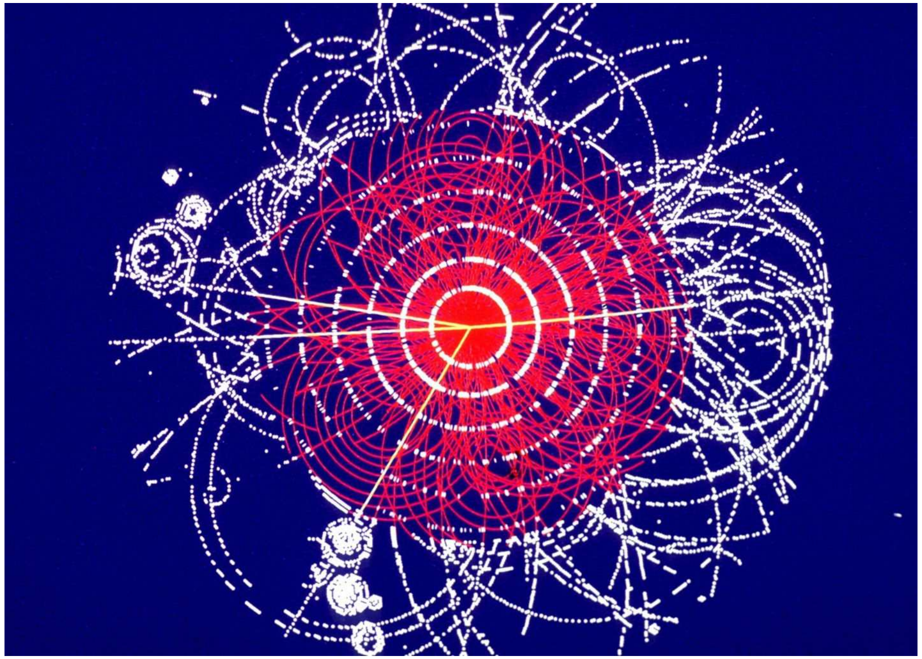
HIGGS AT LHC: THEORY OVERVIEW

Dieter Zeppenfeld
Universität Karlsruhe, Germany

ATLAS-UK Physics Meeting, IPPP Durham, September 18 - 20, 2006

- Goals of Higgs Physics
- SM Channels at the LHC
- QCD Corrections
- HVV vertex structure
- Signs of CP violation
- Early measurements
- Conclusions



Goals of Higgs Physics

Higgs Search = search for dynamics of $SU(2) \times U(1)$ breaking

- Discover the Higgs boson
- Measure its couplings and probe
  mass generation for gauge bosons and fermions

Fermion masses arise from Yukawa couplings via $\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_d^{ij} \bar{Q}_L'^i \Phi d_R'^j - \Gamma_d^{ij*} \bar{d}_R'^i \Phi^\dagger Q_L'^j + \dots \qquad = -\Gamma_d^{ij} \frac{v+H}{\sqrt{2}} \bar{d}_L'^i d_R'^j + \dots$$

$$= -\sum_f m_f \bar{f} f \left(1 + \frac{H}{v}\right)$$

- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_f / v$
- Observation of $H f \bar{f}$ Yukawa coupling is no proof that v.e.v exists

Higgs coupling to gauge bosons

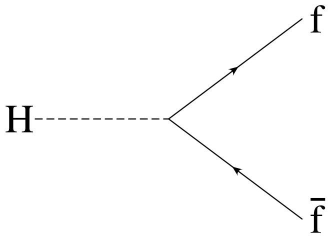
Kinetic energy term of Higgs doublet field:

$$(D^\mu \Phi)^\dagger (D_\mu \Phi) = \frac{1}{2}\partial^\mu H \partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu +} W^-_\mu + \frac{1}{2} \frac{(g^2 + g'^2)\, v^2}{4} Z^\mu Z_\mu \right] \left(1 + \frac{H}{v}\right)^2$$

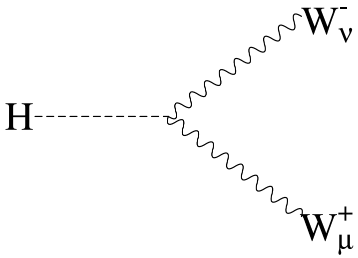
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\, m_V^2/v \sim g^2\, v$ within SM

Measurement of WWH and ZZH couplings is essential for identification of H as agent of symmetry breaking: Without a v.e.v. such a trilinear coupling is impossible at tree level

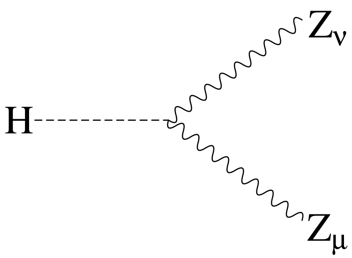
Feynman rules



$-i\frac{m_f}{v}$



$i g\, m_W\, g_{\mu\nu}$



$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, g_{\mu\nu}$

Verify tensor structure of HVV couplings. Loop induced couplings lead to $HV_{\mu\nu}V^{\mu\nu}$ effective coupling and different tensor structure: $g_{\mu\nu} \quad \longrightarrow \quad q_1 \cdot q_2\, g_{\mu\nu} - q_{1\nu} q_{2\mu}$

The MSSM Higgs sector

The SM uses the conjugate field $\Phi_c = i\sigma_2\Phi^*$ to generate down quark and lepton masses. In supersymmetric models this must be an independent field

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d \bar{Q}_L \Phi_1 d_R - \Gamma_e \bar{L}_L \Phi_1 e_R + \text{h.c.} \\ &\quad -\Gamma_u \bar{Q}_L \Phi_2 u_R + \text{h.c.}\end{aligned}$$

Two complex Higgs doublet fields Φ_1 and Φ_2 receive mass and v.e.v.s v_1, v_2 from generalized Higgs potential. Mass eigenstates constructed out of these 8 real fields are

Neutral sector:

2 CP even Higgs bosons: h and H

1 CP odd Higgs boson: A

1 Goldstone boson: χ_0

Charged sector:

charged Higgs bosons: $H^\pm$

charged Goldstone boson: $\chi^\pm$

Goldstone bosons absorbed as longitudinal degrees of freedom of $Z, W^\pm$

Couplings of the MSSM neutral Higgses: h, H, A

Fermions

Two doublet fields Φ_1,Φ_2 mix, two v.e.v's $v_1 = v\cos\beta$, $v_2 = v\sin\beta$:

$$\begin{aligned}
\mathcal{L}_{\text{Yuk.}} &= -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.} \\
&= -\Gamma_b \bar{b}_L \frac{v_1 + H\cos\alpha - h\sin\alpha + iA\sin\beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H\sin\alpha + h\cos\alpha + iA\cos\beta}{\sqrt{2}} t_R + \ldots
\end{aligned}$$

Expressed in terms of masses the Yukawa Lagrangian is

$$\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v}\bar{b}\left(v + H\frac{\cos\alpha}{\cos\beta} - h\frac{\sin\alpha}{\cos\beta} - i\gamma_5 A\tan\beta\right) b - \frac{m_t}{v}\bar{t}\left(v + H\frac{\sin\alpha}{\sin\beta} + h\frac{\cos\alpha}{\sin\beta} - i\gamma_5 A\cot\beta\right) t$$

$\Longrightarrow$ coupling factors compared to SM hff coupling $-i\, m_f/v$

Gauge Bosons

extra coupling factors for hVV and HVV couplings as compared to SM

$$hVV \sim \sin(\beta-\alpha) \qquad\qquad HVV \sim \cos(\beta-\alpha)$$

SM Higgs mass fit to EW precision data

$$m_H = 91^{+45}_{-32}\ \text{GeV}$$

Including theory uncertainty

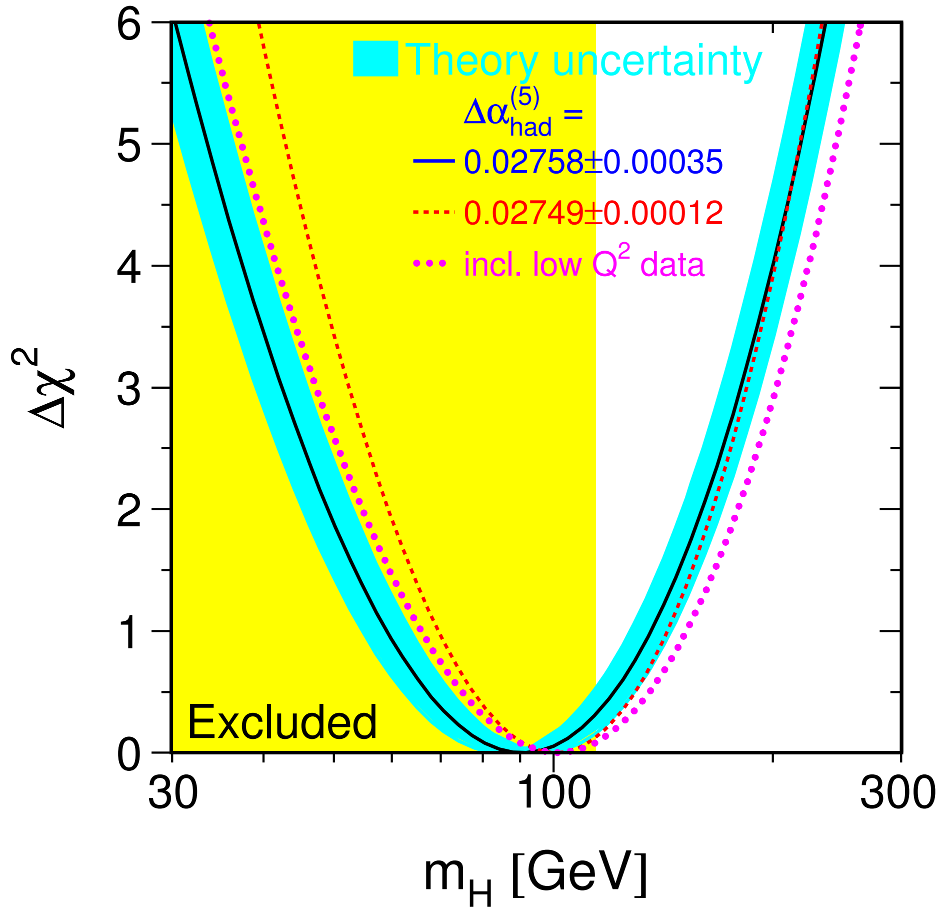
$$m_H < 186\ \text{GeV} \quad (95\%\ \text{CL})$$

