Bremsstrahlung – high energy

in context of electroweak corrections for Z, W production and decays at LHC

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- **(1)** W measurements use LEP obtained Z properties as reference. Lepton univesality help to combine/compare results from e, μ, τ channels but their detector response differs. Direction of leptons are best measured quantities at LHC! QED FSR is not separable from detector studies.

What is better? Divide TH predictions into parts: worry/profit from that, or use overall black-box TH MC.

- **(2)** Decision depend on complexity of detector response and theoretical system. The higher precision the more details on theoretical AND experimental sides needed.

FSR first ...

- **(1)** FSR QED is the part of electroweak correction which is not lepton universal. Not only because of different collinear logarithms $\ln \frac{Q^2}{m_l^2}$, but also detector responses.
- **(2)** *How precisely QED FSR separates from the rest of spin amplitudes (or distributions):* genuine weak corrections, ISR, ISR$\times$PS, ISR-FSR interference.
- **(3)** *Claim:* Precision of FSR radiation MC simulation using PHOTOS algorithm is not worse for W, Z observables at LHC than 0.2%. Also separation of FSR correction from the rest of EW, can be controlled at necessary precision level.
- **(4)** To justify this claim I will present some results. Talk of Stanislaw Jadach will explain method for further tests or even new tool for LHC applications.
- **(5)** Precision claims are for PHOTOS F77 version 2.15, P. Golonka and Z. Was, EPJC 45 (2006) 97. It was until now in use by experiments.
- **(6)** Recent papers with tests: Thi Kieu Oanh Doan, W. Placzek, Z. Was arXiv:1303.2220, Phys. Lett. B in print, A.B. Arbuzov, R.R. Sadykov, Z. Was, arXiv:1212.6783 help to establish precison for all FSR at 0.2 % (0.1% for photonic bremstrahlung only).

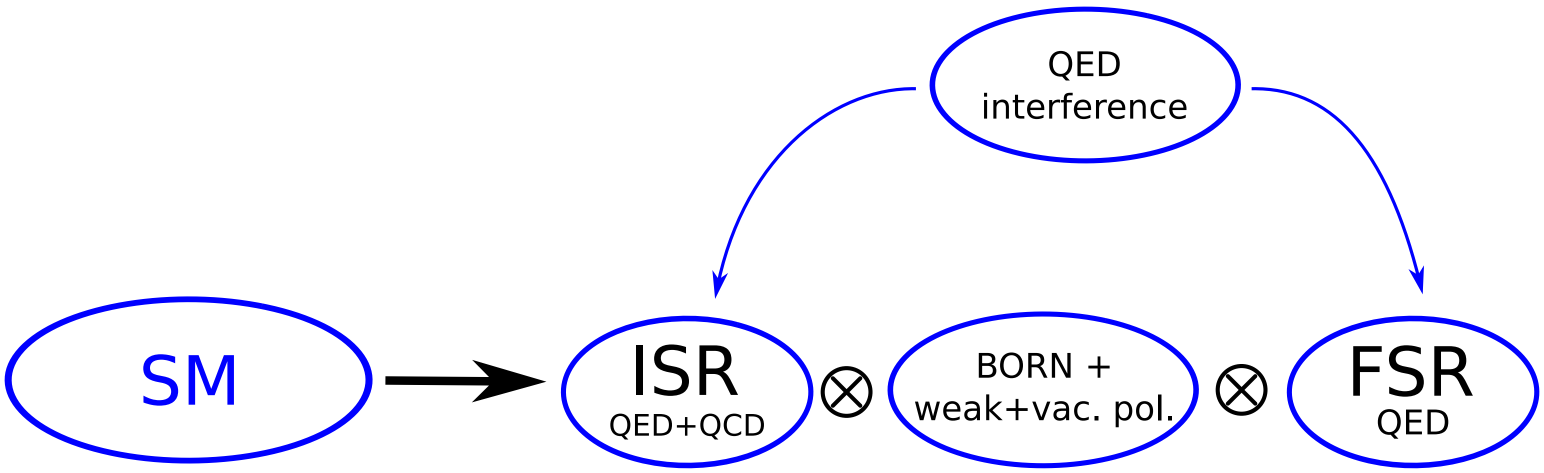
What FSR mean: spin amplitude level.

- At Born level cross section involving W and Z propagators is singular: $\frac{1}{s-M^2_{Z,W}}$. This is seemingly trivial to heal. Replace propagator with the effective one $\frac{1}{s-M^2_{Z,W}+i\Gamma_{Z,W}M_{Z,W}}$. Partial resummation of loop corrections to all orders must be performed!

- By-product: separation of other parts of amplitudes, such as QED/QCD ISR, QED FSR. No loss of precision is then involved. See eg. The standard model in the making: Precision study of the electroweak interactions. Dmitri Yu. Bardin, (Dubna, JINR) , G. Passarino, Oxford, UK: Clarendon (1999) 685 p.

