Markus Klute (KIT/ETP) 03-15-2022 9th KSETA Plenary Workshop 2022

# Collider Physics

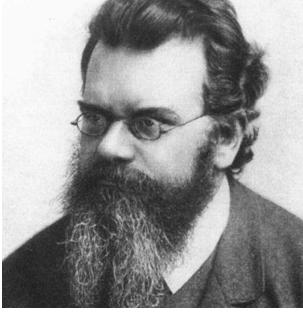
### ... at the energy frontier



1999

# **Collider Physics** ... Experimental Approach

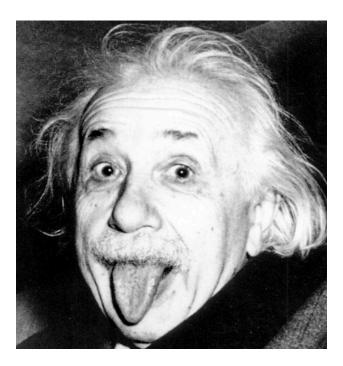
- Accelerate and collide particles at high energies
- Study particle interactions, resulting products, and features
- Measure energies, directions and identity of collision products
- Higher energies allow us
  - E ~ 1/size To look deeper into matter
  - E = kTTo probe conditions of the early universe
  - To discover new heavier particle •  $E = mc^2$
- All this in a controlled way in a laboratory



Ludwig Boltzmann



Louis de Broglie



Albert Einstein



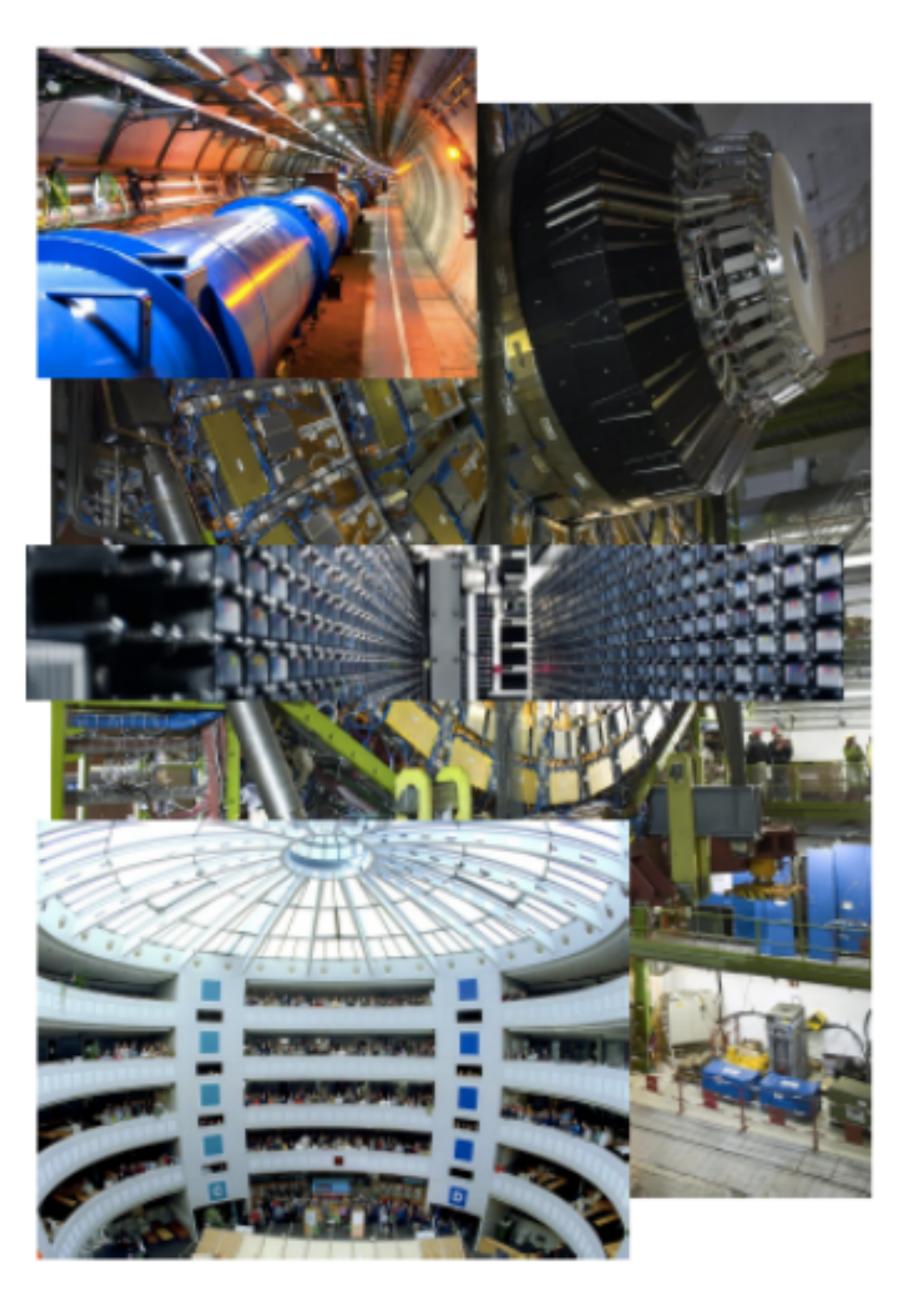






# **Collider Physics** ... Requirements

- Accelerator: powerful machine to accelerate particles to extreme high energy and collide them
- Detector: gigantic instruments to record collisions and resulting particles
- Computing: infrastructure to collect, distribute, and analyse the vast amount of data produced
- People: scientists and engineers to design, build, and operate the complex machines and to extract physics













3103 PHYSICISTS

(1050 STUDENTS)

1031

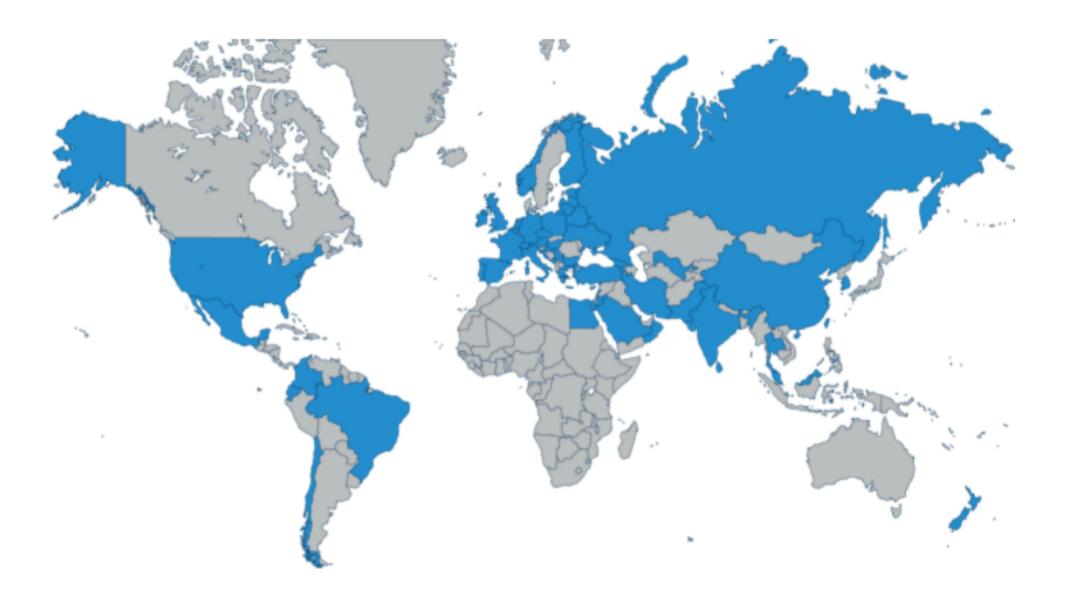
ENGINEERS

TECHNICIANS

269

241

54 countries & regions



#### The Details

The CMS collaboration has around:

#### 5494

ACTIVE PEOPLE (PHYSICISTS, ENGINEERS, TECHNICAL, ADMINISTRATIVE, STUDENTS, ETC.)

Of these members there are about:

2053 PHD PHYSICISTS

(1689 MEN, 364 WOMEN)

### 1050

PHYSICS DOCTORAL STUDENTS (792 MEN, 258 WOMEN) 1031

ENGINEERS (895 MEN, 136 WOMEN) 978

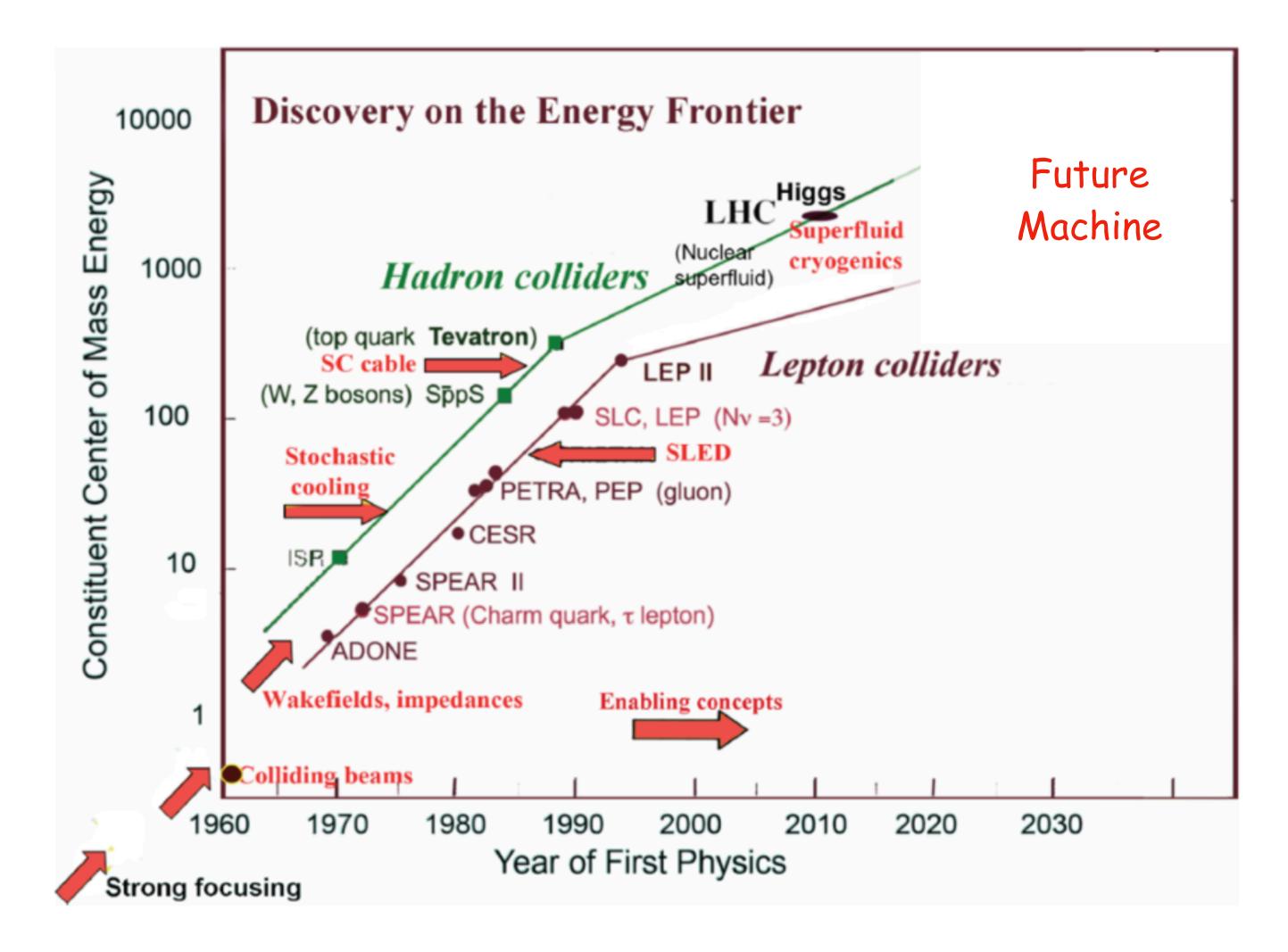
UNDERGRADUATES (708 MEN, 270 WOMEN)





# Accelerators

#### ... Livingston plot

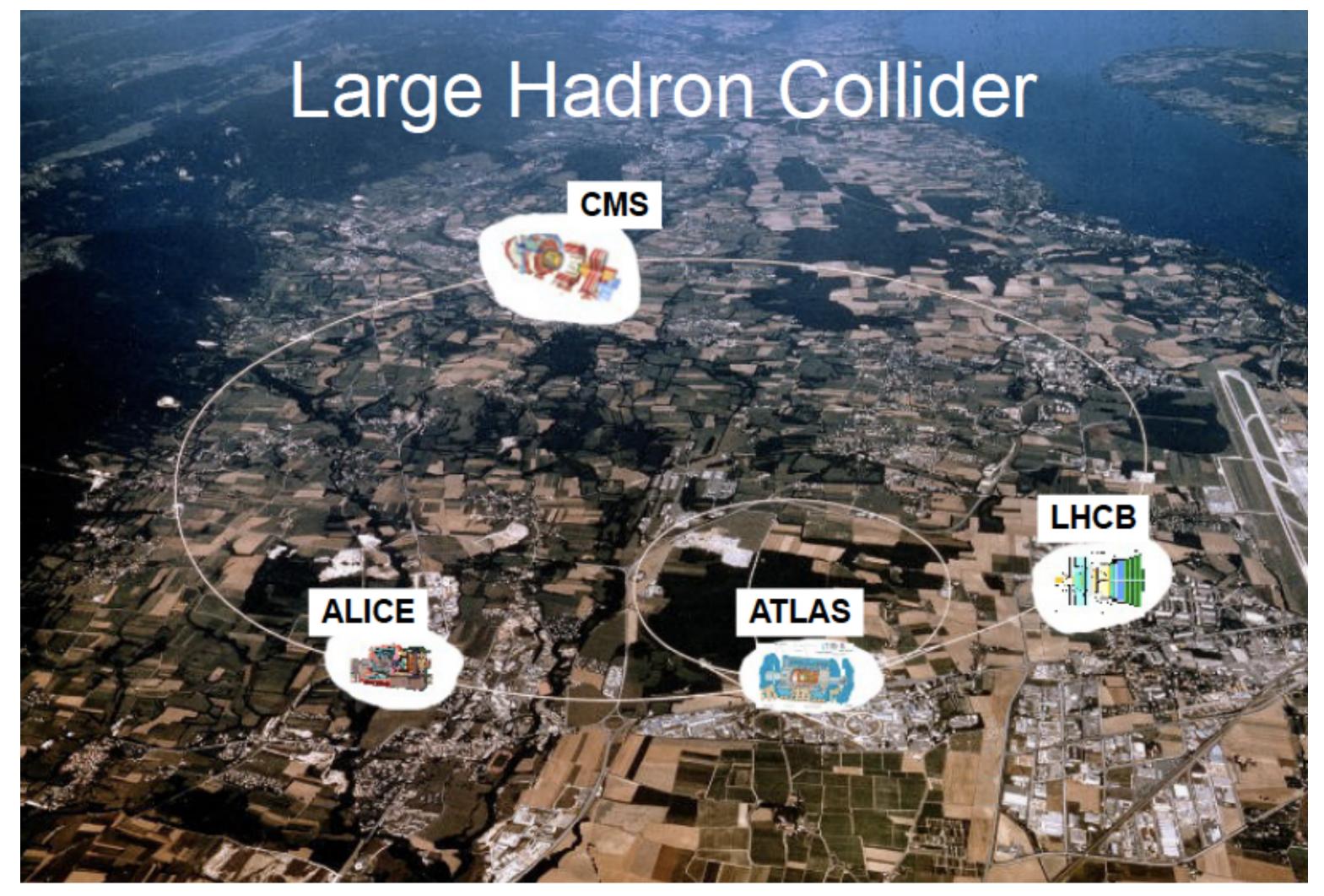






# Accelerators

#### ... LHC at the Energy Frontier



CERN tour April 7-9

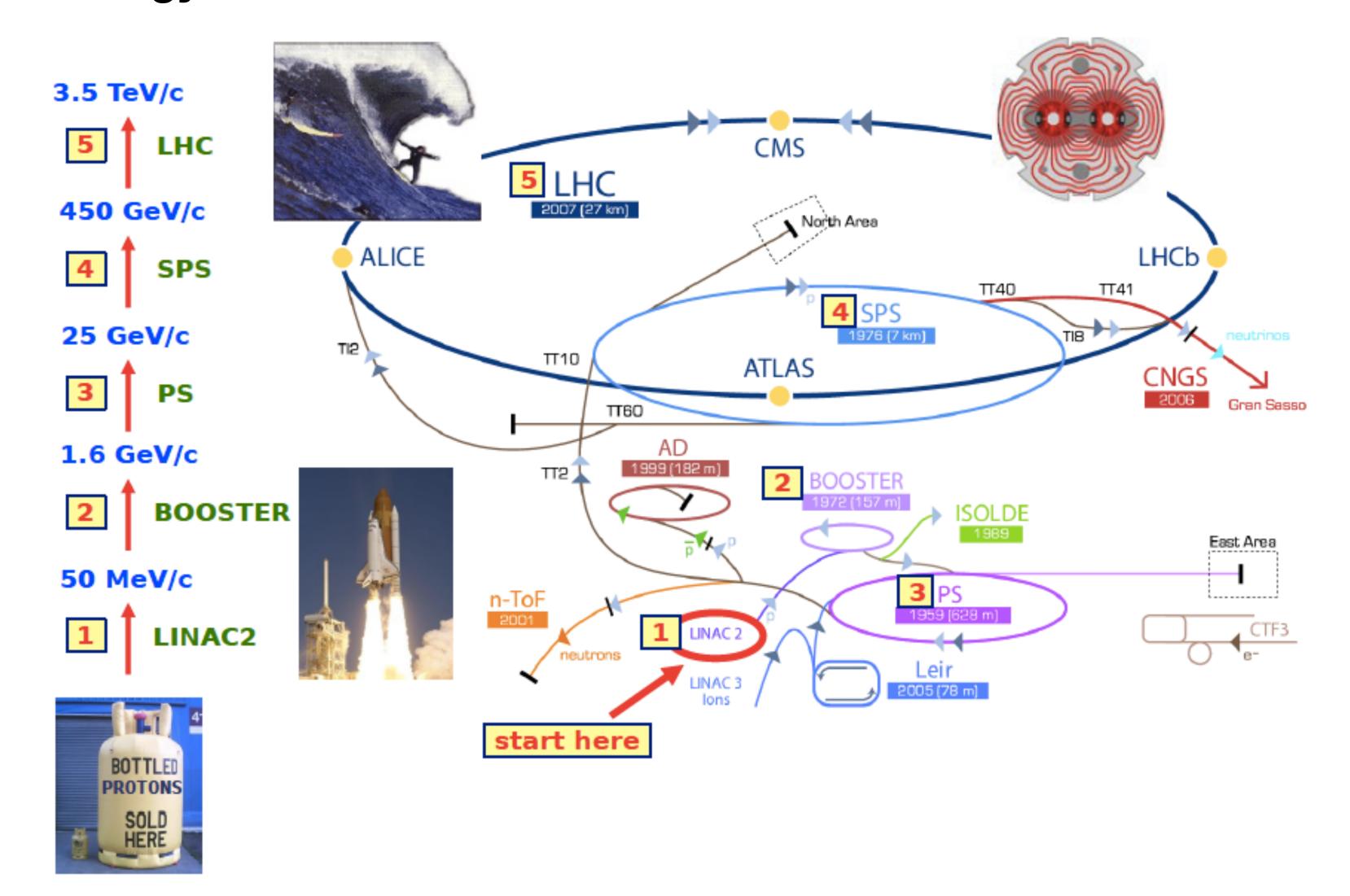








### Accelerators ... LHC at the Energy Frontier









### Accelerators ... LHC at the Energy Frontier

1984	Workshop on installing a Large
1987	CERN's long-range plann
re	commends Large Hadron Collid
1989	LEP collider starts operation
1992	First concepts for LHC Experi
1994	LHC Approved, ATLAS and CN
1998	Construction begins
2000	CMS assembly begins above gr
2003	ATLAS underground cavern del
2005	CMS experiment cavern deliver
2008	LHC & Experiments ready for E
2009	LHC & Experiments ready for
	First proton-

#### Hadron Collider (LHC) in the LEP tunnel ning committee chaired by Carlo Rubbia der as the right choice for CERN's future

#### riments, Evian les Bains MS approved (Technical Proposals)

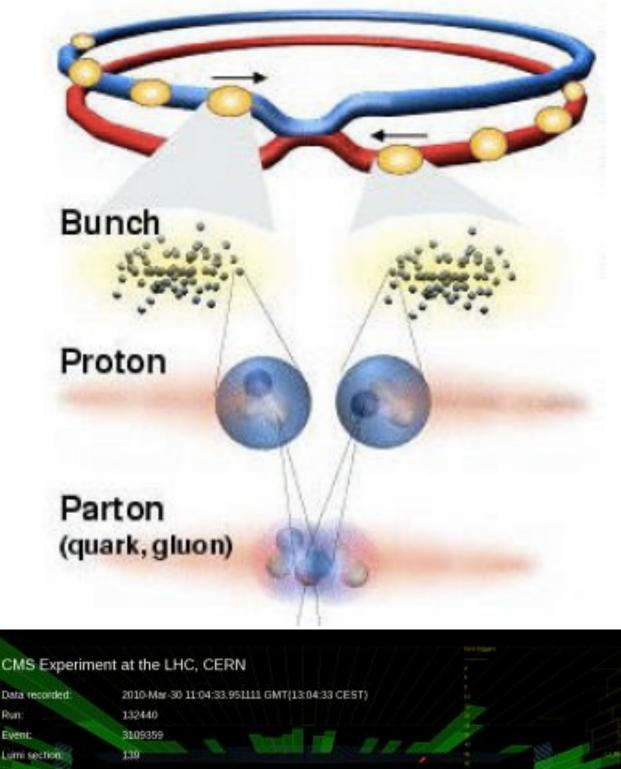
- round; LEP Collider closes
- livered and assembly underground begins
- red
- Beam. September incident.
- r Beam.
- -proton Collisions !!!



