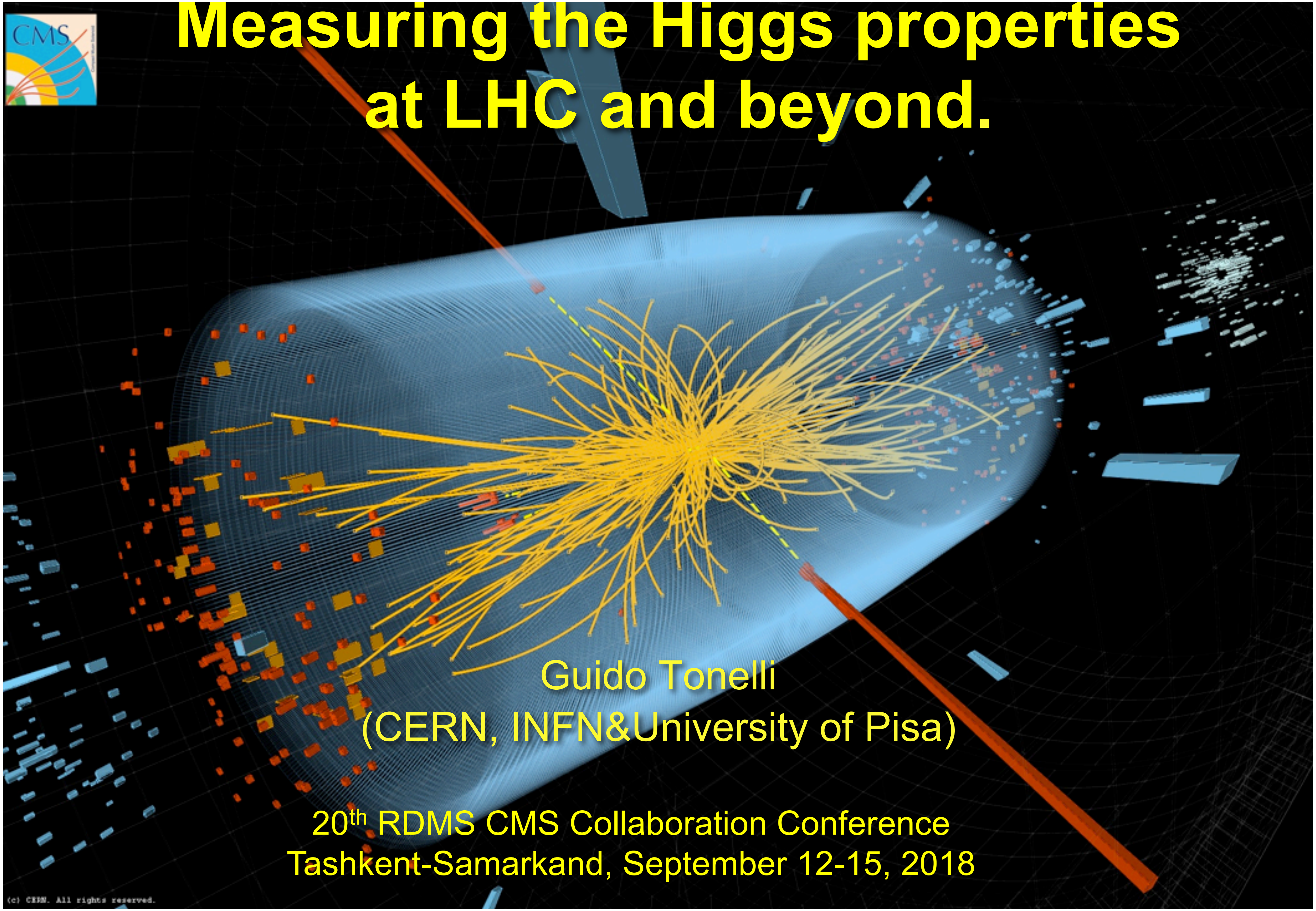
Measuring the Higgs properties at LHC and beyond.



Guido Tonelli
(CERN, INFN&University of Pisa)

20th RDMS CMS Collaboration Conference
Tashkent-Samarkand, September 12-15, 2018

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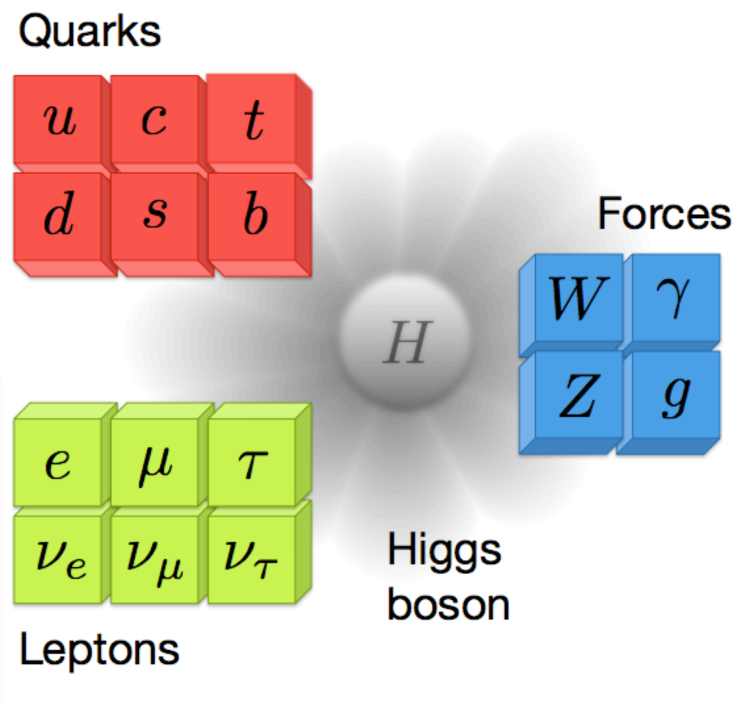
The problematic triumph of the Standard Model

Despite this further success, we know that the SM does not explain several important observations:

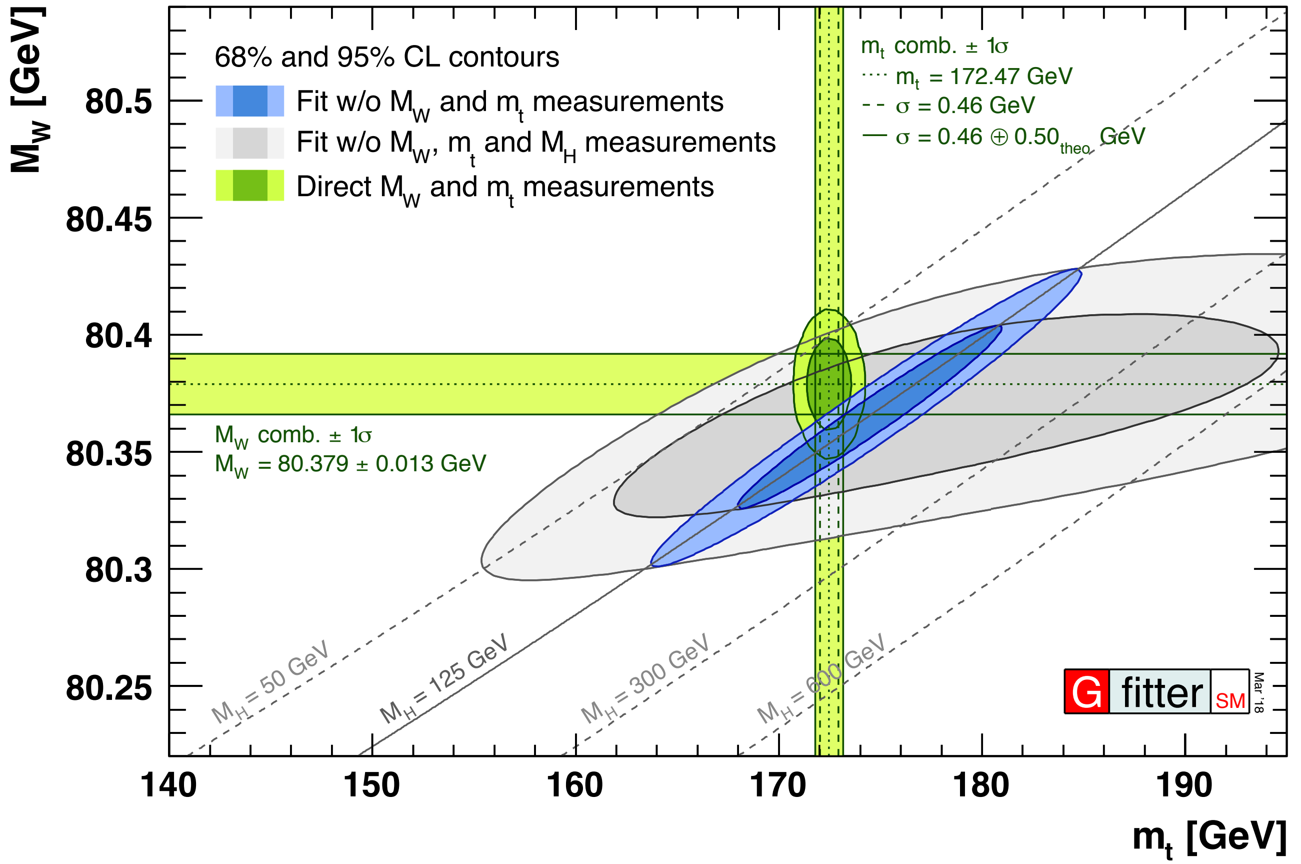


- **Dark matter.**
- **Dark energy.**
- **Inflation.**
- **Unification of forces and role of gravity.**
- **Neutrinos masses and hierarchy.**
- **Matter anti-matter asymmetry.**
- **Leptogenesis and bariogenesis.**
- **..**

To understand all this we need to look for physics beyond the Standard Model; **but at which energy scale?**

No much room left for new physics.

New Electroweak fit



New physics, if it does exists, appears to be weakly coupled to the Electroweak scale.

We have entered a new era.

Physics in the last 40 years.

We have entered a new era.

Physics in the next 40 years.

New challenges.

We are back to the pioneering times of the **exploration of unknown seas.**

We don’t’ know **in which direction** we are going to have better chance.

We dont’ know **where and when** we’ll have a new major discovery.

We know, however, that the Higgs boson itself could be used as a new, very sensitive tool for the indirect detection of massive particles or new interactions.

Two complementary paths.

Low-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\mathrm{EW}}^2/\Lambda^2$

- require **accuracy:** large lumi, low syst. and th. err

High-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- benefit from high **energy and** high **accuracy**

Where are we today?

- **LHC RUN I**: 2012 run ended with ~23fb^{-1}
  - Combined with 2011 run (5.6fb^{-1}), a total **~25fb^{-1}**

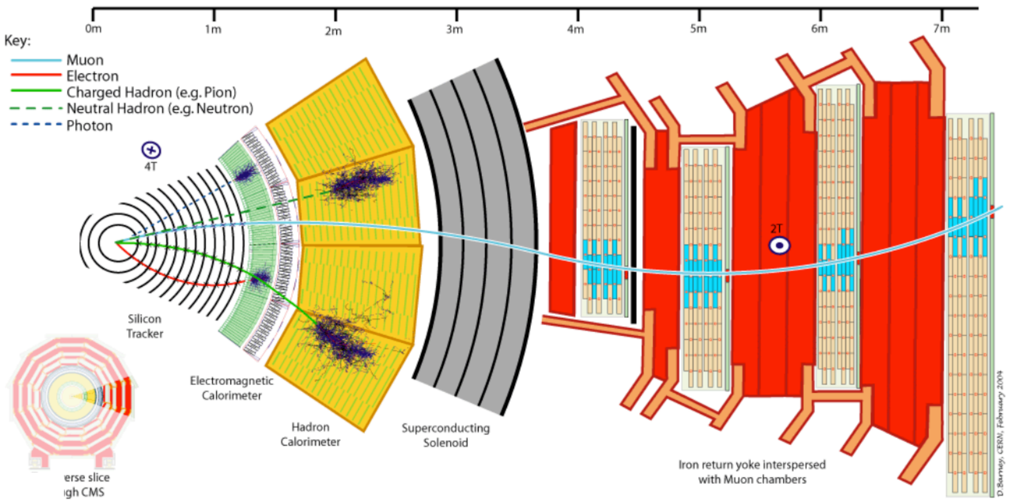
- Spring 2013 – 2014: shutdown (**LS1**) to go to 13TeV.
- **LHC RUN II a)**: 2015 – 2017 @13TeV, $\mathcal{L}$~10^{34}, **~150fb^{-1}**

- 2019-2020: Shut-down (**LS2)**
- **LHC RUN II b)**: 2021 – 2024 @14TeV, $\mathcal{L}$~2x10^{34}, **~300fb^{-1}**

- 2024 – 2026: Shut-down (**LS3**)
- **LHC RUN III:** 2026 – 2040 @14TeV, $\mathcal{L}$~5x10^{34} (**HL-LHC**), **~3000fb^{-1}**

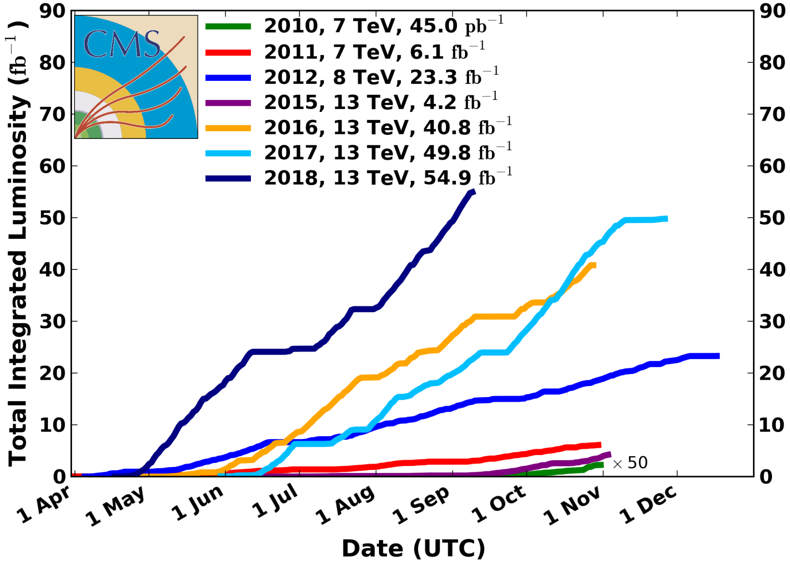
Excellent performance of LHC and CMS

- Particle Flow event reconstruction
- Jets: anti - k_T clustering with R=0.4
- b-jets: combined secondary vertex
- Hadronic τ: Hadron-plus-strip algo.

