QCD Corrections to Gauge-Boson Pair Production With Anomalous Couplings

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LoopFest, Northwestern University (May 12, 2011)

In The Memory of Uli Baur

My Collaboration with Uli:

Early interactions in Madison during 1989 - 1990

Started collaboration in Davis 1993
(with Jim Ohnemus, a postdoc then)

Uli and I have long genuine interests in EW physics;
Jim was a leading perturbative QCD expert.

Projects:

QCD corrections to gauge boson pair production
At hadron colliders.

Decays, spin correlations, fully differential.

Motivation for VV Physics:

VOLUME 43, NUMBER 11 PHYSICAL REVIEW LETTERS 10 SEPTEMBER 1979

Magnetic Moment of Weak Bosons Produced in pp and $p\bar{p}$ Collisions

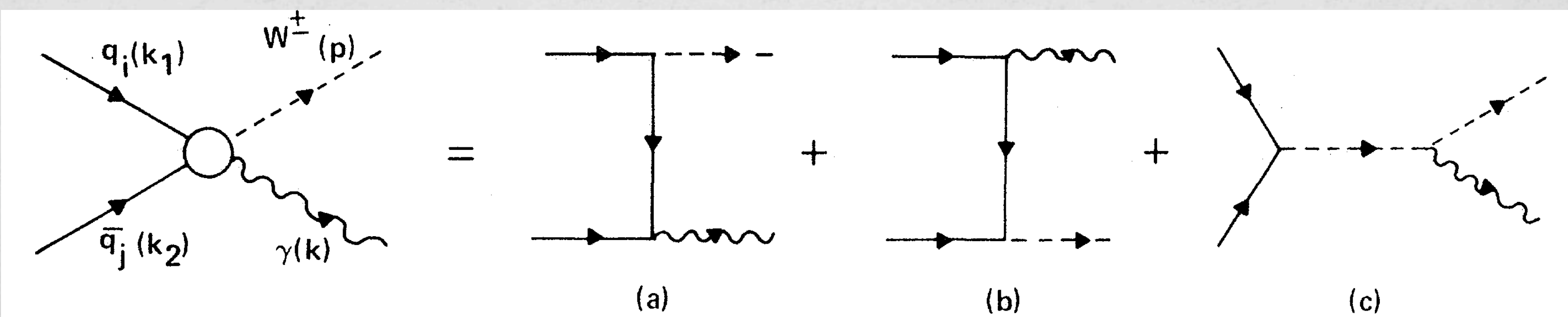
K. O. Mikaelian and M. A. Samuel
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74074

and

D. Sahdev
Physics Department, Case Western Reserve University, Cleveland, Ohio 44106

(Received 5 June 1979)

We suggest that the reactions $pp \to W^{\pm}\gamma X$ and $p\bar{p} \to W^{\pm}\gamma X$ are good candidates for measuring the magnetic moment parameter κ in $\mu_W = (e/2M_W)(1+\kappa)$. The angular distribution of the W bosons in $p\bar{p} \to W^{\pm}\gamma X$ is particularly sensitive to this parameter. For the gauge-theory value of $\kappa = 1$, we have found a peculiar zero in $d\sigma(d\bar{u} \to W^{-}\gamma)/d\cos\theta$ at $\cos\theta = -\frac{1}{3}$, the location of this zero depending on the quark charge through $\cos\theta = -(1+2Q_d)$. A similar zero occurs in $d\sigma(u\bar{d} \to W^{+}\gamma)/d\cos\theta$. We can offer no explanation for this behavior.

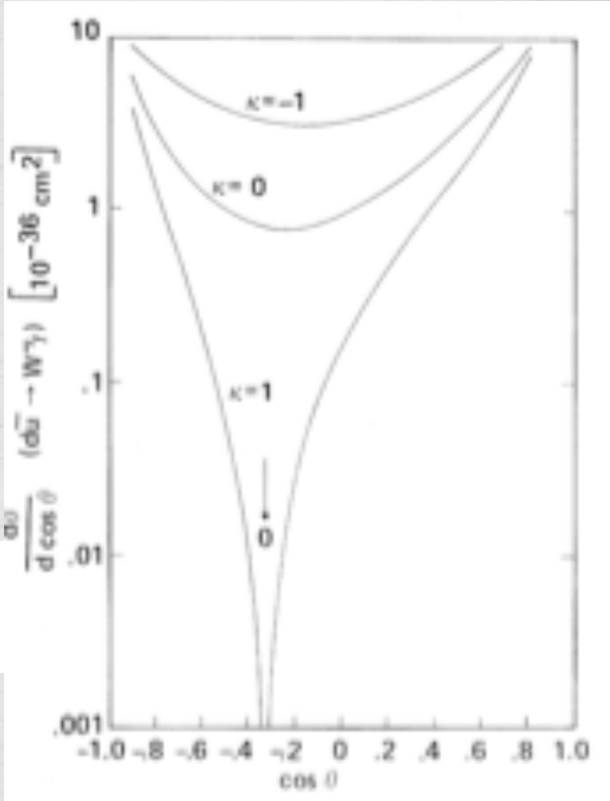


Motivation for VV Physics: con'd 1

The Radiation Amplitude Zero:

$$e^4 \frac{|U_{q_1 q_2}|^2}{2 x_W} \frac{(Q_1 t + Q_2 u)}{t+u} \left[Q_1 F^W(t,u) + Q_2 F^W(u,t) \right]$$

parton-level subprocess RAZ at:
cos θ = (Q1 + Q2)/(Q1 – Q2) → -1/3



$$\mathcal{L}_{WW\gamma} = -i\, e \left[W^\dagger_{\mu\nu} W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu} + \kappa W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu F^{\nu\lambda} \right]$$

$$\mu_W = \frac{e}{2M_W} (1 + \kappa + \lambda)$$

$$Q_W = -\frac{e}{M_W^2} (\kappa - \lambda) \, .$$

Anomalous couplings ruin it !

QCD corrections ruin it too!

It is essential to evaluate the QCD effects, in order to test the EW gauge theory.

The three-body contribution to the NLO cross section is

$$\sigma_{3\text{ body}}(p\overset{(-)}{p} \to W\gamma + X) = \sum_{a,b,c} \int d\hat{\sigma}(ab \to W\gamma c)\left[G_{a/p}(x_1, M^2)\, G_{b/\overset{(-)}{p}}(x_2, M^2) + (x_1 \leftrightarrow x_2)\right] dx_1\, dx_2\,, \tag{9}$$

where the sum is over all partons contributing to the three subprocesses $q_1\bar{q}_2 \to W\gamma g$, $q_1 g \to W\gamma q_2$, and $g\bar{q}_2 \to W\gamma\bar{q}_1$. The $2 \to 3$ subprocess is labeled by $p_1 + p_2 \to p_3 + p_4 + p_5$ and the kinematic invariants s_{ij} and t_{ij} are defined by $s_{ij} = (p_i + p_j)^2$ and $t_{ij} = (p_i - p_j)^2$. The integration over three-body phase space and $dx_1\, dx_2$ is done numerically by standard Monte Carlo techniques. The kinematic invariants s_{ij} and t_{ij} are first tested for soft and collinear singularities. If an invariant for a subprocess falls in a soft or collinear region of phase space, the contribution from that subprocess is not included in the cross section.

Except for the virtual contribution, $d\hat{\sigma}^{\text{virt}}/dv$ in Eq. (3), the $O(\alpha_s)$ corrections are all proportional to the Born cross section. It is easy to incorporate the decay $W \to \ell\nu$ into those terms which are proportional to the Born cross section; one simply replaces $d\hat{\sigma}^{\text{Born}}(q_1\bar{q}_2 \to W\gamma)$ with $d\hat{\sigma}^{\text{Born}}(q_1\bar{q}_2 \to W\gamma \to \ell\nu\gamma)$ in Eq. (3). It is likewise easy to include the W decay in the NLO bremsstrahlung, the hard collinear, and the real emission contributions by making analogous replacements. When working at the amplitude level, the W decay is trivial to implement; one simply replaces the W-boson polarization vector $\epsilon_\mu(k)$ with the $W \to \ell\nu$ decay current $J_\mu(k)$ in the amplitude. Details of the amplitude level calculations for the Born and real emission subprocesses can be found in Ref. [19].

The only term in which it is more difficult to incorporate the W decay is the virtual contribution. Rather than undertake the nontrivial task of recalculating the virtual

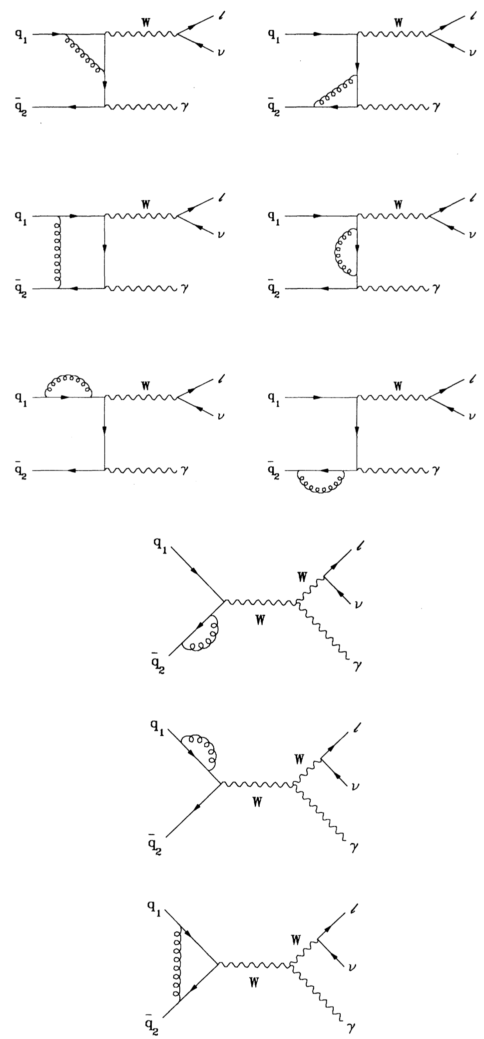


FIG. 2. Feynman diagrams for the virtual subprocess $q_1\bar{q}_2 \to W\gamma \to \ell\nu\gamma$. Not shown are the diagrams obtained by interchanging the W and γ.

