Higgs 2023, Nov, IHEP, Beijing

Search the charged and neutral scalars at the LHC

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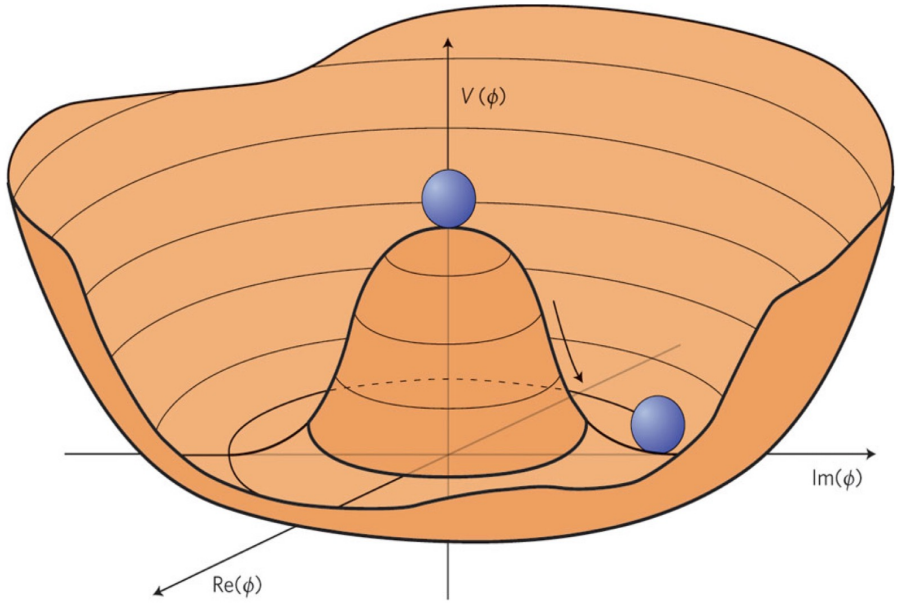
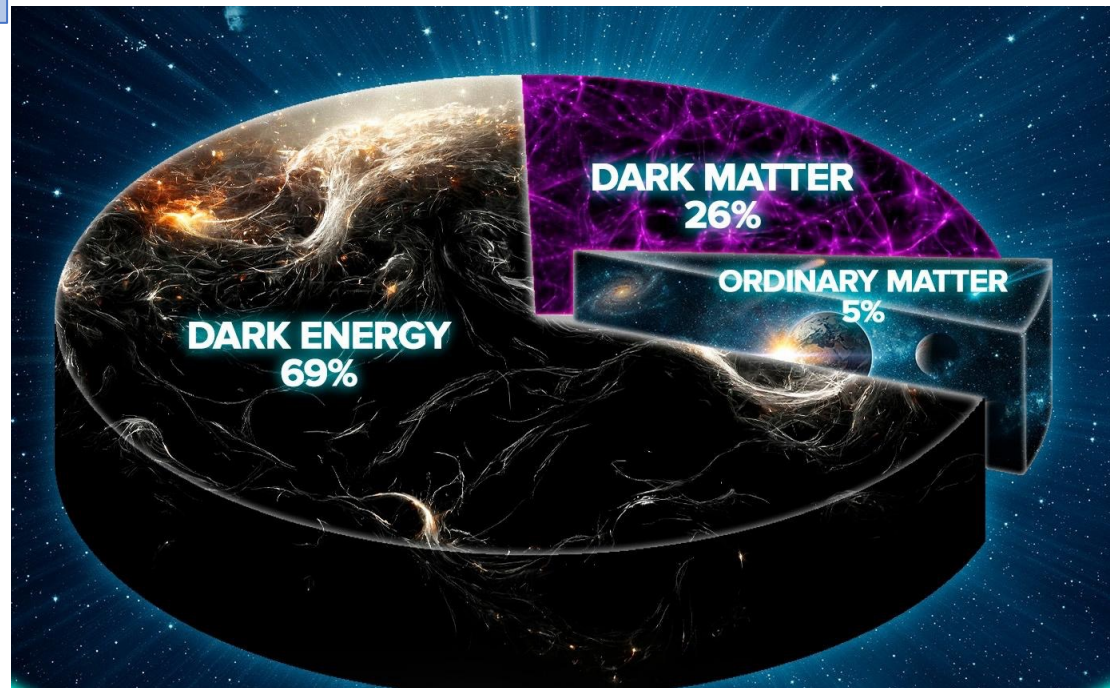
Outline

- 2HDM and Higgs measurement at (HL-) LHC
- Direct searches: H, A, and $H^{\pm}$
- Indirect searches: Global fit
- Physics implications
- Conclusion

BSM scalars?

baryon asymmetry of the Universe (BAU)





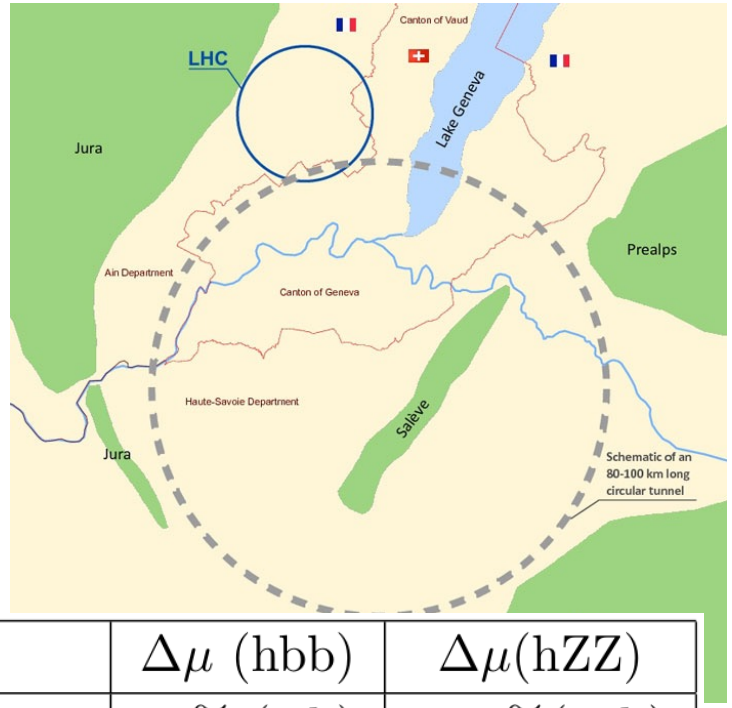
SM: Cross-over around T=100 GeV

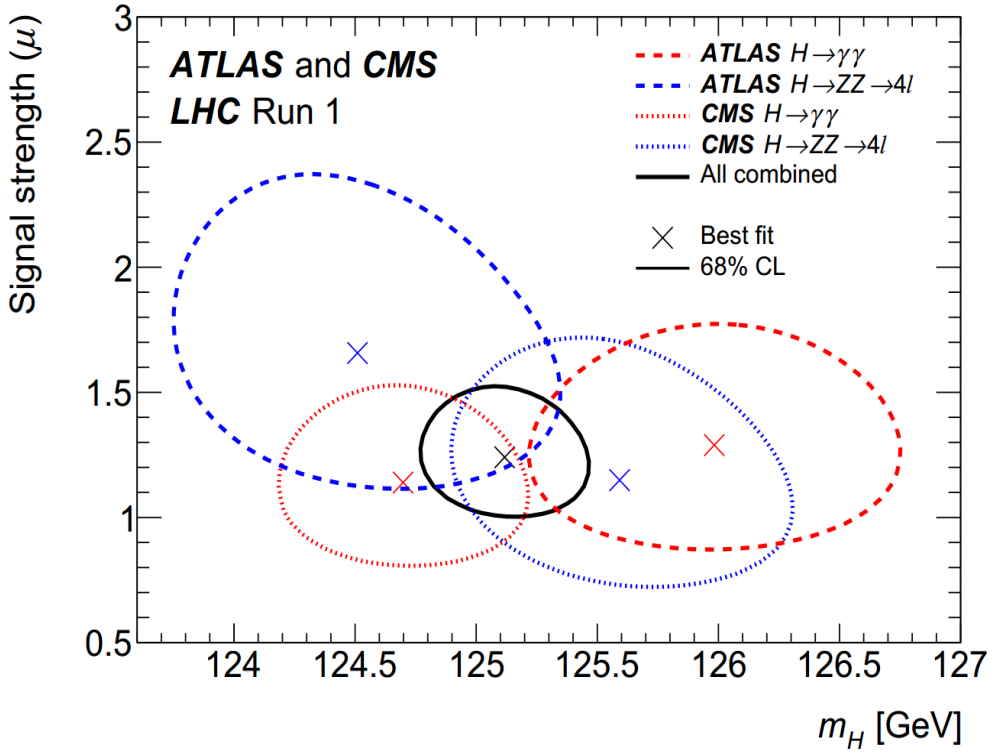
BSM: bubble formation → asymmetry

Various evidence about DM

The way to it/them

CMS-HIG-14-042
ATLAS-HIGG-2014-14





Collider	$\Delta\mu$ (hbb)	$\Delta\mu$(hZZ)
LHC Run-I	50% (wh)	≈32%(ggh)
LHC 14 TeV $300fb^{-1}$	26%	7%
LHC 14 TeV $3000fb^{-1}$	12%	4%
CEPC 240 GeV $5ab^{-1}$ (zh)	0.28%	4.3%
FCC-ee 240 GeV $10ab^{-1}$ (zh)	0.2%	3.1%
ILC 240 GeV $2ab^{-1}$ (zh)	0.42%	6.7%
ILC 350 GeV $0.2ab^{-1}$ (zh)	1.6%	28%
ILC 500 GeV $4ab^{-1}$ (vvh)	0.24%	2.9%

