NYU

Center for Cosmology and Particle Physics

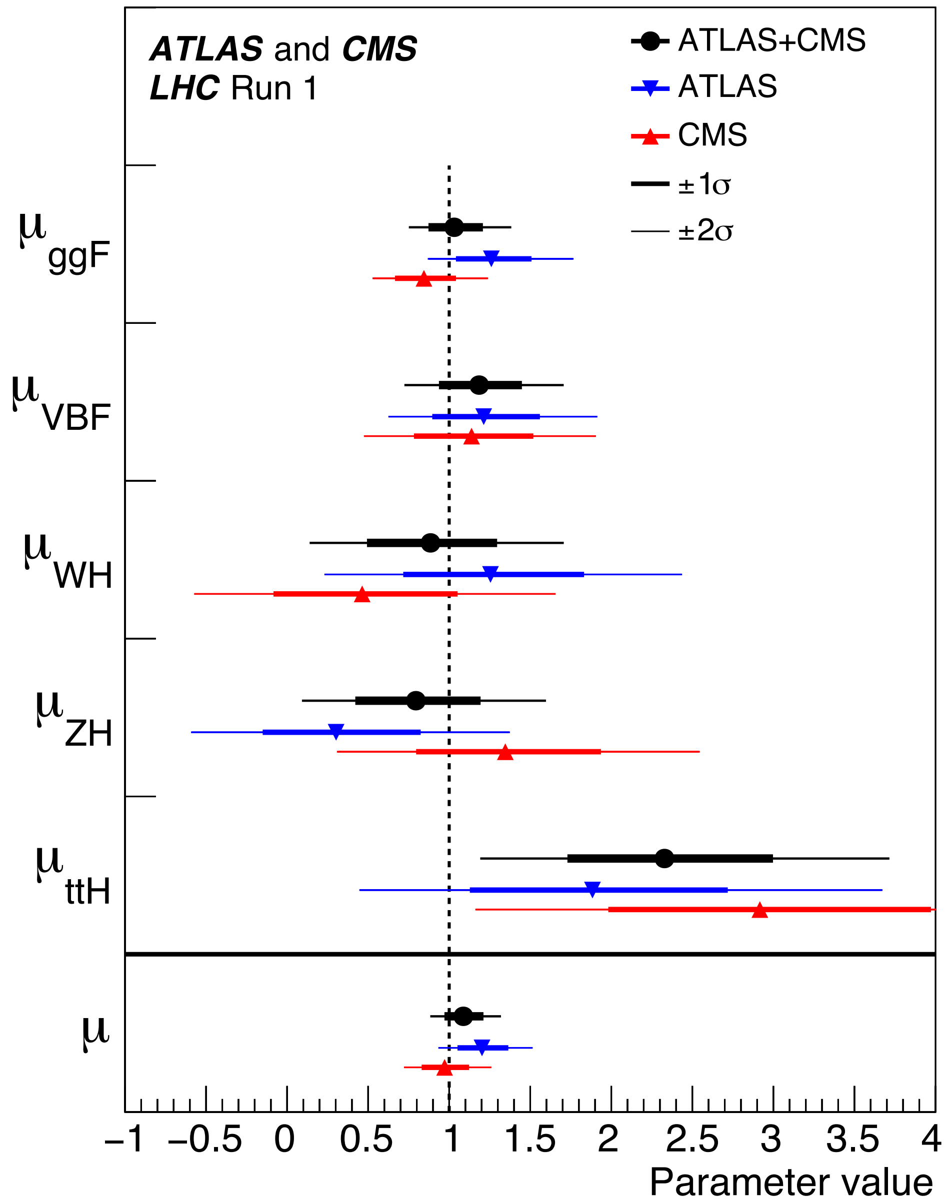
CERN

Revealing the Higgs Sector at Future Colliders

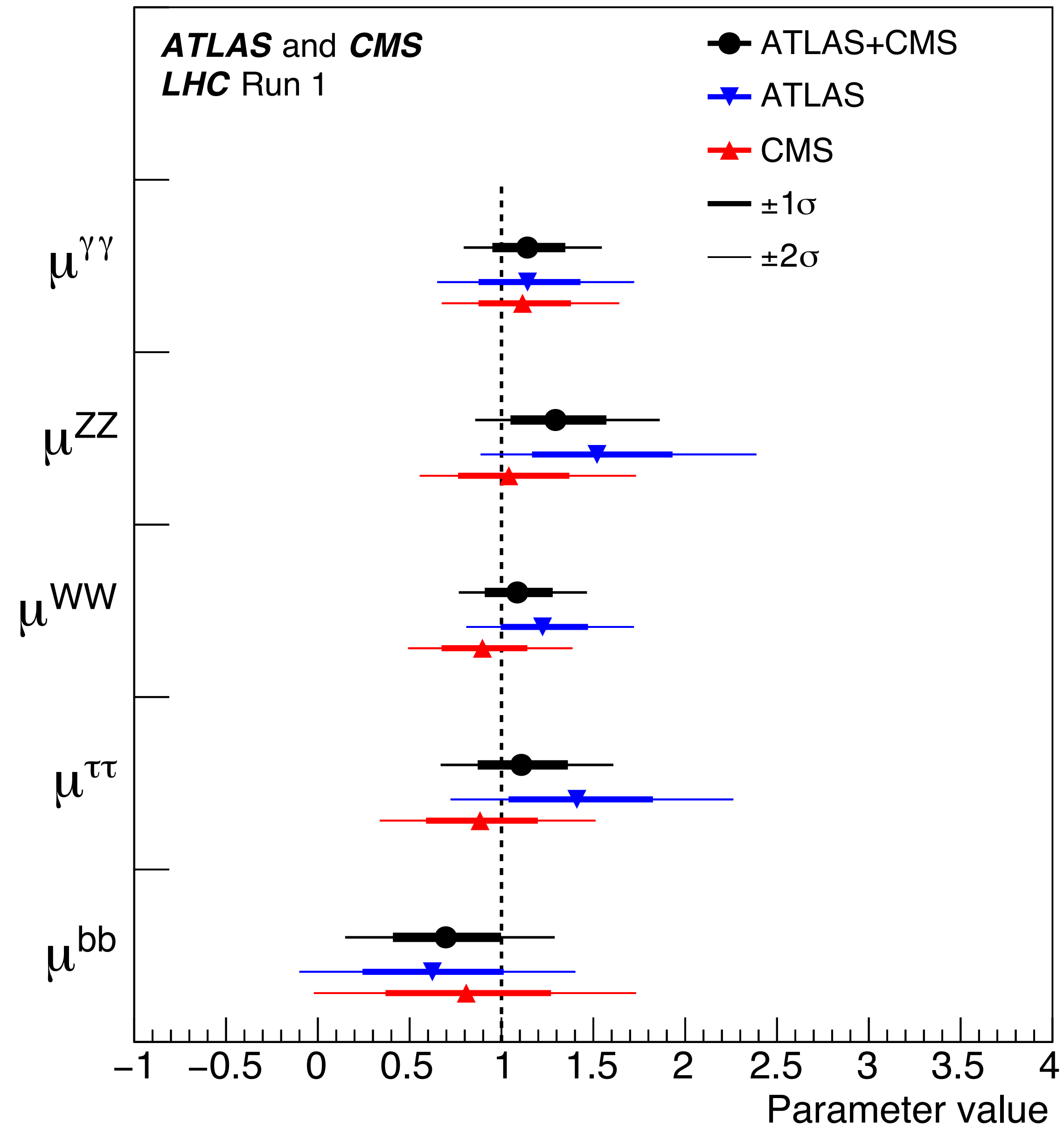
Josh Ruderman
(NYU, CERN)
@CERN Faculty Meeting
6/1/2018

The Higgs After Run 1

production



decay



punchline: agrees with SM predictions at ~10s% precision

ATLAS and CMS, **1606.02266**

Precision Higgs Program

Future colliders can carry out a precision Higgs program (~0.1-1%)

What will we learn?

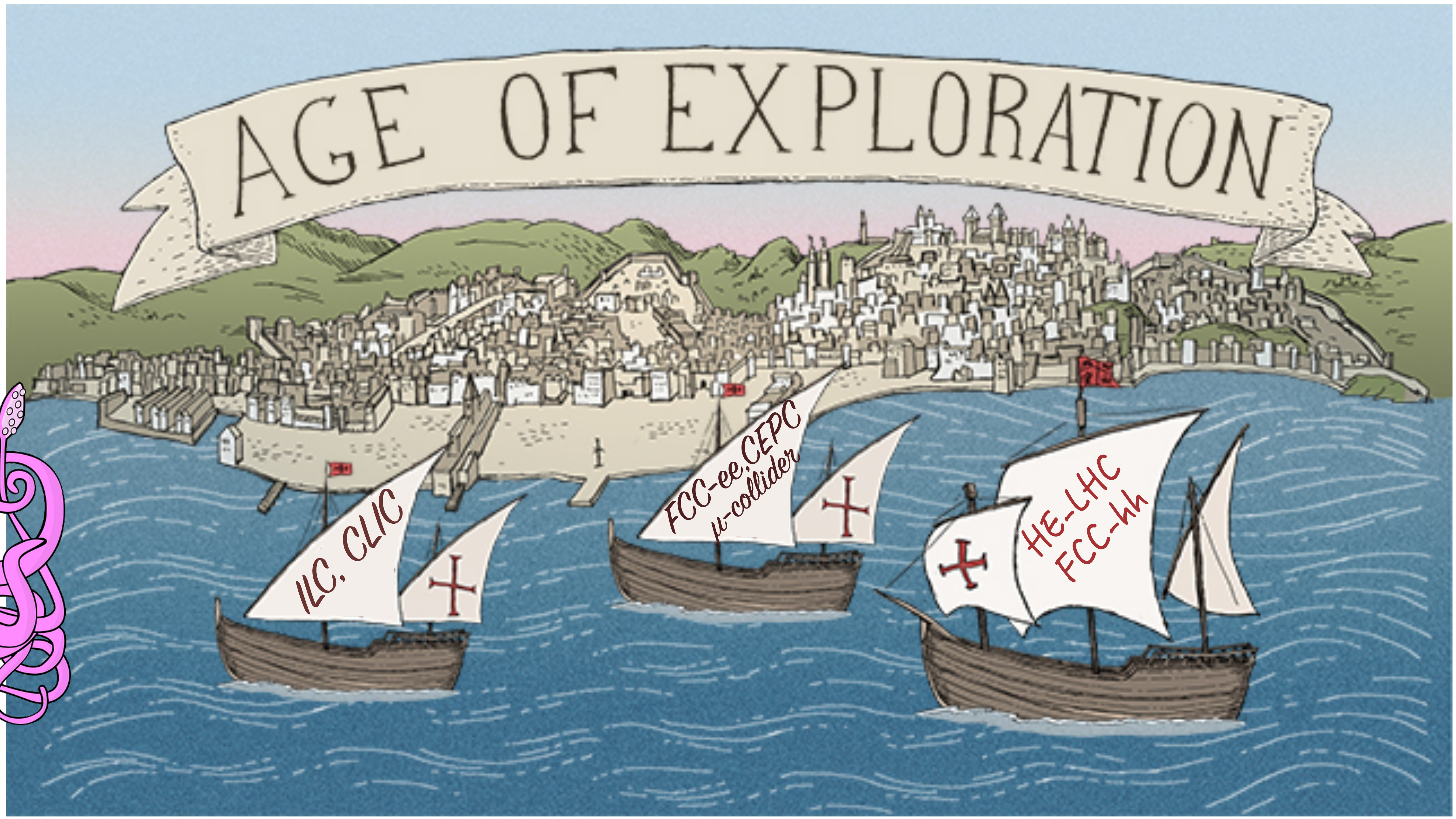
Plan

I. Collider Comparison

II. Effective Field Theory

III. Beyond the Standard Model

I. Collider Comparison



Higgs Properties

HL-LHC

(Andreas' talk)

signal strengths

Channel	Inclusive	VBF	VH	ttH
γγ	3	10	12	8
ZZ*	3	12	15	18
WW*	5	11	–	15 ?
ττ	–	10	–	
μμ	8	–	–	18
bb	–	?	10 ?	?
Zγ	18	–	–	–

VV: ~3-5%

rare decays: ~10-20%

Linear Colliders

(Philipp's talk)

ILC

P(e⁻) = +80%, P(e⁺) = -30%, L = 250 fb⁻¹

invisible: 0.6%

bb: 1%

$+80\%$ e^-, -30% e^+ polarization: (total projected lumi. is 2/ab)

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	2.0		1.8		4.2	
$h \to invis.$	0.61		1.3		2.4	
$h \to b\bar{b}$	1.3	33	1.5	7.5	2.5	3.8
$h \to c\bar{c}$	8.3		11	79	18	36
$h \to gg$	7.0		8.4	32	15	24
$h \to WW$	4.6		5.6	24	7.7	14
$h \to \tau\tau$	3.2		4.0	66	6.1	40
$h \to ZZ$	18		25	81	35	48
$h \to \gamma\gamma$	34		39	180	47	110
$h \to \mu\mu$	72		87	670	120	420

CLIC

$\sqrt{s}$ = 350 GeV:

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.86 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	14 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		6.1 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	26 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		10 %

$\sqrt{s}$ = 1.4 & 3 TeV:

Channel	Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3 TeV 3.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	36 MeV
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	3.3 %†	5.6 %†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	6.1 %	5.6 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	3.5 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	4.2 %	3.6 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	38 %	20 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	8 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	24 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	1.0 %	0.6 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	5.6 %	3.2 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1.8 %	1.9 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	7.3 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	54 %	24 %
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarisation	λ	40 %	18 %

WBF x (h>bb, h>WW): 0.3, 0.6%

ttH: 7%

di-Higgs: 18%

FCC

FCC-ee

(Patrick's talk)

