Separating electroweak and strong interaction effect:

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

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My supposed goal was to provide slides for discussion. The actual questions were not specified. Instead we had a dinner yesterday ...

LEP Heritage: effective Born $\times$ genuine weak effects.

- References: 1609.02536 1605.05450, Nucl.Phys. B387 (1992) 3, Comput.Phys.Commun. 29 (1983) 185, Nucl.Phys. B347 (1990) 67

- Numerical results (important shapes): for electroweak effects No formal proofs, just practical aspects of single Z or W production.

- Future; work with SANC group, but also use of LEP electroweak libraries.

- Comment on final state lepton pair emission in PHOTOS MC.

> ## *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.**

Production and decay for Bosons
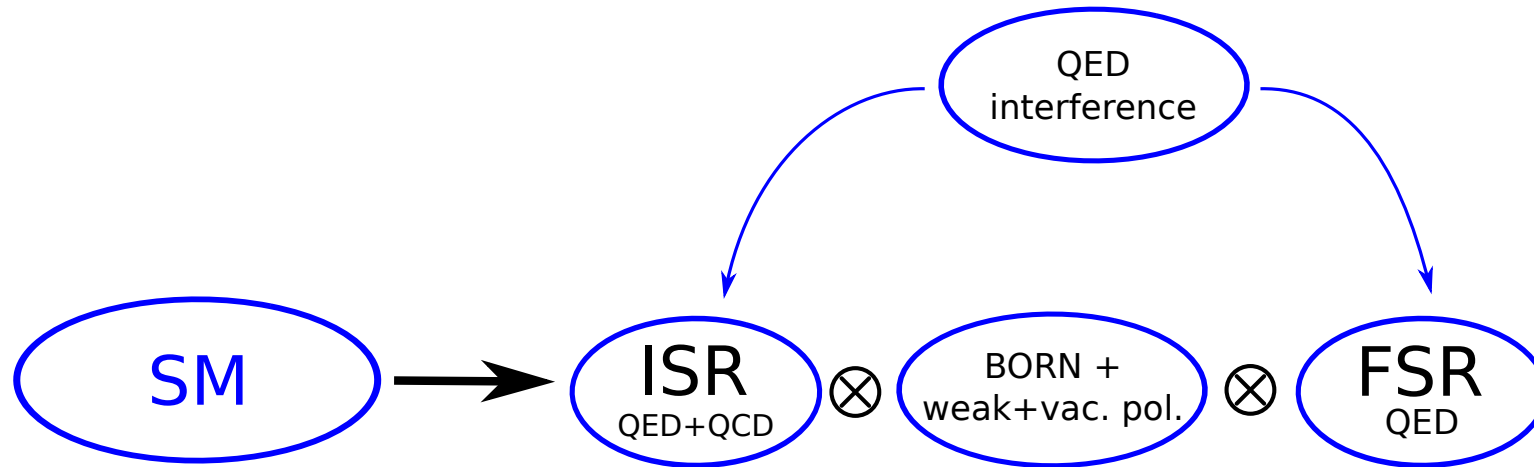
- That is the picture we inherit.

- 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)

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.

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

where

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

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

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

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 ...

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

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

(6)

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

$$F_0(s) = \frac{\pi\alpha^2}{2s}[q_f^2 q_\ell^2 \cdot \chi_\gamma^2(s) + 2 \cdot \chi_\gamma(s)Re\chi_Z(s)\,q_f q_\ell v_f v_\ell + |\chi_Z^2(s)|^2(v_f^2+a_f^2)(v_\ell^2+a_\ell^2)],$$

$$F_1(s) = \frac{\pi\alpha^2}{2s}[2\chi_\gamma(s)Re\chi(s)\,q_f q_\ell v_f v_\ell + |\chi^2(s)|^2\,2v_f a_f 2v_\ell a_\ell],$$

(7

$$F_2(s) = \frac{\pi\alpha^2}{2s}[2\chi_\gamma(s)Re\chi(s)\,q_f q_\ell v_f v_\ell + |\chi^2(s)|^2\,(v_f^2+a_f^2)2v_\ell a_\ell],$$

$$F_3(s) = \frac{\pi\alpha^2}{2s}[2\chi_\gamma(s)Re\chi(s)\,q_f q_\ell v_f v_\ell + |\chi^2(s)|^2\,(v_f^2+a_f^2)2v_\ell a_\ell],$$

