The Little Channels

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Higgs results 2012-2013

Fundamental questions

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Higgs results 2012-2013

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psychologically: looked for Higgs, so found a Higgs

CP-even spin-0 scalar expected
spin-1 vector unlikely
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coupling after fixing operator basis [eventually defined in UV completion?]
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The 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??

Higgs results 2012-2013

Limitations of inclusive searches

- non-perfect purity for $H \to WW$
- deadly background to $H \to b\bar{b}$
- too little boost for $H \to \tau\tau$
- deadly Drell-Yan background to $H \to \mu\mu$ [ATLAS-CONF-2013-010]
- no trigger for $H \to$ invisible

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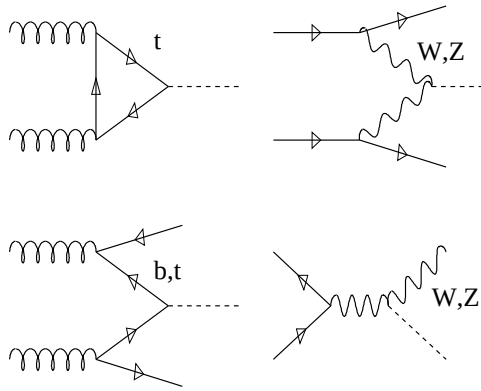
Promising first results [many of them presented here]

- ATLAS $H \to \tau\tau$ [ATLAS-CONF-2012-160: $\sigma/\sigma_{\text{SM}} < 1.9$ getting there]
- ATLAS $ZH, H \to$ invisible [ATLAS-CONF-2013-011: BR $> 65\%$]
- ATLAS $VH, H \to b\bar{b}$ [ATLAS-CONF-2012-161; get to this later]
- CMS $H \to \tau\tau$ [CMS-HIG-12-043: $\sigma/\sigma_{\text{SM}} < 1.63$ getting there]
- CMS $VH, H \to \tau\tau$ [CMS-HIG-12-051; $\sigma/\sigma_{\text{SM}} < 4.68$]
- CMS $WH, H \to WW$ [CMS-HIG-13-009: $\sigma/\sigma_{\text{SM}} < 3.3$]
- CMS $VH, H \to b\bar{b}$ [CMS-HIG-12-044; also later]

$\Rightarrow$ still energy and/or rate limited

Alternative 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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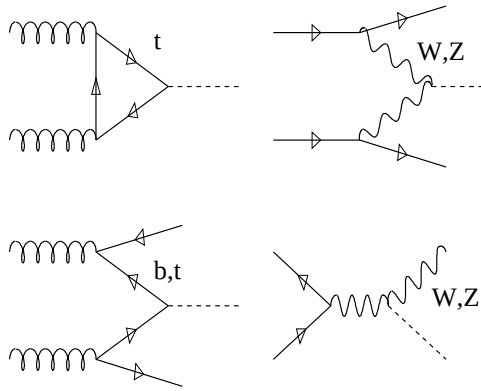

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WH/ZH production

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- – low rate, tricky QCD backgrounds [Vbb]
- – missing energy in WH, few leptonic Z decays

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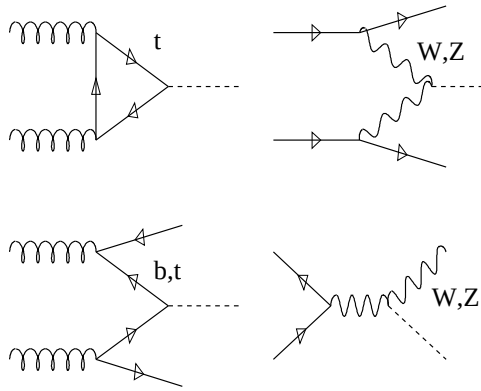

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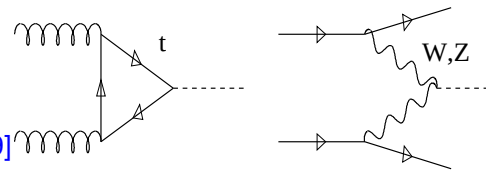
$\Rightarrow$ accessible $H \to b\bar{b}$

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

- – low rate, complex final state
- – large $t\bar{t}$+jets background

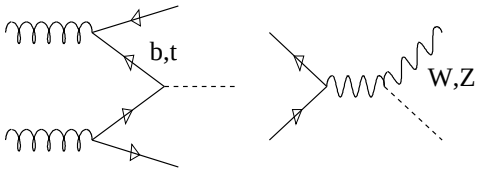
$\Rightarrow$ accessible $gg \to t\bar{t}H$

Higgs couplings



Big moment of little channels [Zeppenfeld et al; Dührssen et al; SFitter 2009]

- assume narrow resonance with SM-like Lagrangian
- couplings from production & decay rates
- measuring g_t in g_g assumes Standard Model [Georg's talk]



