Higgs Couplings

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Universität Heidelberg

Standard Model@LHC, 4/2013

Higgs physics 2013-20XX

Fundamental questions

1– What is the ‘Higgs’ Lagrangian? [Maggie’s talk]

Higgs physics 2013-20XX

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spin-2 graviton unexpected

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couplings require operator basis [hard for spin-2]
eventually renormalization [mass dimension]
'anomalous couplings' in addition

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Elephant channel in the room

– inclusive searches = gluon fusion
– couplings discovered $g_{Hgg}, g_{H\gamma\gamma}, g_{HZZ}, g_{HWW}$
– eventually $H \to Z\gamma$ [ATLAS-CONF-2013-009, CMS-HIG-13-006]

$\Rightarrow$ to amuse yourself:

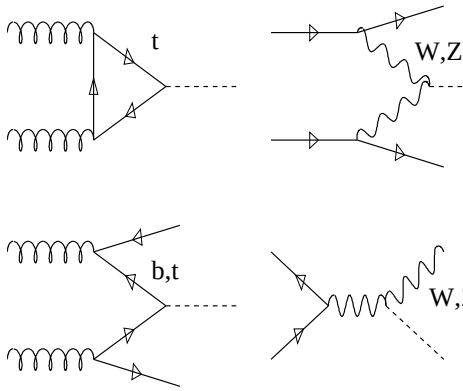
Who would build this LHC+ATLAS+CMS to
(1) discover a particle which couples to mass??
(2) probe unitarity/renormalizability of the weak Lagrangian??

Additional production channels

WBF production

- \+ second-largest rate [small QCD corrections]
- \+ tagging jets to trigger and get $S/B \sim 1$ [m_{jj} very useful]
- – sensitive to pile-up
- – tricky jet veto

$\Rightarrow$ accessible $H \to WW, \tau\tau, \mu\mu$, invisible



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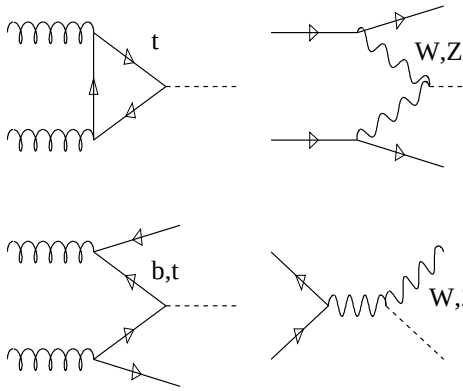

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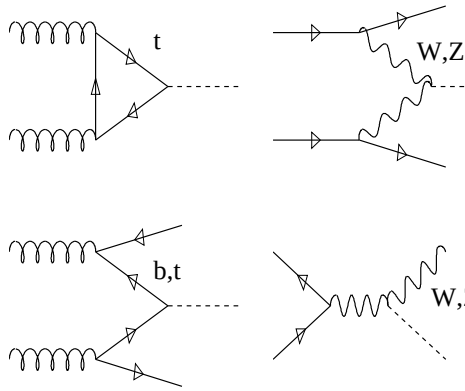

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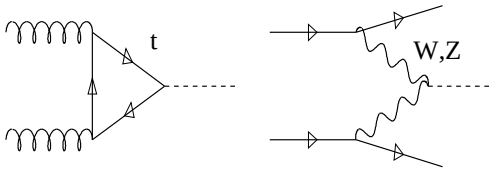
$t\bar{t}H$ production [$b\bar{b}H$ only in 2HDM]

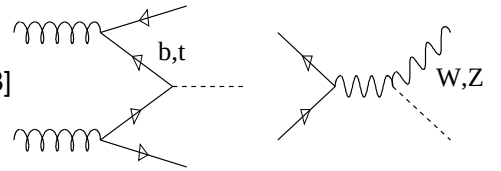
- – low rate, complex final state
- – decays $\gamma\gamma > WW > b\bar{b}$ at high luminosities [trying to change this]

$\Rightarrow$ accessible $gg \to t\bar{t}H$

Higgs couplings



Coupling for SM operators [Zeppenfeld et al; Dührssen et al; SFitter 2009]



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- couplings from production & decay rates [observables: S,B]
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$\Rightarrow$ straightforward except for width and theory errors