Does not include
Direct search limit from LEP

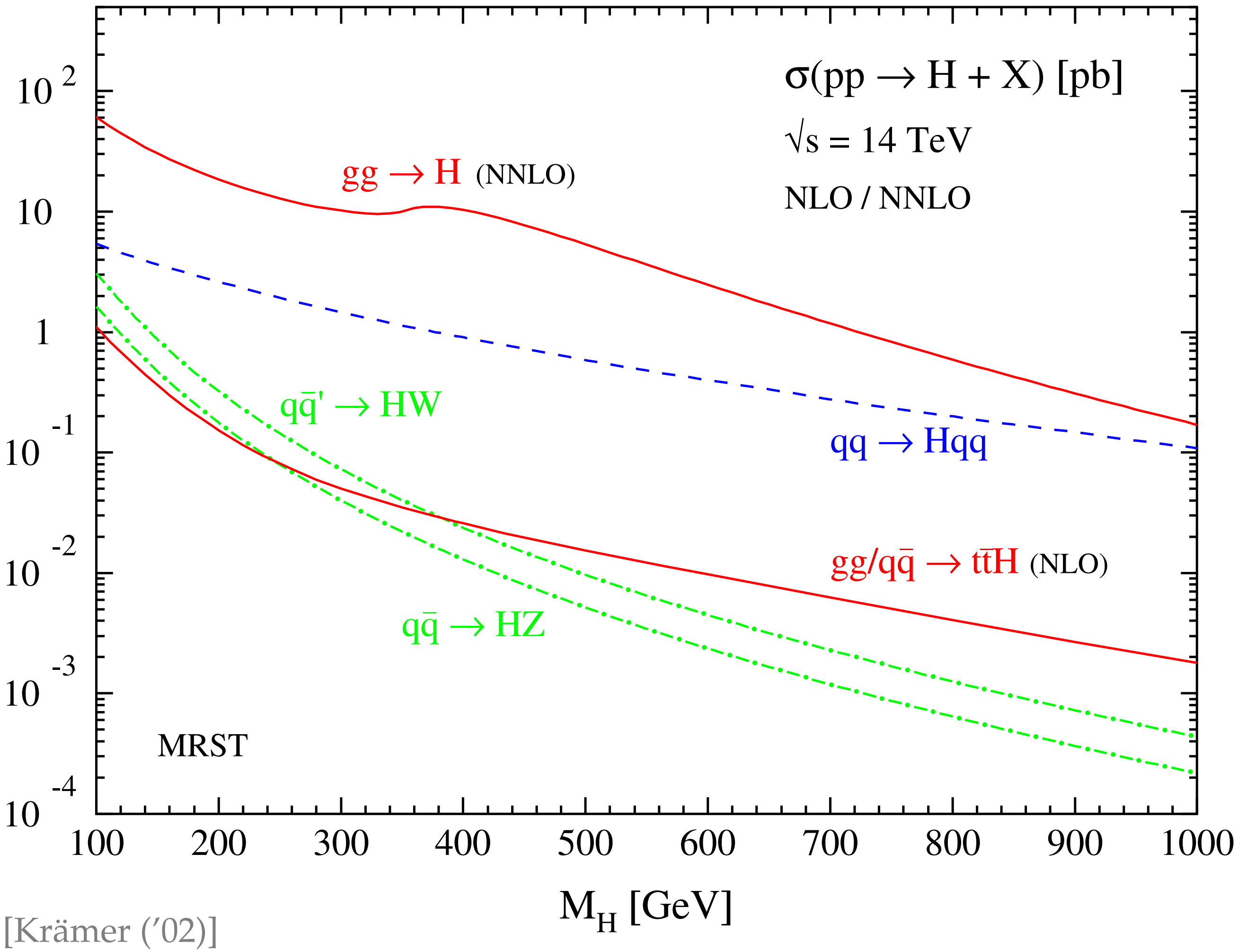
$$m_H > 114\ \text{GeV} \quad (95\%\ \text{CL})$$

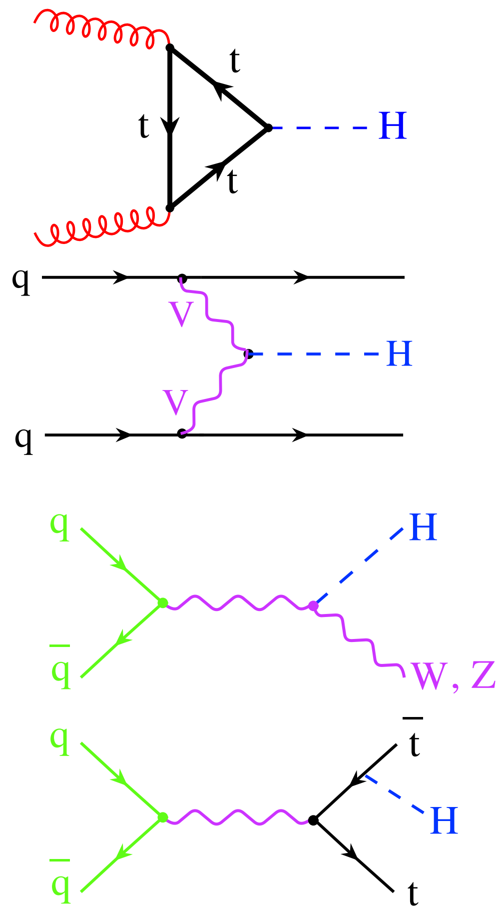
Renormalize probability for
$m_H > 114$ GeV to 100%:

$$m_H < 219\ \text{GeV} \quad (95\%\ \text{CL})$$



Total SM Higgs cross sections at the LHC

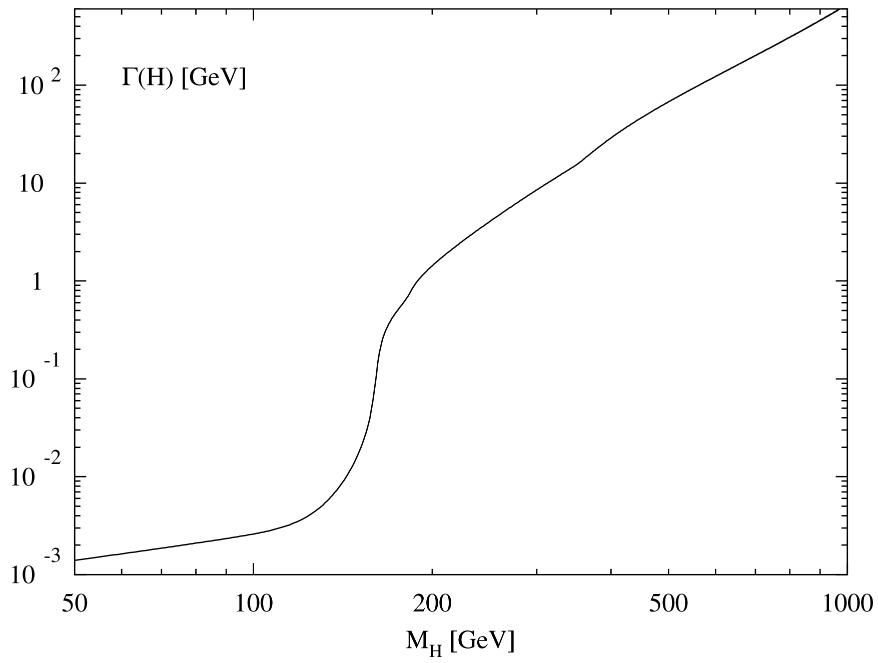


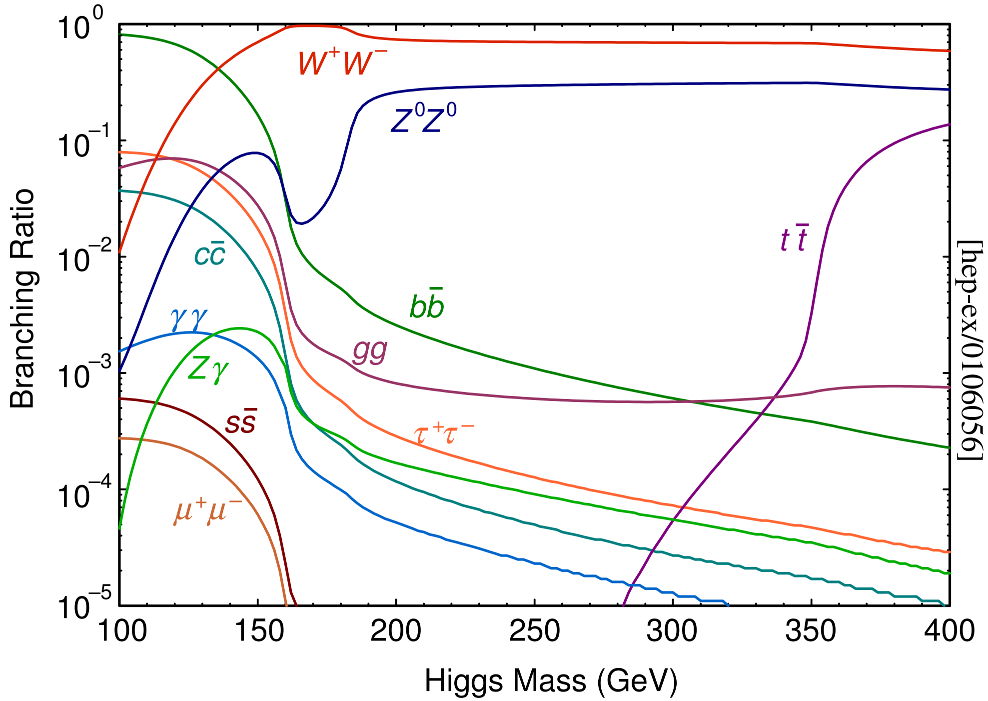


[Krämer ('02)]

