Event generators for tau and low multiplicity events

Swagato Banerjee

UNIVERSITY OF LOUISVILLE

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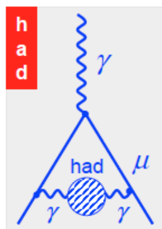
Topics covered

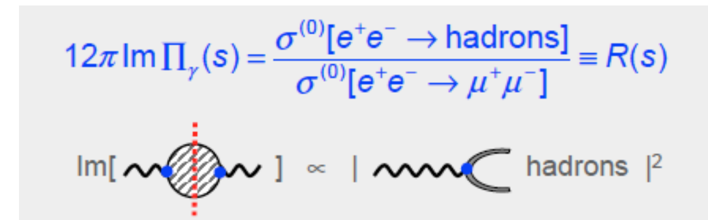
- **Muon and tau pair production cross-sections**
- **General introduction to tau decays**
- **Adaptation of tau branching fractions from HFLAV/PDG fits**
- **General formalism of KK2F, TAUOLA, PHOTOS Monte Carlo for τ-pairs**
- $\tau^- \to \pi^- \nu_\tau$ **vs** $\tau^- \to \rho^- \nu_\tau$ **modeling**
- **Lepton flavor violation:** $\tau^- \to \ell^- \alpha$
- **Alternate parametrizations of hadronic currents**
- **Pre-sampler optimization for lepton pair emissions:** $\tau^- \to \bar{\nu}_\ell \ell^- \ell^- \ell^+ \nu_\tau$, $\tau^- \to \pi^- \ell^- \ell^+ \nu_\tau$
- **Dark scalar production in tau decays decaying to a pair of leptons**
- **Electric and magnetic dipole moments**
- **Low multiplicity generators: MADGRAPH, EKHARA, AAFH, WHIZARD**

Revisiting vacuum polarization

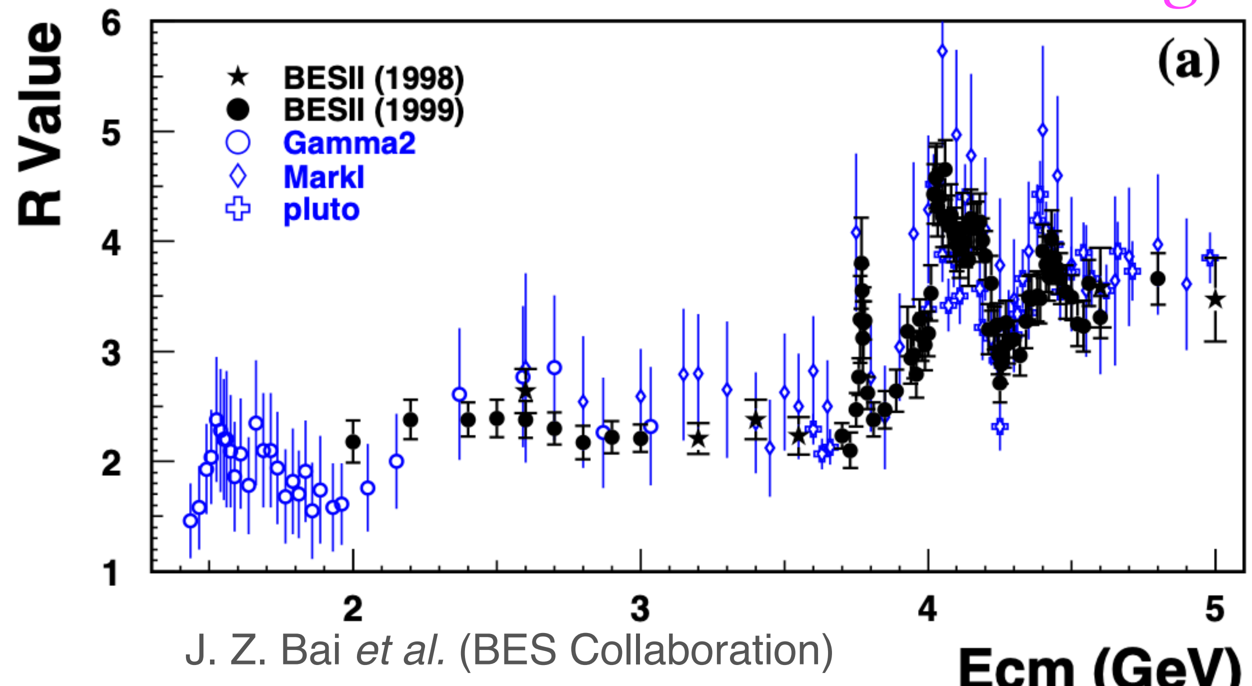
- *Until 2007:* $\sigma_{\tau\tau}^{\mathrm{KORALB}} = 0.91$ nb, $\sigma_{\tau\tau}^{\mathrm{KK2F}} = 0.89$ nb, $\Rightarrow \Delta\sigma_{\tau\tau} = 2.22$ %
- *Default implementation of vacuum polarization in KK2F did NOT calculate the hadronic part for E < 40 GeV*



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



- *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

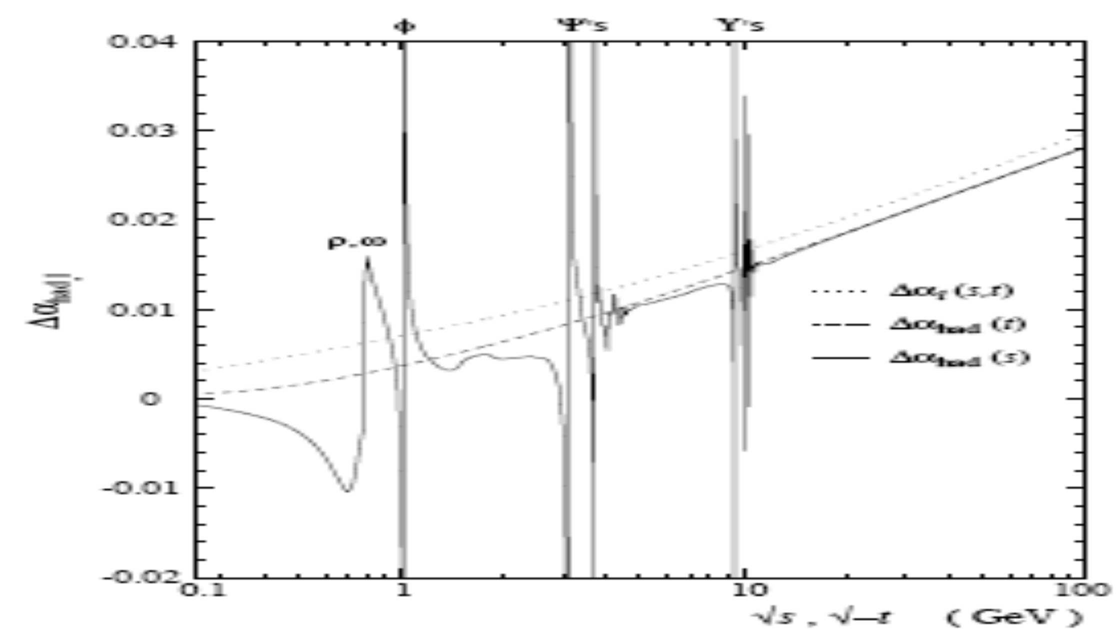
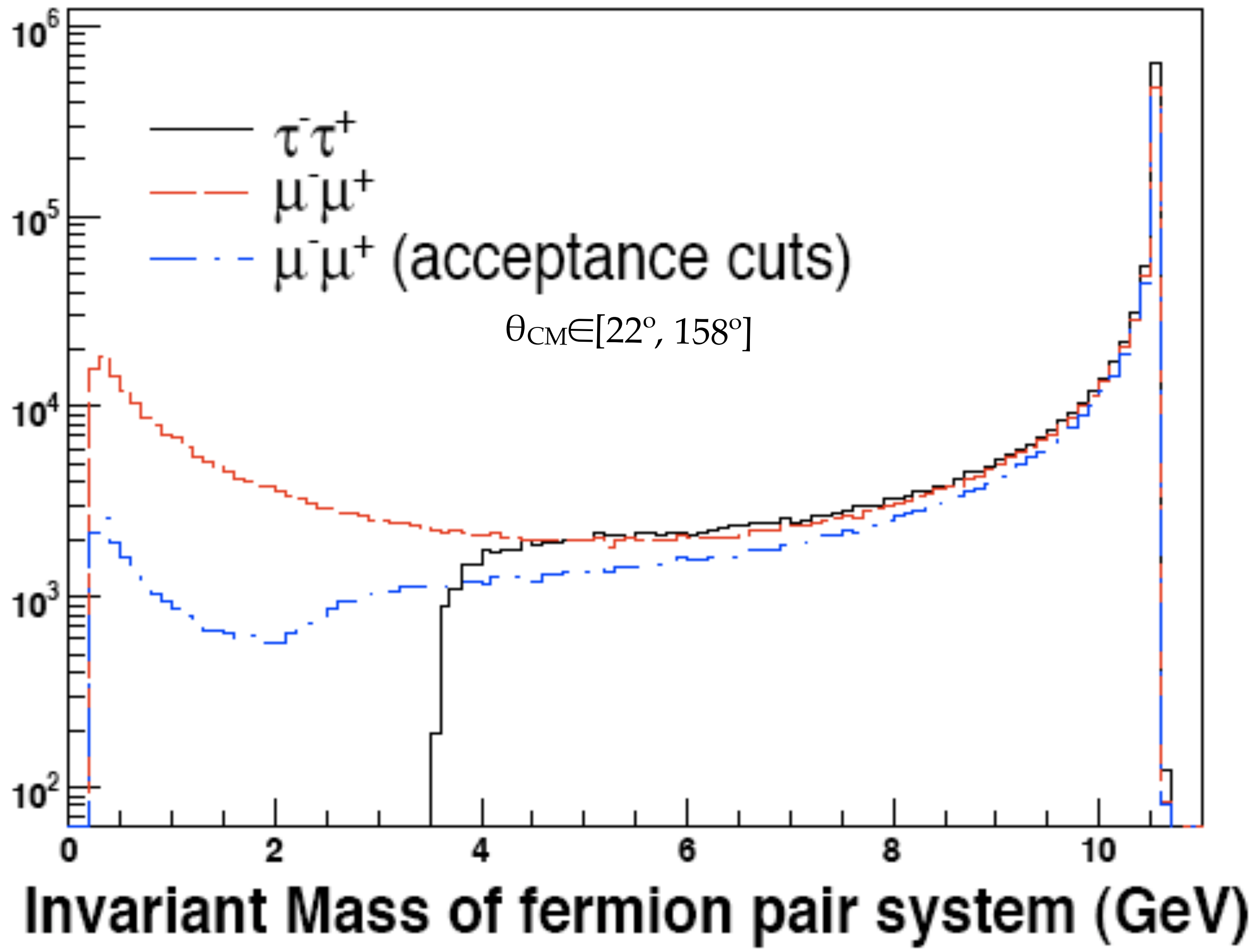


Fig. 1. Δα_l (dotted line) and Δα_had at several energies in the t (dashed line) and s channel (solid line).

[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

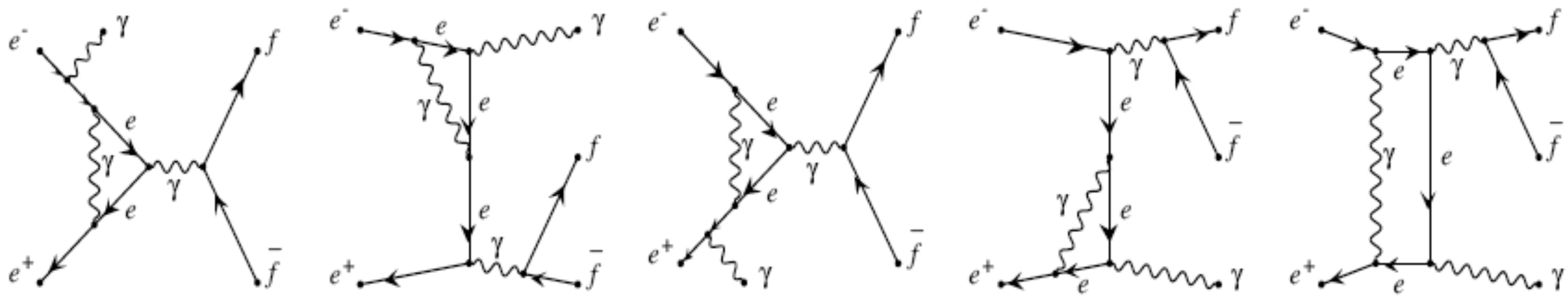


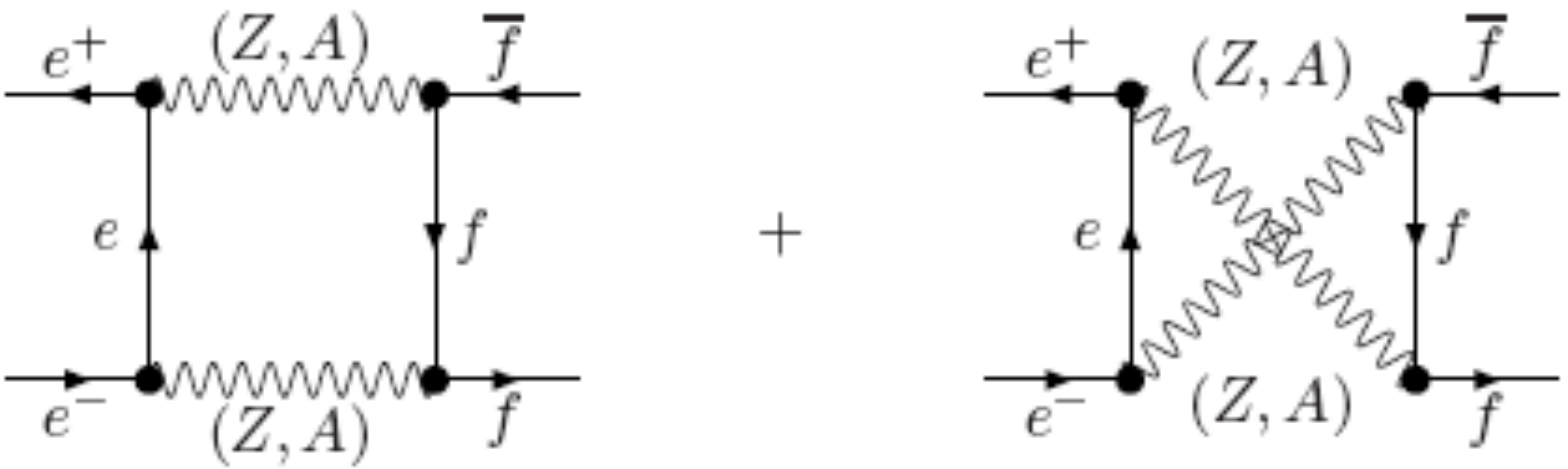
Figure 3. Representative graphs for the $1\gamma_{real} + 1\gamma_{virtual}$ correction in 2f processes.

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

- *Baseline: Born-level agreement between KORALB & KK2F*
- *First order correction from initial state:* $(1-\sigma^{\rm KORALB}_{\rm NO\ VP}/\sigma^{\rm KORALB}_{\rm BORN})$ *~ 11%*
- *Second order* $\sim 0.11^2/2 = 0.0061 \Rightarrow$ *Validate* $\sigma^{\rm KK}_{\rm NO\ VP}/\sigma^{\rm KORALB}_{\rm NO\ VP}$ *~ 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)* $\Rightarrow \Delta(\sigma) < 0.1\%$
- *Verify factorization:* $\sigma^{\rm KK} = \sigma^{\rm KK}_{\rm NO\ VP} \times (\sigma^{\rm KK}_{\rm NO\ BREM}/\sigma^{\rm KK}_{\rm BORN})$
- *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

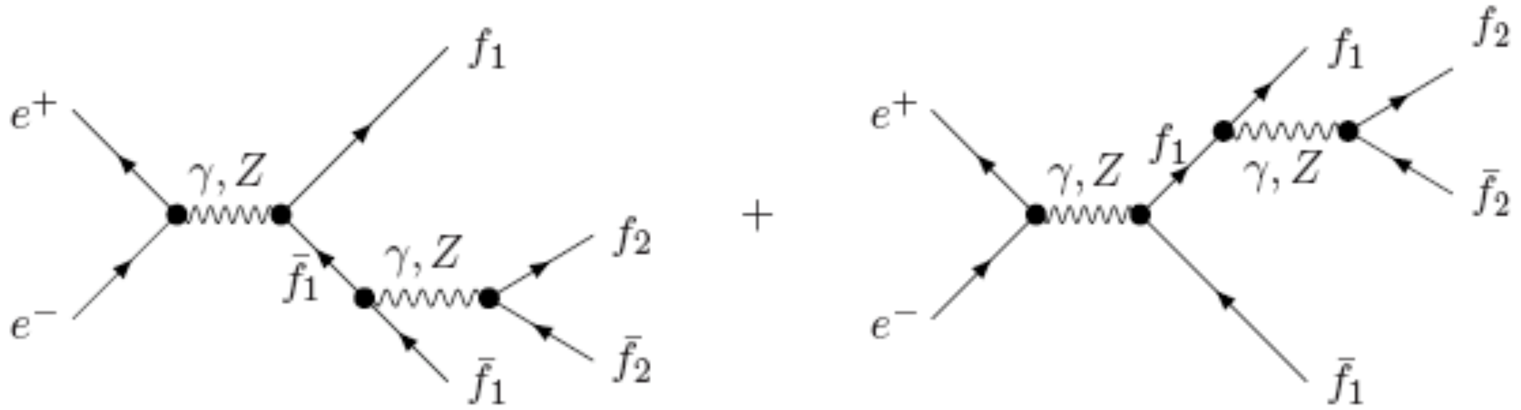


Fig. 4: Second eight diagrams belonging to the NC24 process.

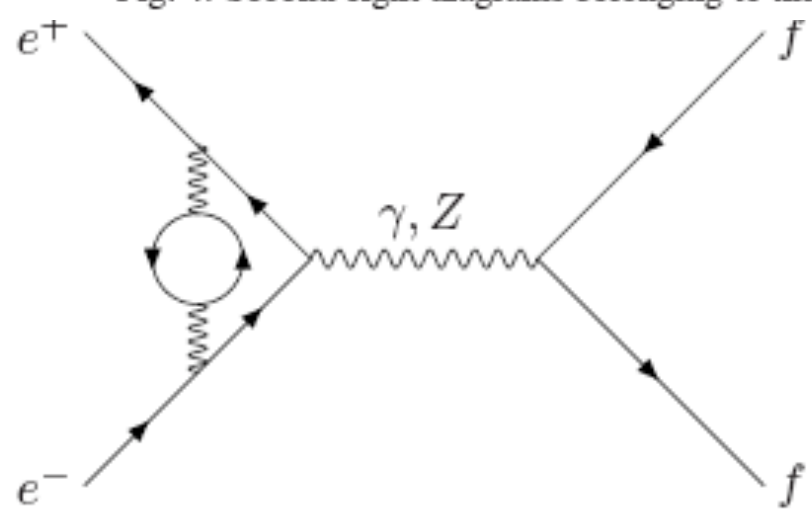


Fig. 6: A typical example of virtual pair correction.

- *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*
- $\Delta(\sigma_{\tau\tau}) = 0.04\%$
- $\Delta(\sigma_{\mu\mu}) = 0.12\%, 0.10\%(\sqrt{s'/s} > 0.1), 0.04\%(\sqrt{s'/s} > 0.4)$

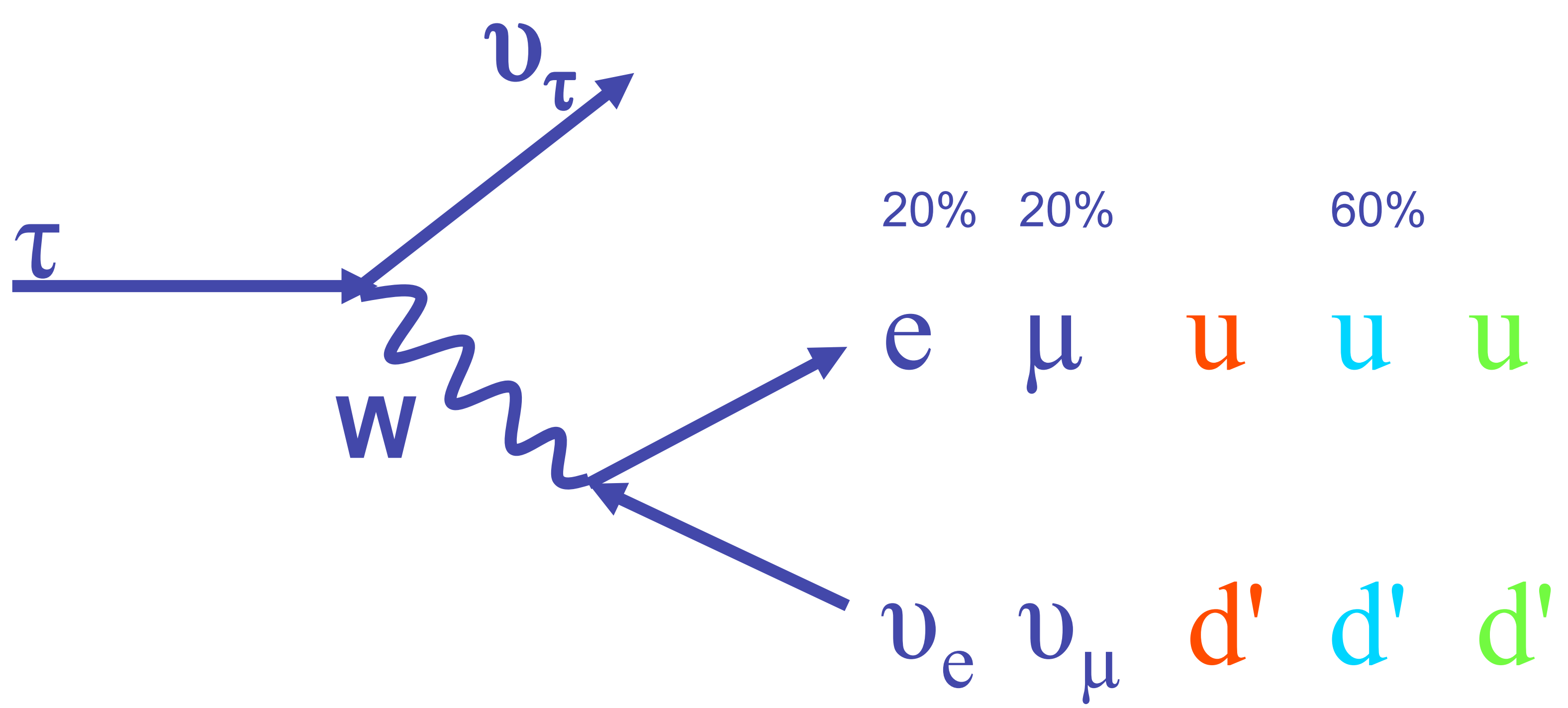
τ-pair and μ-pair cross-section at 10.58 GeV

	$\sigma(\tau\tau)$	$\sigma(\mu\mu)$	$\sigma_{cuts}(\mu\mu)$	$\sigma(\tau\tau)/\sigma(\mu\mu)$
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%

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

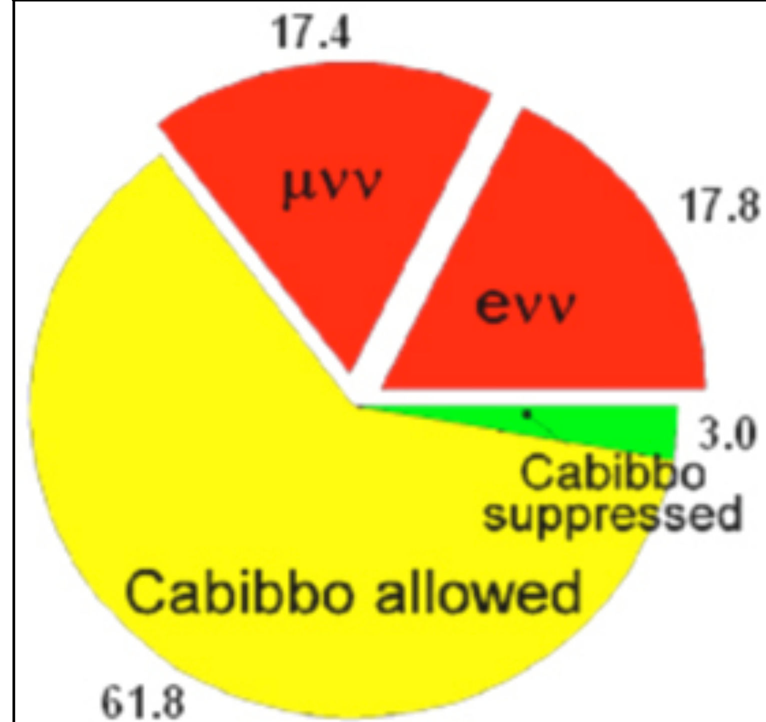
SwB, B. Pietrzyk, J.Roney, Z.Was Phys.Rev.D 77 (2008) 054012

Naive prediction:



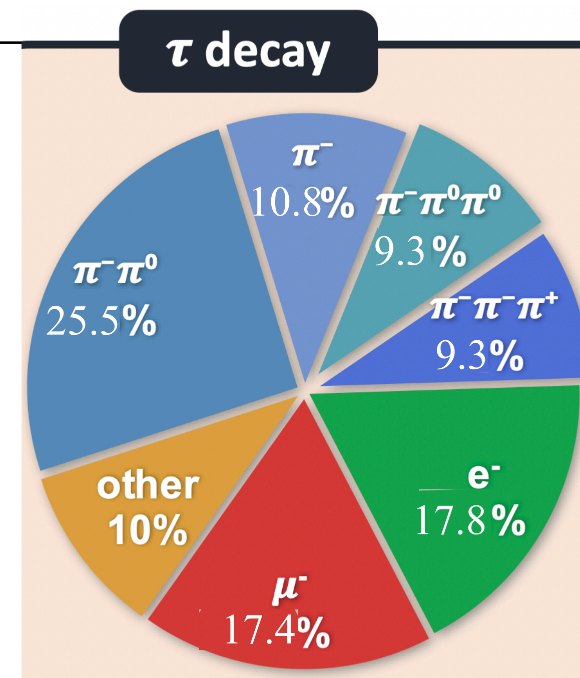
$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$$

Including QED & QCD corrections:



τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^-$ ≥ 0 neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.24 ± 0.06) %		–
particle$^-$ ≥ 0 neutrals $\geq 0K^0_L\nu_\tau$		(84.58 ± 0.06) %		–
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g]	(17.39 ± 0.04) %		885
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[e]	(3.67 ± 0.08) × 10^{-3}		885
$e^-\overline{\nu}_e\nu_\tau$	[g]	(17.82 ± 0.04) %		888
$e^-\overline{\nu}_e\nu_\tau\gamma$	[e]	(1.83 ± 0.05) %		888
$h^- \geq 0K^0_L\ \nu_\tau$		(12.03 ± 0.05) %		883
$h^-\nu_\tau$		(11.51 ± 0.05) %		883
$\pi^-\nu_\tau$	[g]	(10.82 ± 0.05) %		883
$K^-\nu_\tau$	[g]	(6.96 ± 0.10) × 10^{-3}		820

The Review of Particle Physics (2021)
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.



