16th International Workshop on Tau lepton physics (TAU2021)

Search for lepton-flavor-violating decays of the Tau lepton at a future muon collider

Based on arXiv: 2106.00505

by

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Presented by

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Outline

- *Lepton-flavor-violating Tau decays via Axion-like particles*
- *Signal process & SM backgrounds*
- *Analysis & polarization-induced effects*
- *Expected limits*

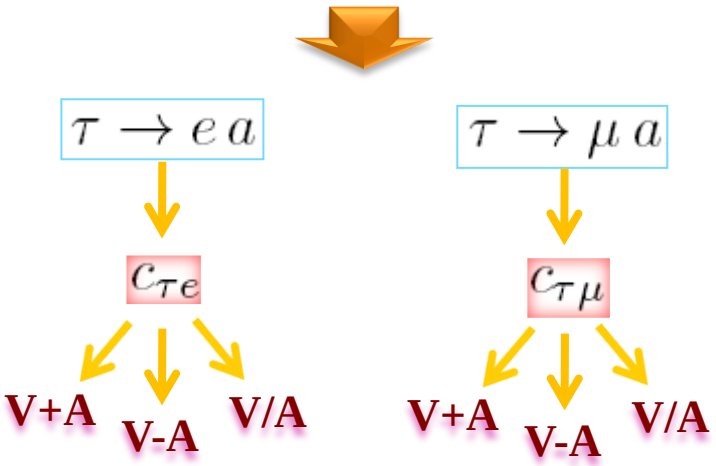
LFV Tau decay via Axion-like particles

$$\mathcal{L}_{\text{eff}} = \sum_{i \neq j} \frac{\partial_\mu a}{2 f_a} \bar{\ell}_i \gamma^\mu (c^V_{\ell_i \ell_j} + c^A_{\ell_i \ell_j} \gamma_5) \ell_j \qquad \ell_i = e, \mu, \tau$$

Assumed chiral structures

- **V+A :** $c_{\ell_i \ell_j}(1+\gamma_5)$
- **V-A :** $c_{\ell_i \ell_j}(1-\gamma_5)$
- **V/A :** $c^V_{\ell_i \ell_j} = 0$ **or** $c^A_{\ell_i \ell_j} = 0$

Research objectives:
Computing limits on



$100\ \text{eV} \leq m_a \leq 1\ \text{MeV}$

Origin of Axion-like particles

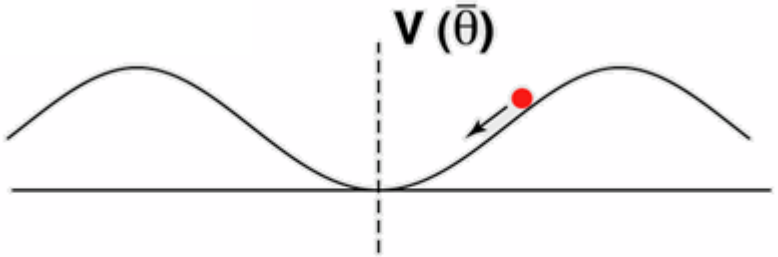
Strong CP problem

- $\mathcal{L}_{\text{strong CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}_a^{\mu\nu}$
  - — Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - — $\bar{\theta} \leq 10^{-10}$
  - — Strong-CP preserving

There is NO reason NOT to have CP-violation in QCD

Peccei-Quinn

- $\bar{\theta}$ a dynamical variable



- — $\bar{\theta}$ dynamically → 0

a new pseudoscalar boson: AXION

$$m_a \propto \frac{1}{f}$$

Axion-like Particles

Origin of Axion-like particles

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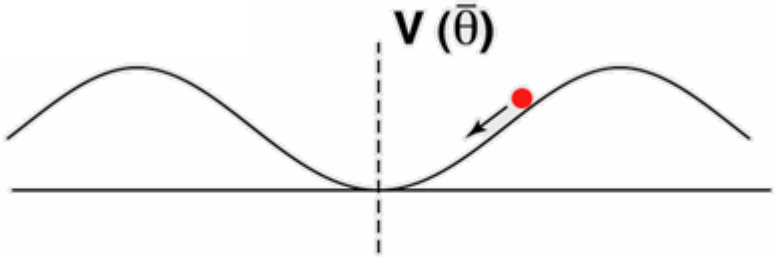

- — $\bar{\theta}$ dynamically → 0

a new pseudoscalar boson: AXION

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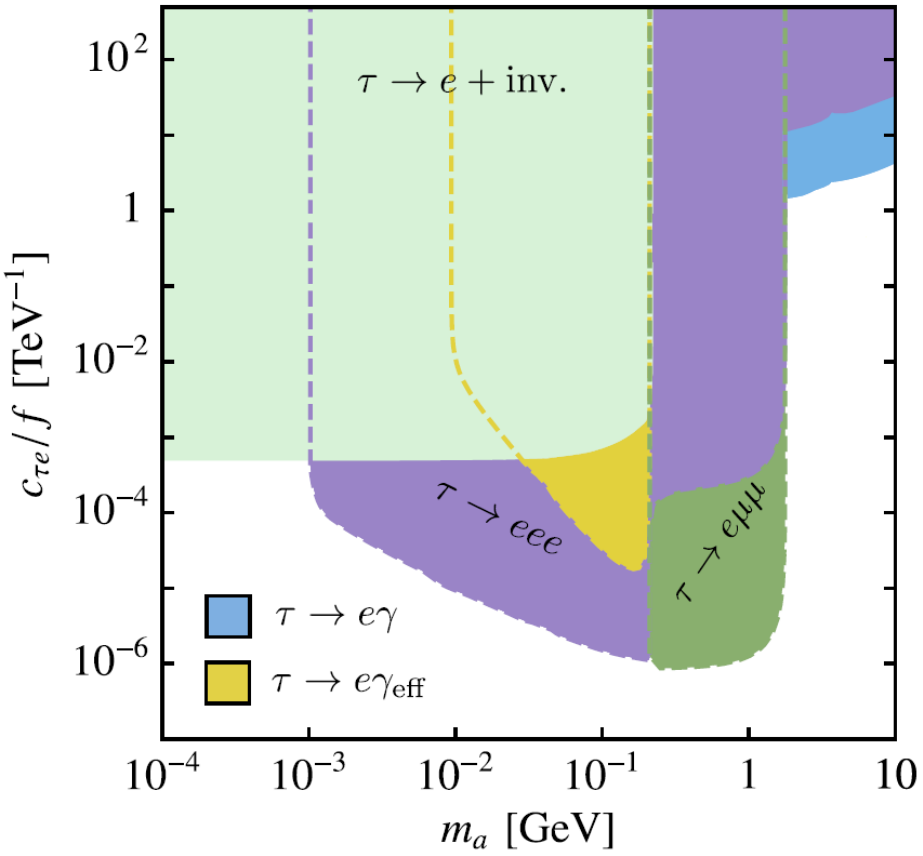
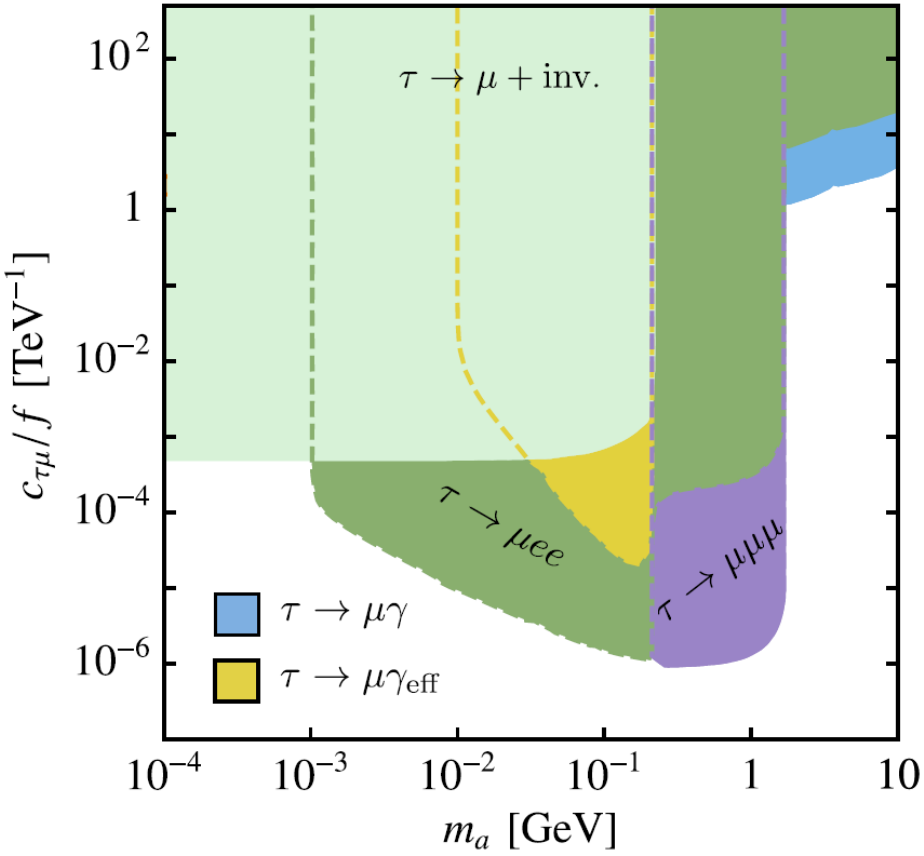
Motivations

- *Strong CP problem*
- *Observed baryon asymmetry*
- *Anomalous magnetic moments of μ and e*
- *Dark matter*

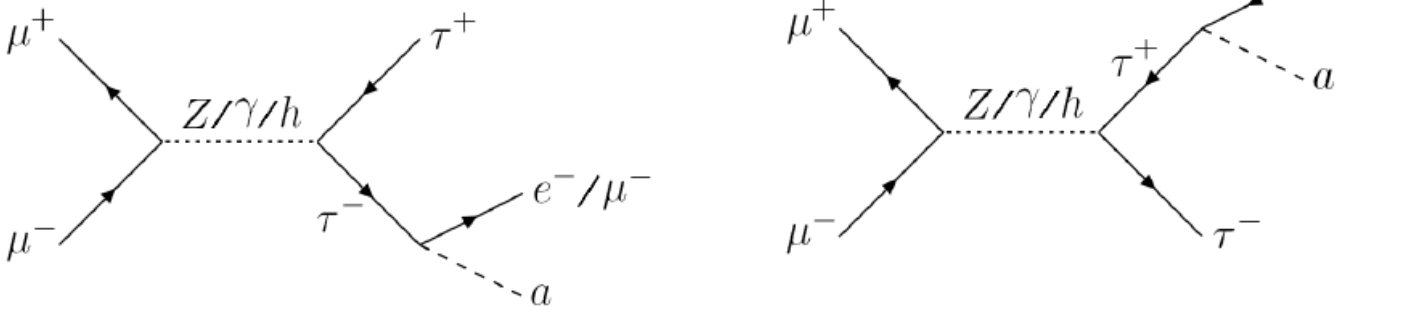
Current experimental limits





arXiv: 1908.00008v1

Signal process



Muon Accelerator Program

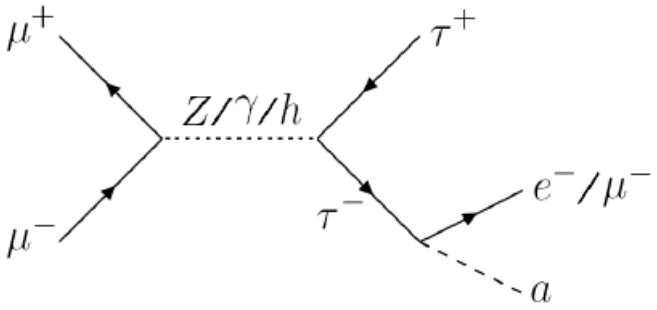
Muon colliders motivations

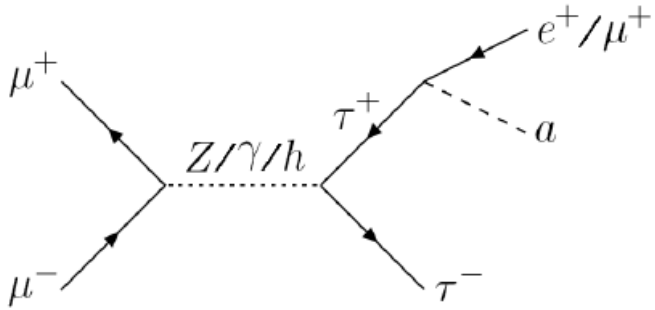
- *More efficient*
- *Muon colliders can be circular*
- *No ambiguity about energies of colliding particles*
- *Much cleaner environment*

operating stages

	Higgs	Top-High Luminosity		Multi-TeV	
Center-of-mass energy [GeV]	126	350	1500	3000	6000
Average luminosity [10^{34}cm^{-2}s^{-1}]	0.008	0.6	1.25	4.4	12

Signal process

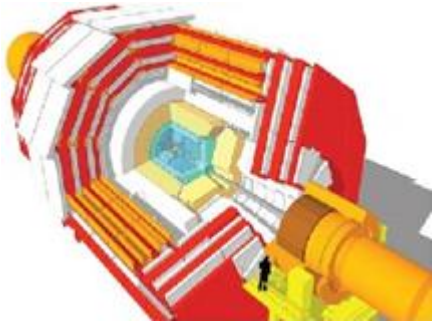




Decay length of light ALPs

$100\ \text{eV} \leq m_a \leq 1\ \text{MeV}$ → $L_a > 2.3 \times 10^{20}\ \text{m}$ $\gg$

