Tauola: Modelling tau decays

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- **(1)** The τ lepton decays: fascinating laboratory for intermediate energy QCD
- **(2)** How to optimize work of inhomogeneous community. From model builders to people managing large experimental data files. From F77 to C++ and Python.
- **(3)** I will use TAUOLA, associated projects and updates as examples.
- **(4)** Main topics on my talk is however on how to handle different component of systematc errors: experiment, theory, choice of quantities for comparisons.
- **(5)** Also on what can/should be the role of MC in this respect.
- **My talk would not be possible without effort of many people and experiments**

Formalism for $\tau^+\tau^-$

- Because narrow τ width approximation can be obviously used for phase space, cross-section for the process $f\bar{f} \to \tau^+\tau^- Y; \tau^+ \to X^+\bar{\nu}; \tau^- \to \nu\nu$ reads:

$$d\sigma = \sum_{spin} |\mathcal{M}|^2 d\Omega = \sum_{spin} |\mathcal{M}|^2 d\Omega_{prod}\; d\Omega_{\tau^+}\; d\Omega_{\tau^-}$$

- This formalism is fine, but because of over 20 τ decay channels we have over 400 distinct processes. Also picture of production and decay are mixed.

- Below only τ spin indices are explicitly written:

$$\mathcal{M} = \sum_{\lambda_1\lambda_2=1}^{2} \mathcal{M}^{prod}_{\lambda_1\lambda_2}\; \mathcal{M}^{\tau^+}_{\lambda_1} \mathcal{M}^{\tau^-}_{\lambda_2}$$

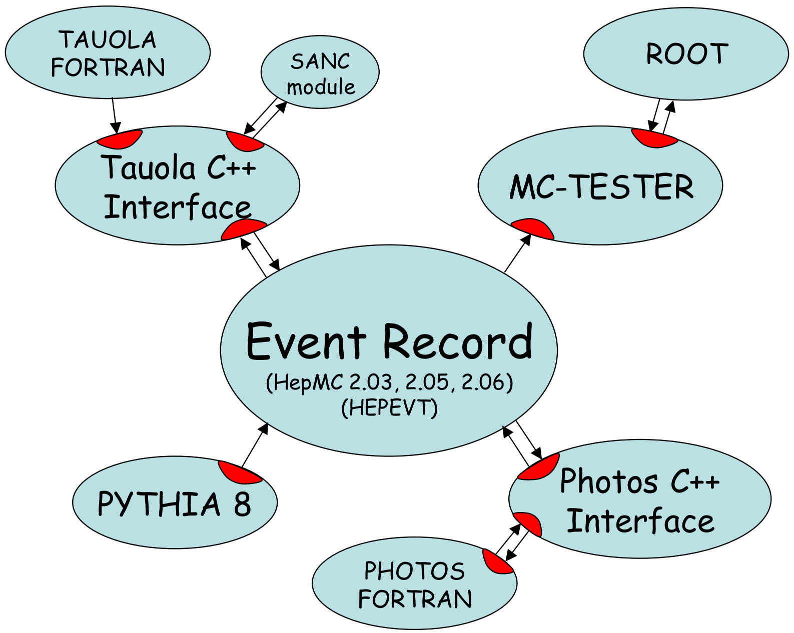
- Cross section can be re-written into **core formula of spin algorithms**

$$d\sigma = \Big(\sum_{spin} |\mathcal{M}^{prod}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^+}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^-}|^2\Big) wt\; d\Omega_{prod}\; d\Omega_{\tau^+}\; d\Omega_{\tau^-}$$

General software organization.

Communication though event record: (for program inerfaces or data files).

Solution for phase space $\times$ $|M|^2$ algorithms.



Parts:

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

- High precision achieved

- Detector studies: acceptance, resolution lepton with or without photon.

Such organization requires:

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

Techniques of weighted events

`TauSpinner`

General software organization.