The way to it/them

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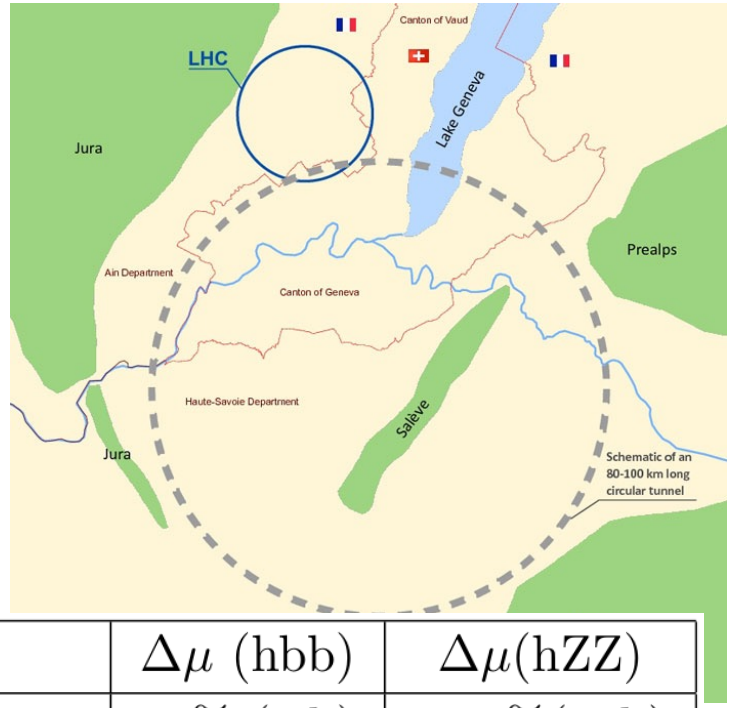

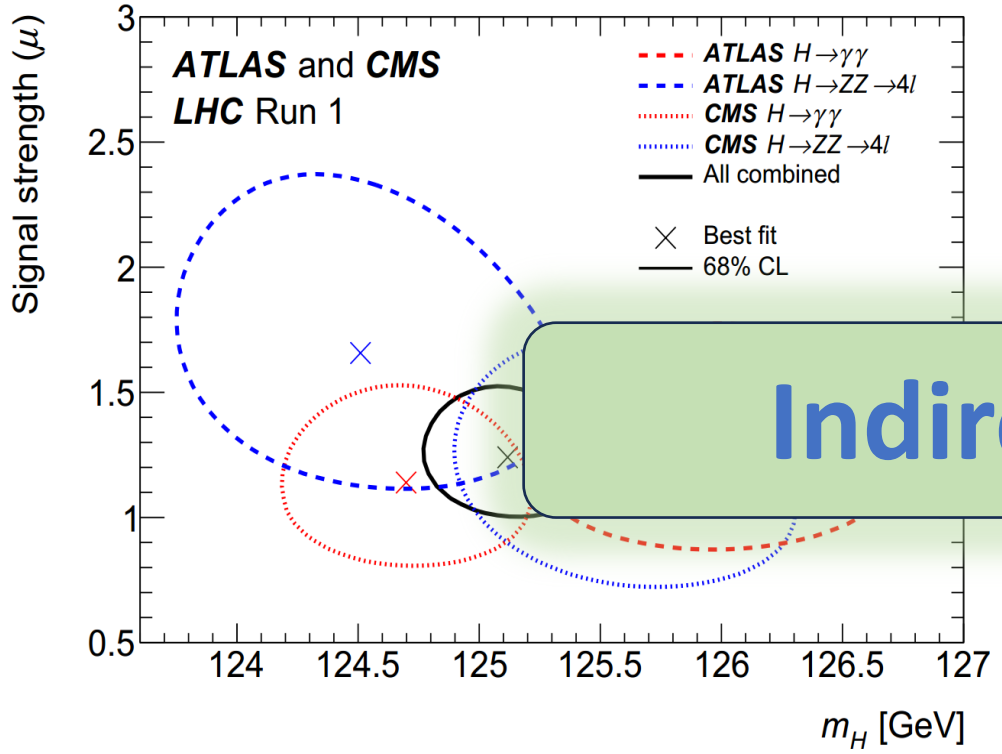

Indirect: Global fit

Collider	$\Delta\mu$ (hbb)	$\Delta\mu$(hZZ)
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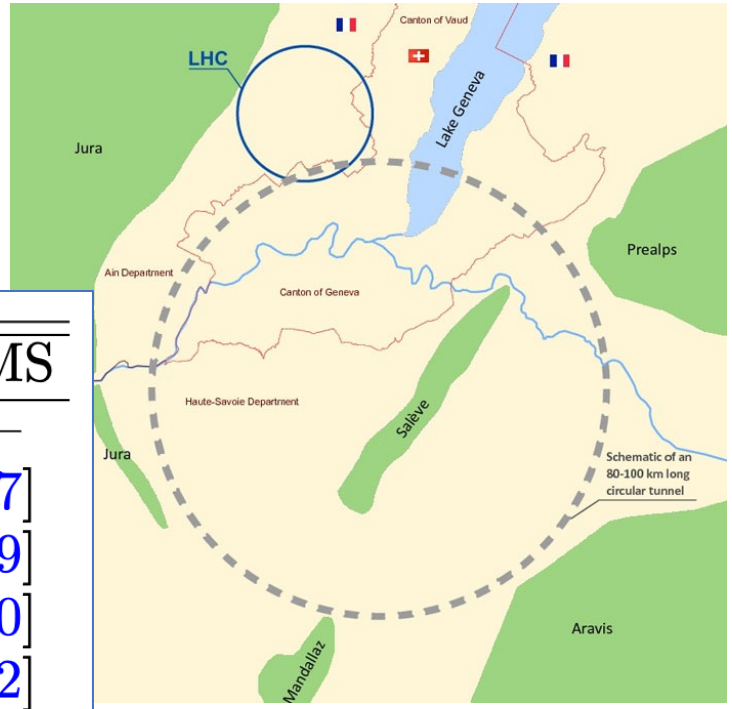
The way to it/them



Conventional channels:

channel	CMS	ATLAS
$A/H \to \mu\mu$	[17]	[18]
$A/H \to bb$	[19]	[20]
$A/H \to \tau\tau$	[21, 22]	[23]
$A/H \to \gamma\gamma$	[24, 25]	[26–28]
$A/H \to tt$	[29]	-
$H \to ZZ$	[30]	[31]
$H \to WW$	[32]	[33]

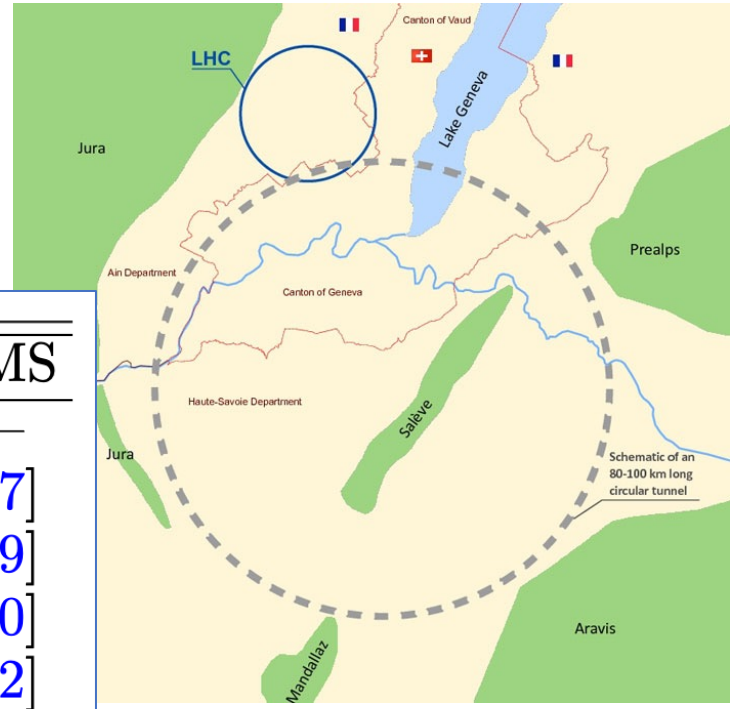
channel	ATLAS	CMS
$h \to AA \to bbbb$	[46]	—
$h \to AA \to bb\tau\tau$	—	[47]
$h \to AA \to bb\mu\mu$	[48]	[49]
$h \to AA \to \tau\tau\tau\tau$	—	[50]
$h \to AA \to \tau\tau\mu\mu$	[51]	[52]
$h \to AA \to \mu\mu\mu\mu$	([53])	([54])

channel	ATLAS	CMS
$A/H \to HZ/AZ \to bb\ell\ell$	[57] (13 TeV)	[58] (13 TeV)
$A/H \to HZ/AZ \to \tau\tau\ell\ell$	—	[59] (8 TeV)

Exotic channels:

channel	ATLAS		CMS	
	8 TeV	13 TeV	8 TeV	13 TeV
$A \to hZ \to bb\ell\ell$	[36]	[37]	[38]	[39]
$A \to hZ \to \tau\tau\ell\ell$	[40]	[41]	[38]	—
$H \to hh$	[42]	[43]	[44]	[45]

The way to it/them



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channel	ATLAS	CMS
$A/H \to HZ/AZ \to 4\ell\ell$	[57] (13 TeV)	[58] (13 TeV)
		[59] (8 TeV)

direct: Simulation / recast

Exotic channels:

channel	ATLAS		CMS	
	8 TeV	13 TeV	8 TeV	13 TeV
$A \to hZ \to bb\ell\ell$	[36]	[37]	[38]	[39]
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Example: 2HDM