$(m_a = 1\ \text{MeV})$



$$\mu^-\mu^+ \to \tau^-\tau^+,\ \tau \to e/\mu + \not{E}$$

SM backgrounds

Signal signature: $\mu^-\mu^+ \to \tau^-\tau^+,\ \tau \to e/\mu + \not{E}$

$\tau^-\tau^+, \tau \to e/\mu + \nu\bar{\nu}$

Only suppressed by polarization-induced effects

$W^-W^+, W \to e/\mu + \nu$

$t\bar{t}$

hZ

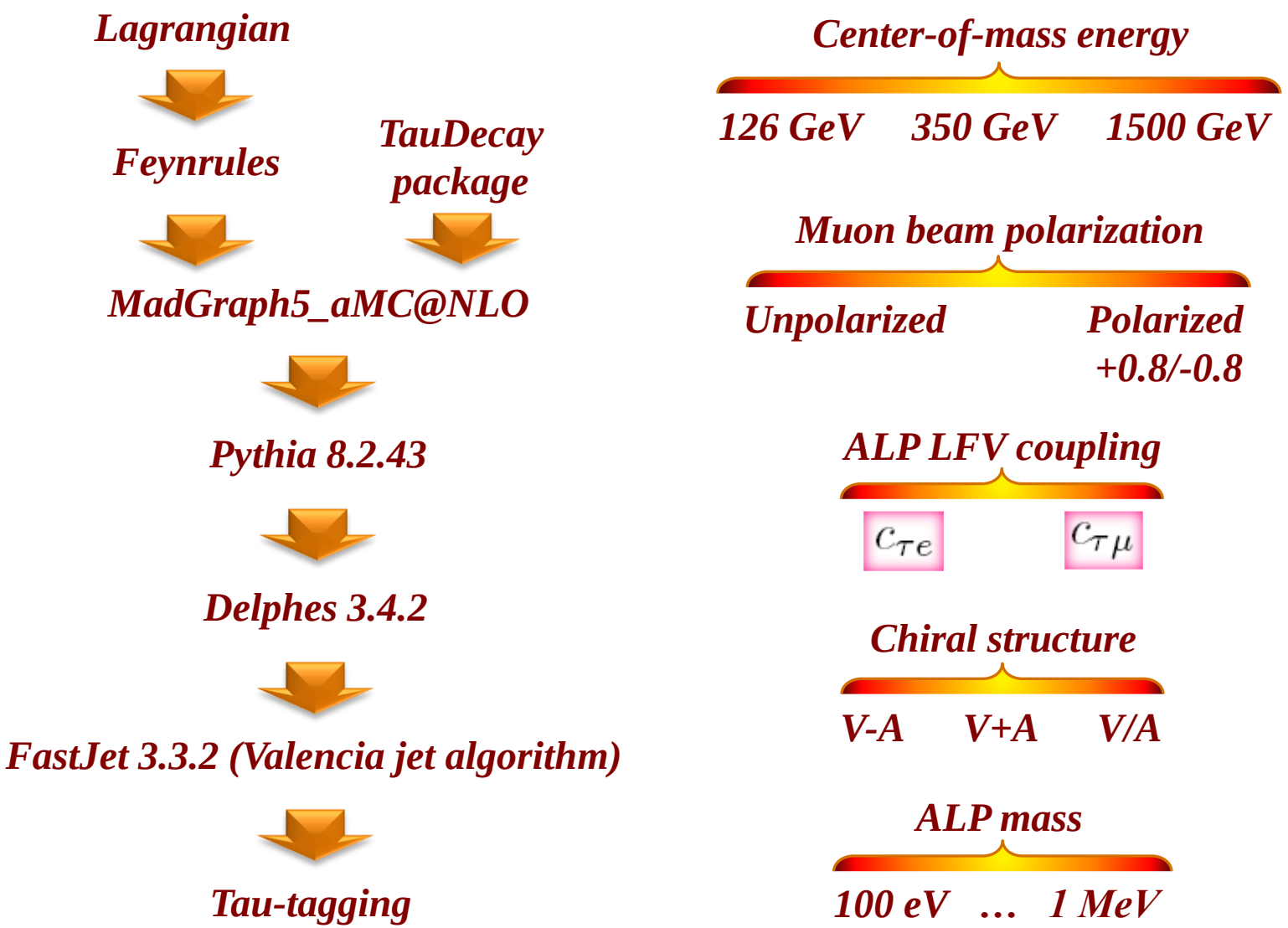
ZZ

$Z\gamma$

$q\bar{q}$

$e^-e^+/\mu^-\mu^+$

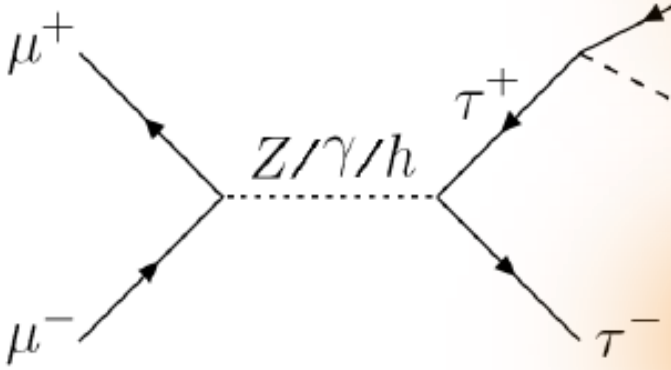
Event generation



Event selection

at most 1 photon with E_{max}^{LFV}

4



2

relative charge sign criterion

3

$\tau^- \to e^-/\mu^- + \nu\bar{\nu}$

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

1

at most 1 photon with E_{max}^{SM}

4

Polarization-induced effects

Signal: $\mu^-\mu^+ \to \tau^-\tau^+,\ \tau \to e/\mu + a$

SM BG: $\mu^-\mu^+ \to \tau^-\tau^+, \tau \to e/\mu + \nu\bar{\nu}$

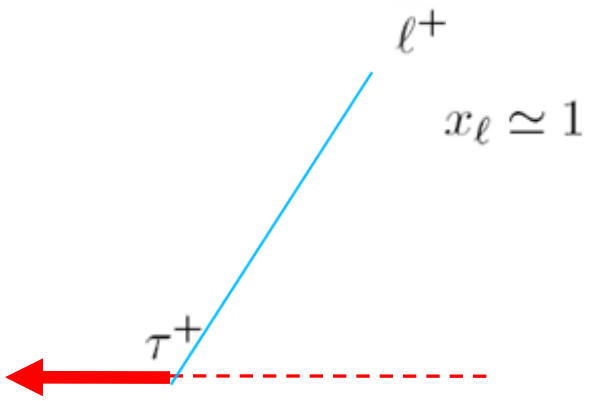
Signal $\tau \to e/\mu + a$

In the tau rest frame:

$$p_\ell = \sqrt{\left(\frac{m_\tau^2 + m_\ell^2 - m_a^2}{2m_\tau}\right)^2 - m_\ell^2} \quad (\ell = e, \mu)$$

$m_a \ll m_\tau \longrightarrow x_\ell \simeq 1$

$$x_\ell = 2E_\ell/m_\tau$$



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$m_a \ll m_\tau \longrightarrow x_\ell \simeq 1$

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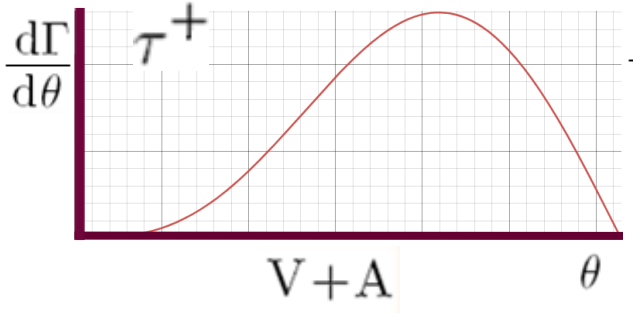
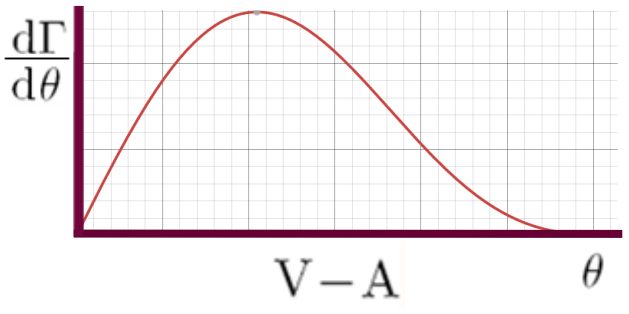
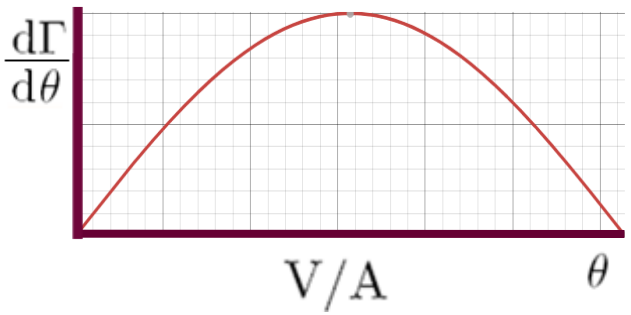
$$\frac{\mathrm{d}\Gamma(\tau^\pm \to \ell^\pm a)}{\mathrm{d}\cos\theta} = \frac{m_\tau^3}{128\pi f_a^2}\left(1 - \frac{m_a^2}{m_\tau^2}\right)^2 \times \begin{cases} 2c_{\tau\ell}^2\,(1 \mp \mathcal{P}_\tau \cos\theta) & \text{V+A} \\ 2c_{\tau\ell}^2\,(1 \pm \mathcal{P}_\tau \cos\theta) & \text{V−A} \\ c_{\tau\ell}^2 & \text{V/A} \end{cases}$$







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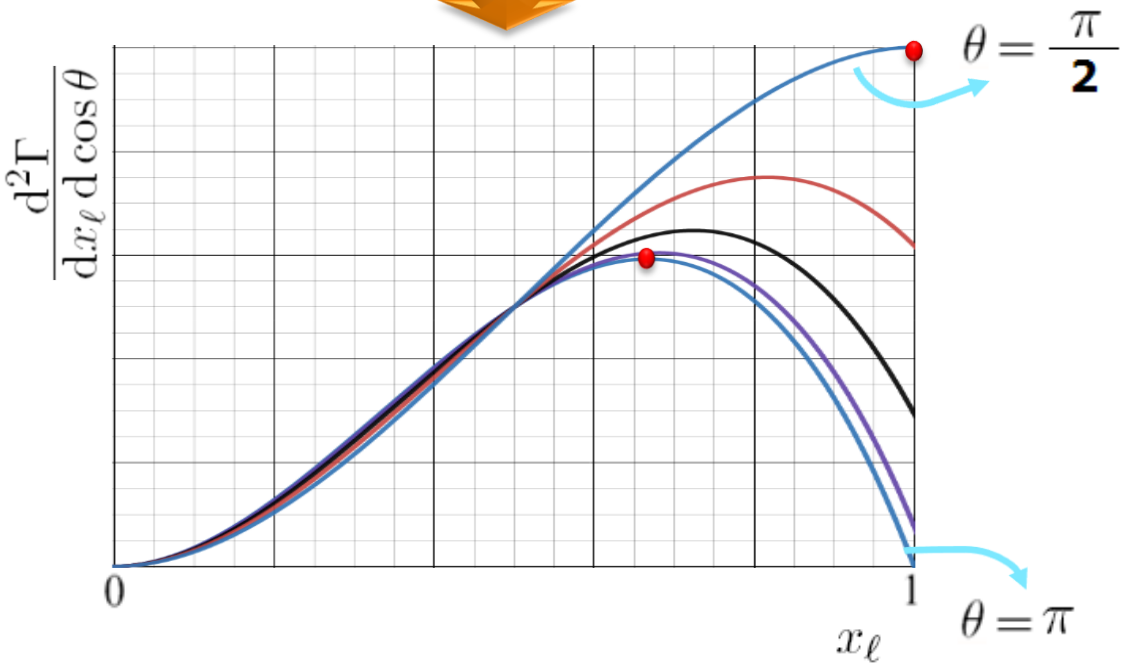
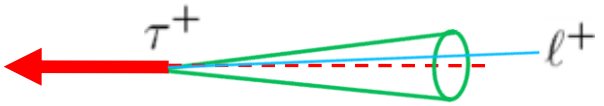
SM BG: $\mu^-\mu^+ \to \tau^-\tau^+, \tau \to e/\mu + \nu\bar{\nu}$

BG $\tau \to e/\mu + \nu\bar{\nu}$

In the tau rest frame:

$$\frac{\mathrm{d}^2\Gamma\left(\begin{array}{l}\tau^+ \to \ell^+\,\nu_\ell\,\bar{\nu}_\tau \\ \tau^- \to \ell^-\,\bar{\nu}_\ell\,\nu_\tau\end{array}\right)}{\mathrm{d}x_\ell\,\mathrm{d}\cos\theta} \simeq \Gamma_\tau\left[\,(3-2x_\ell) \pm \mathcal{P}_\tau(2x_\ell-1)\cos\theta\right]x_\ell^2$$





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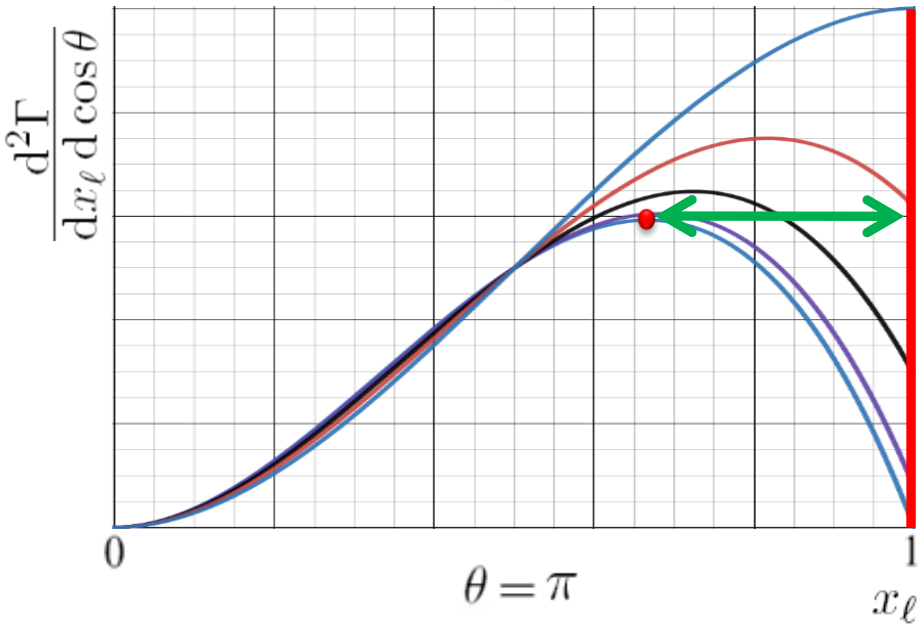
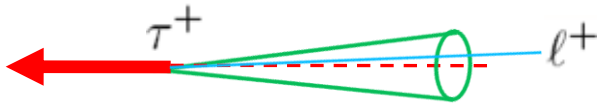
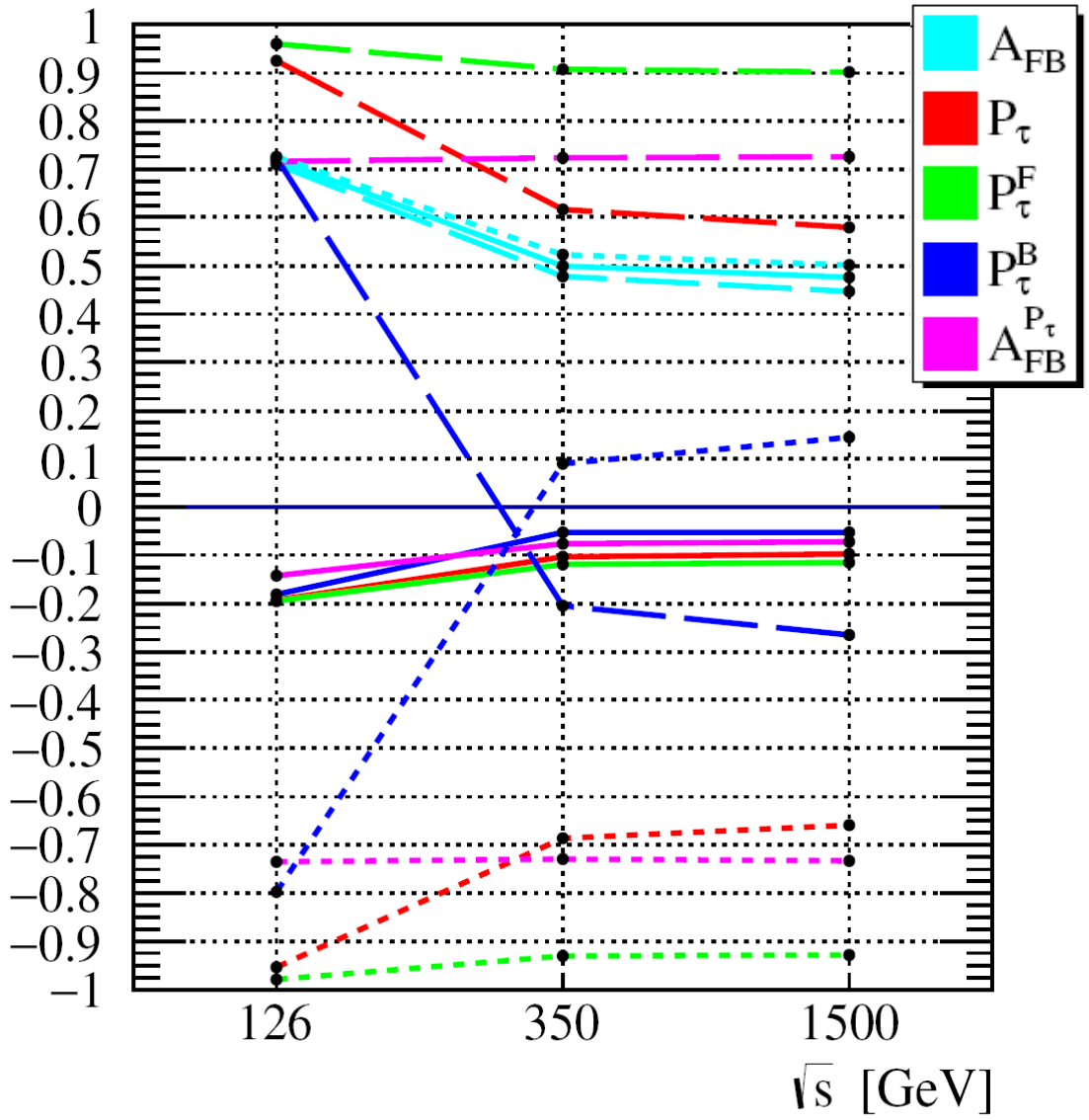