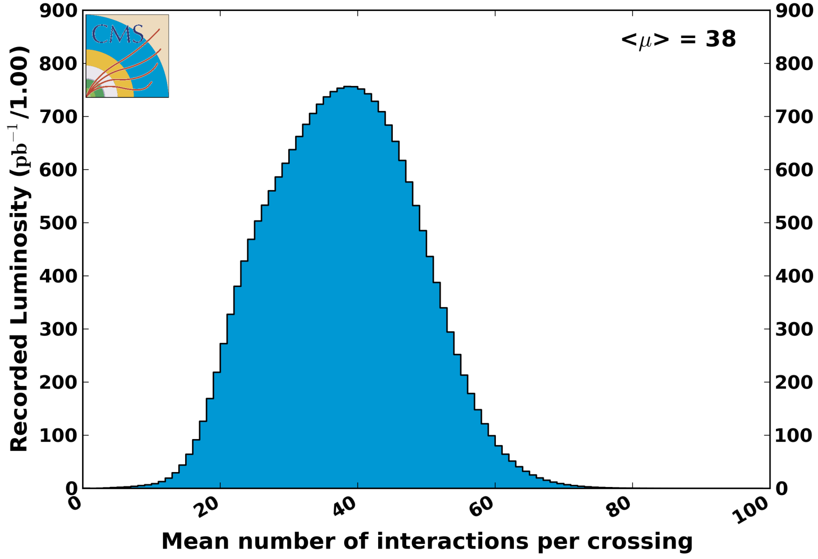


CMS Integrated Luminosity, pp

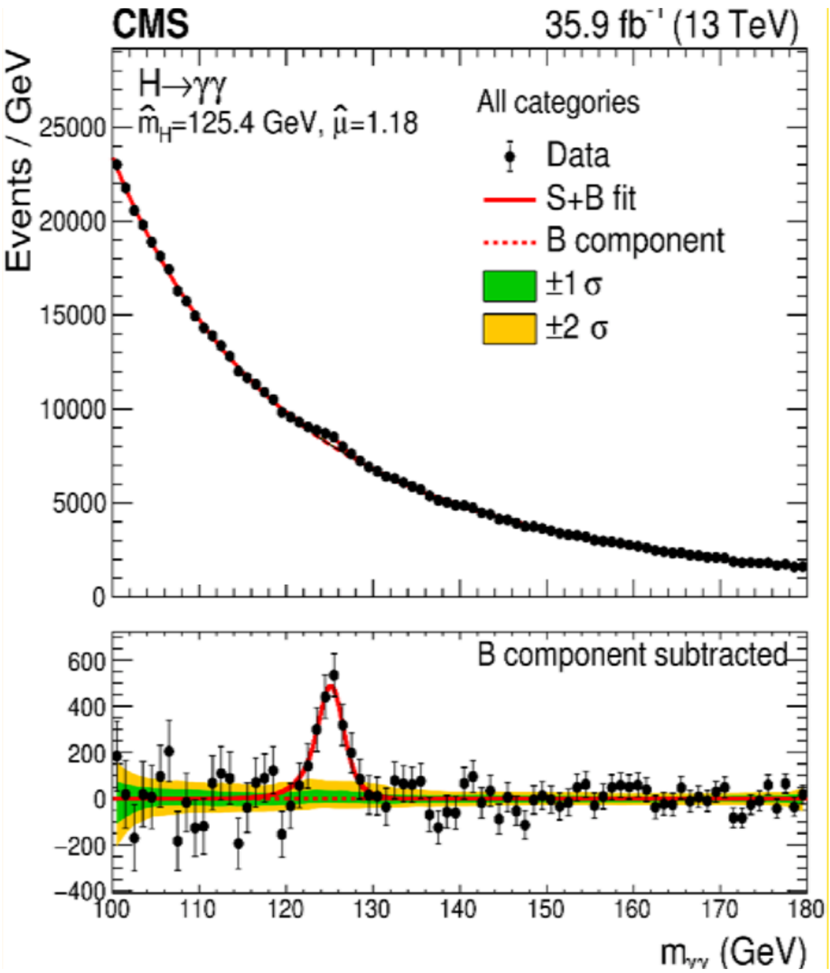
Data included from 2010-03-30 11:22 to 2018-09-09 06:02 UTC



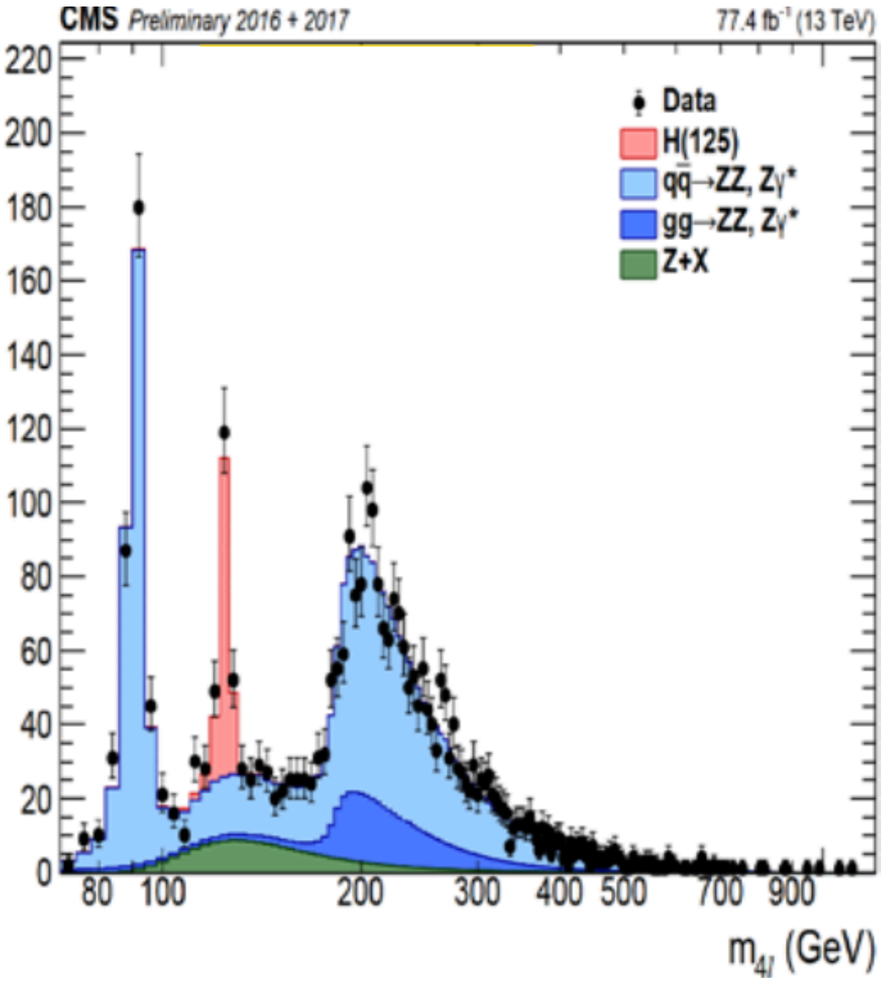
CMS Average Pileup, pp, 2018, $\sqrt{s} = 13$ TeV



Higgs re-discovery at 13TeV.



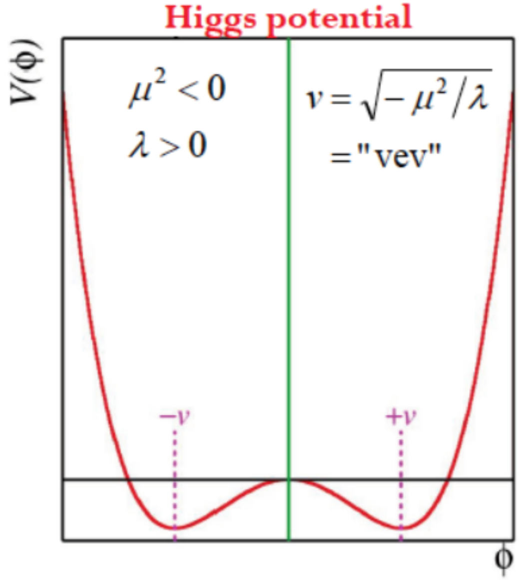
2016



2016+2017

From search to precision measurement.

In the post-discovery era, focus moves from search to precision measurements.



Characteristics of the SM Higgs:

Mass and width.

Coupling to other SM particles.

Rare decay modes.

Self-coupling.

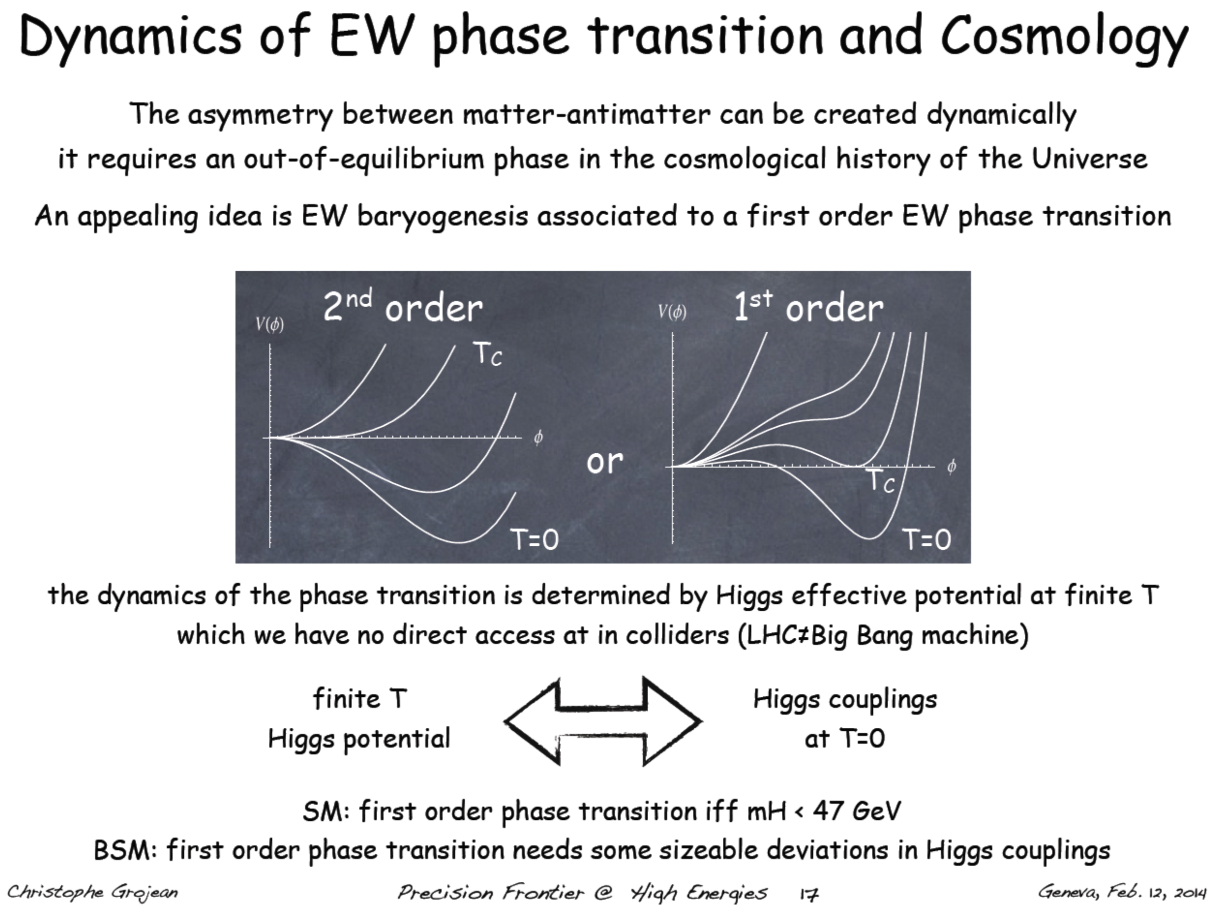
$$L = \left(D_\mu \phi\right)^* \left(D^\mu \phi\right) - \left(\mu^2 \phi^2 + \lambda \phi^4\right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$$g_{HVV} = 2\frac{m_V^2}{v} \qquad g_{Hff} = \frac{m_f}{v}$$

$$m_H = \sqrt{2\lambda} v$$

λ, μ unknown → m_H is a free parameter of the SM

Precision study of the EW Phase Transition



Dynamics of EW phase transition and Cosmology

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition

the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC$\neq$Big Bang machine)

finite T Higgs potential ⟺ Higgs couplings at T=0

SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

Christophe Grojean Precision Frontier @ High Energies 17 Geneva, Feb. 12, 2014

1. **O(1%) precision in measuring the Higgs couplings could be as important as direct searches for new physics.**
2. **Study of triple Higgs coupling (… and quadruple).**
3. **Search for new sources of CP violation connected to Higgs interactions.**

LHC combined measurement of m_H.