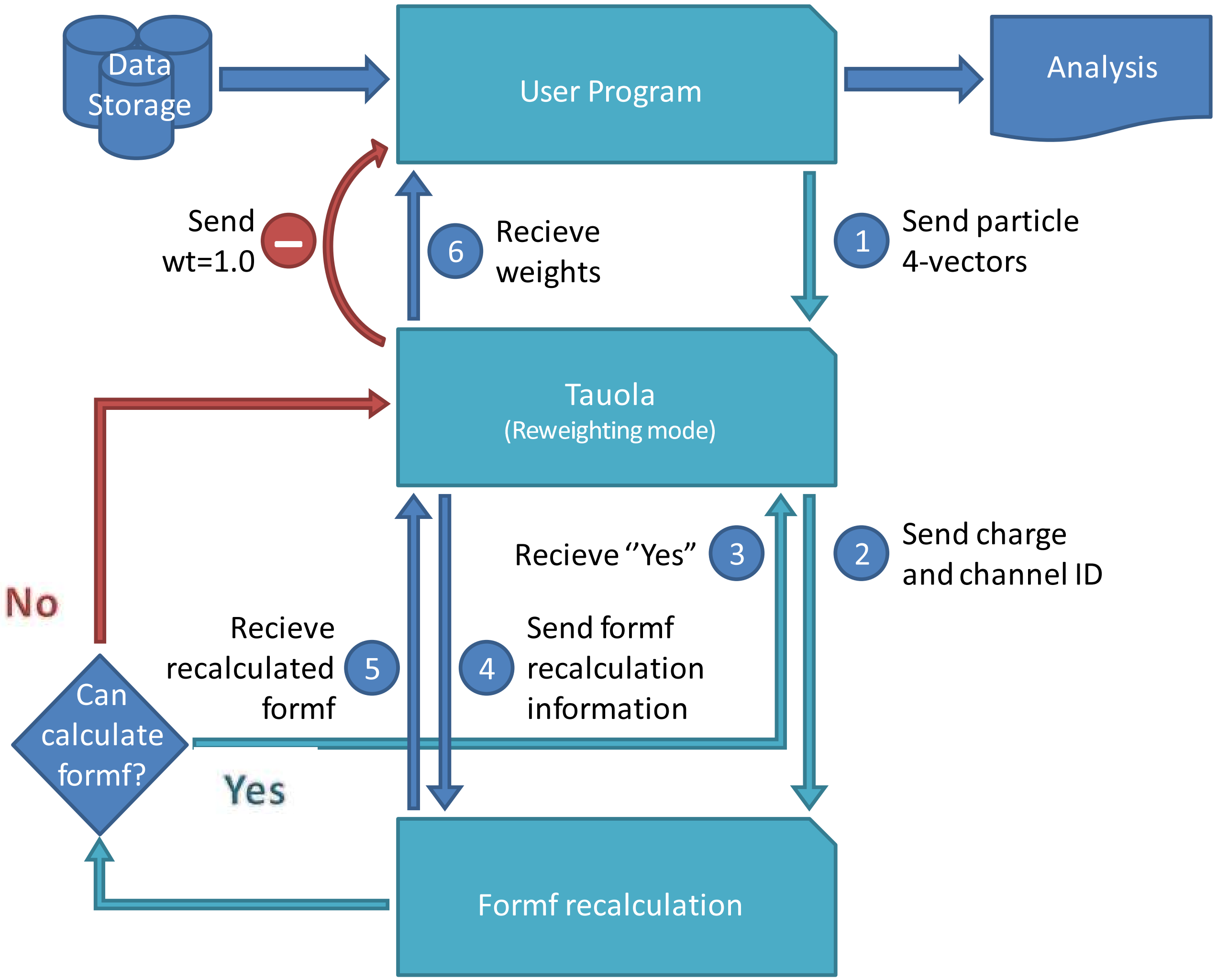
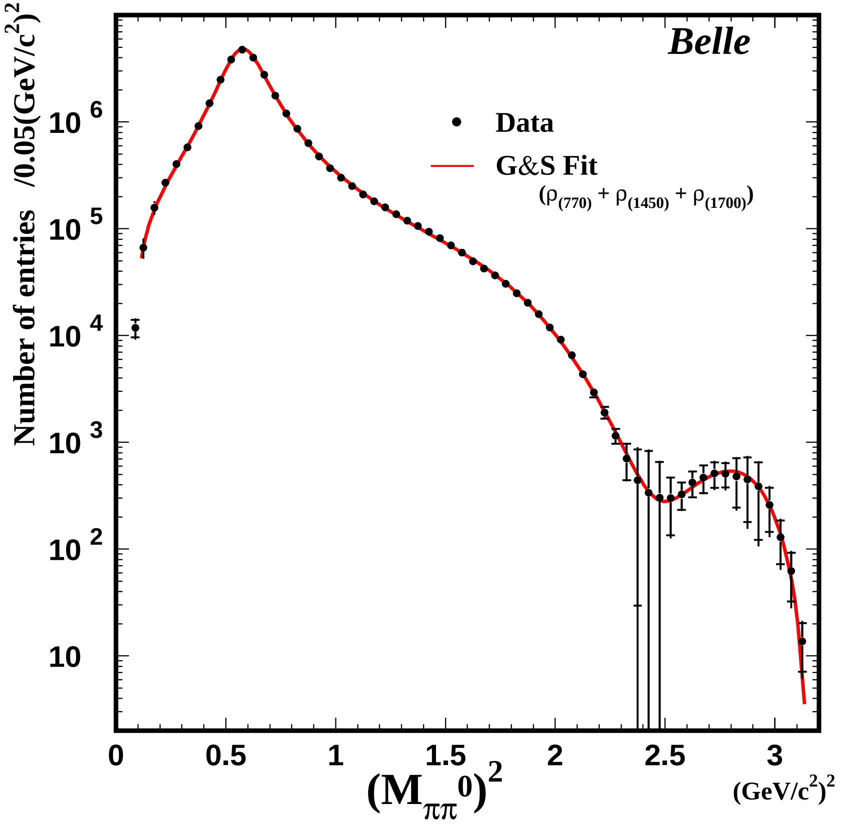


Figure 1: Flow chart for communication when already stored events are modified with the weights. Useful at LHC and at low energy applications as well.

TAUOLA perspective of τ decays themselves.

1. **I want to adress following contexts: fit strategy, experimental, theoretical syst. errors., cooperation between sub-communities.**
   (a) I am introducing changes into TAUOLA keeping this constraints in mind.
   (b) Temporary location of TAUOLA with new hadronic currents, 200 decay channels, which can be manipulated by user: http://annapurna.ifj.edu.pl/˜tprzedzinski/tmp/TAUOLA-FORTRAN.tgz
   (c) I would like to discuss if it is going in right direction, before making the release.
   (d) What should be included in standard initialization(s). Quality stamps from the side of theory, experiment, technical precision.



- **Already 4 years ago:** publicly available TAUOLA hadronic current is not good to match experimental data.
- Quite in contrary, the internal Belle collaboration parametrization used in TAUOLA is making perfect match for invariant mass of $\pi^+\pi^0$-pair in $\tau \to \pi^+\pi^0\nu$ decay channel.
- **Single channel improvement, OK, but can it destroy global properties, like average charged energy?**
- Theoretical progress or better description of the data. What is more important? Who should take the decision and when.
- General purpose initialization or multitude of options.

New theory model + precision simulation: easy.

