Radiative corrections and MC generators for physics at flavor factories

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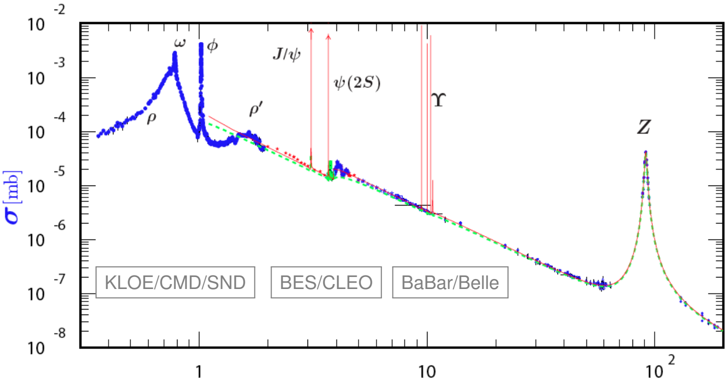
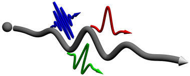
Physics at flavor factories



- Flavor physics
- Measurement of $\sigma_{\text{had}} \longrightarrow g-2$ and $\Delta\alpha_{\text{had}}(q^2)$
- Search for QCD exotic states and studies of QCD
- Precision tests of the SM and searches for New Physics (dark photon, light Higgs...)
- Physics of the τ lepton

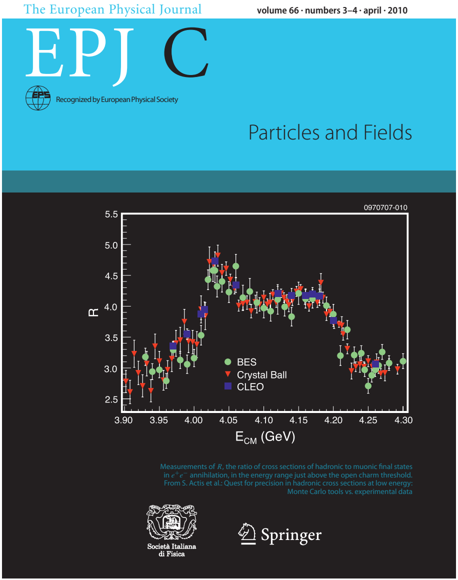
- Intensity frontier $\longrightarrow$ **precision calculations**
  - ISR and radiative return
  - FSR and bremsstrahlung in decays
  - Precision luminosity (Bhabha scattering / $\gamma\gamma$) and normalization ($\mu^+\mu^-\gamma$)
  - QED processes (signals and backgrounds)



- **Monte Carlo generators** needed for simulations and data–theory comparison under complex selection criteria

- **Theoretical methods**
  - Fixed–order: QED at NLO, NNLO
  - QED resummation: collinear Structure Functions, Parton Shower, exclusive exponentiation (YFS, CEEX)
  - Matching: NLO $\otimes$ resummation

The quest for precision



S. Actis *et al.*
Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data
Eur. Phys. J. C66 (2010) 585-686

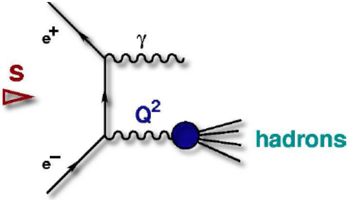
WG coordinated by H. Czyż and G. Venanzoni
`http://www.lnf.infn.it/wg/sighad/`

- Luminosity
- R measurement
- ISR
- Tau
- Hadronic VP, $g-2$ and $\Delta\alpha$
- $\gamma\gamma$ physics
- FSR models

Radiative return: the PHOKHARA generator

Arbuzov *et al.*, 1998

- ▷ Measurement of $\sigma_{\rm had}$ over the full range of energies, from threshlod to $\sqrt{s}$
- ▷ Large luminosity compensates α/π from photon radiation



$$\boxed{d\sigma(e^+e^- \to {\rm hadrons} + \gamma_{\rm ISR})} =$$
$$\boxed{d\sigma(e^+e^- \to {\rm hadrons})(s = Q^2)H(Q^2, \theta_\gamma)}$$

