

*Search for lepton-flavor-violating ALPs at a future muon collider  
and  
utilization of polarization-induced effects*

*Based on  
arXiv: 2106.00505*

*by*

*Gholamhossein Haghghat, Mojtaba Mohammadi Najafabadi*

*Presented by*

*Gholamhossein Haghghat*

July 14, 2021

Institute for Research in Fundamental Sciences  
School of Particles and Accelerators

## Outline

- *Lepton-flavor-violating Axion-like particles*
- *LFV ALPs production & SM backgrounds*
- *Analysis & polarization-induced effects*
- *Expected limits*

# 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.  $|d_n| < 10^{-25} \text{ e} \cdot \text{cm}$

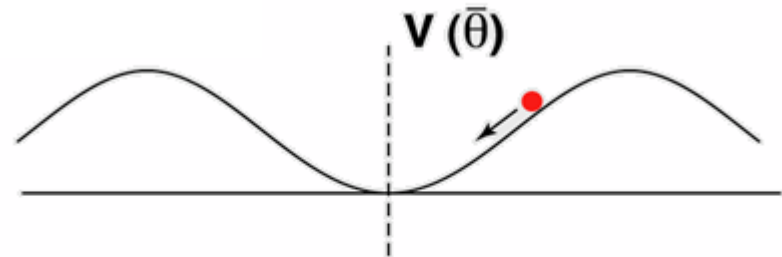
- $\bar{\theta} \leq 10^{-10}$

- Strong-CP preserving

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

## Peccei-Quinn

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



- $\bar{\theta}$  dynamically  $\rightarrow 0$

*a new pseudoscalar boson: AXION*

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

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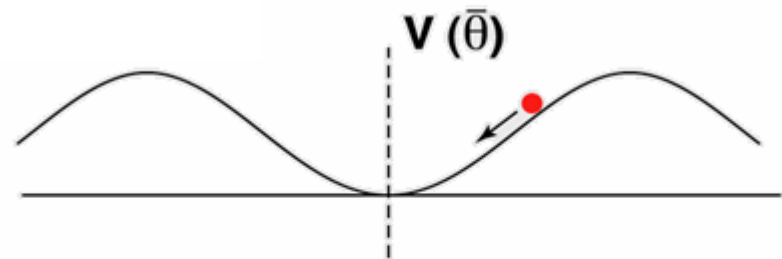
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*Axion-like Particles*

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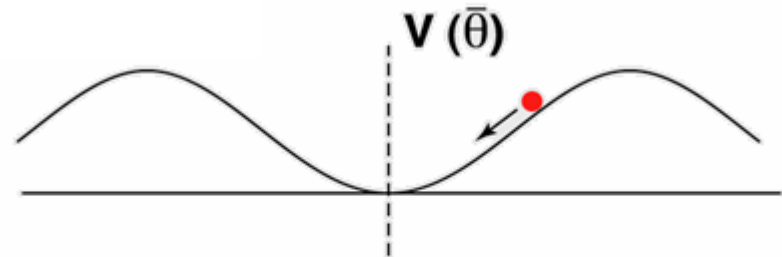
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## Motivations

- Strong CP problem
- Observed baryon asymmetry
- Anomalous magnetic moments of  $\mu$  and  $e$
- Dark matter

## LFV ALPs effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \sum_{i \neq j} \frac{\partial_{\mu} a}{2f_a} \bar{l}_i \gamma^{\mu} (c_{l_i l_j}^V + c_{l_i l_j}^A \gamma_5) l_j \quad l_i = e, \mu, \tau$$

### Assumed chiral structures

- **V+A**:  $c_{l_i l_j} (1 + \gamma_5)$
- **V-A**:  $c_{l_i l_j} (1 - \gamma_5)$
- **V/A**:  $c_{l_i l_j}^V = 0$  **or**  $c_{l_i l_j}^A = 0$



$$\tau \rightarrow e a$$



$$c_{\tau e}$$

$$\tau \rightarrow \mu a$$



$$c_{\tau \mu}$$

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

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$$\tau \rightarrow e a$$

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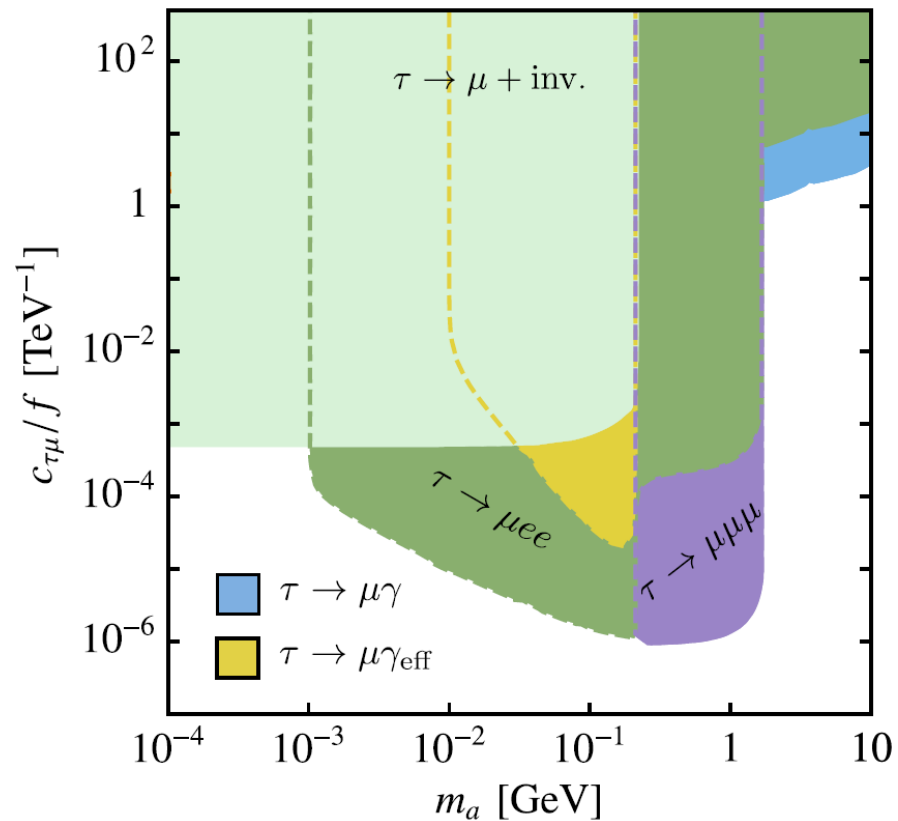
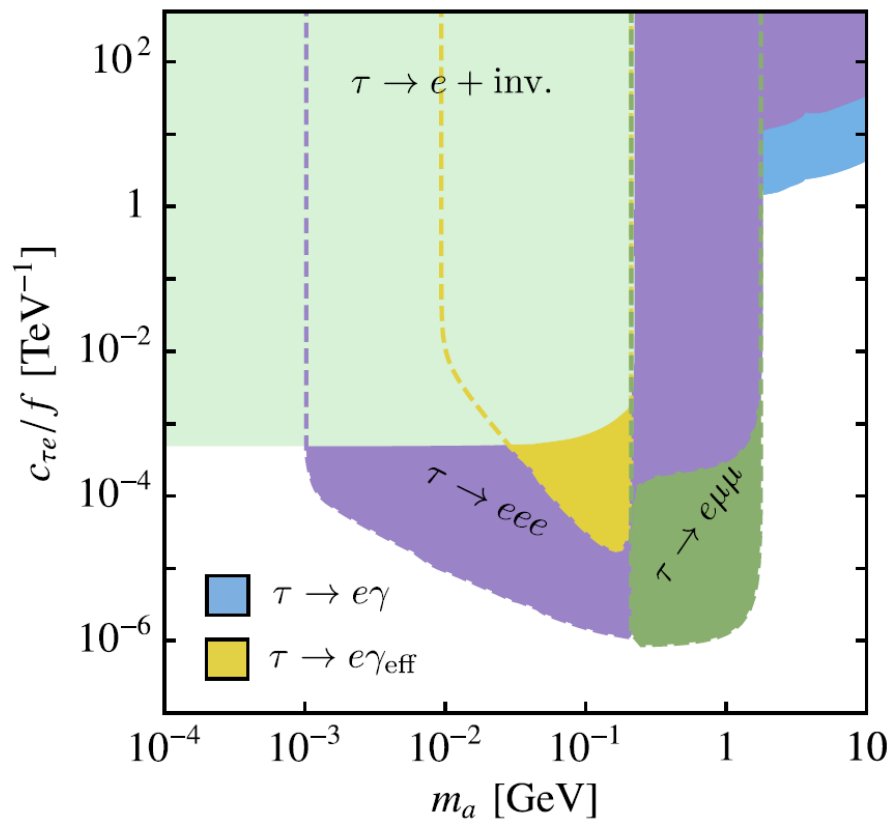
$$c_{\tau \mu}$$

V+A  
V-A  
V/A

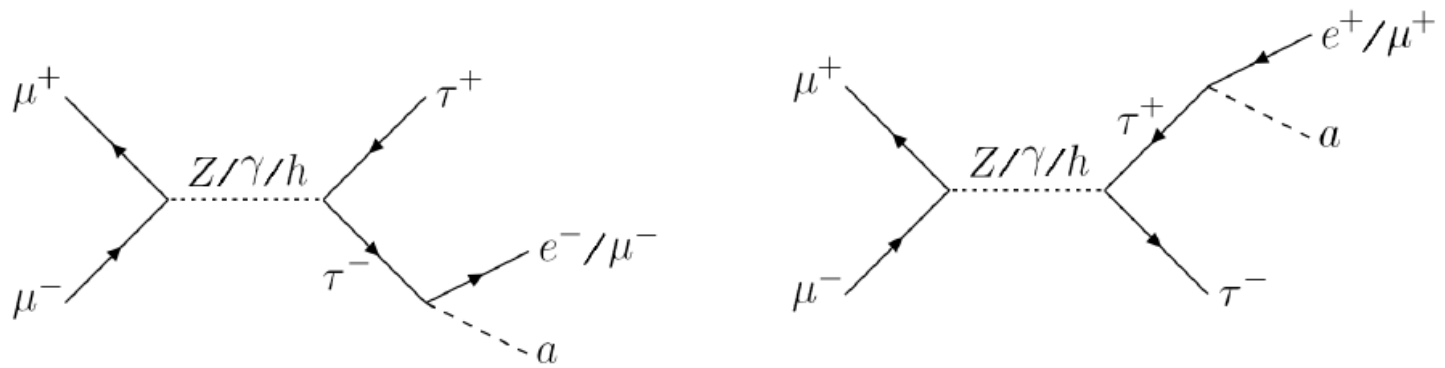
V+A  
V-A  
V/A

**Research objectives:**  
**Computing limits on**

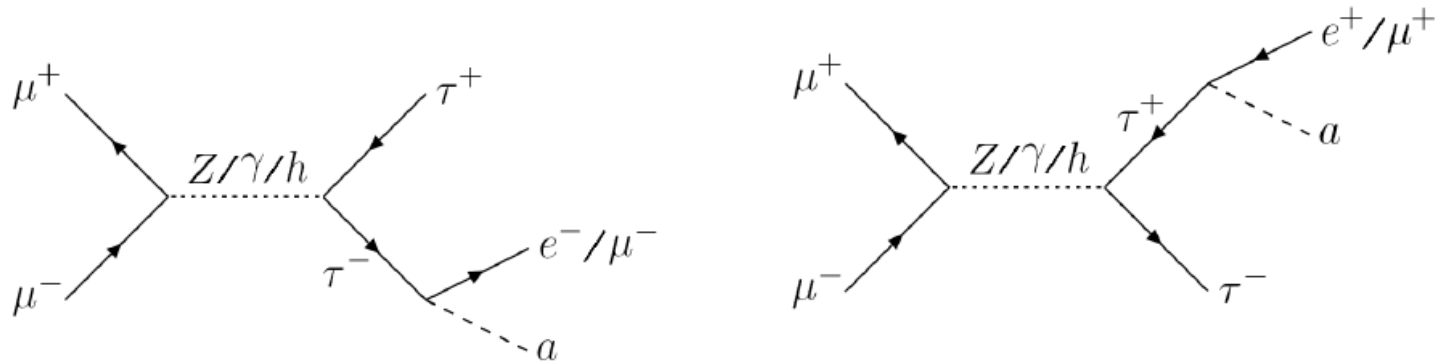
# Current experimental limits



# Signal process



## Signal process



Muon Accelerator Program

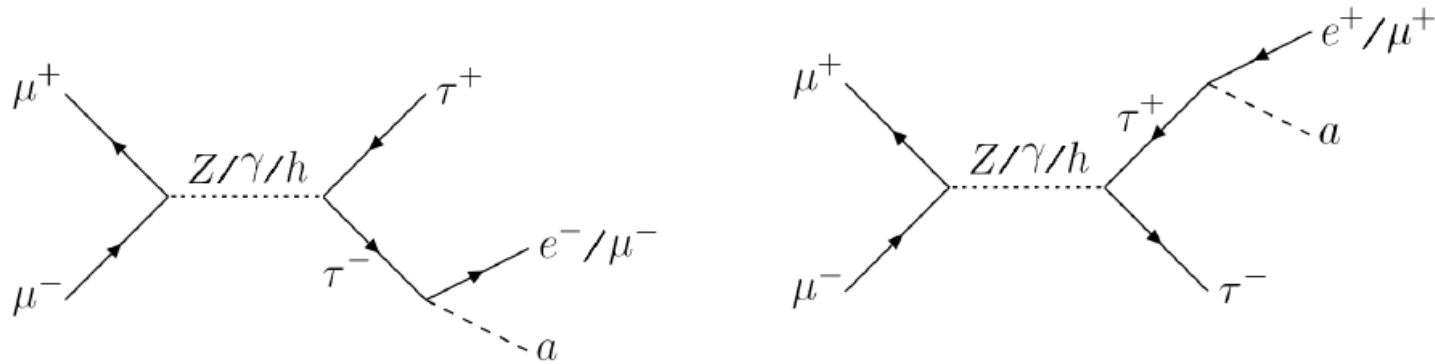
### Muon colliders motivations

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

### operating stages

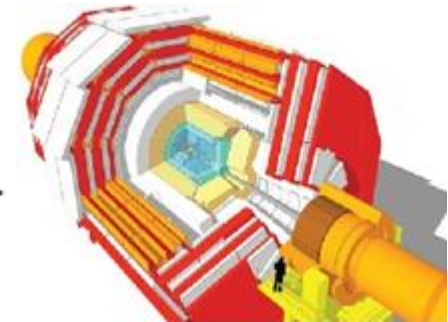
	Higgs	Top-High	Luminosity	Multi-TeV	
Center-of-mass energy [GeV]	126	350	1500	3000	6000
Average luminosity [ $10^{34} \text{cm}^{-2} \text{s}^{-1}$ ]	0.008	0.6	1.25	4.4	12

## Signal process



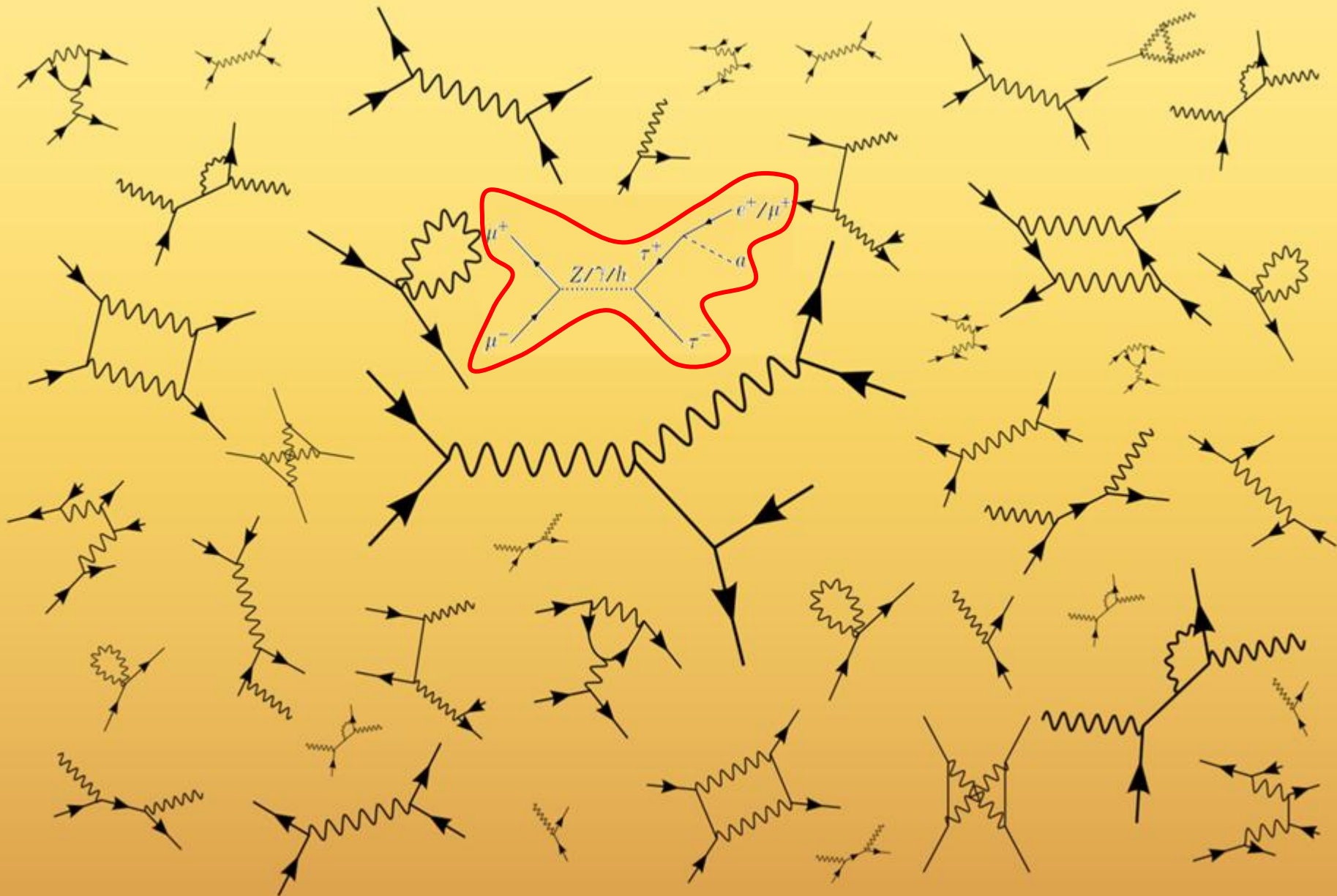
## Decay length of light ALPs

$$100 \text{ eV} \leq m_a \leq 1 \text{ MeV} \quad \longrightarrow \quad L_a > 2.3 \times 10^{20} \text{ m} \quad \gg \quad (m_a = 1 \text{ MeV})$$



$$\mu^- \mu^+ \rightarrow \tau^- \tau^+, \quad \tau \rightarrow e/\mu + \cancel{E}$$

# SM backgrounds



## *SM backgrounds*

*Signal signature:*

$$\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + \cancel{E}$$

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

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

$$t \bar{t}$$

$$hZ$$

$$ZZ$$

$$Z\gamma$$

$$q\bar{q}$$

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

## *SM backgrounds*

*Signal signature:*

$$\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + \cancel{E}$$

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

*Only suppressed by polarization-induced effects*

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

$$t\bar{t}$$

$$hZ$$

$$ZZ$$

$$Z\gamma$$

$$q\bar{q}$$

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

# *Event generation*

*Lagrangian*

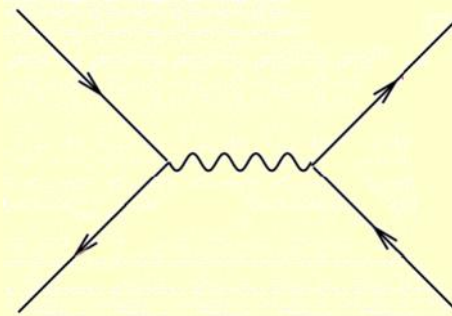


*Feynrules*



*MadGraph5\_aMC@NLO*

*TauDecay  
package*



# Event generation

*Lagrangian*



*Feynrules*

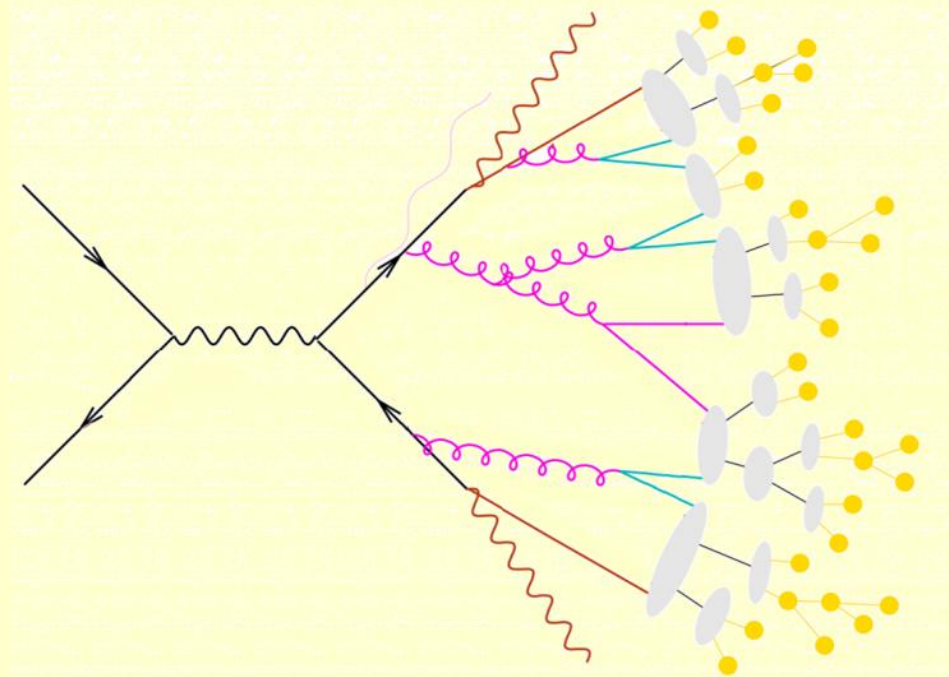


*MadGraph5\_aMC@NLO*



*Pythia 8.2.43*

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# Event generation

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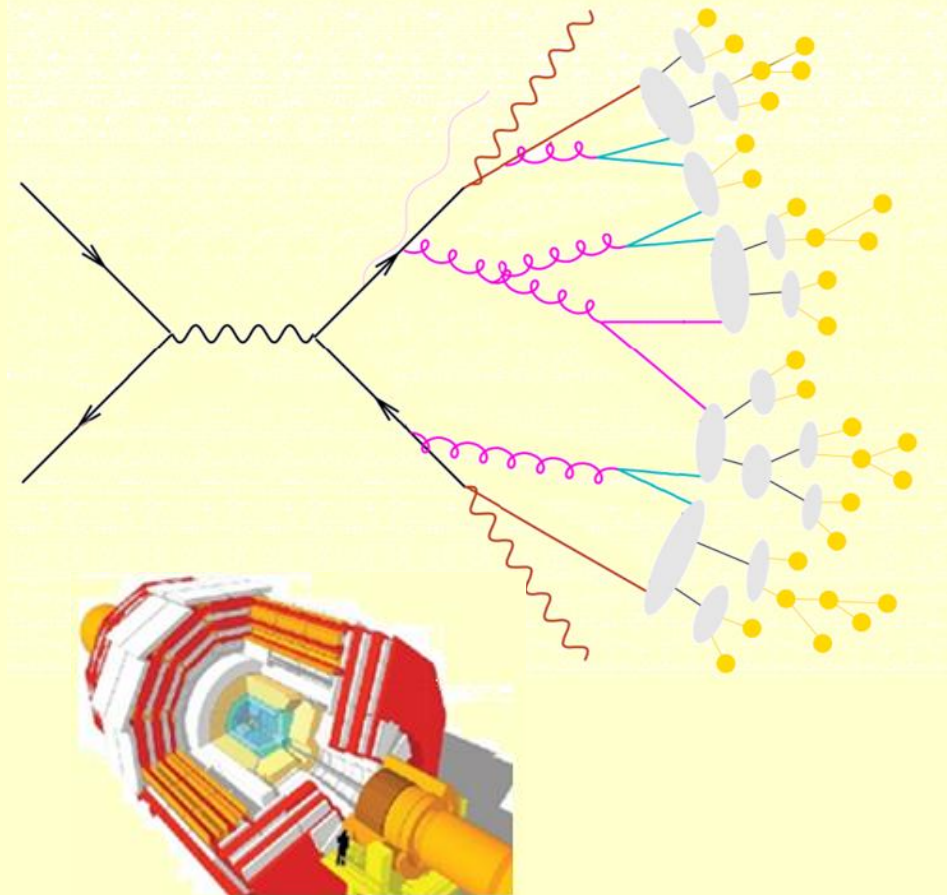
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*Delphes 3.4.2*



