Higgs@LHC — still a moving target

Completely biased pseudo-overview

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Higgs decays to bottoms

$H \to b\bar{b}$ as of 2007 [2/3 of all Higgses at 120 GeV]

- gluon-fusion: killed by QCD background [CMS: $S/B \sim 1/80$]
- WBF H: no trigger, killed by QCD backgrounds [WH, γH might work]
- VH: killed by low rate and NLO background
- $t\bar{t}H$: killed by combinatorics etc

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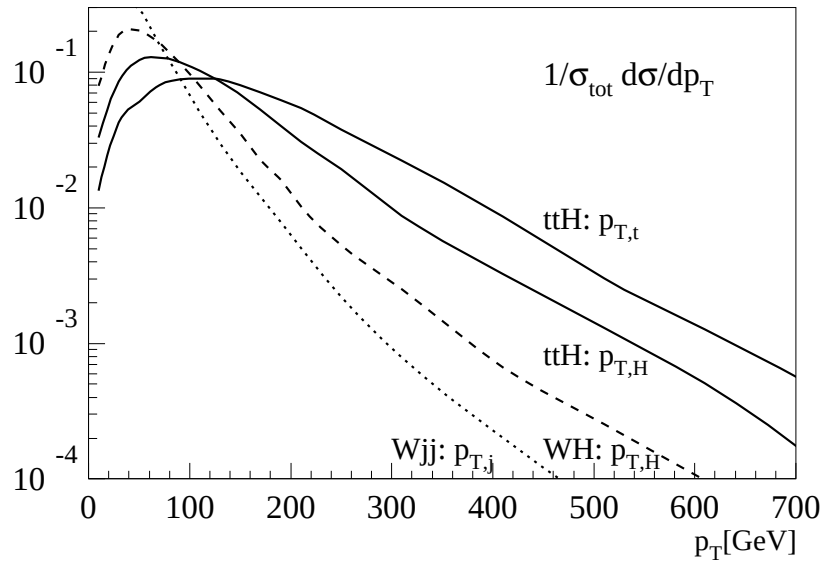
Changing everything [Butterworth, Davison, Rubin, Salam; Seymour...]

- S: large m_{bb}, boost-dependent R_{bb}
  B: large m_{bb} only for large R_{bb}
  S/B: large m_{bb} and small R_{bb}, so boosted Higgs
- fat Higgs jet $R_{bb} \sim 2m_H/p_T < 1$
- $q\bar{q} \to V_\ell H_b$ viable [bbV notorious but possible]



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$\Rightarrow$ non-trivial challenge to jet algorithms

	σ_S/fb	σ_B/fb	$S/\sqrt{B}_{30}$
C/A, $R = 1.2$, MD-F	0.57	0.51	4.4
$k_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	1.2
SISCone, $R = 0.8$	0.49	1.33	2.3

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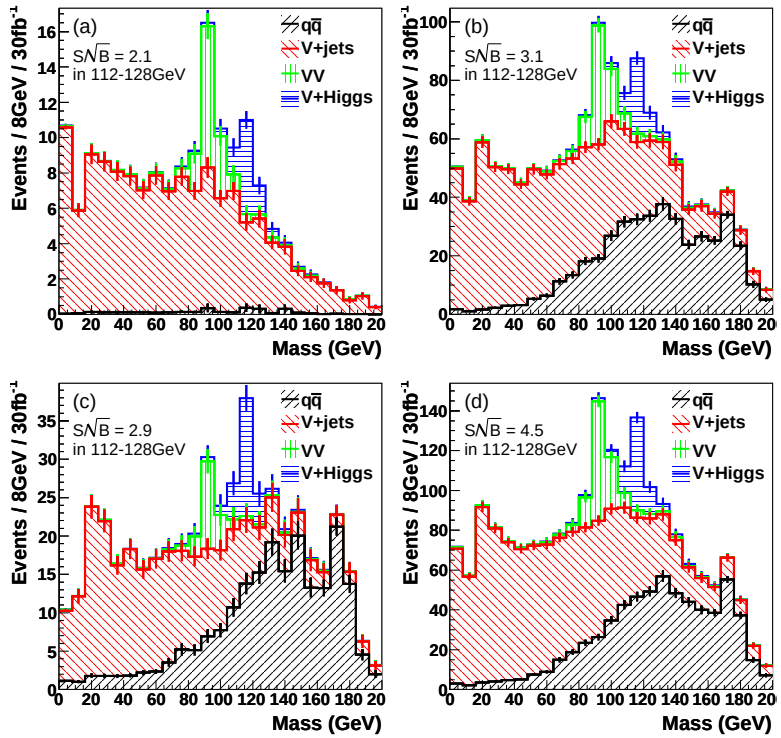
VH production

- combined channels $V \to \ell\ell, \nu\nu, \ell\nu$
- Z peak as sanity check
- confirmed to 20% [Piquadio]
  subjet b tag excellent [70%/1%]
  charm rejection challenging
  $m_H \pm 8$ GeV tough
- improvements possible [Soper, Spannowsky]

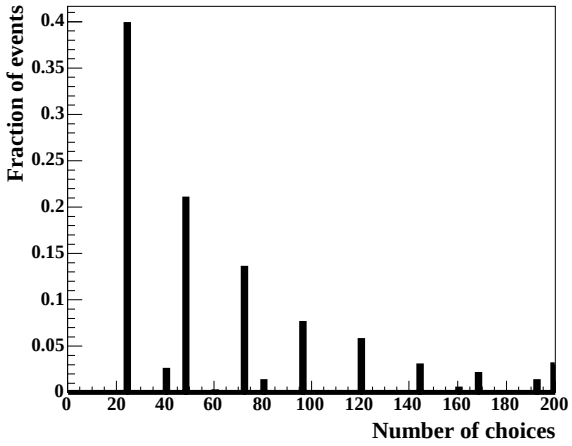
$\Rightarrow$ crucial for Higgs sector studies



