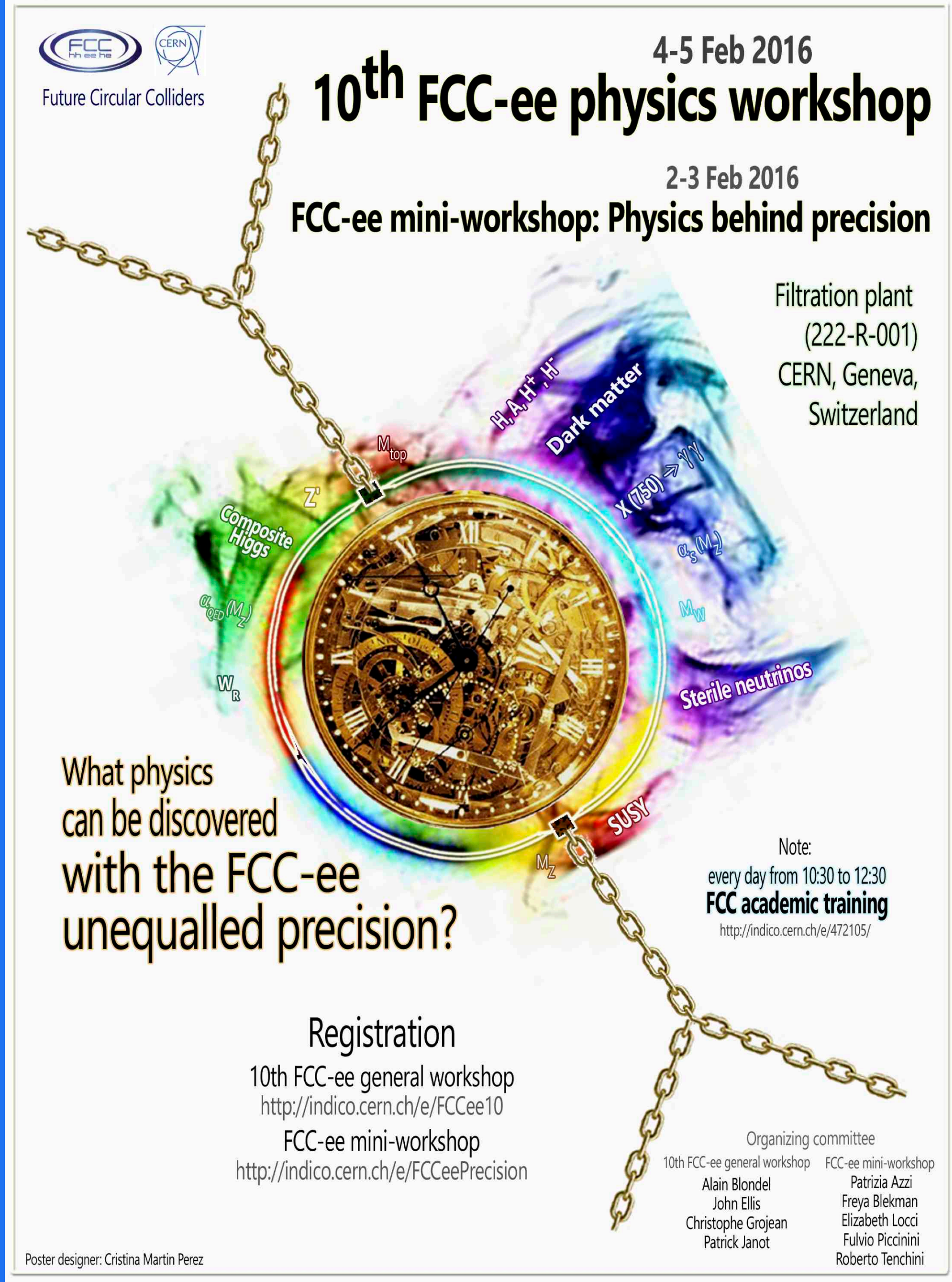
Theory & FCC-ee

G.F. Giudice



LHC Run 1 taught us that we live in a metastable state

I don't refer to the EW vacuum, but to the HEP community

- State of confusion about what lies beyond the SM
- Any new hint in EXP or TH can make our present state collapse into unknown directions

Many of our past expectations have been shattered

based on naturalness

Technicolor → no fundamental Higgs

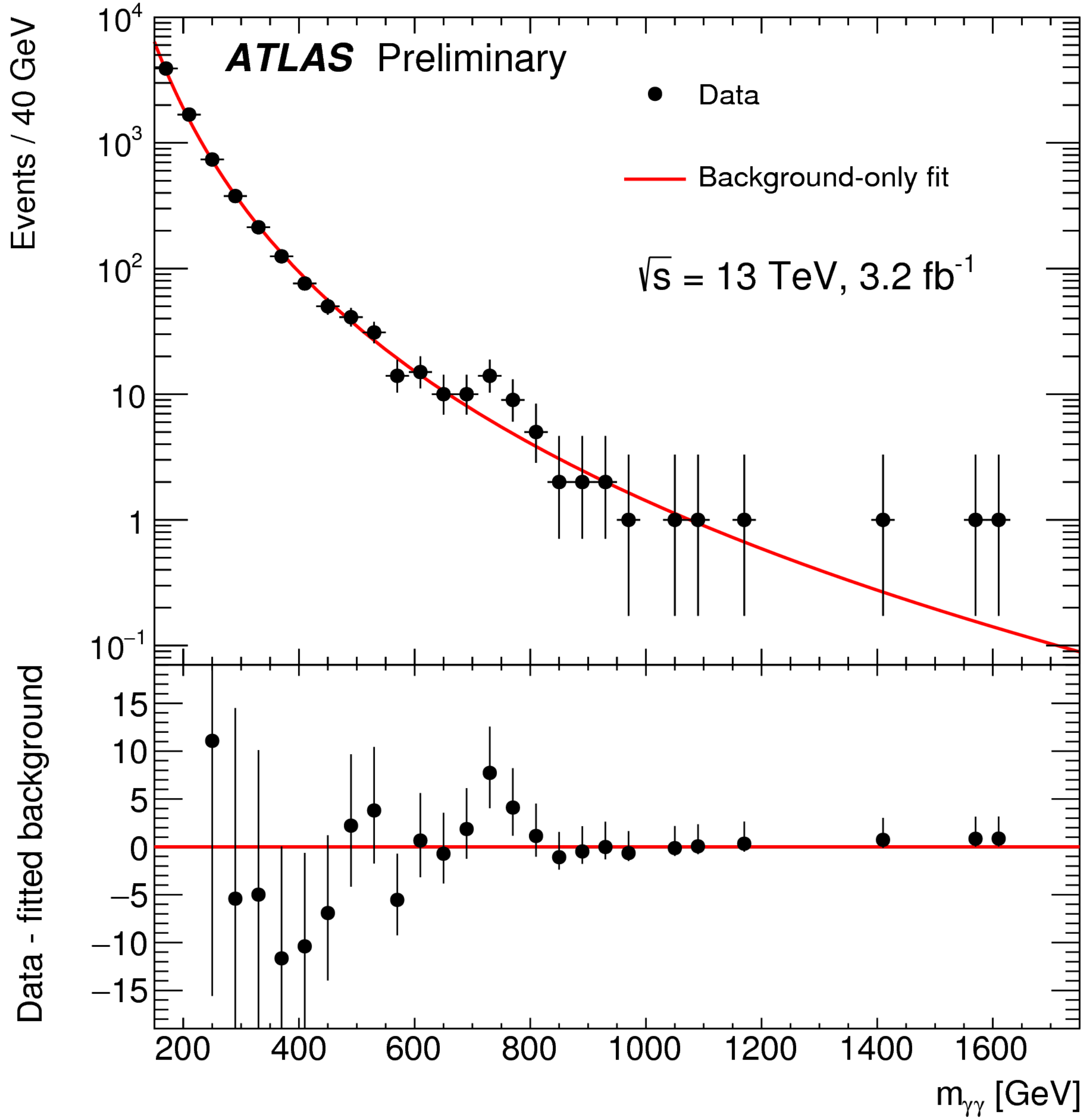
Supersymmetry → $m_h \lesssim 120$ GeV,
$\tilde{m}_t \lesssim 300$ GeV, $\tilde{m}_g \lesssim 1$ TeV

