$W\gamma\gamma$ at NLO QCD

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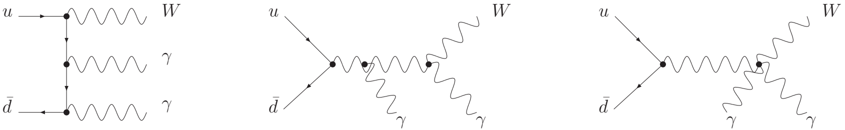
Outline

1. Introduction
2. Calculation
3. Results

Anomalous couplings in $W\gamma\gamma$



process contains $W\gamma\gamma$ and $WW\gamma\gamma$ vertices.

CP conserving couplings, em gauge invariance [Gaemers, Gounaris; Hagiwara et al.]

$$\mathcal{L}_{\text{eff}} = -ie \left[\kappa_\gamma W_\mu^\dagger W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{M_W^2} G_{\lambda\mu}^\dagger G_\nu^\mu F^{\nu\lambda} \right]$$

$G_{\mu\nu} = W_{\mu\nu} - ie(A_\mu W_\nu - A_\nu W_\mu)$

2 parameters: κ_γ (=1 in SM) and λ_γ (=0 in SM)

	LEP 2	error from σ at LHC (100 fb^{-1})
$\Delta\kappa_\gamma$	0.026 ± 0.04	0.2
λ_γ	-0.028 ± 0.02	0.007

Radiation zero

related to photon radiation from charged particles

first: dips in distributions in $W\gamma$ production [Brown, Sahdev, Mikaelian, '79]
dips are exact amplitude zero [Mikaelian, Samuel, Sahdev '79]

theorem [Brodsky, Brown, Kowalsky, '82]
consider: n external charged particles (p_i, Q_i) and 1 photon (q):

$$\text{if all } \frac{Q_i}{p_i \cdot q} \text{ the same} \Rightarrow M_{\text{tree}} = 0$$

even with > 1 photons if all collinear

smeared by: PDF's, finite widths, photon emission from decay leptons, qcd corrections
$\longrightarrow$ dip

Radiation zero: example $W\gamma$

consider $p\bar{p} \to W^*\gamma \to \nu l\gamma$

radiation zero at $\cos\theta^*_W = \frac{Q_u - Q_{\bar{d}}}{Q_u + Q_{\bar{d}}} = -1/3$

$\theta^*_W = \angle(W, u)$ in partonic cms frame

partonic cms tricky to reconstruct

lepton preferentially emitted in W direction

look instead at rapidity difference

$$\Delta\eta(\gamma, l) = \eta(\gamma) - \eta(l)$$

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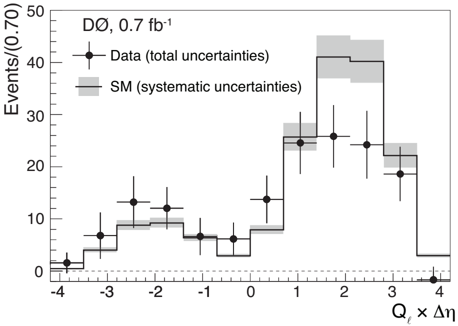


Radiation zero: $W\gamma\gamma$

amplitude zero: only for collinear photons

want 2 photons: separation cut, photons not collinear
but: still large dip if photons in same hemisphere

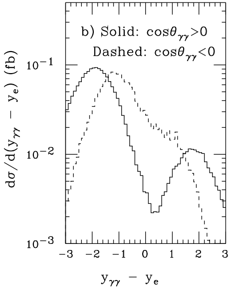
look at $\Delta\eta(\gamma\gamma, l) = \eta(\gamma\gamma) - \eta(l)$
photons in

- same hemishpere: dip
- opposite hemishpere: no dip

is dip filled up by QCD corrections?

