The 2020 International Workshop on the High Energy CEPC
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CP Violation in Higgs-τ-τ Coupling

Collaborators
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Brief introduction of the 2HDM

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CPV and $H\tau\tau$ coupling

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How to measure the coupling

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Expected Results from CEPC

The 2 Higgs Double Model

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The 2HDM changes the scalar content [Front.Phys. 80 (2000) 1-404]:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \quad \text{and} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

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where α is the angle diagonalizing the neutral scalar mass matrix,

$\tan 2\alpha = \frac{4v_1v_2(\lambda_5-4\lambda_3)}{(\lambda_5-4\lambda_3)(v_2^2-v_1^2)+4v_1^2\lambda_1-4v_2^2\lambda_2}$

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Also, $m_h < m_H$. So that h is the SM-like scalar

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The interaction with h can be calculated [Phys. Rept. **516**, 1-102 (2012)],

$$\mathcal{L}_{Y_h} = -\frac{m_\tau}{v}\left(\text{Re}[y_\tau]\overline{\tau}\tau + i\text{Im}[y_\tau]\overline{\tau}\gamma_5\tau\right)h$$

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$$y_\tau = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\sqrt{2}m_\tau}(v_1Y_2 - v_2Y_1)$$

$\tan\beta = v_2/v_1$ (Notice that relation above is written in the mass basis of leptons)

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Notice

$\mathrm{Im}[y_\tau] = 0$ $(\sin\Delta = 0)$ and $|y_\tau| = 1$ $\rightarrow$SM

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Moreover, the presence of the imaginary term allows the presence physical CP phases

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In this model $\mathrm{Im}[J_A]$ controls the CPV source term responsible for BAU

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3) C and CP violation
Can be obtained by CPV in Leptonic Yukawa sector: $\mathrm{Im}[J_A] \neq 0$.
Since $\mathrm{Im}[J_A] \propto \mathrm{Im}[y_\tau]$ BAU$\rightarrow$ $|\mathrm{Im}[y_\tau]| > 0.233$ [Phys.Rev.D 96 (2017) 11, 115034].

Angular distribution of τ's dauther particles

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Since Parity: $\mathbf{p} \to -\mathbf{p}$ but $\mathbf{s} \to \mathbf{s}$: $\mathbf{p} \cdot \mathbf{s}$ are specially sensitive to Δ value.

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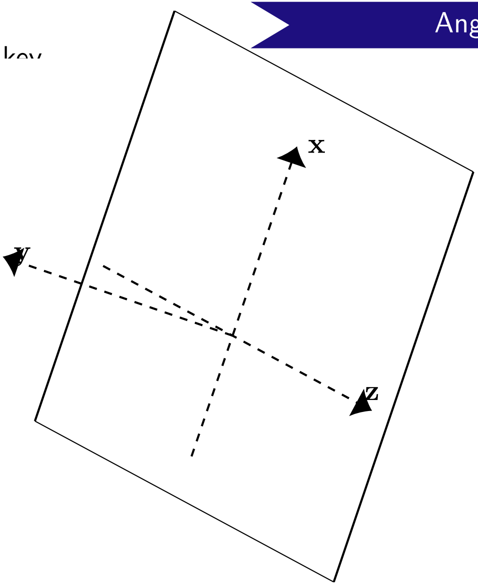

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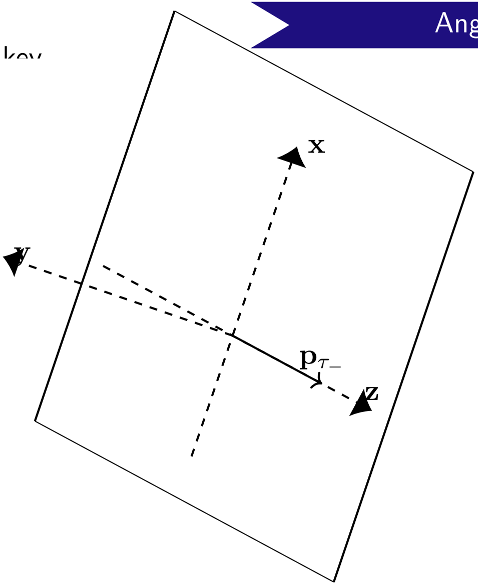

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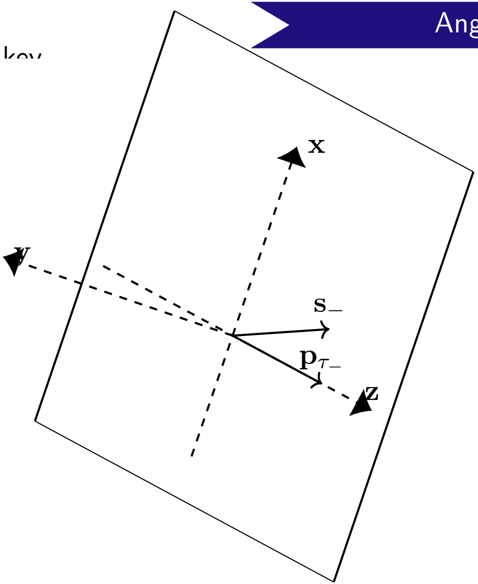

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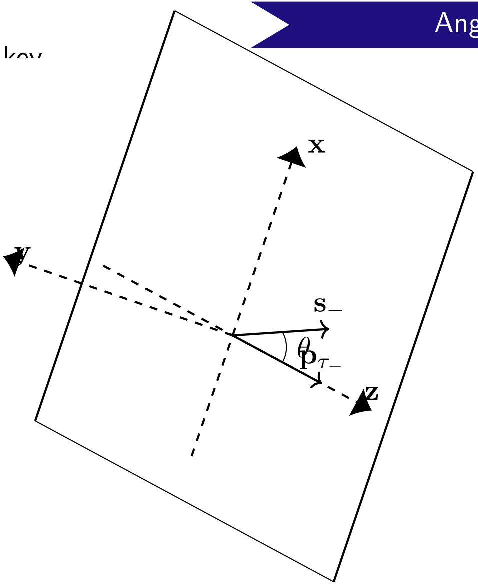

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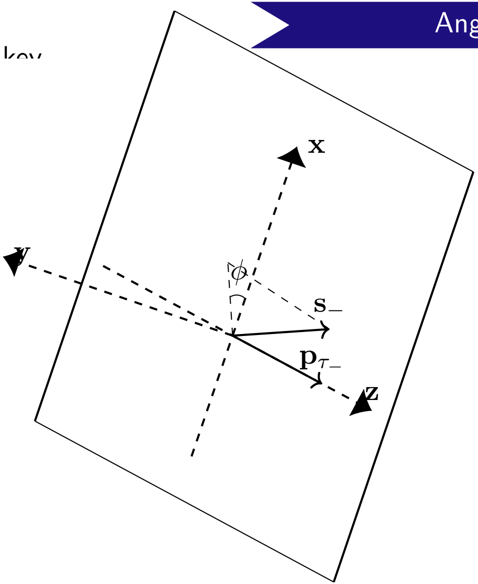

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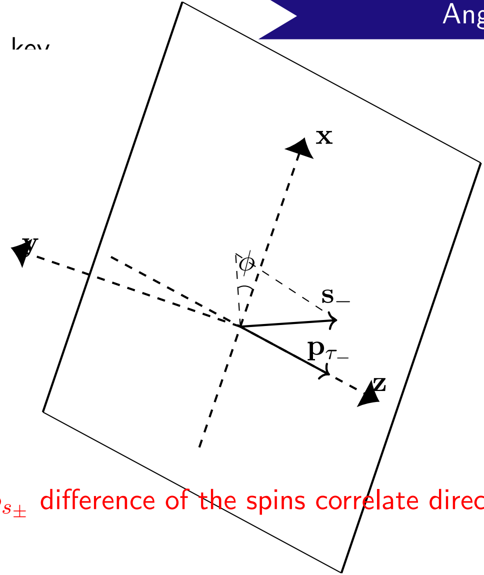

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But this does not work for *helicity eigenstates*, since $\phi_{s_\pm} = 0$...

