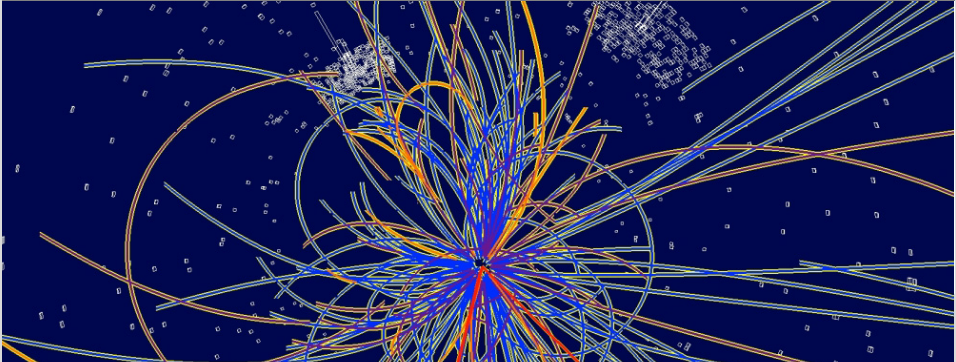
INSTITUTE FOR THEORETICAL PHYSICS, HEIDELBERG UNIVERSITY

Results in precision multiboson+jet phenomenology

Christoph Englert | 26.09.2011

RADCOR 2011 SYMPOSIUM, MAMALLAPURAM



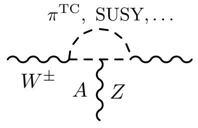
Why anomalous couplings?

LHC starts to test the Fermi scale...

$$\mathcal{L} = \mathcal{L}_{\text{SM w/o Higgs}} + \mathcal{L}_{[SU(2)\times U(1)/U(1)]} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{(6)} + \dots$$

Try to measure $\mathcal{L}$ in model-independent way: bottom-up phenomenology of $\mathcal{L}^{(n)}$

Focus on the SM extended by operators modifying the *WWV* gauge vertices

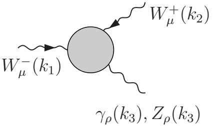


$$\left\langle J_A^\mu(p) J_A^\nu(-p) \right\rangle = (p^2 g^{\mu\nu} - p^\mu p^\nu)\left(\frac{F_\pi^2}{p^2} + \sum_n \frac{F_n^2}{p^2 - m_n^2}\right)$$

['t Hooft '74], [Witten '79]

$$\begin{aligned}
\mathcal{L}_{WW\gamma} = & -ie\big[W_{\mu\nu}^\dagger W^\mu A^\nu - W_\mu^\dagger A_\nu W^{\mu\nu} \\
& + \kappa_\gamma(Q^2) W_\mu^\dagger W_\nu F^{\mu\nu} + \frac{\lambda_\gamma(Q^2)}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu F^{\nu\lambda}\big] \\
\mathcal{L}_{WWZ} = & -ie\cot\theta_w\,\big[g_1^Z(Q^2)\left(W_{\mu\nu}^\dagger W^\mu A^\nu - W_\mu^\dagger A_\nu W^{\mu\nu}\right) \\
& + \kappa_Z(Q^2) W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda_Z(Q^2)}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu Z^{\nu\lambda}\big]
\end{aligned}$$

[Hagiwara, Peccei, Zeppenfeld, Hikasa '87]



modified production cross section, shape-deviations from the SM for large Q^2

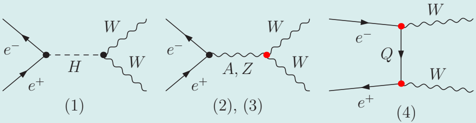
LHC vs ILC: $\sqrt{s}$ vs $\Delta\sigma$

How can we measure and constrain anomalous parameters?

indirect measurement via $e^+e^- \to W^+W^- + X$ at LEP & ILC

[ALEPH, DELPHI, L3, OPAL, arXiv:hep-ex/0612034]

