Separating electroweak and strong interaction effect:

angular coefficients, effective Born, genuine weak QED and QCD effects

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My goal is to to provide slides for discussion on points, which may bring less attention during talks of Marzieh or Brian.

Heritage: effective Born $\times$ genuine weak effects $\times$ ISR/FSR QED.

- References. New: Eur.Phys.J. C77(2017)111, Eur.Phys.J. C76 2016)473, Higgs CP Phys.Rev. D94(2016)093001 Old: Nucl.Phys. B387 (1992) 3, Comput.Phys.Commun. 29 (1983) 185, Nucl.Phys. B347 (1990) 67
- Numerical results (important shapes): for electroweak QCD effects. I will concentrate on numerics mainly for single Z W production, H CP mashine leraning exercise will be left aside.
- Future; checks with SANC group, of old LEP electroweak libraries results.

What Z, W, H signatures may mean?

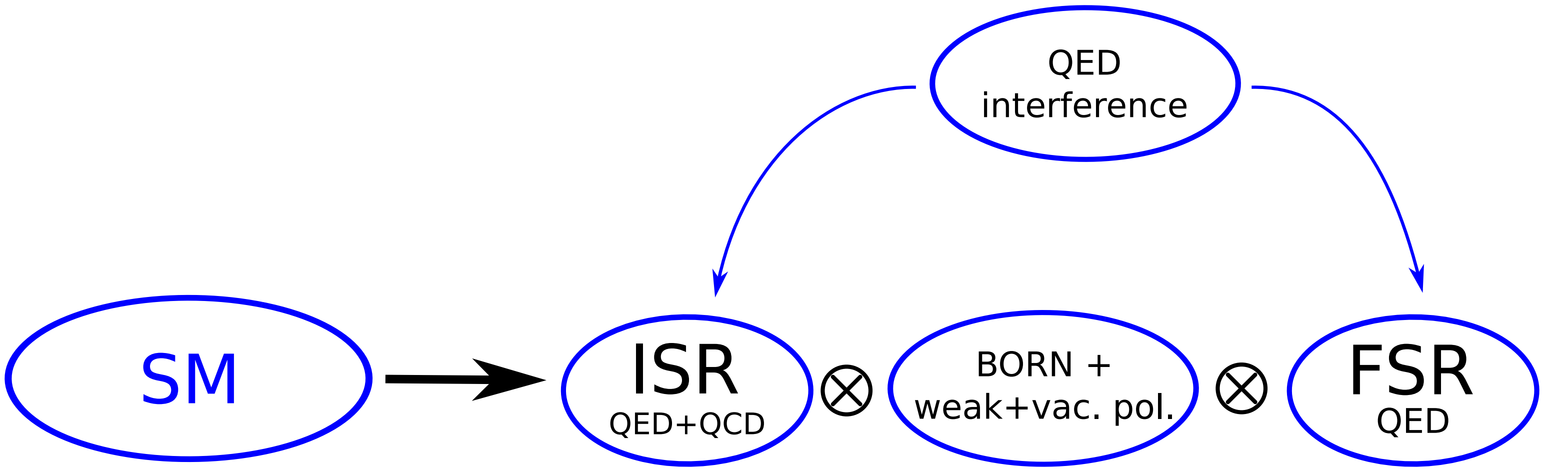
- Even if physical gauge is chosen and bosons acquire masses, at Born level of SM, W, H and Z propagators are singular: $\frac{1}{s-M^2}$.
  This seems trivial:
  Replace propagator with the effective one $\frac{1}{s-M^2+i\Gamma M}$.
  Partial resummation of loop corrections to all orders must be performed to get $i\Gamma M$!

- Resulting approach, make bosons into physics states of definite properties, including width. It required massive effort at LEP. Results are used by CDF D0 as state-of-art today also. See Arie Bodek talk, CERN Jan 31, 2017, https://indico.cern.ch/event/571075/

- **I will not go into all details necessary for fundaments. I will concentrate on practical aspects/results.**

Introduction

Production and decay for Bosons



- That is the picture we inherit.
- Let me present some details and later how it works in case when $2 \to 4$ matrix elements are used.
- For the precison to be controlled one must be able to define for each program phase space parametrization (which is best to be precise and explicit) and matrix elements (there approximations can be then numerically evaluated)

Topics:

A. Effective Born

B. Effective Born and jets ..

C. Electroweak form factors

– Summary

* Extras:

  D. Extra pair emission in PHOTOS MC

  E. slides FROM SANC TEAM

  F. KKMC and IFI interference

part A: Effective Born

Let us start with the lowest order coupling constants (without EW corrections) of the Z boson to fermions, where $s_W^2 = 1 - m_W^2/m_Z^2$ denotes $\sin\theta_W^2$ in the on-line scheme and T_3^f denotes third component of the isospin.

The vector v_e, v_f and axial a_e, a_f couplings for leptons and quarks respectively are defined with formulas below.

$$
\begin{aligned}
v_e &= (2 \cdot T_3^e - 4 \cdot q_e \cdot s_W^2)/\Delta \\
v_f &= (2 \cdot T_3^f - 4 \cdot q_f \cdot s_W^2)/\Delta \\
a_e &= (2 \cdot T_3^e)/\Delta \\
a_f &= (2 \cdot T_3^f)/\Delta
\end{aligned}
\qquad (1)
$$

where

$$
\Delta = \sqrt{16 \cdot s_W^2 \cdot (1 - s_W^2)} \qquad (2)
$$

part A: Effective Born

With this notation, matrix element for the $q\bar{q} \to Z/\gamma^* \to l^+l^-$, denoted as ME_{Born}, can be written as:

$$\begin{aligned} ME_{Born} &= [\bar{u}\gamma^\mu v g_{\mu\nu}\bar{v}\gamma^\nu u] \cdot (q_e \cdot q_f) \cdot \frac{\chi_\gamma(s)}{s} \\ &+ [\bar{u}\gamma^\mu v g_{\mu\nu}\bar{\nu}\gamma^\nu u \cdot (v_e \cdot v_f) + \bar{u}\gamma^\mu v g_{\mu\nu}\bar{\nu}\gamma^\nu\gamma^5 u \cdot (v_e \cdot a_f) \\ &+ \bar{u}\gamma^\mu\gamma^5 v g_{\mu\nu}\bar{\nu}\gamma^\nu u \cdot (a_e \cdot v_f) + \bar{u}\gamma^\mu\gamma^5 v g_{\mu\nu}\bar{\nu}\gamma^\nu\gamma^5 u \cdot (a_e \cdot a_f)] \cdot \frac{\chi_Z(s)}{s} \end{aligned} \tag{3}$$

and Z-boson and photon propagators defined respectively as

$$\chi_\gamma(s) = 1 \tag{4}$$

$$\chi_Z(s) = \frac{G_\mu \dot{M}_z^2}{\sqrt{2} \cdot 8\pi \cdot \alpha_{QED}(0)} \cdot \Delta^2 \cdot \frac{s}{s - M_Z^2 + i \cdot \Gamma_Z \cdot M_Z} \tag{5}$$

At the peak of resonance $|\chi_Z(s)|(v_e \cdot v_f) > (q_e \cdot q_f)$ and as a consequence angular distribution asymmetries of leptons are proportional to $v_e = (2 \cdot T_3^e - 4 \cdot q_e \cdot s_W^2)$. This gives good sensitivity for s_W^2 measurement.