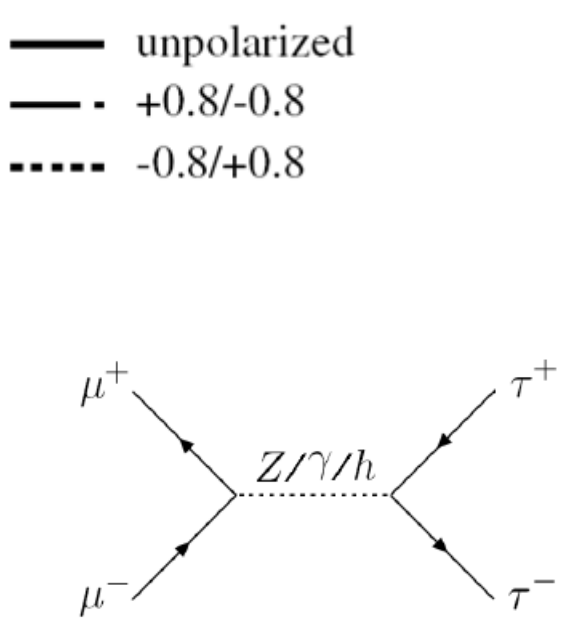


$x_\ell \simeq 1$ ***for signal***

x_ℓ ***helps suppress background***

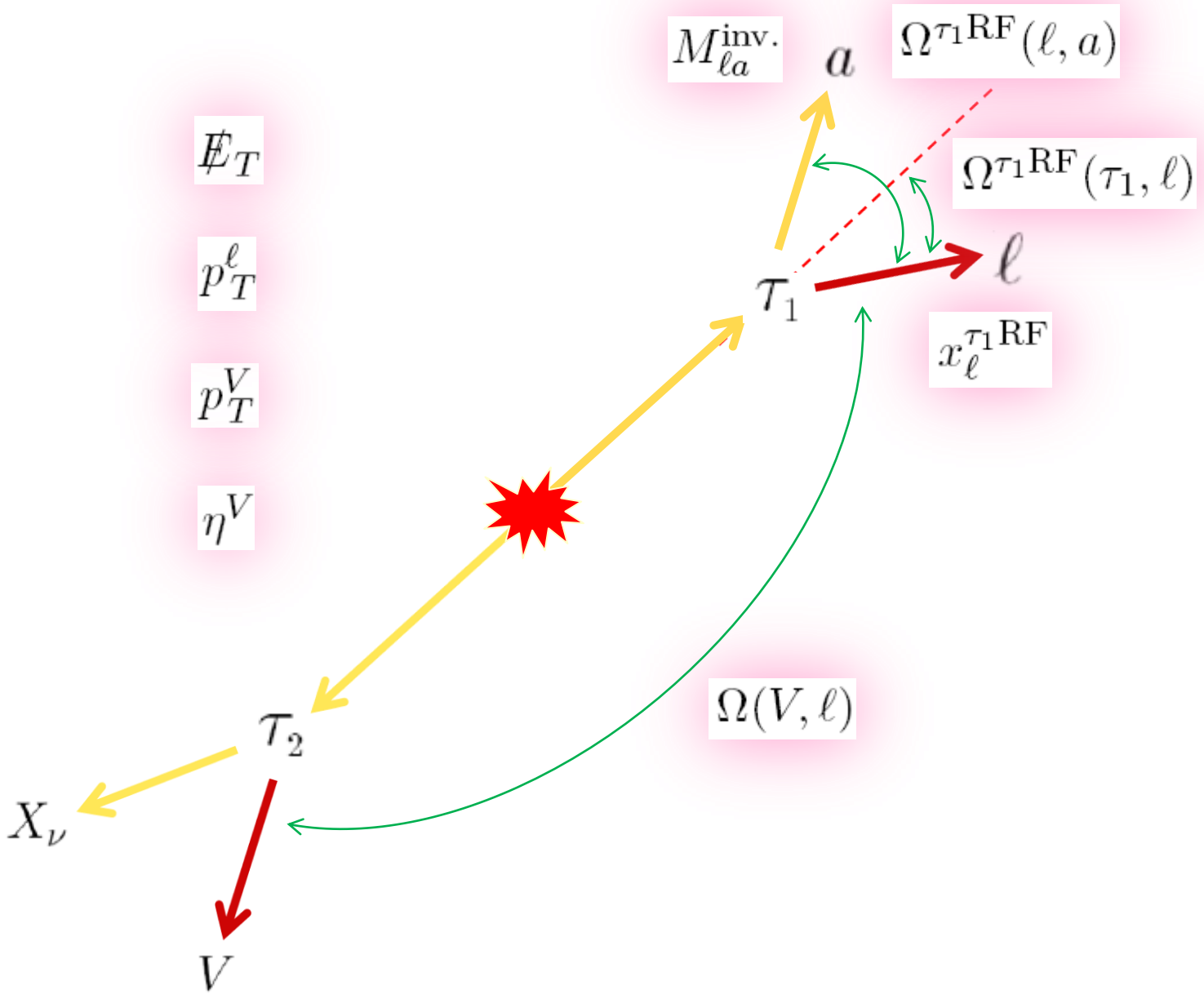
How to produce highly polarized tau leptons?





$$A_{\rm FB} = \frac{\sigma^{\rm F} - \sigma^{\rm B}}{\sigma_{\rm total}} \qquad P_\tau = \frac{(\sigma_{++} + \sigma_{+-}) - (\sigma_{-+} + \sigma_{--})}{\sigma_{\rm total}} \qquad P_\tau^{\rm F/B} = \frac{\sigma^{\rm F/B}(h_\tau = +1) - \sigma^{\rm F/B}(h_\tau = -1)}{\sigma^{\rm F/B}}$$

Discriminating variables



Discriminating variables

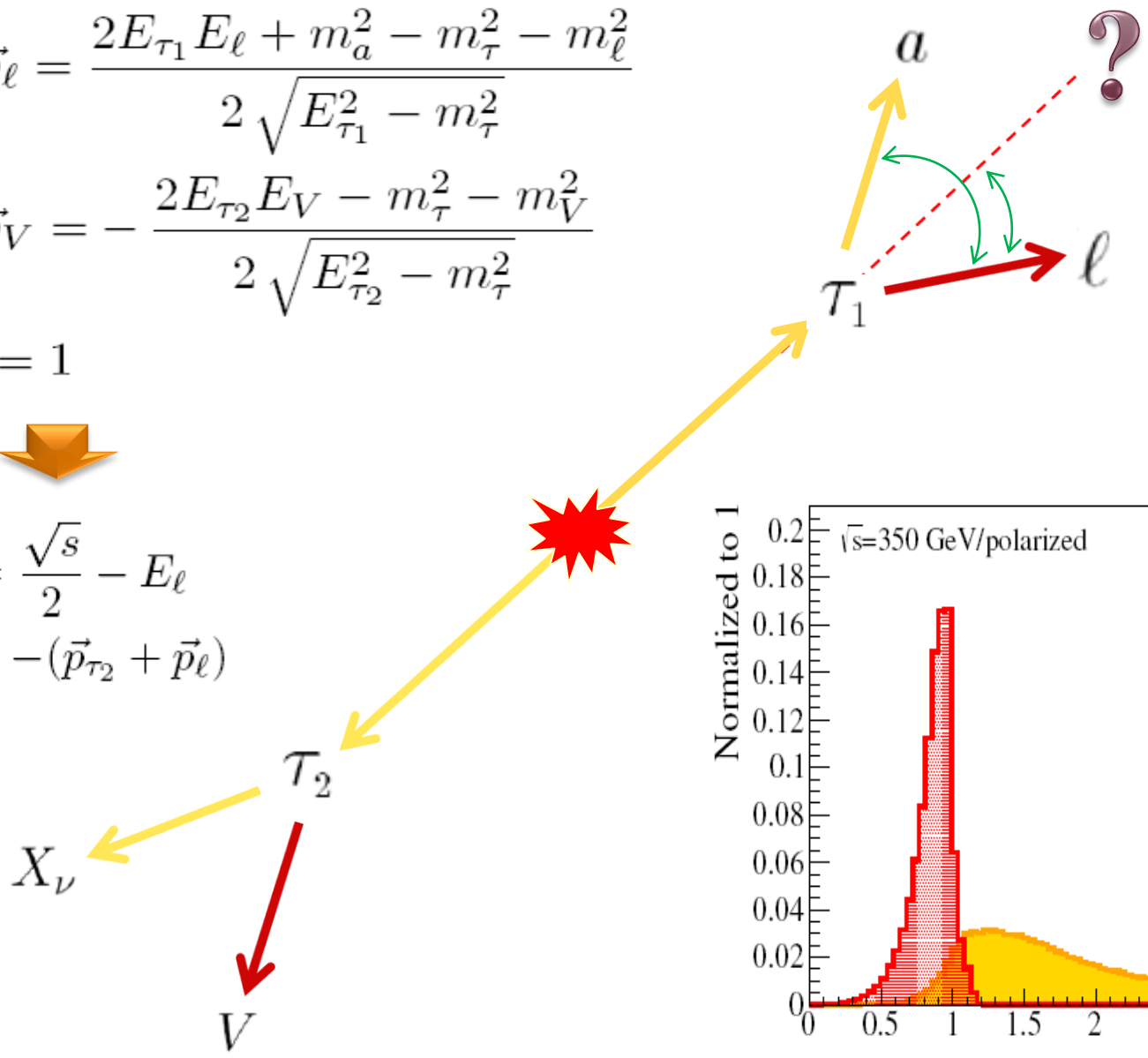
$$\hat{v}_1 . \vec{p}_\ell = \frac{2E_{\tau_1}E_\ell + m_a^2 - m_\tau^2 - m_\ell^2}{2\sqrt{E_{\tau_1}^2 - m_\tau^2}}$$

$$\hat{v}_1 . \vec{p}_V = -\frac{2E_{\tau_2}E_V - m_\tau^2 - m_V^2}{2\sqrt{E_{\tau_2}^2 - m_\tau^2}}$$

$$|\hat{v}_1| = 1$$

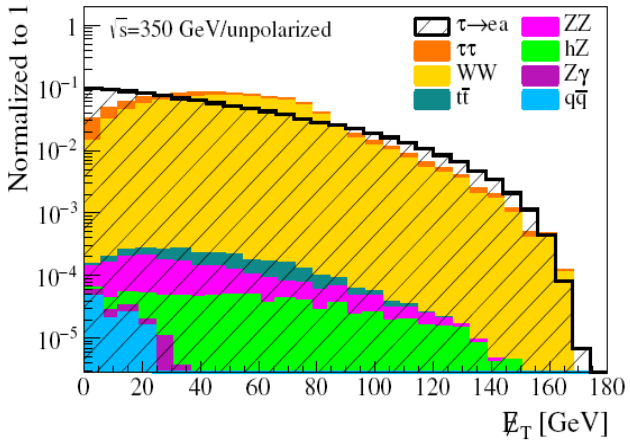
$$E_a = \frac{\sqrt{s}}{2} - E_\ell$$

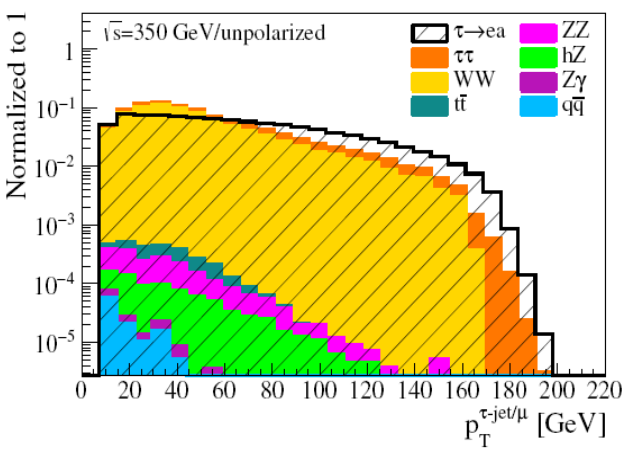
$$\vec{p}_a = -(\vec{p}_{\tau_2} + \vec{p}_\ell)$$

