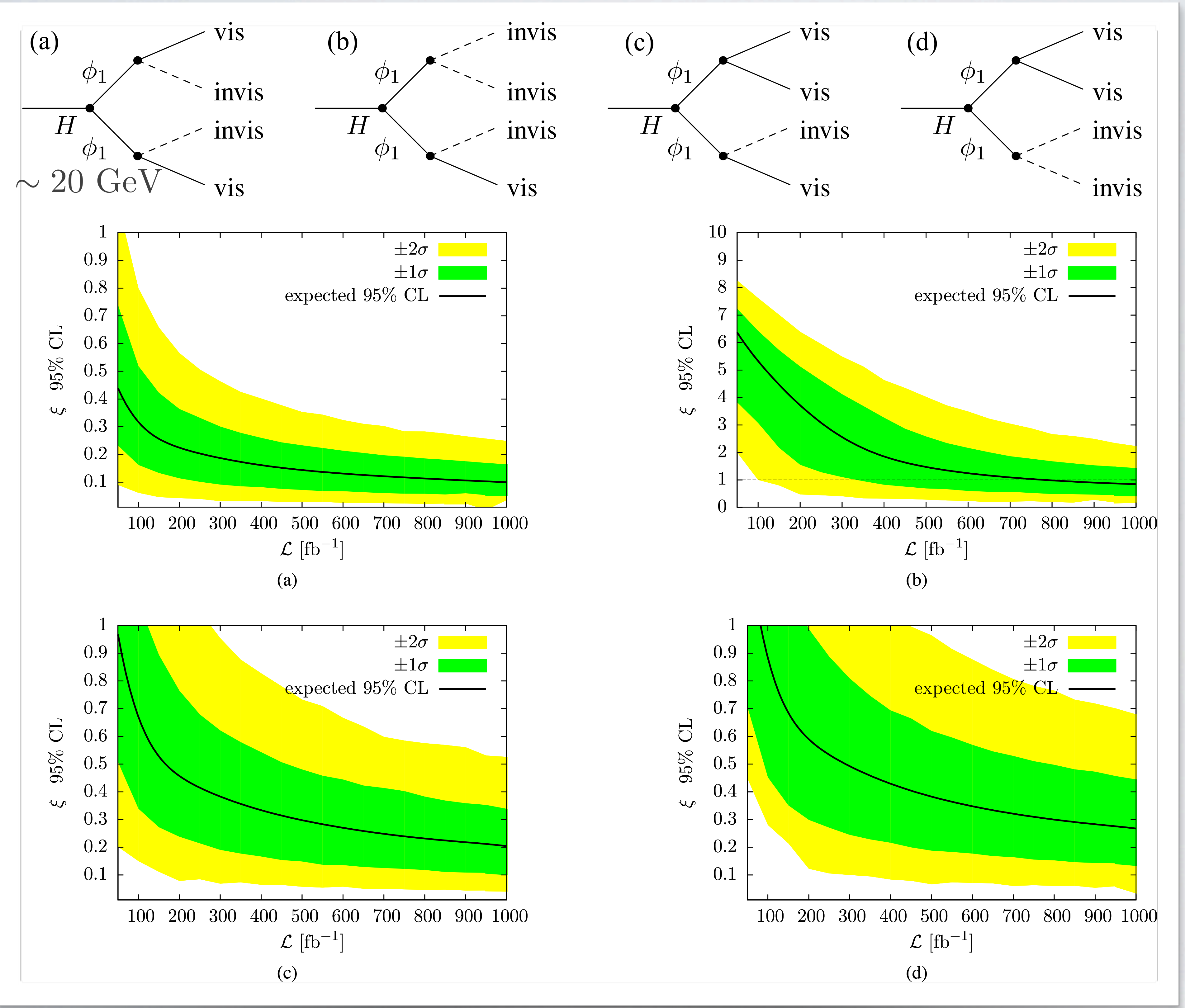

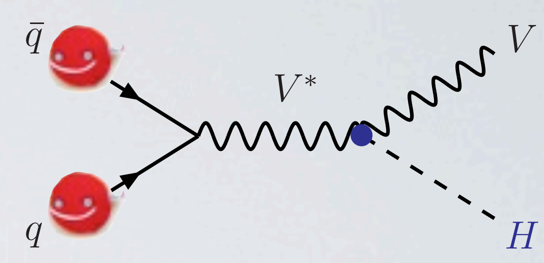

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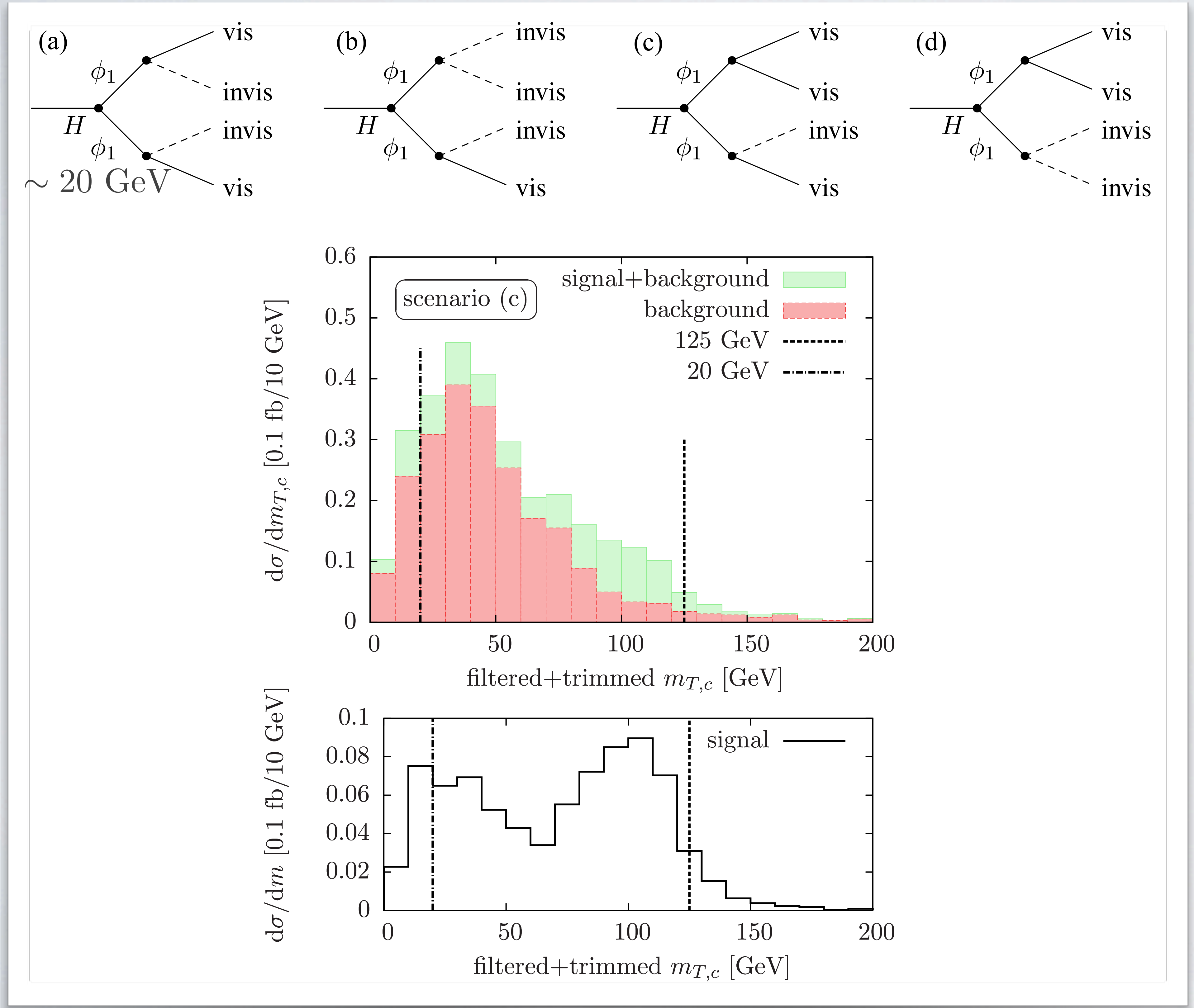

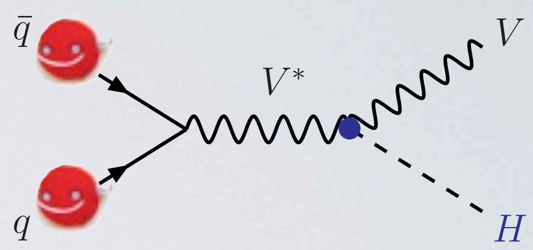

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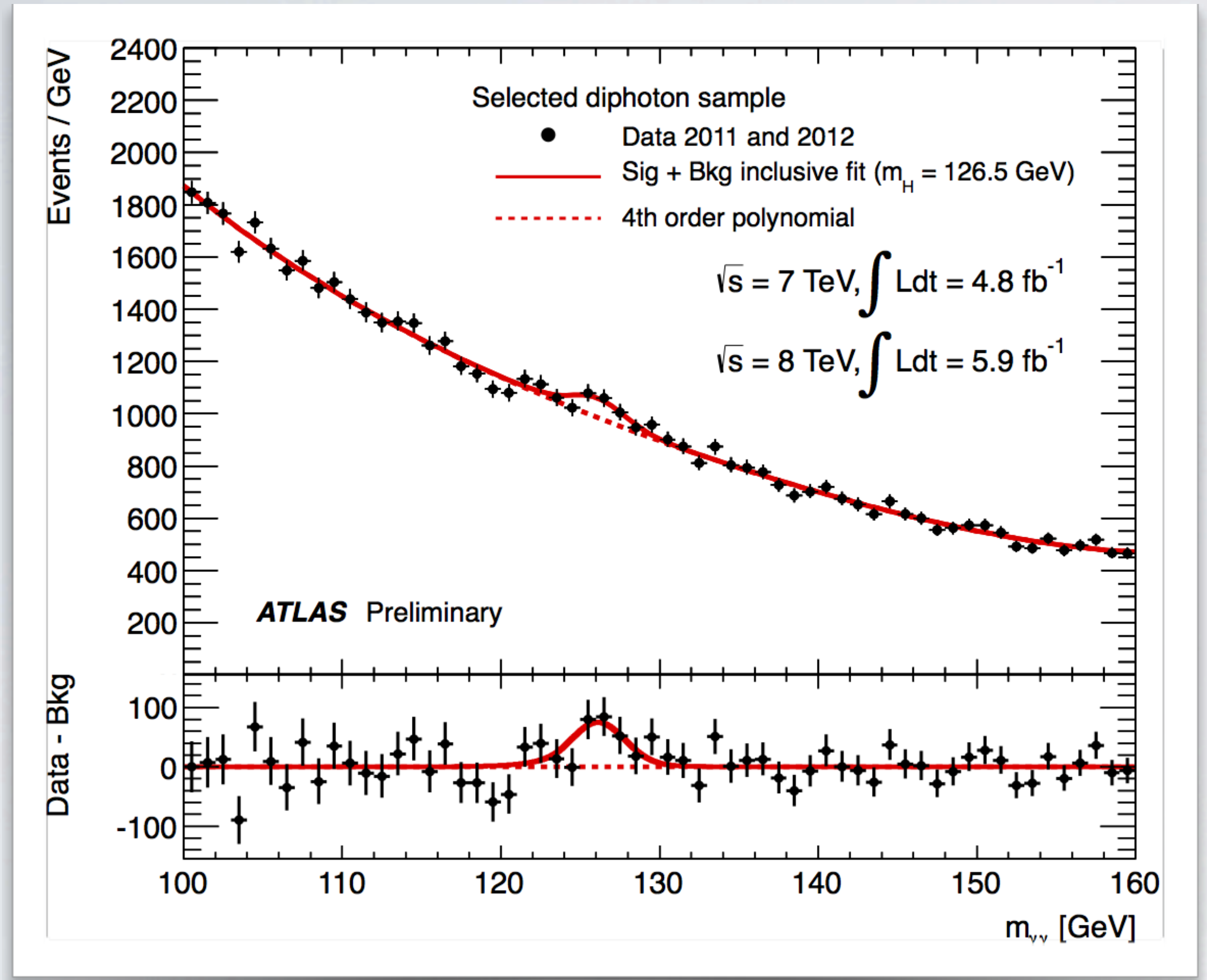
Higgs boson spin and CP



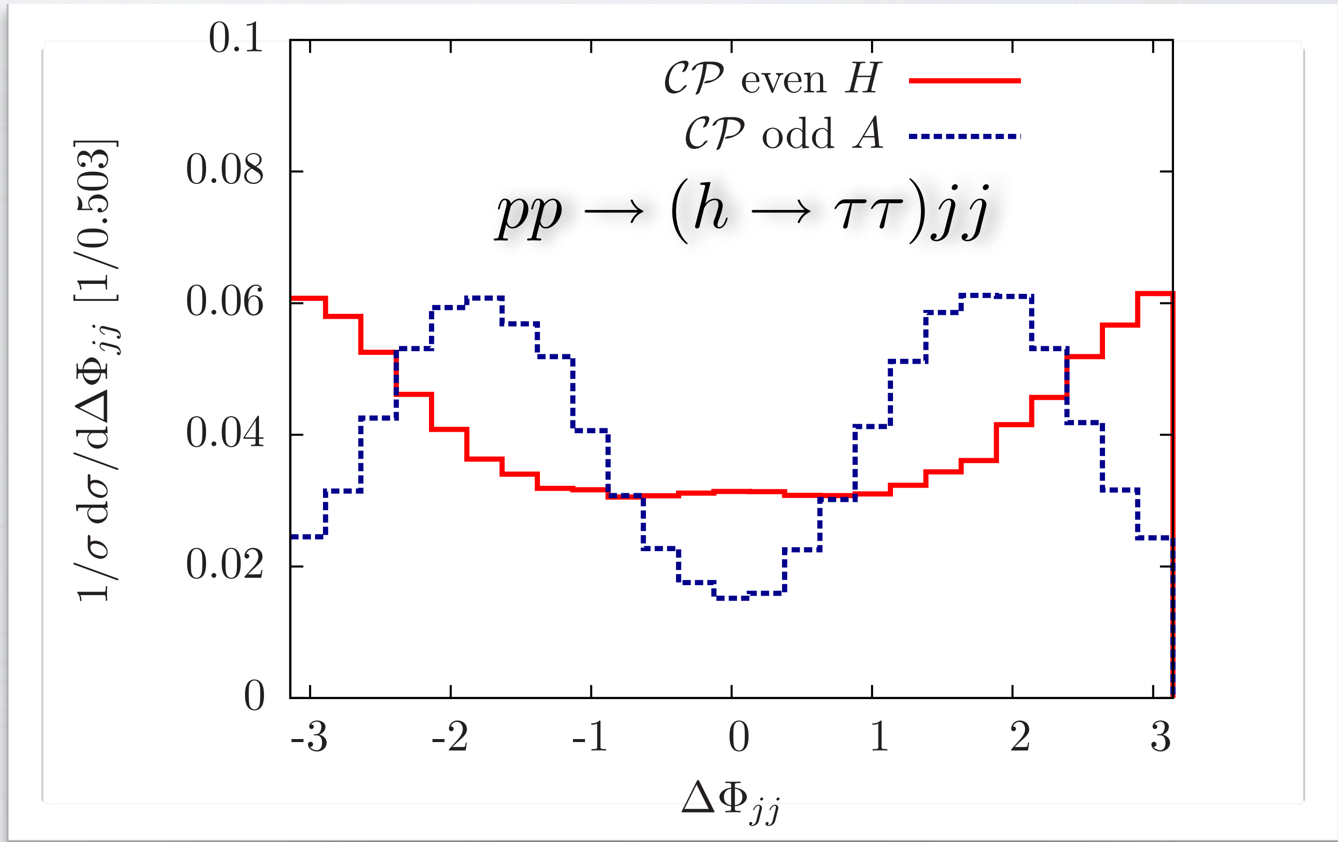
- Landau-Yang: cannot be spin 1
- spin 2 is a theoretical stretch

but we want to measure that
[CE, Goncalves, Mawatari, Plehn, in prep]

- What's the resonance's CP ?

$\Delta\Phi_{jj}$ in h+2j events

[Plehn, Rainwater, Zeppenfeld `01]



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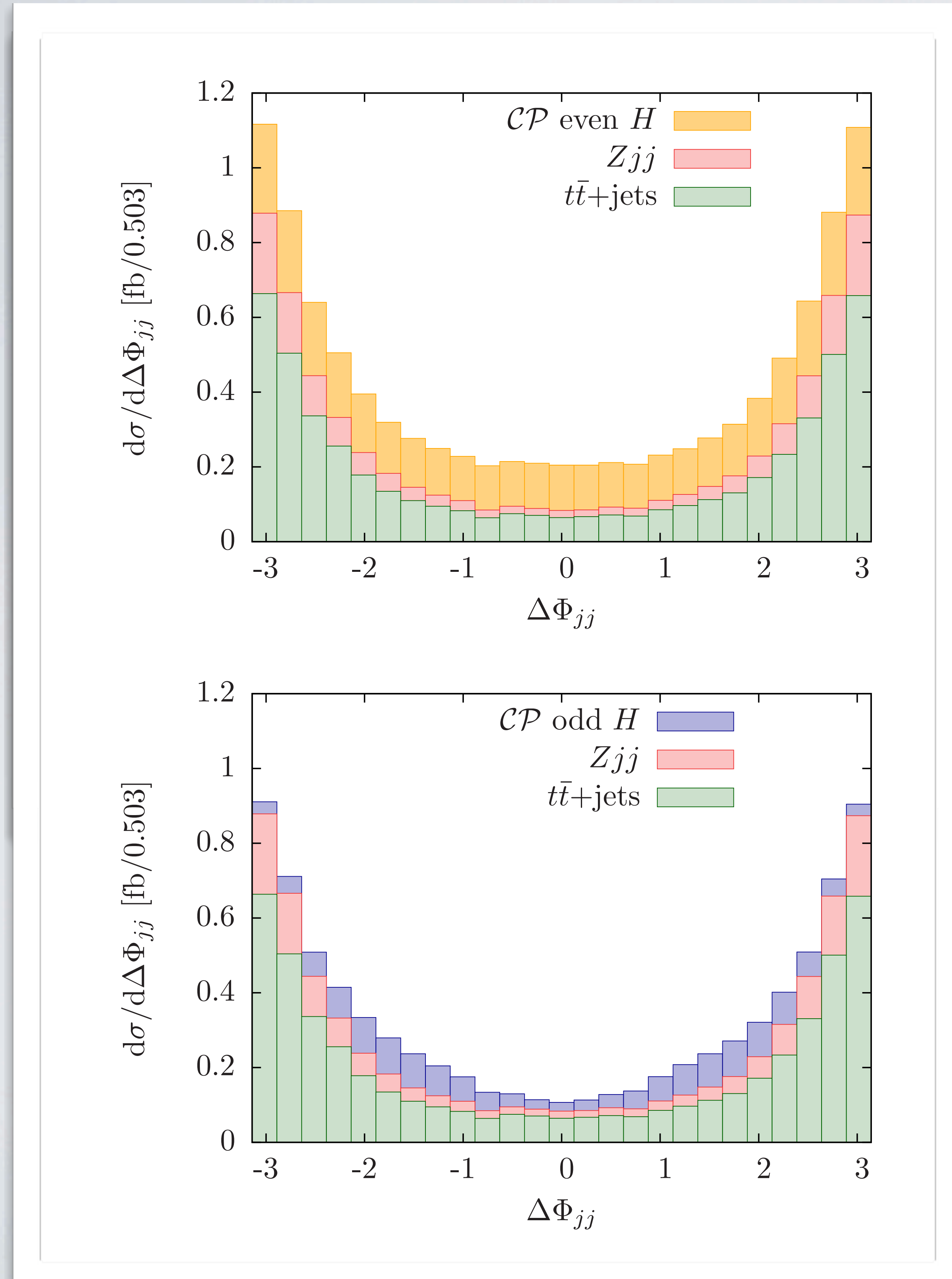