Channel	Width [GeV]	reference	In `tauola/RChL-currents` directory channel's current: `file` $\rightarrow$ `routine`
$\pi^-\pi^0$	$5.2678 \cdot 10^{-13} \pm 0.01\%$	Subsection 2.4	`frho_pi.f` $\rightarrow$ `CURR_PIPI0`
$K^-\pi^0$	$5.853 \cdot 10^{-15} \pm 0.02\%$	Subsection 2.4	`fkpipl.f` $\rightarrow$ `CURR_KPI0`
π^-K^0	$1.1025 \cdot 10^{-14} \pm 0.03\%$	Subsection 2.4	`fkpipl.f` $\rightarrow$ `CURR_PIK0`
K^-K^0	$2.415 \cdot 10^{-15} \pm 0.02\%$	Subsection 2.4	`fk0k.f` $\rightarrow$ `CURR_KK0`
$\pi^-\pi^-\pi^+$	$2.08 \cdot 10^{-12} \pm 0.017\%$	Subsection 2.1	`f3pi_rcht.f` $\rightarrow$ `F3PI_RCHT`*
$\pi^0\pi^0\pi^-$	$2.126 \cdot 10^{-12} \pm 0.017\%$	Subsection 2.1	`f3pi_rcht.f` $\rightarrow$ `F3PI_RCHT`*
$K^-\pi^-K^+$	$3.8467 \cdot 10^{-15} \pm 0.04\%$	Subsection 2.2	`fkkpi.f` $\rightarrow$ `FKKPI`*
$K^0\pi^-\bar{K}^0$	$3.5935 \cdot 10^{-15} \pm 0.03\%$	Subsection 2.2	`fkkpi.f` $\rightarrow$ `FKKPI`*
$K^-\pi^0K^0$	$2.769 \cdot 10^{-15} \pm 0.04\%$	Subsection 2.3	`fkk0pi0.f` $\rightarrow$ `FKK0PI0`*
			* The F_i of form-factors.

Table 1: Collection of numerical results from paper: O. Shekhovtsovaa, T. Przedzinski, P. Roig and Z. Was *Resonance Chiral Lagrangian currents and τ decay Monte Carlo*, Phys.Rev. D86 **(2012)** 113008. References to subsections of that paper. Last column includes references to routines of the currents code. It looked like mission accomplished. Just fine tuning of some parameters.

New theory model + precision simulation: easy.

- Those new hadronic currents (more than 88 % of hadronic τ decay width) version installed with the 0.05 % technical tag: O. Shekhovtsovaa, T. Przedzinski, P. Roig and Z. Was *Resonance Chiral Lagrangian currents and τ decay Monte Carlo*, Phys.Rev. D86 (2012) 113008
- **But** physics precision was definitely **NOT** as good as 0.05 %.
- Over the last two years we worked on preparing confrontation env. with the data keeping precision in mind.
- But despite partial success for 3π modes, we are nearly as far from the complete solution as in 2012.
- **Useful for further work:**
- We have investigated technical aspects for fitting using weights. It is of interest in case when experimental cuts are present, multidimensional distributions are used and no semi-analytical results can be easily obtained.
- We have returned to the semi-analytical 1-dim distributions for fits. Similar as in 90's.
- Such distributions are essential for technical tests of our code, but also for fits and evaluation how experimental errors propagate to parameters of the models.

General formalism for semileptonic decays

- Matrix element used in TAUOLA for semileptonic decay

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

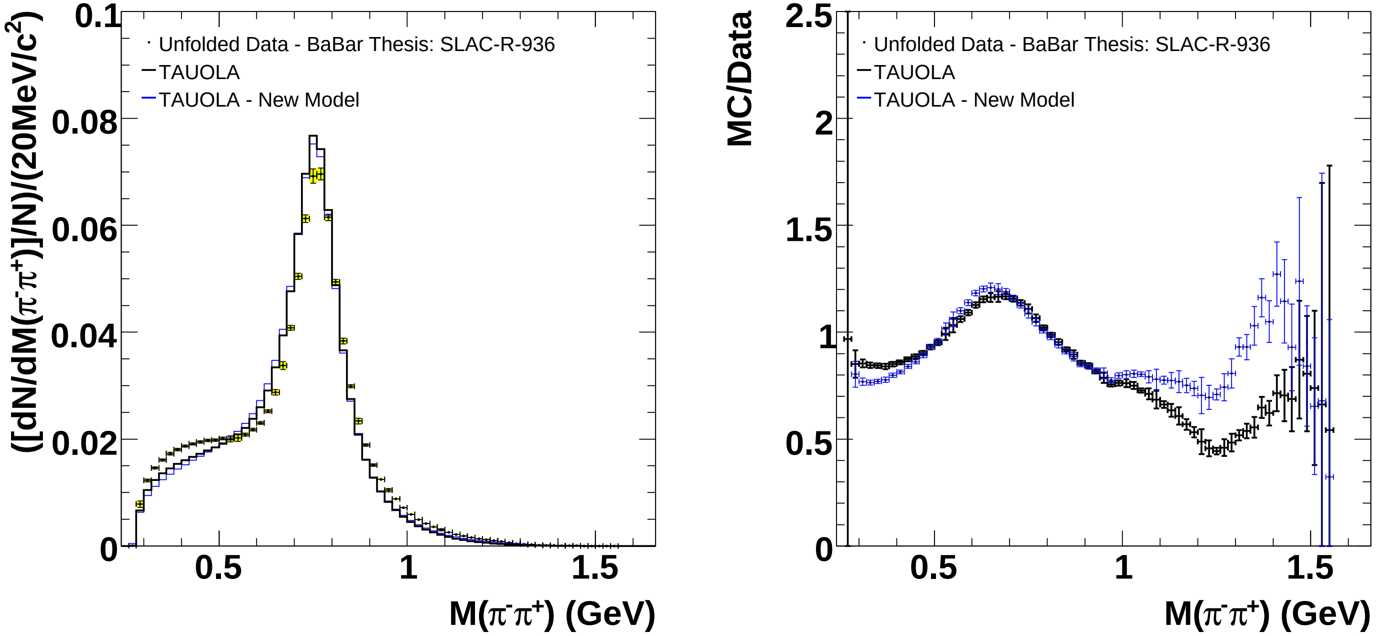
- J_μ the current depends on the momenta of all hadrons

