Istanbul, Iran-Turkey Conference
on LHC and related topics
June 10-15th, 2019

The long way from the discovery of W and Z to the Brout-Englert-Higgs boson….. and what next?

D. Denegri,
CEN Saclay/IRFU/SPP and CERN/Ph

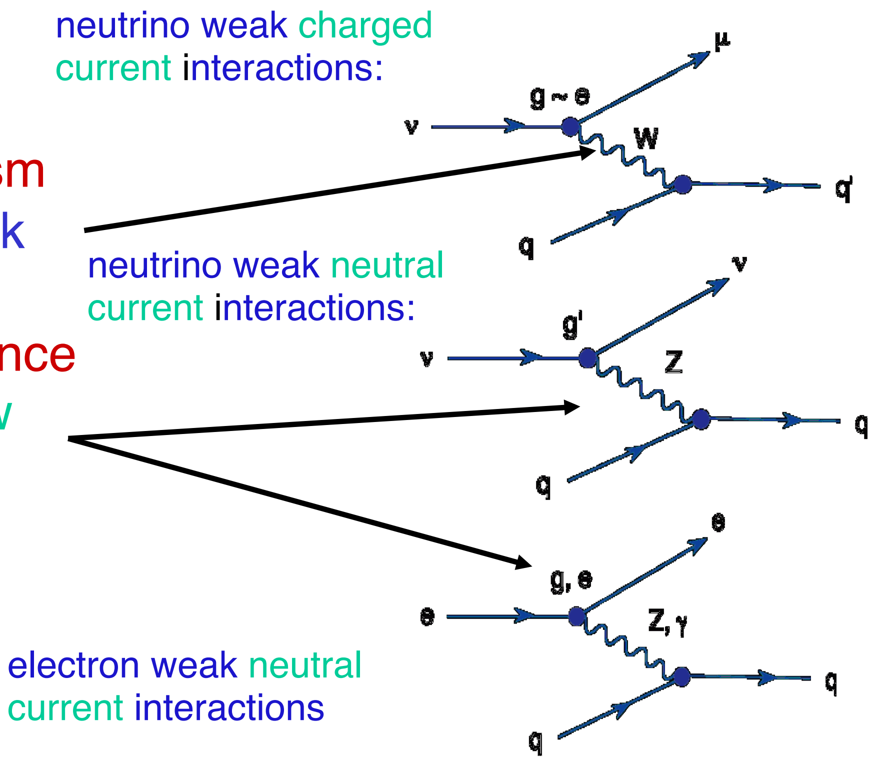
key steps in establishing the Standard Model
from W, Z discovery
and the beginnings of the LHC and CMS
to the discovery of the Brout-Englert-Higgs boson
what next?

Towards electroweak unification (~1964 - 1967)

In 1965/67 S. Weinberg, A. Salam, J. Ward, S.L. Glashow… proposed a theory providing a unified description of electromagnetic and weak interactions in terms of a spontaneously broken local gauge symmetry SU(2) x U(1) - i.e. with a Brout-Englert-Higgs mechanism (proposed in 1964) to give mass to the weak field quanta;
the short range of weak interactions (< 10^{-15}cm) implied large masses for the W^+ and W^- force carriers (intermediate vector bosons) as $R_{\text{force}} \sim 1/M_{\text{field quantum}}$

- This unified scheme however implied the existence of four field quanta:
  γ - which remains massless – for electromagnetism
  W^+ and W^- - for charged weak interactions ("weak charged currents"),
  Z^0 - a sort of "heavy photon" - implying the existence of "neutral current" weak interactions i.e. of a new type of weak interactions, unknown at that time!

- The theory had a single parameter, the weak mixing angle θ_ω, the W,Z and their masses and couplings to fermions depending on this angle


neutrino weak charged current interactions:

neutrino weak neutral current interactions:

electron weak neutral current interactions

Towards the Standard Model (period ~1970 - 1979)

- In 1971 G.'t Hooft, M. Veltman, B. Lee and J. Zinn-Justin show that electroweak theory is renormalizable

→ at this point this theory began to be taken seriously by theorists!

- In 1973 discovery of neutral-current neutrino interactions at CERN (Gargamelle):
  first experimental evidence in favour of the unified electro-weak theory!

- In 1970 the GIM mechanism was invented, the charm quark proposed and found in 1974 as J/ψ - the most "tangible" evidence for existence of quarks, then in 1977 - the Υ system with b-quarks, a still more spectacular quark-antiquark system;

- In 1973 QCD was introduced with SU(3) as the gauge symmetry - for the three colors of quarks (Nobels of 2004, Gross, Wilczek, Politzer), with " confinement" and its prediction of "asymptotic freedom" - our present day SM was falling in place!

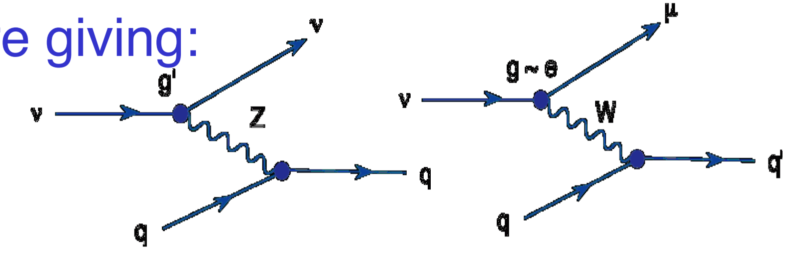
- parity violation in electron-nucleon scattering as expected from electro-weak theory was found at SLAC in 1978 and angular asymmetry in e^+e^- to $\mu^+\mu^-$ as expected at DESY in 1979

- in 1979 Weinberg, Salam and Glashow got the Nobel Prize for the electro-weak unification and the prediction of the existence of the Z

→ ……things were getting serious!

W, Z, H how it all really started….I

- First measurements (in 70's) of charged and neutral current neutrino interactions interpreted in this unified electroweak scheme were giving:



$\sin^2\theta_w \sim 0.3 - 0.5$

with:

$m_W = [\pi\alpha_{em}/(\sqrt{2}G_F)]^{1/2}/\sin\theta_w = 37.4\ \mathrm{GeV}/\sin\theta_w$ $m_Z = m_W/\cos\theta_w$

implying that: $m_{W,Z} \sim 50 - 100\ \mathrm{GeV}$

but existing machines, for ex. ISR or the CERN SPS in a fixed target mode, could not give more than $\sqrt{s} \sim 30 - 40$ GeV !! …….and the LEP was still far in the future, at least ten years away…….(ISABELLE….)

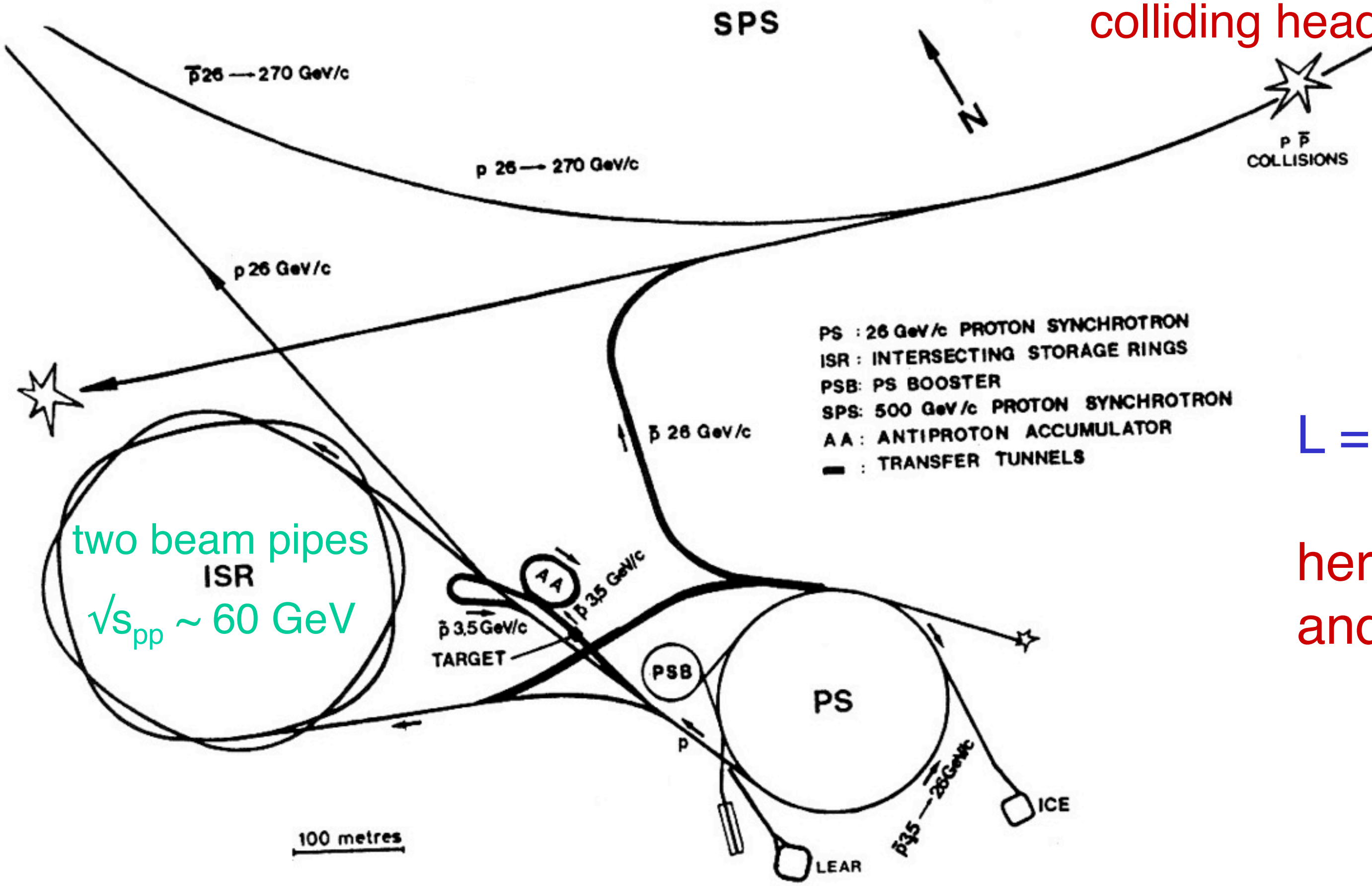
here came the suggestion of Cline, McIntyre, Rubbia to convert an existing proton -synchrotron into an antiproton-proton collider!

Event rate = L σ [s^{-1}] (L ≡ luminosity)

requiring ~1 (W, Z leptonic) event / day L » 2.5 x 10^{29} cm^2 s^{-1} was needed!

The CERN antiproton-proton collider complex (1980-90)

protons and antiprotons counter-rotating in same beam pipe - as in an e+e- machine! colliding head-on at $\sqrt{s} \sim 500 - 600$ GeV



two beam pipes

$\sqrt{s_{pp}} \sim 60$ GeV

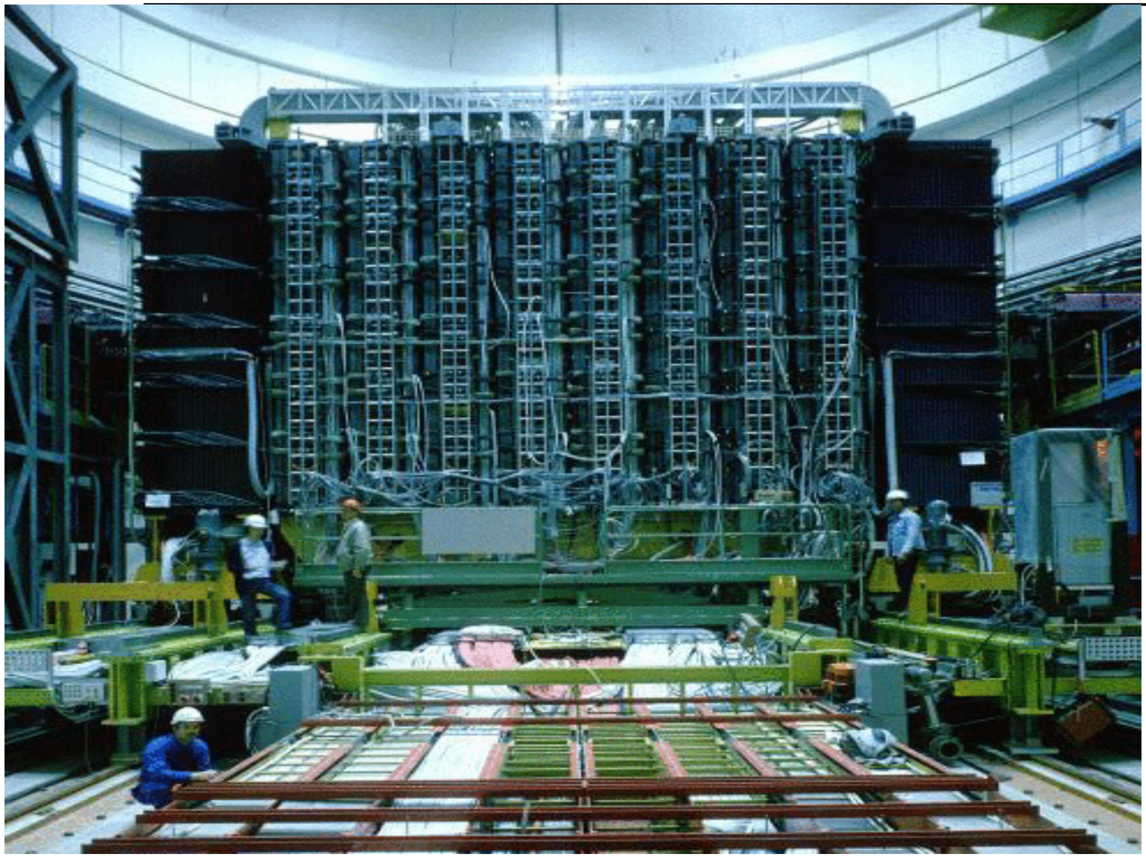
Luminosity:

$L = n(p)n(\text{anti-}p)f/(4\pi\rho^2)$

here comes S. Van der Meer and stochastic cooling….

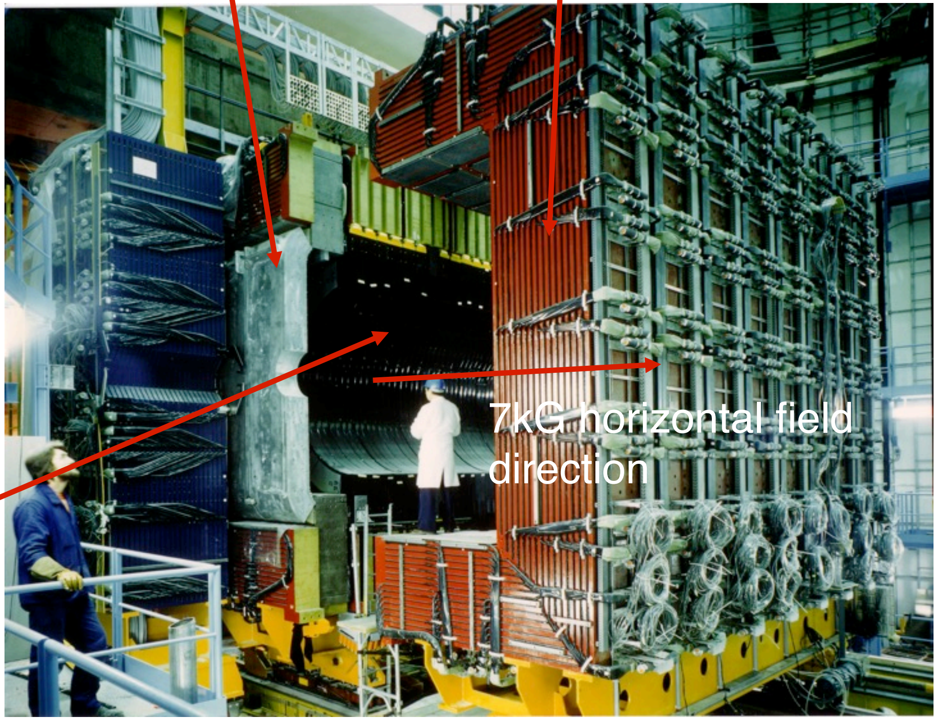
The transformation of the SPS into a collider at C. Rubbia's initiative was accomplished by the summer of 1981 - in ~ < 3 years!

UA1 detector under construction (1979/81!!!)



UA1 detector: ~10 x 6 x 6 m^3,
~ 2000 tons ~130 physicists
calorimetric coverage $|\eta| < 5.0$
tracker coverage $|\eta| < 3.0$
muon system coverage $|\eta| < 2.3$

UA1 designed and built in < 3 years!!



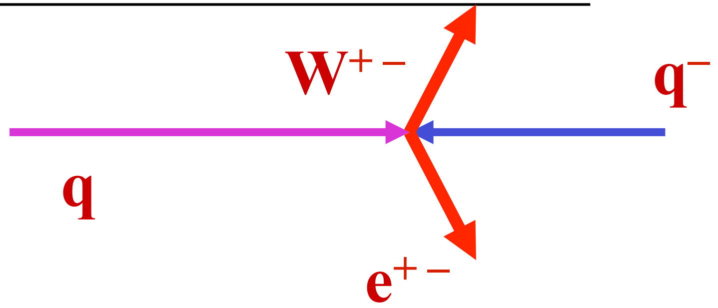
warm Al coil,
7kG horizontal field,

HCAL
5cm iron/1cmScint.
3.5 λ_{int} deep

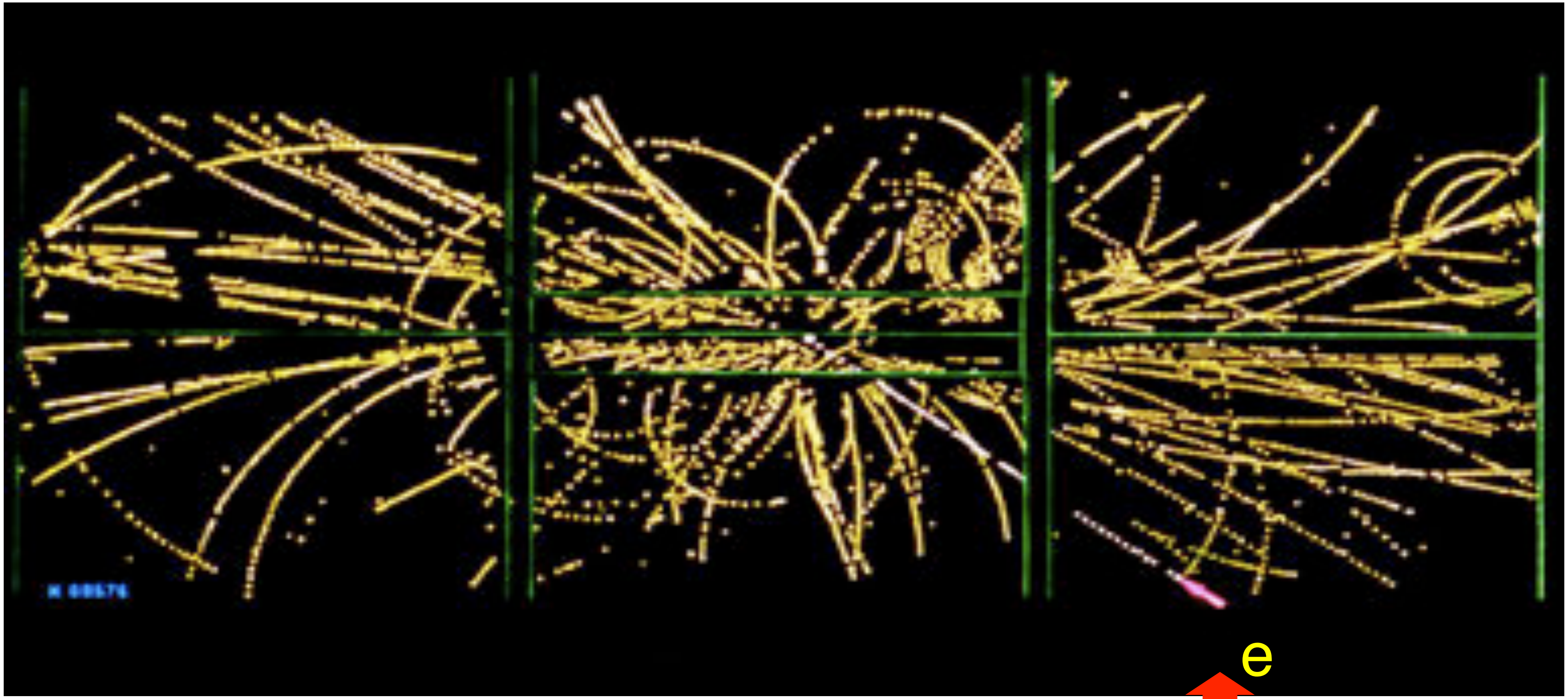
ECAL Scint.-Pb sandwich

W → eν candidate in UA1 tracker

An “electronic bubble chamber”!
6176 proportional sense wires……

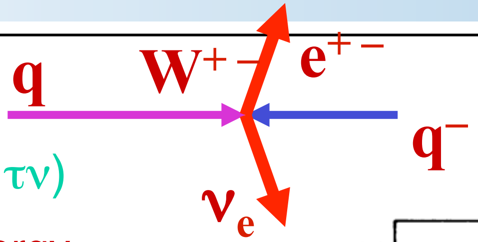


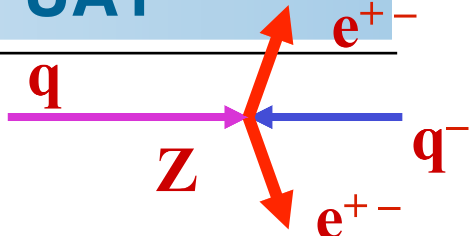
No visible jet on the away side!



