NLO, Higgs and other Theory Issues: Workshop Closing Talk

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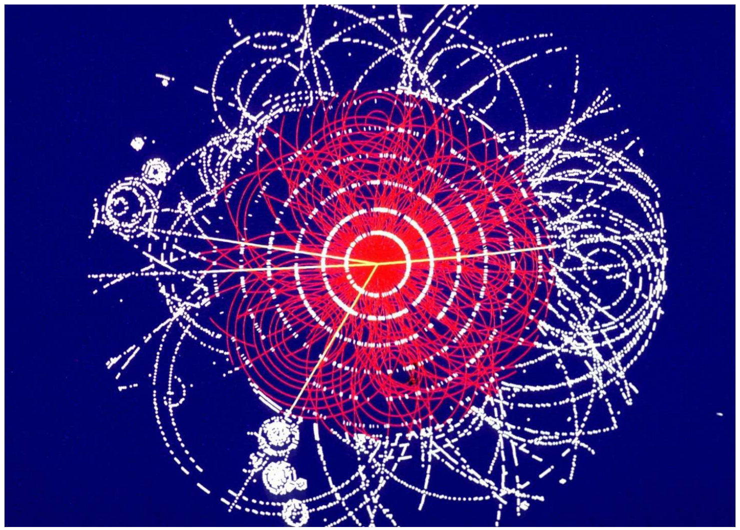
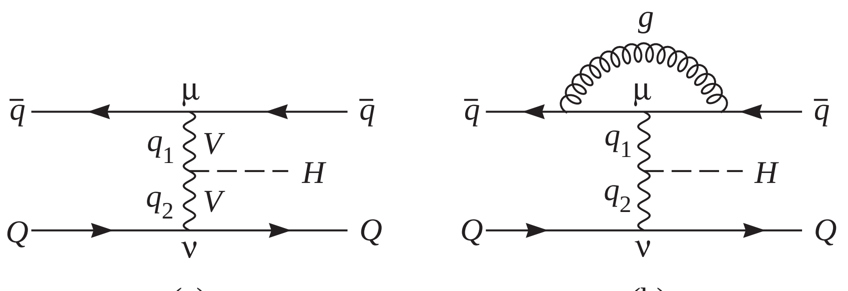
Theory Experiment Interplay at the LHC, April 8–9, 2010, RHUL

- Higgs + 2 Jets
- NLO QCD
- VBFNLO
- Conclusions



Tensor structure of the HVV coupling

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



(a) (b)

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

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

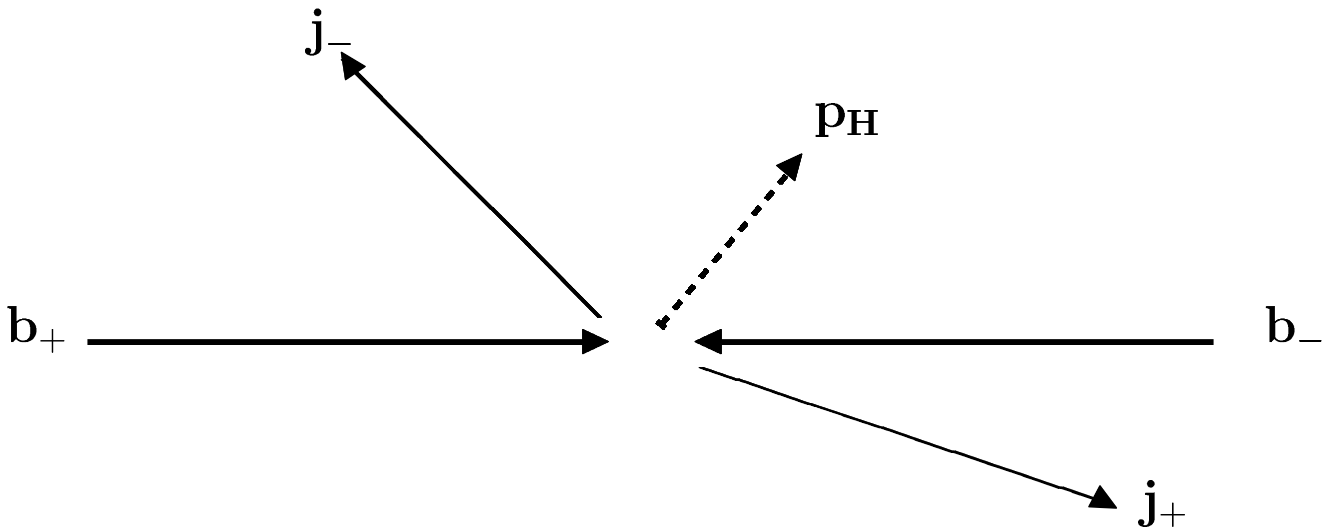
CP even $\mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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 distribution and Higgs CP properties

Kinematics of Hjj event:



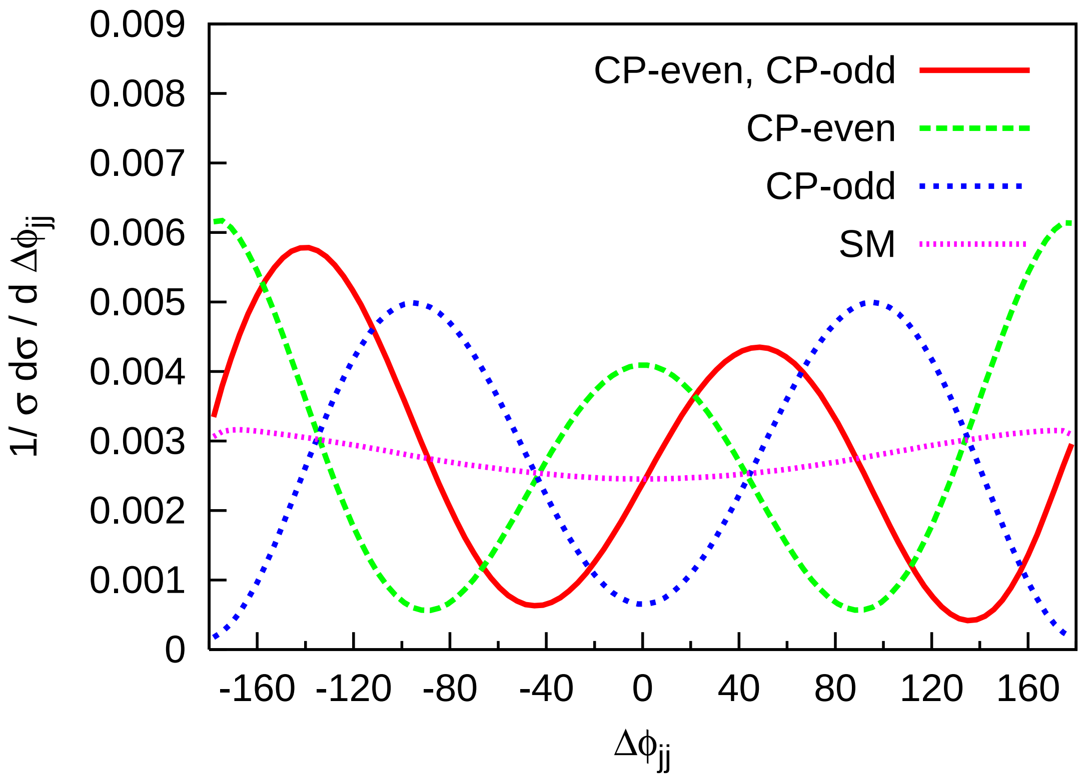
Define azimuthal angle between jet momenta j_+ and j_- via

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

- $\Delta\phi_{jj}$ 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 $\pi - \alpha$

Gluon Fusion as a signal channel

Heavy quark loop induces effective Hgg vertex:

$$\text{CP}-\text{even}: \qquad i\frac{m_Q}{v} \quad \rightarrow \quad \mathcal{L}_{eff} = \frac{\alpha_s}{12\pi v} H\, G^a_{\mu\nu} G^{\mu\nu,a}$$

$$\text{CP}-\text{odd}: \qquad -\frac{m_Q}{v}\gamma_5 \quad \rightarrow \quad \mathcal{L}_{eff} = \frac{\alpha_s}{8\pi v} A\, G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} = \frac{\alpha_s}{16\pi v} A\, G^a_{\mu\nu} G^a_{\alpha\beta} \varepsilon^{\mu\nu\alpha\beta}$$

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced Φjj signal to probe structure of Hgg vertex
- Measure size of coupling (requires NLO corrections for precision)
- Find cuts to enhance gluon fusion over VBF and other backgrounds

$\Longrightarrow$ Study by Gunnar Klämke in $m_Q \rightarrow \infty$ limit (hep-ph/0703202, PhD thesis, and paper in preparation, with Michael Rauch)

Gluon fusion signal and backgrounds

Signal channel (LO):

- $pp \to Hjj$ in gluon fusion with $H \to W^+W^- \to l^+l^-\nu\bar{\nu}$, ($l = e,\ \mu$)
- $m_H = 160\,\text{GeV}$

dominant backgrounds:

- W^+W^--production via VBF (including Higgs-channel): $pp \to W^+W^-jj$
- top-pair production: $pp \to t\bar{t},\ t\bar{t}j,\ t\bar{t}jj$ *(N. Kauer)*
- QCD induced W^+W^--production: $pp \to W^+W^-jj$

applied inclusive cuts (minimal cuts):

- 2 tagging-jets

  $$p_{Tj} > 30\,\text{GeV}, \qquad |\eta_j| < 4.5$$

- 2 identified leptons

  $$p_{Tl} > 10\,\text{GeV}, \qquad |\eta_l| < 2.5$$

- separation of jets and leptons

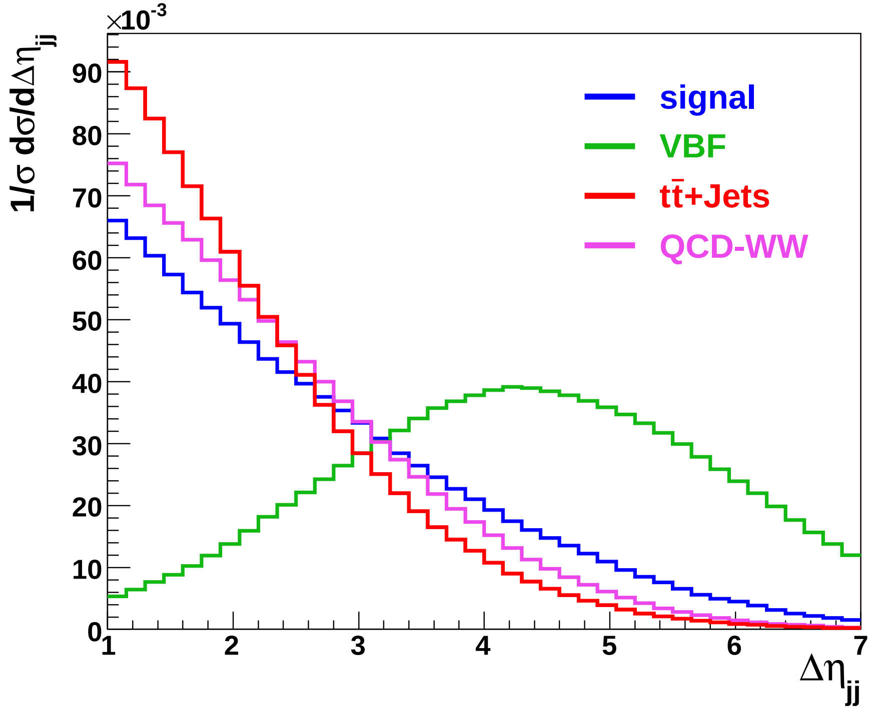
  $$\Delta\eta_{jj} > 1.0, \qquad R_{jl} > 0.7$$

process	σ [fb]
GF $pp \to H + jj$	**115.2**
VBF $pp \to W^+W^- + jj$	**75.2**
$pp \to t\bar{t}$	**6832**
$pp \to t\bar{t} + j$	**9518**
$pp \to t\bar{t} + jj$	**1676**
QCD $pp \to W^+W^- + jj$	**363**

