Analysis of BaBar three meson tau decay data with Monte Carlo generator TAUOLA. Status and perspectives.

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in collaboration with

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OUTLINE

Introduction and motivation

Resonance Chiral Lagrangian and results for $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$

Fitting to BaBar $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ data. Strategy and results

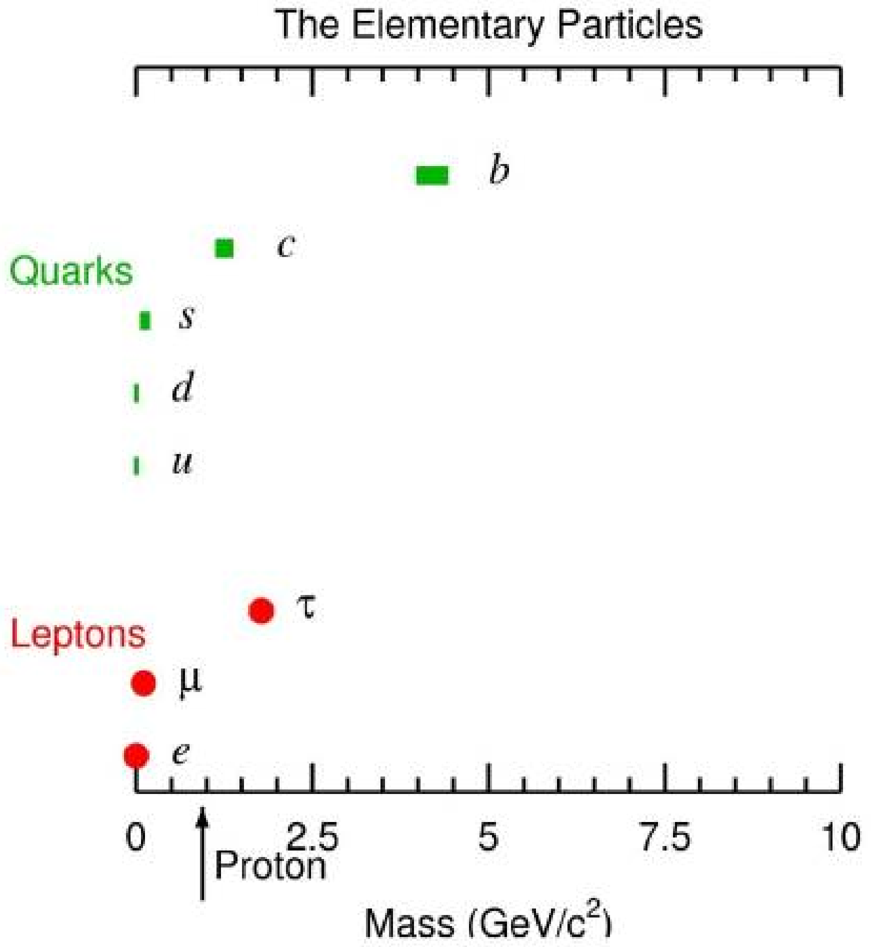
Conclusion and plans

What Physics does the τ Provide Access to?

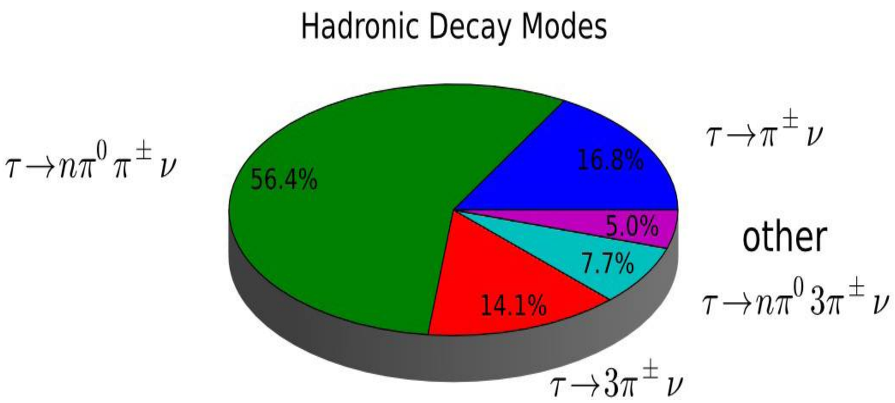
The τ is the most massive charged lepton,

as such it provides:

- A unique environment to determine $|V_{us}|$
- Test the Charged Lepton Universality assumption in the Standard Model
- Provides a clean environment to study QCD
  - Strong coupling constant $\alpha_s(M_\tau)$
  - Search for second class currents (allowed by QCD but never observed)
  - Wess-Zumino Anomaly
  - Resonance structure
  - Okubo-Zweig-Iizuka Suppression
  - Test of Charged Vector Current (CVC)
- Search for New Physics
  - Lepton Flavour Violation (LFV)
- τ mass measurement
- τ life time measurement

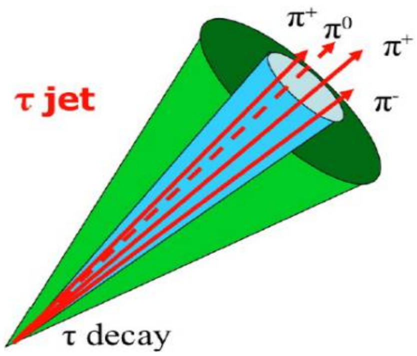


Morever, the tau invariant mass distributions are essential to update the simulation of tau decays for LHC, SuperB factories...



Tau Lepton Properties

- m_τ = 1.78 GeV → *decays in hadrons*
- $c\tau$ = 87 μm
- BR($\tau\rightarrow l\nu\nu$) = 35.2%
- BR($\tau\rightarrow$hadrons) = 64.8%



