VECTOR BOSON SCATTERING

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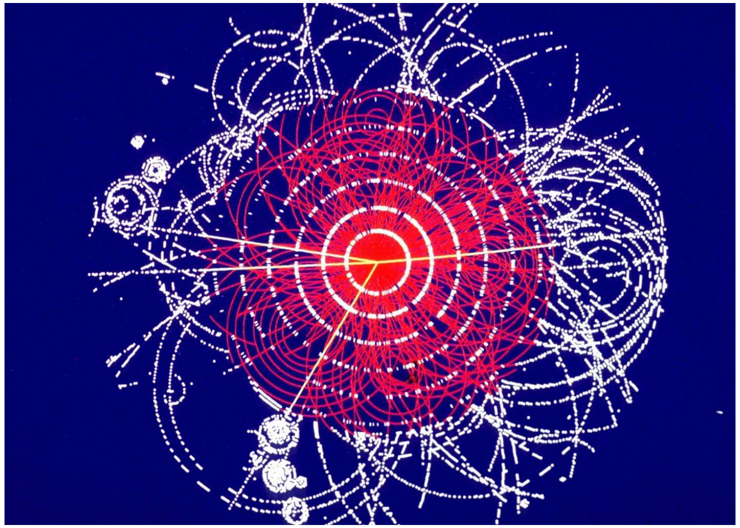
- Introduction
- Vector Boson Fusion
- Tensor structure of HVV coupling
- NLO QCD corrections to VV scattering
- New physics in VV scattering at high energy
- Conclusions



Electroweak symmetry breaking: Higgs (and more?)

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

- 2012: Discovery of a Higgs-like resonance at 126 GeV
- TASK: Measure its couplings and probe
  mass generation for gauge bosons and fermions
  unitarization of cross section for vector boson scattering

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

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

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

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

Higgs coupling to gauge bosons

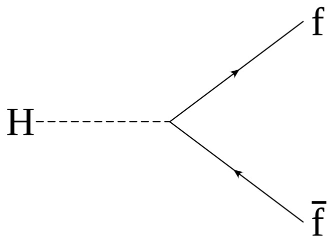
Kinetic energy term of Higgs doublet field:

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

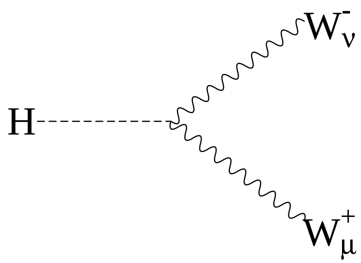
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples proportional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

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

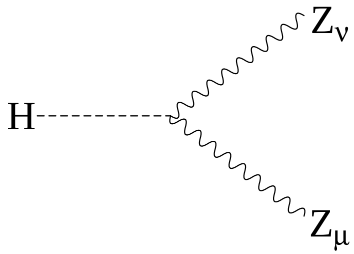
Feynman rules for SM Higgs couplings



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



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



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

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

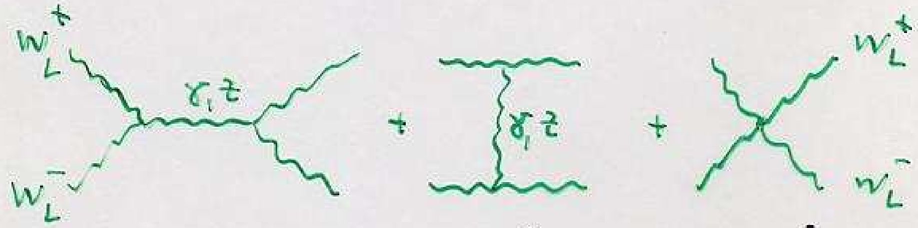
WW scattering and unitarity

Consider longitudinal W's

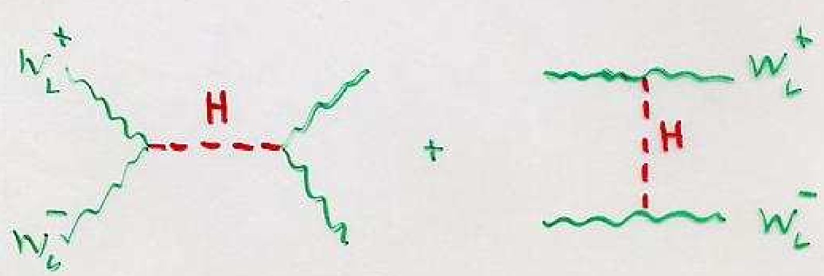
$$W_L^+ W_L^- \to W_L^+ W_L^-$$

Polarisation vector

$$\varepsilon_L^\mu = \frac{p^\mu}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$



$$\mathcal{M} \sim \underbrace{\frac{s^2}{m_W^4} \qquad \frac{s^2}{m_W^4} \qquad \frac{s^2}{m_W^4}}_{s/m_W^2}$$



$$\frac{s}{m_W^2} \qquad \frac{s}{m_W^2}$$

sum $\sim s^0$ for $s \gg m_H^2$

Unitarity of WW scattering

Partial wave amplitudes are bounded by a constant

$\Longrightarrow$ $\mathcal{M} \sim \frac{s}{m_W^2}$ violates unitarity at sufficiently high energy

Without the Higgs contribution, the $J = 0$ partial wave violates unitarity for $\sqrt{s} > 1.2$ TeV

Destructive interference between Higgs exchange amplitudes and gauge boson scattering amplitudes works for $s > m_H^2$ only

$\Longrightarrow$ $m_H \lesssim 1$ TeV or new physics at the TeV scale or both

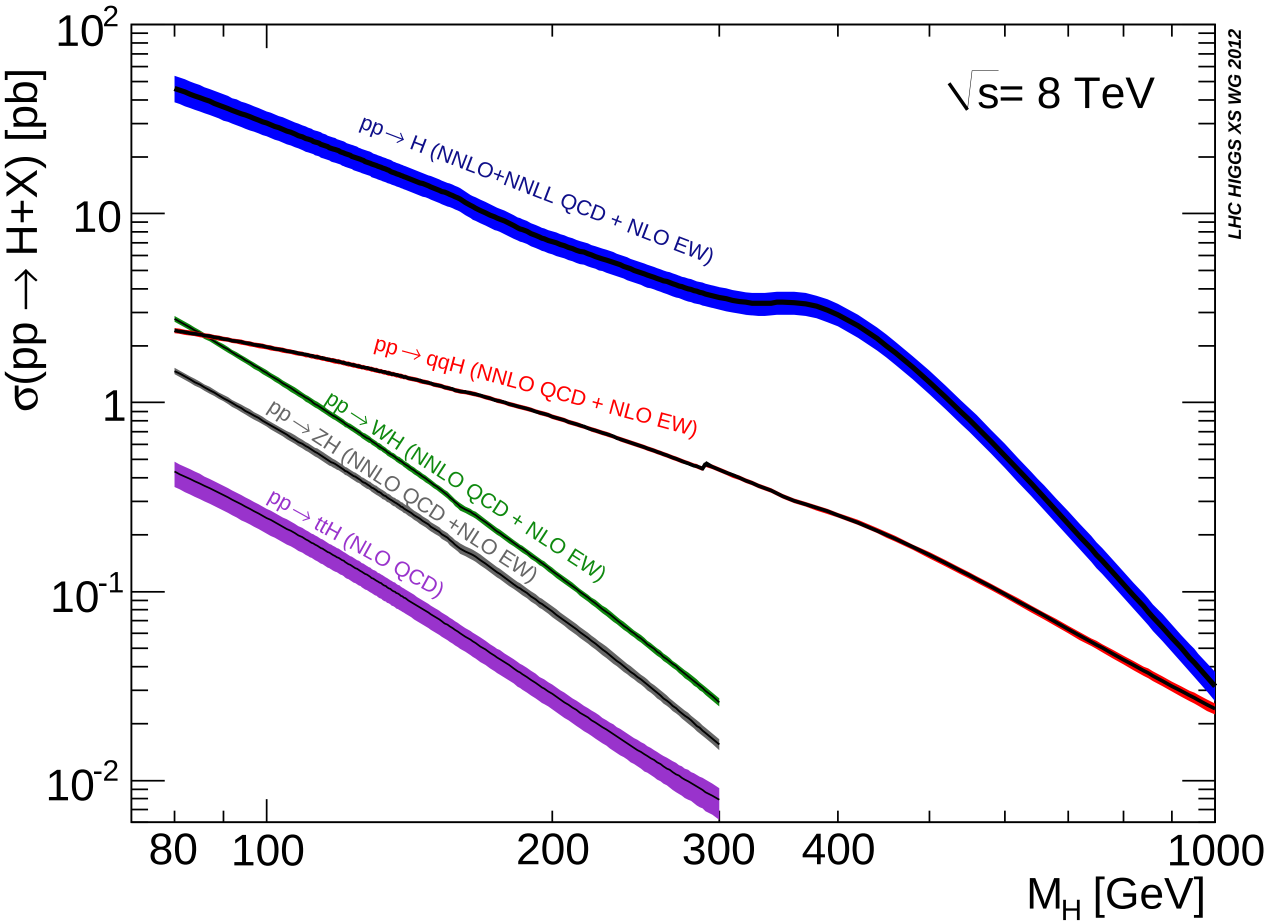
If the HVV coupling is not precisely given by its SM value $2m_V^2/v$ then tree level unitarity is still violated in VV scattering unless

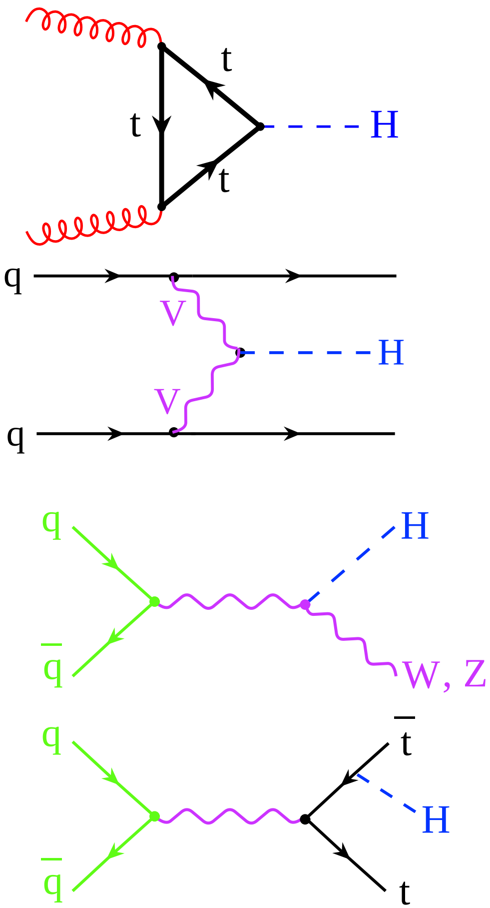
- There are several (sufficiently light) scalar resonances whose h_iVV couplings satisfy the sum rules

$$\sum_i g^2_{h_iWW} = g^2_{HWW,SM} = \frac{4m_W^4}{v^2}\,, \qquad \sum_i g_{h_iWW}\, g_{h_iZZ} = g_{HWW,SM}\, g_{HZZ,SM}$$

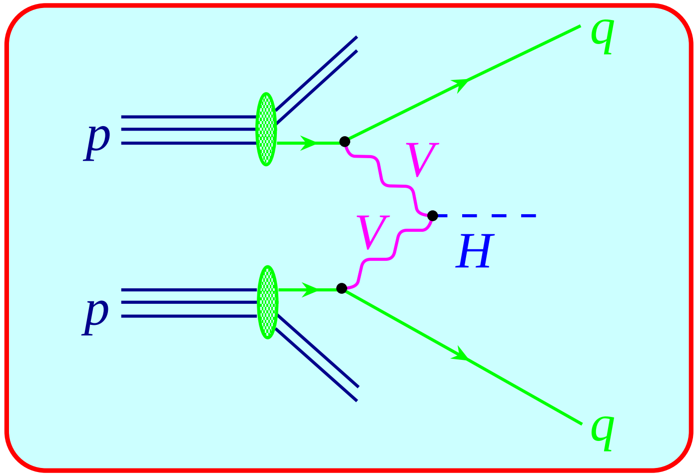
- There are other new phenomena in VV scattering