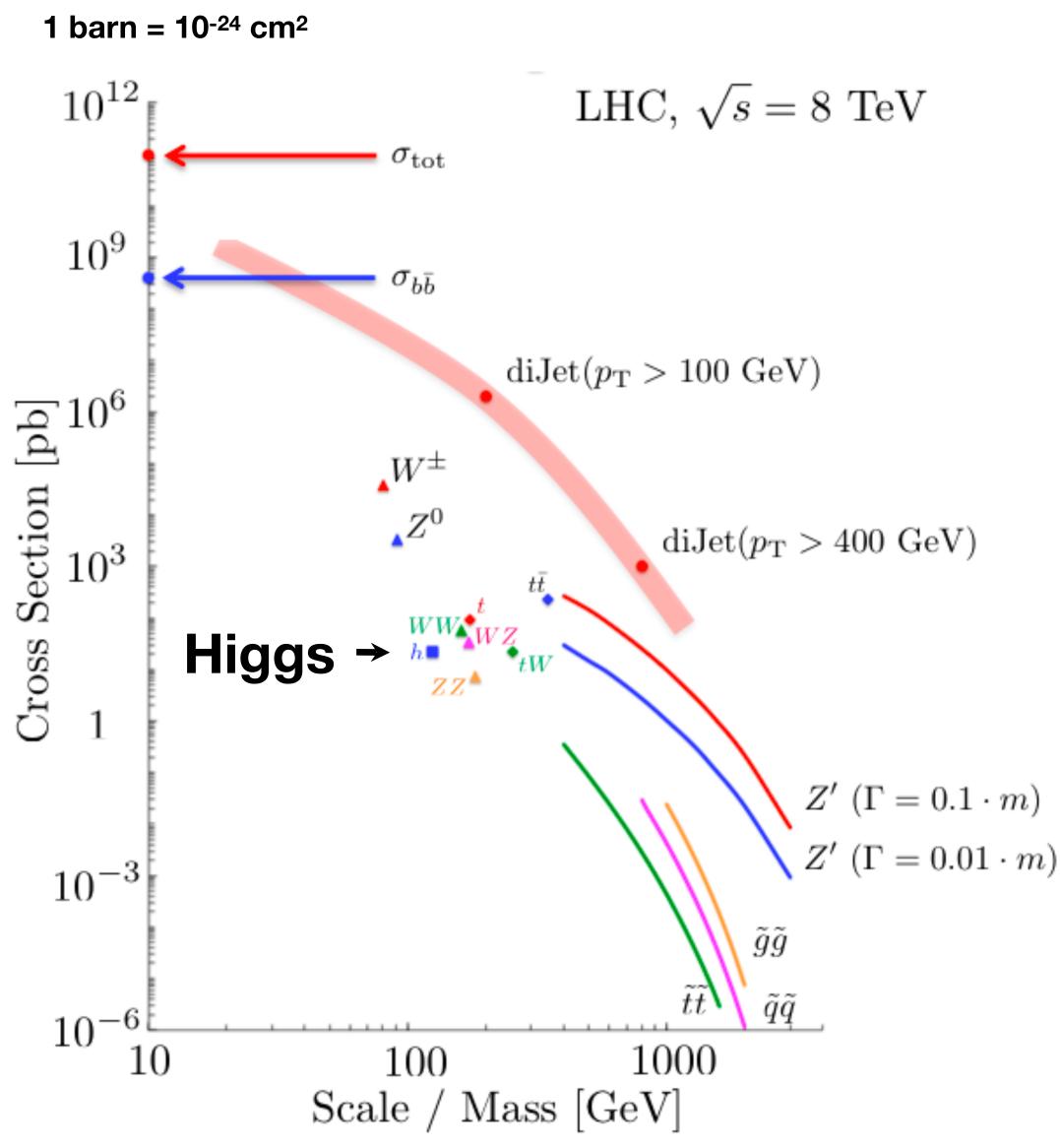




# Accelerators ... LHC Collisions











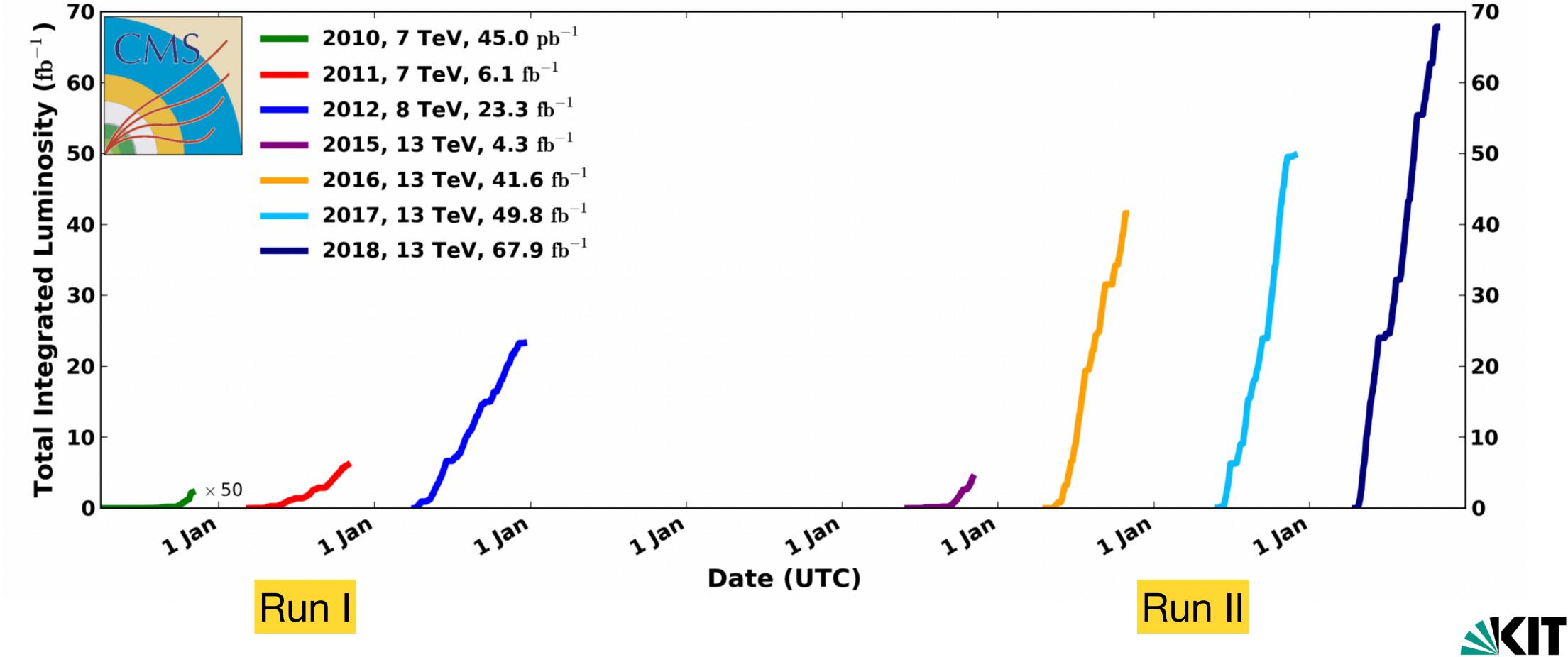




# Accelerators

#### CMS Integrated Luminosity Delivered, pp

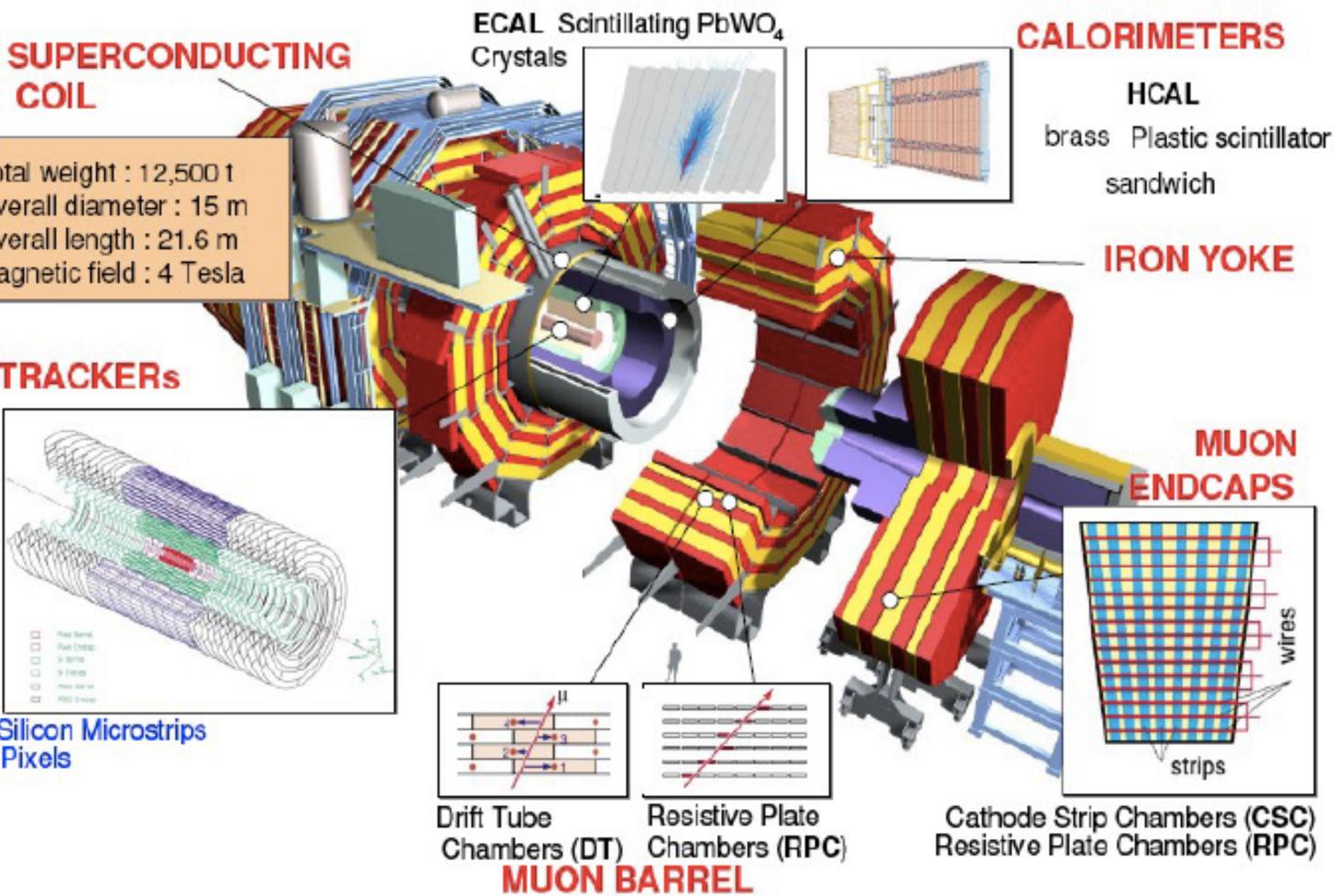
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC

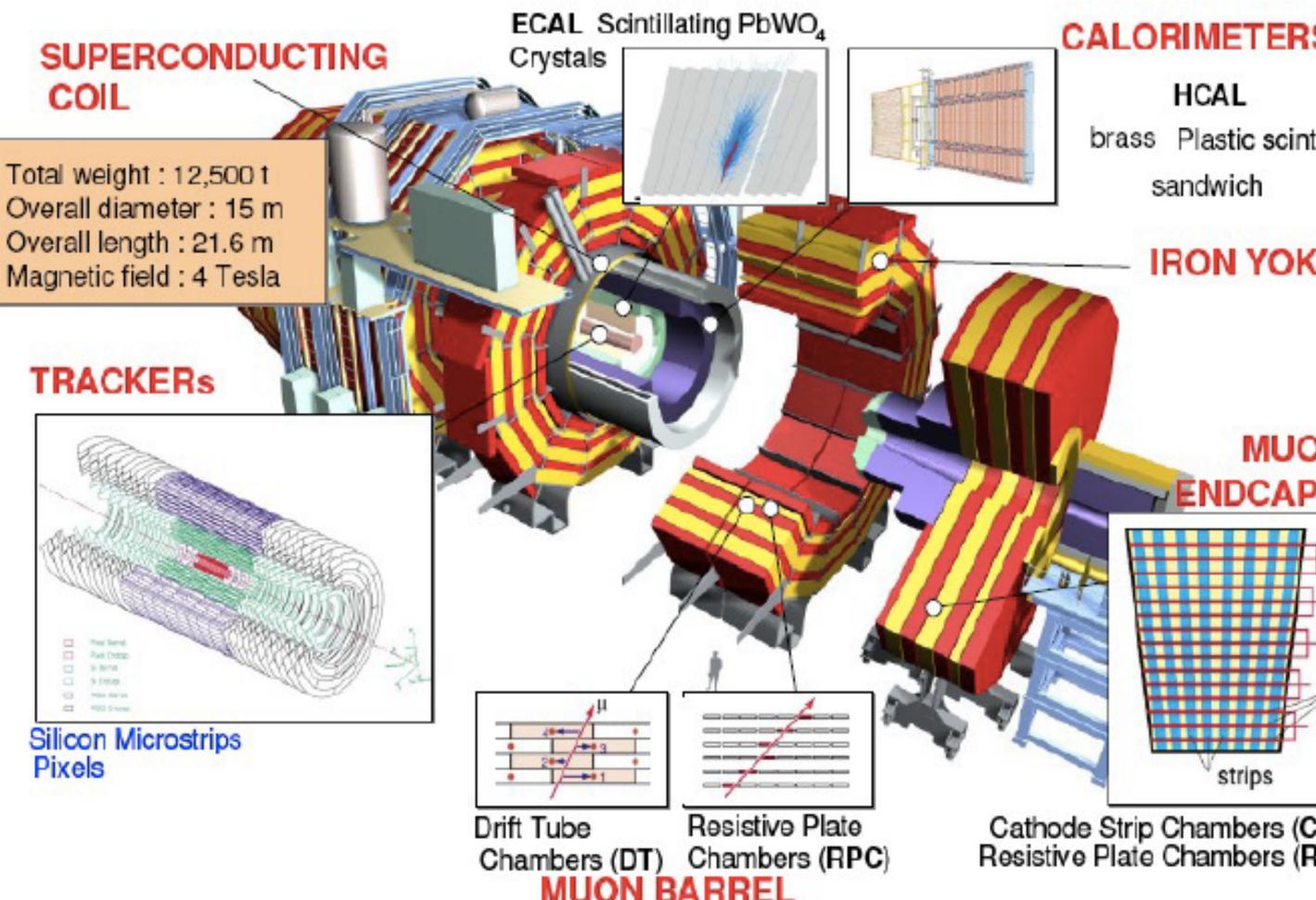




# **Particle Detectors** ... CMS at the LHC

- Many synchronous cameras
- Order of 100 million channels
- 40 MHz shutter speed
- Real time filtering (trigger)









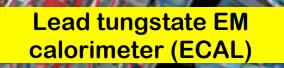






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### **Particle Detectors** ... CMS at the LHC

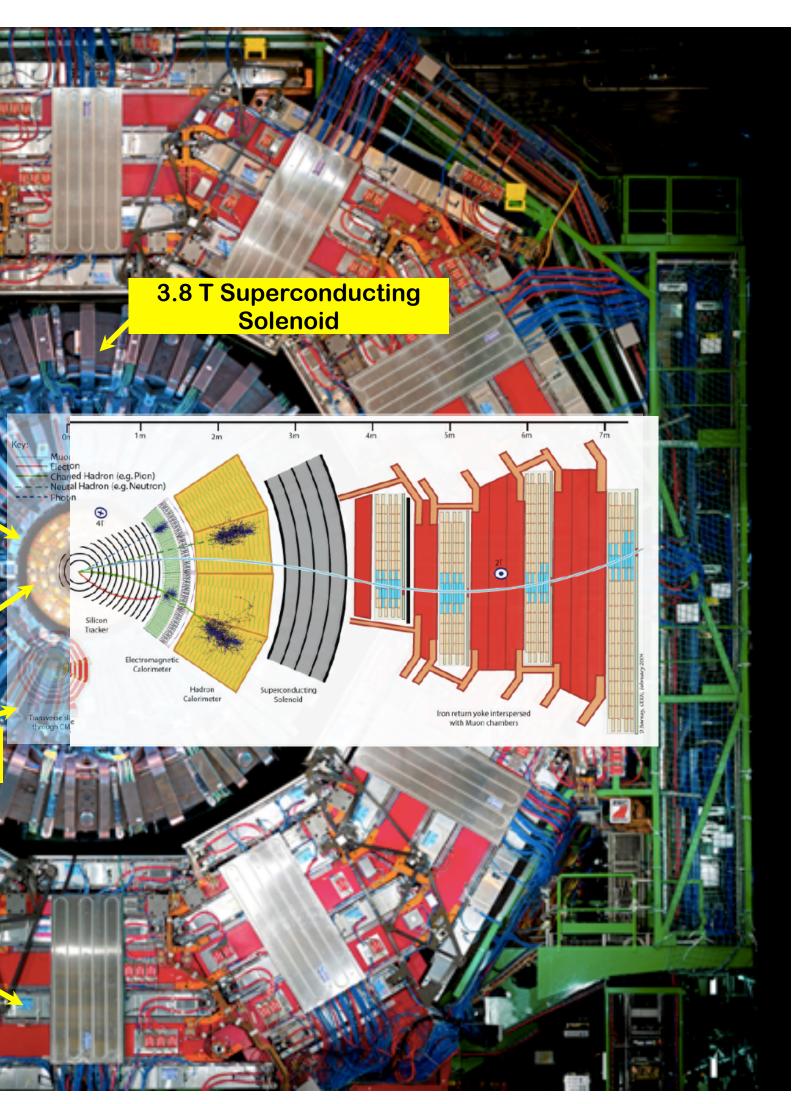


All silicon tracker (pixel and strips)

Scintillator & brass hadron calorimeter (HCAL)

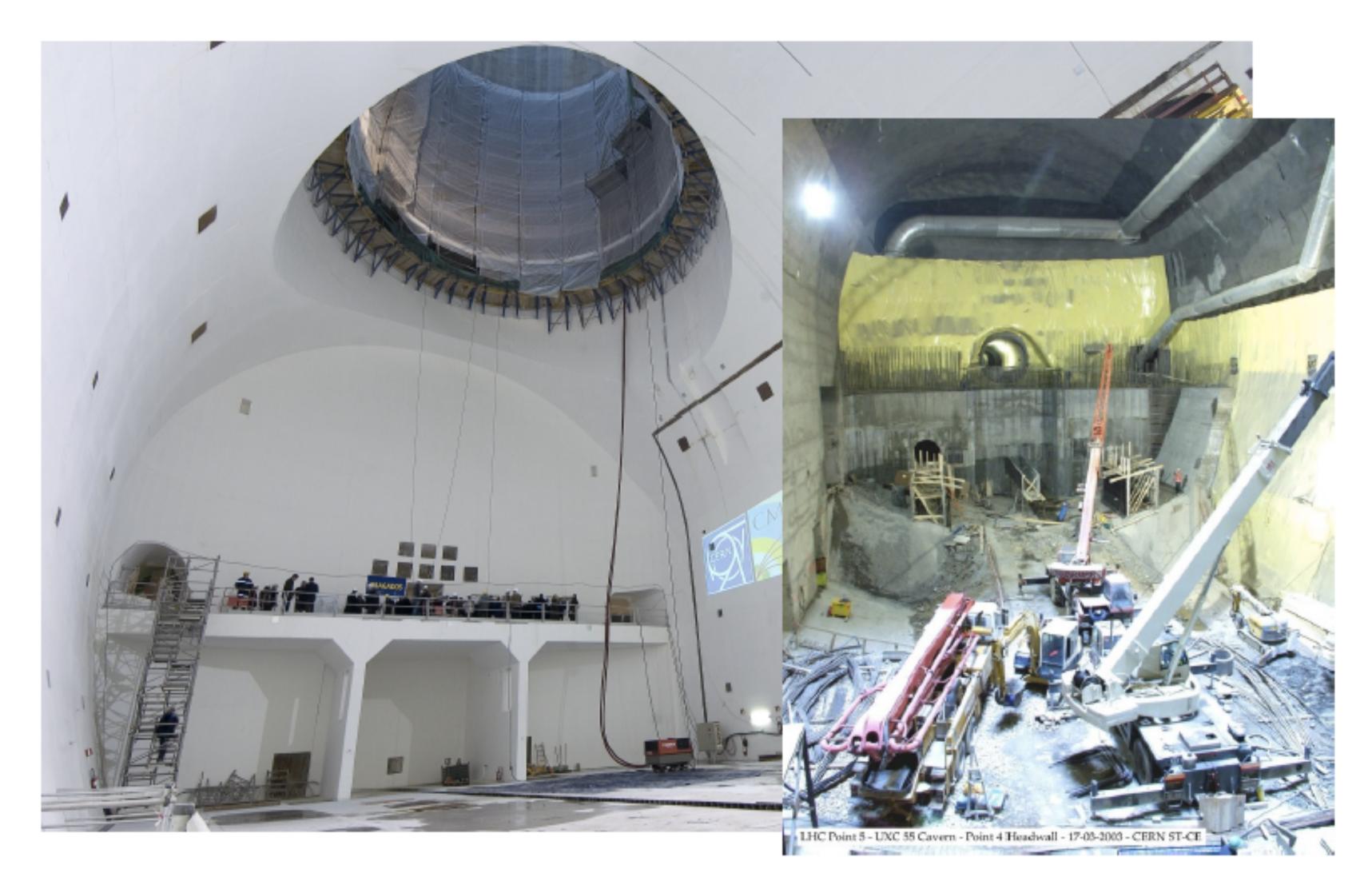
Redundant muon system (RPCs, drift tubes, cathode strip chambers)