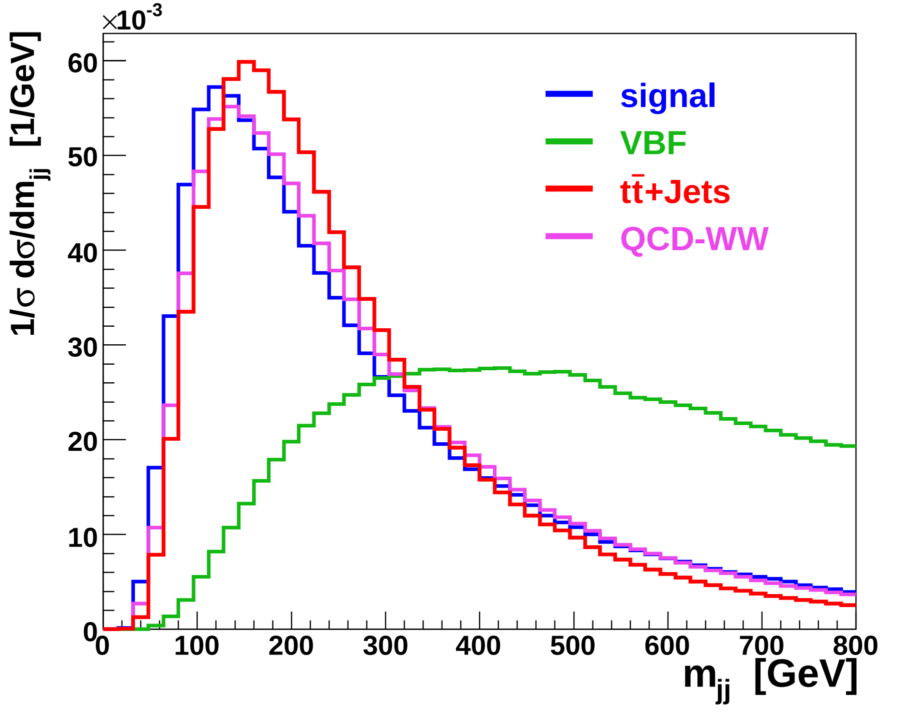
Characteristic distributions

Separation of VBF Hjj signal from QCD background is much easier than separation of gluon fusion Hjj signal

tagging jet rapidity separation



dijet invariant mass



Selection continued

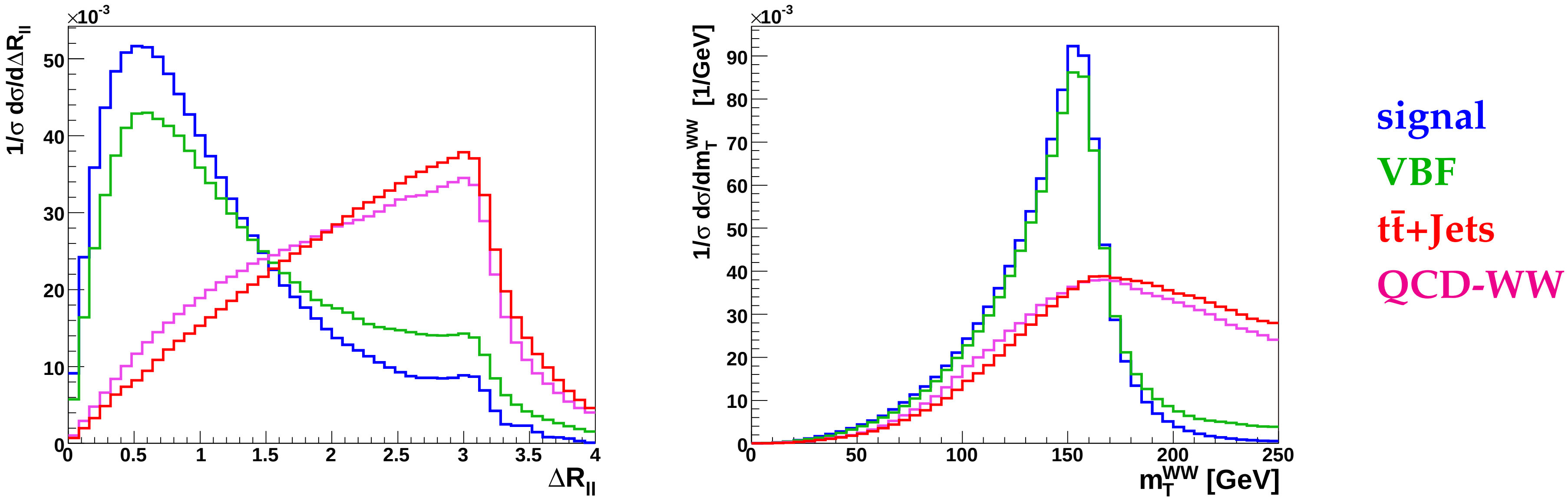
- b-tagging for reduction of top-backgrounds. *(CMS Note 06/014)*
  - (η, p_T) - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

- <u>selection cuts:</u>

  $p_{Tl} > 30\,\mathrm{GeV}$, $M_{ll} < 75\,\mathrm{GeV}$, $M_{ll} < 0.44 \cdot M_T^{WW}$, $R_{ll} < 1.1$,

  $M_T^{WW} < 170\,\mathrm{GeV}$, $\not{p}_T > 30\,\mathrm{GeV}$

$$M_T^{WW} = \sqrt{(\not{E}_T + E_{T_{ll}})^2 - (\vec{p}_{T_{ll}} + \vec{\not{p}}_T)^2}$$



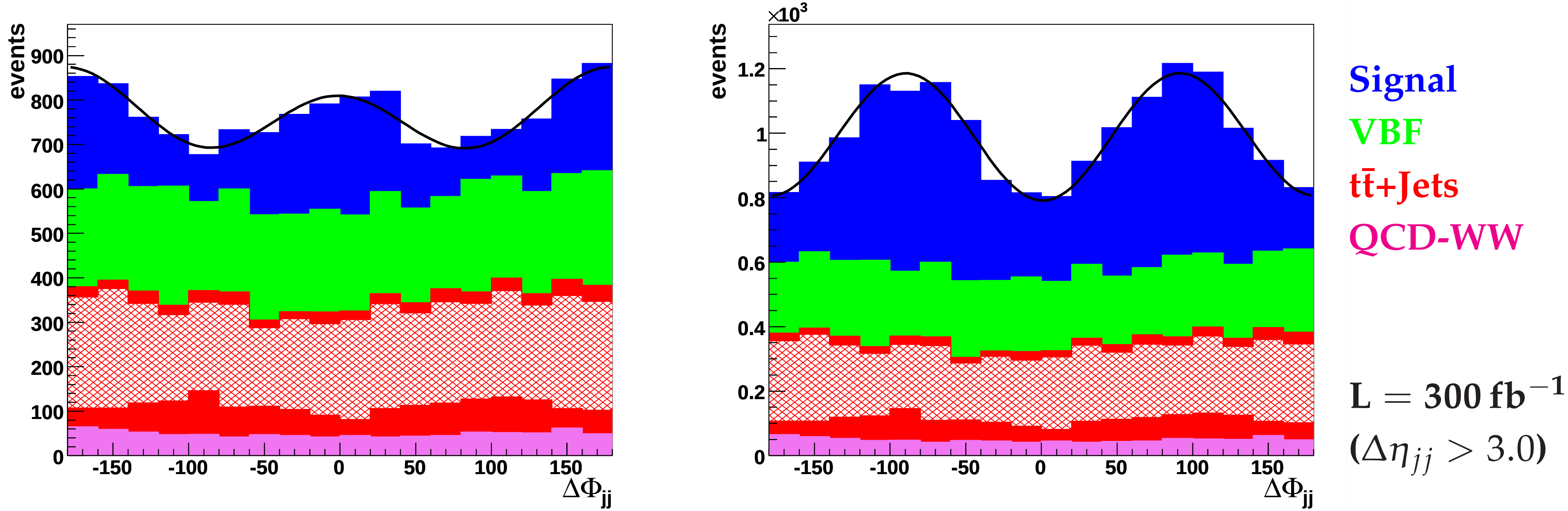
Results

process	σ [fb]	events/ 30 fb^{-1}
GF $pp \to H + jj$	**31.5**	**944**
VBF $pp \to W^+W^- + jj$	**16.5**	**495**
$pp \to t\bar{t}$	**23.3**	**699**
$pp \to t\bar{t} + j$	**51.1**	**1533**
$pp \to t\bar{t} + jj$	**11.2**	**336**
QCD $pp \to W^+W^- + jj$	**11.4**	**342**
Σ backgrounds	**113.5**	**3405**

$\Rightarrow \mathbf{S/\sqrt{B} \approx 16.2}$ for 30 fb^{-1}

$\Delta\Phi_{jj}$-Distribution in gluon fusion: WW case

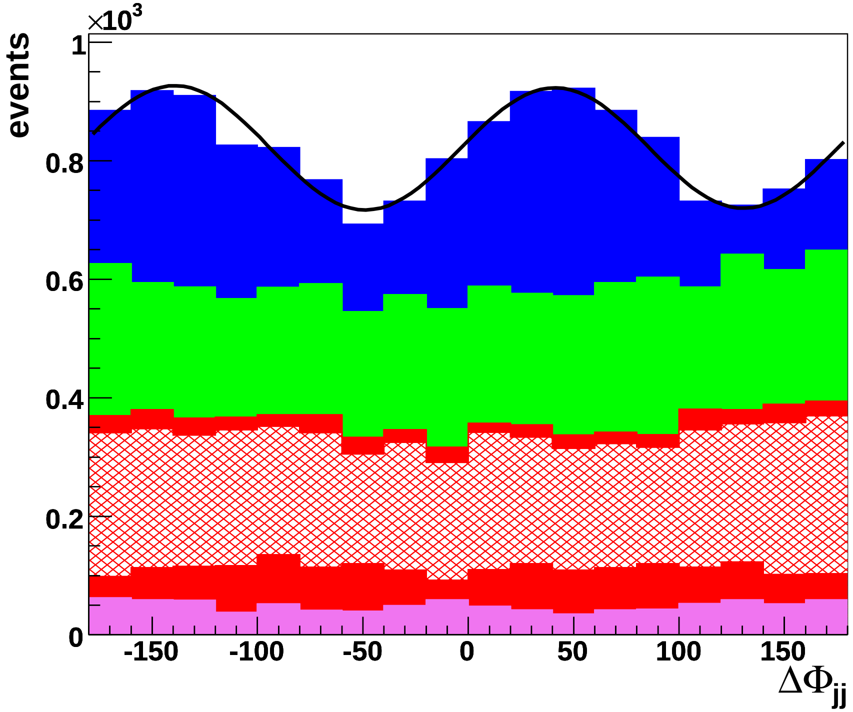
Fit to Φ_{jj}-distribution with function $f(\Delta\Phi) = N(1 + A\cos[2(\Delta\Phi - \Delta\Phi_{max})] - B\cos(\Delta\Phi))$



CP-even	CP-odd
$A = 0.100 \pm 0.039$	$A = 0.199 \pm 0.034$
$\Delta\Phi_{max} = 5.8 \pm 15.3$	$\Delta\Phi_{max} = 93.7 \pm 5.1$

fit of the background only : $A = 0.069 \pm 0.044$ and $\Delta\Phi_{max} = 64 \pm 25$
(mean values of 10 independent fits of data for $L = 30\, fb^{-1}$ each)

$\Delta\Phi_{jj}$-Distribution: CP violating case



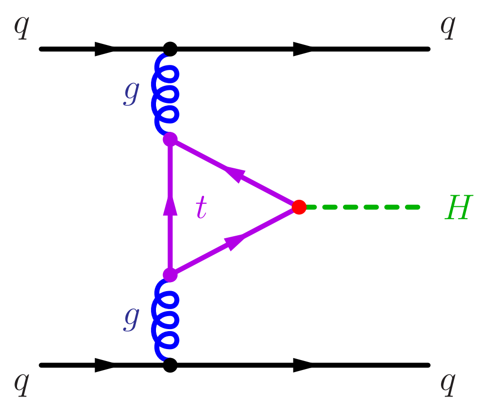
CP-mixture: equal CP-even and CP-odd contributions

$$A = 0.153 \pm 0.037$$

$$\Delta\Phi_{max} = 45.6 \pm 7.3$$

Higgs + 2 Jets in Gluon Fusion, $H \to \tau\tau \to \ell^+\ell^-\nu\bar{\nu}$

- this channel has not been studied so far
- interesting for SM Higgs ($\approx$ 120 GeV) and SUSY scenario with large $\tan\beta$ ($m_H \approx m_A \gtrsim 150$ GeV)
- x-section times branching ratio of $\approx$ 50 fb looks promising (SM)
- has potential for study of Higgs CP-properties



Studied so far (by Gunnar Klämke):

- Study of signal and SM backgrounds for $m_H = 120$ GeV case (simple cut based analysis)
- same for one MSSM scenario $m_A = 200$ GeV, $\tan\beta = 50$

  Questions:
- How many signal and background events are there after cuts (what's the statistical significance)
- What are the prospects of CP-measurements via jet-jet azimuthal angle correlation

finite detector resolution

The detector has a finite resolution. The measured jet energy and missing transverse energy have large uncertainties. Parameterization (from CMS NOTE 2006/035, CMS NOTE 2006/036):