$\cos\theta$ 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:

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

$$
\begin{aligned}
\frac{d\sigma}{dp_T^2 \, dY \, d\cos\theta \, d\phi} \;=\; & \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^2 \, dY} \Big[(1 + \cos^2\theta) + \\
1/2 \, A_0 (1 - 3\cos^2\theta) \;+\; & A_1 \sin(2\theta)\cos\phi + 1/2 \, A_2 \sin^2\theta \cos(2\phi) + A_3 \sin\theta \cos\phi \\
+ A_4 \cos\theta \;+\; & A_5 \sin^2\theta \sin(2\phi) + A_6 \sin(2\theta)\sin\phi + A_7 \sin\theta \, \sin\phi \Big]
\end{aligned}
$$

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 $\vec{e_{y_{1,2}}}$ versors and with their help later $\phi_{1,2}$ as:

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

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

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

and similarly for ϕ_2:

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

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

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

– 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

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

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

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).
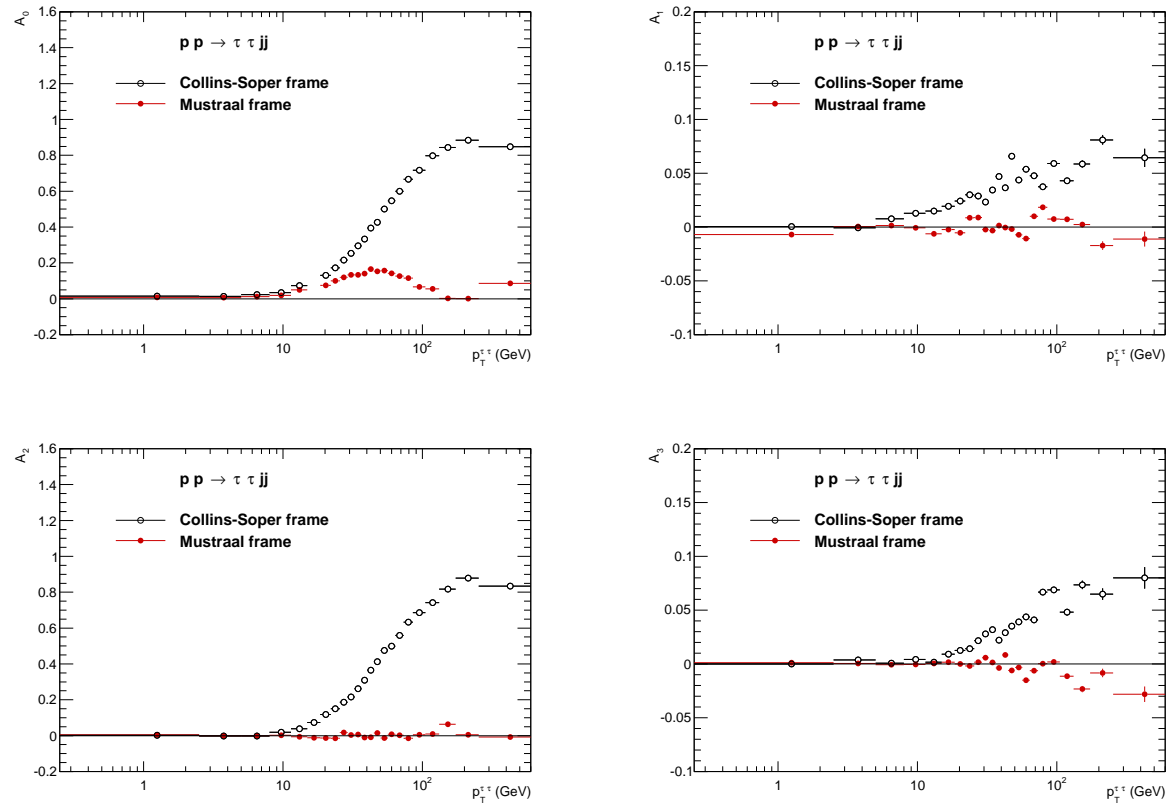
Figure 1: **arXiv:1605.05450**: The A_i coefficients of Eq. (8)) calculated in Collins-Soper (black) and in `Mustraal` (red) frames for $pp \to \tau\tau jj$ process generated with `MadGraph`. Details of initialization are given in the reference.
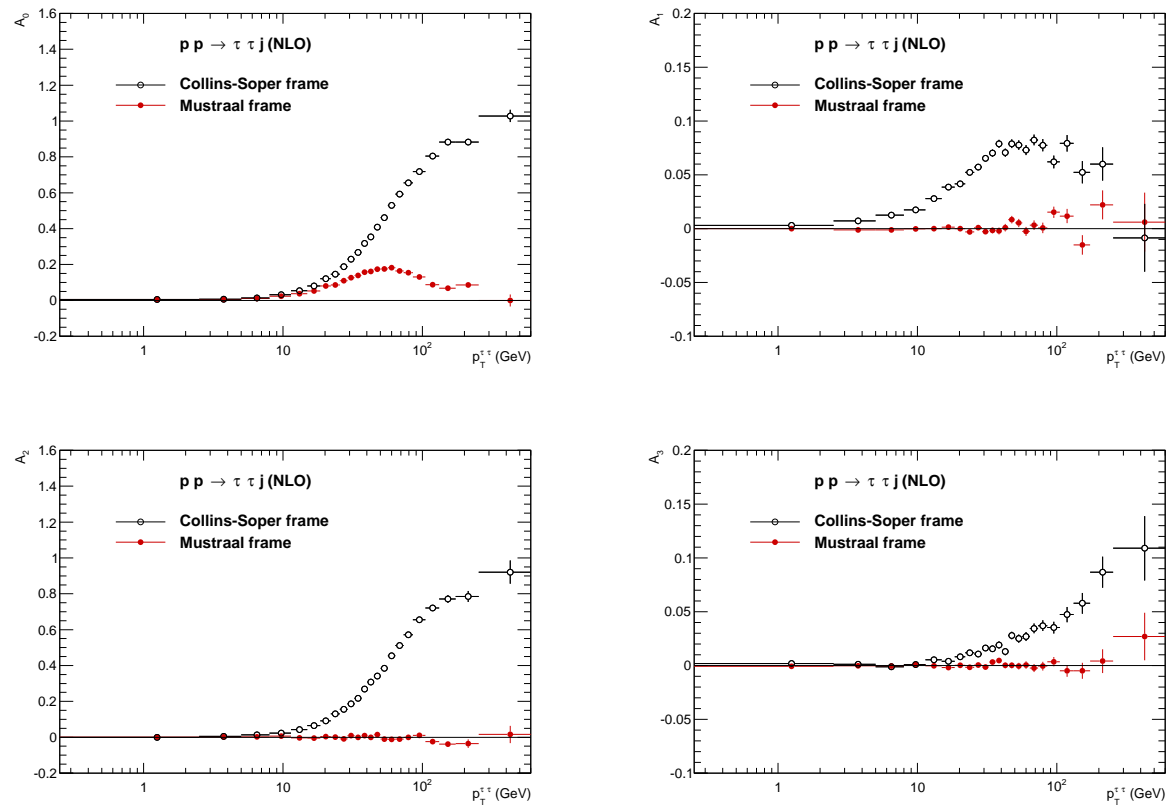
Figure 2: **arXiv:1605.05450**: The A_i coefficients of Eq. (8)) calculated in Collins-Soper (black) and in `Mustraal` (red) frames for $pp \to \tau\tau j$ (NLO) process generated with `Powheg+MiNLO`. Details of initialization are given in the reference.

- 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.