Run of winter 1982, W discovery, followed by run of spring 1983 and Z discovery in UA1

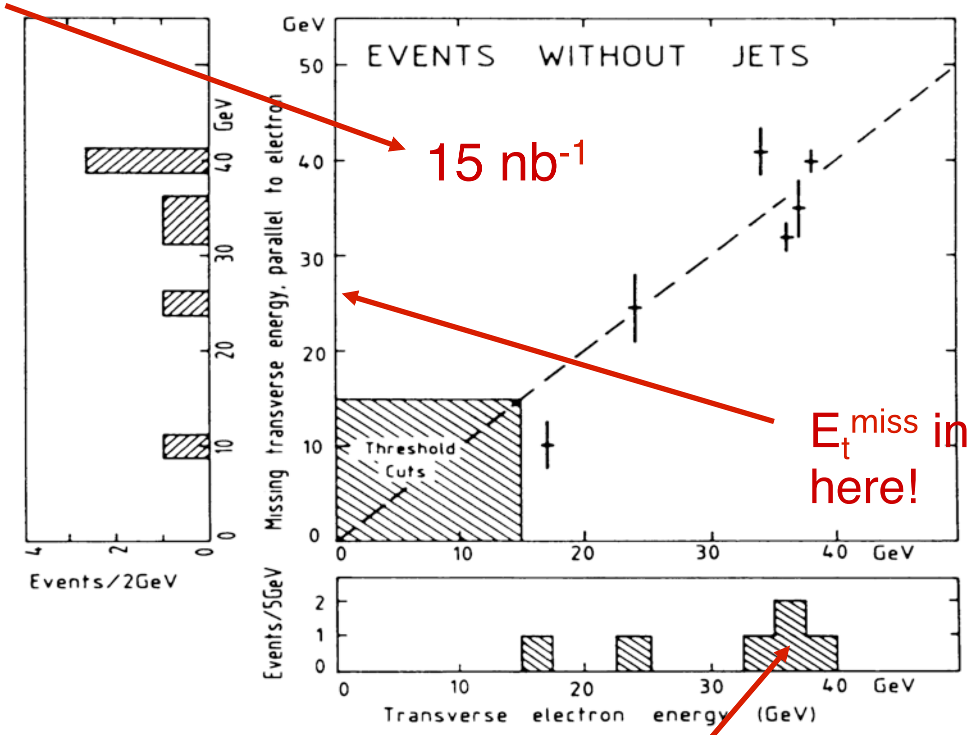
Search for leptonic decays:





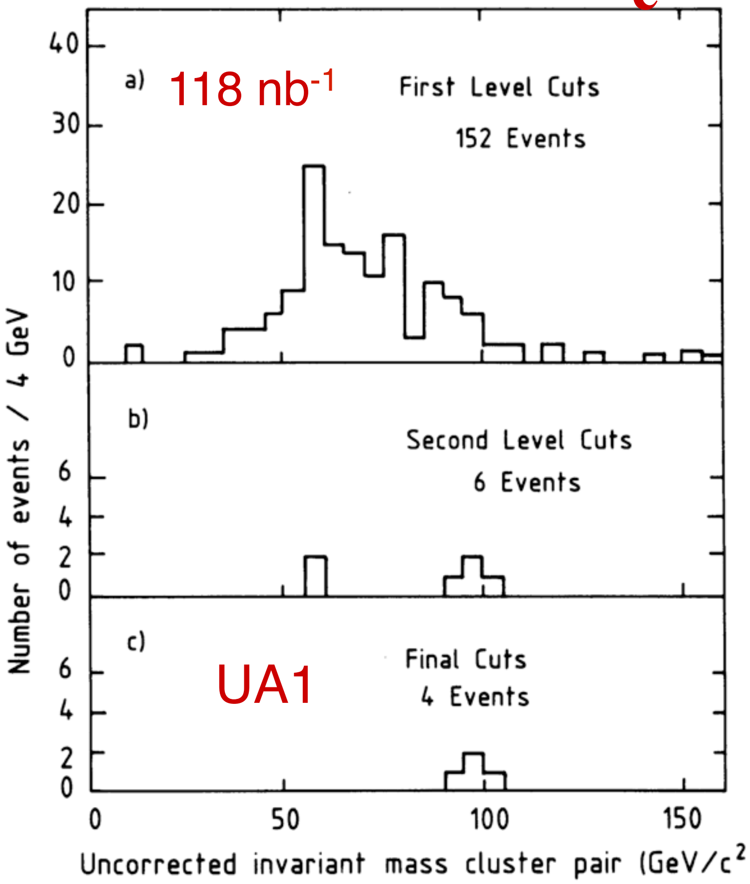
➡ 6 events selected (5 $W\rightarrow e\nu$ + 1 $W\rightarrow \tau\nu$)

Correlation between missing transverse energy and e^{+-} transverse energy for the first W events



15 nb^{-1}

E_t^{miss} invented here!



118 nb^{-1}

UA1

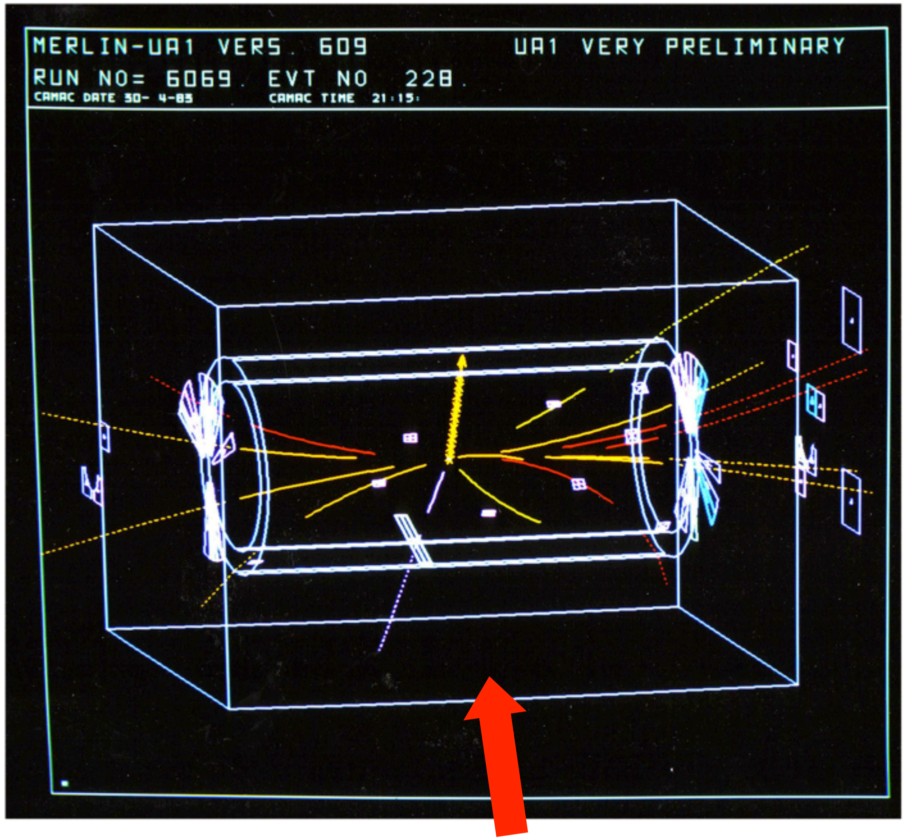
➡ $m_W = 81 \pm 5$ GeV (UA1)

from first "Jacobian peak"

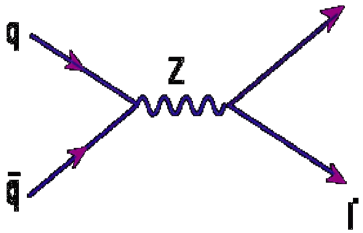
➡ $m_Z = 95.5 \pm 2.5 \pm (3.0)$ GeV (UA1)

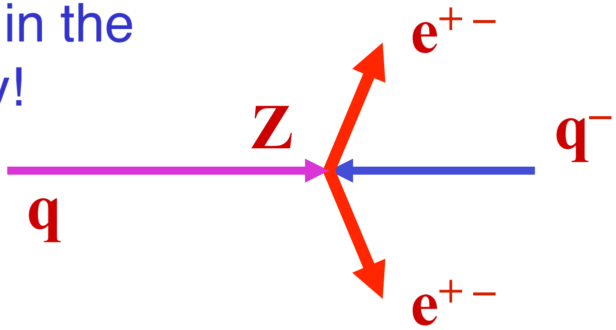
$\sigma_Z BR(Z \longrightarrow ll) = 41 \pm 21\ (\pm 7)$ pb

First W → eν events in UA1 (Dec.1982, Jan.1983) and first Z → e+e- events in UA1 (May 1983)

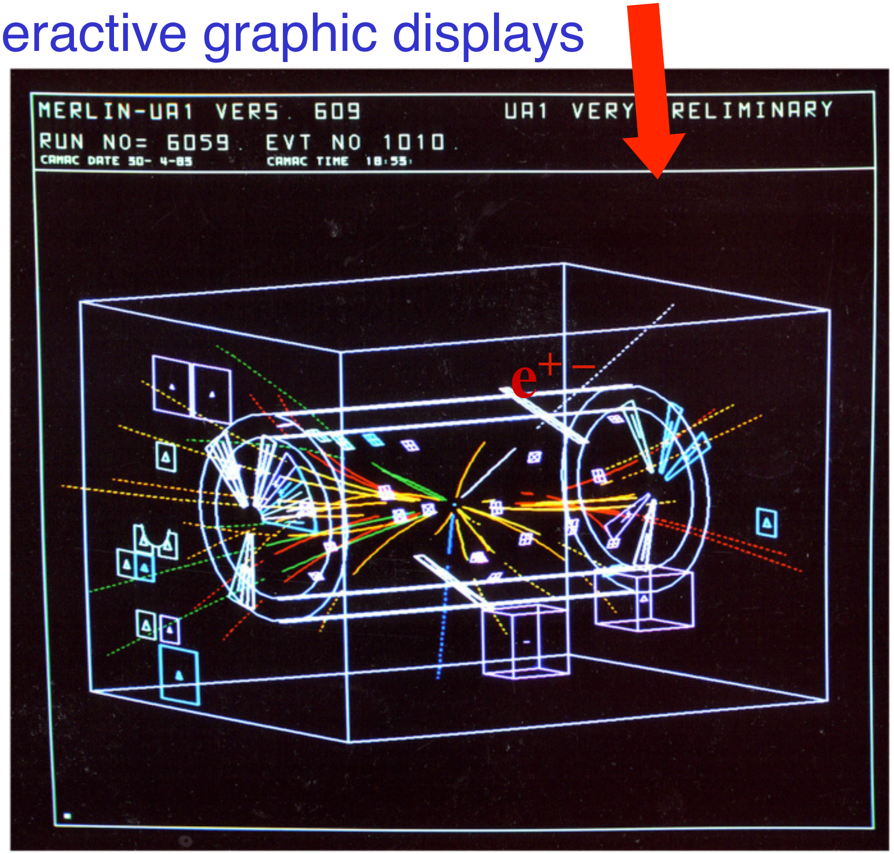


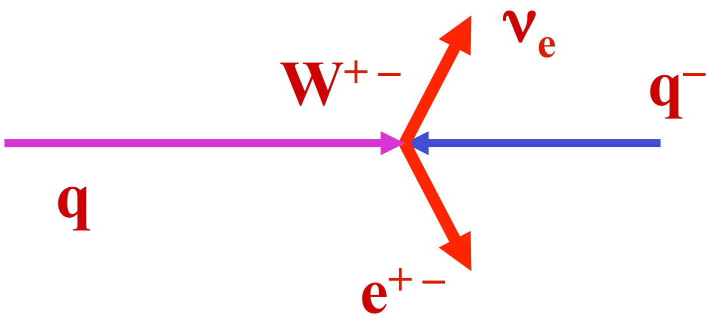
First W's and Z's in the history of humanity!

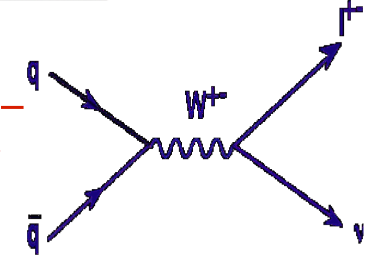




Megatek interactive graphic displays







….

…..after W, Z discovery the obvious next goal was elucidating the origin of electroweak symmetry breaking, the masses of W and Z, through the Higgs (BEH) or other alternative mechanism……..

…..there was a possibility to discover the Higgs boson at LEP - provided it was light enough - but theoretical upper limits on m_H in ~1990 were m_H <~ 1000 GeV, thus much stronger machines, SSC or LHC were required……

The Large Hadron Collider (LHC) - the genesis

The LHC project started at the initiative (and with the daring!!) of C. Rubbia

The Aachen Conference marked the real start-up, since then work on the collider and magnets, various detector designs and understanding physics issues went on without let-up

Scientifico-diplomatic trips in 1990/91/92 to Japan, India, Russia, USA, Canada etc

LHC vs SSC: Rubbia's arguments: savings!

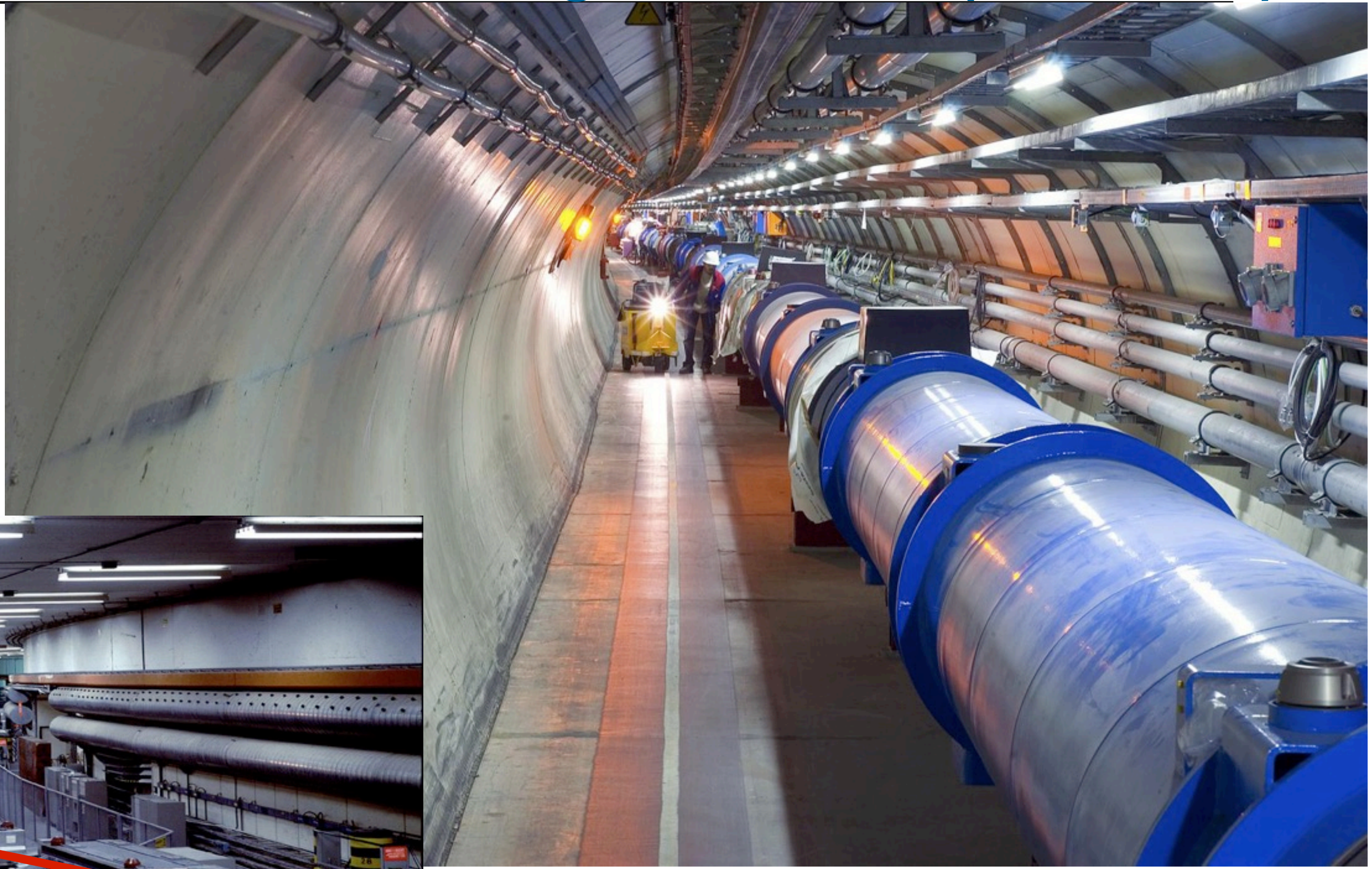
- existing LEP tunnel ~1 GCHF
- existing infrastructure at CERN (PS. SPS, etc) ~ 1 GCHF
- "two-in-one" scheme for dipoles saves ~ half the cost of magnet ~ 0.7 to 1 GCHF

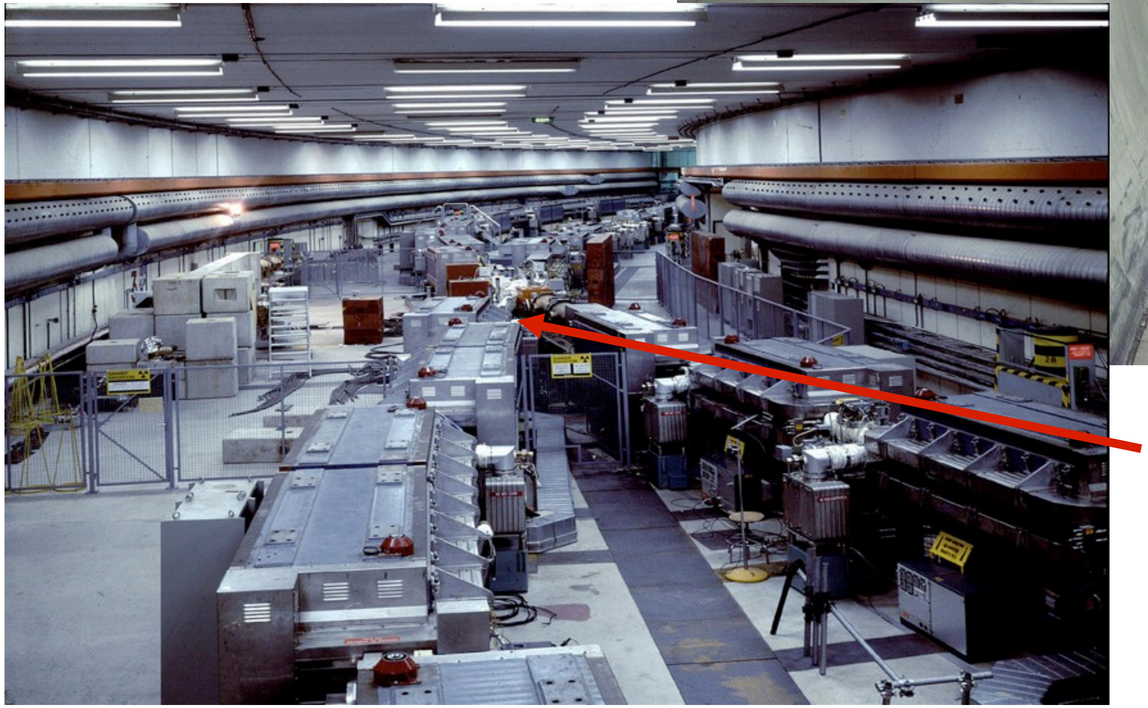
thus overall LHC cost ~ 3 GCHF

- will be ready by 1998 - 2000 !!