Reference MC – PHOKHARA http://ific.uv.es/~rodrigo/phokhara

successor of EVA for $e^+e^- \to \pi^+\pi^-\gamma, 4\pi + \gamma$ [ISR at LO + QED Structure Functions]

Binner, Kühn and Melnikov, 1999

Czyż and Kühn, 2001

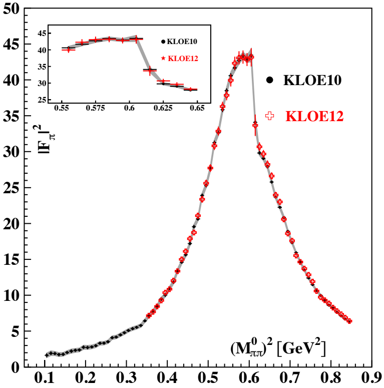
- Channels: $\pi^+\pi^-, \mu^+\mu^-, 3\pi, 4\pi, N\bar{N}, KK, \Lambda\bar{\Lambda}, J/\psi, \psi(2S)$
- Tagged or untagged photons
- ISR at NLO for all channels ($\sim 0.5\%$ precision due to missing h.o. corrections)
- FSR at NLO (point-like approx.): $\pi^+\pi^-, p\bar{p}, K^+K^-$
- Complete NLO corrections to $\mu^+\mu^-\gamma$

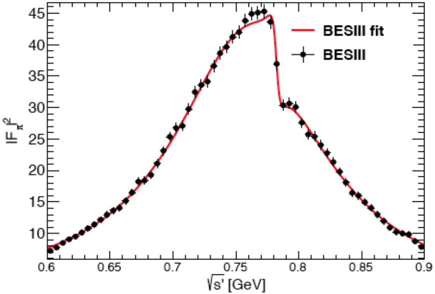
Campanario *et al.*, 2014

$e^+e^- \to \pi^+\pi^-\gamma$: measurements using PHOKHARA

KLOE

BESIII





The pion form factor from KLOE10 [ArXiv:1006.5313] and KLOE12 [ArXiv:1212.4524] measurements.

The pion form factor from BESIII [ArXiv:1507.08188]

Generators for energy scan

- MCGPJ. By Dubna–Novosibirsk group. Used at VEPP–2M.

  Arbuzov *et al.*, 2005

  - Channels: $\pi^+\pi^-, K^+K^-, K^0\bar{K^0}$. New multihadron final states in progress.
  - Complete NLO plus collinear Structure Functions.
  - FSR using scalar QED. Coulomb correction.
  - Theoretical accuracy: $\sim 0.2\%$

- PHOKHARA 8.0

  Czyż *et al.*, 2013

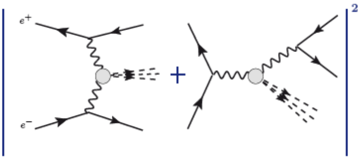
  - Channels: same as in PHOKHARA.
  - ISR at NNLO w/o multiple photon emission. No FSR.
  - Few 0.1% agreement with MCGPJ and KKMC (muon pair).

- `carlomat 3.0` – Automatic tool for complex topologies.

  Kolodziej, 2015

  - Channels: hadrons + photons + lepton pairs, based on Resonance Chiral Lagrangian ($R\chi L$) Theory or Hidden Local Symmetry model.
  - No radiative corrections.

$\gamma\gamma$ physics



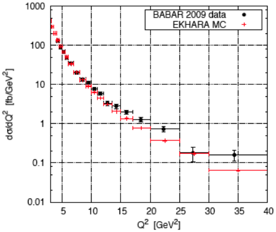
- ▷ Test of QCD and measurement of photon–meson transition form factors
- ▷ Constrain models for LbyL contribution to $g-2$

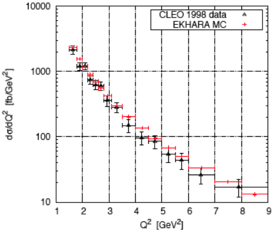
- Various codes using Equivalent Photon Approximation (EPA), among which TREPS (Uheara, 2013) used by Belle.
- **Reference MC** – EKHARA

http://prac.us.edu.pl/~ekhara

Czyż and Ivashyn, 2008-2012

  - Channels: $e^+e^- \to e^+e^-\pi^+\pi^-$ and $e^+e^- \to e^+e^-\pi^0, \eta, \eta'$ beyond EPA.
  - Forthcoming feature: inclusion of radiative corrections.





