ISSUES AT THE LHC: HIGGS PHYSICS

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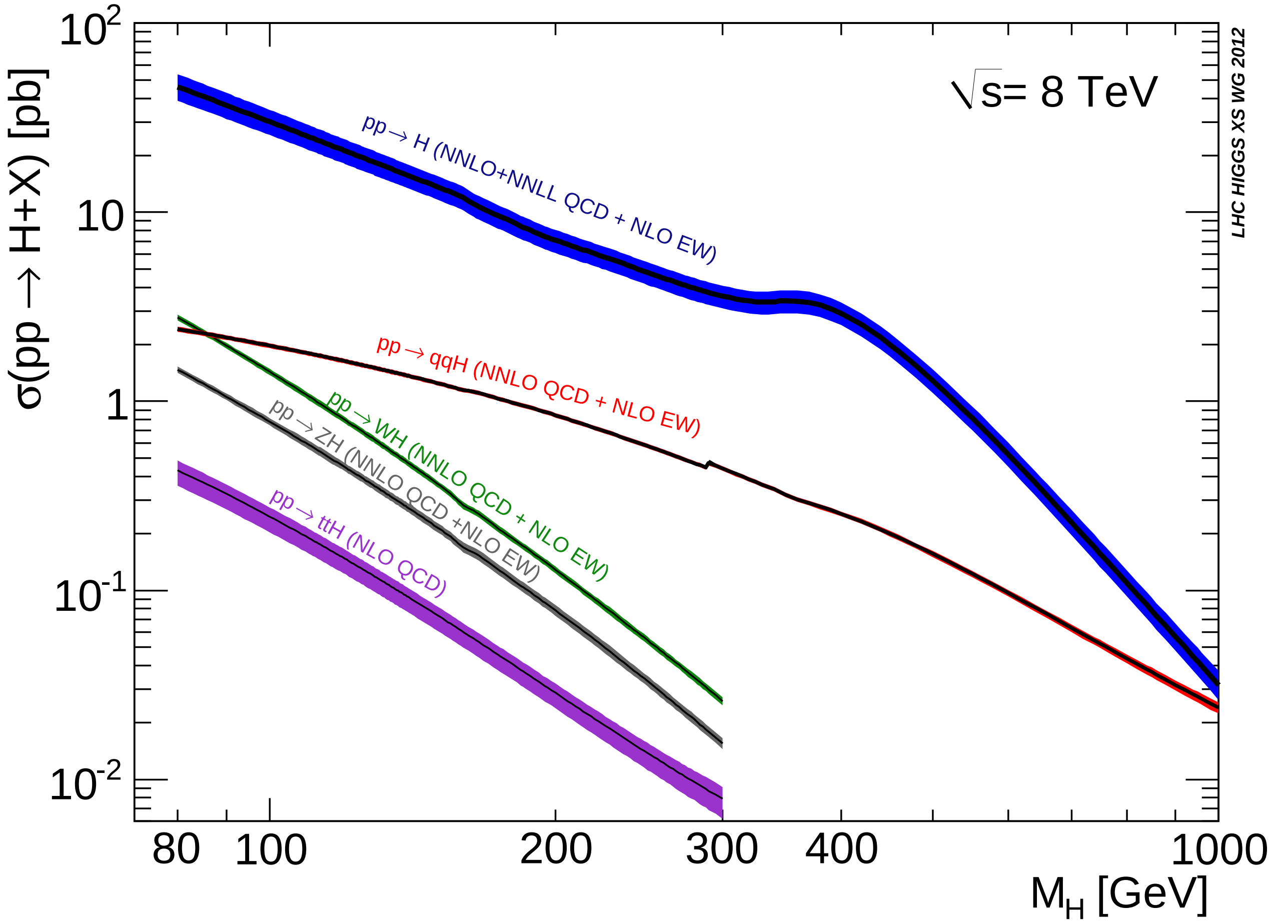
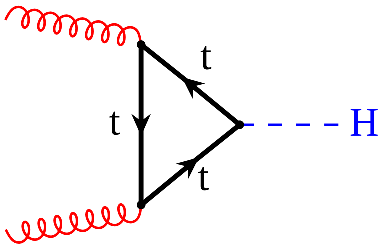
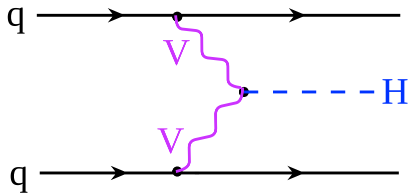
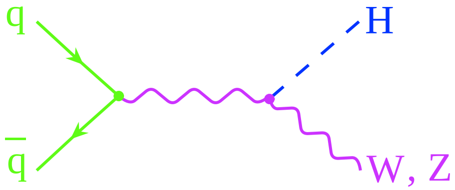
- Higgs boson signals at LHC
- Higgs coupling measurement

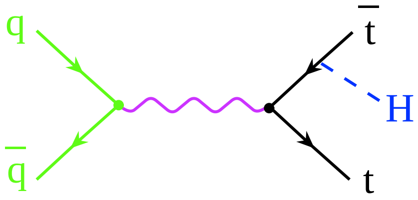
Total cross sections at the LHC



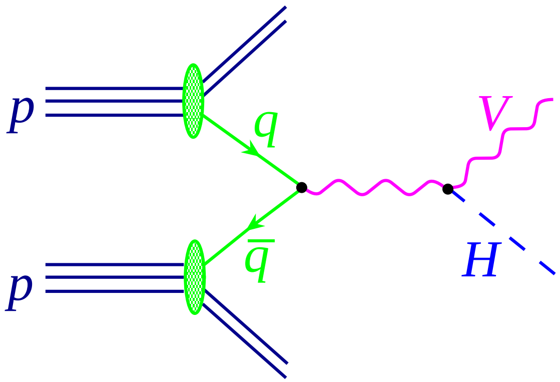




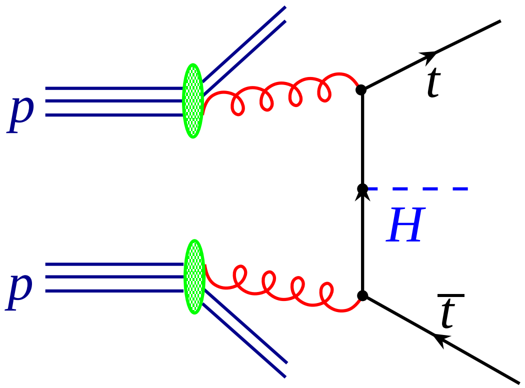




Higgs Strahlung and $t\bar{t}H$ Production



Higgs Strahlung



$t\bar{t}H$

- Trigger on leptonic decay of Z or W (from $t \rightarrow bW$)
- Search for subsequent decay $H \rightarrow b\bar{b}$
- Higgs Strahlung provides information on Hbb coupling once HVV coupling has been measured in VBF or $H \rightarrow ZZ$ decay
- Higgs Strahlung was leading signal channel at the Tevatron for m_H below 140 GeV
- LHC backgrounds to Higgs Strahlung worse than at Tevatron

New strategy for Higgsstrahlung

Proposed in 2008 by Butterworth, Davison, Rubin, Salam: arXiv:0802.2470

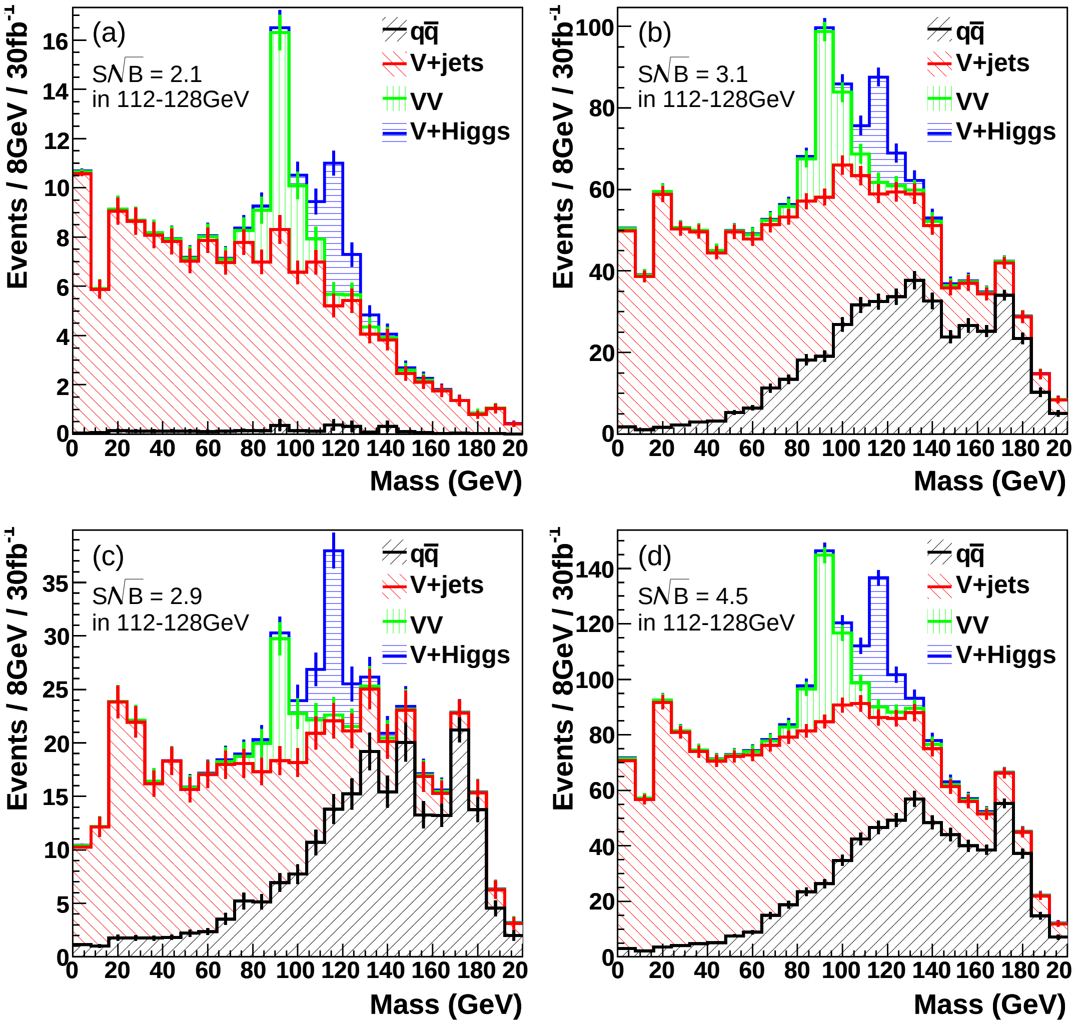
- $q\bar{q} \rightarrow WH\ ,\ ZH$
  trigger on leptonic decay of W or Z, look for $H \rightarrow b\bar{b}$
- concentrate on high $p_T(H) > 200$ GeV events
- Transverse boost results in fat *Higgs jet* with $b\bar{b}(g)$ subjet structure
- small separation of b-quark jets from $H \rightarrow bb$ decay $\Longrightarrow$ better $b\bar{b}(g)$ invariant mass resolution
- lower background fraction than at low $p_T(H)$

Expected signal in HZ and HW at $p_T(H) > 200$ GeV

Example: $m_H = 120$ GeV, $\int L dt = 30\ \text{fb}^{-1}$

- Search in
  (a) HZ with $Z \rightarrow ll$
  (b) HZ with $Z \rightarrow \nu\nu$ and
  (c) $WH \rightarrow l\nu b\bar{b}$ samples
- Need excellent b tagging and non-b rejection efficiencies (assumed: 60% and 2% respectively)
- Promising signal with 30 fb^{-1} when combining all 3 channels

Butterworth, Davison, Rubin, Salam arXiv:0802.2470



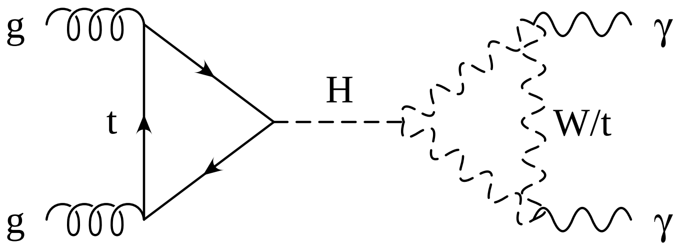
Main channels for Higgs observation

- inclusive production, 90% of which is gluon fusion, with subsequent decay
  - $H \to \gamma\gamma$ invariant-mass peak, for $m_H < 150$ GeV
  - $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ for $m_H \geq 120$ GeV and $m_H \neq 2m_W$.
  - $H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$ for $120 \text{ GeV} \leq m_H \leq 190$ GeV
  - $H \to \tau\tau$ for $115 \text{ GeV} \leq m_H \leq 150$ GeV

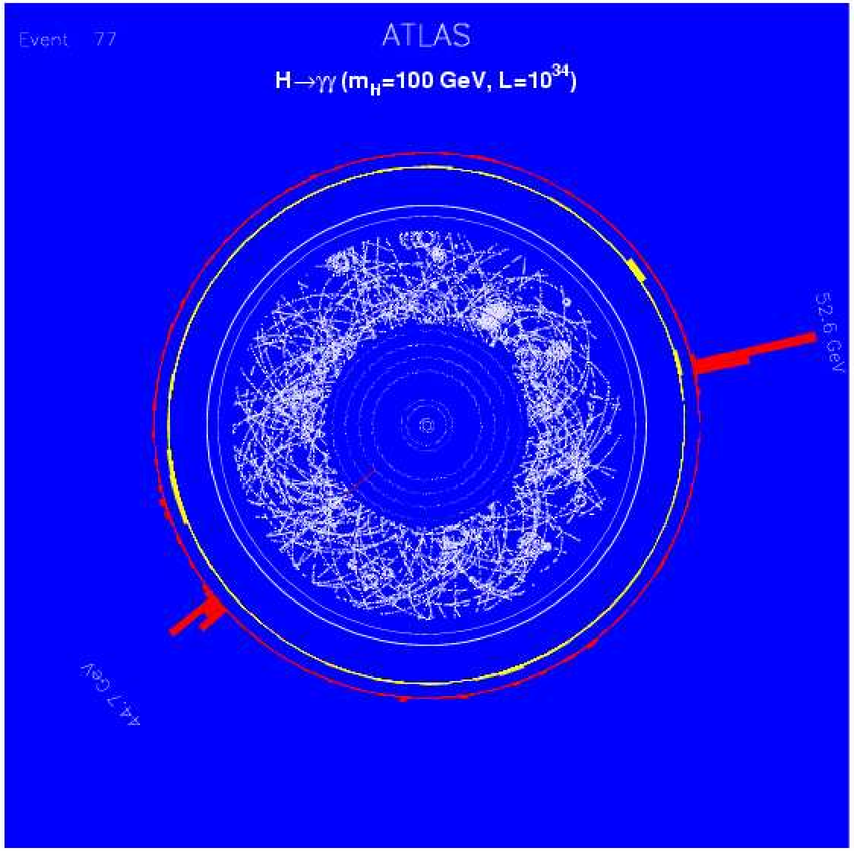
- VBF searches for
  - $H \to \gamma\gamma$ for $115 \text{ GeV} \leq m_H \leq 150$ GeV
  - $H \to \tau\tau$ for $115 \text{ GeV} \leq m_H \leq 150$ GeV
  - $H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$ for $115 \text{ GeV} \leq m_H \leq 190$ GeV

- Search for boosted Higgs in VH associated production
  - $H \to b\bar{b}$ for $115 \text{ GeV} \leq m_H \leq 140$ GeV

$H \longrightarrow \gamma\gamma$



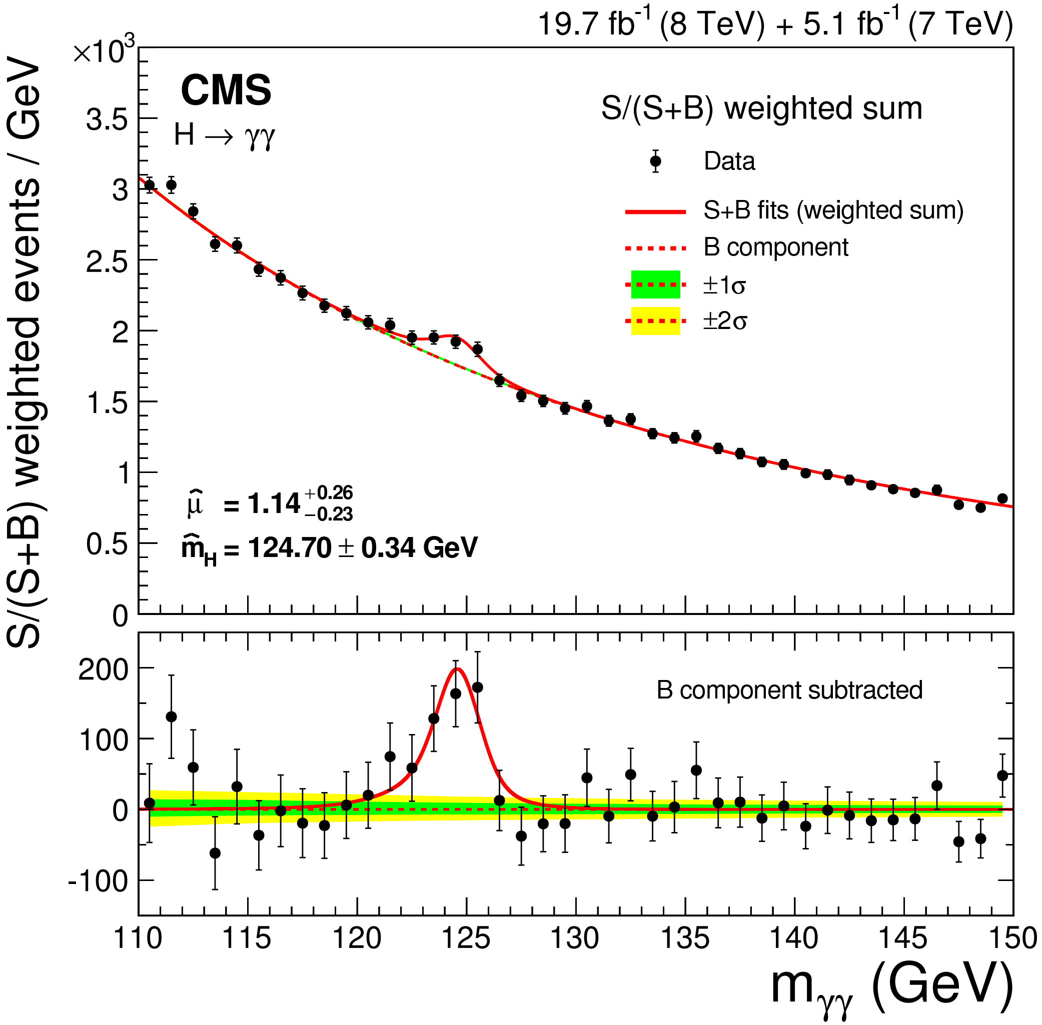
- $\mathrm{BR}(H \rightarrow \gamma\gamma) \approx 2 \cdot 10^{-3}$
- large backgrounds from $q\bar{q} \rightarrow \gamma\gamma$, $gg \rightarrow \gamma\gamma$ and jets misidentified as photons
- but CMS and ATLAS have excellent photon-energy resolution (order of 1%)



Rate is sensitive to Higgs couplings to top-quark and W.