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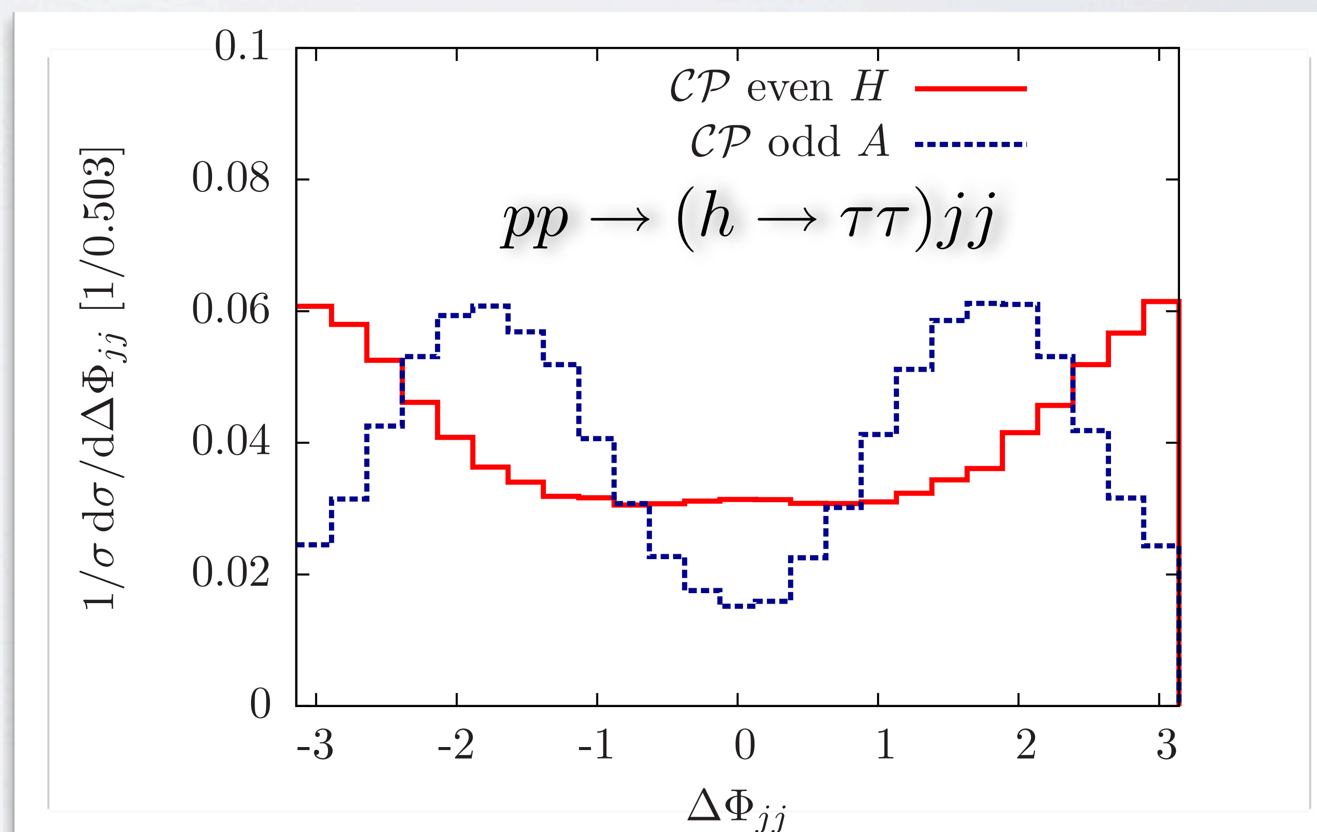
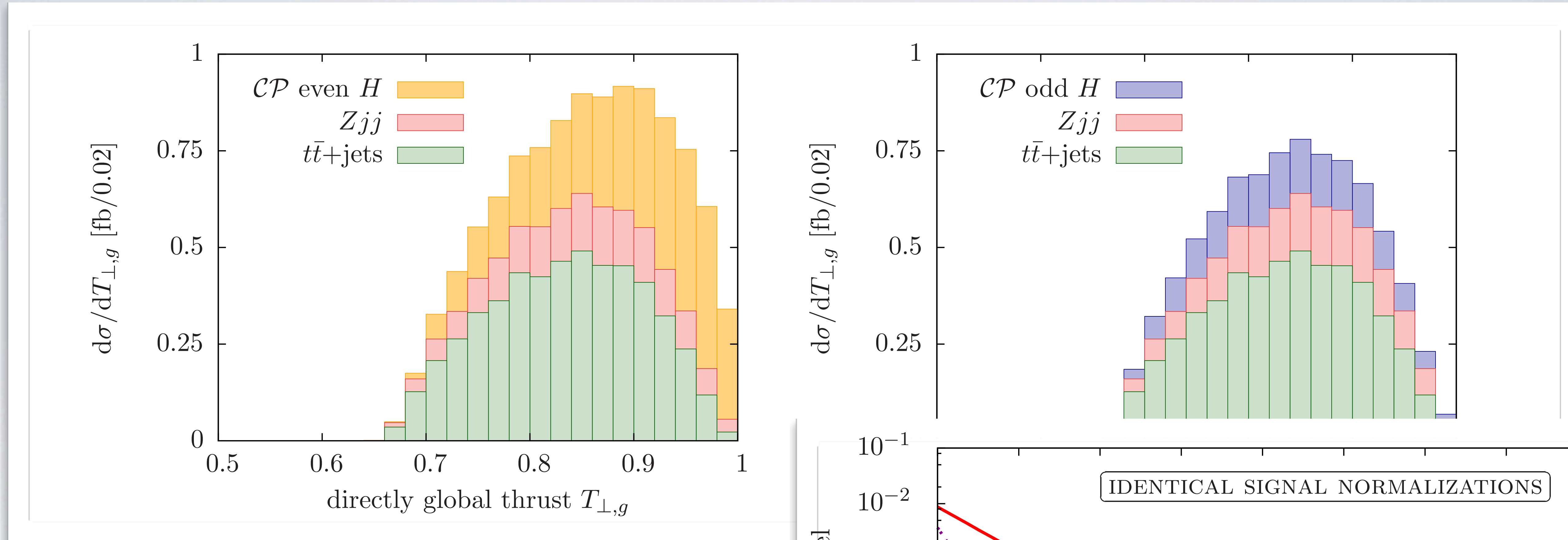


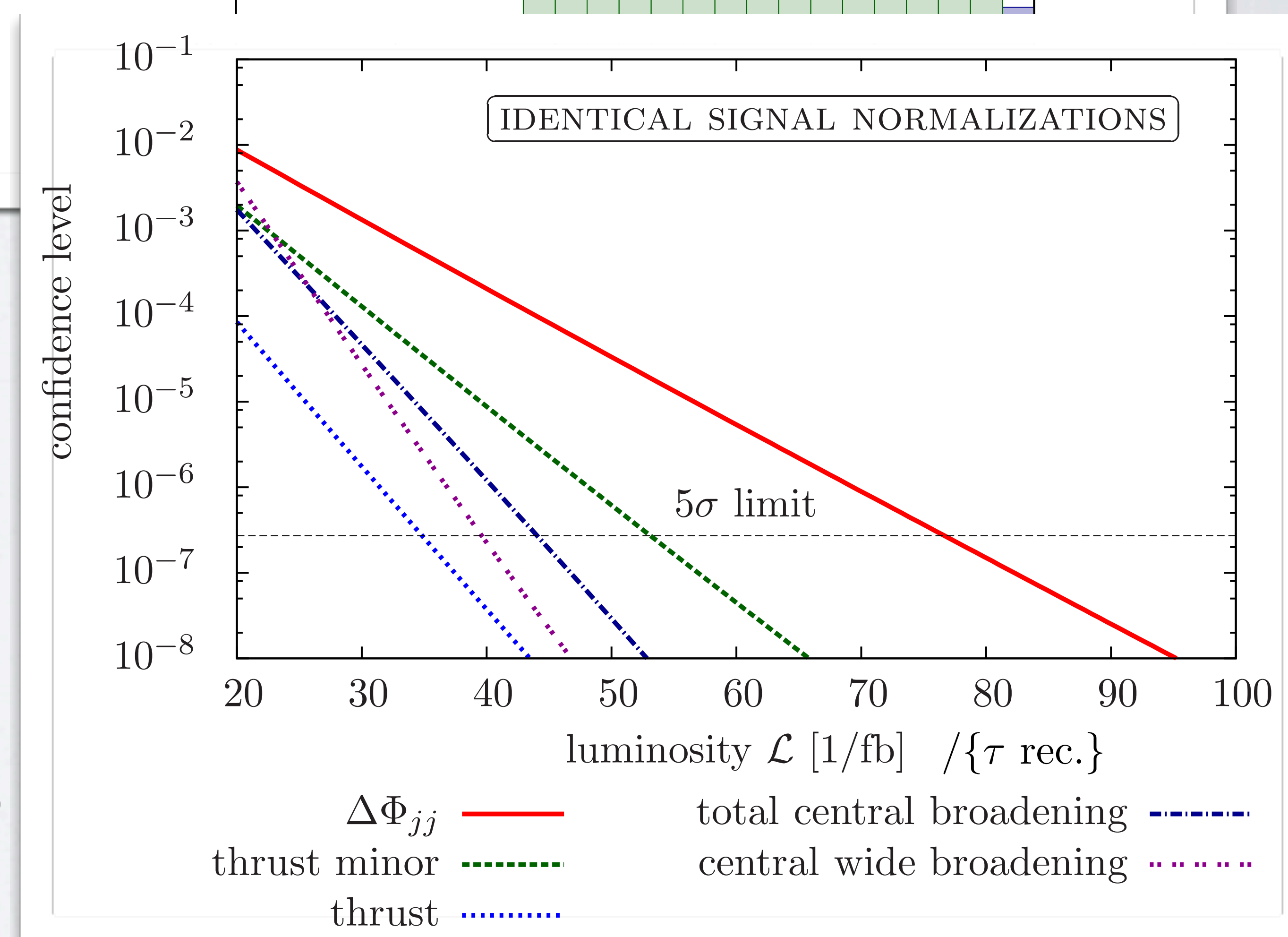
Higgs CP with event shape-like observables

- Event shape observables do much better than $\Delta\Phi_{jj}$ at the inclusive level !



[CE, Spannowsky, Takeuchi '12]

$$T_{\perp,g} = \max_{\mathbf{n}_T} \frac{\sum_i |\mathbf{p}_{\perp,i} \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|} .$$



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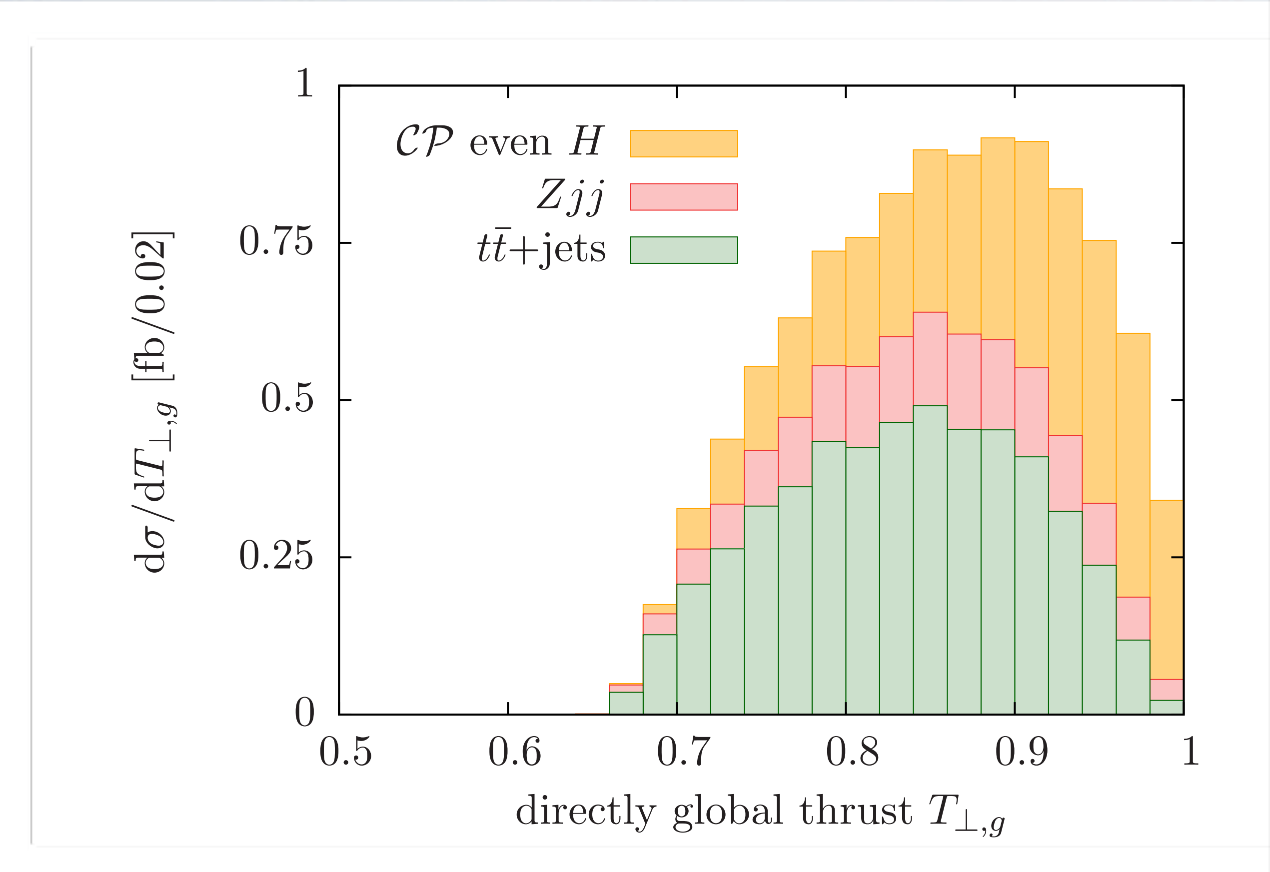

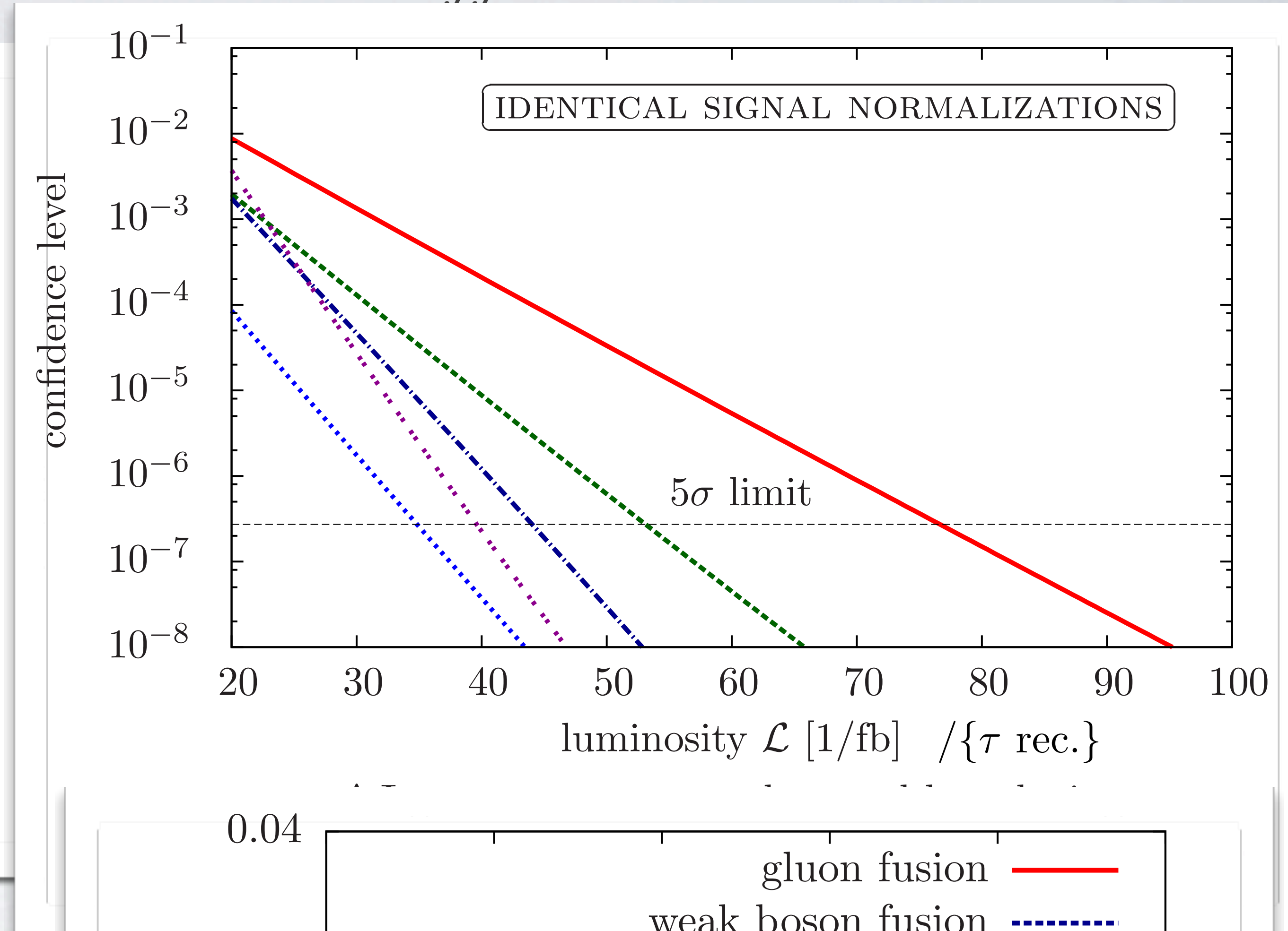

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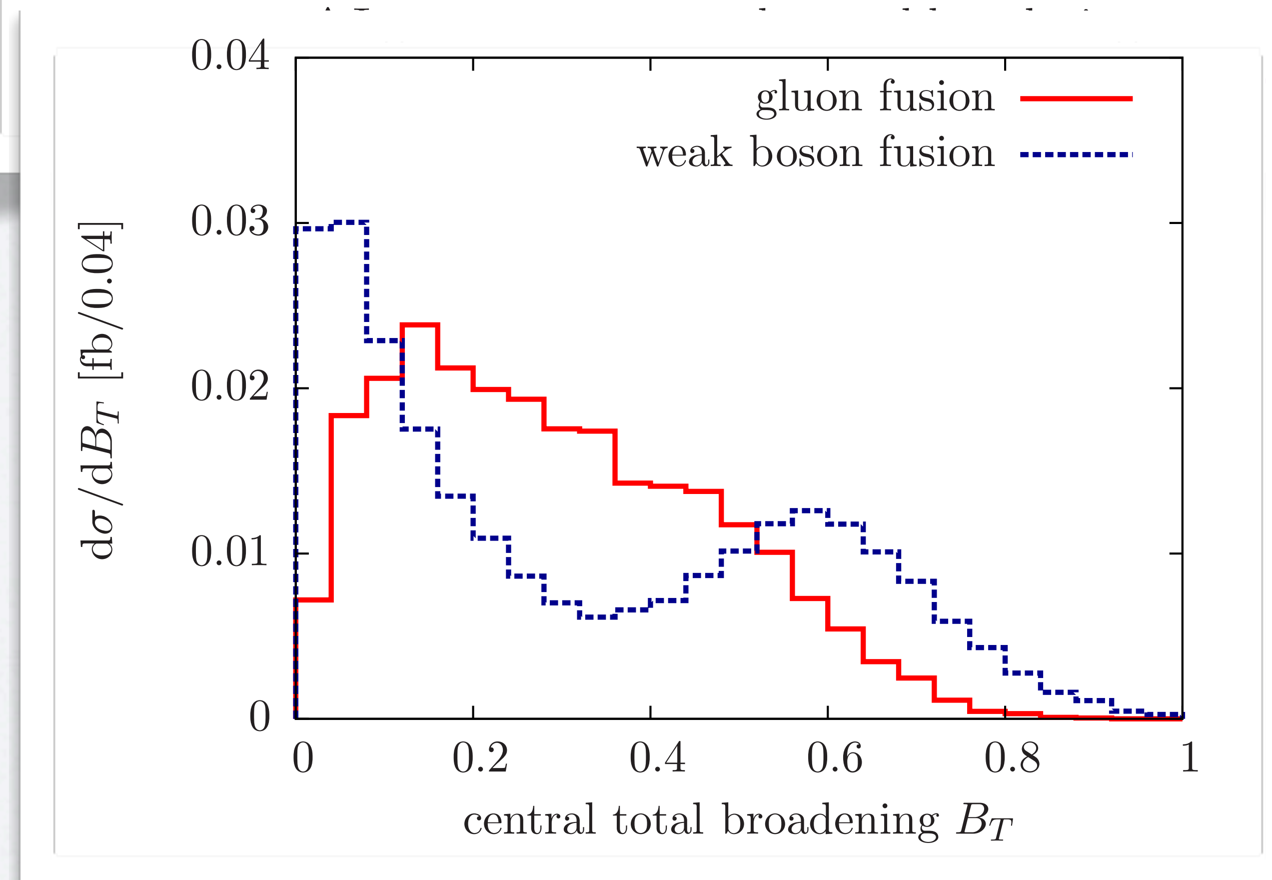


- event shape observables also serve to separate WBF/GF contributions

Why is WBF / GF separation important?

