

KKMC: new tau decays, vector/scalar resonances of New Physics

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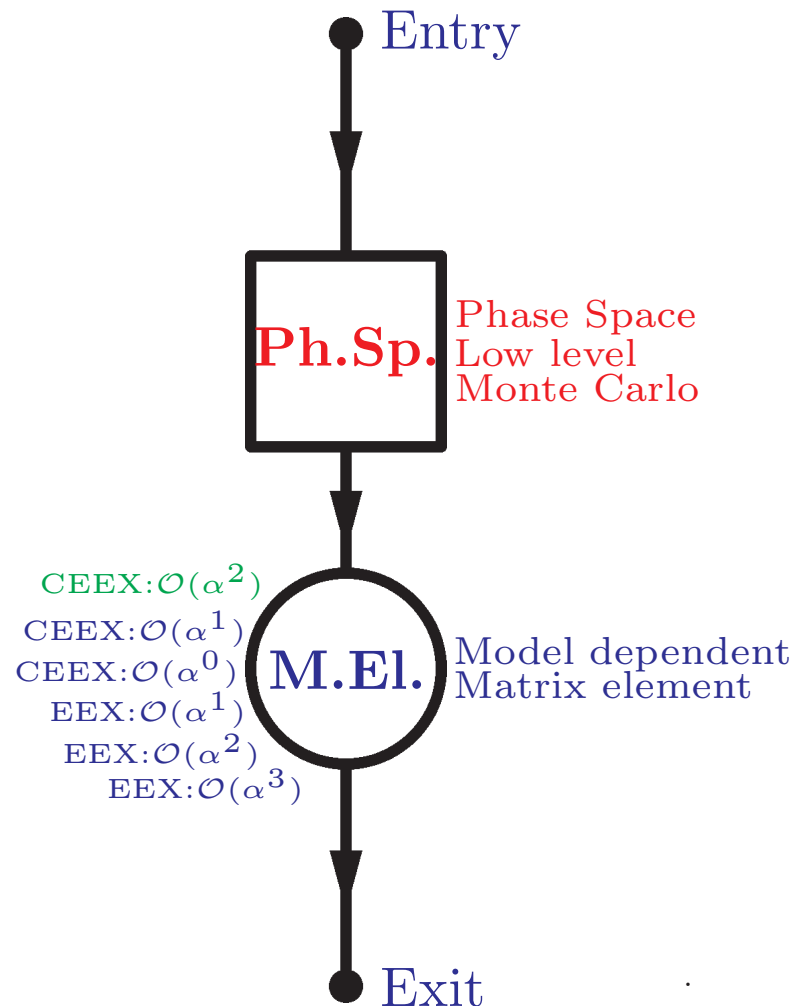
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- Activity started upon request from Belle2 collaboration. The code of `KKMC+tauola+photos.f+photospp` communicate through standard event record, now it is installed in Belle2 `basf2` software system.

Broader interest, due to τ -lepton anomalous $g - 2$? Reason of my talk.

- Technicalities: new `tauola` presamplers of τ decay phase space, Tau21 contribution: 2111.05914 [hep-ph]
- Extra lepton pairs along $\tau^+\tau^-$ KKMC events: `photospp` the *c* version of `photos` Monte Carlo. Emission through: SM virtual (or dark) photon, exotic scalar or pseudo-scalar.
- New τ decays.
- Summary.

“matrix element \times full phase space” means flexibility too.



- Phase-space module produce “raw events” of raw matrix elements.
- Library of models (often perturbative results) provide input for “model weight”: ratio of model to raw ME^2 . Monte Carlo may work as formal integrator over required phase space region.
- **As a matter of principle we use exact phase space and explicit form of matrix elements.**
- Convenient for ML training samples.
- *For the programs to be efficient we need “raw event” distribution to approximate peaks of the final one.* Narrow width limit is indispensable for many analytical tests.

`tauola` for tau decays, `photospp` for extra pairs.