$W^-\gamma\gamma$ at Tevatron

[Baur et al, '97]



Motivation

$pp \to W\gamma\gamma$ tests Standard Model

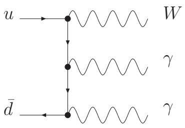
- sensitive to anomalous couplings
- amplitude has radiation zero

in general at LHC: large QCD corrections.
similar processes (VVV and $W\gamma$): large QCD corrections

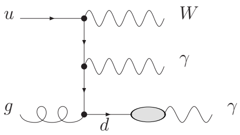
$\Rightarrow$ need NLO QCD for $pp \to W\gamma\gamma$

$W\gamma\gamma$ leading order

direct



fragmentation



direct contribution

$$d\sigma^D = \int dx_1\, dx_2\, f(x_1, \mu_f) f(x_2, \mu_f) d\hat{\sigma}_{W\gamma\gamma}$$

fragmentation contribution

$$d\sigma^F = \int dx_1\, dx_2\, f(x_1, \mu_f) f(x_2, \mu_f) \int dz\, D_{\gamma/q}(z, \mu_{\text{frag}}) d\hat{\sigma}_{W\gamma q}$$

- $W\gamma q$ production followed by collinear $q \to \gamma$ fragmentation
- fragmentation function $D_{\gamma/q}(z)$ formally $\mathcal{O}(\frac{\alpha}{\alpha_s})$
  $\Rightarrow$ same order as direct process

$W\gamma\gamma$ leading order

fragmentation contribution

- collinear hadronic remnant in final state
- suppression by photon isolation cut

$E_{T,had} < \epsilon E_{T,\gamma}$ inside cone $\Delta R(\gamma, had) < R_{cone}$

$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

$\sigma(pp \to W^+\gamma\gamma)$ in fb, $\sqrt{s} = 14\,\text{TeV}$ $\epsilon = 0.15$ $R_{\text{cone}} = 0.7$

	no isolation	with isolation
LO direct	7.253(5)	7.253(5)
LO frag	24.30(2)	1.505(1)

$\to$ effective suppression

$W\gamma\gamma$ next-to-leading order

contributions

- direct: NLO
- fragmentation: suppressed by photon isolation. only at LO

ingredients:

- virtual $u\bar{d} \to W\gamma\gamma$ amplitude
- real amplitudes
  $u\bar{d} \to W\gamma\gamma g$, $ug \to W\gamma\gamma d$, $\bar{d}g \to W\gamma\gamma\bar{u}$

Evaluation of 1-loop integrals

general 1-loop integral

$$T^n_{\{0,\mu,\mu\nu\}} = \frac{(2\pi\mu)^{4-D}}{i\pi^2} \int d^D k \, \frac{\{1, k_\mu, k_\mu k_\nu\}}{D_0 \cdot \ldots \cdot D_{n-1}}$$

with denominator $D_i = (q + p_i)^2 - m_i^2$
decomposition

$$T^\mu = \sum_i p_i^\mu T_i \qquad T^{\mu\nu} = g^{\mu\nu} T_{00} + \sum_{i,j} p_i^\mu p_j^\nu T_{ij}$$

Passarino-Veltman reduction of tensor loop integrals

- express tensor coefficients T_i, T_{ij} by scalar integrals
- kinematical determinants (Gram determinants) in denominator
- Gram determinants may vanish
  but: tensor integrals regular
  $\rightarrow$ cancellations in numerator
  $\rightarrow$ numerical instabilities

Loop integrals: stabilization

possible solutions

- avoid Gram determinants: modified/different reduction
  different basis integrals [Denner, Dittmaier], [Binoth et al]
- numerical integration [Feroglia et al], [Kurihara et al], [de Doncker et al], [Nagy, Soper]

we use

- 5-point reduction: [Denner, Dittmaier '05]
  uses 4-dimensionality of spacetime
  $\longrightarrow$ no inverse Gram determinants
- 3/4-point reduction
  Passarino-Veltman
- higher precision
  QD library by D. Baily: quadruple/octuple precision
  quadruple precision: slowdown factor 10-20
  $\longrightarrow$ too slow to use everywhere
  $\Rightarrow$ high precision only for unstable points