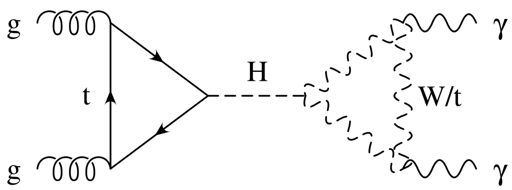
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM

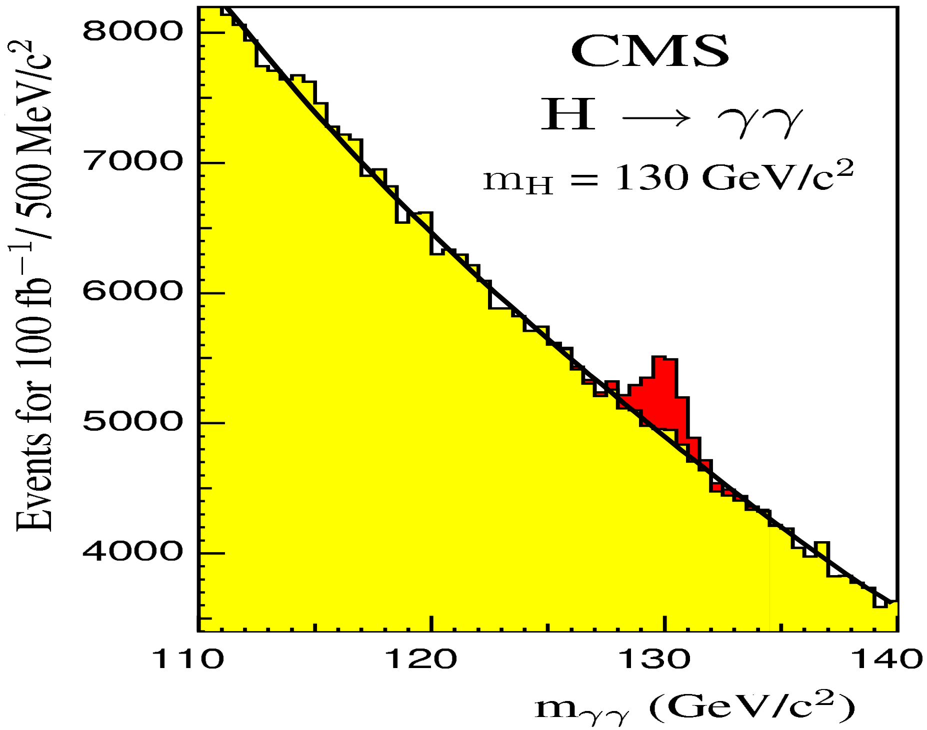




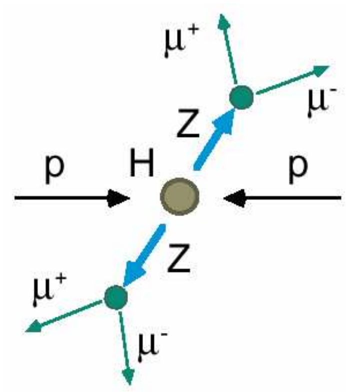
$H \to \gamma\gamma$

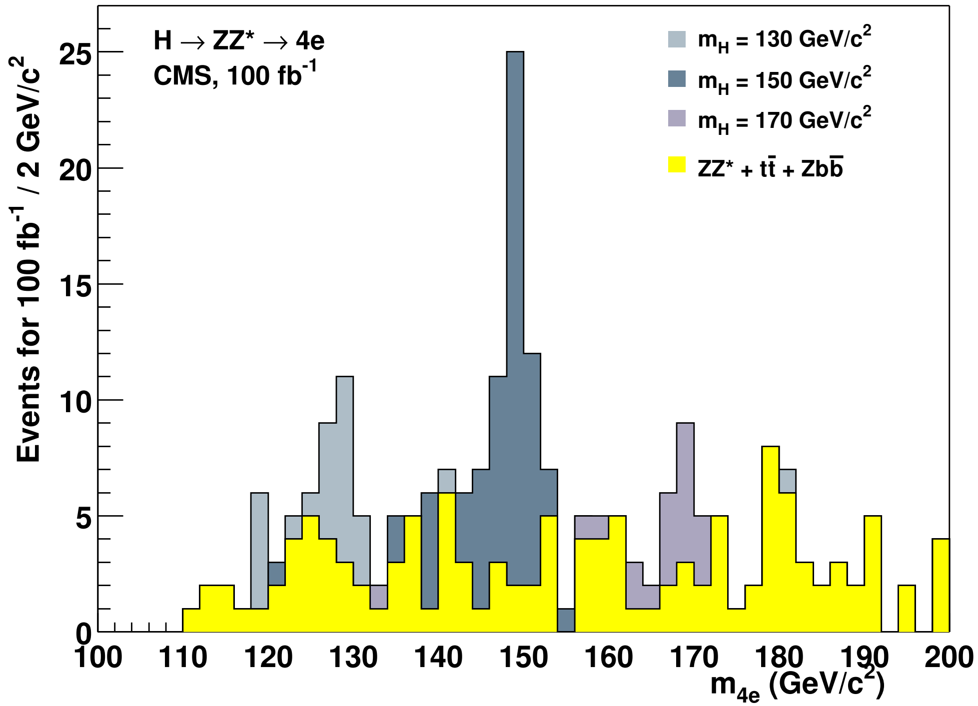


- ✗ BR($H \to \gamma\gamma$) $\approx 10^{-3}$
- ✗ large backgrounds from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)
- ✓ Look for a narrow $\gamma\gamma$ invariant mass peak
- ✓ extrapolate background into the signal region from sidebands.



$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$





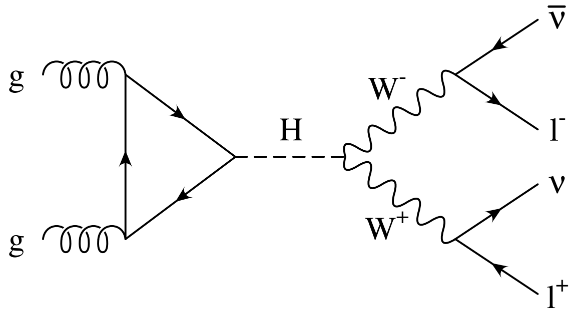
✓ invariant mass of the charged leptons fully reconstructed

For $m_H \approx 0.6$–1 TeV, use the "silver-plated" mode $H \to ZZ \to \nu\bar{\nu}\ell^+\ell^-$

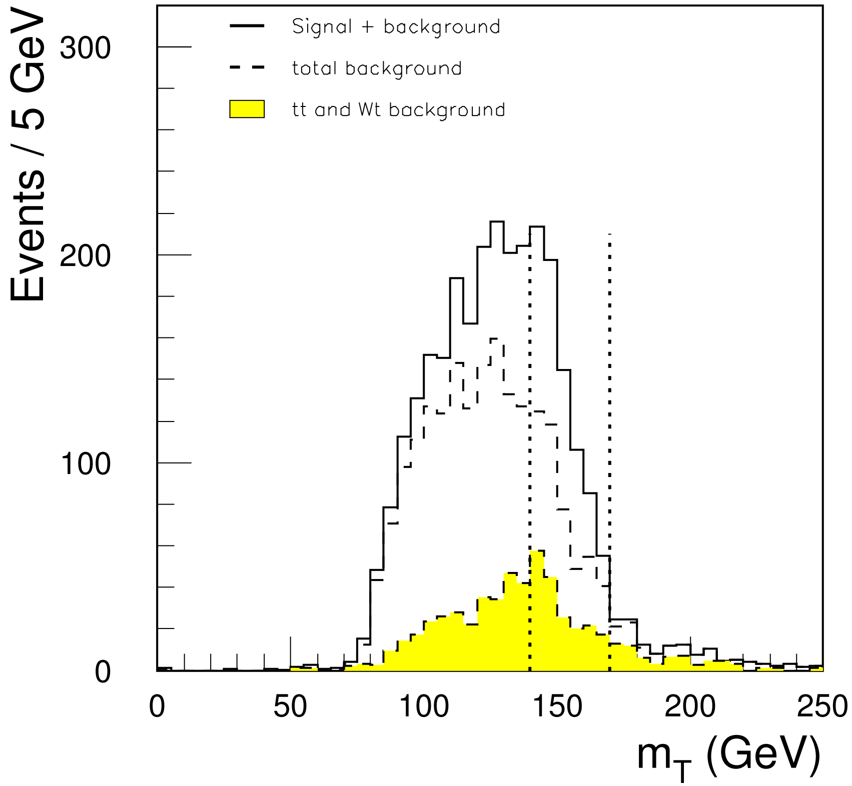
✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$

✓ the large missing E_T allows a measurement of the transverse mass

$H \to WW \to \ell^+ \bar{\nu} \ell^- \nu$



ATLAS TDR



✓ Exploit $\ell^+\ell^-$ angular correlations

✓ measure the transverse mass with a Jacobian peak at m_H

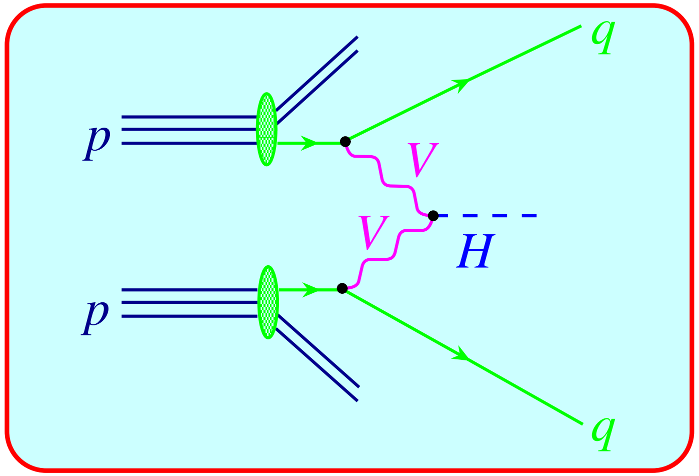
$$m_T = \sqrt{2\, p_T^{\ell\ell}\, \not{E}_T \,(1 - \cos(\Delta\Phi))}$$