Luminosity/QED generators

Luminosity measured with $0.1 \div 1\%$ precision using **large–angle Bhabha** (and $e^+e^- \to \gamma\gamma$) as reference process, **simulated with two independent generators**

$$\boxed{\mathcal{L} = \frac{N_{\rm obs}}{\sigma_{\rm theory}}}$$

Generator	Processes	Theory	Accuracy
BabaYaga 3.5	$e^+e^-, \gamma\gamma, \mu^+\mu^-$	QED Parton Shower	$\sim 0.5\%$
BabaYaga@NLO	$e^+e^-, \gamma\gamma, \mu^+\mu^-$	$\mathcal{O}(\alpha)$ + QED PS	$\sim 0.1\%$
BHWIDE	e^+e^-	$\mathcal{O}(\alpha)$ YFS	$\sim 0.1\%$
MCGPJ	$e^+e^-, \gamma\gamma, \mu^+\mu^-$	$\mathcal{O}(\alpha)$ + coll. SF	$\sim 0.2\%$
KKMC	$\mu^+\mu^-, \tau^+\tau^-, \ldots$	$\mathcal{O}(\alpha)$ CEEX	$\sim 0.1\%$

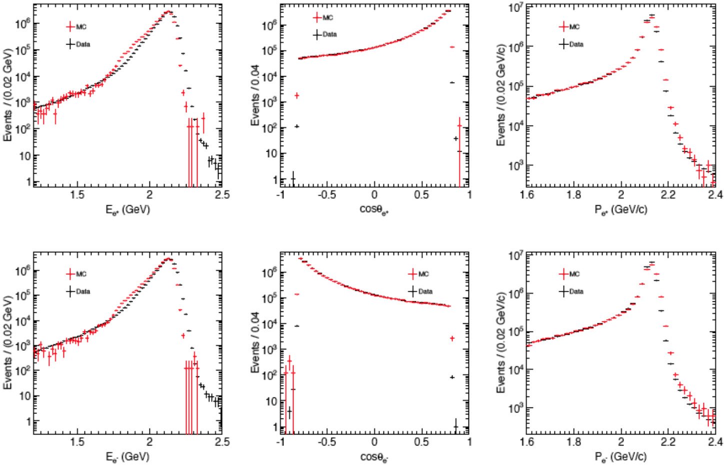
- BabaYaga 3.5/BabaYaga@NLO `http://www2.pv.infn.it/~hepcomplex/babayaga.html`
  Used by BaBar, Belle, BESIII, CLEO, KEDR and KLOE.
  Carloni Calame *et al.*, 2000 / 2006, 2008
- BHWIDE `http://placzek.web.cern.ch/placzek/bhwide/`
  Used by BaBar, BESIII, KEDR, KLOE and SND.
  Jadach, Placzek and Ward, 1997
- MCGPJ `http://cmd.inp.nsk.su/~sibid/`
  Used by CMD, Belle and SND.
  Arbuzov *et al.*, 2005 / Eidelman *et al.*, 2011
- KKMC `http://jadach.web.cern.ch/jadach/KKindex.html`
  Used by BaBar, Belle and BESIII (τ physics, ISR and NP studies).
  Jadach *et al.*, 2000

Luminosity measurement using BabaYaga

BESIII Coll., `ArXiv:1503.03408`

$\mathcal{L}$ to 1% precision using Bhabha events

+ MC = BabaYaga 3.5



▷ New BESIII measurement of $e^+e^- \to \pi^+\pi^-$ cross section based on $\mathcal{L}$ measurement with total 5‰ uncertainty (BabaYaga@NLO)