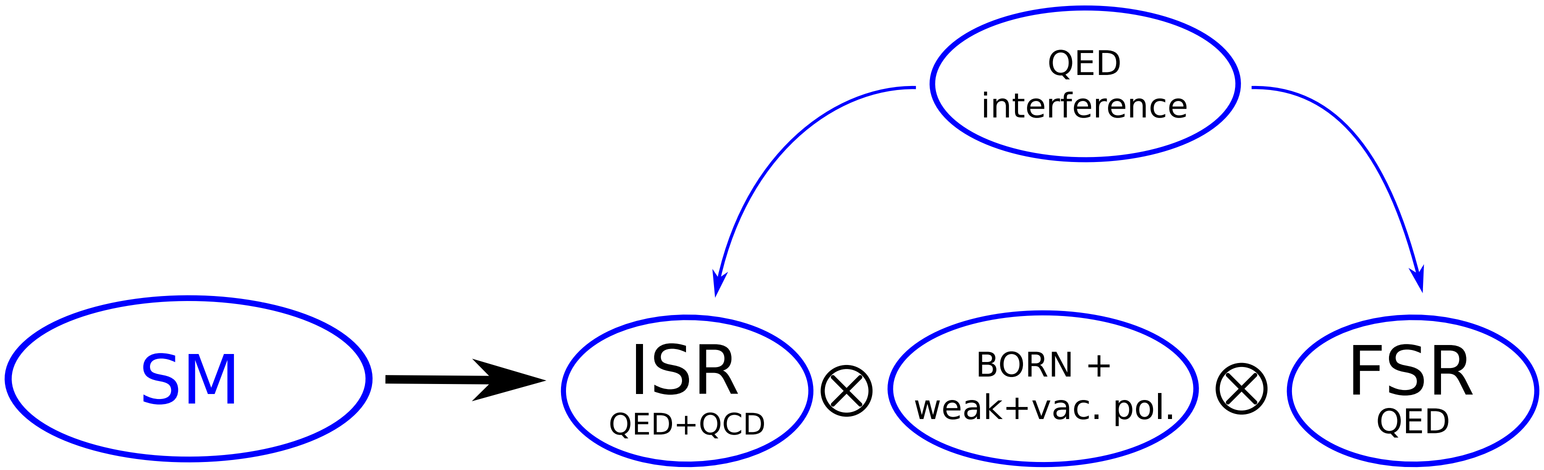
- Leading pole approximation as in U. Baur NLO calculation for $W\gamma$ anomalous coupling (Phys. Rev. D 47 (1993) 4889), simplifies the issue of QED FSR separation from rest of EW effects. Nearly direct consequence of formula:
$$\frac{1}{\left((P+k)^2-M_W^2\right)\left(P^2-M_W^2\right)} = \left(\frac{1}{P^2-M_W^2} - \frac{1}{(P+k)^2-M_W^2}\right)\frac{1}{2Pk}$$

What FSR mean: distribution level.



- Use of leading pole approximation as in NLO calculation of U. Baur simplifies the issues of QED ISR-FSR interference.
- For W or Z signatures QED ISR-FSR interference is suppresed by a factor $\Gamma_{Z,W}/M_{Z,W}$ and remain at sub-permille level. Consequence of boson's lifetime separating ISR and FSR effects. Hold if selection cuts are not too strict to damage separation by uncertainty principle (Phys.Lett.B465:254,1999).

What FSR mean: data analysis strategy.



- BORN + weak+ vac pol $\longrightarrow$ Signature definition; theorist way
- ISR will change signature. Smearing must be understood in context of other measurements PDF's UE's detector response to extra jets, uncertainties on missing p_T, etc.
- FSR must be understood in context of detector response.

  The same is true for τ decays.

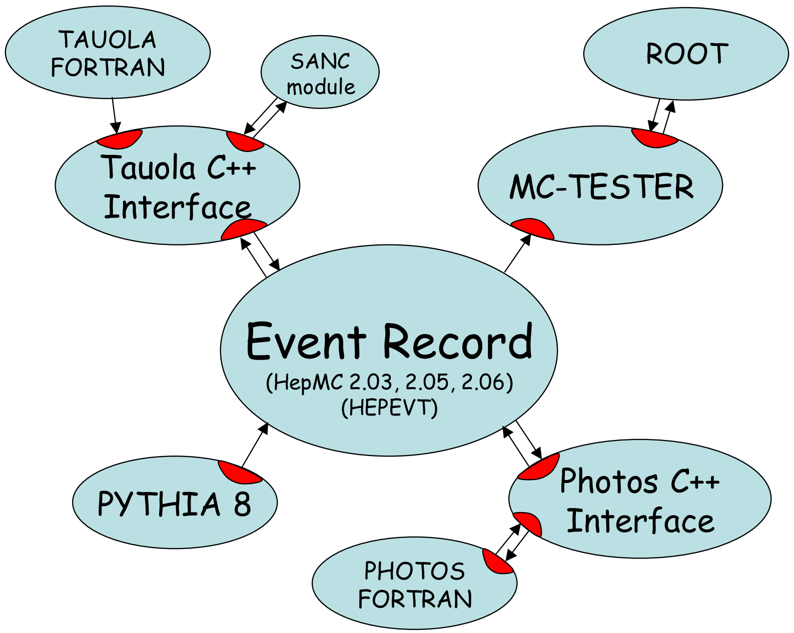
Introduction to numerical precision

- One want to measure W using known properties of Z: for example energy scale calibration for e.
- Theoretical predictions need to concentrate on common parts which may be not known and distinct ones which must be controlled very well including detector effects
- FSR bremsstrahlung on/off
- Parts of FSR which are specific to Z and W decays on off.
- Common ground for final states with e, μ, τ channels must be found.

  Discussed Alternatives:
  - lepton electromagnetic shower cone,
  - FSR and τ decays removed to obtain distributions FSR free.

programs organization

For detector level studies simulation parts should communicate through event record:



- Parts:

- hard process: (Born, weak, **new physics**),
- parton shower,
- τ decays
- QED bremsstrahlung

- High precision achieved

- Detector studies: acceptance, resolution lepton with or wihout photon.

Such organization requires:

- Good control of factorization (theory)
- Good understanding of tools on user side.

In interface no (or limited) use of non-measurable quantities.

Projects in collaboration with: N. Davidson, Piotr Golonka, G. Nanava, T. Przedzinski, E. Richter-Was, Q. Xu, O. Shekhovtsova, P. Roig.

