Bremsstrahlung, electroweak corrections τ-leptons in 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. FSR bremsstrahlung photon(s) complicate things even more.

How to separate complex problem: better to 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.

- **(3)** My presentation can be understood as an attempt to explain part of pheno effort , eg. for ATLAS papers:

Measurement of Wγ and Zγ production at $\sqrt{s}$ = 7 TeV with the ATLAS, Detector ATLAS-CONF-2011-013.

The ATLAS Collaboration, G. Aad et al., Measurement of the $W \to l\nu$ and $Z/\gamma^* \to ll$ production cross sections in proton-proton collisions at $\sqrt{s}$ s = 7 TeV with the ATLAS detector, JHEP 1012 (2010) 060, arXiv:1010.2130.

FSR

- **(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 old and new results obtained thanks to interaction with Atlas, CMS and CDF members. Important results from R. Sadykov and D. Bardin.
- **(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)** Later papers were for mising at that time tests. Improved program version is available now, but it is for future applications.

What FSR mean: spin amplitude level.

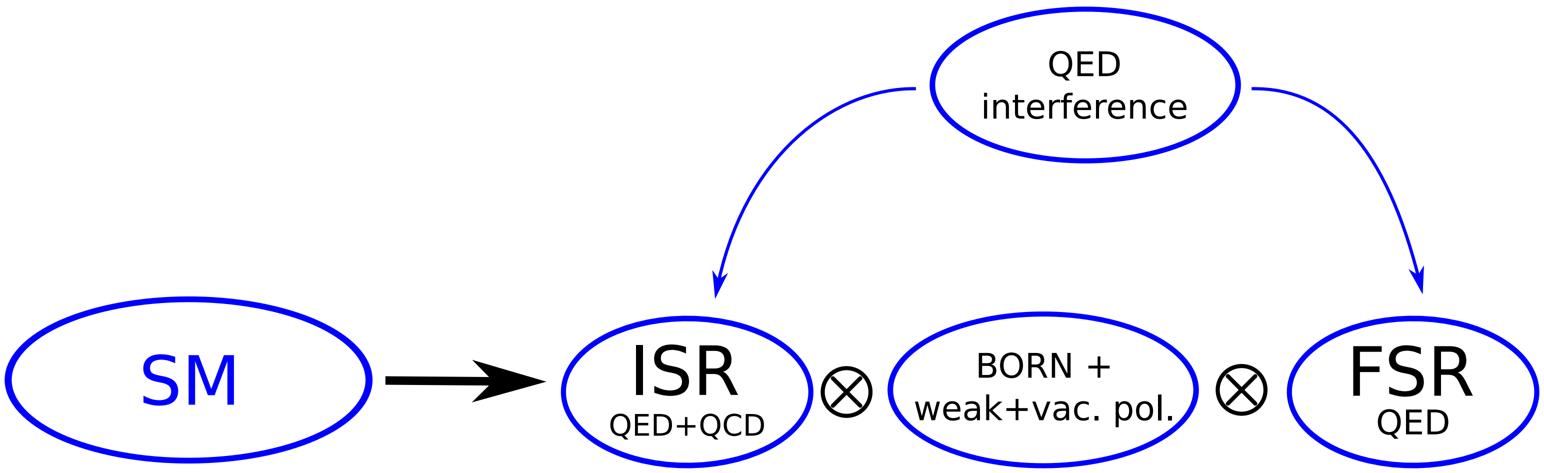
- At Born level cross section involving W and Z propagators is singular: $\frac{1}{s-M^2_{Z,W}}$. This is seemingly trivial to heal. Replace propagator with the effective one $\frac{1}{s-M^2_{Z,W}+i\Gamma_{Z,W}M_{Z,W}}$. Partial resummation of loop corrections to all orders must be performed!

- 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.



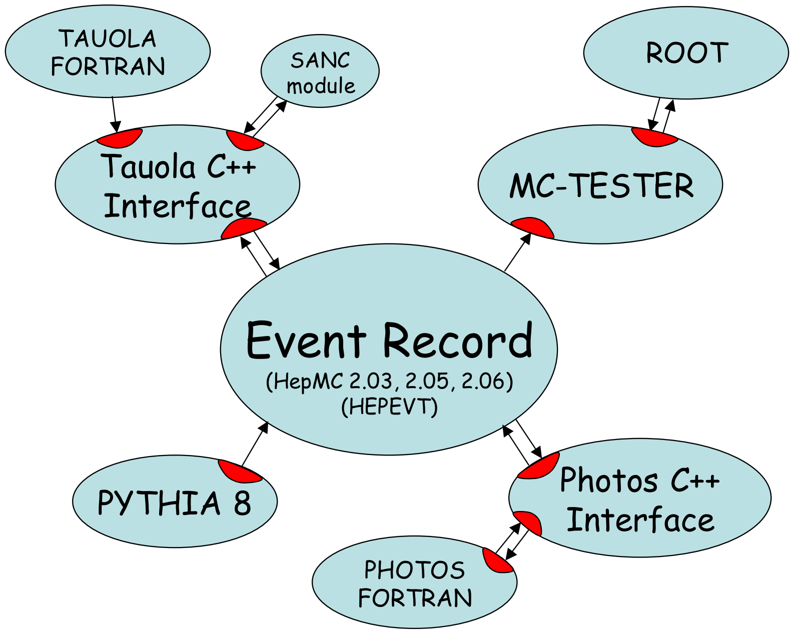
- Use of leading pole approximation as in NLO calculation of U. Baur simplifies the issues of QED ISR-FSR interference.
- For W or Z signatures QED ISR-FSR interference is suppresed by a factor $\Gamma_{Z,W}/M_{Z,W}$ and remain at sub-permille level. Consequence of boson's lifetime separating ISR and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

Introduction

- 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 programs in experimental use.**

1. References+ basic principles

- **Presentation of new versions 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.

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 public.
- 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. Internal loop is over emitters, then 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. Presently used in experiments!
- 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

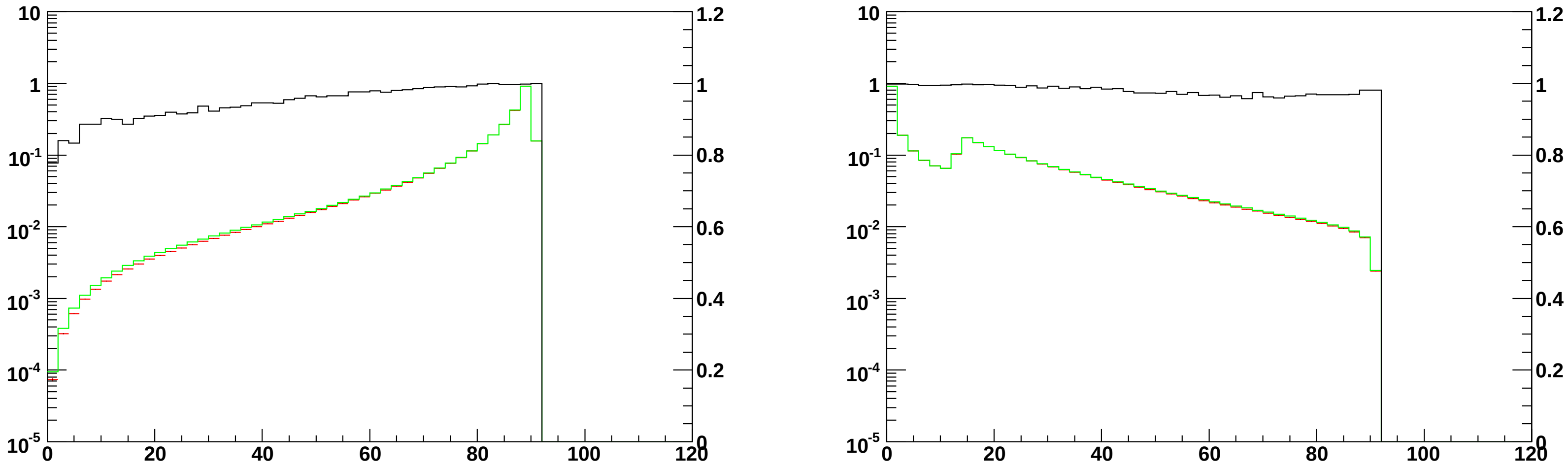


*Figure 1: Comparison of standard PHOTOS and KORALZ (*Comput. Phys. Commun. **66** *(1991) 276) for single photon emission. In the left frame the invariant mass of the $\mu^+\mu^-$ pair; SDP=0.00534. In the right frame the invariant mass of $\mu^-\gamma$; SDP=0.00296. The histograms produced by the two 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.*

