Vector Boson Fusion: Theory

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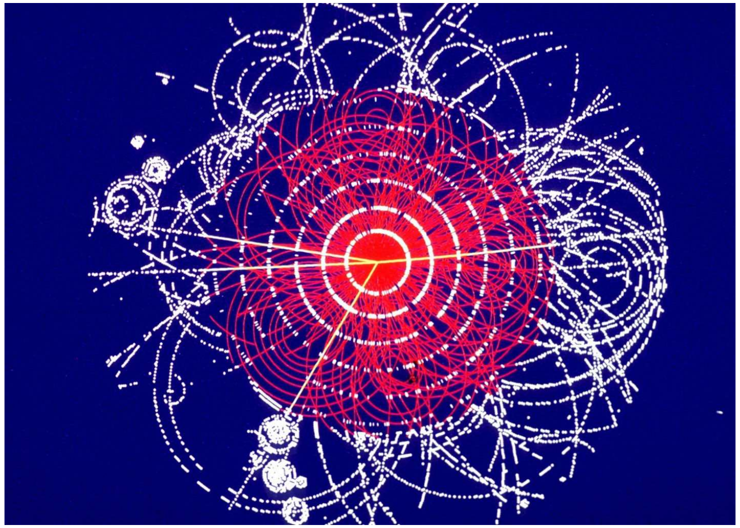
IOP Half day meeting on Vector Boson Fusion, Oxford Univ., Feb. 23, 2011

- Aspects of Higgs Theory
- Characteristics of VBF
- Central Jet Veto
- NLO corrections
- Structure of *HWW* Vertex
- 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 $\quad \Phi^\dagger \to (0, \frac{v+H}{\sqrt{2}})$

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

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

- 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

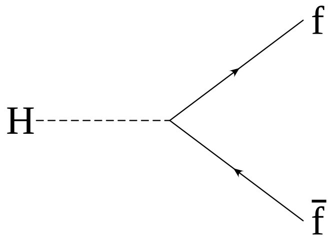
Kinetic energy term of Higgs doublet field:

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

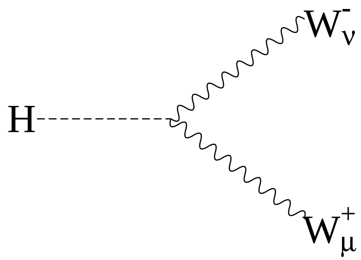
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\, m_V^2/v \sim g^2 v$ within SM

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

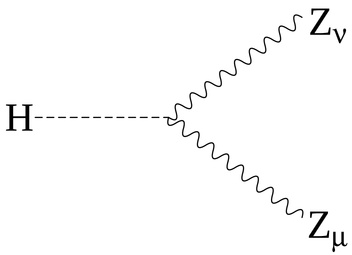
Feynman rules for SM Higgs couplings



$$-i\frac{m_f}{v}\,1$$



$$ig\,m_W\,g_{\mu\nu}$$

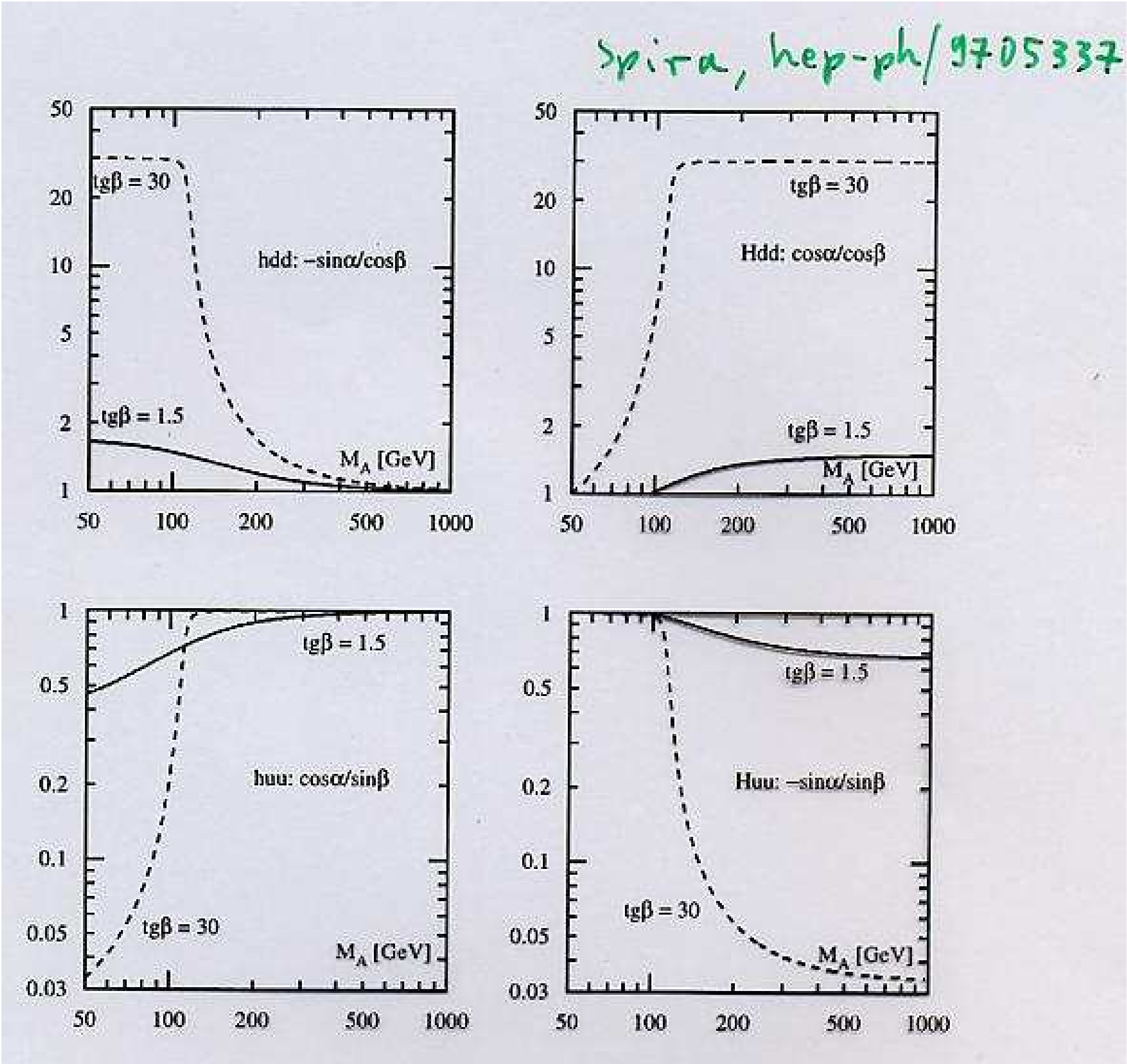


$$i\,g\,\frac{1}{\cos\theta_W}\,m_Z\,g_{\mu\nu}$$

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

Distinguish scalar from pseudoscalar Higgs couplings to fermions.

Large changes in coupling strengths possible, e.g.in MSSM



Most probable discovery region: below 200 GeV

$$m_H = 89^{+35}_{-26}\ \text{GeV}$$

Including theory uncertainty

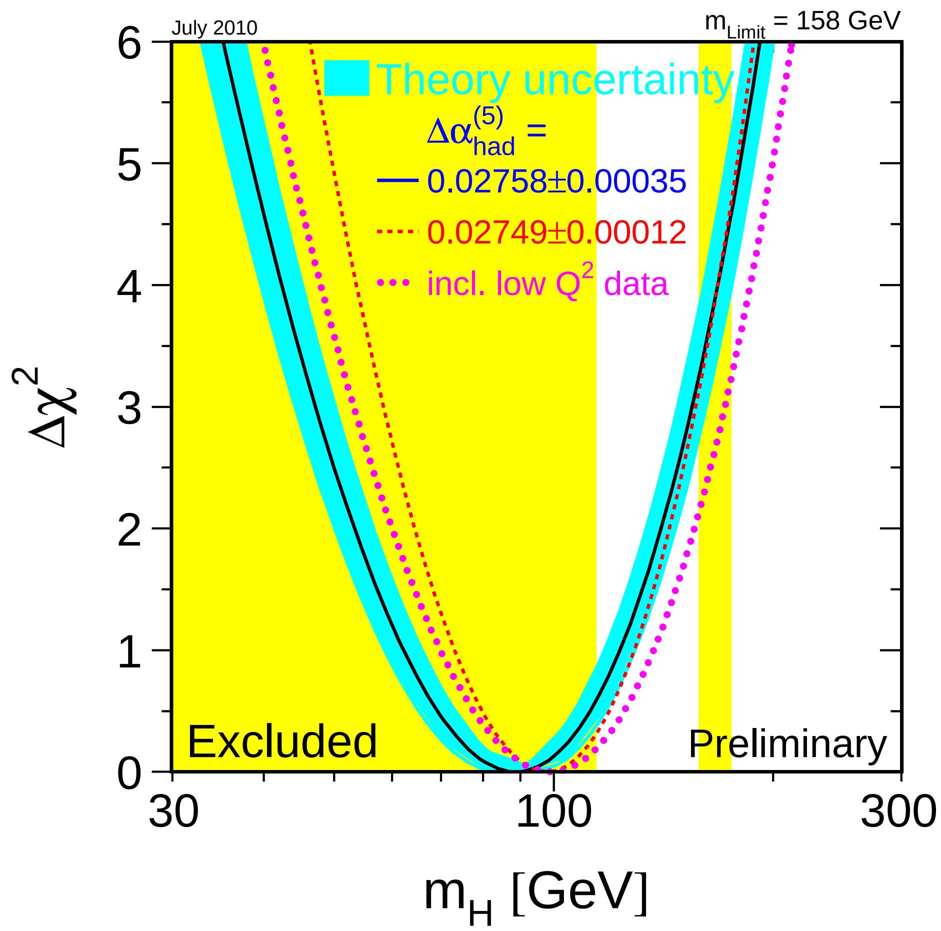
$$m_H < 158\ \text{GeV} \quad (95\%\ \text{CL})$$

