

Testing a light Higgs of 95 GeV at the CEPC

朱经亚 (Jingya Zhu)

zhujiy@henu.edu.cn

河南大学 (Henan University)

Based on our works arXiv: 2510.24662; 2506.21454;
2410.13636; 2402.11232; 2312.17599; 2212.11739

2025.11.07, Guangzhou

明德新民 止於至善

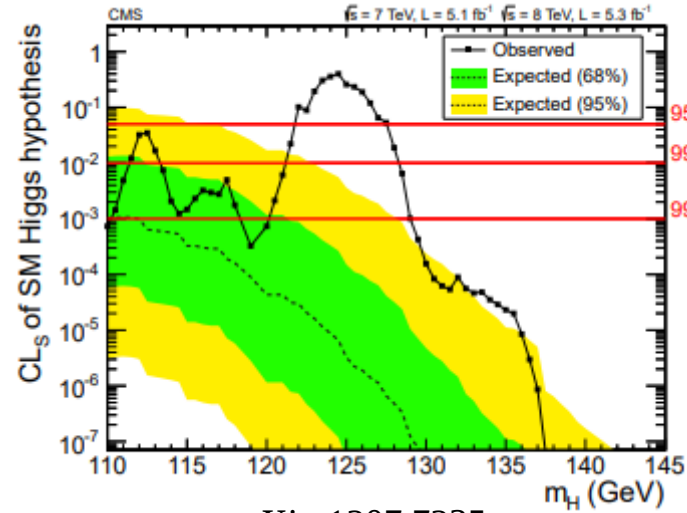


- 1. Backgrounds and motivations**
- 2. Models**
- 3. 95 GeV light Higgs at CEPC: cut-based analysis**
- 4. 95 GeV light Higgs at CEPC: machine learning**
- 5. 95 GeV light Higgs at CEPC: energy at 210 GeV**
- 6. 95 GeV light Higgs at hadron colliders**
- 7. Conclusions and outlooks**

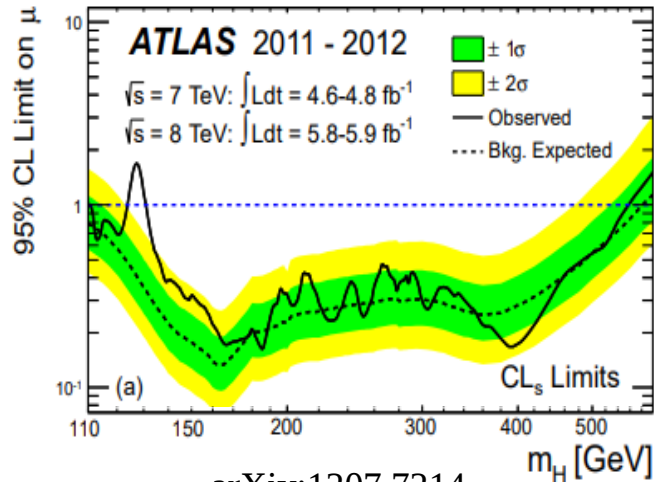
1. Backgrounds and motivations



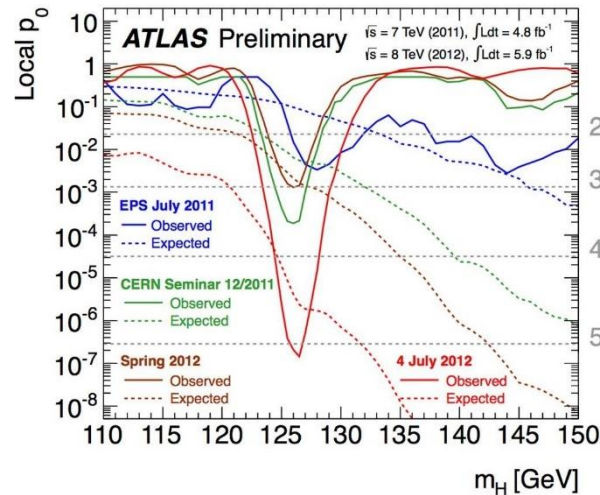
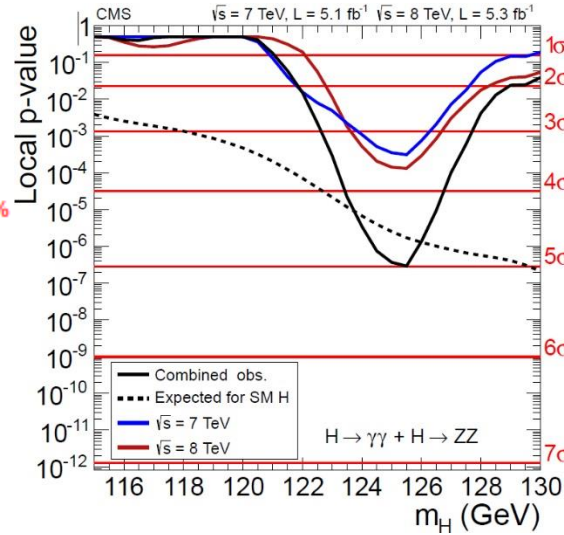
A 125 GeV Higgs discovered!



arXiv:1207.7235

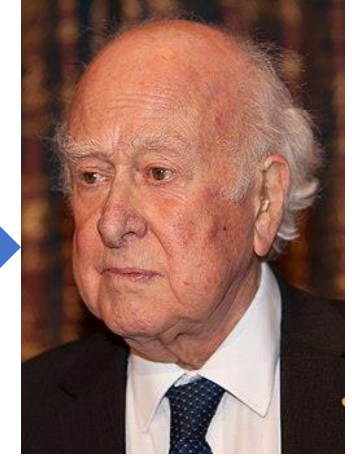


arXiv:1207.7214

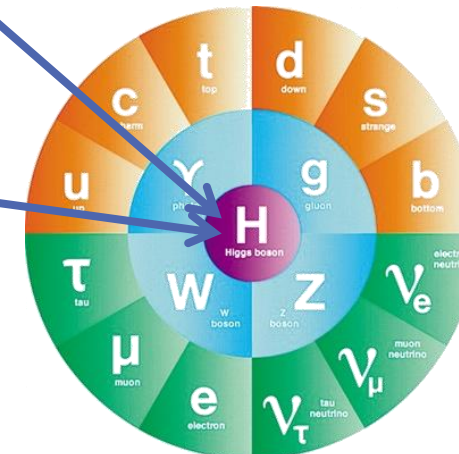


1964

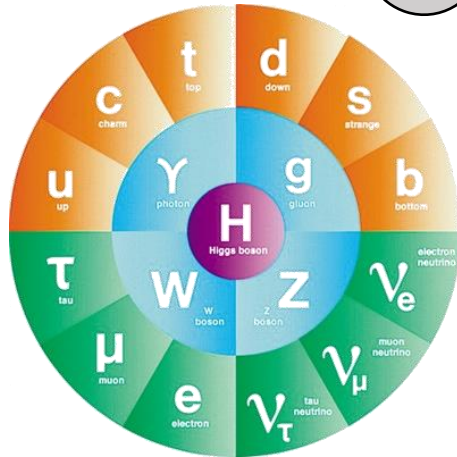
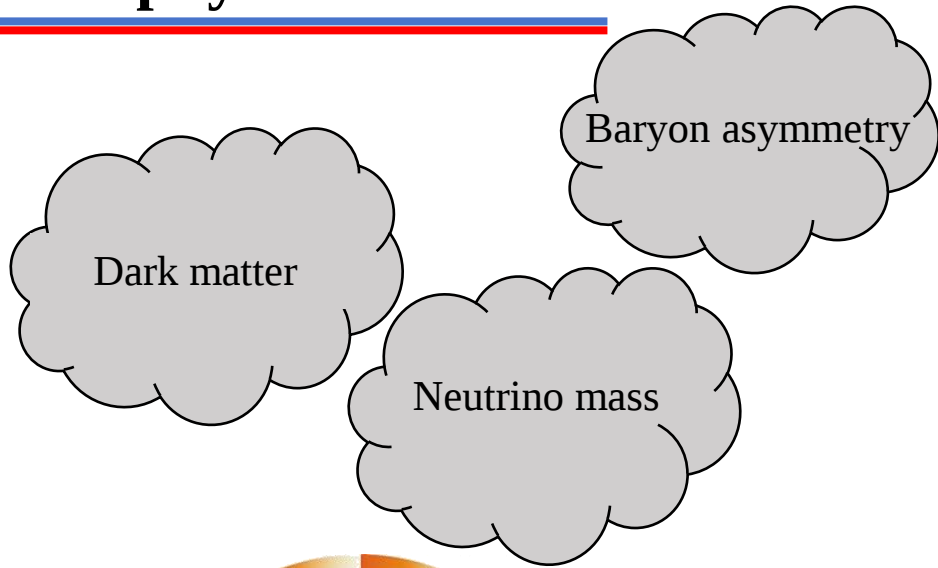
2013



add the final piece



New physics needed!



.....
Grand unification
Strong CP problem
Hierarchy problem

- ◆ precisely measuring properties of the Higgs
- ◆ searching for new physics beyond the SM



An important question: The properties of Higgs boson and the origin of mass



- ◆ HL-LHC
- ◆ HE-LHC
- ◆ SppC
- ◆ FCC-hh
- ◆ FCC-ee
- ◆ ILC

Colliders	Type	Energy	Luminosity Plan
LHC Run I & II	pp	13 TeV	$\sim 150 \text{ fb}^{-1}$
HL-LHC	pp	14 TeV	3000 fb^{-1}
HE-LHC	pp	27 TeV	10000 fb^{-1}
CEPC	e^+e^-	90-360 GeV	20000 fb^{-1}
SppC/FCC-hh	pp	100 TeV	30000 fb^{-1}
FCC-ee	e^+e^-	90-350 GeV	
ILC	e^+e^-	250-1000 GeV	

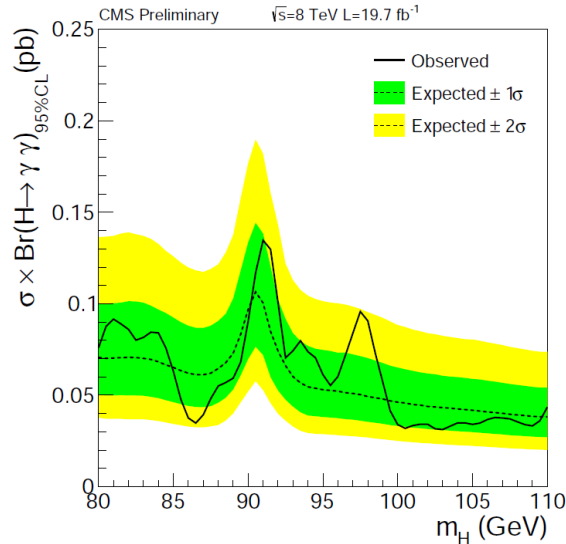
02 希格斯粒子性质和质量起源

CEPC（环形正负电子对撞机）项目瞄准标准模型的核心，对质量起源以及超出标准模型的新物理信号进行高精度、多方位的探索。CEPC建成后，将无可争议地成为国际高能粒子物理实验的最前沿阵地，很有可能取得国际瞩目的重大突破。CEPC及其升级项目将在半个世纪的时间尺度上，使我国在高能物理实验领域处于世界领跑者地位。

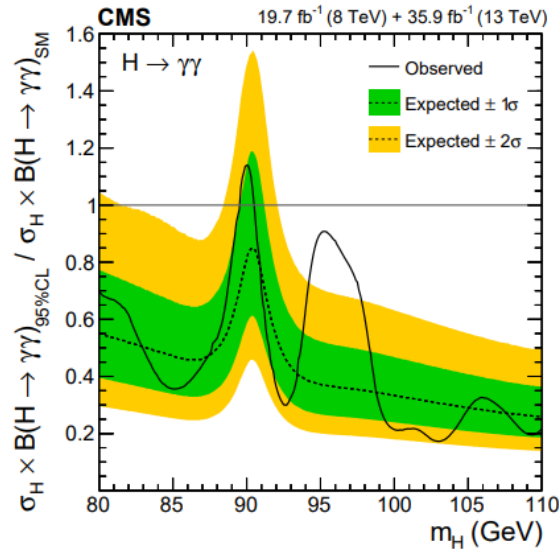
CEPC对技术发展将起到不可估量的引领和推动作用。CEPC将在低温、超导、高频、微波功率源、电子学与自动控制等一批关键技术领域大幅提升自主创新能力，对工艺新技术的发展、大规模工业制造将起到巨大的推动作用。

CEPC也将给我们带来一个国际化的科研中心，会对我国的科技体制改革、创新能力的提高以及人才培养等产生重大影响，会提高我们作为一个大国的硬实力、软实力和国际地位。

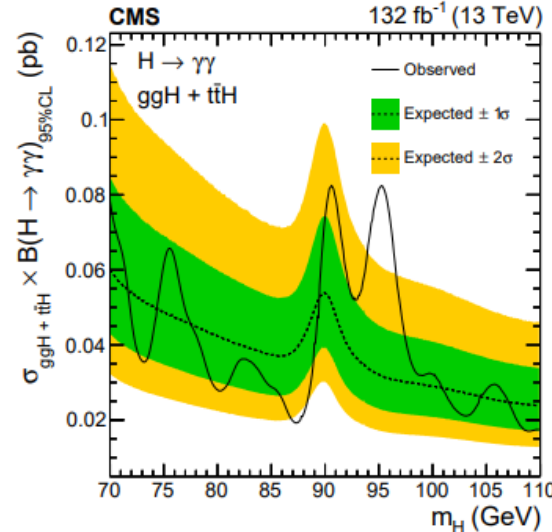
Another Higgs boson? A 95 GeV Higgs may be hinted



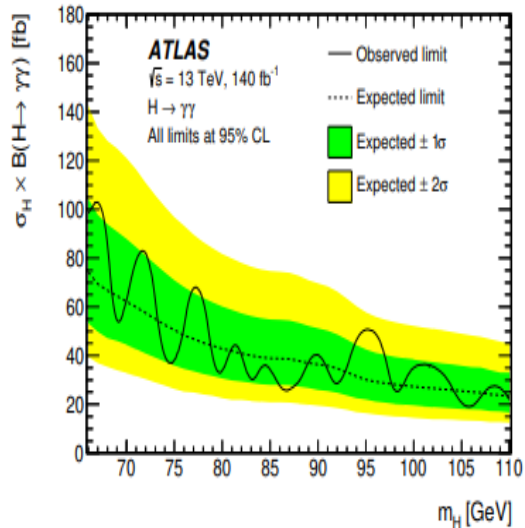
CMS-HIG-14-037, 2σ



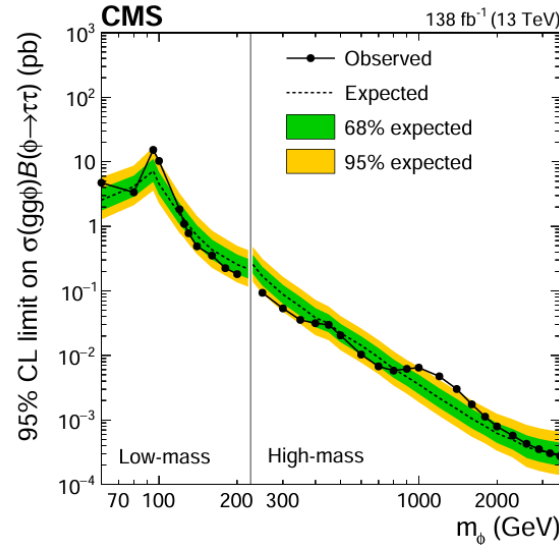
1811.08459, 2.8σ



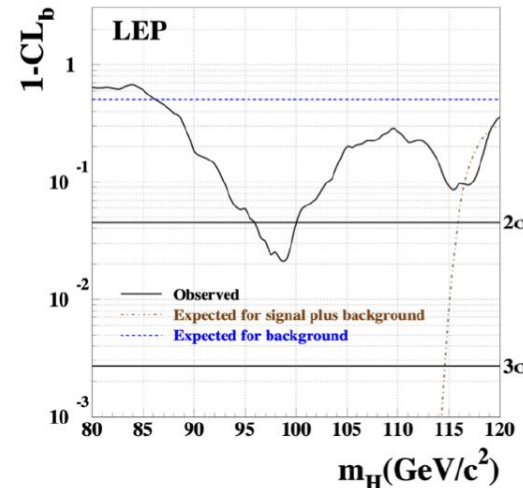
2407.07546, 2.9σ



2405.18149, 1.7σ



2208.02717, 3.1σ



hep-ex/0306033, 2.3σ

- ◆ Only one scalar in SM
- ◆ Additional scalar particle?
Nature and important question.
Far from been solved!

➤ ATLAS+CMS

$$\mu_{\gamma\gamma}^{\text{ex}} = 0.24^{+0.09}_{-0.08}$$

➤ CMS

$$\mu_{\tau\tau}^{\text{ex}} = 1.2 \pm 0.5$$

➤ LEP

$$\mu_{bb}^{\text{ex}} = 0.117 \pm 0.057$$

2. Models



Works	models	Different scenarios of mass generated
2402.11232 Wang, JZ	Minimal Dilaton Model	Top quark by both Higgs and dilaton
2410.13636 Dong, Wang, JZ	2HDM Type-I	All SM particles by the same doublet
2312.17599 Li, Qiao, Wang, JZ	NMSSM II	Charged leptons & down-type quarks by the same doublet
2212.11739 Li, Qiao, JZ		
2506.21454 Dong, Ruan, Wang, Yang, JZ	N2HDM-Flipped	Charged leptons & up-type quarks by the same doublet
2510.24662 Dong, Ruan, Wang, Yang, JZ		

Minimal Dilaton Model

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{\text{without } V(H)} - \frac{1}{2} \partial_\mu S \partial^\mu S - \bar{T} \left(\not{D} + \frac{M}{f} S \right) T - [y' \bar{T}_R (q_{3L} \cdot H) + \text{h.c.}] - \tilde{V}(S, H),$$

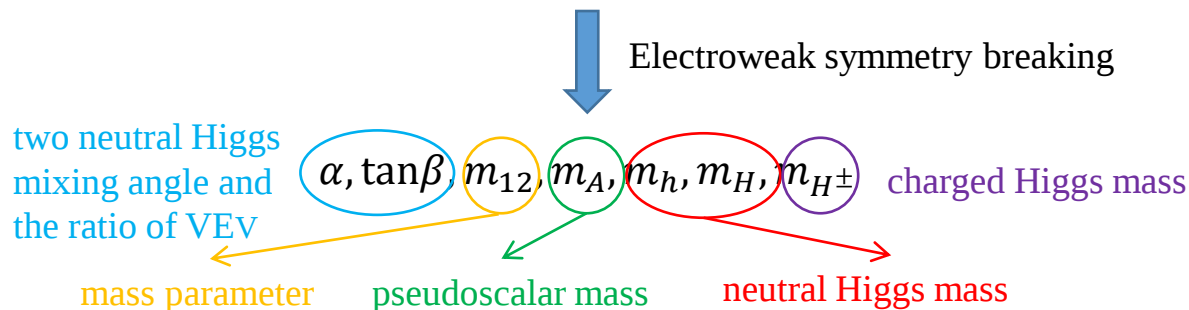
$$\tilde{V}(S, H) = m_H^2 |H|^2 + \frac{\lambda_H}{4} |H|^4 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4 + \frac{\kappa}{2} S^2 |H|^2,$$

$$S = f + h \sin \theta_S + s \cos \theta_S, \\ H^0 = \frac{1}{\sqrt{2}} (v + h \cos \theta_S - s \sin \theta_S), \\ q_{3L}^u = \cos \theta_L t_L + \sin \theta_L t'_L, \\ T_L = -\sin \theta_L t_L + \cos \theta_L t'_L.$$

2HDM Type-I

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

$m_{11}, m_{22}, m_{12}, \lambda_i (i = 1, 2, 3, 4, 5)$



Coupling of Higgs to bosons

$$C_{hVV} = C_{hVV}^{\text{SM}} \times \sin(\alpha - \beta), \\ C_{HVV} = C_{HVV}^{\text{SM}} \times \cos(\alpha - \beta)$$

Coupling of Higgs to fermions

$$C_{hff} = C_{hff}^{\text{SM}} \times \cos \alpha / \sin \beta, \\ C_{Hff} = C_{Hff}^{\text{SM}} \times \sin \alpha / \sin \beta$$

NMSSM (Type-II)

$$V^{\text{SUSY}} = V_F + V_D + V_{\text{soft}}$$

$$V_F = F^{*i} F_i, F^{*i} = -W^i = -\frac{\delta W}{\delta \hat{\Phi}_i}$$

$$W^{\text{NMSSM}} = W_F + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

$$W_F = \bar{u} Y_u \hat{Q} \cdot \hat{H}_u - \bar{d} Y_d \hat{Q} \cdot \hat{H}_d - \bar{e} Y_e \hat{L} \cdot \hat{H}_d$$

$$V_{\text{soft}}^{\text{NMSSM}} = \tilde{m}_{H_u}^2 |H_u|^2 + \tilde{m}_{H_d}^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + \left(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + h.c. \right)$$

$$S = \frac{v_S + \phi_S + i\varphi_S}{\sqrt{2}}$$

N2HDM-Flipped (Type-Y)