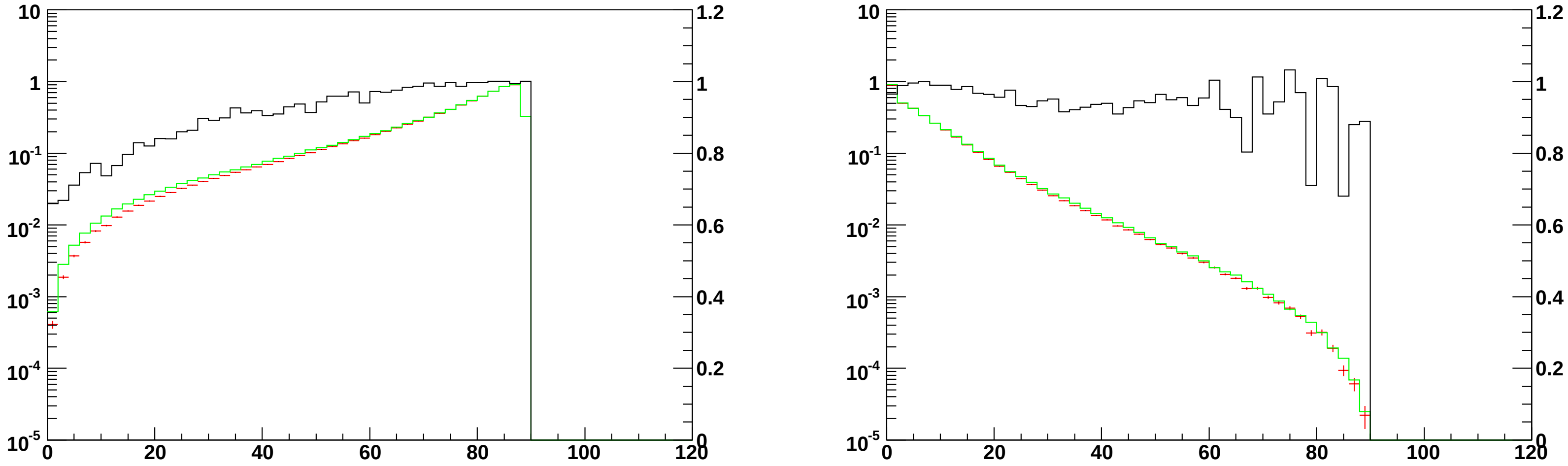


Figure 5: Comparisons of standard PHOTOS with multiple photon emission and KKMC with second order matrix element and exponentiation (Comput. Phys. Commun. **130** *(2000) 260). In the left frame the invariant mass of the $\mu^+\mu^-$ pair; SDP= 0.00918 (shape difference parameter). In the right frame 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.*

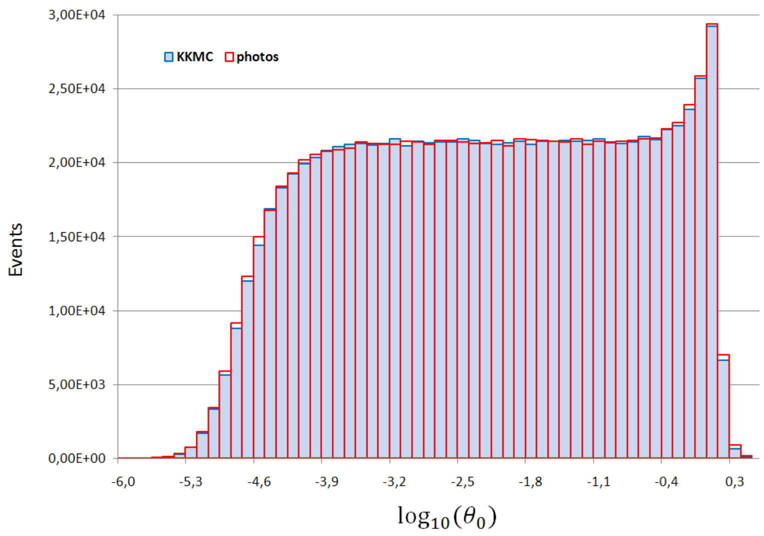
Precision for realistic observables.

- *Histograms of photon angle with respect to closer fermion:* $E_\gamma > 4$ *MeV,*
- *In case of* Z *decay:*
- *Comparisons with PHOTOS including complete matrix element; version of 2007 or C++ version.*
- *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.*

- *For mathing FSR with the rest of EW corrections: comparisons of PHOTOS of complete ME but single photon emissions only with SANC package.*



- *This is for* $Z \to e^+e^-$. *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. No other cuts applied yet.*

PHOTOS

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

http://annapurna.ifj.edu.pl/∼wasm/results-nlo.ps 169 pages

http://annapurna.ifj.edu.pl/∼wasm/results-lo.ps 169 pages

Input: Z virtuality 97.187 GeV (to get large A_{FB}). Selection cuts: lepton's $p_T > 20GeV$. pseudorapidity smaller than 2.4. Photon plots filled only if $E_\gamma >$ 0.1 GeV.

Consecutive 28 groups of 6 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:

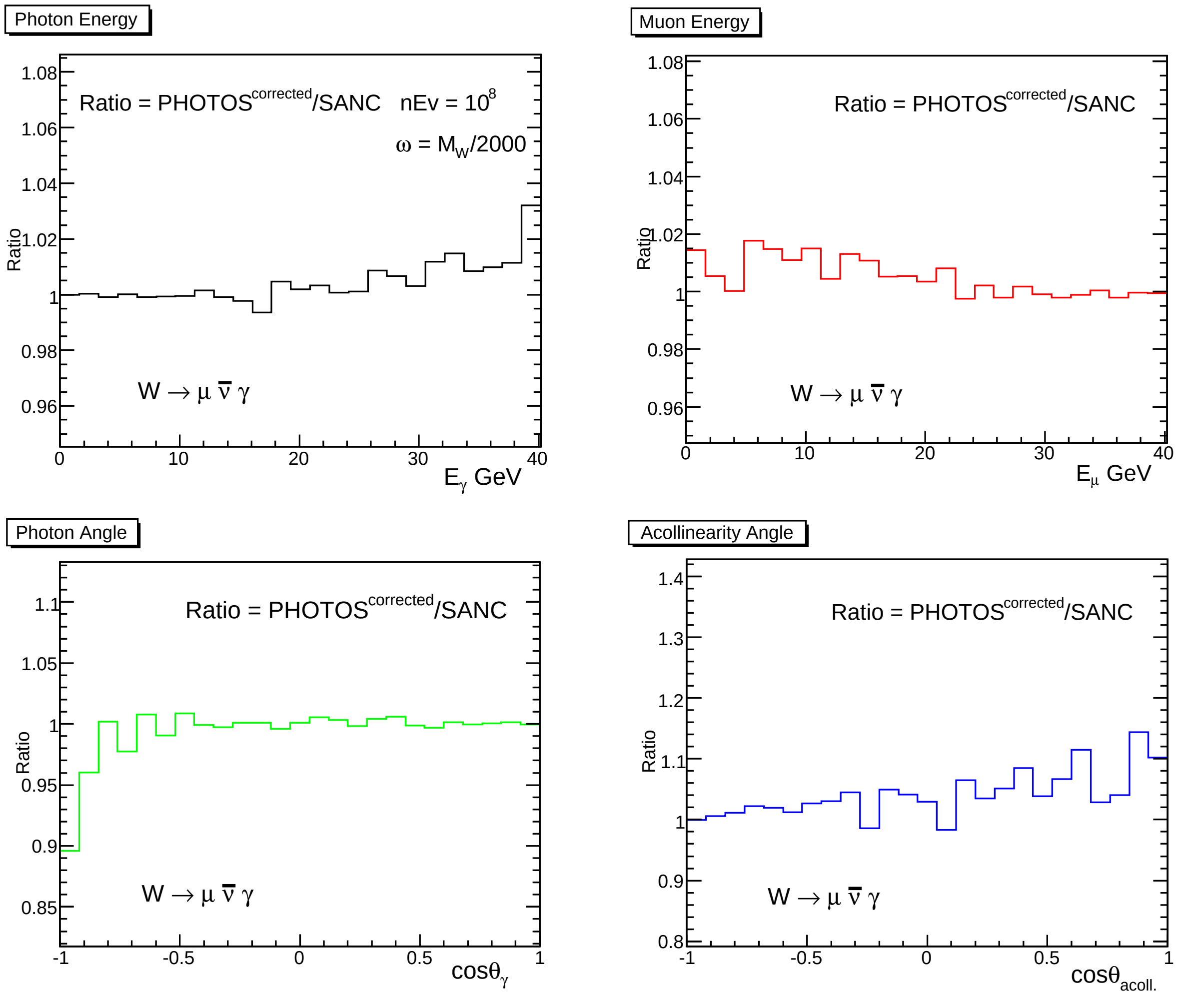
- LOG$_{10}$ of the angle of closer lepton to photon (if $E_\gamma >$0.1 GeV): pages 6n+2.