Extra dimensions → hell breaks loose at TeV

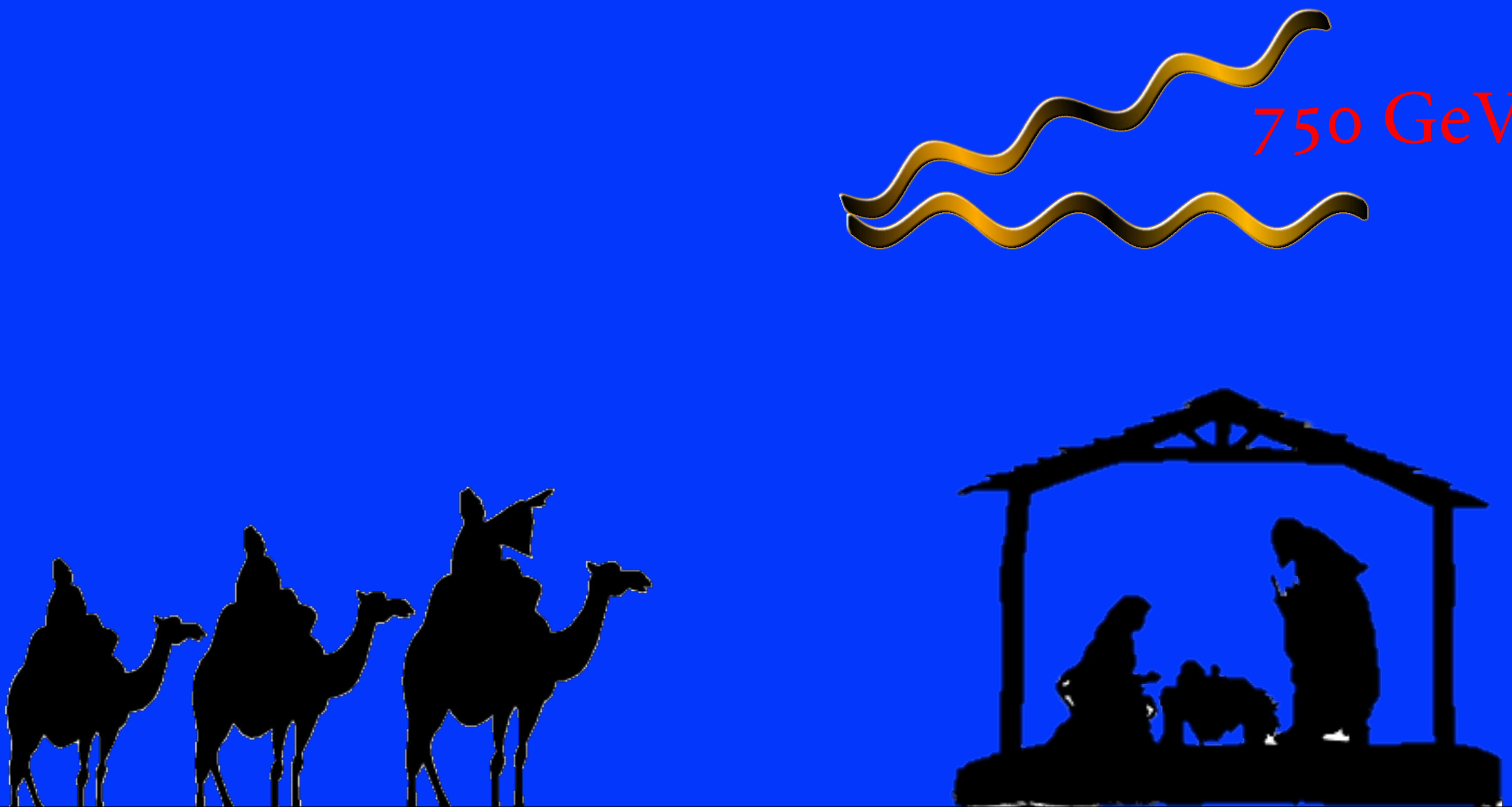
Composite Higgs → $\Delta BR_h \sim O(1)$

Is the naturalness principle not valid for EW
or are we implementing it in the wrong way?