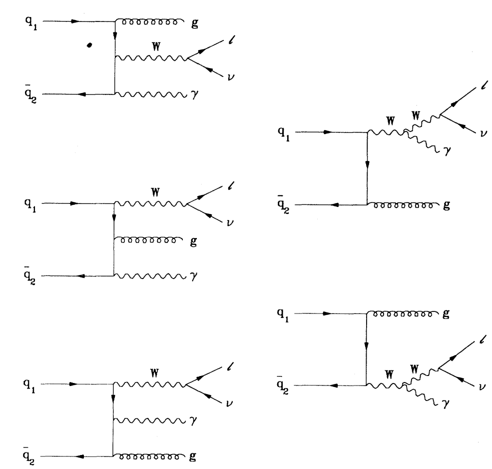
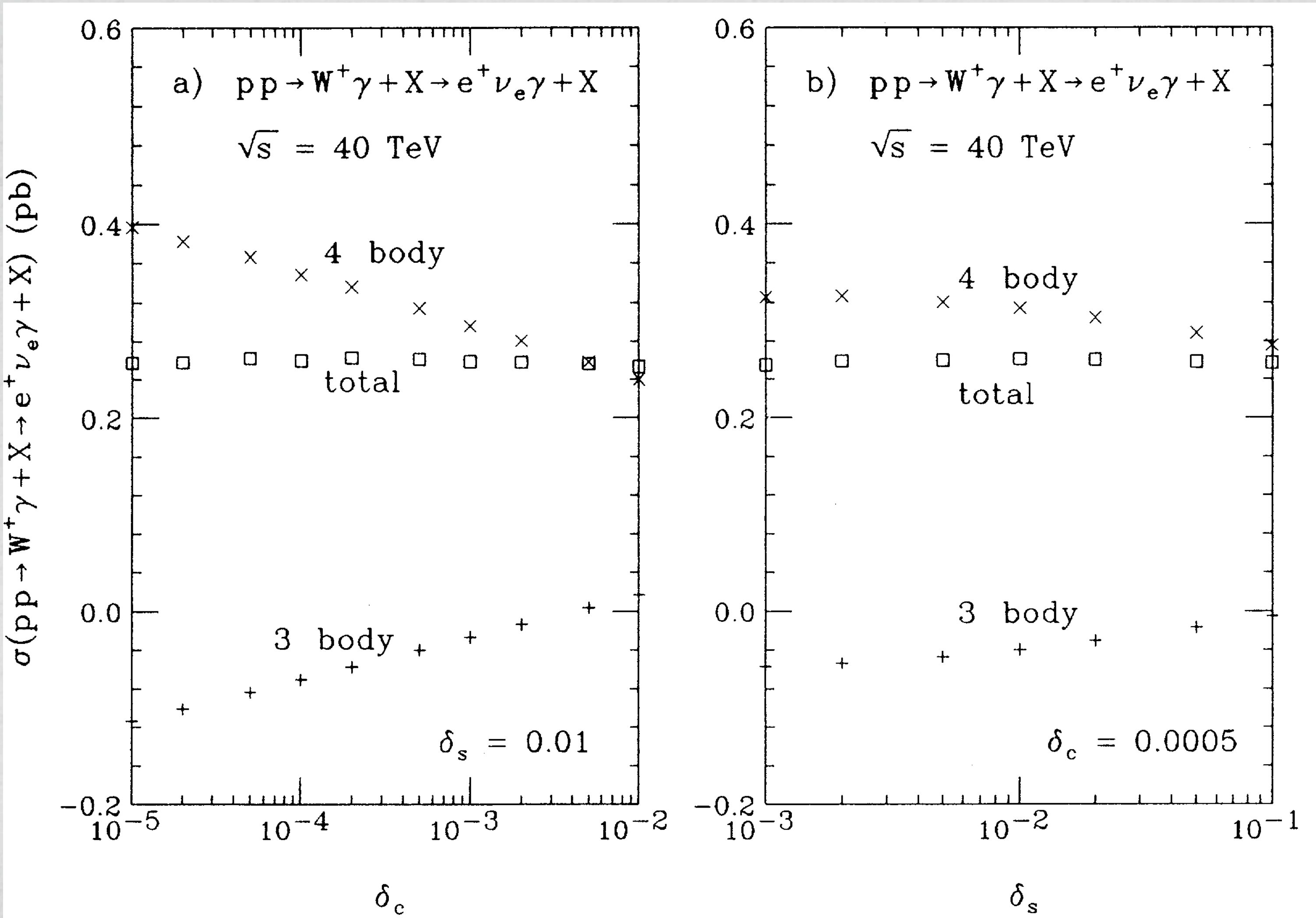