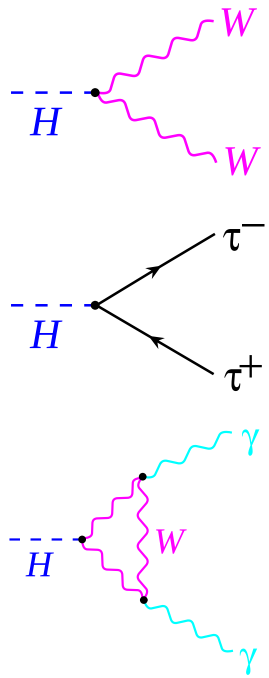
Total cross sections at the LHC





Vector Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

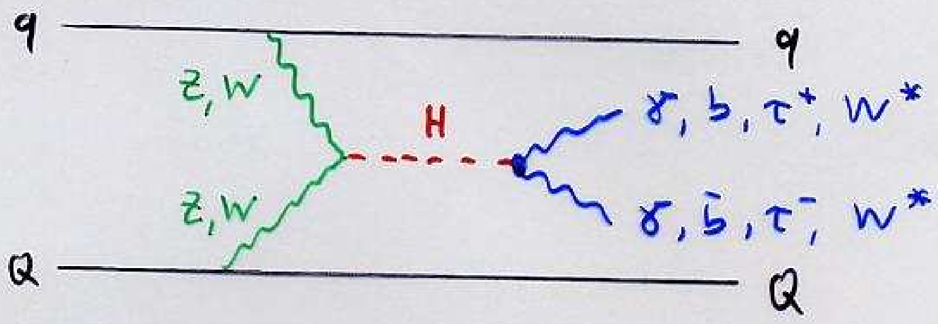
$m_H < 150$ GeV

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

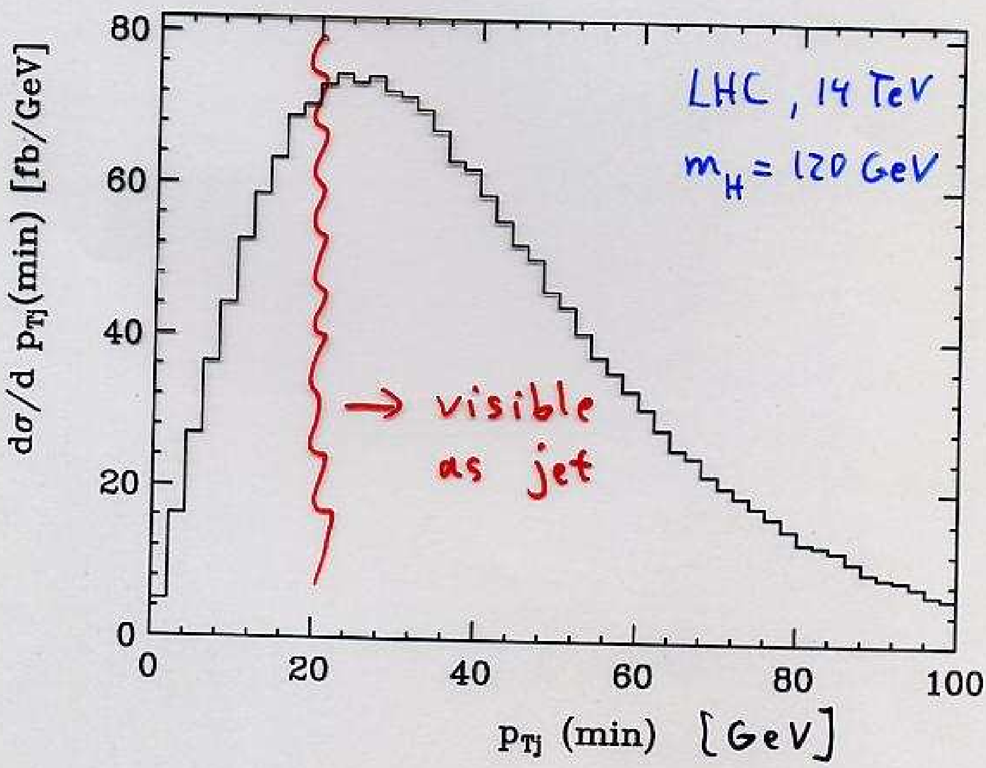
Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10%.

Would like theory errors below 5% $\Longrightarrow$ Need NLO corrections

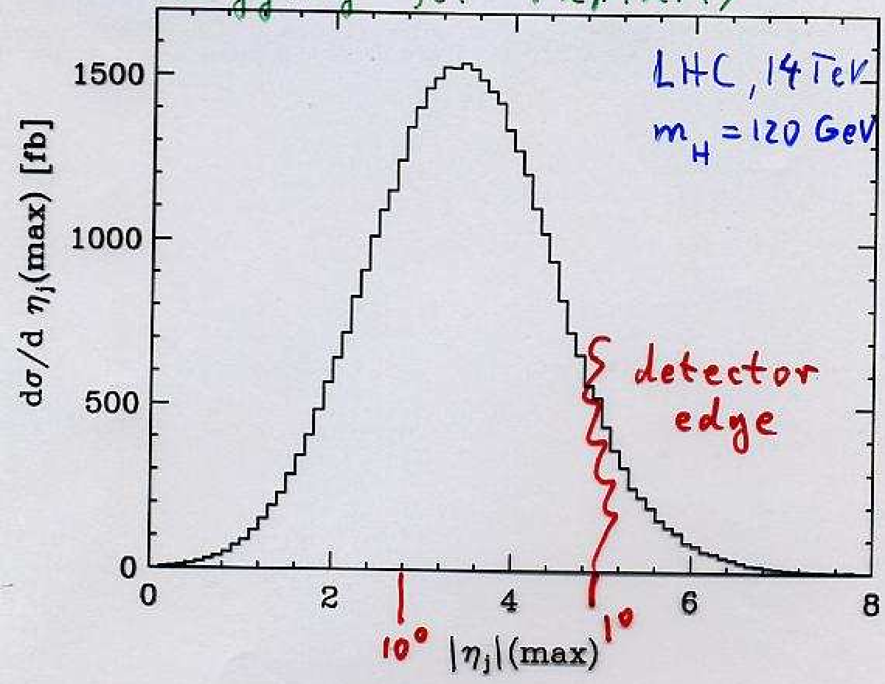
Characteristics of weak boson fusion



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



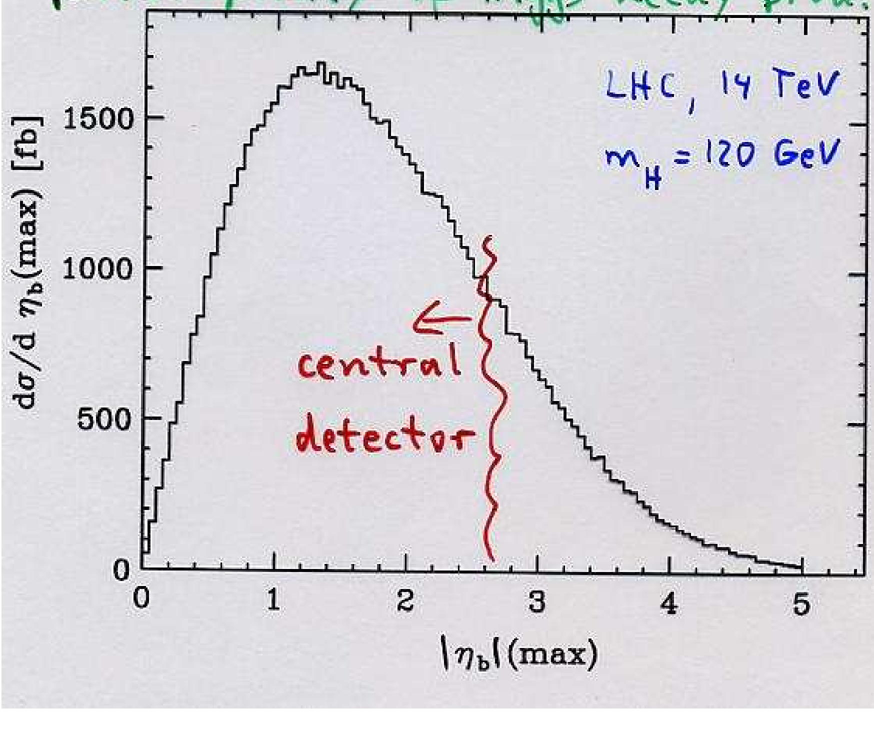
tagging jet rapidity



tagging je
forward bu
well inside
detector

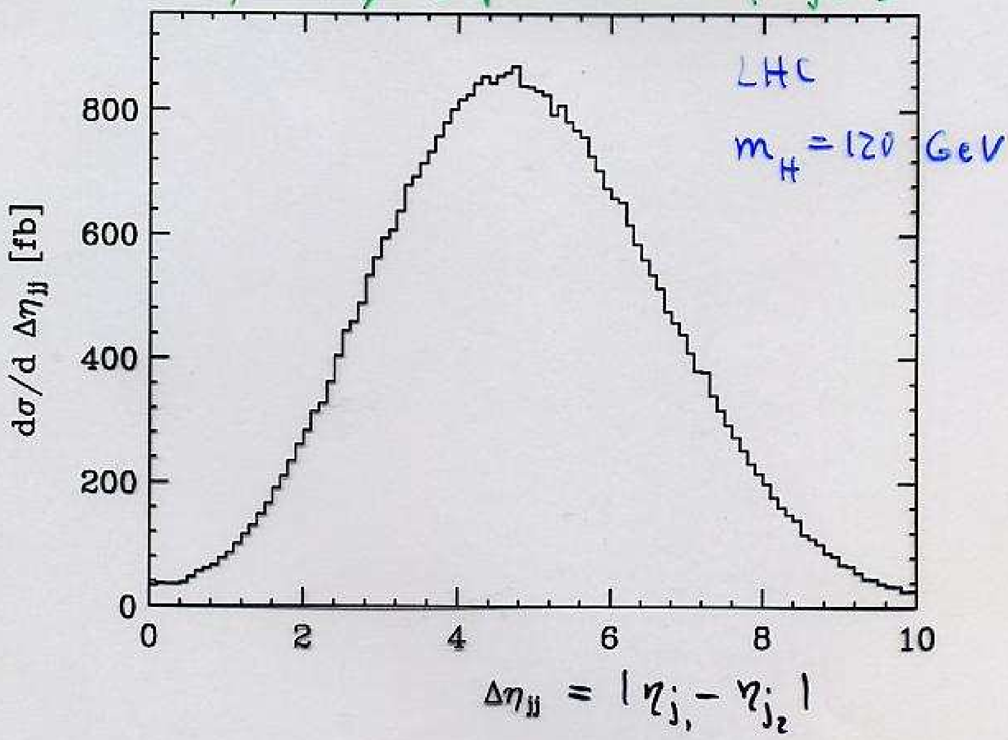
$\eta = \frac{1}{2} \ln \frac{1+\cos}{1-\cos}$

pseudorapidity of Higgs decay prod.



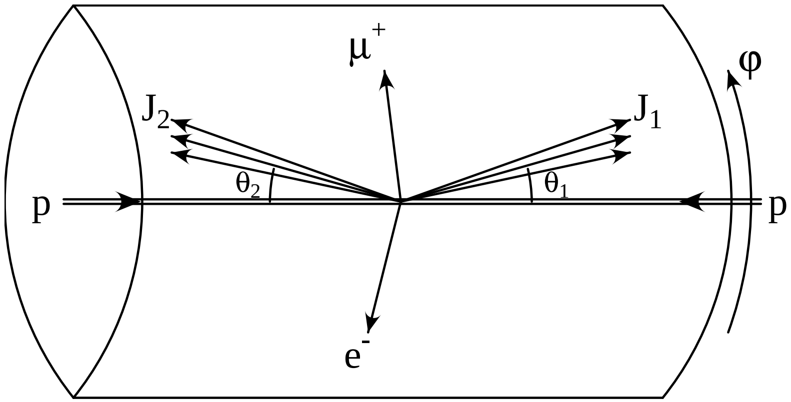
Higgs deca
products
are quite
central

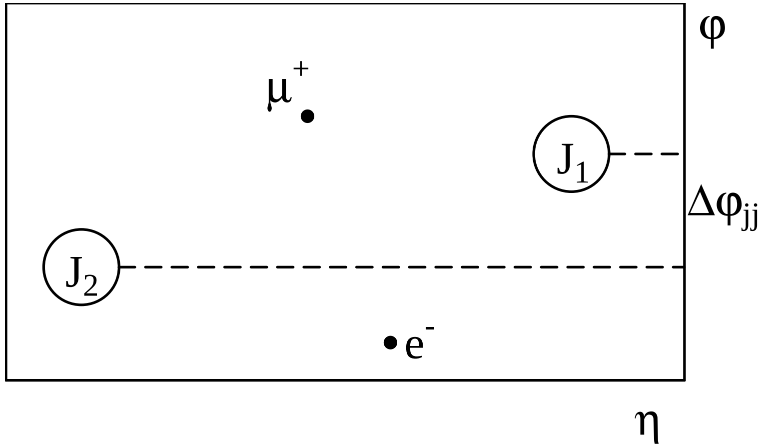
rapidity separation of jets



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

VBF signature



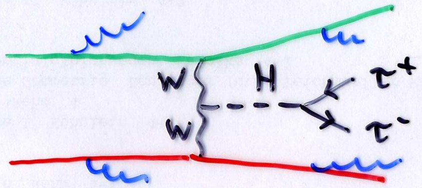


Characteristics:

- 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)

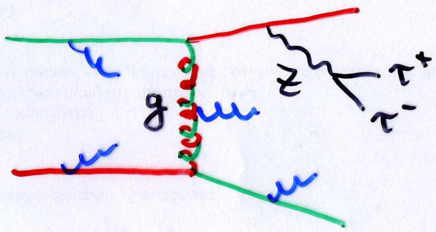
Central jet veto

- $t\bar{t}$ + 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

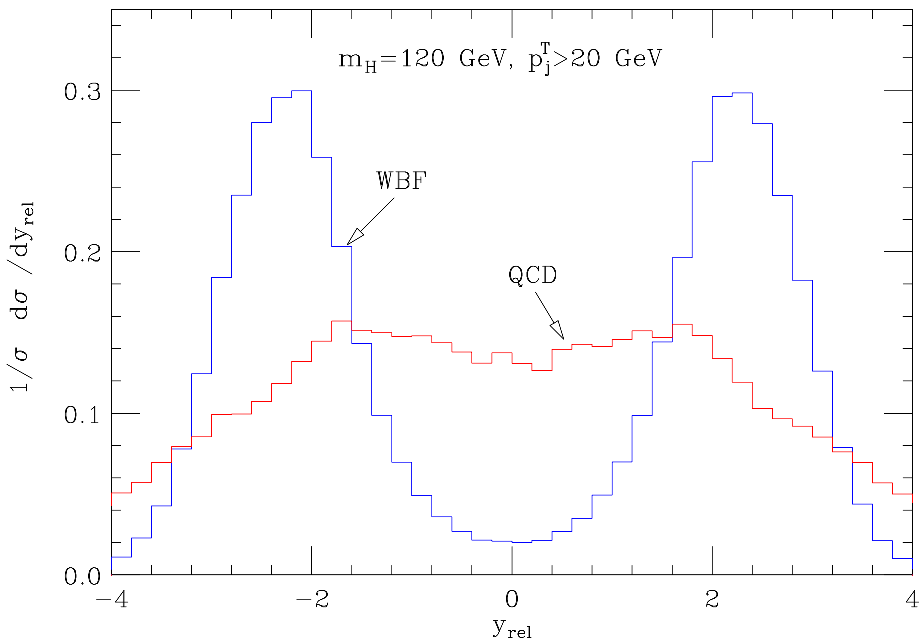
- Major QCD backgrounds: t-channel color octet exch.

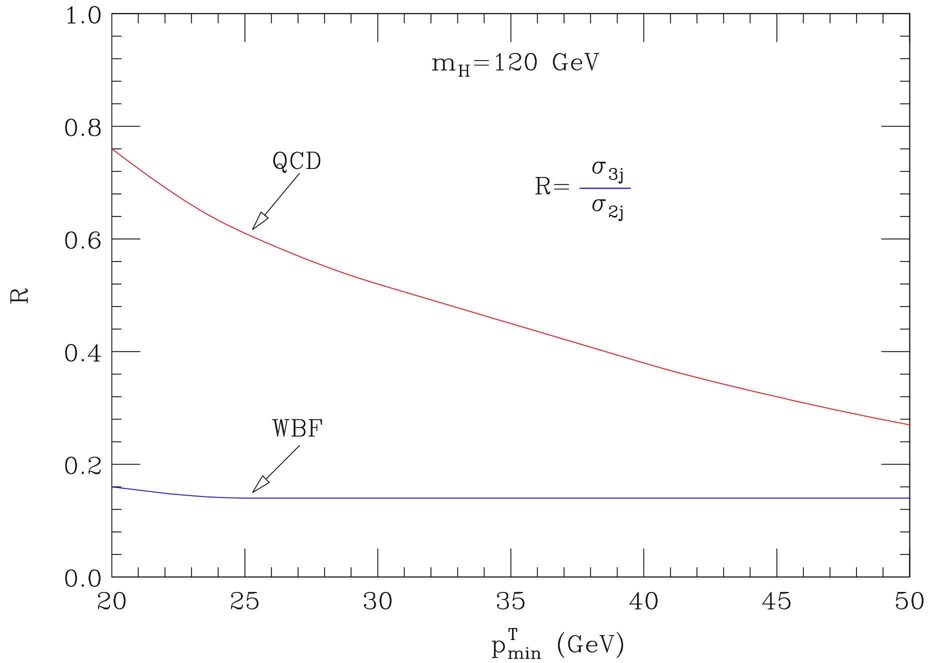


deflection of color charge by ~180° $\Rightarrow$ strong color acceleration
$\Rightarrow$ enhanced central gluon emis.

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

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

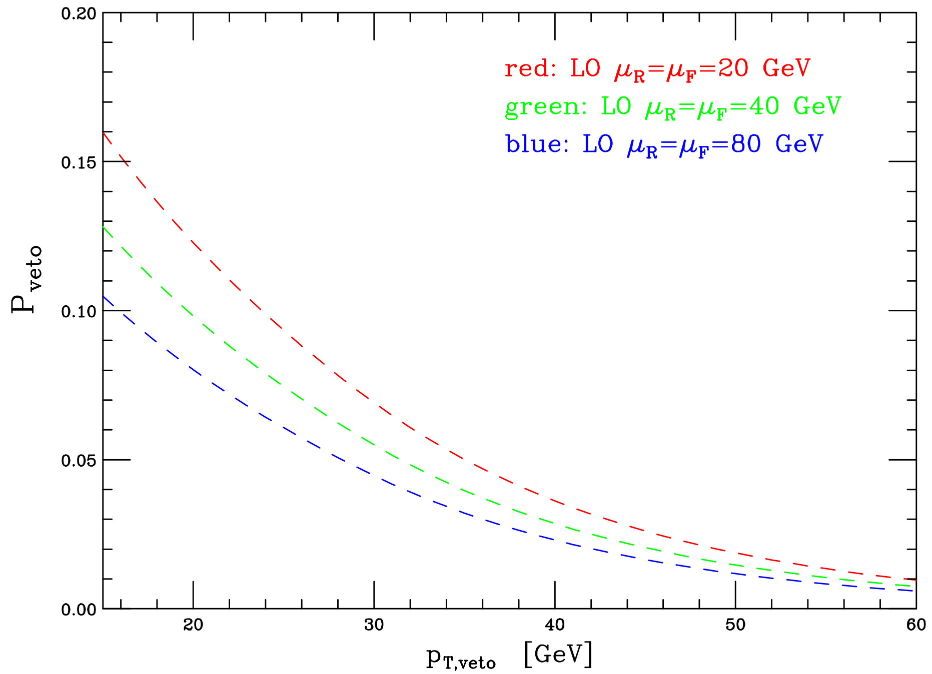




[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- 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

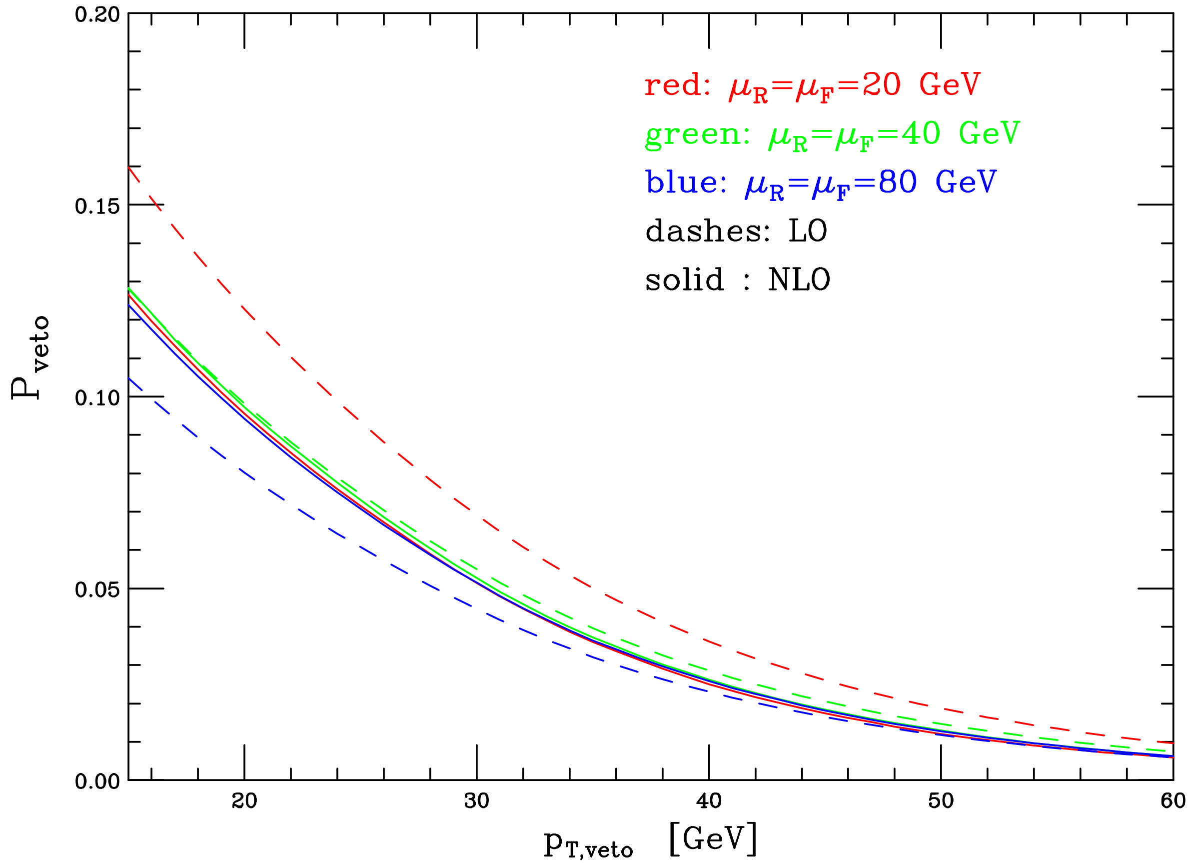


$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag 1}}, \eta_j^{\text{tag 2}})$$

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

- 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)

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%

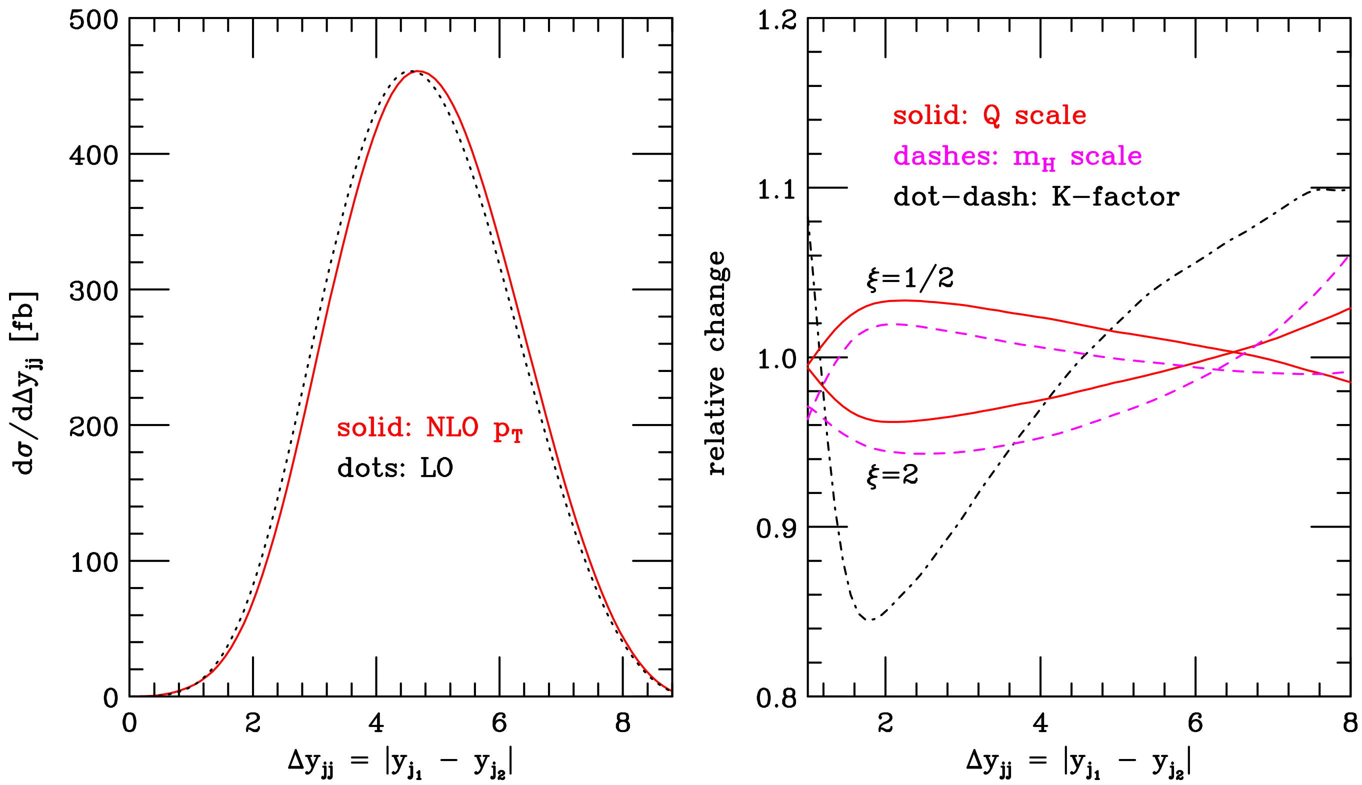
Reliable prediction for perturbative part of veto probability at NLO

