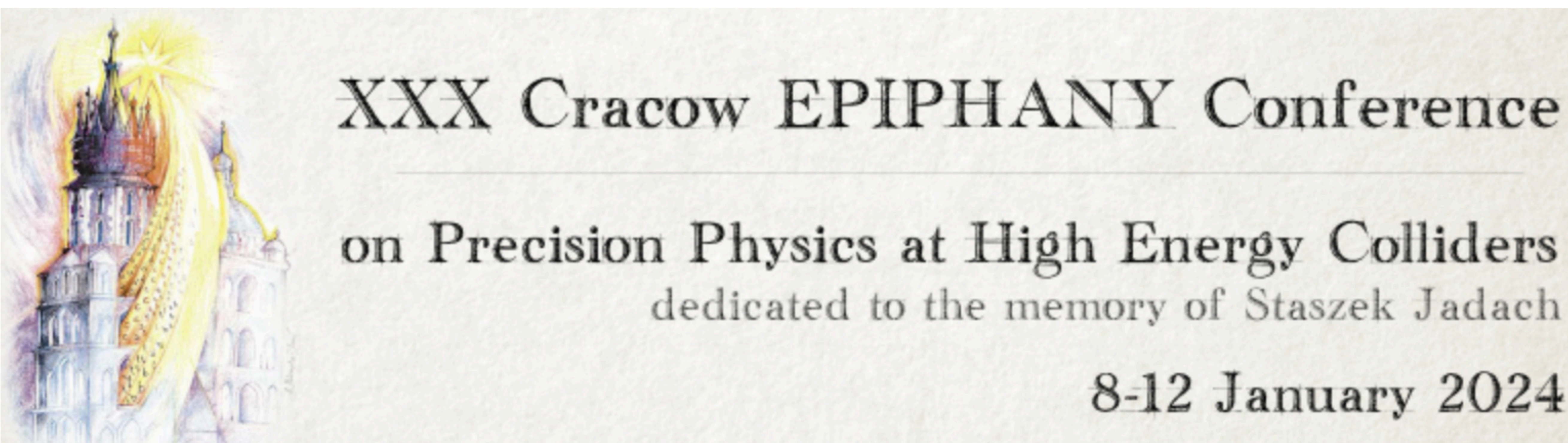
Monte Carlos for tau lepton in Standard Model and New Physics signatures

Swagato Banerjee

UNIVERSITY OF LOUISVILLE



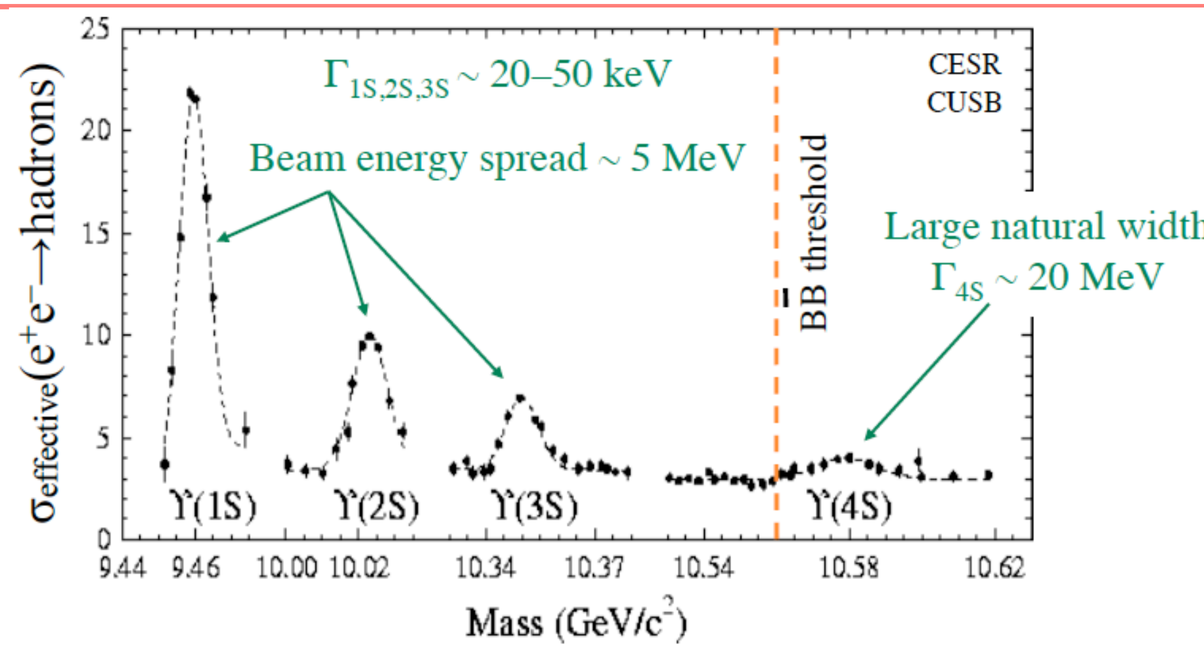
Tau production and decays at $\sqrt{s} = 10.58$ GeV

Production:

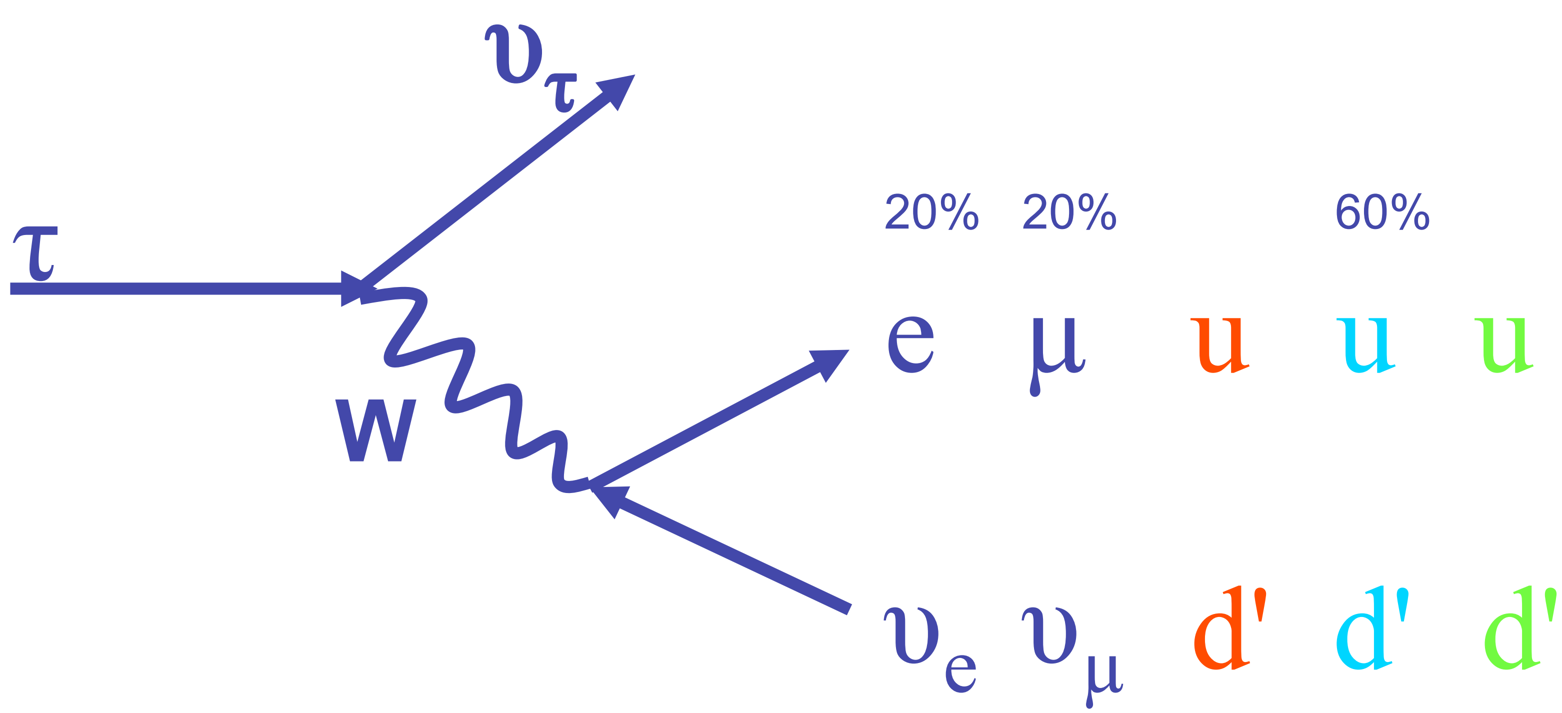
At $\Upsilon(4S)$: $e^+e^- \to Z^*/\gamma \to \tau^+\tau^-$.

Also $e^+e^- \to \Upsilon(nS) \to \tau^+\tau^-$ for n = 1, 2, 3

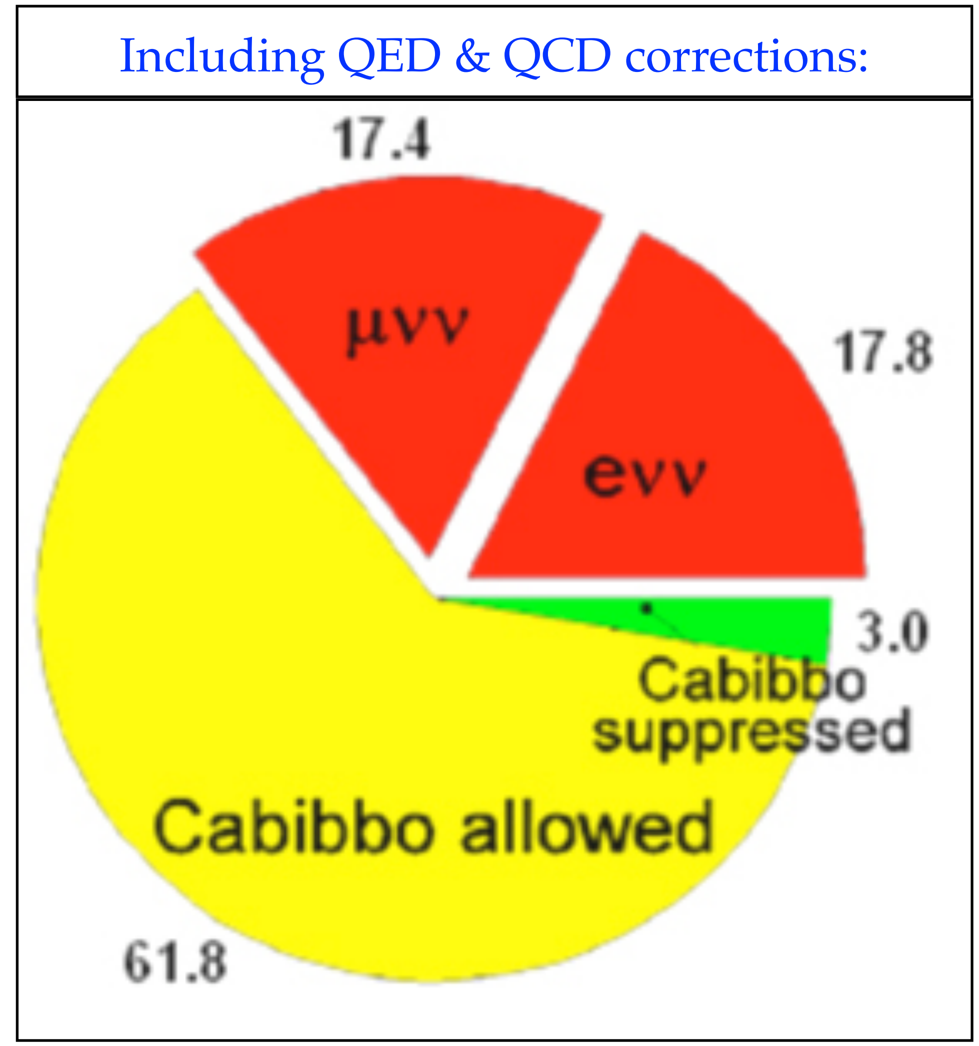
$B(\Upsilon(1,2,3S) \to \tau^+\tau^-) \sim 2\%$, $< 0.002\%$ at $\Upsilon(4S)$



Decays:

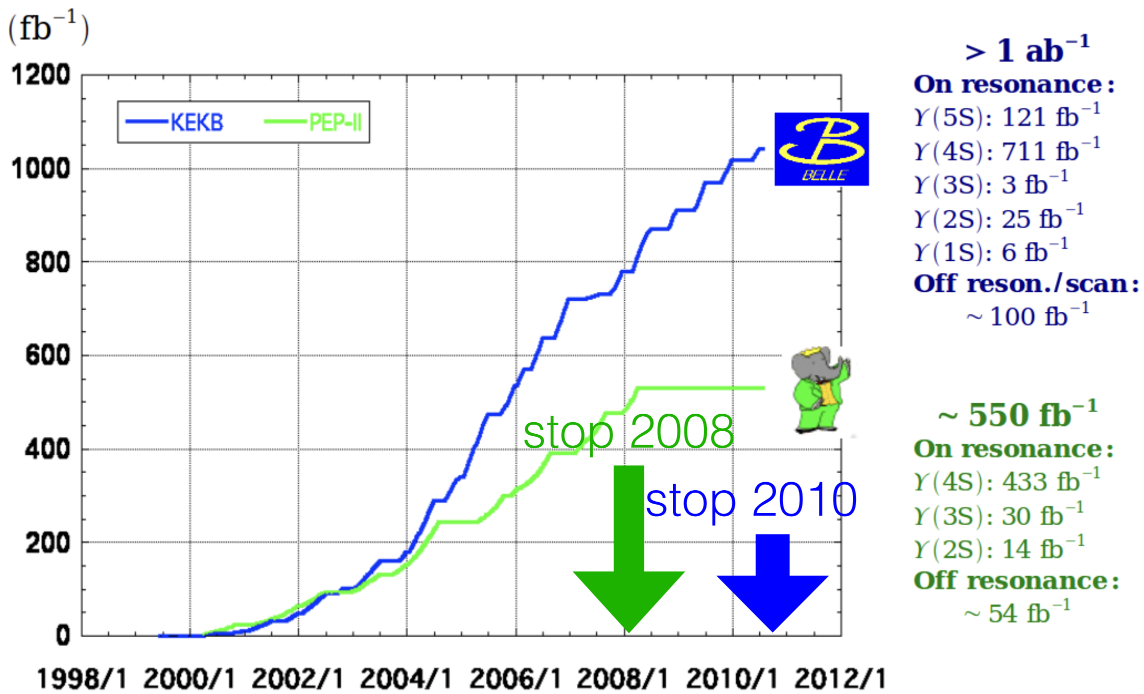


$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$

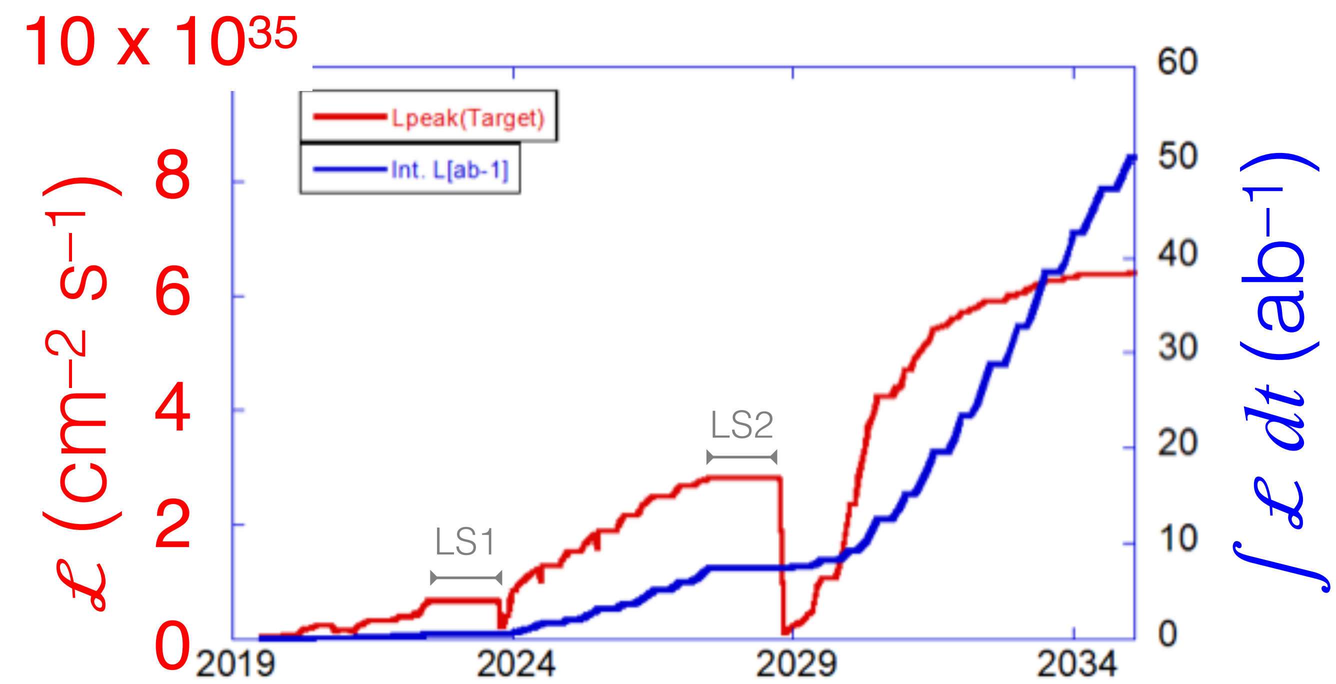


B factories are also τ factories

Integrated luminosity of B factories



Projected luminosity at SuperKEKB/Belle II



500 million τ-pairs produced at BABAR with $\simeq 0.5\ ab^{-1}$ of data

1 billion τ-pairs produced at Belle with $\simeq 1\ ab^{-1}$ of data

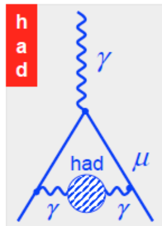
50 billion τ-pairs expected at Belle II with $\simeq 50\ ab^{-1}$ of data

World's largest dataset of τ-leptons studied with Monte Carlos:

- KK2F [S.Jadach, B.F.L.Ward, Z.Was, Comput.Phys.Commun. 130 (2000) 260]
- TAUOLA [S.Jadach, Z.Was, R.Decker, J.H.Kuhn, Comput.Phys.Commun. 76 (1993) 361]
- PHOTOS [E.Barberio, Z.Was, Comput.Phys.Commun. 79 (1994) 291]

Revisiting vacuum polarization

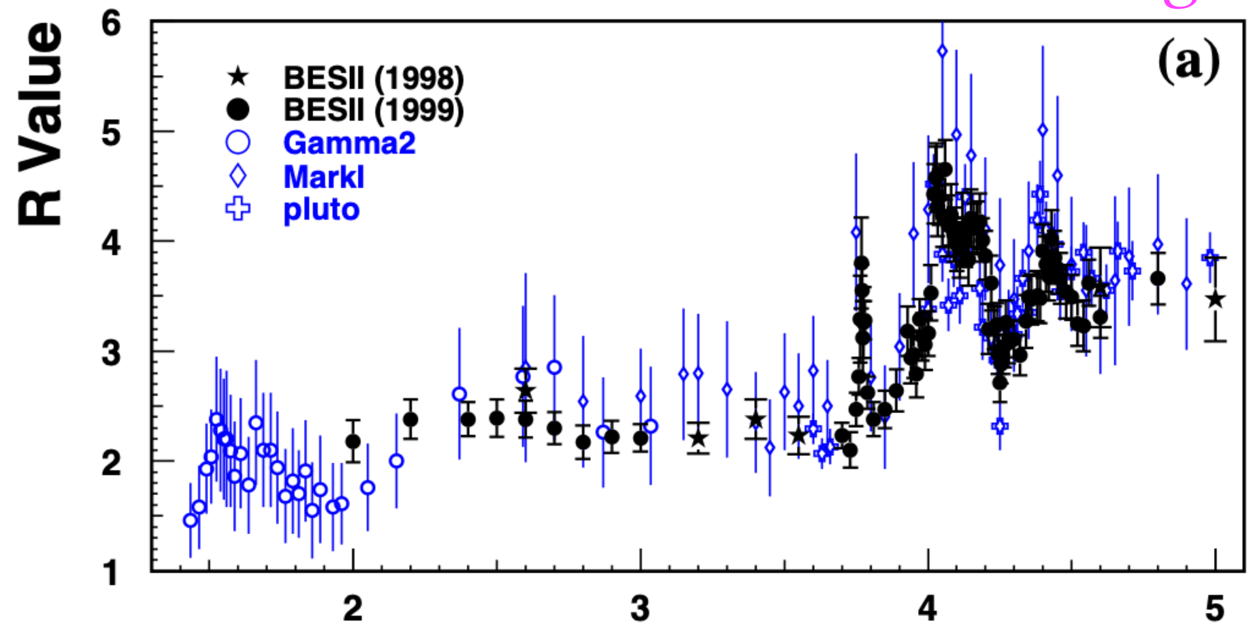
- *Until 2007:* $\sigma_{\tau\tau}^{\mathrm{KORALB}}$ = 0.91 nb, $\sigma_{\tau\tau}^{\mathrm{KK2F}}$ = 0.89 nb, $\Rightarrow \Delta\sigma_{\tau\tau}$ = 2.22 %
- *Default implementation of vacuum polarization in KK2F did NOT calculate the hadronic part for E < 40 GeV*



$$\Delta\alpha_{\mathrm{had}}(s) = -\frac{\alpha s}{3\pi}\mathrm{Re}\int_0^\infty ds' \frac{R(s')}{s'(s'-s)-i\varepsilon}$$

$$12\pi \,\mathrm{Im}\,\Pi_\gamma(s) = \frac{\sigma^{(0)}[e^+e^- \to \mathrm{hadrons}]}{\sigma^{(0)}[e^+e^- \to \mu^+\mu^-]} \equiv R(s)$$

- *New input on* $R = (e^+e^- \to q\bar{q})/(e^+e^- \to \mu^+\mu^-)$ *from BES (2 to 5 GeV, 2002), Crystal Ball (5 to 7.4 GeV, 1990)*
- *Incorporating new calculation (REPI) of vacuum polarization into KORALB & KK2F makes the cross-sections agree...*