Thanks for discussions with LCG/Genser, ATLAS, CMS, CDF, Belle BaBar members.

programs organization

- **Presentation of PHOTOS**

1. References+ basic principles

- **Presentation of new version and programs used for tests.**

1. References+ basic principles

- **Discussion of systematic errors.**

1. Physical uncertainty, technical uncetrainty, quality of environment, dependence on observable definition.
2. All this is repetition of what was done at LEP.

Presentation

- PHOTOS (by E.Barberio, B. van Eijk, Z. W., P.Golonka) is used to simulate the effect of radiatiative corrections in decays, since 1989.
- Full events combining complicated tree structure of production and subsequent decays are fed into PHOTOS, usually with the help of HEPEVT event record of F77
- PHOTOS version for HepMC event record used in C++ applications is in GENSER LCG library: F77 and C++ too.
- At every branching of event tree, PHOTOS intervene. With certain probability extra photon(s) are added and kinematics of other particles adjusted.
- PHOTOS algorithm is iterative. First over emitters; interference (or matrix element) weight is used. Iteration over consecutive emissions is external.
- Solution enables full multiphoton phase space coverage, compatibility with exponentiation and resummation of collinear terms at the same time.

Main References

- E. Barberio, B. van Eijk and Z. Was, Comput. Phys. Commun. **66**, 115 (1991): single emission
- E. Barberio and Z. Was, Comput. Phys. Commun. **79**, 291 (1994). double emission introduced, tests with second order matrix elements
- P. Golonka and Z. Was, EPJC 45 (2006) 97 multiple photon emisson introduced, tests with precioson second order exponentiation MC. used in experiments until 2011
- P. Golonka and Z. Was, EPJC 50 (2007) 53 full ME in Z decay, test version
- G. Nanava, Z. Was, Eur.Phys.J.C51:569-583,2007, best description of phase space
- G. Nanava, Z. Was, Q. Xu, Eur.Phys.J.C70:673,2010. full ME for W decay, test version
- N. Davidson, T. Przedzinski, Z. Was, arXiv:1011.0937 program C++ web page: http://www.ph.unimelb.edu.au/˜ndavidson/photos/doxygen/index.html HepMC interfacefull ME in Z decay presently used in experiments.

Phase Space: exact

Orthodox exact Lorentz-invariant phase space (*Lips*) is in use in PHOTOS!

$$
\begin{aligned}
& dLips_{n+1}(P) = \\
& \frac{d^3k_1}{2k_1^0(2\pi)^3} \cdots \frac{d^3k_n}{2k_n^0(2\pi)^3} \frac{d^3q}{2q^0(2\pi)^3} (2\pi)^4 \delta^4\Big(P - \sum_1^n k_i - q\Big) \\
= \quad & d^4p\delta^4(P-p-q) \frac{d^3q}{2q^0(2\pi)^3} \frac{d^3k_1}{2k_1^0(2\pi)^3} \cdots \frac{d^3k_n}{2k_n^0(2\pi)^3} (2\pi)^4 \delta^4\Big(p - \sum_1^n k_i\Big) \\
= \quad & d^4p\delta^4(P-p-q) \frac{d^3q}{2q^0(2\pi)^3} dLips_n(p \to k_1 ... k_n).
\end{aligned}
$$

Integration variables, the four-vector p, compensated with $\delta^4\big(p - \sum_1^n k_i\big)$, and another integration variable M_1 compensated with $\delta\big(p^2 - M_1^2\big)$ are introduced.

Phase Space Formula of Photos

$$dLips_{n+1}(P \to k_1...k_n, k_{n+1}) = dLips_n^{+1\ tangent} \times W_n^{n+1},$$

$$dLips_n^{+1\ tangent} = dk_\gamma d\cos\theta d\phi \times dLips_n(P \to \bar{k}_1...\bar{k}_n),$$
$$\{k_1, \ldots, k_{n+1}\} = \mathbf{T}\big(k_\gamma, \theta, \phi, \{\bar{k}_1, \ldots, \bar{k}_n\}\big). \quad (1)$$

1. One can verify that if $dLips_n(P)$ was exact, then this formula lead to exact parametrization of $dLips_{n+1}(P)$
2. Practical implementation: Take the configurations from n-body phase space.
3. Turn it back into some coordinate variables.
4. construct new kinematical configuration from all variables.
5. **Forget about temporary** $k_\gamma\theta\phi$. **From now on, only weight and four vectors count.**
6. A lot depend on $\mathbf{T}$. Options depend on matrix element: must tangent at singularities. Simultaneous use of several $\mathbf{T}$ is possible and necessary/convenient if more than one charge is present in final state.

Phase Space: (main formula)

If we choose

$$G_n \;:\; M^2_{2\dots n}, \theta_1, \phi_1, M^2_{3\dots n}, \theta_2, \phi_2, \dots, \theta_{n-1}, \phi_{n-1} \;\longrightarrow\; \bar{k}_1 \dots \bar{k}_n \qquad (2)$$

and

$$G_{n+1} \;:\; k_\gamma, \theta, \phi, M^2_{2\dots n}, \theta_1, \phi_1, M^2_{3\dots n}, \theta_2, \phi_2, \dots, \theta_{n-1}, \phi_{n-1} \;\longrightarrow\; k_1 \dots k_n, k_{n+1} \qquad (3)$$

then

$$\mathbf{T} = G_{n+1}(k_\gamma, \theta, \phi, G_n^{-1}(\bar{k}_1, \dots, \bar{k}_n)). \qquad (4)$$

The ratio of the Jacobians form the phase space weight W_n^{n+1} for the transformation. Such solution is universal and valid for any choice of G's. However, G_{n+1} and G_n has to match matrix element, otherwise algorithm will be inefficient (factor 10^{10} ...).