- we always observe superpositions of Higgs boson production

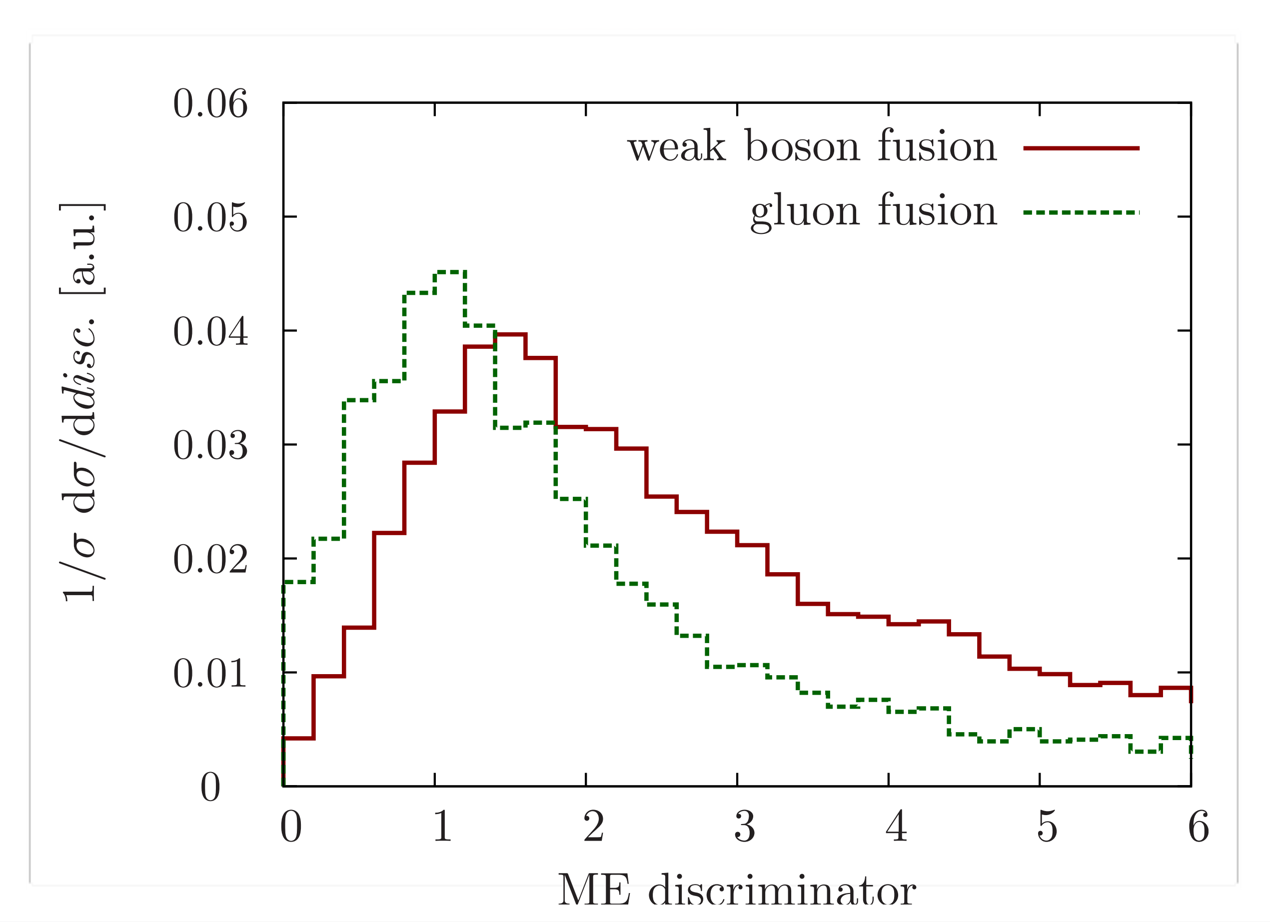
$$\sum_p \sigma_p \times \mathrm{BR}_d \sim \sum_p \frac{\Gamma_p \Gamma_d}{\Gamma_{\mathrm{tot}}} \sim \sum_p \frac{g_p^2 g_d^2}{\sum_{\mathrm{modes}} g_k^2}$$

- GF is sensitive Yukawas, WBF is sensitive to W, Z couplings, same order of magnitude in typical Higgs searches.

- systematic limitation of Higgs coupling extraction!

- alternative to event shapes:
  - use rec. higgs also for discrimination
  - construct likelihood based on matrix elements for fixed multiplicities
  - by definition maximum discrimination

[Andersen, CE, Spannowsky, in prep]



OUTLINE

- A tell-tale story of Higgs physics √
- Higgs couplings √
- Higgs Spin & CP √
- Higgs self-interactions

Self-coupling measurements

$$= \lambda_{\rm SM} = g^2 m_h^2 / m_W^2$$

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

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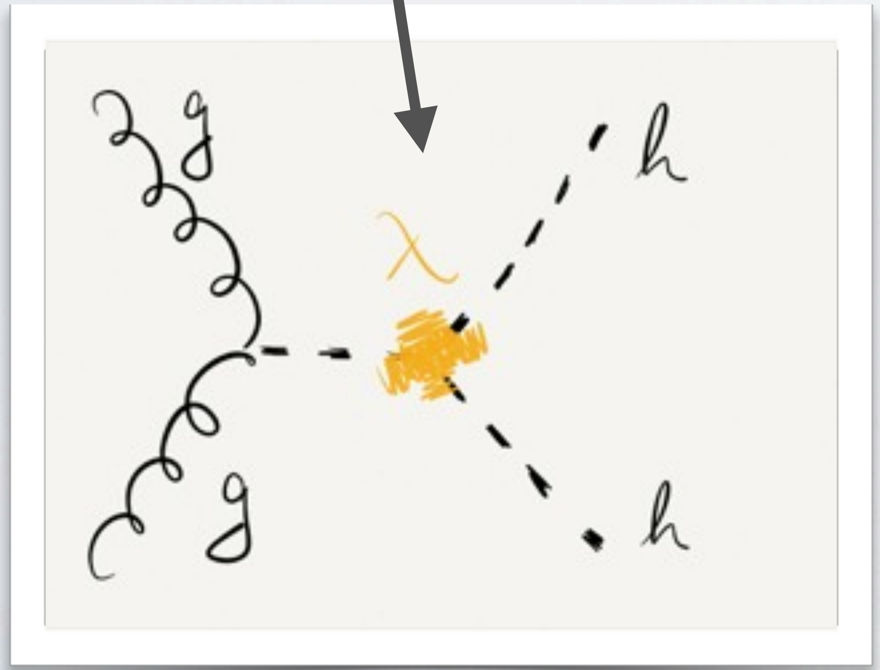

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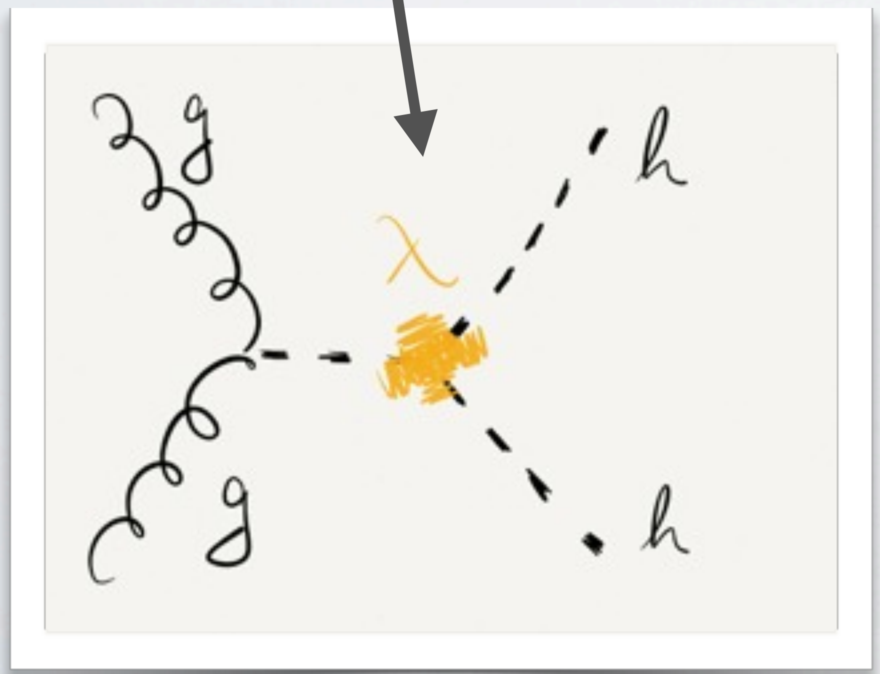

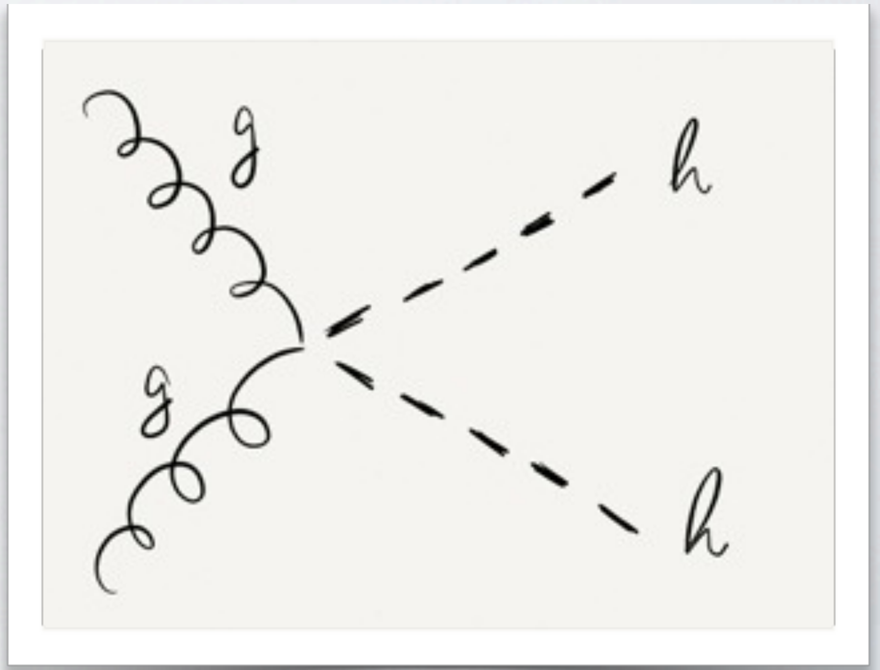

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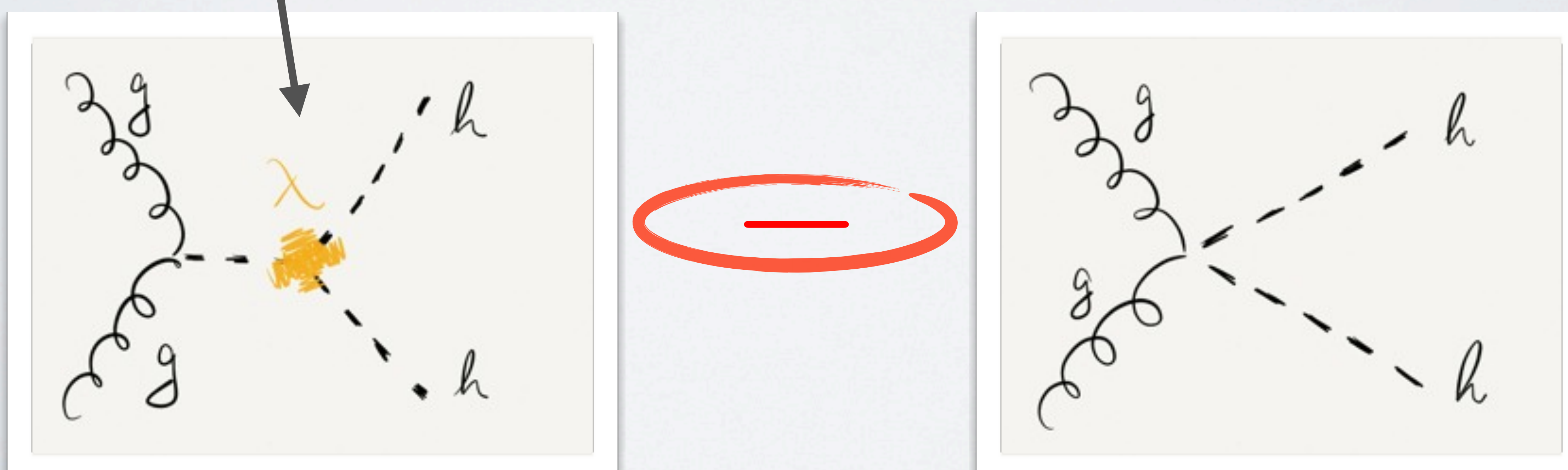

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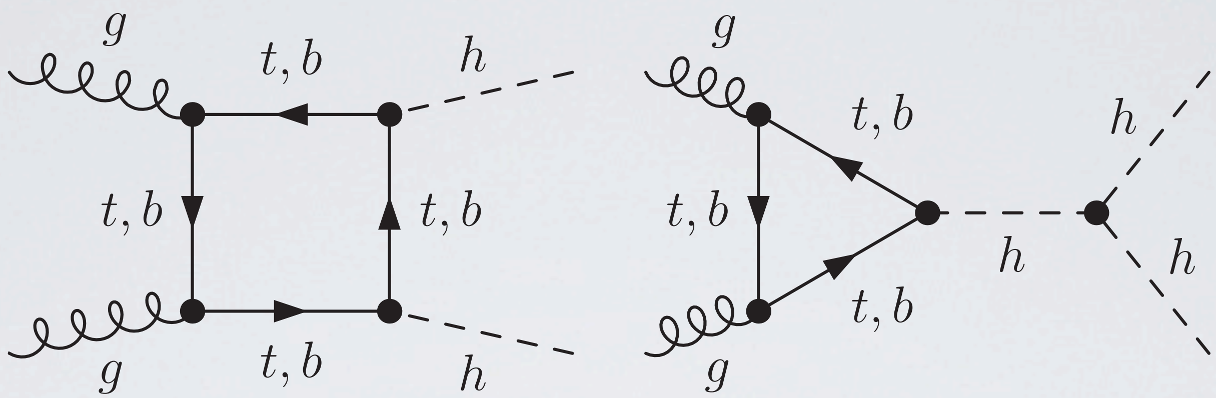
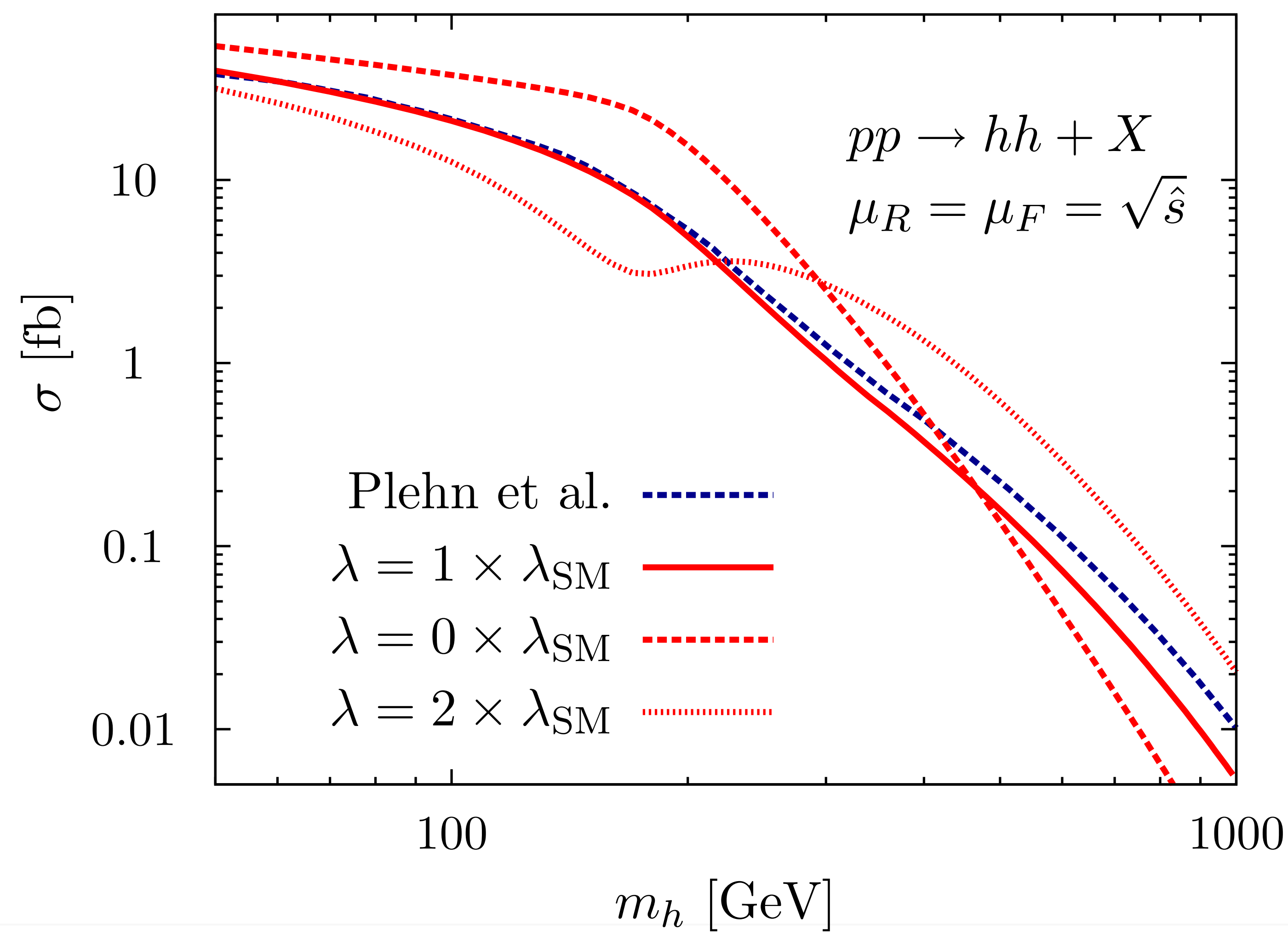


[Plehn, Spira, Zerwas `96] .... [Dolan, CE, Spannowsky `12]



- massive quark loops are resolved for $p_{T,h} \gtrsim m_t$

  [Baur, Plehn, Rainwater `03, `04]

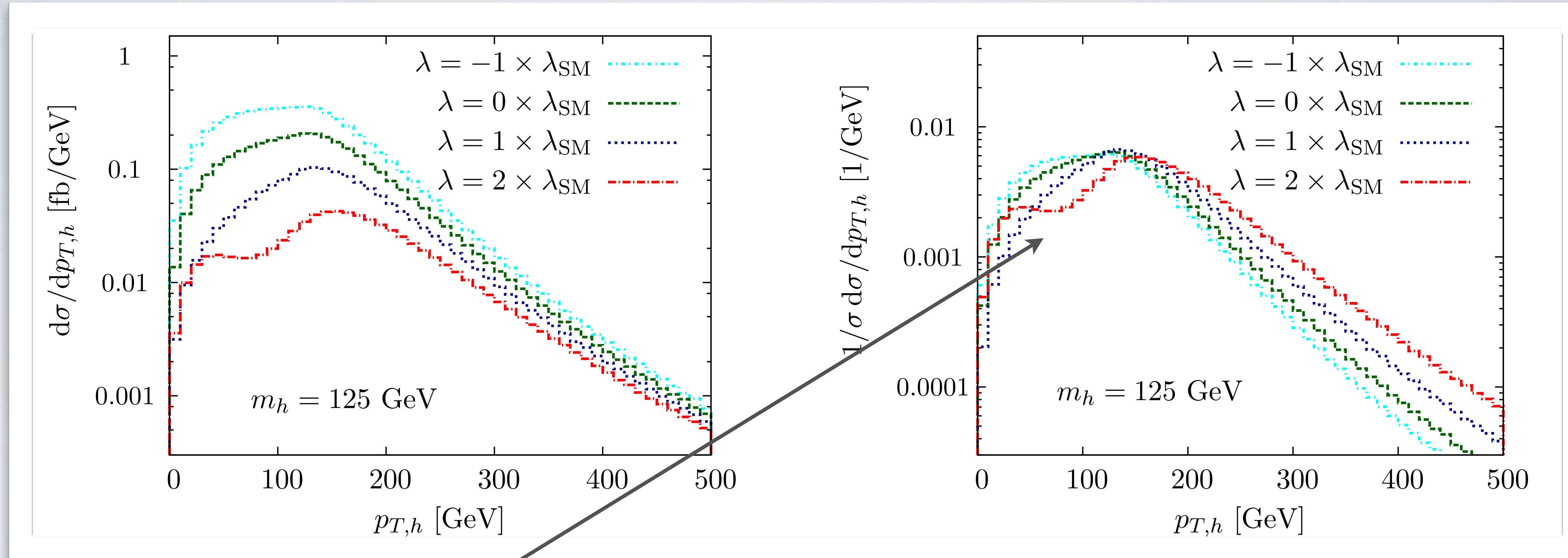
- NLO QCD corrections are large ~2

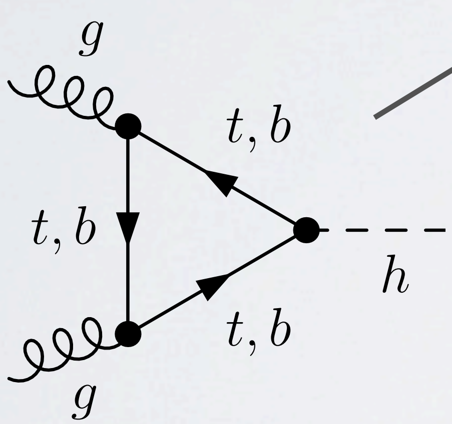
  [Dawson, Dittmaier, Spira `98]

- good *a priori* sensitivity to λ for $m_h = 125$ GeV

Self-coupling measurements

[Dolan, CE, Spannowsky `12]





has maximum contribution for $m_h^2 = 4m_t^2$

[Georgi et al. `78]

for dihiggs production this becomes $s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$

