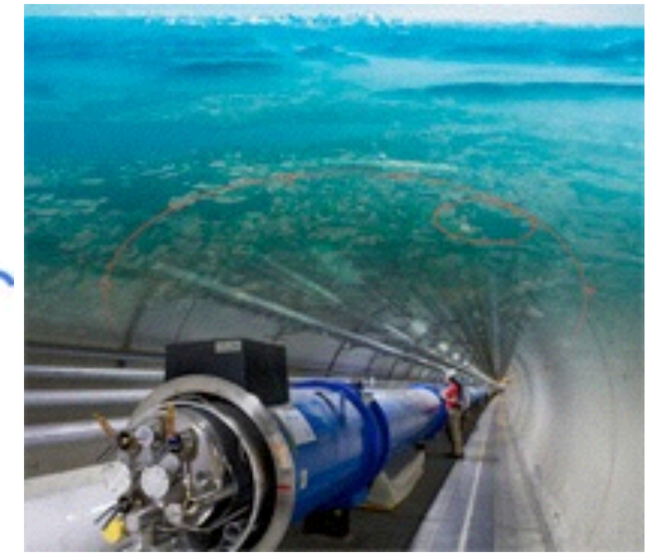
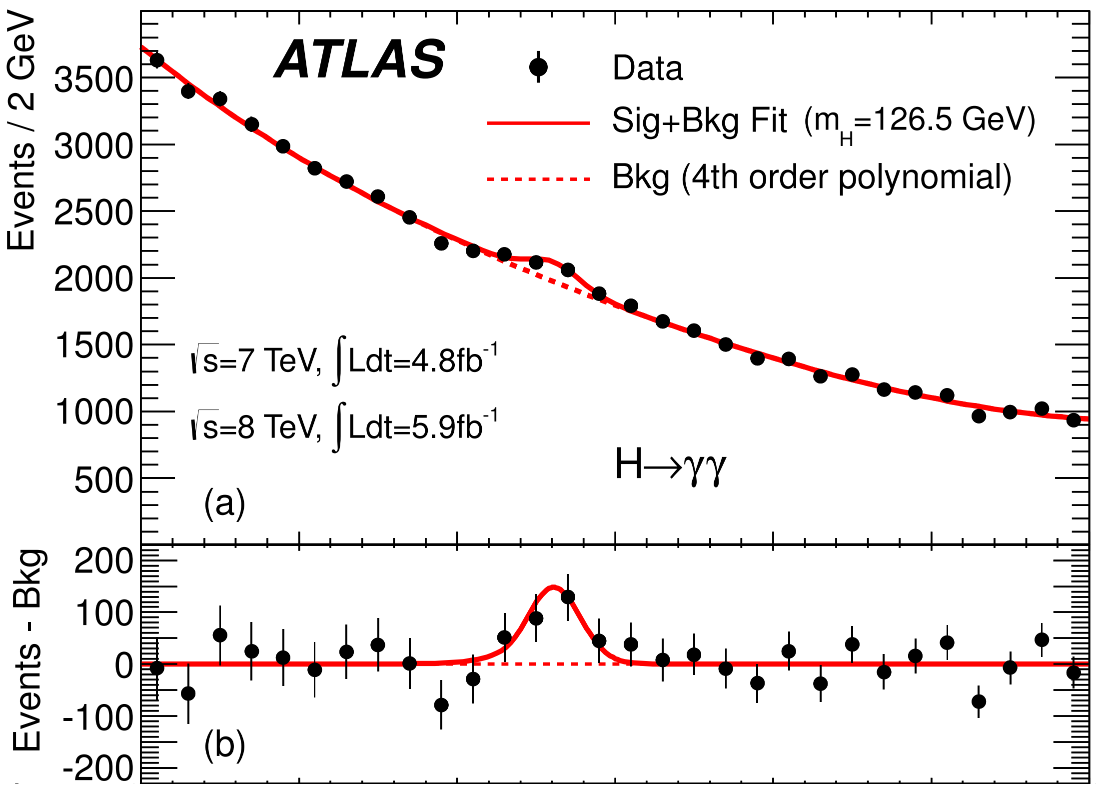


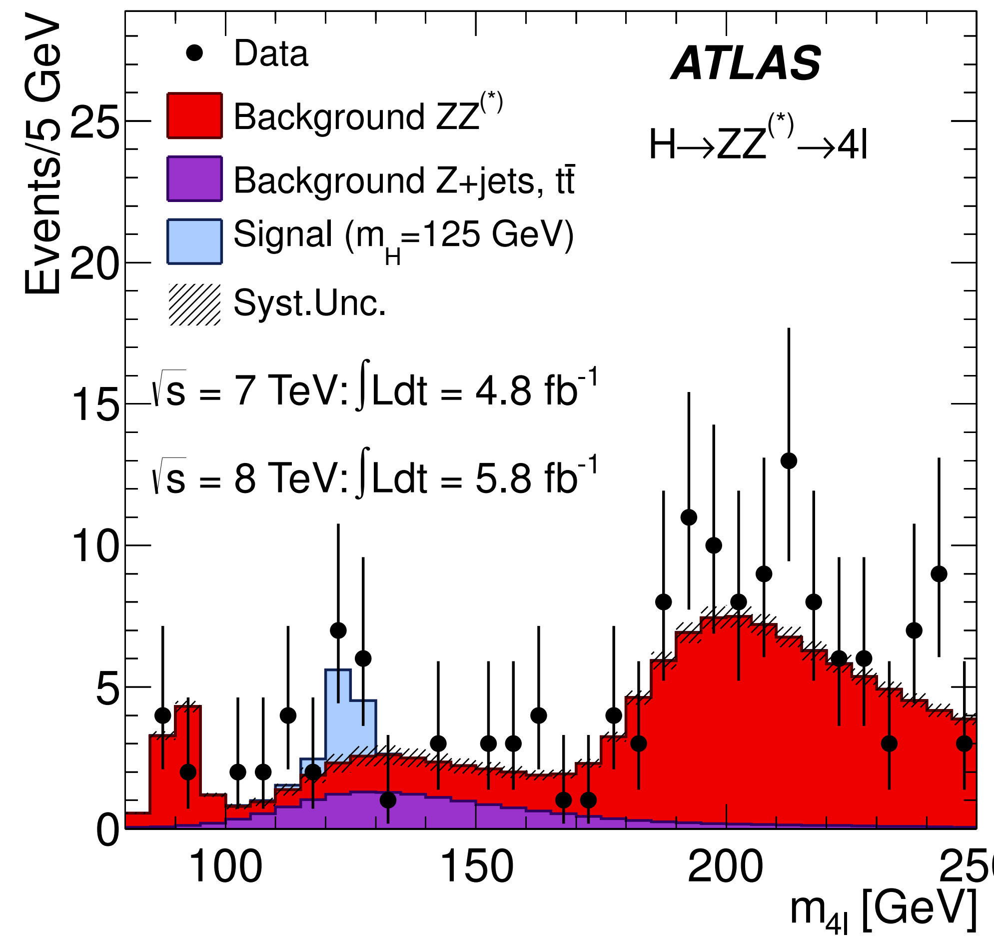
Higgs physics after Higgs discovery

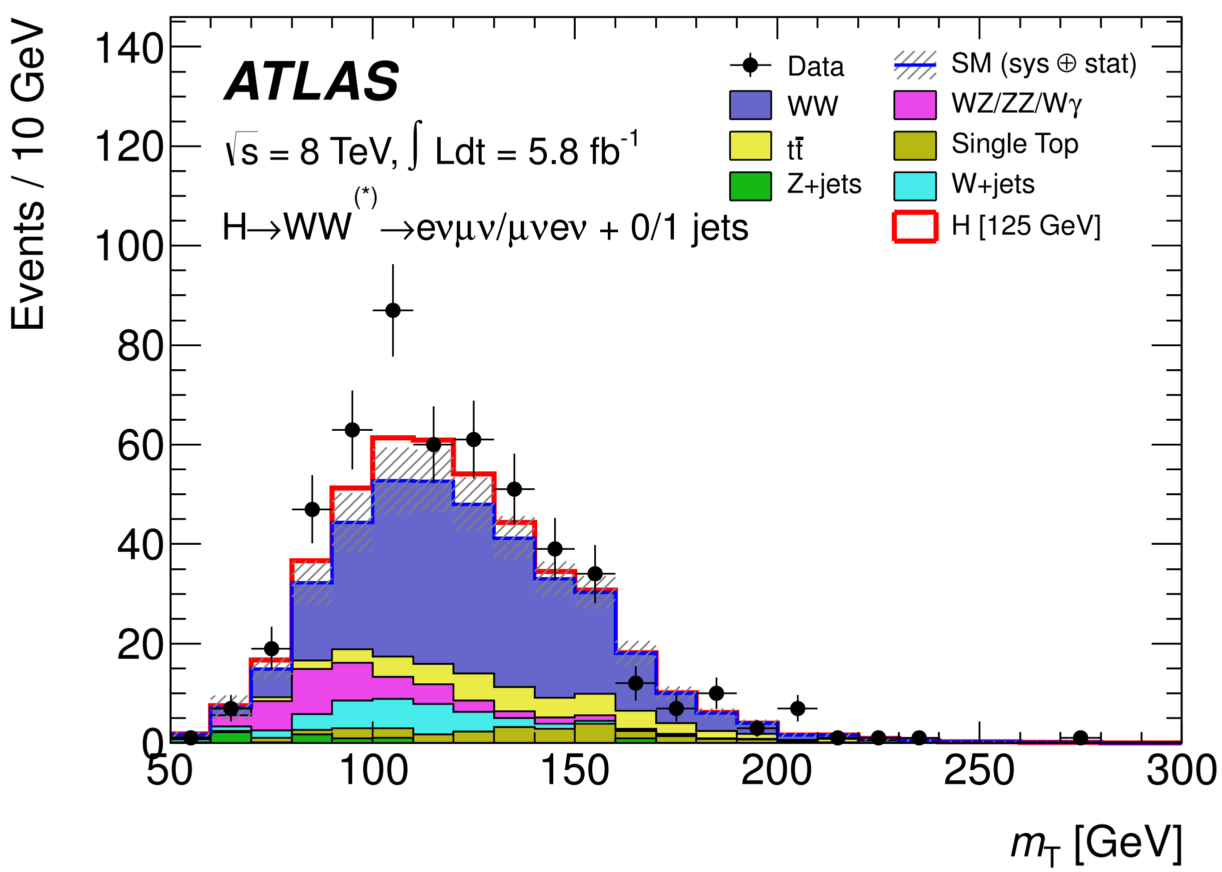
Michael Spannowsky

IPPP, Durham University

7 + 8 TeV data:





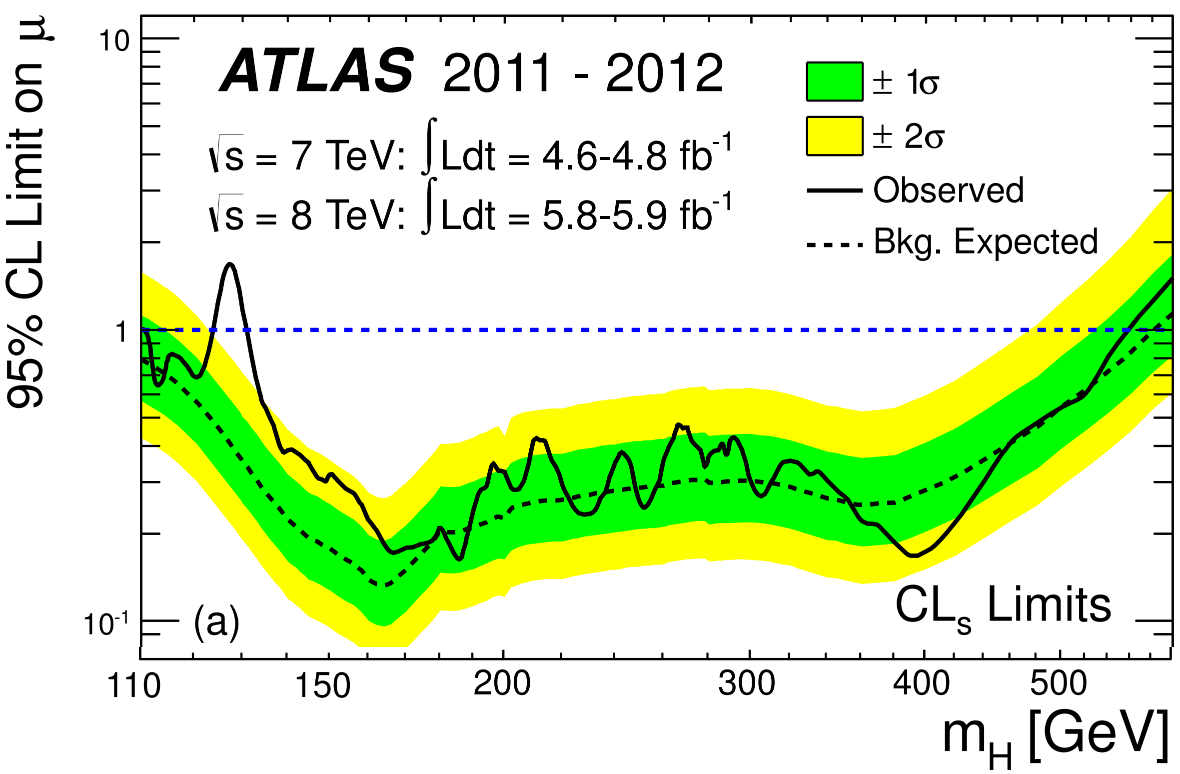


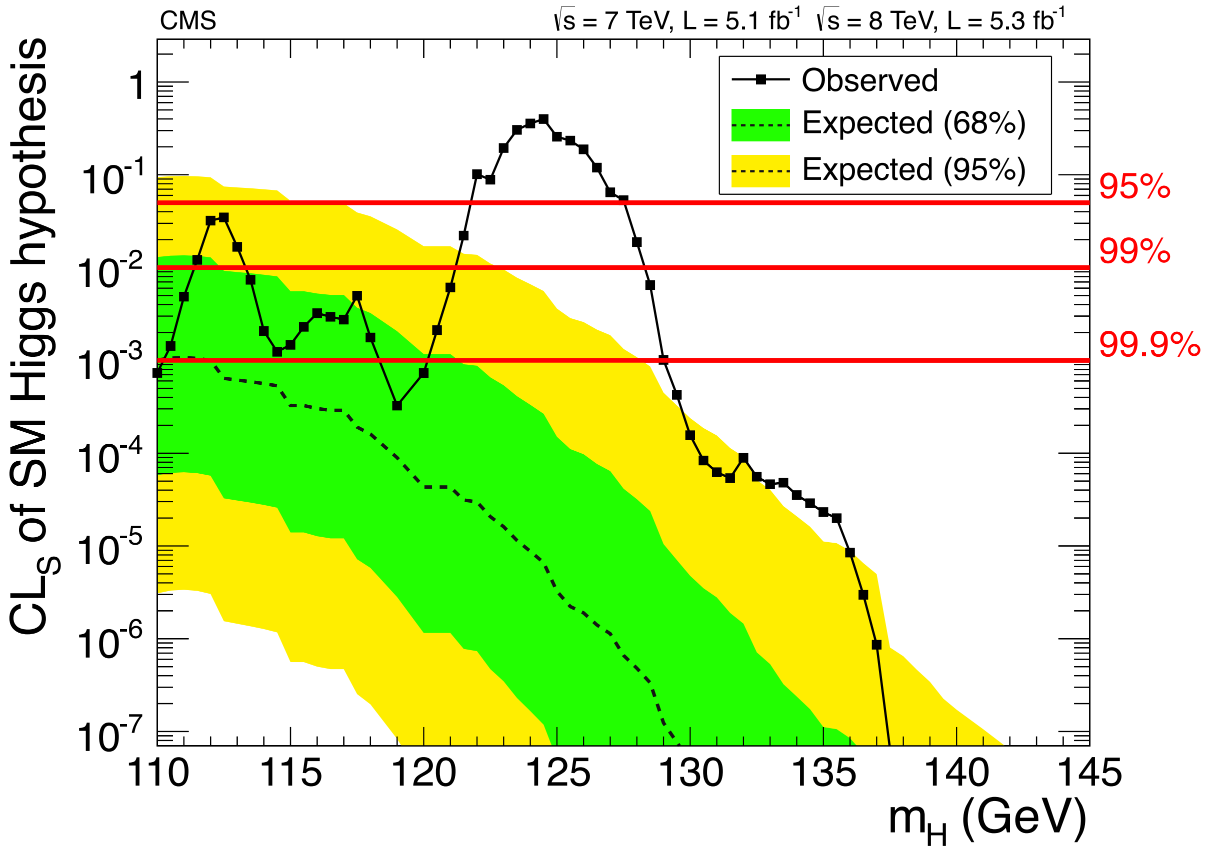
Higgs observed in clean channels, mainly:

- 2 Photons
- 4 Leptons (electrons/muons)
- 2 Leptons (electrons/muons) + MET

Lately • taus

Combined results for each experiment





- ATLAS has a local significance of 5.9 sigma
- CMS has a local significance of 5.8 sigma

→ Discovery

- Particle consistent with Higgs boson, predicted 50 years ago
- Huge international and intergenerational success!

Impact on theory

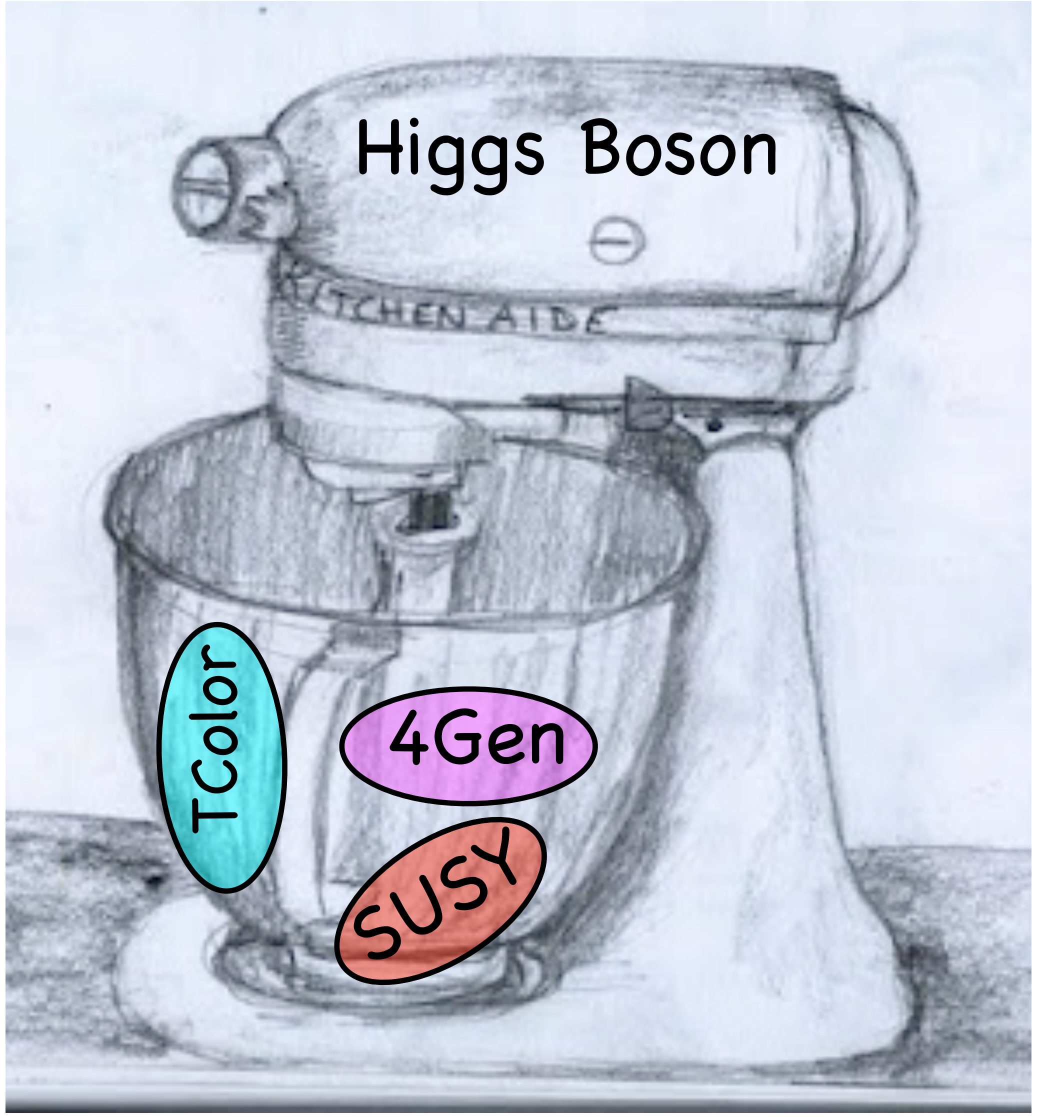
- Used to build models around question of electroweak symmetry breaking

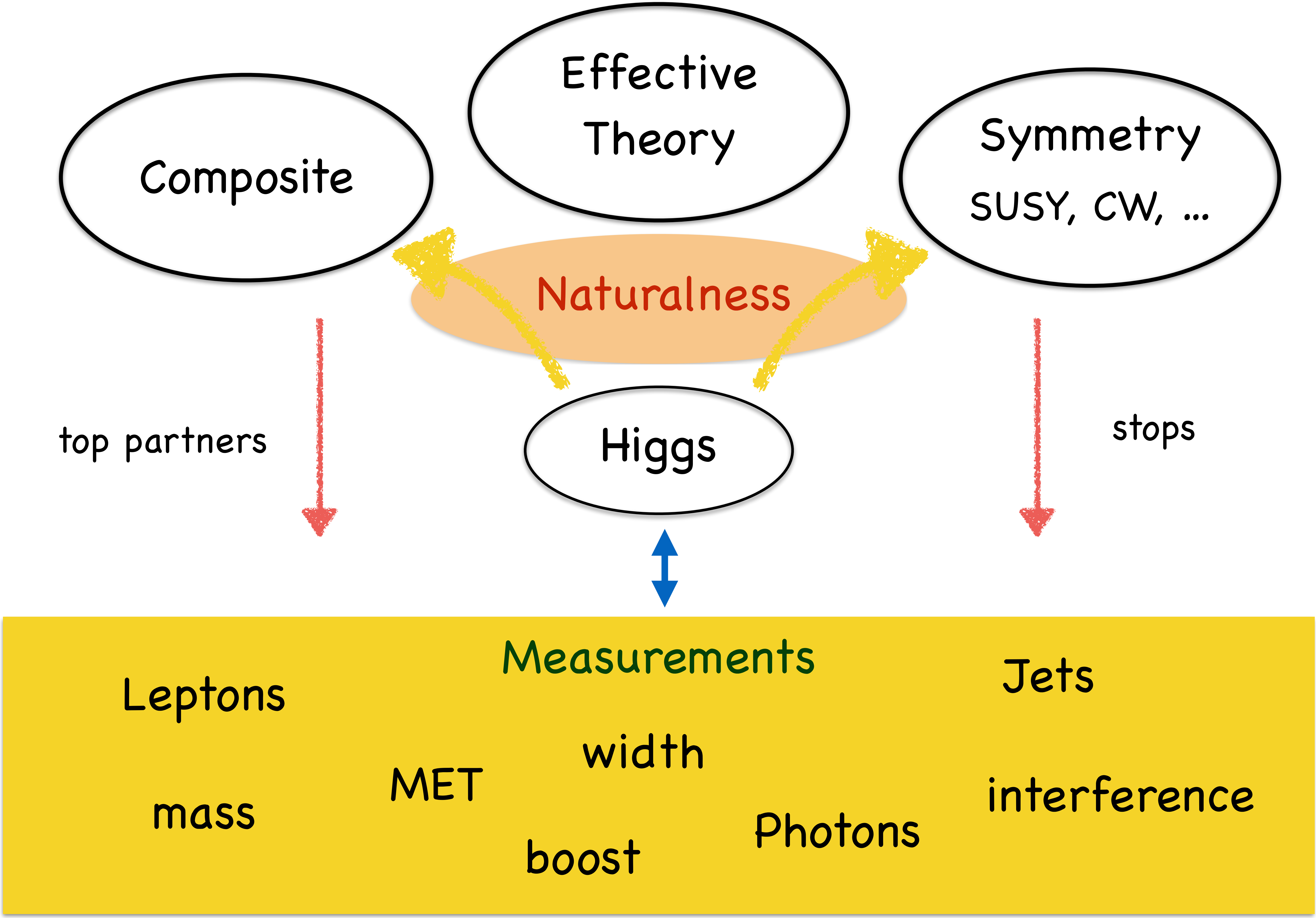
- Recent Higgs boson discovery huge success of the Standard Model

  → steers up all predicted New Physics scenarios

- Many observations cannot be explained by SM alone but last guiding principle for New Physics scale is

Naturalness





Effective Theory
Composite
Symmetry
SUSY, CW, ...
Naturalness
top partners
Higgs
stops
Measurements
Leptons
Jets
width
MET
mass
interference
Photons
boost

Ongoing feedback between theory and experiment

- Is what we observe "THE HIGGS BOSON"?
- Is minimal SSB mechanism realized in nature?

