τ Physics at Z pole

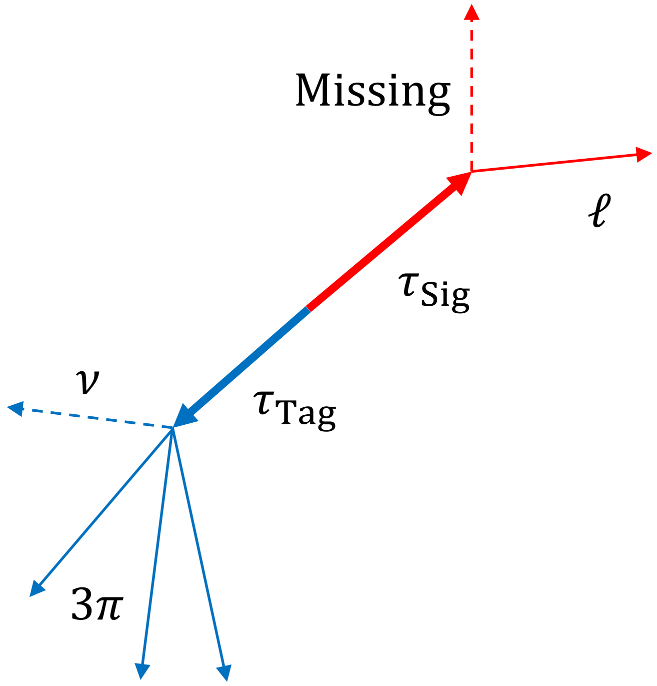
(Preliminary)

Anson

2023-05-05 CEPC Flavor session

Brief note: https://www.overleaf.com/project/6440e6544374dde1f12f262f

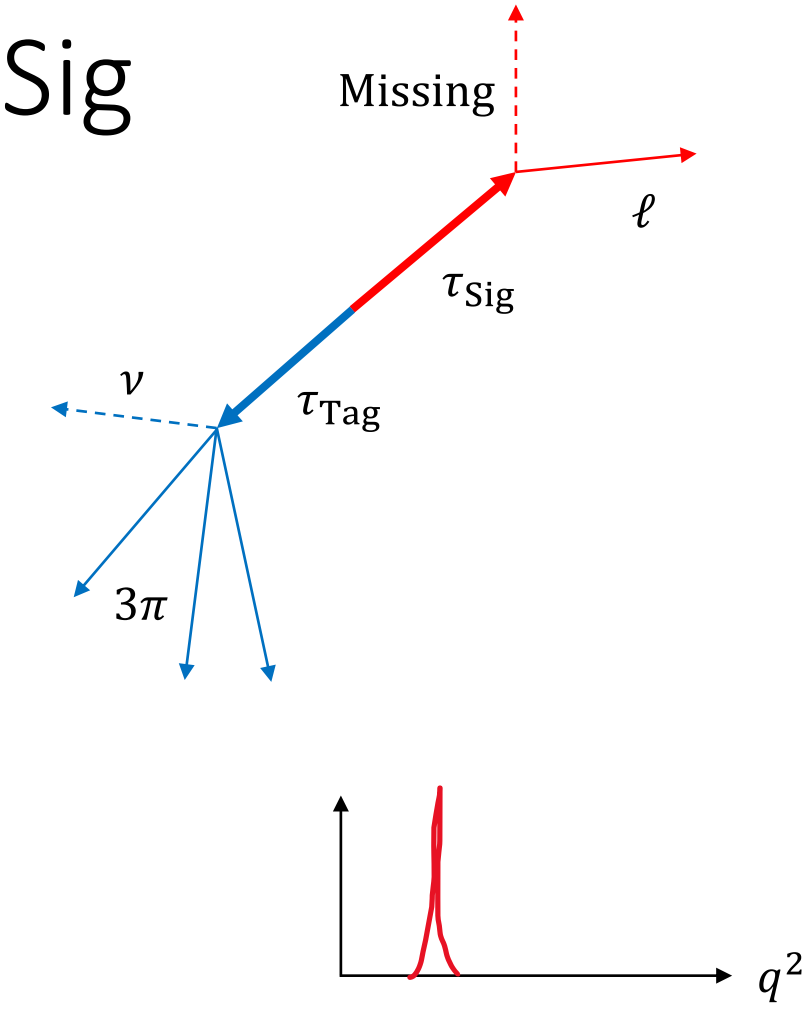
$Z \to \tau(\to \ell + \mathrm{Missing})\tau(\to 3\pi\nu)$