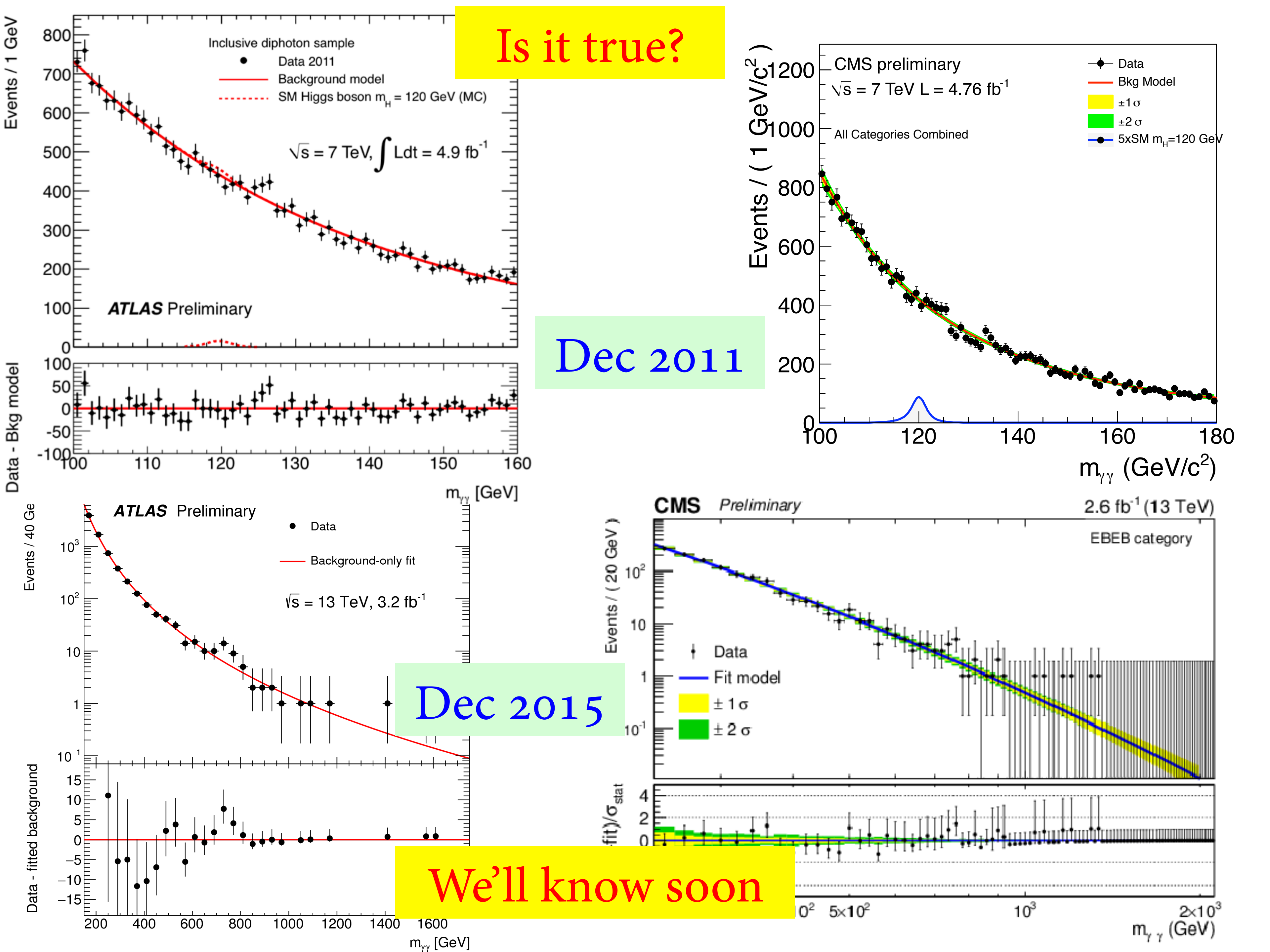
The instability of our present state has been recently confirmed



The epiphany of a new era...



Most theoreticians were willing to abandon old customs
(like spending time with their families during Christmas)
to embrace the new religion

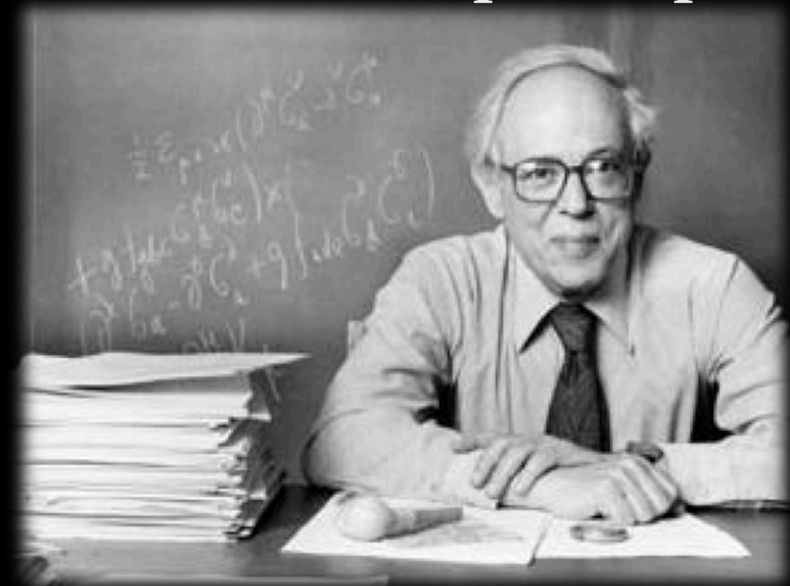

Is it true?
Dec 2011
Dec 2015
We'll know soon
Inclusive diphoton sample
Data 2011
Background model
SM Higgs boson m_H = 120 GeV (MC)
√s = 7 TeV, ∫ Ldt = 4.9 fb-1
ATLAS Preliminary
Events / 1 GeV
Data - Bkg model
m_γγ [GeV]
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM m_H=120 GeV
Events / (1 GeV/c2)
m_γγ (GeV/c2)
ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb-1
Data - fitted background
m_γγ [GeV]
CMS Preliminary
2.6 fb-1 (13 TeV)
EBEB category
Data
Fit model
± 1 σ
± 2 σ
Events / (20 GeV)
m_γγ (GeV)

Lessons

- Sociological behaviour of the HEP community
- We live in uncertain times: key questions can suddenly change
- Today measuring the Higgs properties is the central issue. No doubt it is a fundamental question, but will people care tomorrow as much as they care today?
- Most of what I say is irrelevant

Should we fear this state of confusion?

Today we live in the midst of upheaval and crisis. We do not know where we are going, nor even where we ought to be going. Awareness is spreading that our future cannot be a straight extension of the past or the present. [...] Progress leads to confusion leads to progress and on and on without respite. Every one of the many major advances [...] created sooner or later, more often sooner, new problems. These confusions, never twice the same, are not to be deplored. Rather, those who participate experience them as a privilege.



Abraham Pais

Confusion and not knowing where we are going may be great for theorists, but how can we plan future colliders while living in a metastable state?