BESIII Coll., `ArXiv:1507.08188`

Sources of uncertainty and Bhabha at NNLO in QED

- Most important h.o. corrections beyond NLO included in the generators:

$$\sum_{n=2}^{\infty} \alpha^n/n!\, L^n \ , \ L = \text{coll. log} \simeq 15 \qquad \text{(exponentiation)}$$

$$\alpha^2/2\, L \qquad \text{(fact. matching/approximated)}$$

- **Sources of uncertainty**: vacuum polarization (parametric, driven by σ_{had}) and incomplete NNLO corrections

- **NNLO QED corrections to Bhabha available $\longrightarrow$ benchmark for MC accuracy**
  - Photonic corrections (dominant contribution)

    Penin, 2005 / 2006
    Becher and Melnikov, 2007
  - Electron loop corrections

    Bonciani *et al.*, 2004 / 2005
    Actis *et al.*, 2007
  - Heavy fermion and hadronic loops

    Becher and Melnikov, 2007
    Bonciani *et al.*, 2008
    Actis *et al.*, 2008
    Kühn and Uccirati, 2009
  - Soft+Virtual corrections to hard bremsstrahlung

    Jadach, Ward *et al.*, 1996, 2001
    Actis *et al.*, 2010

Luminosity: total theoretical uncertainty

Updated from: Actis *et al.*, EPJ C66 (2010) 585
arXiv:0912.0749

Source of unc. (%)	1–2 GeV	BESIII	BaBar/Belle
	Vacuum Polarization [1]		
$\|\delta_{\rm VP}\|$ [Jegerlehner]	—	0.01	0.03
$\|\delta_{\rm VP}\|$ [HMNT]	0.02	0.01	0.02
	NNLO		
$\|\delta^{\alpha^2}_{\rm photonic}\|$ [2]	0.02	0.02	0.02
$\|\delta^{\alpha^2}_{\rm pairs}\|$ [3]	0.03	0.02	$0.03 \div 0.07$
$\|\delta^{\alpha^2}_{\rm SV,H}\|$ [4]	0.05 / 0.03	0.05 / 0.03	0.05 / 0.03
$\|\delta^{\alpha^2}_{\rm HH}\|$	—	—	—
$\|\delta_{\bf total}\|$ **quadrature**	$\mathbf{0.07/0.05}$	$\mathbf{0.06/0.04}$	$\sim \mathbf{0.07 \div 0.09}$

- ▷ **Comparable to luminosity theoretical uncertainty at LEP**
- ▷ In proximity of ψ/Υ's resonances, accuracy deteriorates: $\mathcal{L}$ affected by $\sigma_{\rm had}$ uncertainty!

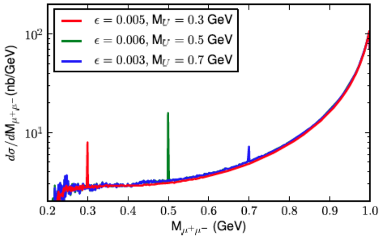
[1] From $\Delta\alpha_{\rm had}(q^2) \pm \delta_{\rm had}$, $\delta_{\rm had}$ returned by VP parameterization.
[2] Carloni Calame *et al.*, 2006: BabaYaga@NLO vs. NNLO photonic by Penin
[3] Carloni Calame *et al.*, 2011: BabaYaga@NLO vs. NNLO (leptonic and hadronic) pairs by DESY Zeuthen – Katowice
[4] Estimated from LEP studies by Jadach, Ward *et al.*
Conservative, WG Report / Less conservative, Jadach *et al.* 1999, 2001

QED processes and New Physics

Signal: $e^+e^- \to A'\gamma$, $A' \to \ell^+\ell^- (\ell = e, \mu)$
A': massive dark photon
ϵ: kinetic mixing parameter