Does not include
Direct search limit from LEP

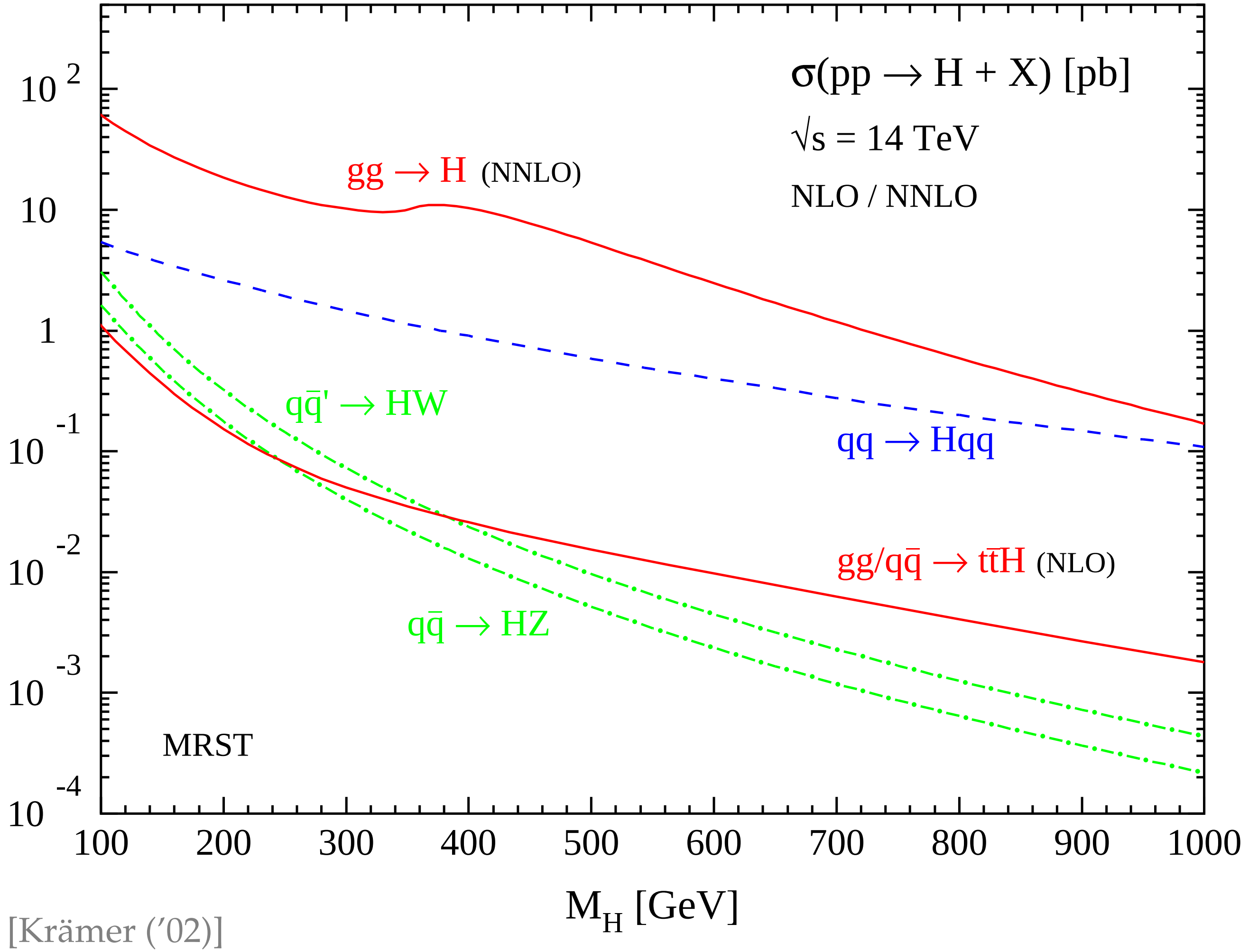
$$m_H > 114\ \text{GeV} \quad (95\%\ \text{CL})$$

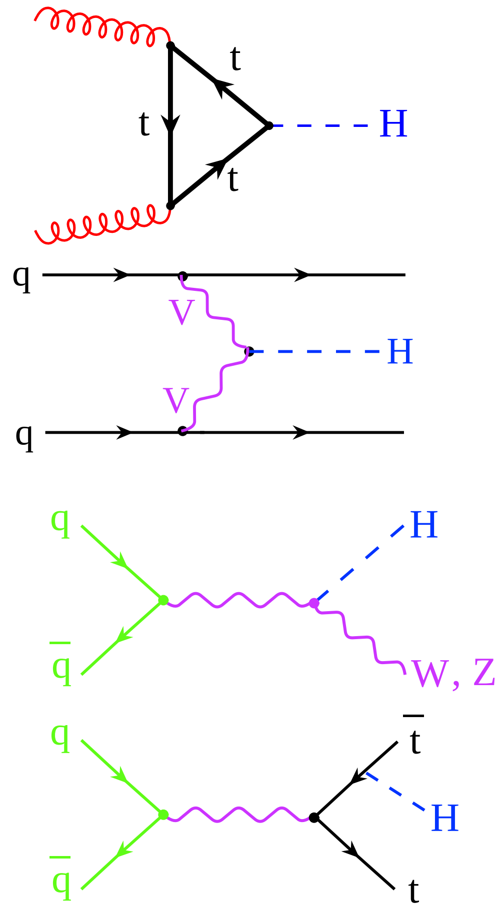
Renormalize probability for
$m_H > 114$ GeV to 100%:

$$m_H < 185\ \text{GeV} \quad (95\%\ \text{CL})$$



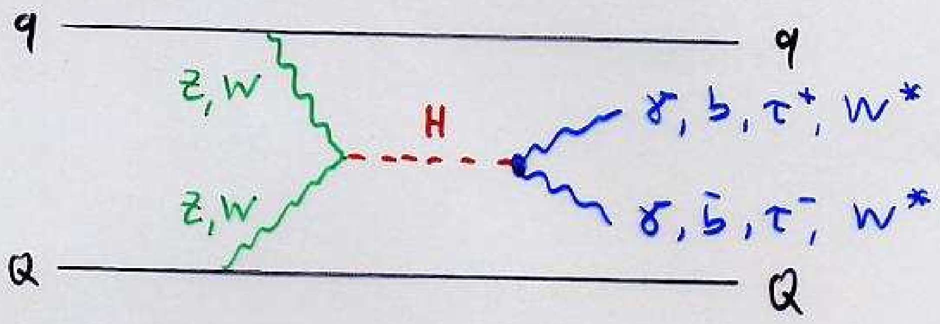
Total cross sections at the LHC



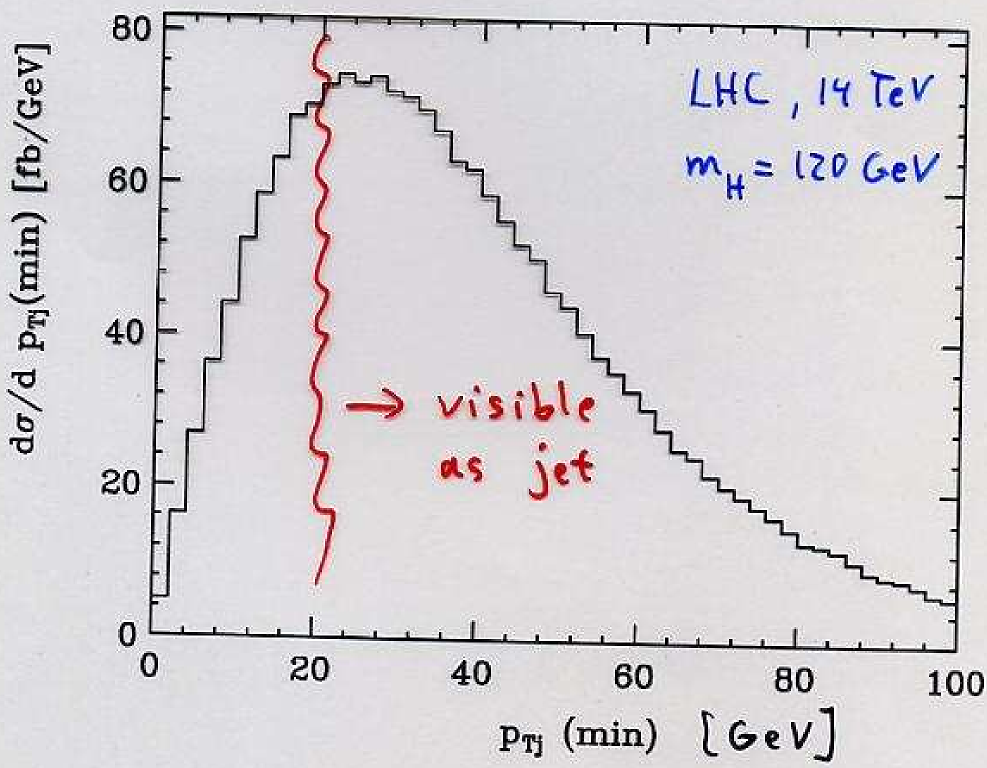


[Krämer ('02)]