D. Denegri; Istanbul, Turkey, Iran-Turkey conf. on LHC, June 2019

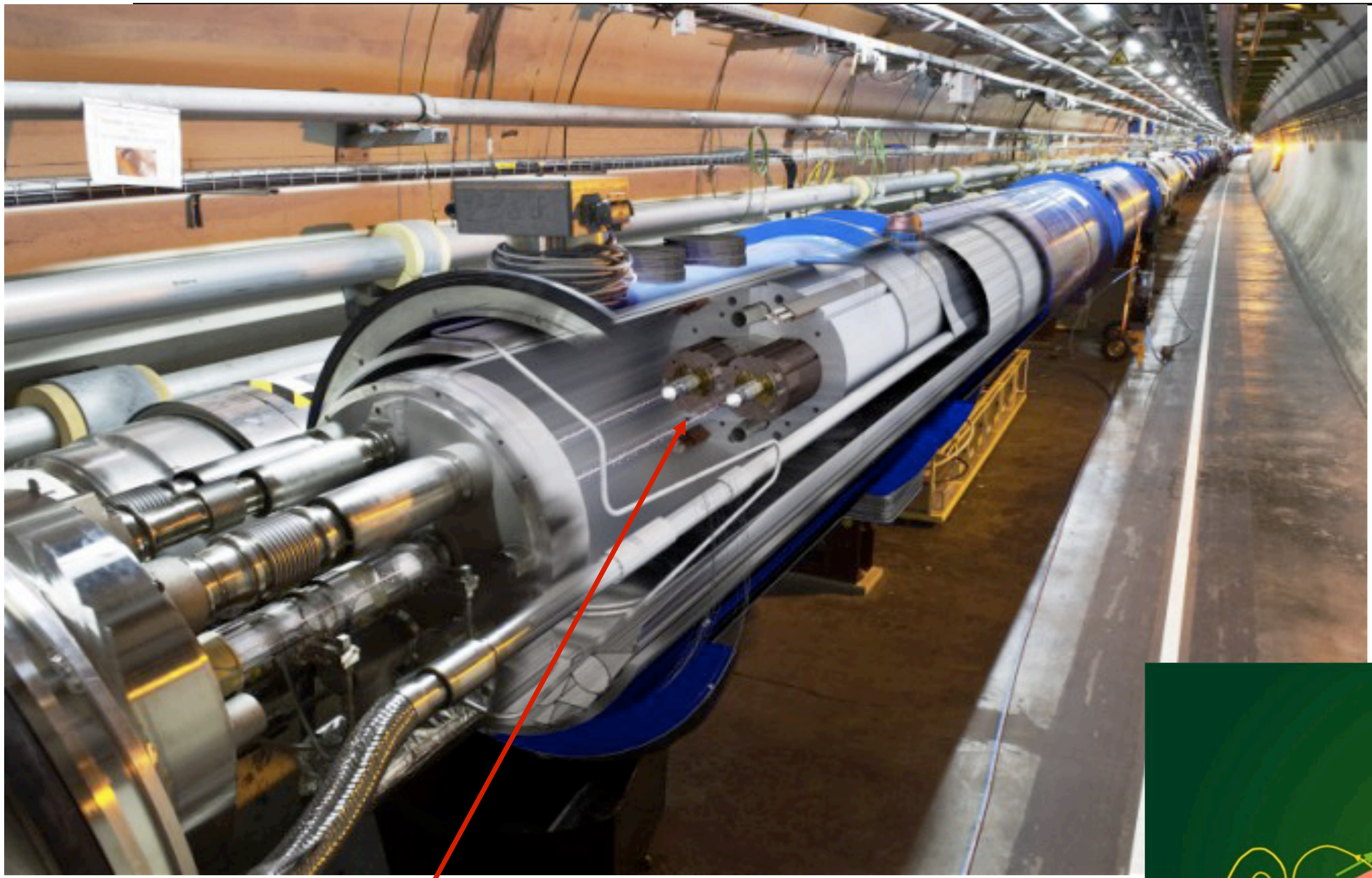
The LHC - a single set of magnets in the tunnel
thanks to the “two-in-one” magnet scheme (R. Palmer)





the ISR - a typical proton-proton collider;
ISABELLE and the SSC were of same design

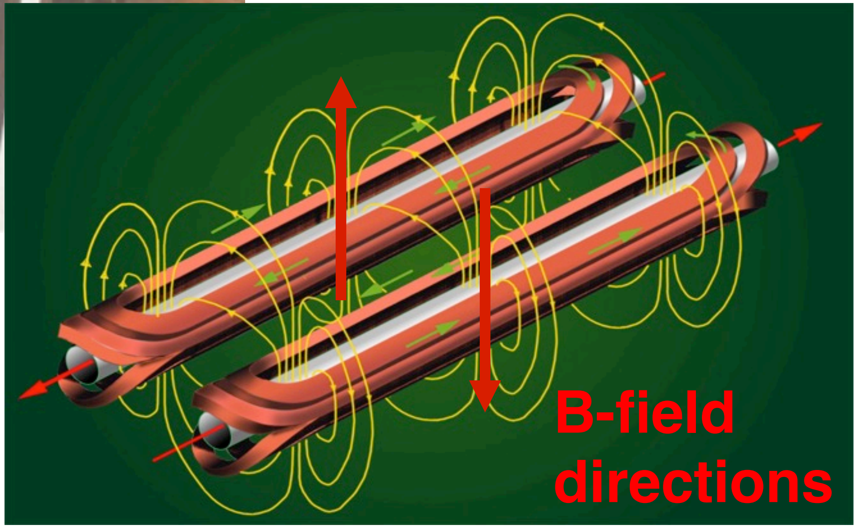
The LHC tunnel - a single set of magnets thanks to the “two-in-one” magnet scheme - II



The magnets have to be aligned with 100μm precision over the 27 km circumference!

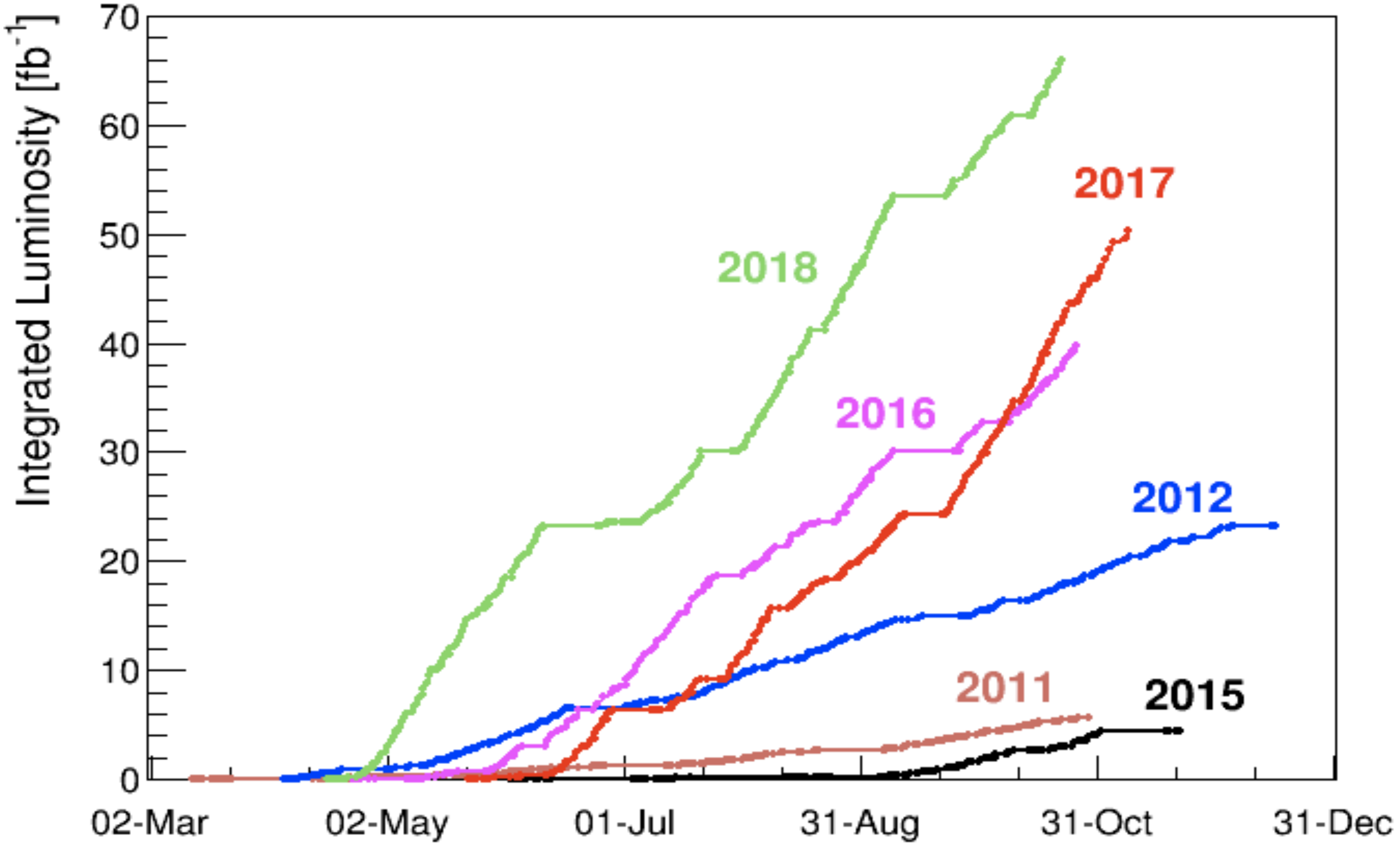
Vacuum in the beam pipe as on the Moon!

Magnetic field lines



the two-in-one magnet
40.000 tons of material at -271 ^{0}C
The coldest place in the Univers!

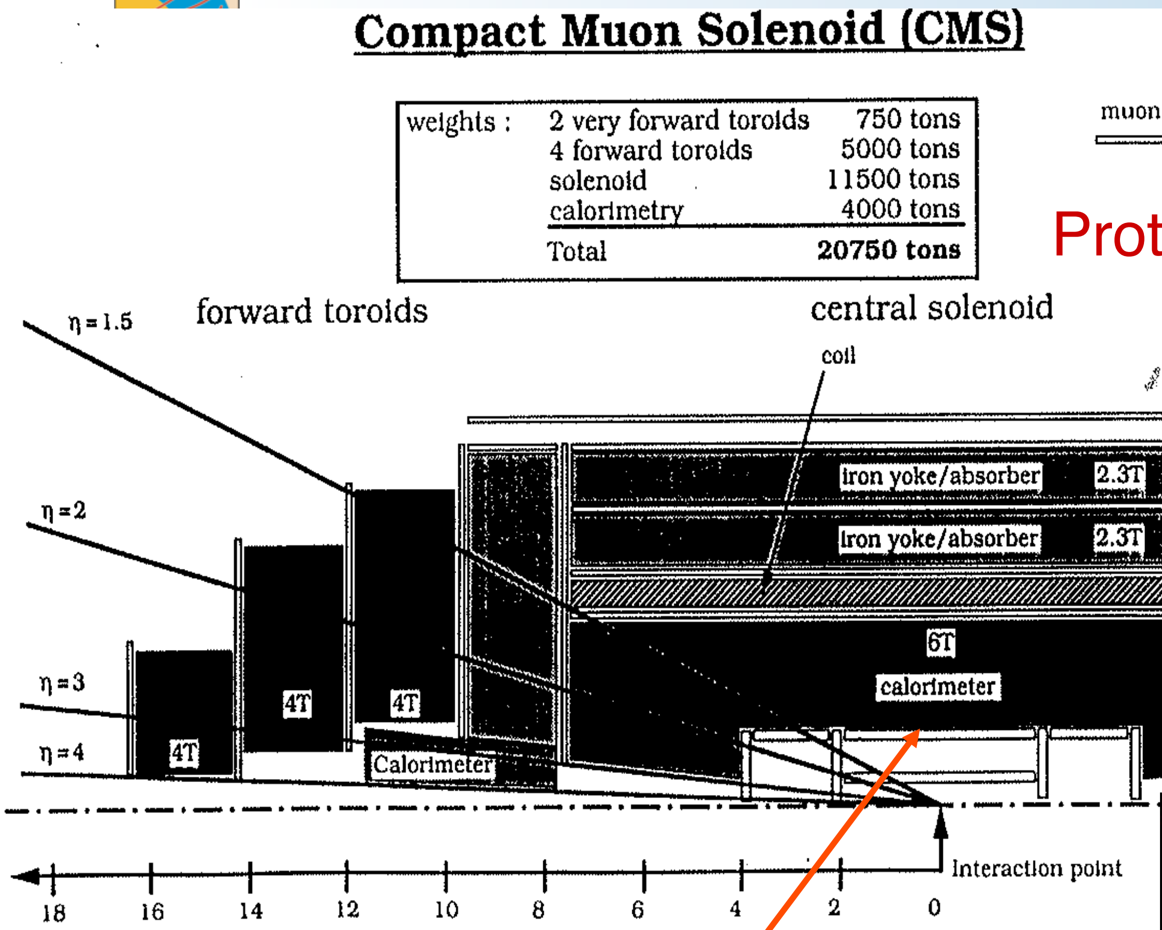
LHC luminosities over years, including 2018



D. Denegri; Istanbul, Turkey, Iran-Turkey conf. on LHC, June 2019

How CMS started in 1990!

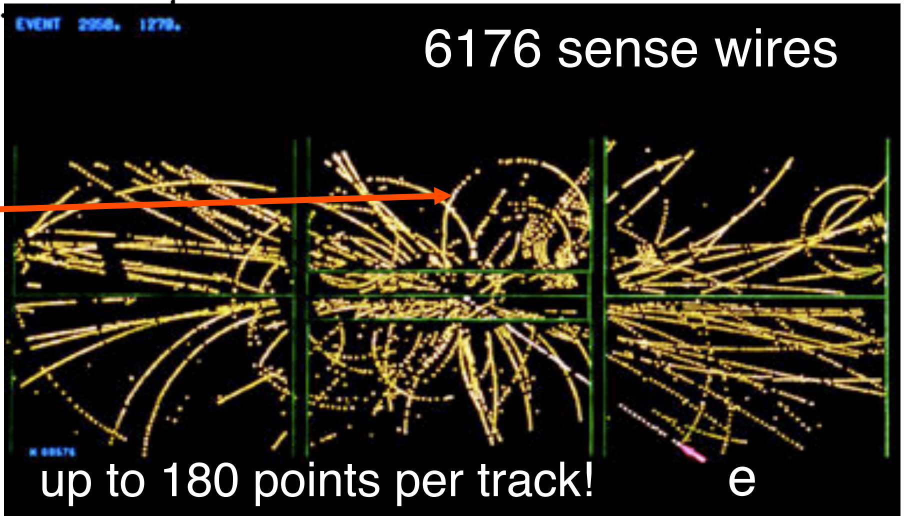
Proto-CMS in 1990…..



weights :		
	2 very forward toroids	750 tons
	4 forward toroids	5000 tons
	solenoid	11500 tons
	calorimetry	4000 tons
	Total	**20750 tons**

The UA1 tracker was by far the most sophisticated in its days, but the p-pbar collider did not exceed $10^{30}cm^{-2}s^{-1}$ and now for the LHC we need $10^{34}cm^{-2}s^{-1}$!! The answer: granularity and fast detector response

- Tracking? …maybe in outermost regions…



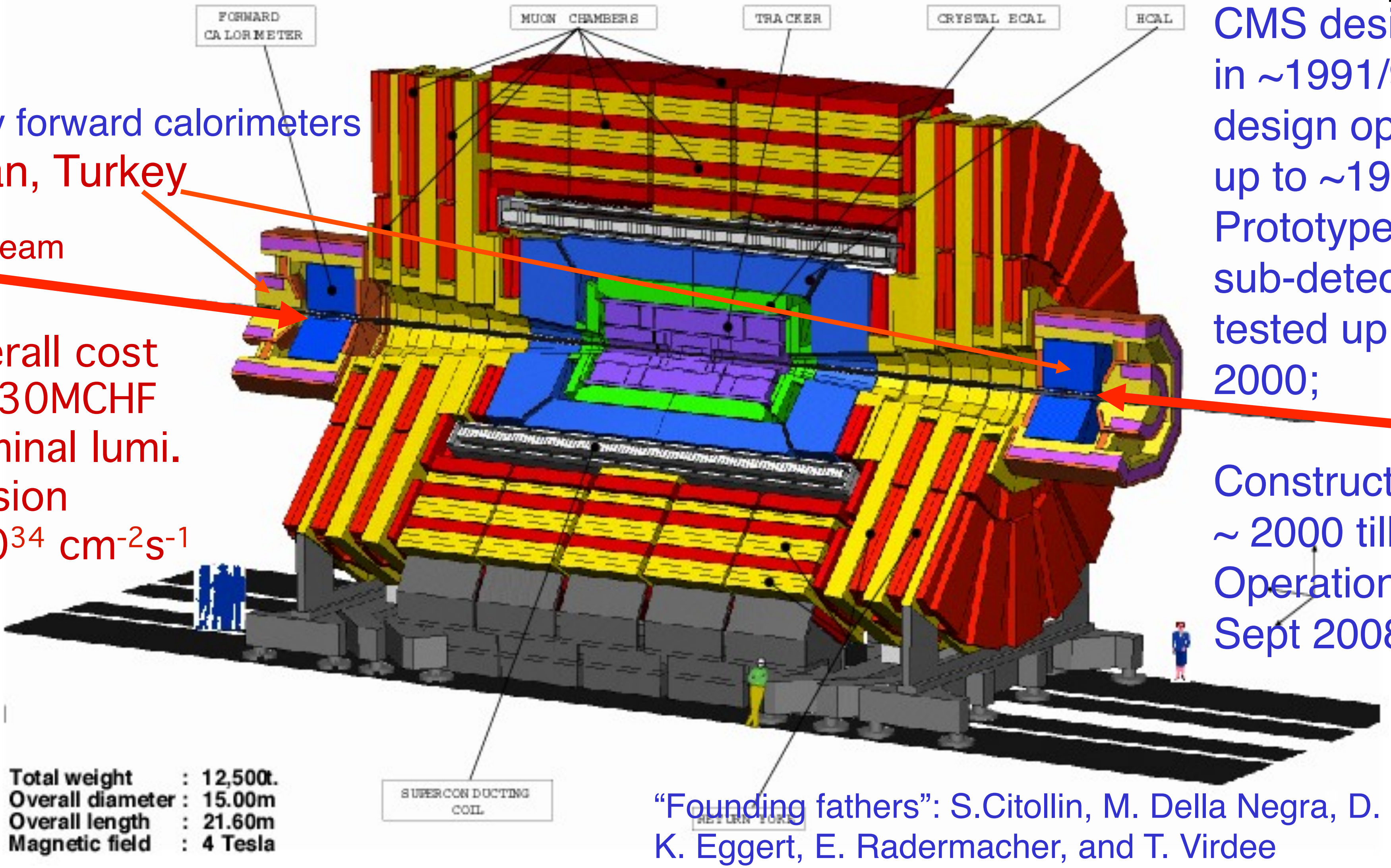
6176 sense wires

up to 180 points per track!

e

- Our test beam and MC studies in 1991/92 led to rapid progress in the detector design.