- H→γγ: Events are divided into different $m_{\gamma\gamma}$ categories to improve sensitivity.
- H→ZZ→$e^-e^+\mu^-\mu^+$, $e^-e^+e^-e^+$, $\mu^-\mu^+\ \mu^-\mu^+$ analyzed separately
  ATLAS: 2D fit to $m_{4\ell}$ and BDT background discriminant
  CMS : 3D fit to $m_{4\ell}$, BDT background discriminant and per-event uncertainty in $m_{4\ell}$

$$\Lambda(\alpha) = \frac{L\left(\alpha, \hat{\hat{\theta}}(\alpha)\right)}{L\left(\hat{\alpha}, \hat{\theta}\right)} = \frac{\text{Maximum likelihood for a given } \alpha}{\text{Global maximum likelihood}}$$

α = parameters of interest (eg. m_H)

θ = nuisance parameters (eg. systematics)

$\hat{\alpha}, \hat{\theta} = \text{Best fit values}$

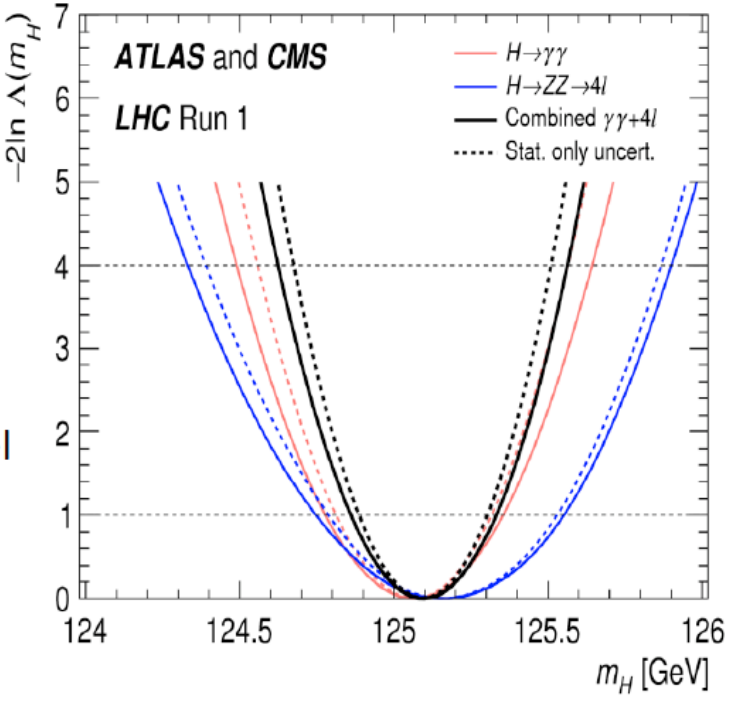
L(α,θ) = product of signal and background PDFs.

To combine: multiply likelihood terms for each channel

$$\Lambda(m_H) = \frac{L\left(m_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}(m_H), \hat{\mu}^{\gamma\gamma}_{VBF+VH}(m_H), \hat{\mu}^{4\ell}(m_H), \hat{\theta}(m_H)\right)}{L\left(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}^{4\ell}, \hat{\theta}\right)}$$

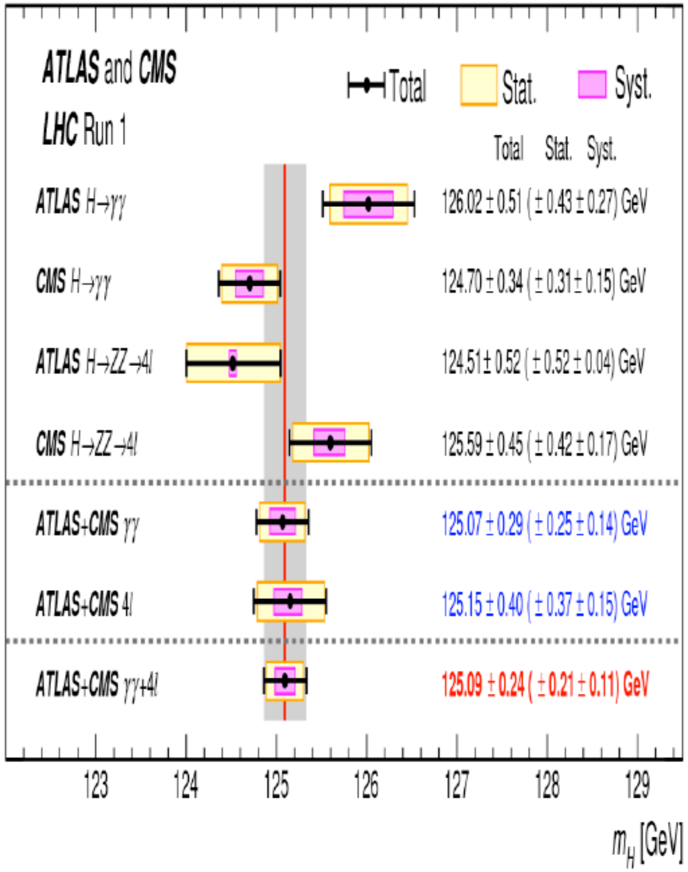
μ = signal strenght modifiers

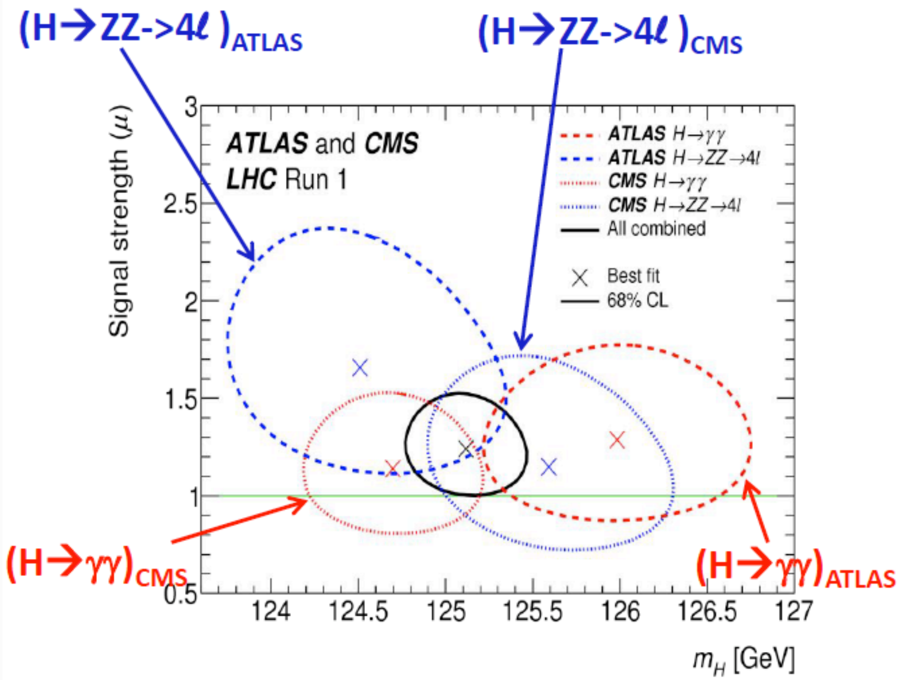
Phys. Rev. Lett. 114 (2015) 191803



Results.

Phys. Rev. Lett. 114 (2015) 191803

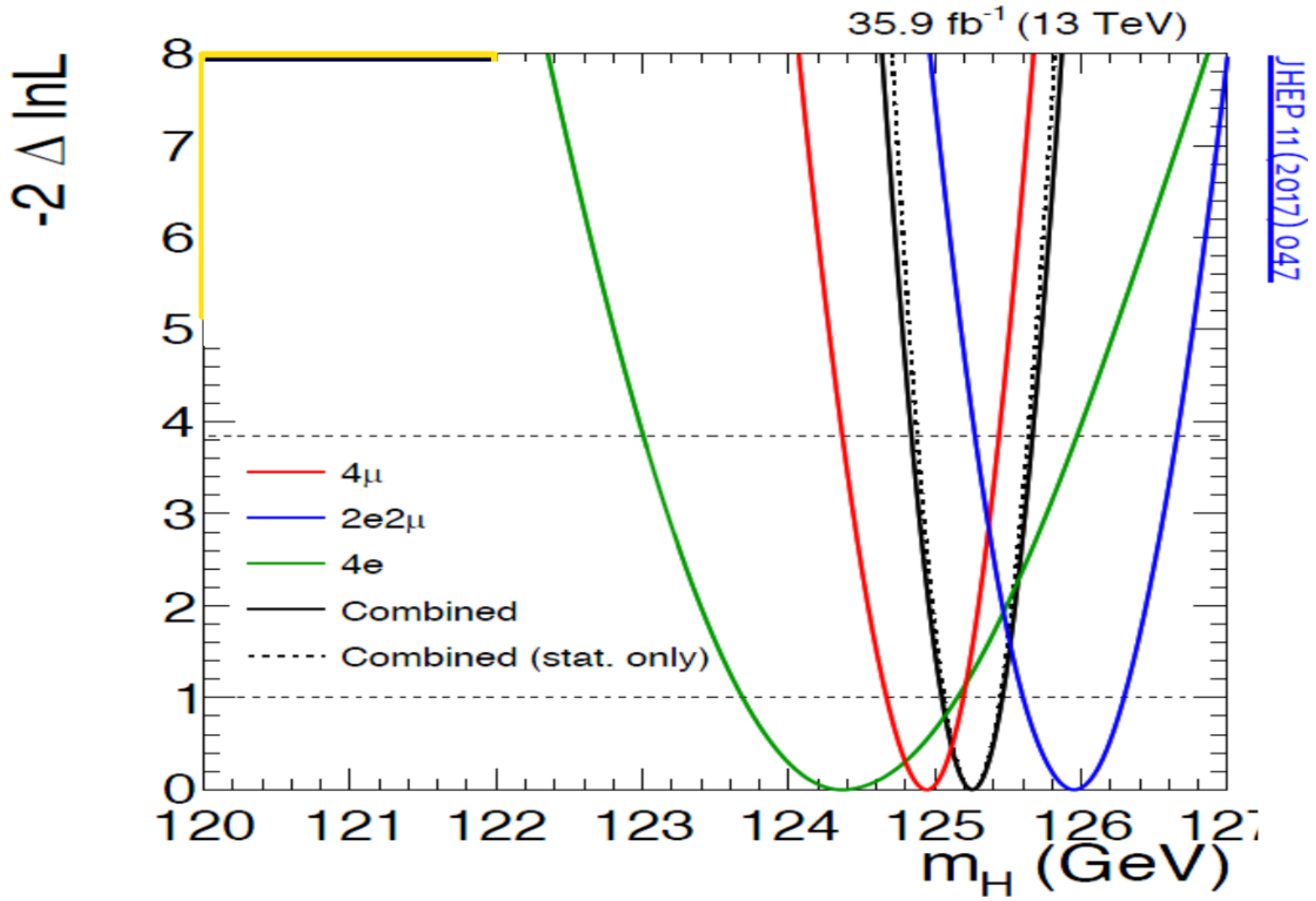




$m_H = 125.09 \pm 0.21 \pm 0.11$ GeV

Statistical uncertainty dominates. Along with theory developments in cross-sections, allows detailed couplings comparisons.

Recent improvement: CMS alone.



M_H=125.26±0.21GeV ±0.17%.

(±0.20 stat±0.08 syst)

We have already entered the Higgs precision era.

Indirect measurement of Γ_H

H→ZZ→4ℓ , H→2ℓ2ν, (ℓ=e,μ),

Breit-Wigner production gg→H→ZZ:

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{\left(m^2_{ZZ}-m^2_H\right)^2 + m^2_H \Gamma^2_H}$$

On-peak (105.6<$m_{4\ell}$<140.6 GeV) and off-peak cross sections ($m_{4\ell}$> 220 GeV):

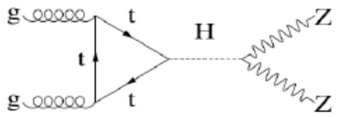
$$\sigma^{\text{on-shell}} = \int_{|m-m_H|\le n\Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

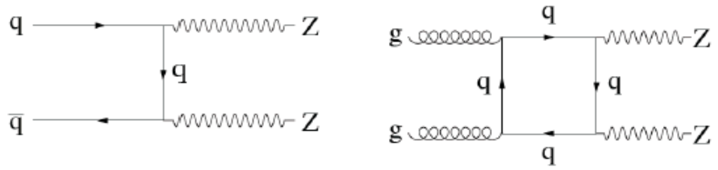
$$\boxed{\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H}$$

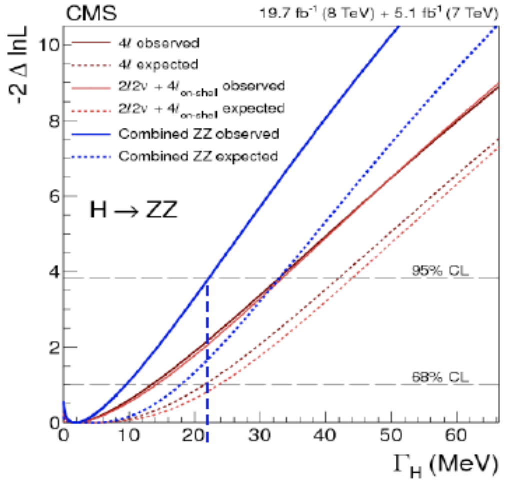
- Must include interference between gg→H→ZZ and gg→Box→ZZ
- K-factor of gg→ZZ not well known, assume the same as signal and add a sytematic uncertainty.