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.]$$

$$+ \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2.$$

$$\Phi_S = v_S + \rho_S$$

$H_a, H_b, H_c; A; H^\pm$

$$C_{Hiff} = \begin{cases} s_{\alpha_1} c_{\alpha_2} / s_\beta, & i = 1, \\ (c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) / s_\beta, & i = 2, \\ -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} c_{\alpha_2}) / s_\beta, & i = 3, \end{cases}$$

$$C_{Hiqdqd} = \begin{cases} c_{\alpha_1} c_{\alpha_2} / c_\beta, & i = 1, \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\alpha_1}) / c_\beta, & i = 2, \\ -(c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_3}) / c_\beta, & i = 3, \end{cases}$$

N2HDM-Flipped (Type-Y)

Parameter space scan

The selection of parameters

The constraints

mass of excess candidate H_1	$95 < m_{H_1} < 96 \text{ GeV}$
mass of SM-like H_2	$m_{H_2} = 125.09 \text{ GeV}$
mass of CP-even H_3 , pseudoscalar A	$300 < m_{H_3,A} < 1500 \text{ GeV}$
mass of charged $H^\pm$	$580 < m_{H^\pm} < 1500 \text{ GeV}$
coupling of H_2 to boson, top quark	$0.7 < C_{H_2 VV}^2 < 1.0,$ $0.7 < C_{H_2 tt}^2 < 1.2$
mixing matrix elements	$\text{sign}(R_{23}) = \pm 1, -1 < R_{12} < 1$
VEV ratio of two doublets	$0.8 < \tan\beta < 10$
VEV of singlet	$1 < v_s < 3000 \text{ GeV}$
Z_2 breaking parameter	$1 \times 10^{-3} < m_{12}^2 < 5 \times 10^5 \text{ GeV}^2$

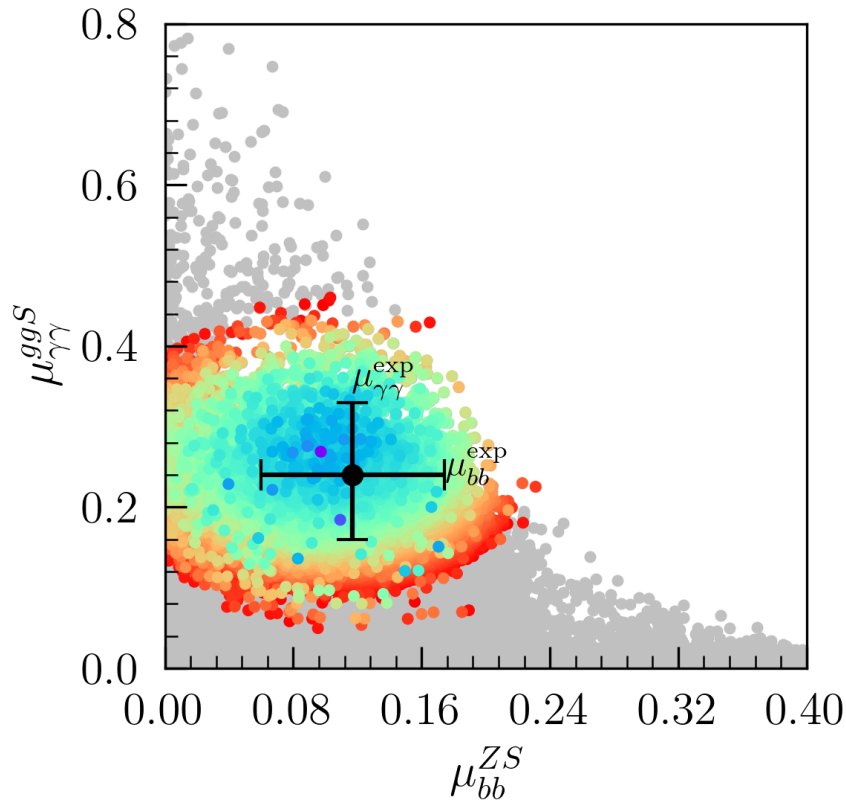
1. Perturbative unitarity.
2. Vacuum stability.
3. B physic.
4. Electroweak precision observables.
5. Direct search for Higgs.
6. 125 GeV Higgs data

N2HDM-Flipped: Surviving samples



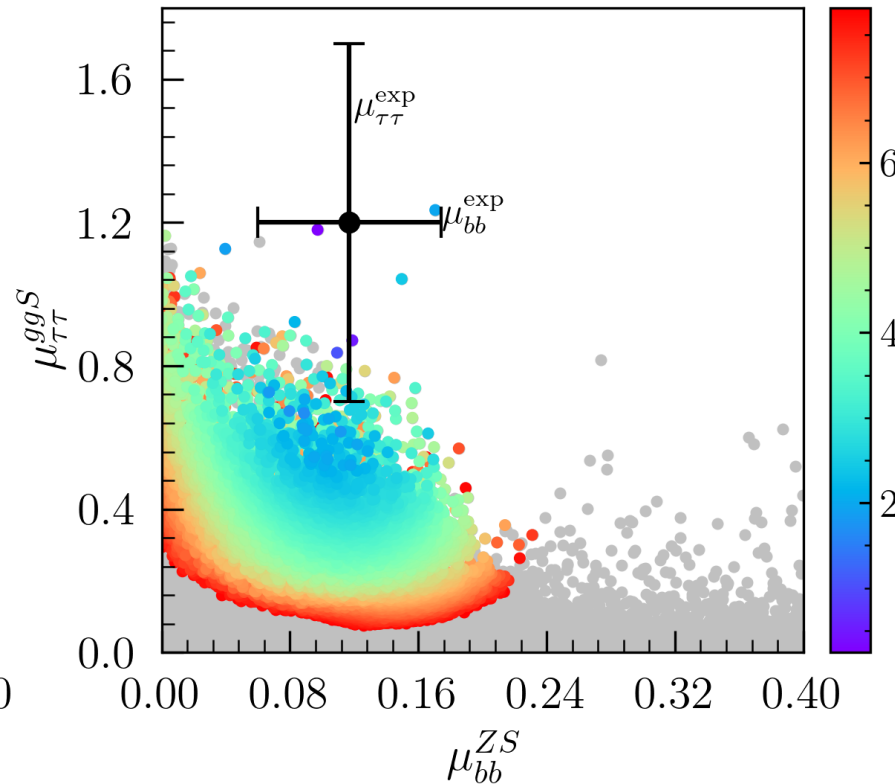
Gluon fusion process

$$\mu_{xx}^{ggS} = \frac{\sigma(gg \rightarrow S) \times \mathcal{B}(S \rightarrow xx)}{\sigma_{SM}(gg \rightarrow H_{95}) \mathcal{B}_{SM}(H_{95} \rightarrow xx)}$$



Higgsstrahlung process

$$\mu_{xx}^{ZS} = \frac{\sigma(ee \rightarrow ZS) \times \mathcal{B}(S \rightarrow xx)}{\sigma_{SM}(ee \rightarrow ZH_{95}) \mathcal{B}_{SM}(H_{95} \rightarrow xx)}$$



Three-channel excesses

$$\mu_{bb}^{exp} = 0.117 \pm 0.057$$

$$\mu_{\tau\tau}^{exp} = 1.2 \pm 0.5$$

$$\mu_{\gamma\gamma}^{exp} = 0.24_{-0.08}^{+0.09}$$

Fit value

$$\chi_S^2 = \sum_{xx=\tau\tau,\gamma\gamma,bb} \frac{(\mu_{xx} - \mu_{xx}^{exp})^2}{(\Delta\mu_{xx}^{exp})^2}$$

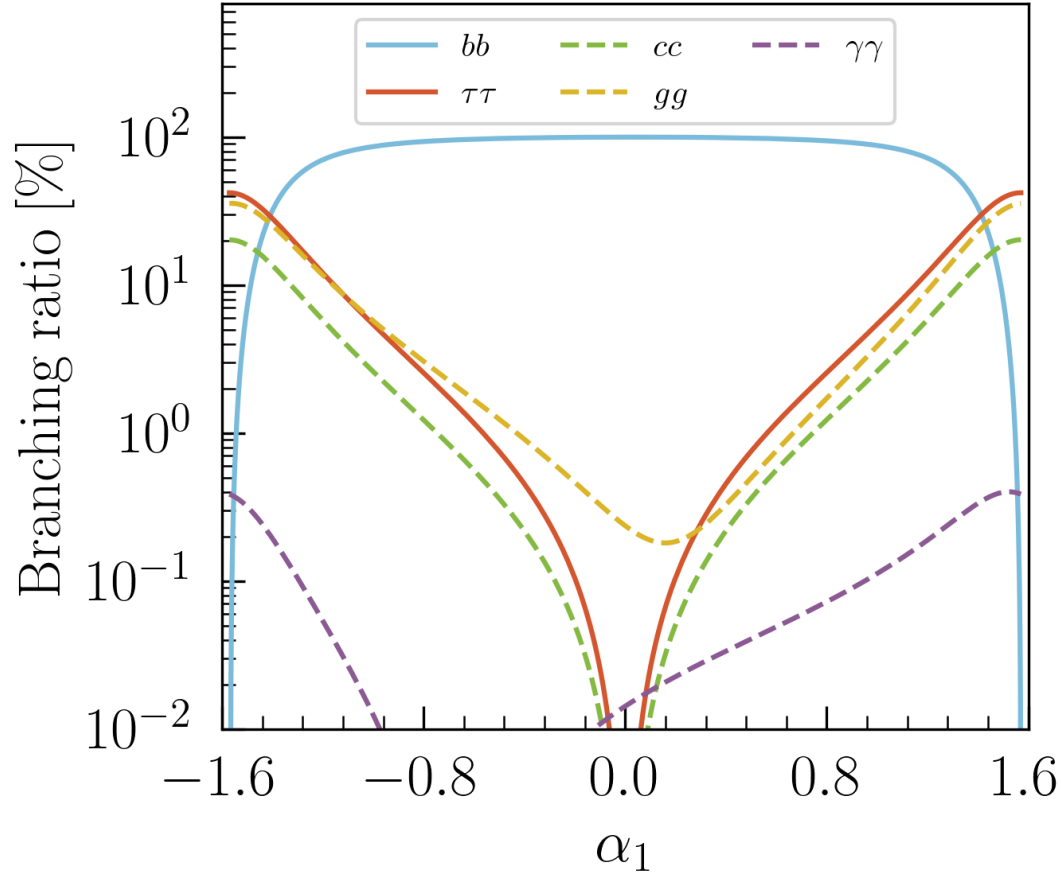
$$< 7.82 \text{ at } 95 \text{ C. L.}$$

3. 95 GeV light Higgs at the CEPC: cut-based analysis

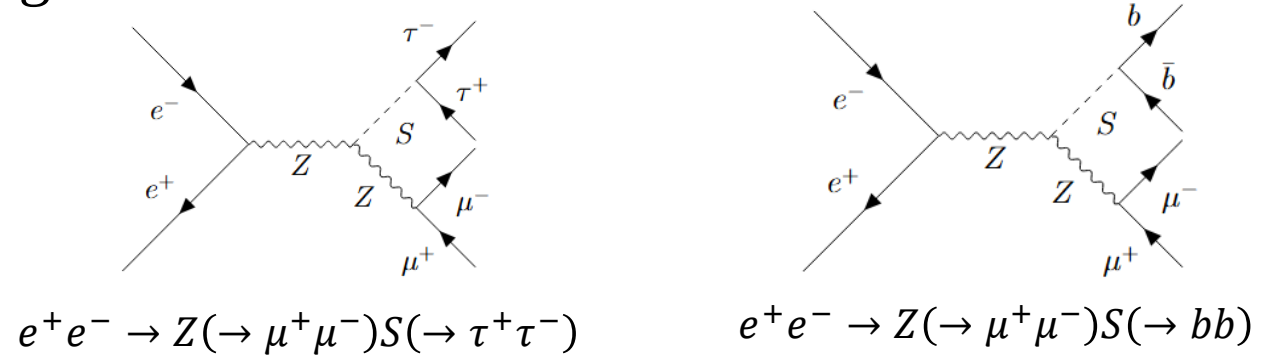


Signals and backgrounds

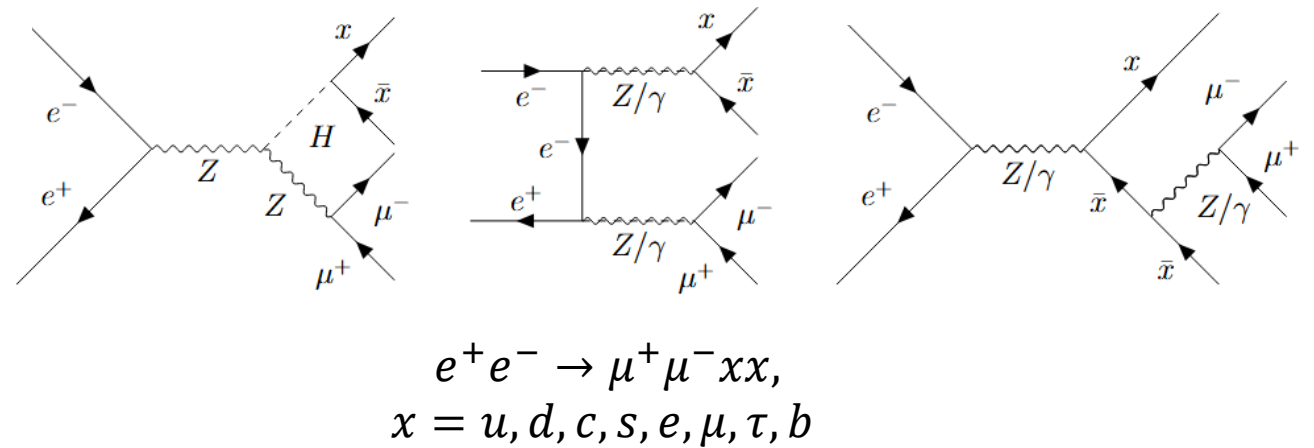
dominant decay channels



Signals



Backgrounds



Cross sections in bb and $\tau\tau$ channels

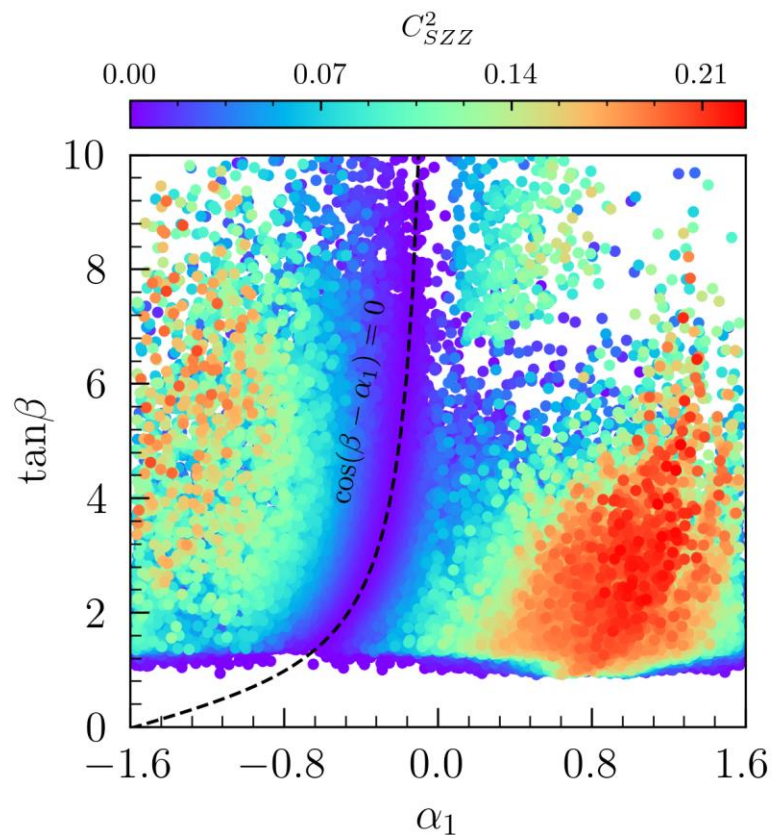


Madgraph5_aMC@NLO

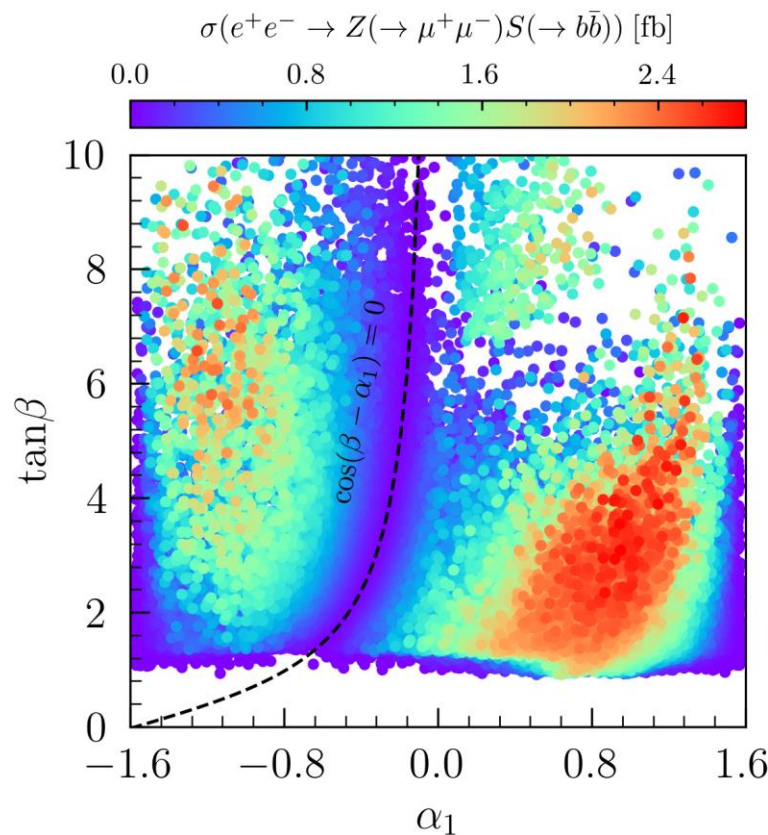
SM value

$$\sigma = \sigma_{SM}(ee \rightarrow ZS)|_{m_H=95.5 \text{ GeV}} \cdot c_{SZZ}^2 \cdot \text{Br}(Z \rightarrow \mu\mu) \cdot \text{Br}(S \rightarrow xx)$$

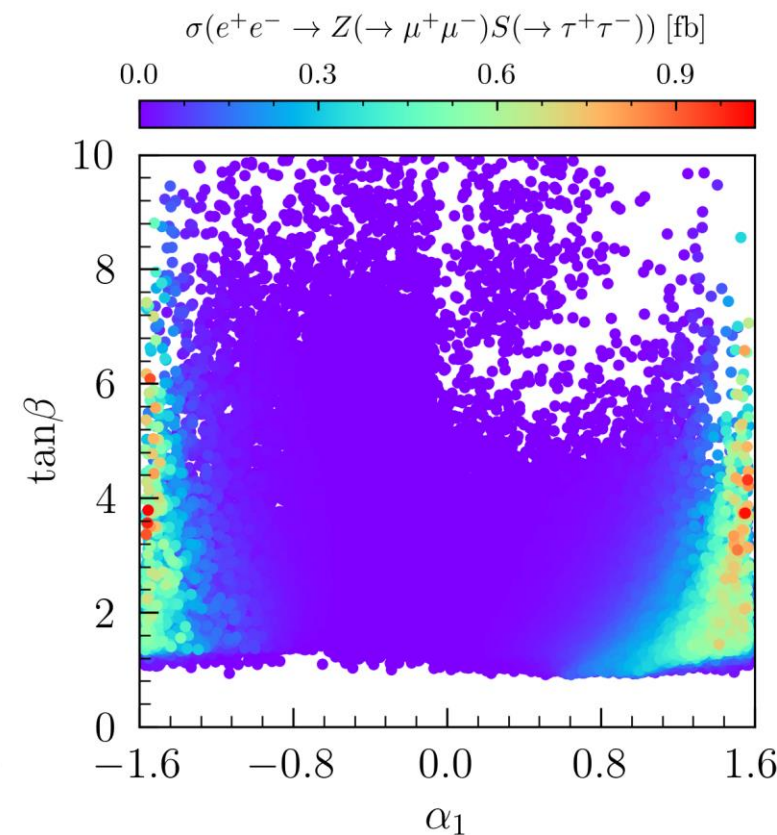
Effective coupling



$$C_{H_1VV} = \cos\alpha_2 \cdot \cos(\beta - \alpha_1)$$



$$C_{H_1bb} = \cos\alpha_1 \cdot \cos\alpha_2 / \cos\beta$$



$$C_{H_1\tau\tau} = \sin\alpha_1 \cdot \cos\alpha_2 / \sin\beta$$

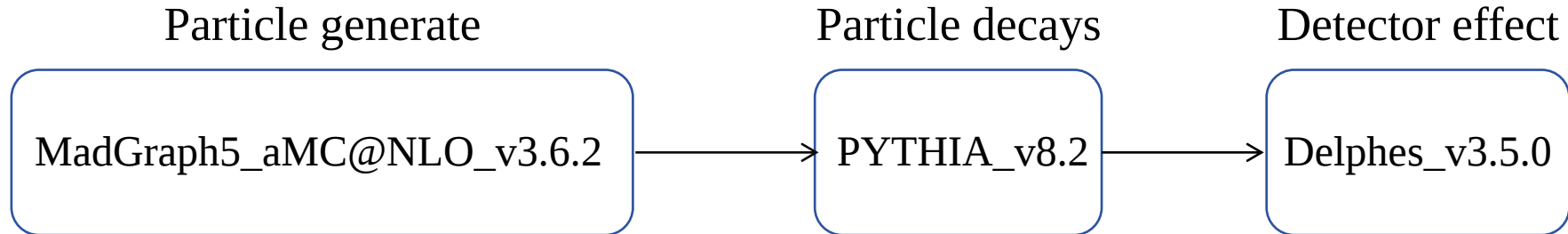
Monte-Carlo Simulation



Event generation and pre cuts

Event generation

generate 1 million signal and background



CEPC 4th card

Pre selections

Basic cuts

$M_{\mu\mu}$ cut

calculate

$$N(\mu) \geq 2, \quad p_T^\mu \geq 10 \text{ GeV}$$
$$\eta(\mu) < 2, \Delta R(\mu_1, \mu_2) > 0.4$$

$$M(\mu_1, \mu_2) > 50 \text{ GeV}$$

$$M_{\text{recoil}} = \sqrt{s + M_{\mu^+\mu^-}^2 - 2\sqrt{s}(E_{\mu^+} + E_{\mu^-})}$$