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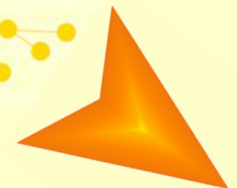
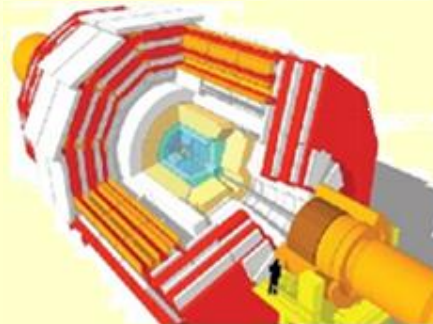
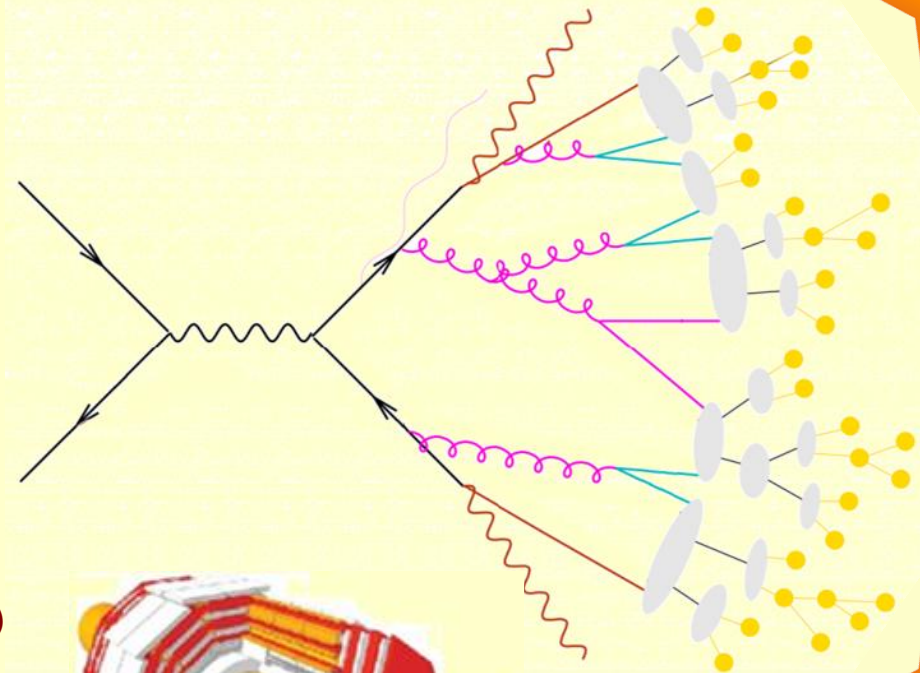


*Delphes 3.4.2*



*FastJet 3.3.2 (Valencia jet algorithm)*

$R = 1.2 \quad \beta = 1$



# Event generation

*Lagrangian*



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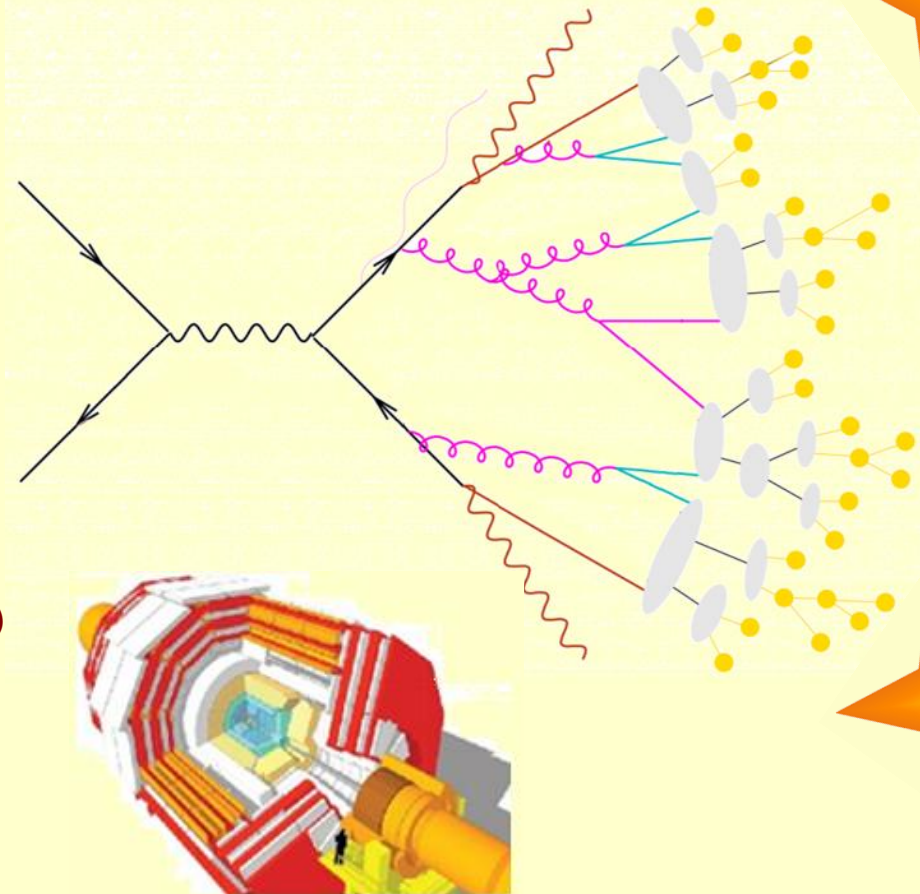


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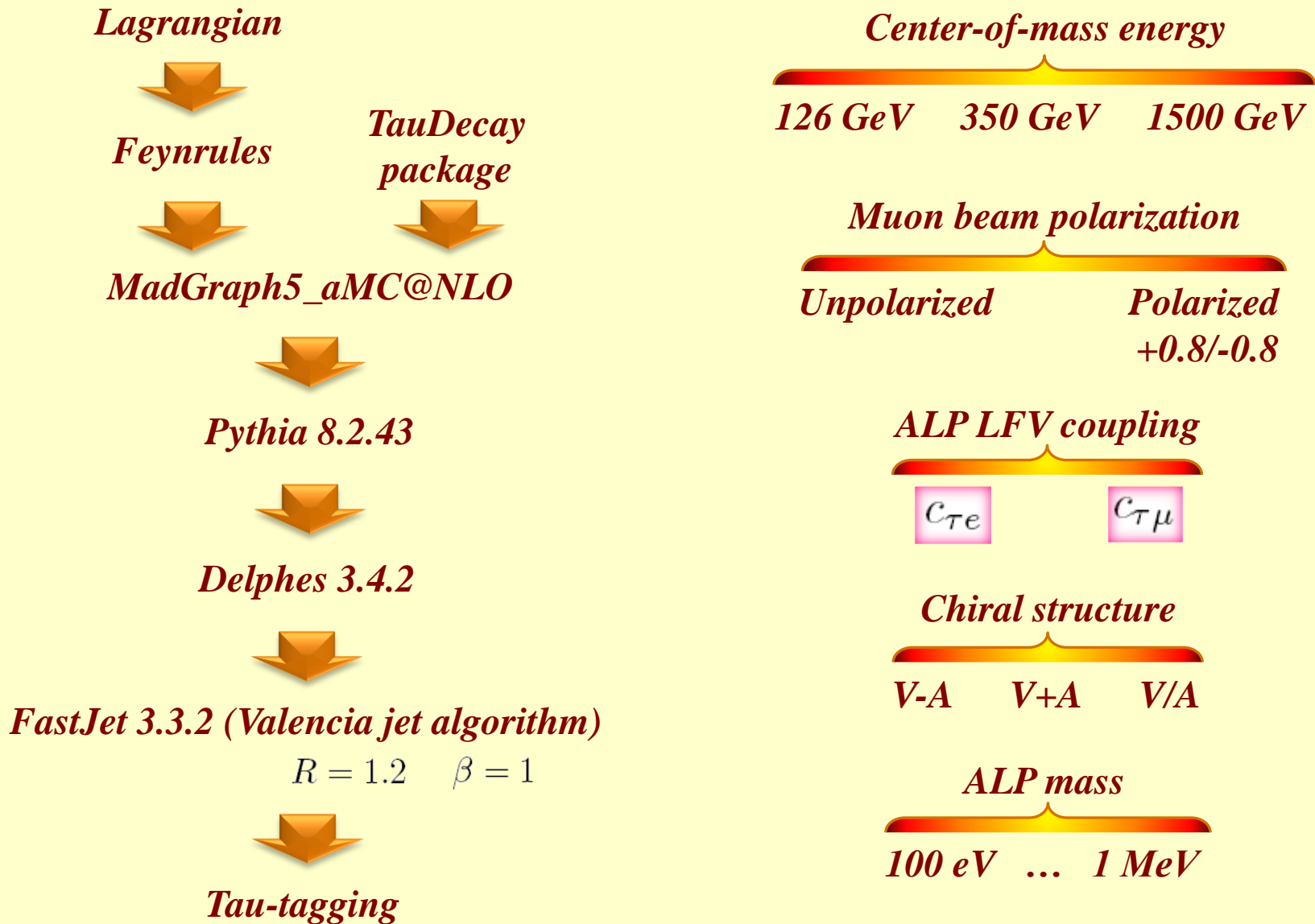
$R = 1.2$     $\beta = 1$



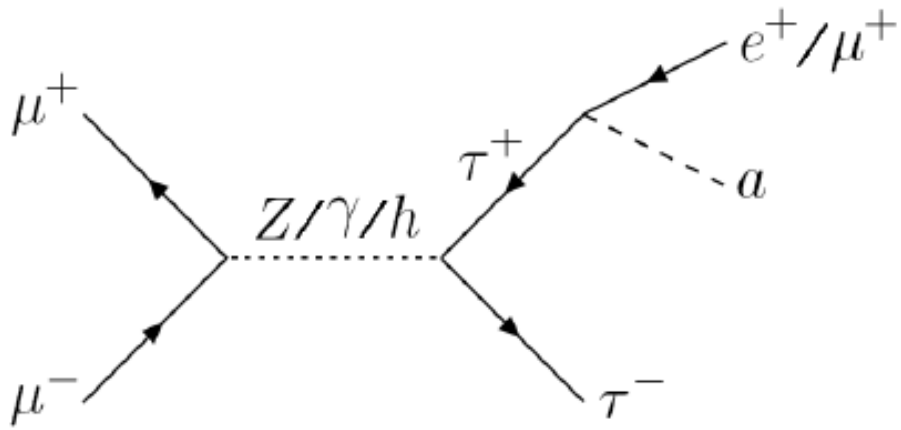
*Tau-tagging*



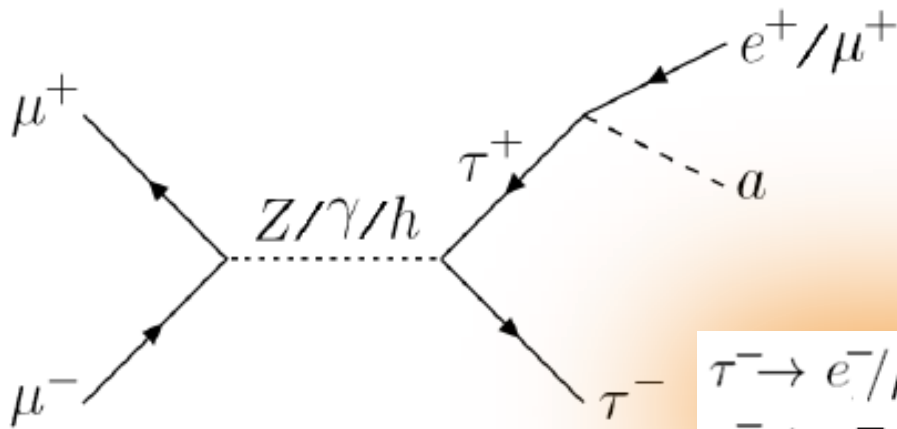
# Event generation



## *Event selection*



## Event selection



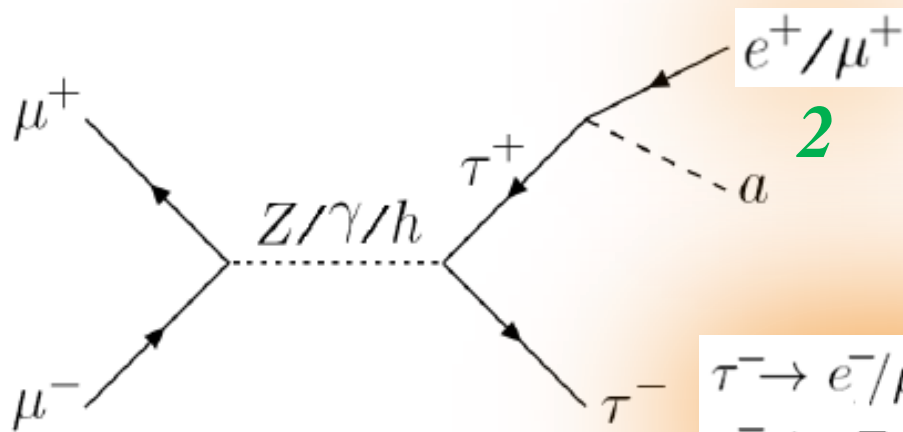
$$\begin{aligned} \tau^+ &\rightarrow e^+/\mu^+ + \nu \\ \tau^- &\rightarrow \pi^-\pi^-\pi^+\nu \end{aligned}$$

$$p_T > 10 \text{ GeV} \quad |\eta| < 2.5 \quad I_{rel}^{\max} = 0.2$$

$$p_T > 30 \text{ GeV} \quad |\eta| < 2.5$$

1

## Event selection



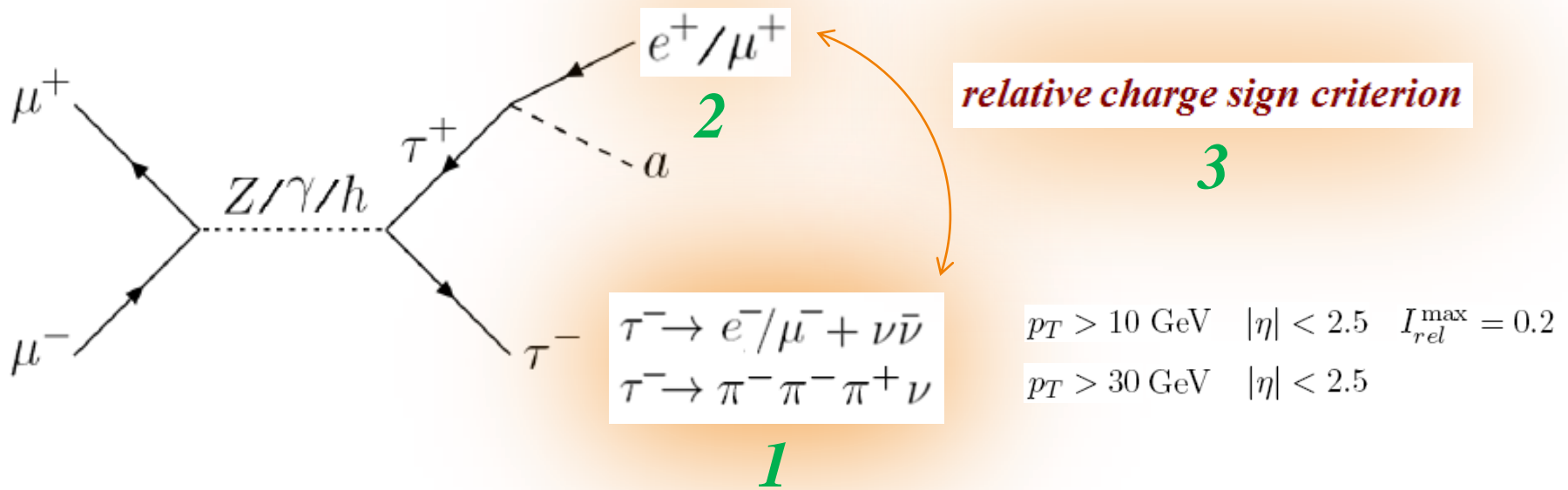
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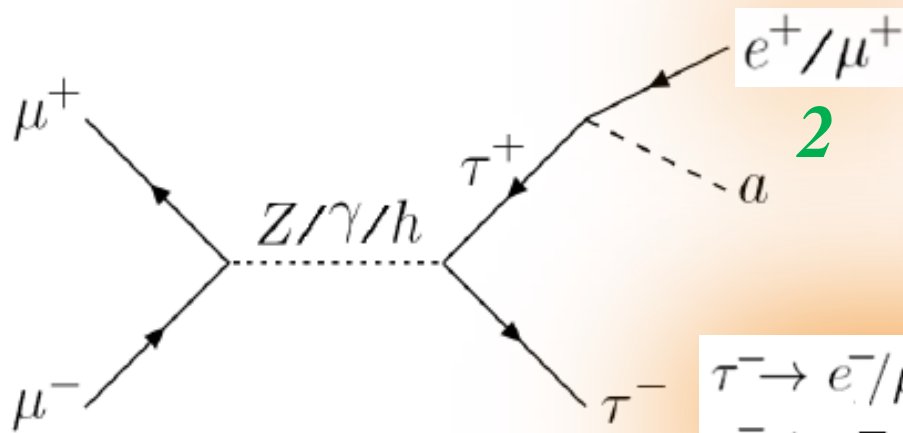
# Event selection

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

126	350	1500	GeV
↓	↓	↓	
35	50	70	GeV

$p_T > 10$  GeV  $|\eta| < 2.5$

4



relative charge sign criterion

3

$p_T > 10$  GeV  $|\eta| < 2.5$   $I_{rel}^{max} = 0.2$

$p_T > 30$  GeV  $|\eta| < 2.5$

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

126	350	1500	GeV
↓	↓	↓	
45	60	90	GeV

4

## Event selection

		signal	$\tau\tau$	$WW$	$t\bar{t}$	$ZZ$	$hZ$	$Z\gamma$	$q\bar{q}$	$ee/\mu\mu$
Unpolarized $c_{\tau e} \neq 0$	1	0.2067	0.1219	0.0518	0.0022	0.0065	0.0070	0.0009	0.0001	0.0731
	2	0.8164	0.5255	0.3987	0.4679	0.0999	0.2244	0.0563	0.0654	0
	3	0.9998	0.9998	0.9998	0.9039	0.8030	0.8860	0.9833	0.8011	0
	4	0.9989	0.9980	0.9980	0.9991	0.9861	0.9966	0.0847	0.9975	0
	total	0.1686	0.0639	0.0206	0.0009	0.0005	0.0014	4.0e-06	6.4e-06	0
Polarized $c_{\tau e} \neq 0$	1	0.2011	0.1131	0.0477	0.0021	0.0065	0.0068	0.0009	9.2e-5	0.0726
	2	0.8818	0.5413	0.4518	0.4656	0.1104	0.2334	0.0573	0.0672	0
	3	0.9999	0.9997	0.9997	0.8933	0.7620	0.8943	0.9841	0.7501	0
	4	0.9987	0.9982	0.9987	0.9991	0.9956	0.9978	0.0968	0.9974	0
	total	0.1771	0.0611	0.0215	0.0009	0.0005	0.0014	4.8e-06	4.6e-06	0
Unpolarized $c_{\tau\mu} \neq 0$	1	0.1985	0.1178	0.0467	0.0021	0.0083	0.0066	0.0010	9.5e-5	0.0002
	2	0.8901	0.5625	0.4441	0.4877	0.0771	0.2399	0.0499	0.0840	0
	3	0.9998	0.9998	0.9998	0.9049	0.8271	0.8896	0.9844	0.8021	0
	4	0.9987	0.9980	0.9983	0.9991	0.9895	0.9966	0.0794	0.9974	0
	total	0.1764	0.0661	0.0207	0.0009	0.0005	0.0014	4.0e-06	6.4e-06	0
Polarized $c_{\tau\mu} \neq 0$	1	0.1952	0.1095	0.0439	0.0021	0.0083	0.0066	0.0010	6.0e-5	0.0003
	2	0.9401	0.5812	0.4945	0.4737	0.0884	0.2490	0.0548	0.1026	0
	3	0.9998	0.9998	0.9997	0.8937	0.7719	0.8934	0.9828	0.7506	0
	4	0.9988	0.9981	0.9987	0.9991	0.9957	0.9995	0.0866	0.9974	0
	total	0.1833	0.0635	0.0217	0.0009	0.0006	0.0015	4.7e-06	4.6e-06	0

## *Polarization-induced effects*

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

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

## Polarization-induced effects

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

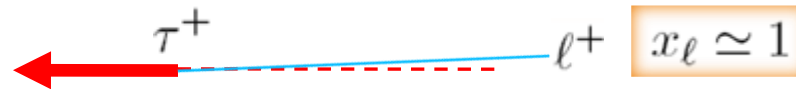
**SM BG:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + \nu \bar{\nu}$

**Signal**  $\tau \rightarrow e/\mu + a$

*In the tau rest frame:*

$$p_\ell = \sqrt{\left(\frac{m_\tau^2 + m_\ell^2 - m_a^2}{2m_\tau}\right)^2 - m_\ell^2} \quad (\ell = e, \mu) \quad \Rightarrow \quad m_a \ll m_\tau \quad \rightarrow \quad x_\ell \simeq 1$$

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



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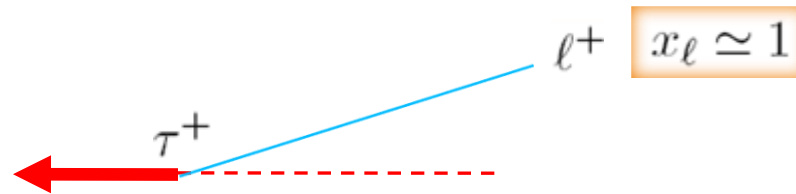
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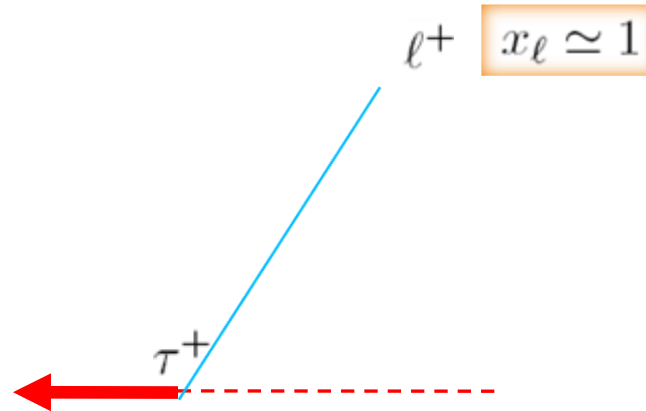
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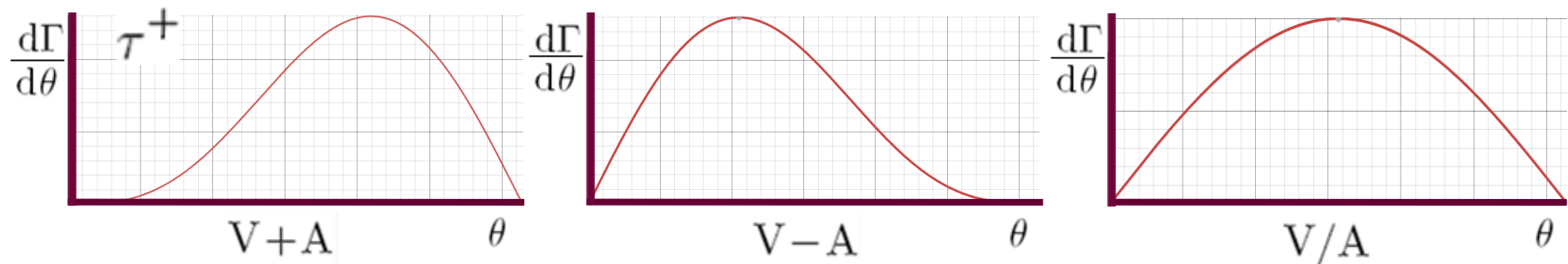
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$$x_\ell = 2E_\ell/m_\tau$$

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



## Polarization-induced effects

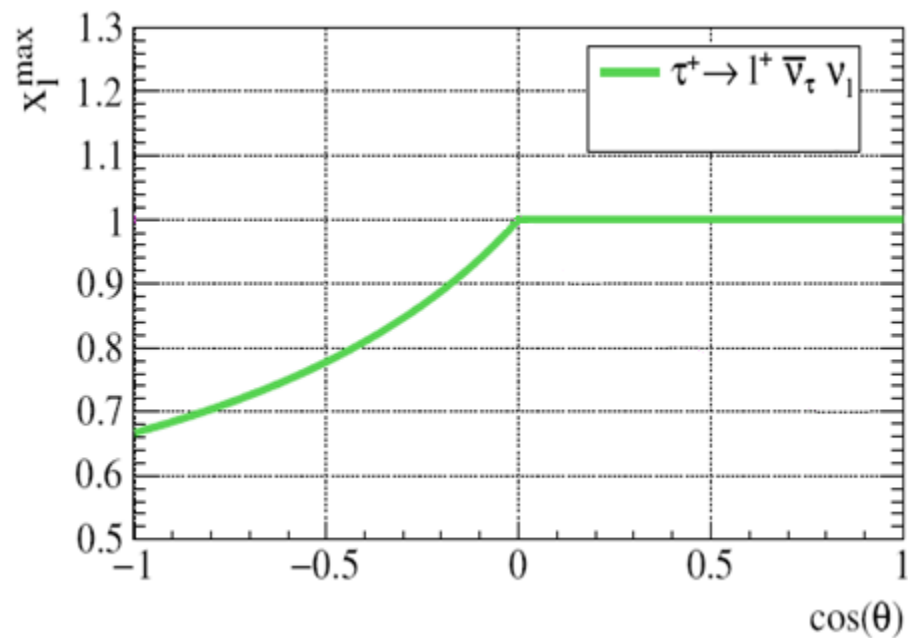
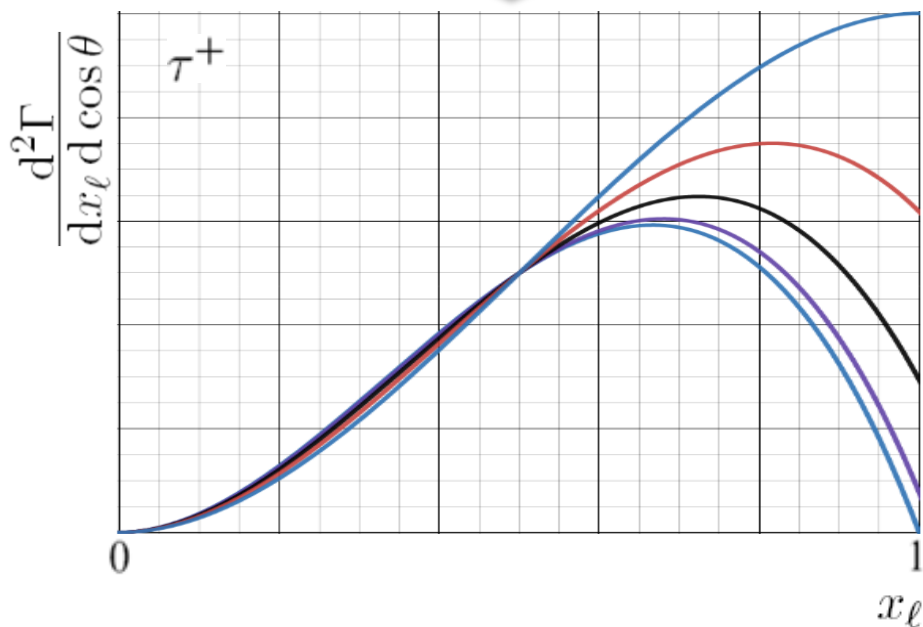
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*In the tau rest frame:*