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

- If unitary constraint is released, $1 - \mathscr{B}_{all} = (0.03 \pm 0.10)$ %
- The fit has χ^2/d.o.f. = 142/129, corresponding to a confidence level CL = 20.13%.
- 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
$\pi^-\bar{K}^0 2\pi^0\nu_\tau$ (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

$\tau^- \to X^- \nu_\tau$

The matrix element for a semi-leptonic decay $\tau^-(P) \to \nu_\tau(N) + X(Q)$

is $\overline{M} = \frac{G}{\sqrt{2}} \bar{u}(N)\gamma^\mu\left(v + a\gamma^5\right)u(P)J_\mu$

where $J_\mu \equiv \left\langle X | V_\mu - A_\mu | 0 \right\rangle$ is the matrix element of the V-A current relevant for the final state X encoding the hadronic form factors and CKM matrix element ($|V_{ud}|$ or $|V_{us}|$) for final state containing contributions from non-strange or strange quarks.

Then the matrix element squared for decay of a τ with spin s is

$$|\mathscr{M}|^2 = \frac{G^2(v^2 + a^2)}{2}(H + s^\mu \omega_\mu)$$

where H is the spin-averaged part of the total width,

s_μ is polarization vector of τ-lepton

and ω_μ is the polarimeter vector encoding channel dependent phase space.

General formalism of τ pair modeling

Matrix element squared of $e^-e^+ \to \tau^-\tau^+$ 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 vertex $e^-e^+ \to \tau^-\tau^+(n\,\gamma)$ are modeled by **KKMC**.

Final state radiation in leptonic tau decays are modeled by **TAUOLA**.

Final state radiation in hadronic tau decays 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]

General shape comes from kinematics of 2-body decay, but photon radiation changes the shape of its energy distribution shown below in the CM frame of $e^- e^+ \to \tau^- \tau^+$.

Figure 1: E(pi-) no ISR

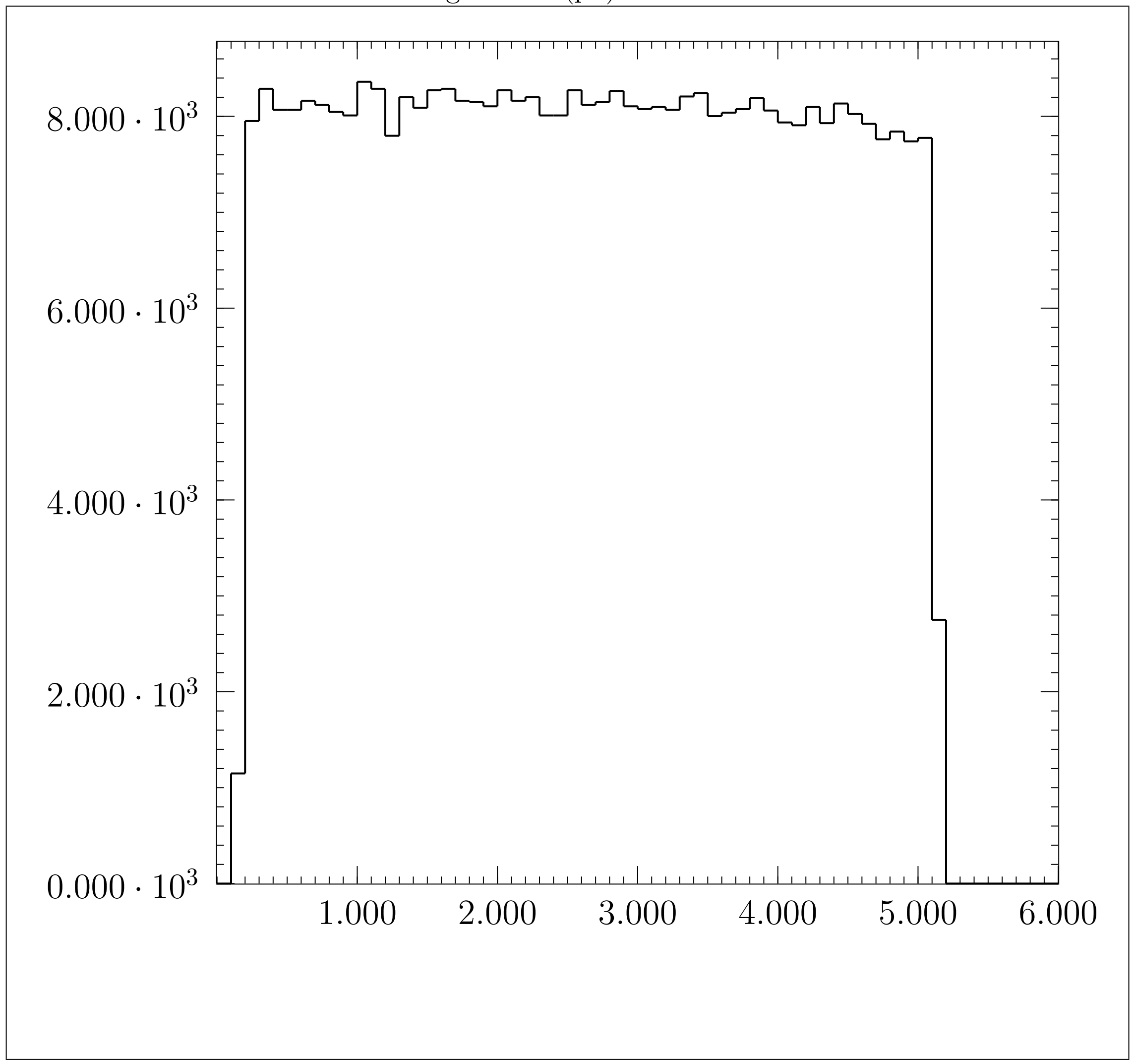
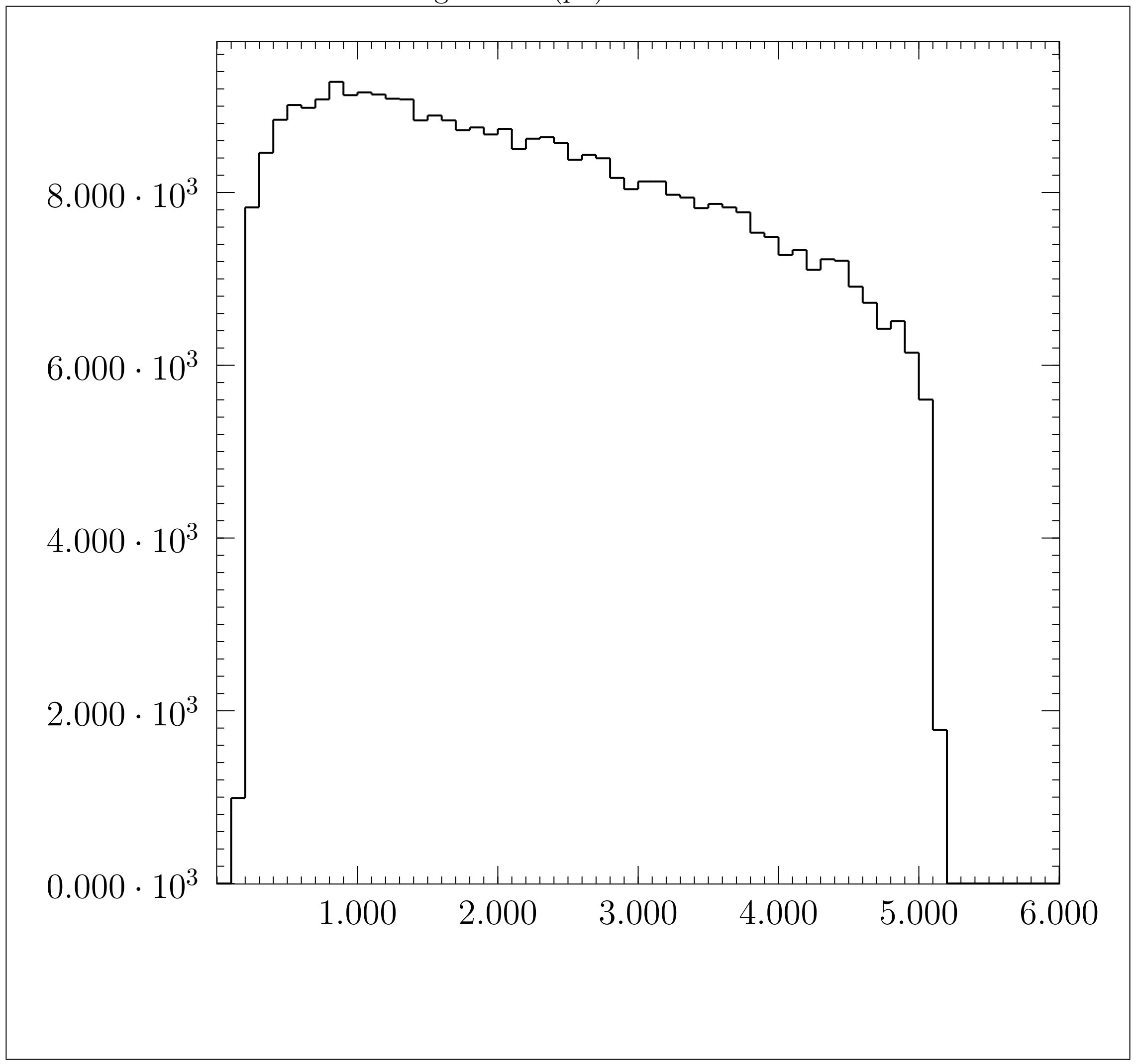
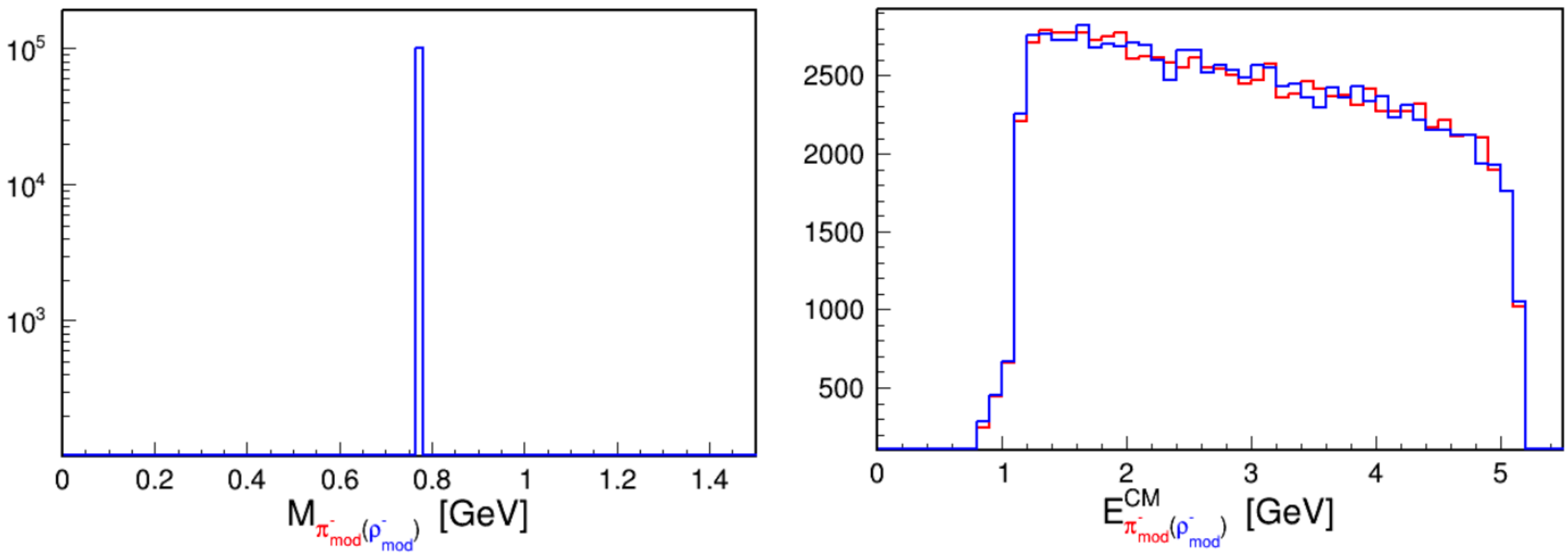


Figure 1: E(pi-) with ISR



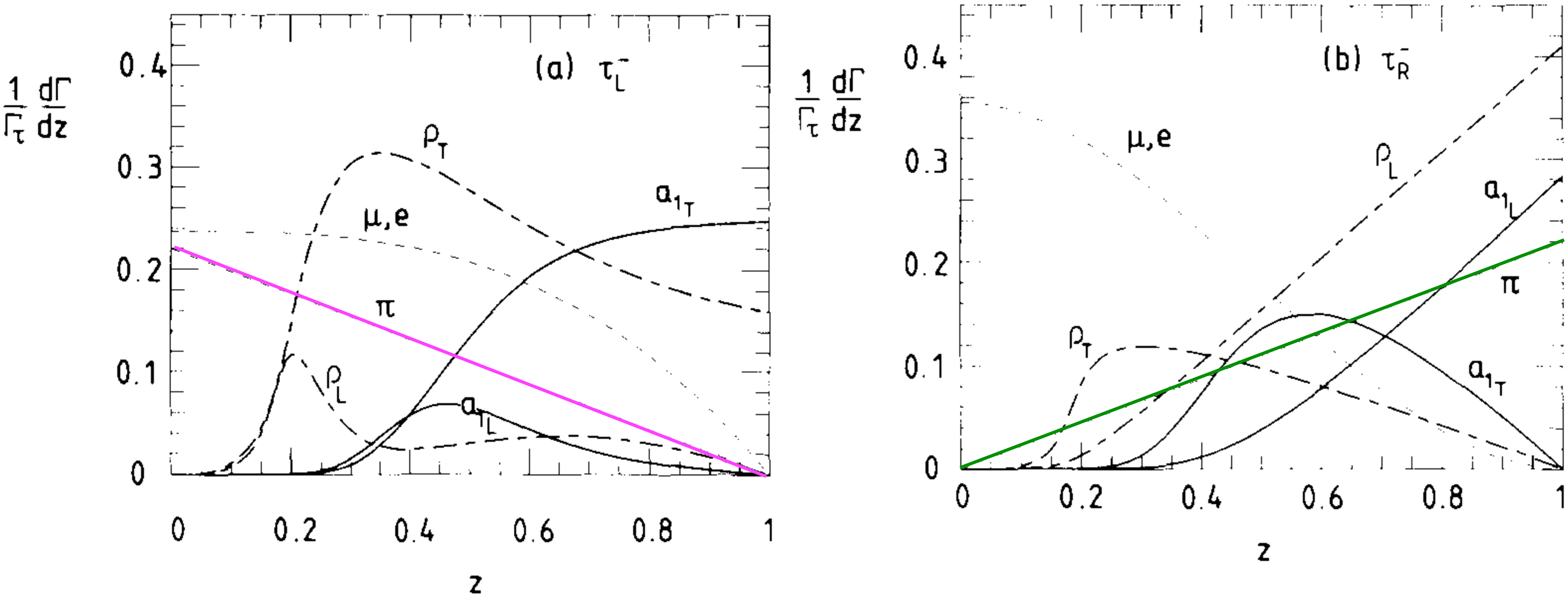
Let us consider, hypothetically, a π^- with mass of $\rho^- = 770$ MeV.
Further, let us ignore the width of ρ^-, and ignore its decay.



Distribution of their energies in the CM frame are same, because with unpolarized beams, we average over τ_L and τ_R.

τ_L vs τ_R decays

Distributions from polarized tau decays are indeed different.

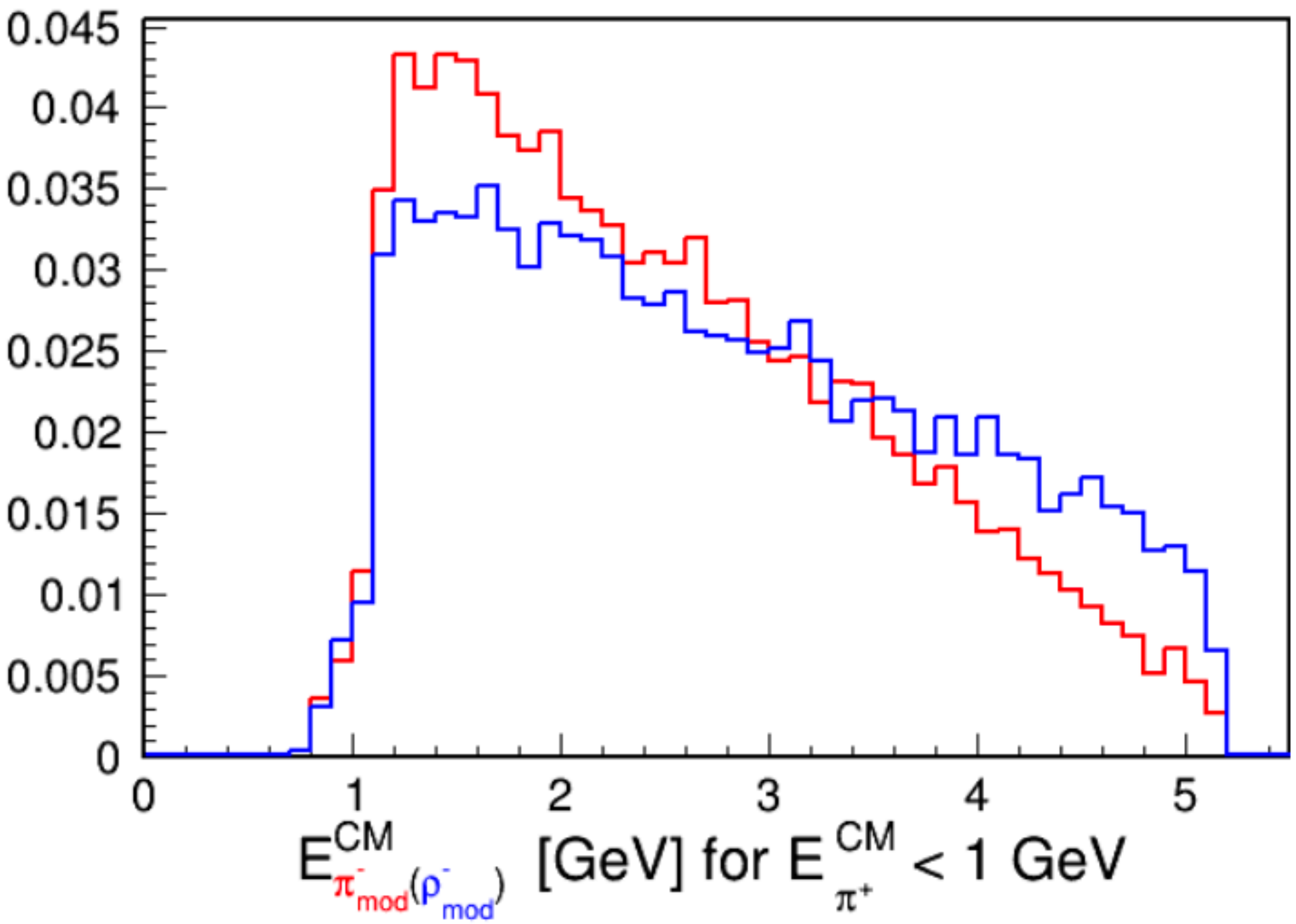


z: fraction of visible energy in τ decays

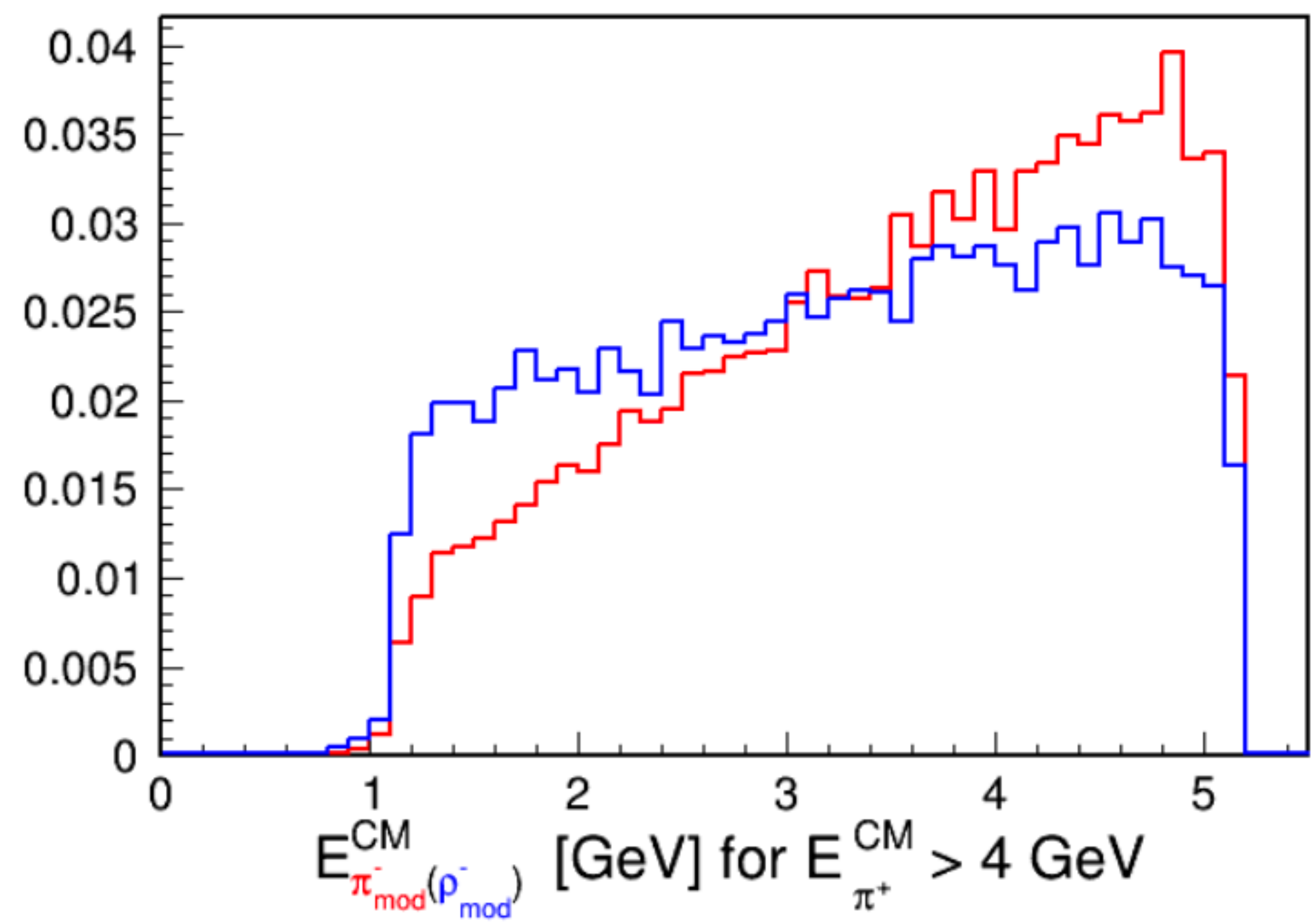
Bullock, Hagiwara, Martin Nucl. Phys. B395 (1993) 499