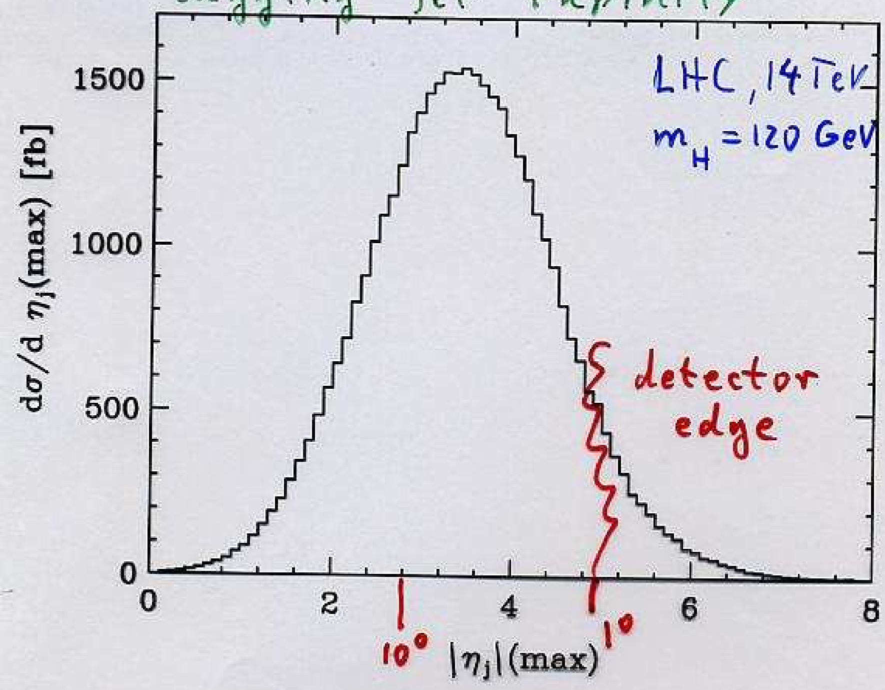
Characteristics of weak boson fusion



- scattered quarks lead to 2 forward tagging jets [Cahn, Kleiss, Stirlin



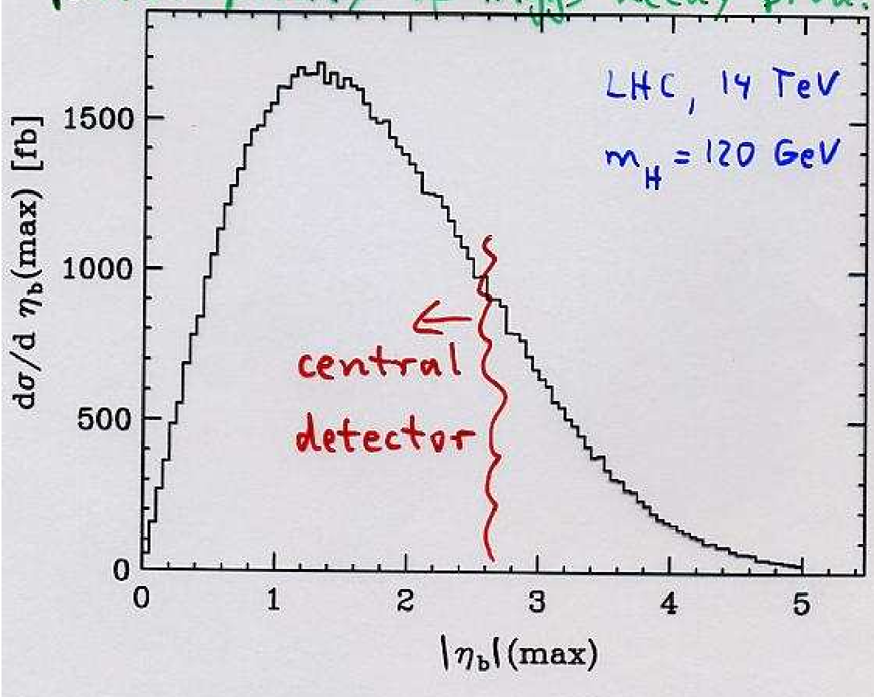
tagging jet rapidity



tagging je
forward bu
well inside
detector

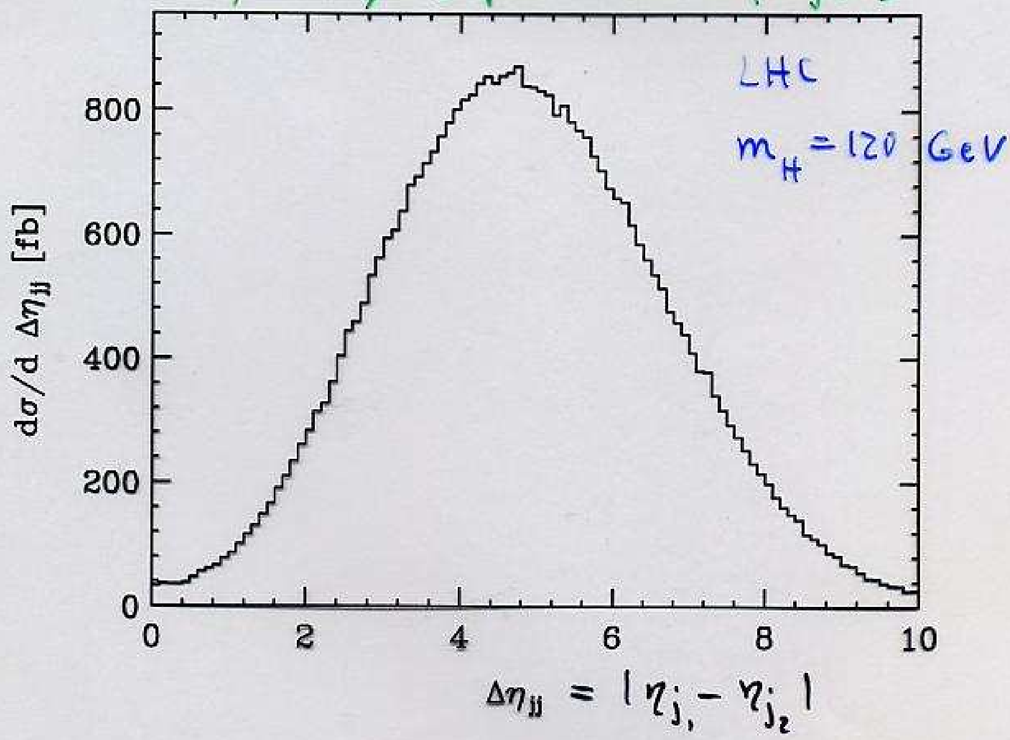
$\eta = \frac{1}{2} \ln \frac{1+\cos}{1-\cos}$

pseudorapidity of Higgs decay prod.



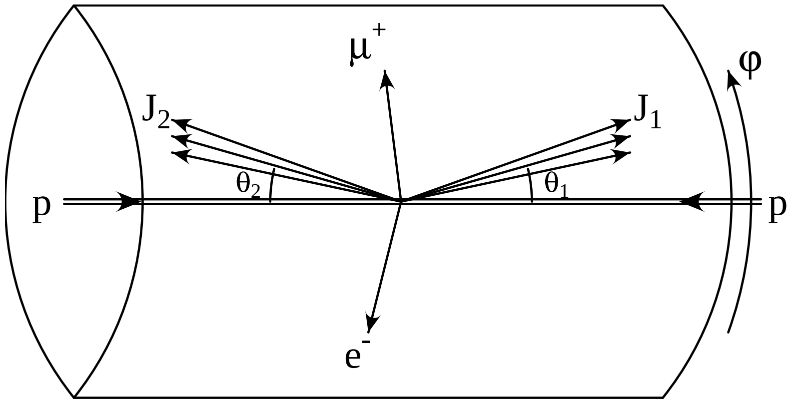
Higgs deca
products
are quite
central

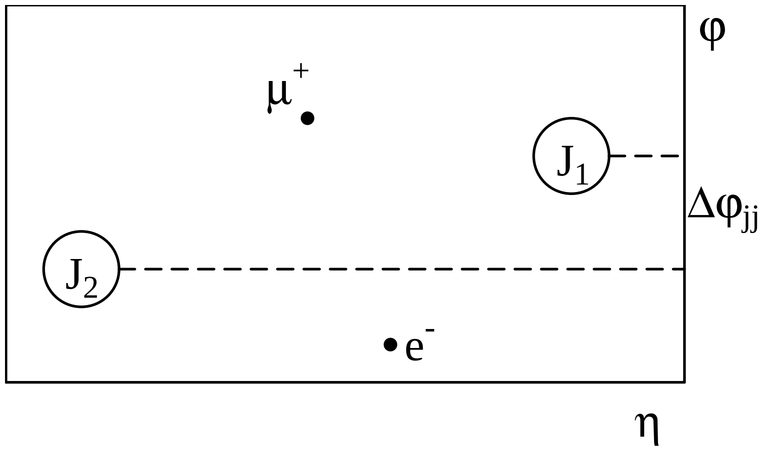
rapidity separation of jets



Tagging jets are typically far apart. Higgs decay products usually between 2 tagging jets

VBF signature



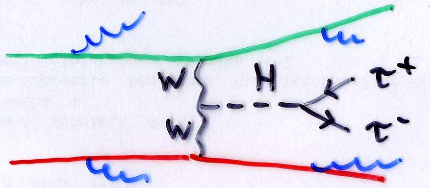


Characteristics:

- 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 between tagging jets)

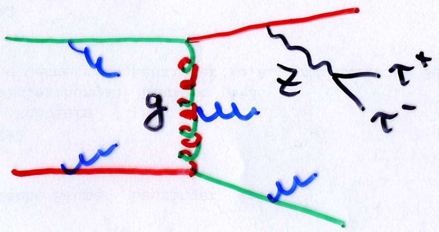
Central jet veto

- $t\bar{t}$ + 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

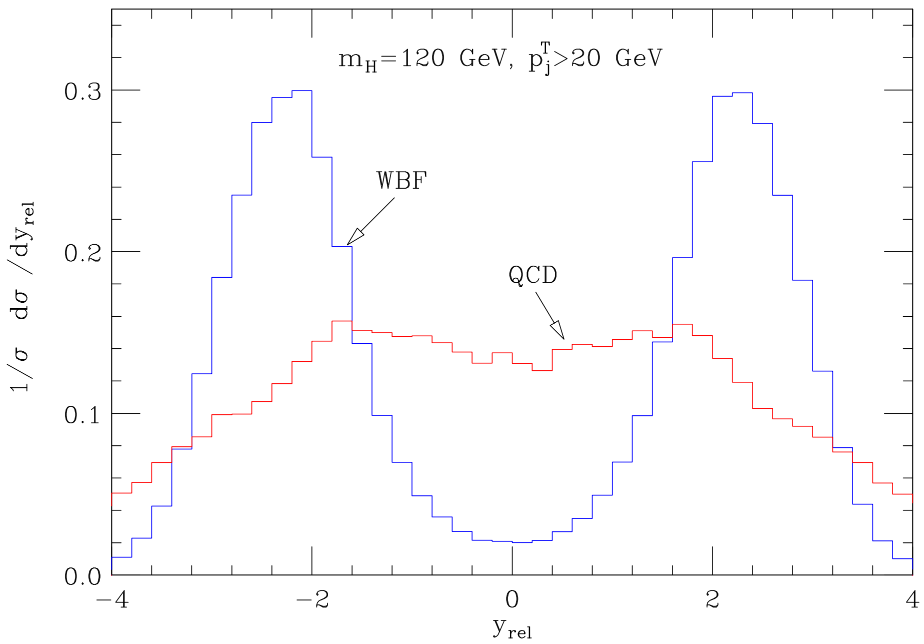
- Major QCD backgrounds: t-channel color octet exch.