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, 0710.4749

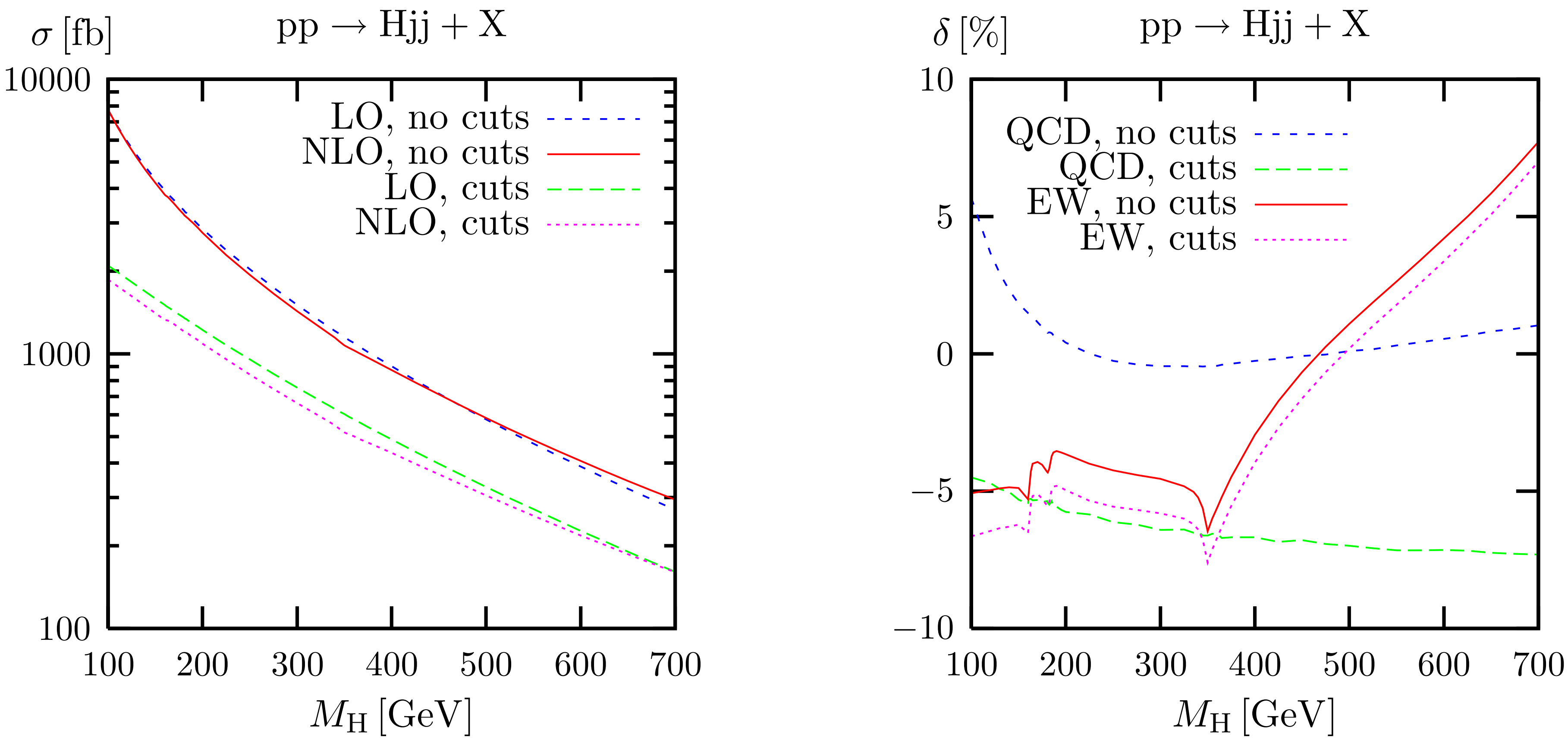
  Figy, Palmer, Weiglein arXiv:1012.4789



$m_H = 120$ GeV, typical VBF cuts

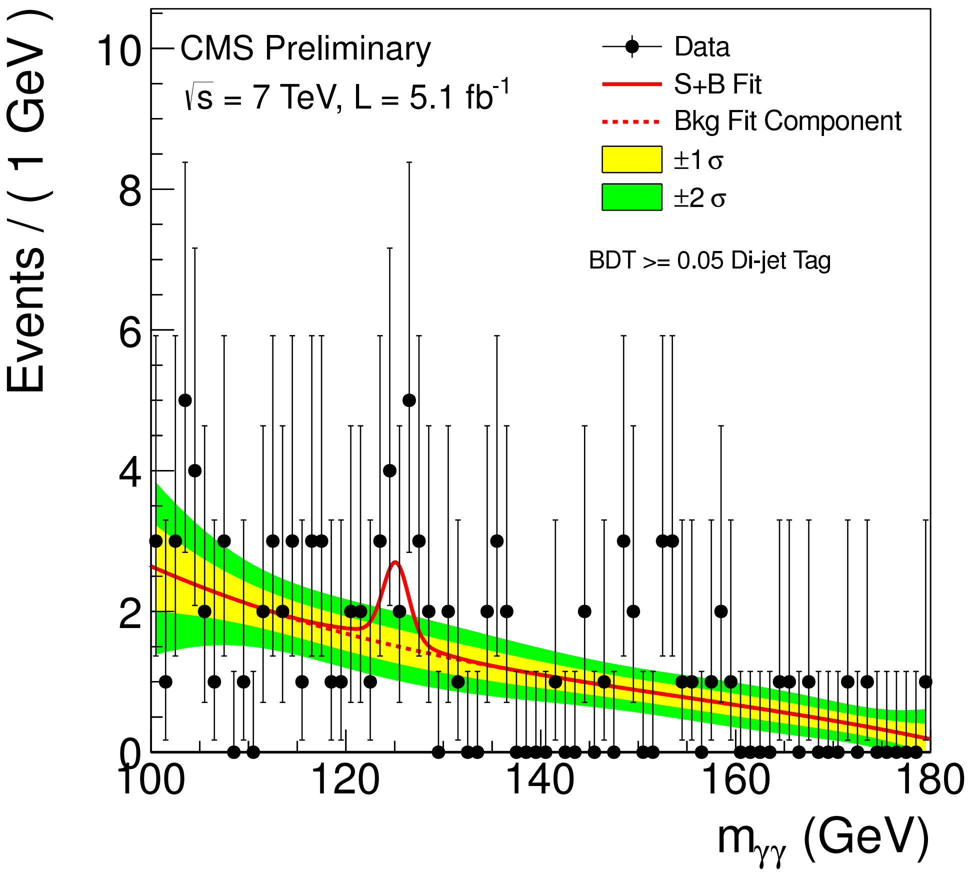
QCD + EW corrections to Hjj production

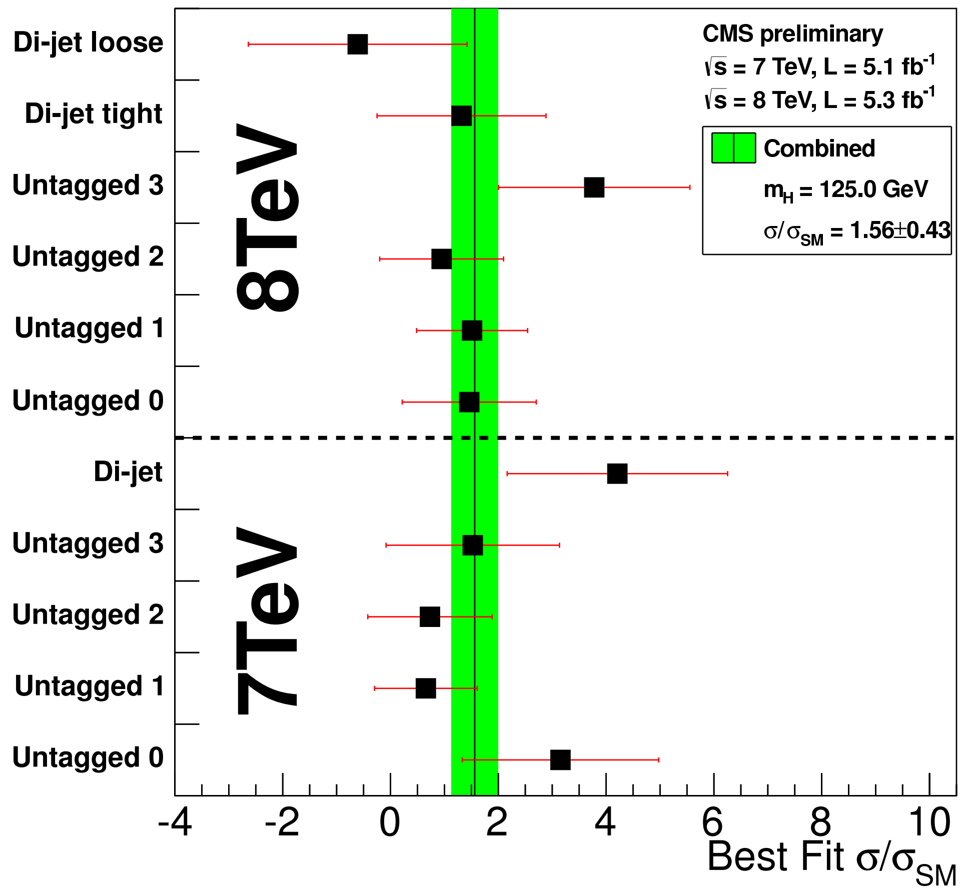
Cross sections without and with VBF cuts: $p_T(j) > 20$ GeV , $|y_{j_1} - y_{j_2}| > 4, \;\; y_{j_1} \cdot y_{j_2} < 0$



Ciccolini, Denner, Dittmaier, arXiv:0710.4749

First evidence for $h \to \gamma\gamma$ in CMS dijet search



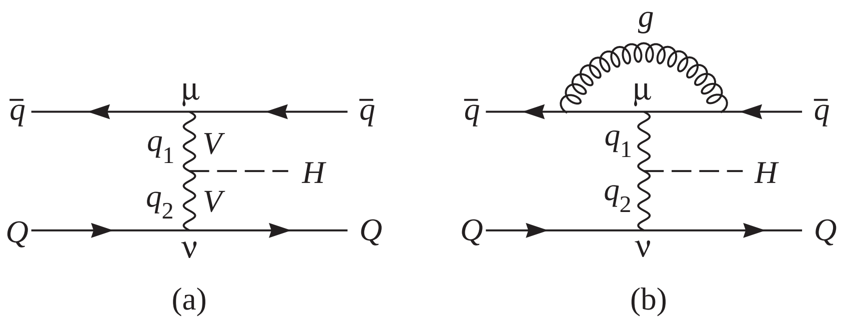


Good signal to background ratio

$\Longrightarrow$ can study distributions for Higgs events with sufficient integrated luminosity

Tensor structure of the HVV coupling

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



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

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

Physical interpretation of terms:

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

loop induced couplings for neutral scalar

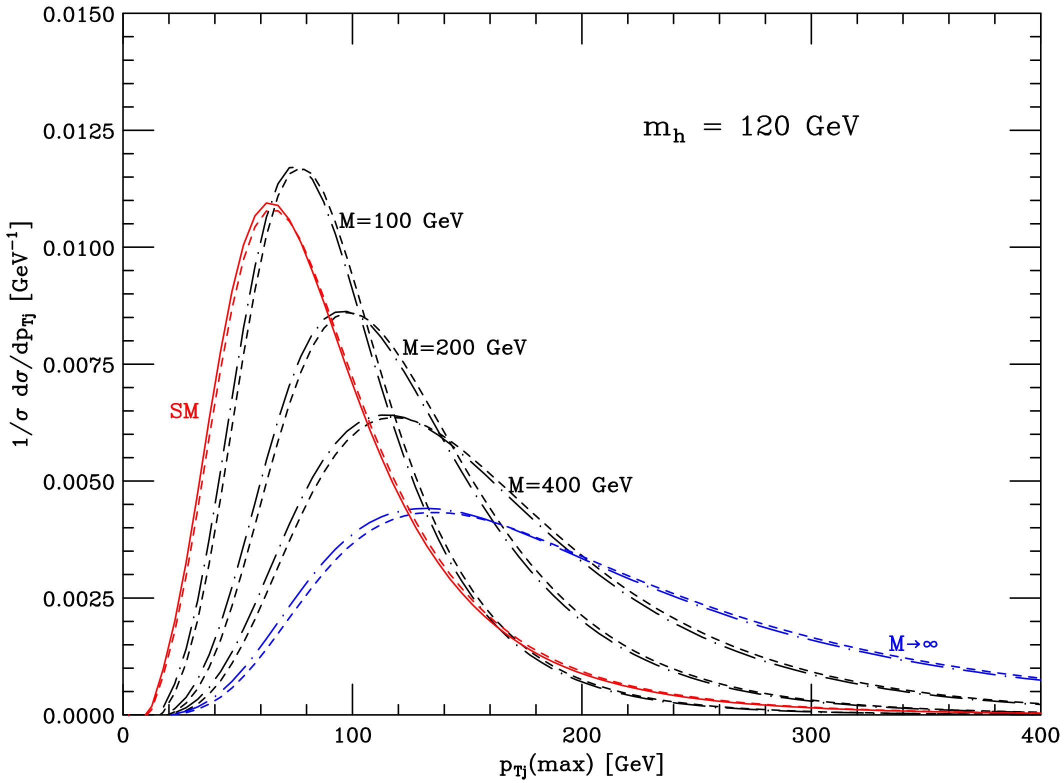
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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

Must distinguish a_1, a_2, a_3 experimentally

Effect of non-standard HVV couplings on p_T of jets

Higher dimensional operators enhance production at large momentum transfer
$\Longrightarrow$ harder p_T spectra of jets for anomalous HVV couplings



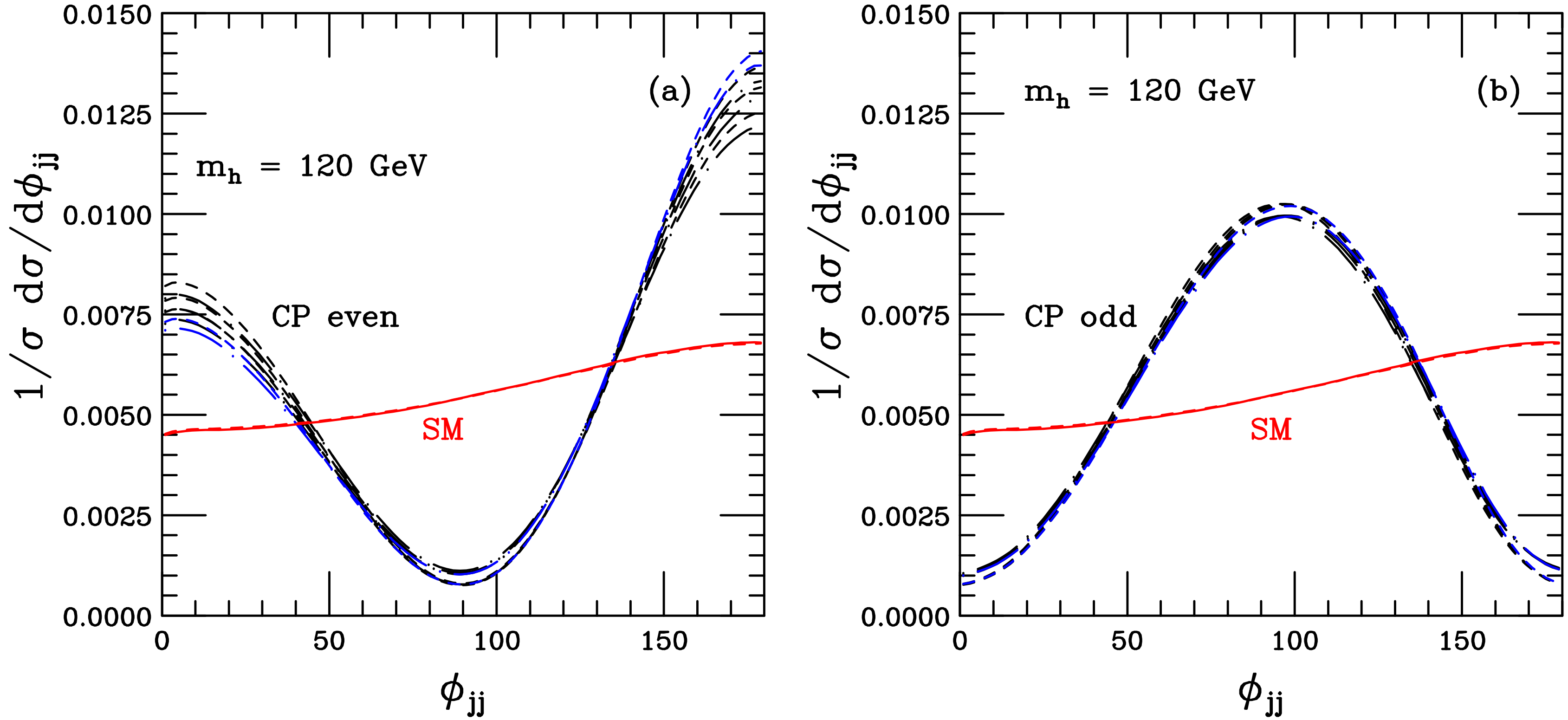
Form factors $a_i(q1, q2)$ chosen as

$$a_i(0,0)\ \frac{M^2}{q_1^2 - M^2}\ \frac{M^2}{q_2^2 - M^2}$$

... unless form-factors are chosen to reproduce SM distributions

Azimuthal angle correlations

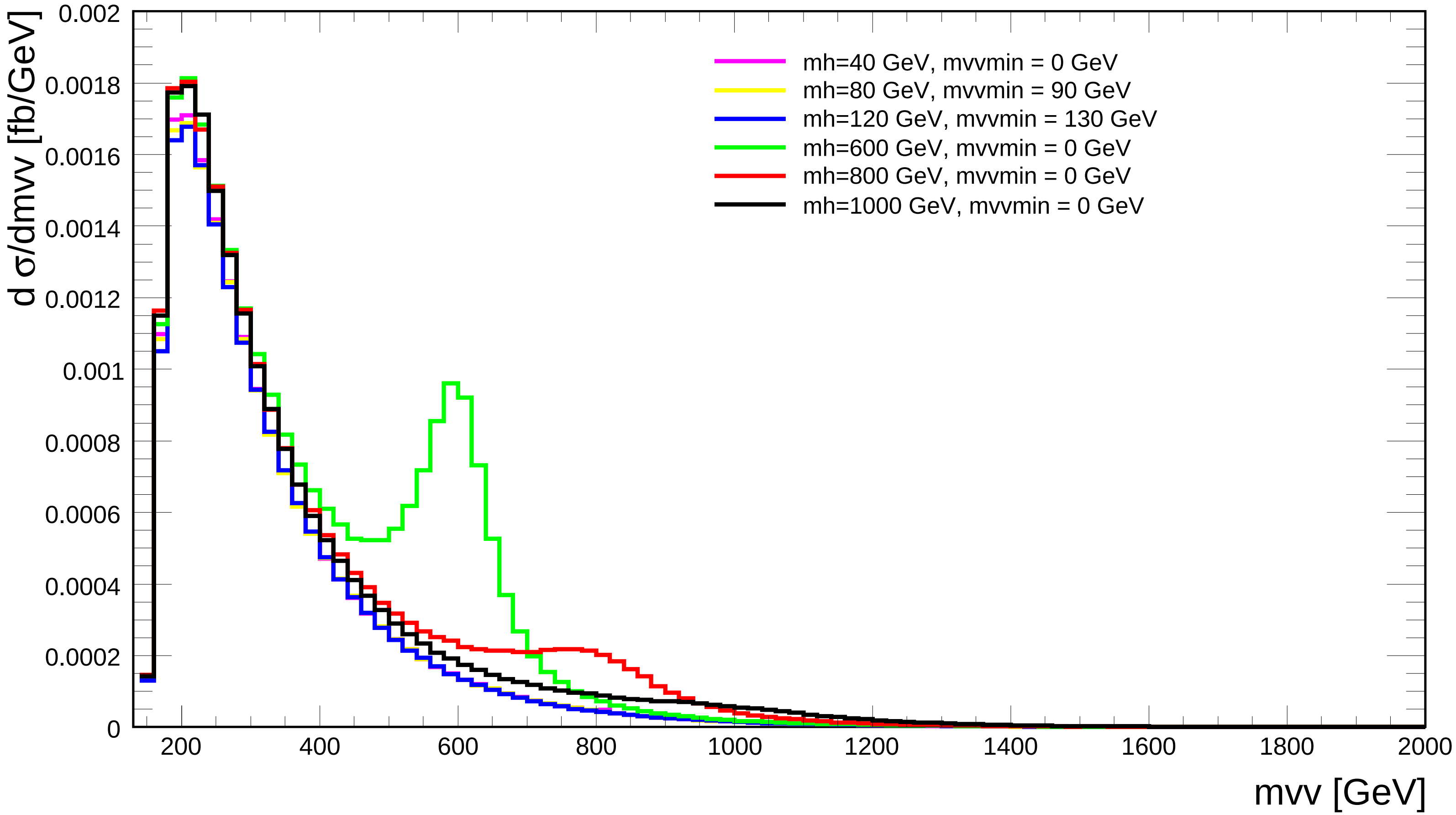
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



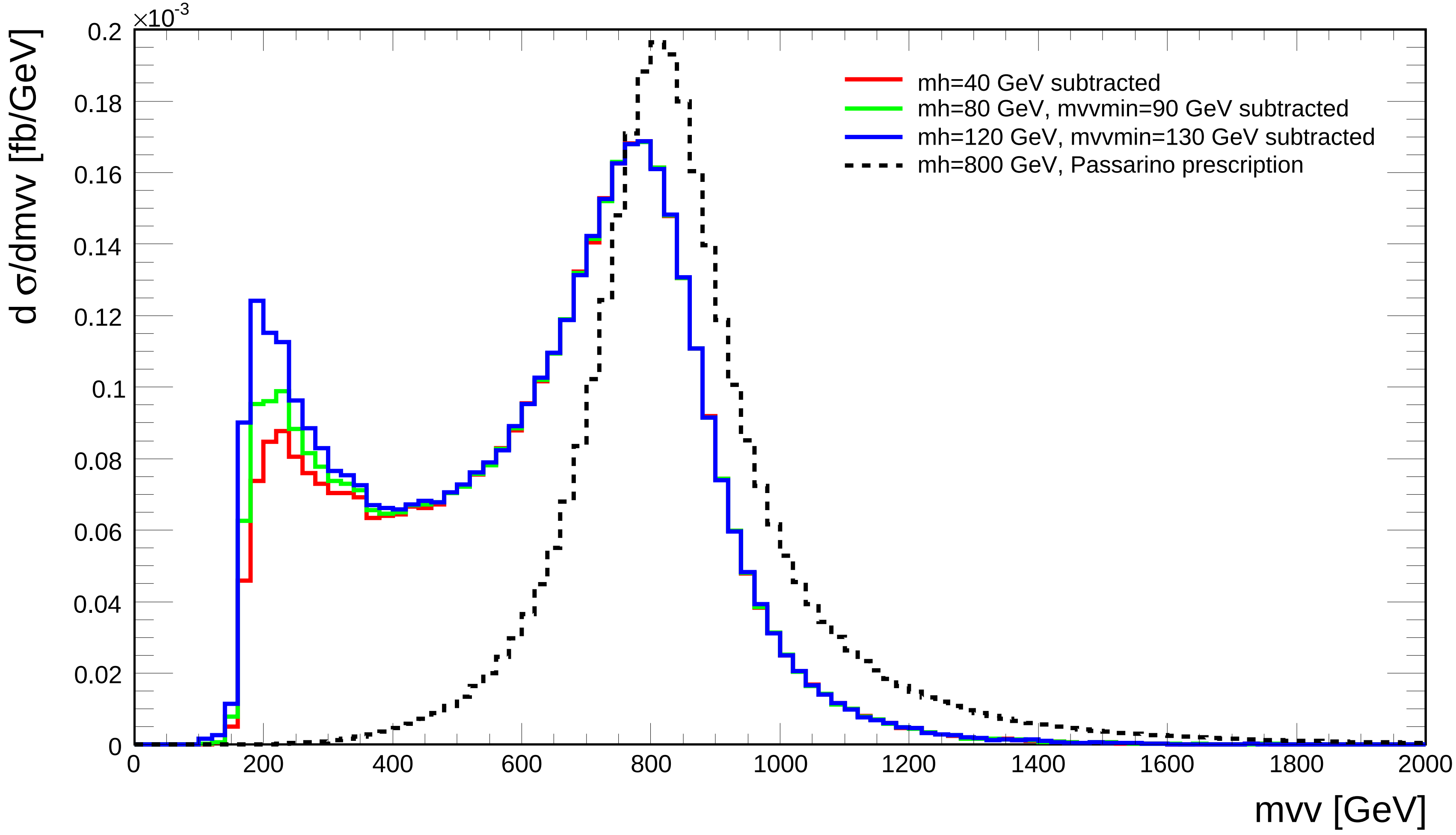
Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

$qq \to qqWW$ scattering: WW invariant mass distribution

Forget $m_H \approx 126$ GeV for the moment .... what would happen for a heavy Higgs?