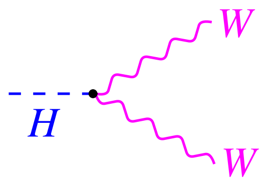
✗ background and signal have similar shape $\Longrightarrow$ must know the background normalization precisely

$m_H = 170\,\text{GeV}$

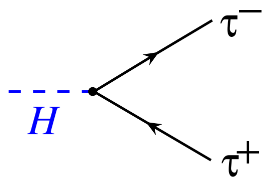
integrated luminosity = 20 fb^{-1}

Weak Boson Fusion

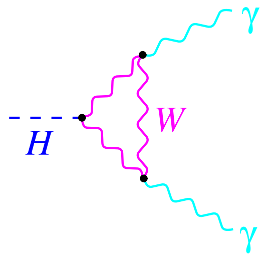




$m_H > 120$ GeV



$m_H < 140$ GeV

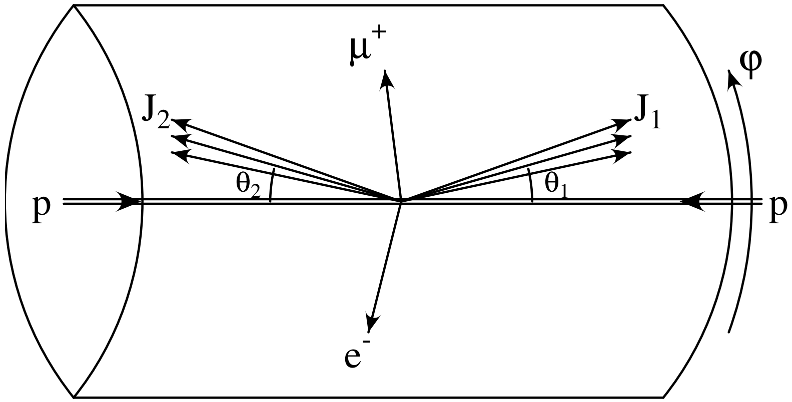


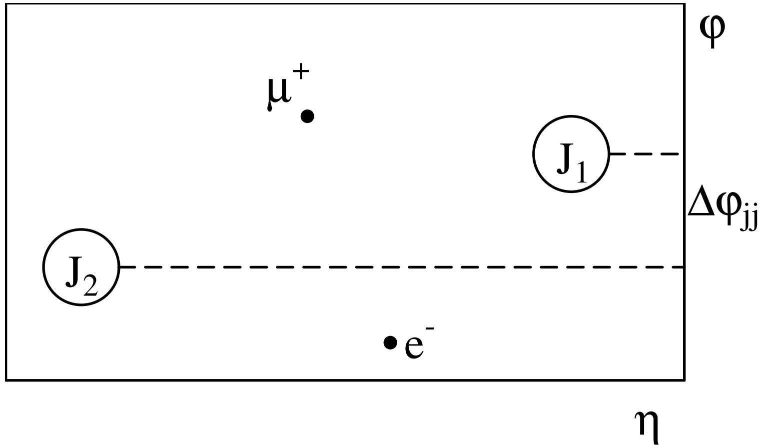
$m_H < 150$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10% (sometimes even better).

WBF signature





Characteristics:

- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)

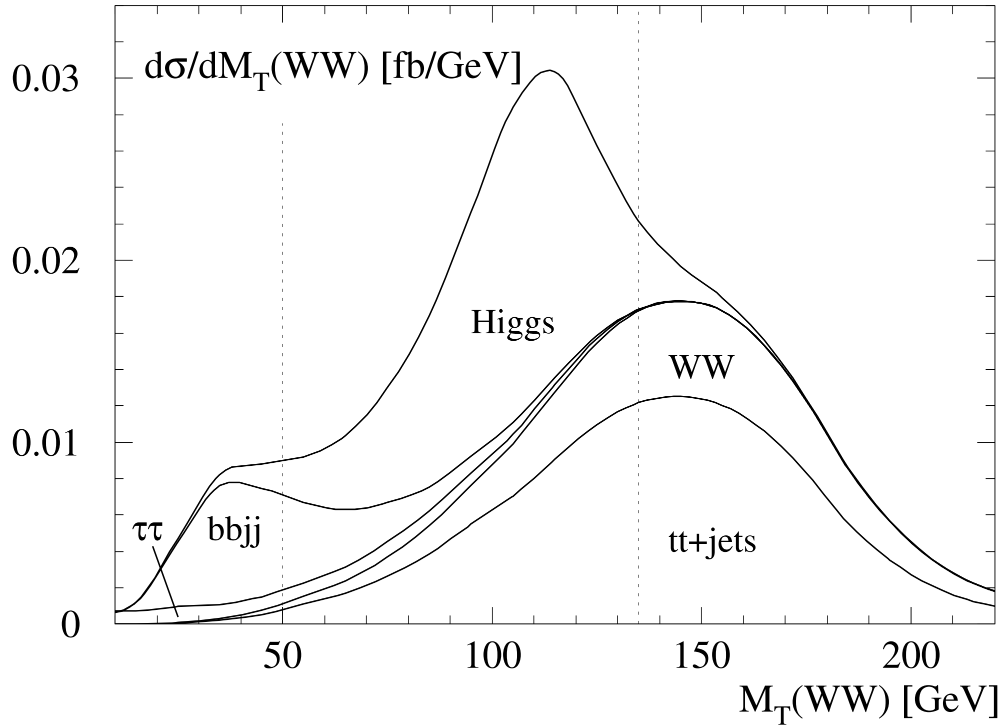
Example: Parton level analysis of $H \rightarrow WW$

Near threshold: W and W^* almost at rest in Higgs rest frame $\Longrightarrow$ use $m_{ll} \approx m_{\nu\nu}$ for improved transverse mass calculation:

$$
\begin{aligned}
E_{T,ll} &= \sqrt{\mathbf{p}_{T,ll}^2 + m_{ll}^2} \\
\not{E}_T &= \sqrt{\not{\mathbf{p}}_T^2 + m_{\nu\nu}^2} \approx \sqrt{\not{\mathbf{p}}_T^2 + m_{ll}^2} \\
M_T &= \sqrt{(\not{E}_T + E_{T,ll})^2 - (\mathbf{p}_{T,ll} + \not{\mathbf{p}}_T)^2}
\end{aligned}
$$

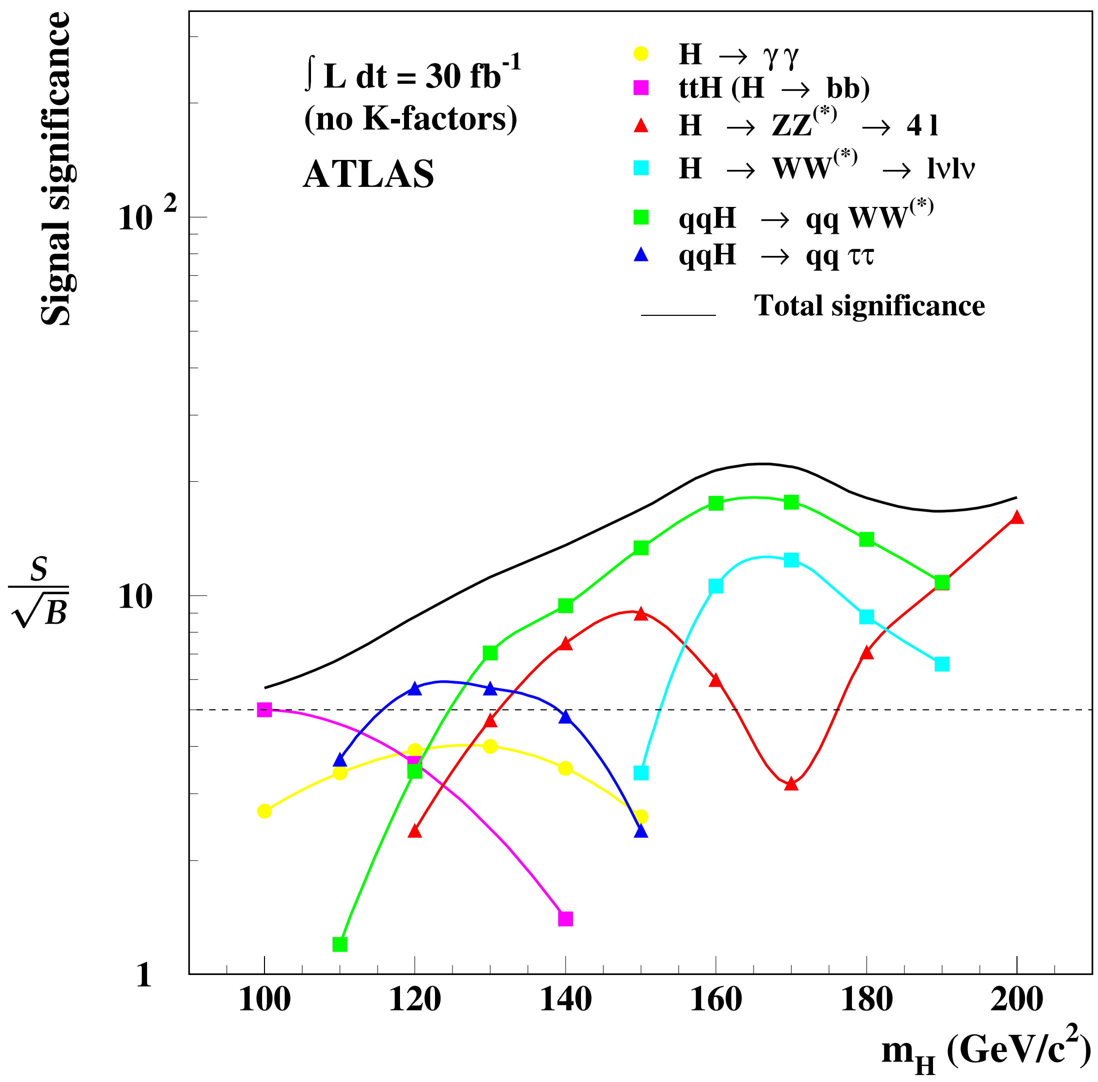
Observe Jacobian peak below $M_T = m_H$

Kauer, Plehn, Rainwater, D.Z. hep-ph/0012351



Transverse mass distribution for $m_H = 115$ GeV and $H \rightarrow WW^* \rightarrow e^{\pm}\mu^{\mp}\not{p}_T$