I THE REAL PROPERTY IN CASE



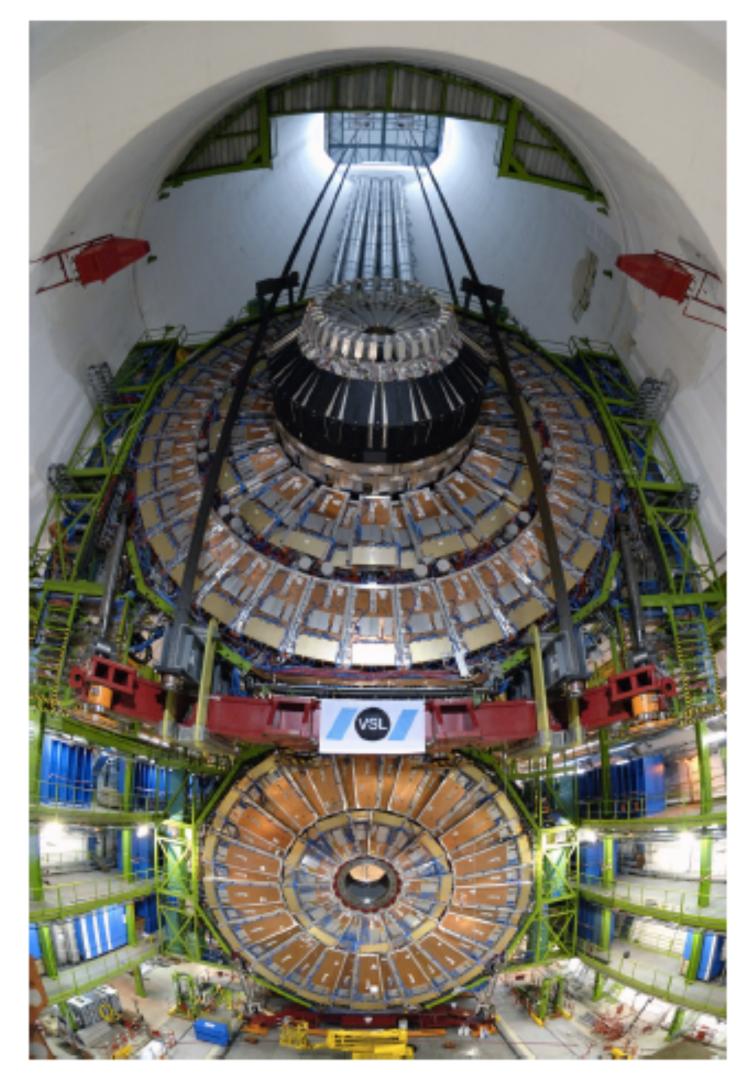


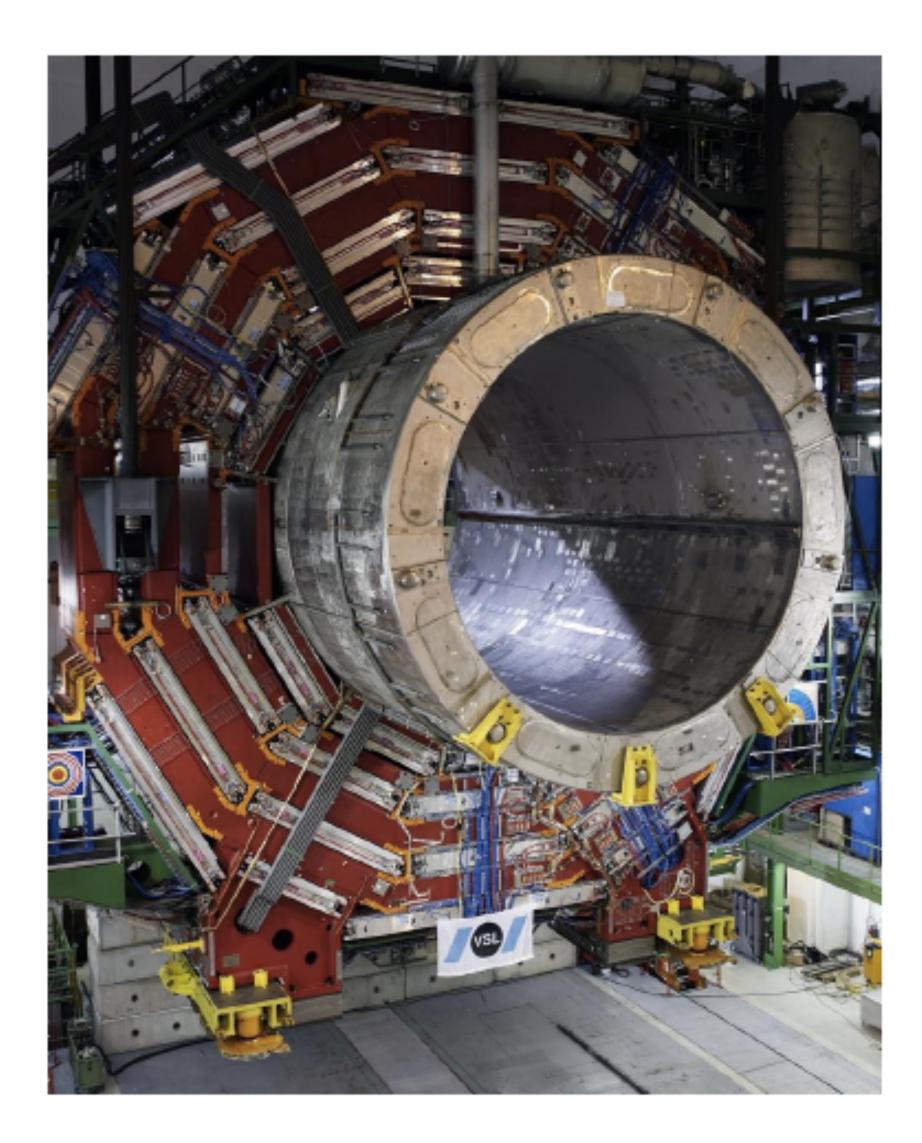
















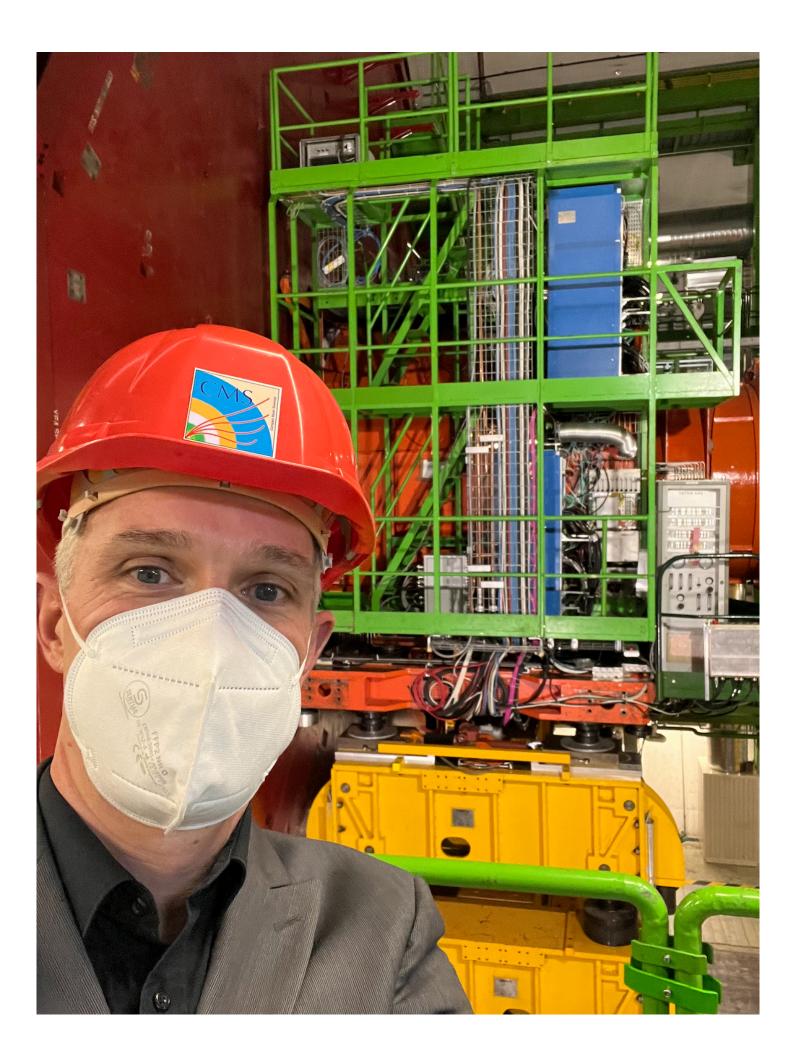




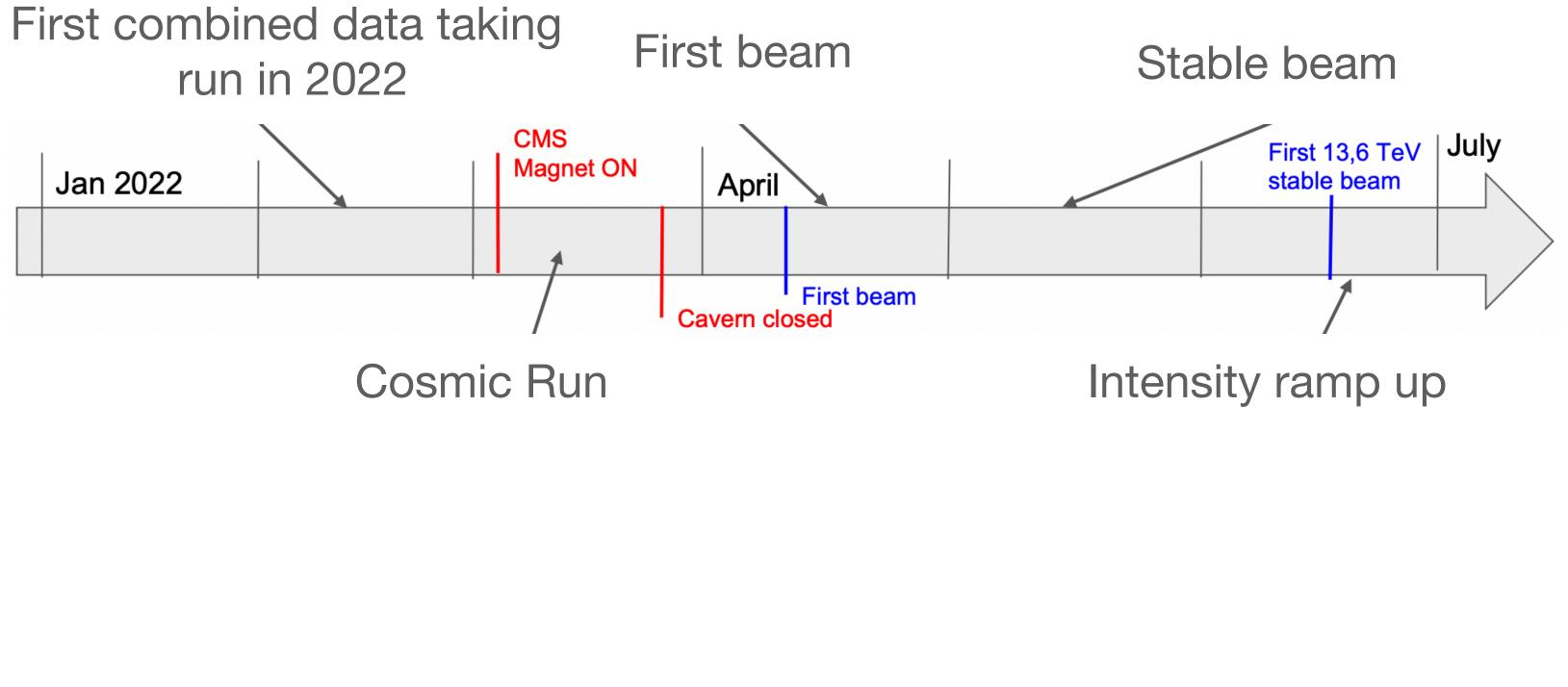




## **Particle Detectors** ... CMS in 2022



# Jan 2022

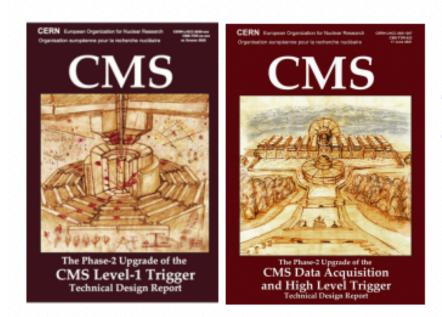






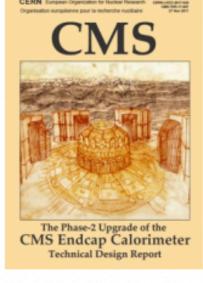
17

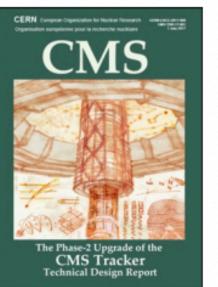
## **Particle Detectors** ... CMS in 2028



L1-Trigger HLT/DAQ https://cds.cern.ch/record/2714892 https://cds.cern.ch/record/2759072

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting





#### **Calorimeter Endcap**

#### https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

#### Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to  $\eta \simeq 3.8$

- Barrel layer: Crystals + SiPMs • Endcap layer: Low Gain Avalanche Diodes

#### **Barrel Calorimeters**

#### https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for  $e/\gamma$  at 30 GeV
- ECAL and HCAL new Back-End boards

#### Muon systems

#### https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- **RPC back-end electronics**
- New GEM/RPC 1.6 < η < 2.4</li>
- Extended coverage to η ≃ 3

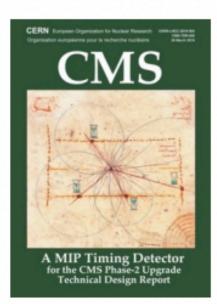
#### **Beam Radiation Instr. and Luminosity** http://cds.cern.ch/record/2759074

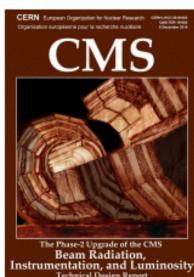
**Bunch-by-bunch luminosity measurement:** 1% offline, 2% online

#### **MIP Timing Detector**

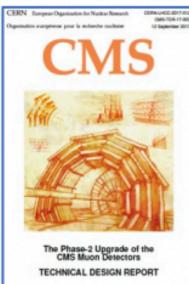
#### https://cds.cern.ch/record/2667167

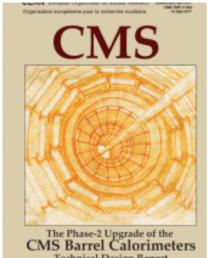
Precision timing with:











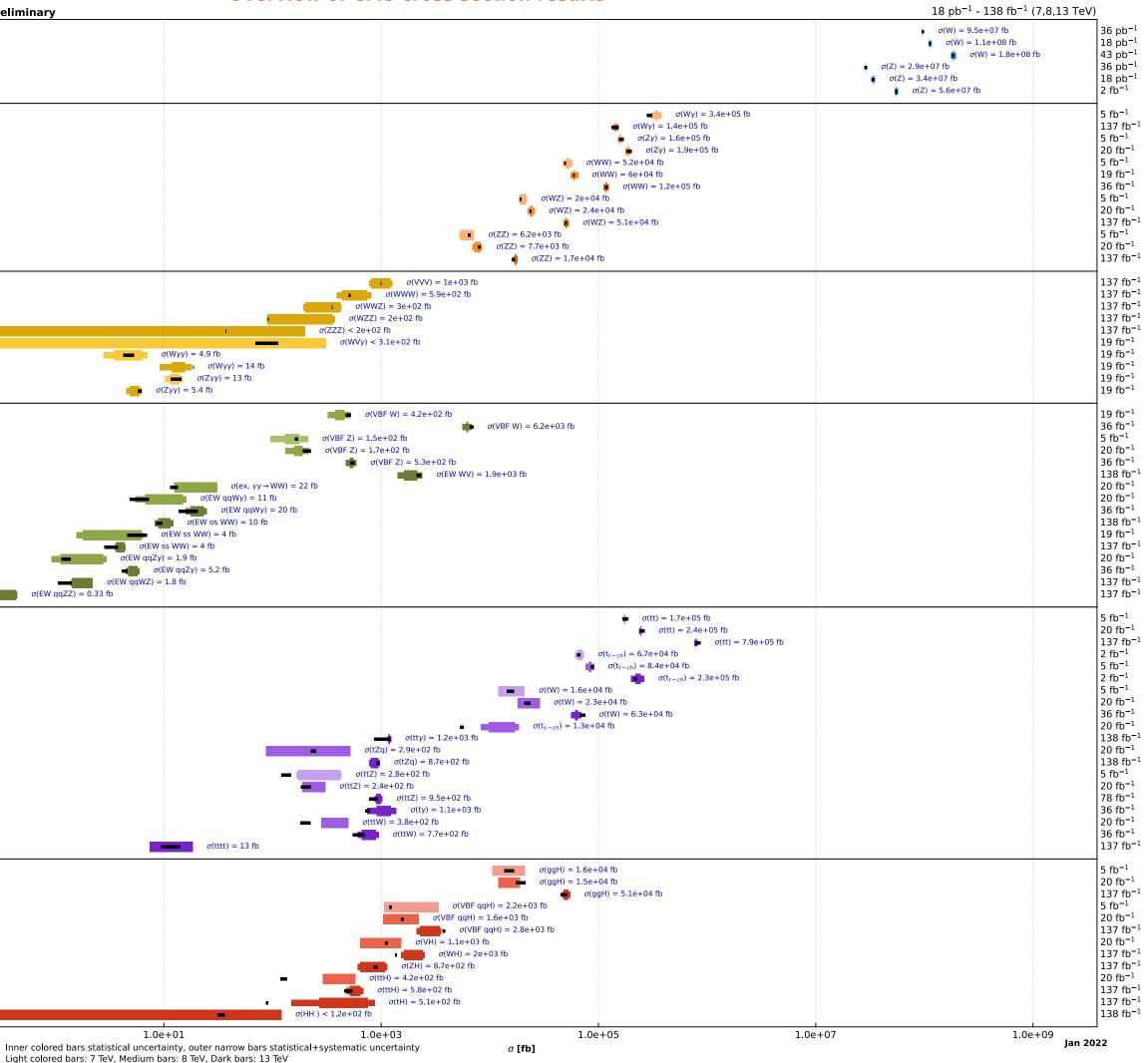


## **Overview of LHC Physics** ... the success story of the Standard Model

		CMS preliminary
Electroweak	Electroweak	W       7 TeV       JHEP 10 (2011) 132         W       8 TeV       PRL 112 (2014) 191802         W       13 TeV       SMP-15-004         Z       7 TeV       JHEP 10 (2011) 132         Z       8 TeV       PRL 112 (2014) 191802         Z       13 TeV       SMP-15-011
di-Boson	di-Boson	Wy         7 TeV         PRD 89 (2014) 092005           Wy         13 TeV         PRL 126 252002 (2021)           Zy         7 TeV         PRD 89 (2014) 092005           Zy         8 TeV         JHEP 04 (2015) 164           WW         7 TeV         EPJC 73 (2013) 2610           WW         8 TeV         EPJC 76 (2016) 401           WW         13 TeV         PRD 102 092001 (2020)           WZ         7 TeV         EPJC 77 (2017) 236           WZ         8 TeV         EPJC 77 (2017) 236           WZ         13 TeV         Submitted to JHEP           ZZ         7 TeV         JHEP 01 (2013) 063           ZZ         8 TeV         PLB 740 (2015) 250           ZZ         13 TeV         EPJC 81 (2021) 200
tri-Boson	tri-Boson	VVV       13 TeV       PRL 125 151802 (2020)         WWW       13 TeV       PRL 125 151802 (2020)         WWZ       13 TeV       PRL 125 151802 (2020)         WZZ       13 TeV       PRL 125 151802 (2020)         ZZZ       13 TeV       PRL 125 151802 (2020)         WVy       8 TeV       PRD 90 032008 (2014)         Wyy       8 TeV       JHEP 10 (2017) 072         Wyy       13 TeV       JHEP 10 (2021) 174         Zyy       8 TeV       JHEP 10 (2017) 072         Zyy       13 TeV       JHEP 10 (2021) 174
VBF and VBS	VBF and VBS	VBF W       8 TeV       JHEP 11 (2016) 147         VBF W       13 TeV       EPJC 80 (2020) 43         VBF Z       7 TeV       JHEP 10 (2013) 101         VBF Z       8 TeV       EPJC 75 (2015) 66         VBF Z       13 TeV       EPJC 78 (2018) 589         EW WV       13 TeV       Submitted to PLB         ex. γγ → WW8 TeV       JHEP 06 (2017) 106         EW qqWy       8 TeV       PLB 811 (2020) 135988         EW os WW       13 TeV       SMP-21-001         EW ss WW       8 TeV       PRL 114 051801 (2015)         EW ss WW       13 TeV       PRL 120 081801 (2018)         EW qqZy       8 TeV       PLB 770 (2017) 380         EW qqWZ       13 TeV       PLB 809 (2020) 135710         EW qqZZ       13 TeV       PLB 812 (2020) 135992
Тор	Тор	tt7 TeVJHEP 08 (2016) 029tt8 TeVJHEP 08 (2016) 029tt13 TeVAccepted by PRD $t_{t-ch}$ 7 TeVJHEP 12 (2012) 035 $t_{c-ch}$ 8 TeVJHEP 06 (2014) 090 $t_{c-ch}$ 13 TeVPLB 72 (2017) 752tW7 TeVPRL 110 (2013) 022003tW8 TeVPRL 112 (2014) 231802tW13 TeVJHEP 09 (2016) 027tty13 TeVSubmitted to JHEPtZq8 TeVJHEP 07 (2017) 003tZq13 TeVSubmitted to JHEPtZ7 TeVPRL 110 (2013) 172002ttZ8 TeVJHEP 01 (2016) 096ttZ13 TeVSubmitted to JHEPtZq8 TeVJHEP 01 (2016) 096ttZ13 TeVSubmitted to JHEPttZ13 TeVJHEP 01 (2016) 096ttt13 TeVJHEP 08 (2018) 011ttW8 TeVJHEP 08 (2018) 011ttW13 TeVEPJC 80 (2020) 75
Higgs	Higgs	ggH       7 TeV       EPJC 75 (2015) 212         ggH       8 TeV       EPJC 75 (2015) 212         ggH       13 TeV       HIG-19-005         VBF qqH       7 TeV       EPJC 75 (2015) 212         VBF qqH       8 TeV       EPJC 75 (2015) 212         VBF qqH       13 TeV       HIG-19-005         VH       8 TeV       EPJC 75 (2015) 212         VBF qqH       13 TeV       HIG-19-005         VH       13 TeV       HIG-19-005         ZH       13 TeV       HIG-19-005         ttH       8 TeV       EPJC 75 (2015) 212         ttH       13 TeV       HIG-19-005         ttH       13 TeV       HIG-19-005         ttH       13 TeV       HIG-19-005         tHH       13 TeV       HIG-19-005         HH       13 TeV       HIG-20-005
		1.0e-01 Easured cross sections and exclusion limits at 95% C.L. Inner colored bars e here for all cross section summary plots Elack bar theory pr Black bar theory pr