Phys. Lett. B 736 (2014) 64



Dominant backgrounds:





Γ_H< 22 MeV at 95% CL

CMS did an excellent job on the couplings

The real challenge is to establish the coupling to fermions.

First observation of H→$\tau^+\tau^-$

arXiv:1708.00373

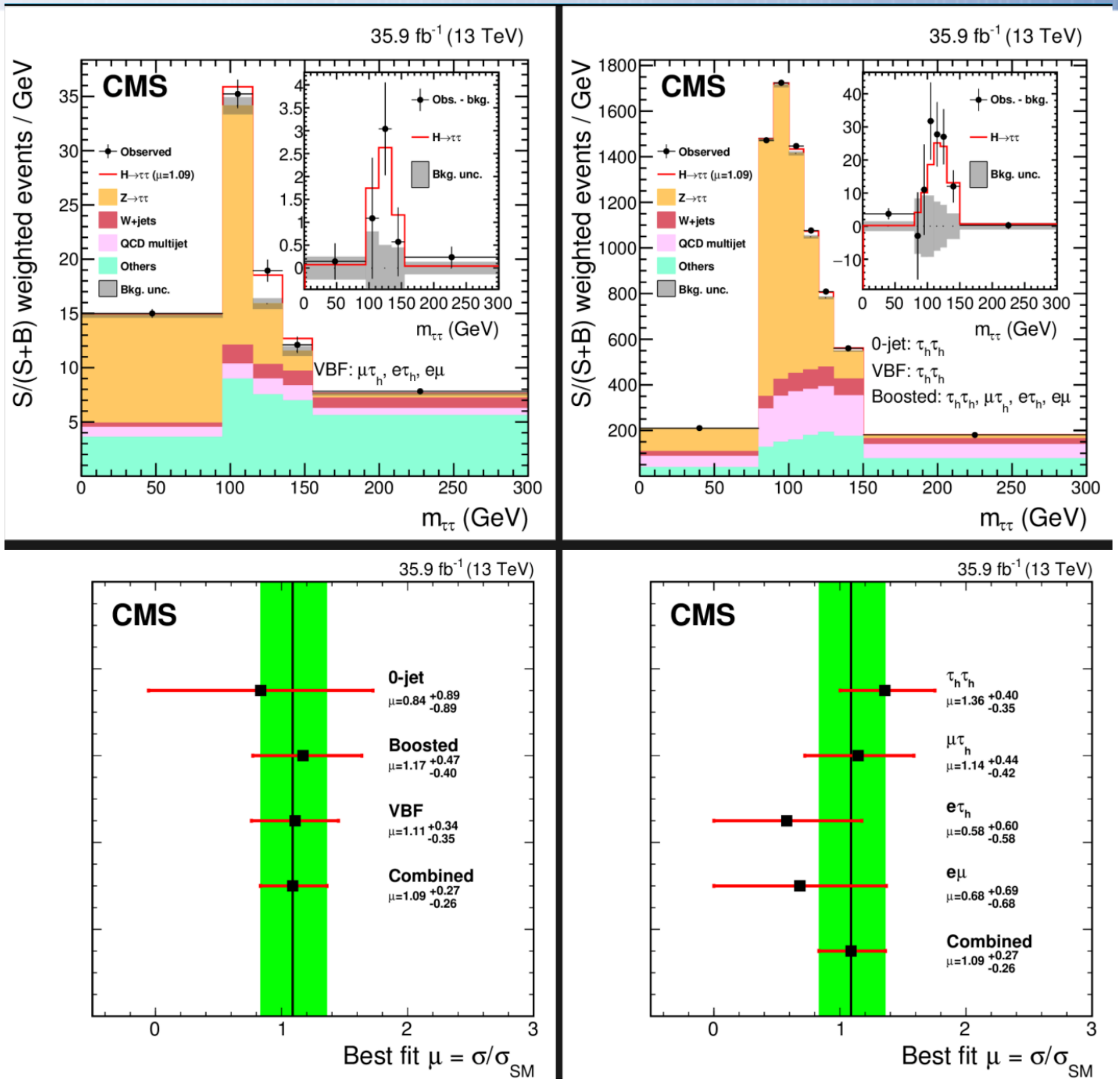
First observation of ttH

arXiv:1804.02610

First observation of H→bb

arXiv:1808.08242

First observation of $H \to \tau^+\tau^-$

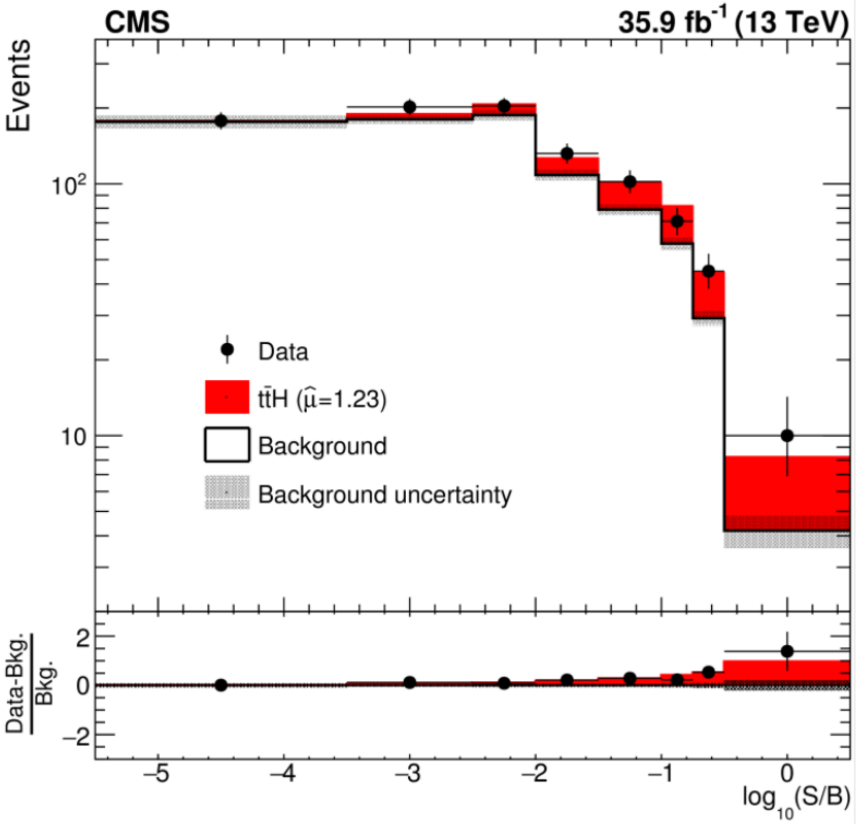


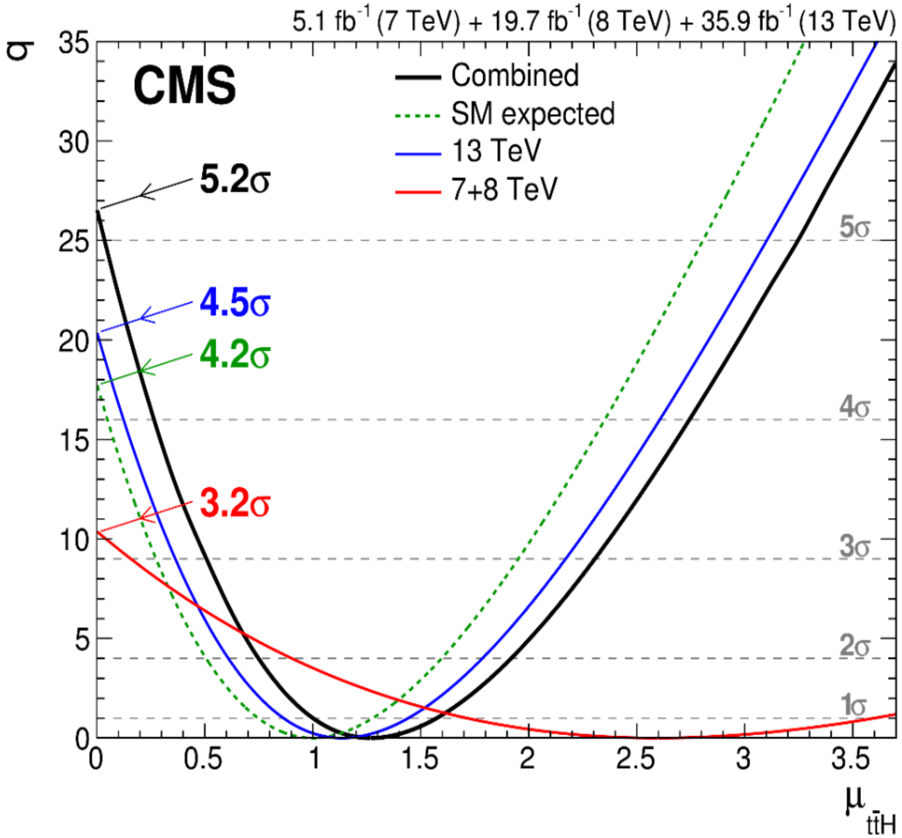
5.9σ (5.9 exp) $\mu = 0.98 \pm 18.$

arXiv:1708.00373

First observation of ttH

Directly sensitive to top Yukawa coupling (only indirectly tested via loops in ggH and Hγγ). Many final states including multi-leptons, b-jets, and γγ.



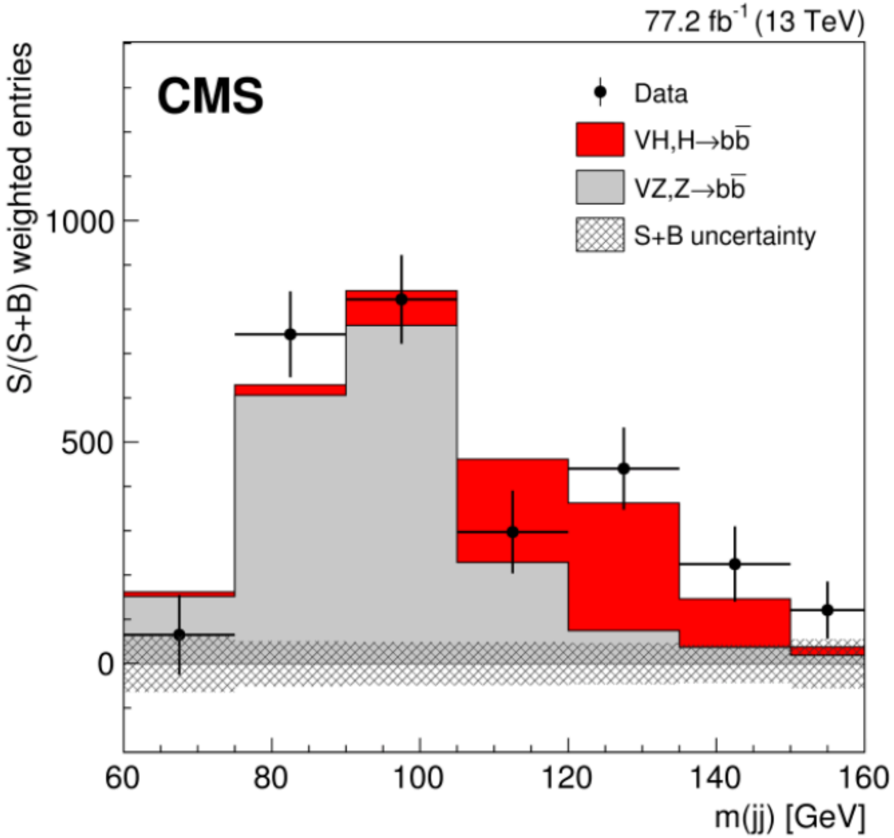


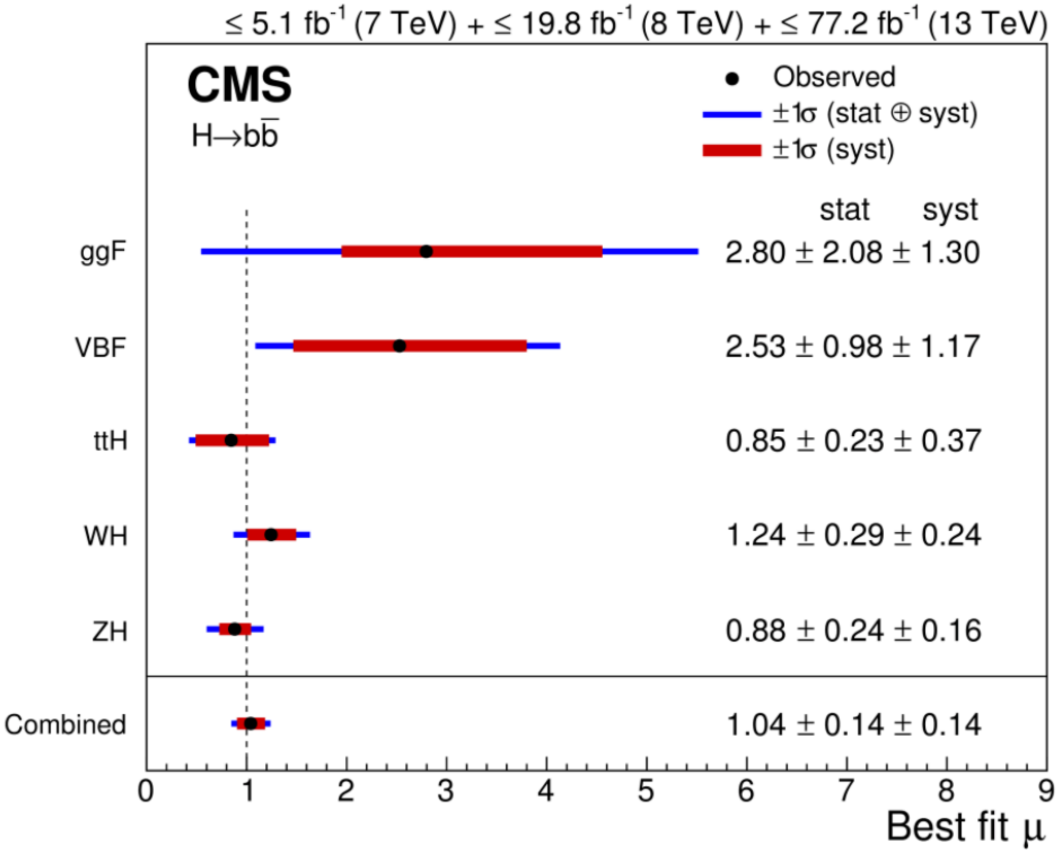
5.2σ (4.2 exp)