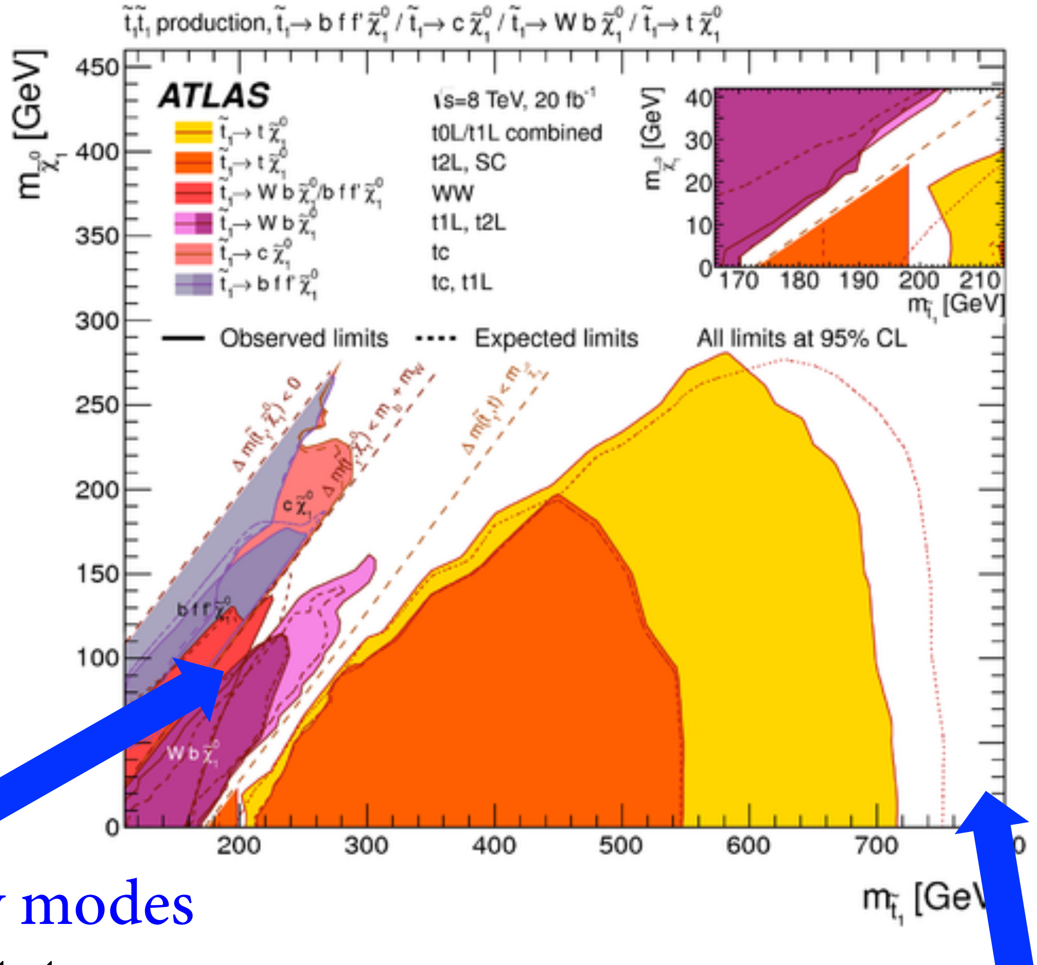
Does FCC-ee contribute to a diversified, farsighted, and ambitious HE program?

Are there new particles to be discovered at FCC-ee?

LHC is suffocating life at $\sqrt{s} \lesssim 2\, m_t$

LHC may leave holes where naturalness can hide

Exploring these holes is a crucial task: some of them may be accidental, but others have good theoretical justifications



Difficult decay modes

- Soft final states (compressed spectra, stealth susy)
- Light quarks (flavour mixing, R violation)

Unnatural spectra

(Split Susy & variations)

In some cases, the “holes” are the only way for discovery

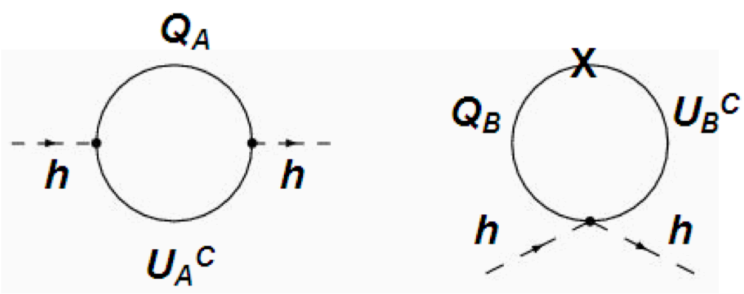
Neutral naturalness

Twin Higgs: discrete symmetry on an enlarged Higgs sector implies an accidental global symmetry at one-loop

$$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2}(H_A^\dagger H_A + H_B^\dagger H_B)$$

