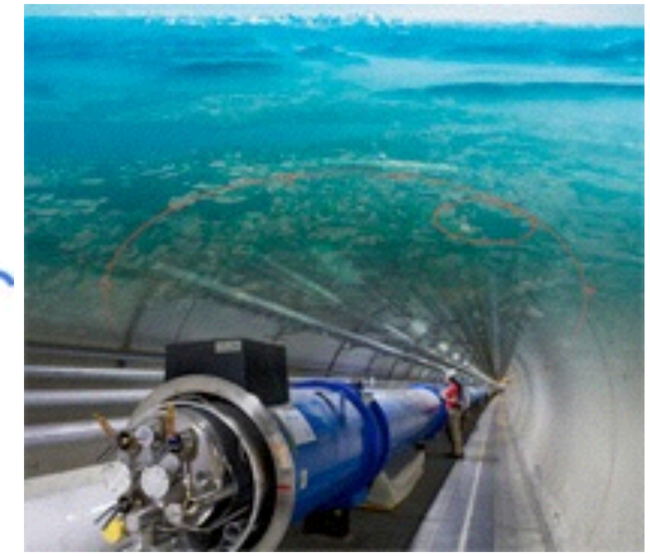
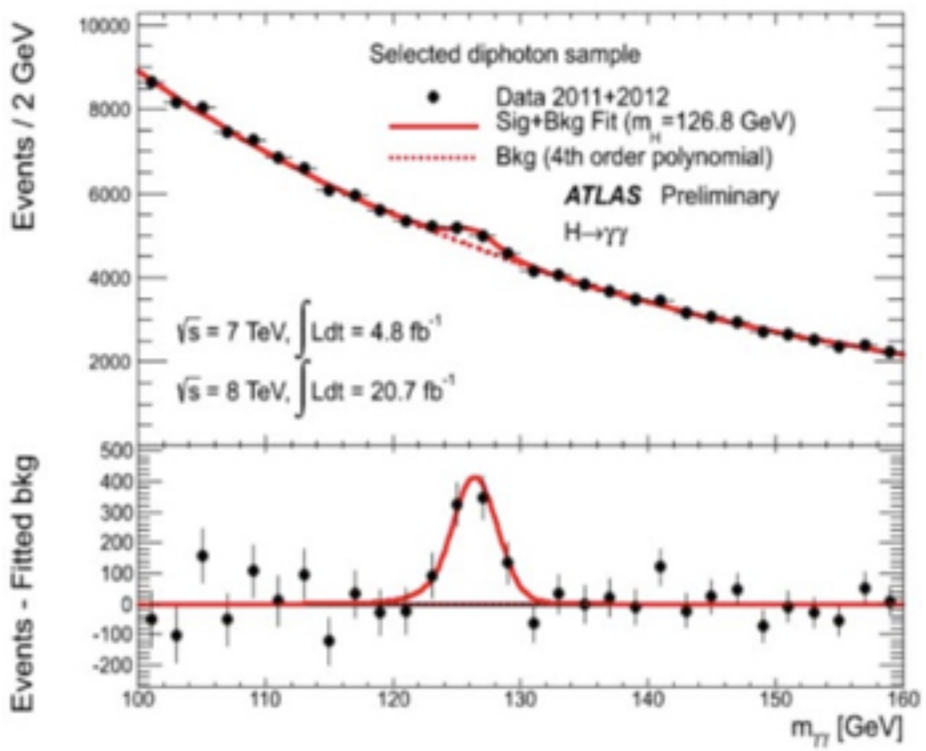


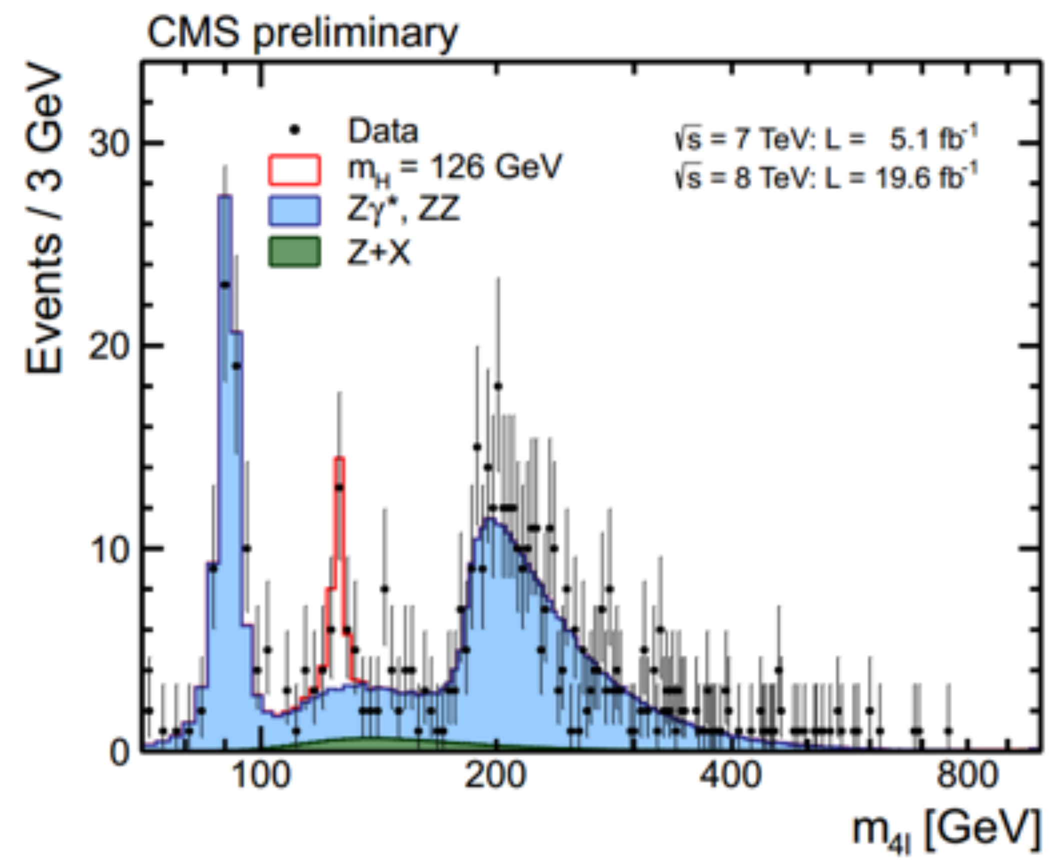
Higgs-top coupling at the LHC

Michael Spannowsky

IPPP, Durham University

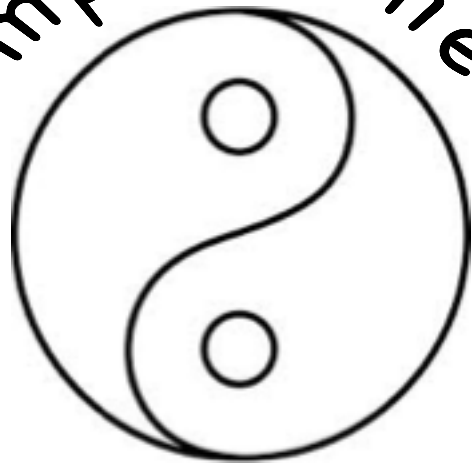
Combined results for each experiment





- Huge international and intergenerational success!
- First observed in clean final states: photons, ZZ, WW
- Now more channels, e.g. taus
- In absence of other resonances Higgs is window to new physics

Compositeness



Effective Theory

$\mathcal{L}_{\text{eff}} = \sum C_i \mathcal{O}_i$

Symmetry

SUSY, CW, ...

Naturalness

fermionic top partners

scalar top partners

Measurements

Jets

Leptons

width

interference

MET

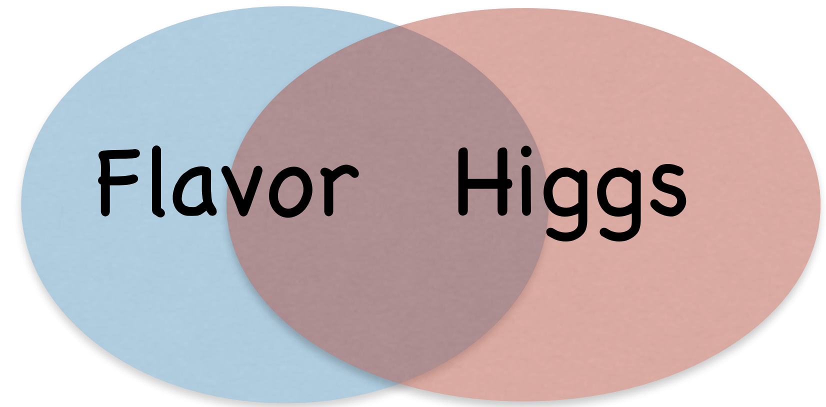
mass

Photons

boost

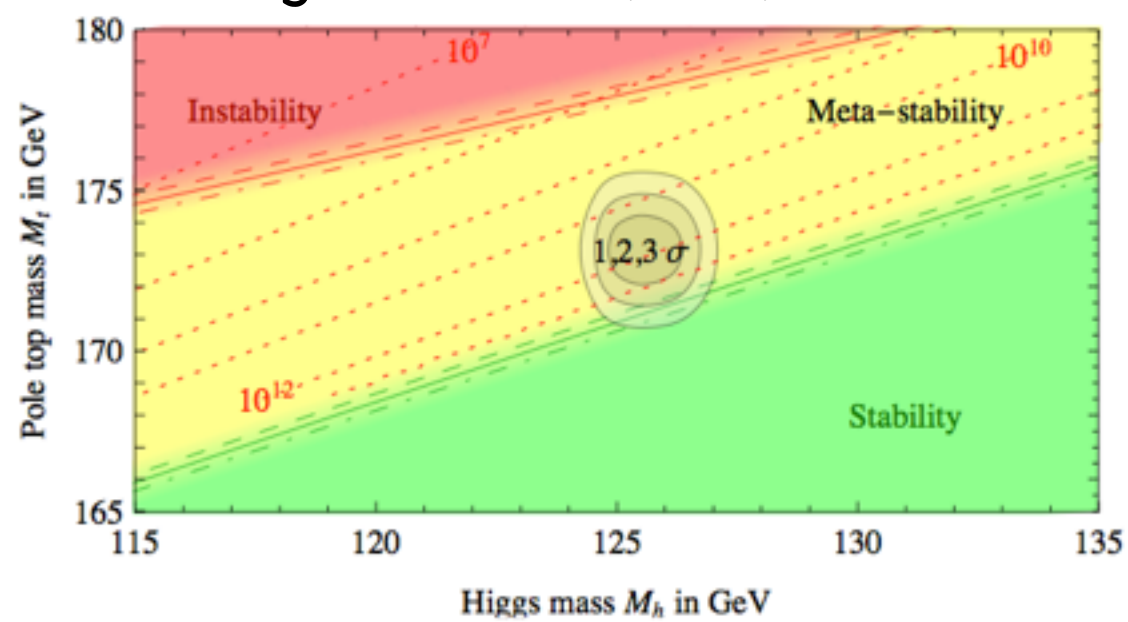
tth coupling of great importance

- As Yossi pointed out, Higgs and Flavor does not need to be related (accident of SM) but there is feedback from Flavor to Higgs sector



- Largest Yukawa coupling in SM

[Degrassi et al (2012)]



- Drives hierarchy problem

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\rm UV}^2 + ...].$$

- Vacuum stability

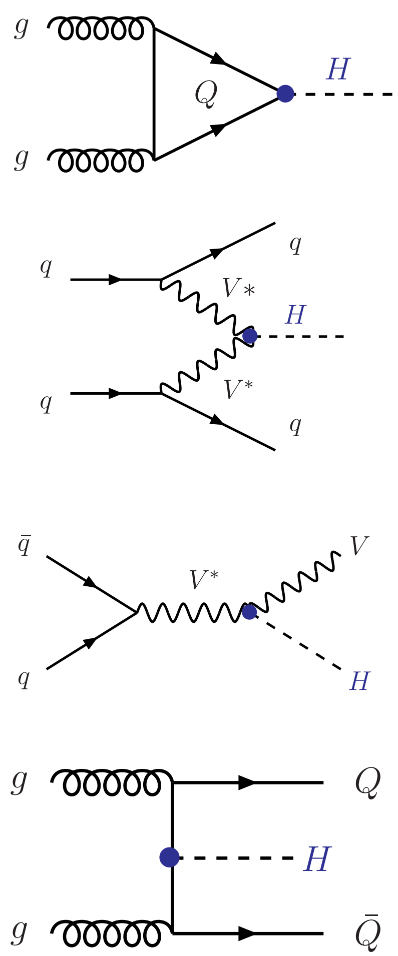
- Modified in many BSM models
  - Composite Higgs

MCHM5: $c_t = \frac{1-2\xi}{\sqrt{1-\xi}}$ MCHM4: $c_t = \sqrt{1-\xi}$ $\xi = v^2/f^2$

  - Supersymmetric Models

f	g_{ffh}	g_{ffH}	g_{ffA}
u	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$

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	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$

[Duehrssen et al]

Decay into spec. channel

Production

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

Sum of all possible decays

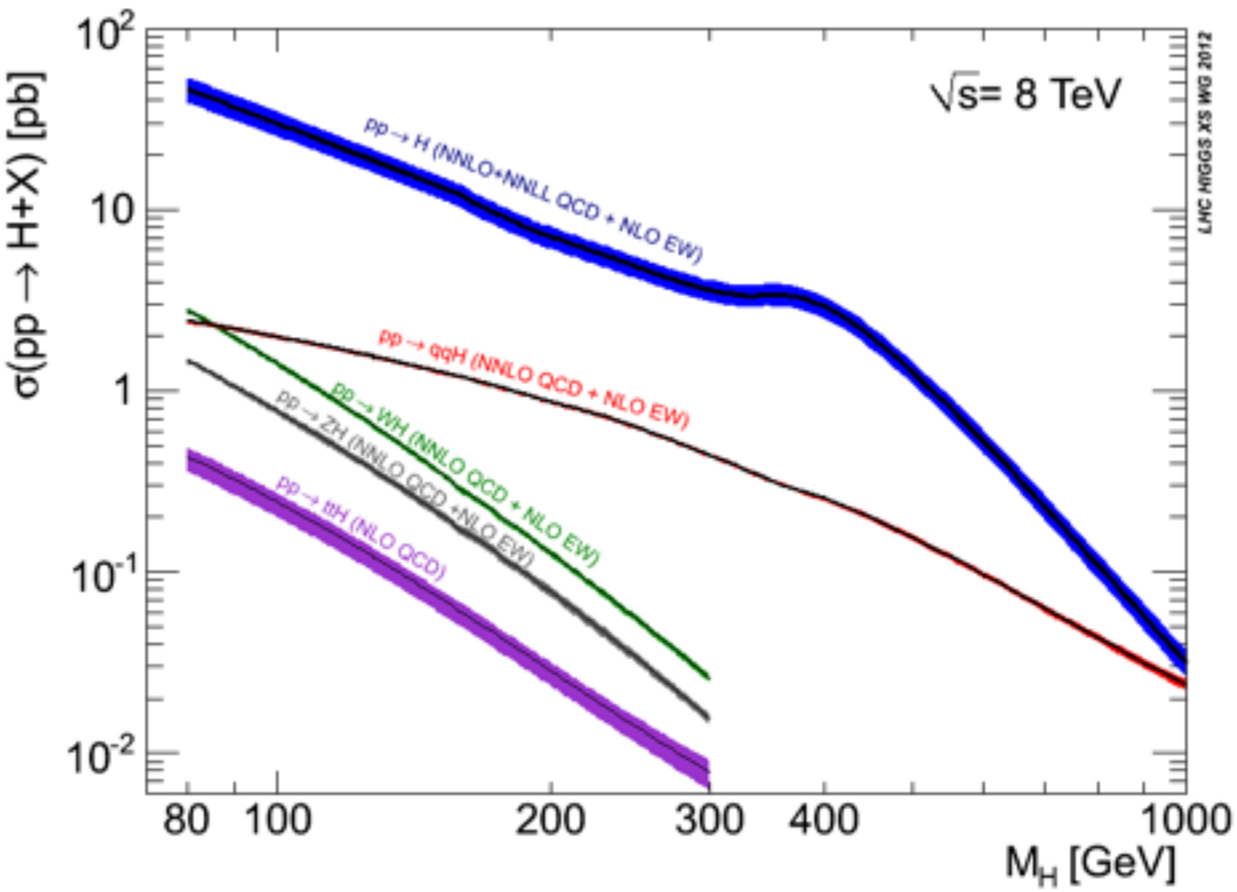
- Every measurement affected by production and decay
- top-Higgs coupling directly accessible only in tth and th+X final states which constitute minor fraction of produced Higgses at LHC
- However, as Higgs does not decay into top quarks only measured in combination with other couplings

Phenomenological status and challenges of tth

Signal calculated at NLO QCD [Beenakker et al (2001), Dawson et al (2003)]

Higgs XS WG for mH=125 GeV: $\sigma(pp \to t\bar{t}H) \simeq 0.1293\ ^{11.6\%}_{-17.2\%}$ pb @ 8 TeV

$\sigma(pp \to t\bar{t}H) \simeq 0.6113\ ^{14.8\%}_{-18.2\%}$ pb @ 14 TeV



tth with fairly large error bands compared to other channels

and matched to parton shower (POWHEG) [Garzelli at all (2011)]

Proposed channels: (14 TeV)

$$\sigma(pp \to t\bar{t}H) \times BR(H \to b\bar{b}) \simeq 352.7 \text{ fb}$$

$$\sigma(pp \to t\bar{t}H) \times BR(H \to WW) \simeq 131.1 \text{ fb}$$

$$\sigma(pp \to t\bar{t}H) \times BR(H \to \tau\tau) \simeq 38.63 \text{ fb}$$

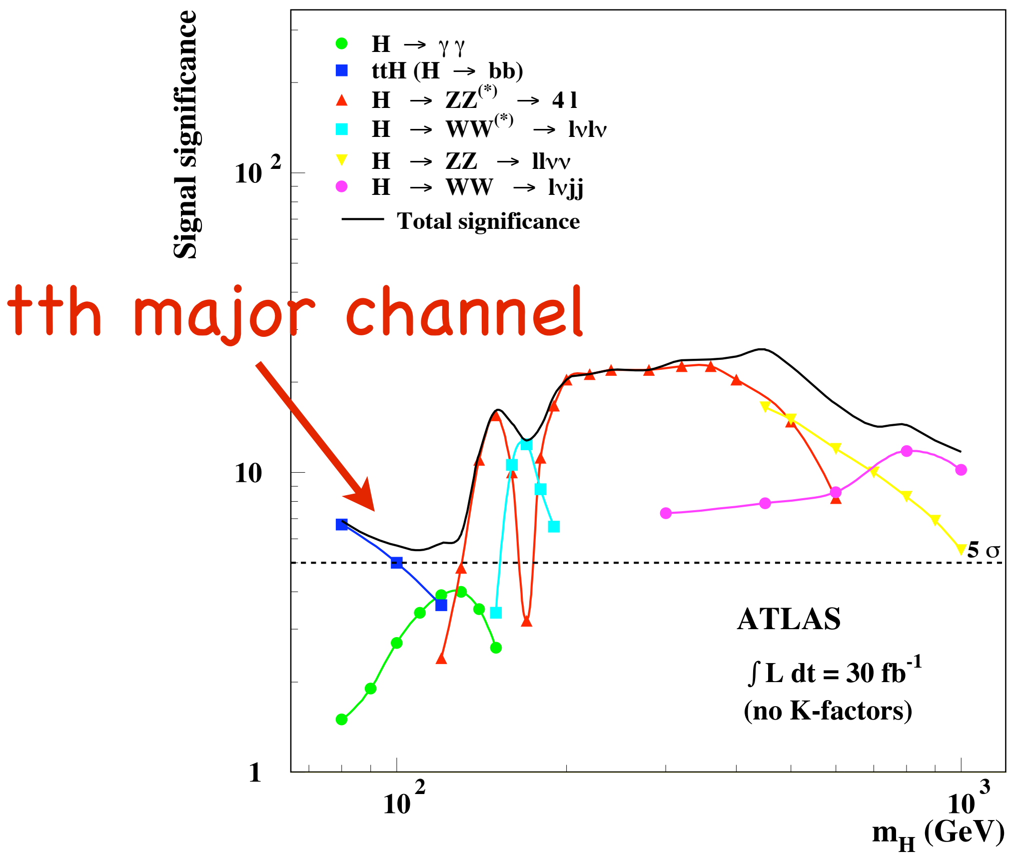
$$\sigma(pp \to t\bar{t}H) \times BR(H \to \gamma\gamma) \simeq 1.39 \text{ fb}$$

Phenomenology special as top decays before hadronization:

$1/m_t <$	$1/\Gamma_t <$	$1/\Lambda <$	m_t/Λ^2
Production time<	Lifetime <	Hadronization time <	Spin decorrelation time

I. tth with h -> bb

High expectations:



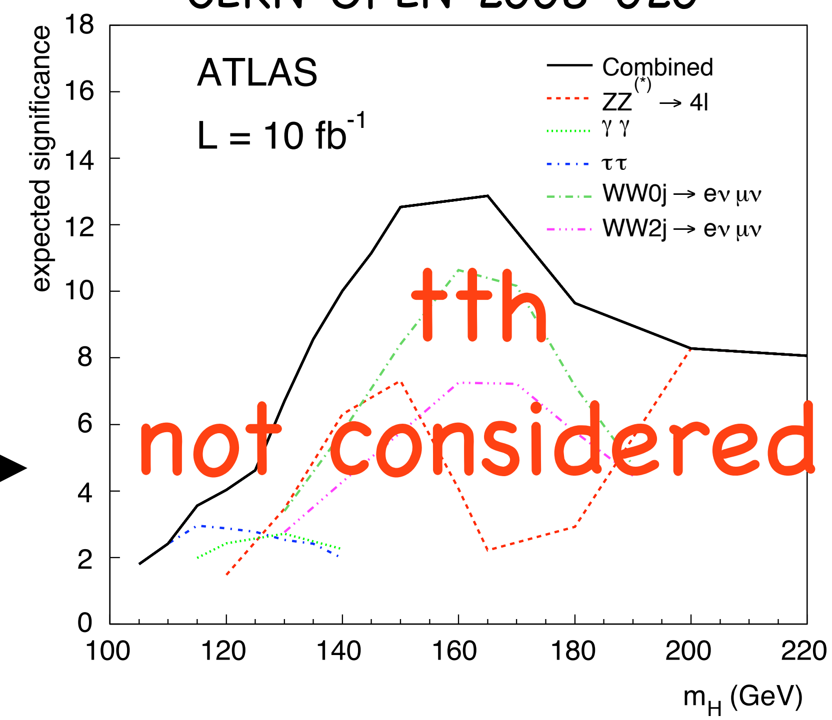
[ATLAS TDR 1999]

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

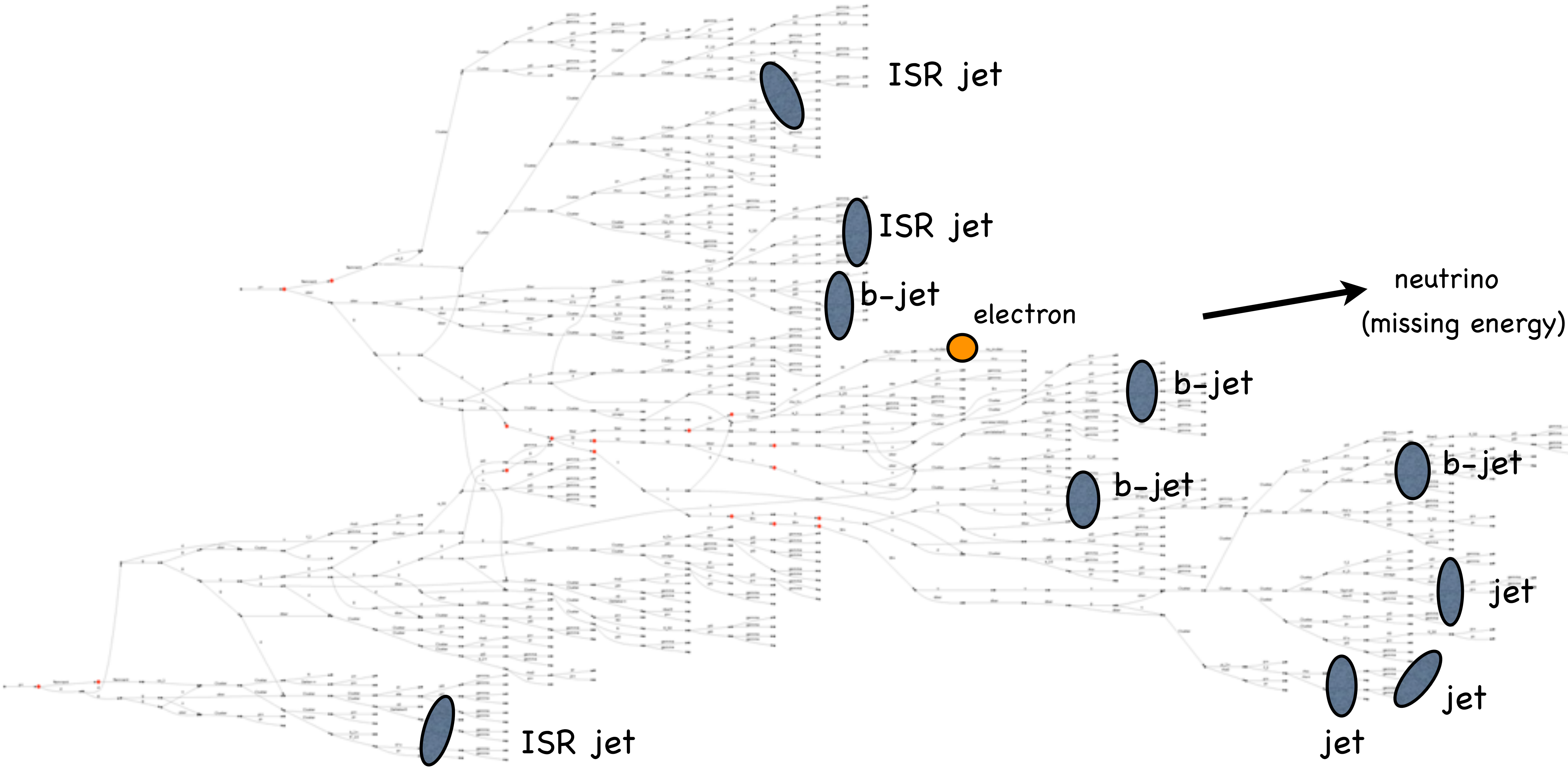


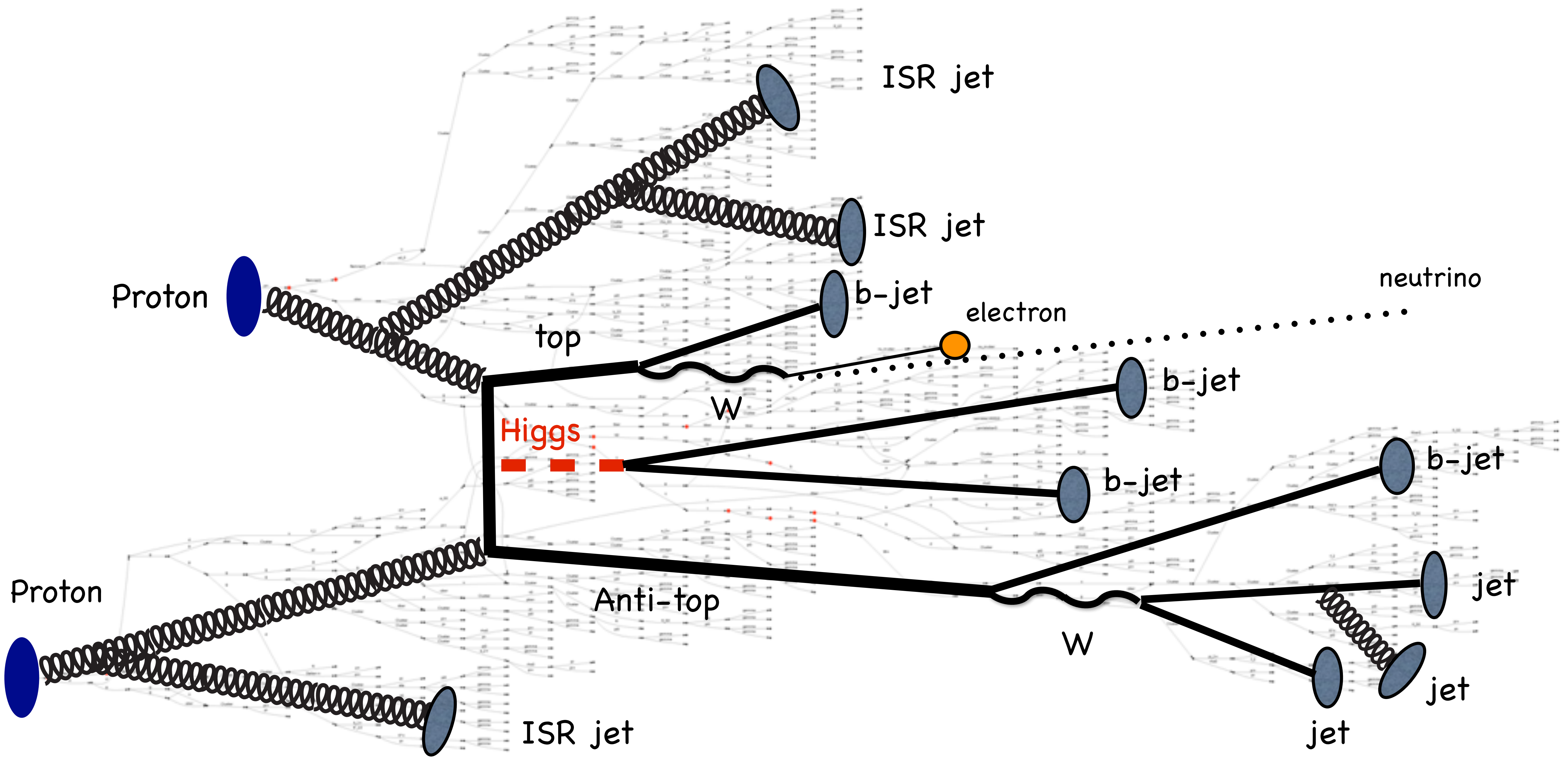
Problems of this channel:

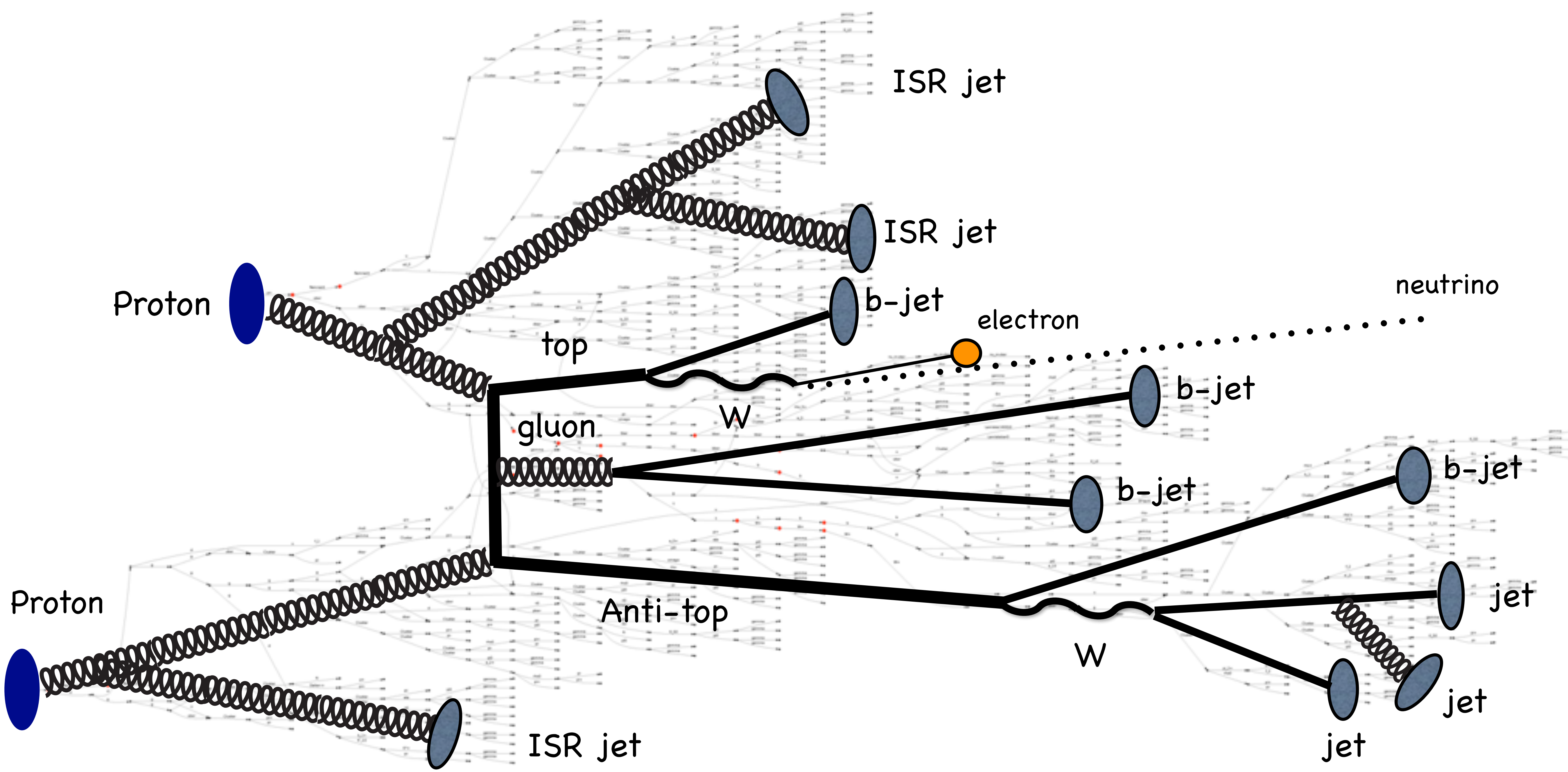
[Cammin and Schumacher, ATL-PHYS-2003-024]

- 4 b -> 6 combinations to reconstruct m_{bb}
- Low event reconst. efficiency due to lost decay prods.
- Systematics/Theory limited

Invers problem




ISR jet
ISR jet
Proton
b-jet
neutrino
electron
top
b-jet
W
Higgs
b-jet
b-jet
Proton
Anti-top
jet
W
jet
ISR jet
jet


ISR jet
ISR jet
Proton
b-jet
neutrino
electron
top
b-jet
W
gluon
b-jet
b-jet
Proton
Anti-top
jet
W
jet
ISR jet
jet

Challenging backgrounds in this channel

ttbb

[Bredenstein et al (2009), Bevilacqua et al (2009)]

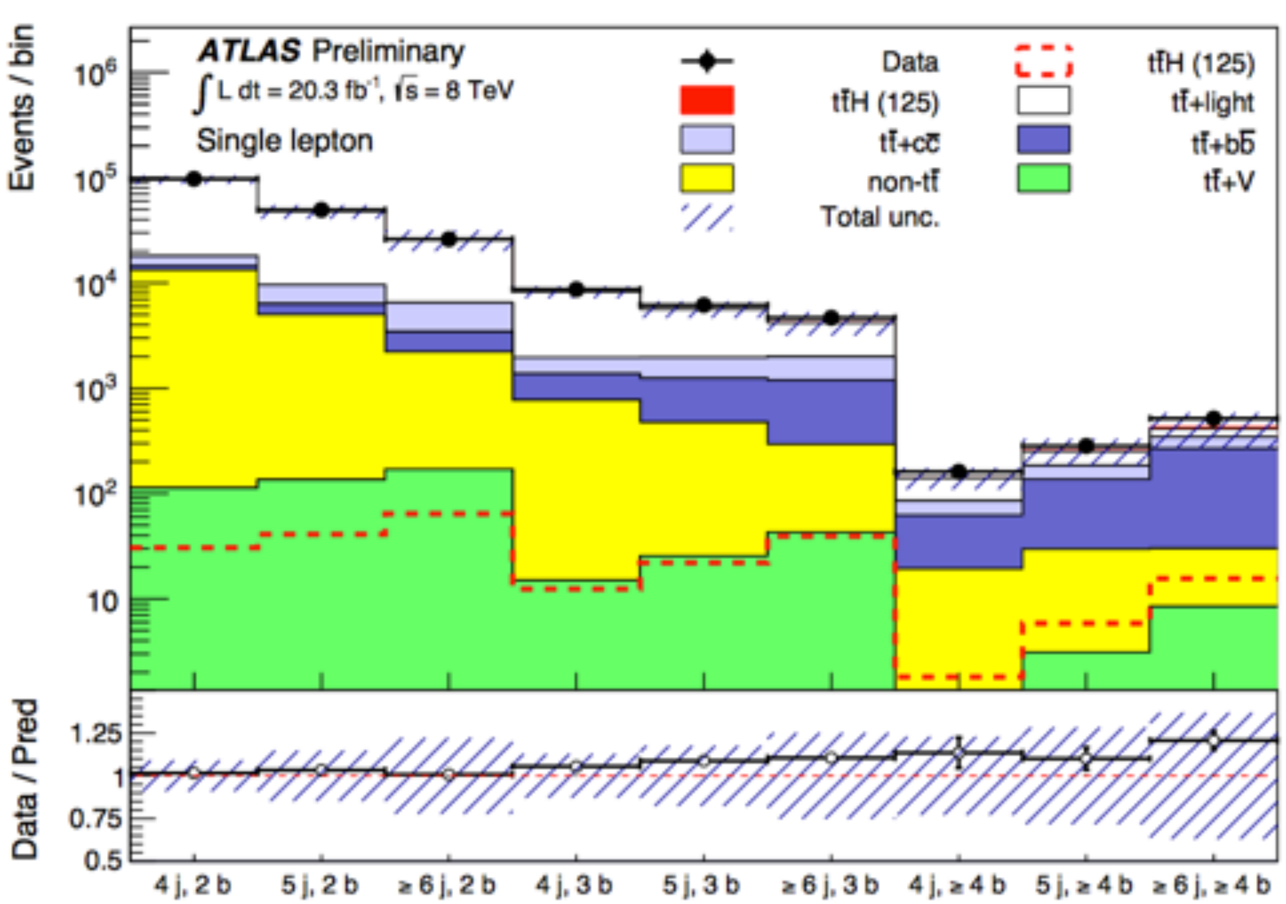
ttjj

[Bevilacqua et al (2009)]

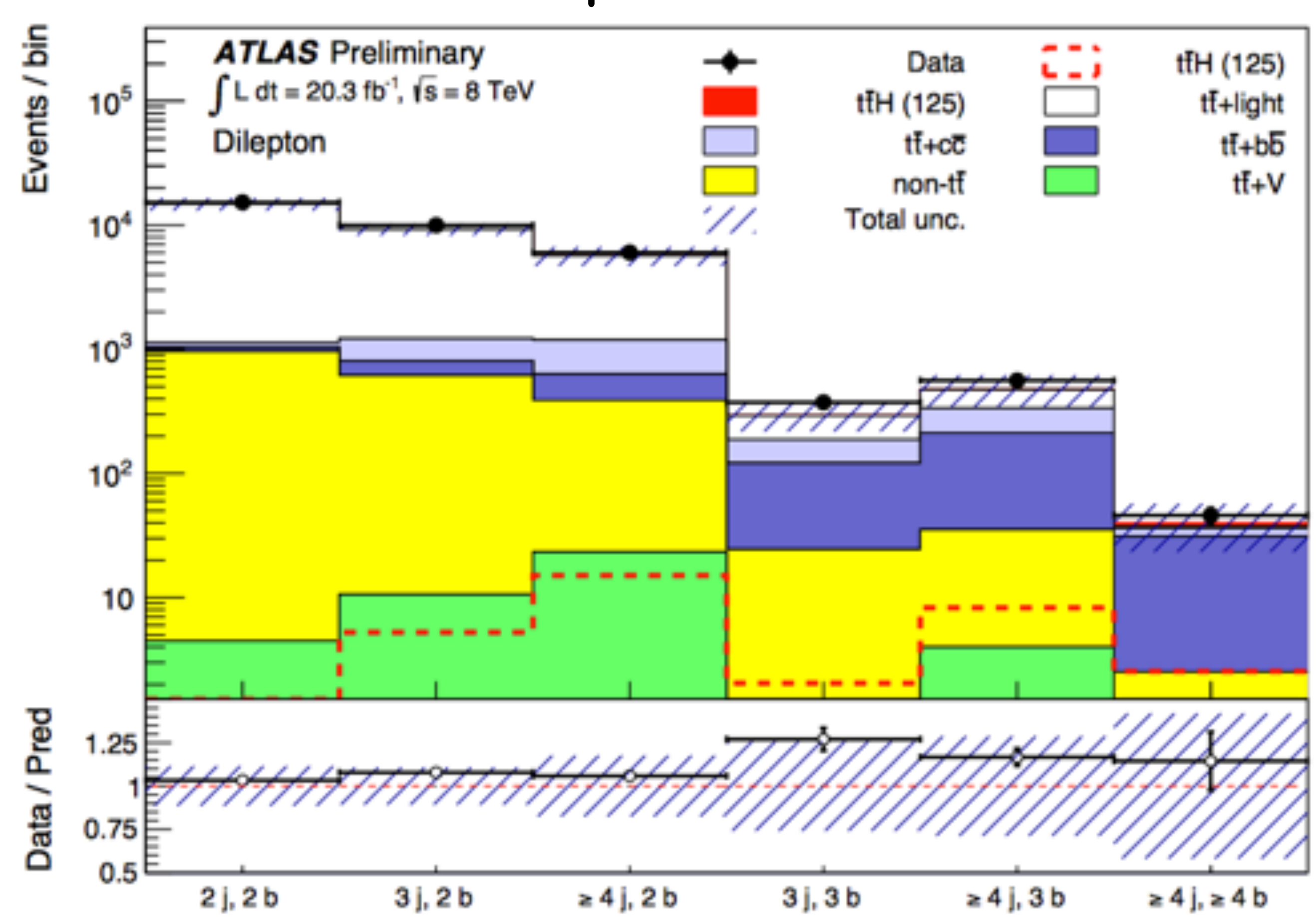
ttZ

[Lazopoulos et al (2008)]

single lepton channel



di-lepton channel

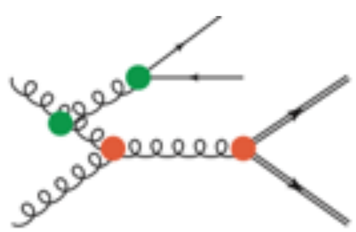


Challenging backgrounds in this channel

After b-tags and selection cuts major background ttbb:

- NLO calculations reduce uncertainty from 80% to 20-30%
- Collider analyses require matching to parton shower
  - Powheg matching to Pythia/Herwig, 5F-scheme (mb=0) [Kardos, Trocanyi (2013)]
  - S-MC@NLO matching to Sherpa, 4F-scheme (finite mb) [Cascioli et al (2013)]

multi-scale process $\sqrt{\hat{s}} \gg m_t, m_h, m_W \gg m_b$ $\longrightarrow$ scale choice tricky



CKKW inspired scale choice gives good perturbative convergence:

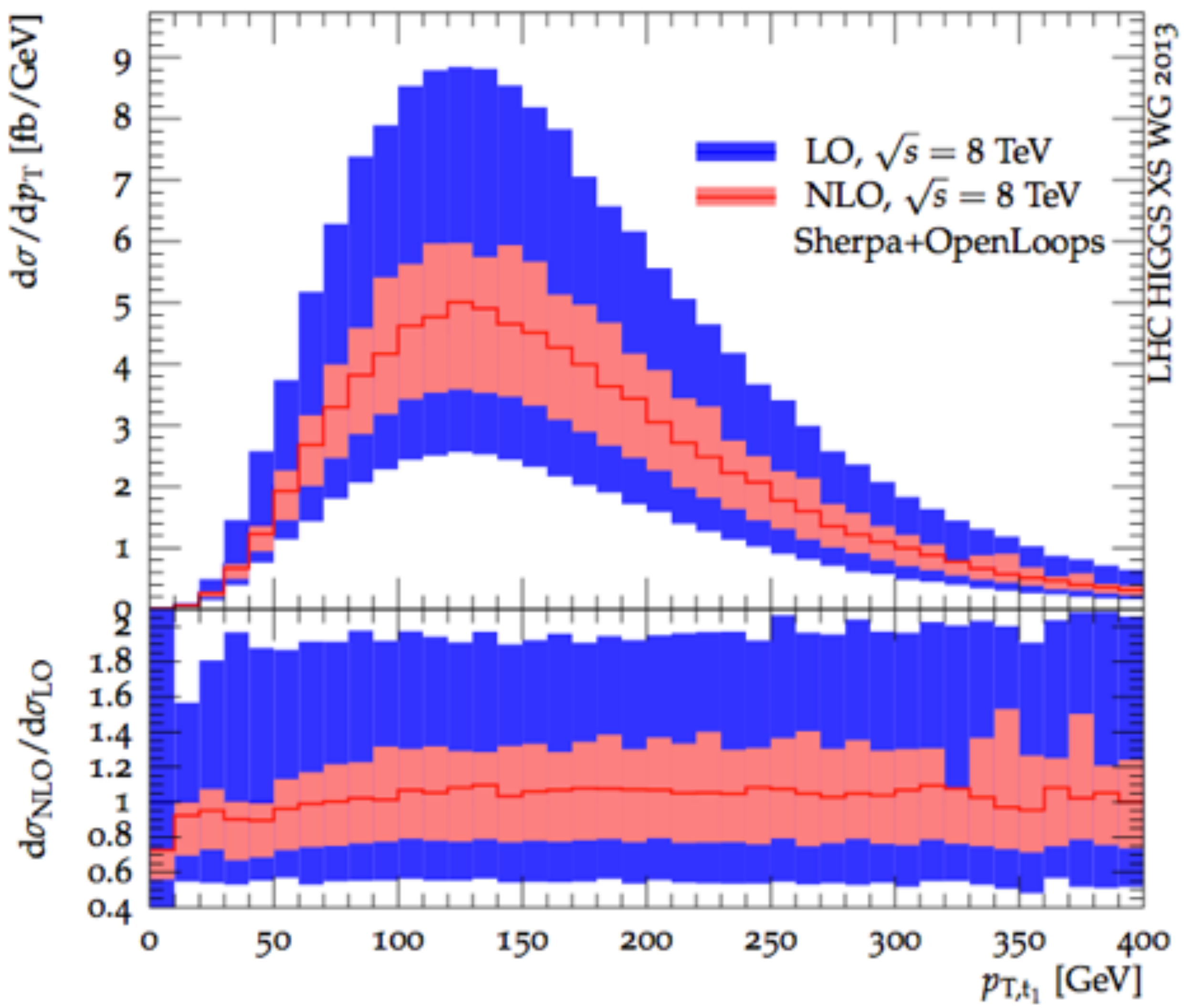
$$\mu_R^4 = E_{T,t} E_{T,\bar{t}} E_{T,b} E_{T,\bar{b}} \quad \Rightarrow \quad \alpha_S^4(\mu_R^2) = \alpha_S(E_{T,t}^2)\alpha_S(E_{T,\bar{t}}^2)\alpha_S(E_{T,b}^2)\alpha_S(E_{T,\bar{b}}^2)$$

	ttb	$ttbb$	$ttbb\,(m_{bb} > 100)$
σ_{LO}[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
σ_{NLO}[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.21	1.15
$\sigma_{MC@NLO}$[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{MC@NLO}/\sigma_{NLO}$	1.01	1.07	1.28

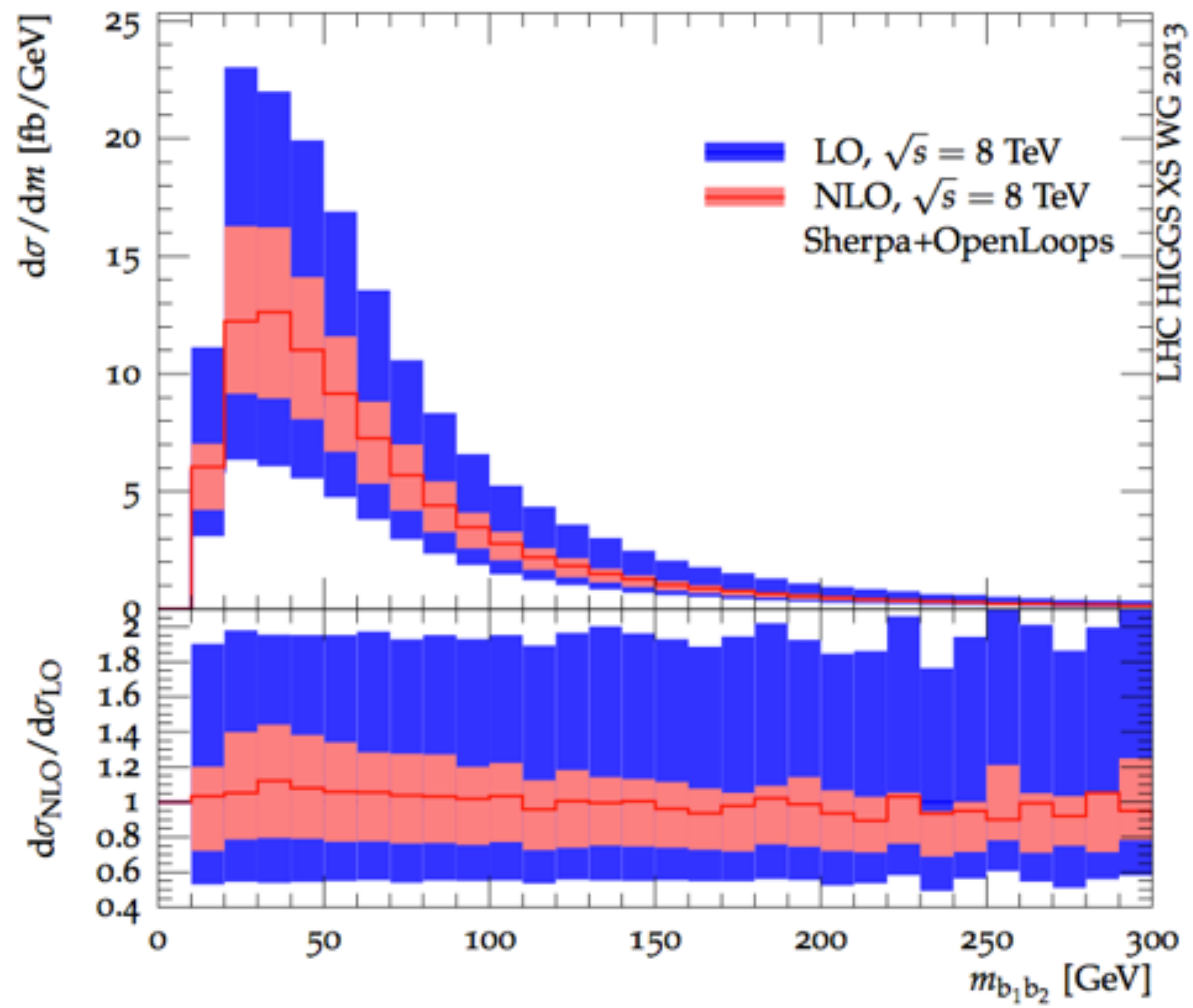
- Scale uncertainties mostly from μ_R
- K-factors moderate, though enhanced in signal region

MSTW2008 NLO(LO) 4F PDFs

Challenging backgrounds in this channel



LO -> NLO large improvements



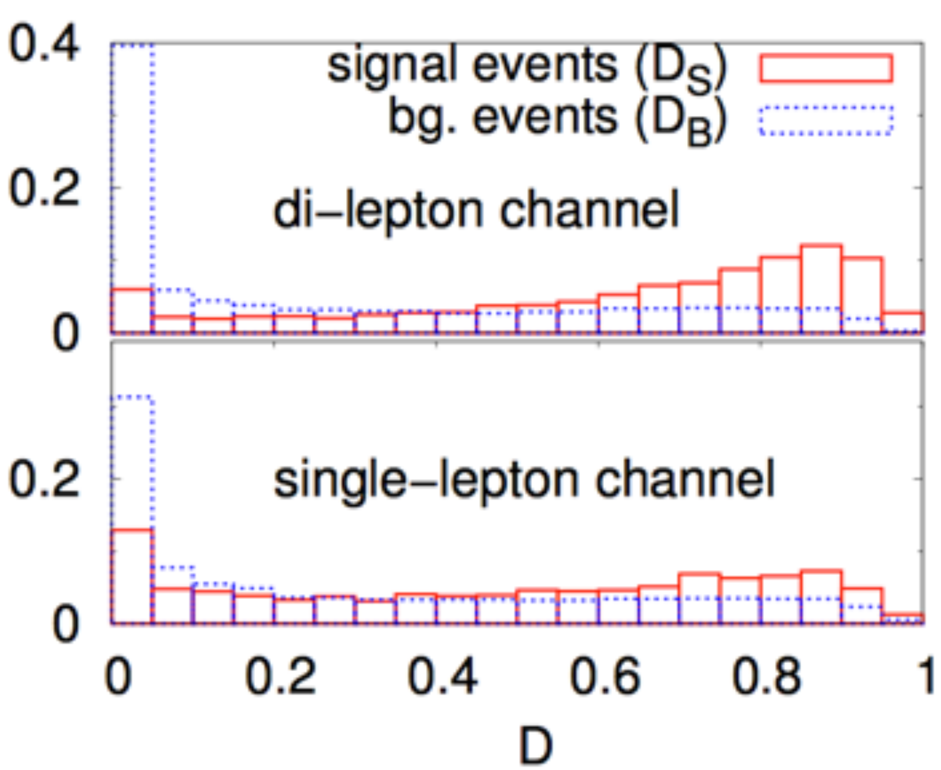
But still significant uncertainties

Which top decay mode is most sensitive?

[Artoisenet et al (2013)]

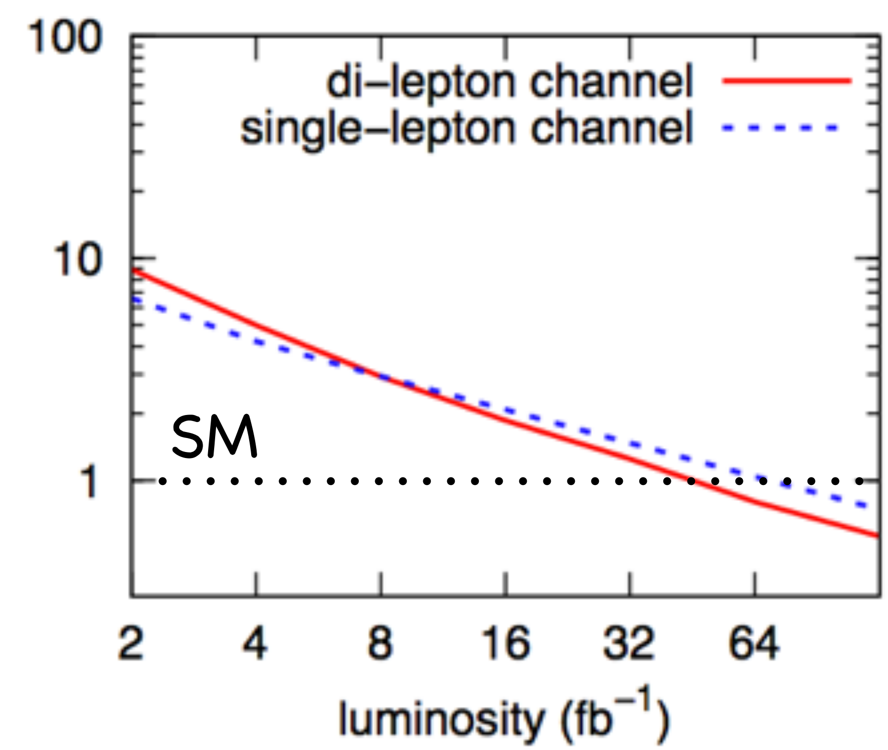
process	incl. σ	efficiency	$\sigma^{\rm rec}$
$t\bar{t}h$, single-lepton	111 fb	0.0485	5.37 fb
$t\bar{t}h$, di-lepton	17.7 fb	0.0359	0.634 fb
$t\bar{t}$+jets, single-lepton	256 pb	0.463×10^{-3}	119 fb
$t\bar{t}$+jets, di-lepton	40.9 pb	0.168×10^{-3}	6.89 fb

Analysis with 4 b-jets and std reconstruction as input to MEM



$$D_i = \frac{P(x_i|S)}{P(x_i|S) + P(x_i|B)}$$

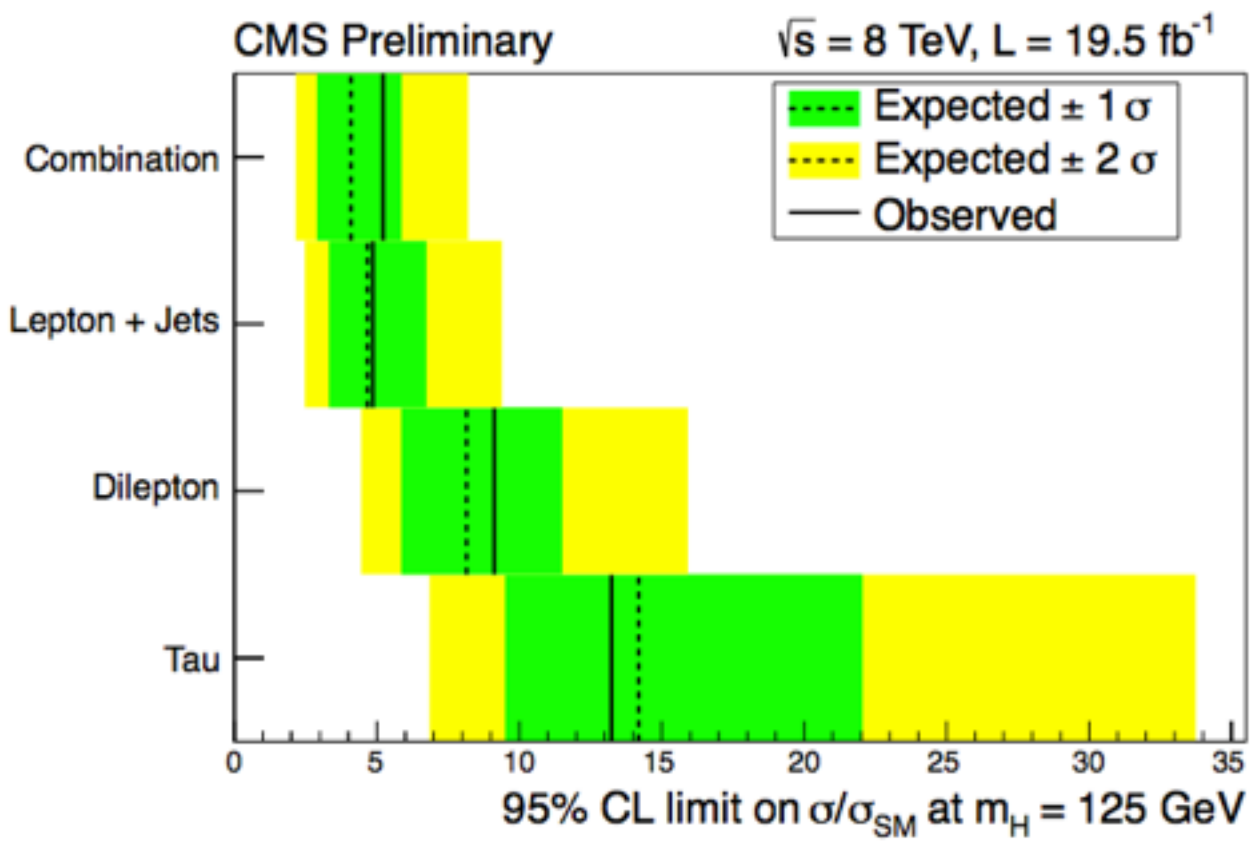
Projection at 14 TeV



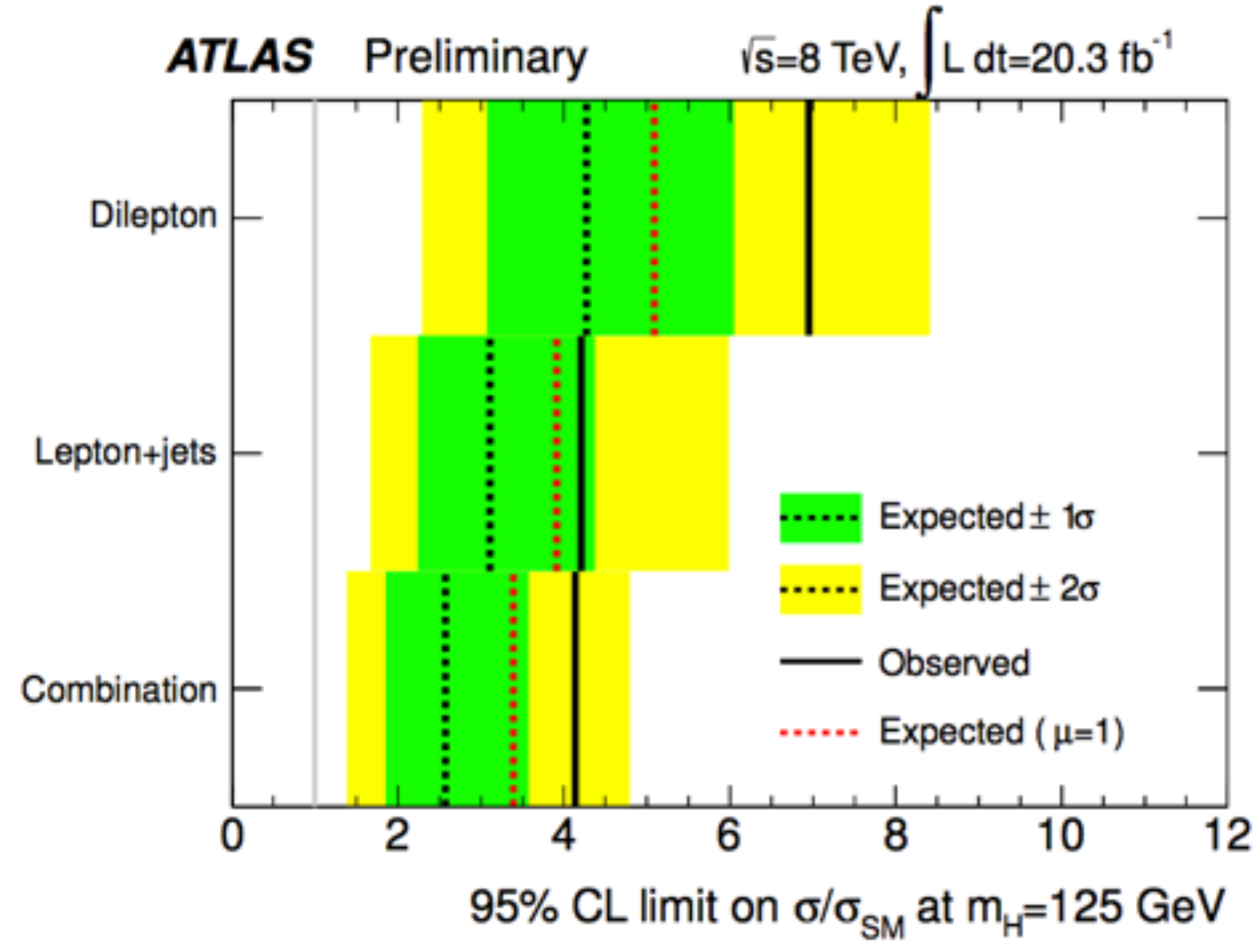
- Using Matrix Element Method di-lepton channel at least as or even more sensitive than single-lepton channel for standard input objects beyond ~ 8 ifb