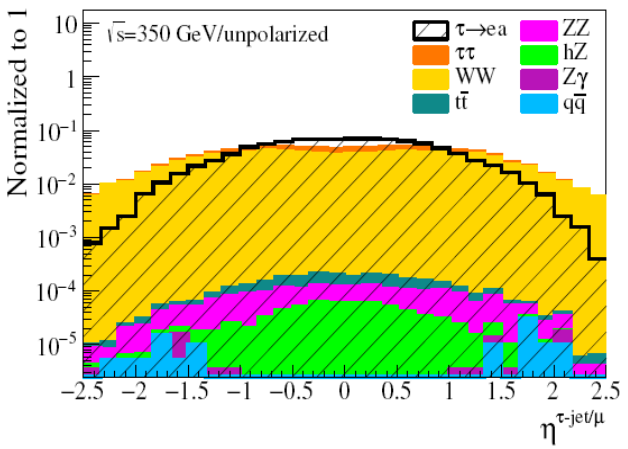


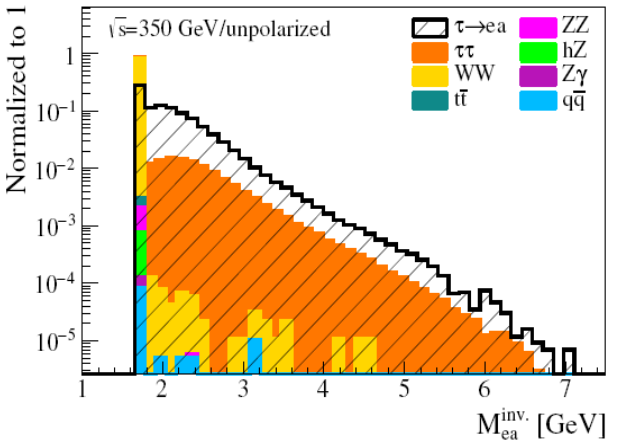
Unpolarized

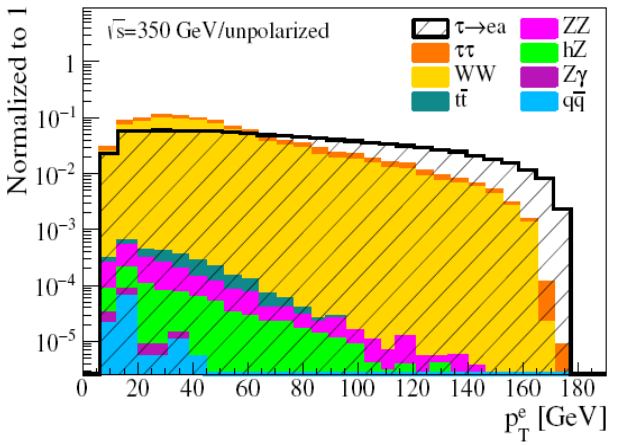
Discriminating variables

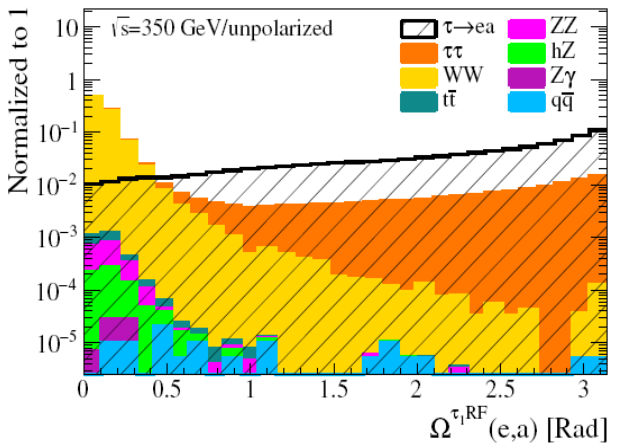


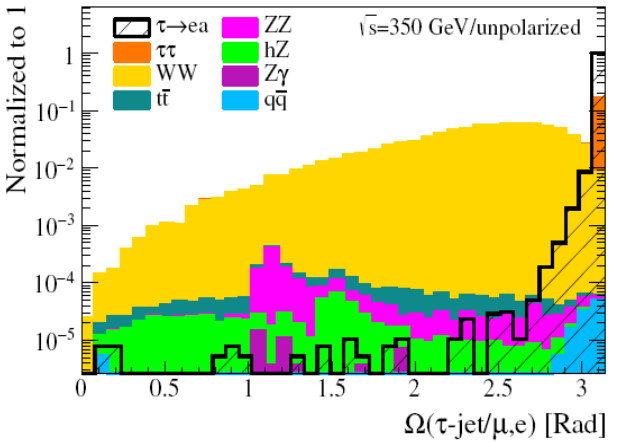


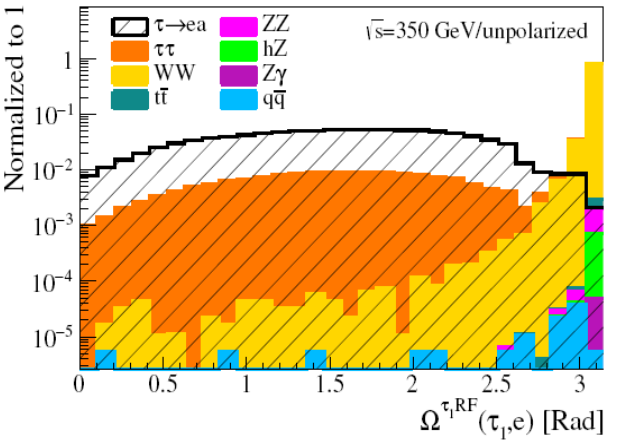


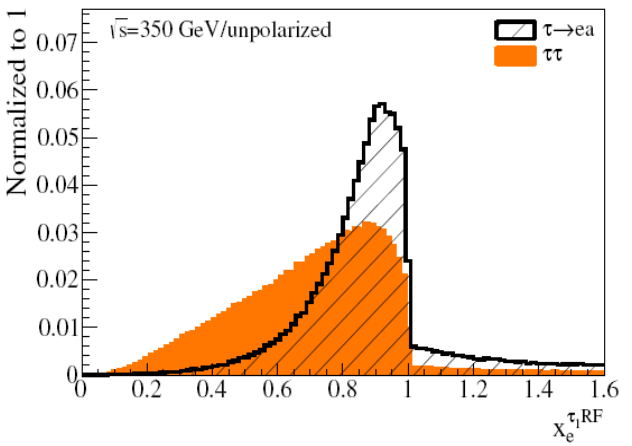




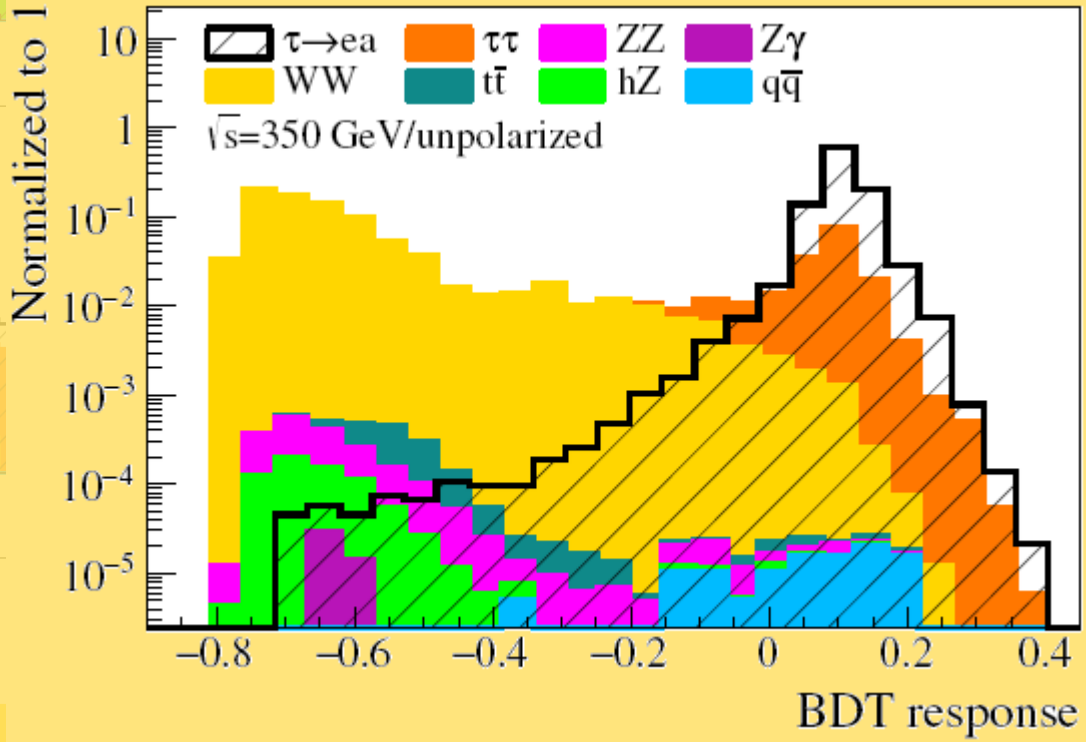






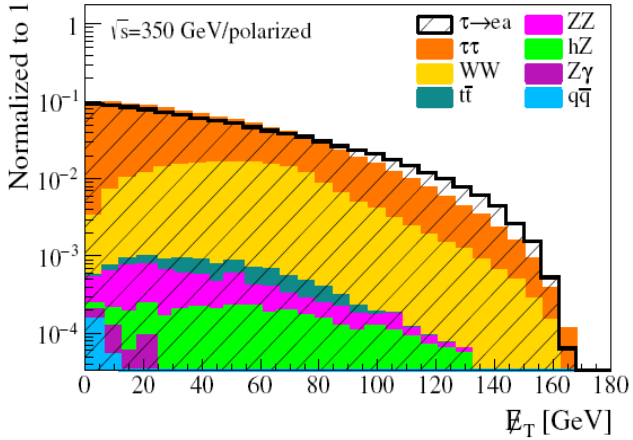


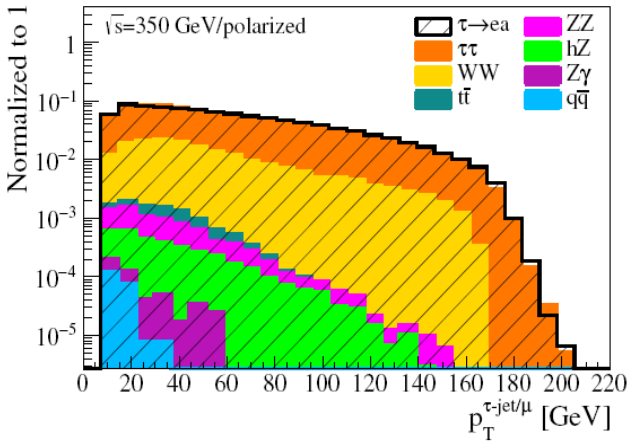
TMVA
(Toolkit for Multivariate Data Analysis)