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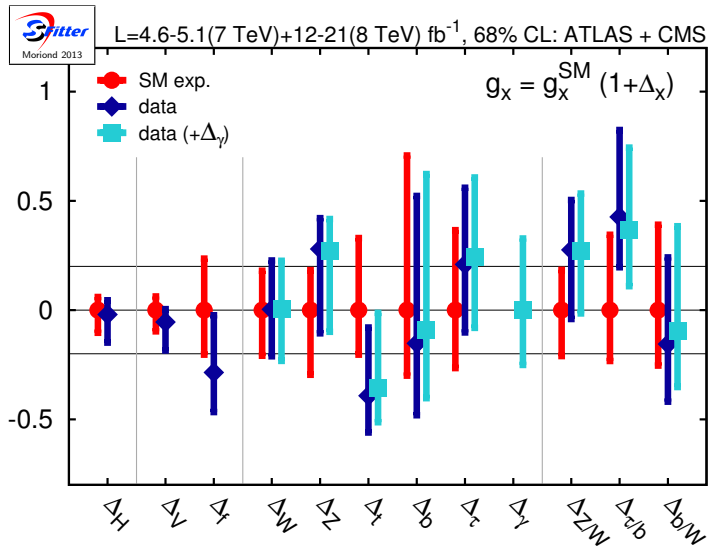
Including Moriond/Aspen data [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

- six couplings from data

  g_b from width
  g_t and g_g not yet possible

  [similar: Ellis etal, Djouadi etal, Pich etal, Strumia etal, Maggie etal]
- poor man's analyses great: $\Delta_H, \Delta_V, \Delta_f$
- moving towards Standard Model?



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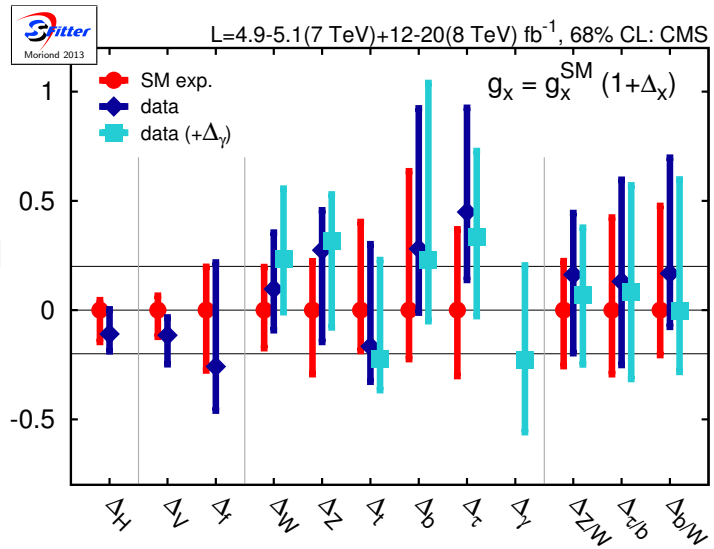

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	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
mixed-in singlet	6%	6%	6%
composite Higgs	8%	tens of %	tens of %
MSSM	$< 1\%$	3%	depends...

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$\Rightarrow$ expected in BSM models [Gupta, Rzehak, Wells]

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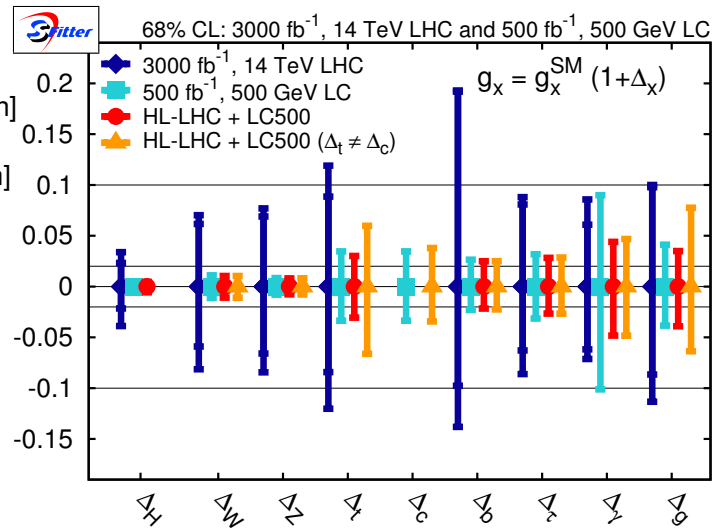

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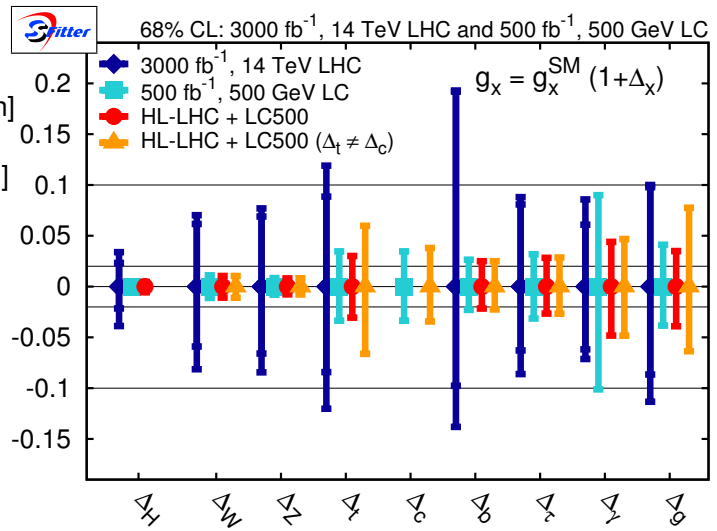
- $t\bar{t}H$ important at LHC and ILC