Jets :

$$\frac{\Delta E_j}{E_j} = \left(\frac{a}{E_{Tj}} \oplus \frac{b}{\sqrt{E_{Tj}}} \oplus c \right)$$

	a	b	c
$\eta_j < 1.4$	5.6	1.25	0.033
$1.4 < \eta_j < 3$	4.8	0.89	0.043
$\eta_j > 3$	3.8	0	0.085

Leptons :

$$\frac{\Delta E_\ell}{E_\ell} = 2\%$$

Missing p_T:

$$\Delta \not{p}_x = 0.46 \cdot \sqrt{\sum E_{Tj}}$$

SM Higgs with 120 GeV mass

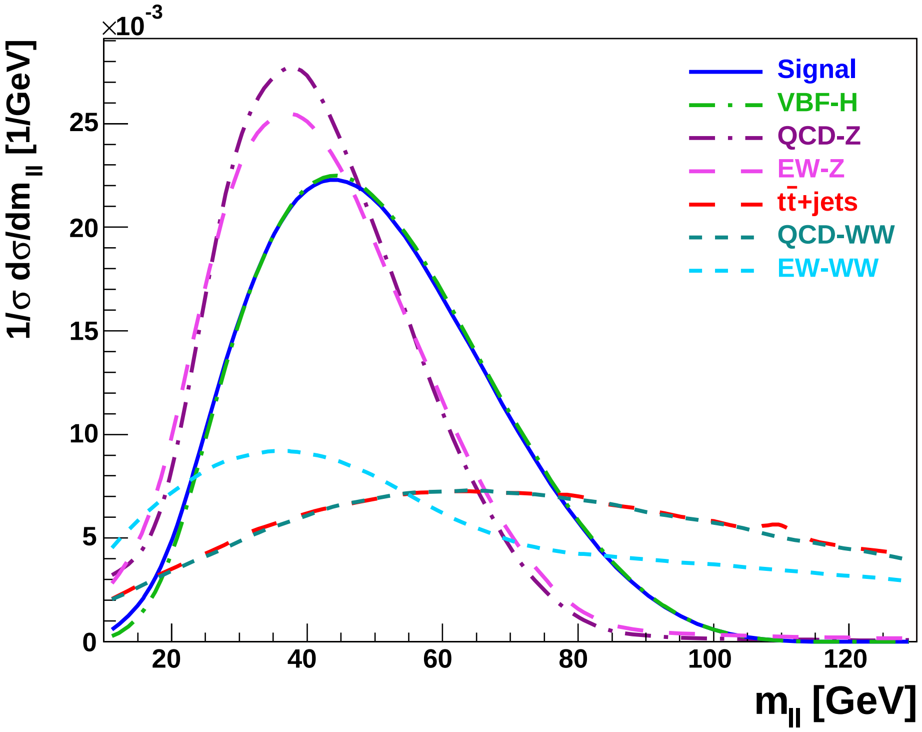
inclusive cuts

$$p_{T,jets} > 30\,\text{GeV}\,, \quad p_{T,\ell} > 10\,\text{GeV}\,, \quad |\eta_j| < 4.5\,, \quad |\eta_\ell| < 2.5\,, \quad \Delta\eta_{jj} > 1.0\,, \quad \Delta R_{j\ell} > 0.7\,,$$

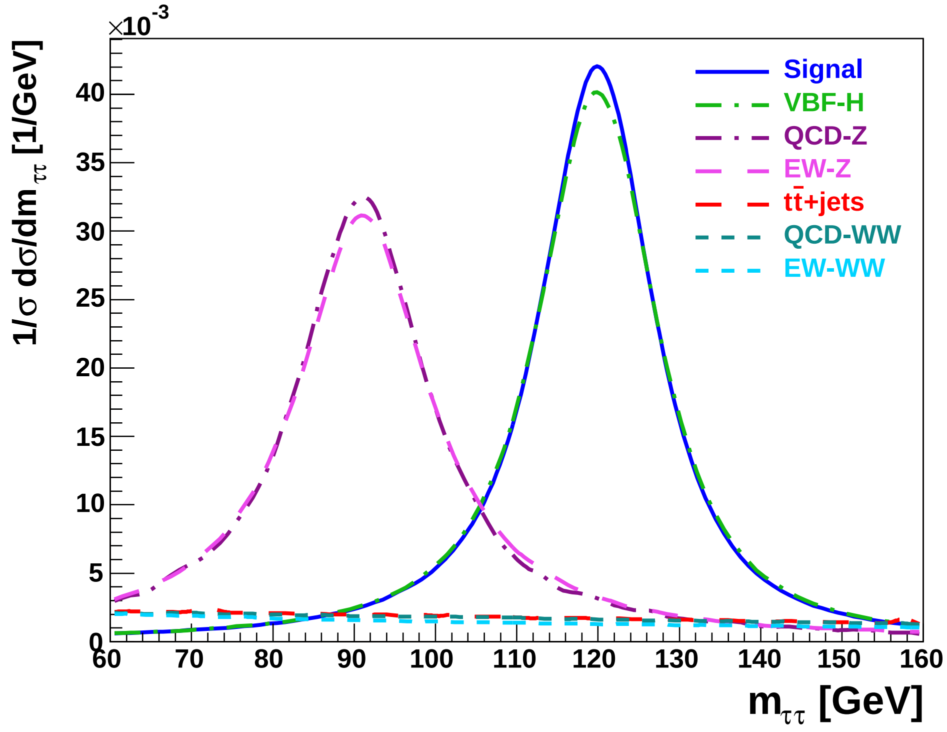
cross sections for inclusive cuts for signal and background

process	σ [fb]	events / 600 fb^{-1}
GF $pp \to H + jj \to \tau\tau jj$	**11.283**	**6770**
GF $pp \to A + jj \to \tau\tau jj$	**25.00**	**15002**
VBF $pp \to H + jj \to \tau\tau jj$	**5.527**	**3316**
QCD $pp \to Z + jj \to \tau\tau jj$	**1652.8**	**991700**
VBF $pp \to Z + jj \to \tau\tau jj$	**15.70**	**9418**
$pp \to t\bar{t}$	**6490**	**3893900**
$pp \to t\bar{t} + j$	**9268**	**5560890**
$pp \to t\bar{t} + jj$	**1629**	**977263**
QCD $pp \to W^+W^- + jj$	**334.2**	**200540**
VBF $pp \to W^+W^- + jj$	**24.78**	**14871**

Distributions



dilepton invariant mass



reconstructed $\tau\tau$ invariant mass

selection cuts

a b-veto was applied to reduce the top backgrounds.

$$R_{\ell\ell} < 2.4\,, \quad \not{p}_T > 30\,\text{GeV}\,, \quad m_{\ell\ell} < 80\,\text{GeV}\,, \quad 110\,\text{GeV} < m_{\tau\tau} < 135\,\text{GeV}\,, \quad 0 < x_i < 1$$

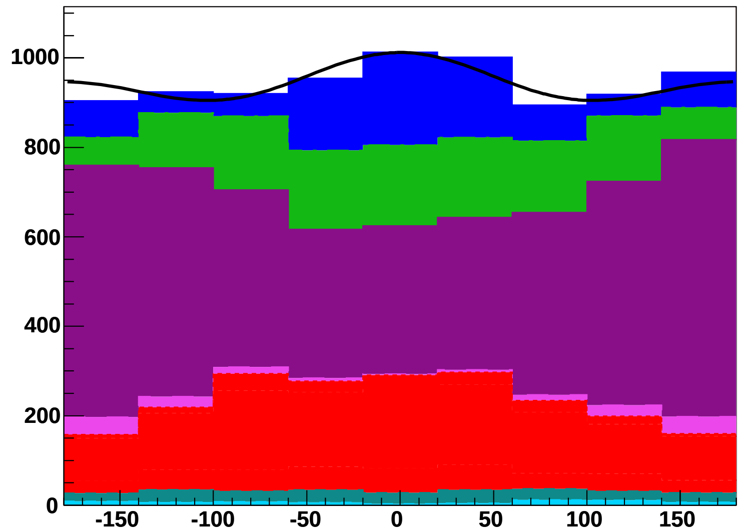
process	σ [fb]	events / 600 fb^{-1}
GF $pp \to H + jj \to \tau\tau jj$	**4.927**	**2956**
GF $pp \to A + jj \to \tau\tau jj$	**11.43**	**6860**
VBF $pp \to H + jj \to \tau\tau jj$	**2.523**	**1514**
QCD $pp \to Z + jj \to \tau\tau jj$	**27.62**	**16573**
VBF $pp \to Z + jj \to \tau\tau jj$	**0.475**	**285**
$pp \to t\bar{t}$	**3.86**	**2316**
$pp \to t\bar{t} + j$	**8.84**	**5306**
$pp \to t\bar{t} + jj$	**3.8**	**2283**
QCD $pp \to W^+W^- + jj$	**1.48**	**887**
VBF $pp \to W^+W^- + jj$	**0.147**	**88**
$\sum$ backgrounds	**48.84**	**29300**

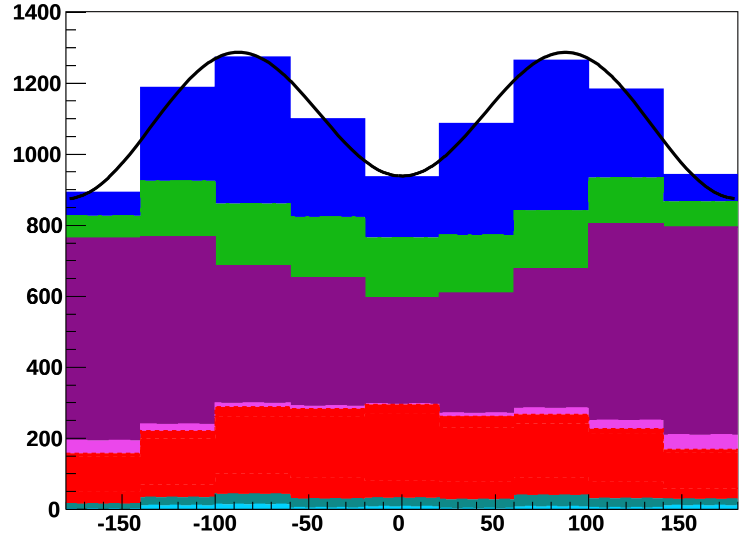
for cp-even higgs: $S/\sqrt{B} \approx 17$ (600 fb^{-1})
this corresponds to: $S/\sqrt{B} \approx 5$ (50 fb^{-1})

for cp-odd higgs: $S/\sqrt{B} \approx 40$ (600 fb^{-1})
this corresponds to: $S/\sqrt{B} \approx 5$ (10 fb^{-1})

$H \to \tau\tau$ case: $\Delta\Phi_{jj}$-distribution with backgrounds

Fit to Φ_{jj}-distribution with function $f(\Delta\Phi) = N(1 + A\cos[2(\Delta\Phi)] - B\cos(\Delta\Phi))$





Signal
VBF-H
QCD-Z
EW-Z
$t\bar{t}$+Jets

$L = 600$ fb^{-1}
($\Delta\eta_{jj} > 3.0$)

CP-even

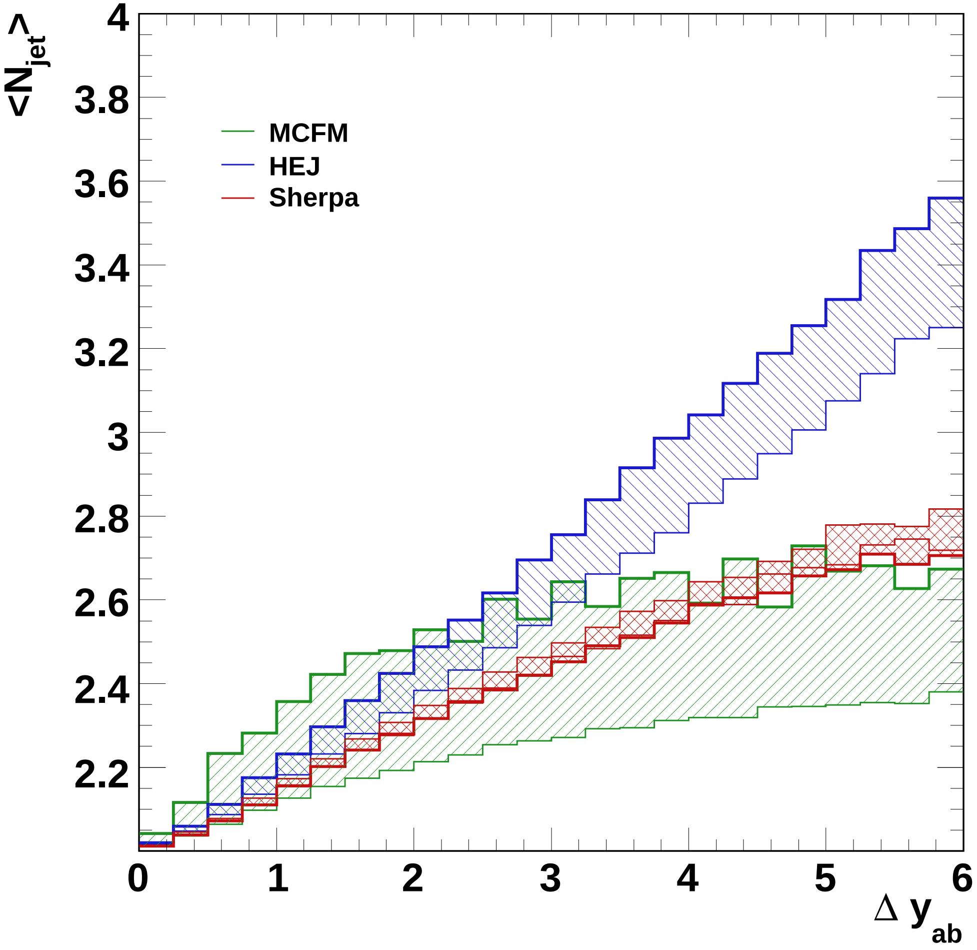
$A = 0.004 \pm 0.015$

CP-odd

$A = -0.161 \pm 0.014$

fit of the background only : -0.043 ± 0.016
$\Rightarrow$ significance for CP-even vs. CP-odd ≈ 8