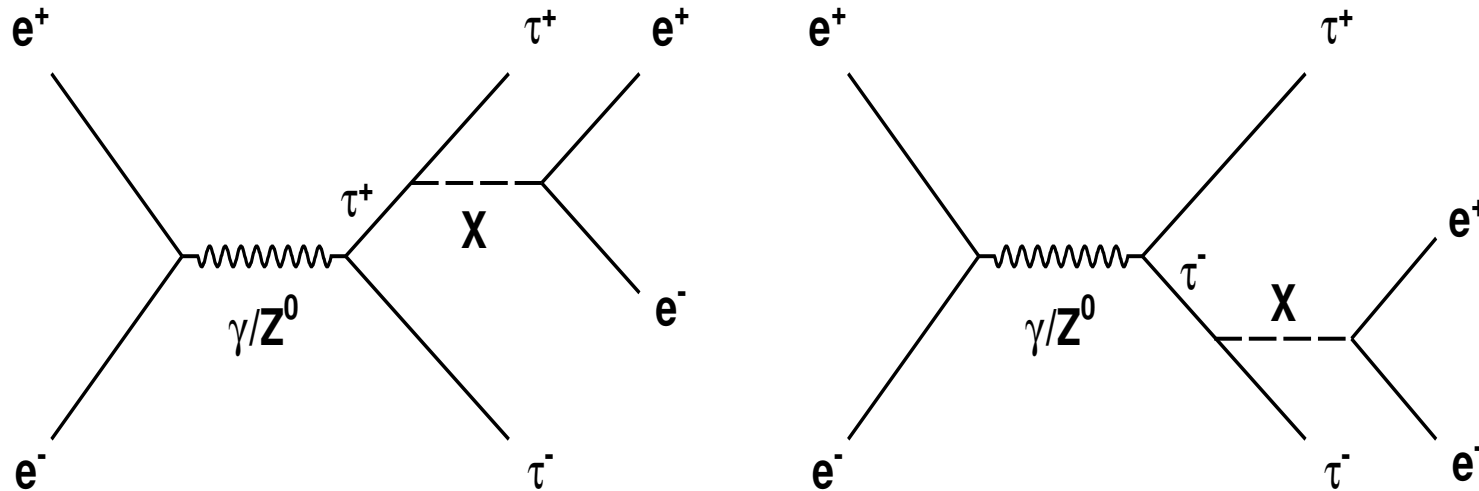
1. `photospp` and `tauola`: phase-space for narrow resonances to lepton pairs ME. Thus can be used to modify events stored in event records. Add extra lepton pairs: from QED or from New Physics.
 - (a) Tests with semianalytical calculations
 - (b) Tests with matrix element exact phase space, event samples...
 - (c) ...from KORALW for FSR QED pair emission in Z decay,
 - (d) ... from MadGraph for $\tau\tau$ scalar(\rightarrow lepton pair) sample (tests like for ML used for Higgs parity Phys.Rev.D 103 (2021), 036003).
2. Tests evolved into physics extensions, **but are first for technical side.**

1. `photos` was first for photons bremsstrahlung in decay of particles and resonances. Now it is for lepton pair emissions too, again with rigorous exact phase space. Approximations in matrix elements.
2. Checked to work with `KKMC+tauola+photos.f` HEPEVT format events
3. ME can be for lepton pairs from QED, or from dark photons/scalars [prompt/long-lived]
4. S. Antropov, “High Precision Lepton Pair Bremsstrahlung with PHOTOS”, *Acta Phys. Pol. B* 51 (2020) 6, 1221
5. This can be used to inject extra pairs/objects to `KKMC` events:
$$Z/\gamma^* \rightarrow \tau\tau X_{\text{scalar/pseudoscalar/vector}}$$
6. no restrictions on τ decay channels $\tau^+\tau^-$ spin correlations preserved.

Belle2 requested:

1. new channels new matrix elements
2. defaults for the start of collaboration work.
3. but modularity of segments to migrate to C and those to C++ preserved,
4. Phase space improvements: S. Antropov, et. al., “TAUOLA Update for Decay Channels with e^+e^- Pairs in the Final State”, e-Print: 1912.11376 [hep-ph]
5. **New channels with dark photons (new scalars) easy to install.**

1. One can easily compare Monte Carlo samples generated by different programs. To minimize human mistakes we have used our `MC-tester` package, *Comput.Phys.Commun.* 182 (2011) 77, which define histograms automatically.
2. We have used KORALW (*Comput.Phys.Commun.* 94 (1996) 216) to generate samples of 4-fermion final states from Z boson decays. When KORALW matrix element installed into `photos` no `photos-KORALW` differences.
3. But this required special non universal choice of event sample configuration.
4. later to identify optimal choice of the kernel used in `photos` Monte Carlo. That is kernel which is close to complete matrix element, but has some factorization in it, that is why can be used also if additional photons are present.
5. Tests were useful for implementation of dark photon channels into `tauola`
6. Similar comparisons of `MadGraph` and `KKMC+photos` for $e^+e^- \rightarrow \tau^+\tau^- X$, $X \rightarrow l\bar{l}$. Adaptation of `photospp` kernel, but approximation to `MadGraph`. Advantage: all τ decay channels, spin correlations, bremsstrahlung included.