Typical detector signature

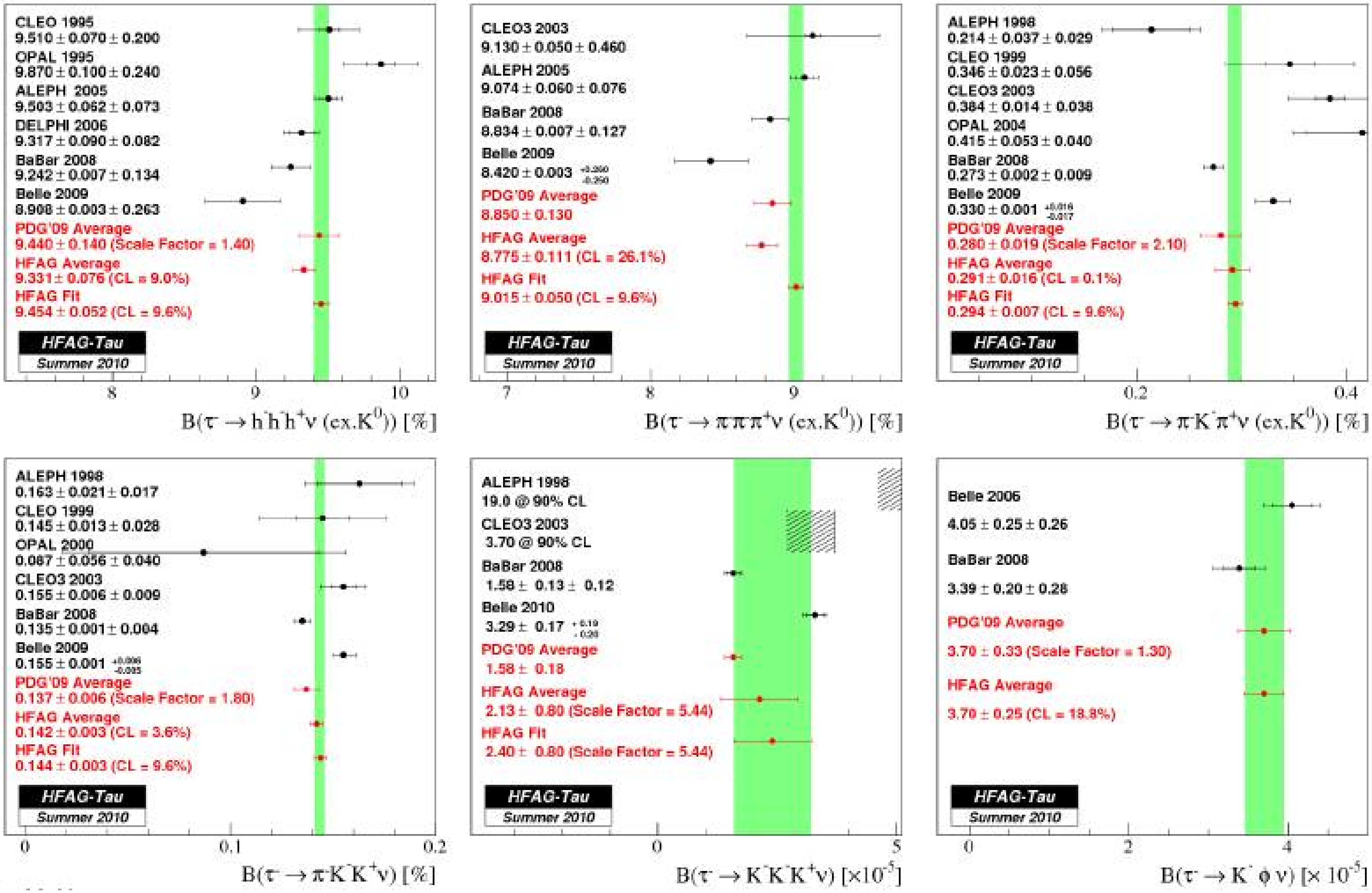
- one or three charged tracks
- collimated calorimeter energy deposits
- large leading track momentum fraction
- possible secondary vertex reconstruction

Precise analysis of available data for 2 pion + 3 pion modes → **BaBar / Belle**

Knowledge of the dynamics is important for Higgs polarization measurement and agreement MC/data, searched for beyond SM physics

Only Belle data is available for two pion mode

BaBar/Belle comparison for 3 meson modes; BR



Only 3 pion mode result within errors

Data / MC ?????

TAUOLA **(Monte Carlo generator for tau decay modes)**

CPC version R. Decker, S.Jadach, M.Jezabek, J.H.Kuhn, Z. Was,
Comp. Phys. Comm. 76 (1993) 361

Cleo version Alain Weinstein : http://www.cithep.caltech.edu/~ajw/korb_doc.html#files

* ***BaBar version***

Aleph version B. Bloch, private communications

~ 20 modes

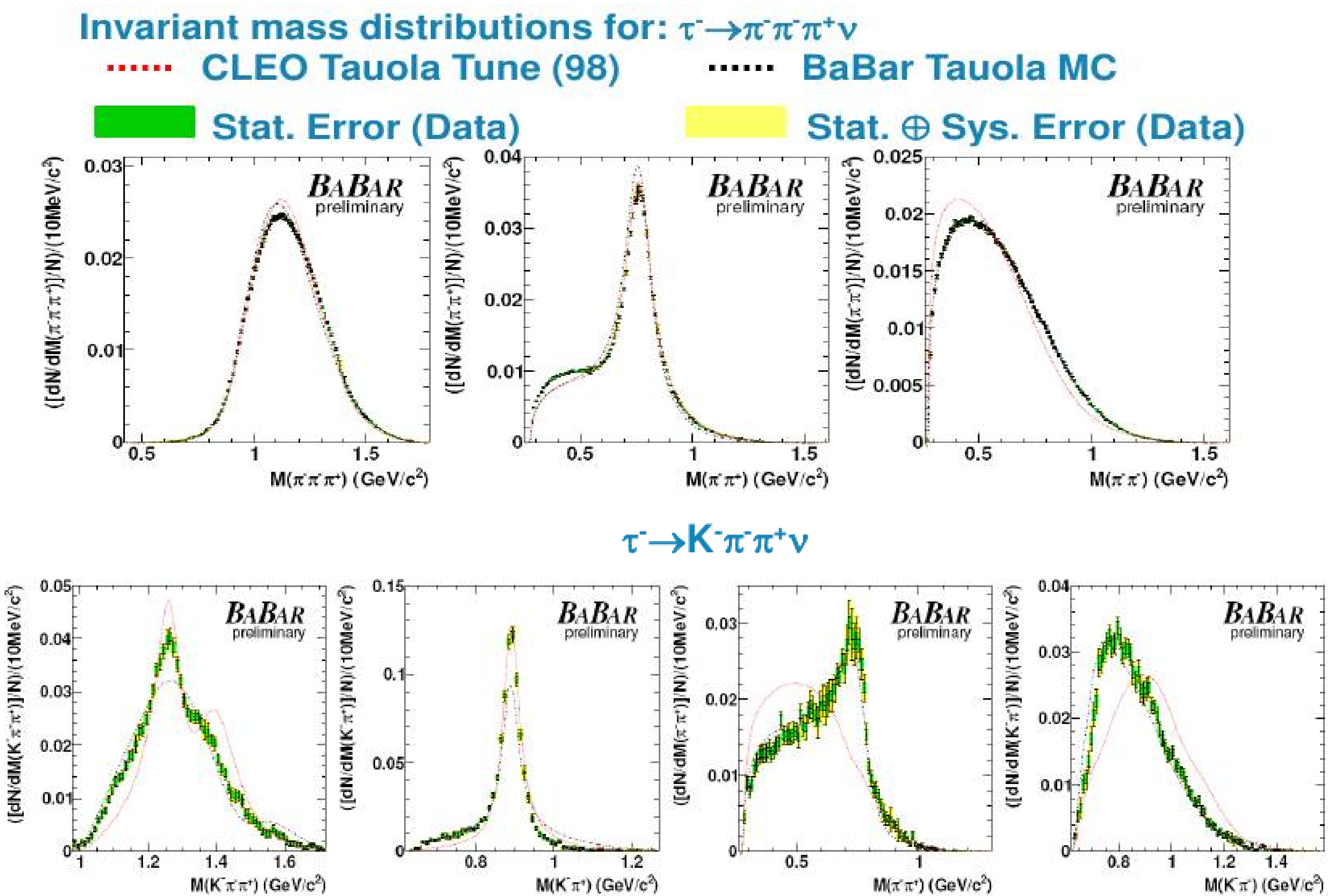
Features of all versions:

* based on VMD, i.e. 3 scalar modes BW(V1)*BW(V2) , reproduces LO ChPT limit
* wrong normalization for 2 scalar modes, except 2π, only vector FF , no scalar FF

* *not correct low energy behaviour of the vector part for $KK\pi$ modes*

* *3 scalar mode results are not able to reproduce experimental data*

Only BaBar mass invariant spectra are available



and other modes: MC does not reproduce the data → *<u>needs "fresh" theoretical input</u>*

we will work only with the hadronic 2 and 3 meson modes

$2\pi\tau$, $2K\ \tau$, $K\pi\tau$, $3\pi\tau$, $KK\pi\tau$ → *<u>88% of tau hadronic width</u>*