- Two Higgs Doublet Model

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

	ϕ_1	ϕ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

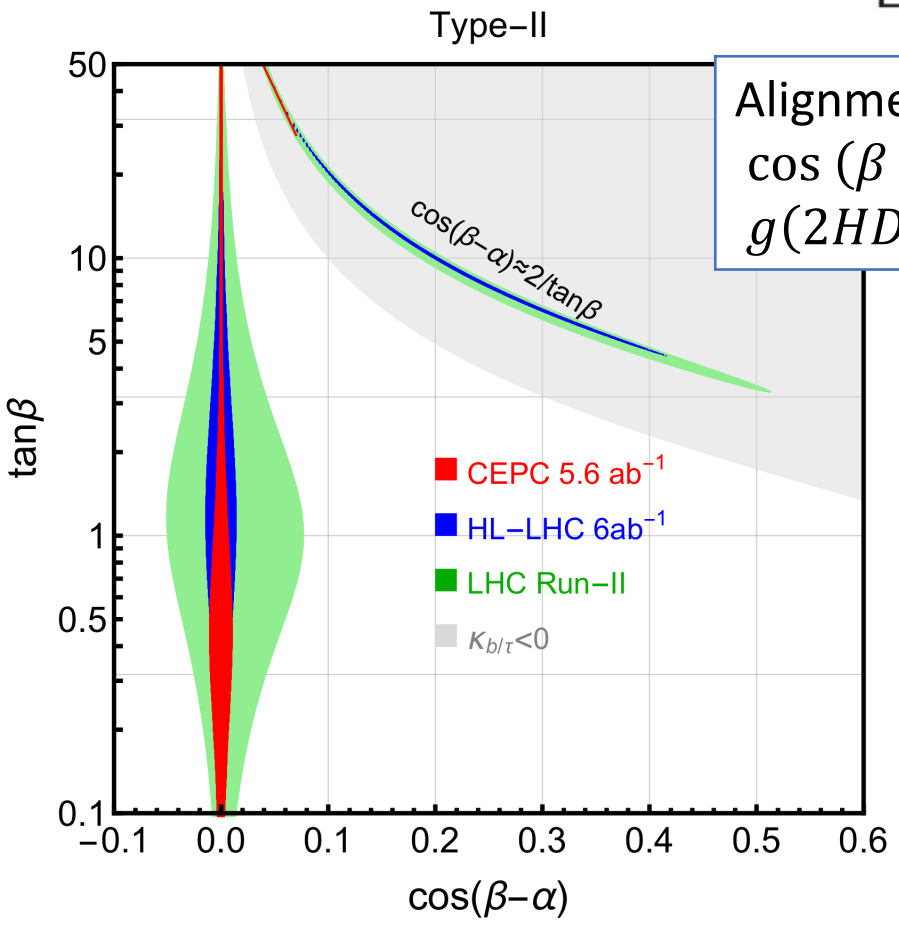
$$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \quad \Rightarrow \quad v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

246 GeV 125. GeV

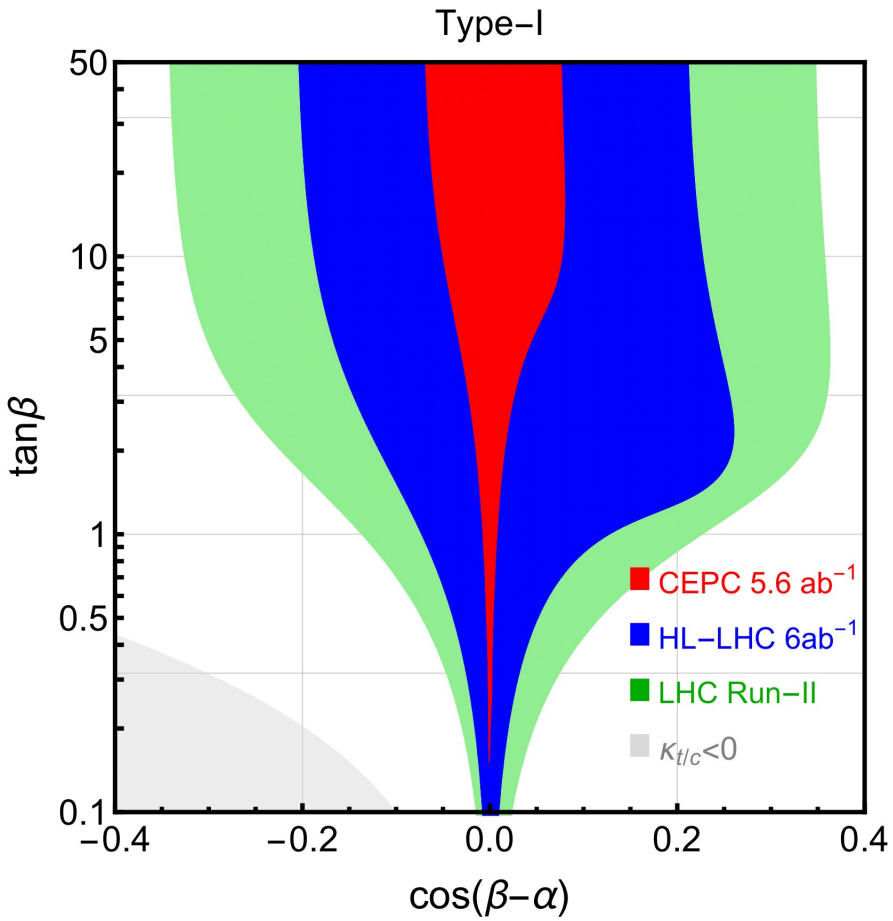
Soft Z_2 symmetry breaking: m_{12}^2

Indirect

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$



Alignment limit :
$\cos(\beta-\alpha)=0$
$g(2HDM)=g(SM)$



1910.06269 WS

Indirect

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
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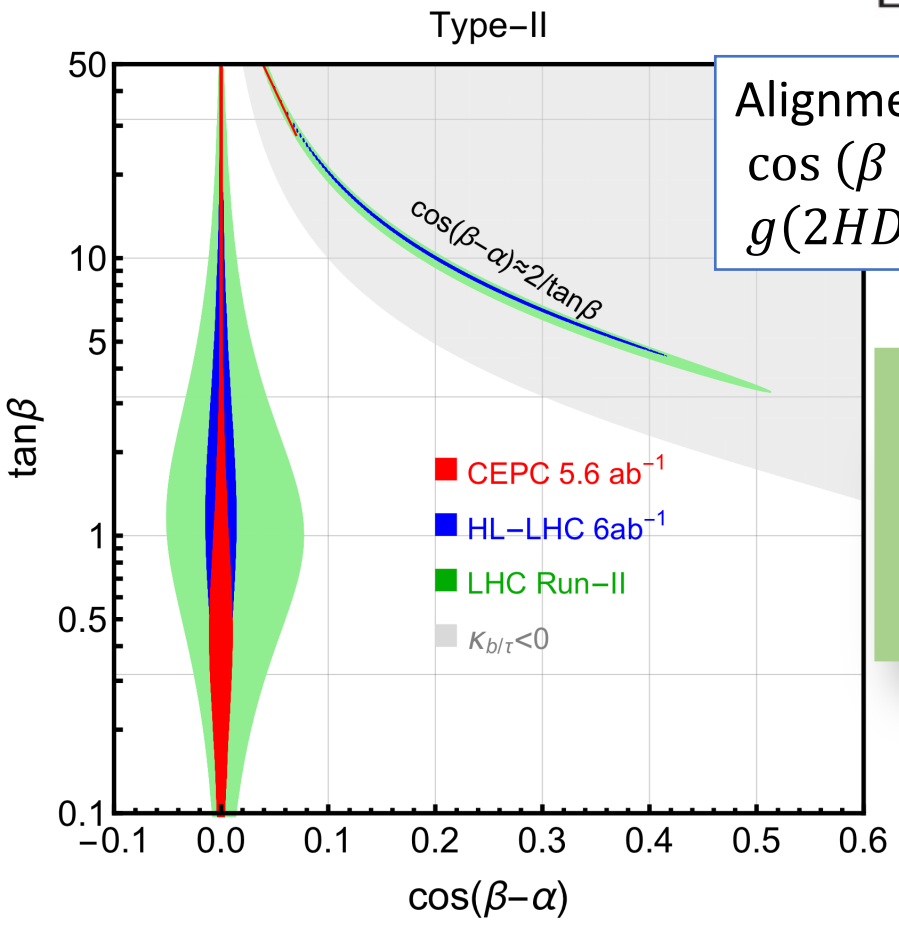
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$