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



## Polarization-induced effects

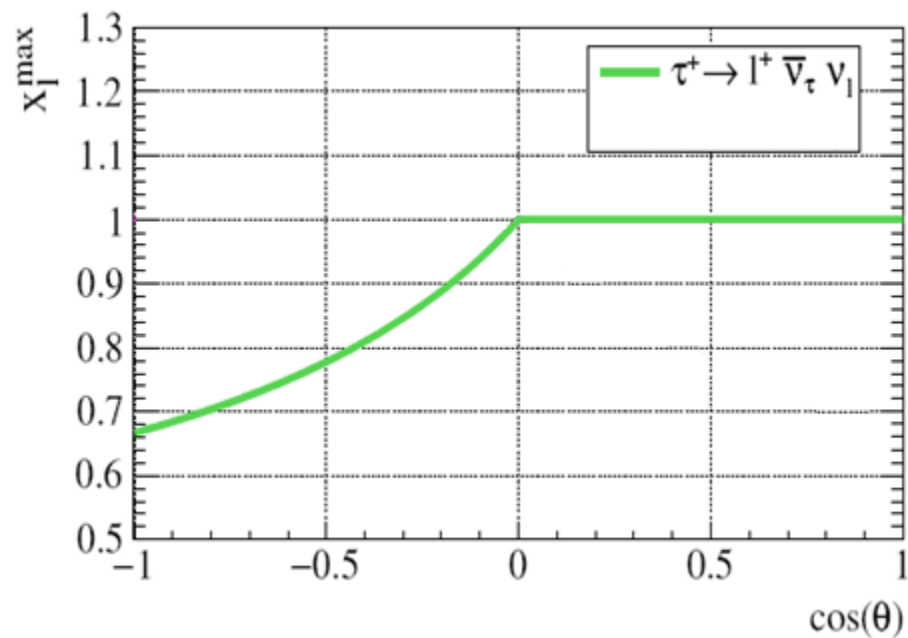
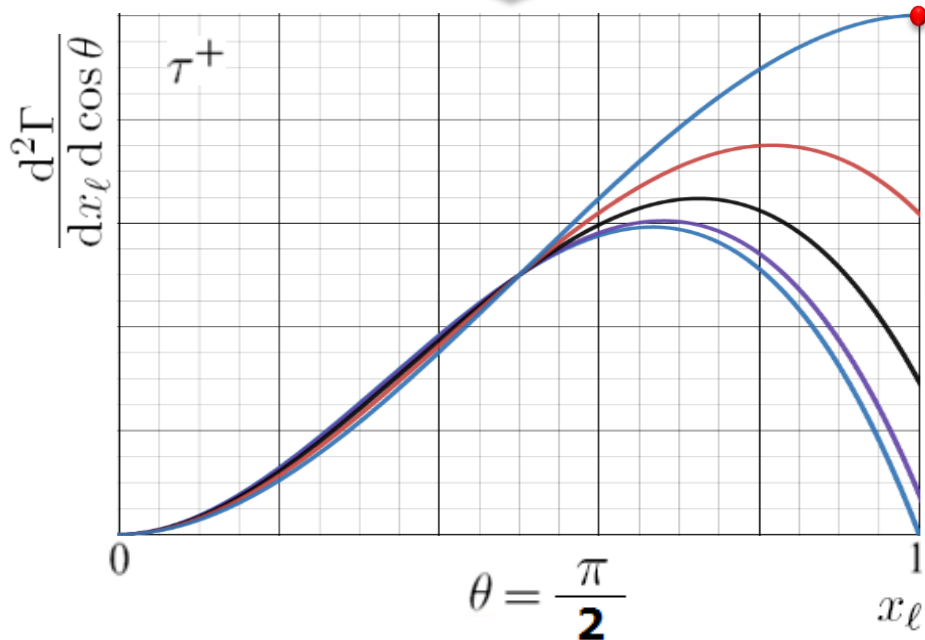
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## Polarization-induced effects

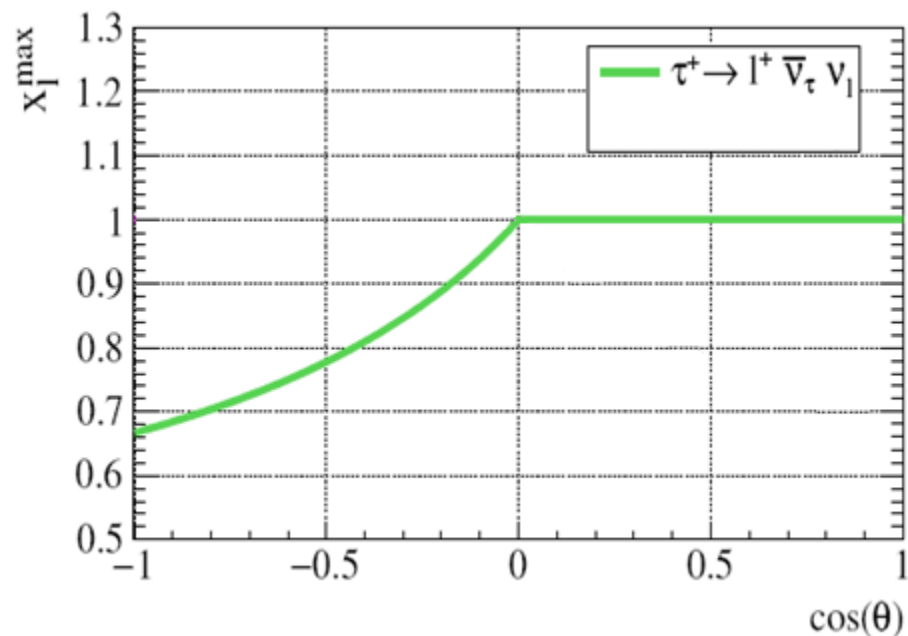
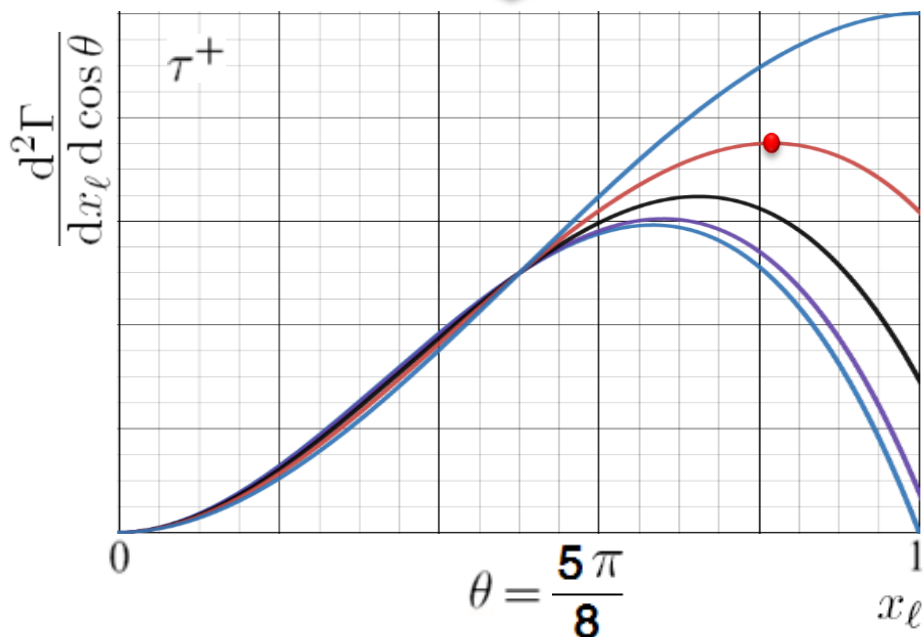
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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

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

*In the tau rest frame:*

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



## Polarization-induced effects

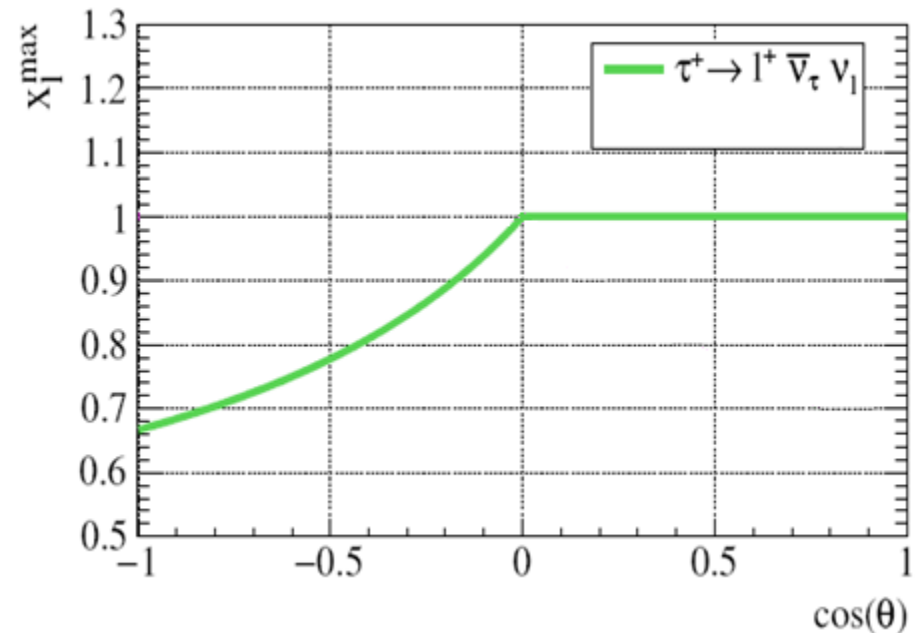
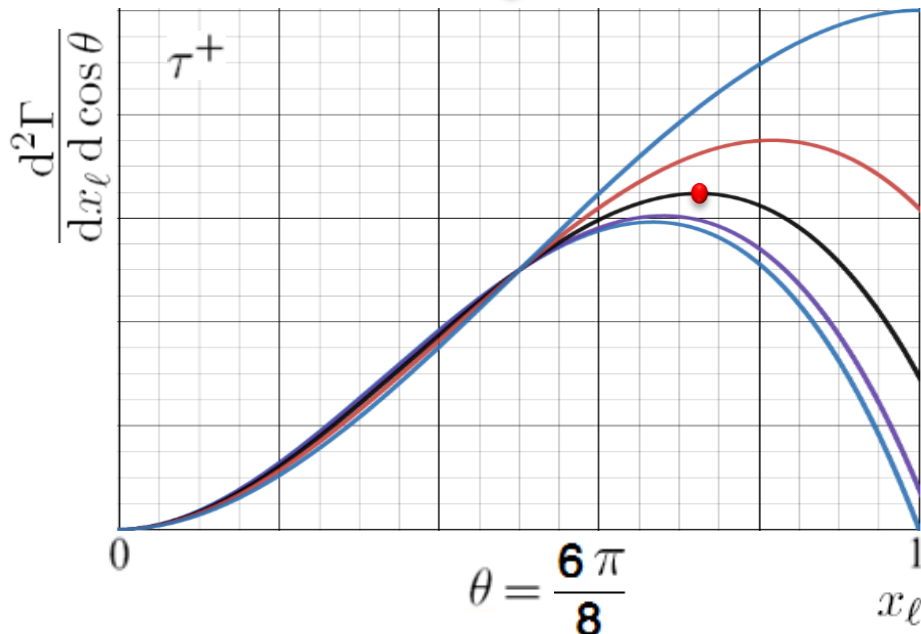
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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



## Polarization-induced effects

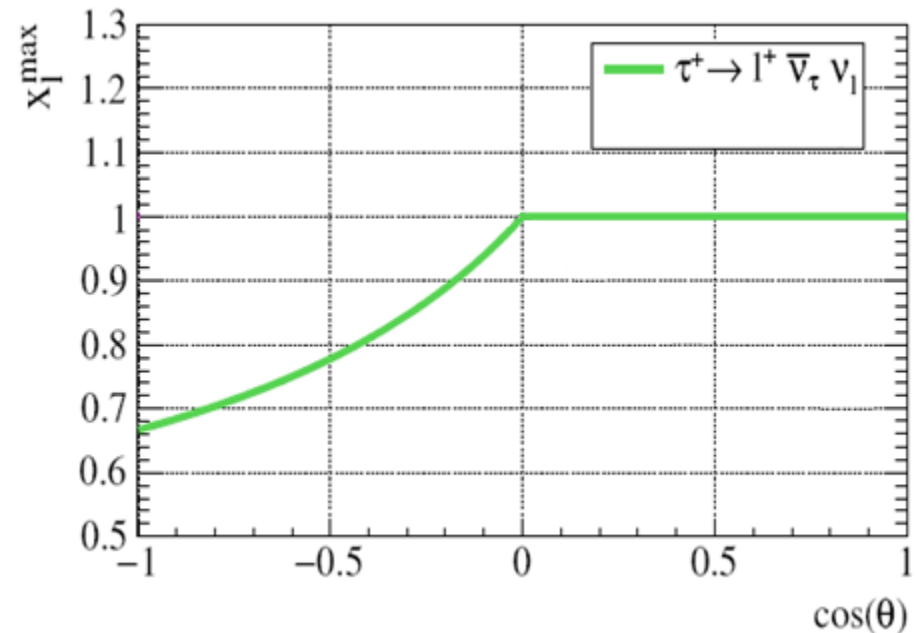
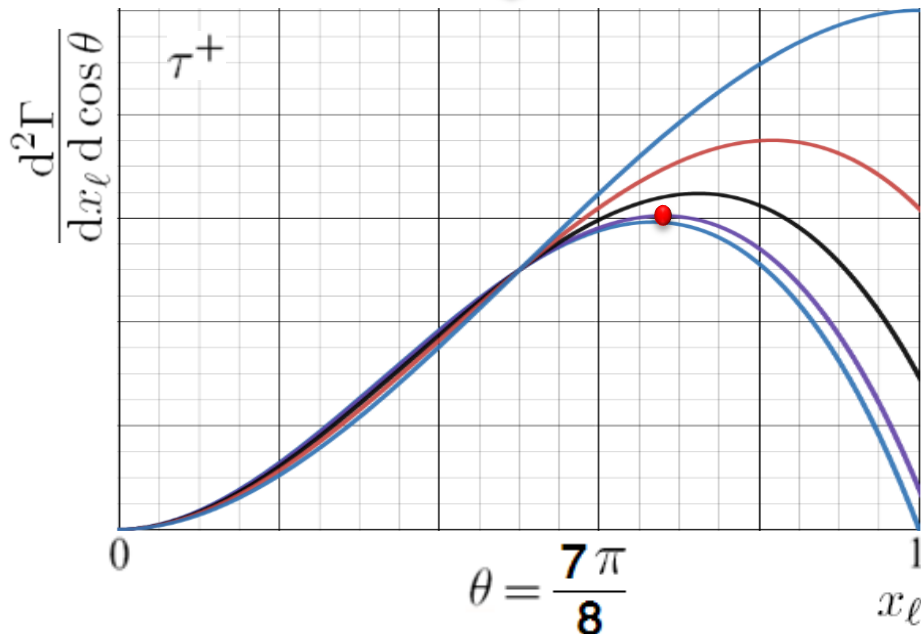
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## Polarization-induced effects

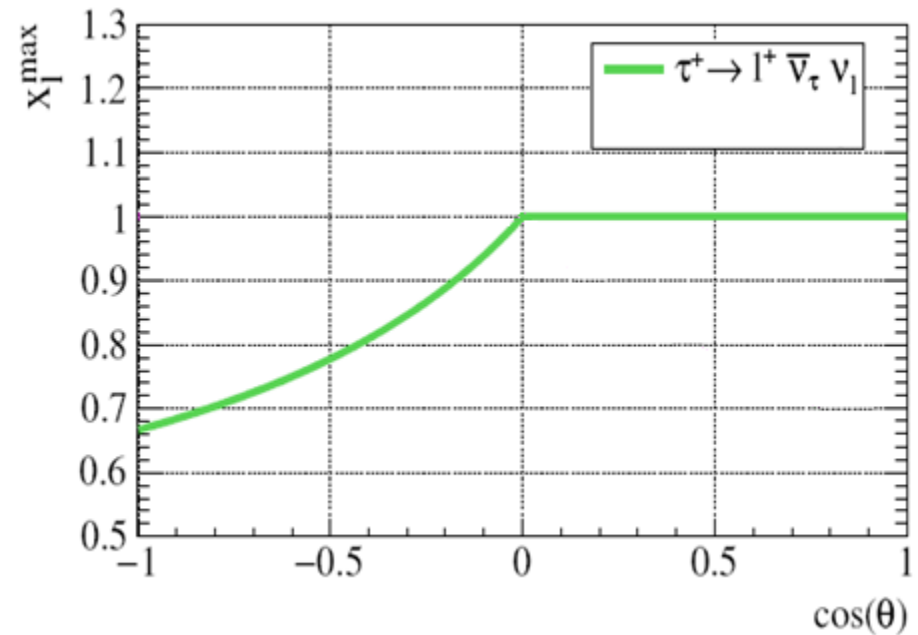
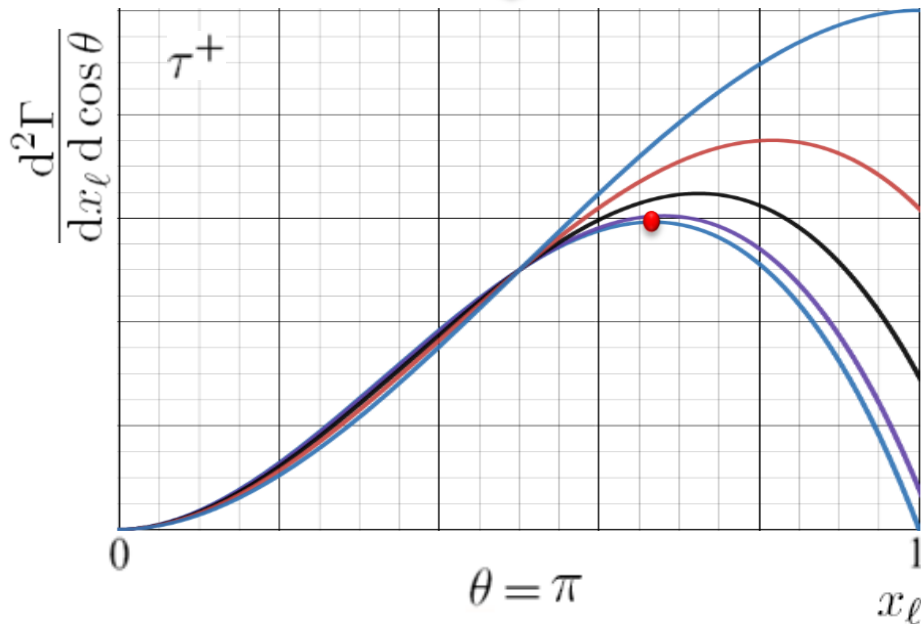
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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

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## Polarization-induced effects

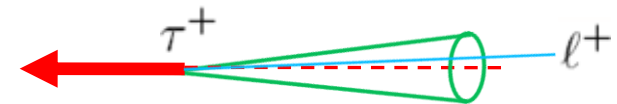
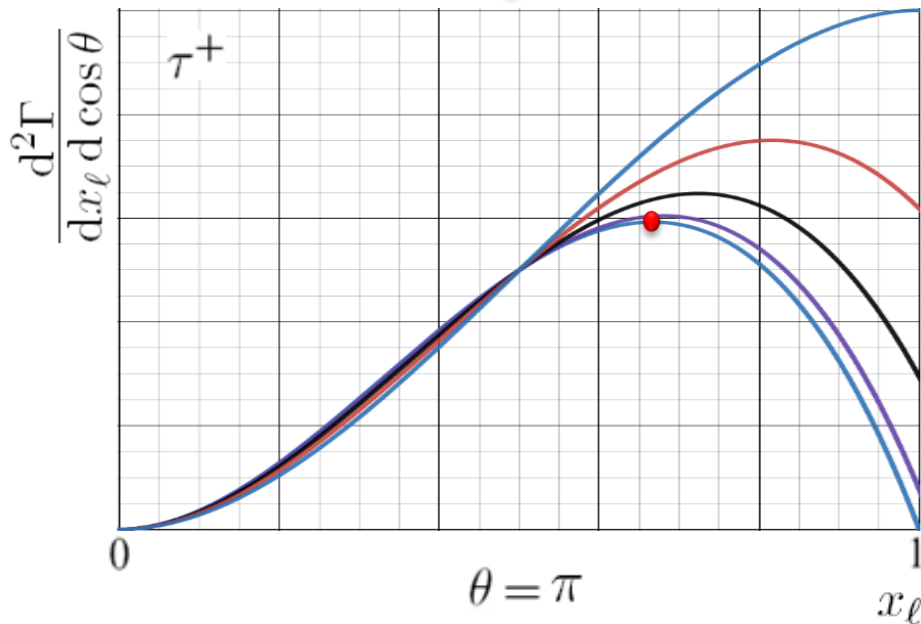
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## Polarization-induced effects

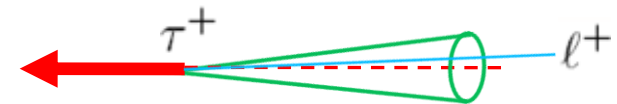
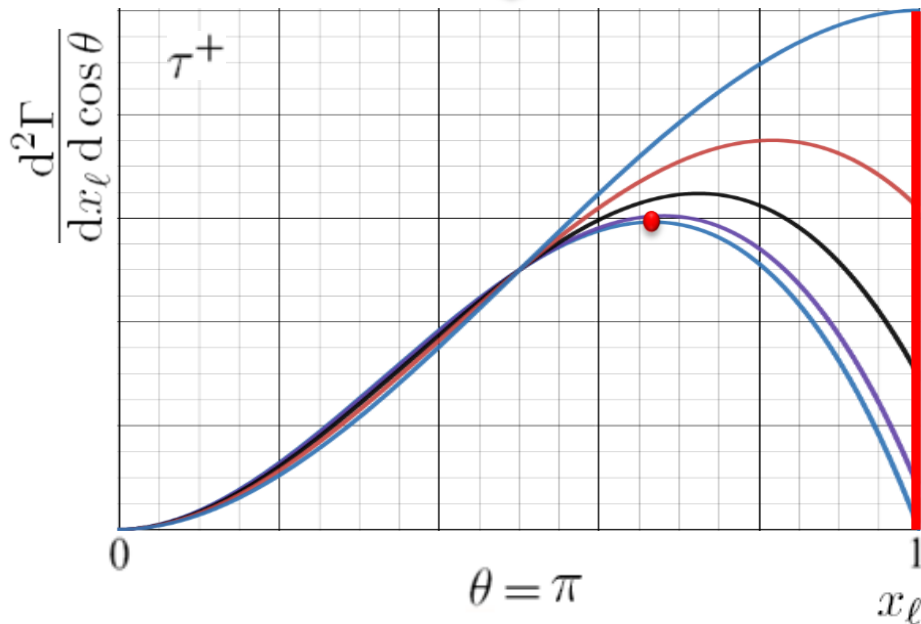
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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$x_\ell \simeq 1$  for signal

## Polarization-induced effects

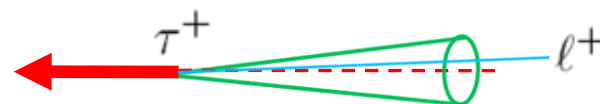
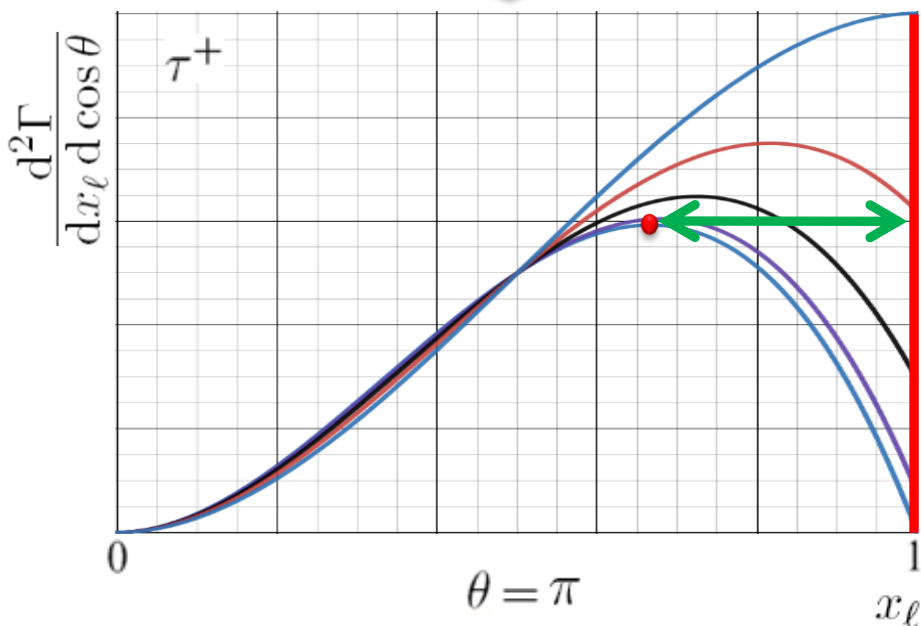
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$$\frac{d^2\Gamma \left( \begin{array}{l} \tau^+ \rightarrow \ell^+ \nu_\ell \bar{\nu}_\tau \\ \tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau \end{array} \right)}{dx_\ell d\cos\theta} \simeq \Gamma_\tau [(3 - 2x_\ell) \pm \mathcal{P}_\tau(2x_\ell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