Associated top-Higgs production

Long death of $t\bar{t}H, H \to b\bar{b}$ [Cammin & Schumacher, CMS-TDR and Atlas-CSC worse]

- trigger: $t \to bW^+ \to b\ell^+\nu$
  reconstruction and rate: $\bar{t} \to \bar{b}W^- \to \bar{b}jj$
- continuum background $t\bar{t}b\bar{b}$, $t\bar{t}jj$ [now to NLO]
- no chance:
  1– combinatorics: m_{bb} from $pp \to 4b_{tag}\ 2j\ \ell\nu$



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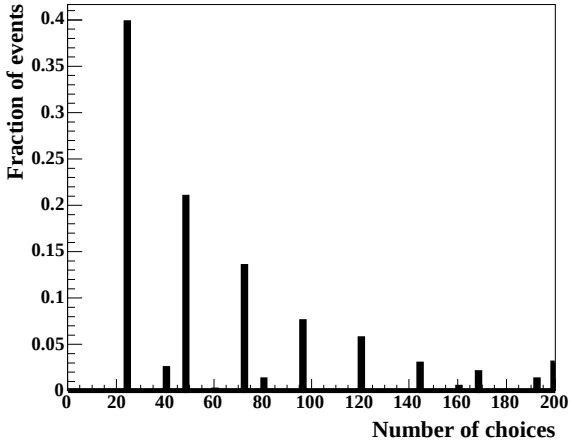

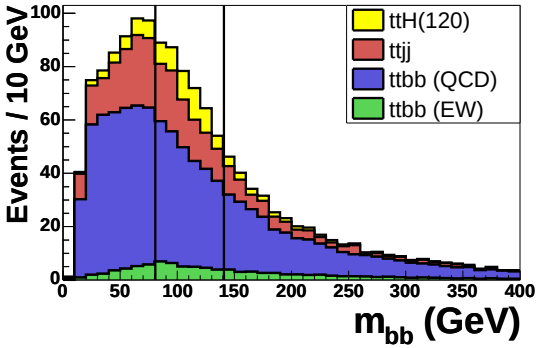

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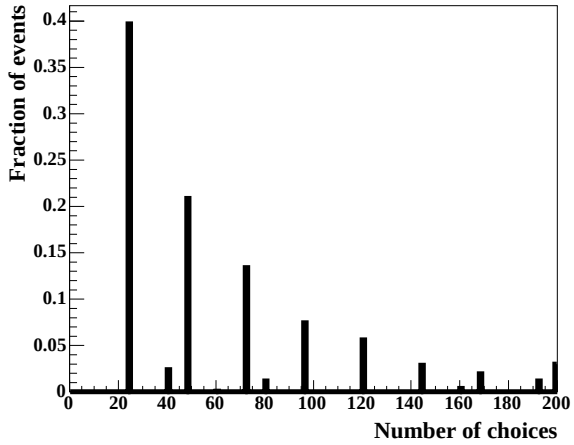

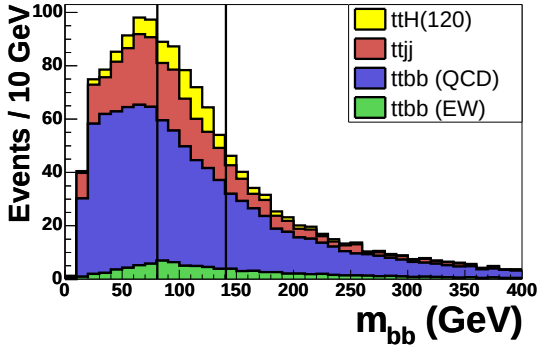

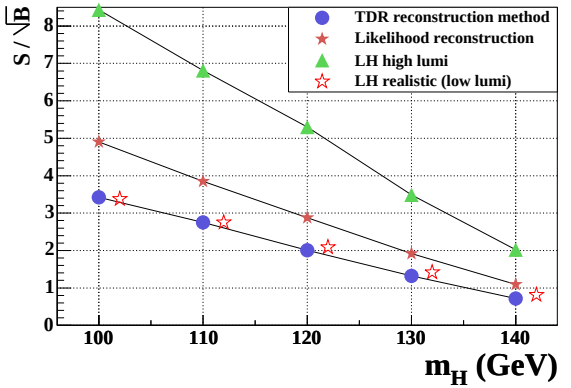

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New analysis

- tagged (boosted) top and Higgs
  trigger on lepton
- add'l continuum b tag [remove 'Higgs' as $t_\ell \to b$ plus QCD]
- side bin in continuum $t\bar{t}b\bar{b}$

per 1 fb^{-1}	signal	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$+jets
events after acceptance	24.1	6.9	191	4160
events with one top tag	10.2	2.9	70.4	1457
events with $m_{bb} = 110 - 130$ GeV	2.9	0.44	12.6	116
corresponding to subjet pairings	3.2	0.47	13.8	121
subjet pairings two b tags	1.0	0.08	2.3	1.4
including a third b tag	0.48	0.03	1.09	0.06

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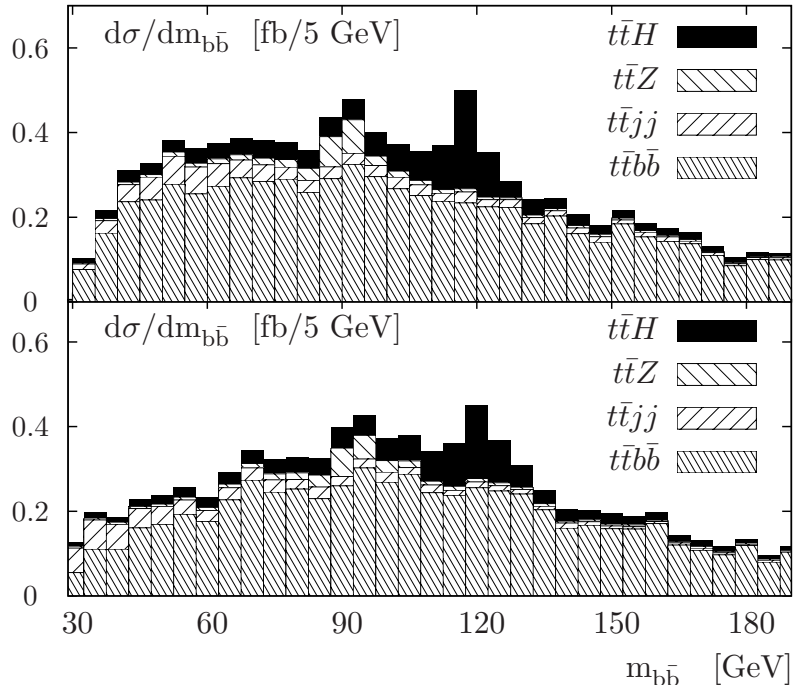
m_H	S	S/B	$S/\sqrt{B}_{100}$
115	57	1/2.1	5.2 (5.7)
120	48	1/2.4	4.5 (5.1)
130	29	1/3.6	2.9 (3.0)