$H \to \gamma\gamma$

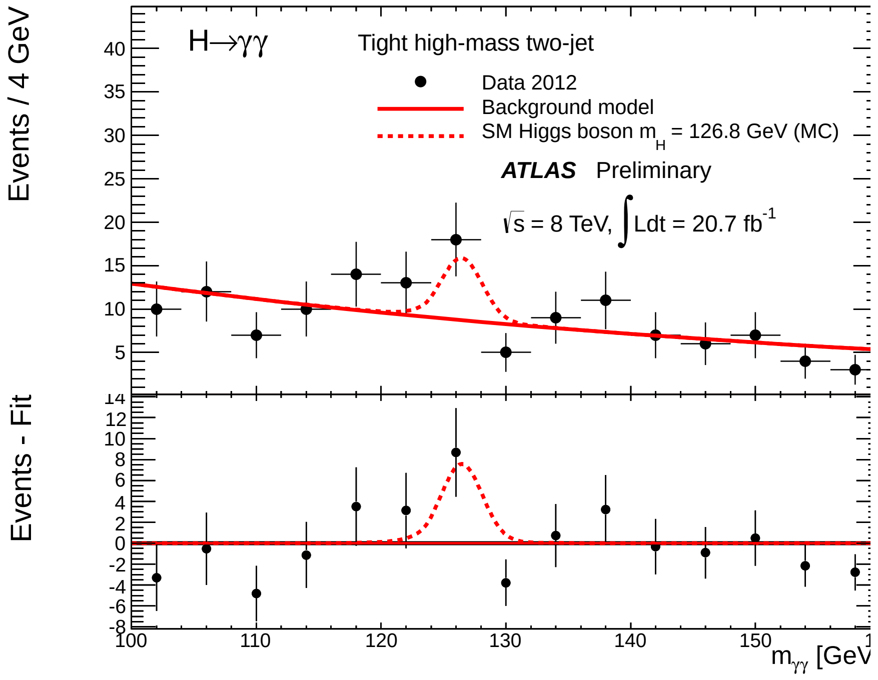
- Look for a narrow $\gamma\gamma$ invariant mass peak
- Extrapolate background into the signal region from sidebands
- Observation of signal at
  $m_{\gamma\gamma} = 126.0 \pm 0.5$ GeV (ATLAS)
  $m_{\gamma\gamma} = 124.7 \pm 0.34$ GeV (CMS)



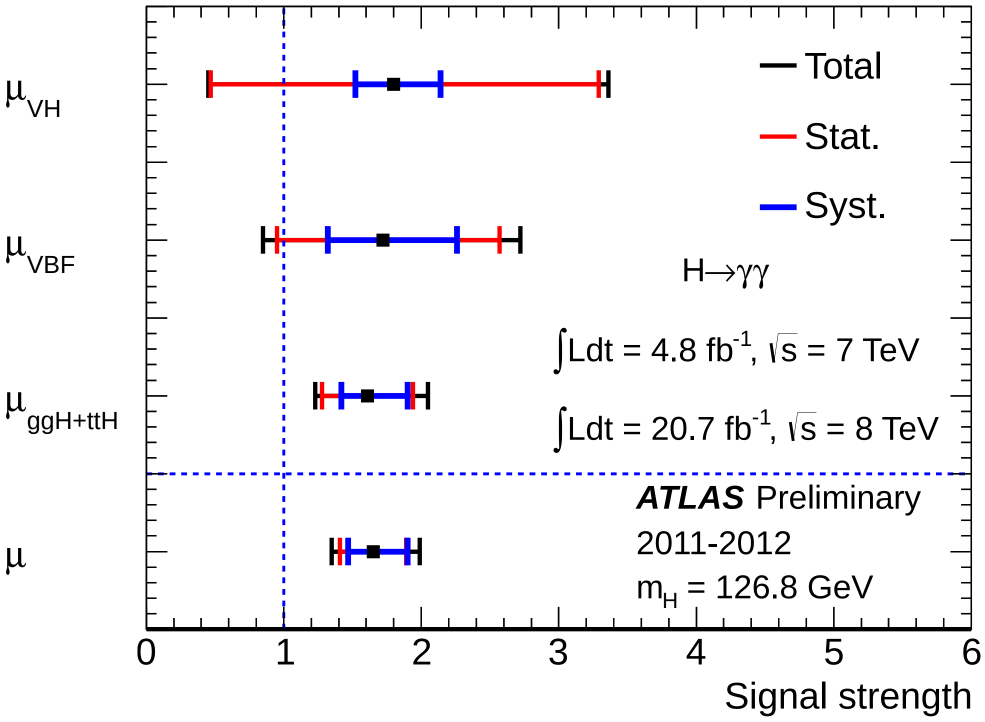
Landau-Yang theorem: $\gamma\gamma$ resonance cannot be spin1
$\Longrightarrow$ New resonance at 125 GeV is most likely spin 0 (or perhaps spin 2)

$H \longrightarrow \gamma\gamma$ in VBF

ATLAS data for VBF dijet selection



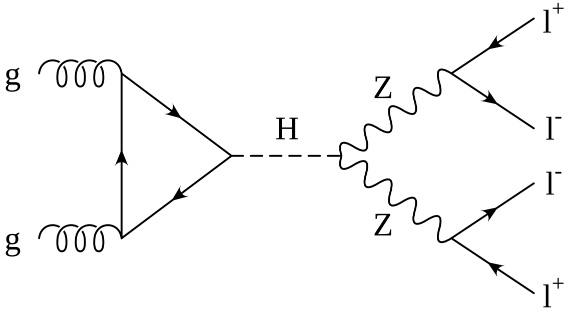
ATLAS $H \to \gamma\gamma$ signal strengths: $\mu = \sigma / \sigma_{SM}$

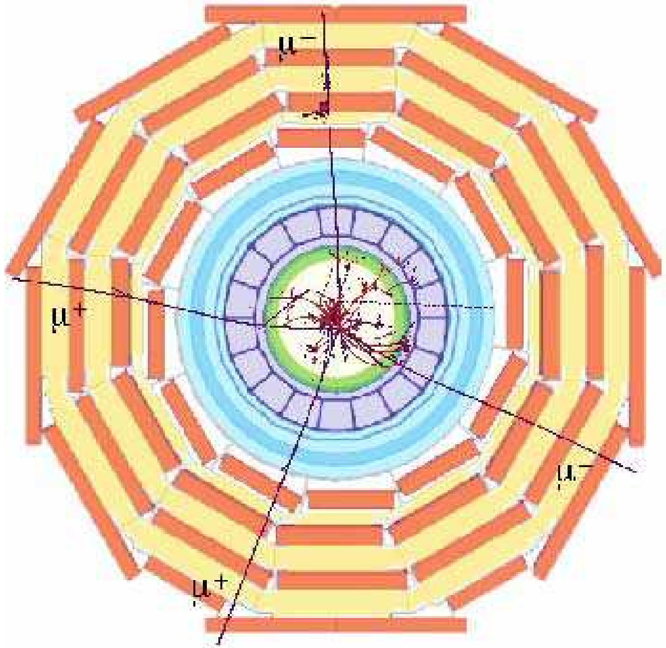


VBF rate is proportional to $Ag_{HWW}^2 + Bg_{HZZ}^2$ times $|cg_{HWW} - dg_{Htt}|^2$

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

The gold-plated mode

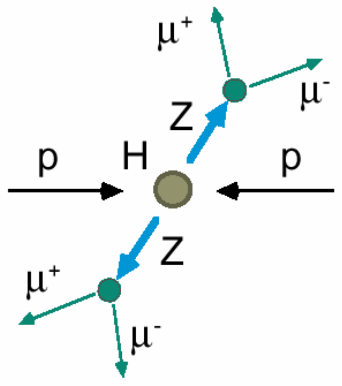




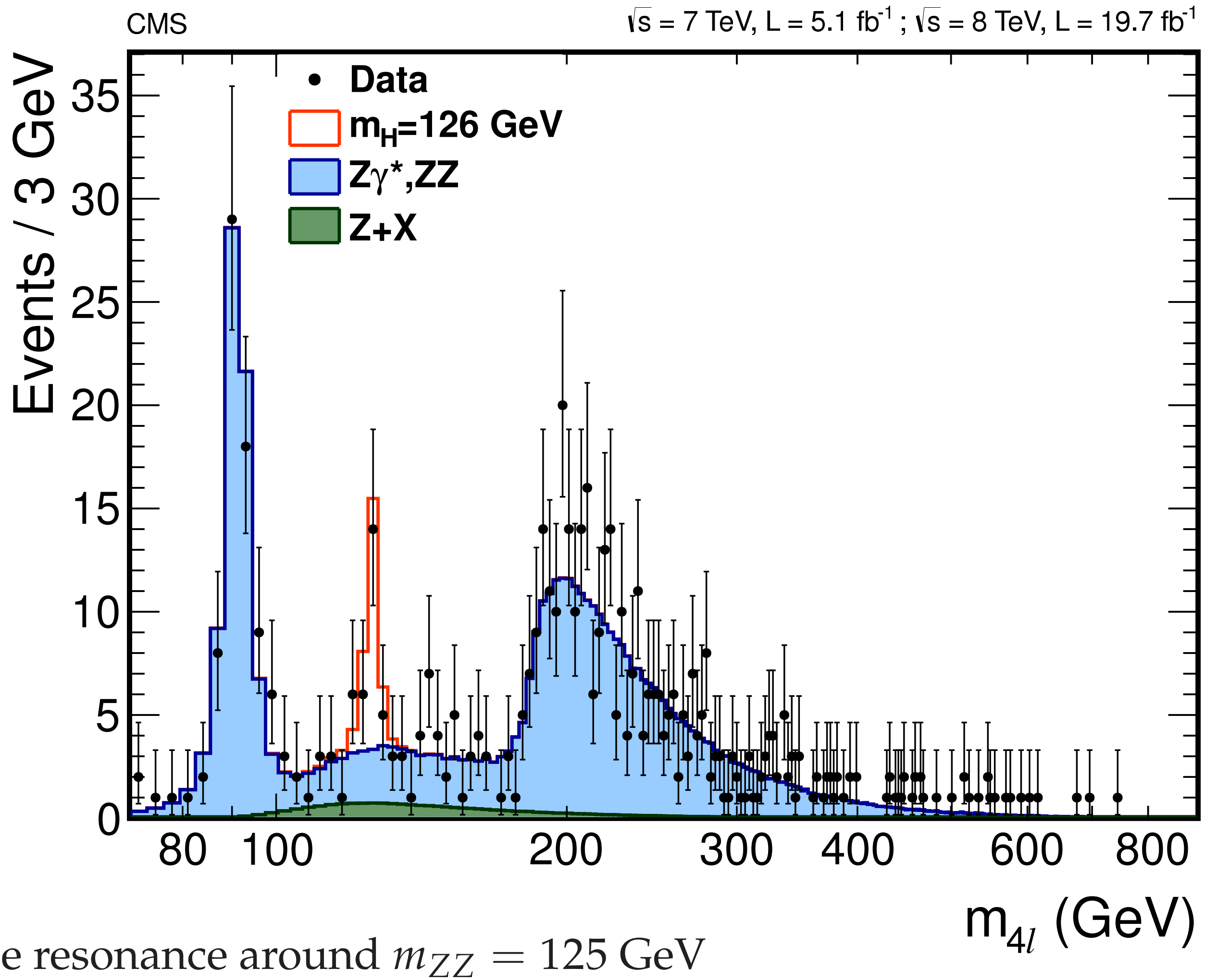
- Most important and clean search mode for $m_H < 600$ GeV (with hole around $2m_W$)
- Continuum, limited, irreducible background from $q\bar{q} \rightarrow ZZ$
- small BR$(H \rightarrow \ell^+\ell^-\ell^+\ell^-) < 0.15\%$ (asymptotic value for $m_H >> 2m_Z$)

Observation confirms sizable HZZ coupling

4-lepton invariant mass spectrum

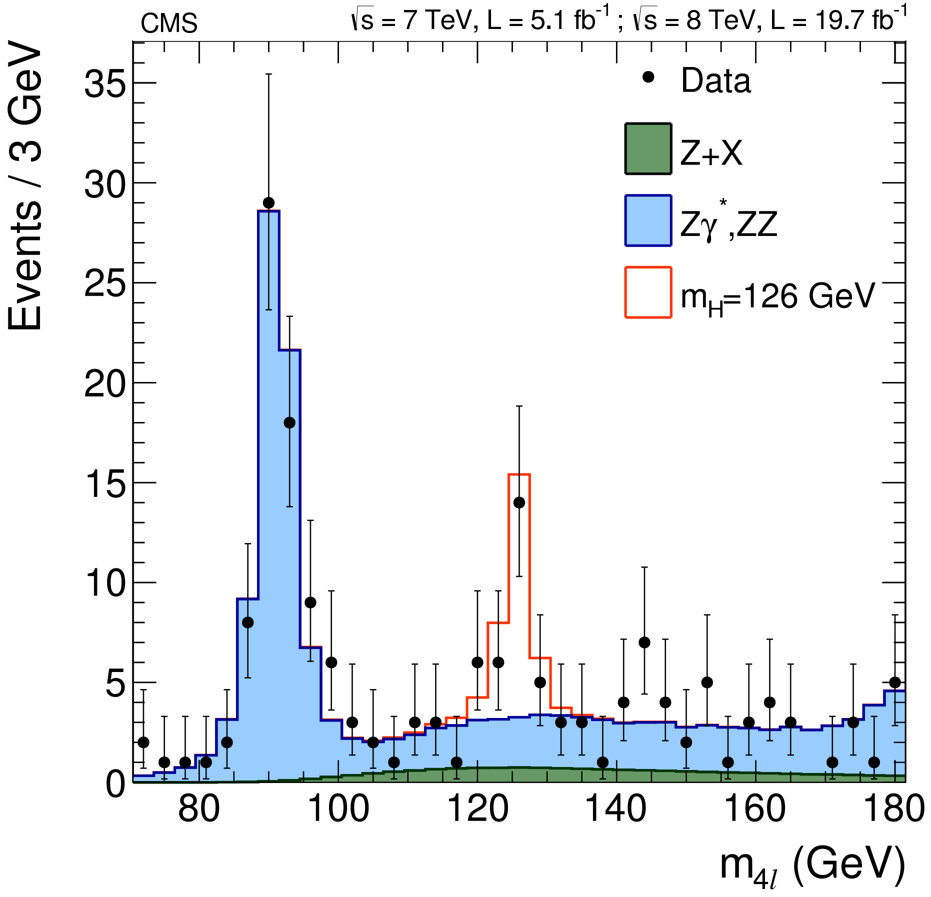


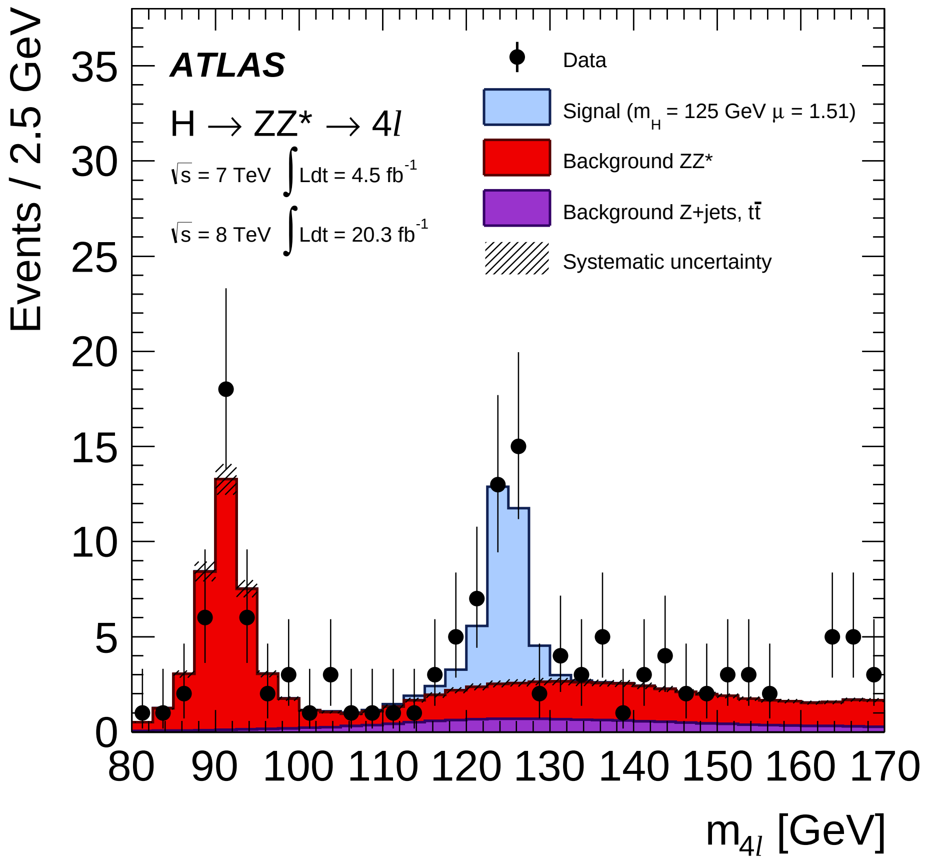
- invariant mass of the charged leptons fully reconstructed