Present results by CMS and ATLAS

based on BDT



based on Neural Net



- Both experiments are sensitive at X-times the SM cross section. However, because channel systematics limited X > 3 is not the challenge
- Recent progress in ttbb and tt+jets will reduce uncertainty in background but what we really want to measure coupling is a **side-band analysis** …

To relax sensitivity on overall Signal and BKG normalization we want this situation:

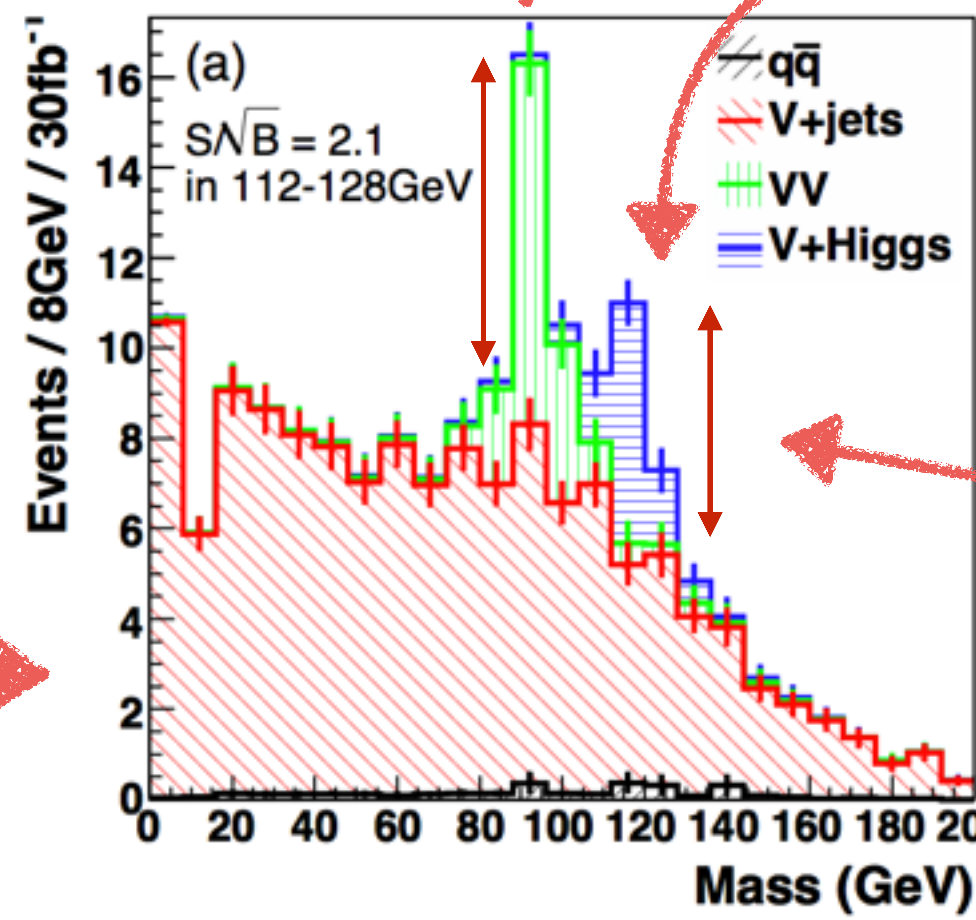
[Butterworth et al (2008)]

Peak of resonance we know the coupling well

Narrow, well separated signal peak

otherwise continuous background

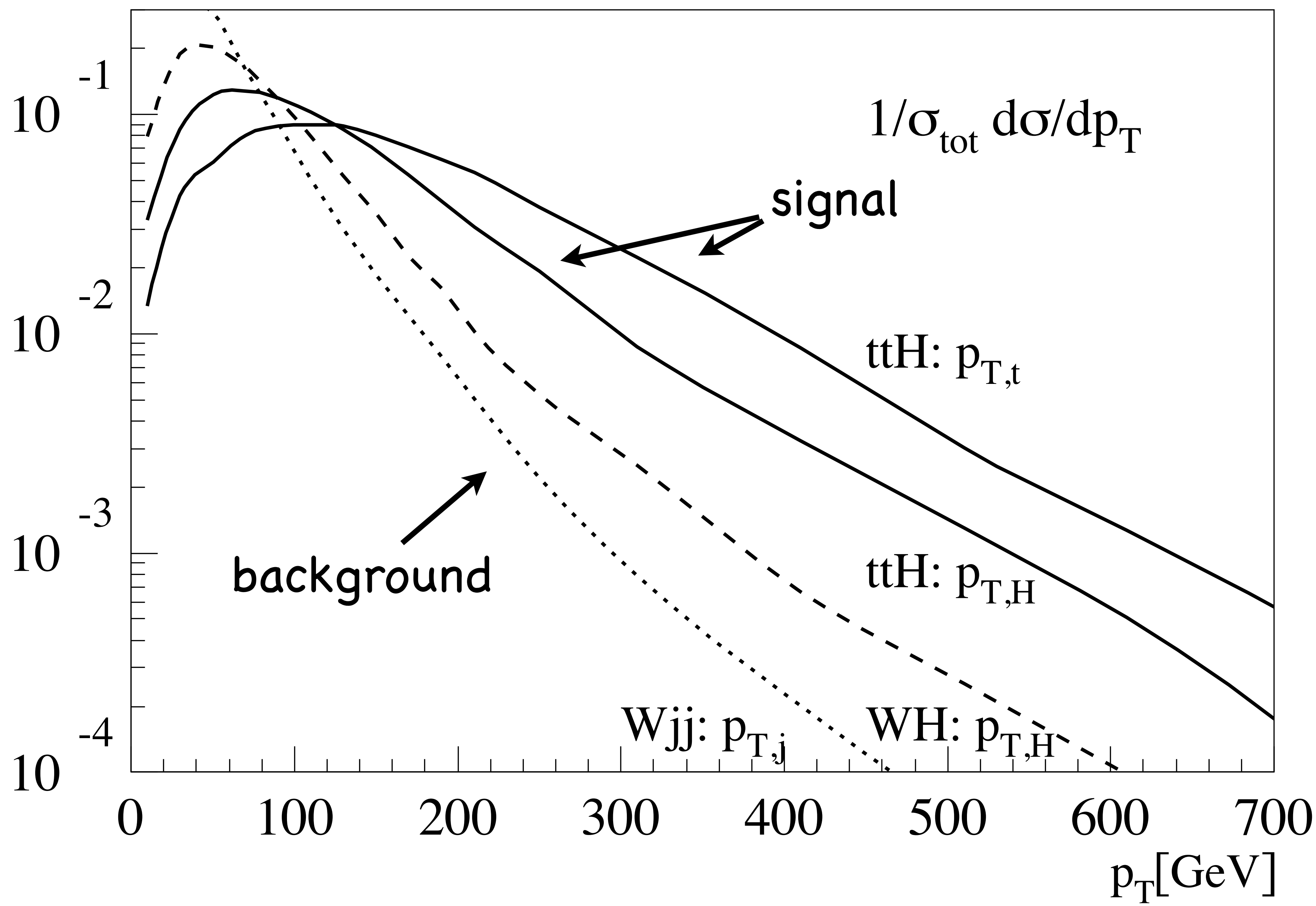
Compare peak height of known and new resonance



- Need reconstruction which gives narrow mbb for resonance
- Need reconstruction that does NOT introduce scale
- Need reconstruction that has same eff. for Z as for H

Can we repeat success of BDRS study in tth?

pT distributions relevant for tth



Problems in event reconstruction:

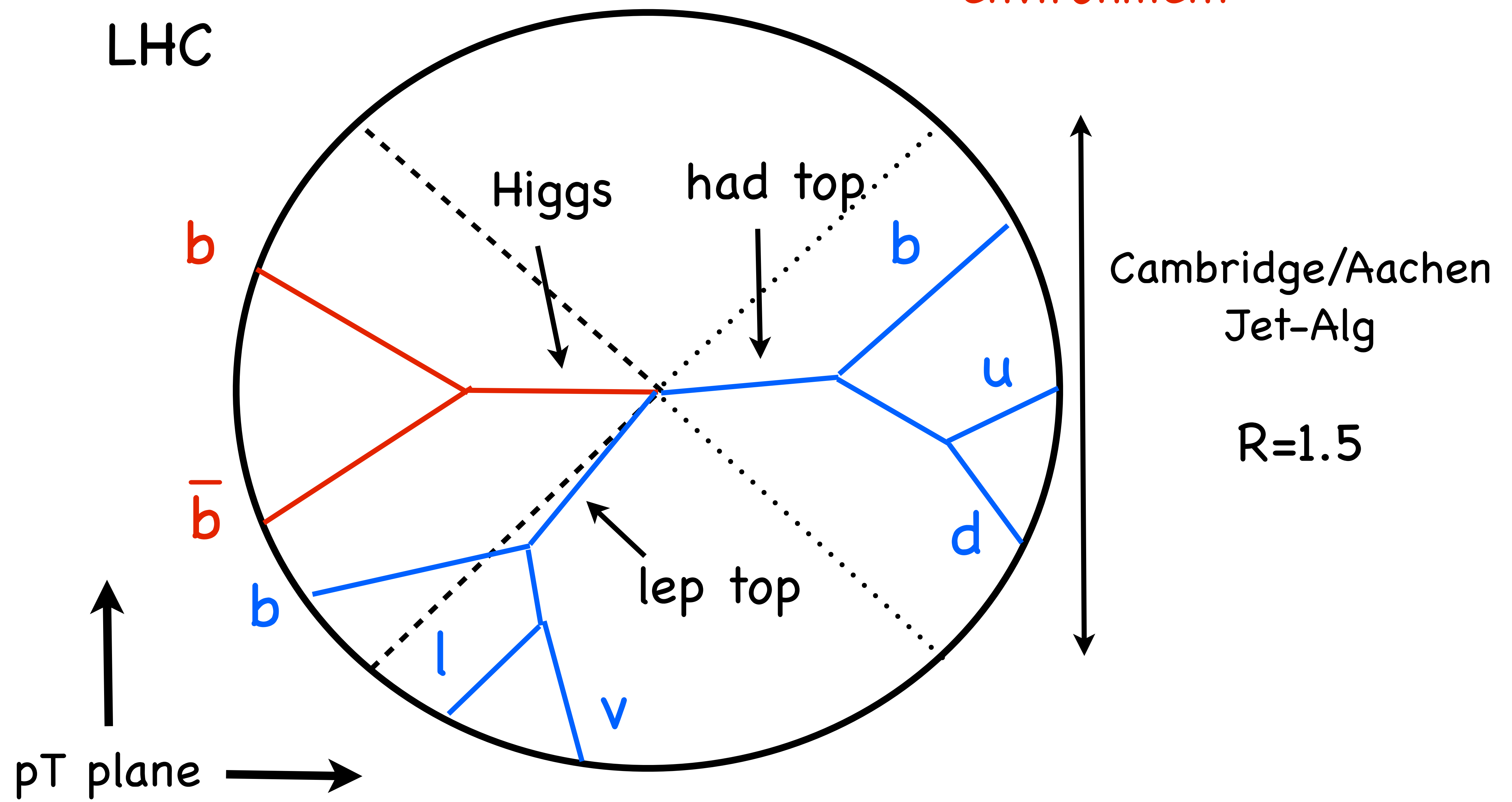
- (b-)jet multiplicity
- reconstruction efficiency

Boost should help

but

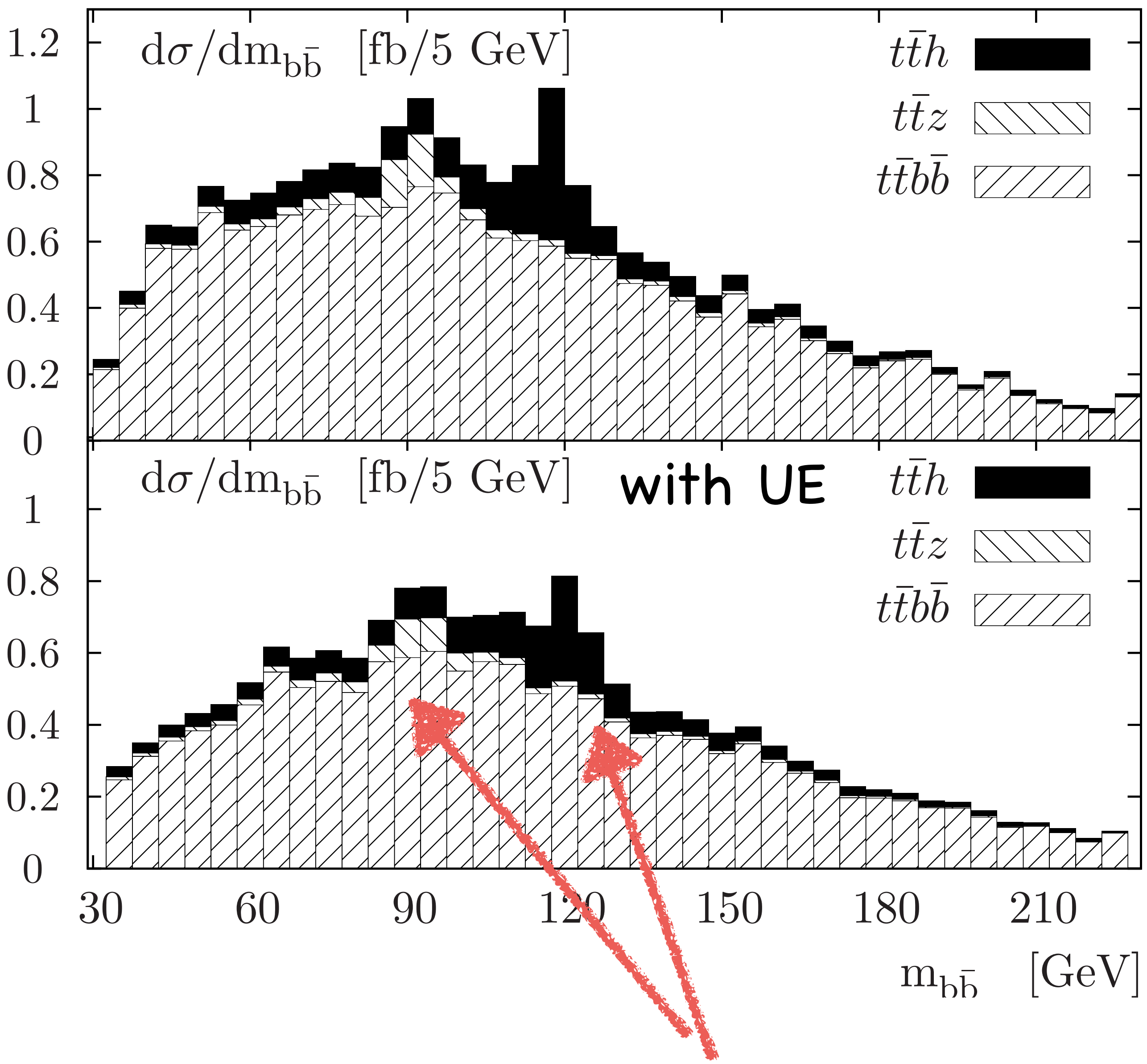
need tagger for this environment

LHC



Results for boosted tth in h->bb

[Plehn at al (2010)]



- 5 sigma sign. with 100 1/fb
- Development of Higgs and top tagger for busy final state
  - Jet substructure methods well established by now
  - HEPTopTagger designed for tth used by ATLAS and CMS
- Improvement of S/B from 1/9 to 1/2

- We find Higgs peak next to Z peak on top of continuous background
- Boosted topology ameliorates problems with combinatorics
- Possible further improvements due to top polarization [Biswal et al (2014)]

II. tth with h -> WW

- Worth measuring in its own right, as in ratio

$$\frac{\sigma(t\bar{t}H)\times \mathrm{BR}(H\to b\bar{b})}{\sigma(t\bar{t}H)\times \mathrm{BR}(H\to WW)} \simeq \frac{g^2_{Hbb}}{g^2_{HWW}}$$

many systematics cancel

- W-rich final state $W^+W^-W^+W^-b\bar{b}$ can be separated in lepton multiplicity of final state [Maltoni et al (2002)]

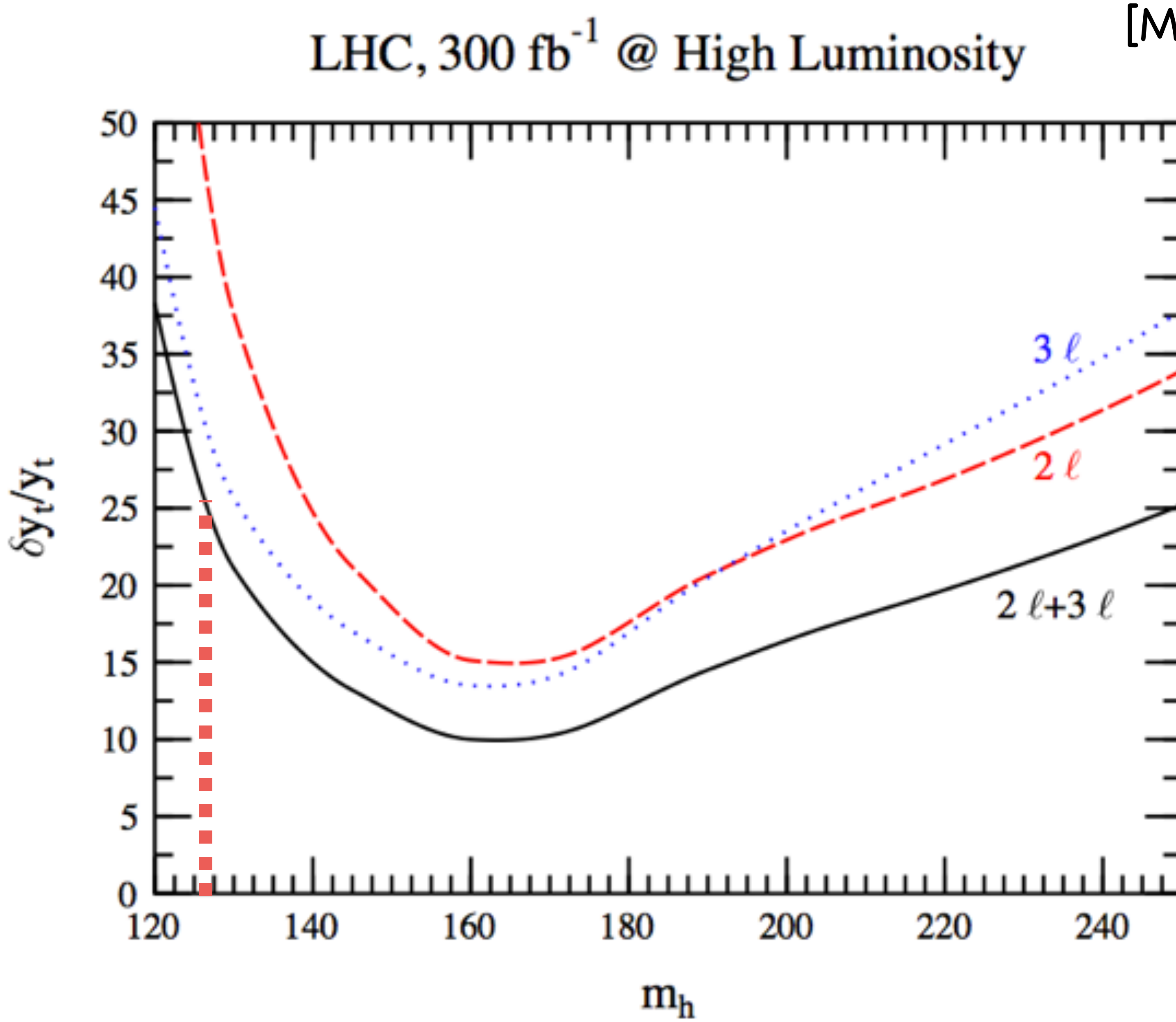
j	$p^T > 15\,(30)$ GeV	$\vert\eta\vert < 4.5$
b	$p^T > 15\,(30)$ GeV	$\vert\eta\vert < 2.5$
l	$p^T > 10$ GeV	$\vert\eta\vert < 2.5$
Trigger lepton: $p^T > 20\,(30)$ GeV		
$\Delta R_{ij} > 0.4$		