$\Rightarrow$ little channels crucial

$$\boxed{\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \quad \longleftrightarrow \quad \boxed{g_x = g_x^{\text{SM}} \; (1 + \Delta_x)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \end{array}}$$

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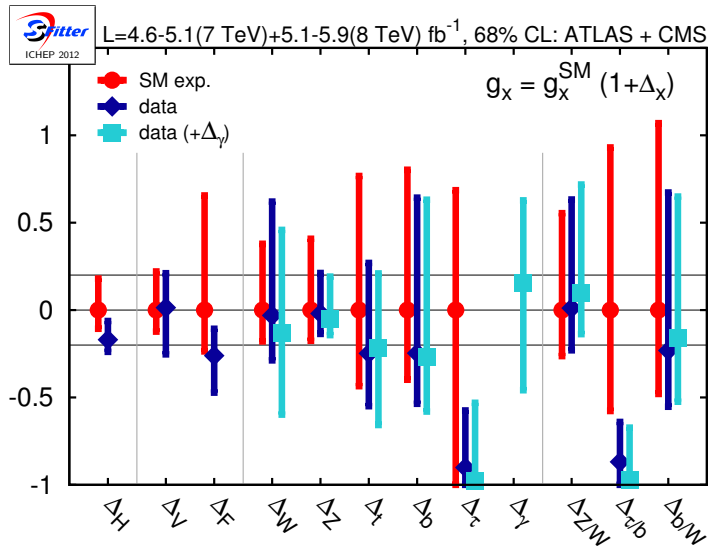
Not yet including Moriond/Aspen data [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

- six couplings from data

  $g_{W,Z}$ okay
  $g_{t,b}$ indirectly
  g_τ poor
  g_γ possible
- poor man's analyses great: $\Delta_H, \Delta_V, \Delta_f$
- moving towards Standard Model?



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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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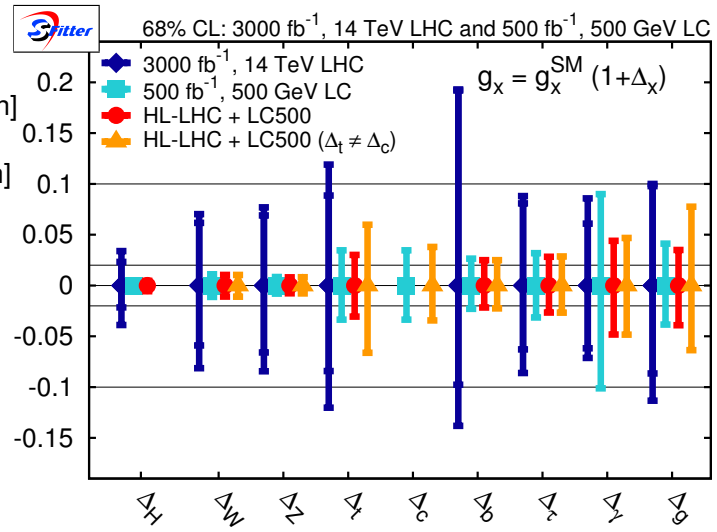

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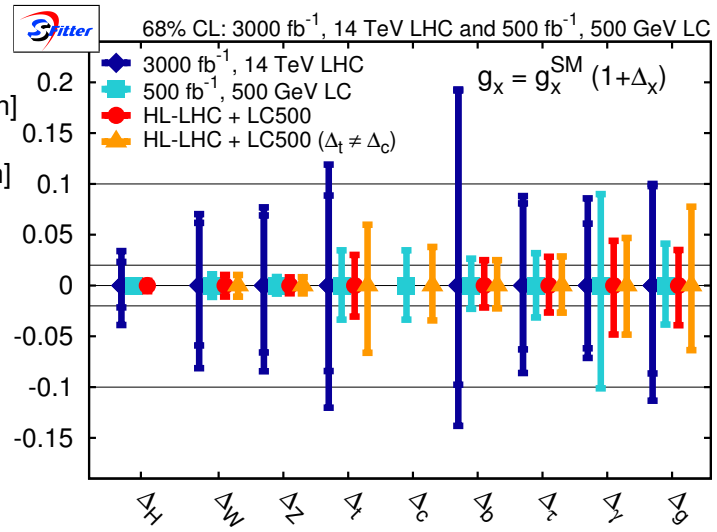
- $t\bar{t}H$ an important little channel at ILC