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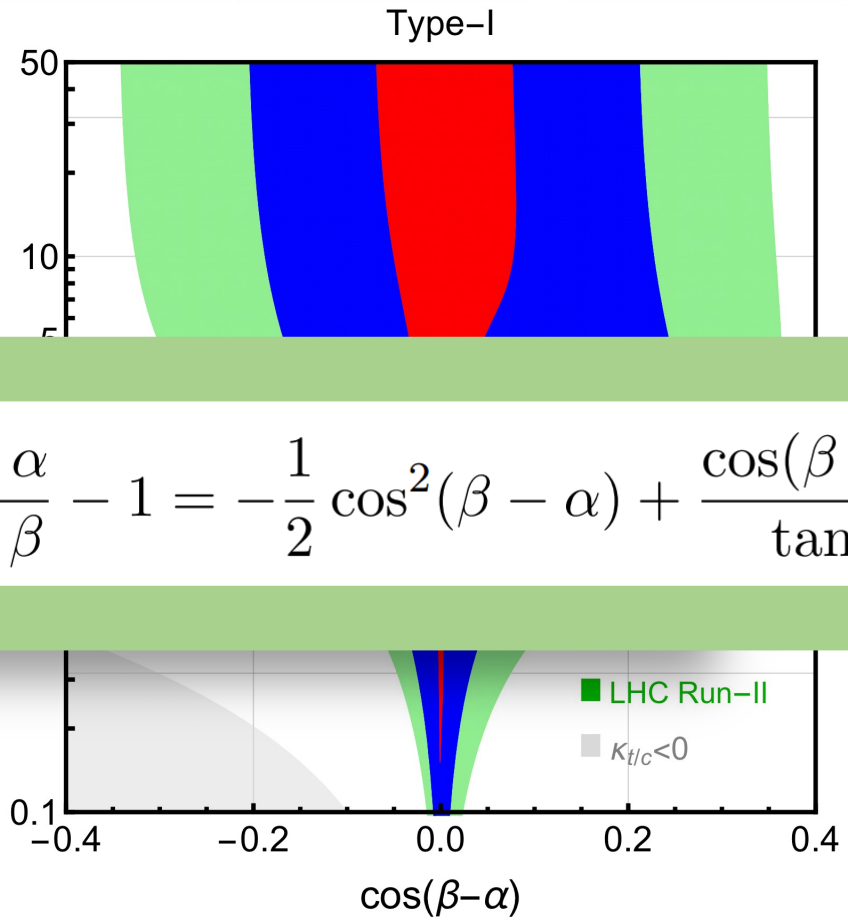
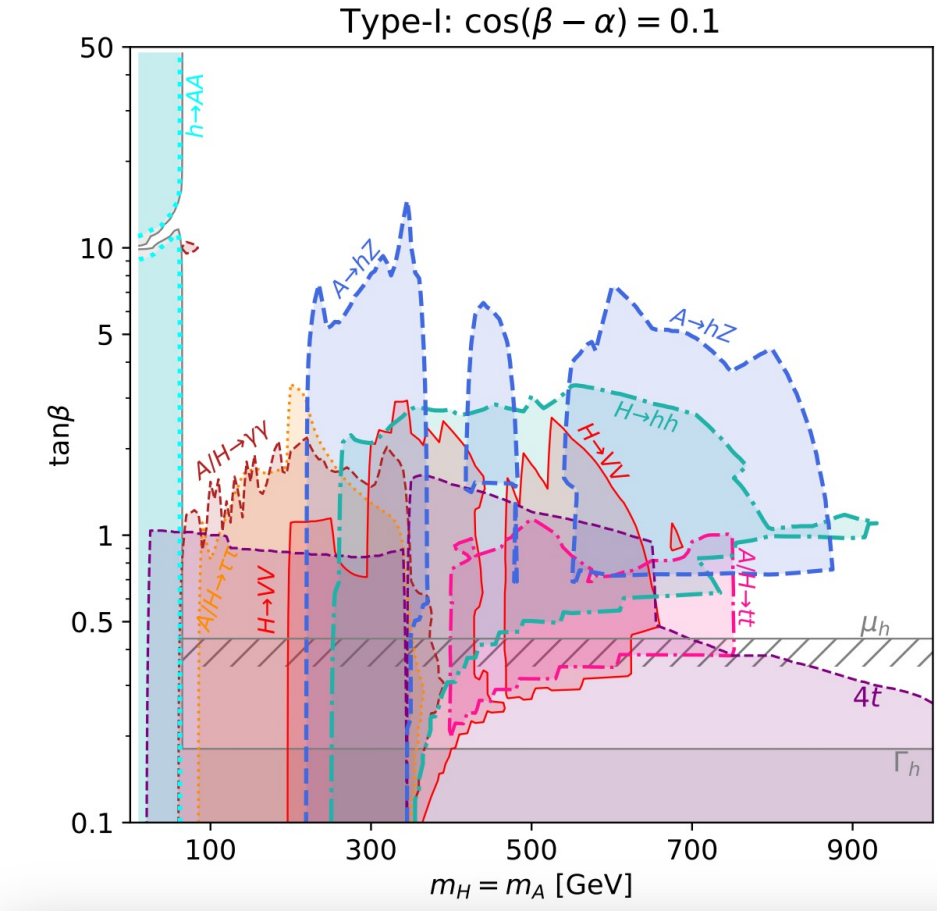
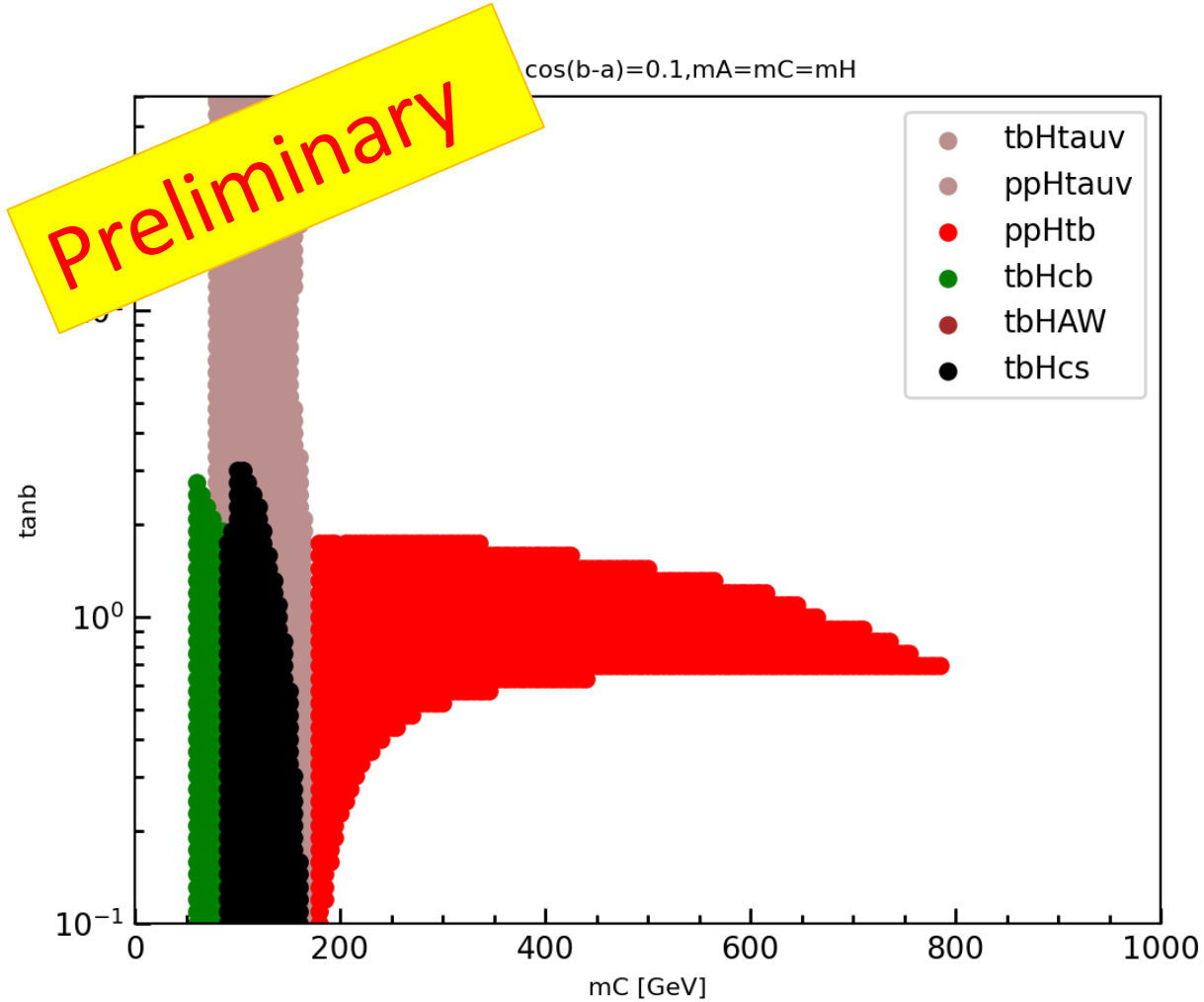