Above and below resonance we are sensitive to lepton charge instead ...

part A: Effective Born

Born cross-section, for $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ can be expressed as:

$$\frac{d\sigma^{q\bar{q}}_{Born}}{d\cos\theta}(s,\cos\theta,p) = (1{+}\cos^2\theta)\,F_0(s){+}2\cos\theta\,F_1(s){-}p[(1{+}\cos^2\theta)\,F_2(s){+}2\cos\theta\,F_3(s)] \tag{6}$$

p denotes polarization of the outgoing leptons, and form-factors read:

$$\begin{aligned}
F_0(s) &= \frac{\pi\alpha^2}{2s}[q_f^2 q_\ell^2 \cdot \chi_\gamma^2(s) + 2\cdot\chi_\gamma(s) Re\chi_Z(s)\, q_f q_\ell v_f v_\ell + |\chi_Z^2(s)|^2 (v_f^2 + a_f^2)(v_\ell^2 + a_\ell^2)], \\
F_1(s) &= \frac{\pi\alpha^2}{2s}[2\chi_\gamma(s) Re\chi(s)\, q_f q_\ell v_f v_\ell + |\chi^2(s)|^2\, 2v_f a_f 2v_\ell a_\ell], \qquad (7 \\
F_2(s) &= \frac{\pi\alpha^2}{2s}[2\chi_\gamma(s) Re\chi(s)\, q_f q_\ell v_f v_\ell + |\chi^2(s)|^2\, (v_f^2 + a_f^2) 2v_\ell a_\ell], \\
F_3(s) &= \frac{\pi\alpha^2}{2s}[2\chi_\gamma(s) Re\chi(s)\, q_f q_\ell v_f v_\ell + |\chi^2(s)|^2\, (v_f^2 + a_f^2) 2v_\ell a_\ell],
\end{aligned}$$

$\cos\theta$ denotes angle between incoming quark and outgoing lepton in the rest frame of outgoing leptons. That is rather simple spherical harmonics of the second order.

What Changes come with jets ...

- E. Mirkes and J. Ohnemus, “Angular distributions of Drell-Yan lepton pairs at the Tevatron: Order $\alpha - s^2$ corrections and Monte Carlo studies,” Phys. Rev. D **51** (1995) 4891
- R. Kleiss, “Inherent Limitations in the Effective Beam Technique for Algorithmic Solutions to Radiative Corrections,” Nucl. Phys. B **347**, 67 (1990).
- F. A. Berends, R. Kleiss and S. Jadach, “Monte Carlo Simulation of Radiative Corrections to the Processes e+ e- —> mu+ mu- and e+ e- —> anti-q q in the Z0 Region,” Comput. Phys. Commun. **29**, 185 (1983).

General form of Born level distribution is preserved but choice of reference frame for lepton pair usually brings in all coefficients for second order spherical harmonics.

IMPORTANT FOR REWEIGHING: whatever the jets, the second order polynomial factorizes out:

Mustraal frame

[18] F. A. Berends, R. Kleiss, and S. Jadach, *Comput. Phys. Commun.* **29** (1983) 185–200.

Mustraal: Monte Carlo for $e^+ e^- \to \mu^+ \mu^-$ (γ)

$$s = 2p_+ \cdot p_-, \quad t = 2p_+ \cdot q_+, \quad u = 2p_+ \cdot q_-$$

$$s' = 2q_+ \cdot q_-, \quad t' = 2p_- \cdot q_-, \quad u' = 2p_- \cdot q_+$$

$$\sigma_{\text{hard}} = \int \mathrm{d}\tau (X_{\text{i}} + X_{\text{f}} + X_{\text{int}}),$$

The explicit forms of the three terms in σ_{hard} read:

$$X_{\text{i}} = \frac{Q^2 \alpha}{4\pi^2 s} \frac{1-\Delta}{k_+ k_-} s'^2 \left[\frac{\mathrm{d}\sigma^B}{\mathrm{d}\Omega}(s', t, u) + \frac{\mathrm{d}\sigma^B}{\mathrm{d}\Omega}(s', t', u') \right], \tag{3.4}$$

$$X_{\text{f}} = \frac{Q'^2 \alpha}{4\pi^2 s} \frac{1-\Delta'}{k'_+ k'_-} s^2 \left[\frac{\mathrm{d}\sigma^B}{\mathrm{d}\Omega}(s, t, u') + \frac{\mathrm{d}\sigma^B}{\mathrm{d}\Omega}(s, t', u) \right], \tag{3.5}$$

$$X_{\text{int}} = \frac{QQ'\alpha}{4\pi^2 s} W \frac{\alpha^2}{2ss'} \left[(u^2 + u'^2 + t^2 + t'^2) \tilde{f}(s, s') + \tfrac{1}{2}(u^2 + u'^2 - t^2 - t'^2) \tilde{g}(s, s') \right]$$
$$+ \frac{QQ'\alpha^3}{4\pi^2 s} \frac{(s-s') M\Gamma}{k_+ k_- k'_+ k'_-} \epsilon_{\mu\nu\rho\sigma} p_+^\mu p_-^\nu q_+^\rho q_-^\sigma \left[\tilde{E}(s, s')(t^2 - t'^2) + \tilde{F}(s, s')(u^2 - u'^2) \right], \tag{3.6}$$

Resulting optimal frame used to minimise higher order corrections from initial state radiation in $e^+e^- \to Z/\gamma^* \to \mu\,\mu$ for algorithms of genuine EW corrections implementation in LEP time Monte Carlo's like Koral Z.

2

Extending definition of Mustraal frame

IFJPAN-IV-2016-11

- We extended this frame to pp -> $l^+ l^-$ j (j) case
  - reconstruct x_1, x_2 of incoming partons from final state kinematics (information on jets used)
  - assume the quark is following x_1 direction (equivalent to what done in CS frame)
  - calculate (θ_1, ϕ_1), (θ_2, ϕ_2) of two Born's, weight with probability calculated not using couplings

$$wt_1 = \frac{E_{p1}^2(1+\cos\theta_1^2)}{E_{p1}^2(1+\cos\theta_1^2)+E_{p2}^2(1+\cos\theta_2^2)}, \quad wt_2 = \frac{E_{p2}^2(1+\cos\theta_2^2)}{E_{p1}^2(1+\cos\theta_1^2)+E_{p2}^2(1+\cos\theta_2^2)}$$

3

Collins-Soper and Mustraal frames.

Instead of Born we get (with $\alpha_s^2 \sim 0.01$ corrections only) for the case when Jets are present:

$$\frac{d\sigma}{dp_T^2 dY\, d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^2 dY} [(1+\cos^2\theta) +$$

$$1/2\, A_0 (1-3\cos^2\theta) + A_1 \sin(2\theta)\cos\phi + 1/2\, A_2 \sin^2\theta \cos(2\phi) + A_3 \sin\theta\cos\phi$$

$$+A_4\cos\theta + A_5 \sin^2\theta \sin(2\phi) + A_6 \sin(2\theta)\sin\phi + A_7 \sin\theta\ \sin\phi]$$

Collins-Soper: the polar θ and azimuthal ϕ angles are constructed in lepton pair rest-frame. Since the Z-boson has usually a transverse momentum, the directions of initial protons are not collinear. The polar axis (z-axis) is bisecting the angle between the momentum of one of the proton and inverse of the momentum of the other one. The sign of the z-axis is defined by the sign of the lepton-pair momentum with respect to z-axis in the laboratory frame. The y-axis is defined as the normal vector to the plane spanned by the two incoming proton momenta.

Mustraal:

- **Definition below is for reference. It is important that every event may contribute with one of two configurations, defined either with the help of first or second beam (reconstructed parton) as seen in the rest frame of lepton pair. The final choice is made with probability independent of any couplings or PDFs.**
- We start from the following information, which turns out to be sufficient: (i) The 4-momenta and charges of outgoing leptons τ_1, τ_2. (ii) The sum of 4-momenta of all outgoing partons.
- The orientation of incoming beams b_1, b_2 is fixed as follows: b_1 is chosen to be always along positive z-axis of the laboratory frame and b_2 is anti-parallel to z axis. The information on incoming partons of p_1, p_2 is

not taken from the event record. It is recalculated from kinematics of outgoing particles and knowledge of the center of mass energy of colliding protons. In this convention the energy fractions x_1 and x_2 of p_1, p_2 carried by colliding partons, define also the 3-momenta which are along b_1, b_2 respectively.