J. Z. Bai *et al.* (BES Collaboration) Phys. Rev. Lett. **88**, 101802

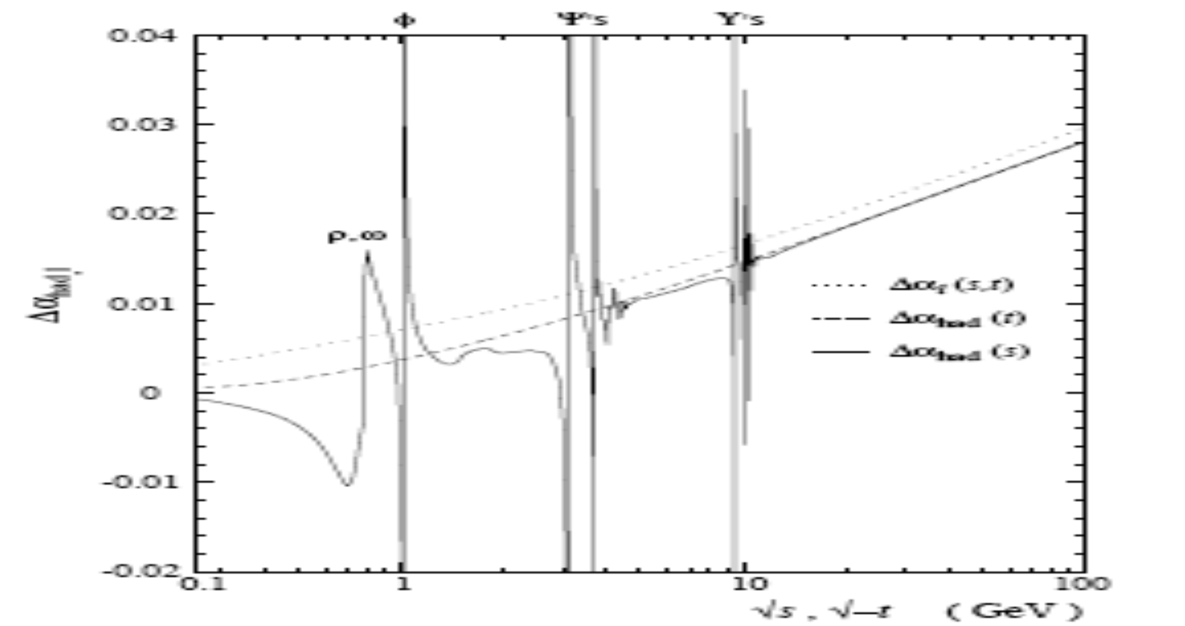
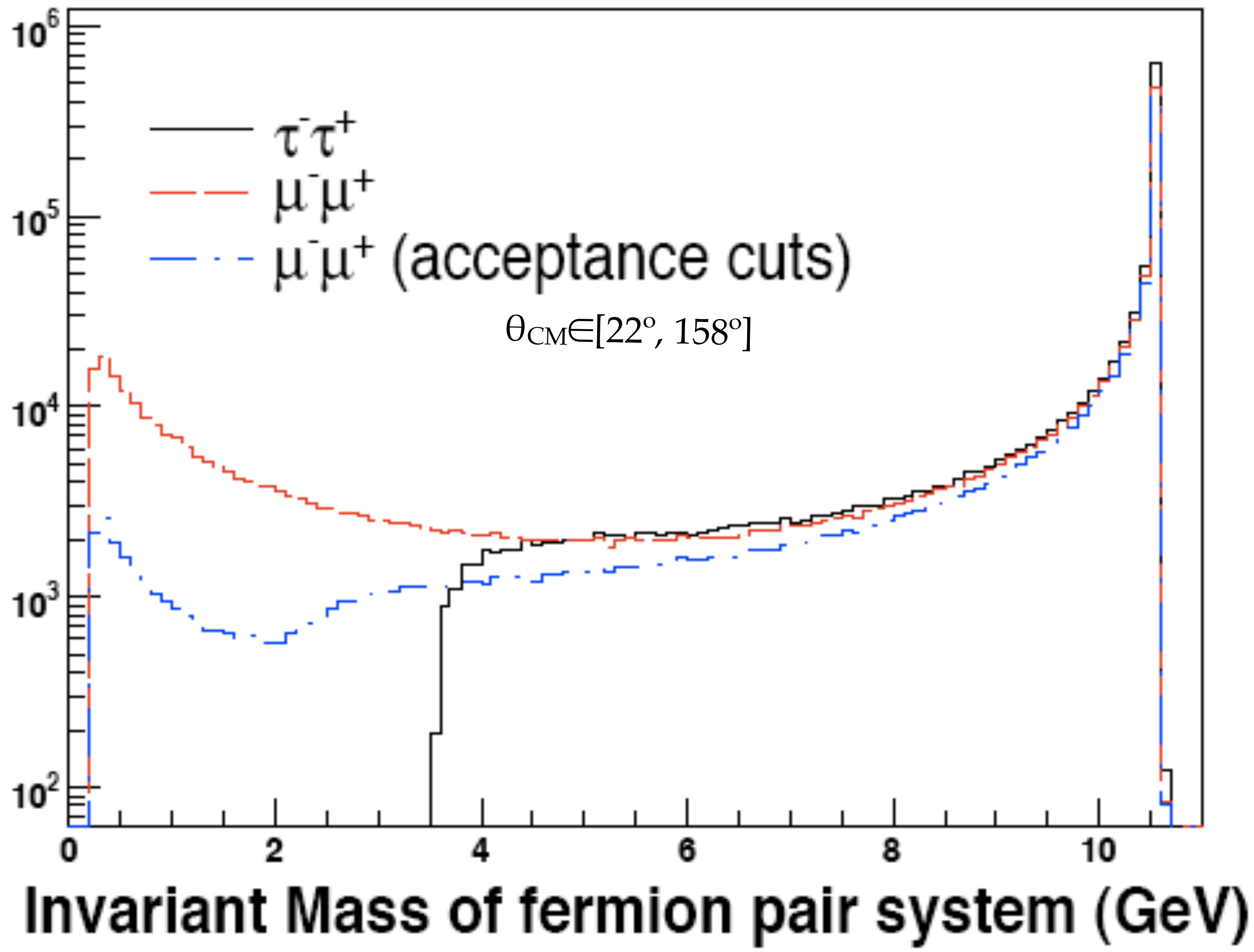


Fig. 1. $\Delta\alpha_l$ (dotted line) and $\Delta\alpha_{had}$ at several energies in the t (dashed line) and s channel (solid line).

[16] D. Karlen and H. Burkhardt, Eur. Phys. J. C **22**, 39 (2001) [arXiv:hep-ex/0105065].

Modeling spectrum in τ-pair and μ-pair production with radiation



With this new implementation of vacuum polarization in KKMC, and assuming a beam energy spread of the order of 5 MeV, the contribution to the uncertainty in cross-section is estimated to be:

$$\Delta(\sigma_{\tau\tau}) = 0.18\%$$
$$\Delta(\sigma_{\mu\mu}) = 0.22\%$$

Bremsstrahlung

hep-ph/0211132

Nucl.Phys.Proc.Suppl. 116 (2003) 73–77

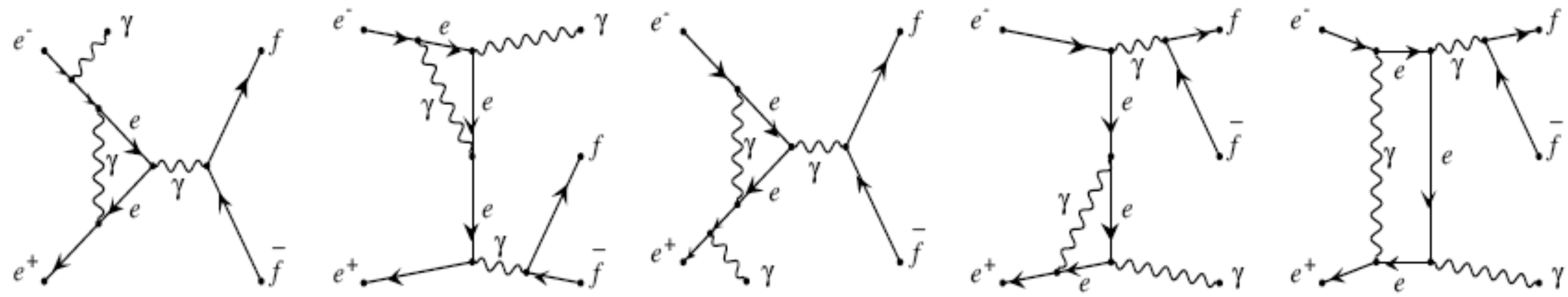


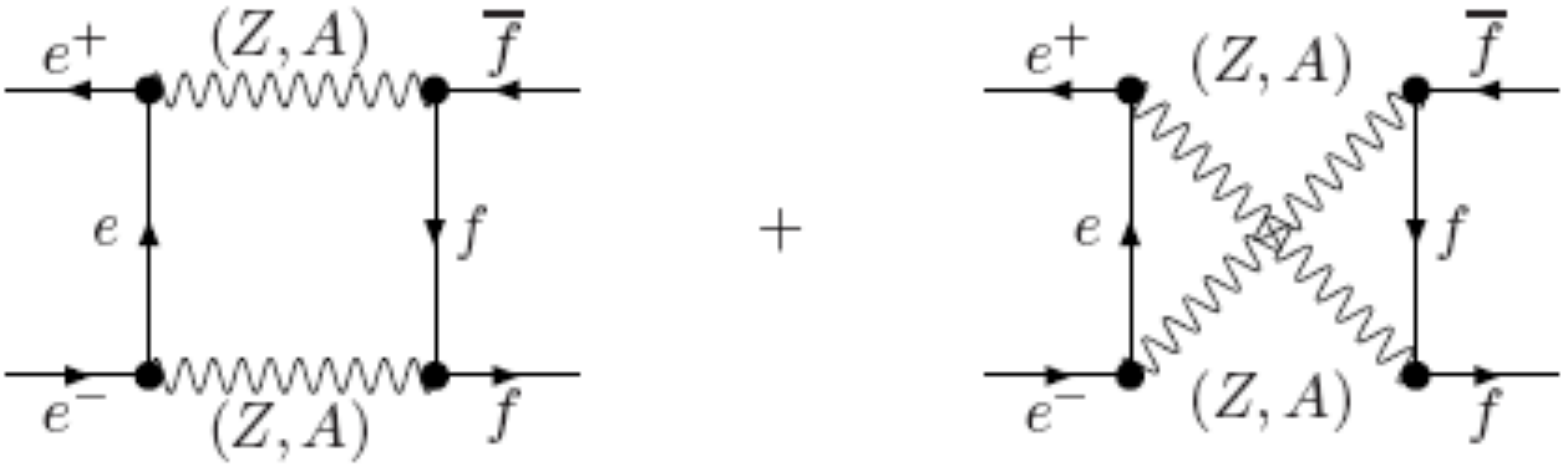
Figure 3. Representative graphs for the $1\gamma_{real} + 1\gamma_{virtual}$ correction in 2f processes.

Precision calculation for e+ e--> 2f: the KK MC project

- *Baseline: Born-level agreement between KORALB & KK2F*
- *First order correction from initial state:* $(1-\sigma^{\mathrm{KORALB}}_{\mathrm{NO\ VP}}/\sigma^{\mathrm{KORALB}}_{\mathrm{BORN}})$ *~ 11%*
- *Second order* $\sim 0.11^2/2 = 0.0061 \Rightarrow$ *Validate* $\sigma^{\mathrm{KK}}_{\mathrm{NO\ VP}}/\sigma^{\mathrm{KORALB}}_{\mathrm{NO\ VP}}$ *~ 1%*
- *Last fully controlled term in KK2F:* $\alpha^2 \log(s/m_e^2) = 0.0011$
- *Also contribution from final state bremsstrahlung:* $\frac{\alpha}{\pi}\frac{4m_\tau^2}{s} = 0.03\%$
- *Vary XK0 (minimum photon energy) ⇒ Δ(σ) < 0.1%*
- *Verify factorization:* $\sigma^{\mathrm{KK}} = \sigma^{\mathrm{KK}}_{\mathrm{NO\ VP}} \times (\sigma^{\mathrm{KK}}_{\mathrm{NO\ BREM}}/\sigma^{\mathrm{KK}}_{\mathrm{BORN}})$
- *Several cross-checks verify precision at < 0.2% level*

Interference

- *Z*/γ interference has negligible impact on σ @ 10.58 GeV*
- *QED interference between ISR-FSR (box diagrams): for both tau and mu-pairs* $\sigma^{\mathrm{KK}}/\sigma^{\mathrm{KK}}_{\mathrm{NO\ INT}} = 1.0004$



Vertex Corrections

Reports of the Working Groups on Precision Calculations for LEP2 Physics

By Two Fermion Working Group

hep-ph/0007180

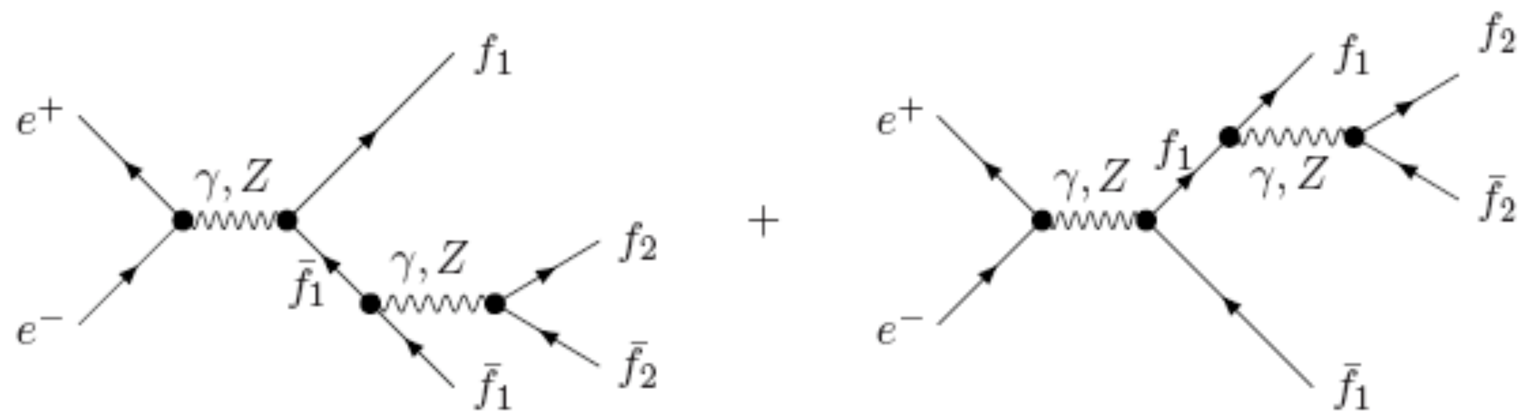


Fig. 4: Second eight diagrams belonging to the NC24 process.

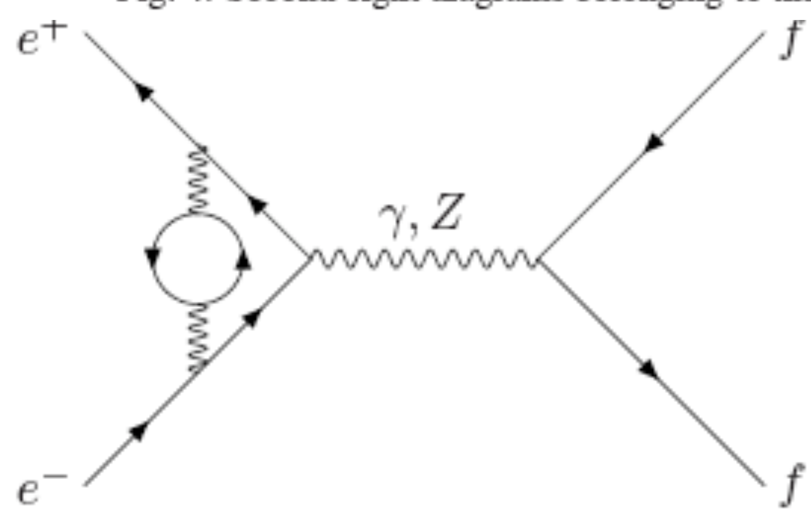


Fig. 6: A typical example of virtual pair correction.

- *These diagrams are not turned on in KK2F by default*
- *Virtual pair production & vertex corrections cancel each other*
- *Assign half the size of vertex corrections as error ~ 0.15%*

Vector Resonances

Intermediate vector resonances, eg. J/Ψ, $\Upsilon(3S)$, ...

Vector Resonance	Γ_{total} (MeV)	BF($\mu^+\mu^-$) (%)	Contribution to $\sigma_{cuts}(\mu^+\mu^-)$ (%)	BF($\tau^+\tau^-$) (%)	Contribution to $\sigma(\tau^+\tau^-)$ (%)
$\Upsilon(4S)(10580)$	20.5	0.0016	0.001	0.0016	0.001
$\Upsilon(3S)(10355)$	0.020	2.18	0.018	2.18	0.016
$\Upsilon(2S)(10023)$	0.032	1.93	0.010	1.7	0.008
$\Upsilon(1S)(9460)$	0.054	2.48	0.015	2.67	0.015
$\Psi(2S)(3686)$	0.337	0.73	0.014	0.28	0.004
$J/\Psi(1S)(3097)$	0.093	5.93	0.040	0.00	0.000
Total			0.10		0.04

- *Estimated from* $\Gamma, \mathcal{B}(V \to \ell^+\ell^-), d\sigma(\ell^+\ell^-)/d\sqrt{s'}$
- *Other resonances in principle contribute but are negligible because of low branching fractions and/or cross-sections*
- $\Delta(\sigma_{\tau\tau}) = 0.04\%$
- $\Delta(\sigma_{\mu\mu}) = 0.12\%, 0.10\%(\sqrt{s'/s} > 0.1), 0.04\%(\sqrt{s'/s} > 0.4)$

τ-pair and μ-pair cross-section at 10.58 GeV

	$\sigma(\tau\tau)$	$\sigma(\mu\mu)$	$\sigma_{cuts}(\mu\mu)$	$\sigma(\tau\tau)/\sigma(\mu\mu)$
Vacuum Polarization	0.18%	0.22%	0.22%	0.05%
Bremsstrahlung	0.2%	0.2%	0.2%	0.2%
Interference	0.04%	0.04%	0.04%	0.04%
Vertex Corrections	0.15%	0.15%	0.15%	-
Vector Resonances	0.04%	0.12%	0.1%	-
Total	0.31%	0.36%	0.35%	0.21%

- $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = (0.919 \pm 0.003)\,\mathrm{nb}$
- $\sigma(e^+e^- \rightarrow \mu^+\mu^-) = (1.147 \pm 0.004)\,\mathrm{nb}$
- $\sigma_{cuts}(e^+e^- \rightarrow \mu^+\mu^-) = (0.835 \pm 0.003)\,\mathrm{nb}$
- $\sigma(\tau^+\tau^-)/\sigma_{cuts}(\mu^+\mu^-) = 1.100 \pm 0.002$

SwB, B. Pietrzyk, J.Roney, Z.Was Phys.Rev.D 77 (2008) 054012

Overview of this talk

- **Standard Model Monte Carlo for tau leptons**
  - **General formalism of KK2F, TAUOLA, PHOTOS**
  - **Tauola-BBB [BaBar, Belle & Belle II] update [2016/2017]**
  - **Adaptation of HFLAV/PDG fits in Belle II version [2020/2021]**
  - **Alternate parametrization of hadronic currents**
  - **Pre-sampler optimization**
- **Search for new physics with tau leptons**
  - **Search for dark sector particles**
    - $e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to e^+e^-/\mu^+\mu^-$
  - **Search for lepton flavor violation, lepton number violation, baryon number violation**
  - **Search for electric and magnetic dipole moments [A. Korchin's talk]**

Spin correlations in τ-lepton pair production due to anomalous magnetic and electric dipole moments

Sw. Banerjee[a], A.Yu. Korchin[b,c,d] and Z. Was[d]

2209.06047 [hep-ph]
Phys.Rev.D 106 (2022) 11, 113010

Electron-positron, parton-parton and photon-photon production of τ-lepton pairs: anomalous magnetic and electric dipole moments spin effects

Sw. Banerjee[a], A.Yu. Korchin[b,c,d], E. Richter-Was[e] and Z. Was[d]

2307.03526 [hep-ph]
Accepted by PRD [Dec23]

General formalism of τ production and decays

Matrix element squared of τ^- decays can be written as $|\mathcal{M}|^2 = G + s^\mu \omega_\mu$,
where G is the spin-averaged part of the total width,
s^μ is polarization vector of τ-lepton
and ω_μ is the polarimeter vector.

Matrix element squared of $e^-e^+ \rightarrow \tau^-\tau^+$ decays takes the form:

$$|\mathcal{M}|^2 = |\mathcal{M}|^2_{\text{spin-av}} + \omega_\mu C^{\mu\nu} \overline{\omega}_\nu$$

where $|\mathcal{M}|^2_{\text{spin-av}}$ is the spin-averaged part
and $C^{\mu\nu}$ is the spin-correlation matrix.

The event generator KKMC calculates the $|\mathcal{M}|^2_{\text{spin-av}}$ and $C^{\mu\nu}$,
whereas ω_μ is done by **TAUOLA**.

Radiation from tau production modeled in $e^-e^+ \rightarrow \tau^-\tau^+(n\,\gamma)$ KKMC,

while radiation in decays of tau leptons are modeled by PHOTOS.

Main references:

- KK2F [S.Jadach, B.F.L.Ward, Z.Was, Comput.Phys.Commun. 130 (2000) 260]
- TAUOLA [S.Jadach, Z.Was, R.Decker, J.H.Kuhn, Comput.Phys.Commun. 76 (1993) 361]
- PHOTOS [E.Barberio, Z.Was, Comput.Phys.Commun. 79 (1994) 291]

Tauola BBB version [BaBar, Belle & Belle II]

IFJ-PAN-IV-2016-24

TAUOLA of τ lepton decays–framework for hadronic currents, matrix elements and anomalous decays.

M. Chrzaszcz[a,b], T. Przedziński[c], Z. Was[b] and J. Zaremba[b].

[a] *Physik-Institute, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*

[b] *Institute of Nuclear Physics Polish Academy of Sciences , PL-31342 Krakow, Poland*

[c] *Institute of Physics, Jagellonian University, Lojasiewicza 11, PL-30-348 Krakow, Poland*

ABSTRACT

We present an update of the Monte Carlo event generator TAUOLA for τ lepton decays, with substantially increased list of decay channels and new initialization options. The core of the program remains written in FORTRAN but necessary arrangements have been made to allow handling of the user-provided hadronic currents and matrix elements at the execution time. Such solution may simplify preparation of new hadronic currents and may be useful for fitting to the experimental data as well.
We have implemented as default for TAUOLA a set of hadronic currents, which is compatible with the default initialization used by BaBar collaboration. Options for currents available in previous releases are still stored in the code, sometimes left defunct or activated by internal flags only. The new version of the program, includes also implementation of Lepton Flavour Violating τ decays.
Finally, we present, as an example, a set of C++ methods for handling user-provided currents, matrix elements or complete new decay channels initialization which can be performed at the program execution time.