σ_{ZH} : 0.5%

bb: 0.3%

invisible: 0.3%

√s (L)	240 GeV (5 ab⁻¹)		365 GeV (1.5 ab⁻¹)	
BR × σ (%)	HZ	ννH	HZ	ννH
H → any	0.5		0.9	
H → bb	0.3	3.1	0.5	0.9
H → cc	2.2		6.5	10
H → gg	1.9		3.5	4.5
H → WW	1.3		2.6	3.0
H → ZZ	4.4		12	10
H → ττ	0.9		1.8	8
H → γγ	9.0		22	
H → μμ	19		40	
H → inv.	< 0.3		< 0.6	

FCC-hh

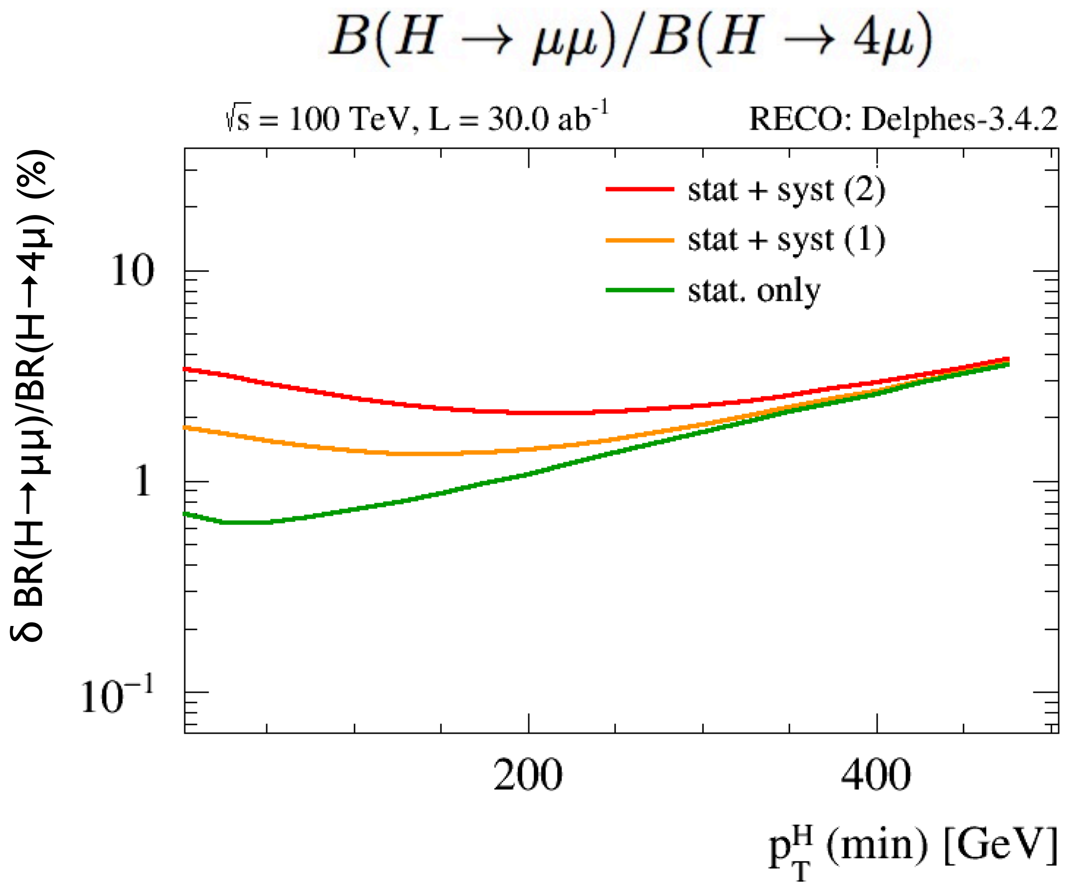
(Michelangelo's talk)

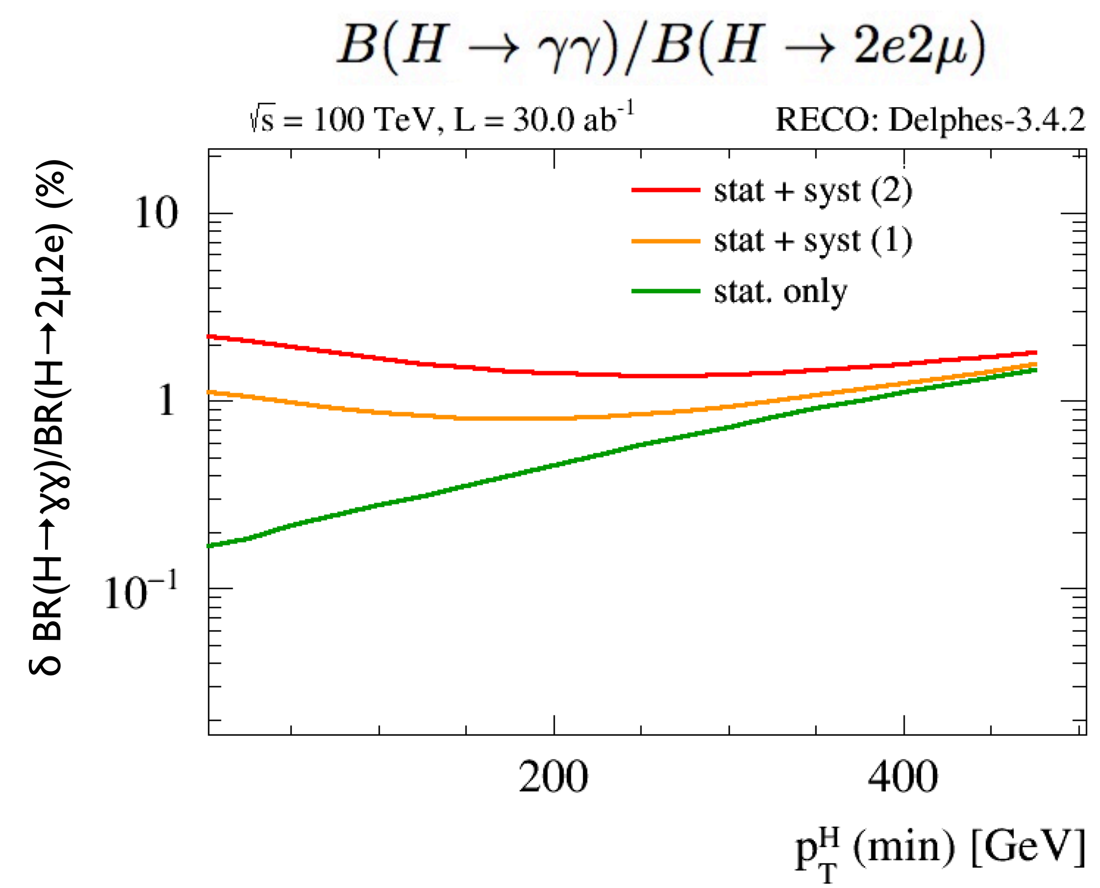
Observable	Parameter	Precision (stat)	Precision (stat+syst)
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.5%	0.9%
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.2%	1.6%
$\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$	$\delta\mu/\mu$	1%	tbd
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	3.5%	5.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.6%	1.4%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

HH: 5%

invisible: few x 10^{-4}

hh/ee Synergy from Rare Channel Ratios





M. Selvaggi, 2nd FCC Physics Workshop

FCC-hh

Observable	Parameter	Precision (stat)	Precision (stat+syst)
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%

+

FCC-ee / CEPC: σ_{ZH} (0.5%)

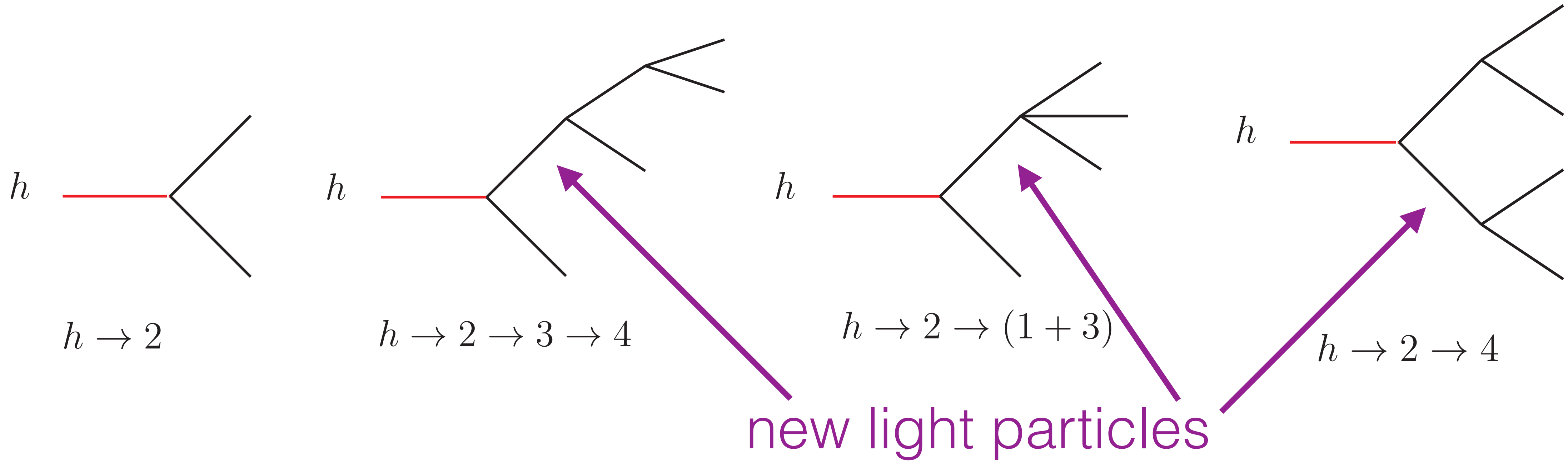
Collider Comparison Punchlines

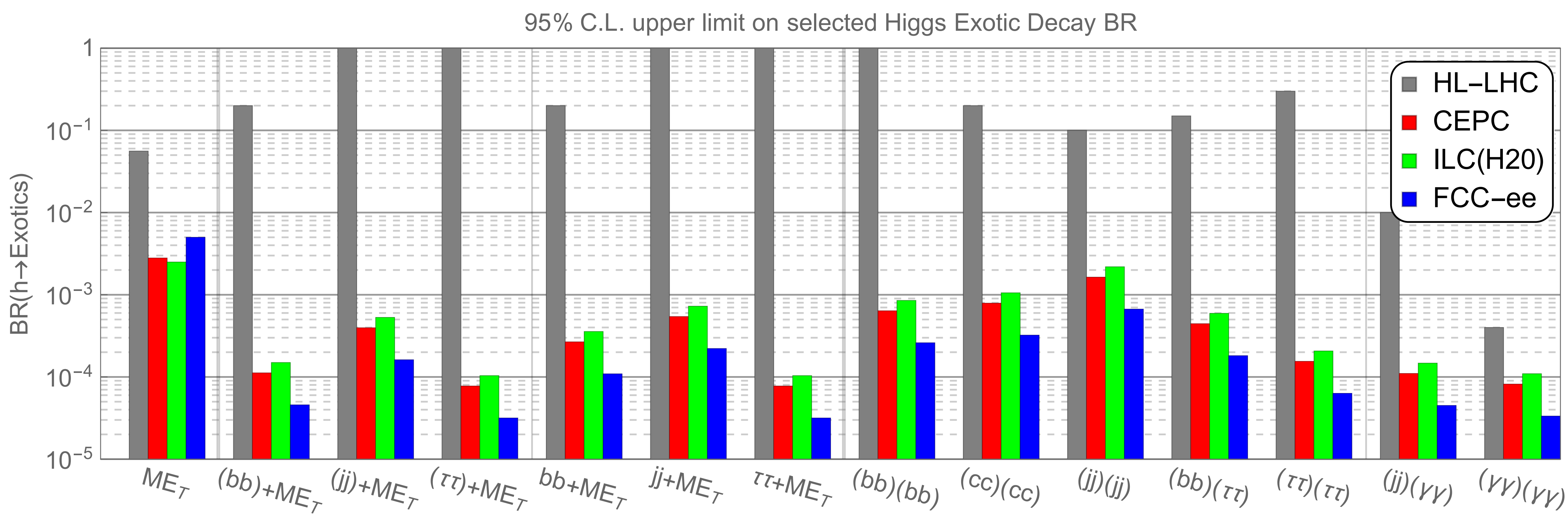
- baseline e^+e^- (FCC-ee, ILC250, CLIC350) perform percent-level measurements of “core” Higgs processes

- FCC-hh and CLIC1.4-3 open up kinematically limited processes (HH, tth)

- FCC-hh precisely measures rare decays (using ratios and combination with e^+e^-) and invisible decays