The CMS (Compact Muon Solenoid) detector



Very forward calorimeters
- Iran, Turkey

beam

beam

Overall cost
~ 630MCHF
nominal lumi.
version
~10^{34} cm^{-2}s^{-1}

CMS designed in ~1991/92, design optimized up to ~1995; Prototypes for sub-detectors tested up to ~ 2000;

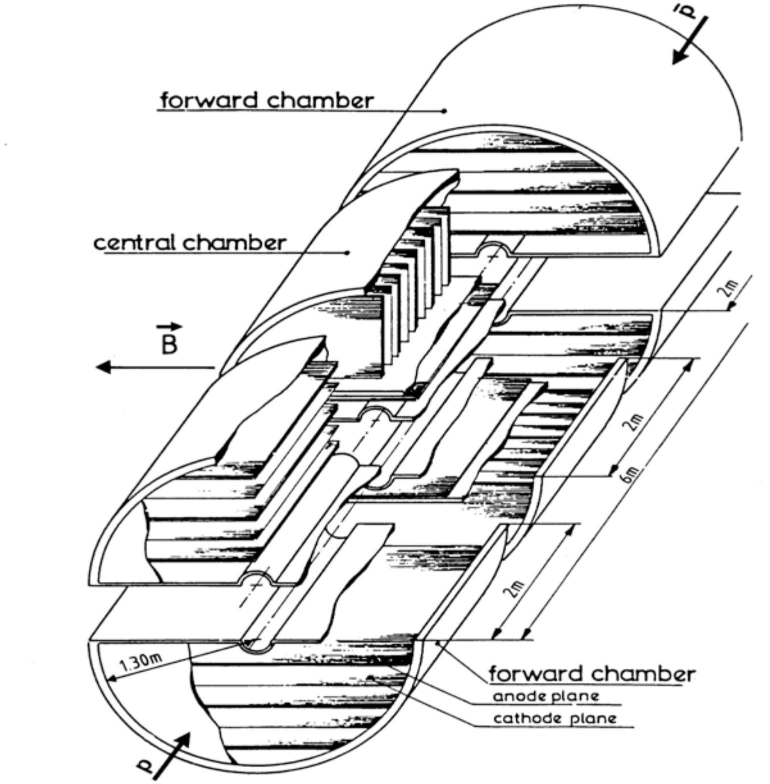
Construction from ~ 2000 till 2008
Operational in Sept 2008

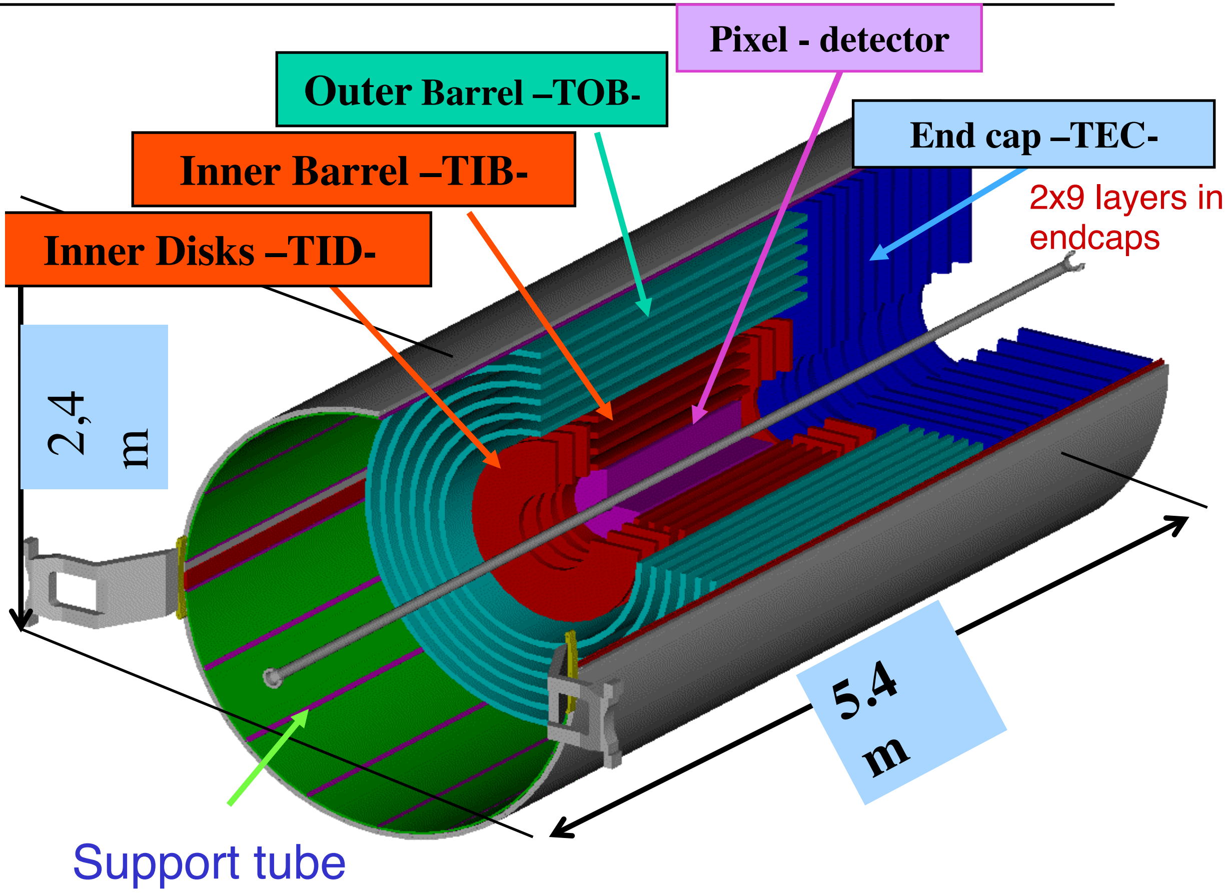
“Founding fathers”: S.Citollin, M. Della Negra, D. Denegri, K. Eggert, E. Radermacher, and T. Virdee

At present undergoing upgrades in several phases to face conditions of HL-LHC running (~10^{35} cm^{-2}s^{-1})

The UA1 tracker and the all-Silicon CMS tracker
- high granularity for pattern recognition and fast detectors

The UA1 tracker was by far the most sophisticated in its days !!



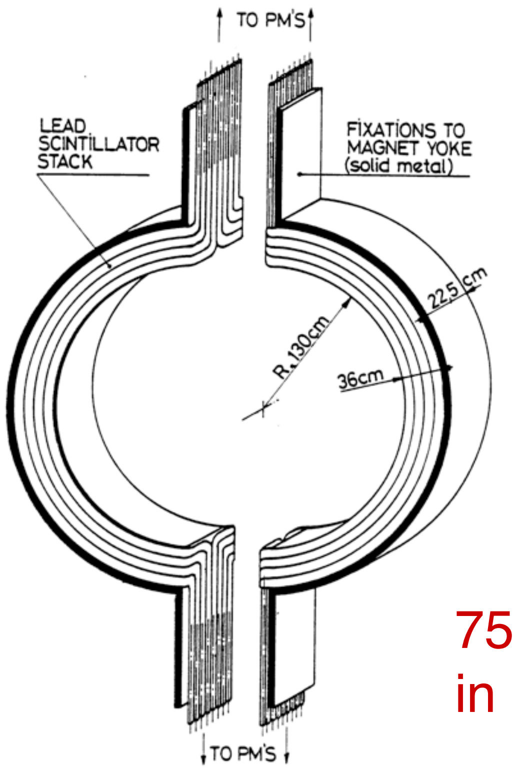


UA1 tracker: Imaging drift chamber, 6m long, 2.3m in diameter, 6176 sense wires, up to 180 hits per track, Acceptance $|\eta| < 3.0$

Factor ~10^4
in granularity!

210 m^2 of silicon sensors
~ 6,000 thin detectors (1 sensor)
~ 9,000 thick detectors (2 sensors)
10 million microstrips and
70 Million pixels (~2 m^2)

From the UA1 electromagnetic calorimeter to the crystal ($PbWO_4$) calorimeter of CMS

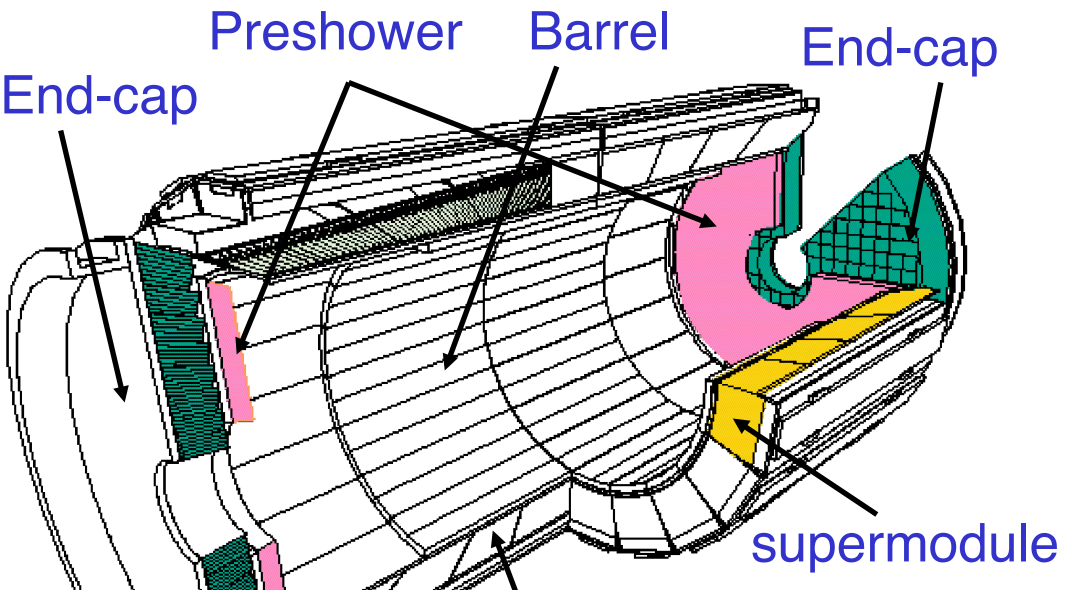


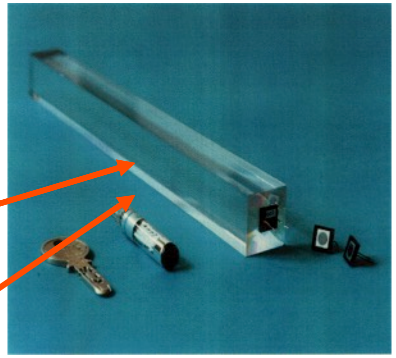
754 PM's
in barrel

UA1 ECAL (2x24 gondolas)
Scint.-Pb sandwich, 1.2mmPb/1.5mmSci
$\Delta\phi\Delta\eta$= 180° x 0.14; $27X_0$ deep,
four segments in depth
ECAL acceptance: $|\eta| < 3.0$

It is here that the W and Z were found!

Factor ~10^2 in granularity!





a TeV em shower contained in a crystal of $24x2x2cm^3$

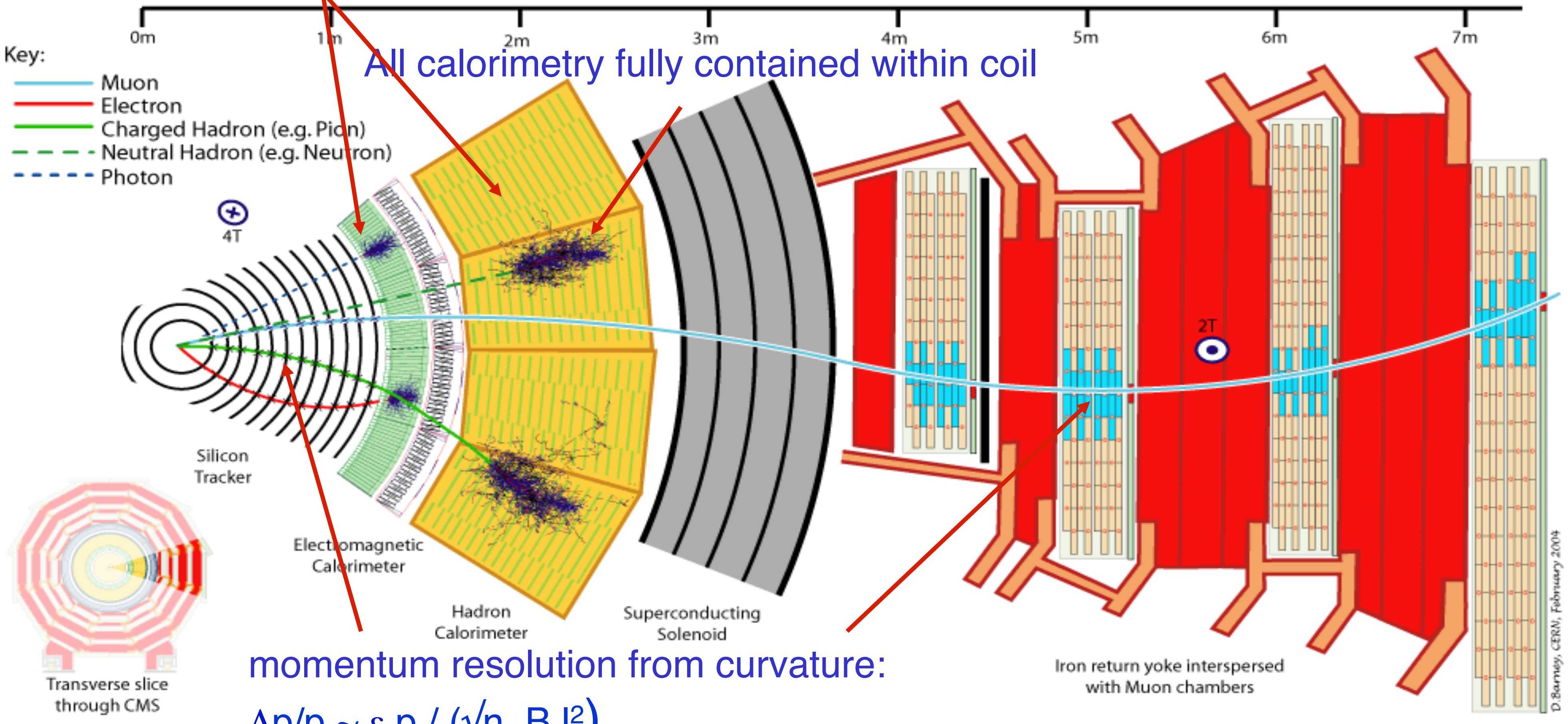
74.000 crystals
L_{rad} = 9mm, R_{mol} = 2cm ($\Delta\eta$ = 0.014)
~10nsec response read out with avalanche photo-diodes in barrel

D. Denegri; Istanbul, Turkey, Iran-Turkey conf. on LHC, June 2019

Central region of CMS; detector functions

Tracking + Ecal + Hcal + Muons for $|\eta|<2.4$

$\Delta E/E \sim \surd((a/\surd E\,)^2 + (b/E)^2 + c^2))$ generic resolution in calorimeters



All calorimetry fully contained within coil

momentum resolution from curvature:

$\Delta p/p \sim \varepsilon\ p\ /\ (\surd n\ \ B\ l^2)$

Redundancy and robustness in muon system

Si TRACKER

Silicon Microstrips
and Pixels

CALORIMETERS

ECAL
Scintillating
$PbWO_4$ crystals

HCAL
Plastic scintillator/brass
sandwich

MUON BARREL

Drift Tube
Chambers (**DT**)

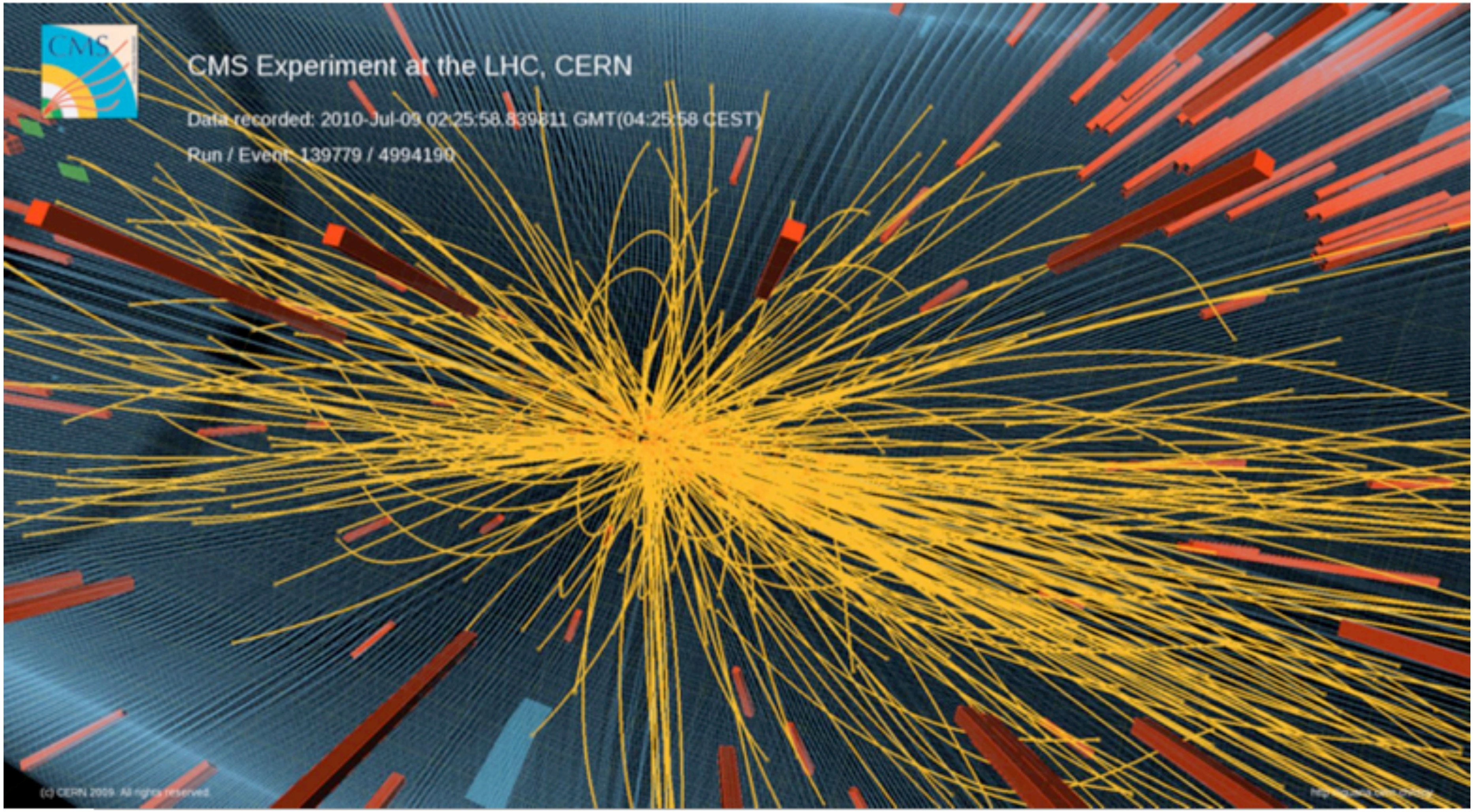
Resistive Plate
Chambers (**RPC**)

A typical proton-proton collision at the LHC,

there are ~ one billion such collisions per second

(in reality they are clustered by ~25 every 25nseconds – pile-up)

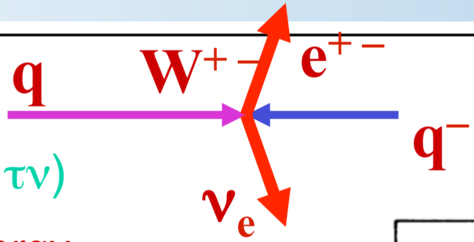
Expected Higgs boson production rate is less than one in a billion pp colisions!