Improvements for multijet situation: Jeppe Andersen

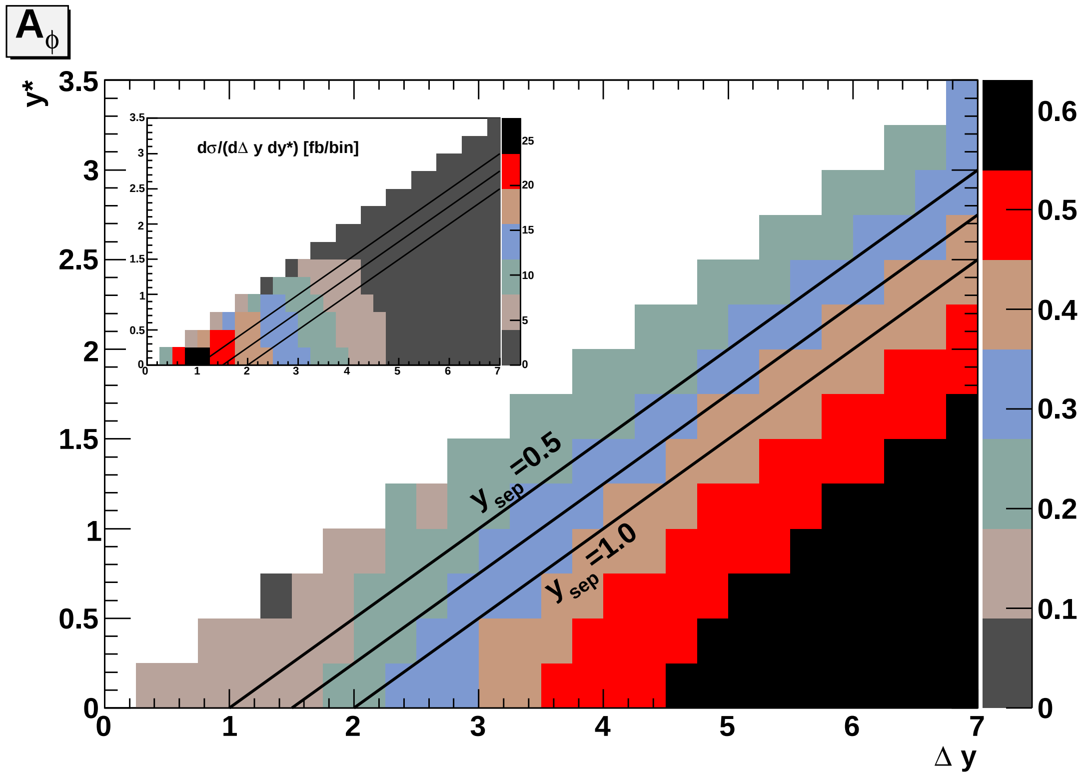


Large probability for additional jets between most forward and backward jets (of $E_T > 40$ GeV)

Define $\Delta\Phi_{jj}$ in terms of jet clusters on either side of Higgs

Quality of $\Delta\Phi_{jj}$ correlation largely preserved in multijet situation

Strong rapidity ordering



Alternative rapidity cuts on jets:

$$min\{|y_j - y_H|\} > y_{sep} \qquad \text{instead of} \qquad \Delta y = |y_{j_1} - y_{j_2}| > 3$$

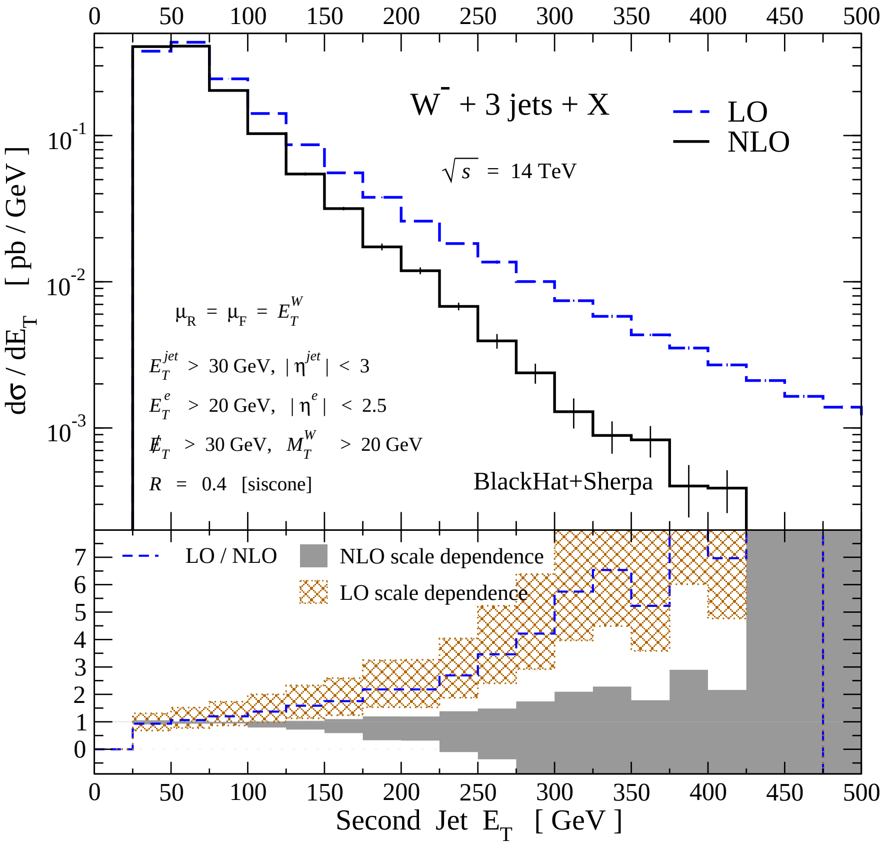
little effect on significance of azimuthal correlations once backgrounds are taken into account

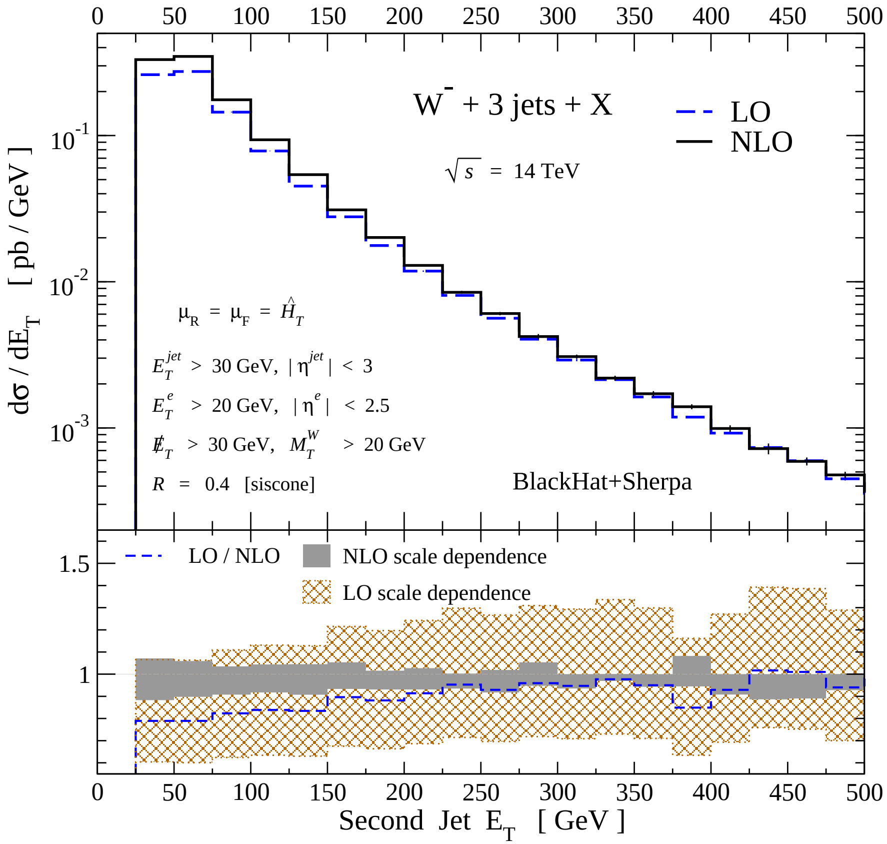
Progress on calculation tools

- Alexander Belyaev: tutorial on Calchep
  great tree level tool for studying SM processes and beyond
- Frank Krauss: progress on Sherpa
- Chris White: $t\bar{t}$ vs Wt production
- Mark Rodgers: how to calculate multileg loops with GOLEM
  impressive tool for calculating pentagons and hexagons
  applications to ZZj production and neutralino pair production
- Darren Forde: automated loop calculations with Blackhat
  Application: $W + 3$ jets and $Z + 3$ jets
- Giulia Zanderighi: $W + 3$ jets at NLO
  Phenomenological studies

Scale choice in $W + 3$ Jet events at LHC: Blackhat...

Consider E_T distribution of second jet (Darren Forde)



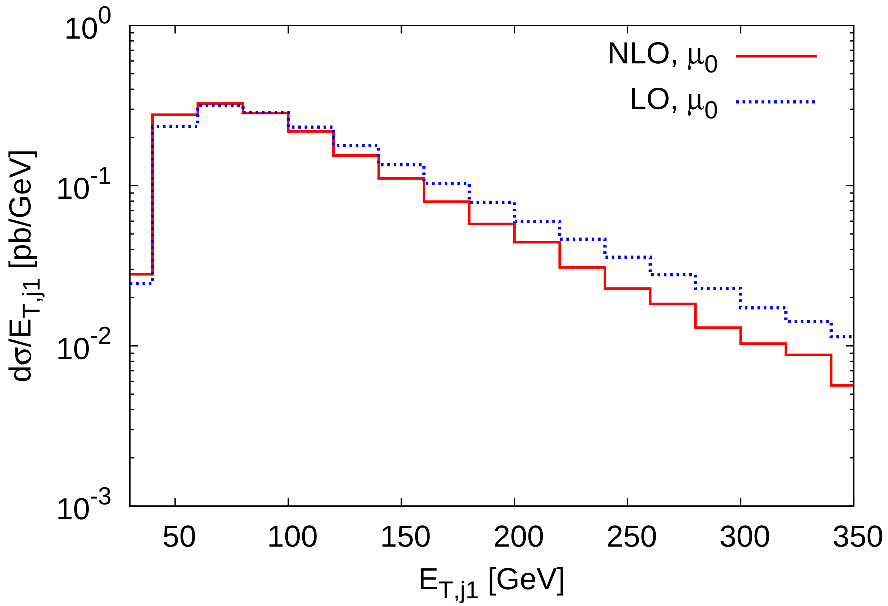


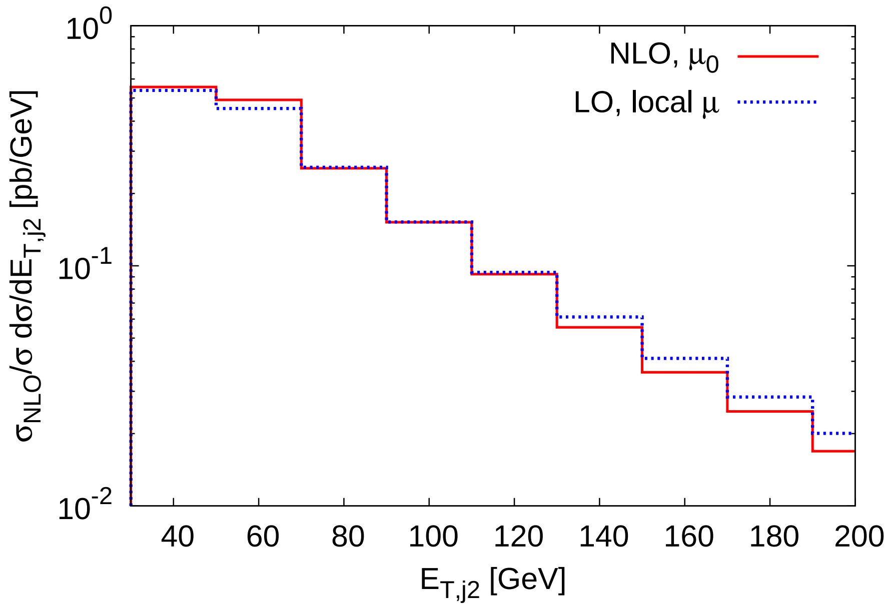
very large NLO scale dependence for $\mu = x \cdot E_{TW}$

Caution: Small scale dependence with $\mu_0 = H_T$ gives underestimate of NLO error

... and using Rocket science

Jet E_T distributions of two leading jets (Giulia Zanderighi)





Blackhat uses $\mu_0 = E_{TW}$: no sign for huge NLO corrections?