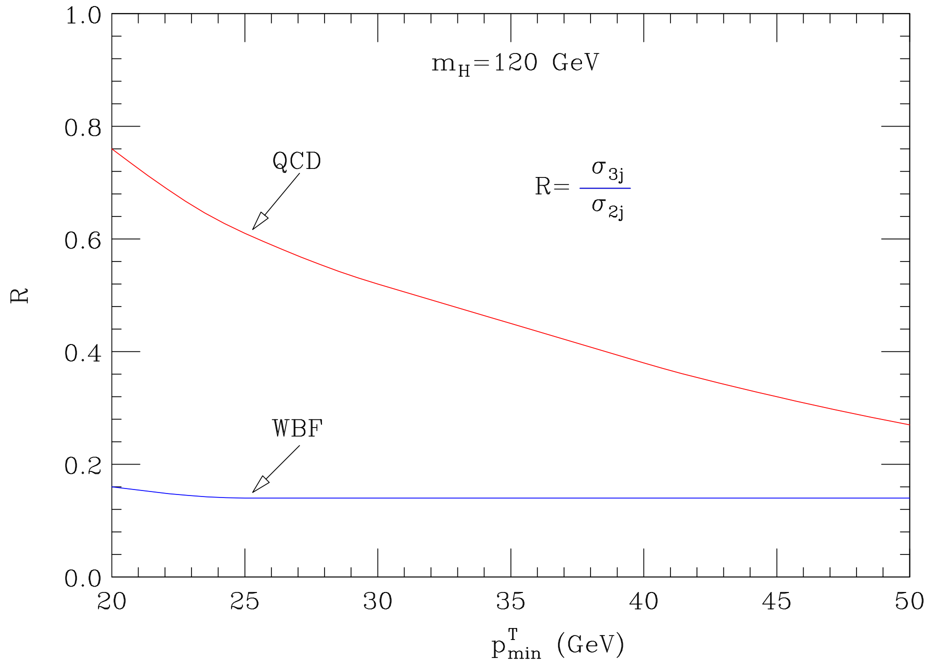


deflection of color charge by ~180° $\Rightarrow$ strong color acceleration
$\Rightarrow$ enhanced central gluon emis.

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

Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion

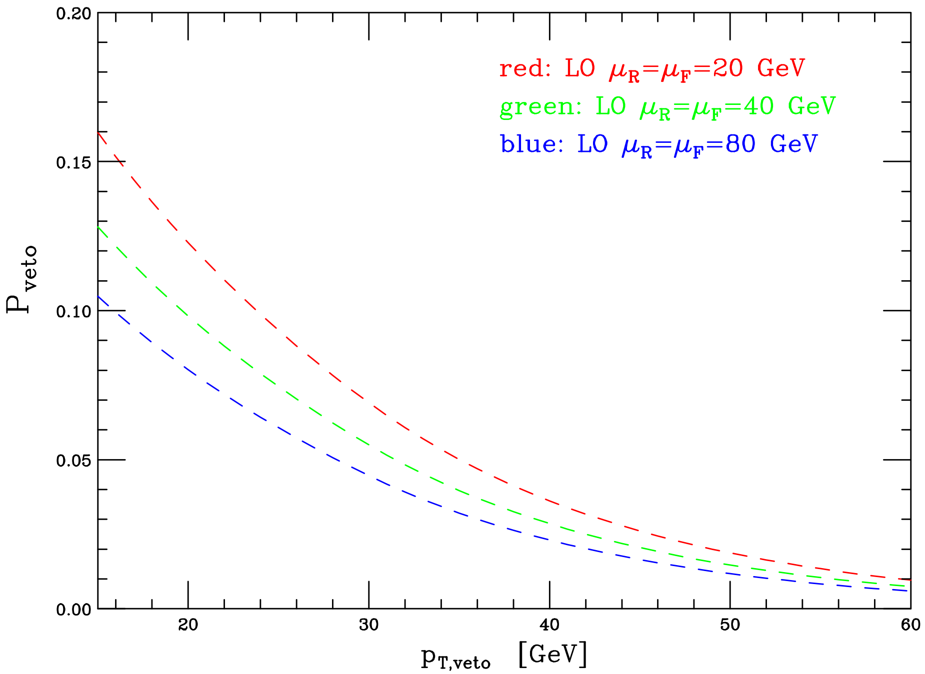




[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF Higgs signal and CJV



$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag 1}}, \eta_j^{\text{tag 2}})$$

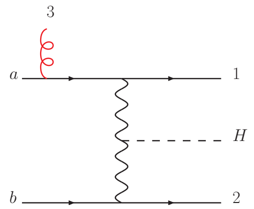
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

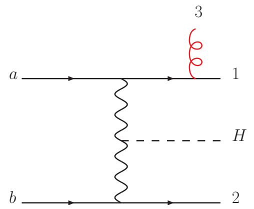
- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621 (JHEP)

Ingredients of the NLO Calculation

- Born: 3 final state partons + Higgs via VBF

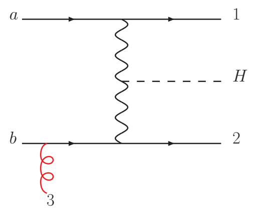
$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \Big[\mathcal{M}_{B,1a} :$$

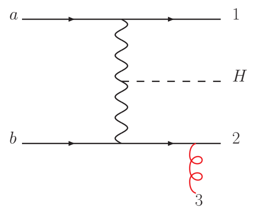




$$\Big]$$

$$+ \ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\mathcal{M}_{B,2b} :$$

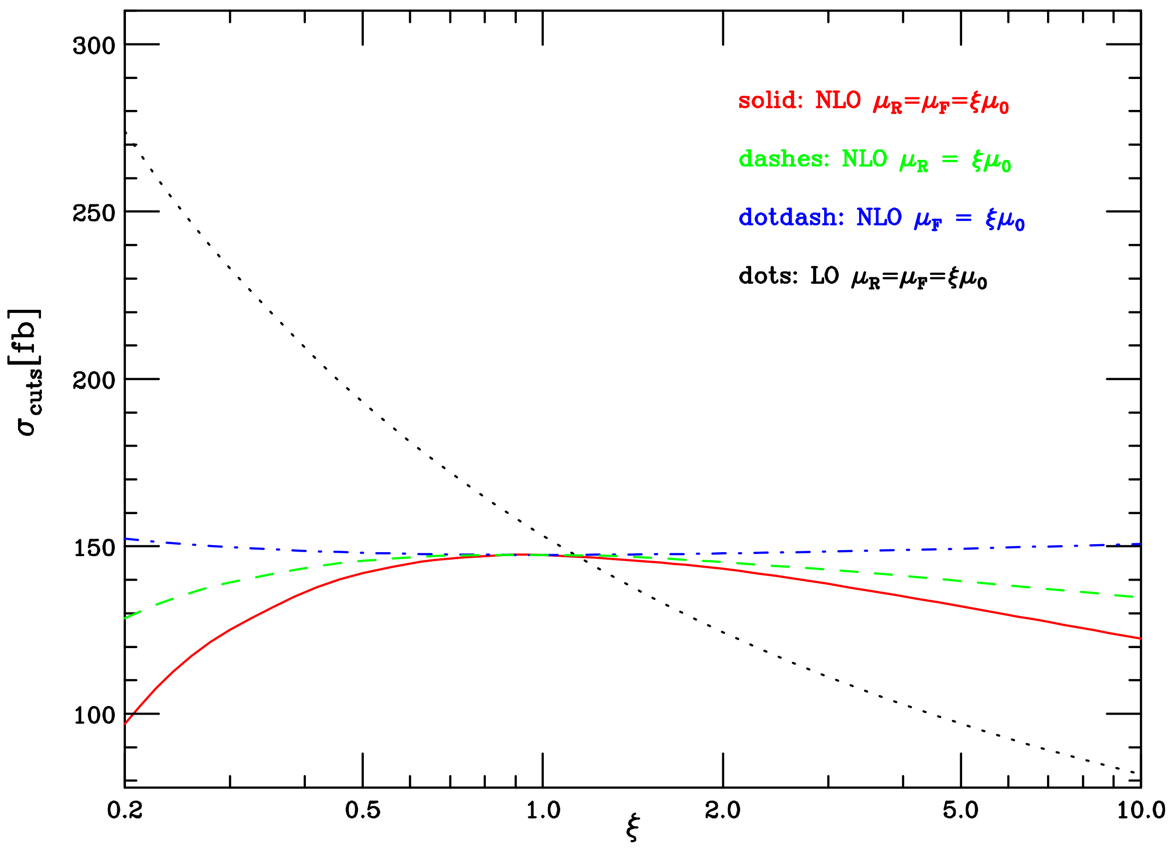




$$\Big]$$

- Catani, Seymour subtraction method
- Real: 4 final state partons + Higgs via VBF
- Virtual: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected

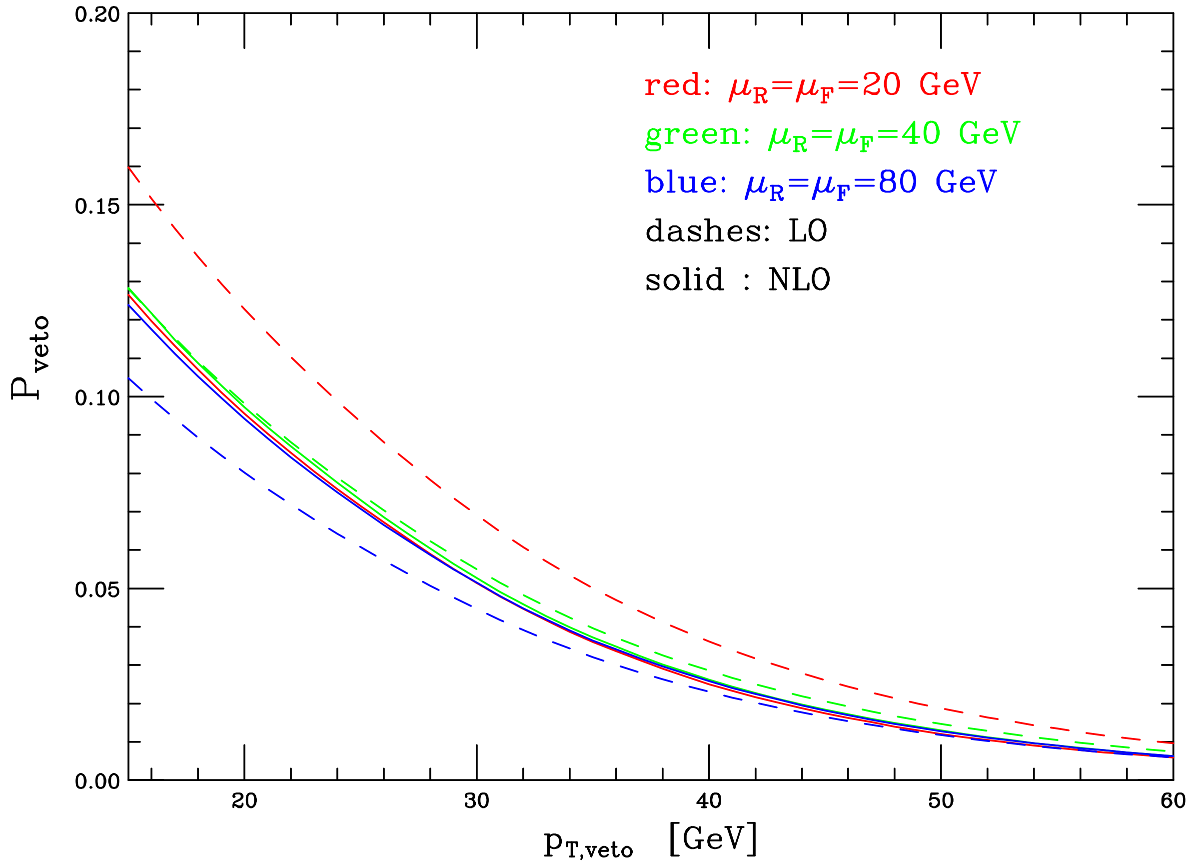
Total $Hjjj$ Cross Section at the LHC: NLO vs LO