μ= 1.26 +0.31-0.26.

arXiv:1804.02610

First observation of H→bb





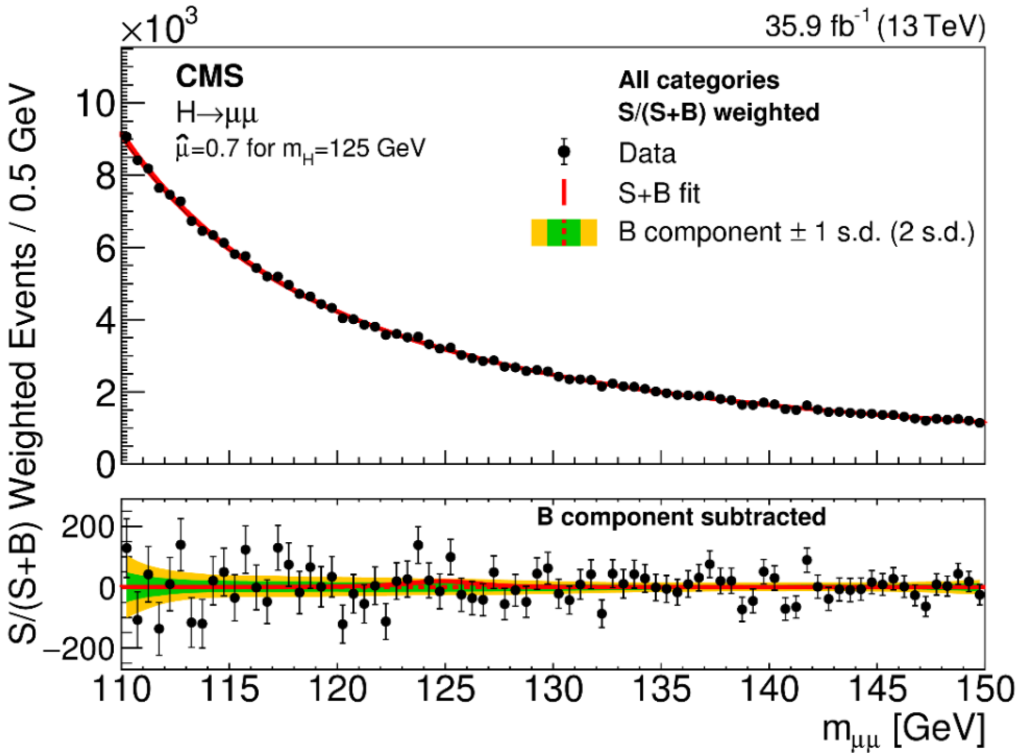
5.6σ (5.5 exp)

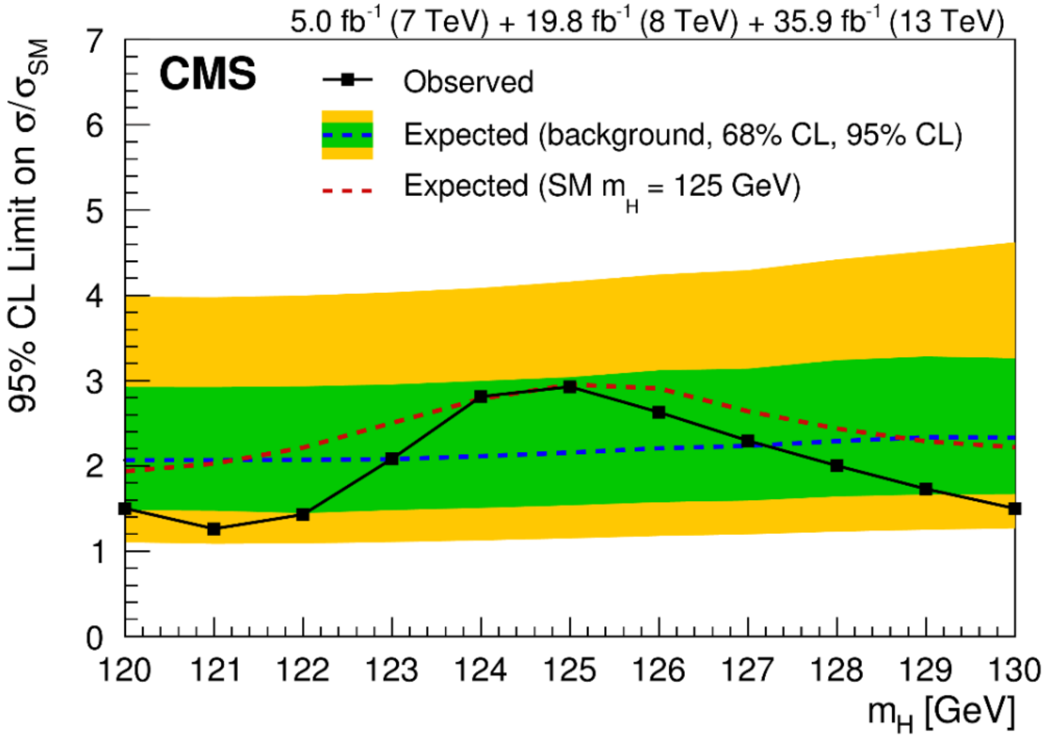
μ= 1.04±0.14±0.14.

arXiv:1808.08242

Very rare decays: H→μμ

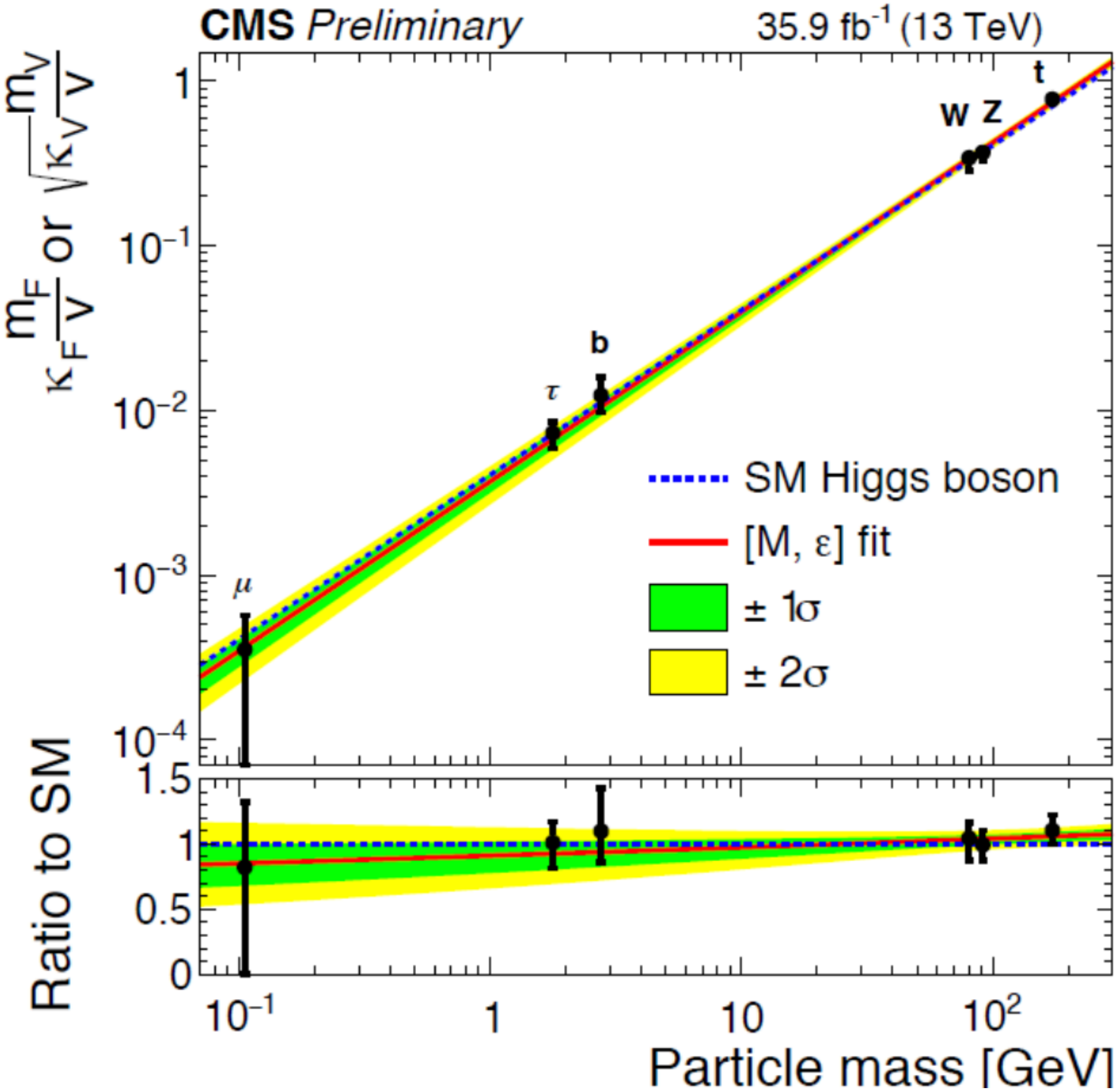
Tiny BR within the SM: 2.2×10^{-4}

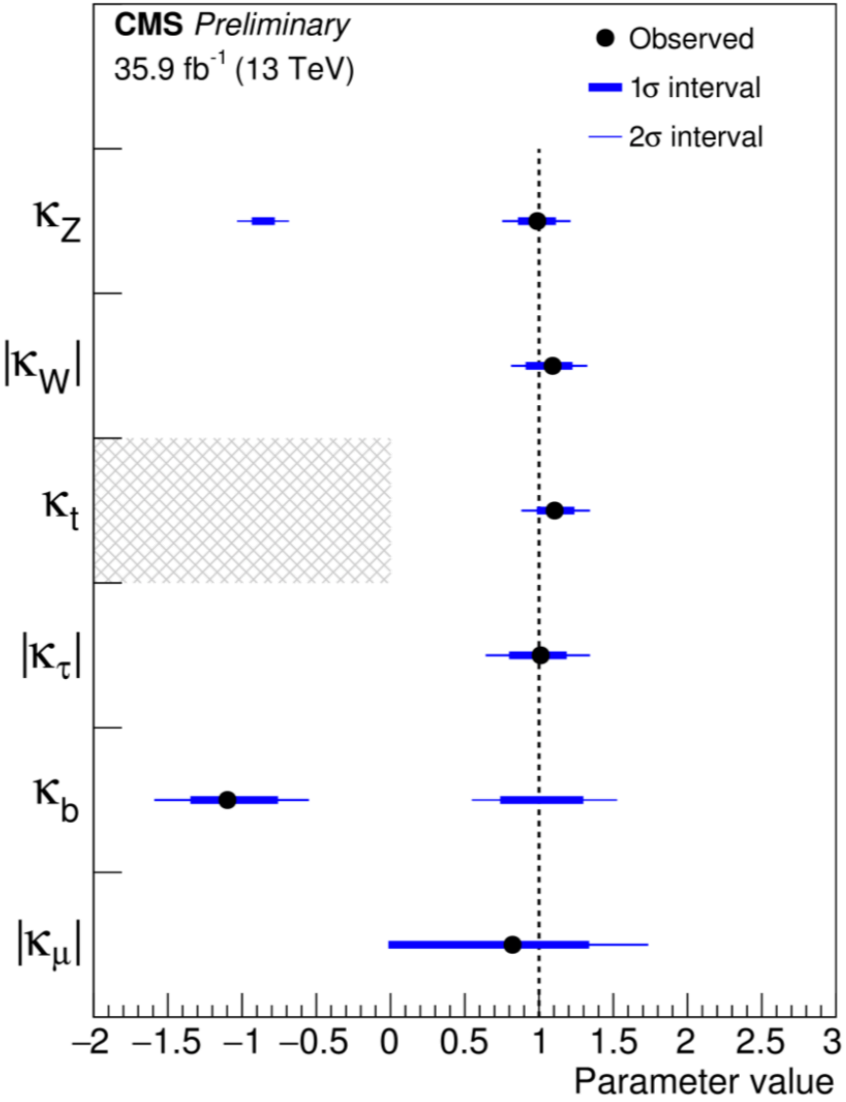




2016 + 7 and 8 TeV data: observed (exp.) upper limits at 95% is 2.9 (2.2) for $\mu = 0$. Observed (exp.) significance 0.9 (1.0) for $\mu = 1$.