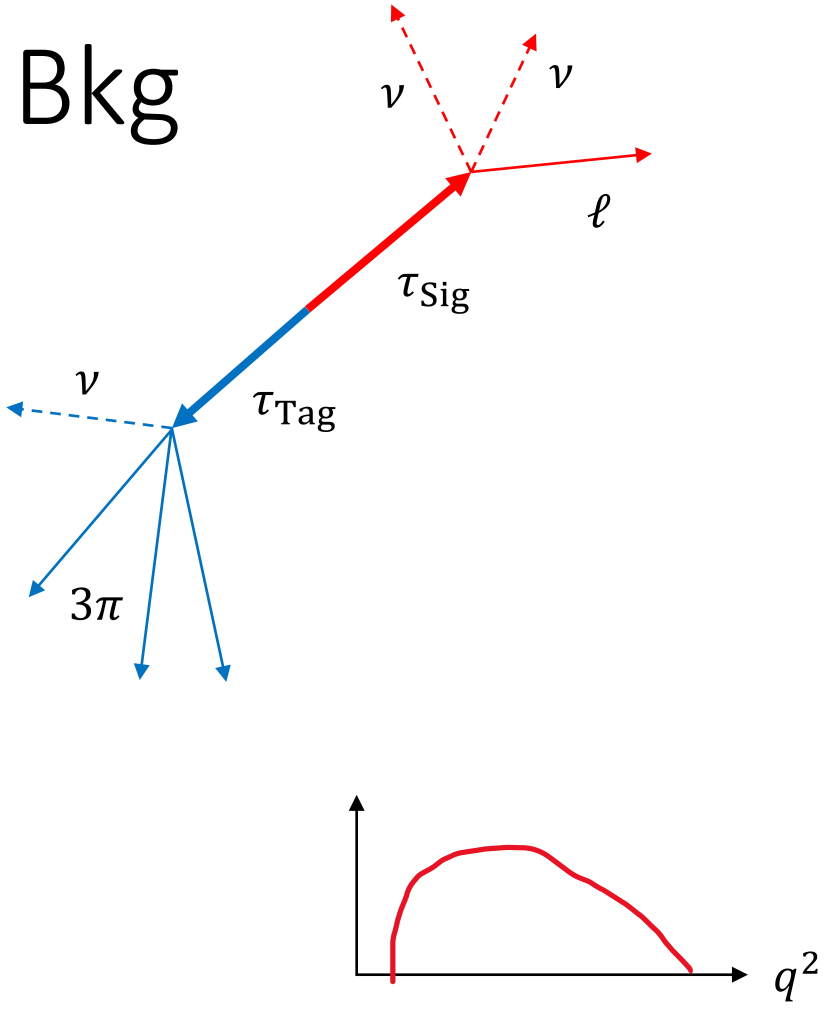
For example:
Missing = ALP

$$\text{Define } q^2 = \left(p_{\tau_{\text{Sig}}} - p_\ell\right)^2$$

Sig



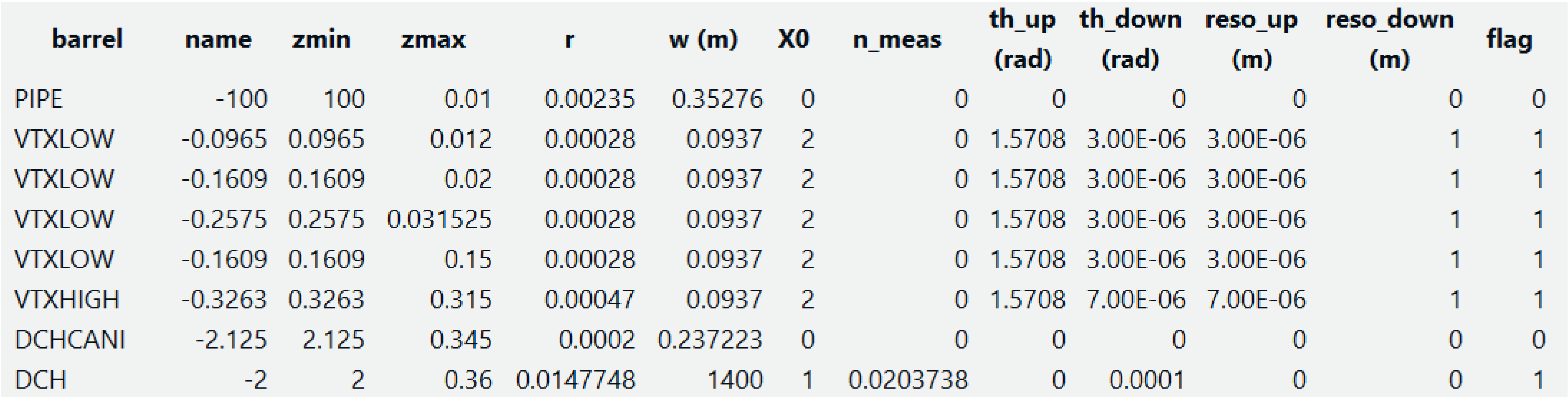
Bkg



Simulation

- Pythia -> Delphes (IDEA card)

- Since vertexing plays a significant role here:
  - Using delphes / external / TrackCovariance / VertexFit.cc to fit the 3π vertex
    - https://github.com/delphes/delphes/blob/master/external/TrackCovariance/VertexFit.cc
  - Takes the track parameters $(d_0, \phi, c, z_0, \cot\theta)$ and output vertex + cov matrix
  - Track parameters is based on IDEA card: https://github.com/delphes/delphes/blob/master/cards/delphes_card_IDEA.tcl



barrel	name	zmin	zmax	r	w (m)	X0	n_meas	th_up (rad)	th_down (rad)	reso_up (m)	reso_down (m)	flag
PIPE	-100	100	0.01	0.00235	0.35276	0	0	0	0	0	0	0
VTXLOW	-0.0965	0.0965	0.012	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1	1
VTXLOW	-0.1609	0.1609	0.02	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1	1
VTXLOW	-0.2575	0.2575	0.031525	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1	1
VTXLOW	-0.1609	0.1609	0.15	0.00028	0.0937	2	0	1.5708	3.00E-06	3.00E-06	1	1
VTXHIGH	-0.3263	0.3263	0.315	0.00047	0.0937	2	0	1.5708	7.00E-06	7.00E-06	1	1
DCHCANI	-2.125	2.125	0.345	0.0002	0.237223	0	0	0	0	0	0	0
DCH	-2	2	0.36	0.0147748	1400	1	0.0203738	0	0.0001	0	0	1

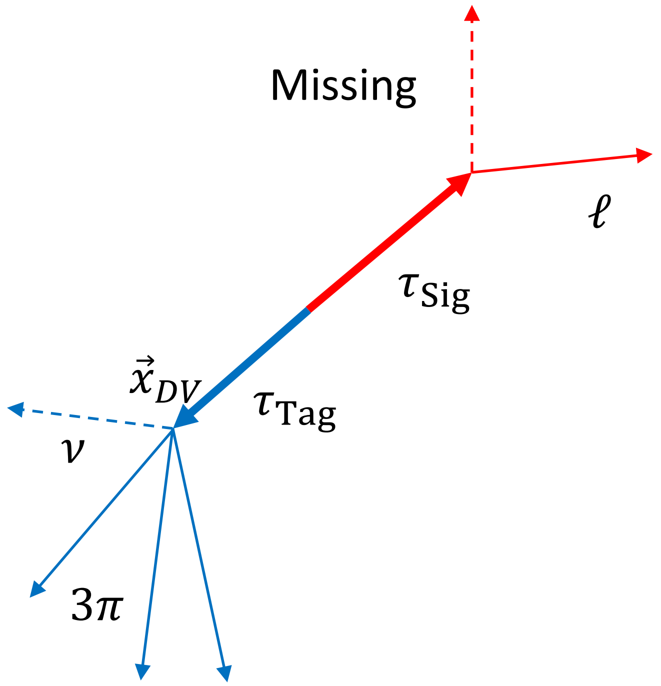
Two Methods of q^2 Reconstruction

(Reconstructing q^2 is the same as saying reconstructing $p_{\tau_{\mathrm{Sig}}}$)

Method 1: Analytic Solution (More naïve solution with assumptions)

Method 2: χ^2 Solution (More realistic)

Analytic Solution (Just approximation)



- Z 2-body decay. So $E_\tau = m_Z/2$
- $\vec{p}_{\tau_{\text{Tag}}} \parallel \vec{x}_{DV}$ (PV=(0,0,0) + perfect DV vertex)
- τ_{Sig} and τ_{Tag} decay back-to-back (no ISR)
- $\left|\vec{p}_{\tau_{\text{Sig}}}\right| = \sqrt{\left(\frac{m_Z}{2}\right)^2 - m_\tau^2}$
- So $p_{\tau_{\text{Sig}}} = \left(\frac{m_Z}{2}, \left|\vec{p}_{\tau_{\text{Sig}}}\right| \hat{x}_{DV}\right)$

χ^2 Method

$$\chi^2 = (\vec{x}_d - \vec{x}_{d,0})^T V_{d,0}^{-1} (\vec{x}_d - \vec{x}_{d,0}) + (\vec{x}_p - \vec{x}_{p,0})^T V_{p,0}^{-1} (\vec{x}_p - \vec{x}_{p,0}) + (\vec{h} - \vec{h}_0)^T V_{h,0}^{-1} (\vec{h} - \vec{h}_0)$$

Target parameters to fitted are:

Still not yet include ISR effect

- Energy of the tau in tag side: E_{tag}
- Energy of the tau in signal side: E_{sig}
- trajectory parameter t, which parametrizes the signal tau decay vertex location

Optimize the χ^2 with the following constraints:

- Energy conservation: $E_{\text{tag}} + E_{\text{sig}} = m_Z$
- Momentum conservation: $\vec{p}_{\text{tag}} + \vec{p}_{\text{sig}} = \sqrt{E_{\text{tag}}^2 - m_\tau^2}\,\frac{\Delta\vec{x}_d}{|\Delta\vec{x}_d|} + \sqrt{E_{\text{sig}}^2 - m_\tau^2}\,\frac{\Delta\vec{x}_\ell}{|\Delta\vec{x}_\ell|} = 0$

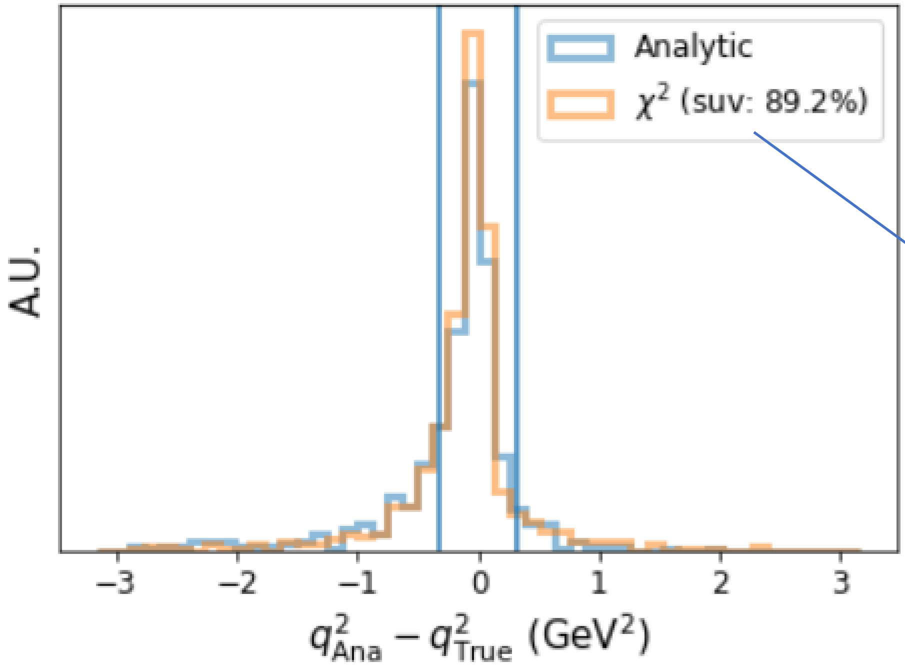
where $\Delta\vec{x}_{d,\ell} = \vec{x}_{d,\ell} - \vec{x}_p$, and $\vec{x}_\ell(t)$ is the signal tau decay vertex.