→

for 300 ifb

	$t\bar{t}h$			backgrounds				
m_h (GeV)	130	160	190	$t\bar{t}W^{\pm}jj$	$t\bar{t}\ell^+\ell^-(jj)$	$t\bar{t}W^+W^-$	$t\bar{t}t\bar{t}$	B
2ℓ	8.1	24	16	19	3.2	2.1	4.2	29
3ℓ	12	27	16	4.6	17	1.8	3.6	27
4ℓ	2.1	3.8	2.0	—	3.9	0.21	0.20	4.3

[Maltoni et al (2002)]



Combination indicates ~ 25% uncertainty measuring Htt with 300 ifb

III. tth with H -> WW and H -> taus

[Craig et al (2013)] and [Curtin et al (2013)] multi-lepton final states, incl taus

↳ special focus on same-sign leptons -> at 8 TeV found to be as sensitive as $H \to b\bar{b}$ and $H \to \gamma\gamma$

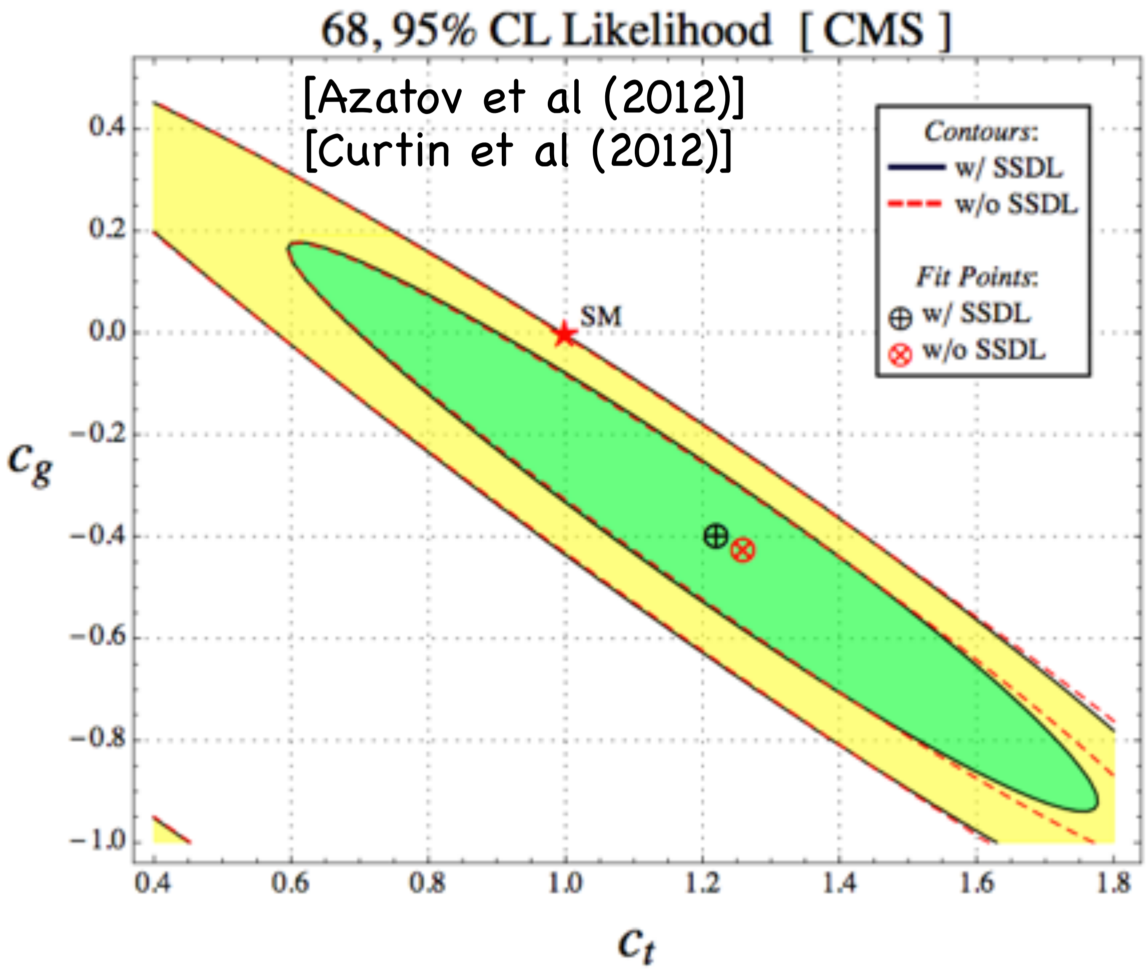
Study SSL final states for tth contribution: [CMS-SUS-12-017] 10 ifb

	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8
No. of jets	≥ 2	≥ 2	≥ 2	≥ 4	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
Lepton charges	$++/--$	$++/--$	$++$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$
E_T^{miss}	>0 GeV	>30 GeV	>30 GeV	>120 GeV	>50 GeV	>50 GeV	>120 GeV	>50 GeV	>0 GeV
H_T	>80 GeV	>80 GeV	>80 GeV	>200 GeV	>200 GeV	>320 GeV	>320 GeV	>200 GeV	>320 GeV
Fake BG	25 ± 13	19 ± 10	9.6 ± 5.0	0.99 ± 0.69	4.5 ± 2.9	2.9 ± 1.7	0.7 ± 0.5	0.71 ± 0.47	4.4 ± 2.6
Charge-flip BG	3.4 ± 0.7	2.7 ± 0.5	1.4 ± 0.3	0.04 ± 0.01	0.21 ± 0.05	0.14 ± 0.03	0.04 ± 0.01	0.03 ± 0.01	0.21 ± 0.05
Rare SM BG	11.8 ± 5.9	10.5 ± 5.3	6.7 ± 3.4	1.2 ± 0.7	3.4 ± 1.8	2.7 ± 1.5	1.0 ± 0.6	0.44 ± 0.39	3.5 ± 1.9
Total BG	40 ± 14	32 ± 11	17.7 ± 6.1	2.2 ± 1.0	8.1 ± 3.4	5.7 ± 2.4	1.7 ± 0.7	1.2 ± 0.6	8.1 ± 3.3
Event yield	43	38	14	1	10	7	1	1	9
N_{UL} (13% unc.)	27.2	26.0	9.9	3.6	10.8	8.6	3.6	3.7	9.6
N_{UL} (20% unc.)	28.2	27.2	10.2	3.6	11.2	8.9	3.7	3.8	9.9
N_{UL} (30% unc.)	30.4	29.6	10.7	3.8	12.0	9.6	3.9	4.0	10.5

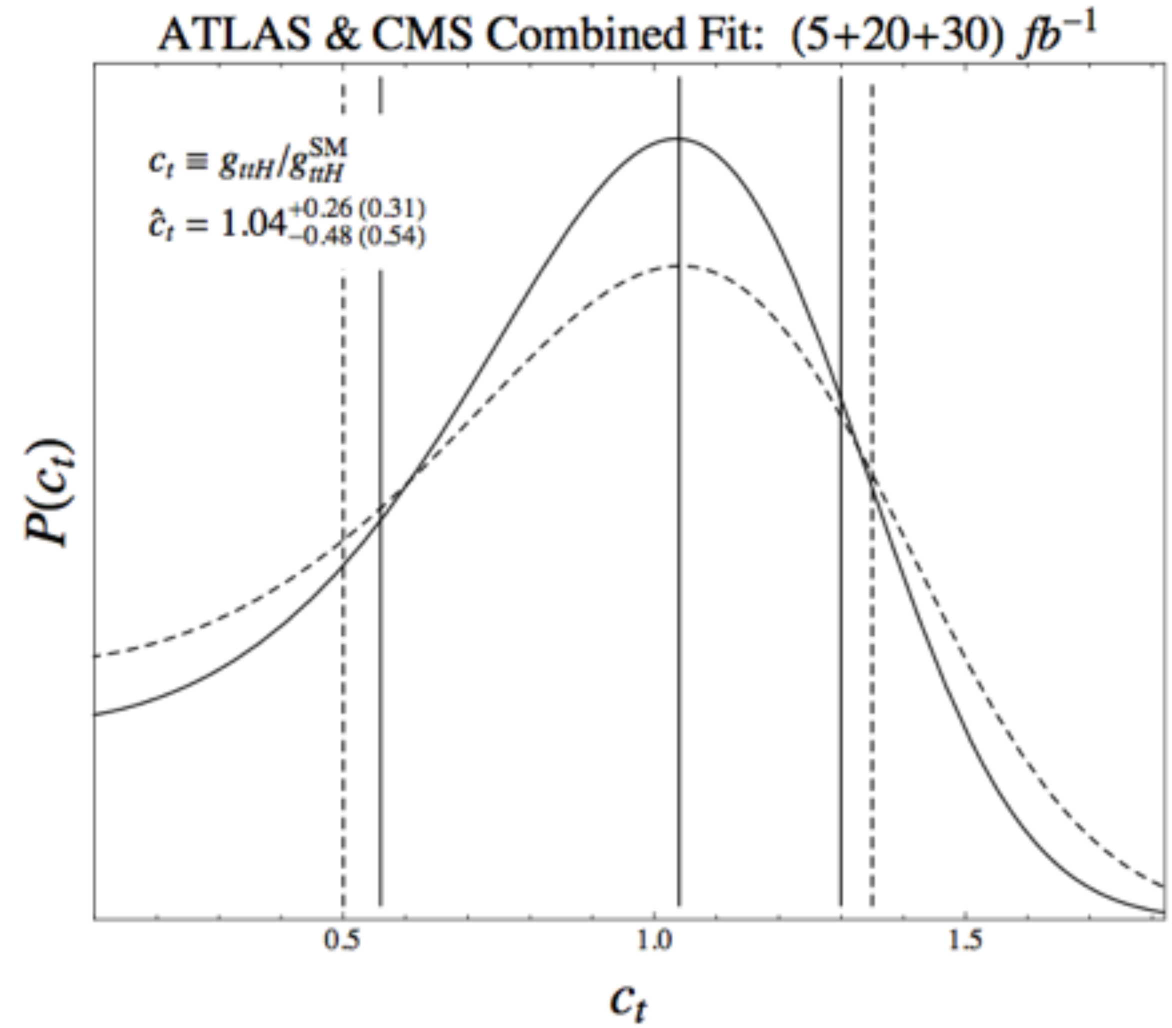
- Recast enhanced tth and set limit

→ $$\mu_{t\bar{t}h}(4b + \ell) \leq 5.8 \; (5.2)$$

Fit for 8 TeV data



Combination 7, 8 and 14 TeV



$$\Delta\mathcal{L}_{\rm eff} = \frac{h}{v} \times \left(c_t m_t \bar{t}t + c_g G^2_{\mu\nu}\right)$$

Advantage: tth coupling measurement disentangled from hbb, i.e.

$$\frac{\sigma(t\bar{t}H) \times {\rm BR}(H \to WW)}{\sigma(HW) \times {\rm BR}(H \to WW)} \simeq \frac{g^2_{Htt}}{g^2_{HWW}}$$

IV. tth with h -> hadronic-taus

- Signal process considered $t\bar{t}H \to b\bar{b}l\nu qq'\tau_h^+\tau_h^-$ [Belyaev et al (2002)]
- Only background electroweak $t\bar{t}Z$

	Background: $pp \to t\bar{t}\tau^+\tau^-$	Signal: $pp \to t\bar{t}H$, $H \to \tau^+\tau^-$			
		110 GeV	120 GeV	130 GeV	140 GeV
Eff. of CUTS I+II+III (%)	0.42	0.50	0.52	0.55	0.58
Number of events/100 fb^{-1}	12	34	25	16	8.8
$S/\sqrt{S+B}$		5.0	4.1	3.0	1.9
S/B		2.8	2.1	1.3	0.7
$\delta\sigma/\sigma$		0.20	0.24	0.33	0.52

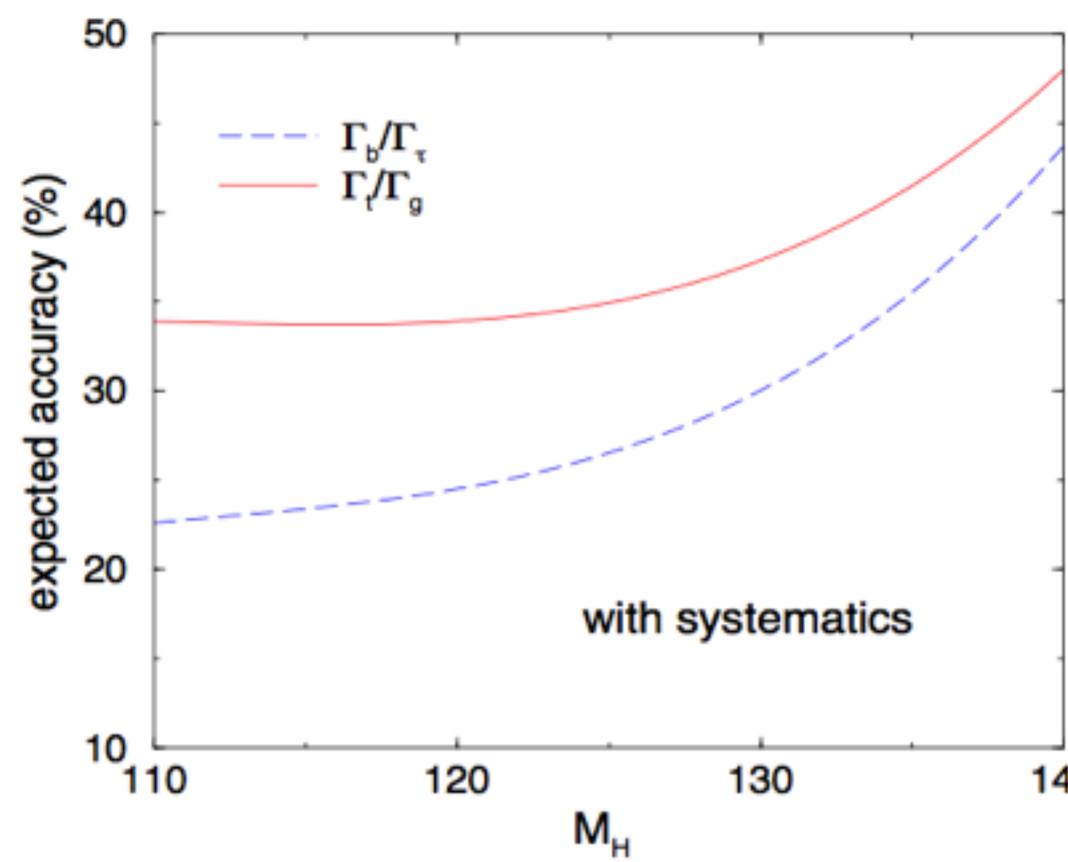
production

decay

$$\frac{\Gamma_b}{\Gamma_\tau} = \frac{Z_b^{(t)}}{Z_\tau^{(t)}}$$

$$\frac{\Gamma_t}{\Gamma_g} = \frac{Z_\tau^{(t)} Z_\gamma^{(w)}}{Z_\tau^{(w)} Z_\gamma^{(g)}}$$

Ratio of couplings can be measured, here very optimistic uncertainties

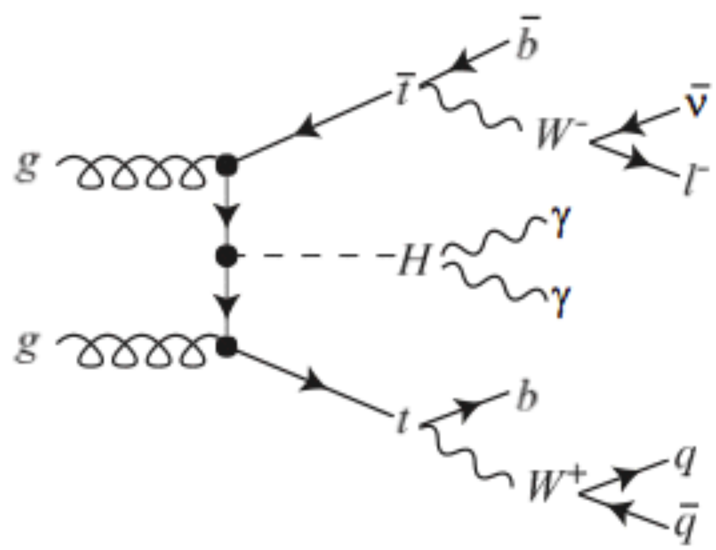


Also possible:
Separate GF and WBF and take

$$\frac{\sigma(t\bar{t}H) \times \mathrm{BR}(H \to \tau\tau)}{\sigma(Hjj) \times \mathrm{BR}(H \to \tau\tau)} \simeq \frac{g^2_{Htt}}{(X\ g^2_{HWW} + Y\ g^2_{HZZ})}$$

V. tth with $H \to \gamma\gamma$

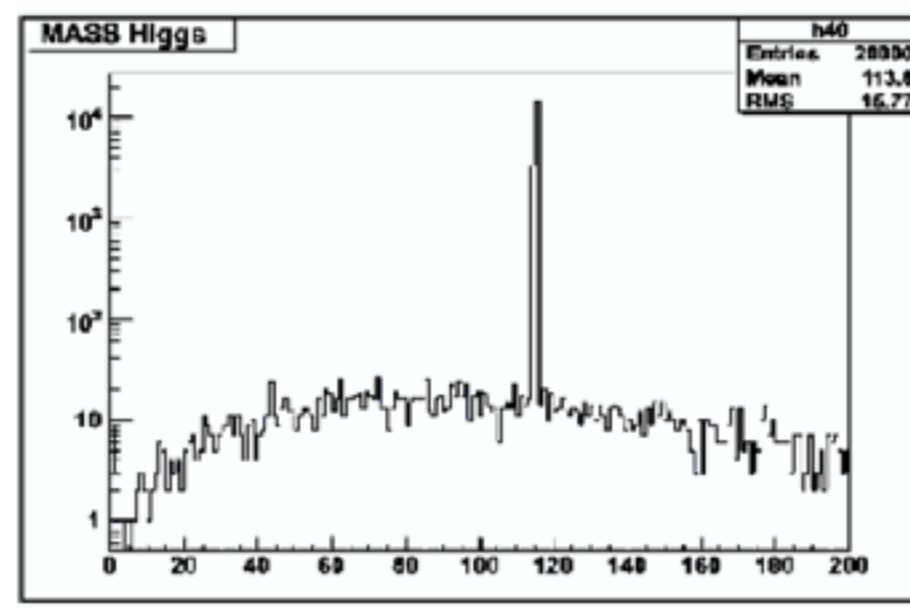
[Buttar et al. (2006)]



with 14 TeV and 100 ifb

Higgs Mass (GeV)	115	120	130	140
Signal Selection Efficiency (%)	19.09	20.78	24.65	25.58
Number Signal Evts (N_S)	13.2	13.5	13.1	9.5
$t\bar{t}\gamma\gamma$ Type 1	0.57	0.38	0.48	0.53
$t\bar{t}\gamma\gamma$ Type 2	0.3	0.5	0.3	0.5
$t\bar{t}\gamma\gamma$ Type 3	<0.5	0.5	<0.5	<0.5
$Z\gamma\gamma$	0.8	0.7	0.8	0.5
$W\gamma\gamma4j$	1.5	3.0	6.2	4.7
$bb\gamma\gamma$	<0.2	0.2	0.2	< 0.2
Total Number Background Evts.(N_B)	3.17	5.28	7.98	6.23
Signal Significance	7.41	5.88	4.64	3.81
$W\gamma\gamma$	1.25	1.35	1.23	1.27