$x_\ell \simeq 1$  for signal

$x_\ell$  helps suppress background

## Polarization-induced effects

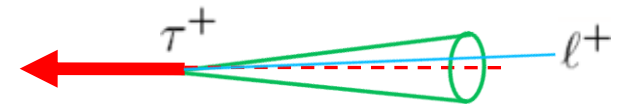
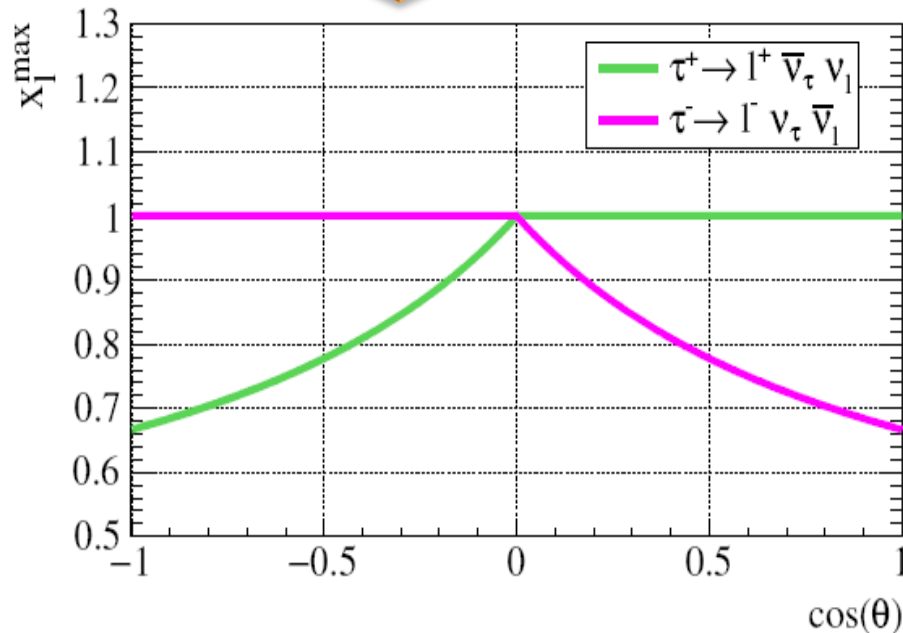
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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

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



## Polarization-induced effects

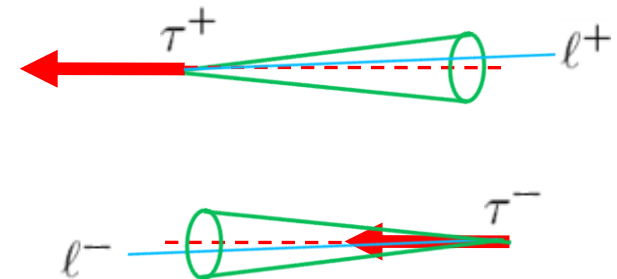
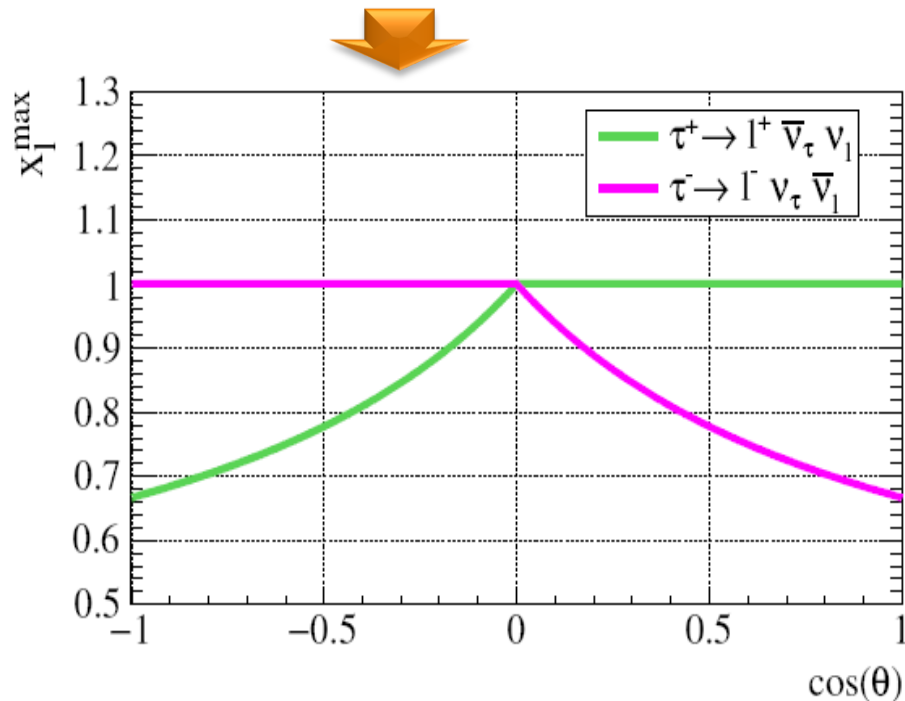
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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

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## Polarization-induced effects

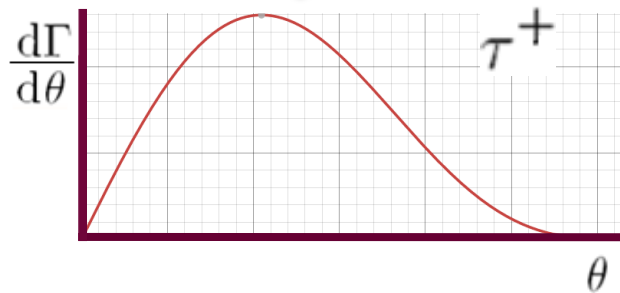
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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

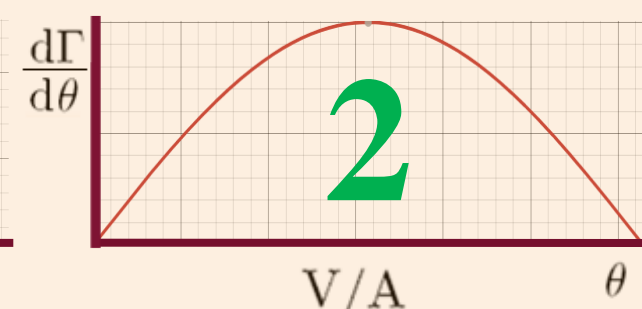
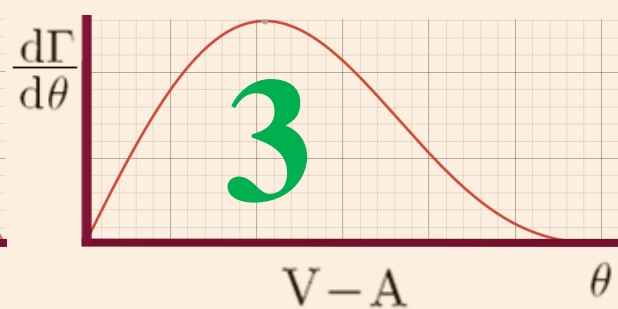
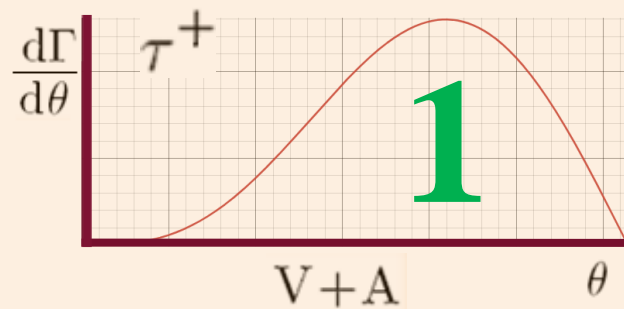
**BG**  $\tau \rightarrow e/\mu + \nu \bar{\nu}$

*In the tau rest frame:*

$$\frac{d^2\Gamma \left( \begin{array}{l} \tau^+ \rightarrow l^+ \nu_l \bar{\nu}_\tau \\ \tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau \end{array} \right)}{dx_l d\cos\theta} \simeq \Gamma_\tau [(3 - 2x_l) \pm \mathcal{P}_\tau(2x_l - 1) \cos\theta] x_l^2$$



*Signal angular distribution*



## Polarization-induced effects

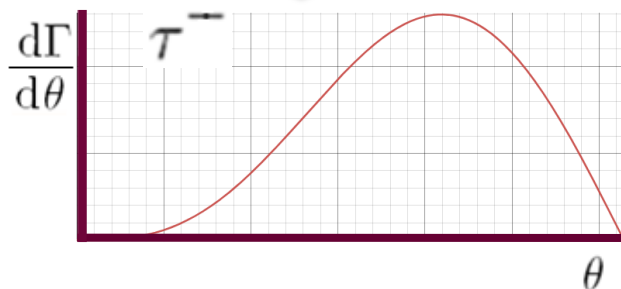
**Signal:**  $\mu^- \mu^+ \rightarrow \tau^- \tau^+, \tau \rightarrow e/\mu + a$

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

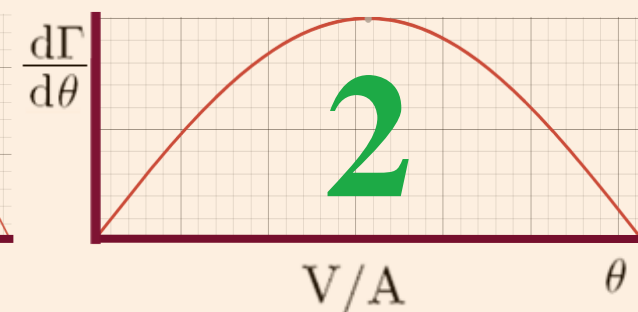
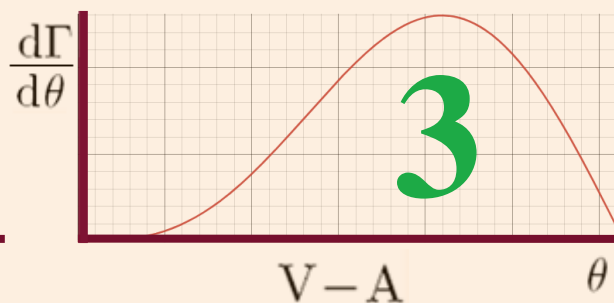
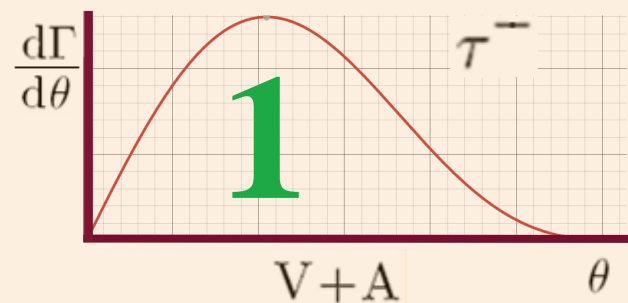
**BG**  $\tau \rightarrow e/\mu + \nu \bar{\nu}$

*In the tau rest frame:*

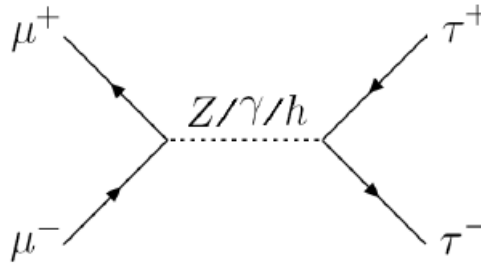
$$\frac{d^2\Gamma \left( \begin{array}{l} \tau^+ \rightarrow l^+ \nu_l \bar{\nu}_\tau \\ \tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau \end{array} \right)}{dx_\ell d \cos \theta} \simeq \Gamma_\tau [(3 - 2x_\ell) \pm \mathcal{P}_\tau (2x_\ell - 1) \cos \theta] x_\ell^2$$



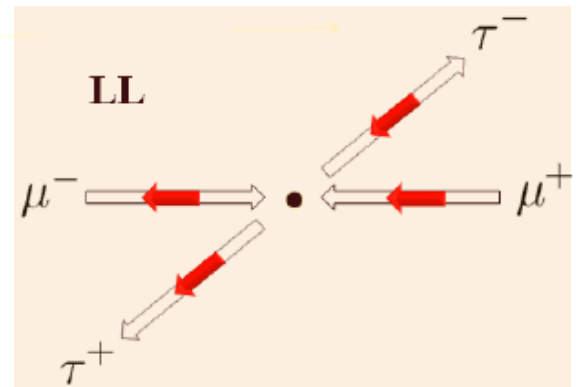
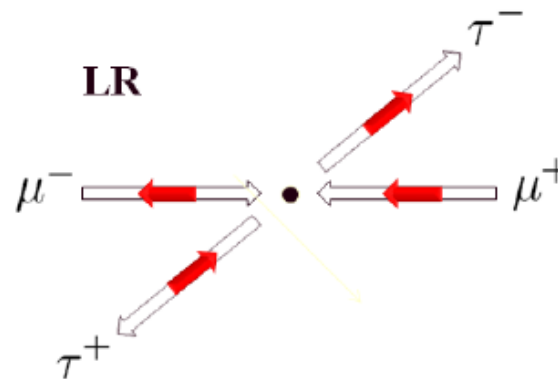
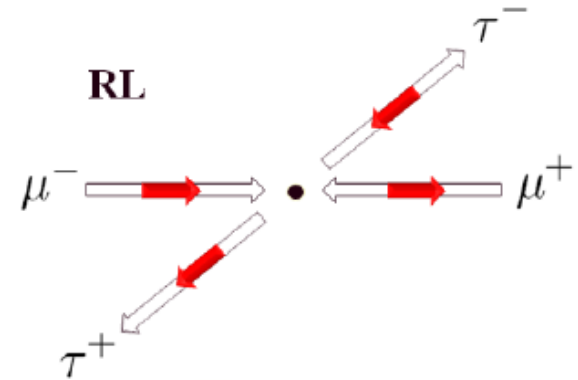
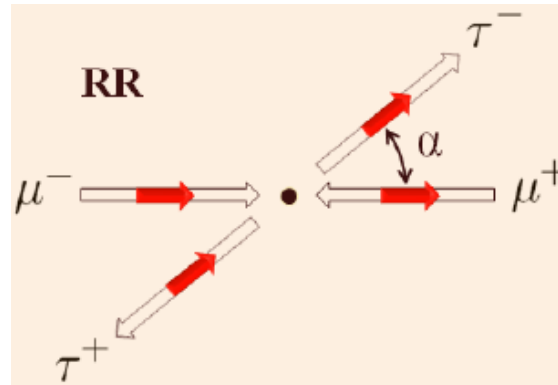
*Signal angular distribution*



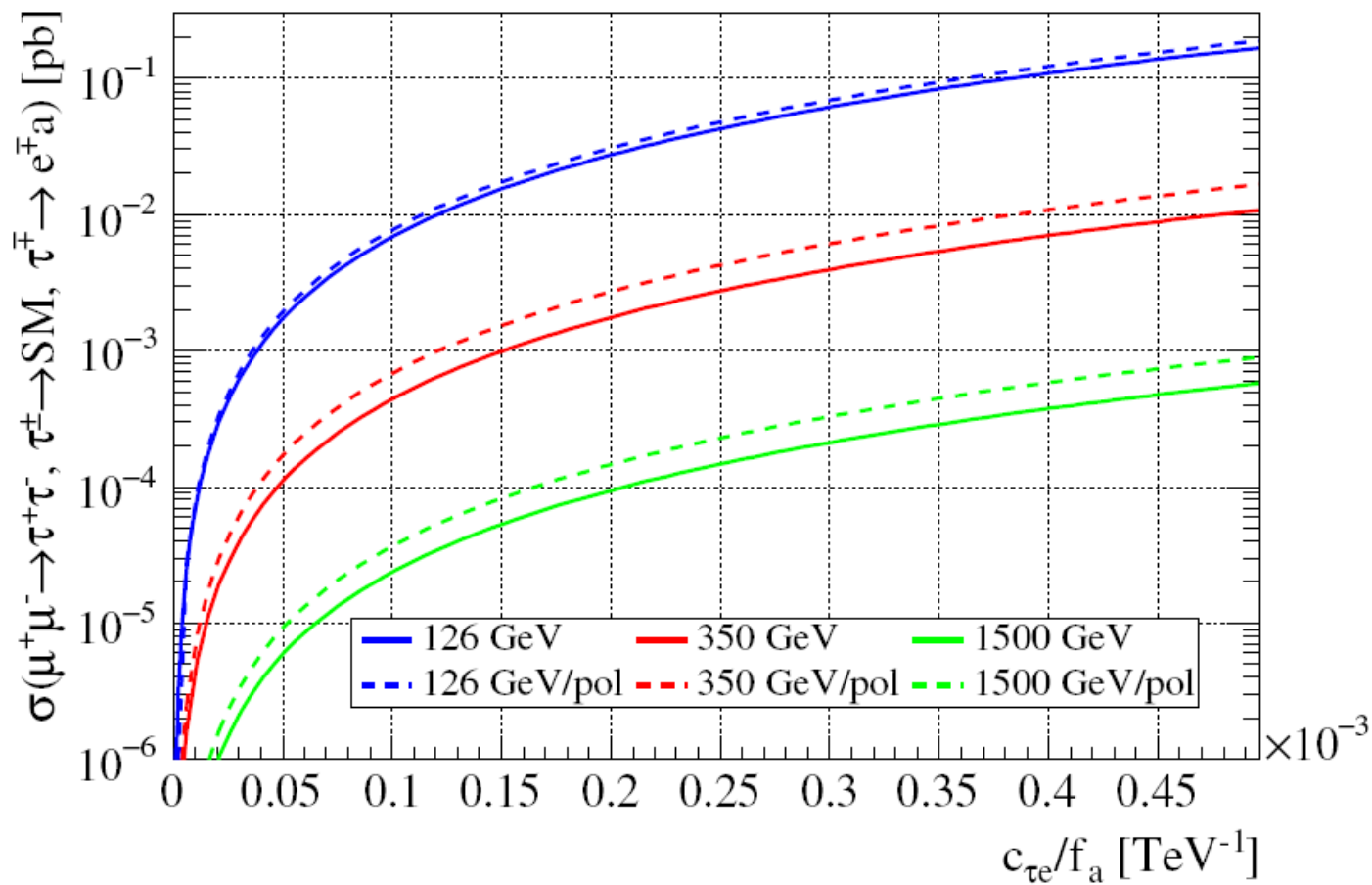
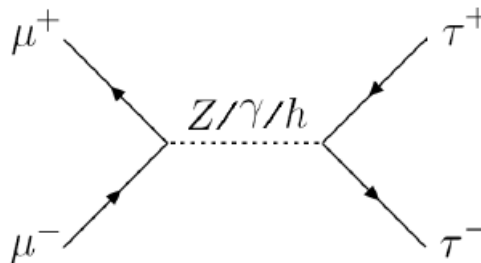
# How to produce highly polarized tau leptons?



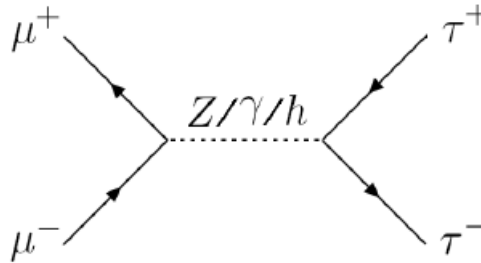
$$m_\tau \ll E_\tau$$



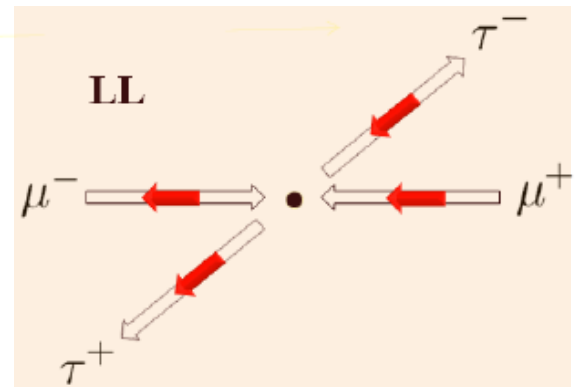
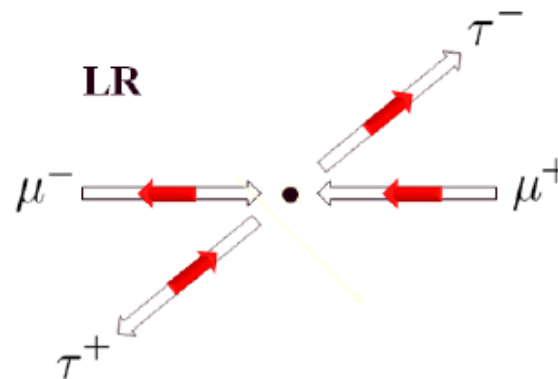
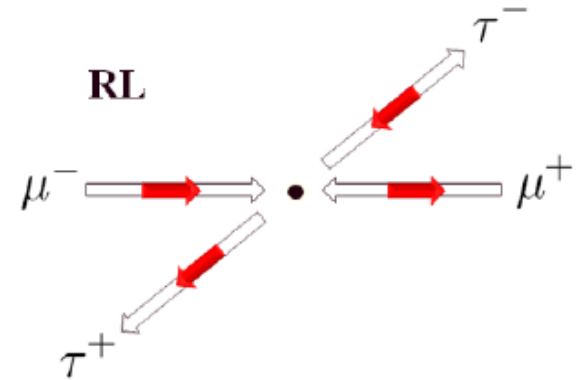
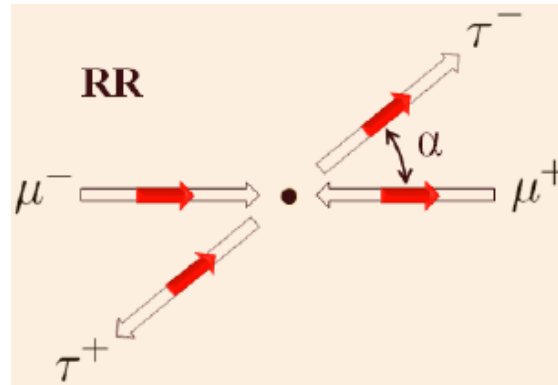
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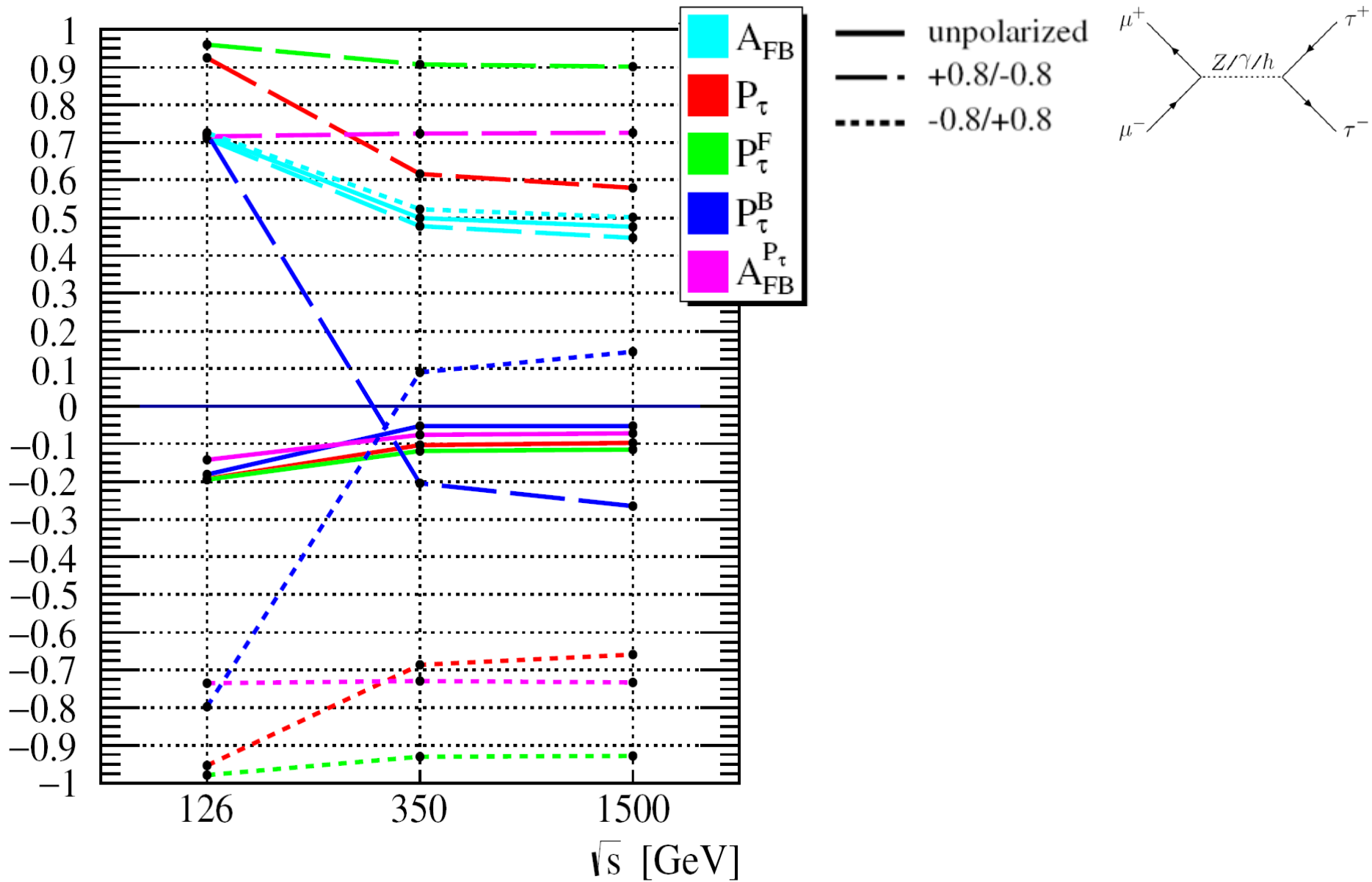