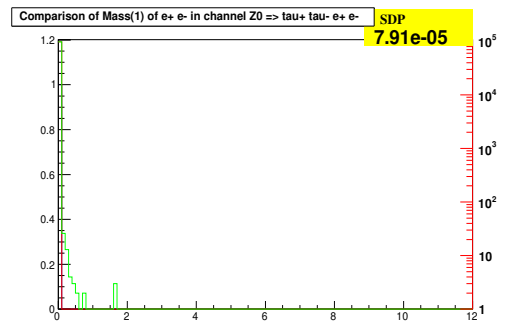
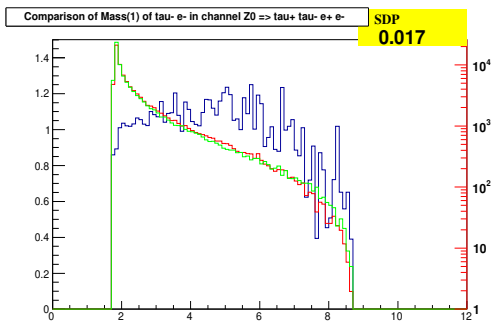
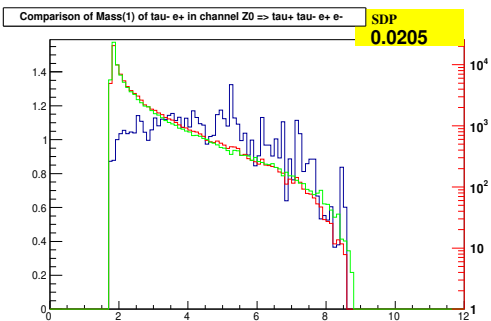
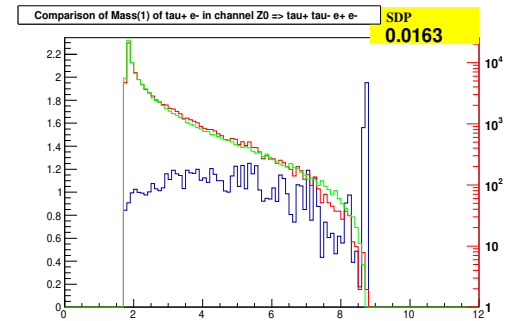
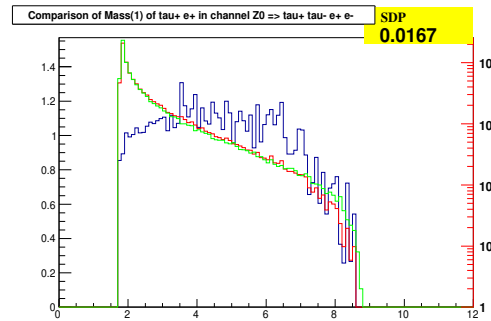
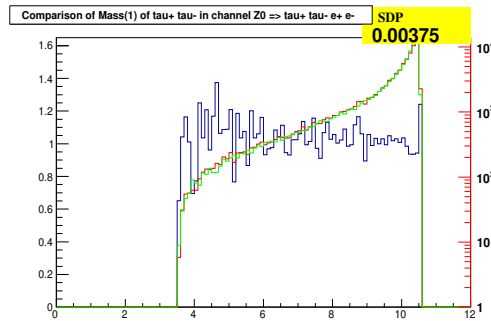
Dominant Feynman diagrams for $e^-e^+ \rightarrow \tau^-\tau^+X(\rightarrow e^-e^+)$ as installed in MadGraph. For our applications dominant part, which can be used together with bremsstrahlung is used. It is an approximation, but validated. Opens gate for simultaneous inclusion of large QED effects. Note that spin state of τ flips if X is scalar. That need to be taken into account for $\tau - \tau$ spin correlations.

$$e^-e^+ \rightarrow \tau^- \tau^+ \phi_{\text{Dark Scalar}} (50 \text{ MeV}) (\rightarrow e^-e^+)$$

Red lines: 50K events from MadGraph (MG5)