Hadronic currents for two and three meson decay modes

Two meson modes:

$$J^\mu = N\left[(p_1 - p_2)^\mu F^V(s) + (p_1 + p_2)^\mu F^S(s)\right]$$

Three meson modes:

$$J^\mu = N\left\{T^\mu_\nu\left[c_1(p_2-p_3)^\nu F_1 + c_2(p_3-p_1)^\nu F_2 + c_3(p_1-p_2)^\nu F_3\right] + c_4 q^\nu F_4 - \frac{i}{4\pi^2 F^2} c_5 \varepsilon^{\mu\nu\rho\sigma} p_{1\nu} p_{2\rho} p_{3\sigma} F_5\right\}$$

Hadronic form factors are:

- **Model: Resonance Chiral Lagrangian** (***Chiral lagrangian with the explicit inclusion of resonances , G.Ecker et al., Nucl. Phys B321(1989)311***)

  * The resonance fields ($V_{\mu\nu}$, $A_{\mu\nu}$ *antisymmetric tensor field*) is added by explicit way

  * Reproduces NLO prediction of ChPT (at least)

  * Correct high energy behaviour of form factors:

$$F_V G_V = f_\pi^2 ,\ F_V^2 - F_A^2 = f_\pi^2 ,\ F_V^2 M_V^2 = F_A^2 M_A^2$$

Finite numbers of parameters (one octet: f_π , F_V, G_V, F_A)

Modes: **2πτ, 2K τ, Kπτ, 3πτ, KKπτ** → **88% of tau hadronic width**

self consistent results within RChL for TAUOLA

Three pseudoscalar modes:

0911.2640; 0911.4436

$\tau^- \to (3\pi)^- \nu_\tau$; $\tau^- \to K^-\pi^-K^+ \nu_\tau$; $\tau^- \to K^0\pi^-K^0 \nu_\tau$, $\tau^- \to K^-\pi^0K^0 \nu_\tau$

$$J^\mu = N\left\{T^\mu_\nu\left[c_1(p_2-p_3)^\nu F_1 + c_2(p_3-p_1)^\nu F_2 + c_3(p_1-p_2)^\nu F_3\right] + c_4 q^\nu F_4 - \frac{i}{4\pi^2 F^2} c_5 \varepsilon^{\mu\nu\rho\sigma} p_{1\nu} p_{2\rho} p_{3\sigma} F_5\right\}$$

$$F_i = F_i^\chi + F_i^R + F_i^{RR}$$

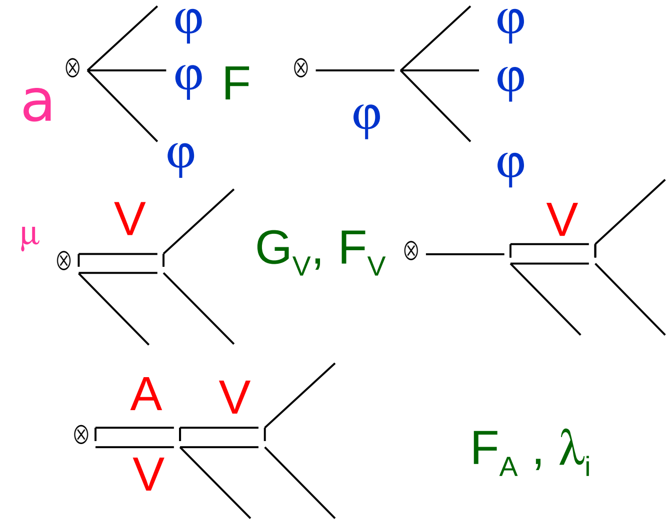
$$F_4 \sim m_\pi^2 / q^2$$

$$T^\nu_\mu = g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}, \quad q^\mu = p_1^\mu + p_2^\mu + p_3^\mu$$

χPT

RχT, 1R

RχT, 2R



No VV vertex for 3 pions

FF: F_1 F_2 F_3 axial-vector, F_5 vector, $F_5(3\pi)=0$ **, F_4 pseudoscalar**

A = *a1*(1260)
V = ρ, ϕ, ω, ρ'

Three meson modes the widths of the resonances:

$$\Gamma_\rho(q^2) = \frac{M_\rho q^2}{96\pi F^2}\left[\sigma_\pi^3(q^2)\theta(q^2-4m_\pi^2) + \frac{1}{2}\sigma_K^3(q^2)\theta(q^2-4m_K^2)\right]$$

$$\Gamma_{\rho'}(q^2) = \Gamma_{\rho'}\frac{q^2}{M_{\rho'}^2}\frac{\sigma_\pi^3(q^2)}{\sigma_\pi^3(M_{\rho'}^2)}\theta\left(q^2-4m_\pi^2\right) \qquad \sigma_P(q^2) \equiv \sqrt{1-4m_P^2/q^2}$$

SU(2) limit

$m_{\pi^\pm} = m_{\pi^0}$

$m_{K^\pm} = m_{K^0}$

a_1 resonance:

$$\begin{aligned}\Gamma_{a_1}(q^2) &= 2\Gamma_{a_1}^\pi(q^2)\theta\left(q^2-9m_\pi^2\right)\\ &+ 2\Gamma_{a_1}^{K^\pm}(q^2)\theta\left(q^2-(m_\pi+2m_K)^2\right) + \Gamma_{a_1}^{K^0}(q^2)\theta\left(q^2-(m_\pi+2m_K)^2\right)\end{aligned}$$

$$\begin{aligned}\Gamma_{a_1}^{\pi,K}(q^2) &= \frac{-S}{192(2\pi)^3F_A^2F^2M_{a_1}}\left(\frac{M_{a_1}^2}{q^2}-1\right)^2\\ &\int dsdt\,(V_1^\mu F_1+V_2^\mu F_2+V_3^\mu F_3)^{\pi,K}\left((V_{1\mu}F_1+V_{2\mu}F_2+V_{3\mu}F_3)^{\pi,K}\right)^*\end{aligned}$$

$$V_i^\mu = c_i T^{\mu\nu}(p_j-p_k)_\nu, \quad i\neq j\neq k=1,2,3$$

$$S = 1/n!$$

a1 width ($\Gamma_{a_1}(q^2)$) is tabulated to avoid problem with triple integration, linear interpolation

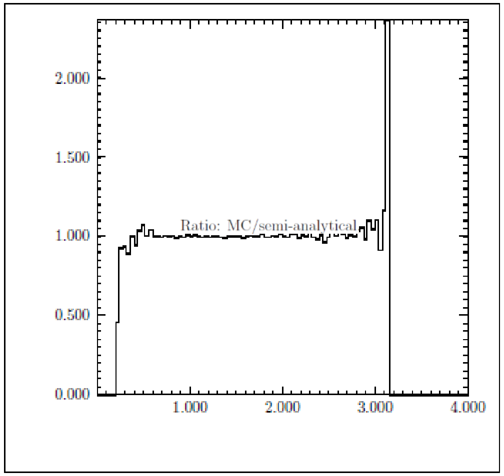
TAUOLA update, main test done, results PRD Phys.Rev. D86 (2012) 113008

Technical tests to check stability of MC

for every mode

- * to check phase space MC / analytical F1 = 1, others = 0
- * MC / analytical for total width
- * MC / analytical result for qq spectrum
- * analytical result (Gauss integration) compared with linear interpolated spectrum

An example: three pions ($\tau \to \pi^- \pi^- \pi^+ \nu_\tau$):