Bottom Yukawa

Challenges in little channels

- WBF production and jet veto tough [talks by Andrea and Thomas]
- VH limited by S/B [talks by Christian and Andrea]
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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 $2 \to 2$
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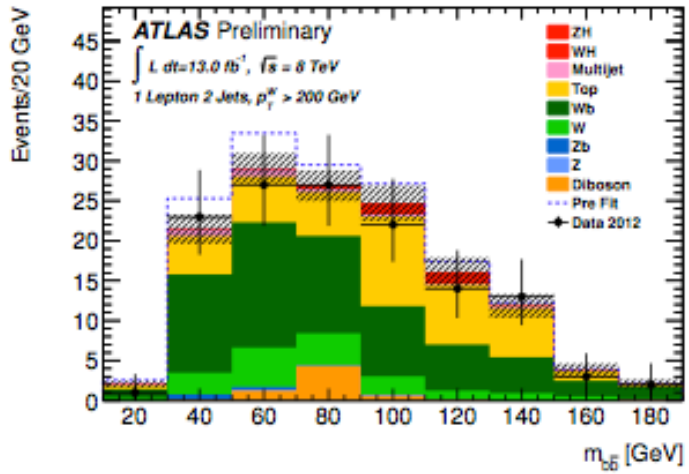

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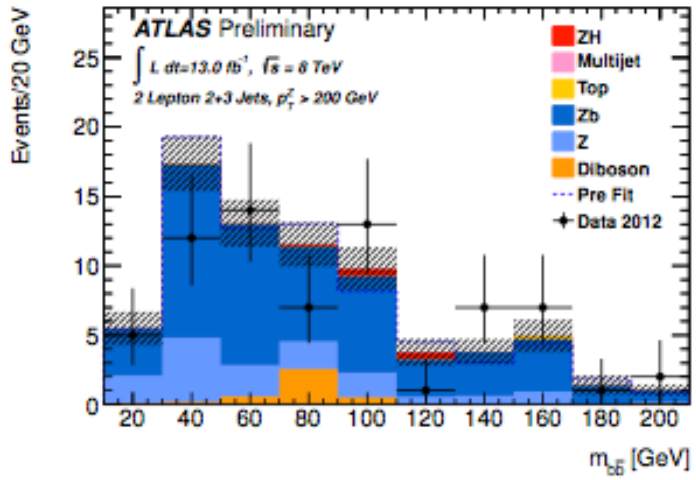

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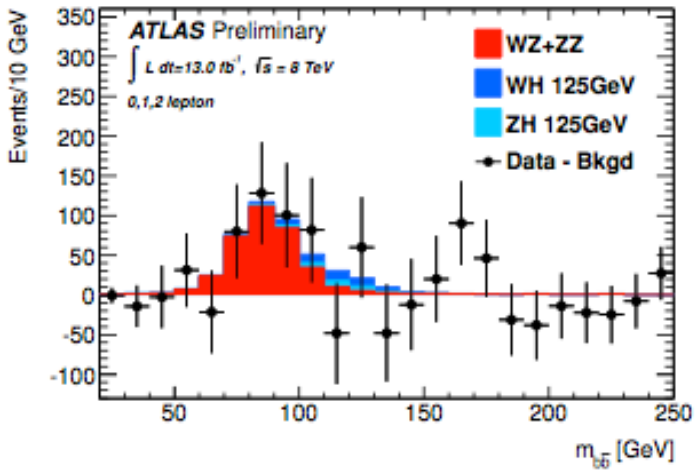

(b) $\sqrt{s} = 8$ TeV

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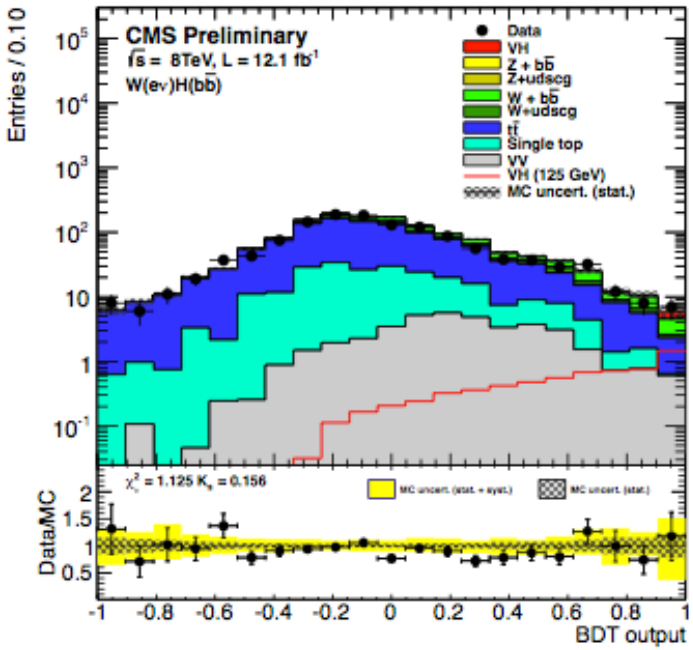

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Variable
p_{Tj}: transverse momentum of each Higgs daughter
m(jj): dijet invariant mass
p_T(jj): dijet transverse momentum
p_T(V): vector boson transverse momentum (or E_T^{miss})
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi$(V,H): azimuthal angle between V (or E_T^{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
$\Delta\phi(E_T^{\text{miss}}$,jet): azimuthal angle between E_T^{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