Higgs and top tagging

Higgs tag for busy QCD environment [TP, Salam, Spannowsky]

- uncluster one-by-one: $j \to j_1 + j_2$
  1– unbalanced $m_{j_1} > 0.8 m_j$ means QCD; discard j_2
  2– soft $m_{j_1} < 30$ GeV means QCD; keep j_1
- double b tag [possibly add balance criterion]
  three leading $J = p_{T,1} p_{T,2} (\Delta R_{12})^4$ vs m_{bb}^{filt}
  no mass constraint — side bin
  QCD rejection 10^{-5}
- jets everywhere
  decay plus one add'l jet at $R_{\text{filt}} \sim R_{jj}/2$
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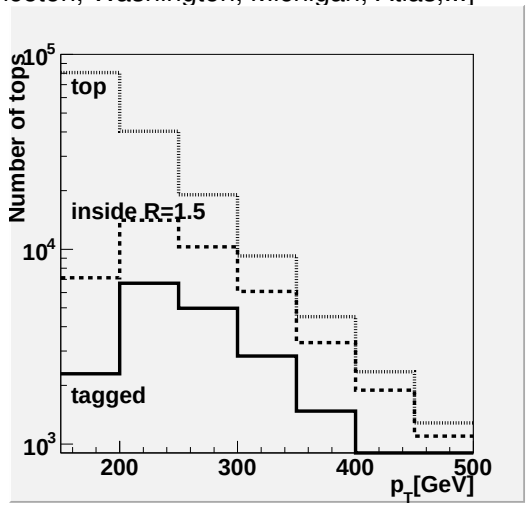
Standard Model top tag [TP, Salam, Spannowsky, Takeuchi]

- known for heavy resonances [Johns Hopkins, Stony Brook, Princeton, Washington, Michigan, Atlas,...]
- testable top tagger for Standard Model?
- start like Higgs tagger [R=1.5]
  kinematic selection [after filtering]
  $m_t^{\text{rec}} = 150 \ldots 200$ GeV
  $m_W^{\text{rec}} = 60 \ldots 95$ GeV
  additional m_{jb} constraint [learn from single tops]
- QCD rejection per-cent



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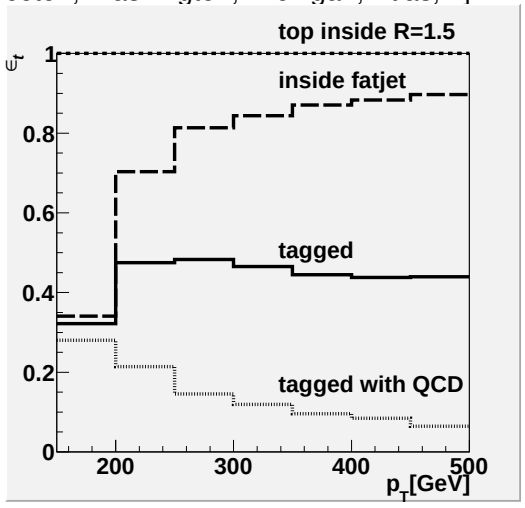
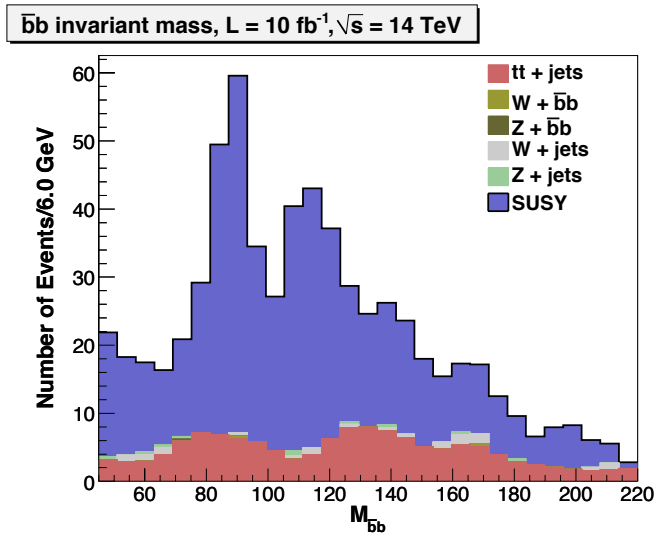


Higgs in SUSY cascades

Higgs in cascade decays [Kribs, Martin, Roy, Spannowsky]

- idea: find Higgs in cascade decays [Cambridge]
- BSM sample after missing energy or hard γ cut
- Higgs tag over the remaining event
- side bin analysis in m_{bb}
- more to follow...