1. cross section is highly sensitive to gauge cancellations



$$[1](s) - 2m_e\big([3]_L(s) + [3]_R(s)\big) = 0$$
$$[3]_R(s) + [3]_L(s) - [4]_L(t) = 0$$
$$[2](s) - [3]_R(s) = 0$$

2. clean handle on final state particles' helicities, polarized beams & $e^\pm\gamma$ option
3. systematics under excellent control, straightforward comparison of data against Monte Carlo, e.g. RACOONWW [Denner, Dittmaier, Roth, Wackeroth '01, '02]

Parameter	68% C.L.	95% C.L.
g_1^Z	$0.991^{+0.022}_{-0.021}$	[0.949, 1.034]
κ_γ	$0.984^{+0.042}_{-0.047}$	[0.895, 1.069]
λ_γ	$-0.016^{+0.021}_{-0.023}$	[−0.059, 0.026]

[hep-ex/0612034]

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500\,\text{GeV}$	$\sqrt{s} = 800\,\text{GeV}$
Δg_1^Z	15.5	12.6
$\Delta\kappa_\gamma$	3.3	1.9
λ_γ	5.9	3.3
$\Delta\kappa_Z$	3.2	1.9
λ_Z	6.7	3.0

$$\sigma(\lambda_\gamma = 0.035)/\sigma^{\rm SM} \simeq 1.11$$

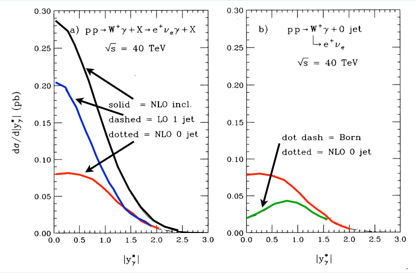
[Menges, LC-PHSM-2001-022]

LHC vs ILC: $\sqrt{s}$ vs $\Delta\sigma$

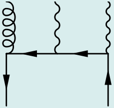
direct measurement via $p\bar{p}$, $pp \to W^{\pm}\gamma + X$ at Tevatron & LHC

[D0, arXiv:0907.4952], [CDF, arXiv:0912.4500]

- radiation zeros: Destructive interference for $q\bar{Q} \to gW\gamma$ in the SM for $y^\star_\gamma \approx 0$

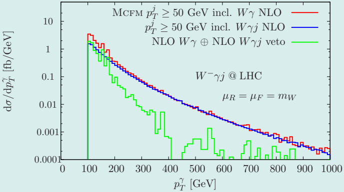


[Baur, Han, Ohnemus ’93]



$\sim \log^2 \dfrac{p^2_{T,\gamma}}{m^2_W}$

$\Rightarrow$ impose jet veto to enhance sensitivity!?



$\sigma^{\rm had}$ are highly dynamical quantities: $\sigma^{W\gamma}/\sigma^{W\gamma+\rm jet} = \mathcal{O}(1)$ @ LHC

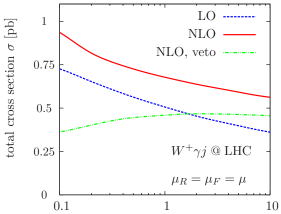
... NNLO / re-summed log contributions significantly affect the jet veto performance.

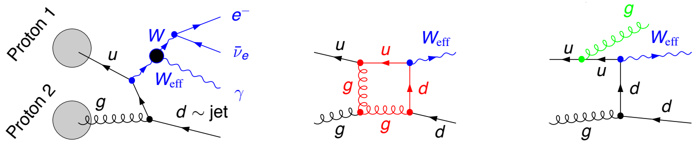
Turning the vetoed contribution into an additional measurement

[Campanario, CE, Spannowsky '10], [Campanario, CE, Spannowsky, Zeppenfeld, '09]

- $pp \to W(\gamma^{(\star)}Z) + jet + X$ is large:
  new partonic channels enter the game! $\rightsquigarrow$ ISR

  Can we use of it instead of excluding it?
  If yes we could constrain TGC from inclusive measurements $\leftarrow$ perturbative QCD
- Improved perturbative precision is mandatory!