F_1 = F, F_{others} = 0 to check phase space

F_1 = physical, F_{others} = 0

\- F_{all} = physical

linear interpolation ~ 0.1% for whole spectrum except for ends

MC (6e6): (2.1013±0.016%)·10^{-13}GeV;

semi-analyt(2.1007±0.02% %)·10^{-13}GeV

… fit for $\pi - \pi - \pi +$ to BaBar data

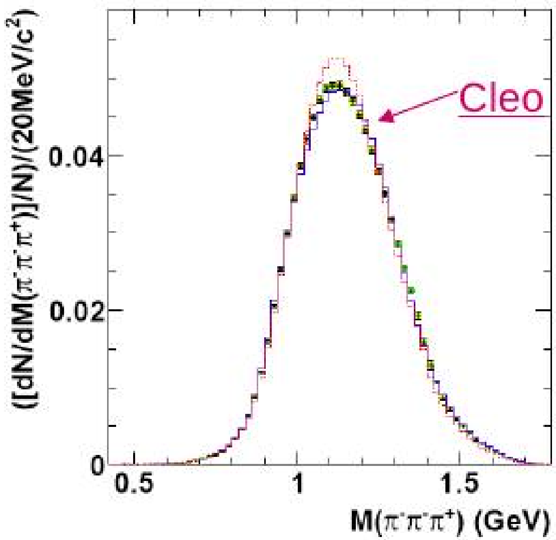
Fit to BaBar 20Mev/bin $\pi - \pi - \pi +$ data (SLAC-R-936)

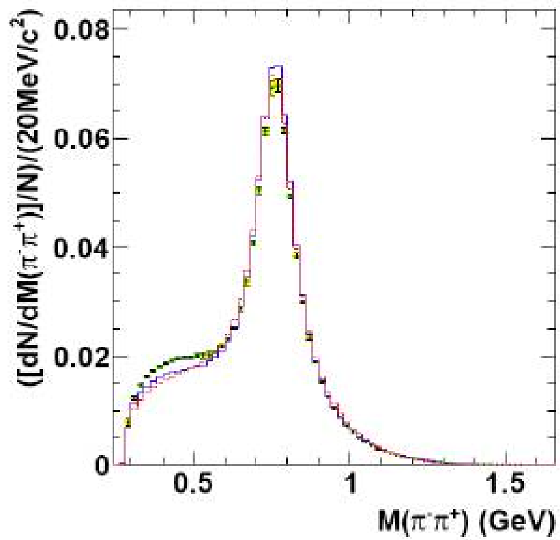
non trivial dynamics, the simplest from the 3 hadronic modes

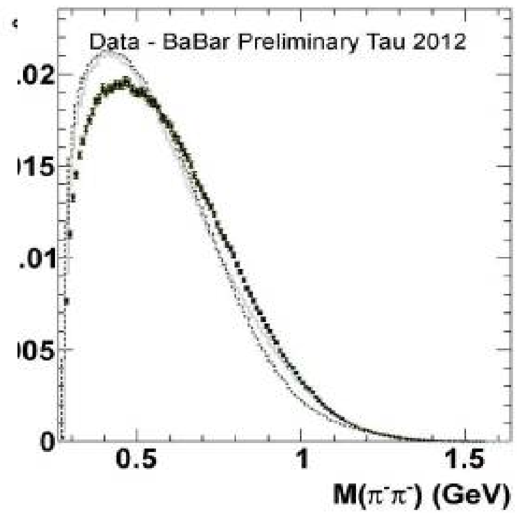
Fit Parameters							
	$M_{\rho'}$	$\Gamma_{\rho'}$	M_{a1}	F	F_V	F_A	$\beta_{\rho'}$
Min.	1.44	0.32	1.00	0.0920	0.12	0.10	-0.36
Max.	1.48	0.39	1.24	0.0924	0.24	0.20	-0.18
Default	1.453	0.40	1.12	0.0924	0.18	0.149	-0.25
Fit	1.4302	0.376061	1.21706	0.092318	0.121938	0.11291	-0.208811

χ^2= 2262.12

ndf=132







(Data -RChL) less 7% $\pi^+ \pi^- \pi^-$

(Data -RChL) less 12% $\pi^+ \pi^-$

main contribution from low energy two pion inavariant mass region !!

RChL without extension cannot describe the data

Modification of RChL → inclusion of σ meson

$$F_1^{\rm R} \;\to\; F_1^{\rm R} + \frac{\sqrt{2}F_V G_V}{3F^2}\left[\alpha_\sigma BW_\sigma(s_1)F_\sigma(q^2,s_1) + \beta_\sigma BW_\sigma(s_2)F_\sigma(q^2,s_2)\right]$$

$$F_1^{\rm RR} \;\to\; F_1^{\rm RR} + \frac{4F_A G_V}{3F^2}\frac{q^2}{q^2 - M_{a_1}^2 - iM_{a_1}\Gamma_{a_1}(q^2)}\left[\gamma_\sigma BW_\sigma(s_1)F_\sigma(q^2,s_1) + \delta_\sigma BW_\sigma(s_2)F_\sigma(q^2,s_2)\right]$$

$$BW_\sigma(x) = \frac{m_\sigma^2}{m_\sigma^2 - x - im_\sigma\Gamma_\sigma(x)} \quad \Gamma_\sigma(x) = \Gamma_\sigma\frac{\sigma_\pi(x)}{\sigma_\pi(m_\sigma^2)} \quad F_\sigma(q^2,x) = \exp\left[\frac{-\lambda(q^2,x,m_\pi^2)R_\sigma^2}{8q^2}\right]$$

New fit parameters $\alpha_\sigma\,,\ \beta_\sigma\,,\ \gamma_\sigma\,,\ \delta_\sigma\,,\ R_\sigma$

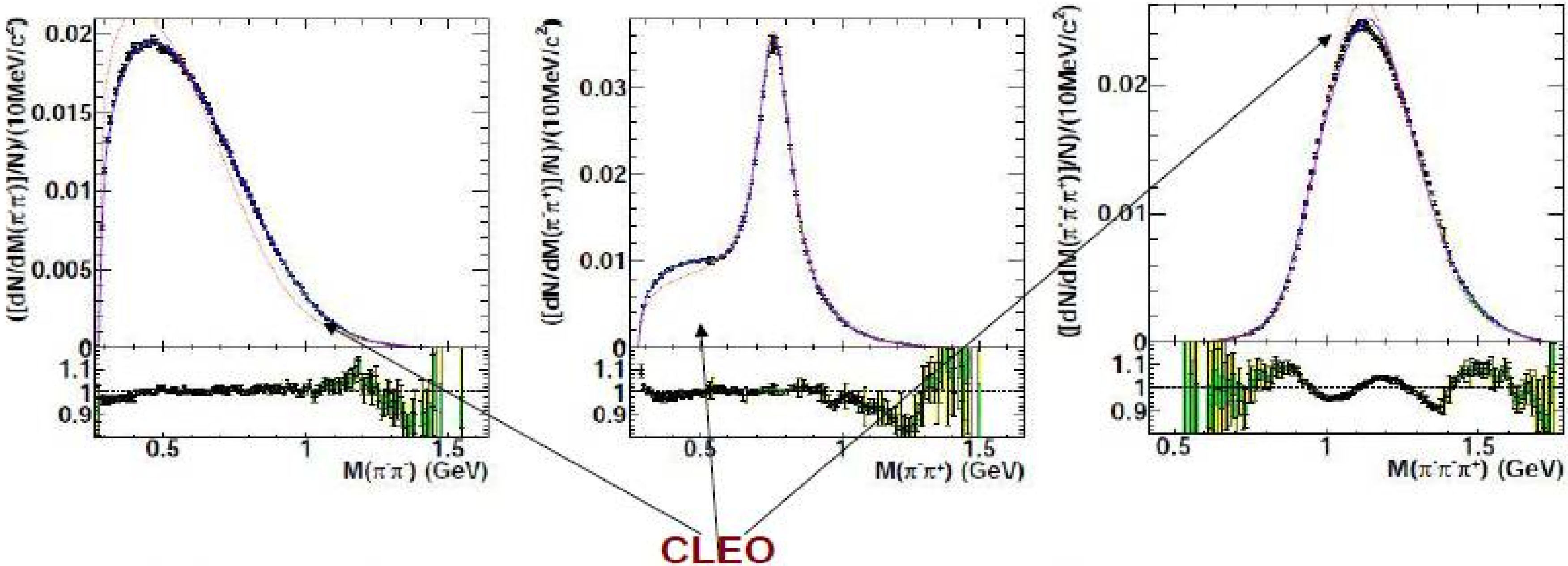
1d dimensional distributions (s1, s2, q2) are fitted to BaBar data