CMS and ATLAS observe resonance around $m_{ZZ} = 125$ GeV

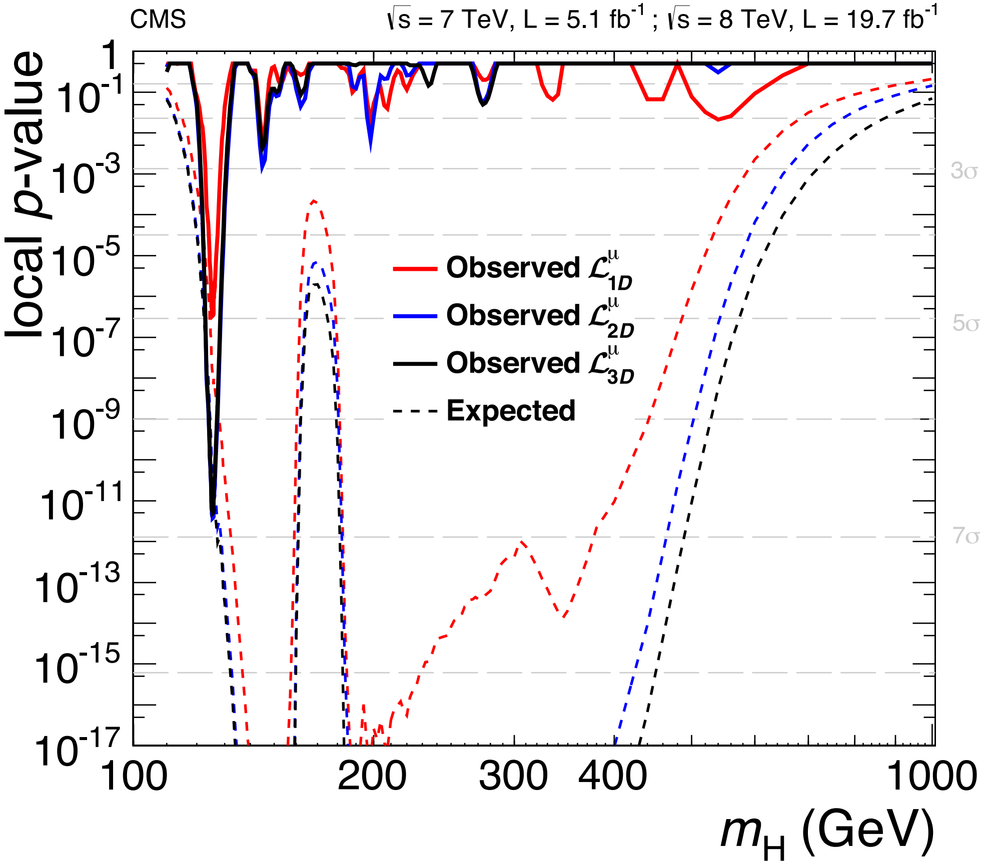
$H \longrightarrow ZZ \longrightarrow \ell^+\ell^-\ell^+\ell^-$

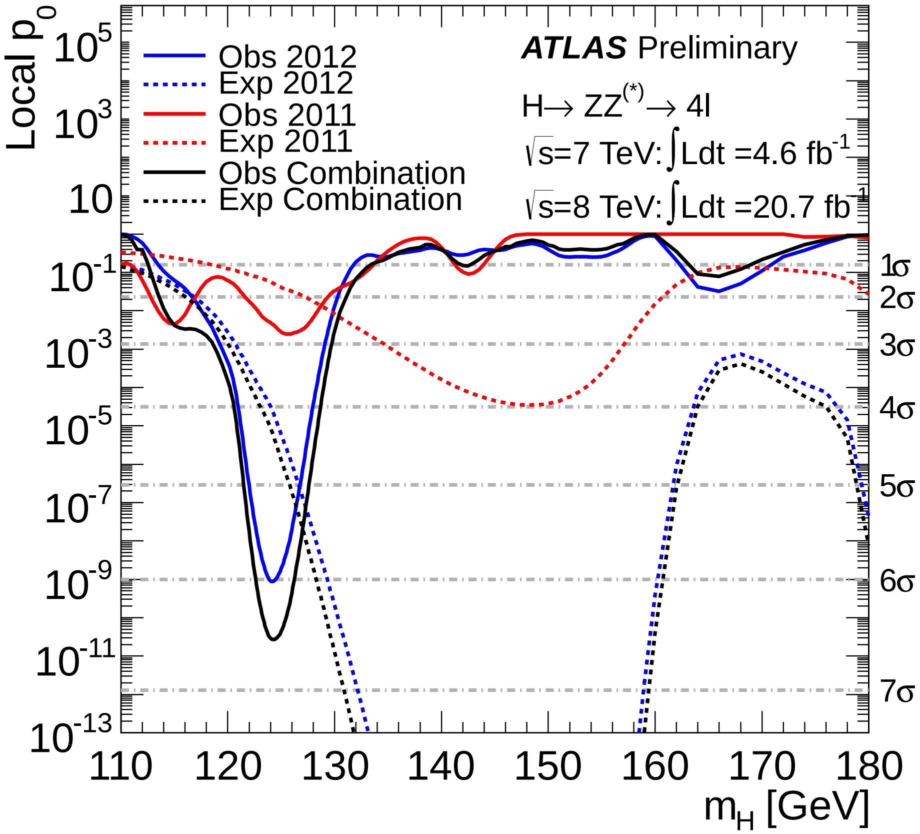




Resonance at CMS: 125.6 ± 0.5 GeV ATLAS: 124.5 ± 0.5 GeV

Significance of $H\to ZZ$ signal





The $H\to ZZ^*\to \ell^+\ell^-\ell^+\ell^-$ channel alone provides a more than 6σ signal in each experiment

Higgs mass measurement of LHC: run I result

Higgs appears as narrow resonance in $H \to \gamma\gamma$ and $H \to ZZ \to llll$

Measurement of peak position:

$H \to ZZ$:

CMS: 125.6 ± 0.5 GeV

ATLAS: 124.5 ± 0.5 GeV

$H \to \gamma\gamma$:

CMS: 124.7 ± 0.34 GeV

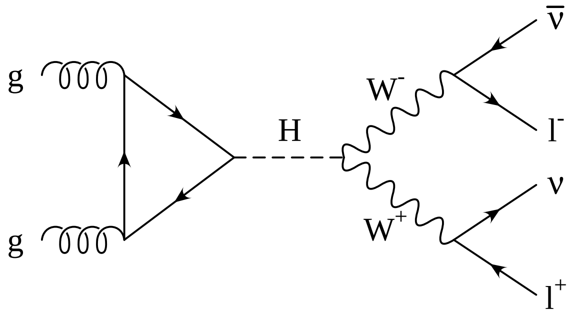
ATLAS: 126.0 ± 0.5 GeV

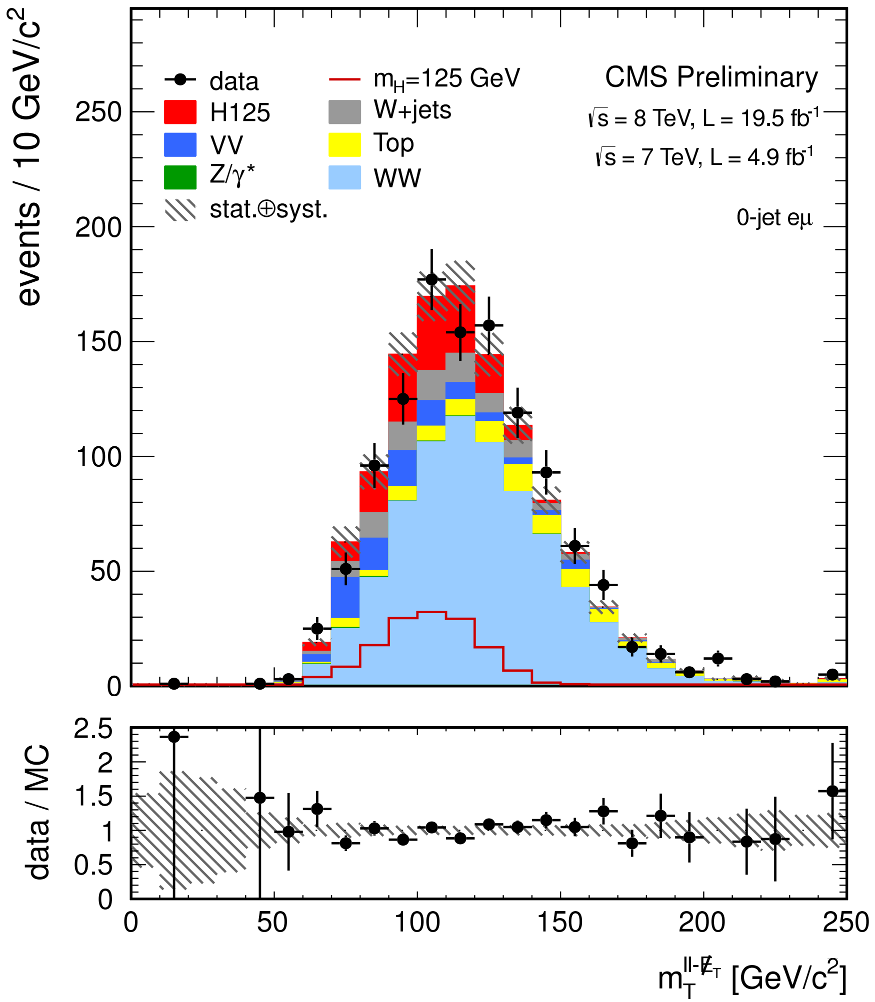
Combination of results:

$$m_H = 125.09 \pm 0.21 \ (\text{stat}) \pm 0.11 \ (\text{syst}) \text{ GeV}$$

With measurement of m_H the SM parameters are completely determined

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



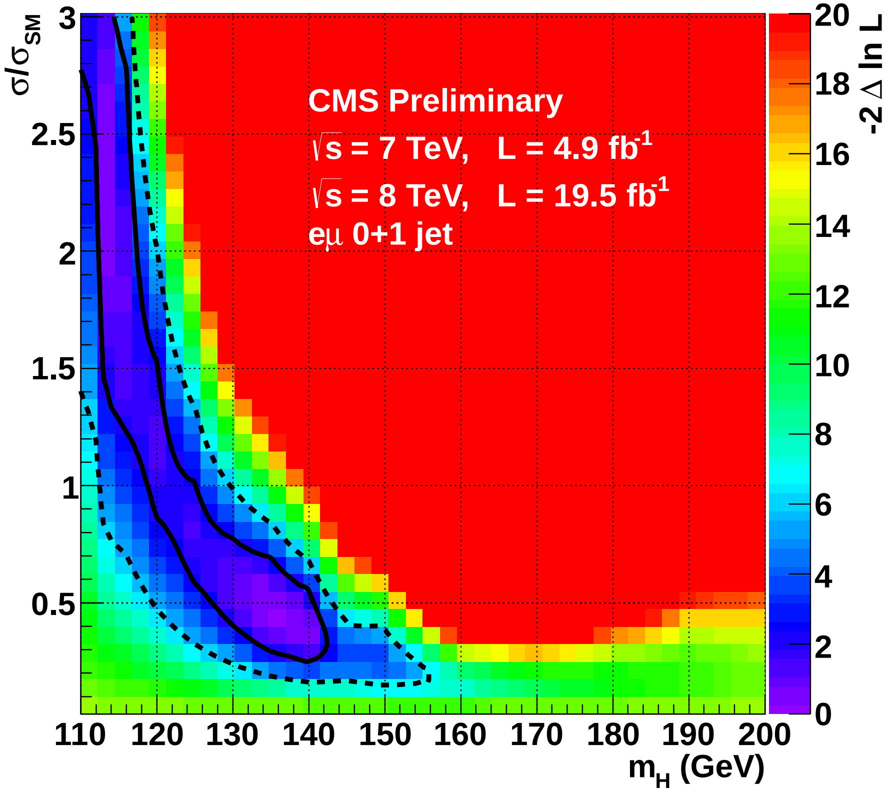


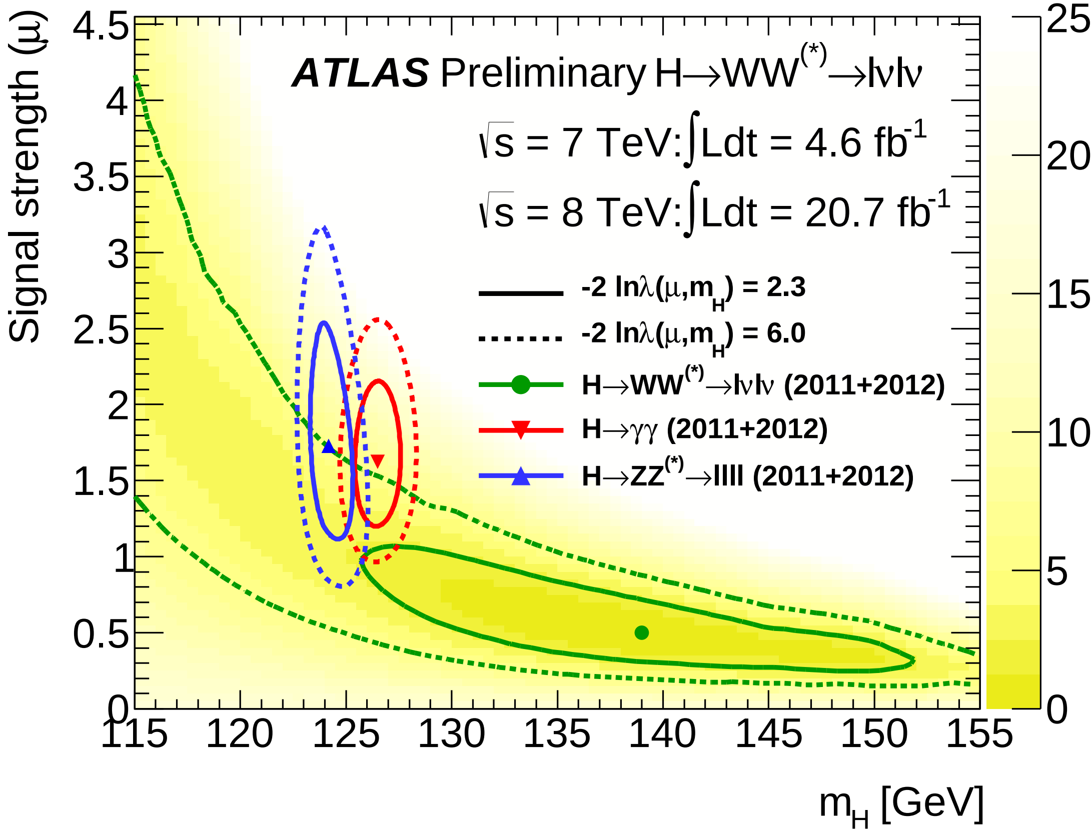
Exploit $\ell^+\ell^-$ angular correlations

measure the transverse mass with a Jacobian peak at m_H

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss})^2}$$

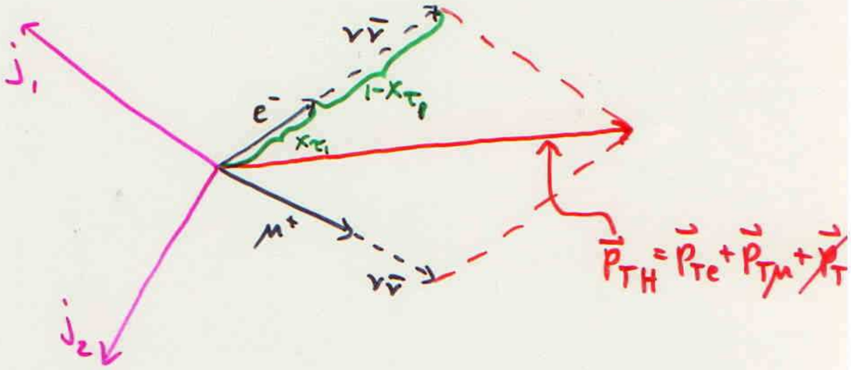
Signal strength of $H \to WW$ signal





Bad mass resolution for $H \to WW$ signal. Signal strength compatible with 125 GeV SM Higgs

