MEASUREMENT OF THE HIGGS POTENTIAL AND GAUGE COUPLING STRUCTURE

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1. $pp \to HH$ multilepton analysis
2. VVH vertex structure

WHAT DOES IT MEAN TO FIND THE HIGGS?

- Higgs is the agent responsible for EWSB
  → must have $g^{\mu\nu}$ gauge couplings to weak bosons
- Higgs generates fermion masses
  → coupling strength proportional to m_f
- Higgs is charge neutral, color singlet, spin zero, CP even (?), etc.
- Additional states may exist (2HDM, etc.)
- Higgs potential relates M_H and self interactions

We must verify/measure all these properties!

Established techniques at LHC can extract most of this information, such as gauge and fermion couplings, mass, spin, color...as well as observe additional physical states.

LHC is also surprisingly capable to examine the more interesting parts of the Higgs sector, such as Higgs potential and fundamental structure of couplings.

HIGGS POTENTIAL MEASUREMENT

[U. Baur, T. Plehn, D. R., hep-ph/0206024]

The Higgs potential in the SM is usually written as:

$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

where λ is a “free parameter” and $\lambda_{SM} = M_H^2/(2v^2)$.

This leads to Higgs 3,4-point self-couplings $-6v\lambda$, -6λ.

To verify that the potential has the form we expect,
one must measure λ, which can be done only by
direct observation of double or triple Higgs production.

$gg \to HH$ is largest HH rate @ LHC
($\approx 40 - 20$ fb for $M_H \sim 100 - 200$ GeV).

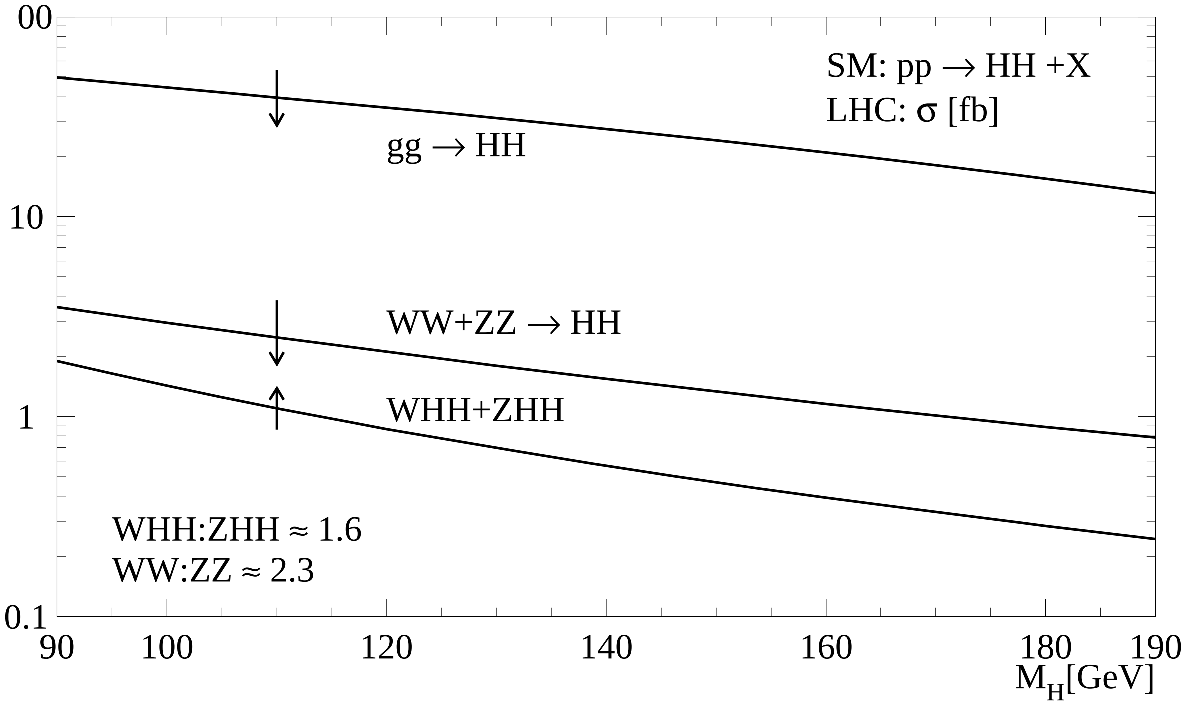
$H \to b\bar{b}$ overwhelmed by QCD,
so analgous to study of $t\bar{t}H, H \to W^+W^-$
[Maltoni, D.R., Willenbrock, hep-ph/0202205],
we examine the distinctive same-sign leptons channel

