BSM in XJJ

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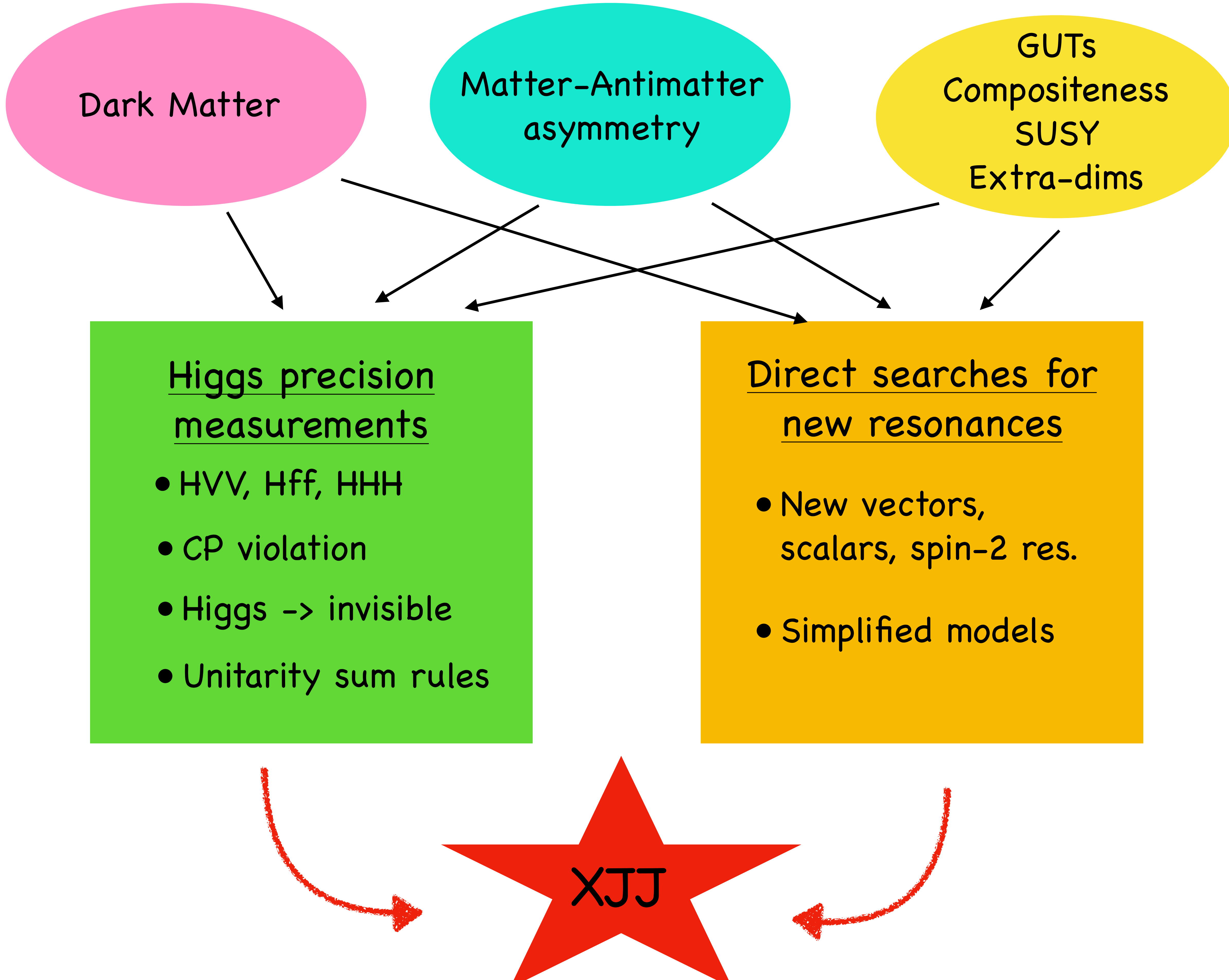
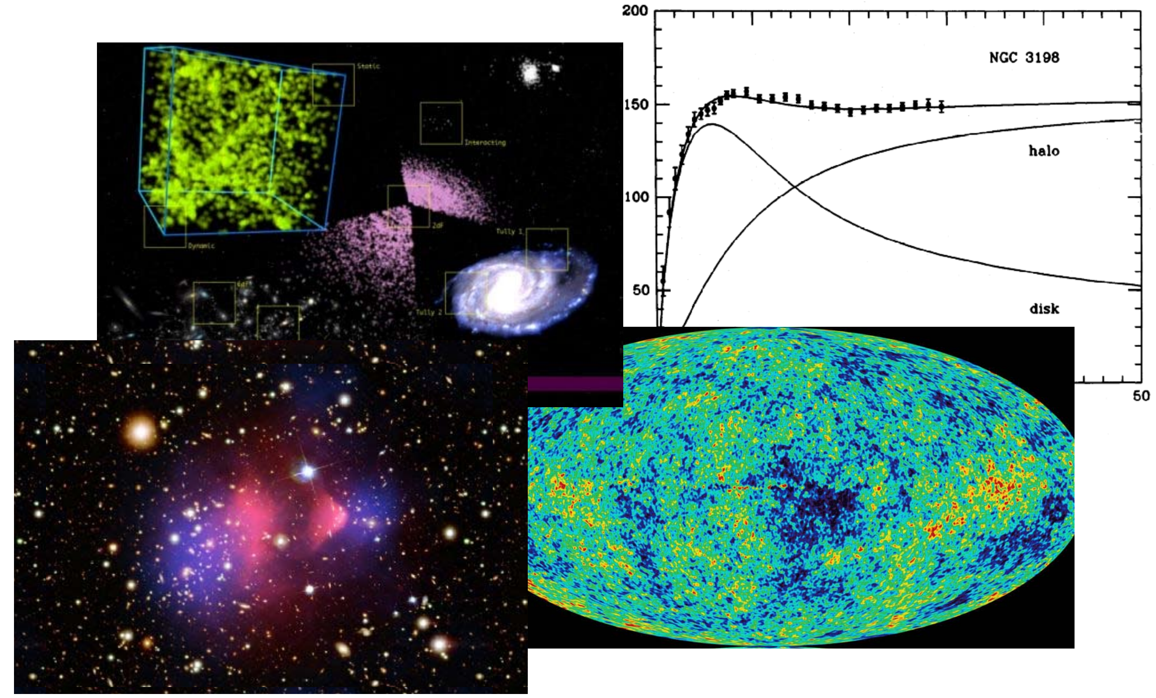
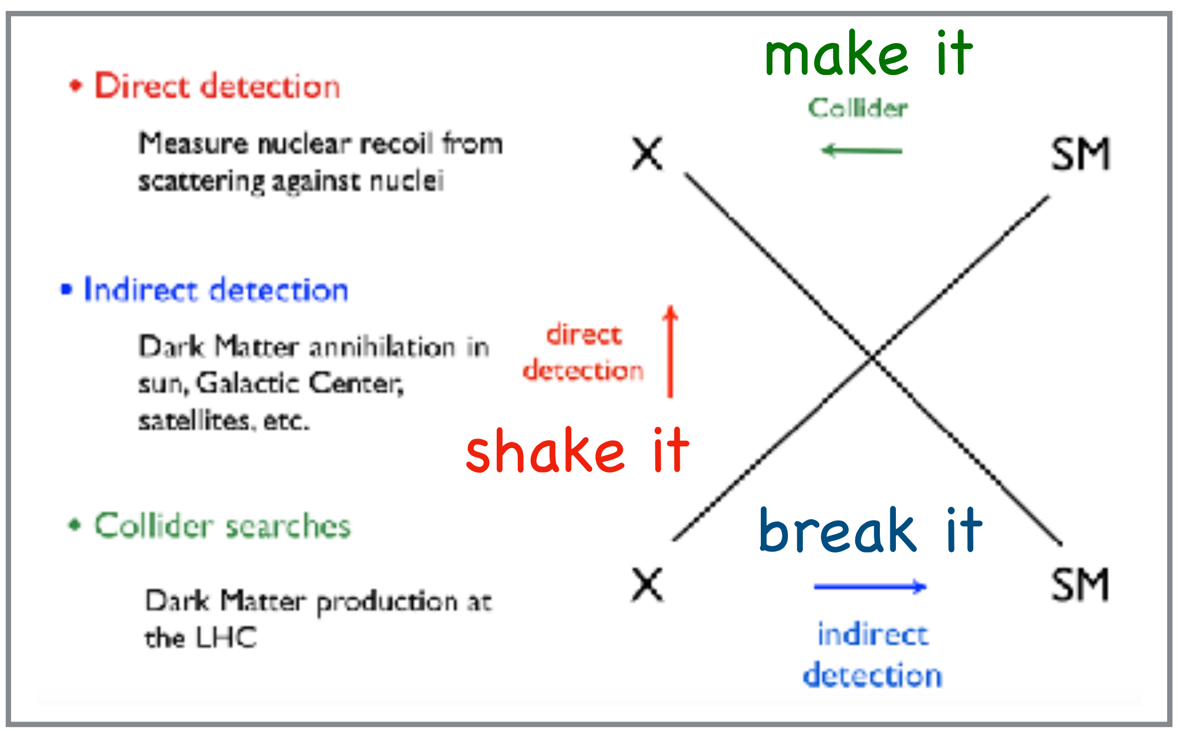

Dark Matter
Matter-Antimatter asymmetry
GUTs
Compositeness
SUSY
Extra-dims
Higgs precision measurements
• HVV, Hff, HHH
• CP violation
• Higgs -> invisible
• Unitarity sum rules
Direct searches for new resonances
• New vectors, scalars, spin-2 res.
• Simplified models
XJJ

Question 1: Dark Matter interactions

Evidence for Dark Matter overwhelming:

- Spiral Galaxy rotation curves
- Gravitational lensing
- Acoustic peaks





Several ways to look for Dark Matter

Which way more sensitive depends mostly on nature of mediator

→ Search for particle to mediate interaction between DM and SM

H-> invisible or production of invisible X

Higgs as mediator - H -> invisible

[Eboli, Zeppenfeld '00]

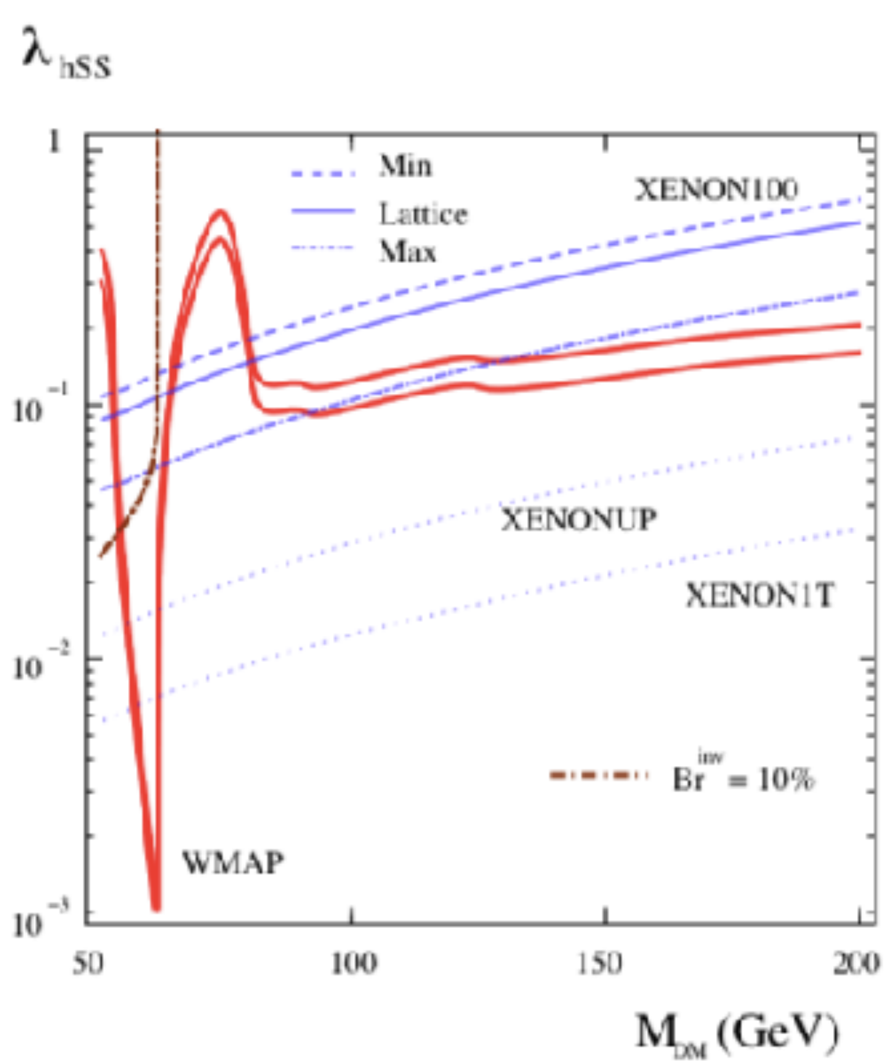
[Bernaciak, Plehn, Schichtel, Tattersall '14]

[Biekoetter et al '17]

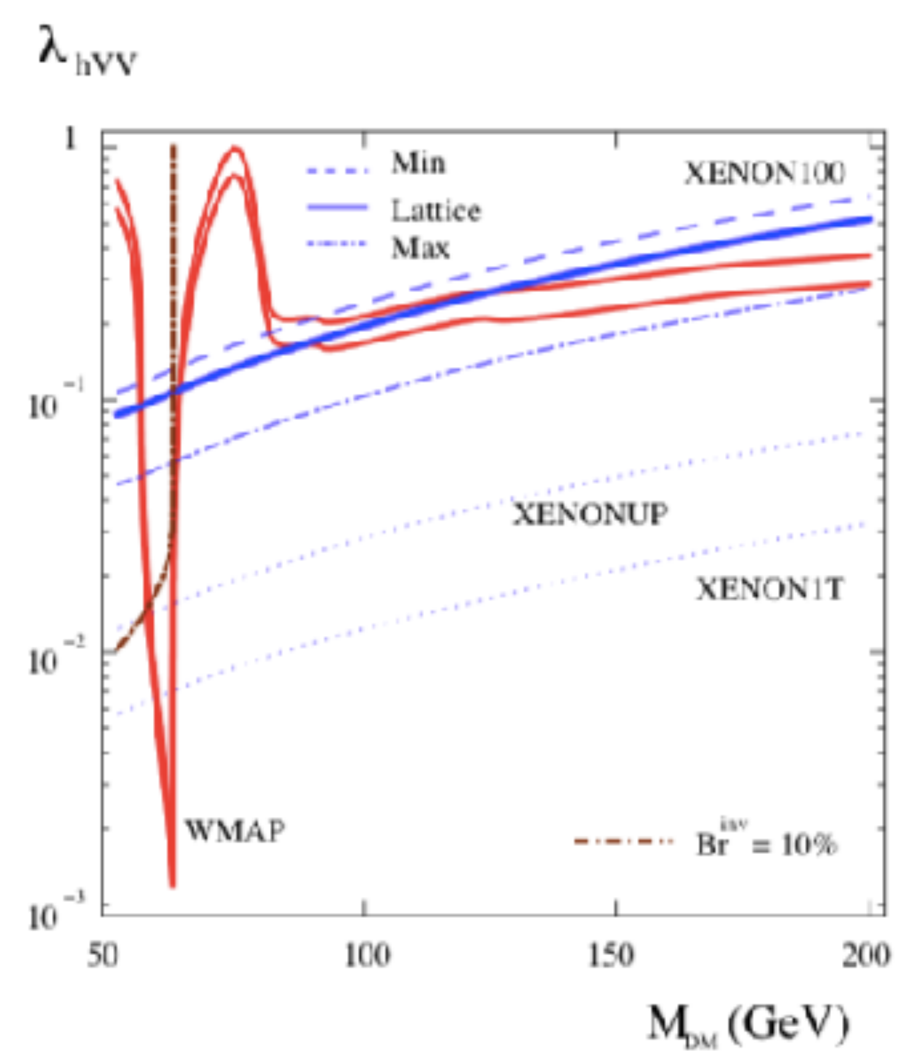
Assume Higgs-portal extension of SM:

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$$

[Djouadi, Lebedev, Mambrini, Quevillion '11]



Vector and fermionic portal can work as well...



Higgs as mediator - H -> invisible

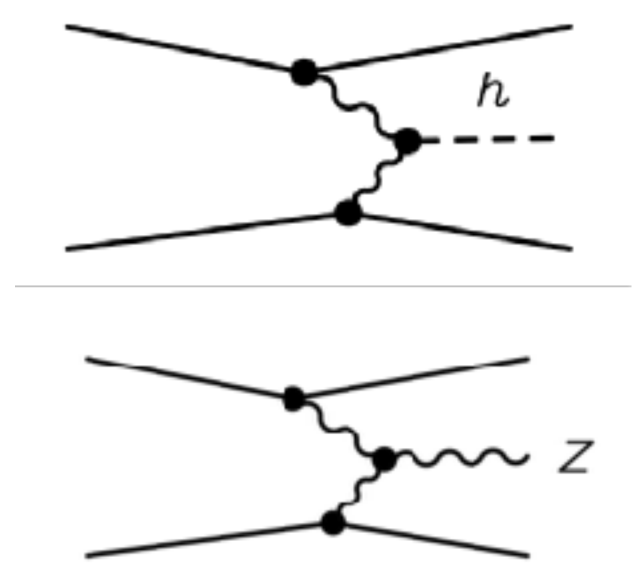
[Eboli, Zeppenfeld '00]

[Bernaciak, Plehn, Schichtel, Tattersall '14]

[Biekoetter et al '17]

- Trigger and selection cuts rely on 2 tagging jets and large MET:

$$p_{T,j} > 20\ (10)\ \text{GeV} \qquad |\eta_j| < 4.5$$
$$\not{p}_T > 100\ \text{GeV} \qquad \Delta\phi_{\not{p}_T,j} > 0.4$$



Construct observables for BDT

$$\{p_{T,j_1},\ \eta_{j_1},\ p_{T,j_2},\ \eta_{j_2},\ \Delta\phi_{j_1,j_2},\ \not{p}_T\} \qquad \text{(2-jet)}$$

$$\{p_{T,j_3},\ \eta_{j_3},\ \Delta\phi_{j_1,j_3}\} \qquad \text{(3-jet)}$$

	$p_{T,j} > 20$ GeV			$p_{T,j} > 10$ GeV		
	2-jets	3-jets	4-jets	2-jets	3-jets	4-jets
S/B after Eq.(1)	$1/240$	$1/360$	$1/475$	$1/213$	$1/303$	$1/429$
ϵ_S	0.01	0.01	0.01	0.01	0.01	0.01
ϵ_B	1.7×10^{-6}	1.3×10^{-5}	2.7×10^{-5}	7.5×10^{-7}	3.2×10^{-6}	2.4×10^{-5}
S/B	$1/2.6$	$1/21$	$1/42$	$1/1.2$	$1/5$	$1/38$

Expected sensitivity for HL-LHC run: BR(H->inv) ~ 2.1%

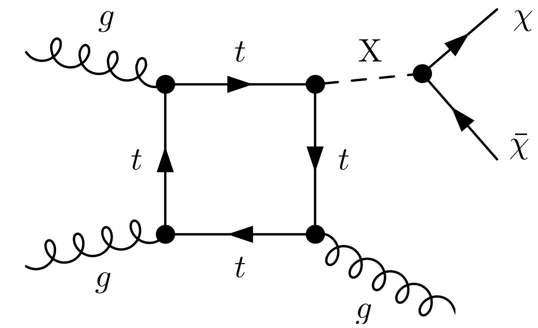
If mediator not Higgs, several possibilities ...