$\tau^- \to \pi^- \nu_\tau$ vs $\tau^- \to \rho^- \nu_\tau$

τ^- decays are generated in signal-side with changed meson masses,
$\tau^+ \to \pi^+ \bar{\nu}_\tau$ decays on the tag-side with usual meson mass.
[with m(π^-) = 770 MeV , m(ρ^-) = 770 MeV , m(π^+) = 139 MeV]



Preferentially select τ_L on the tag-side,
$\Rightarrow \tau_R$ on the signal-side

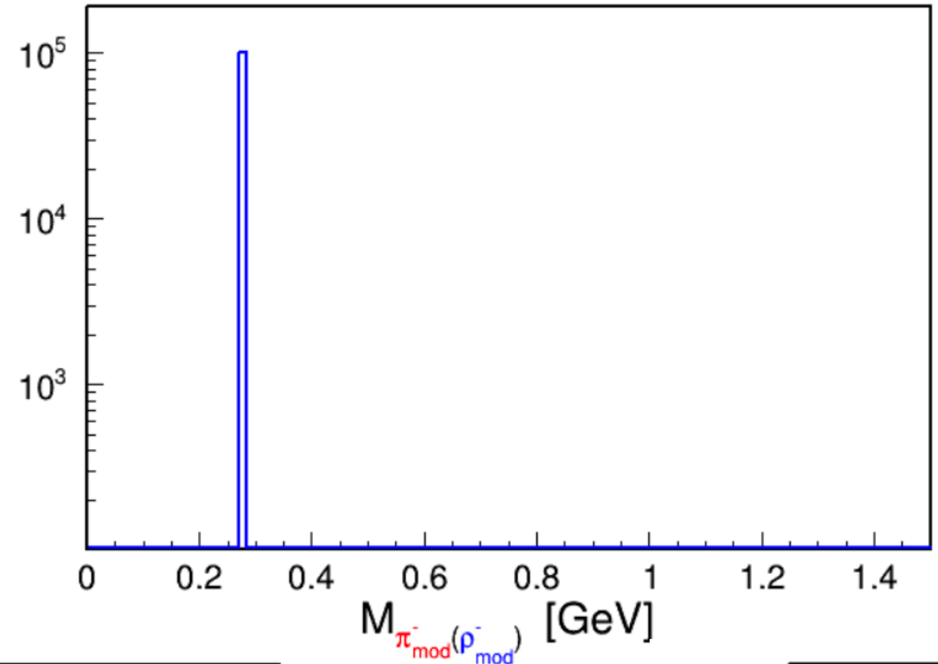


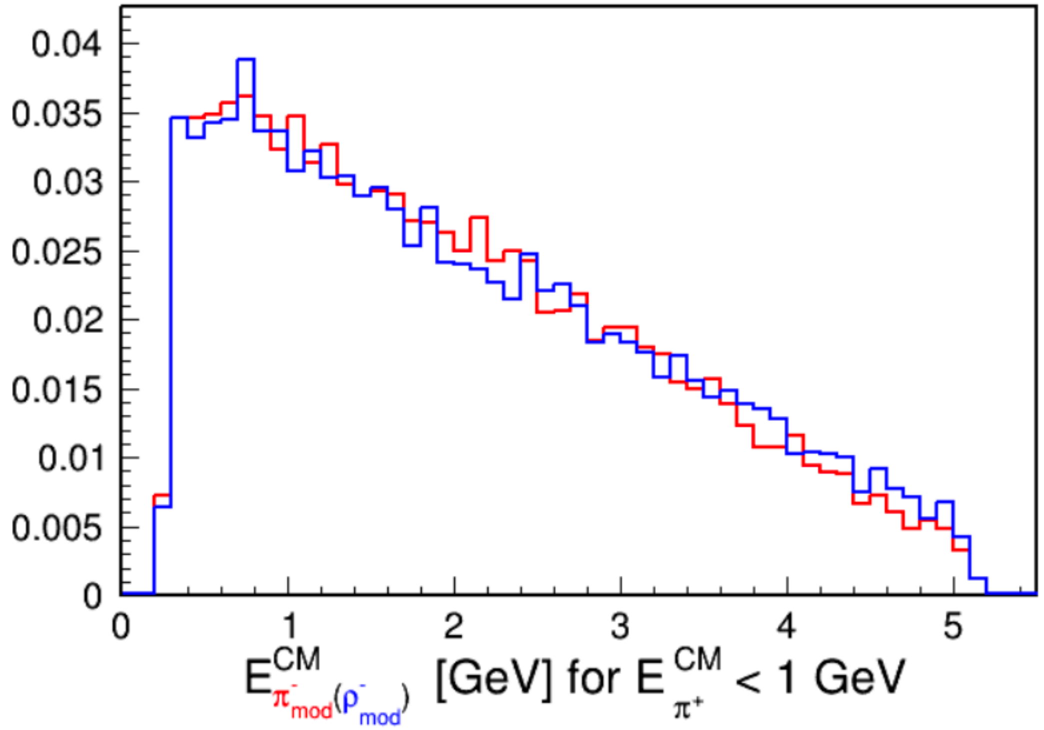
Preferentially select τ_R on the tag-side,
$\Rightarrow \tau_L$ on the signal-side

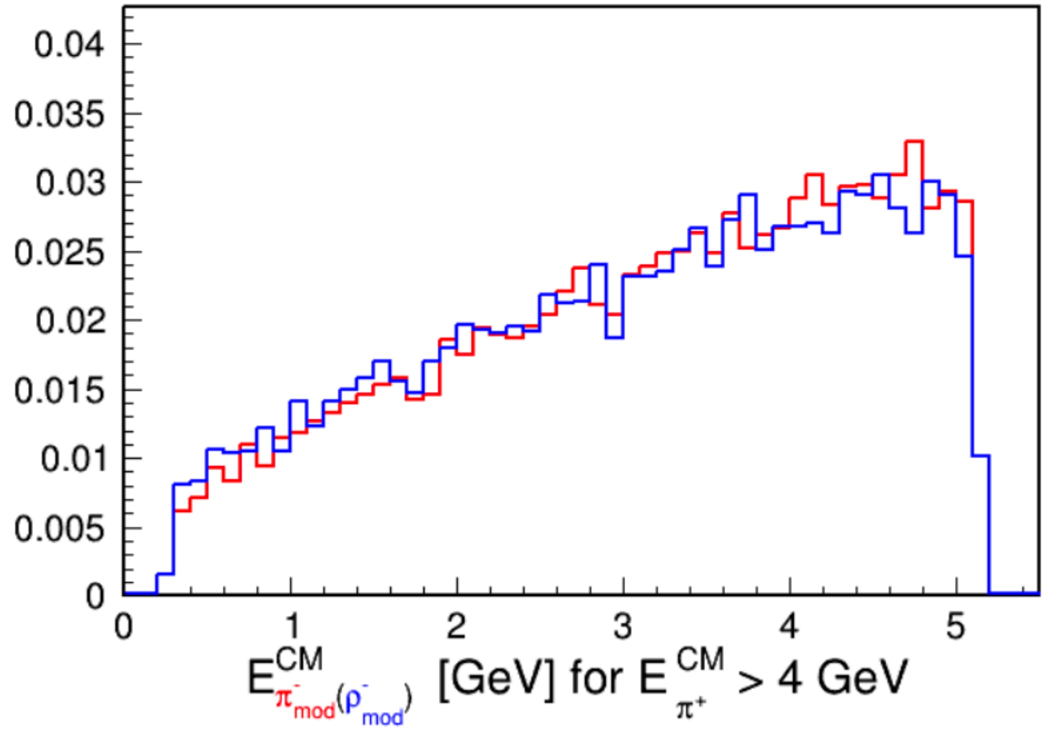
Distributions from polarized tau decays are indeed different.

$\tau^- \to \pi^- \nu_\tau$ vs $\tau^- \to \rho^- \nu_\tau$

Let us consider, hypothetically, both π^- and ρ^- with mass = 274 MeV.



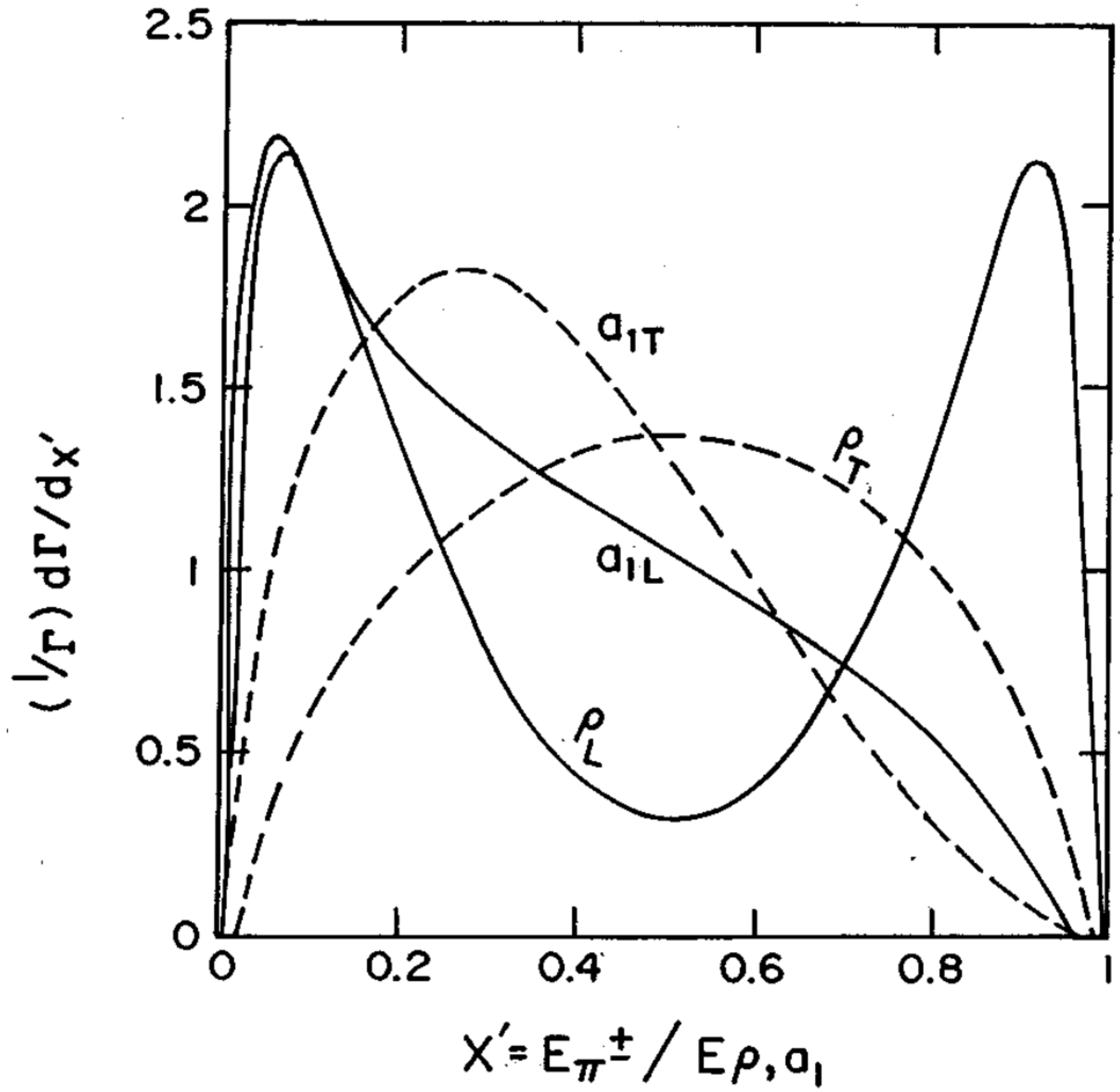




Setting mass of mesons to be same, washes out differences.

Distribution of decays products of the meson

Decay products of the meson are sensitive to polarization effects



S.Raychaudhuri, D.P.Roy Phys. Rev. D53 (1996) 4902

$\tau^- \to \ell^- \alpha$ [α: axion-like invisible particle]

Matrix element of $\tau^-(\vec{p}_1) \to \ell^-(\vec{p}_2) X(\vec{k})$: $|\mathcal{M}|^2 \propto (\omega + H_\mu s^\mu)$

<u>X is Scalar:</u> [Coupling = (A + γ_5 B)]

$$\omega^{scalar} = 2\left(A_S^2 + B_S^2\right) p_1 p_2 + 2\left(A_S^2 - B_S^2\right) m_1 m_2$$
$$H_\mu^{scalar} = 4 A_S B_S \cdot m_1 \left(p_2\right)_\mu / \omega^{scalar}$$

<u>X is Vector:</u> [Coupling = (A + γ_5 B)γ_μ]

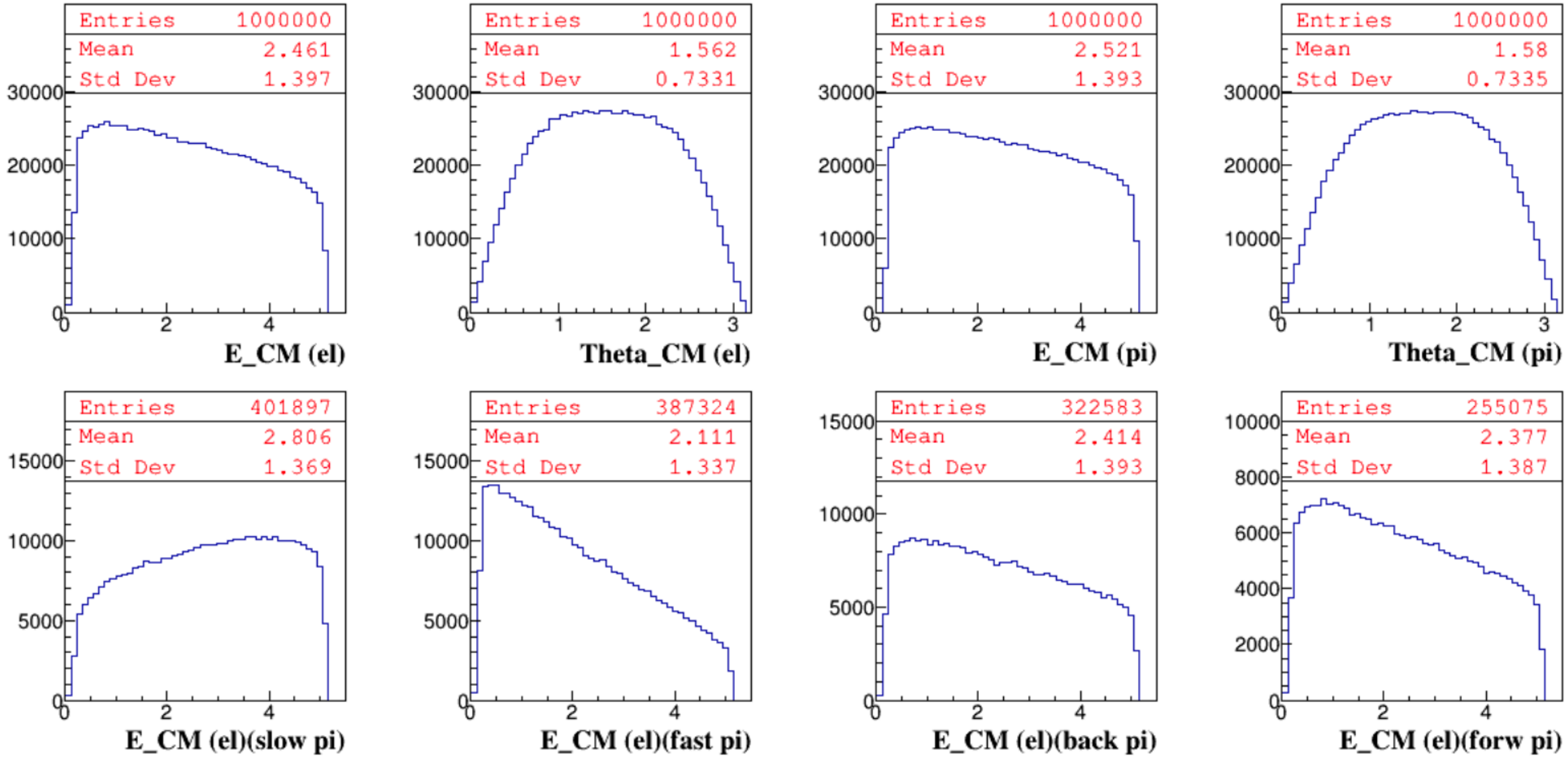
$$\omega^{vector} = 4\left(A_S^2 + B_S^2\right) p_1 p_2 - 4\left(A_S^2 - B_S^2\right) m_1 m_2$$
$$H_\mu^{vector} = 8 A_S B_S \cdot m_1 \left(p_2\right)_\mu / \omega^{vector}$$

- No spin dependence unless $A * B \neq 0$
- Spin dependence same for scalar and vector cases because spin state of X can not be measured with unpolarized beams.

$\tau^- \to \ell^- \alpha$ [α: axion-like invisible particle]

$M_\alpha = 0$ (Spin=0) [Coupling = $(A + \gamma_5 B)$]

TauolaBelle2 using DAM1PI_wrap:
AMINVI, ISPNVI, VCINVI, ACINVI = 0.00000000 0 0.500000000 0.500000000

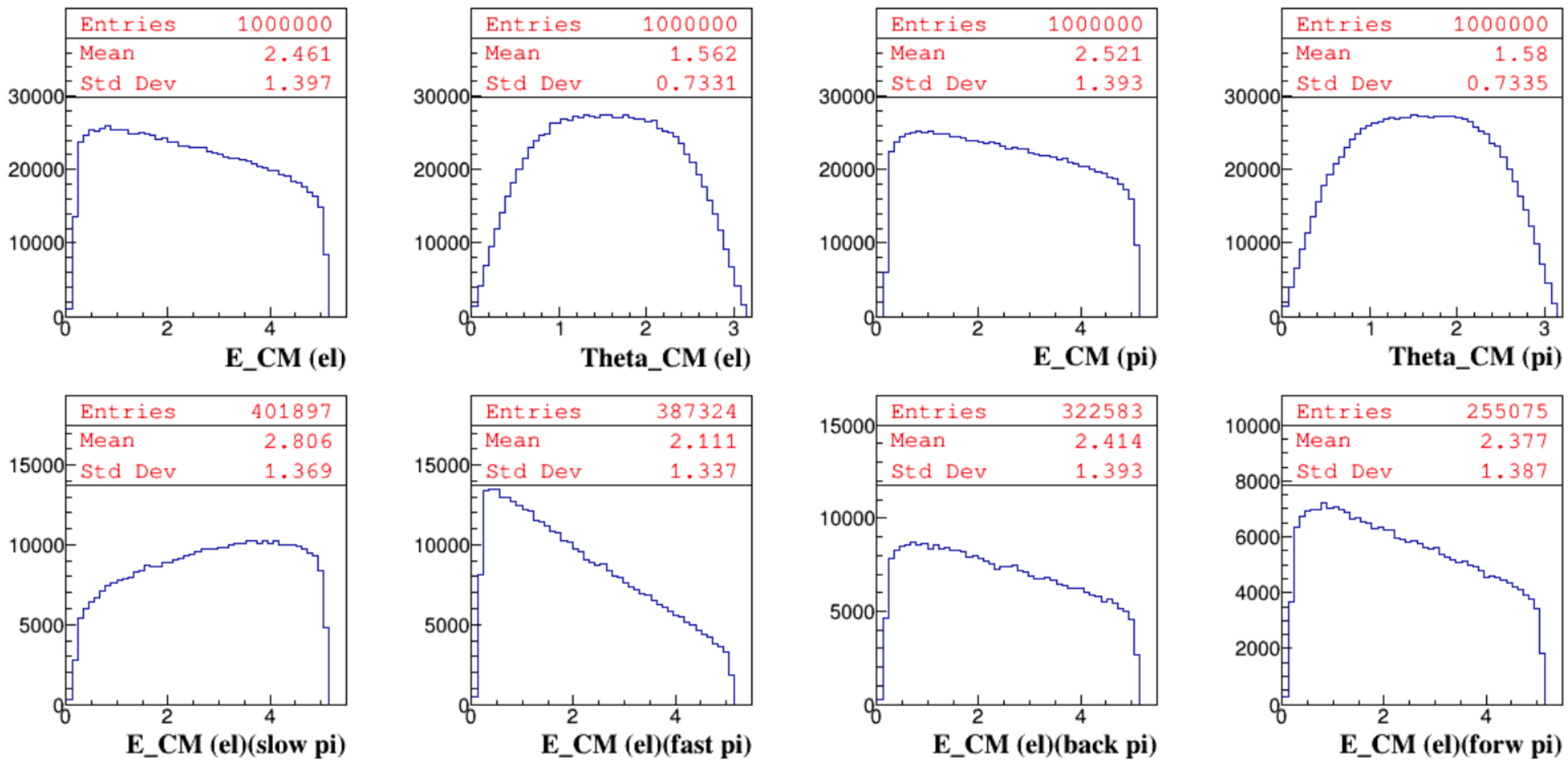


slow: $\mathrm{E}^{\pi}_{\mathrm{CM}} < 2.0\mathrm{GeV}$; fast: $\mathrm{E}^{\pi}_{\mathrm{CM}} > 3.0\mathrm{GeV}$; back: $\theta^{\pi}_{CM} > 2.0^c$; forw: $\theta^{\pi}_{CM} < 1.0^c$.