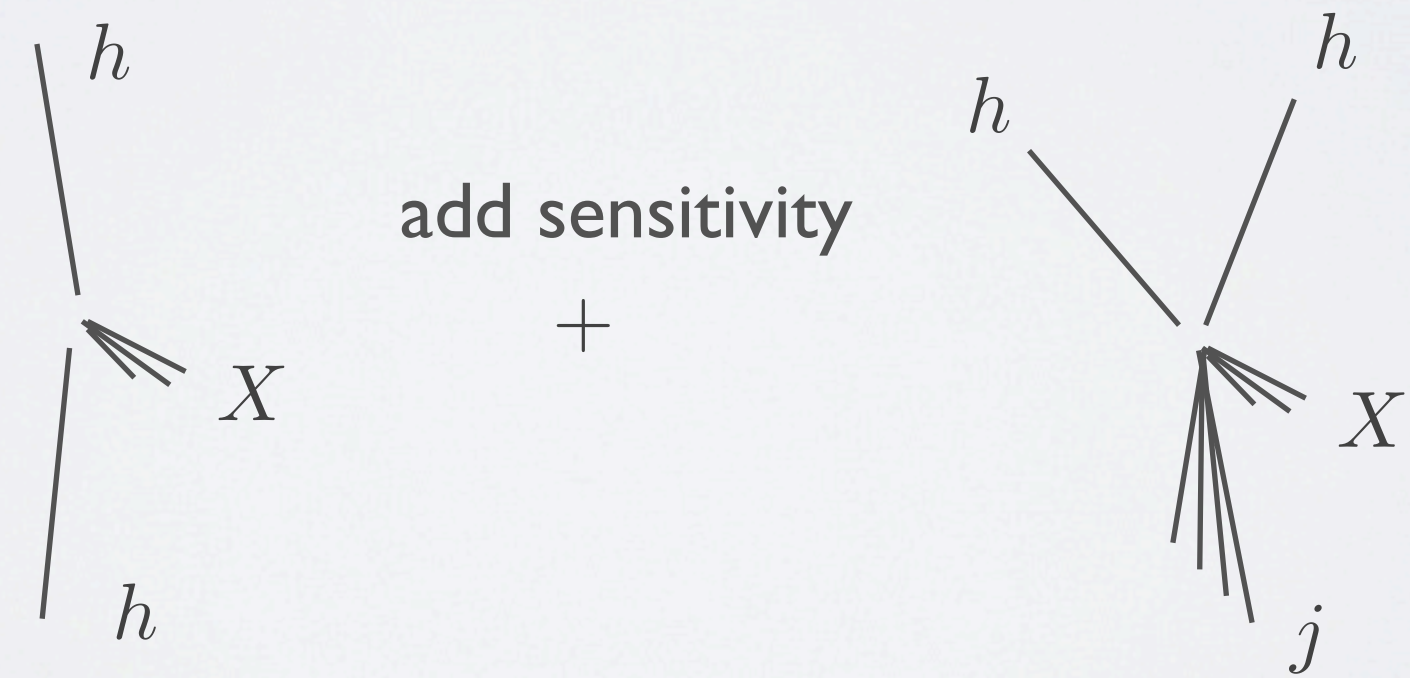
sensitivity to the trilinear coupling for $m_h \simeq 125$ GeV is in the <u>boosted regime</u>

Self-coupling measurements with “ISR”

[Dolan, CE, Spannowsky `12]

- inclusive cross sections are small, need as many channels as possible to improve constraints!
- phase space in inclusive dihiggs production is limited due to small phase space for the back-to-back configuration at rather small invariant masses $2m_t$
- open up the phase space by accessing small invariant masses in a collinear configuration:

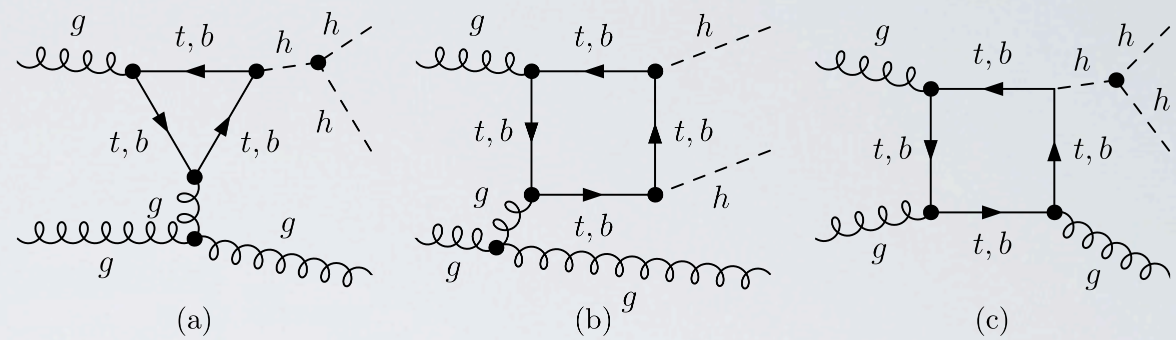
[Campanario, CE, Spannowsky `11]

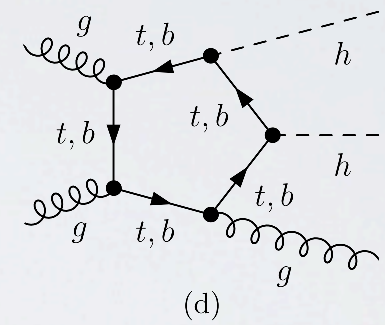


Self-coupling measurements with "ISR"

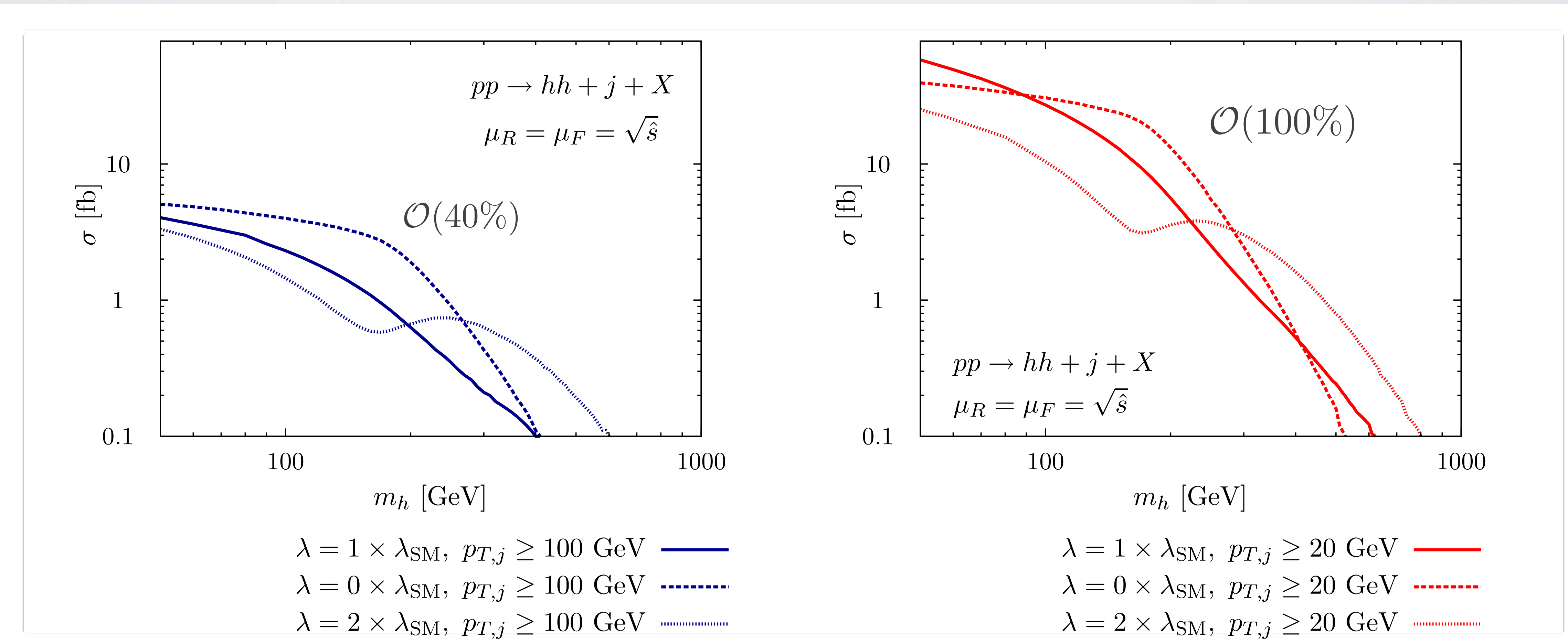
[Dolan, CE, Spannowsky `12]

- need to work a little harder:





+ quark & gluon induced



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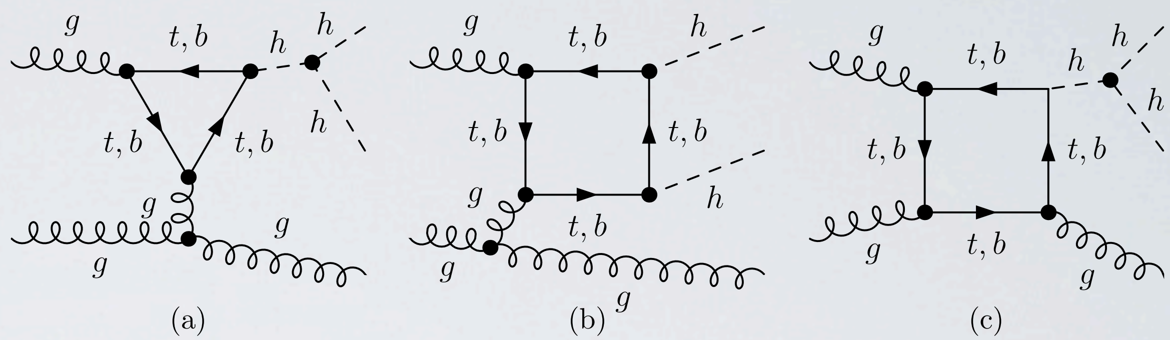

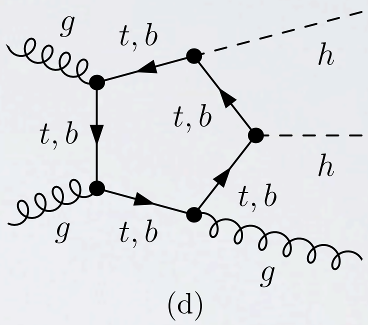

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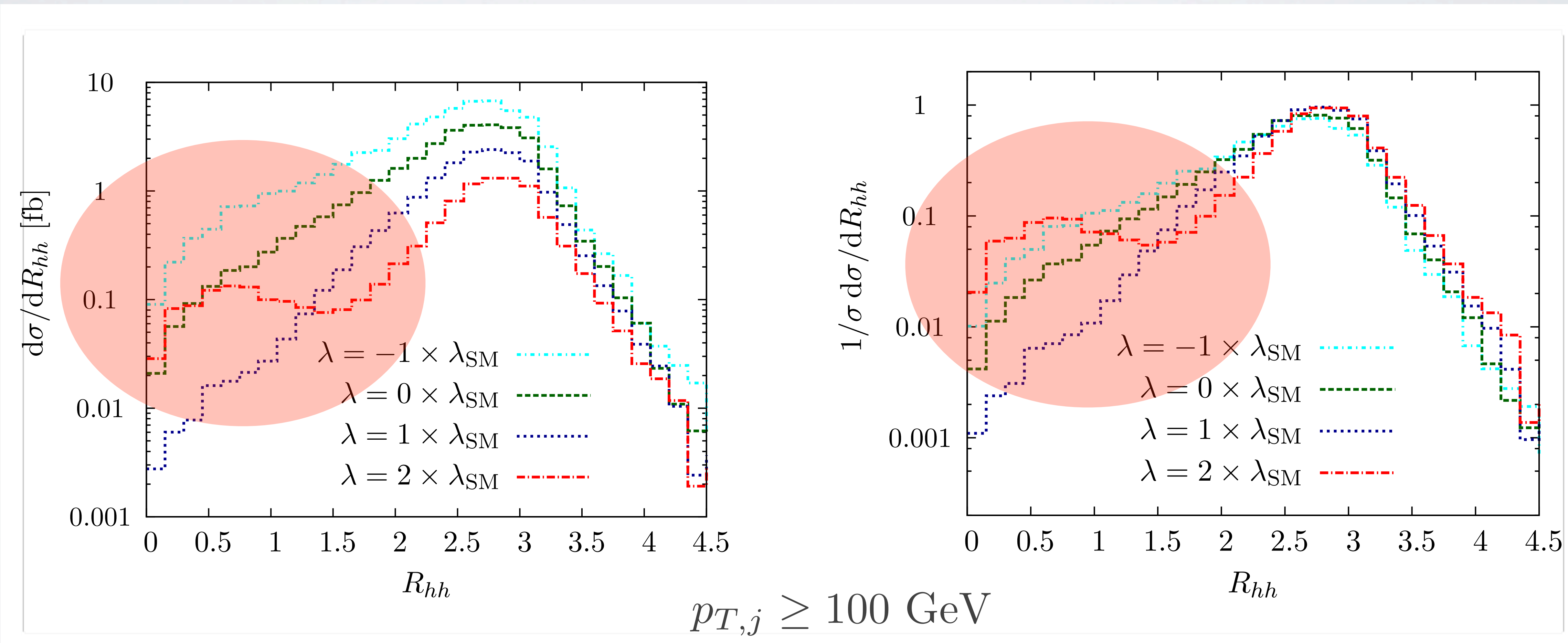
sensitivity at small invariant masses and small dihiggs opening angles



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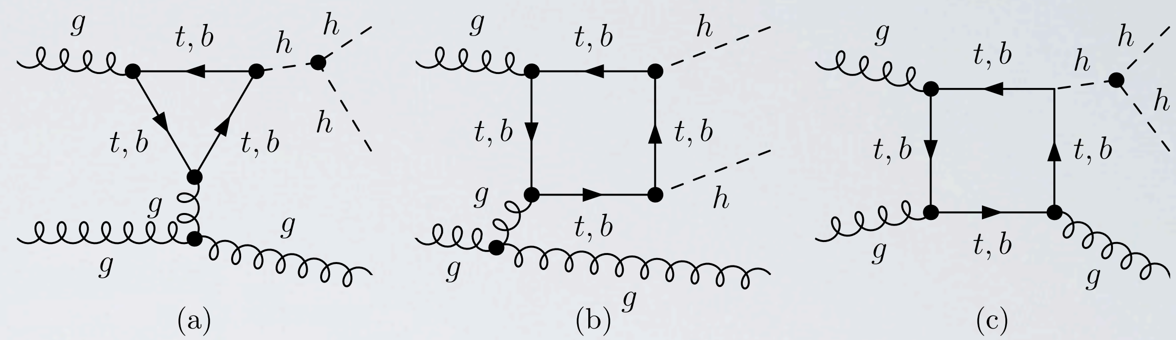

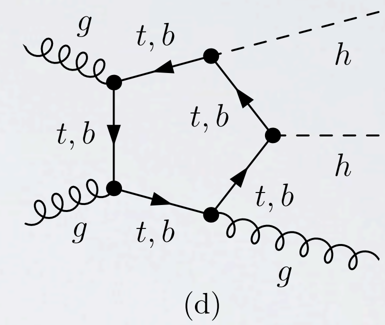

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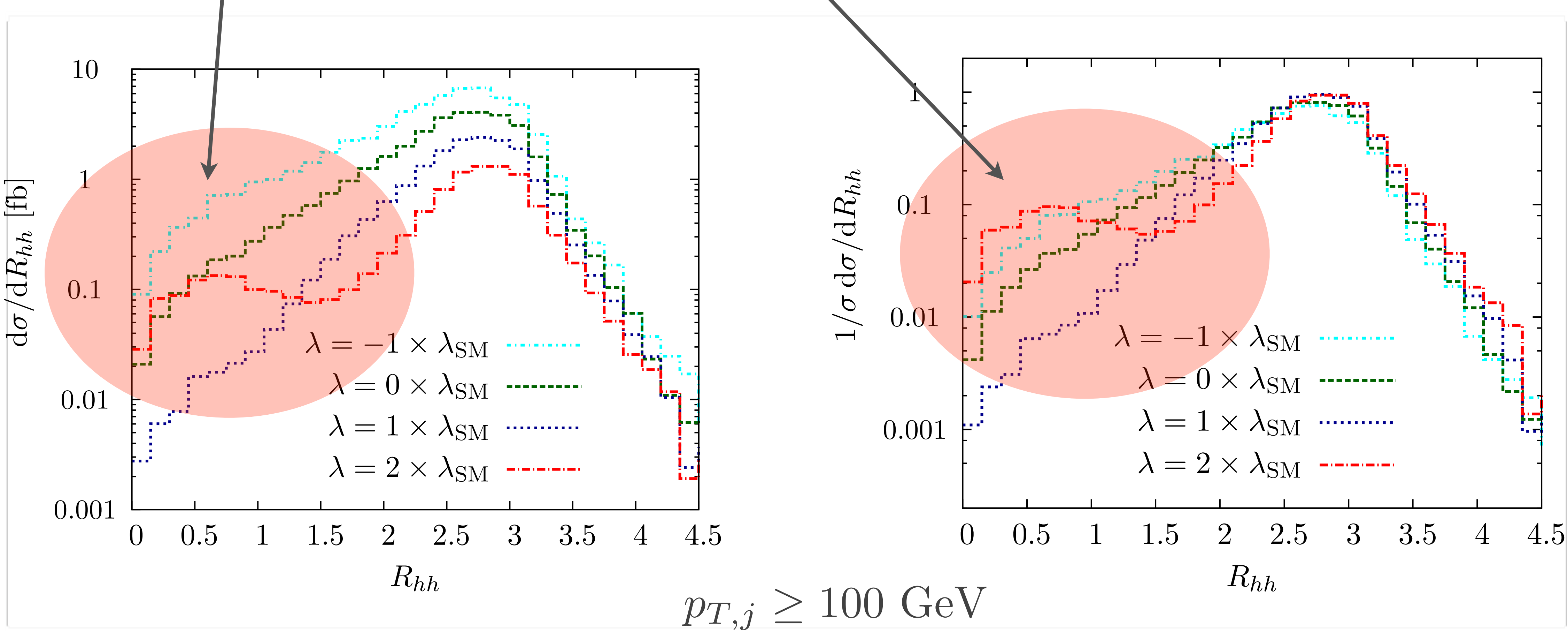
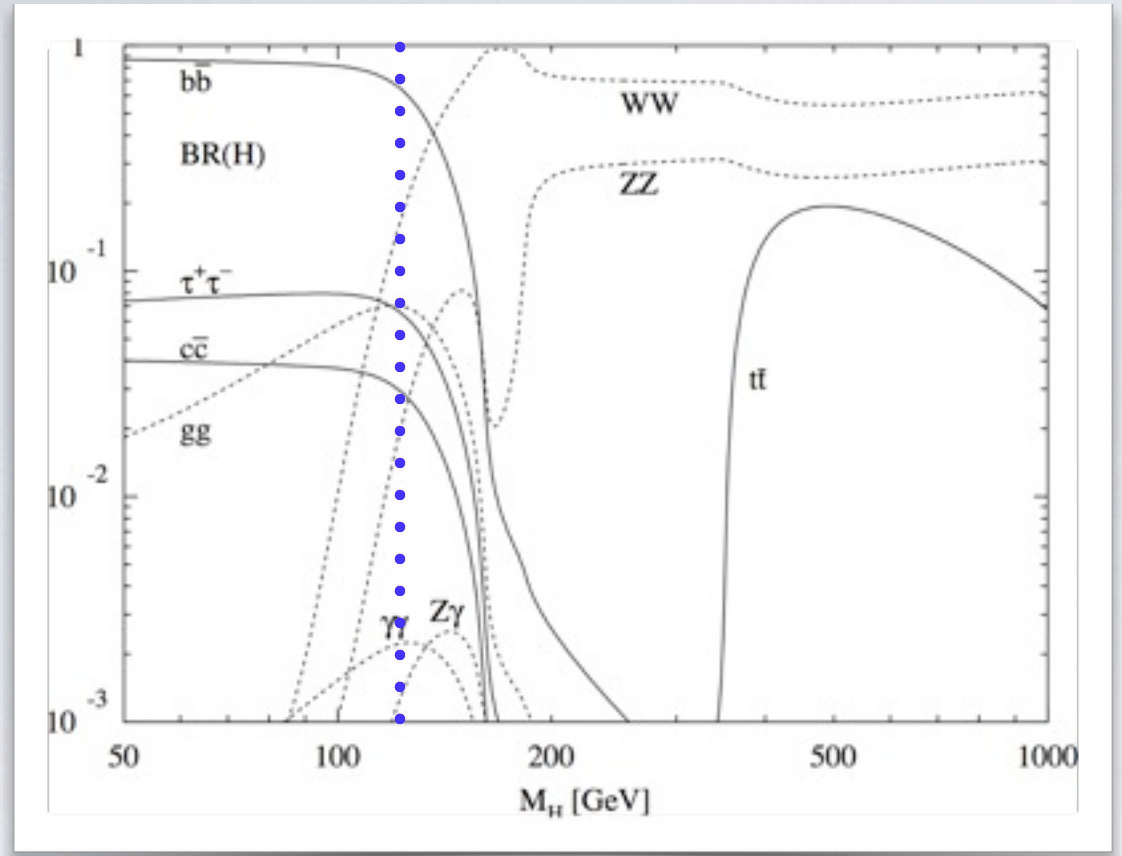
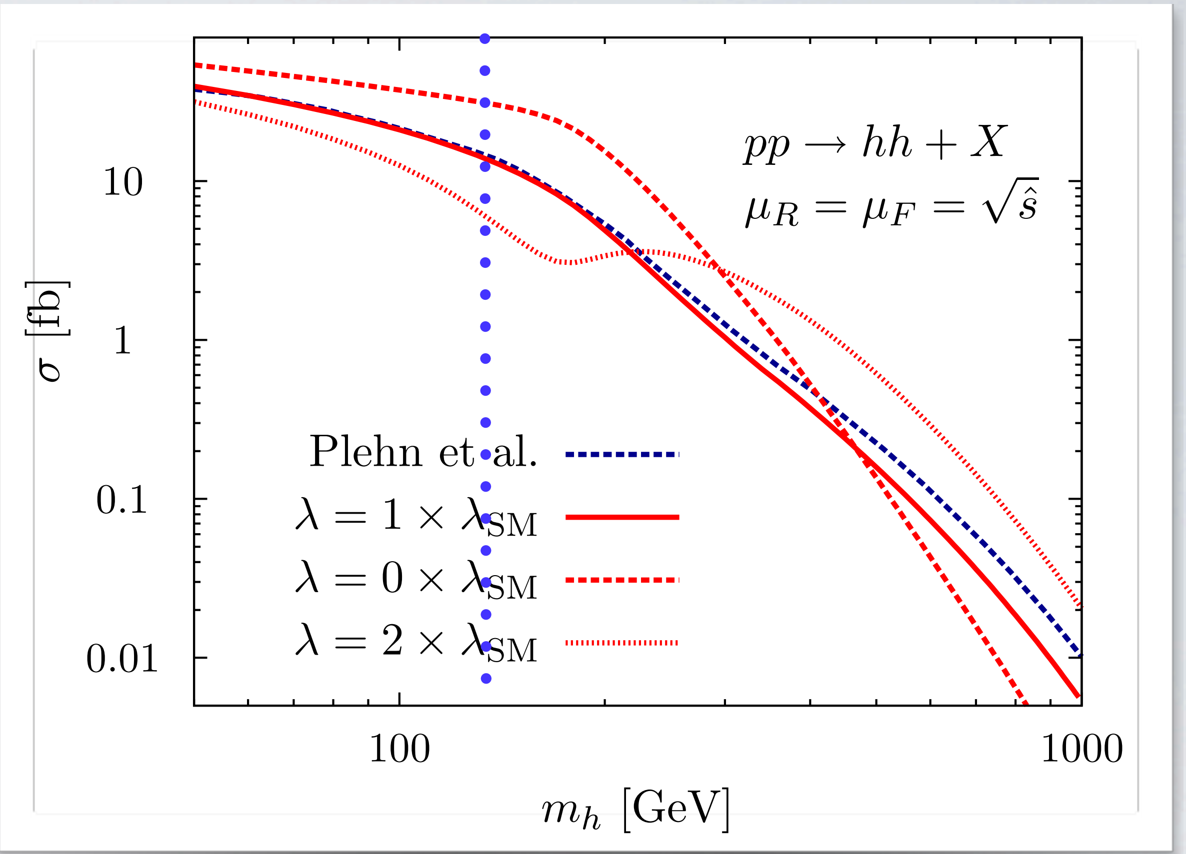