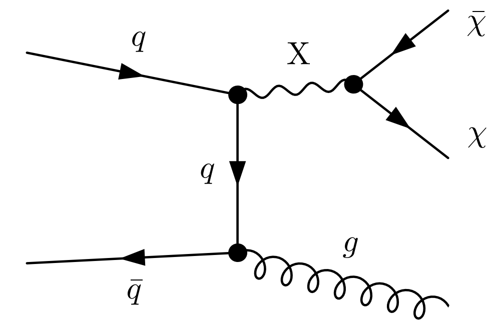
$$\mathcal{L}_{\rm scalar} \supset -\frac{1}{2}m_{\rm MED}^2 S^2 - g_{\rm DM} S\,\bar{\chi}\chi - \sum_q g_{SM}^q S\,\bar{q}q - m_{\rm DM}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\rm pseudo-scalar} \supset -\frac{1}{2}m_{\rm MED}^2 P^2 - i g_{\rm DM} P\,\bar{\chi}\gamma^5\chi - \sum_q i g_{SM}^q P\,\bar{q}\gamma^5 q - m_{\rm DM}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\rm vector} \supset \frac{1}{2}m_{\rm MED}^2 Z'_\mu Z'^\mu - g_{\rm DM} Z'_\mu\bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu\bar{q}\gamma^\mu q - m_{\rm DM}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\rm axial} \supset \frac{1}{2}m_{\rm MED}^2 Z''_\mu Z''^\mu - g_{\rm DM} Z''_\mu\bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu\bar{q}\gamma^\mu\gamma^5 q - m_{\rm DM}\bar{\chi}\chi$$





Mediators can be probed in different ways:

With Direct Detection

Vector(SI)

Spin independent

Extremely good

Axial(SD)

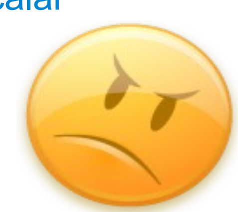
Spin dependent

Not so great

Scalar(SI)

So-so
Spin independent

Pseudoscalar



Forget about it*

With Collider

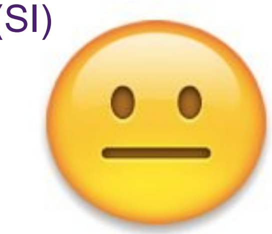
Vector(SI)

Large cross section

Axial (SD)

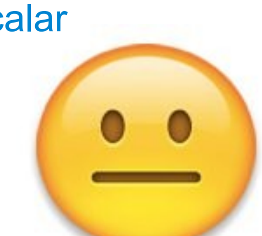
Same as vector

Scalar(SI)



Low-ish cross section

Pseudoscalar



Better than scalar
Small cross section

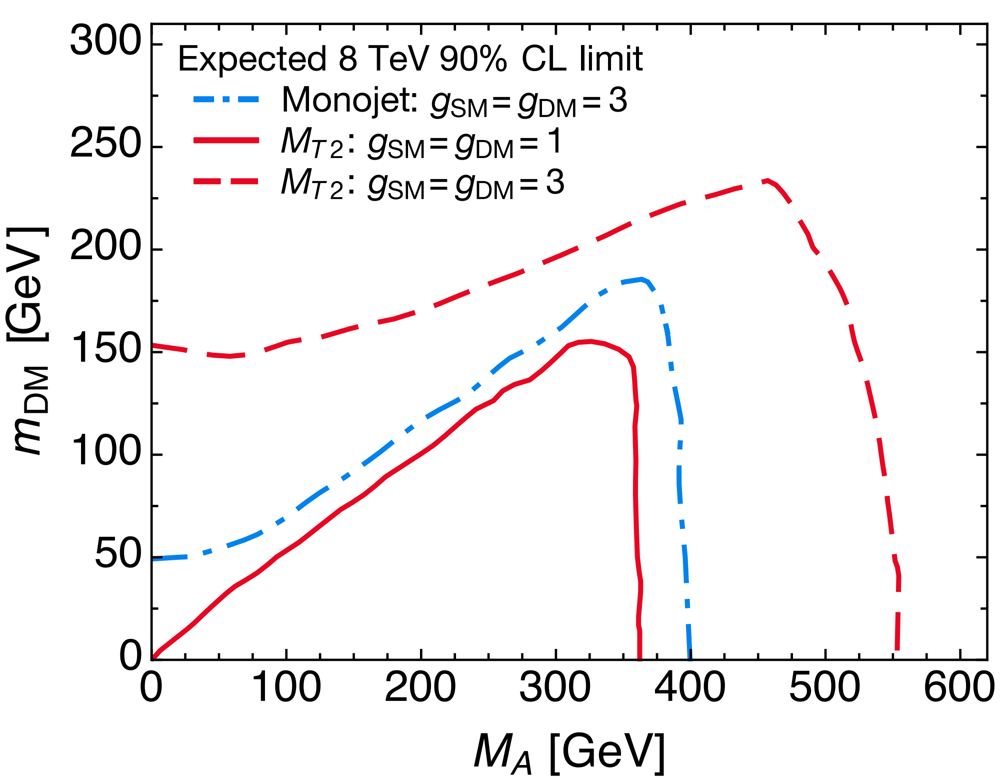
MET+2jet more sensitive than MET+1j

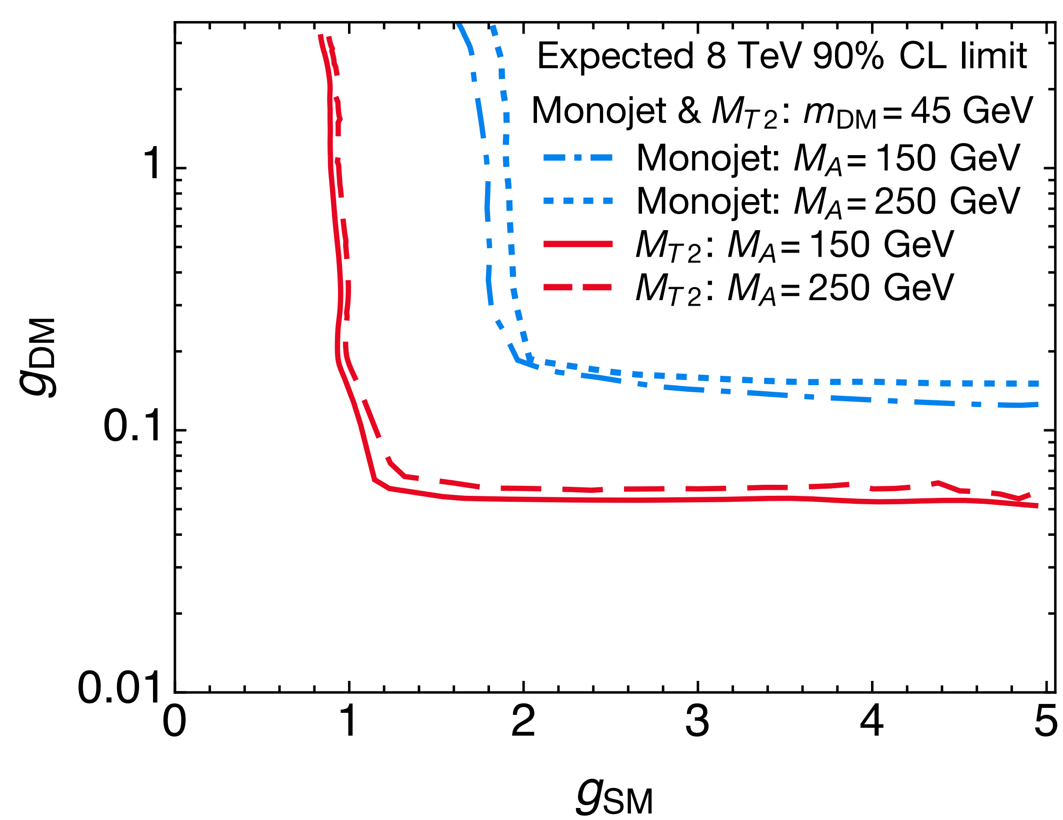
- Most prominent search strategy for scalar mediators is to recoil against hard jet (mono-jet search)

- For CP-odd mediator $$\mathcal{L}_{\rm int} = i g_{\rm DM} A \bar{\chi}\gamma^5\chi + i g_{\rm SM} \sum_q \frac{m_q}{v} A\, \bar{q}\gamma^5 q$$

  Ajj multi-jet search can be more sensitive than the mono-jet search due to kinematic features, exploitable using MT2

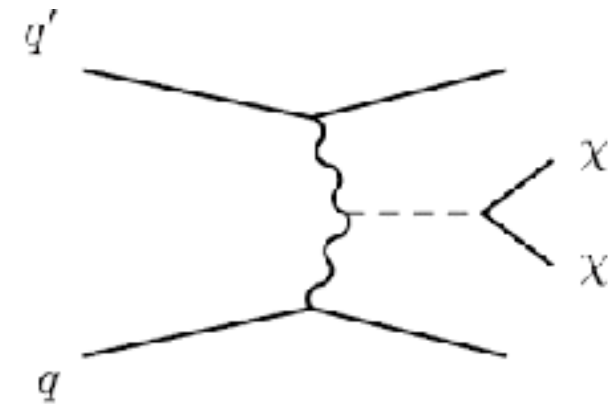
[Buchmueller, Malik, McCabe, Penning '15]





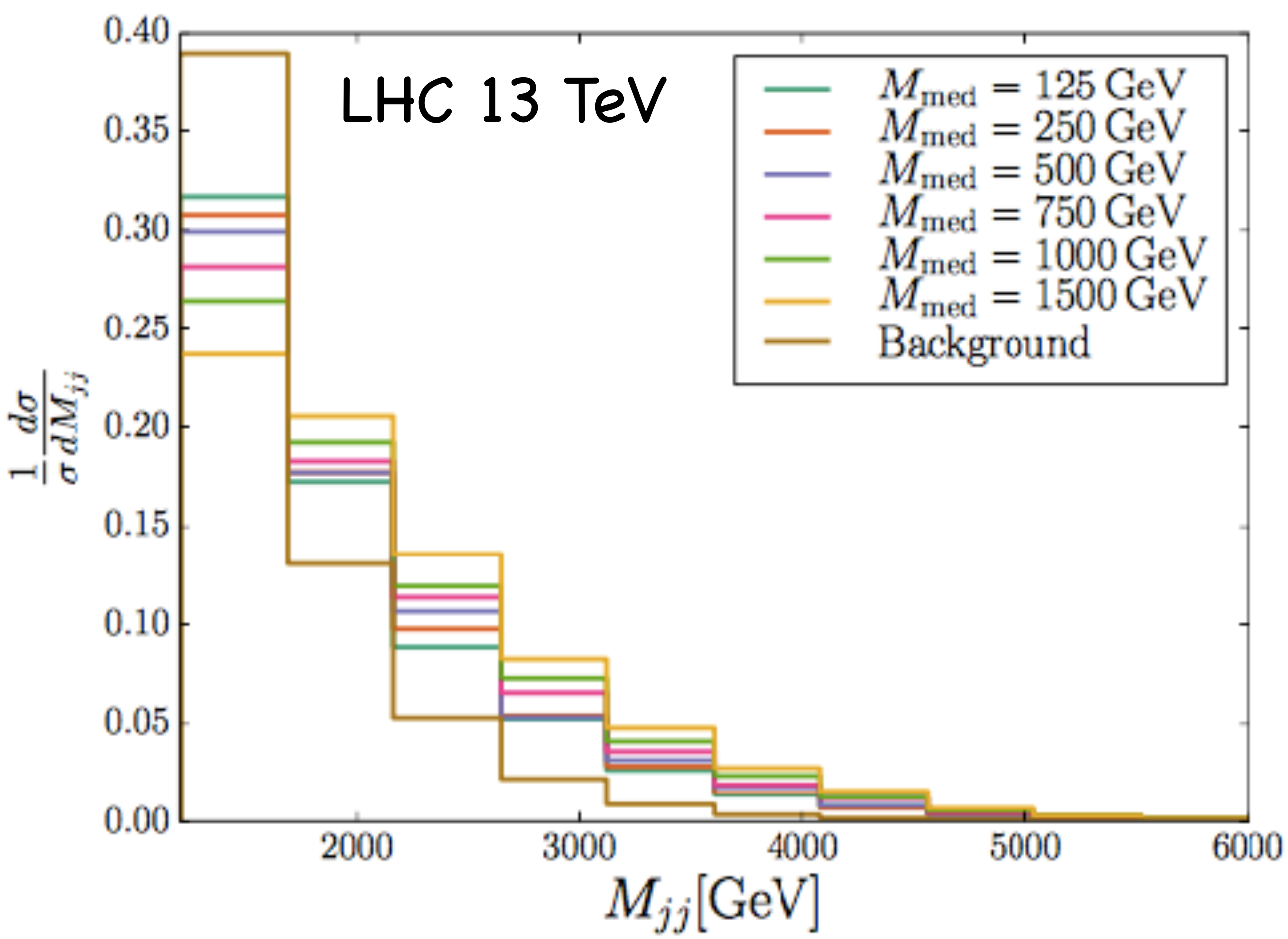
Measuring the mediator mass at the LHC

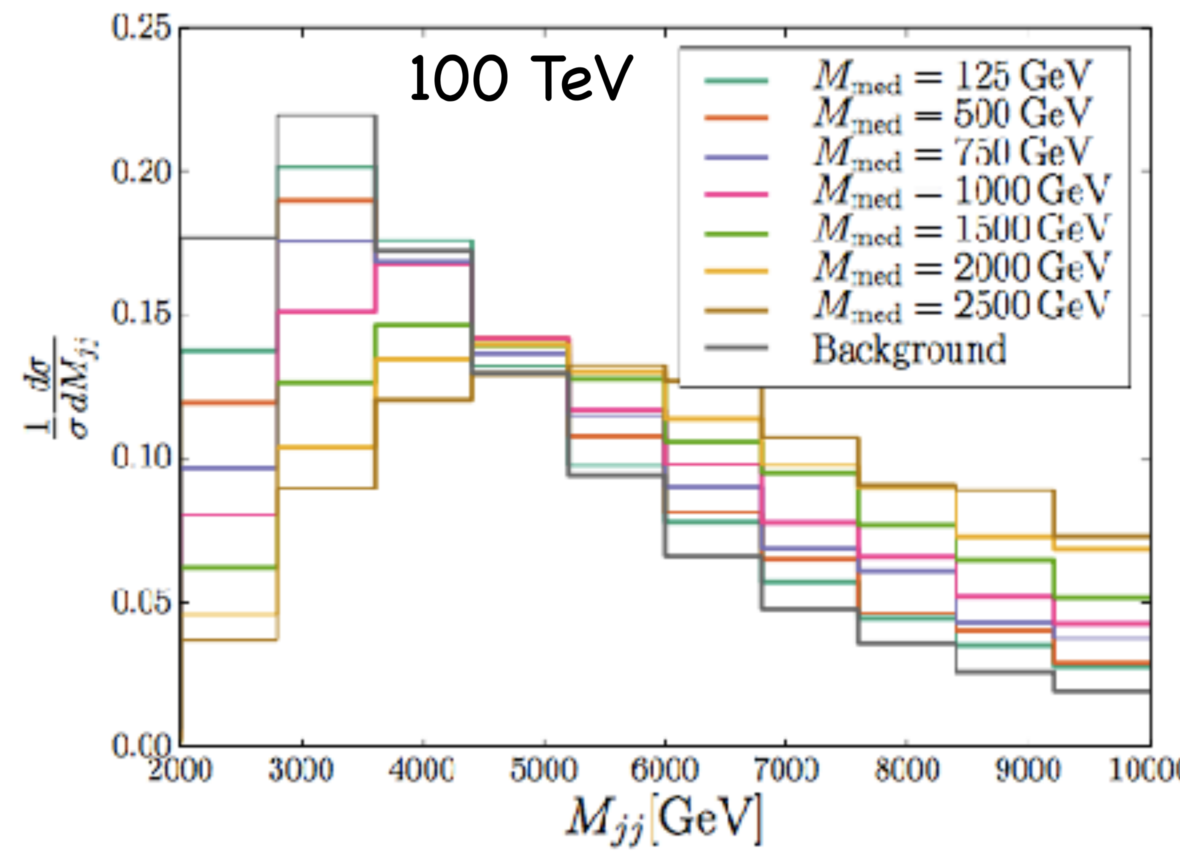
[Khoze, Ro, MS '15]



- See also [Andersen, Rauch, MS '13] for e+e- collider

$$\mathcal{L} = \sqrt{\kappa}\left(\frac{2M_W^2}{v}W_\mu^+W^{-\,\mu} + \frac{M_Z^2}{v}Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\bar{f}f\right)\phi - g_{\rm DM}\,\bar{\chi}\chi\phi - \frac{1}{2}M_{\rm med}^2\phi^2 - m_\chi\bar{\chi}\chi$$





Question 2: Electroweak Baryogenesis

Baryon-to-photon ratio $Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ [Planck Data]

asymmetry parameter $\frac{\eta_B - \eta_{\bar{B}}}{\gamma} \simeq 10^{-9}$

Pre-inflation asymmetry would have been washed out

Sakharov conditions: (for dynamical generation of Baryon asymmetry)