$$|\mathcal{M}|^2 = G^2 \frac{v^2+a^2}{2}(\omega + H_\mu s^\mu)$$
$$\omega = P^\mu(\Pi_\mu - \gamma_{va}\Pi^5_\mu)$$
$$H_\mu = \frac{1}{M}(M^2\delta^\nu_\mu - P_\mu P^\nu)(\Pi^5_\nu - \gamma_{va}\Pi_\nu)$$
$$\Pi_\mu = 2[(J^*\cdot N)J_\mu + (J\cdot N)J^*_\mu - (J^*\cdot J)N_\mu]$$
$$\Pi^{5\mu} = 2\,\mathrm{Im}\,\epsilon^{\mu\nu\rho\sigma}J^*_\nu J_\rho N_\sigma$$
$$\gamma_{va} = -\frac{2va}{v^2+a^2}$$
$$\hat{\omega} = 2\frac{v^2-a^2}{v^2+a^2}m_\nu M(J^*\cdot J)$$
$$\hat{H}^\mu = -2\frac{v^2-a^2}{v^2+a^2}m_\nu\,\mathrm{Im}\,\epsilon^{\mu\nu\rho\sigma}J^*_\nu J_\rho P_\sigma$$

New theory model + precision simulation: easy.

- Improvements for ρ channel are technically straightforward: single distribution to be fitted with real function to fit:
  $J^\mu = (p_{\pi^\pm} - p_{\pi^0})^\mu F_V(Q^2) + (p_{\pi^\pm} + p_{\pi^0})^\mu F_S(Q^2)$ ($F_S \simeq 0$).
- 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? Not necessarily. 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 $J_5^\mu \sim \epsilon(\mu, p_1, p_2, p_3)$.
- Model independent methods, 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 but worth a try. It was easier for Cleo, where τ were produced nearly at rest.

Attempt: comparison with experimental distr.



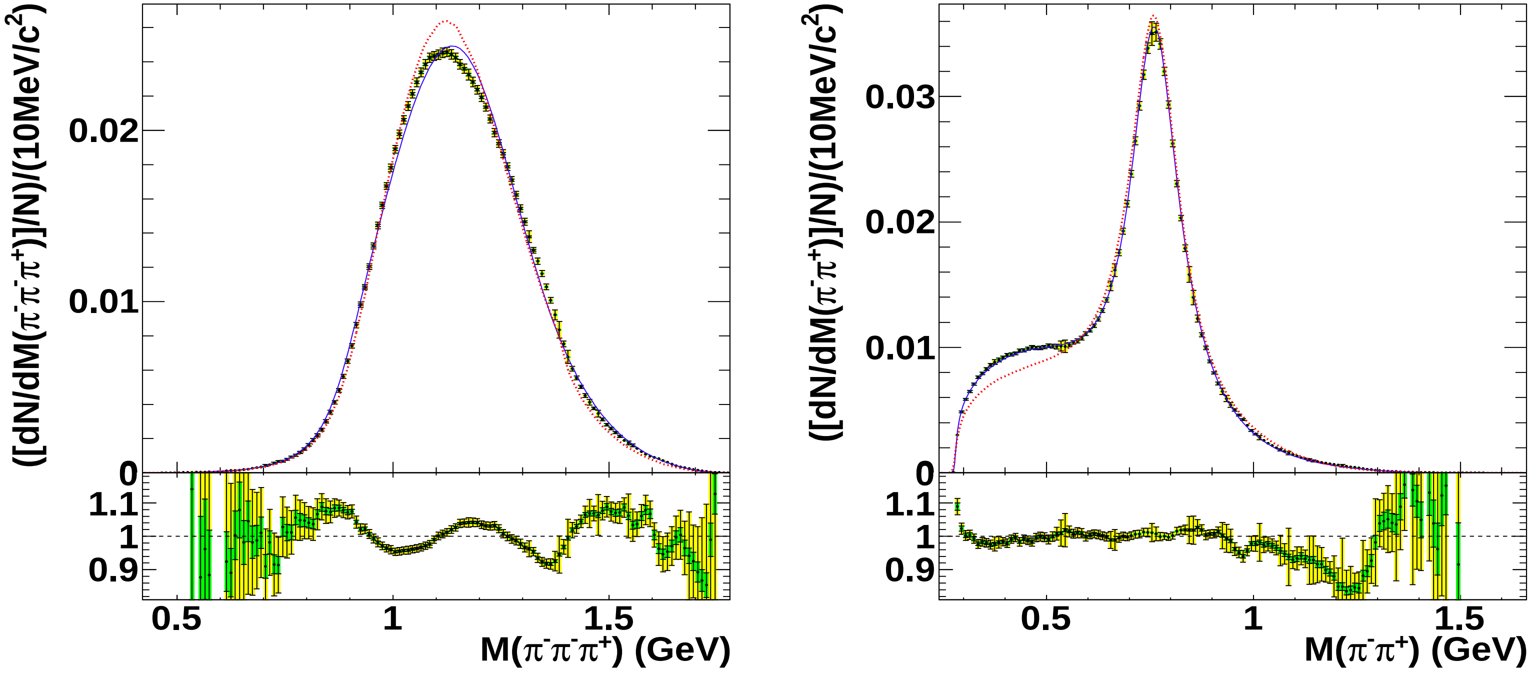
(a) A (b) B

Figure 2: Invariant mass distribution of the $\pi^+\pi^-$ pair in $\tau \to \pi^+\pi^-\pi^-\nu$ decay. Histogram is from our model. Unfolded BaBar data are taken from PhD thesis of Ian Nugent. Left hand side, mass distribution. On the right hand side, ratios of Monte Carlo results and data. Homework to do.

Attempt: comparison with experimental distr.

New currents for $\tau \to 3\pi$ and $\tau \to 2\pi$ decays

Currents based on Resonance Chiral Lagrangian approach and fits to BaBar data. Experimental systematic errors considered. Software environment for fiÅ§s was prototyped but used in non automated way. From: *Resonance Chiral Lagrangian Currents and Experimental Data for $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$*, I.M. Nugent, T. Przedzinski, P. Roig, O. Shekhovtsova, Z. Was, Phys. Rev. D 88, 093012 (2013).