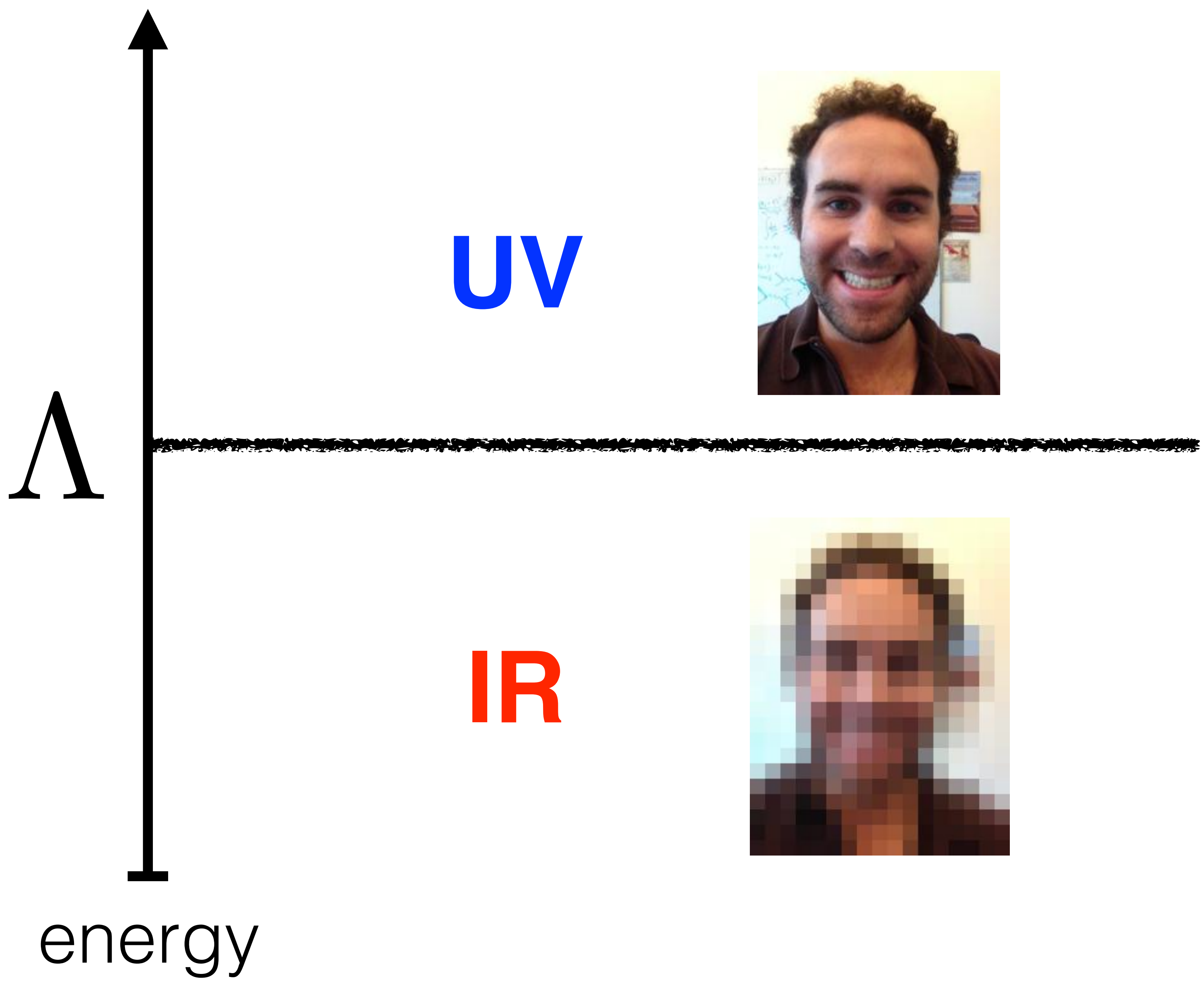
Exotic Higgs Decays



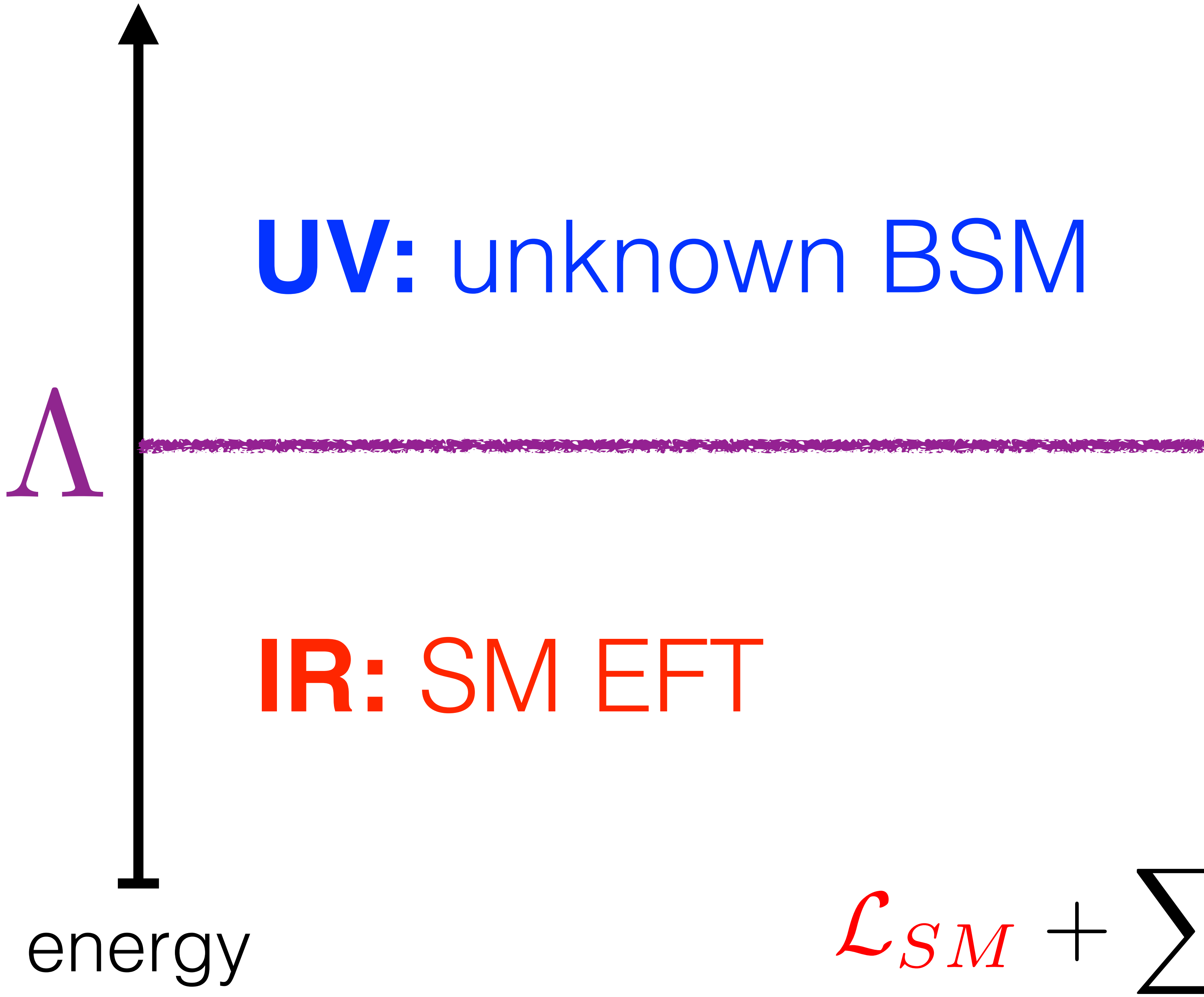


Liu, Wang, Zhang, **1612.09284**

II. Effective Field Theory



SM EFT



new operators

$(d_i > 4)$

$$\mathcal{L}_{SM} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^{d_i - 4}}$$

Standard Model

unknown coefficients

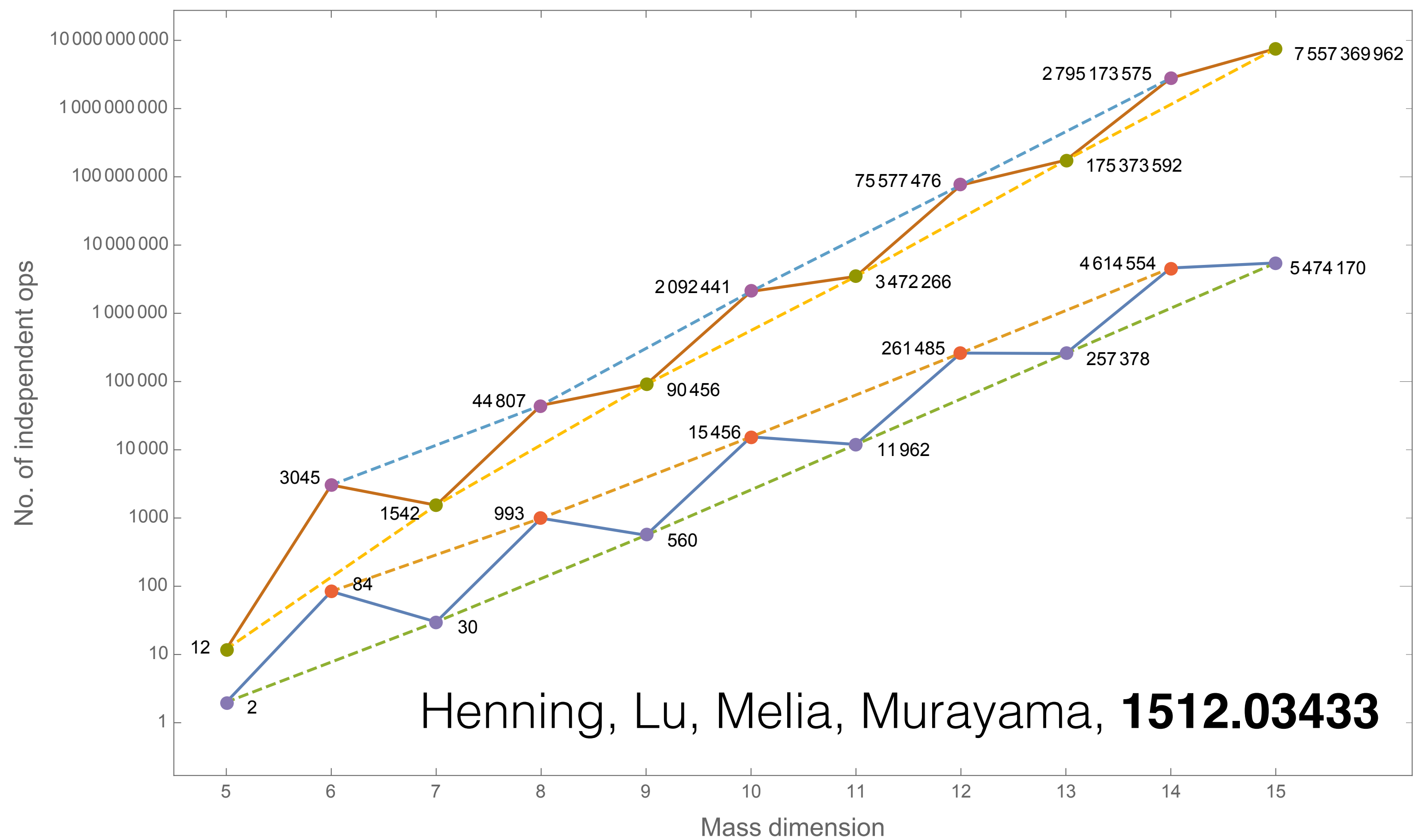
SM EFT

- **dim 5:** Majorana neutrino mass $\frac{(LH)^2}{\Lambda}$ $m_\nu = \frac{v^2}{2\Lambda}$

$\Lambda \sim 10^{14}$ GeV

- **dim 6:** 2499 baryon number conserving operators

- **beyond dim 6:**



Henning, Lu, Melia, Murayama, **1512.03433**

EFT Fit from Higgs Measurements

Jorge de Blas prepared a *global* EFT fit using the projections presented in today's talks

- included:
  - LEP electroweak
  - future Higgs coupling measurements
    - a) HL-LHC alone
    - b) HL-LHC combined with future colliders
- not included:
  - Higgs kinematic fits
  - theoretical uncertainties
  - **future electroweak precision**

warning: this was done quickly, so results are preliminary

see also: Jorge de Blas, *"Global fits to EW and Higgs observables at the FCC,"* **FCC Week 2018**, *April 11, 2018.*