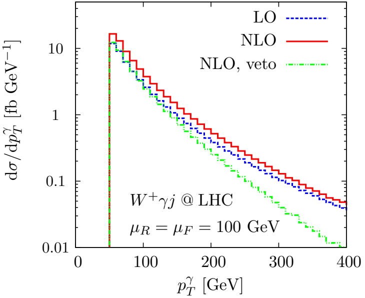
Numerical calculation, implementation and checks ... more details later

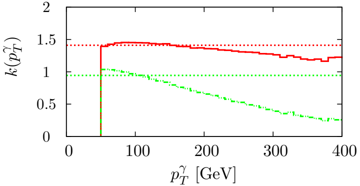
- Catani-Seymour dipole subtraction
- cross & gauge checks
- optimization, cache systems
- redundant calculations, ...

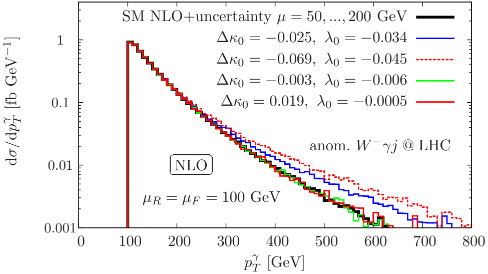
Turning the vetoed contribution into an additional measurement

[Campanario, CE, Spannowsky '10]

QCD correction necessary to reach quantitative results from cut-optimized $\mathrm{d}\sigma/\mathrm{d}p_T^\gamma$







VVj qualitatively same behavior:

- *WWj* [Dittmaier, Kallweit, Uwer '07] [Campbell, Ellis, Zanderighi '07]
- *ZZj* [Binoth, Gleisberg, Karg, Kauer, Sanguinetti '09]
- $W\gamma j$ [Campanario, CE, Spannowsky, Zeppenfeld, '09]
- $W(\gamma^\star, Z)j$ [Campanario, CE, Kallweit, Spannowsky, Zeppenfeld, '10]

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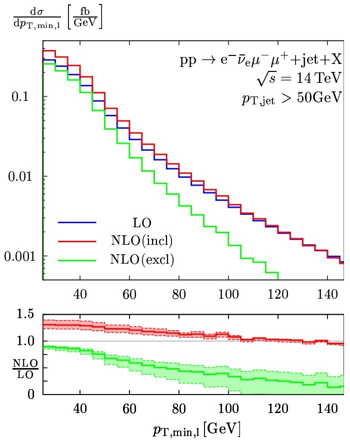

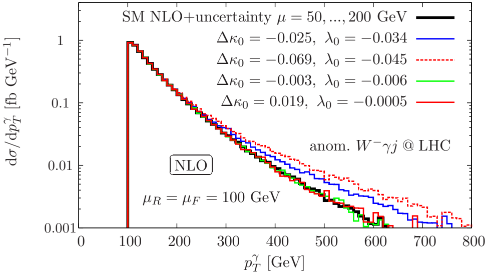

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Is this of any help?

- W+jets background negligible to first approximation for $W\gamma$ searches

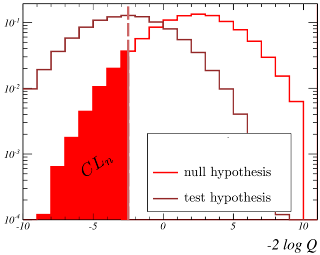
$$\text{jet fakes } \gamma \ll 10^{-5} \text{ for large } p_T^{\gamma} \geq 100 \text{ GeV}$$

[Escalier *et al.* , ATL-PHYS-PUB-2005-018]

- binned log-likelihood analysis, “simple hypothesis test” à la LEPHWG

[Barate *et al.* ’03]