Excellent job on the couplings .. but still





What precision is necessary on the couplings?

- SM couplings can be modified by new physics entering the loops.
- Typical effect on the couplings from a heavy particle M or new physics at scale M with v=246 GeV.

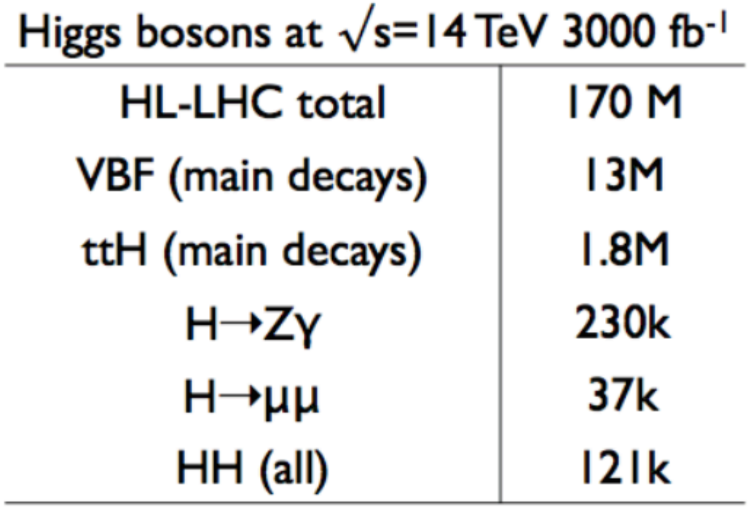
$$\Delta \sim \left(\frac{v}{M}\right)^2$$

- **For new physics at the ~1-10TeV mass scale →Δ~5%-0.05%.** Higher scales imply smaller effects.

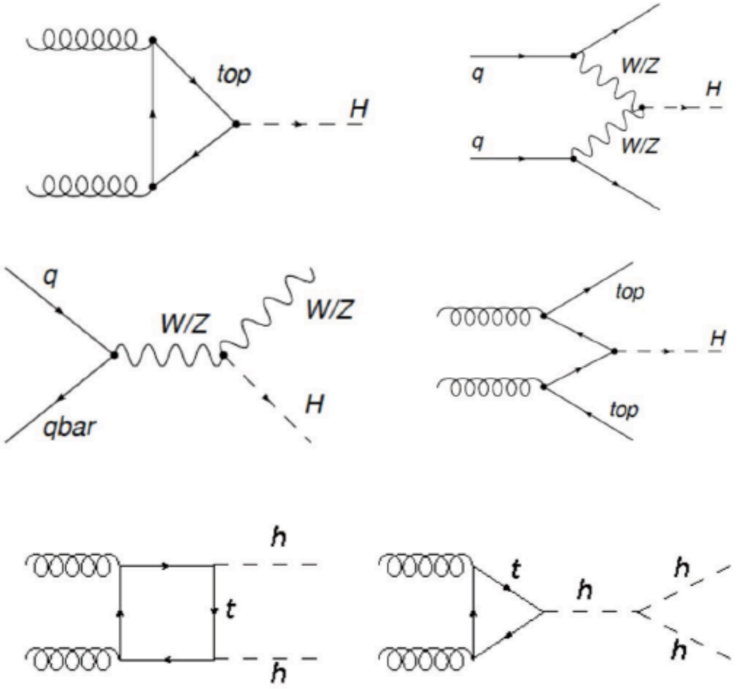
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arXiv:1310.8361

HL-LHC is a Higgs factory



Higgs bosons at $\sqrt{s}$=14 TeV 3000 fb^{-1}	
HL-LHC total	170 M
VBF (main decays)	13M
ttH (main decays)	1.8M
H→Zγ	230k
H→μμ	37k
HH (all)	121k



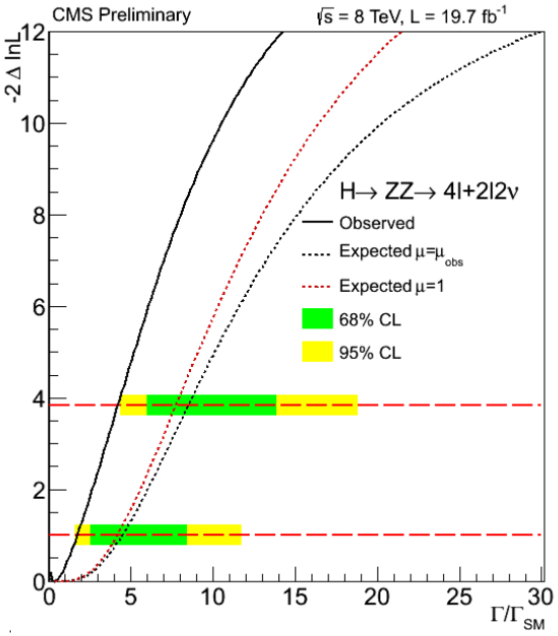
- Higgs physics goals
  - Rare decays and couplings
  - Spin/parity
  - Higgs pair productions

LHC will produce 150-200 million Higgs.

Higgs mass and width at HL-LHC

The large statistics in H→γγ and H→ZZ*→4l will allow a measurement of m_H challenging the systematics errors. We could also make the best use of VBF and possibly other exclusive channels. Large effort needed on the theory side: 50MeV on Δm_H corresponds to 0.5% uncertainty on the BR measurement.

Expectations for Δm_H@3000fb^{-1}: 15MeV(stat)±25MeV(syst).
It could be challenged only by a dedicated lepton Collider.



For the measurement of the width we'll continue using the powerful constraints from the off-shell Higgs.

The high statistics will bring sensitivity on the width down to the SM-level: $\Gamma_H=4.2^{+1.5}_{-2.1}$ MeV.
An independent handle to check for significant anomalous BR.

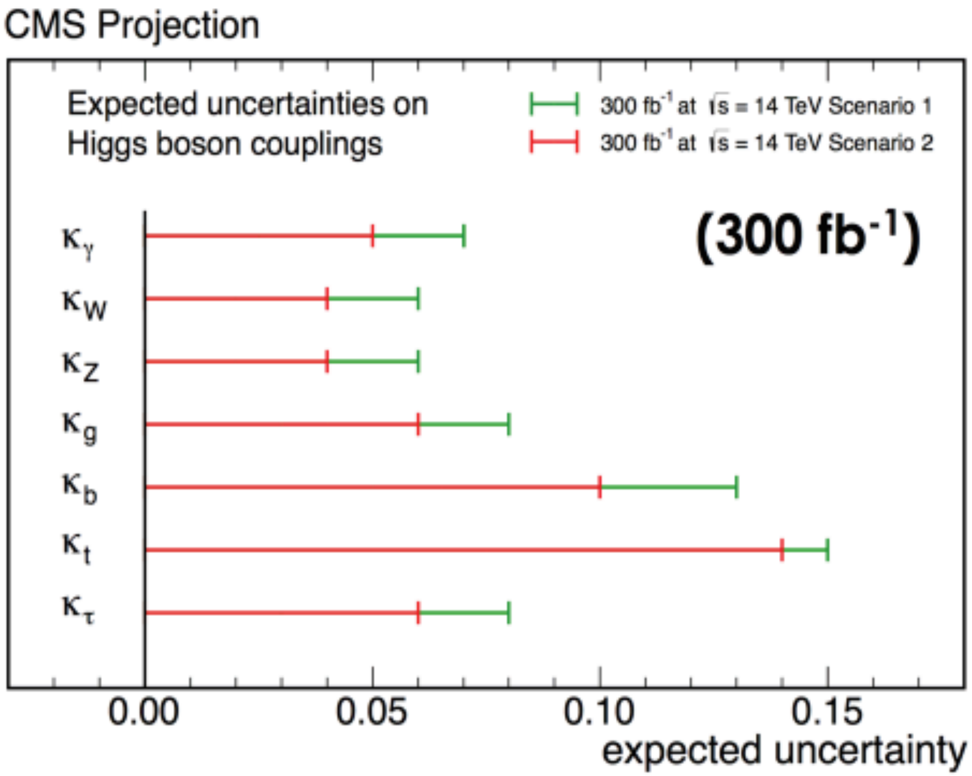
Observe rare/difficult decays with 3000fb^{-1}

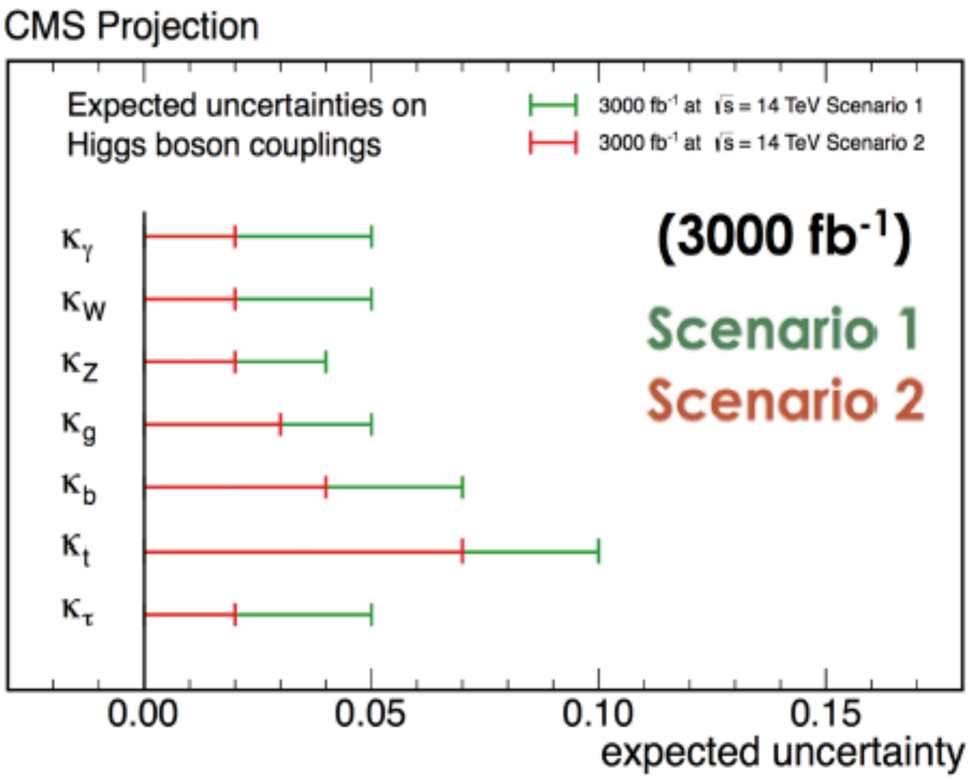
- **ttH**

  Signal observation 7-8σ in single decay modes (i.e. ttH($\gamma\gamma$)); projected sensitivity on k_{top}~10%.
- **H→Zγ**
- Signal observation ~4σ; 20-25% precision on the signal strength
- **H→$\mu\mu$**

  Signal observation >7σ; 10-15% precision on the signal strength. Measure the coupling the second lepton generation.