- The flavour of incoming partons (quark or antiquark) is attributed as follows: incoming parton of larger x_1 (x_2) is assumed to be the quark. This is equivalent to choice that the quark follow direction of the outgoing $\ell\ell$ system, similarly as it is defined for the Collins-Soper frame. This choice is necessary to fix sign of $\cos\theta_{1.2}$ defined later.
- The 4-vectors of incoming partons and outgoing leptons are boosted into lepton-pair rest frame.
- To fix orientation of the event we use versor $\hat{x}_{lab}$ of the laboratory reference frame. It is boosted into lepton-pair rest frame as well. It will be used in definition of azimuthal angle ϕ, which has to extend over the range $(0, 2\pi)$.
- We first calculate $\cos\theta_1$ (and $\cos\theta_2$) of the angle between the outgoing lepton and incoming quark (outgoing anti-lepton and incoming anti-quark) directions.

$$\cos\ \theta_1 = \frac{\vec{\tau_1}\cdot\vec{p_1}}{|\vec{\tau_1}||\vec{p_1}|}, \qquad \cos\ \theta_2 = \frac{\vec{\tau_2}\cdot\vec{p_2}}{|\vec{\tau_1}||\vec{p_2}|} \tag{8}$$

- The azimuthal angles ϕ_1 and ϕ_2 corresponding to θ_1 and θ_2 are defined as follows. We first define $e_{\vec{y_{1,2}}}$ versors and with their help later $\phi_{1,2}$ as:

$$\vec{e_y} = \frac{\vec{x_{lab}} \times \vec{p_2}}{|\vec{e_y}|}, \quad \vec{e_x} = \frac{\vec{e_y}\times\vec{p_2}}{|\vec{e_x}|}$$

Collins-Soper and Mustraal frames.

$$\cos\ \phi_1 = \frac{\vec{e_x}\cdot\vec{\tau_1}}{\sqrt{(\vec{e_x}\cdot\vec{\tau_1})^2+(\vec{e_y}\cdot\vec{\tau_1})^2}}$$

$$\sin\ \phi_1 = \frac{\vec{e_y}\cdot\vec{\tau_1}}{\sqrt{(\vec{e_x}\cdot\vec{\tau_1})^2+(\vec{e_y}\cdot\vec{\tau_1})^2}} \quad (9)$$

and similarly for ϕ_2:

$$\vec{e_y} = \frac{\vec{x_{lab}}\times\vec{p_1}}{|\vec{e_y}|}, \quad \vec{e_x} = \frac{\vec{e_y}\times\vec{p_1}}{|\vec{e_x}|}$$

$$\cos\ \phi_2 = \frac{\vec{e_x}\cdot\vec{\tau_2}}{\sqrt{(\vec{e_x}\cdot\vec{\tau_2})^2+(\vec{e_y}\cdot\vec{\tau_2})^2}}$$

$$\sin\ \phi_2 = \frac{\vec{e_y}\cdot\vec{\tau_2}}{\sqrt{(\vec{e_x}\cdot\vec{\tau_2})^2+(\vec{e_y}\cdot\vec{\tau_2})^2}}. \quad (10)$$

- Each event contributes with two Born-like kinematics configurations $\theta_1\phi_1$, ($\theta_2\phi_2$), respectively with wt_1 (and wt_2) weights; $wt_1 + wt_2 = 1$ where

$$wt_1 = \frac{E_{p1}^2(1+\cos^2\theta_1)}{E_{p1}^2(1+\cos^2\theta_1)+E_{p2}^2(1+\cos^2\theta_2)},$$

$$wt_2 = \frac{E_{p2}^2(1+\cos^2\theta_2)}{E_{p1}^2(1+\cos^2\theta_1)+E_{p2}^2(1+\cos^2\theta_2)}. \quad (11)$$

In the calculation of the weight, incoming partons energies E_{p1}, E_{p2} in the rest frame of lepton pair are used, but not their couplings or flavours. That is also why, instead of $\sigma_B(s, \cos\theta)$ the simplification $(1+\cos^2\theta)$ is used in Eq. (11).

part B: Numerical results, Born recovered?

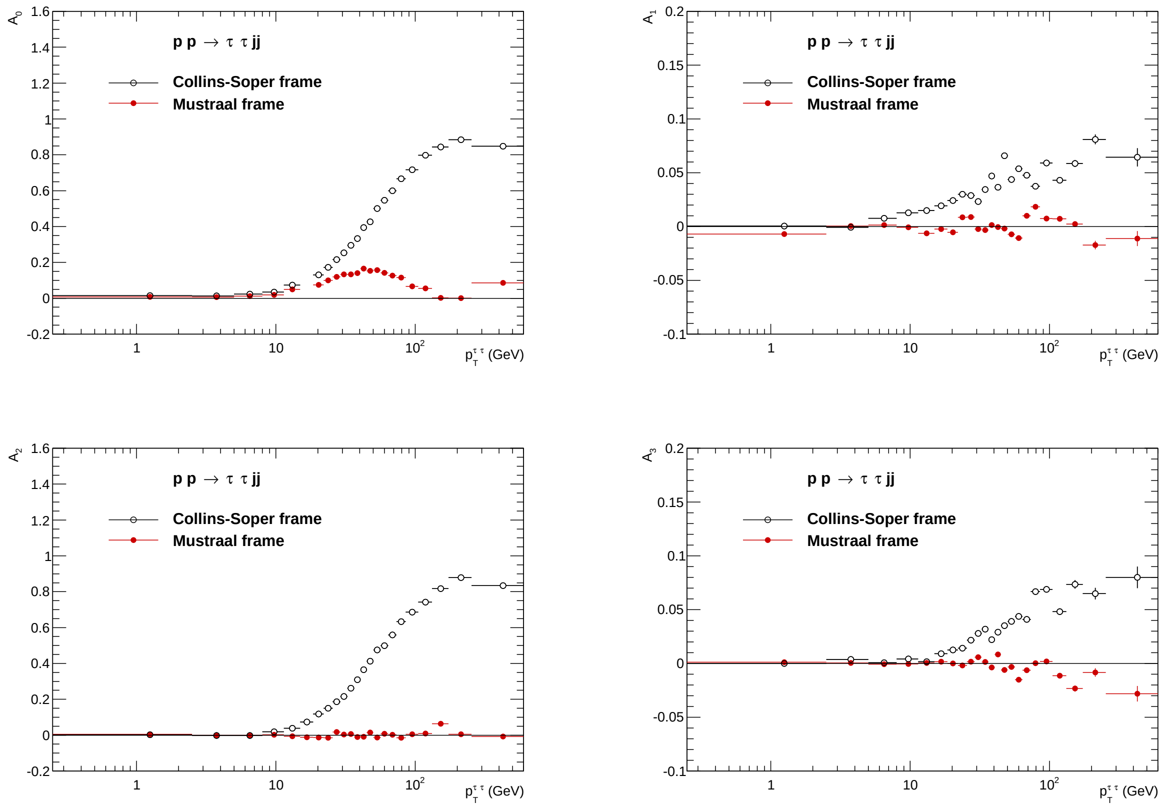


Figure 1: **arXiv:1605.05450**: The A_i coefficients of Eq. (8)) calculated in Collins-Soper (black) and in `Mustraal` (red) frames for $pp \to \tau\tau jj$ process generated with `MadGraph`. Details of initialization are given in the reference.

part B: Numerical results, Born recovered?