- include perturbative shape uncertainty of the SM hypothesis as a nuisance parameter and compute confidence levels



$\underline{\kappa_\gamma = 0, \lambda_\gamma = 0.035}$ $\quad \sigma = 3 : 25 \text{ fb}^{-1}$

$\sigma = 5 : 50 \text{ fb}^{-1}$

@LHC14

Towards quartic couplings

[Campanario, CE, Rauch, Zeppenfeld '11]

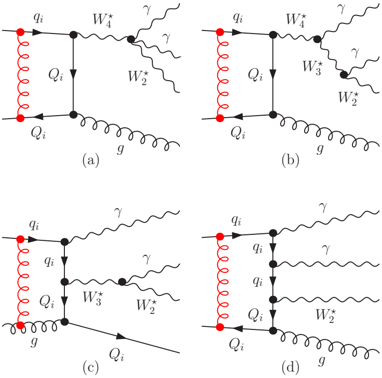
- triple gauge boson production at NLO QCD is fully known

  [Lazopoulos, Melnikov, Petriello '07]
  [Hankele, Zeppenfeld '07]
  [Binoth, Ossola, Papadopoulos, Pittau '08]
  [Campanario, Hankele, Oleari, Prestel, Zeppenfeld]
  [VBFNLO '08 '11]

- *K* factors are large due to ISR
  $\rightsquigarrow$ situation identical to $VV(j)$

- NLO prediction for 1-jet inclusive production mandatory to quantitatively model these effects

  [Campanario, CE, Rauch, Zeppenfeld '11]



technicalities

Virtual contributions

- split virtual corrections into classes of diagrams with 2,3,4 attached effective gauge boson polarizations + fermionic loops

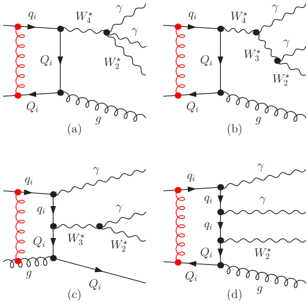
  [Passarino, Veltman '79] [Denner, Dittmaier '03]

- classes related by Slavnov-Taylor identities:

  (i) gauge checks

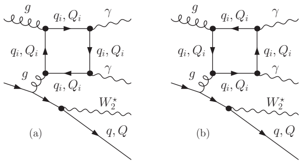
  (ii) hexagons $\rightsquigarrow$ pentagons $\rightsquigarrow$ ...

- classes are non-QED gauge invariant, however no cancellation

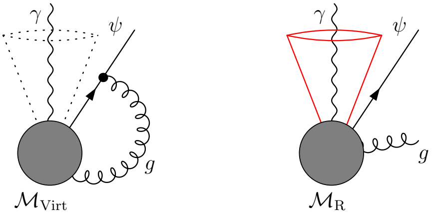


Real emission contributions

- straightforward application of Catani-Seymour formalism [Catani, Seymour '96]
- optimization: cache systems, avoid redundancy, ...



IR safety ↯ isolated γs



IR-safe γ-isolation

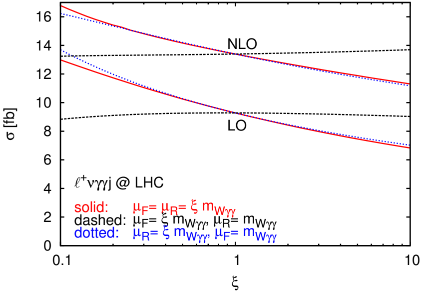
[Baur, Han, Ohnemus '93], [Frixione '98]