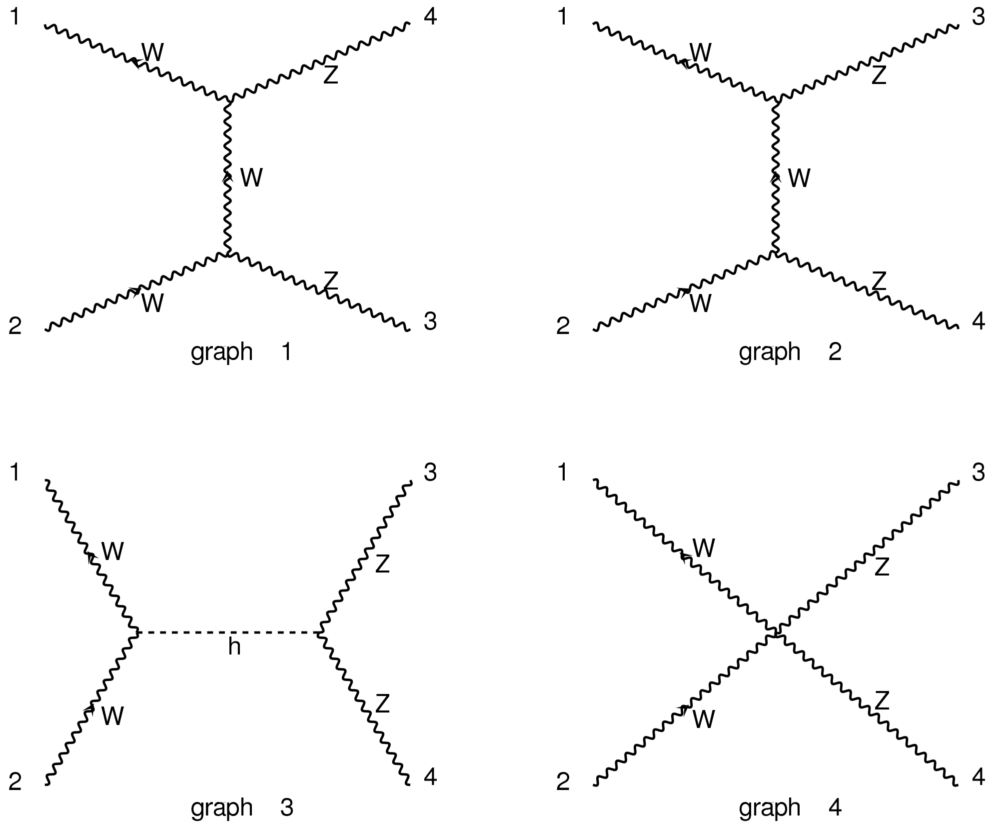


Resonance shape for heavy Higgs: $WWjj$ case



Comparison of shape without and with interference to EW continuum

Limitations of the $qq \to qqH$ picture



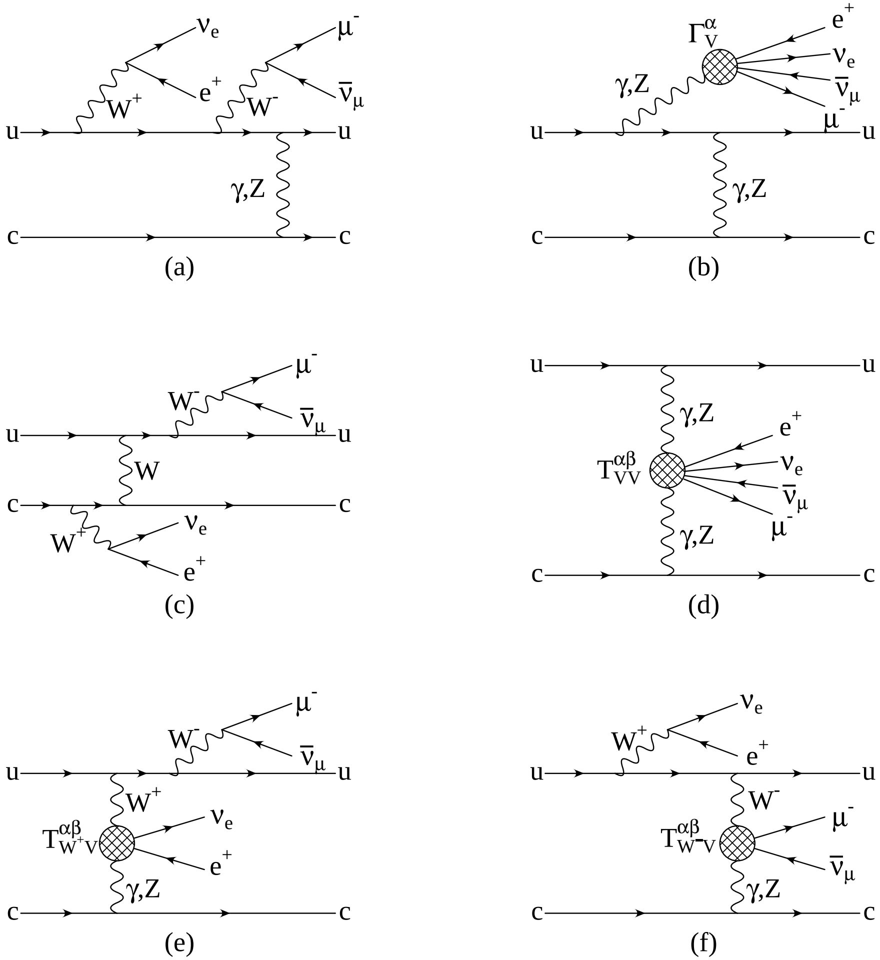
At $m_H >$ few hundred GeV (for say $\Gamma_H / m_H > 0.1$) we need to take interference with continuum electroweak into account

- Higgs resonance is just one contribution to vector boson scattering
- Tagging jets from $q \to qV$ splitting are essential for experimental observation
- Consider full processes $qq \to qqVV$ or $qq \to qq\bar{f}_1 f_2 \bar{f}_3 f_4$

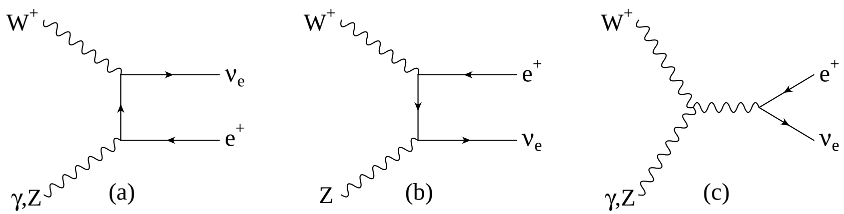
Full processes are needed for any model without a light Higgs which fully unitarizes VV scattering

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

- 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



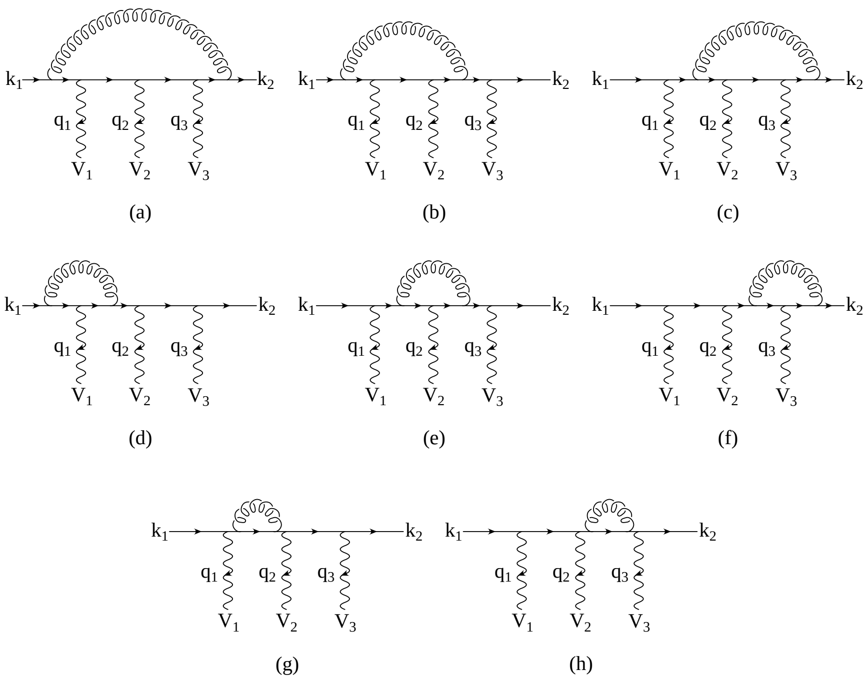
Use modular structure, e.g. leptonic tensor



Calculate once, reuse in different processes

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

$$\begin{aligned} \mathcal{M}_V^{(i)} &= \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon) \\ & \qquad \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\rm virt}\right] \\ &+ \widetilde{\mathcal{M}}^{(i)}_{V_1V_2V_3,\tau}(q_1,q_2,q_3) + \mathcal{O}(\epsilon) \end{aligned}$$

- 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

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

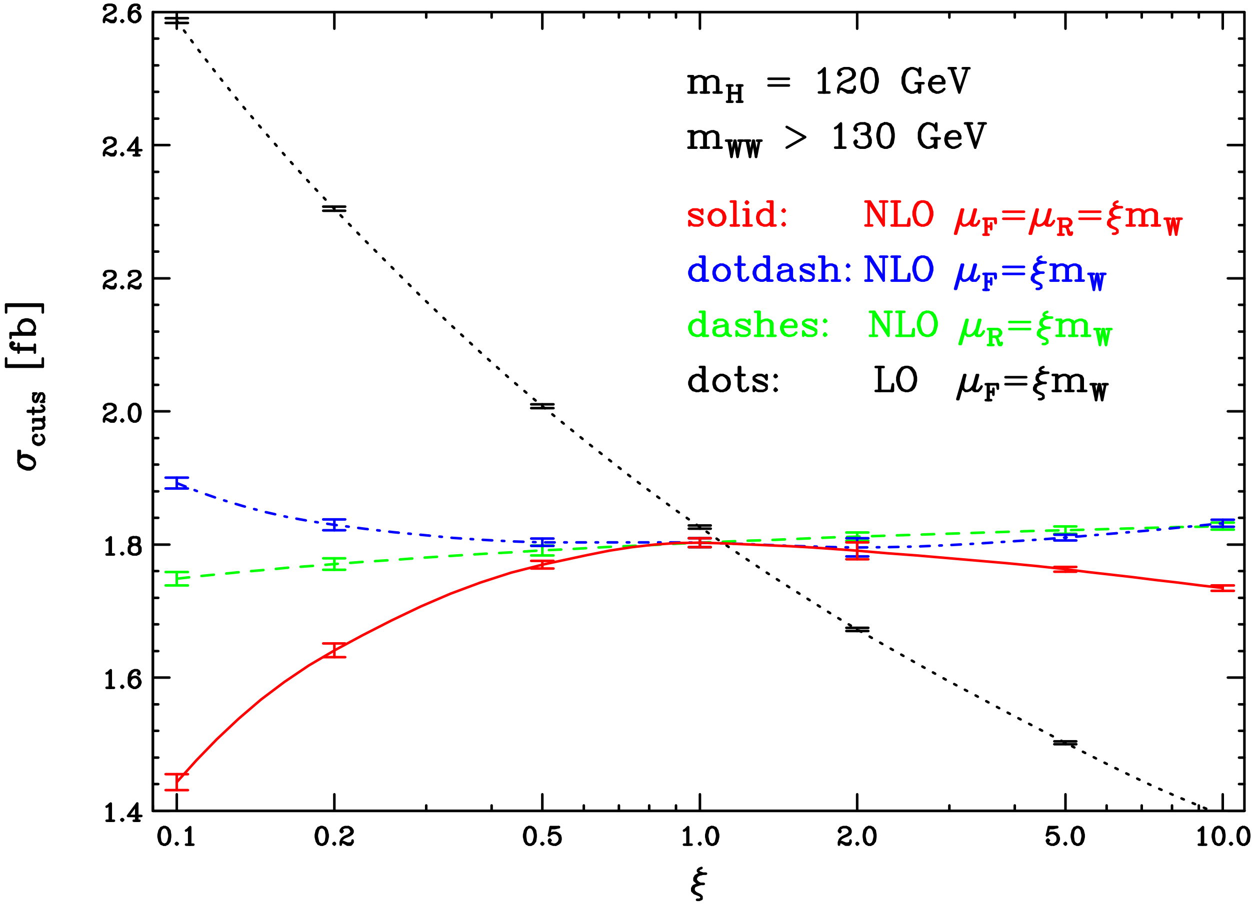
For scale dependence studies we have considered

