(Non-SM) $W\gamma j$ production at NLO QCD

PHENO '10, MADISON

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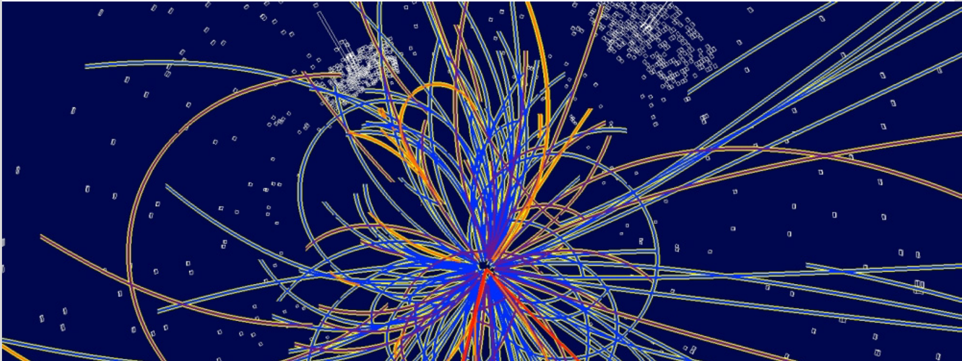


Quick motivation

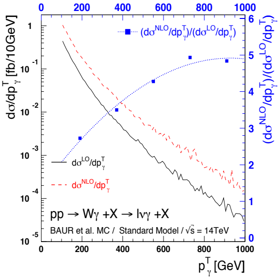
- $W\gamma$, *WZ* (+ jet) production important at hadron colliders [Baur, Han, Ohnemus '93,'95]

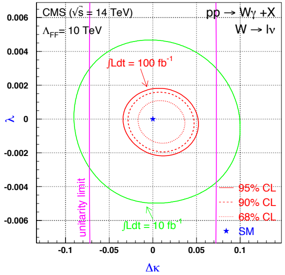
  large rates, anomalous couplings, ...

- QCD corrections to diboson+jet are highly relevant (driven by kinematics) [Dittmaier *et al.* '08, Campanario, CE, Spannowsky, Zeppenfeld '09]

- $\sigma(W\gamma + \text{jet})/\sigma(W\gamma) \simeq 2.5$: jet emission controls uncertainty! (MC veto?)

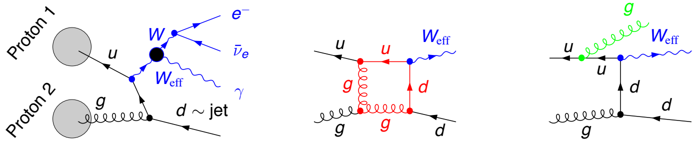
- Can we get a handle on anomalous couplings in inclusive measurements?





[Müller *et al.* '00]

Technicalities



Analytical calculation

à la Catani–Seymour [Catani, Seymour '96]

$$
\begin{aligned}
\sigma^{\rm NLO}_{4-2\varepsilon} =& \sigma^{\rm B} + \left[\sigma^{\rm V} + \sigma^{\rm A}\right] + \left[\sigma^{\rm R} - \sigma^{\rm A}\right] + \sigma^{\rm C} \\
\to& \sigma^{\rm B} + \int_{m+1} \left[\left(d\sigma^{\rm R}\right)_{\varepsilon=0} - \left(\sum_{\rm dipoles} d\sigma^{\rm B} \otimes dV_{\rm dipole} \right)_{\varepsilon=0} \right] \\
&+ \int_m \left[d\sigma^{\rm V} + d\sigma^{\rm B} \otimes \boldsymbol{I} \right]_{\varepsilon=0} + \int_0^1 dx \int_m \left[d\sigma^{\rm B} \otimes \left(\boldsymbol{P}(x,\mu_F^2) + \boldsymbol{K}(x) \right) \right]
\end{aligned}
$$

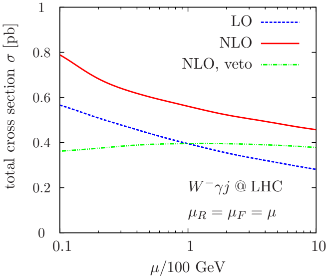
Numerical calculation

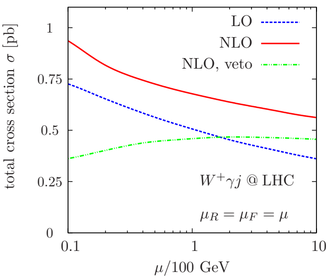
- in-house metacode
- cross & gauge checks
- optimization, cache systems
- redundant calculations, ...

Results: μ_R, μ_F dependence of σ

LHC $\sqrt{s} = 14$ TeV, inclusive cuts:

$$p_T^\gamma, p_T^j \geq 50\ \text{GeV}, p_T^\ell \geq 20\ \text{GeV}, \text{coverage and min. separation}$$

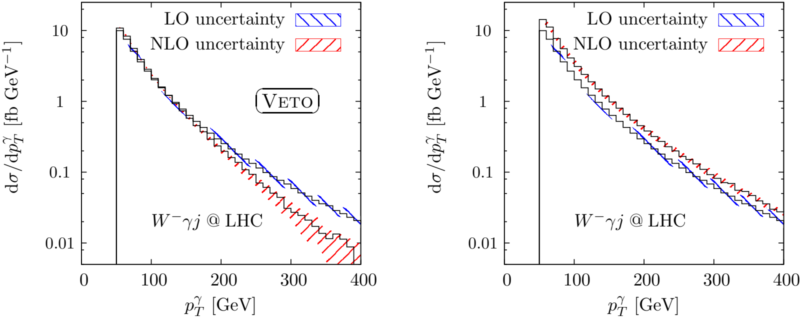




	σ^{NLO} [fb]	$\sigma^{\text{NLO}}/\sigma^{\text{LO}}$	$\mu = 100$ GeV
$W^-\gamma j$	615.3 ± 2.8	1.491	inclusive
$W^+\gamma j$	736.5 ± 3.5	1.411	
$W^-\gamma j$	429.2 ± 1.8	1.041	veto 2$^{\text{nd}}$ jet
$W^+\gamma j$	459.1 ± 2.0	0.910	

$\leftarrow$ Stabilization is superficial!