Example: $\tau \to \mu\nu\nu$ reconstruction

```
Analytic RMS in range: [-3.1572  3.1572]: 0.5576 GeV^2
Analytic % in range    [-0.3157  0.3157]: 59.9000 %

chi2 RMS in range:     [-3.1572  3.1572]: 0.5085 GeV^2
chi2 % in range        [-0.3157  0.3157]: 62.2000 %

<matplotlib.legend.Legend at 0x7f7eb4ca5460>
```



$$q^2 = (m_Z/2 - E_\ell)^2 - (\sqrt{(m_Z/2)^2 - m_\tau^2} \cdot \hat{x}_{\mathrm{DV}} - \vec{p}_\ell)^2$$

$$\left|\frac{\partial q^2}{\partial \hat{x}_{\mathrm{DV}}}\right| = 2(\sqrt{(m_Z/2)^2 - m_\tau^2} \cdot \hat{x}_{\mathrm{DV}} - \vec{p}_\ell) \times (\sqrt{(m_Z/2)^2 - m_\tau^2} \cdot d\hat{x}_{\mathrm{DV}})$$

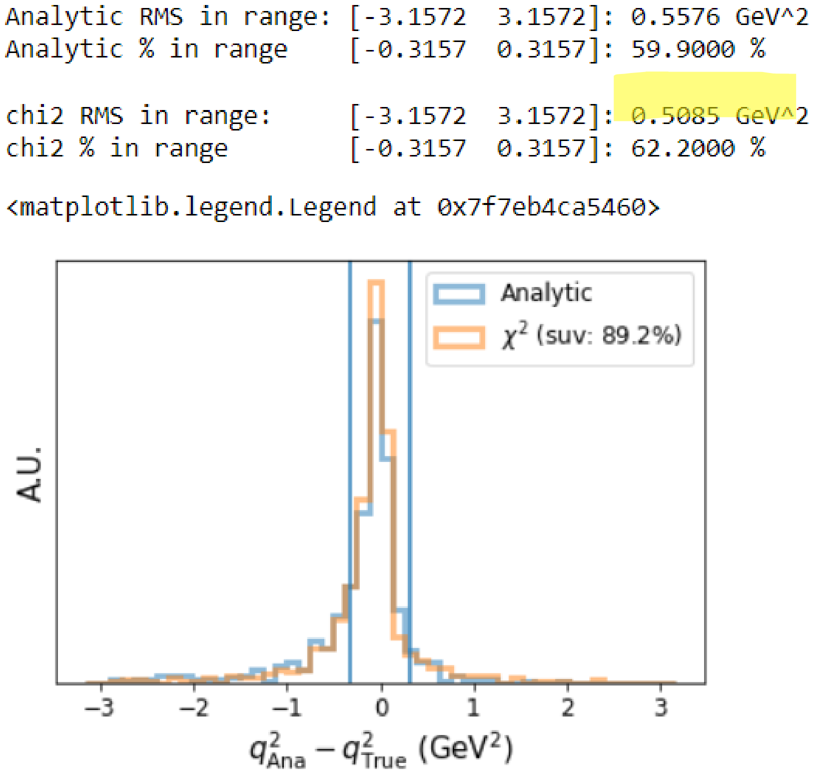
$$\left|\frac{\partial q^2}{\partial \vec{x}_{\mathrm{DV,T}}}\right| = 2 \cdot (\sim \mathcal{O}(10\ \mathrm{GeV})) \cdot (\sim 45\ \mathrm{GeV}) \cdot \frac{1}{(\sim 2\ \mathrm{mm})}(\sim 0.002\ \mathrm{mm})$$

$$\left|\frac{\partial q^2}{\partial \vec{x}_{\mathrm{DV,T}}}\right| = (\sim \mathcal{O}(10\ \mathrm{GeV})) \cdot (\sim 45\ \mathrm{GeV}) \cdot (\sim 0.002) \sim 0.9\ \mathrm{GeV}$$