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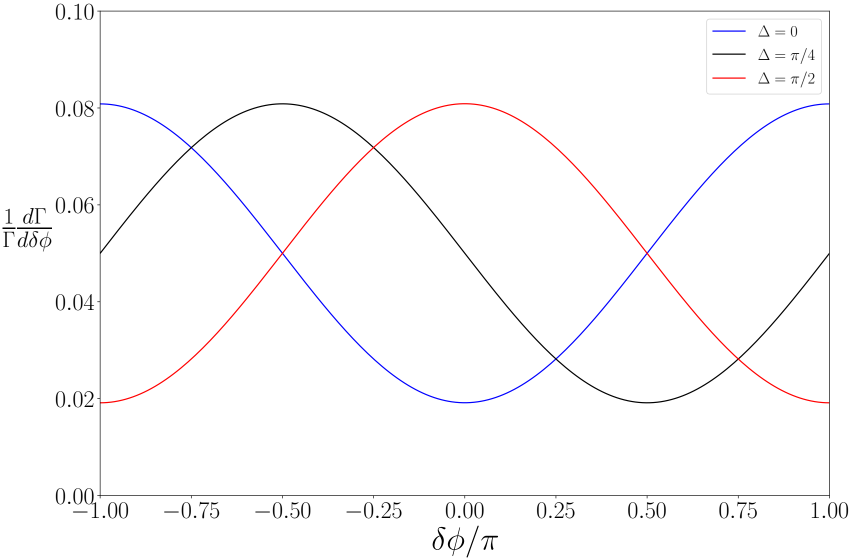

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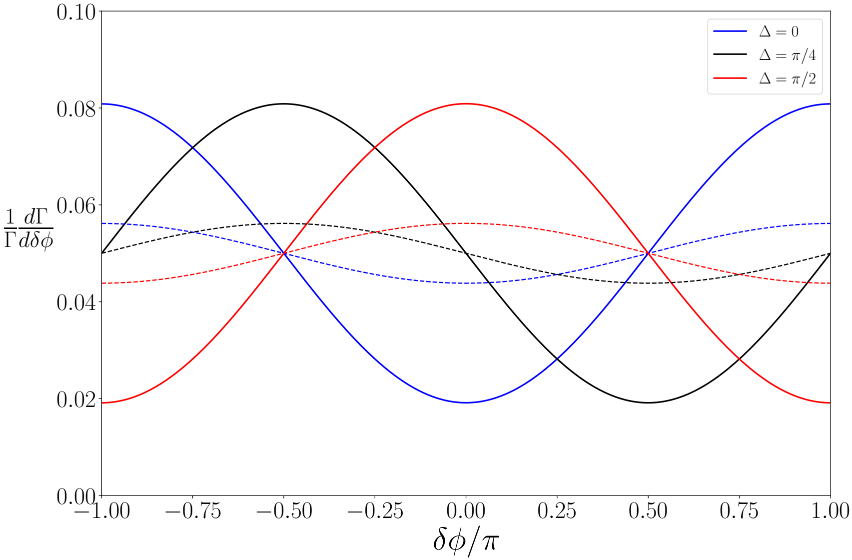

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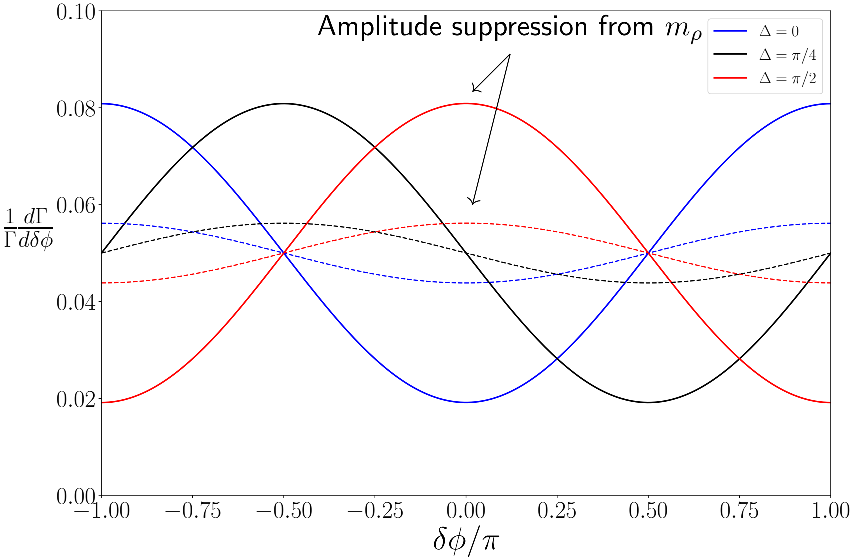

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There … decay.

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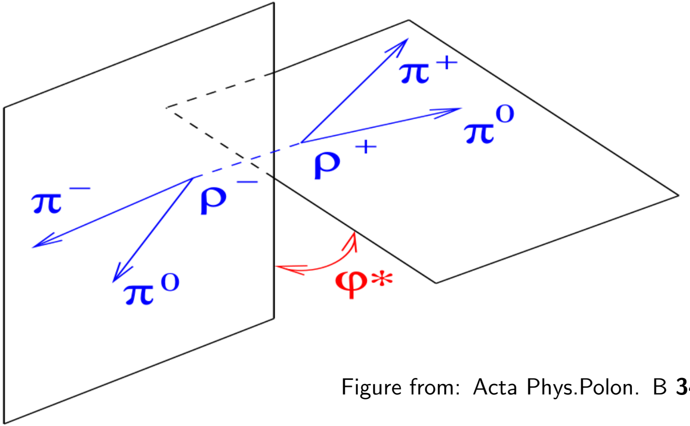

Figure from: Acta Phys.Polon. B **34**, 4549-4560 (2003)

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The τ decay lagrangian is,

$$\mathcal{L} \propto J^X_\mu \overline{\tau}\gamma^\mu P_L \nu_\tau \longrightarrow M_{\tau^-\to\nu_\tau X^-} \propto J^X_\mu \overline{u}_\tau \gamma^\mu P_L u_\nu$$

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It can be shown that [Nuclear Physics B236 (1984) 16-34]

$$|\mathcal{M}^{\text{total}}|^2 \propto \text{Tr}\left[\left(\not{p}_- + m_\tau\right)\left(1+\gamma_5\not{r}_-\right)\mathcal{O}\left(\not{p}_+ - m_\tau\right)\left(1-\gamma_5\not{r}_+\right)\overline{\mathcal{O}}\right]$$

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Compare with, $r^\alpha \propto (m_\tau^2 g^{\alpha\beta} - p_\tau^\alpha p_\tau^\beta)(4J^\beta p_\nu \cdot J - 2p_\nu^\beta J^2)$ (If $\text{Im}[J] = 0$)