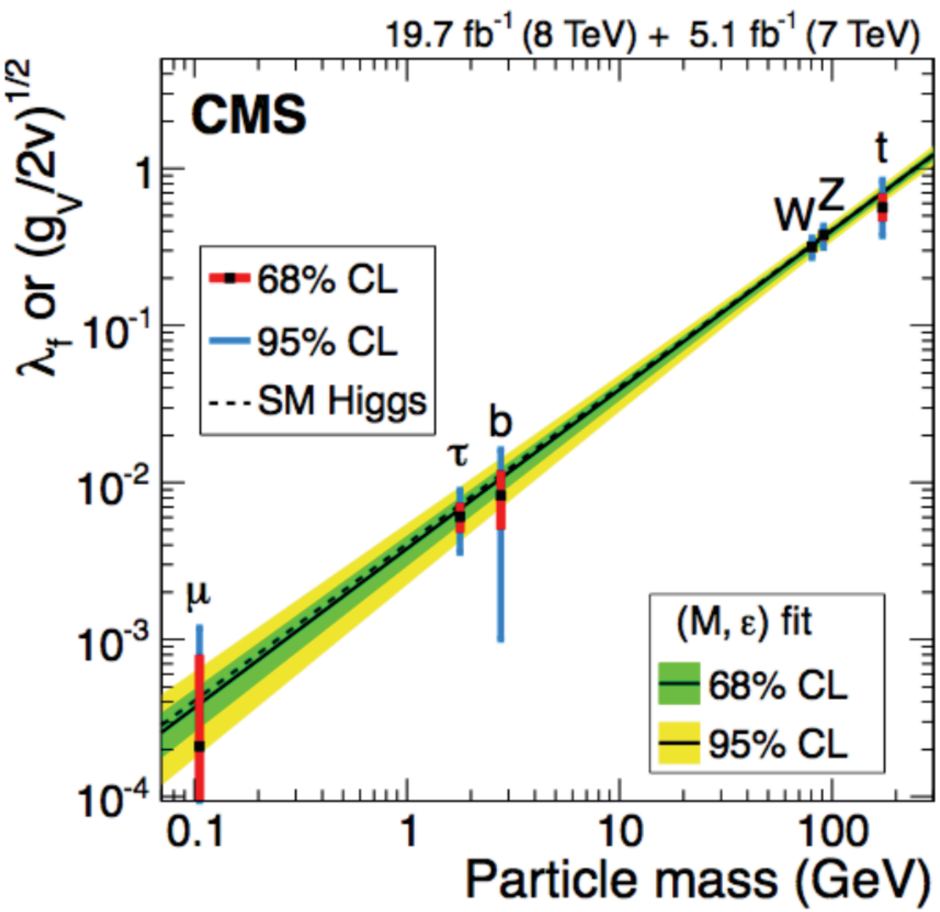
Perspectives on the couplings

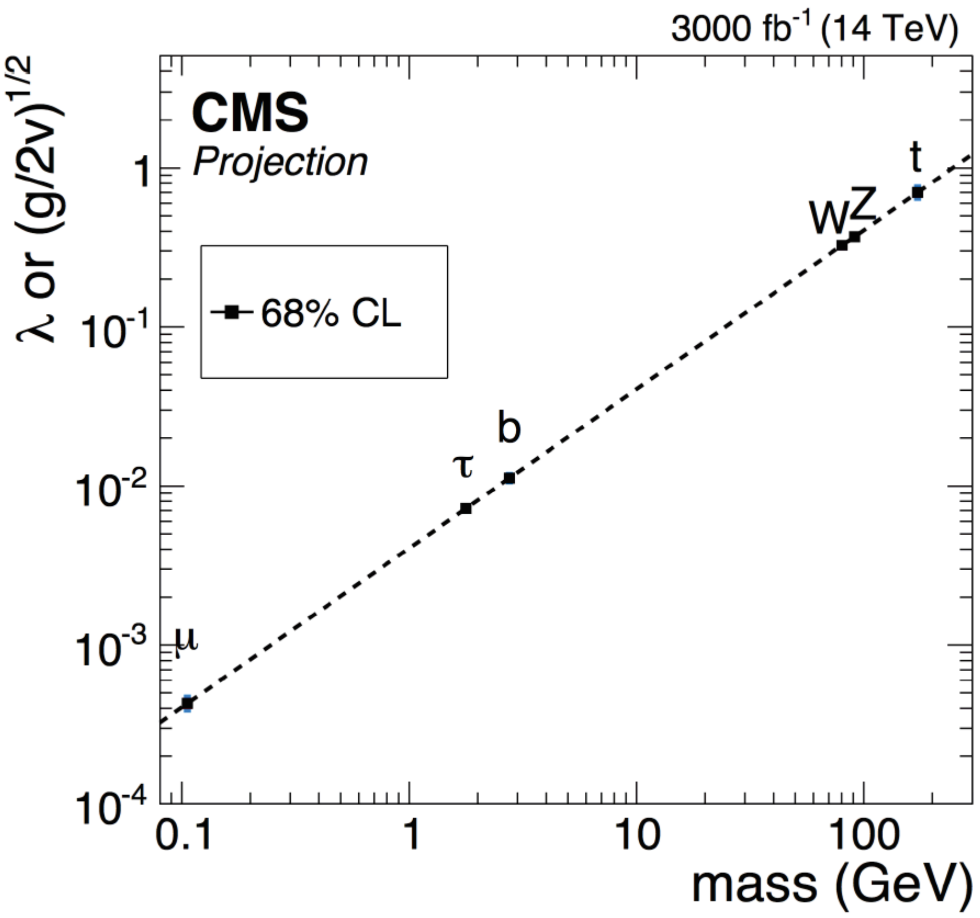




Allowing new physics entering the loops: ultimate precision will be 2-10%.

Perspectives on the couplings

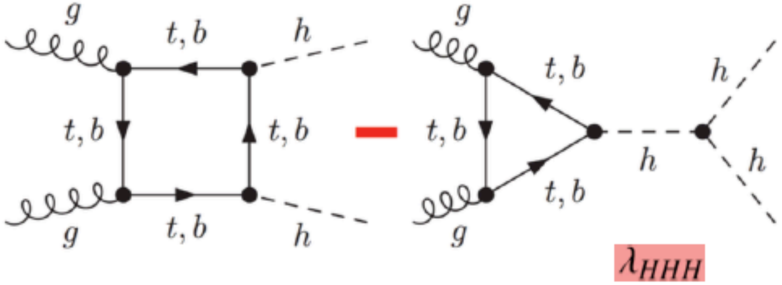


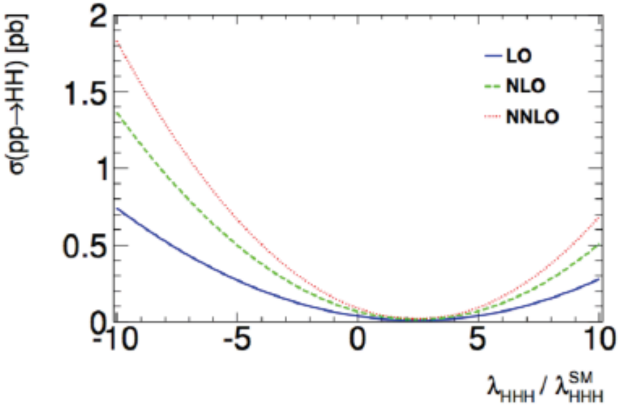


Allowing no new physics: percent level precision for most of the couplings

H self-coupling: HH production

- Probe Higgs self-interaction
  - crucial to test the Higgs sector to its full extent
  - primary channel to extract information on the Higgs potential → structure of the EWK Phase Transition
- Two interfering diagrams (destructive)





- SM cross section @ 14 TeV: 40.8 fb (NNLO)

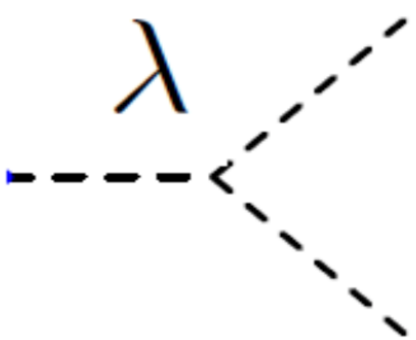
~10^5 HH events produced with $3000fb^{-1}$ at HL-LHC ……but very large background (or tiny BR).

Higgs self coupling

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

$$\lambda = \lambda' = M_H^2/(2v^2) = 0.13$$

In the SM the Higgs mass is directly related to Higgs dynamics



HH in the final states

HHH in the final states

Deviations at the level of 20%-2%→ BSM

Higgs-pair production at HL-LHC

- bb$\gamma\gamma$ established channel
- bbWW looks very difficult (~10^4 events but very large background)
- bb$\tau\tau$ seems more promising
- bb2l2ν could be interesting (~700 events)
- bbbb?!?! others?!?!

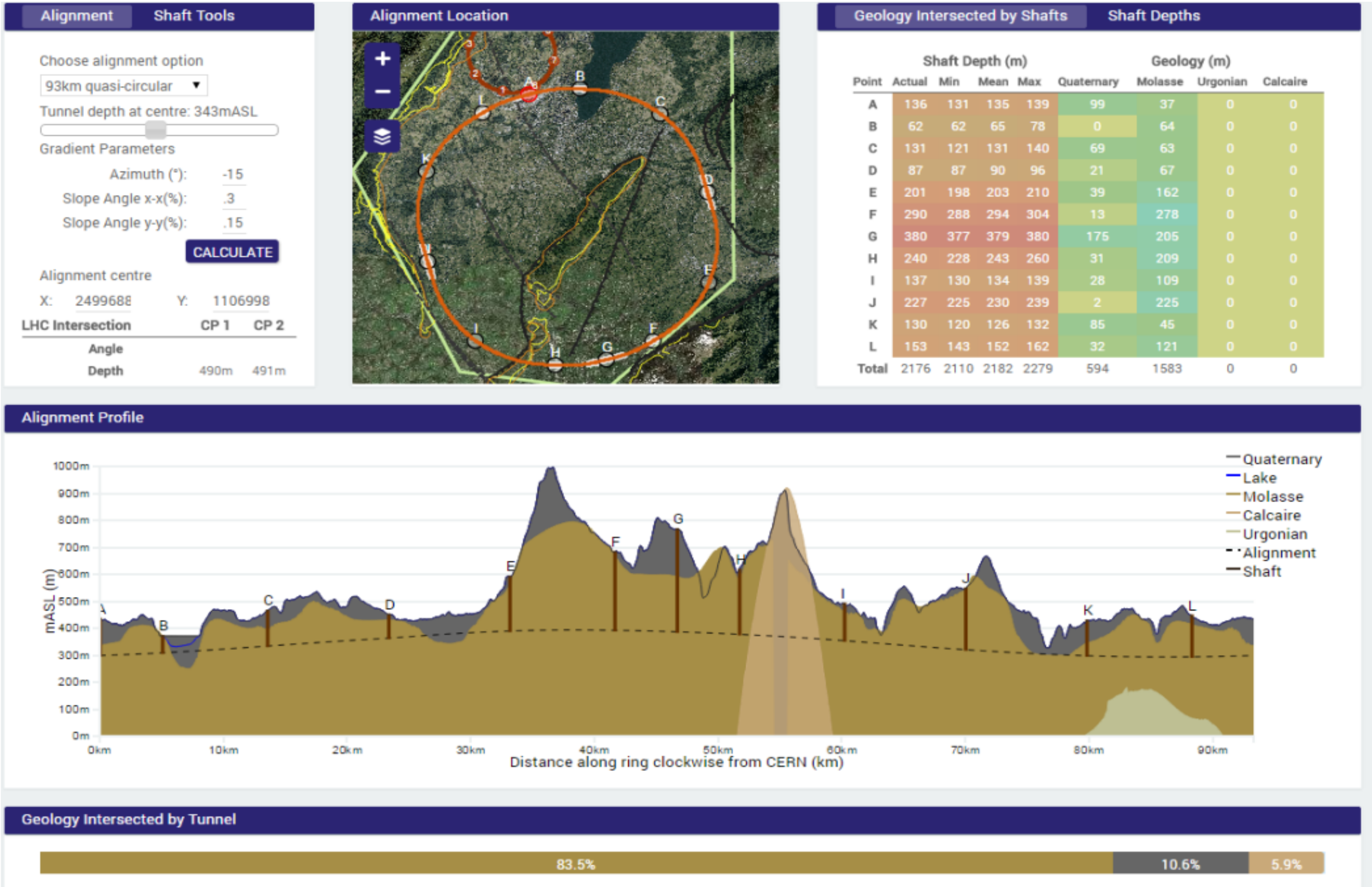
- With simple extrapolations one would expect to reach 3σ per experiment. We could even think of improving things by deploying new ideas **to observe** the Higgs pair production at HL-LHC.
- **It will be however extremely difficult to extract λ with accuracy better than 40%. At the end of LHC a fundamental parameter of nature will be still not measured with acceptable accuracy.**

A look into the future

- **New machines will be necessary.**
- **Very close to define the strategy.**

The dream machine

FCCee (240GeV, 2x10^6 ZH)+FCChh 100TeV, 10^{10}H)



Choose alignment option: 93km quasi-circular

Tunnel depth at centre: 343mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): .15

Alignment centre

X: 2499688 Y: 1106998

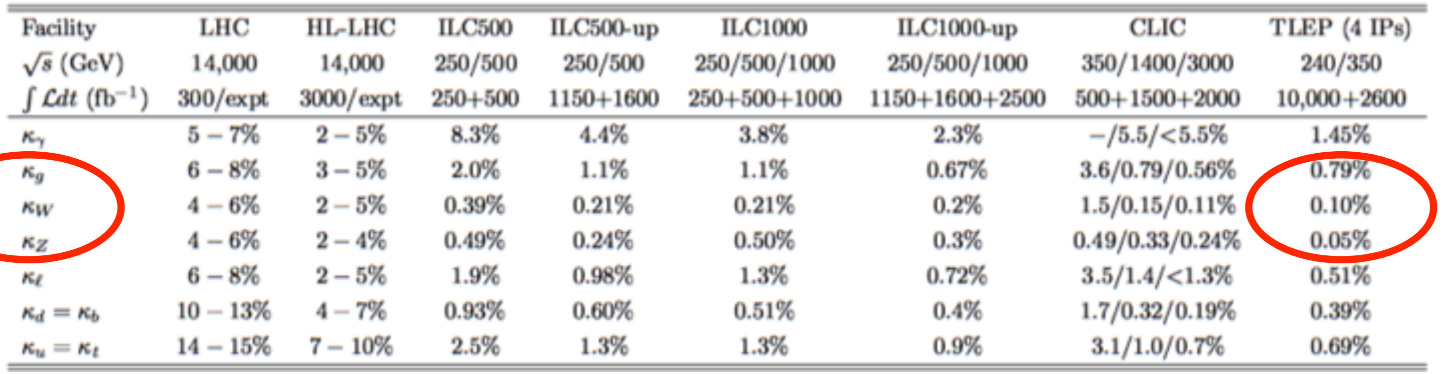
LHC Intersection	CP 1	CP 2
Angle		
Depth	490m	491m

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	136	131	135	139	99	37	0	0
B	62	62	65	78	0	64	0	0
C	131	121	131	140	69	63	0	0
D	87	87	90	96	21	67	0	0
E	201	198	203	210	39	162	0	0
F	290	288	294	304	13	278	0	0
G	380	377	379	380	175	205	0	0
H	240	228	243	260	31	209	0	0
I	137	130	134	139	28	109	0	0
J	227	225	230	239	2	225	0	0
K	130	120	126	132	85	45	0	0
L	153	143	152	162	32	121	0	0
Total	2176	2110	2182	2279	594	1583	0	0

Higgs Physics with a 100km machine

There is a “natural” complementarity between FCC-ee and FCC-hh for what concerns the Higgs couplings.