$\mu_0 = 40$ GeV
$\xi = 2^{\mp 1}$ scale variations:

- LO: +26% to −19%
- NLO: less than 5%

Veto Probability for the VBF Signal



$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3}{dp_{Tj}^{veto}}$$

Scale variations, $p_{T,veto} = 15$ GeV:

- LO: +33% to −17%
- NLO: −1.4% to −3.4%

Reliable prediction for perturbative part of veto probability at NLO

Corrections for Higgs production cross sections

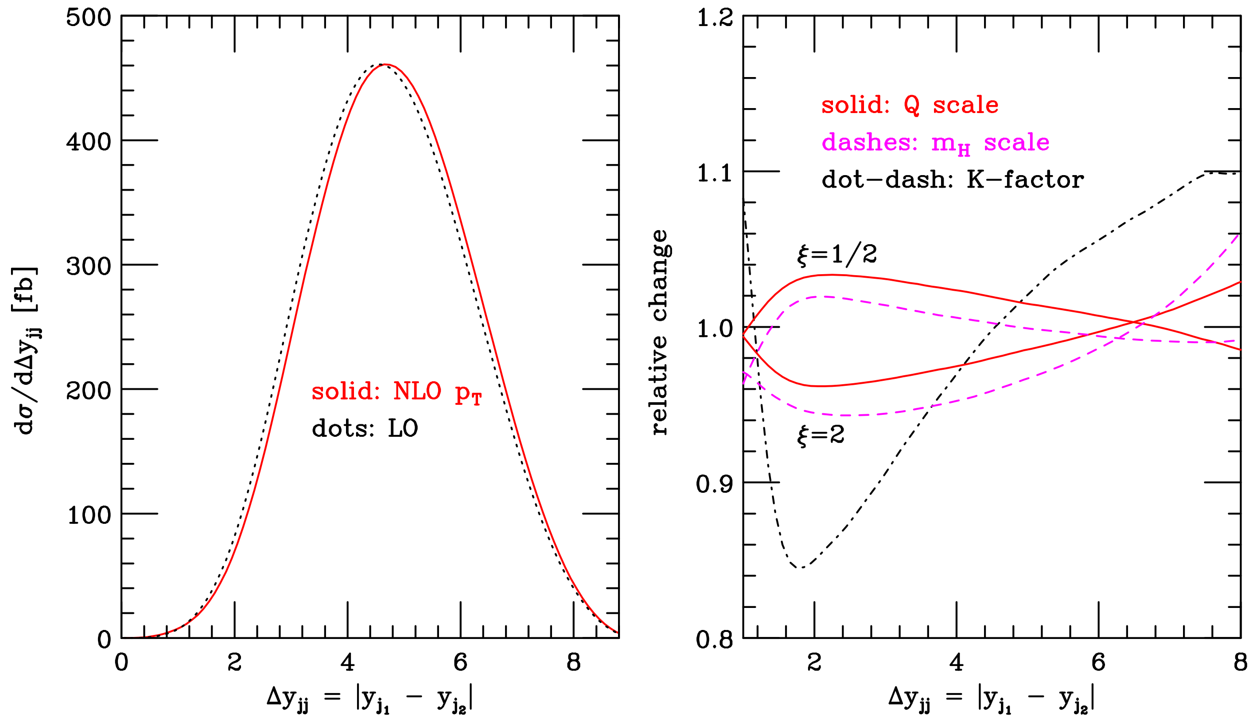
Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

$\Longrightarrow$ need QCD corrections to production cross sections. Much progress in recent years

- $gg \to H$ (all but NLO in $m_t \to \infty$ limit)
  - NNLO: Harlander, Kilgore (2001); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)
  - N^3LO in soft approximation: Moch, Vogt (2005)
- Hjj by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2006)
- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)
  - distributions at NLO: Figy, Oleari, D.Z (2003); Campbell, Ellis, Berger (2004)
  - 1-loop EW corrections: Ciccolini, Denner, Dittmaier (2007)
  - approx. NLO QCD to $Hjjj$: Figy, Hankele, D.Z (2007)
- $\bar{t}tH$ 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)

NLO QCD corrections to VBF

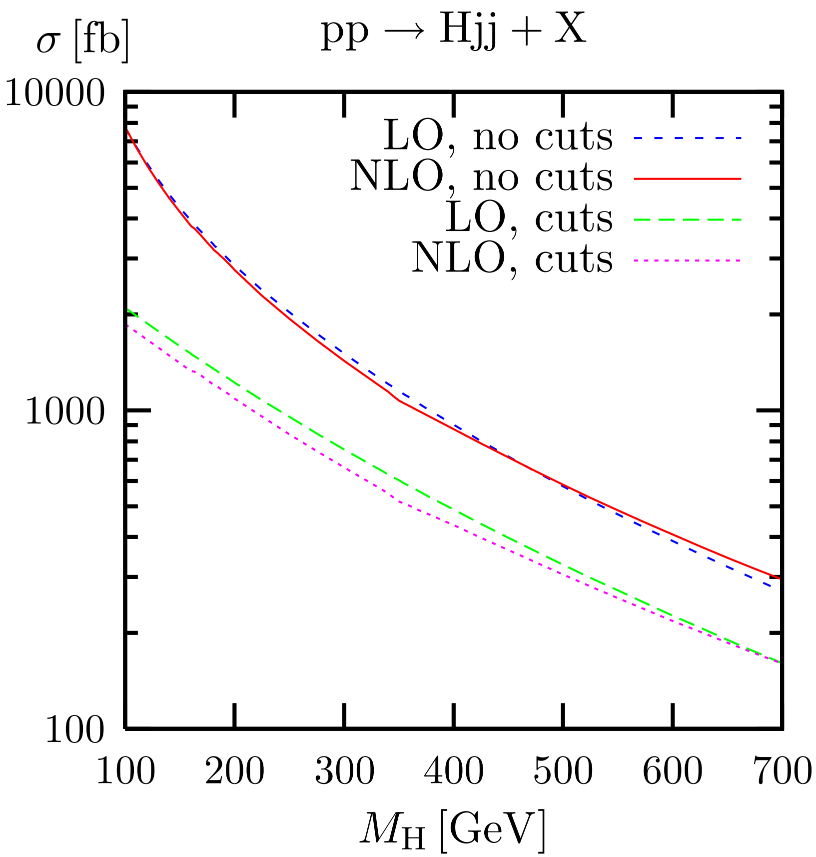
- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- K-factor is phase space dependent
- QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty
  Ciccolini, Denner, Dittmaier, arXiv:0710.4749

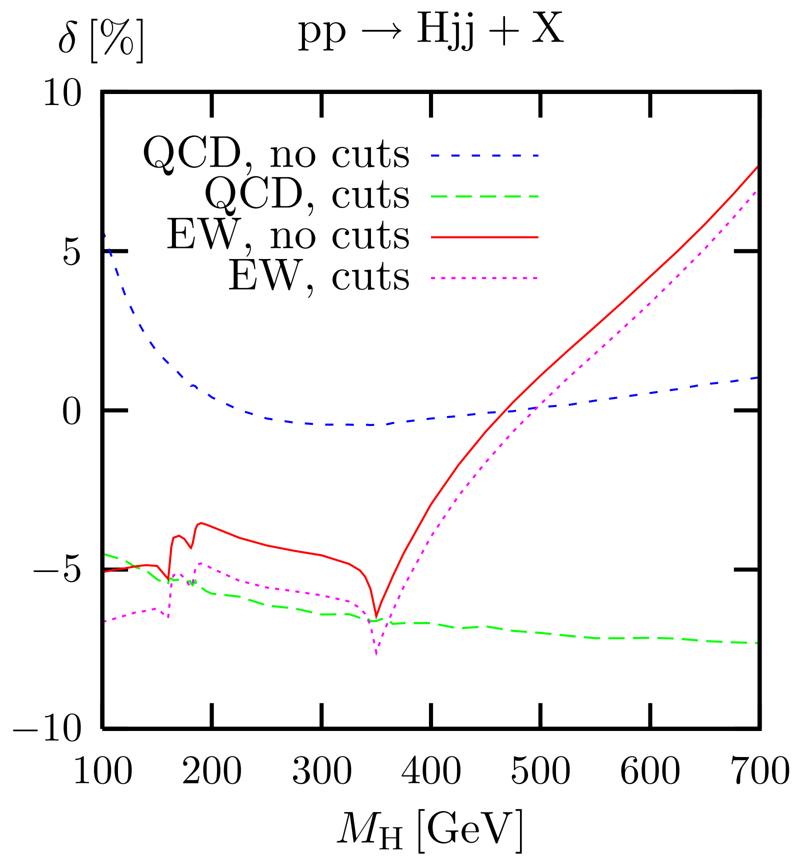


$m_H = 120$ GeV, typical VBF cuts

QCD + EW corrections to Hjj production

Cross sections without and with VBF cuts: $p_T(j) > 20$ GeV $\quad |y_{j_1} - y_{j_2}| > 4, \;\; y_{j_1} \cdot y_{j_2} < 0$