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In its c

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For τ –

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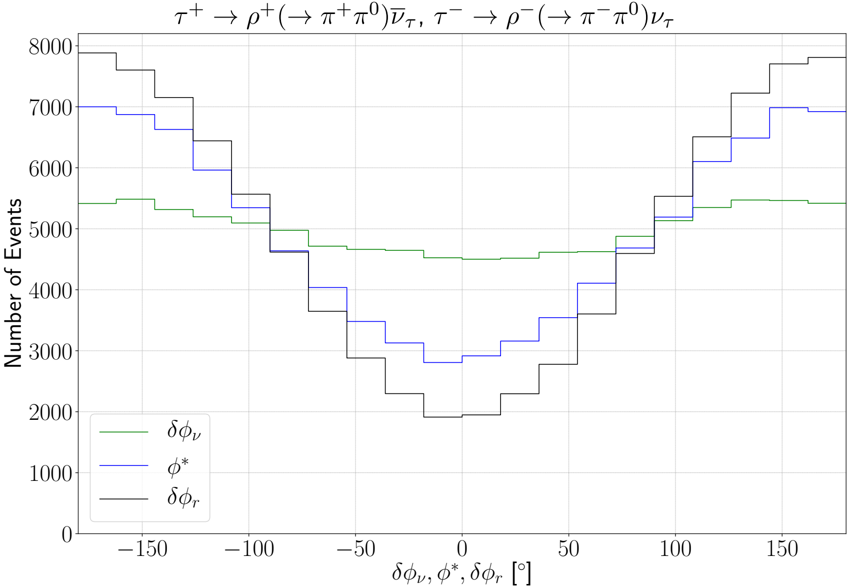

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Notice: This requires the reconstruction of the $\tau^\pm$ CM

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We can almost solve all the variables: There is a two-fold ambiguity

We need to use the impact parameter!

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This gives an extra information that can be incorporated to reconstruct $p_{\tau^\pm}$

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10.8%: $\tau \to \pi\nu$		25%: $\tau \to \rho\nu$
(π^+, π^-) ≈ 175 events	(π, ρ) ≈ 810 events	(ρ^+, ρ^-) ≈ 940 events

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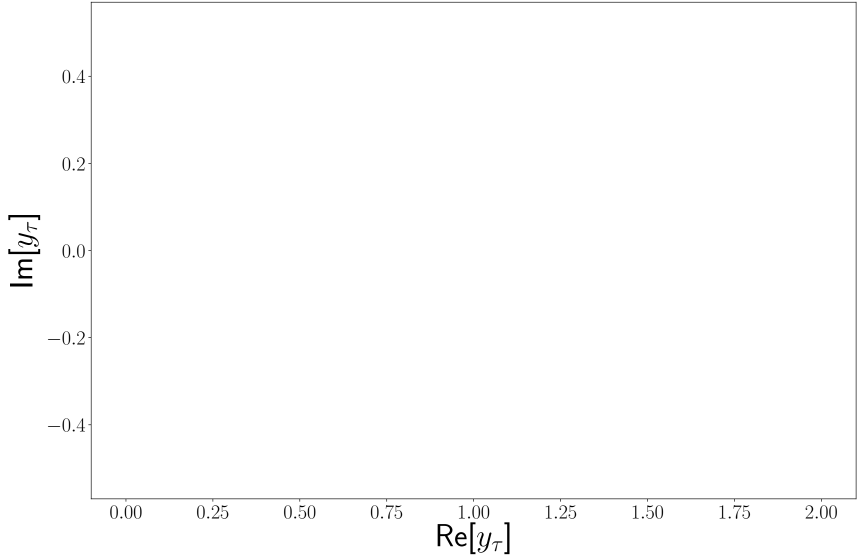
Using the $h \to \tau^+\tau^-$ Channel

CEPC is very precise!



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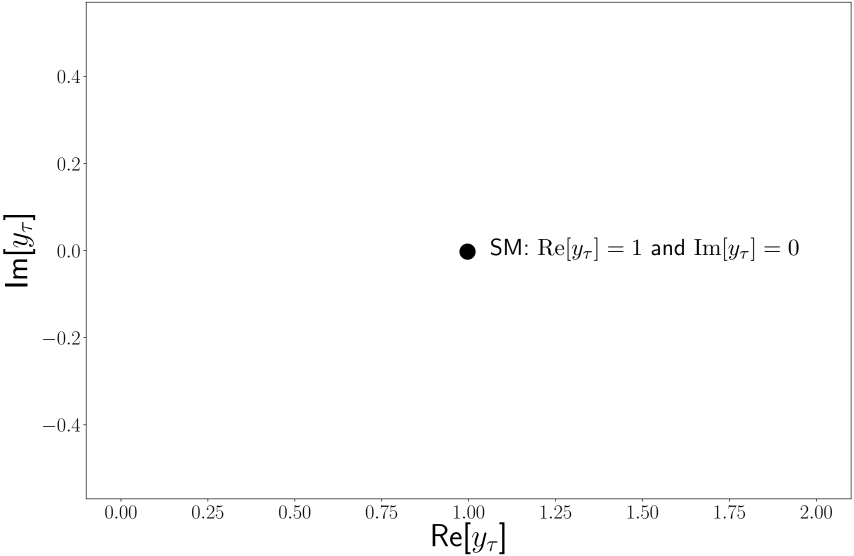
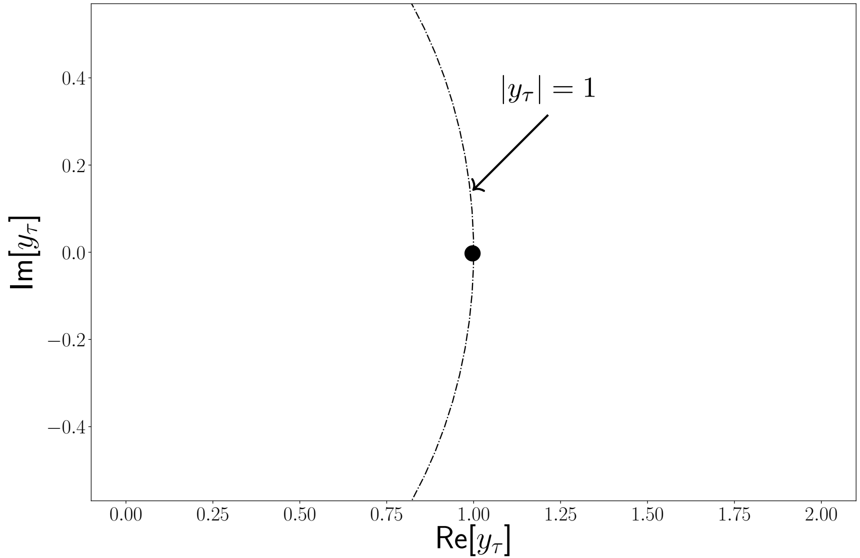
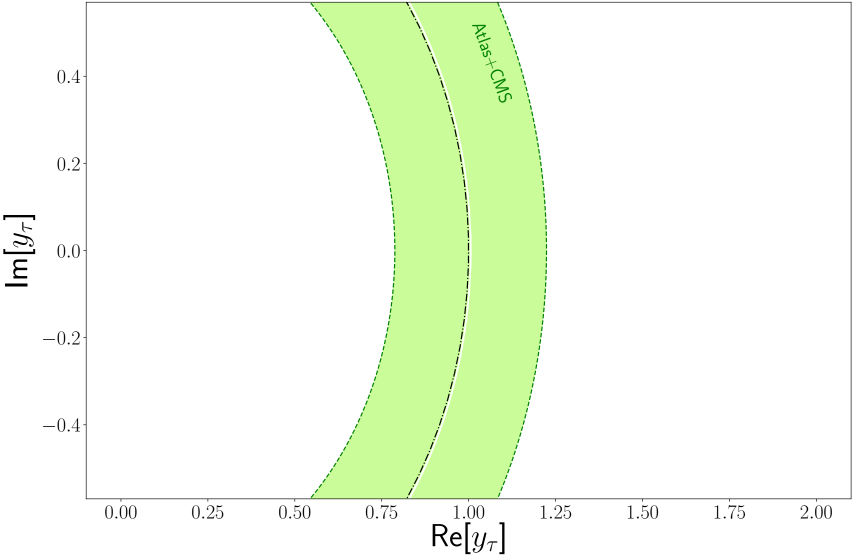