Babar improved analysis

***10 MeV/bin (twice decreased)**

*** separated statistical and systematical errors**

2013



	M_ρ [8]	$M_{\rho'}$	$\Gamma_{\rho'}$	M_{a_1}	M_σ	Γ_σ	F	F_V
Min	0.767	1.35	0.30	0.99	0.400	0.400	0.088	0.11
Max	0.780	1.50	0.50	1.25	0.550	0.700	0.094	0.25
Fit	0.771849	1.350000	0.448379	1.091865	0.487512	0.700000	0.091337	0.168652

	F_A	$\beta_{\rho'}$	α_σ	β_σ	γ_σ	δ_σ	R_σ
Min	0.1	-0.37	-10.	-10.	-10.	-10.	-10.
Max	0.2	-0.17	10.	10.	10.	10.	10.
Fit	0.131425	-0.318551	-8.795938	9.763701	1.264263	0.656762	1.866913

χ^2/ndf = 6658/401 stat

χ^2/ndf = 889/401 stat+syst

$$\Gamma_{\tau^-\to\pi^-\pi^-\pi^+\nu_\tau} = 2.0001\cdot 10^{-13}\ \mathrm{GeV}$$

Validation of results

* Statistical errors and correlations between model parameters

* Convergence of the fitting procedure to verify that the found minimum is a global minimum

* Toy MC studies to check of behaviour near the minimum

* Estimation of systematic uncertainties

Validation of results

* Statistical errors and correlations between model parameters
  - Hesse algorithm of Minuit package

	α_σ	β_σ	γ_σ	δ_σ	R_σ	M_ρ	$M_{\rho'}$	$\Gamma_{\rho'}$	M_{a_1}	M_σ	Γ_σ	F_π	F_V	F_A	$\beta_{\rho'}$
α_σ	1	0.60	0.36	-0.29	-0.41	-0.69	0.46	0.68	-0.77	-0.09	0.02	0.78	0.76	0.52	-0.78
β_σ	0.60	1	0.44	-0.39	-0.42	-0.75	0.55	0.79	-0.89	-0.16	0.04	0.89	0.88	0.58	-0.88
γ_σ	0.36	0.44	1	-0.56	-0.22	-0.59	0.16	0.37	-0.47	-0.28	0.00	0.49	0.45	0.30	-0.45
δ_σ	-0.29	-0.39	-0.56	1	0.46	0.46	-0.24	-0.42	0.49	0.01	0.01	-0.49	-0.47	-0.31	0.47
R_σ	-0.41	-0.42	-0.22	0.46	1	0.42	-0.33	-0.56	0.62	0.34	0.02	-0.53	-0.56	-0.42	0.48
M_ρ	-0.69	-0.75	-0.59	0.46	0.42	1	-0.27	-0.64	0.79	0.29	-0.02	-0.83	-0.74	-0.48	0.75
$M_{\rho'}$	0.46	0.55	0.16	-0.24	-0.33	-0.27	1	0.67	-0.61	-0.13	0.03	0.61	0.66	0.37	-0.65
$\Gamma_{\rho'}$	0.68	0.79	0.37	-0.42	-0.56	-0.64	0.67	1	-0.88	-0.24	0.03	0.86	0.88	0.57	-0.88
M_{a_1}	-0.77	-0.89	-0.47	0.49	0.62	0.79	-0.61	-0.88	1	0.28	-0.03	-0.96	-0.97	-0.62	0.95
M_σ	-0.09	-0.16	-0.28	0.01	0.34	0.29	-0.13	-0.24	0.28	1	-0.02	-0.30	-0.29	-0.20	0.30
Γ_σ	0.02	0.04	0.00	0.01	0.02	-0.02	0.03	0.03	-0.03	-0.02	1	0.03	0.03	0.03	-0.04
F_π	0.78	0.89	0.49	-0.49	-0.53	-0.83	0.61	0.86	-0.96	-0.30	0.03	1	0.95	0.55	-0.97
F_V	0.76	0.88	0.45	-0.47	-0.56	-0.74	0.66	0.88	-0.97	-0.29	0.03	0.95	1	0.63	-0.96
F_A	0.52	0.58	0.30	-0.31	-0.42	-0.48	0.37	0.57	-0.62	-0.20	0.03	0.55	0.63	1	-0.56
$\beta_{\rho'}$	-0.78	-0.88	-0.45	0.47	0.48	0.75	-0.65	-0.88	0.95	0.30	-0.04	-0.97	-0.96	-0.56	1

Strong correlation > 0.95 $M_{a_1}, F_\pi, F_V, \beta_{\rho'}$

Validation of results

*

* Convergence of the fitting procedure to verify that the found minimum is a global minimum

- start with random scan of 210 K points
- select 1K with the best chi2
- from these 1k select 20 points that maximaze the distance
- use them as a start point for the full fit and apply the full fit procedure

> 50% converge to the minimum
(*others falls with number of parameters at their limits,*
converge to local minimum with highet chi2)

Indicates that the found minimum point is a global minimum

Validation of results

*

*

* Toy MC studies to check of behaviour near the minimum
  8 MC samples (different seeds) of 20 million generated with
  (I) the fit parameter values, i.e. difference is “statistical error”
  (II) the start point for fitting
then these samples are fitted as they are experimental data

The results of fit are consistent, I.e. the fitting procedure is table

Validation of results

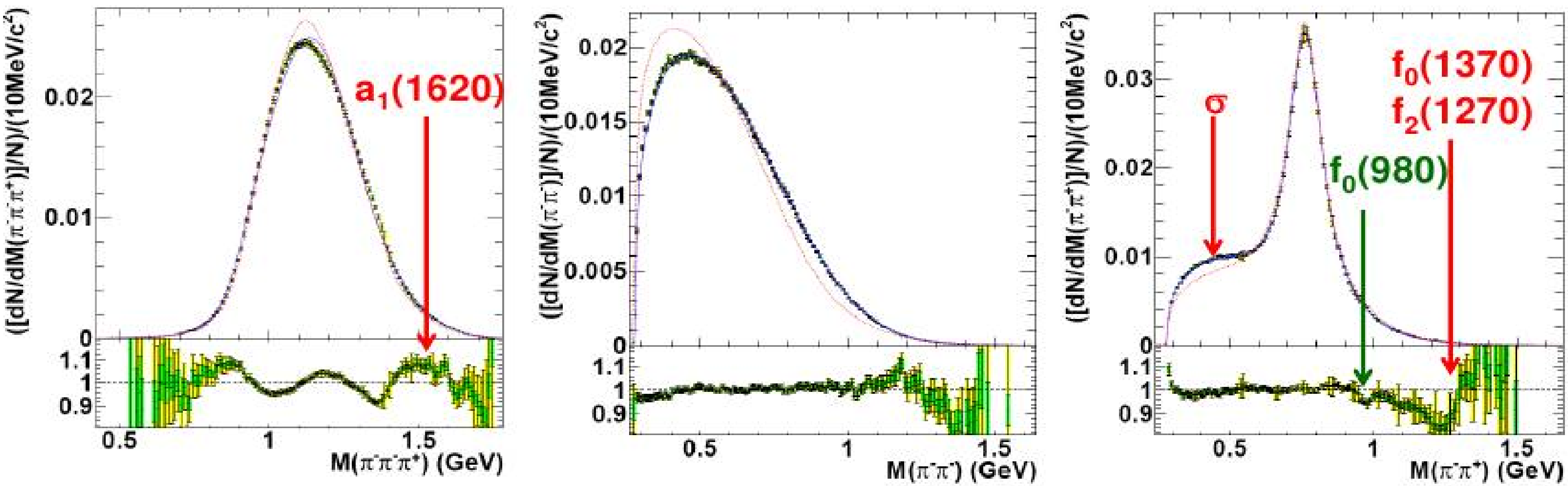
*
*
*

* Estimation of systematic uncertainties
  Used systematical covariance matrix from BaBar experiment to include the correlations between bins

Issues Related to Model Limitations

Missing resonances can be observed in difference plots

- Additional resonances can also be seen $f_0(980)$ ~5.8σ*



No data for π0 π0 π- !!!!