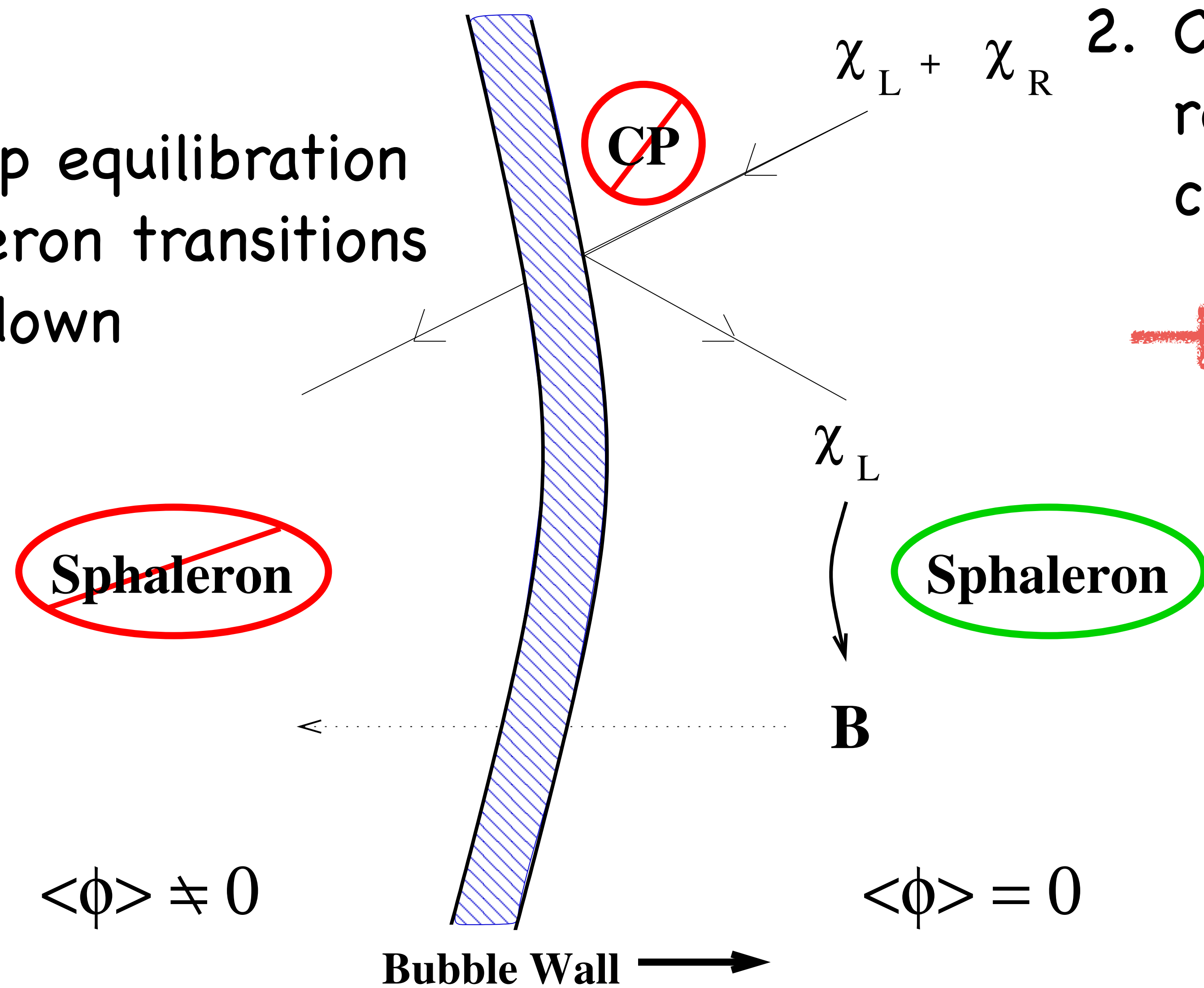
- B violation ✓ **Sphaleron**
- CP violation ϟ not enough
- Departure from thermal equilibrium ϟ not enough

Electroweak Baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '85]

[Cohen, Kaplan, Nelson '91]

1. Nucleation and expansion of bubbles of broken phase



2. CP violation at phase interface responsible for mechanism of charge separation

→ chiral flux in front of wall

3. In symmetric phase, very active sphalerons convert chiral asymmetry into baryon asymmetry

4. To stop equilibration sphaleron transitions shut down

[Morrissey, Ramsey-Musolf '12]

How to modify the Higgs potential to get SEWPT?

$$V_{\text{eff}}(h,T) = V_0(h) + V_0^{\text{loop}}(h) + V_T(h,T)$$

tree-level potential | loop corrections | thermal corrections

[Morrissey, Ramsey-Musolf '12]

thermal: add new bosons to the plasma to generate a thermal barrier

loop: add new particles whose loops reduce vac. energy difference, so that W/Z loops create a barrier

tree-level: new scalars to modify tree-level potential (Higgs portal)

non-ren operators, e.g. H^6 (SM with low cut-off)

[Grojean, Servant, Wells '05]

Search for new resonances or modified Higgs self-interaction

Search for new sources of CP violation

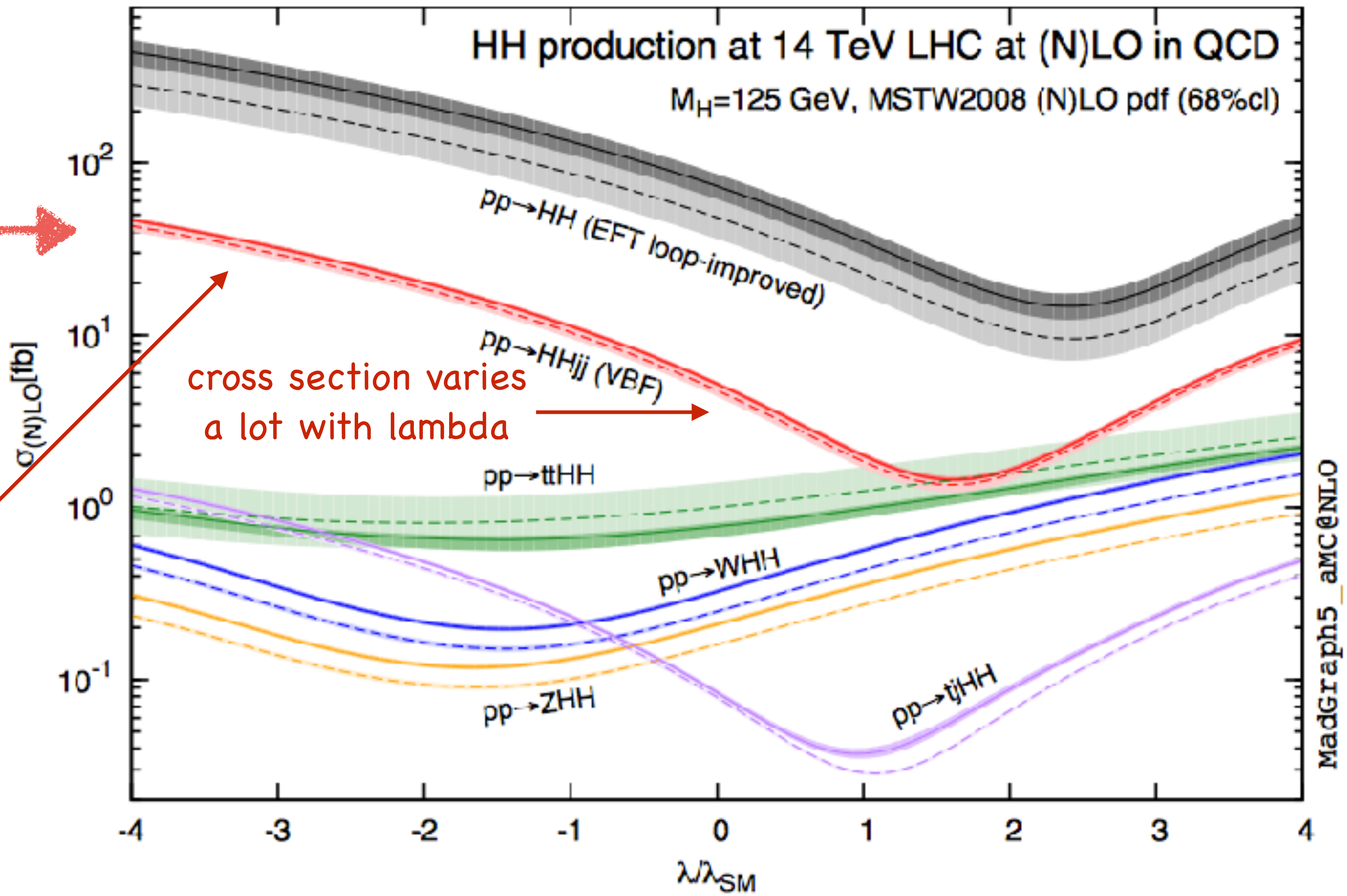
Higgs selfcoupling and Higgs gauge coupling

[Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torielli, Vryonidou, Zaro '14]

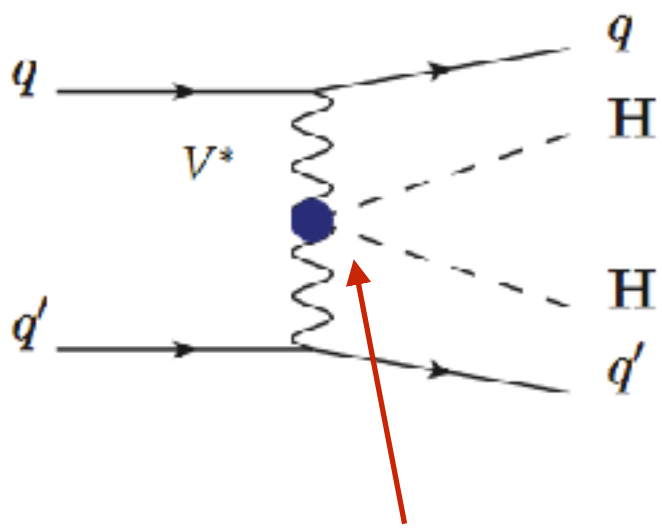
Second largest production process

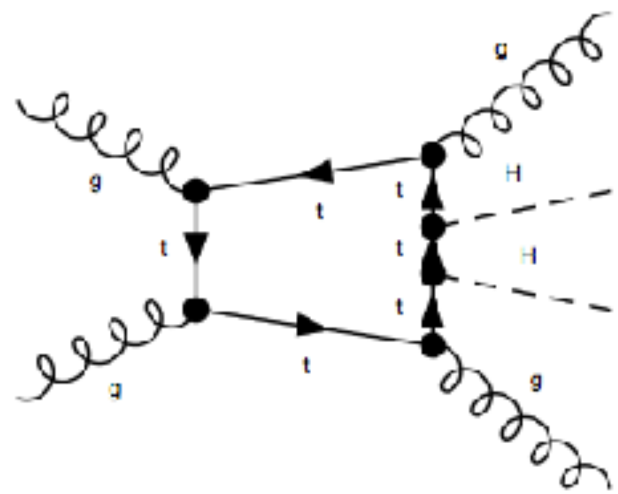
small uncertainties

cross section varies a lot with lambda



Higgs selfcoupling in HHjj+X





[Contino et al. JHEP 1005]

[Baglio et al. JHEP 1304]

[Dolan, Englert, Greiner, MS]

- Want to study VVHH
  Directly related to long. gauge boson scattering $V_L V_L \to hh$

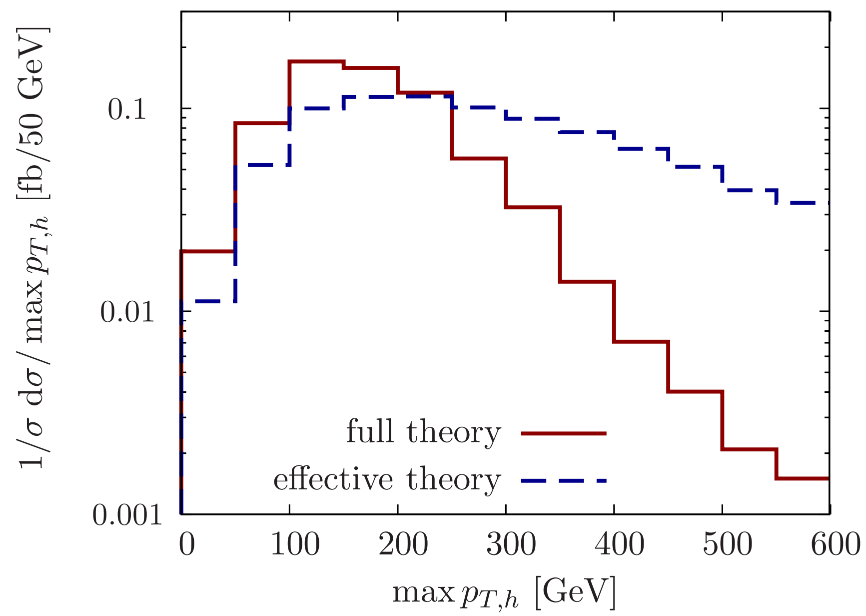
- In SM fixed: $g_{WWhh} = e^2/(2s_w^2)$ $\quad g_{ZZhh} = e^2/(2c_w^2 s_w^2)$

- However in BSM models, e.g. composite (strongly coupled light) Higgs models, can be strongly modified

- Higher-dim operators momentum dependent -> enhanced in high-pT region

- Separation of WBF and gluon fusion channel non-trivial

Higgs selfcoupling in HHjj+X



- For kinematic distributions full loop recommended in gluon fusion
- Analysis in $\bar{b}b\tau^+\tau^-$
- For 4b analysis, see [Bishara, Contino, Rojo '16]
- Very bad S/B, but expected to improve easily...

So far very rudimentary analysis:

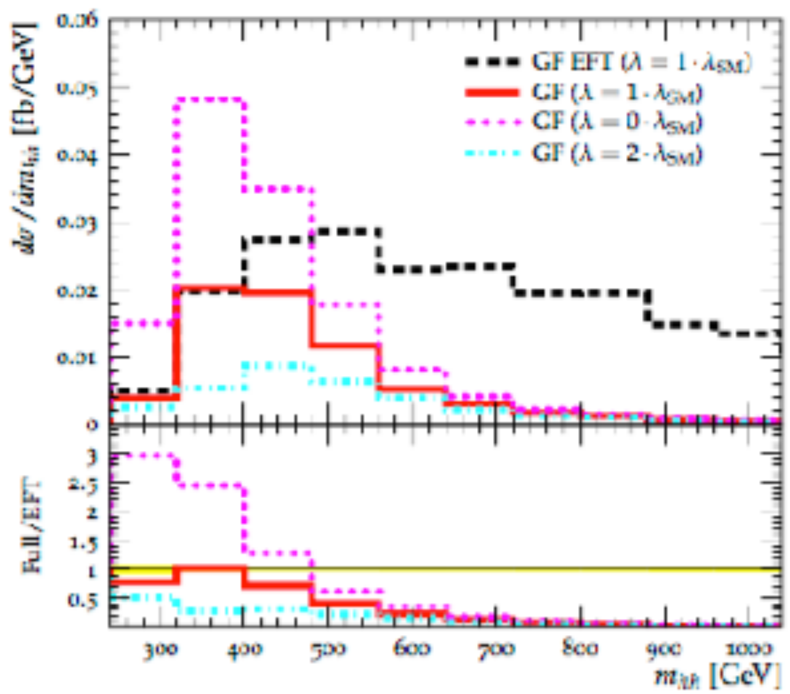
	Signal with $\xi \times \lambda$			Background		S/B
	$\xi = 0$	$\xi = 1$	$\xi = 2$	$t\bar{t}jj$	Other BG	ratio to $\xi = 1$
tau selection cuts	0.212	0.091	0.100	3101.0	57.06	0.026×10^{-3}
Higgs rec. from taus	0.212	0.091	0.100	683.5	31.92	0.115×10^{-3}
Higgs rec. from b jets	0.041	0.016	0.017	7.444	0.303	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

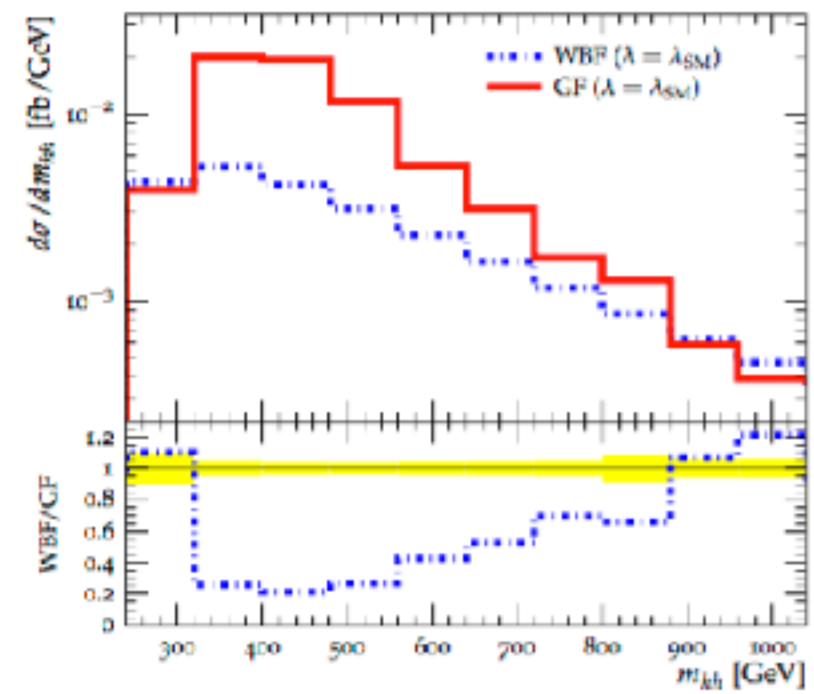
WBF only

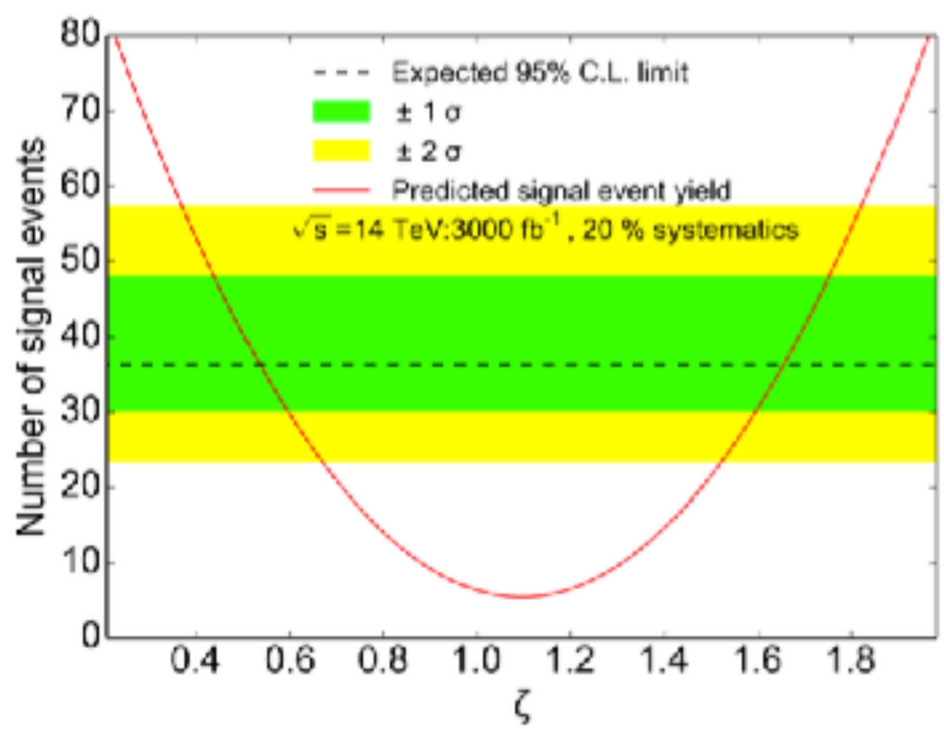
GF+WBF

	Signal with $\zeta \times \{g_{WWhh}, g_{ZZhh}\}$			Background	
	$\zeta = 0$	$\zeta = 1$	$\zeta = 2$	$t\bar{t}jj$	Other BG
tau selection cuts	1.353	0.091	0.841	3101.0	57.06
Higgs rec. from taus	1.352	0.091	0.840	683.5	31.92
Higgs rec. from b jets	0.321	0.016	0.207	7.444	0.303
2 tag jets/re-weighting	0.184	0.010	0.126	5.284	0.236
incl. GF after cuts/re-weighting	0.273	0.099	0.214	5.284	0.236

[Dolan, Englert, Greiner, Nordstrom, MS '15]