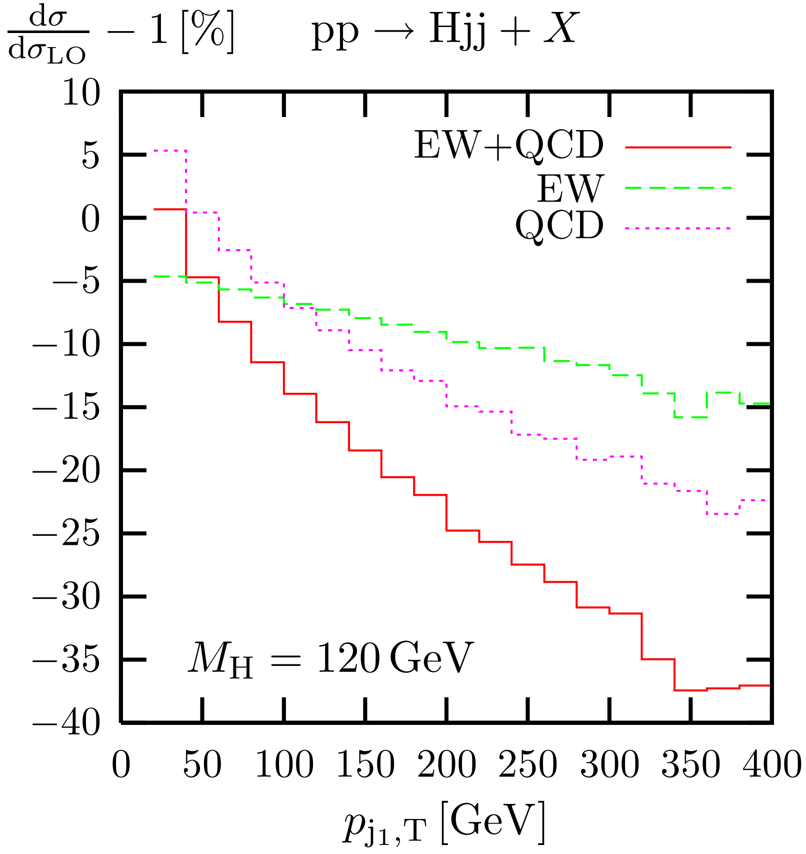


Ciccolini, Denner, Dittmaier, arXiv:0710.4749

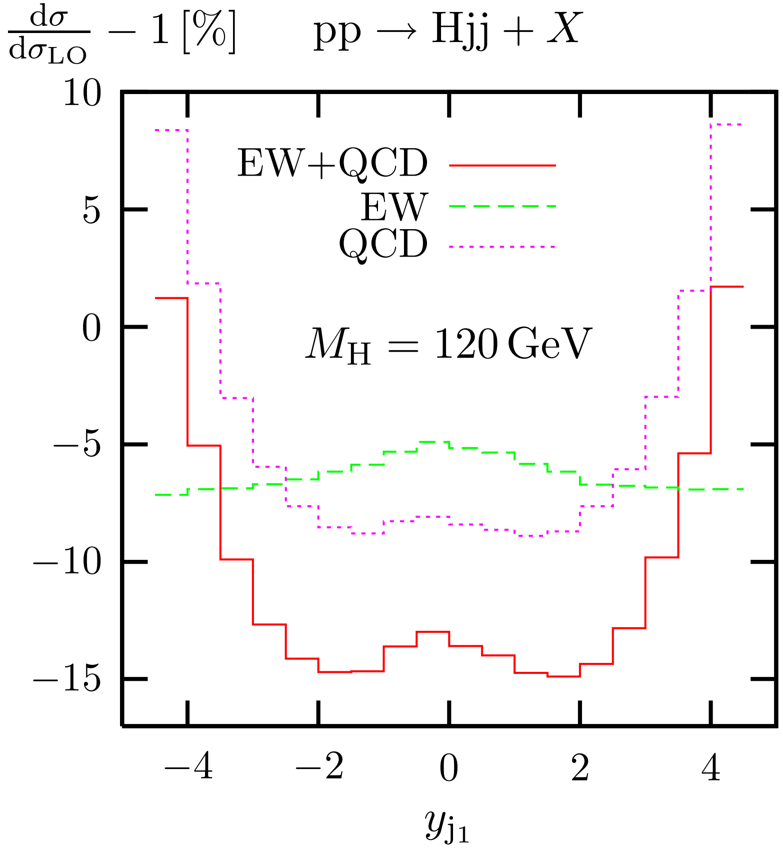
Relative size of 1-loop corrections

Consider distributions of hardest jet in the event:

p_T distribution



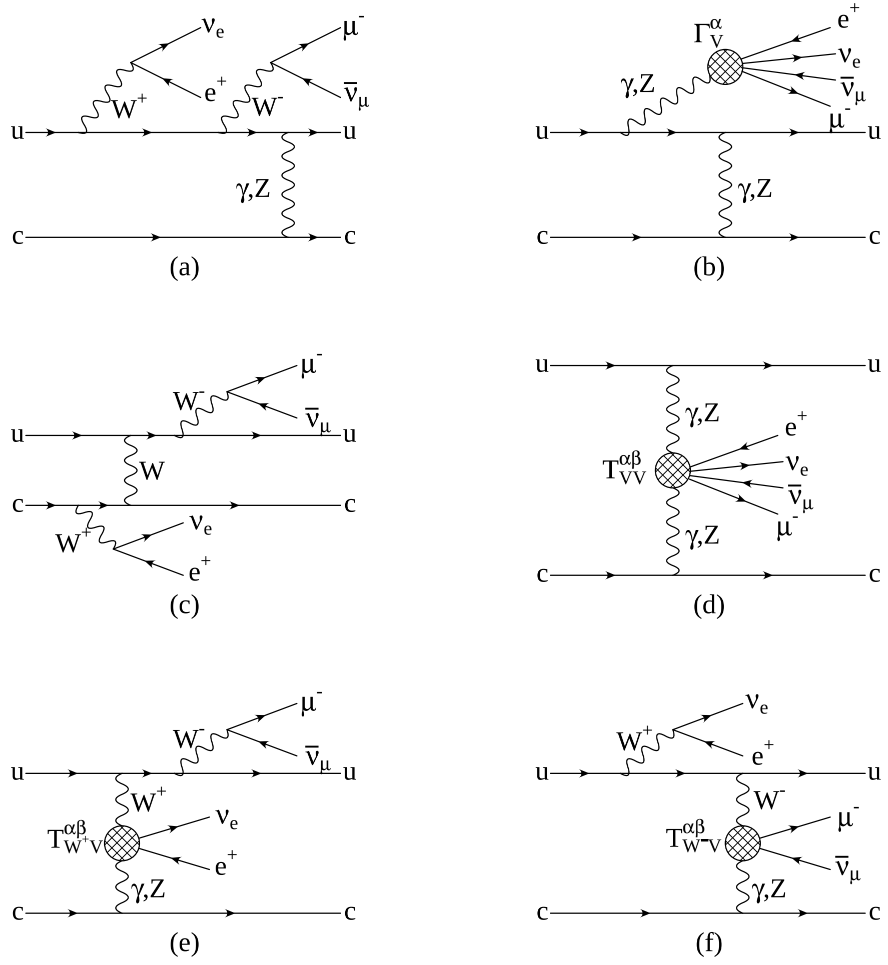
rapidity distribution



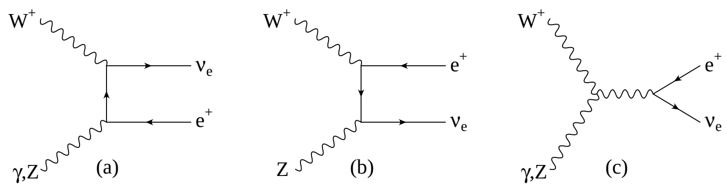
strong shape changes by QCD corrections, EW corrections affect mostly normalization

Weak boson scattering: $qq\to qqWW$, $qqZZ$, $qqWZ$ at NLO

- example: WW production via VBF with leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO



Use modular structure, e.g. leptonic tensor

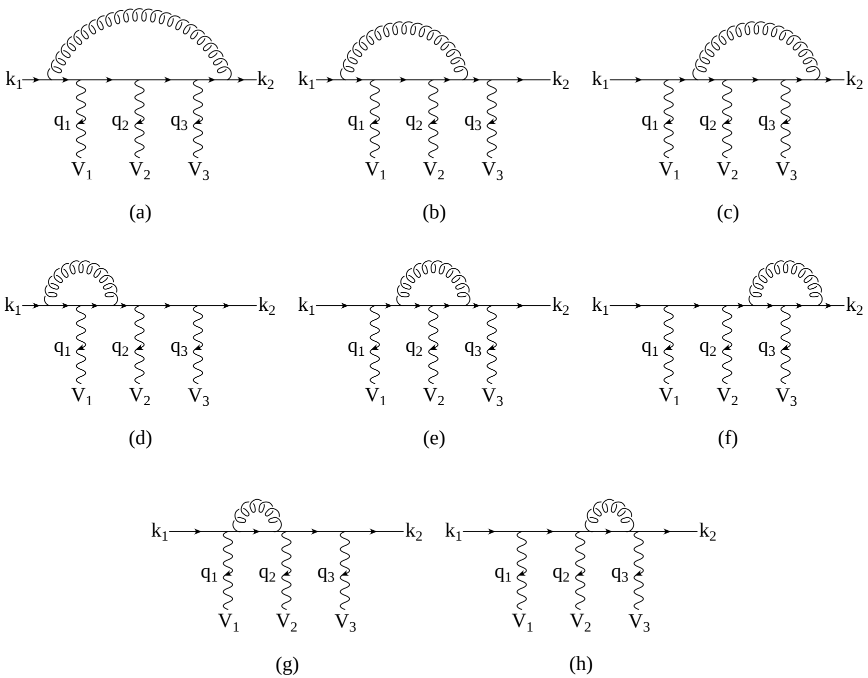


Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to MadGraph for real emission corrections

Most challenging for virtual: pentagon corrections

Virtual corrections involve up to pentagons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

The sum of all QCD corrections to a single quark line is simple

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2} \right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}} \right] + \widetilde{\mathcal{M}}^{(i)}_{V_1 V_2 V_3,\tau}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)$$

- Divergent pieces sum to Born amplitude: canceled via Catani Seymour algorithm
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Pentagon tensor reduction with Denner-Dittmaier is stable at 0.1% level

Phenomenology

Study LHC cross sections within typical VBF cuts

- Identify two or more jets with k_T-algorithm ($D = 0.8$)

$$p_{Tj} \geq 20\ \text{GeV}\,, \qquad |y_j| \leq 4.5$$

- Identify two highest p_T jets as tagging jets with wide rapidity separation and large dijet invariant mass

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad M_{jj} > 600\ \text{GeV}$$