Cut-based analysis on $\tau\tau$ channel



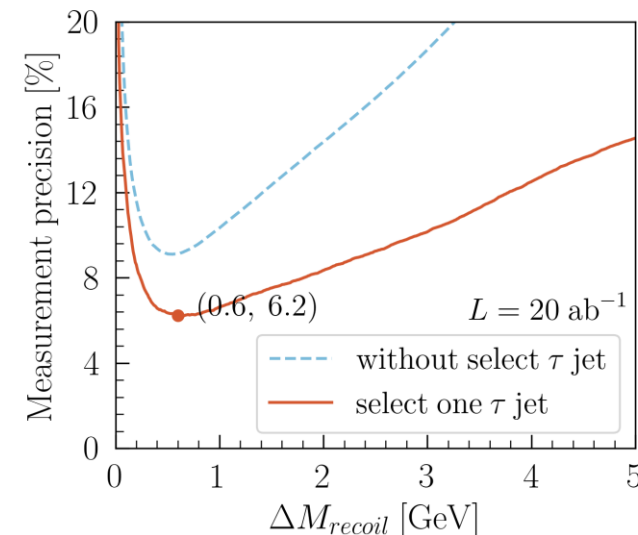
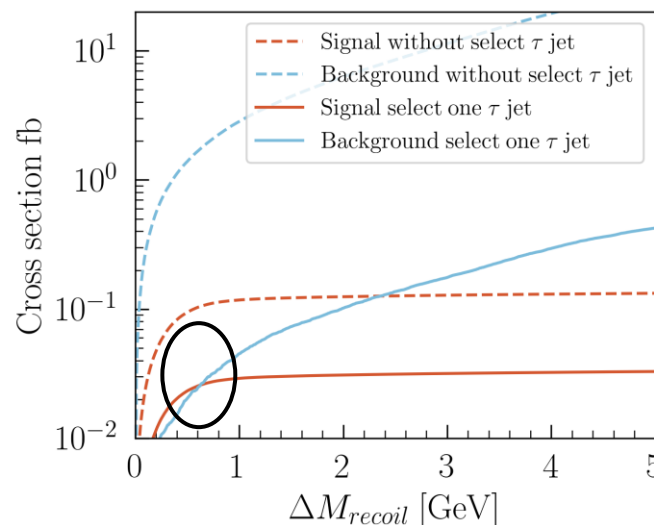
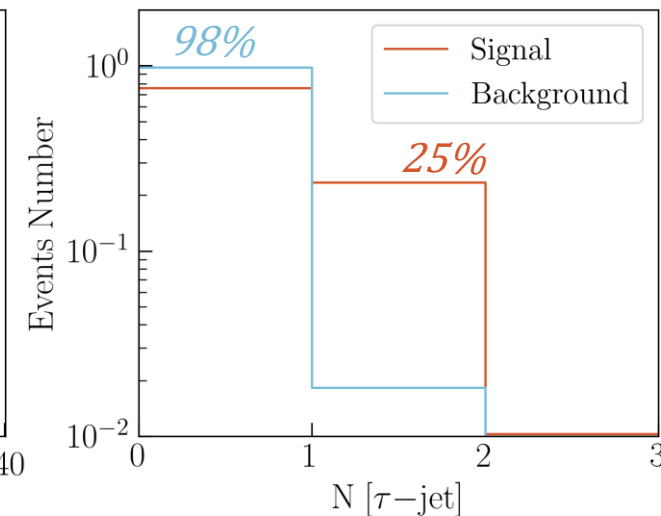
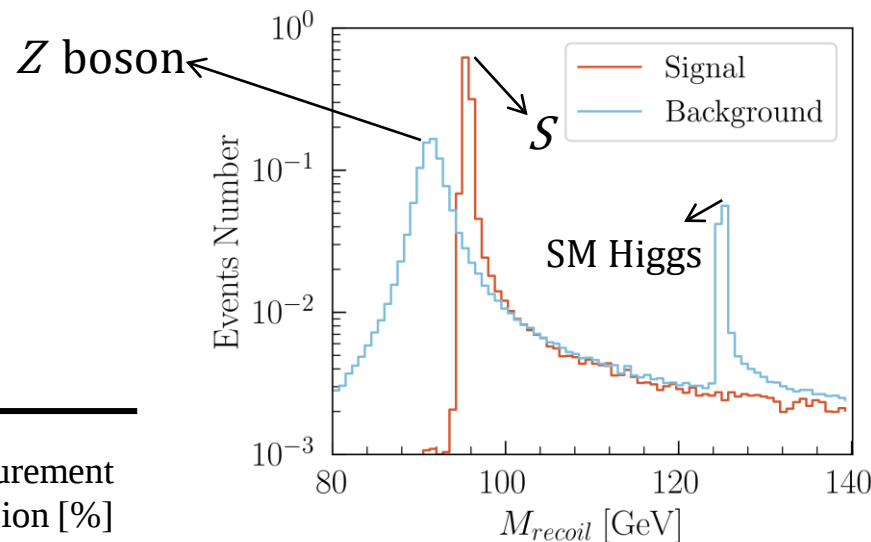
Measurement precision

$$\Delta = \frac{\sqrt{S+B}}{S}$$

The cut flow with $L = 20 \text{ ab}^{-1}$

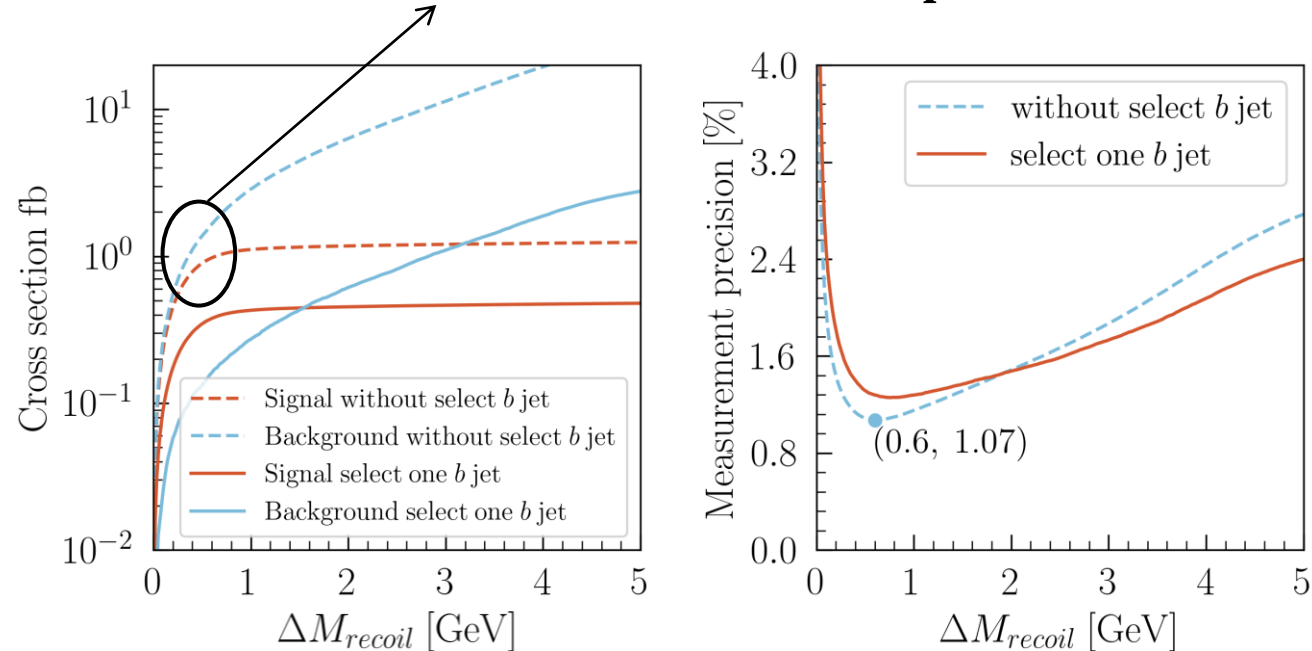
Cuts	Cross section [fb]		Measurement precision [%]
	Signal	Background	
Initail	0.218	84.250	29.8
Basic	0.177	72.202	34.1
$M_{\mu_1\mu_2} > 50 \text{ GeV}$	0.165	58.617	32.9
$N[\tau\text{-jet}] \geq 1$	0.040	1.094	18.7
$\Delta M_{recoil} = 0.6 \text{ GeV}$	0.026	0.026	6.2

xsec is set to 0.2 SM value for signal





The cross section can comparable



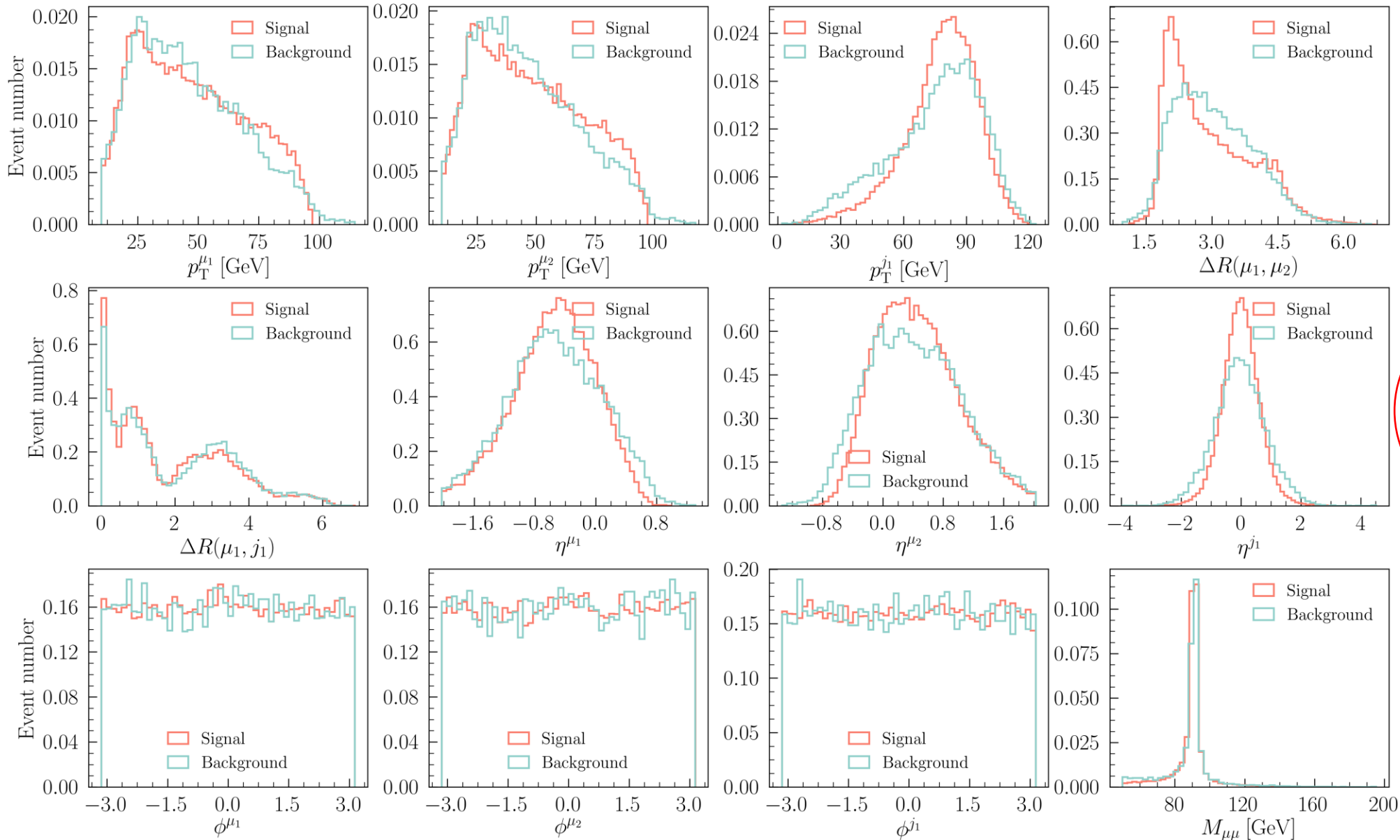
The cut flow with $L = 20 \text{ ab}^{-1}$

Cuts	Cross section [fb]		Measurement precision [%]
	Signal	Background	
Initial	2.099	84.250	3.13
Basic	1.700	72.244	3.58
$M_{\mu_1\mu_2} > 50 \text{ GeV}$	1.633	58.552	3.36
$\Delta M_{recoil} = 0.6 \text{ GeV}$	1.094	1.633	1.07

xsec is set to 0.2 SM value for signal

How to improve precision?

Event distributions for other observables

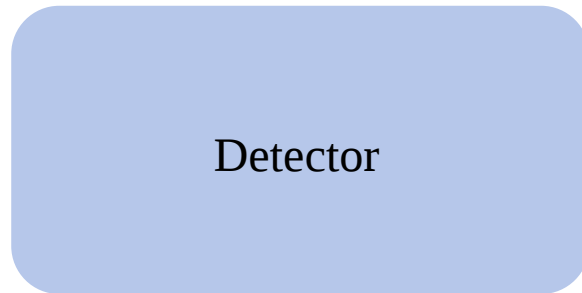
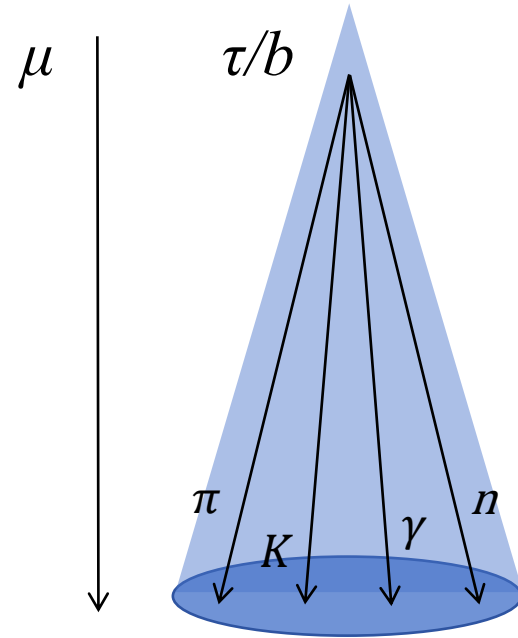


The precision can hardly be improved significantly by these observables!

4. 95 GeV light Higgs at CEPC: machine learning

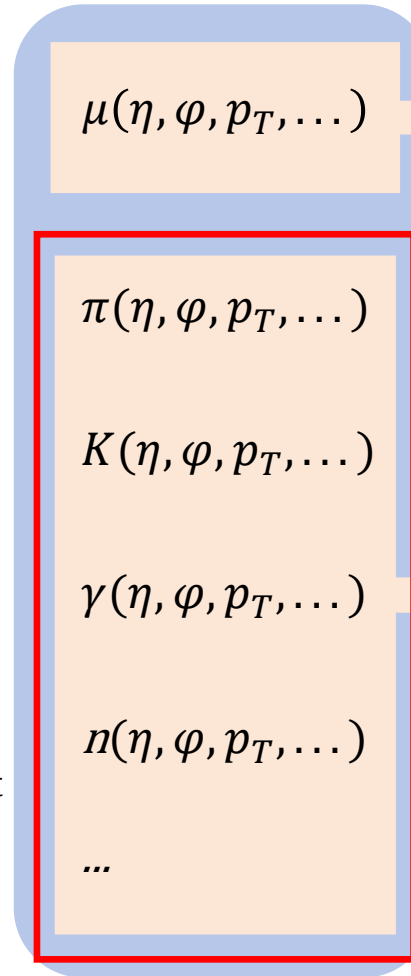


Feature structure



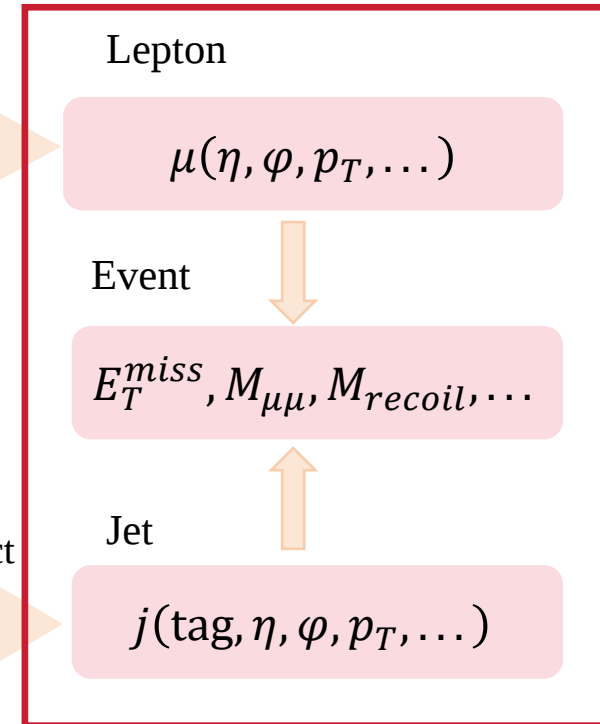
Extract

Particle level



Construct

Cut-based analysis



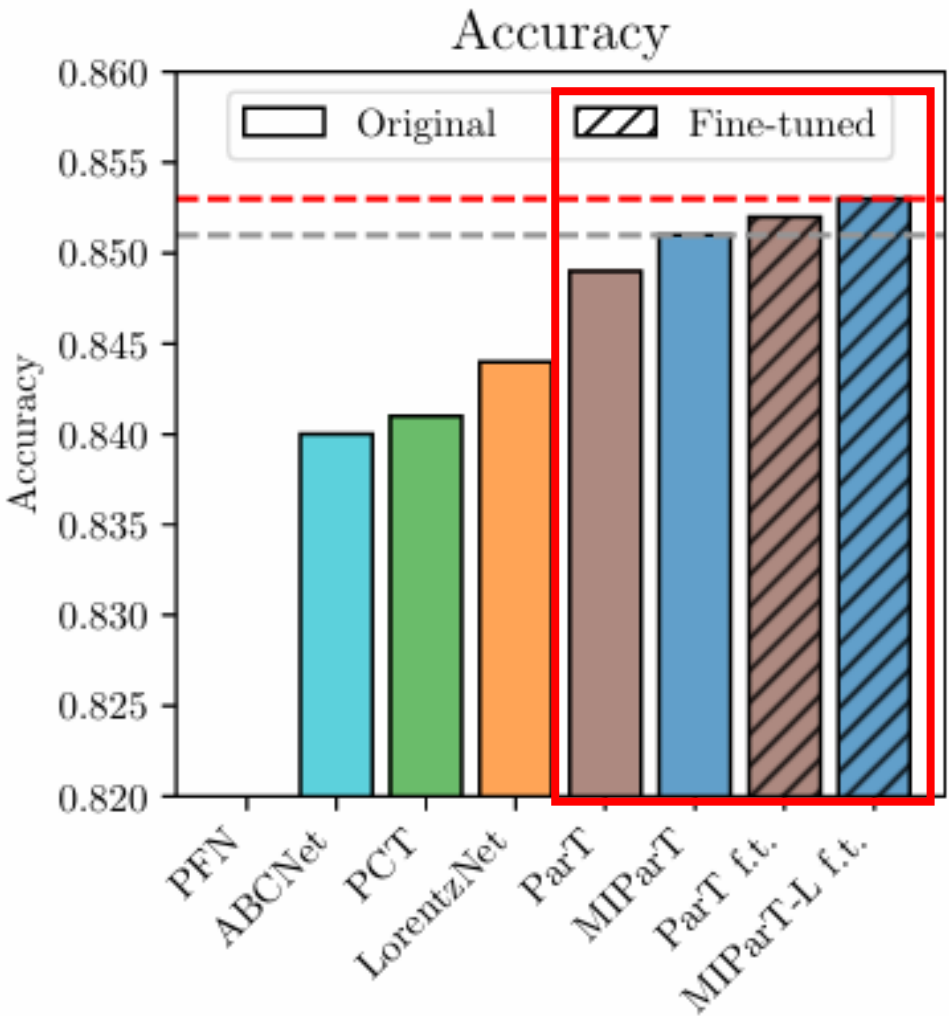
Information missed and
need ML to use

ML performance in jet tagging



Performance in QuarkGluon tagging

Advanced ParT and MIPaT + particle level feature



Detailed performance

	ACC	AUC
ParT	0.849	0.9203
MIPaT	0.851	0.9215
ParT.f.t	0.852	0.9230
MIPaT.f.t	0.853	0.9237