Subtlety: Not all χ^2 fit converged

Cut Flow

Channel	Found final states	$\lvert x_{\mathrm{DV}} \rvert > 0.25$ mm	$p_T(\mu) > 3$ GeV
$\tau \to \mu\nu\nu$	0.96	0.87	0.83
$\tau \to \mu a(1)$	0.98	0.87	0.81
$\tau \to \mu a(0.1)$	0.97	0.90	0.90
$\tau \to \mu a(0.01)$	0.97	0.89	0.92



```
Analytic RMS in range: [-3.1572  3.1572]: 0.5576 GeV^2
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chi2 RMS in range:     [-3.1572  3.1572]: 0.5085 GeV^2
chi2 % in range        [-0.3157  0.3157]: 62.2000 %

<matplotlib.legend.Legend at 0x7f7eb4ca5460>
```
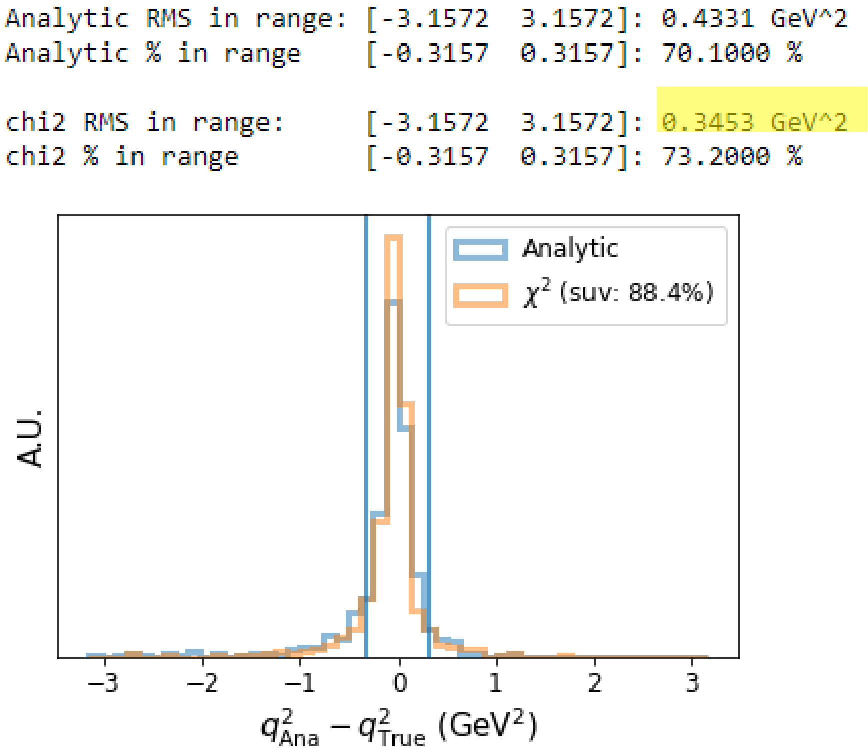
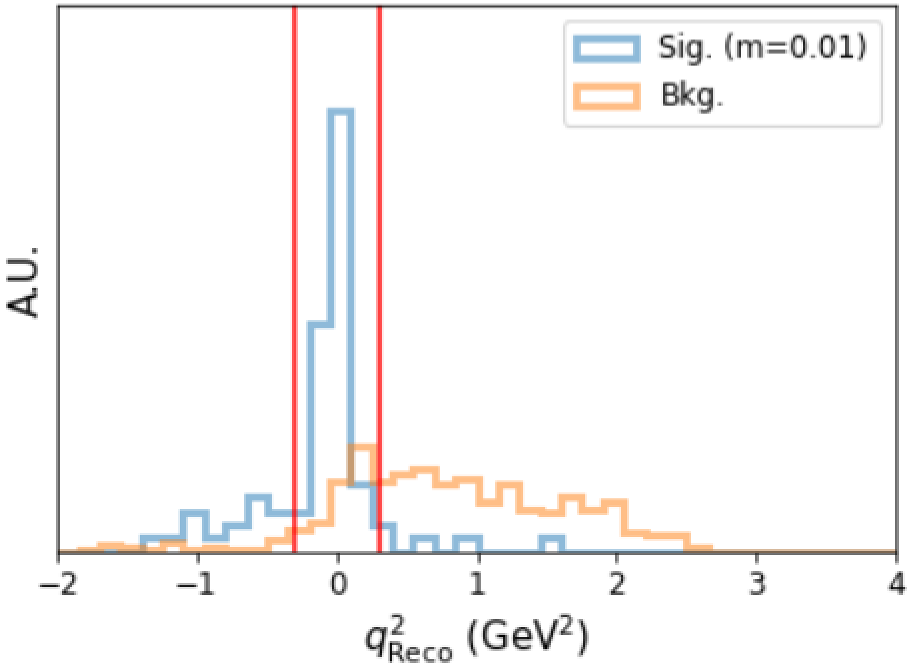
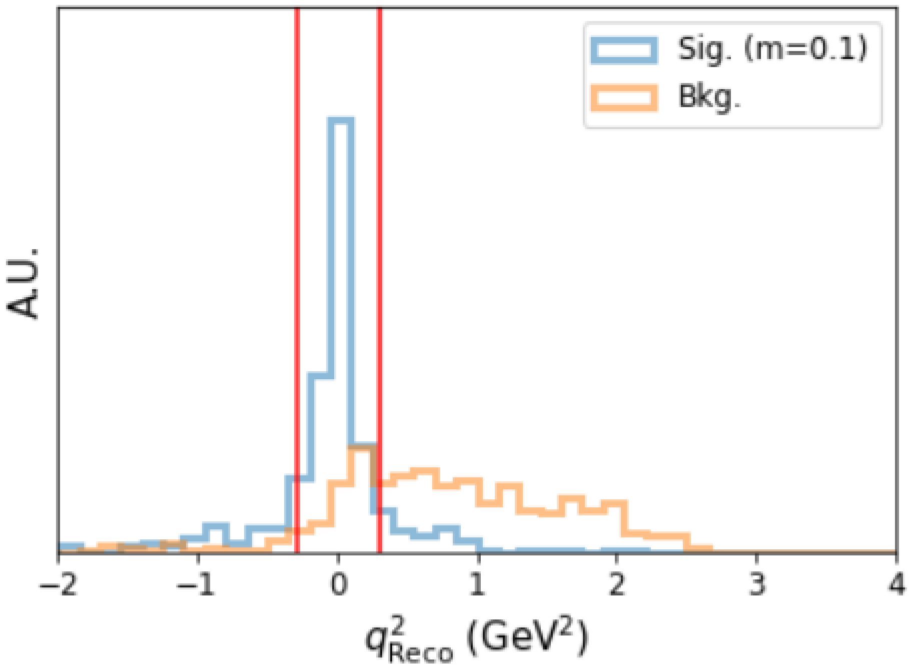
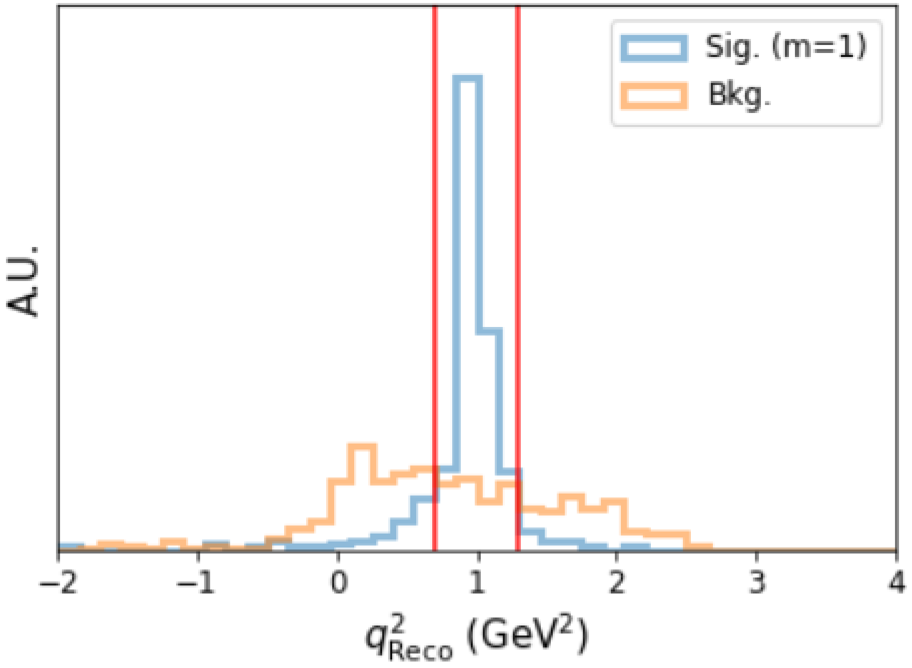

$\tau \to \mu\nu\nu$ Reconstruction
Before and After cuts



```
Analytic RMS in range: [-3.1572  3.1572]: 0.4331 GeV^2
Analytic % in range    [-0.3157  0.3157]: 70.1000 %

chi2 RMS in range:     [-3.1572  3.1572]: 0.3453 GeV^2
chi2 % in range        [-0.3157  0.3157]: 73.2000 %
```