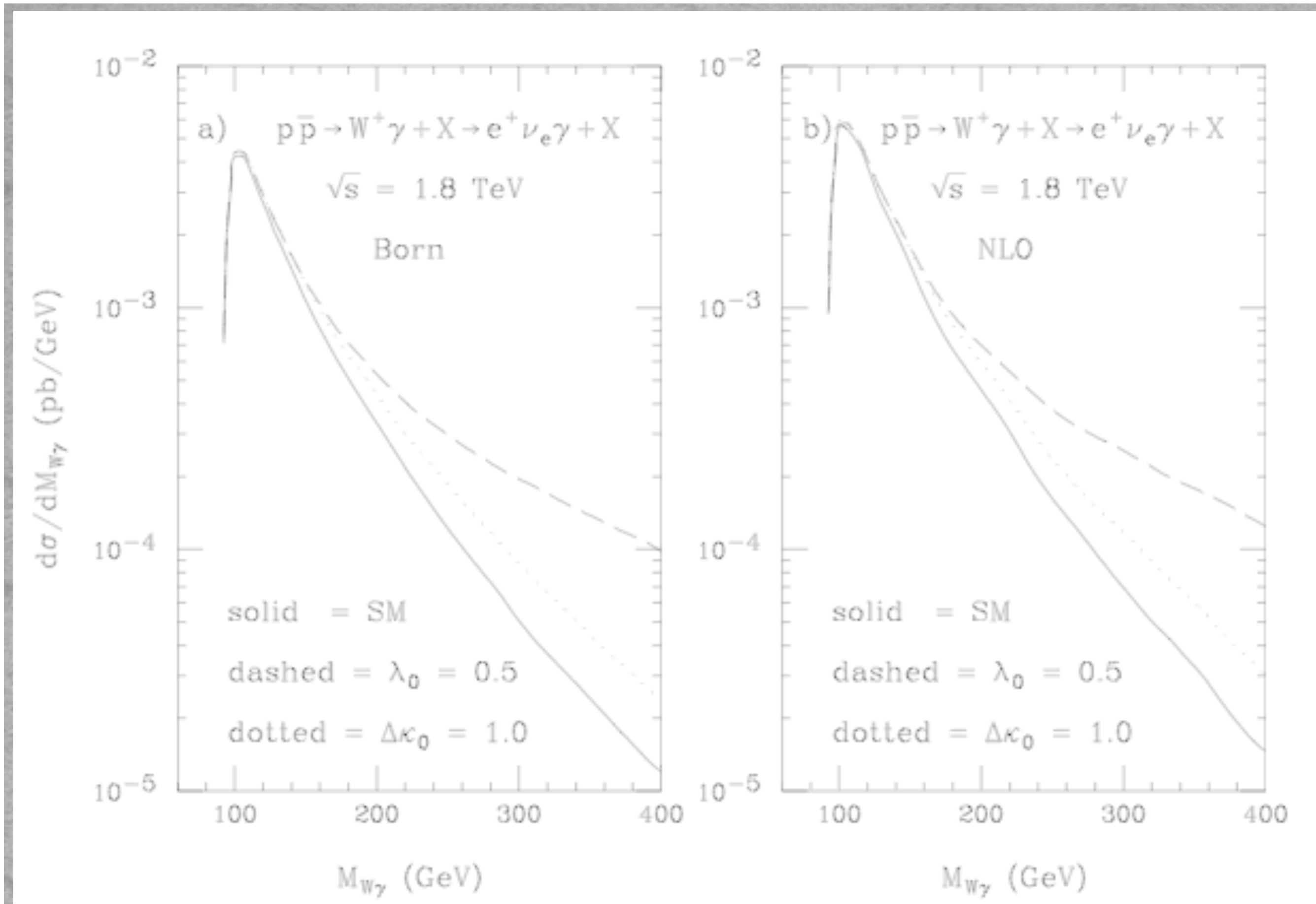