… and will be not available in near future.

Difference is with the sigma meson contribution

fit SIGMA parameters to **π0 π0 π-** BaBar data

$$F_1^{R} \rightarrow F_1^{R} + \frac{\sqrt{2}F_V G_V}{3F^2}\alpha_\sigma^0 BW_\sigma(s_3)F_\sigma(q^2, s_3),$$

$$F_1^{RR} \rightarrow F_1^{RR} + \frac{4F_A G_V}{3F^2}\frac{q^2}{q^2 - M_{a_1}^2 - iM_{a_1}\Gamma_{a_1}(q^2)}\gamma_\sigma^0 BW_\sigma(s_3)F_\sigma(q^2, s_3).$$

π+π− π− $\alpha_\sigma = \beta_\sigma, \gamma_\sigma = \delta_\sigma$

$$\alpha_\sigma = 1.139486, \gamma_\sigma = 0.889769, R_\sigma = 0.000013, M_\sigma = 0.550 \quad \Gamma_\sigma = 0.700.$$

$$\alpha_\sigma^0 = \alpha_\sigma \cdot Scaling_{factor}^\gamma$$

CLEO

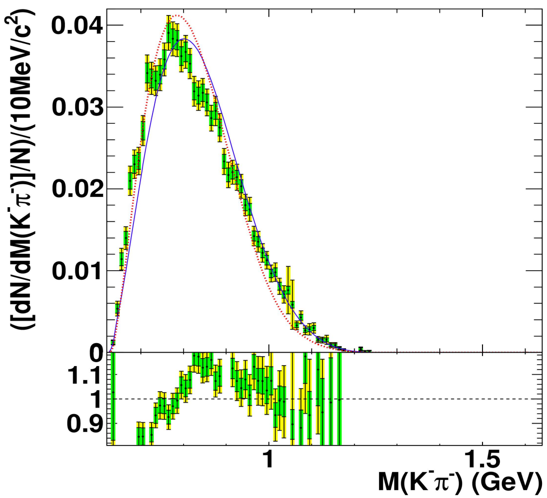
$$Scaling_{factor}^\gamma = 2.1/3.35 = 0.63$$

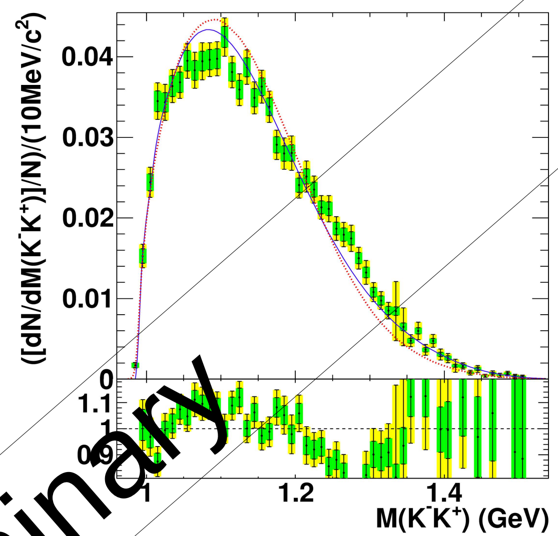
$$\Gamma = (2.1440 \pm 0.02\%) \cdot 10^{-13}$$