In case of PHOTOS G_n's

$$W_n^{n+1} = k_\gamma \frac{1}{2(2\pi)^3} \times \frac{\lambda^{1/2}(1, m_1^2/M^2_{1\dots n}, M^2_{2\dots n}/M^2_{1\dots n})}{\lambda^{1/2}(1, m_1^2/M^2, M^2_{2\dots n}/M^2)}, \qquad (5)$$

Phase Space: (multiply iterated)

By iteration, we can generalize formula (1) and add l particles:

$$dLips_{n+l}(P \to k_1...k_n, k_{n+1}...k_{n+l}) = \frac{1}{l!} \prod_{i=1}^{l} \Big[dk_{\gamma_i} d\cos\theta_{\gamma_i} d\phi_{\gamma_i} W^{n+i}_{n+i-1} \Big]$$
$$\times dLips_n(P \to \bar{k}_1...\bar{k}_n), \qquad (6)$$
$$\{k_1, \dots, k_{n+l}\} = \mathbf{T}\Big(k_{\gamma_l}, \theta_{\gamma_l}, \phi_{\gamma_l}, \mathbf{T}\Big(\dots, \mathbf{T}\Big(k_{\gamma_1}, \theta_{\gamma_1}, \phi_{\gamma_1}, \{\bar{k}_1, \dots, \bar{k}_n\}\Big) \dots\Big).$$

Note that variables $k_{\gamma_m}, \theta_{\gamma_m}, \phi_{\gamma_m}$ are used at a time of the $m-$th step of iteration only, and are not needed elsewhere in construction of the physical phase space; the same is true for invariants and angles $M^2_{2...n}, \theta_1, \phi_1, \dots, \theta_{n-1}, \phi_{n-1} \ \to \ \bar{k}_1 \dots \bar{k}_n$ of (2,3), which are also redefined at each step of the iteration. Also intermediate steps require explicit construction of temporary $\bar{k}'_1 \dots \bar{k}'_n \dots \bar{k}'_{n+m}$, statistical factor $\frac{1}{l!}$ added.

We have **exact distribution** of **weighted** events over l and $n + l$ body phase spaces.

- Fully differential single photon emission formula in Z decay reads:

$$X_f = \frac{Q'^2\alpha(1-\Delta)}{4\pi^2 s} s^2 \quad \left\{ \frac{1}{(k'_+ k'_-)} \left[\frac{\mathrm{d}\sigma_B}{\mathrm{d}\Omega}(s,t,u') + \frac{\mathrm{d}\sigma_B}{\mathrm{d}\Omega}(s,t',u) \right] \right\}$$

- Variables in use:

$$s = 2p_+ \cdot p_-, \quad s' = 2q_+ \cdot q_-, \quad t = 2p_+ \cdot q_+, \quad t' = 2p_+ \cdot q_-,$$
$$u = 2p_+ \cdot q_-, \quad u' = 2_- \cdot q_+, \quad k'_\pm = q_\pm \cdot k, \quad x_k = 2E_\gamma/\sqrt{s}$$

- The Δ term is responsable for final state mass dependent terms, p_+, p_-, q_+, q_-, k denote four-momenta of incoming positron, electron beams, outcoming muons and bremsstrahlung photon.

- Factorization of first order matrix element and fully differential distribution breaks at the level $\frac{\alpha^2}{\pi^2} \simeq 10^{-4}$

- after trivial manipulation it can be written as:

$$X_f = \frac{Q'^2\alpha(1-\Delta)}{4\pi^2 s} s^2 \quad \left\{ \frac{1}{(k'_+ + k'_-)}\frac{1}{k'_-}\left[\frac{d\sigma_B}{d\Omega}(s,t,u') + \frac{d\sigma_B}{d\Omega}(s,t',u)\right] + \frac{1}{(k'_+ + k'_-)}\frac{1}{k'_+}\left[\frac{d\sigma_B}{d\Omega}(s,t,u') + \frac{d\sigma_B}{d\Omega}(s,t',u)\right]\right\}$$

- In PHOTOS the following kernel is used (decay channel, decay particle orientation, independent):

$$X_f^{PHOTOS} = \frac{Q'^2\alpha(1-\Delta)}{4\pi^2 s} s^2 \left\{ \frac{1}{k'_+ + k'_-}\frac{1}{k'_-}\left[(1+(1-x_k)^2)\frac{d\sigma_B}{d\Omega}\left(s, \frac{s(1-\cos\Theta_+)}{2}, \frac{s(1+\cos\Theta_+)}{2}\right)\right]\frac{(1+\beta\cos\Theta_\gamma)}{2} + \frac{1}{k'_+ + k'_-}\frac{1}{k'_+}\left[(1+(1-x_k)^2)\frac{d\sigma_B}{d\Omega}\left(s, \frac{s(1-\cos\Theta_-)}{2}, \frac{s(1+\cos\Theta_-)}{2}\right)\right]\frac{(1-\beta\cos\Theta_\gamma)}{2}\right\}$$

$$\text{where}: \Theta_+ = \angle(p_+, q_+),\ \Theta_- = \angle(p_-, q_-)$$

$\Theta_\gamma = \angle(\gamma, \mu^-)$ are defined in (μ^+, μ^-)-pair rest frame