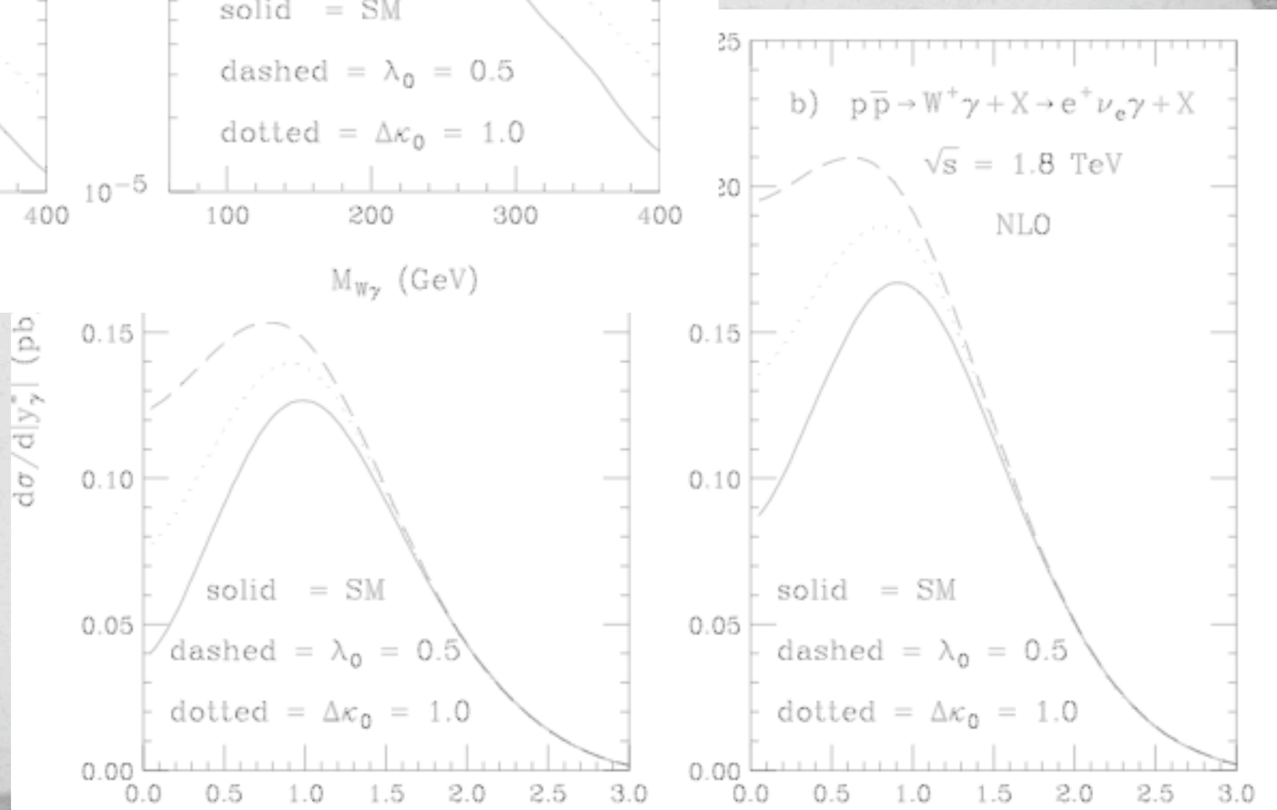
FIG. 3. Feynman diagrams for the real emission subprocess $q_1\bar{q}_2 \to W\gamma g \to \ell\nu\gamma g$. Not shown are the diagrams obtained by interchanging the W and γ.