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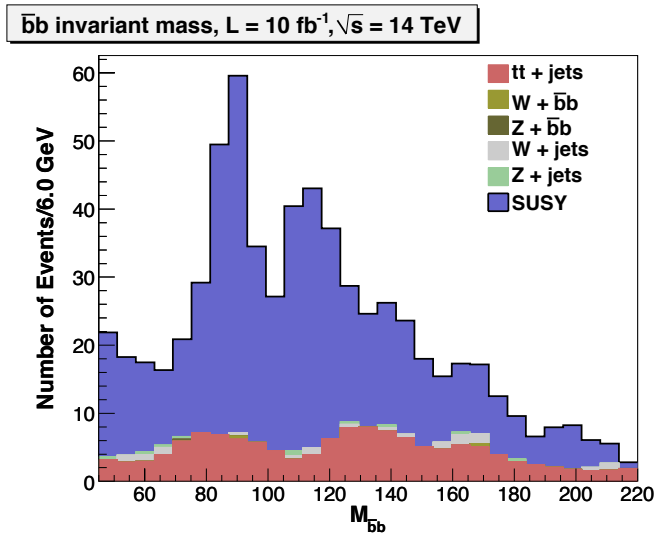


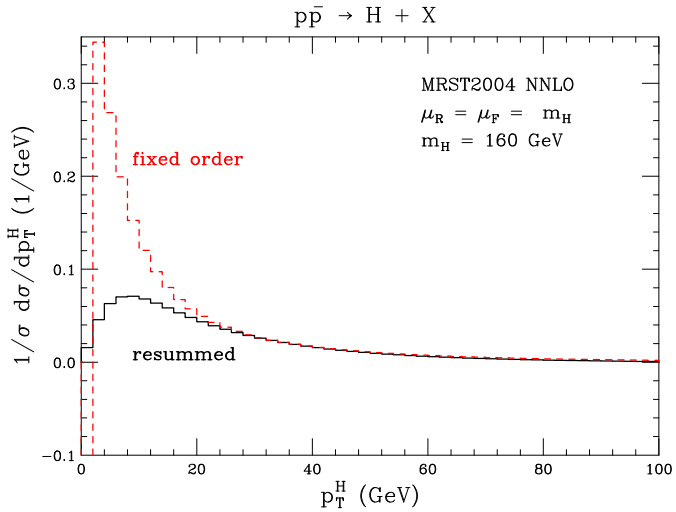
Fat jets — Aspirin of LHC phenomenology

- *VH*: curing QCD backgrounds
- $t\bar{t}H$: curing combinatorics
- *SUSY*: curing lack of strategie
- heavy resonances: curing calorimeter resolution
- try using it against your headache...

Analysis errors

Worries about $H \to \gamma\gamma$ etc [Anastasiou, Dissertori, Grazzini, Stockli, Webber; Anastasiou, Melnikov, Petriello]

- used to be easy: double side-bin analysis
- learning from Tevatron $H \to WW$: $p_{T,H}$, $\phi_{\ell\ell}$ and n_{jets} in NN
  combine 'slices' of side-bins
- typical tool to improve 3σ to 5σ
- NN and theory uncertainties?
  sensitive to p_T resummation tricky
  sensitive to first jet challenging
  sensitive to n_{jets} nightmare



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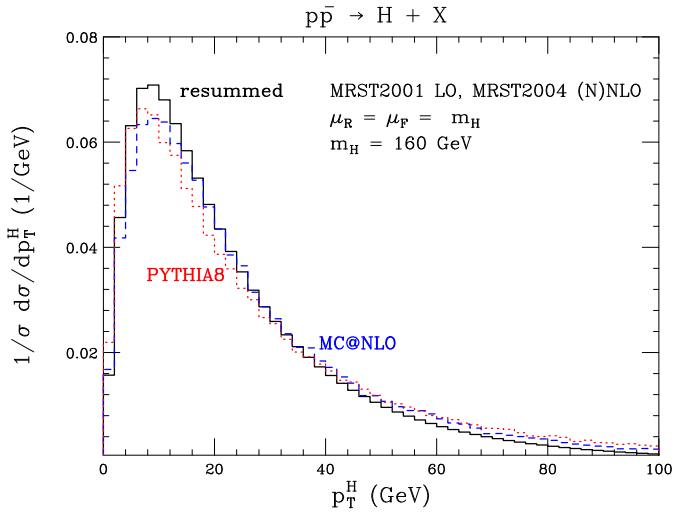

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- combination of scale uncertainties [Tevatron, improvable with MCFM]

$$\frac{\Delta N}{N} = 60\% \cdot \begin{pmatrix} +5\% \\ -9\% \end{pmatrix} + 29\% \cdot \begin{pmatrix} +24\% \\ -23\% \end{pmatrix} + 11\% \cdot \begin{pmatrix} +91\% \\ -44\% \end{pmatrix} = \begin{pmatrix} +20.0\% \\ -16.9\% \end{pmatrix}$$

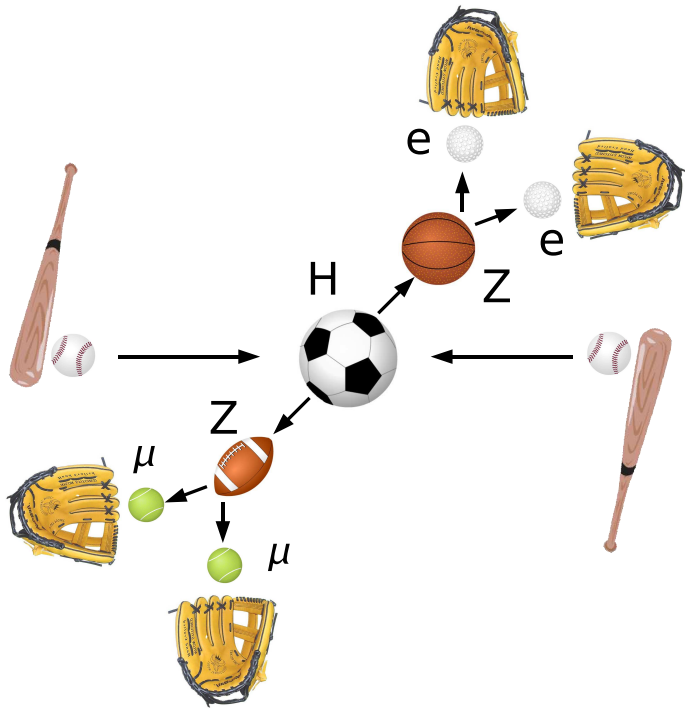
- high stat'l significance at high p_T
  increasing theory error at high p_T
  no higher-order predictions for exclusive n_{jets}
  dangerously small individual S/B
- advanced analyses finally getting me scared...

