Final states with photons and missing energy

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Outline

- neutrino counting (whose importance already stressed yesterday by A. Blondel)
  - invisible width: theoretical issues
  - $\nu\bar{\nu}\gamma$: theoretical status
- Anomalous gauge couplings
- $\nu\bar{\nu}\gamma(\gamma)$ and TQGC
- $\nu\bar{\nu}\gamma\gamma(\gamma)$ and QCG

N_ν from Z invisible width

$$R^0_{\rm inv} = \frac{\Gamma_{\rm inv}}{\Gamma_{ll}} = \sqrt{\frac{12\pi R^0_l}{\sigma^0_{\rm had} m_Z^2}} - R^0_l - (3 + \delta_\tau)$$

- assuming lepton universality

$$\left(R^0_{\rm inv}\right)_{\rm exp} = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{ll}}\right)_{\rm SM}$$

- from LEP Z-peak measurements

$$\begin{aligned} N_\nu &= 2.9840 \pm 0.0082 \\ \delta N_\nu &\simeq 10.5 \frac{\delta n_{\rm had}}{n_{\rm had}} \oplus 3.0 \frac{\delta n_{\rm lept}}{n_{\rm lept}} \oplus 7.5 \frac{\delta \mathcal{L}}{\mathcal{L}} \\ \frac{\delta \mathcal{L}}{\mathcal{L}} &= 0.061\% \Longrightarrow \delta N_\nu = 0.0046 \end{aligned}$$

ADLO, SLD and LEPEWWG, Phys. Rept. 427 (2006) 257, hep-ex/0509008

- δN_ν severely afftected by luminosity uncertainty (theory dominated at LEP)

prospects for improvements on the theory side

- theoretical error in SABH at LEP1

Type of correction/error	(%)	(%)	updated (%)
missing photonic $O(\alpha^2 L)$	0.100	0.027	0.027
missing photonic $O(\alpha^3 L^3)$	0.015	0.015	0.015
vacuum polarization	0.040	0.040	0.040
light pairs	0.030	0.030	0.010
Z-exchange	0.015	0.015	0.015
total	0.110	0.061	0.054

I column: S. Jadach, O. Nicrosini et al. Physics at LEP2 YR 96-01, Vol. 2
A. Arbuzov et al., Phys. Lett. B389 (1996) 129
II column: B.F.L. Ward, S. Jadach, M. Melles, S.A. Yost, hep-ph/9811245
III column: G. Montagna et al., Nucl. Phys. B547 (1999) 39

- recent progress in complete two-loop pure photonic contributions to QED Bhabha scattering

Bern, Dixon, Ghinculov Phys. Rev. D63 (2001) 053007
A. Penin Phys. Rev. Lett., 95 (2005) 010408
Becher, Melnikov, JHEP 0706 (2007) 084

  - $\Longrightarrow$ building blocks available for MC programs with th. precision below 0.1% on the perturbative side

Vacuum polarization: historical perspective

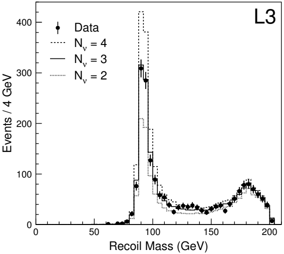
- two kinds of contributions
  - contribution to NLO corrections (and higher orders)
  - irreducible contribution to NNLO corrections
    Bonciani, Ferroglia, Mastrolia, Remiddi, van der Bij, 2004, 2005
    Actis, Czakon, Gluza and Riemann, 2007; Kühn, Uccirati, 2009; Carloni Calame et al., 2011
- reliably calculated for leptons and heavy particles
- calculation not reliable for light hadrons in the loop $\Longrightarrow$ dispersion relations using data for $e^+e^- \to$hadrons
- recent progress in hadronic contributions, thanks to precise data at low energies e^+e^- meson factories   Actis et al., EPJC66 (2010) 585
- $\Delta\alpha(M_Z^2) = 0.0280 \pm 0.0007 \Longrightarrow \alpha^{-1}(M_Z^2) = 128.89 \pm 0.09$
  H. Burkhardt and B. Pietrzyk, Phys. Lett. B356 (1995) 398
- $\Delta\alpha(M_Z^2) = 0.02750 \pm 0.00033$ H. Burkhardt and B. Pietrzyk, Phys. Rev. D84 (2011) 037502
- $\Delta\alpha(M_Z^2) = 0.027498 \pm 0.000135[0.027510 \pm 0.000218]$
  F. Jegerlehner, arXiv:1107.4683
- $\Delta\alpha(M_Z^2) = 0.02757 \pm 0.0001$ Davier, Hoecker, Malaescu, Zhang, arXiv:1010.4180
- $\Delta\alpha(M_Z^2) = 0.027626 \pm 0.000138$ T. Teubner et al., Nucl. Phys. Proc. Suppl. 225 (2012) 282

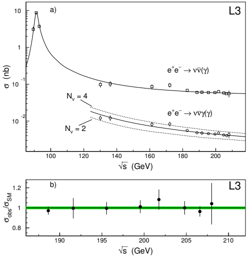
What would be now the uncertainty induced on SABS?