IFJ-PAN-IV-2016-24
Updated version as of May 2017

HFLAV/PDG fits to all measured tau branching fractions

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-tau-branching-fractions.pdf

decay mode	fit result (%)	coefficient
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.3937 ± 0.0384	1.0000
$e^-\bar{\nu}_e\nu_\tau$	17.8175 ± 0.0399	1.0000
$\pi^-\nu_\tau$	10.8164 ± 0.0512	1.0000
$K^-\nu_\tau$	0.6964 ± 0.0096	1.0000
$\pi^-\pi^0\nu_\tau$	25.4941 ± 0.0893	1.0000
$K^-\pi^0\nu_\tau$	0.4328 ± 0.0148	1.0000
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.2595 ± 0.0964	1.0021
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.0647 ± 0.0218	1.0000
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.0429 ± 0.0707	1.0000
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.0478 ± 0.0212	1.0000
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.1118 ± 0.0391	1.0000
$\pi^-\bar{K}^0\nu_\tau$	0.8384 ± 0.0138	1.0000

- TauolaBelle2 has 92 channels initialized to PDG 2020 branching fractions which add up to unity as generic τ -pair cocktail

- BELLE2-NOTE-PH-2020-055_v2

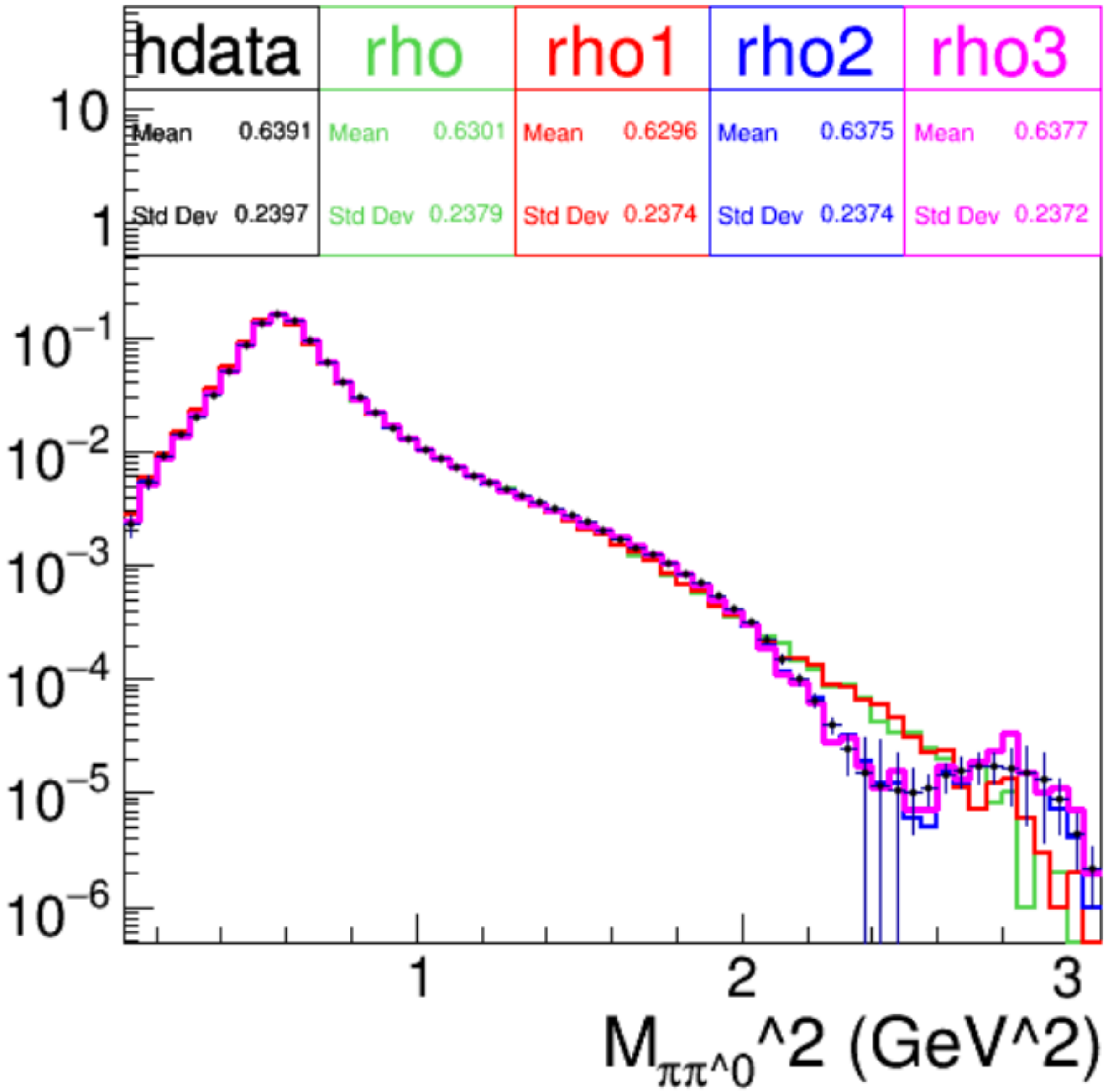
decay mode	fit result (%)	coefficient
$K^-K^0\nu_\tau$	0.1486 ± 0.0034	1.0000
$\pi^-\bar{K}^0\pi^0\nu_\tau$	0.3817 ± 0.0129	1.0000
$K^-\pi^0K^0\nu_\tau$	0.1500 ± 0.0070	1.0000
$\pi^-\bar{K}^02\pi^0\nu_\tau$ (ex. K^0)	0.0263 ± 0.0226	1.0000
$\pi^-K^0_SK^0_S\nu_\tau$	0.0235 ± 0.0006	2.0000
$\pi^-K^0_SK^0_L\nu_\tau$	0.1081 ± 0.0241	1.0000
$\pi^-\pi^0K^0_SK^0_S\nu_\tau$	0.0018 ± 0.0002	2.0000
$\pi^-\pi^0K^0_SK^0_L\nu_\tau$	0.0325 ± 0.0119	1.0000
$\bar{K}^0h^-h^-h^+\nu_\tau$	0.0247 ± 0.0199	1.0000
$\pi^-\pi^-\pi^+\nu_\tau$ (ex. K^0, ω)	8.9868 ± 0.0513	1.0021
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0, ω)	2.7404 ± 0.0710	1.0000
$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0, ω, η)	0.0981 ± 0.0356	1.0000
$\pi^-K^-K^+\nu_\tau$	0.1435 ± 0.0027	1.0000
$\pi^-K^-K^+\pi^0\nu_\tau$	0.0061 ± 0.0018	1.0000
$\pi^-\pi^0\eta\nu_\tau$	0.1389 ± 0.0072	1.0000
$K^-\eta\nu_\tau$	0.0155 ± 0.0008	1.0000
$K^-\pi^0\eta\nu_\tau$	0.0048 ± 0.0012	1.0000
$\pi^-\bar{K}^0\eta\nu_\tau$	0.0094 ± 0.0015	1.0000
$\pi^-\pi^+\pi^-\eta\nu_\tau$ (ex. K^0)	0.0220 ± 0.0013	1.0000
$K^-\omega\nu_\tau$	0.0410 ± 0.0092	1.0000
$h^-\pi^0\omega\nu_\tau$	0.4085 ± 0.0419	1.0000
$K^-\phi\nu_\tau$	0.0044 ± 0.0016	0.8320
$\pi^-\omega\nu_\tau$	1.9494 ± 0.0645	1.0000
$K^-\pi^-\pi^+\nu_\tau$ (ex. K^0, ω)	0.2927 ± 0.0068	1.0000
$K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0, ω, η)	0.0394 ± 0.0142	1.0000
$\pi^-2\pi^0\omega\nu_\tau$ (ex. K^0)	0.0072 ± 0.0016	1.0000
$2\pi^-\pi^+3\pi^0\nu_\tau$ (ex. K^0, η, ω, f_1)	0.0014 ± 0.0027	1.0000
$3\pi^-2\pi^+\nu_\tau$ (ex. K^0, ω, f_1)	0.0775 ± 0.0030	1.0000
$K^-2\pi^-2\pi^+\nu_\tau$ (ex. K^0)	0.0001 ± 0.0001	1.0000
$2\pi^-\pi^+\omega\nu_\tau$ (ex. K^0)	0.0084 ± 0.0006	1.0000
$3\pi^-2\pi^+\pi^0\nu_\tau$ (ex. K^0, η, ω, f_1)	0.0038 ± 0.0009	1.0000
$K^-2\pi^-2\pi^+\pi^0\nu_\tau$ (ex. K^0)	0.0001 ± 0.0001	1.0000
$\pi^-f_1\nu_\tau$ ($f_1 \to 2\pi^-2\pi^+$)	0.0052 ± 0.0004	1.0000
$\pi^-2\pi^0\eta\nu_\tau$	0.0195 ± 0.0038	1.0000

Alternate parameterization for hadronic currents

- TauolaBelle2 version allows several new parameterizations of hadronic currents:
  - Currents for $\tau^- \to \pi^-\pi^0\nu$ decays controlled by FF2PIRHO flag
  - Currents for $\tau^- \to \pi^-2\pi^0\nu$ and $2\pi^-\pi^+\nu$ decays controlled by IRCHL3PI flag
  - Currents for $\tau^- \to \pi^-\pi^+K^-\nu$ and $\pi^-\pi^0K^0\nu$ decays controlled by IFKPIPI flag
  - Currents for $\tau^- \to \pi^-3\pi^0\nu$ and $2\pi^-\pi^+\pi^0\nu$ decays controlled by IFCURR4PI flag
  - New parameterization of $\tau^- \to \pi^-4\pi^0\nu$ and $2\pi^-\pi^+2\pi^0\nu$ decays added

- With appropriate choice of flags [FF2PIRHO, IRCHL3PI, IFKPIPI, IFCURR4PI] old behavior can be recovered, or new ones turned on.
  - Older version is still maintained for backward compatibility in new updates

2-pion decays



Visible mass squared in $\tau^- \to \pi^-\pi^0\nu_\tau$ decays:

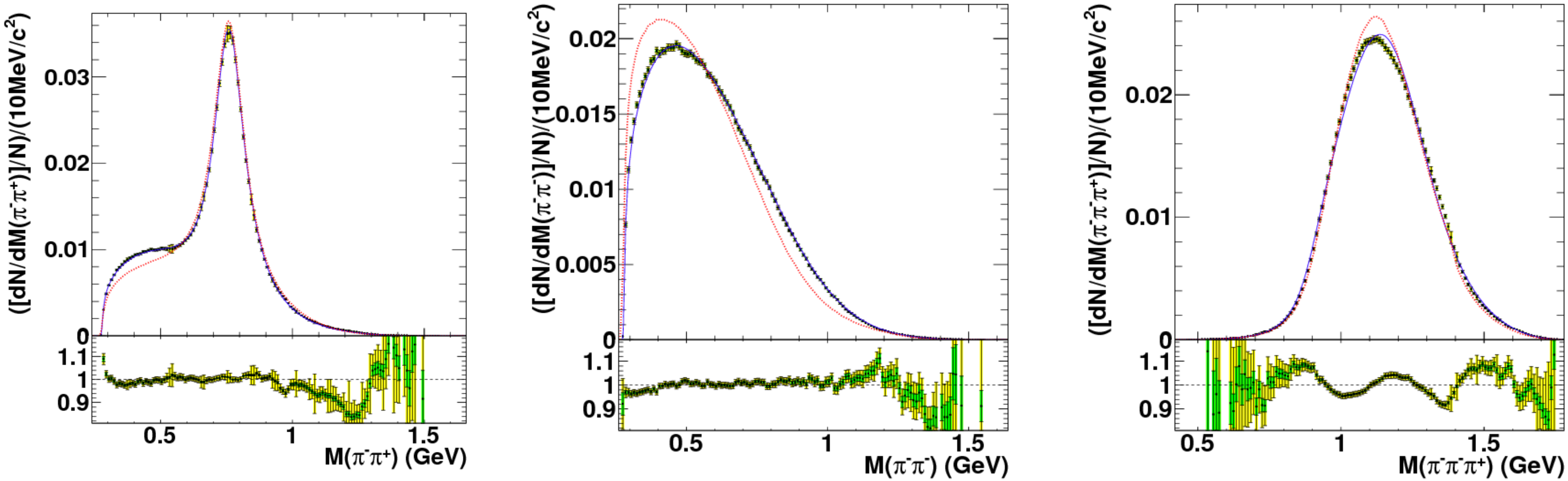
hdata is obtained from the distribution published by Belle: M. Fujikawa et al., "High-Statistics Study of the tau- → pi- pi0 nu(tau) Decay", Phys. Rev. D 78 (2008) 072006, arXiv:0805.3773 [hep-ex].

rho is generated with **TauolaBelle**

rho1, **rho2**, and **rho3** correspond to different parametrizations available on **TauolaBelle2 with FF2PIRHO = 1, 2, 3**

Default is FF2PIRHO = 2 in TauolaBelle2

3-pion decays



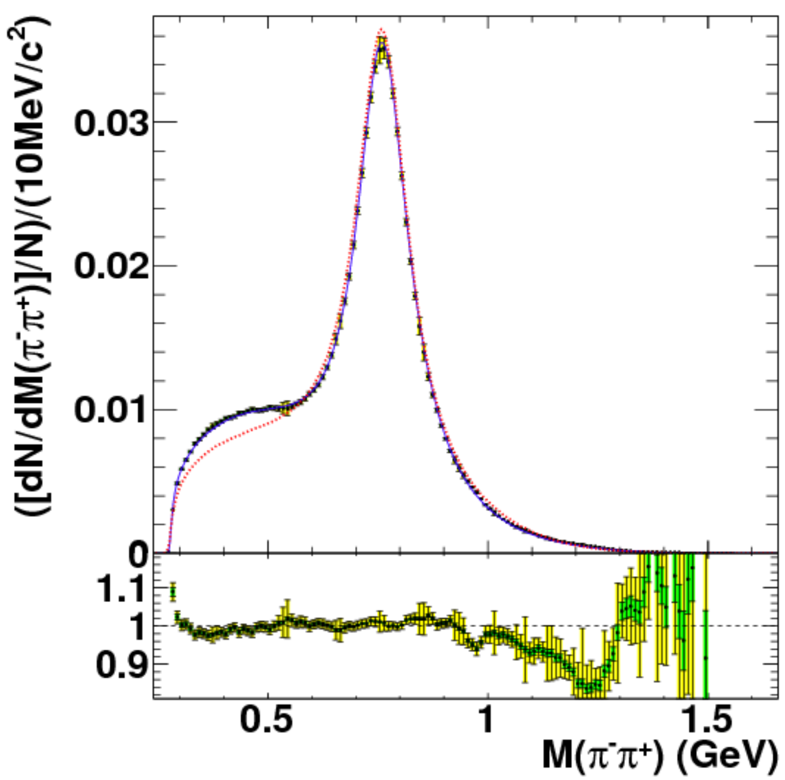
Resonance chiral Lagrangian currents and experimental data for $\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau$

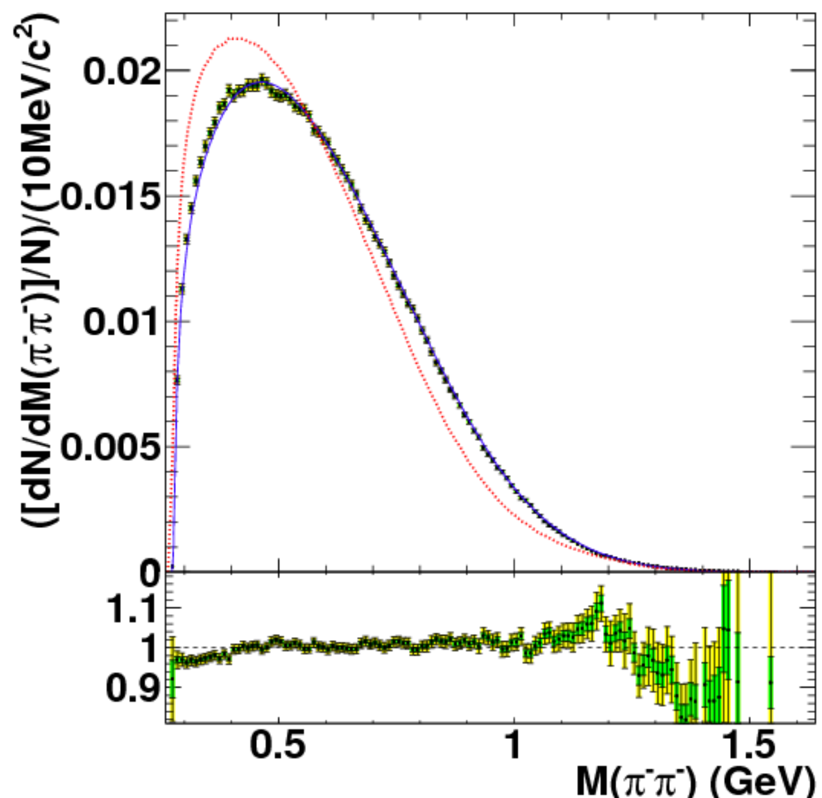
I.M. Nugent (RWTH Aachen U.), T. Przedzinski (Jagiellonian U.), P. Roig (UNAM, Mexico), O. Shekhovtsova (Kharkov, KIPT & Cracow, INP), Z. Was (Cracow, INP & CERN)

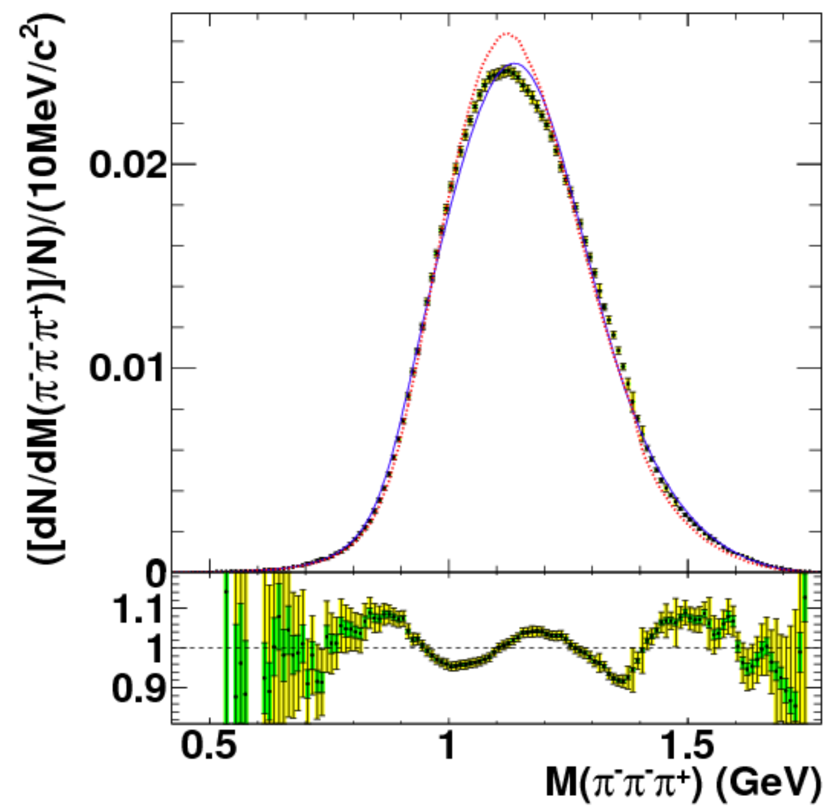
Oct 3, 2013 - 14 pages

Phys.Rev. D88 (2013) 093012
(2013-11-26)
DOI: 10.1103/PhysRevD.88.093012
IFJPAN-2013-5, UAB-FT-731
e-Print: arXiv:1310.1053 [hep-ph] | PDF