Our Results for Tevatron:

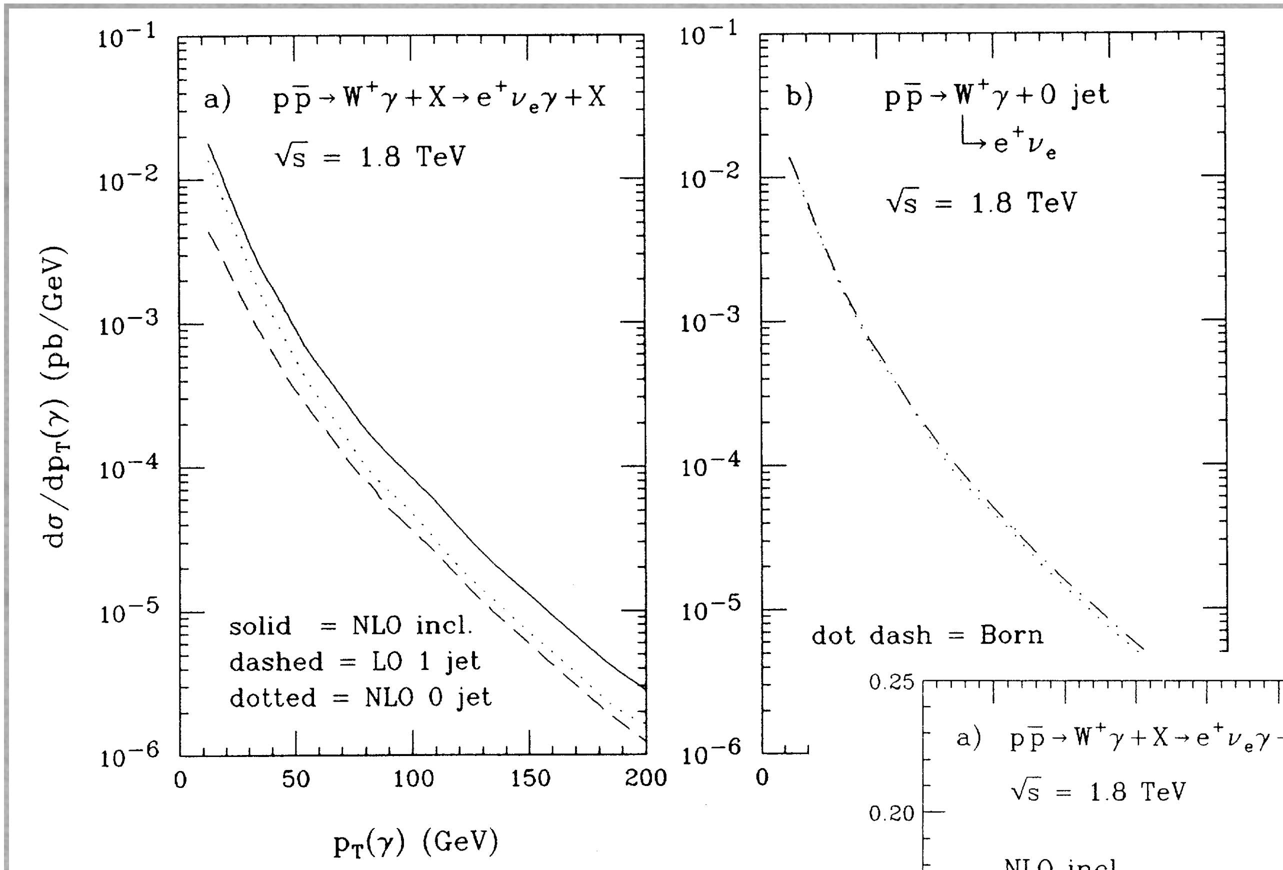


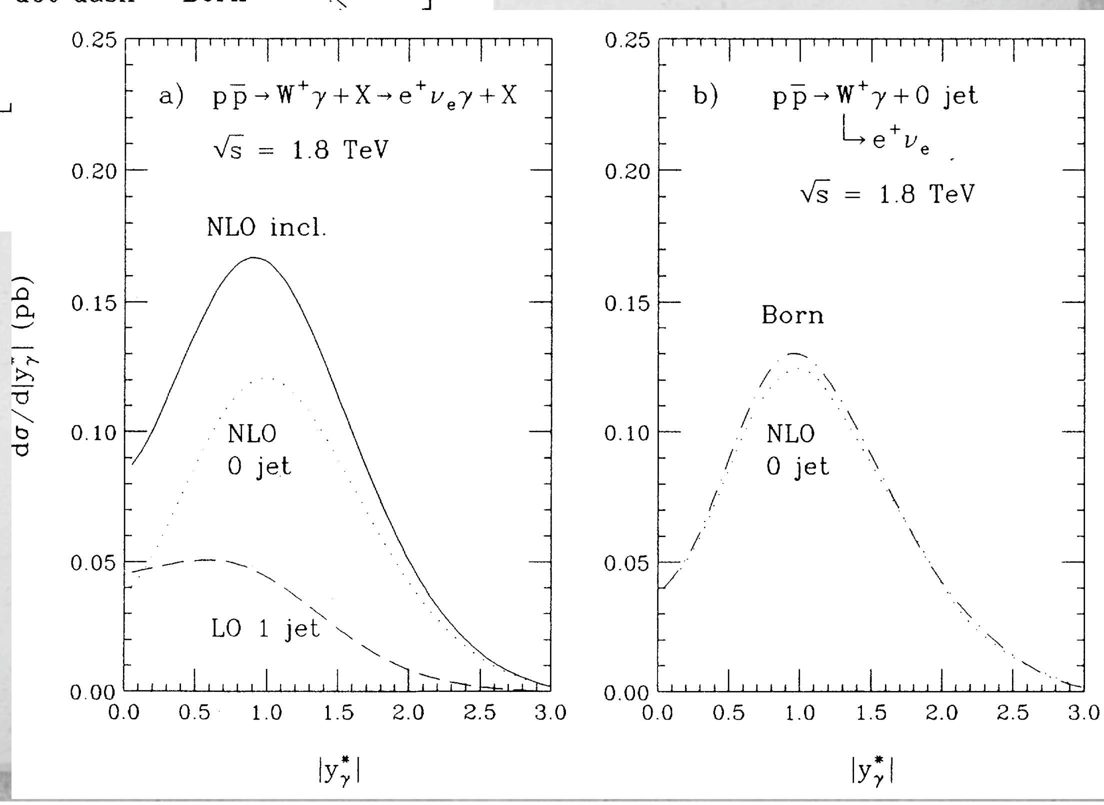


a) $p\bar{p} \to W^+\gamma + X \to e^+\nu_e\gamma + X$
$\sqrt{s}$ = 1.8 TeV
Born
b) $p\bar{p} \to W^+\gamma + X \to e^+\nu_e\gamma + X$
$\sqrt{s}$ = 1.8 TeV
NLO
$d\sigma/dM_{W\gamma}$ (pb/GeV)
$M_{W\gamma}$ (GeV)
solid = SM
dashed = λ_0 = 0.5
dotted = $\Delta\kappa_0$ = 1.0



b) $p\bar{p} \to W^+\gamma + X \to e^+\nu_e\gamma + X$
$\sqrt{s}$ = 1.8 TeV
NLO
$d\sigma/d|y^*_\gamma|$ (pb
solid = SM
dashed = λ_0 = 0.5
dotted = $\Delta\kappa_0$ = 1.0