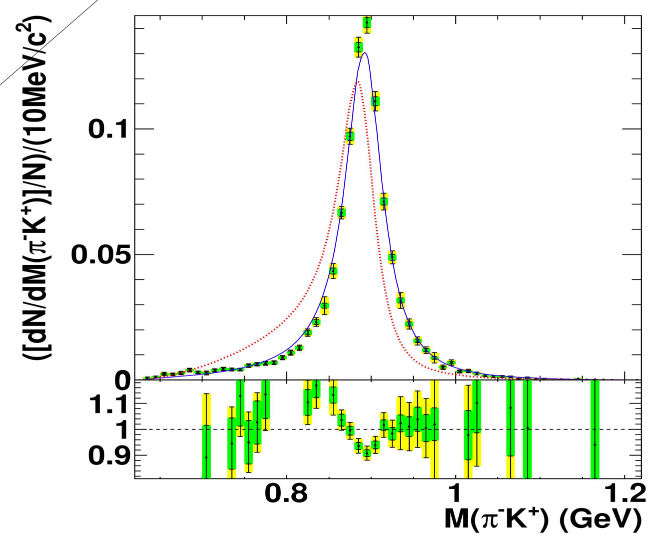
2.1% higher than the PDG value

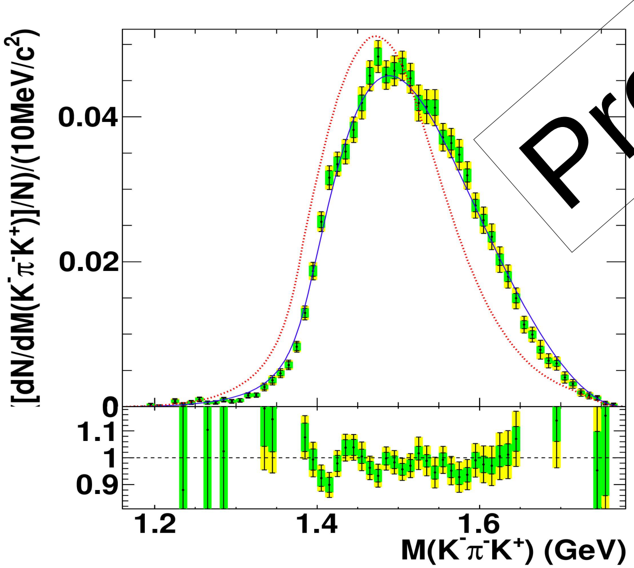
$\tau^- \to K^+ K^- \pi^- \nu$

First fitting results to BaBar data , fixed table for the a1 width







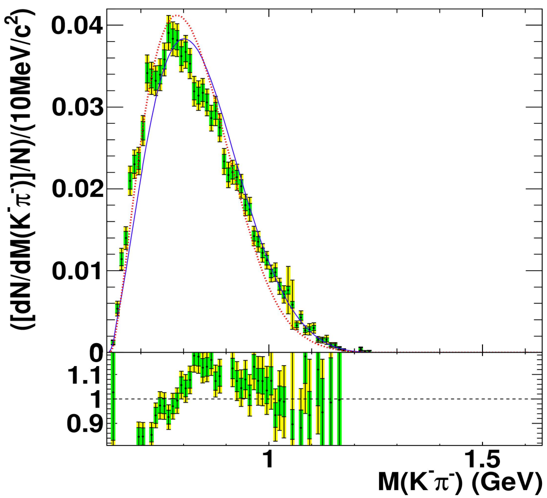


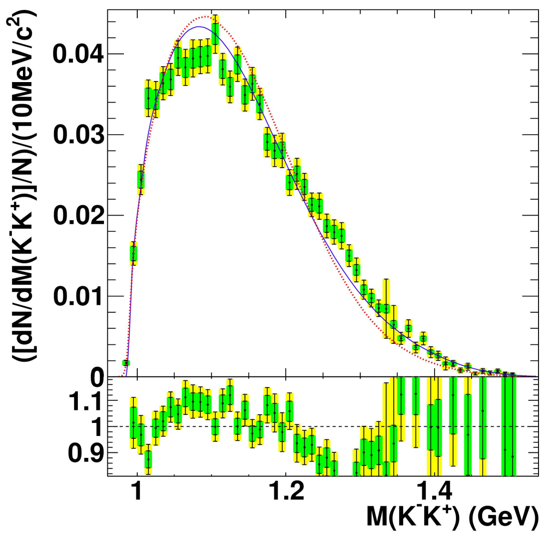
Blue – RChL Red – Cleo

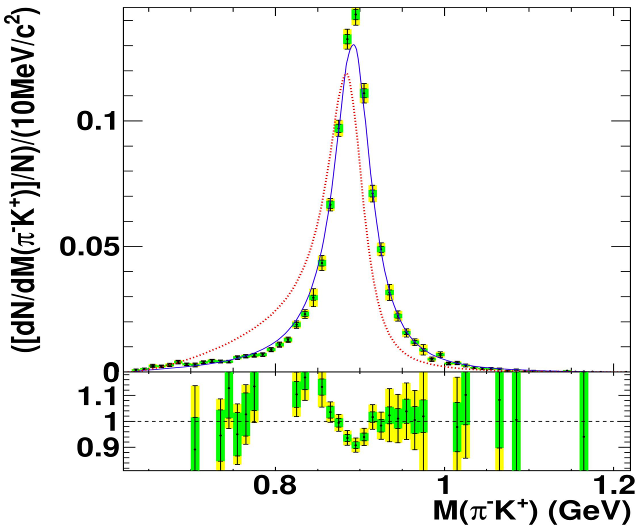
Common fit to $\pi^+\pi^-\pi^-$ and $K^+K^-\pi^-$

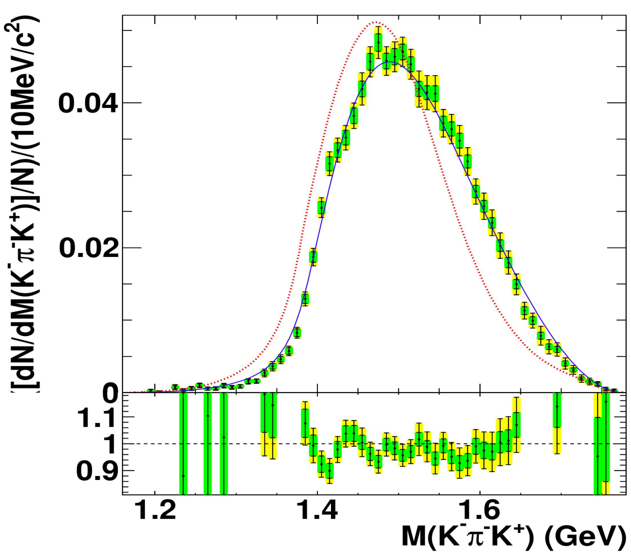
$\tau^- \to K^+ K^- \pi^- \nu$

First fitting results to BaBar data , fixed table for the a1 width









Blue – RChL   Red – Cleo
some parameters on their limits ...

Common fit to $\pi^+\pi^-\pi^-$ and $K^+K^-\pi^-$

Project tauola-bbb

Z. Was, P. Golonka. TAUOLA as tau Monte Carlo for future applications
Nucl.Phys.Proc.Suppl. 144 (2005) 88

Cleo + a place for new 60 modes (empty)

June 2014

- A start point is Tauola - BaBar default version (more than 60 channels)
- Added 3 pion RChL fitted to BaBar data

  other modes after the corresponding study

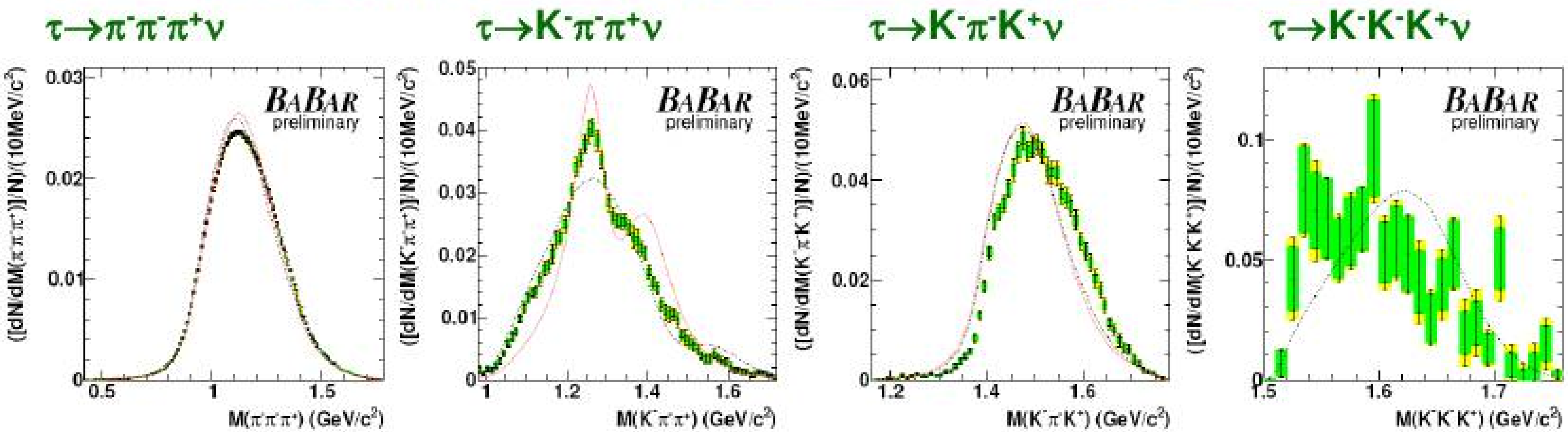
- LFV processes based using flate phase space

- fitting strategy

Conclusion and plans

BaBar data

Currently there are (preliminary) 1d invariant mass spectra available for:



Fitting 1d distributions in $\tau \to \pi^- \pi^- \pi^+ \nu$ has already given us insight into fitting models of low energy QCD (RCHL):

- Information on missing resonances
- Problems and with multi-dimensional fitting – data provided by collaborations

- 1d projection → multi-dimentional fit for 3 pion mode
- K K π mode fit (*next slides*)

- 2 pion RChL current fit to Belle data
- 4 pion RChL current in Tauola and fit to BaBar data