Green lines: 100K events from KKMC+photos

First check: ISR bremsstrahlung effects turned off in both generators

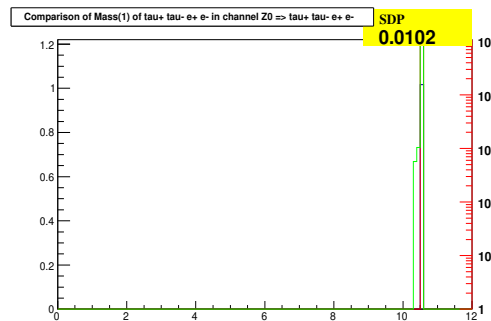
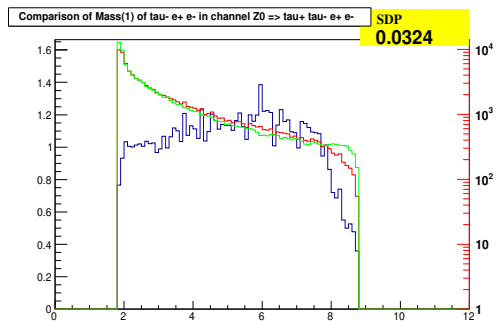
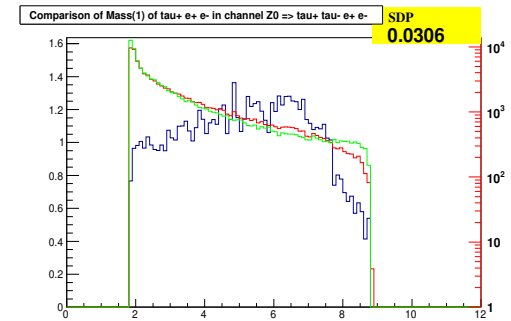
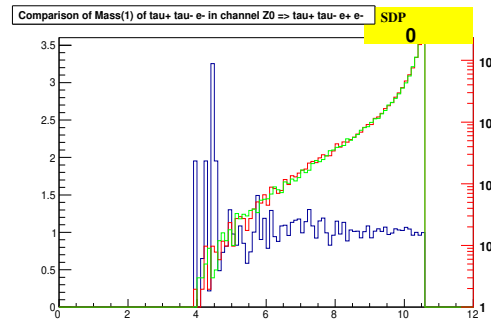
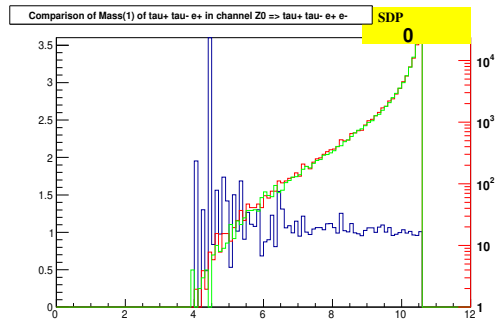


$$e^-e^+ \rightarrow \tau^- \tau^+ \phi_{\text{Dark Scalar}} (50 \text{ MeV}) (\rightarrow e^-e^+)$$

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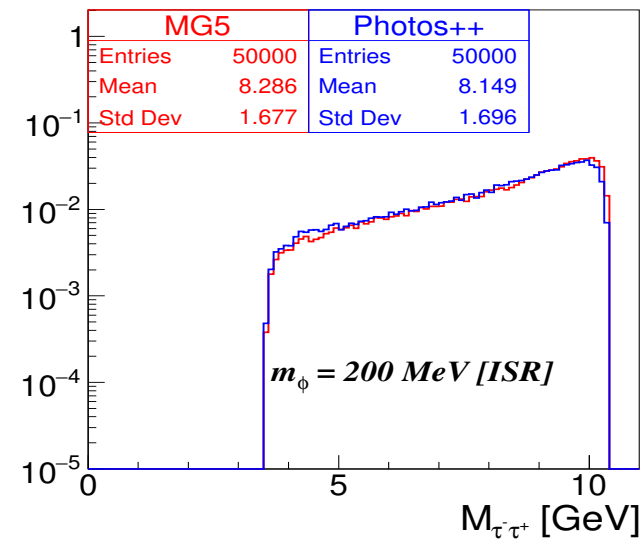
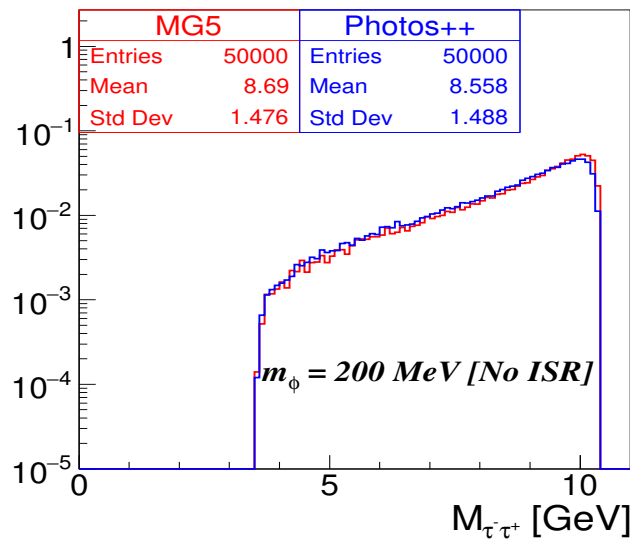
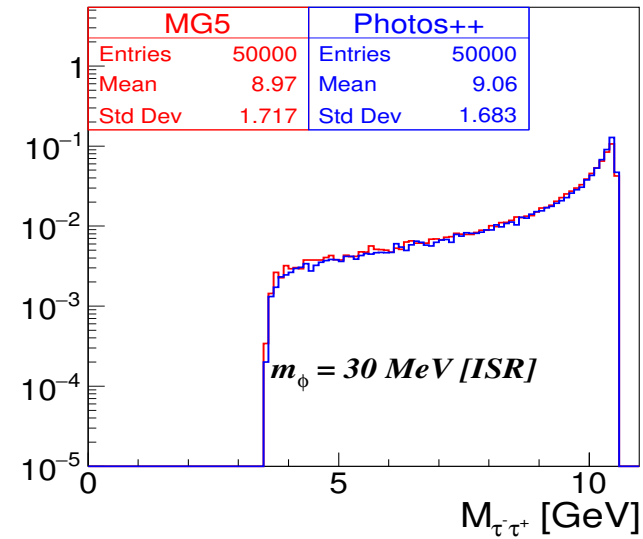
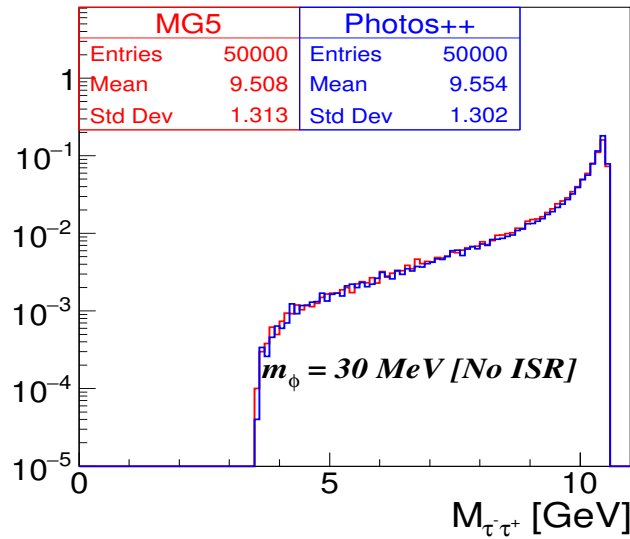
Green lines: 100K events from KKMC+photos