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

Single bin histogram for all selected events is introduced too. Its ratio for the KKMC/PHOTOS runs is used to show that normalization: Pages 6n+7.

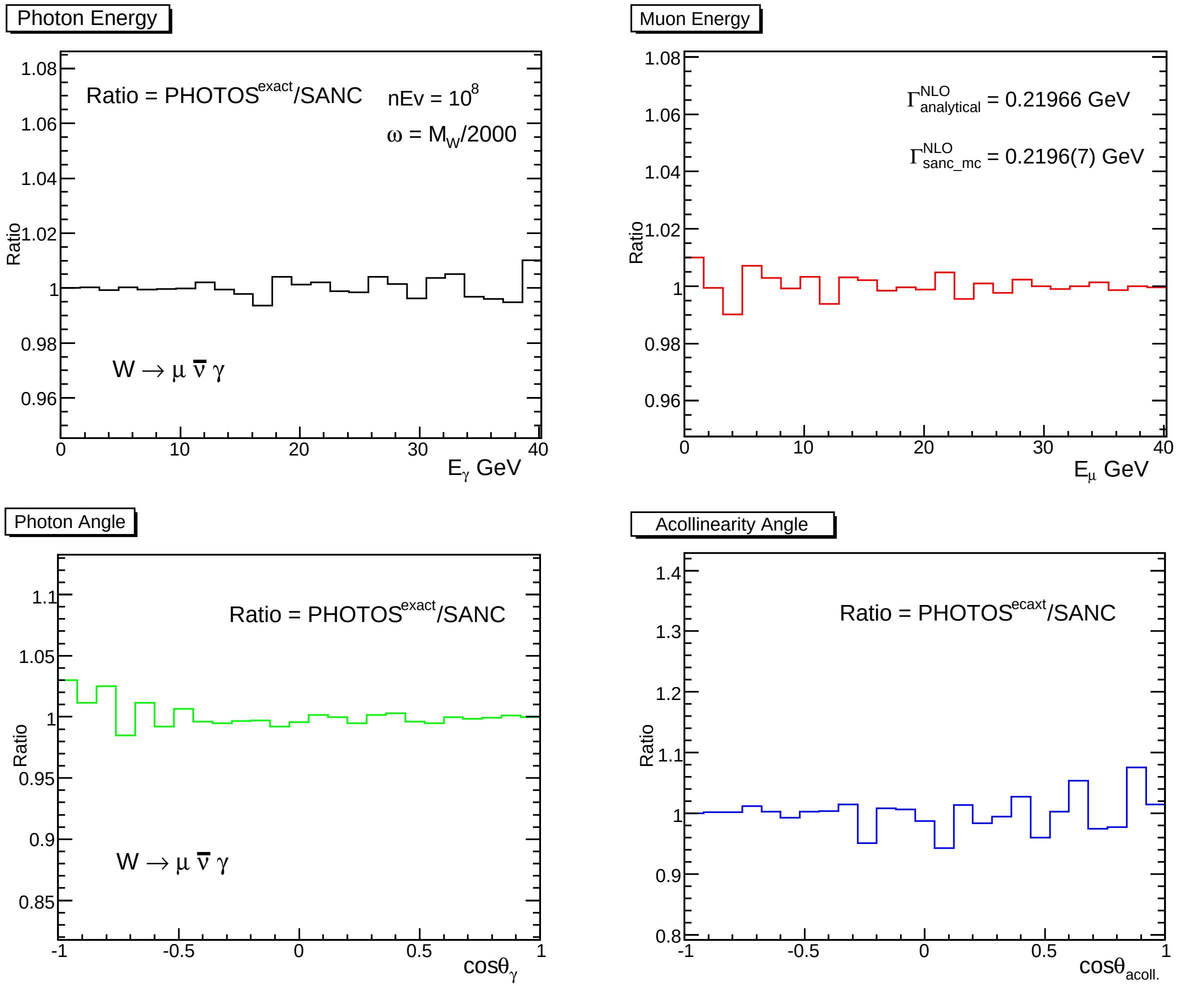
- *Differences of ∼ 0.1 % in no of selected events is found. Further work in particular on lepton pair bremsstrahlung needed. Results with more realistic acceptance cuts will become available soon.*

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



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 matring 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

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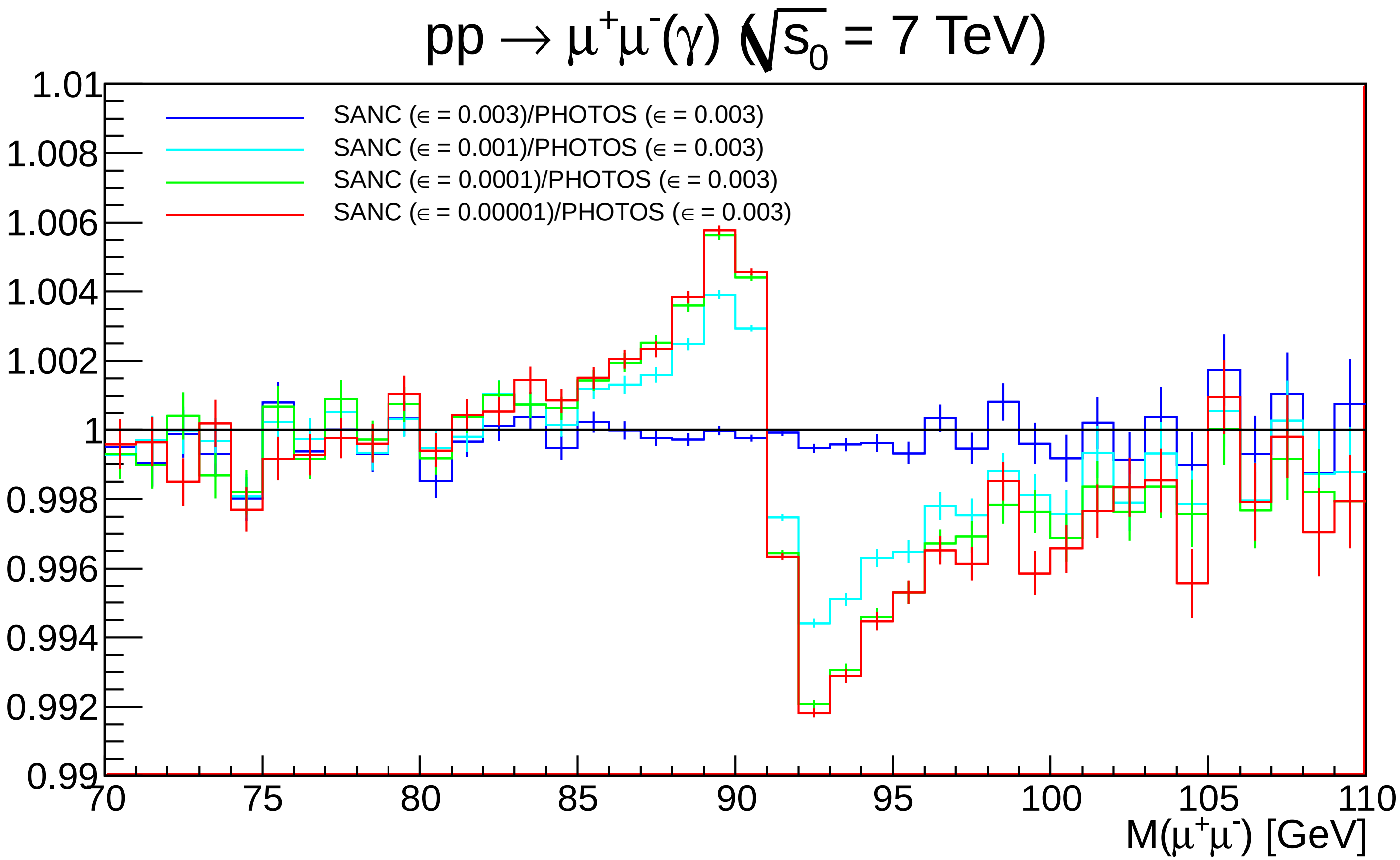


- *Invariant mass of $\mu^+\mu^-$ pair produced with Pythia 8.1, courtesy of R. Sadykov and D. Bardin.*

- *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^* complete NLO kernel is installed already now.

6. PHOTOS theoretical basis was not presented. Emphasis was on strategy for tests of theoretical uncertainty for evolving (refining) observables.

PHOTOS and TAUOLA: 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. is progessting. Goal: for W (as for Z) decays understand matching 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.
- TAUOLA features interface to HepMC and electroweak library of SANC. It can be used to re-weight events with weak corrections + new physics effects.
- 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.