Operators Included in This Fit

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$

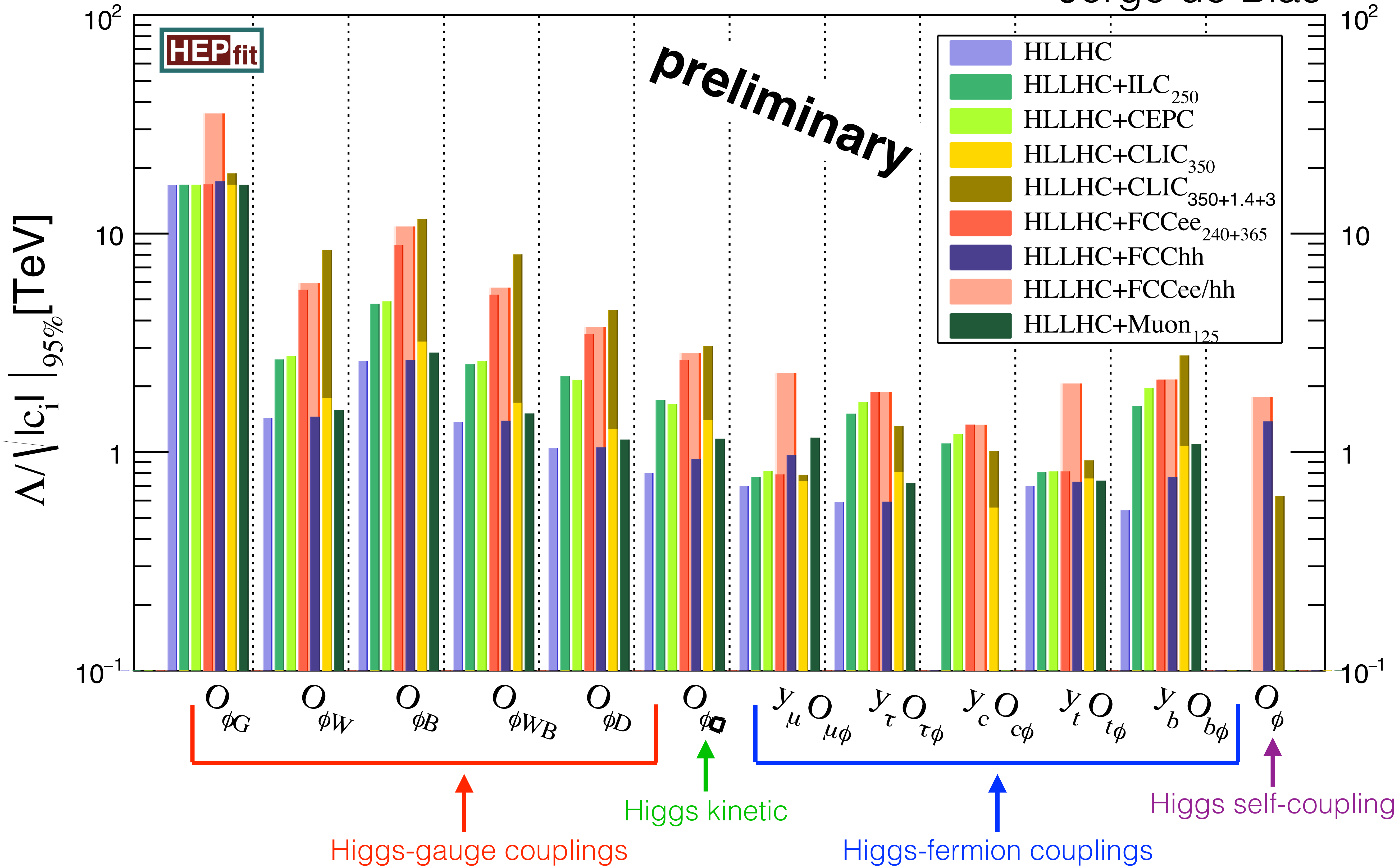
fit

float

"Warsaw Basis," Grzadkowski, Iskrzynski, Misiak, Rosiek, **1008.4884**

Global EFT Fit

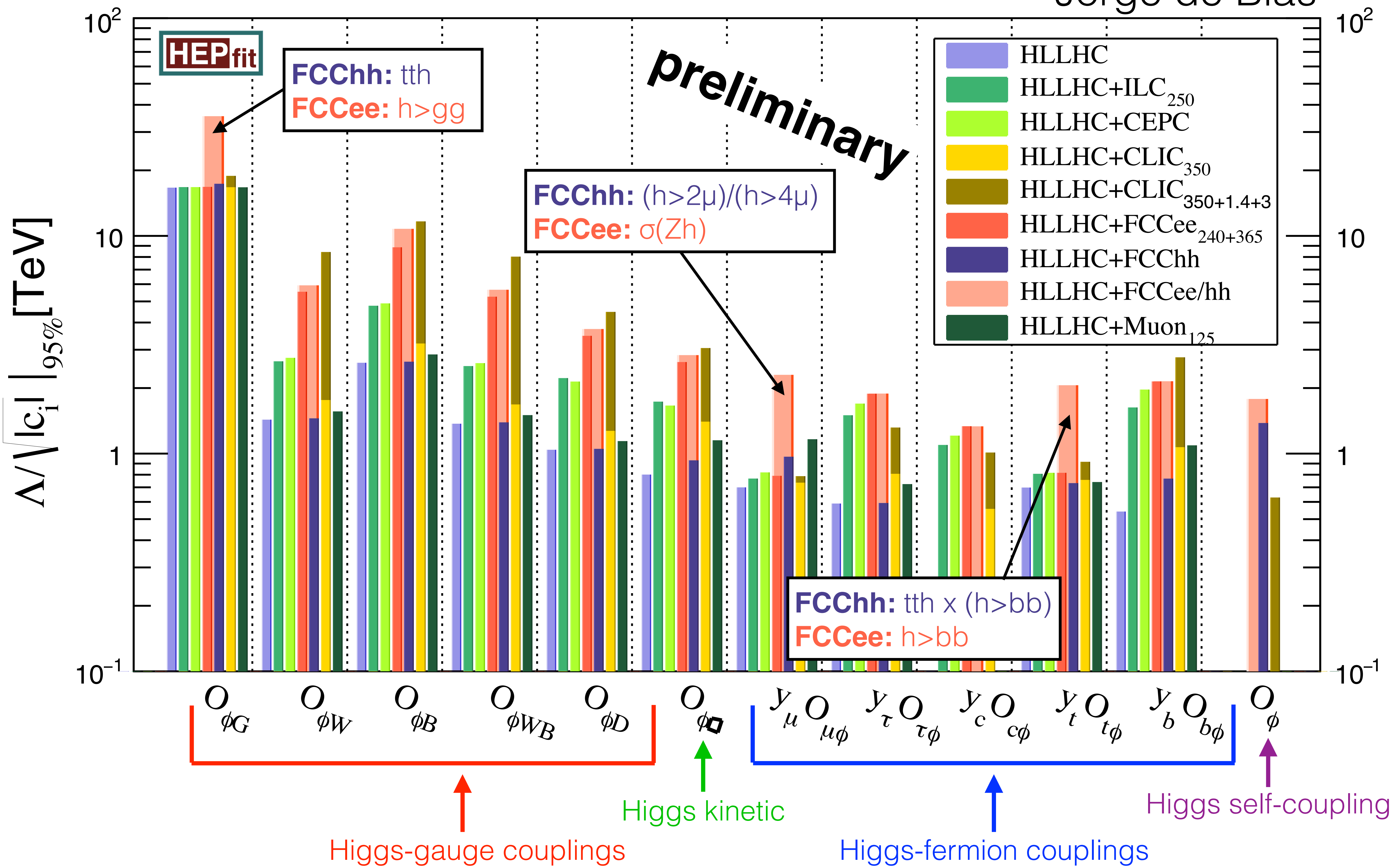
Jorge de Blas



*important information is also contained in the correlations

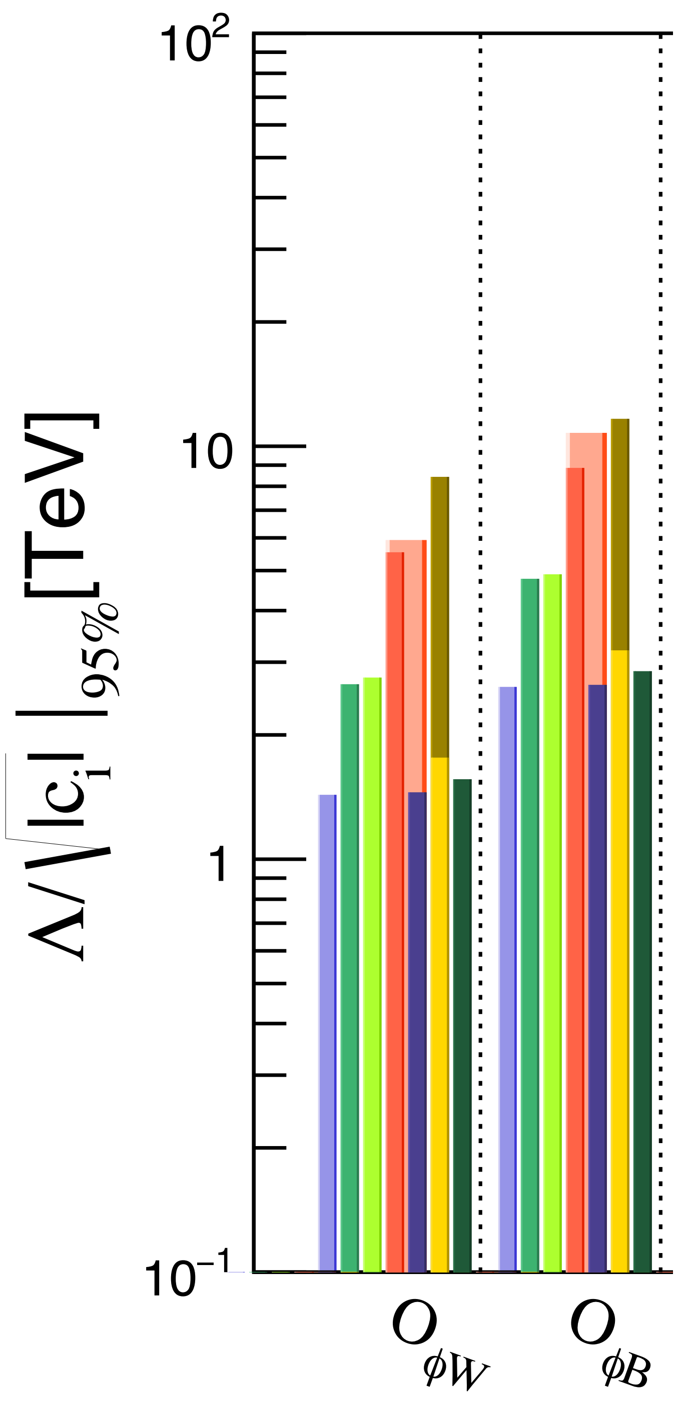
Global EFT Fit

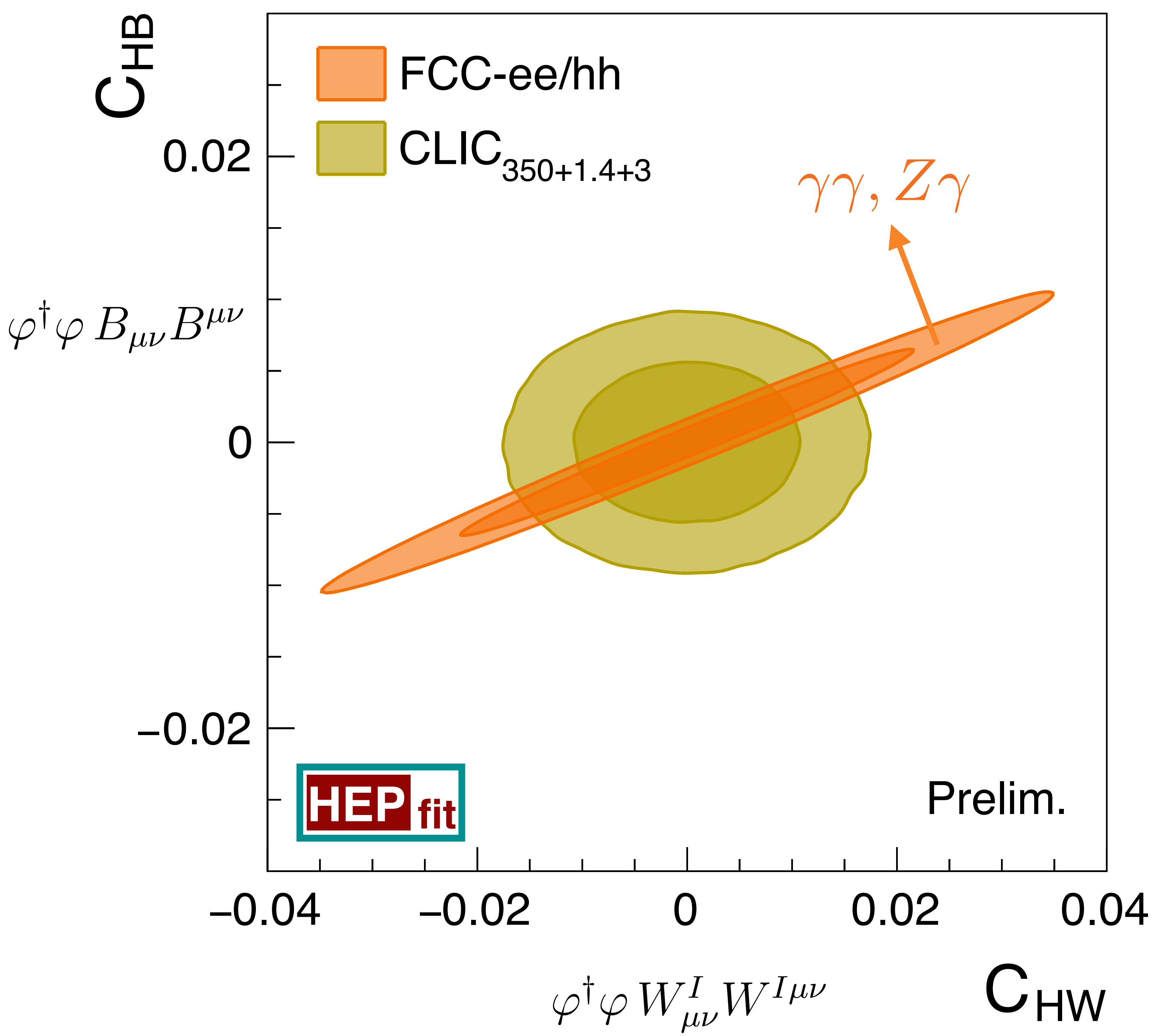
Jorge de Blas



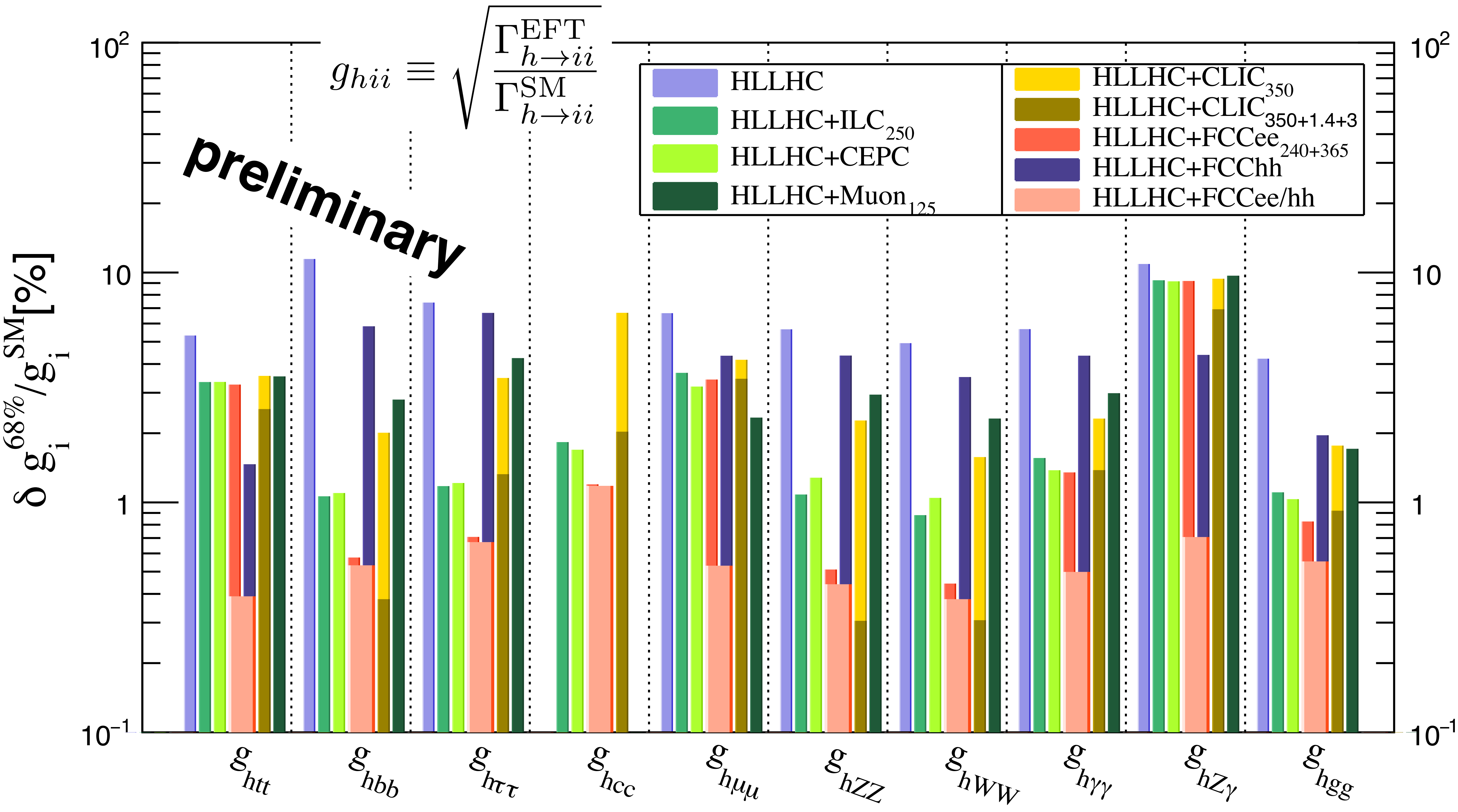
*important information is also contained in the correlations

In a Global Fit, Correlations Matter!