τ-pair mass reconstruction



τ relativistic $\Rightarrow$ $\tau \to \ell\nu\bar{\nu}$ all collinear

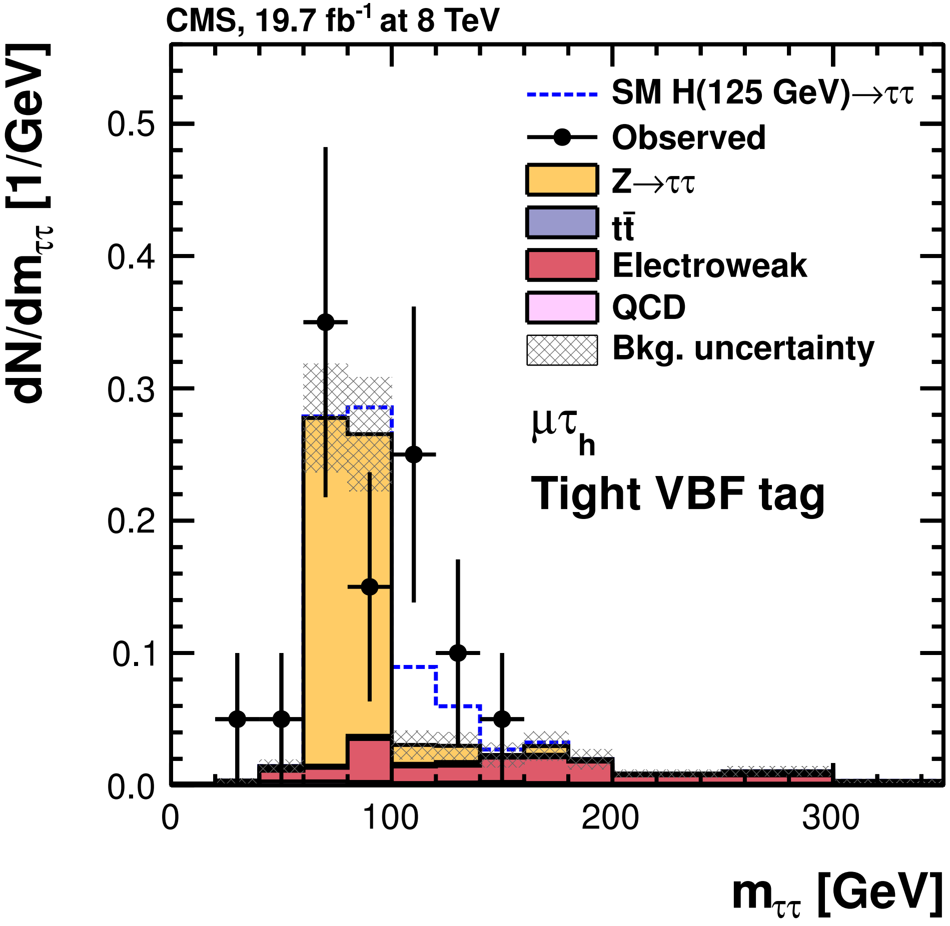
reconstruct τ momenta from transv. momentum parallelogram

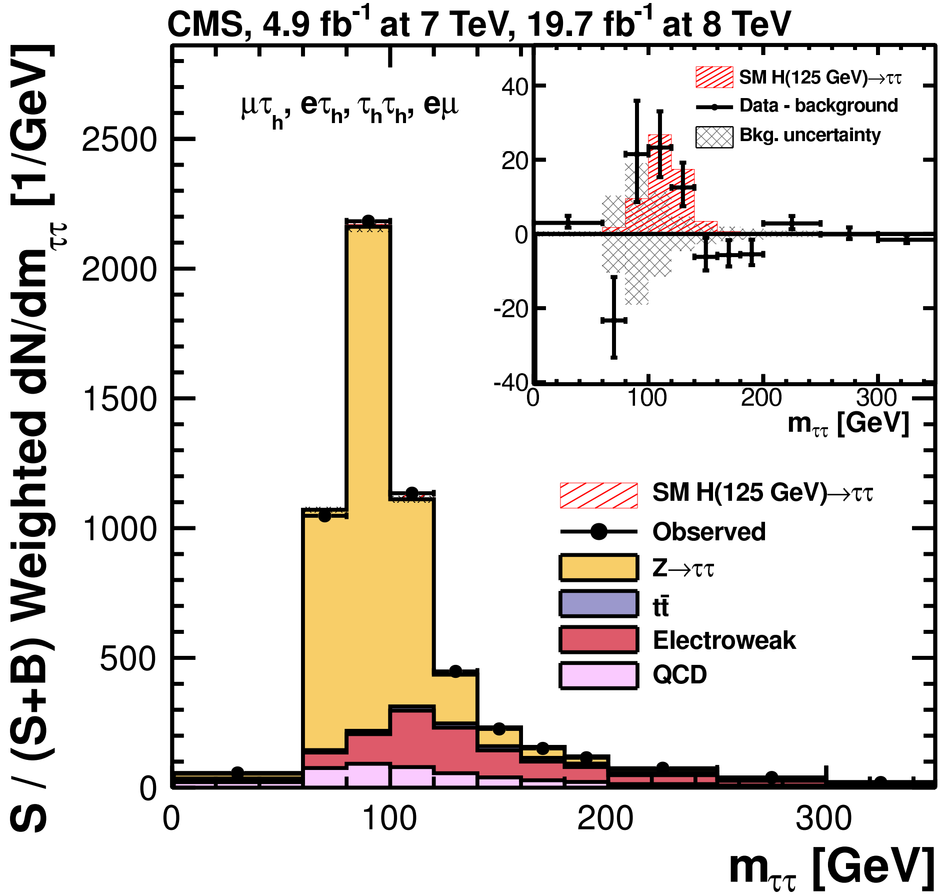
$\Rightarrow$ determines lepton energy fraction x_τ

$$p_\tau = p_e \frac{1}{x_\tau}$$

Higgs decay to tau pairs

Most sensitive search channel is via VBF. But consider all...

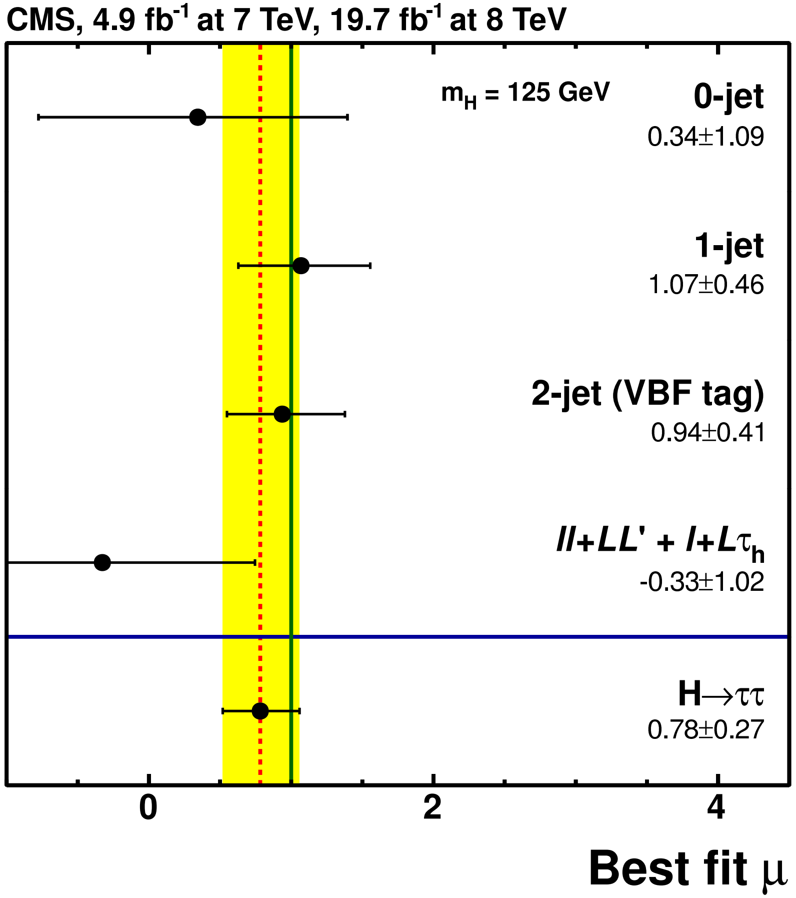




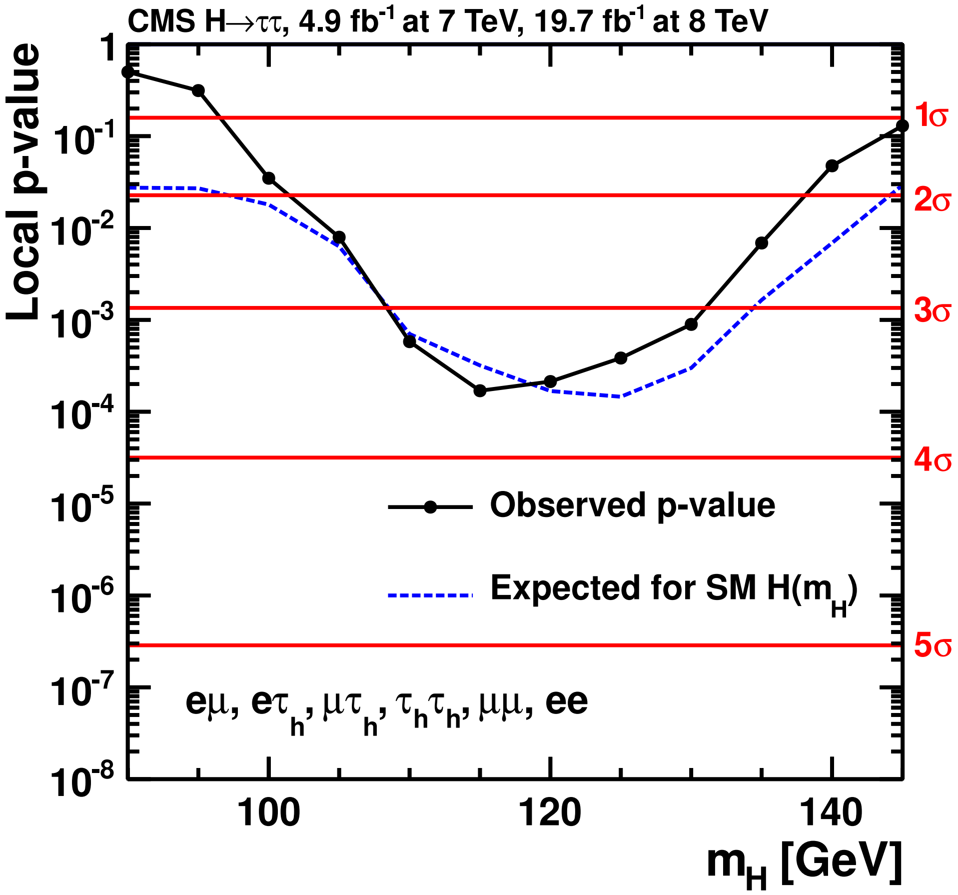
Clearly visible indication for Higgs decay to tau-lepton pairs around 120 GeV

Comparison of $\tau\tau$ signal with SM expectation

Best fit of signal strength

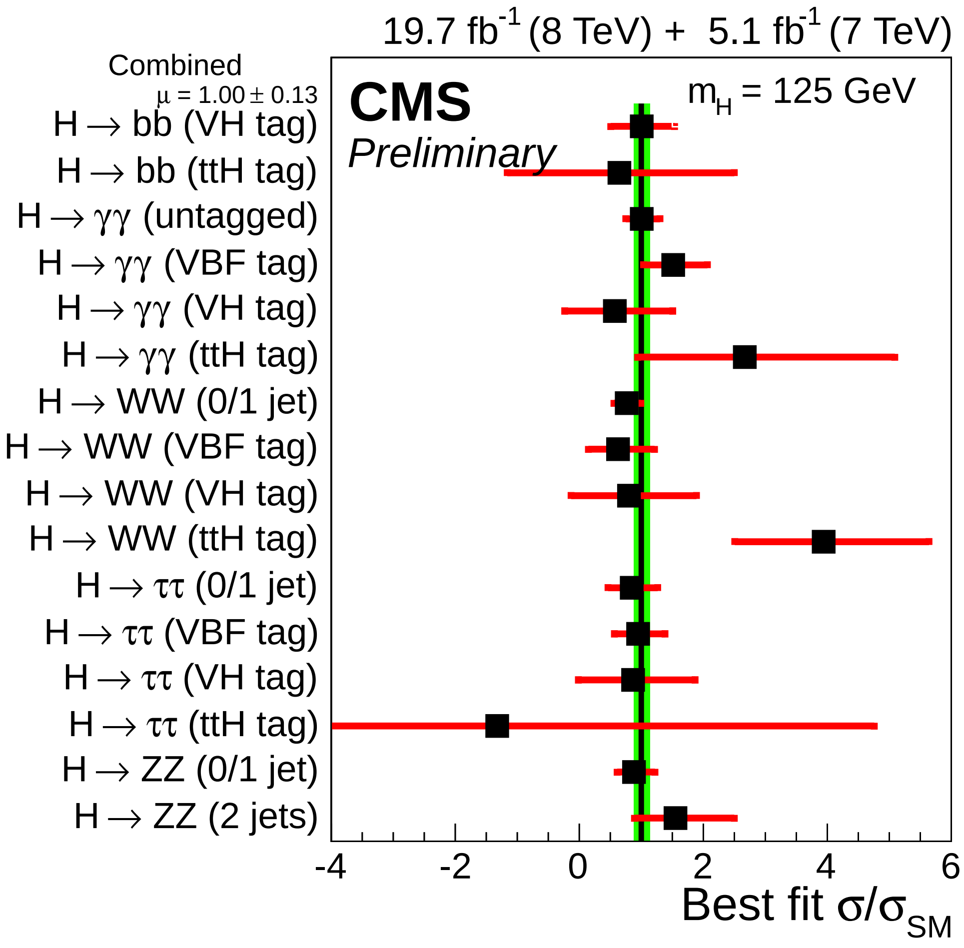


Probability of background fluctuation

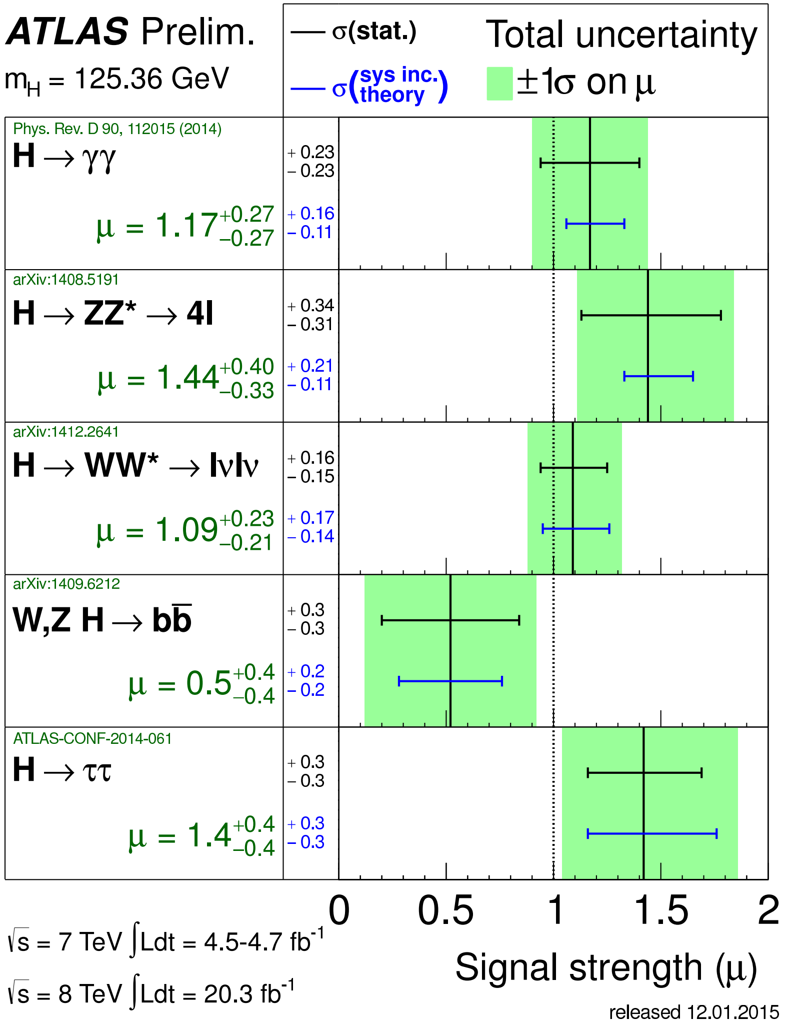


Summary of measured channels

CMS data



ATLAS data



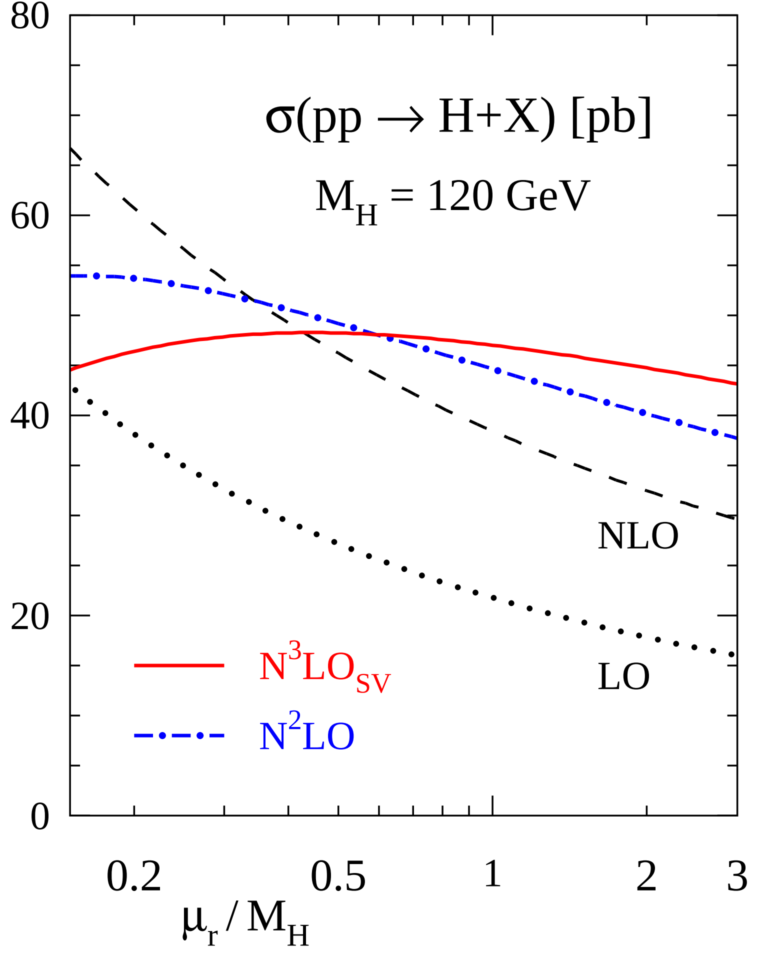
Corrections for Higgs production cross sections