Loop integrals: stabilization

runtime impact of higher precision

- fraction of quadruple precision points

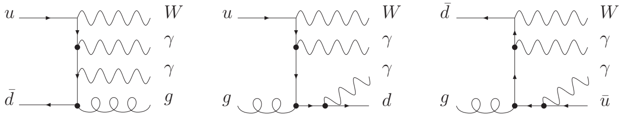
3-point	$3 \cdot 10^{-5}$
4-point	0.001
5-point	0.03

- runtime dominated by real corrections

$\Rightarrow$ high precision evaluations have almost no impact on overall runtime

Real corrections

real amplitudes



$ug \to W\gamma\gamma d$ and $\bar{d}g \to W\gamma\gamma\bar{u}$ amplitudes

- contain QED singularity if q and photon collinear
  can't be completely removed by cuts
  $\to$ need to include fragmentation contribution
- fragmentation contribution generates counterterm
  $D_{\gamma/q}(z) = D_{\gamma/q}(z, M_f^2) + \frac{1}{\epsilon}\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{M_f^2}\right)^{\epsilon}\int_z^1 \frac{dy}{y} D_{\gamma,c}(z/y) P_{cq}(y)$
  analogous to PDF counterterm

$\Rightarrow$ singularity absorbed into fragmentation function

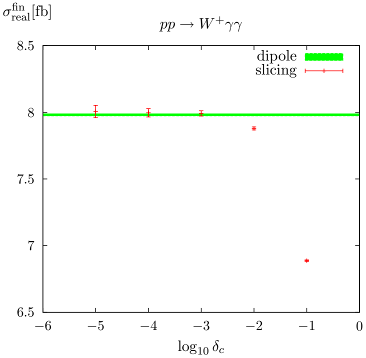
Real corrections

amplitudes: MadGraph

real/virtual combination

- dipole formalism
  a la Catani, Seymour
  with Nagy modification of subtraction functions
  $\longrightarrow$ cross check
- 2 cutoff phase space slicing

$\Rightarrow$ agree well



Numerical results: setup

All results preliminary !

cuts

- standard

$$p_{T,\gamma} > 30\,\text{GeV} \qquad \eta_\gamma < 2.5$$

$$\Delta R_{\gamma\gamma} > 0.4 \qquad \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- optional photon isolation

$$E_{T,had} < \epsilon E_{T,\gamma} \quad \text{inside cone} \quad \Delta R(\gamma, had) < R_{cone}$$

$$\epsilon = 0.15 \qquad R_{\text{cone}} = 0.7$$

- optional jet veto

$$\text{veto if} \quad p_{Tj} > 50\,\text{GeV} \quad \text{and} \quad |\eta_j| < 3$$

parton densities: LO (NLO): CTEQ6LL (CTEQ6M)
fragmentation functions: leading log approximation (Duke, Owens)

Numerical results: cross section

$\sigma(pp \to W^+\gamma\gamma)$ in fb, $\sqrt{s} = 14\,\text{TeV}$

	no isolation	with isolation	iso & jet veto
LO direct	7.253(5)	7.253(5)	7.253(5)
LO frag	24.30(2)	1.505(1)	1.501(1)
LO total	31.55	8.758	8.754
NLO	39.33(6)	25.62(4)	11.83(4)
K factor	1.25	2.93	1.35

no isolation: fragmentation contribution dominant
with isolation: huge NLO corrections, mostly from hard jet radiation
jet veto: corrections moderate (35 %)