Tauola version with C++ classes for currents

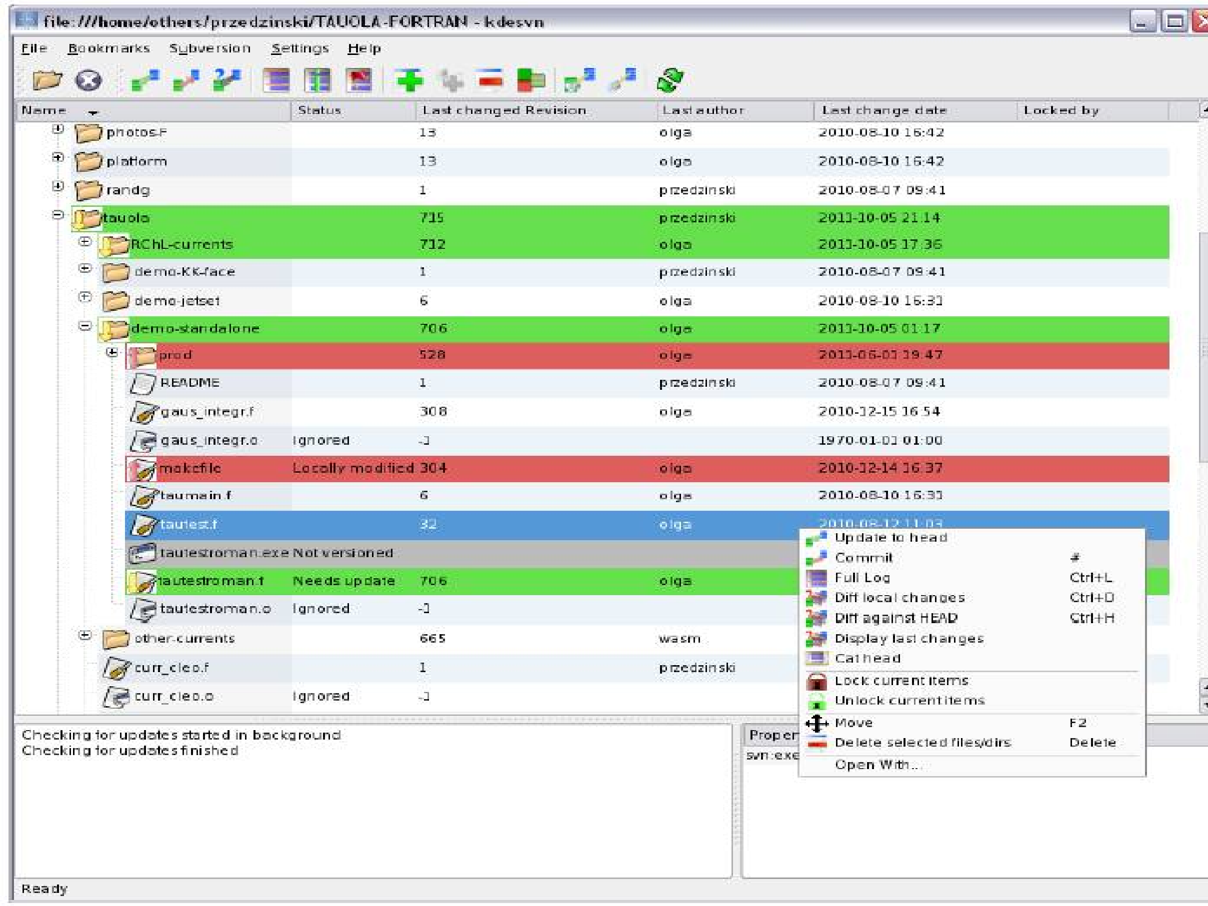
Belle data analysis ??

Backup Slides

TAUOLA repository

Code management

- SVN revision control system
  - displaying recent changes
  - branching different approaches
  - tagging milestones and stable revisions
  - when bug is found – "blame" to check who and when
  - GUI: kdesvn



Z. Was, T. Przedzinski, O.Shekhovtsova kasztan@ifj.edu.pl

higgstools

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

ESR19

JUNIOR ESR (PHD) AT INSTITUTE OF NUCLEAR PHYSICS, KRAKOW (PO)

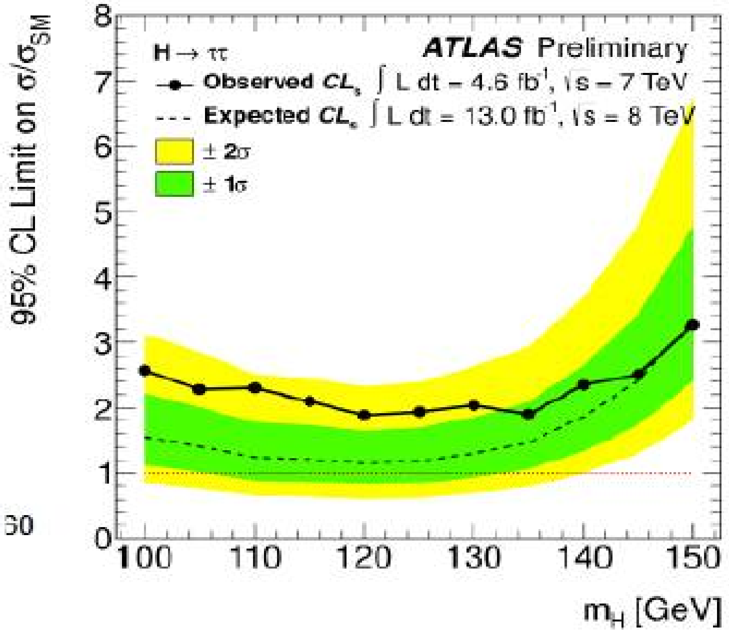
Host Institution:	IFJ PAN Cracow (PO)
Number of months:	18 (+18)
Period:	October 2014 - September 2017
Supervisor:	Professor Zbigniew Was
Objectives:	The candidate will use low energy data from Belle and BaBar experiments and predictions from QCD based models of medium energy QCD, such as Resonance Chiral Lagrangians approach, for better understanding and Monte Carlo simulations of tau decays (WP3).
Secondments:	Short visits to any of the partners, particularly CERN depending on the development of the project. Three months at CERN for training on experimental aspects and a secondment in one of our private sector partners Maplesoft, Wolfram Research and Shell.

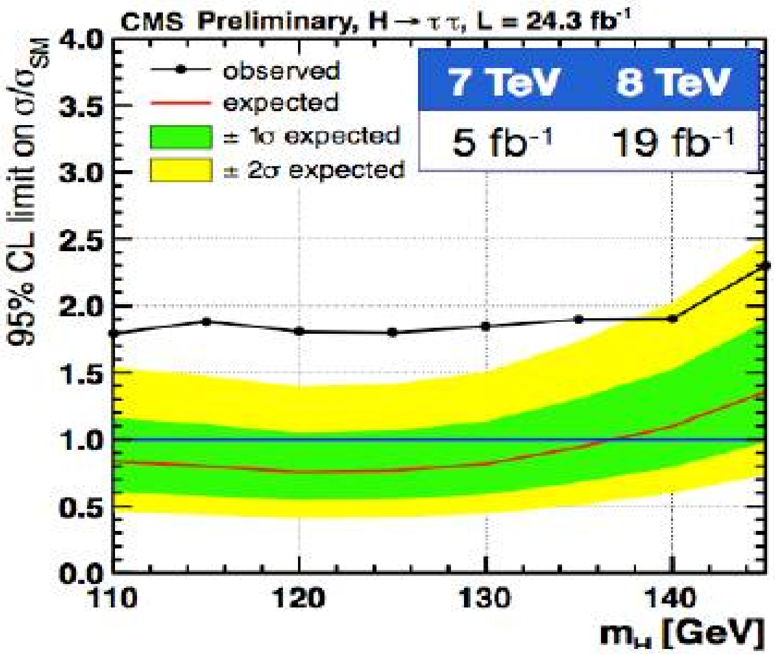
Submitted by owng on Sat, 15/02/2014 - 18:06

http://wasm.web.cern.ch/wasm/

Application for LHC

H→ττ





no conclusive signal yet

local significance 2.9 σ

Just the discovery of the Higgs boson is not sufficient to validate the minimal version of the Higgs sector as implemented in the SM

τ is used a tag dynamics is not studied

however

Next steps are to measure: spin, parity, elementary or composite, strength and tensor structure of couplings