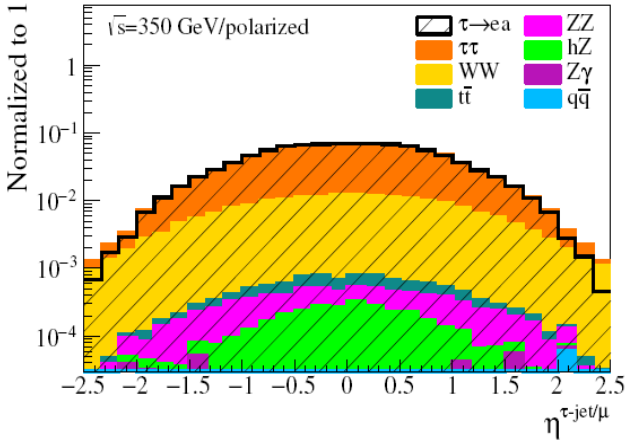


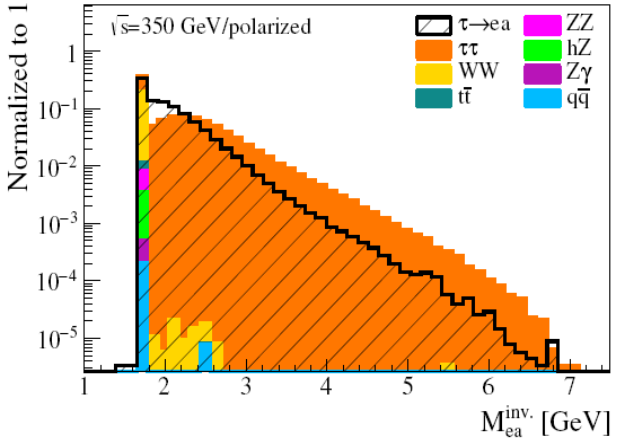
Polarized

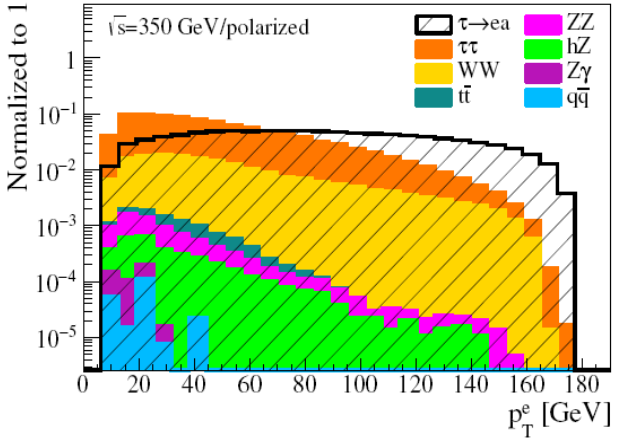
Discriminating variables

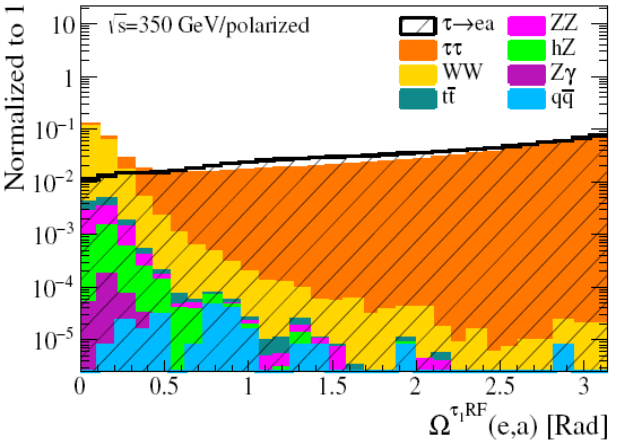


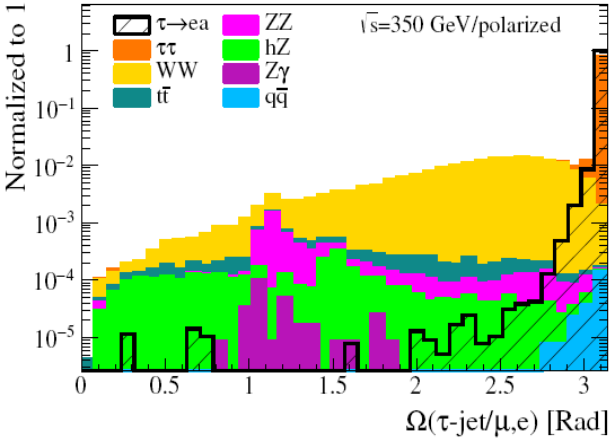


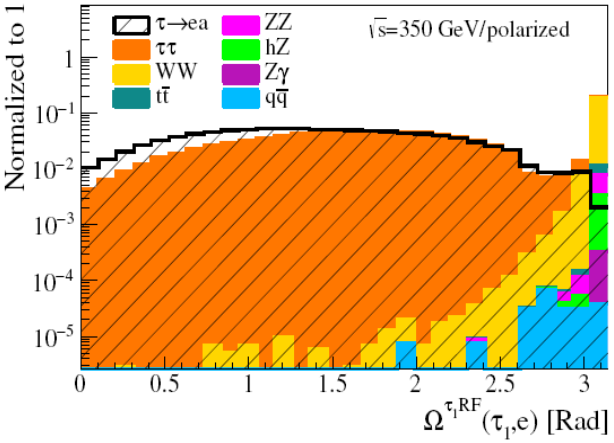


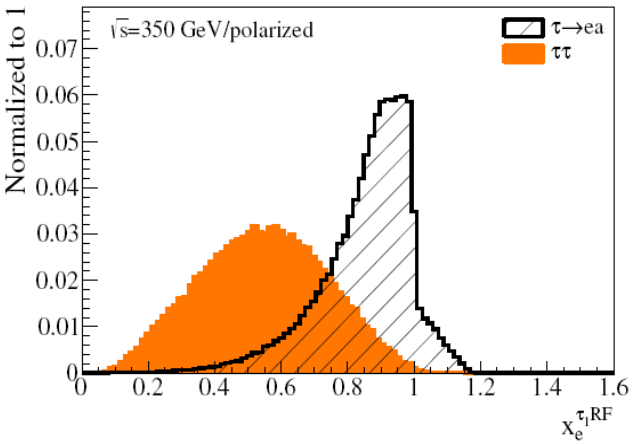






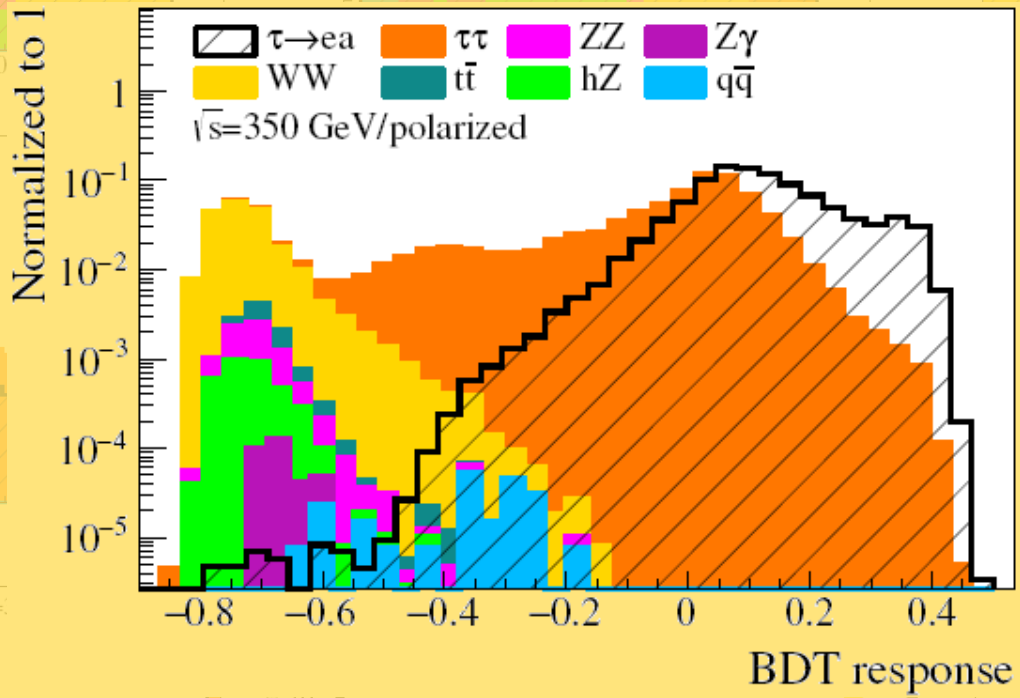




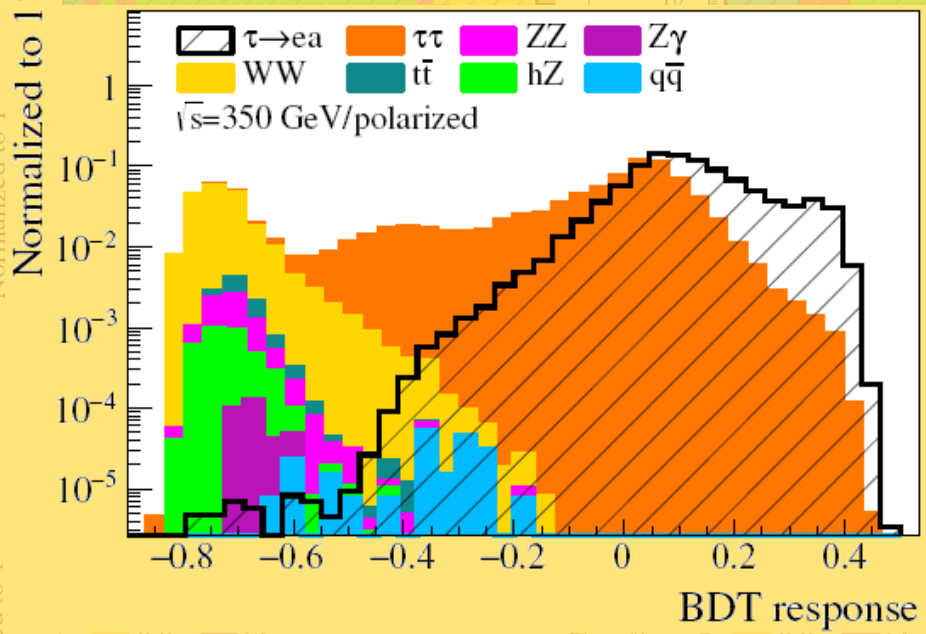


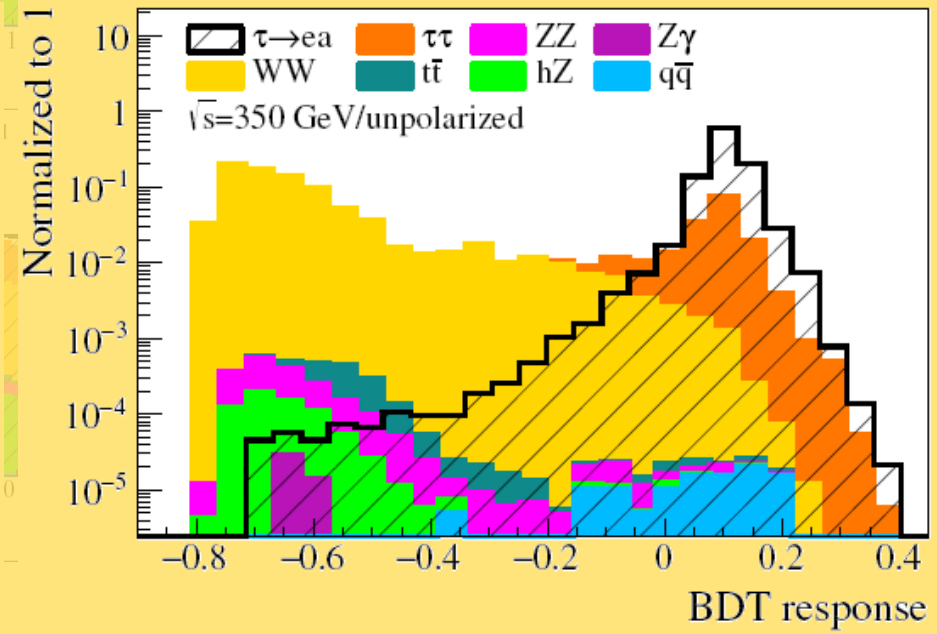
Polarized

Discriminating variables



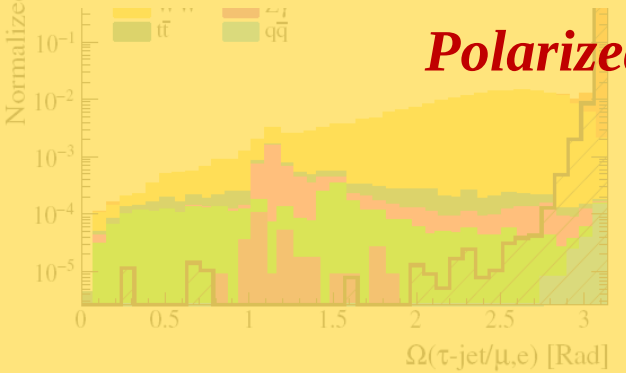
Discriminating variables

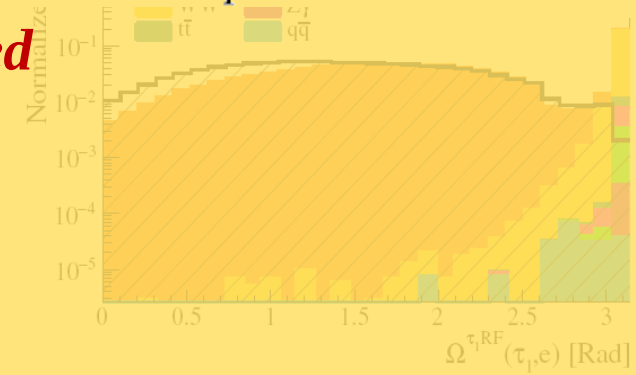


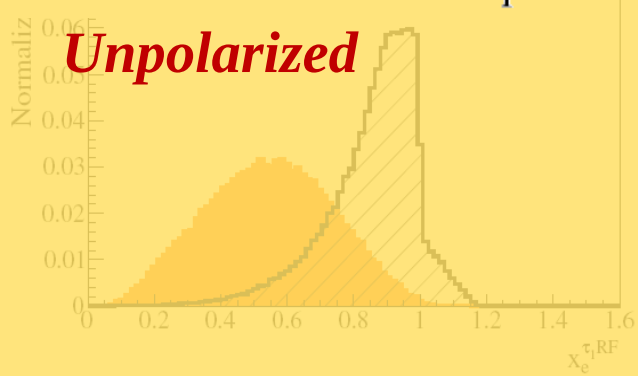


Polarized

Unpolarized







$c_{\tau e}/f_a$

Constraints

		m_a [MeV]	V+A	V−A	V/A
126 GeV	Unpolarized	1	9.02 (9.73)	8.46 (9.12)	12.24 (13.21)
	Polarized	1	2.96 (3.18)	7.32 (7.90)	5.54 (5.97)
350 GeV	Unpolarized	0.0001	6.63 (7.01)	6.53 (6.90)	9.37 (9.90)
		0.1	6.68 (7.06)	6.57 (6.94)	9.37 (9.90)
		0.2	6.69 (7.07)	6.52 (6.88)	9.39 (9.92)
		0.3	6.69 (7.08)	6.55 (6.91)	9.38 (9.91)
		0.4	6.71 (7.10)	6.54 (6.91)	9.40 (9.93)
		0.5	6.71 (7.10)	6.55 (6.91)	9.36 (9.88)
		0.6	6.69 (7.08)	6.53 (6.90)	9.40 (9.93)
		0.7	6.71 (7.09)	6.53 (6.90)	9.35 (9.88)
		0.8	6.70 (7.09)	6.52 (6.89)	9.37 (9.91)
		0.9	6.73 (7.12)	6.51 (6.87)	9.39 (9.91)
		1	6.70 (7.08)	6.52 (6.89)	9.34 (9.87)
	Polarized	0.0001	2.45 (2.57)	4.59 (4.92)	4.11 (4.34)
		0.1	2.44 (2.56)	4.59 (4.92)	4.13 (4.35)
		0.2	2.40 (2.52)	4.57 (4.90)	4.16 (4.39)
		0.3	2.40 (2.52)	4.58 (4.91)	4.05 (4.27)
		0.4	2.41 (2.53)	4.63 (4.96)	4.08 (4.30)
		0.5	2.41 (2.53)	4.58 (4.90)	4.16 (4.39)
		0.6	2.39 (2.51)	4.56 (4.88)	4.14 (4.37)
		0.7	2.43 (2.55)	4.58 (4.90)	4.10 (4.32)
		0.8	2.40 (2.52)	4.56 (4.88)	4.16 (4.38)
		0.9	2.41 (2.53)	4.56 (4.88)	4.16 (4.38)
		1	2.36 (2.48)	4.58 (4.90)	4.14 (4.37)
1500 GeV	Unpolarized	1	12.48 (13.15)	12.24 (12.90)	17.41 (18.35)
	Polarized	1	4.80 (5.04)	9.12 (9.75)	7.14 (7.51)

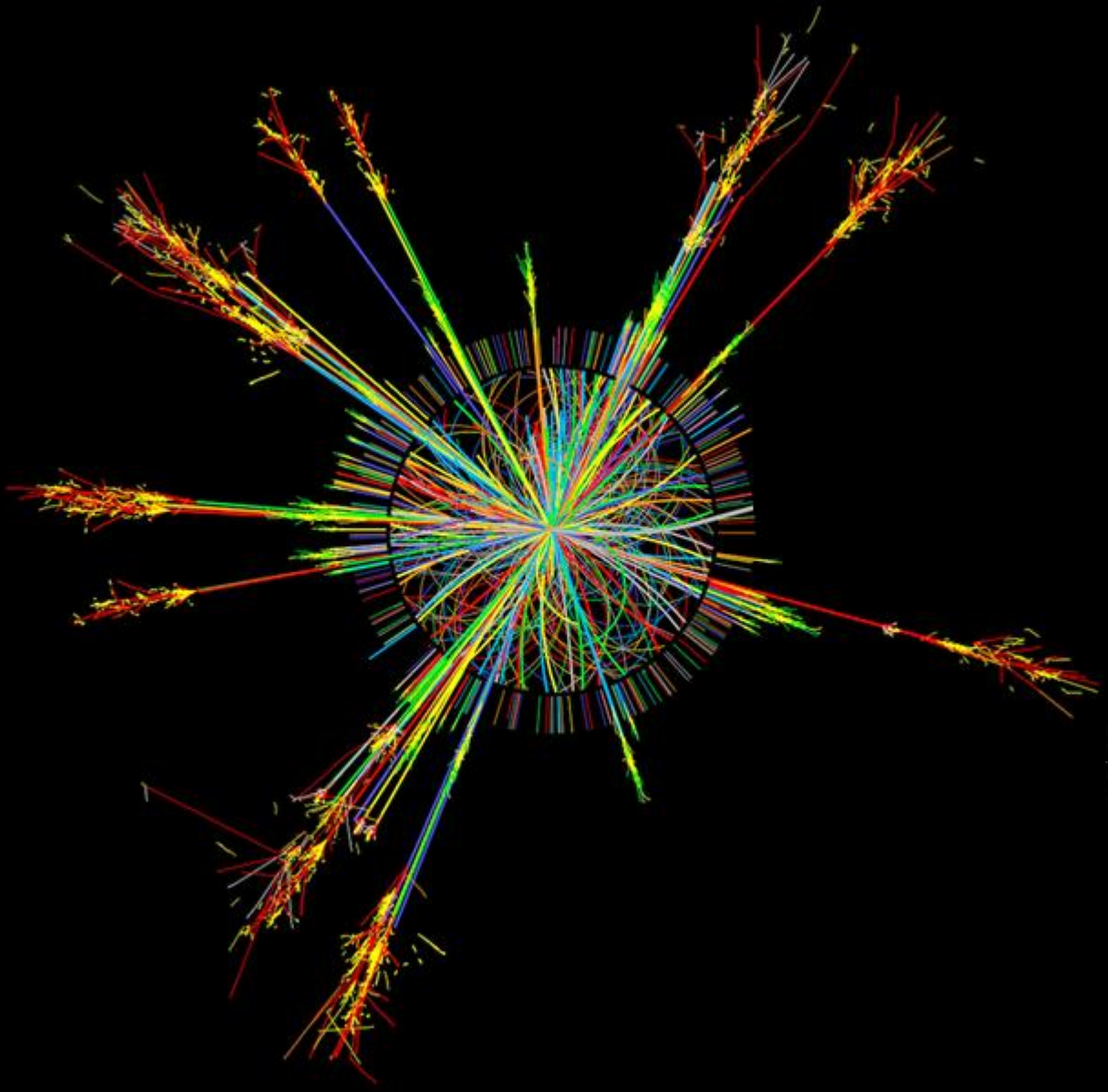
Expected 95% CL upper limit on $c_{\tau e}/f_a$ [10^{-5} TeV^{-1}]

Constraints

$c_{\tau\mu}/f_a$

		m_a [MeV]	V+A	V−A	V/A
126 GeV	Unpolarized	1	8.87 (9.57)	8.50 (9.17)	12.26 (13.23)
	Polarized	1	2.87 (3.08)	7.25 (7.83)	5.11 (5.51)
350 GeV	Unpolarized	0.0001	6.63 (7.01)	6.46 (6.82)	9.25 (9.77)
		0.1	6.62 (6.99)	6.43 (6.79)	9.25 (9.77)
		0.2	6.62 (6.99)	6.42 (6.78)	9.25 (9.77)
		0.3	6.60 (6.98)	6.44 (6.80)	9.26 (9.78)
		0.4	6.63 (7.01)	6.45 (6.81)	9.23 (9.74)
		0.5	6.62 (6.99)	6.42 (6.78)	9.27 (9.80)
		0.6	6.63 (7.00)	6.43 (6.79)	9.27 (9.80)
		0.7	6.63 (7.01)	6.38 (6.74)	9.27 (9.80)
		0.8	6.66 (7.04)	6.43 (6.78)	9.25 (9.77)
		0.9	6.65 (7.03)	6.48 (6.84)	9.24 (9.76)
		1	6.62 (7.00)	6.43 (6.79)	9.19 (9.71)
	Polarized	0.0001	2.23 (2.34)	4.45 (4.75)	3.76 (3.96)
		0.1	2.15 (2.25)	4.46 (4.74)	3.77 (3.97)
		0.2	2.18 (2.29)	4.45 (4.75)	3.79 (3.99)
		0.3	2.13 (2.23)	4.45 (4.75)	3.72 (3.92)
		0.4	2.18 (2.28)	4.49 (4.80)	3.76 (3.96)
		0.5	2.17 (2.28)	4.38 (4.68)	3.75 (3.95)
		0.6	2.14 (2.24)	4.47 (4.78)	3.76 (3.95)
		0.7	2.21 (2.31)	4.47 (4.78)	3.57 (3.75)
		0.8	2.15 (2.25)	4.44 (4.74)	3.75 (3.93)
		0.9	2.10 (2.20)	4.50 (4.81)	3.77 (3.98)
		1	2.17 (2.27)	4.38 (4.68)	3.74 (3.92)
1500 GeV	Unpolarized	1	12.29 (12.95)	12.13 (12.77)	17.29 (18.22)
	Polarized	1	4.49 (4.71)	8.84 (9.44)	7.86 (8.27)

Expected 95% CL upper limit on $c_{\tau\mu}/f_a$ [10^{-5} TeV^{-1}]



Thank You!

Backup slides

Polarization-induced effects

Signal: $\mu^-\mu^+ \to \tau^-\tau^+,\ \tau \to e/\mu + a$

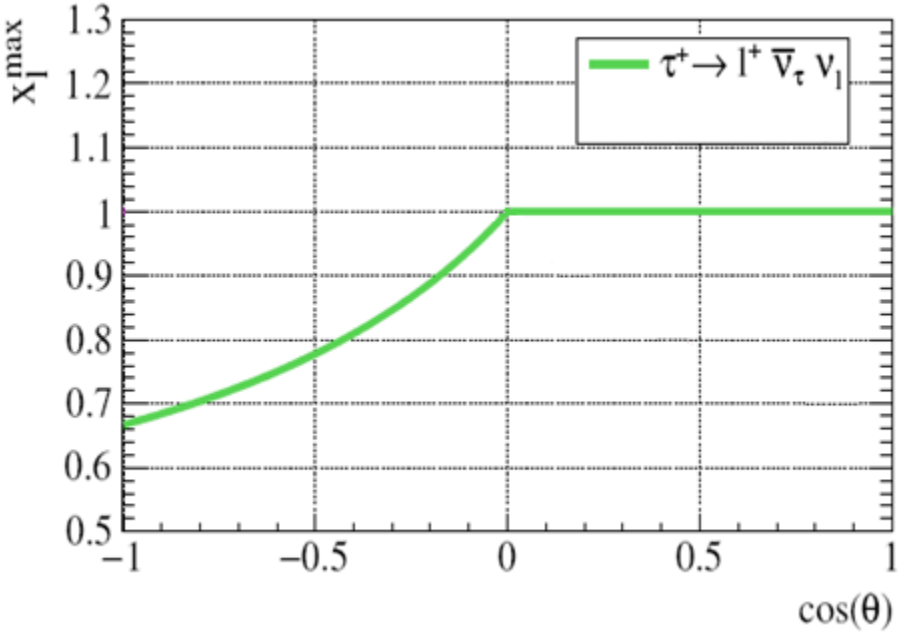
SM BG: $\mu^-\mu^+ \to \tau^-\tau^+, \tau \to e/\mu + \nu\bar{\nu}$

BG $\tau \to e/\mu + \nu\bar{\nu}$

In the tau rest frame:

$$\frac{\mathrm{d}^2\Gamma\left(\begin{array}{c}\tau^+ \to \ell^+\,\nu_\ell\,\bar{\nu}_\tau \\ \tau^- \to \ell^-\,\bar{\nu}_\ell\,\nu_\tau\end{array}\right)}{\mathrm{d}x_\ell\,\mathrm{d}\cos\theta} \simeq \Gamma_\tau\big[\,(3-2x_\ell) \pm \mathcal{P}_\tau(2x_\ell-1)\cos\theta\big]x_\ell^2$$

$$x_{\ell^\pm}^{\max} = \frac{3 \mp \mathcal{P}_\tau\cos\theta}{3(1 \mp \mathcal{P}_\tau\cos\theta)}$$