$$gg \to HH \to (W^+W^-)\,(W^+W^-) \to (jj\ell^\pm\nu)\,(jj\ell'^\pm\nu)$$

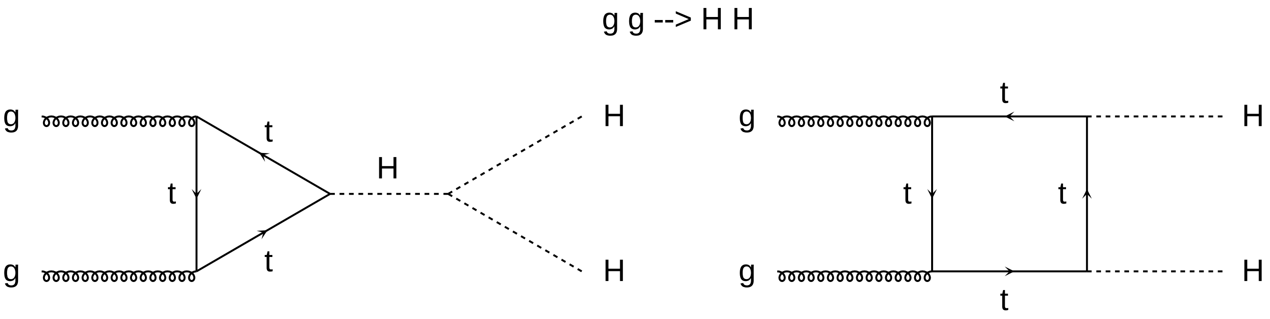
Simultaneous attempt to study this channel for sLHC –
thorough study of backgrounds, but implied negative results
for the planned LHC: [F. Gianotti *et al.*, hep-ph/0204087].

HH PRODUCTION AT LHC

[Djouadi, Kilian, Mulleitner and Zerwas, 1999]



SM diagrams are the following:



HH SIGNAL AND BACKGROUNDS

Must consider any backgrounds that give two same-sign leptons plus four jets:

$W^\pm W^\pm jjjj$	(very small)
$W^\pm W^+ W^- jj$	(one hadronic W decay)
$t\bar{t}W^\pm$	(no b tags)
$t\bar{t}j$	(no b tags, 1 b semilep. decay)
$W^\pm Zjjjj$	(1 lepton from Z/γ^* lost)
$t\bar{t}t\bar{t}$	(some jets/b lost or merged)

$t\bar{t}j,\ W^\pm Zjjjj,\ t\bar{t}t\bar{t}$ are together $\approx 5\%$ contribution [hep-ph/0204087];
we calculate in detail only the dominant backgrounds from $W^\pm W^+ W^- jj,\ \ t\bar{t}W^\pm$.

SIGNAL V. BACKGROUND ANALYSIS

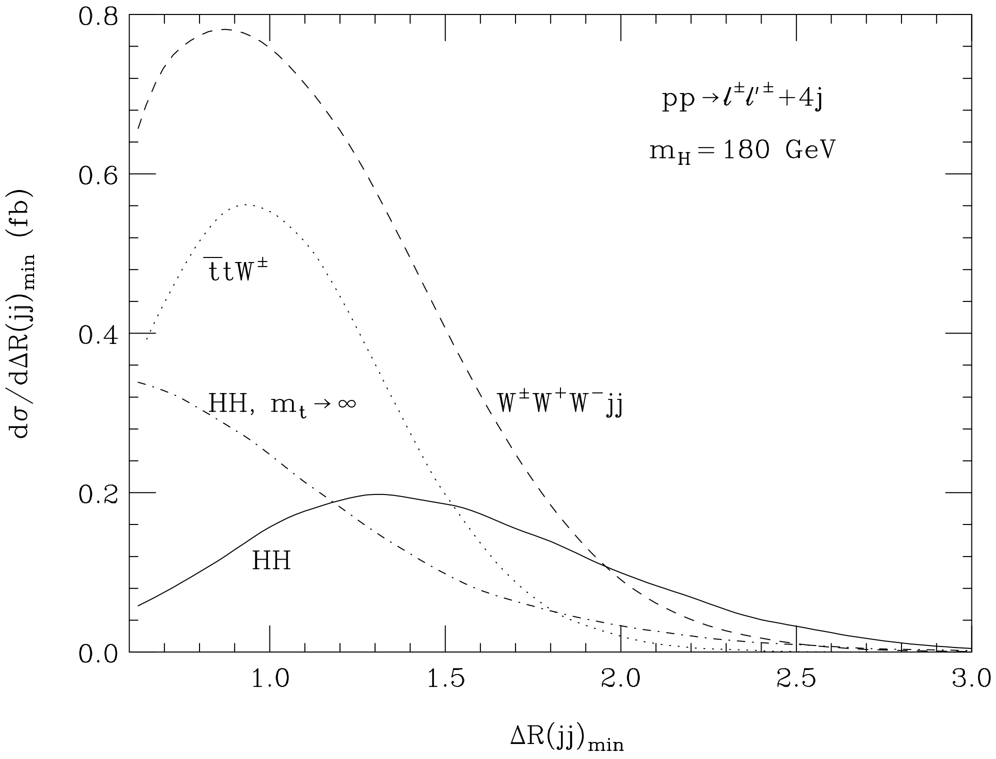
We performed a parton-level Monte Carlo analysis of the signal and dominant backgrounds using realistic kinematic cuts for detector acceptance, but no detector simulation:

$$\begin{array}{ccc} p_T(j) > 30, 30, 20, 20\,\mathrm{GeV}, & & p_T(\ell) > 15, 10\,\mathrm{GeV}, \\ |\eta(j)| < 3.0, & & |\eta(\ell)| < 2.5, \\ \Delta R(jj) > 0.6, & \Delta R(j\ell) > 0.4, & \Delta R(\ell\ell) > 0.2, \end{array}$$