Higgs discovery potential



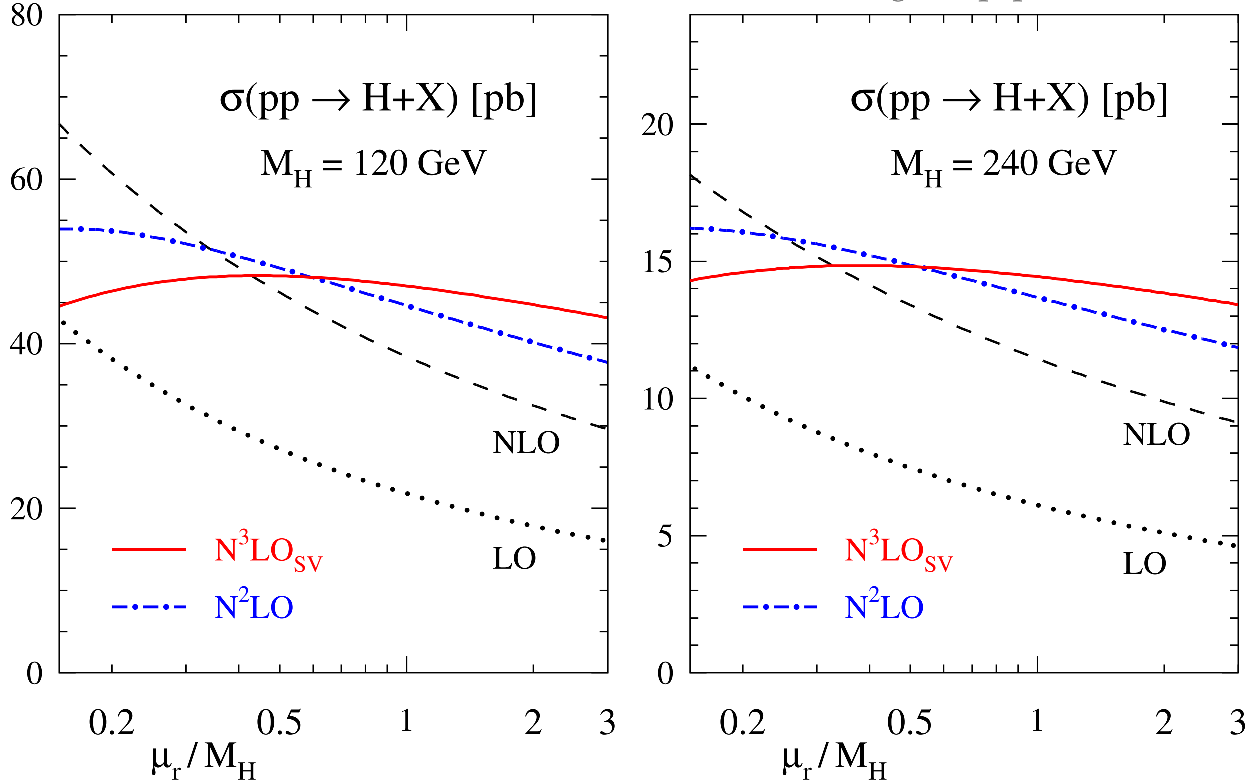
QCD corrections for Higgs production

Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better
$\Longrightarrow$ need QCD corrections to production cross sections. Much progress in recent years

- $gg \to H$ (all but NLO in $m_t \to \infty$ limit)
  - NLO for finite m_t: Graudenz, Spira, Zerwas (1993)
  - NNLO: Harlander, Kilgore (2001); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)
  - NNLL: Catani, de Florian, Grazzini, Nason (2003)
  - N^3LO in soft approximation: Moch, Vogt (2005)
- Hjj by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2005)
- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)
  - distributions at NLO: Figy, Oleari, D.Z (2003); Campbell, Ellis, Berger (2004)
- $\bar{t}tH$ associated production at NLO: Beenakker et al.; Dawson, Orr, Reina, Wackeroth (2002)
- $\bar{b}bH$ associated production at NLO: Dittmaier, Krämer, Spira; Dawson et al. (2003)

QCD corrections to $gg \to H$

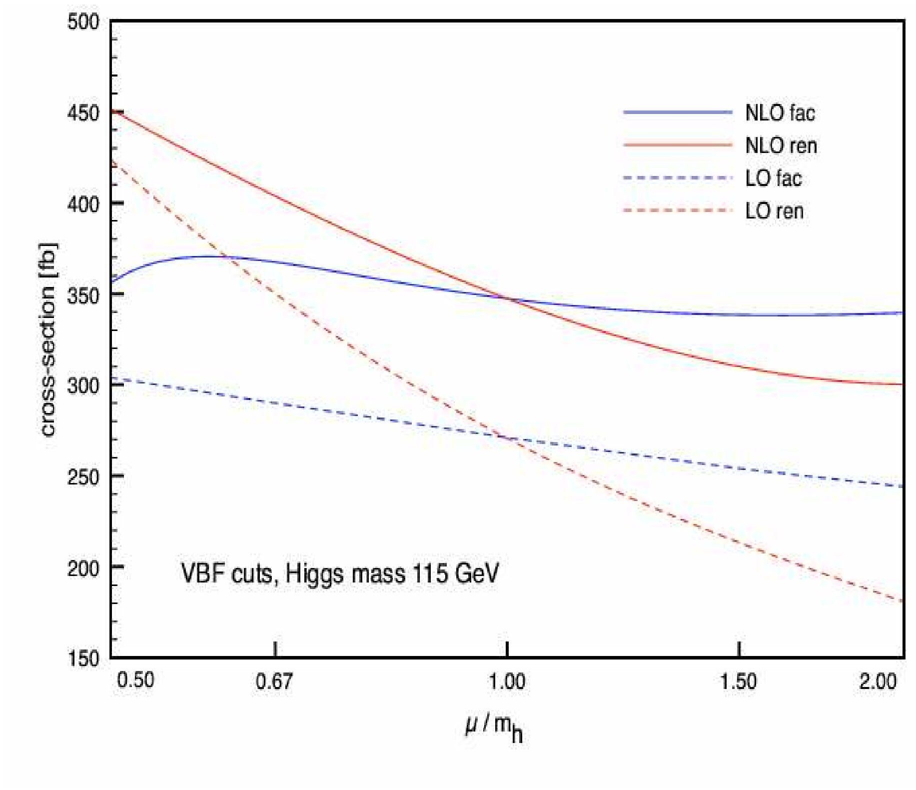
Moch & Vogt, hep-ph/0508265

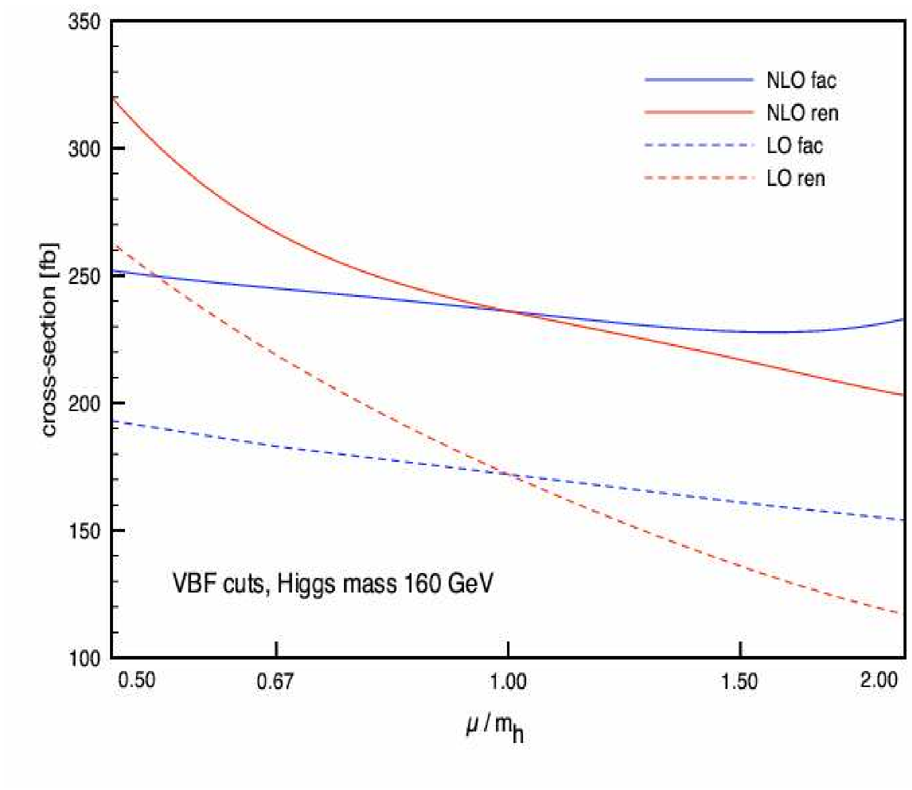


- ✓ Huge improvement in recent years
- ✓ Remaining scale uncertainty below 10%
- ✓ Uncertainty from gluon pdf $\approx 4-7\%$
- ✗ What is K-factor for cross section with cuts? Most problematic: central jet veto against $\bar{t}t$ background for $H \to WW$ search

Hjj cross section for gluon fusion

Calculation of Hjj cross section at NLO in $m_t \to \infty$ limit by Campbell, Ellis, Zanderighi, hep-ph/0608194