$|y_\tau| = 1$
0.4
0.2
0.0
−0.2
−0.4
$\mathrm{Im}[y_\tau]$
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
$\mathrm{Re}[y_\tau]$



Atlas+CMS
0.4
0.2
0.0
−0.2
−0.4
Im[y_τ]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Re[y_τ]

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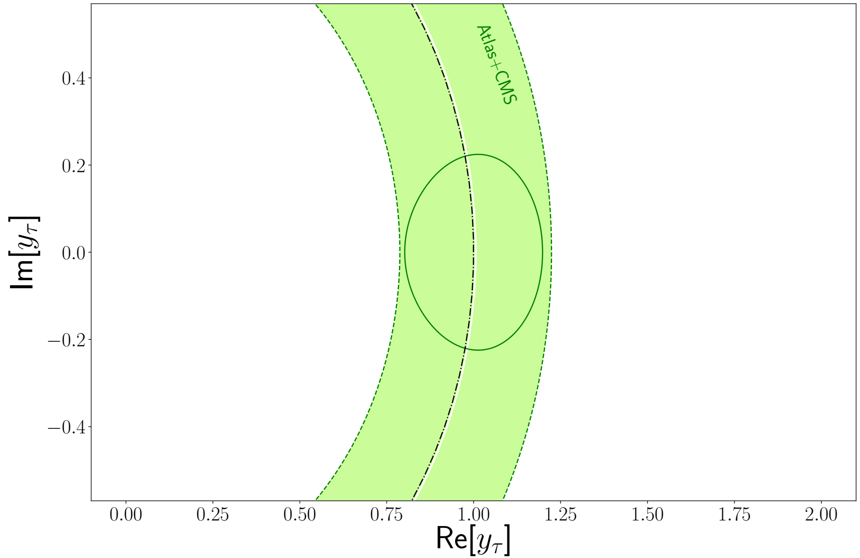

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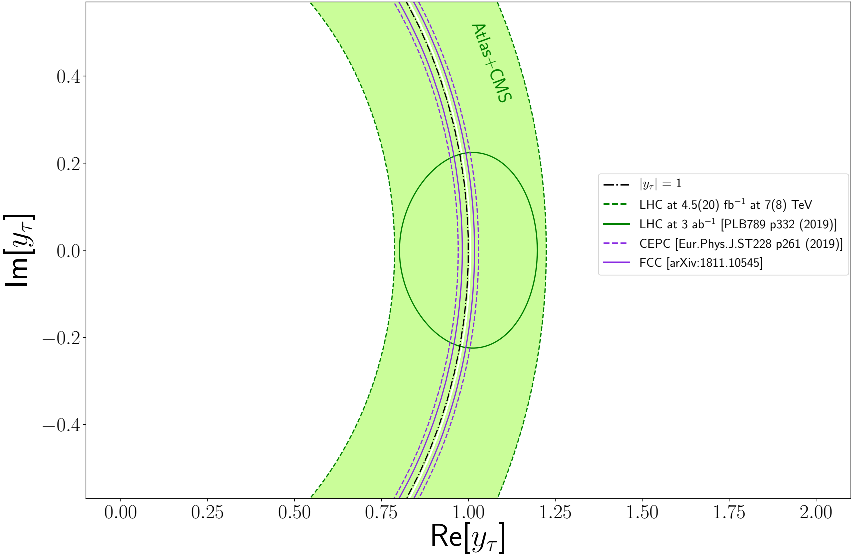

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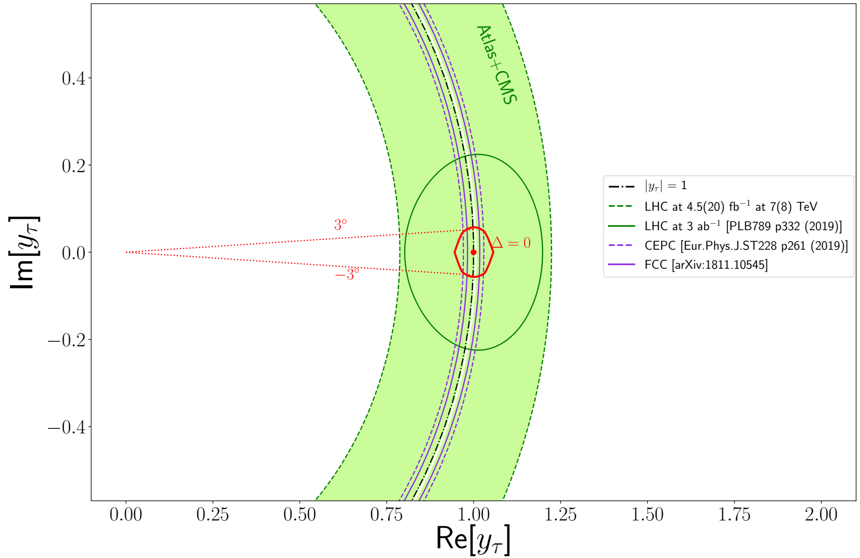

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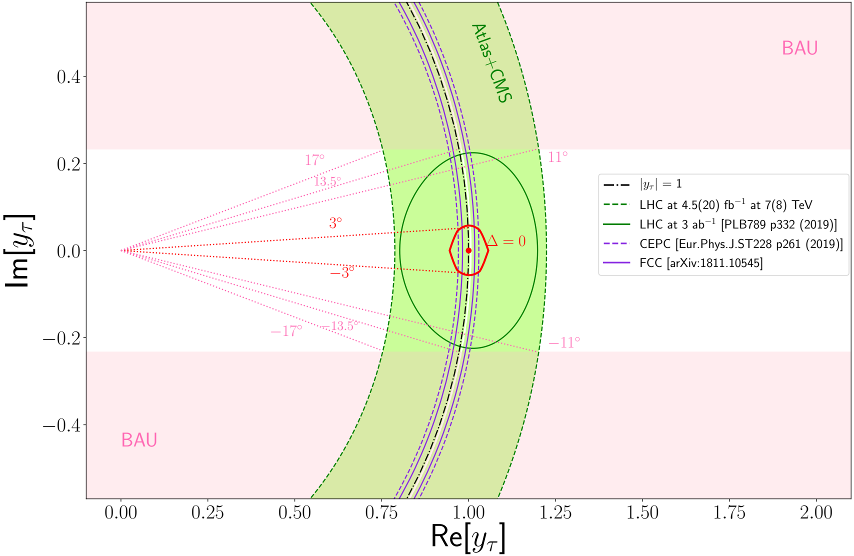