Self-coupling measurements at the hadron level





- We're dealing with small xsections, hence need to look for large BRs for theoretical improvements: $h \to b\bar{b}, W^+W^-, \tau^+\tau^-$
- MC with unweighted event output for $pp \to hh + X,\ pp \to hh + j + X$ interfaced to Herwig++ [Bähr et al. \`08] for shower & hadronization
- backgrounds from MadEvent [Alwall et al. \`11] and Sherpa [Gleisberg et al. \`09]
- apply fatjet/subjet methods [Butterworth et al. \`08]

Self-coupling measurements at the hadron level

- unboosted searches hopeless execpt for $b\bar{b}\gamma\gamma$ [Baur, Plehn, Rainwater `03, `04]
- boosted searches better

$m_h = 125$ GeV

$bb\tau\tau$ (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	$3.2\cdot10^{-5}$
reconstructed Higgs from τs	4.05	1.94	0.91	2.51	1.10	1507.99	$1.9\cdot10^{-3}$
fatjet cuts	2.27	1.09	0.65	1.29	0.84	223.21	$4.8\cdot10^{-3}$
kinematic Higgs reconstruction ($m_{b\bar{b}}$)	0.41	0.26	0.15	0.104	0.047	9.50	$2.3\cdot10^{-2}$
Higgs with double b-tag	0.148	0.095	0.053	0.028	0.020	0.15	0.48

$bb\tau\tau + j$ (assuming small tau fake rate) [Dolan, CE, Spannowsky `12]

	$\xi=0$	$\xi=1$	$\xi=2$	$b\bar{b}\tau^+\tau^-j$	$b\bar{b}\tau^+\tau^-j$ [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	$1.9\cdot10^{-2}$
2 τs	0.44	0.22	0.12	37.0	0.94	7.44	$4.8\cdot10^{-3}$
Higgs rec. from taus + fatjet cuts	0.29	0.16	0.10	2.00	0.150	0.947	$5.1\cdot10^{-2}$
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

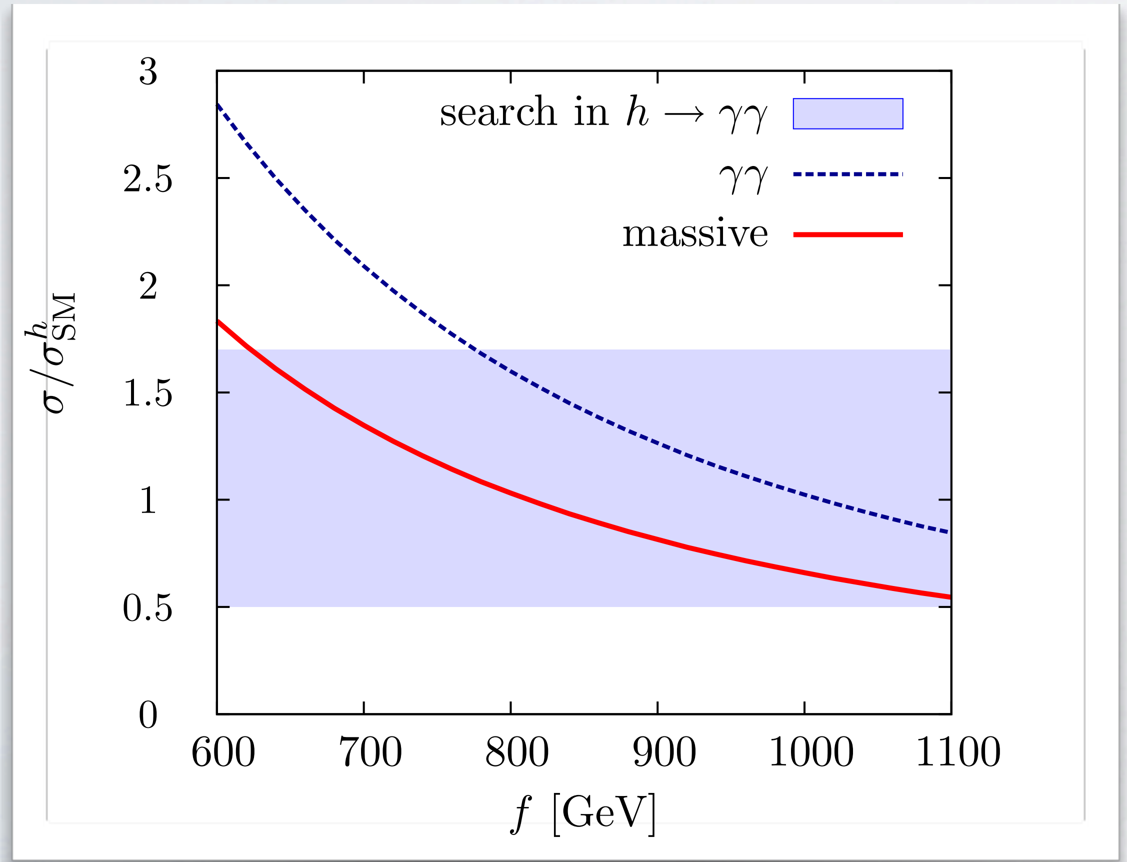
What about Higgs boson imposters / BSM Higgs sectors ?

[Dolan, CE, Spannowsky, in prep.]

Dilaton

- PNGB of spontaneously broken conformal invariance
- couples to

$$T^\mu_\mu \sim m_W^2 W^+_\mu W^{-\,\mu} + \frac{m_w^2}{\cos^2\theta_w} Z_\mu Z^\mu + \sum_f m_f \bar{f} f + \ldots$$

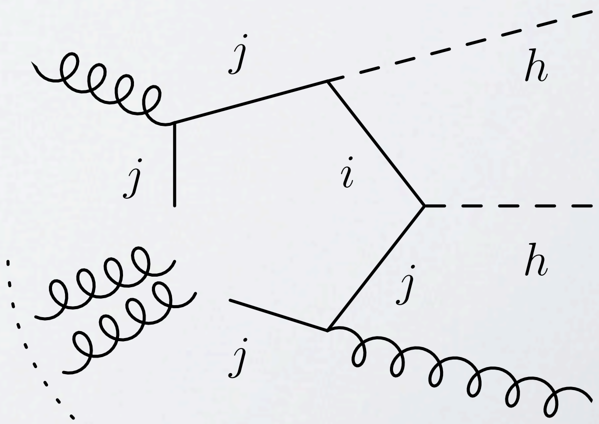


composite Higgs

- entire Higgs doublet is a set of NGB, e.g.

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$

- gauging a subgroup: breaking global invariance and the NGB picks up a mass + EWSB
- partial compositness: heavy fermions through mixing
- new heavy fermionic resonances

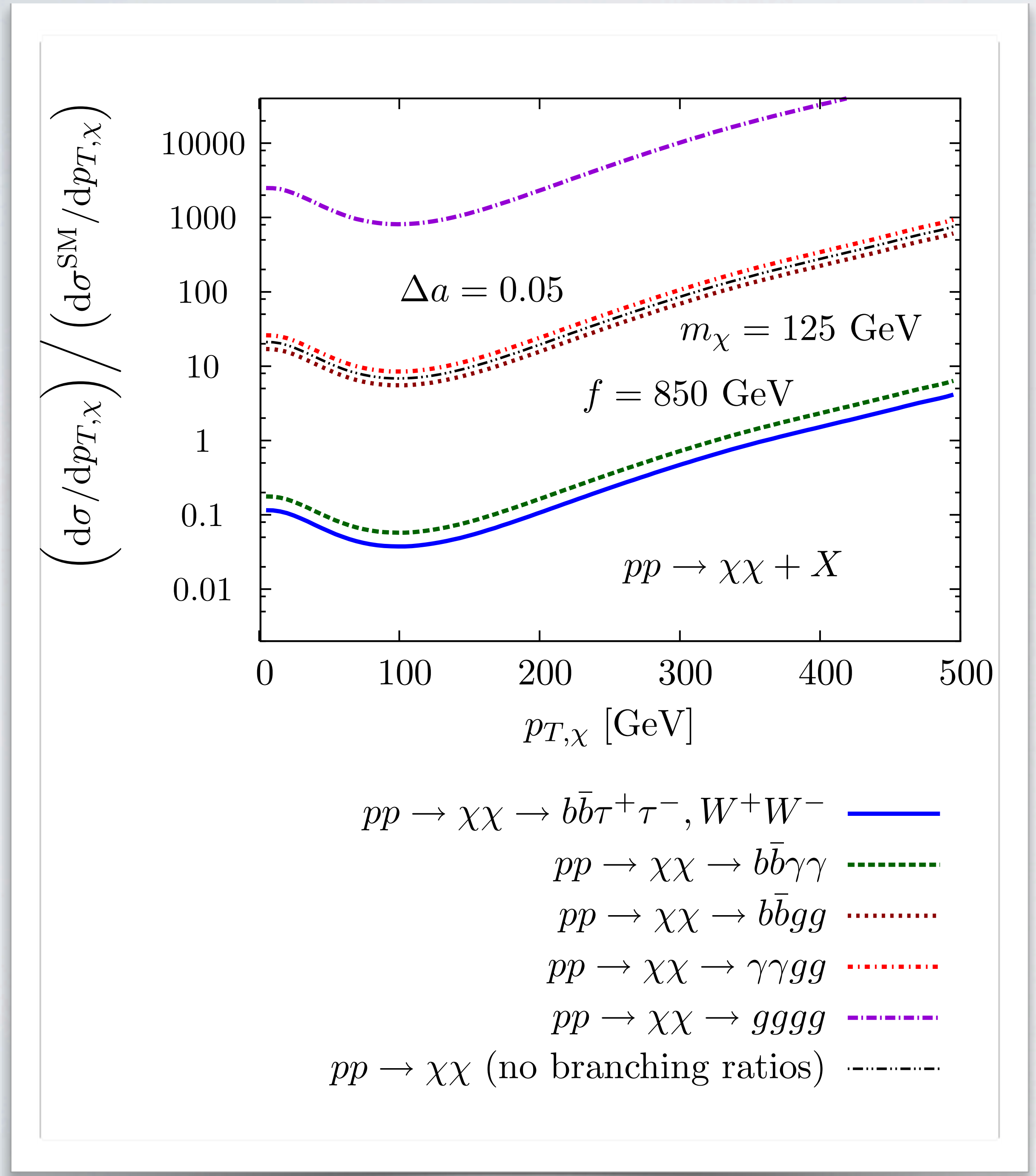


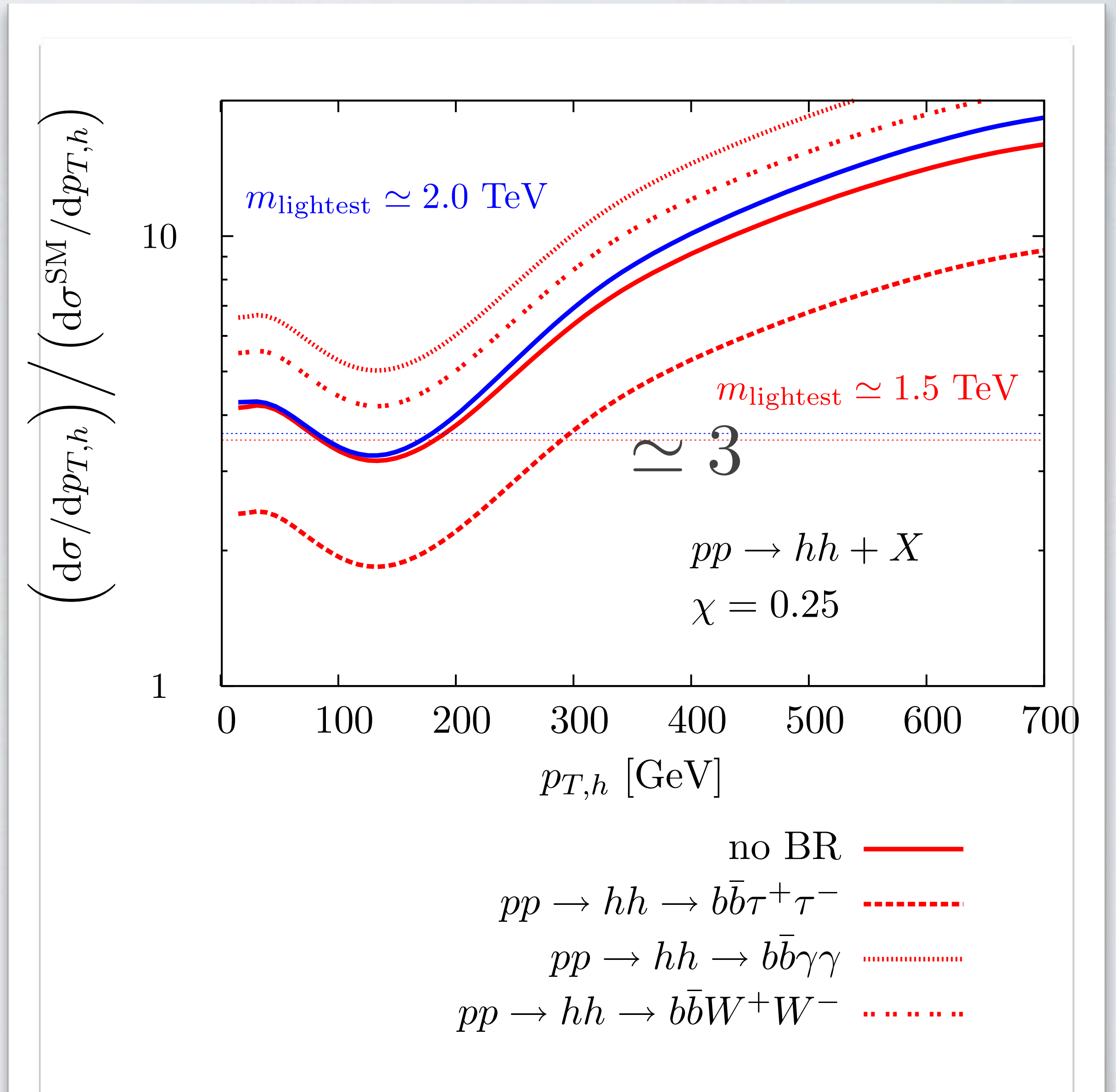
What about Higgs boson imposters / BSM Higgs sectors

[Dolan, CE, Spannowsky, in prep.]

Dilaton **composite Higgs**

entirely different di-"Higgs" phenomenology





$$\sigma(hh+j)/\sigma(\mathrm{SM}) \simeq 4.6 \text{ !!!}$$

SUMMARY

- Well, this one we ordered and we finally got it

- .... but this is not the end!

- What are the properties of this resonance? Is it really a 30 yr old idea coming to life, or is it something more involved?

time ↓

  - spin and CP
  - couplings, (exotic) branching ratios
  - reconstruction of the symmetry-breaking potential

- New insights in phenomenological QCD and its interplay with the ELW sector allows to sharpen the LHC search potential

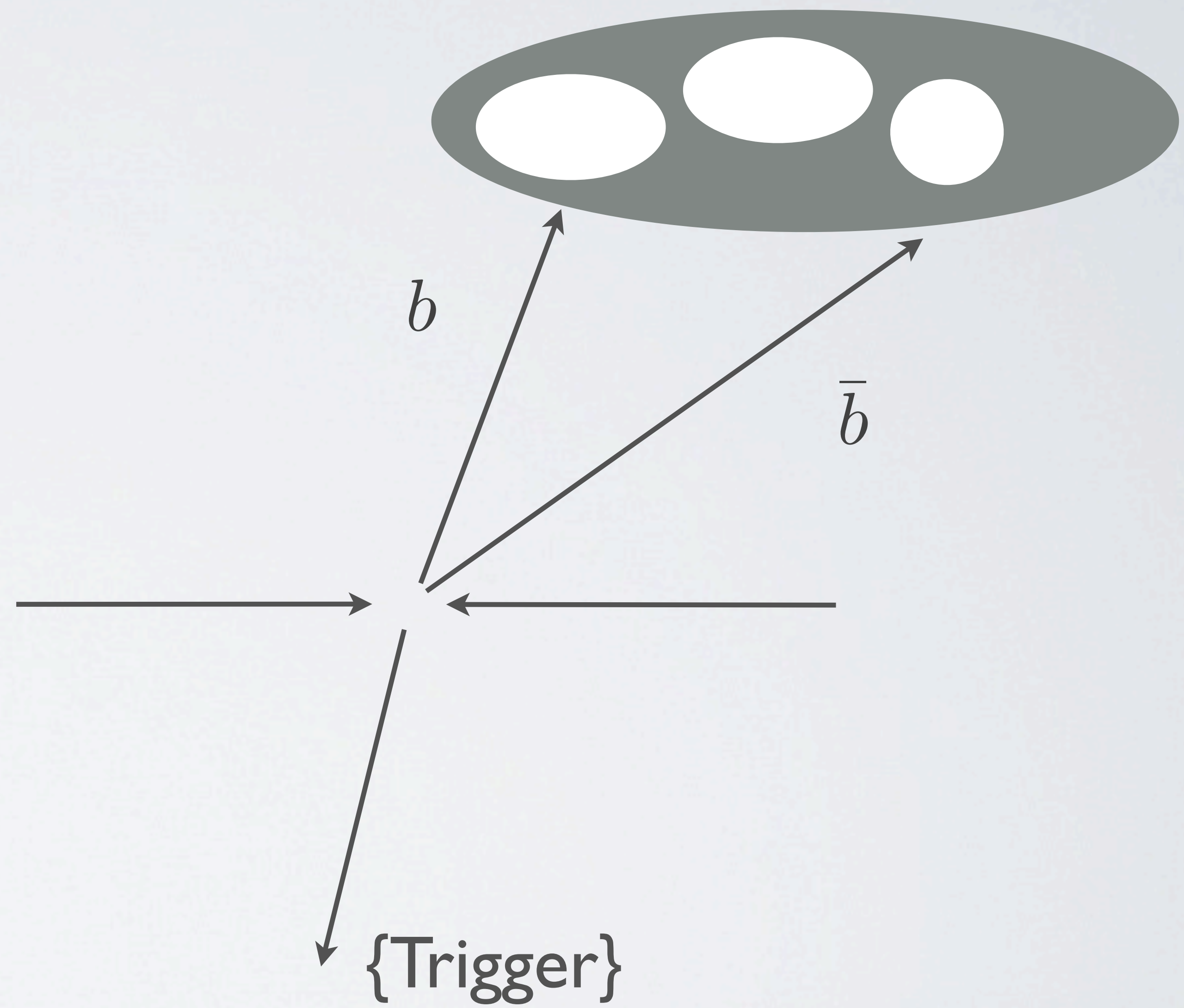
  - subjet technology
  - (non-global) event shape observables, matrix element method

BACKUP

Higgs subjet taggers in a nutshell

- apply fatjet/subjet methods (in a nutshell) [Butterworth, Davison, Rubin, Salam `08]