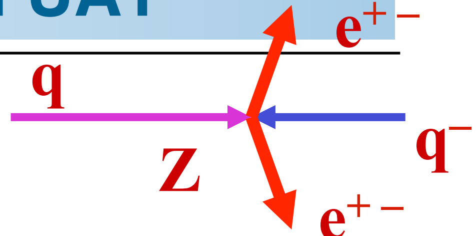


Physics
jets, W, Z, top, Higgs boson

Run of winter 1982, W discovery, followed by run of spring 1983 and Z discovery in UA1

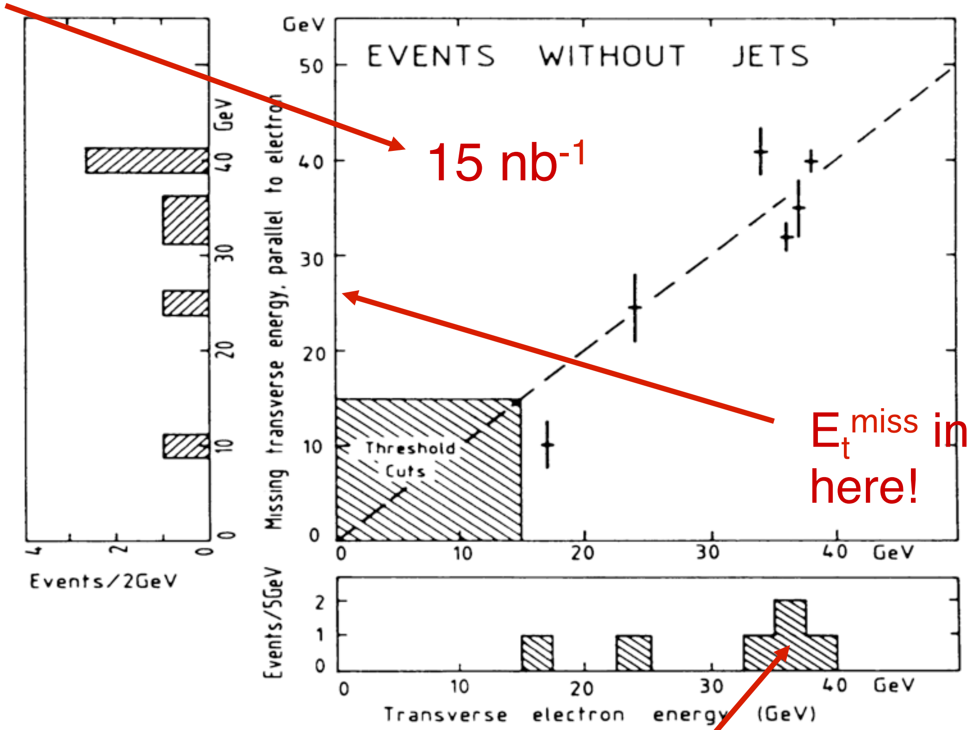
Search for leptonic decays:





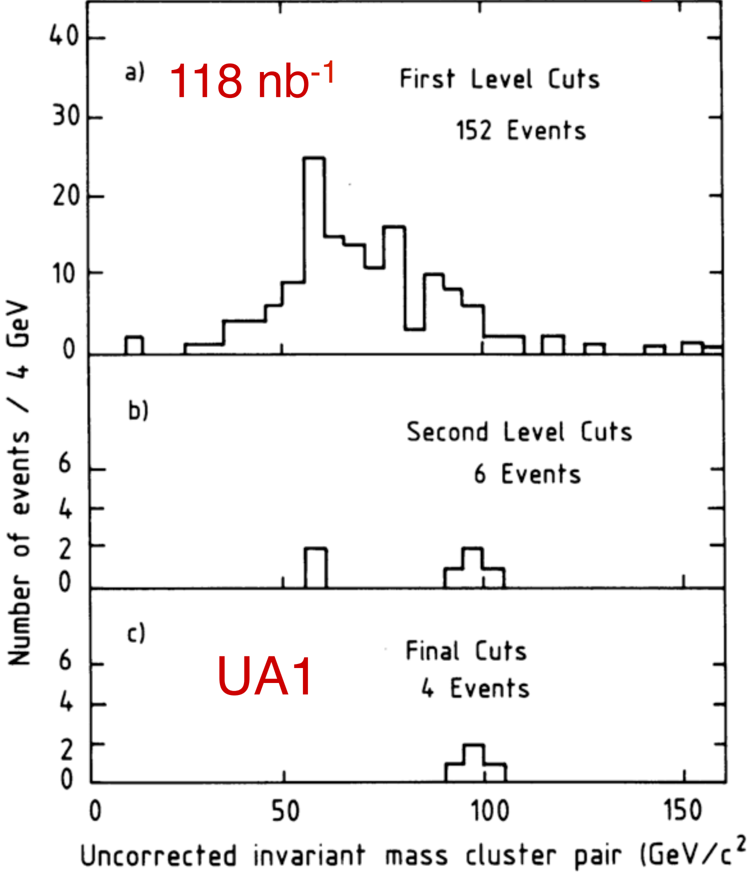
6 events selected (5 W→ eν + 1 W→ τν)

Correlation between missing transverse energy and e+- transverse energy for the first W events



$15\ nb^{-1}$

E_t^{miss} invented here!



$118\ nb^{-1}$

UA1

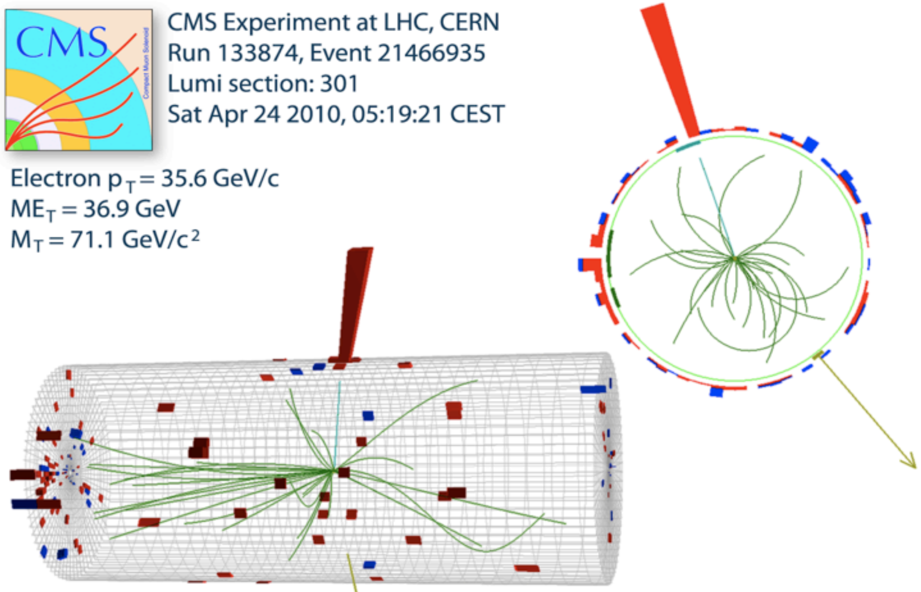
$m_W = 81 \pm 5$ GeV (UA1)

from first “Jacobian peak”

$m_Z = 95.5 \pm 2.5 \pm (3.0)$ GeV (UA1)

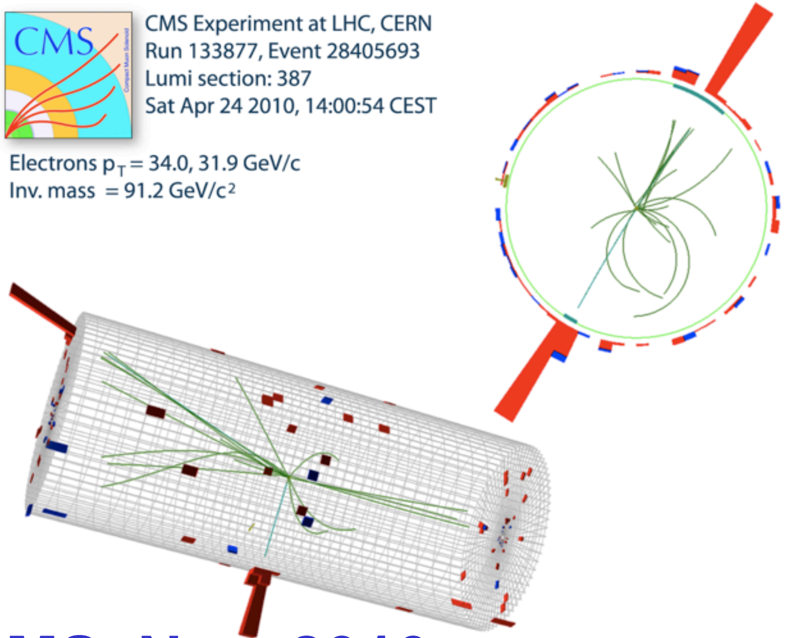
$\sigma_Z BR(Z \rightarrow ll) = 41 \pm 21\ (\pm 7)$ pb

LHC : First W $\rightarrow e\nu$ and Z $\rightarrow e^+e^-$ events, April 2010



CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

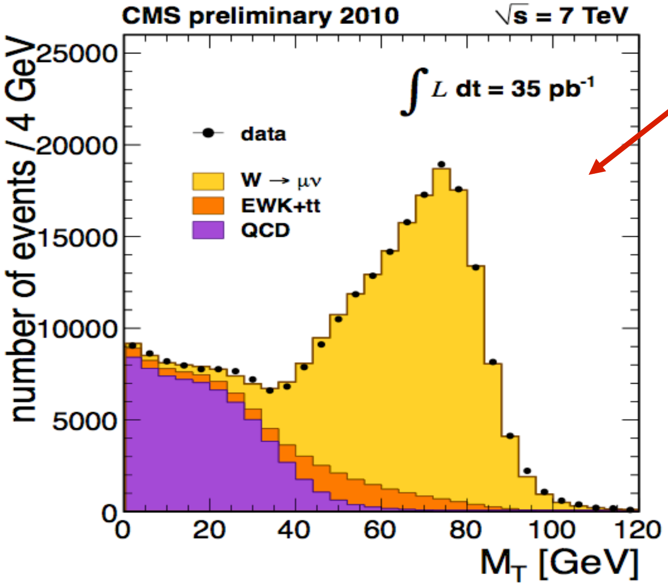
Electron $p_T = 35.6$ GeV/c
$ME_T = 36.9$ GeV
$M_T = 71.1$ GeV/c^2



CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

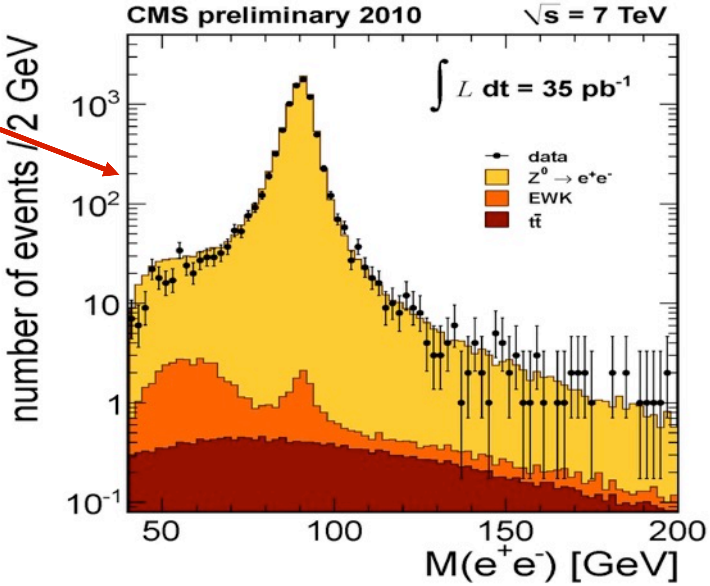
Electrons $p_T = 34.0, 31.9$ GeV/c
Inv. mass $= 91.2$ GeV/c^2

W and Z spectra in CMS, Nov. 2010

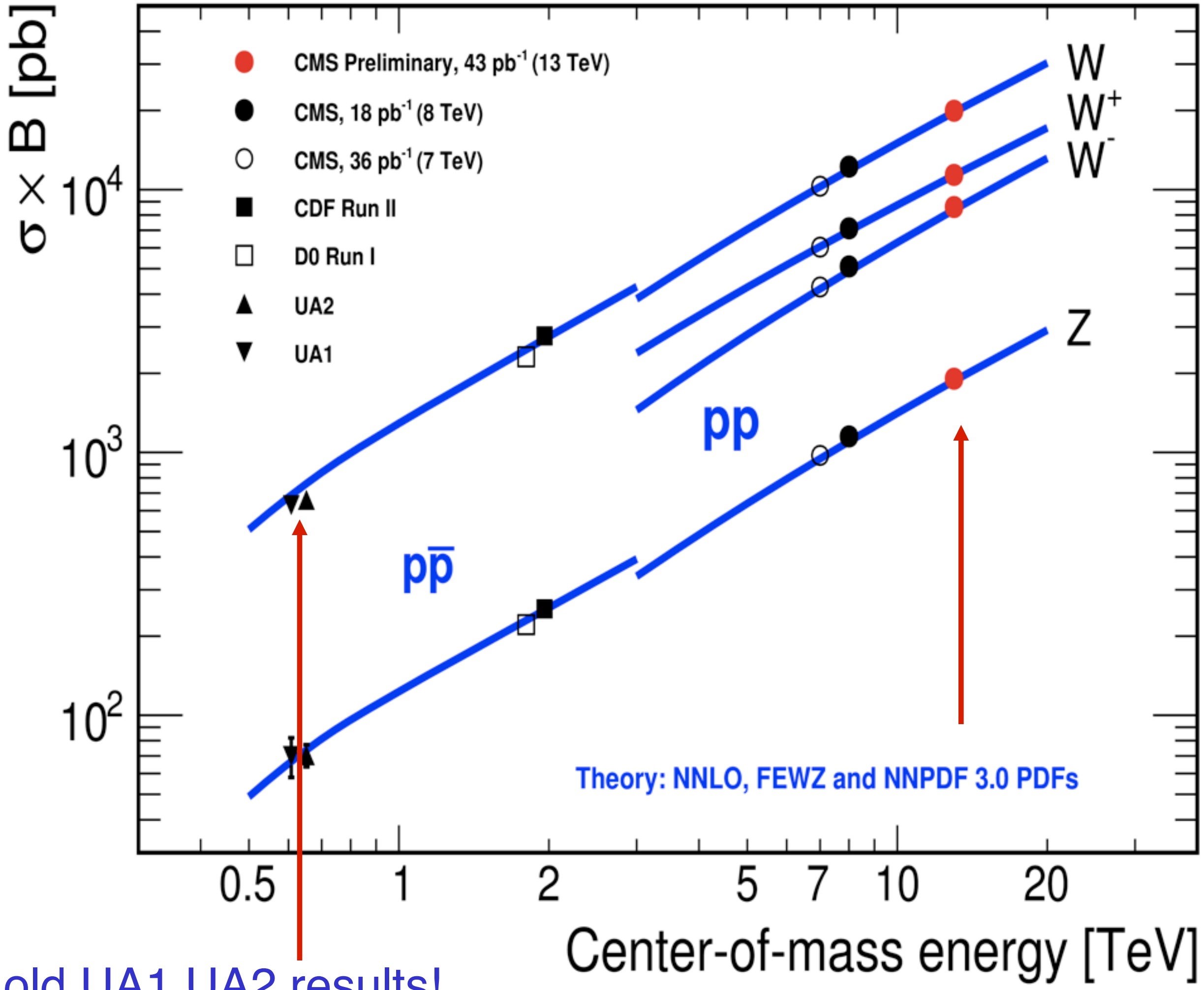


By end-2012 we had ~150.000.000 W and ~15.000.000 Z decaying leptonically!!

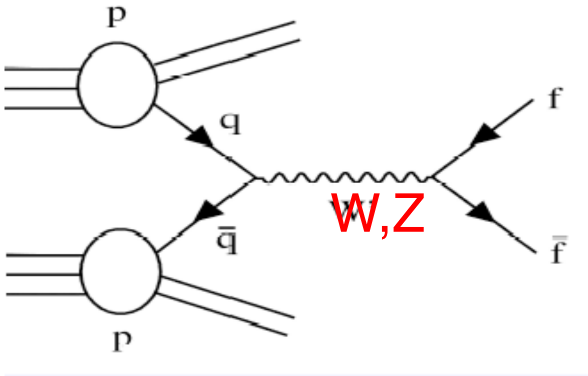
Note progress since first UA1 W, Z!



W, Z ATLAS and CMS studies, 2018, total cross sections from the CERN pp-bar collider to the Tevatron and the LHC



old UA1,UA2 results!



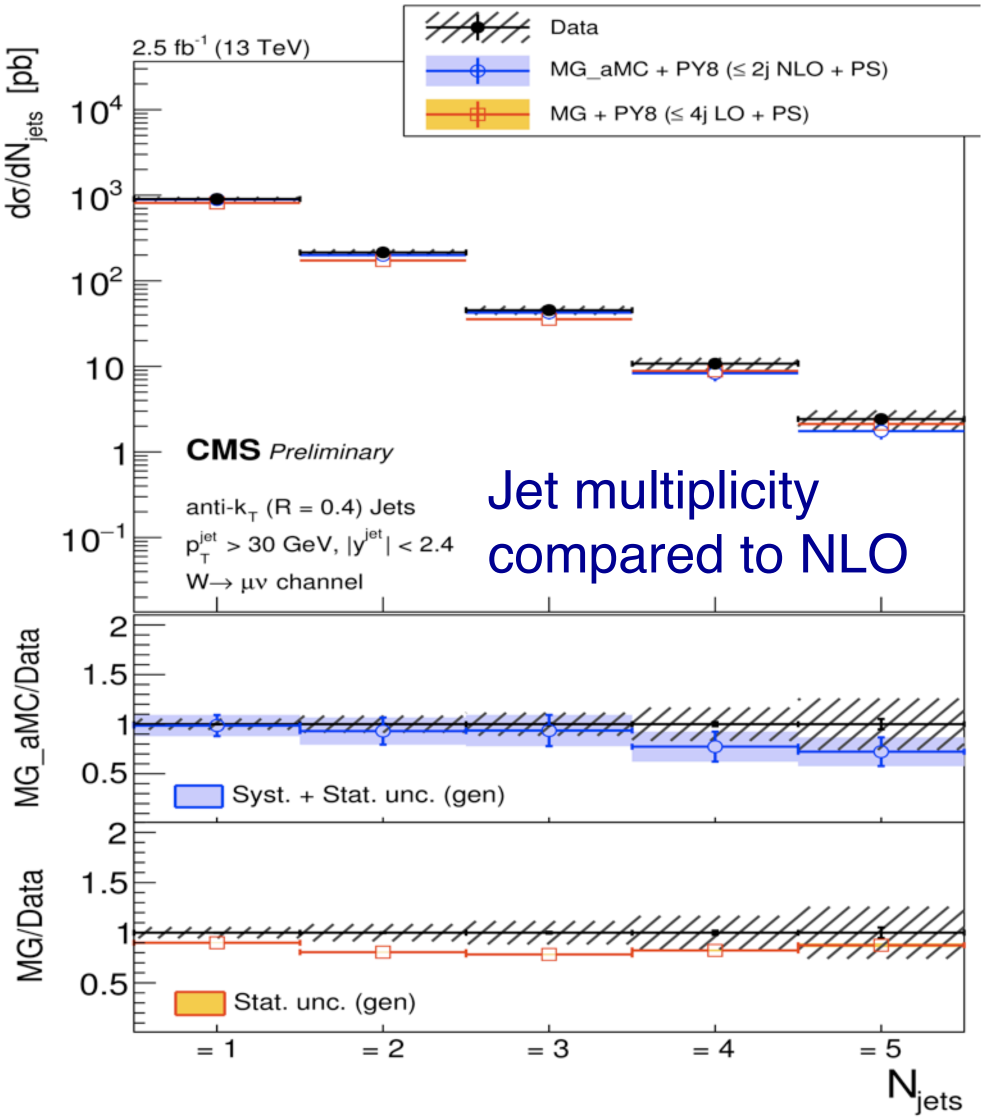
Comprehensive W and Z results from ATLAS and CMS

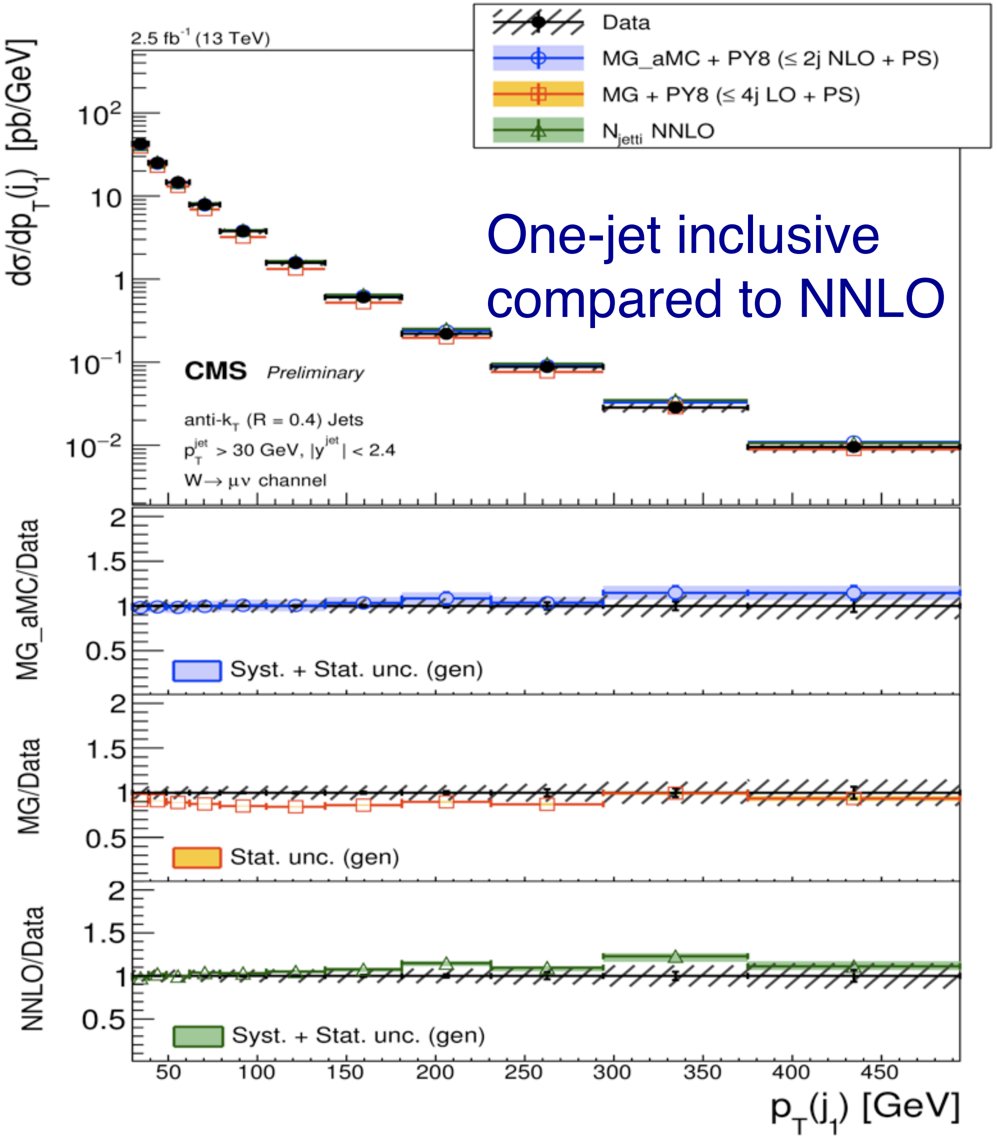
– New results available at 7, 8 and 13 TeV