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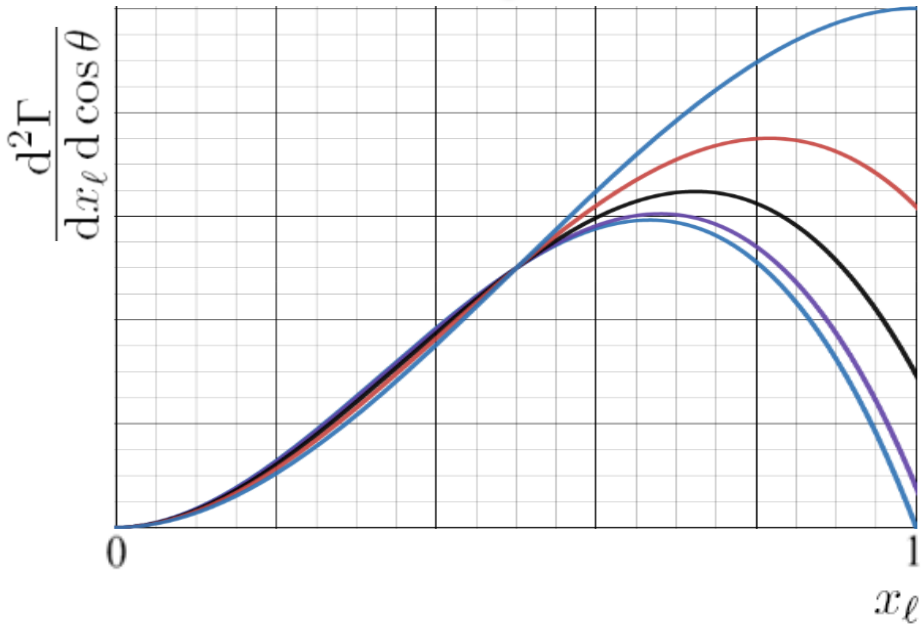

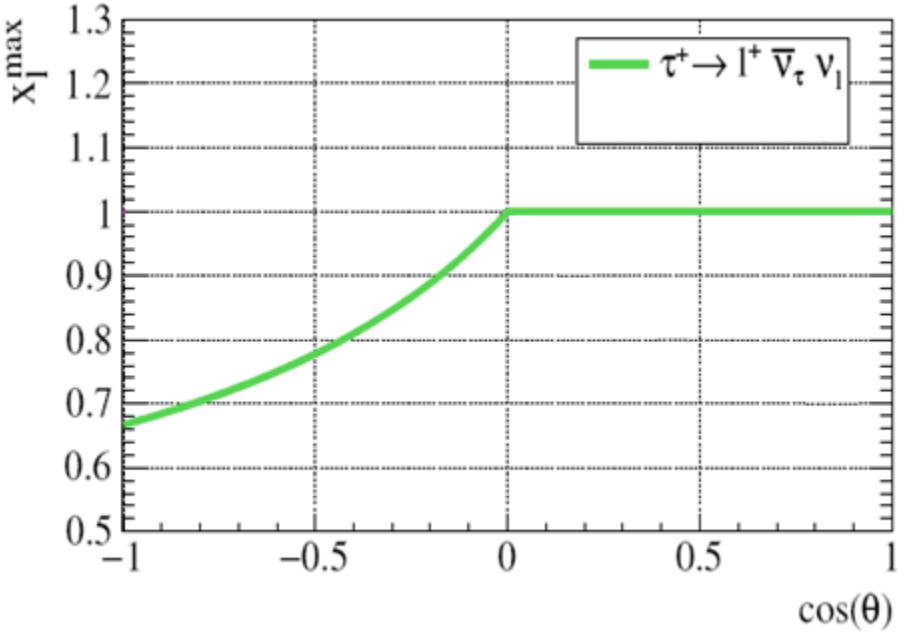

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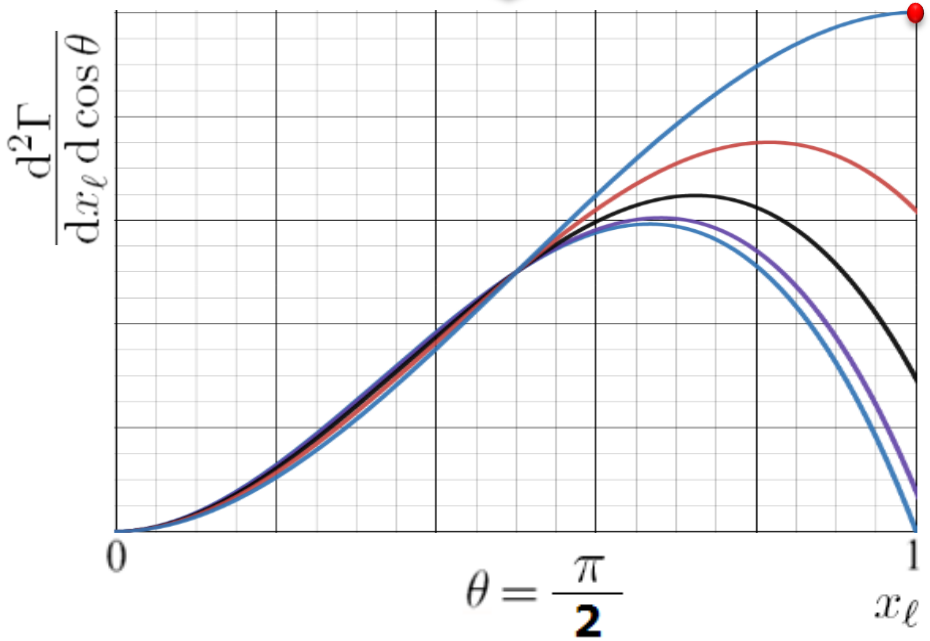

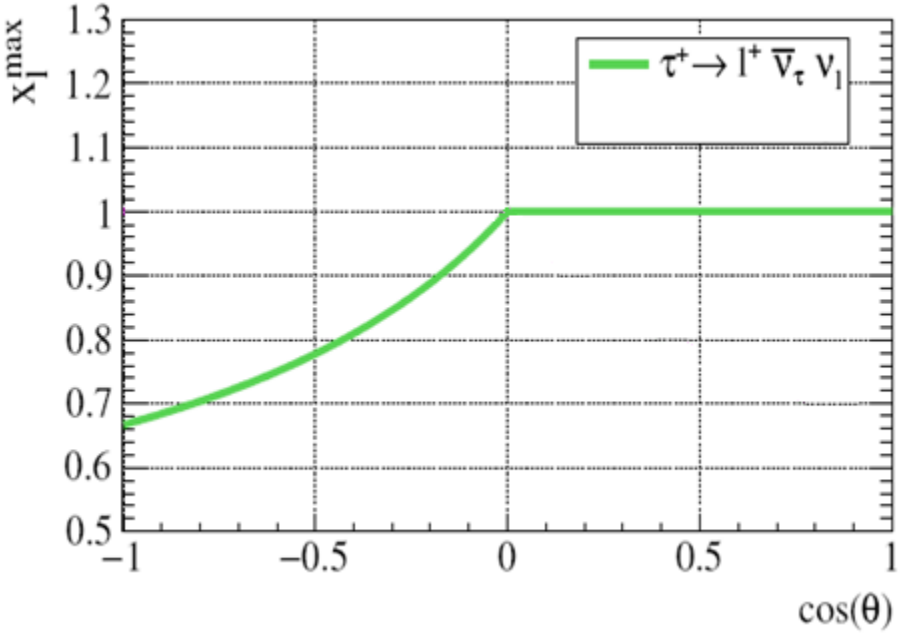

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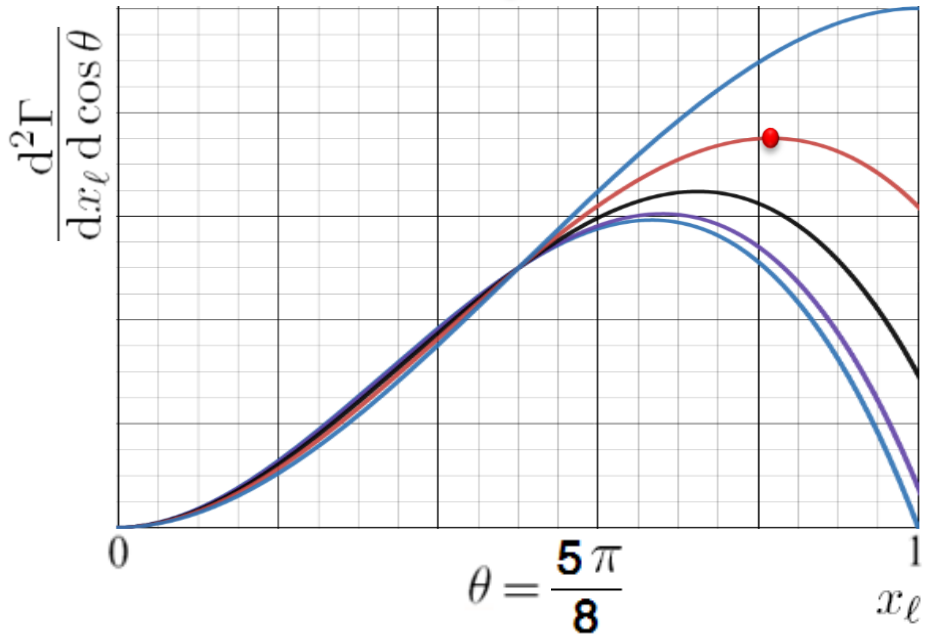

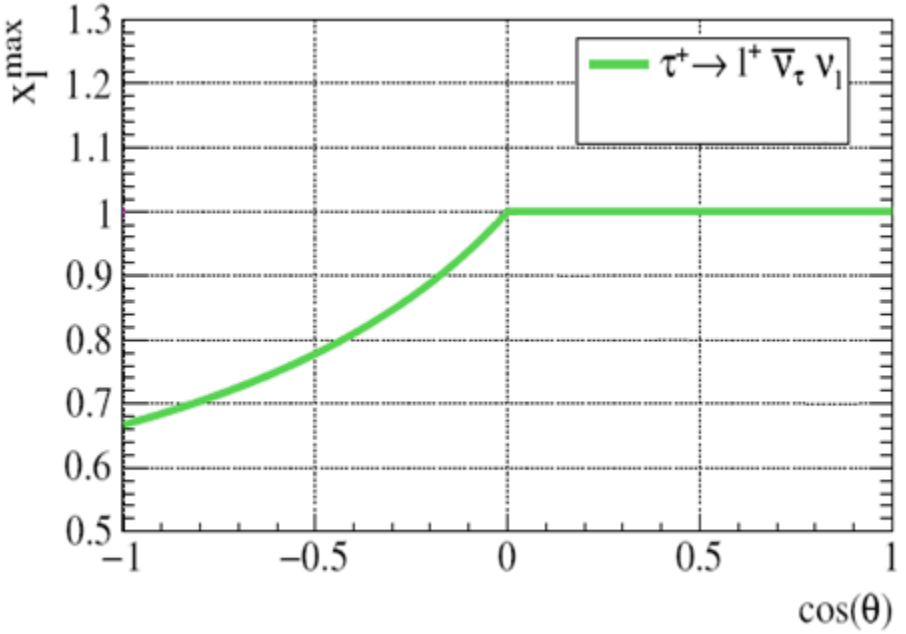

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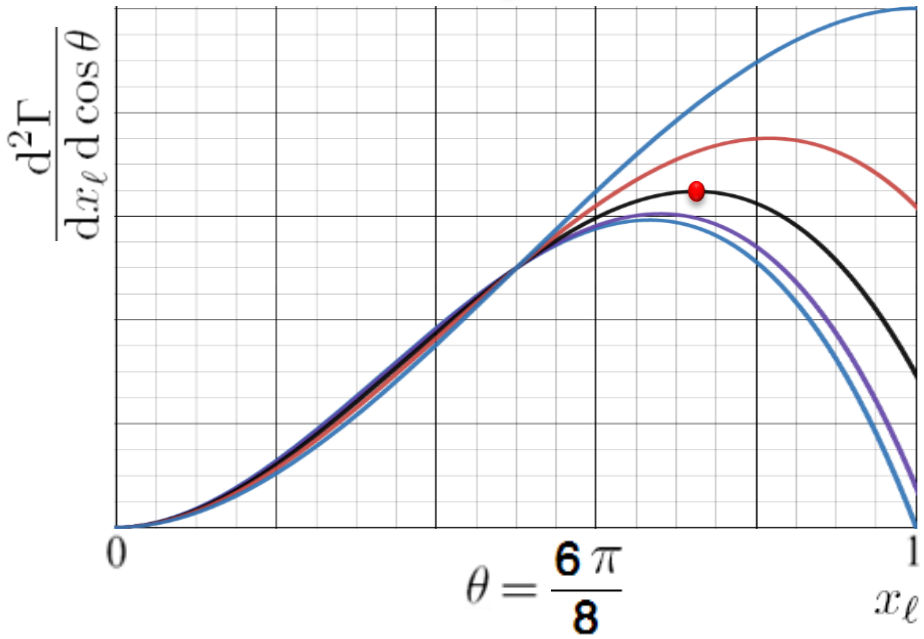

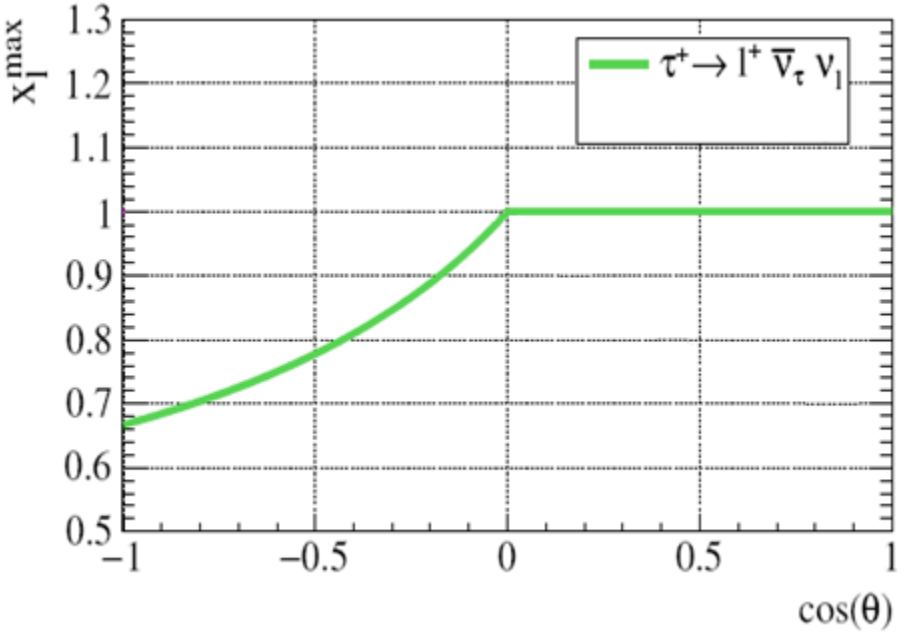

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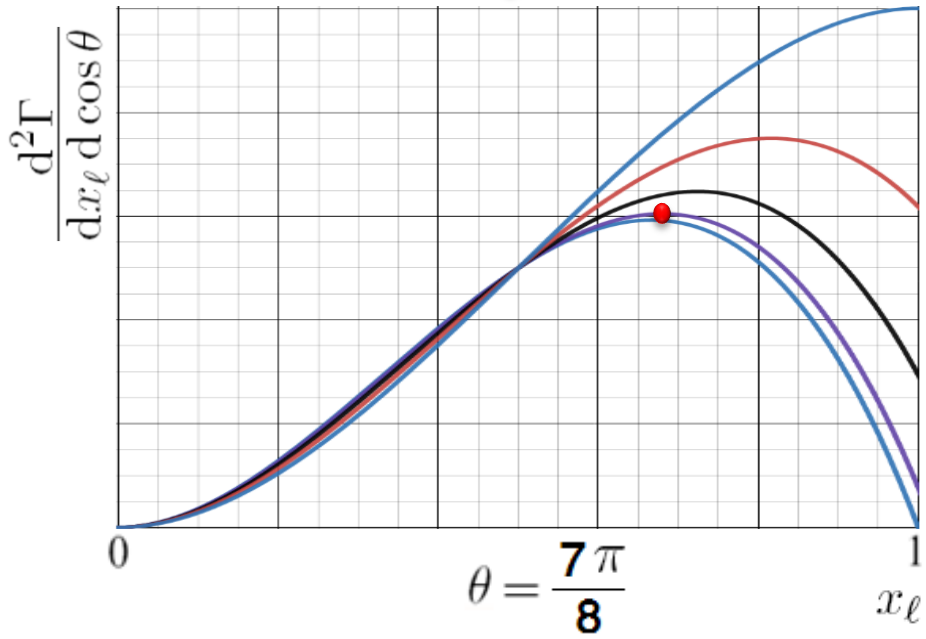