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

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

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:

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

further terms are straightforward:

$$v_e = (2 \cdot T_3^e - 4 \cdot q_e \cdot s_W^2 \cdot K_e(s,t))/\Delta$$

$$v_f = (2 \cdot T_3^f - 4 \cdot q_f \cdot s_W^2 \cdot K_f(s,t))/\Delta \qquad (14)$$

$$a_e = (2 \cdot T_3^e)/\Delta$$

$$a_f = (2 \cdot T_3^f)/\Delta$$

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:

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

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

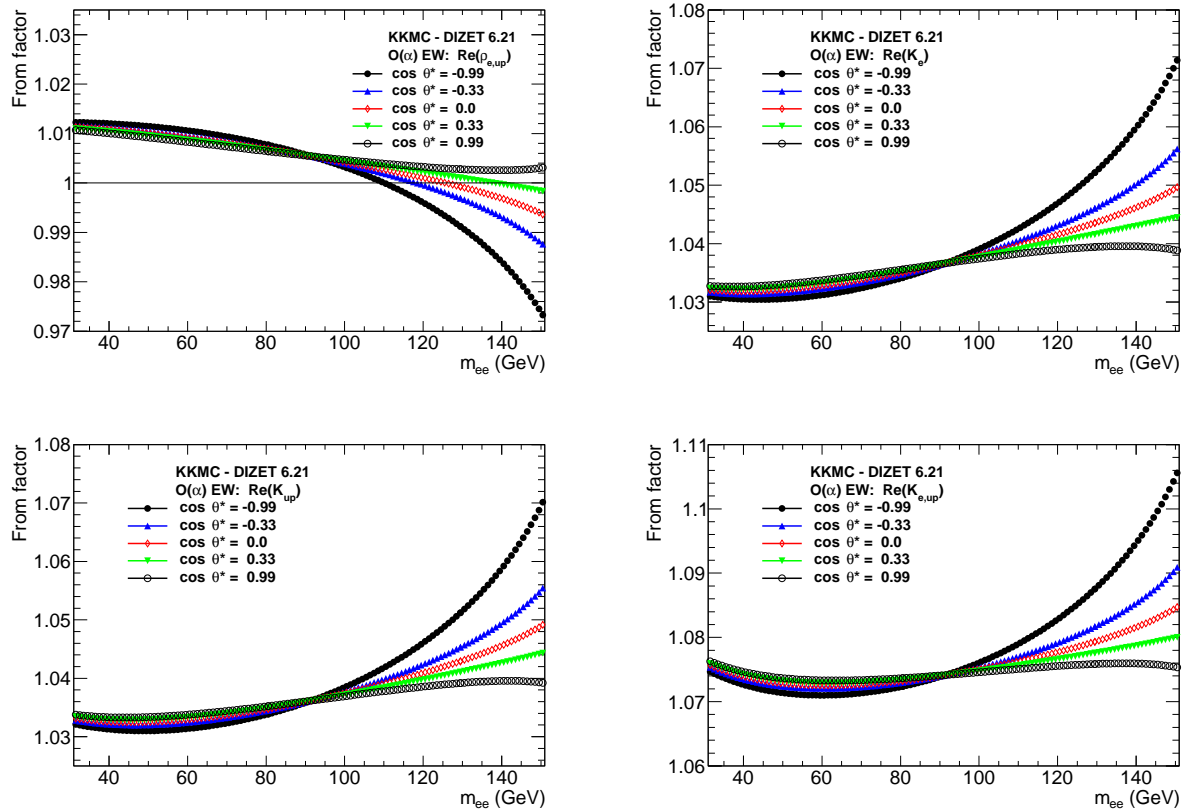$$Z_{V_\Pi} = \rho_{e,f}(s,t) \qquad (16)$$