$\tau^- \to \ell^- \alpha$ [α: axion-like invisible particle]

$M_\alpha = 0$ (Spin=1) [Coupling = $(A + \gamma_5 B)\gamma_\mu$]

TauolaBelle2 using DAM1PI_wrap:
AMINVI, ISPNVI, VCINVI, ACINVI = 0.00000000 1 0.500000000 0.500000000

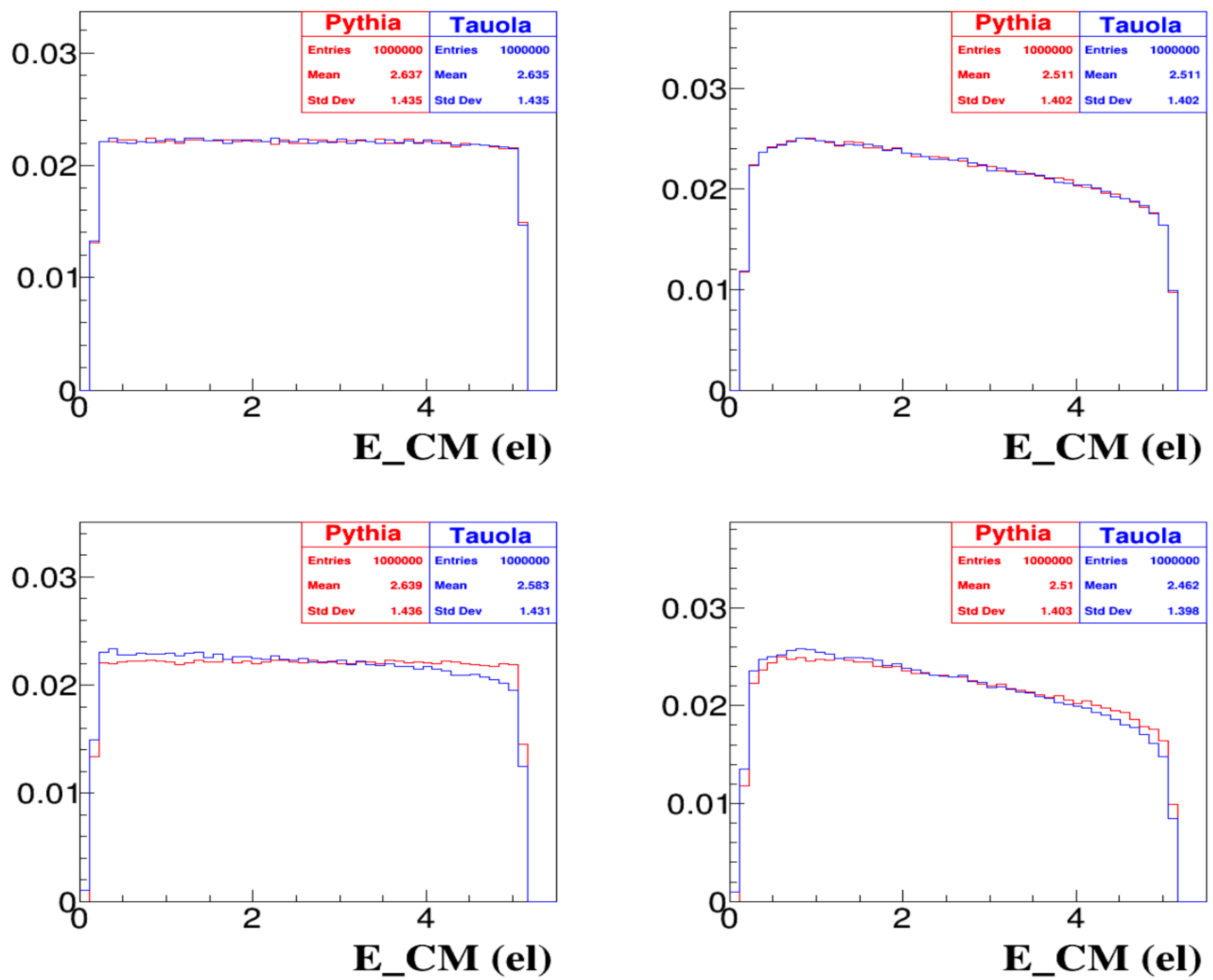


slow: $E^\pi_{CM} < 2.0$GeV; fast: $E^\pi_{CM} > 3.0$GeV; back: $\theta^\pi_{CM} > 2.0^c$; forw: $\theta^\pi_{CM} < 1.0^c$.

$\tau^- \to \ell^- \alpha$ [α: axion-like invisible particle]

TauolaBelle (Pythia) vs TauolaBelle2

Photos: Off; ISR: Off	Photos: Off; ISR : On



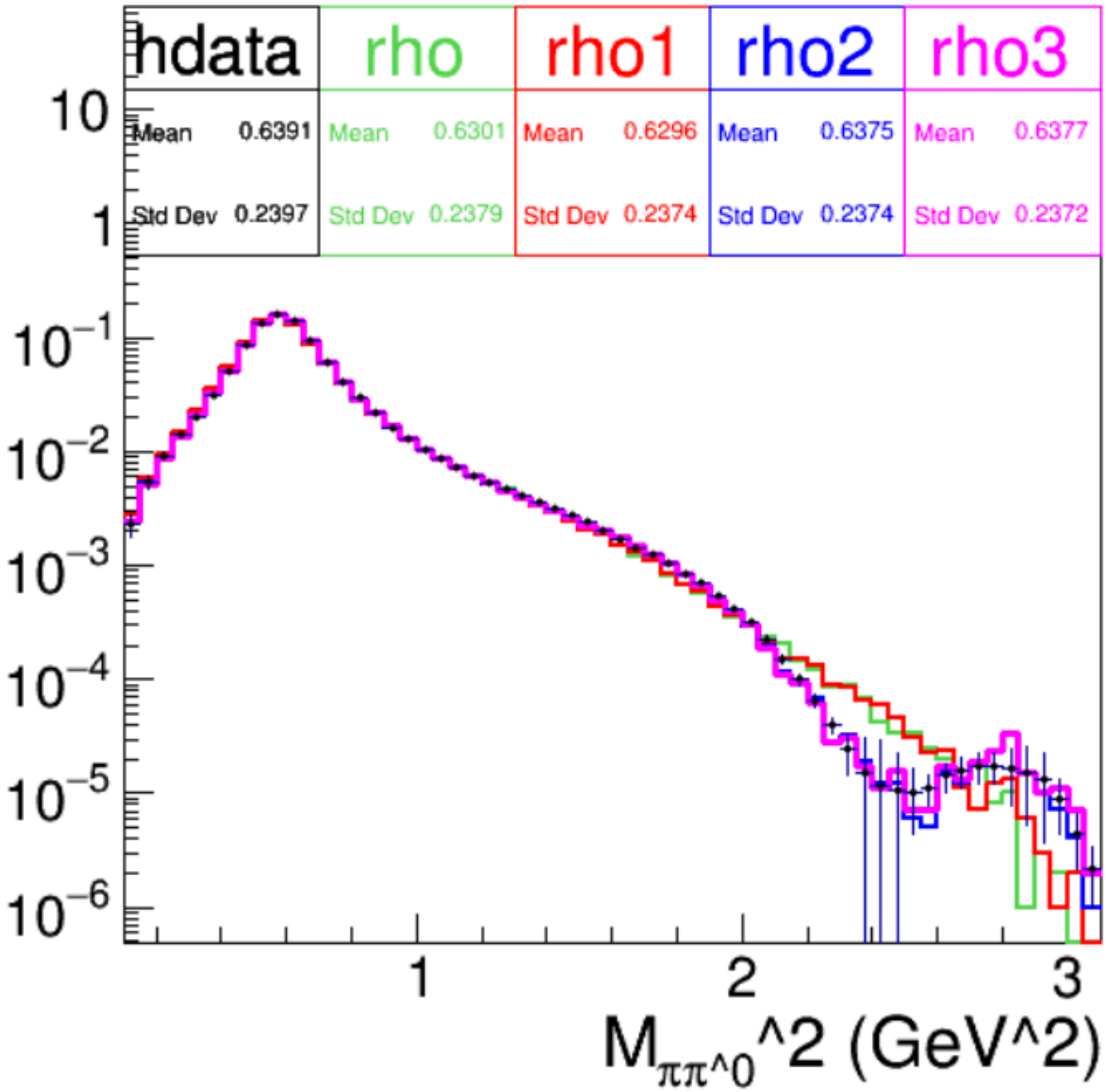
Photos: On; ISR: Off	Photos: On; ISR : On

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:

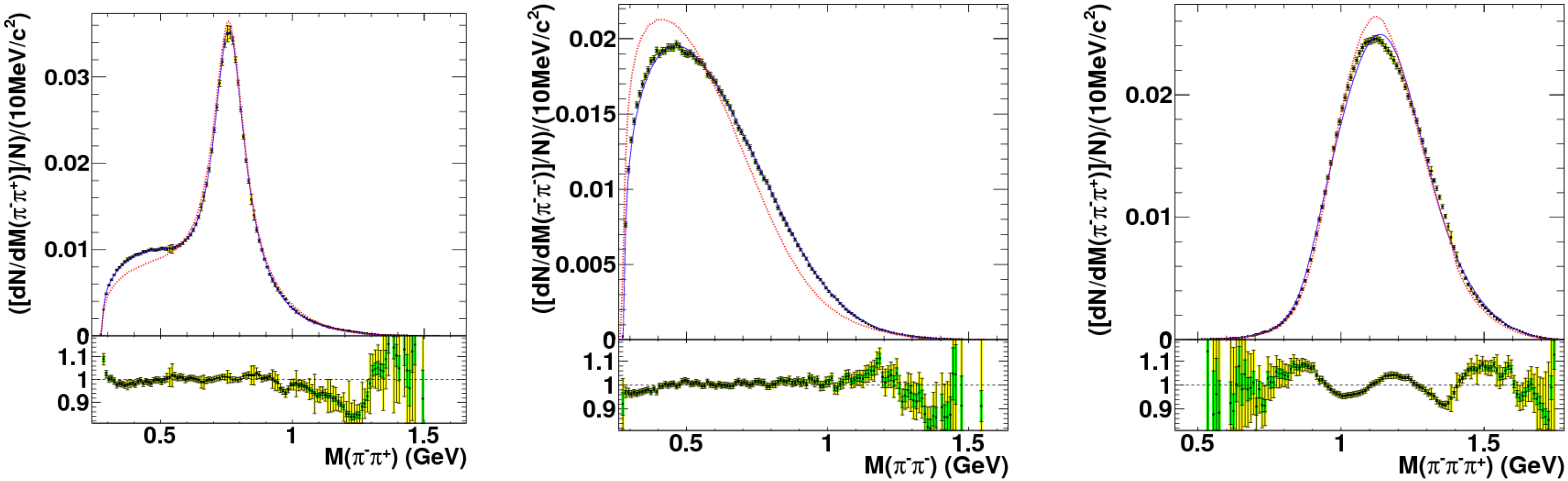
hdata is obtained from the distribution published by Belle: M. Fujikawa et al., "High-Statistics Study of the tau- → pi- pi0 nu(tau) Decay", Phys. Rev. D 78 (2008) 072006, arXiv:0805.3773 [hep-ex].

rho is generated with **TaoulaBelle**

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



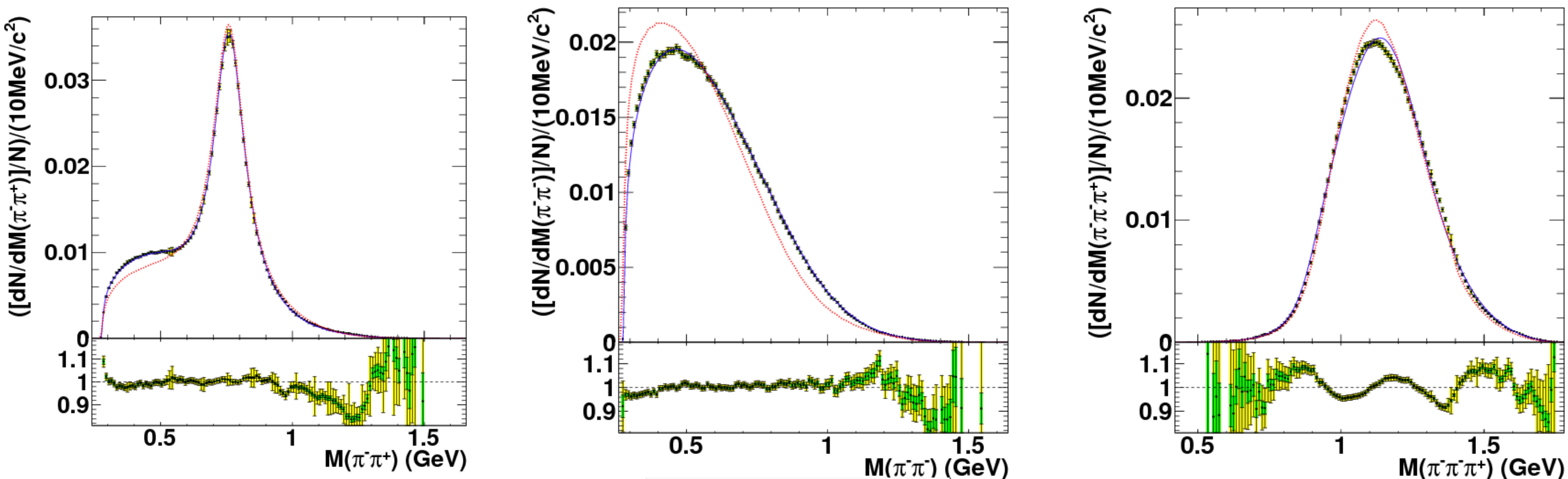
Resonance chiral Lagrangian currents and experimental data for $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$

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)

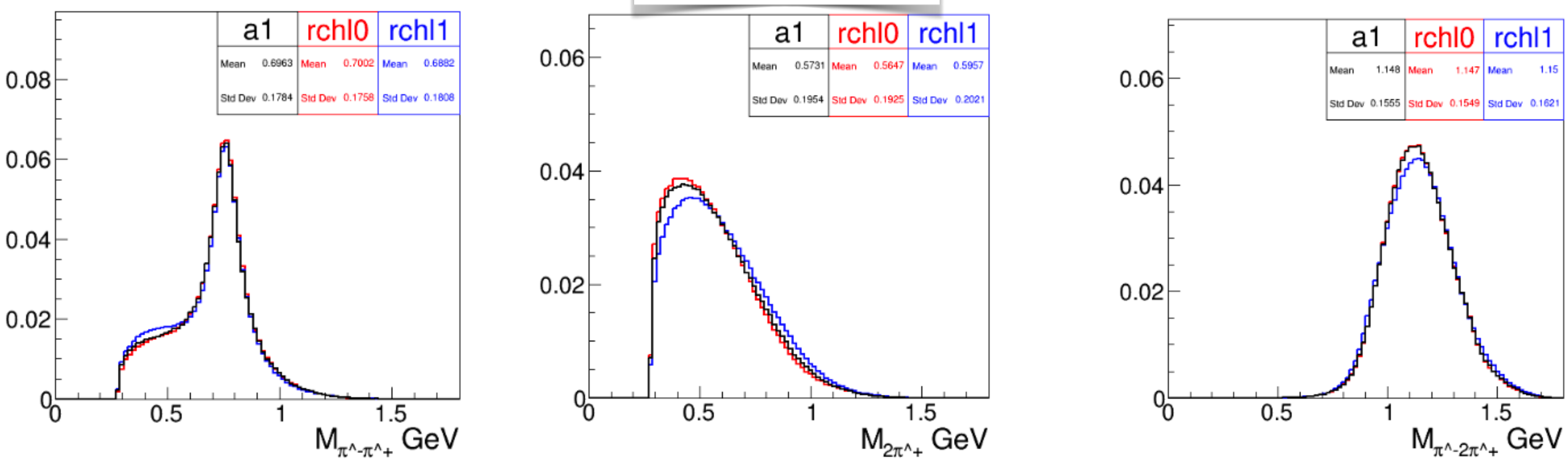
Oct 3, 2013 - 14 pages

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



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



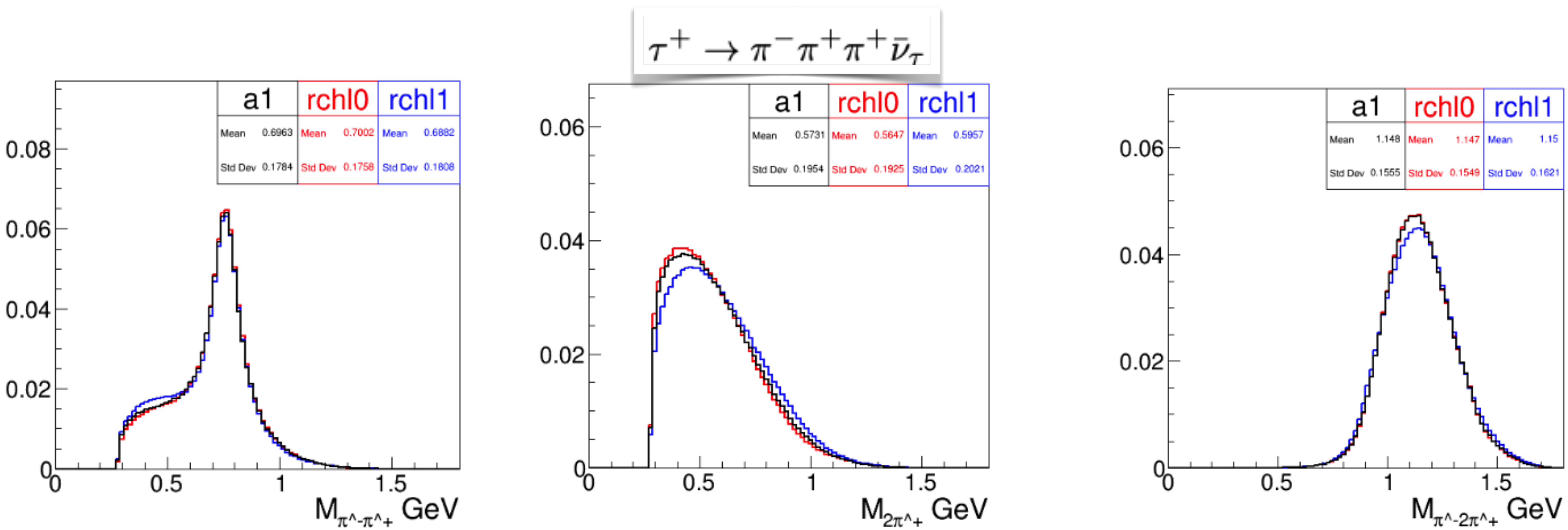
3-pion decays

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.



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

K1(1270) + K1(1400) interference

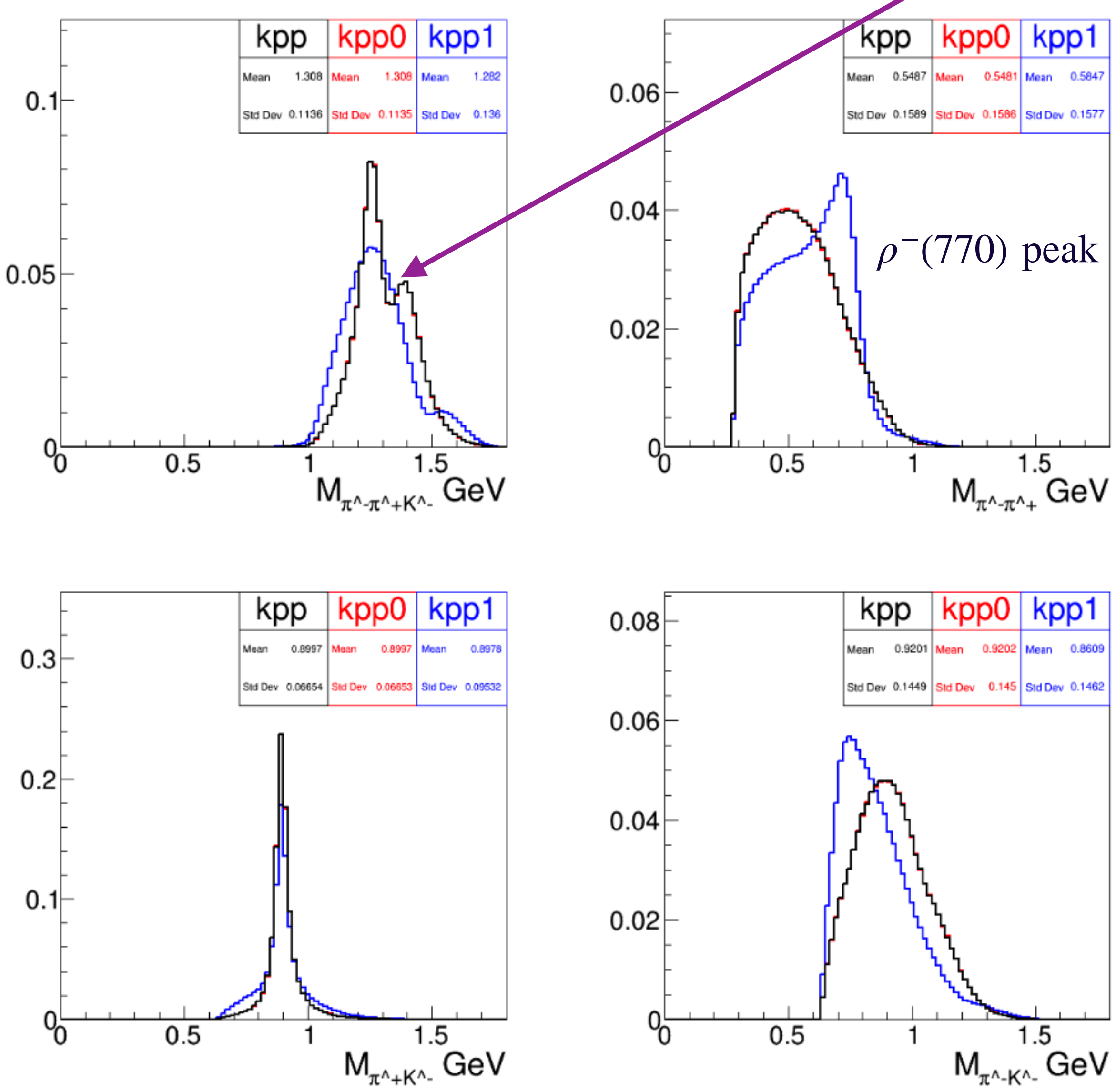


FIG. 96. Invariant mass distributions in $\tau^- \rightarrow \pi^-\pi^+K^-\nu_\tau$ decays.