Higgs operator basis

Spin and CP of $X \to ZZ \to ee\mu\mu$

- $H \to ZZ$ useful for $m_H \gtrsim 200$ GeV and low luminosity
  good S/B in golden channel legendary
  angle between decay planes classical [Nelson]
  including complete set of angles next step
- spin-0: $g^{\mu\nu}$ or $g^{\mu\nu} - p_1^\mu p_2^\nu / (p_1 p_2)$ or $\epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}$ [Hagiwara, Szalapski, Zeppenfeld]
  spin-1: vector vs axial-vector
  spin-2: big mess [WBF: Hagiwara, Kanzaki, Li, Mawatari]
- 3σ distinction with $20 \cdots 100$ events [de Rujula, Lykken, Pierini, Rogan, Spiropulu]

$\Rightarrow$ reconstruct Higgs operator basis



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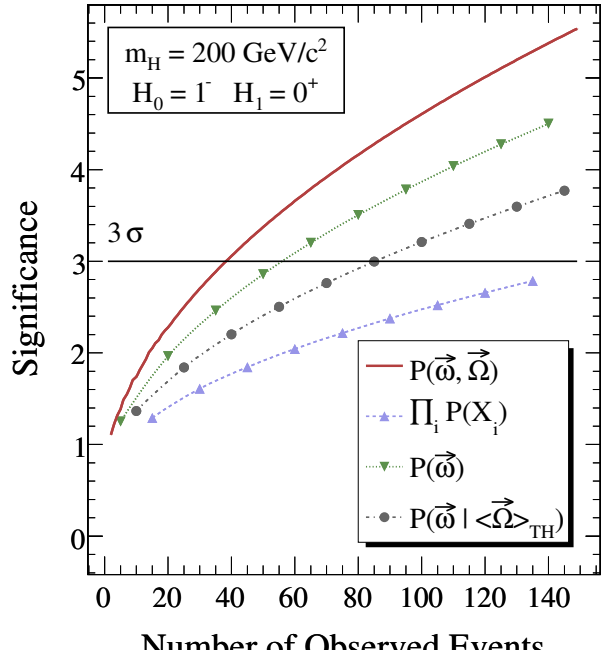

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- similar likelihood analysis, also CMS+theory [Gritsan, Melnikov,...]

	0^-	1^+	1^-	2^+_m
0^+	0.0/0.0/3.9/4.1/4.1	0.8/1.0/1.8/1.9/2.3	0.9/1.0/2.5/2.6/2.6	0.8/0.9/2.4/2.5/2.8
0^-		0.8/1.2/2.8/3.0/3.1	0.9/1.0/2.5/2.8/3.0	0.8/0.8/1.7/2.0/2.4
1^+			0.0/1.1/1.1/1.2/2.2	0.1/1.2/1.3/1.4/2.6
1^-				0.1/0.1/1.3/1.5/1.8

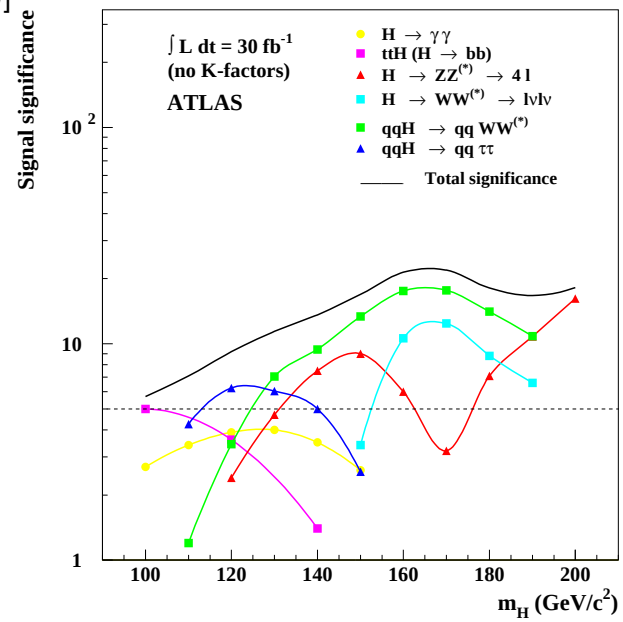
- example for Higgs analyses with low-ish luminosity
- more on D5 operators in Ian Low's talk [watch out for their $Z\gamma$ sales pitch]
- extended to WBF channels...

$\Rightarrow$ reconstruct Higgs operator basis

Higgs coupling analysis

Higgs-sector analysis [Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

- next, prefactors
- light Higgs: 10 main channels ($\sigma \times BR$)
- measurements: $GF : H \to ZZ, WW, \gamma\gamma$
  $WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$
  $VH : H \to b\bar{b}$ [Butterworth, Davison, Rubin, Salam]
  $t\bar{t}H : H \to \gamma\gamma, WW, (b\bar{b})...$
- parameters: couplings $W, Z, t, b, \tau, g, \gamma$ [plus m_H]



Errors

Sources of uncertainty

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian
- LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong
  means theory likelihood flat centrally and zero far away
- profile likelihood construction: RFit [CKMFitter]

$$-2 \log \mathcal{L} = \chi^2 = \vec{\chi}_d^T \; C^{-1} \; \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\ \dfrac{|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})}}{\sigma_i^{(\text{exp})}} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})} \end{cases} ,$$

- measuring ratios [Zeppenfeld,...; Low, Lykken]
  useless if statistics dominated
  theory errors — same initial states
  systematic errors — same final states
  ???