Measurement of Higgs couplings from measured signal rates
$\Longrightarrow$ need QCD corrections to production cross sections.

- $gg \to H$ (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)
  - N^{3}LO: Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)
- Hjj by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2006)
- Higgsstrahlung: implemented in MC@NLO Frixione, Webber
- weak boson fusion
  - 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)

QCD corrections to $gg \to H$

Moch & Vogt, hep-ph/0508265



- Large QCD corrections: K-factor of about 2
- Stabilization of scale dependence needs N^{3}LO or at least NNLO corrections
- Cross section estimate for $m_H = 125$ GeV at 8 TeV from LHC XS WG, determined at NNLL QCD and NLO EW

$$\sigma(gg \to H) = 19.27\,\text{pb} \pm 14.7\%$$

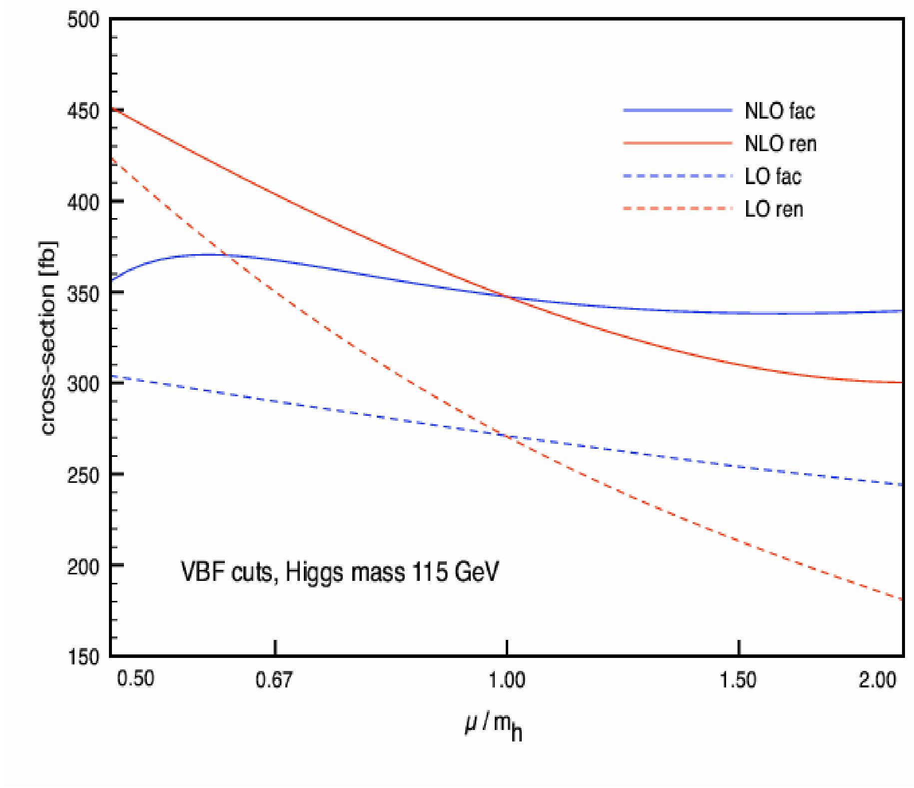
- Recently improved with N^{3}LO corrections to

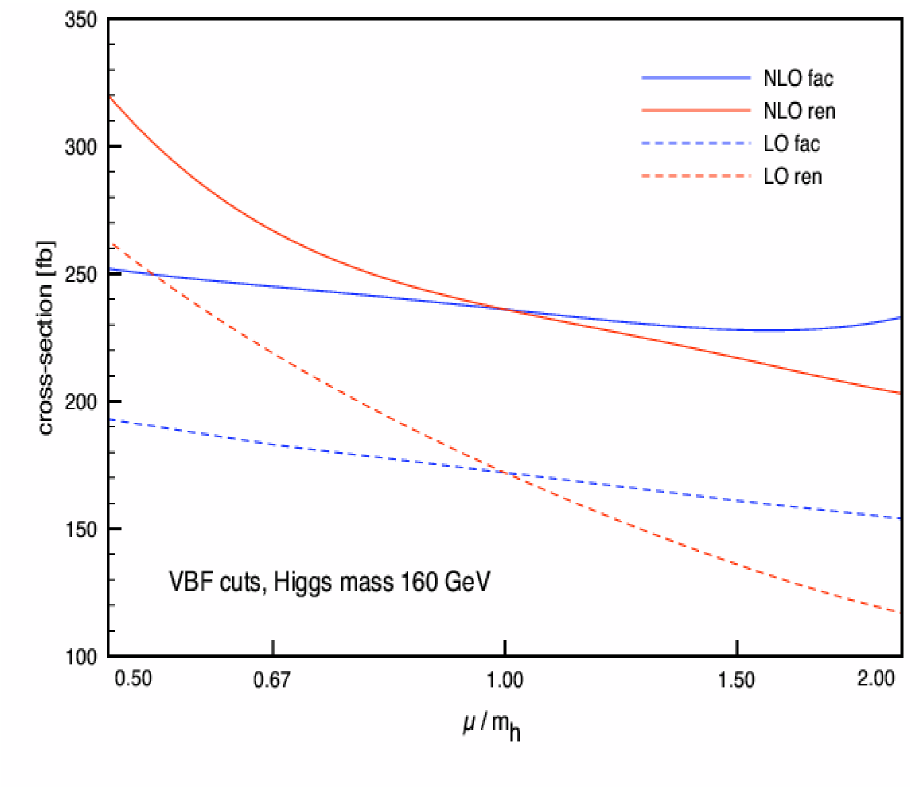
$$\sigma(gg \to H) = 21.42\,\text{pb} \pm 9\%$$

- Additional uncertainty from use of effective hgg vertex (heavy top approximation) is estimated to be below 2%

Hjj cross section for gluon fusion

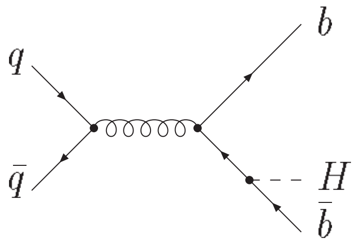
Calculation of Hjj cross section at NLO in $m_t \to \infty$ limit by Campbell, Ellis, Zanderighi, hep-ph/0608194

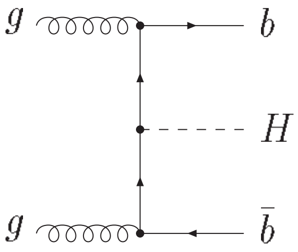




- Modest increase of cross section at 1-loop: K-factor of order 1.2 - 1.4
- Reduced scale dependence at NLO: remaining scale uncertainty $\approx \pm 20\%$

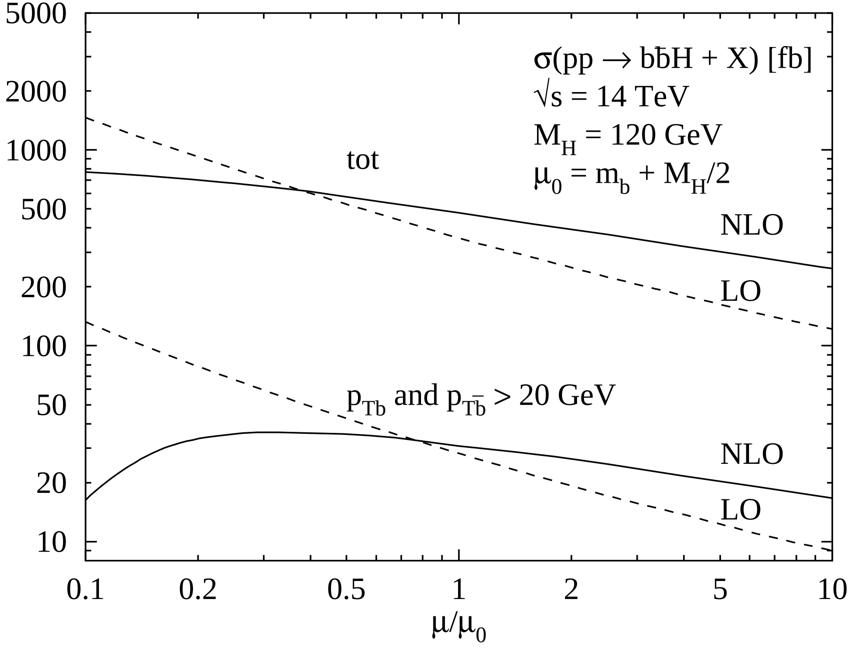
NLO QCD corrrections to $b\bar{b}H$ production





- 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



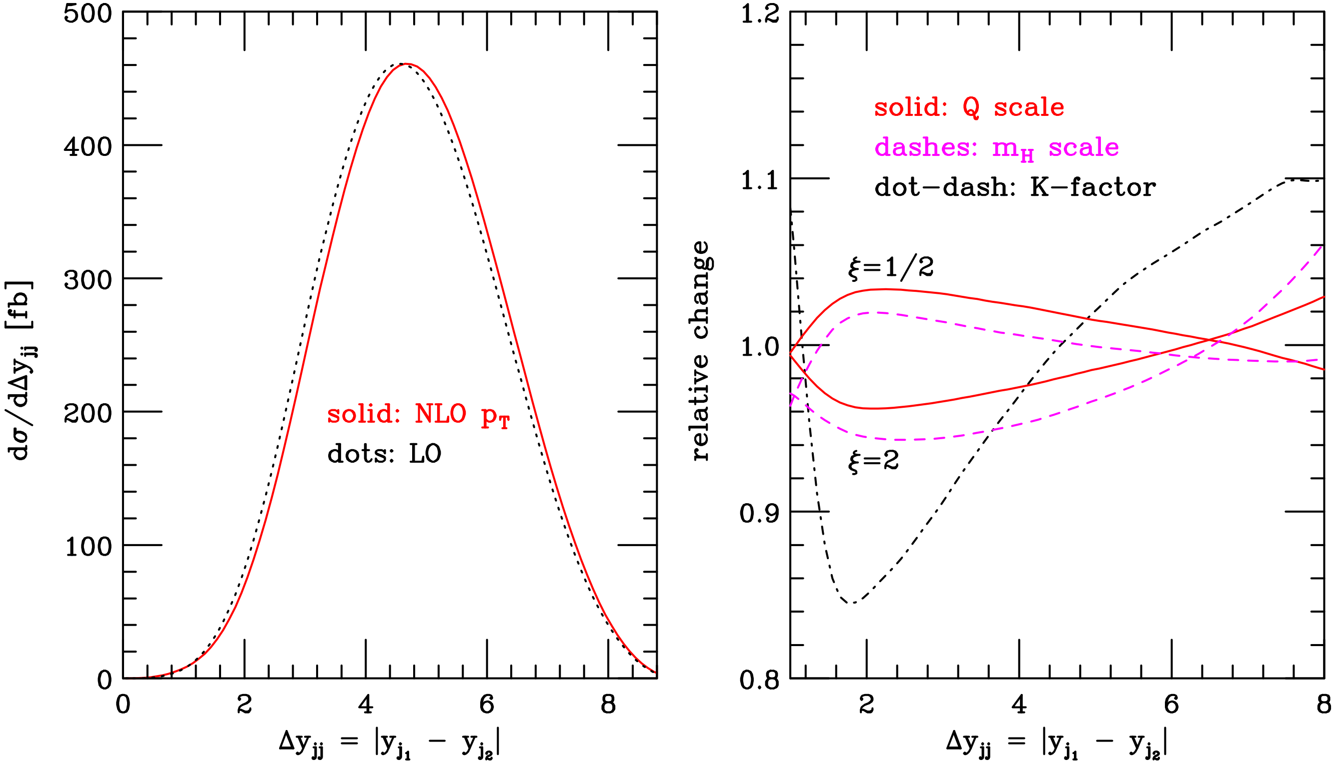
scale dependence of inclusive vs. double b-tagged cross section

NLO corrections to VBF

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 1\%$ for σ_{total}
- pdf error is below 3% since pdf's are dominated by valence quarks
- $\approx \; -5\%$ EW corrections included

  Ciccolini, Denner, Dittmaier, 0710.4749

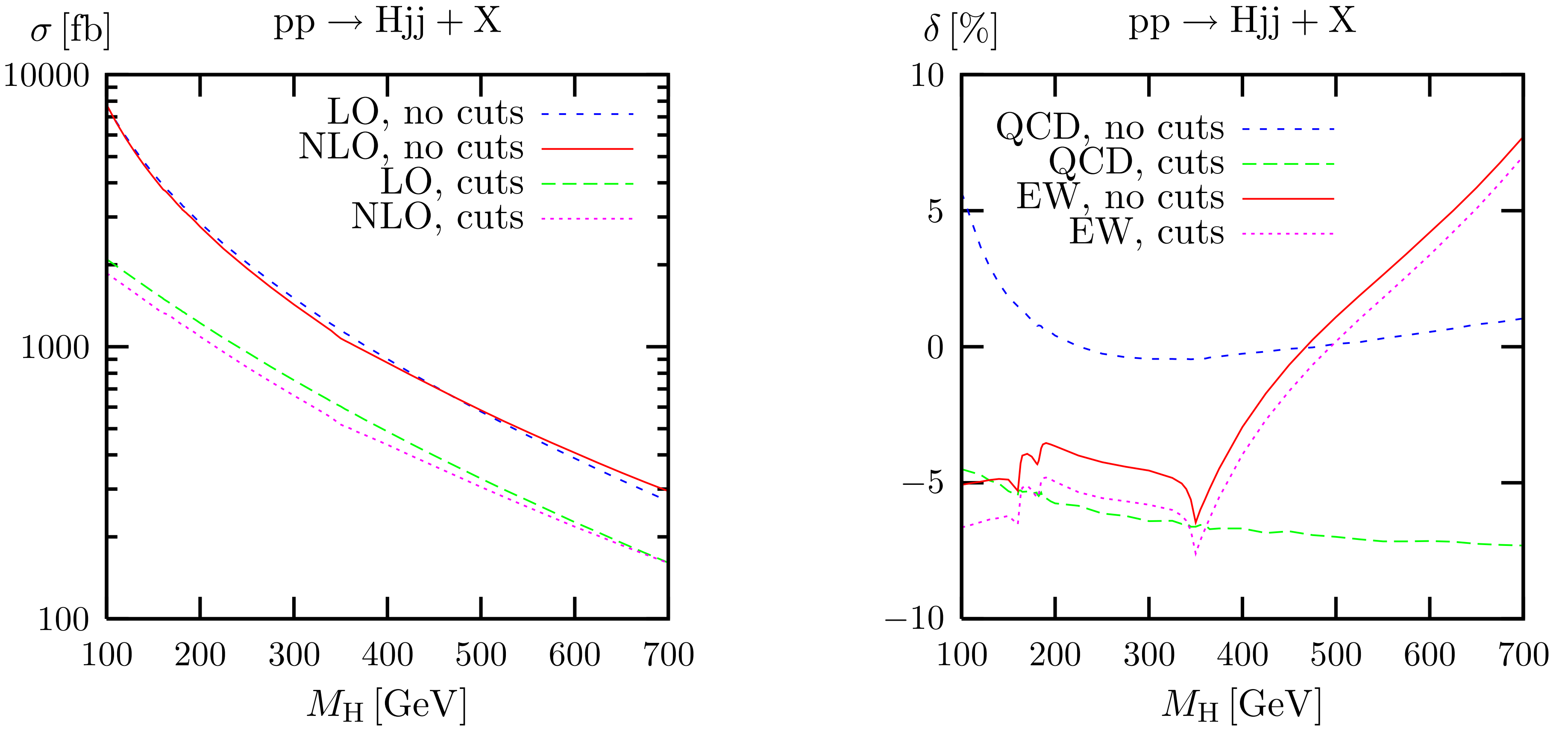
  Figy, Palmer, Weiglein arXiv:1012.4789
- Very small cross section error of about 3% for $m_H = 125$ GeV