Test of universal kernel, case of Z decay

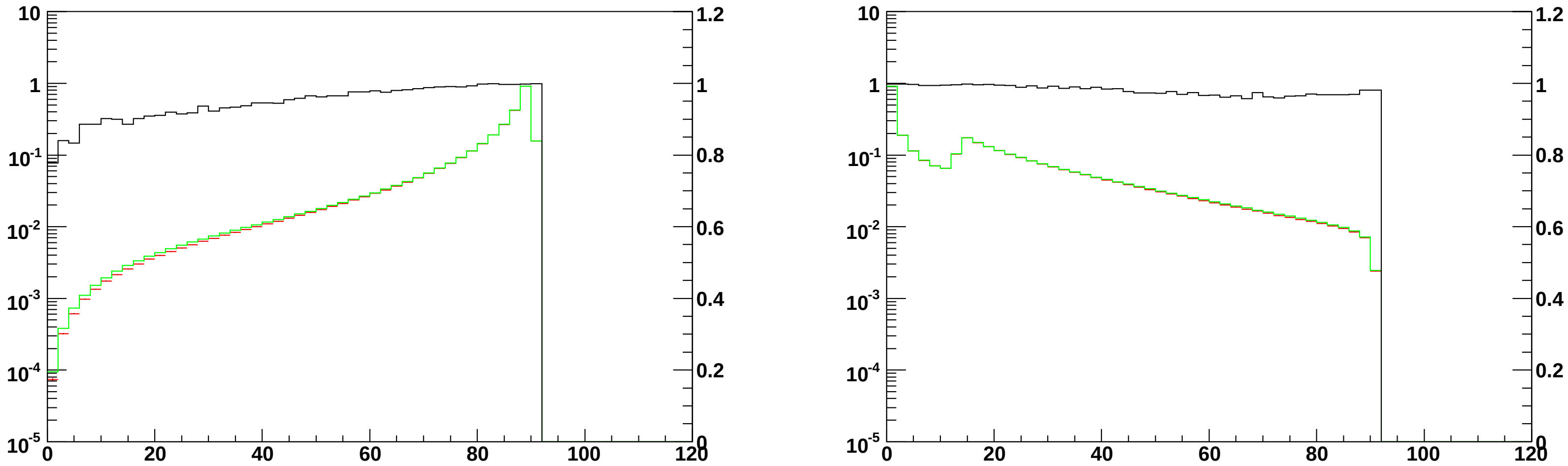


Figure 1: Comparison of standard PHOTOS and KORALZ (Comput. Phys. Commun. **66** *(1991) 276) for single photon emission. In the left frame the invariant mass of the $\mu^+\mu^-$ pair; SDP=0.00534. In the right frame the invariant mass of $\mu^-\gamma$; SDP=0.00296. The histograms produced by the two programs (logarithmic scale) and their ratio (linear scale, black line) are plotted in both frames. The fraction of events with hard photon was 17.4863 $\pm$ 0.0042% for KORALZ and 17.6378 $\pm$ 0.0042% for PHOTOS.*

PHOTOS 2.15 multiple emission

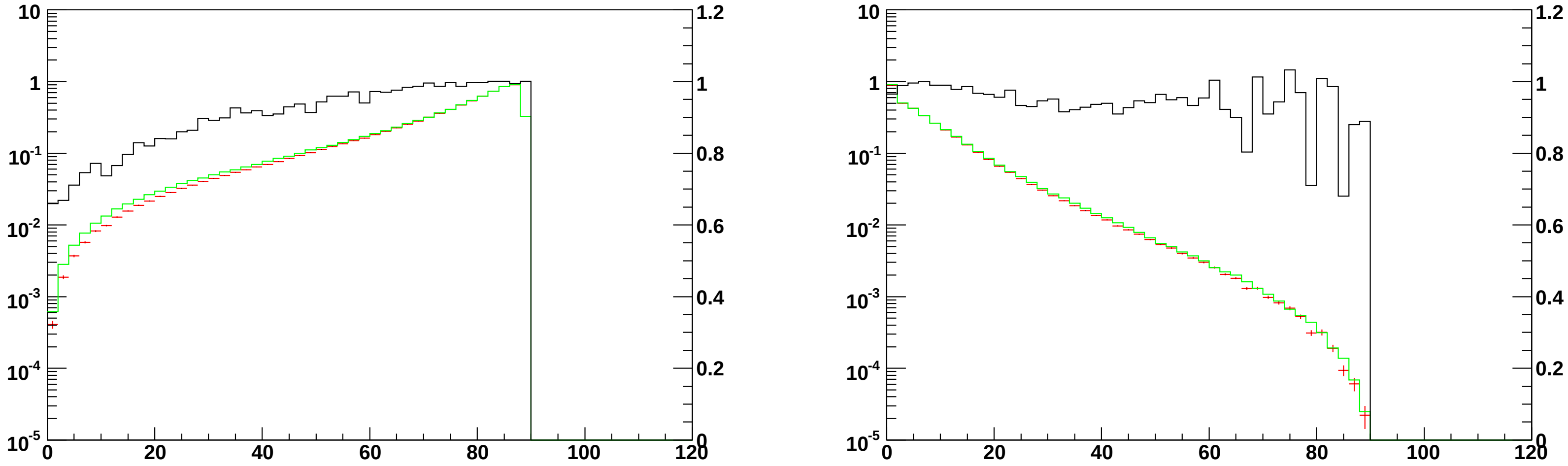


Figure 5: Comparisons of standard PHOTOS with multiple photon emission and KKMC with second order matrix element and exponentiation (Comput. Phys. Commun. **130** *(2000) 260). In the left frame the invariant mass of the $\mu^+\mu^-$ pair; SDP= 0.00918 (shape difference parameter). In the right frame the invariant mass of the $\gamma\gamma$ pair; SDP=0.00268. The fraction of events with two hard photons was 1.2659 $\pm$ 0.0011% for KKMC and 1.2952 $\pm$ 0.0011% for PHOTOS.*

Precision for realistic observables.