No mass to the extra Goldstones

Chacko, Goh, Harnik

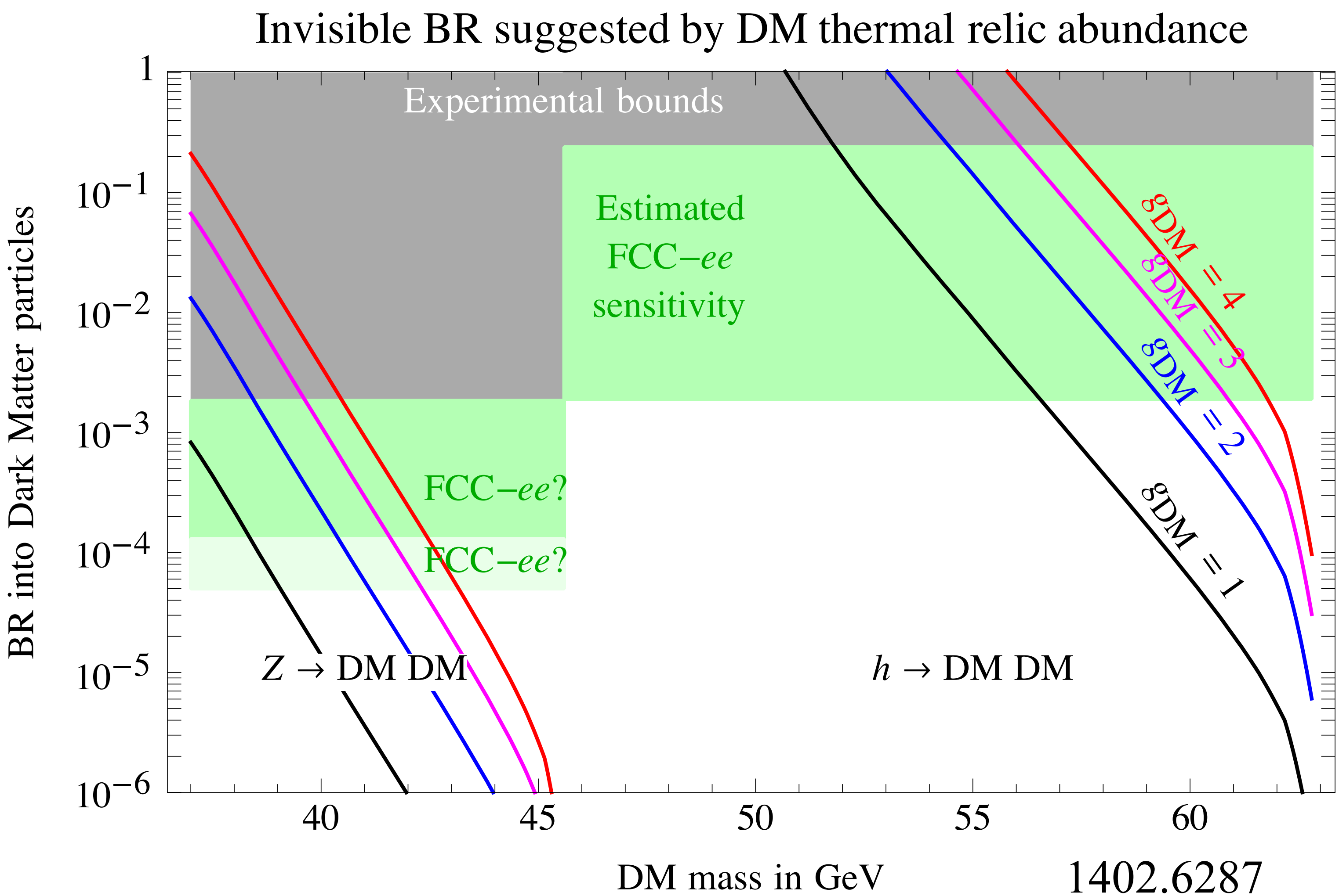


Naturalness ⇒ new states necessarily charged under EW, but not QCD

In general, LHC will leave “holes” in the search for EW particles

Rare decays of Z and H

Ex.: Near-resonant DM annihilation escapes direct detection



1402.6287

In general, weakly-interacting particles with 'difficult' decay modes can escape both LHC and FCC-hh

Examples:

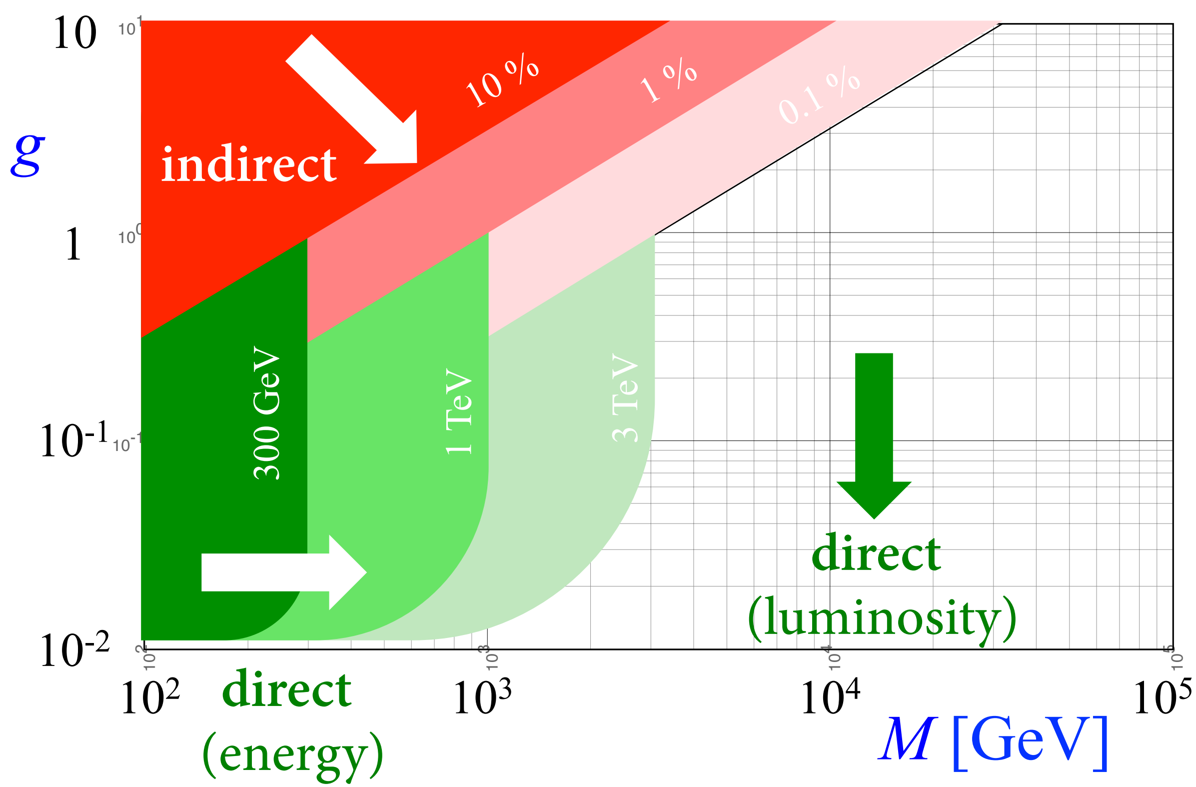
- nearly-degenerate weak multiplets
- DM models

Testable beyond mass threshold through quantum corrections (see Strumia's talk)

We are looking for new phenomena (not just particles)
The strength of FCC-ee lies in precision

Direct searches probe M (with energy) and g (with luminosity)