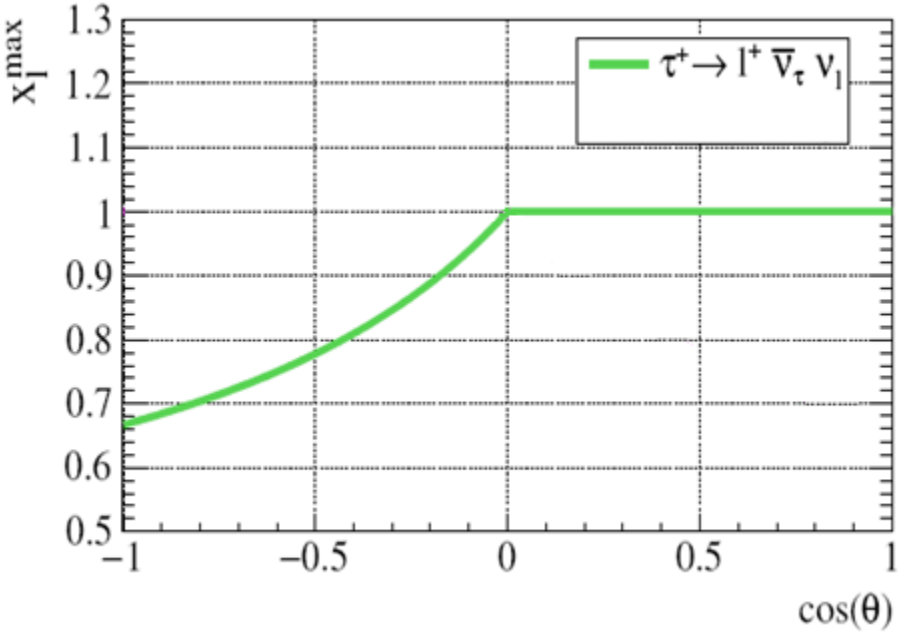

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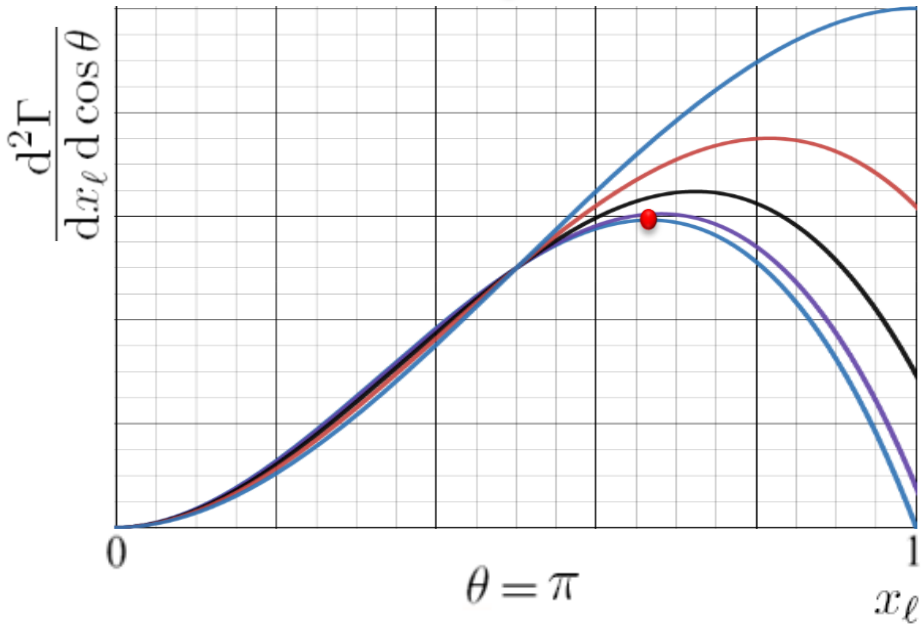

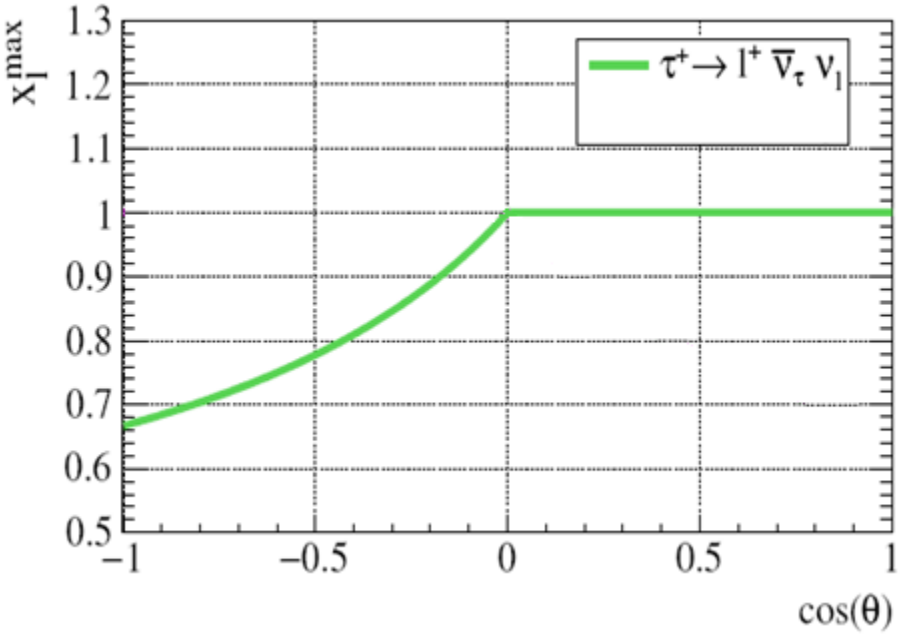

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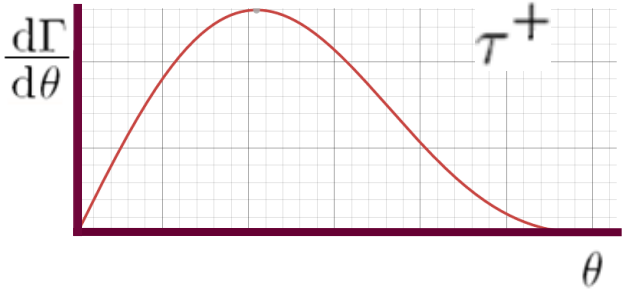
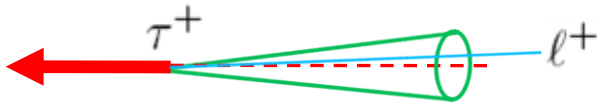
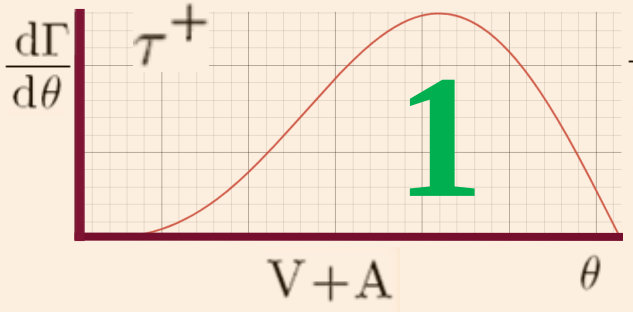
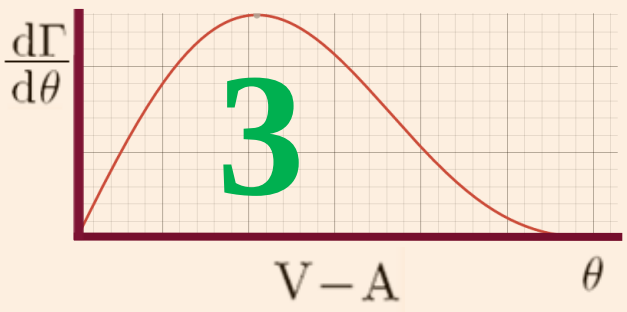
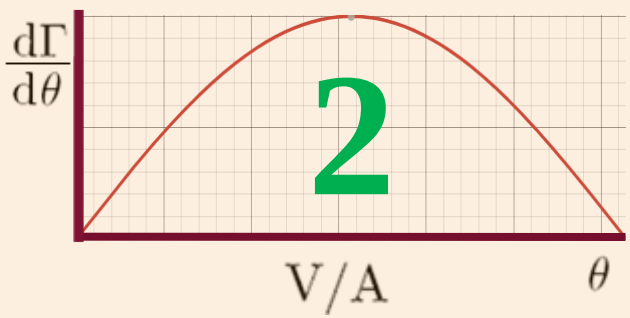




Signal angular distribution







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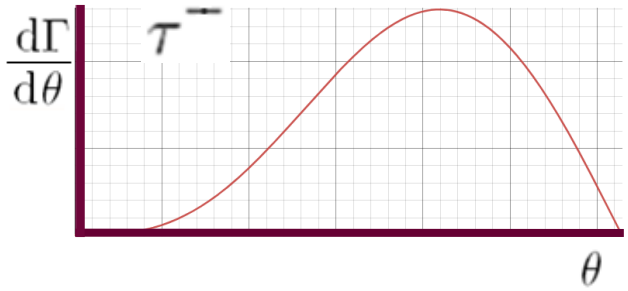
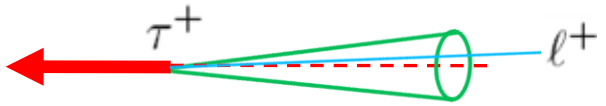
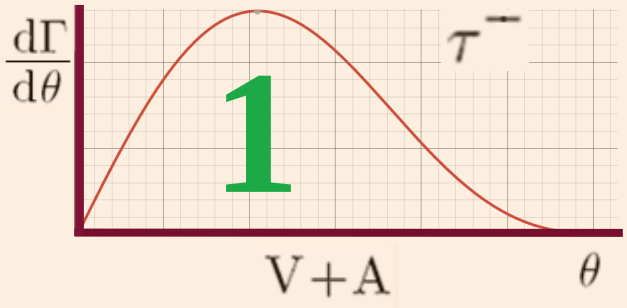
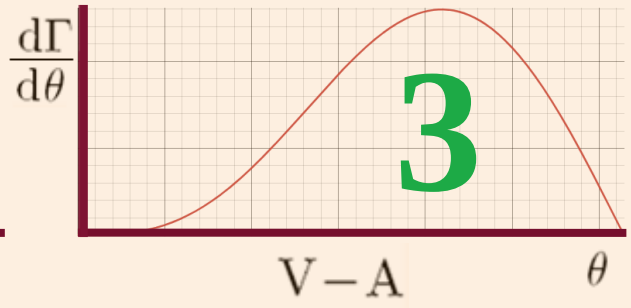
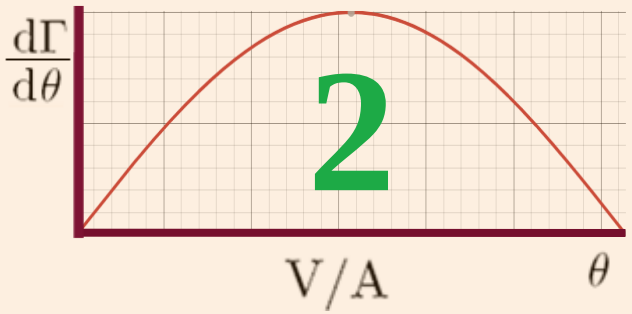




Signal angular distribution







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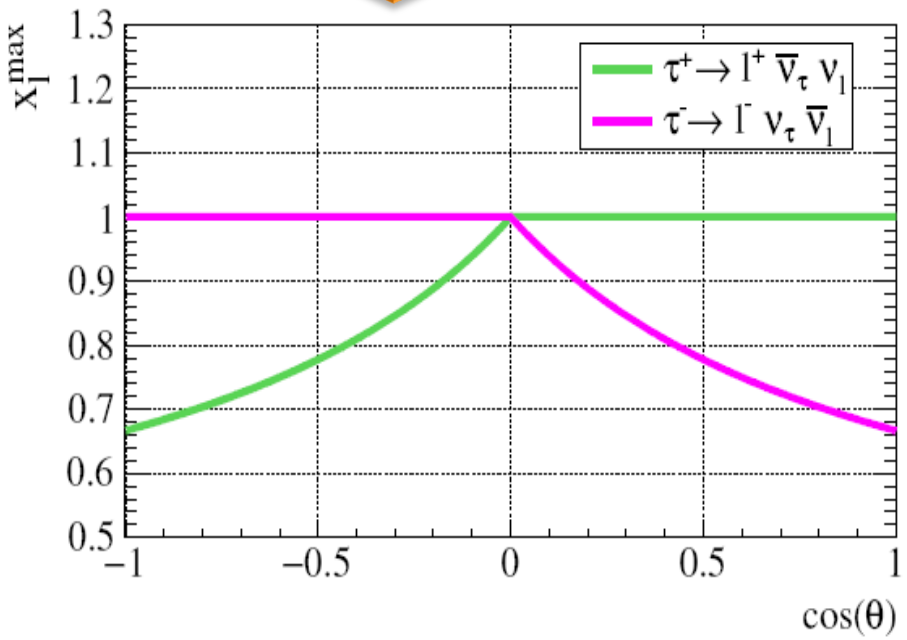
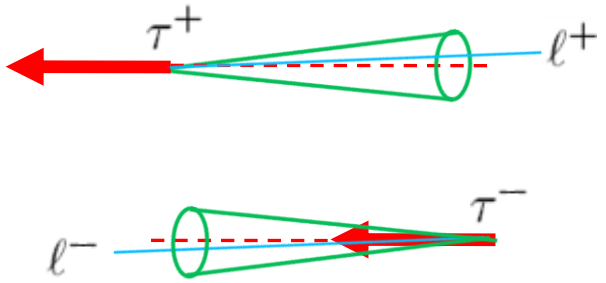
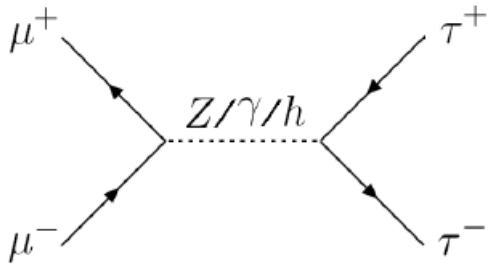
In the tau rest frame:

$$\frac{\mathrm{d}^2\Gamma\left(\begin{array}{l}\tau^+ \to \ell^+\,\nu_\ell\,\bar{\nu}_\tau \\ \tau^- \to \ell^-\,\bar{\nu}_\ell\,\nu_\tau\end{array}\right)}{\mathrm{d}x_\ell\,\mathrm{d}\cos\theta} \simeq \Gamma_\tau\left[\,(3-2x_\ell) \pm \mathcal{P}_\tau(2x_\ell-1)\cos\theta\right]x_\ell^2$$

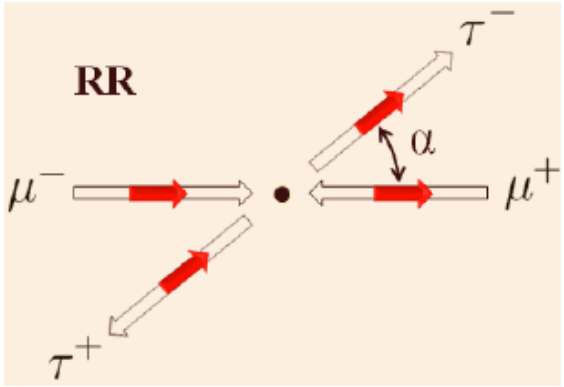


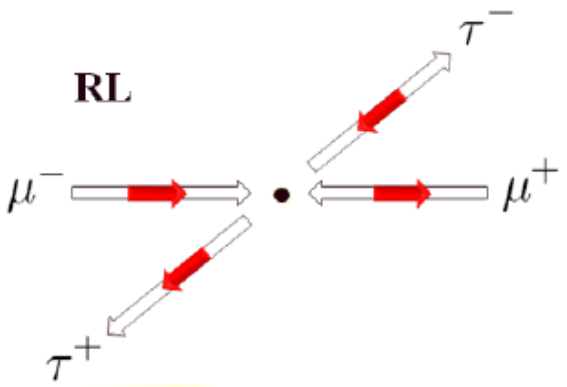


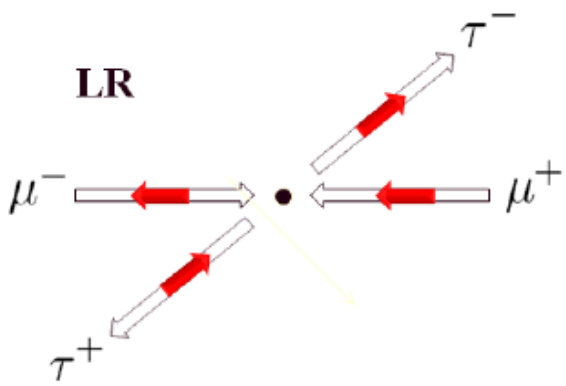
How to produce highly polarized tau leptons?