Couplings to Fermions

Couplings to Gauge Bosons

Only one SU(2) doublet

Higgs potential and selfcoupling

CP property of Resonance

Spin of Resonance

Brief recollection of results from Run 1

Mass:

ATLAS	CMS (new ZZ(4l) not used)
125.5 +-0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV	125.7 +- 0.3(stat) +- 0.3(syst) GeV

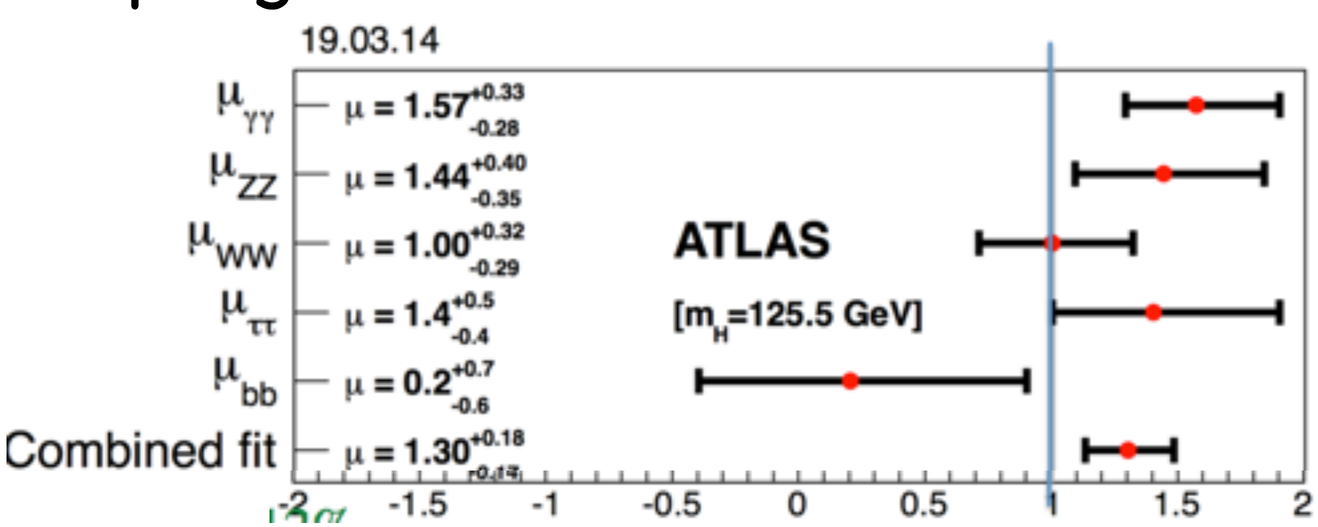
Spin / CP

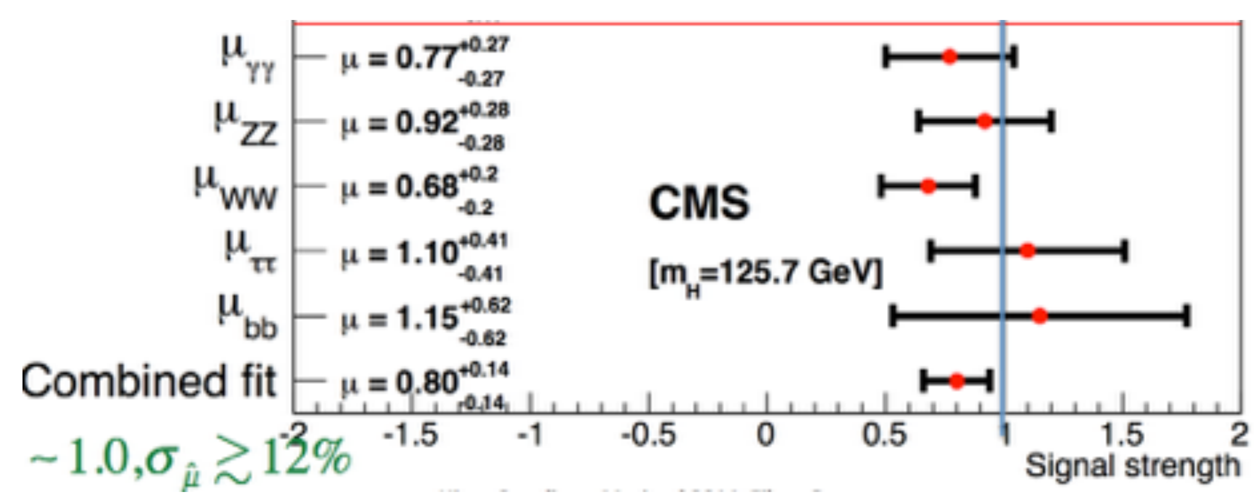
- Tested spin-1 and 0^- excluded with 1-CLs>0.99%
- Tested Spin-2 models excluded with 1-CLs>0.95%

width

- Combine 4l and 2l2n decay channels.
- **Observed (expected)** 95%CL limits: Γ **< 8.5(4.2) x** Γ_{SM}

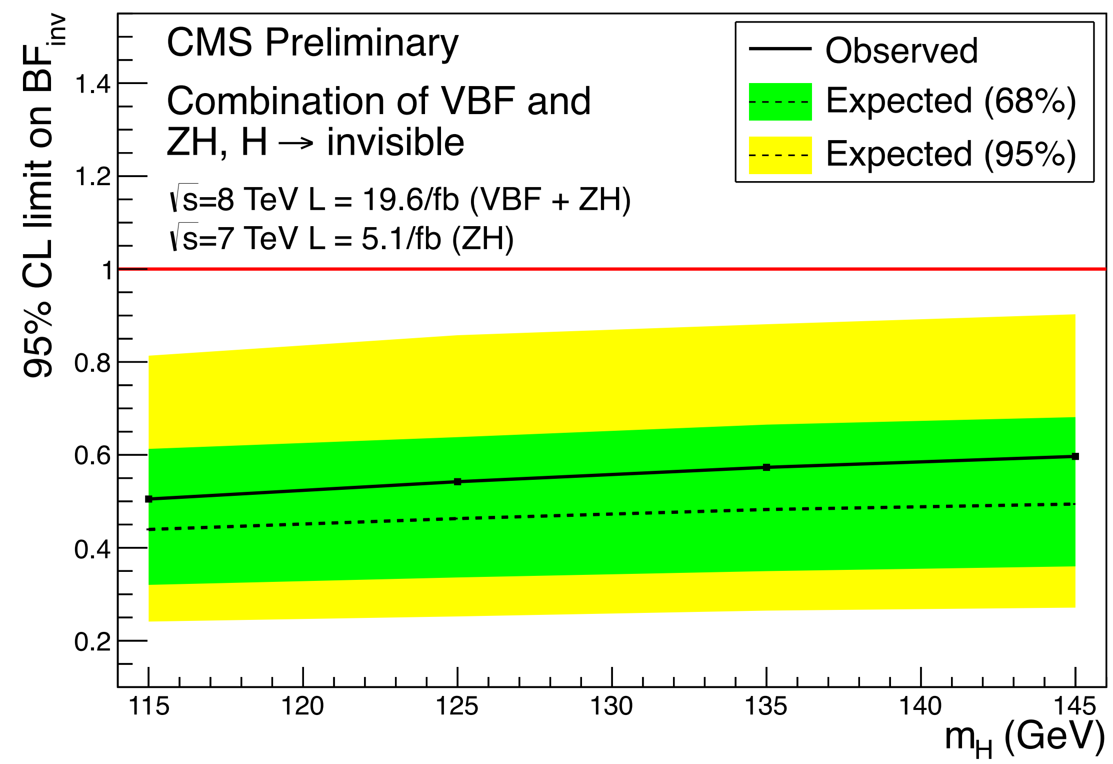
Couplings



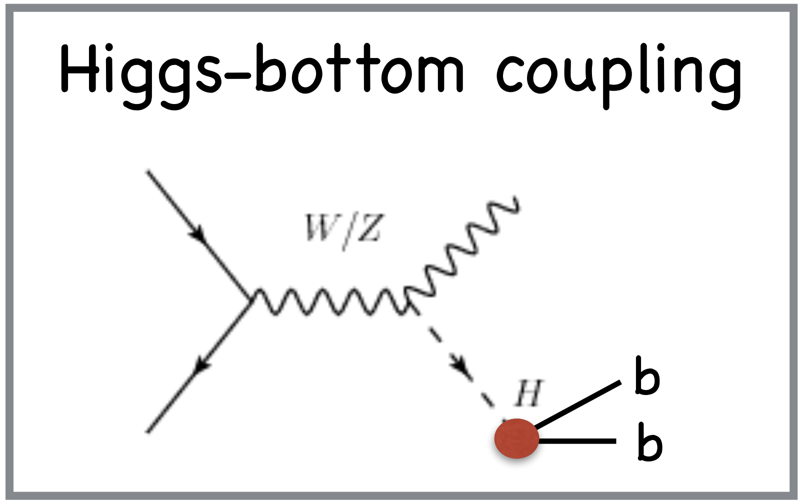


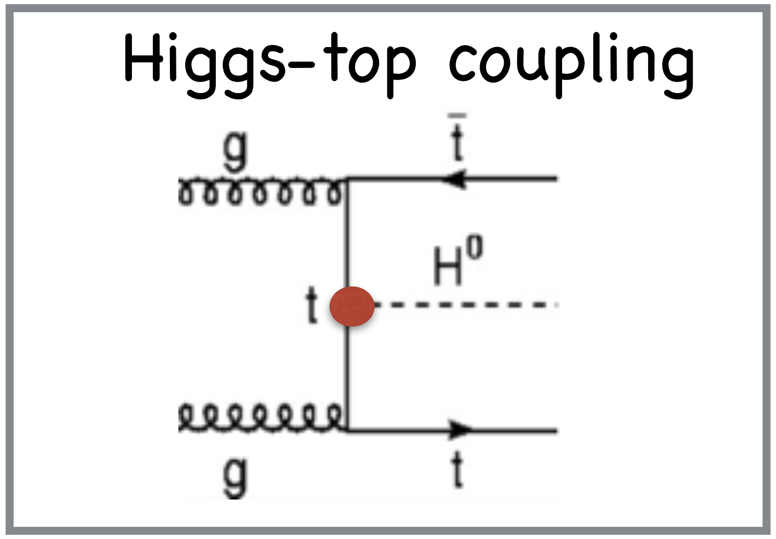
Invisible Higgs decays:

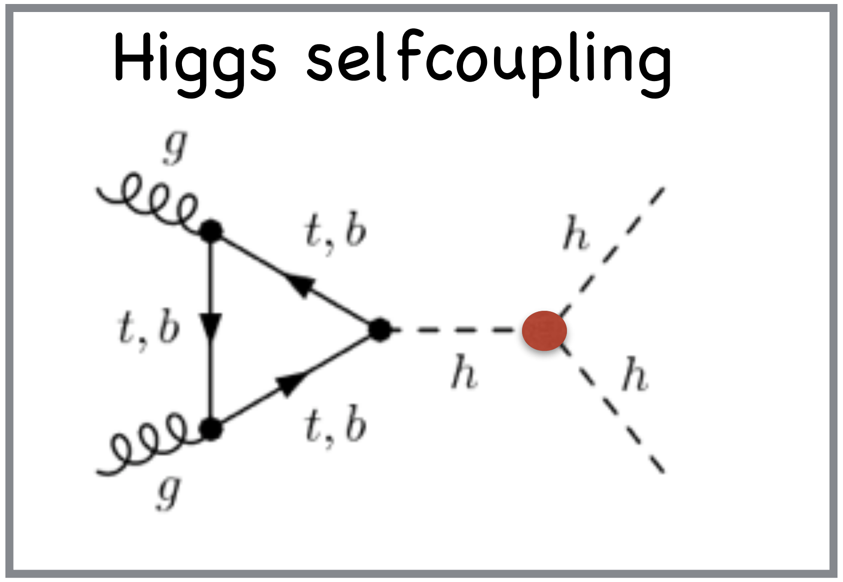
The invisible Higgs Branching ratio is constrained to be < 54%



Biggest tasks for Run 2:

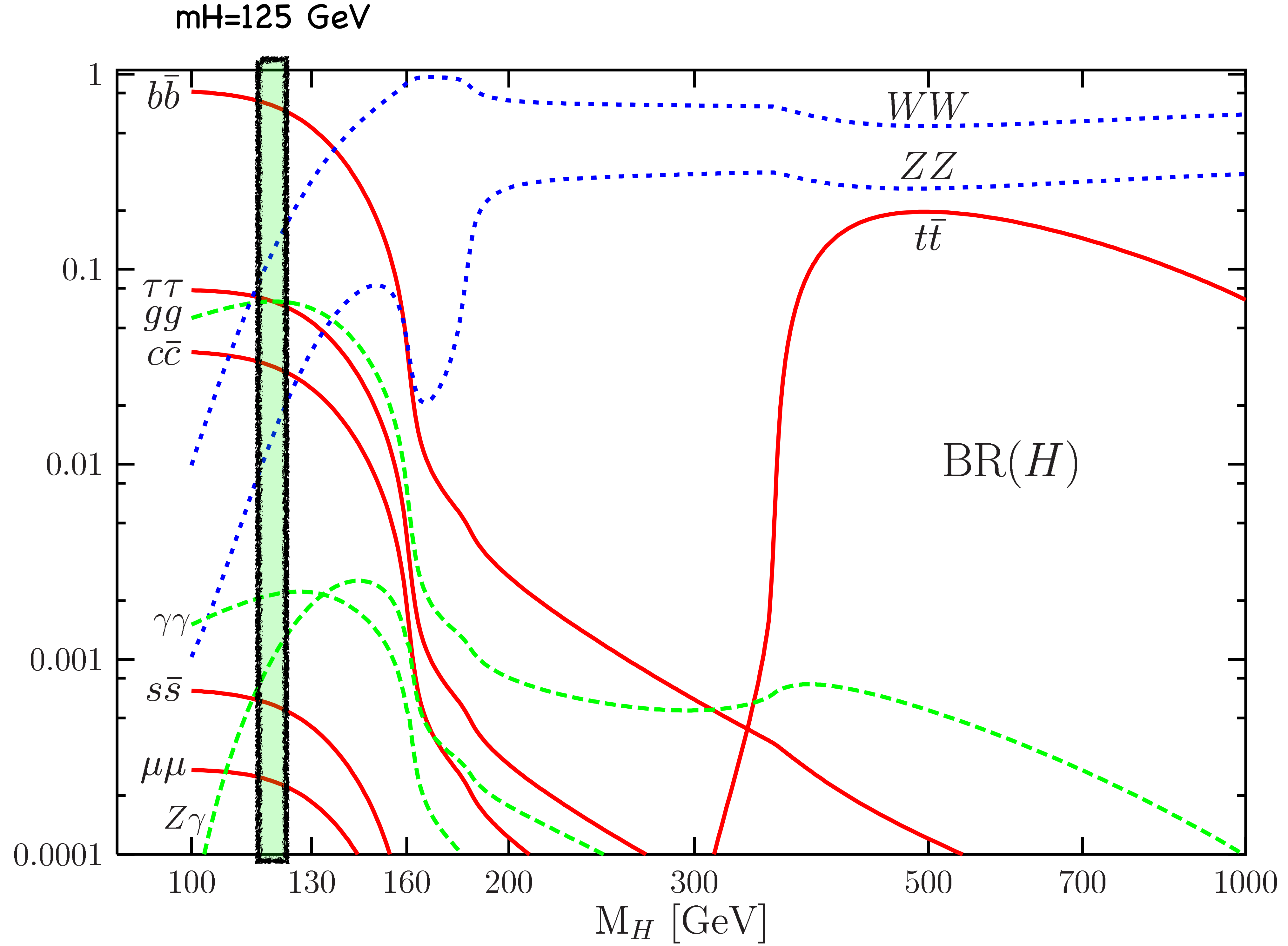




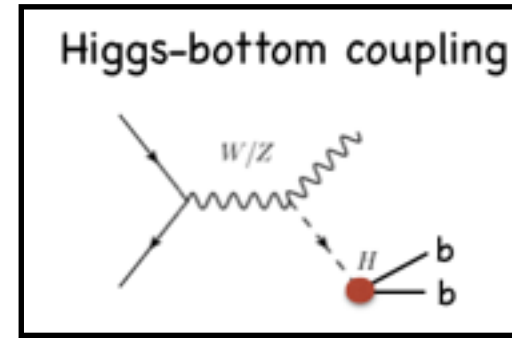


- Measure/constrain rare/unusual Higgs decays
- CP violation in Higgs sector

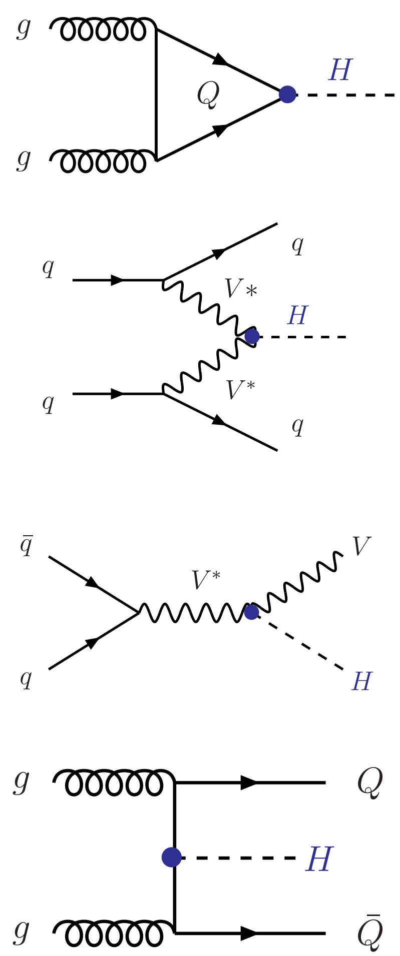
Predicted decay channels



mH = 125 GeV is smooth spot. Important couplings accessible



For Higgs boson coupling measurements:



production	decay
$gg \to H$	ZZ
qqH	ZZ
$gg \to H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
inclusive	$\gamma\gamma$
qqH	$\gamma\gamma$
$t\bar{t}H$	$\gamma\gamma$
WH	$\gamma\gamma$
ZH	$\gamma\gamma$
qqH	$\tau\tau(2\ell)$
qqH	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$

[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]

Decay into spec. channel

Production

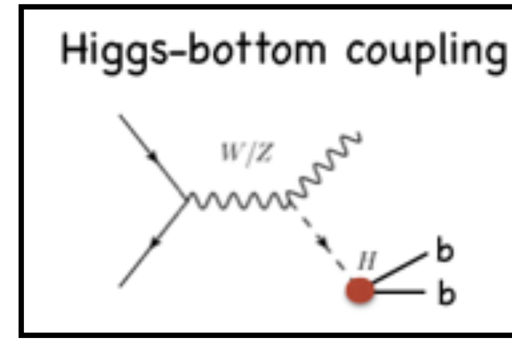
$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

Sum of all possible decays

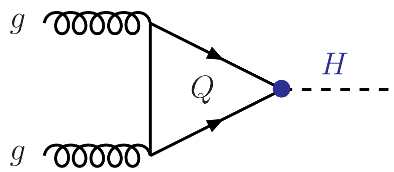
- Every measurement affected by production and decay