Bottom Yukawa

Challenges in additional channels

- WBF production and jet veto tough
- VH limited by S/B
- $t\bar{t}H$ problems all over [Jochen Cammin's ATLAS thesis]

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Example: $q\bar{q} \to VH, H \to b\bar{b}$ and S/B

- backgrounds

  continuum $Vb\bar{b}$: $p_{T,bb} > m_H$
  top pairs: jet veto

- $qg \to Zg \to Z(b\bar{b})$ effectively $2 \to 2$
  $gg \to Zb\bar{b}$ really $2 \to 3$
  $qg \to Zqb\bar{b}$ really $2 \to 4$

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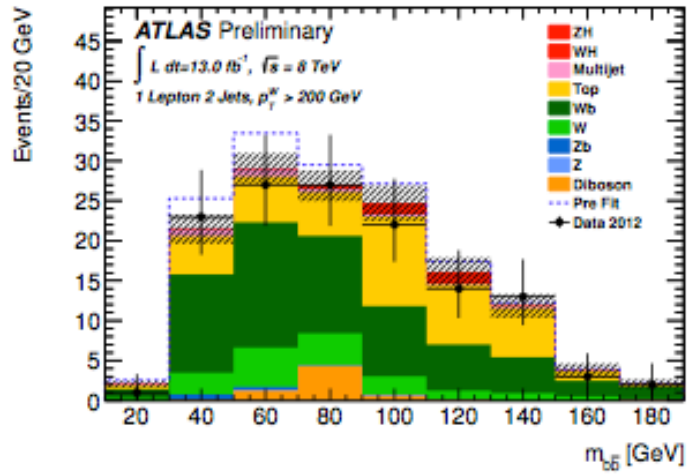

(e) $p_{\text{T}}^{W} > 200$ GeV

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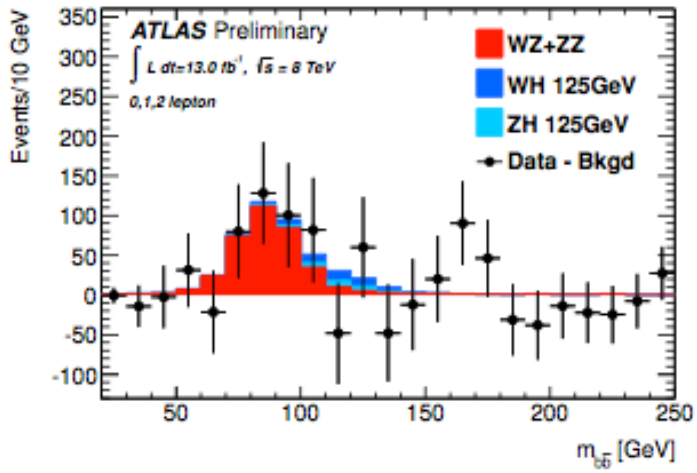

(b) $\sqrt{s} = 8$ TeV

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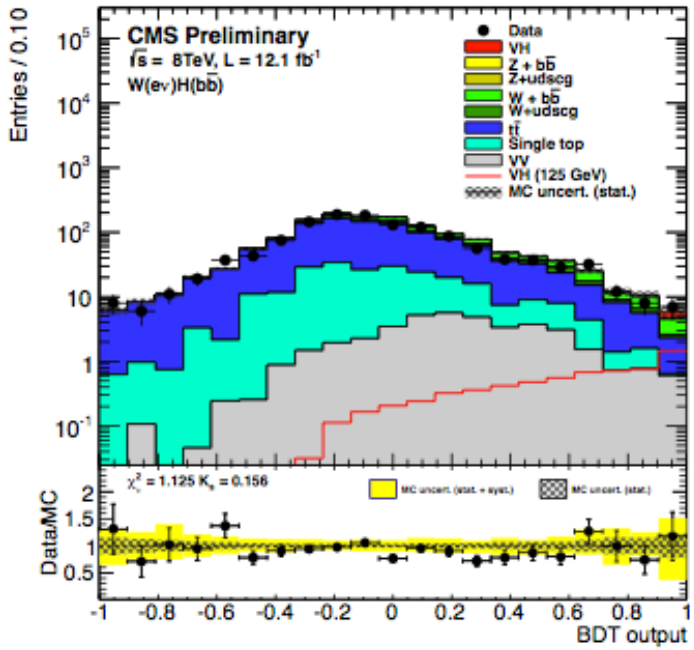

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- CMS: $\sigma/\sigma_{\text{SM}} > 2.5$ [CMS-HIG-12-044]