Veto unreliable . . .

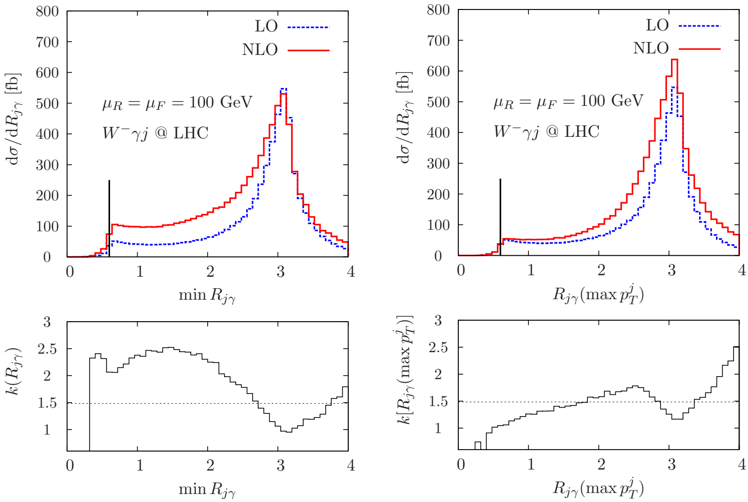


- uncertainty bands: $\mu_R = \mu_F = 50\text{ GeV}\ldots 200\text{ GeV}$

  optimistic but only minor modifications for dyn. scales
- NLO inclusive μ dep. equally distributed over p_T
- NLO exclusive μ dep. small low in p_T, but large at high p_T, and cancellations

→ μ dependence cured superficially by the veto (p_T steep)

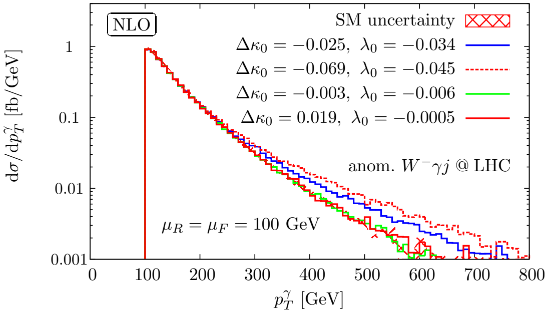
Phase space dependence of $\sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}}$



Non-SM $W\gamma j$ meets LEP bounds [hep-ex/0612034]

Anomalous couplings [Hagiwara *et al.* '86]

$$\mathcal{L}_{WW\gamma} = -ie\left[W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu} + [1+\Delta\kappa]W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda}{m_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu F^{\nu\lambda}\right]$$



- anomalous couplings pronounced at high p_T
- no sensitivity beyond perturbative uncertainty on the σ level for inclusive cuts

Summary & Conclusions

- (anomalous) $W\gamma j$ production computed @ NLO-QCD
- total corrections are sizable

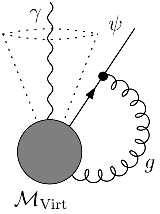
$$1.2 \lesssim \sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}} \lesssim 1.5$$

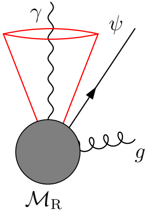
- relative modifications even more significant

$$\mathrm{dK} \lesssim 3 \text{ (inclusive)} - 5 \text{ (exclusive)}$$

- sensitivity of $W\gamma j$ to $(\Delta\kappa, \lambda)$ in p_T^γ fits $\rightarrow$ inclusive studies?

IR safety ↯ isolated γs





IR-safe γ-isolation

[Baur *et al.* '93,Frixione '98]

- naive isolation limits phase space of soft gluons
- one has to allow soft radiation into the photon cone
- at the same time reject hard collinear configurations (fragmentation unwanted)

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

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

Impact of non-standard $WW\gamma$ couplings

anomalous $WW\gamma$ Lagrangian, discarding $\mathcal{CP}$-violating operators [Hagiwara *et al.* '87]

$$\mathcal{L}_{WW\gamma} = -ie\left[W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu} + [1+\Delta\kappa]W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda}{m_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu F^{\nu\lambda}\right]$$

relates to

$$\mu_W = \frac{e}{2m_W}(2+\Delta\kappa+\lambda)\,, \quad Q_W = -\frac{e}{m_W^2}(1+\Delta\kappa-\lambda)$$

Current bounds — highly consistent with zero → we shoot for the SM!

$1+\Delta\kappa_0 = 0.984^{+0.042}_{-0.047}$	$\lambda = -0.016^{+0.021}_{-0.023}$	**LEP**
$1+\Delta\kappa_0 = 0.973^{+0.044}_{-0.045}$	$\lambda = -0.028^{+0.020}_{-0.021}$	**DØ**

anomalous couplings add to $W\gamma j$ production

- modified $WW\gamma$ vertex from *FeynRules*.
- analytical checks & code via *FeynCalc* → new *Helas* routines
- numerical checks (sign conventions)