Operators

Angular correlations in little channels

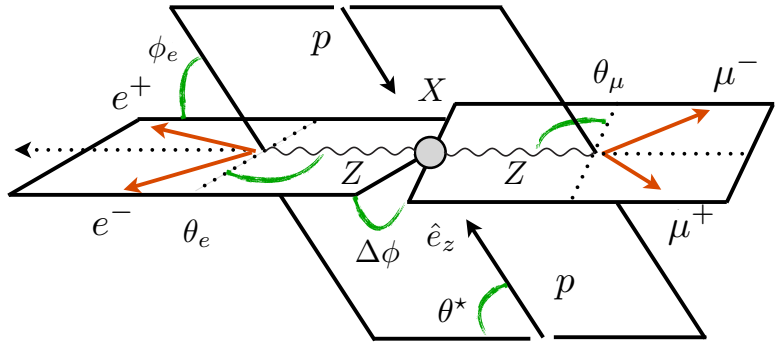
– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Englert, Spannowsky, Takeuchi]

$$\cos\theta_e = \hat{p}_{e-} \cdot \hat{p}_{Z_\mu}\Big|_{Z_e} \qquad \cos\theta_\mu = \hat{p}_{\mu-} \cdot \hat{p}_{Z_e}\Big|_{Z_\mu} \qquad \cos\theta^* = \hat{p}_{Z_e} \cdot \hat{p}_{\text{beam}}\Big|_X$$

$$\cos\phi_e = (\hat{p}_{\text{beam}} \times \hat{p}_{Z_\mu}) \cdot (\hat{p}_{Z_\mu} \times \hat{p}_{e-})\Big|_{Z_e}$$

$$\cos\Delta\phi = (\hat{p}_{e-} \times \hat{p}_{e+}) \cdot (\hat{p}_{\mu-} \times \hat{p}_{\mu+})\Big|_X$$



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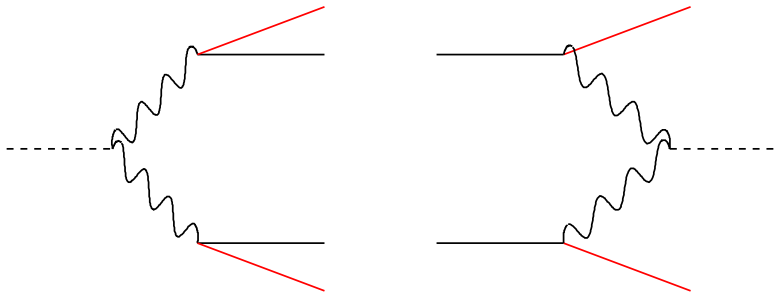
- Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]

  [Rainwater, TP, Zeppenfeld; Hagiwara, Li, Mawatari; Englert, Mawatari, Netto, TP]



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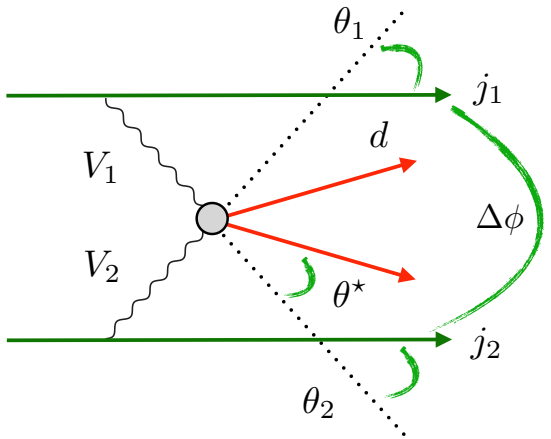
$$\cos\phi_1 = (\hat{p}_{V_2} \times \hat{p}_d) \cdot (\hat{p}_{V_2} \times \hat{p}_{j_1})\Big|_{V_1\,\text{Breit}}$$

$$\cos\Delta\phi = (\hat{p}_{q_1} \times \hat{p}_{j_1}) \cdot (\hat{p}_{q_2} \times \hat{p}_{j_2})\Big|_X \,.$$



Operators

Angular correlations in little channels

– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Englert, Spannowsky, Takeuchi]

– Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]

[Rainwater, TP, Zeppenfeld; Hagiwara, Li, Mawatari; Englert, Mawatari, Netto, TP]

$$\cos\theta_1 = \hat{p}_{j_1} \cdot \hat{p}_{V_2}\Big|_{V_1\,\text{Breit}} \qquad \cos\theta_2 = \hat{p}_{j_2} \cdot \hat{p}_{V_1}\Big|_{V_2\,\text{Breit}} \qquad \cos\theta^* = \hat{p}_{V_1} \cdot \hat{p}_d\Big|_X$$