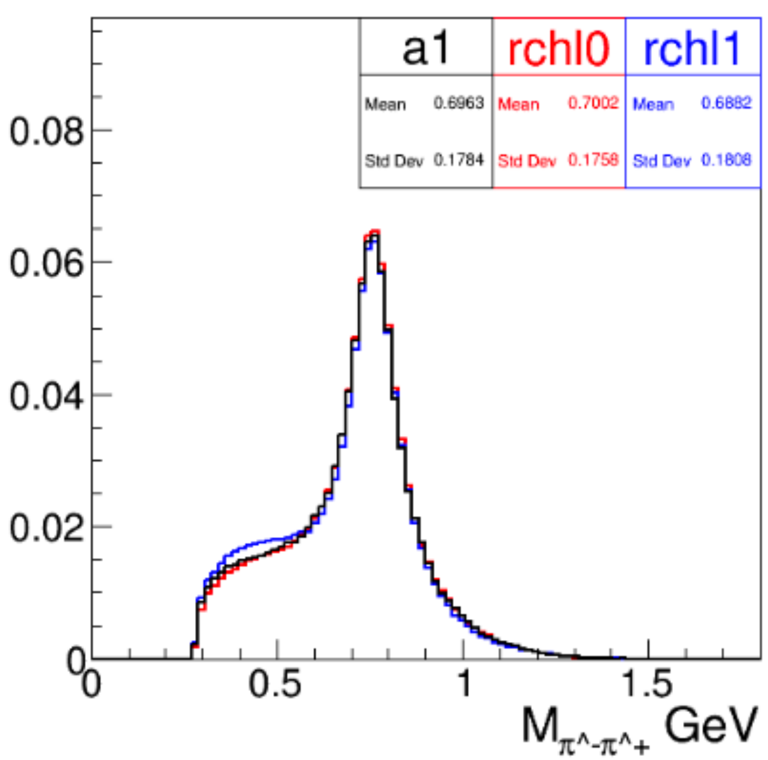
3-pion decays

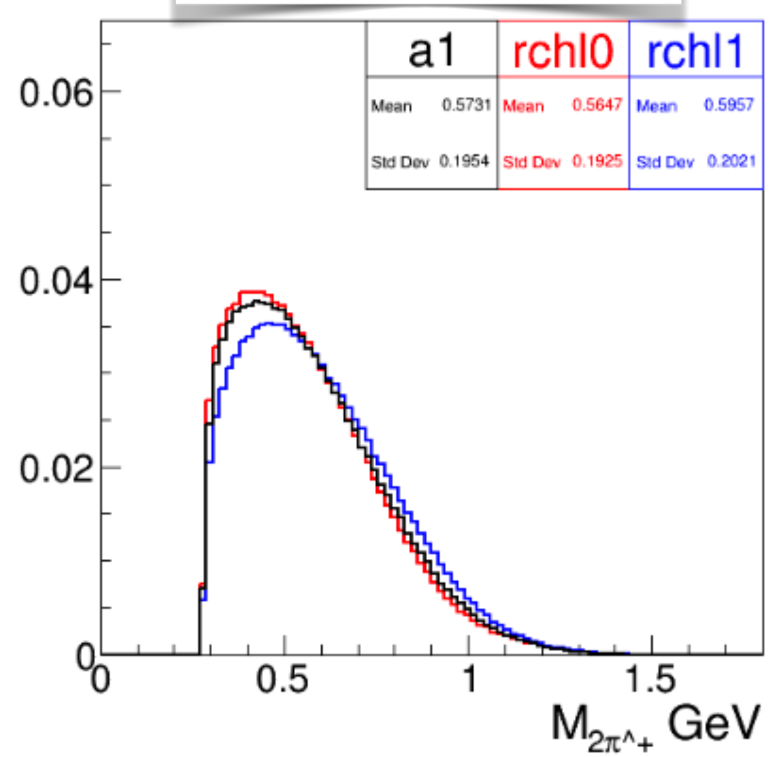


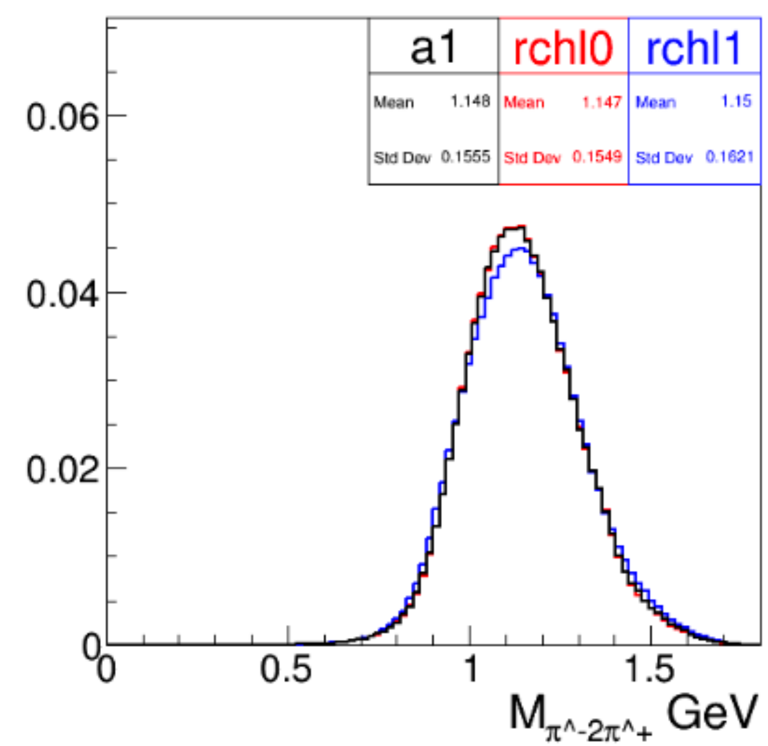




$\tau^+ \to \pi^- \pi^+ \pi^+ \bar{\nu}_\tau$







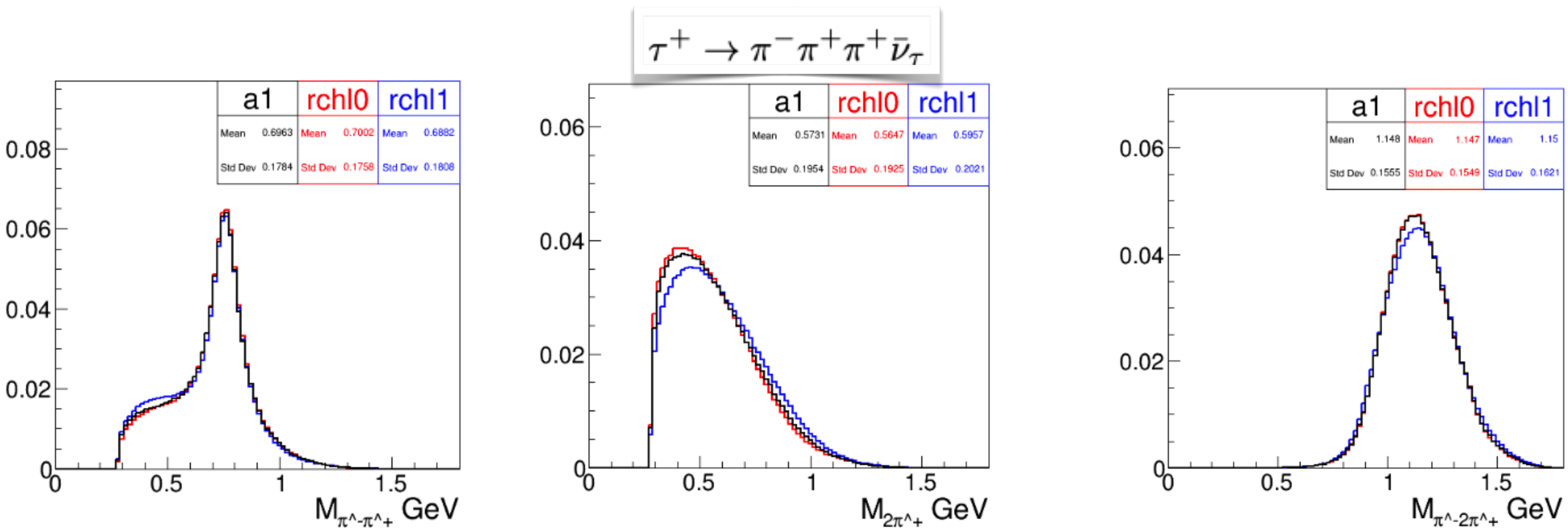
3-pion decays

a1 is generated with **TauolaBelle**

rchl0 and rchl1 correspond to different parametrizations available on **TauolaBelle2 with IRCHL3PI = 0, 1.**

Default is IRCHL3PI = 1 in TauolaBelle2.

Plan to validate with BELLE II data to check if IRCHL3PI=1 is better match or not.



3-pion decays

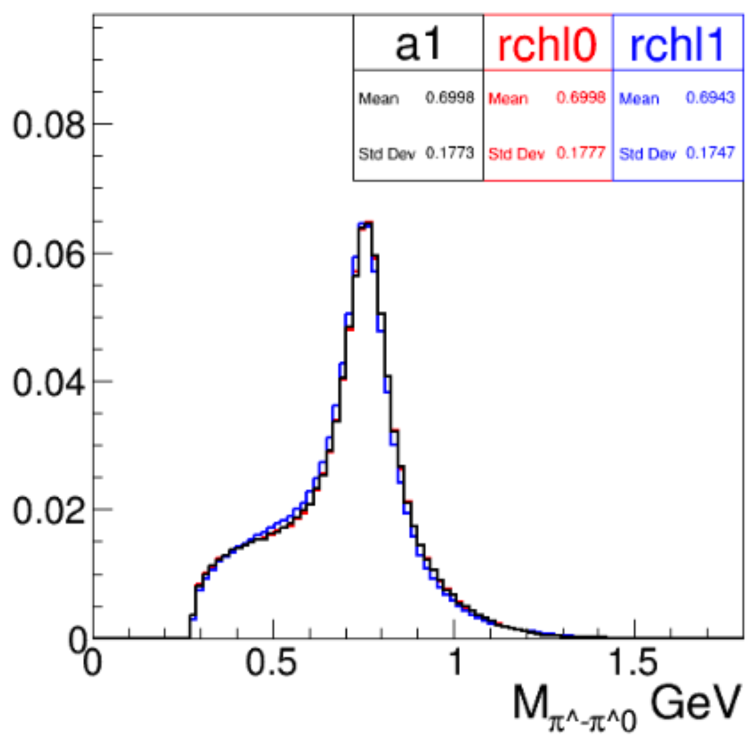
a1 is generated with **TauolaBelle**

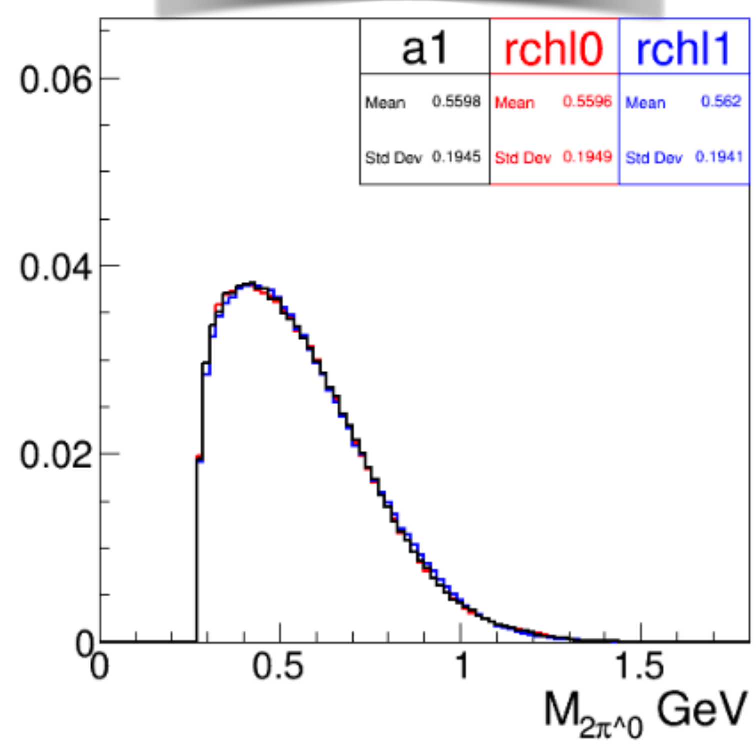
rchl0 and rchl1 correspond to different parametrizations available on **TauolaBelle2 with IRCHL3PI = 0, 1.**

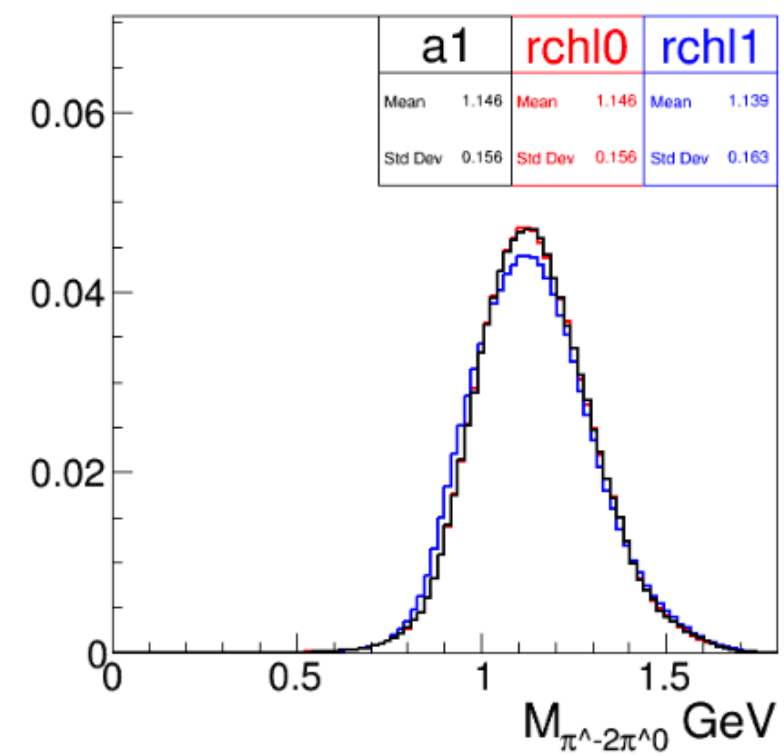
Default is IRCHL3PI = 1 in TauolaBelle2.

Plan to validate with BELLE II data to check if IRCHL3PI=1 is better match or not.

$$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$$







$\tau^- \to (K\pi\pi)^-\nu$

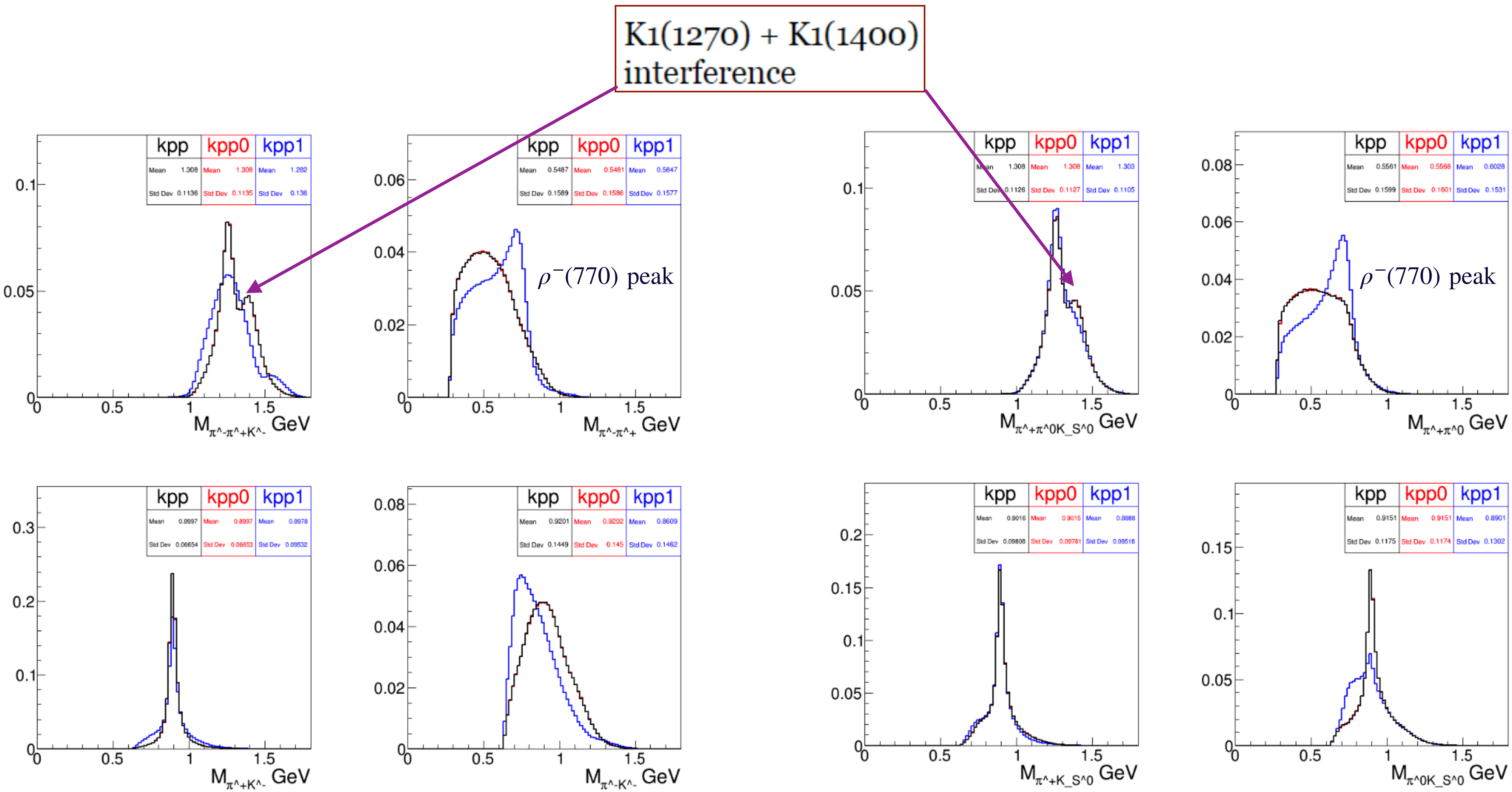


FIG. 96. Invariant mass distributions in $\tau^- \to \pi^-\pi^+K^-\nu_\tau$ decays.

FIG. 97. Invariant mass distributions in $\tau^+ \to \pi^+\pi^0K^0_S\bar{\nu}_\tau$ decays.

Currents for $\tau^- \to \pi^-\pi^+K^-\nu$ and $\pi^-\pi^0K^0\nu$ decays are tunable by IFKPIPI flag

4-pion decays

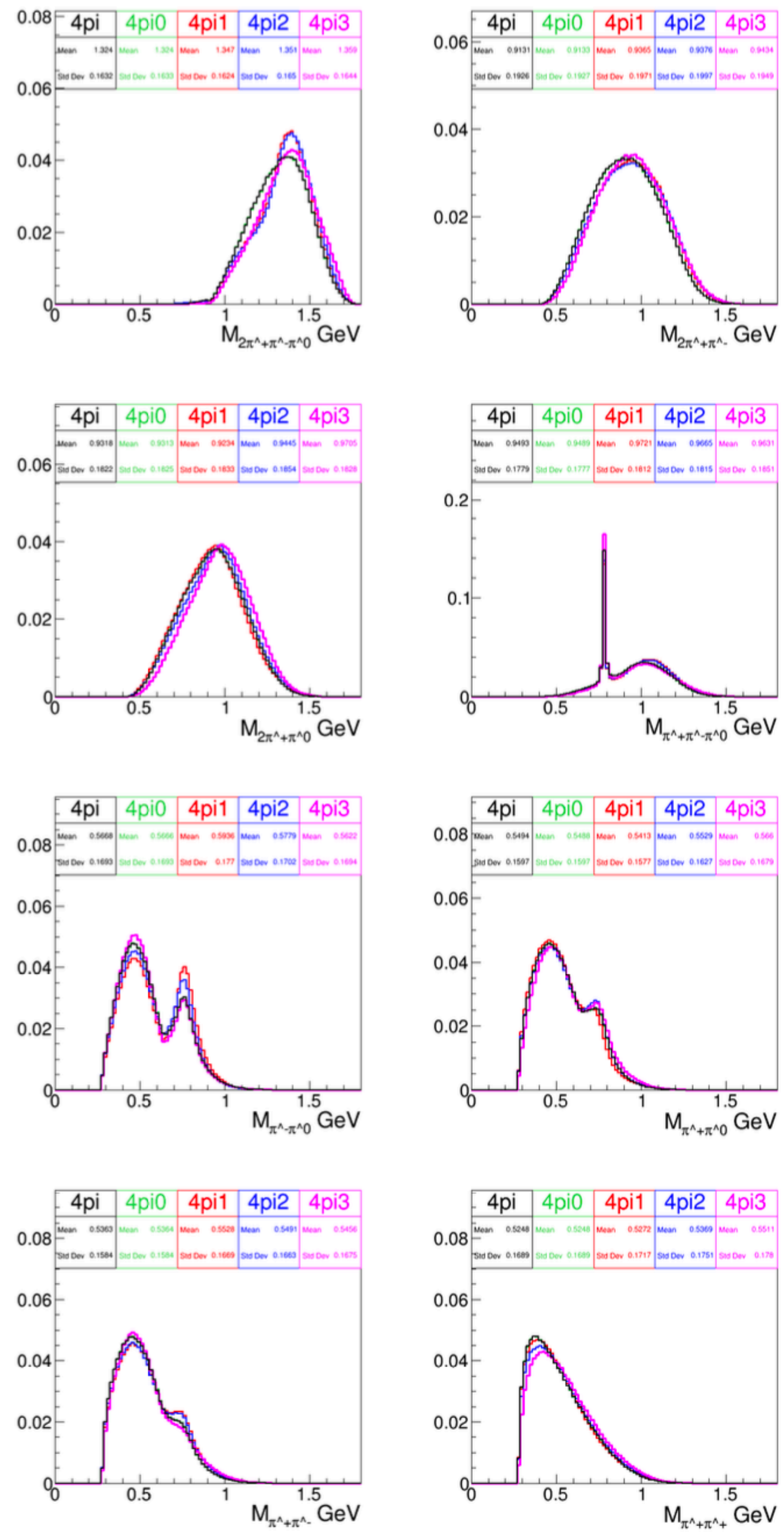


FIG. 98. Invariant mass distributions in $\tau^+ \to 2\pi^+\pi^-\pi^0\bar{\nu}_\tau$ decays.

$\tau^+ \to 2\pi^+\pi^-\pi^0\nu_\tau$ decays

Default value IFCURR4PI = 0 in TauolaBelle2 agrees with Novosibirsk parameterization previously implemented in TauolaBelle

4-pion decays

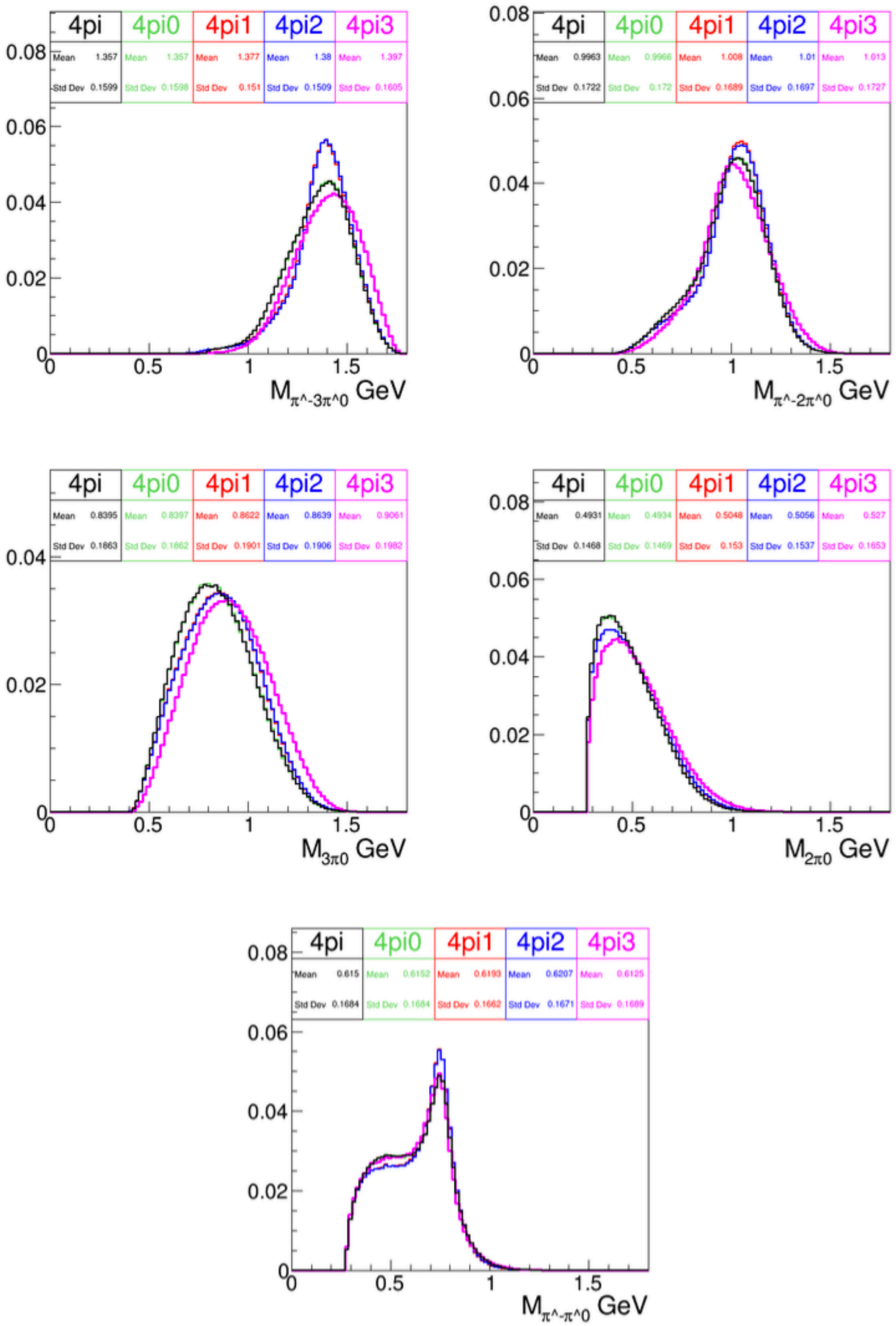


FIG. 99. Invariant mass distributions in $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ decays.