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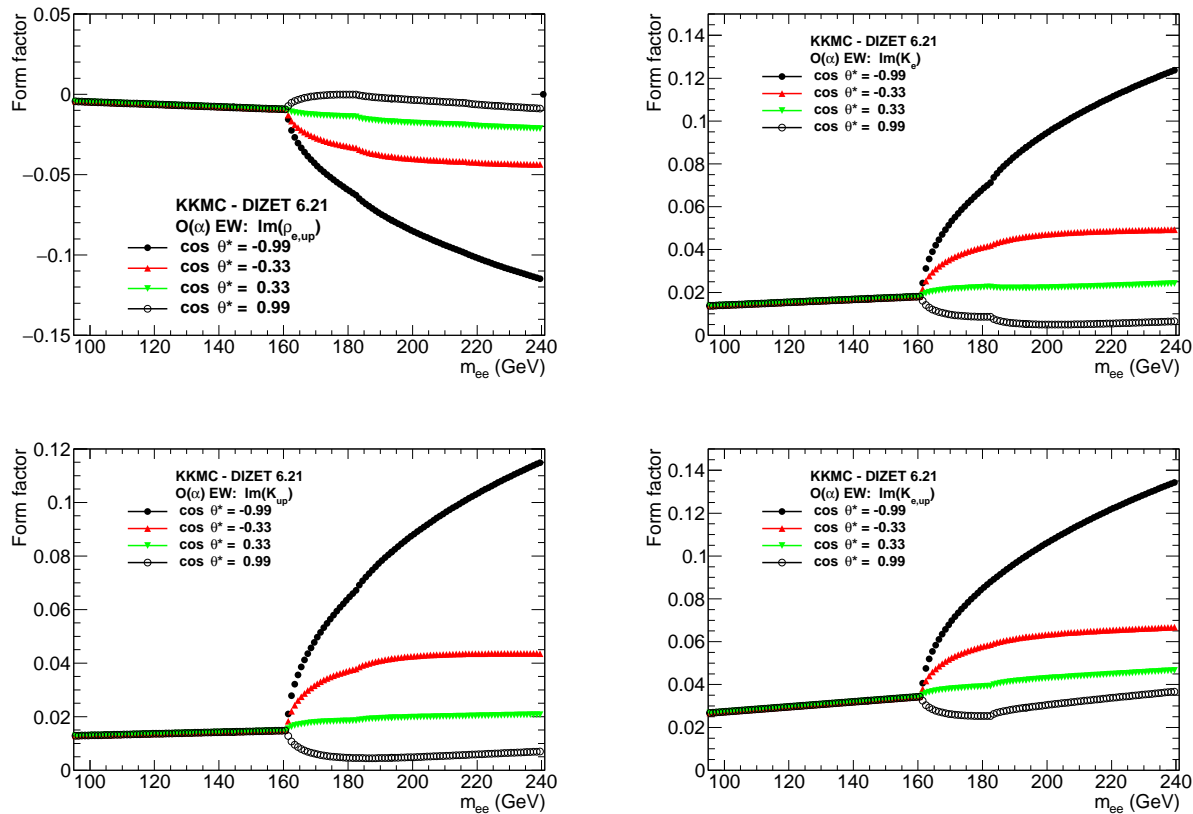
Figure 4: Imaginary part of $\rho_{e,u}$, K_e, K_{up} and $K_{e,up}$ a function of m_{ee} for few values of $\cos \theta^*$ and u-type quark flavour (left). Same for the down-type on the right. Note the WW and ZZ threshold effects which exhibits as discontinuity. Electroweak effects complicate picture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

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.