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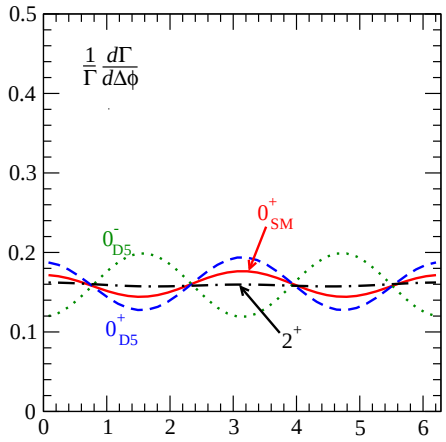

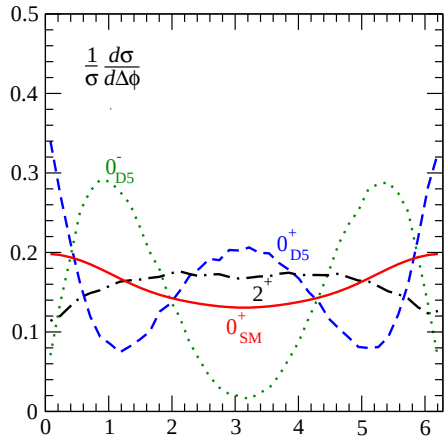

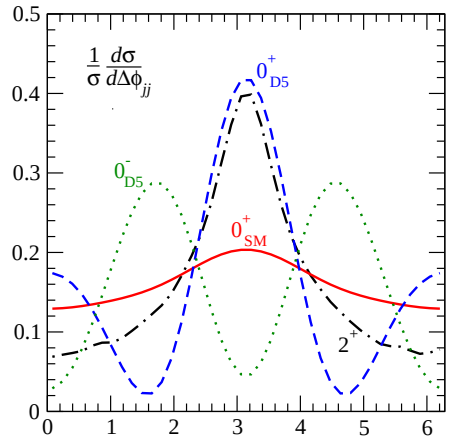

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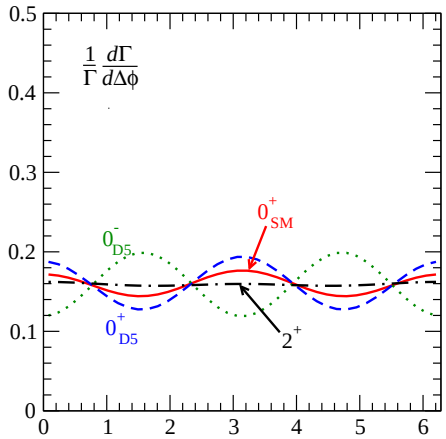
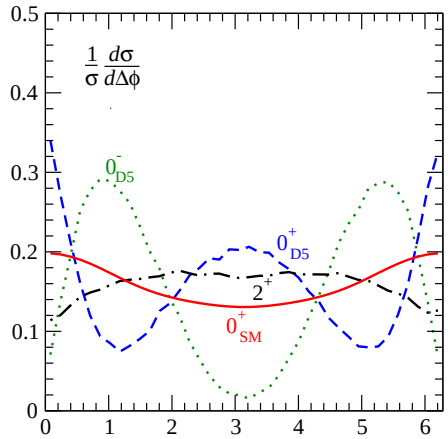
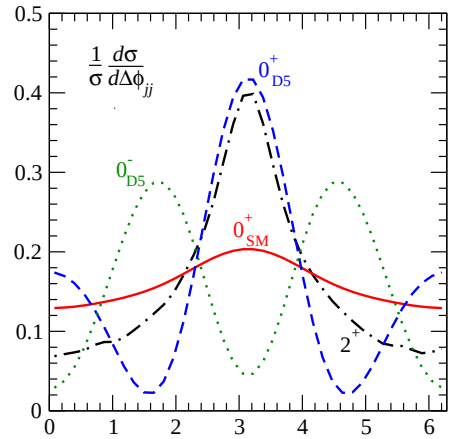




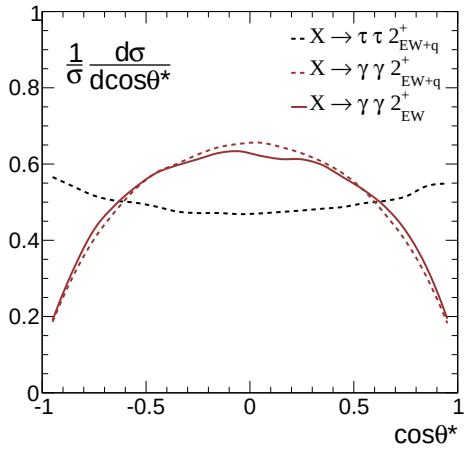


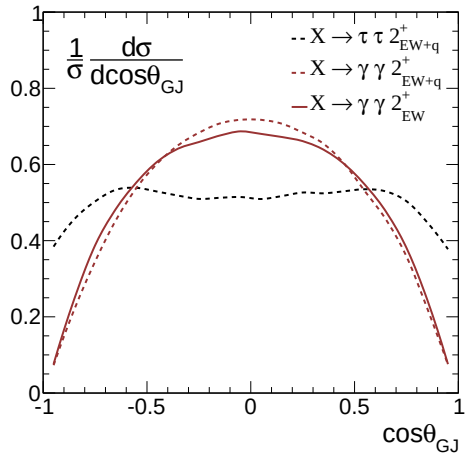
$\Rightarrow$ different channels, same physics