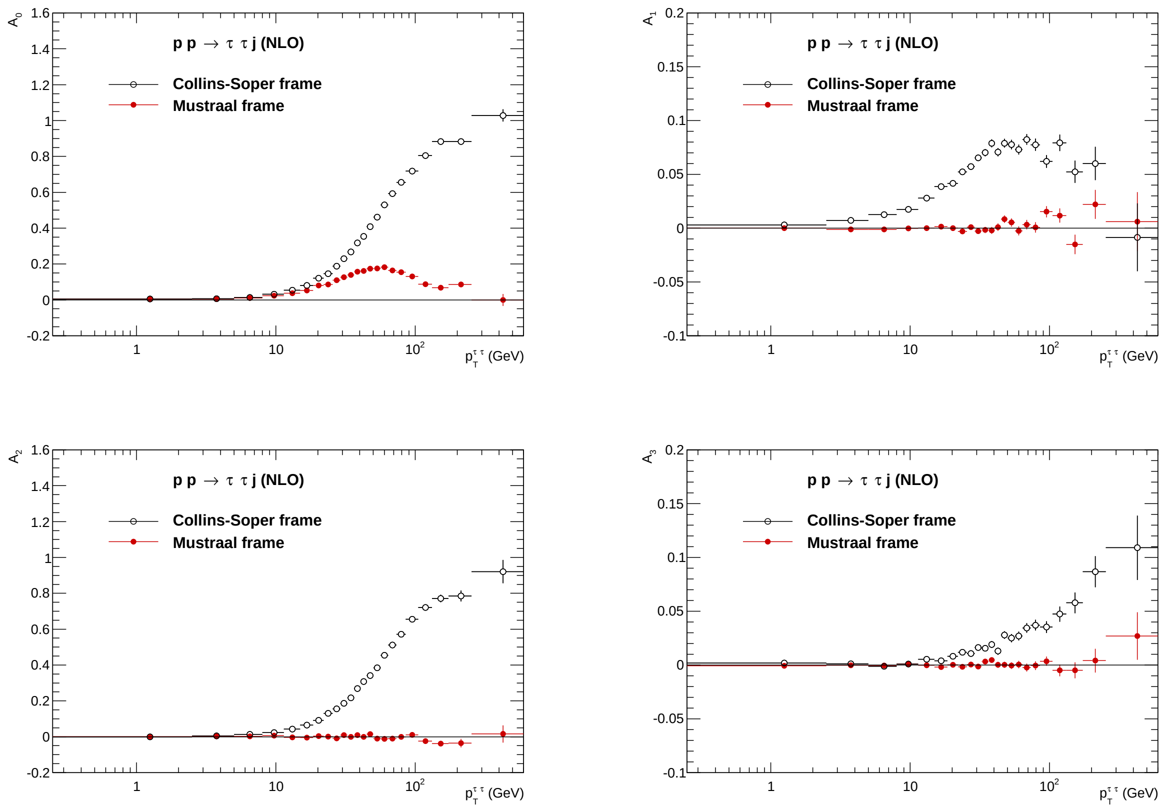


Figure 2: **arXiv:1605.05450**: The A_i coefficients of Eq. (8)) calculated in Collins-Soper (black) and in `Mustraal` (red) frames for $pp \to \tau\tau j$ (NLO) process generated with `Powheg+MiNLO`. Details of initialization are given in the reference.

part B: Numerical results, Born recovered?

- The choice of Mustraal frame is result of careful study of single photon (gluom) emission)
- In Ref of 1982 it was shown, that differential distribution is a sum of two born-like distributions convoluted with emission factors.
- This is a consequence of Lorentz group representation and that is why it generalizes to the case of double gluon or even double parton emissions.
- Presence of jets is like change of orientation of frames.
- That is why use of electroweak Borns I will discuss later is justified.
- More elegant proof may come from common work with SANC team.
- For the moment figures demonstrating how proper choice of frames can turn high p_T events into electroweak Born must be sufficient.
- Far more detailed studies were performed for the purpose of LEP Monte Carlo programs and matching of genuine weak corrections with QED bremsstrahlung.

part C: Electroweak form factors

We can write amplitude for Born with EW loop corrections, $ME_{Born+EW}$, as:

$$\begin{aligned} ME_{Born+EW} &= [\bar{u}\gamma^{\mu} v g_{\mu\nu} \bar{v}\gamma^{\nu} u] \cdot (q_e \cdot q_f) \cdot \Gamma_{V_\Pi} \cdot \frac{\chi_\gamma(s)}{s} \\ &+ [\bar{u}\gamma^{\mu} v g_{\mu\nu} \bar{\nu}\gamma^{\nu} u \cdot (v_e \cdot v_f \cdot vv_{ef}) + \bar{u}\gamma^{\mu} v g_{\mu\nu} \bar{\nu}\gamma^{\nu}\gamma^{5} u \cdot (v_e \cdot a_f) \\ &+ \bar{u}\gamma^{\mu}\gamma^{5} v g_{\mu\nu} \bar{\nu}\gamma^{\nu} u \cdot (a_e \cdot v_f) + \bar{u}\gamma^{\mu}\gamma^{5} v g_{\mu\nu} \bar{\nu}\gamma^{\nu}\gamma^{5} u \cdot (a_e \cdot a_f)] \frac{\chi_Z(s) Z_{V_\Pi}}{s} \end{aligned} \tag{12}$$

One has to take into account, the angle dependent double-vector coupling extra correction, which breaks structure of the couplings into ones associated with Z boson production and decay:

$$\begin{aligned} vv_{ef} = & \frac{1}{v_e \cdot v_f} [(2 \cdot T_3^e)(2 \cdot T_3^f) - 4 \cdot q_e \cdot s_W^2 \cdot K_f(s,t) - 4 \cdot q_f \cdot s_W^2 \cdot K_e(s,t) \\ & + (4 \cdot q_e \cdot s_W^2)(4 \cdot q_f \cdot s_W^2) K_{ef}(s,t)] \frac{1}{\Delta^2} \end{aligned} \tag{13}$$

further terms are straightforward:

part C: Electroweak form factors

$$\begin{aligned} v_e &= (2 \cdot T_3^e - 4 \cdot q_e \cdot s_W^2 \cdot K_e(s,t))/\Delta \\ v_f &= (2 \cdot T_3^f - 4 \cdot q_f \cdot s_W^2 \cdot K_f(s,t))/\Delta \\ a_e &= (2 \cdot T_3^e)/\Delta \\ a_f &= (2 \cdot T_3^f)/\Delta \end{aligned} \quad (14)$$

The form-factors $K_e(s,t)$, $K_f(s,t)$ are functions of two Mandelstam invariants (s,t) due to the WW and ZZ box contributions.