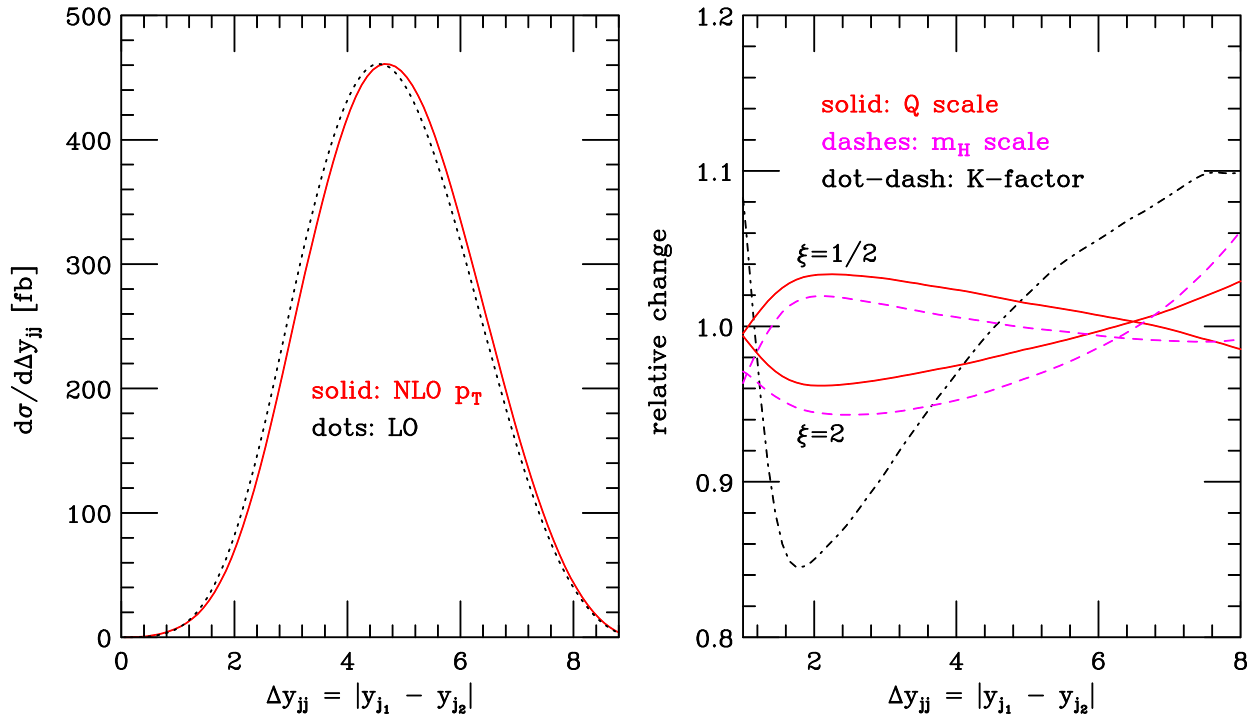




- Modest increase of cross section at 1-loop: K-factor of order 1.2 - 1.4
- Reduced scale dependence at NLO: remaining scale uncertainty $\approx \pm 20\%$

NLO QCD corrections to VBF

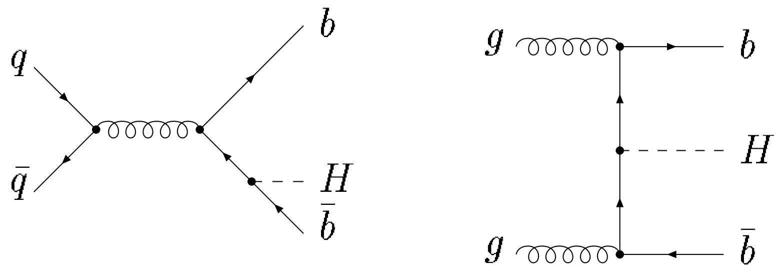
- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty



$m_H = 120$ GeV, typical VBF cuts

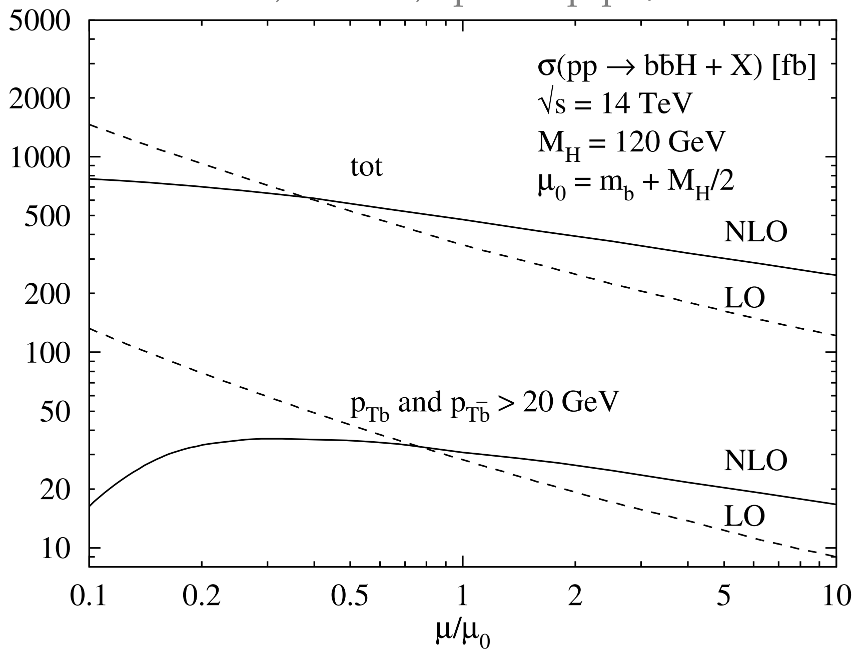
NLO QCD correction for VBF now available in VBFNLO: Figy, Hankele, Jäger, Klämke, Oleari, DZ, ...
parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production

NLO QCD corrrections to $b\bar{b}H$ production



- Discovery channel for H/A in the MSSM at sizeable tan β
- NLO corrections known for $\bar{b}bH$ final state
- b-quarks at low p_T: effective process is $\bar{b}b \rightarrow H$: cross section known at NNLO Harlander, Kilgore (2003)

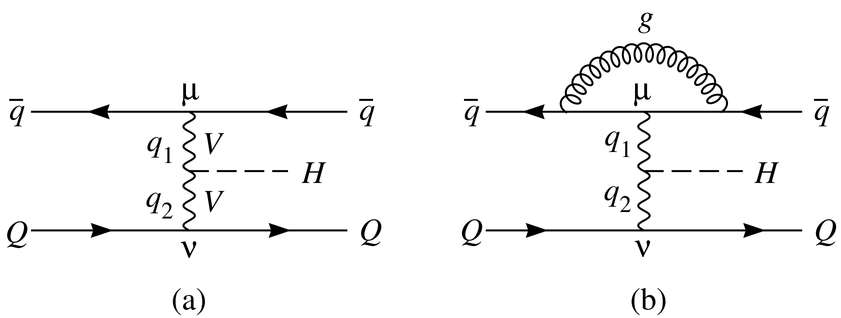
Dittmaier, Krämer, Spira hep-ph/0309204



scale dependence of inclusive vs. double b-tagged cross section

Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$
\begin{aligned}
T^{\mu\nu} &= a_1 \, g^{\mu\nu} + \\
&\quad a_2 \, \left(q_1 \cdot q_2 \, g^{\mu\nu} - q_1^\nu q_2^\mu\right) + \\
&\quad a_3 \, \varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\qquad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

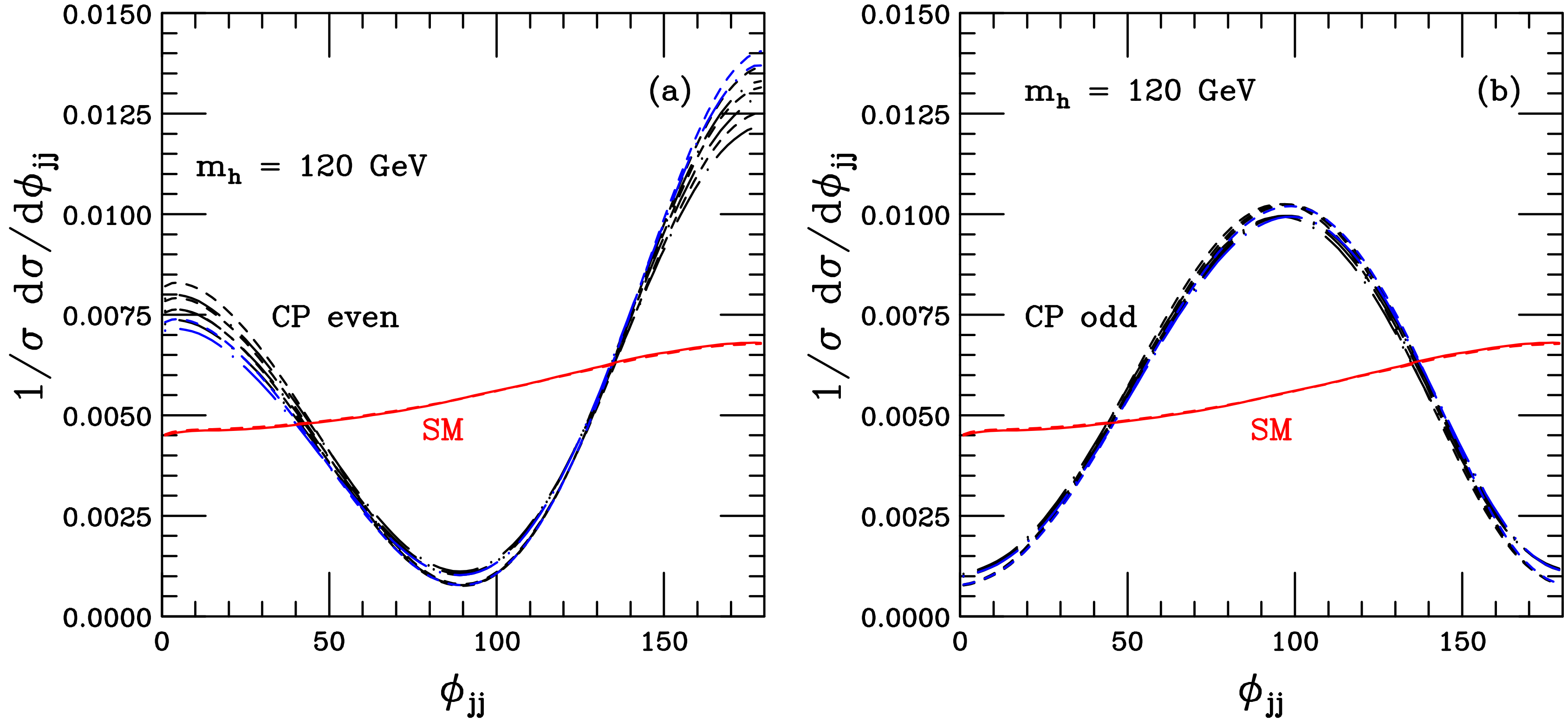
CP even $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Azimuthal angle correlations