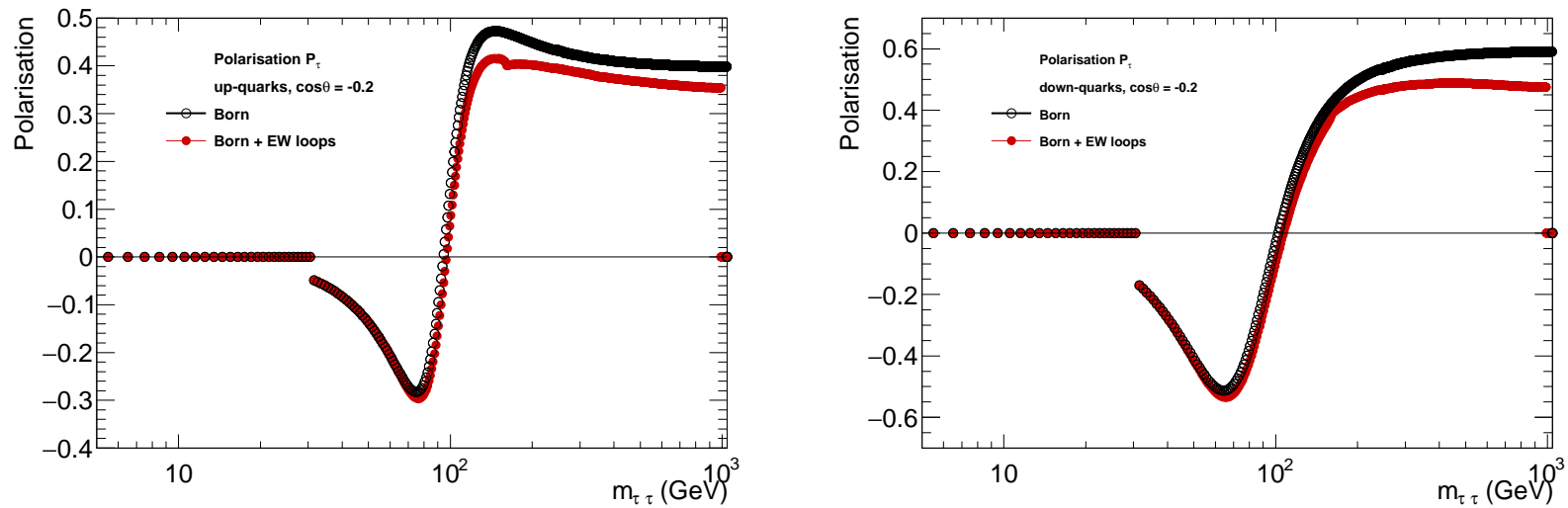-

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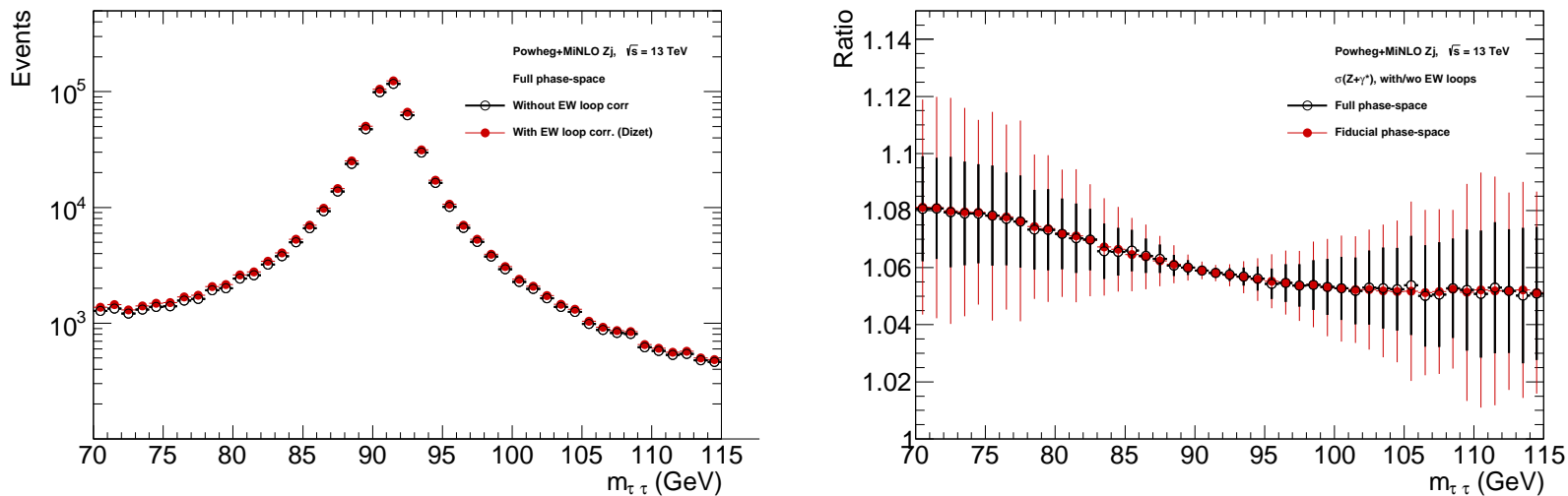
Figure 6: The line-shape of $\tau\tau$ pairs, with and without EW loop corrections and the ratio of the cross-section $\sigma(Z + \gamma^*)$ in full and fiducial phase-space. Note an overall 6-8% correction due Born of on-shell scheme. Fiducial mean:τ-lepton transverse momenta $p_T > 25$ GeV and pseudorapidity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