Reduction of GF HHjj 'background' highly challenging

GF contribution only can be purified to $S/B \simeq 1/7.5$

and $S/\sqrt{B} \simeq 1.66$ for 3000 ifb

limit on coupling modification $\zeta = g_{VVhh}/g^{\mathrm{SM}}_{VVhh}$

Measuring CP-odd interactions of the Higgs boson

bosons

[see talk by A. Loesle]

$$\frac{g_2^2}{2}\tilde{c}_{WW}h^2\widetilde{W}^+_{\mu\nu}W^{\mu\nu -} \qquad \frac{g_Z^2}{2}\tilde{c}_{ZZ}h^2\widetilde{Z}_{\mu\nu}Z^{\mu\nu}$$

$$\frac{e^2}{2}\tilde{c}_{\gamma\gamma}h^2\widetilde{F}_{\mu\nu}F^{\mu\nu} \qquad \frac{g_s^2}{2}\tilde{c}_{gg}h^2\widetilde{G}_{\mu\nu}G^{\mu\nu}$$

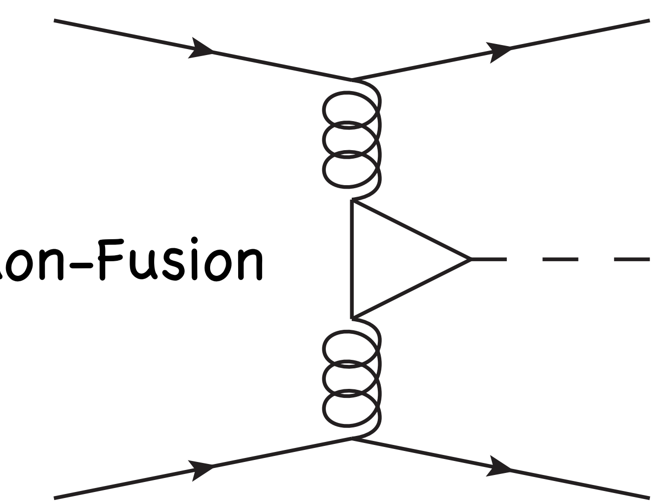
fermions

$$|c_f|\frac{m_f}{v}\bar{f}(\cos\phi_f + i\gamma_5\sin\phi_f)f h_{\text{phys}}$$

- For light Higgs with 125 GeV CP can be measured using angular correlations of tagging jets in Gluon Fusion with 2 additional jets

[Plehn, Rainwater, Zeppenfeld PRL 88 (2002)]

$$\mathcal{L} = \frac{\alpha_s}{12\pi v}HG^a_{\mu\nu}G^{a\,\mu\nu} + \frac{\alpha_s}{16\pi v}AG^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$



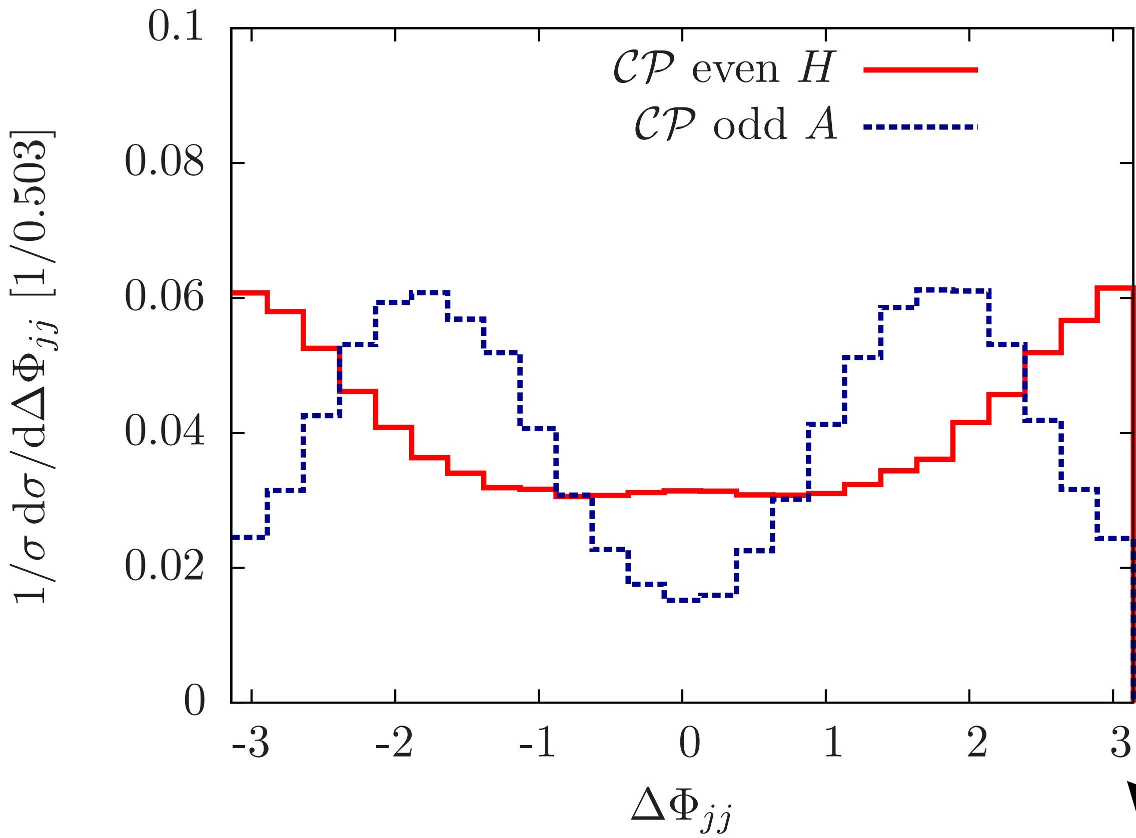
For tagging jets with $|p_z^J| \gg |p_{x,y}^J|$

$$\mathcal{M}_{\text{even}} \sim J_1^\mu J_2^\nu \left[g_{\mu\nu}(q_1\cdot q_2) - q_{1\nu}q_{2\mu}\right]$$

$$\sim \left[J_1^0 J_2^0 - J_1^3 J_2^3\right]\mathbf{p}_T^{J_1}\cdot\mathbf{p}_T^{J_2} \sim 0 \text{ for } \Delta\phi_{jj} = \pi/2$$

$\mathcal{M}_{\text{odd}}$ contains Levi-Civita tensor which is 0 if two of momenta linearly dependent, i.e. if $\Delta\phi_{jj} = 0$ or $\Delta\phi_{jj} = \pi$

Tagging jets approach:

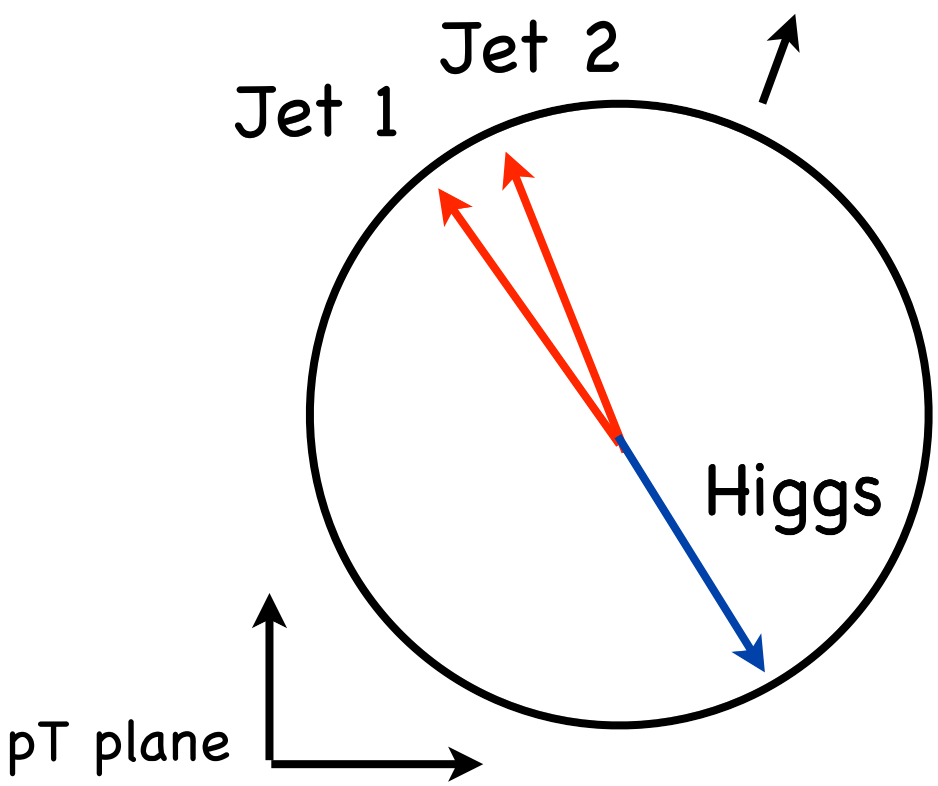


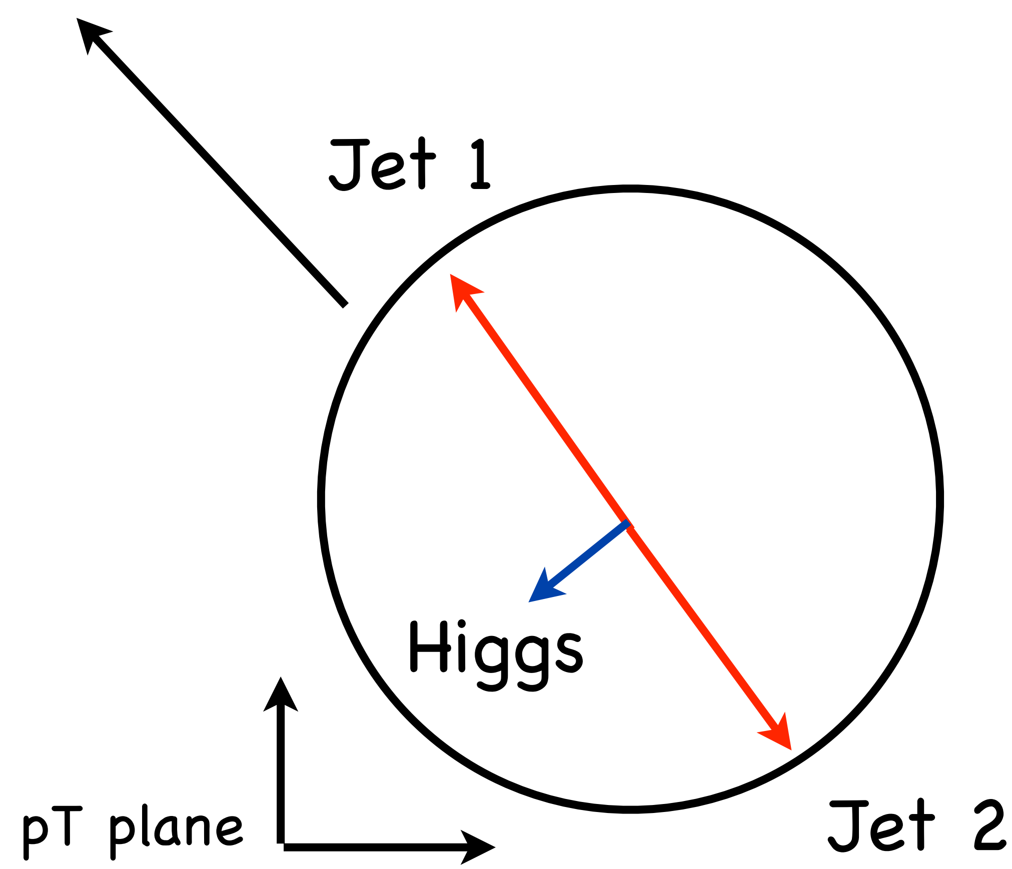
azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

$$p^\mu_< = \sum_{j\in\{\text{jets: } y_j<y_h\}} p^\mu_j$$

$$p^\mu_> = \sum_{j\in\{\text{jets: } y_j>y_h\}} p^\mu_j$$

$$\Delta\Phi_{jj} = \phi(p_>) - \phi(p_<)$$





Higgs has CP-odd as well as CP-even interactions

[Dolan, Harris, Jankowiak, MS '15]

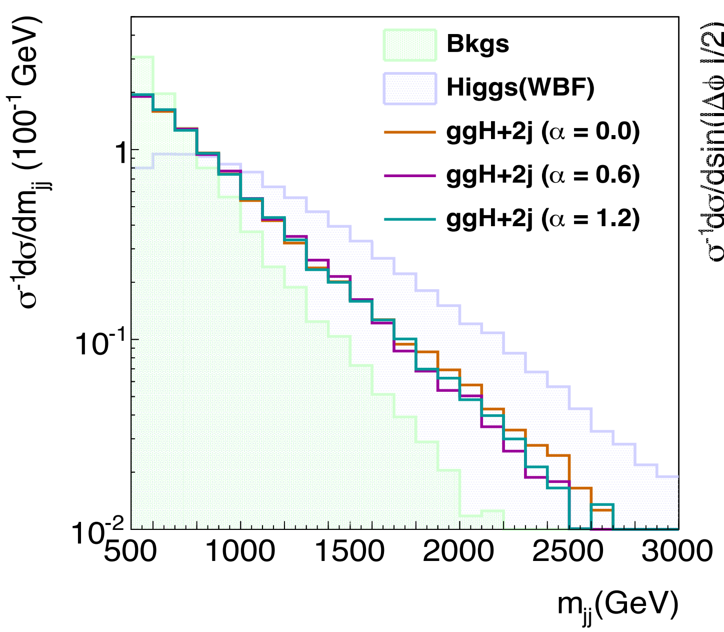
Assume, only CP-violating interactions in fermion sector
(e.g. CP no good quantum number in Higgs sector)

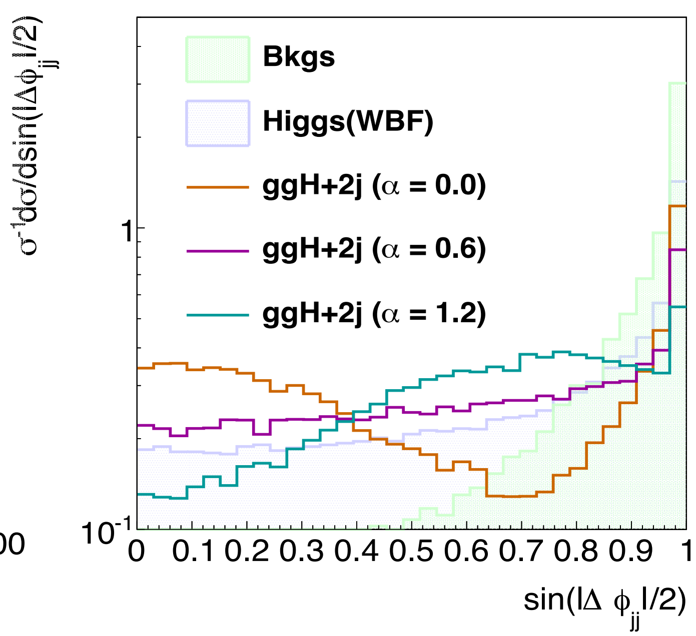
[E. Accomando et al '06]

$$\mathcal{L}_{h\bar{f}f} = \cos\alpha\, y_f \bar{\psi}_f \psi_f h + \sin\alpha\, \widetilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h$$

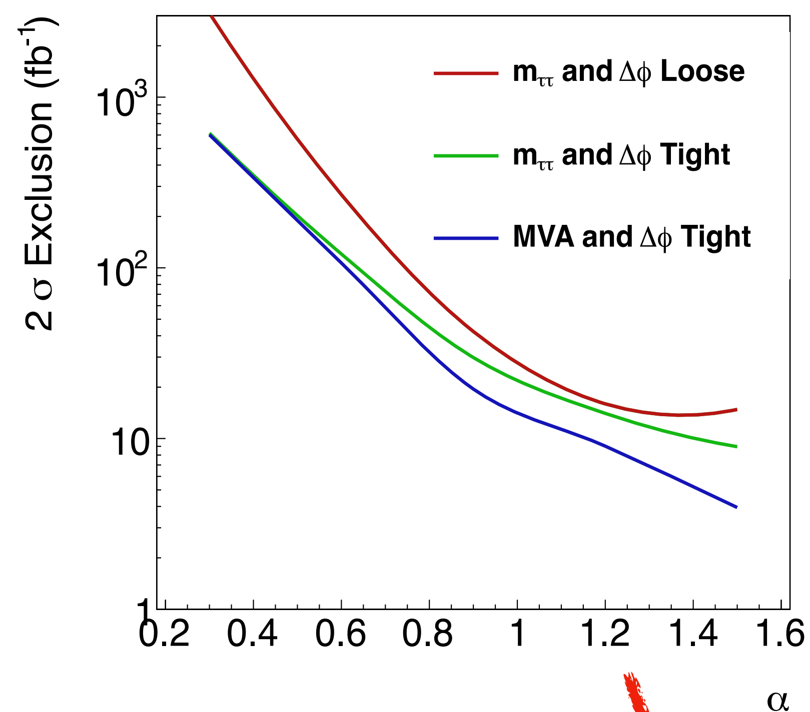
generates

$$\mathcal{L}_{hgg} = \cos\alpha\, \frac{\alpha_S}{12\pi v} h G^a_{\mu\nu} G^{a,\mu\nu} + \sin\alpha\, \frac{\alpha_S}{4\pi v} h G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$





MVA



$\alpha \geq 0.3$ can be excluded with $500\ \mathrm{fb}^{-1}$

Hypothesis testing with Event shapes

[Englert, MS, Takeuchi '12]

- Event shapes well studied experimentally and theoretically

  [Bethke, Nucl.Phys.Proc.Suppl. 121 (2003)] [Kluth. et al, EPJC 21 (2011)]

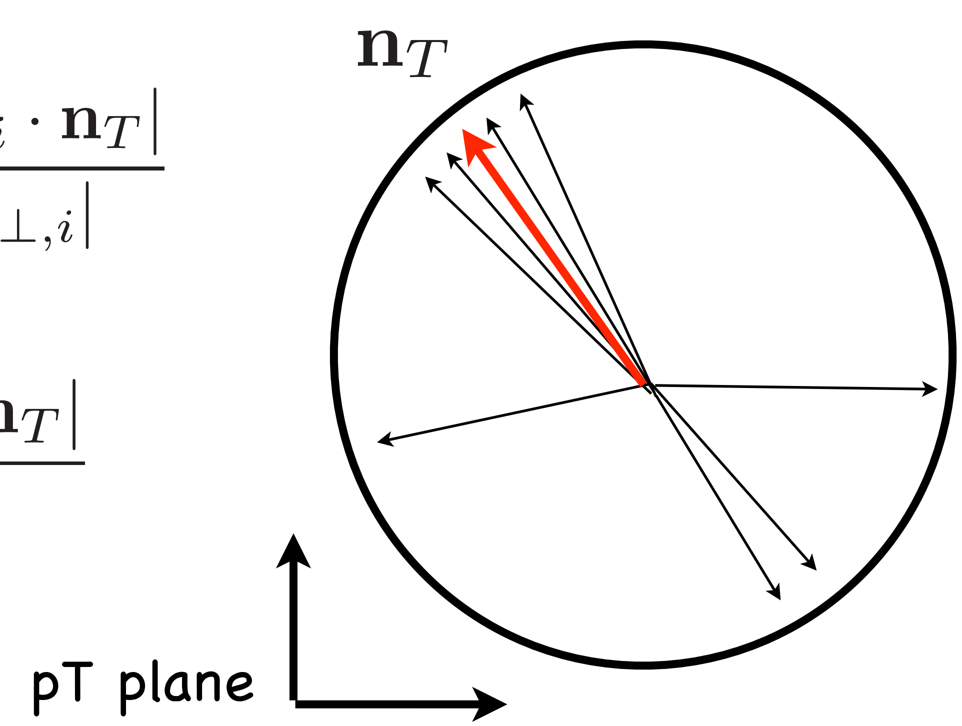
  [Banfi et al., JHEP 0408] [Gehrmann-De Ridder et al., JHEP 0712]