TAUOLA interface also for EW weights

1. Internal τ decay dynamic is still of secondary interest at LHC. It is challenging for low energy precision measurements: see hep-ph/0912.0749. That is why internal part of TAUOLA project remain in FORTRAN.

2. Event record interface is now also in C++ .

3. Physics quality of that HepMC interface is already better than its FORTRAN predecessor, but tests are less profound.

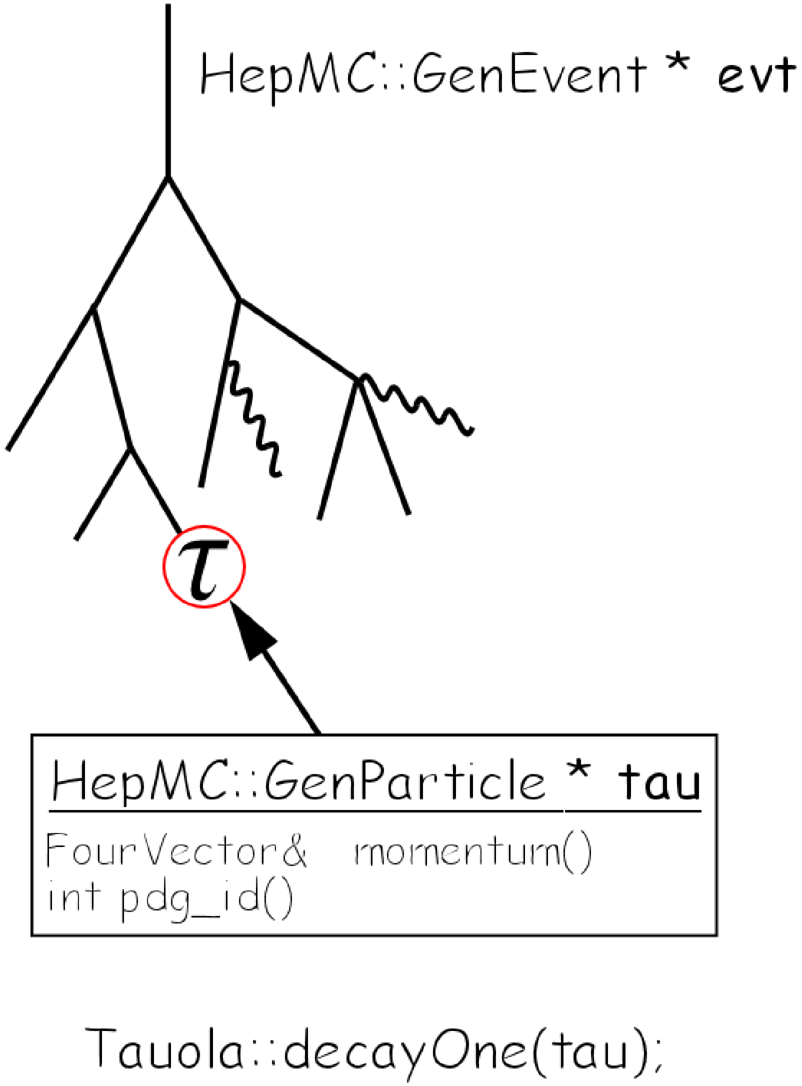
4. Web pages of TAUOLA C++
   www.ph.unimelb.edu.au/˜ndavidson/tauola/doxygen/index.html

5. Reference: arXiv:1001.0070 [hep-ph]

6. High precision must be assured. At the same time only information as available in measurements. One does not need to rely on guessing but profound studies of spin amplitudes are necessary (A. van Hameren). The challenge: detector level lepton universality $\longrightarrow$ control backgrounds of $H \rightarrow \tau^+\tau^-$ signatures.

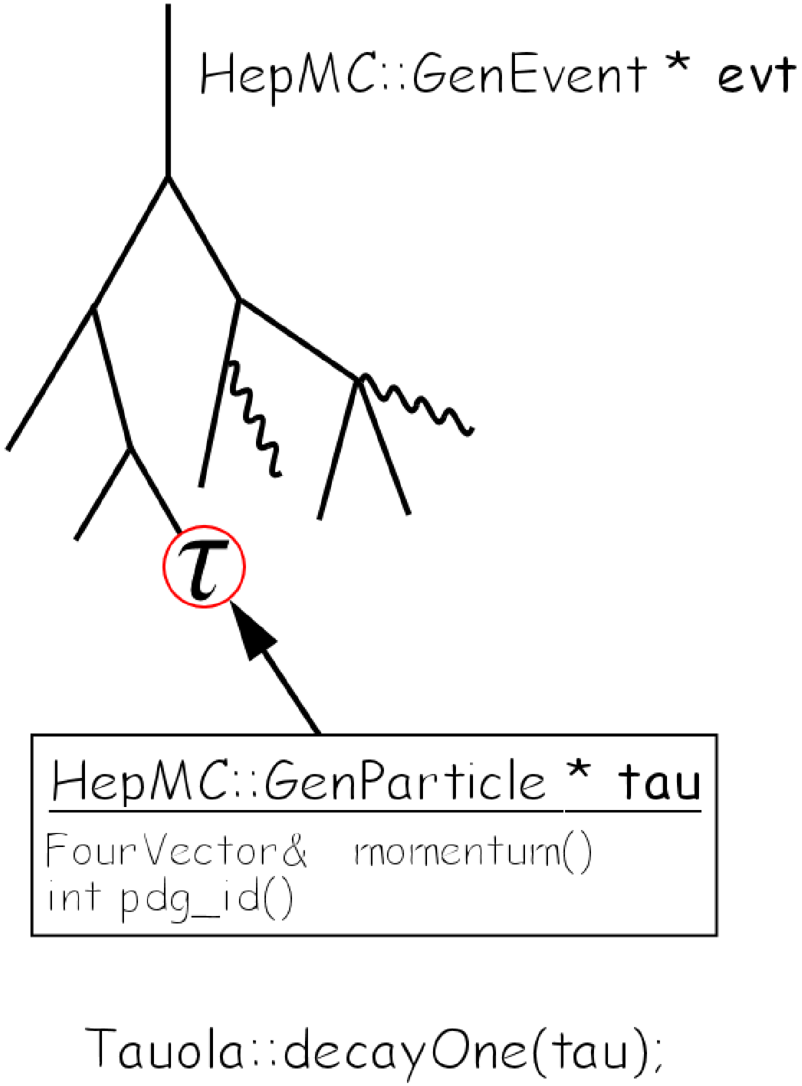
www.ph.unimelb.edu.au/˜ndavidson/photos/doxygen/index.html$\longrightarrow$ PHOTOS C++/HepMC

Single tau decay $\longrightarrow$ NEW



- For the individual τ decay method `Tauola::decayOne()` is provided
- Pointer `tau` to τ in `HepMC` must be known.
- Unpolarized τ decay will be performed, decay products will be transferred to lab. frame using τ 4-momentum. Event record will be updated.
- Tau polarization vector, flag to re-decay already decayed τ and pointer to user defined method for boosting from τ rest-frame to lab frame can be passed as well.
- **Interface is prepared for use in user applications when exact spin effects are required (like in EvtGen** if TAUOLA needed there).