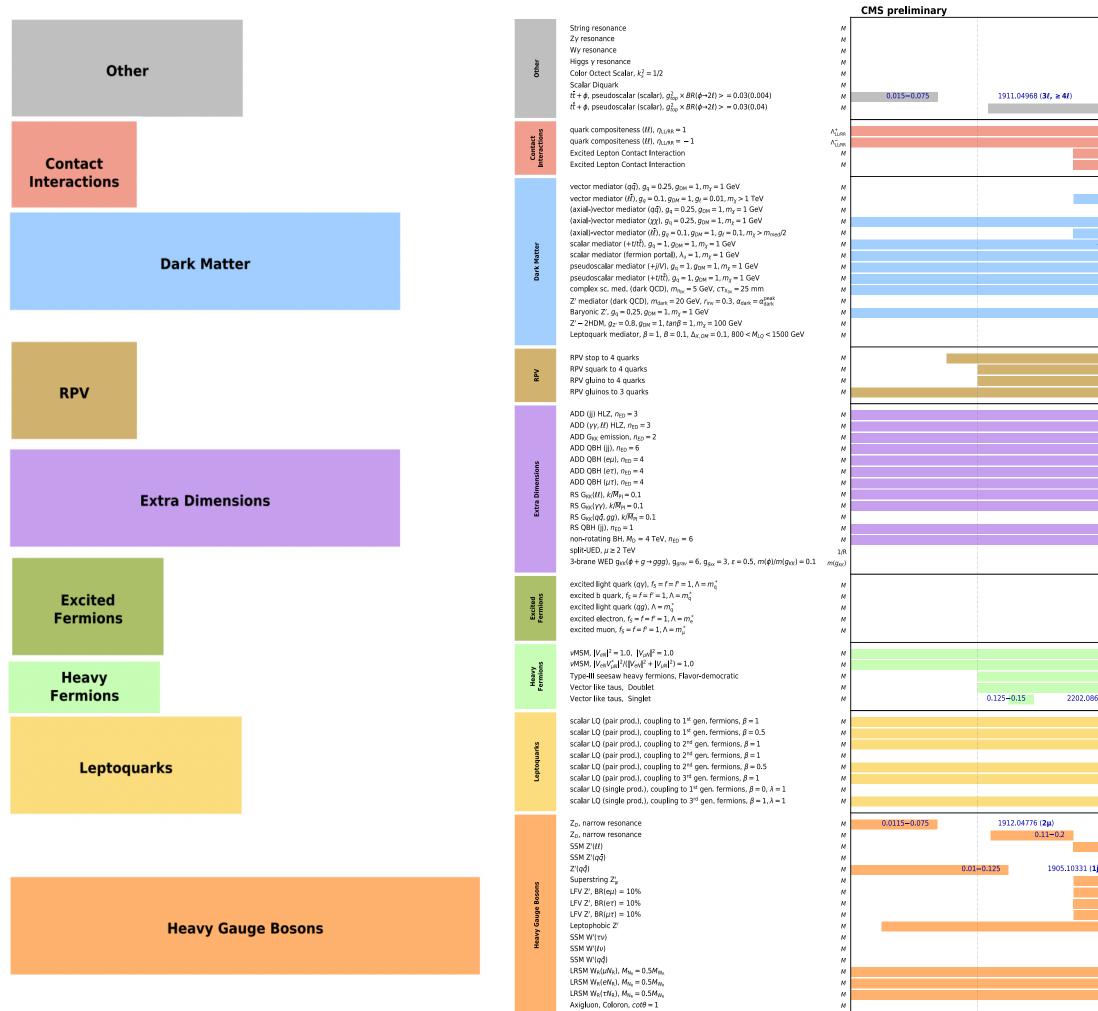
Black bar theory prediction

#### **Overview of CMS cross section results**





### **Overview of LHC New Physics Searches** ... example: CMS Exotic Searches



0.1 TeV

#### **Overview of CMS EXO results**

		16-140 fb <sup>-1</sup> (13 TeV)
	0.5-7.9 1911.039 0.35-4 1712.03143 ( <b>2µ + 1y; 2e + 1y; 2j + 1</b>	
	1.5-8 2106.105	
	0.72–3.25 1808.01257 ( <b>1j + 1</b> γ) 0.5–3.7 1911.03947 ( <b>2</b> j)	
	0.5-7.5 1911.03947	7 (2j)
0.108-0.34 1911.04968 ( <b>3</b> <i>ℓ</i> , ≥ 4 <i>ℓ</i> )		
		<24 2103.02708 ( <b>2</b> <i>l</i> )
	0.2–5.6 2001.04521 ( <b>2e + 2j</b> )	<36 2103.02708 ( <b>2</b> ℓ)
	0.2-5.0 2001.04321 (20 + 2) 0.2-5.7 2001.04521 (2µ + 2j)	
0.35-0.7 1911.03761	( ≥ 3j)	
	0.2–1.92 2103.02708 ( <b>2e, 2</b> µ)	
	0.5-2.8         1911.03947 (2j)           <1.95	
1001 01552 (0 14 + > 2: + = miss)	0.2–4.64 2103.02708 ( <b>2e, 2</b> μ)	
<0.29 1901.01553 ( <b>0</b> , $1l + \ge 2j + p_T^{miss}$ )	<1.5 2107.13021 ( $\geq 1j + p_T^{miss}$ )	
<0.47         2107.13021 ( $\geq$ 1j + p <sub>T</sub> <sup>miss</sup> )           <0.3         1901.01553 (0, 1l + $\geq$ 2j + p <sub>T</sub> <sup>miss</sup> )		
	<1.54 1810.10069 ( <b>4j</b> )	
	1.5-5.1         2112.11125 (2j + p_T^{miss})           <1.6	
	0.5–3.1 1908.01713 ( <b>h</b> + <b>p</b> <sup>miss</sup> )	
0.3–0.6 1811.10151 ( <b>1</b> µ +	<b>LJ + P</b> <sub>7</sub> <sup>(m)</sup> )	
0.08-0.52 1808.03124 ( <b>2j; 4j</b> ) 0.1-0.72 1806.0105	8 (21)	
0.1 0.72 1000.0100	0.1-1.41 1806.01058 ( <b>2j</b> )	
	<1.5 1810.10092 ( <b>6</b> j)	
		<12 1803.08030 ( <b>2j</b> )
		12.10443 (2γ, 2ℓ) 8 2107.13021 (≥ 1j + p <sub>T</sub> <sup>miss</sup> )
	<8.2 1803.08	8030 ( <b>2j</b> )
	<5.6 CMS-PAS-EXO-19-014 (et) <5.2 CMS-PAS-EXO-19-014 (et)	
	<5 CMS-PAS-EXO-19-014 (μτ) <4.79 2102 03709 (20)	
	<4.78 2103.02708 (2ℓ) <4.1 1809.00327 (2γ)	
	0.5–2.6 1911.03947 (2j) <5.9 1803.08030 (2j)	
	<9.7	1805.06013 ( ≥ 7j(ℓ, γ))
	0.4−2.8 2202.06075 (ℓ + p <sub>T</sub> <sup>miss</sup> ) 2−4.3 2201.02140 (2j)	
	<u>1-1.8</u> 1711.04652 ( <b>γ</b> + <b>j</b> ) 1711.04652 ( <b>γ</b> + <b>j</b> )	
	0.5–6.3 1911.03947 (2j) 0.25–3.9 1811.03052 (γ + 2e)	
	0.25-3.8 1811.03052 (γ + 2μ)	
	0.001-1.43 1802.02965; 1806.10905 ( <b>3ℓ(μ, e);</b> ≥ 1j + 2ℓ(μ, e))	
	0.02−1.6 1806.10905 ( $\ge$ 1j + $\mu$ + e)	
	$2202.08676 (3l, \ge 4l)$ $2202.08676 (3l, \ge 4l)$	
8676 ( <b>3ℓ, ≥ 4ℓ</b> )		
	<1.44 1811.01197 ( <b>2e + 2j</b> )	
	<pre>&lt;1.27 1811.01197 (2e + 2j; e + 2j + p_1<sup>miss</sup>) <pre>&lt;1.53 1808.05082 (2µ + 2j)</pre></pre>	
	<b>0.8–1.5</b> 1811.10151 ( <b>1µ + 1j + p</b> <sup>miss</sup> )	
<1.02	<1.29 1808.05082 (2µ + 2j; µ + 2j + p <sub>T</sub> <sup>miss</sup> ) 1811.00806 (2⊤ + 2j)	
	1–1.6 2107.13021 (≥ $1j + p_T^{miss}$ )	
<0.74 1806.034	72 ( <b>2</b> τ + b)	
1912.04776 ( <b>2µ</b> )		
1012.07//0 ( <b>EM</b> )	0.2–5.15 2103.02708 ( <b>2e, 2</b> µ)	
(11, 1y)	0.5–2.9 1911.03947 ( <b>2j</b> )	
(1j, 1y)	0.2–4.6 2103.02708 ( <b>2e, 2μ</b> )	
( <b>1</b> j, <b>1</b> γ)	0.2–4.6 2103.02708 ( <b>2e, 2µ</b> ) 0.2–5 CMS-PAS-EXO-19-014 ( <b>eµ</b> )	
	0.2–4.6 2103.02708 ( <b>2e, 2μ</b> )	
( <b>1j</b> , <b>1Y</b> ) 0.05-0.45 1909.04114 ( <b>2j</b> )	0.2-4.6       2103.02708 (2e, 2μ)         0.2-5       CMS-PAS-EXO-19-014 (eμ)         0.2-4.3       CMS-PAS-EXO-19-014 (eτ)         0.2-4.1       CMS-PAS-EXO-19-014 (μτ)	
	0.2-4.6       2103.02708 (2e, 2μ)         0.2-5       CMS-PAS-EXO-19-014 (eμ)         0.2-4.3       CMS-PAS-EXO-19-014 (er)         0.2-4.1       CMS-PAS-EXO-19-014 (μr)         0.4-4       1807.11421 (τ + p <sub>1</sub> <sup>miss</sup> )         0.4-5.7       2202.06075 ( <i>l</i> + p <sub>1</sub> <sup>miss</sup> )	
	0.2-4.6 2103.02708 ( <b>2e</b> , <b>2</b> μ) 0.2-5 CMS-PAS-EXO-19-014 ( <b>e</b> μ) 0.2-4.3 CMS-PAS-EXO-19-014 ( <b>e</b> τ) 0.2-4.1 CMS-PAS-EXO-19-014 ( <b>e</b> τ) 0.2-4.1 CMS-PAS-EXO-19-014 ( <b>μ</b> τ) 0.4-4 1807.11421 ( <b>τ</b> + <b>p</b> <sup>miss</sup> ) 0.4-5.7 2202.06075 ( <i>l</i> + <b>p</b> <sup>miss</sup> ) 0.5-3.6 1911.03947 ( <b>2</b> )	
( <b>1</b> j, <b>1</b> γ) 0.05-0.45 1909.04114 ( <b>2</b> j)	0.2-4.6       2103.02708 (2e, 2μ)         0.2-5       CMS-PAS-EXO-19-014 (eμ)         0.2-4.3       CMS-PAS-EXO-19-014 (er)         0.2-4.1       CMS-PAS-EXO-19-014 (μr)         0.4-4       1807.11421 (τ + p <sub>1</sub> <sup>miss</sup> )         0.4-5.7       2202.06075 ( <i>l</i> + p <sub>1</sub> <sup>miss</sup> )	



1 TeV

**10 TeV** 

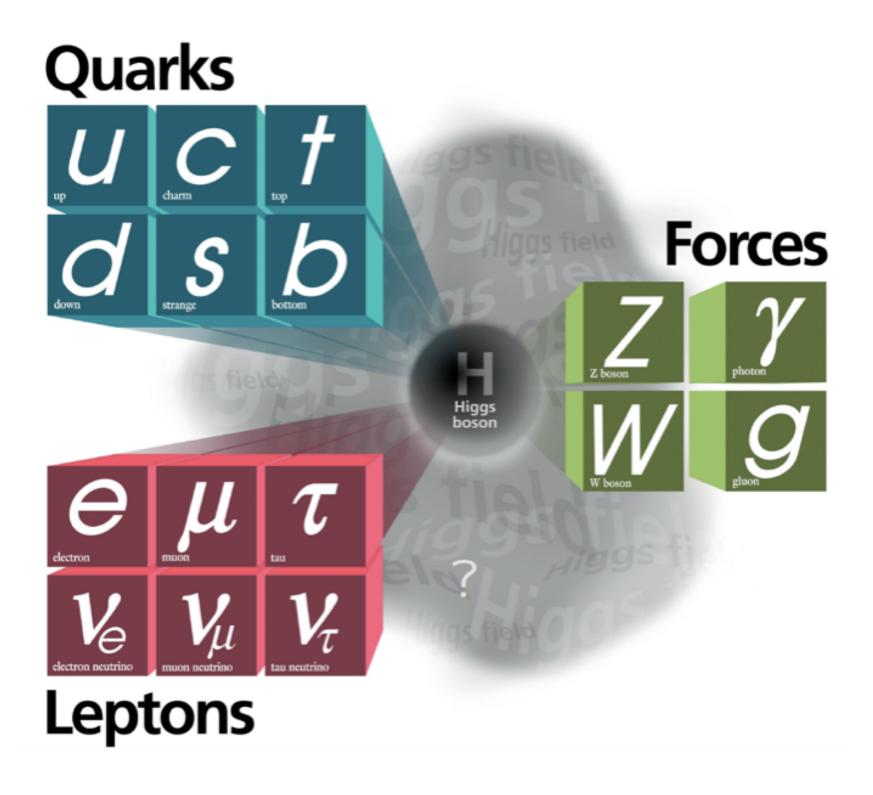
Moriond 2022



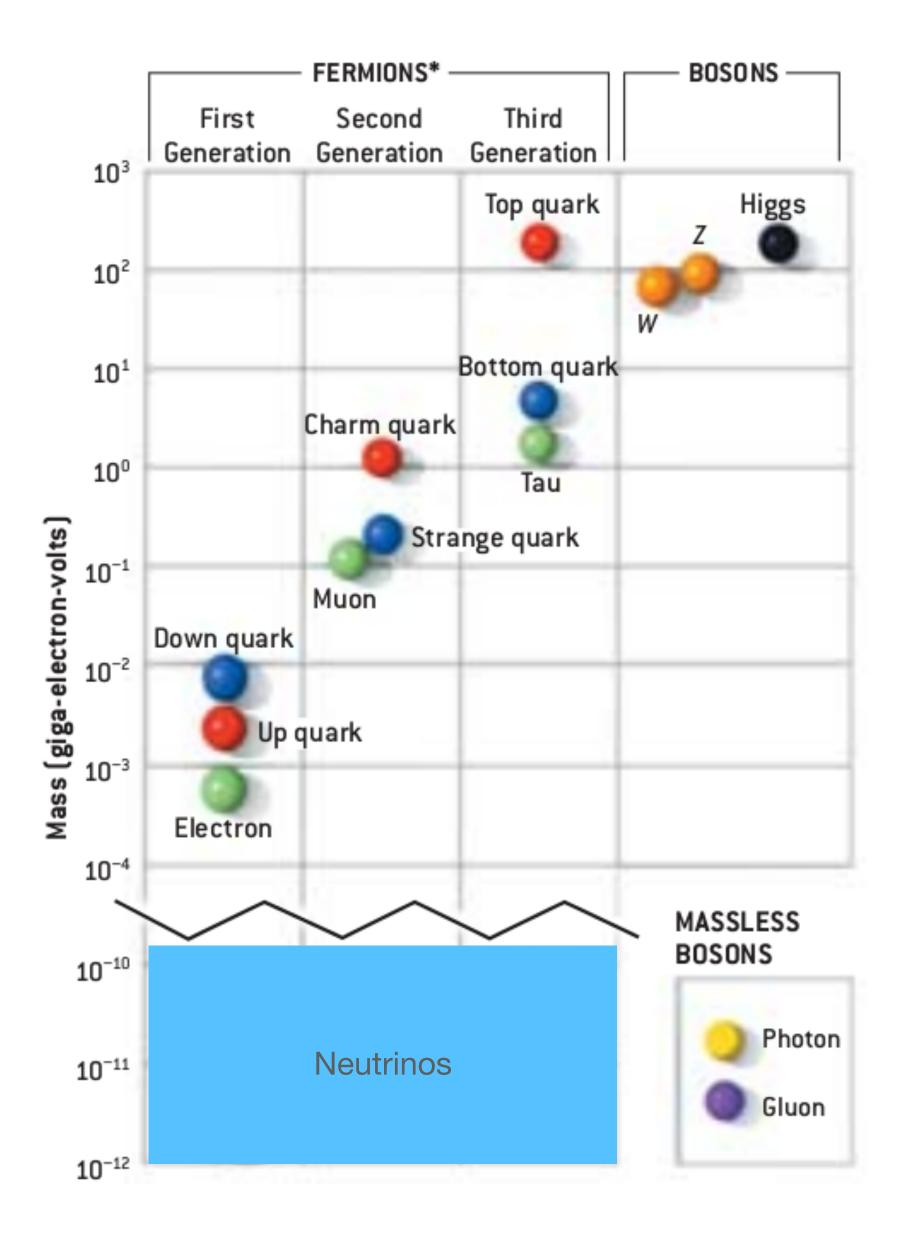
nology

## **Energy Frontier Today** .... where is everybody else?

Complete theory valid to very high energies



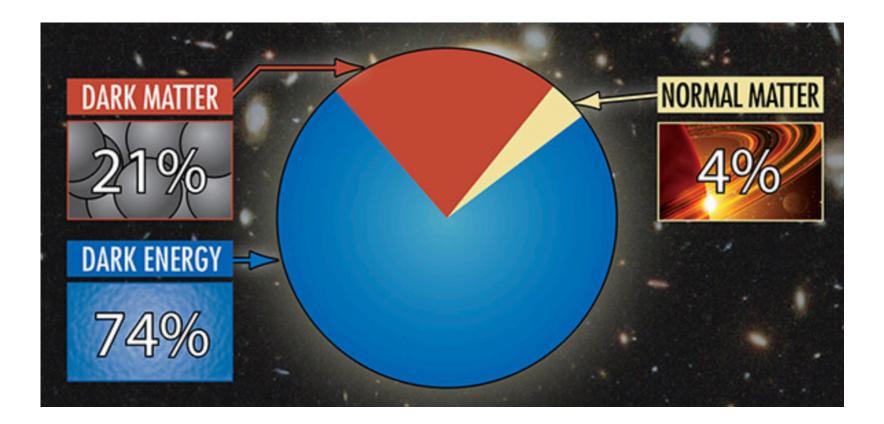
... but it is not enough

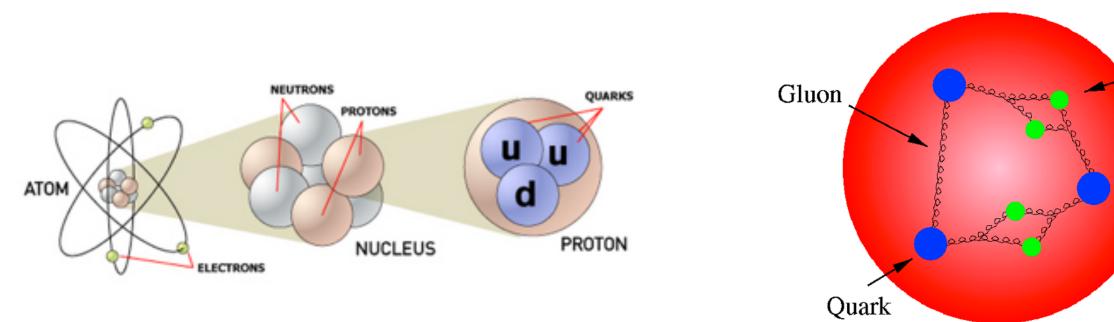






# Mass and the Universe ... the big picture





#### Ten most common elements in the Milky Way Galaxy estimated spectroscopically<sup>[3]</sup>

<b>Z</b> \$	Element +	Mass fraction (ppm)
1	Hydrogen	739,000
2	Helium	240,000
8	Oxygen	10,400
6	Carbon	4,600
10	Neon	1,340
26	Iron	1,090
7	Nitrogen	960
14	Silicon	650
12	Magnesium	580
16	Sulfur	440
	Total	999,060

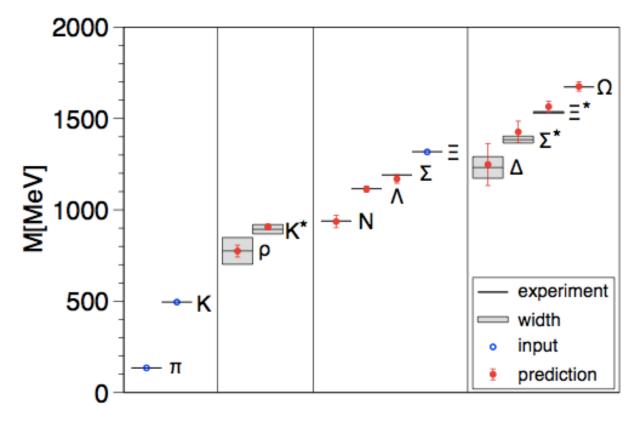
Most abundant nuclides						
in th	ne <mark>Sol</mark>	ar System <sup>[8]</sup>				
		Mass	At			
		fraction	frac			
Nuclide 🗢	<b>A \$</b>	in parts 🗢	in p			
		per	р			
		million	mil			
Hydrogen-1	1	705,700	9			
Helium-4	4	275,200				
Oxygen-16	16	9,592				
Carbon-12	12	3,032				
Nitrogen-14	14	1,105				
Neon-20	20	1,548				