Indirect searches probe g^2/M^2



Indirect searches are more effective for strongly-int theories

Theoretical predictions are more reliable for weakly-int theories

LCC-ee 4 phases of precision physics

$Z \longrightarrow$ 90 GeV

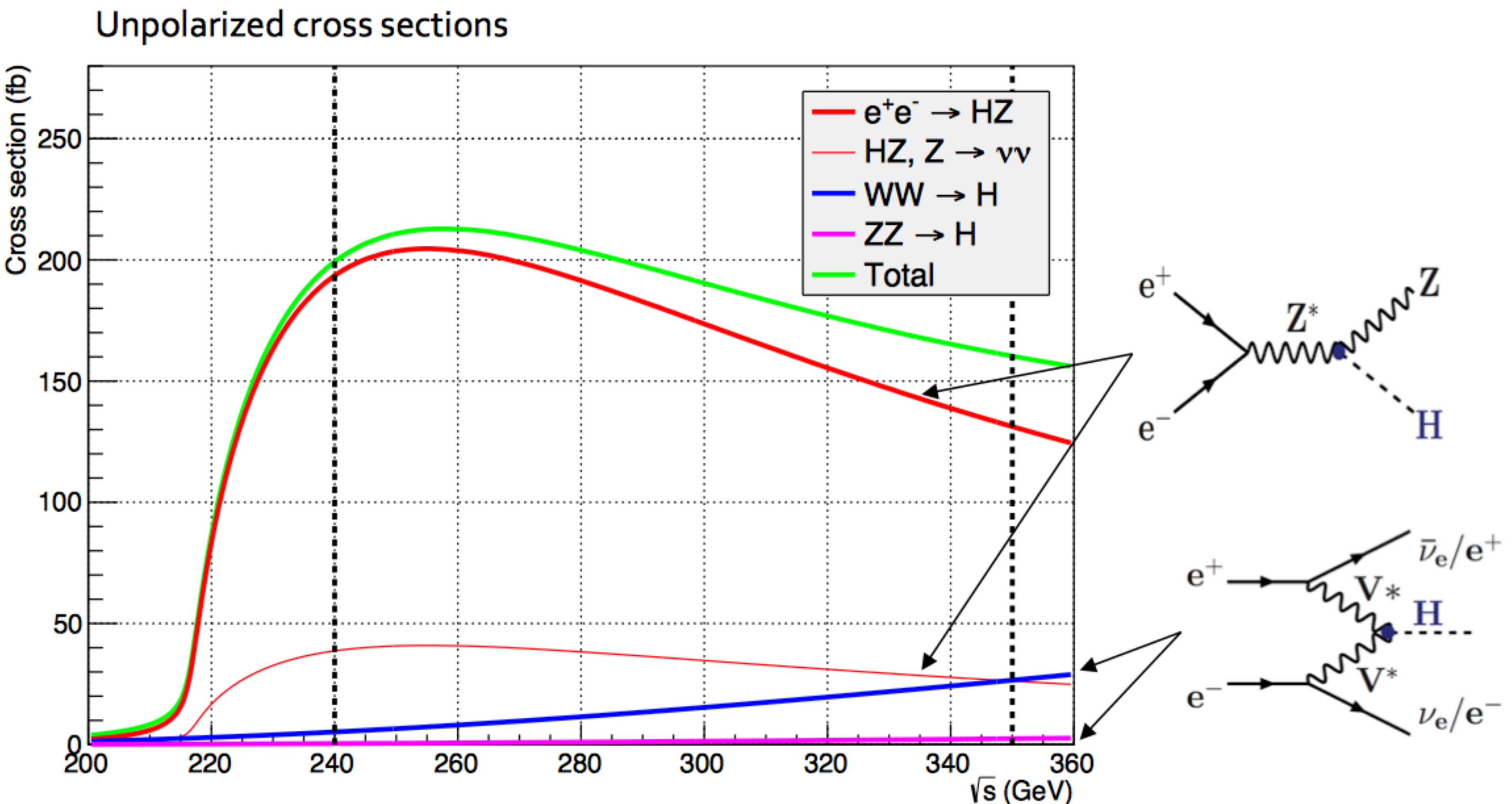
$WW \longrightarrow$ 160 GeV

$HZ \longrightarrow$ 240 GeV

$tt \longrightarrow$ 350 GeV

Higgs production

- Large rate
- Recoil mass in $e^+e^- \rightarrow HZ$ gives 0.05% precision in $\sigma_{e+e- \rightarrow HZ}$ (hence in g_{HZZ})
- Tagged Higgs invisible decays



Error on	μμ Collider	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

(P. Janot, talk at FCC-ee, 24 Sep 2015)

Comparison of precision (after ~ 10 yrs data)

Higher luminosity than LC (for $\sqrt{s} \leq 400$ GeV)

Precise knowledge of beam energy ($E_{beam} \sim 0.1$ MeV)

Triple Higgs through quantum corrections

McCullough 1312.3322

(A. Nisati, talk at IAS, 20 Jan 2016)

		K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ
300fb^{-1}	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb^{-1}	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb^{-1}	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

$$\Delta = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale } \; 4\pi f > \sqrt{\frac{0.1\%}{\Delta}} \; 100 \text{ TeV}$$

Precise test of g_{Hcc}: Higgs couplings to 1st and 2nd generation may reveal secrets about flavour

$$H\bar{\psi}_L^{(3)}\psi_R^{(3)} \quad + \quad \frac{(H^+H)^{n_{ij}}}{\Lambda^{2n_{ij}}} H\bar{\psi}_L^{(i)}\psi_R^{(j)}$$

$$\downarrow \qquad\qquad \downarrow$$

$H\psi$

$$m^{(3)} = O(v) \qquad m^{(ij)} = O\left(\frac{v^{2n_{ij}+1}}{\Lambda^{2n_{ij}}}\right)$$

$$y^{(3)} = \frac{m^{(3)}}{v} \qquad y^{(ij)} = (2n_{ij}+1)\frac{m^{(ij)}}{v}$$

$$\frac{y^{(3)}}{y_{SM}^{(3)}} = 1 \qquad \frac{y^{(ij)}}{y_{SM}^{(ij)}} = 2n_{ij}+1$$

0804.1753

Enhanced Higgs couplings to light generations

$$H\bar{\psi}_L^{(3)}\psi_R^{(3)} \quad + \quad \phi\bar{\psi}_L^{(ij)}\psi_R^{(ij)}$$

$+$ small mixing $\phi - H$

$$\langle H \rangle \approx v \qquad \langle \phi \rangle << v$$

Ghosh et al. 1508.01501

Suppressed Higgs couplings to light generations

Couplings to 1st and 2nd generation quarks?

Higgs exclusive decays

$$H \to V\gamma \quad V = \rho, \omega(y_u, y_d),\ \phi(y_s),\ J/\Psi(y_c)$$

Kagan et al. 1406.1722

Couplings to electrons?

5-σ observation with 75 ab^{-1} on the Higgs resonance with energy spread less than Higgs width (4.1 MeV)

D'Enterria, Wojcik, Aleksan,
8th FCC-ee Workshop, Paris 2014
Jadach, Kycia 1509.02406

$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (VV → H)
$\mathscr{L}$/IP (cm^{-2} s^{-1})	$2.2{\cdot}10^{36}$	$1.1{\cdot}10^{36}$	$3.8{\cdot}10^{35}$	$8.7{\cdot}10^{34}$	$2.1{\cdot}10^{34}$	$2.1{\cdot}10^{34}$
$\mathscr{L}_{\rm int}$ (ab^{-1}/yr/IP)	22	11	3.8	0.87	0.21	0.21
Events/year (4 IPs)	$3.7{\cdot}10^{12}$	$1.3{\cdot}10^{4}$	$6.1{\cdot}10^{7}$	$7.0{\cdot}10^{5}$	$4.2{\cdot}10^{5}$	$2.5{\cdot}10^{4}$
Years needed (4 IPs)	2.5	1.5	1	3	0.5	3

D'Enterria 1601.06640

A lot of physics can be done with 10^{12} Z (10^6 at LEP1), 10^8 W pairs (10^4 at LEP2), 10^6 top pairs (and 3×10^{10} τ pairs and 2×10^{11} b)