– Allow to test the SM with sub-percent uncertainties

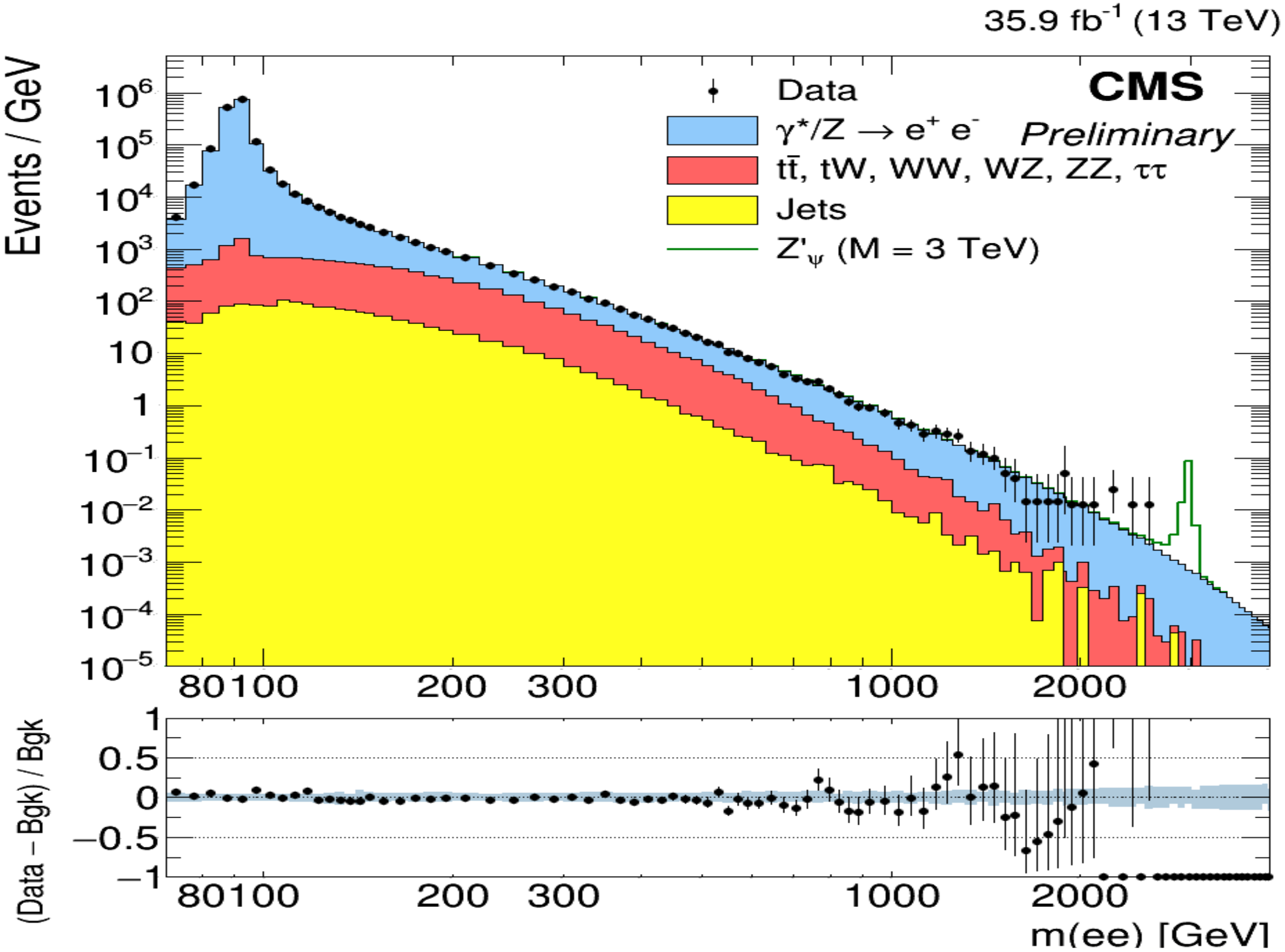
– Measured cross sections agree with NNLO QCD and NLO EW

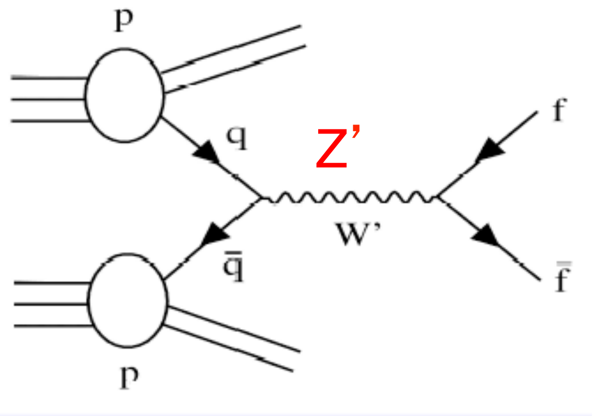
W + jets differential cross sections
compared to QCD expectations, NLO, NNLO


Jet multiplicity compared to NLO


One-jet inclusive compared to NNLO

Z’ searches with dileptons, CMS, status in 2018

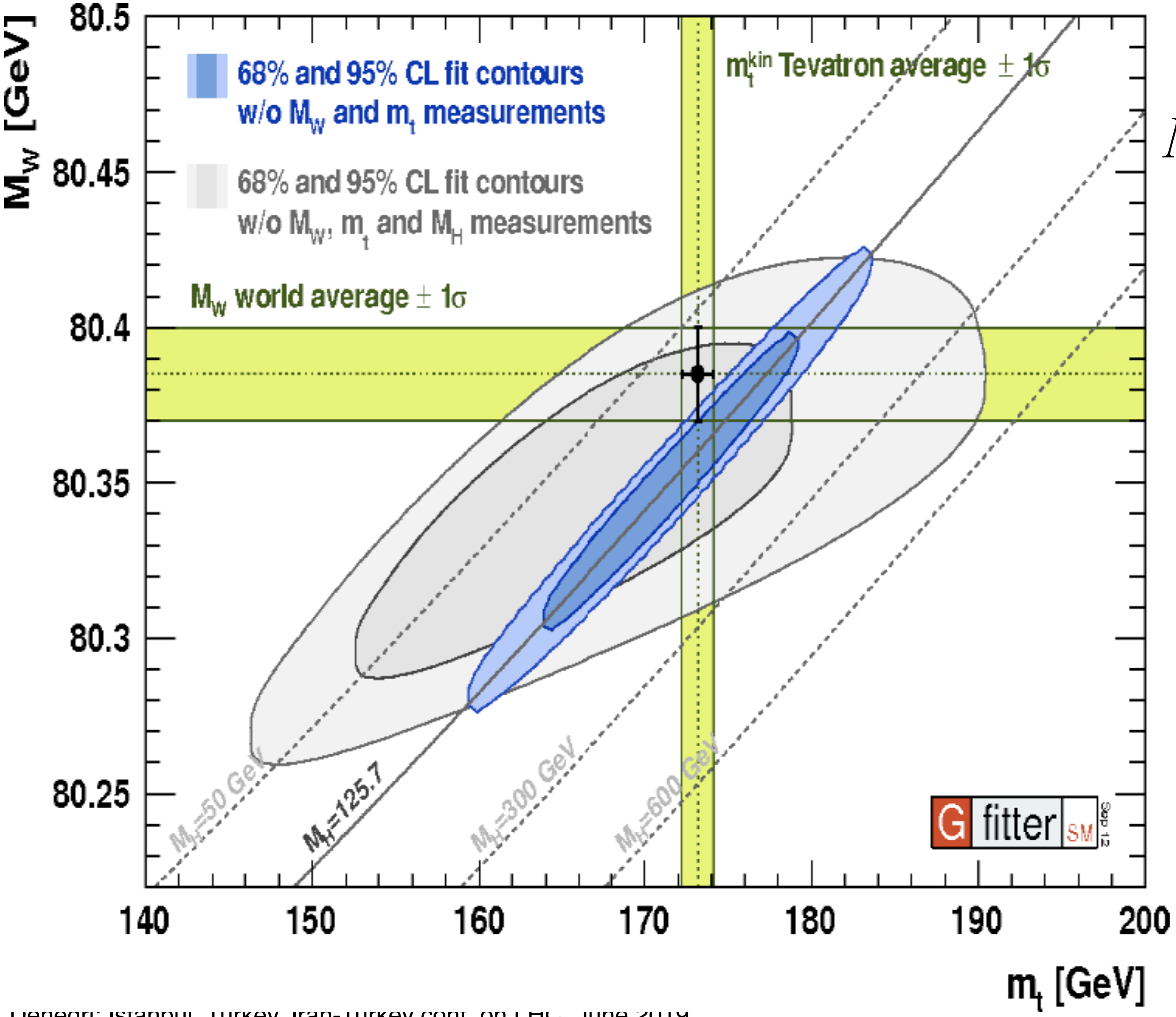




Limits extending beyond 4 TeV!

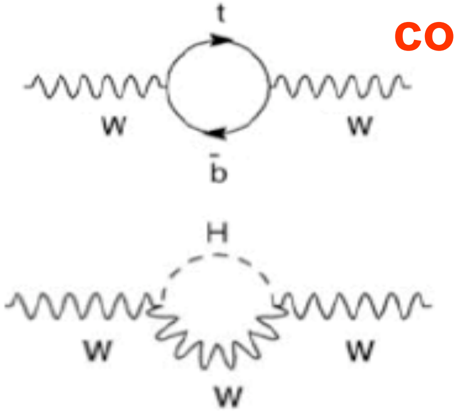
Channel	Model	Obs. limit (TeV)	Exp. limit (TeV)
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_ψ	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_ψ	4.1	4.1

Testing the coherence of the Standard Model - importance of precision measurements of W, top and Higgs masses - all correlated through radiative corrections!



$$M_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W}\frac{1}{(1+\Delta r)}$$

radiative corrections



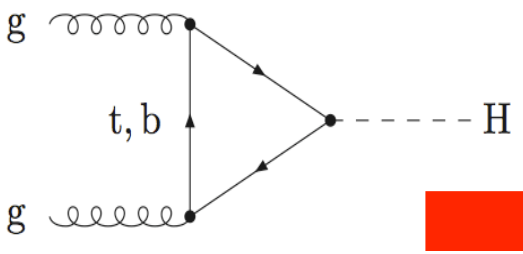
$$(\Delta r)_{top} \approx \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{\tan^2\theta_W}$$

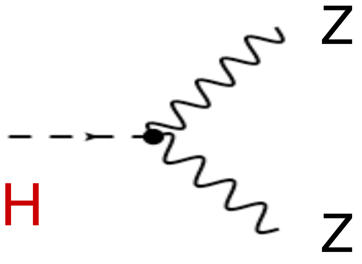
$$(\Delta r)_{Higgs} \approx \frac{11G_F M_Z^2\cos^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}$$

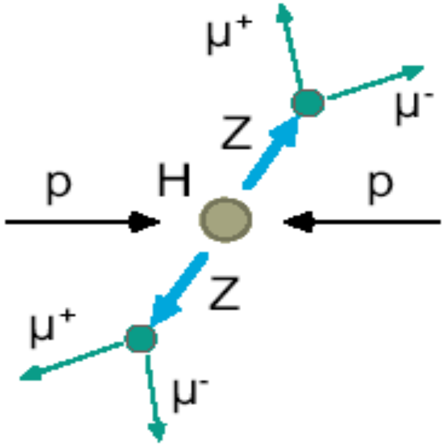
the Higgs…..

Production and detection of the Higgs in CMS – if $m_H \sim 150$ GeV ($H \longrightarrow ZZ/ZZ^* \longrightarrow 4$ leptons)

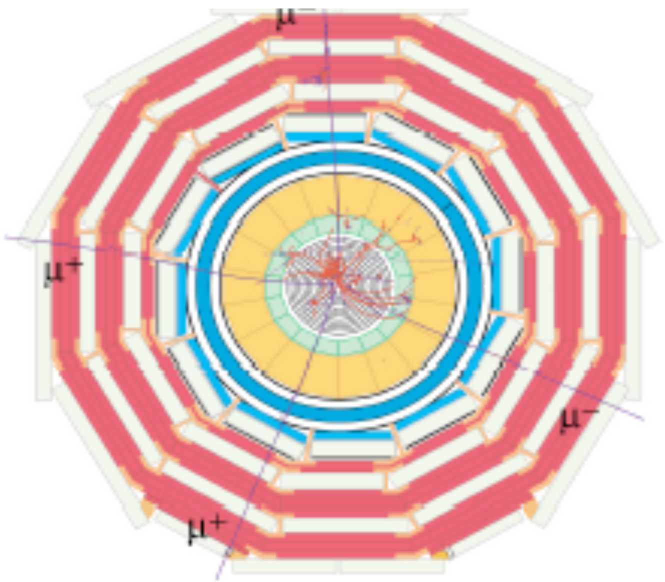
expectations from 1992!



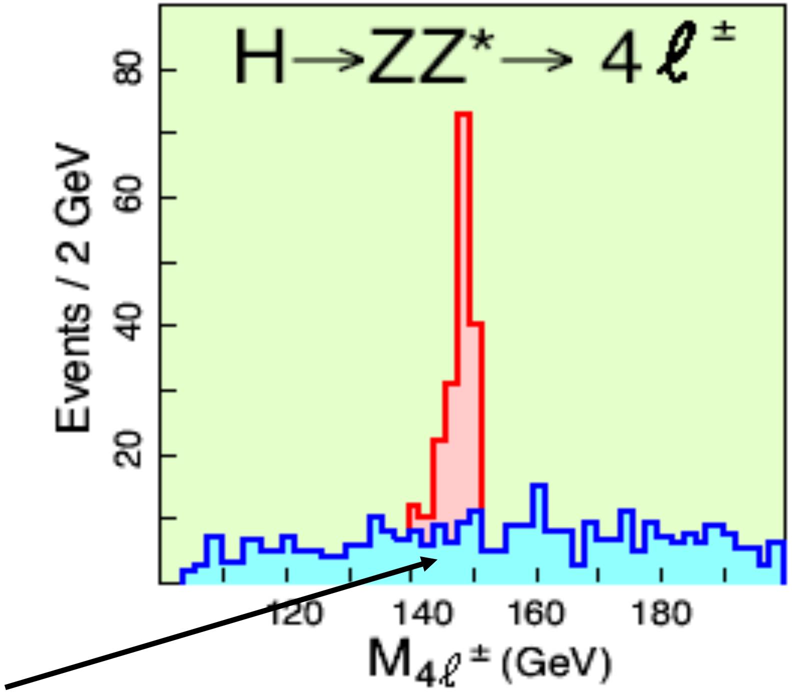




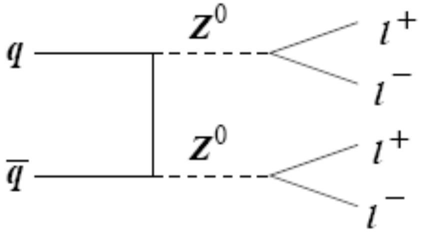
Expectations for signal and background if the Higgs has a mass ~ 150 GeV
Similar situation in the mass range ~ 130 - ~ 400 GeV



M_{Higgs} = 150 GeV

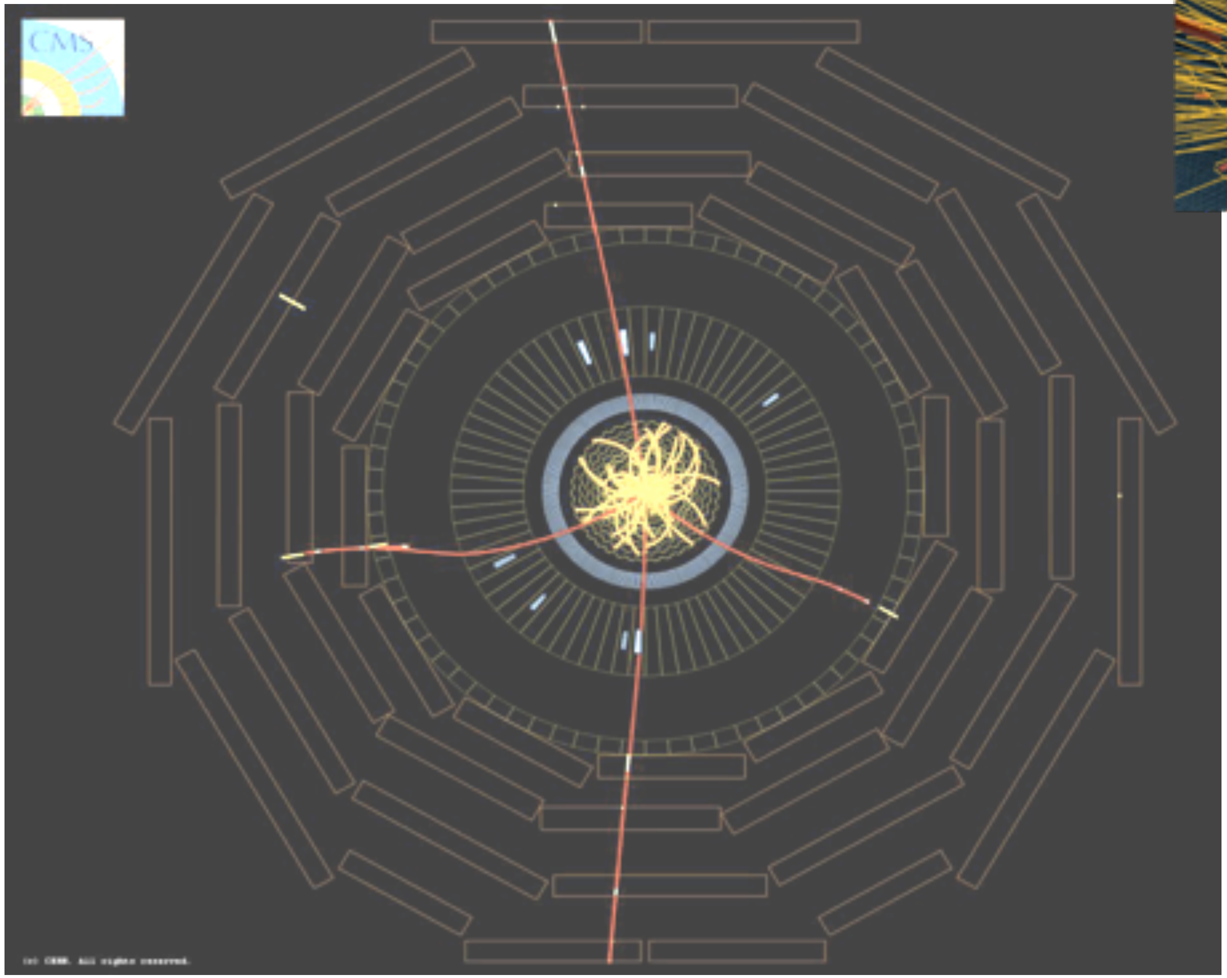


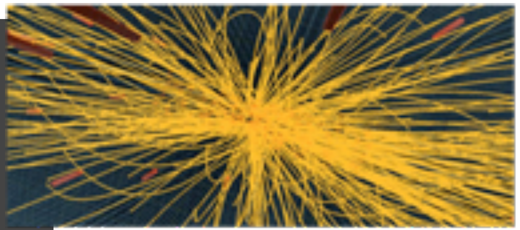
Electroweak ZZ background!!