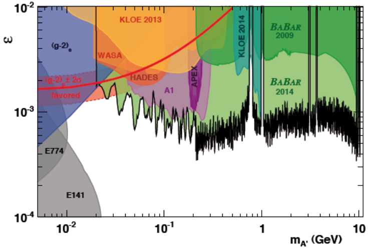
Backgrounds: QED radiative processes

Signature: narrow bump in the $\ell^+\ell^-$ invariant mass spectrum



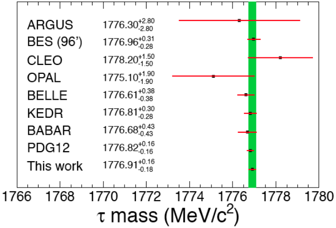
Reference MCs

- KLOE: upgrade of BabaYaga for signal and backgrounds (Barzè *et al.*, 2011)
- BABAR: MadGraph/MadEvent (Alwall *et al.*, 2007) for signal, BHWIDE/KKMC for backgrounds



Physics of the τ lepton

- τ mass and lifetime
- Branching fractions, spectral functions, rare and forbidden decays...



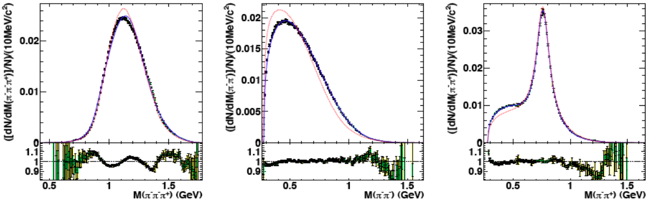
Reference MCs (BaBar, Belle, BESIII)

- $\tau\tau$ production: KKMC / KORALB (Jadach and Was, 1985, 1995)
- τ decays: TAUOLA + PHOTOS `http://wasm.web.cern.ch/wasm/Welcome.html`

TAUOLA: Jadach, Was *et al.*, 1990s / PHOTOS: Barberio, Was *et al.*, 1990s

Recent work in TAUOLA: hadronic currents from $R\chi L$ theory

Roig, Shekhovtsova and Was, 2012–2015



Summary

- Physics at flavor factories needs for **precision calculations** encoded into **MC generators** for
  - hadronic signal processes
  - luminosity and normalization
  - QED processes
  - New Physics searches and physics of the τ lepton

- **Significant progress** over the last decade(s) in predictions and generators for
  - **radiative return**
  - **Bhabha scattering** (Bhabha at NNLO in QED)

- Theory and generators for **luminosity, QED processes, New Physics searches and τ physics** greatly benefited from **LEP experience**

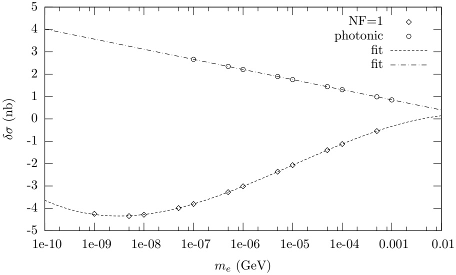
- **Progress expected** in
  - generators for energy scan and $\gamma\gamma$ physics
  - luminosity theoretical precision at the sub–per mille level

Extra

Comparison to NNLO Bhabha: accuracy of BabaYaga@NLO

NNLO Photonic (Penin)

Carloni Calame *et al.*, 2006



- $\delta\sigma \doteq \sigma^{\rm NNLO}_{\rm Penin} - \sigma^{\rm NNLO}_{\rm BabaYaga@NLO}$
  $\delta\sigma \leq 0.2\,‰\ \sigma_{\rm LO}$
- $\delta\sigma/\sigma_{\rm LO} \propto \alpha^2 L$ and infrared–safe