# How to produce highly polarized tau leptons?



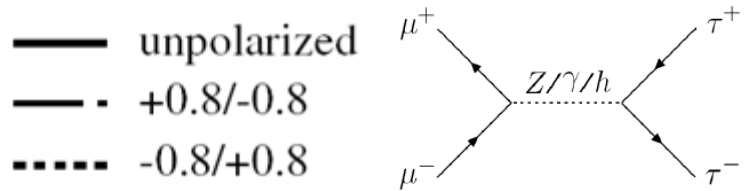
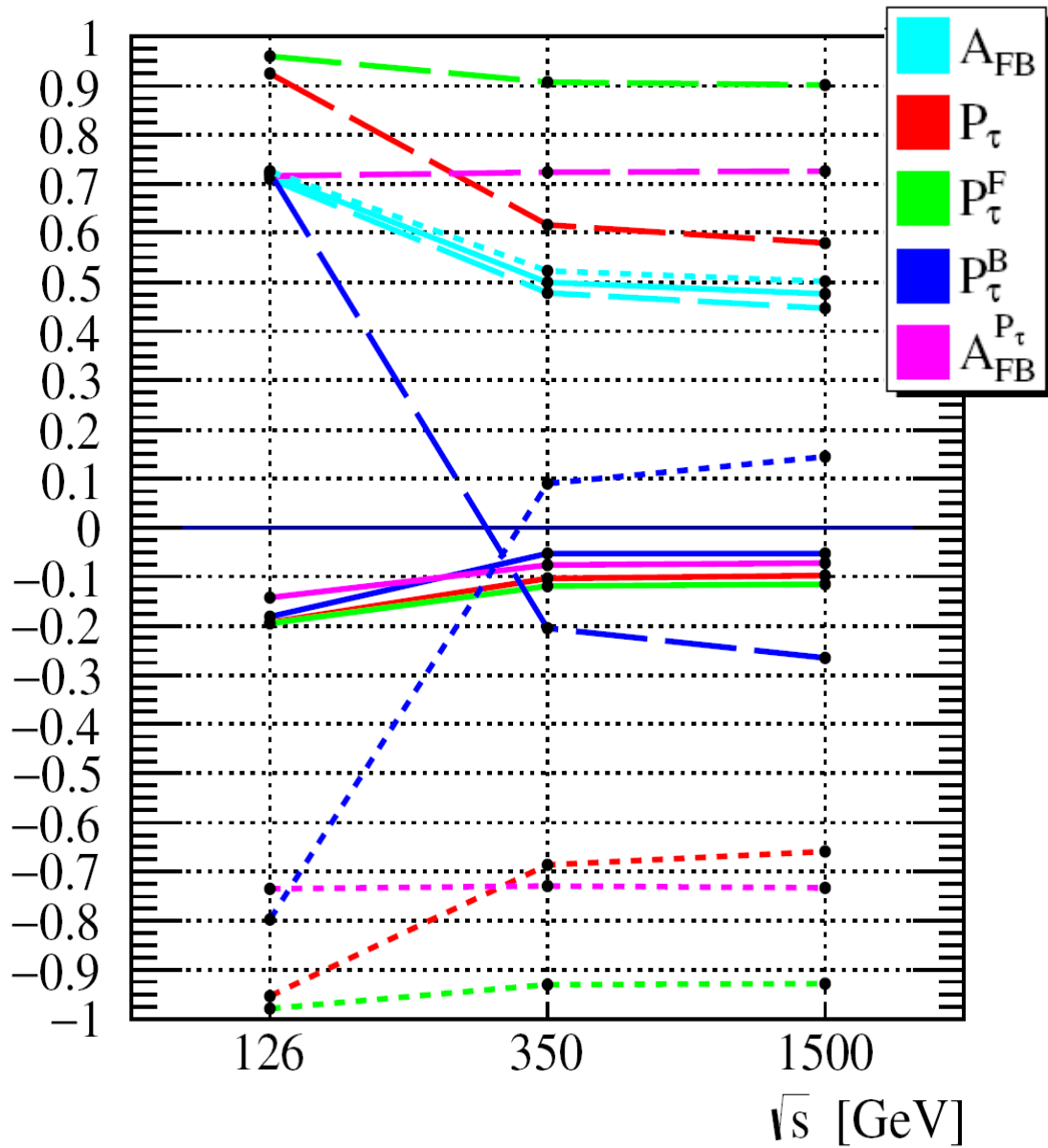
$$m_\tau \ll E_\tau$$





$$A_{\text{FB}} = \frac{\sigma^{\text{F}} - \sigma^{\text{B}}}{\sigma_{\text{total}}}$$

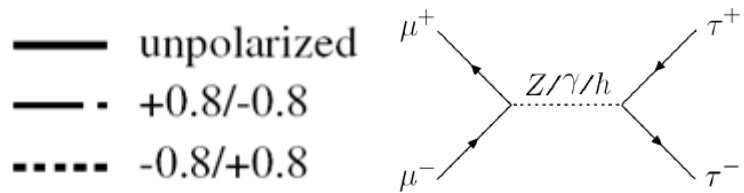
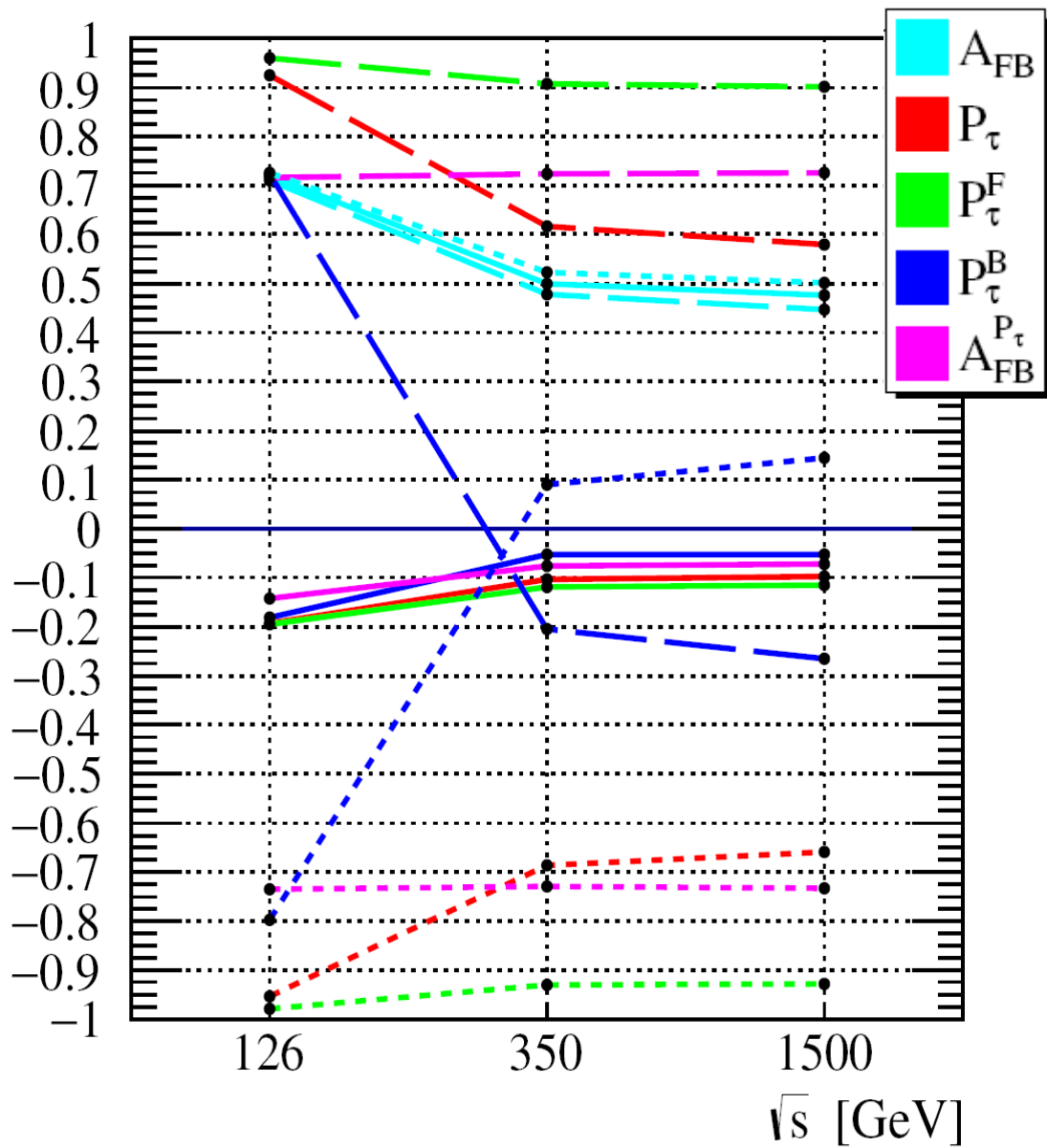
$$P_\tau^{\text{F/B}} = \frac{\sigma^{\text{F/B}}(h_\tau = +1) - \sigma^{\text{F/B}}(h_\tau = -1)}{\sigma^{\text{F/B}}}$$



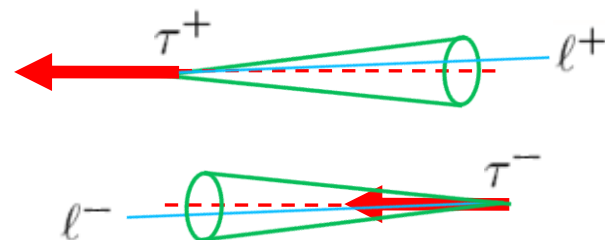
	+0.8/-0.8	-0.8/+0.8
<i>backward</i> $\tau^+$	$< -0.9$	$> +0.9$
<i>forward</i> $\tau^-$	$> +0.9$	$< -0.9$

$$A_{\text{FB}} = \frac{\sigma^{\text{F}} - \sigma^{\text{B}}}{\sigma_{\text{total}}}$$

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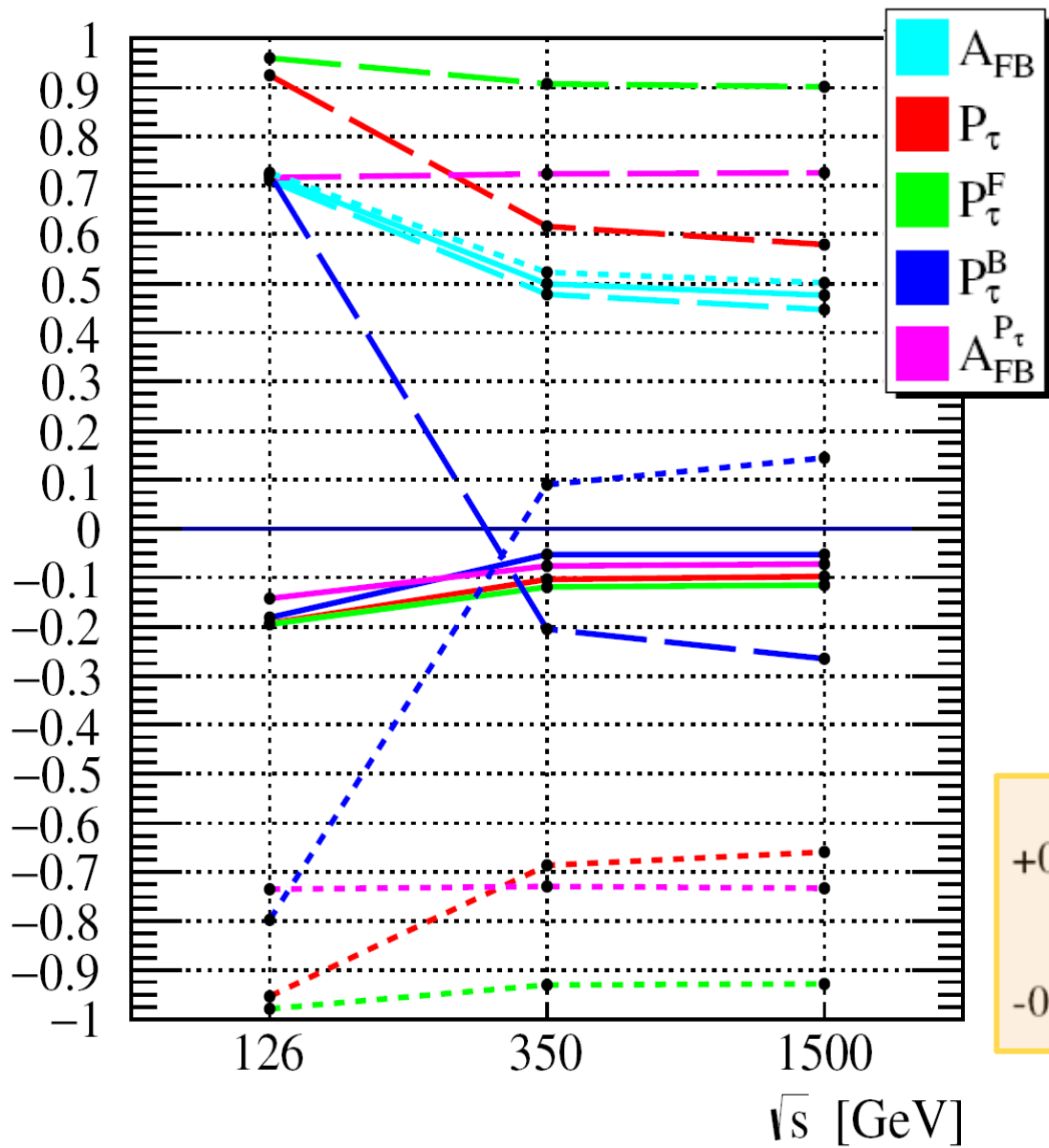


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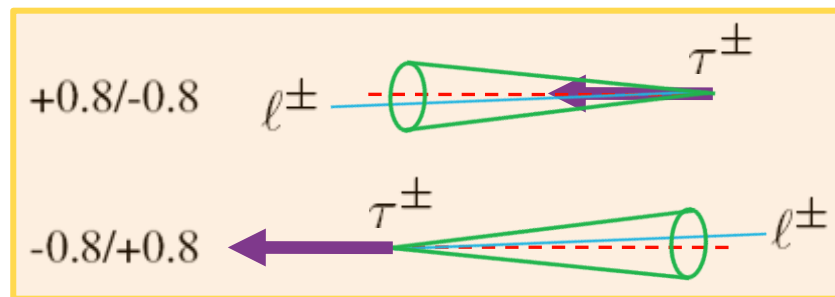
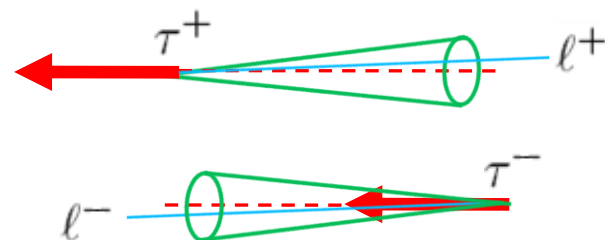


$$A_{\text{FB}} = \frac{\sigma^{\text{F}} - \sigma^{\text{B}}}{\sigma_{\text{total}}}$$

$$P_\tau^{\text{F/B}} = \frac{\sigma^{\text{F/B}}(h_\tau = +1) - \sigma^{\text{F/B}}(h_\tau = -1)}{\sigma^{\text{F/B}}}$$



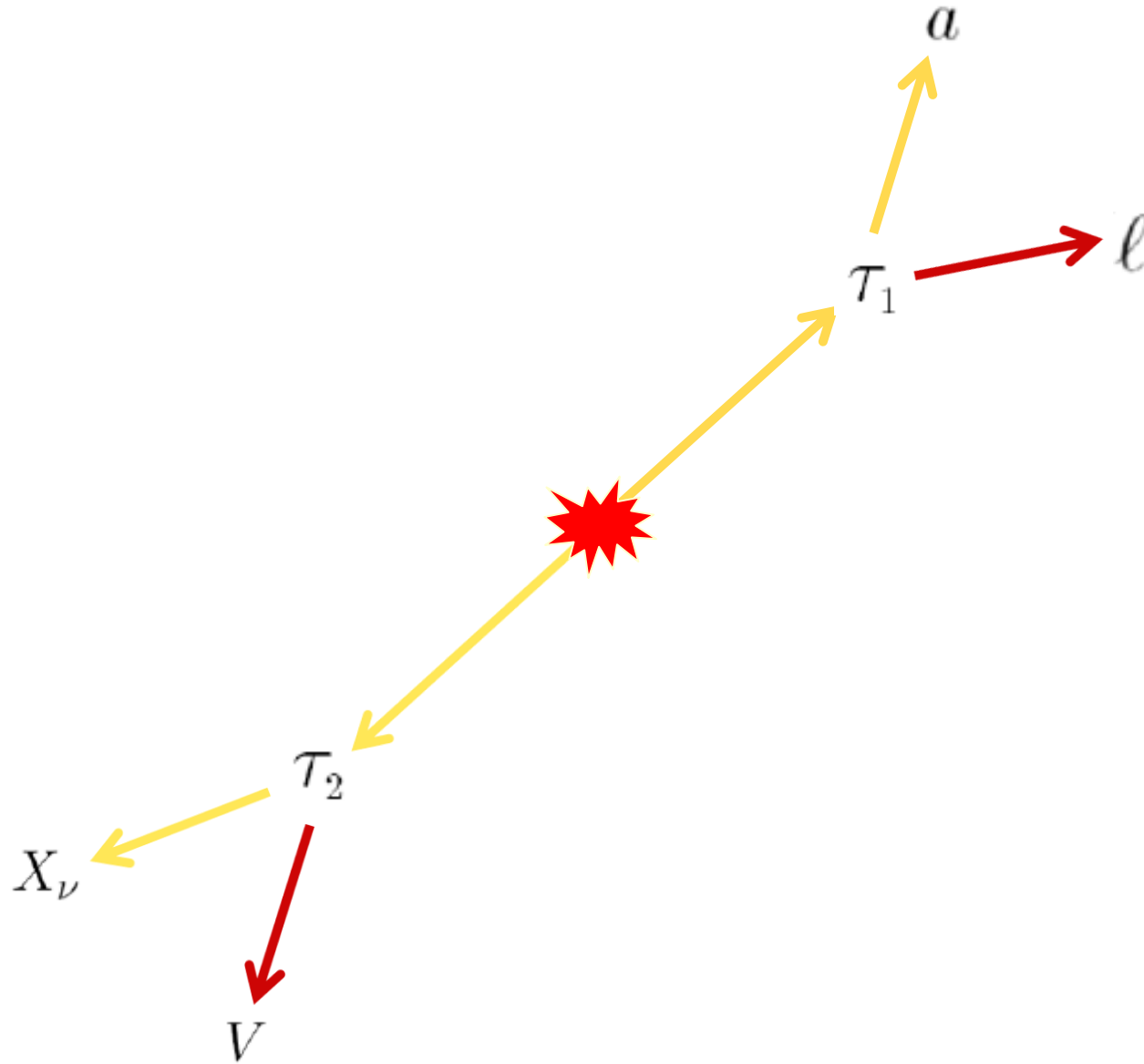
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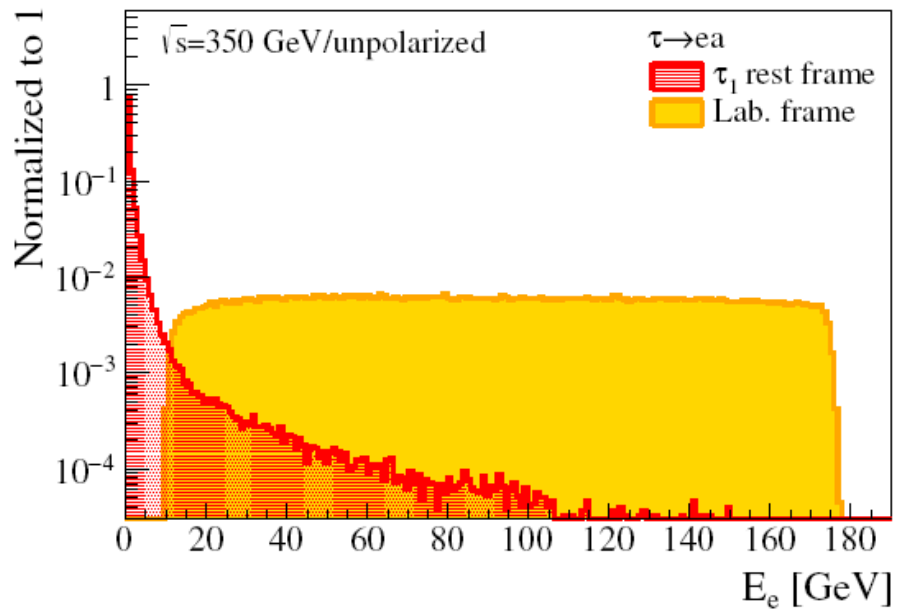
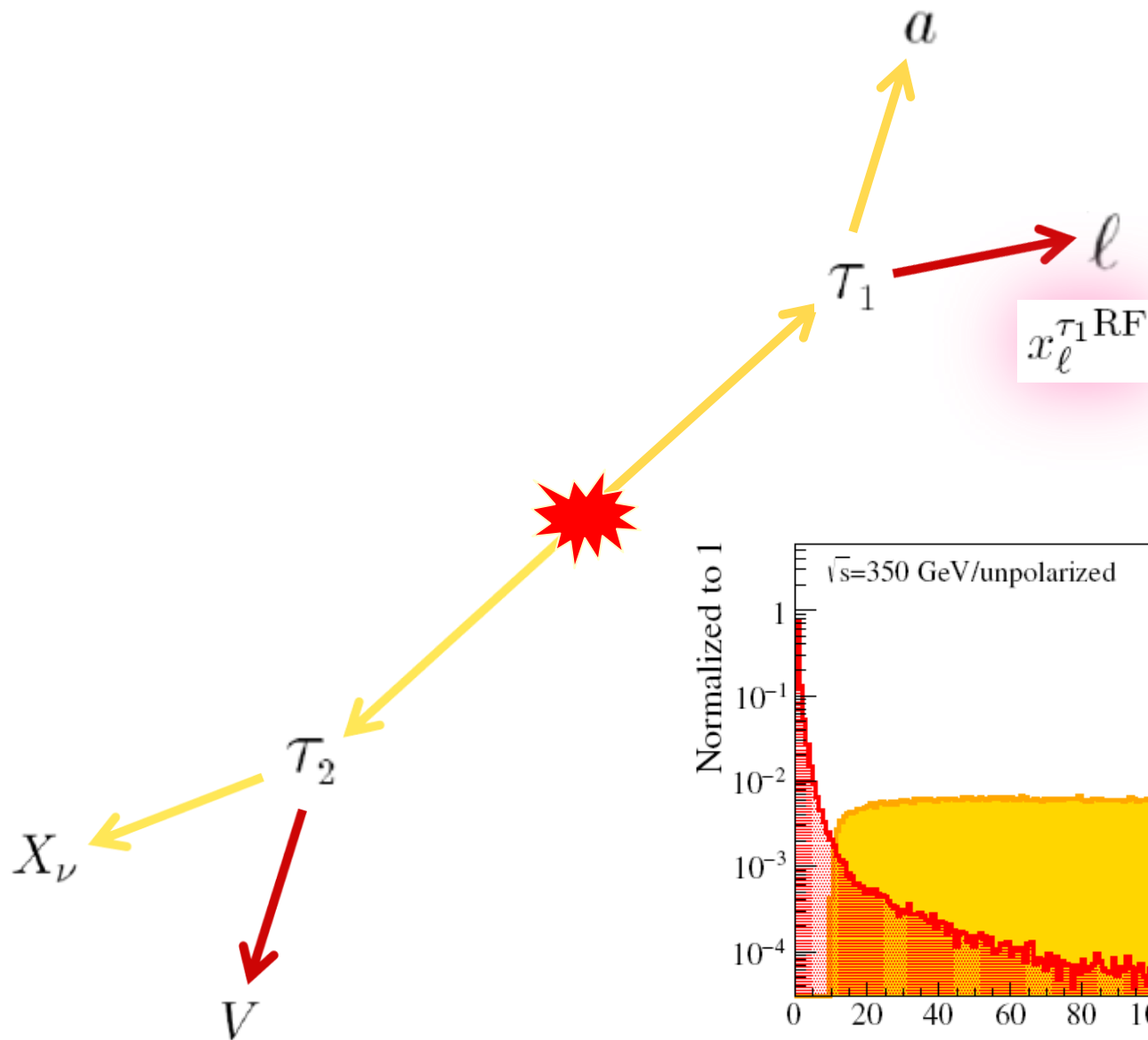
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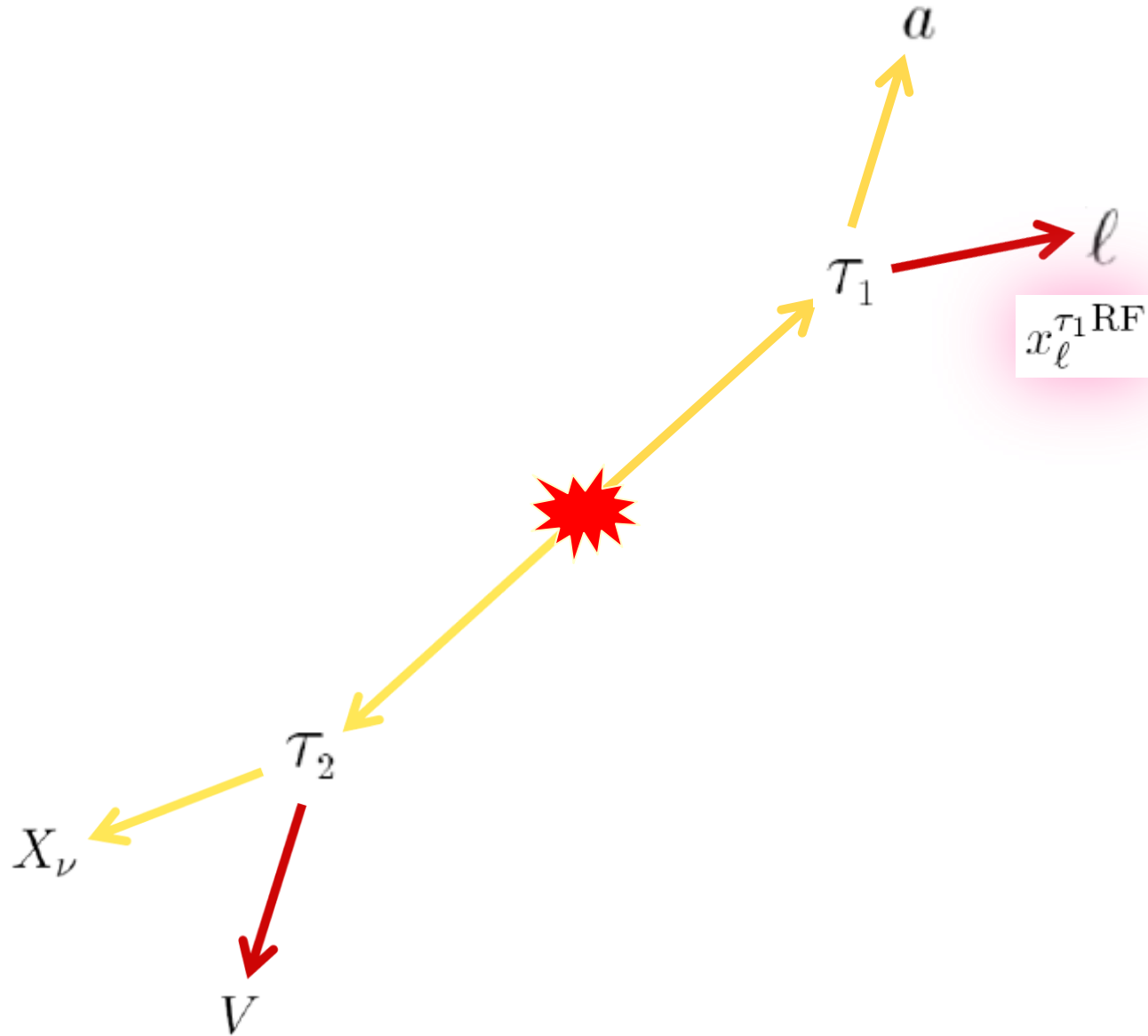
## *Discriminating variables*