Operators

Spin-2 test? [Englert, Mawatari, Netto, TP]

- unitarization affecting all energy variables
- try Gottfried-Jackson angle [$\hat{p}_{X,lab}$ vs $\hat{p}_{d,X}$; Frank, Rauch, Zeppenfeld; Schumacher]





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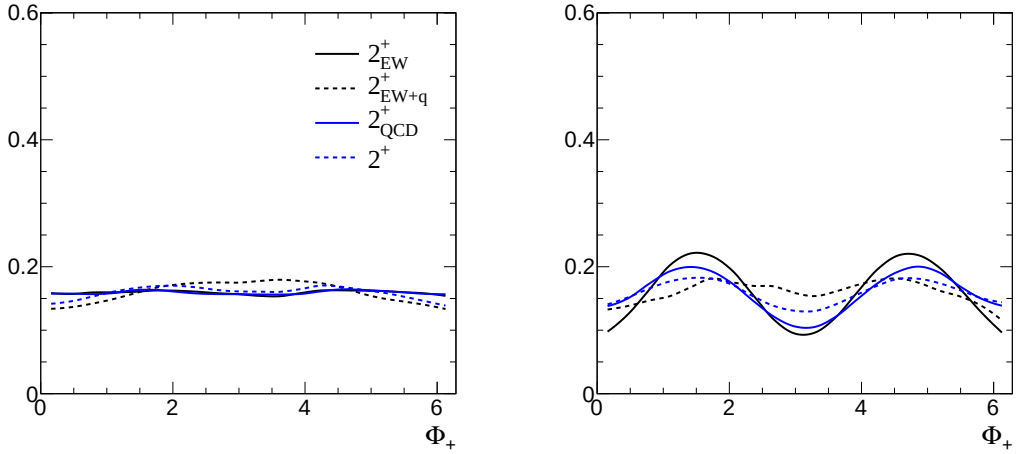
- alternatively $\phi_1 + \phi_2$ after unitarization [Hagiwara, Li, Mawatari]



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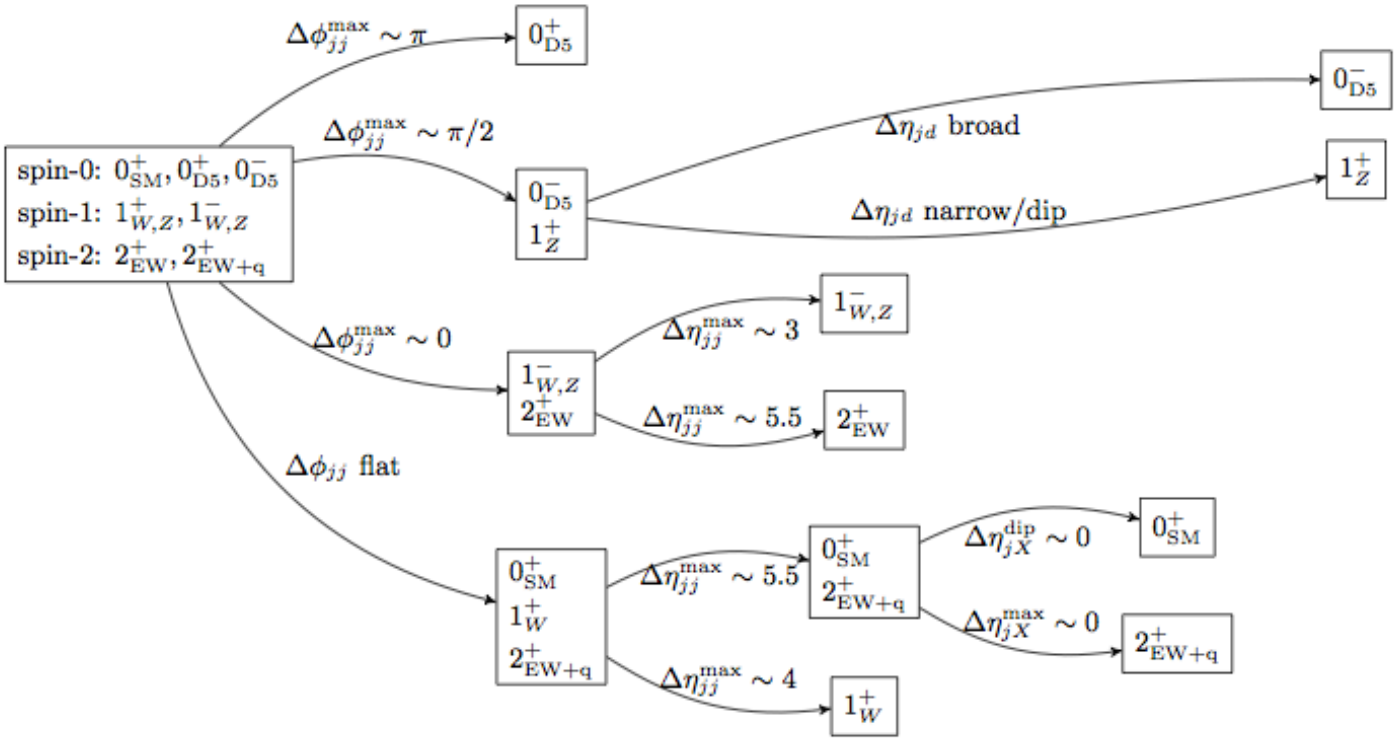
- diagrammatic analysis for WBF [$\Delta\eta_{jj}$ useful]