Attempt: comparison with experimental distr.

To progress in case of $\tau \to 3\pi\nu_\tau$ we had to:

- Modify the model (contribution of σ)
- Work simultaneously with fits using weights (at this time only to cross-check results for big mistakes). We had difficulties with stability because of strong correlations of parameters. Template method I have learned at ALEPH time requires better understanding if model parameters are strongly correlated and for some of them dependencies is weak. Necessity to linearize dependencies because of CPU-time constraints in case when model was not giving perfect predictions complicated things further.
- We relied on fitting semi-analytical formulas.
  - We had to assure that derivaties of results are continuous.
  - We had to speed up calculations using different methods of pretabulation/interpolation of results for Q-dependent a_1 width (unitarity constraint).
  - We relied on 1-dimensional invariant mass distributions.

Attempt: comparison with experimental distr.

- Not anymore separation into theoretical, experimental and computing aspects. Even for the simple case of 1-dimensional unfolded distribution.
- **NONETHELESS:**
- We got substantial improvement for 3π modes.
- Control of experimental systematic errors.
- No control of systematic due to limitation to 1-dim histograms.
- Experience for the future steps, but no organized software solution.
- What is the best input from experimental side?
- Multidimensional histograms, number of bins comparable with size of measured sample? Moments, bias due to model assumptions?
- How to coordinate work?
- **Not acceptable: theorist/experimentalist have to wait for ...**

Possible warning message

- Biases in art, Giuseppe Arcimboldo (1572 - 1593).

- Already for 3-scalar final states theoretical predictions and experimental data: distributions over 8-dimensional space. We fit 1- (2-) dim. histos. Result depend on model assumptions. Models inspired with results ... Fitting setup $\rightarrow$ biases.
- Our algorithms are far less elaborate than human eye/brain.
- Who in charge? (TH, EXP?)
- How to facilitate dialog, role of MC. Defalut initialization, but also from user defined objects: **ChannelForTauola class**, useful?

ChannelForTauola class


```
// get information about existing decay channel
ChannelForTauola *demo_modify = GetChannel(87);

demo_modify->setName( demo_modify->getName() + " modified" );
demo_modify->setBr( demo_modify->getBr() * 1234 );

// redefine decay products
vector<int> products = demo_modify->getProducts();
products[0] = -3; //K-
products[1] =  4; //K0
demo_modify->setProducts(products);

// register modified channel
Tauolapp::RegisterChannel( 87, demo_modify );
demo_modify->print();

// set ME type to flat phase space
demo_modify->setMeType(1);

// register into first available free slot
Tauolapp::RegisterChannel( -1, demo_modify );
demo_modify->print();
```

- Use `tauola-bbb/tauola-c/ChannelForTauola.h` to define user channels. No need to link Tauola library.
- New matrix element or current provided by a pointer to user function. Arguments of the function checked at compile time.
- Use `RegisterChannel` for `*demo_modify` object.
- Can be also used to modify existing channels (change name, BR, decay products, etc.)
- New channel can substitute existing one or be added at the end of the list
- All, except ponters to user provided functions of hadronic currents (ME's) re-initialize content of F77 common blocks: minimal changes in old F77 code.

Installation and running the example


```
demo-KK-face:
  README
  KK2f_defaults_adendum.txt
  Tauface.f

demo-tauolapp:
  README
  tauola_extras.f
  tauolapp.patch

demo-standalone:
  README
  iniofc.c
  lfv.c
  makefile
  MEutils.c
  MEutils.h
  pipi0.c
  pipi0.h
  prod
  taumain.f
  tauola-random.h
  TestCommunication.c

tauola-c:
  README
  ChannelForTauola.h
  ChannelForTauolaInterface.c
  ChannelForTauolaInterface.h
  channels_wrappers.c
  TauolaStructs.h
```

- Execute `make` and `make run` in `tauola-bbb/demo-standaone` : a stand-alone ready to use example of new functionality.
- See `tauola-bbb/demo-standalone/iniofc.c` on channel reinitialization.
- See `tauola-bbb/demo-KK-face` on how to install into KKMC.
- See `tauola-bbb/demo-tauolapp` on how to install into Tauola++ and TauSpinner.
- The `tauola-c` include interface to C++. If replaced by dummy Fortran routiones new version of Tauola is reduced to the same style fortran as in the past.

Low energies

- **Achieved:**
- TAUOLA MC with 200 decay channels, solution similar as presented on TAU04 and used by BaBar. Neutrinoless channels available.
- **Default BaBar Tauola initialization.**
- Alternatively, for 2 and 3 π's, new currents with comparison with experimental data prepared.
- Theoretically motivated currents, 4 and 5 π's decay modes, also as alternative.
- No fits to global properties such as average charged energy. For alternatives, no experimental quality stamps.
- User can re-initialize TAUOLA with own (C++ coded) currents (or matrix elements).

- **Non complete tasks:**
- Results for 3-scalar modes with K's are not incorporated, need quality fits. See e.g. Olga talk.
- Many alternative parametrizations, eg. for 2K 2π modes (BaBar) are not incorporated, even though these are missing channels, at present only flat phase space.
- Environments for fits are not well structured for model independent use.