Avoid large K-factors in distributions by choosing local scale in LO results (inspired by k_T clustering)

Progress on VBFNLO

Originally: NLO QCD predictions for vector boson fusion processes at the LHC:

$qq \to qqH$ Han, Valencia, Willenbrock (1992); Figy, Oleari, DZ (2003); Campbell, Ellis, Berger (2004)

- Higgs coupling measurements

$qq \to qqZ$ and $qq \to qqW$ Oleari, DZ: hep-ph/0310156

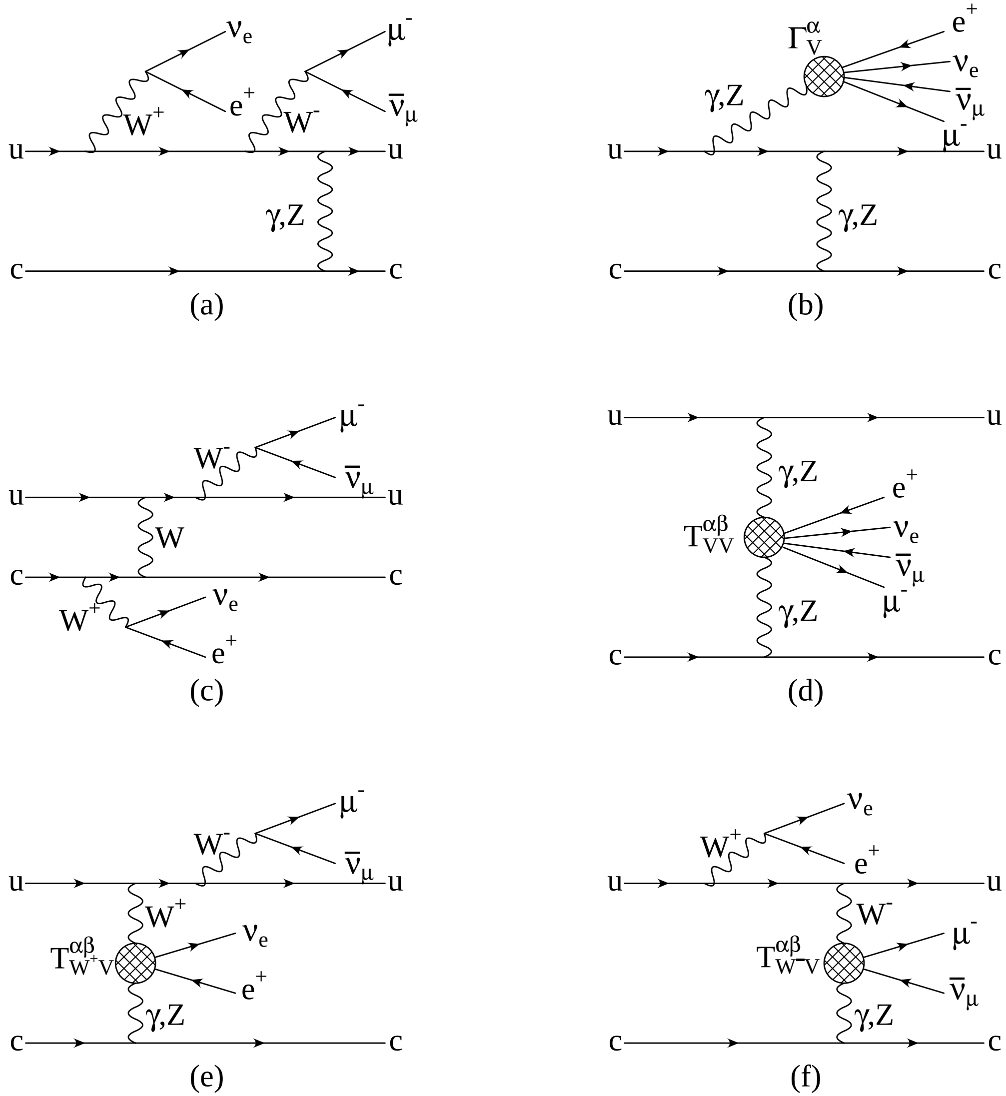
- $Z \to \tau\tau$ as background for $H \to \tau\tau$
- measure central jet veto acceptance at LHC

$qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$ Jäger, Oleari, Bozzi, DZ: hep-ph/0603177, hep-ph/0604200, hep-ph/0701105, arXiv:0907.0580

- $qqWW$ is background to $H \to WW$ in VBF
- underlying process is weak boson scattering: $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$ etc.

$qq \rightarrow qqVV$: 3 weak bosons on a quark line

- NLO corrections to $qq \rightarrow qqVV$ contain all loops with a virtual gluon attached to a quark line with one, two or three weak bosons
- Crossing and replacing one quark line by a lepton line yields $q\bar{q} \rightarrow VVV$ production processes with leptonic decays of the weak bosons
- Recycle virtual contributions from NLO corrections to VBF
- Decompose calculation into modules which can be used in different NLO calculations



Extending VBFNLO: VVV and VVj Production at NLO QCD

New processes implemented in 2008 release of VBFNLO:

- Triple weak boson production: $VVV = W^{\pm}W^{\mp}W^{\pm}$, W^+W^-Z and $W^{\pm}ZZ$ with leptonic decay of the weak bosons and full $H \to WW$ and $H \to ZZ$ contributions
  Work in collaboration with V. Hankele, S. Prestel, C. Oleari and F. Campanario

New processes already available for future releases:

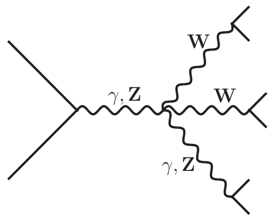
- $W^+W^-\gamma$ and $ZZ\gamma$ production with leptonic decay of weak bosons
  Work in collaboration with G. Bozzi and F. Campanario
- $W^{\pm}\gamma j$ production (with W leptonic decay and final state photon radiation)
  Work in collaboration with C.Englert, F. Campanario and M. Spannowsky

Code is available at http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb

VVV Production: Motivation

- Standard Model background for SUSY processes with multi-lepton + $\not{p}_T$ signature

- Possibility to obtain information about quartic electroweak couplings.

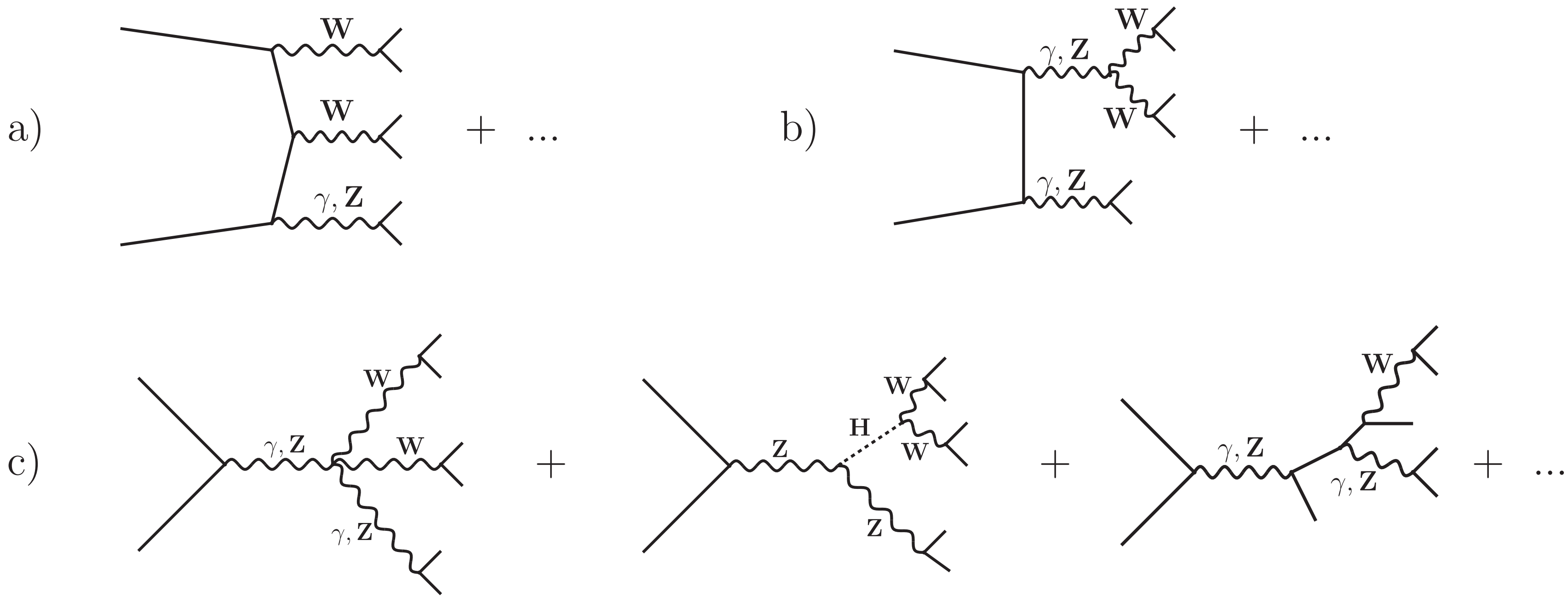


- QCD corrections to $pp \to$ VVV + X on experimentalist's wishlist:

  [The QCD, EW, and Higgs Working Group: hep-ph/0604120]

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton

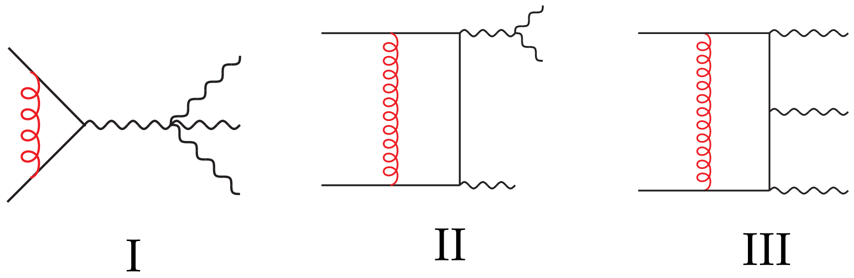
Example: Contributions to WWZ production

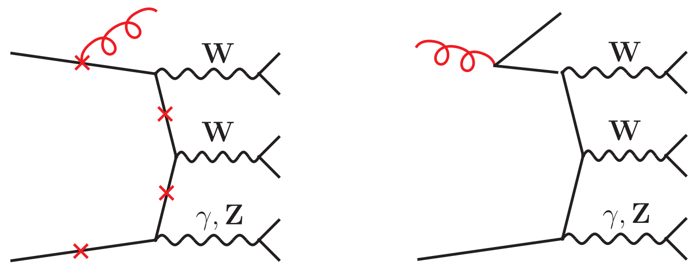


- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contribution included.
- Interference terms due to identical particles in the final state have been neglected.
- All fermion mass effects neglected. ($H\tau\tau$-coupling = 0)

1-loop matrix elements and real emission matrix elements

Three different topologies:





I Vertex correction proportional to Born matrix element.

II Maximally 4-point integrals appear.