ParT (Particle Transformer): arXiv 2202.03772

MIPaT (More Interaction Particle Transformer): arXiv 2407.08682

Input features

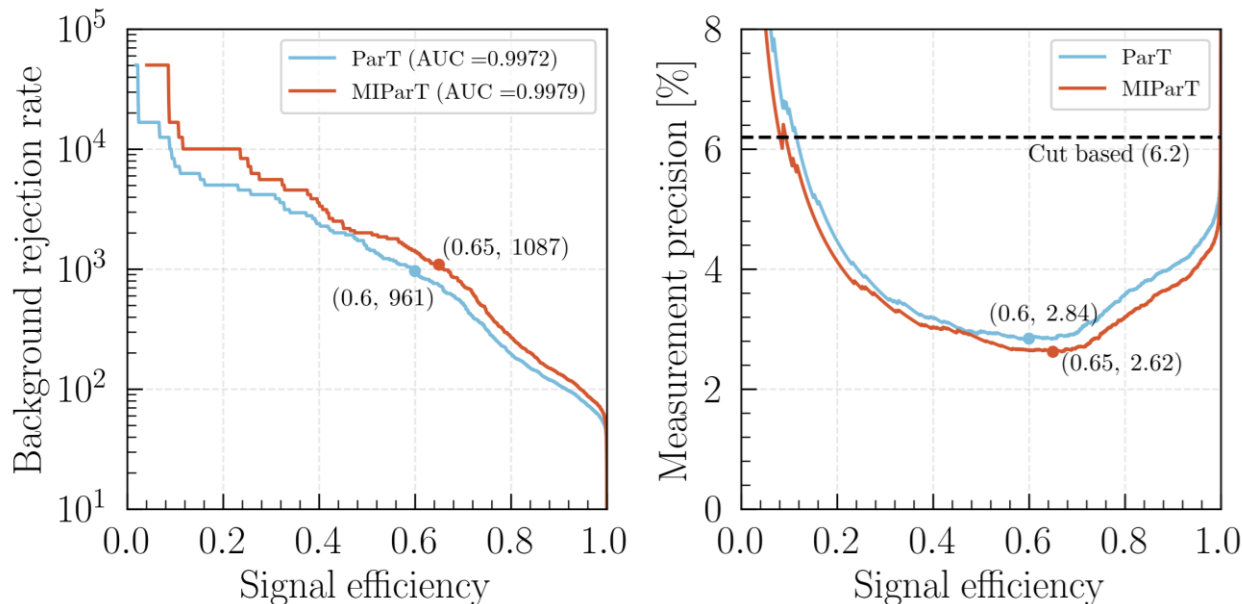
Event level:

- Recoil mass: M_{recoil}
- Invariant mass: $M_{\mu\mu}$
- Average azimuthal angle: $\varphi = (\varphi_{\mu_1} + \varphi_{\mu_2})/2$
- Average pseudorapidity: $\eta = (\eta_{\mu_1} + \eta_{\mu_2})/2$

Particle level (max length=50):

- Transverse momentum: P_T^p
- Energy: E^p
- Renormalized P_T : $P_T^p / (P_T^{\mu_1} + P_T^{\mu_2})$
- Renormalized E : $E^p / (E^{\mu_1} + E^{\mu_2})$
- Regularization φ : $\Delta\varphi = \varphi^p - \varphi$
- Regularization η : $\Delta\eta = \eta^p - \eta$
- Angular separation: $\sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$
- Charge: C
- Particle kind.

The ML performance

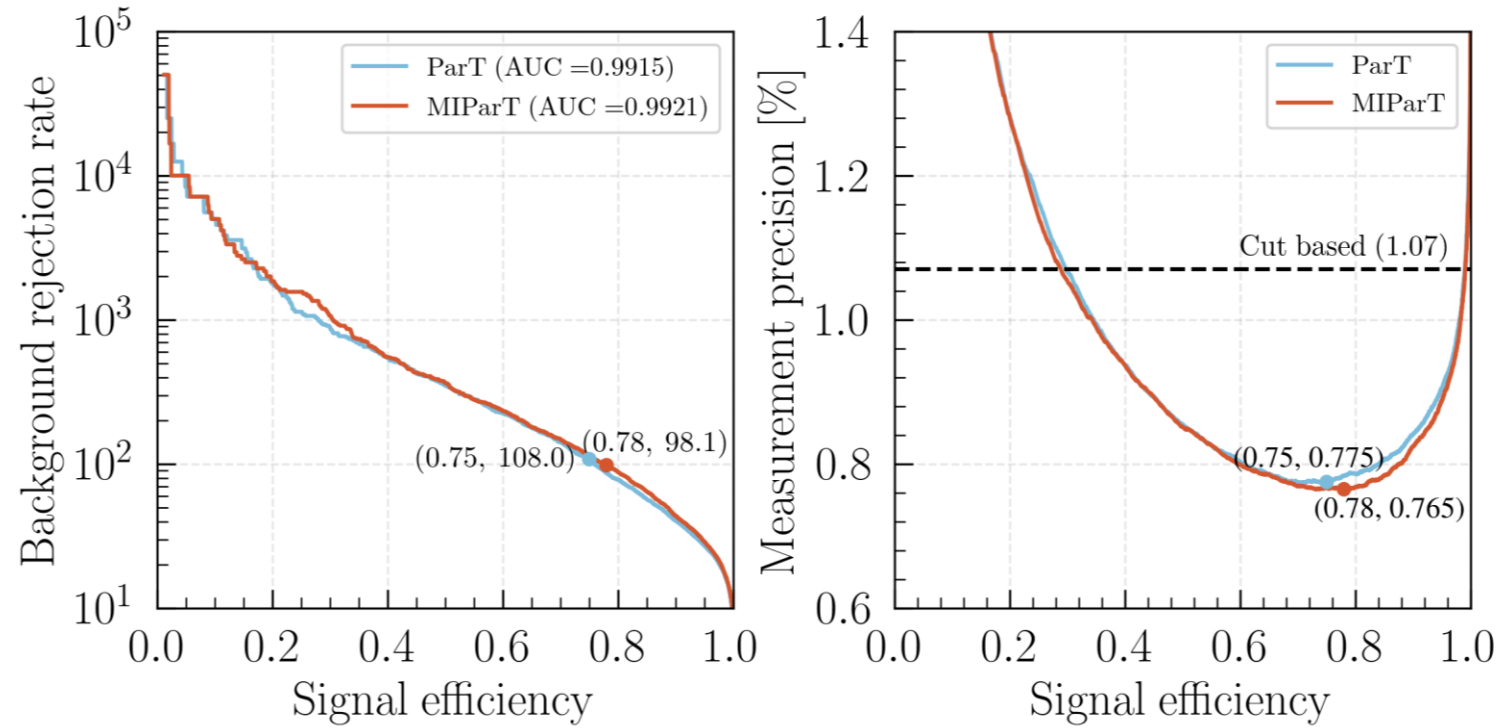


Performance comparison

Method	Signal efficiency	background rejection rate	Measurement precision [%]
Cut based	0.15	2777	6.2
ParT	0.60	916	2.8
MIParT	0.65	1087	2.6

↑ 58%

The ML performance



Performance comparison

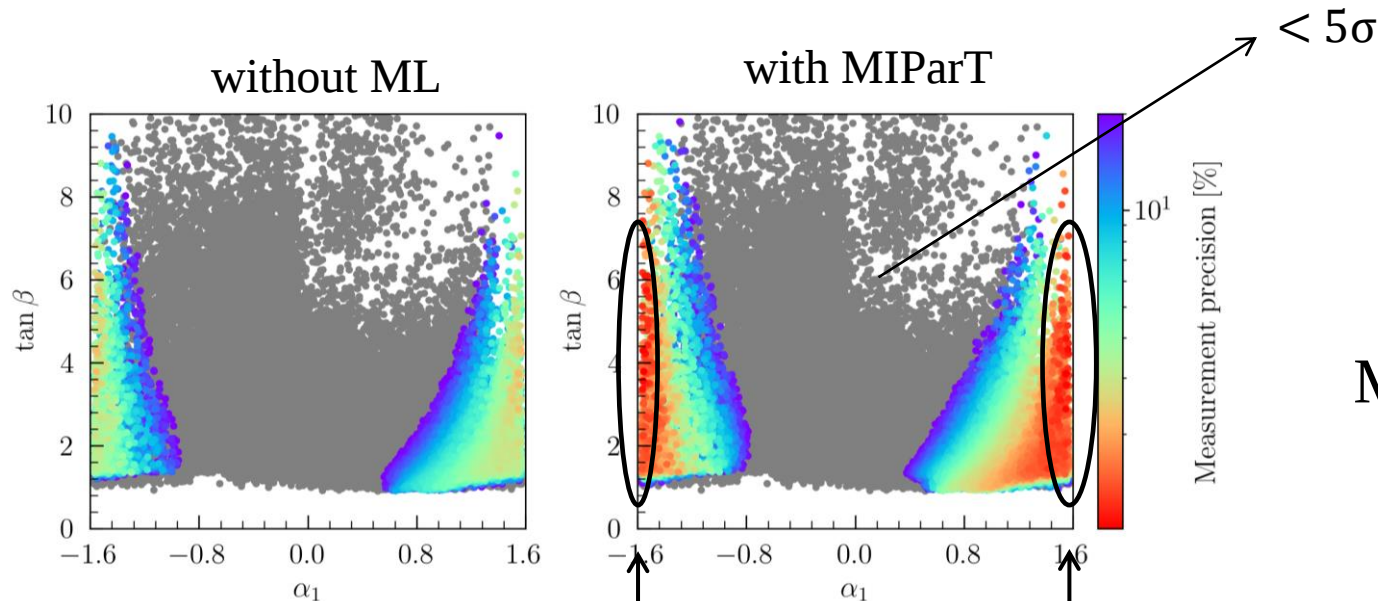
Method	Signal efficiency	background rejection rate	Measurement precision [%]
Cut based	0.64	43.3	1.07
ParT	0.75	108	0.78
MIParT	0.78	98.1	0.77

↑ 28%

CEPC detection ability for surviving samples



$\tau\tau$
channel



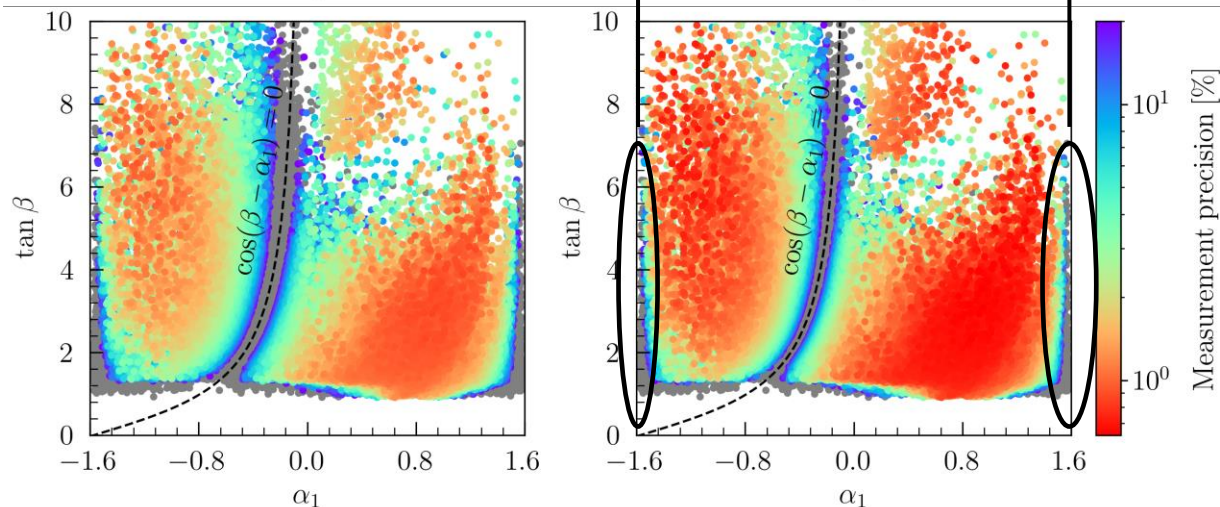
Signal significance

$$\mathcal{S} = \sqrt{2 \left[(S + B) \ln \left(1 + \frac{S}{B} \right) - S \right]}$$

Measurement precision

$$\Delta = \frac{\sqrt{S + B}}{S}$$

bb
channel



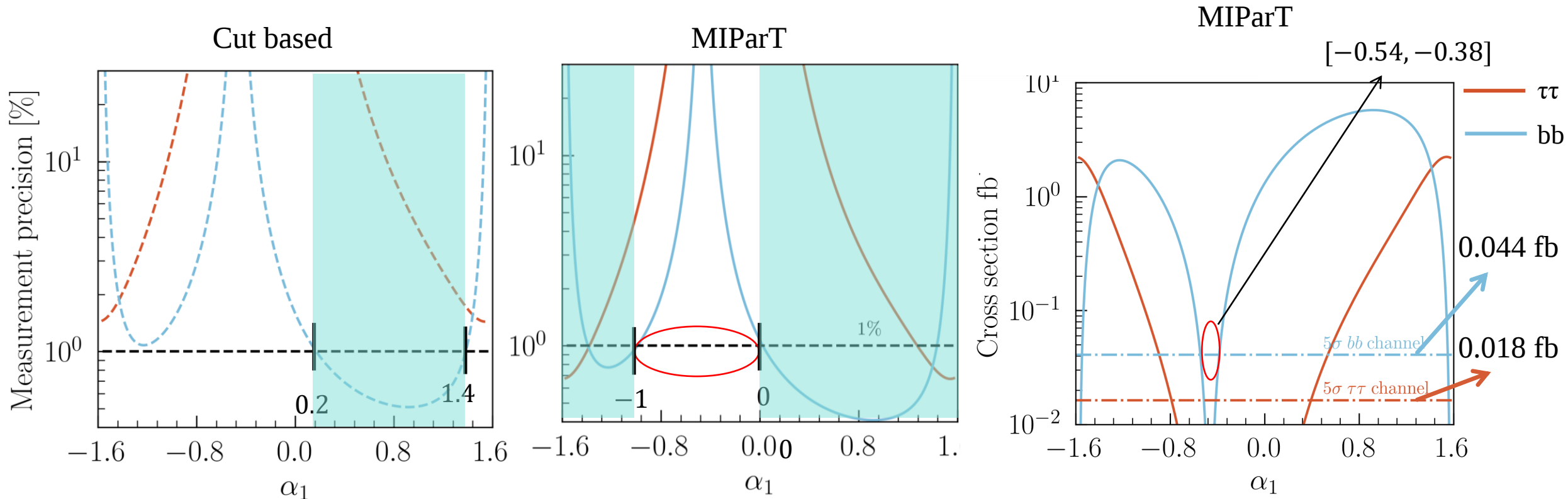
For the surviving samples

Channel	Max cross section [fb]	Max precision [%]	
		Without ML	MIParT
$\tau\tau$	1.03	2.3	1.0
bb	2.8	0.86	0.63

CEPC detection ability for benchmark points



High-precision detection range has been significantly increased



$$\tan\beta = 2, \cos\alpha_2 = \sqrt{2}/2, \text{ and } \cos(\beta - \alpha_1) = 0 \text{ for } \alpha_1 = -0.46$$

5. 95 GeV light Higgs at CEPC: 210 GeV

Higgsstrahlung $\tau\tau$ channel

Signal

$$e^+e^- \rightarrow Z(\rightarrow \mu^+\mu^-)S(\rightarrow \tau^+\tau^-)$$

Backgrounds

$$Z\tau\tau: e^+e^- \rightarrow Z(\rightarrow \mu^+\mu^-)\tau^+\tau^-$$

$$Zjj: e^+e^- \rightarrow Z(\rightarrow \mu^+\mu^-)xx, x \text{ is } e, \mu, \text{jet}$$

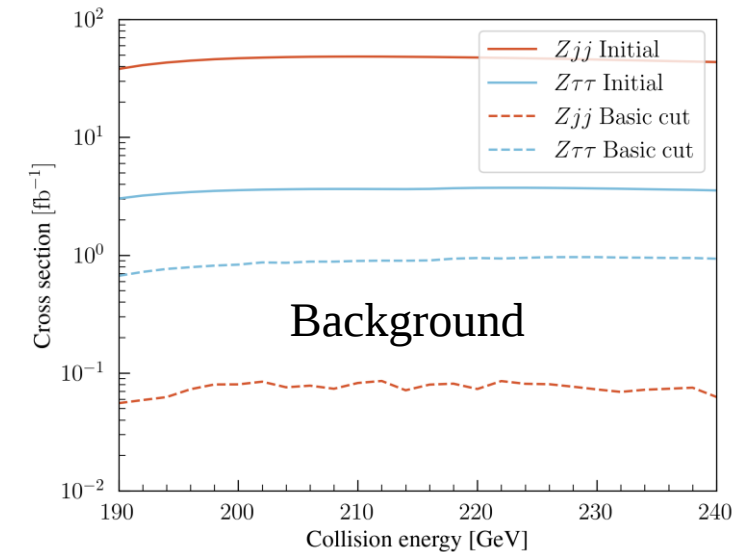
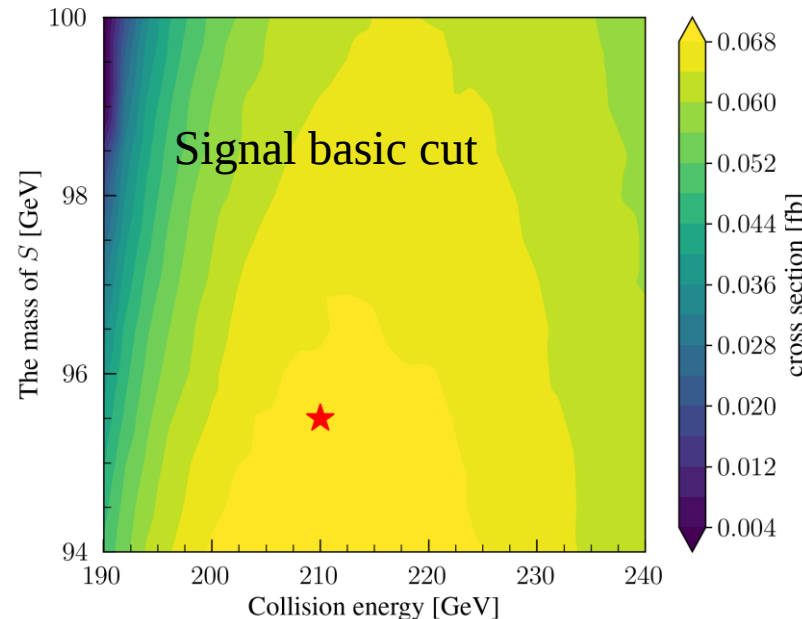
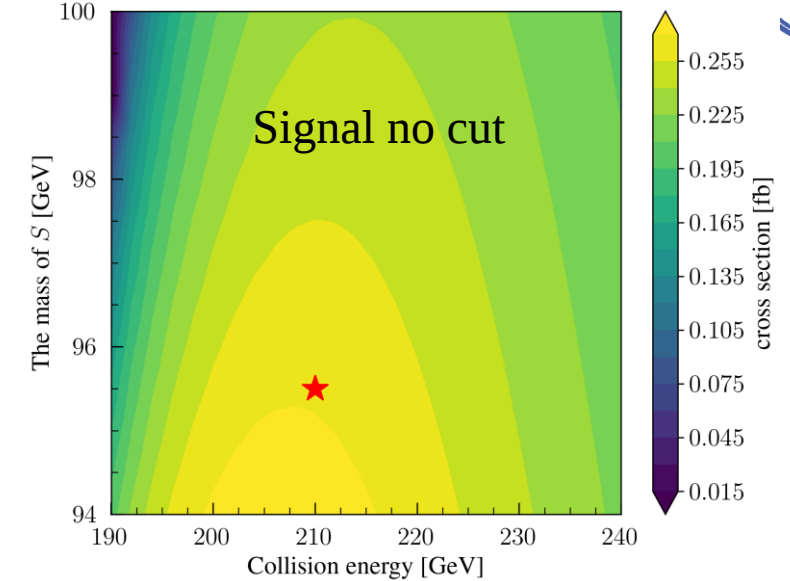
With cross section
at 0.2 of SM

$$M_S \in [94, 100] \text{ GeV}$$

$$\sqrt{s} \in [190, 240] \text{ GeV}$$

Basic Cuts

Two muon, one tau jet,
 $p_{T_\mu} > 10 \text{ GeV}, |\eta_\mu| < 2.5,$
 $\Delta R(\mu_1, \mu_2) > 0.4$