$R = 1.2 \ldots 1.5$



1. mass drop $m_{j_1} < 0.66 m_j$

2. check asymmetry

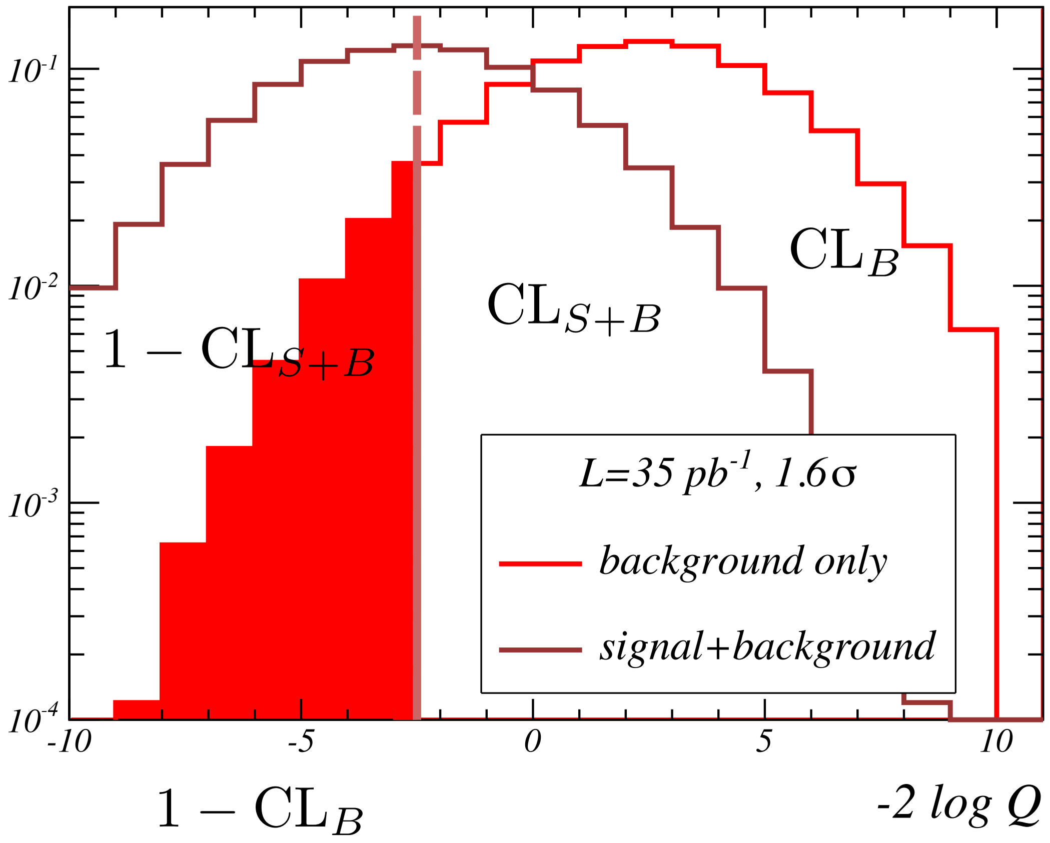
$$\frac{\min(p_{T,j1}^2, p_{T,j2}^2)}{m_j^2} \Delta R_{j1,j2}^2 > y_{\rm cut}$$

3. apply "filtering" to clean up UEV

4. take 3 hardest subjets

5. b tagging on the two hardest ones

Comparing phenomenology: the CL_S method



$1-\mathrm{CL}_{S+B}$	discovery potential
CL_{S+B}	false rejection (type II error)
CL_B	exclusion potential
$1-\mathrm{CL}_B$	false discovery (type I error)

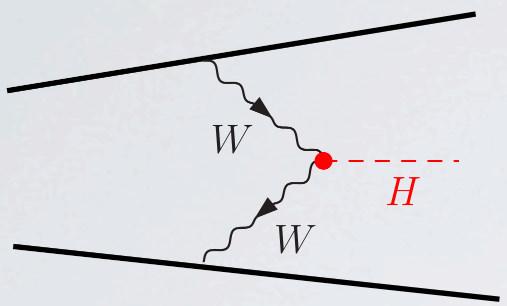
A modified Frequentist analysis: the CL_S method [LEPHWG '98] [Read '00]

- data gives a downward fluctuation wrst to "B" $\rightsquigarrow$ exclusion of $\sigma(S)=0$ at 95% CL
- this is a statement about observing a similar or stronger exclusion in the future, not about the existence of "S" however
- $\mathrm{CL}_S = \mathrm{CL}_{S+B}/\mathrm{CL}_B$ and define confidence $1-\mathrm{CL}_S \geq \mathrm{CL}$

exclusion @ 95%: $\mathrm{CL}_s \leq 0.05$ — false exclusion is not more than 5% of the potential exclusion

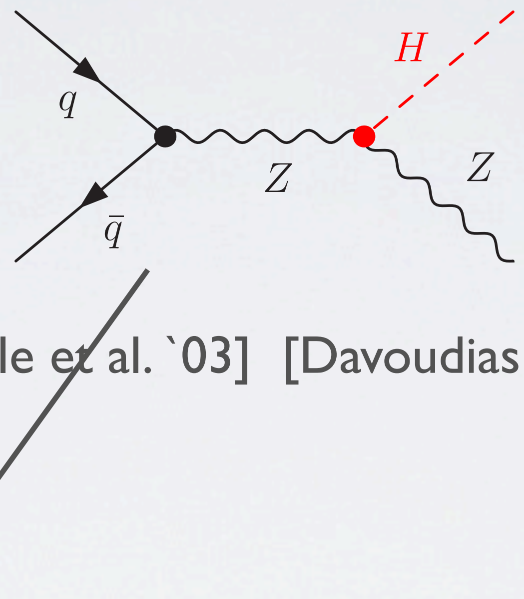
invisible Higgs boson searches at the LHC

weak boson fusion



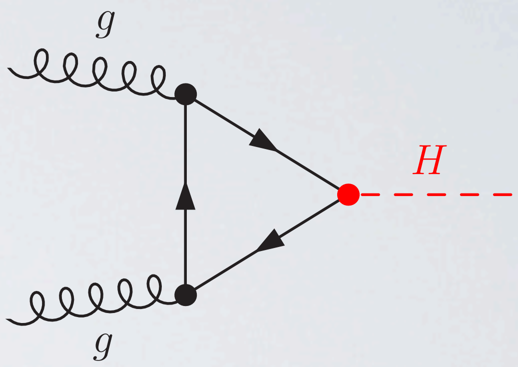
[Eboli, Zeppenfeld `00]

associated production



[Godbole et al. `03] [Davoudiasl et al. '05]

gluon fusion



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theoretically & experimentally challenged:
pile up, systematics of CJV, forward JES

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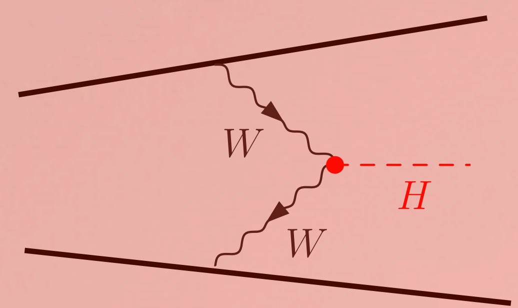

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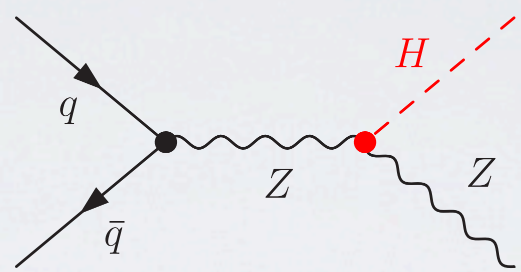

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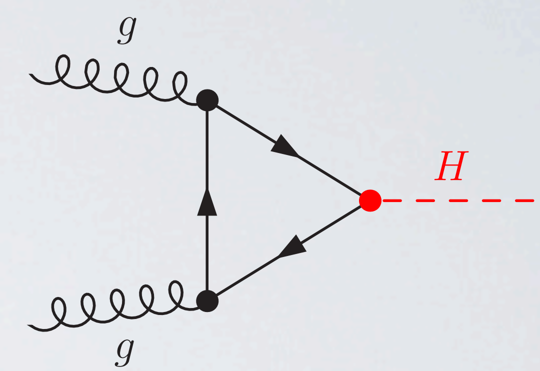

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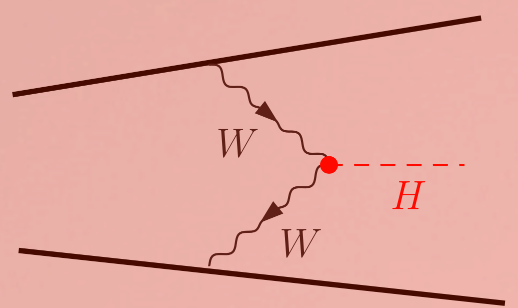

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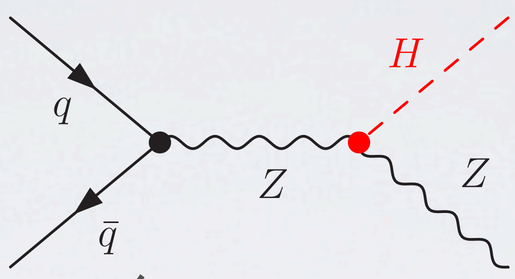

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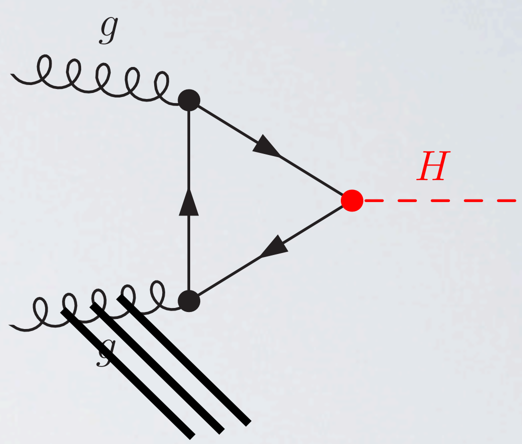

Initial state radiation

[CE, Jaeckel, Re, Spannowsky `11]

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[Atlas Conf 2011-096]

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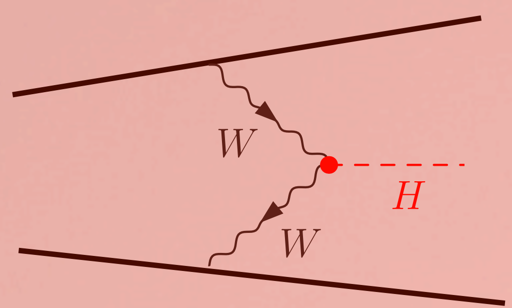

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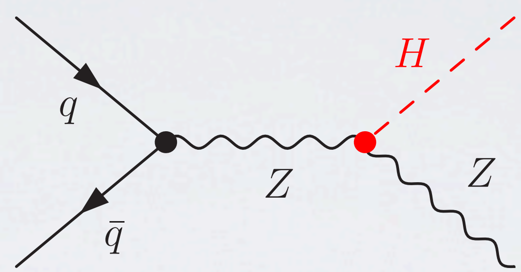

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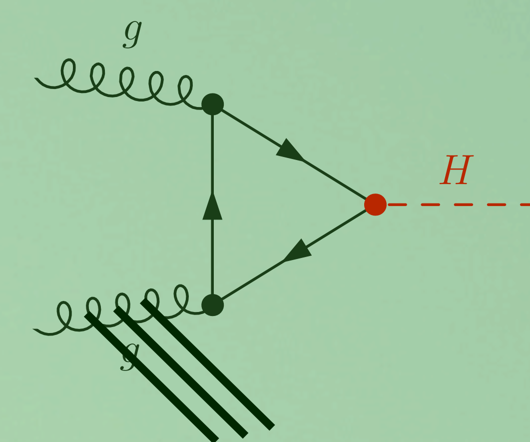

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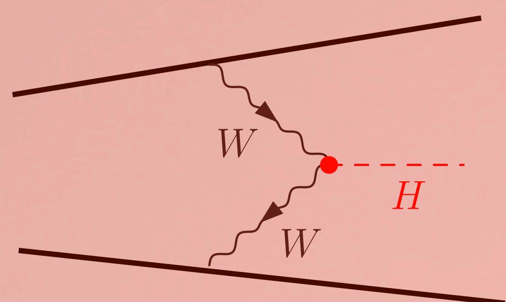

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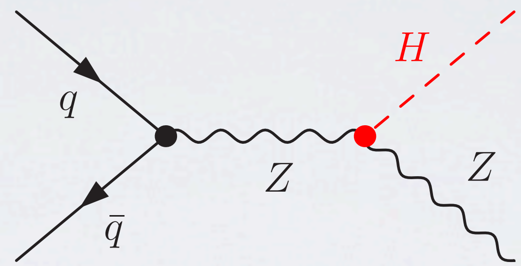

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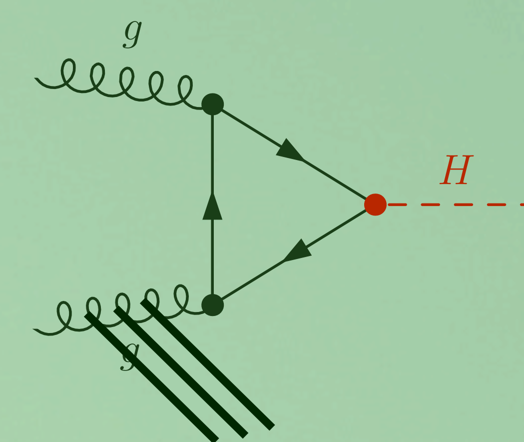
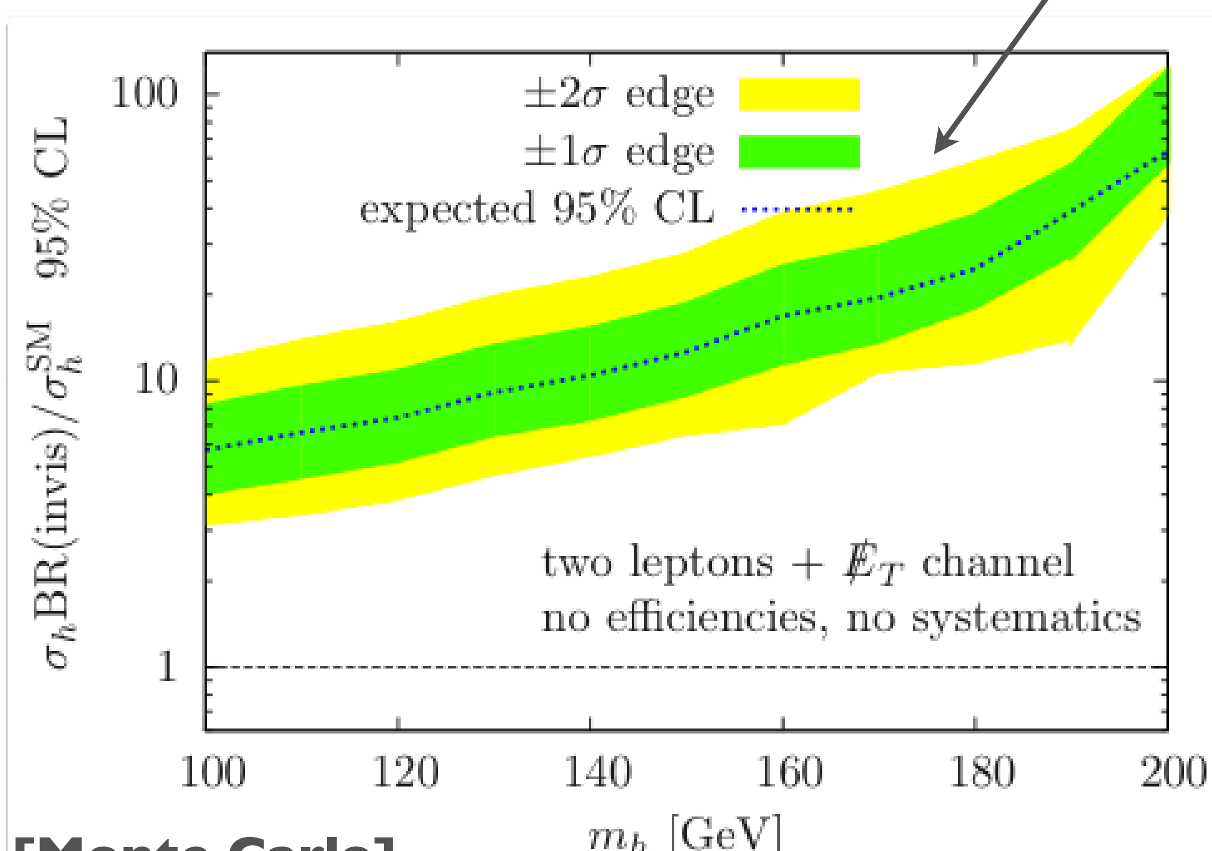
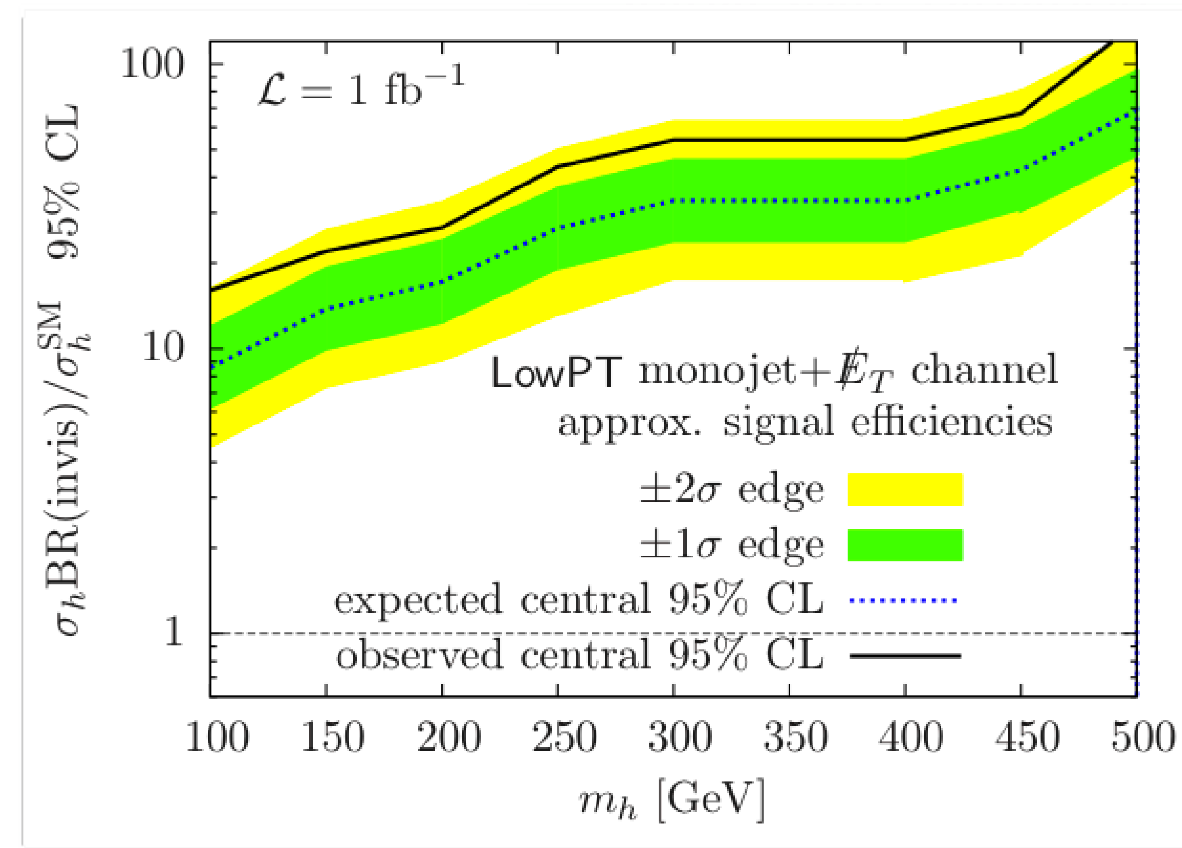




[Monte Carlo]