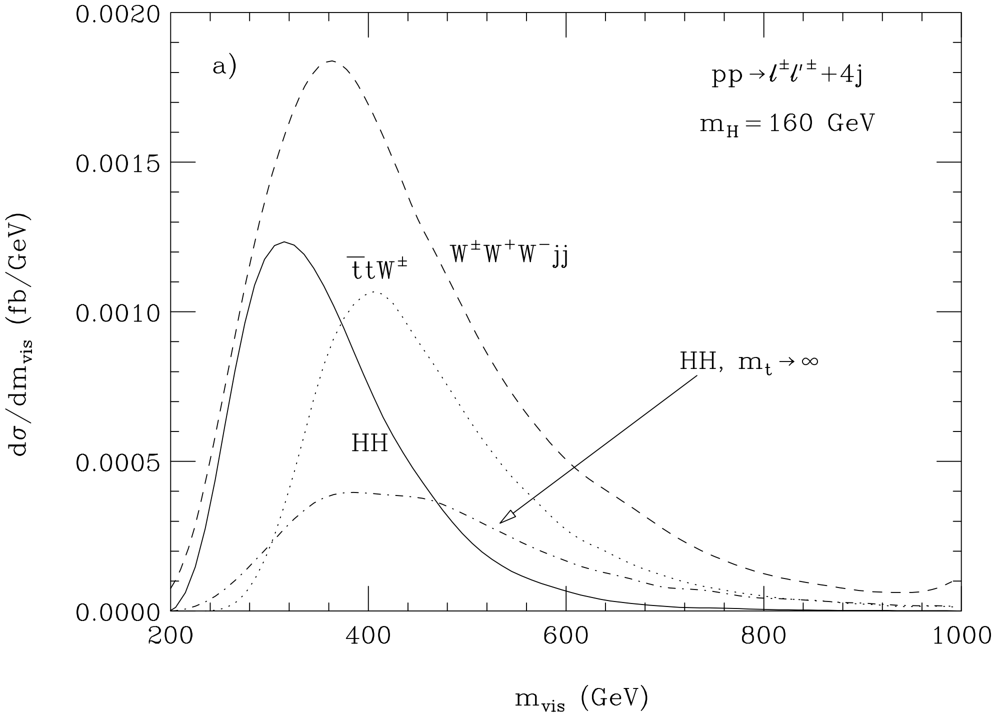
However, we do apply realistic lepton efficiency factors, $\epsilon_\ell^2 = 0.85^2$ (averaged over e and μ).

We apply a (known) K-factor to the signal of 1.65.
Since the background NLO results are not know,
we perform a chi-squared analysis with 30% typical QCD uncertainty included for all backgrounds.

SIGNAL CHARACTERISTICS

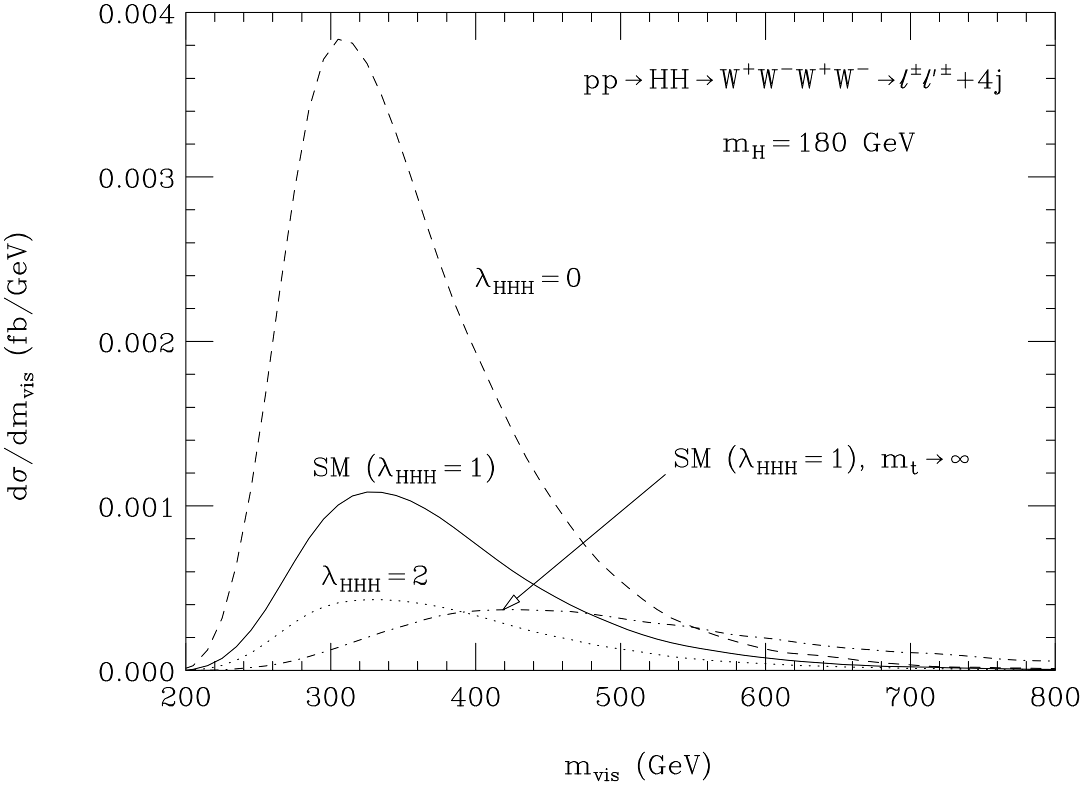


Jets typically much further apart in HH signal events.