1. **Is the size of EW effect $(\alpha\alpha_S)$ of relevance for W mass or s_W^2 measurements ?**

2. Complications due to weak Sudakovs etc.

3. But one can not drop out effects which are known to be substantial.

4. We have 3 sources of formfactors

   - DIZET 6.21 as encapsulated in KKMC, see talk by S. Yost

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

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

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.

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

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

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:

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

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

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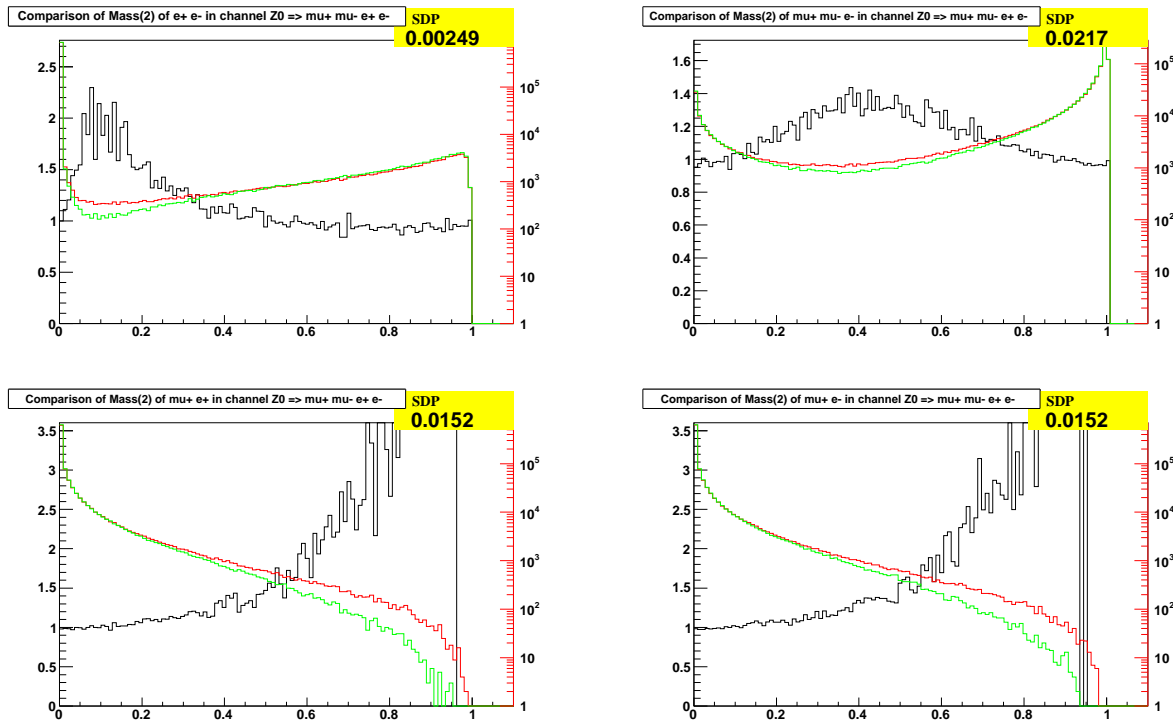
Figure 7: Comparison of PHOTOS with results from KORALW Monte Carlo of artificially narrow Z width and run at Z peak. For KORALW sample of $e^+ e^+ - \mu^+ + \mu^+ -$ events is used for Photos it is combination of samples $e^+ e^+ - (\mu^+ + \mu^+ -)$ and $\mu^+ + \mu^+ - (e^+ e^+ -)$

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

$\mathrm{M_W}$ **meeting, 2017**

MCSANC integrator

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

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

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

- A_{fb} histograms

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
  $(\alpha_t\alpha_s^2, \alpha_t\alpha_s^3, \alpha_t^2\alpha_s, \alpha_t^3, \alpha_{bos}^2)$ 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