Variable
$p_{\text{T}j}$: transverse momentum of each Higgs daughter
m(jj): dijet invariant mass
p_{T}(jj): dijet transverse momentum
p_{T}(V): vector boson transverse momentum (or $E_{\text{T}}^{\text{miss}}$)
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi$(V, H): azimuthal angle between V (or $E_{\text{T}}^{\text{miss}}$) and dijet
$\lvert\Delta\eta$(jj)$\rvert$: difference in η between Higgs daughters
ΔR(jj): distance in η–ϕ between Higgs daughters
N_{aj}: number of additional jets
$\Delta\phi(E_{\text{T}}^{\text{miss}}$, jet): azimuthal angle between $E_{\text{T}}^{\text{miss}}$ and the closest jet (only for Z($\nu\nu$)H)
$\Delta\theta_{\text{pull}}$: color pull angle [35]

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$\Rightarrow$ need to target boosted MC studies and tools [BDRS, Piquadio]

Anomalous couplings

Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

- assume Higgs is largely Standard Model
- additional higher-dimensional couplings

$$\begin{aligned}\mathcal{L}_{\text{eff}} = &- \frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}(\Phi^\dagger\Phi)G_{\mu\nu}G^{\mu\nu} + \frac{f_{WW}}{\Lambda^2}\Phi^\dagger W_{\mu\nu}W^{\mu\nu}\Phi \\ &+ \frac{f_W}{\Lambda^2}(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) + \frac{f_B}{\Lambda^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) + \frac{f_{WWW}}{\Lambda^2}\text{Tr}(W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}) \\ &+ \frac{f_b}{\Lambda^2}(\Phi^\dagger\Phi)(\overline{Q}_3\Phi d_{R,3}) + \frac{f_\tau}{\Lambda^2}(\Phi^\dagger\Phi)(\overline{L}_3\Phi e_{R,3})\end{aligned}$$

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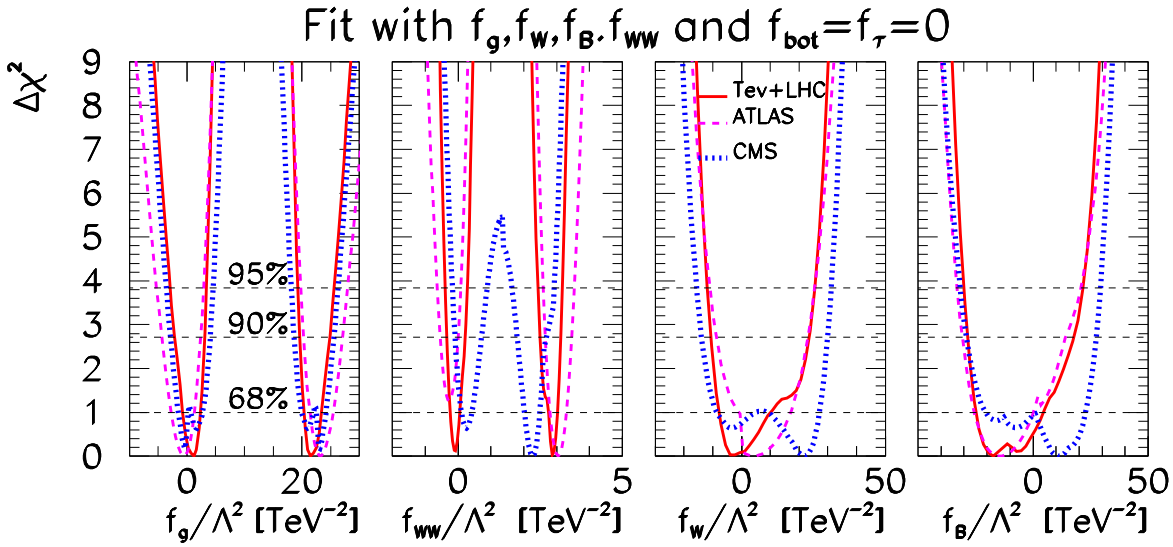