- Good significance after 100 ifb for SM value
- However, variation of htt partly compensated by destructive interference with W loop in decay
- No other peak to compare

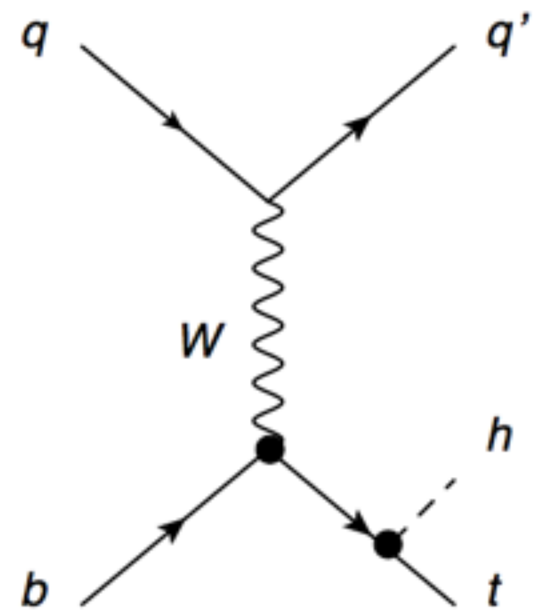


top-Higgs associated production

Three SM-like production processes:

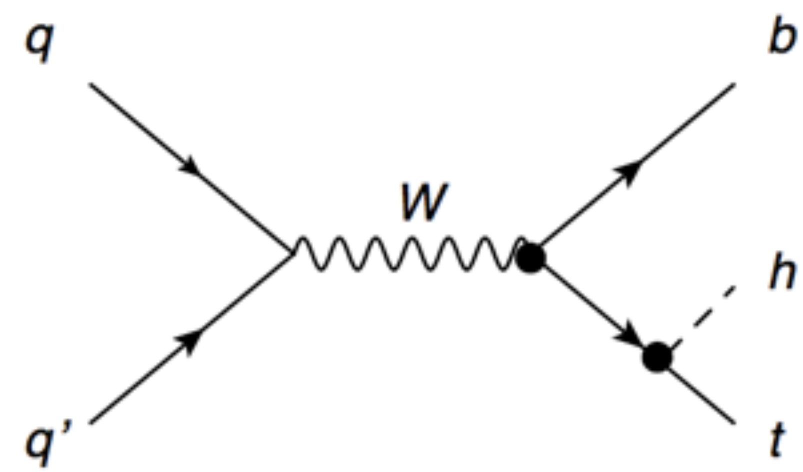
[Maltoni et al (2001)]
[Biswas et al (2002)]

t-channel



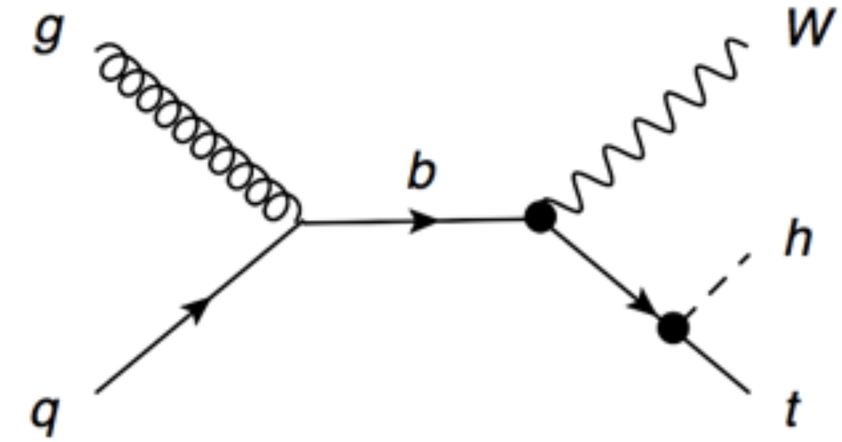
$$\sigma(q\,b \to t\,q'H)^{SM} \simeq 71.8 \text{ fb}$$
$$\sigma(q\,b \to t\,q'H)^{C_t=0} \simeq 276. \text{ fb}$$
$$\sigma(q\,b \to t\,q'H)^{C_t=-1} \simeq 893. \text{ fb}$$

s-channel



$$\sigma(q\,\bar{q}' \to t\,b\,H)^{SM} \simeq 2.26 \text{ fb}$$
$$\sigma(q\,\bar{q}' \to t\,b\,H)^{C_t=0} \simeq 1.49 \text{ fb}$$
$$\sigma(q\,\bar{q}' \to t\,b\,H)^{C_t=-1} \simeq 0.39 \text{ fb}$$

tW-associated channel

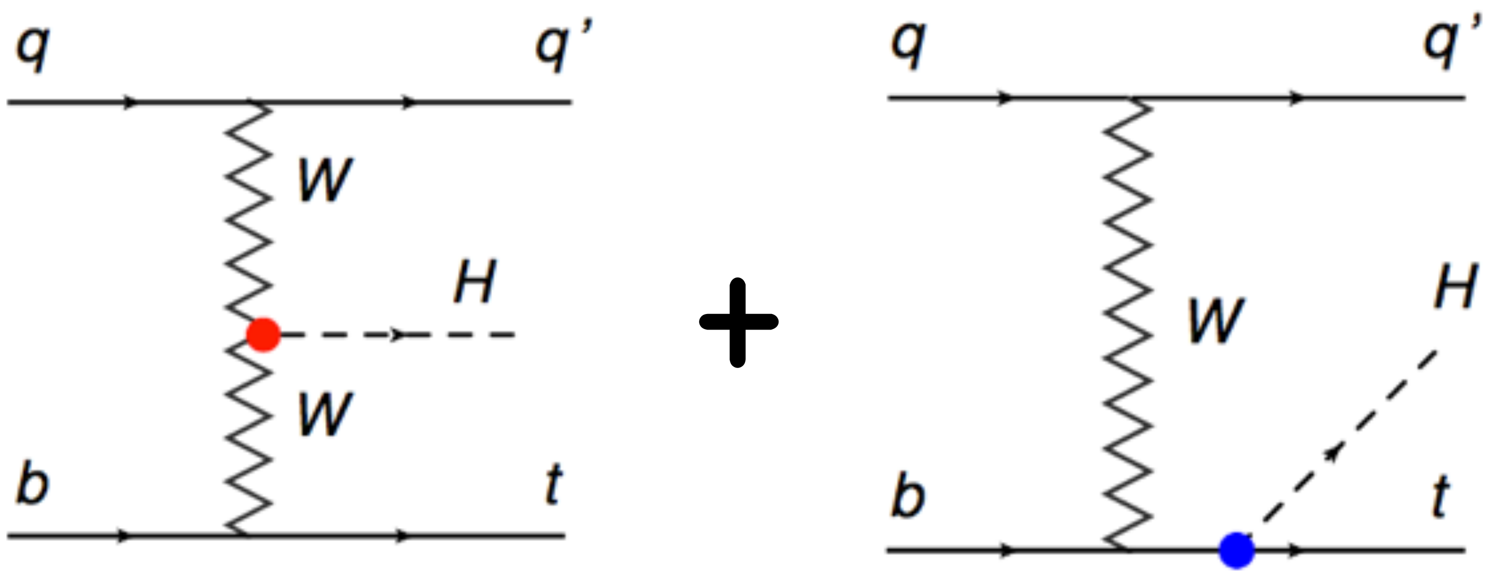


$$\sigma(g\,b \to WtH)^{SM} \simeq 16.0 \text{ fb}$$
$$\sigma(g\,b \to WtH)^{C_t=0} \simeq 34.9 \text{ fb}$$
$$\sigma(g\,b \to WtH)^{C_t=-1} \simeq 139. \text{ fb}$$

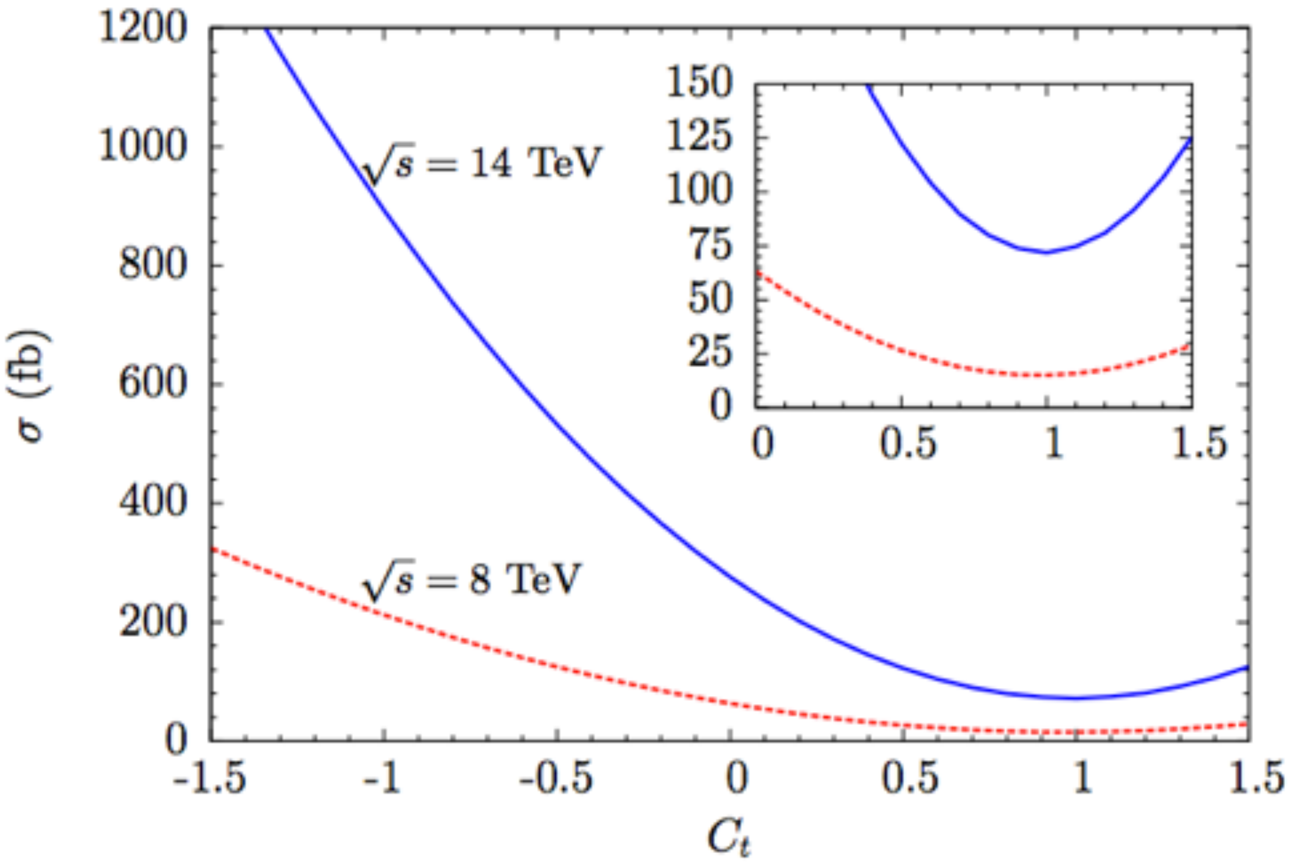
- Largest CS t-channel, despite negative interference between Higgs emission off top or W

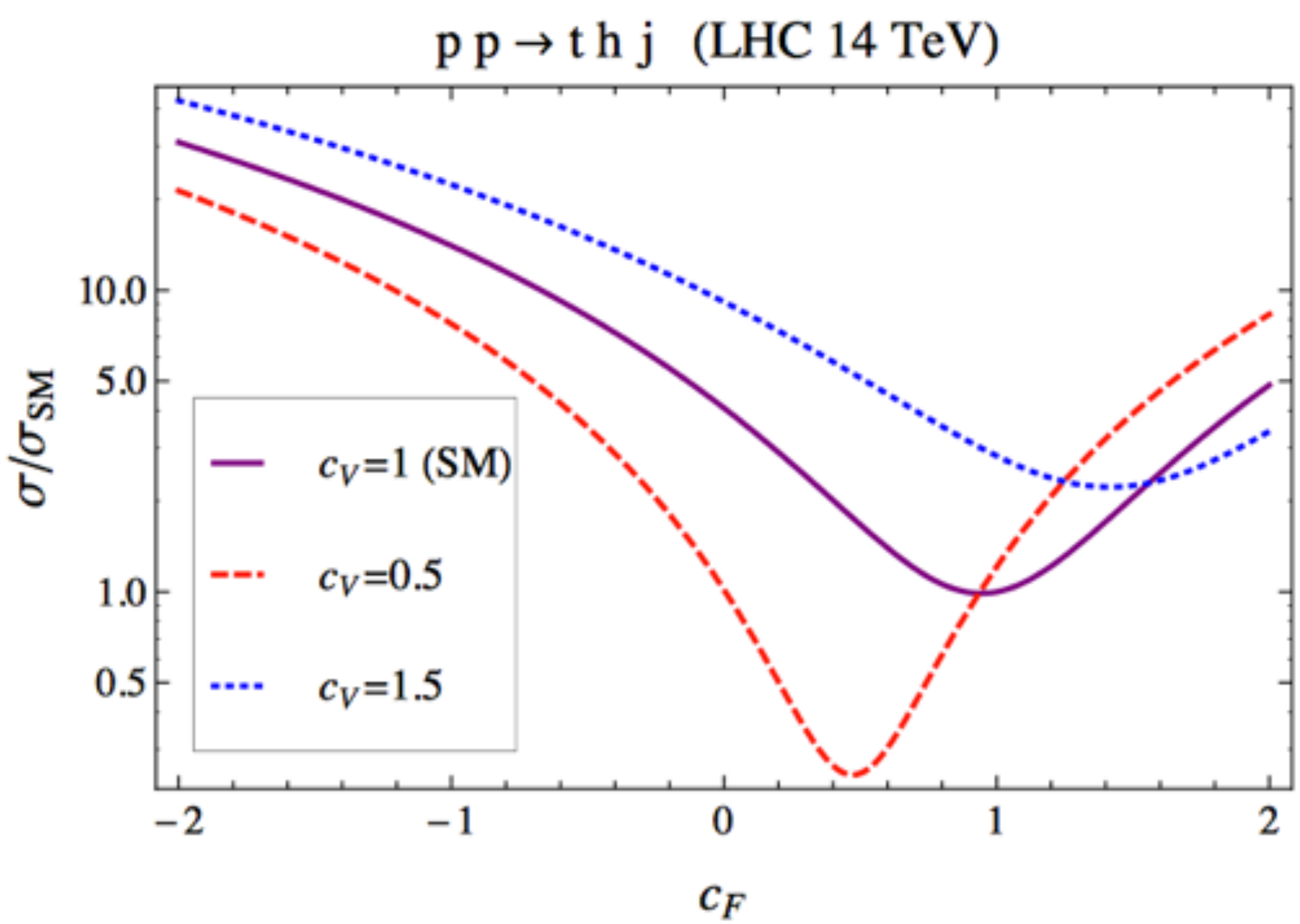
- However, this strong interference results in sensitivity of sign of Htt coupling

Total rate very sensitive to interplay between C_t and C_V

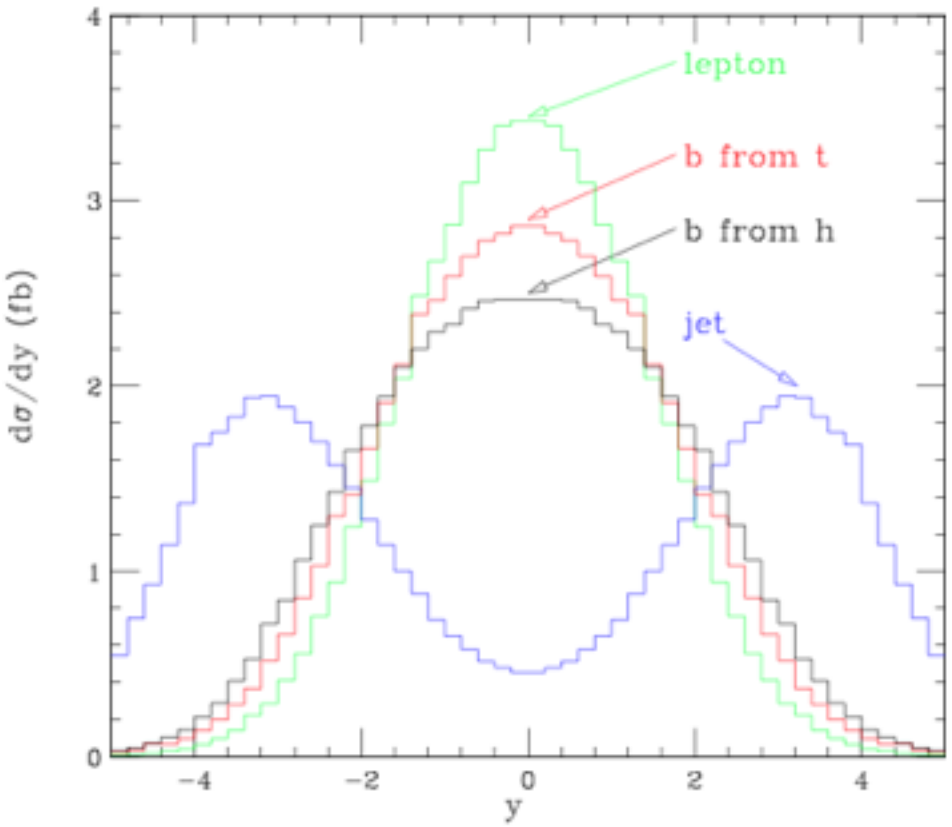


[Grojean et al (2013)]





Beyond total rates



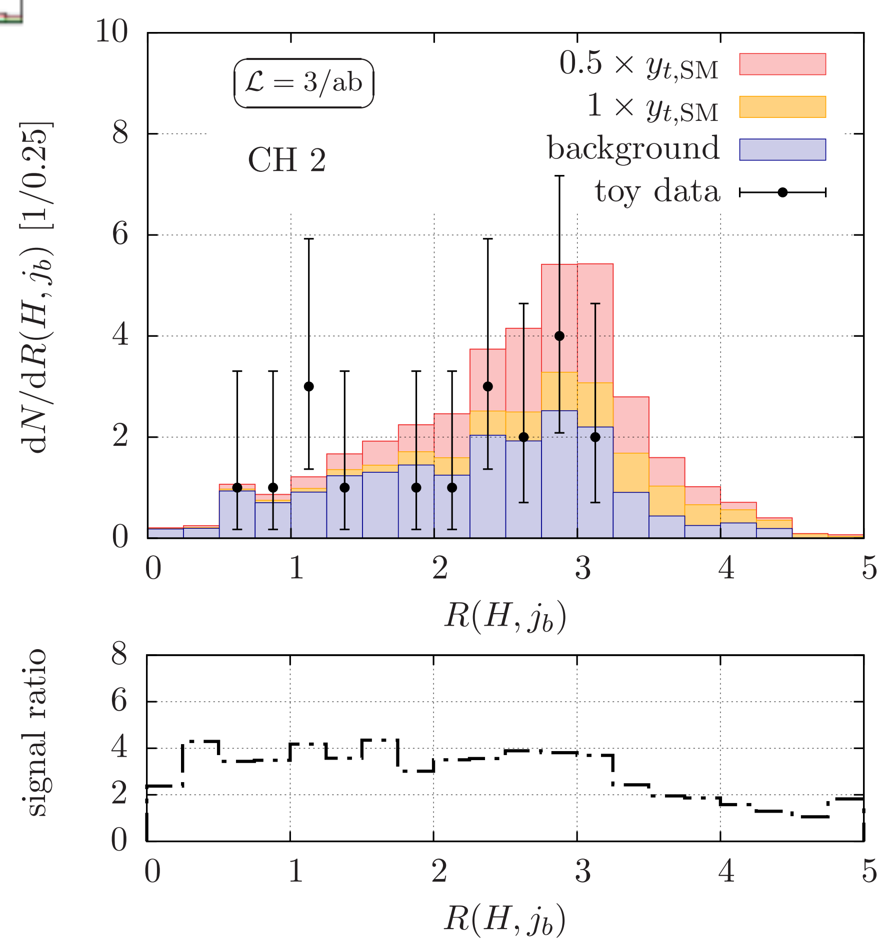
Distinctive kinematic features due to forward jet

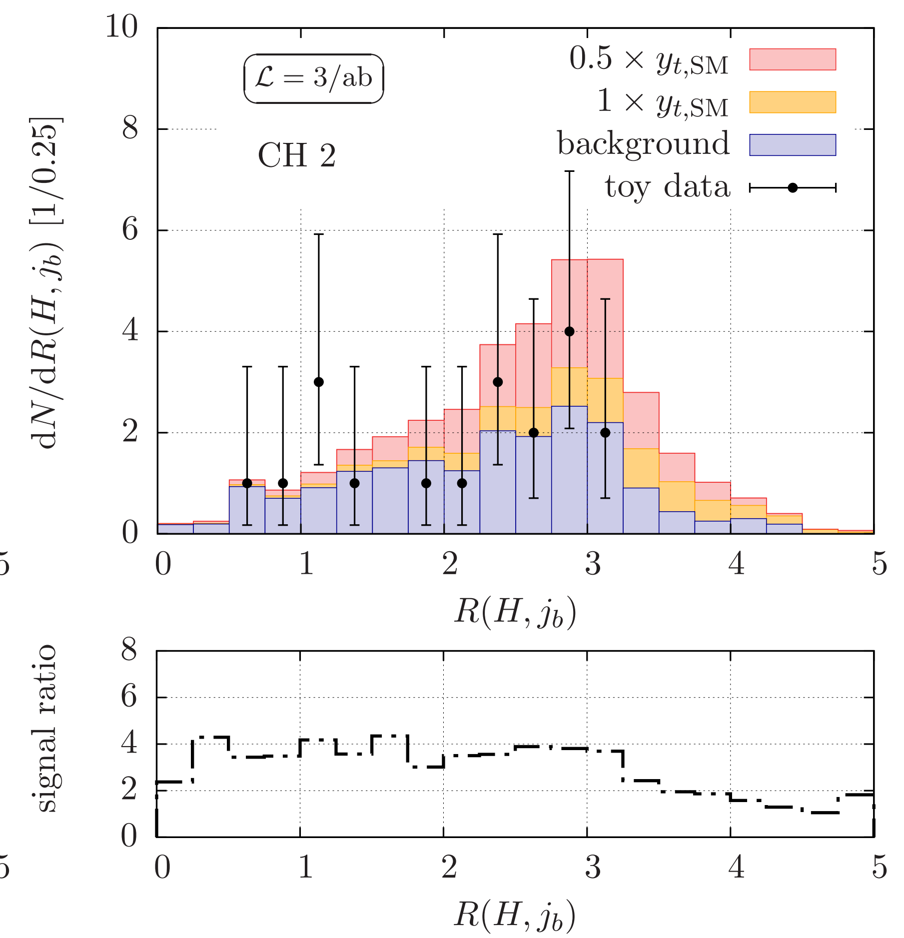
[Englert et al (2013)]

- Angular correlations can improve sensitivity

- In $H \to \gamma\gamma$ at 95% C.L.