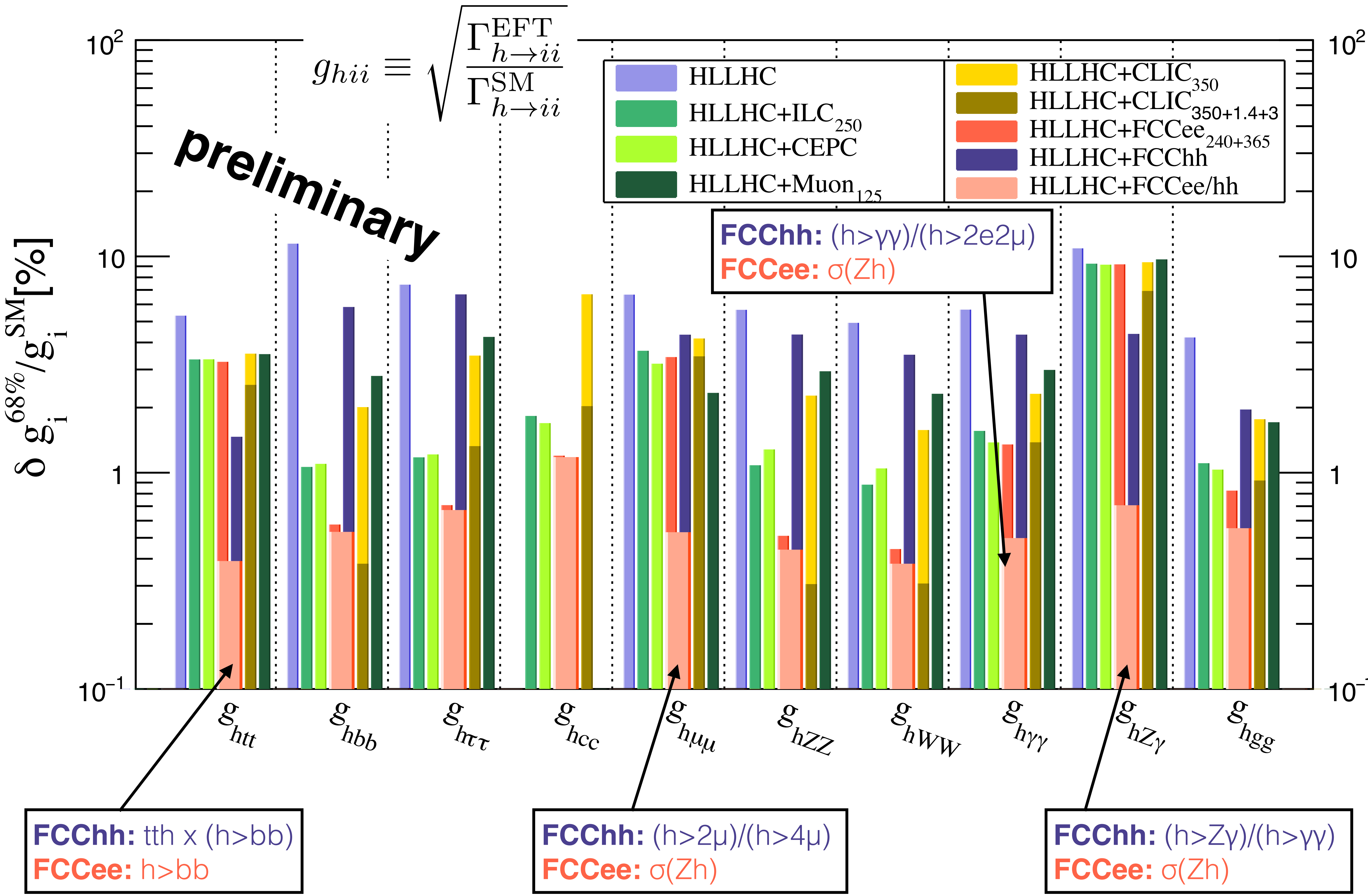




Global EFT Fit - Partial Width Constraints



Global EFT Fit - Partial Width Constraints



III. Beyond the Standard Model

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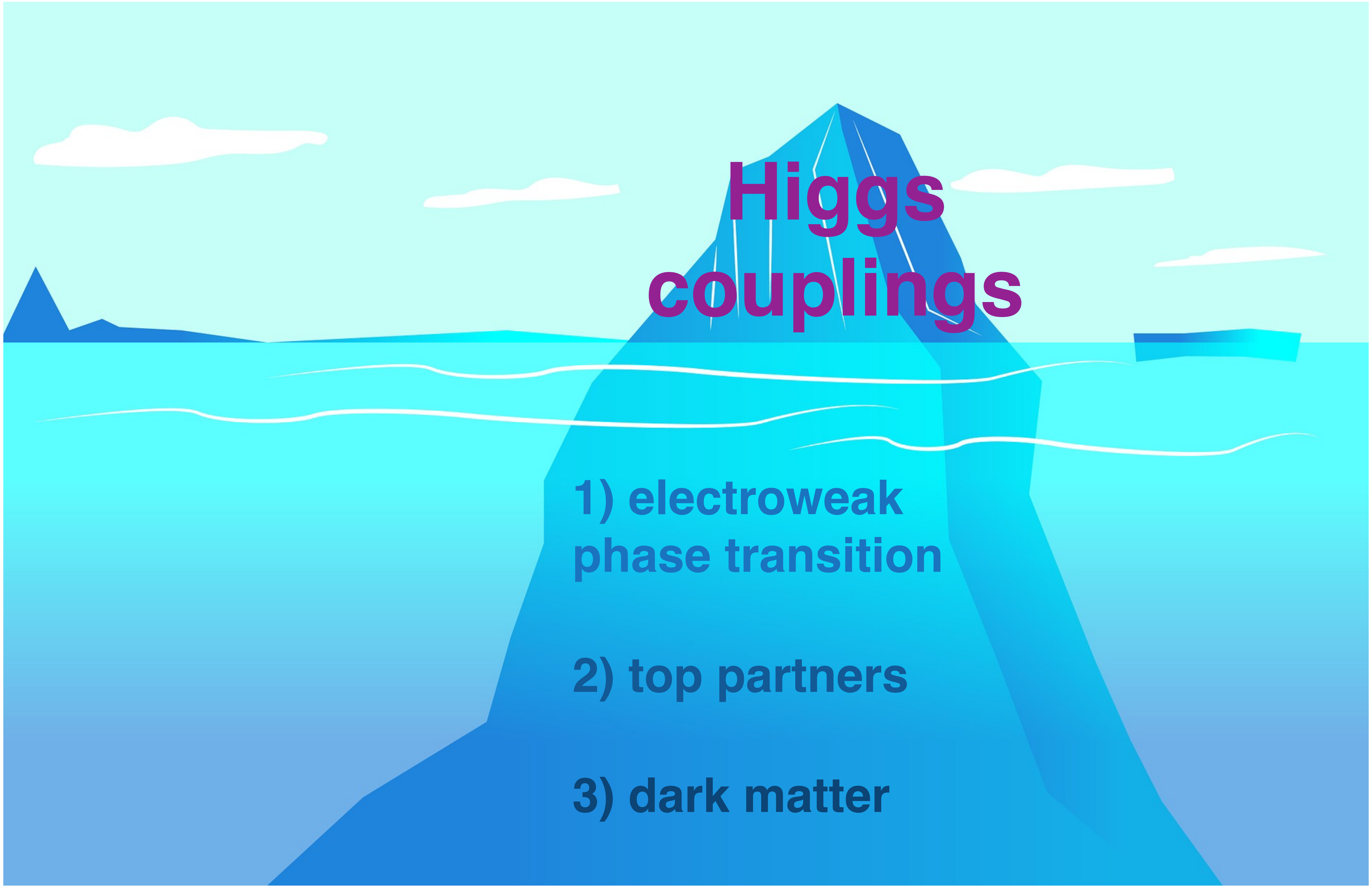
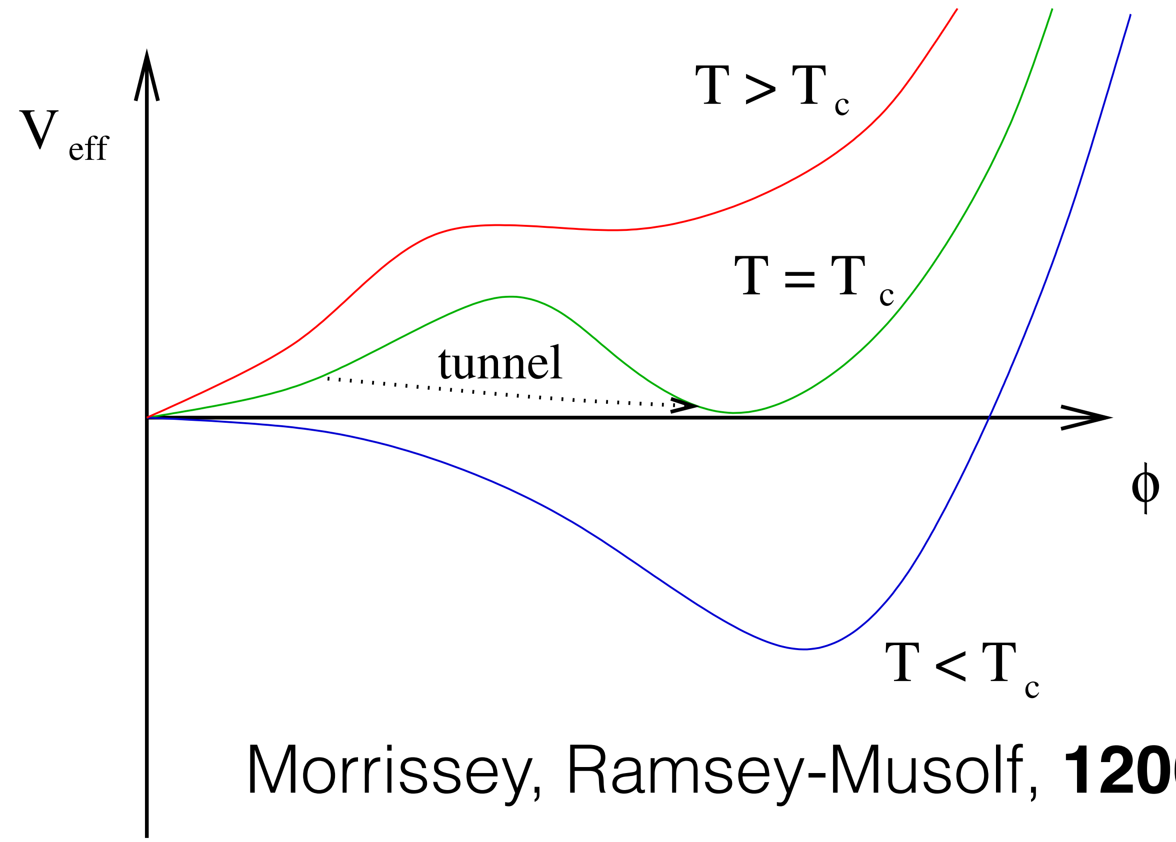


Electroweak Phase Transition

Was the electroweak phase transition first order?