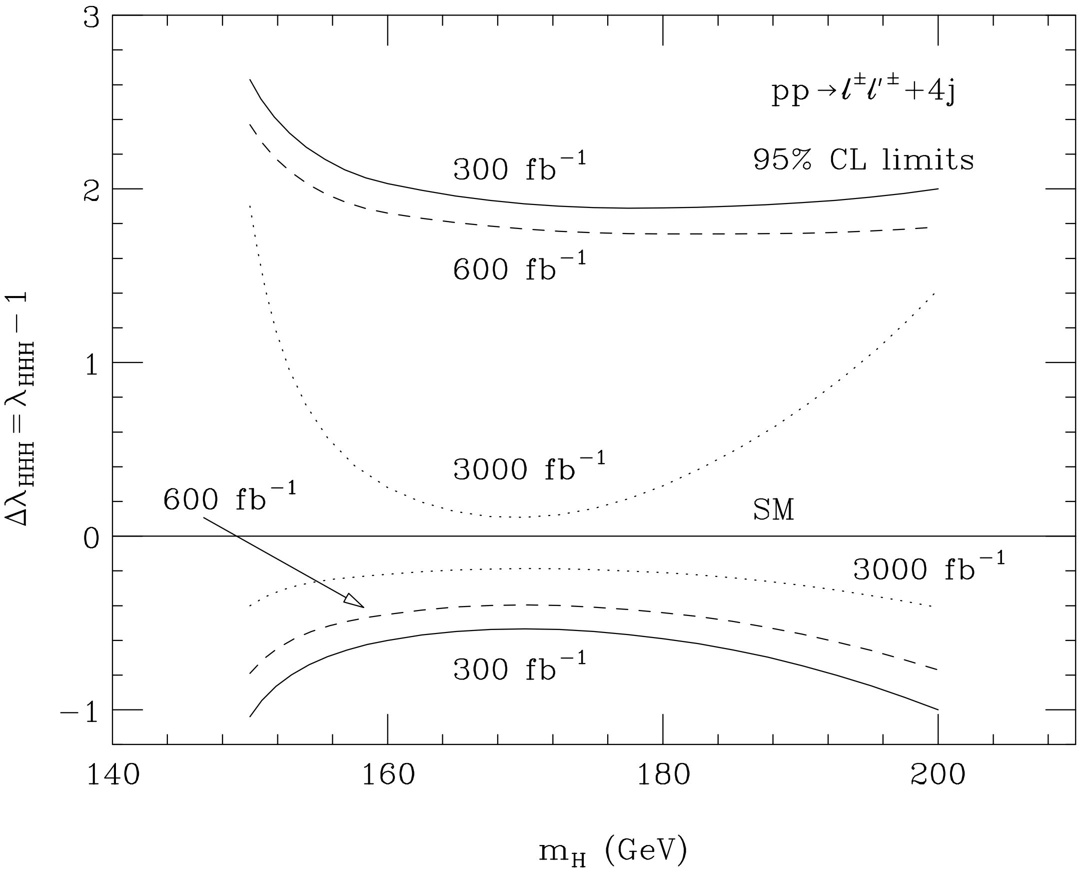
HH signal events exhibit m_{vis} peak much closer to threshold, as expected for 2-body production.

VARIATION OF THE SELF COUPLING



Variation of λ from 0 to twice the SM value produces significant changes in the signal cross section at low m_{vis}, as expected from the threshold behavior of the triangle-loop $H \to HH$ contribution.

RESULTS FOR HH ANALYSIS



1. Vanishing λ is excluded at $\geq 95\%$ c.l. for only 300 fb^{-1} for $150 < M_H < 200$ GeV
2. Doubling luminosity improves bounds by $10 - 25\%$
3. λ determined at $20 - 30\%$ for 3000 fb^{-1}

VVH VERTEX STRUCTURE

[T. Plehn, D. R., D. Zeppenfeld, hep-ph/0105325]

Relies on observation of the weak boson fusion channels.

Final state consists of central Higgs decay products plus two far foward/backward “tagging” jets: configuration preferred by EW events (WBF); QCD events suppressed.

We have previously explored several channels in $pp \to Hjj$: $H \to W^+W^-, \tau^+\tau^-$; all-leptonic and semileptonic τ decays.

[D.R. and Zeppenfeld, PRD 60, 113004;

Kauer, Plehn, D.R. and Zeppenfeld, PLB 503, 113;

Hagiwara, D.R. and Zeppenfeld, PRD 59, 014037;

Plehn, D.R. and Zeppenfeld, PRD 61, 093005]

$Hjj, H \to \tau^+\tau^-$ is particularly important for no-lose coverage of MSSM parameter space.