Leptonic and hadronic pairs

Carloni Calame *et al.*, 2011

	$\sqrt{s}$		$\sigma_{\rm BY}$(nb)	$S_{e^+e^-}$ [‰]	$S_{\rm lep}$ [‰]	$S_{\rm had}$ [‰]	$S_{\rm tot}$ [‰]
KLOE	1.020	NNLO		-3.935(5)	-4.472(5)	1.02(4)	-3.45(4)
		BabaYaga	455.71	-3.445(2)	-4.001(2)	0.876(5)	-3.126(5)
BES	3.650	NNLO		-1.469(9)	-1.913(9)	–1.3(1)	-3.2(1)
		BabaYaga	116.41	-1.521(4)	-1.971(4)	-1.071(4)	-3.042(5)
BaBar	10.56	NNLO		-1.48(2)	-2.17(2)	-1.69(8)	-3.86(8)
		BabaYaga	5.195	-1.40(1)	-2.09(1)	-1.49(1)	-3.58(2)
Belle	10.58	NNLO		-4.93(2)	-6.84(2)	-4.1(1)	-10.9(1)
		BabaYaga	5.501	-4.42(1)	-6.38(1)	-3.86(1)	-10.24(2)

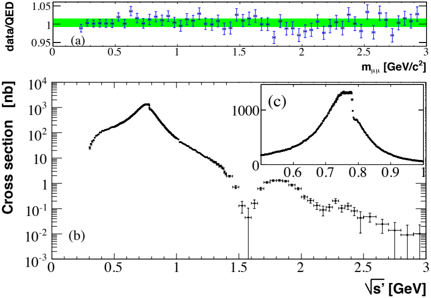
- BabaYaga@NLO accuracy (well) below 1‰

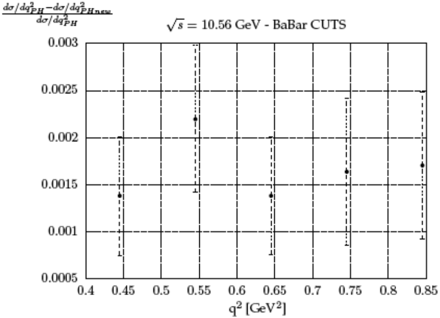
Radiative return

BABAR DATA

Phokhara test of $\mu^+\mu^-\gamma$ at NLO

ArXiv:1312.3610

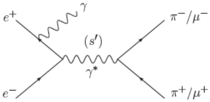


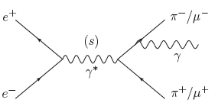


$\pi^+\pi^-$ cross section from $e^+e^- \to \pi^+\pi^-\gamma$ normalized to $e^+e^- \to \mu^+\mu^-\gamma$. ArXiv:0908.3589

Radiative return: QED tests

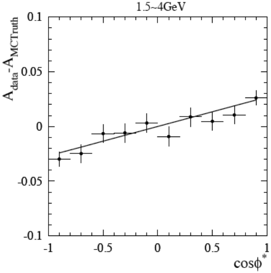
BaBar Coll., `1508.040080`
with AfkQed, Arbuzov *et al.*, 1997 + PHOKHARA



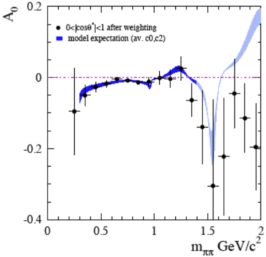


$$\mathcal{A} = \frac{|\mathcal{M}|^2 - |\mathcal{M}(\mu^+/\pi^+ \leftrightarrow \mu^-/\pi^-)|^2}{|\mathcal{M}|^2 + |\mathcal{M}(\mu^+/\pi^+ \leftrightarrow \mu^-/\pi^-)|^2} = \frac{2\,\mathcal{R}e\,\mathcal{M}_{\rm ISR}\mathcal{M}^*_{\rm FSR}}{|\mathcal{M}_{\rm ISR}|^2 + |\mathcal{M}_{\rm FSR}|^2}$$

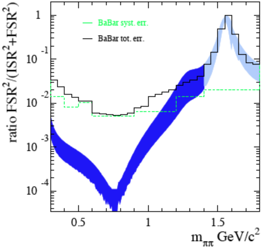
Muon Asymmetry



Pion Asymmetry



Pion FSR



- ▷ Muon ISR-FSR interference in substantial agreement with QED, but with some deviation
- ▷ Pion FSR: inconsistency with scalar QED around ρ / negligible contribution to $a_\mu^{\rm had,LO}$