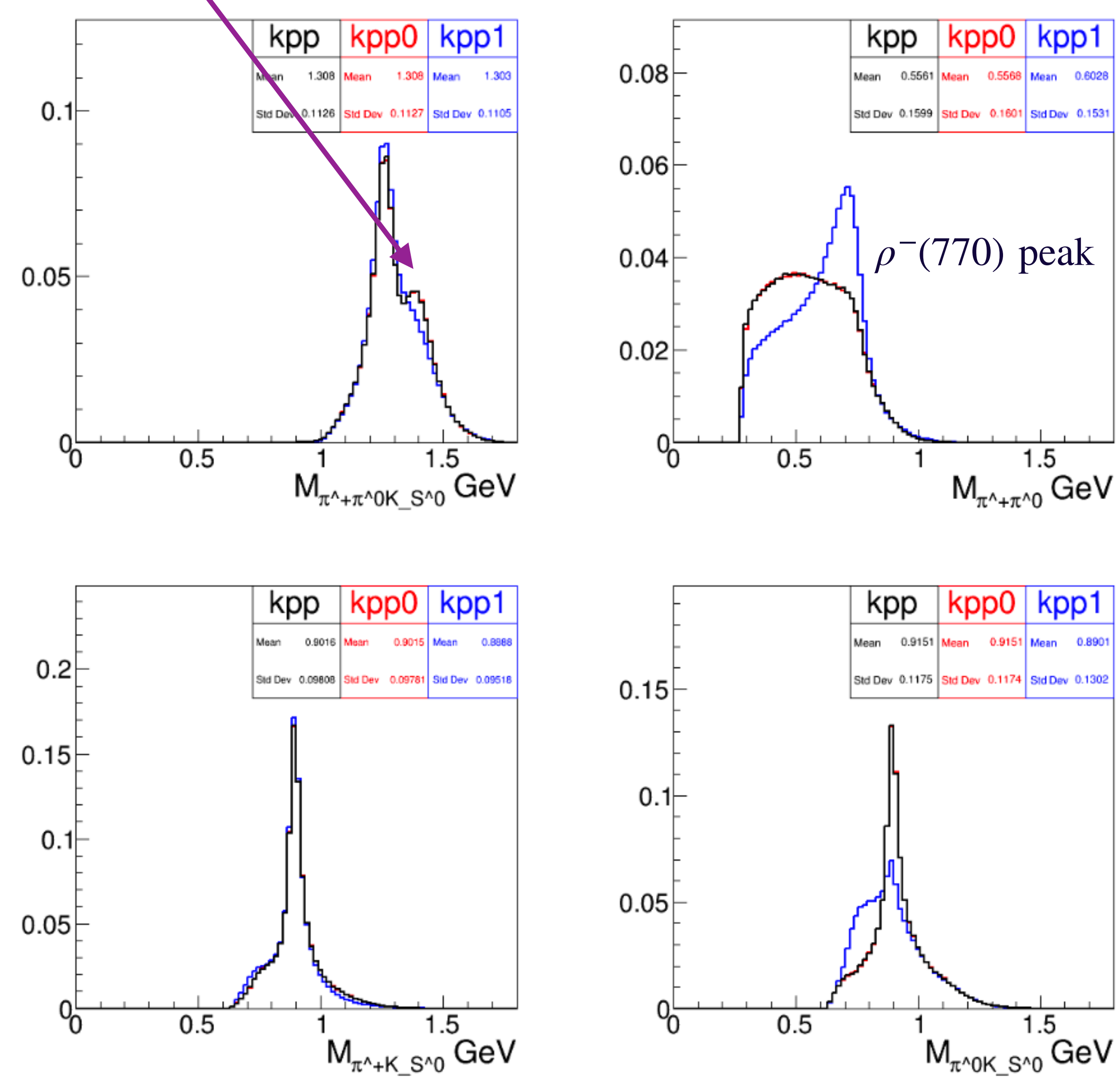


FIG. 97. Invariant mass distributions in $\tau^+ \rightarrow \pi^+\pi^0K^0_S\bar{\nu}_\tau$ decays.

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

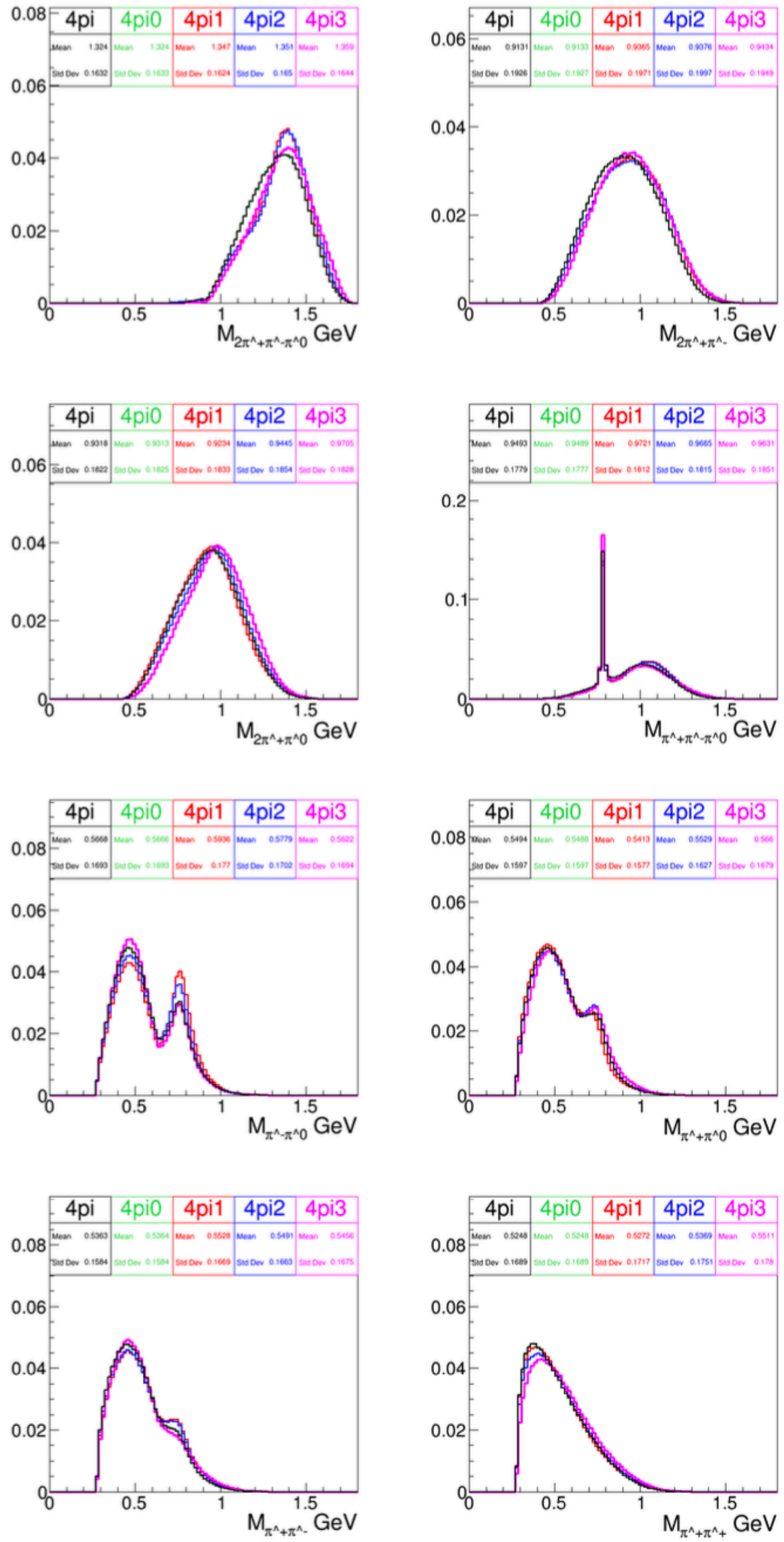


FIG. 98. Invariant mass distributions in $\tau^+ \to 2\pi^+\pi^-\pi^0\bar{\nu}_\tau$ decays.

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

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

4-pion decays

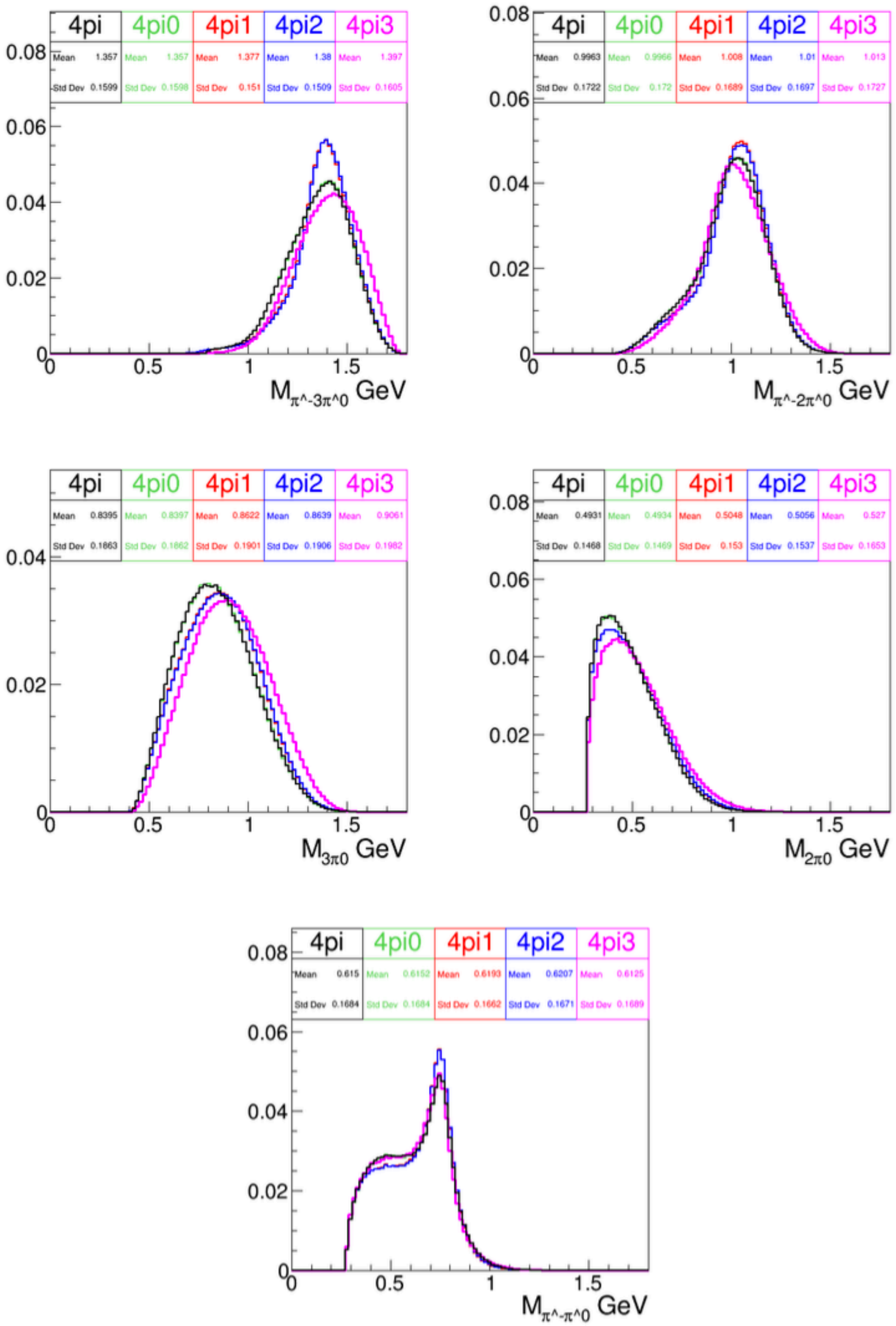


FIG. 99. Invariant mass distributions in $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ decays.

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

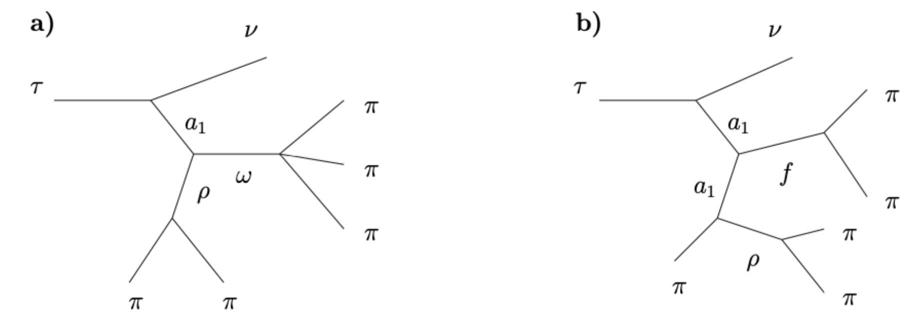
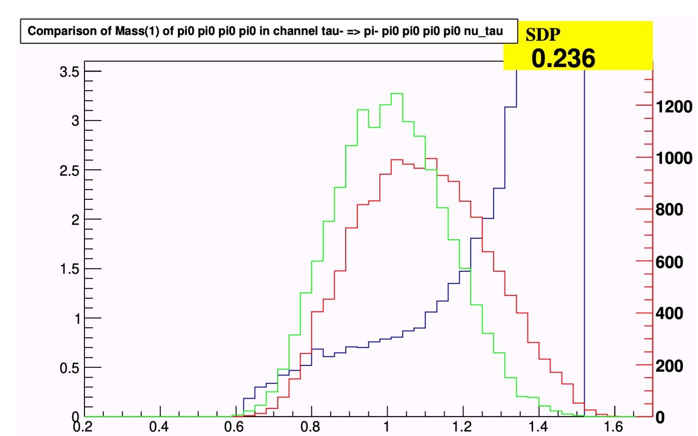
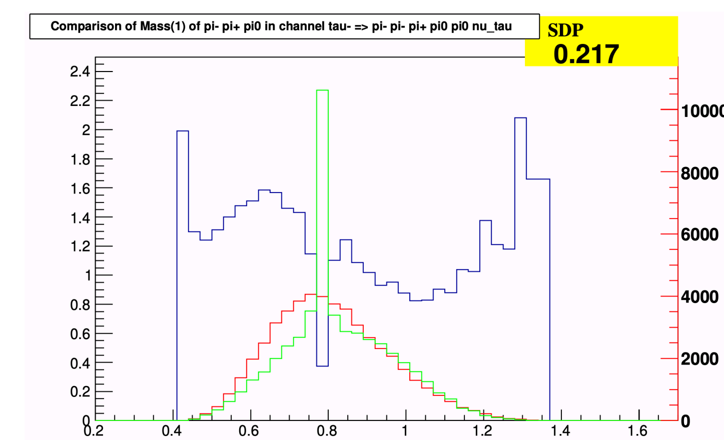


Figure 1: *Dominant decay amplitude for the decay of τ into five pions through an ω plus a ρ resonance (a) and through an f_0 plus $a_1(\to \rho\pi)$ (b).*

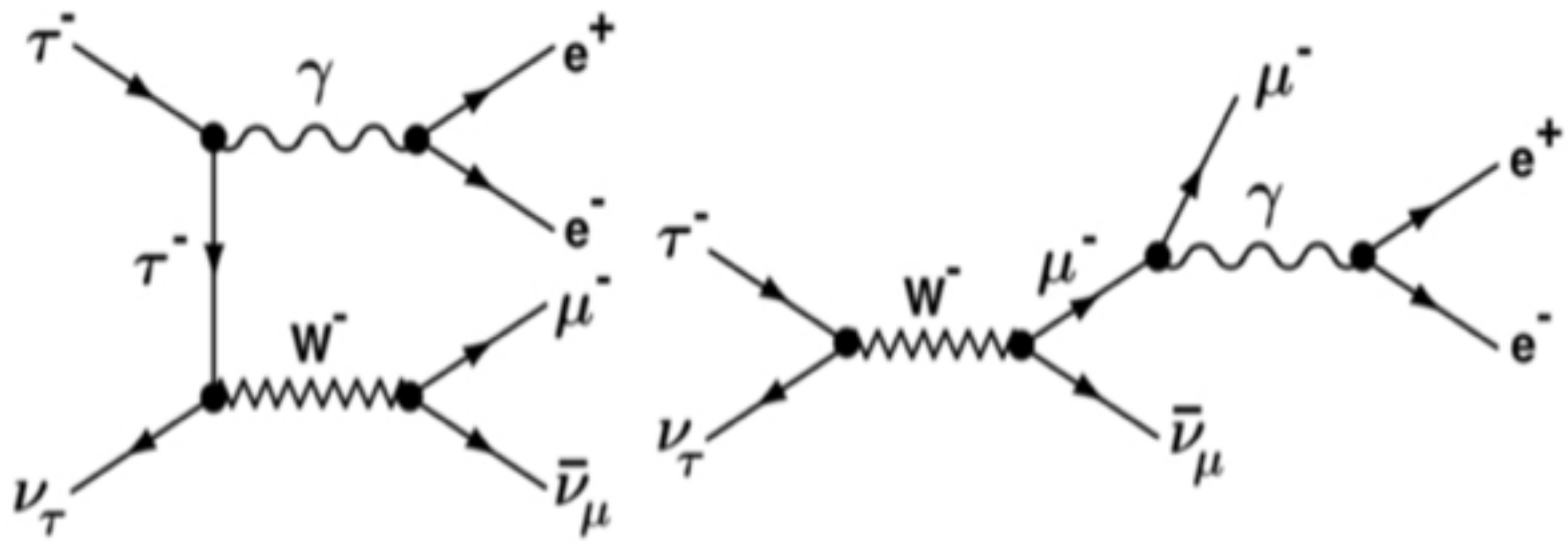
$\tau^- \to \pi^- 4\pi^0 \nu$ and $2\pi^-\pi^+2\pi^0\nu$ decays





Green: TauolaBelle2
Red: TauolaBelle
Blue: Ratio

Tau decays into three charged leptons and two neutrinos



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:

$$\int |M|^2 \, dLips_5(p_\tau, p_{e-}, p_{e+}, p_\nu, p_{\bar{\nu}}, p_\mu) =$$
$$= \int |M_F|^2 \frac{d^3 p_{e-}}{(2\pi)^3 2p^0_{e-}} \frac{d^3 p_{e+}}{(2\pi)^3 2p^0_{e+}} \, d^4R \, \delta^4(R - p_\tau + p_{e-} + p_{e+}) \times$$
$$\times \int |M(p_\tau, p_\nu, p_{\bar{\nu}}, p_\mu)|^2 \frac{d^3 p_\nu}{(2\pi)^3 2p^0_\nu} \frac{d^3 p_{\bar{\nu}}}{(2\pi)^3 2p^0_{\bar{\nu}}} \frac{d^3 p_\mu}{(2\pi)^3 2p^0_\mu} (2\pi)^4 \delta^4(R - p_\nu - p_{\bar{\nu}} - p_\mu), \quad (11)$$

Soft lepton pair emission at the low boundary of phase space.

PHOTOS++ [N. Davidson, T. Przedzinski, Z. Was, Comput.Phys.Commun. 199 (2016) 86-101]

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}.

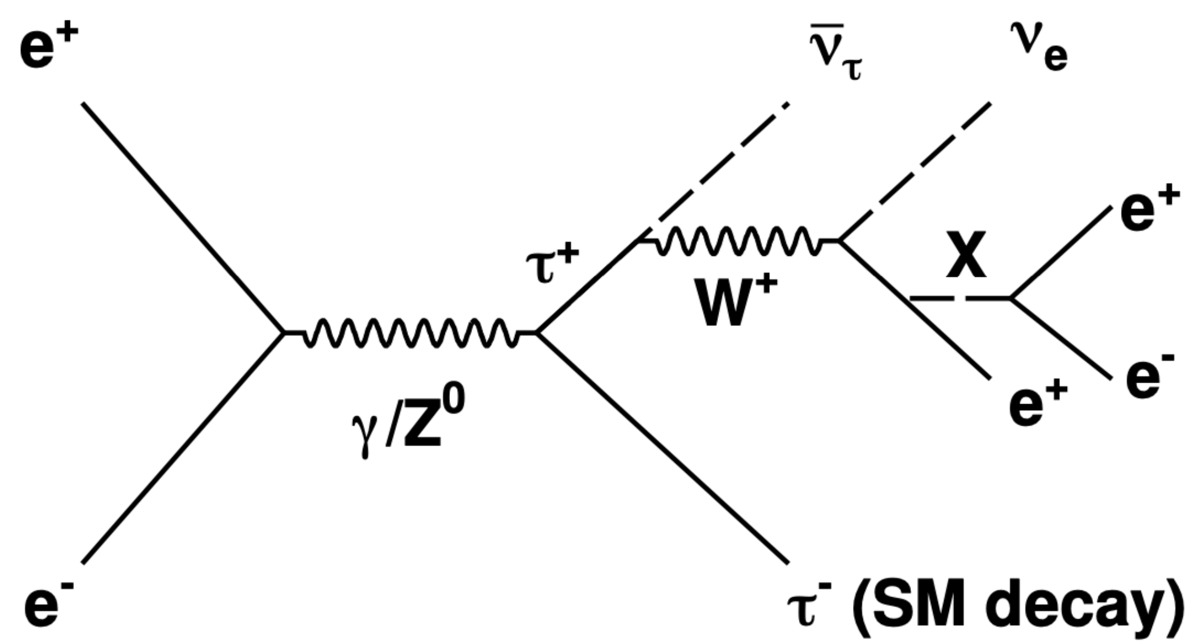
The presampler parameters available through user interface are:

- 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},

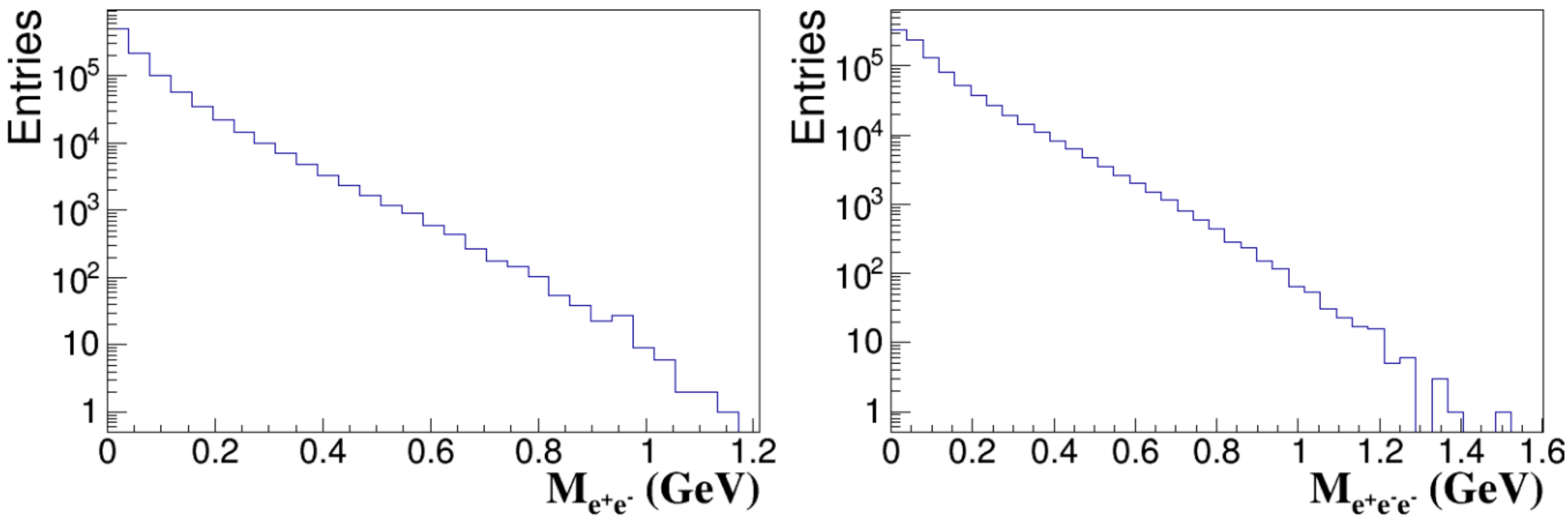
A.5 Phase space for decays into N and 2 particles

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.