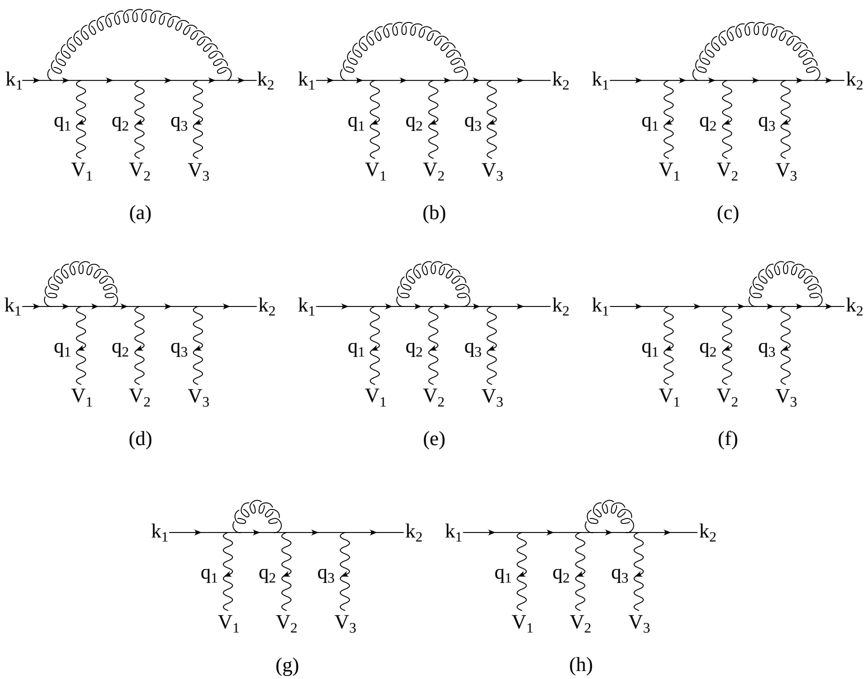
III Up to five external legs (Pentagons):

- Two independent calculations.
- Numerically stable results with Denner Dittmaier method.

- Two different classes: final state gluon and initial state gluon.
- Each of them consists of several hundred Feynman-Graphs.
- Soft and collinear singularities subtracted with Catani-Seymour presription

$qqVVV$ amplitude: pentline 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

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

- Divergent terms sum to Born sub-amplitude
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Denner-Dittmaier reduction of pentagon tensors is stable: indication of numerical problems for less than 0.2% of phase space points

Virtual corrections

Born sub-amplitude is multiplied by same factor as found for pure vertex corrections
$\Rightarrow$ when summing all Feynman graphs the divergent terms multiply the complete $\mathcal{M}_B$

Complete virtual corrections

$$\mathcal{M}_V = \mathcal{M}_B \; F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right] + \widetilde{\mathcal{M}}_V$$

where $\widetilde{\mathcal{M}}_V$ is finite, and is calculated with amplitude techniques.
The interference contribution in the cross-section calculation is then given by

$$2\,\mathrm{Re}\left[\mathcal{M}_V \mathcal{M}_B^*\right] = 2\,|\mathcal{M}_B|^2 F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right] + 2\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_V \mathcal{M}_B^*\right]$$

The divergent term, proportional to $|\mathcal{M}_B|^2$, cancels against the subtraction terms which have the same structure as for single W or Z production.

Input variables for LHC phenomenology

- **PDFs**: CTEQ6L1 at LO and CTEQ6M, $\alpha_S(m_Z) = 0.118$ at NLO.

- **Cuts and Masses**:

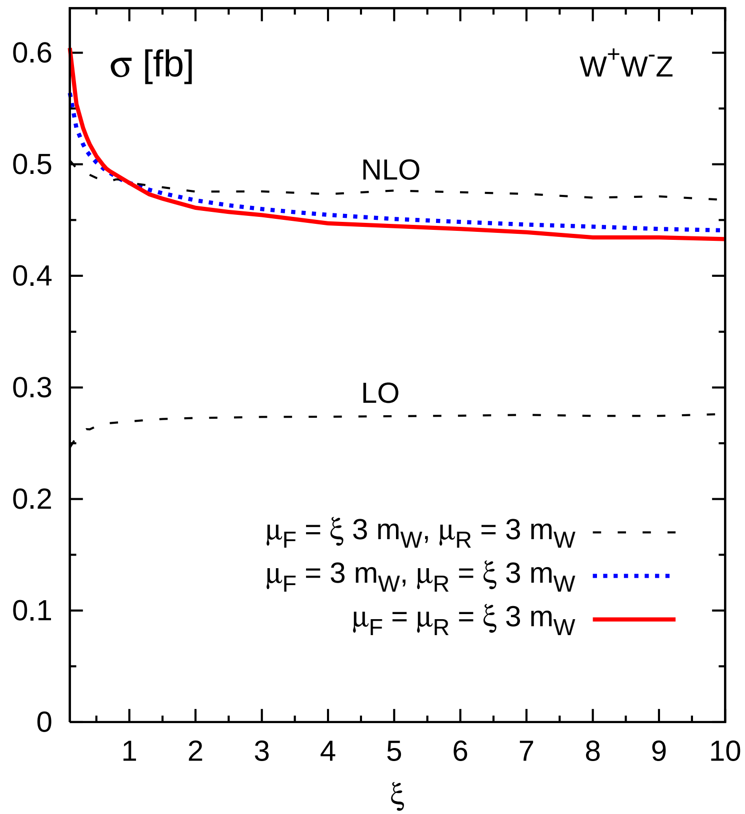
$$p_{T_\ell} > 10 \text{ GeV}, \qquad |\eta_\ell| < 2.5, \qquad m_{\ell^+\ell^-} > 15 \text{ GeV}, \qquad m_H = 120 \text{ GeV}.$$

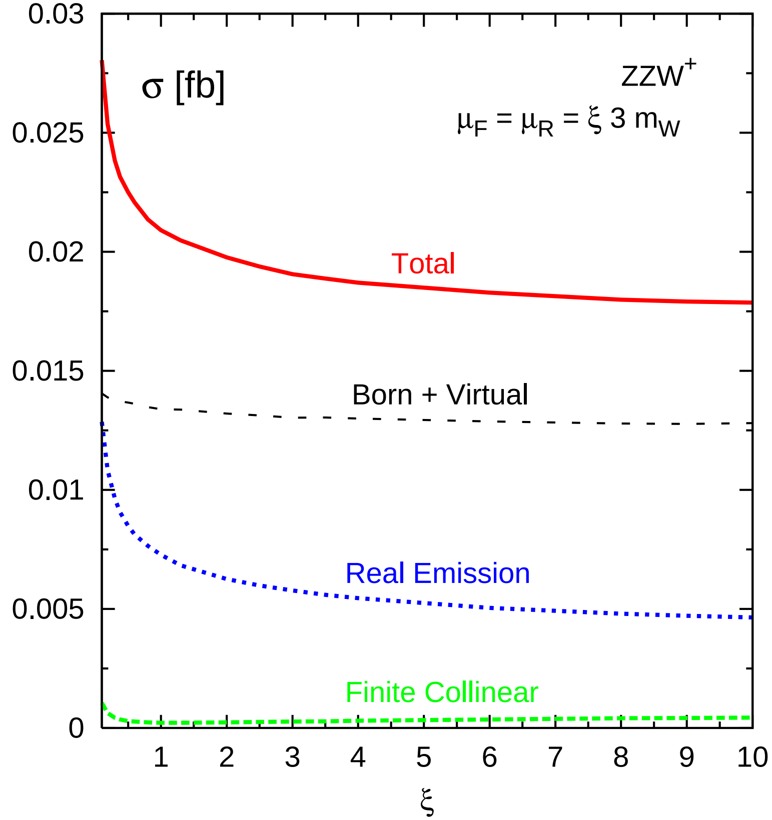
- **Renormalization- and Factorization Scale**: $\mu_F = \mu_R = 3\, m_W$.

Following results are for electrons and/or muons in the final state:

$\Longrightarrow$ Combinatorial factor of 8/4 for the $W^+W^-Z/ZZW^\pm$ production compared to three different lepton families in the final state.

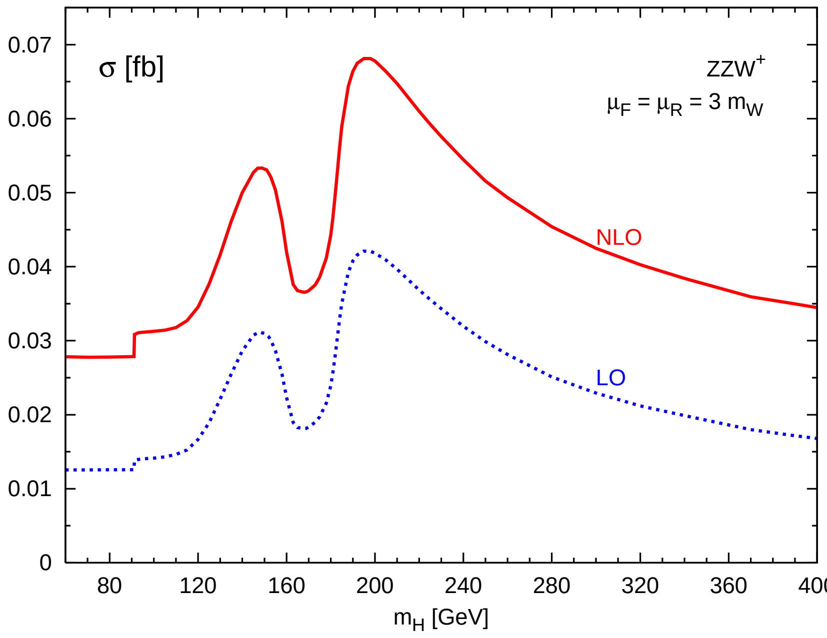
Scale Dependence

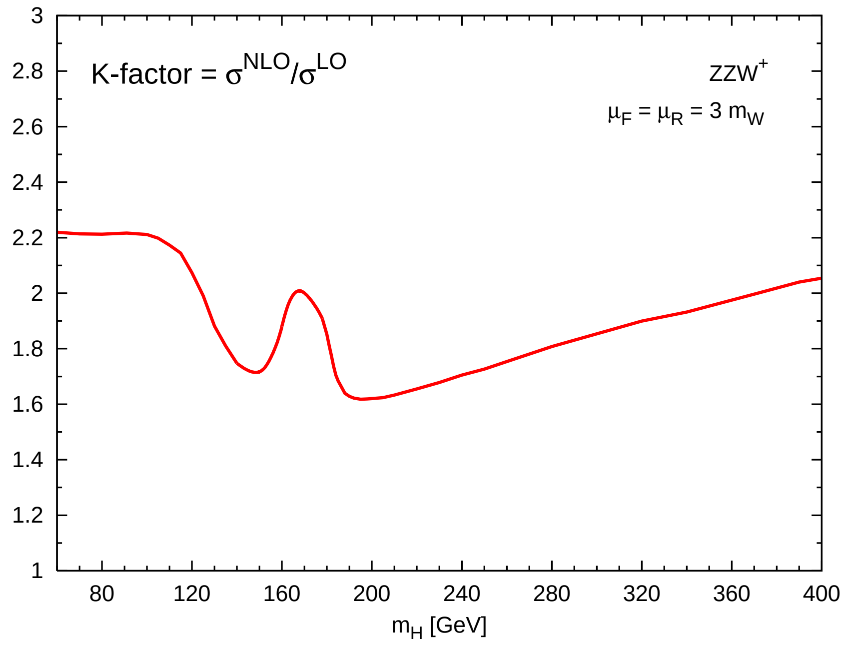


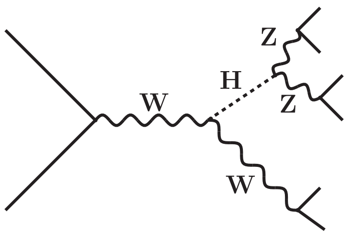


- At LO only small μ_F-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.