[Plehn, D.R. and Zeppenfeld, PLB 454, 297]

DETECTOR STUDIES OF Hjj

Various CMS and ATLAS groups
(cf. K Jakobs, A. Nikitenko, E. Richter-Was)
have investigated these channels with full detector simulation and optimized analyses to improve expectations:

1. $pp \to Hjj \to W^+W^-jj \to \ell^+\ell^-jj\not{p}_T$
2. $pp \to Hjj \to \tau^+\tau^-jj \to \ell^+\ell^-jj\not{p}_T$
3. $pp \to Hjj \to \tau^+\tau^-jj \to \ell^\pm jjj\not{p}_T$

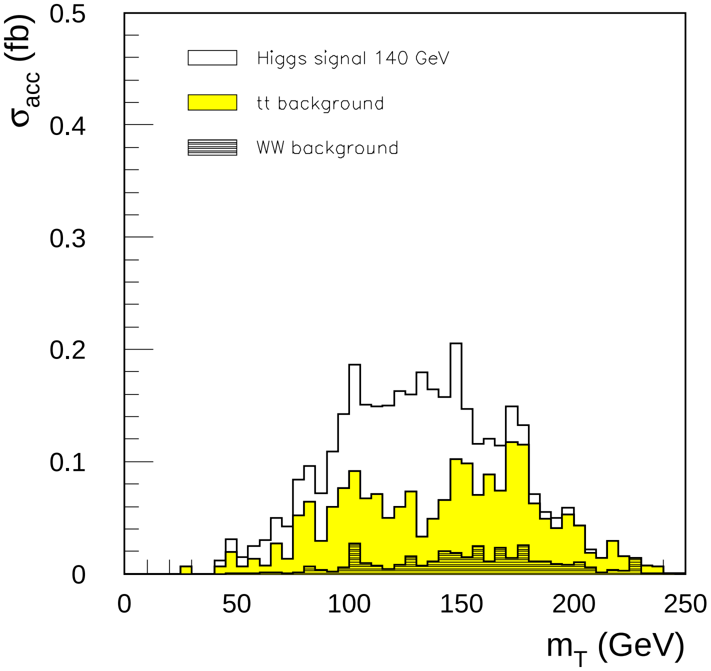
The results are highly encouraging, and support our prediction of $S/B >> 1/1$.

(Detailed issures remain, *e.g.* effect of the minijet veto, but experimental analysis very conservative compared to theoretical expectations.)

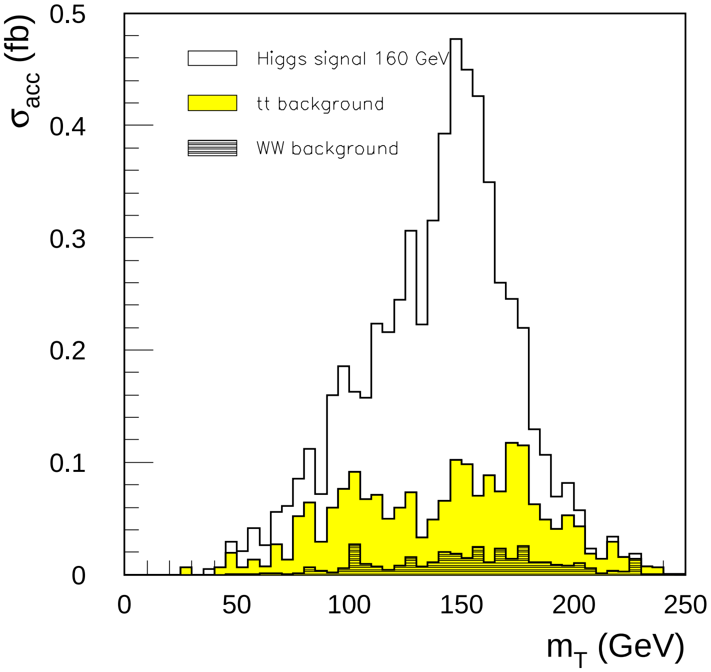
RESULTS FOR $Hjj \to W^+W^-jj$

[Azuelos, Buttar, Cavasinni, Costanzo, Figy, Harper, Jakobs, Klute, Mazini, Nikitenko, Richter-Was, Vivarelli, Zeppenfeld]

$M_H = 140$ GeV:



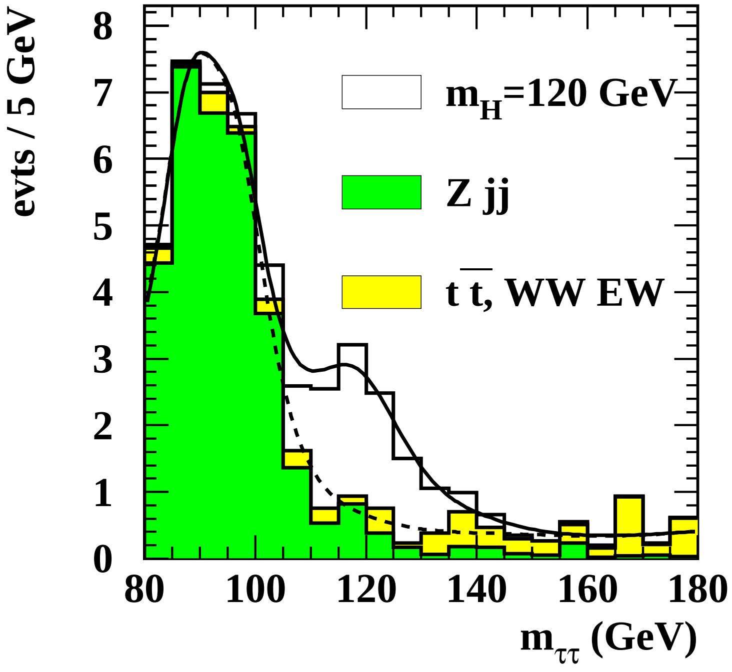
$M_H = 160$ GeV:



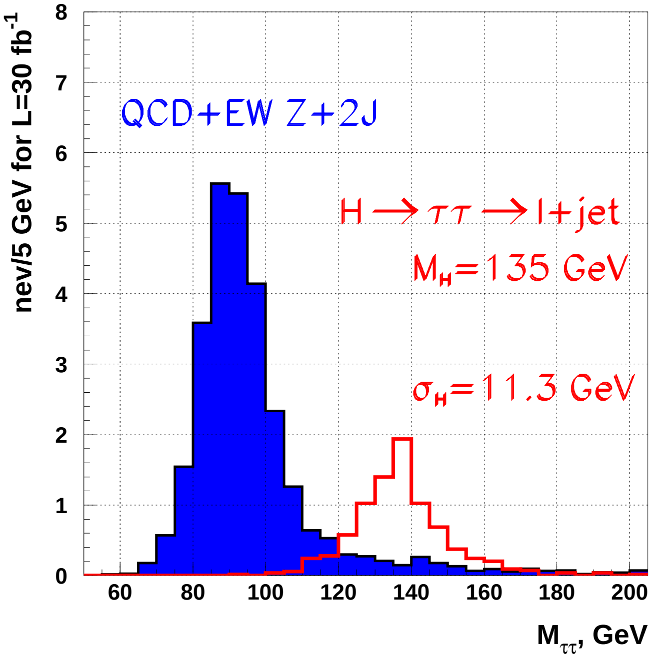
RESULTS FOR $Hjj \to \tau^+\tau^- jj$

[Azuelos, Buttar, Cavasinni, Costanzo, Figy, Harper, Jakobs, Klute, Mazini, Nikitenko, Richter-Was, Vivarelli, Zeppenfeld]

$H \to \tau^+\tau^- \to \ell^+\ell^-$ GeV (30 fb^{-1}):



$H \to \tau^+\tau^- \to \ell^\pm j$ GeV (30 fb^{-1}):



ANGULAR INFORMATION IN TAGGING JETS

A spin-0 field can couple to two gauge bosons via higher-D operators. Gauge invariant D6 possibilities:

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda_{e,6}^2}(\Phi^\dagger\Phi)\mathrm{V}_{\mu\nu}\mathrm{V}^{\mu\nu} + \frac{g^2}{2\Lambda_{o,6}^2}(\Phi^\dagger\Phi)\tilde{\mathrm{V}}_{\mu\nu}\mathrm{V}^{\mu\nu}$$

which after Φ acquires a vev gives the following effective D5 operators:

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}}HW^+_{\mu\nu}W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}}H\tilde{W}^+_{\mu\nu}W^{-\mu\nu}$$

For D5 CP-even operator, matrix element is distinctive:

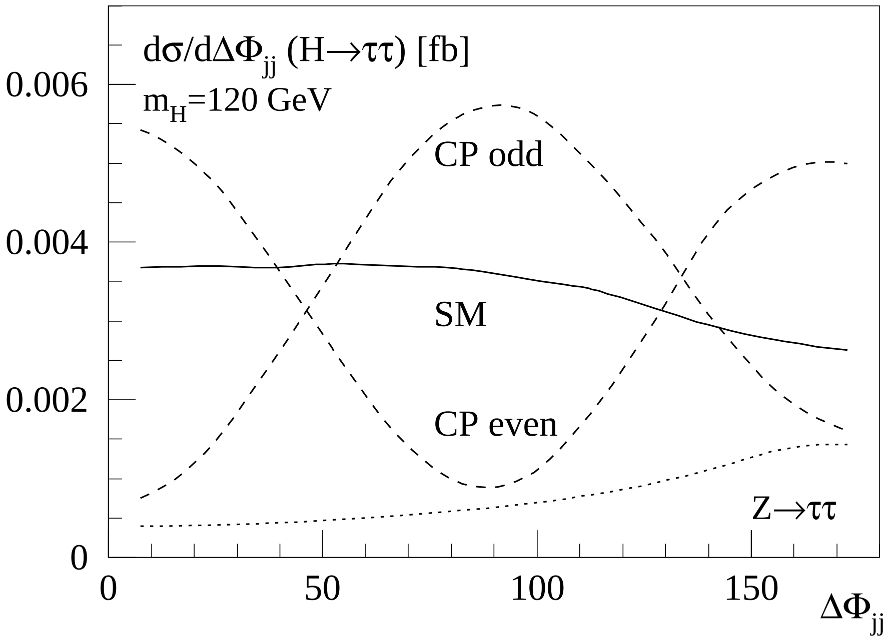
$$\mathcal{M}_{e,5} \propto \frac{1}{\Lambda_{e,5}}J_1^\mu J_2^\nu\,[g_{\mu\nu}(q_1\cdot q_2) - q_{1\nu}q_{2\nu}]$$

$$\sim \frac{1}{\Lambda_{e,5}}[J_1^0 J_2^0 - J_1^3 J_2^3]\,\vec{p}_T^{\,(tag1)}\cdot\vec{p}_T^{\,(tag2)}$$

For D5 CP-odd operator, $\epsilon_{\mu\nu\rho\delta}$ gives nonzero result only when four external momenta are independent.