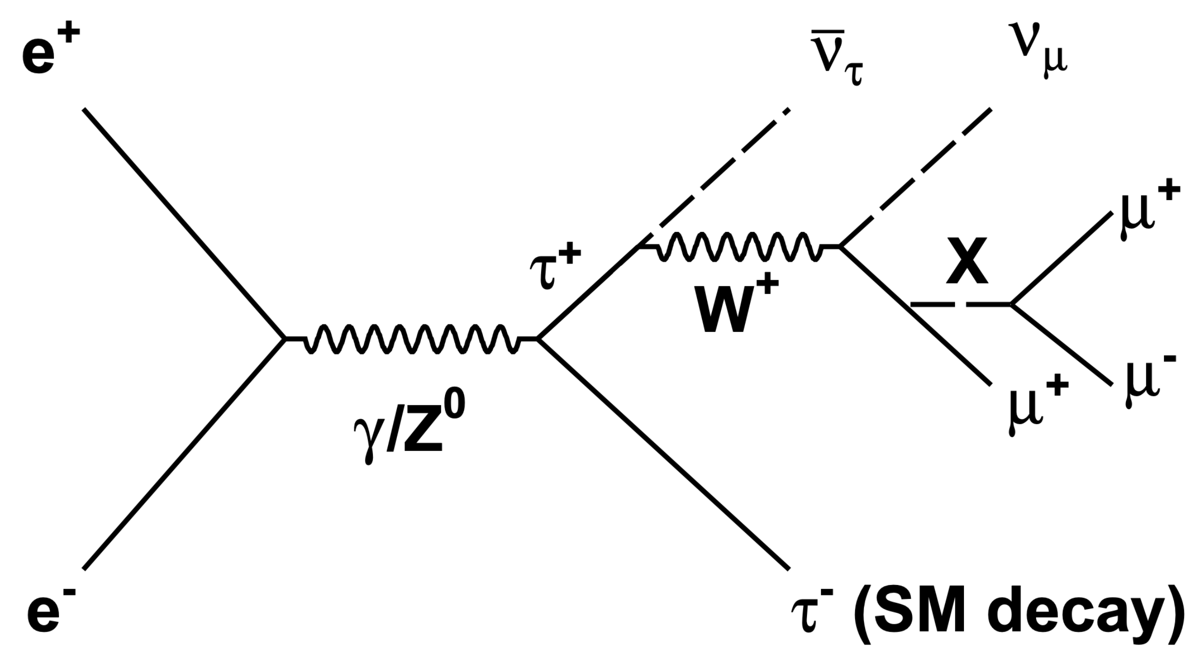
$\tau^- \to \bar{\nu}_e e^- e^- e^+ \nu_\tau$



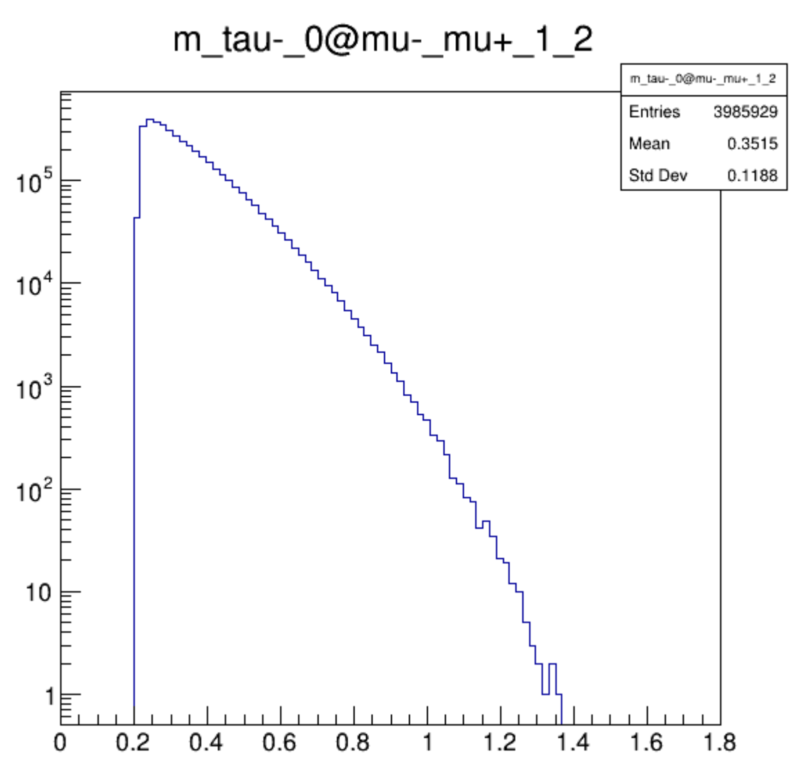
Matrix element from https://arxiv.org/pdf/1912.11376.pdf

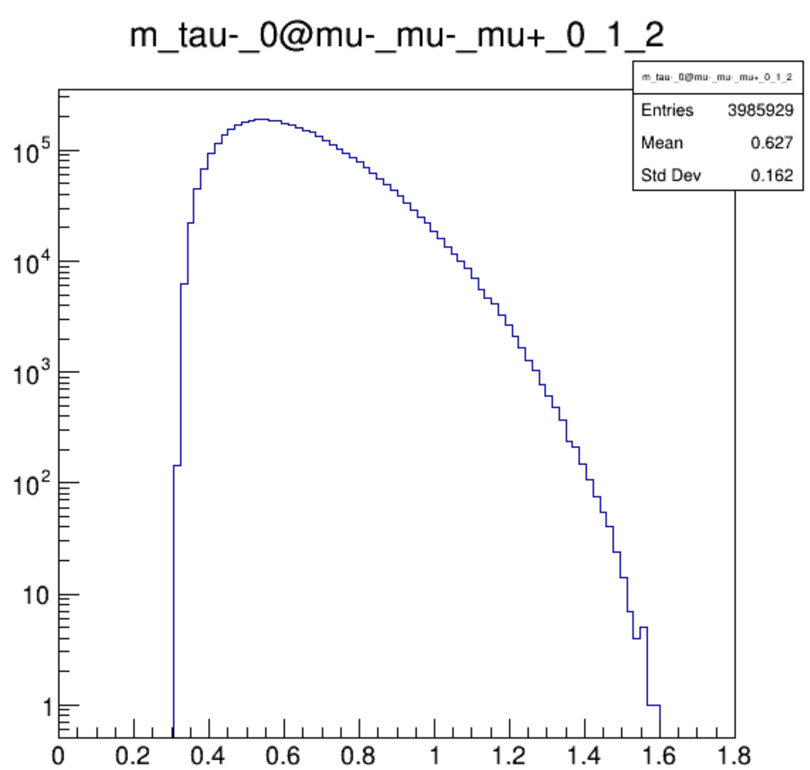


$\tau^- \to \bar{\nu}_\mu \mu^- \mu^- \mu^+ \nu_\tau$



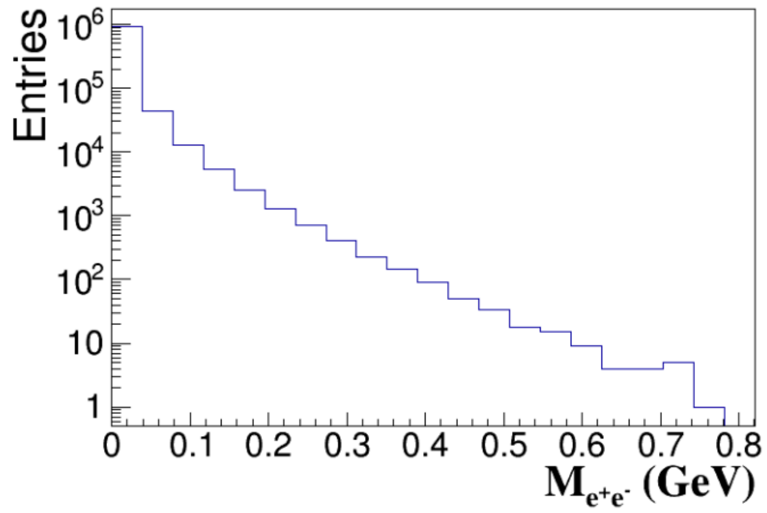
Matrix element from https://arxiv.org/pdf/1912.11376.pdf

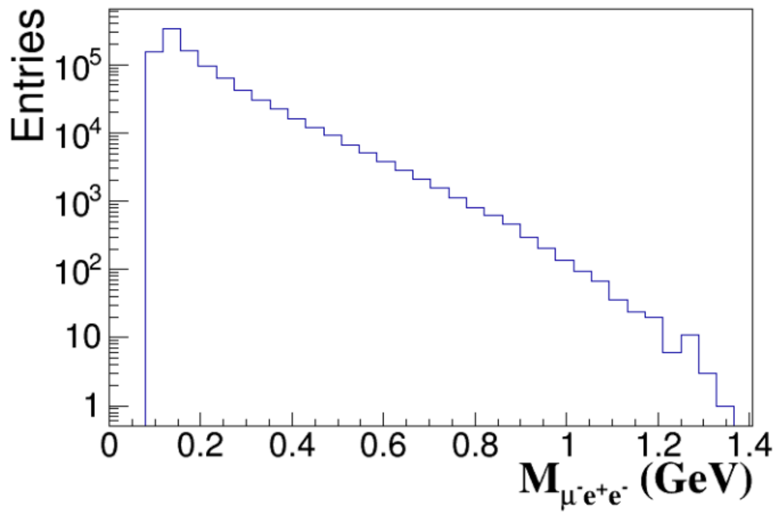




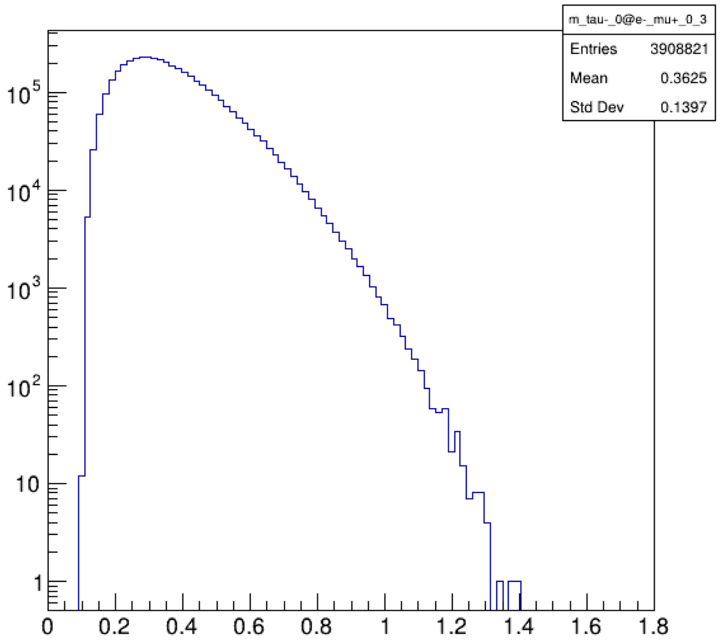
Pre-sampler optimizations

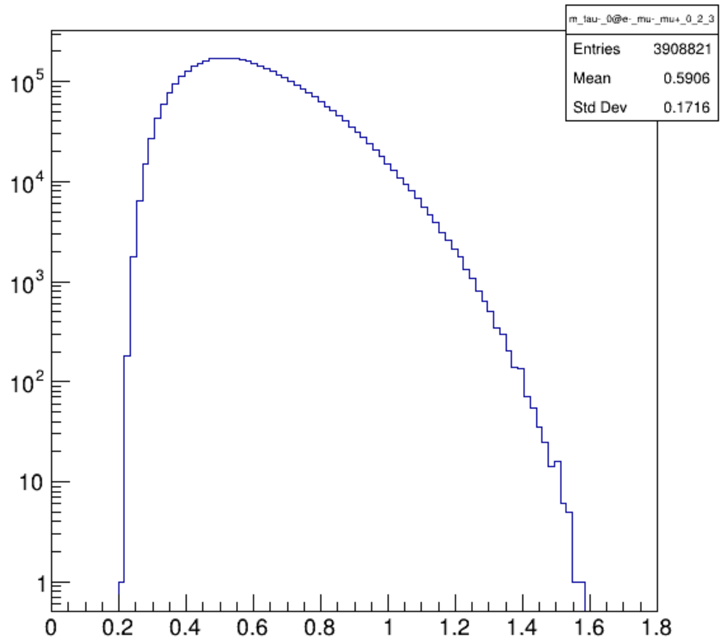
$$\tau^- \rightarrow \bar{\nu}_e \mu^- e^- e^+ \nu_\tau$$





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





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

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.

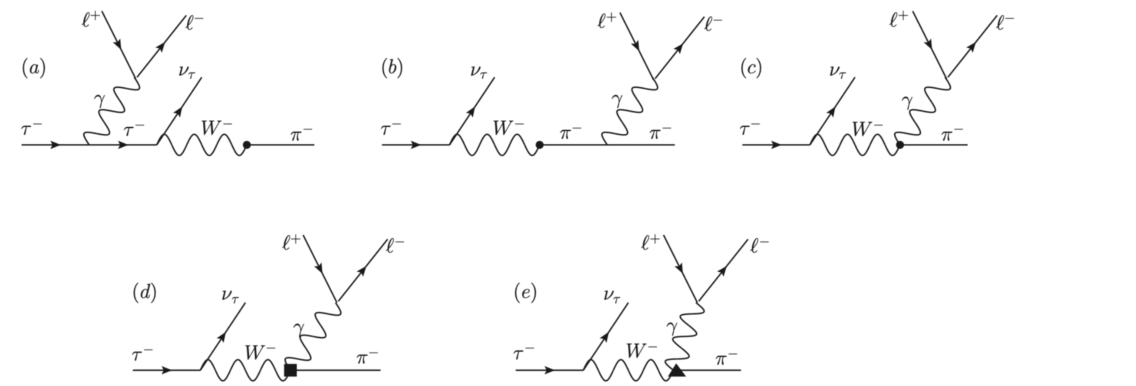
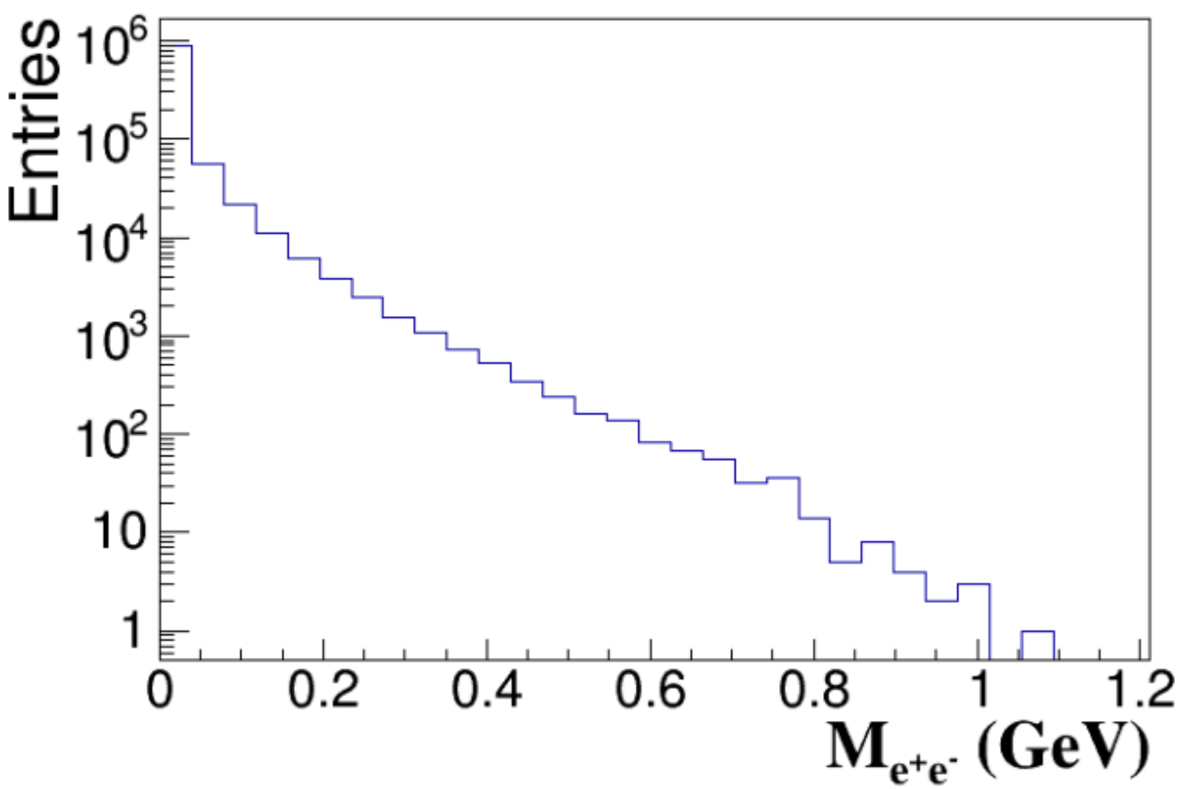
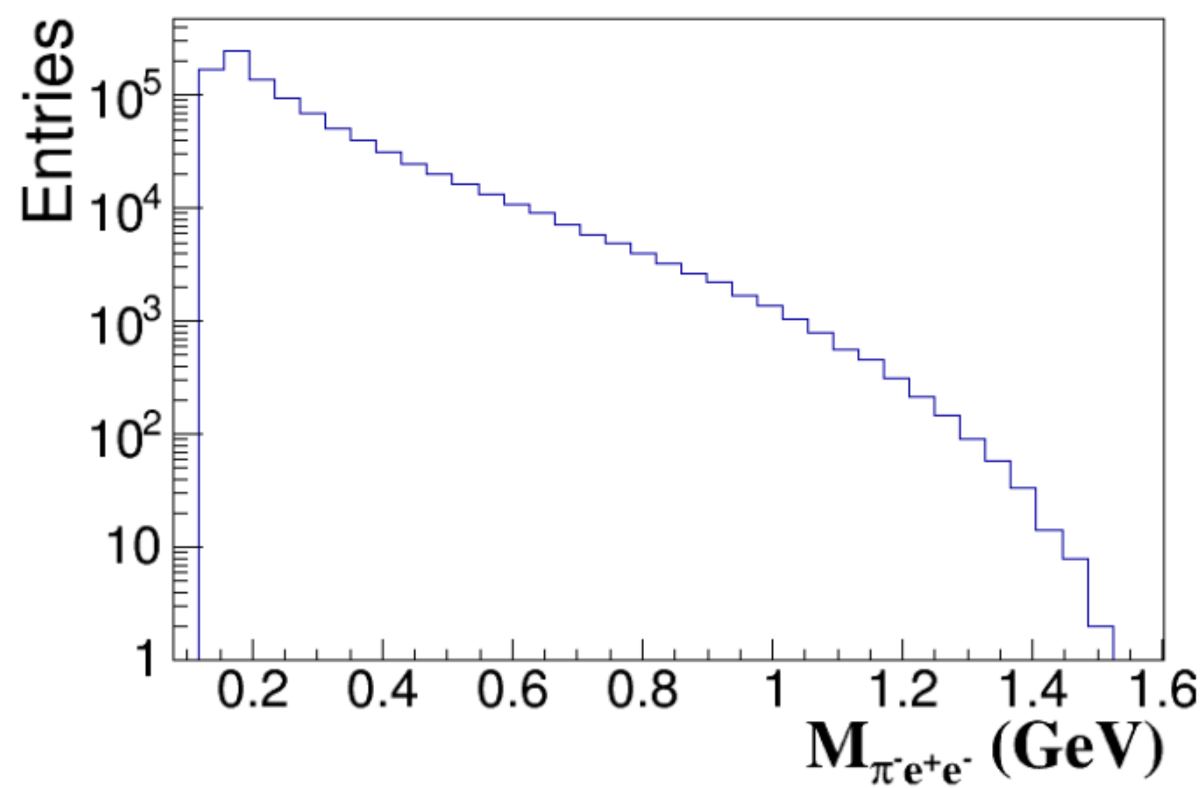


Figure 1: Feynman diagrams for the different kinds of contributions to the $\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ decays, as explained in the main text. The dot indicates the hadronization of the QCD currents. The solid square (triangle) represents the SD contribution mediated by the axial-vector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

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

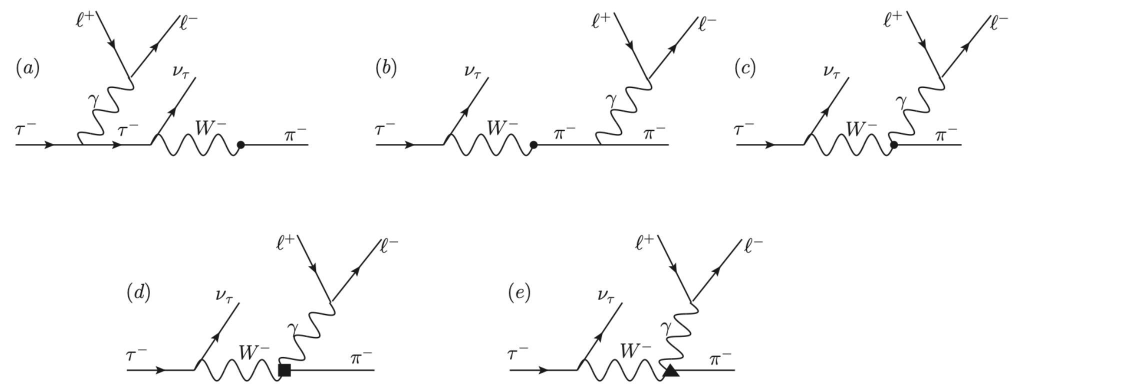
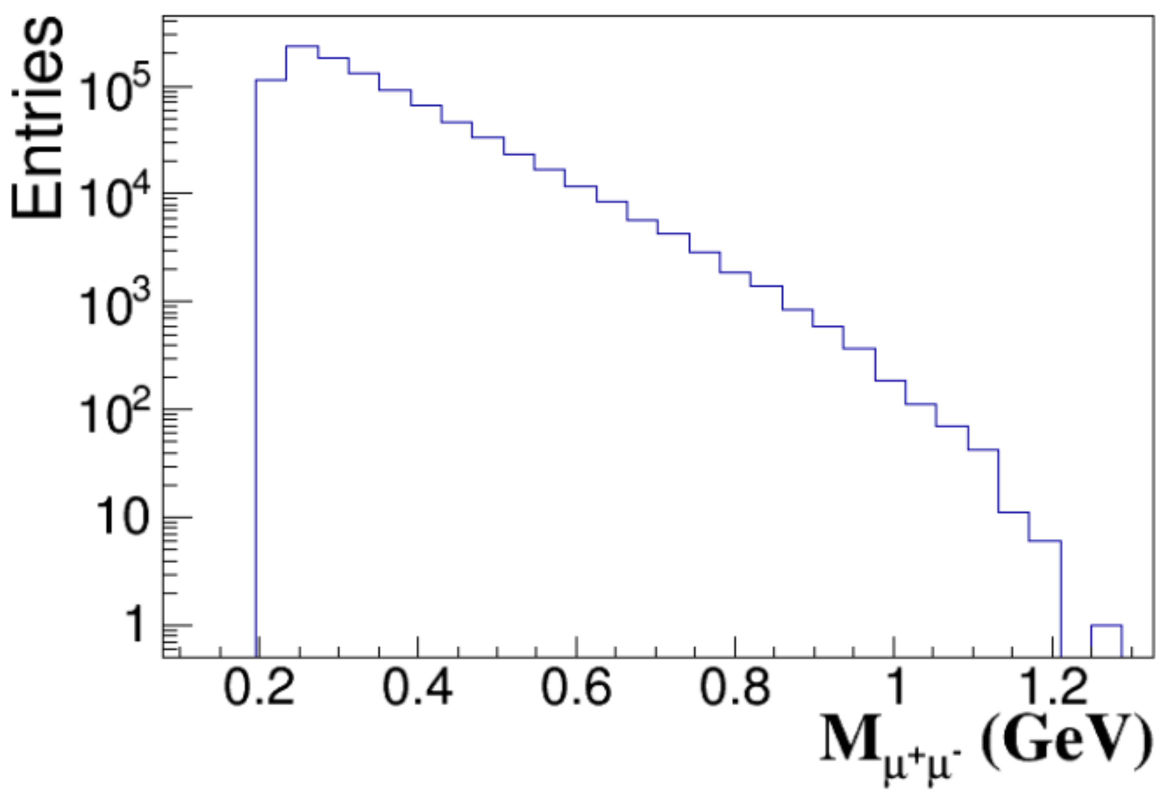
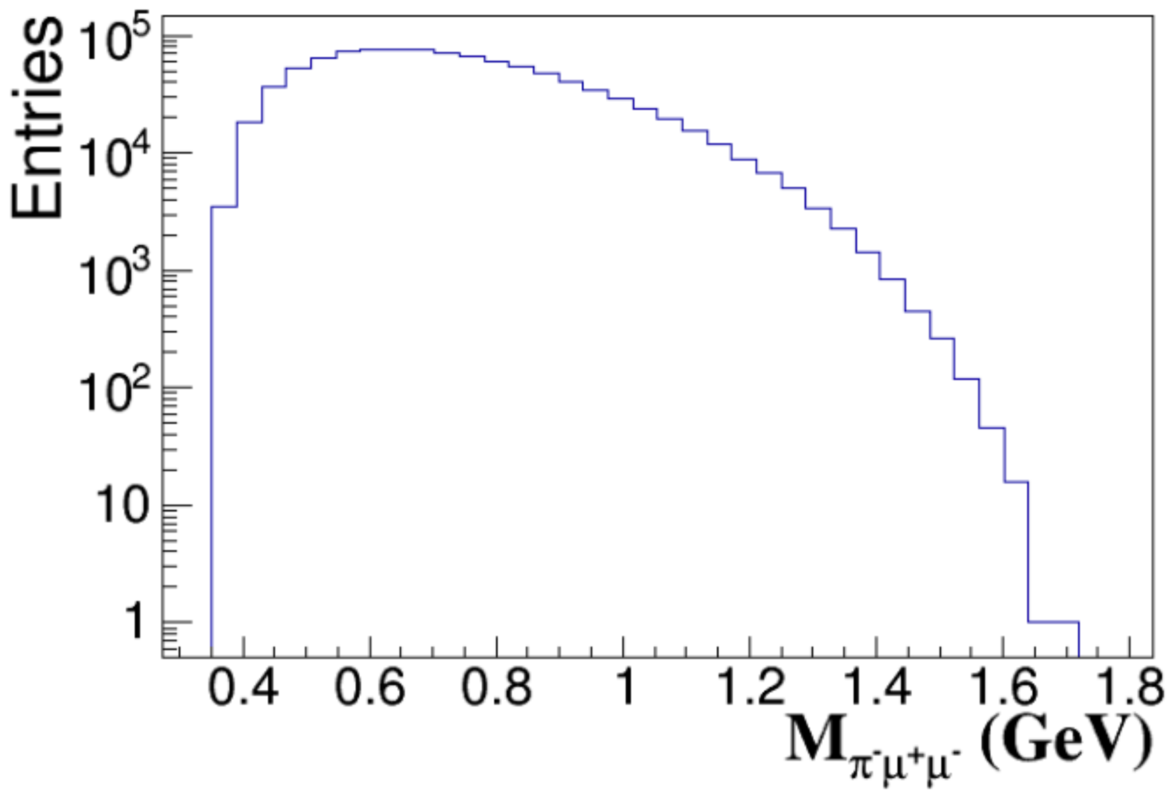