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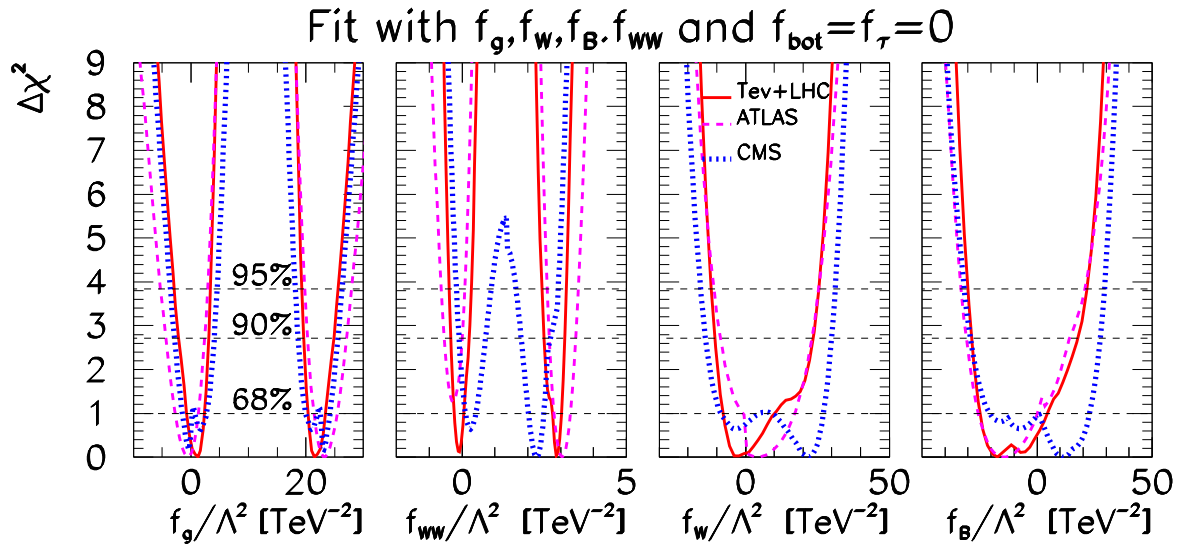
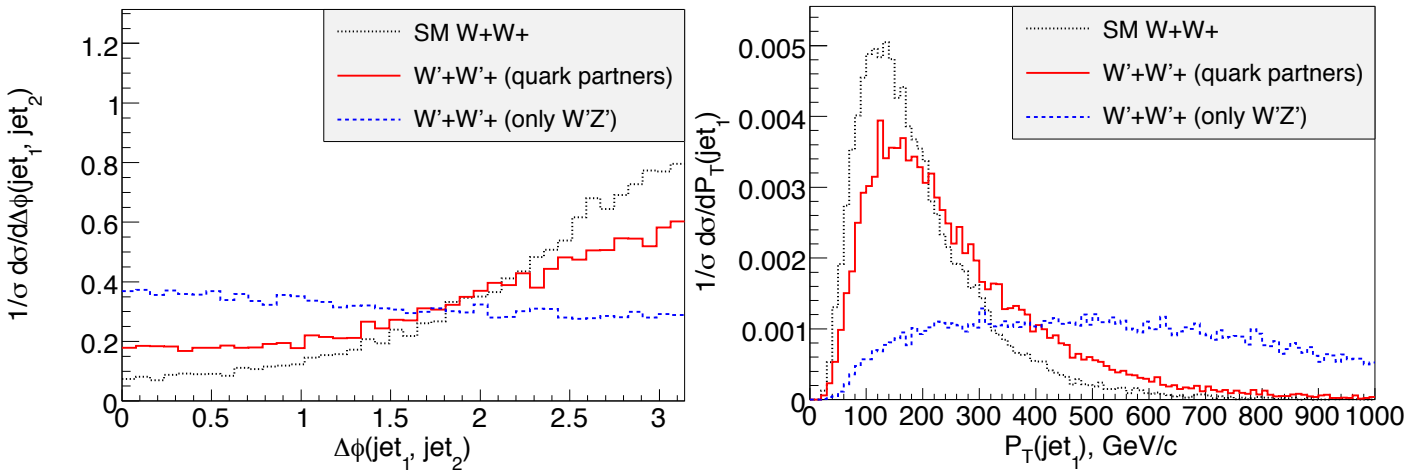


$\Rightarrow$ remember what your operators are!

Energy dependence

Consistent models beyond spin-0 [e.g. Alwall, TP, Rainwater]

- WBF $\chi^+\chi^+$ vs W^+W^+ production
- problem with UV behavior for spin-1



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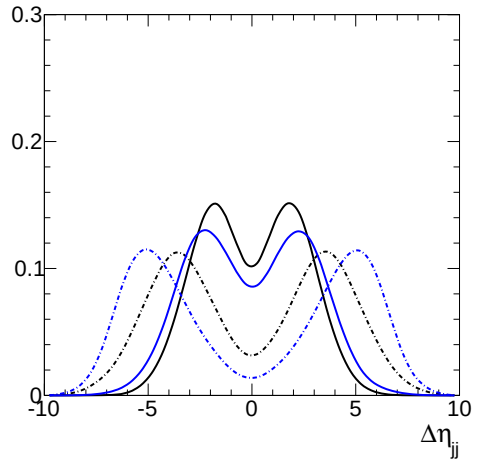
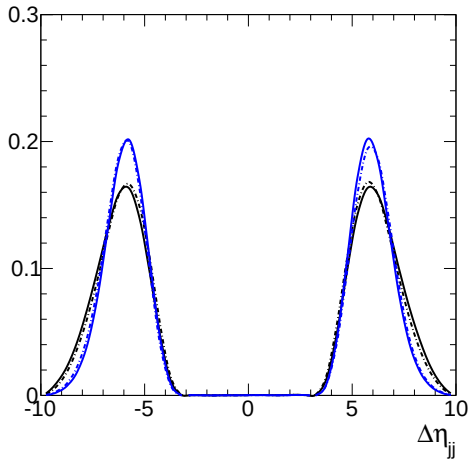
Energy dependent spin-2 couplings