- *In case of Z decay:*

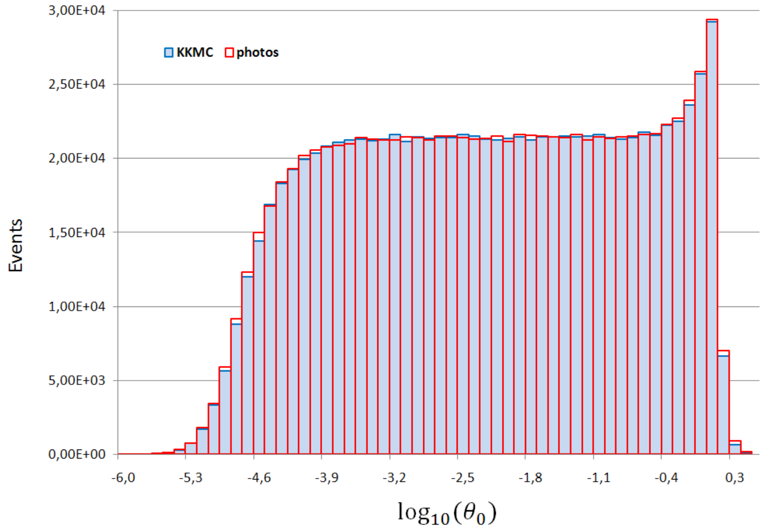
- *Comparisons with KKMC: Monte Carlo used at LEP for precision tests of the SM. KKMC features second order matrix element and exponentiation. Initial state must be monohromatic quarks.*

The only avaiable generator with exponentiation and second order matrix element!

Imoprtant especially for $H \to \gamma\gamma$ background.

- *Histogram of photon angle with respect to closer fermion: $E_\gamma > 4$ MeV,*

PHOTOS 2.15 multiple emission



- *This is for $Z \rightarrow e^+e^-$. Plateau checks LL, left side ultra-collinear photons. Right side is solely populated by hard non-collinear photons.*

- *Starting point for tests requested by experiments (CDF later ATLAS). No other cuts applied yet.*

PHOTOS 2.15 multiple emission

- Large Booklets of KKMC PHOTOS comparisons for $u\bar{u} \to \mu^+\mu^-$:

http://annapurna.ifj.edu.pl/∼wasm/ryskiNLO.ps ryskiNLOee.ps 140+2 pages

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Input: Z virtuality 97.187 GeV (to get large A_{FB}). Typical selection cuts: lepton's $p_T > 20GeV$. pseudorapidity smaller than 2.4. Photon plots filled only if $p_{T_\gamma} >$ 20 GeV.

Consecutive 28 groups of 5 plots each, differ by p_T and rapidity of the Z (selection cuts are applied in laboratory frame). The following plots include results from KKMC an PHOTOS superimposed:

- LOG$_{10}$ of the angle of closer lepton to photon (if $E_\gamma >$0.1 GeV): pages 5n+3.

- LOG$_{10}$ of (1+c)/(1-c); c is cosine of angle between lepton direction and z axis: pages 5n+6.

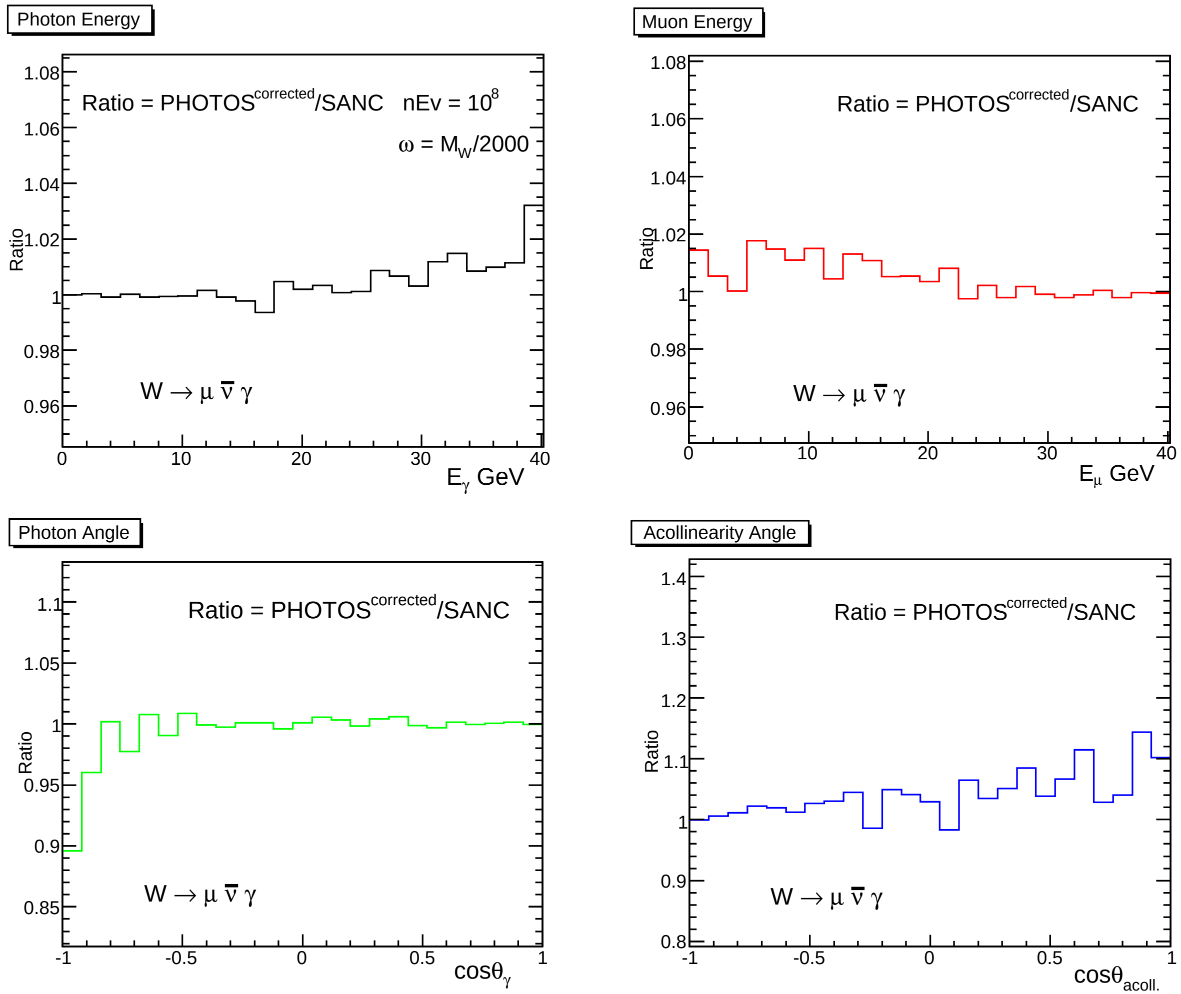
- Single bin histogram for all selected events is introduced too. Its ratio for the KKMC/PHOTOS runs is used to show that normalization: Pages 5n+7.