$\tau^- \to \pi^- 3\pi^0 \nu_\tau$ decays

Default value IFCURR4PI = 0 in TauolaBelle2 agrees with Novosibirsk parameterization previously implemented in TauolaBelle

5-pion decays

CERN-PH-TH/2006-025,
TTP06-01, IFJPAN-IV-2006-1

τ Decays to Five Mesons in TAUOLA

Johann H. Kühn
Institut für Theoretische Teilchenphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
and
Z. Wąs
PH-TH Dept. CERN, 1211 Geneva 23, Switzerland
and
Institute of Nuclear Physics, PAN, Kraków, ul. Radzikowskiego 152, Poland

ABSTRACT

The τ-decay library TAUOLA has gained popularity over the last decade. However, with the continuously increasing precision of the data, some of its functionality has become insufficient. One of the requirements is the implementation of decays into five mesons plus a neutrino with a realistic decay amplitude. This note describes a step into this direction. For the $2\pi^-\pi^+2\pi^0$ mode the three decay chains $\tau^- \to a_1^-\nu \to \rho^-(\to \pi^-\pi^0)\omega(\to \pi^-\pi^+\pi^0)\nu$, $\tau^- \to a_1^-\nu \to a_1^-(\to 2\pi^-\pi^+)f_0(\to 2\pi^0)\nu$, and $\tau^- \to a_1^-\nu \to a_1^-(\to \pi^-2\pi^0)f_0(\to \pi^+\pi-)\nu$ are introduced with simple assumptions about the couplings and propagators of the various resonances. Similar amplitudes (without the $\rho\omega$ contributions) are adopted for the $\pi^-4\pi^0$ and $3\pi^-2\pi^+$ modes.

The five-pion amplitude is thus based on a simple model, which, however, can be considered as a first realistic example. Phase-space generation includes the possibility of presampling the ω and a_1 resonances, in one channel only, however. This is probably sufficient for the time being, both for physics applications and for tests.

The technical test of the new part of the generator is performed by comparing Monte Carlo and analytical results. To this end a non-realistic, but easy to calculate, purely scalar amplitude for the decay into five massless pions was used.

CERN-PH-TH/2006-025,
TTP06-01, IFJPAN-IV-2006-1
February, 2006

The pictorial illustration of this decay amplitude is shown in Fig. 1a.

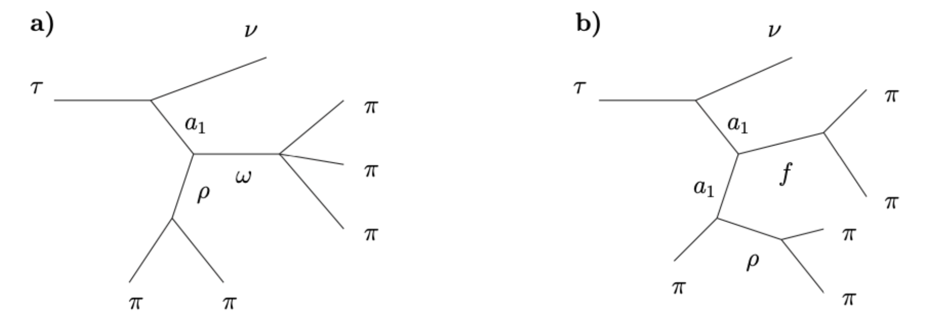
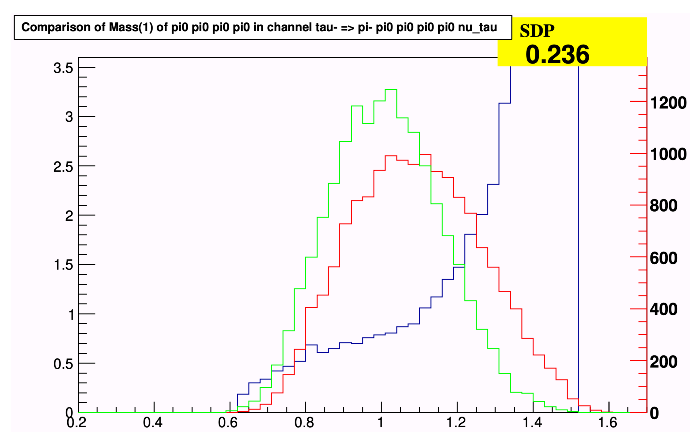
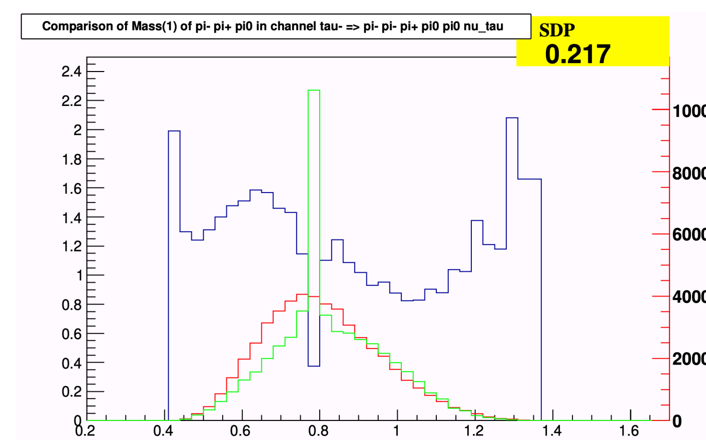


Figure 1: *Dominant decay amplitude for the decay of τ into five pions through an ω plus a ρ resonance (a) and through an f_0 plus $a_1(\to \rho\pi)$ (b).*

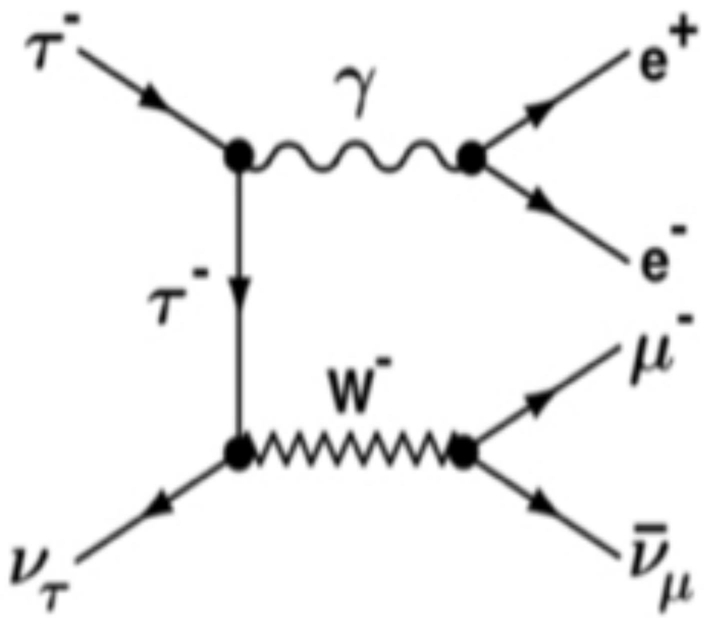
$\tau^- \to \pi^-4\pi^0\nu$ and $2\pi^-\pi^+2\pi^0\nu$ decays

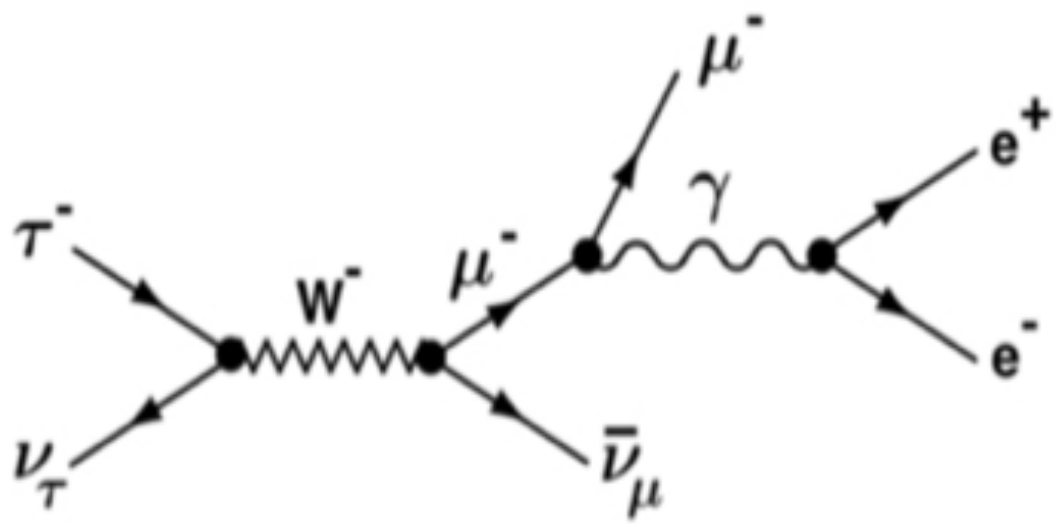




Green: TauolaBelle2
Red: TauolaBelle
Blue: Ratio

Tau decays into three charged leptons and two neutrinos





3 body decay

An integral of matrix element squared $|M|^2 \equiv |M(p_\tau, p_\nu, p_{\bar\nu}, p_\mu)|^2$ over 3-body phase space $dLips_3(p_\tau, p_\nu, p_{\bar\nu}, p_\mu)$ reads:

$$\int |M|^2 \, dLips_3(p_\tau, p_\nu, p_{\bar\nu}, p_\mu) = \int |M|^2 \frac{d^3 p_\nu}{(2\pi)^3 2p^0_\nu} \frac{d^3 p_{\bar\nu}}{(2\pi)^3 2p^0_{\bar\nu}} \frac{d^3 p_\mu}{(2\pi)^3 2p^0_\mu} (2\pi)^4 \delta^4(p_\tau - p_\nu - p_{\bar\nu} - p_\mu) =$$

$$= \frac{1}{2^{11}\pi^5} \int_{m^2_\mu}^{(m_\tau - m_\mu)^2} dM^2_{\bar\nu\mu} \int_{-1}^{1} dcos\theta_\nu \int_0^{2\pi} d\varphi_\nu \left(1 - \frac{M^2_{\bar\nu\mu}}{m^2_\tau}\right) \int_{-1}^{1} dcos\theta_{\bar\nu} \int_0^{2\pi} d\varphi_{\bar\nu} \left(1 - \frac{m^2_\mu}{M^2_{\bar\nu\mu}}\right) |M|^2, \quad (9)$$

5 body decay

We proceed with writing a cross section for the 5-body decay $\tau^- \to \bar\nu_\mu \mu^- e^- e^+ \nu_\tau$ assuming the matrix element $|M|^2 \equiv |M(p_\tau, p_{e-}, p_{e+}, p_\nu, p_{\bar\nu}, p_\mu)|^2$ can be factorized. We focus on soft pair emissions:

$$|M|^2 = |M(p_\tau, p_\nu, p_{\bar\nu}, p_\mu)|^2 \times |M_F(p_{e-}, p_{e+})|^2 . \quad (10)$$

Therefore:

$$\int |M|^2 \, dLips_5(p_\tau, p_{e-}, p_{e+}, p_\nu, p_{\bar\nu}, p_\mu) =$$

$$= \int |M_F|^2 \frac{d^3 p_{e-}}{(2\pi)^3 2p^0_{e-}} \frac{d^3 p_{e+}}{(2\pi)^3 2p^0_{e+}} \, d^4R \, \delta^4(R - p_\tau + p_{e-} + p_{e+}) \times$$

$$\times \int |M(p_\tau, p_\nu, p_{\bar\nu}, p_\mu)|^2 \frac{d^3 p_\nu}{(2\pi)^3 2p^0_\nu} \frac{d^3 p_{\bar\nu}}{(2\pi)^3 2p^0_{\bar\nu}} \frac{d^3 p_\mu}{(2\pi)^3 2p^0_\mu} (2\pi)^4 \delta^4(R - p_\nu - p_{\bar\nu} - p_\mu), \quad (11)$$

Pre-sampler optimizations

Comput.Phys.Commun. 283 (2023) 108592
e-Print: 1912.11376 [hep-ph]

IFJ-PAN-IV-2019-17
September 27, 2022

TAUOLA update for decay channels with e^+e^- pairs in the final state.

S. Antropov[a], Sw. Banerjee[b], Z. Was[a], J. Zaremba[a]

A.1 Phase space for decays into 6 particles

- flat $M^2_{12345} \to$ flat $M^2_{1234} \to$ flat $M^2_{234} \to$ flat M^2_{34},
- resonant $M^2_{12345} \to$ flat $M^2_{1234} \to$ flat $M^2_{234} \to$ flat M^2_{34},
- flat $M^2_{12345} \to$ flat $M^2_{1234} \to$ resonant $M^2_{234} \to$ flat M^2_{34},
- resonant $M^2_{12345} \to$ flat $M^2_{1234} \to$ resonant $M^2_{234} \to$ flat M^2_{34}.

The presampler parameters are:

- P_A - probability of resonant type phase space in M^2_{12345},
- P_B - probability of resonant type phase space in M^2_{234},
- MA - mass-like parameter for M^2_{12345},
- GA - width-like parameter for M^2_{12345},
- MB - mass-like parameter for M^2_{234},
- GB - width-like parameter for M^2_{234}.

A.2 Phase space for decays into 5 particles

- resonant $M^2_{1234} \to$ flat $M^2_{234} \to$ flat M^2_{34},
- resonant $M^2_{1234} \to$ flat $M^2_{234} \to$ resonant M^2_{34},
- resonant $M^2_{1234} \to$ resonant $M^2_{234} \to$ flat M^2_{34},
- resonant $M^2_{1234} \to$ resonant $M^2_{234} \to$ resonant M^2_{34},
- resonant $M^2_{1234} \to$ resonant $M^2_{134} \to$ flat M^2_{34},
- resonant $M^2_{1234} \to$ resonant $M^2_{134} \to$ resonant M^2_{34}.

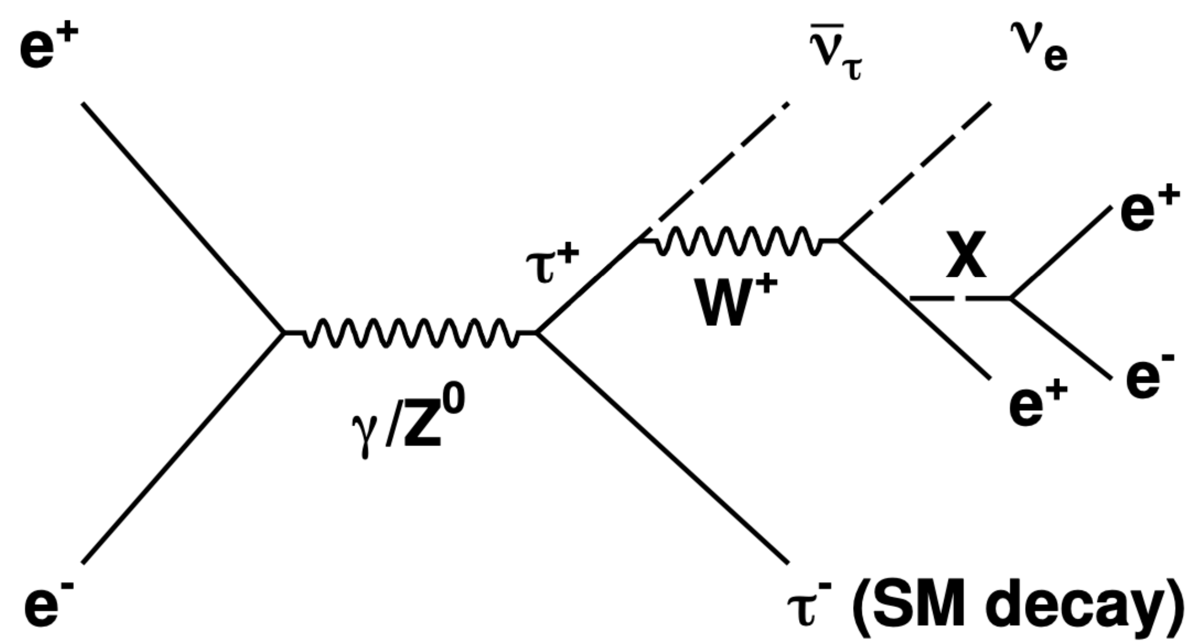
The presampler parameters available through user interface are:

- P_A - probability of resonant type phase space in M^2_{234} and M^2_{134},
- P_B - redundant parameter with same meaning and P_A,
- MR - mass-like parameter for M^2_{1234},
- GR - width-like parameter for M^2_{1234},
- MA - mass-like parameter for M^2_{234} and M^2_{134},
- GA - width-like parameter for M^2_{234} and M^2_{134},

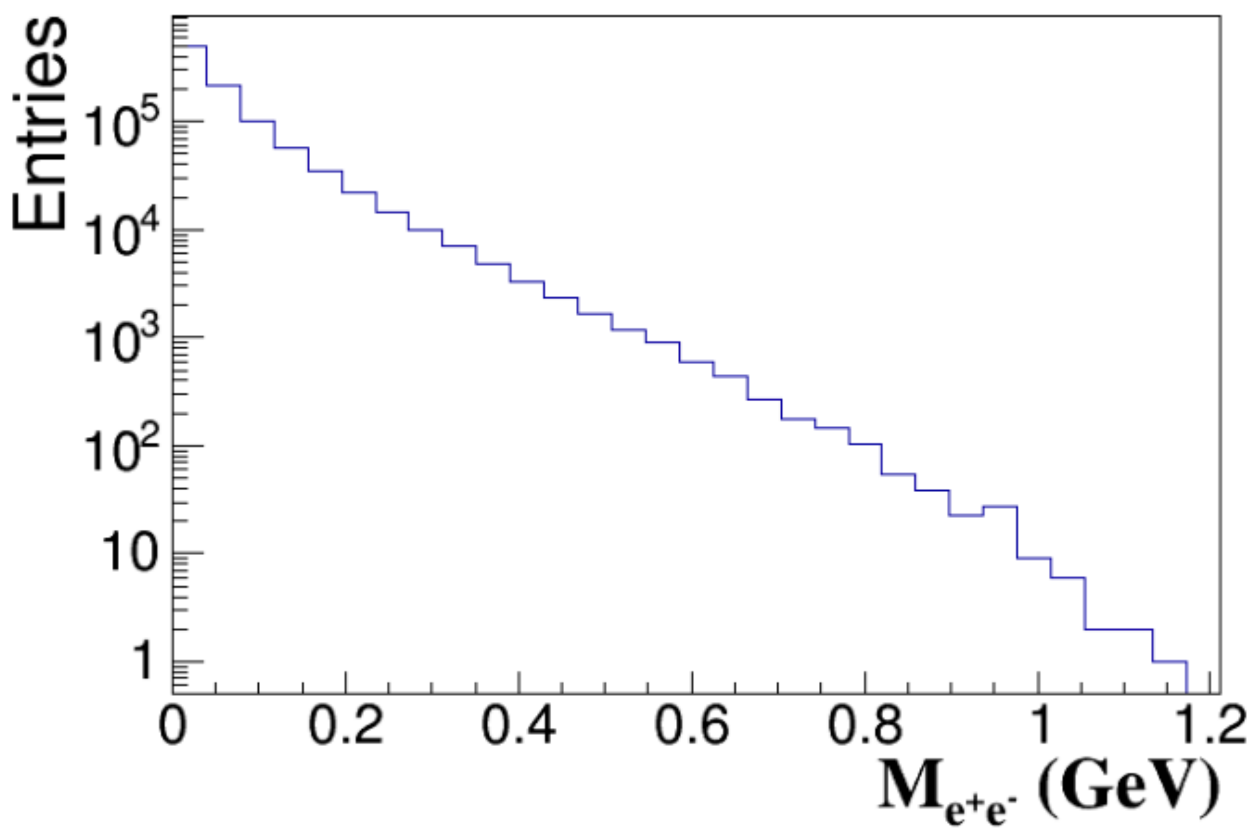
A.5 Phase space for decays into N and 2 particles

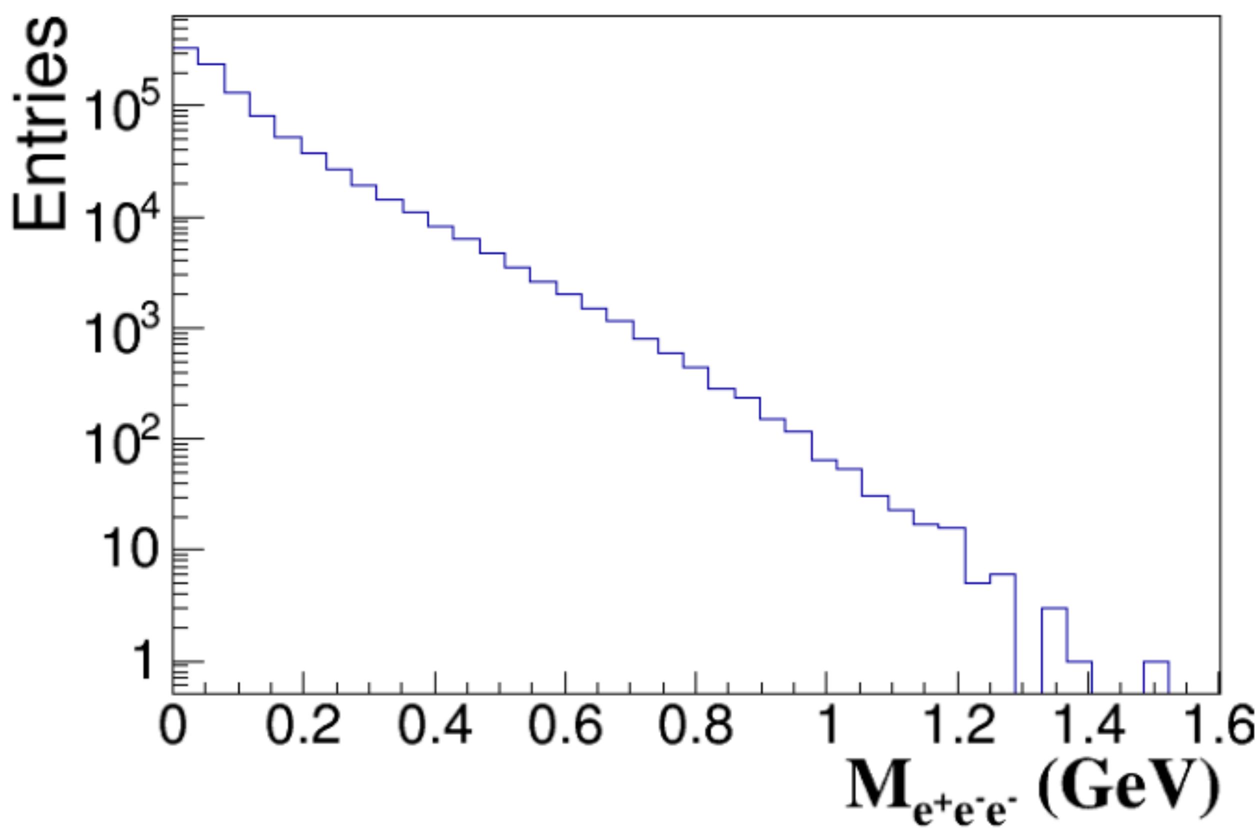
Presamplers for decays into 2 and N particles do not have any parameters. Decay into 2 particles does not need parameters for obvious reason. Presampler for N particles can be used for up to 9 particles in final state but always uses flat phase space for invariant mass squared of every system with descending number of particles e.g. for N=9: $M^2_{12345678}, M^2_{2345678}, \ldots, M^2_{678}, M^2_{78}$. Use of matrix element is restricted.