Alternative way for ν count: $\nu\bar{\nu}\gamma$ and LEP2 results

- no need to tune the collider energy at the Z peak (radiative return)
- provided large enough luminosity available to be competitive with $\Gamma_{\rm inv}$ method

$$190 \text{ GeV} \leq \sqrt{s} \leq 208 \text{ GeV}, \ \mathcal{L} \sim 600 \text{ pb}^{-1}$$





L3 Collab., P. Achard et al., CERN-EP/2003-068 (2003)

- agreement data vs. SM at the % level
- $N_\nu = 2.98 \pm 0.05 \pm 0.04$ (L3) (important but not competitive with the $\Gamma_{\rm inv}$ method)
- similar results for ALEPH, DELPHI and OPAL

Theoretical tools used @LEP

- target theoretical precision $\sim$ % level
- tree-level approximation supplemented with large higher order QED corrections and universal running coupling corrections
- two main different approaches
  - KORALZ/KKMC Jadach, Ward, Was, Nucl. Phys. Proc. Suppl. 116 (2003) 77; CPC (1994)
    - add QED corrections to the kernel $e^+e^- \to \nu\bar{\nu}$ via YFS formalism
  - NUNUGPV (Grc$\nu\bar{\nu}\gamma$)
    Montagna, Moretti, Nicrosini, Piccinini, NPB541 (1999) 31
    Montagna, Nicrosini, Piccinini, Trentadue, NPB452 (1995) 161
    Kurihara, Fujimoto, Ishikawa, Shimizu, CPC136 (2001) 250
    - add QED corrections on top of the $e^+e^- \to \nu\bar{\nu}\gamma$ kernel (through structure functions or QED parton shower)
    - removal of double counting from ISR hard photons and matrix element ones (the QED analog of CKKW approach to the QCD showerand matrix element corrections @LHC)

$$\sigma^{1\gamma(\gamma)} = \int dx_1 dx_2 dc_\gamma^{(1)} dc_\gamma^{(2)}\, \tilde{D}(x_1, c_\gamma^{(1)}; s) \tilde{D}(x_2, c_\gamma^{(2)}; s) \Theta(cuts) \times \left(d\sigma^{1\gamma} + d\sigma^{2\gamma} + d\sigma^{3\gamma} + ...\right)$$

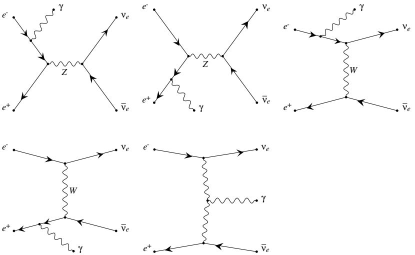
$\nu\bar{\nu}\gamma$: ratio measurements at TLEP

- a factor $10^3/10^4$ of improvement in luminosity @TLEP w.r.t. LEP allows to exploit the ratios

$$\frac{d\sigma(e^+e^- \to \nu\bar{\nu}\gamma)}{d\sigma(e^+e^- \to \mu^+\mu^-\gamma)}$$

in order to cancel common systematics (such as luminosity)

see talk by A. Blondel



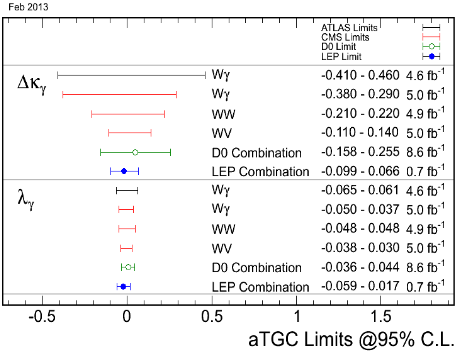
- $\mu^+\mu^-$ only $s-$channel but ISR and FSR
- ν_μ and ν_τ f.s.: only $s-$channel FSR
- ν_e f.s.: ISR with $t-$channel
- ν_e f.s.: also W radiation

- QED and EW corrections do not cancel completeley in the ratio
- but now the technology for $2 \to 3$ EW one-loop calculations is available!

$\nu\bar{\nu}\gamma$ as a signature to study the $WW\gamma$ vertex

$$\mathcal{L}_{WWV} = g_{WWV}\Big[i g_1^V V_\mu \left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+ \right) + i(1 + \Delta\kappa_V) W_\mu^- W_\nu^+ V_{\mu\nu} + i \frac{\lambda_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda}$$
$$+ g_4^V W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu\right) + g_5^V \epsilon_{\mu\nu\lambda\rho} \left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+ \right) V_\rho$$
$$+ i\tilde{\kappa}_V W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + i \frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda} \Big]$$