- Event shape measurements established in experimental collaborations already now [CMS, PLB 699 (2011)]

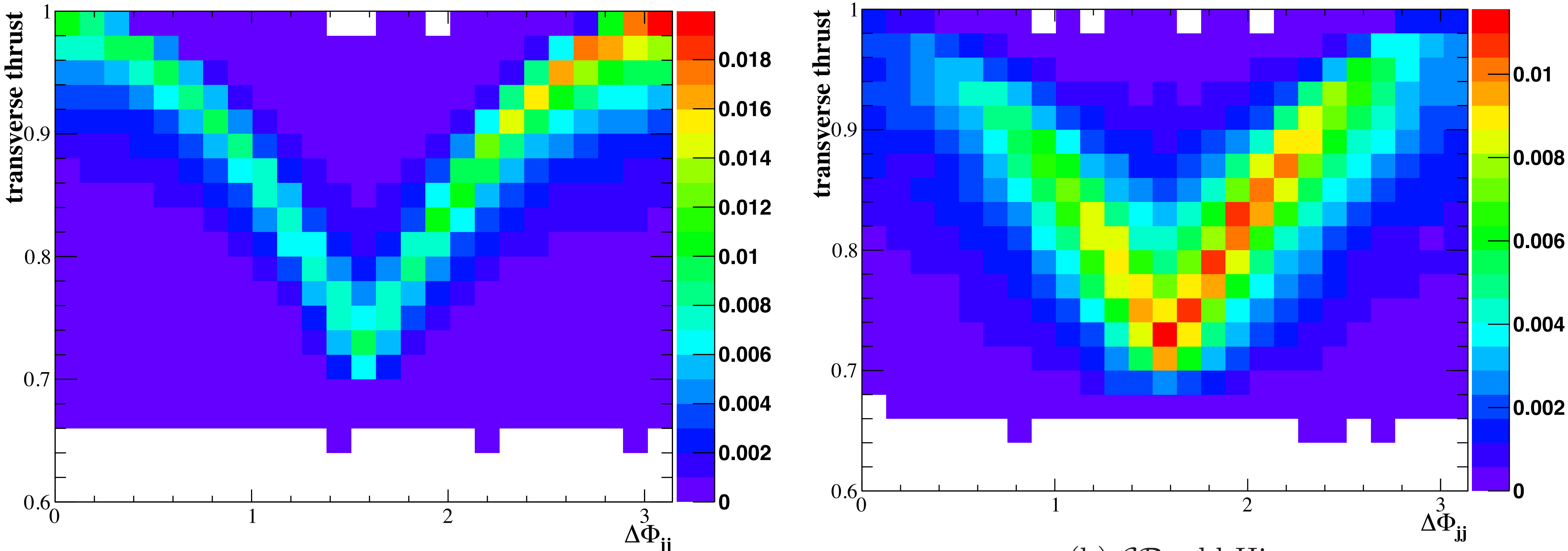
e.g.

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

transverse thrust minor $$T_{m,g} = \frac{\sum_i |\mathbf{p}_{\perp,i} \times \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|}$$



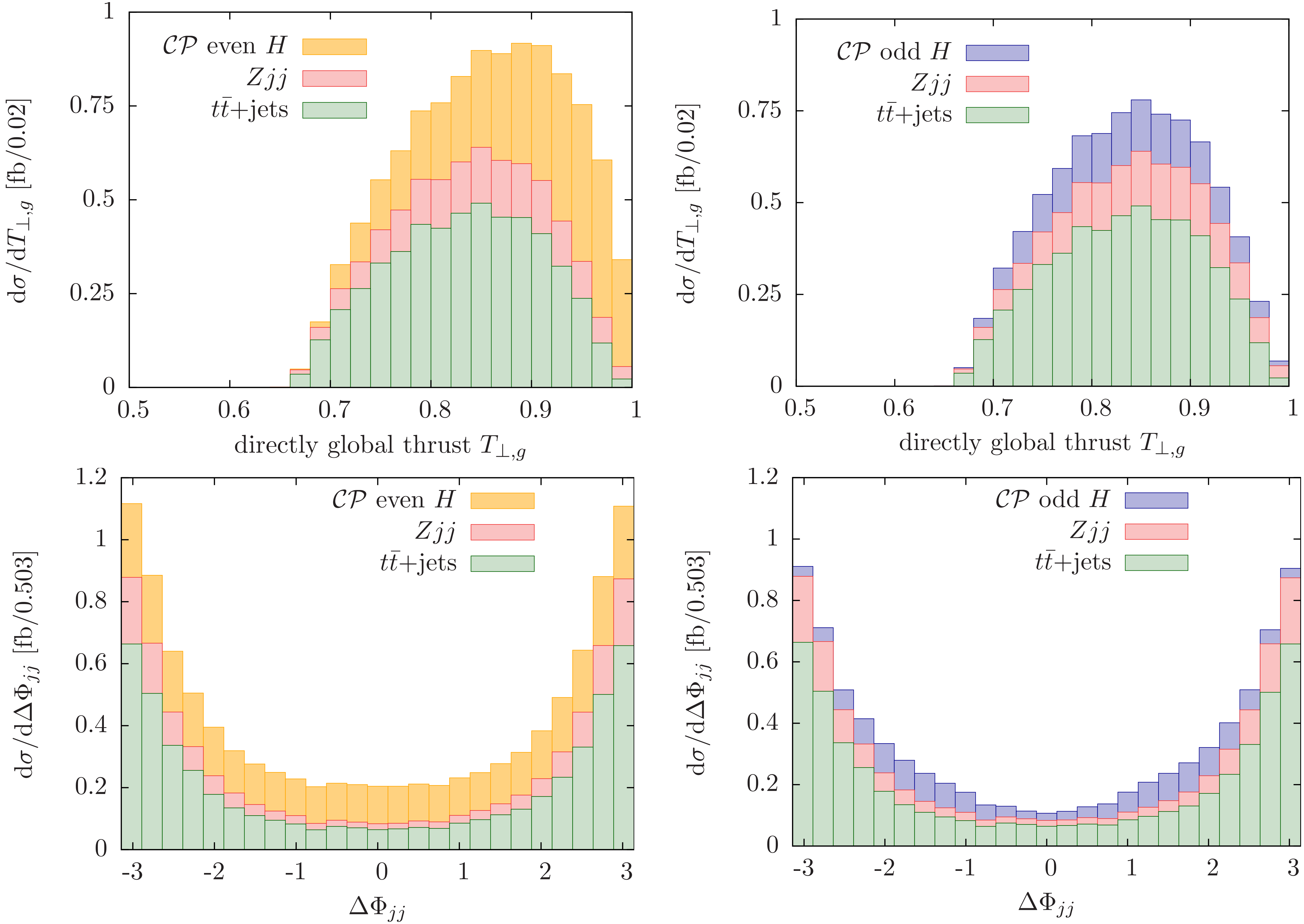
Obvious correlation between thrust and $\Delta\Phi_{jj}$



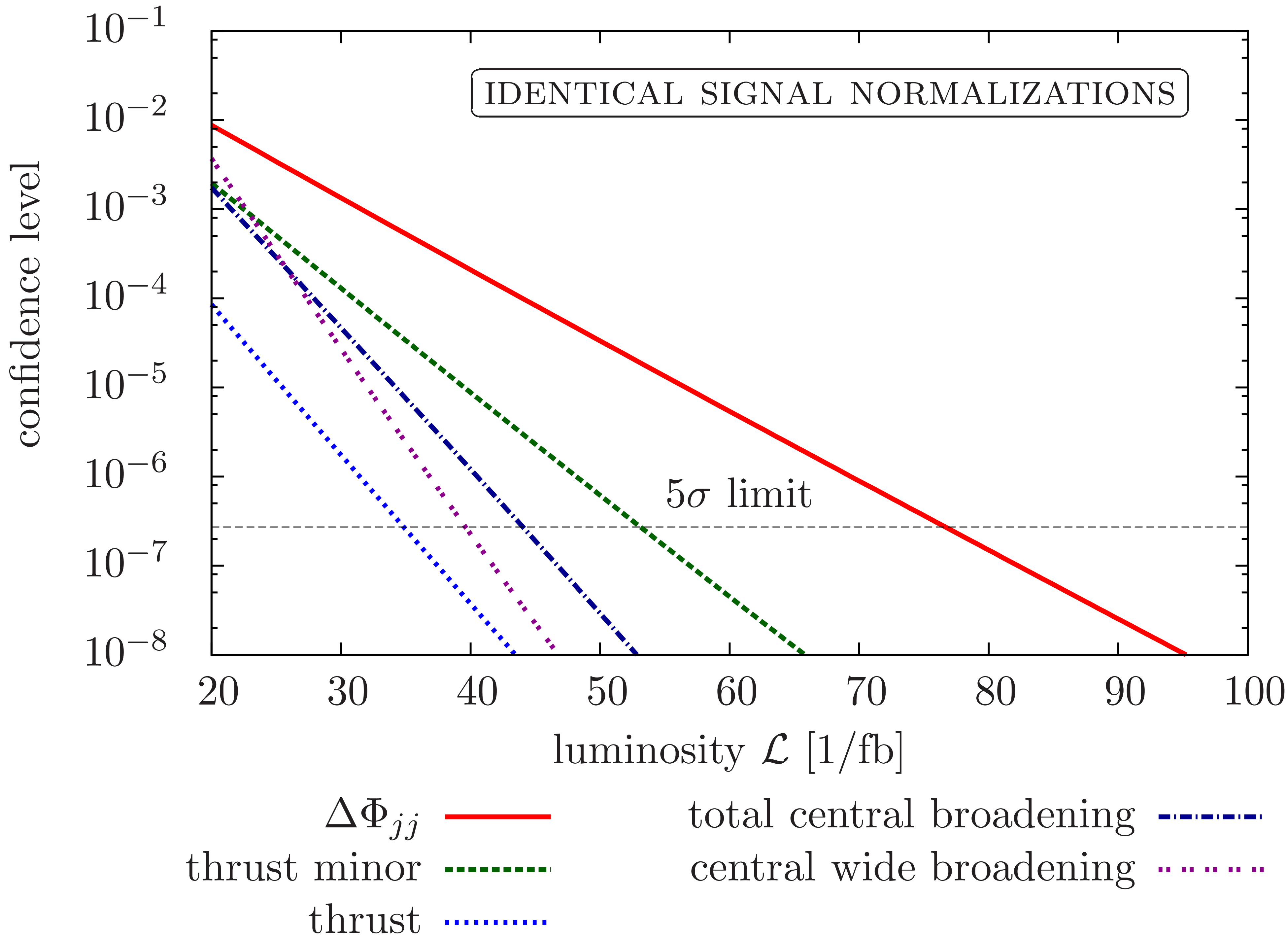
(a) $\mathcal{CP}$ even Higgs

(b) $\mathcal{CP}$ odd Higgs

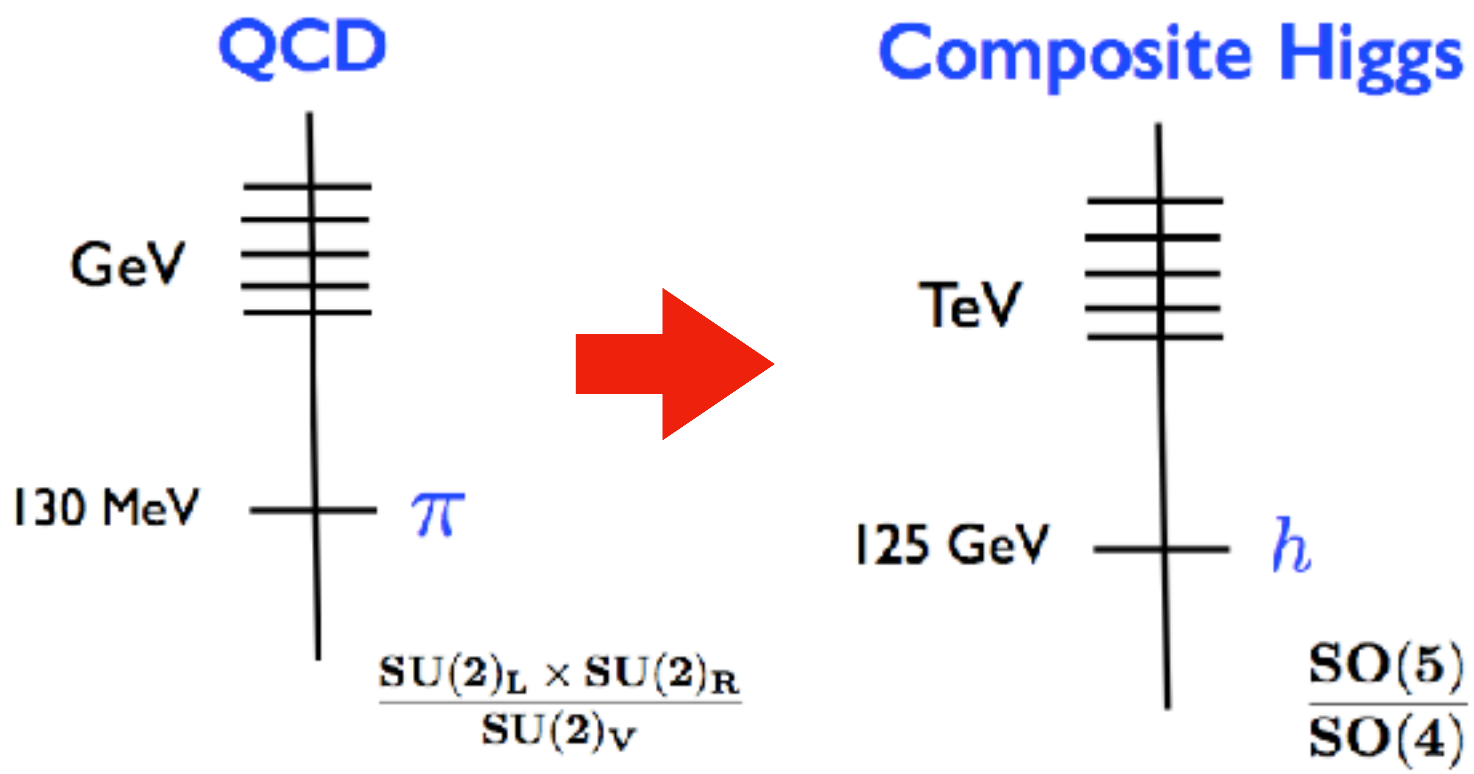
Distributions CP-odd vs CP-even



Sensitivity for discrimination between CP-even and CP-odd (normalized signal rates)



Question 3: Composite Higgs models



Higgs is lightest state (PGB) of new strong resonances

[Giudice, Grojean, Pomarol, Rattazzi '07]

In minimal realisation Higgs couplings follow well-defined (global) pattern:

$$\frac{g_{hWW}}{g_{hWW}^{SM}} = \sqrt{1 - \frac{v^2}{f^2}} \qquad \frac{g_{hff}}{g_{hff}^{SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}} \qquad n = \underset{\text{MCHM4}}{0}, \underset{\text{MCHM5}}{1}, 2, \cdots$$

→ Indirect limit via Higgs coupling measurements

Separation of GF vs WBF important to improve coupling measurement

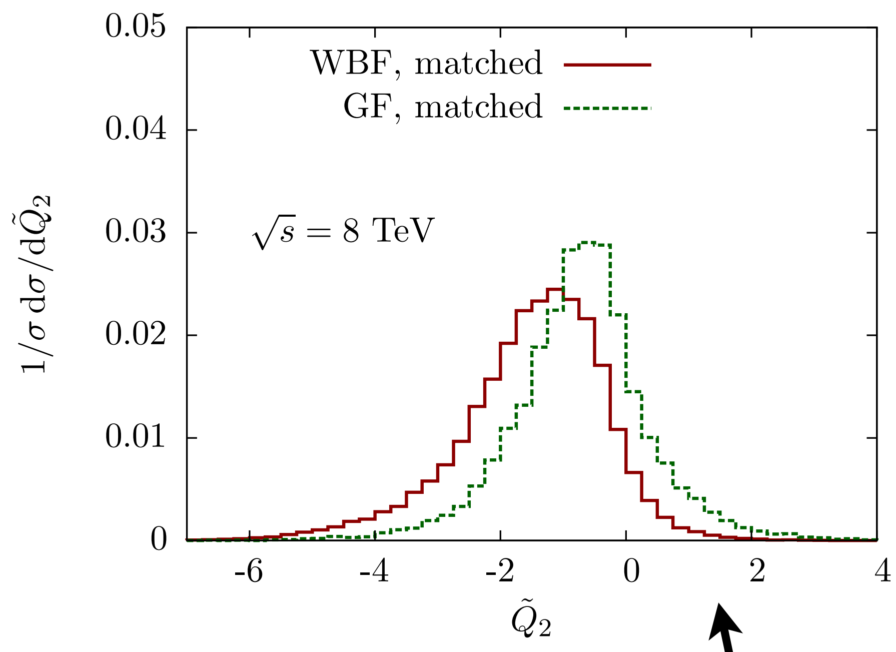
$$\sigma(H) \times \mathrm{BR}(YY) \sim \left(\sum_p g_p^2\right) \frac{g_{HYY}^2}{\sum_{\text{modes}} g_i^2}$$

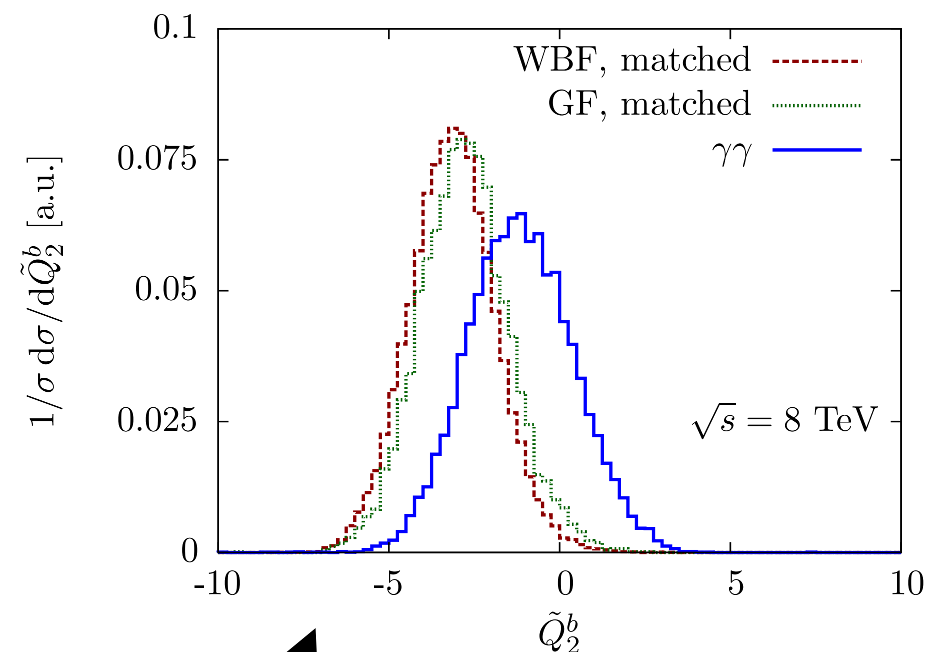
need separate production modes to optimise coupling measurements

Possible to construct discriminating observable based on matrix element information:

$$\tilde{Q}_n(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2}{|\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2}\right]$$

$$\tilde{Q}_n^b(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{\{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2 + |\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2\}}{|\mathcal{M}^{2\gamma}(pp \to \gamma\gamma j^n)|^2}\right]$$





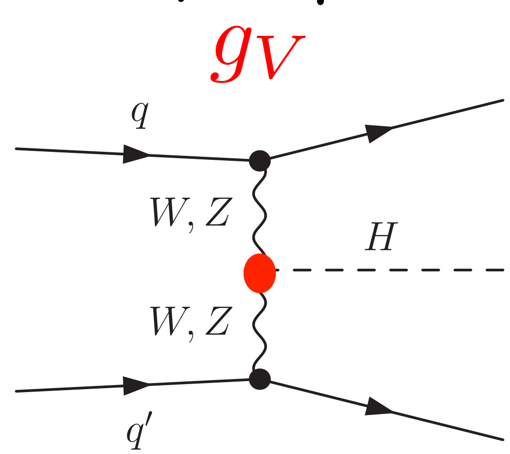
- Method separates GF vs WBF and reduces backgrounds

We want to study more objects in final state -> Transfer function limits us. Do we always need it?