- *Differences of ∼ 0.1 % in no of selected events is found. Further work in particular on lepton pair bremsstrahlung needed.*

Results with more realistic acceptance cuts will become available soon.

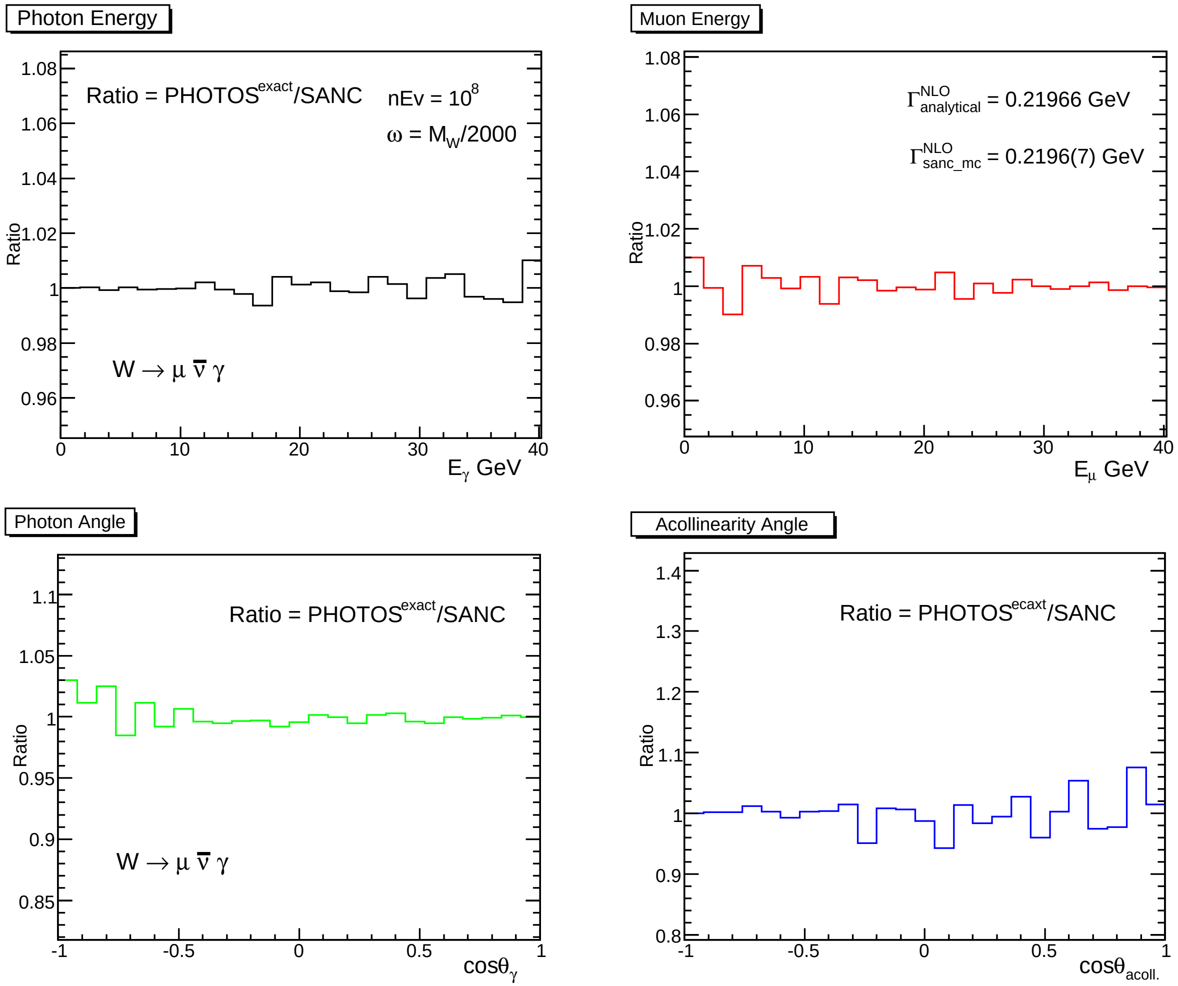
Preliminary. Samples of 40 Mevts used. Results confirm 0.2 % precision tag.