- unitarization affecting energy variables [Alboteanu, Kilian, Reuter]
- WBF cutoff $p_{T,j} < 100$ GeV [Englert, Mawatari, Netto, TP]





Energy dependence

Consistent models beyond spin-0 [e.g. Alwall, TP, Rainwater]

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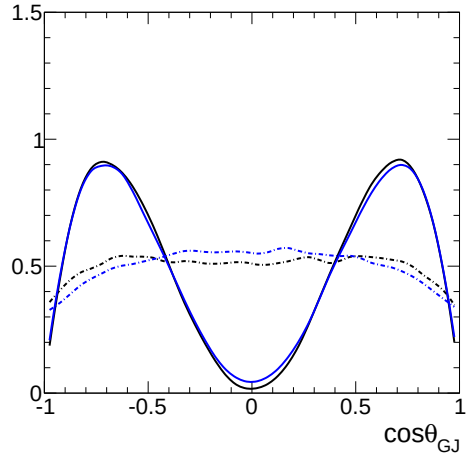

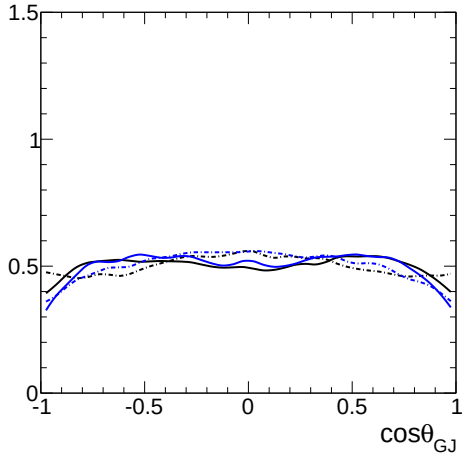

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$\Rightarrow$ solvable issues beyond spin-0

Outlook

Higgs@LHC

- discovery an amazing experimental success
- weakly interacting field theory established

- coupling measurements established
- do not listen too much to theorists, for now straightforward
- additional channels will make the difference [where are the great papers by youngsters??]

$\Rightarrow$ Higgs moved on from discovery to precision studies

Part of this work was funded by the BMBF Theorie-Verbund which is ideal for hard and relevant LHC work

Bundesministerium
für Bildung
und Forschung

Theory games

Light Higgs as a Goldstone boson [Giudice, Grojean, Pomarol, Rattazzi]

- strongly interacting models predicting heavy broad resonance(s)
- light state if protected by Goldstone's theorem [Georgi & Kaplan]
- interesting if $v \ll f < 4\pi f$ [little Higgs $v \sim g^2 f/(2\pi)$]

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- postulate new $f \gtrsim v$ and $m_\rho \to 4\pi f$ [$c_j \sim 1$] [assume custodial symmetry]

$$
\begin{aligned}
\mathcal{L}_{\text{SILH}} = & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) \\
& + \frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
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\end{aligned}
$$

- leading terms in wave function renormalization and H^n

$\Rightarrow$ collider phenomenology of mostly $(H^\dagger H)$ terms [Mühlleitner etal]

Uncertainties

SFitter details [Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]

production	decay	$S+B$	B	S	$\Delta S^{(\text{exp})}$	$\Delta S^{(\text{theo})}$
$gg \to H$	ZZ	13.4	6.6 ($\times$ 5)	6.8	3.9	0.8
qqH	ZZ	1.0	0.2 ($\times$ 5)	0.8	1.0	0.1
$gg \to H$	WW	1019.5	882.8 ($\times$ 1)	136.7	63.4	18.2
qqH	WW	59.4	37.5 ($\times$ 1)	21.9	10.2	1.7
$t\bar{t}H$	$WW(3\ell)$	23.9	21.2 ($\times$ 1)	2.7	6.8	0.4
$t\bar{t}H$	$WW(2\ell)$	24.0	19.6 ($\times$ 1)	4.4	6.7	0.6
inclusive	$\gamma\gamma$	12205.0	11820.0 ($\times$ 10)	385.0	164.9	44.5
qqH	$\gamma\gamma$	38.7	26.7 ($\times$ 10)	12.0	6.5	0.9
$t\bar{t}H$	$\gamma\gamma$	2.1	0.4 ($\times$ 10)	1.7	1.5	0.2
WH	$\gamma\gamma$	2.4	0.4 ($\times$ 10)	2.0	1.6	0.1
ZH	$\gamma\gamma$	1.1	0.7 ($\times$ 10)	0.4	1.1	0.1
qqH	$\tau\tau(2\ell)$	26.3	10.2 ($\times$ 2)	16.1	5.8	1.2
qqH	$\tau\tau(1\ell)$	29.6	11.6 ($\times$ 2)	18.0	6.6	1.3
$t\bar{t}H$	$b\bar{b}$	244.5	219.0 ($\times$ 1)	25.5	31.2	3.6
WH/ZH	$b\bar{b}$	228.6	180.0 ($\times$ 1)	48.6	20.7	4.0