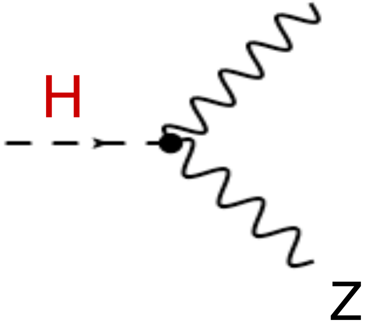


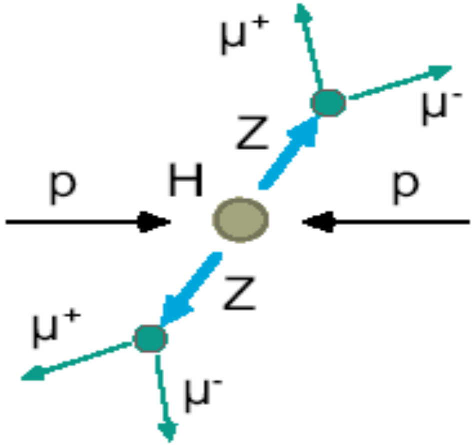
Electroweak ZZ background

First events: H → ZZ → μμμμ candidate event in CMS, √s = 8 TeV data, 2012



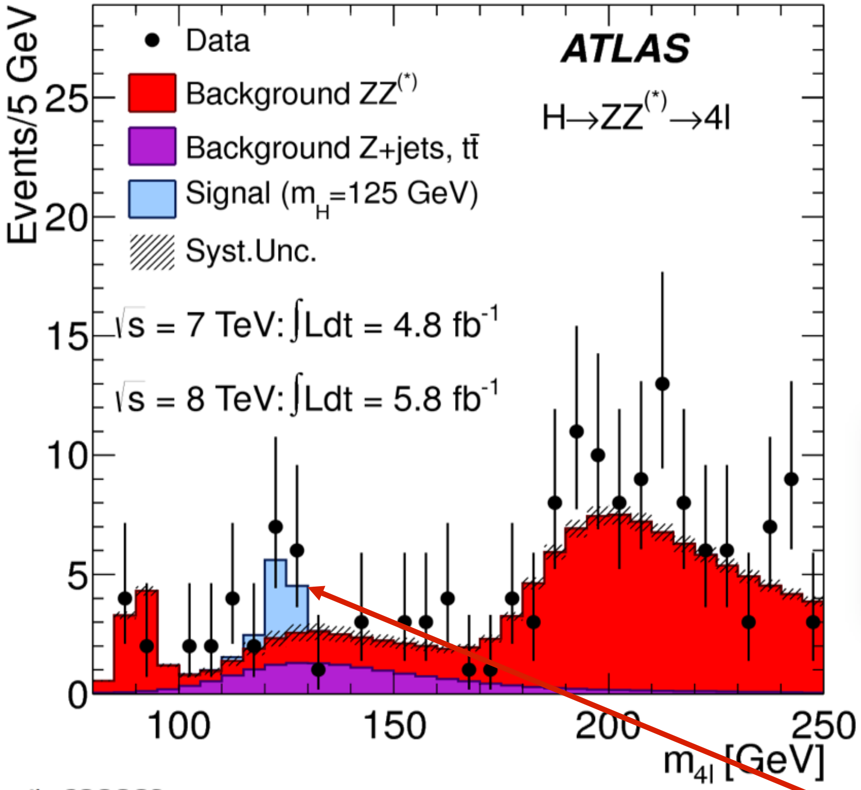


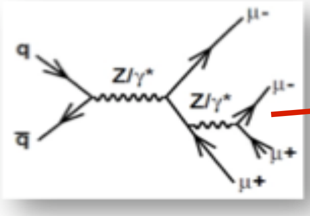


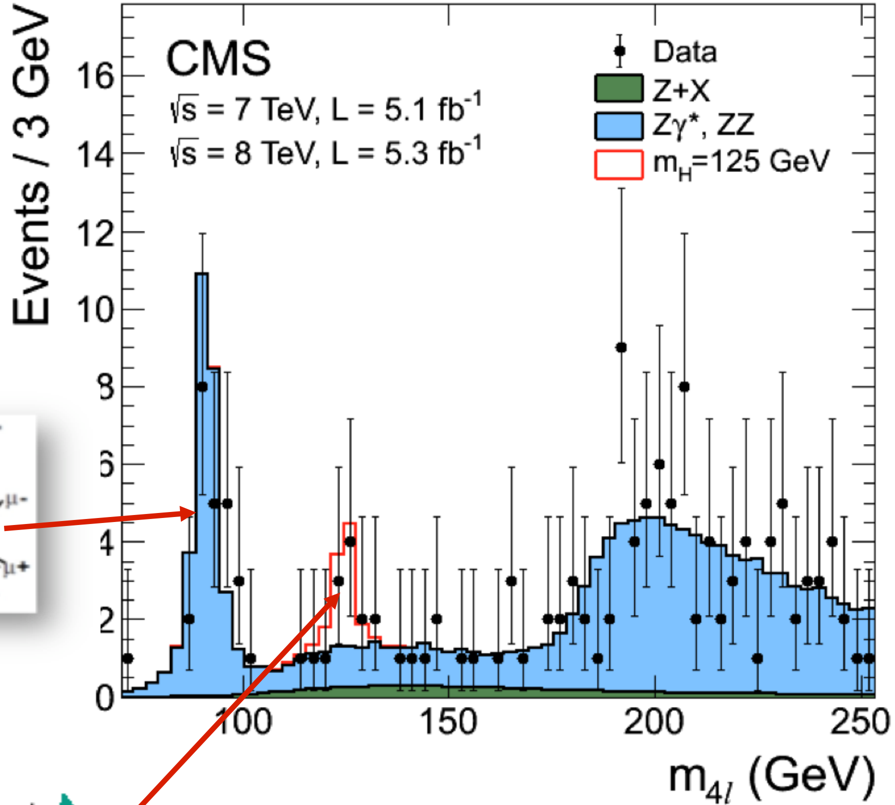


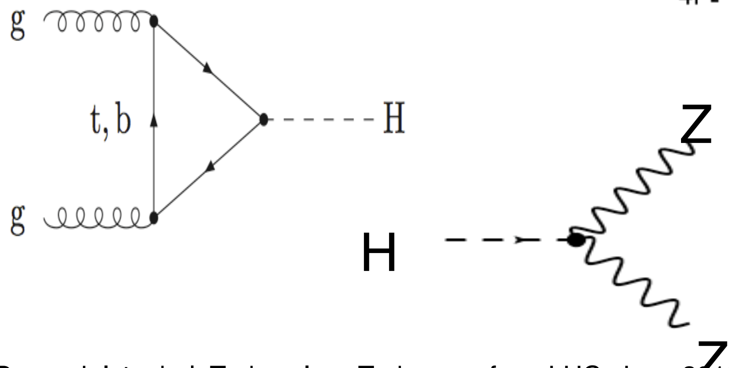
Such an event with a Higgs bozon decaying into 4 muons appears about once in 10^{15} proton-proton collisions in the LHC

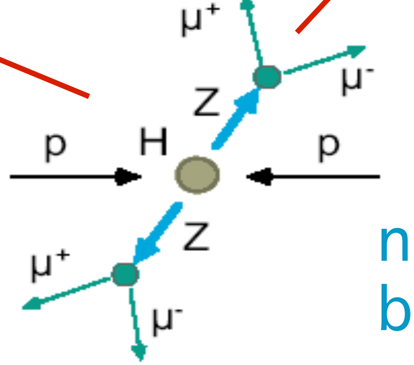
Higgs decay to 4 leptons, ATLAS and CMS, July 4th 2012





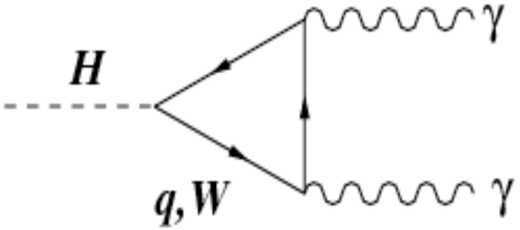


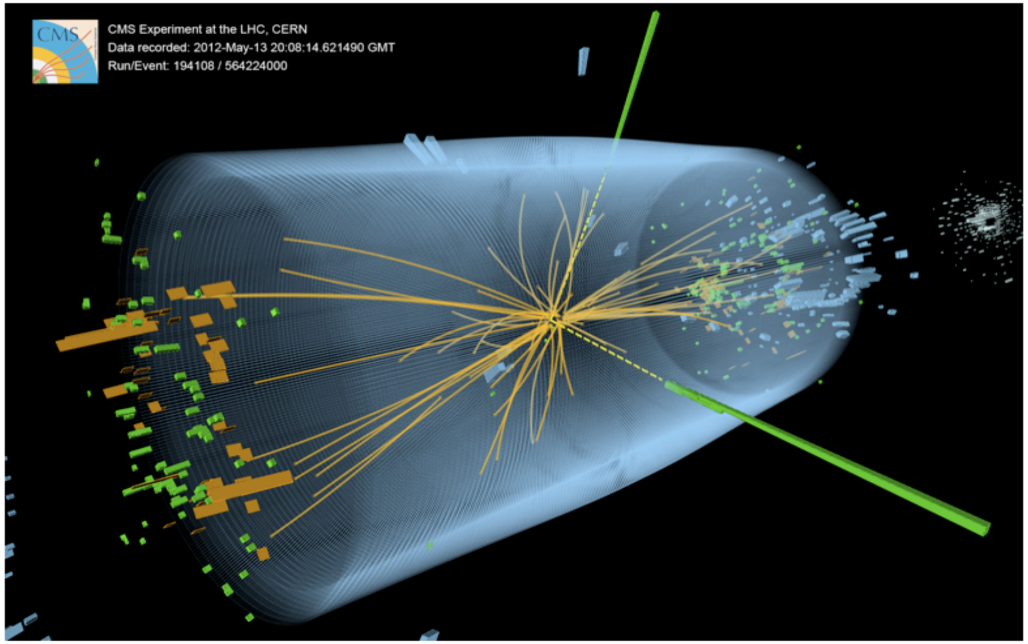


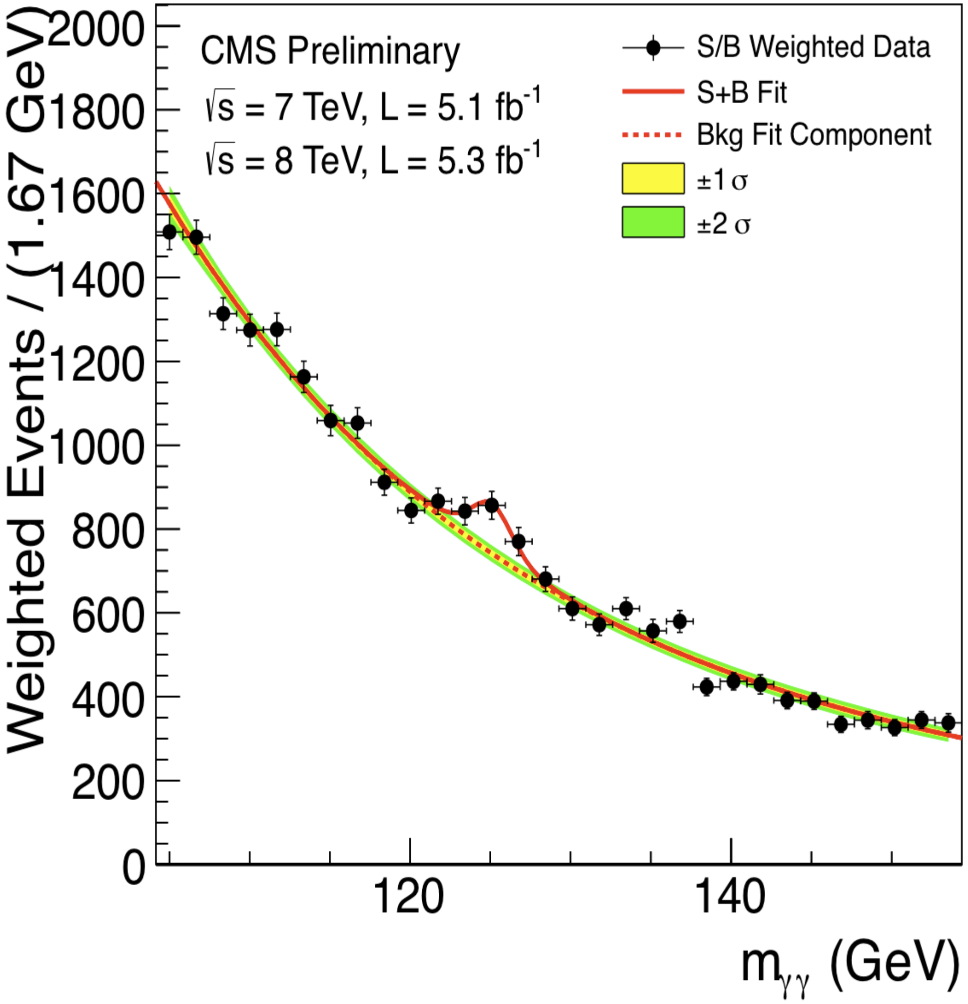


notice these modest beginnings! As for W, Z!

H → γγ candidate in CMS, situation July 2012

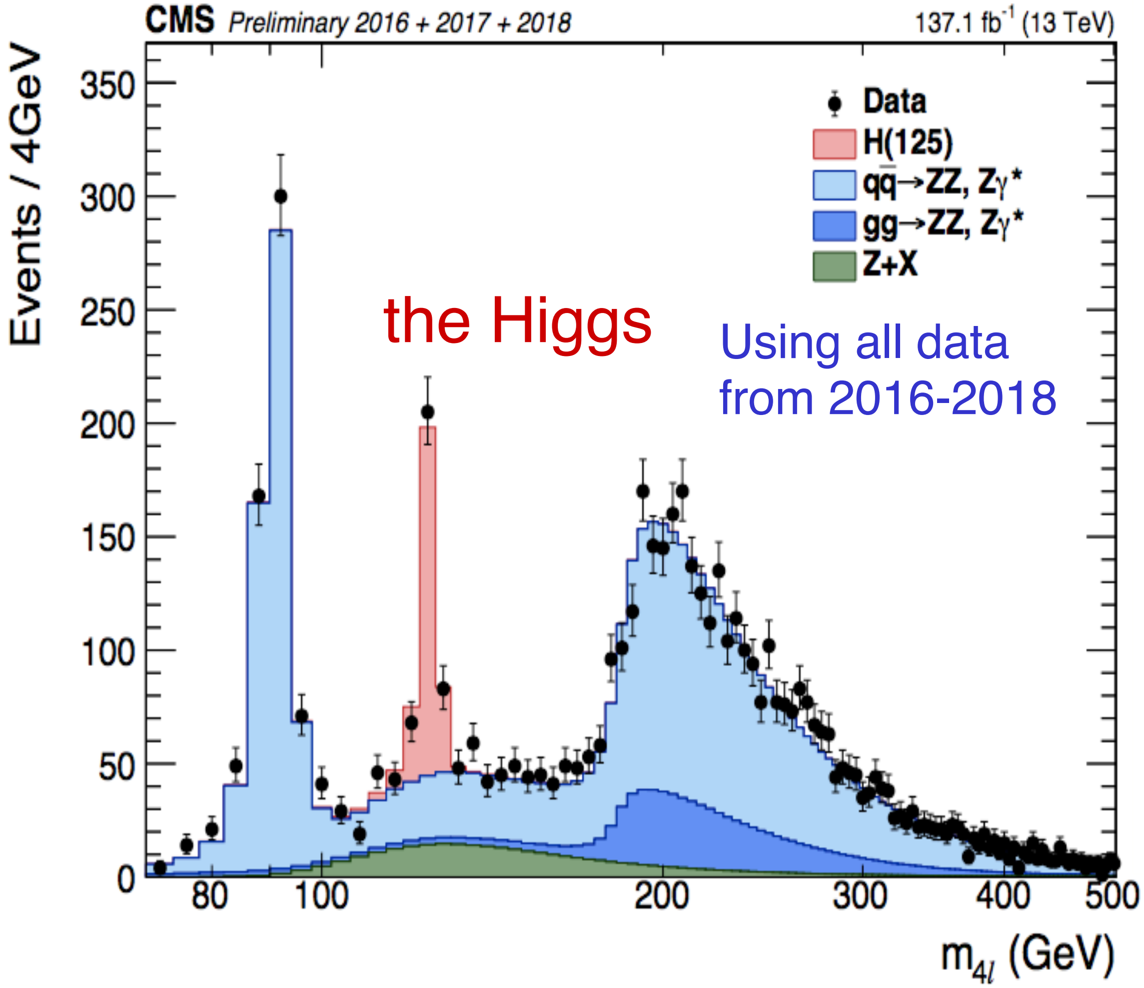






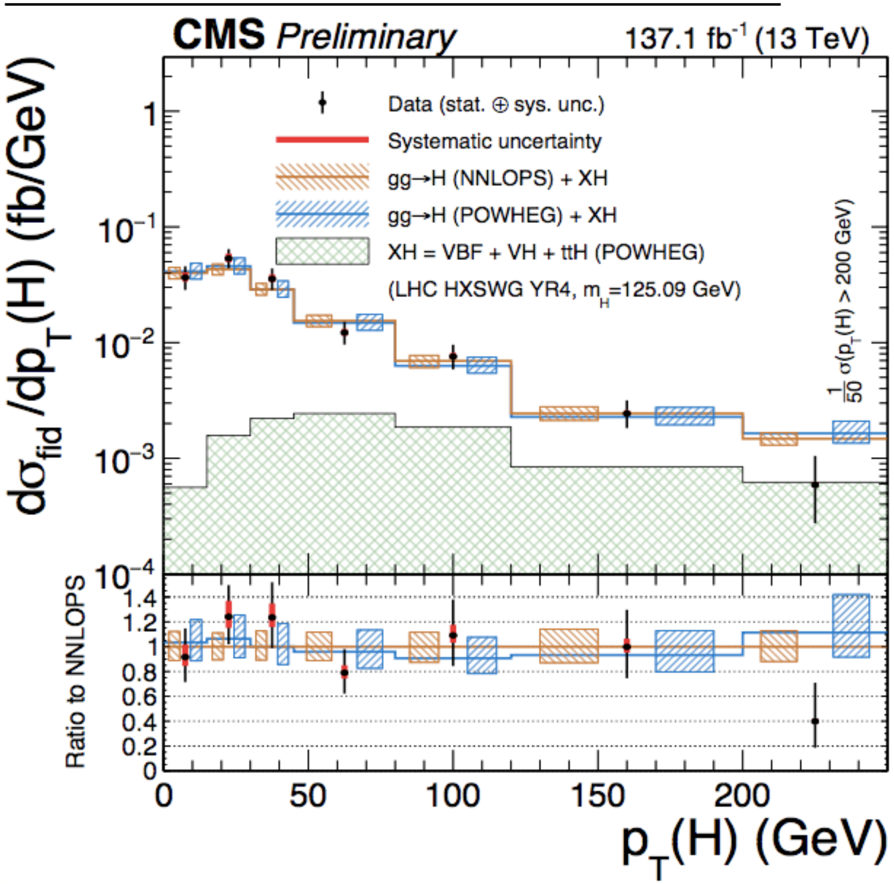
$$m^2_{\gamma\gamma} = 2 E_1 E_2 (1 - \cos\theta_{12})$$