$m_H = 120$ GeV, typical VBF cuts

QCD + EW corrections to Hjj production

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

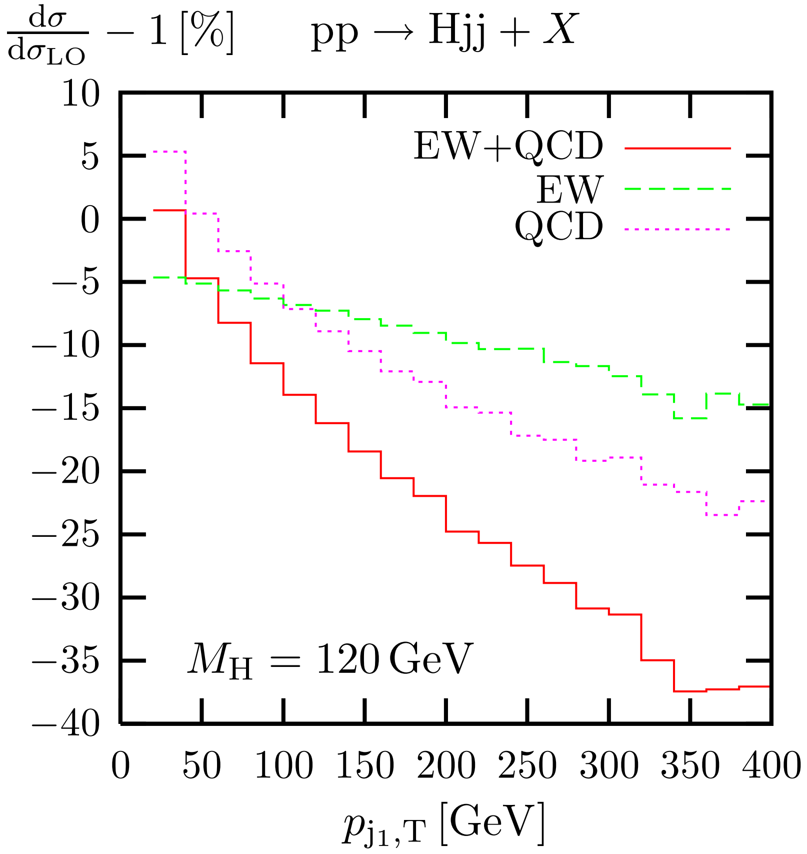


Ciccolini, Denner, Dittmaier, arXiv:0710.4749

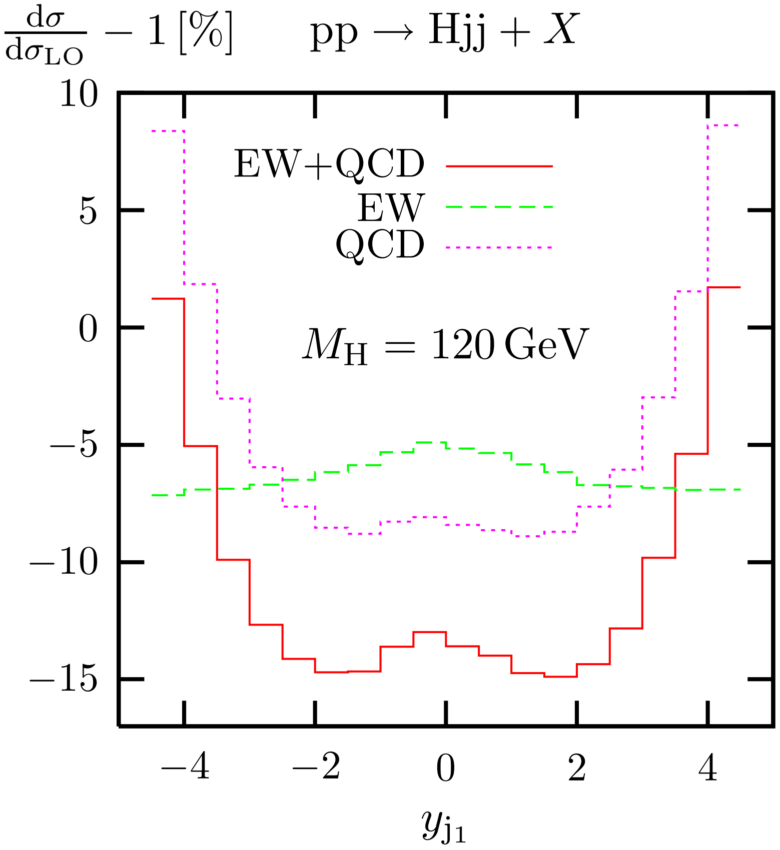
Relative size of 1-loop corrections

Consider distributions of hardest jet in the event:

p_T distribution



rapidity distribution



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

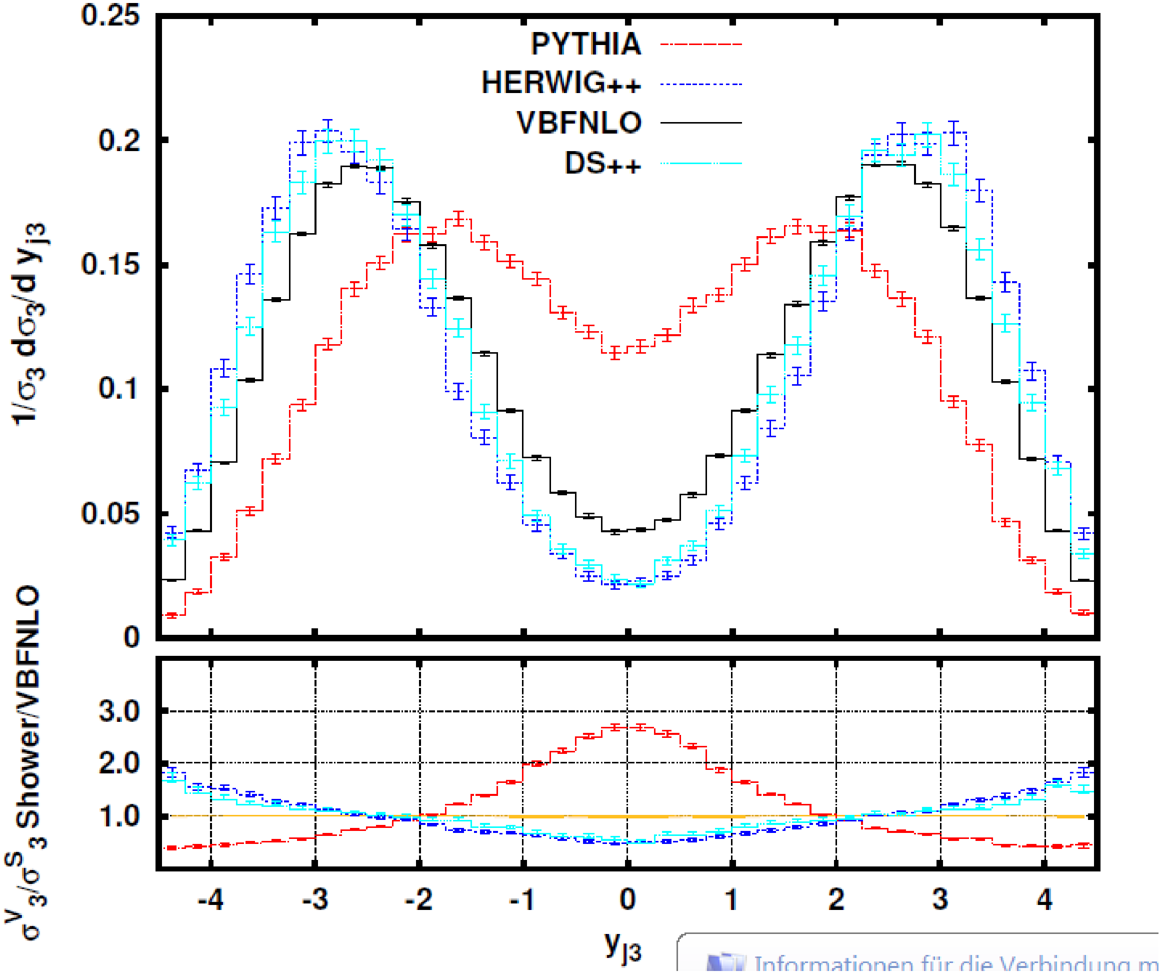
Veto jets beyond fixed order

Interface of NLO calculations with Herwig and PYTHIA via Powheg approach has been implemented by Franziska Schissler

- How well can “veto jets” be modeled directly by parton shower approach?
- Differences between basic shower models
  (PYTHIA vs. default Herwig shower vs. dipole shower)
- Improvements when adding true NLO corrections

Veto jet distribution: LO $qq \rightarrow qqh$ matrix elements

Schissler thesis, 2014



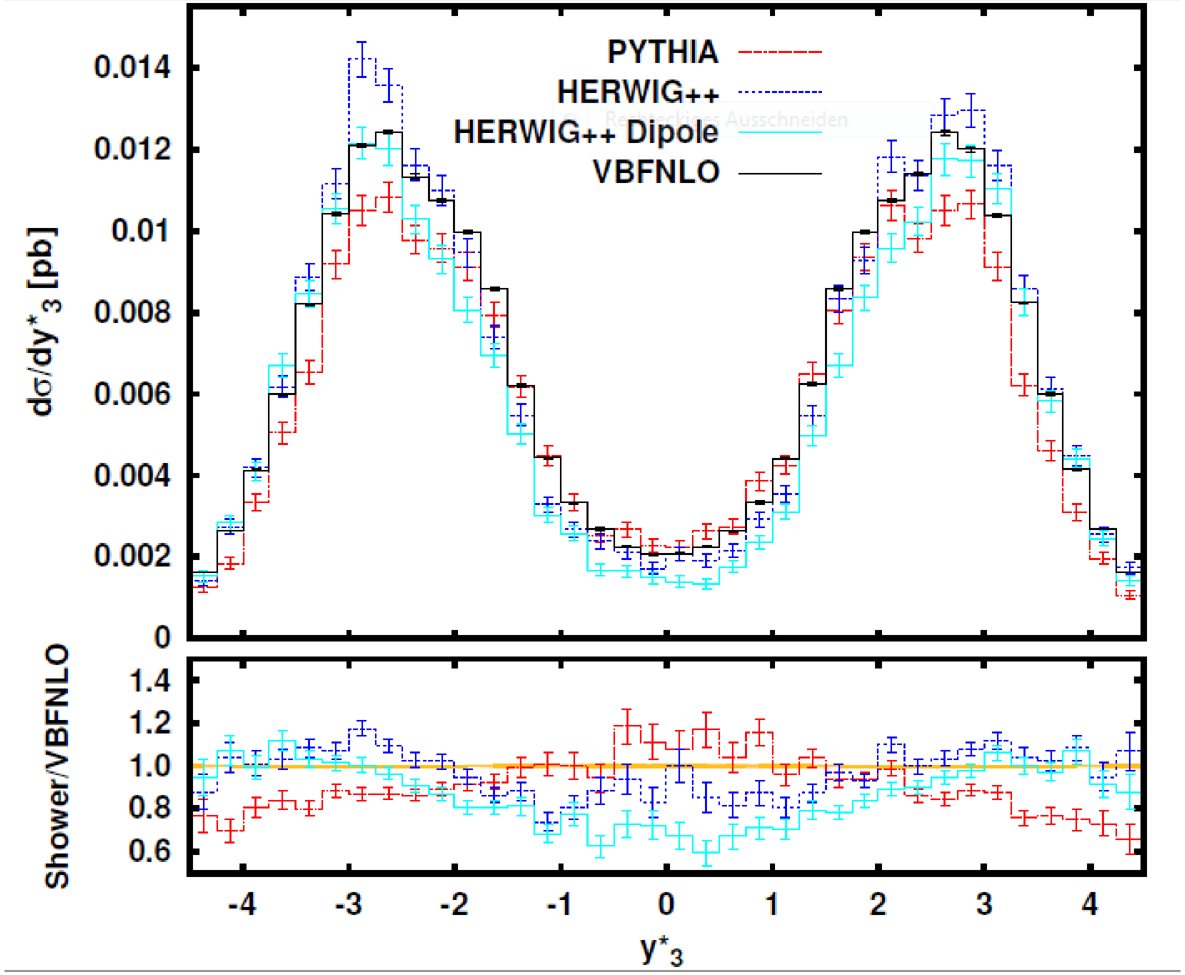
Pure parton-shower generation of central jets does not produce reliable results

Collinear approximation inherent in PS approach is not valid in veto region for VBF events

Extra parton must be included in hard matrix element

Veto jet distribution: VBF $Wjjj$ production at LO

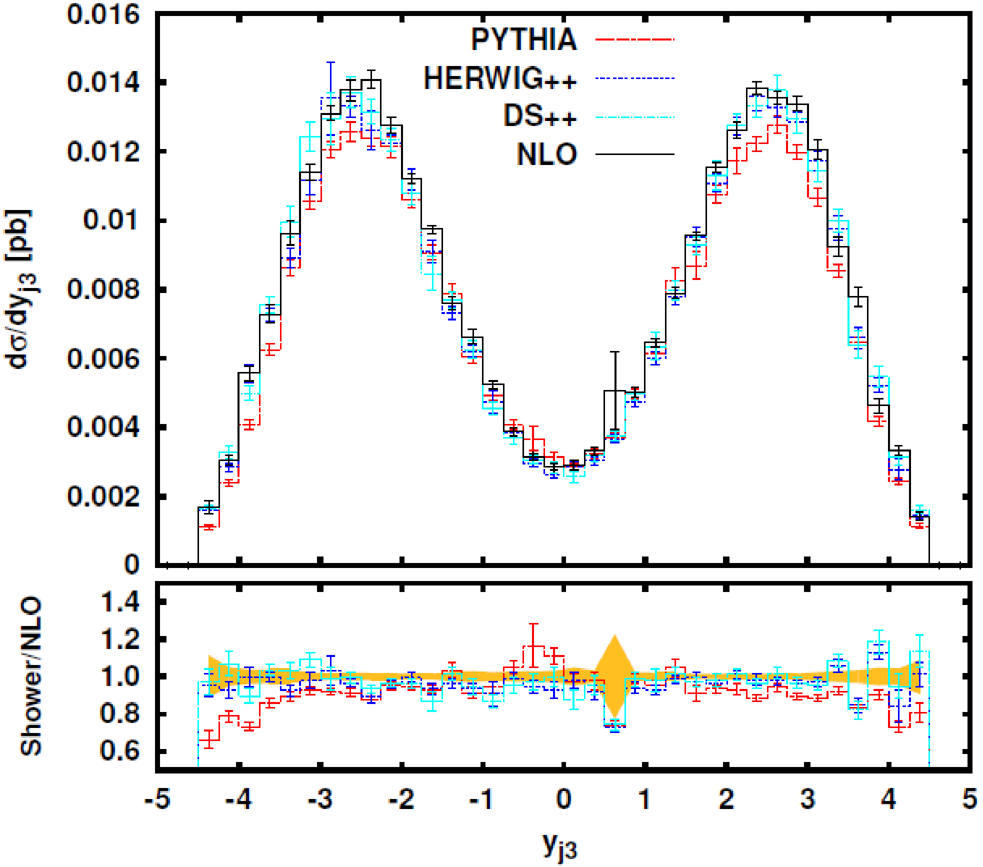
Schissler,DZ arXiv:1302.2884



Inclusion of third parton at ME level produces reasonable agreement between NLO Vjj calculations and parton shower programs

Veto jet distribution: VBF $hjjj$ production at NLO

Jäger, Schissler,DZ arXiv:1405.6950



Further improvement with NLO $hjjj$ calculation matched to PS programs

Reliable simulation of veto jet candidates is possible but requires matrix elements with sufficiently high parton multiplicity

Measuring Higgs couplings at LHC

LHC rates for partonic process $pp \to H \to xx$ given by $\sigma(pp \to H) \cdot BR(H \to xx)$

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma} \,,$$

Measure products $\Gamma_p \Gamma_x / \Gamma$ for combination of processes ($\Gamma_p = \Gamma(H \to pp)$)

Problem: rescaling fit results by common factor f

$$\Gamma_i \to f \cdot \Gamma_i \,, \qquad \Gamma \to f^2 \Gamma = \sum_{obs} f \Gamma_i + \Gamma_{rest}$$

leaves observable rate invariant $\Longrightarrow$ no model independent results at LHC