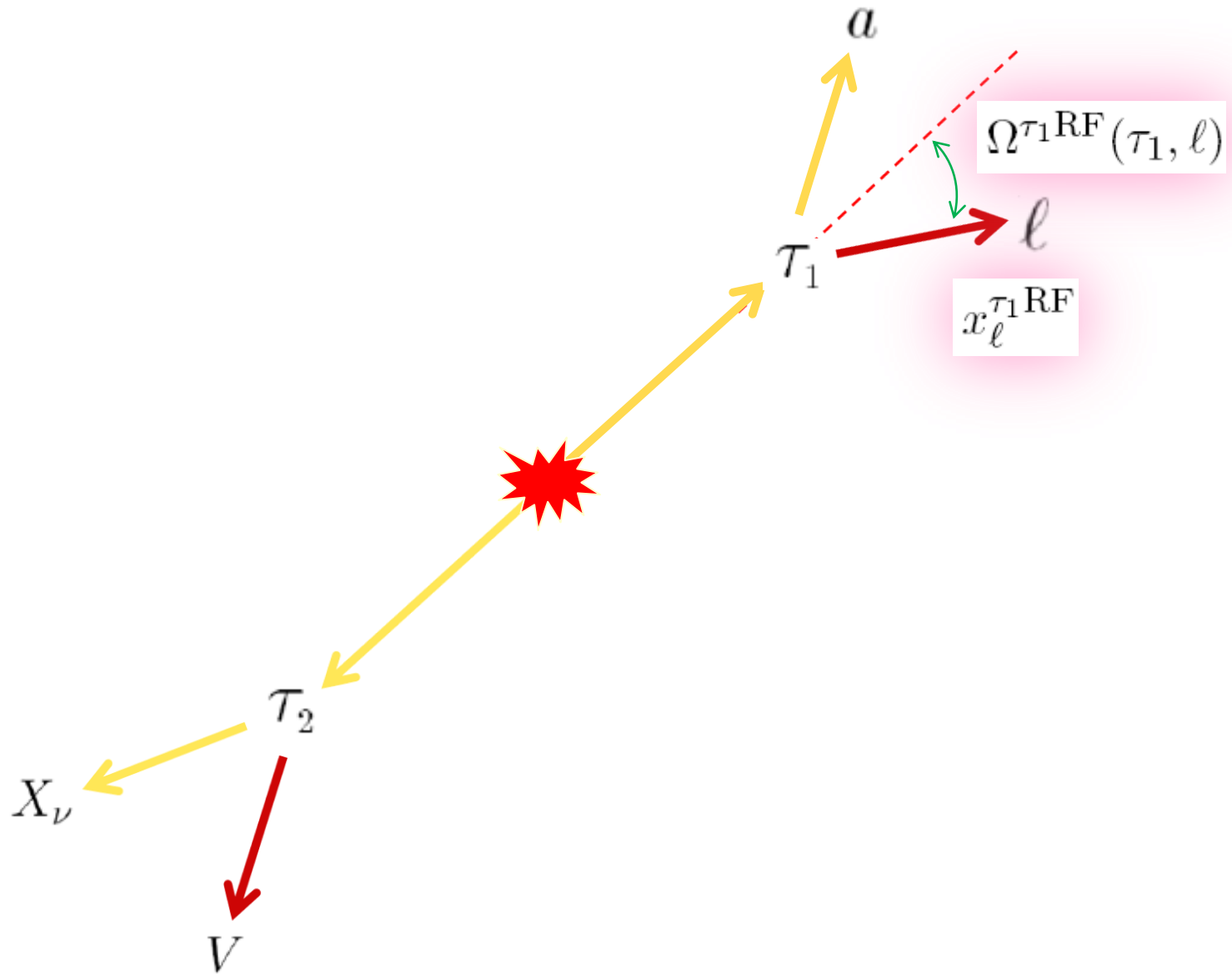
# Discriminating variables



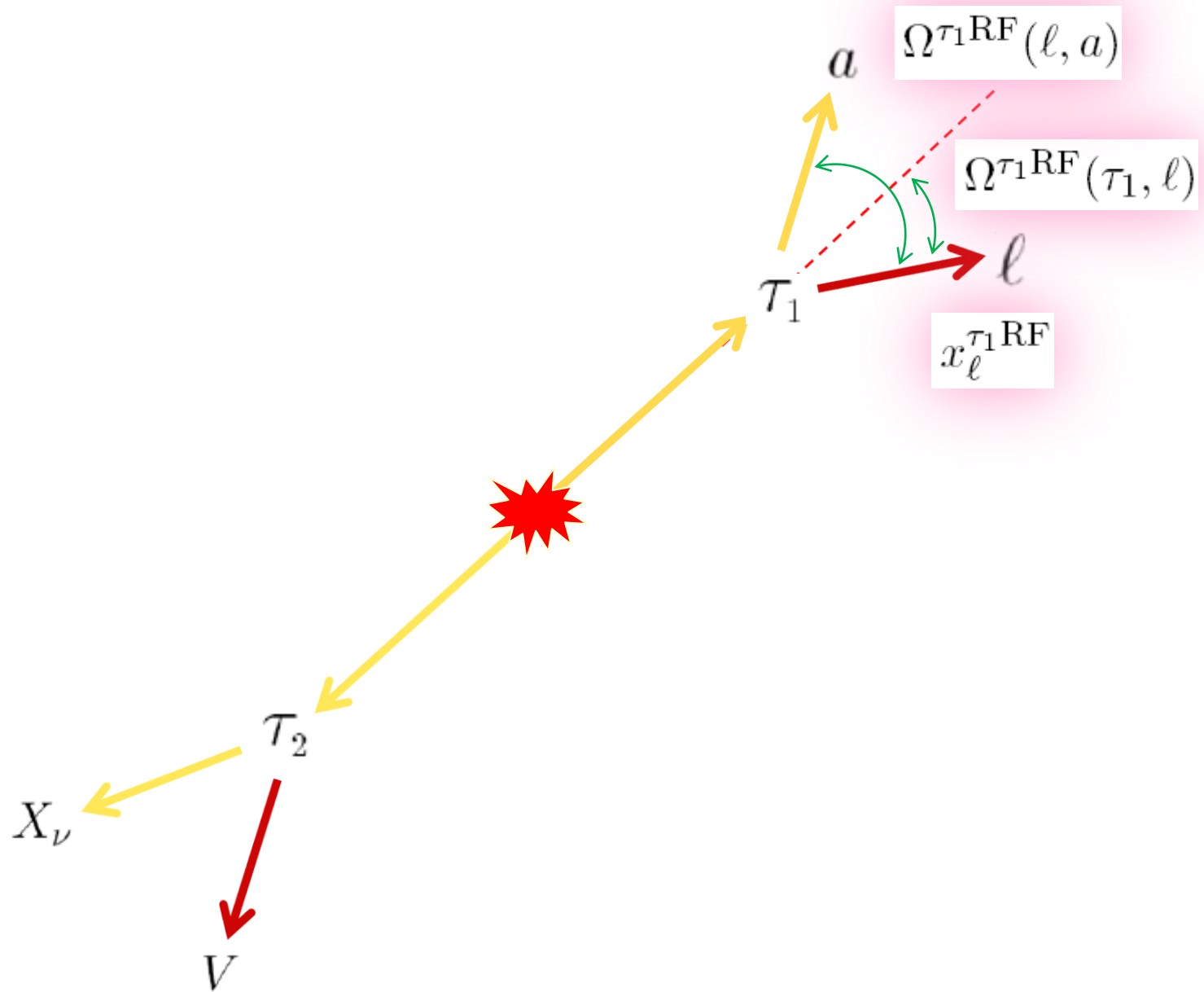
## *Discriminating variables*



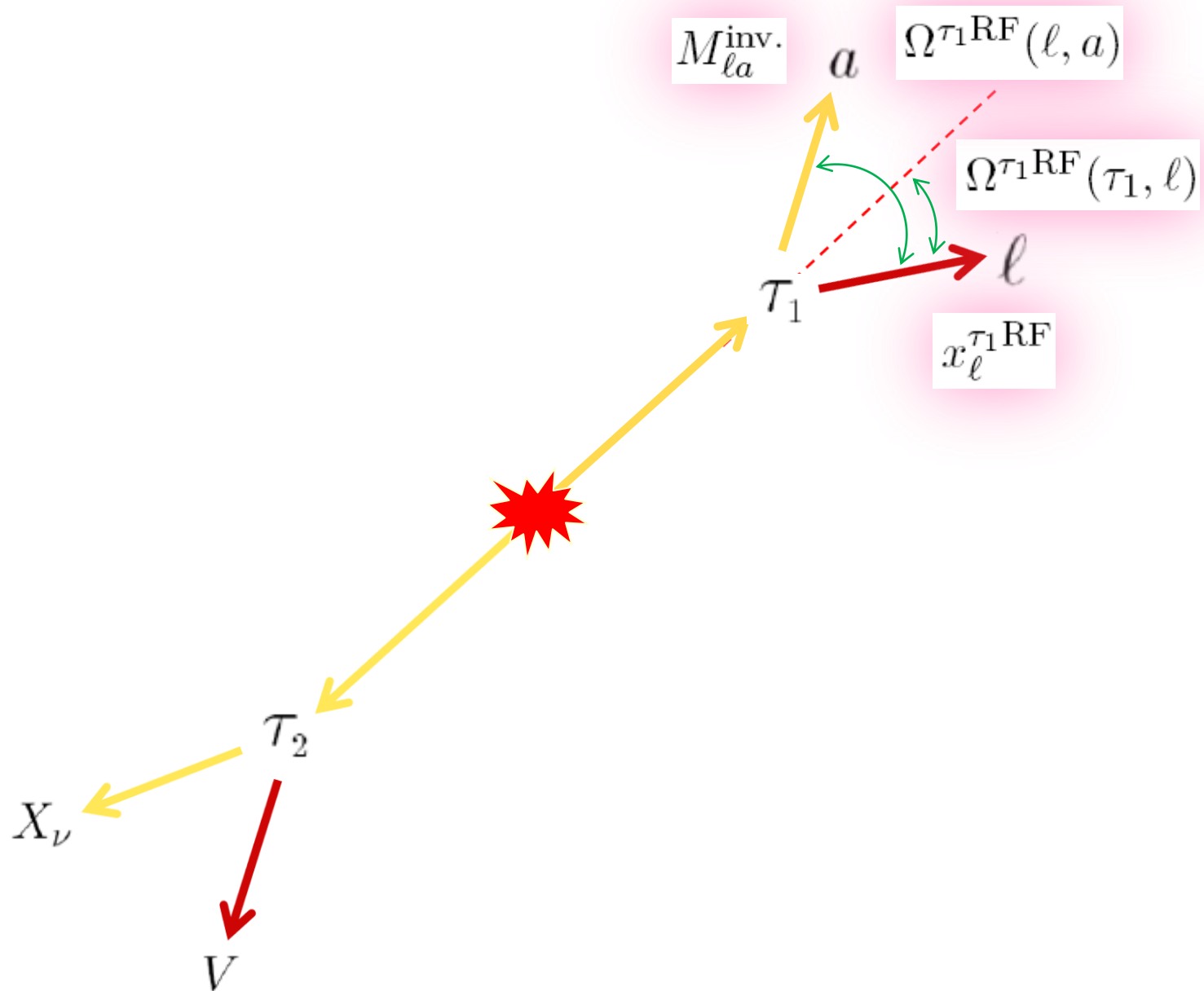
## *Discriminating variables*



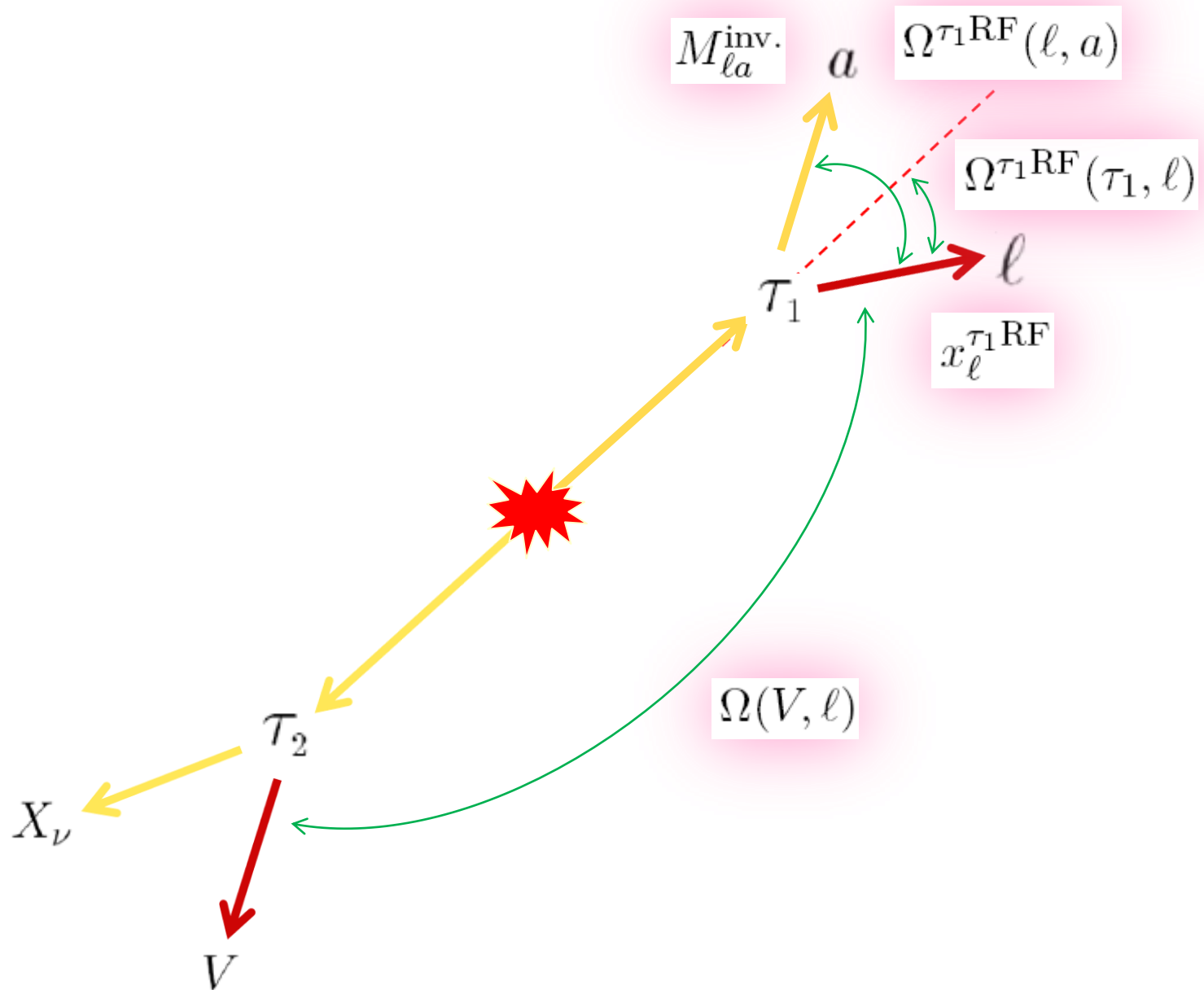
## *Discriminating variables*



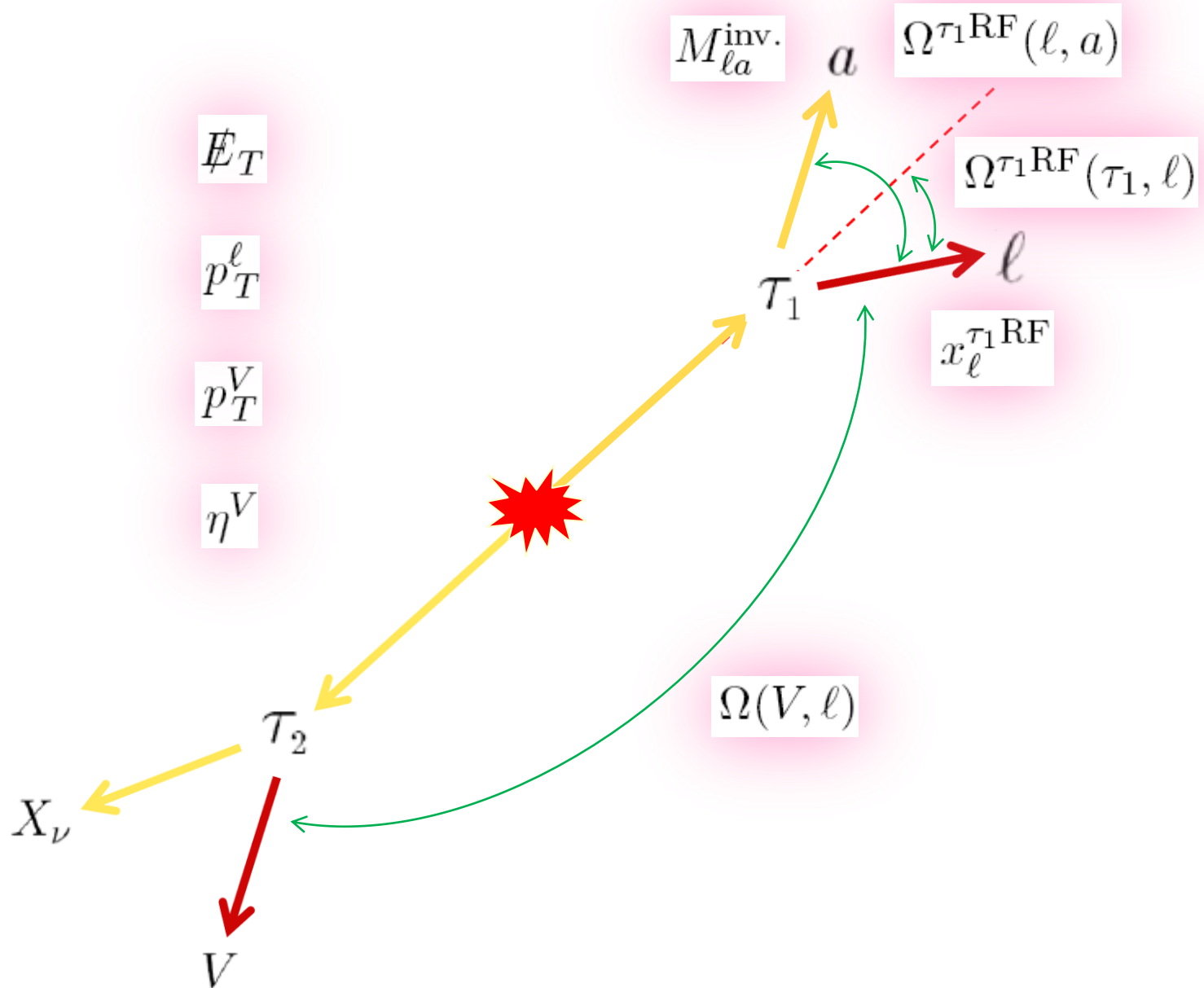
## Discriminating variables



# Discriminating variables



# Discriminating variables



## Discriminating variables

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

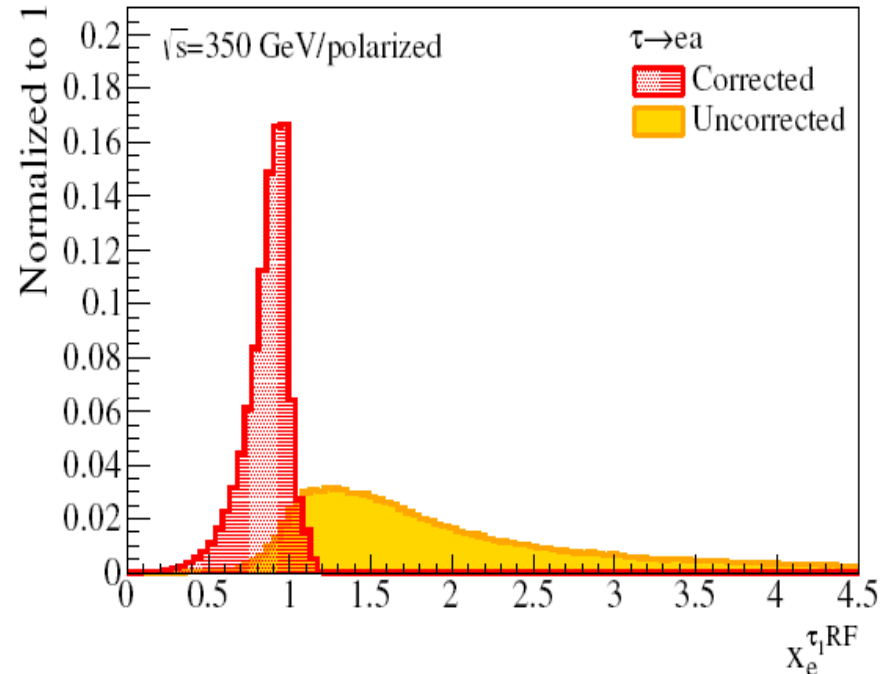
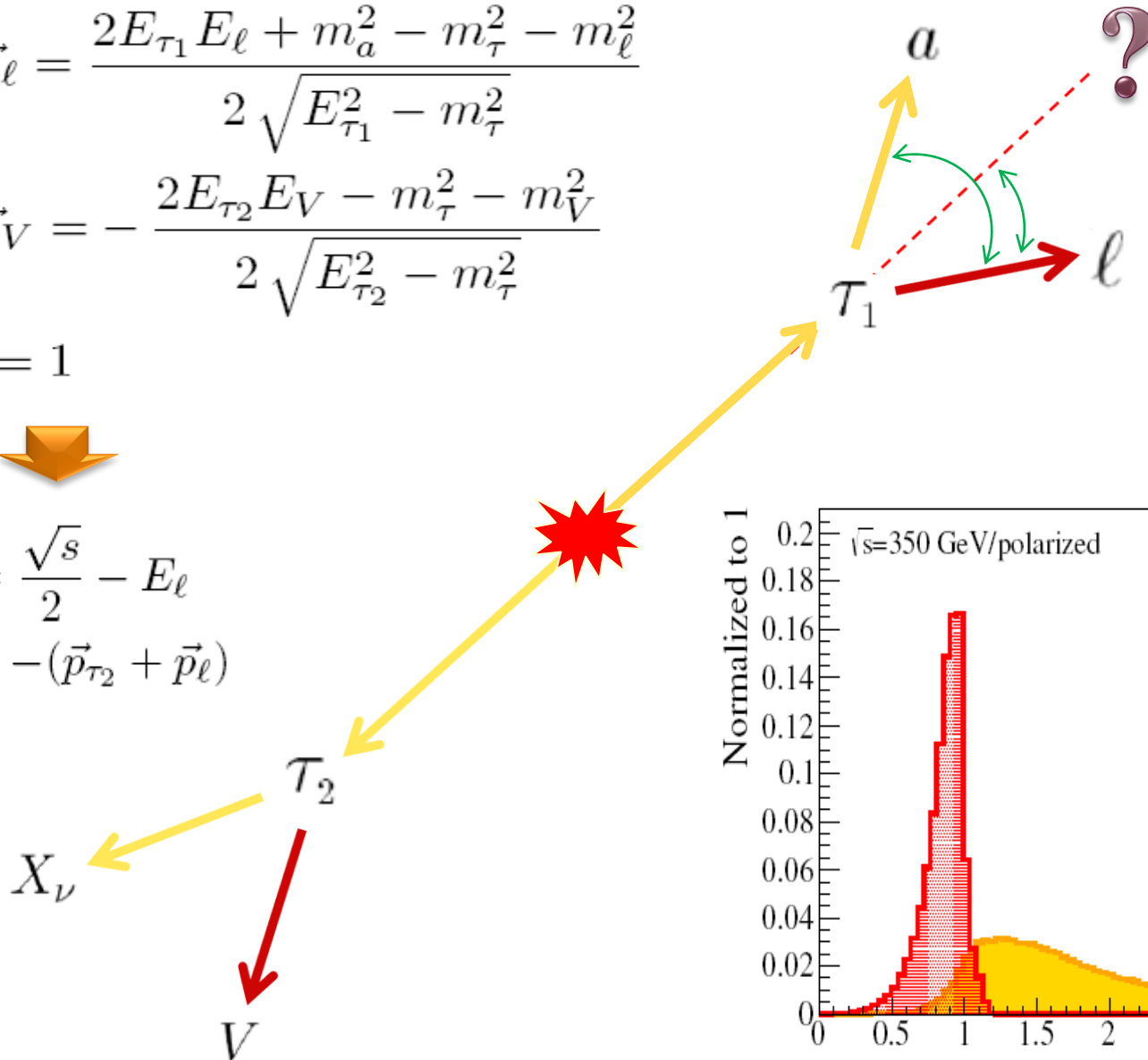
$$\hat{v}_1 \cdot \vec{p}_V = -\frac{2E_{\tau_2} E_V - m_\tau^2 - m_V^2}{2\sqrt{E_{\tau_2}^2 - m_\tau^2}}$$