Higgs couplings

SFitter analysis [Dührssen, Lafaye, TP, Rauch, Zerwas]

- all couplings varied around SM values $g_{HXX} = g_{HXX}^{\text{SM}} \, (1 + \delta_{HXX})$
  $\delta_{HXX} \sim -2$ means sign flip [$g_{HWW} > 0$ fixed]
- need assumption about loop-induced couplings $g_{ggH}, g_{\gamma\gamma H}$
- likelihood map and local errors from SFitter
- experimental/theory errors on signal and backgrounds [do not ask theorists!]

luminosity measurement	5 %
detector efficiency	2 %
lepton reconstruction efficiency	2 %
photon reconstruction efficiency	2 %
WBF tag-jets / jet-veto efficiency	5 %
b-tagging efficiency	3 %
τ-tagging efficiency (hadronic decay)	3 %
lepton isolation efficiency ($H \to 4\ell$)	3 %

σ (gluon fusion)	13 %
σ (weak boson fusion)	7 %
σ (VH-associated)	7 %
σ ($t\bar{t}$-associated)	13 %

Higgs couplings

SFitter analysis [Dührssen, Lafaye, TP, Rauch, Zerwas]

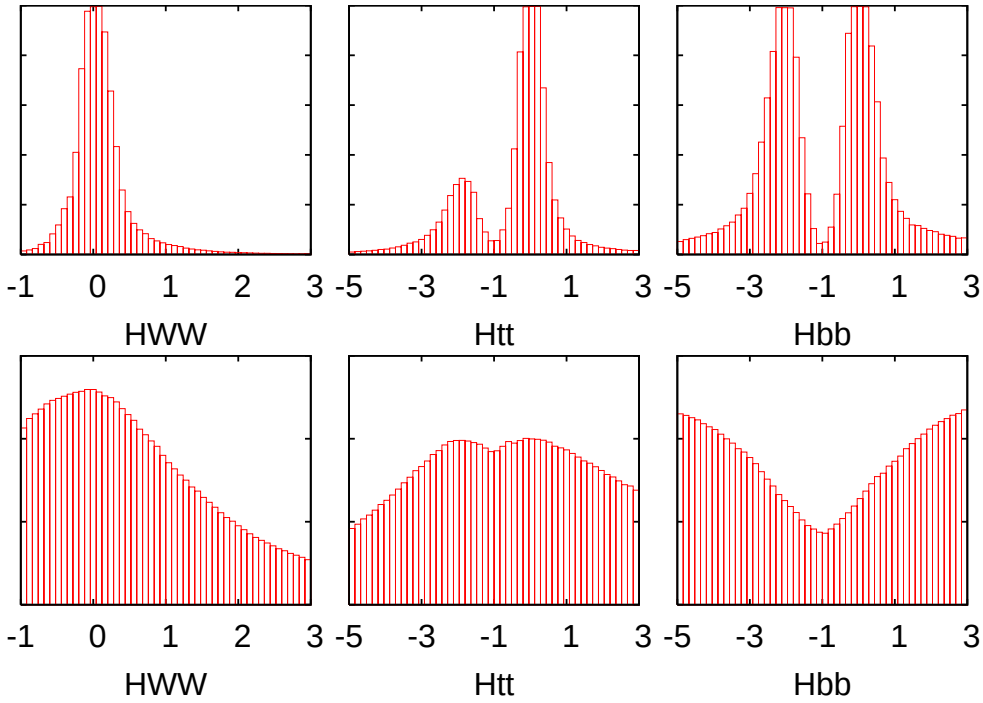
- all couplings varied around SM values $g_{HXX} = g_{HXX}^{\text{SM}} \, (1 + \delta_{HXX})$
  $\delta_{HXX} \sim -2$ means sign flip [$g_{HWW} > 0$ fixed]
- need assumption about loop-induced couplings $g_{ggH}, g_{\gamma\gamma H}$
- likelihood map and local errors from SFitter
- experimental/theory errors on signal and backgrounds [do not ask theorists!]
- error bars for Standard Model hypothesis [smeared data point, 30fb^{-1}]

coupling	without eff. couplings			including eff. couplings		
	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}
δ_{WWH}	± 0.23	-0.21	$+0.26$	± 0.24	-0.21	$+0.27$
δ_{ZZH}	± 0.50	-0.74	$+0.30$	± 0.44	-0.65	$+0.24$
$\delta_{t\bar{t}H}$	± 0.41	-0.37	$+0.45$	± 0.53	-0.65	$+0.43$
$\delta_{b\bar{b}H}$	± 0.45	-0.33	$+0.56$	± 0.44	-0.30	$+0.59$
$\delta_{\tau\bar{\tau}H}$	± 0.33	-0.21	$+0.46$	± 0.31	-0.19	$+0.46$
$\delta_{\gamma\gamma H}$	—	—	—	± 0.31	-0.30	$+0.33$
δ_{ggH}	—	—	—	± 0.61	-0.59	$+0.62$
m_H	± 0.26	-0.26	$+0.26$	± 0.25	-0.26	$+0.25$
m_b	± 0.071	-0.071	$+0.071$	± 0.071	-0.071	$+0.072$
m_t	± 1.00	-1.03	$+0.98$	± 0.99	-1.00	$+0.98$

Higgs couplings

One-dimensional distributions to check....