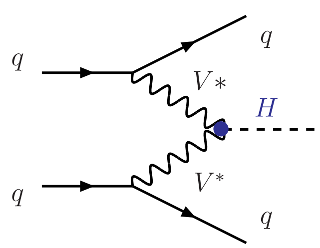
assumed: $\Gamma_H = \Sigma_{SM}\Gamma_i \quad \Gamma_i \sim g_d^2$

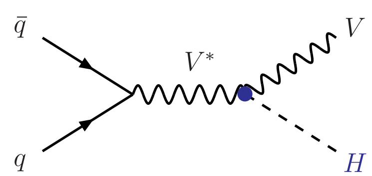
Uncertainty of all coupling measurements driven by total width, i.e. H-> bb

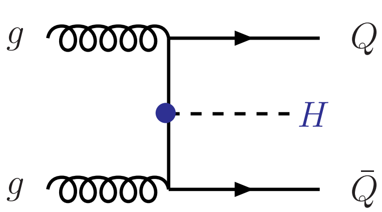


For Higgs boson coupling measurements: assumed 30 ifb









production	decay
$gg \to H$	ZZ
qqH	ZZ
$gg \to H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
inclusive	$\gamma\gamma$
qqH	$\gamma\gamma$
$t\bar{t}H$	$\gamma\gamma$
WH	$\gamma\gamma$
ZH	$\gamma\gamma$
qqH	$\tau\tau(2\ell)$
qqH	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$
WH/ZH	$b\bar{b}$ (subjet)

[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]

Decay into spec. channel

Production

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

Sum of all possible decays

- Every measurement affected by production and decay

assumed: $\Gamma_H = \Sigma_{SM}\Gamma_i \quad \Gamma_i \sim g_d^2$

Uncertainty of all coupling measurements driven by total width, i.e. H-> bb

Including jet substructure HV, H->bb (BDRS) all uncertainties reduced:

$\Delta_{bbH} = \pm 0.78$ —BDRS→ $\Delta_{bbH} = \pm 0.44$

$\Delta_{WWH} = \pm 0.33$ —BDRS→ $\Delta_{WWH} = \pm 0.24$

$\Delta_{ZZH} = \pm 0.59$ —BDRS→ $\Delta_{ZZH} = \pm 0.31$

Measuring the Higgs-bottom coupling

e.g. BDRS [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \times \Gamma(H \to b\bar{b})$$

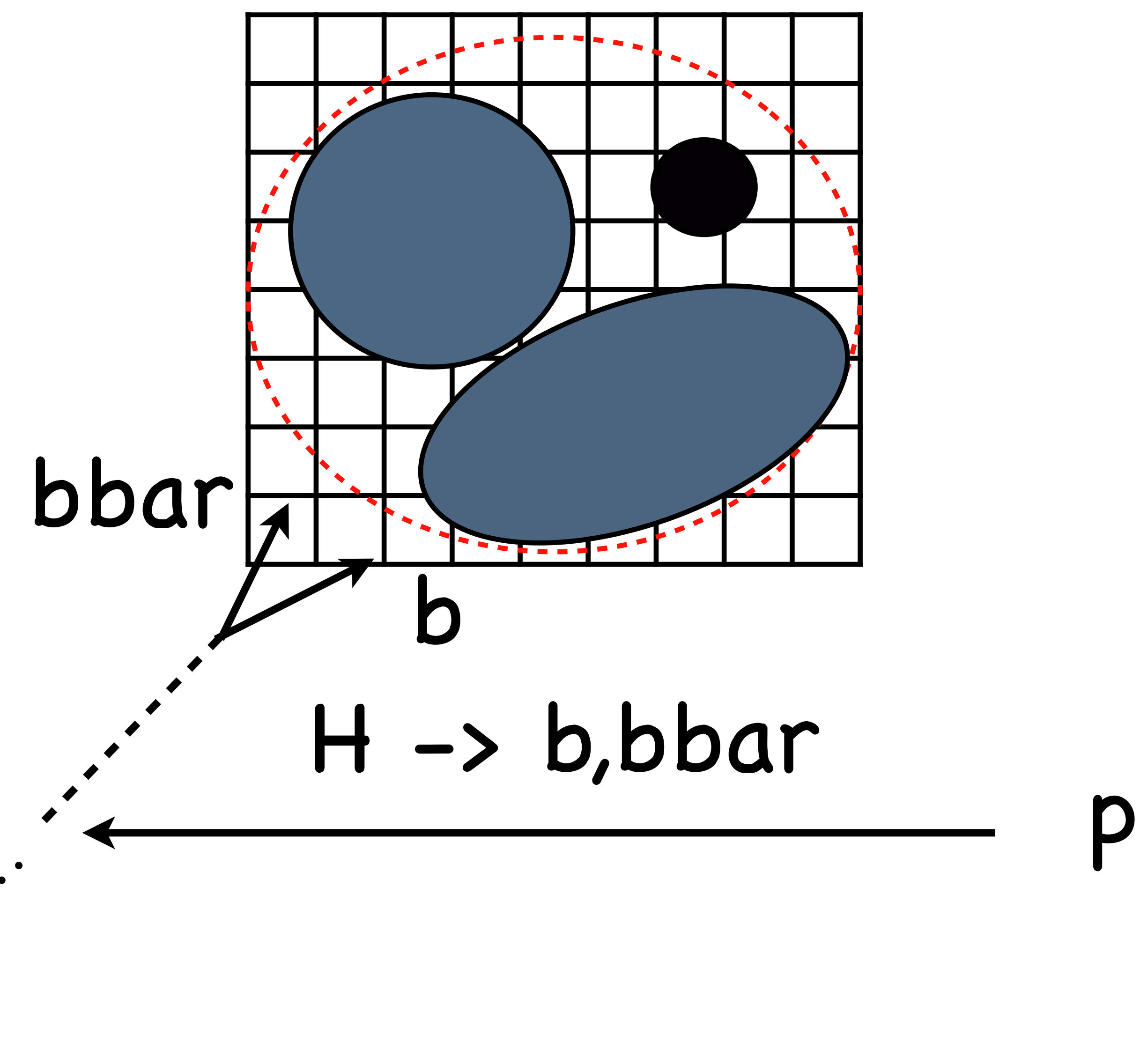
mass drop:

1) check for mass drop

$m_{j1} < 0.66\, m_j$

2) check "asymmetry"

$$y = \frac{\min\left(p_{t_{j1}}^2, p_{t_{j2}}^2\right)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\mathrm{cut}}$$

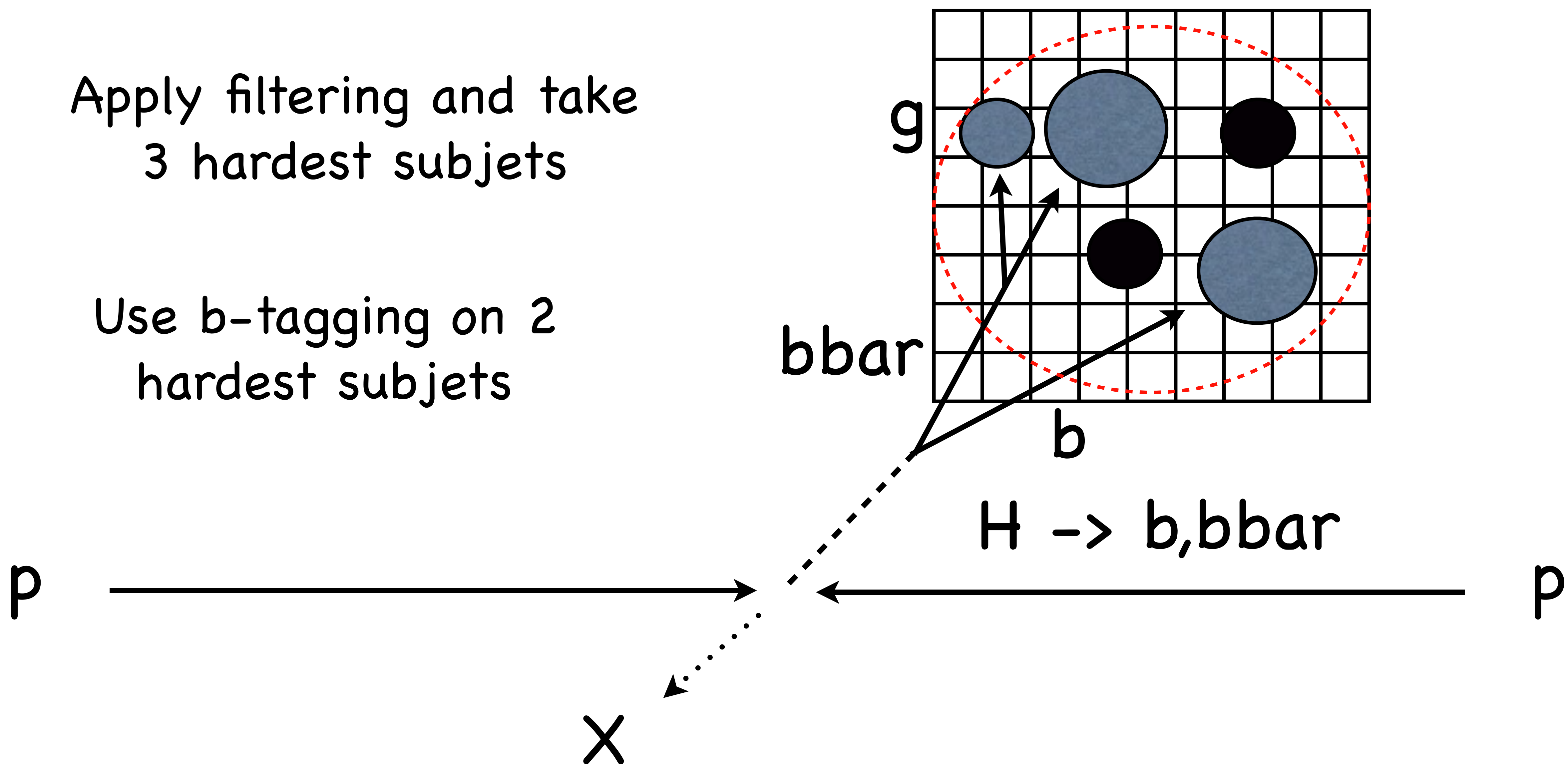


e.g. BDRS [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \times \Gamma(H \to b\bar{b})$$

Apply filtering and take 3 hardest subjets

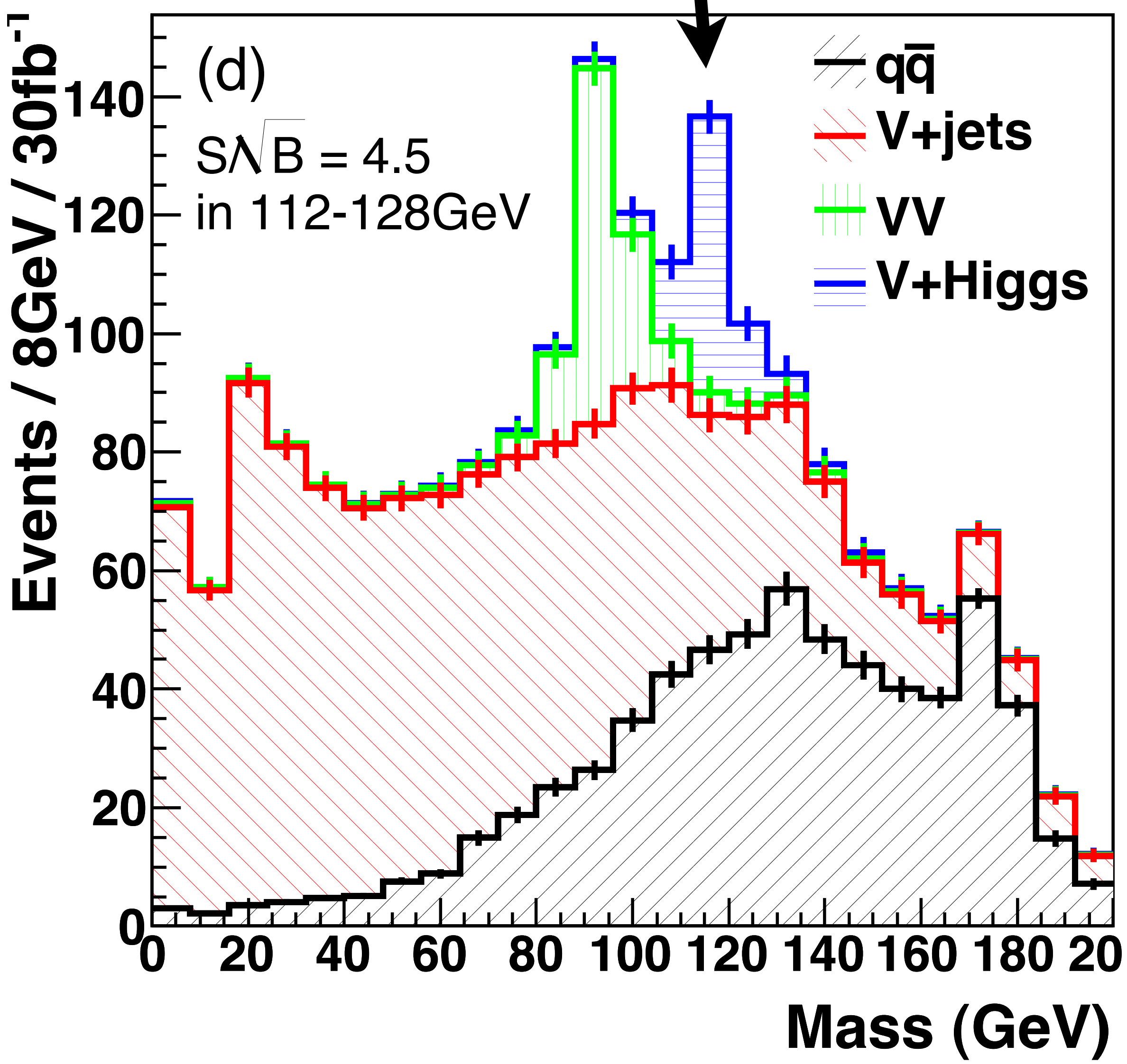
Use b-tagging on 2 hardest subjets



$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \times \Gamma(H \to b\bar{b})$$

Higgs pT spectrum

select final state



Confirmed in ATLAS full detector simulation

[ATL-PHYS-PUB-2009-088]

Measuring the Higgs-top coupling

tth (Signal)

Beenakker et al., PRL 87 2001; Reina et al., PRD 65 2002

↳ K=1.57

ttbb

Bredenstein et al., PRL 103 2009; Belivacqua et al., JHEP 0909 2009

↳ K=2.3

tt+jets

Dittmaier et al, PRL 98 2007 Bevilacqua et al., PRL 104 2010

↳ K=1.0

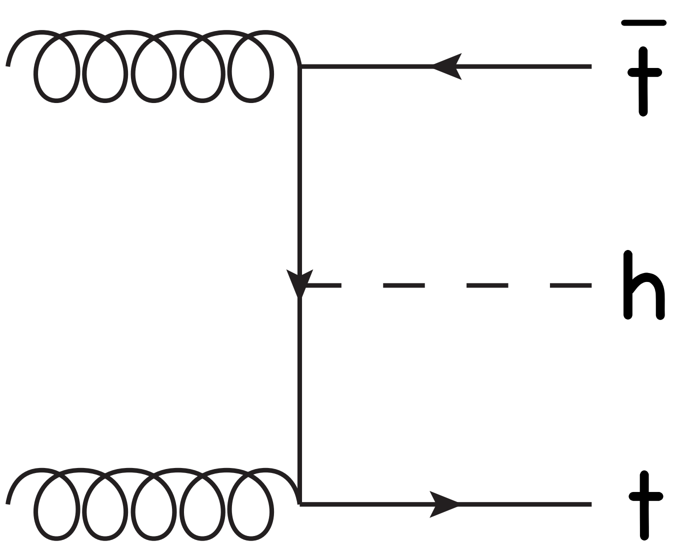
ttz

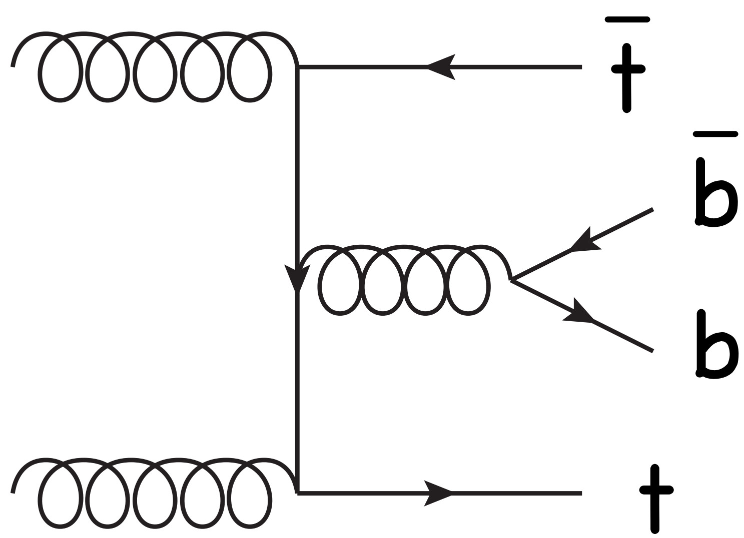
Lazopoulos et al., PLB 666 2008

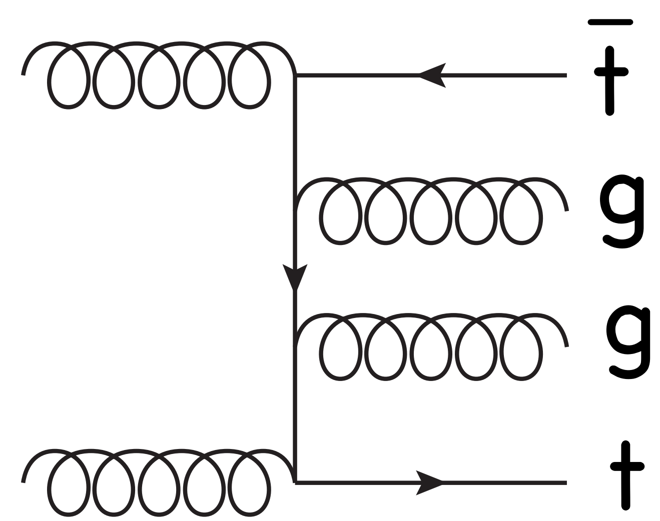
↳ k=1.53

w+jets

negligible after b-tags and taggers



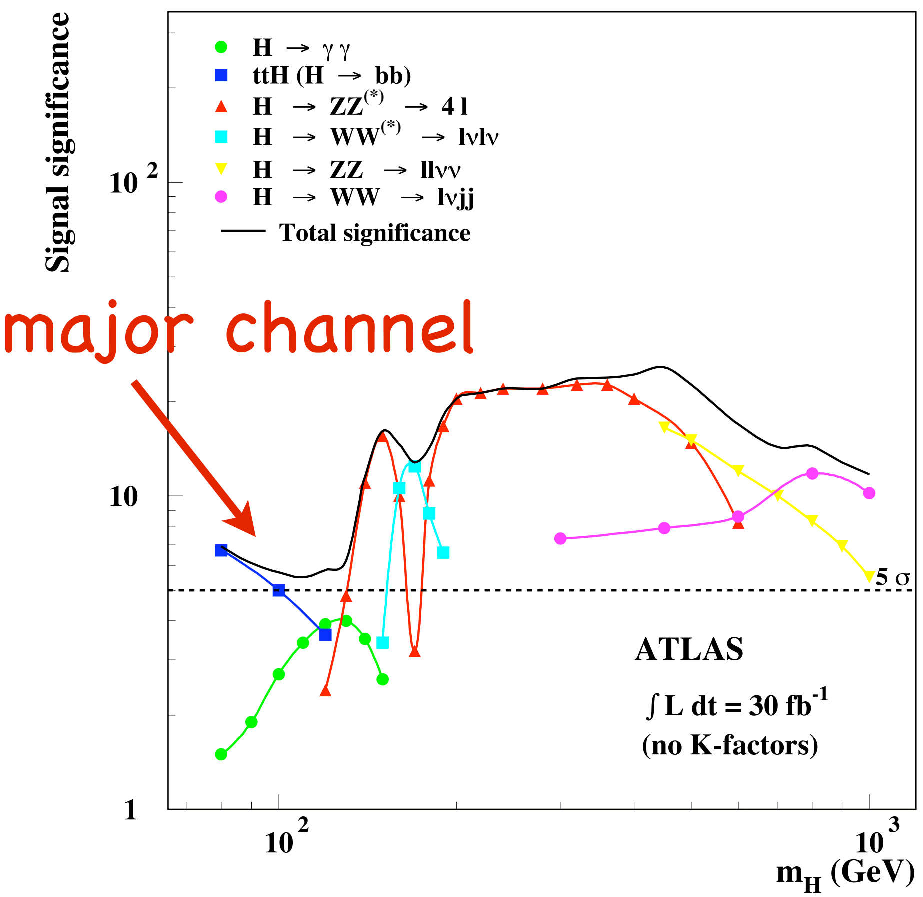




tth
as busy as it gets in the SM

Motivation:
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

High expectations:



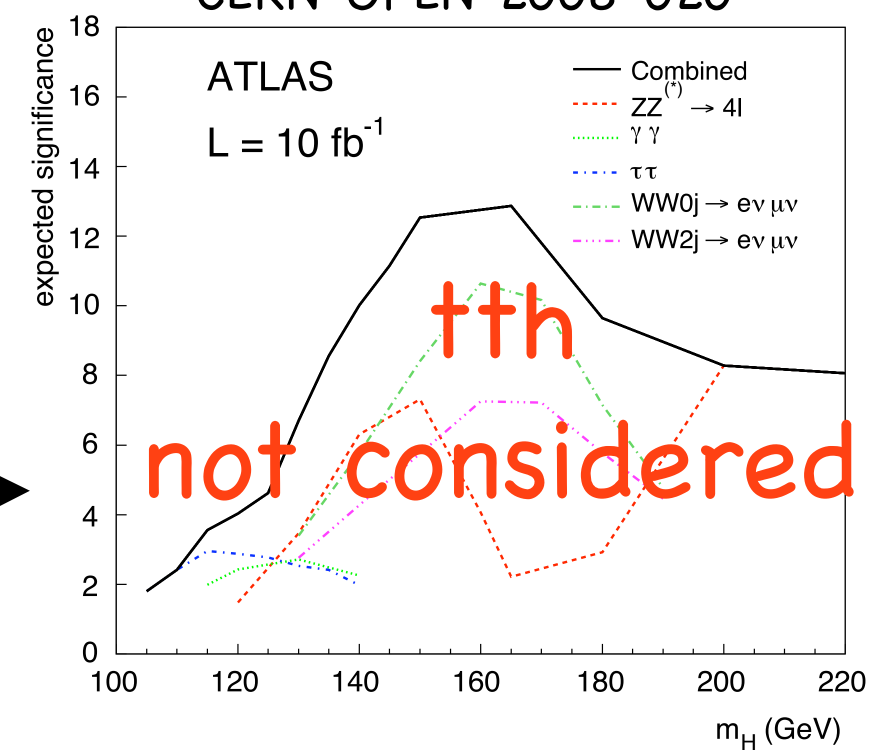
[ATLAS TDR 1999]

Cammin and Schumacher (ATLAS)

$S/B \simeq 1/9$

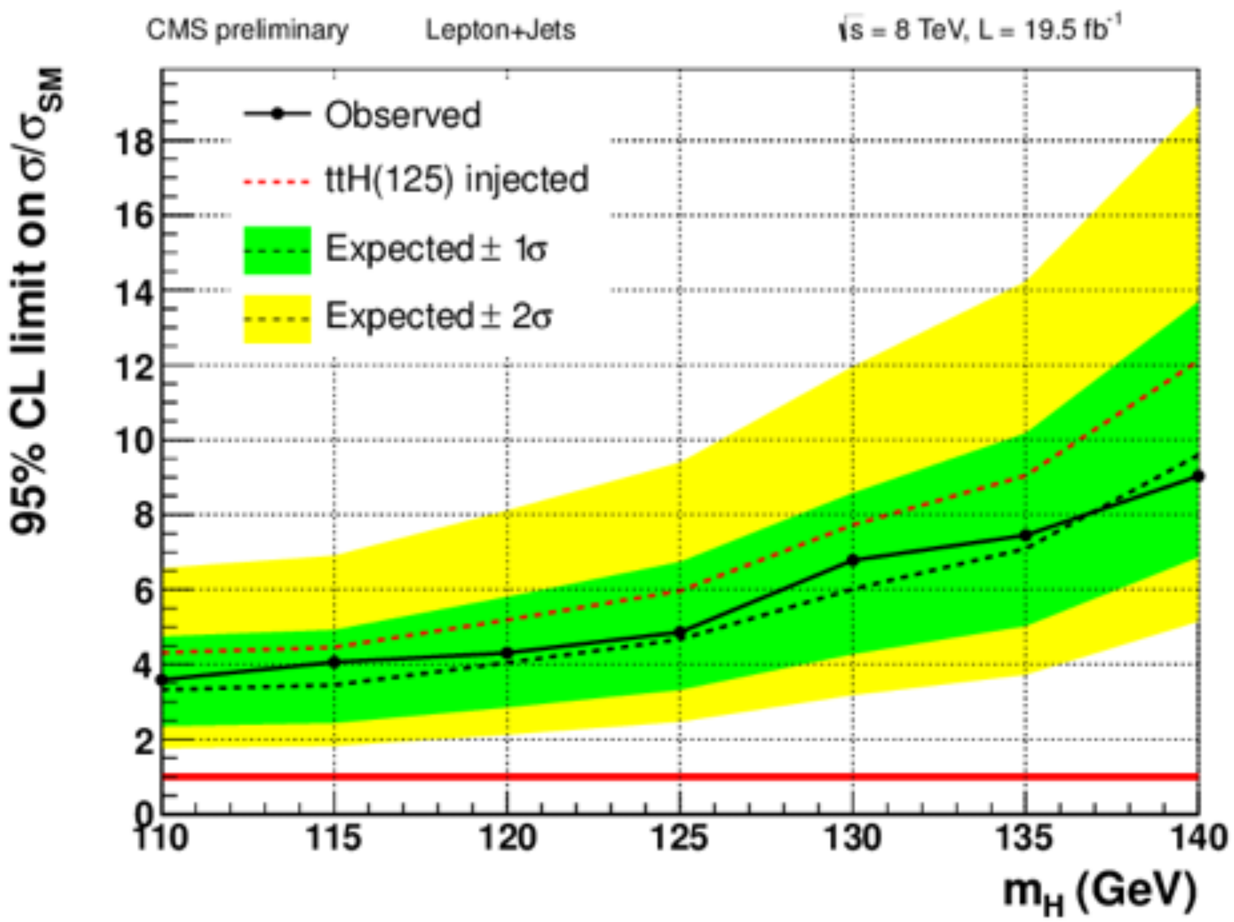
$S/\sqrt{B} \simeq 2.2$

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020

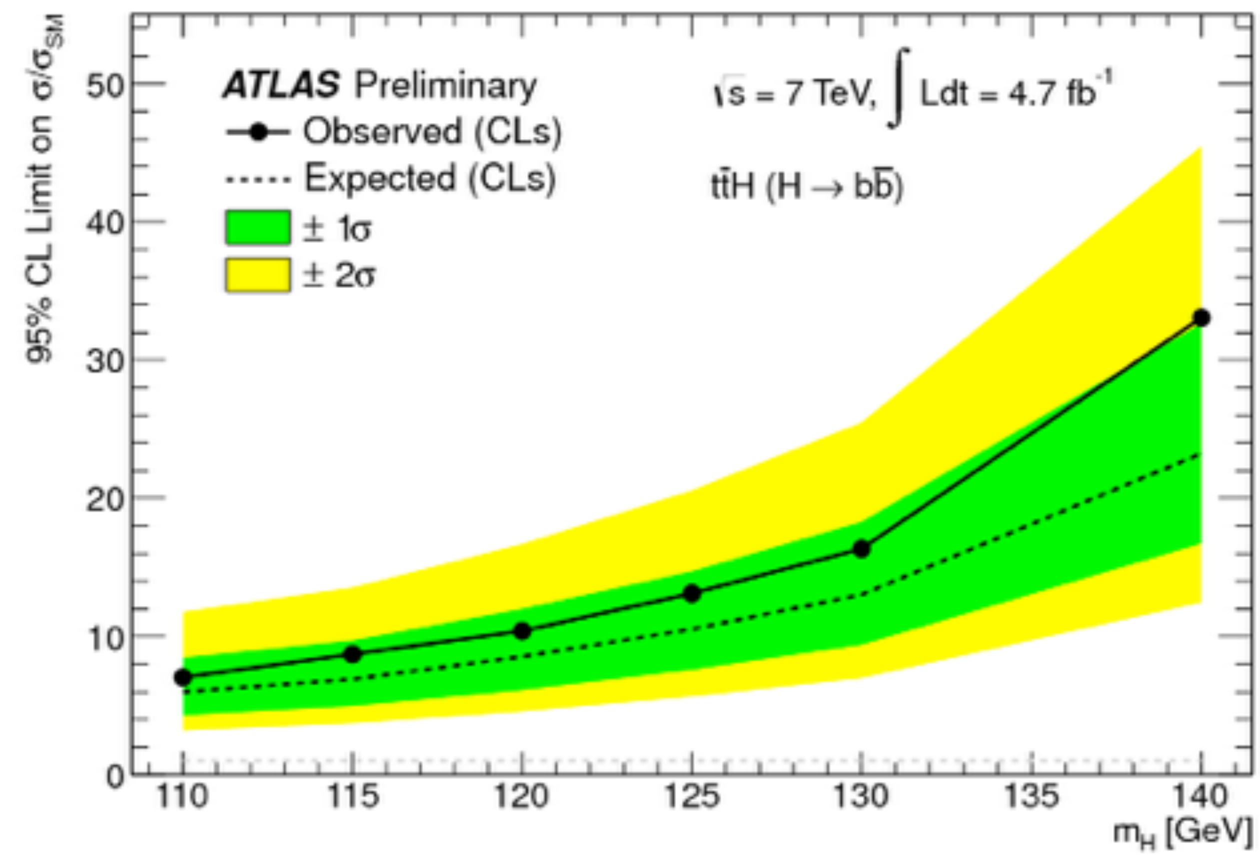


Present results by CMS and ATLAS

CMS, 8 TeV data



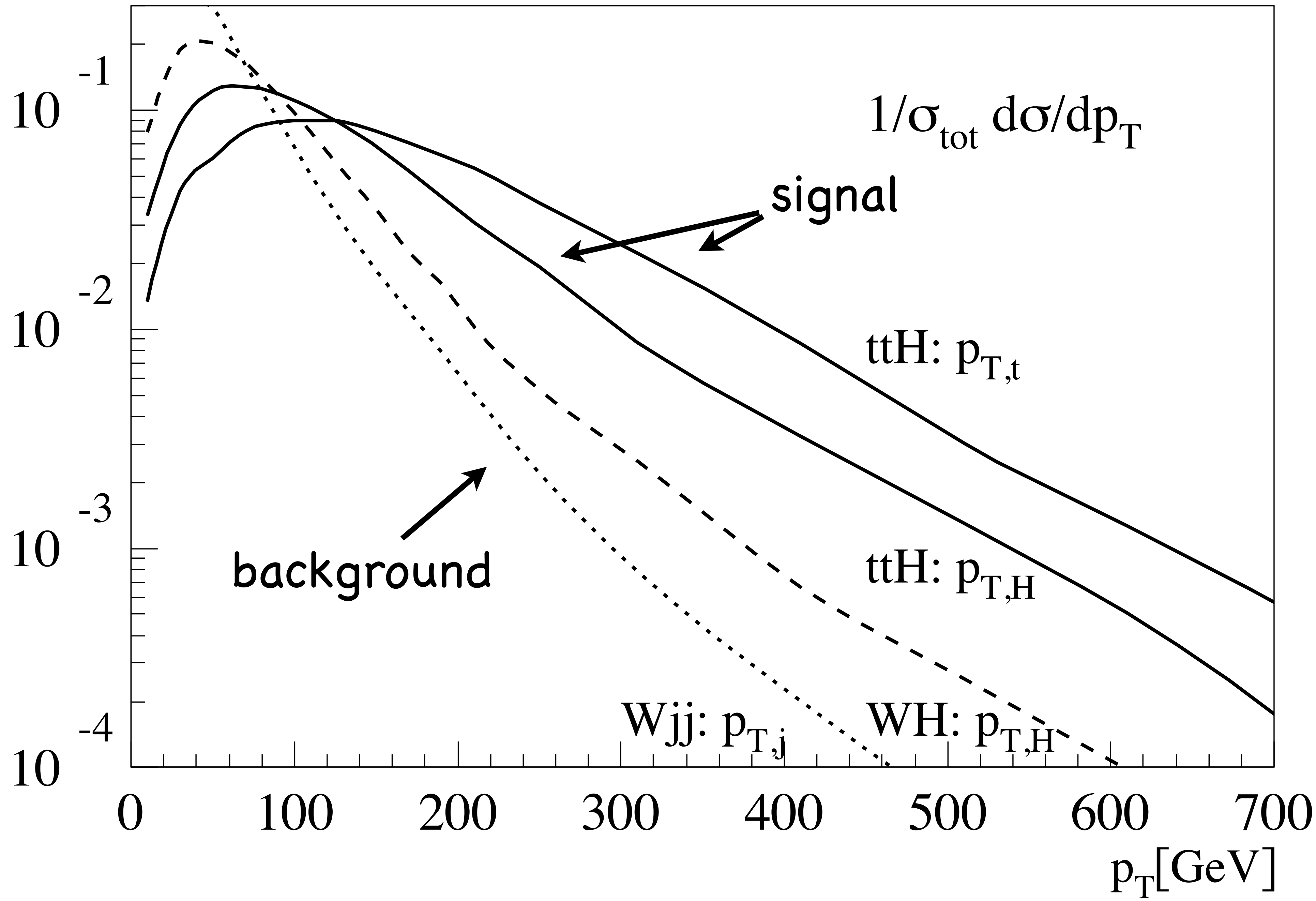
ATLAS, 7 TeV at 4.7 ifb



Both experiments are sensitive at X-times the SM cross section

However, tth coupling measurement will be systematics limited. Low S/B will render measurement notoriously difficult with standard reconstruction techniques.

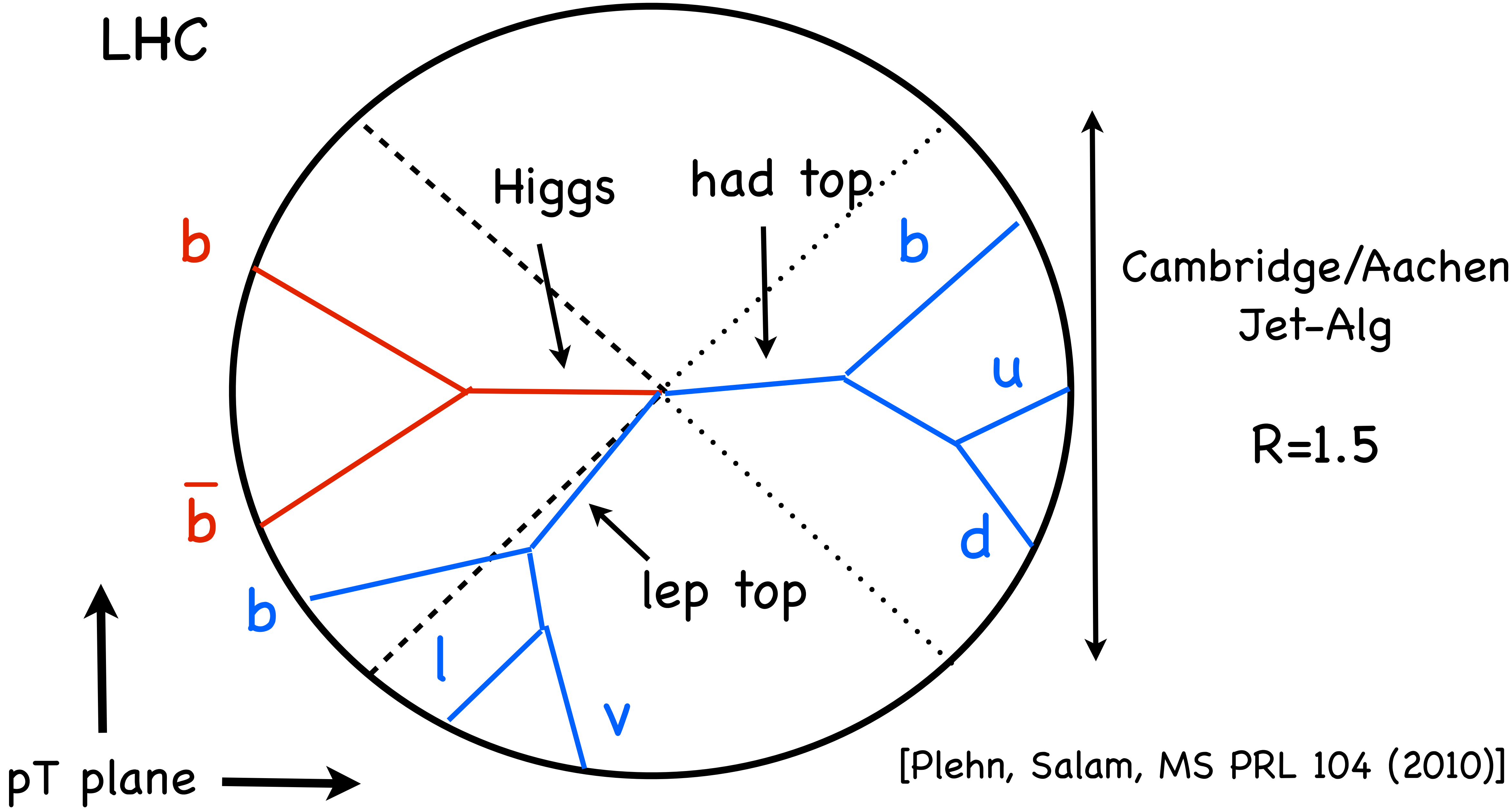
pT distributions relevant for tth



Problems in event reconstruction:

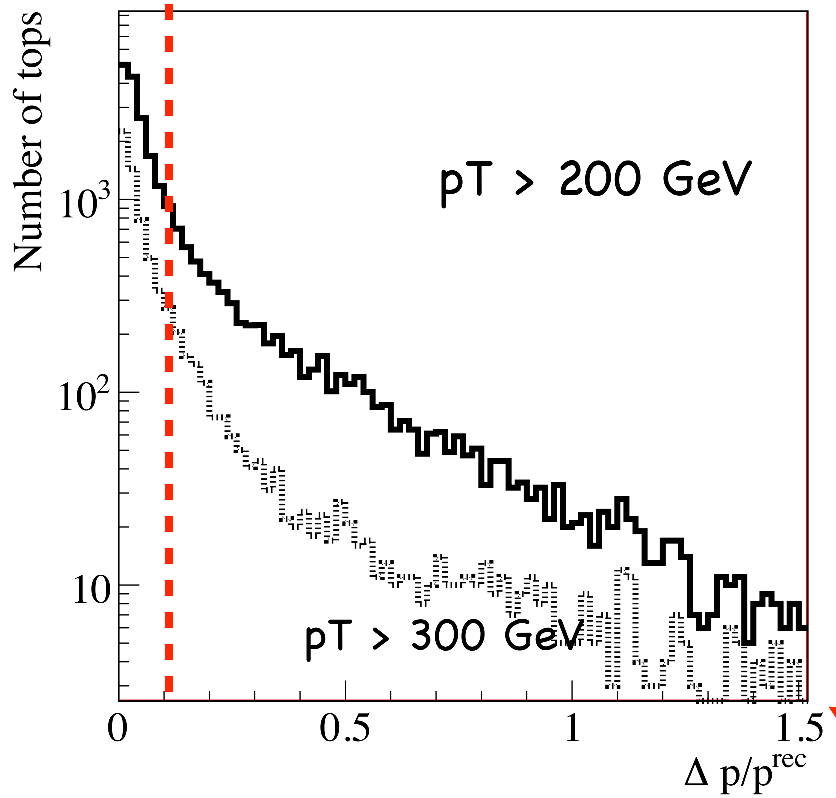
- (b-)jet multiplicity
- reconstruction efficiency

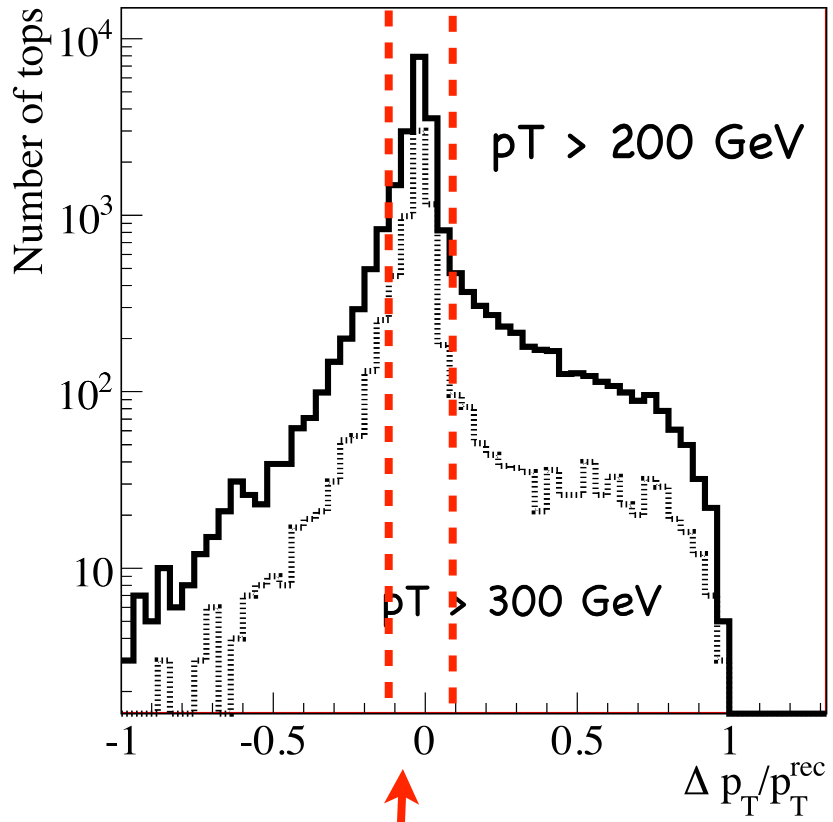
Boost should help
but
need tagger for this environment

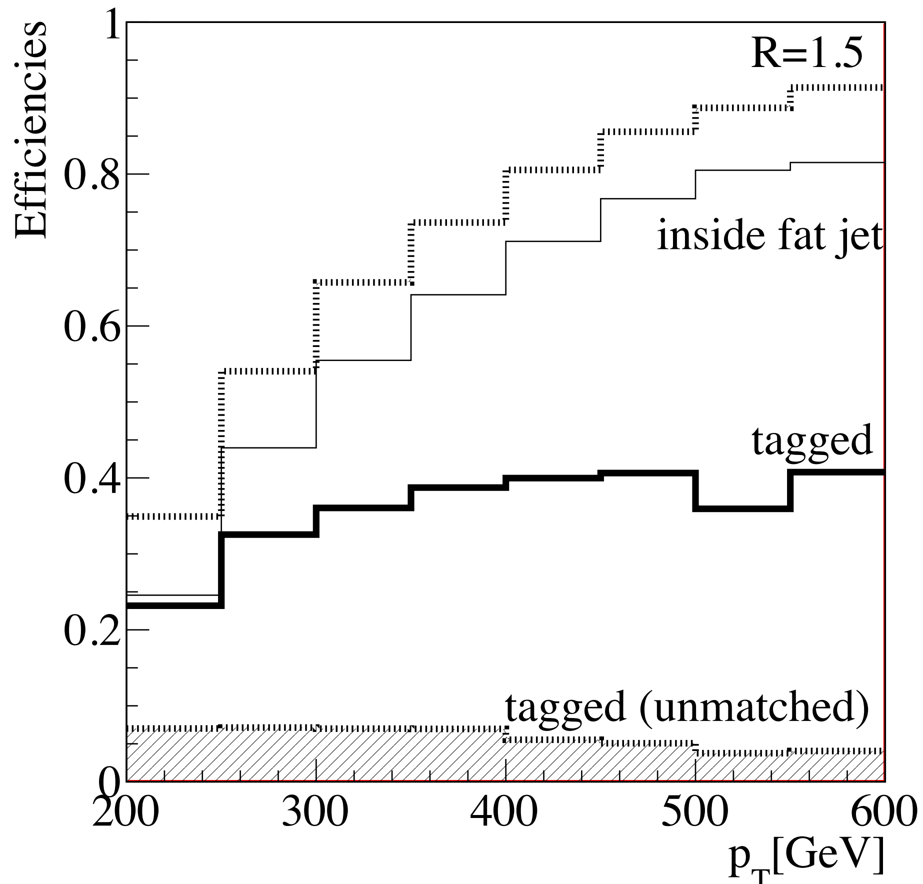


[Plehn, Salam, MS PRL 104 (2010)]