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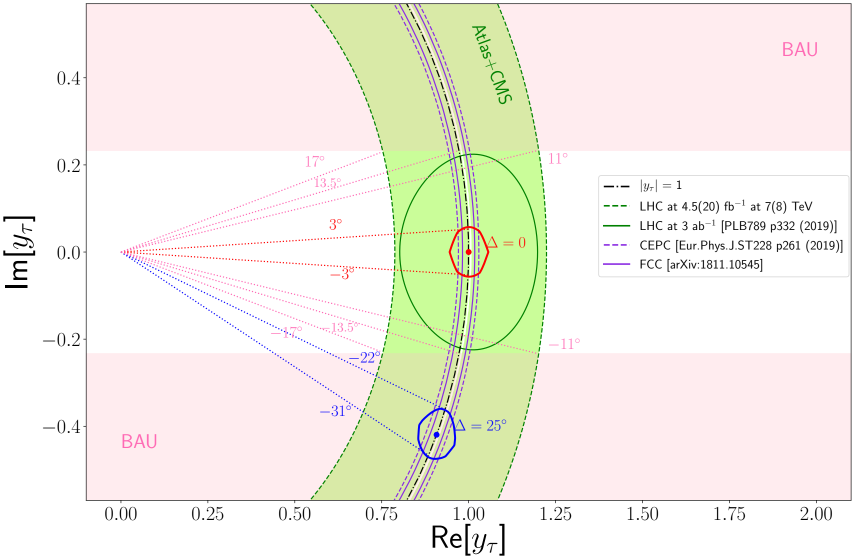
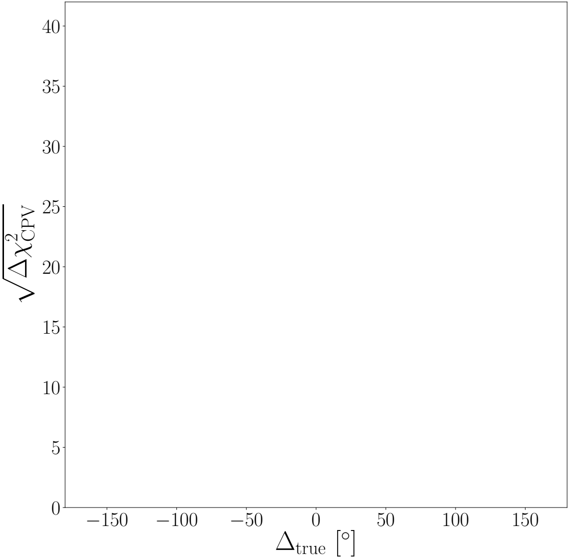
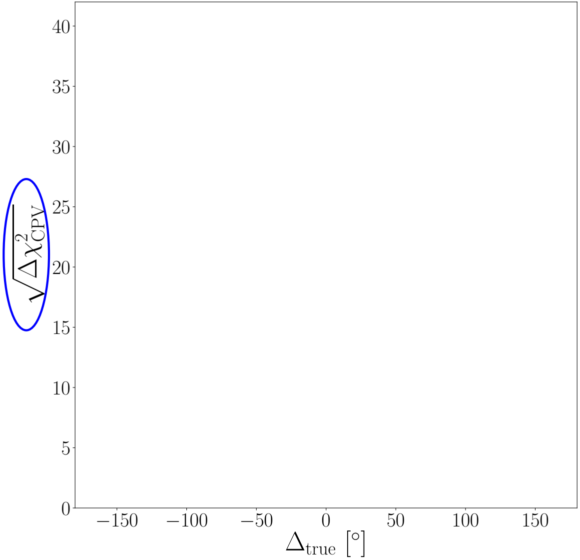


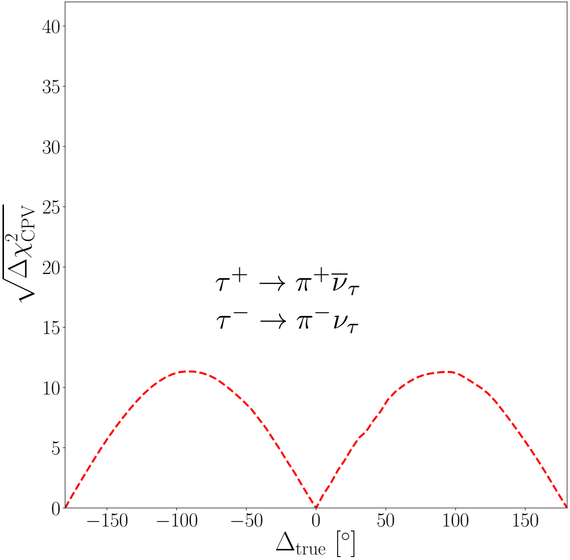


$\sqrt{\Delta\chi^2_{\mathrm{CPV}}}$
40
35
30
25
20
15
10
5
0
−150
−100
−50
0
50
100
150
Δ_{true} [°]

CEPC is very precise!



$$\Delta\chi^2_{\text{CPV}} = \min[\Delta\chi^2(\Delta = 0), \Delta\chi^2(\Delta = 180°)]$$



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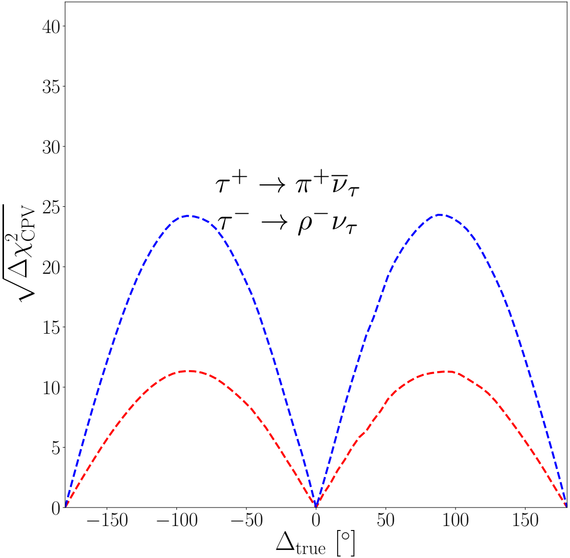

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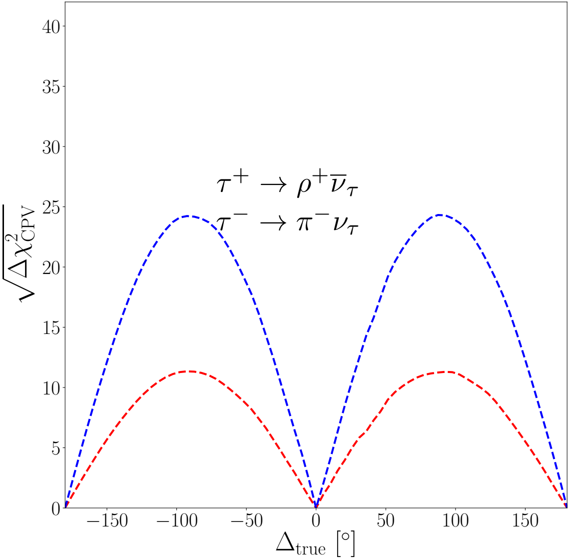