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 %

	$\Delta B^{(\text{syst})}$	corr.
$H \to ZZ$	1%	yes
$H \to WW$	5%	no
$H \to \gamma\gamma$	0.1%	yes
$H \to \tau\tau$	5%	yes
$H \to b\bar{b}$	10%	no

plus: $t\bar{t}H$ with $S \to S/2$ and ZH subjet analysis a la Piquadio

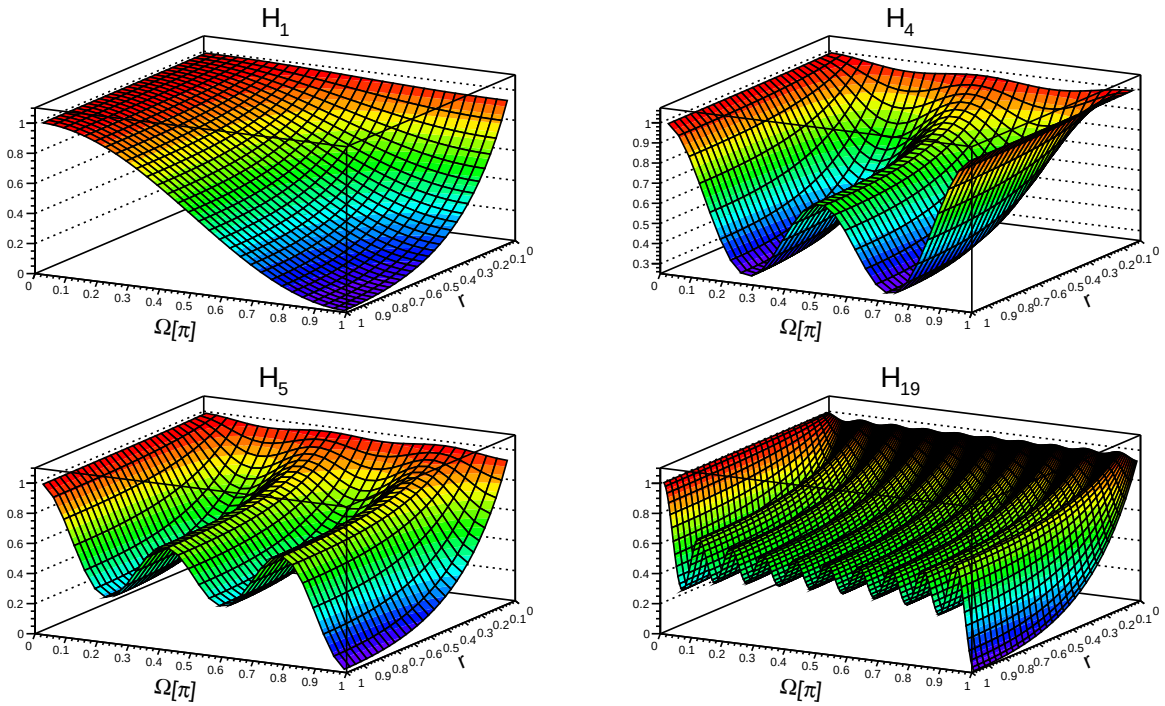
Fox-Wolfram moments

Series in spherical harmonics [Field, Kanev, Tayebnejad; Bernaciak, Buschmann, Butter, TP]

– originally alternative to event shapes

$$H_\ell^T = \frac{4\pi}{2\ell+1} \sum_{m=-\ell}^{\ell} \left| \sum_{i=1}^{N} Y_\ell^m(\Omega_i) \, \frac{p_{T,i}}{p_{T,\text{tot}}} \right|^2 = \sum_{i,j=1}^{N} \frac{p_{T,i} p_{T,j}}{p_{T,\text{tot}}^2} P_\ell(\cos\Omega_{ij}) \; ,$$

– defined on separated jets for a start



	$H_\ell < 0.3$	$0.3 < H_\ell < 0.7$	$0.7 < H_\ell < 1$
even ℓ	forbidden	democratic	ordered, collinear, back-to-back
odd ℓ	back-to-back	democratic	collinear, ordered