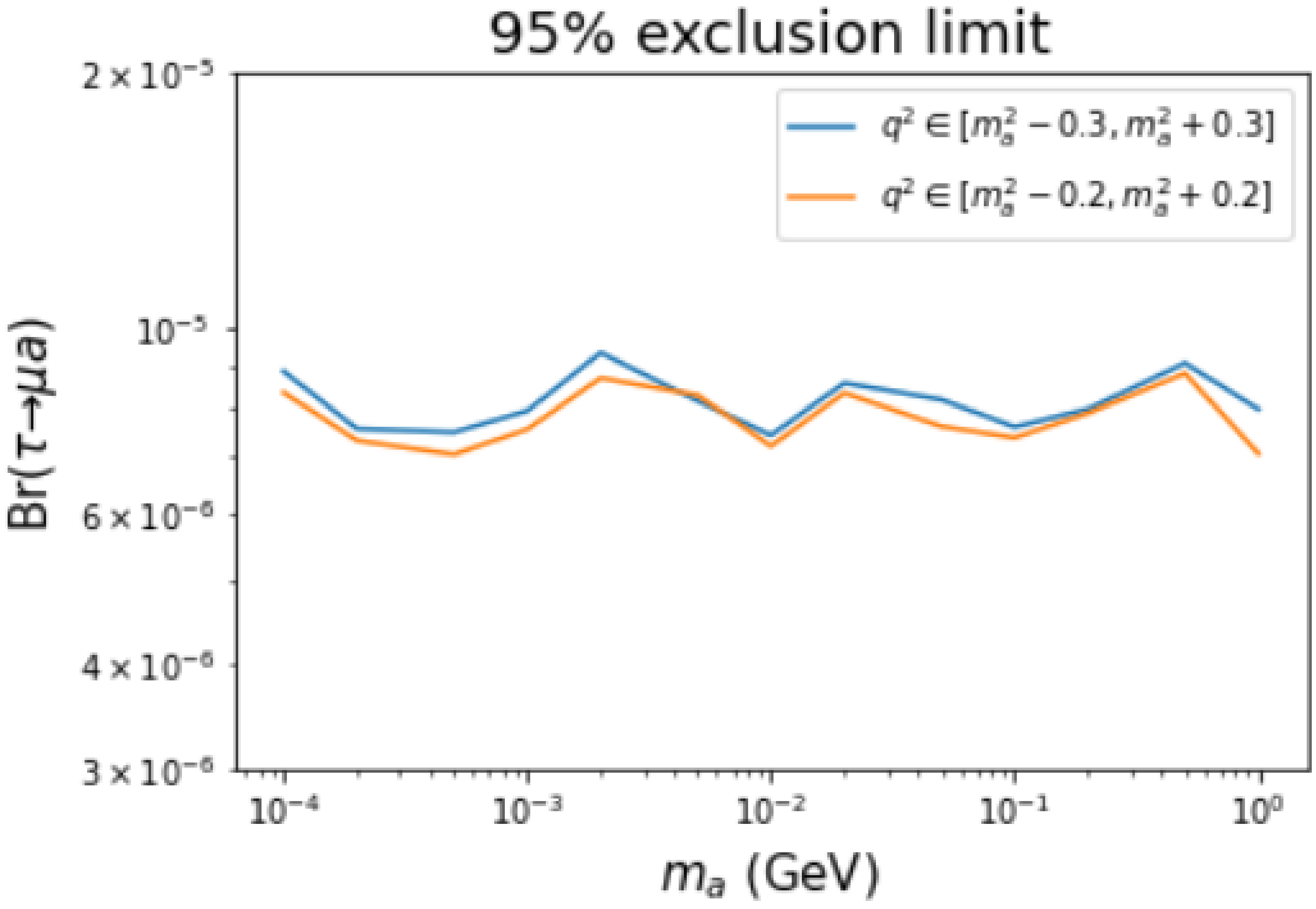




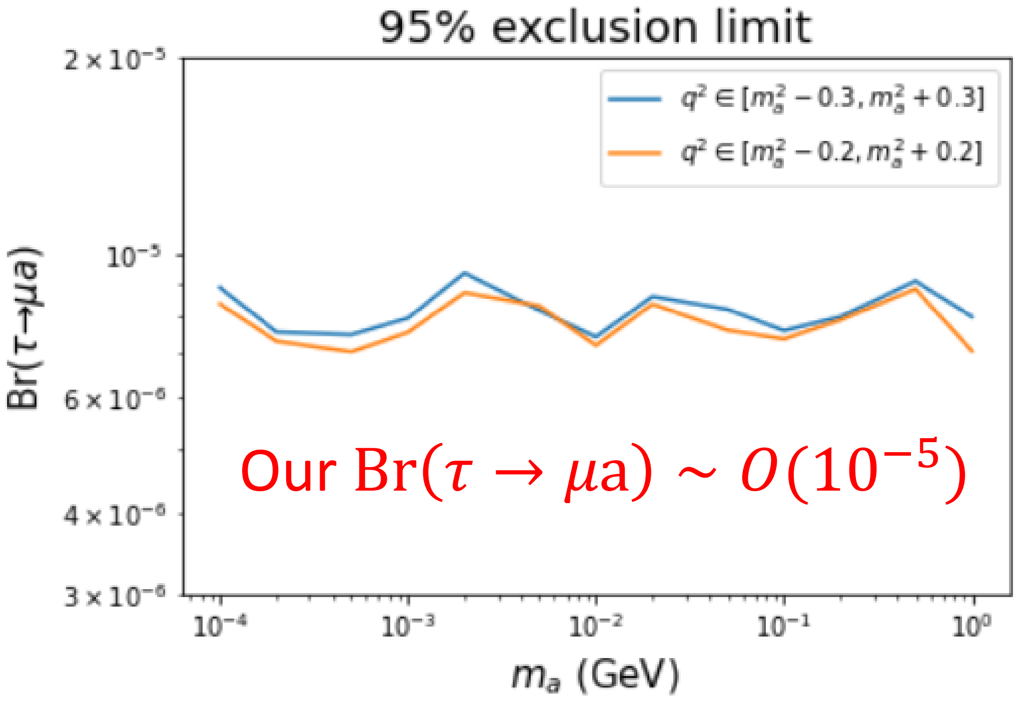


(subtlety:
If χ^2 solution is not converged,
Then use analytic solution)