$$\Delta\kappa_{u,d,e}=\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

1910.06269 WS

Direct: degenerate





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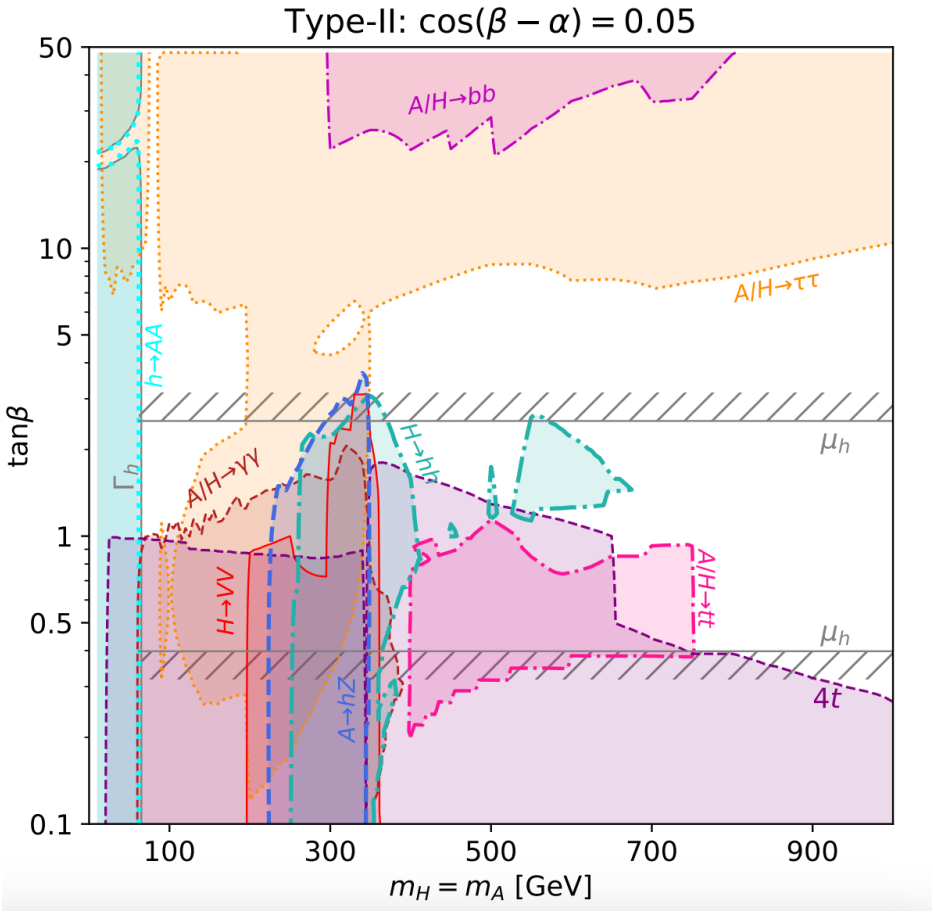
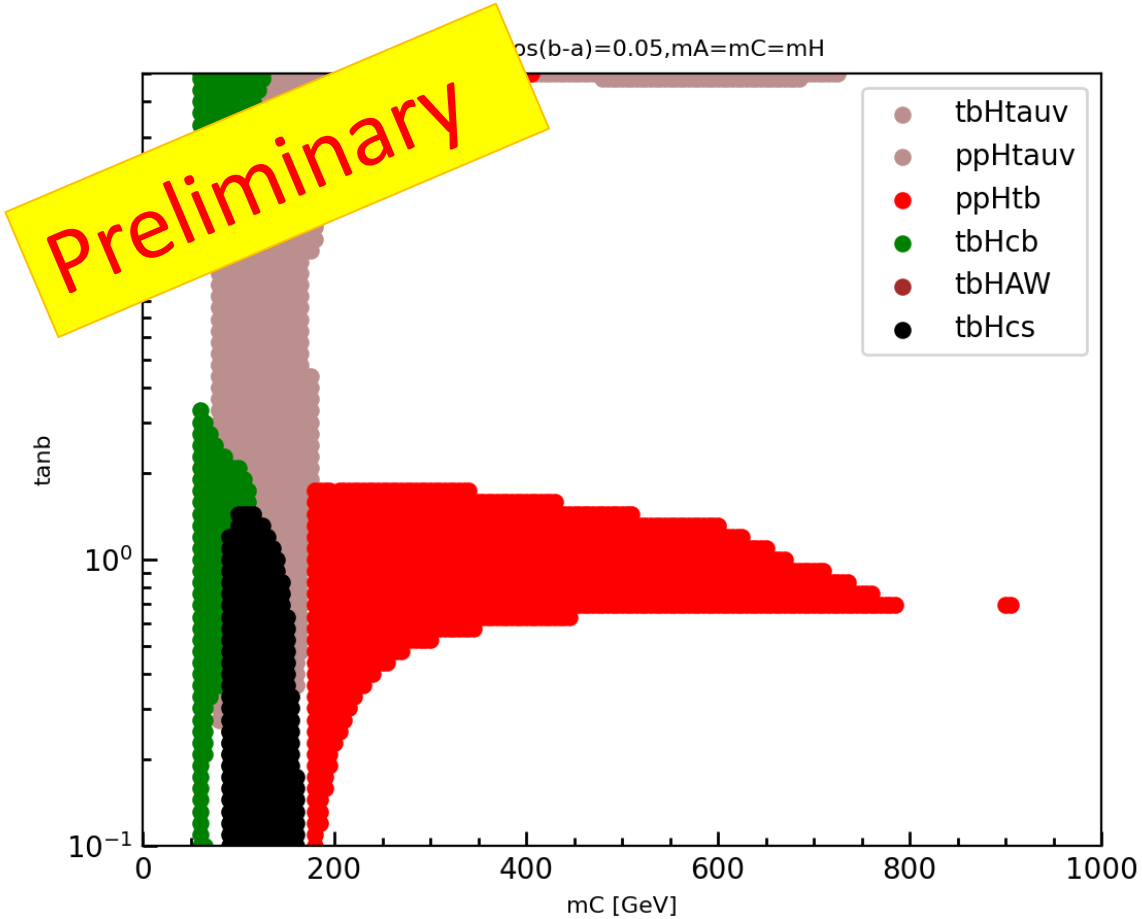
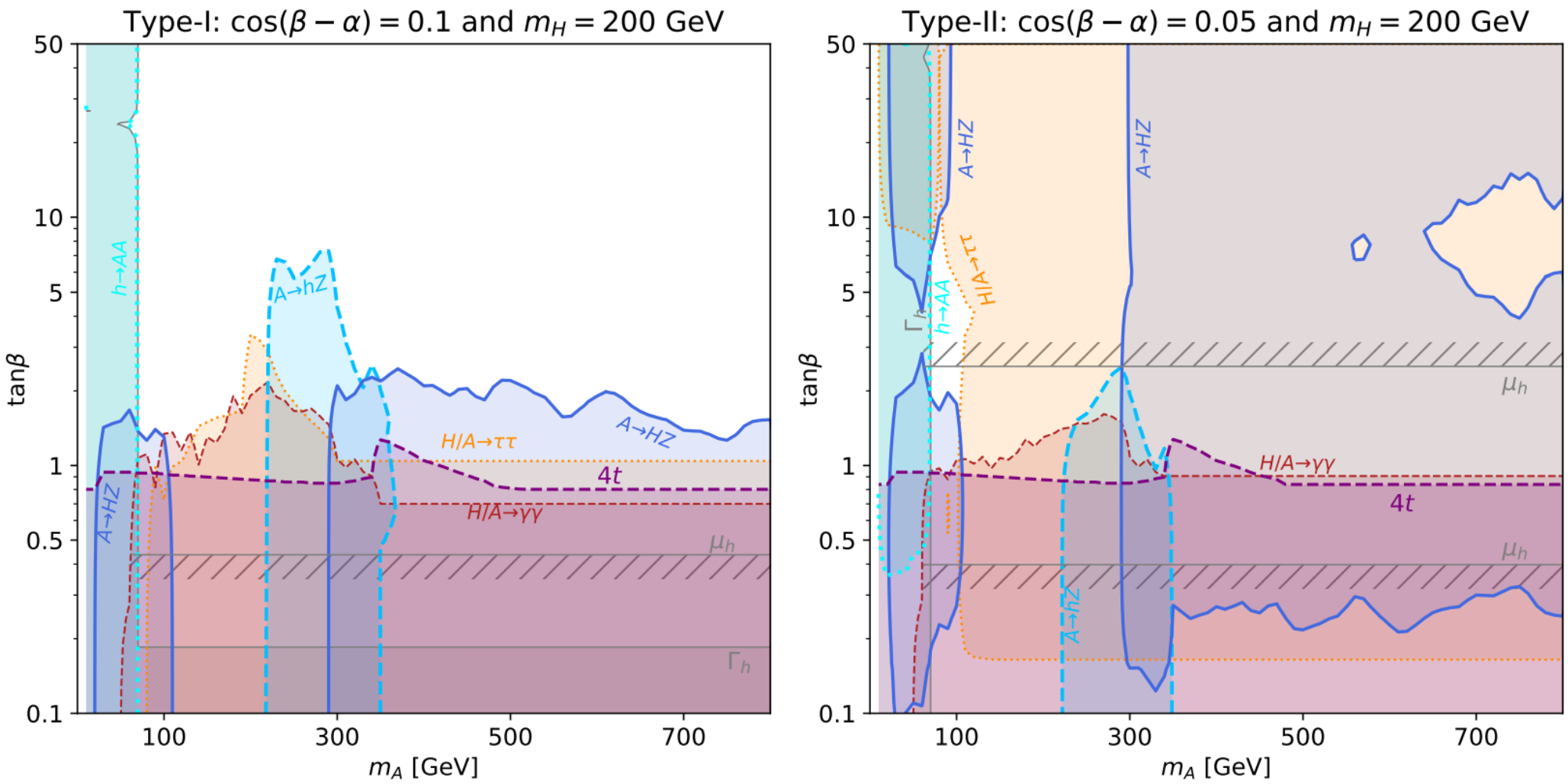