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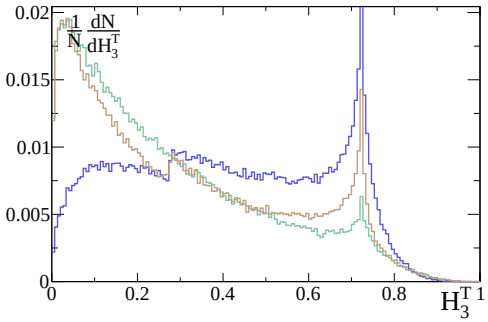

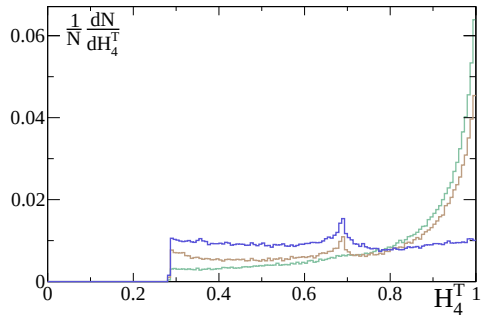

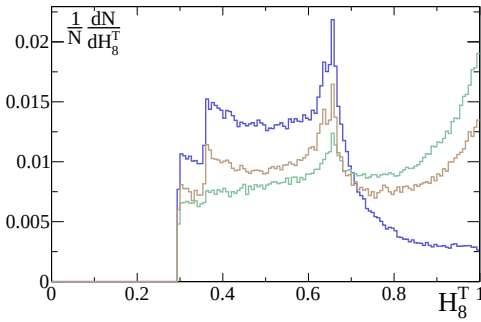

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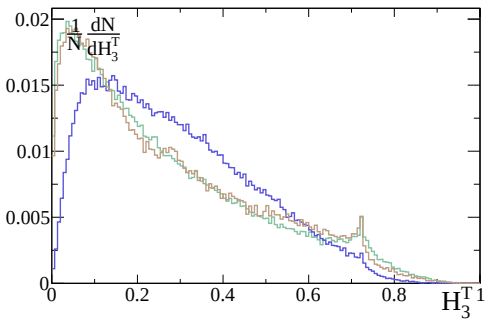

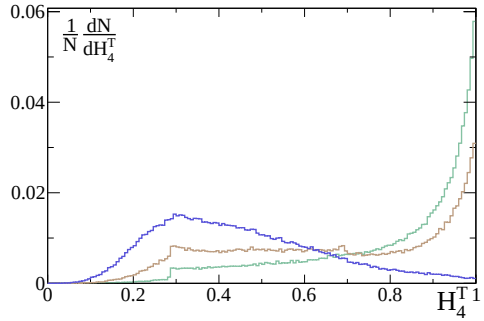

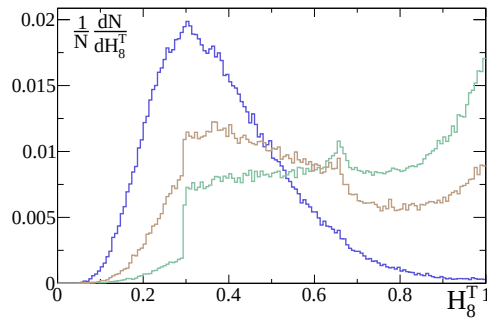

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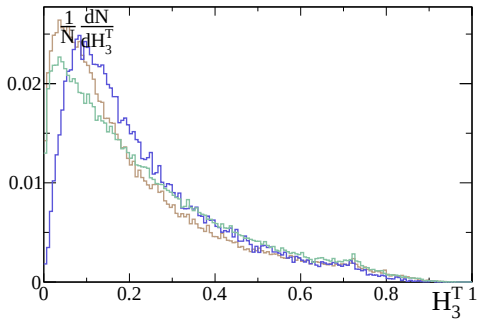

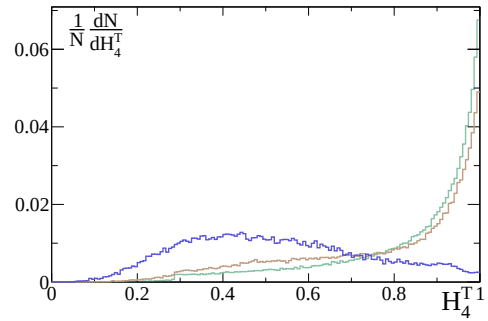

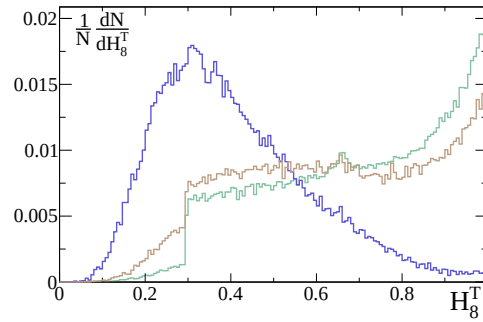

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  tuned resolution via variable ℓ [not too correlated]
- adjust weight factor?
  adjust objects entering FWMs?

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$\Rightarrow$ might be useful eventually