Top quark momentum reconstruction

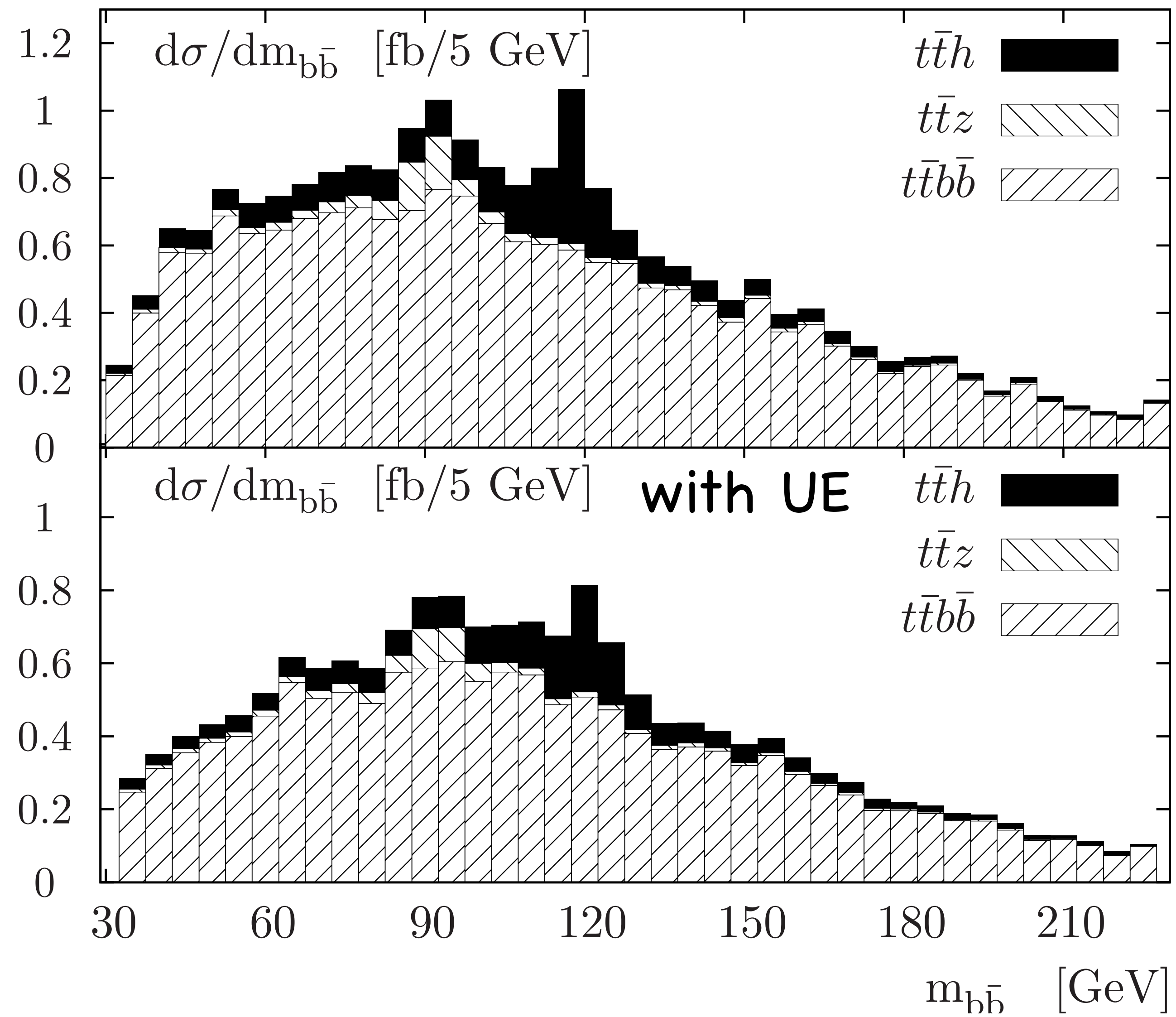






- Great reconstruction of top quark momentum
- 35% tagging efficiency
  2% W+jets fake rate
- Tagger used in resonance searches in ATLAS: 1207.2409

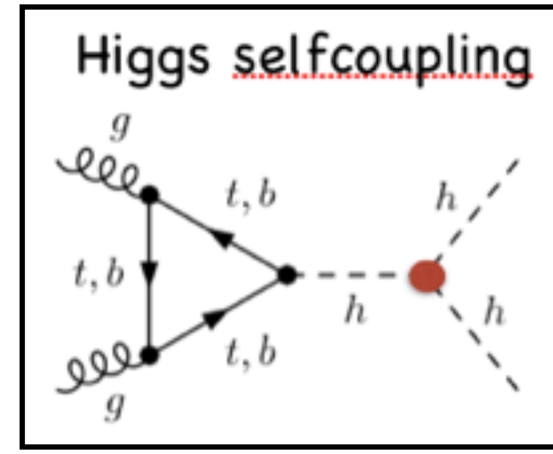
Results for tth



- 5 sigma sign. with 100 1/fb
- Development of Higgs and top tagger for busy final state
- Improvement of S/B from 1/9 to 1/2

⟶ tth might be a window to Higgs-top coupling

Measuring the Higgs self-coupling



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

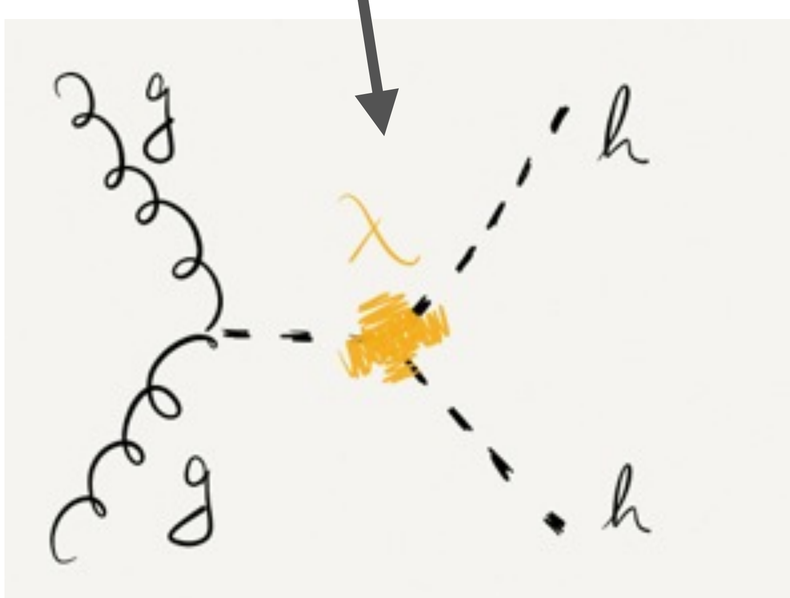
$$-\mathcal{L} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

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

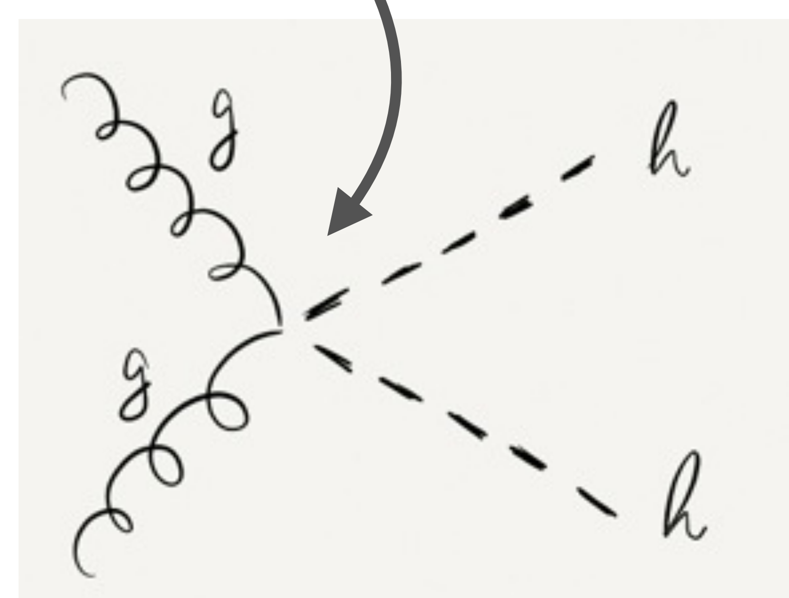
$$- \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$= -\frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h + \frac{\alpha_s}{24\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 + \ldots$$

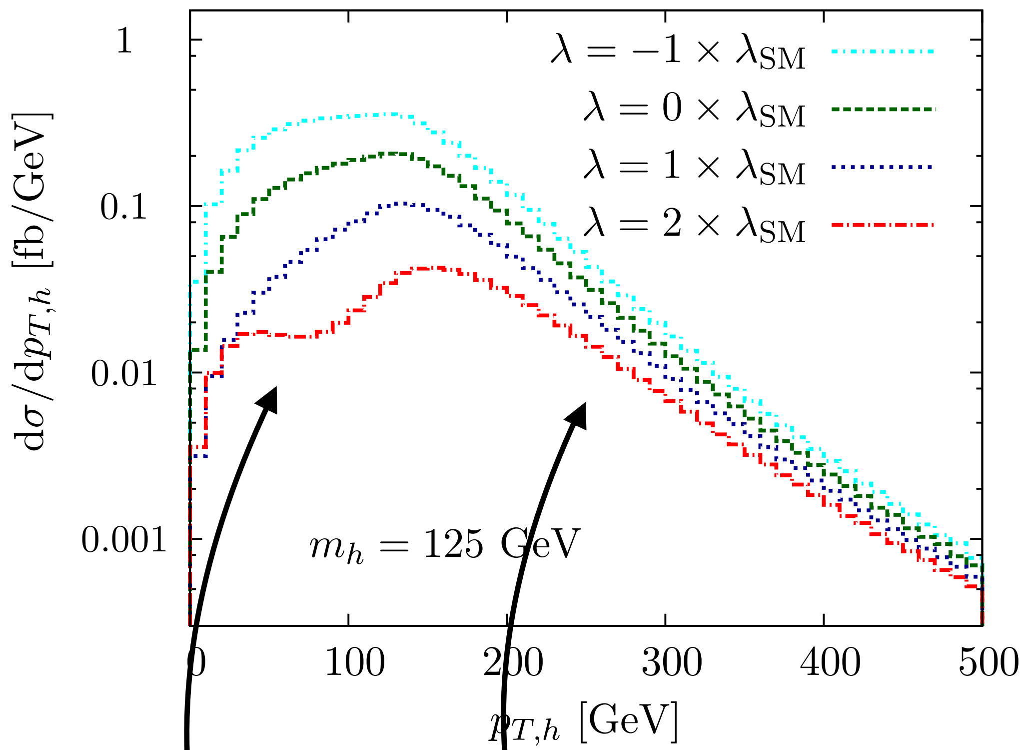
→ Potential needs at least dihiggs production!

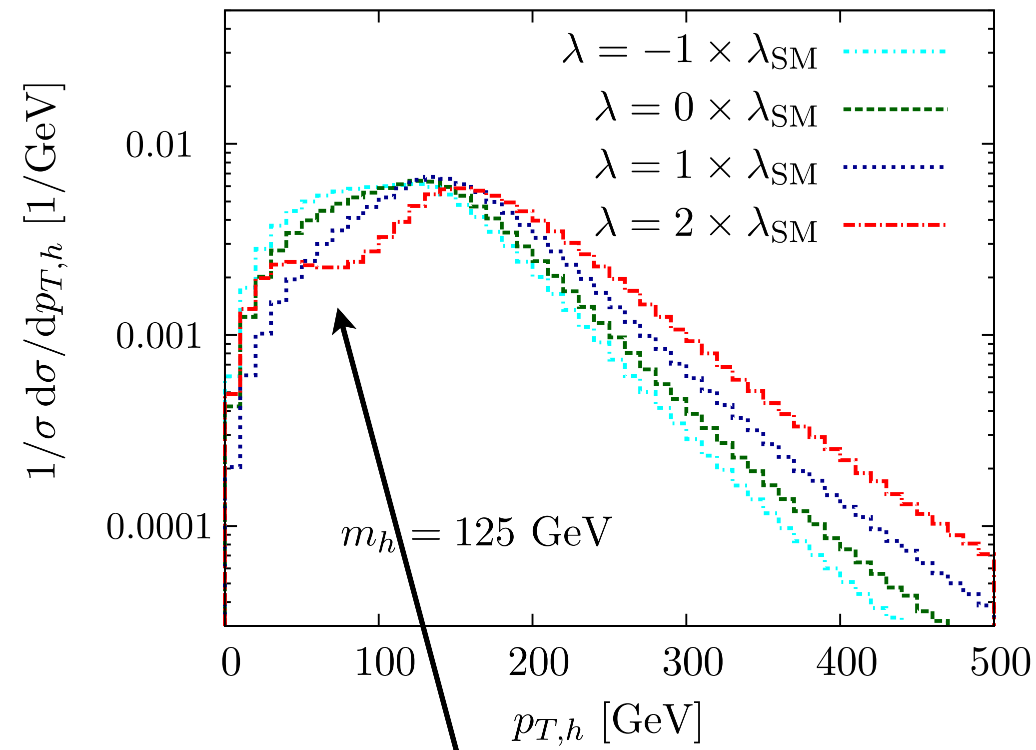


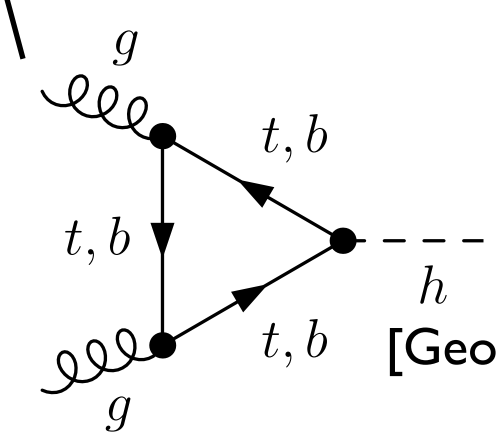
$-$



Higgs selfcoupling in HH+X



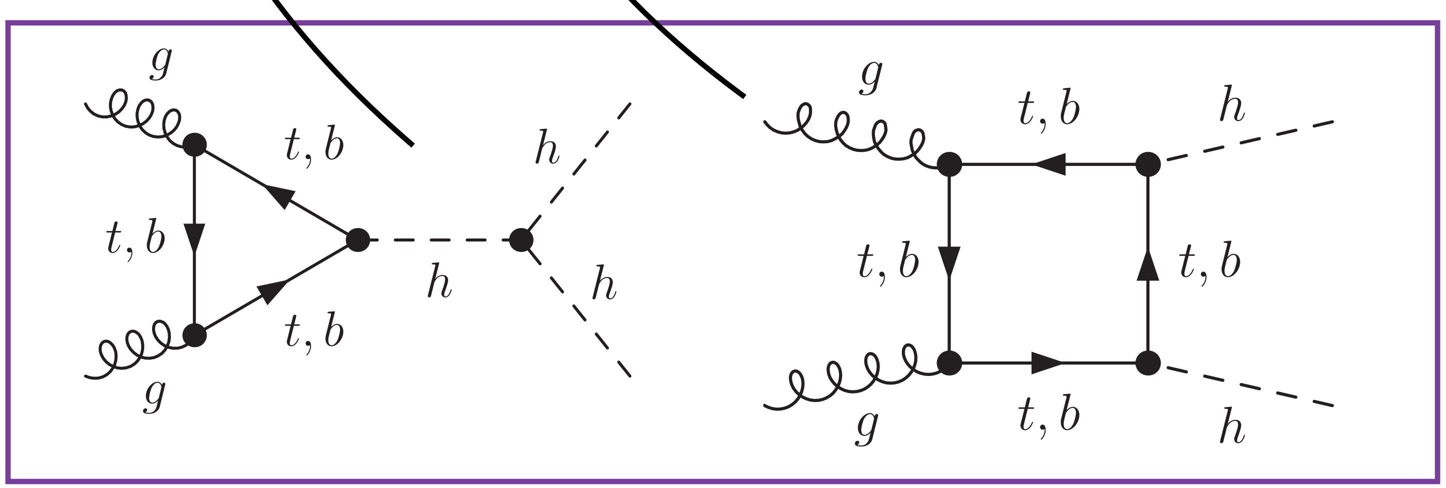




[Georgi et al. `78]

has maximum contribution for

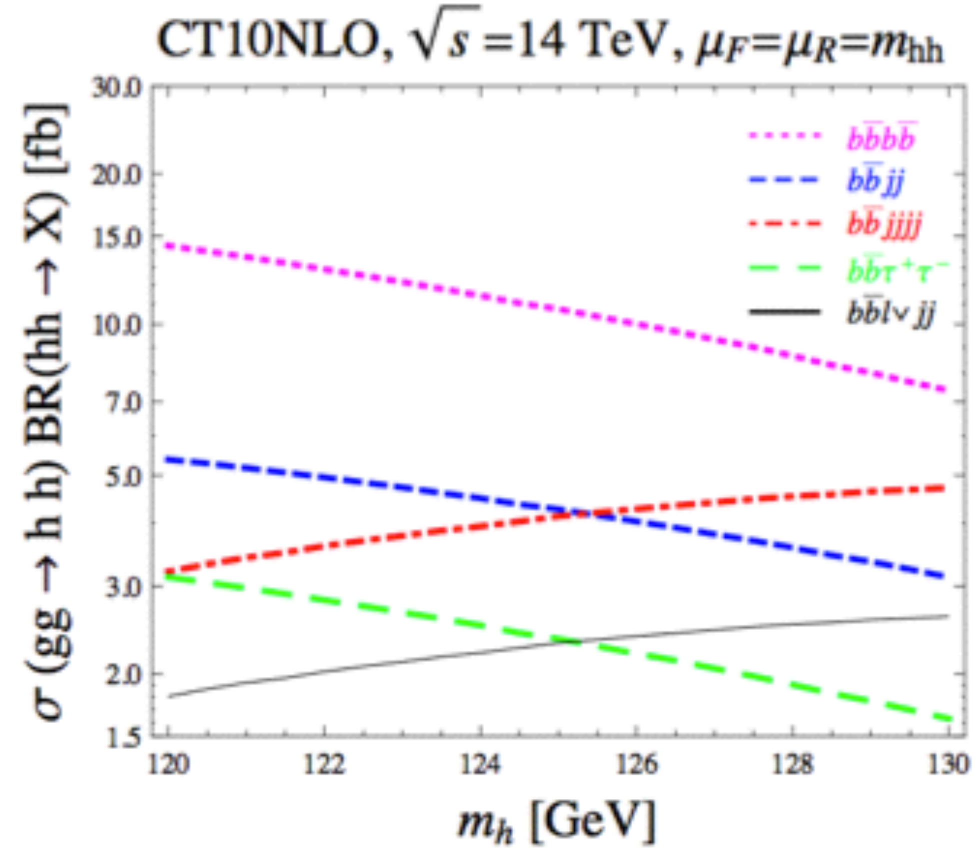
$$s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$$



Where is sensitivity located?

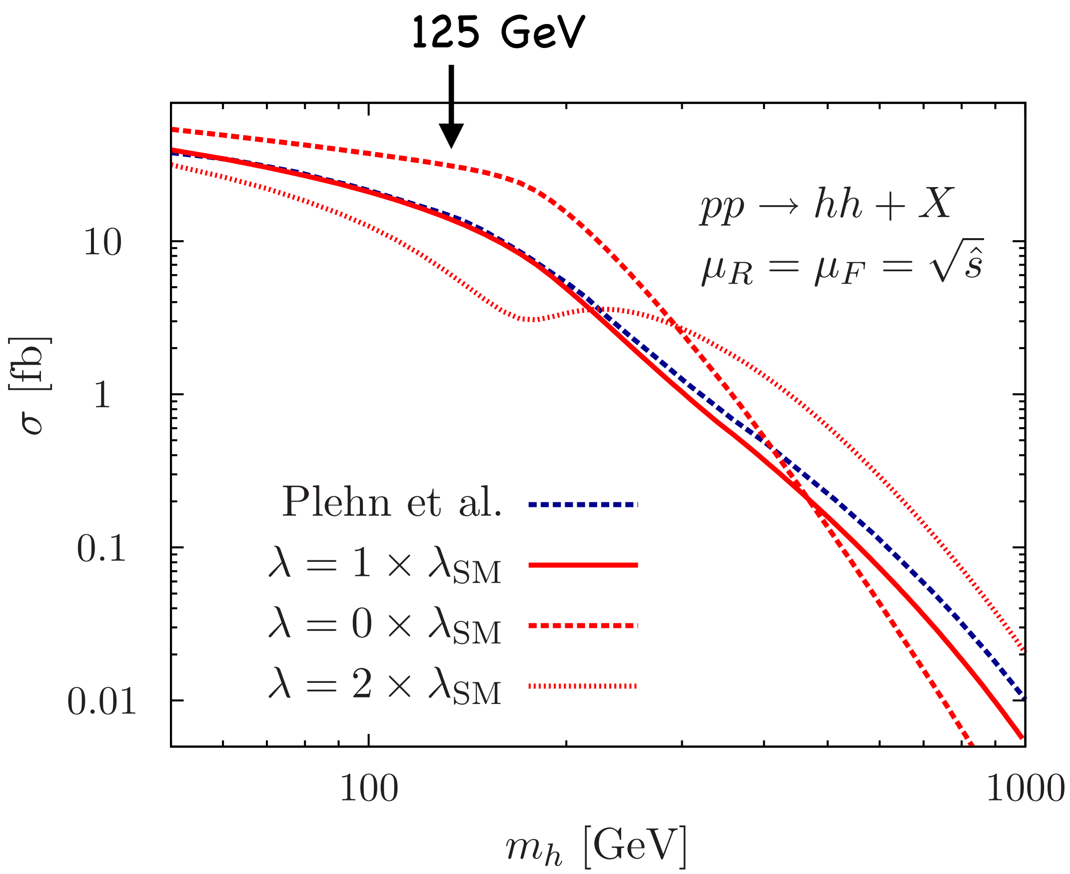
Measuring this small cross section in an inclusive search is very challenging at the HL-LHC: compromise between branching ratio and cleanliness of the signal

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



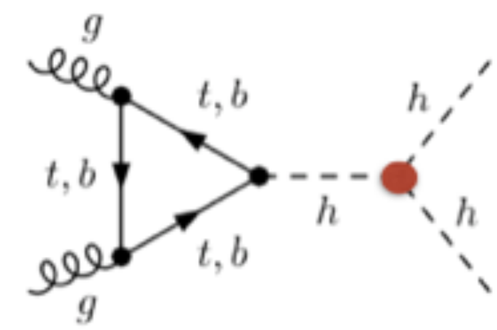
Several channels are currently under study by the collaborations

[James Ferrando, Talk at Royal Society Meeting]



Cross section small at LHC inclusively ~ 30 fb.