Most abundant nuclides

Quark-Antiquark-Pair Proton mass m<sub>P</sub> = 938 MeV Quark masses m<sub>u</sub> = 1.5-4.5 MeV

m<sub>d</sub> = 5.0-8.5 MeV

Inertial mass mostly QCD effects



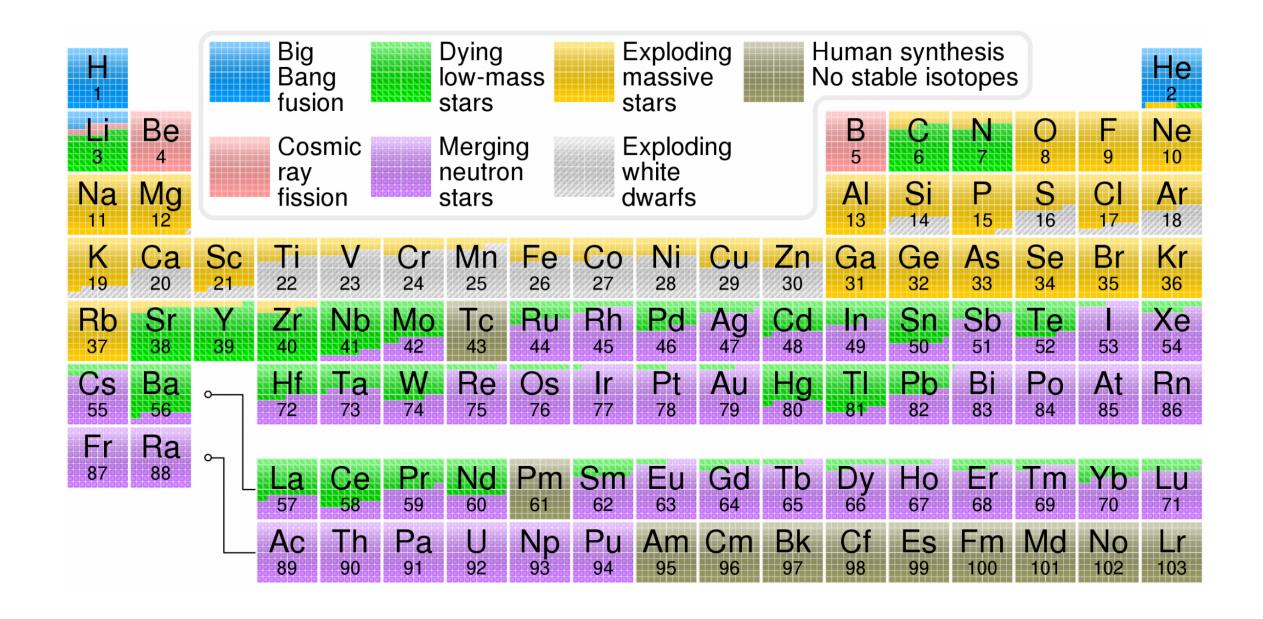






## **Higgs Boson Properties** ... a universe with modified Higgs Yukawa couplings

- Quarks: modified quark masses would have profound consequences for nucleosynthesis;
- Electrons: a massless electron would not be trapped by a protons to form a hydrogen atom; a modified electron mass would have profound consequences for chemistry

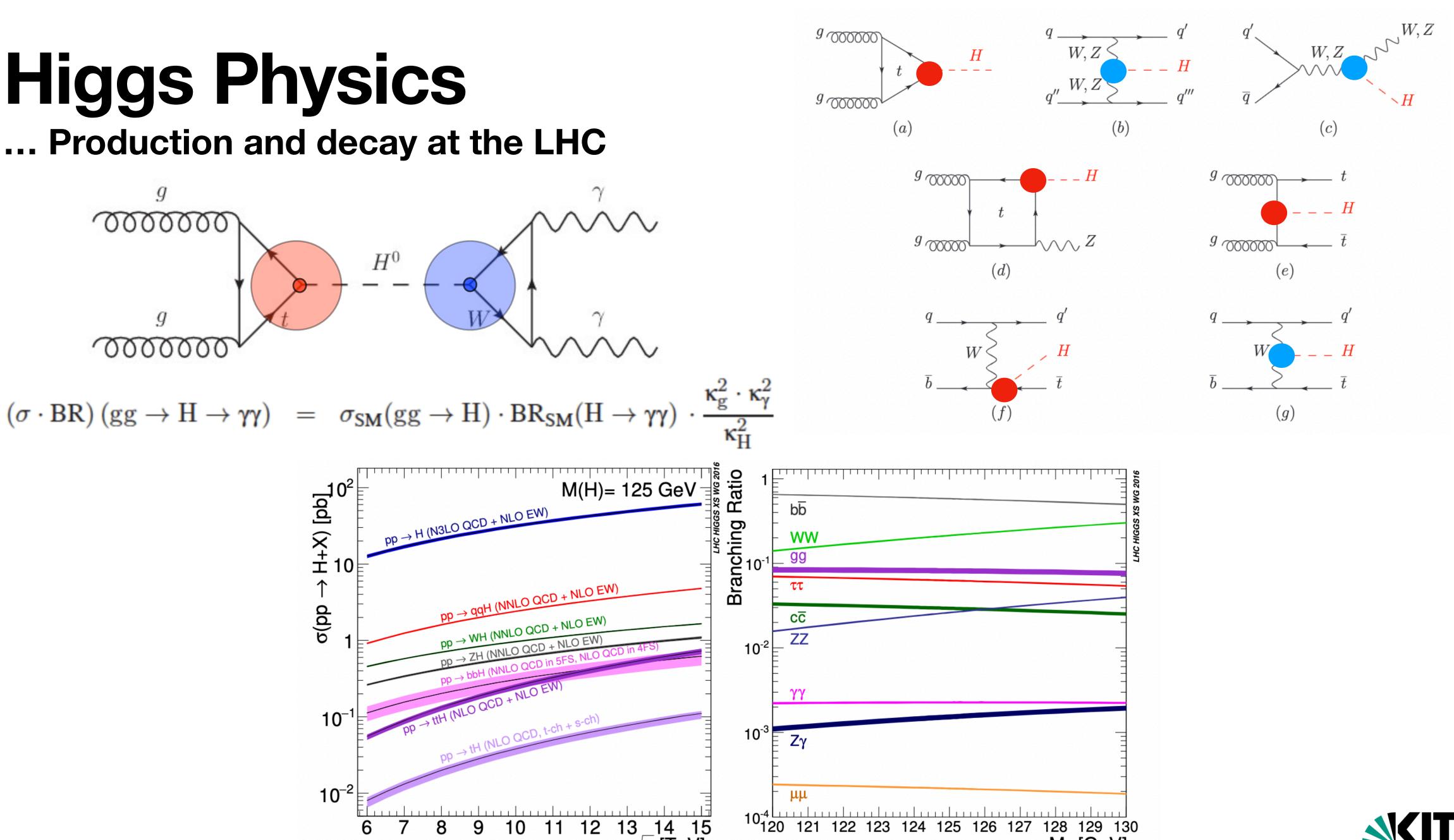


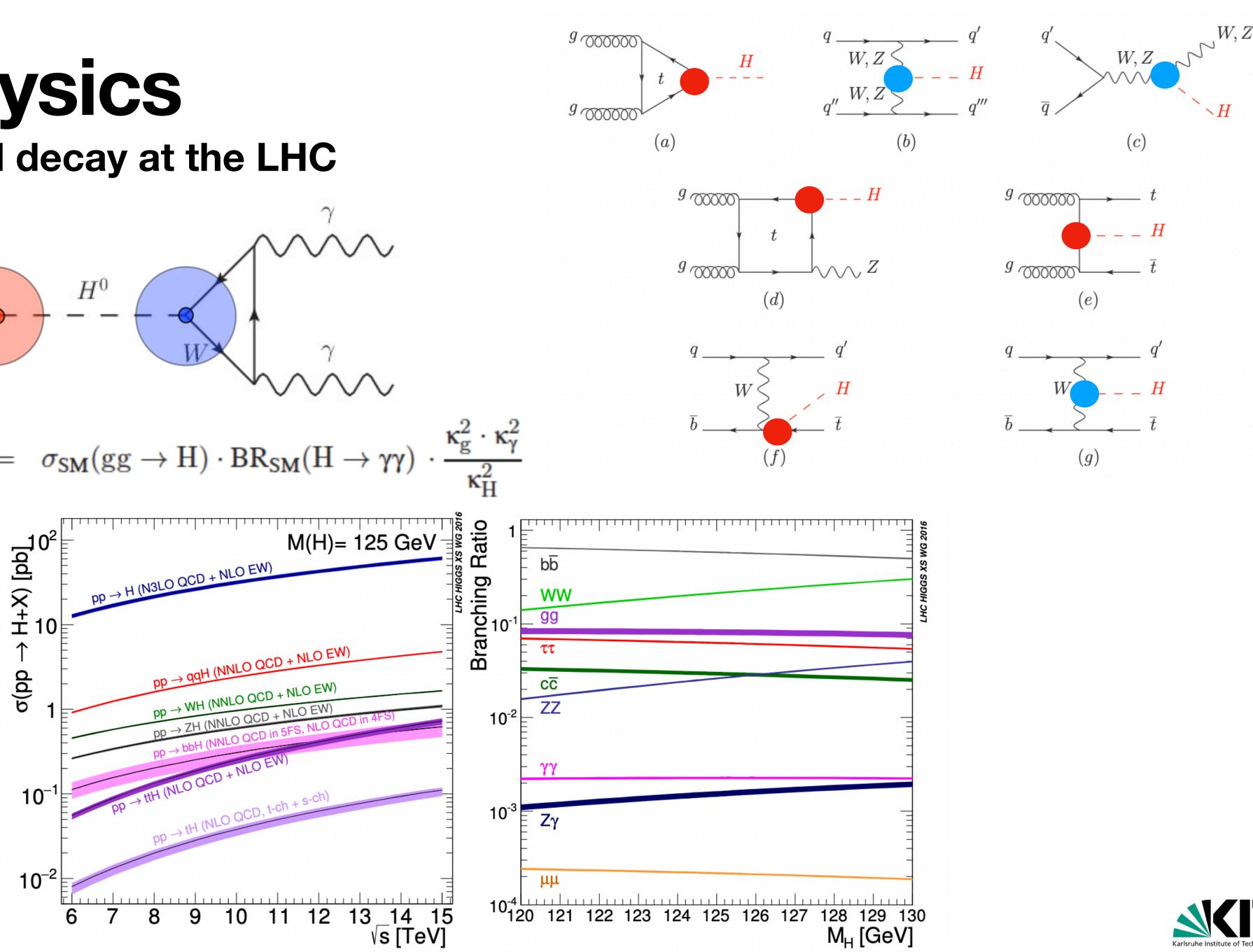






### **Higgs Physics** ... Production and decay at the LHC

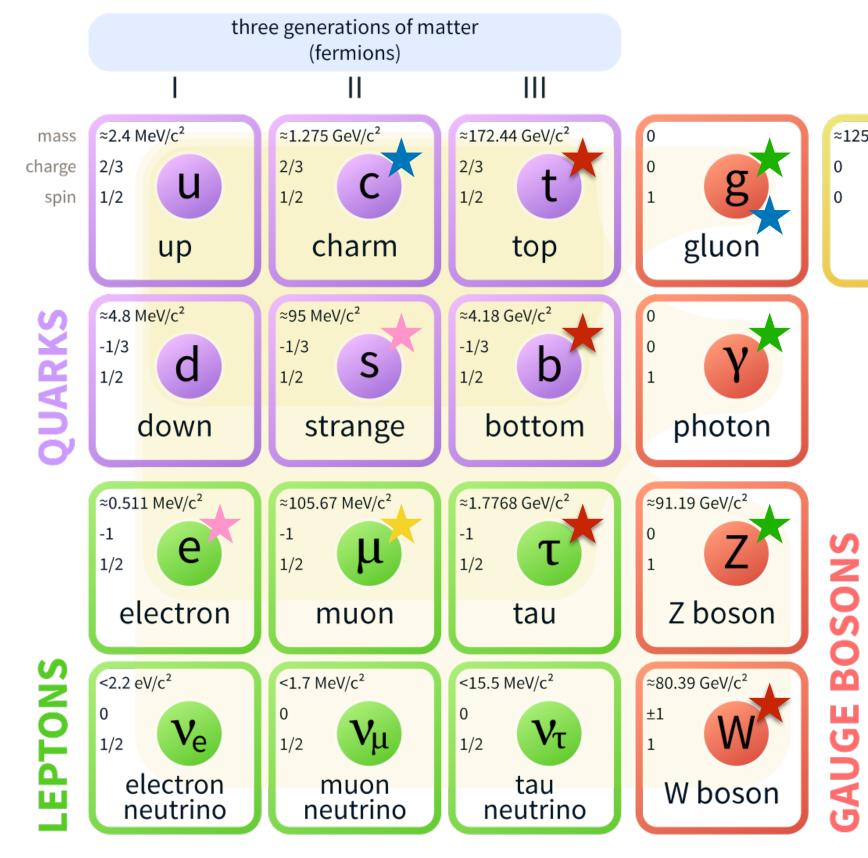




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# **Higgs Physics** ... Status of Higgs Coupling Measurements

### **Standard Model of Elementary Particles**





**Observed** in 2012

★ Observed

**±** Evidence today



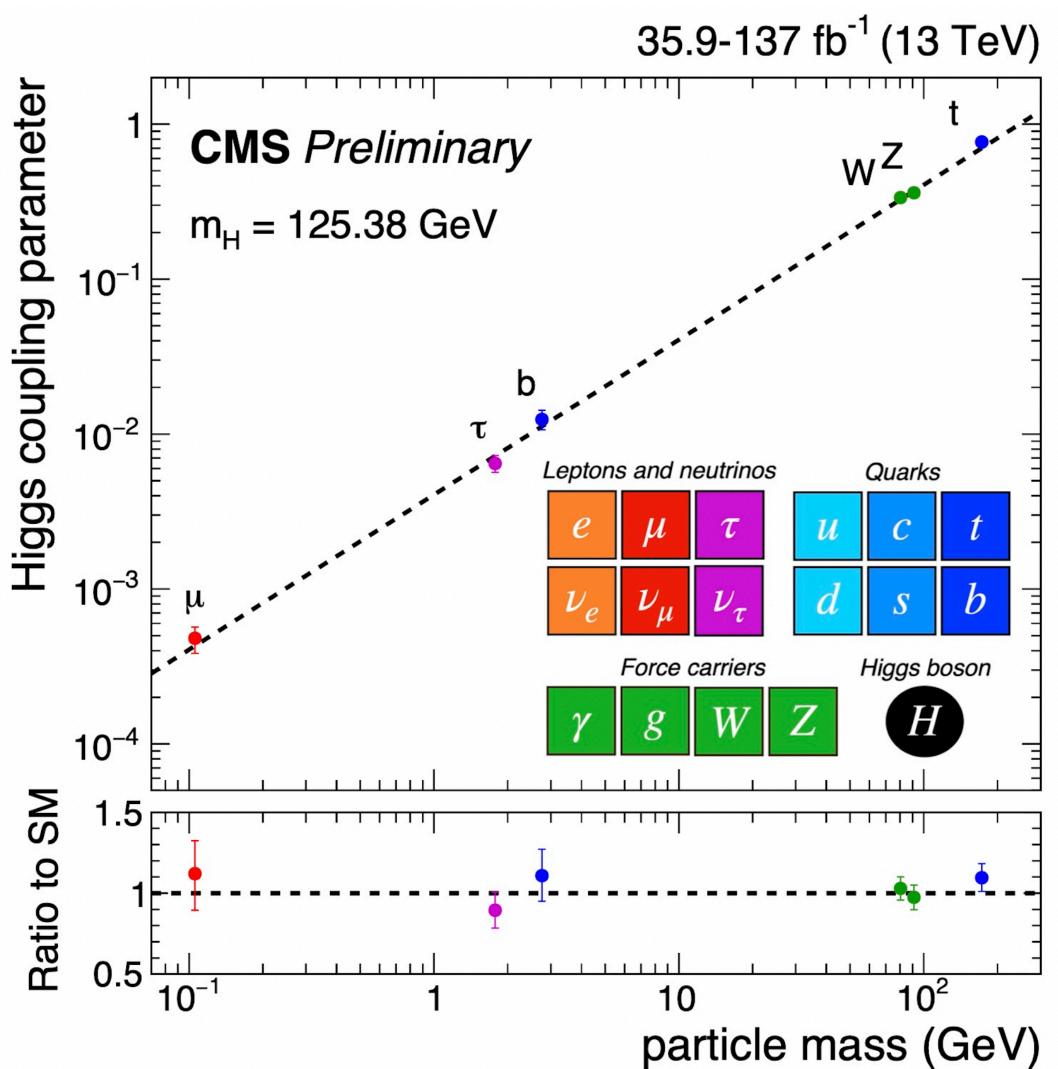
**Getting there with the LHC** 

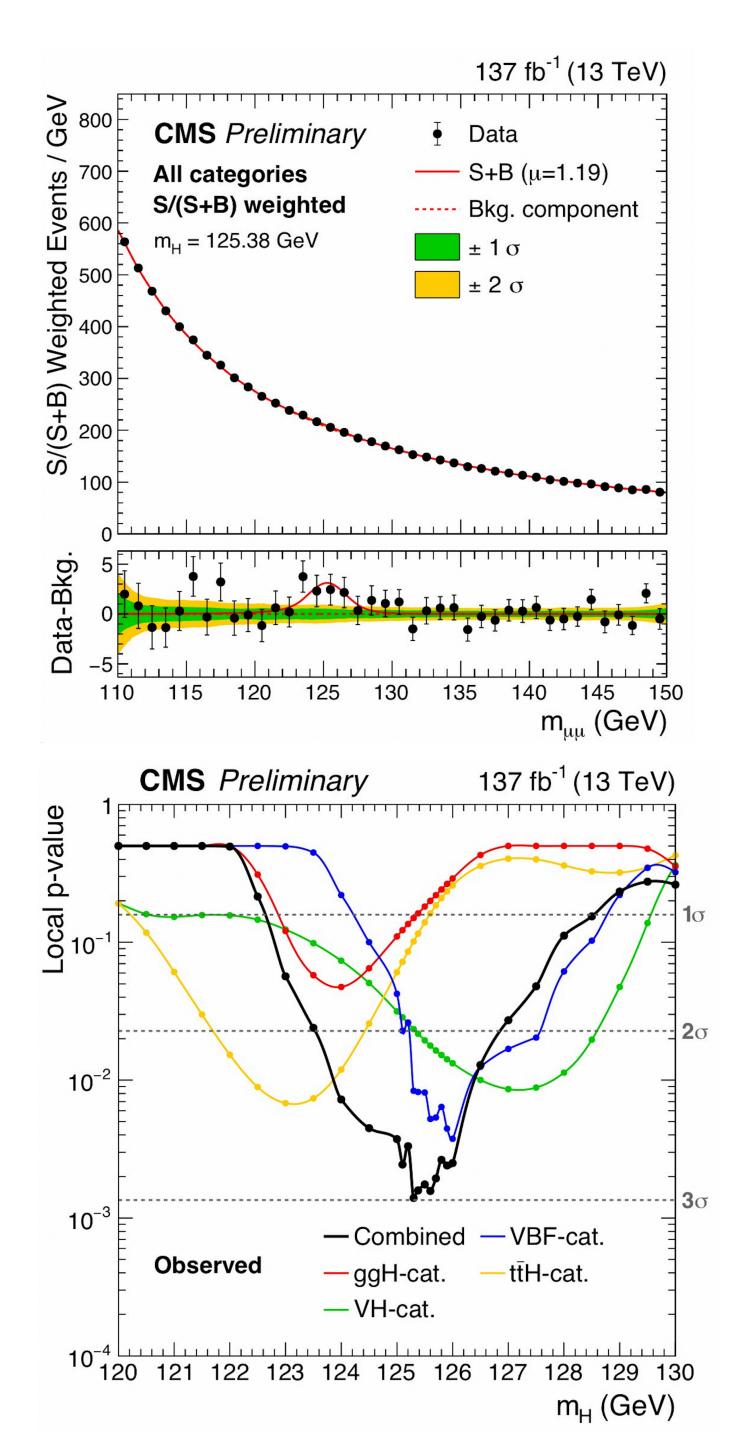
**Studies with e**+e- Higgs Factory





## **Higgs Physics** ... latest results





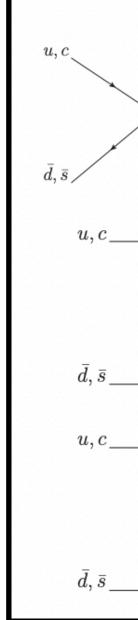


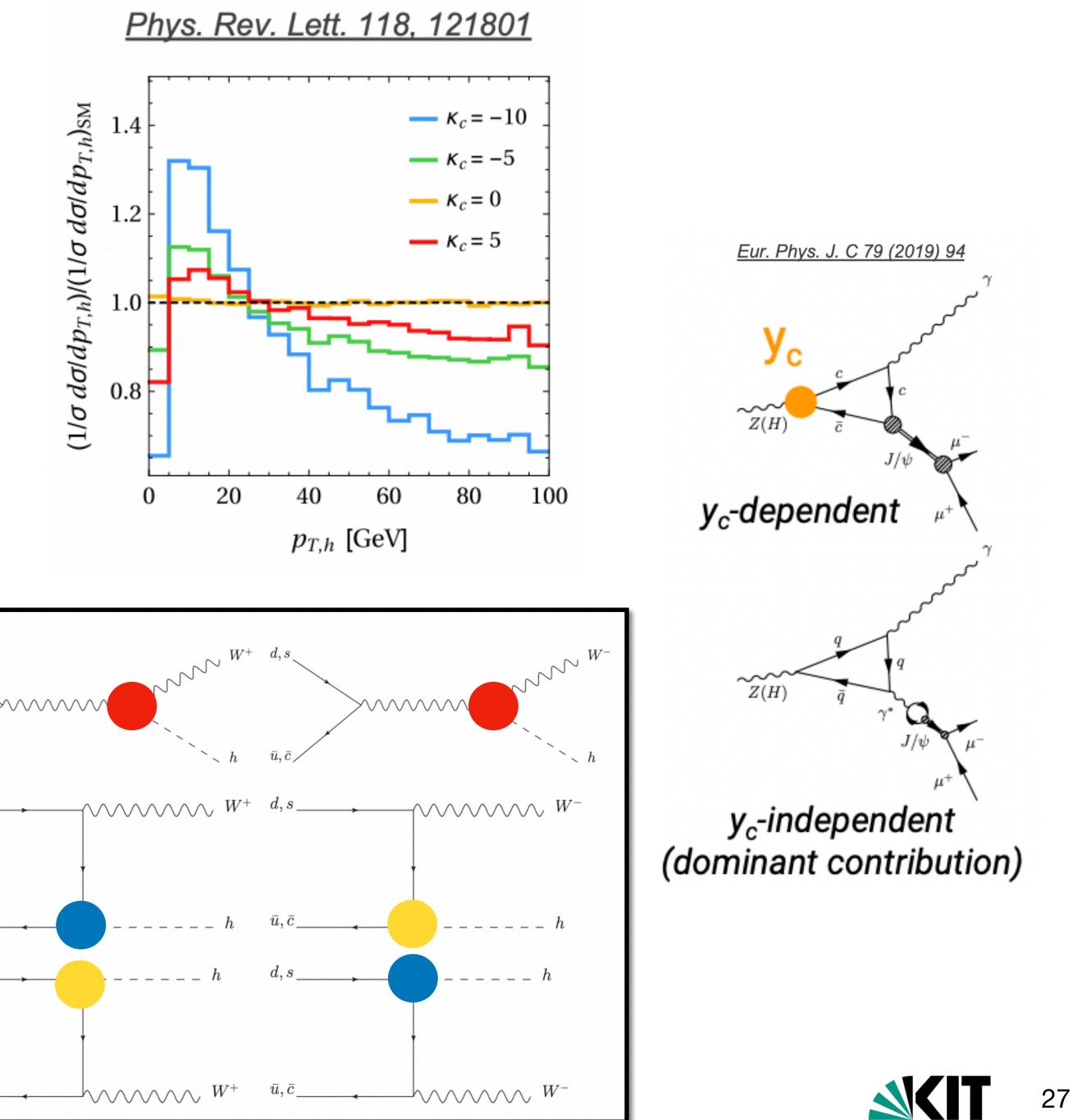




# **Higgs Physics** ... how charming is the Higgs Boson?

- Several methods to explore light quark (charm) Higgs Yukawa couplings
  - Indirect constraint from Higgs kinematics
  - Search for exclusive Higgs decays (H  $\rightarrow J/\psi \gamma$ )
  - Study of charge asymmetry in WH production
  - Direct search for Higgs decays