Machine Learning: DNN



DNN

```
# 定义 DNN 模型
class DNN(nn.Module):
    def __init__(self, input_size):
        super(DNN, self).__init__()
        self.Sequential = nn.Sequential(
            nn.Linear(input_size, 64),
            nn.BatchNorm1d(64),
            nn.Dropout(0.2),
            nn.ReLU(),

            nn.Linear(64, 48),
            nn.BatchNorm1d(48),
            nn.Dropout(0.2),
            nn.ReLU(),

            nn.Linear(48, 32),
            nn.BatchNorm1d(32),
            nn.ReLU(),

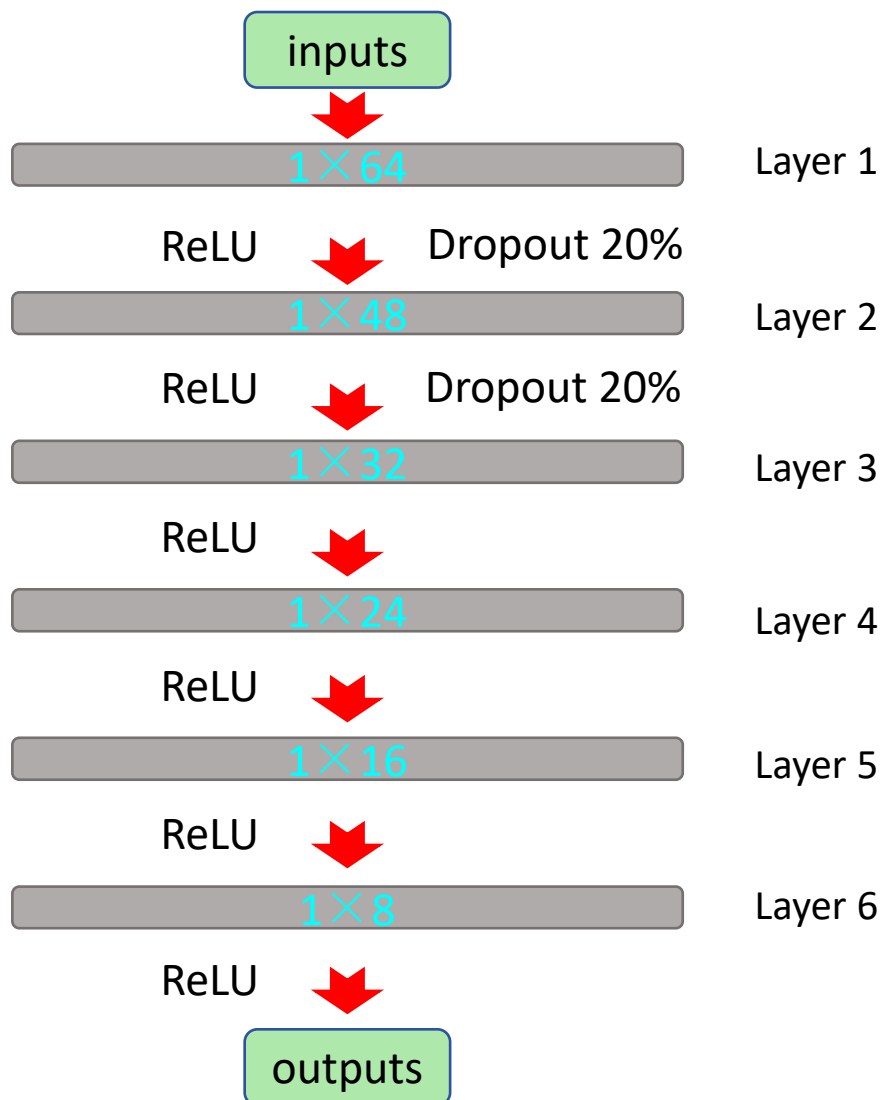
            nn.Linear(32, 24),
            nn.BatchNorm1d(24),
            nn.ReLU(),

            nn.Linear(24, 16),
            nn.BatchNorm1d(16),
            nn.ReLU(),

            nn.Linear(16, 8),
            nn.BatchNorm1d(8),
            nn.ReLU(),

            nn.Linear(8, 1),
            nn.Sigmoid()
        )

    def forward(self, x):
        return self.Sequential(x)
```



Data

train : 50000 * 0.7
test: 50000 * 0.3

Optimizer

Adam optimizer
Learn rate = 0.0001

Loss

Binary Cross Entropy

Training

epochs = 200
batch_size=128

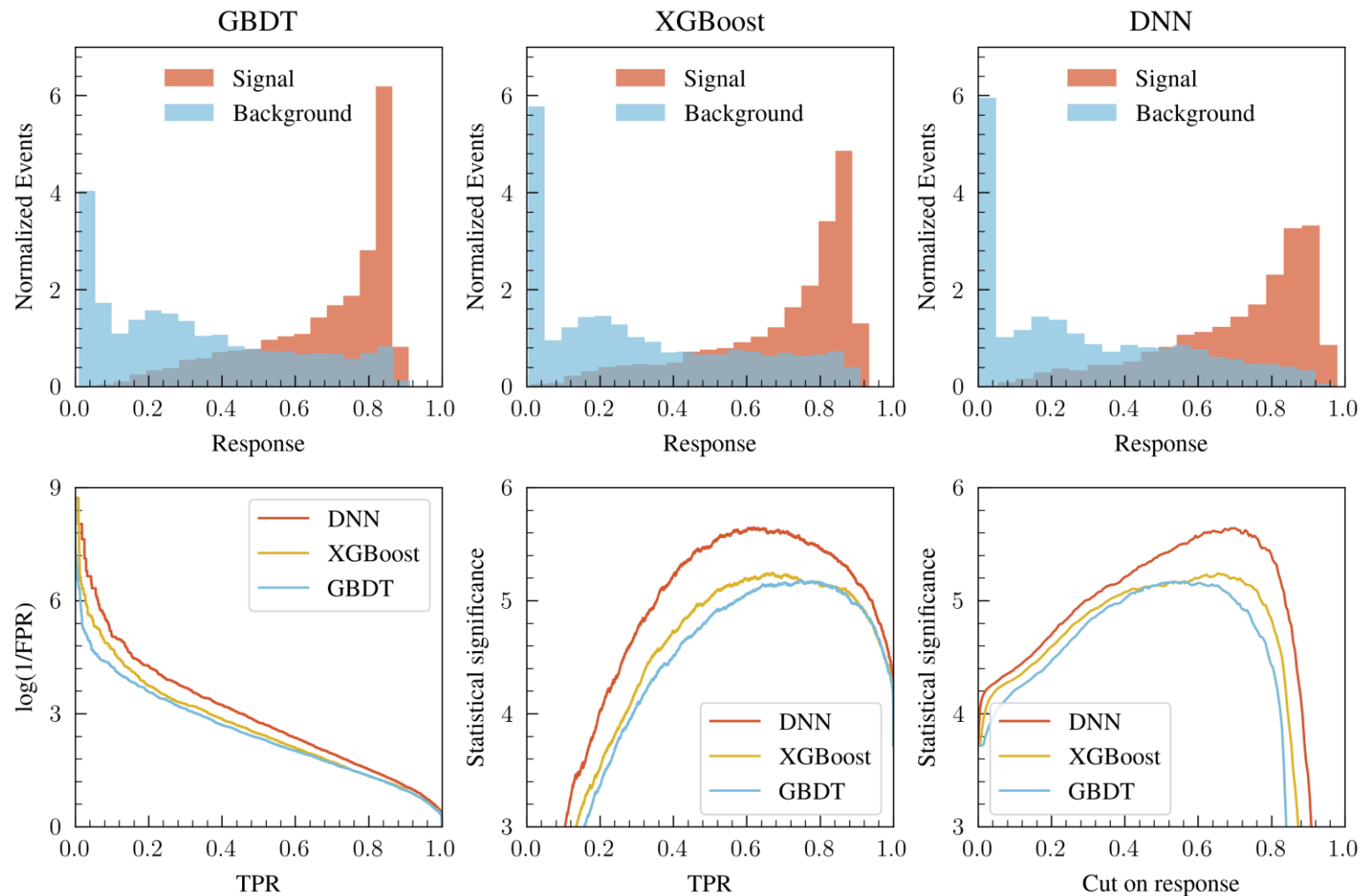
Machine Learning (ML)

22 features

Feature extraction

- Four-momenta P of two muon and one tau jet;
- Transverse momenta P_T and pseudorapidities η of two muon and one tau jet;
- Spatial separation ΔR of two muon and one tau jet;
- The recoil mass.

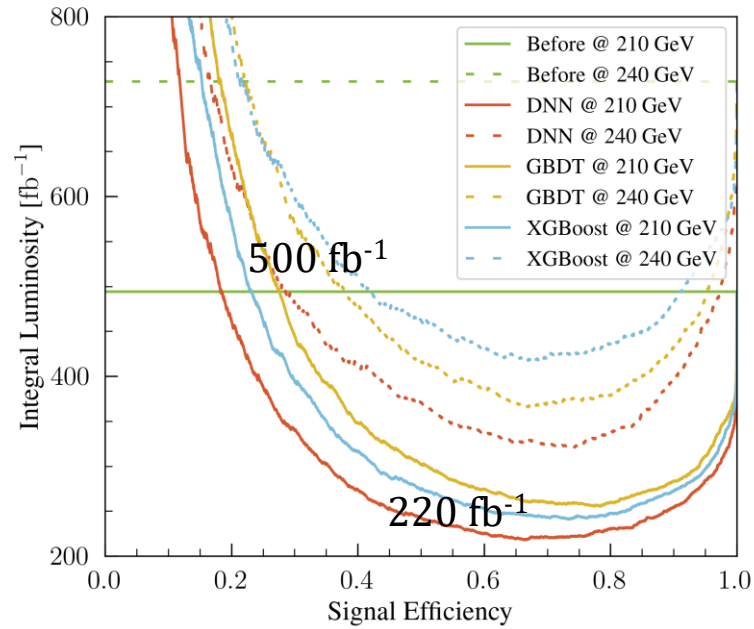
ML response



CEPC detection ability: model-independent



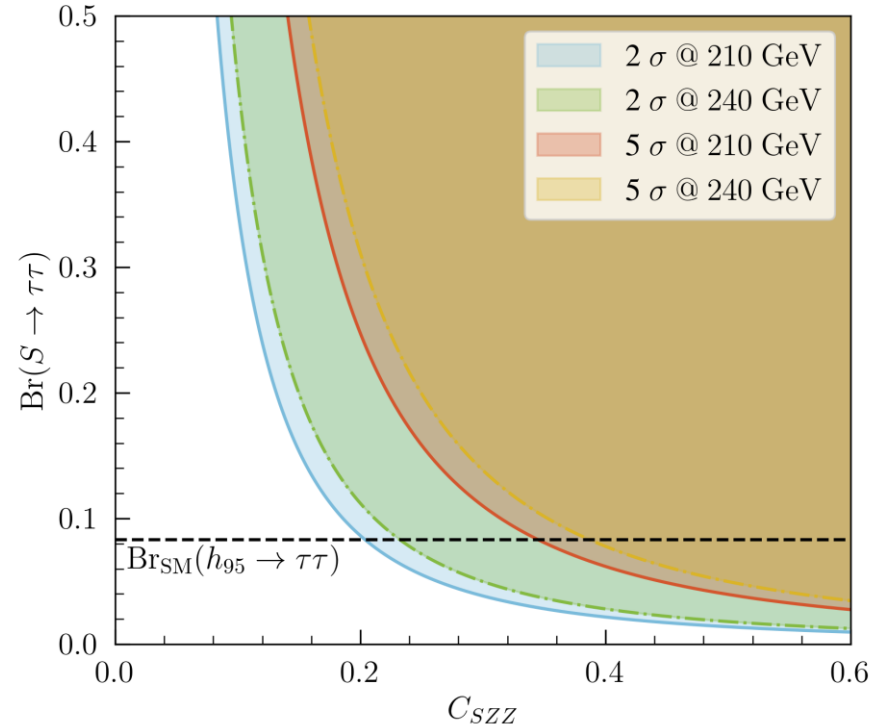
ML Result



$L=500 \text{ fb}^{-1}, \sqrt{s} = 210 \text{ (240) GeV}$

Cuts	ZS	$Z\tau\tau$	Zjj	$Z[\sigma]$
Initial	134 (109)	1819 (1769)	24187 (21745)	0.83 (0.7)
Basic	57.6 (51.2)	752.8 (797.5)	45.5 (55.9)	2.0 (1.7)
M_{recoil}	45.4 (37.6)	63.5 (65.2)	4.1 (5.7)	5.0 (4.1)
ML	30.0 (26.3)	7.6 (9.8)	0.5 (0.9)	7.6 (6.3)

CEPC coverage ($L=500 \text{ fb}^{-1}$)



210 GeV, 500 fb^{-1}

$$\mu_{\tau\tau}^{ZH} > 0.041 \text{ (2}\sigma\text{)}$$

$$\mu_{\tau\tau}^{ZH} > 0.116 \text{ (5}\sigma\text{)}$$

240 GeV, 500 fb^{-1}

$$\mu_{\tau\tau}^{ZH} > 0.052 \text{ (2}\sigma\text{)}$$

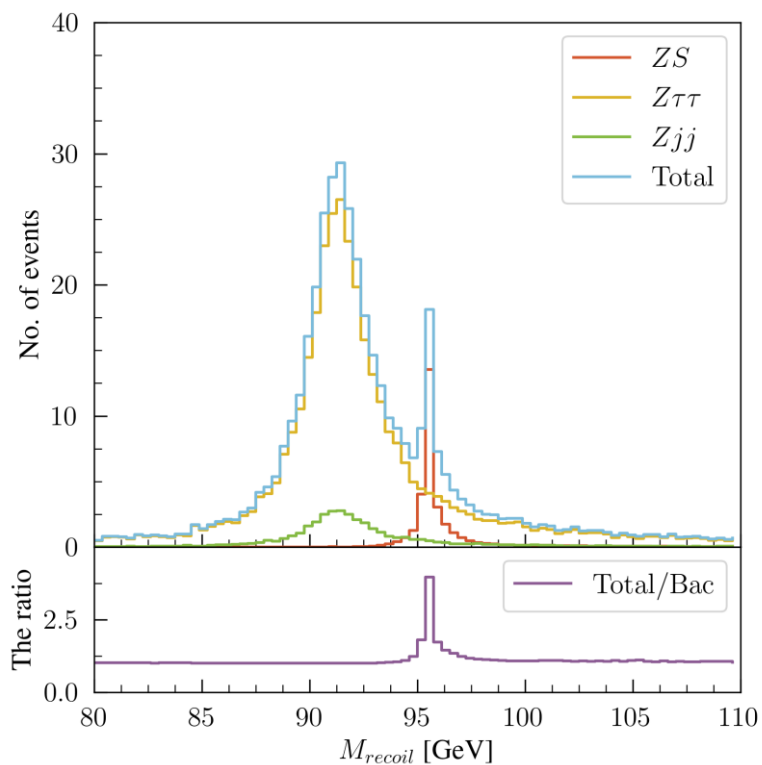
$$\mu_{\tau\tau}^{ZH} > 0.150 \text{ (5}\sigma\text{)}$$

$$\mu_{\tau\tau}^{ZH} \equiv k_Z^2 \cdot \frac{\text{Br}(S \rightarrow \tau\tau)}{\text{Br}_{\text{SM}}(h_{95} \rightarrow \tau\tau)}.$$

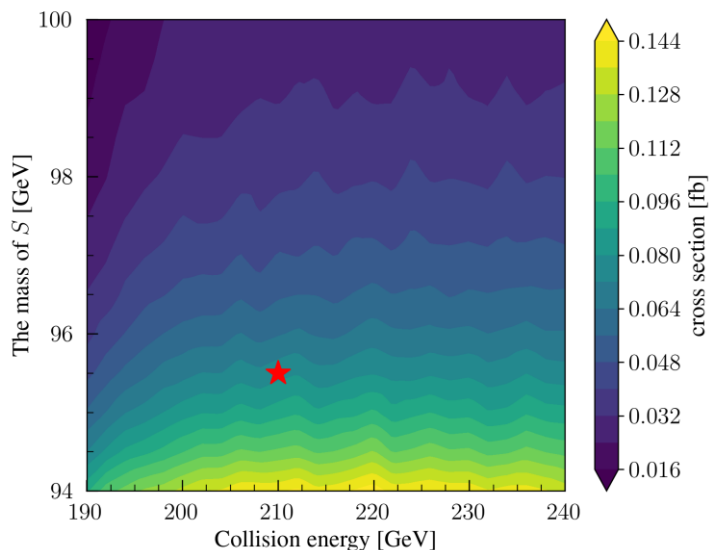
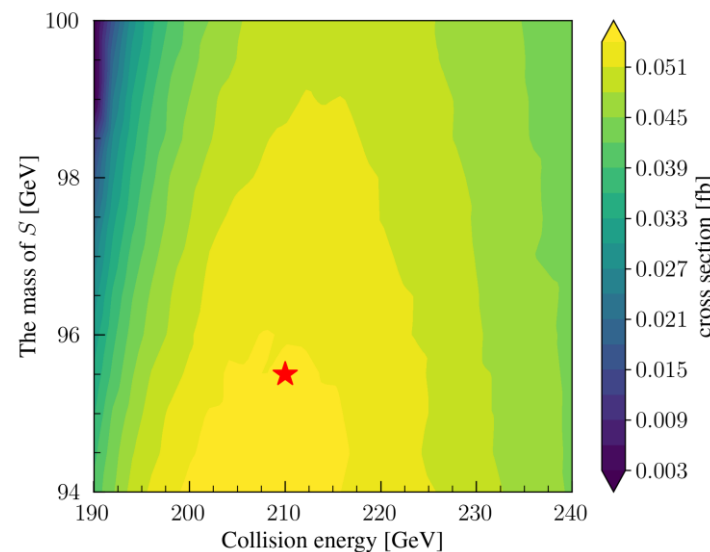
Finding the most effective collision energy

Low $\tau\tau$ reconstruction efficiency,
so use recoil mass instead of $M_{\tau\tau}$

$$M_{\text{recoil}} = \sqrt{s + M_{\mu^+\mu^-}^2 - 2\sqrt{s}(E_{\mu^+} + E_{\mu^-})}$$



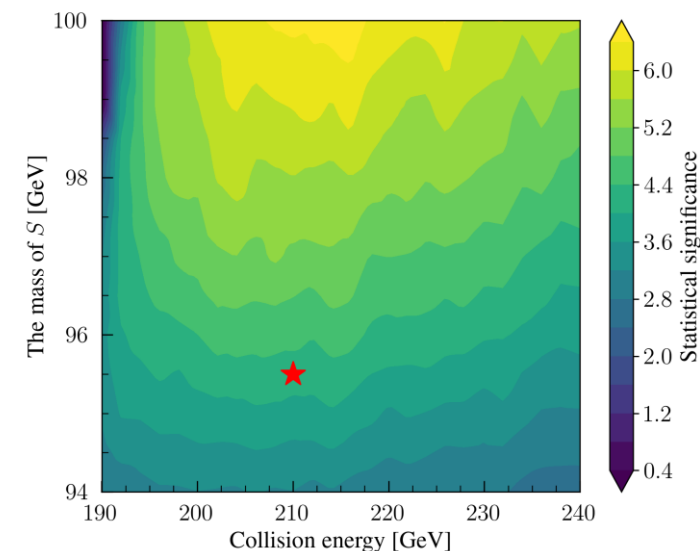
Cut: $m_S - 1.5 < M_{\text{recoil}} < m_S + 1.5$



$$\mathcal{Z} = \sqrt{2L \left[(S + B) \ln \left(1 + \frac{S}{B} \right) - S \right]}$$

Cuts	ZS	$Z\tau\tau$	Zjj	$\mathcal{Z}[\sigma]$
Initial	134 (109)	1819 (1769)	24187 (21745)	0.83 (0.7)
Basic	57.6 (51.2)	752.8 (797.5)	45.5 (55.9)	2.0 (1.7)
M_{recoil}	45.4 (37.6)	63.5 (65.2)	4.1 (5.7)	5.0 (4.1)