Higgs mass dependence

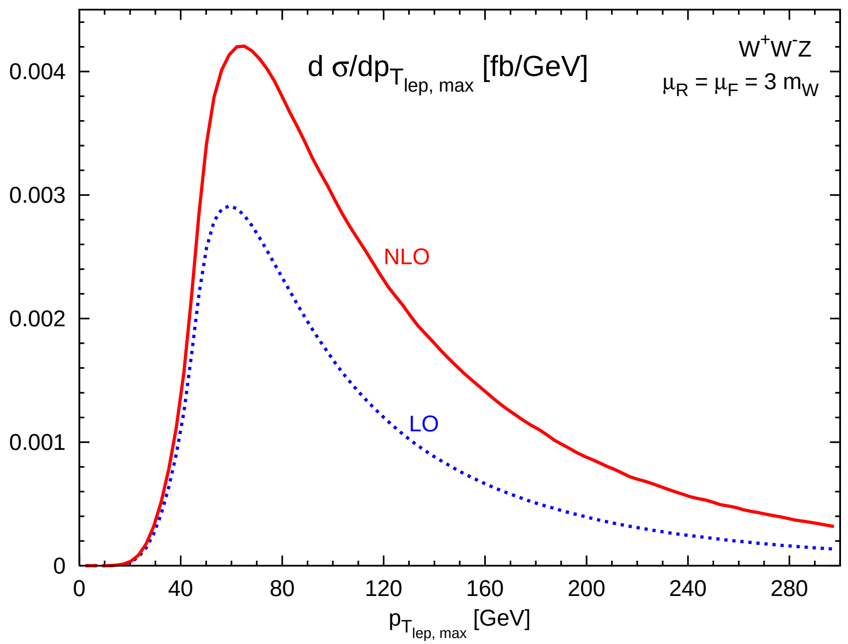


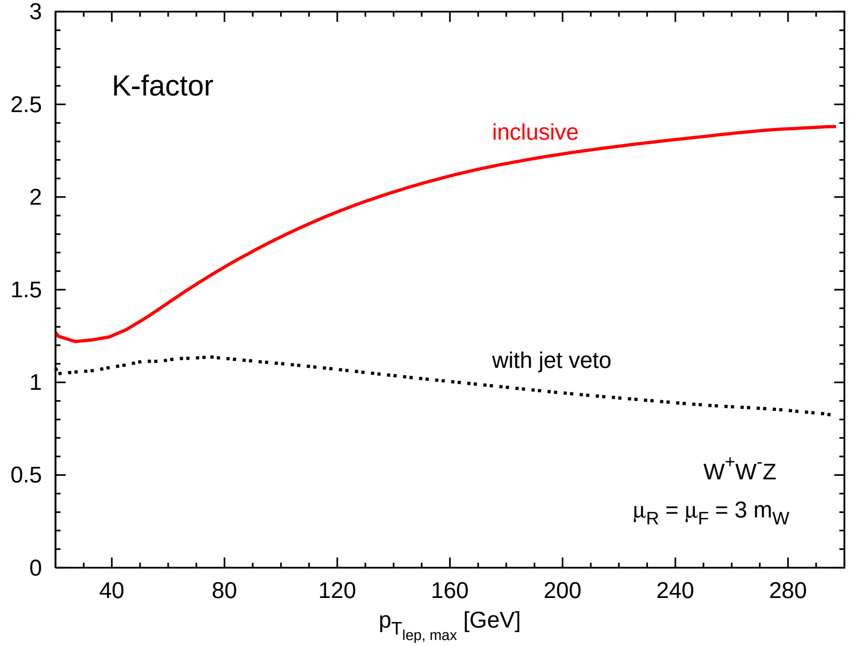




- Cross section reflects behavior of $BR(H \to ZZ)$
- K-factor is reduced by Higgs contribution.
  K-factor for $pp \to ZH$ production is about K = 1.3
  $\Longrightarrow$ Different K-factor for resonance production (see also Wt case, talk by Chris White)

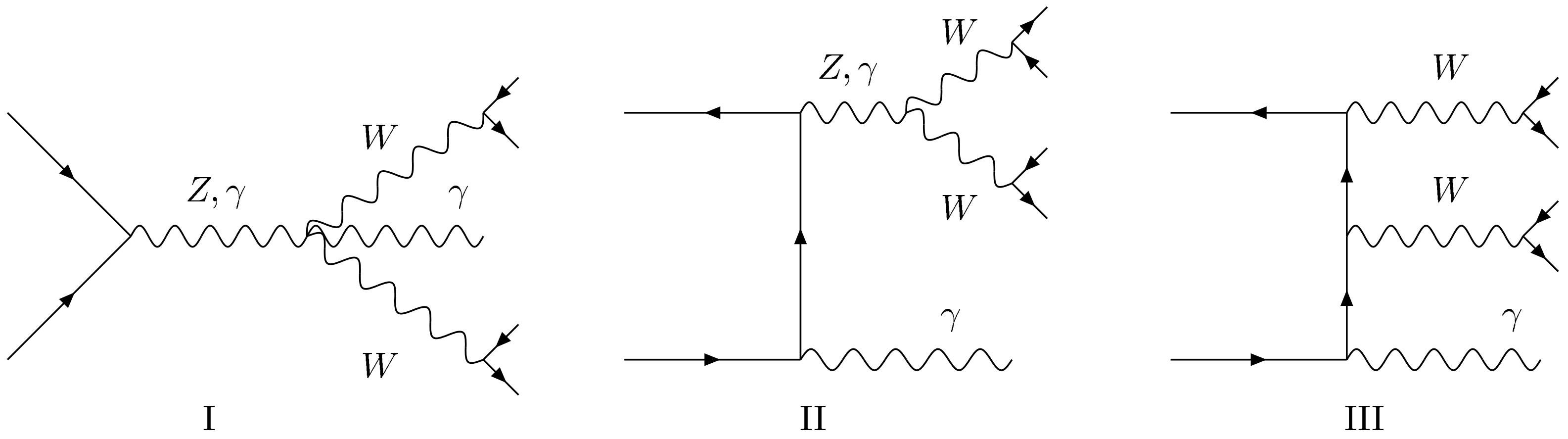
Differential cross section and K-factor for the highest-p_T-lepton





- K-factor increases with transverse momentum (p_T) by almost a factor of 2.
- Strong phase space dependence due to events with high p_T jets recoiling against the leptons.
- Veto on jets with $p_T > 50$ GeV leads to fairly flat K-factor.

Extension to $W^+W^-\gamma$ and $ZZ\gamma$ Production



New elements of calculation:

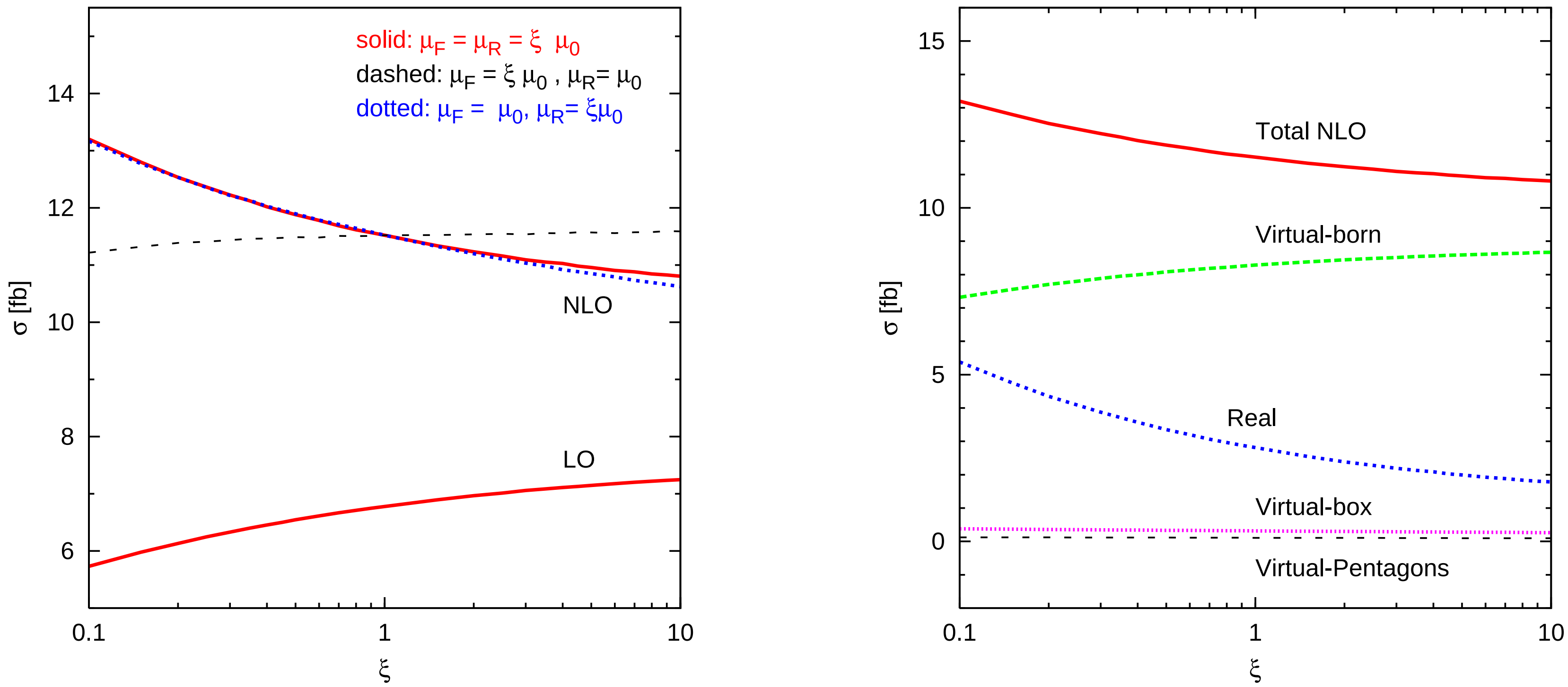
- Different infrared divergence structure of individual loop integrals but same final virtual expressions in terms of finite parts of C_{ij}, D_{ij}, and E_{ij} functions
- Photon isolation from jets for real emission contributions: use Frixione isolation

$$\Sigma_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq p_{T_\gamma} \frac{1-\cos\delta}{1-\cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0)$$

- Final state photon radiation becomes important: adapt phase space to this

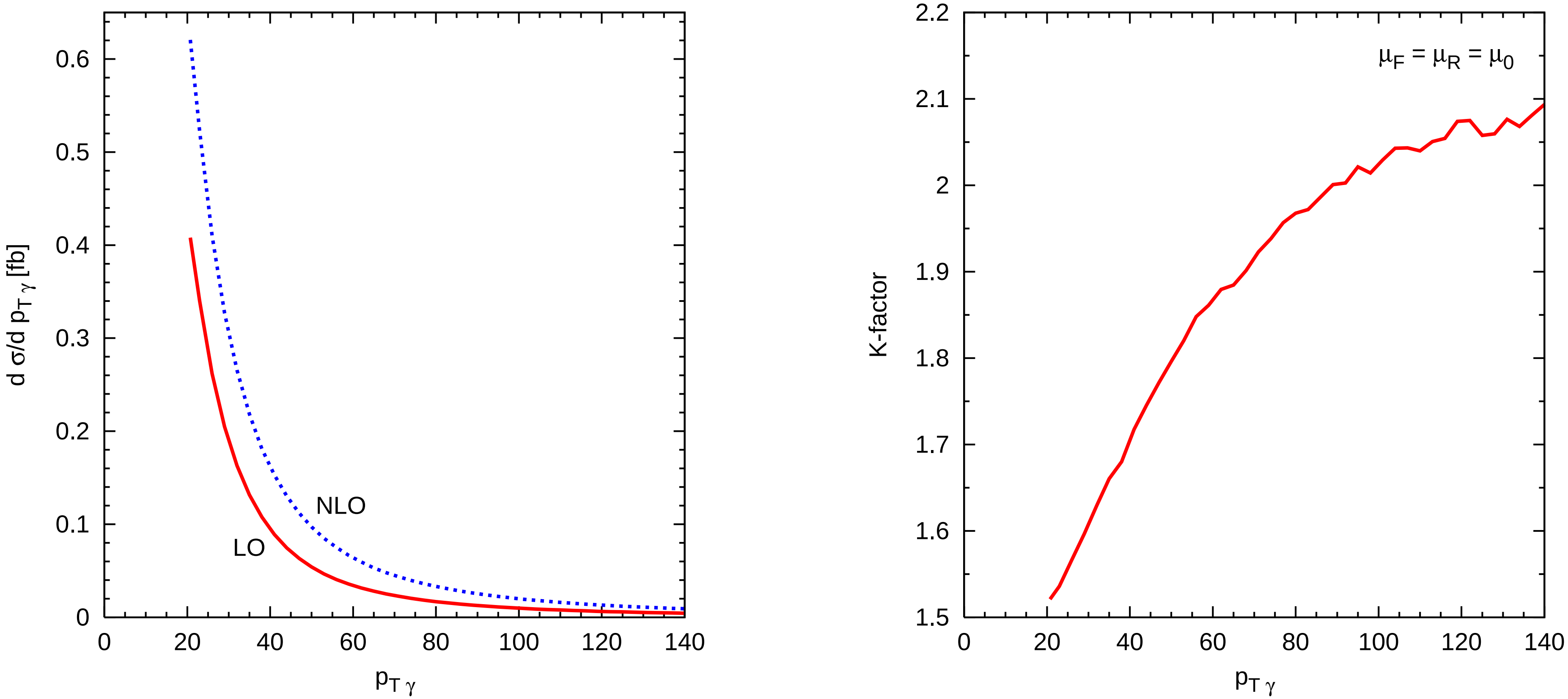
Scale dependence of integrated cross sections