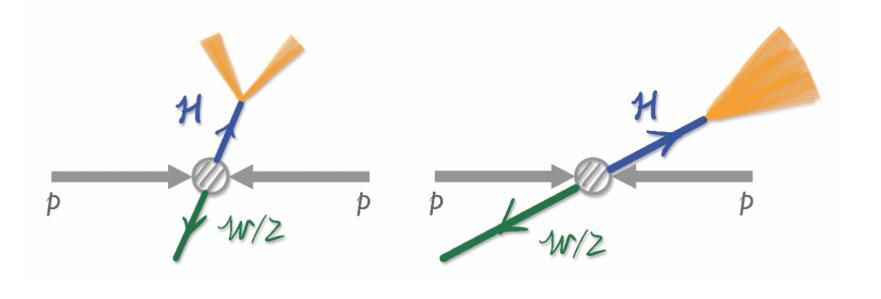


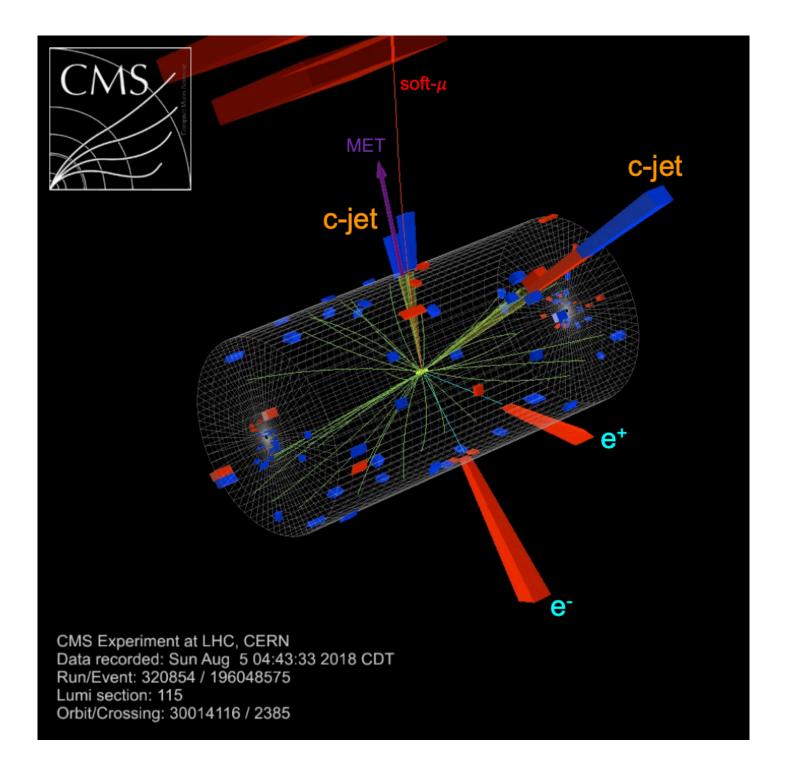


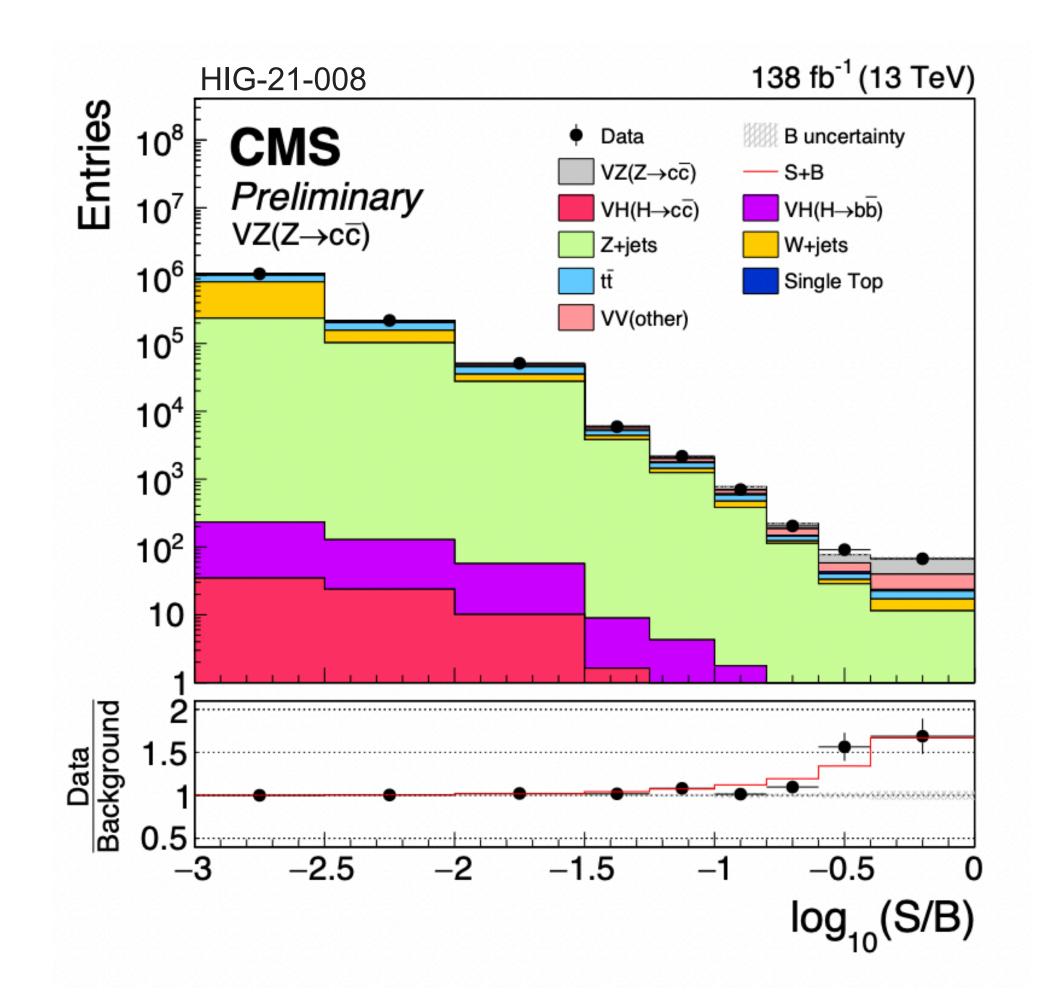
nology

# Higgs Physics

#### ... how charming is the Higgs Boson?







#### • Measured VZ ( $Z \rightarrow cc$ ) production

- Cross section consistent with SM expectation ~20% uncertainty
- First observation (5.7 $\sigma$ ) of Z  $\rightarrow$  cc at a hadrons collider

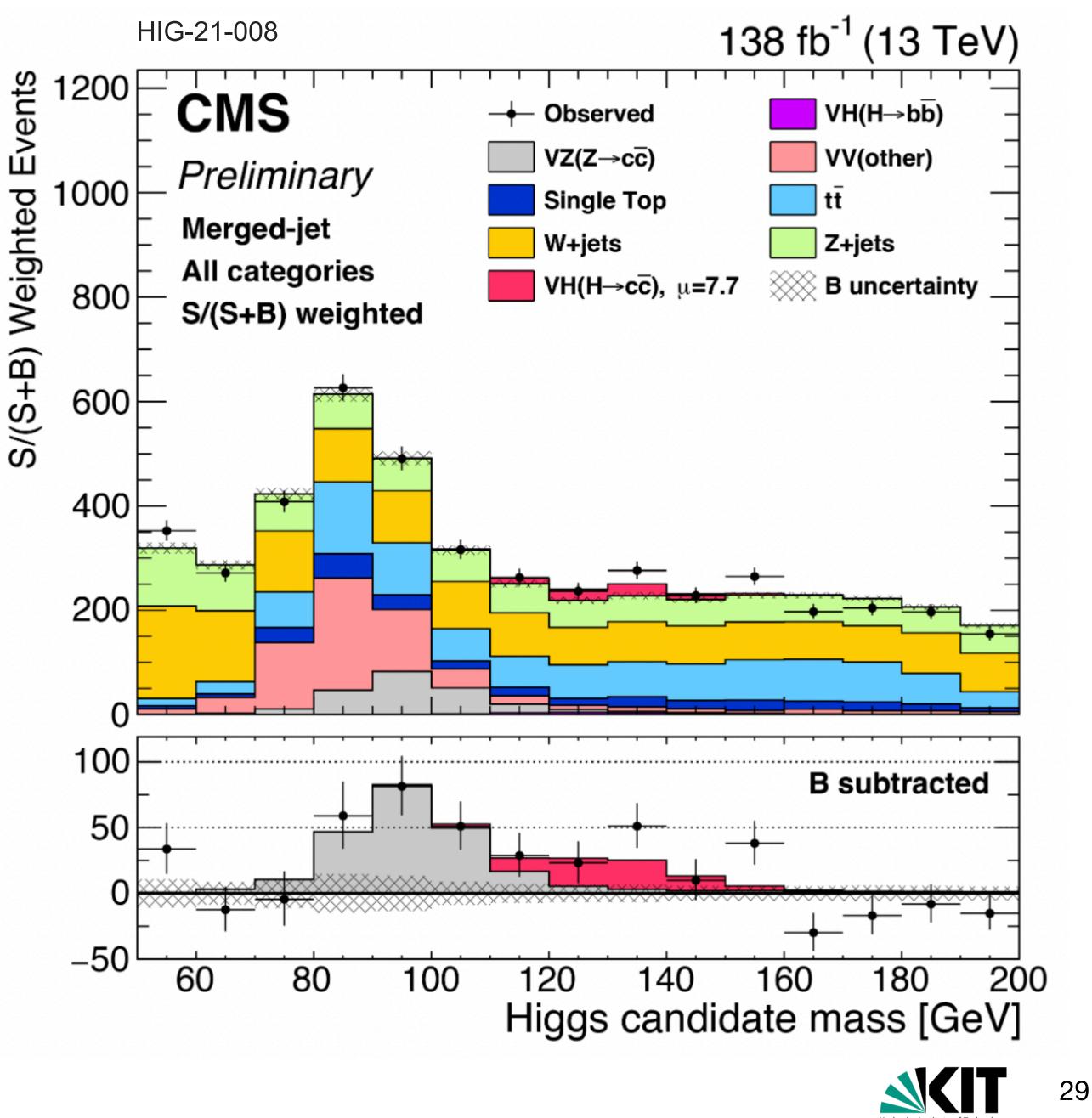


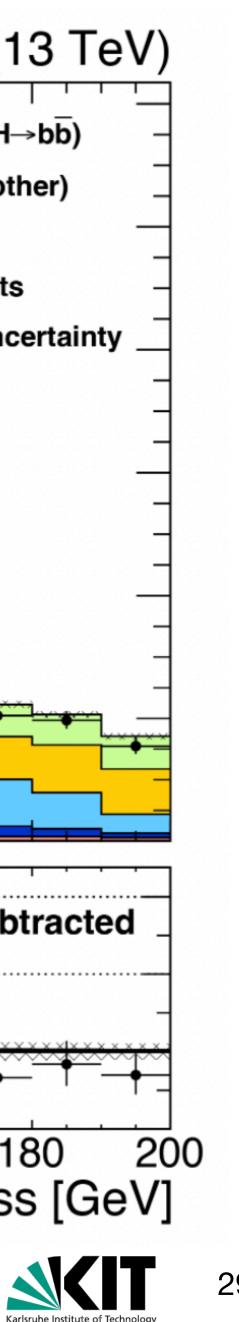


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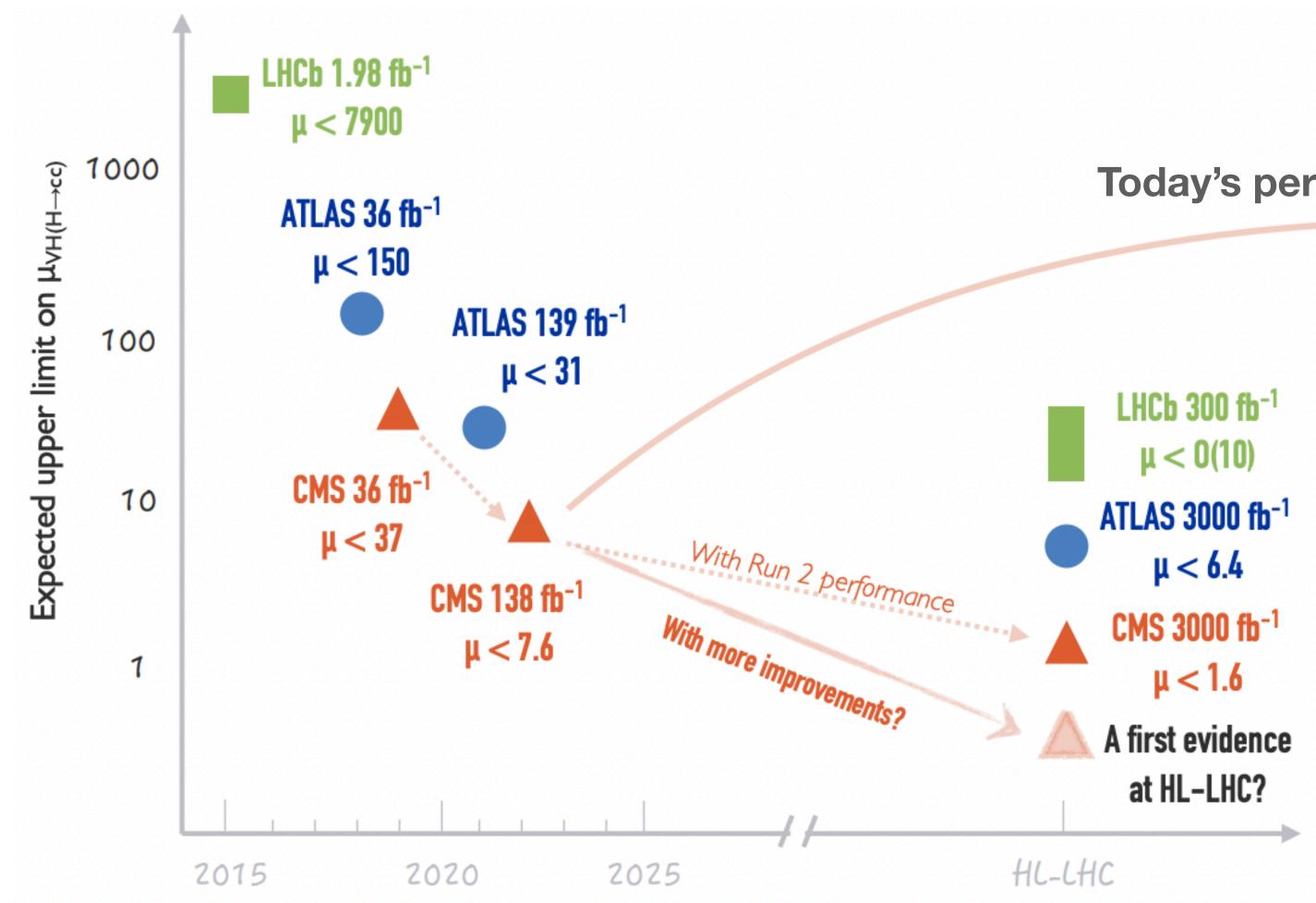
## **Higgs Physics** ... how charming is the Higgs Boson?

- Upper limits on VH (H  $\rightarrow$  cc) production
  - Excluding cross section 14 times SM expectation (7.6 exp. limit)
  - Constraints on Higgs-charm coupling 1.1< | Kc | < 5.5  $(|\mathbf{K}\mathbf{c}| < 3.4 \text{ exp. limit})$





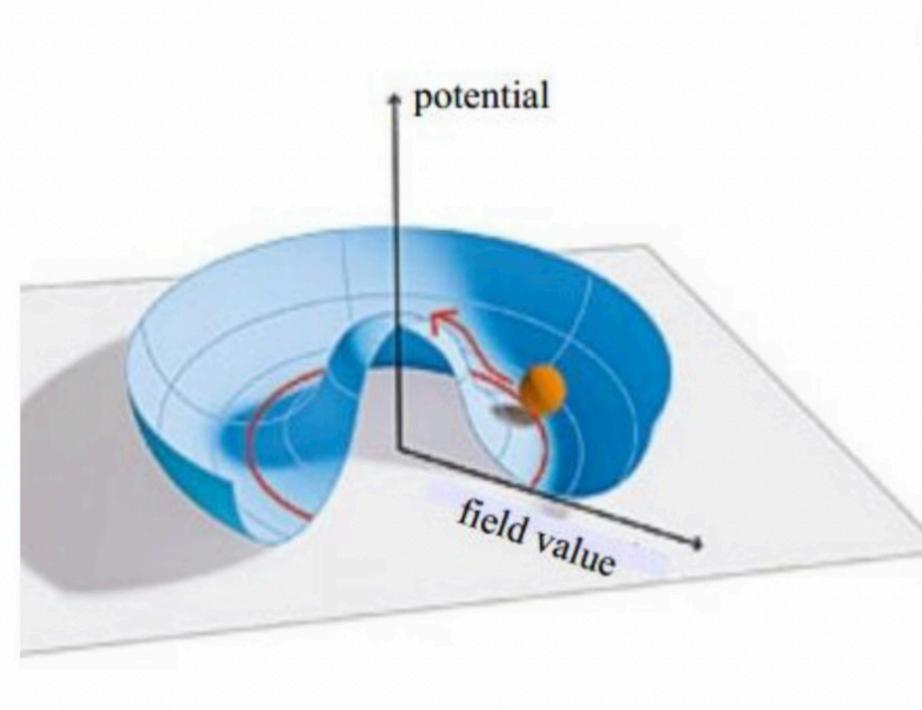
### **Higgs Physics** ... how charming is the Higgs Boson?