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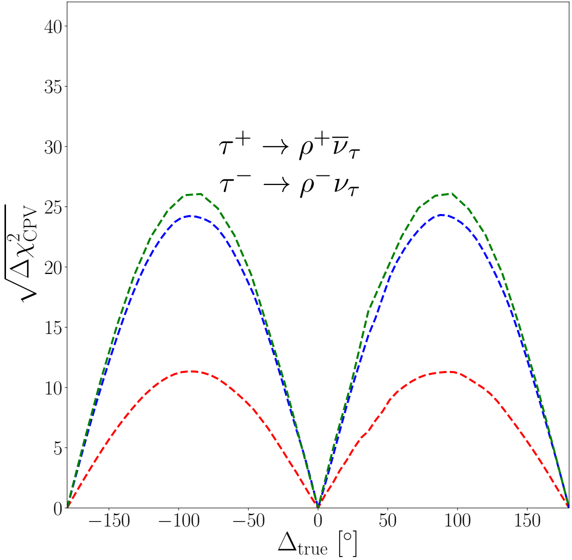

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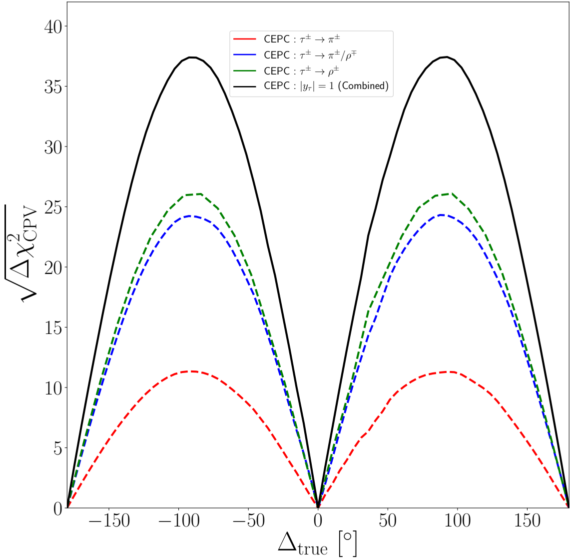

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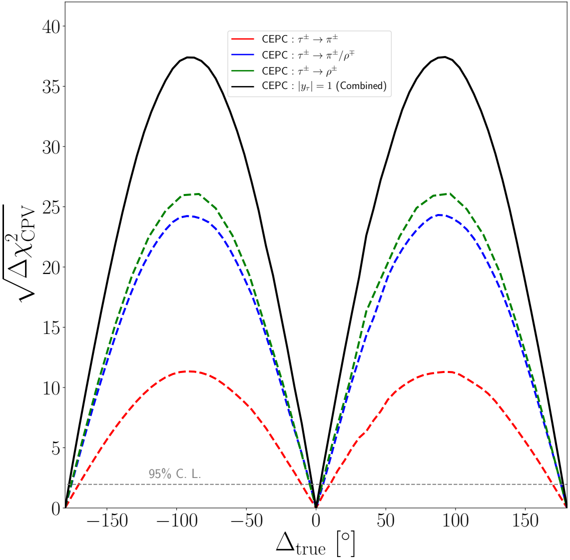

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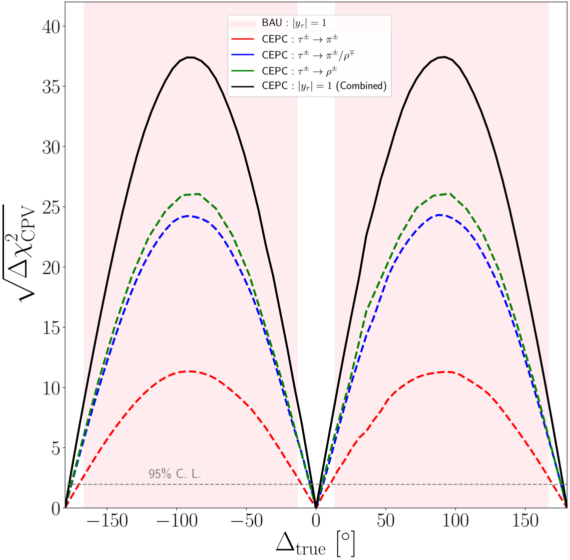

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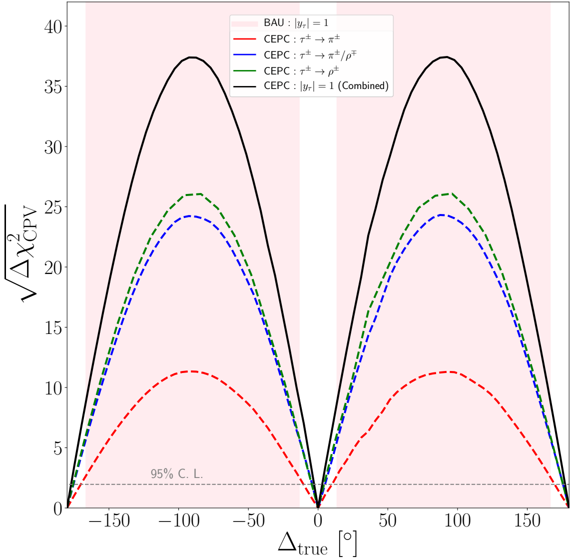

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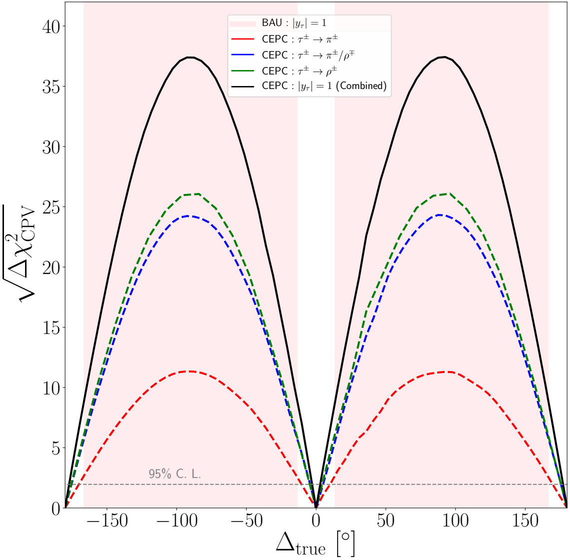
This plot assumes $|y_\tau^{\rm true}| = 1$