PHOTOS 2.15 W decay



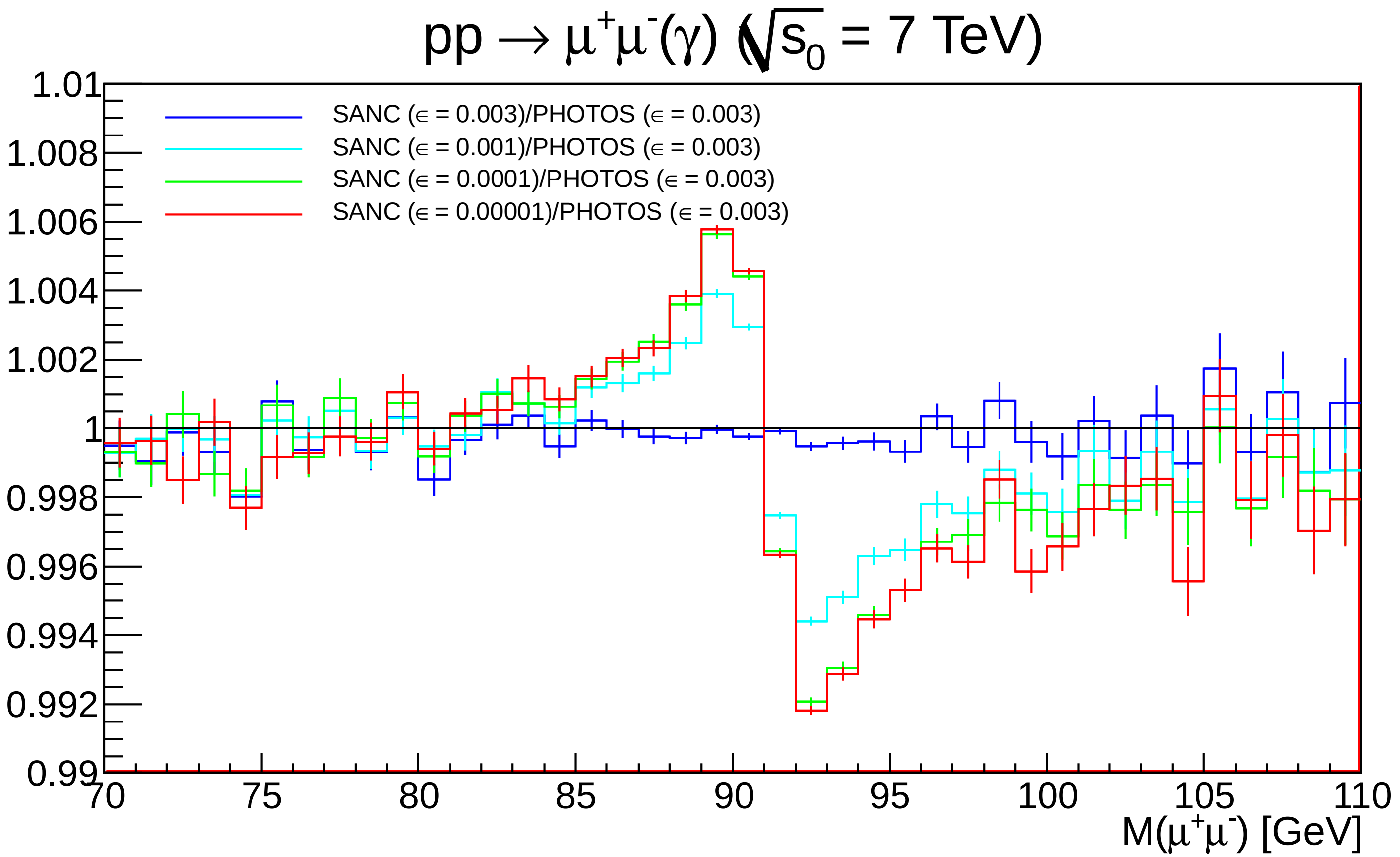
Matrix element test for W decay, single bremsstrahlung mode only. No available reference simulation with double bremsstrahlung as in case of Z. Version of PHOTOS as available eg. in Atlas software. From Eur.Phys.J.C70:673,2010, by G. Nanava, Qingjun Xu, Z. Was

Results for FSR matching with EW corrections.



Matrix element test for W decay, single bremsstrahlung mode only. No available reference simulation with double bremsstrahlung as in case of Z. With correcting weight installed. From Eur.Phys.J.C70:673,2010, by G. Nanava, Qingjun Xu, Z. Was

Results for FSR matching with EW corrections.



- *Invariant mass of $\mu^+\mu^-$ pair produced with Pythia 8.1, courtesy of R. Sadykov and D. Bardin.*
- *Ratio of distributions generated by PHOTOS and by SANC limited to FSR only. Dependence on technical parameter $XK0$ studied.*

Status of tests

1. PHOTOS Monte Carlo is for simulation of multiphoton FSR bremsstrahlung.
2. Generates correlated samples: events with and without FSR bremsstrahlung.
3. For processes mediated by Z/γ' and W's high precision is investigated for 0.2% precision tag for semi inclusive observables.
4. For Z/γ' tests are more advanced, thanks to KKMC. Tests need to be extended only to more realistic experimental selections. **Theoretical uncetrtainty is a property depending on observable**.
5. Program version using C++ `HepMC` event record is public now. In case of Z/γ^*, W, B complete NLO kernel is installed for C++ uses.
6. PHOTOS theoretical basis was not presented. Emphasis was on strategy for tests of uncertainty for evolving (refining) observables.

PHOTOS: main properties

Status: practical

- PHOTOS feature complete exact phase space for multiphoton radiation.
- Unique double iteration algorithm: Internal loop is over emitting particles external one over consecutive photons: one can benefit from parton shower *and* exponentiation.
- Studies of single/double photon spin amplitudes were essential.
- Comparisons with SANC by D. Bardin et al. Achieved goal: for W (as for Z) decays understand matching of QED FSR and genine weak at least at 0.03 % precision level. It is necessary to control well technical/numerical aspects separation of genuine weak and QED corrections. Standard must be much better than physic precision.
- Comparisons with KKMC to confirm physics precision of FSR. KKMC is the program used at LEP precision measurements of Z. KKMC is based on exclusive exponentiation and features second order matrix element for FSR. Agreement better than 0.2 % in experimental cuts (ATLAS CDF) between PHOTOS and KKMC was found.
- Comparisons with SANC to estimate effects of emissions of extra lepton pair and QED ISR-FSR interference. See the next talk for new tool useful for such tests.