Vacuum polarisation corrections Γ_{V_Π} to γ propagator are expressed as:

$$\Gamma_{V_\Pi} = \frac{1}{2 - (1 + \Pi_{\gamma\gamma})} \quad (15)$$

Normalisation correction Z_{V_Π} to Z-boson propagator is expressed as

$$Z_{V_\Pi} = \rho_{e,f}(s,t) \quad (16)$$

part C: Electroweak form factors

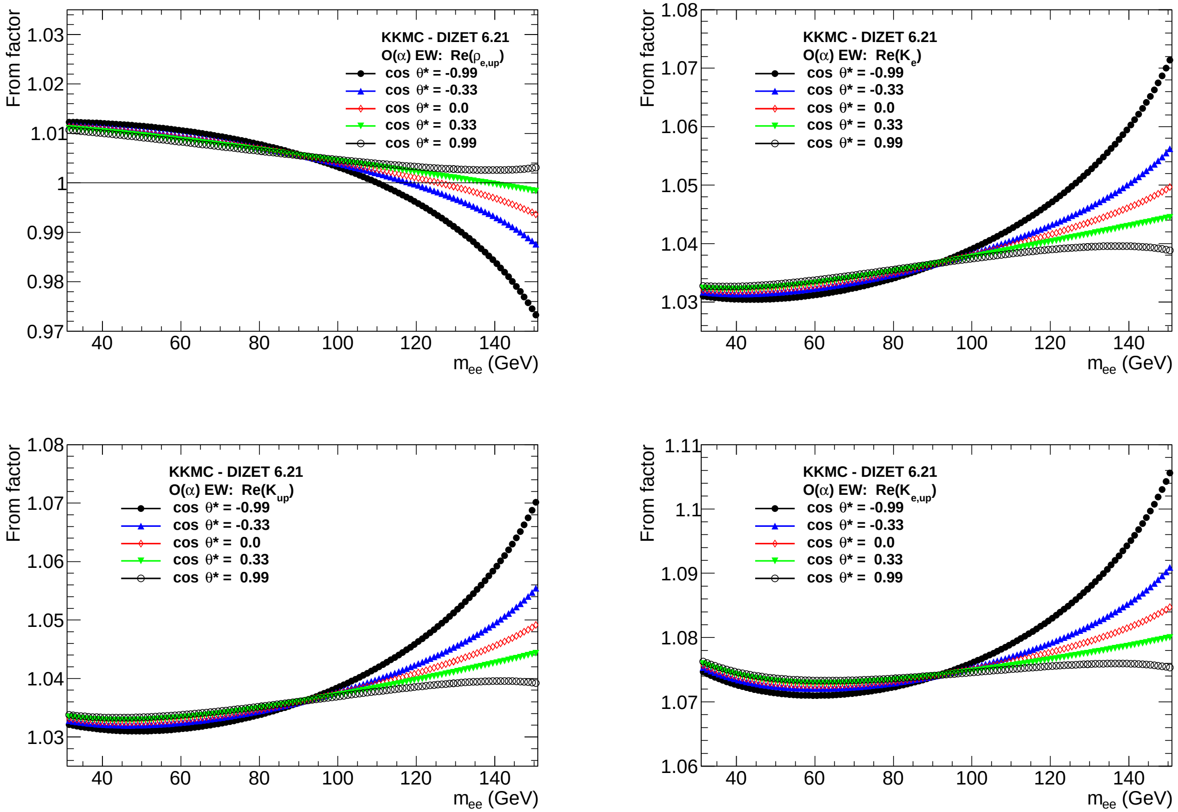


Figure 3: Real part of $\rho_{e,up}$, K_e, K_{up} and $K_{e,up}$ EW form factors as a function of m_{ee} for few values of $\cos\theta^*$ and u-type quark flavour. Note that close to the Z peak angular dependence is minimal. For lower virtualities photon exchange dominates. Electroweak effects do not damage picture of spherical harmonics. Plots selected from Elzbieta's set.

part C: Electroweak form factors

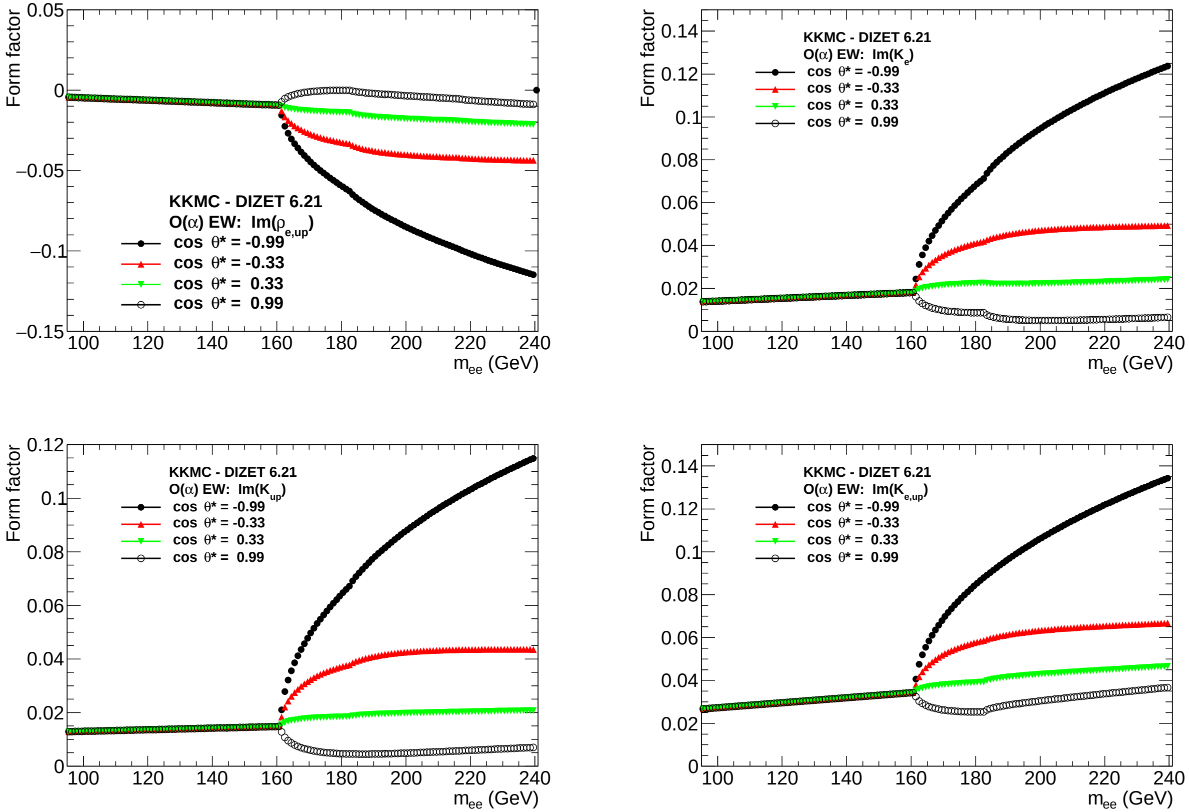


Figure 4: Imaginary part of $\rho_{e,u}$, K_e, K_{up} and $K_{e,up}$ a function of m_{ee} for few values of $\cos\theta^*$ and u-type quark flavour (left). Same for the down-type on the right. Note the WW and ZZ threshold effects which exhibits as discontinuity. Electroweak effects complicate picture of spherical harmonics at virtualities above WW threshold. Plots selected from Elzbieta's set.

Observations

- Formfactors break, but in numerically not significant manner, the lepton angular distributions, which are not anymore spherical harmonics of second order.
- This is a constraint for the re-weight algorithm if used at histogram level.
- We need to explore Mustraal frames for reweighting algorithms, which can then be used to install better genuine weak effects into ‘any’ MC sample, provided in its generation known (constant) couplings of Z bosons were used.
-
- Let us present example numerical results as ‘appetizer’:

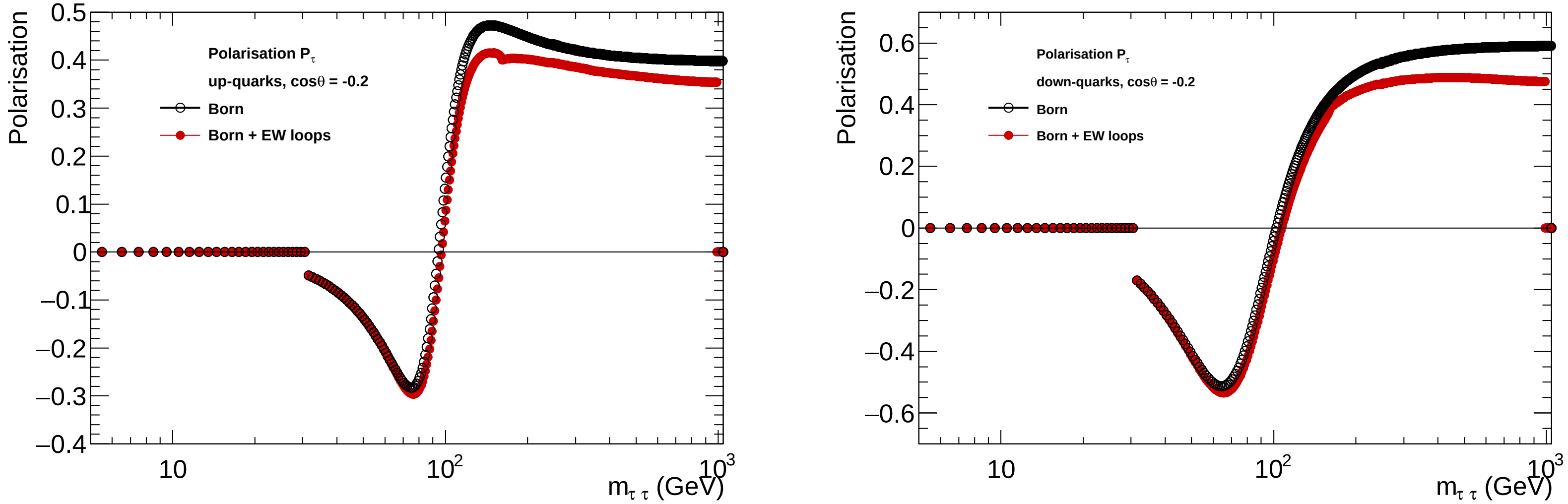


Figure 5: Benchmark distribution comparing with `Tauola Universal Interface` documentation possible, there SANC as of 2010 was used. Polarisation for τ-leptons produced from up-quarks (left) and down-quarks (right) for $\cos\theta = -0.2$ and as a function of invariant mass of τ-lepton pairs, drawn for $m_{\tau\tau} > 30$ GeV only. The red points are with EW loop corrections, black ones are for Standard Model Born level. Plots selected from Elzbieta's set.

part C: results of some phenomenology interest.

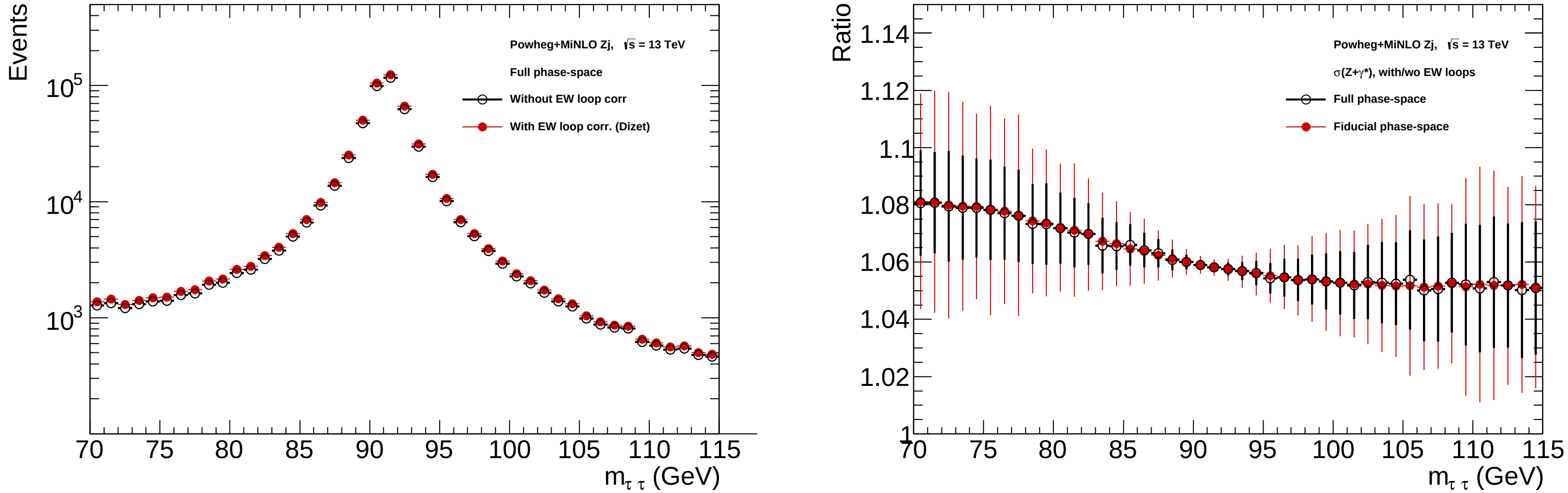
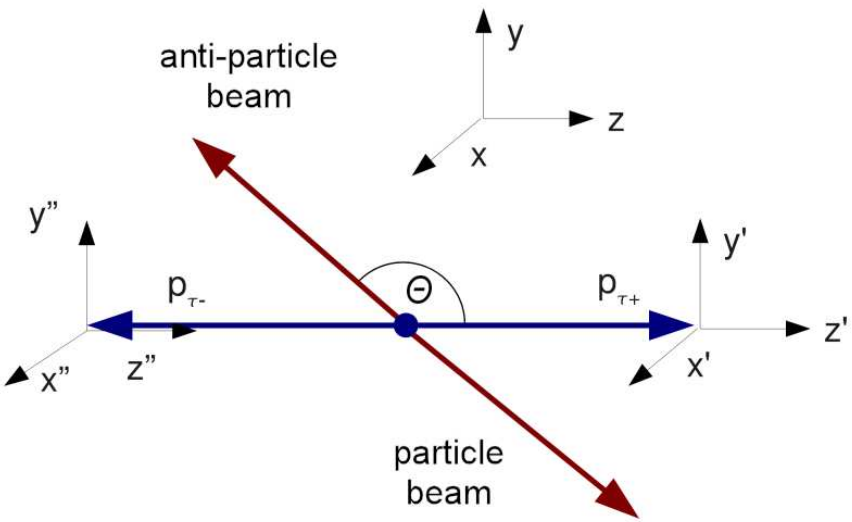


Figure 6: The line-shape of $\tau\tau$ pairs, with and without EW loop corrections and the ratio of the cross-section $\sigma(Z + \gamma^*)$ in full and fiducial phase-space. Note an overall 6-8% correction due Born of on-shell scheme. Fiducial mean:τ-lepton transverse momenta $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.5$. Plots selected from Elzbieta's set.

part C: results of some phenomenology interest.



- Higgs CP in $H \to \tau\tau$, $\tau \to 3(2)\pi\nu$ Phys.Rev. D94(2016)093001
- Extension of the previous considerations to the case of spin is straightforward.
- Hard process: flavors and 4-momenta of incoming quarks and outgoing τ's (ν_τ) can be attributed with help of PDFs and Mustraal frame parametrization of Born.
- Algorithm for spin correlations has no approximation.
- Method to calculate density matrix usually will impose approximations.
- Density matrix including EW corrections with Mustraal frame is a good option.
- This is of some (minor) relevance to discussions of systematic theoretical errors.

Summary, points for discussion

1. **Tools for discussions of the size of EW effects, $(\alpha\alpha_S)$ and observables for New Physics, also of relevance for W mass or s_W^2 measurements.**

2. Complications due to weak Sudakovs etc. would favour other calculations.

3. But one can not drop out effects which are known to be substantial. Also relation to phenomenology solutions of LEP and TEVATRON are of importance.

4. We have 3 sources of formfactors

   - DIZET 6.21 as encapsulated in KKMC, LEP time Monte Carlo used e.g. in interpretatiuons of Z mass measurements.