First check: ISR bremsstrahlung effects turned off in both generators

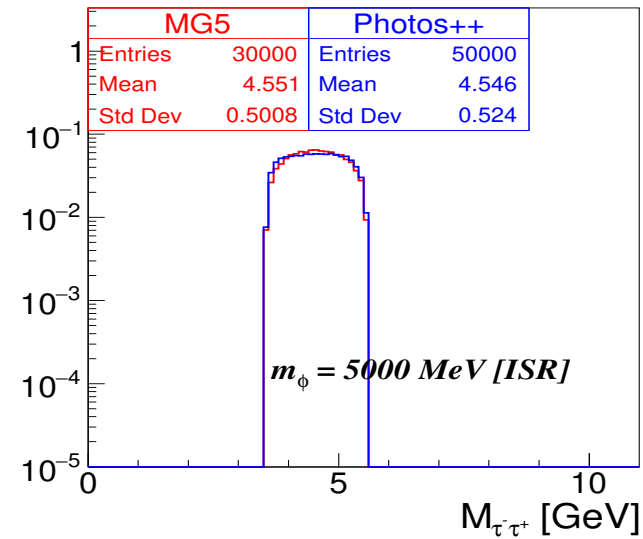
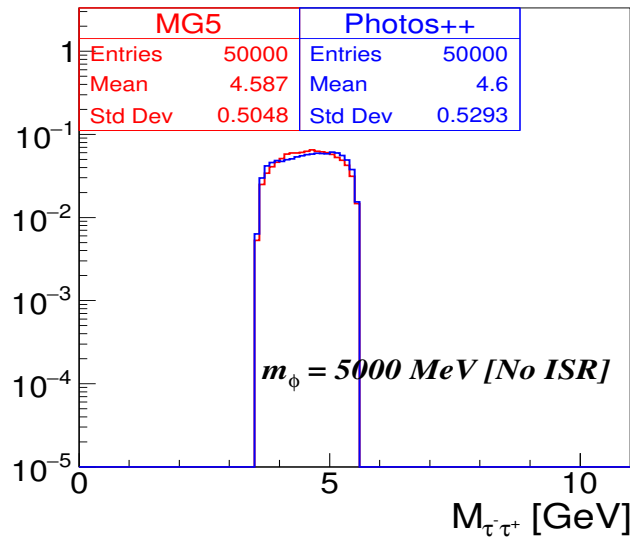
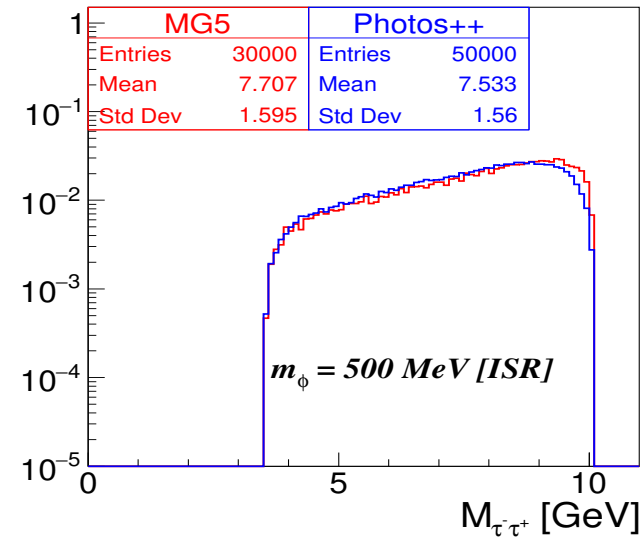
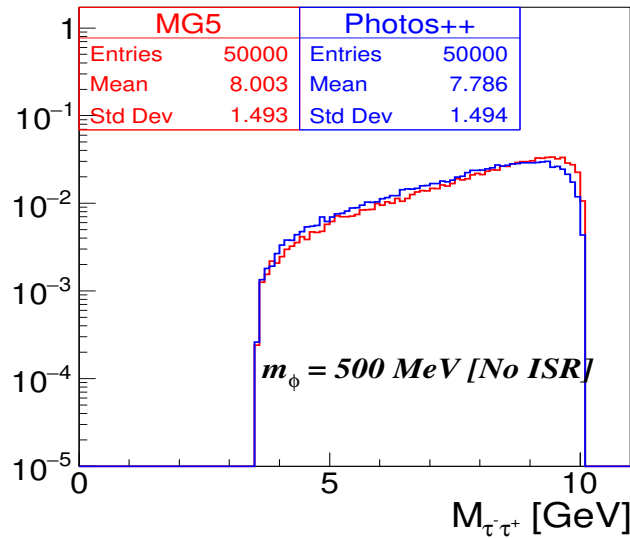