1– noisy environment preferring profile likelihoods [no effective couplings, 30 fb^{-1}]



Higgs couplings

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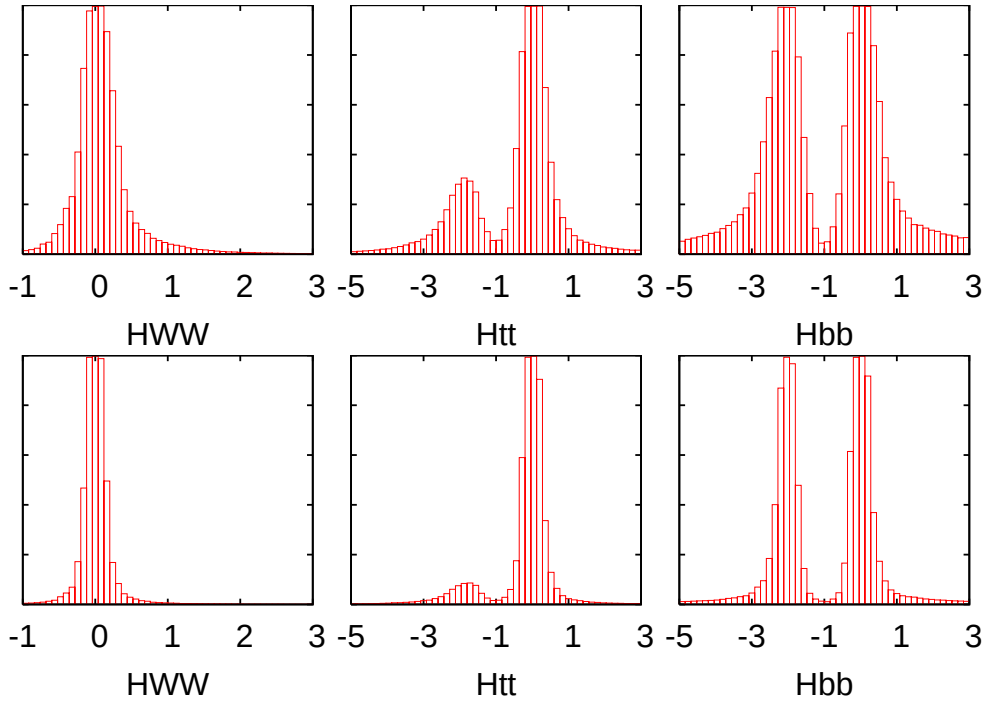
2– higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb^{-1}]



Higgs couplings

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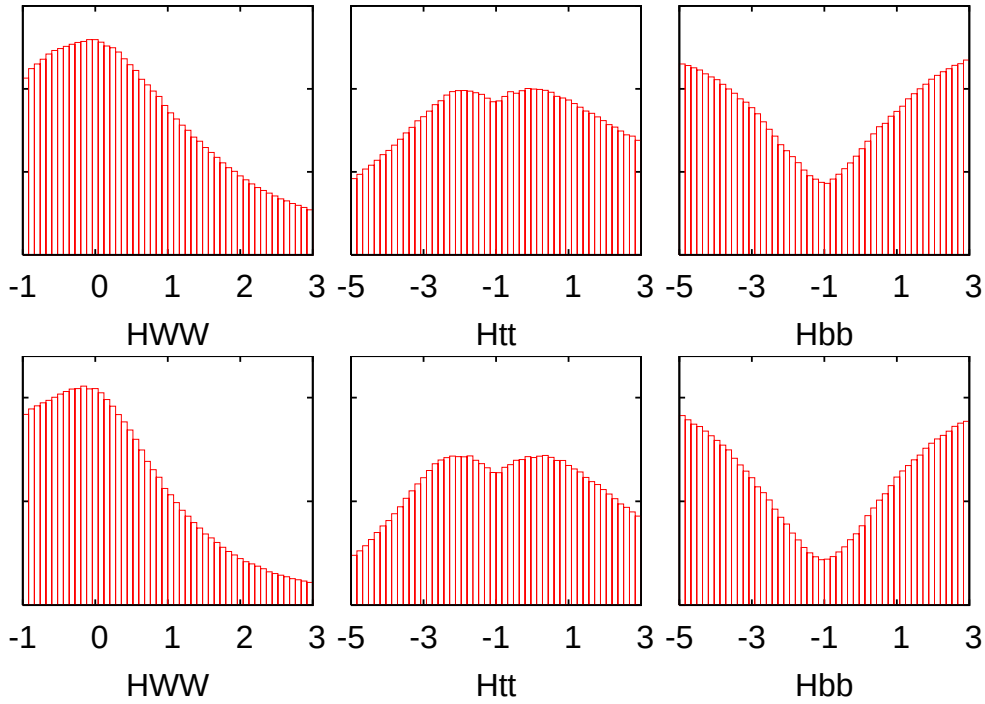

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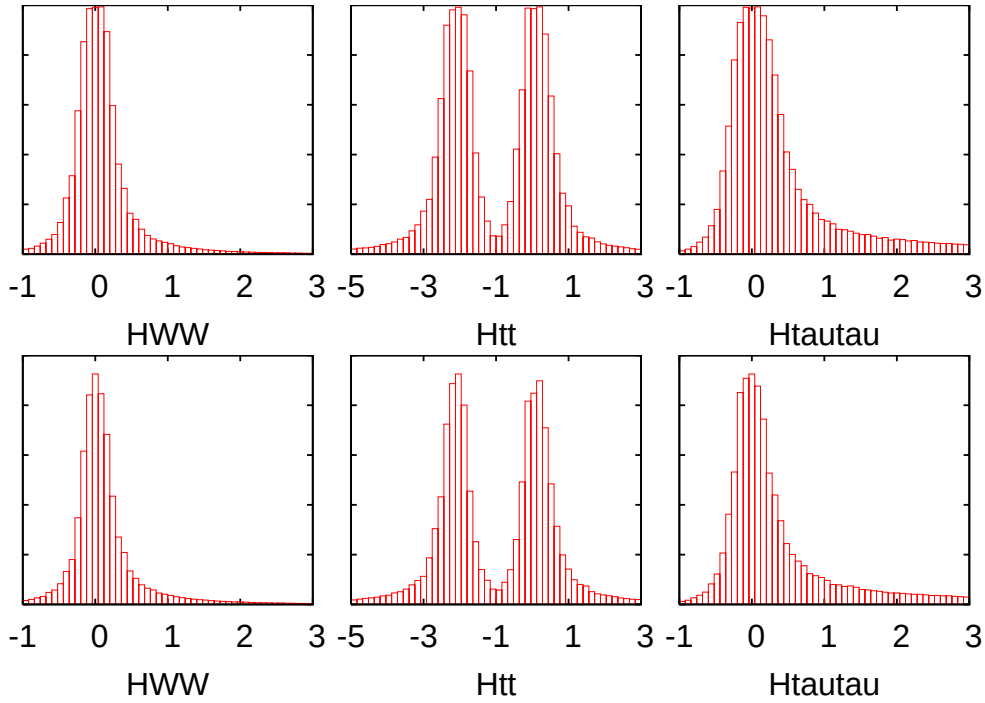
3– but not saving Bayesian statistics [no effective couplings, 300 fb^{-1}]