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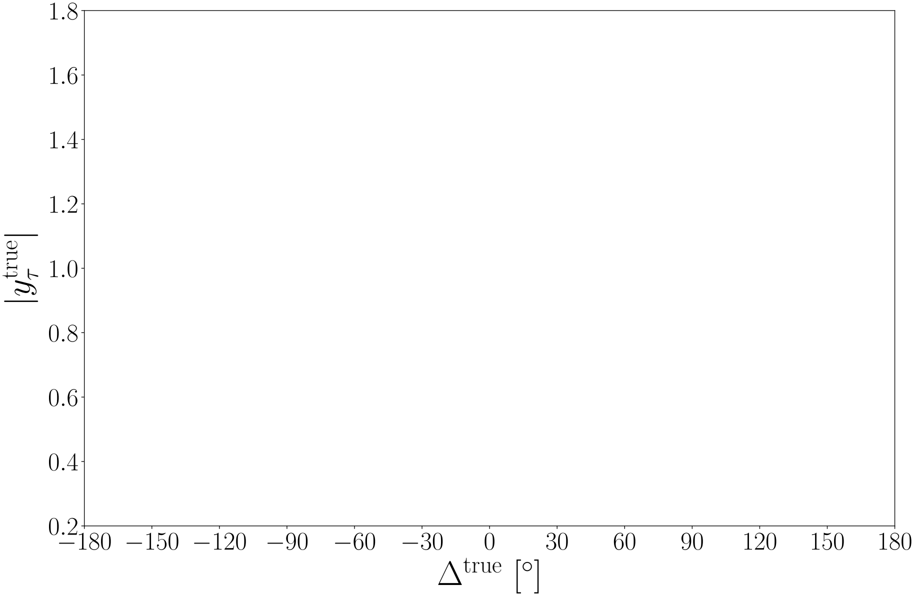
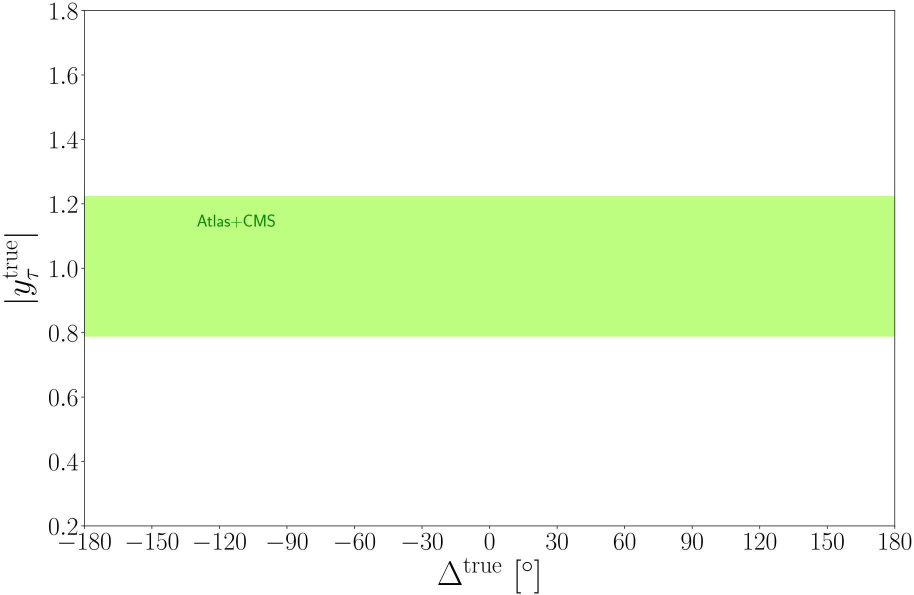
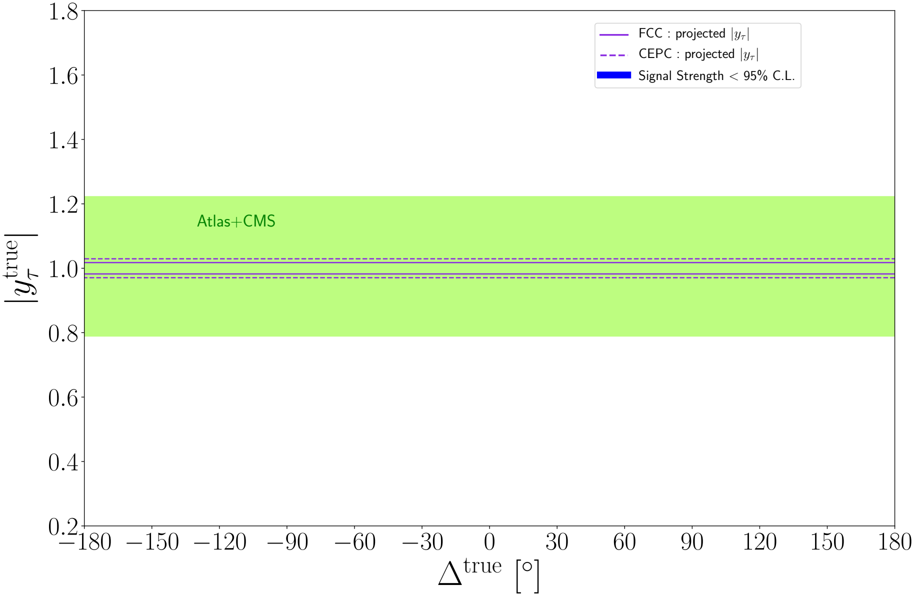
How about $|y_\tau^{\rm true}| \neq 1$?


1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$|y_\tau^{\rm true}|$
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
$\Delta^{\rm true}$ [°]


Atlas+CMS
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$|y_\tau^{\mathrm{true}}|$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
Δ^{true} [°]



1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$|y_\tau^{\mathrm{true}}|$
FCC : projected $|y_\tau|$
CEPC : projected $|y_\tau|$
Signal Strength < 95% C.L.
Atlas+CMS
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
Δ^{true} [°]

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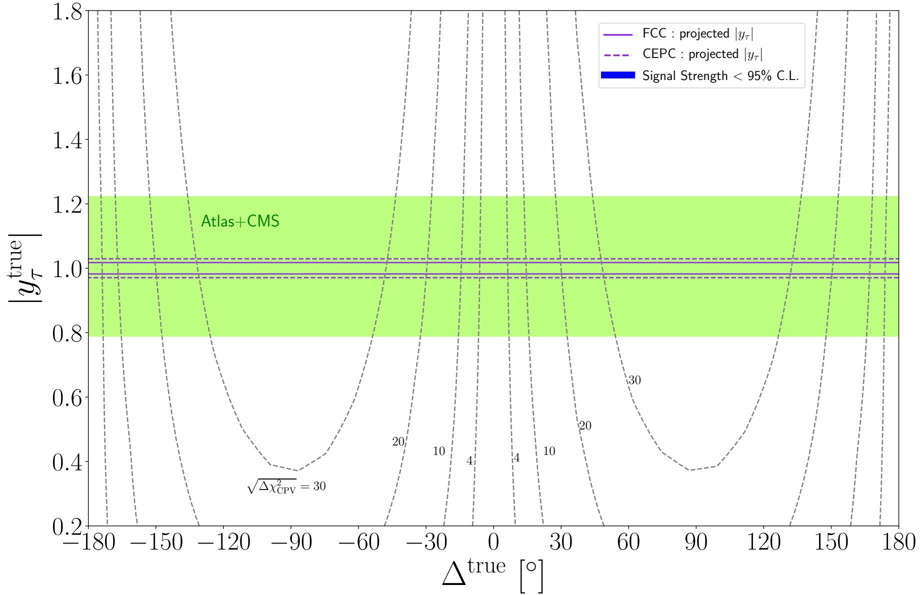
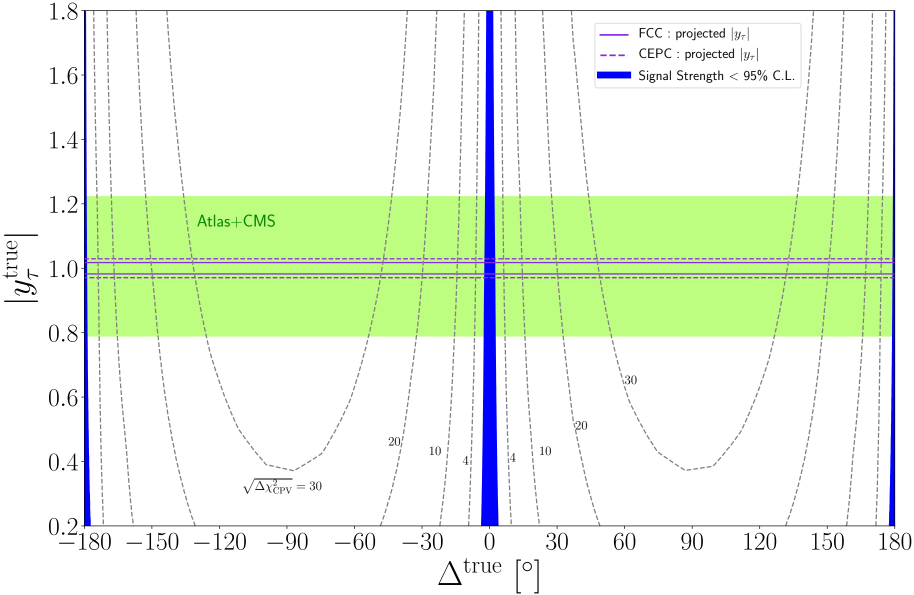
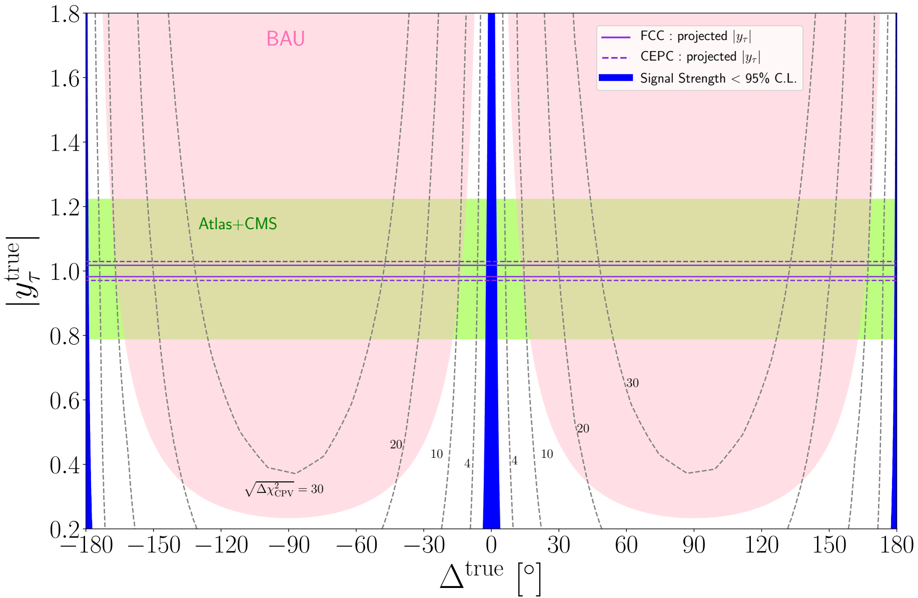