- Charged decay leptons ($\ell = e,\ \mu$) of W and/or Z must satisfy

$$p_{T\ell} \geq 20\ \text{GeV}\,, \qquad |\eta_\ell| \leq 2.5\,, \qquad \triangle R_{j\ell} \geq 0.4\,,$$
$$m_{\ell\ell} \geq 15\ \text{GeV}\,, \qquad \triangle R_{\ell\ell} \geq 0.2$$

and leptons must lie between the tagging jets

$$y_{j,min} < \eta_\ell < y_{j,max}$$

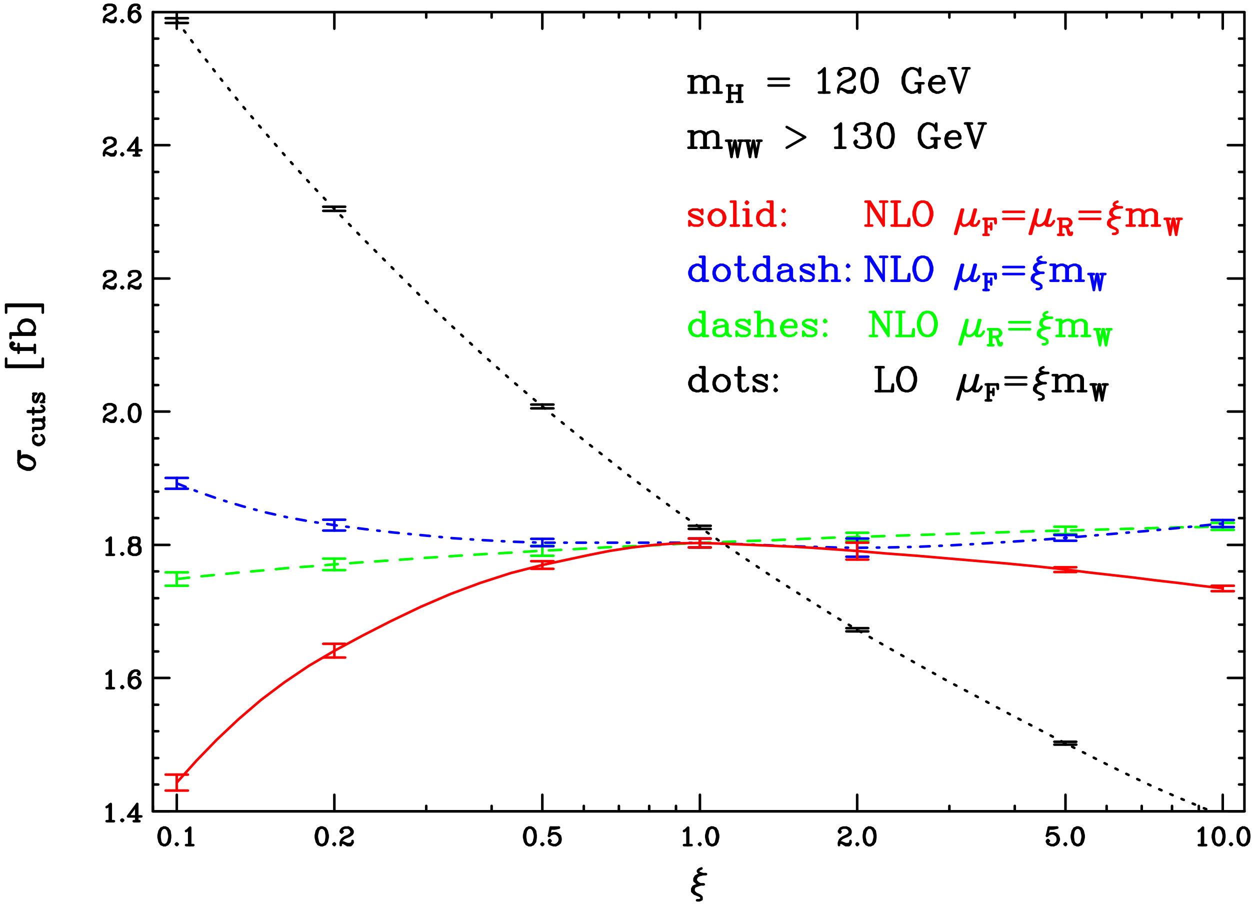
For scale dependence studies we have considered

$\mu = \xi\ m_V$ fixed scale $\qquad$ $\mu = \xi\ Q_i$ weak boson virtuality : $Q_i^2 = 2k_{q_1} \cdot k_{q_2}$

WW production: $pp \to jj e^+ \nu_e \mu^- \bar{\nu}_\mu X$ @ LHC

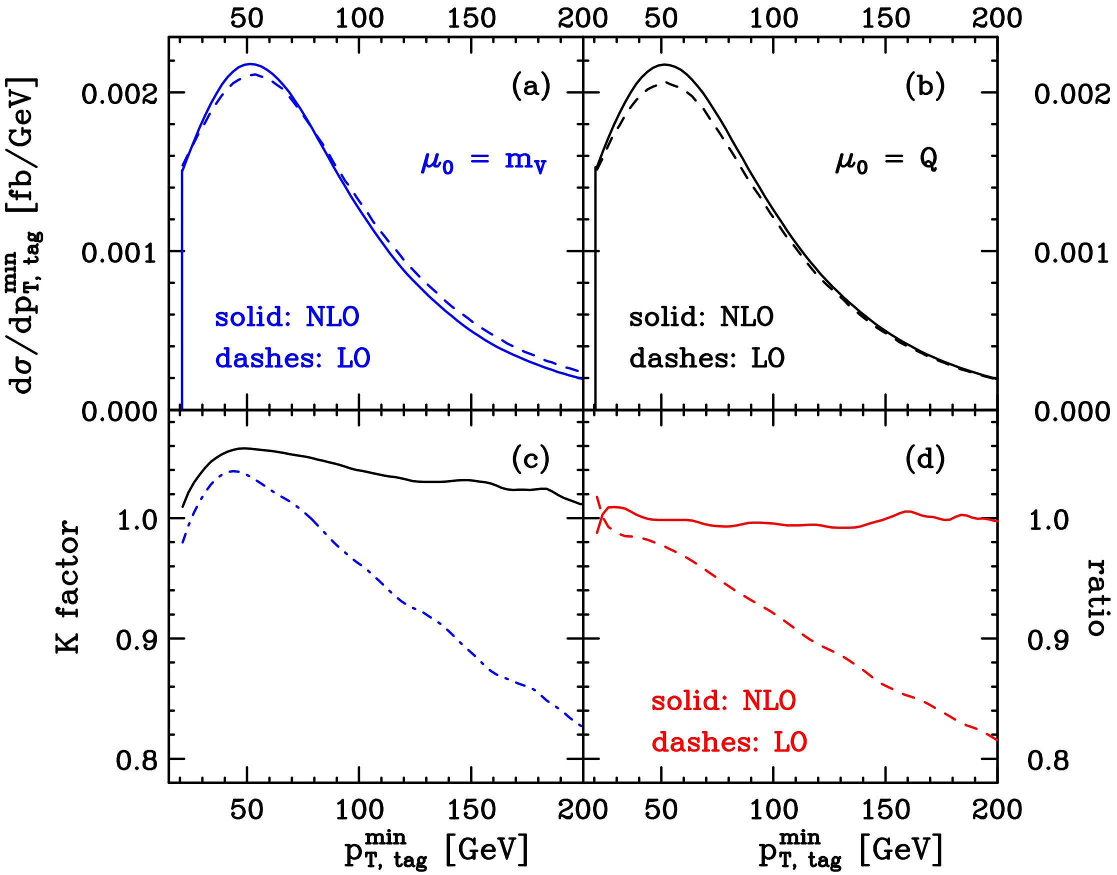
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



WZ production in VBF, $WZ \to e^+ \nu_e \mu^+ \mu^-$

Transverse momentum distribution of the softer tagging jet

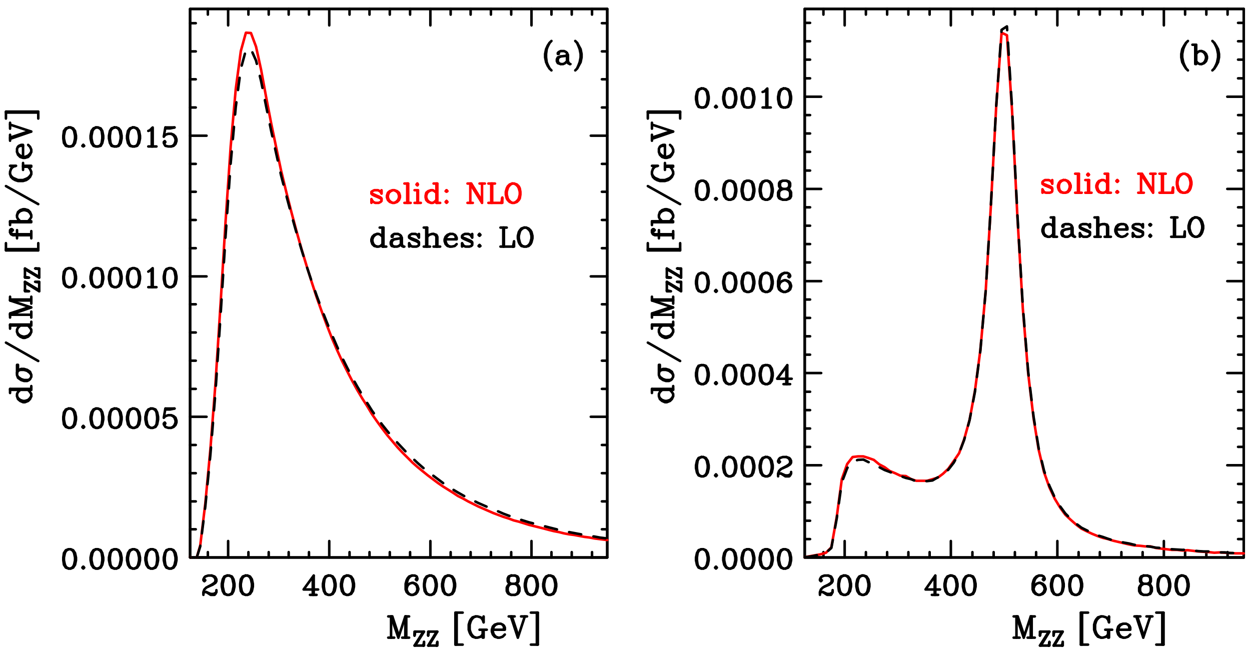


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

Use $\mu_F = Q$ at LO to best approximate the NLO results

ZZ production in VBF, $ZZ \to e^+e^-\mu^+\mu^-$

4-lepton invariant mass distribution without/with Higgs resonance



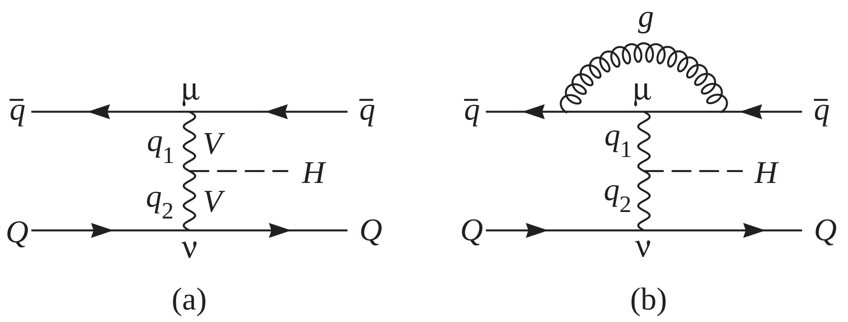
Good agreement of LO and NLO due to low scale choice $\mu = m_Z$. Alternative choice $\mu = m_H$ or $\mu = m_{4\ell}$ leads to smaller LO cross section at high $m_{4\ell}$