a) $p\bar{p} \to W^+\gamma + X \to e^+\nu_e\gamma + X$
$\sqrt{s}$ = 1.8 TeV
solid = NLO incl.
dashed = LO 1 jet
dotted = NLO 0 jet
b) $p\bar{p} \to W^+\gamma + 0$ jet $\hookrightarrow e^+\nu_e$
$\sqrt{s}$ = 1.8 TeV
dot dash = Born
$d\sigma/dp_T(\gamma)$ (pb/GeV)
$p_T(\gamma)$ (GeV)


a) $p\bar{p} \to W^+\gamma + X \to e^+\nu_e\gamma + X$
$\sqrt{s}$ = 1.8 TeV
NLO incl.
NLO 0 jet
LO 1 jet
b) $p\bar{p} \to W^+\gamma + 0$ jet $\hookrightarrow e^+\nu_e$
$\sqrt{s}$ = 1.8 TeV
Born
NLO 0 jet
$d\sigma/d|y^*_\gamma|$ (pb)
$|y^*_\gamma|$

“First study of the radiation-amplitude zero in $W \gamma$ production and limits on anomalous $W W \gamma$ couplings at $ \sqrt{s}$ = 1.96- TeV.”

By Do Collaboration
Phys.Rev.Lett.100:241805,2008.

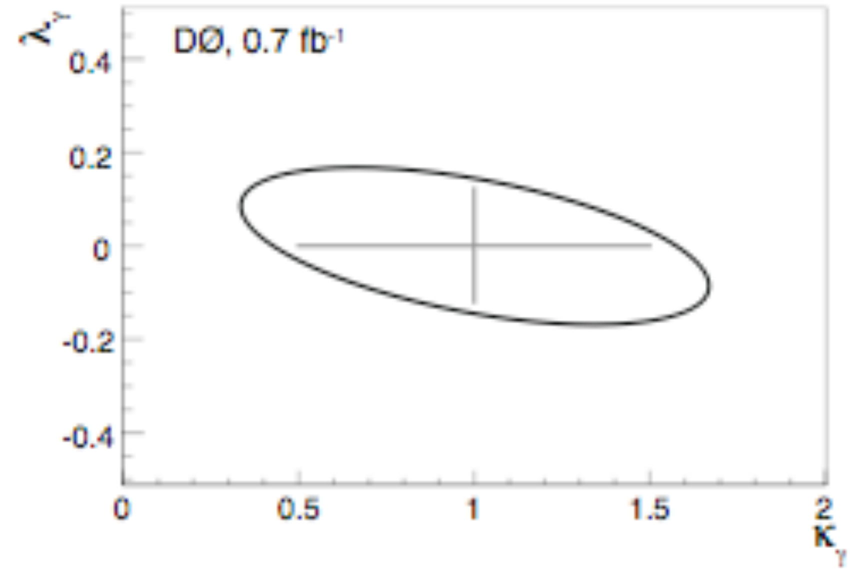
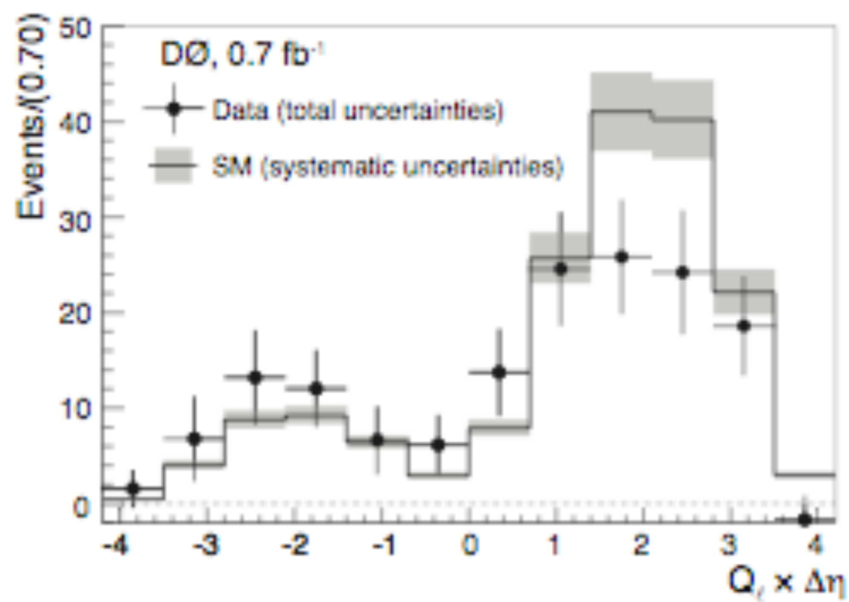


FIG. 2: The ellipse is the 95% C.L. limit contour in $\kappa_\gamma - \lambda_\gamma$ space. One-dimensional 95% C.L. limits are shown as the horizontal and vertical bars.