Direct: non- degenerate

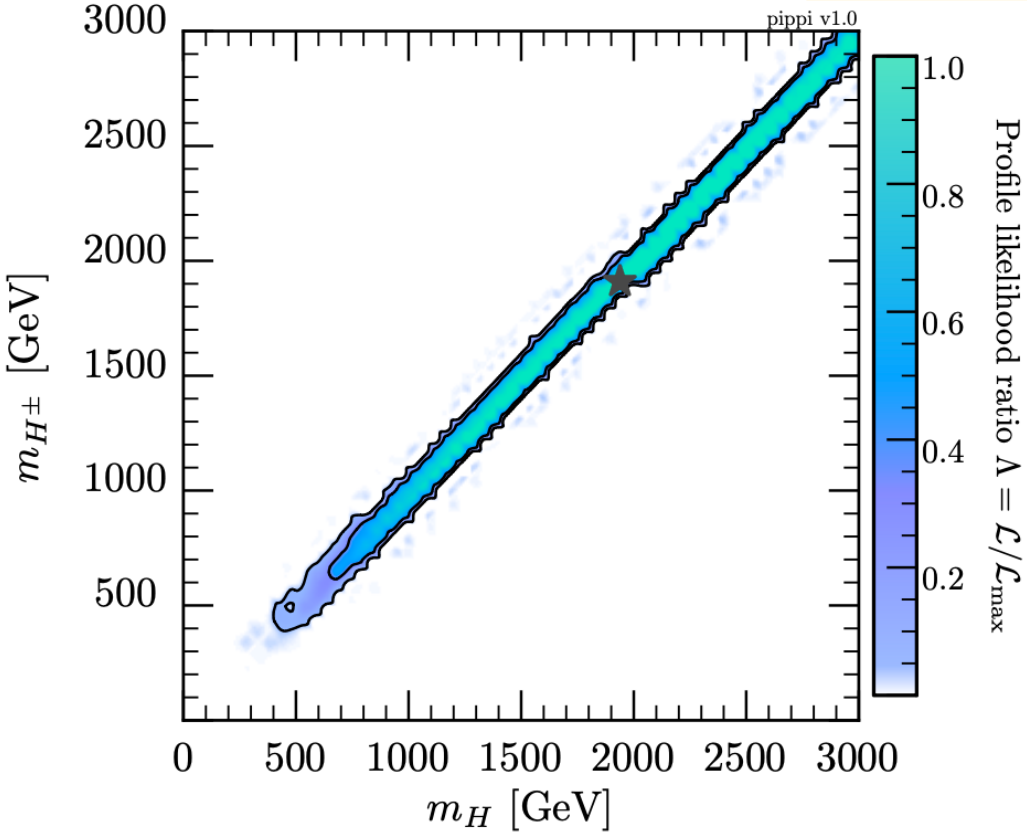


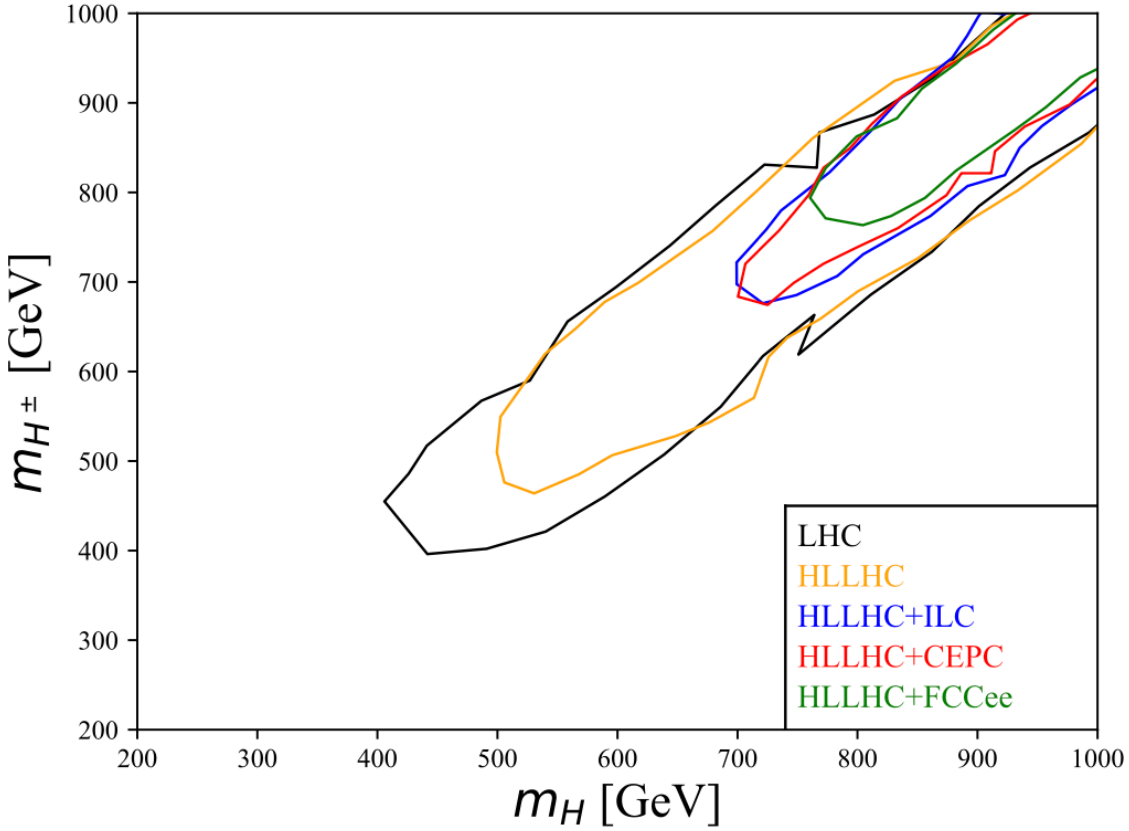
Indirect + Direct

m_H>400 GeV
+ HL-LHC m_H>500 GeV
+ CEPC m_H>700 GeV
+ FCCee m_H>800 GeV

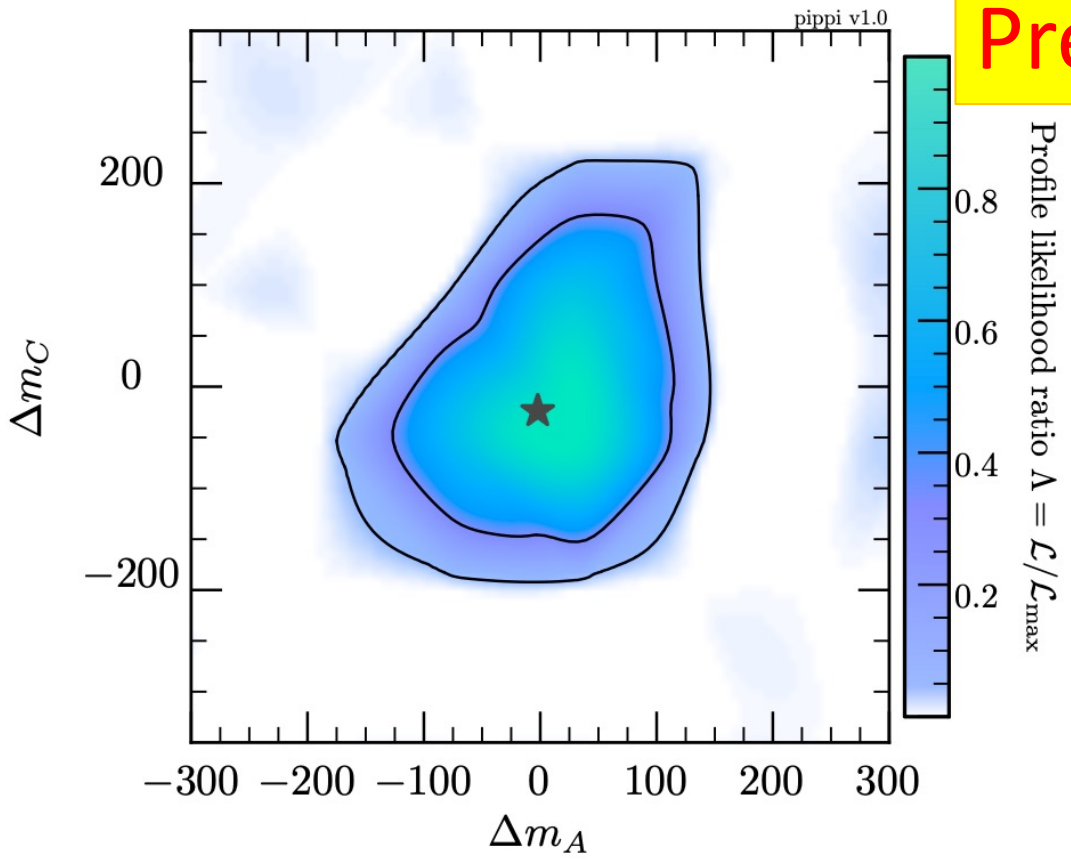
- Flavour, LHC, theory …

Preliminary





Indirect + Direct



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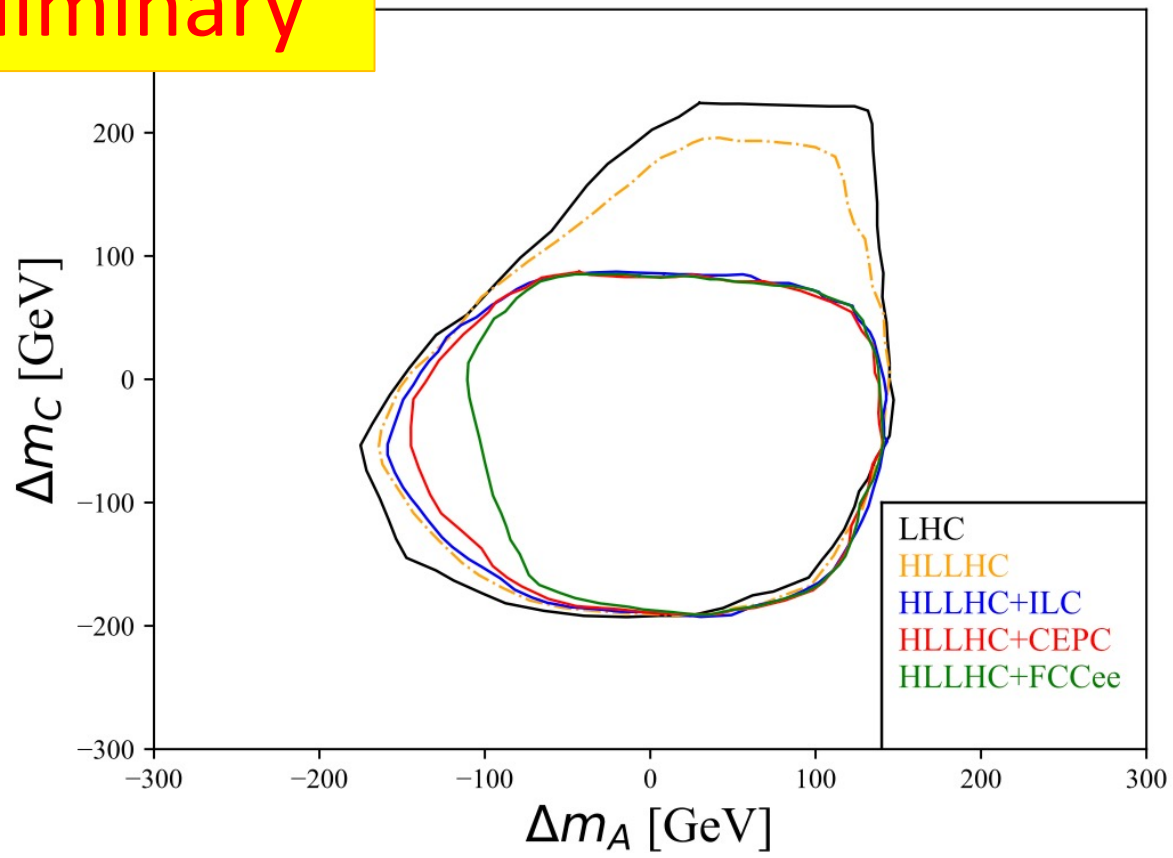
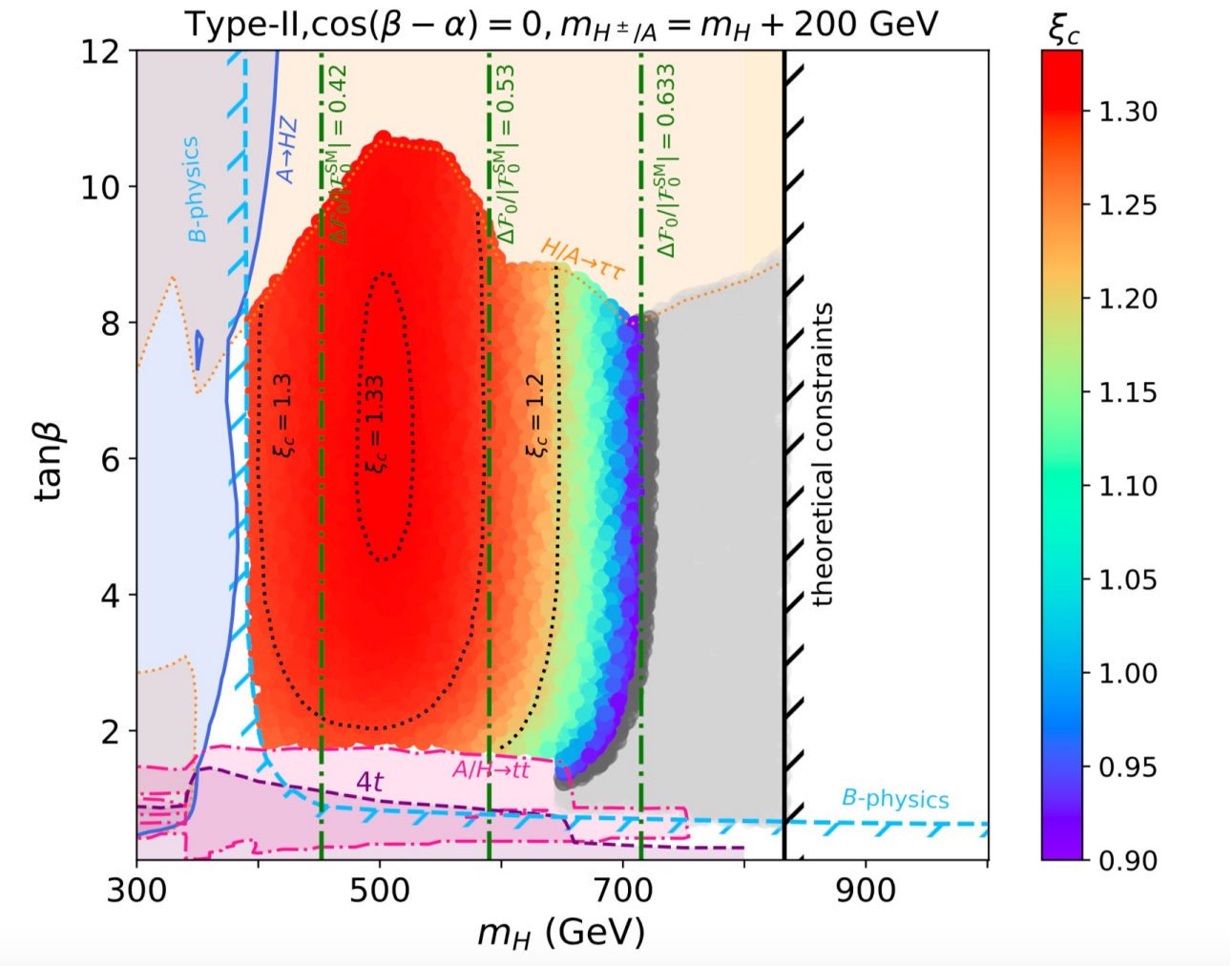