NLO QCD correction for VBF available in VBFNLO: parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production (and more) $\Longrightarrow$ talk by Sophy Palmer

Available at http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/

Tensor structure of the HVV coupling

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



$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, (q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}$$

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

Physical interpretation of terms:

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

loop induced couplings for neutral scalar

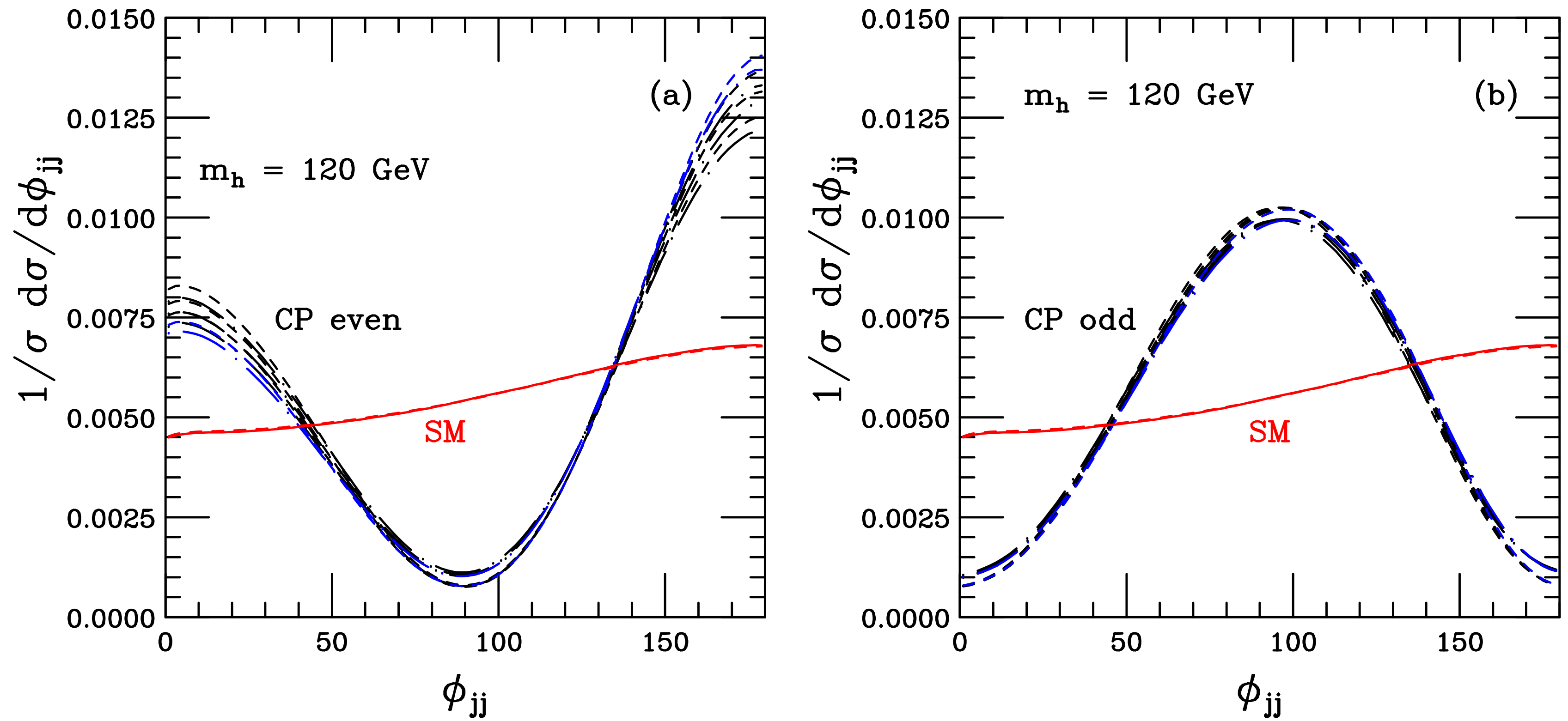
CP even $\mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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

Must distinguish a_1, a_2, a_3 experimentally

Azimuthal angle correlations

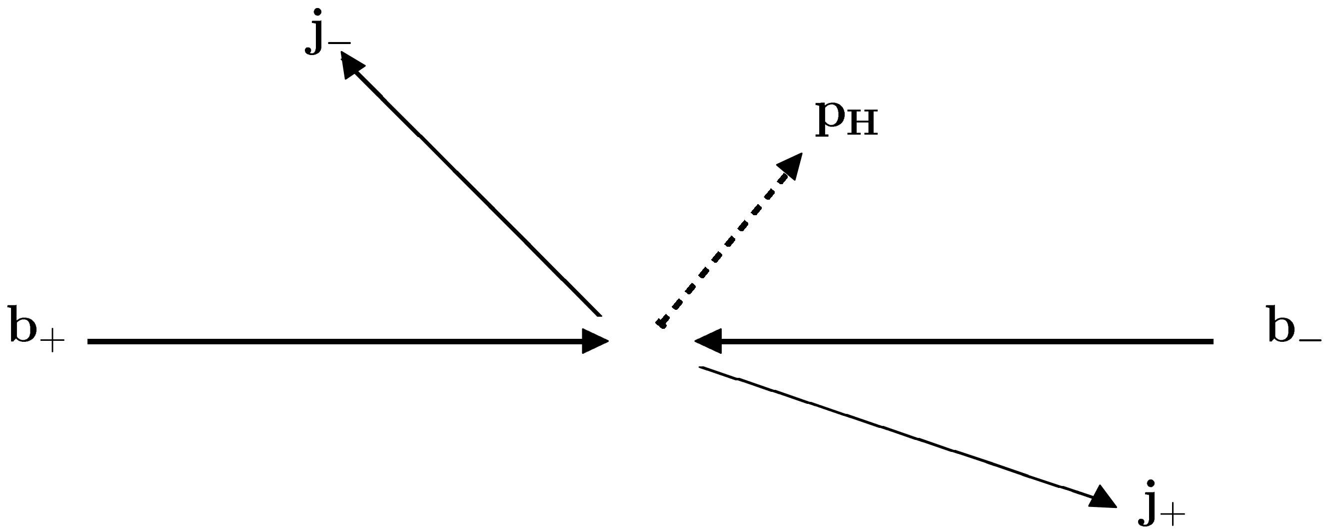
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



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:

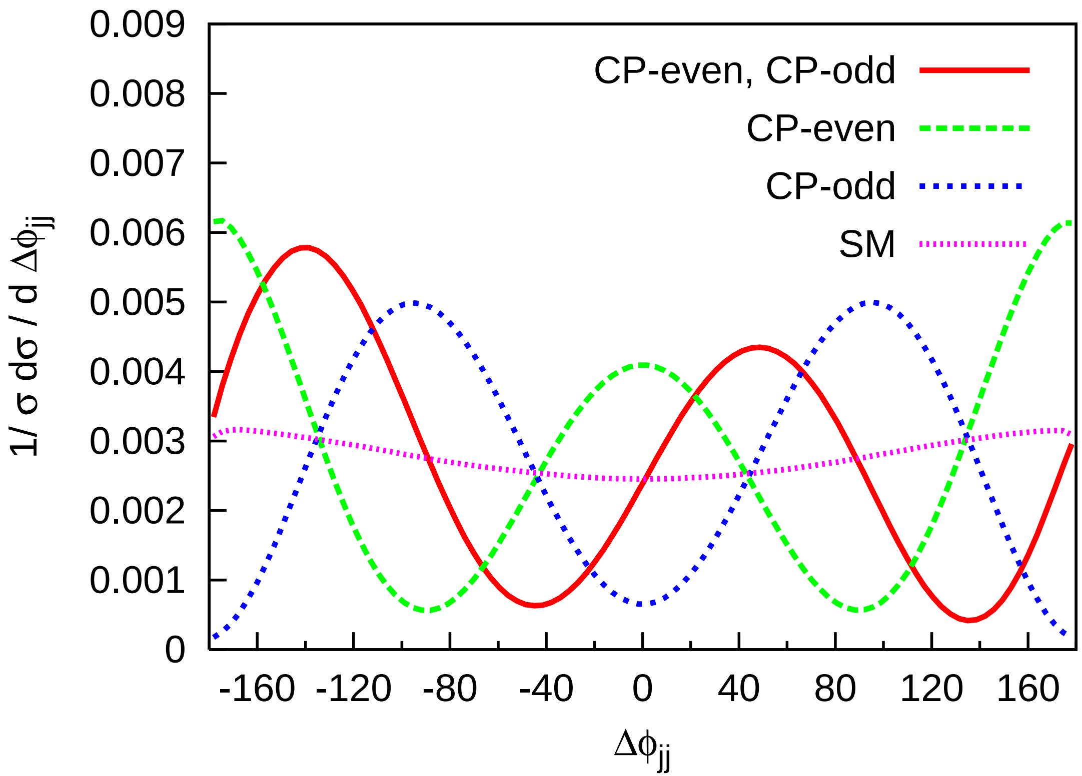


Define azimuthal angle between jet momenta j_+ and j_- via

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

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

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 $\pi - \alpha$

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
- Gauge boson fusion processes provide important facets of this information, both on absolute values of couplings but also on their tensor structure.
- Loop corrections on signal processes provide predictions for Higgs cross sections and distrbutions with 10% accuracy or better.
- VBF processes are particularly well understood theoretically, with theory uncertainties well below 10% (below 5% for $qq \to qqH$).