1. **Previous 3 slides of automated test:** comparisons between MadGraph and KKMC+photospp samples for $e^+e^- \rightarrow \tau^+\tau^-X$, are not technical only, but the result of work on matrix element.
2. In case of photospp adaptation/interpolation of matrix element to configurations where additional photons are present was needed.
3. Only dominant part of Matrix Element generated by MadGraph was used.
4. Its identification was not as formal as in case of lepton pair from virtual photon.
5. Then Gauge invariance and symmetries were used to identify parts. Now it was rather analogy and similarity for singular terms.
6. Spin of X is zero, and not 1. Back of the envelope calculations to identify differences.
7. **comparisons for distribution of belle2 physics interest** → next two slides.

$$e^-e^+ \rightarrow \tau^-\tau^+\phi_{\text{Dark Scalar}} (\rightarrow e^-e^+)$$



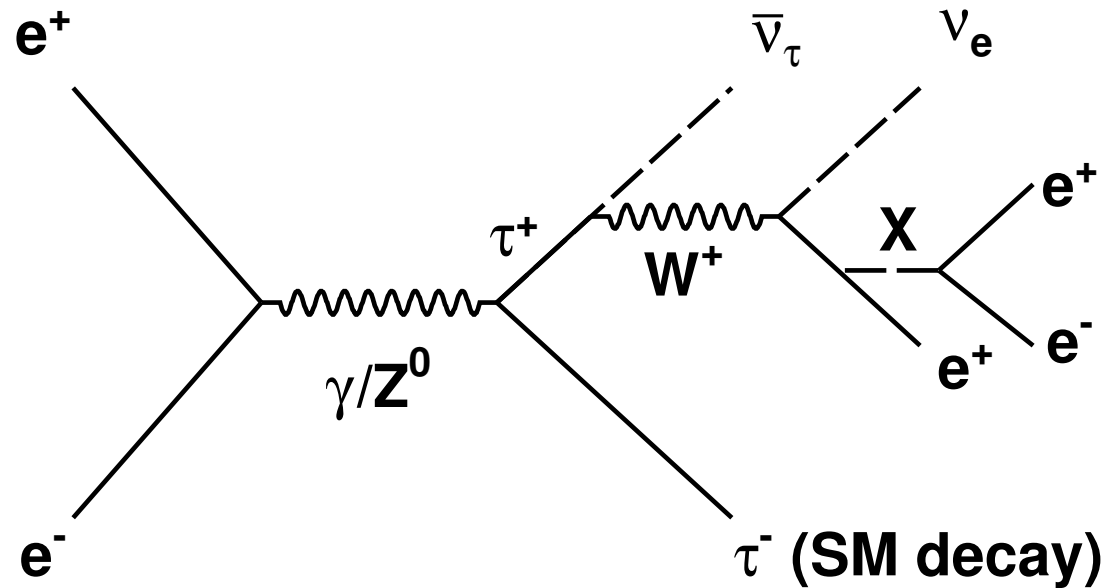
$$e^-e^+ \rightarrow \tau^-\tau^+ \phi_{\text{Dark Scalar}} (\rightarrow \mu^-\mu^+)$$



1. This work was quick, because of previous steps and installation into `photospp` possibility to generate lepton pairs:
 - (a) produced through virtual photon Comput.Phys.Commun. 199 (2016) 86
1912.11376
 - (b) produced through narrow vector resonance (like dark photon) footnote 9 in
1912.11376
2. `tauola` and `photos` have similar (but not identical) phase space parametrisations.
3. Technical changes were introduced earlier in `tauola` but it will be presented only now.