$\Rightarrow$ many observables, avoid cutting on them

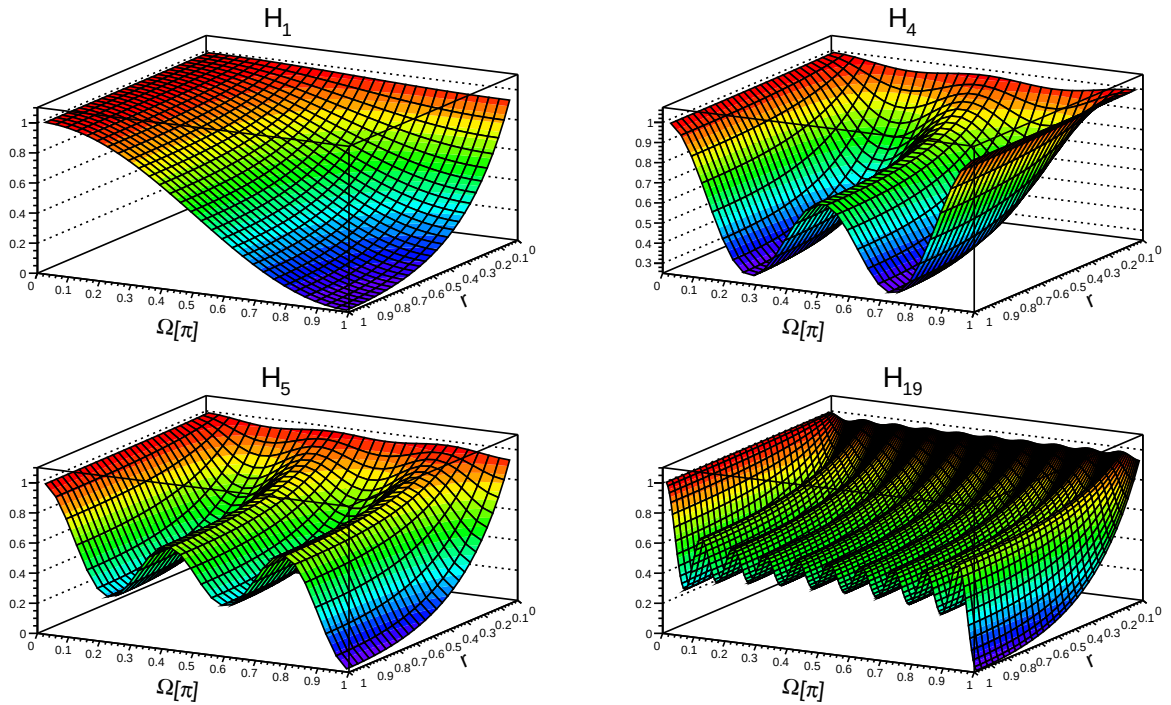
Fox-Wolfram moments

Weighted 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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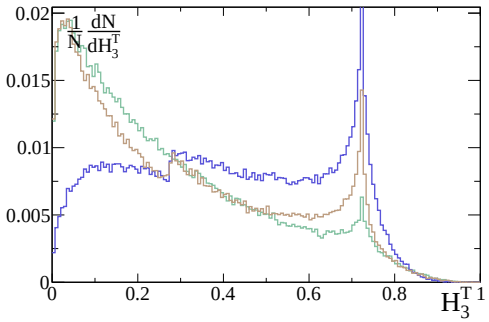
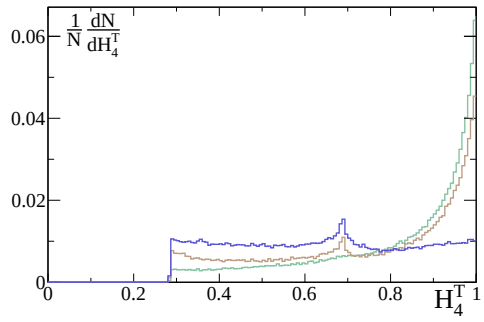
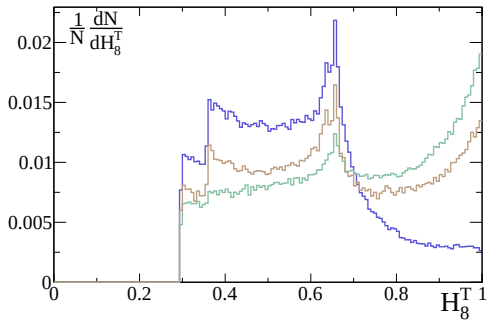
- defined on separated jets for a start
- applied to tagging jets in WBF $[m_{jj} > 600 \text{ GeV}]$







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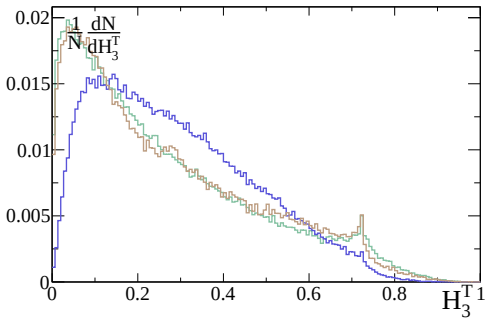
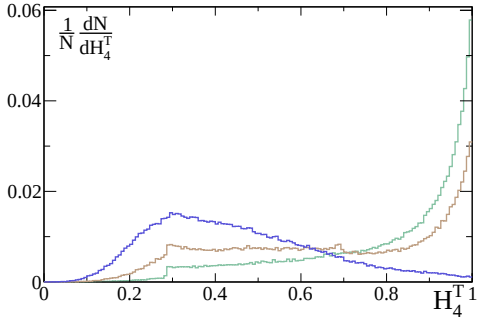
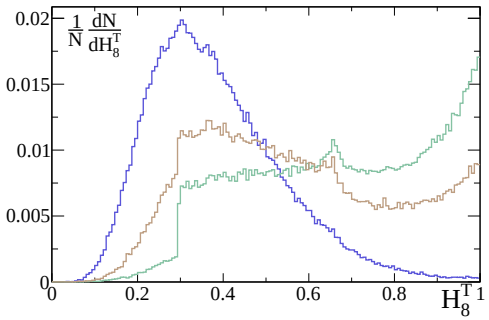
- applied to all jets in WBF







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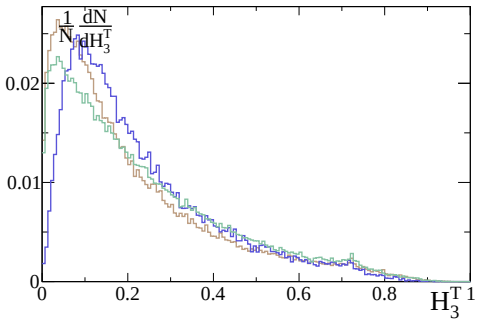

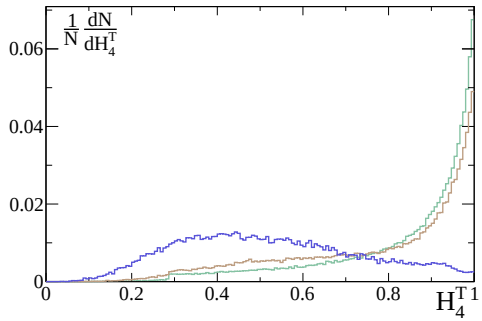

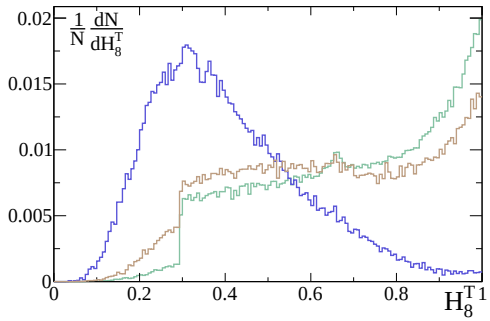

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- useful information left
  tuned resolution via variable ℓ [not too correlated]
- adjust weight factor?
  adjust objects entering FWMs?

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$\Rightarrow$ might be useful eventually

Outlook

Higgs@LHC

- discovery an amazing experimental success
- confirmation of field theory as a universal framework

- little channels will make the difference [where are the great papers by youngsters??]
- 13+ TeV needed for WBF, VH, $t\bar{t}H$
- good ideas welcome/needed for little searches

$\Rightarrow$ Higgs measurement era incredible!

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

Bundesministerium
für Bildung
und Forschung