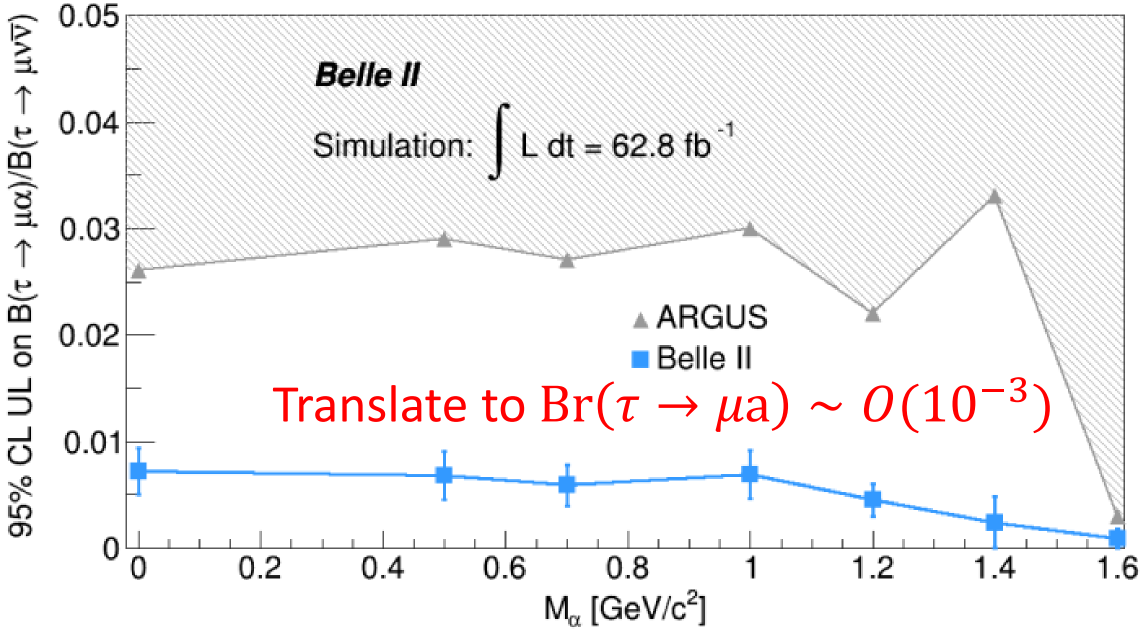
Preliminary Limit



Comparison

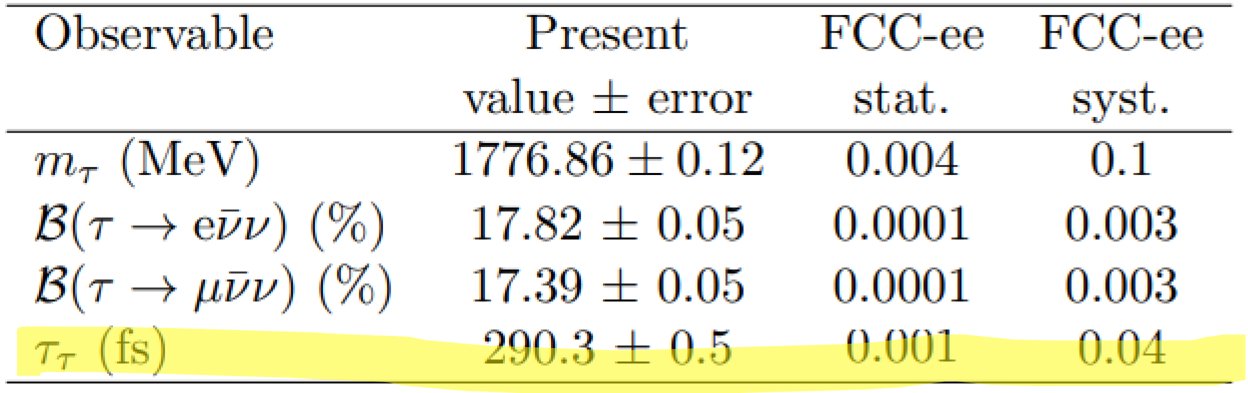


Our $\mathrm{Br}(\tau \to \mu a) \sim O(10^{-5})$



Translate to $\mathrm{Br}(\tau \to \mu a) \sim O(10^{-3})$

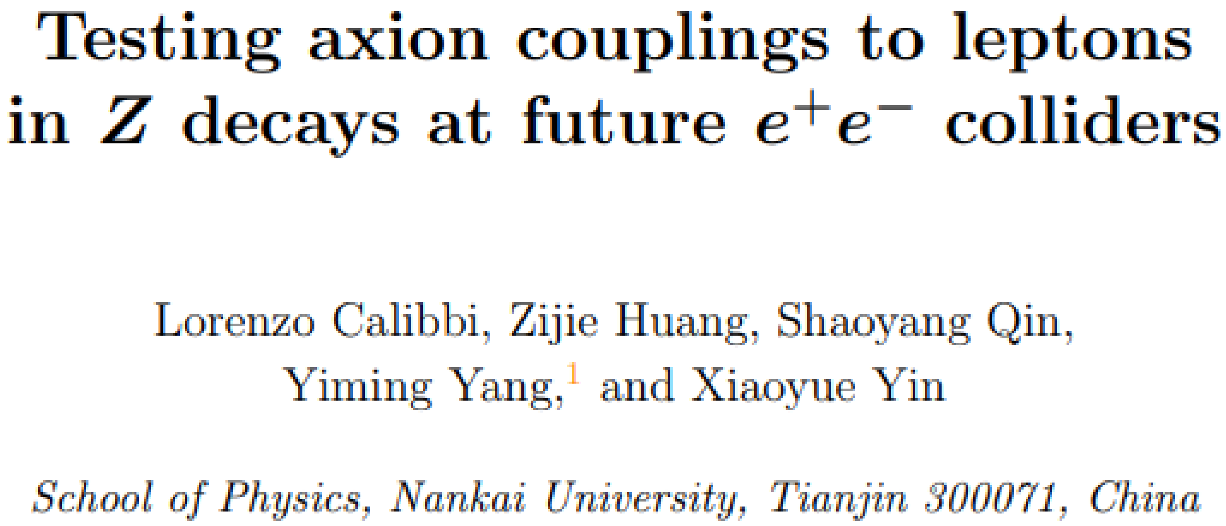
(b) Muon channel.



Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

Translate to $\mathrm{Br}(\tau \to \mu a) \sim O(10^{-4})$

Preliminary Result
(based on Lorenzo’s paper: 2212.02818)

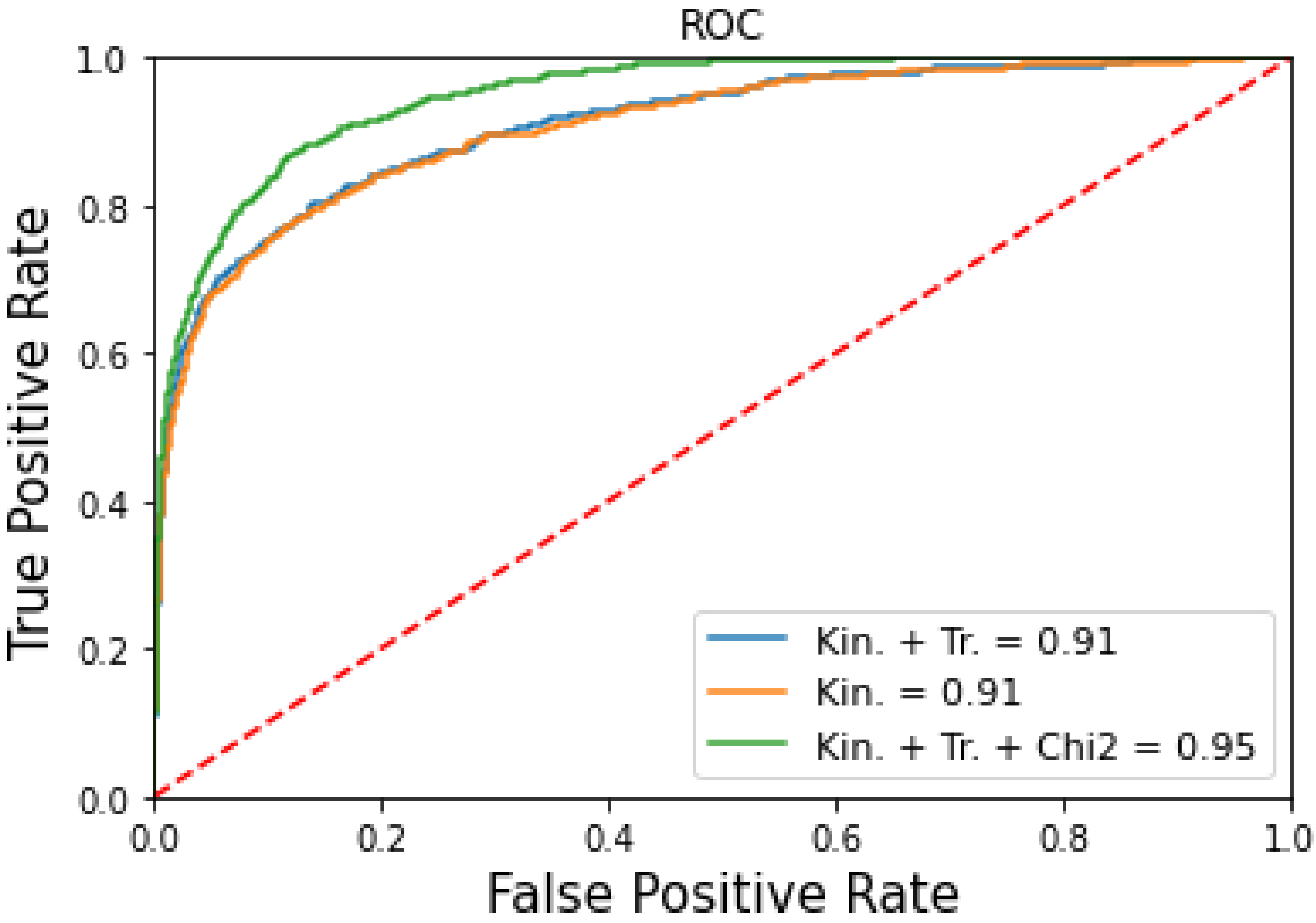


Testing axion couplings to leptons in Z decays at future e^+e^- colliders

Lorenzo Calibbi, Zijie Huang, Shaoyang Qin,
Yiming Yang,[1] and Xiaoyue Yin

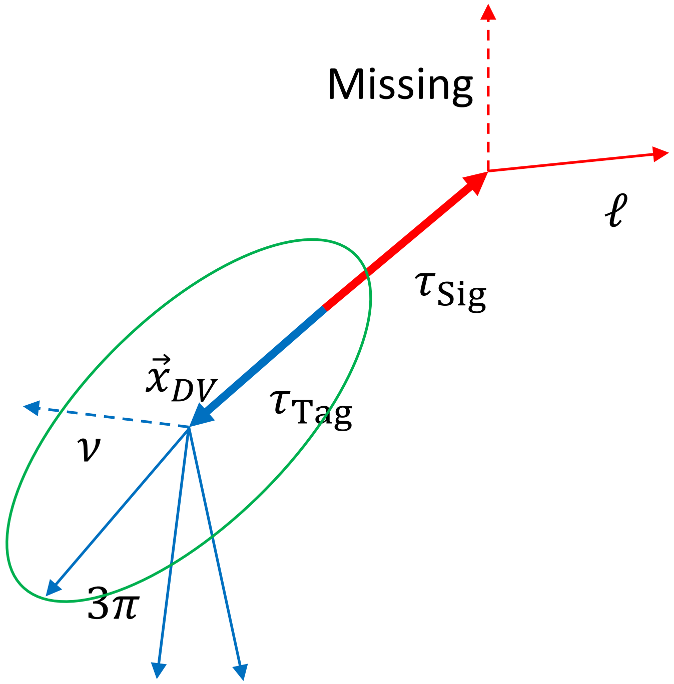
School of Physics, Nankai University, Tianjin 300071, China