$L=500 \text{ fb}^{-1}, \sqrt{s} = 210 (240) \text{ GeV}$



CEPC detection ability: N2HDM-Flipped



χ^2 analysis

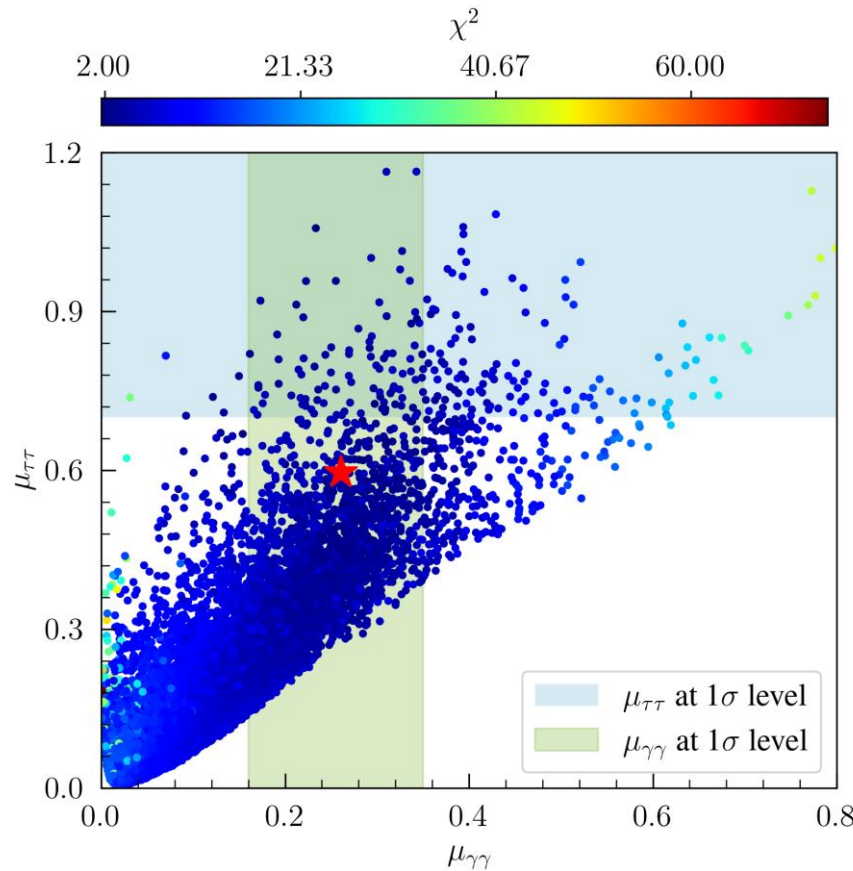
$$\mu_{bb}^{\text{ex}} = 0.117 \pm 0.057$$

$$\mu_{\tau\tau}^{\text{ex}} = 1.2 \pm 0.5$$

$$\mu_{\gamma\gamma}^{\text{ex}} = 0.24^{+0.09}_{-0.08}$$

$$\chi^2 = \sum \frac{(\mu_{xx} - \mu_{xx}^{\text{exp}})^2}{(\Delta\mu_{xx}^{\text{exp}})^2},$$

$$\chi^2 < 8.23 \text{ at 95\% CL.}$$

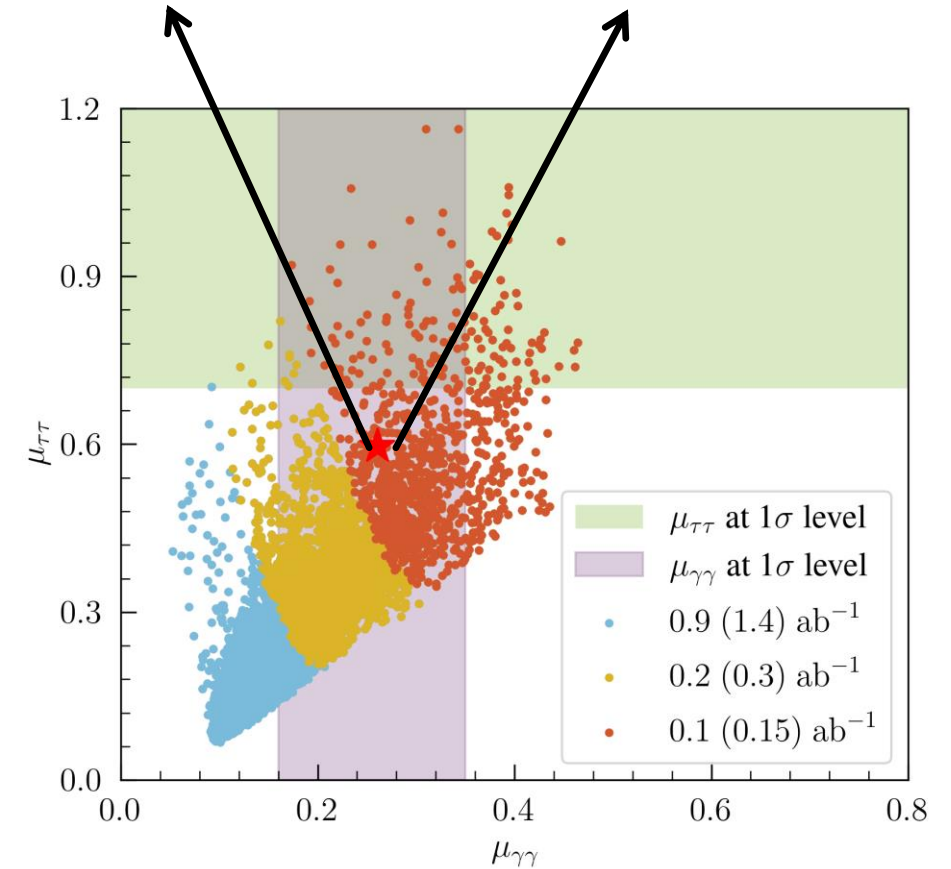


210 GeV

14 fb⁻¹ 2σ
87 fb⁻¹ 5σ

240 GeV

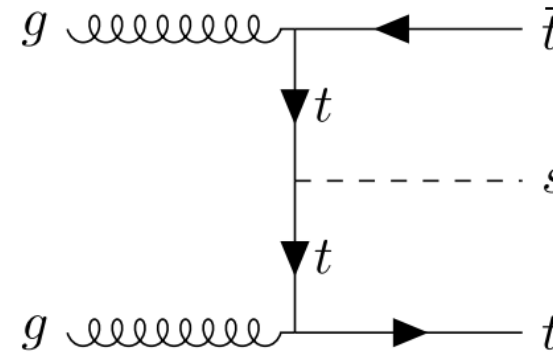
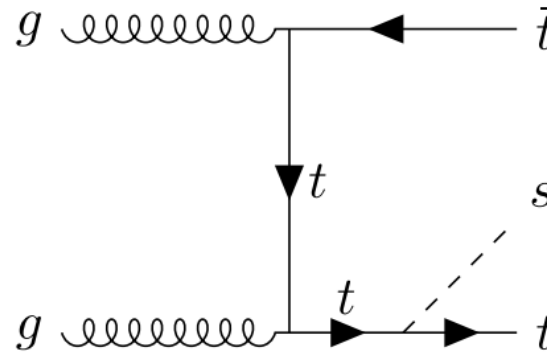
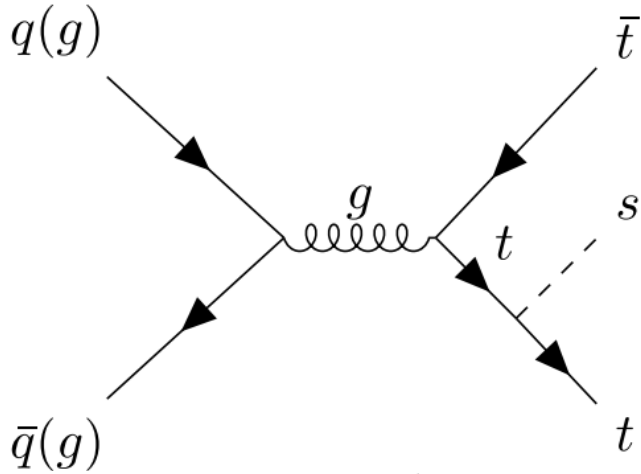
21 fb⁻¹ 2σ
126 fb⁻¹ 5σ



6. 95 GeV light Higgs at the LHC

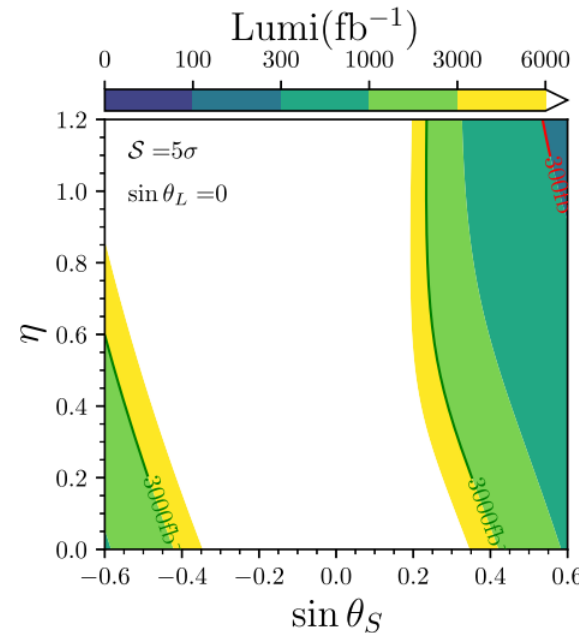
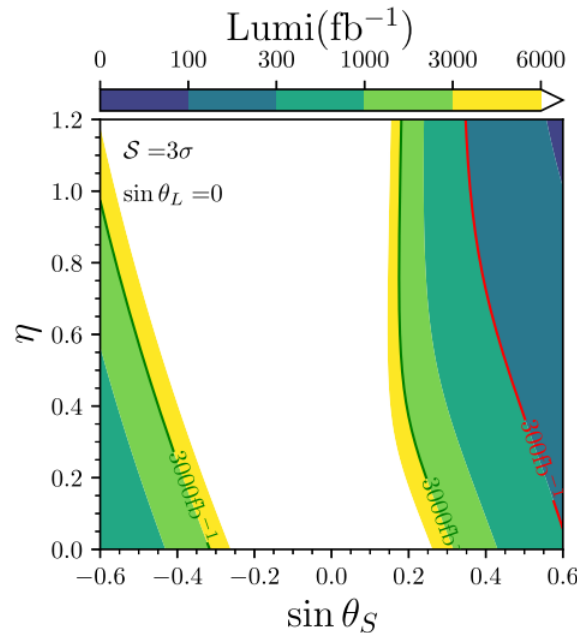
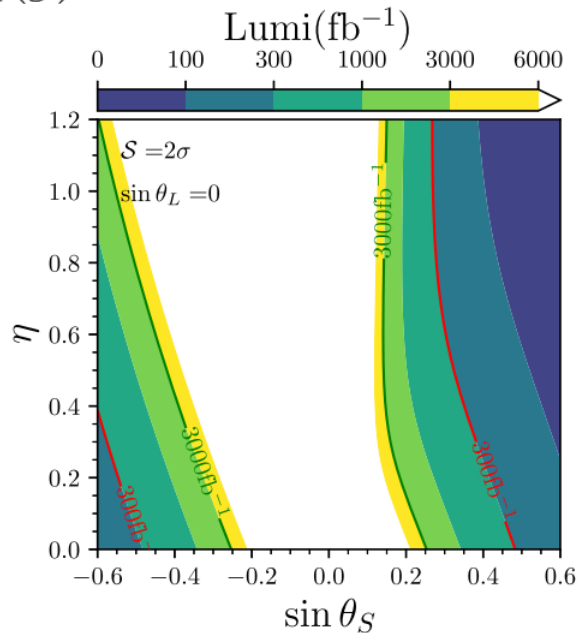


Signal: $pp \rightarrow t\bar{t}h(h \rightarrow \gamma\gamma)$



**top-pair-associated
diphoton channel**

- ◆ light Higgs mass close to Z boson
- ◆ Z decays into e^-e^+ pairs & be misjudged as diphoton by detectors
- ◆ in associated with top pairs reduce this bkg



Minimal Dilaton Model:
With an integrated luminosity of 3000 fb^{-1} , regions of $|\sin \theta| > 0.2$ can be covered over the 3σ level.

95 GeV light Higgs at future hadron colliders



2HDM-I: under current constraints

$$m_h = 95 \text{ GeV}, m_H = 125 \text{ GeV}$$

Parameter
space

$$\begin{aligned} \alpha &\in [-\pi/2, \pi/2], \\ \tan\beta &\in [0, 20], \\ m_{12} &\in [-10 \text{ TeV}, 10 \text{ TeV}], \\ m_{H^\pm} = m_A &\in [150 \text{ GeV}, 1000 \text{ GeV}] \end{aligned}$$

Constraints

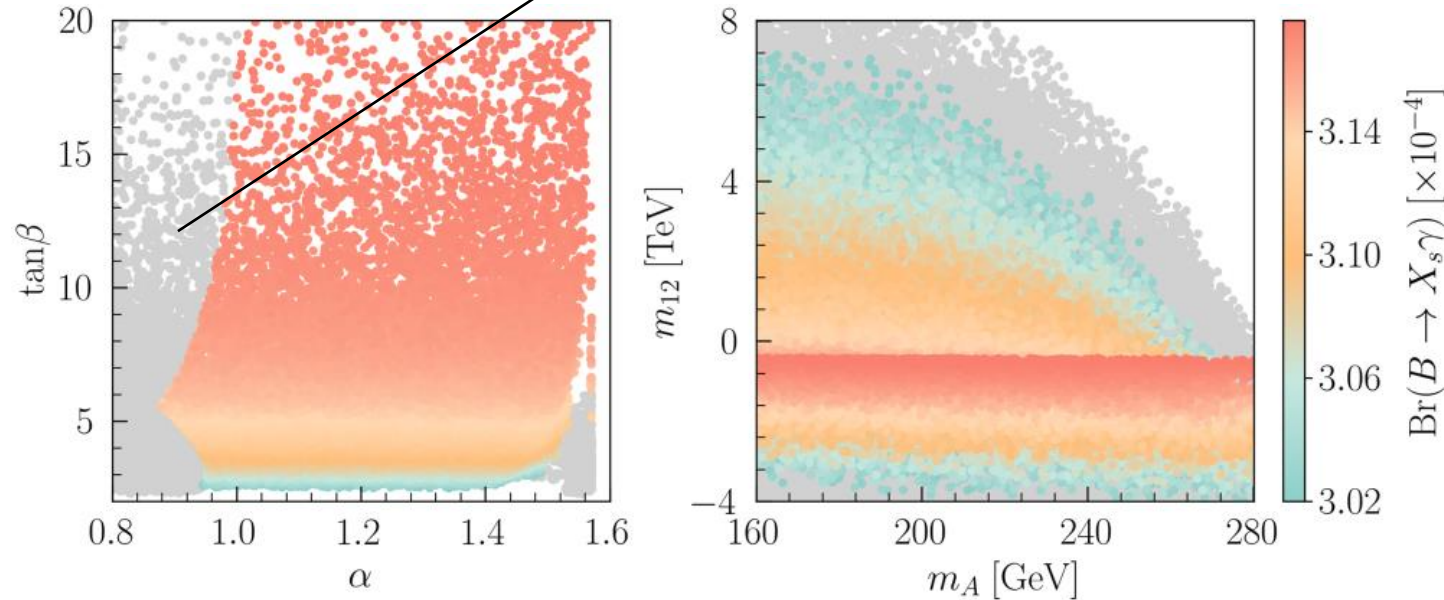
Theoretical

Experimental

unitarity
vacuum stability
perturbativity

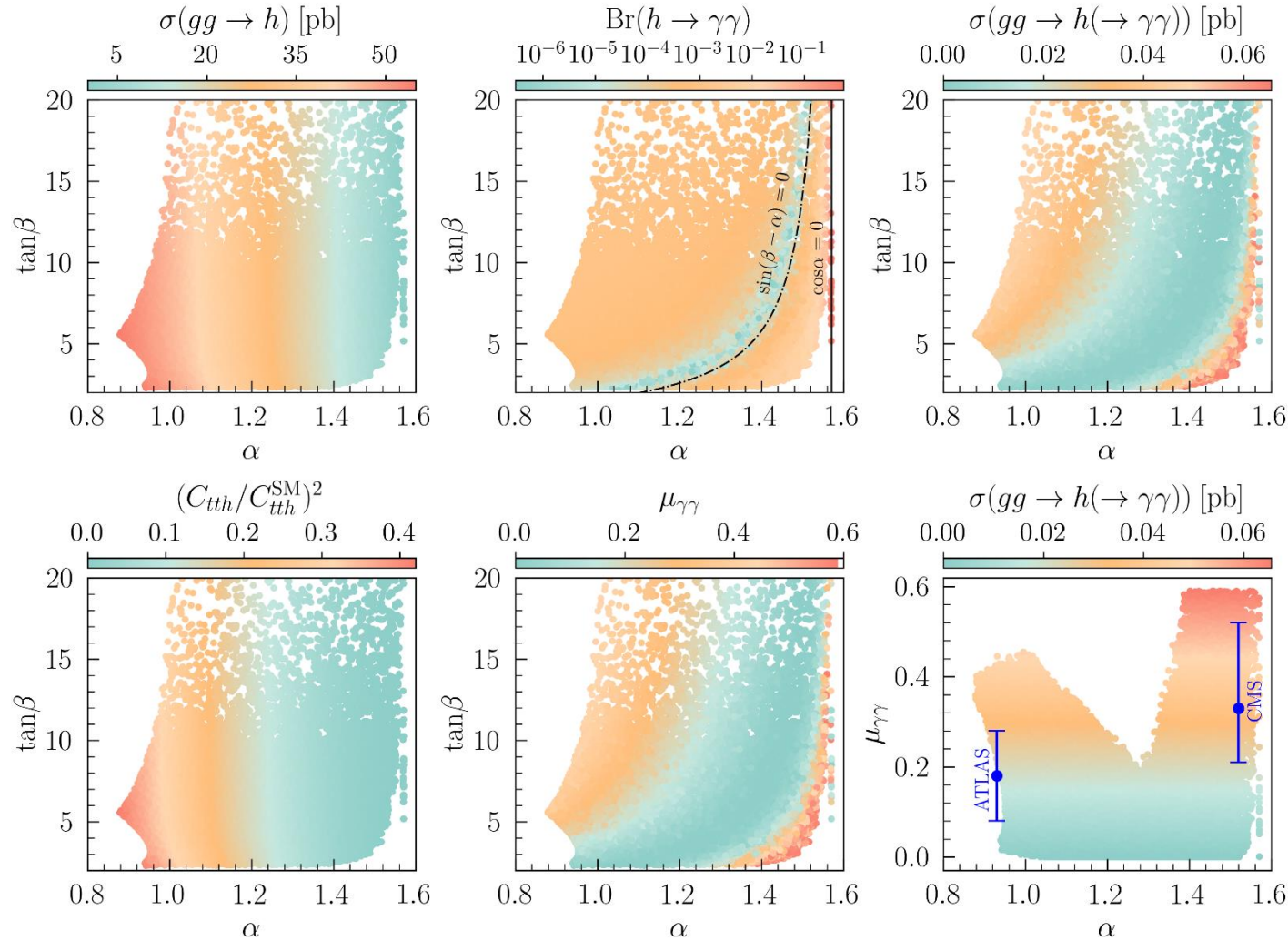
Higgs searches
EWPO
B physics
.....

Excluded by Higgs direct searches



Surviving samples in the $\tan\beta$ vs α
and m_{12} vs m_A planes.

A 95 GeV light Higgs boson in 2HDM-I



Surviving samples in the $\tan\beta$ vs α and $\mu_{\gamma\gamma}$ vs α planes.