Single tau decay → NEW



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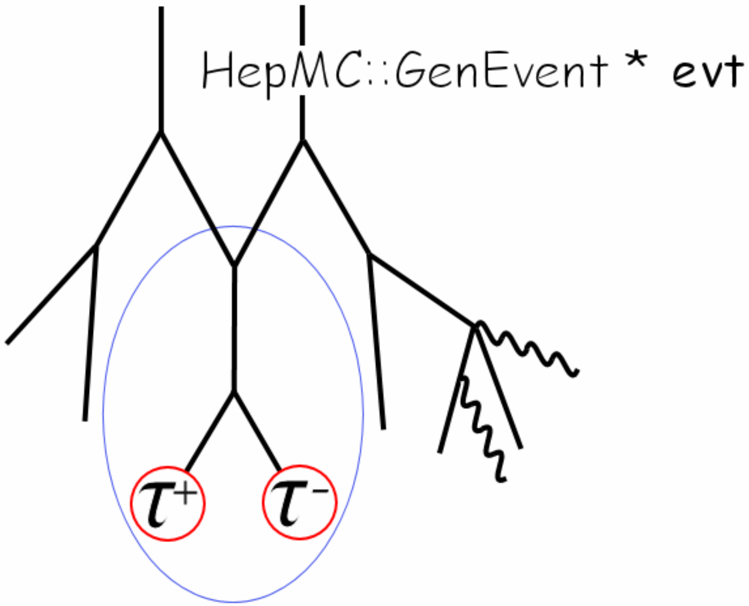
Decay of $\tau^+\tau^-$ ($\tau^\pm\nu_\tau$) pair.




```
//Create object
TauolaHepMCEvent t_evt(evt);
//Decay taus
t_evt.decayTaus();

TauolaParticlePair - get
mothers/grandmothers
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- Interface was checked to work well with main processes as produced by PYTHIA 8.1.
- Further testing means checking correctness of HepMC trees.

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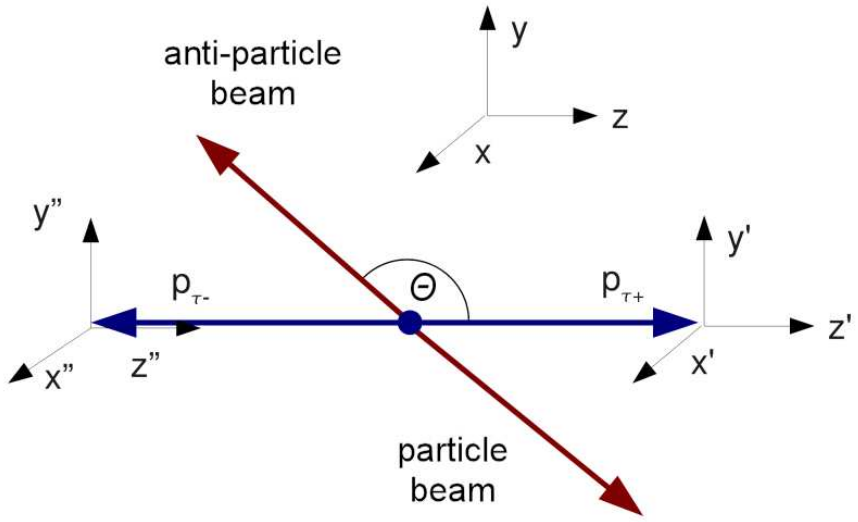
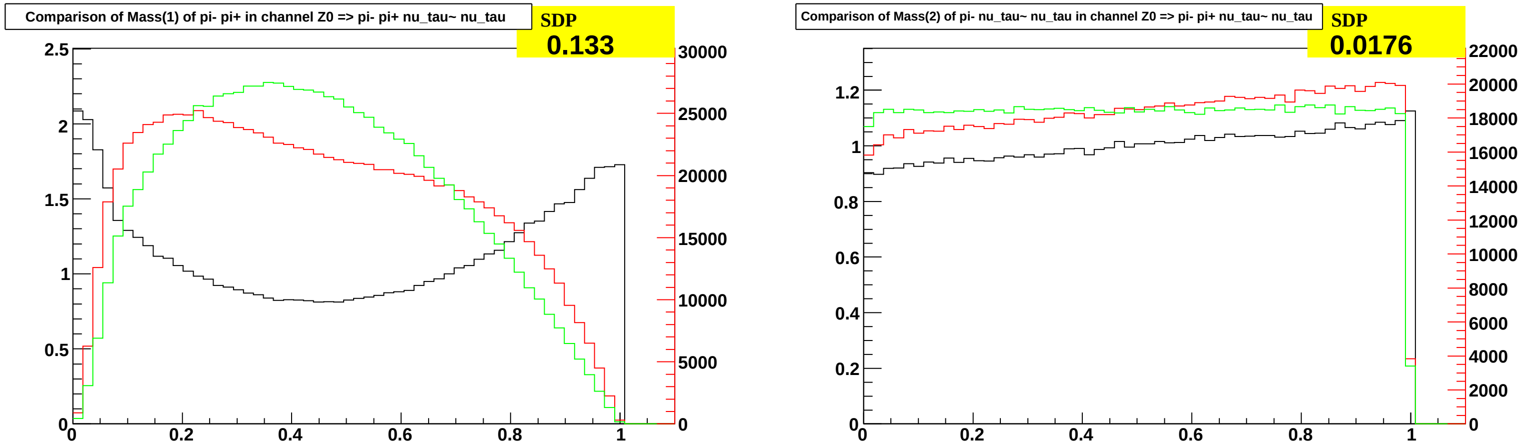


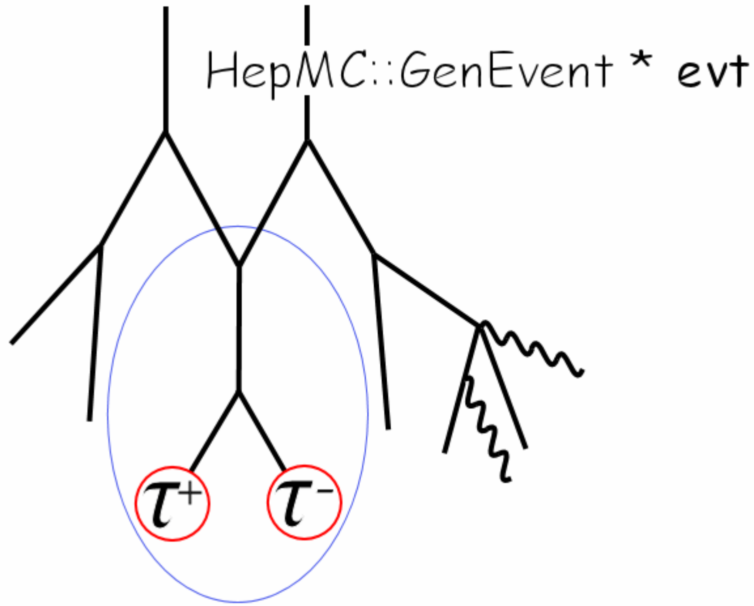
- Configuration of hard process: flavors and 4-momenta of incoming quarks and outgoing τ's (ν_τ)
- **NEW:** algorithm for spin correlations has no approximation.
- However, method to calculate density matrix from that input usually will impose approximations.
- **NEW:** Density matrix including EW corrections is an option. This arrangement can be used to add Z' or to play with spin correlation component by component.
- **NEW:** Helicity states are attributed at the end (approximation is then used). Useful for some LEP style analyses.