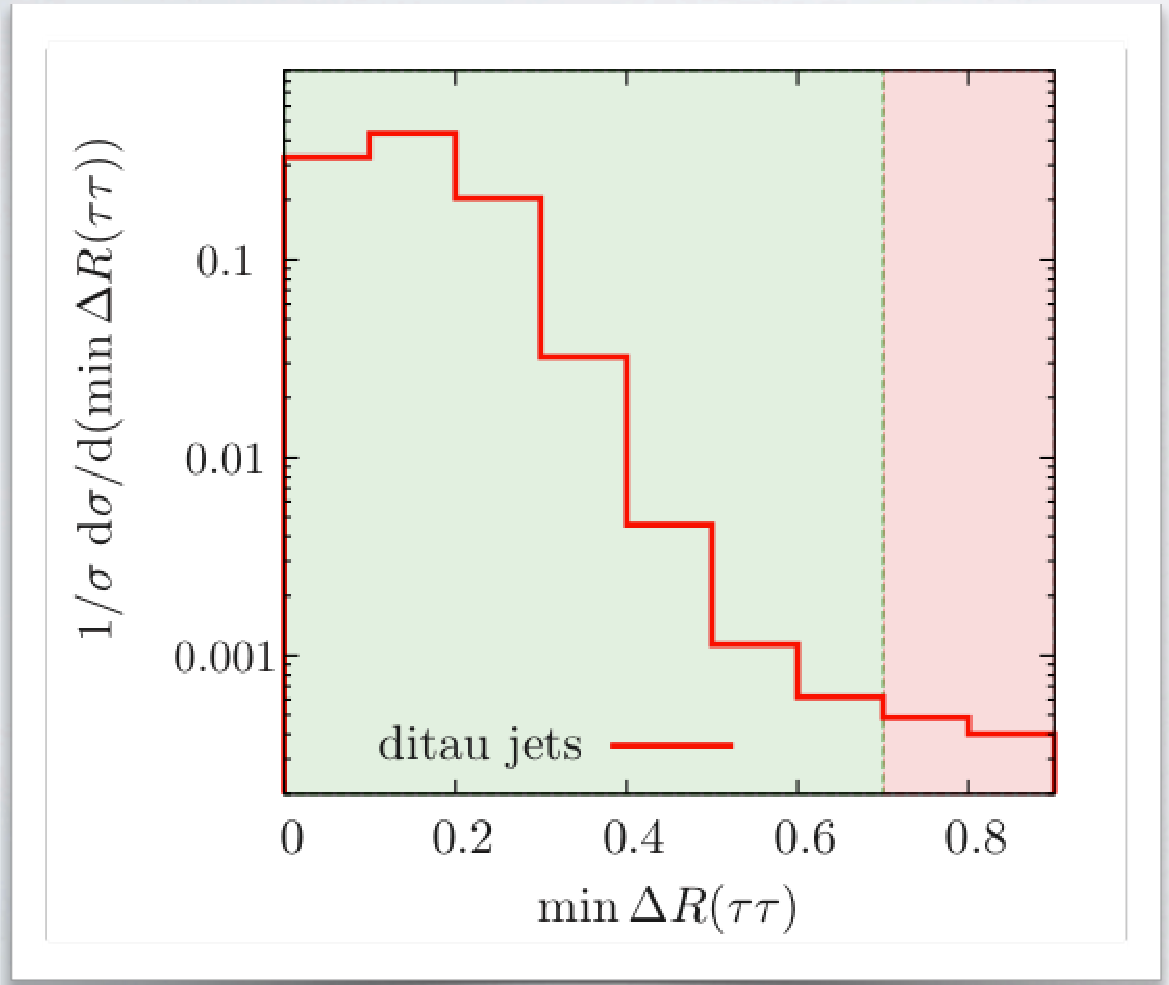
[CE, Jaeckel, Re, Spannowsky `11]

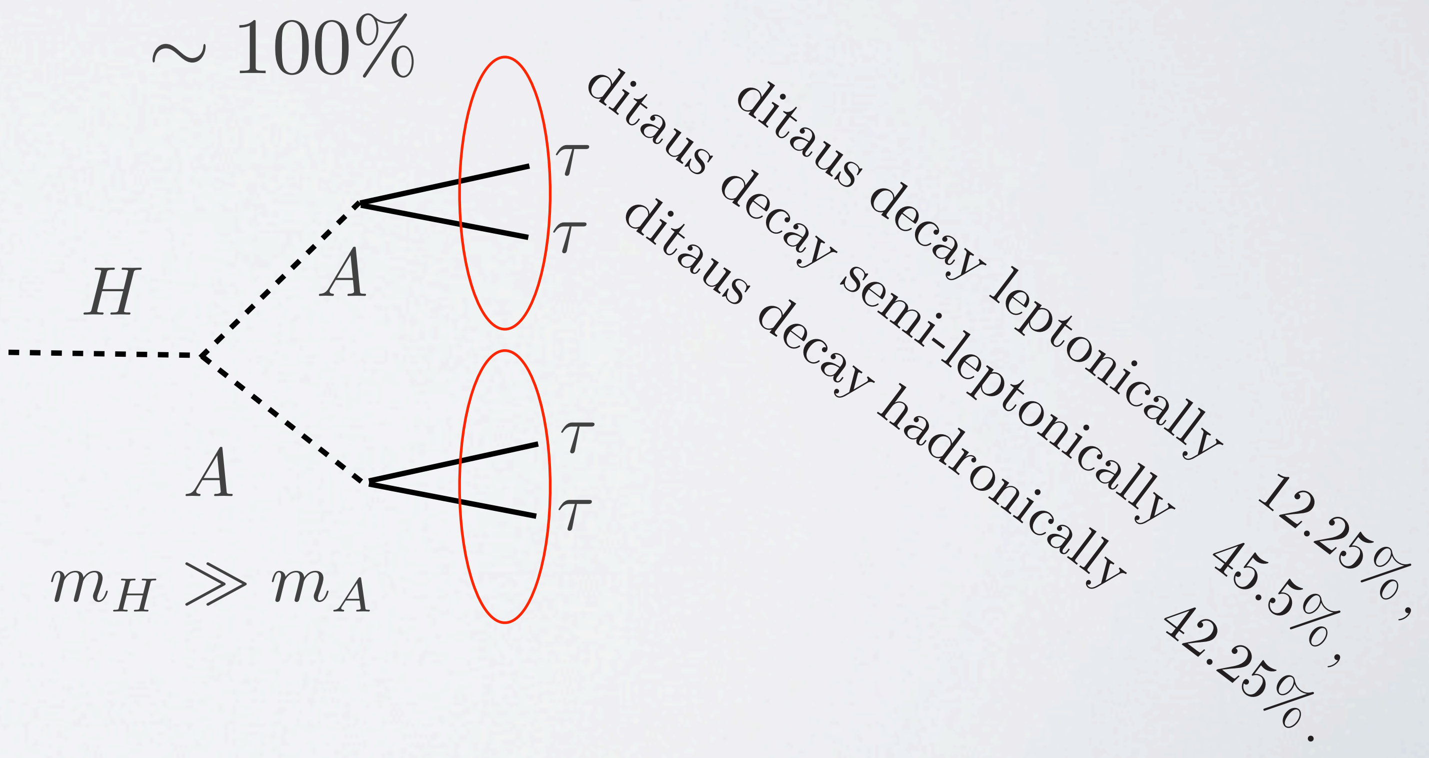
Higgs hide outs

"Buried" Higgs bosons show up in many models with extended electroweak sectors.

A known example is the NMSSM for $\tan\beta \simeq 5,\ m_A \simeq 10\ \mathrm{GeV}$

[Ellwanger, Gunion, Hugonie `05]





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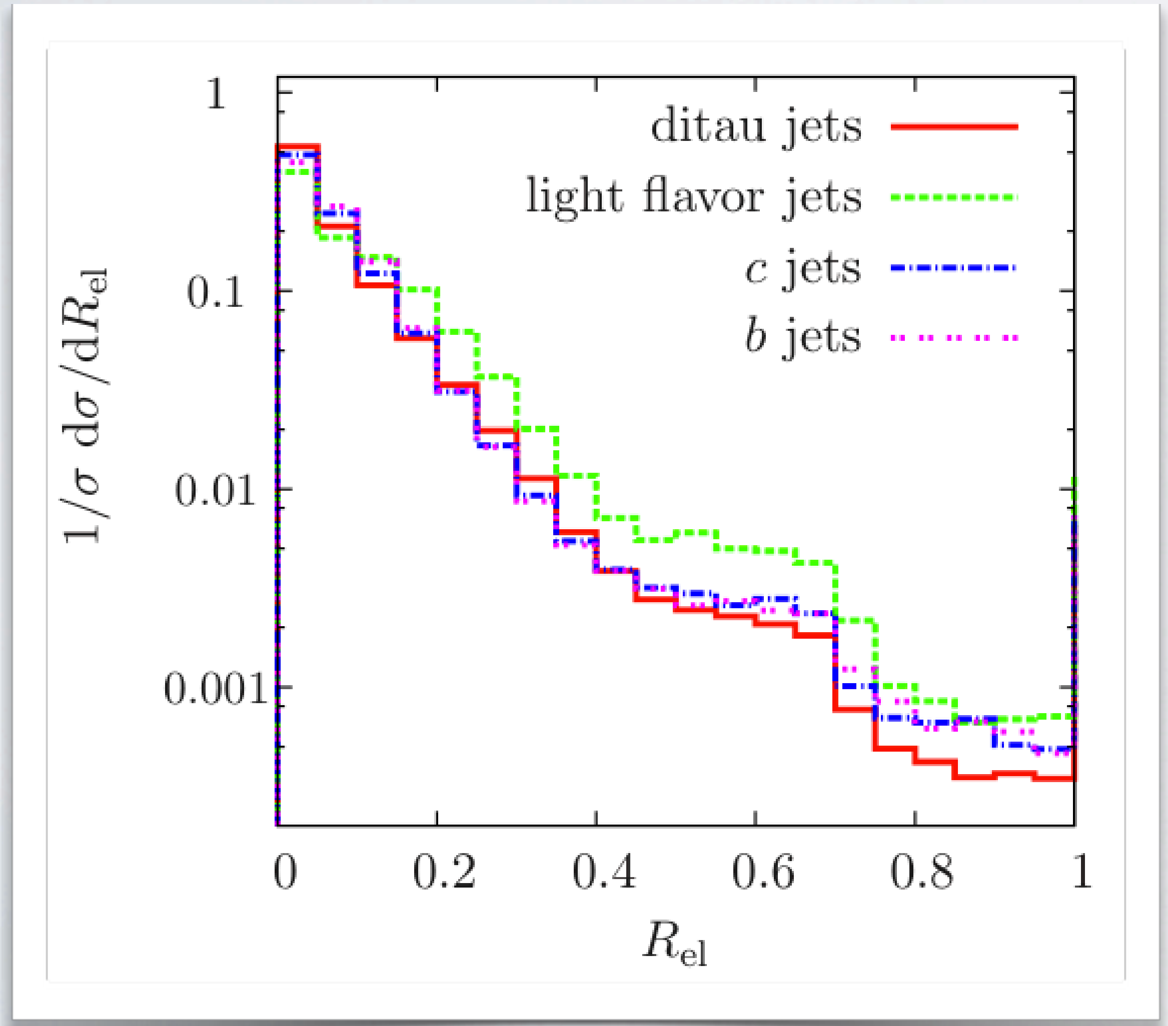

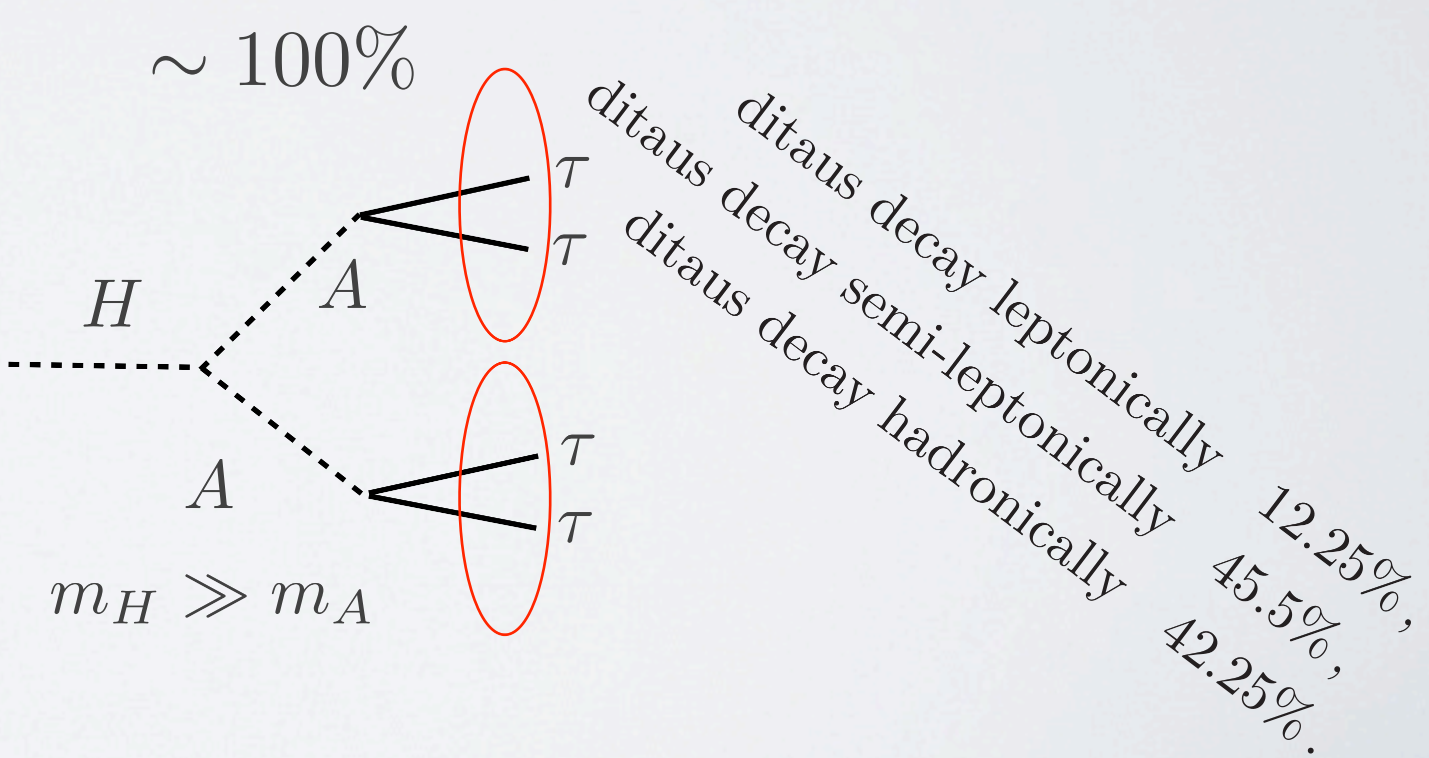

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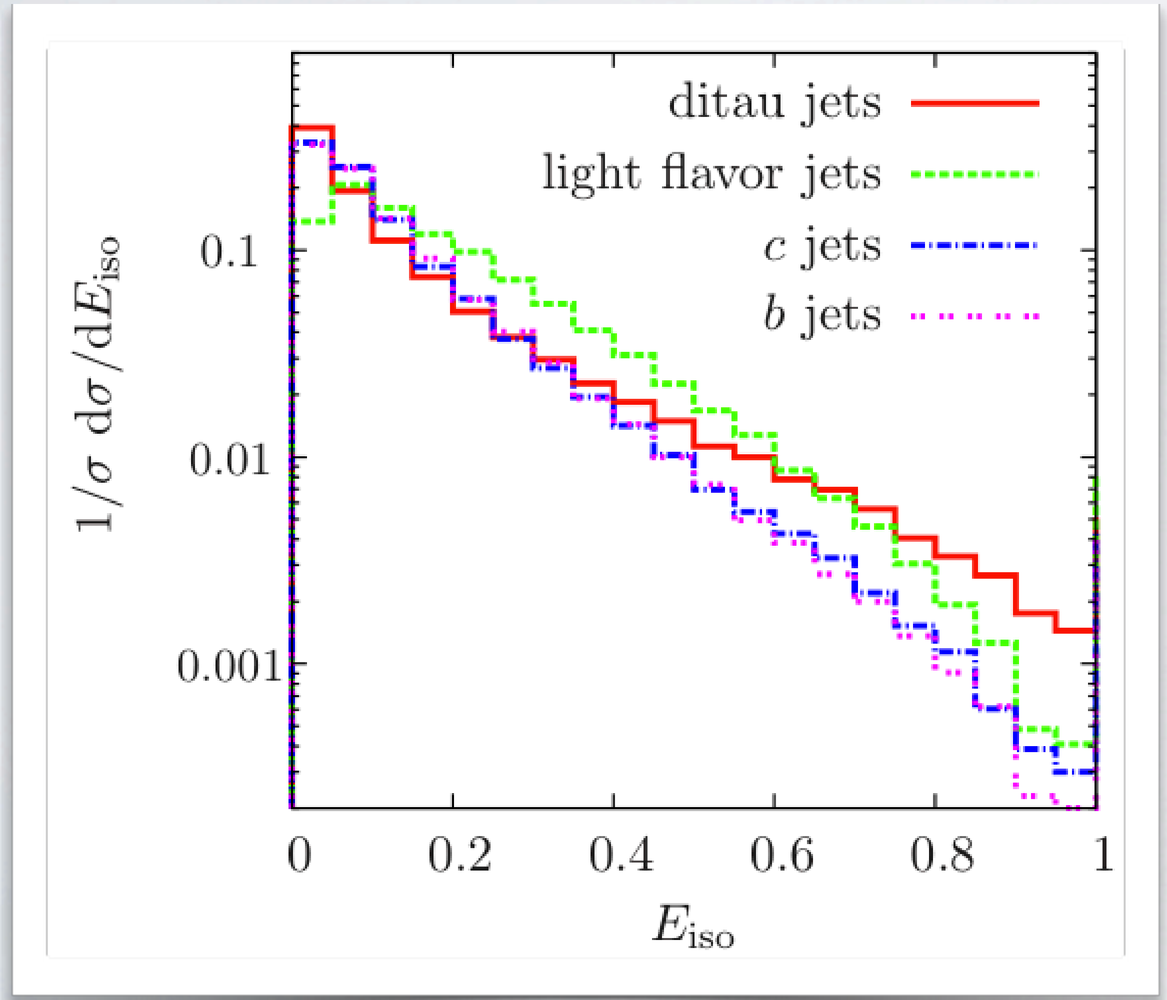

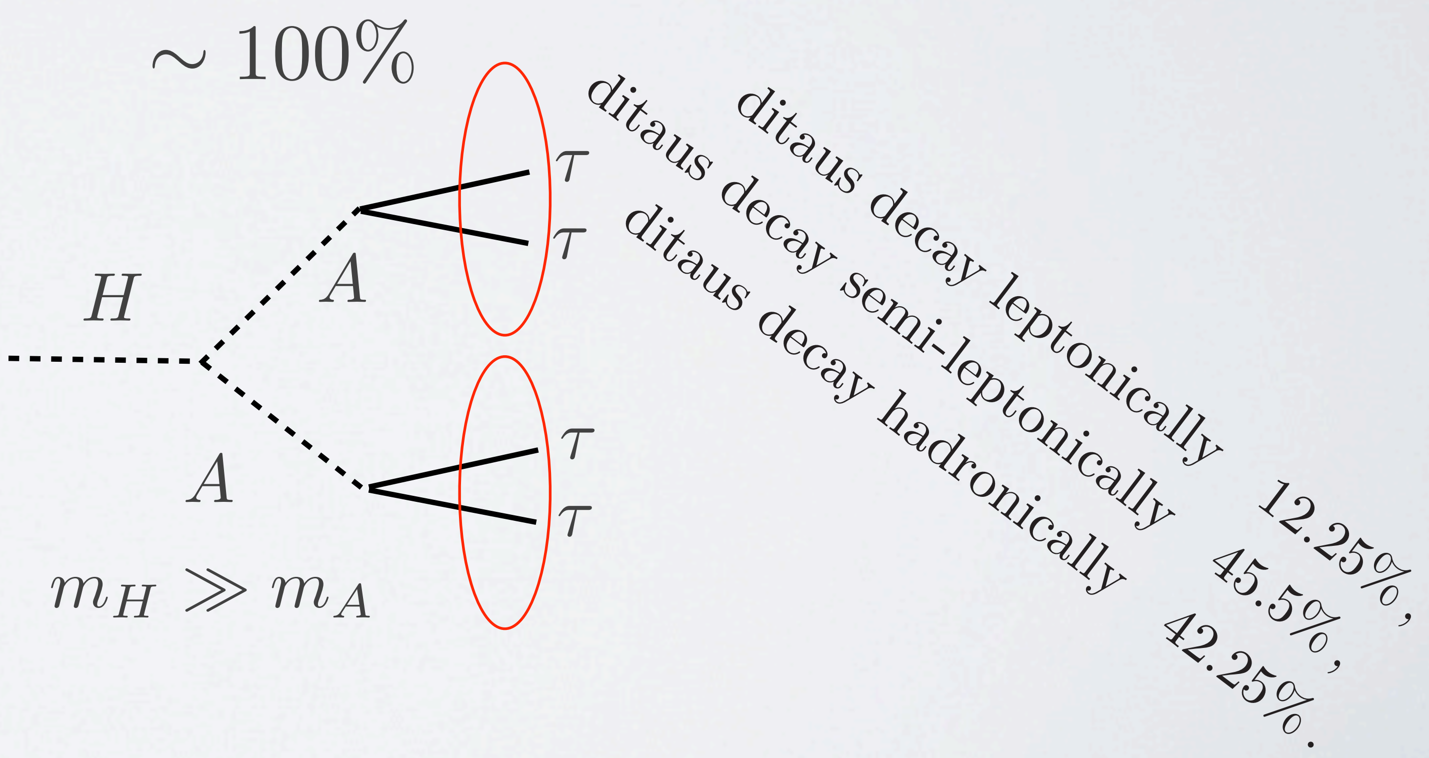

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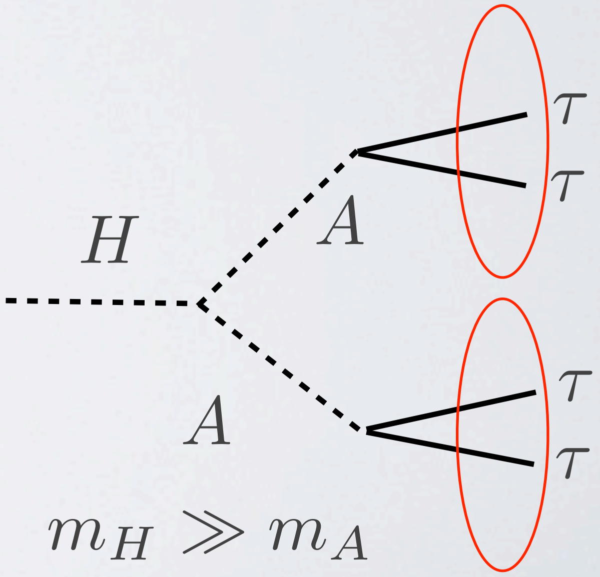
- ditau jet is still a light, yet boosted object with little QCD activity:

  use a combination of subjettiness and jet active area $\sim p_T^j/m_j$

[Stewart, Tackmann, Waalewijn `10] [Thaler, Van Tilburg `11]

$$\tau_N = \frac{\sum_k p_{T,k} \min\left(\Delta R(1,k), \ldots, \Delta R(N,k)\right)}{\sum_j p_{T,j}\, R}$$