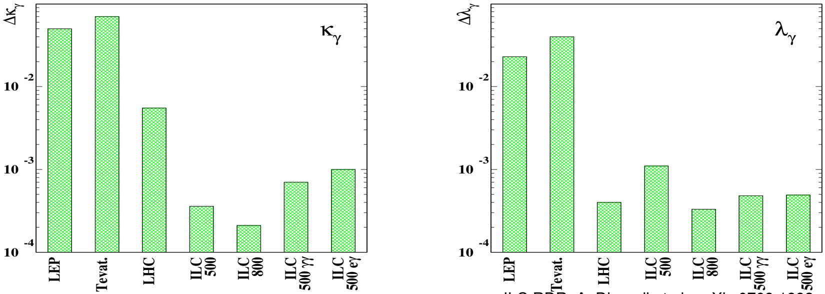
K. Hagiwara et al., Nucl. Phys. B282 (1987) 253



V. Lombardo, on behalf of ATLAS and CMS, arXiv:1305.3773

Comparison on γ TGC's among different machines

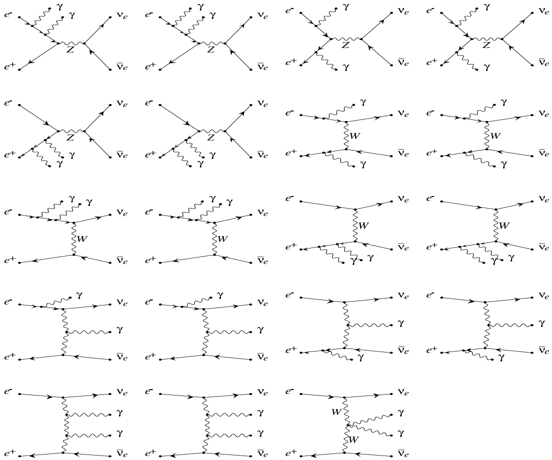
- a factor of $\sim 10^4$ increase in $\mathcal{L}$ w.r.t. LEP at $\sqrt{s}$ above WW threshold allows TLEP to be competitive with ILC on Δk_γ and λ_γ



ILC RDR, A. Djouadi et al., arXiv:0709.1893

EW NLO corrections necessary because they mask possible non standard values

$\nu\bar{\nu}\gamma\gamma$: a window on genuine QAGC



$WW\gamma\gamma$ (and $ZZ\gamma\gamma$) QAGC

- a parameterization of genuine QAGC with at least one photon can be given in terms of dimension six operators which do not lead to TGCs

G. Belanger and F. Boudjema, Phys. Lett. B288 (1992) 201

- with the requirement of C, P, $U(1)_{em}$ and $SU(2)_c$ symmetries two different Lorentz structures contribute

$$\mathcal{L}_0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}\vec{W}^{\alpha}\vec{W}_{\alpha}$$
$$\mathcal{L}_c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}\vec{W}^{\alpha}\vec{W}_{\beta}$$

- In terms of physical fields, $\mathcal{L}_0$ and $\mathcal{L}_c$ give rise to $WW\gamma\gamma$ and $ZZ\gamma\gamma$ interactions

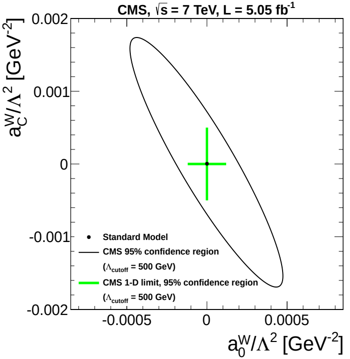
present limits on QAGC

- at LEP studies performed with $\nu\bar{\nu}\gamma\gamma$ and $q\bar{q}\gamma\gamma$ channels for QAGC's involving $ZZ\gamma\gamma$

Parameter	ALEPH	L3	OPAL	Combined
a_c^Z/Λ^2 [GeV^{-2}]	$[-0.041, \ +0.044]$	$[-0.037, \ +0.054]$	$[-0.045, \ +0.050]$	$[-0.029, \ +0.039]$
a_0^Z/Λ^2 [GeV^{-2}]	$[-0.012, \ +0.019]$	$[-0.014, \ +0.027]$	$[-0.012, \ +0.031]$	$[-0.008, \ +0.021]$

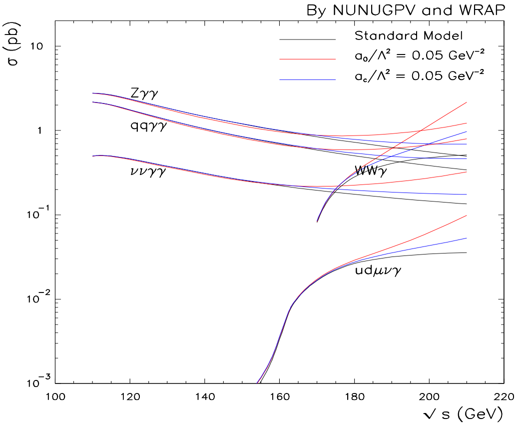
LEP Coll. and LEPEWWG, hep-ex/0612034

- at LHC, strong constraints with first studies of $\gamma\gamma \to W^+W^-$



CMS Coll., arXiv:1305.5596

Comparison of cross sections at (T)LEP energies



Montagna, Moretti, Nicrosini, Osmo, Piccinini, Phys. Lett. B515 (2001) 197; Eur. Phys. J. C21 (2001) 291