(a) $M_{\pi^+\pi^-}$ (b) $1 - 2\frac{E_{\pi^+}}{M_Z}$

Figure 1: Longitudinal spin observables for the Z boson. Distributions are shown for spin effects switched on (red), spin effects switched off (green) and the ratio between spin on and off (black). Left plot show effect of correlation between τ^+ and τ^- decays, right one is for polarization. Figures are obtained with the help of MC-TESTER.

EW effects with weight.

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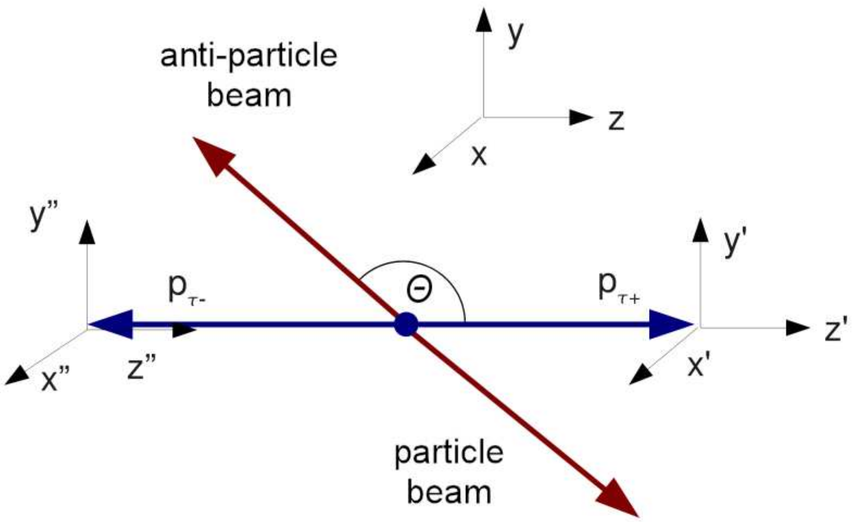
- Further testing means checking correctness of HepMC trees, we will come to this point later.

EW effects with weight.



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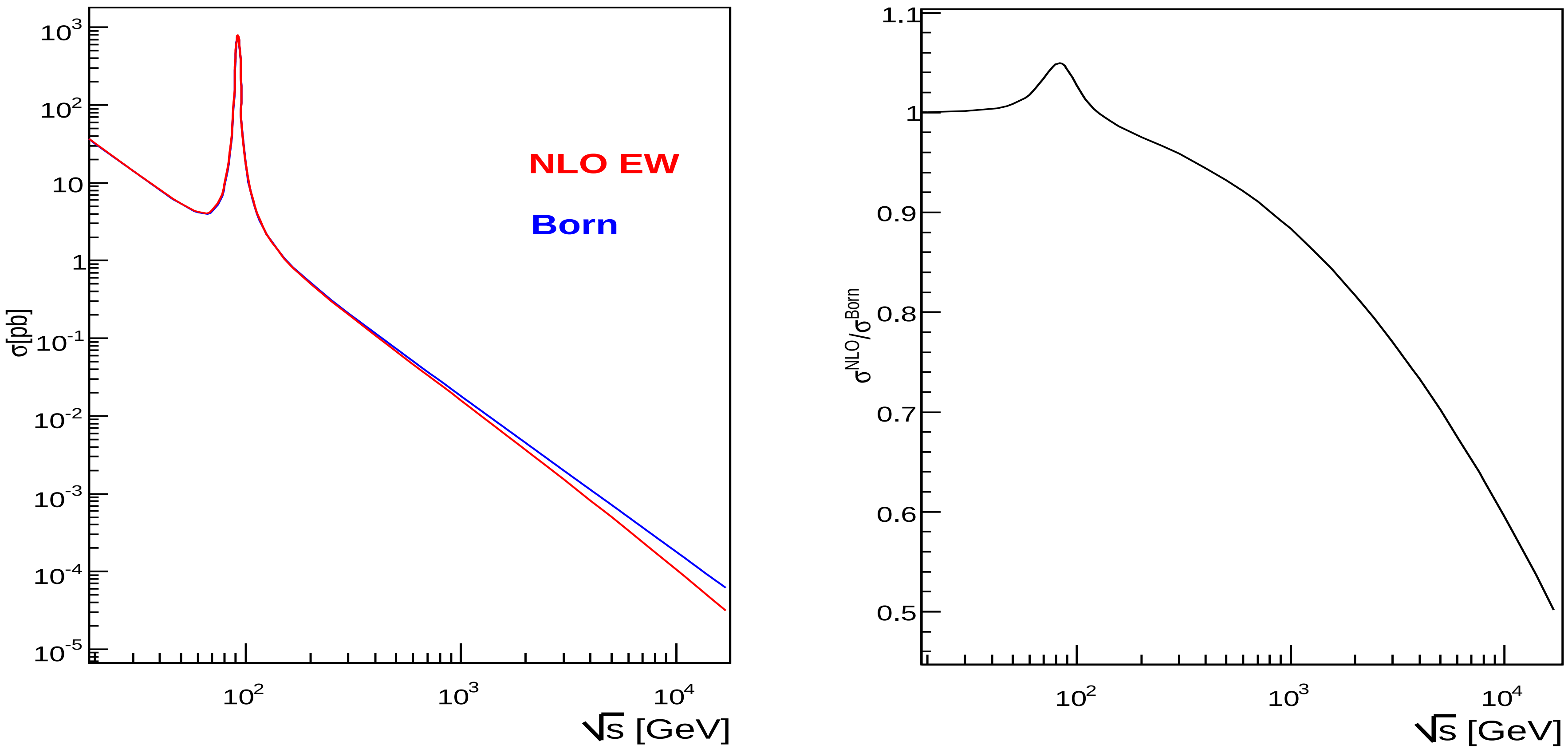
- However, method to calculate density matrix from that input usually will impose approximations.
- **NEW:** Density matrix including EW corrections is an option. This arrangement can be used to add Z' or to play with spin correlation component by component.
- **NEW:** Helicity states are provided (extra approximation used); Eric Torrence encouragements. Useful to exploit spin in LEP style analyzes.

Numerical results, tests.

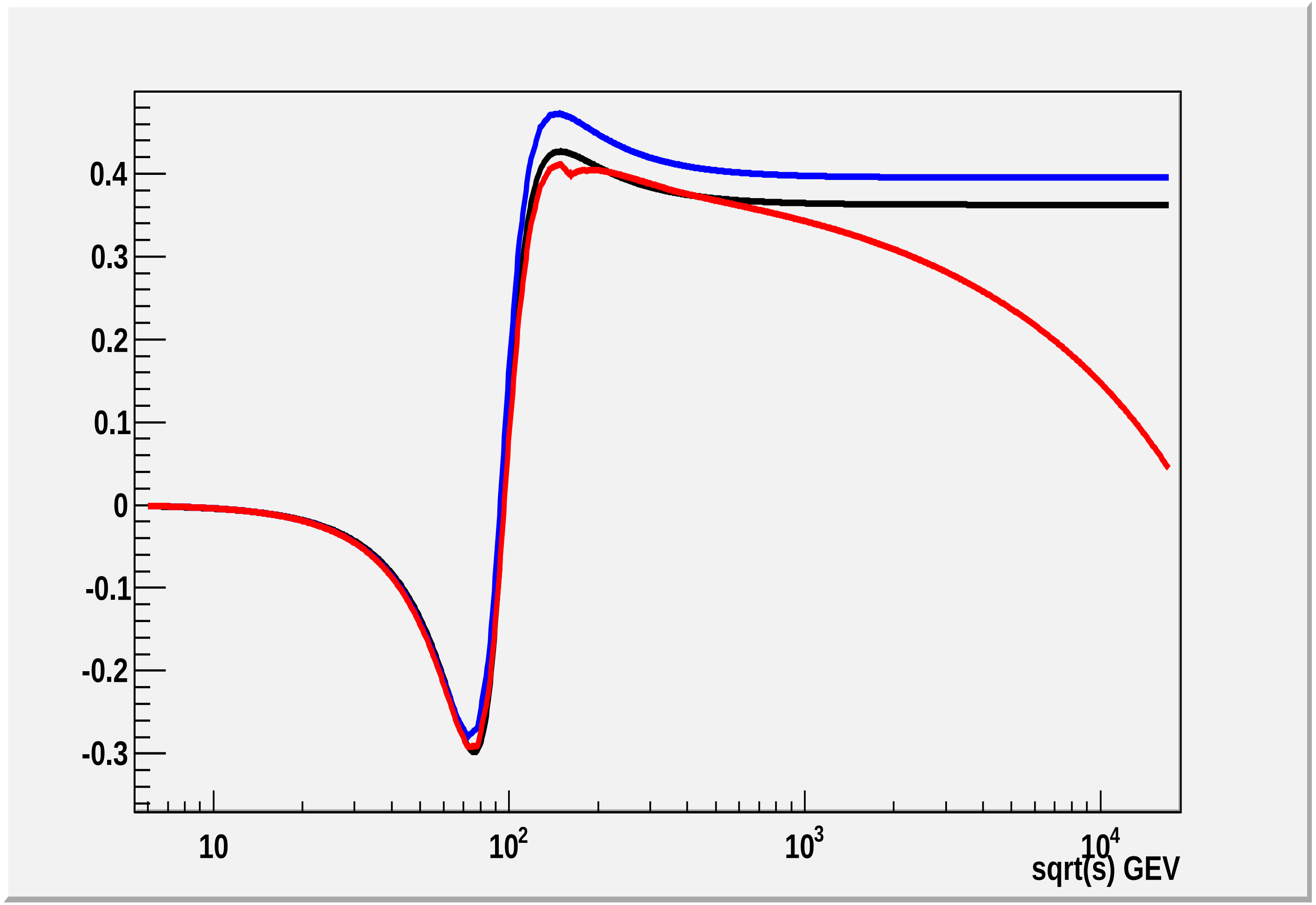


Effect of electroweak corrections on τ-pair production, up quarks, alpha scheme.