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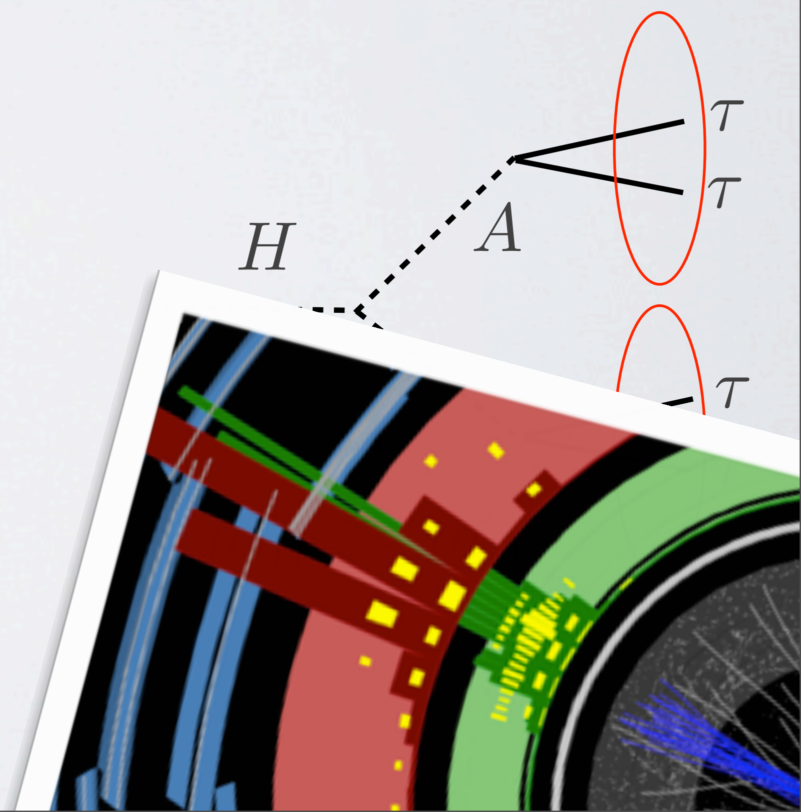

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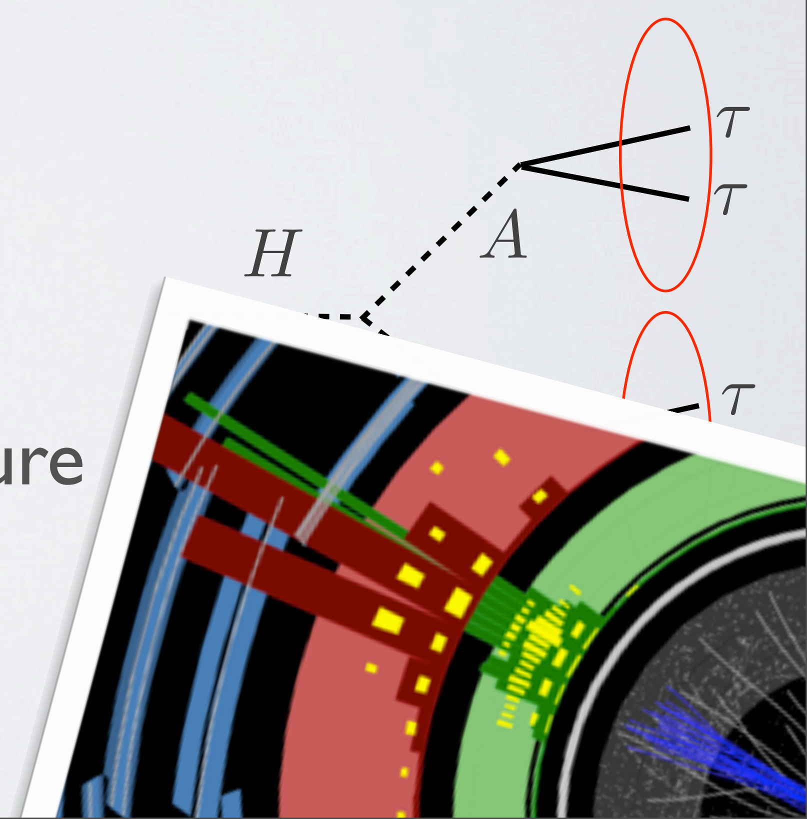
how N-"clumpy" is the jet substructure



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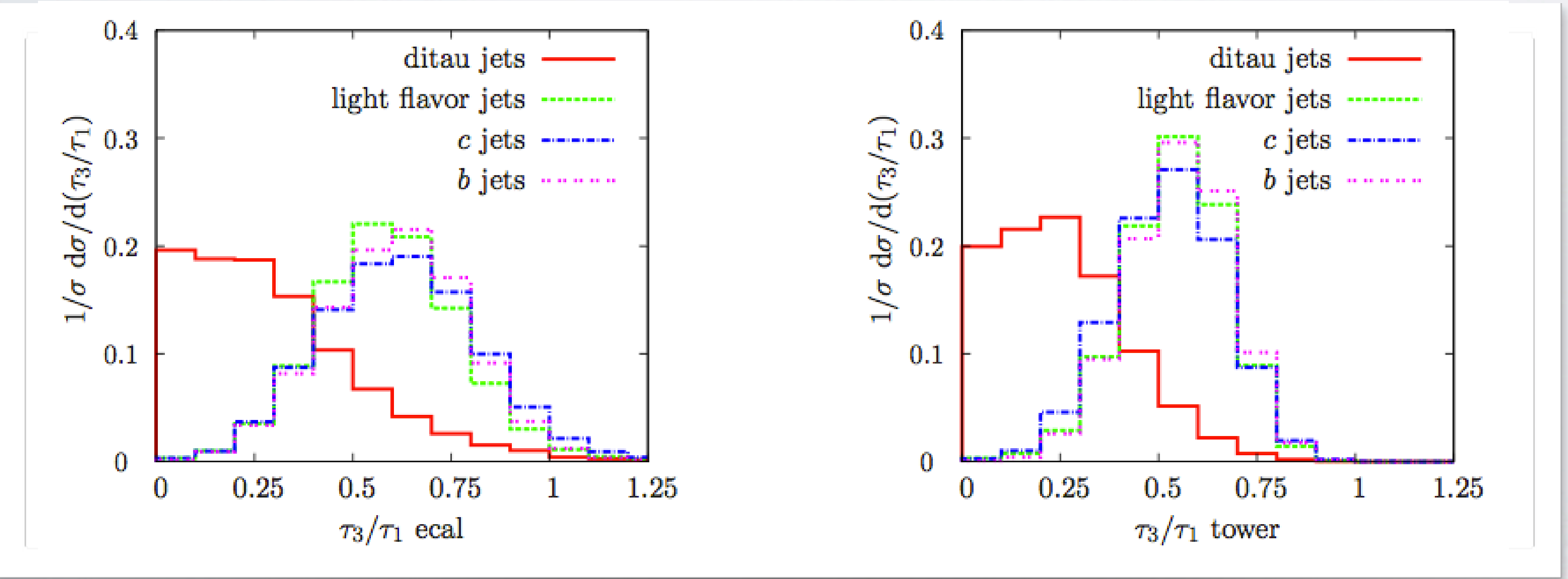

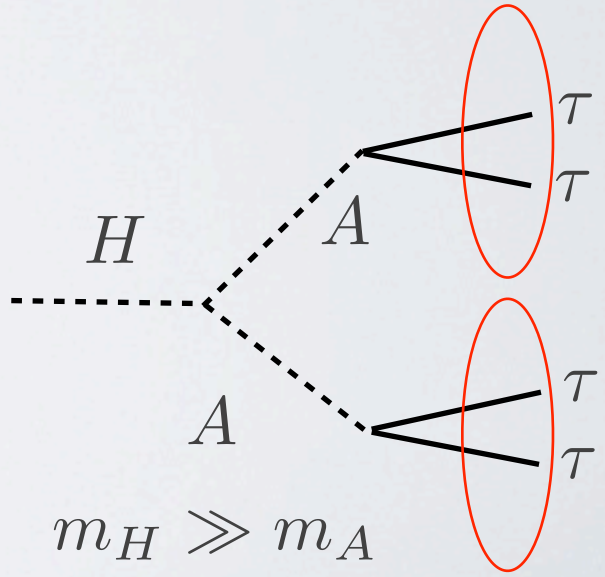

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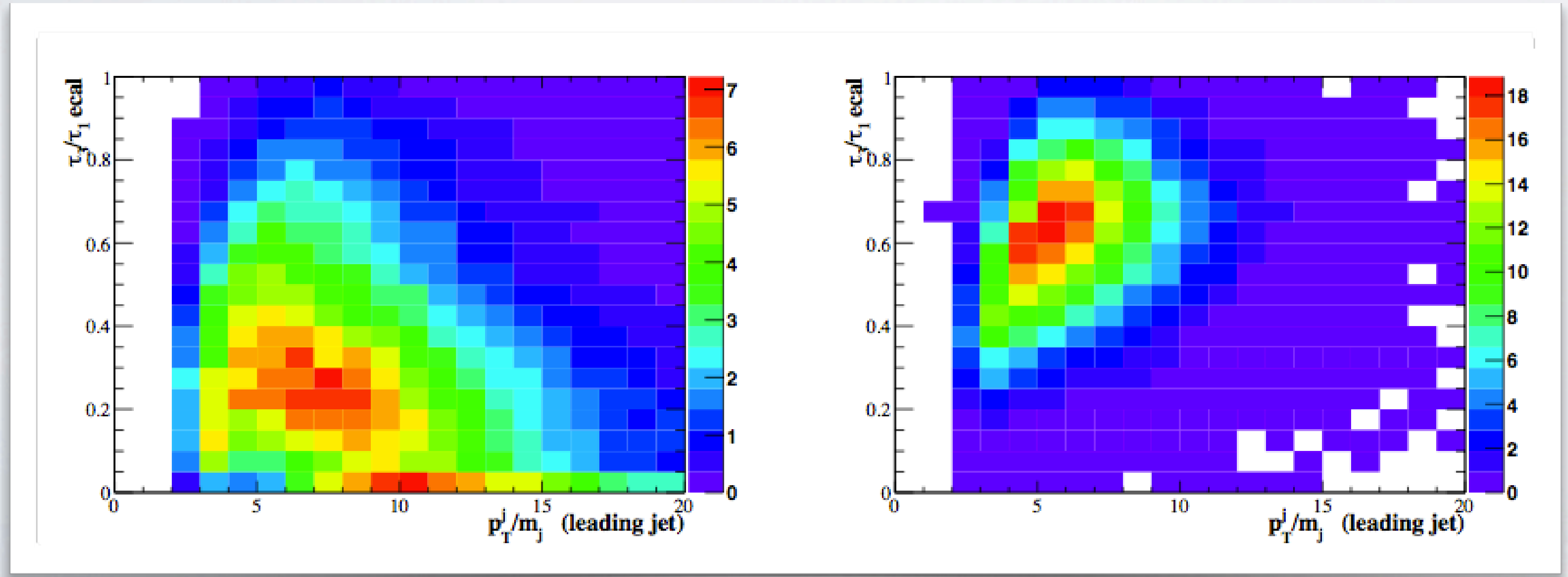

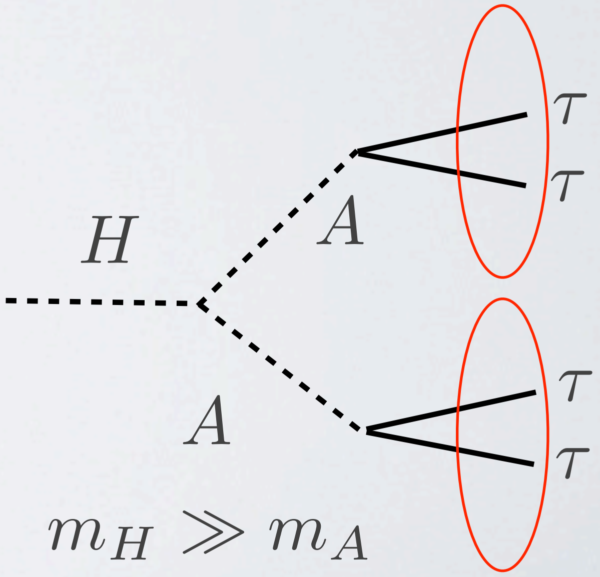

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Buried Higgs

$pp \to (Z \to 2\ell) + \not{E}_T + j + X$	ditaus	ZZj	WZj	WWj	$t\bar{t}$
	1.00	1.00	1.00	1.00	1.00
$n_\ell = 2$, Z mass reconstruction with e^+e^- or $\mu^+\mu^-$	0.416	0.217	0.130	0.011	0.026
$\max(p_T^\ell, p_T^{\ell'}) \geq 80$ GeV, $p_T^Z \geq 150$ GeV	0.216	0.048	0.035	0.00019	$3.9\ 10^{-4}$
$n_j \geq 1$ with $p_T^j \geq 30$ GeV, no $\Delta R(j_{50}, Z) \leq 1.5$	0.199	0.0402	0.029	0.00019	$3.0\ 10^{-4}$
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$\tau_3/\tau_1\lvert_{\text{ecal}} \leq 0.5$ (leading jet)	0.125	0.011	0.0084	$5.4\ 10^{-5}$	$2.1\ 10^{-5}$
$p_T^j/m_j \geq 7$ (leading jet)	0.083	0.0018	0.0020	$3.0\ 10^{-6}$	$7.2\ 10^{-6}$
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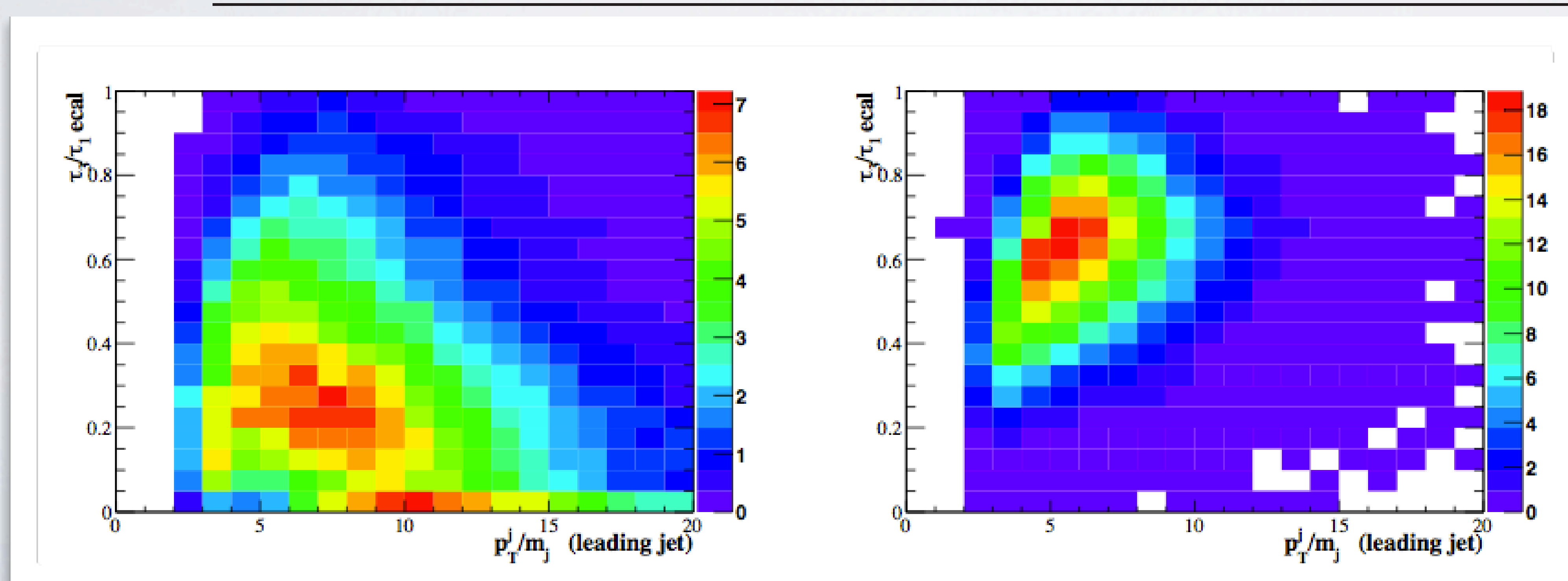

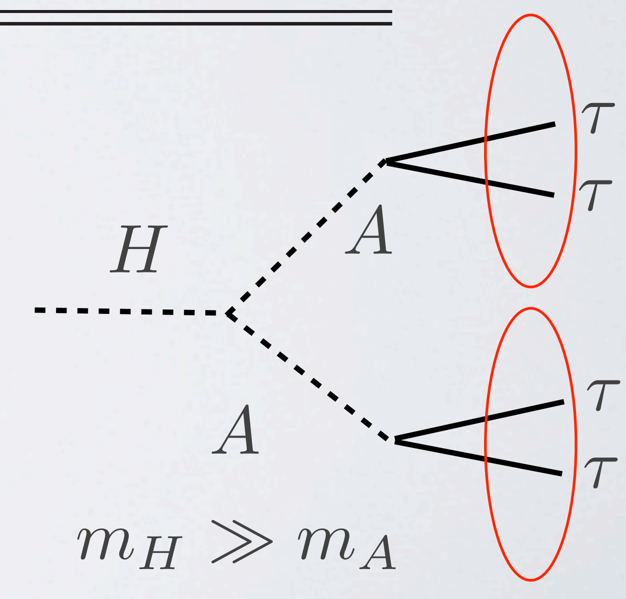

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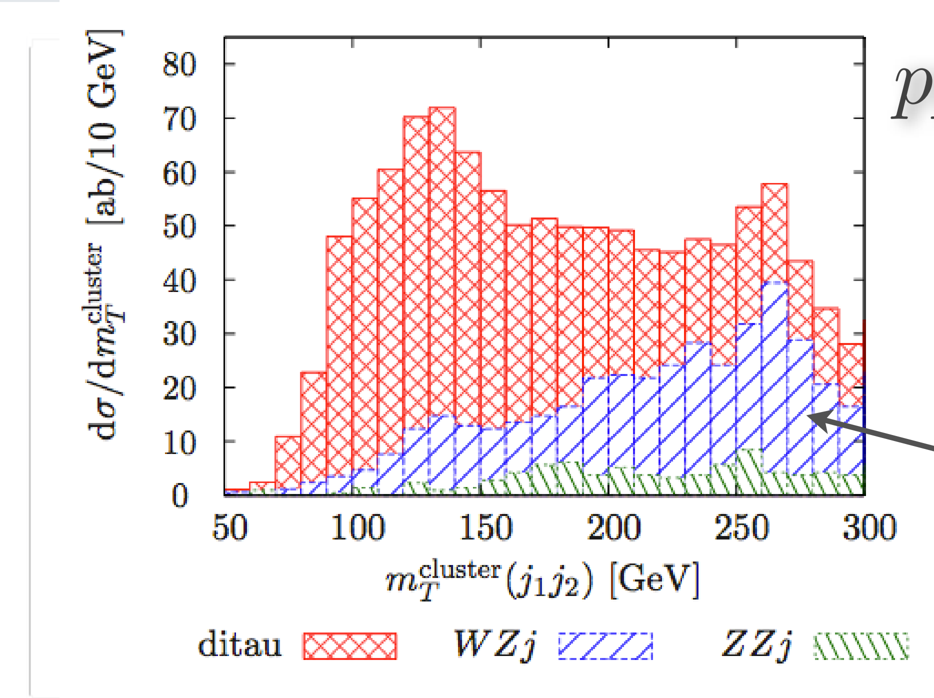


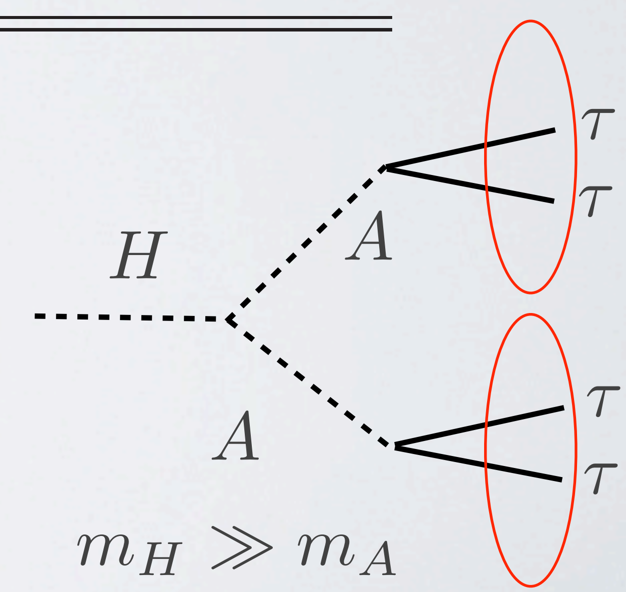
$$pp \to (Z \to 2\ell) + \not{E}_T + 2j + X$$

sensitivity $S/\sqrt{B} = 5$ for

$\mathcal{L} = 12\ \text{fb}^{-1}$ ($\sqrt{s} = 14$ TeV)

NLO QCD $K = 0.86$

[Campanario, CE, Spannowsky `10]
[Campanario, CE, Kallweit et al. `10]



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