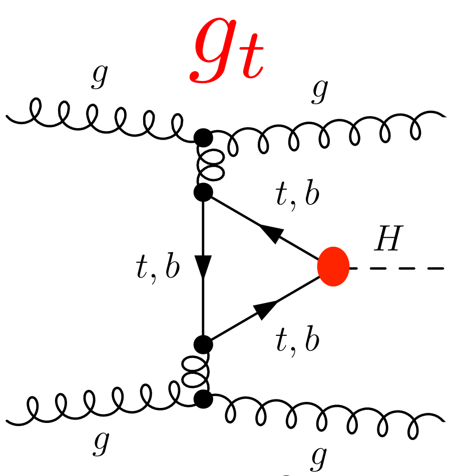
Transfer functions only important if matrix element varies quickly:

Example

[Andersen, Englert, MS '13]

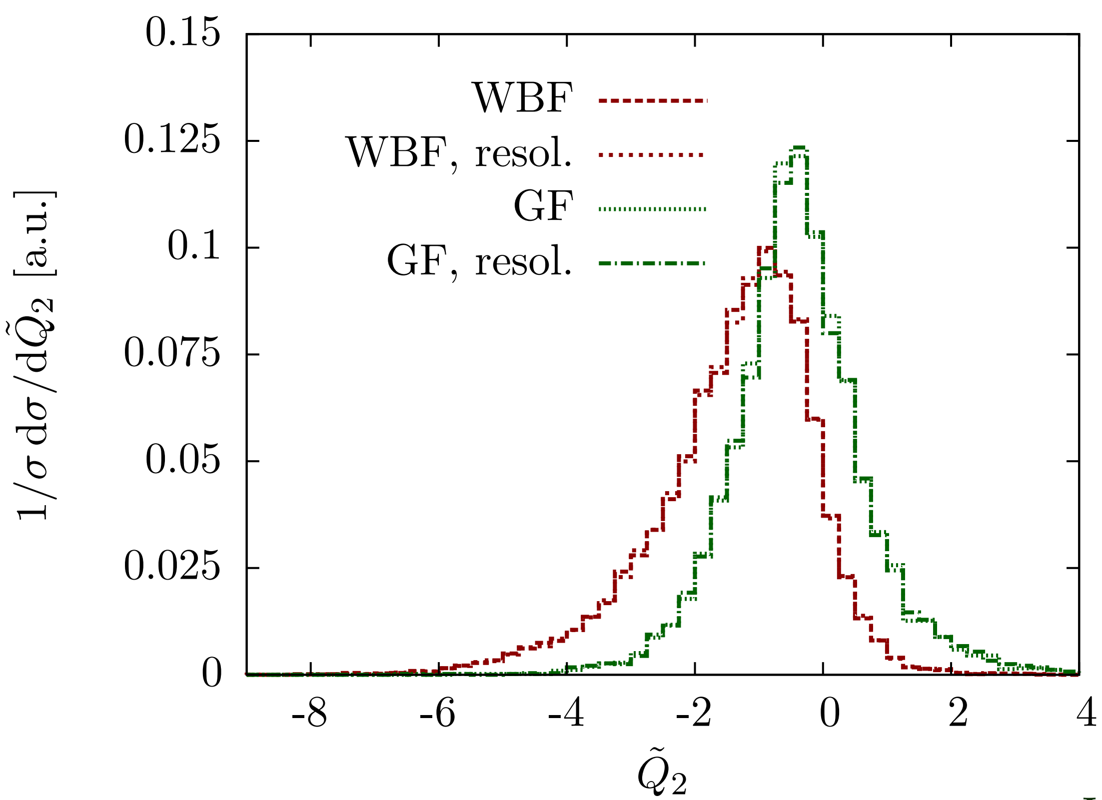


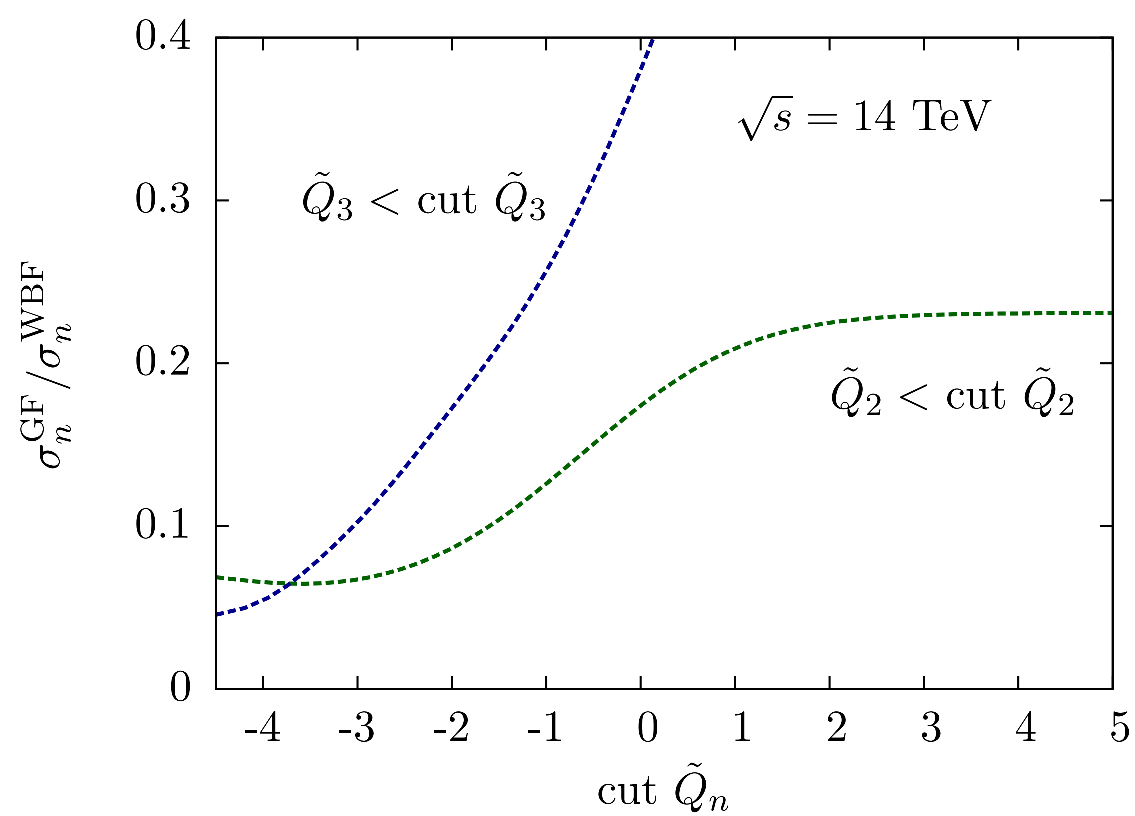
vs



in $H \to \gamma\gamma$

Higgs reconstructed, but no transfer function for jets:





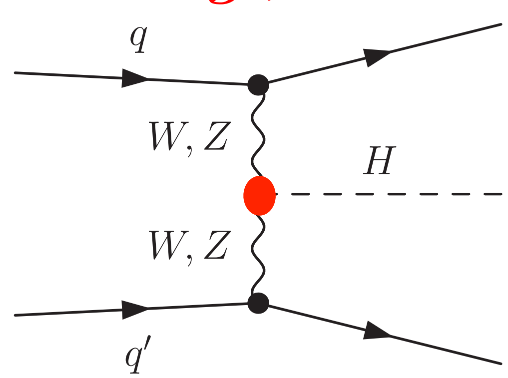
$$\tilde{Q}_n = -\log\left[\frac{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2}{|\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2}\right]$$

We want to study more objects in final state ->

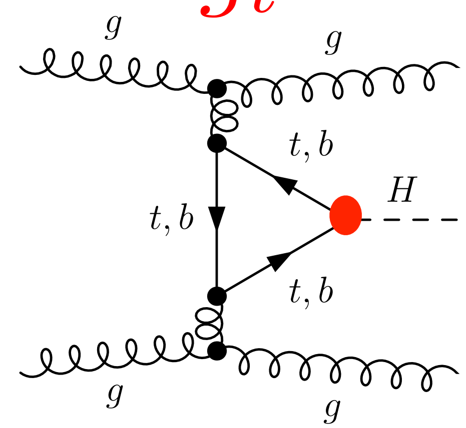
Transfer function limits us. Do we always need it?

Transfer functions only important if matrix element varies quickly:

Example g_V

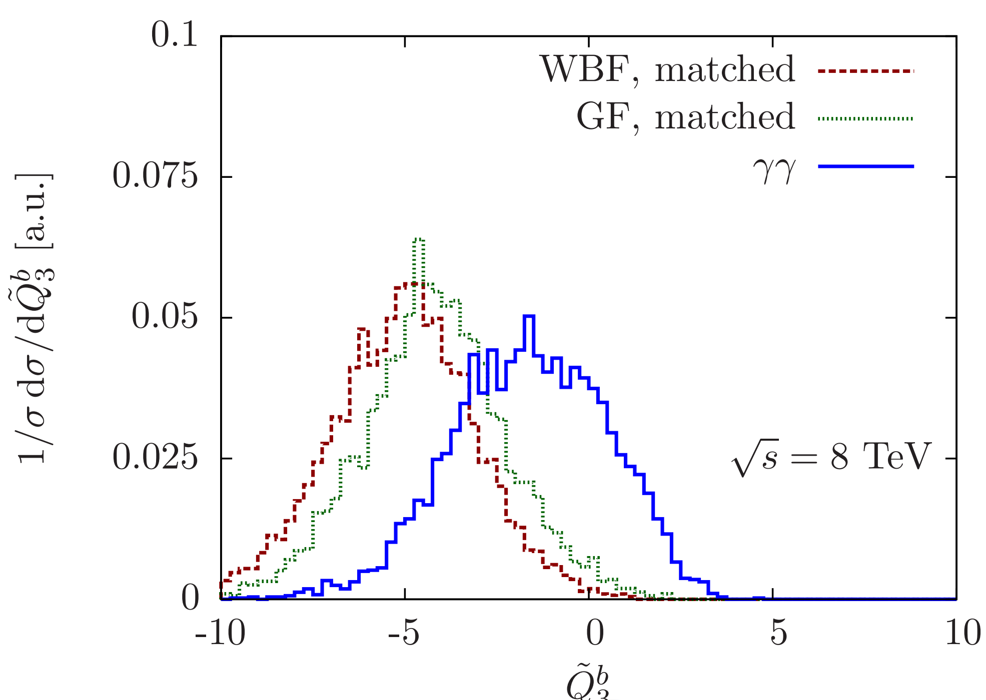


vs g_t



in $H \to \gamma\gamma$

Higgs reconstructed, but no transfer function for jets:



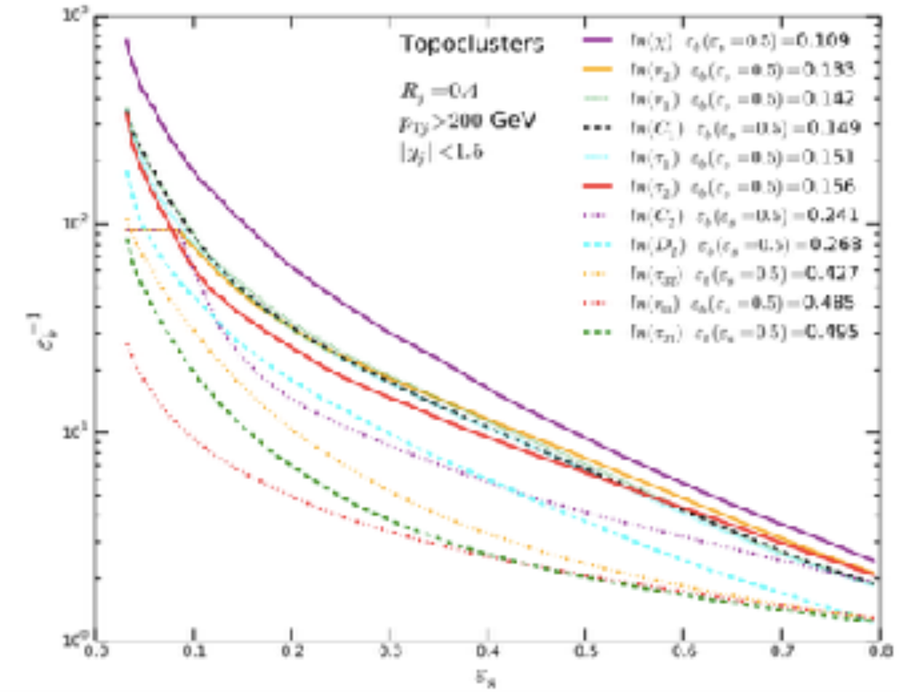
$S/B \nearrow 100\%$

$$\tilde{Q}_n^b(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{\{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2 + |\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2\}}{|\mathcal{M}^{2\gamma}(pp \to \gamma\gamma j^n)|^2}\right]$$

Quark and Gluon tagging to purify Hjj signal

[Ferreira de Lima,
Petrov, Soper, MS '17]

Quark-gluon tagging becomes viable tool, particularly well suited for VBF topology



example $\quad pp \to jj(H \to ZZ^* \to 4l)$

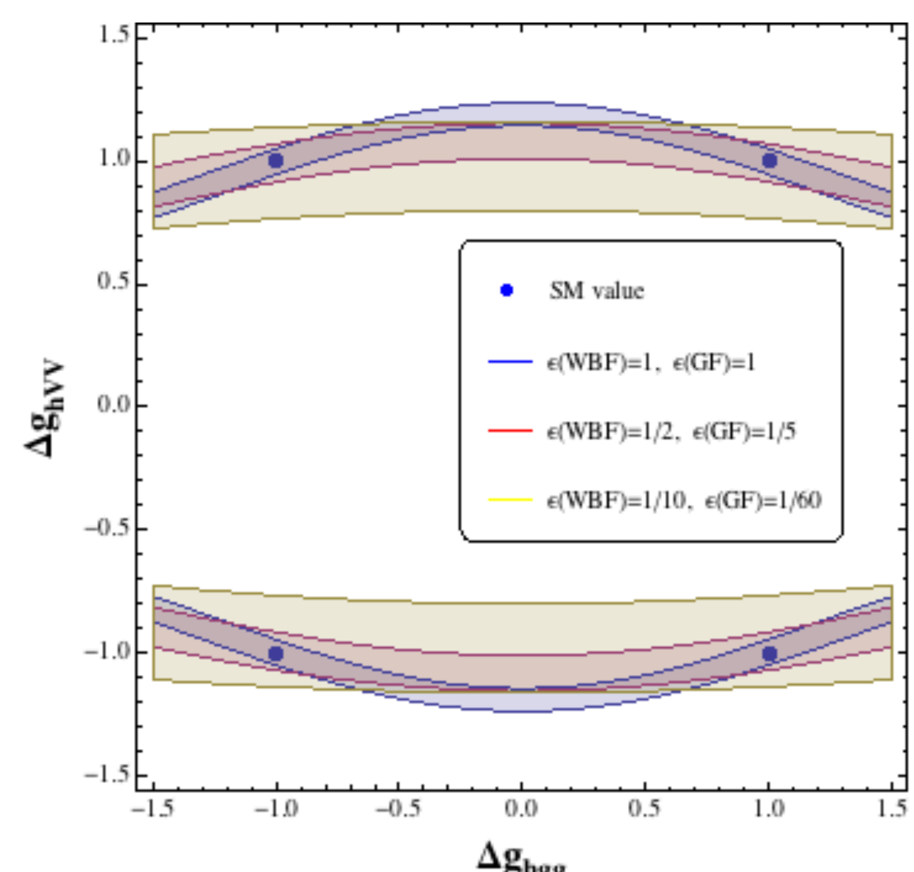
$$N(\mathrm{WBF}) \equiv \epsilon(\mathrm{WBF}) \cdot \sigma(\mathrm{WBF}) \cdot \mathrm{Br}(H \to 4l) \cdot \mathcal{L}$$

$$N(\mathrm{GF}) \equiv \epsilon(\mathrm{GF}) \cdot \sigma(\mathrm{GF}) \cdot \mathrm{Br}(H \to 4l) \cdot \mathcal{L}$$

$$N_{\mathrm{tot}} = \Delta g_{hgg}^2 \Delta g_{hVV}^2 N(\mathrm{GF}) + \Delta g_{hVV}^4 N(\mathrm{WBF})$$