Q: What Born parameters are used in PYTHIA?

What effects are (are not) in EW segment. Discussion with Gizo today.

Numerical results, tests.



Effect of electroweak corrections on τ-polarization, up quarks. Red line includes electroweak corrections, Black is TAUOLA standard and blue is Born, alpha scheme. Scattering angle $\cos\theta = -0.2$

Summary

1. We have presented pros and cons for use of TH MC for Z,W production in LHC applications where FSR Born+EW ISR+PS are separated and interfaces are controlled by experiment.

2. Tests point to 0.2% precision tag for PHOTOS MC version 2.15 from 2005 in **investigated class of realistic applications** at LHC (note: for FSR alone).

3. For combined applications work is on-going. In particular work on matching of genuine weak segment with Born must be completed.

4. Further technical checks like: what is Born version used in PYTHIA (MCatNLO ...) has to be completed.

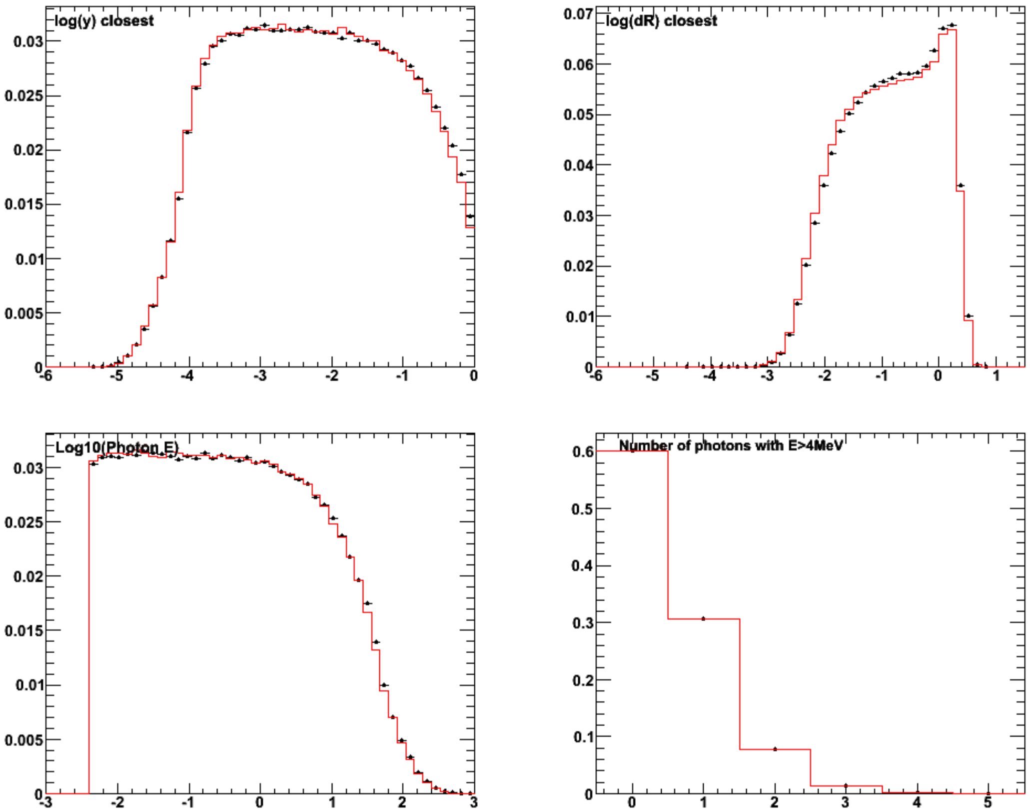
5. This is needed for theoretical precision studies which must be organized around dtailed observable definition.

EXTRA TRANSPARENCIES

MOSTLY NUMERICAL TESTS

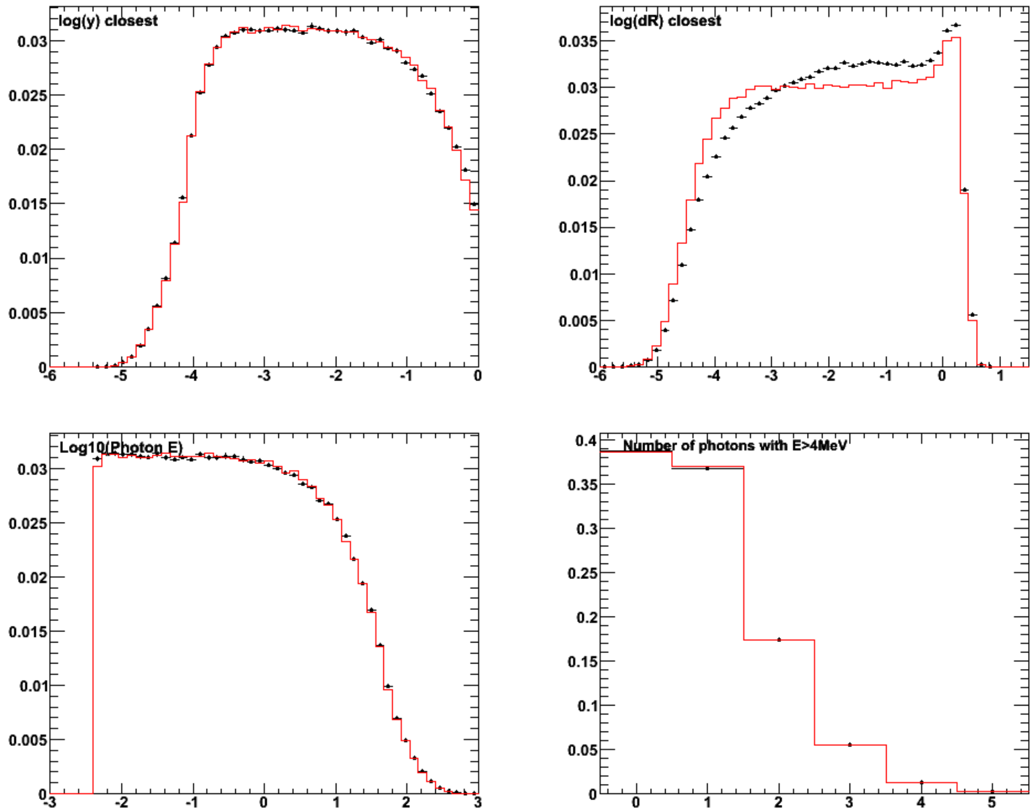
EXTRA TRANSPARENCIES

EXTRA TRANSPARENCIES