CEPC is very precise!



CEPC is very precise!



Thanks for your attention

Backup Slides

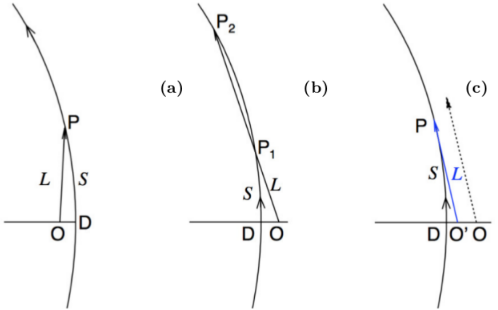
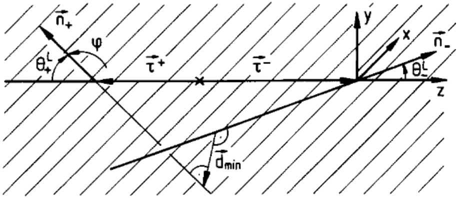


Fig. 2. Plots demonstrating the tau flight vector, the track trajectory and the point of closest approach for three cases: (a) the collision point O is inside the track curvature, (b) O is outside the track curvature with two intersection points, (c) O is outside the track curvature with no intersection.

From: Eur.Phys.J.C **77**, no.10, 697 (2017)

$$\mathbf{d}_{\min} = \boldsymbol{\ell} - \frac{\boldsymbol{\ell}\cdot\mathbf{n}_+}{\mathbf{n}_-\cdot(\mathbf{n}_+\times\mathbf{n}_-\times\mathbf{n}_+)}\mathbf{n}_- - \frac{\boldsymbol{\ell}\cdot\mathbf{n}_-}{\mathbf{n}_+\cdot(\mathbf{n}_-\times\mathbf{n}_-\times\mathbf{n}_+)}\mathbf{n}_+$$



From: Physics Letters B 313 (1993)458-460

TABLE II. Selection cuts [see text for details; (energies, momenta, and masses) in GeV/c$^{(0,1,2)}$], signal selection efficiencies ϵ (in %), and number of expected background events (BG) at various stages of the selection in the three selection channels e, μ, q. Event numbers are scaled to the 2 ab^{-1} of 250 GeV data of the "H20-staged" running scenario.

	leptonic preselection				hadronic preselection		
event property	requirement	ϵ_e	ϵ_μ	BG_{lep}	requirement	ϵ_q	BG_{had}
		100	100	142 M		100	142 M
chg. PFOs	$4 \to 7$	91	93	10.1 M	≥ 8	98	95.7 M
$Z \to ll$ candidate	≥ 1	88	90	1.03 M			
isolated prongs					≥ 2	91	45.8 M
opp. chgd. prongs		84	87	903 k		84	33.5 M
min. prong score					> 0.8	77	14.5 M
impact par. error	$< 25\mu m$	76	79	491 k	$< 25\mu m$	74	13.2 M
extra cone energy		72	75	438 k			
m_Z					$60 \to 160$	72	5.58 M
m_{recoil}					$50 \to 160$	71	4.90 M
τ decay mode		63	65	236 k		64	1.99 M

full selection		$Z \to ee$		$Z \to \mu\mu$			$Z \to qq$	
event property	requirement	ϵ_e	BG_e	ϵ_μ	BG_μ	requirement	ϵ_q	BG_q
good $\tau^+\tau^-$ fit		57	112 k	59	99.5 k		58	1.64 M
$m_{\tau\tau}$	$100 \to 140$	46	618	52	366	$100 \to 140$	42	42.9 k
event p_T	< 5	43	309	50	268	< 20	42	30.9 k
m_{recoil}	> 120	42	252	50	162	> 100	41	22.8 k
m_Z	$80 \to 105$	41	186	49	136	$80 \to 115$	38	6.34 k
$\lvert\cos\theta_Z\rvert$	< 0.96	40	168	47	124	< 0.96	37	5.64 k
event p_z	< 40	40	144	47	105	< 40	37	4.69 k
$\lvert\cos\theta_P\rvert_{min}$	< 0.95	40	140	47	102	< 0.95	37	4.69 k
Sample purity (%)		19		26			11	

Bkg

$$e^+e^- \to ZZ, Z \to \tau\tau, Z \to \ell\ell$$

$$e^+e^- \to Zh, Z \to \tau\tau, h \to bb$$

$$e^+e^- \to Zh, Z \to \tau\tau, h \to \ell\ell$$

From: Phys.Rev.D 98 (2018) 1, 013007

$$V_\Phi \supset \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \left[\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)^2(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right]$$

$$m_{H,h}^2 = v^2(\lambda_5 + 4\lambda_3) + 4v_1^2\lambda_1 + 4v_2^2\lambda_2 \pm \sqrt{\left[(\lambda_5 - 4\lambda_3)(v_2^2 - v_1^2) + 4v_1^2\lambda_1 - 4v_2^2\lambda_2\right]^2 + 16v_1v_2(\lambda_5 - 4\lambda_3)}$$