Physics implications



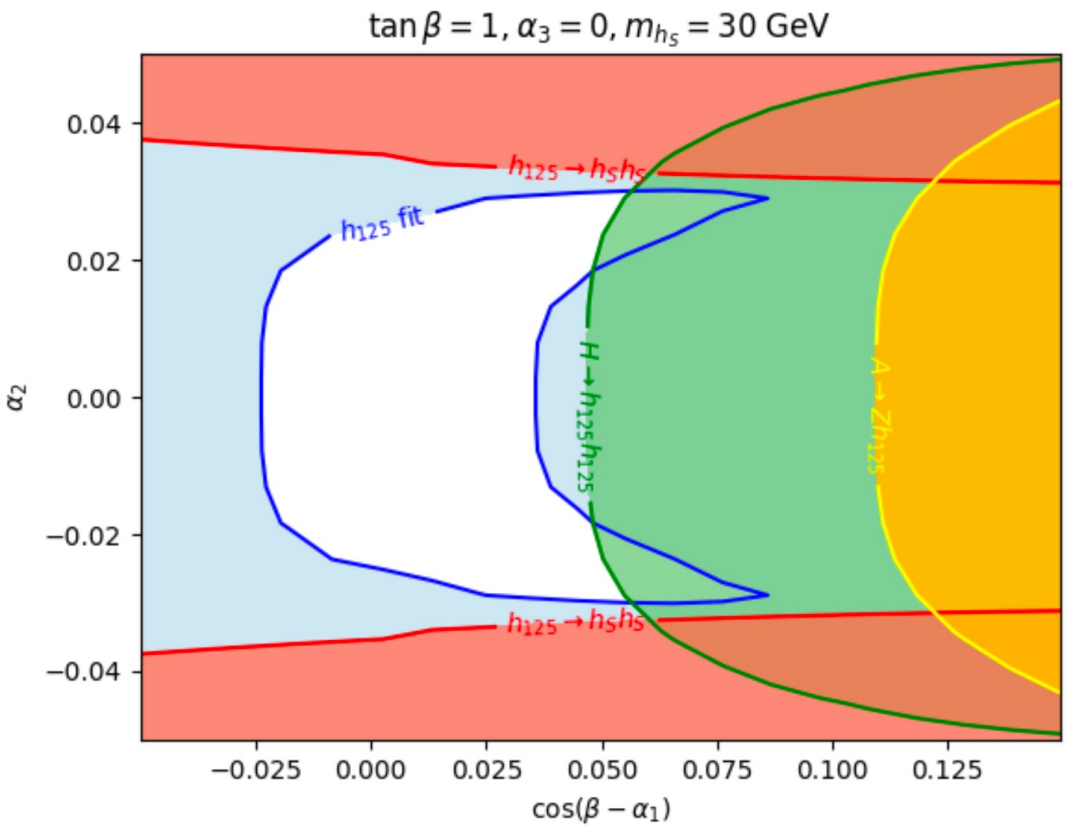
Type-II
fixed mass splitting 200 GeV

$m_H < 710$ GeV
$tan\beta \in (1.8,10)$

Next To 2HDM: 2HDM+scalar

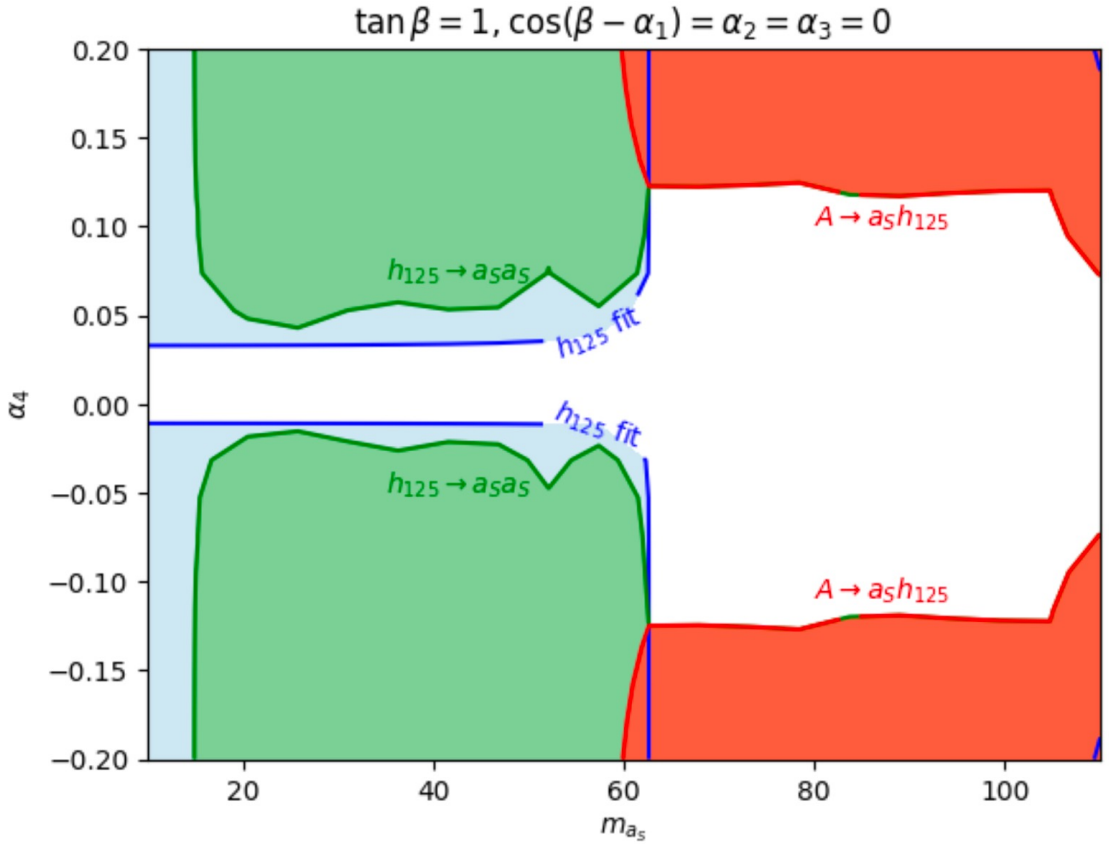
Preliminary

light CP-even singlet $2m_S < 125$ GeV



Open closed channels

light CP-even + heavy CP- even



Open new channels

Next To 2HDM: 2HDM+scalar

Preliminary

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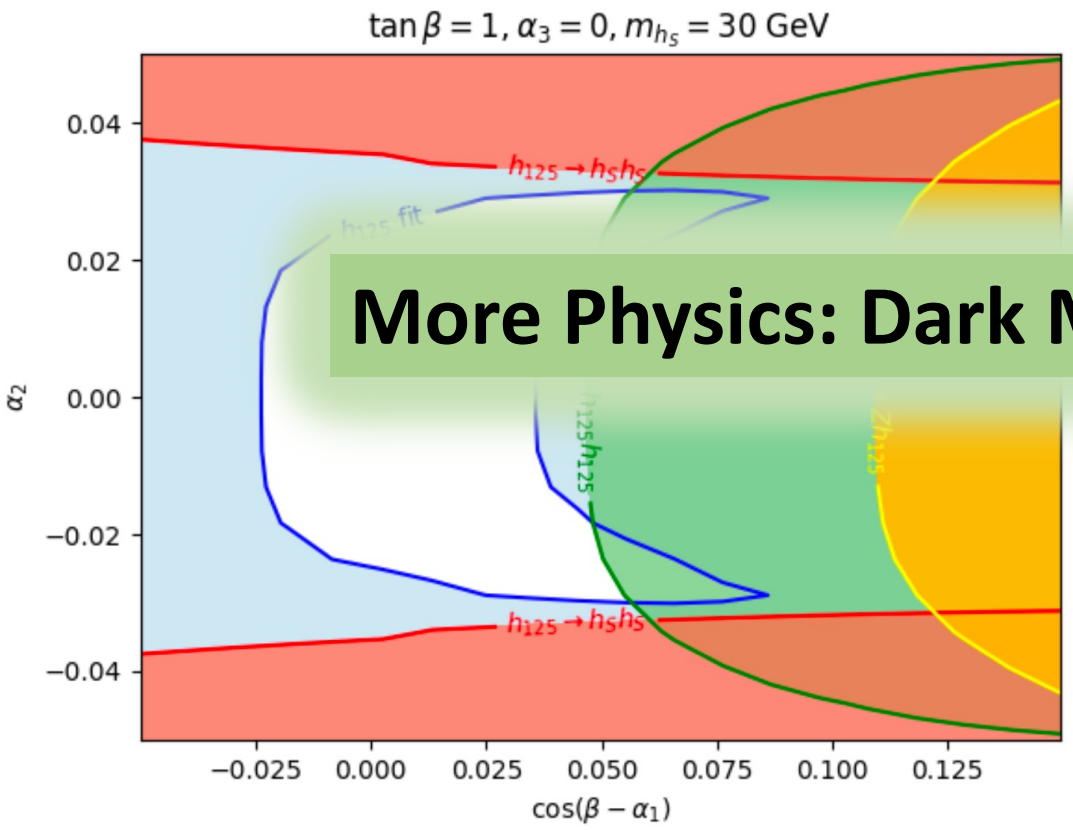