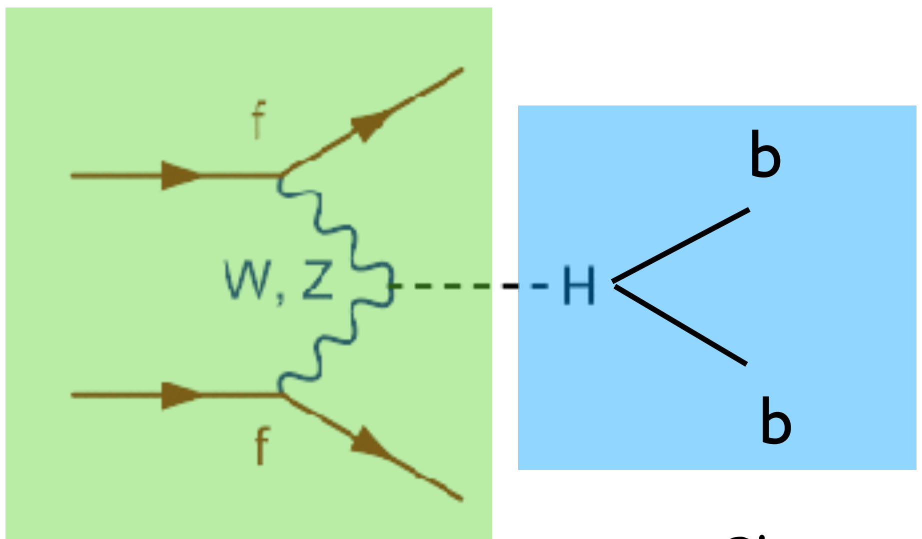
$$\Delta g_i \equiv g_{i,\mathrm{mod}} / g_{i,\mathrm{SM}}$$

running on different QG-tagging working points breaks degeneracy



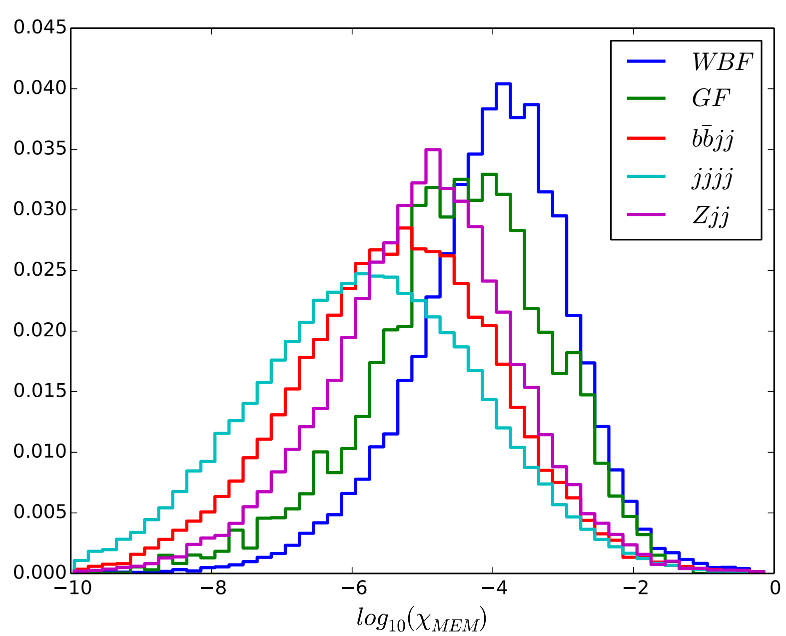
GF and WBF for H->bb

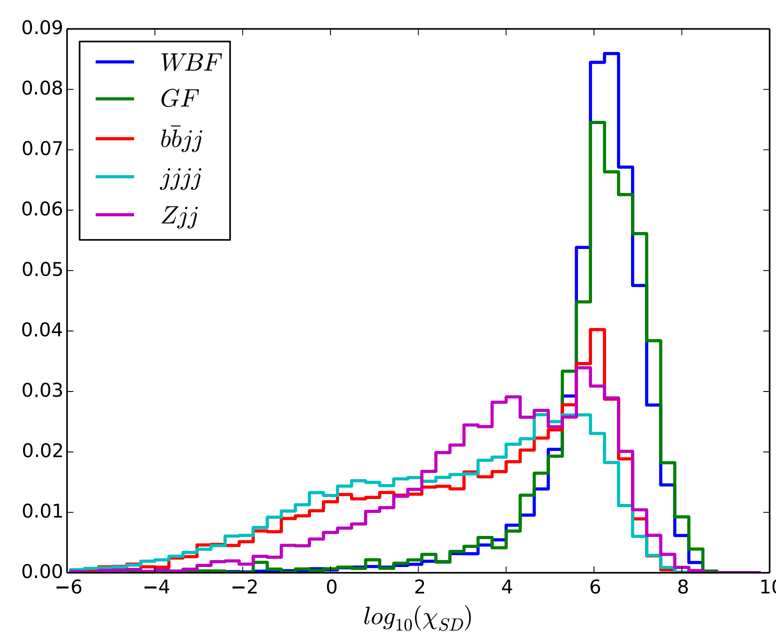
- considered to be impossible [Mangano et al. '03]
- Use Event Deconstruction to improve [Englert, Mattelaer, MS '15]



Matrix Element Method

Shower Deconstruction





Extrapolated to 600 ifb

$$0.82 < y_b/y_b^{\mathrm{SM}} < 1.14$$

MEM + SD

Indirect limit on total width of the Higgs boson

indirect width measurement a la [Caola, Melnikov 2013]

Measure coupling off-shell -> limit denominator on-shell

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

less freedom to break relation (-> less model dependence) in WBF

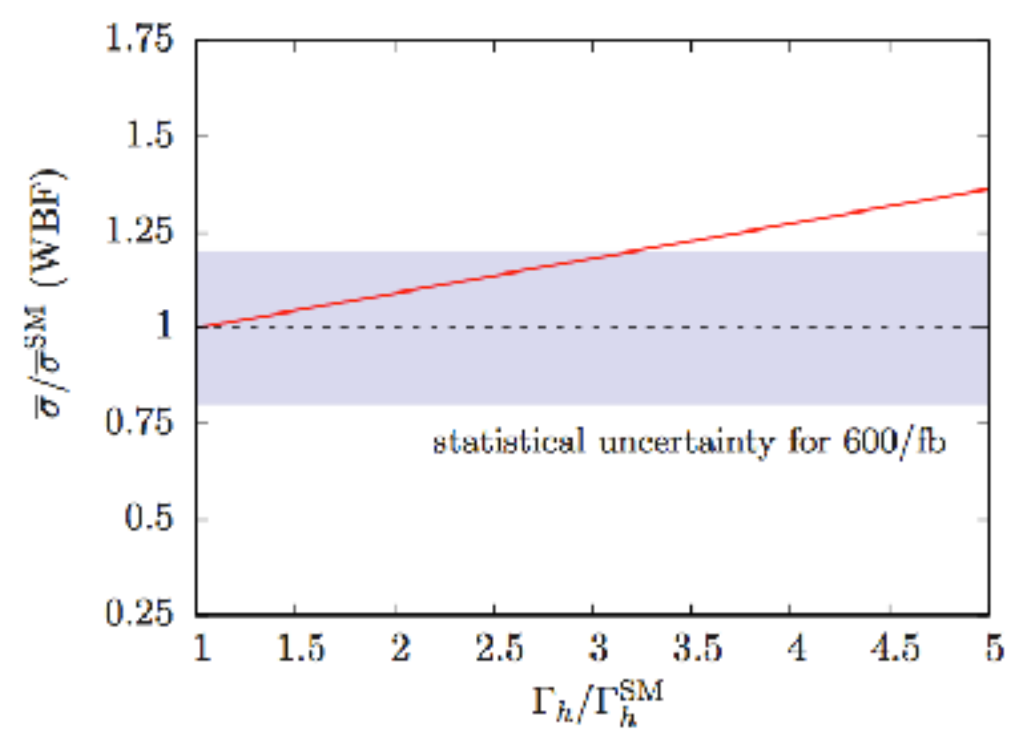
Same tree-level coupling in production and decay

T parameter links WWH and ZZH

$$\mathcal{L}_{HD} = F_{HD}\ \mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right]\cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})\right]$$

assumed $\quad hW^+_\mu W^-_\nu: \quad ig M_W g_{\mu\nu}\frac{v^2 F_{HD}}{2}$

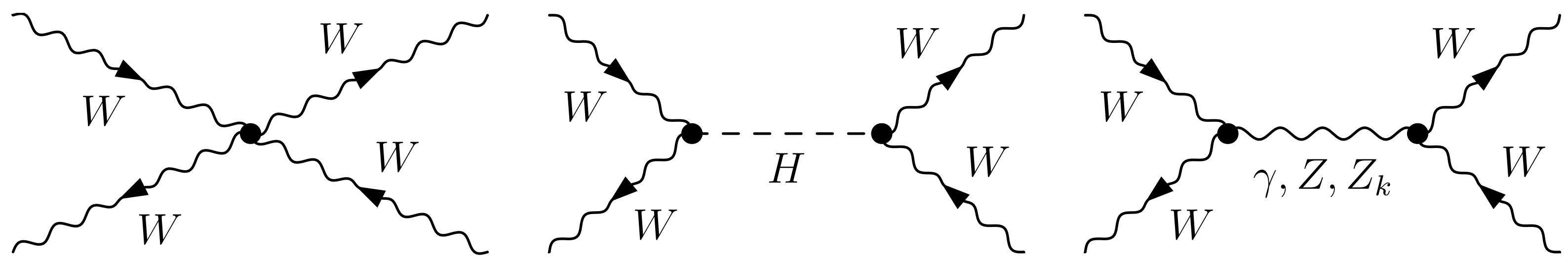
$$hZ_\mu Z_\nu: \quad ig\frac{M_W}{\cos^2\theta_W} g_{\mu\nu}\frac{v^2 F_{HD}}{2}$$



[Englert, MS '14] [Ellis, Campbell '15]

Question 3: Models with new resonances

New resonances can affect gauge-boson scattering



Leads to unitarity sum rules

WW scattering

$$g_{WWWW} = g^2_{WW\gamma} + \sum_i g^2_{WWZ_i}$$

$$4m_W^2 g_{WWWW} = \sum_i 3m_i^2 g^2_{WWZ_i} + \sum_i g^2_{WWH_i}$$

$i = 1:$ SM W,Z,H

$i > 1:$ isotriplet W', Z'

isosinglet H'

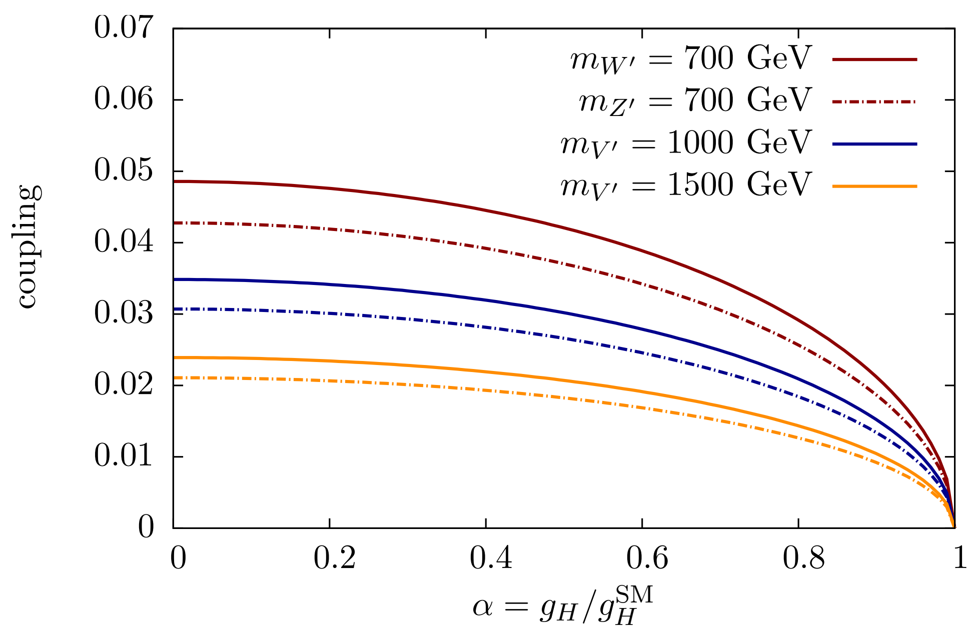
$WW \to ZZ$ scattering

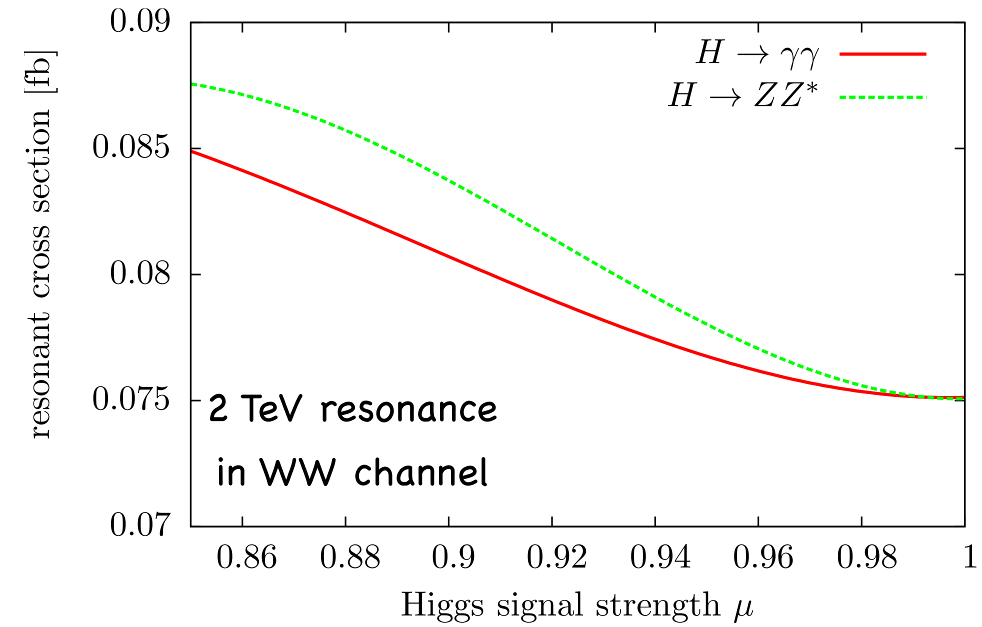
$$g_{WWZZ} = \sum_i g^2_{W_i WZ}$$

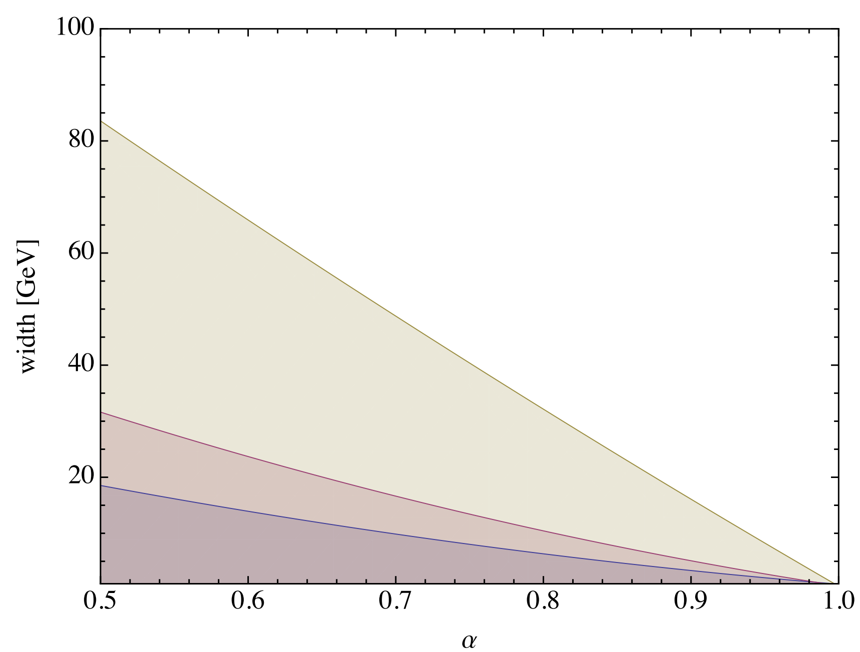
$$2(m_W^2 + m_Z^2) g_{WWZZ} = \sum_i \left(3m_i^2 - \frac{(m_Z^2 - m_W^2)^2}{m_i^2}\right) g^2_{W_i WZ} + \sum_i g_{WWH_i} g_{ZZH_i}$$

e.g. [Bellazini, Csaki, Hubisz, Serra, Terning '12]

Searches for new resonances in WZ and WW final states



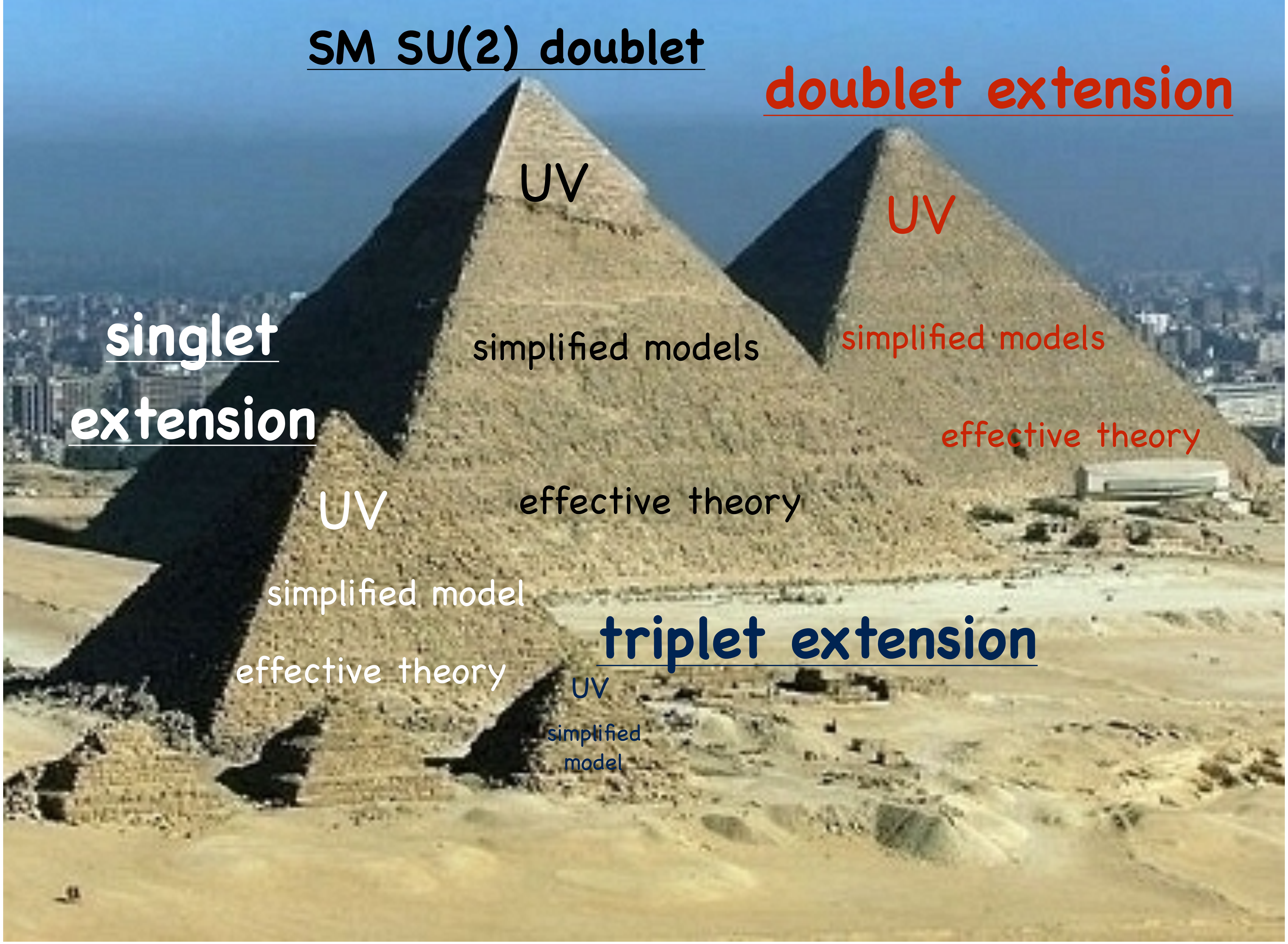




(b) 95% confidence level exclusion contours for 700 GeV (blue), 1000 GeV (red) and 1500 GeV (yellow) for a nominal luminosity of 100/fb.