$C_t \gtrsim 0.5$





New Physics in tth

Received much less attention than eg HH

CP properties of Higgs

[Ellis et al (2013)]

Higgs could be mixture of CP-even and CP-odd state:

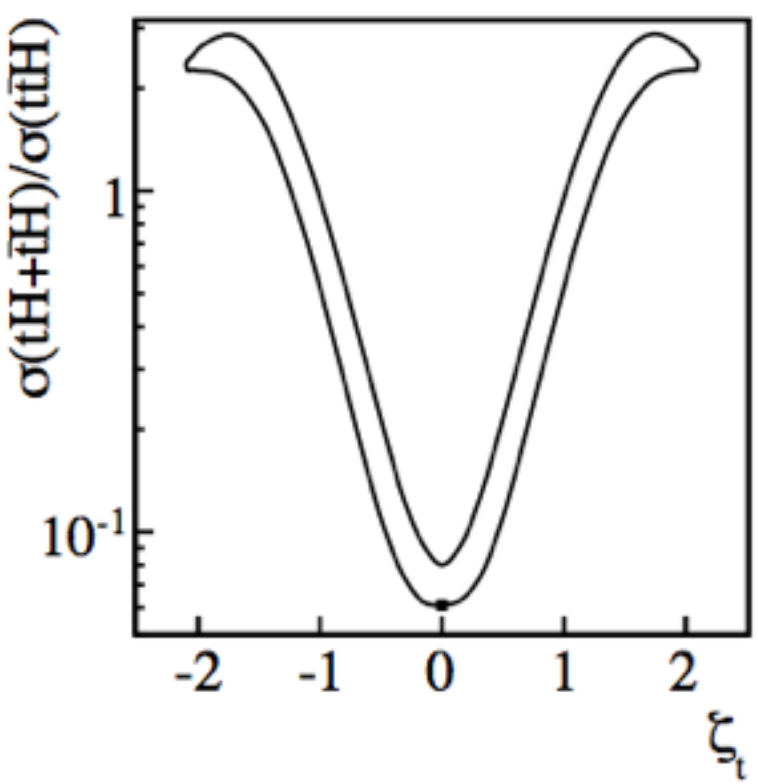
$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

where SM $(\kappa_t, \tilde{\kappa}_t) = (1, 0)$

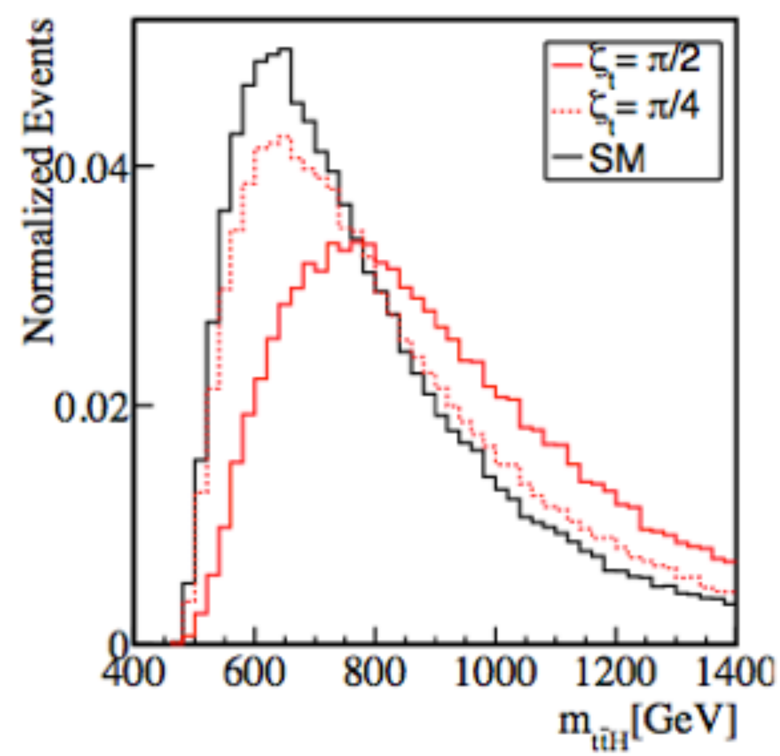
In $H \to \gamma\gamma$

define $\zeta_t \equiv \arctan\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right)$

Affects cross sections:



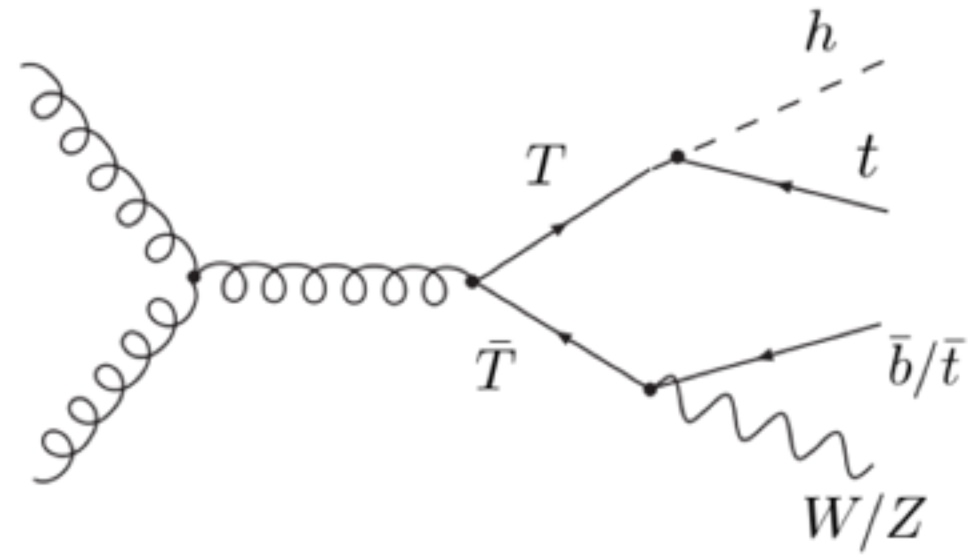
and shapes:



tth from vector-like quarks

Assume VLQ with $T = (3,1)_{2/3}$ and $T^c = (\bar{3},1)_{-2/3}$

see e.g. comp-Higgs models, little Higgs...



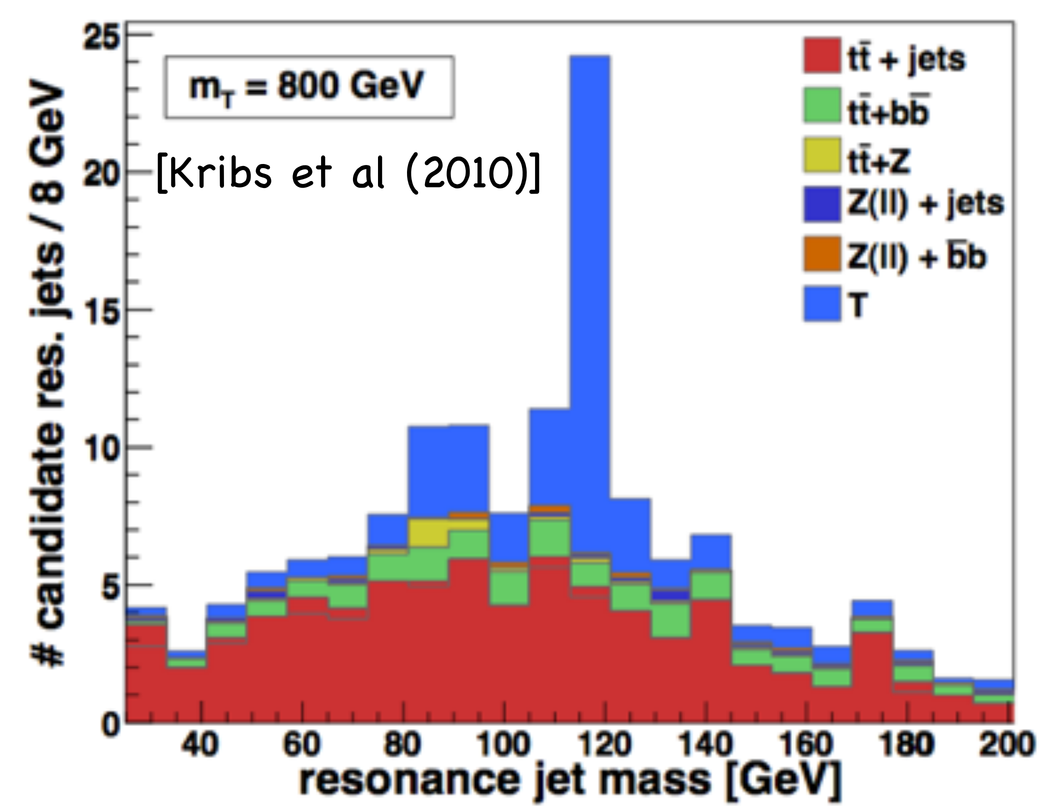
Add $\mathcal{L} \supset y_1 Q_3 H t^c + \delta T t^c + M T T^c$

$$(t \ \ T)\begin{pmatrix} m & 0 \\ \delta & M \end{pmatrix}\begin{pmatrix} t^c \\ T^c \end{pmatrix}$$

Limit inf. T mass

$$BR(T \to t + h) \sim 25\%$$
$$BR(T \to t + Z) \sim 25\%$$
$$BR(T \to b + W) \sim 50\%$$

m_T	$\sigma(pp \to T\bar{T})$
400 GeV	12.7 pb
600 GeV	1.29 pb
800 GeV	0.229 pb
1 TeV	0.054 pb

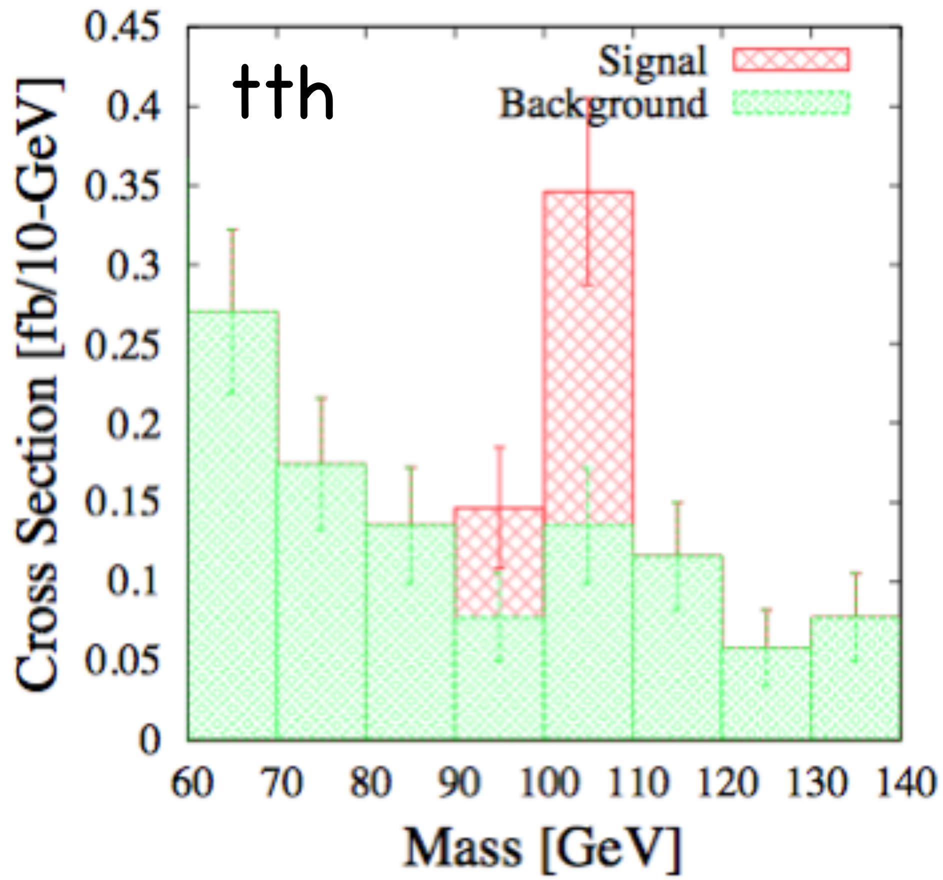


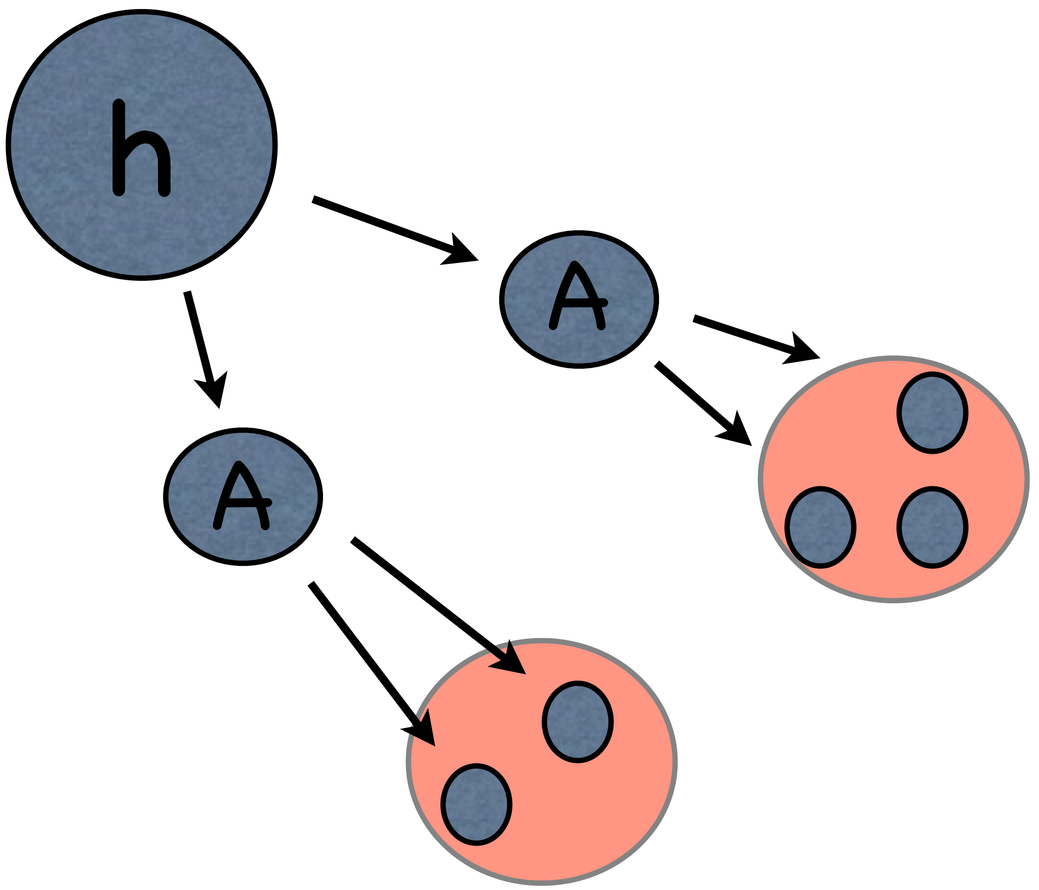
Burried Higgs

- Higgs decays into CP-odd scalar (10 GeV) with subsequent decay into gluons
- Jet substructure used in leptonic tth
- Sudakov suppression exploited for low jet mass

[Bellazzini et al (2009)]

[Falkowski et al (2010)]





Conclusions

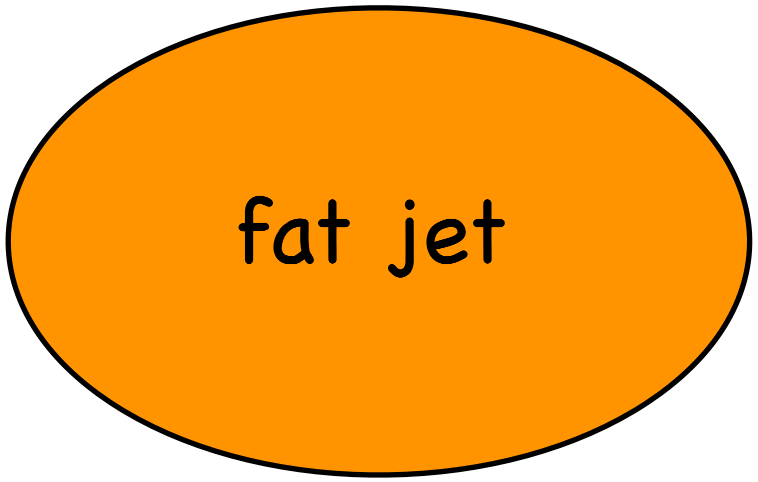
- tth one of most crucial coupling measurements for 14 TeV run
- Final state tth is one of the most complex SM final states
    - Measurement in H->bb mostly systematics limited
    - New techniques are needed/available to reconstruct
- thj interesting final state to eliminate sign-ambiguity of tth coupling
- Worth recasting first tth results in terms of new physics models

How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{\mathrm{daughter}_1} < 0.8\, m_{\mathrm{mother}}$ to keep both daughters



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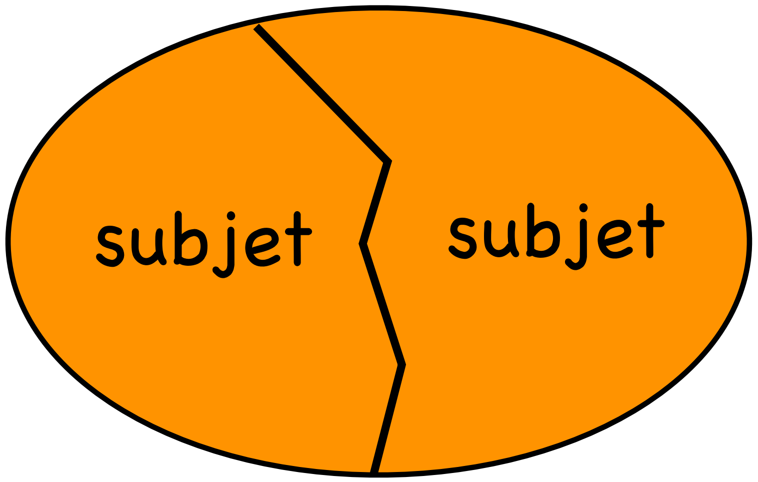