#### **Today's performance**







Higgs potential in the standard model:

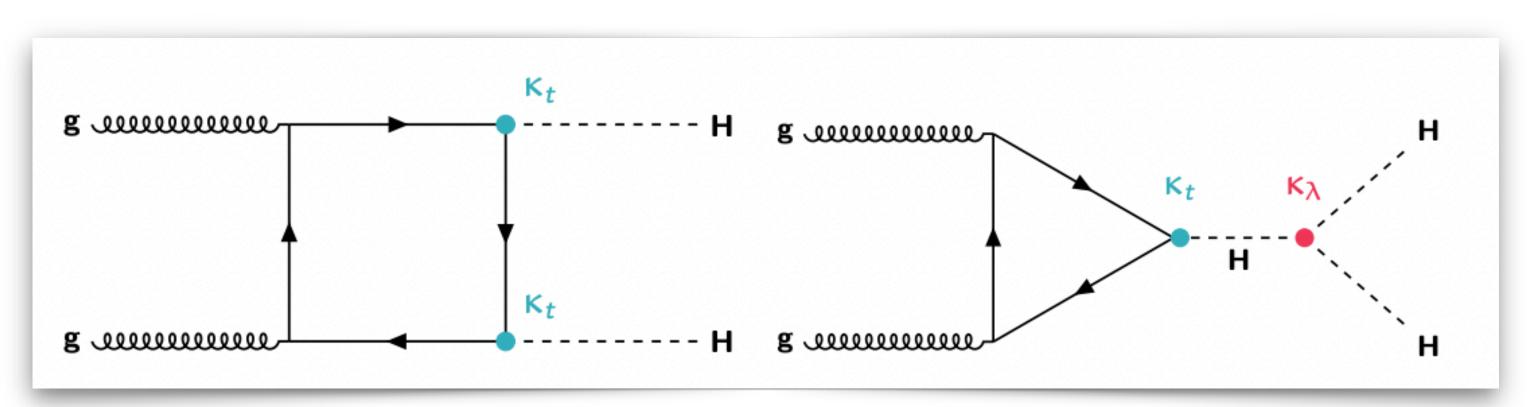
$$V(\Phi) = \mu^{2} \Phi^{+} \Phi + \eta (\Phi^{+} \Phi)^{2}$$
expansion around the minimum
$$\frac{1}{2} m_{H}^{2} h^{2} + \sqrt{\frac{\eta}{2}} m_{H} h^{3} + \frac{\eta}{4} h^{4}$$

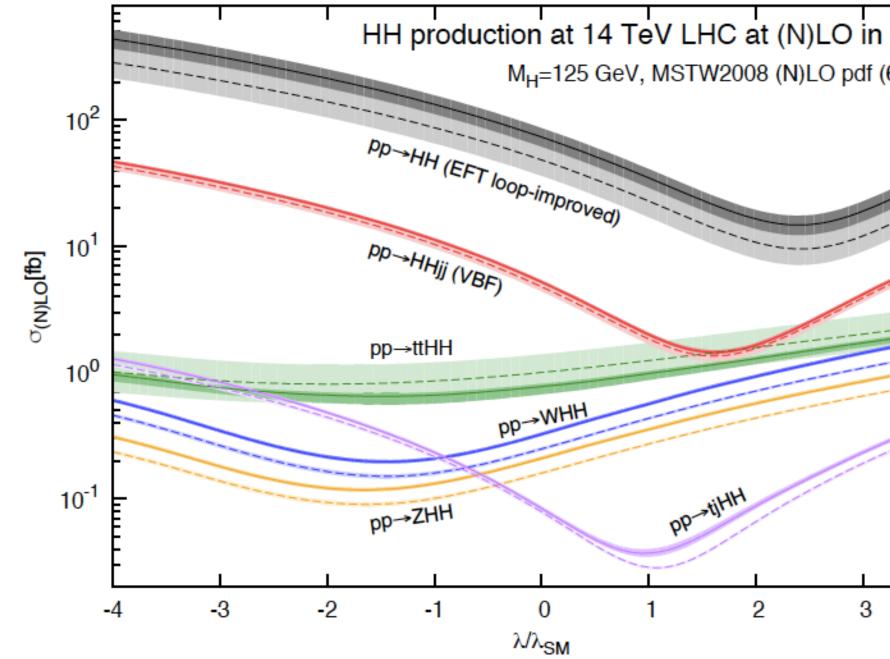
$$h = h$$

$$h = h$$









QCD (68%cl)	
	aMC@NLO
	MadGraph5_
	4

		bb	ww	тт	ZZ	
bł	)	34%				
W	N	25%	4.6%			
тт	-	7.3%	2.7%	0.39%		
ZZ	Z	3.1%	1.1%	0.33%	0.069%	
Y١	(	0.26%	0.10%	0.028%	0.012%	0.0

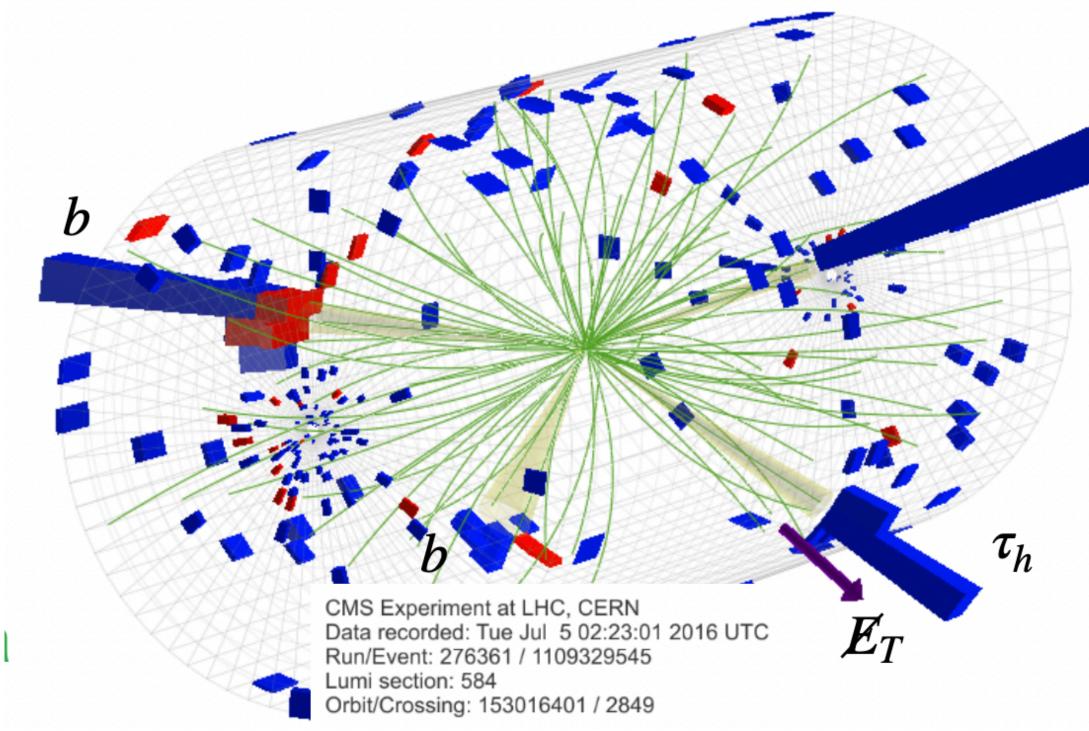


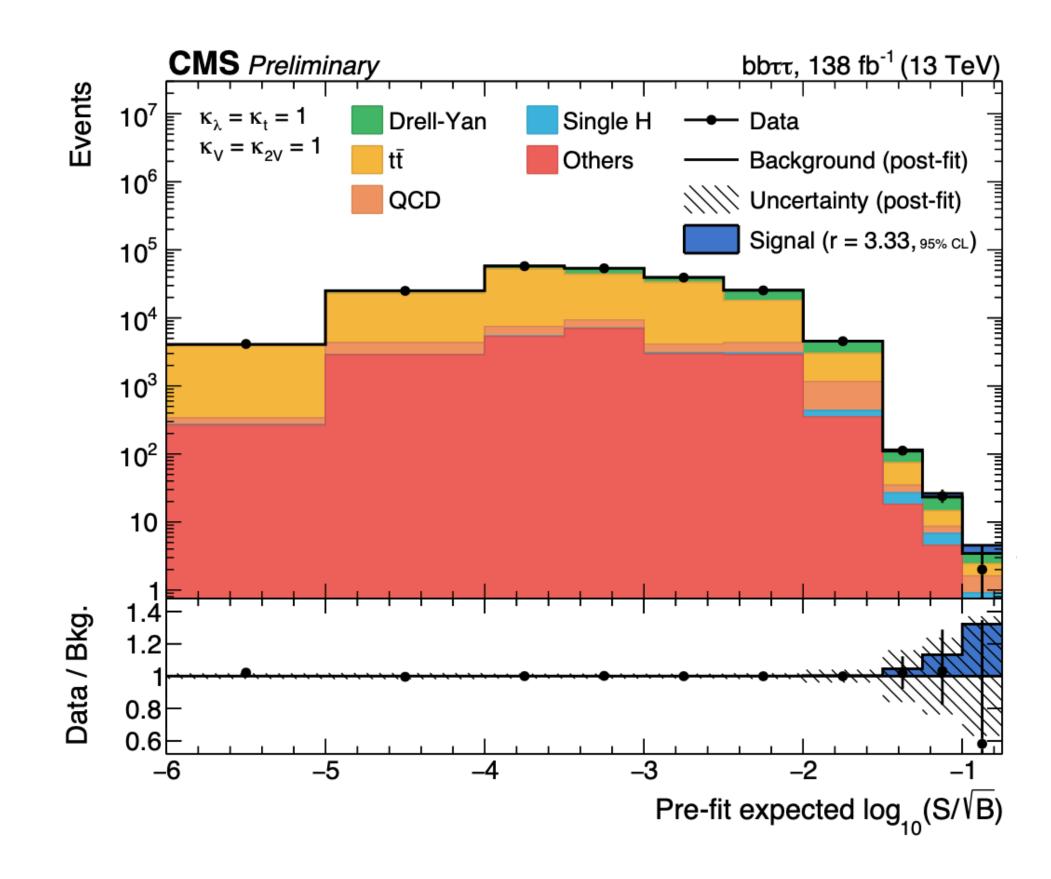






#### • HH $\rightarrow$ bb $\tau\tau$





CMS-HIG-20-010

 $au_h$ 

 $\sigma(pp \to HH) = 3.3(5.2) \times \sigma^{SM}_{ggF+VBF}$ 





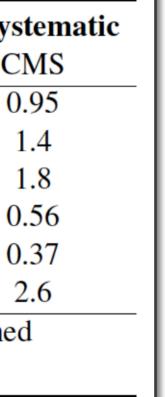


		$\sigma_{HH}/\sigma_{HH}^{SM}$ 95% CL			$\kappa_{\lambda}$ 9	$\kappa_{\lambda}$ 95% CL		
		Improvement						
		Obs.	Exp.	wrt. 36 fb $^{-1}$	Obs.	Exp.		
				tot. (w/o lumi)				
$HH  ightarrow bb \gamma \gamma$	ATLAS	4.1	5.5	×5.1 (2.5)	[-1.5, 6.7]	[-2.4, 7.7]		
$TTT \rightarrow DD'\gamma'\gamma$	CMS	7.7	5.2	×3.9 (2)	[-3.3, 8.5]	[-2.5, 8.2]		
HH  ightarrow bb  au  au	ATLAS	4.7	3.9	×3.8 (2)	[-2.4, 9.2]	[-2.0, 9.0]		
	CMS	3.3	5.2	—	_	—		
HH  ightarrow bbbb	ATLAS	_	—	—	_	_		
	CMS	3.9	7.8	×5.1 (2.6)	[-2.3, 9.4]	[-5.0, 12.0]		
$HH \rightarrow bbZZ$	ATLAS	—	—	—	_	_		
	CMS	30	37	—	[-9.0, 14.0]	[-10.5, 15.5]		
Multilepton	ATLAS	—	—	—	_	_		
wurnepton	CMS	21.8	19.6	—	[-7.0, 11.7]	[-7.0, 11.2]		
Combination	ATLAS	3.1	3.1	$\times 3.5 (1.8)^{a}$	[-1.0, 6.6]	[-1.2, 7.2]		
$(bb\gamma\gamma+bb au au)$	CMS	—	—	—	_	—		

#### $\sqrt{s}$ = 14 TeV, 3000 fb<sup>-1</sup> per experiment

	Statistic	al-only	Statistical +		
	ATLAS	CMS	ATLAS	C	
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	(	
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1		
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0		
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	(	
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	(	
combined	3.5	2.8	3.0		
	Comb	ined	Co	ombine	
	4.5	5		4.0	









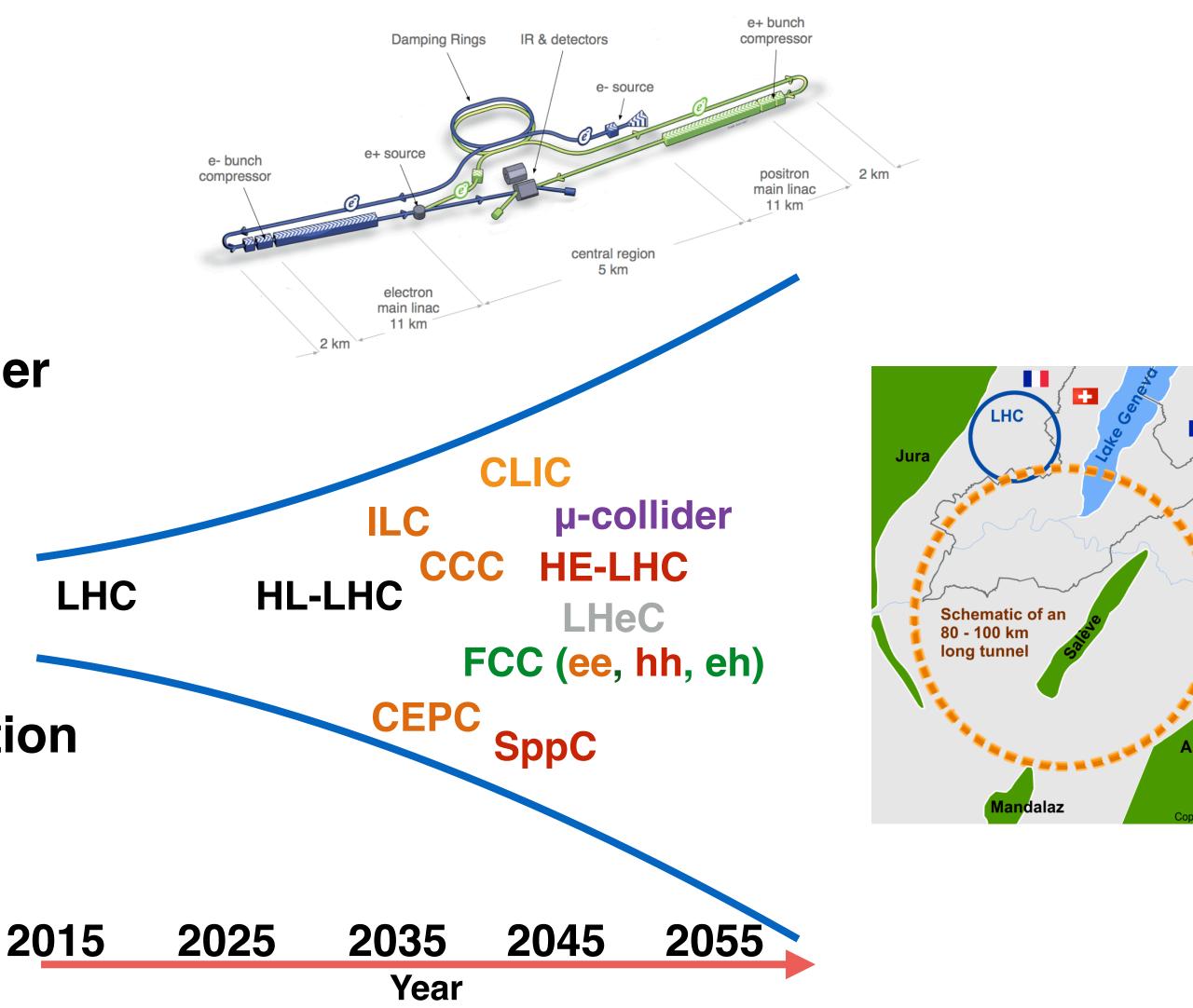
# **Higgs Physics** ... beyond the LHC

### LHC (and HL-LHC) is the energy frontier for foreseeable future

Fantastic opportunity for great physics

#### **Exploring / preparing the next generation** of machines

- Lepton collider for ultimate Higgs measurements and much more
- Future high energy hadron collider







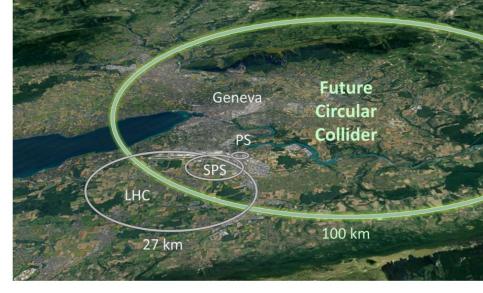




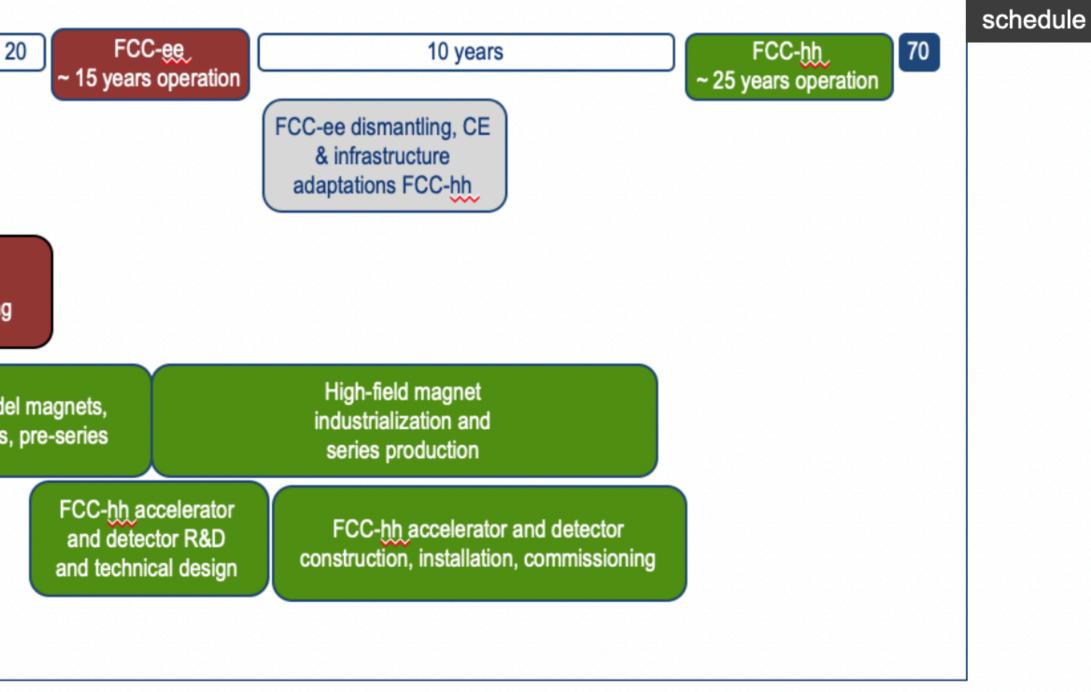
# **Future Circular Collider**

... a roadmap for particle physics at the energy frontier

1 2 3	4 5	6	7	8	9	10	11				19	2
Feasibilit	y Study Geological ir detailed desig	nvestig							, site and technic ucture constructi			
FCC-ee accelerator and detector R&D and technical FCC-ee accelerator and detector design FCC-ee accelerator and detector construction, installation, commissioning												
	Superconducting magnets R&D Long mode prototypes,											
	√s		L /IP	) (cm-2	s-1)	Int.	L /IP(	(ab <sup>-1</sup> )	Comments			
e⁺e⁻ FCC-ee	~90 GeV 160 240 ~365	Z WW H top	2 8.	0 x10 8 5 5	34	75 5 2. 0.	5		2-4 experim Total ~ 15 yea operation			
рр FCC-hh	100 TeV			x 10 <sup>3</sup> 0	4	2	20-30		2+2 experiments Total ~ 25 years of operation		-	
PbPb FCC-hh	√ <u>s<sub>NN</sub></u> = 39T	ēV	3 x	10 <sup>29</sup>		100 nb <sup>-1</sup> /run		/run	1 run = 1 mor operation	nth		
<mark>ep</mark> Fcc-eh	3.5 TeV		1.5	10 <sup>34</sup>		2 8	ab <sup>-1</sup>		60 GeV e- fro Concurrent of with pp for ~ 2	peratio	n	
e-Pb Fcc-eh	√s <sub>eN</sub> = 2.2	TeV	0.5	10 <sup>34</sup>		1 ft	0 <sup>-1</sup>		60 GeV e- fro Concurrent of with PbPb			



Technical



F. Gianotti

- □ Feasibility Study: 2021-2025
- □ If project approved before end of decade  $\rightarrow$  construction can start beginning 2030s
- □ FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++





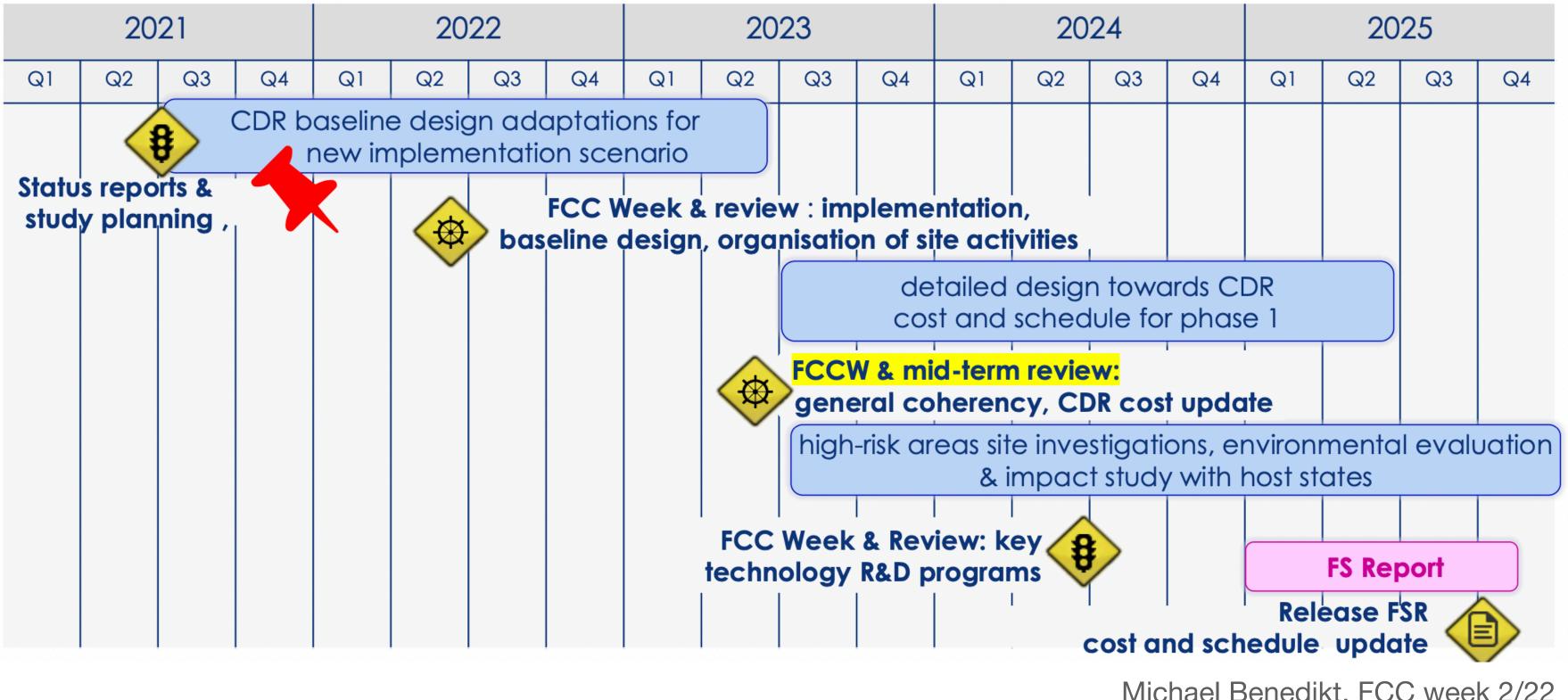




# **Future Circular Collider**

### ... a roadmap for particle physics at the energy frontier

- □ Feasibility Study: 2021-2025
- If project approved before end of decade  $\rightarrow$  construction can start beginning 2030s
- □ FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++