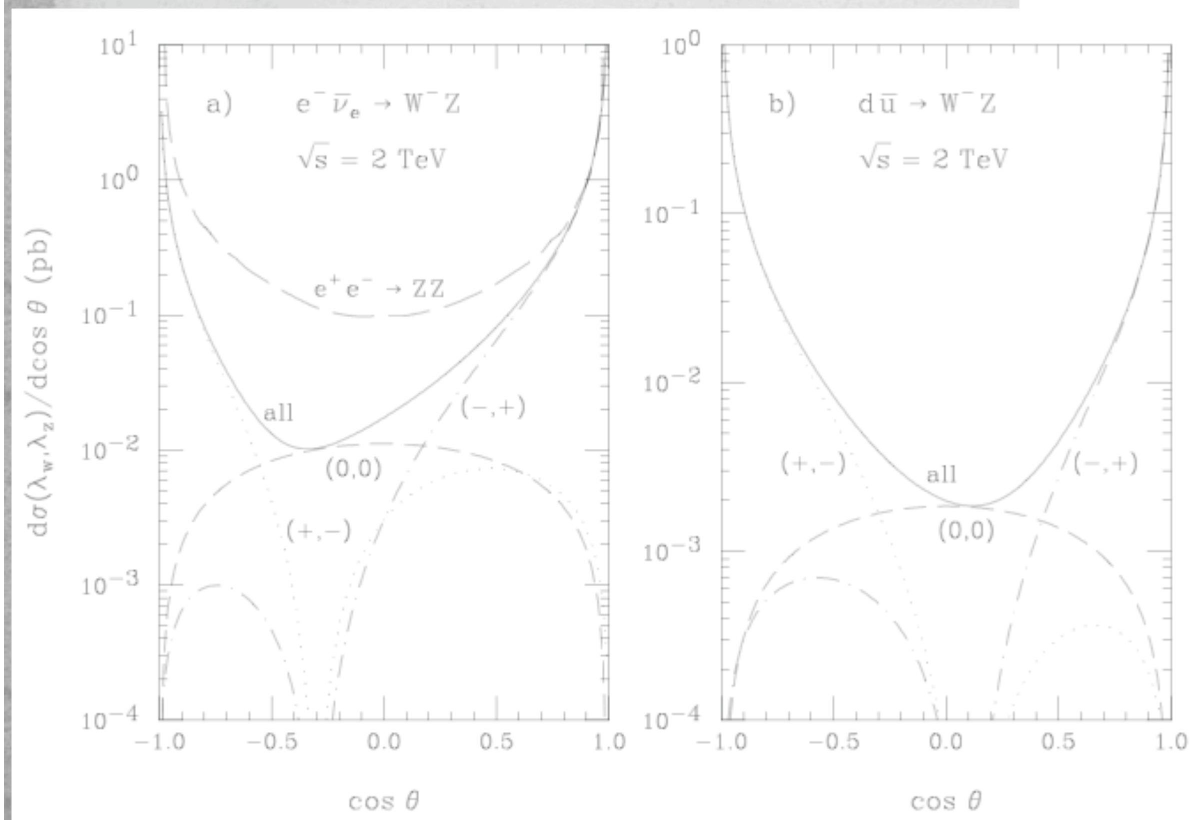


What about WZ production?

The Radiation Amplitude Zero?

M(∓) = F sin θ (λw – cos θ)(g^f1/u + g^f2/t)

$$\cos\theta_0 \simeq \begin{cases} \frac{1}{3}\tan^2\theta_w \simeq 0.1 & \text{for } d\bar{u} \to W^-Z\,, \\ -\tan^2\theta_w \simeq -0.3 & \text{for } e^-\bar{\nu}_e \to W^-Z\,, \\ -\frac{1}{3}\tan^2\theta_w \simeq -0.1 & \text{for } u\bar{d} \to W^+Z\,, \\ \tan^2\theta_w \simeq 0.3 & \text{for } \nu_e e^+ \to W^+Z\,. \end{cases}$$



pproximate zeros !

5 publications by U. Baur, T. Han, and J. Ohnemus:

- **QCD corrections to hadronic Wγ production with nonstandard WWγ couplings. Phys.Rev.D48, 5140 (1993).**
- **Amplitude zeros in W^{+-} Z production. Phys.Rev.Lett.72, 3941 (1994).**
- **WZ production at hadron colliders: Effects of nonstandard WWZ couplings and QCD corrections. Phys.Rev.D51, 3381 (1995).**
- **QCD corrections and nonstandard three vector boson couplings in $W^+ W^-$ production at hadron colliders. Phys.Rev.D53, 1098 (1996).**
- **QCD corrections and anomalous couplings in Zγ production at hadron colliders Phys.Rev.D57, 2823 (1998).**

The Baur-Han-Ohnemus program:
Based on the works:

- **QCD corrections to hadronic Wγ production with nonstandard WWγ couplings**
- **WZ production at hadron colliders: Effects of nonstandard WWZ couplings and QCD corrections**
- **QCD corrections and nonstandard three vector boson couplings in $W^+ W^-$ production at hadron colliders**
- **QCD corrections and anomalous couplings in Zγ production at hadron colliders**

The "BHO" package

- Any VV pair production
- V decay with spin correlations
- NLO QCD corrections
  with full kinematics (phase space slicing)
- Anomalous couplings BSM