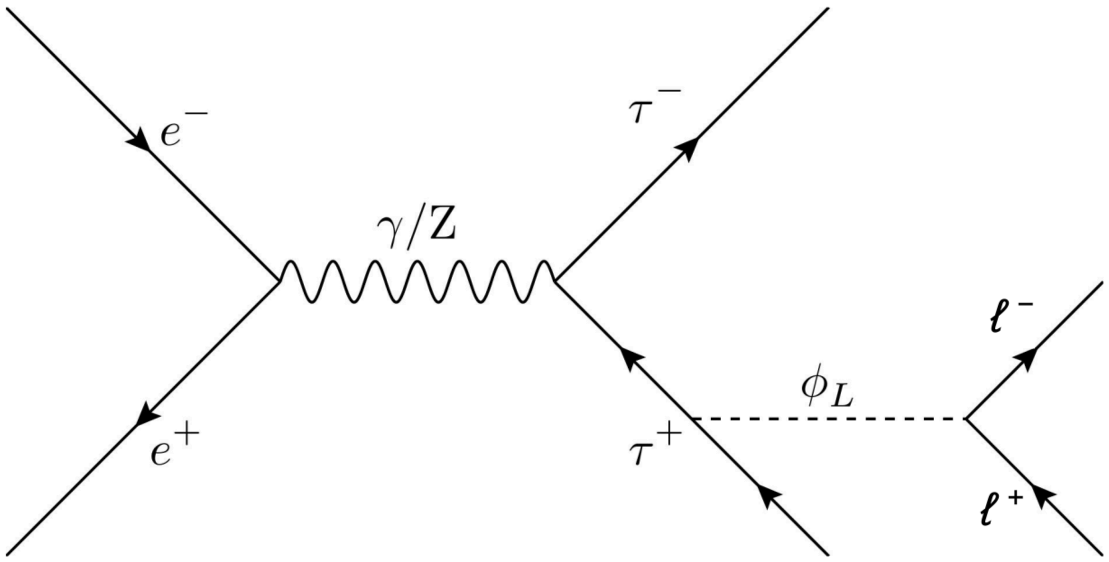
Figure 1: Feynman diagrams for the different kinds of contributions to the $\tau^- \to \pi^-\nu_\tau\ell^+\ell^-$ decays, as explained in the main text. The dot indicates the hadronization of the QCD currents. The solid square (triangle) represents the SD contribution mediated by the axial-vector (vector)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

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





Dark leptophilic scalar decaying into a pair of leptons



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

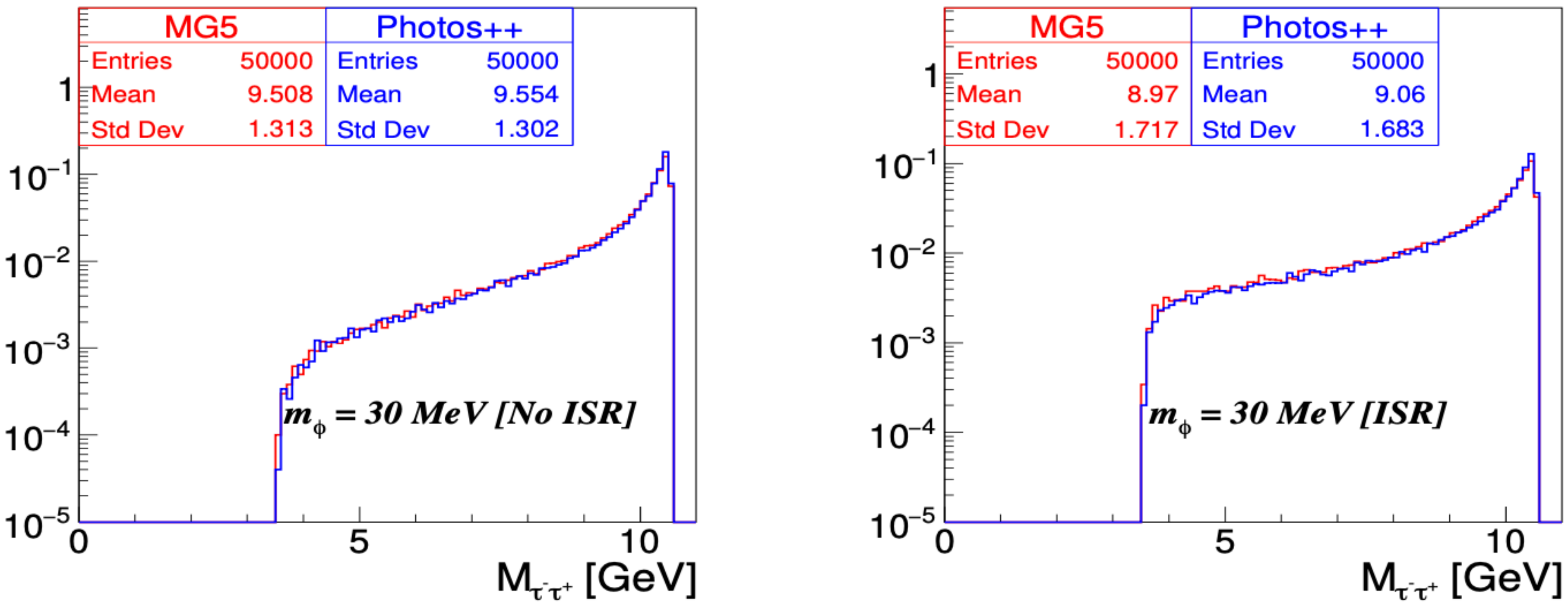
ξ is the lepton flavor independent coupling constant,
m_ℓ is mass of the lepton the dark scalar couples with,
v is the vacuum expectation value = 246 GeV

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.

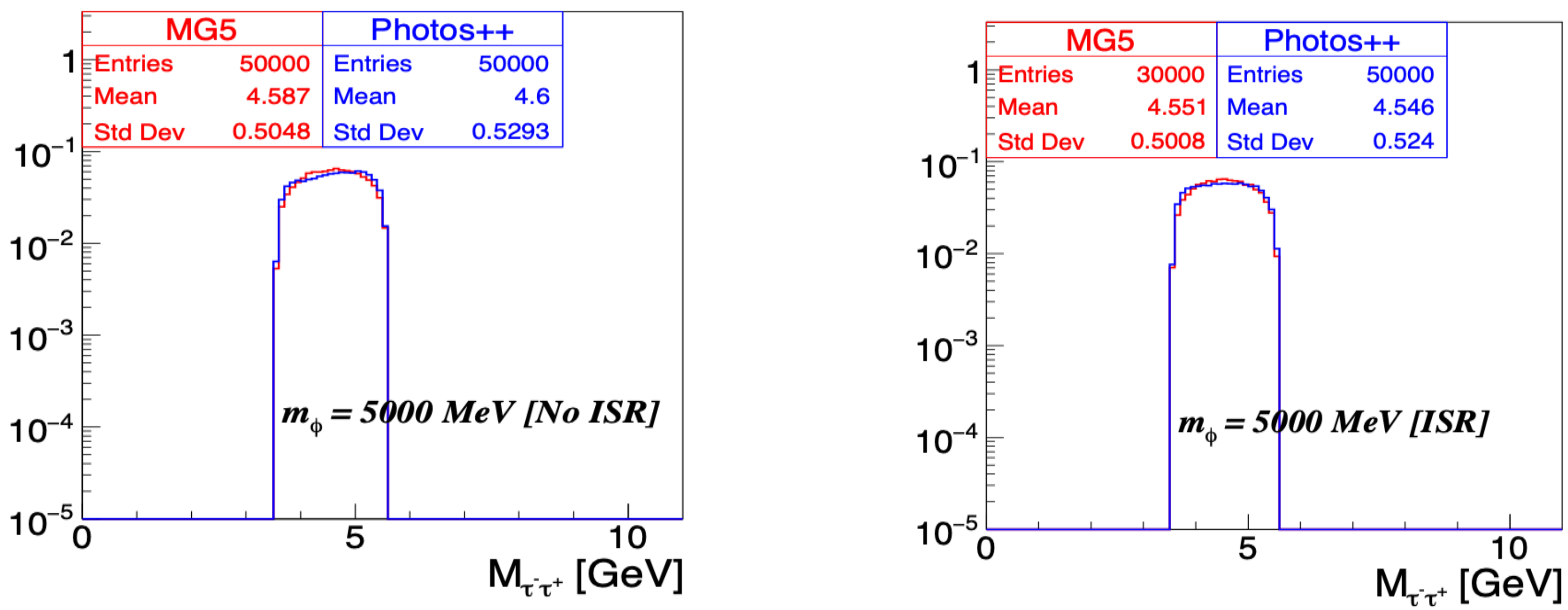
- ϕ_L decays to a lepton pair: search for narrow peak in lepton pair invariant mass distribution.
  - $\phi_L \to e^+e^-$ for $m_{\phi_L} < 2m_\mu$
  - $\phi_L \to \mu^+\mu^-$ for $m_{\phi_L} > 2m_\mu$
- High production cross-section times branching ratio in the region 40 MeV < m_{ϕ_L} < 6.5 GeV.

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

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

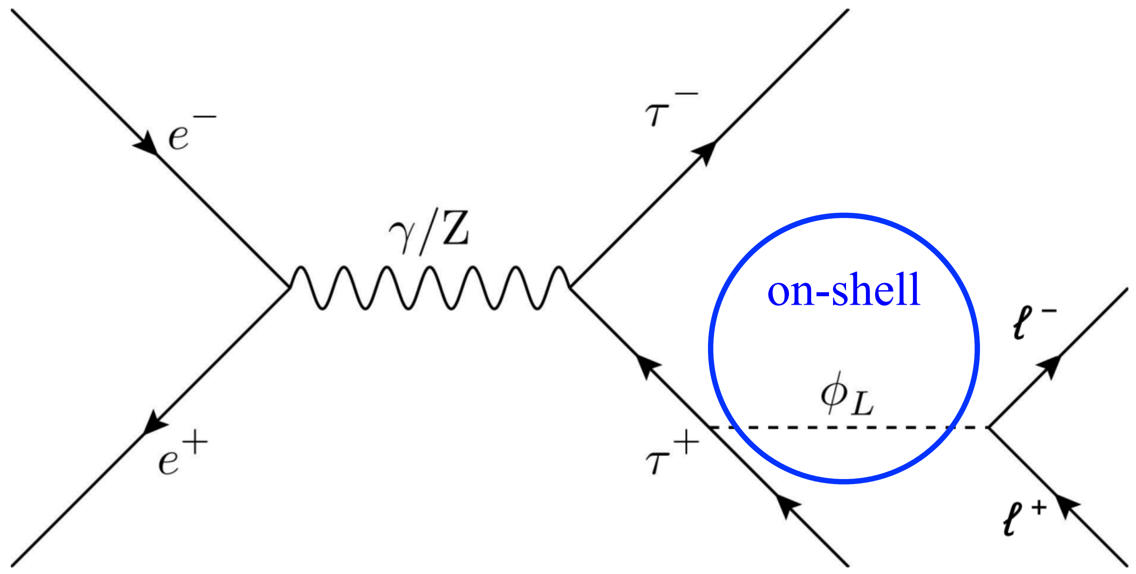


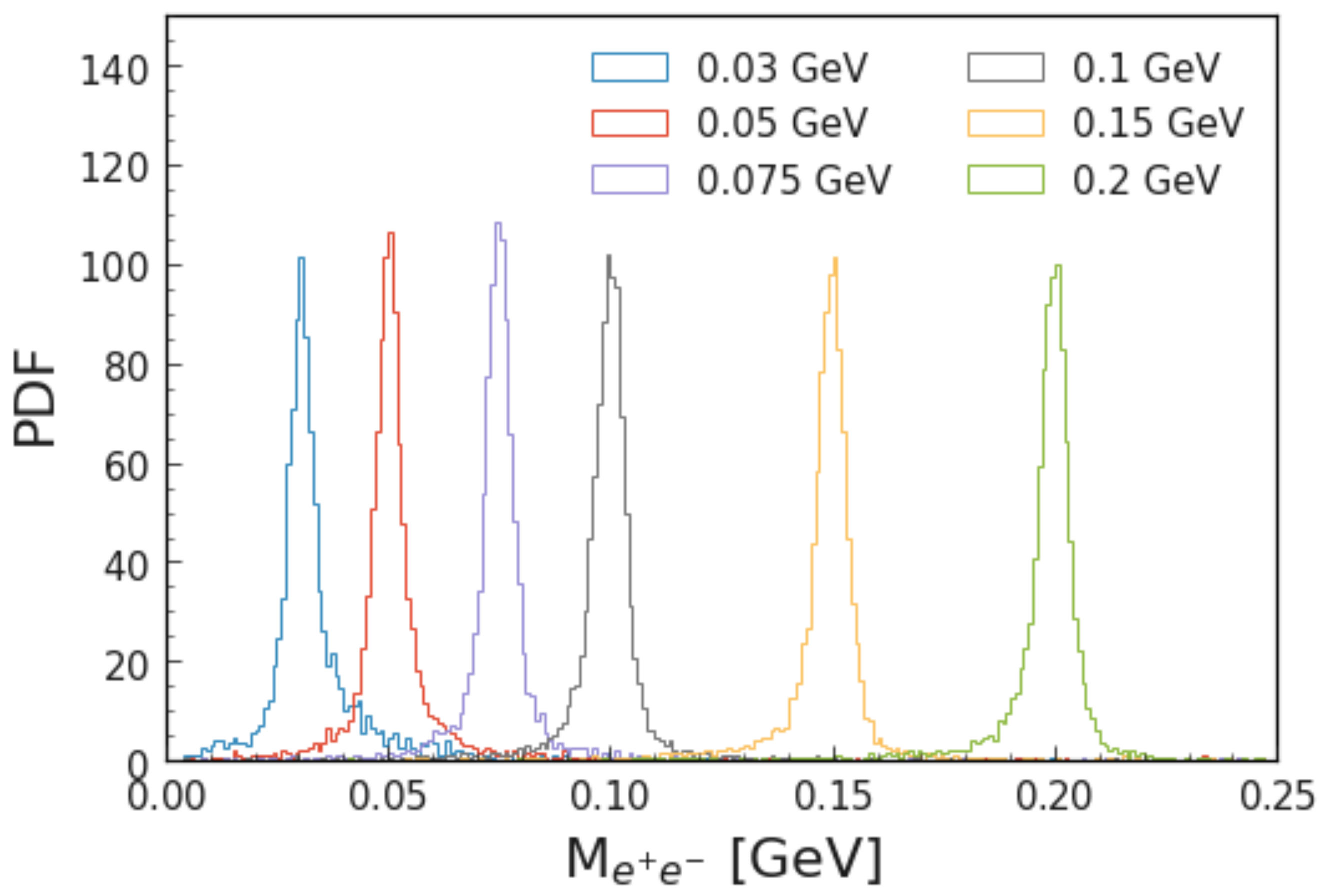
$e^-e^+ \to \tau^-\tau^+\phi_{\text{Dark Scalar}}(\to \mu^-\mu^+)$

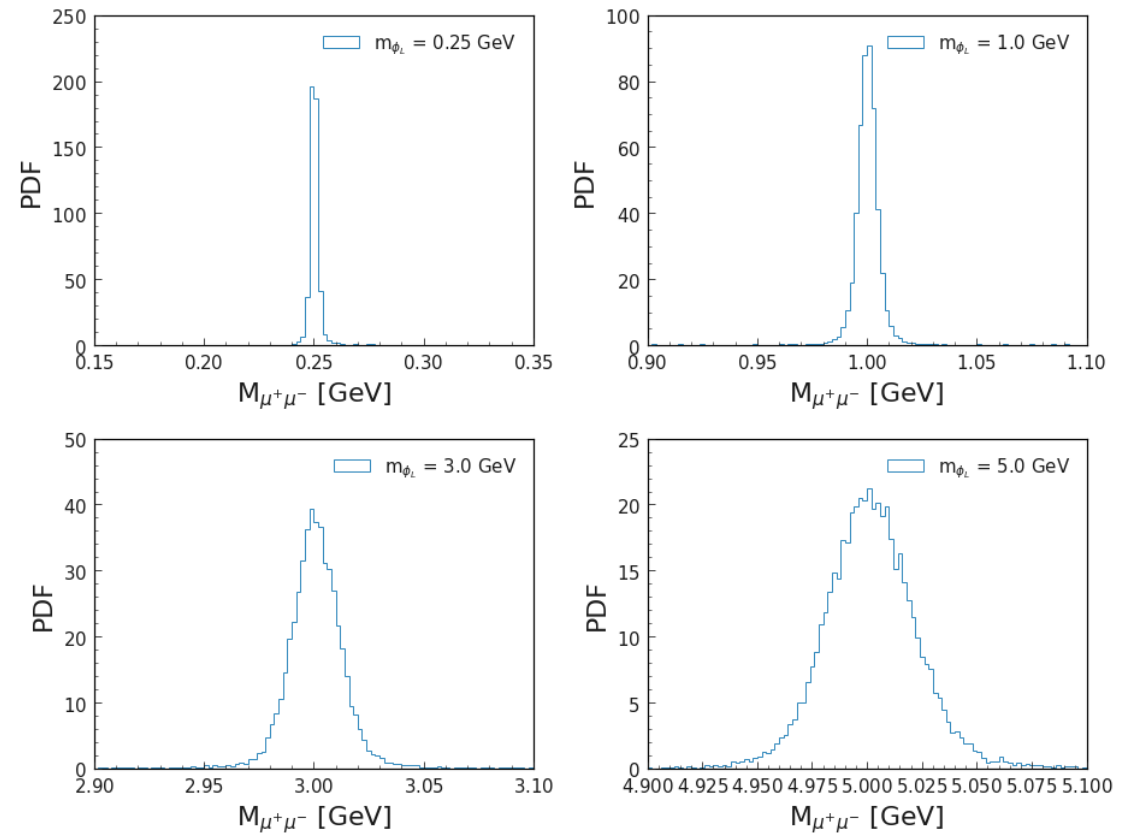


Św.B, D. Biswas, T. Przedzinski, Z. Was, e-Print: 2112.07330 [hep-ph]

Event generation with TauolaBelle2 and Photos++

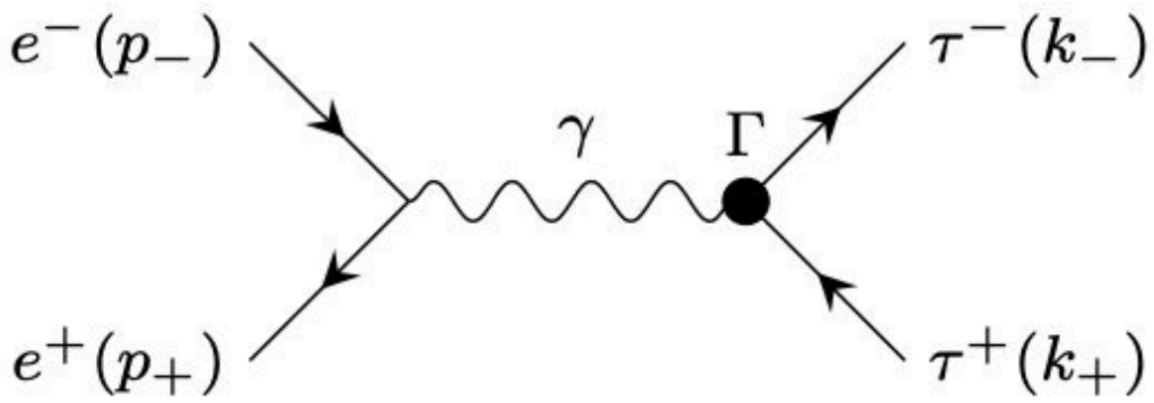






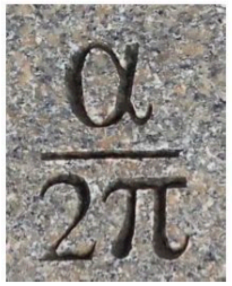
Resolution varies from 5 to 30 MeV, increasing at larger values of m_{ϕ_L}

Electric and magnetic dipole moments



$$\Gamma^\mu = \underbrace{F_1\left(q^2\right)\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2\left(q^2\right)\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3\left(q^2\right)\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

- $F_1\left(q^2\right)$, $F_2\left(q^2\right)$ are called the Dirac and Pauli; $F_1(0) = 1$; $F_2(0) = a_\tau$
- $g = 2\cdot[F_1(0) + F_2(0)] = 2 + 2F_2(0)$ $d_\tau^\gamma = \frac{e}{2m_\tau}\cdot F_3(0)$



Leading term

$\approx 0.001\ 161\ 4$

We assume that the electromagnetic vertex for the τ lepton has the following structure

$$\Gamma^\mu = \gamma^\mu + \frac{\sigma^{\mu\nu}q_\nu}{2m}\left[ia(s) + \gamma_5 b(s)\right], \qquad (3)$$

Spin re-weighting technique

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

$$\frac{d\sigma}{d\Omega} = \frac{\beta}{64\pi^2 s}|\mathcal{M}|^2.$$

$$|\mathcal{M}|^2 = \sum_{i,j=1}^{4} R_{ij}\, s_i^- s_j^+.$$

$$R_{11} = \frac{e^4}{4\gamma^2}\left(4\gamma^2\,\mathrm{Re}(a) + \gamma^2 + 1\right)\sin^2(\theta),$$

$$R_{12} = -R_{21} = \frac{e^4}{2}\beta\sin^2(\theta)\,\mathrm{Re}(b),$$

$$R_{13} = R_{31} = \frac{e^4}{4\gamma}\left[(\gamma^2+1)\mathrm{Re}(a) + 1\right]\sin(2\theta),$$

$$R_{22} = -\frac{e^4}{4}\beta^2\sin^2(\theta),$$

$$R_{23} = -R_{32} = -\frac{e^4}{4}\beta\,\gamma\sin(2\theta)\,\mathrm{Re}(b),$$

$$R_{33} = \frac{e^4}{4\gamma^2}\left[\left(4\gamma^2\,\mathrm{Re}(a) + \gamma^2 + 1\right)\cos^2(\theta) + \beta^2\gamma^2\right],$$

$$R_{14} = -R_{41} = \frac{e^4}{4}\beta\,\gamma\sin(2\theta)\,\mathrm{Im}(b),$$

$$R_{24} = R_{42} = \frac{e^4}{4}\beta^2\,\gamma\sin(2\theta)\,\mathrm{Im}(a),$$

$$R_{34} = -R_{43} = -\frac{e^4}{2}\beta\sin^2(\theta)\,\mathrm{Im}(b),$$

$$R_{44} = \frac{e^4}{4\gamma^2}\left[4\gamma^2\,\mathrm{Re}(a) + \beta^2\gamma^2\cos^2(\theta) + \gamma^2 + 1\right].$$

R_{ij} depends on a, b, CM energy s, scattering angle θ, τ velocity β, and Lorentz factor γ.