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Z lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corrs.
Γ_Z (MeV)	Z lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corrs.
R_ℓ	Z peak	20.767 ± 0.025	0.0001	< 0.001	QED corrs.
R_b	Z peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to b\bar{b}$
$A_{FB}^{\mu\mu}$	Z peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meas.
N_ν	Z peak	2.984 ± 0.008	0.00004	0.004	Lumi meas.
N_ν	$e^+e^- \to \gamma Z(\text{inv.})$	2.92 ± 0.05	0.0008	< 0.001	–
$\alpha_s(m_Z)$	$R_\ell, \sigma_{had}, \Gamma_Z$	0.1196 ± 0.0030	0.00001	0.00015	New physics
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ around Z peak	128.952 ± 0.014	0.004	0.002	EW corr.
m_W (MeV)	WW threshold scan	80385 ± 15	0.3	< 1	QED corr.
$\alpha_s(m_W)$	B_{had}^W	$B_{had}^W = 67.41 \pm 0.27$	0.00018	0.00015	CKM matrix
m_t (MeV)	threshold scan	173200 ± 900	10	10	QCD
$F_{1V,2V,1A}^{\gamma t, Zt}$	$d\sigma^{t\bar{t}}/dx\, d\cos(\theta)$	4%–20% (LHC-14 TeV)	(0.1–2.2)%	(0.01–100)%	–

D'Enterria 1601.06640

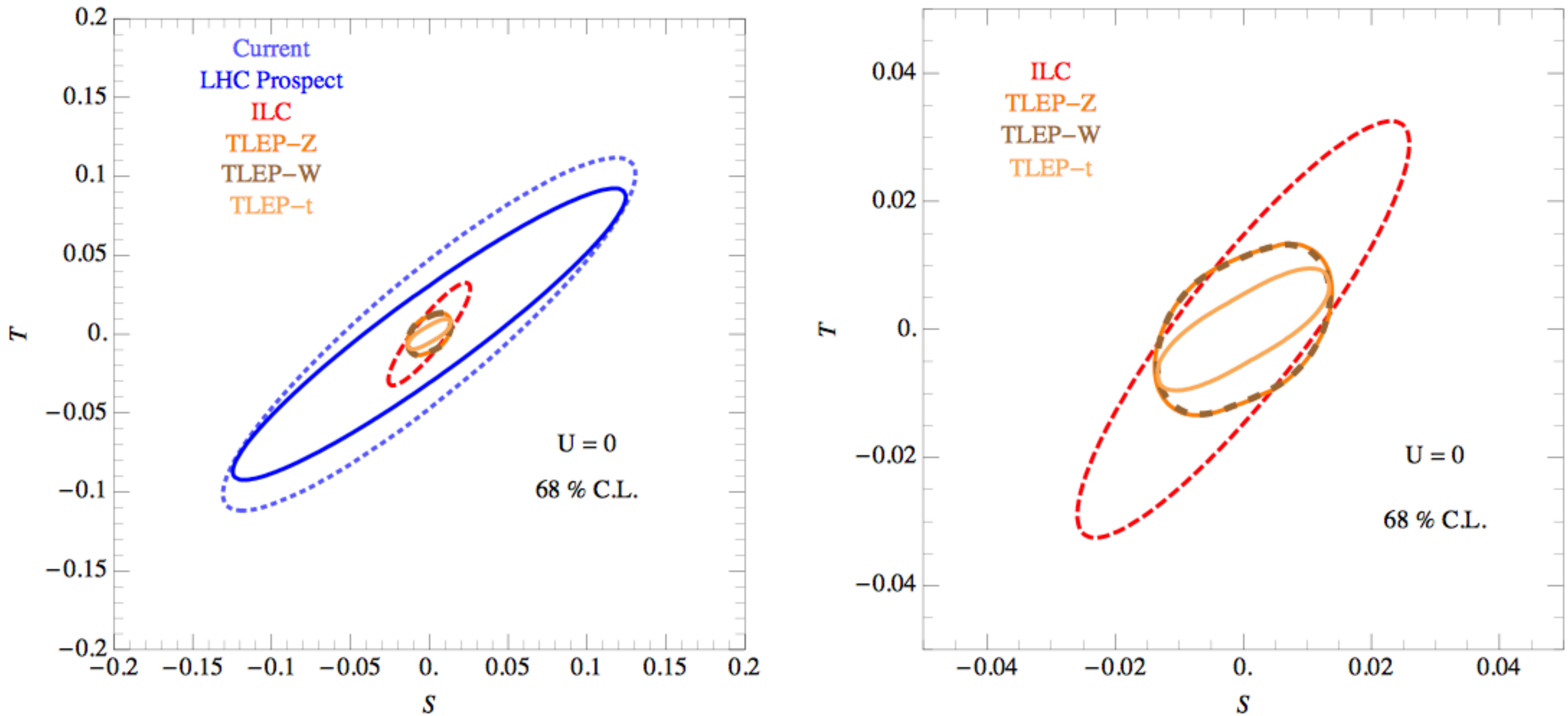
$\delta m_Z \approx 100$ keV ($\delta m_{Z\text{today}} / \delta m_Z \approx 20$)

$\delta m_W \approx 500$ keV ($\delta m_{W\text{today}} / \delta m_W \approx 30$, $\delta m_{W\text{LHC}} / \delta m_W \approx 16$)

$\delta N_\nu \approx 10\text{-}4 \times 10^{-4}$ ($\delta N_{\nu\text{today}} / \delta N_\nu \approx 8\text{-}20$)

$\delta \alpha_s(m_Z)_{\text{today}} / \delta \alpha_s(m_Z) \approx 10\text{-}100$ (see Workshop on high-precision α_s measurements from LHC to FCC-ee, 12-13 Oct 2015)

$\delta \alpha_{QED}(m_Z)_{\text{today}} / \delta \alpha_{QED}(m_Z) \approx 3\text{-}4$



Fan et al. 1411.1054

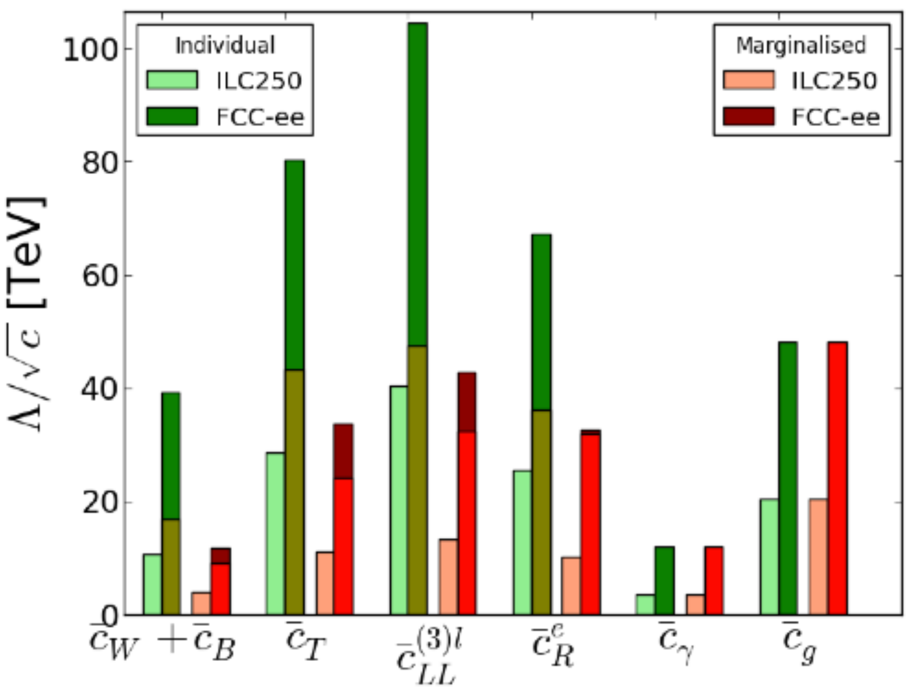
S and T improve by a factor 10, while ILC promises 2-3