   - SANC as encapsulated in Tauola Universal Interface (no double loop QCD effects)

   - Up to date SANC which to be available soon (April 2017) see extra slides below (part E), and we want to make that avialable immediately (through `TauSpinner`).

part D: Extra pair emission in PHOTOS MC

1. `Photospp` algorithm is searching for the decay vertex in event record; with certain probability replaces it with the one with extra photons added. For matrix element calculation predeceasing vertices are used too.

2. The original kinematic configuration is used to obtain some angles which are used to parametrize phase space when photons are added, that is why resulting parametrization of phase space with photons added is exact.

3. Exact 4-fermion phase space generator $\times$ Matrix Element for pair emissions too. Flat phase space generation mode is available for basic technical checks.

4. Work in that direction was started already in 90's but because other bigger effects were not taken into account it was left aside.

5. Option with pair emission is implemented now into `Photospp`.

6. Simple matrix element is explicit. It is coded as function of four-vectors; can be replaced with more sophisticated one easily.

7. Matrix Element from *journals.aps.org/prd/pdf/10.1103/PhysRevD.49.1178* is used. This paper of S. Jadach M. Skrzypek B.F.L. Ward is also used for basic numerical tests.

part D: Extra pair emission in PHOTOS MC

1. The matrix element squared for the pair emission differ from Born by the factor

$$(\frac{2p}{-2pq} - \frac{2p'}{-2p'q})^\mu (\frac{2p}{-2pq} - \frac{2p'}{-2p'q})^\nu \ \frac{4q_1^\mu q_2^\nu - q^2 g^{\mu\nu}}{2q^4}, \tag{17}$$

   where q_1, q_2 are momenta of the additional pair, $q = q_1 + q_2$ and p, p' of the original leptons. This is for Z decay. For W decay it is poor approximation, valid only for collinear pairs; one presampler channel, no emissions along neutrino.

2. If the phase space for the emission is restricted to emitted pair energy smaller than $\Delta << \sqrt{s}$, then probability for such emission is given by:

$$\frac{4}{3}(\frac{\alpha}{\pi})^2 [\frac{1}{3}\mathcal{L}_\mu^3 + (\frac{31}{36} - \frac{\pi^2}{6})\mathcal{L}_\mu + \zeta(3) - \frac{197}{324}], \tag{18}$$

   with $\mathcal{L}_\mu = \log(2\Delta/\mu)$ and μ denoting emitted lepton mass.
   This formula provide useful test, such phase space restriction can be easily and temporarily introduced into `Photospp`.

3. Result can be extended to case when emitted leptons are different than emitting ones

part D: Extra pair emission: PHOTOS tests

- M =91.2175, Left Bin border=91.183, Right Bin border=91.252
- From PHOTOS:

	(emitted)	Delta =1	Delta =5	Delta =10
Z0 => e+ e-	(e+ e-)	0.00093850	0.00167783	0.00205299
Z0 => mu+ mu-	(e+ e-)	0.00093176	0.00162154	0.00194601
Z0 => e+ e-	(mu+ mu-)	0.00001507	0.00010231	0.00017137
Z0 => mu+ mu-	(mu+ mu-)	0.00001480	0.00010191	0.00017026

- From Semianalytic calculation

Semianalytic formula as implemented by PhD student Serge Antropov

	(emitted)	Delta =1	Delta =5	Delta =10
Z0 => e+ e-	(e+ e-)	0.00094772	0.00171442	0.00212938
Z0 => mu+ mu-	(e+ e-)	0.00093813	0.00165131	0.00201747
Z0 => e+ e-	(mu+ mu-)	0.00001466	0.00010409	0.00017804
Z0 => mu+ mu-	(mu+ mu-)	0.00001466	0.00010408	0.00017801

part D: Extra pair emission: PHOTOS tests

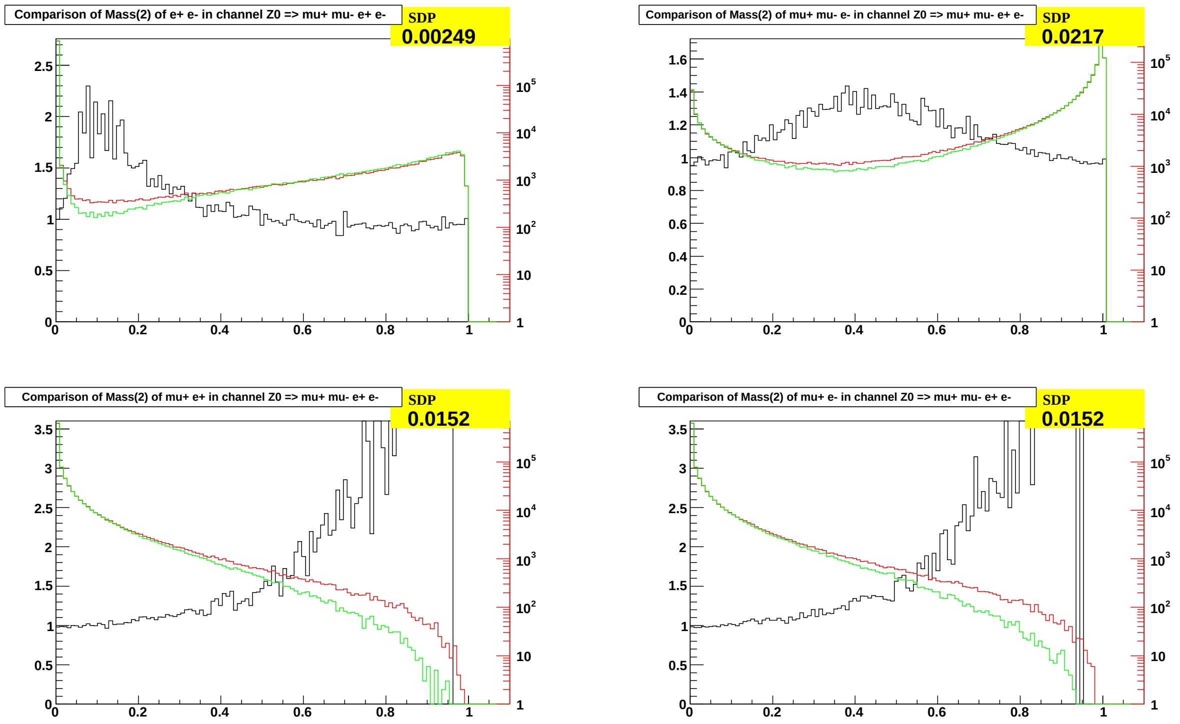


Figure 7: Comparison of PHOTOS with results from KORALW Monte Carlo of artificially narrow Z width and run at Z peak. For KORALW sample of $e^+e^+ - \mu^+ + \mu^+-$ events is used for Photos it is combination of samples $e^+e^+ - (\mu^+ + \mu^+-)$ and $\mu^+ + \mu^+ - (e^+e^+-)$

part D: Extra pair emission: PHOTOS tests

Systematic error of pair emission effect can be estimated at 20 % of its size now.

Comparisons with SANC rather low priority $\rightarrow$ not completed.

The topics of part E are more important...

NLO EW corrections in SANC

$\mathbf{M_W}$ meeting, 2017

MCSANC integrator

$\mathbf{mcsanc\_v\_1.01} \longrightarrow \mathbf{mcsanc\_v\_1.20}$

– $\gamma q, \gamma\gamma$ processes to DY NC&CC reactions

– higher order radiative corrections: $\alpha\alpha_s$, α^2_{ferm} for DY NC

– A$_{fb}$ histograms

A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, U. Klein, V. Kolesnikov, L. Rumyantsev, R. Sadykov, A. Sapronov.

"Update of the MCSANC Monte Carlo integrator, v. 1.20".