Higgs selfcoupling



Two channels viable at LHC:

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

[Baur, Plehn, Rainwater]

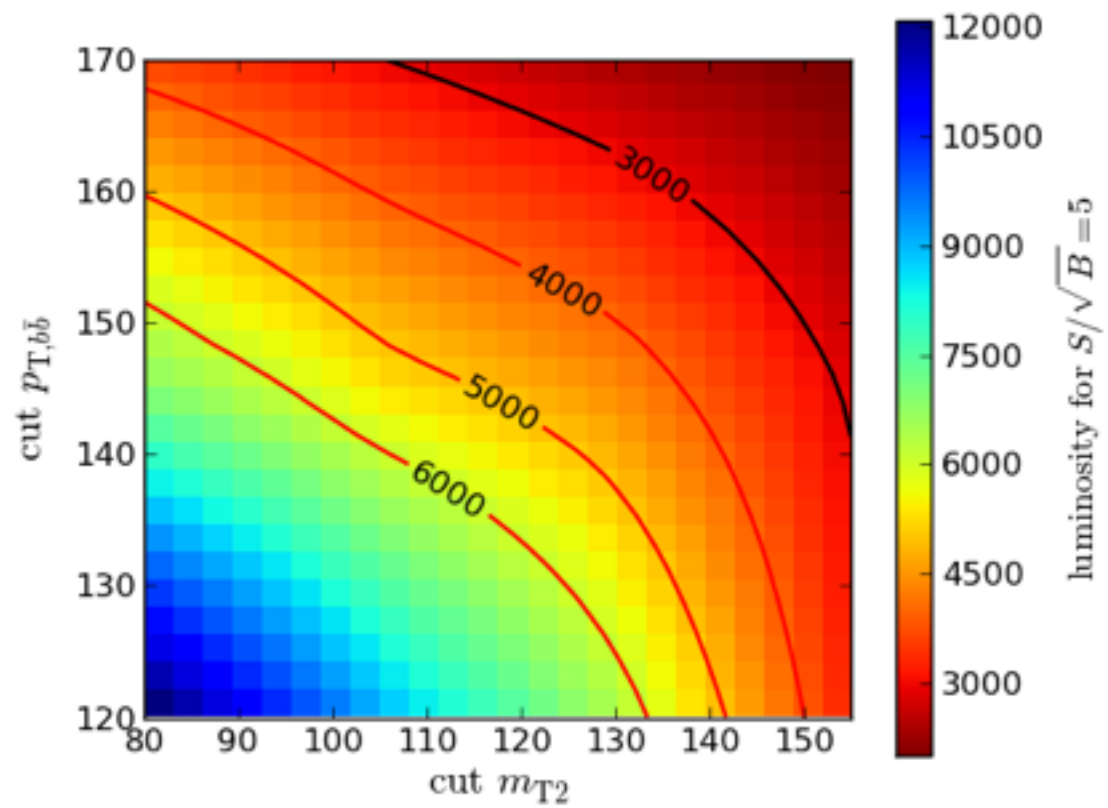
$b\bar{b}\tau^+\tau^-$

[Dolan, Englert, MS]
[Barr, Dolan, Englert, MS]

straightforward to obtain S/B ~ 1/5

Exclusion at 95% CL:

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



boost resurrects this channel

New Physics for 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

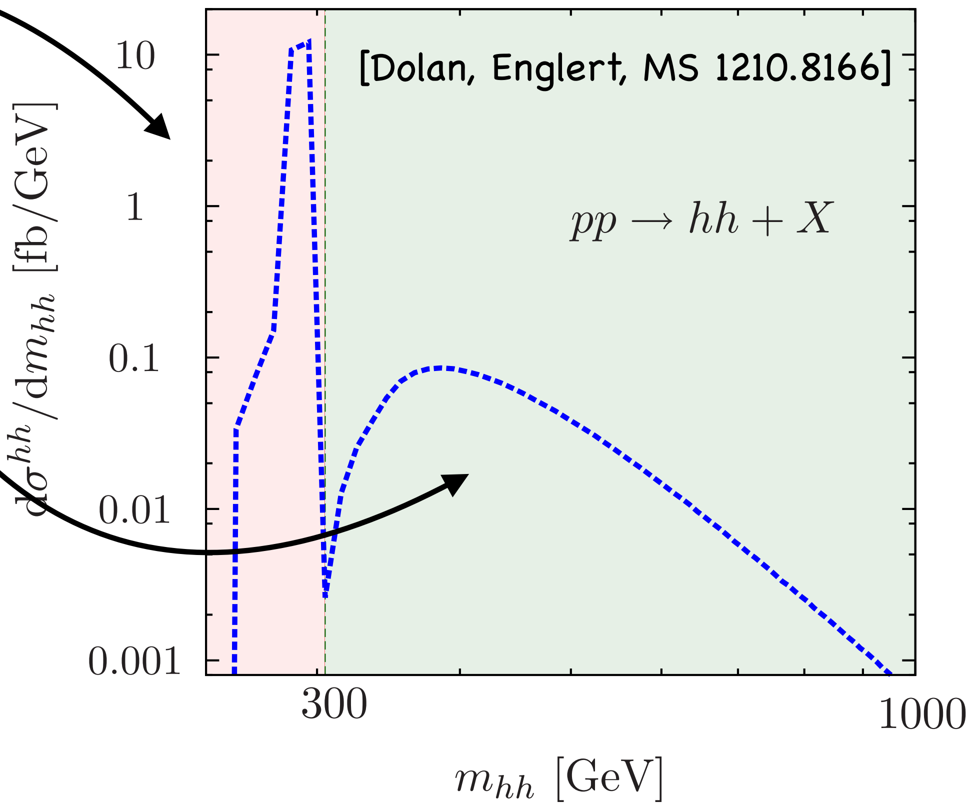
- E-dim, G -> hh -> 4b

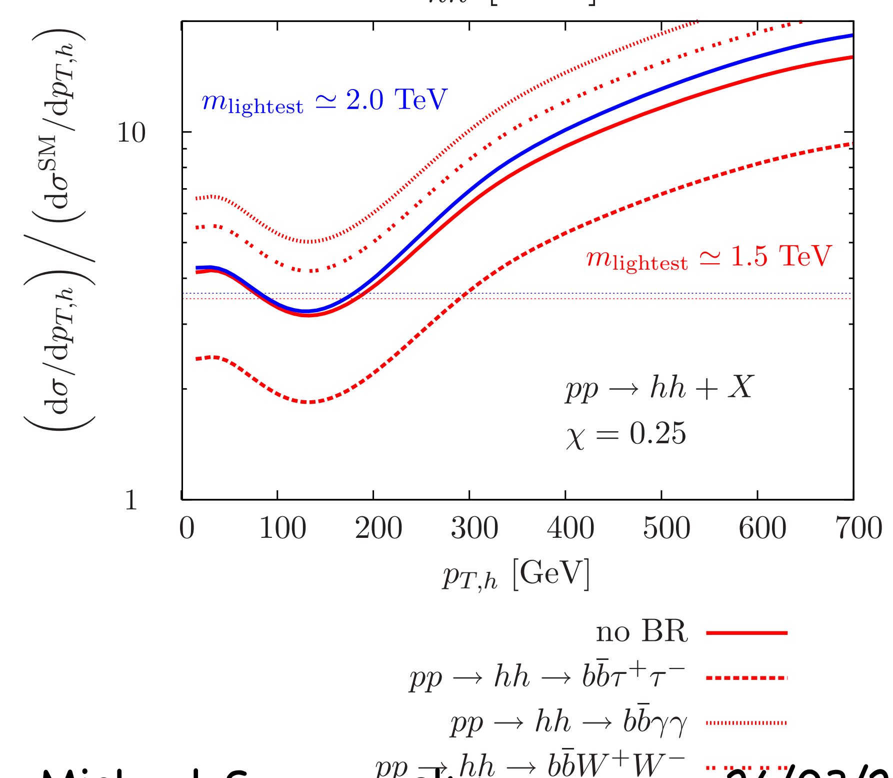
  see [Gouzevitch et al. 1303.6636]

- Higgs portal

  see [No, Ramsey-Musolf 1310.6035]

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





Continuous/Loop enhancement

- Composite Higgs
- 4th generation

  see [Kribs, Plehn, Tait, MS 0706.3718]

- Other theories modifying $hh\bar{t}_i t_j$ or $h\bar{t}_i t_j$

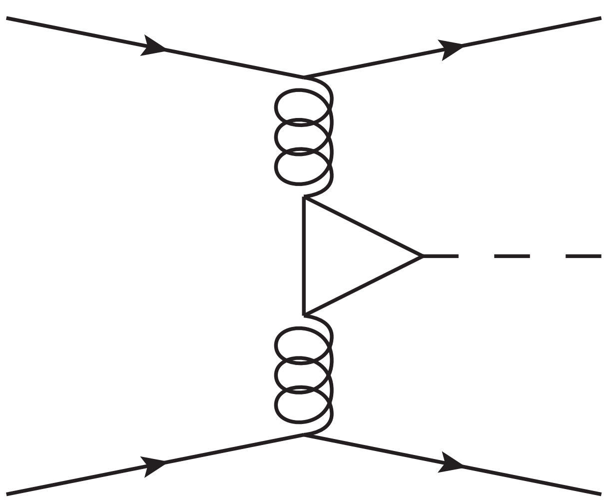
Measuring the CP of the Higgs boson

- 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)]

Interaction:

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



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

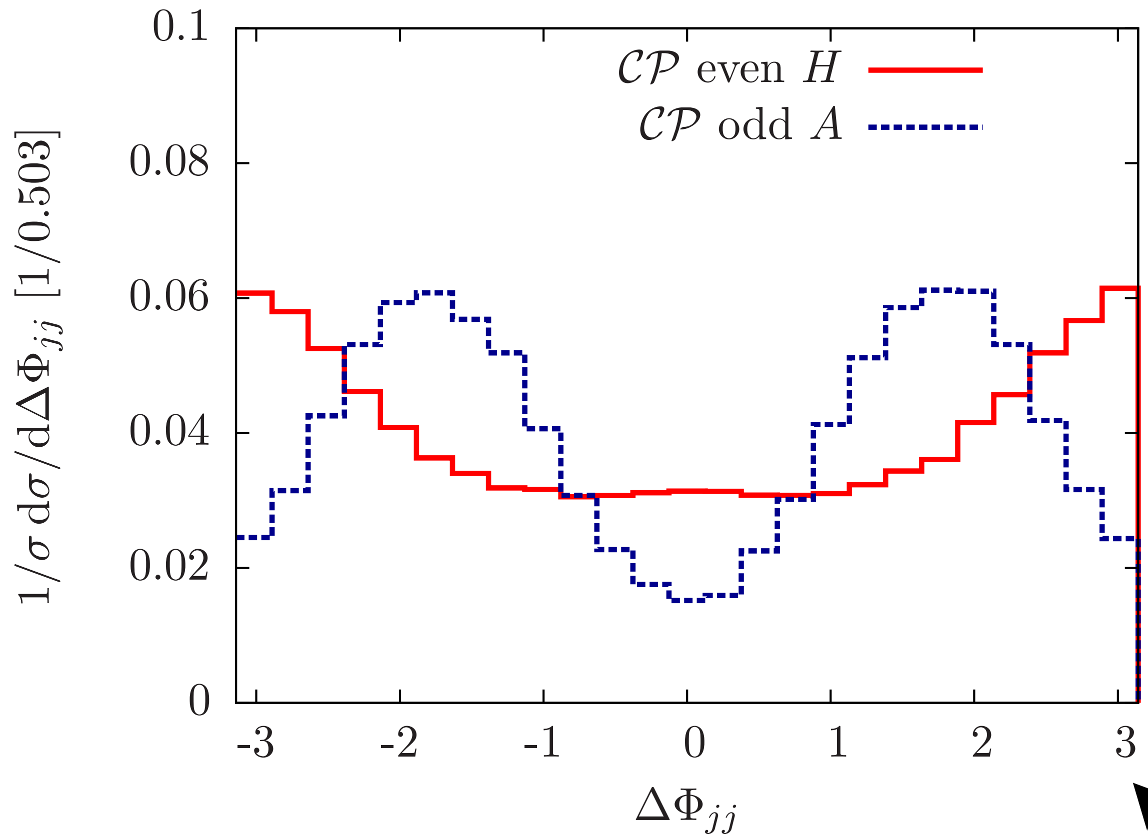
$$\mathcal{M}_{\rm even} \sim J_1^\mu J_2^\nu \left[g_{\mu\nu}(q_1 \cdot q_2) - q_{1\nu} q_{2\mu} \right]$$

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

$\mathcal{M}_{\rm odd}$ 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:

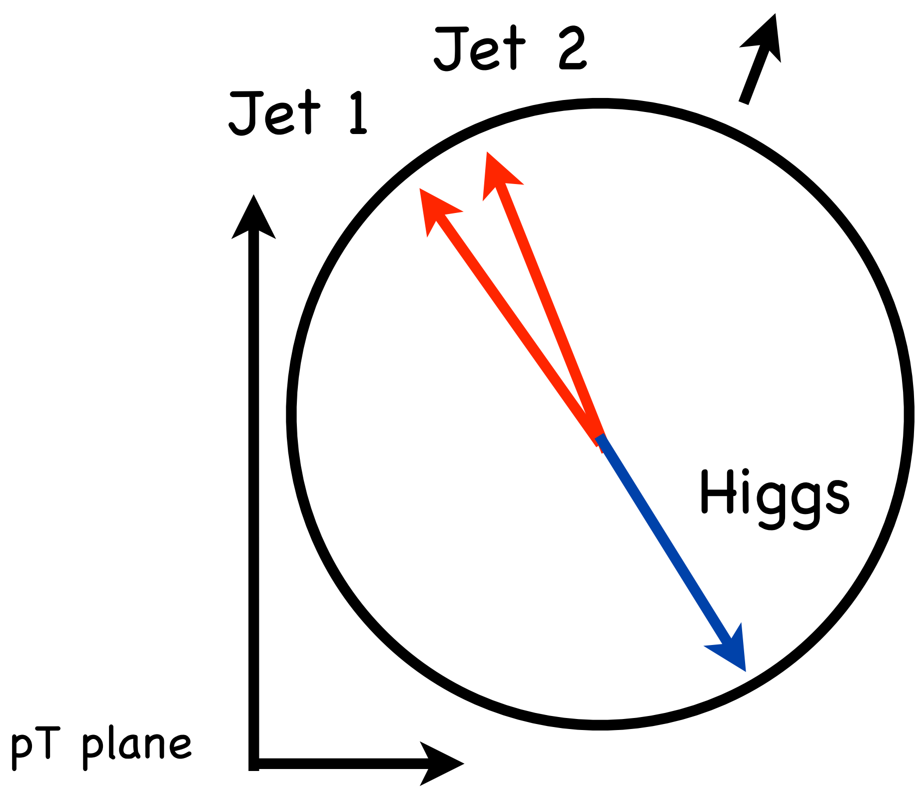
azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

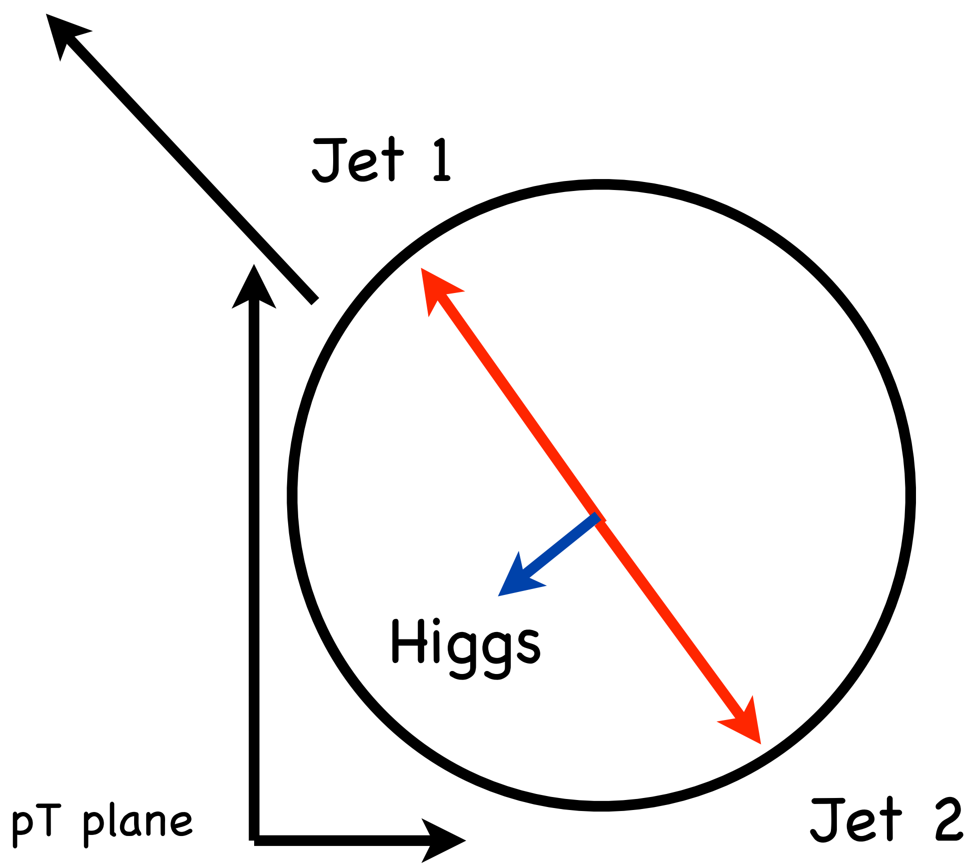


$$p^\mu_< = \sum_{j\in\{\text{jets: } y_j<y_h\}} p^\mu_j$$

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

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





Some implications on BSM physics

'The Higgs-top connection'

In some scenarios top physics and Higgs physics connected by naturalness:

SUSY
composite Higgs models

Quite minimal extensions using scalars

Precision Higgs couplings and new Higgs states:

Higgs portals
Higher Higgs reps
Classical scale invariant (Coleman-Weinberg)

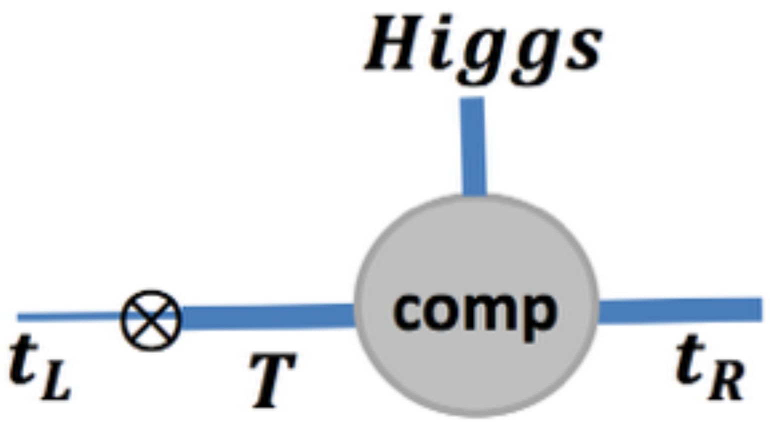
Totally agnostic: Effective Field Theory approach

Minimal composite Higgs Model $SO(5)/SO(4)$

[Agashe, Contino, Pomarol 2005]
[Contino, Da Rold, Pomarol 2007]

- Partial compositeness:

  Fully composite RH top;
  Partial composite LH top, bottom



- Custodial symmetry protected

- Top partner in $4_{2/3}$ of SO(4)

[De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663]

$$\mathcal{L} = \mathcal{L}_{\rm kin} - \bar{\Psi}\not{e}\Psi - M_\Psi \bar{\Psi}\Psi$$

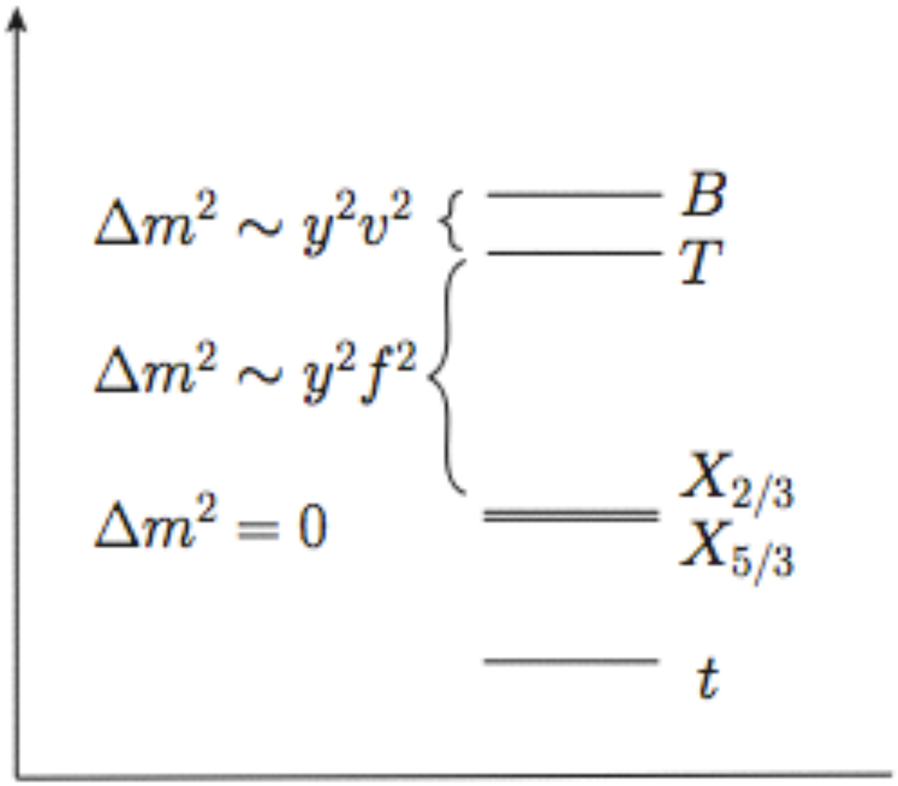
$$+ i\, c_1 (\bar{\Psi}_R)_i \gamma^\mu d^i_\mu t_R + y\, f\, (\bar{Q}^{\mathbf{5}}_L)^I U_{I\,i} \Psi^i_R + y\, c_2\, f (\bar{Q}^{\mathbf{5}}_L)^I U_{I\,5} t_R + \text{h.c.}$$

Single production $g_X \bar{X} V t_R$

Elementary-composite mixing

See talk by C. Delaunay

Typical top partner spectrum



Free parameters:

$$(f,\, y,\, c_1,\, c_2,\, M_\Psi)$$

(constrain 1 with top mass)

i.e.