Open closed channels

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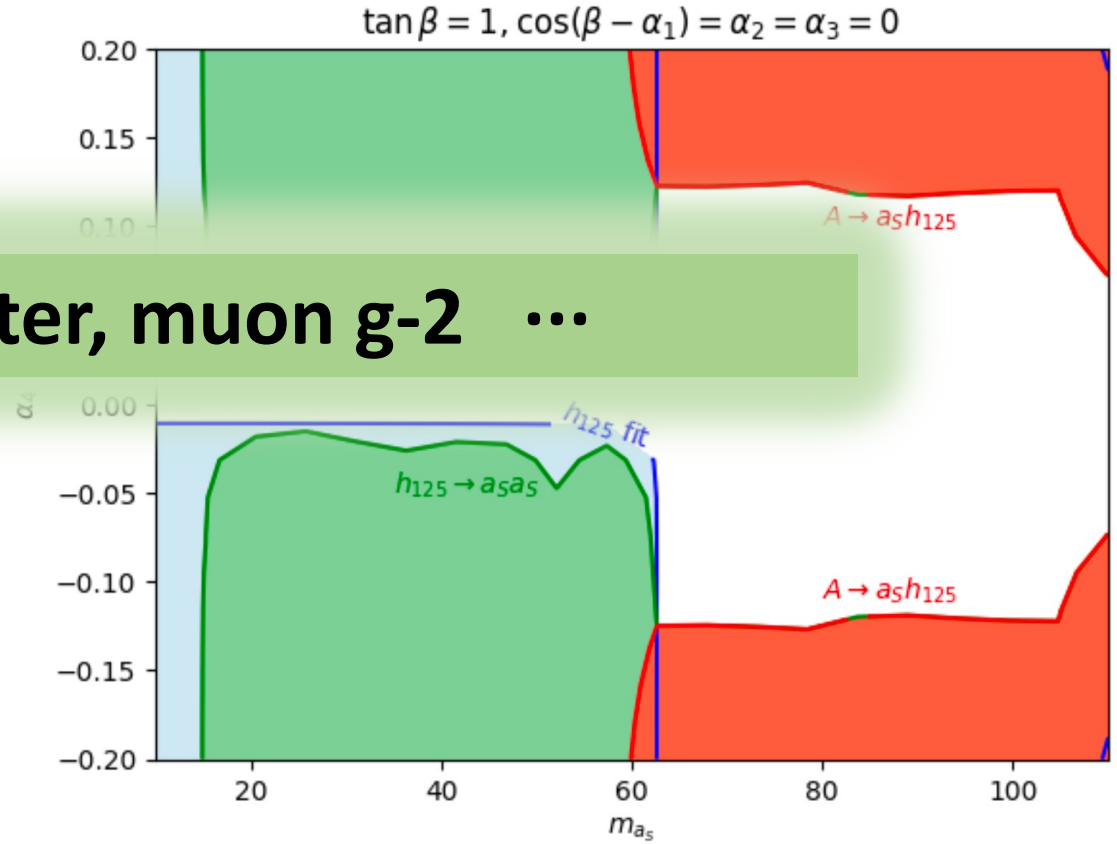
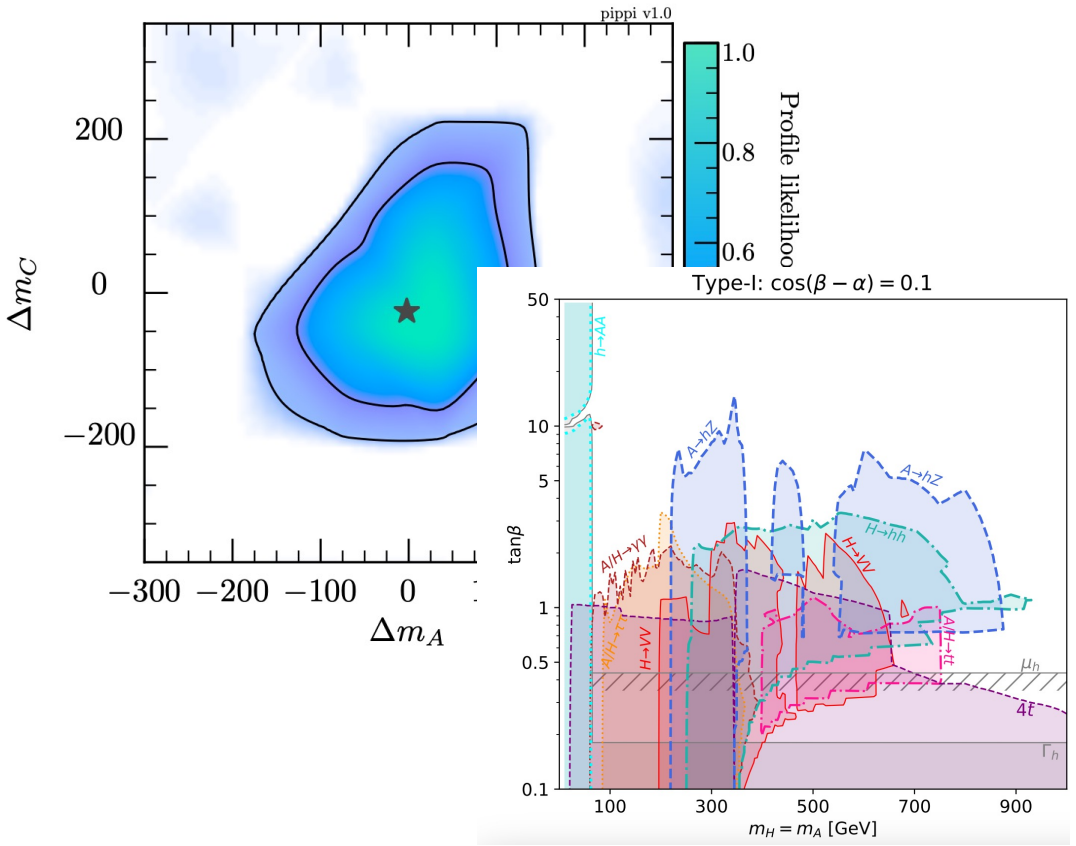


Open new channels

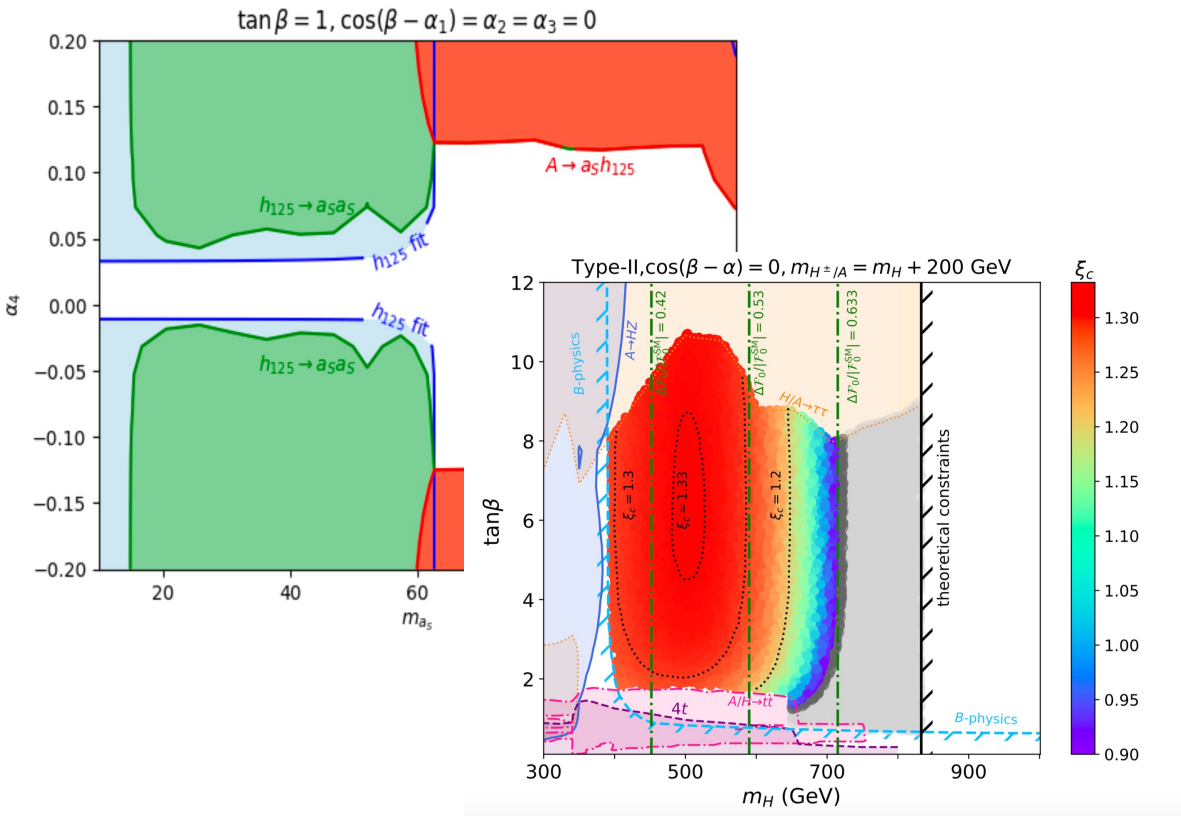
More Physics: Dark Matter, muon g-2 …

conclusion

- New particle discovery / constrain



- Hints to other phyiscs: DM, EWPT



Thanks!