JETP Lett. 103 (2016) no.2, 131-136.

DOI: 10.1134/S0021364016020041. arXiv:1509.03052 [hep-ph]

MCSANC integrator

- to incorporate higher order radiative corrections into MCSANC through the form factors
- to add new processes with pp and e^+e^- beams

mcsanc_*v_1.30* (the end of April – middle of May, 2017)

- library of form factors with the higher order radiative corrections ($\alpha_t\alpha_s^2$, $\alpha_t\alpha_s^3$, $\alpha_t^2\alpha_s$, α_t^3, α_{bos}^2) for NC 4-fermion processes
- 2-loop leading weak corrections in the Sudakov regime
- NLO EW corrections for polarized Bhabha scattering
- NLO EW corrections for pp $\rightarrow t\bar{t}$ reaction

part F: KKMC and IFI interference

Main references for the KKMC:

1. KK MC S. Jadach, B. F. L. Ward, and Z. Wąs *Comput.Phys.Commun.* **130** (2000) 260

2. Scott Yost
   https://indico.cern.ch/event/595512/contributions/2467332/attachments/1410737/2158788/yost-wmass17-v2.pdf

3. Details on KKMC-hh can be found in Phys. Rev. D94 (2016) 074006 (arXiv:1608.01260)

part F: KKMC and IFI interference

A. KK MC is LEP time Monte Carlo, featuring exclusive exponentiation of second order QED matrix element and also complete electroweak corrections.

B. It was tested to a very high precision.

C. In particular numerical effects of QCD corrections (perturbative and not) for Z propagator were taken into account.

D. For tests one can switch on/off:

- second order QED matrix element,
- genuine weak corrections, parts of higher order QCD corrections to line-shape of Z.
- QED ISR/FSR interference, QED ISR, QED FSR
- extra pair emission contribution to vertex corrections, in a way compatible to new version of Photospp.

E. In the past initial state had to be e^+e^-. Now KKMC feature incoming quarks (of $p_T = 0$ but of x_i distributed accordingly to PDFs).

F. I used KK MC for tests of PHOTOS (Photospp).

part F: KKMC and IFI interference

G. KKMC was equipped with an algorithm for beamstrahlung: it is used for generating incoming quarks accordingly to PDF distributions.

H. The p_T^Z can be generated independently, as in our paper on ϕ^*_η and implemented at the time of histograming for observables with cuts.

I. It is not ideal solution, but already good step forward, probably enough for program used for evaluation of systematic errors on some effects

J. Work on how to combine KKMC with Monte Carlo simulation chain, such as HERWIG is on-going.

** New class of tests for theoretical systematic errors of observables with cuts is to be explored, also for ISR-FSR interference already now!

part F: KKMC and IFI interference

QED second order matrix element

- Algorithms of KK MC and SHERPA are based on exclusive exponentiation. SHERPA features first order QED FSR matrix element only. The LEP legacy generator KK MC features second order matrix element as default.
- KK MC offers excellent benchmark for evaluating importance of the second order matrix element as it can be also downgraded to first order only.

  LIMITATION, RECENT IMPROVEMENT: it can be used for fixed flavour incoming quarks with PDF distributions but so far no p_T.

  Effects of for **ISR-FSR interference and second order matrix element** embedded in exclusive exponentiation can be calculated. **KKMC is the only program available for this purpose.**

  We use this opportunity regularly for benchmarking PHOTOS, we have used it for ϕ^*_η observable.

part F: KKMC and IFI interference

- **Thanks to the tests with KK MC we could confirm:** second order matrix element of QED FSR is not a problem at precision level for ϕ^*_η of 0.3% .
- When precision improves to 0.1%, these studies have to be revisited as well as simulation of pair emision.
- There is room for improving TH precision on leptonic degrees of freedom! Total systematic error for luminosity (Bhabha scattering) **at LEP reached 0.04%**.

part F: KKMC and IFI interference

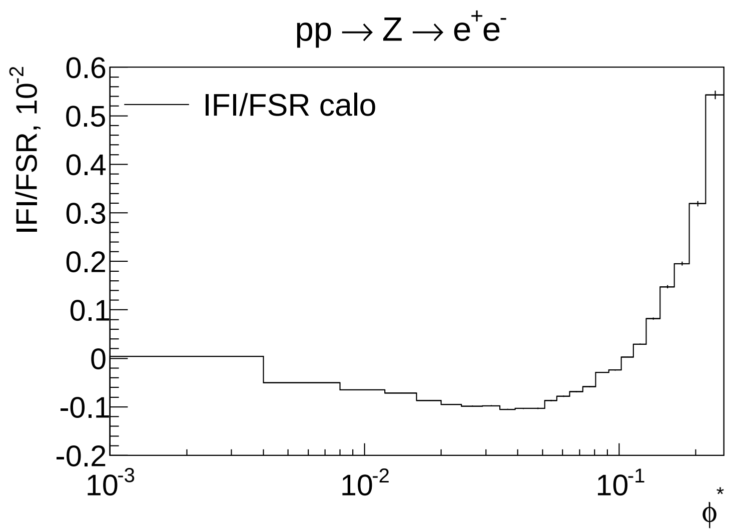


Figure 8: **arXiv:1212.6783 1303.2220**: *IFI/FSR ratio in Z decay for ϕ^*_η distribution. For $\phi^*_\eta > 0.2$ interference effects become sizable.*

In PHOTOS only QED FSR emission is taken into account

ISR-FSR radiation interference is omitted

In general, this effect is expected to be of order of α_{QED} but for Z or W observables suppression factor $\frac{\Gamma}{M}$ is expected for large class of cuts

Effect is small, can be neglected for 0.3% precision level and present day selection cuts for ϕ^*_η.

It is important that proper calculation scheme is used. Mismatch between QED FSR and remaining genuine weak corrections must be avoided.

part F: KKMC and IFI interference

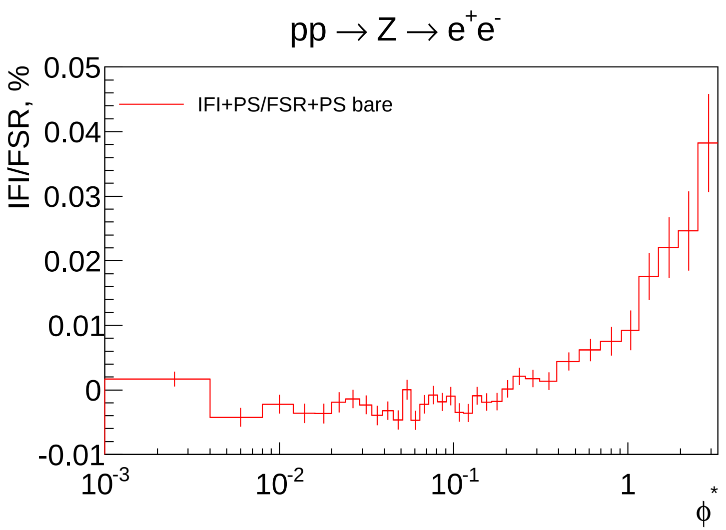


Figure 9: **arXiv:1212.6783 1303.2220**: *IFI/FSR ratio in Z decay for ϕ^*_η distribution. For $\phi^*_\eta > 0.2$ interference effects is negligible because parton shower brings dominant effect.*

In **PHOTOS** only QED FSR emission is taken into account

ISR-FSR radiation interference is omitted

In general, this effect is expected to be of order of α_{QED} but for Z or W observables suppression factor $\frac{\Gamma}{M}$ is expected for large class of cuts

It can be neglected for 0.3% precision level and present day selection cuts for ϕ^*_η.

It is important that proper calculation scheme is used. Mismatch between QED FSR and remaining genuine weak corrections must be avoided.