New results for high energies

1. **TauSpinner: replace, with the help of weights, properties of hard process: spin effects, hard process, tau decay reconstruction options.**
2. **Main publications:**
   (a) *"TauSpinner: a tool for simulating CP effects in H to tau tau decays at LHC"*, T. Przedzinski, E. Richter-Was and Z. Was,arXiv:1406.1647
   (b) *"Ascertaining the spin for new resonances decaying into tau+ tau- at Hadron Colliders"*, S. Banerjee, J. Kalinowski, W. Kotlarski, T. Przedzinski and Z. Was, Eur. Phys. J. C **73**, 2313 (2013)
   (c) *"TauSpinner Program for Studies on Spin Effect in tau Production at the LHC"*, Z. Czyczula, T. Przedzinski and Z. Was, Eur. Phys. J. C **72**, 1988 (2012)
3. **Also, bremsstrahlung in decays of Z, W, H; PHOTOS is now 100% C:**
   (a) *Observable ϕ^*_η at LHC and second-order QED matrix element in $Z/\gamma \to l^+ l^-$ decays"*, T. K. O. Doan, W. Placzek and Z. Was, Phys. Lett. B 725 (2013) 92
   (b) *"QED Bremsstrahlung in decays of electroweak bosons"*, A. B. Arbuzov, R. R. Sadykov and Z. Was,Eur. Phys. J. C **73**, 2625 (2013

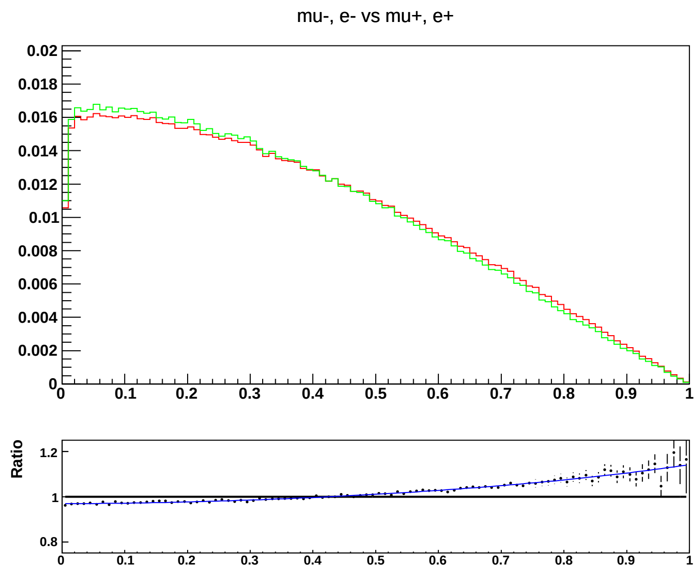
TauSpinner, using wt at LHC

Evaluating size of the spin effect

Left: $\tau \rightarrow l\nu_l\nu_\tau$ green line – spin effects removed with TauSpinner

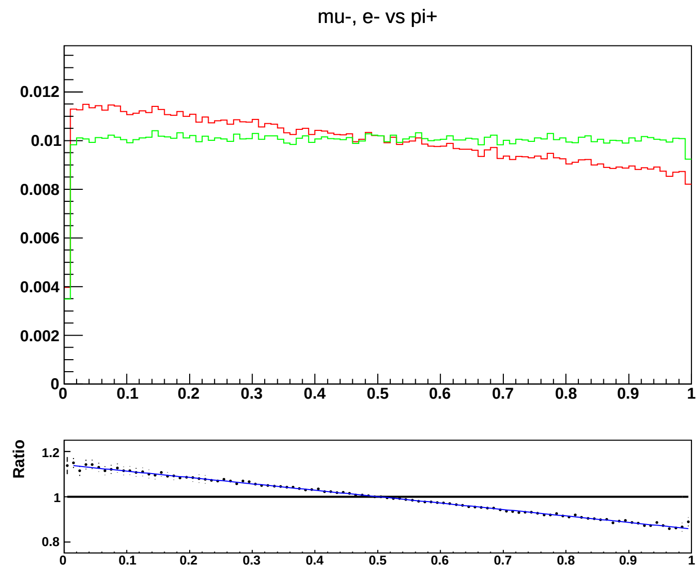
Right: $\tau \rightarrow \pi\nu_\tau$

Similar plots for other τ decay channels automatically created for events stored on the production files. Also for spin correlation effects. Taken from *Application of* `TauSpinner` *for studies on τ-lepton polarization and spin correlations in Z, W and H decays at LHC*, A. Kaczmarska J. Piatlicki, T. Przedziński, E. Richter-Wąs and Z. Wąs, arXiv:1402.2068



P_{orig} = -1.89e-01 ± 3.70e-03

$P_{unweighted}$ = -3.98e-02 ± 4.20e-03



P_{orig} = -1.48e-01 ± 1.98e-03

$P_{unweighted}$ = -6.20e-03 ± 2.41e-03

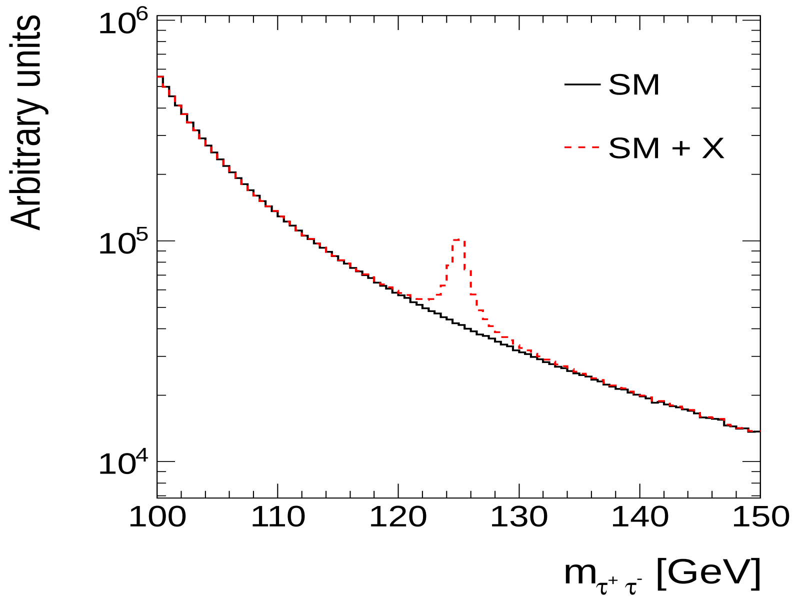
TauSpinner, using $\left(\sum_{spin} |\mathcal{M}^{prod}|^2\right)$ at LHC