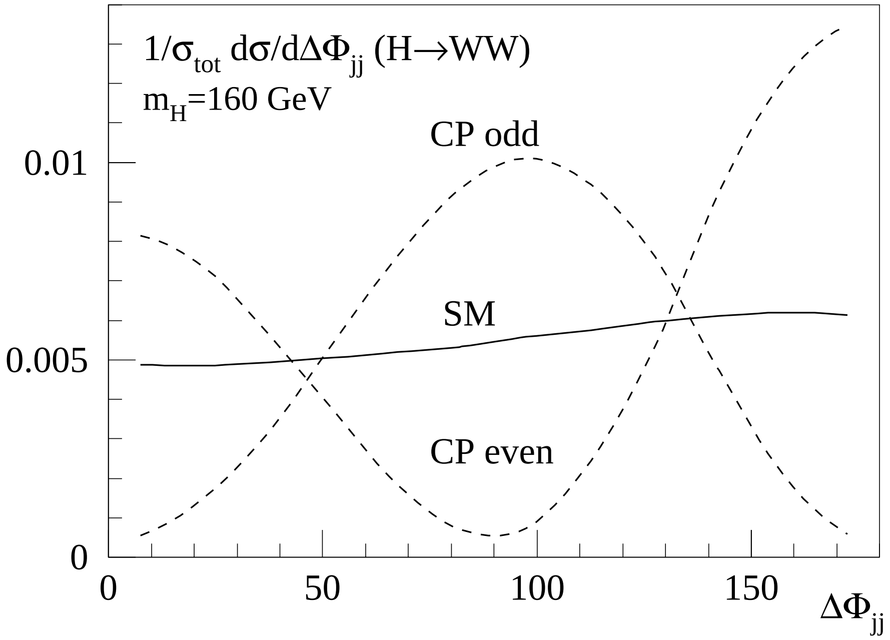
Again distinctive!

AZIMUTHAL JET DISTRIBUTIONS



WBF $H \to \tau\tau$ analyses do not rely on angular information, so these operators reveal themselves quite clearly.

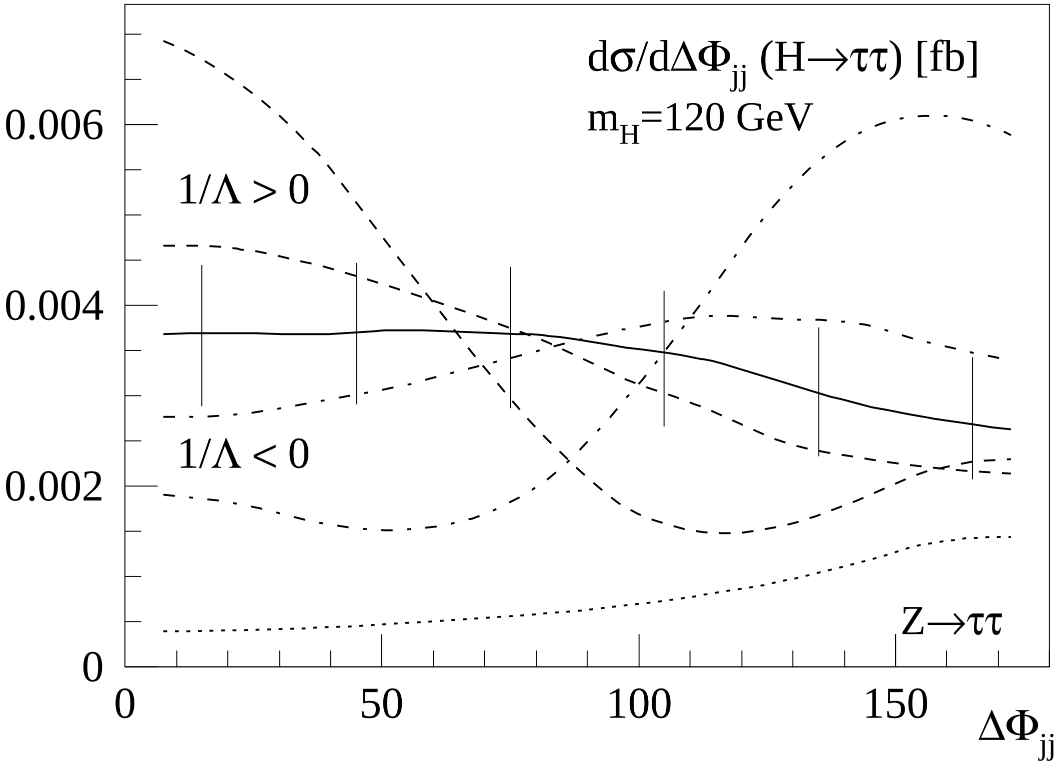
$\Lambda_5 = 480$ GeV to reproduce SM rate.



WBF $H \to W^+W^-$ works just as well, so the technique is independent of M_H!