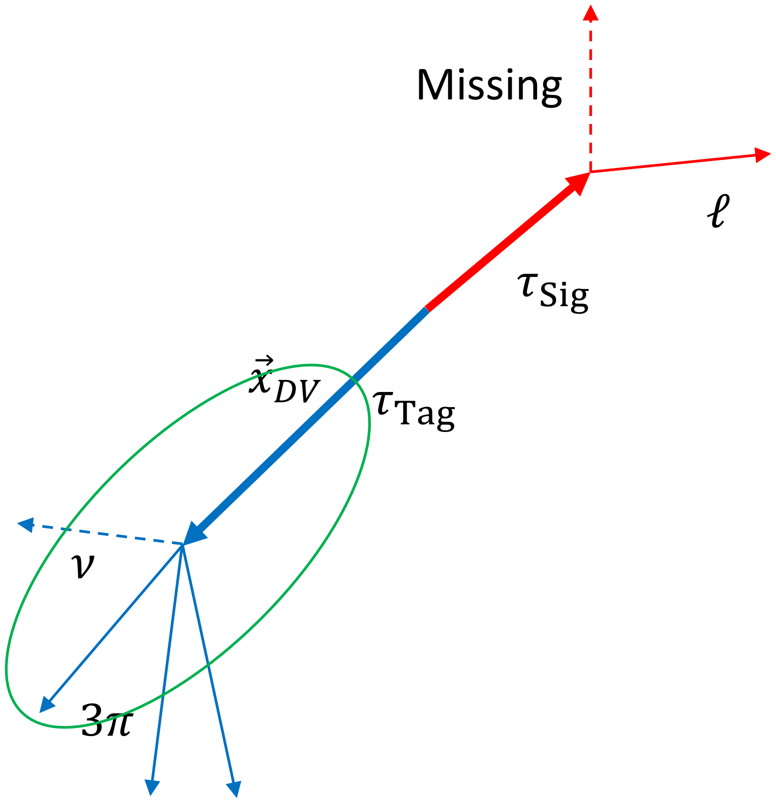
- $Z \to \tau(3\pi\nu)\tau(\ell\nu\nu)a$
- Use BDT, and add Track / Chi2 info.

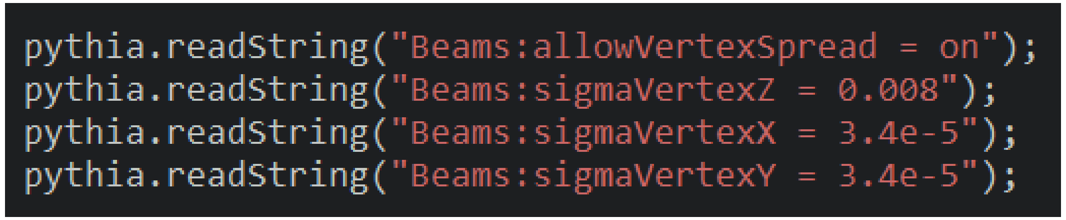

ROC
1.0
0.8
0.6
0.4
0.2
0.0
True Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
False Positive Rate
Kin. + Tr. = 0.91
Kin. = 0.91
Kin. + Tr. + Chi2 = 0.95

Backups

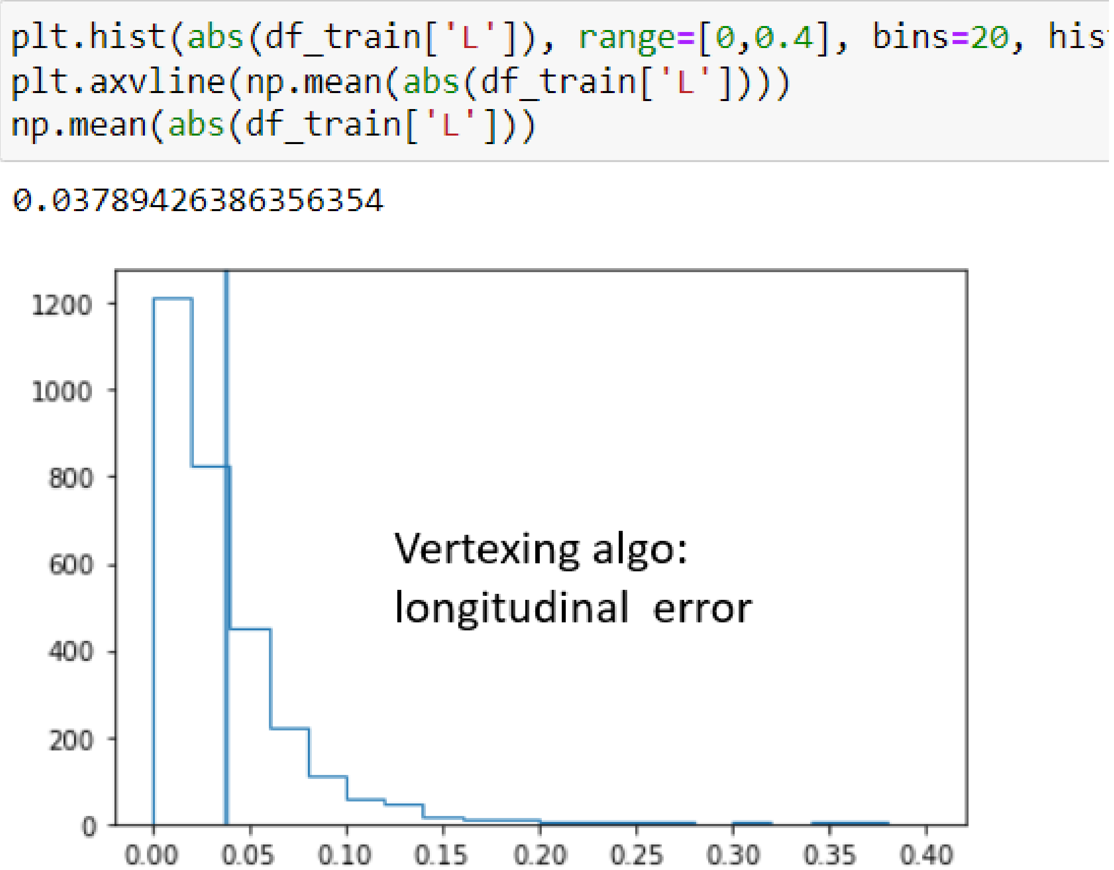
Relative uncertainty matters





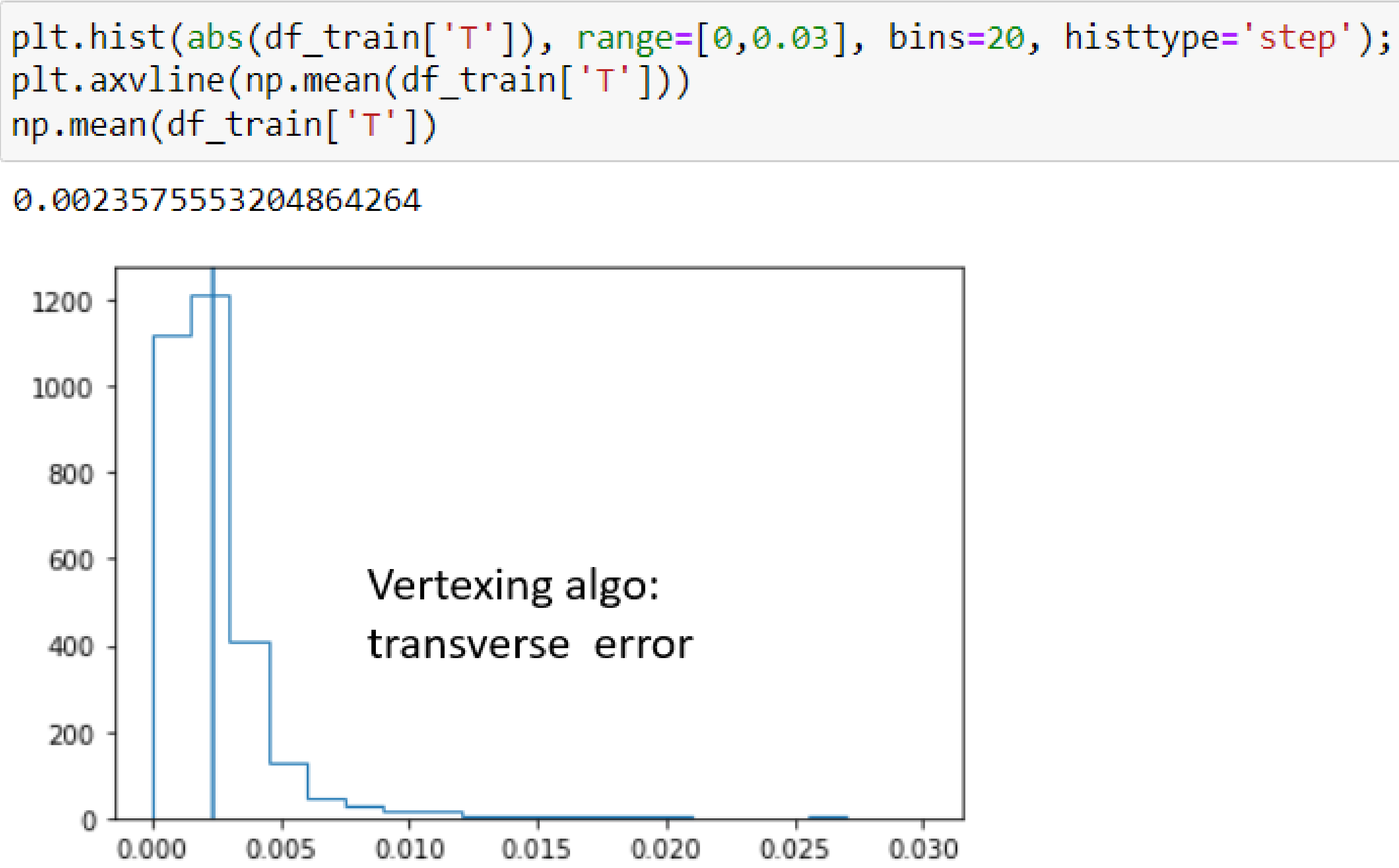


```
pythia.readString("Beams:allowVertexSpread = on");
pythia.readString("Beams:sigmaVertexZ = 0.008");
pythia.readString("Beams:sigmaVertexX = 3.4e-5");
pythia.readString("Beams:sigmaVertexY = 3.4e-5");
```



```
plt.hist(abs(df_train['L']), range=[0,0.4], bins=20, his
plt.axvline(np.mean(abs(df_train['L'])))
np.mean(abs(df_train['L']))
```

```
0.037894263863563 54
```