4– theory errors not dominant for 30 fb^{-1} [with effective couplings, 30 fb^{-1}]

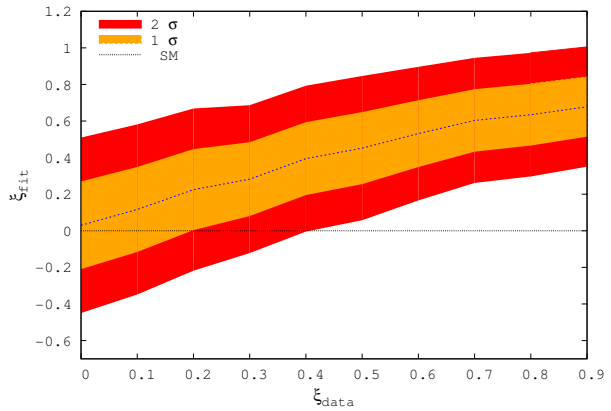


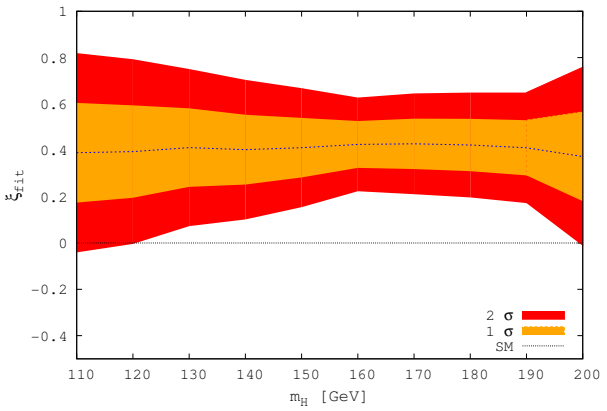
$\Rightarrow$ profile likelihood promising for 30 fb^{-1}, errors a mess

Refining Higgs hypotheses

Strongly interacting Higgs at LHC [Espinosa, Grojean, Mühlleitner]

- looking like fundamental Higgs
- 1– all couplings scaled $g \to g\sqrt{1-\xi}$
- one-parameter fit in SFitter [SFitter + Bock, P Zerwas]
- 30 fb^{-1} and 120 GeV Higgs: $\Delta g/g \sim 10\%$
  best around $m_H \sim 160$ GeV: $\Delta g/g \sim 5\%$





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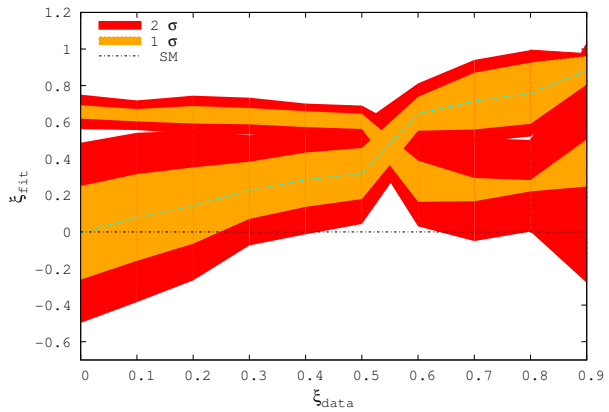

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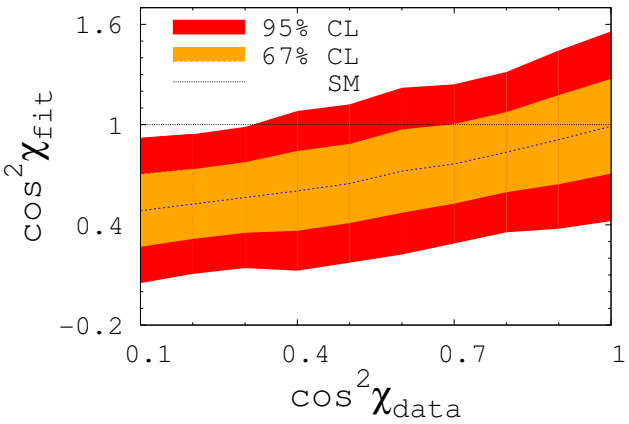
Higgs portal

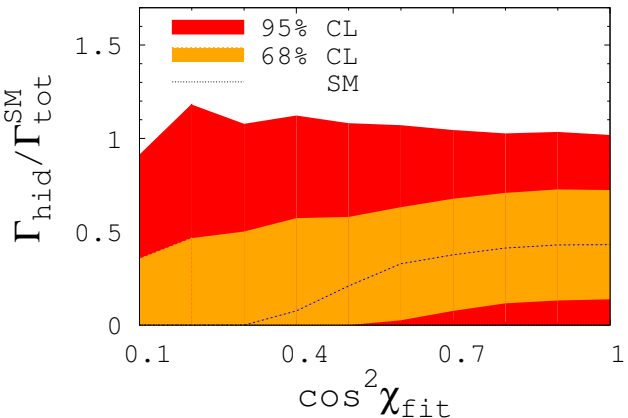
– universal scaling $\sqrt{1-\xi} \equiv \cos\chi$

– invisible Higgs decay measurable [Eboli & Zeppenfeld]
two-parameter fit, project out Γ_{hid} or $\cos\chi$

– to appear soon...

$\Rightarrow$ hypotheses testable with 30 fb^{-1}





Outlook

Higgs at LHC a restless guy

- decay to bottoms running at us
- analysis techniques running away
- operator analysis moving towards 30 fb^{-1}
- parameter analysis moving towards 30 fb^{-1}
- not early running, but exciting times