Variation of μ_F, μ_R about $\mu_0 = m_{WW\gamma}$



- Behaviour similar to VVV production: LO scale variation much smaller than NLO correction
- NLO scale dependence largely due to real emission contributions $\Longrightarrow$ jet veto will reduce it
- Box and pentagon contributions ($\tilde{\mathcal{M}}_V$ terms) are quite small: 3% and $< 1\%$ of total

NLO Corrections to Distributions: p_T of photon



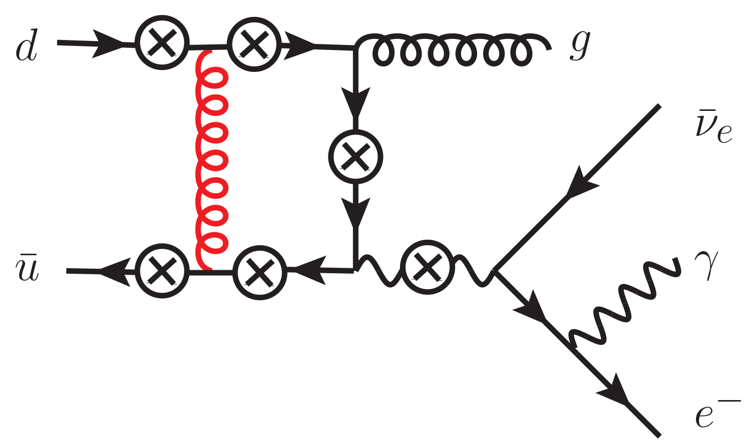
Strong phase space dependence of K-factors (depends on LO scale choice)

NLO QCD Corrections to $W\gamma j$ Production

- Provide NLO QCD corrections including leptonic W decay, e.g.

$$pp \to e^+ \nu_e \gamma j\,, \qquad pp \to e^- \bar{\nu}_e \gamma j$$

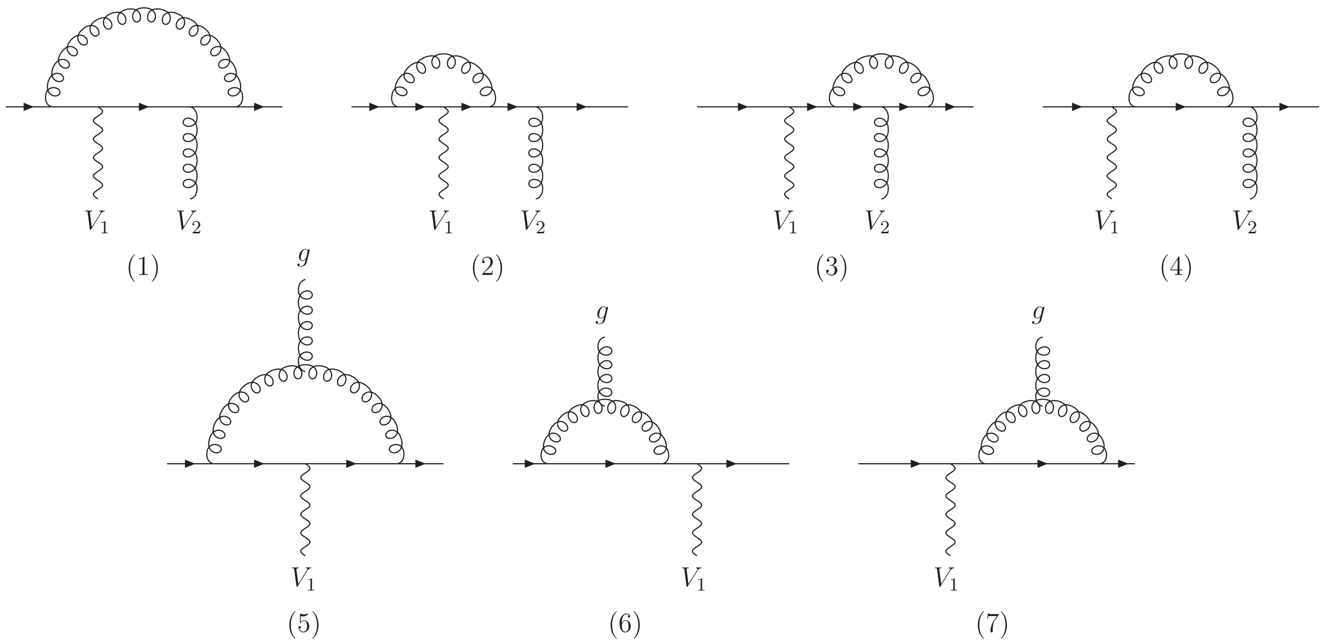
- Sizable cross section at LHC (1.2 pb) and Tevatron (15 fb) for $p_{Tj}, p_{T\gamma} > 50$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO
- Photon isolation à la Frixione probed at NLO level



- Initial and final state photon radiation. Final radiation from lepton is important
- Virtual corrections up to pentagons
- External gluon already at tree level $\Longrightarrow$ *nonabelian* boxes with three gluon vertex
- Larger number of subtraction terms

Virtual Corrections: nonabelian Contributions

Example: non-abelian extension of boxline graphs. Keep modular structure of calculation



$$\left(C_F - \frac{1}{2}C_A\right) \left(A_1(12) + A_3(12)\right)$$

$$+C_F \quad \left(A_2(12) + A_4(12)\right)$$

$$C_A \left(A_5 + A_6 + A_7\right)$$

Combine to two boxline amplitudes $M_V(12)$ and $M_V(21)$ and new nonabelian combination

$$M_V(12, boxline) = (C_F - \frac{1}{2}C_A) \sum_{i=1,4} A_i(12)$$

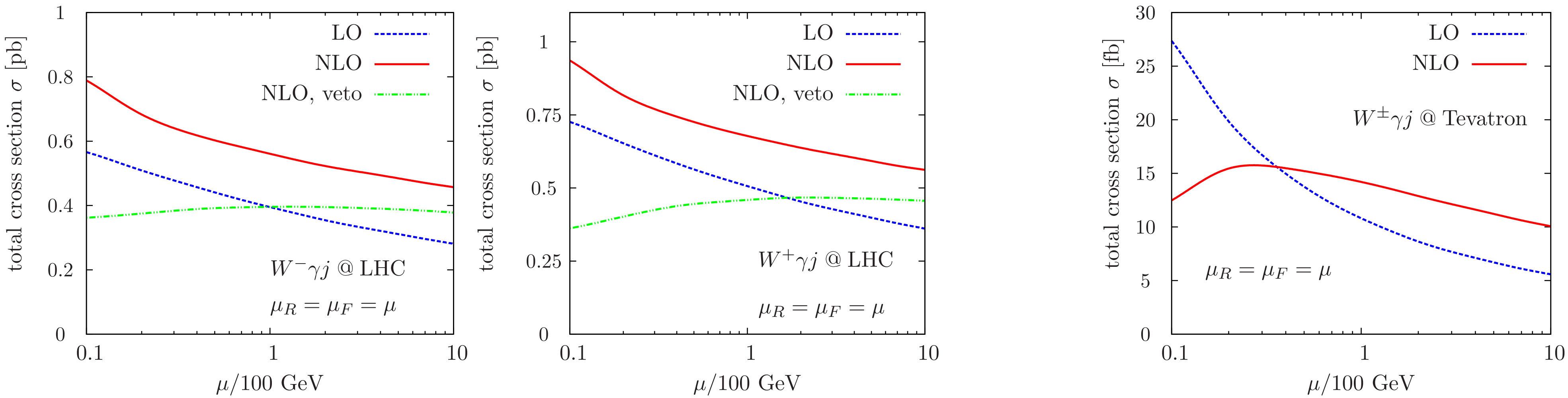
$$M_V(na) = \frac{1}{2}C_A\left(A_2(12) + A_4(12) + A_3(21) + A_4(21)\right) + C_A\left(A_5 + A_6 + A_7\right)$$

Scale dependence: LHC and Tevatron

Identify lepton, photon and one or more jets with k_T-algorithm ($D = 0.7$)

$p_{Tj,\gamma} \geq 50\,\text{GeV}\,, \quad |y_j| \leq 4.5\,, |\eta_\gamma| \leq 2.5, \qquad p_{Tl} \geq 20\,\text{GeV}\,, \quad |\eta_l| \leq 2.5 \qquad R_{l,\gamma}, R_{l,j} > 0.2$

Frixione isolation of photons with $\delta_0 = 1$ Cross sections are for $W \to e\nu_e$ only

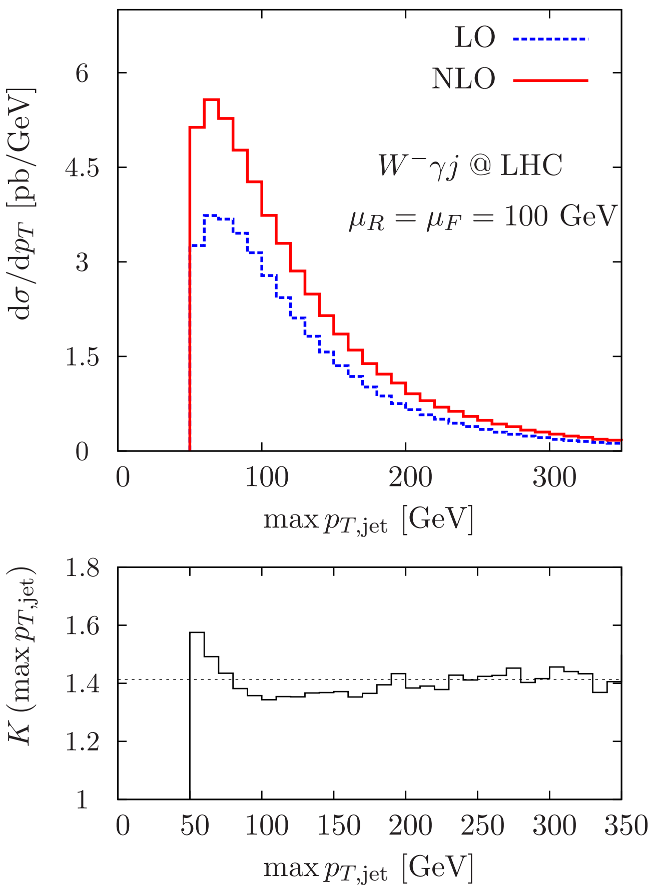


Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot 100$ GeV: $\pm 11\%$ at LO reduced to $\pm 7\%$ at NLO

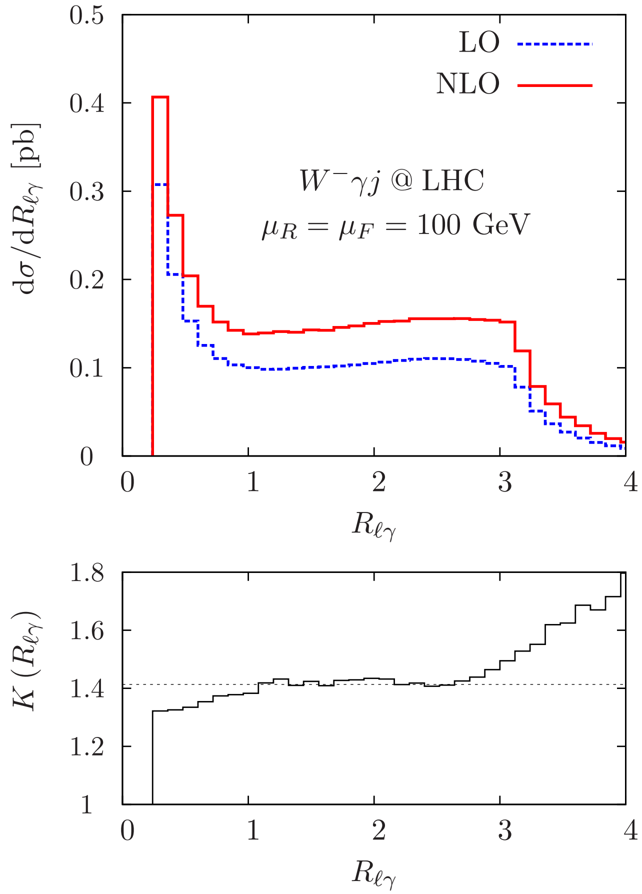
Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV should be taken as accidental and not as a measure of NLO uncertainties

NLO corrections to distributions

p_T of hardest jet



lepton photon separation



- Clear shape changes of distributions when going from LO to NLO
- Average K-factor of 1.4 at LHC is significantly larger than LO scale variation

Conclusions

- Much progress on Higgs physics, Monte Carlo tools, NLO corrections in recent years
- We are all ready for LHC data

Thank you, Nikolas, for a great workshop