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

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

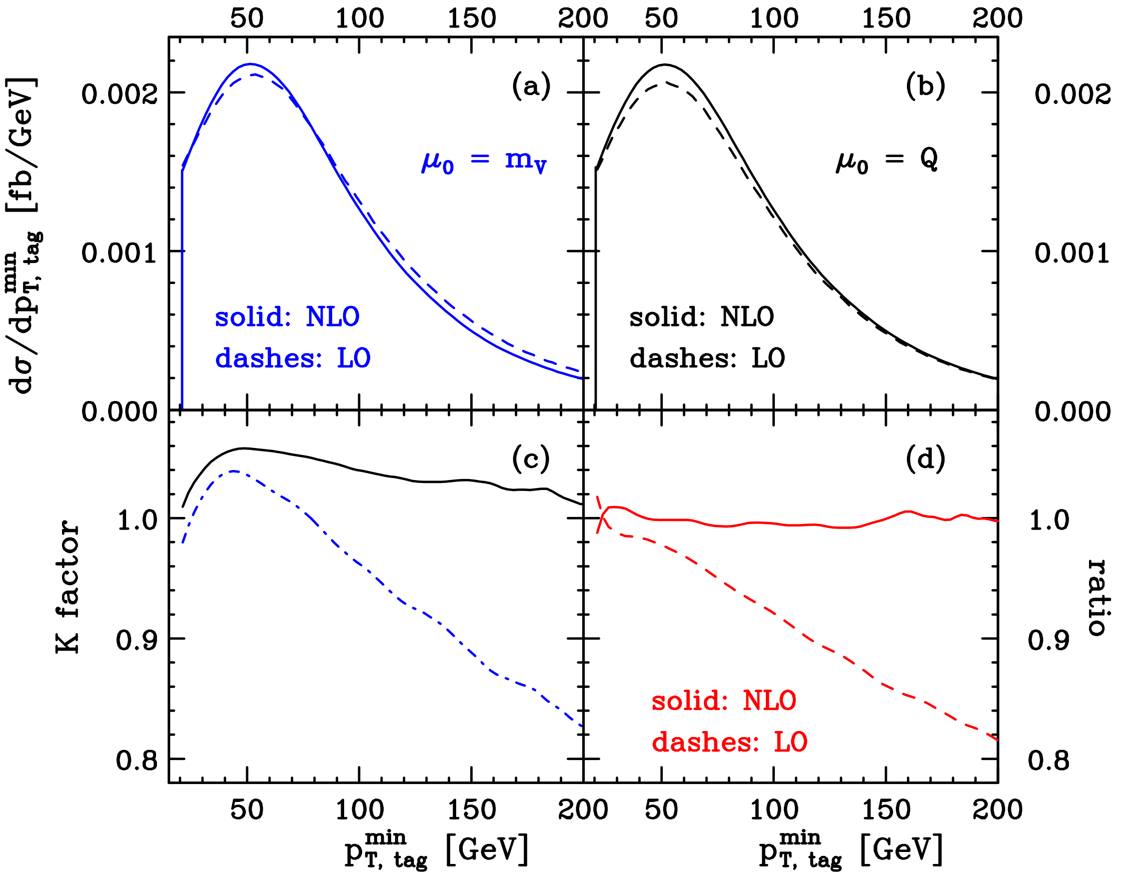
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



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

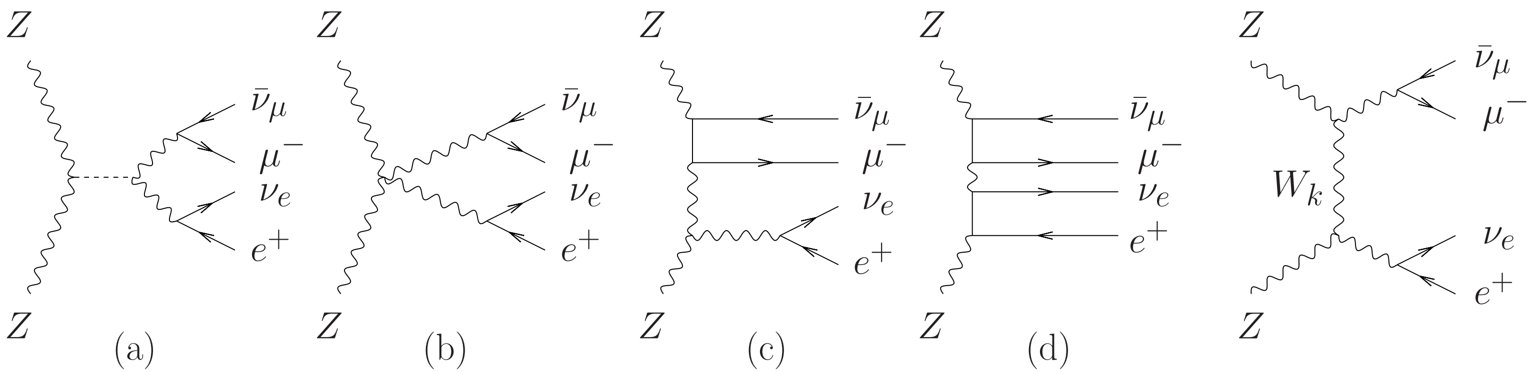
Transverse momentum distribution of the softer tagging jet



- 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

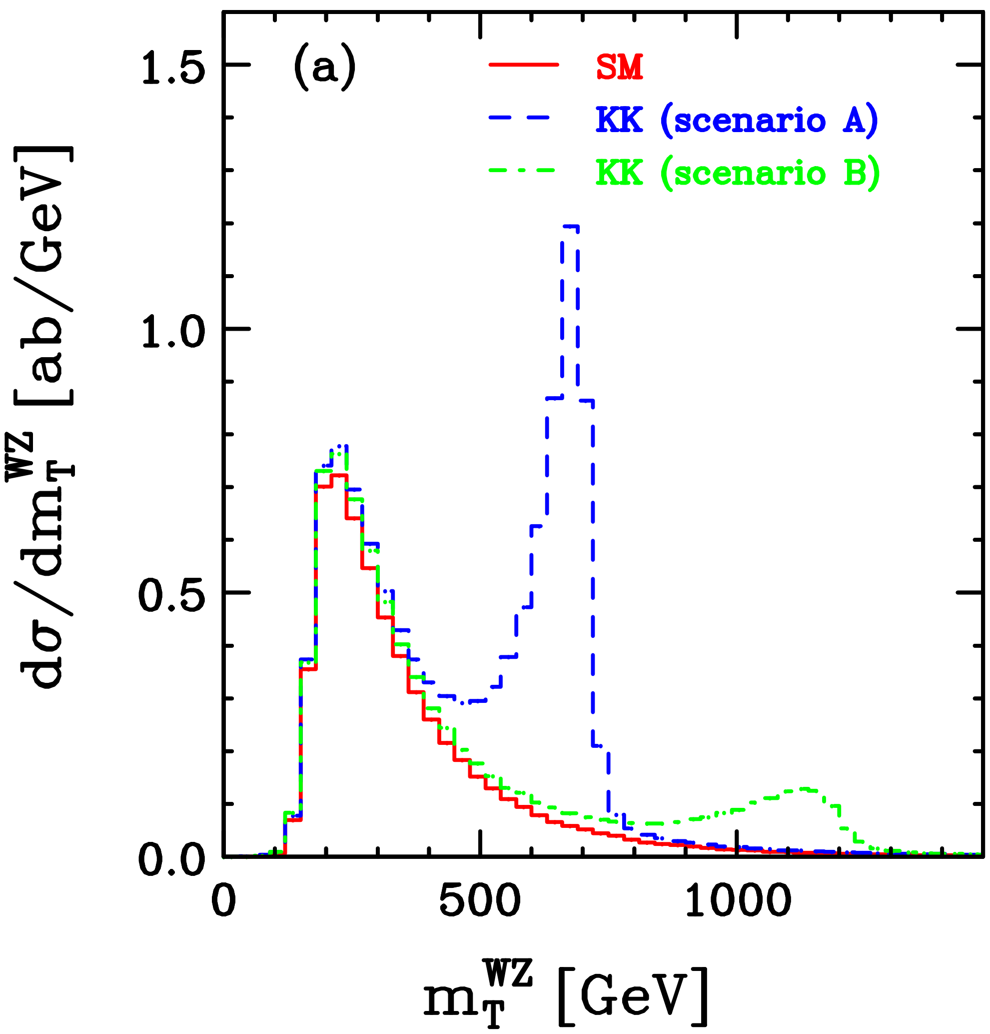
Use $\mu_F = Q$ at LO to best approximate the NLO results

Exploiting the leptonic tensors for BSM



- Entire weak boson scattering amplitude enters via leptonic tensor: same for LO and NLO QCD cross section.
- Easy to modify: include contributions from extra particle exchange or other new physics which unitarizes VV scattering
- Implemented in VBFNLO: Kaluza-Klein towers of vector resonances in higgsless models

Technirho or KK resonance in WZ scattering at NLO QCD



- Extra vector resonance clearly visible in transverse mass distribution
- Implementation of NLO QCD corrections
- Implementation of other BSM effects in leptonic tensors is straightforward
- Define signal as enhancement over SM light Higgs cross section:

$$\sigma_S = \sigma_{BSM} - \sigma_{SM}(m_H = 126\,\text{GeV})$$

Options for BSM in VV scattering

- Second heavy Higgs which saturates the sum rules for VVh_i couplings

$$\sum_i g^2_{h_iWW} = g^2_{HWW,SM}\,, \qquad \sum_i g_{h_iWW}\, g_{h_iZZ} = g_{HWW,SM}\, g_{HZZ,SM}$$

- Extra vector resonances (technirho in technicolor, Kaluza Klein partners of W and Z in models with extra dimensions) which delay unitarity violation beyond reach of LHC

- Missing Higgs contribution in VV scattering amplitude is unitarized by new strong dynamics. Model this by ad hoc unitarization of partial wave amplitude, e.g. *K-matrix scheme*

$$a^{J=0}(s) = f(s) \qquad \longrightarrow \qquad \hat{a}^{J=0}(s) = \frac{1}{\mathrm{Re}\, 1/f(s) - i}$$

  which guarantees unitarity relation $\mathrm{Im}\hat{\mathrm{a}} = |\hat{\mathrm{a}}|^2$

- ... your or your friends favorite

Can we distinguish such models from SM at the LHC?