Signal strength

$$\mu_{\gamma\gamma} = \frac{\sigma(gg \rightarrow h) \times \text{Br}(h \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(gg \rightarrow h_{95}) \times \text{Br}_{\text{SM}}(h_{95} \rightarrow \gamma\gamma)}$$

$$\sigma_{\text{SM}}(gg \rightarrow h_{95}) = 79.83 \text{ pb}$$

$$\text{Br}_{\text{SM}}(h_{95} \rightarrow \gamma\gamma) = 1.39 \times 10^{-3}$$

$$\text{CMS} : \mu_{\gamma\gamma}^{\text{CMS}} = 0.33^{+0.19}_{-0.12}$$

$$\text{ATLAS} : \mu_{\gamma\gamma}^{\text{CMS}} = 0.18^{+0.1}_{-0.1}$$

Signal vs backgrounds at HL-LHC



Events selecting

$$p_T^{j/b} > 20 \text{ GeV}, p_T^{\ell/\gamma} > 10 \text{ GeV}, |\eta_i| < 5, \\ \Delta R[i, j] > 0.4. (i, j = j, b, \ell, \gamma)$$

1. Basic Cuts:

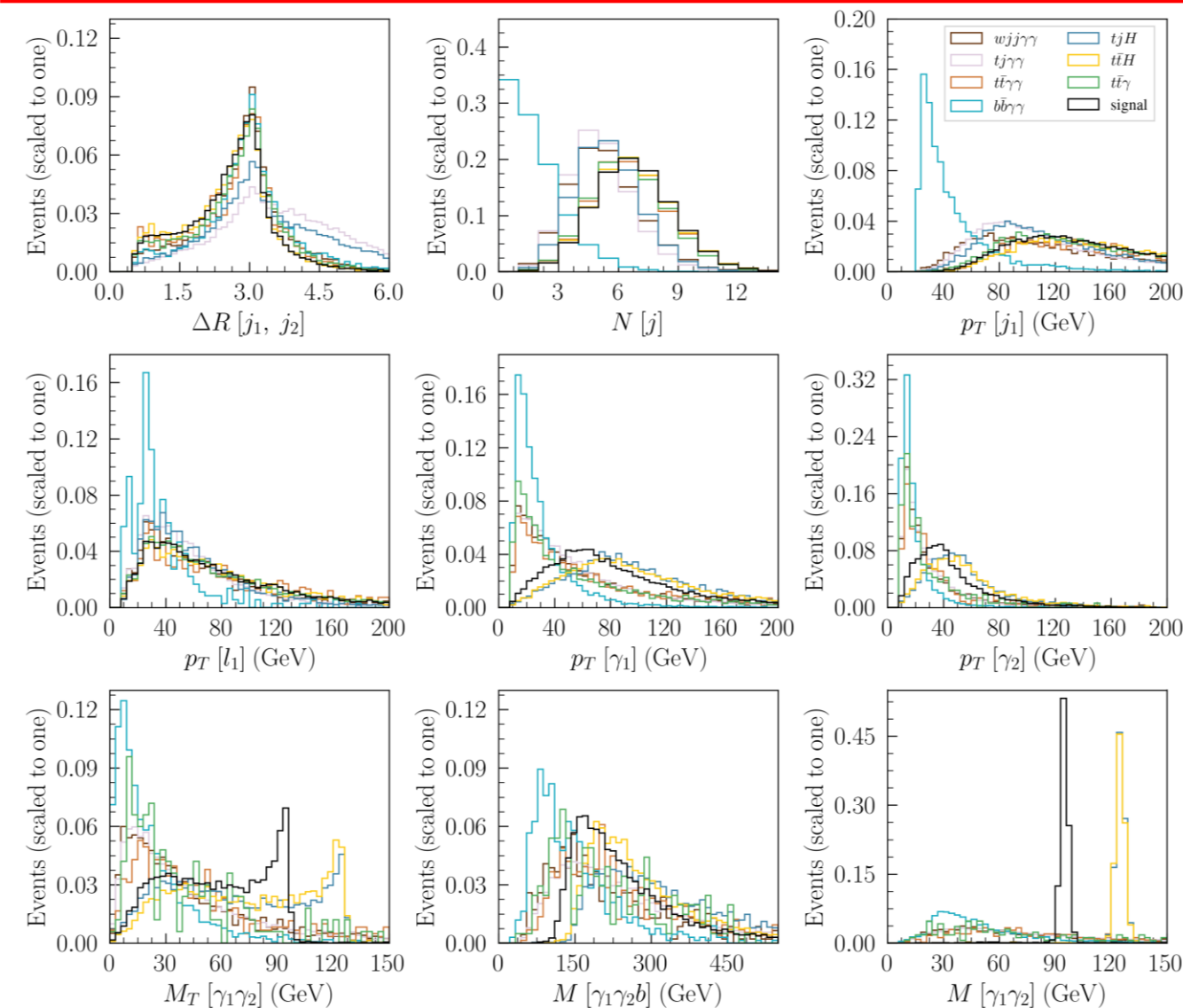
$$N(l) \geq 1, N(\gamma) \geq 2, N(j) \geq 2, N(b) \geq 1, \\ p_T[\gamma_1] > 30 \text{ GeV}, p_T[j_1] > 40 \text{ GeV}, p_T[j_2] < 220 \text{ GeV}, \\ \Delta R[j_1, j_2] < 4, \Delta R[\gamma_1, \gamma_2] < 3.6, \\ 0.2 < \theta_{b_1} < 3, \eta_{j_1} > -2.6, \eta_{l_1} > -2.5, \gamma_{j_1} < 50.$$

2. Mass Cuts:

$$92 \text{ GeV} < M[\gamma_1, \gamma_2] < 98 \text{ GeV}, M[\gamma_1, \gamma_2] < 390 \text{ GeV}, \\ M_T[\gamma_1] < 300 \text{ GeV}, M_T[\gamma_1, \gamma_2] < 98 \text{ GeV}.$$

3. Energy Cuts:

$$E_T > 200 \text{ GeV}, H_T < 900 \text{ GeV}, \\ 10 \text{ GeV} < E_T^{\text{miss}} < 190 \text{ GeV}, H_T^{\text{miss}} > 30 \text{ GeV}.$$



HL-LHC Events distribution

Cut flows at LHC and future hardon colliders



Cut flows

Cuts	Signal($\sigma \times L$)	Background($\sigma \times L$)						
	$t\bar{t}h$	$t\bar{t}\gamma$	$t\bar{t}H$	tjH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	$tj\gamma\gamma$	$Wjj\gamma\gamma$
Initial	60	1536000	168	23	2293800	3354	5253	65400
Basic cut	5.27	4577.3	17.25	0.712	848.7	200.0	89.61	268.1
Mass cut	4.13	46.08	0.029	0.0	0.0	6.47	2.67	4.58
Energy cut	3.76	0.0	0.029	0.0	0.0	5.8	1.91	3.27

14 TeV HL-LHC 3 ab⁻¹

Cuts	Signal($\sigma \times L$)	Background($\sigma \times L$)						
	$t\bar{t}h$	$t\bar{t}\gamma$	$t\bar{t}H$	tjH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	$tj\gamma\gamma$	$Wjj\gamma\gamma$
Initial	192	3168000	927	115	3408000	14178	19920	206009
Basic cut	13.92	6874.6	80.06	3.23	1192.8	776.6	358.5	995.0
Mass cut	9.14	0.0	0.111	0.002	68.16	17.22	5.13	12.36
Energy cut	8.59	0.0	0.111	0.002	0.0	16.27	3.21	10.3

27 TeV HE-LHC 10 ab⁻¹

Cuts	Signal($\sigma \times L$)	Background($\sigma \times L$)						
	$t\bar{t}h$	$t\bar{t}\gamma$	$t\bar{t}H$	tjH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	$tj\gamma\gamma$	$Wjj\gamma\gamma$
Initial	2325	33120000	11724	1005	14856000	141570	138120	1255800
Basic cut	101.42	53985	621	17.1	6388.1	4764.2	1446.7	4897.6
Mass cut	64.94	662.4	1.06	0.0	148.6	91.0	24.82	37.67
Energy cut	59.75	0.0	0.821	0.0	0.0	78.86	21.28	25.12

100 TeV FCC-hh 30 ab⁻¹

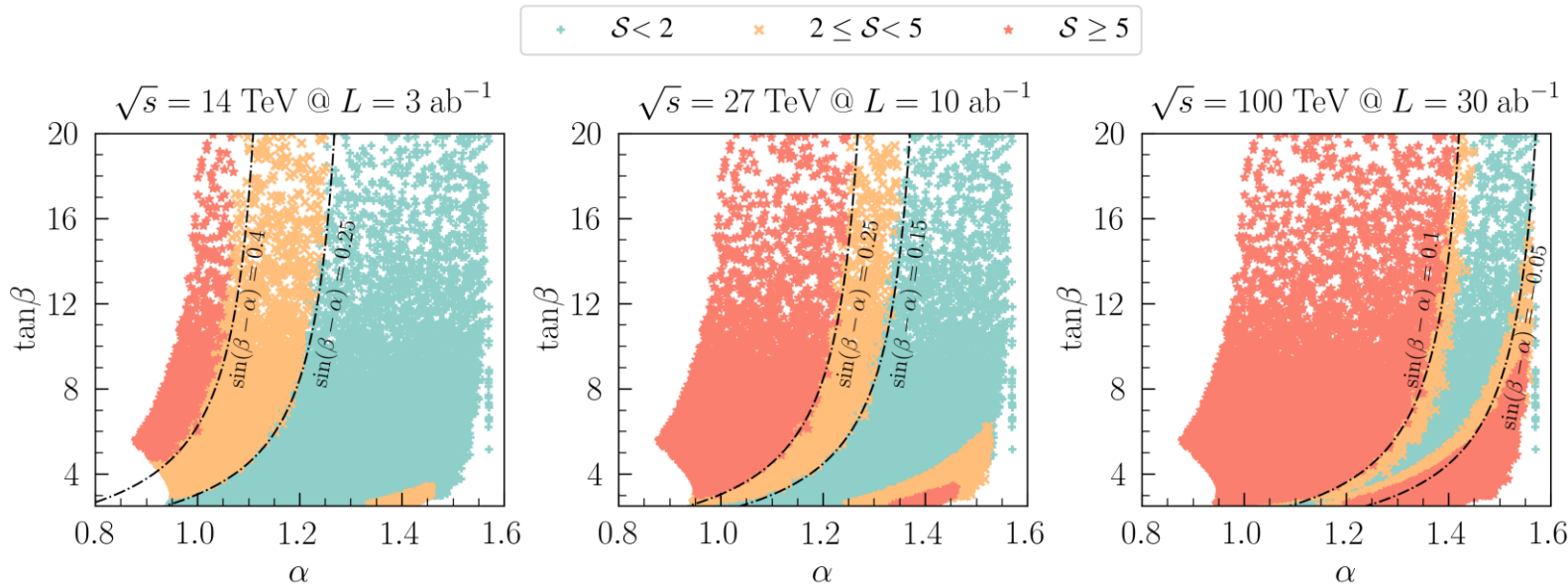
Checking a 95 GeV light Higgs boson at LHC and future hadron colliders

Signal significance

$$\mathcal{S} = \sqrt{2L \left[(S+B) \ln \left(1 + \frac{S}{B} \right) - S \right]}$$

required minimum luminosity

	2σ	5σ
14 TeV HL-LHC	240 fb ⁻¹	1.4 ab⁻¹
27 TeV HE-LHC	120 fb ⁻¹	750 fb ⁻¹
100 TeV FCC-hh	12 fb ⁻¹	71 fb ⁻¹



Covered parameter space in 2HDM-I

HL-LHC 3 ab⁻¹ :

5 σ cover $\sin(\alpha-\beta) > 0.4$,
2 σ cover $\sin(\alpha-\beta) > 0.25$

HE-LHC 10 ab⁻¹ :

5 σ cover $\sin(\alpha-\beta) > 0.25$,
2 σ cover $\sin(\alpha-\beta) > 0.15$

FCC-hh 30 ab⁻¹ :

5 σ cover $\sin(\alpha-\beta) > 0.1$ 或 < -0.05

6. Conclusions and outlooks



MC result in $e^+e^- \rightarrow Z(\rightarrow \mu^+\mu^-)S$
process at CEPC with $L=20 \text{ ab}^{-1}$ shows:

Particle level features and **MIParT** network
can improve measurement precision

- $S \rightarrow \tau\tau$: $6.2\% \rightarrow 2.6\%$ (**↑58%**)
- $S \rightarrow bb$: $1.07\% \rightarrow 0.77\%$ (**↑28%**)

CEPC detection ability in our method

Channel	5σ significance covered	1% detected precision
$S \rightarrow \tau\tau$	$\mu = 0.016$	$\mu = 0.96$
$S \rightarrow bb$	$\mu = 0.0042$	$\mu = 0.13$

Based on arXiv: 2510.24662

Higgsstrahlung $\tau\tau$ channel at the CEPC

1. The signal excesses around 95 GeV or a little heavier, setting the collision energy to **210 GeV is the most appropriate at lepton collider.**
2. After applying DNN, the required integral luminosity is **reduced to more than 1/2** to cover the benchmark point.
3. When $L=500 \text{ fb}^{-1}$, $\mu_{\tau\tau}^{ZH} > 0.041$ (0.052) can be covered at 2σ level and $\mu_{\tau\tau}^{ZH} > 0.116$ (0.15) can be covered at 5σ level for 210 (240) GeV collision energy.
4. The best fit point can be covered at **2σ level for $L=14$ (21) fb^{-1} and 5σ level for $L=87$ (126) fb^{-1}** for 210 (240) GeV collision energy.

top-pair-associated diphoton channel at the LHC and future hadron colliders

1. Higgs direct search data can exclude the most region with $\alpha \leq 0.95$.
2. Surviving samples can get maximum cross sections of the process $pp \rightarrow tth(\rightarrow \gamma\gamma)$ at the **0.44 fb, 1.42 fb, and 17.21 fb** at HL-LHC, HE-LHC, and FCC-hh, respectively.
3. To achieve a 5σ significance at HL-LHC, HE-LHC, and FCC-hh, the required luminosity are at least **1.4 ab^{-1} , 750 fb^{-1} , and 71 fb^{-1} .**
4. At 3 ab^{-1} HL-LHC, 10 ab^{-1} HE-LHC and 30 ab^{-1} FCC-hh, 2HDM-I with $\sin(\beta-\alpha) \geq 0.4$, 0.25, and 0.1 can be covered at 5σ level.

Thanks!

Backup slides

Key Performance Metrics

Accuracy:

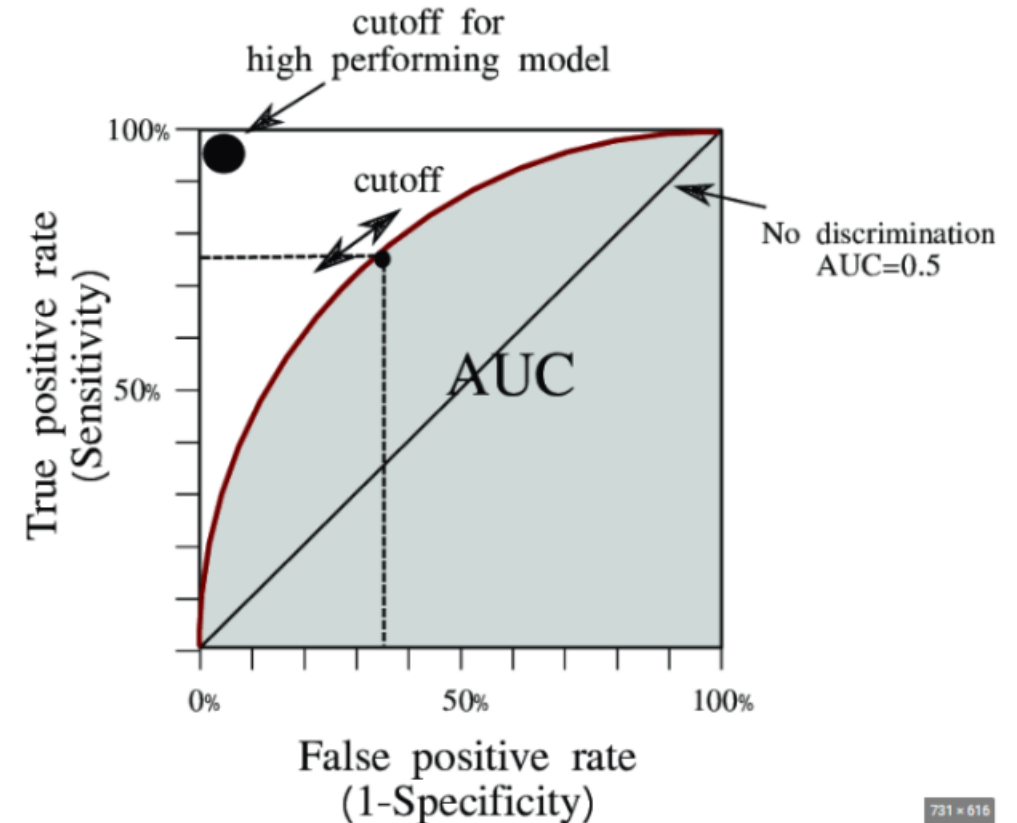
$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FN + FP},$$

Background Rejection at a Certain Signal Efficiency:

$$\text{Rej}_{X\%} = \frac{1}{\text{FPR}} \Big|_{\text{TPR}=X\%}$$

For example, a $\text{Rej}_{30\%}$ value of 2500 indicates that at a TPR of 30%, the inverse of the FPR is 2500. This equates to only one false positive for every 2500 negative instances

AUC:



ACC (Accuracy)
AUC (Area Under the Curve)

- **True Positive Rate (TPR, Sensitivity/Recall)** $TPR = \frac{TP}{TP+FN}$

Interpretation: Fraction of real signals correctly identified.

- **False Positive Rate (FPR)** $FPR = \frac{FP}{FP+TN}$

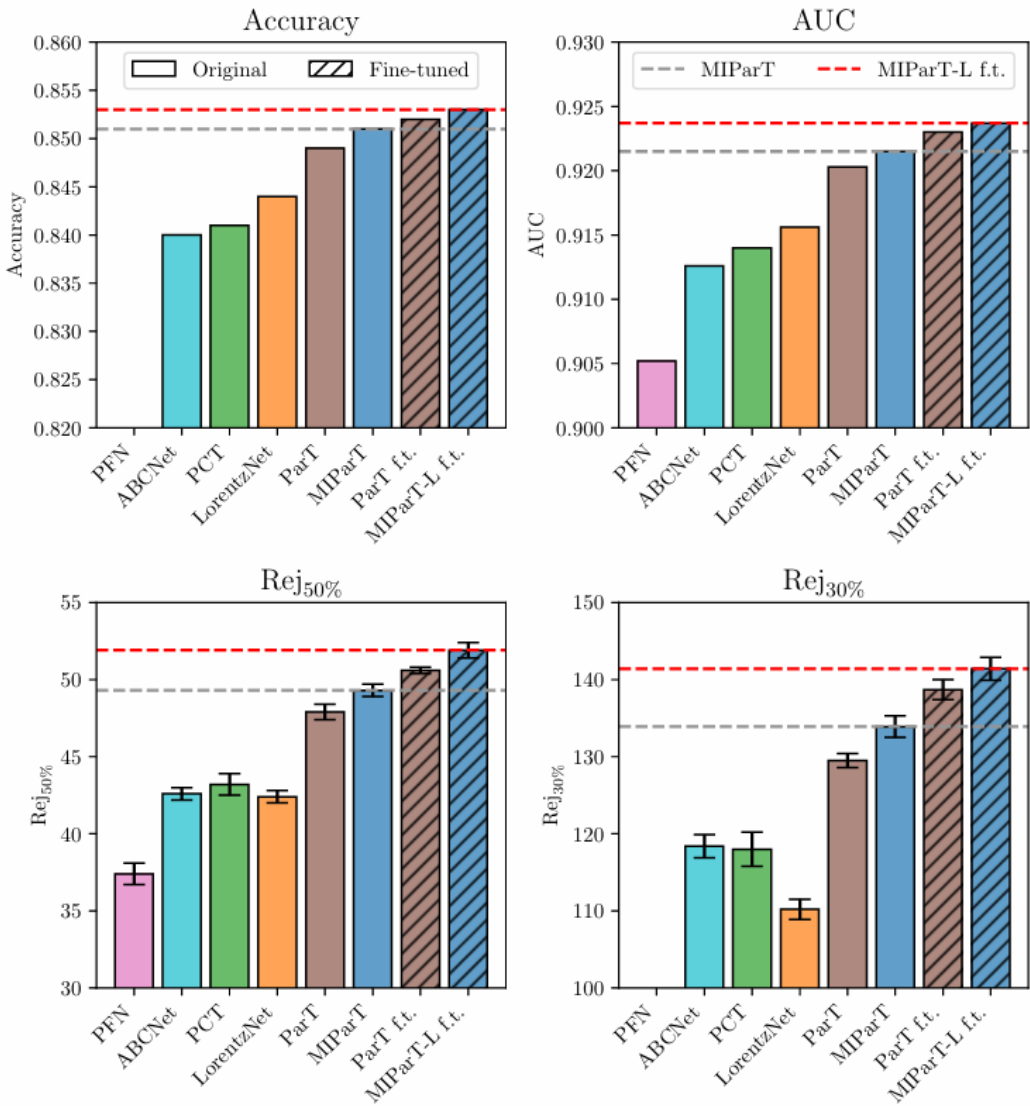
Interpretation: Fraction of backgrounds incorrectly classified as signals.

- **True Negative Rate (TNR, Specificity)** $TNR = \frac{TN}{FP+TN} = 1 - FPR$

Interpretation: Fraction of backgrounds correctly rejected.

- **False Negative Rate (FNR)** $FNR = \frac{FN}{TP+FN} = 1 - TPR$

Interpretation: Fraction of signals missed.



Performance on QuarkGluon

	ACC	AUC
ParT	0.849	0.9203
MIPaT	0.851	0.9215
ParT.f.t	0.852	0.9230
MIParT.f.t	0.853	0.9237

ML can enhance the light Higgs search potential?