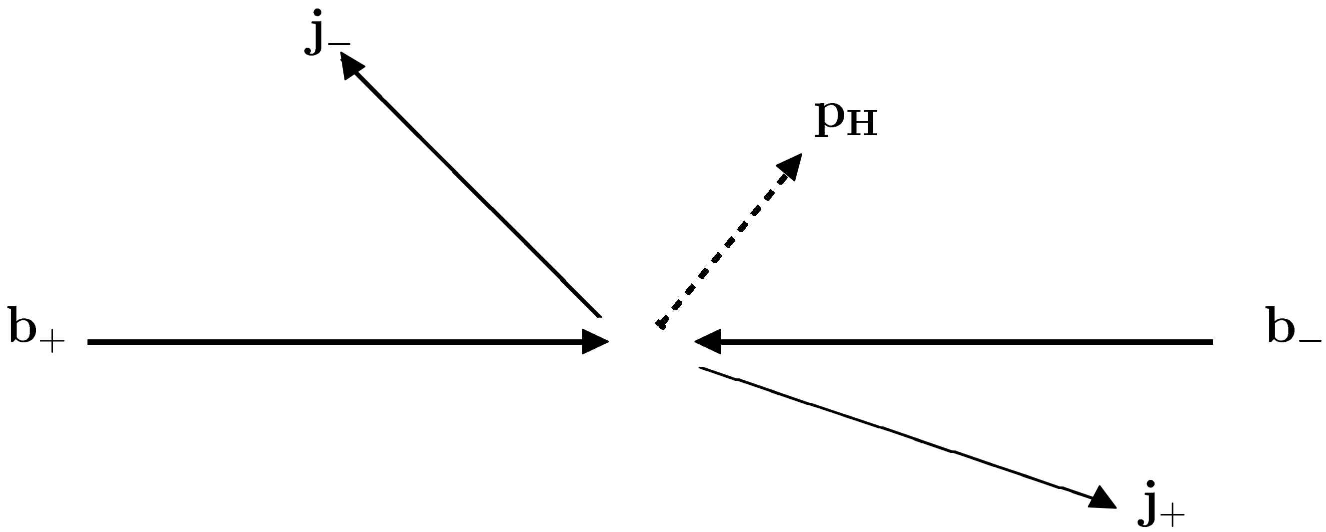
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Azimuthal angle distribution and Higgs CP properties

Kinematics of Hjj event:



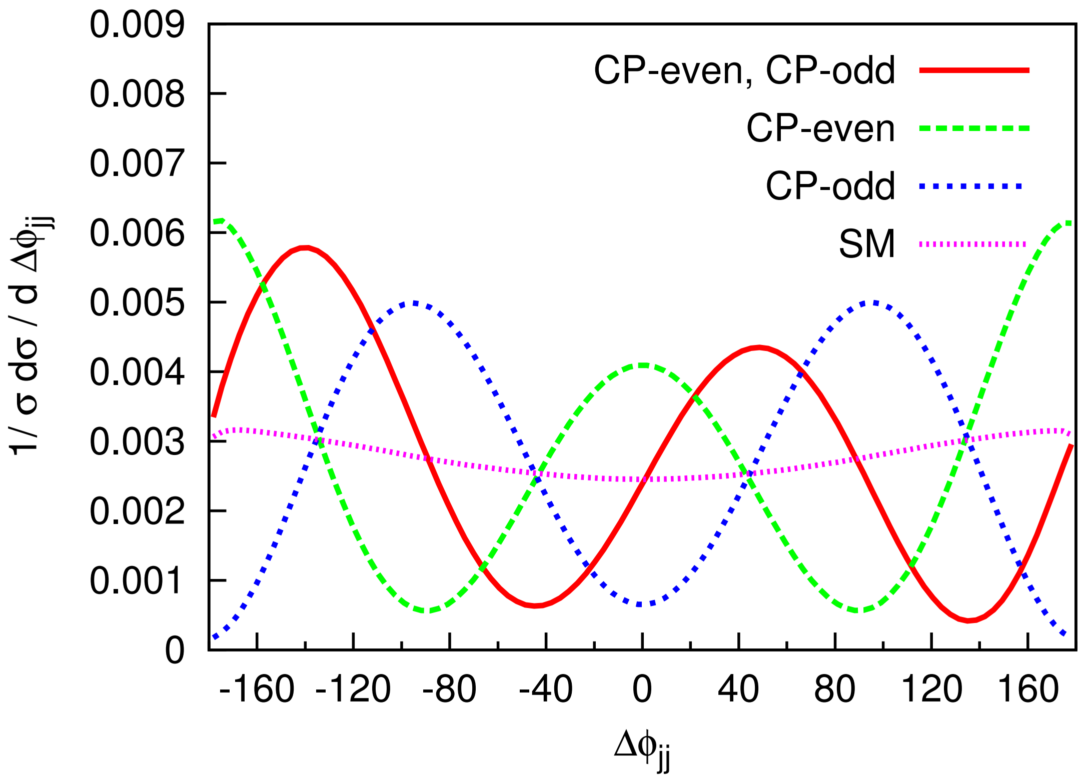
Define azimuthal angle between jet momenta j_+ and j_- via

$$\varepsilon_{\mu\nu\rho\sigma} b_+^\mu j_+^\nu b_-^\rho j_-^\sigma = 2 p_{T,+} p_{T,-} \sin(\phi_+ - \phi_-) = 2\; p_{T,+} p_{T,-} \sin \Delta\phi_{jj}$$

- $\Delta\phi_{jj}$ is a parity odd observable
- $\Delta\phi_{jj}$ is invariant under interchange of beam directions $(b_+, j_+) \leftrightarrow (b_-, j_-)$

Work with Vera Hankele, Gunnar Klämke and Terrance Figy: hep-ph/0609075

Signals for CP violation in the Higgs Sector



mixed CP case:
$a_2 = a_3, a_1 = 0$

pure CP-even case:
a_2 only

pure CP odd case:
a_3 only

Position of minimum of $\Delta\phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

$$a_1 = 0, \qquad a_2 = d\ \sin\alpha, \qquad a_3 = d\ \cos\alpha,$$

$\Longrightarrow$ Minimum at $-\alpha$ and $\pi - \alpha$

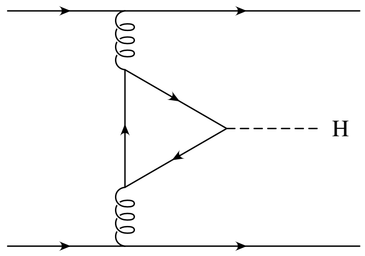
Azimuthal angle correlations in gluon fusion

Effective Hgg vertex is induced via top-quark loop

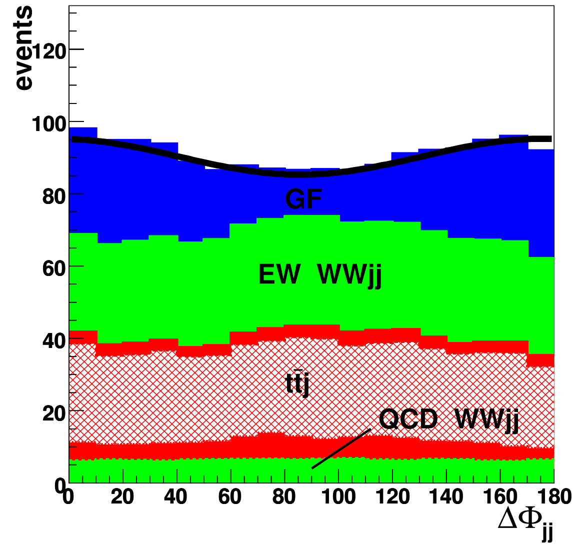
$$\text{CP}-\text{even}: \qquad i\frac{m_t}{v} \quad \rightarrow \quad H\, G^a_{\mu\nu} G^{\mu\nu,a} \text{ coupling}$$

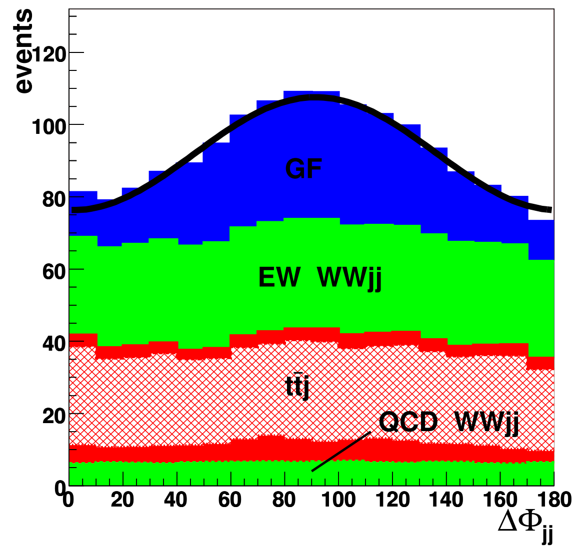
$$\text{CP}-\text{odd}: \qquad \frac{m_t}{v}\,\gamma_5 \quad \rightarrow \quad H\, G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \text{ coupling}$$

Consider Hjj production via gluon fusion, e.g.



(a)





Parton level analysis with relevant backgrounds

(Hankele, Klämke, DZ, hep-ph/0605117)

$\Longrightarrow$ Difference visible in Hjj, $H \rightarrow WW \rightarrow l^+ l^- \not{p}_T$ events at $m_H \approx 160$ GeV with 30 fb^{-1} at 6σ level

Method can be generalized for any Higgs mass. Problem is lower signal rate for $h \rightarrow \tau\tau$ or $h \rightarrow \gamma\gamma$

Early measurements for Higgs physics

Discovery of Higgs boson may take 5–10 fb^{-1}, perhaps more ...
It certainly requires a well understood and calibrated detector

- optimistic case: $m_H \approx 160$ GeV, $H \to WW$
- challenging case: $m_H \approx 120$ GeV, $H\tau\tau$ and Hbb couplings substantially enhanced by large $\tan\beta$ effects

$\Longrightarrow$ no visible $H \to \gamma\gamma$, $H \to ZZ$ or $H \to WW$ signals

$\Longrightarrow$ must search in VBF channel $qq \to qqH$, $H \to \tau\tau$ or in $t\bar{t}H$, $H \to b\bar{b}$

Early data will settle many open questions

- underlying event structure and pile-up at high luminosity

$\Longrightarrow$ does forward jet tagging work at high luminosity?