Loose bounds on scaling factor:

$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

Total width below experimental resolution of Higgs mass peak ($\Delta m = 1 \ldots 2$ GeV)

$$f^2 \Gamma < \Delta m \qquad \Longrightarrow \qquad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(20)$$

Off-shell Higgs exchange contribution: $f^2 < \mathcal{O}(5)$

SFitter analysis of Higgs couplings at LHC

Analysis by D. Lopez-Val, T. Plehn, M. Rauch, arXiv:1308.1979

- Parameterize deviations from SM couplings

$$g_i = g_i^{\mathrm{SM}} \; (1 + \Delta_i) = g_i^{\mathrm{SM}} \; \kappa_i$$

- Five free parameters $i = W, Z, t, b, \tau$ plus generation universality
- Loop-induced couplings change from modifying contributing tree-level couplings
- Δ_H: common parameter modifying all (tree-level) couplings
- Assume no add. contribution to total width

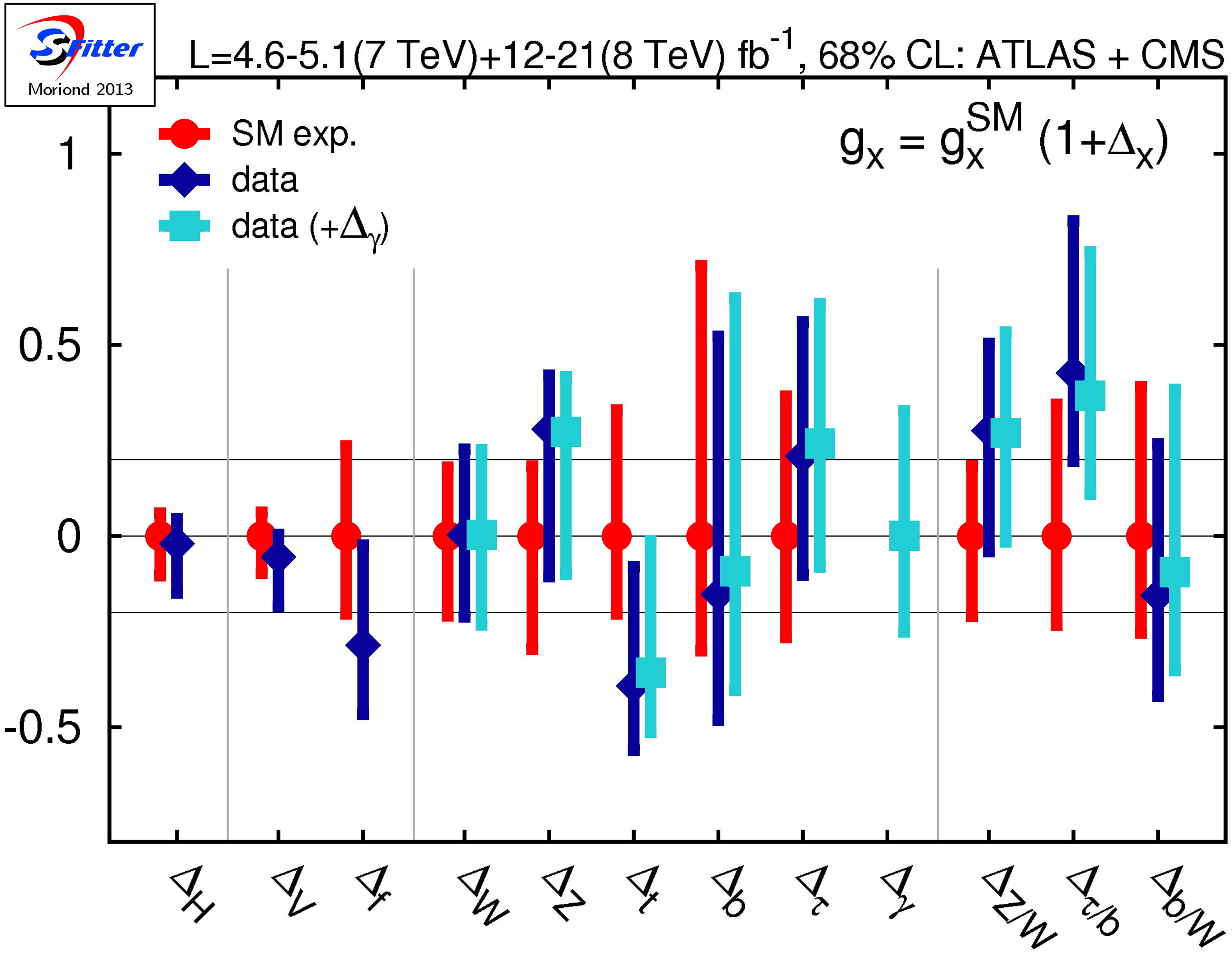
- Background expectations, exp. errors, etc. from published analyses

List of input channels for 2011 data

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
$ZZ \to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	$ZZ \to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	$Z(\to \ell\bar{\ell})H$	$b\bar{b}$	$Z(\to \ell\bar{\ell})H$
$b\bar{b}$	$Z(\to \nu\bar{\nu})H$	$b\bar{b}$	$Z(\to \nu\bar{\nu})H$

plus (longer) list of 2012 data

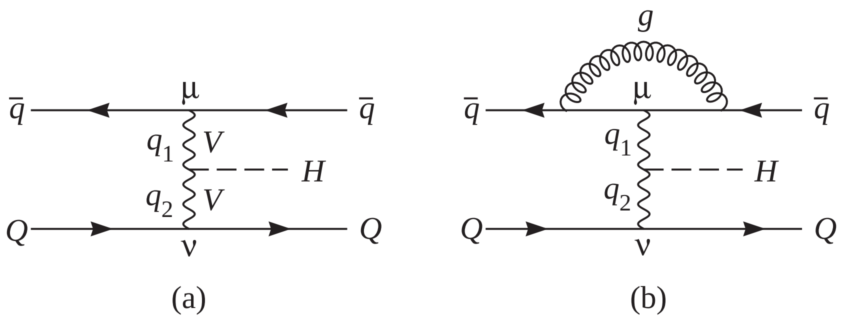
Central values and errors on couplings



- SM provides good overall description

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

Connection to effective Lagrangian

We need model of the underlying UV physics to determine the form factors $a_i(q_1, q_2)$

Approximate its low-energy effects by an effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_\phi}{\Lambda^2} \left(\phi^\dagger \phi - \frac{v^2}{2} \right) (D_\mu \phi)^\dagger D^\mu \phi + \cdots + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

Gives leading terms for form factors, e.g. for hWW coupling

$$\begin{aligned} a_1 &= \frac{2m_W^2}{v} \left(1 + \frac{f_\phi}{\Lambda^2} \frac{v^2}{2} \right) + \sum_i c_i^{(1)} \frac{f_i^{(8)}}{\Lambda^4} v^2 q^2 + \cdots \\ a_2 &= c^{(2)} \frac{f_{WW}}{\Lambda^2} v + \sum_i c_i^{(2)} \frac{f_i^{(8)}}{\Lambda^4} v q^2 + \cdots \\ a_3 &= c^{(3)} \frac{\tilde{f}_{WW}}{\Lambda^2} v + \sum_i c_i^{(3)} \frac{\tilde{f}_i^{(8)}}{\Lambda^4} v q^2 + \cdots \end{aligned}$$

Describe same physics (for a particular vertex) by taking some minimal set of effective Lagrangian coefficients f_i as form factors

Implementation in VBFNLO

Start from effective Lagrangians (set PARAMETR1=.true. in anom_HVV.dat)

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively, (set PARAMETR3=.true. in anom_HVV.dat)

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

see VBFNLO manual for details on how to set the anomalous coupling choices

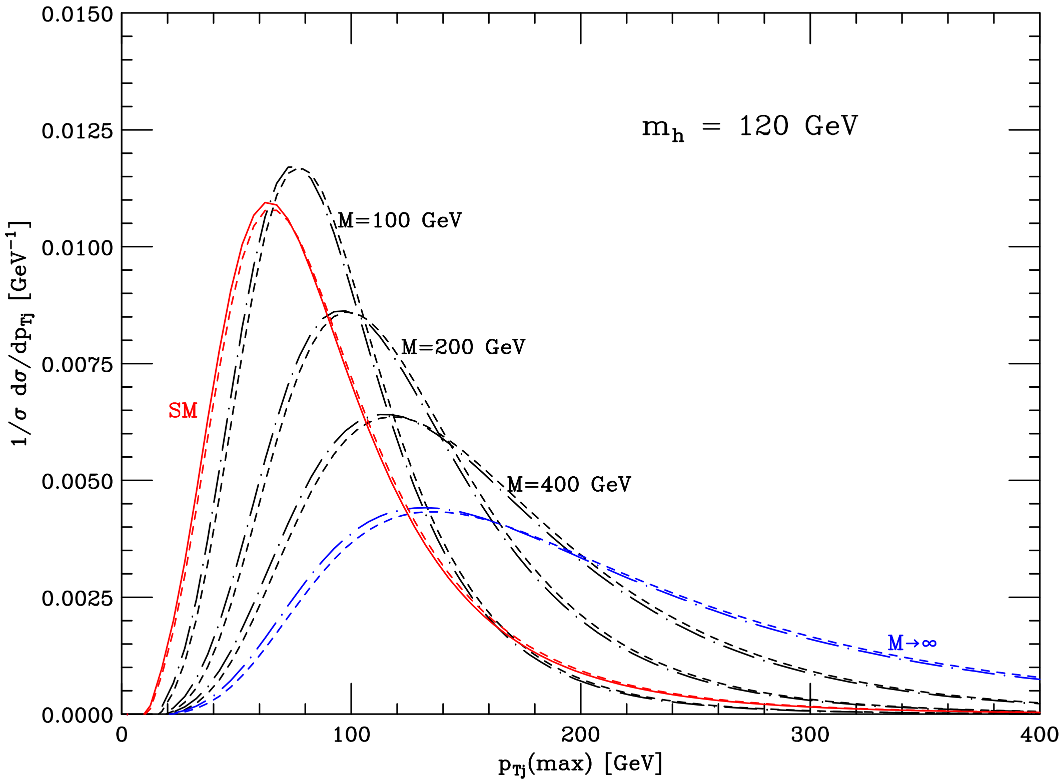
Remember to choose form factors in anom_HVV.dat

$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad \text{or} \qquad F_2 = -2\, M^2\, C_0\Big(q_1^2, q_2^2, (q_1 + q_2)^2, M^2\Big)$$

Jet transverse momentum

Form factors affect momentum transfer and thus jet transverse momenta (Here: a_2 only)

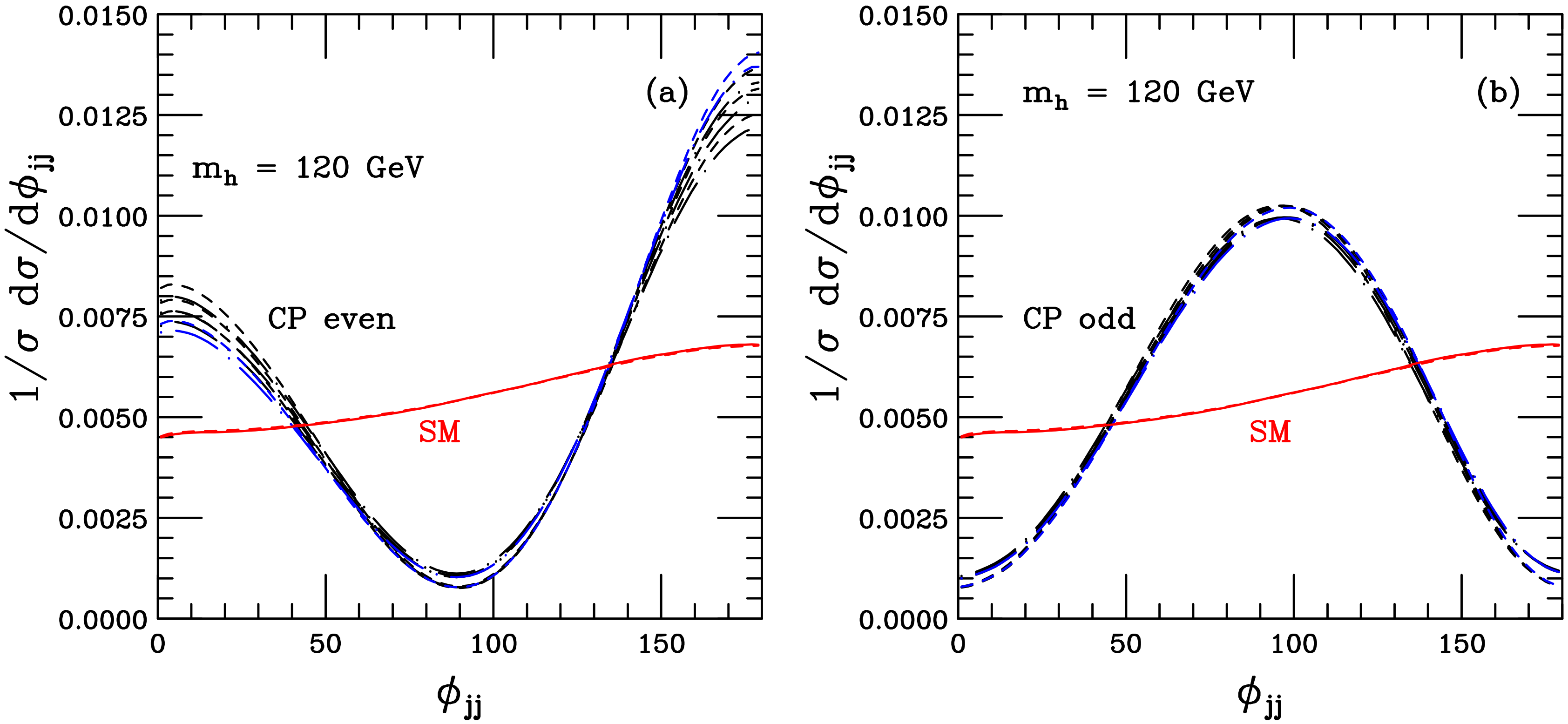
Figy, DZ hep-ph/0403297



- Change in tagging jet p_T distributions is sensitive indicator of anomalous couplings
- Can choose form-factor such as to approximate SM p_T distributions of the two tagging jets

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.

Same physics in decay plane correlations for $h \to ZZ^* \to 4$ leptons

Size estimates for a_2 terms

a_2 for the four HVV combinations can be derived from effective Lagrangian

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^{+}_{\mu\nu} W^{\mu\nu}_{-} + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu}$$

- SU(2) multiplets in triangle graphs producing these effective couplings tend to produce all four of same order of magnitude
- However
  - $H \to ZZ \to 4\ell$ and $H \to WW \to \ell^+\ell^-\nu\bar{\nu}$ partial widths are strongly suppressed by being off-shell and by small leptonic branching ratios
  - No such suppressions for $H \to \gamma\gamma$

  $\Longrightarrow$ Need $g_{5e}^{HZZ} \approx g_{5e}^{HWW} \approx 1000\, g_{5e}^{H\gamma\gamma}$ in absence of SM a_1 term
- $HZ\gamma$ coupling must also be suppressed (would see on-shell $H \to Z\gamma \to \ell^+\ell^-\gamma$ otherwise)

$\Longrightarrow$ Substantial fine tuning needed

$\Longrightarrow$ Loop induced HWW and HZZ couplings, i.e. a_2 or a_3 couplings as primary origin of observed $H \to WW$ and $H \to ZZ$ decays can be ruled out

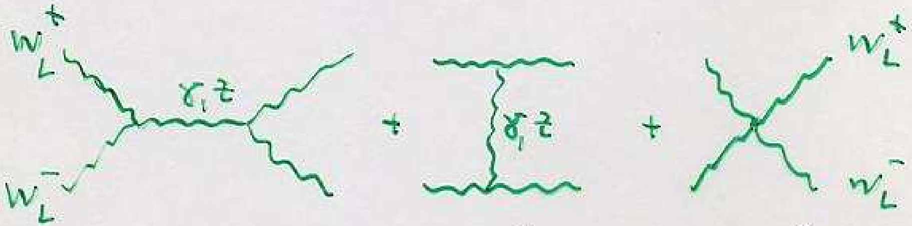
WW scattering and unitarity

Consider longitudinal W's

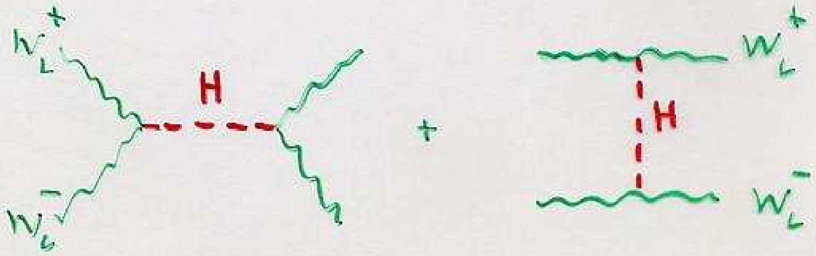
$$W_L^+ W_L^- \to W_L^+ W_L^-$$

Polarisation vector

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



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



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

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

Vector boson scattering

The $m_h = 125$ GeV Higgs will unitarize $VV\to VV$ scattering provided it has SM hVV couplings