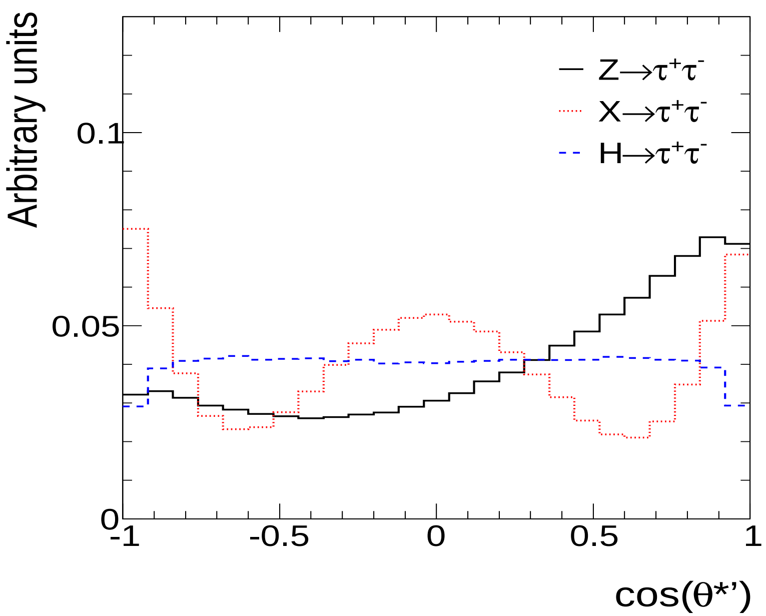
Implementing resonance with TauSpinner weights case of X_2

Left: invariant mass of the τ pair, SM black line, red line with effect from X.

The $\cos(\theta^\star)$ for $Z \to \tau^+\tau^-$, $X \to \tau^+\tau^-$, and $H \to \tau^+\tau^-$ events, invariant mass of $\tau^+\tau^-$ pair: 125 GeV a $\pm$ 3 GeV.

Ascertaining the spin for new resonances decaying into tau+ tau- at Hadron Colliders S. Banerjee, J. Kalinowski, W. Kotlarski, T. Przedzinski, Z. Was, Eur.Phys.J. C73 (2013) 2313