Advantages

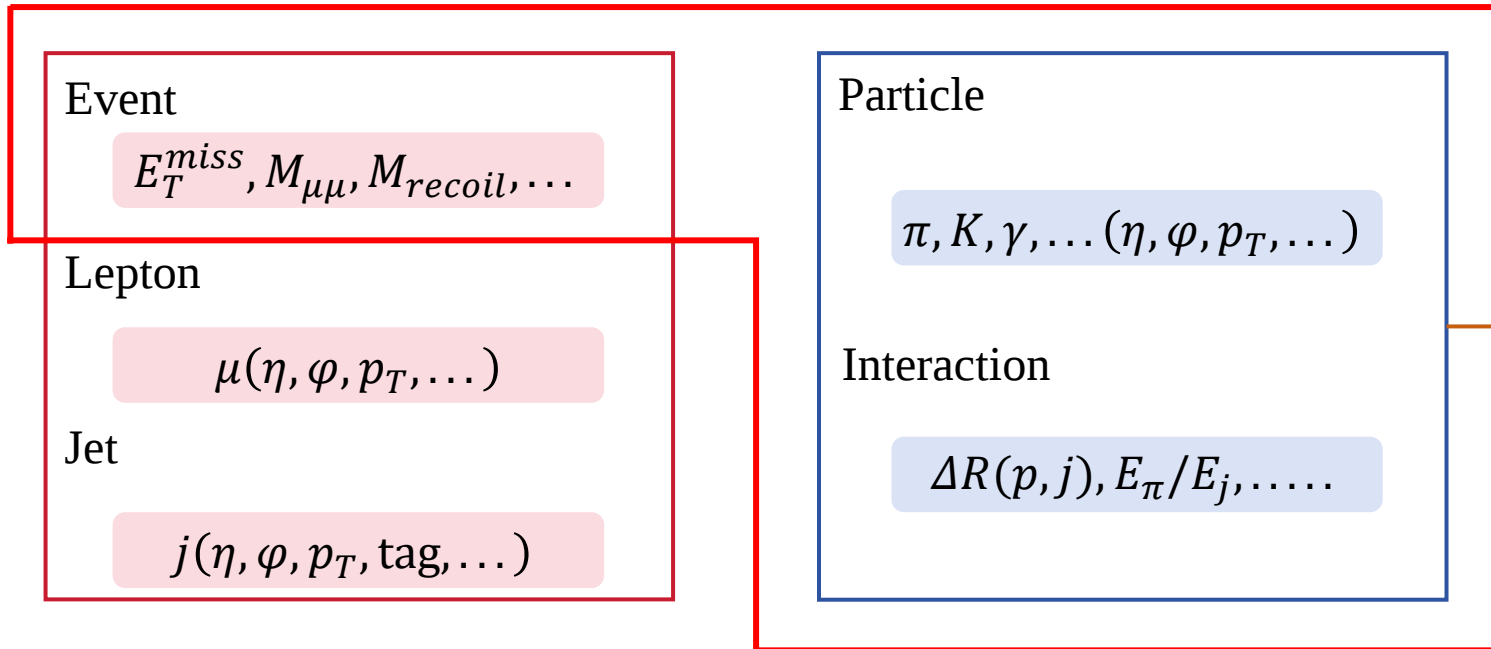
1. Deal multiple features big data
2. Feature interaction extraction capability
3. Balance signal efficiency and background rejection rate
4. Automation, high efficiency

Disadvantages

Black box

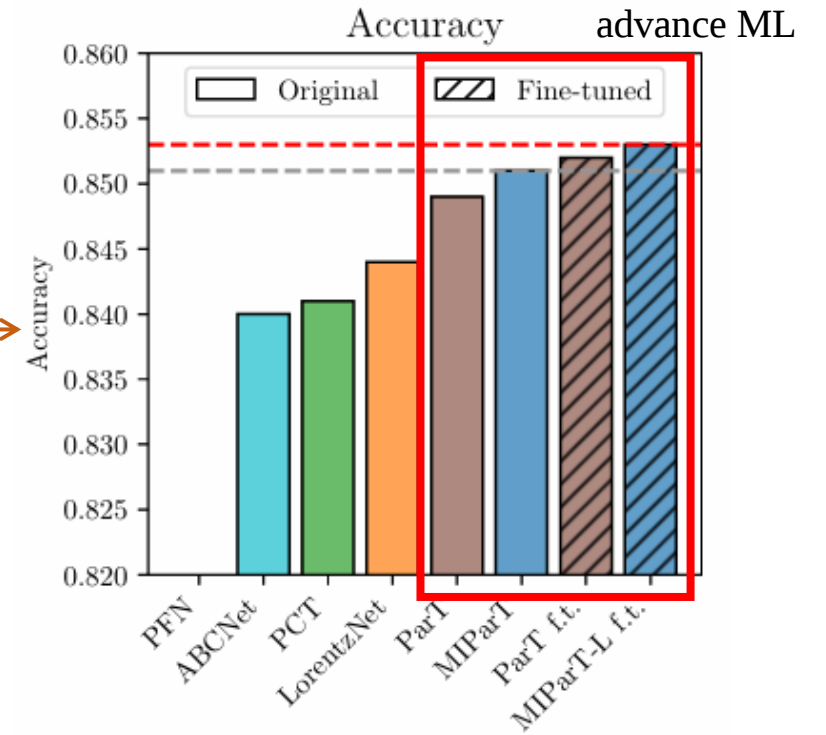
More features + advance ML = improve?

Our features



Cut-based features

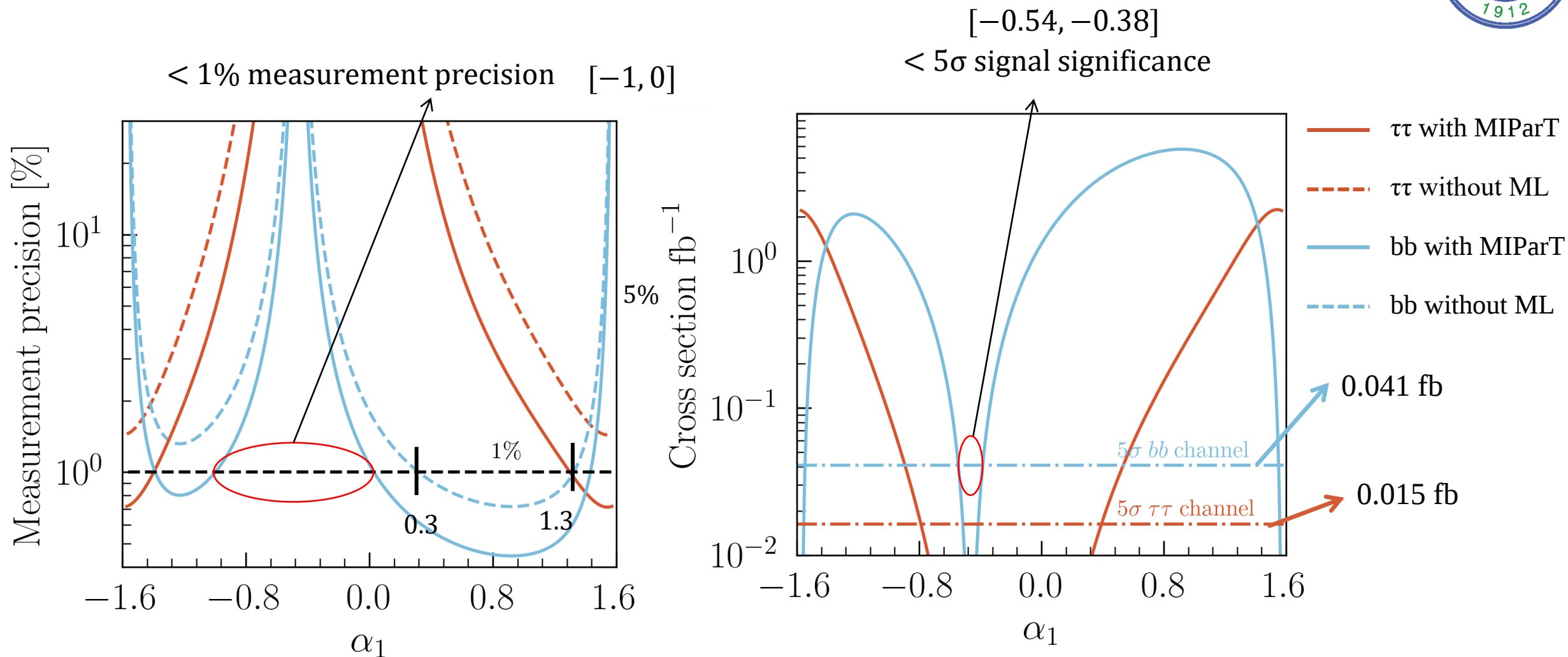
ML features



ML performance¹

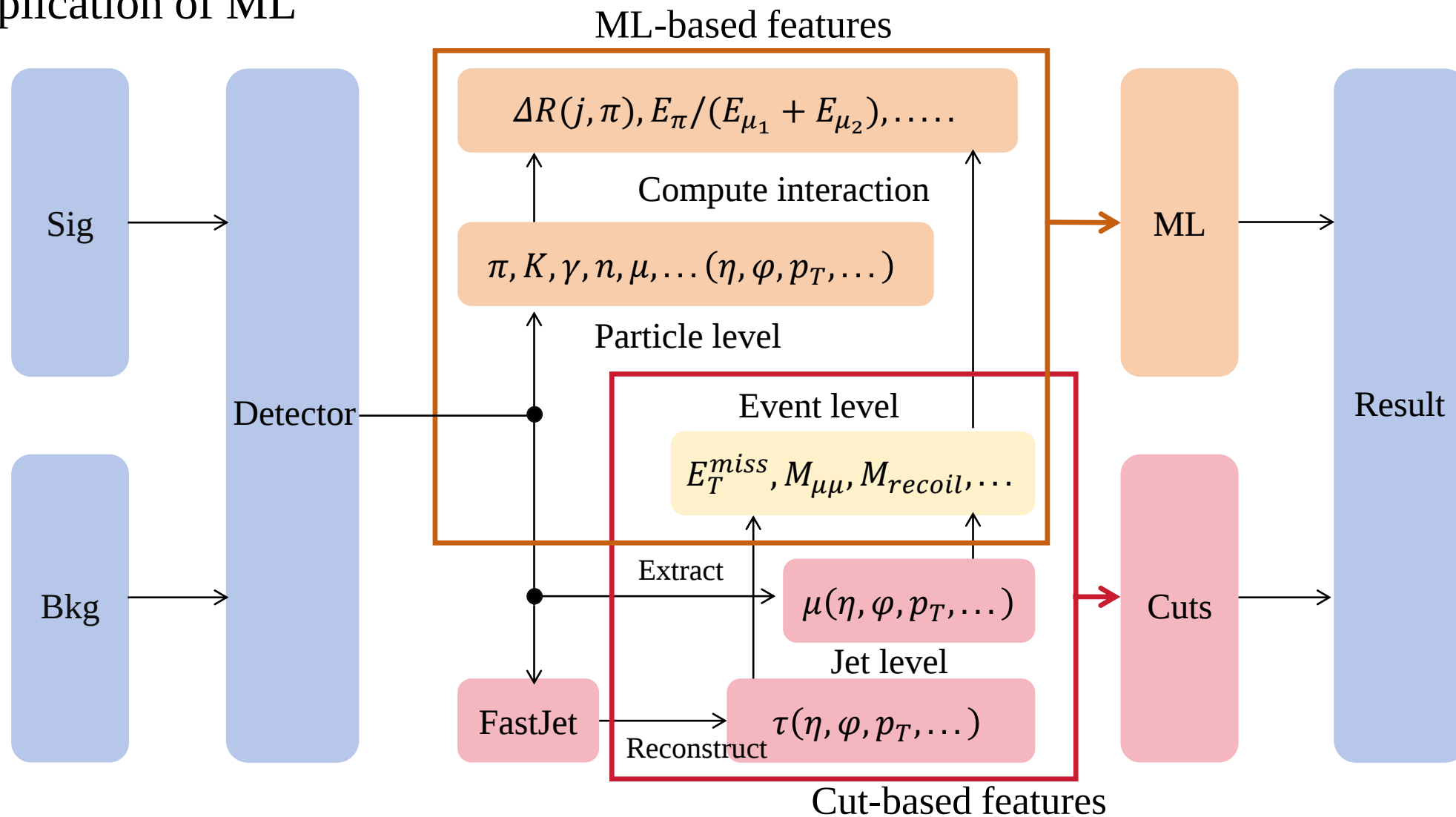
1. arXiv: 2407.08682

CEPC detect range for benchmark

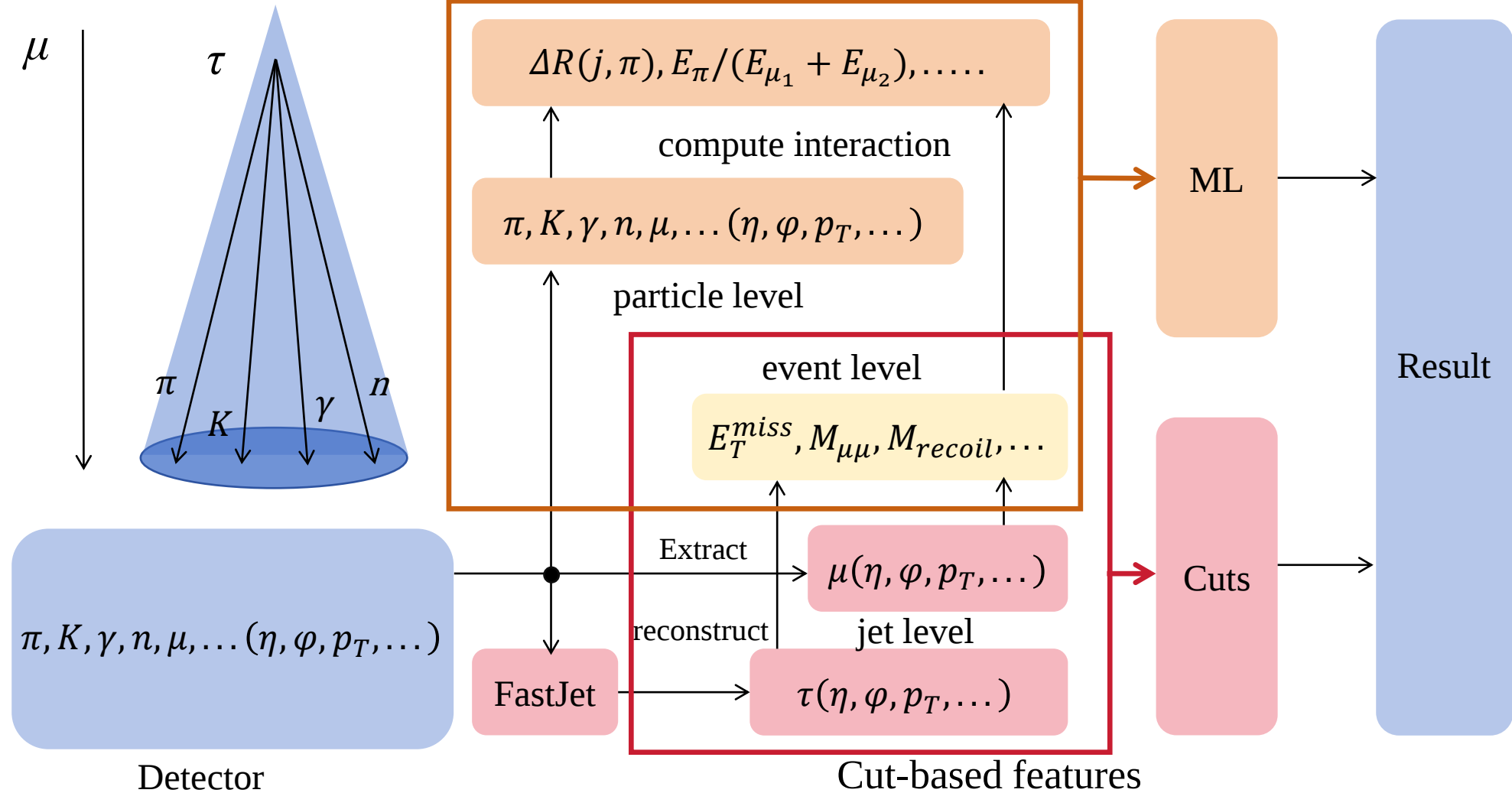


$\tan\beta = 2, \cos\alpha_2 = \sqrt{2}/2, \text{ and } \cos(\beta - \alpha_1) = 0 \text{ for } \alpha_1 = -0.46$

The Application of ML



The Application of ML



Applying to special models: N2HDM-Flipped

N2HDM-Flipped

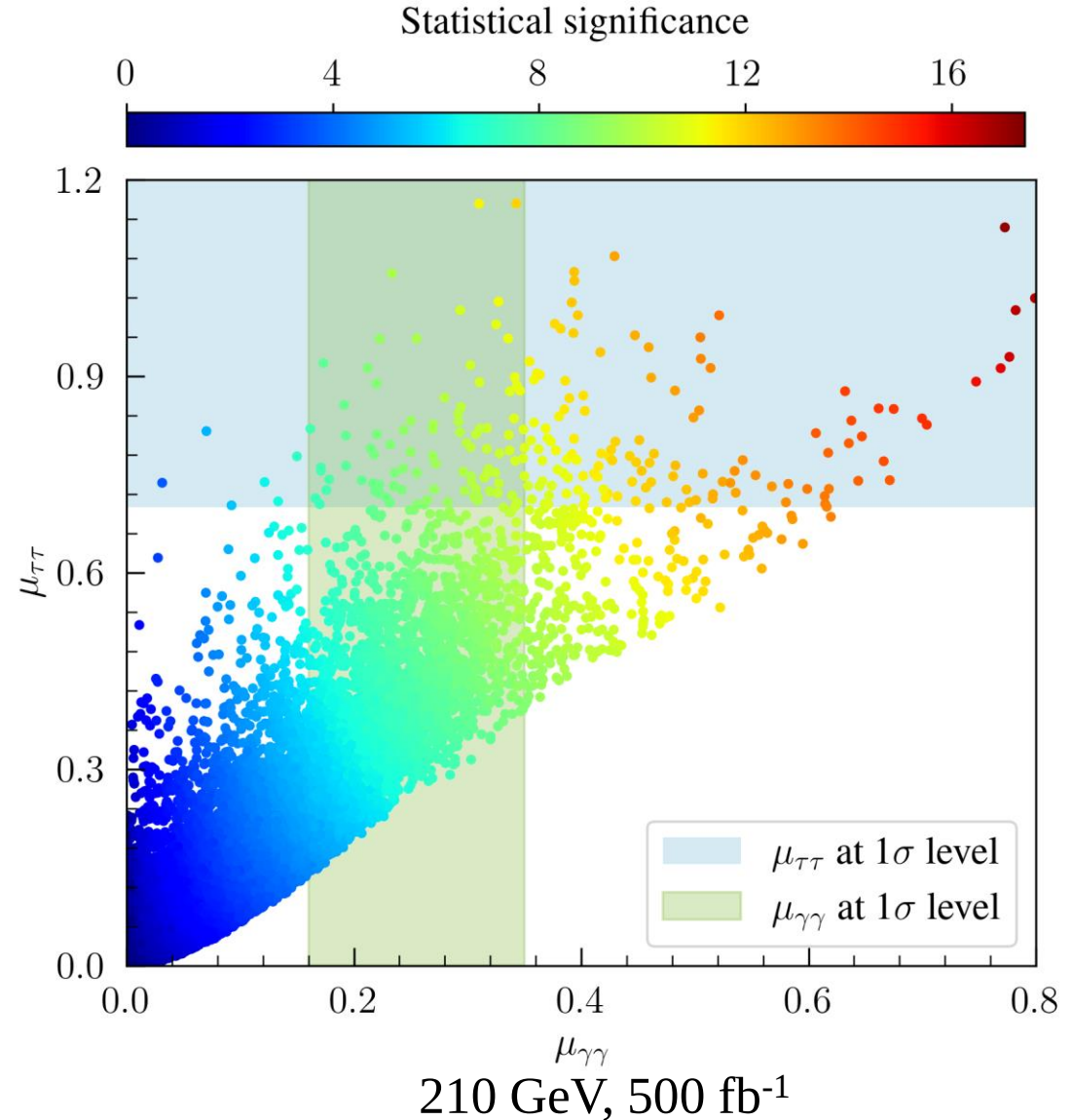
$H_a, H_b, H_c; A; H^\pm$

Parameter space: 12

$$\begin{aligned} m_{H_a} &= 125.09 \text{ GeV}, m_{H_b} \in [95, 96] \text{ GeV} \\ m_{H_c, A} &\in [300, 1500] \text{ GeV}, m_{h^\pm} \in [580, 1500] \text{ GeV}, \\ \tan\beta &\in [0.8, 10], \sin R_{ac, bc} \in [-1, 1], \\ C_{H_a VV}^2 &\in [0.7, 1], C_{H_a tt}^2 \in [0.7, 1.2], \\ m_{12}^2 &\in [10^{-3}, 5 \cdot 10^5], v s \in [1, 3000]. \end{aligned}$$

The constraints taken into consideration

- 125 GeV Higgs data
- Direct searches for Higgs
- B physics
- Electroweak precision observables
- Vacuum stability
- Perturbative unitarity



Technologies