$\Longrightarrow$ Check this by either

- precise measurements of the hVV couplings at the light Higgs resonance
- measurement of $VV\to VV$ differential cross sections at high p_T and invariant mass

Full $qq\to qqVV$ with VV leptonic and semileptonic decay is implemented in VBFNLO with NLO QCD corrections and large set of dimension 6 and 8 terms in the effective Lagrangian

Going beyond dimension 6

Reason for dimension 8 operators like

$$\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]
\end{aligned}$$

- Dimension 6 operators only do not allow to parameterize $VVVV$ vertex with arbitrary helicities of the four gauge bosons

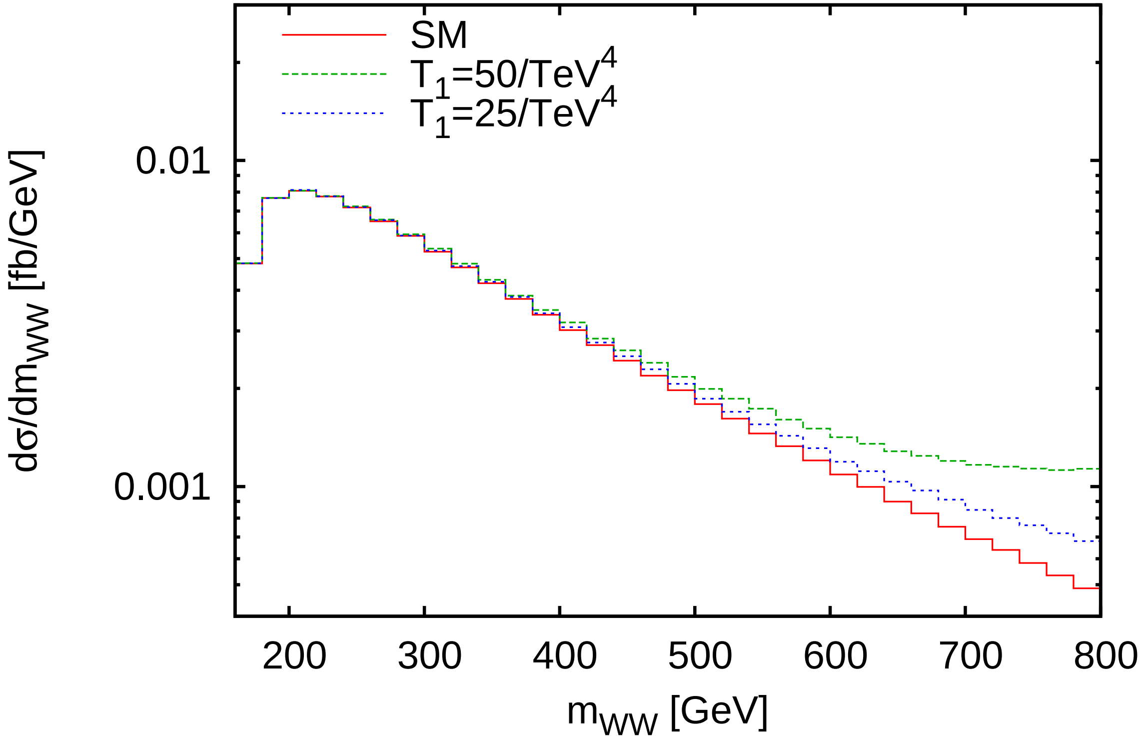
For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \to V_L V_L$ scattering

- New physics may appear at 1-loop level for dimension 6 operators but at tree level for some dimension 8 operators

$VV \to W^+W^-$ with dimension 8 operators

Effect of $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$

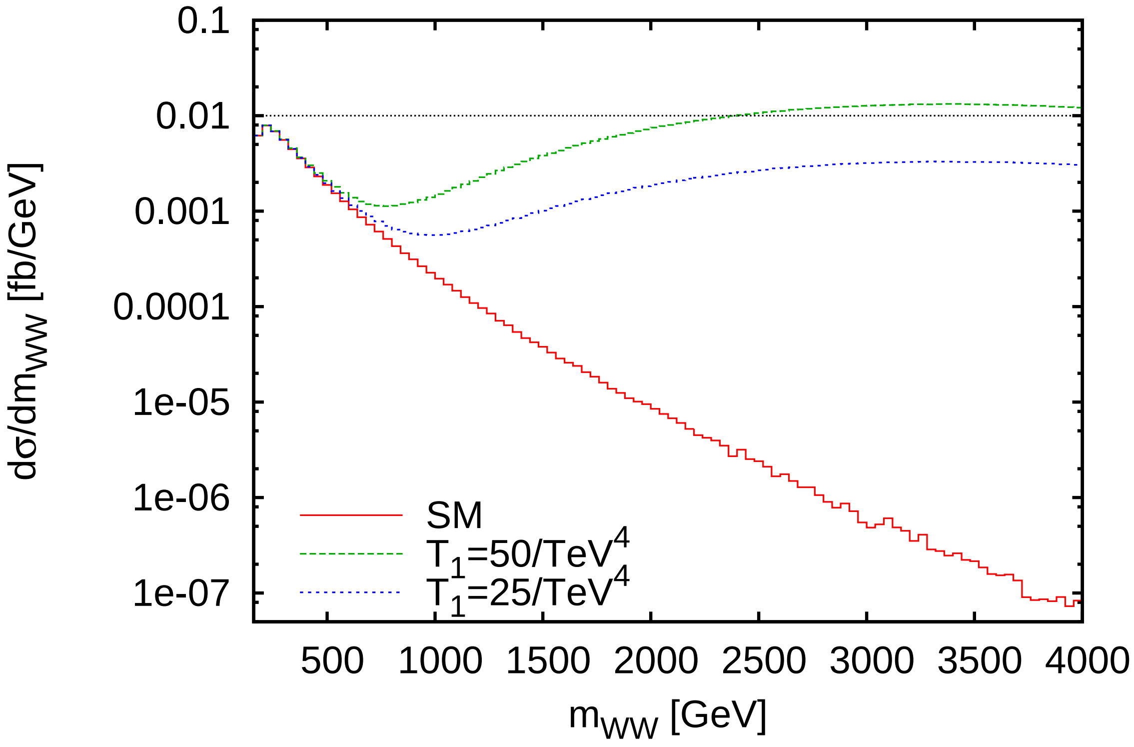
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^-jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Small increase in cross section at high *WW* invariant mass??

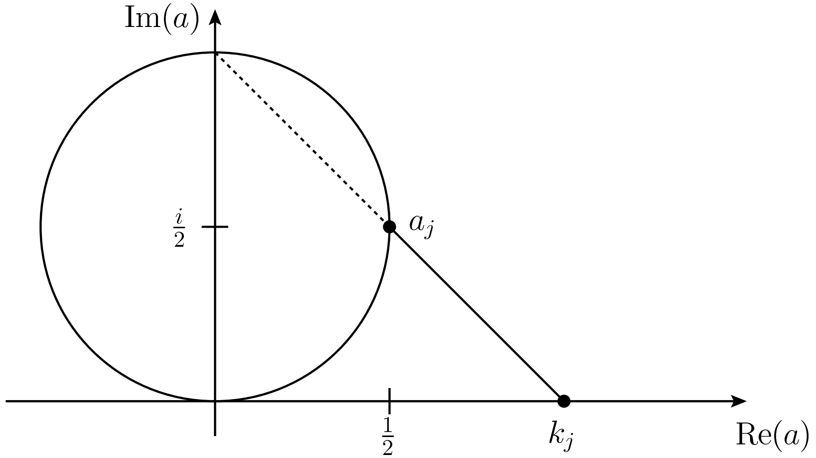
$VV \to W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure

K matrix unitarization

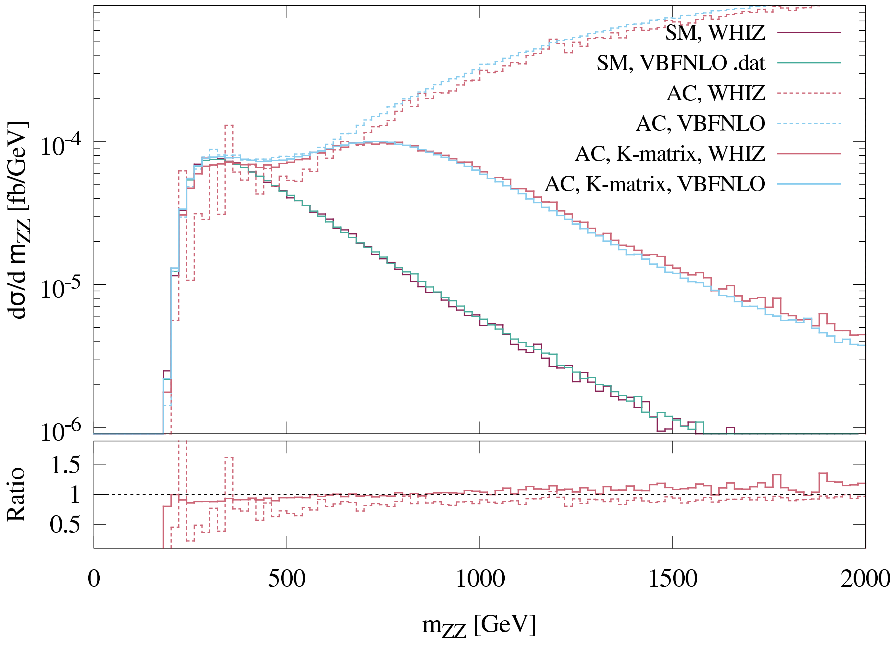


Project amplitude k_j, which exceeds (tree-level) unitarity, back onto Argand circle
→ K matrix unitarized amplitude a_j

[VBFNLO implementation: Löschner, Perez;

following: Alboteanu, Kilian, Reuter]

Comparison with Whizard, which has this method already implemented: [Kilian, Ohl, Reuter, Sekulla, et al.]



Example: VBF-ZZ ($e^+e^-\mu^+\mu^-$)

good agreement between both codes for longitudinal ops. at LO
→ can now generate distributions also at NLO via VBFNLO

Extension to mixed and transverse operators not straight-forward
→ work ongoing

Phenomenology: Size of NLO corrections to VBS

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

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

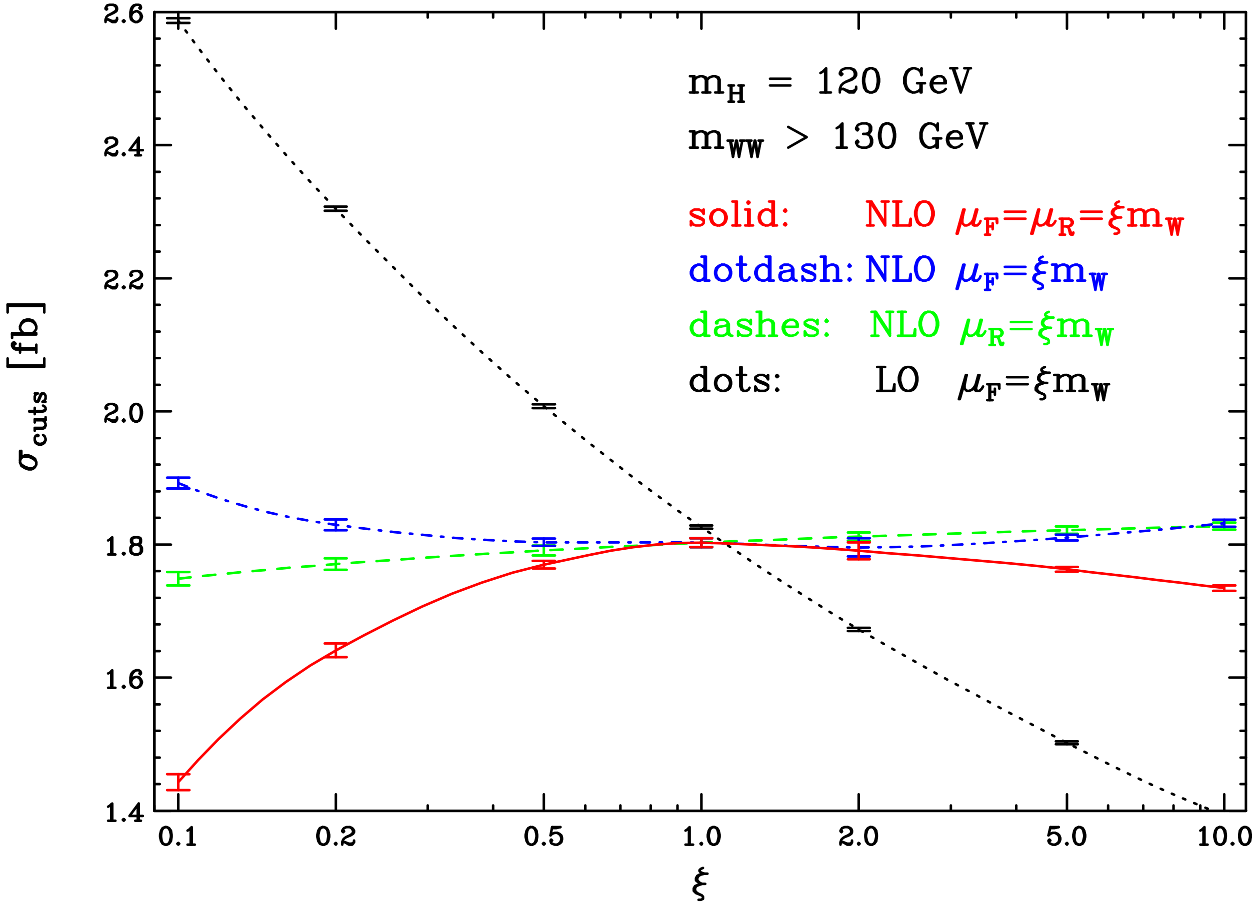
For scale dependence studies we have considered

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

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

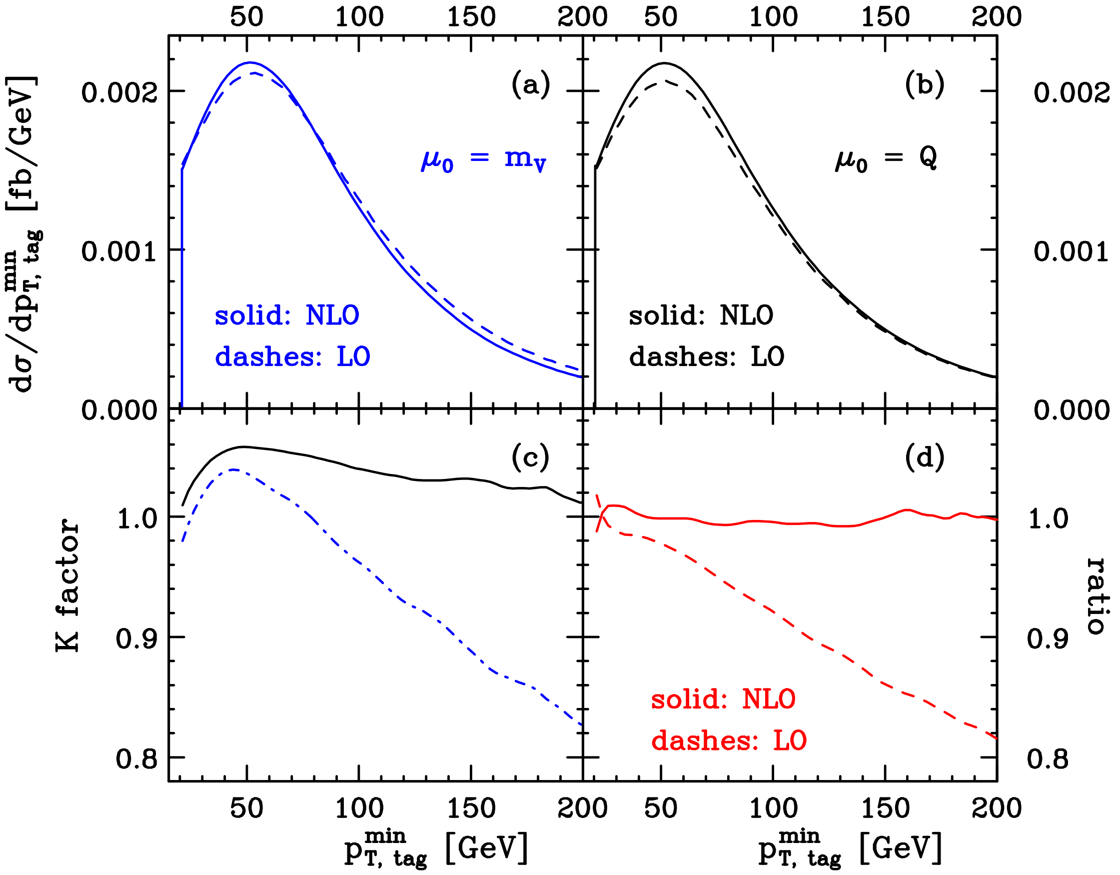
Stabilization of scale dependence at NLO

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

Conclusions

- The Higgs mechanism of the SM provides for a simple and efficient mechanism for mass generations for weak bosons and fermions.
- LHC has observed a boson, H, at 125 GeV whose couplings are compatible with the SM Higgs boson.
- Improved measurement of Higgs coupling strengths will be continuing task for the coming years.
- At the same time the search for additional Higgs bosons from extended Higgs sectors will continue.
- Many other interesting studies and searches at the LHC: SUSY, VBS, other BSM physics...
- Exciting times ahead of us.