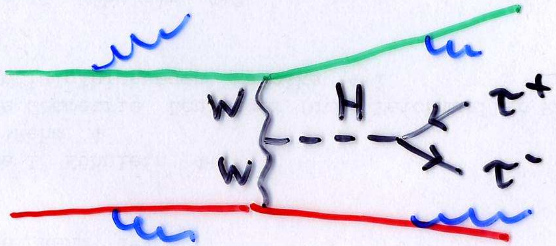
- measure dominant backgrounds: $t\bar{t}$, jets, DY+jets, ...
- study actual event characteristics

Central jet veto

- $t\bar{t}$ + jets background for $qq \to qqH$, $H \to W^+W^-$

  $\Rightarrow$ veto b-jets from $t \to bW$

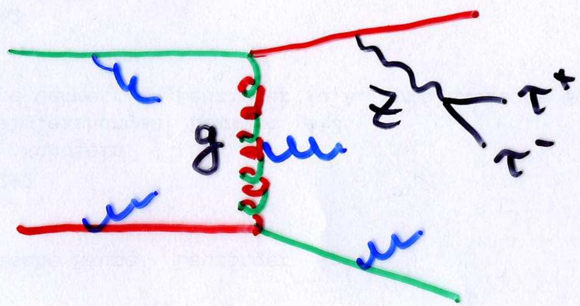
- t-channel color singlet exchange



"synchrotron" radiation between initial and final quark direction

$\Rightarrow$ central jets suppressed

- Major QCD backgrounds: t-channel color octet exch.



deflection of color charge by ~180° $\Rightarrow$ strong color acceleration

$\Rightarrow$ enhanced central gluon emis.

$\Rightarrow$ central jet veto suppresses QCD backgrounds to weak boson fusion

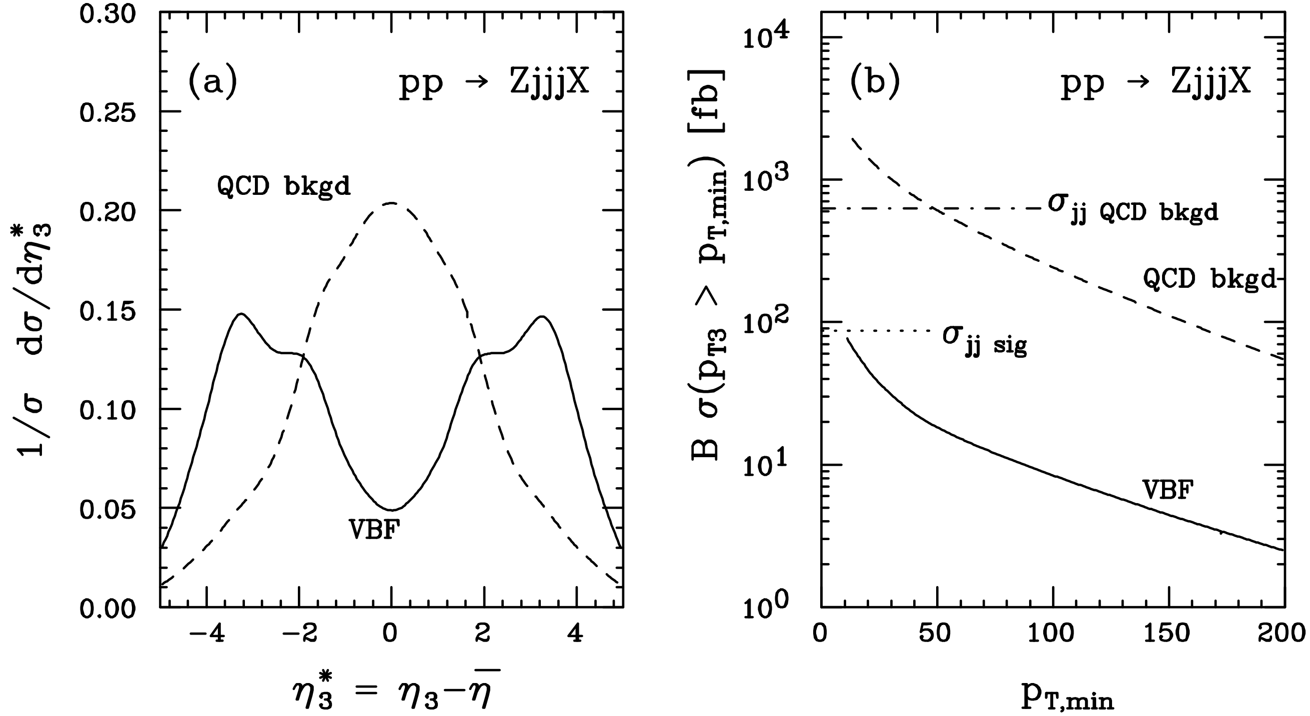
Gluon radiation in Zjj events

Analyze Zjj, $Z \to \mu^+\mu^-, e^+e^-$ events with 2 well separated jets: $p_{Tj} > 40$ GeV, $|\eta_{j_1} - \eta_{j_2}| > 4.4$

- VBF: Gluon radiation is forward/backward
- QCD: central gluons dominate
- Probability for gluon emission is much larger in QCD processes due to t-channel color octet exchange

$\Longrightarrow$ probe these predictions experimentally

VBF Zjj signal vs.QCD Zjj bckground; hep-ph/9605444



QCD predictions are LO only: large uncertainties for probability to see additional jets

$\Longrightarrow$ need data to judge effectiveness of central jet veto

LHC measurements can be made in phase space region relevant for VBF with ≈ 1 fb^{-1} of data

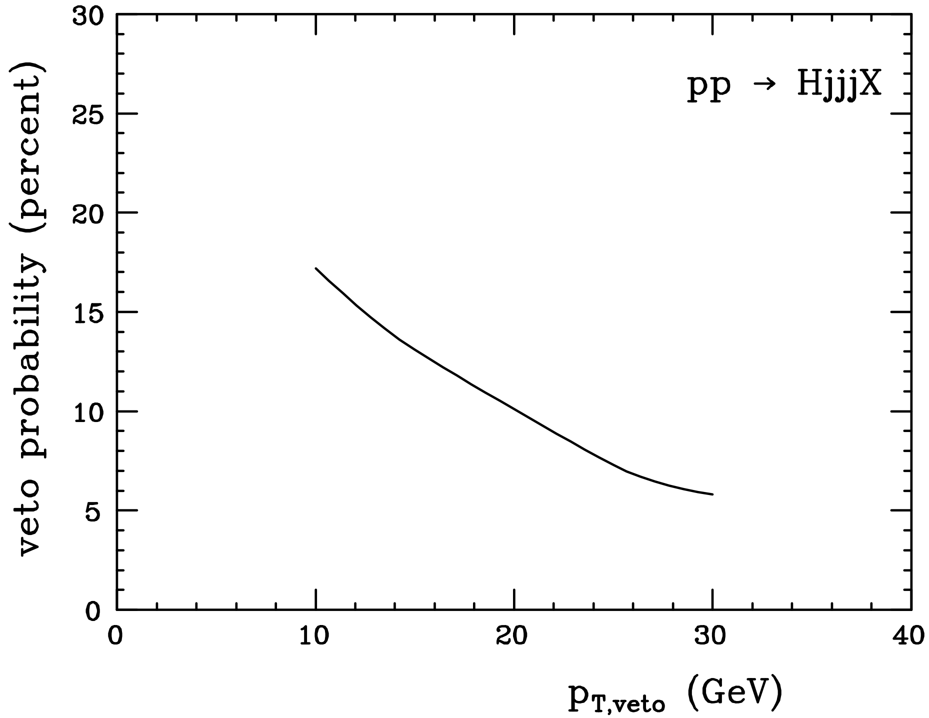
Central jet veto: contn'd

- Hard gluon radiation in Hjj signal sufficiently rare to allow for low p_T threshold for jet veto
- Example:

  $m_H = 120$ GeV Higgs signal

  $p_{T,tag} > 30$ GeV, $|\eta_{j_1} - \eta_{j_2}| > 4$

  veto jet of $p_T > p_{T,veto}$ between tagging jets at parton level



Limiting factors for central jet veto expected from soft hadron activity

- fake jets from underlying event
- fake jets from pile-up LHC data must provide answers! Use to tune PYTHIA, Herwig, . . .

How low a p_T cutoff is possible for central jets? When does signal efficiency suffer?

$\tau^+\tau^-$ invariant mass measurement

$H\to\tau^+\tau^-$ in VBF is one of the most important search channels for the Higgs because it is robust against possible enhancements of Hff couplings compared to the SM

$\tau^+\tau^-$ invariant mass can be reconstructed in $\tau^+\tau^-\to l^+l^-\not{p}_T$ or $\tau^+\tau^-\to h^\pm l^\mp\not{p}_T$ events: $\not{p}_T$ comes from neutrinos alligned with charged τ decay products

Use Zj events of moderate $p_{Tj}\gtrsim 100$ GeV to study invariant mass resolution of $Z\to\tau\tau$: high statistics sample can be collected early on

Problem: Resolution of reconstructed $m_{\tau\tau}$ crucially depends on missing p_T resolution of detector

Measure τ identification efficiency by comparing with Zj events decaying via $Z\to\mu^+\mu^-$

Conclusions

- LHC will observe a SM-like Higgs boson in multiple channels, with $5 \ldots 20\%$ statistical errors
  $\Longrightarrow$ great source of information on Higgs couplings
- NLO QCD corrections and improved simulation tools are important for precise measurements with full LHC data.
- Higgs boson CP properties and structure of the HVV and Hgg vertices from jet-angular correlations in WBF and gluon fusion
- Early LHC data will sharpen our strategies for Higgs search with crucial information on soft physics.