[Englert, Harris, MS, Takeuchi '15]

Simplified models: Pheno of extended Higgs sectors



Simplified Models

Choose custodial symmetry as guiding principle for extensions (Practicality):

$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$ indicates that an approximate global symmetry exits, broken by the vev to the diagonal 'custodial' symmetry group $SU(2)_L \times SU(2)_R \to SU(2)_{L-R}$

Thus the Higgs field transforms $SU(2)_L \times SU(2)_R :$ $\quad \Phi \to L \Phi R^\dagger$

A. Singlet extension (Higgs portals):

$$\mathcal{V} \supset \eta_\chi |\phi_s|^2 |\phi_h|^2 \quad \longrightarrow \quad (2,2) \otimes (1,1) \simeq 3 \oplus 1 \oplus 1$$

new scalar

observed Higgs 125 GeV

eaten would-be Goldstones

B. Higgs doublet extension:

$$\Phi = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix} \quad \longrightarrow \quad (2,2) \otimes (2,2) \simeq 3 \oplus 3 \oplus 1 \oplus 1$$

U_L $\quad U_R^\dagger$

observed Higgs 125 GeV

H^+ and A

H

C. Higgs triplet extension:

$$\Xi = \begin{pmatrix} \chi_3^* & \xi_1 & \chi_1 \\ -\chi_2^* & \xi_2 & \chi_2 \\ \chi_1^* & -\xi_1^* & \chi_3 \end{pmatrix} \quad \longrightarrow \quad (3,3) \otimes (2,2) \simeq 5 \oplus 3 \oplus 3 \oplus 1 \oplus 1$$

U_L $\quad U_R^\dagger$

gaugephobic

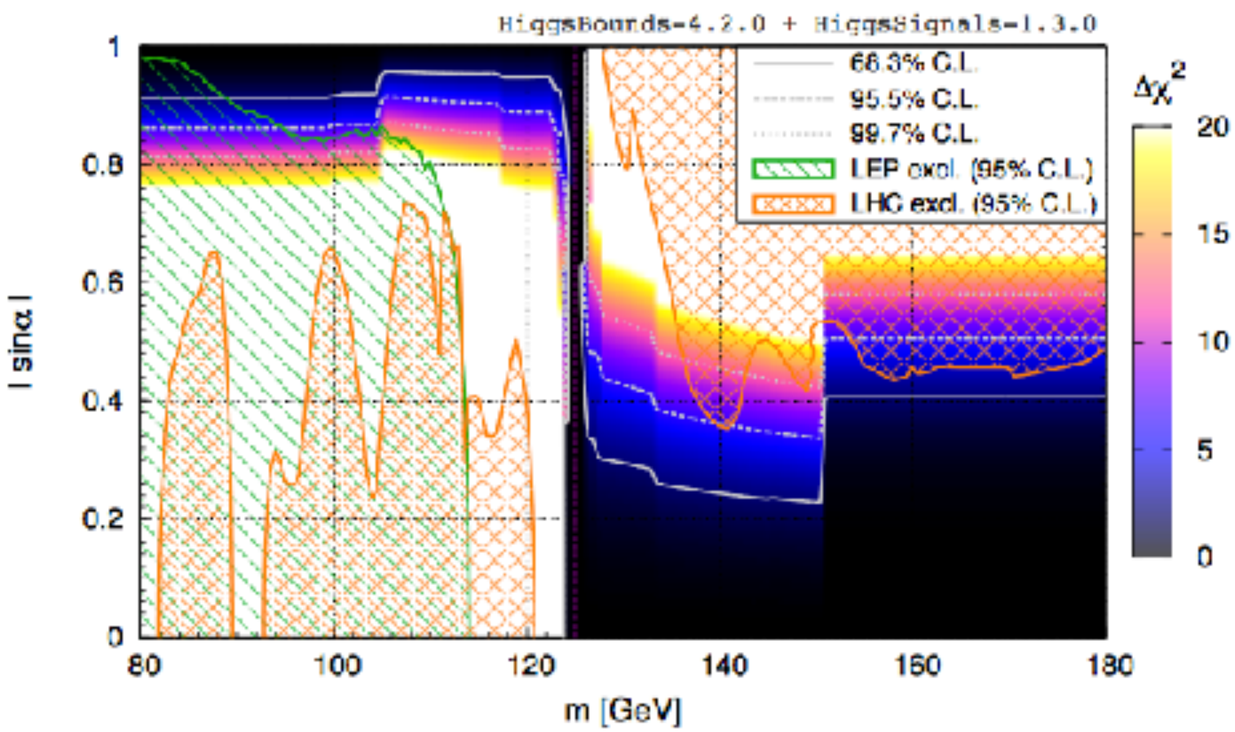
fermiophobic

$H^{\pm\pm}$

[Georgi, Machacek '85]

Singlet extension:

[Robens, Stefaniak '15]

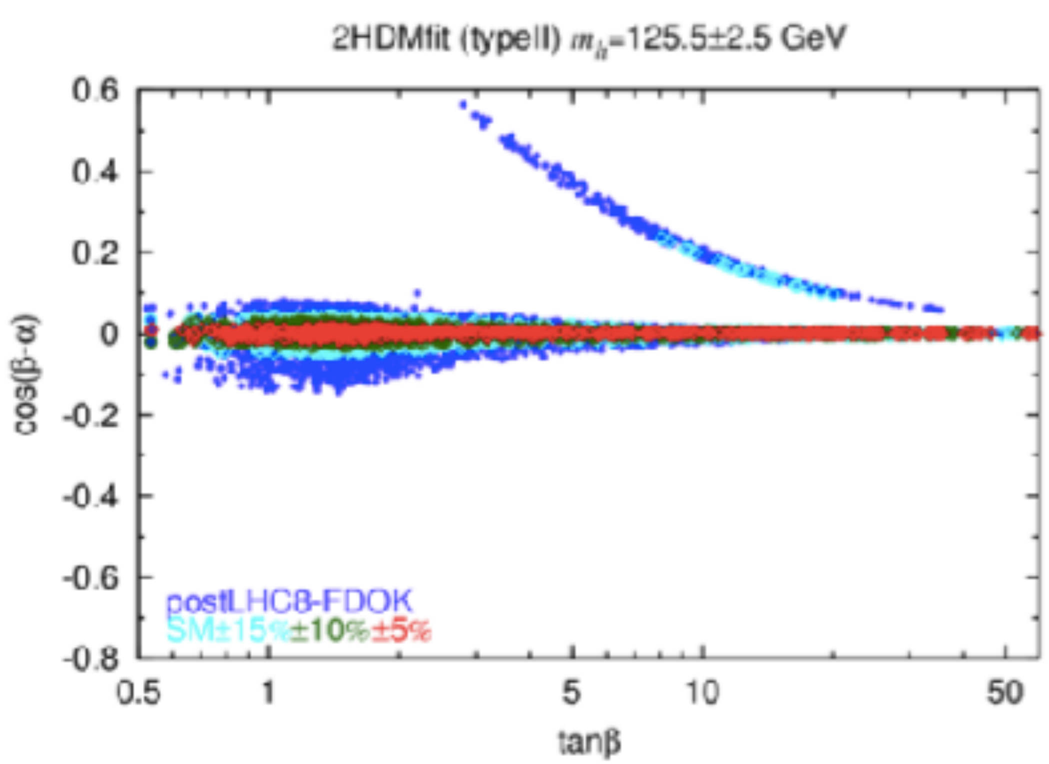


Hjj in singlet extension

WBF cross section for
H1 and H2 globally
rescaled by mixing angle

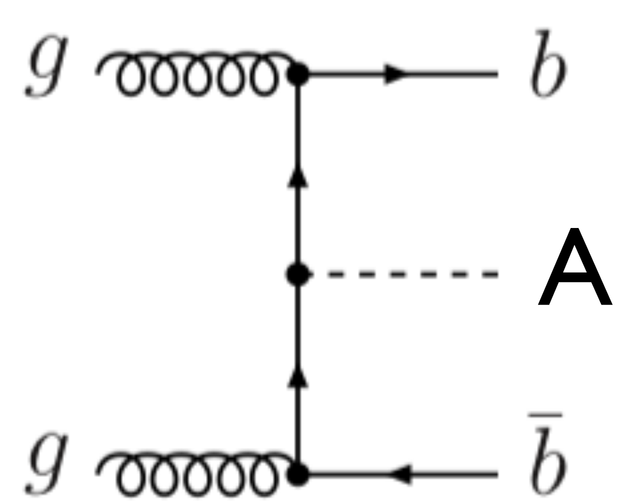
Doublet extension:

[Dumont, Gunion, Jiang, Kraml '14]



Ajj in doublet extension

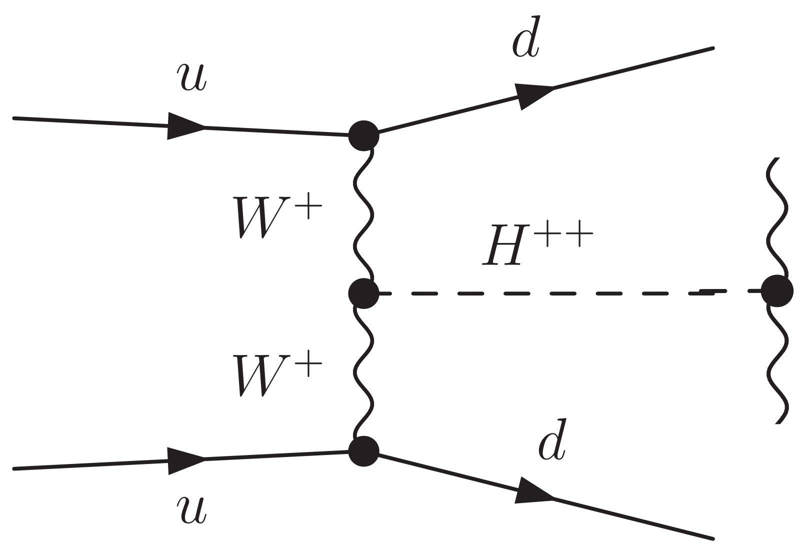
In type-II 2HDM Abb strongly
enhanced for large tanb

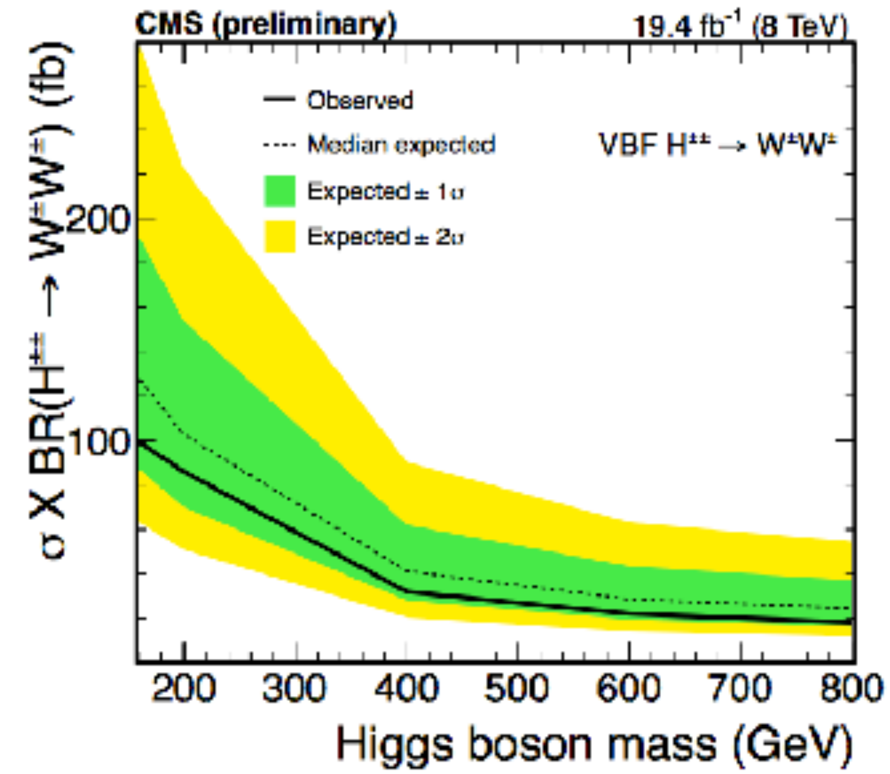


Triplet extension

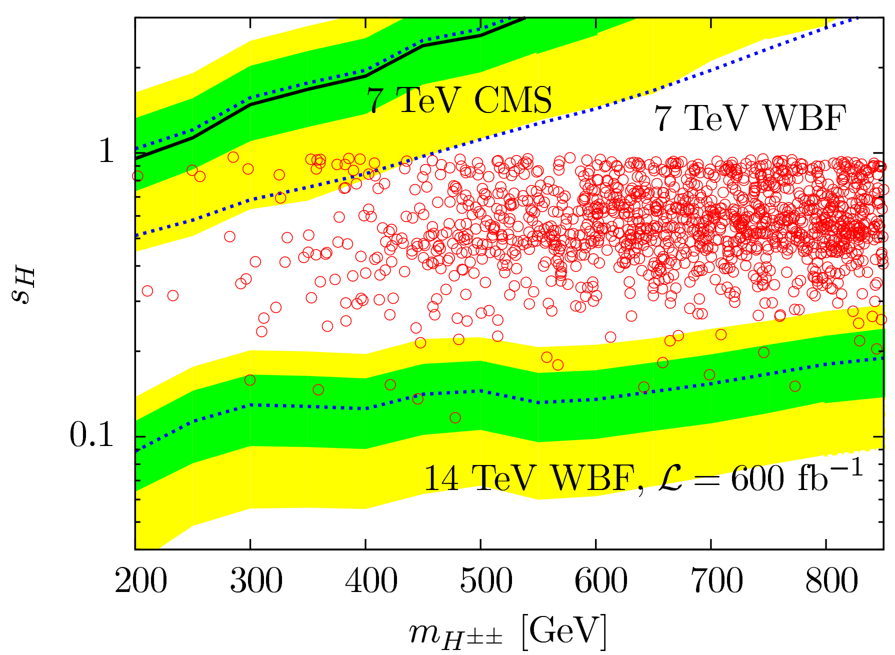
[CMS-PAS-SMP-13-015]

Use H++ in GM Model in WBF

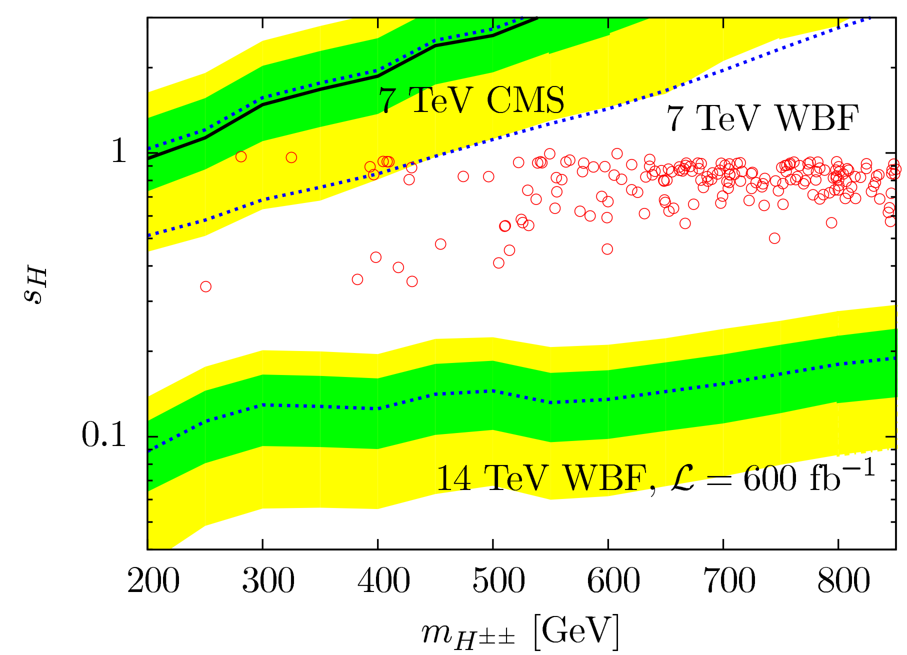




Georgi-Machacek doubly charged Higgs can be entirely excluded at LHC

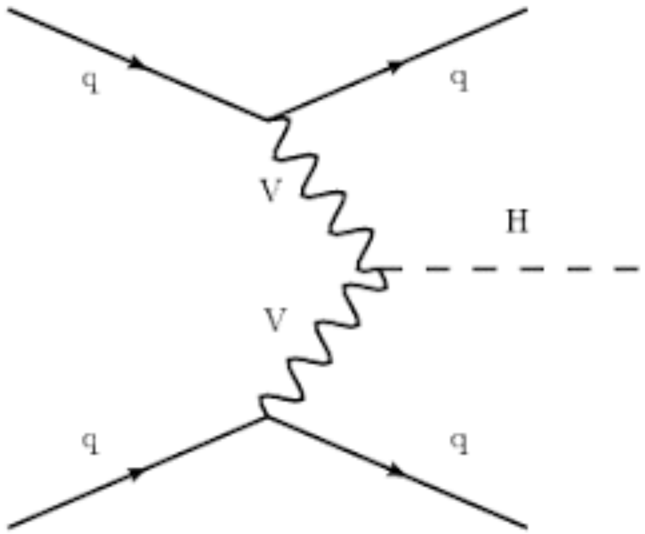


(a) Higgs to diphoton branching ratio enhanced: $1.3 \leq \xi_{H\to\gamma\gamma} \leq 2.3$

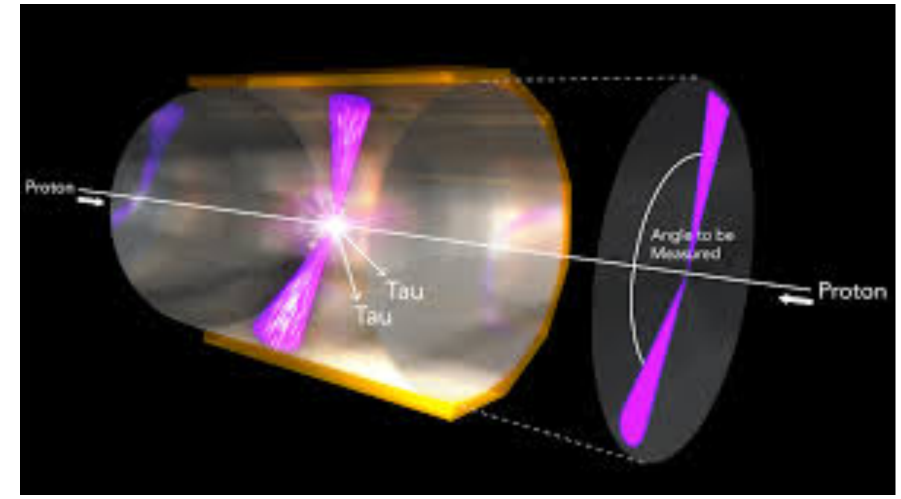


(b) Higgs to diphoton branching ratio SM-like: $0.8 \leq \xi_{H\to\gamma\gamma} \leq 1.2$

[Englert, Re, MS '13]



Summary



- XJJ, in particular GF or WBF, one of most important event topology at LHC
- Allows to relate to most fundamental questions in nature in plethora of ways
- Process ideally suited for upcoming higher energies and higher luminosities of LHC