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



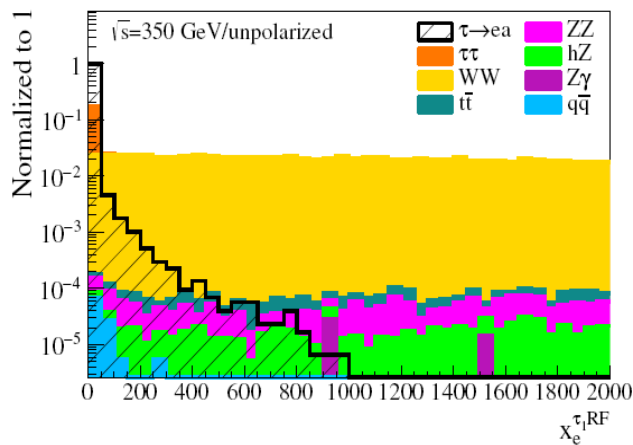
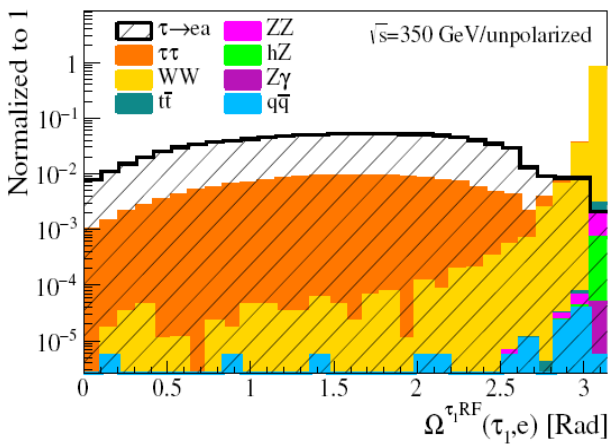
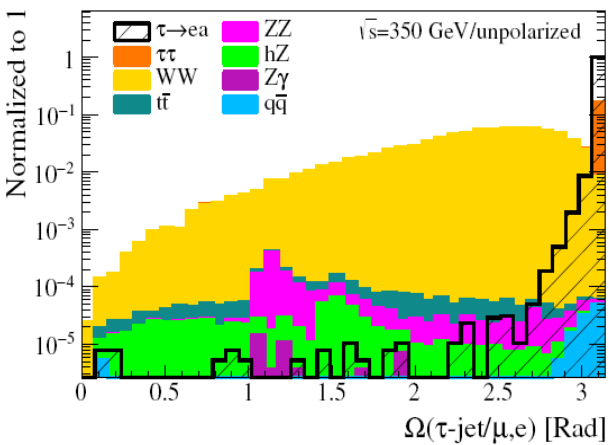
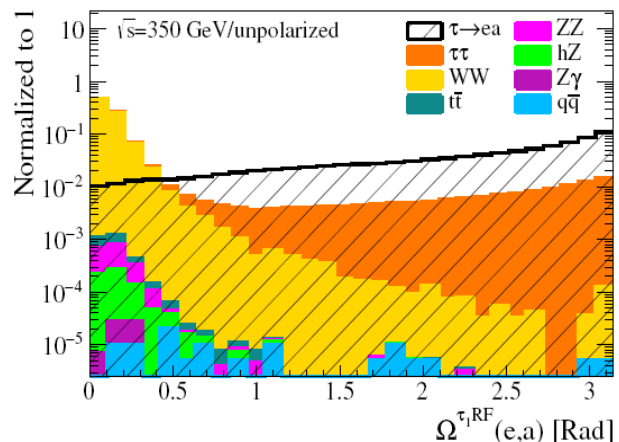
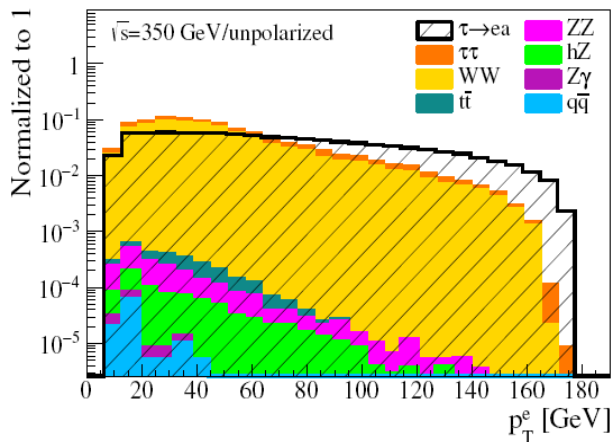
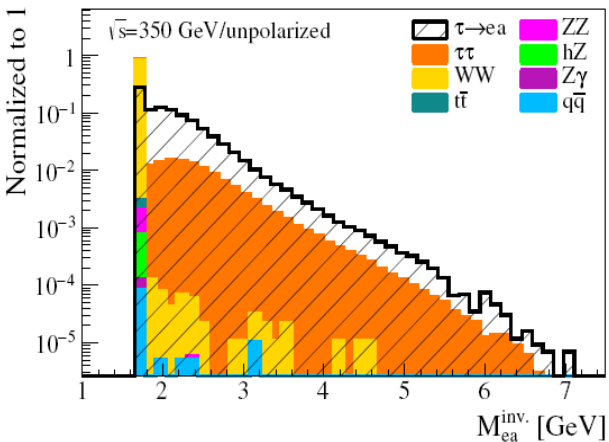
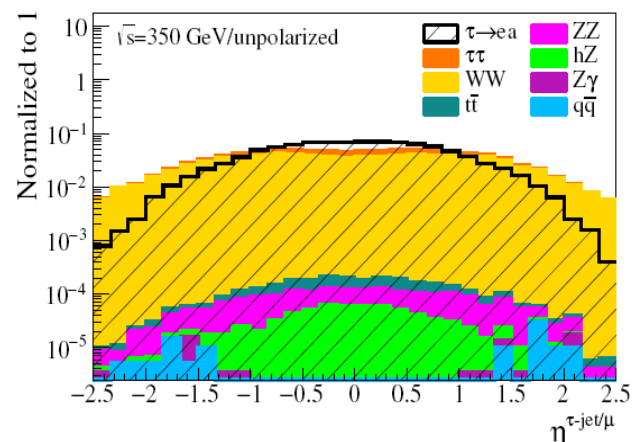
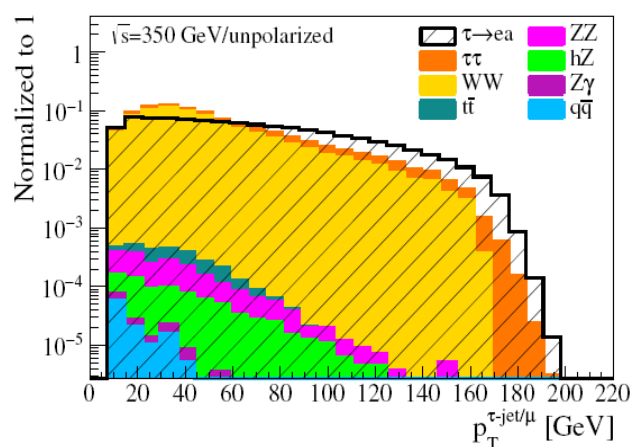
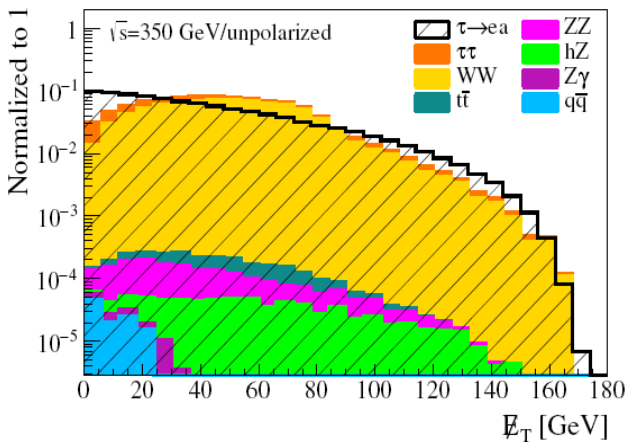
$$E_a = \frac{\sqrt{s}}{2} - E_\ell$$

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



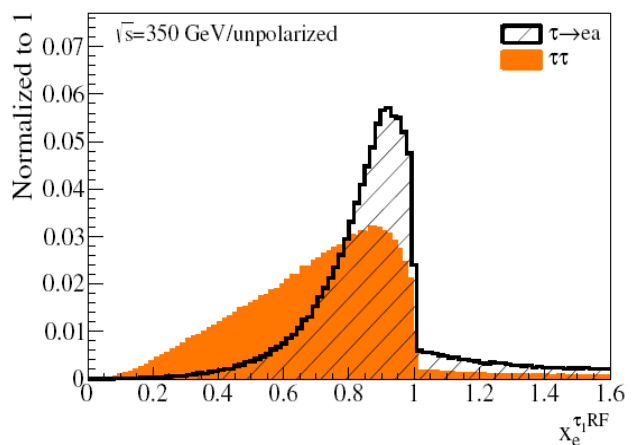
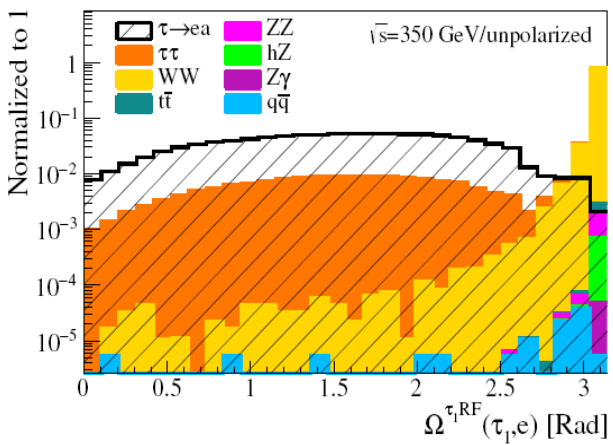
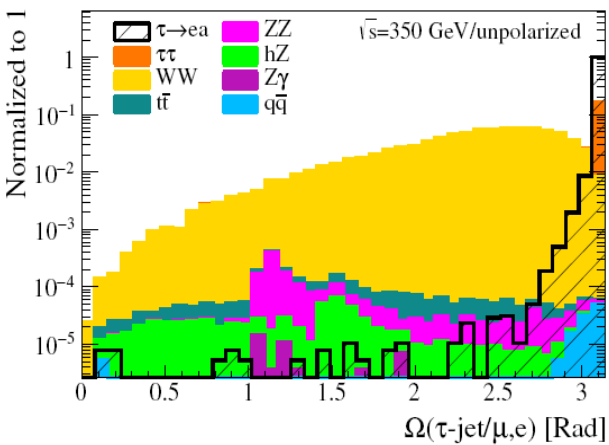
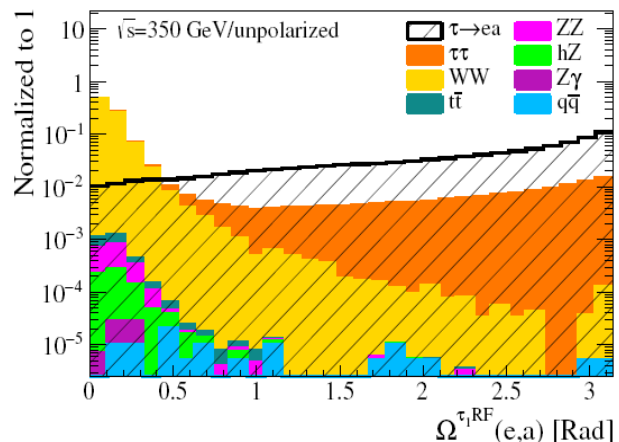
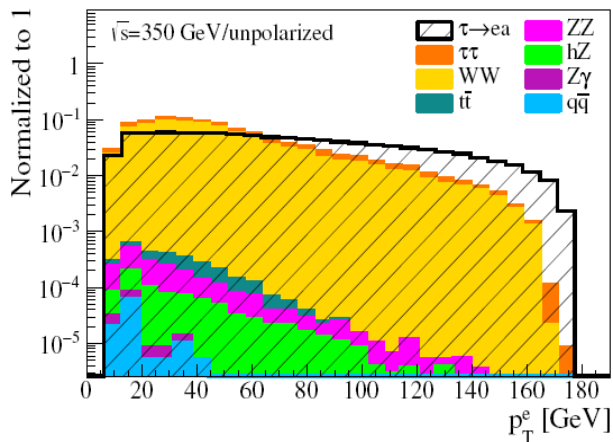
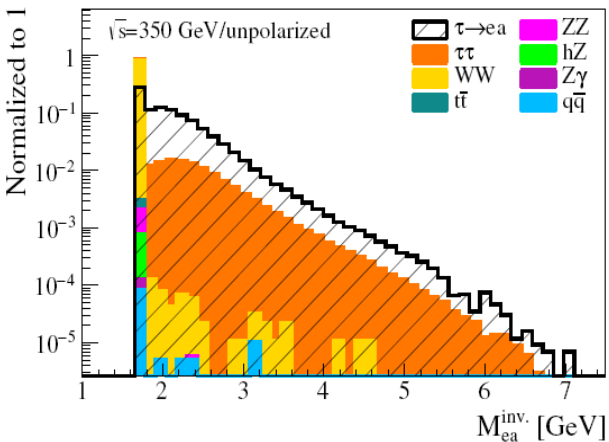
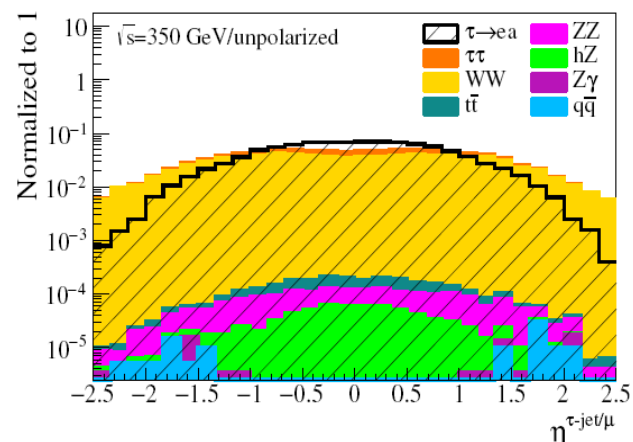
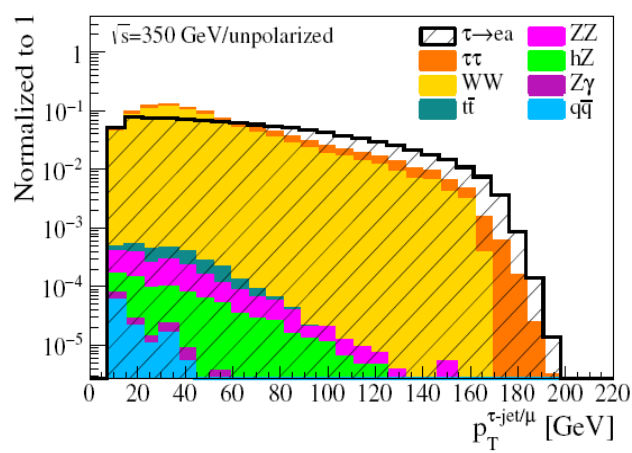
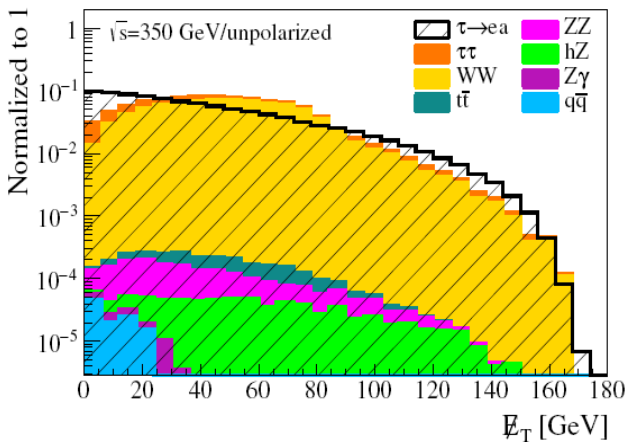
# Unpolarized

# Discriminating variables



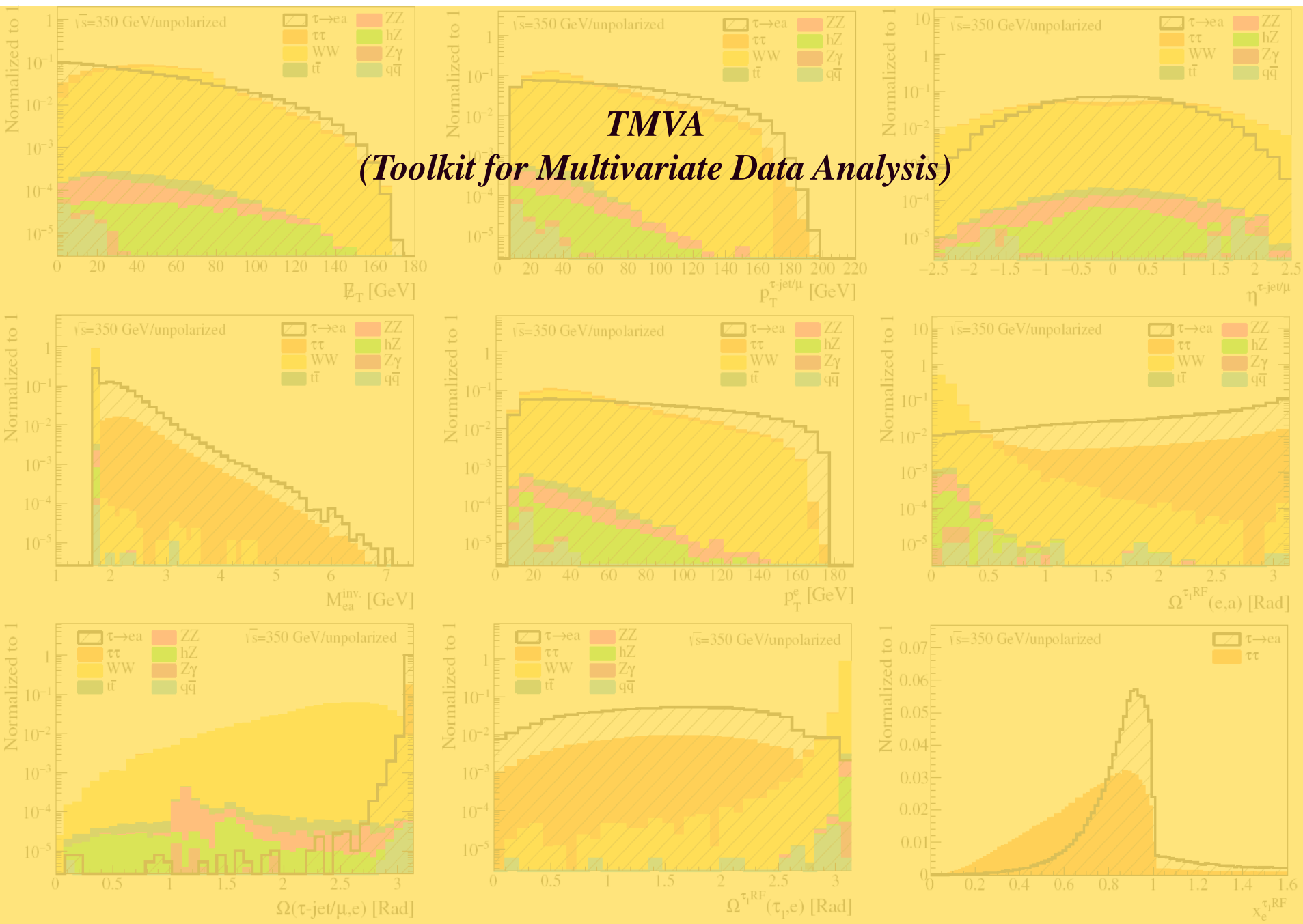
# Unpolarized

# Discriminating variables



# Unpolarized

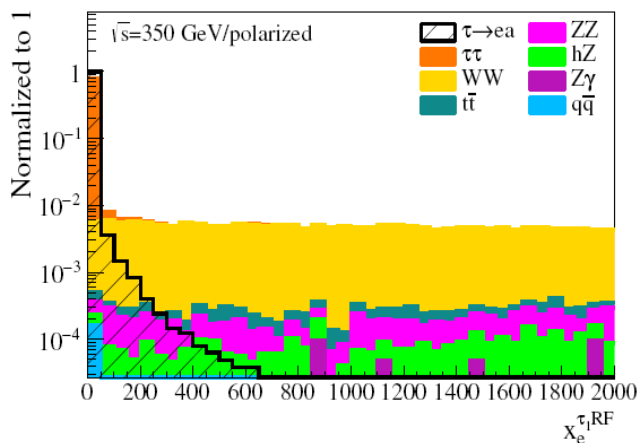
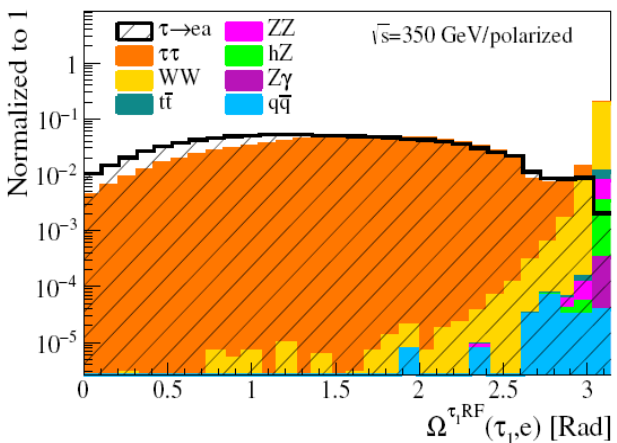
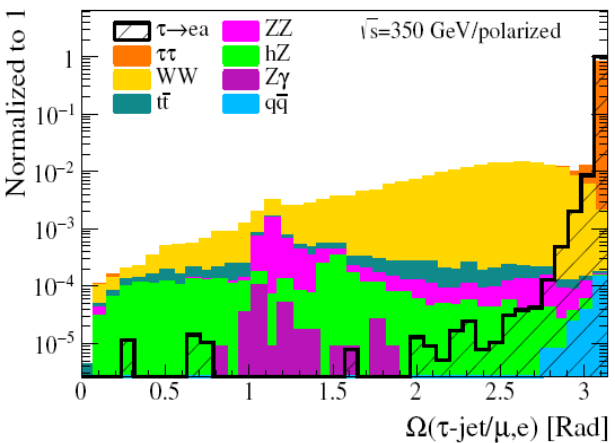
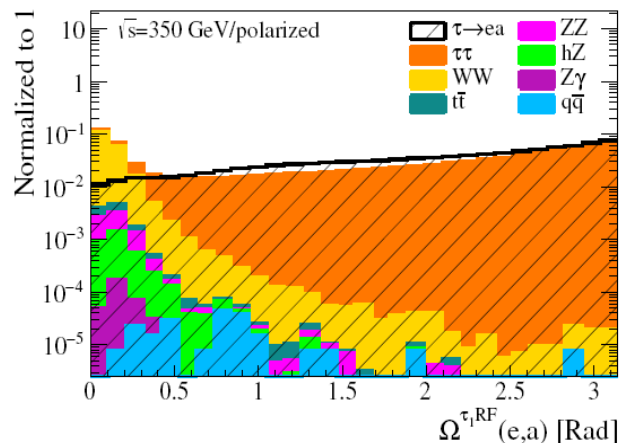
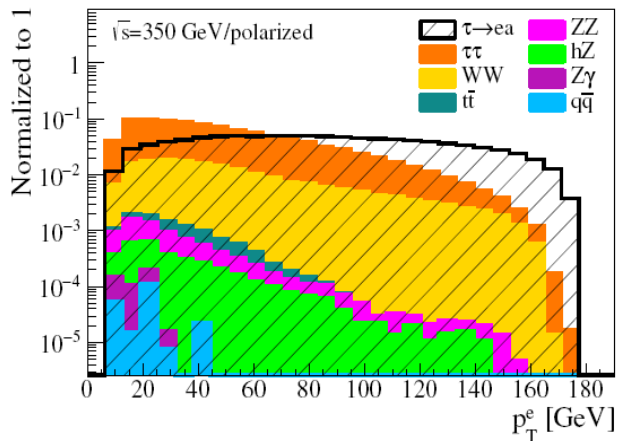
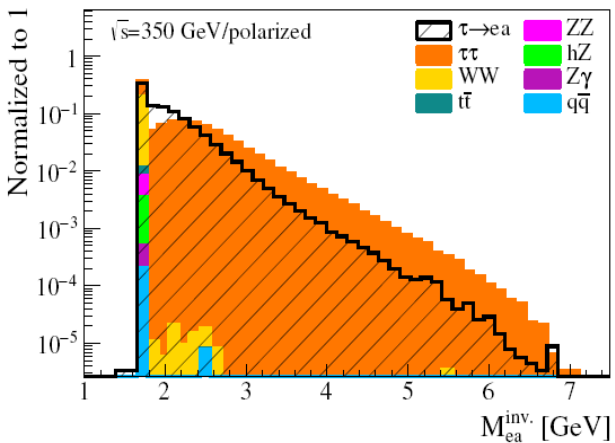
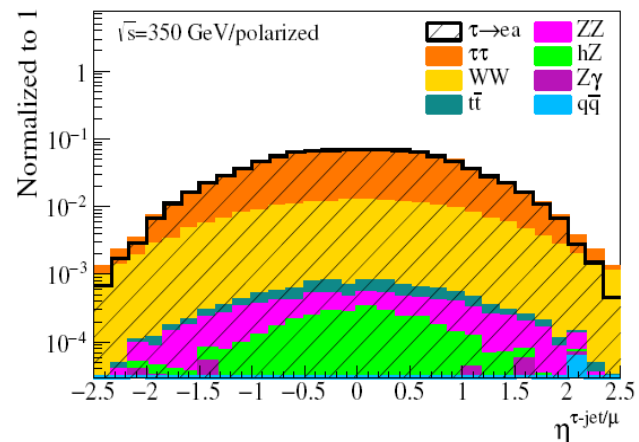
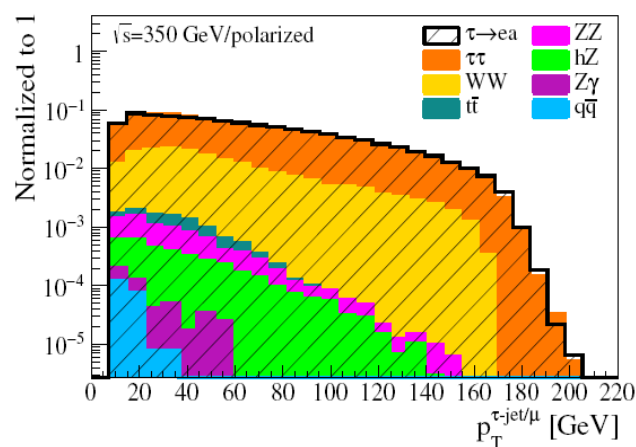
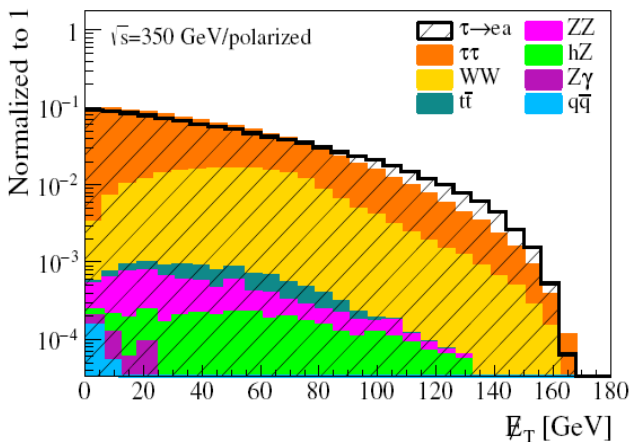
# Discriminating variables