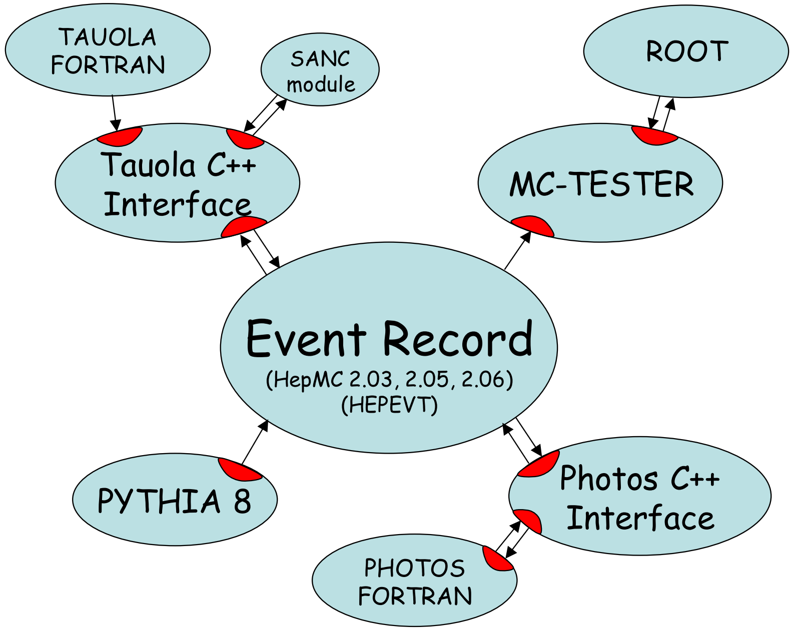


EXTRA TRANSPARENCIES

EXTRA TRANSPARENCIES



Simulation parts communicate through event record:



- Parts:

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

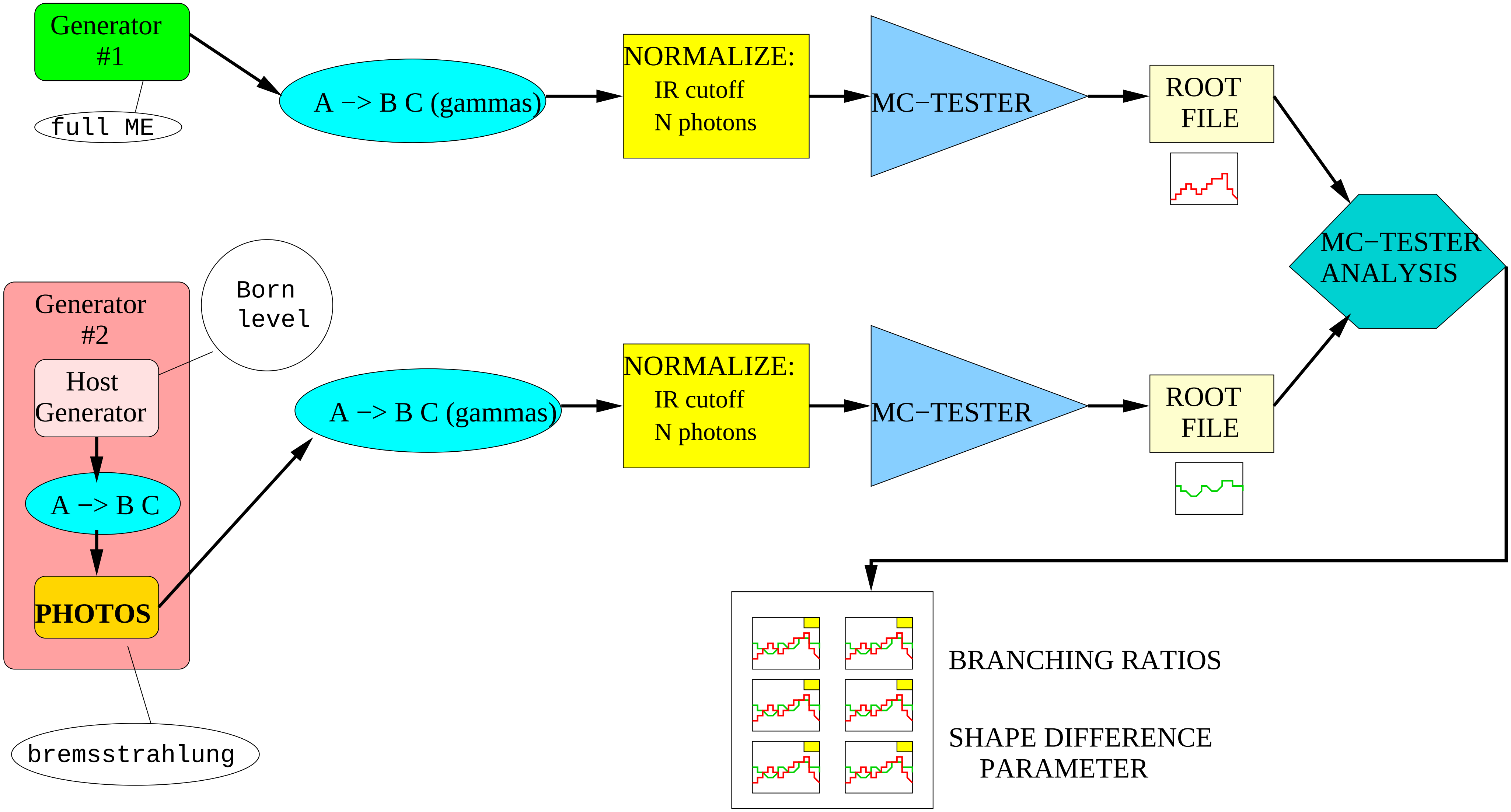
- High precision achieved

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

Such organization requires:

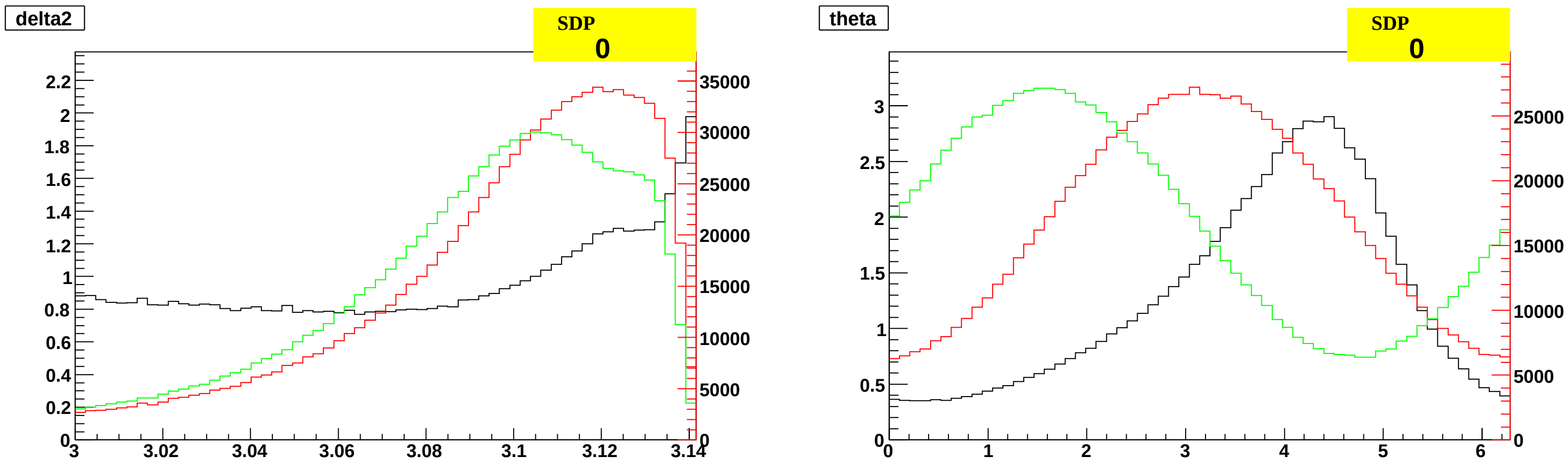
- Good control of factorization (theory)
- Good understanding of tools on user side.

MC-TESTER to test PHOTOS/TAUOLA



Extra transparencies: MC-TESTER

Example: Distribution for Higgs parity



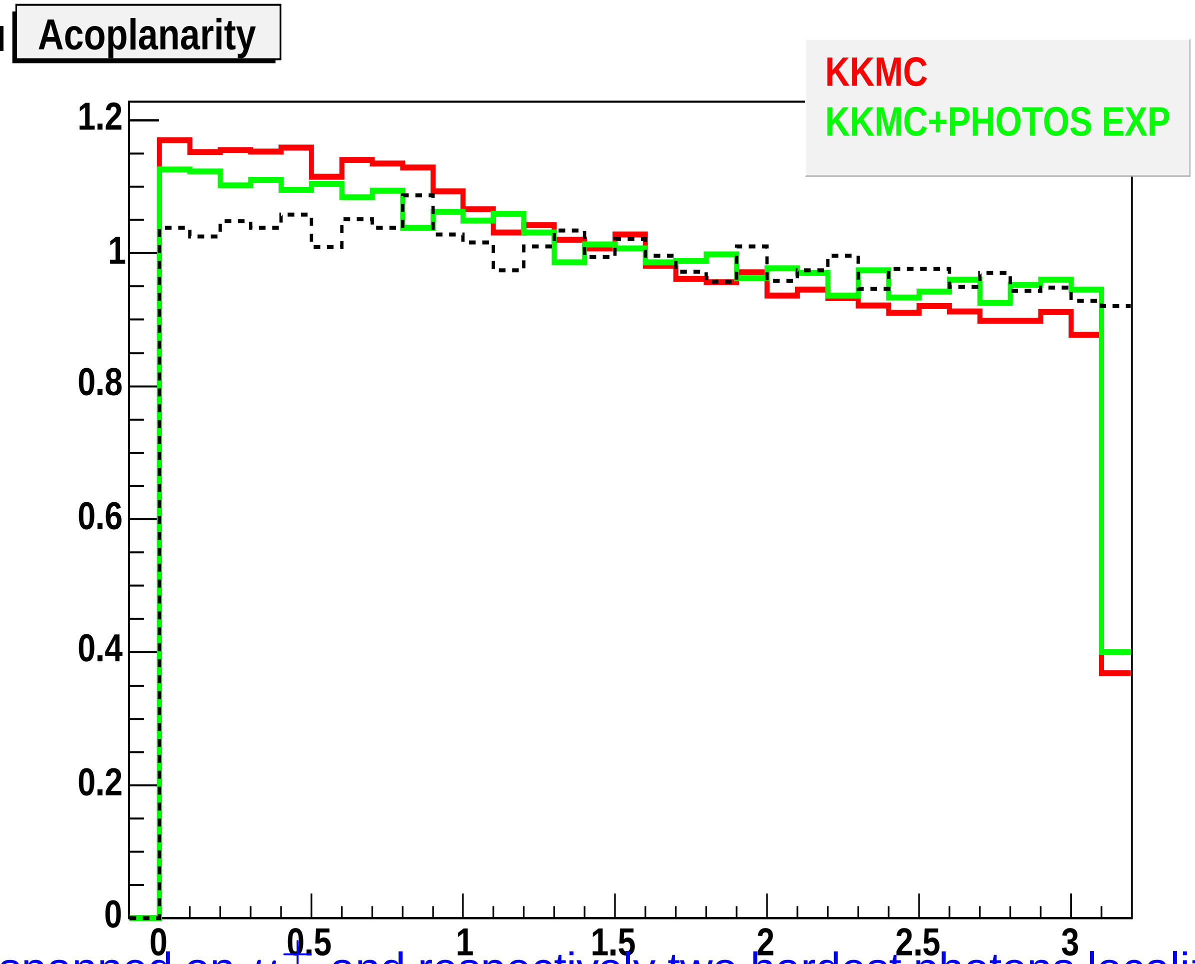
(a) $\pi^+\pi^-$ acollinearity distribution ($\approx \pi$))

(b) $\pi^+\pi^-$ acoplanarity distribution

Figure 2: Transverse spin observables for the H boson for $\tau^\pm \rightarrow \pi^\pm \nu_\tau$. Distributions are shown for scalar higgs (red), scalar-pseudoscalar higgs with mixing angle $\frac{\pi}{4}$ (green) and the ratio between the two (black).

Extra transparencies: MC-TESTER

Acoplanarity distribution – Looks good



Two plane spanned on μ^+ and respectively two hardest photons localized in the same hemisphere as μ^+. In exlusive exponentiation this asymmetry appears with second order matrix element only.