Morrissey, Ramsey-Musolf, **1206.2942**

Sakharov's Conditions:

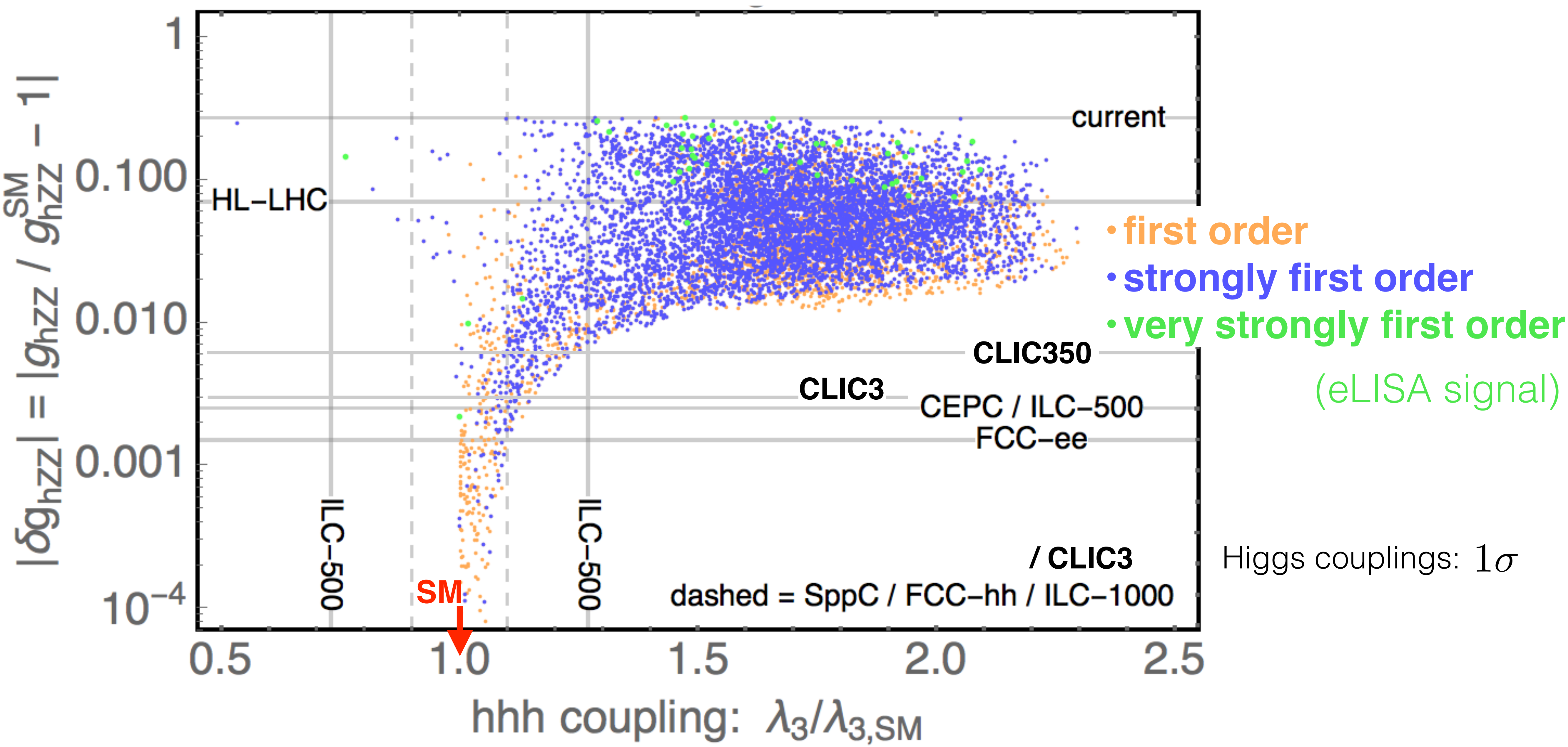
1. baryon number violation
2. **C** and **CP** violation
3. departure from equilibrium

SM: not first order, no electroweak baryogenesis

BSM: can be first order but predicts Higgs deviations

Real Scalar Singlet Model

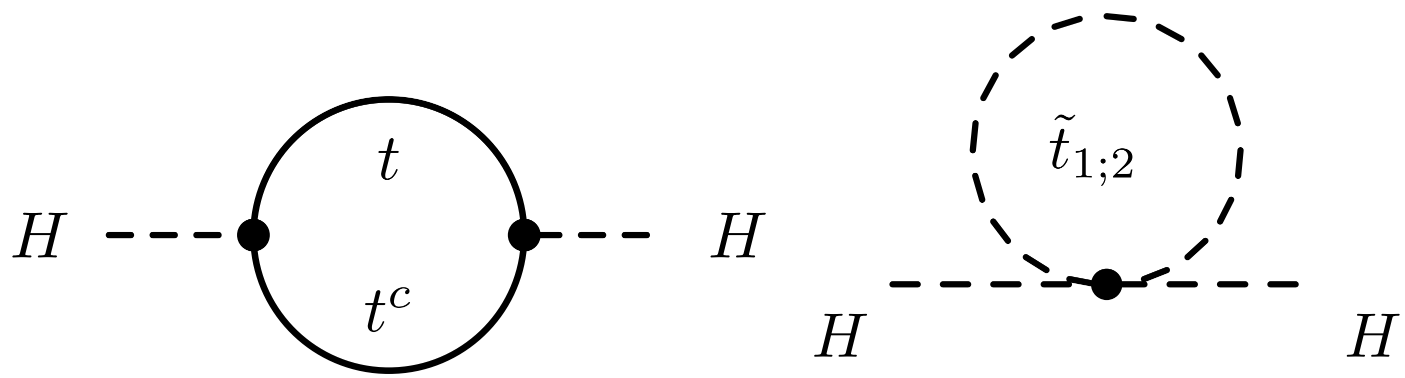
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - t_s S - \frac{m_s^2}{2}S^2 - \frac{a_s}{3}S^3 - \frac{\lambda_s}{4}S^4 - \lambda_{hs}\Phi^\dagger\Phi S^2 - 2a_{hs}\Phi^\dagger\Phi S$$



Huang, Long, Wang, **1608.06619**

Naturalness Predicts Light Top Partners

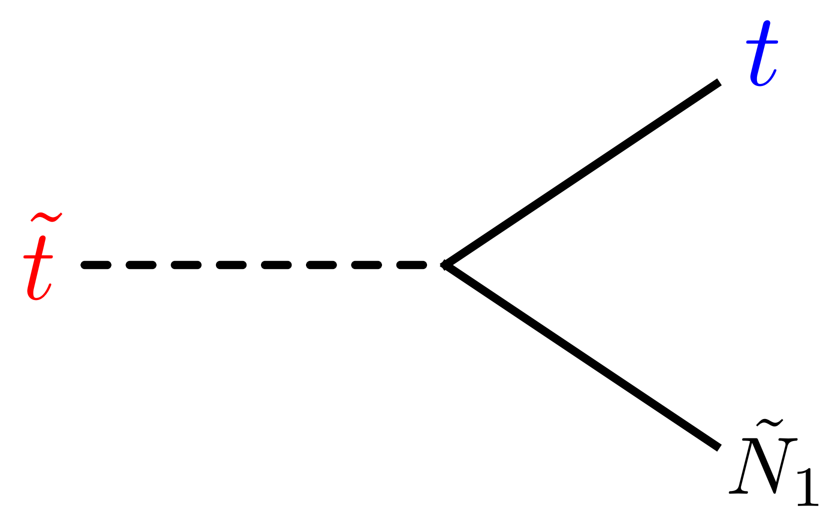
ex) stops in supersymmetry



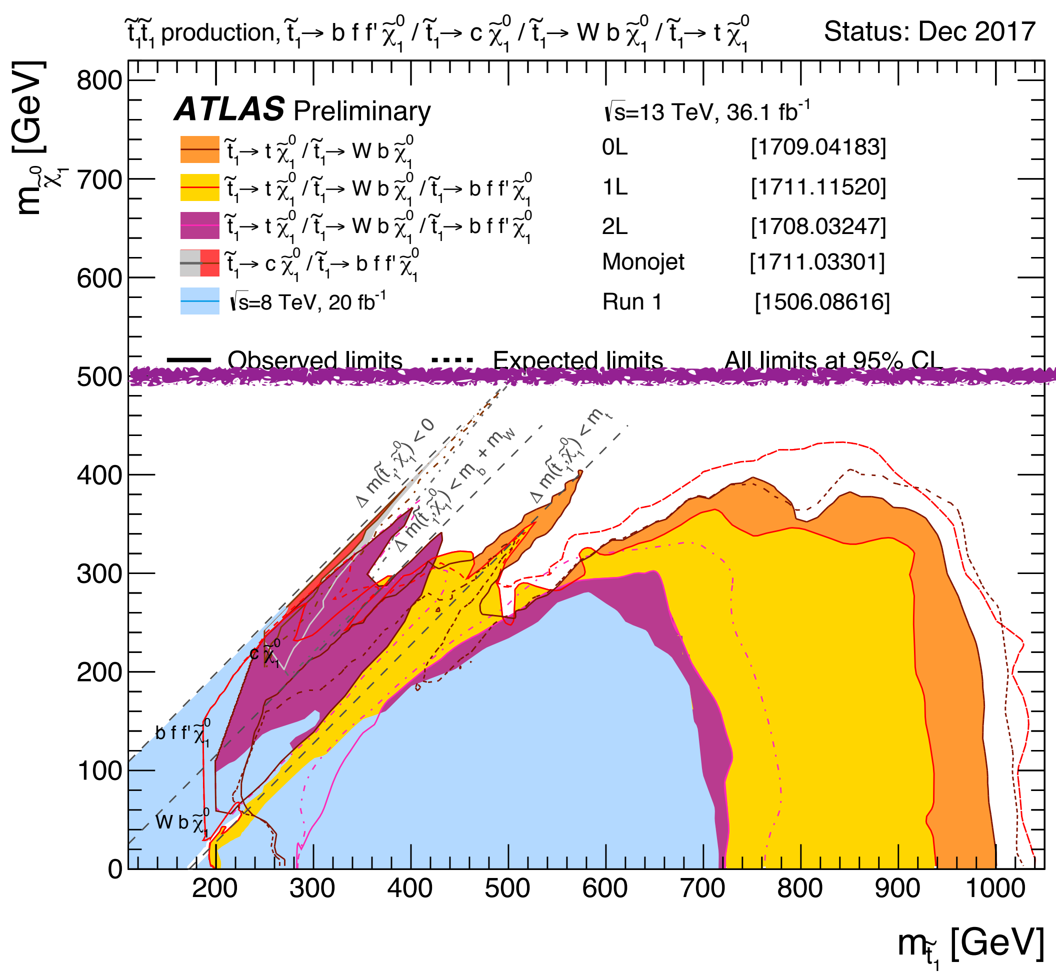
$$\text{tuning} \sim 0.1 \left(\frac{700\,\text{GeV}}{m_{\tilde{t}_1} + m_{\tilde{t}_2}} \right)^2$$