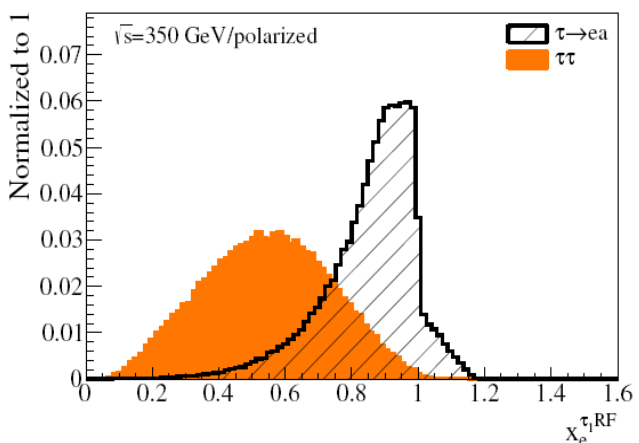
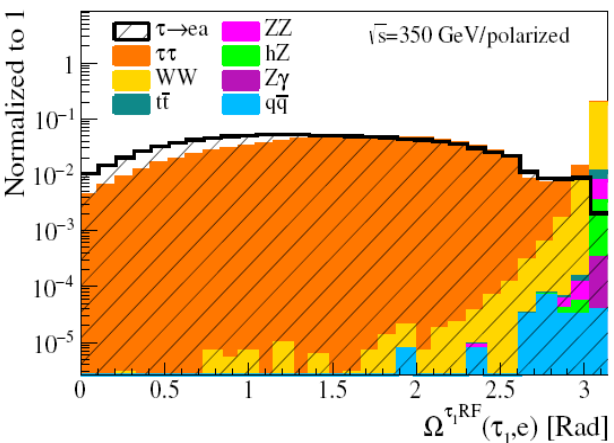
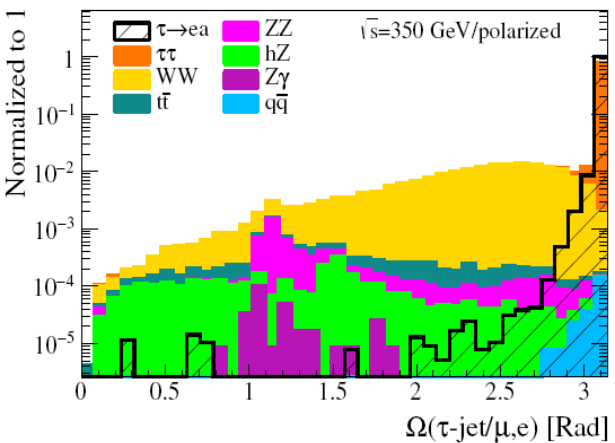
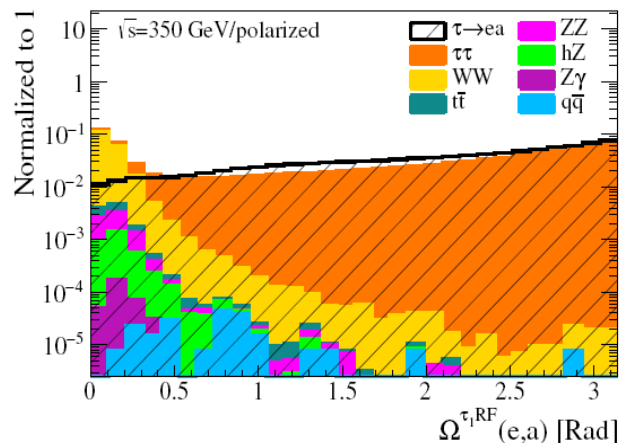
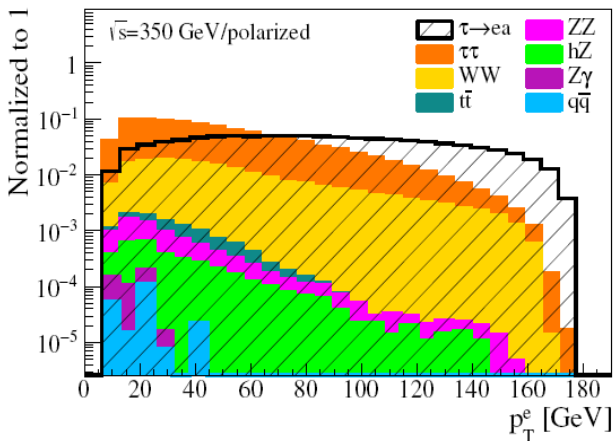
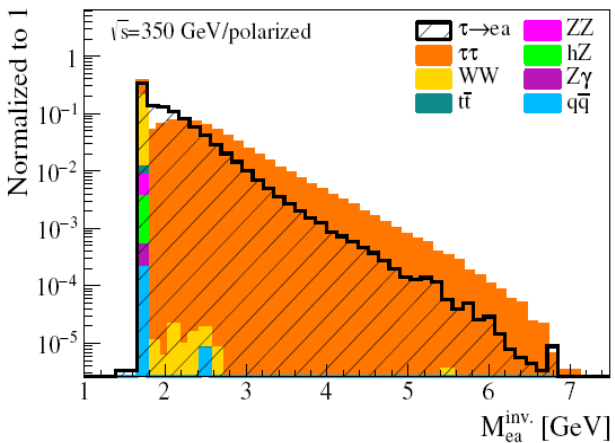
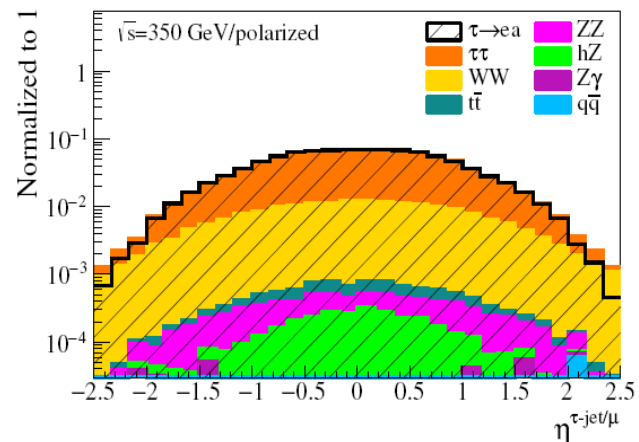
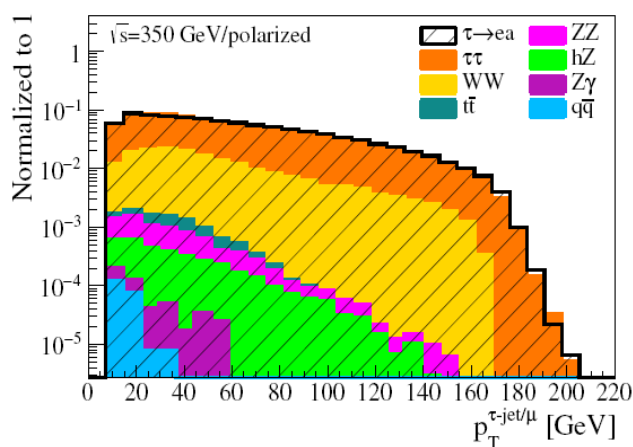
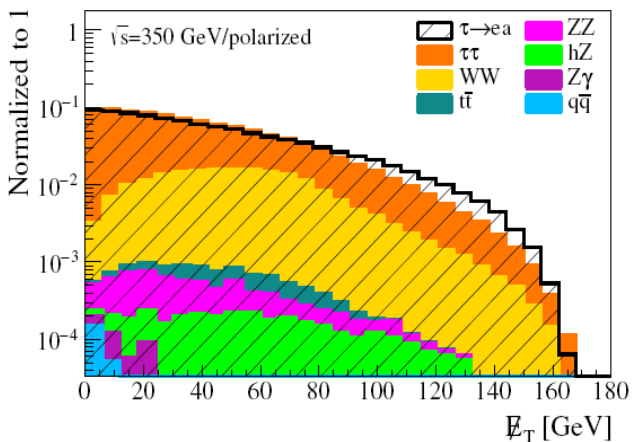
# Polarized

# Discriminating variables



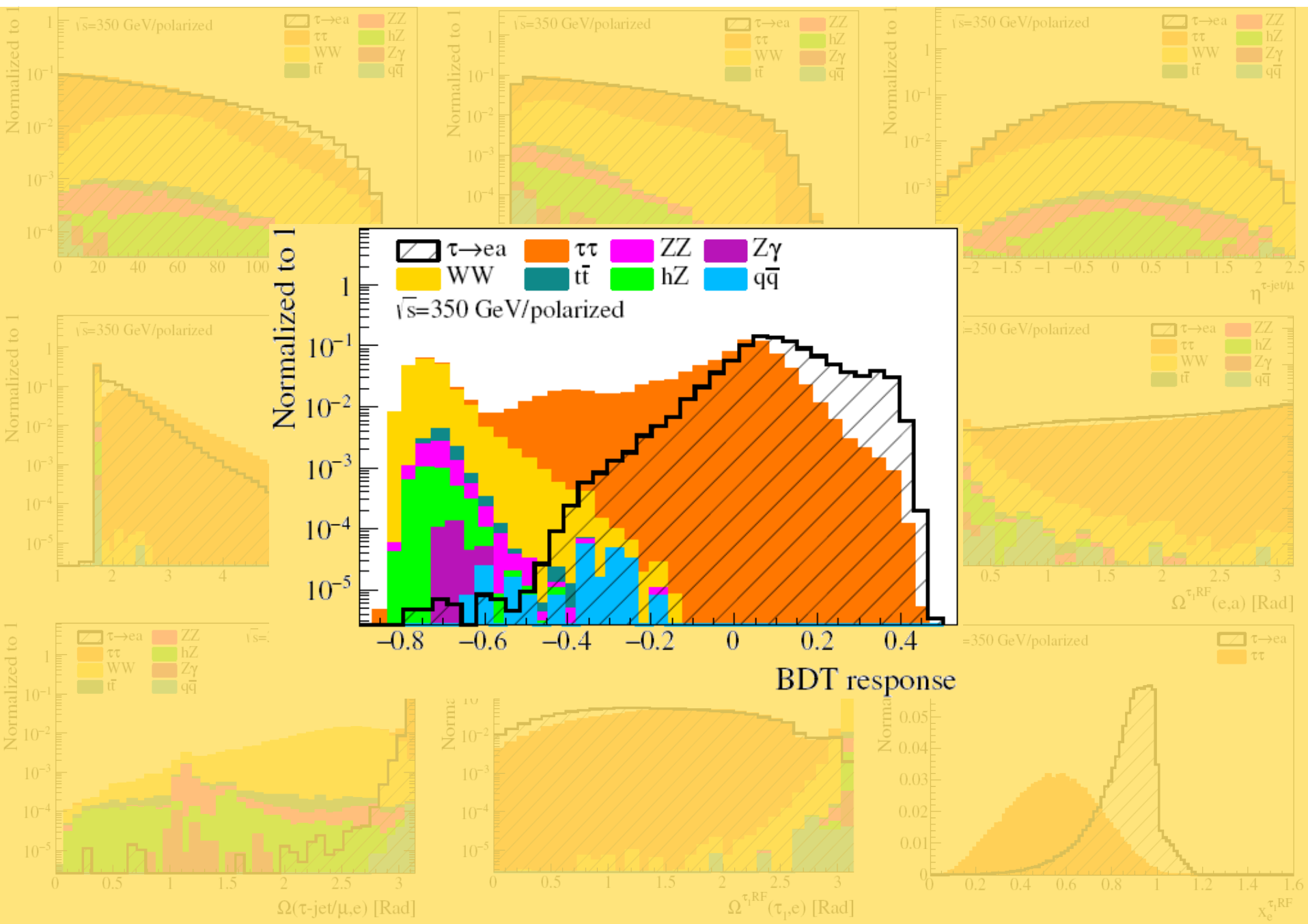
# Polarized

# Discriminating variables



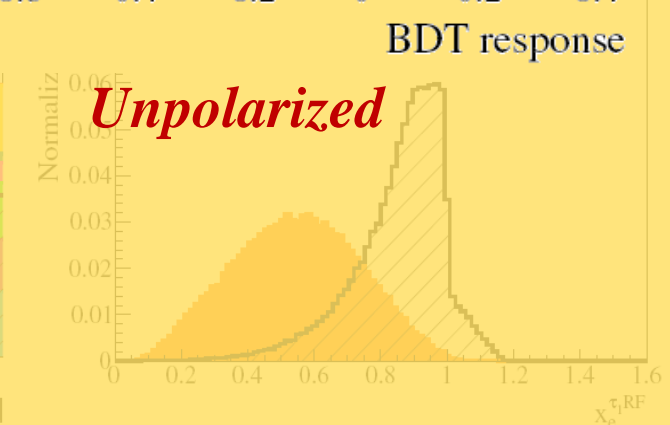
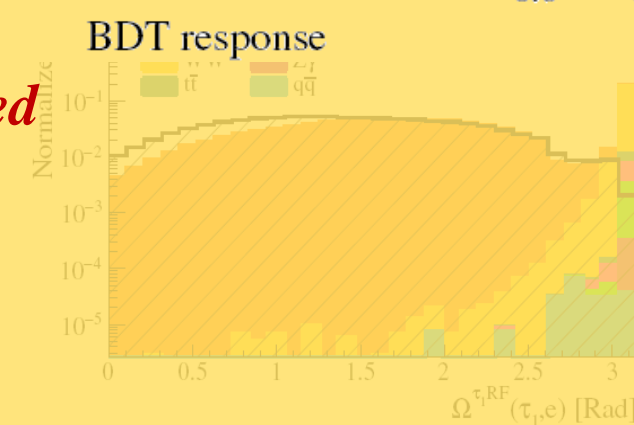
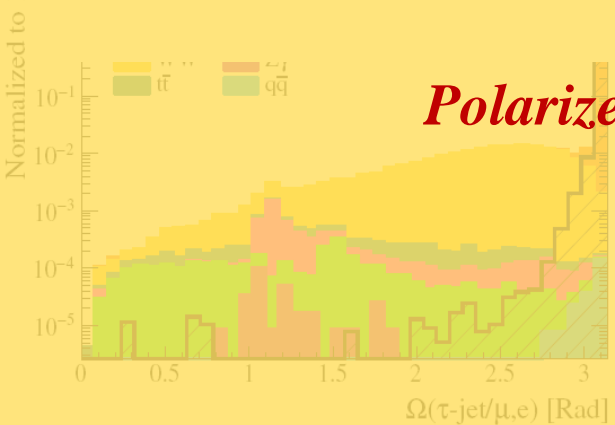
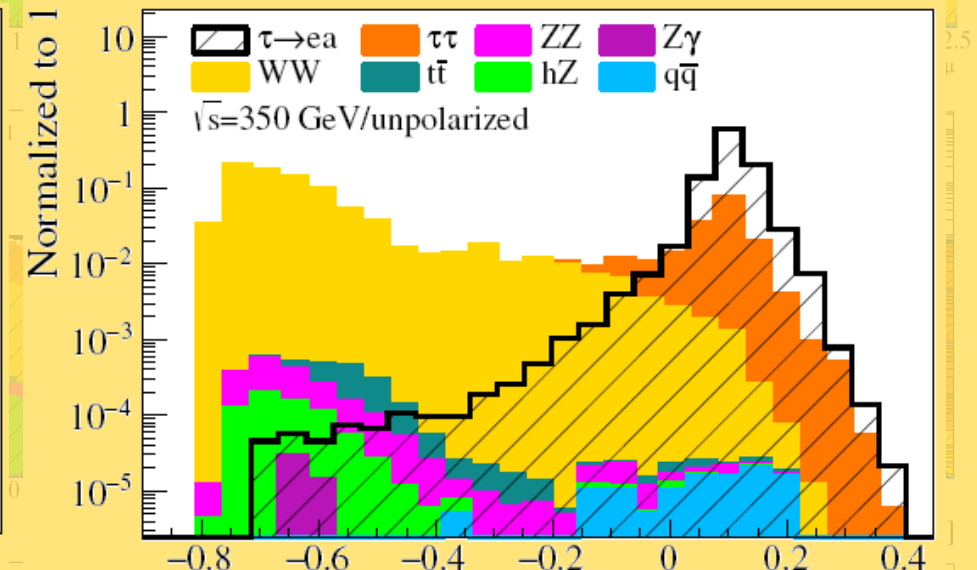
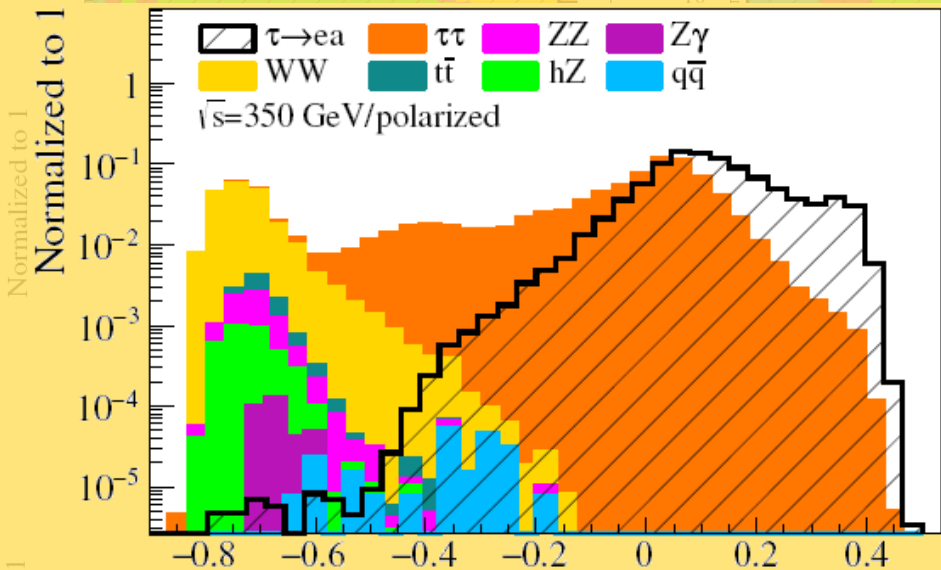
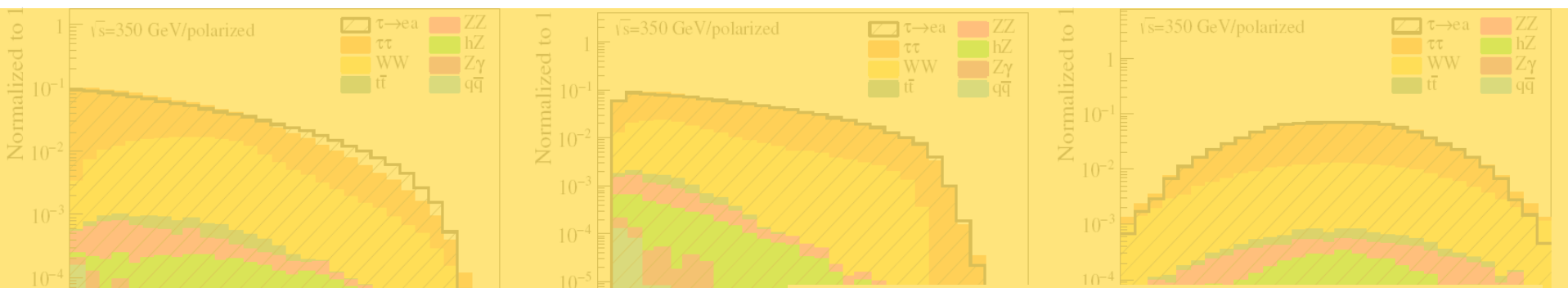
# Polarized

# Discriminating variables



*Polarized*

*Discriminating variables*



*Polarized*

*Unpolarized*

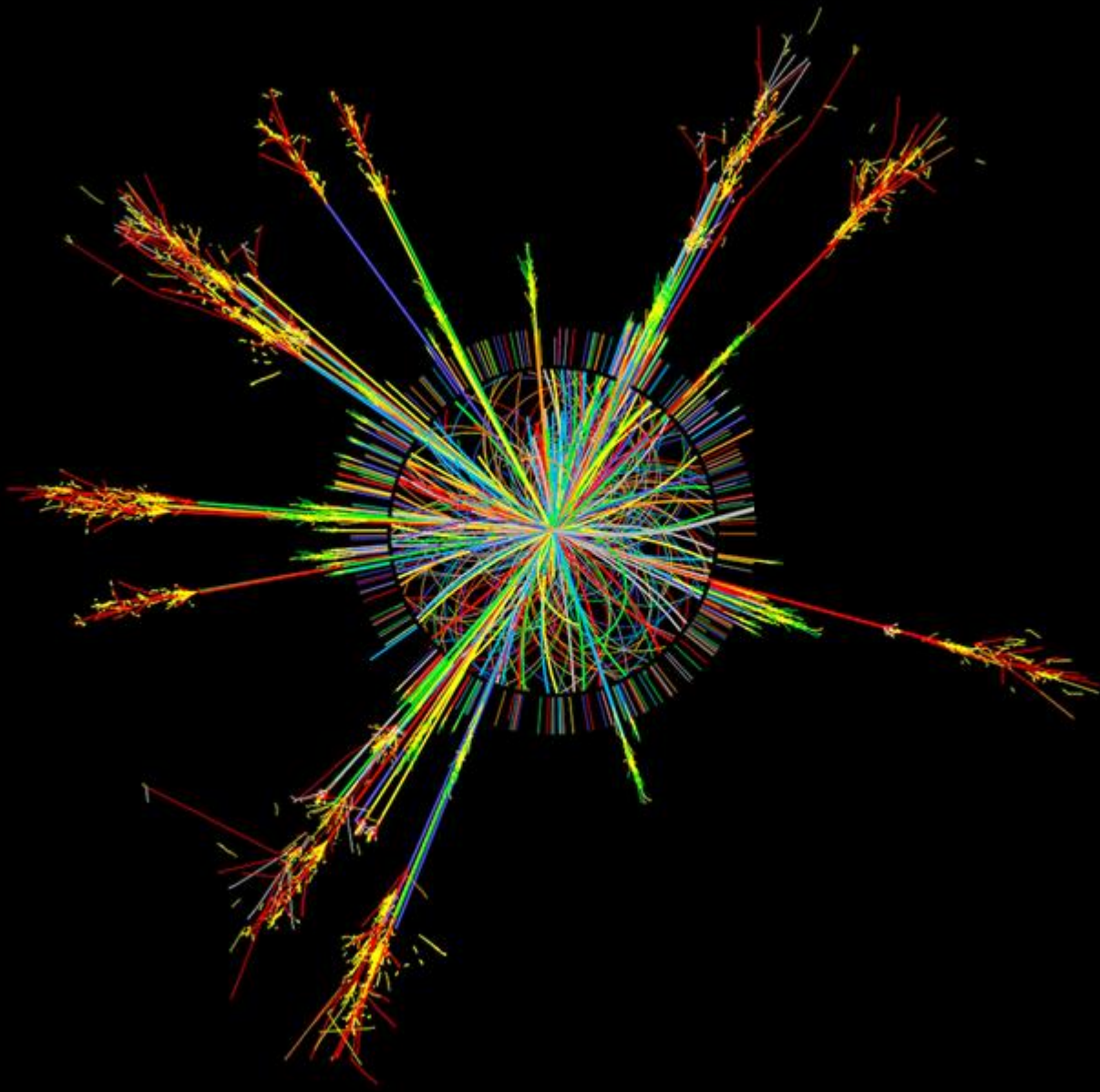
$c_{\tau e}/f_a$		<i>Constraints</i>					
		$m_a$ [MeV]	V+A	V-A	V/A		
126 GeV	Unpolarized	1	9.02 (9.73)	8.46 (9.12)	12.24 (13.21)		
	Polarized	1	2.96 (3.18)	7.32 (7.90)	5.54 (5.97)		
350 GeV	Unpolarized	0.0001	6.63 (7.01)	6.53 (6.90)	9.37 (9.90)		
		0.1	6.68 (7.06)	6.57 (6.94)	9.37 (9.90)		
		0.2	6.69 (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)		
		350 GeV	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 $^{-1}$ ]

$c_{\tau\mu}/f_a$ **Constraints**

		$m_a$ [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)		
		350 GeV	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*

# The Valencia jet algorithm

Valencia jet algorithm combines the good features of lepton collider algorithms  
**Durham-like distance criterion**

$$d_{ij} = \min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos \theta_{ij})/R^2$$

with the **robustness against background** of the longitudinally invariant  $k_t$  algorithm

$$d_{iB} = p_T^{2\beta}$$

$\beta$  allows to *tune* the background rejection level

The algorithm has been implemented as a **plugin for the *FastJet*** package

<https://fastjet.hepforge.org/trac/browser/contrib/contribs/ValenciaJetAlgorithm>

# Discriminating variables