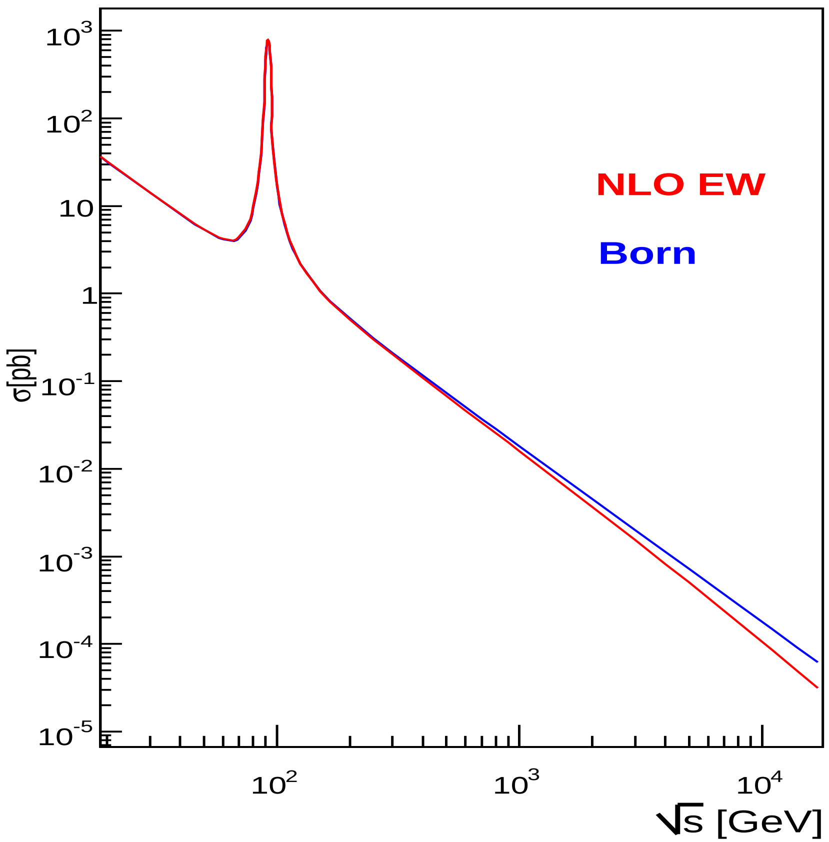


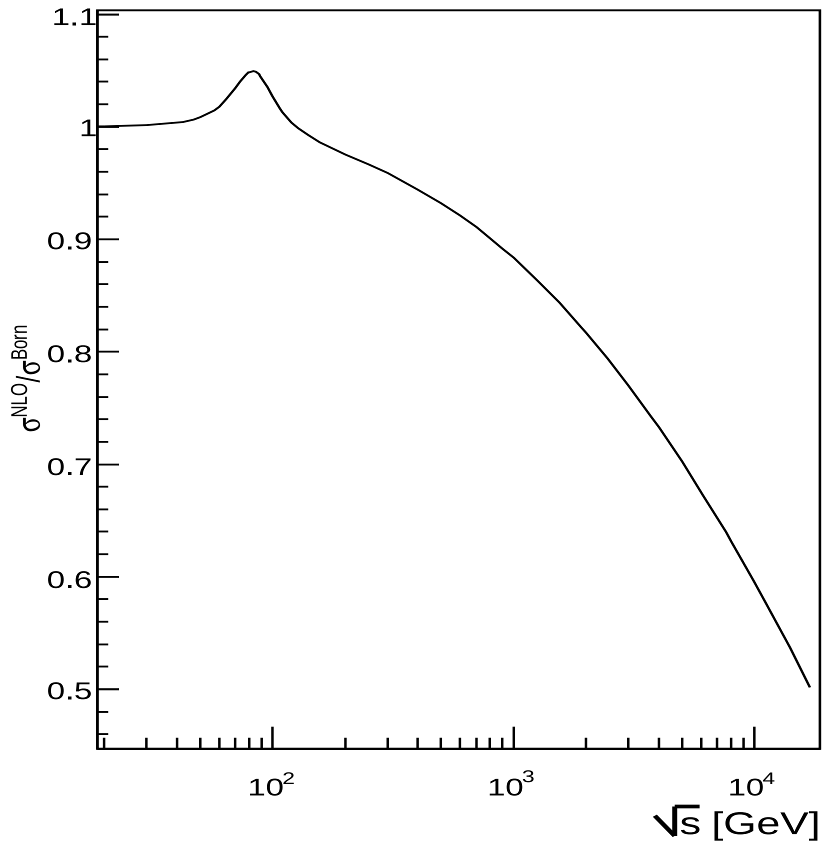


Summary

- How should we proceed to get most from experimental data for understanding intermediate energy hadronic interactions?
- (i) Experimental systematic errors (ii) Theoretical systematic errors
- Systematic errors due to cross biasing.
- What are the constraints on organization of Monte Carlo and fitting environments?
- I have prepared version of TAUOLA summarizing our recent effort.
- Flexibility for re-definition of dynamic of tau decays and initialization based on work of BaBar/Belle collaborations and some older works was achieved with the help of plug-ins.
- I delegate details to private discussions. Solution must be convenien for many people.
- We have collected some experience on requirements for building fitting environments, but we are not at the level of automated approach.
- Context of systematic errors, in case of fits to multi-dimensional representation of data, require further discussion and implementation.
- Question of manpower and training as well as motivation of involved people.
- Use of τ leptons for high energy applications.

Electroweak effects

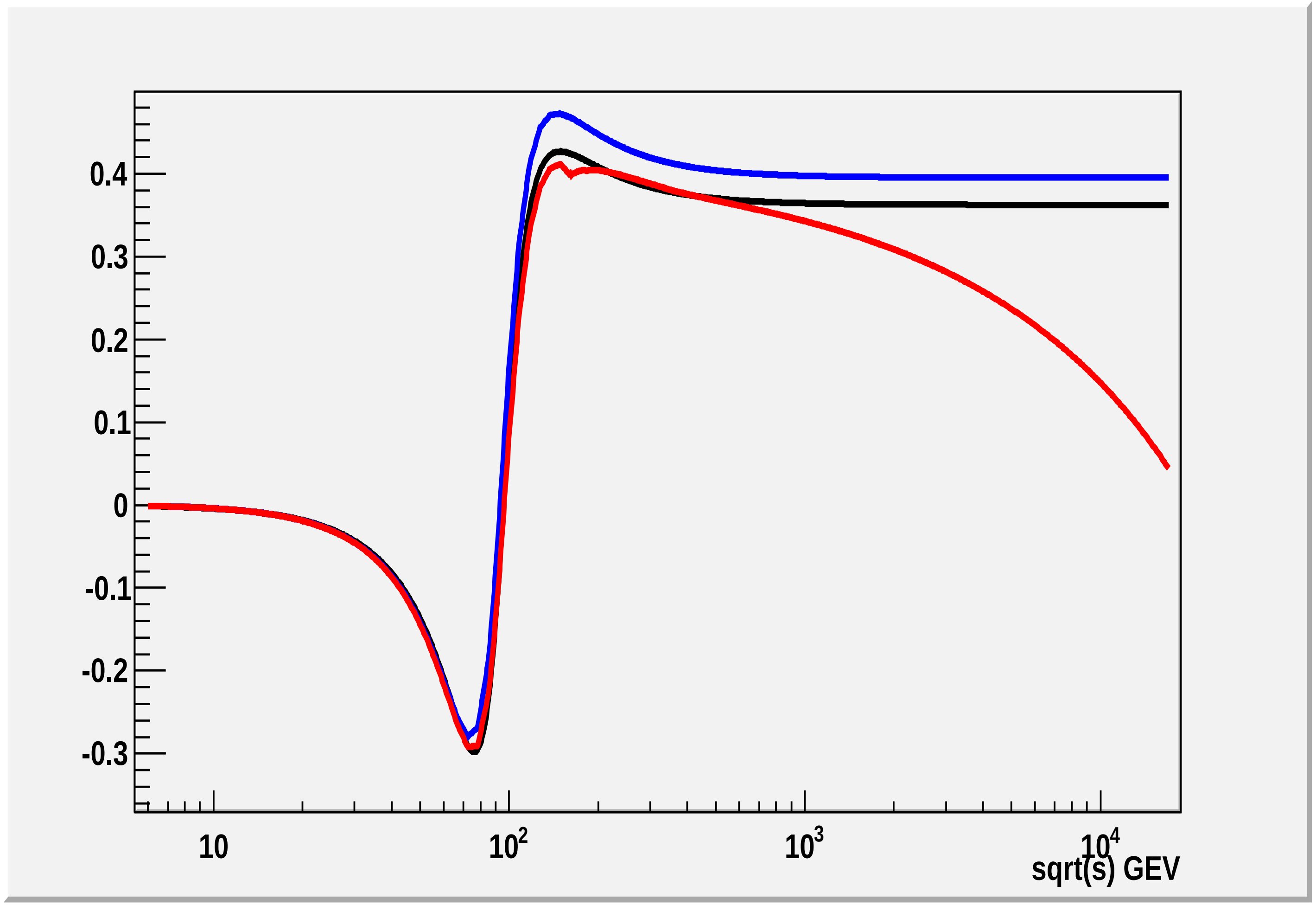




Effect of electroweak corrections on τ-pair production, up quarks, alpha scheme.

Q: What Born parameters are used in PYTHIA?

Electroweak effects



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 $\cos\theta = -0.2$