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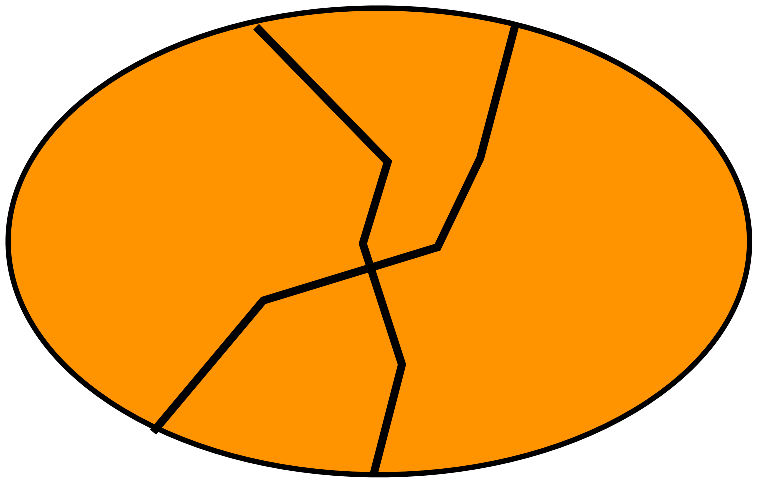

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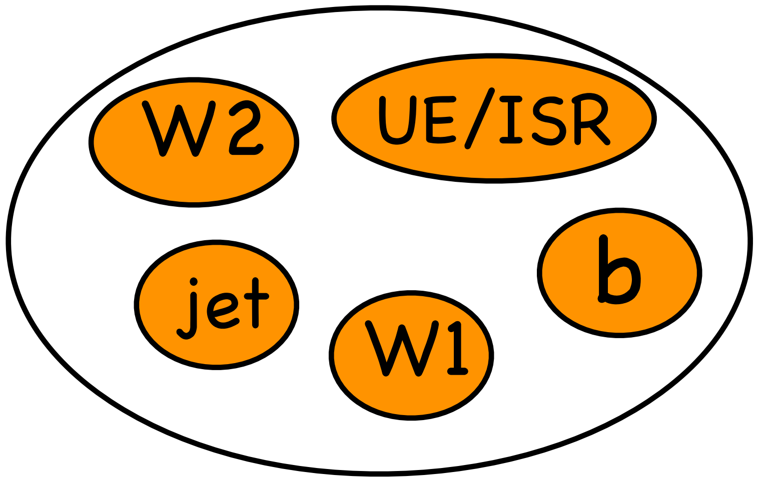
III. Apply jet grooming to get top decay candidates



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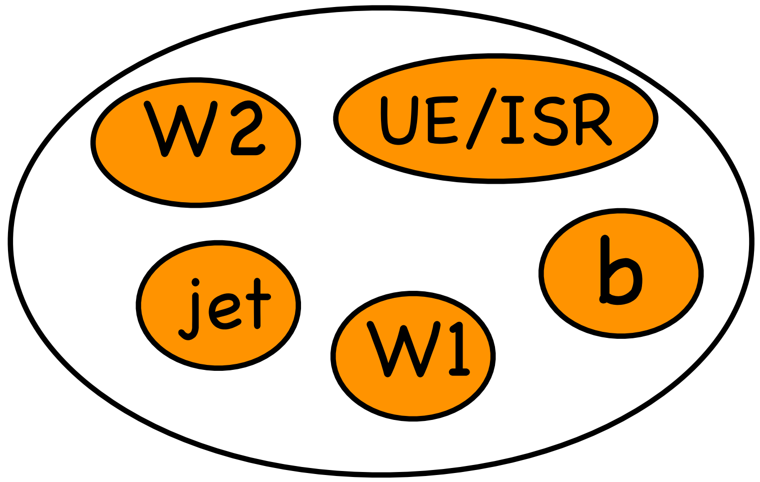
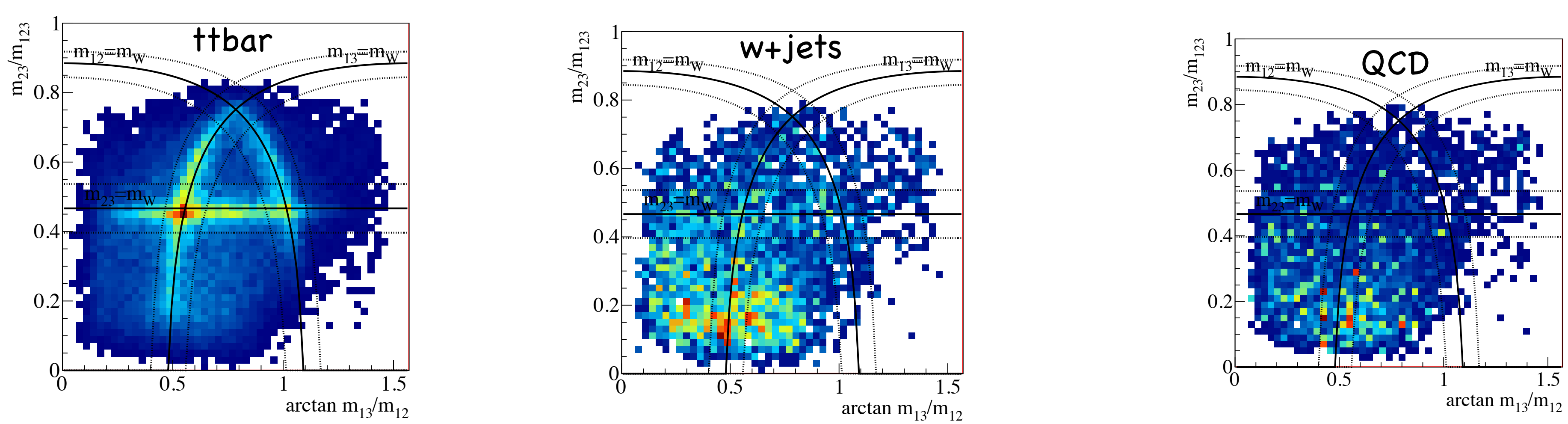
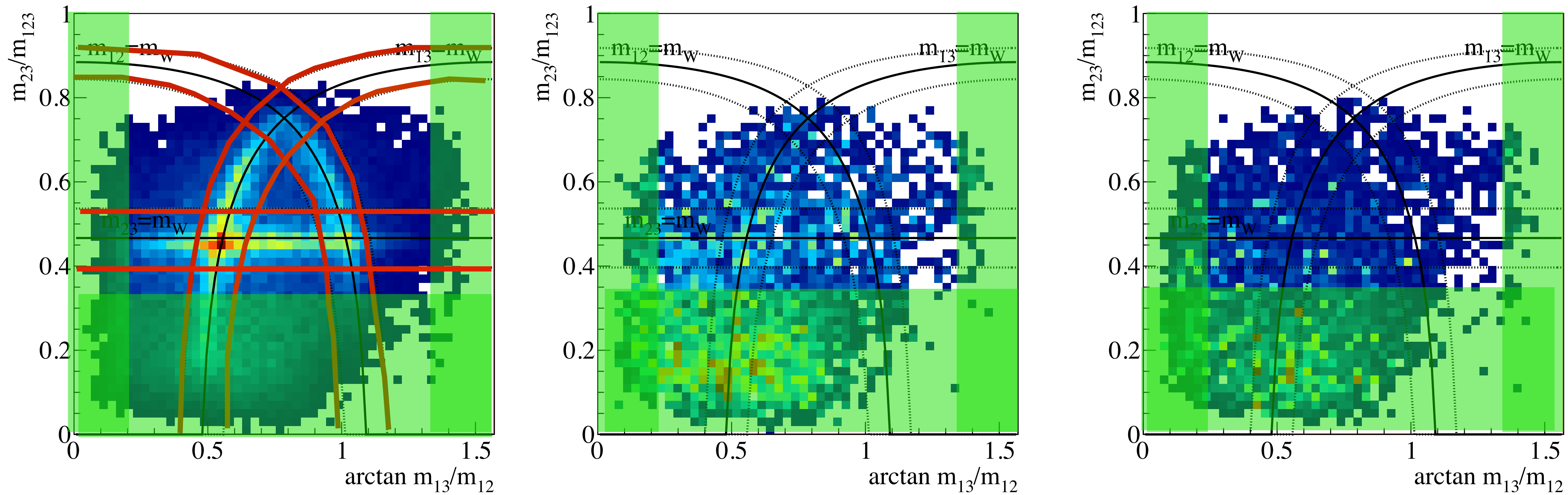


IV. Choose pairing based on kinematic correlation, e.g. top mass, W mass and invariant subjet masses



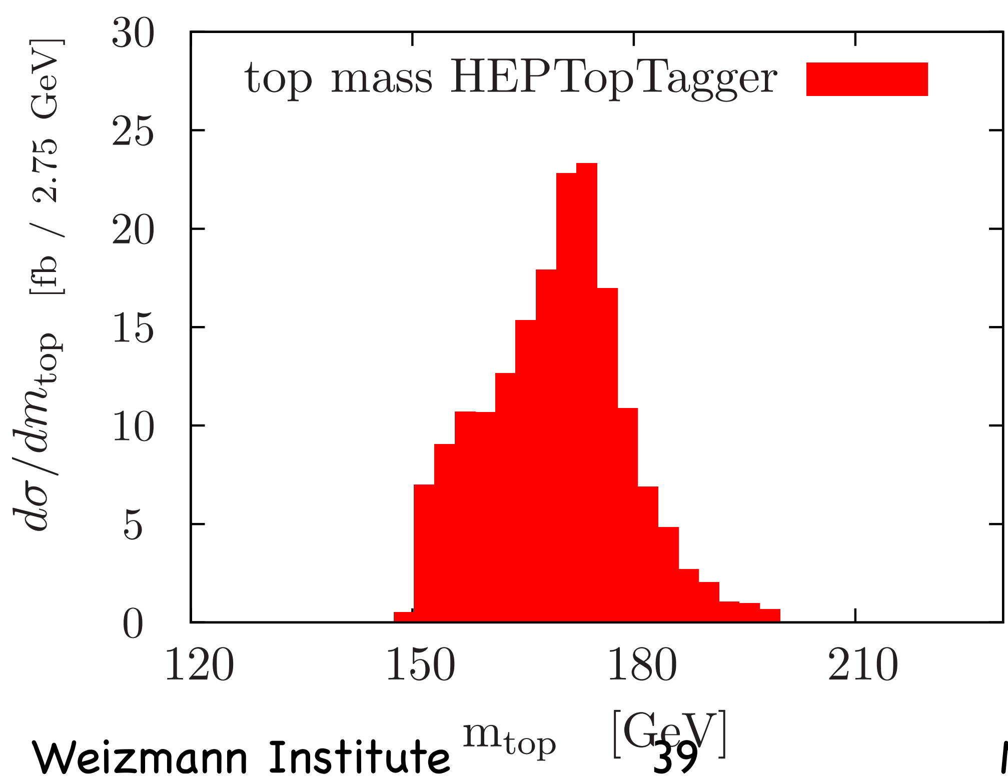
IV. check mass ratios

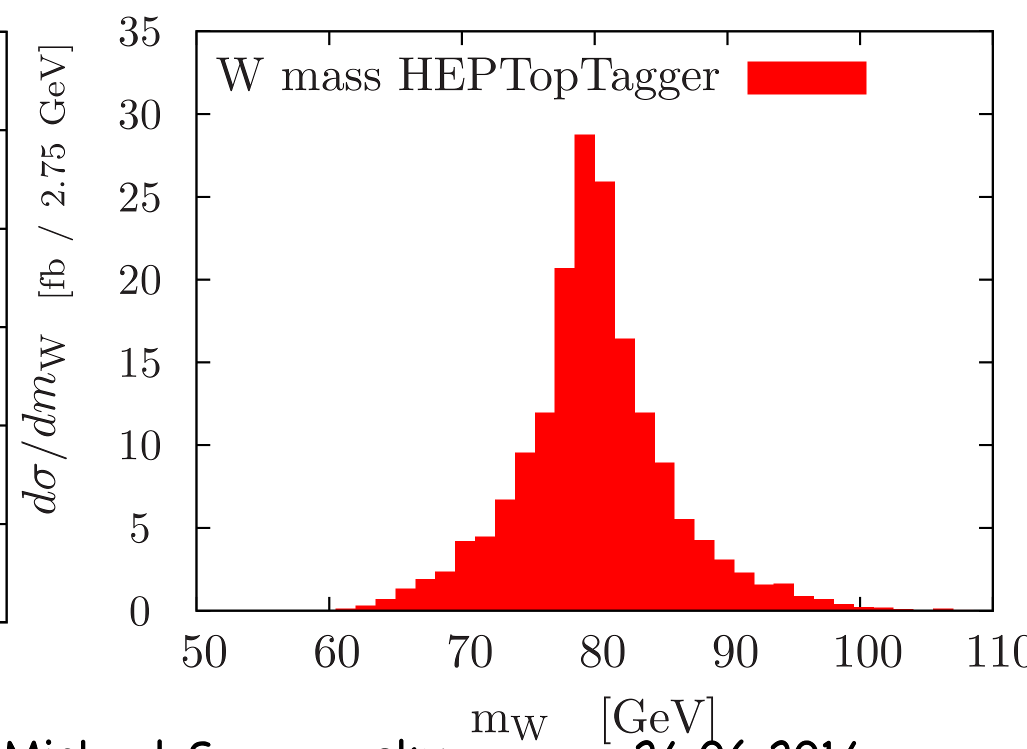
Cluster top candidate into 3 subjets j_1, j_2, j_3



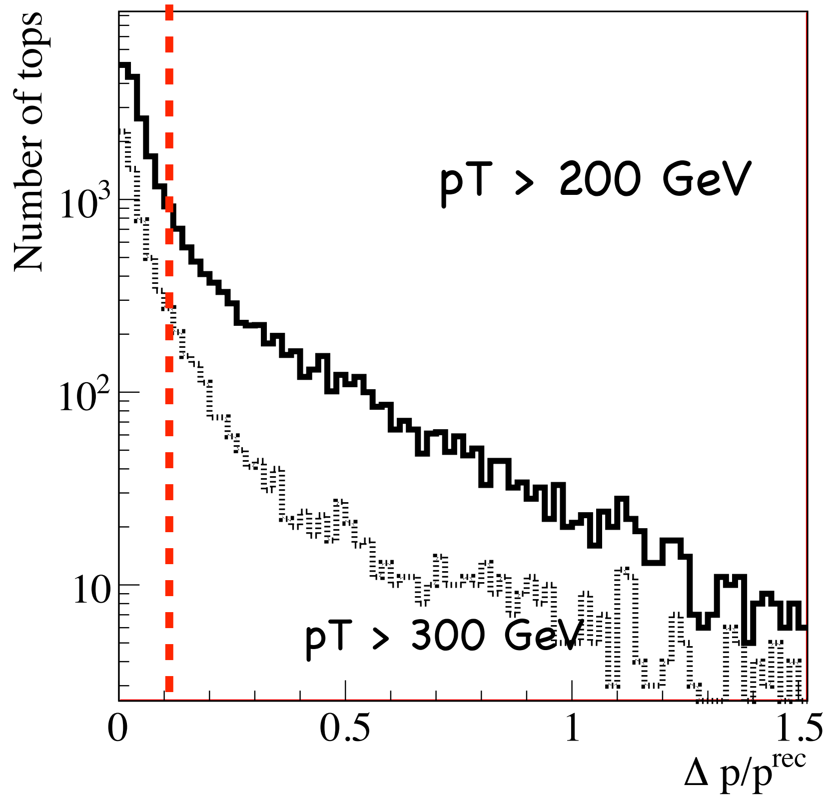
No fix pairing for W mass reconstruction

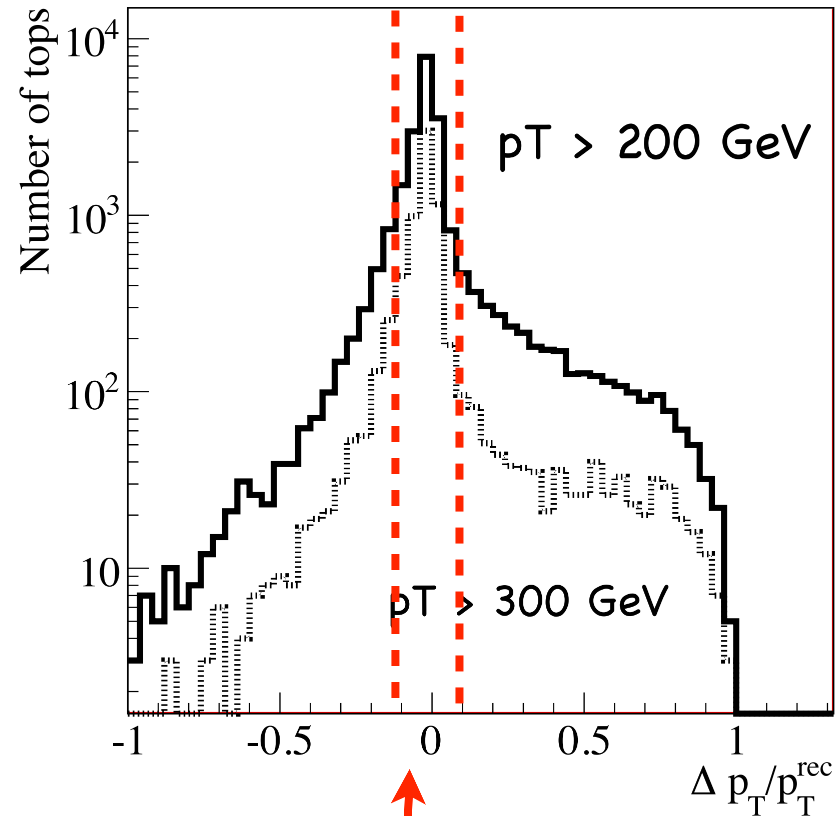
Only invariants for reconstruction

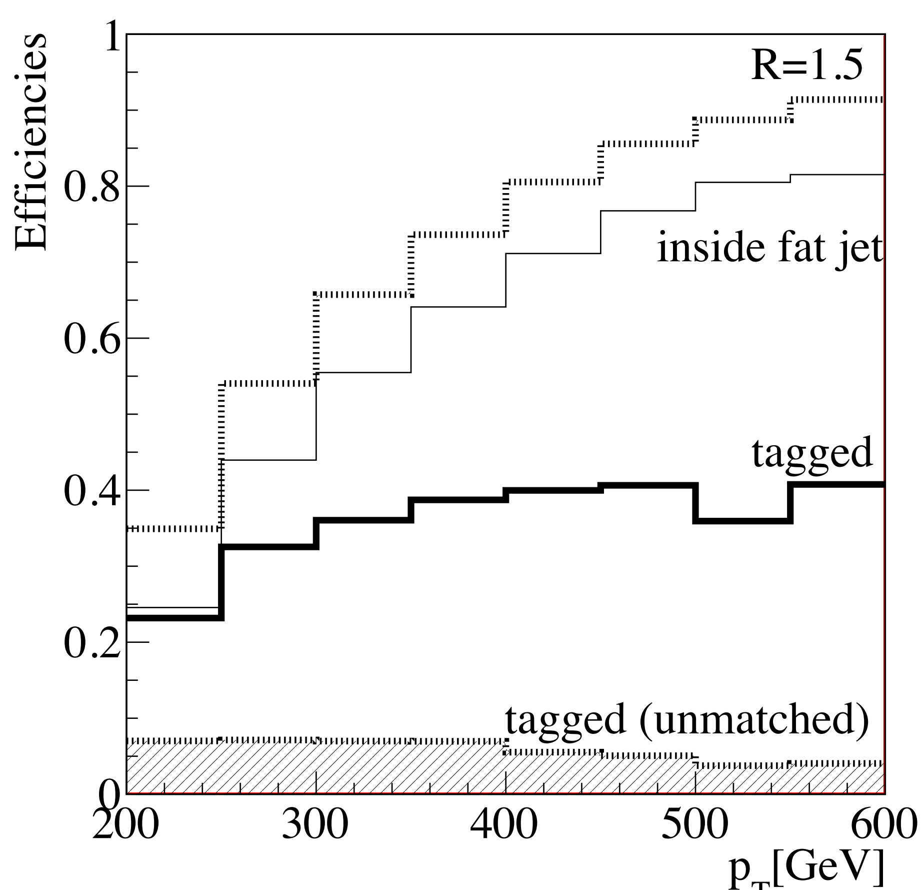




Top quark momentum reconstruction







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