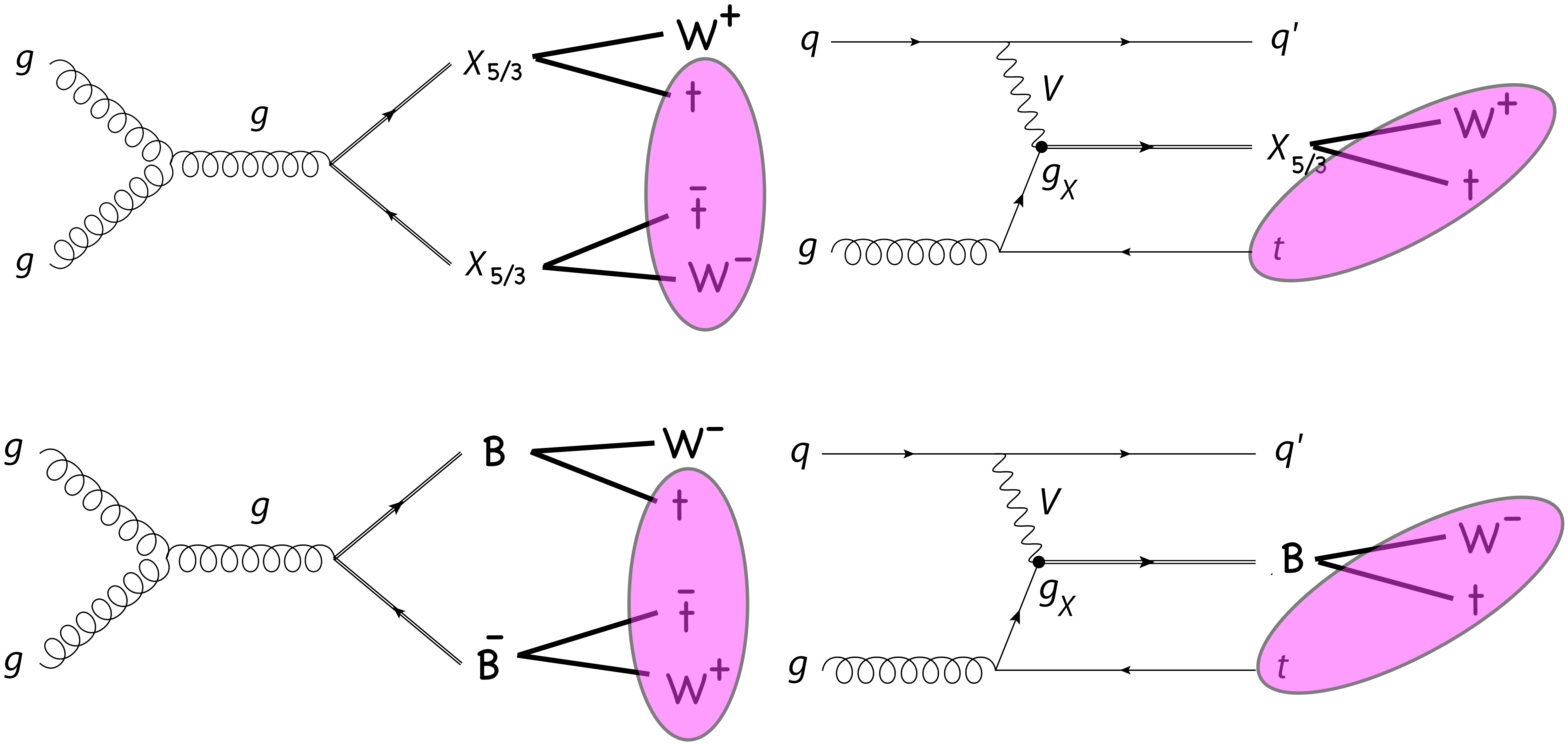
$$m_{X_{5/3}} = M_\Psi$$

$$m_B = \sqrt{m^2_{X_{5/3}} + (yf)^2}$$

➡ Use lightest top partner $X_{5/3}$ to constrain all other top partners

➡ Mass splitting between B and $X_{5/3}$ tells compositeness scale

Different top partners share common final state



➡ All processes and top partners share signature of ttW final state

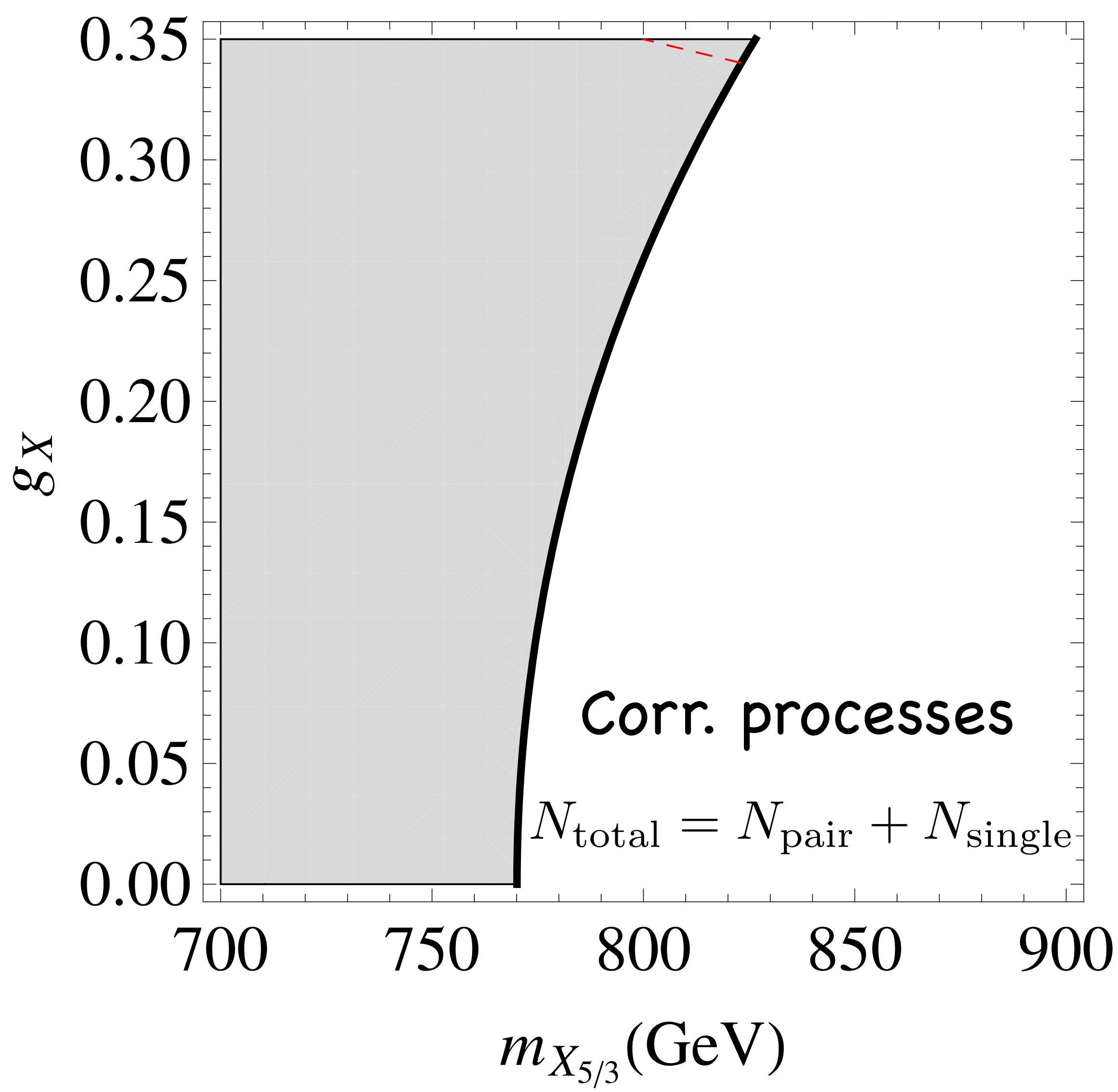
➡ Requesting ttWW reconstruction kills single top partner production

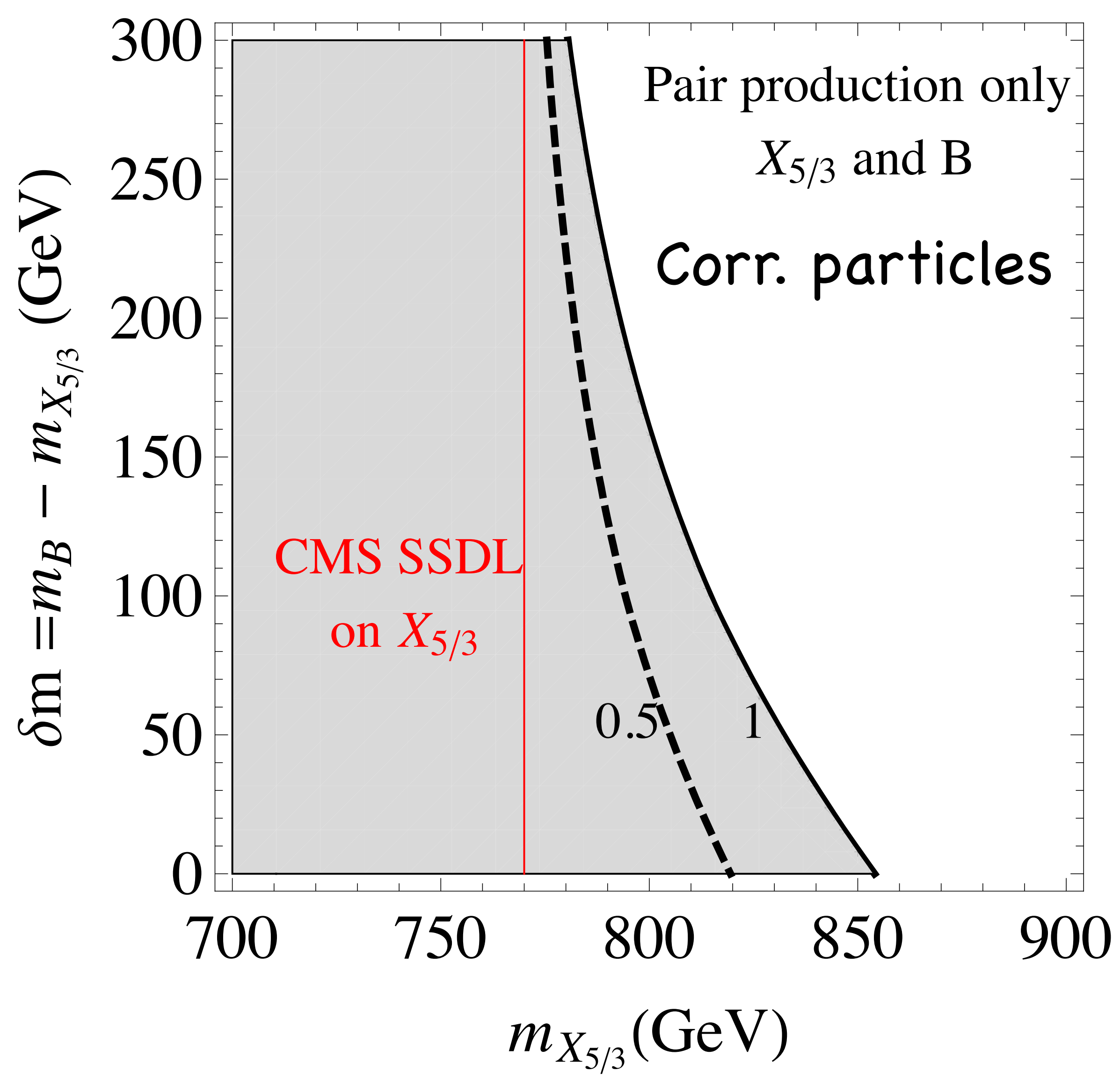
➡ For heavy top partners single production mode is dominating

Two relevant CMS analyses using full 8 TeV data set:

CMS: B2G-12-015 SSDL, two OSDL, trileptons using BDT -> impossible to recast

CMS: B2G-12-012 Search of $X_{5/3}$ via SSDL 770 GeV @95% CL



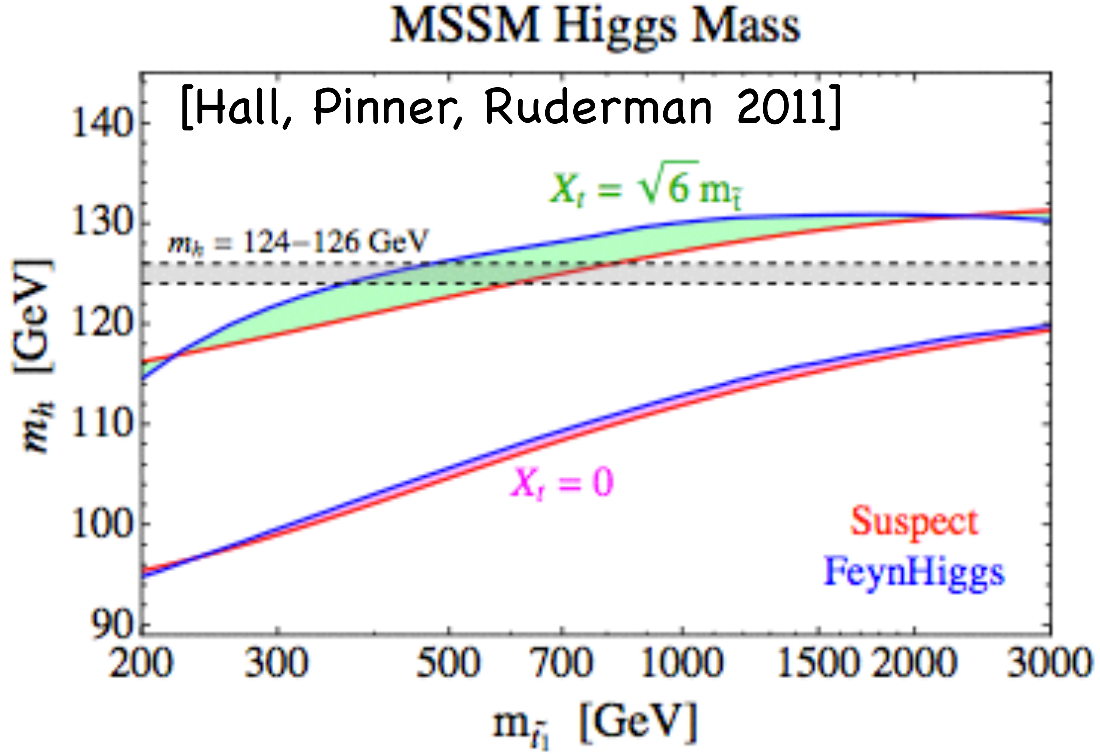


In MSSM large Higgs mass in tension with light stops

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde t}^2}\right)\right]$$

$$X_t = A_t - \mu\cot\beta$$

Higgs mass wants stops to be heavy (at least one)



[Papucci, Ruderman, Weiler 2011]

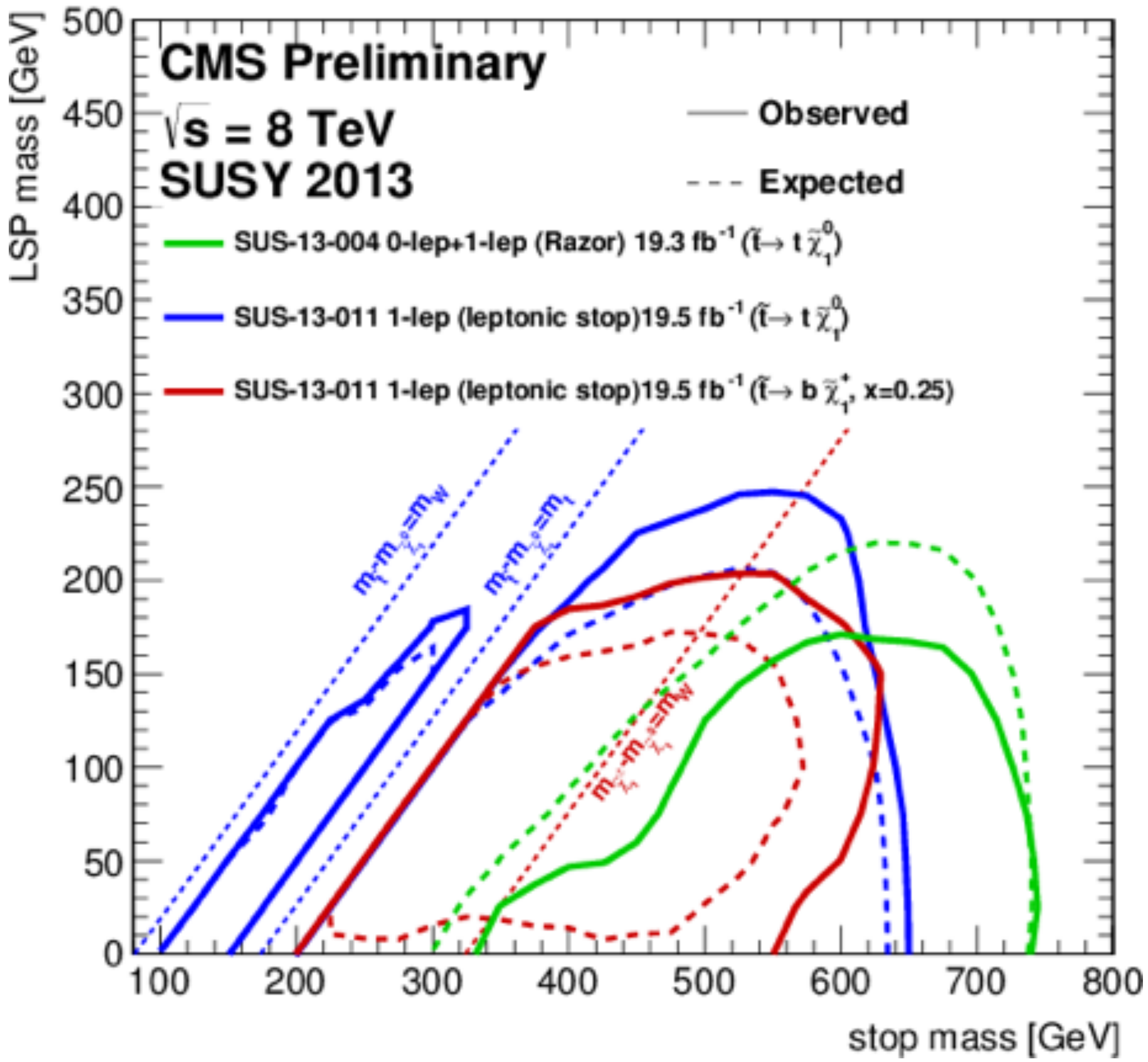
However, natural MSSM wants the stops to be light:

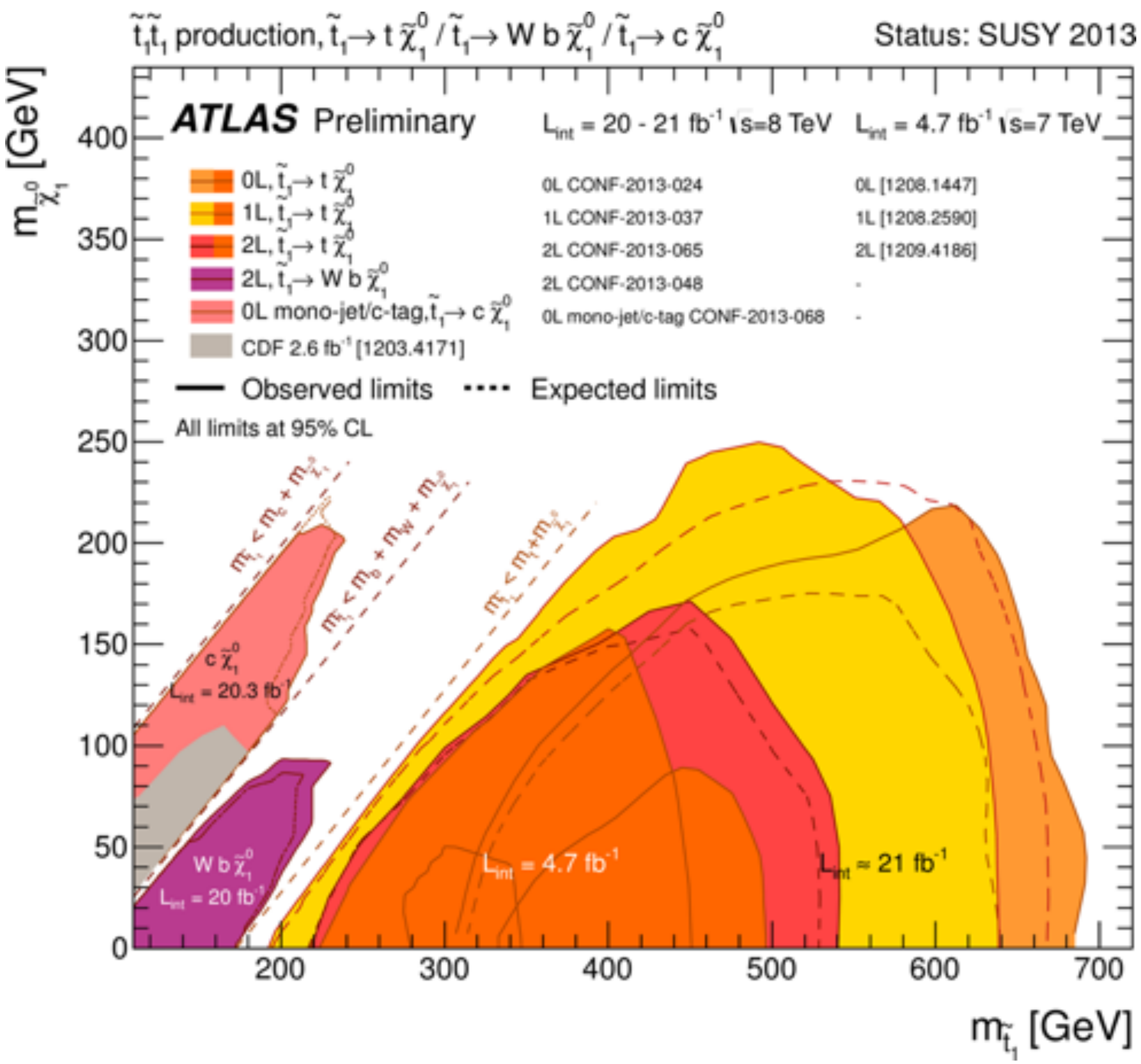
$$\sqrt{m_{\tilde t_1}^2 + m_{\tilde t_2}^2} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{(1+x_t^2)^{1/2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{m_h}{120\,\mathrm{GeV}}\right)\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

➡ Bound on heavier stop mass

$$x_t = A_t/\sqrt{m_{\tilde t_1}^2 + m_{\tilde t_2}^2}.$$

$\tilde{t}$-$\tilde{t}$ production





➡ In standard stop searches experiments in good shape and agreement

➡ Some parameter regions kinematically challenging

Higgs Portal to New Physics

See talk by O. Lebedev

Motivation: No sign of low-energy supersymmetry or top partners -> maybe look for other ways

[Coleman & Weinberg 1973, Hempfling 1996, Khoze et al 2013]

Could be worth thinking about

minimally extended Standard Model with classical scale-invariance

Single occurrence of non-dynamical scale in SM - negative-valued $\mu^2_{\rm SM}$

$$V^{\rm SM}_{\rm cl}(H) = \mu^2_{\rm SM}\, H^\dagger H + \frac{\lambda_{\rm H}}{2}\left(H^\dagger H\right)^2$$

Replace by Higgs portal interaction with new ϕ to make $V_{\rm cl}$ scale inv.

$$V_{\rm cl}(H,\phi) = -\lambda_{\rm P}(H^\dagger H)|\phi|^2 + \frac{\lambda_{\rm H}}{2}(H^\dagger H)^2 + \frac{\lambda_\phi}{4!}|\phi|^4$$

Radiatively generated vev gives $\mu^2_{\rm SM} = -\lambda_{\rm P}|\langle\phi\rangle|^2 = -\frac{1}{2}\, m_h^2 = -\frac{1}{2}\,\lambda_{\rm H}\, v^2$

Use Coleman-Weinberg mechanism in dark sector U(1)

$$\langle \phi \rangle \sim M_{UV} \times \exp\left[-\frac{\text{const}}{g_{CW}^2}\right] \ll M_{UV}$$

gauge coupling of ϕ

Have to ensure $m^2|_{\phi=0} := V''(\phi)\Big|_{\phi=0} = 0$

In dim. reg. masslessness eqn is automatic. Since no explicit mass scales at outset, no finite corrections to mass terms at origin are generated

Classical scale invariance is broken anomalously by logarithmically running couplings → generates dynamical scale $\langle \phi \rangle \ll M_{UV}$

→ scale invariance is broken by anomaly in controlled way
- order parameter is $\langle |\phi|^2 \rangle$

The new U(1) sector gives two new d.o.f's:
the scalar ϕ and the Z'

$$m_\varphi^2 = \frac{3g_{CW}^4}{8\pi^2}\,|\langle\phi\rangle|^2 \quad \ll \quad m_{Z'}^2 = g_{CW}^2\,|\langle\phi\rangle|^2$$

The Standard Model Higgs and the hidden Higgs mix via the portal interaction

The mass matrix is

$$m^2 = \begin{pmatrix} m_h^2 + \Delta m_{h,\mathrm{SM}}^2 & -\kappa\, m_h^2 \\ -\kappa\, m_h^2 & m_\varphi^2 + \kappa^2 m_h^2 \end{pmatrix}, \quad \kappa = \sqrt{\frac{2\lambda_\mathrm{P}}{\lambda_H}}$$

$$m_h^2 = \lambda_\mathrm{H} v^2, \quad \Delta m_{h,\mathrm{SM}}^2 = \frac{1}{16\pi^2}\frac{1}{v^2}\left(6m_W^4 + 3m_Z^4 + m_h^2 - 24m_t^4\right) \approx -2200\,\mathrm{GeV}^2$$

Diagonalized via

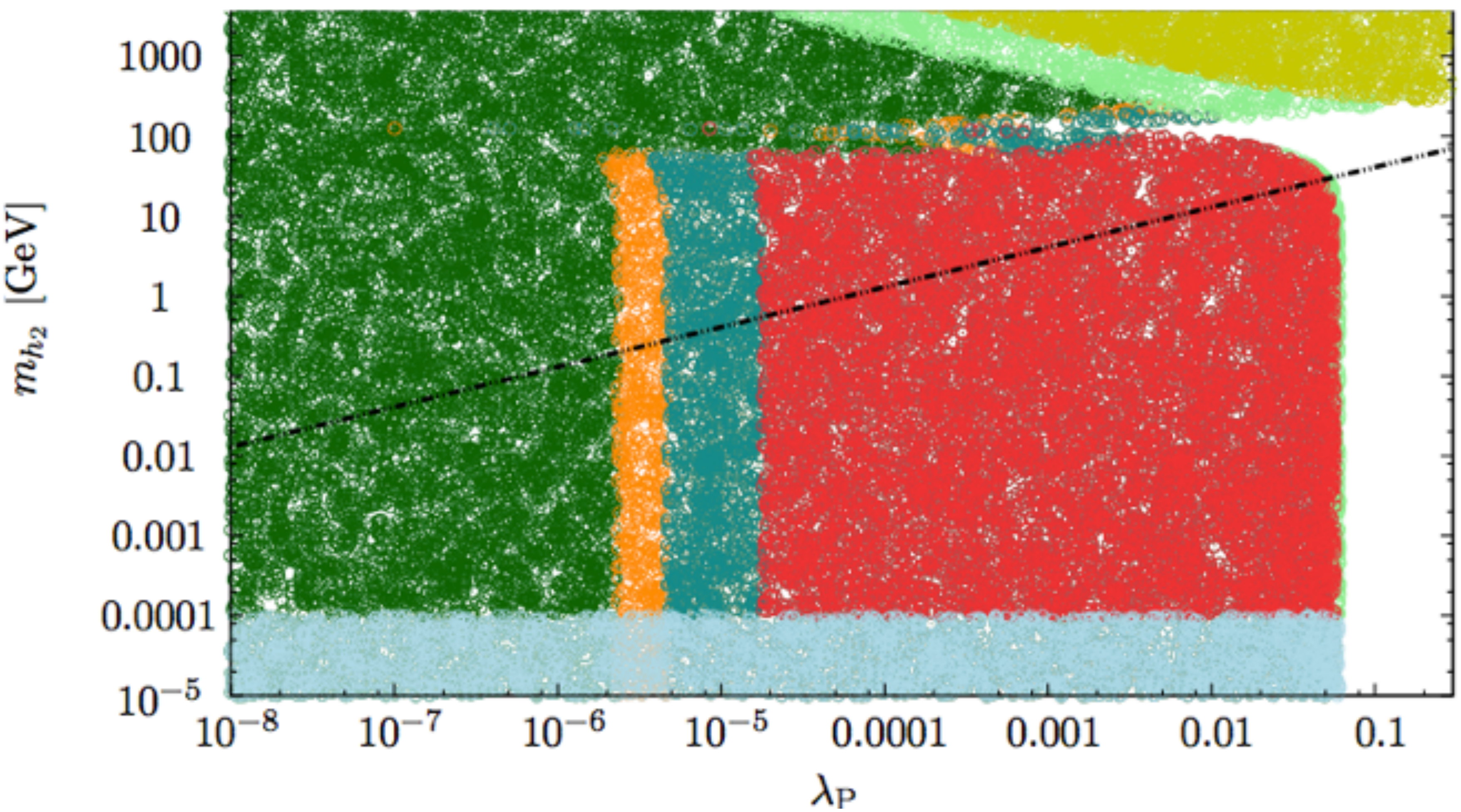
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}\begin{pmatrix} h \\ \varphi \end{pmatrix}, \quad \vartheta \approx \kappa\frac{m_h^2}{m_\varphi^2 - m_h^2 - \Delta m_{h,\mathrm{SM}}^2} \ll 1$$

If $m_{h_1} > 2m_{h_2}$ the SM Higgs can decay into two hidden Higgses

$$\Gamma_{h_1 \to h_2 h_2} = \frac{4\lambda_P^2 v^2}{16\pi} \frac{[m_{h_1}^2 - 4m_{h_2}^2]^{1/2}}{m_{h_1}^2}$$

In simplest setup there are no light hidden sector particles, thus h_2 decays back into visible particles via mixing with Higgs boson

h_2 becomes extremely narrow resonance



Red already excluded

Cyan can be probed by HL LHC

Orange can be probed by combination of LC and HL LHC

Green is allowed

points below black dashed line require fine-tuning

The agnostics: The effective field theory approach

Highly complex:

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

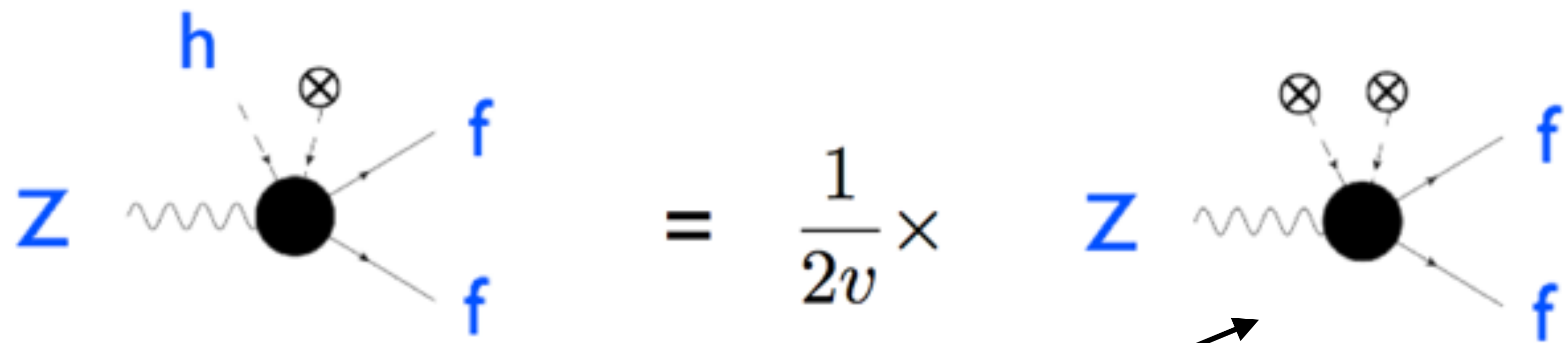
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_\mu G^B_{\nu\rho} G^{C\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u \vert H\vert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \vert H\vert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \vert H\vert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$		$\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{u}_R \gamma^\mu T^A u_R)$	$\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{d}_R \gamma^\mu T^A d_R)$	
$\mathcal{O}^u_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{RR} = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_{LL} = (\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{Q}_L \gamma^\mu T^A Q_L)$		
$\mathcal{O}^{ql}_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{L}_L \gamma^\mu L_L)$		
$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L \gamma^\mu \sigma^a Q_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$		
$\mathcal{O}^{qe}_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{e}_R \gamma^\mu e_R)$		
$\mathcal{O}^{lu}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^{ld}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{d}_R \gamma^\mu d_R)$	
$\mathcal{O}^{ud}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{d}_R \gamma^\mu d_R)$		
$\mathcal{O}^{(8)\,ud}_{RR} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{d}_R \gamma^\mu T^A d_R)$		
$\mathcal{O}^{ue}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}^{de}_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{e}_R \gamma^\mu e_R)$	
$\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$		
$\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$		
$\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$		
$\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}^{r\alpha}_L e_R)\epsilon_{rs}(\bar{L}^s_L u^\alpha_R)$		
$\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$	$\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$	$\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$
$\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	

Talk by Pomarol at Moriond:

Observation 1:

Many Higgs operator indirectly constrained by EWP measurements

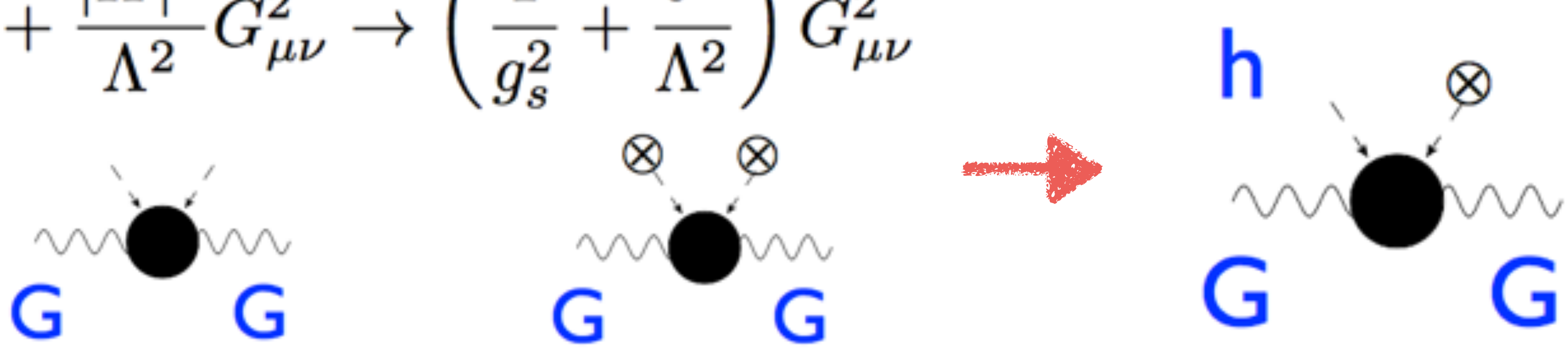


constrained by LEP at permille level

Observation 2:

Potentially large effects from operators with same structure as SM coupling

for example: $\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$



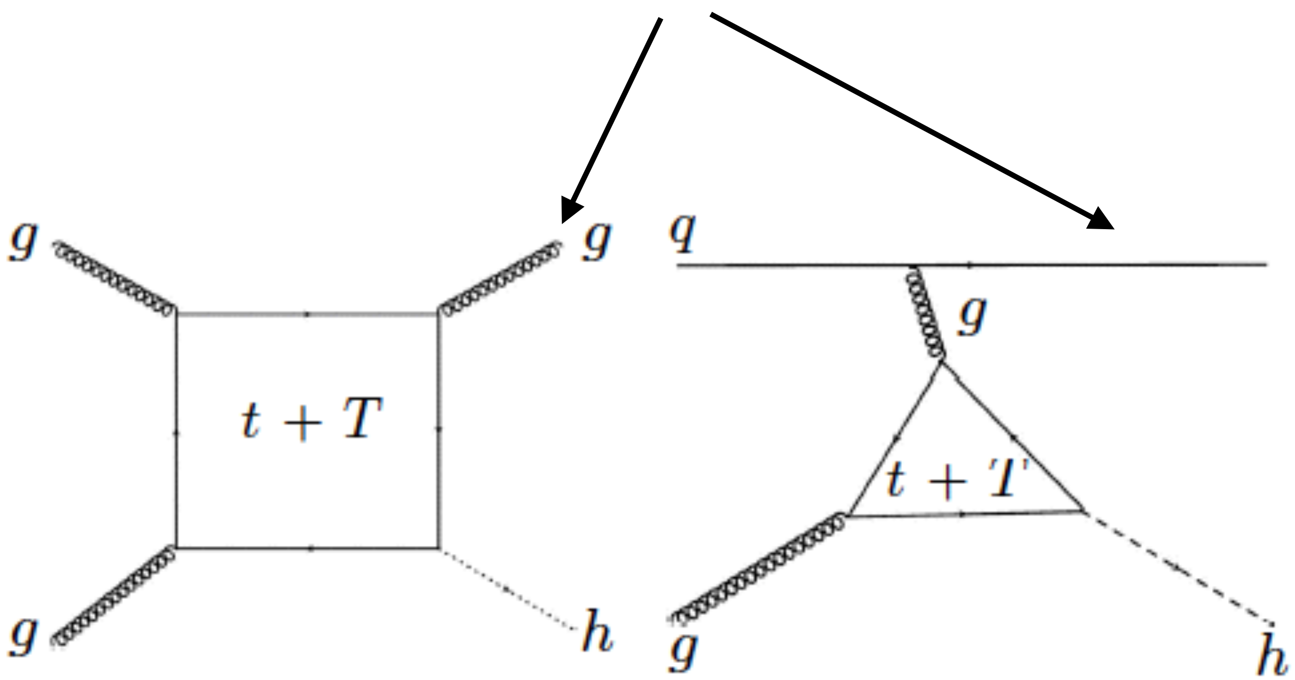
(not physical)

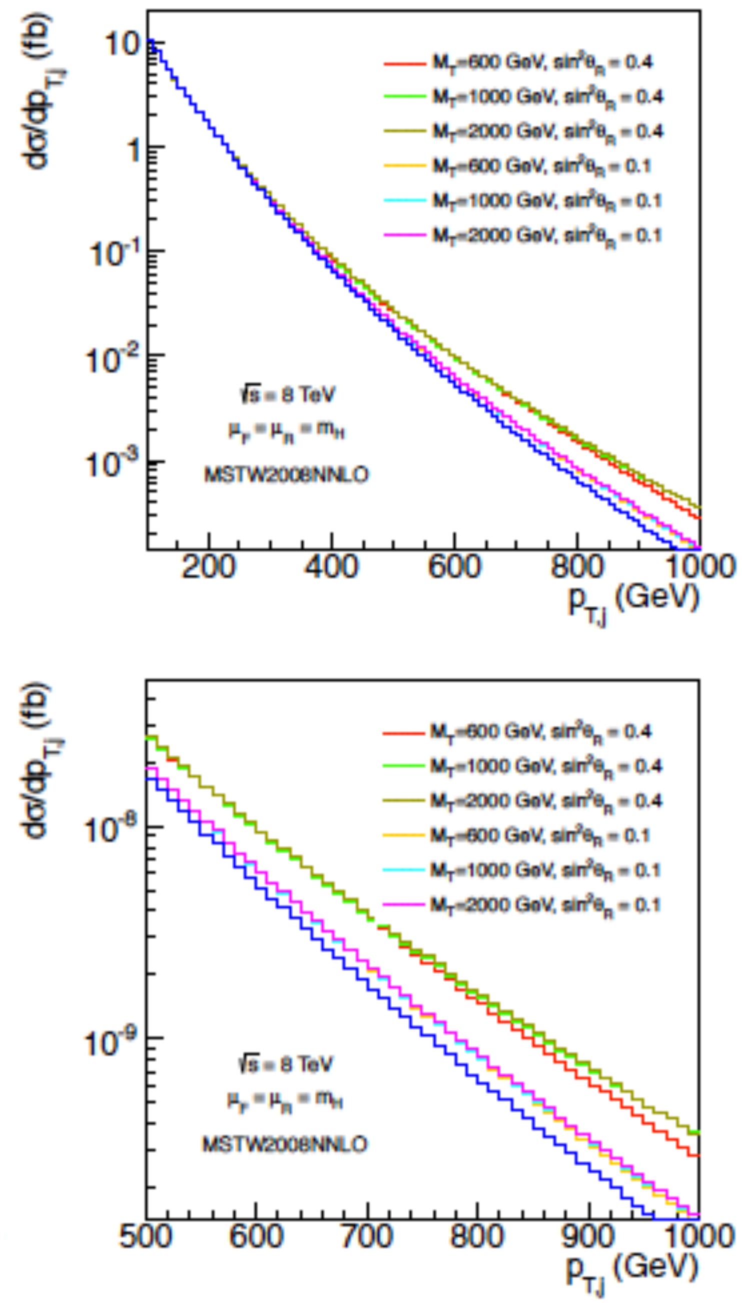
Sizeable effect in gg -> h

On the one hand these operators are being probed, e.g. gluon fusion Higgs production

on the other operator is momentum dependent, can be enhanced:

high-pT jet





[Banfi, Martin, Sanz 1308.4771]

See talk by V. Sanz

Summary

Discovery of Higgs boson shines some light on electroweak symmetry breaking

Measuring more Higgs properties during Run 2 precisely poses large problems

→ need novel reconstruction techniques

Discovery of Higgs boson has direct effect on many BSM models

Crucial will be interplay with other measurements, e.g. top partner, elw precision, astro, ...