Compare (i) SM (with $m_H = 120$ GeV), (ii) heavy scalar resonance (SM with $m_H = 1000$ GeV) and (iii) isotriplet of vector resonances ($\rho^{\pm}, \rho^0$) to get a feeling for LHC reach

Processes to consider

Signal processes

- $qq \to qqW^+W^- \to qql^+\nu_l l^- \bar{\nu}_l$
- $qq \to qqW^\pm Z \to qql^\pm \nu_l l^+ l^-$
- $qq \to qqZZ \to qq4l$
- $qq \to qqW^\pm W^\pm \to qql^\pm \nu_l l^\pm \nu_l$
- The above with hadonic decay of either one W or one Z

Background processes

- QCD $V_1 V_2 jj$ production (with gluon exchange)
- $t\bar{t} + n$ jet production with $t\bar{t} \to W^+W^- b\bar{b}$
- Electroweak background (expected $VVjj$ events for SM with $m_H = 126$ GeV)
- QCD induced $W + 4$ jet and $Z + 4$ jet events
- Rare processes like $t\bar{t}W$ or $t\bar{t}Z$ production with one top-quark decaying hadronically

Many possibilities, each requiring specific cuts to reduce large QCD backgrounds and to optimize signal significance $\Longrightarrow$ consider only a few examples

which are taken from Englert, Jäger, Worek, D.Z. arXiv:0810.4861

Ballestrero, Franzosi, Oggero, Maina arXiv:1112.1171

Typical selection cuts

Study LHC cross sections for $\sqrt{s} = 14$ TeV collisions within cuts

- INCLUSIVE: Identify two or more jets with k_T-algorithm ($D = 0.7$)

$$p_{Tj} \geq 30\,\text{GeV}\,, \qquad |y_j| \leq 4.5$$

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

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

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

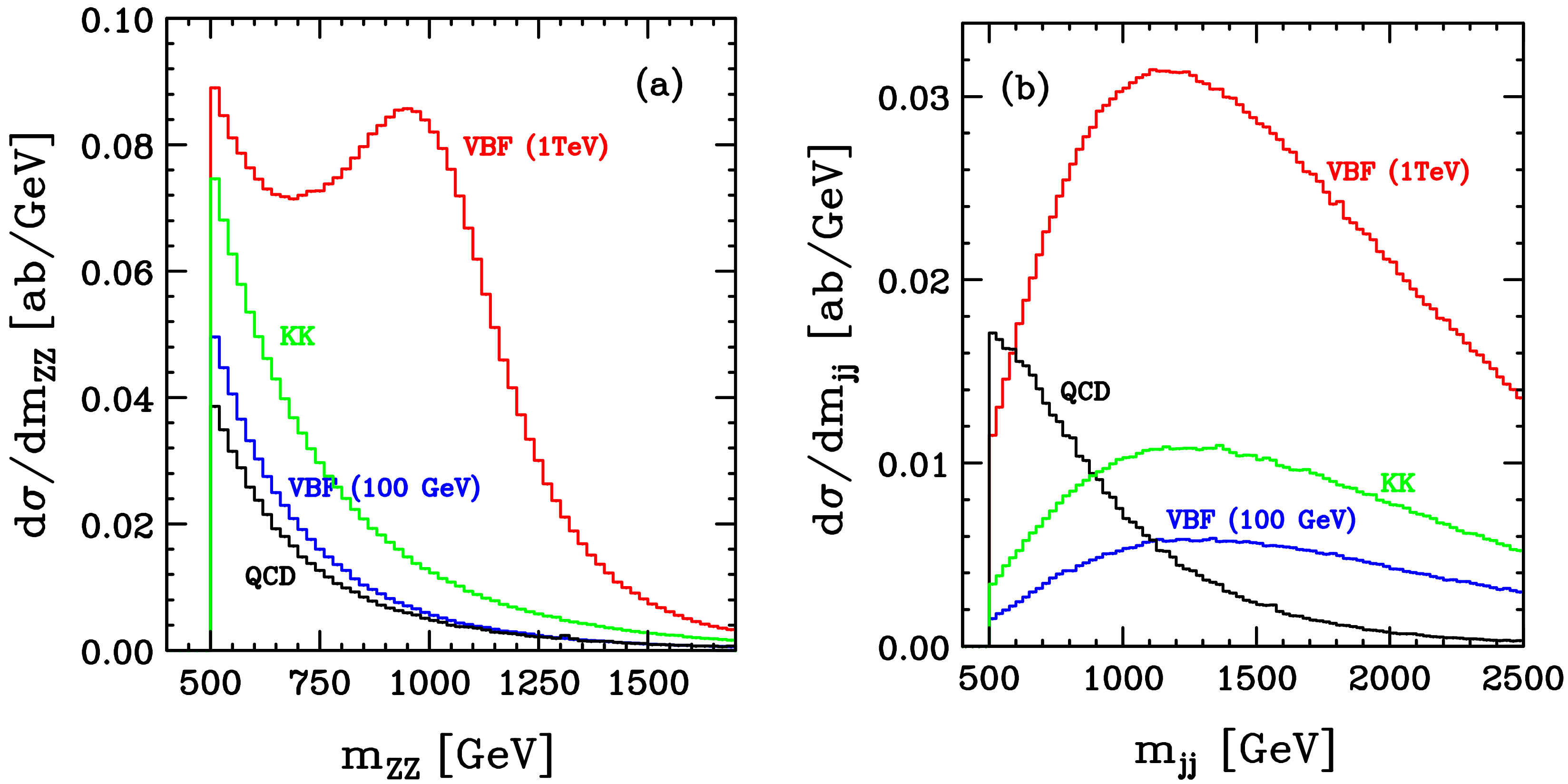
$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad m_{jj} > m_{jj}^{\text{min}} \qquad \text{with } m_{jj}^{\text{min}} = 500\ (1000)\ \text{GeV}$$

  leptons must lie between the tagging jets

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

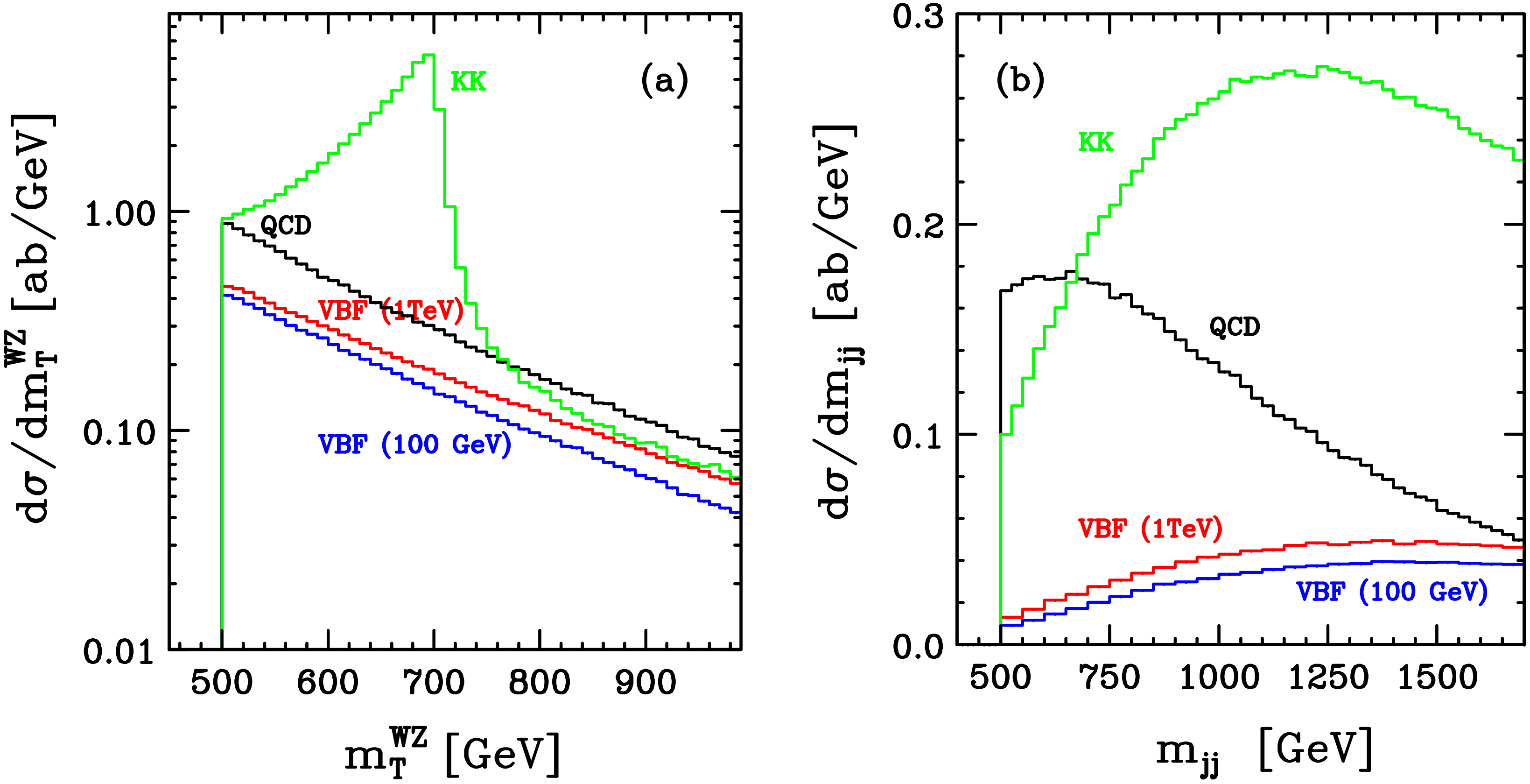
- LEPTONS: In addition require process specific cuts on the VV decay products = decay leptons, like $m_{ZZ} > 500$ GeV and $p_T(l^+l^-) > 0.2\, m_{ZZ}$ for $qqZZ \rightarrow jj4l$ events etc.

Example: $qqZZ \to jj + 4$ leptons



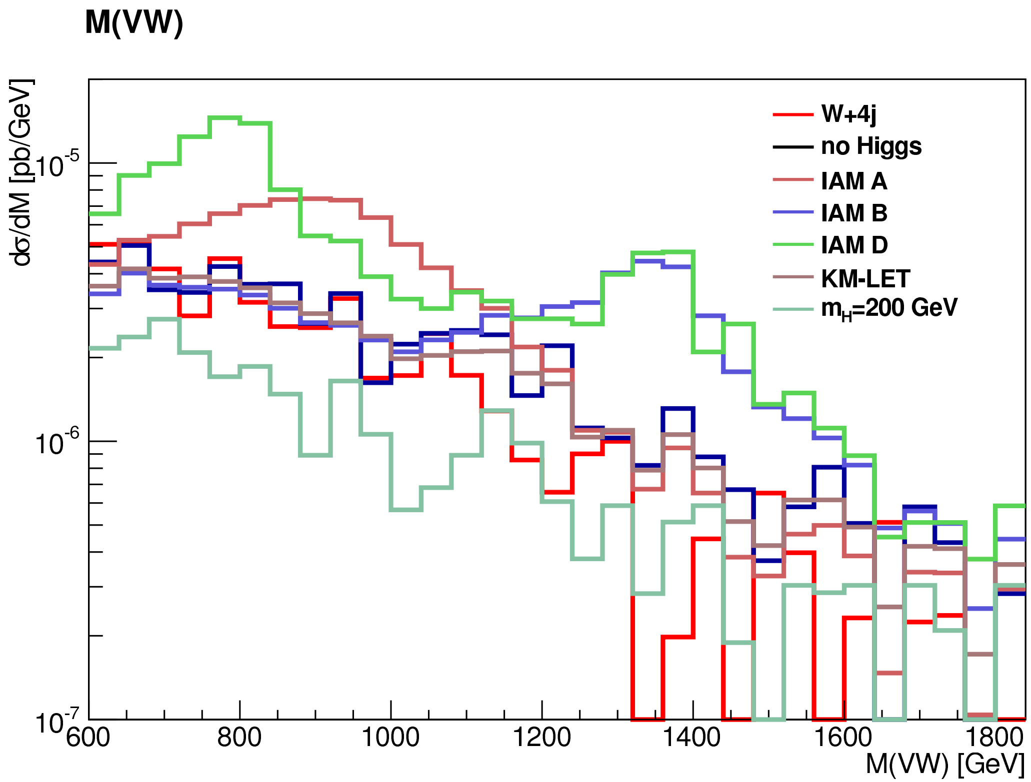
cut level	QCD $ZZjj$	VBF, $m_H = 100$ GeV	VBF, $m_H = 1$ TeV	KK, $M_V \approx 700$ GeV
inclusive	3.8 fb	0.23 fb	0.31 fb	0.27 fb
all	9.5 ab	12 ab	59 ab	21 ab

Example: $qqW^+Z \to jjl^+\nu_l l^+l^-$



cut level	QCD W^+Zjj	VBF, $m_H = 100$ GeV	VBF, $m_H = 1$ TeV	KK, $M_V \approx 700$ GeV
inclusive	55 fb	1.8 fb	1.9 fb	2.7 fb
all	170 ab	89 ab	108 ab	540 ab

Example: qqW^+W^- , $qqW^{\pm}Z \to l^{\pm}\nu_l + 4$ jets



Ballestrero et al.

$W + 4$j	$t\bar{t} + 2$j	VBF, $m_H = 200$ GeV	VBF, $m_H = \infty$	IAM B, $M_V \approx 1.4$ TeV
2.0 fb	0.43 fb	1.05 fb	2.4 fb	3.0 fb

Summary of vector boson scattering

- LHC requires high energy running (13 to 14 TeV) and high luminosity (100fb^{-1} or larger) to probe vector boson scattering
- The best chance for a discovery is given if new resonances exist in the 1 TeV region. An isotriplet vector resonance ("technirho") which is sufficiently light might be discovered within this decade
- A broad cross section enhancement at high VV invariant mass is much more difficult to discover. Proving that VV cross sections are well below the unitarity limit, as expected for the SM with $m_H = 126$ GeV, is quite challenging

Conclusions

- Weak boson scattering processes are a very important source of information on the dynamics of electroweak symmetry breaking
- For the 126 GeV Higgs, vector boson fusion at the LHC provides coupling measurements and information on the tensor structure of the hVV interactions
- Vector boson scattering in the 500 GeV to 2 TeV region allows tests on the unitarization of $VV \to VV$ scattering amplitudes. However, these tests require integrated LHC luminosities of order 100fb^{-1} or larger, even at $\sqrt{s} = 14$ TeV.

The fun has just started!