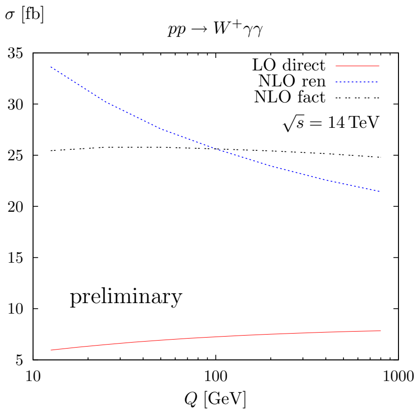
Scale dependence

with isolation cuts

total scale dependence increased

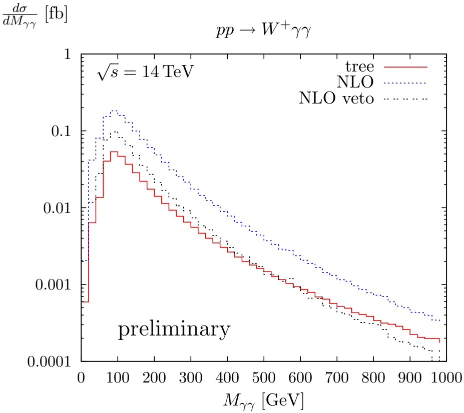
NLO scale dependence
from renormalization scale

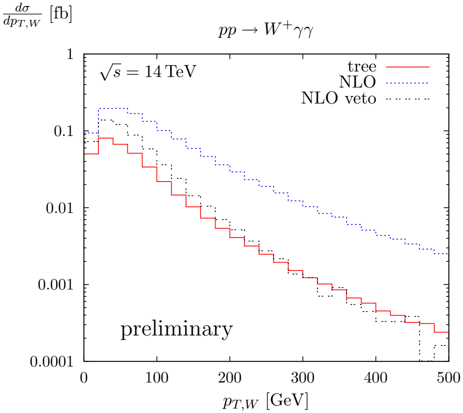
NLO factorization scale
dependence stabilized



Distributions and jet veto

with isolation cuts





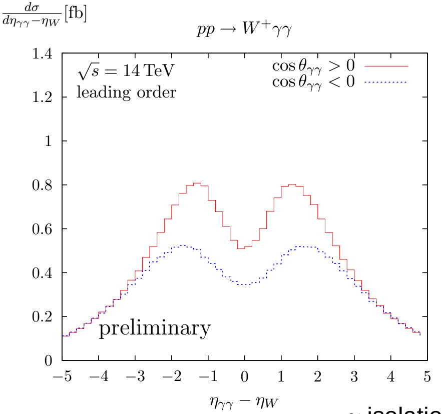
jet veto if $p_{Tj} > 50\,\text{GeV}$ and $|\eta_j| < 3$

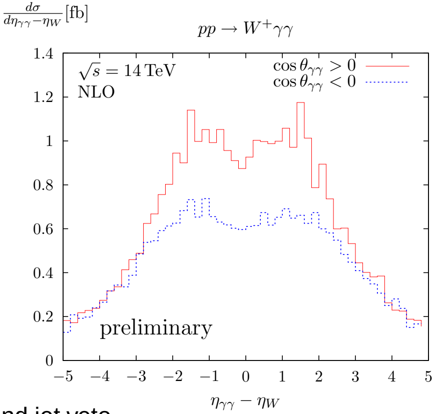
$\rightarrow$ removes tails in p_T and $M_{\gamma\gamma}$.

Radiation zero

radiation zero for collinear photons

$\rightarrow$ difference between $\cos\theta_{\gamma\gamma} > 0$ and $\cos\theta_{\gamma\gamma} < 0$





γ isolation and jet veto

only moderate effect at LO

NLO corrections fill in dips

Conclusions

$W\gamma\gamma$ production at LHC interesting test of Standard Model
$\rightarrow$ anomalous couplings, radiation zero

calculation of QCD NLO corrections

- corrections large, dominated by hard radiation
- total scale dependence increased.
  factorization scale dependence decreased.

outlook

- anomalous couplings
- W decays