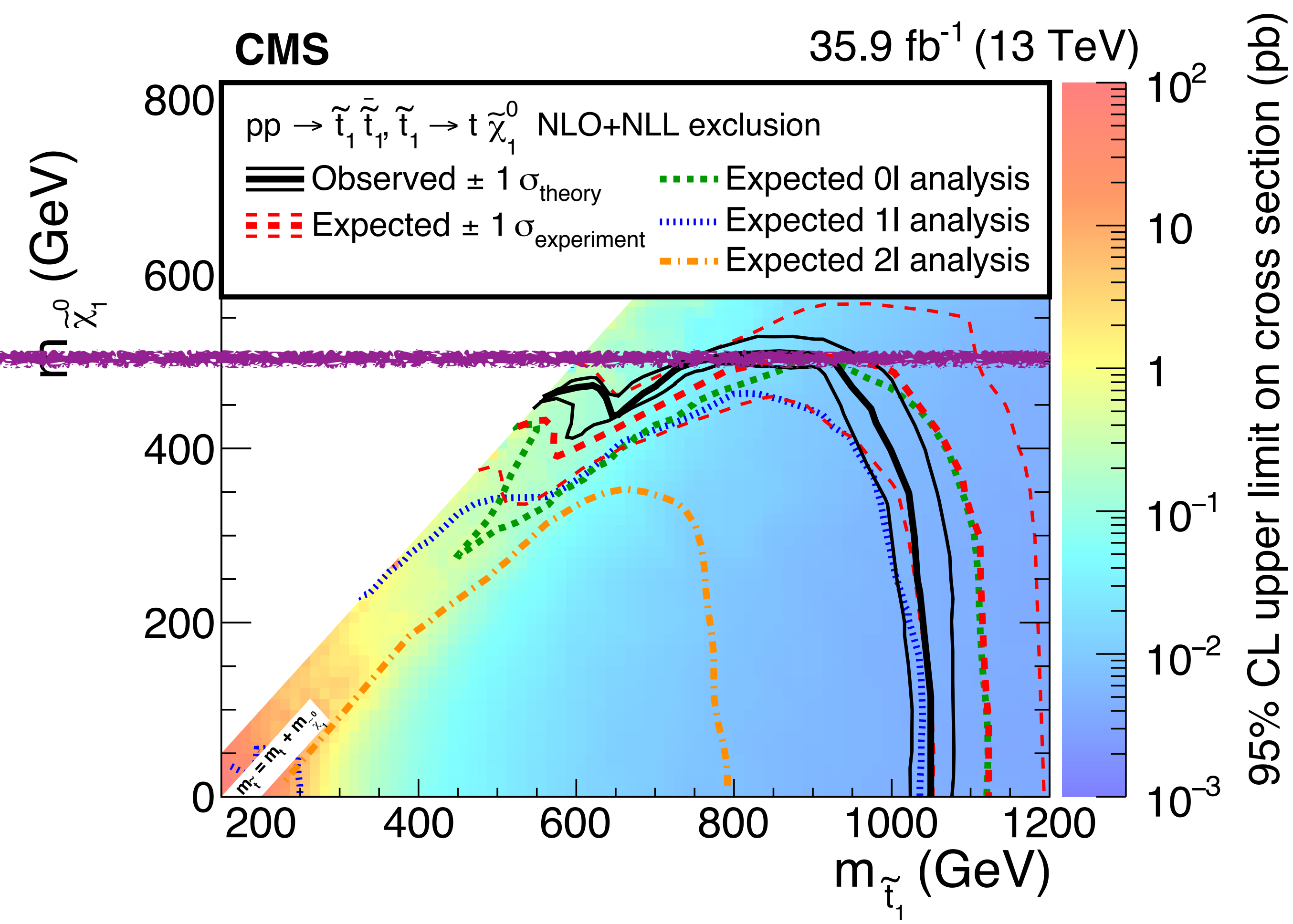
10%

State of Stops



limit depends strongly on neutralino mass

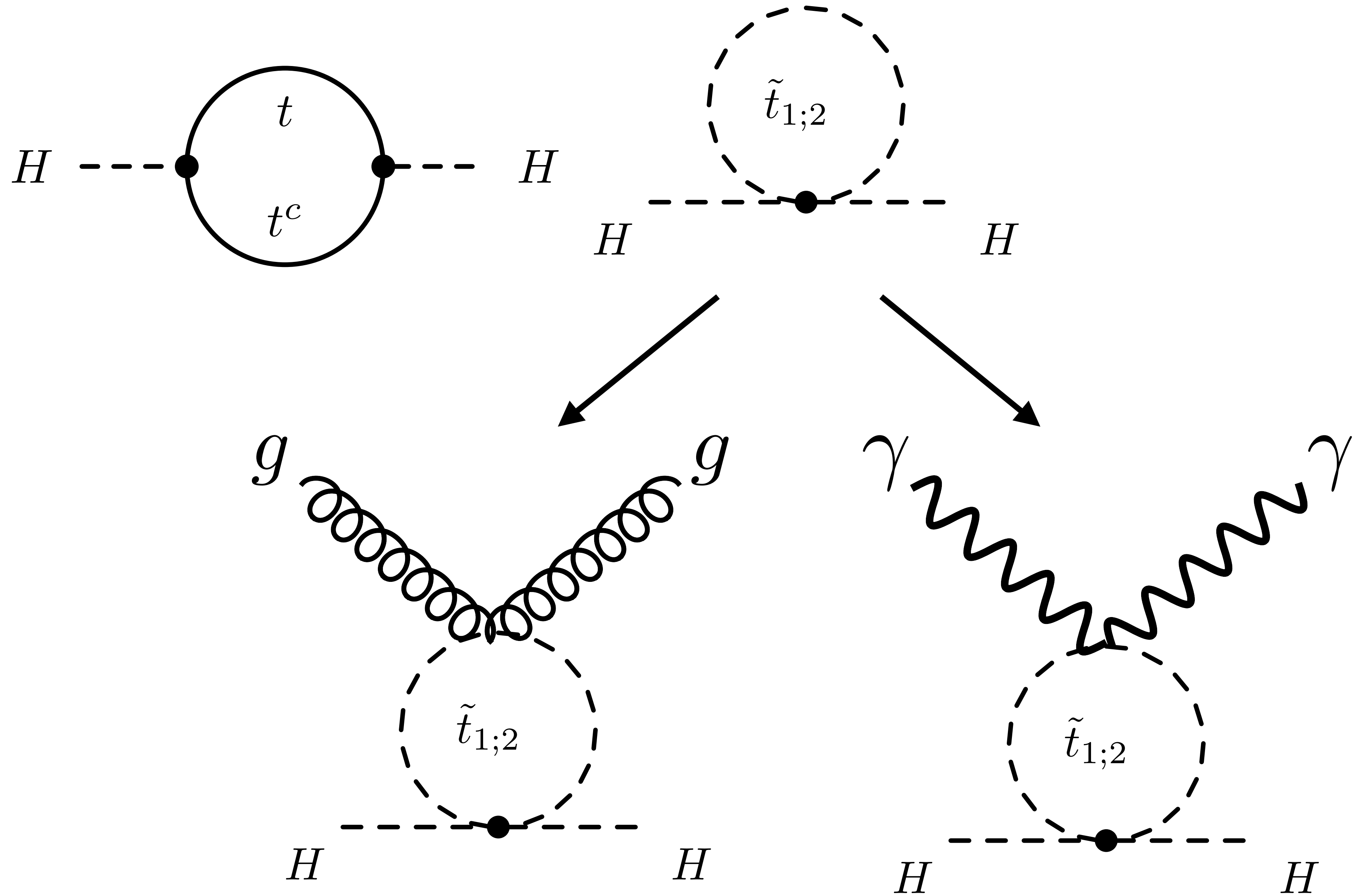




CMS, **1711.00752**

ex) no limit when: $m_{\tilde{N}_1} \gtrsim 500$ GeV

Light Top Partners Predict Higgs Deviations

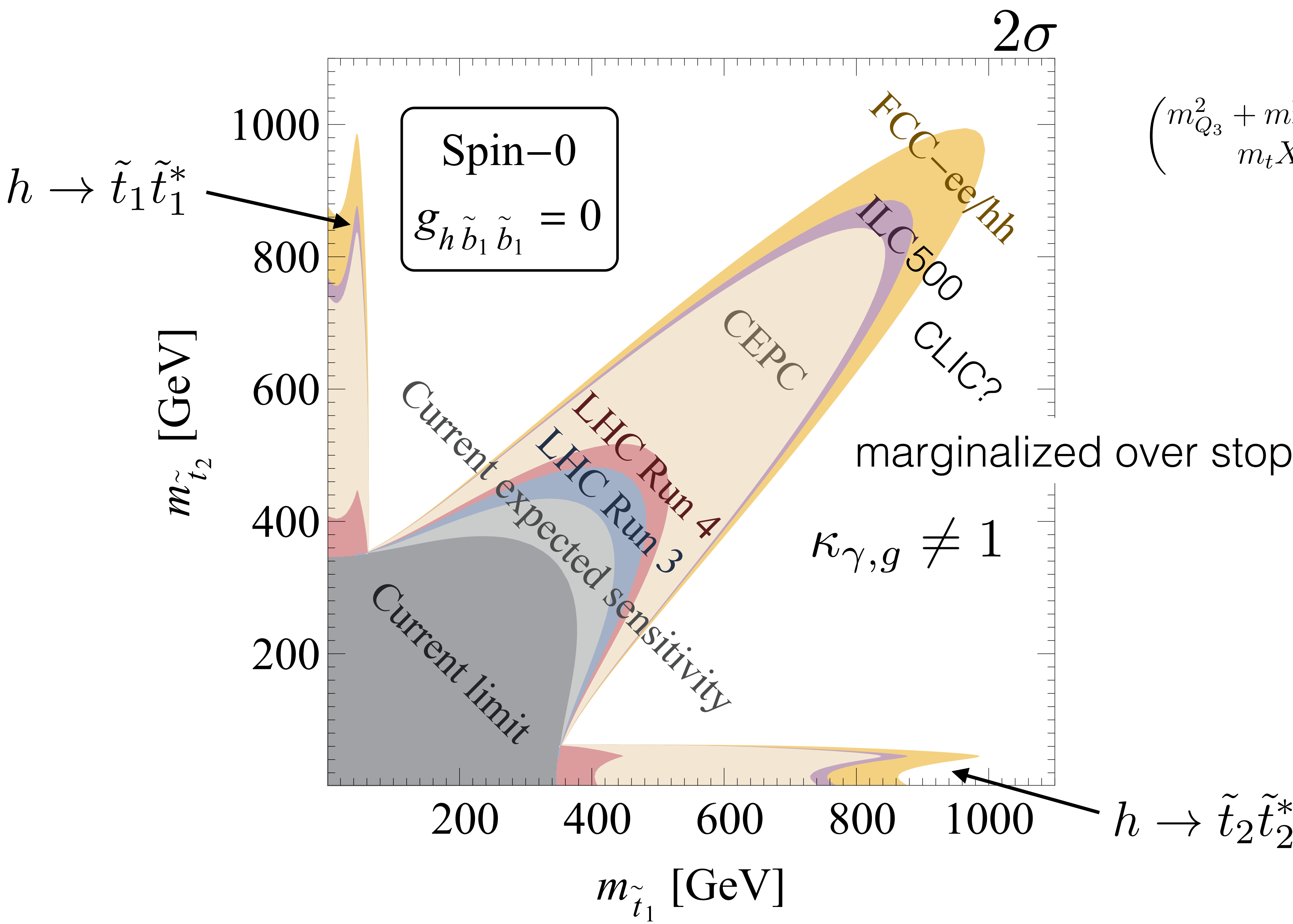


$$\mathcal{O}_{\phi G} = \left(\phi^\dagger \phi\right) G^{A}_{\mu\nu} G^{A\,\mu\nu}$$

$$\mathcal{O}_{\phi B} = \left(\phi^\dagger \phi\right) B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi\right) W^{a}_{\mu\nu} W^{a\,\mu\nu}$$

Higgs Probes Stops

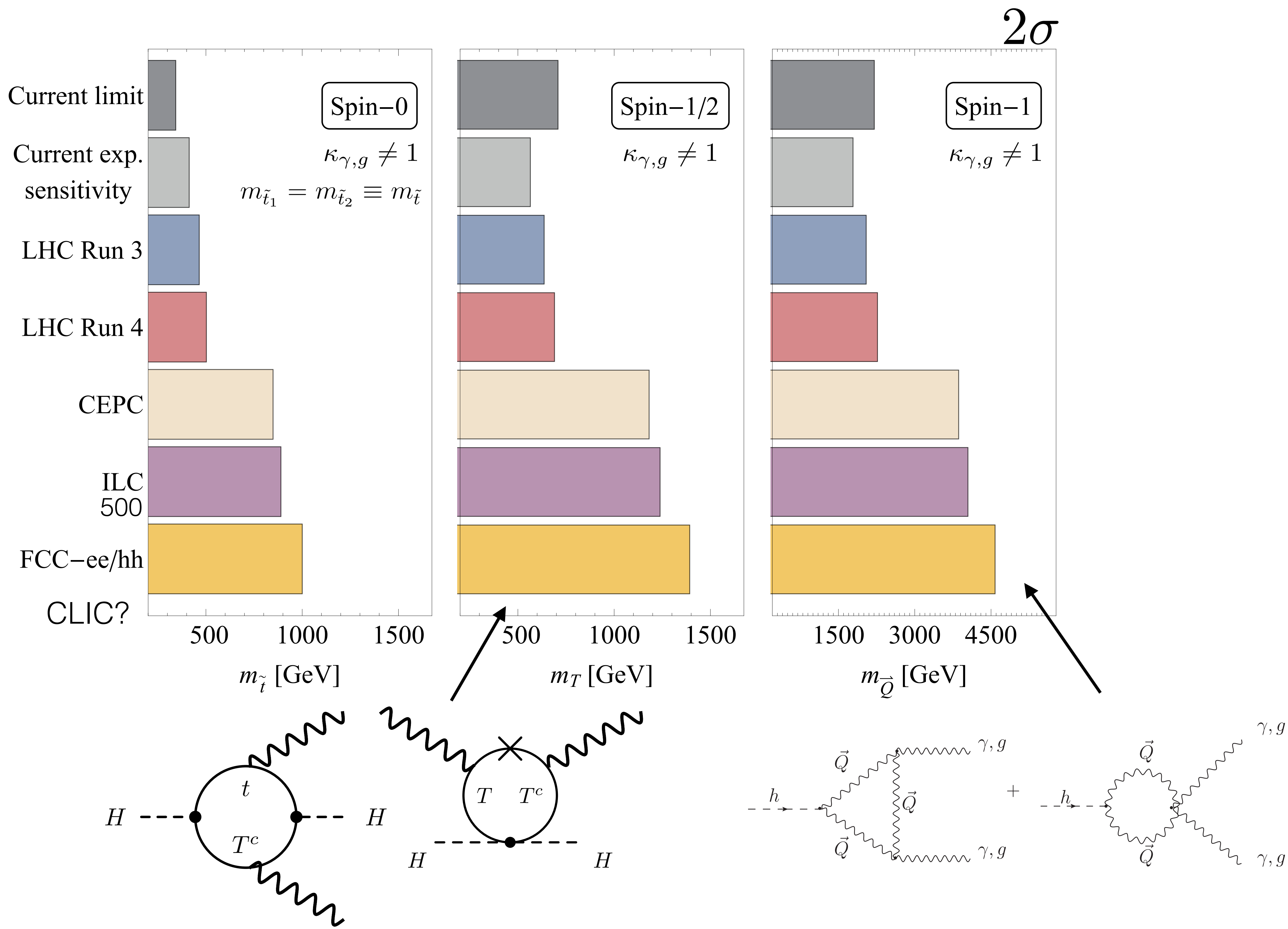


$$\begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L^t & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + D_R^t \end{pmatrix}$$

marginalized over stop mixing X_t

Essig, Meade, Ramani, Zhong, **1707.03399**

Higgs Probes Top Partners

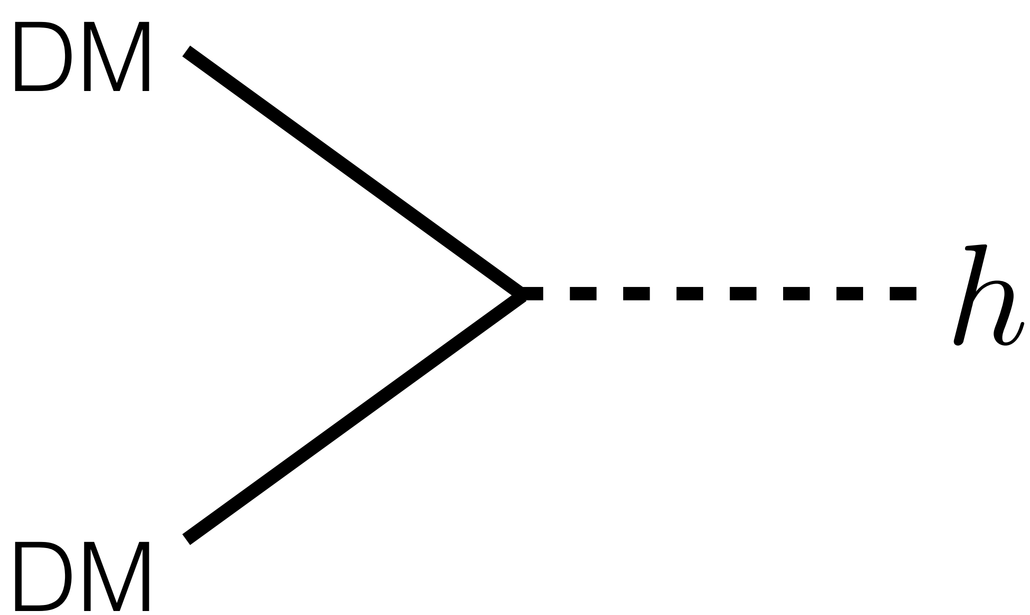


Essig, Meade, Ramani, Zhong, **1707.03399**

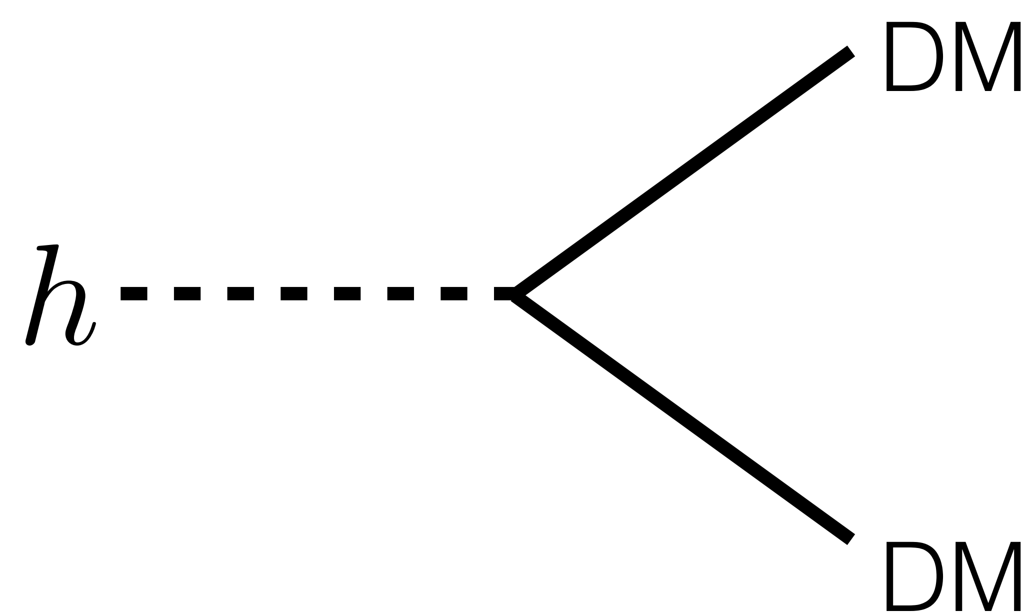
Dark Matter at the Higgs Pole

$$m_{\mathrm{DM}} \approx \frac{m_h}{2}$$

in the early Universe:

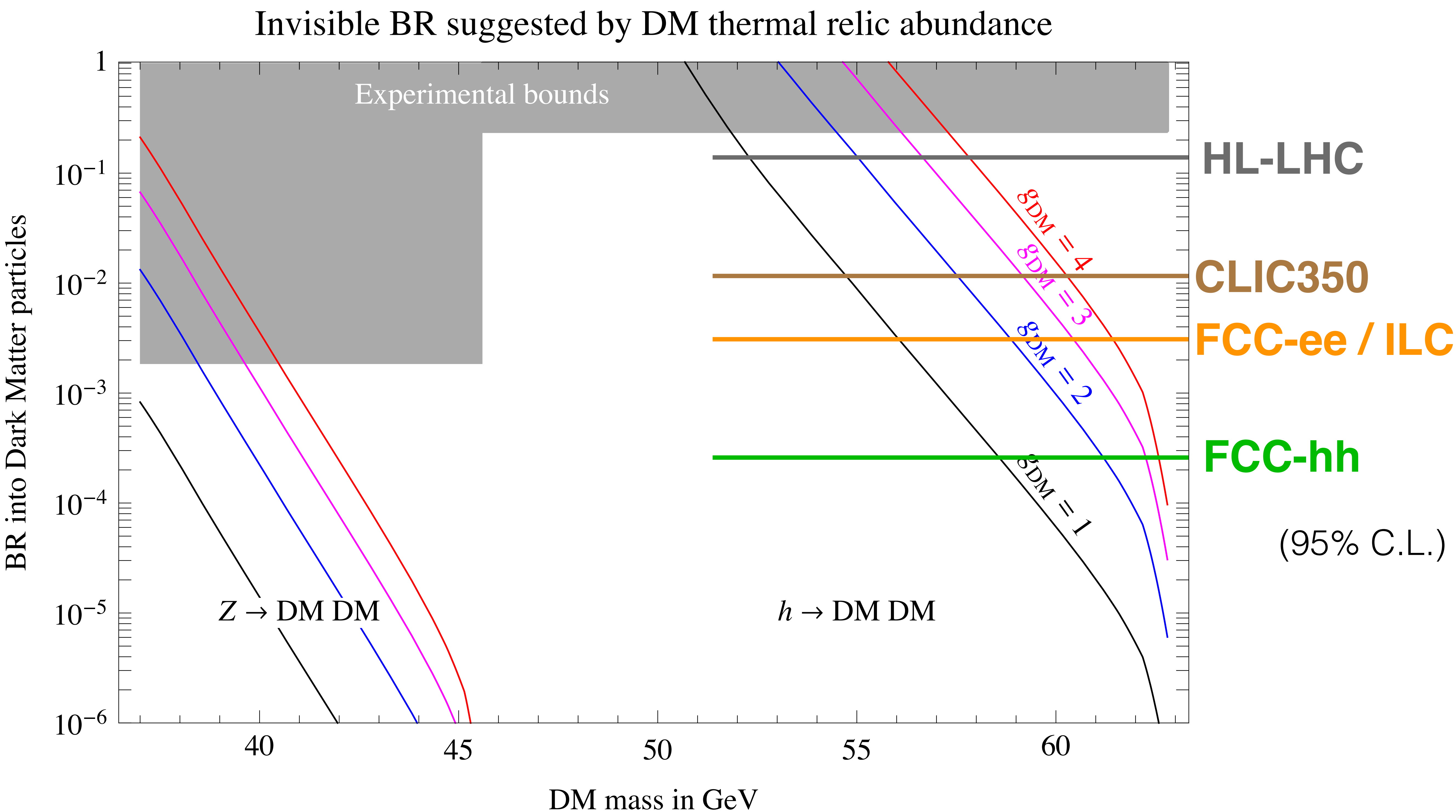


at the LHC:



de Simone, Giudice, Strumia, **1402.6287**

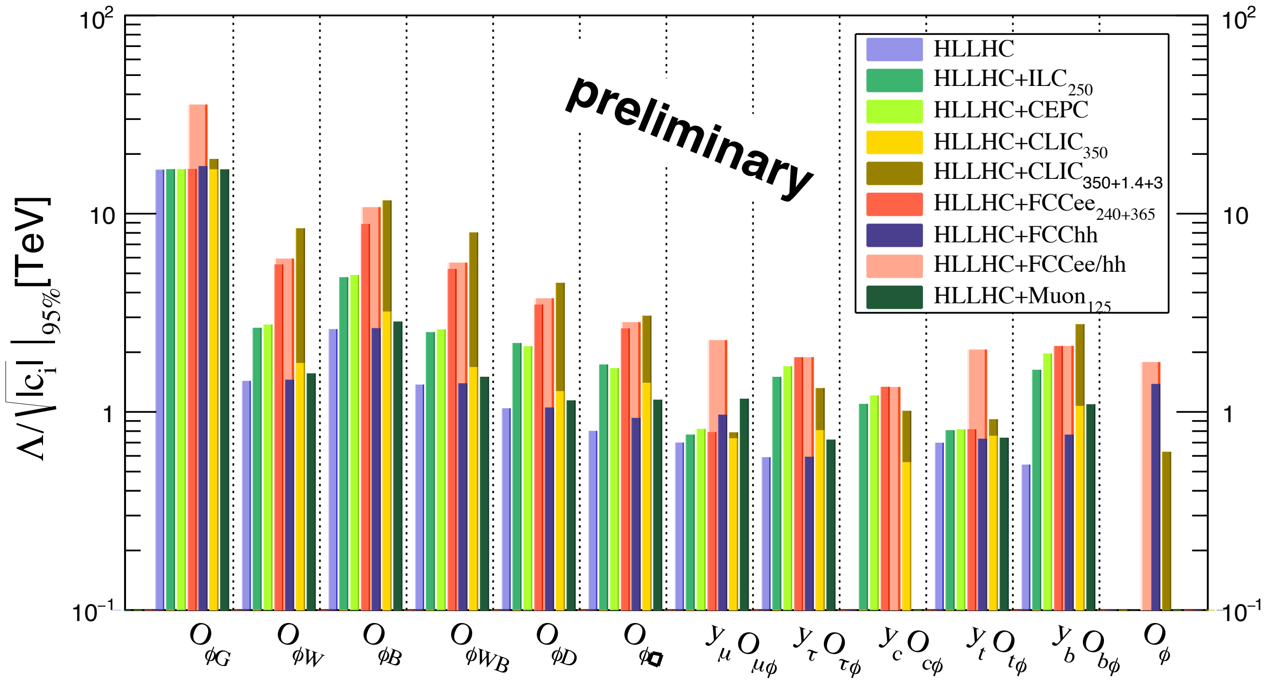
Dark Matter at the Higgs Pole



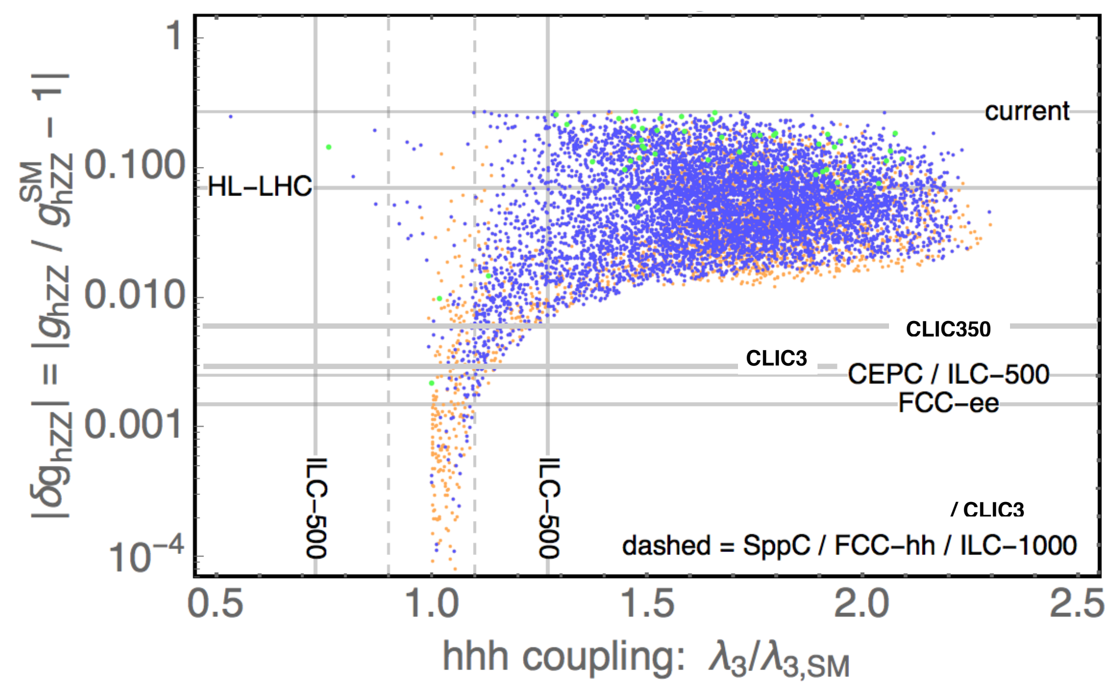
de Simone, Giudice, Strumia, **1402.6287**

Conclusions

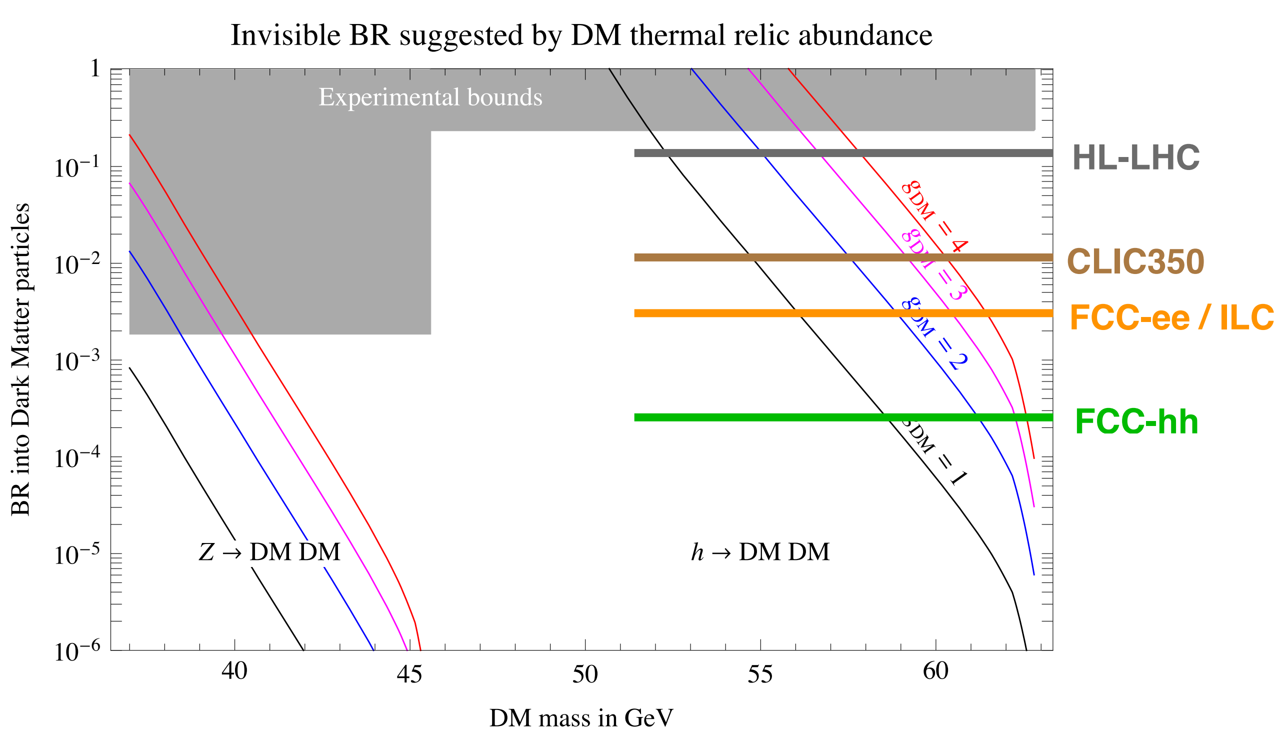
EFT



Electroweak Phase Transition



dark matter



naturalness