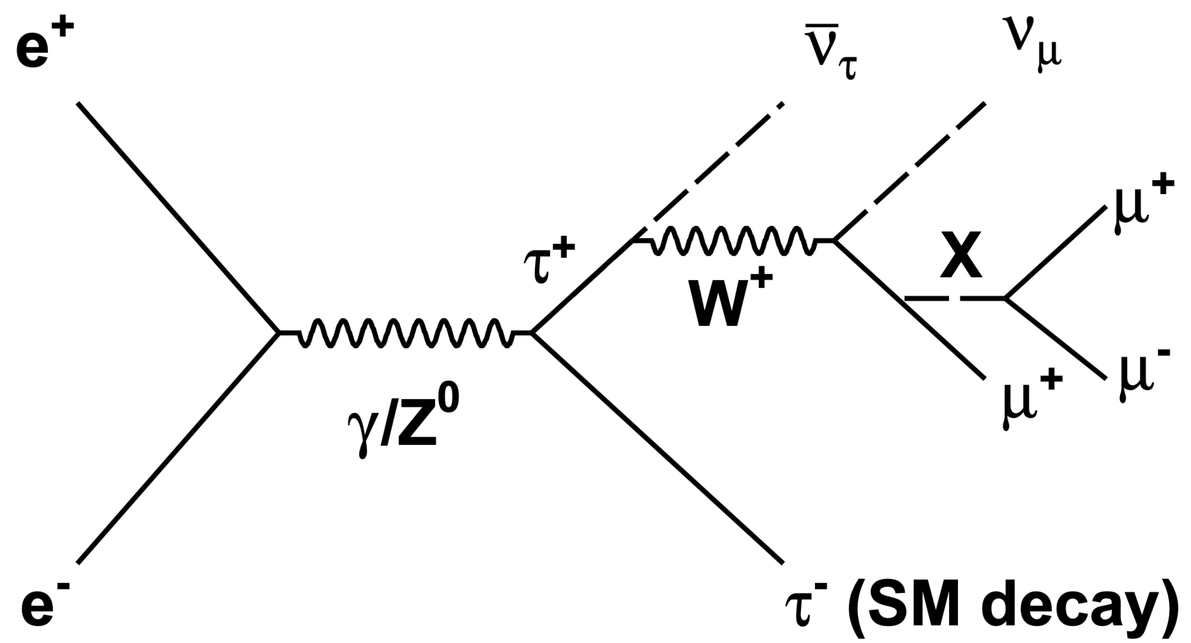
$\tau^- \to \bar{\nu}_e e^- e^- e^+ \nu_\tau$



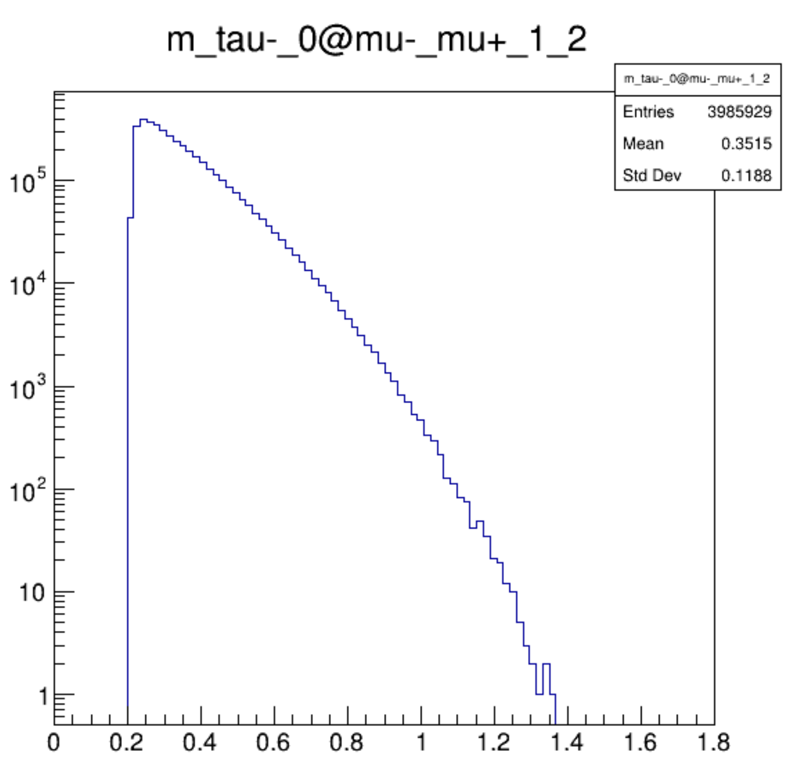
Matrix element from https://arxiv.org/pdf/1912.11376.pdf

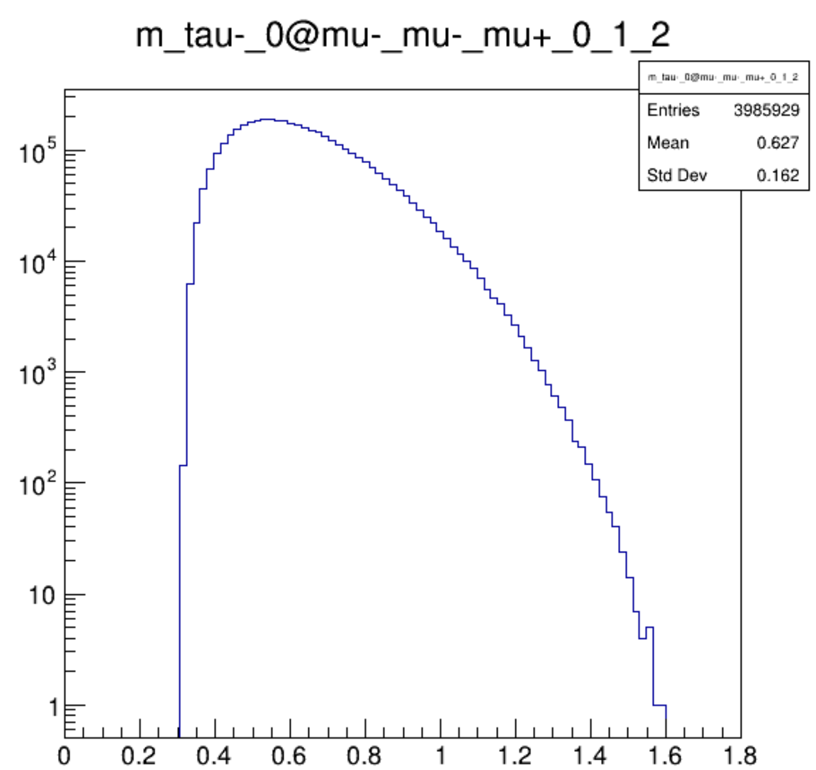






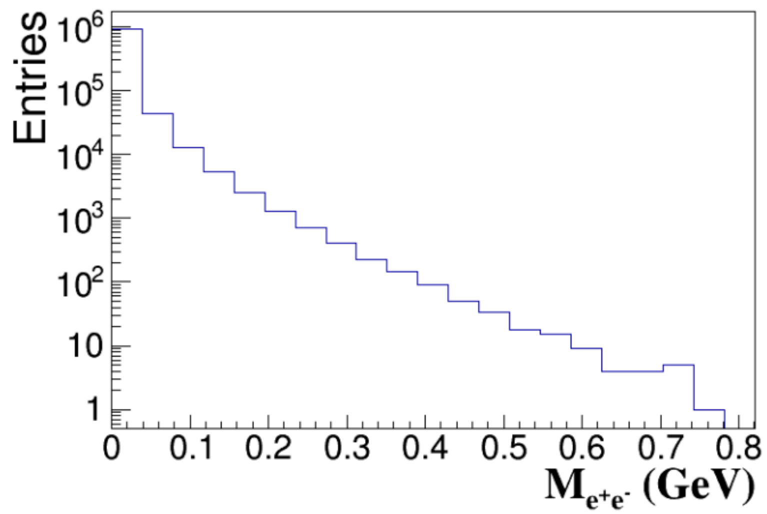
Matrix element from https://arxiv.org/pdf/1912.11376.pdf

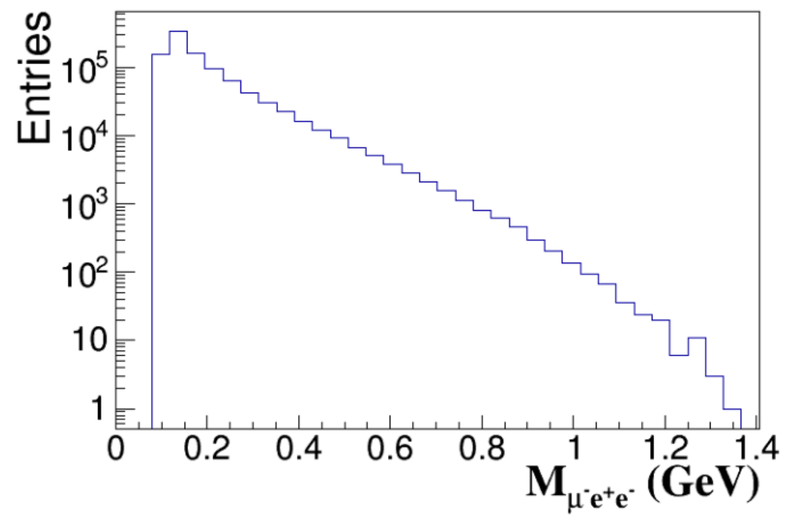




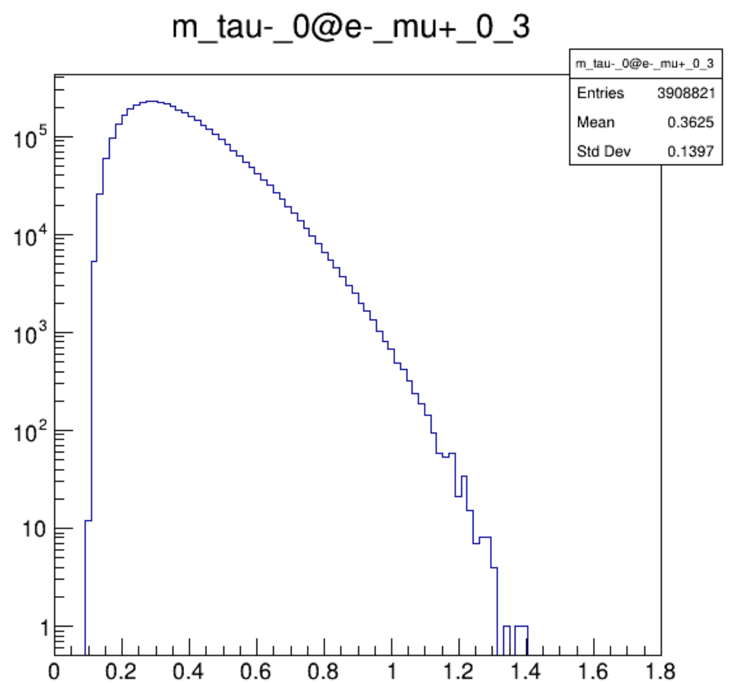
Pre-sampler optimizations

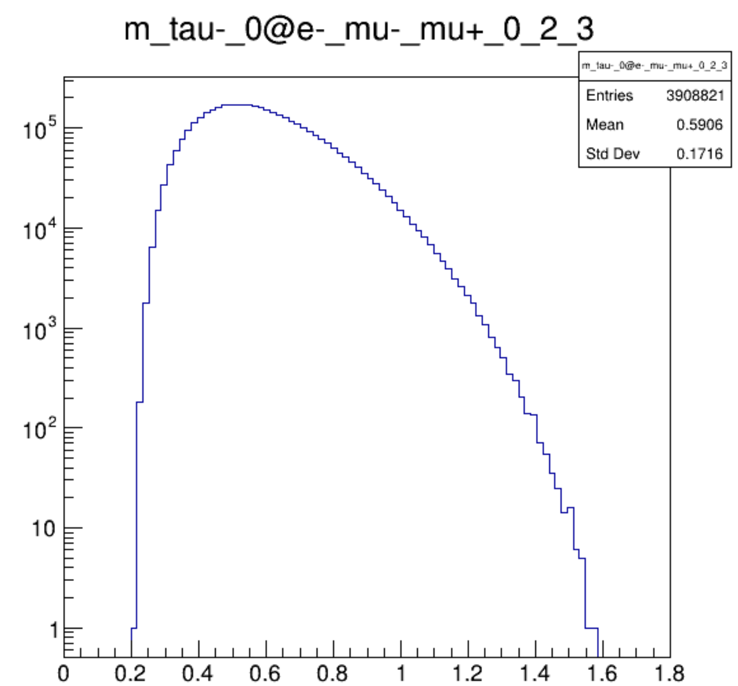
$$\tau^- \rightarrow \bar{\nu}_e \mu^- e^- e^+ \nu_\tau$$





$$\tau^- \rightarrow \bar{\nu}_e e^- \mu^- \mu^+ \nu_\tau$$





$\tau^- \to \pi^- e^- e^+ \nu_\tau$

The weak radiative pion vertex in $\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ decays

Physical Review D88 (2013) 033007

arXiv:1306.1732 **[hep-ph]**

A. Guevara[1], G. López Castro[1], and P. Roig[2],

[1] Departamento de Física, Centro de Investigación y de Estudios Avanzados, Apartado Postal 14-740, 07000 México D.F., México.

[2] Grup de Física Teòrica, Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain.

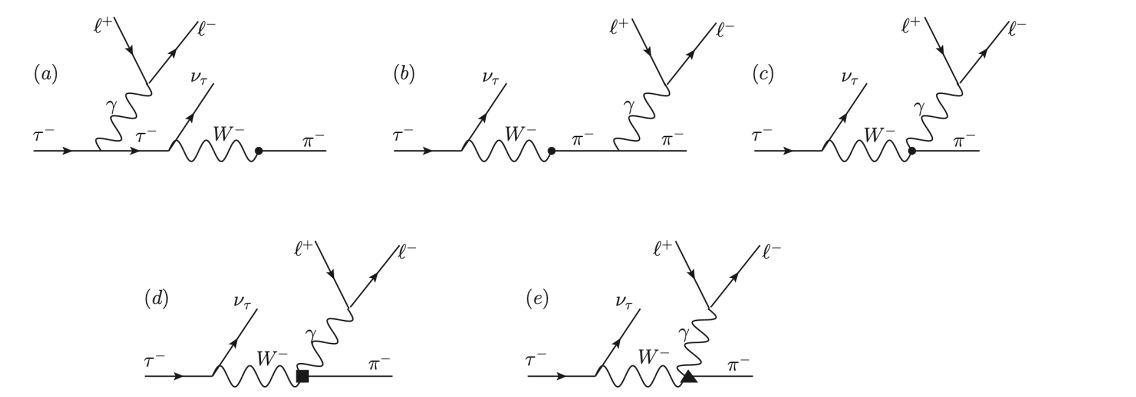
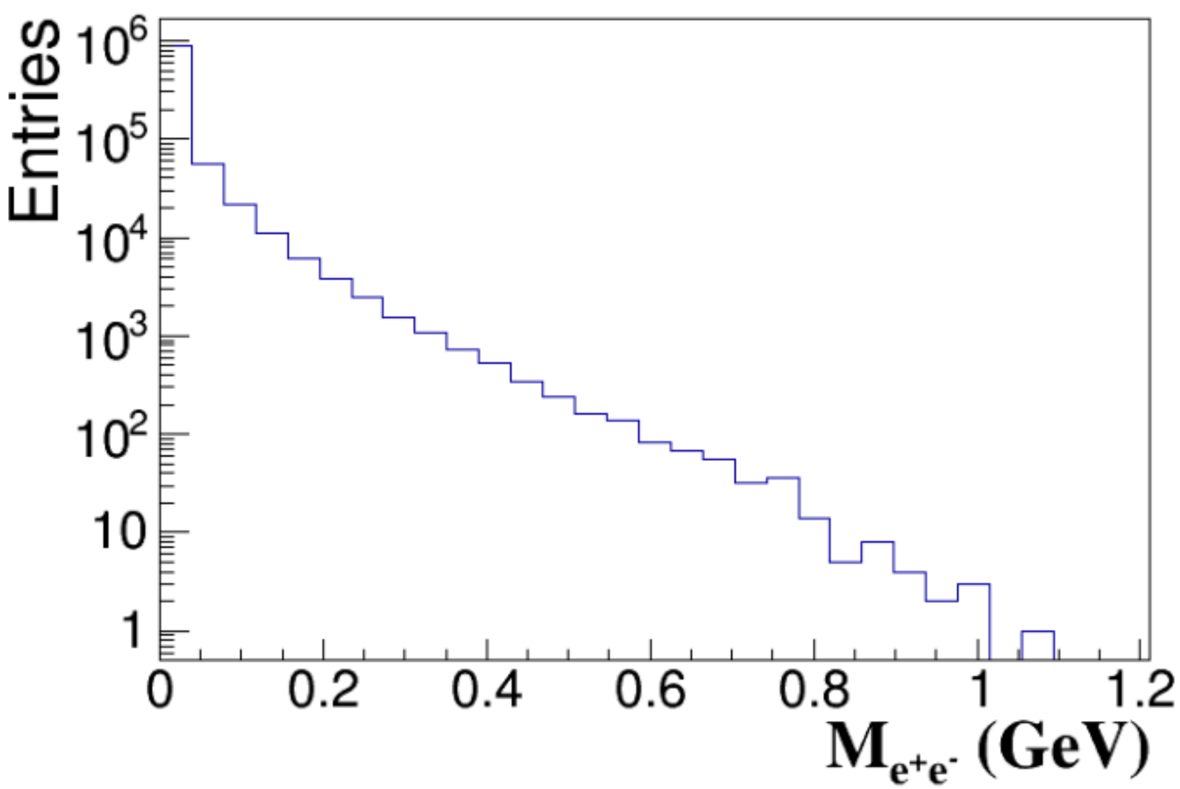
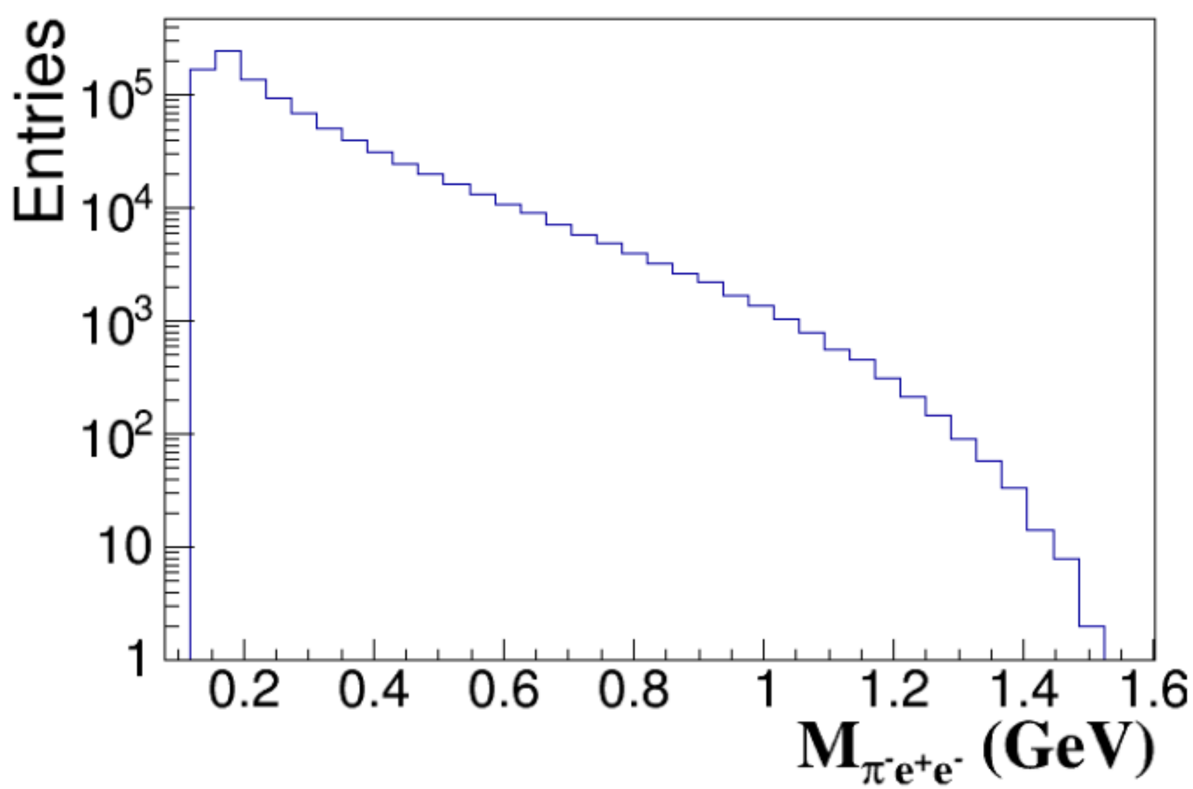


Figure 1: Feynman diagrams for the different kinds of contributions to the $\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ decays, as explained in the main text. The dot indicates the hadronization of the QCD currents. The solid square (triangle) represents the SD contribution mediated by the axial-vector (vector) current.