For simulations in Belle II large number of channels prepared:

1. Total number of decay channels: 278
2. 2 body neutrinoless non SM decays: 58
3. 3 body neutrinoless non SM decays: 46
4. Number of generic SM decay channels : 92 [initialized with PDG2020 Branching Fractions]. For matrix elements choices from older versions of parametrisations were taken, but ...
 - (a) ...for high precision data, new parametrisations will be needed.
 - (b) Theoretical uncertainty of models is worse than quality of data.
5. New decay modes with lepton pair radiated from SM photons or from Dark photon with mass $\in [50, 1500]$ MeV (ME cross-validated with MadGraph)
 - $\tau^- \rightarrow \nu_\tau \bar{\nu}_\ell \ell^- \ell^+ \ell^-$ [see next page]
 - $\tau^- \rightarrow \nu_\tau \pi^- \ell^+ \ell^-$



Once we could rely on tests for SM pairs, we could include safely $X \rightarrow e^- e^+$.

Feynman diagram for $e^- e^+ \rightarrow \tau^-$ (SM decay) $\tau^+ (\rightarrow \bar{\nu}_\tau \nu_e e^+ X (\rightarrow e^- e^+))$
 process with X emitted in τ^+ decay.

- Final states with dark scalar/photon decaying to the lepton pair introduced in τ pair production with the help of `photospp` and in τ decay with `tauola`.
- Effort on channels parametrisations, extended list of channels in `basf2` of Belle2 collaboration was mentioned.
- Algorithm work on content of event records. Thus can be used with other programs storing events in event record and not only with `KKMC`.
- Possibly presented solutions are of interest outside Belle2...
...may be even outside of `KKMC` based applications.
- Possible if event records of standard format are used.
- Comparisons with results from programs like `MadGraph` can be helpful in future, for developments of new ME variants.
- **Thank you for listening**

General formalism for semileptonic decays

- Matrix element used in TAUOLA for semileptonic decay

$$\tau(P, s) \rightarrow \nu_\tau(N) X$$

$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}(N) \gamma^\mu (v + a\gamma_5) u(P) J_\mu$$

Matrix element squared contracted with spin density matrix:

$$|\mathcal{M}|^2 = G^2 \frac{v^2 + a^2}{2} (\omega + H_\mu s^\mu)$$

$$\omega = P^\mu (\Pi_\mu - \gamma_{va} \Pi_\mu^5)$$

$$H_\mu = \frac{1}{M} (M^2 \delta_\mu^\nu - P_\mu P^\nu) (\Pi_\nu^5 - \gamma_{va} \Pi_\nu)$$

$$\Pi_\mu = 2[(J^* \cdot N) J_\mu + (J \cdot N) J_\mu^* - (J^* \cdot J) N_\mu]$$

$$\Pi^{5\mu} = 2 \text{Im} \epsilon^{\mu\nu\rho\sigma} J_\nu^* J_\rho N_\sigma$$

$$\gamma_{va} = -\frac{2va}{v^2 + a^2}$$

- J_μ the current; depends on the momenta of all hadrons and is expected to be build from Lorentz invariants, vectors or tensors.

- For two scalar decay channels all is rather simple: single distribution in Q^2 (in cases with kaons also in $\cos \theta_{\pi^\pm}$) to be measured and fitted with:

$$J^\mu = (p_{\pi^\pm} - p_{\pi^0})^\mu F_V(Q^2) + (p_{\pi^\pm} + p_{\pi^0})^\mu F_S(Q^2) \quad (F_S \simeq 0).$$

- For 3-scalar channels: 4 complex function of 3 variables to fit. Role of theoretical assumptions (oversimplifications?) is essential. Agreement on 1-dim distribution is just a consistency check.

- No go for model independent measurements? Use of all dimensions for data distributions: invariant masses Q^2 , s_1 , s_2 as arguments of form-factors. Angular asymmetries help to separate currents: scalar $J_4^\mu \sim Q^\mu = (p_1 + p_2 + p_3)^\mu$, vector $J_1^\mu \sim (p_1 - p_3)^\mu|_{\perp Q}$ and $J_2^\mu \sim (p_2 - p_3)^\mu|_{\perp Q}$ and finally pseudovector $J_5^\mu \sim \epsilon(\mu, p_1, p_2, p_3)$.