With precision on S and $T \sim 10^{-2}$

Strongly-interacting theory $$S \approx 4\pi \frac{v^2}{M^2} \quad \Rightarrow \quad M \sim 10 \text{ TeV}$$

Weakly-interacting theory $$S \approx \alpha_W \frac{v^2}{M^2} \quad \Rightarrow \quad M \sim 500 \text{ GeV}$$

(stop-like) $$T \approx \frac{y_t^4}{64\pi^2\alpha} \frac{v^2}{M^2} \quad \Rightarrow \quad M \sim 1 \text{ TeV}$$



FCC-ee can explore some FCC-hh territory

Ellis & You 1510.04561

EFT analysis misses correlations between EW & Higgs observables

$$\left(H^+\overleftrightarrow{D}^\mu H\right)\left(H^+\overleftrightarrow{D}_\mu H\right) \quad \Rightarrow \quad \Delta\rho \qquad\qquad (T)$$

$$\partial^\mu\left(H^+H\right)\partial_\mu\left(H^+H\right) \Rightarrow \text{Higgs wavefunction} \quad (\delta g_H)$$

Strong (model-dependent) correlation

Some examples:

Composite Higgs

If dominant effect comes from

$$\frac{1}{2f^2}\partial^\mu\left(H^+H\right)\partial_\mu\left(H^+H\right), \quad \xi \equiv \frac{v^2}{f^2}$$

Uniquely determined by the σ-model algebra

$$T = -\frac{3\xi}{8\pi\cos^2\theta_W}\ln\frac{\Lambda}{m_h} = -0.7\xi\left(1+0.2\ln\frac{\Lambda}{10\text{ TeV}}\right)$$

$$S = \frac{\xi}{6\pi}\ln\frac{\Lambda}{m_h} = 0.2\xi\left(1+0.2\ln\frac{\Lambda}{10\text{ TeV}}\right)$$

S, $T \sim 10^{-2}$ $\Leftrightarrow$ Higgs couplings: few %

Stop left

$$T = \frac{m_t^2}{4\pi\sin^2\theta_W m_W^2}\delta g_{Hgg} = 1.6\,\delta g_{Hgg}$$

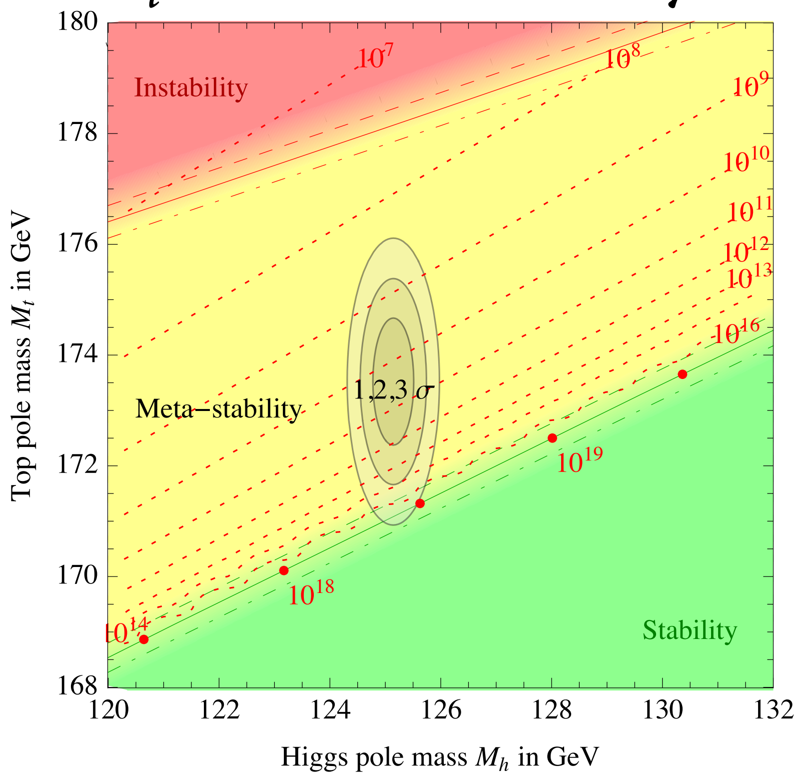
$T \sim 10^{-2}$ $\Leftrightarrow$ Higgs-gluon coupling: 0.6%

Top mass measurements at threshold

	m_{top}	Γ_{top}	g_{Htt}
TLEP	10 MeV	11 MeV	13%
ILC	31 MeV	34 MeV	40%

	LHC		ILC		FCCee	
	exp.	th.	exp.	th.	exp.	th.
Δm_W (MeV)	10	4	7	1.0	0.5	1.0
Δm_{top} (MeV)	600	250	34	100	10	100
Δm_H (MeV)	100		35		7	

N³LO calculations can relate such measurements to a well-defined m_t with an accuracy below 50 MeV



1307.3536

m_t is an input not only in EW data, but also in flavour

Lattice QCD promises 1% precision in hadronic parameters in 10 yrs

Example:

$B_s \to \mu^+\mu^-$ (first observed by CMS/LHCb in 2014 with 25% accuracy)

Theory prediction

$$BR(B_s \to \mu^+\mu^-) = 3.33\times 10^{-9}\left(1 \pm 7.2\% \pm 3.06\,\frac{\Delta m_t}{m_t}\right)$$

from CKM and hadronic parameters

strong dependence

Conclusions

- LEP program turned out to be precision, although it aimed also at discovery
- LEP main legacy: SM as an EFT (separation of scales)

- FCC-ee aims at precision; can it make discoveries too (rare *Z*, *H*, *t* decays, ‘holes’ left by LHC)?
- FCC-ee main goal: probe the SM cutoff (new phenomena)

- FCC-ee can explore territory beyond LHC and fill ‘holes’ invisible to FCC-hh (rare decays, nearly-degenerate weak multiplets, DM models)