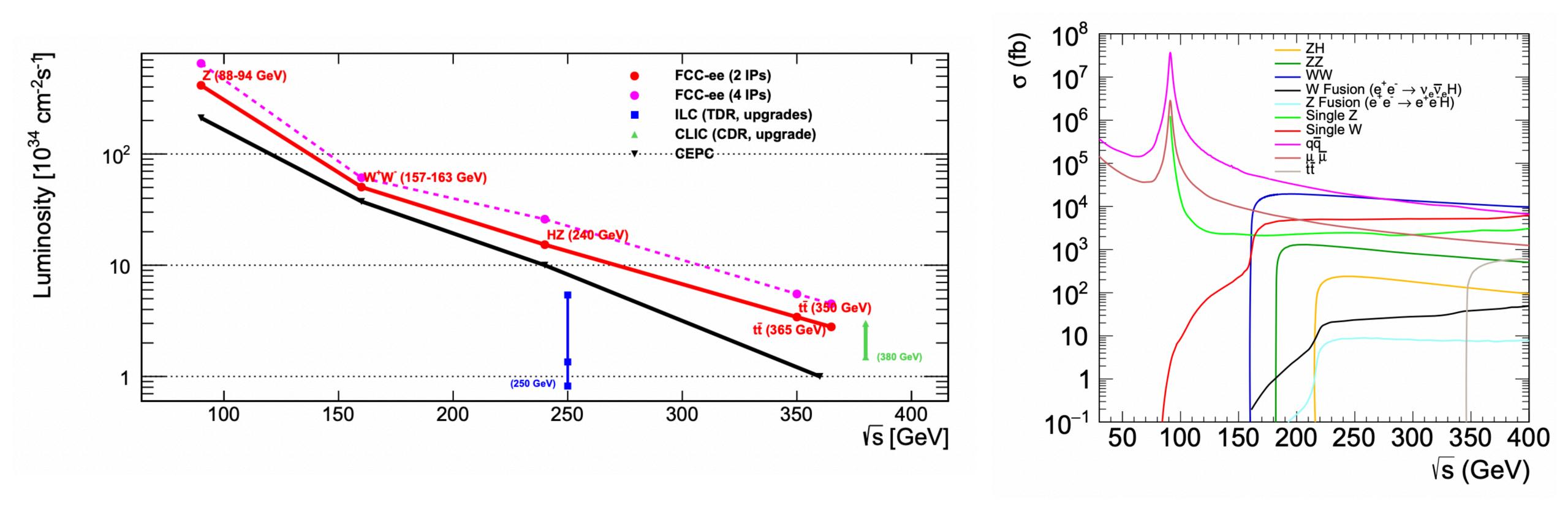
Michael Benedikt, FCC week 2/22





## Future Circular Collider ... a roadmap for particle physics at the energy frontier

arXiv:2203.06520

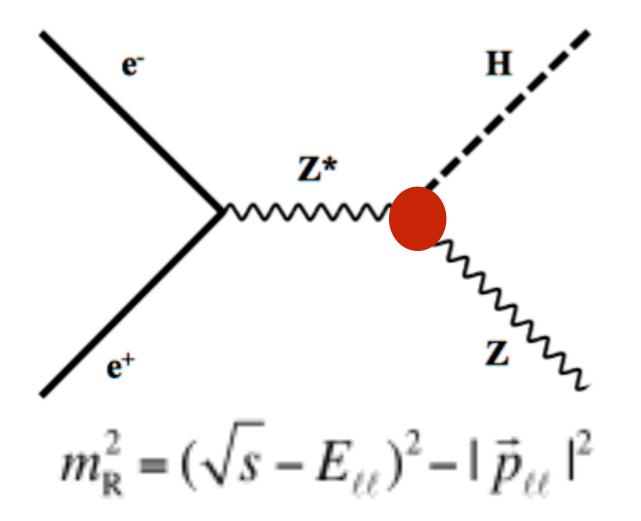


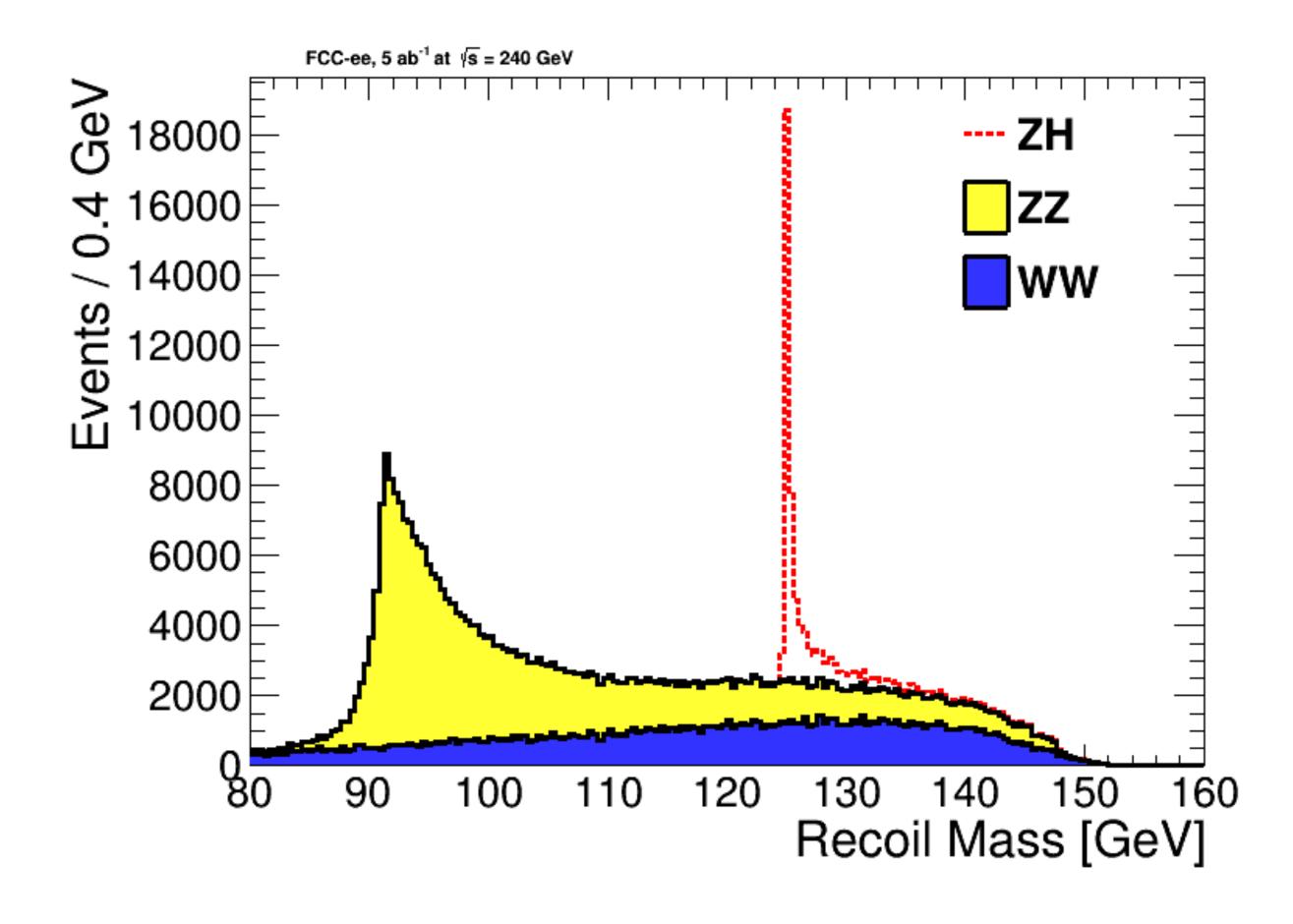




# Higgs Physics ... at Lepton Collider

- Recoil method provides unique opportunity for model independent measurement of HZ coupling
  - Higgs events are tagged Higgs decay mode independent
- Total width can be extracted from a combination of measurements







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# Higgs Physics ... with the HL-LHC and Beyond

Collider	HL-LHC	$FCC-ee_{240\rightarrow 365}$	FCC-ee	FCC-INT
			+ HL-LHC	
Int. Lumi $(ab^{-1})$	3	5 + 0.2 + 1.5	_	30
Years	10	3 + 1 + 4	_	25
$g_{\mathrm{HZZ}}$ (%)	1.5	0.18	0.17	0.17
$g_{\rm HWW}$ (%)	1.7	0.44	0.41	0.20
$g_{ m Hbb}~(\%)$	5.1	0.69	0.64	0.48
$g_{ m Hcc}~(\%)$	SM	1.3	1.3	0.96
$g_{ m Hgg}~(\%)$	2.5	1.0	0.89	0.52
$g_{\mathrm{H} au au}$ (%)	1.9	0.74	0.66	0.49
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9	3.9	0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9	1.3	0.32
$g_{\mathrm{HZ}\gamma}$ (%)	11.	_	10.	0.71
$g_{ m Htt}$ (%)	3.4	_	3.1	1.0
$g_{ m HHH}$ (%)	50.	44.	33.	3–4
$\Gamma_{ m H}~(\%)$	SM	1.1	1.1	0.91

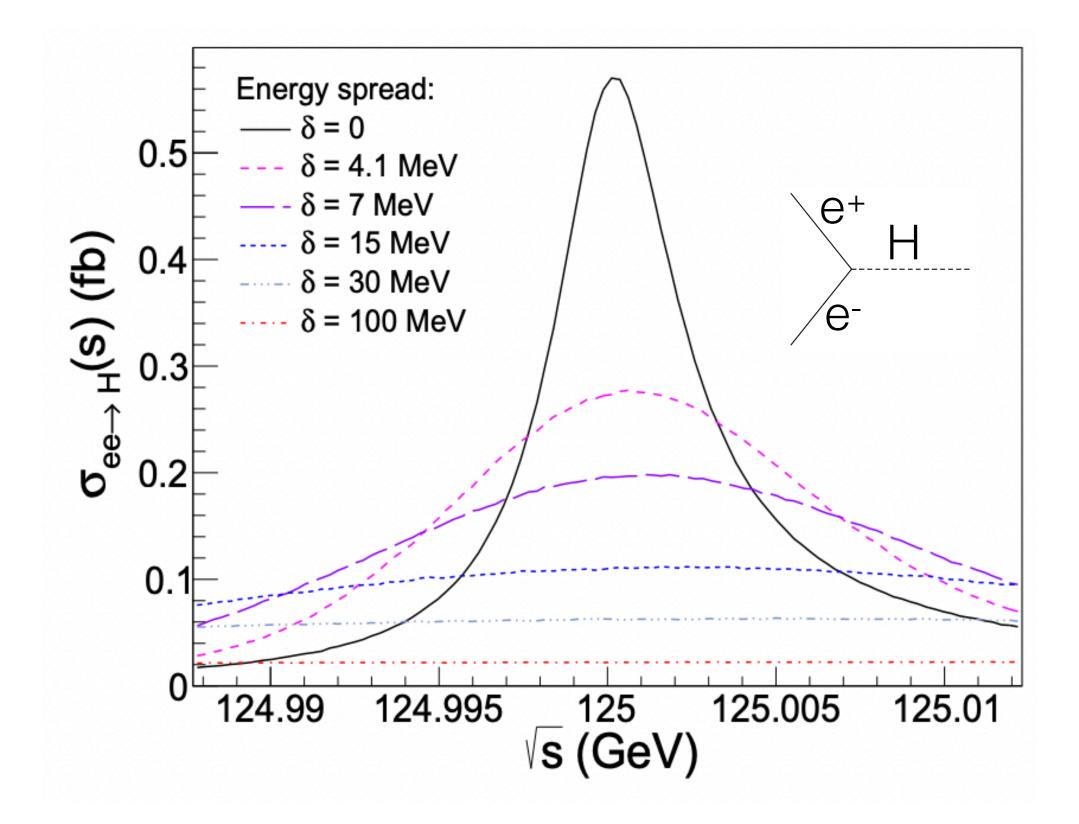




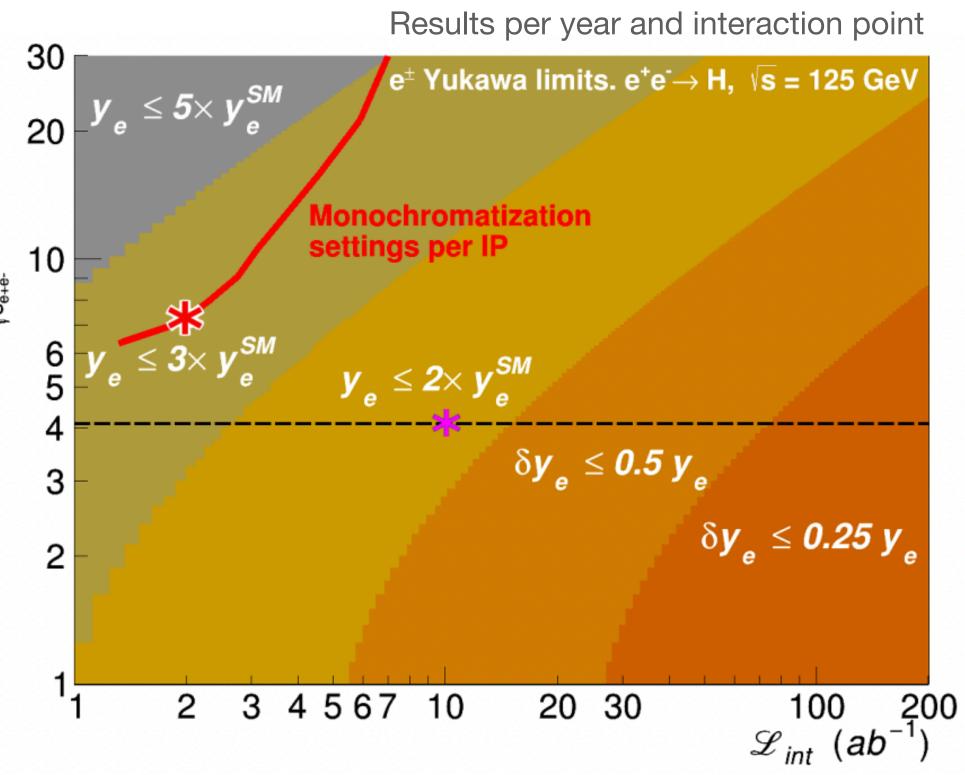
# **Higgs Physics** ... with the HL-LHC and Beyond

### First generation Higgs couplings

is an interesting add-on



#### • Not part of baseline run plan but a few years at $\sqrt{s}$ = mH with high luminosity and monochromatization







# **Higgs Factories** ... with rich physics program beyond the Higgs boson

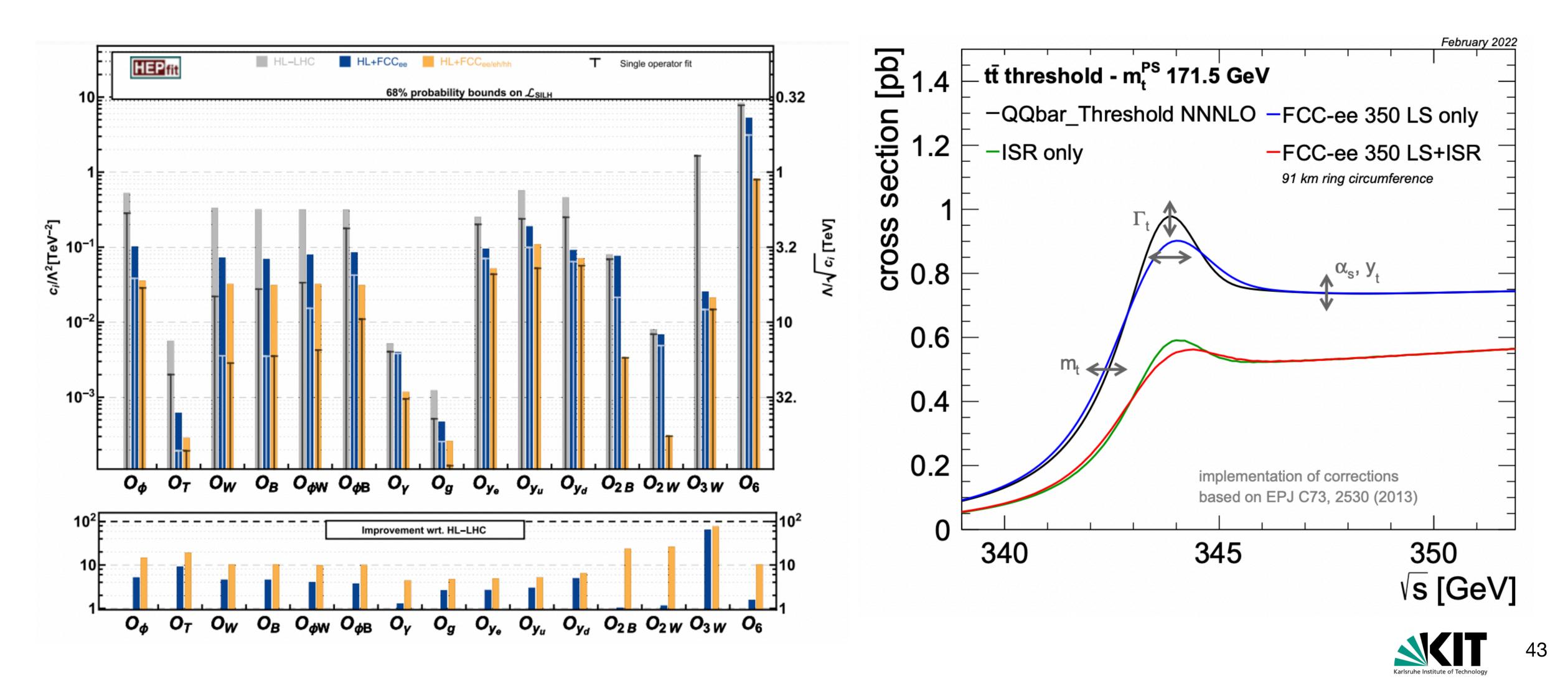
Observable	Present	FCC-ee	FCC-e
	value $\pm \text{ error}$	Stat.	Syst.
$m_{\rm Z}~({ m keV})$	$91,186,700\pm 2200$	4	100
$\Gamma_{\rm Z}~({ m keV})$	$2,495,200 \pm 2300$	4	25
$R^{ m Z}_\ell~( imes 10^3)$	$20,767\pm25$	0.06	0.2 - 1
$lpha_S(m_{ m Z}^2)~( imes 10^4)$	$1,196\pm30$	0.1	0.4 - 1
$R_b ~( imes 10^6)$	$216,290\pm 660$	0.3	< 60
$\sigma_{\rm had}^0~( imes 10^3)~({\rm nb})$	$41,541\pm37$	0.1	4
$N_{\nu}$ (×10 <sup>3</sup> )	$2,996\pm7$	0.005	1
$\sin^2  heta_{ m W}^{ m eff} ( imes 10^6)$	$231,480\pm160$	1.4	1.4
$1/lpha_{ m QED}(m_{ m Z}^2)~( imes 10^3)$	$128,952\pm14$	3.8	1.2
$A_{ m FB}^{b,0}~( imes 10^4)$	$992\pm16$	0.02	1.3
$A_{e} \; ( imes 10^{4})$	$1,498\pm49$	0.07	0.2
$m_{ m W}~({ m MeV})$	$80,350\pm15$	0.25	0.3
$\Gamma_{\rm W}~({\rm MeV})$	$2,085\pm42$	1.2	0.3
$N_{\nu}$ (×10 <sup>3</sup> )	$2,920\pm50$	0.8	$\operatorname{Small}$
$lpha_S(m_{ m W}^2)~( imes 10^4)$	$1,170\pm420$	3	$\operatorname{Small}$

Comment and dominant exp. error ee From Z lineshape scan; beam energy calibration From Z lineshape scan; beam energy calibration Ratio of hadrons to leptons; acceptance for leptons 1.0 From  $R_{\ell}^{\rm Z}$  above 1.6Ratio of bb to hadrons; stat. extrapol. from SLD Peak hadronic cross section; luminosity measurement Z peak cross sections; luminosity measurement From  $A_{\rm FB}^{\mu\mu}$  at Z peak; beam energy calibration From  $A_{\rm FB}^{\mu\mu}$  off peak *b*-quark asymmetry at Z pole; from jet charge from  $A_{\rm FB}^{\rm pol,\tau}$ ; systematics from non- $\tau$  backgrounds From WW threshold scan; beam energy calibration From WW threshold scan; beam energy calibration Ratio of invis. to leptonic in radiative Z returns From  $R^W_{\ell}$ 





## **Higgs Factories** ... with rich physics program beyond the Higgs boson



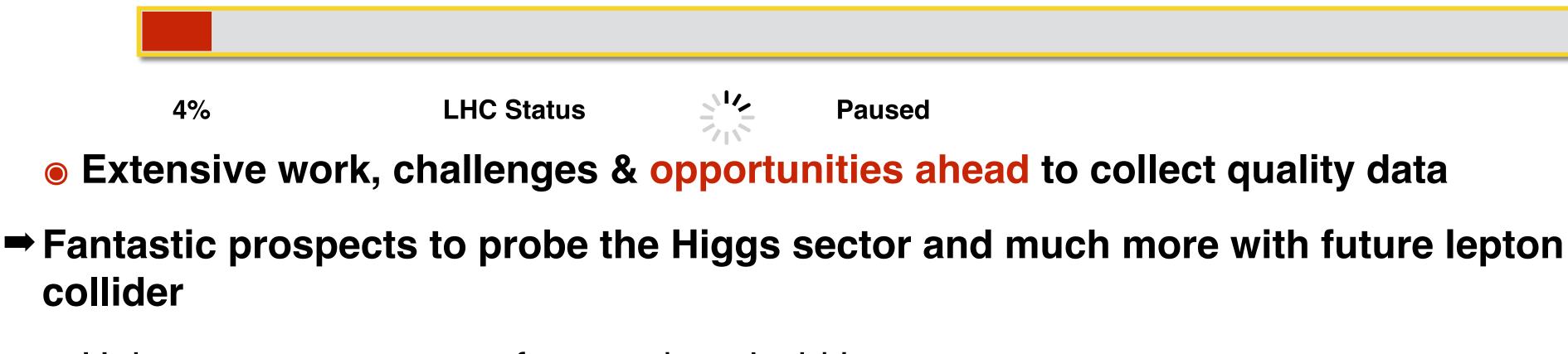
## Summary and Outlook ... only discussed the tip of the iceberg

#### The Higgs Boson is cornerstone of the LHC physics program

Precision measurement probing SM - no significant deviation so far

• 2nd generation and Higgs self coupling are work in progress

(HL-) LHC datasets will start growing again this summer



 $\bullet$  Unique measurements of  $g_{HZ}$  and total width

Precision measurements of the Higgs boson and more