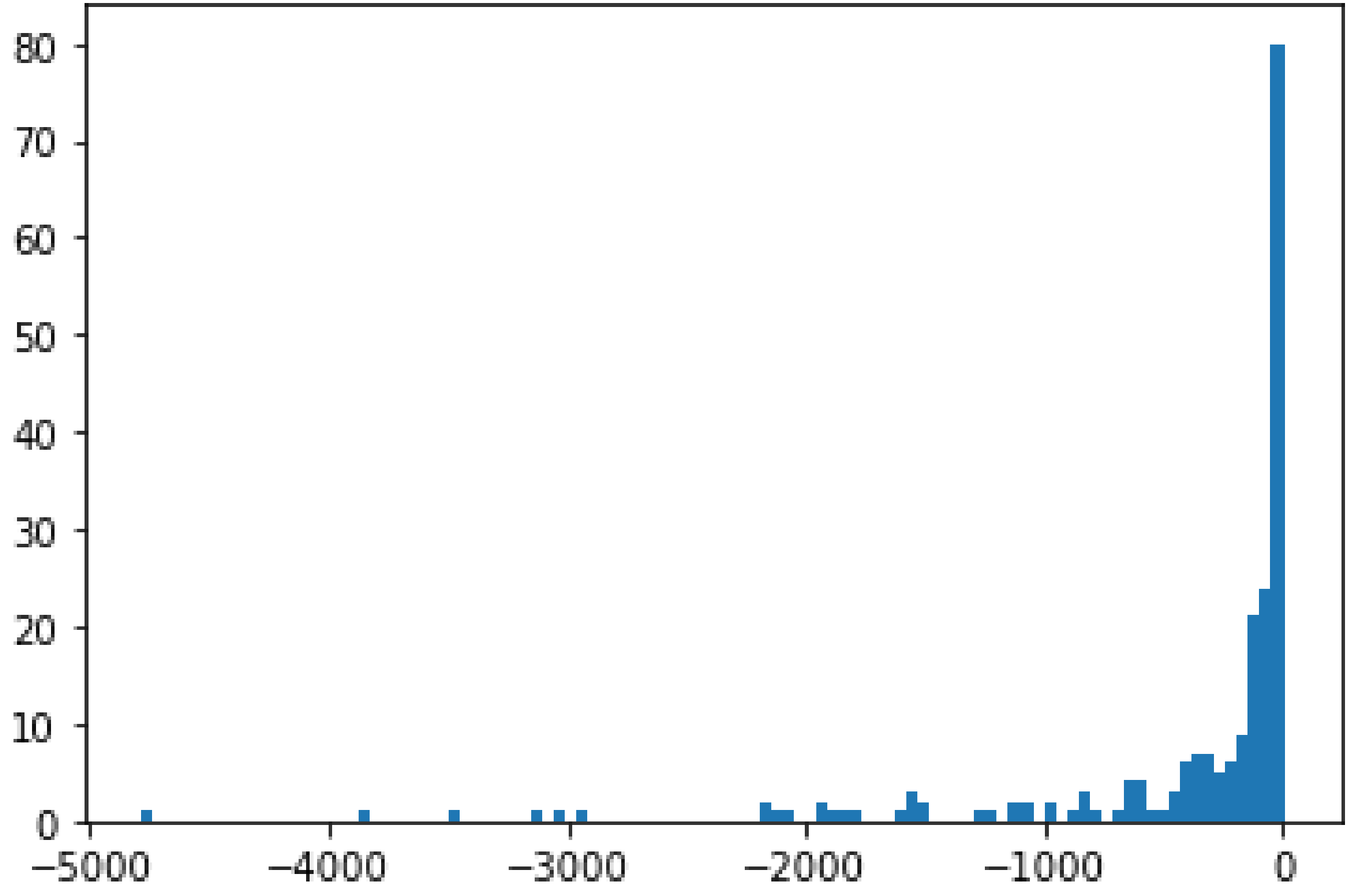


```
plt.hist(abs(df_train['T']), range=[0,0.03], bins=20, histtype='step');
plt.axvline(np.mean(df_train['T']))
np.mean(df_train['T'])
```

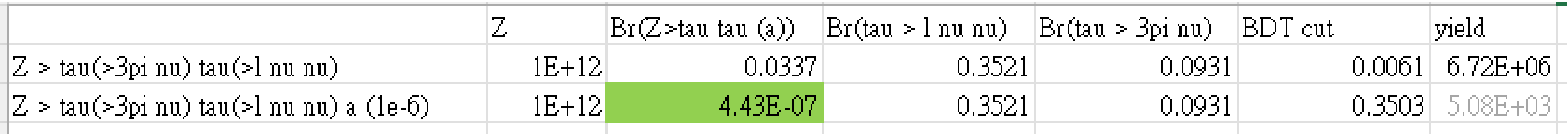
```
0.0023575553204864264
```

Chi2 info.

- Only ~20% of the $Z \rightarrow \tau\tau a$ events give “satisfactory” q^2 from χ^2 fit.



Kin. + Track info to train BDT



	Z	Br(Z>tau tau (a))	Br(tau > l nu nu)	Br(tau > 3pi nu)	BDT cut	yield
Z > tau(>3pi nu) tau(>l nu nu)	1E+12	0.0337	0.3521	0.0931	0.0061	6.72E+06
Z > tau(>3pi nu) tau(>l nu nu) a (1e-6)	1E+12	4.43E-07	0.3521	0.0931	0.3503	5.08E+03

Later

- $Z \rightarrow \tau(3\pi\nu)\tau(\ell\nu\nu)a$:
  - Fit a straight line with χ^2 (connecting DV, PV, track)
- $Z \rightarrow \tau(3\pi\nu)\tau(3\pi\nu)a$:
  - Fit a straight line with χ^2 (connecting 2 DV, PV)

$Z \to \tau(3\pi\nu)\tau(\ell\nu\nu)a$ BDT features

```python
features = ['pPion1', 'etaPion1', 'phiPion1', 'pTPion1', 'EPion1',
            'pPion2', 'etaPion2', 'phiPion2', 'pTPion2', 'EPion2',
            'pPion3', 'etaPion3', 'phiPion3', 'pTPion3', 'EPion3',
            'm3Pions',
            'ELep', 'pxLep', 'pyLep', 'pzLep', 'pTLep', 'etaLep',
            'XTag', 'YTag', 'ZTag', 'vtxChi2',
            'D0Lep', 'PhiLep', 'CLep', 'DZLep', 'CtgThetaLep',
            'q2Chi2']
```