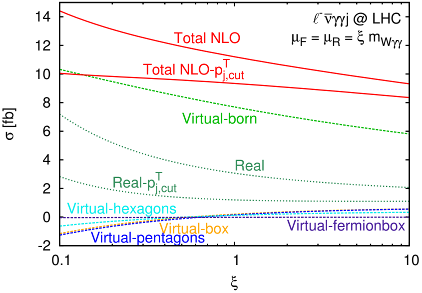
- naive isolation limits phase space of soft gluons
- allow soft radiation into the photon cone to assure cancellation of soft divergencies
- at the same time reject hard collinear configurations (veto jet fragmentation)

$$\sum_{i,R_{i\gamma}<R} p_T^{\text{parton},i} \leq \Xi(\mathcal{E}(p_\gamma), R)\,, \qquad \lim_{R\to 0} \Xi(\mathcal{E}, R) = 0\,,$$

$$\Xi(\mathcal{E}, R) = \frac{1-\cos R}{1-\cos \delta_0} p_T^{(\gamma)}$$

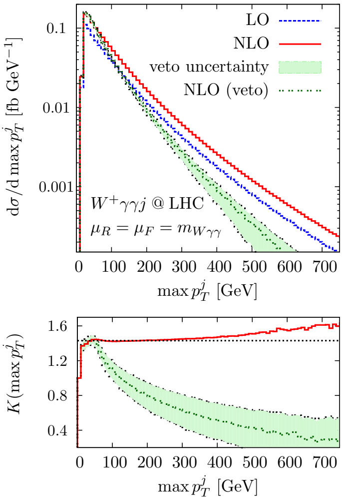
SM $W\gamma\gamma j$ @ NLO

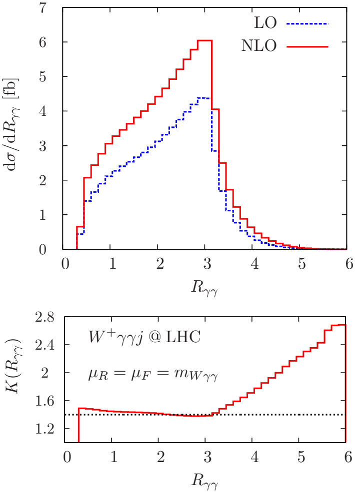




	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$K = \sigma^{\rm NLO}/\sigma^{\rm LO}$	
$W^{\pm}\gamma\gamma$+jet	1.191	1.754	1.47	Tevatron
$W^{+}\gamma\gamma$+jet	4.640	6.634	1.43	LHC
$W^{-}\gamma\gamma$+jet	3.803	5.644	1.48	

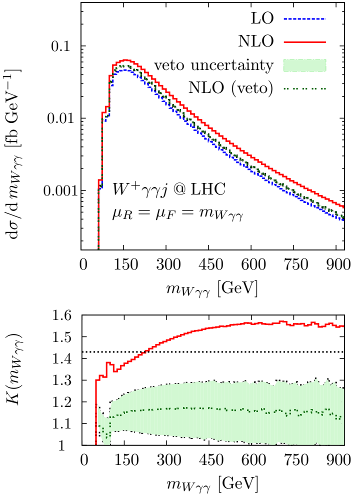
differential corrections





- veto is badly modelled in fixed order perturbation theory
- additional jet radiation dominant, significant modification of LO kinematics

differential corrections



- differential corrections sizable for intermediate $m_{W\gamma\gamma}$
- this is the region where we can expect enhanced cross sections due to anomalous couplings
- QCD corrections, if not included, fake anomalous couplings in data vs theory comparisons
- Other processes *VVVj* to follow

Summary

- the race for the weak scale is on!
- non-trivial energy scale-dependent modifications of the electroweak sector give rise to a modified phenomenology at large mass scales

  $\rightsquigarrow$ anomalous couplings as a paradigm

  - modifications of differential cross sections lead to same overall K factors

    $\rightsquigarrow$ application of control regions

  - differential QCD corrections need to be taken into account in for precise CLs
- QCD corrections will remain crucial to interpret LHC results on a quantitative level

  it's crucial to have codes publicly available

  [MCFM, BLACKHAT+SHERPA, VBFNLO, MADLOOP ...]
- interface with shower picture necessary to add precision beyond the first hard emission