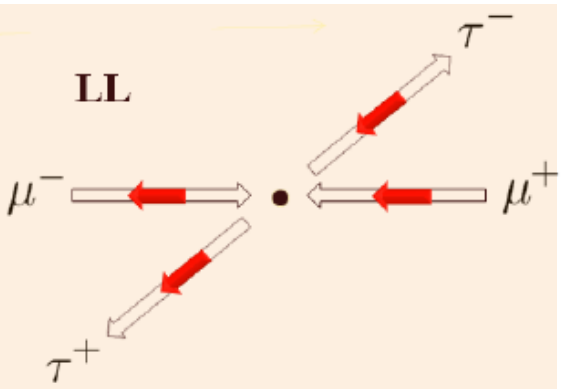


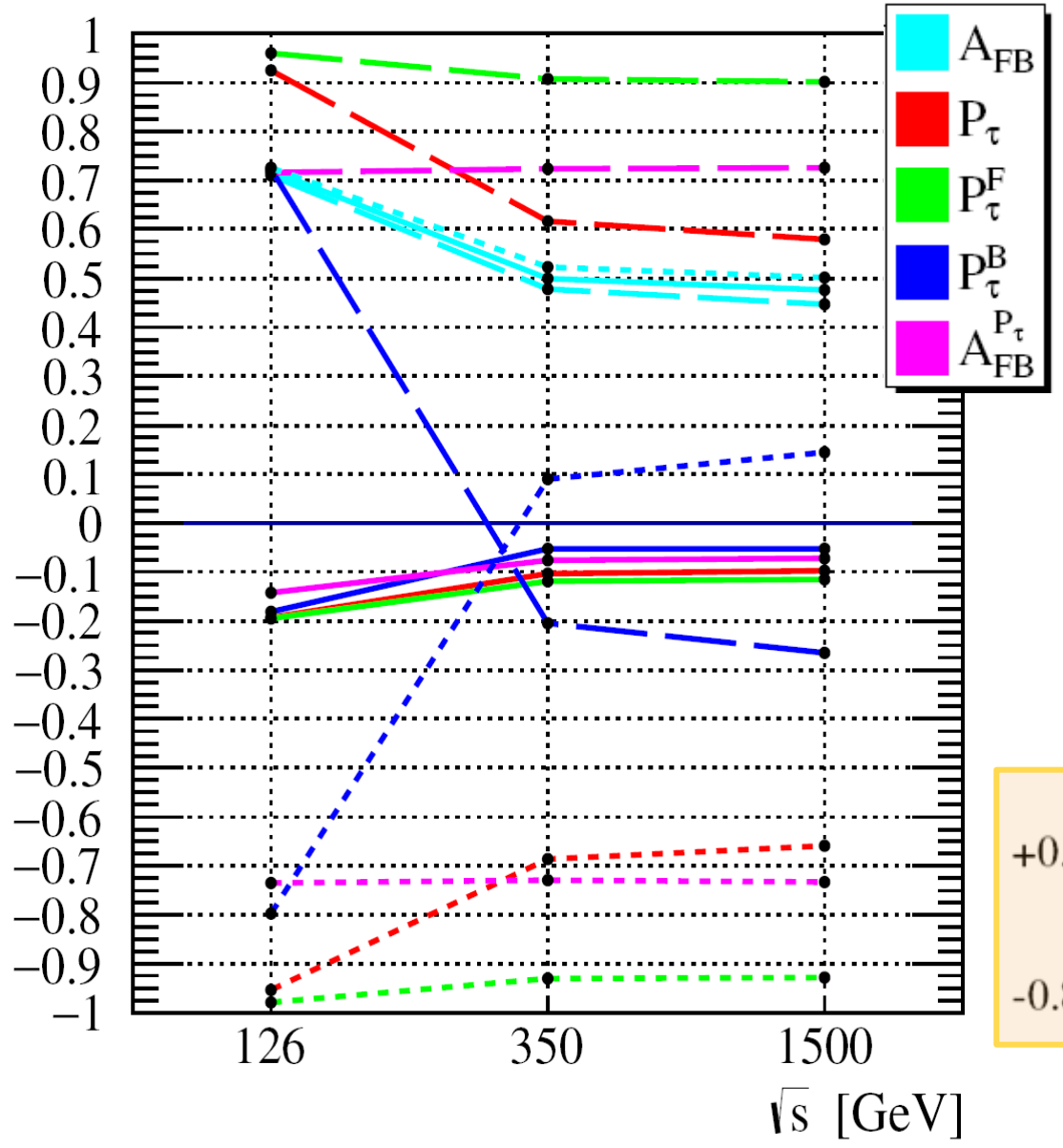
$m_\tau \ll E_\tau$









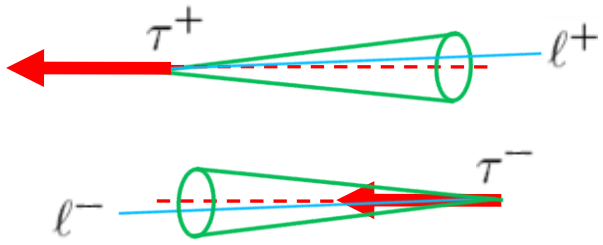


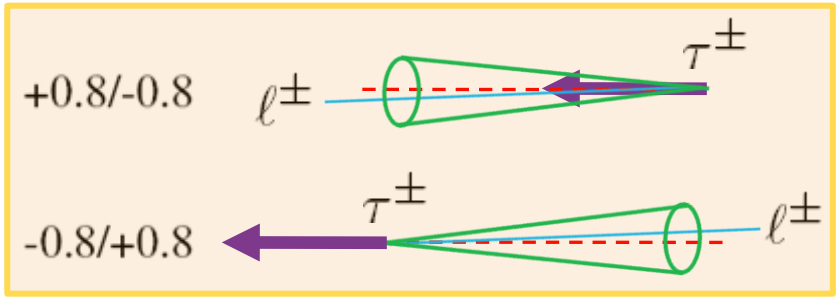
unpolarized

+0.8/-0.8

-0.8/+0.8

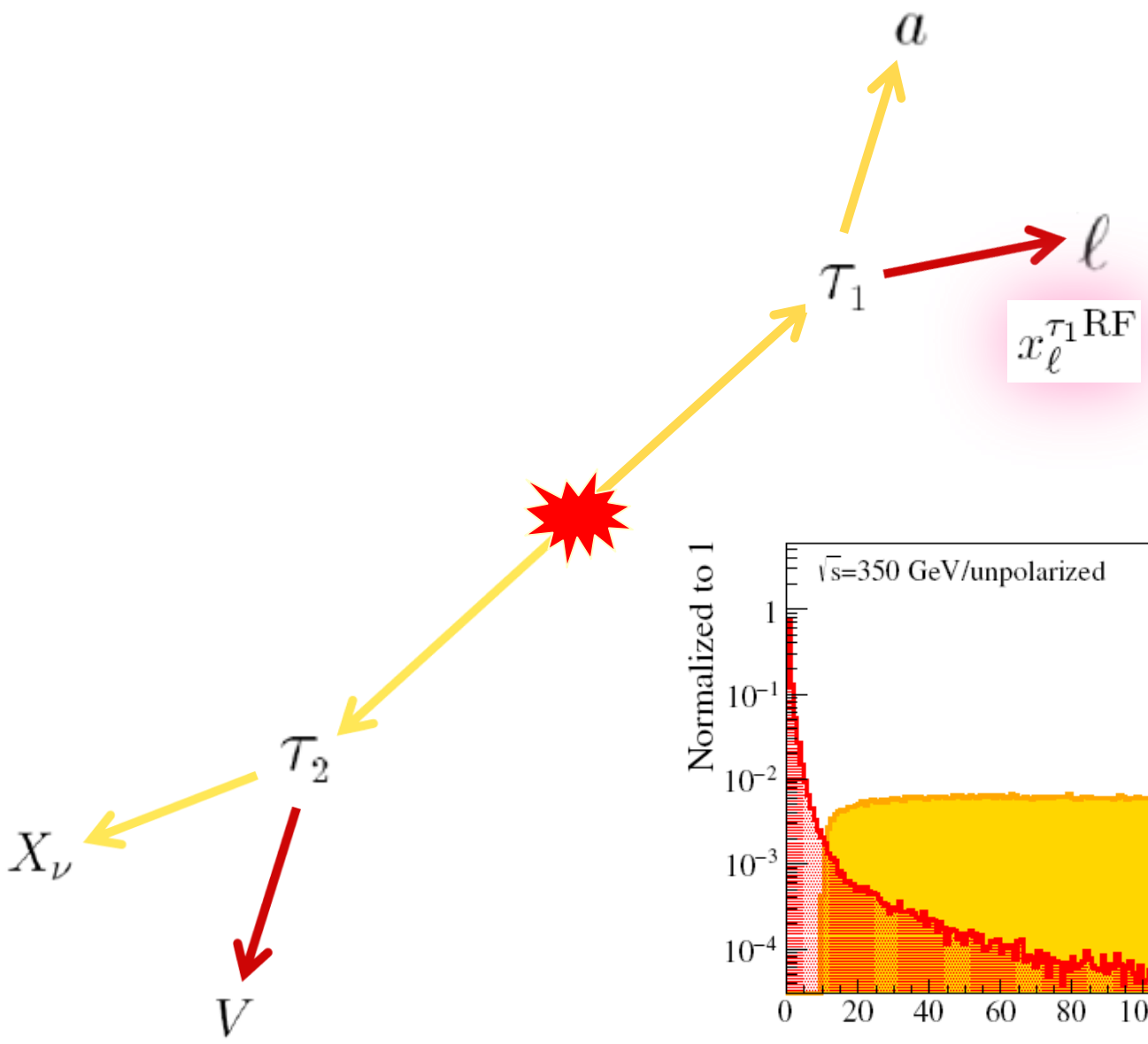
	+0.8/-0.8	-0.8/+0.8
forward τ^-	**> +0.9**	**< –0.9**
backward τ^+	**< –0.9**	**> +0.9**





$$A_{\rm FB} = \frac{\sigma^{\rm F} - \sigma^{\rm B}}{\sigma_{\rm total}} \qquad P_\tau = \frac{(\sigma_{++} + \sigma_{+-}) - (\sigma_{-+} + \sigma_{--})}{\sigma_{\rm total}} \qquad P_\tau^{\rm F/B} = \frac{\sigma^{\rm F/B}(h_\tau = +1) - \sigma^{\rm F/B}(h_\tau = -1)}{\sigma^{\rm F/B}}$$

Discriminating variables

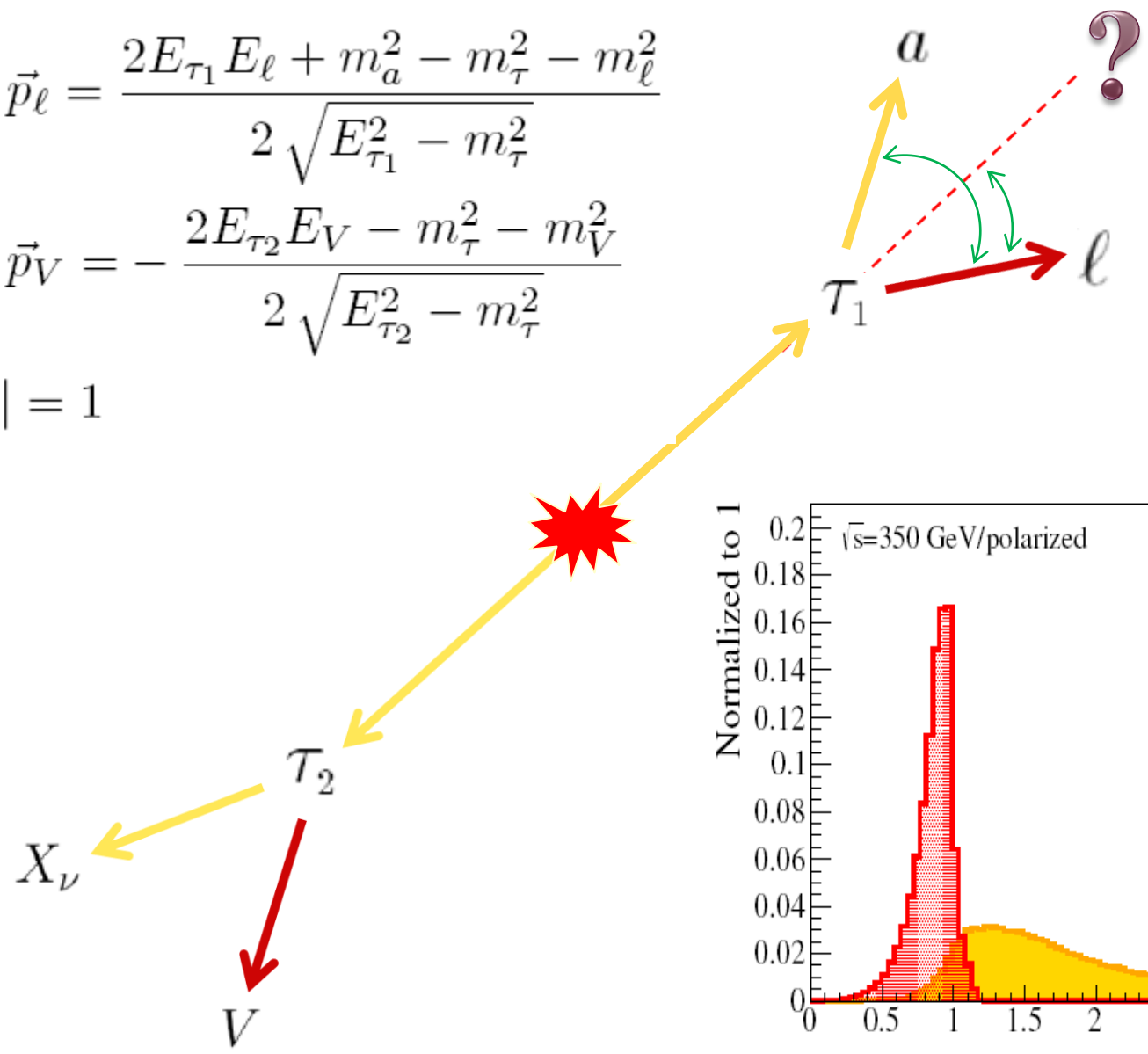


Discriminating variables

$$\hat{v}_1 . \vec{p}_\ell = \frac{2E_{\tau_1}E_\ell + m_a^2 - m_\tau^2 - m_\ell^2}{2\sqrt{E_{\tau_1}^2 - m_\tau^2}}$$

$$\hat{v}_1 . \vec{p}_V = -\frac{2E_{\tau_2}E_V - m_\tau^2 - m_V^2}{2\sqrt{E_{\tau_2}^2 - m_\tau^2}}$$

$$|\hat{v}_1| = 1$$



Discriminating variables