Coupling like HWW and HZZ are already strongly constrained by EWPT and deviations from the SM values (if any) are supposed to be small.
FCC-ee could do here a great job:

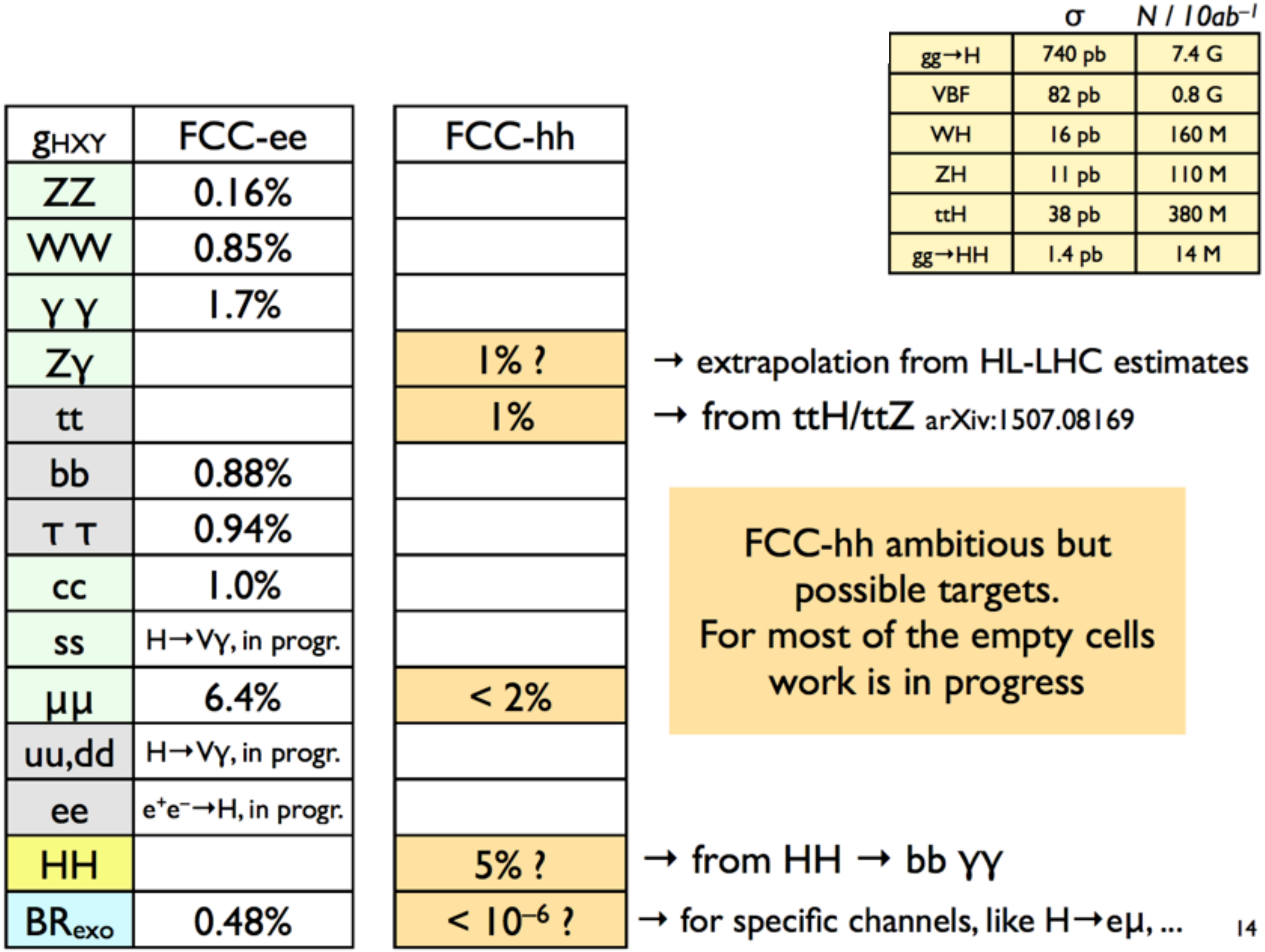


Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 − 7%	2 − 5%	8.3%	4.4%	3.8%	2.3%	−/5.5/<5.5%	1.45%
κ_g	6 − 8%	3 − 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 − 6%	2 − 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 − 6%	2 − 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 − 8%	2 − 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 − 13%	4 − 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 − 15%	7 − 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Coupling involved in rare decays H→$\mu\mu$ H→Zγ and HHH will be much less constrained even by FCC-ee.

FCC-hh is the big player for λ, λ_t, k_μ $k_{Z\gamma}$

Ideal interplay FCCee-FCChh



	σ	N / 10ab^{-1}
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
$\gamma\gamma$	1.7%	
$Z\gamma$		1% ?
tt		1%
bb	0.88%	
$\tau\tau$	0.94%	
cc	1.0%	
ss	$H\to V\gamma$, in progr.	
$\mu\mu$	6.4%	< 2%
uu,dd	$H\to V\gamma$, in progr.	
ee	$e^+e^-\to H$, in progr.	
HH		5% ?
BR_{exo}	0.48%	$< 10^{-6}$?

→ extrapolation from HL-LHC estimates

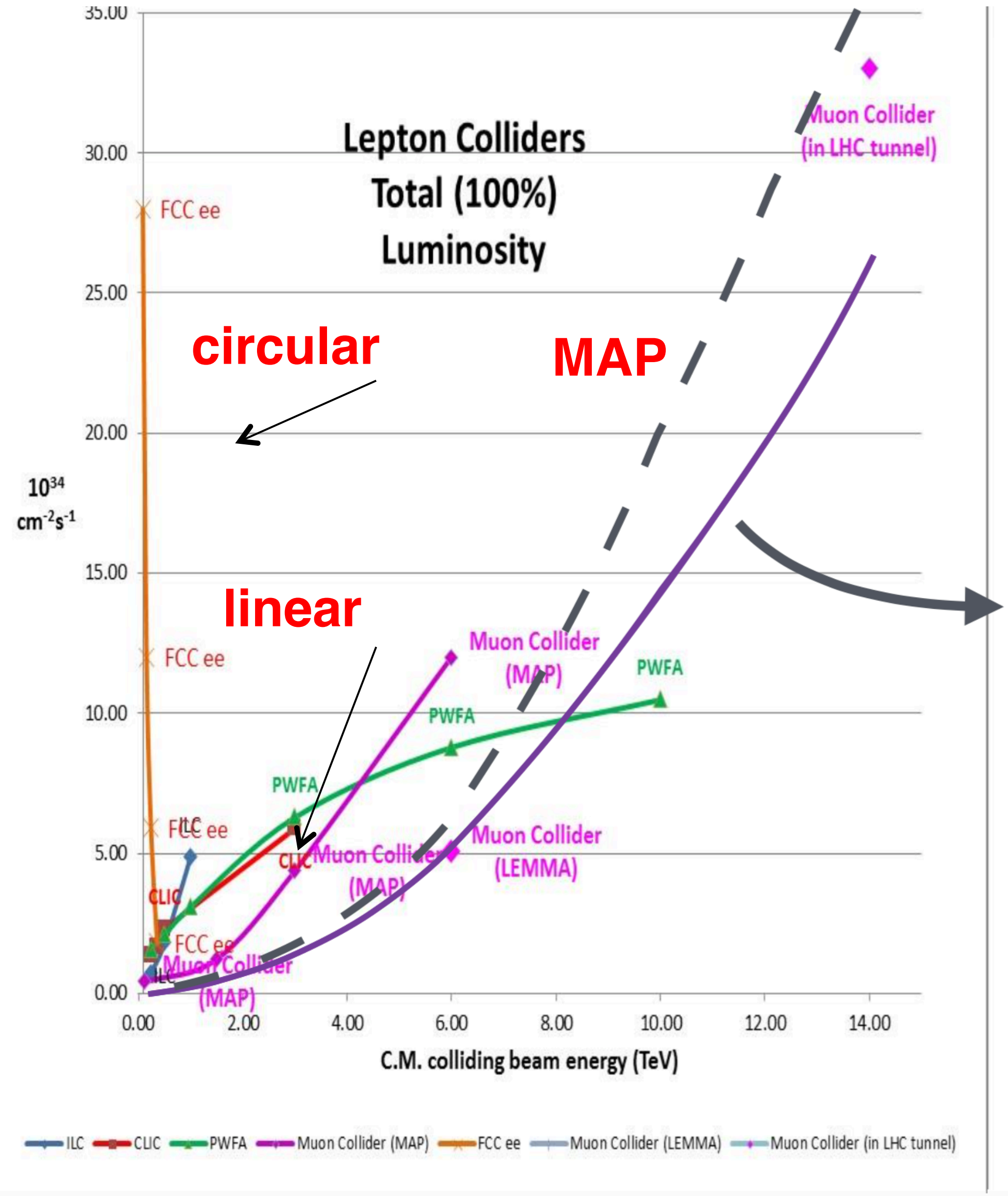
→ from ttH/ttZ arXiv:1507.08169

FCC-hh ambitious but possible targets.
For most of the empty cells work is in progress

→ from HH → bb $\gamma\gamma$

→ for specific channels, like $H\to e\mu$, ...

Since we are dreaming: HE muon collider



LEMMA

The discovery potential of a muon collider running at an energy >10TeV and L=10^{34}cm^{-2}s^{-1} is amazing.

- **14TeV$\mu^+\mu^-$~ 100TeV pp.**
- **30TeV$\mu^+\mu_-$ beyond imagination.**

But we don’t know yet how to build it.

Two different approaches

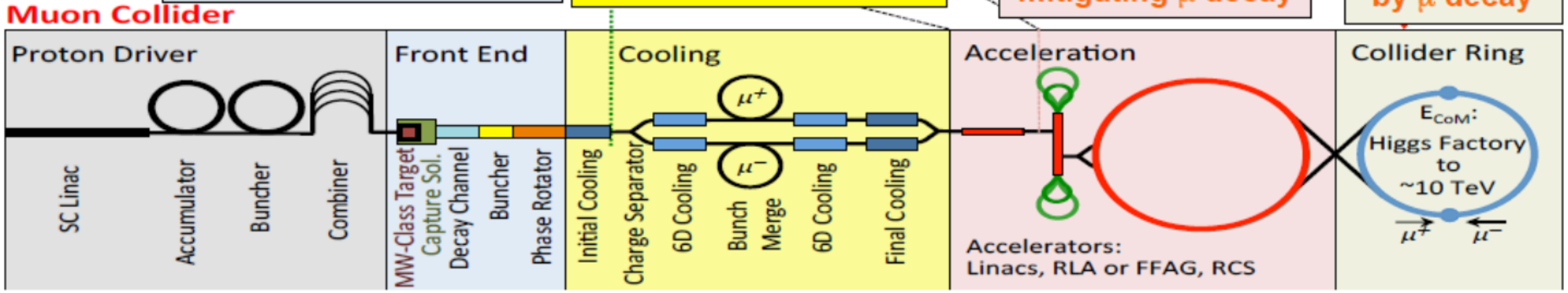
MAP

Key R&D

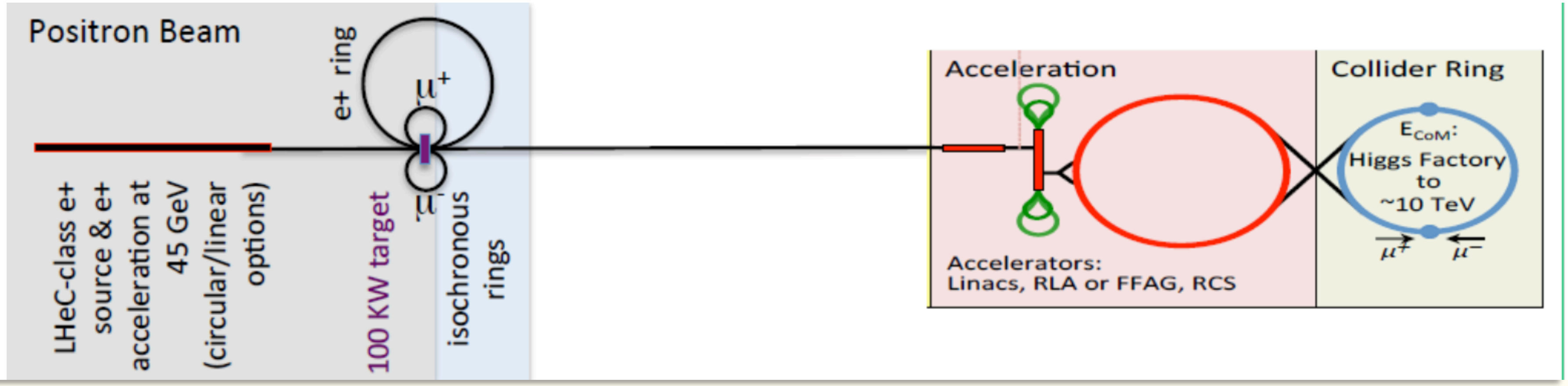
- MW proton driver
MW class target
NCRF in magnetic field
- Ionization cooling
High field solenoids (30T)
High Temp Superconductor
- Cost eff. low RF SC
Fast pulsed magnet (1kHz)
- Detector/ machine interface

Key Challenges

- $\sim 10^{13}$-10^{14} μ / sec
Tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay



LEMMA



Key Challenges

$\sim 10^{11}$ μ / sec from e+e-$\rightarrow \mu+\mu-$

Key R&D

10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

Conclusion

- The discovery of the Higgs boson has opened a new era in physics.
- From now on the hunt for physics beyond the standard model will proceed along two deeply connected lines of research:
  - a) direct searches based on the study of collisions at the largest possible energy
  - b) indirect searches based on precision measurement of the Higgs properties and couplings
- While we'll continue looking for new particles and new interactions at LHC, we have already entered the era of Higgs precision measurements.
- Ultimate precision on key parameters for Higgs physics will be achievable only with new powerful accelerators.
- Time to take strategic decisions.