Matrix element from https://arxiv.org/pdf/1306.1732.pdf





The weak radiative pion vertex in $\tau^- \to \pi^-\nu_\tau\ell^+\ell^-$ decays

Physical Review D88 (2013) 033007

arXiv:1306.1732 [hep-ph]

A. Guevara[1], G. López Castro[1], and P. Roig[2],

[1] Departamento de Física, Centro de Investigación y de Estudios Avanzados, Apartado Postal 14-740, 07000 México D.F., México.

[2] Grup de Física Teòrica, Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain.

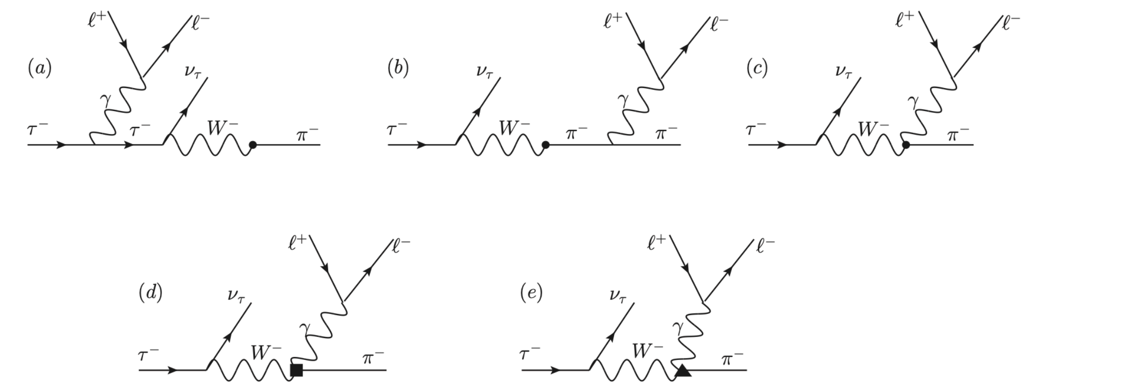
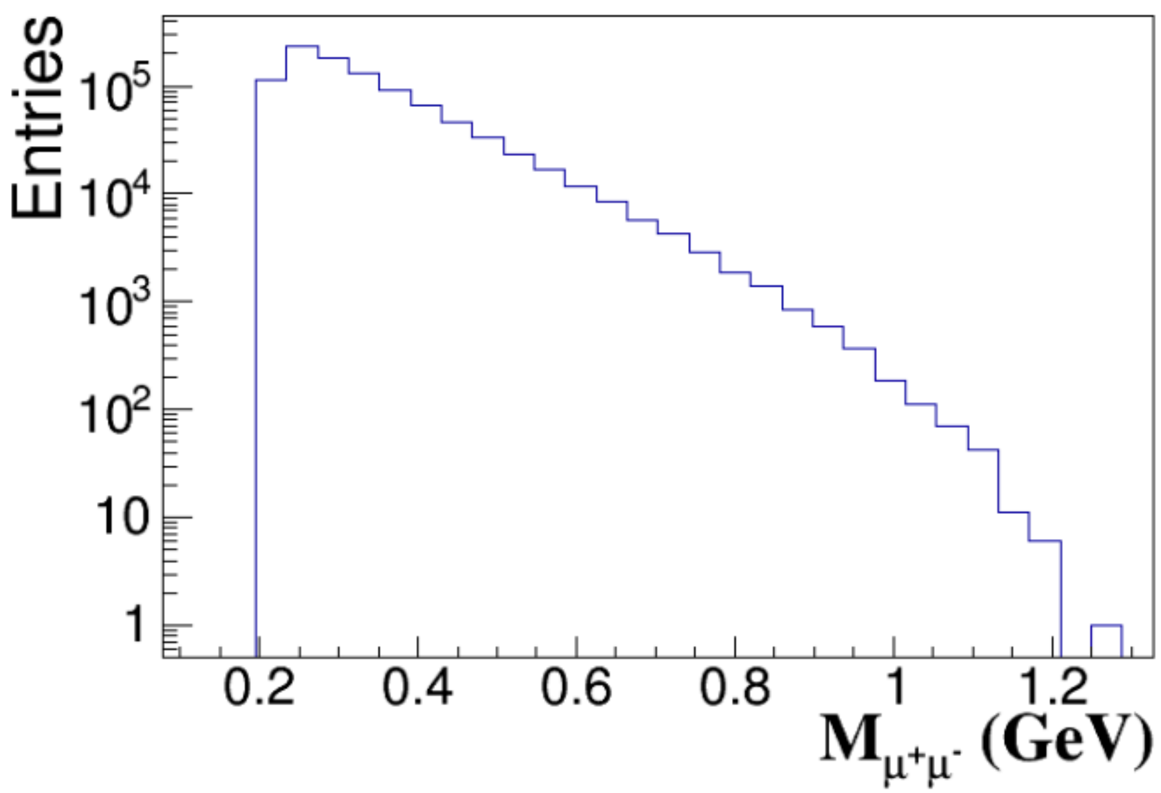
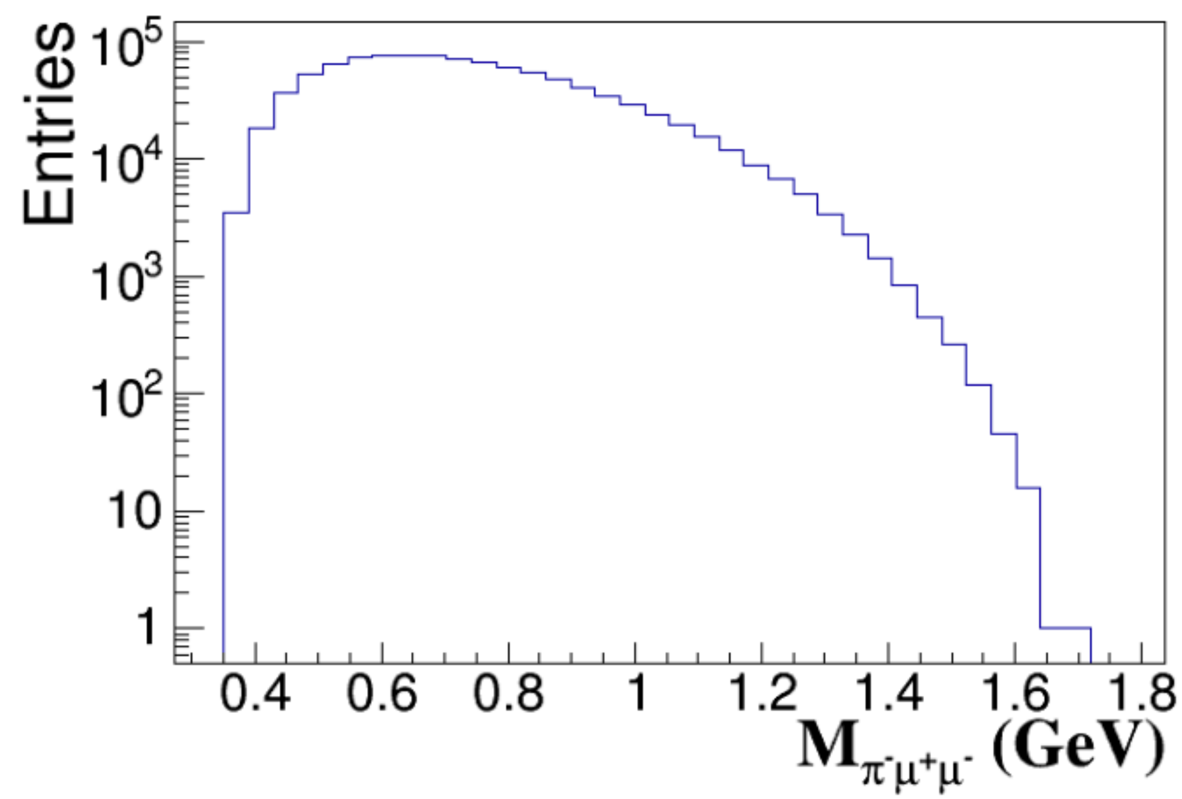


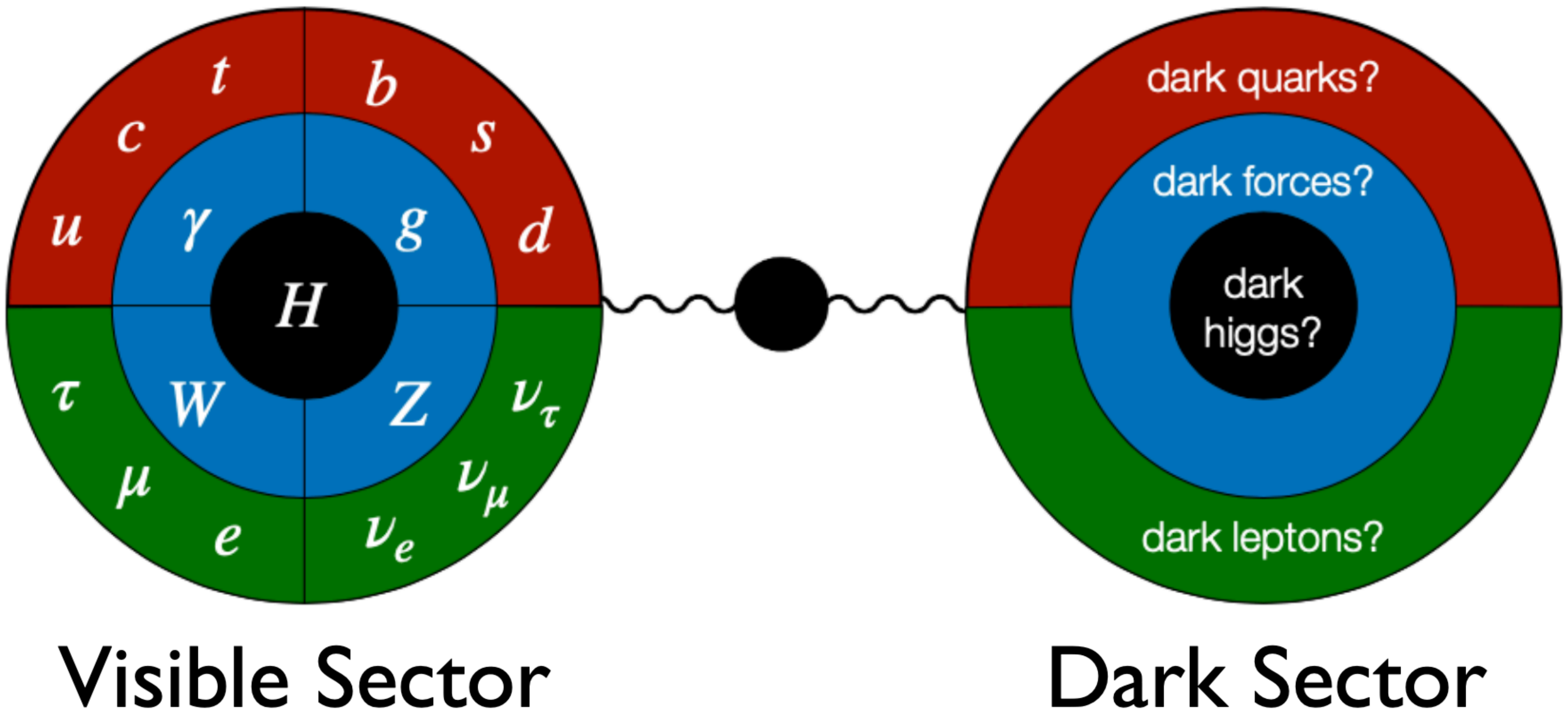
Figure 1: Feynman diagrams for the different kinds of contributions to the $\tau^- \to \pi^-\nu_\tau\ell^+\ell^-$ decays, as explained in the main text. The dot indicates the hadronization of the *QCD* currents. The solid square (triangle) represents the *SD* contribution mediated by the axial-vector (vector) current.

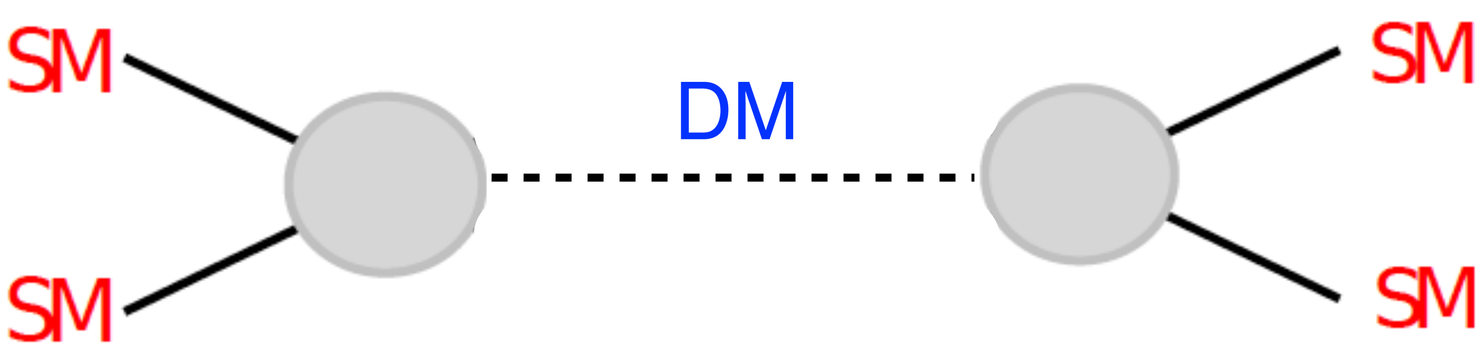
Matrix element from https://arxiv.org/pdf/1306.1732.pdf





Portal between SM and DM



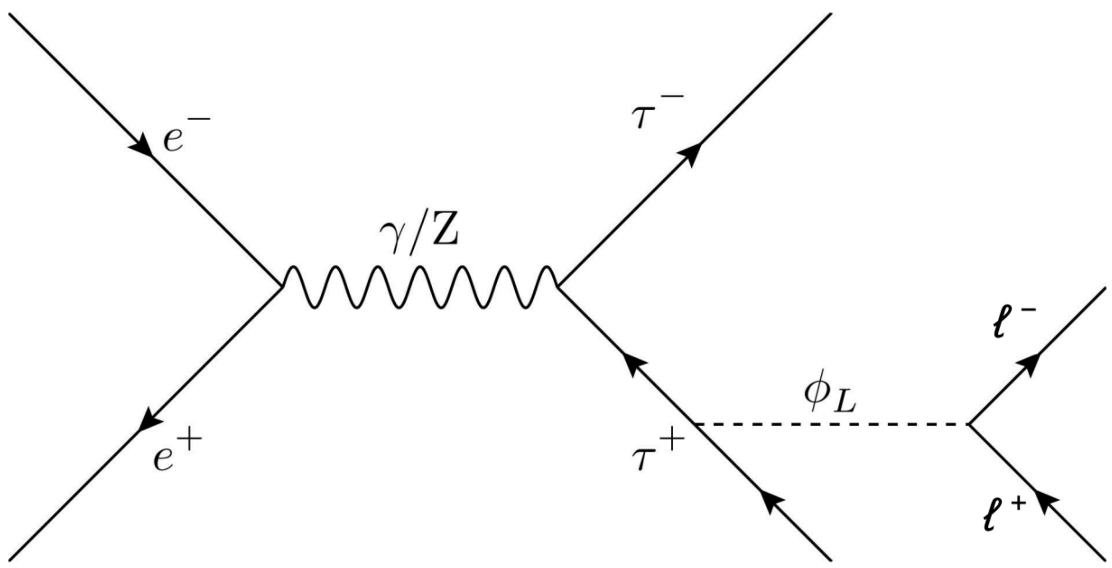


Dark leptophilic scalar

Dark sector portal can explain $(g\text{-}2)_\mu$ excess and lepton flavor universality violation:

- Many of the beyond standard model (BSM) theories predict the existence of additional scalars other than the Higgs boson.
- The mixing between this dark scalar and the SM Higgs boson gives rise to couplings proportional to SM fermion masses.
- If this new scalar couples to both quarks and leptons, the existence of such particles is strongly constrained by the searches for rare flavor-changing neutral current decays of mesons, e.g. $B \to K\phi$ and $K \to \pi\phi$.

However, these bounds are evaded if the coupling of the scalar to quarks is suppressed and this scalar interacts preferentially with leptons.

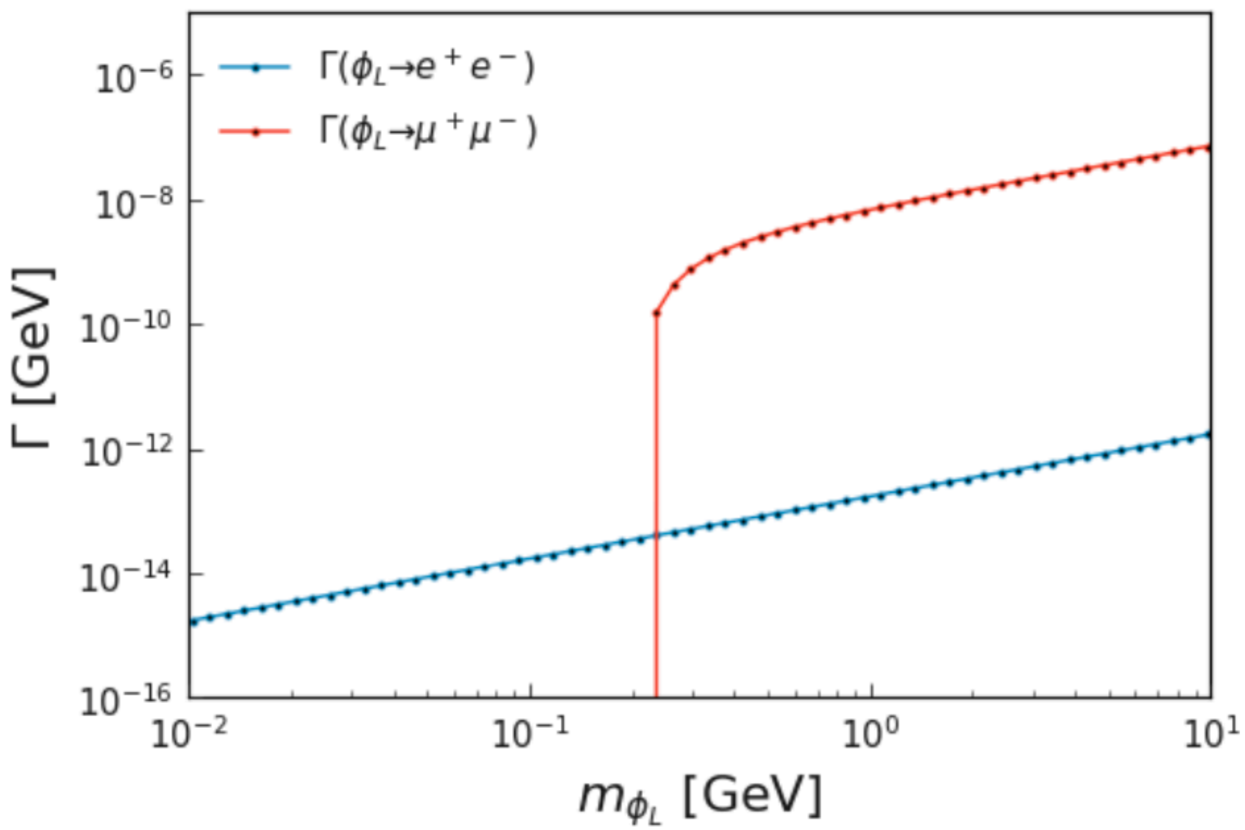


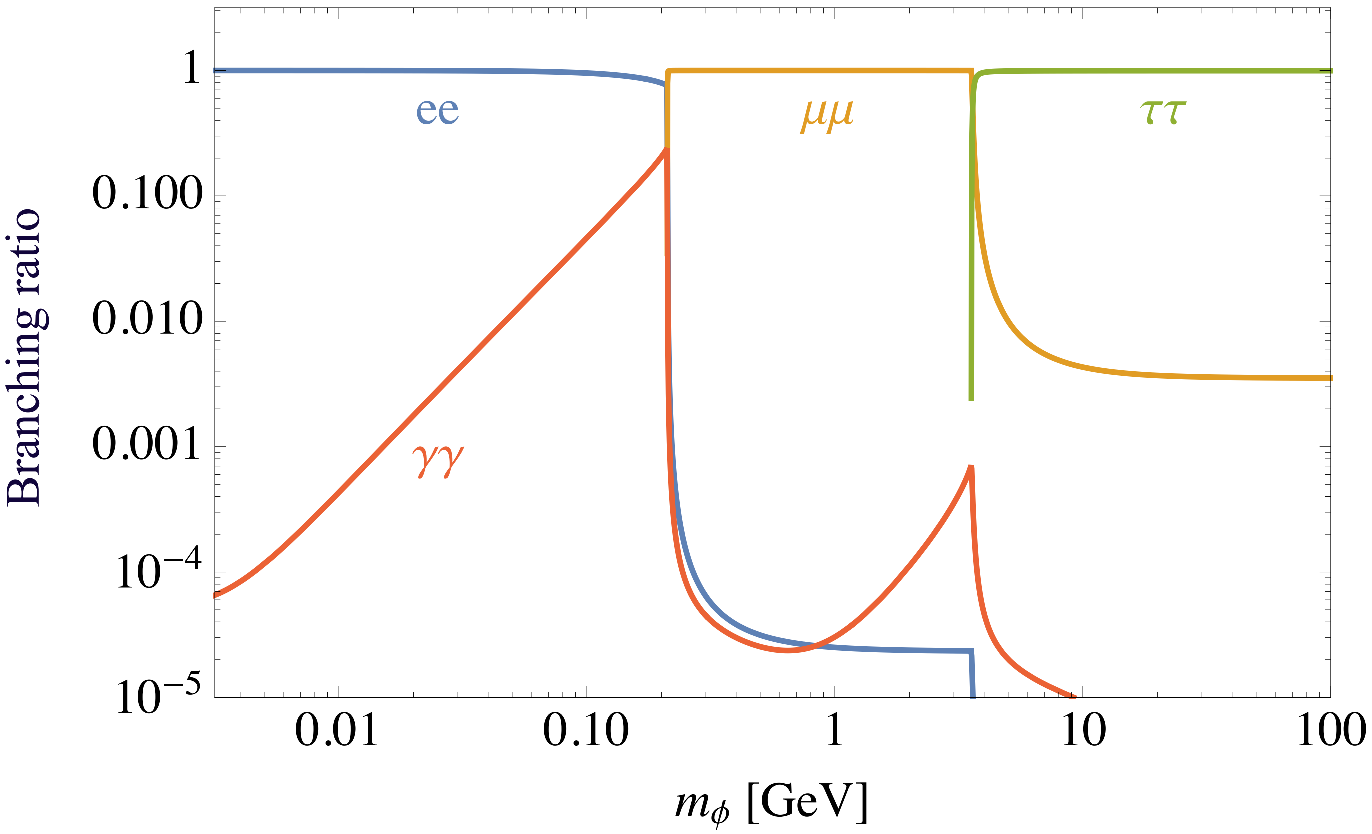
$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\,\phi_L \ell$$

ξ is the lepton flavor independent coupling constant,
m_ℓ is mass of the lepton the dark scalar couples with,
v is the vacuum expectation value = 246 GeV

B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, "Muon anomalous magnetic moment through the leptonic higgs portal," Phys. Rev. D 95 (2017) 075003.