Spin re-weighting technique

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Phys.Rev.D 106 (2022) 11, 113010

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

$$\tau^- \to \rho^-\nu_\tau, \tau^+ \to \rho^+\bar{\nu}_\tau$$

$$y_1 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}, \qquad y_2 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}.$$

φ : acoplanarity between ρ^- and ρ^+

$$\begin{aligned} wt^{SM}_{spin} &= R^{SM}_{ij} h^-_i h^+_j \,/ R^{SM}_{tt}, \\ wt_{spin} &= R_{ij} h^-_i h^+_j \,/ R_{tt} \,/ wt^{SM}_{spin}, \\ wt &= R_{tt} \,/ R^{SM}_{tt}, \end{aligned}$$

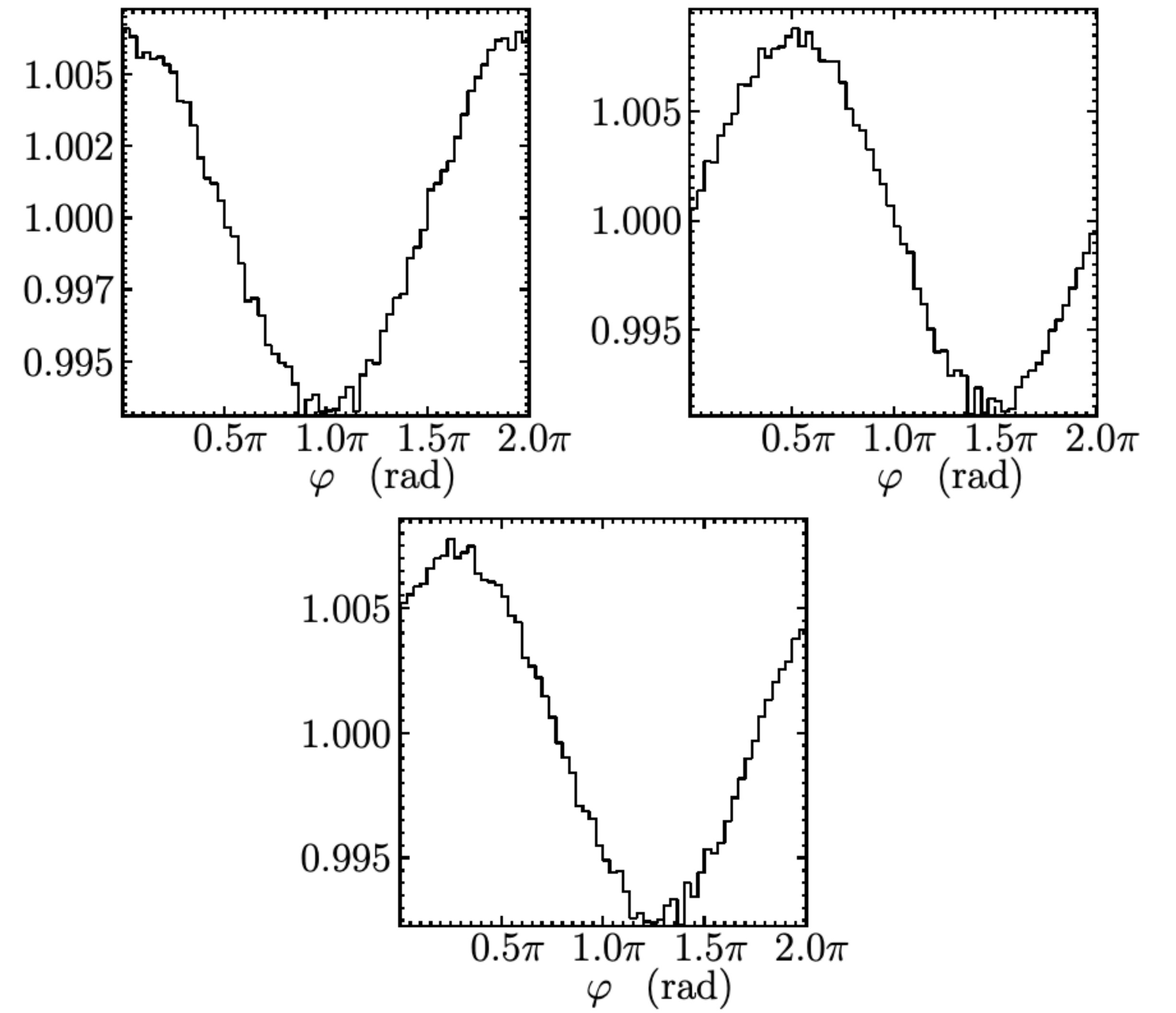


Figure 2: Distribution of the wt_{spin} as a function of the acoplanarity angle φ at $\sqrt{s} = 10.58$ GeV with the constraint $y_1 y_2 > 0$. For the top left plot, $\mathrm{Re}(a_{NP}) = 0.04$ and other couplings are zero. For the top right plot, $\mathrm{Re}(b_{NP}) = 0.04$ and other couplings are zero. For the bottom plot, $\mathrm{Re}(a_{NP}) = 0.04\cos(\pi/4)$, $\mathrm{Re}(b_{NP}) = 0.04\sin(\pi/4)$ and other couplings are zero.

Spin re-weighting technique

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

2307.03526 [hep-ph]
Phys.Rev.D 109 (2024) 1, 013002

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

$$R_{i,j} = R^{(\gamma)}_{i,j} + R^{(Z)}_{i,j} + R^{(\gamma Z)}_{i,j}$$

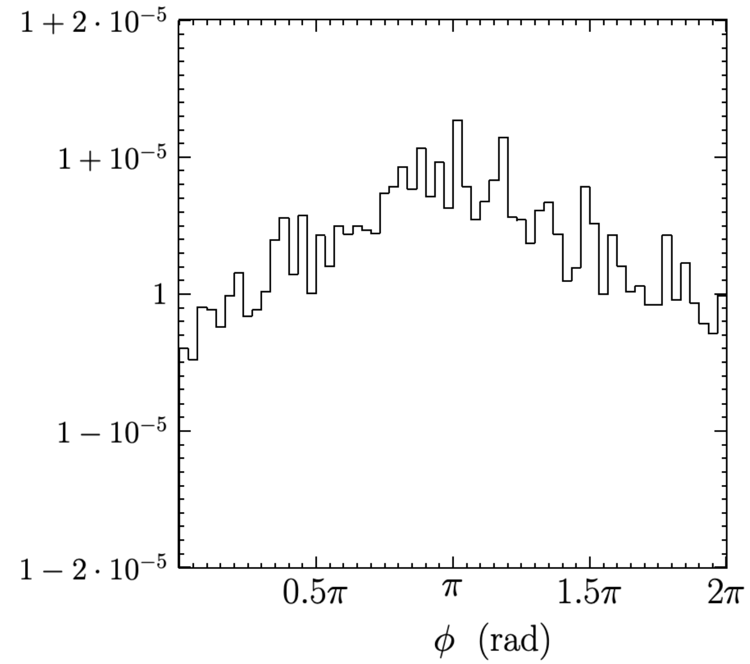


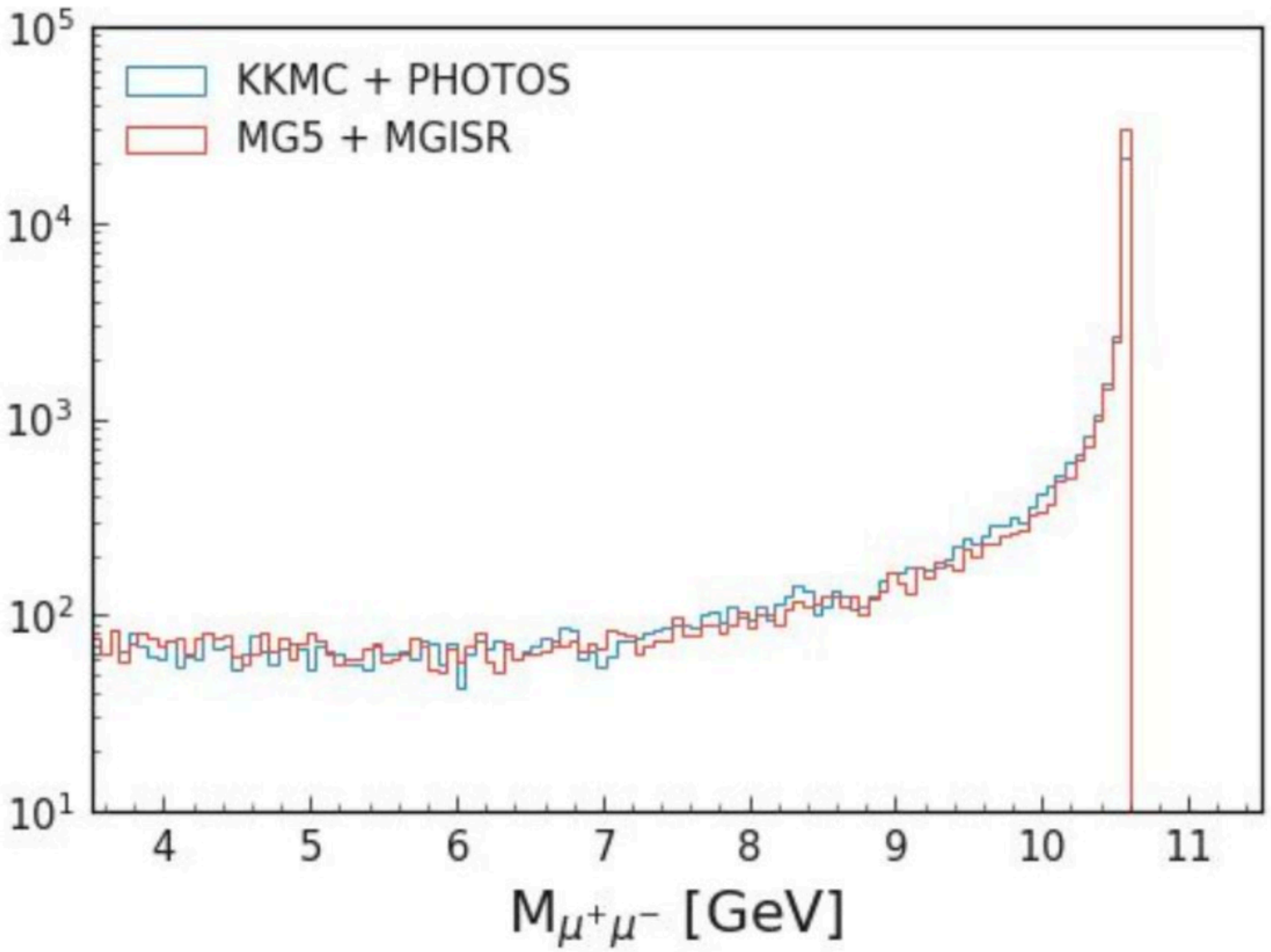
Figure 5: Impact of Z-exchange to the acoplanarity of $\pi^\pm\pi^0$ planes of $\tau^\pm$ decay products. The production process $e^+e^- \to \tau^+\tau^- n\gamma$, and decays $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ at the c.m. energy 10.58 GeV are used. Events are selected so that there is the same sign of energy differences for the charged and neutral pions coming from decays $\tau^- \to \pi^-\pi^0\nu_\tau$ and $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$. The detailed definition of presented observable is given in Ref. [11]. The ratio of the acoplanarity distributions with and without Z-boson contribution is shown.

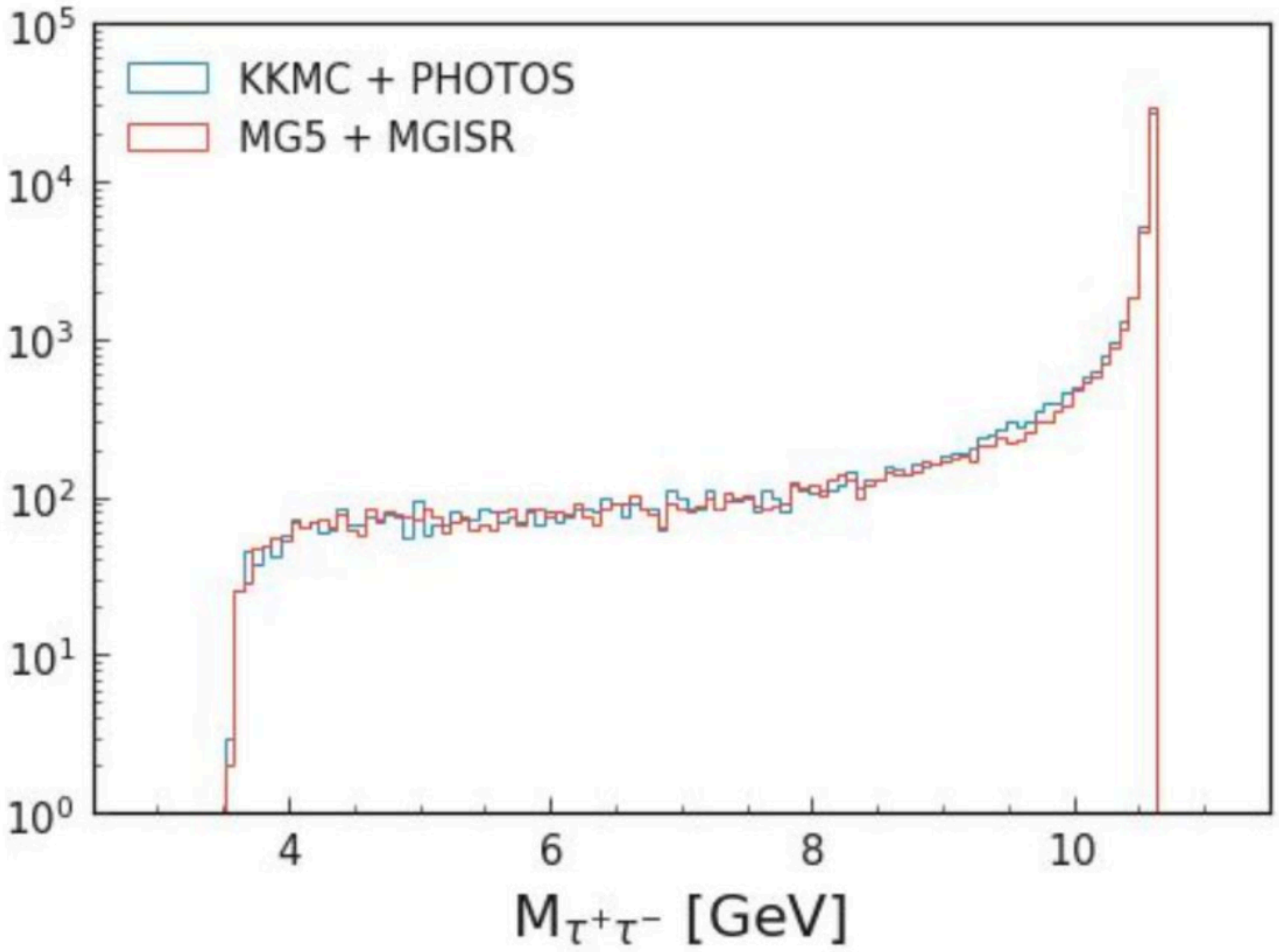
Madgraph and EKHARA generators

- MadGraph is currently the main generator for producing signal samples for Dark Sector signatures. MadGraph 3.4.0 available via external library includes ISR and beamstrahlung effects [+Python 3 support]
- LHEInput module could not boost MCParticles from CMS to LAB.
  New module: LHEInput → BoostMCParticles → SmearPrimaryVertex introduced to take beam properties directly from Conditions Database
  This new module can also be used with other generators providing LHEInput files.
- EKHARA is a generator for some specific two-photon processes:
  - $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ (EKHARA 1.X: arXiv/hep-ph/0510287)
  - $e^+e^- \rightarrow e^+e^-\pi^0$ (EKHARA 2.X: arXiv/1009.1881)
  - $e^+e^- \rightarrow e^+e^-\eta$, $e^+e^-\eta'$, $e^+e^-\chi_{c1}$ (EKHARA 3.0: arXiv/1805.07756)
  - C++ based user interface available around EKHARA 3.0

Madgraph vs KKMC

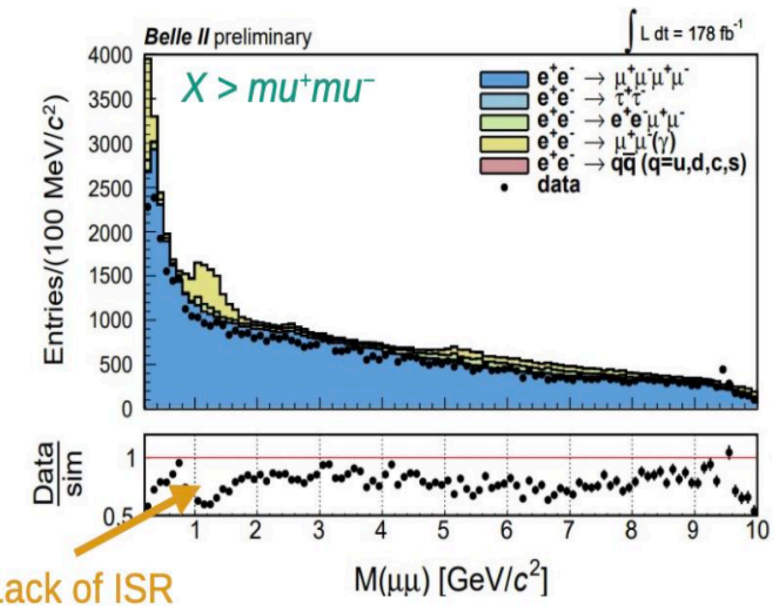
ISR modeling in $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \tau^+\tau^-\gamma$

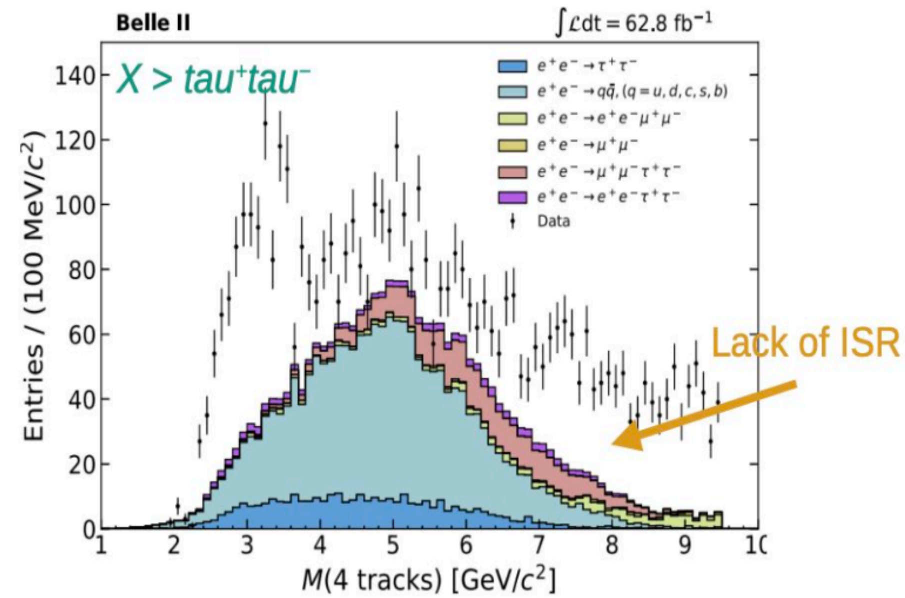




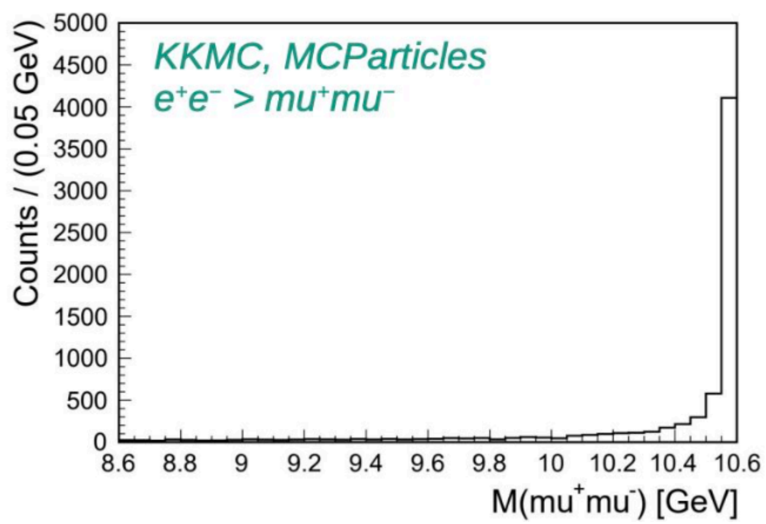
Comparison between Madgraph and KKMC shows good agreement

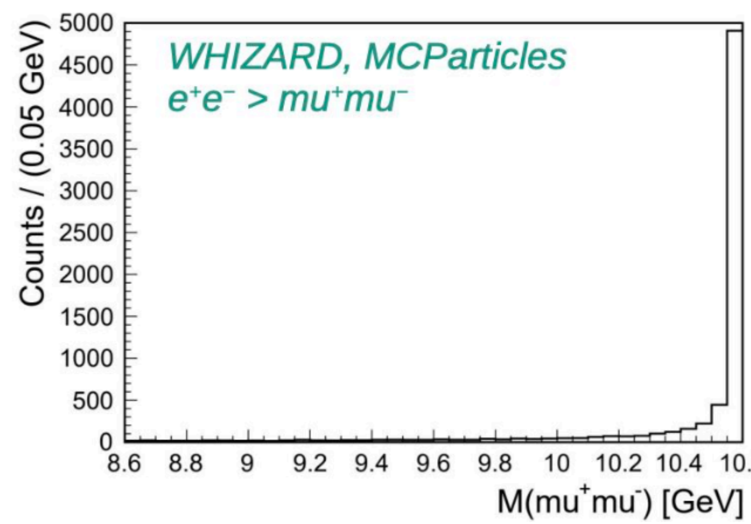
AAFH and WHIZARD generators





- AAFH used to generate 4-leptons final states; not including ISR/FSR effects
- WHIZARD can simulate ISR effects for dark sector, low multiplicity analyses
- WHIZARD available; stores events in LHEF files; import via LHEInput





Validation ongoing

Topics covered

- **Muon and tau pair production cross-sections**
- **General introduction to tau decays**
- **Adaptation of tau branching fractions from HFLAV/PDG fits**
- **General formalism of KK2F, TAUOLA, PHOTOS Monte Carlo for τ-pairs**
- $\tau^- \to \pi^- \nu_\tau$ **vs** $\tau^- \to \rho^- \nu_\tau$ **modeling**
- **Lepton flavor violation:** $\tau^- \to \ell^- \alpha$
- **Alternate parametrizations of hadronic currents**
- **Pre-sampler optimization for lepton pair emissions:** $\tau^- \to \bar{\nu}_\ell \ell^- \ell^- \ell^+ \nu_\tau$, $\tau^- \to \pi^- \ell^- \ell^+ \nu_\tau$
- **Dark scalar production in tau decays decaying to a pair of leptons**
- **Electric and magnetic dipole moments**
- **Low multiplicity generators: MADGRAPH, EKHARA, AAFH, WHIZARD**