SM-D5 INTERFERENCE

SM $g^{\mu\nu}$ and D5 CP-even couplings interfere, distorting the ϕ_{jj} distribution.

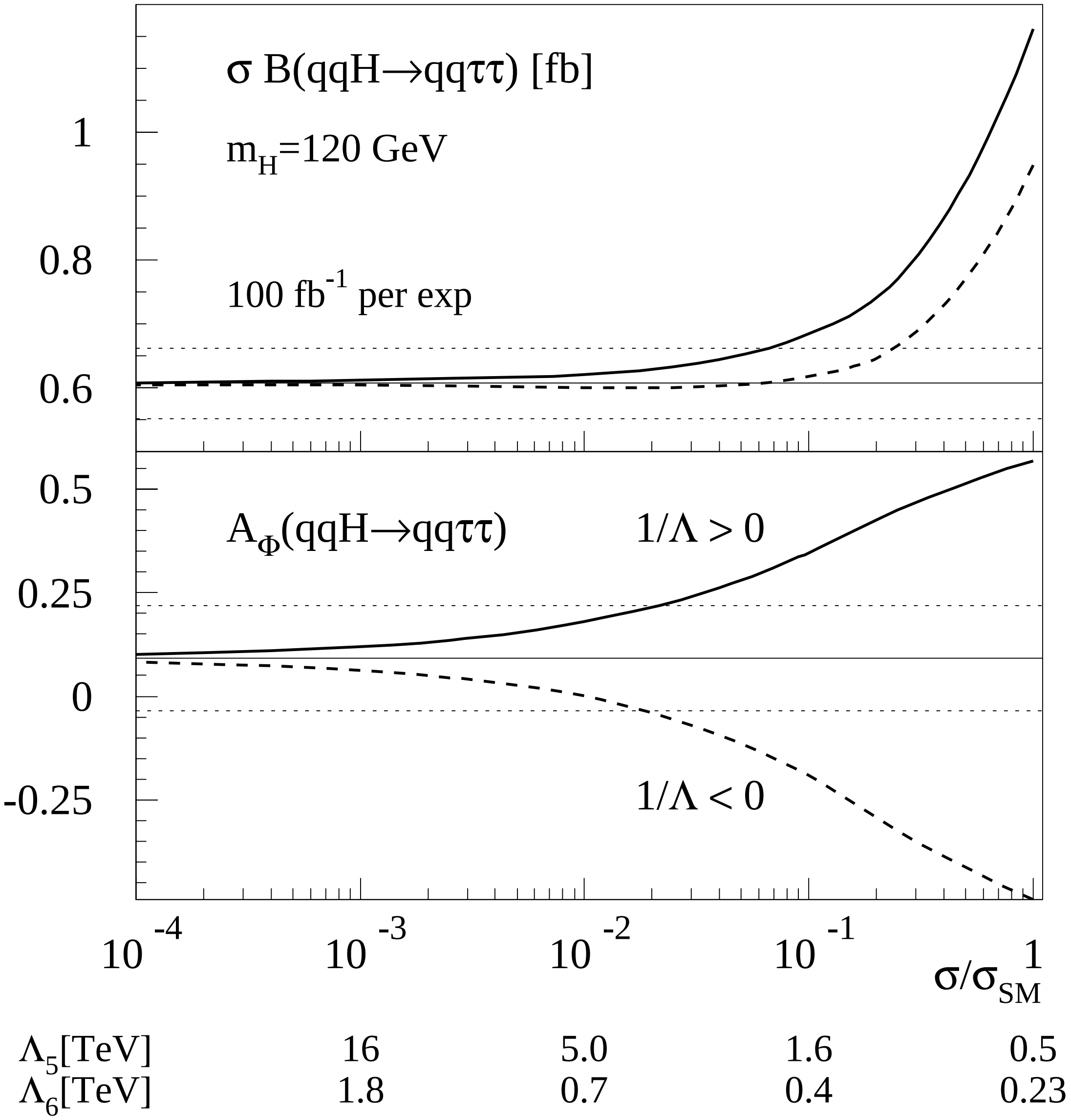


An obvious choice is to introduce an asymmetry observable,

$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \pi/2) - \sigma(\Delta\phi_{jj} > \pi/2)}{\sigma(\Delta\phi_{jj} < \pi/2) + \sigma(\Delta\phi_{jj} > \pi/2)}$$

SM-D5 INTERFERENCE

$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \pi/2) - \sigma(\Delta\phi_{jj} > \pi/2)}{\sigma(\Delta\phi_{jj} < \pi/2) + \sigma(\Delta\phi_{jj} > \pi/2)}$$



Roughly, measurement is sensitive to $\Lambda_6 \sim 1$ TeV, all channels combined.

SUMMARY

- If $150 \lesssim M_H \lesssim 200$ GeV, LHC can observe HH production and show $\lambda \neq 0$ at $> 95\%$ c.l.

- Possible improvements remain in HH analysis, from addition of other channels (work in progress).

  $m_t \to \infty$ approximation *NOT* good for phenomenological analyses.

- Detector studies of $pp \to Hjj$ have validated the parton-level studies for all the important channels ($H \to W^+W^-, \tau^+\tau^-$).

- WBF Higgs channels allow for quite good verification of the tree-level $g_{\mu\nu}$ structure of the Higgs weak gauge coupling.