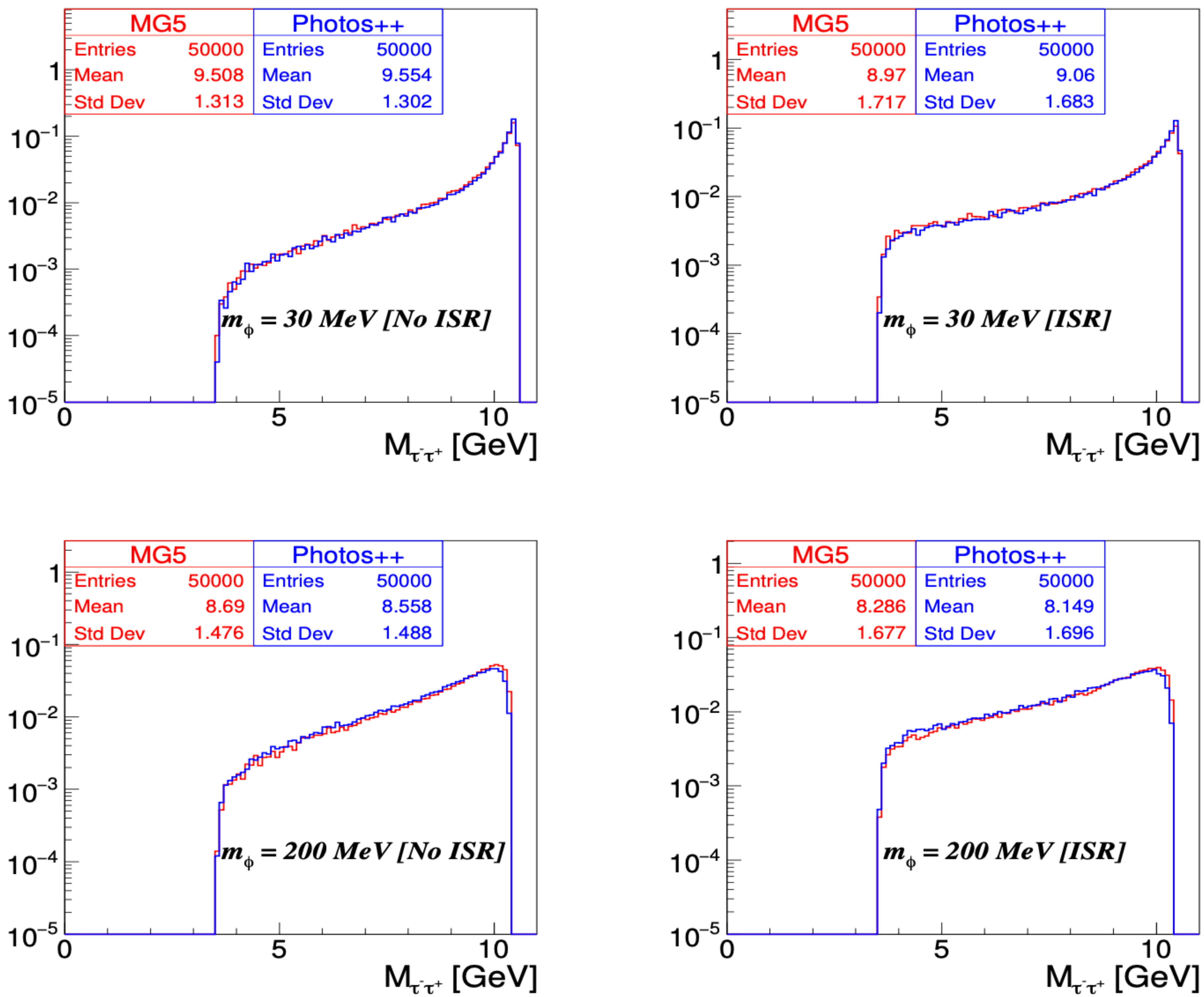
Madgraph model



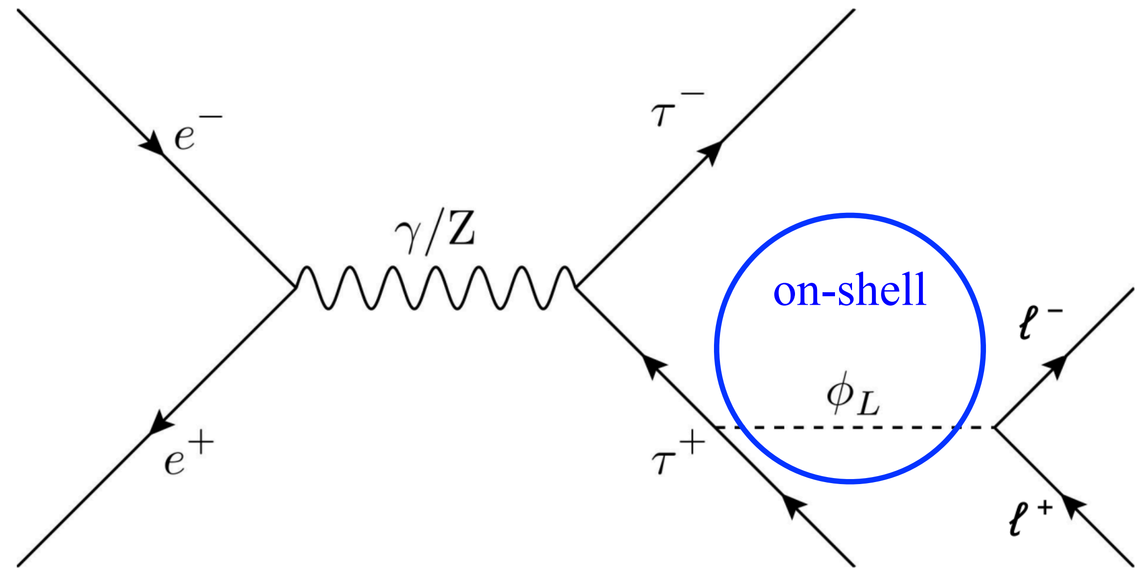


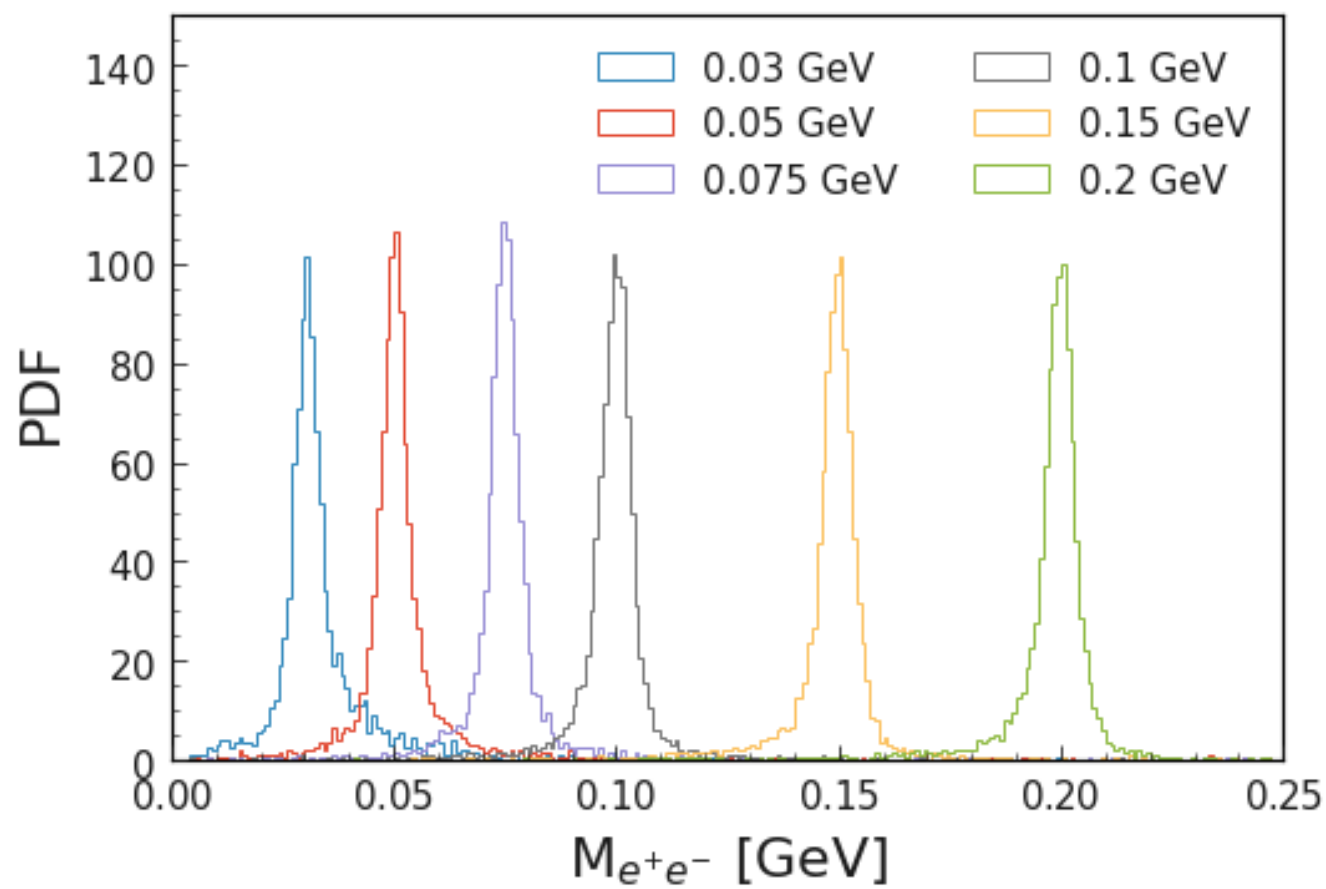
- ϕ_L decays to a lepton pair: search for narrow peak in lepton pair invariant mass distribution.
  - $\phi_L \to e^+e^-$ for $m_{\phi_L} < 2m_\mu$
  - $\phi_L \to \mu^+\mu^-$ for $m_{\phi_L} > 2m_\mu$
- High production cross-section times branching ratio in the region 40 MeV < m_{ϕ_L} < 6.5 GeV.

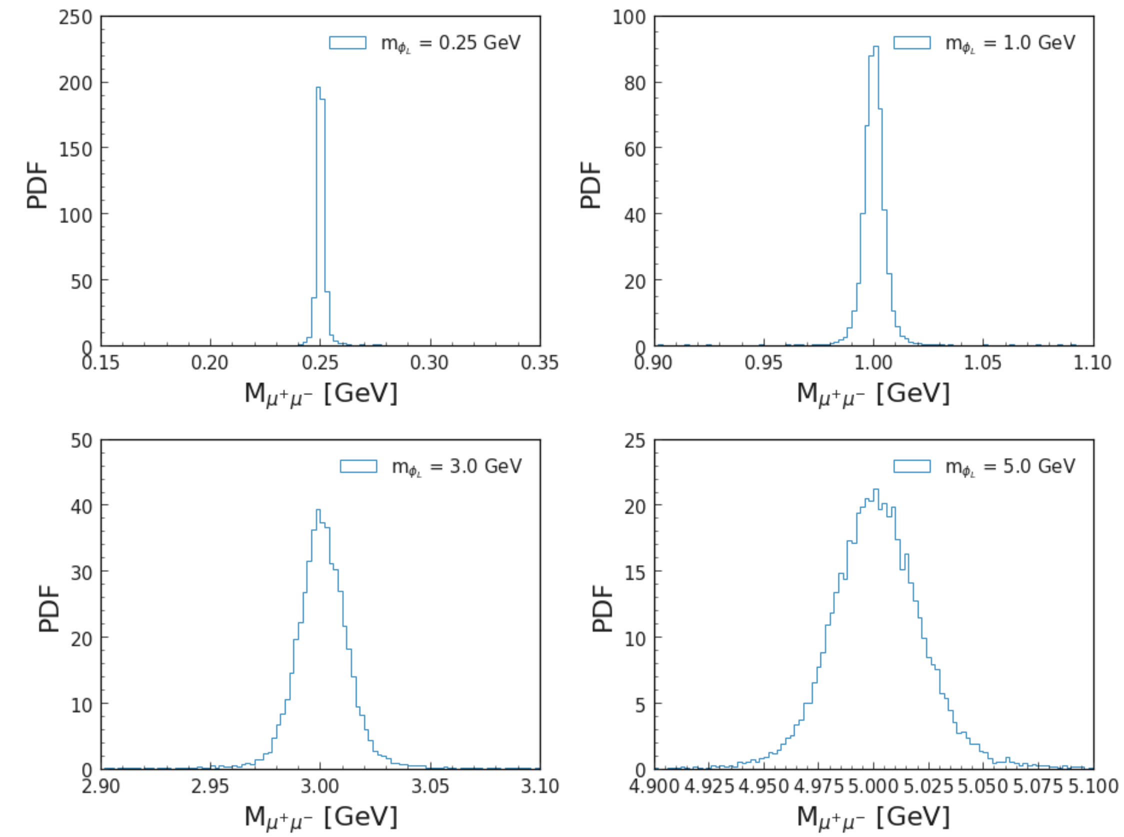
$e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to e^+e^-/\mu^+\mu^-$



Event generation with TauolaBelle2 and Photos++



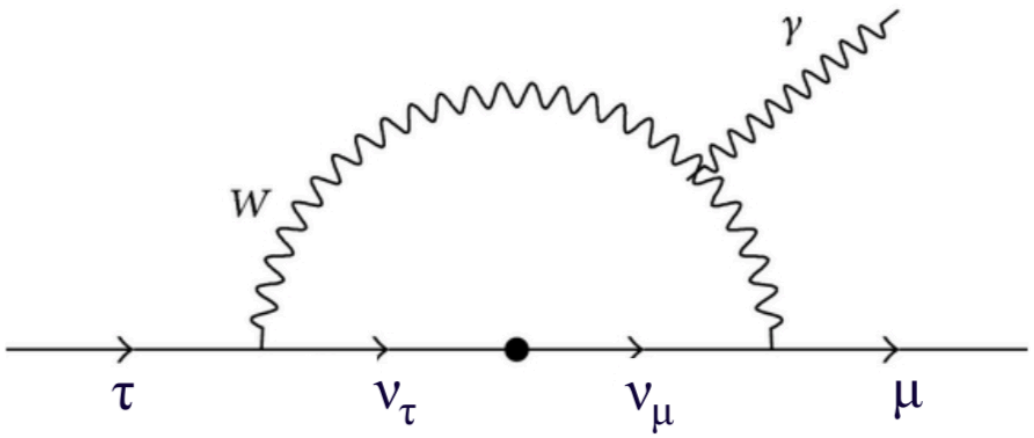




Resolution varies from 5 to 30 MeV, increasing at larger values of m_{ϕ_L}

Charged Lepton flavor violation in τ decays

In SM, finite neutrino mass allows LFV via following diagram:



$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)$ — Lee & Shrock: Phys.Rev.D 16 (1977) 1444

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,{\rm eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,{\rm eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

many orders below experimental sensitivity!

Any observation of LFV ⇒ unambiguous signature of new physics

⇒ Several models prediction LFV in tau sector at 10^{-8} - 10^{-10} level which is just below current experimental sensitivity

About fifty τ decay modes & many transitions with τ in the final state

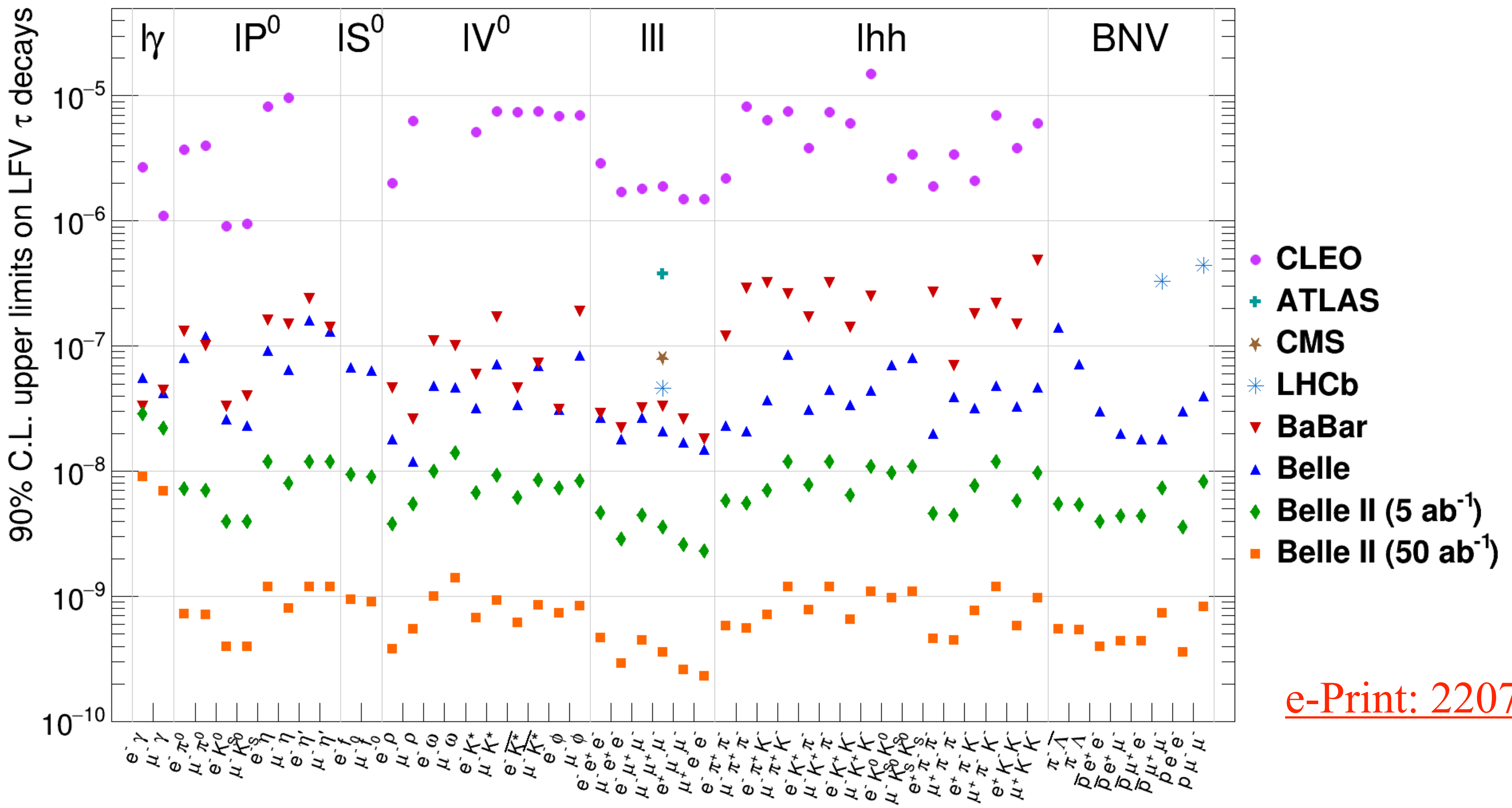
- **Lepton flavor violation (charge conjugate modes implied)**
  - $\tau \to e/\mu\ \gamma$ (Belle II, STCF, FCC-ee)
  - $\tau \to e/\mu$ (scalar/pseudoscalar/vector mesons) (Belle II)
  - $\tau \to e\ e\ e$ (Belle II)
  - $\tau \to \mu\ \mu\ \mu$ (Belle II, ATLAS, CMS, LHCb, STCF, FCC-ee)
  - $\tau \to e\ \mu\ \mu$, $\mu\ e\ e$ (Belle II)
  - $\tau \to e/\mu\ h\ h$ (non-resonant final states with $h=\pi/K$) (Belle II, STCF)
  - $\tau \to e/\mu$ invisible (α) (Belle II)
  - $H \to e\ \tau$, $\mu\ \tau$ (ATLAS, CMS)
  - $Z(Z') \to e\ \tau$, $\mu\ \tau$ (ATLAS, CMS)
  - $e \to \tau$ transitions (EIC)

- **Lepton number violation**
  - $\tau^- \to e^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (Belle II)
  - $\tau^- \to \mu^+\ h^-\ h^-$ (non-resonant final states with $h=\pi/K$) (Belle II)

- **Baryon number violation**
  - $\tau^- \to \Lambda\ \pi^-$, $\bar{\Lambda}\ \pi^-$ (Belle II)
  - $\tau^- \to \bar{p}\ \mu^+\ \mu^-$, $p\ \mu^-\ \mu^-$ (Belle II, LHCb)

Projected limits at Belle II

Belle II to probe LFV in several channels ≃ $\mathcal{O}(10^{-10})$ to $\mathcal{O}(10^{-9})$ with 50 ab^{-1}



Projections

e-Print: 2207.06307 [hep-ex]

All these LFV decays are implemented in TauolaBelle2

Lots of interesting tau physics with KK2F, TAUOLA & PHOTOS