- Possible if: (i) enough data, (ii) absolute precision, (iii) no background, (iv) full detector coverage can assured. We need that for orthogonality conditions.
- It is a challenge. Long time ago, for Cleo it was easier, τ were produced nearly at rest.

1. Hadronic currents, or decay matrix elements in principle can be provided by the user, with c++ pointer, but this possibility is temporarily postponed in `basf2` as it require software fine tunings of the collaboration libraries.
2. Note, that in contrary to old `tauola` paper Comp. Phys. Commun. 76 (1993) 361, separation into hadronic current and SU(2) Clebsh-Gordan coefficients and couplings is not necessarily useful in all possible models.
3. Phase space coefficients $\sqrt{1/n!}$, for identical bosons, need to be watched in channel dependent matrix elements. *Sorry for that*, they are decay channel specific, thus also user choice input is needed.

To illustrate, **4-body phase space** from Appendix A of Reference: S. Antropov, et. al., “Extra lepton pair emission corrections to Drell-Yan processes in PHOTOS and SANC”, Acta Phys.Polon.B 48 (2017) 1469, e-Print: 1706.05571 [hep-ph]

$$\begin{aligned}
 \Omega &= \int \frac{d^3 q_1}{2(q_1)_0(2\pi)^3} \cdot \frac{d^3 q_2}{2(q_2)_0(2\pi)^3} \cdot \frac{d^3 p}{2p_0(2\pi)^3} \cdot \frac{d^3 p'}{2p'_0(2\pi)^3} (2\pi)^4 \delta^4(R - p - p' - q_1 - q_2) = \\
 &= \int d^4 q d^4 Q \frac{d^3 q_1}{2(q_1)_0(2\pi)^3} \cdot \frac{d^3 q_2}{2(q_2)_0(2\pi)^3} \cdot \frac{d^3 p}{2p_0(2\pi)^3} \cdot \frac{d^3 p'}{2p'_0(2\pi)^3} (2\pi)^4 \times \\
 &\times \delta^4(R - p - p' - q_1 - q_2) \delta^4(q - q_1 - q_2) \delta^4(Q - p - p') \tag{1}
 \end{aligned}$$

$$\int \frac{d^3 q_1}{2(q_1)_0} \frac{d^3 q_2}{2(q_2)_0} \delta^4(q - q_1 - q_2) = \int \frac{|\vec{q}_1| d \cos \theta_{q_1} d\phi_{q_1}}{4\sqrt{q^2}},$$

$$\int \frac{d^3 p}{2(p)_0} \frac{d^3 p'}{2(p')_0} \delta^4(Q - p - p') = \int \frac{|\vec{p}| d \cos \theta_p d\phi_p}{4\sqrt{p^2}},$$

$$\int d^4 q d^4 Q \delta^4(R - Q - q) = \int (d \cos \theta_q d\phi_q) dM_Q^2 dM_q^2 \frac{\sqrt{\lambda}}{8s}$$

We get finally:

$$\Omega = \frac{1}{(2\pi)^8} \int dM_q^2 dM_Q^2 d \cos \theta_{q_1} d\phi_{q_1} d \cos \theta_p d\phi_p d \cos \theta_q d\phi_q \frac{1}{8} \sqrt{1 - \frac{4\mu^2}{q^2}} \frac{1}{8} \sqrt{1 - \frac{4m^2}{Q^2}} \frac{\sqrt{\lambda(s, M_Q^2, M_q^2)}}{8s}. \tag{2}$$

1. We have invariant masses M_q, M_Q available for variable changes with Jacobians of minimum where matrix element peak, e.g.:

$$\alpha_{min/max} = \arctan \frac{M_{Q,min/max}^2 - M_R^2}{\Gamma_R M_R},$$

$$\alpha = \alpha_{min} + (\alpha_{max} - \alpha_{min}) \cdot x,$$

$$M_Q^2 = M_R^2 + \Gamma_R M_R \tan \alpha, \tag{3}$$

2. Jacobian of this is used to cancel matrix element enhancements due to resonance propagators (or near-real photon).
3. Angular variables can be used for collinear singularities or matrix elements.
4. **Parametrizations of that type are used in tauola and photos for phase-space with pair of light leptons added or not.** In practice, multi-channel generators are necessary. Jacobians of parametrisations are combined. That is used for lepton pairs from virtual photons or dark scalars/vectors.
5. Why not use automated solutions? In part, because one want to use narrow width limit for numerical tests. These are necessary for our tests with analytical semi-analytical results. **These results are useful to build intuitions.**