H → ZZ → 4 leptons, full 13TeV stat. April 2019



the Higgs

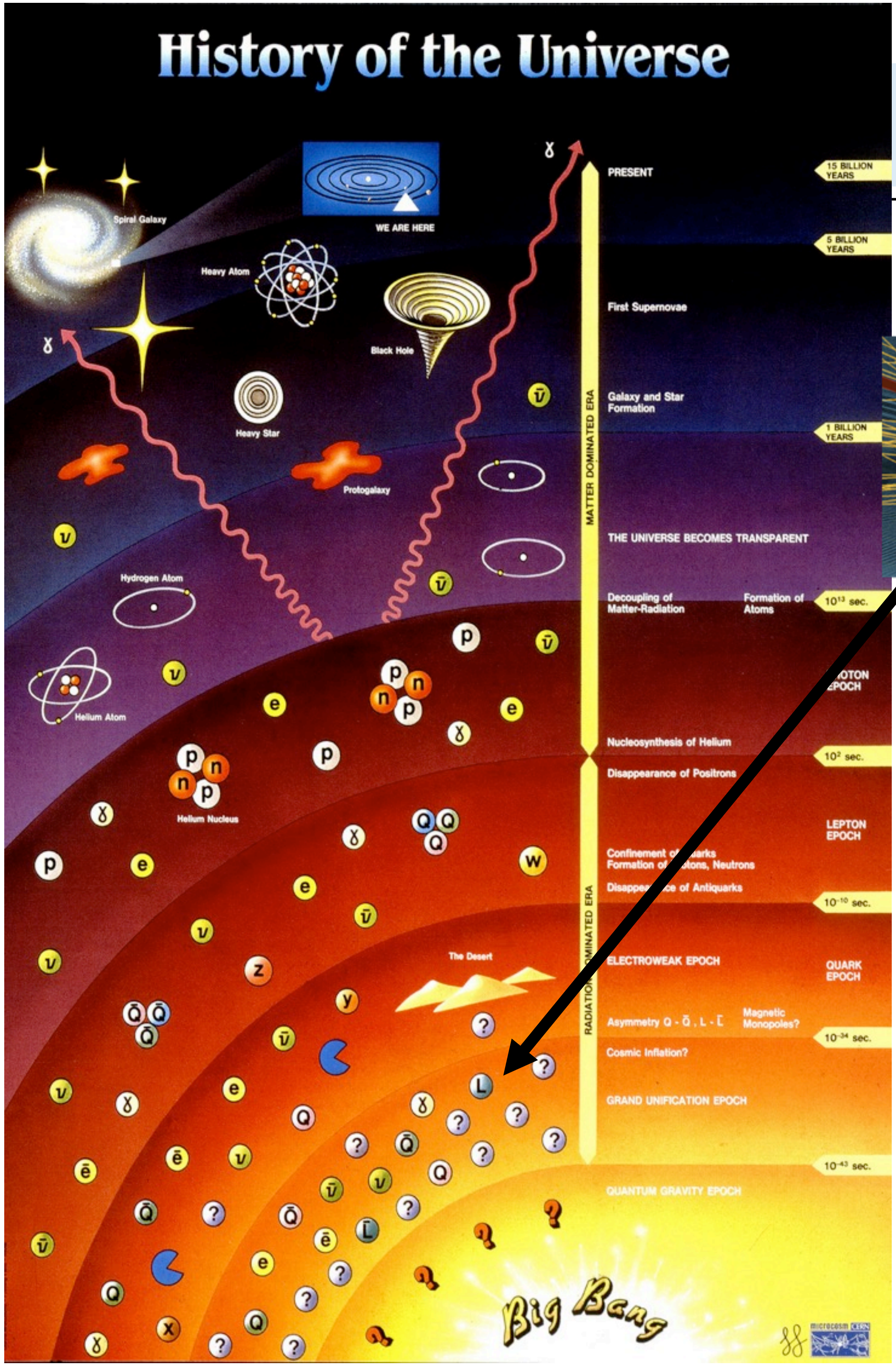
Using all data from 2016-2018



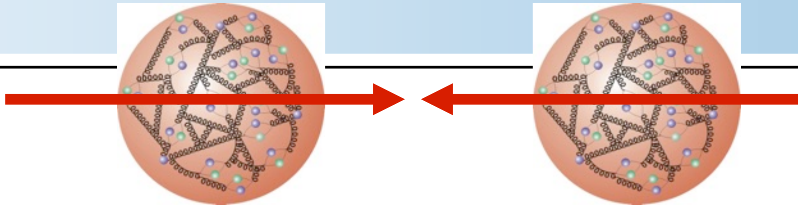
Large dataset allows now for studies of differential distributions

σ_{ZZ}= 17.1 ± 0.3(stat) ± 0.4(syst) ± 0.4(theo.) ± 0.3(lumi) pb

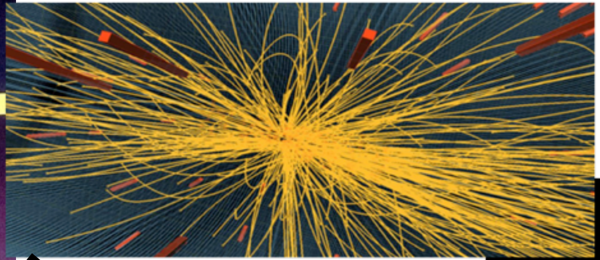
$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26} \qquad m_H = 124.50^{+0.48}_{-0.46}\ \text{GeV} = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})\ \text{GeV}$$

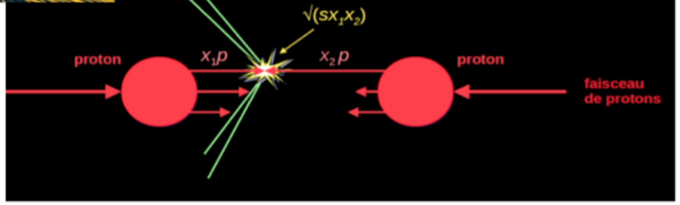


Mini Big-Bangs and the Higgs

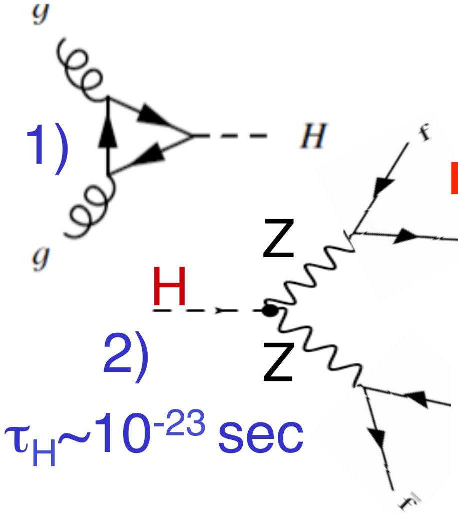


protons from collider beams





once in ~10^{15} collisions this will happen:

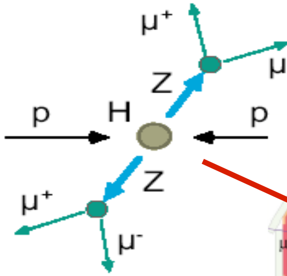


1)

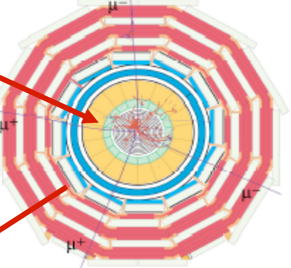
2)

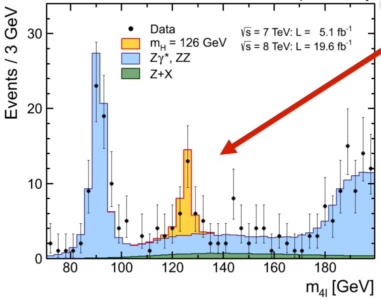
$\tau_H \sim 10^{-23}$ sec

$\tau_Z \sim 10^{-23}$ sec



after 20 years of construction



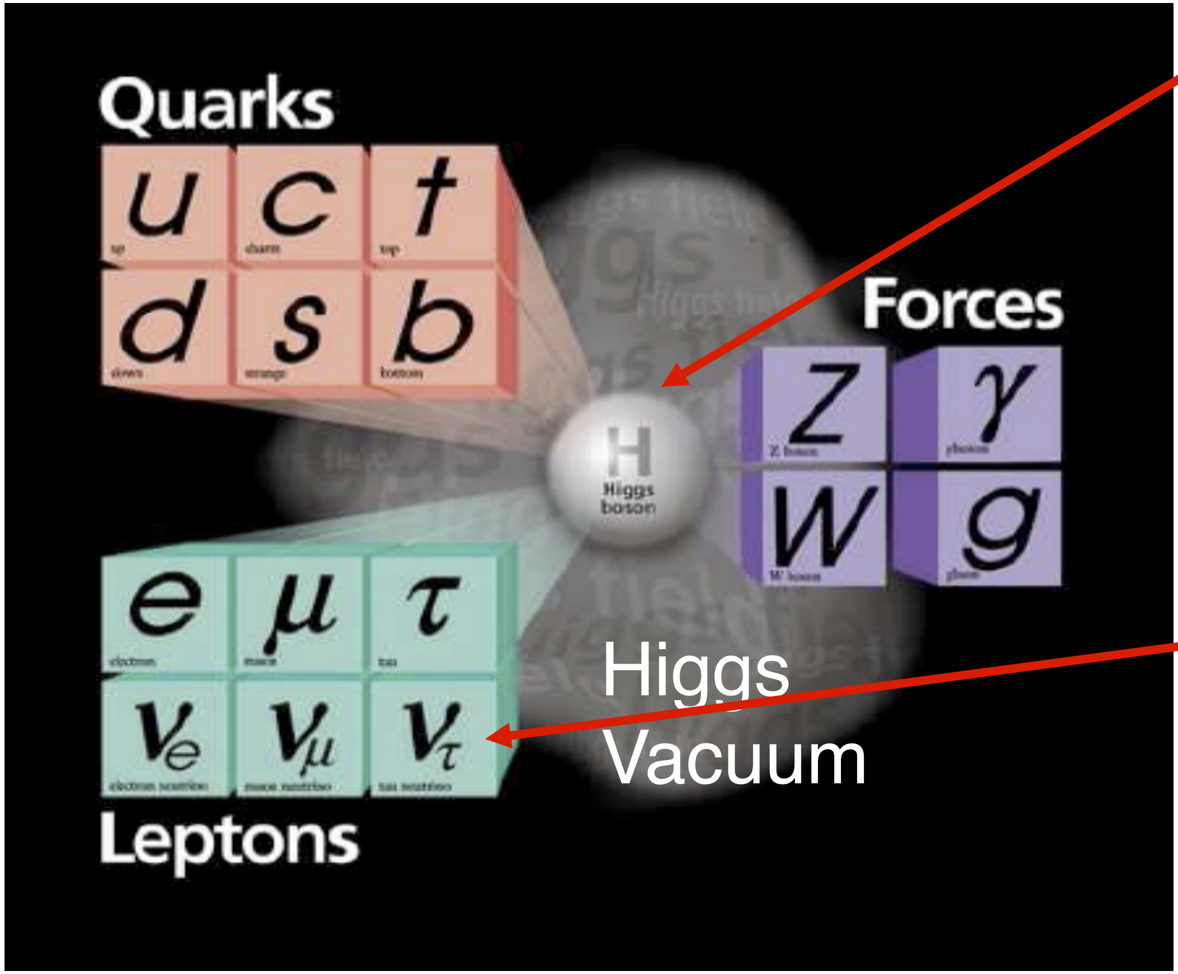


and after 3 years of collisions

Particle content of the Universe - status studies and questions for the future

Matter

Intermediate bosons



Higgs Vacuum

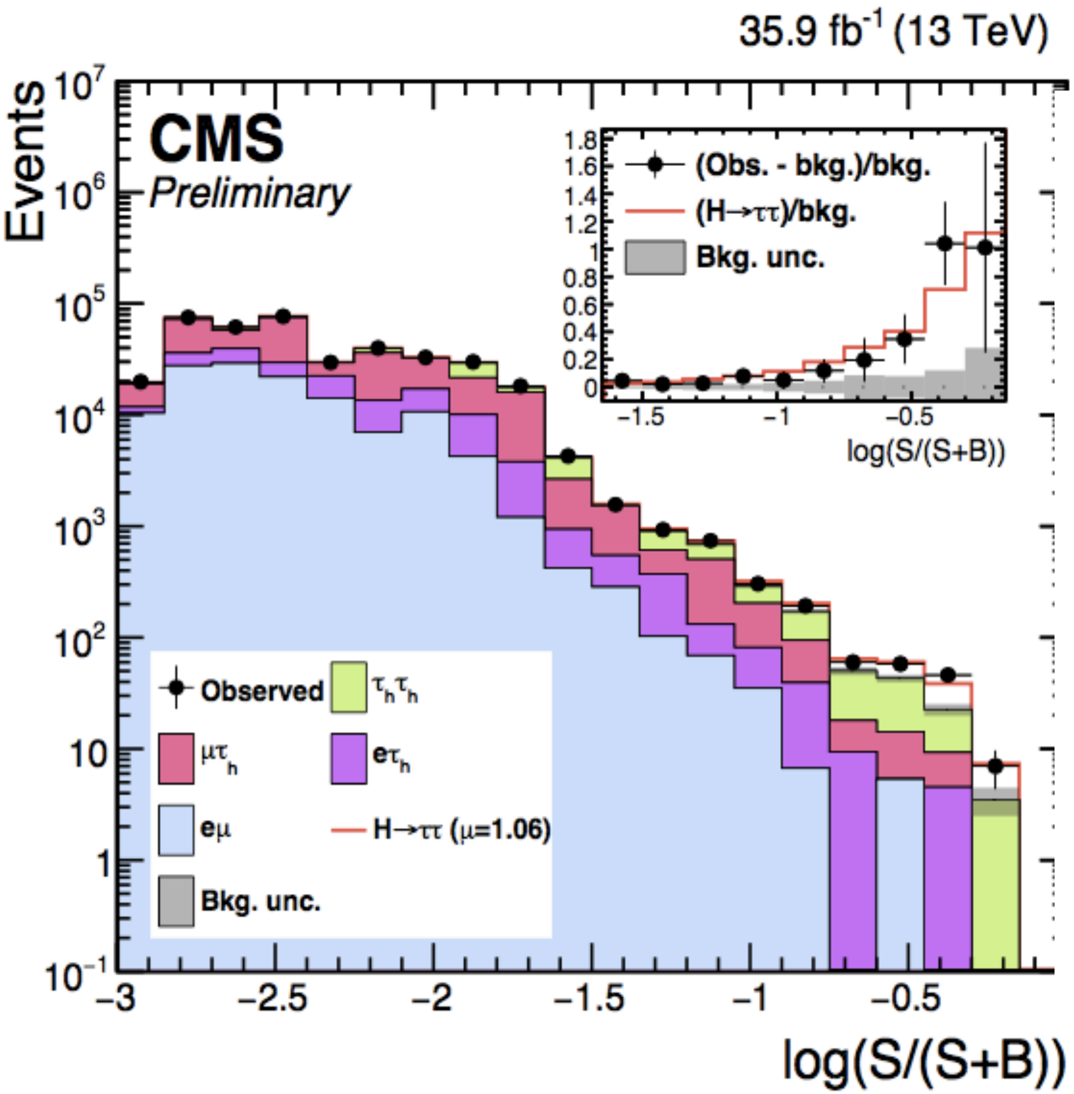
New Higgs sector
- Properties
- Couplings
- Symmetry breaking
- Vacuum stability

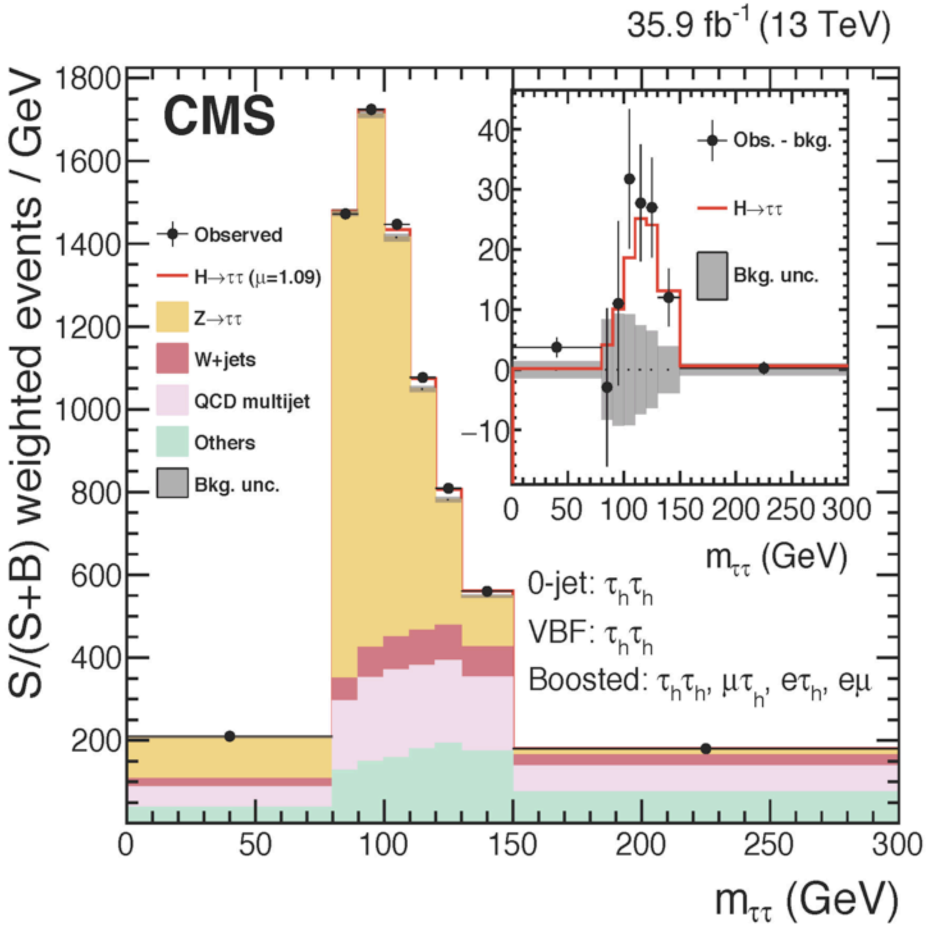
Neutrino sector
- Majorana/Dirac
- Masses & mixings
- CP violation
- Lepton flavor violation

The World Lagrangian our entire knowledge of the material world in this concise formulation, except for gravity - requiring a different formulation (General Relativity)

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&+ i \bar{\psi} \not{D} \psi + h.c. \\
&+ \psi_i y_{ij} \psi_j \phi + h.c. \\
&+ |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

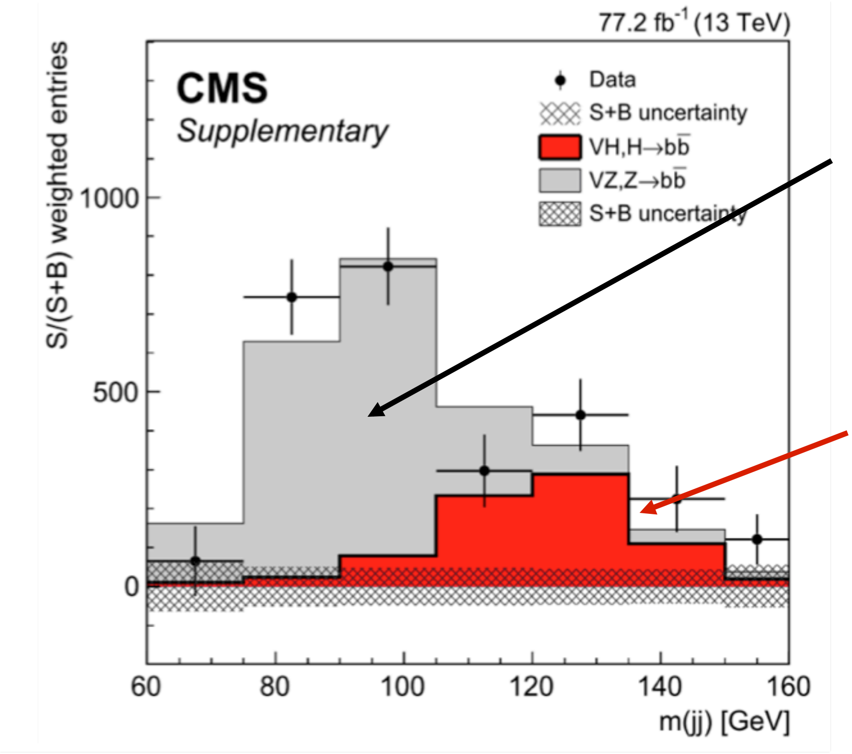
Higgs → $\tau^+\tau^-$, CMS





Observation of H → bb decay

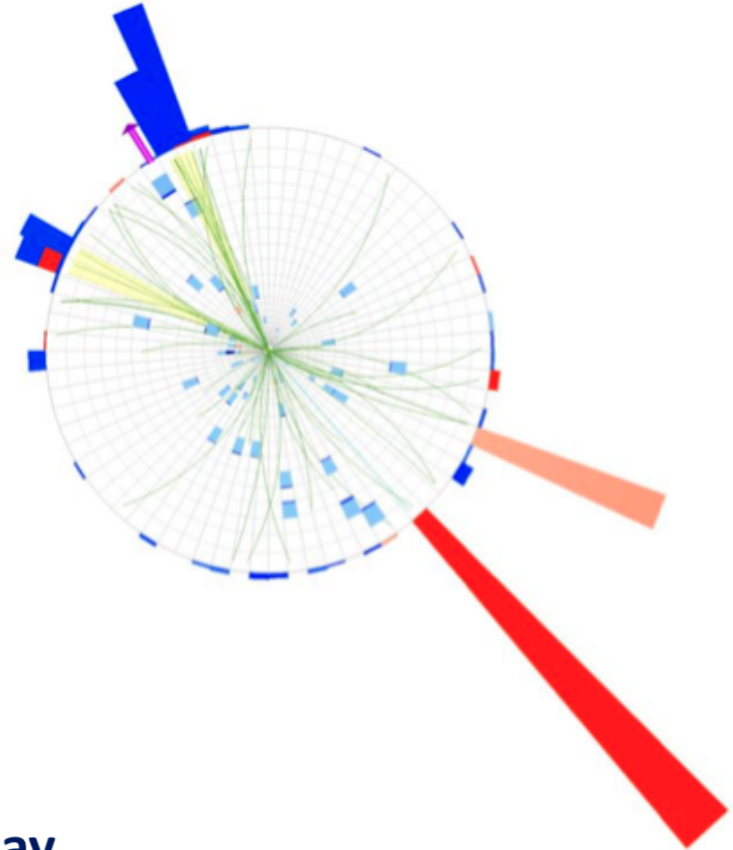
Candidate for HZ production followed by Z → ee and H → bb



ZZ → ee + bb

ZH → ee + bb

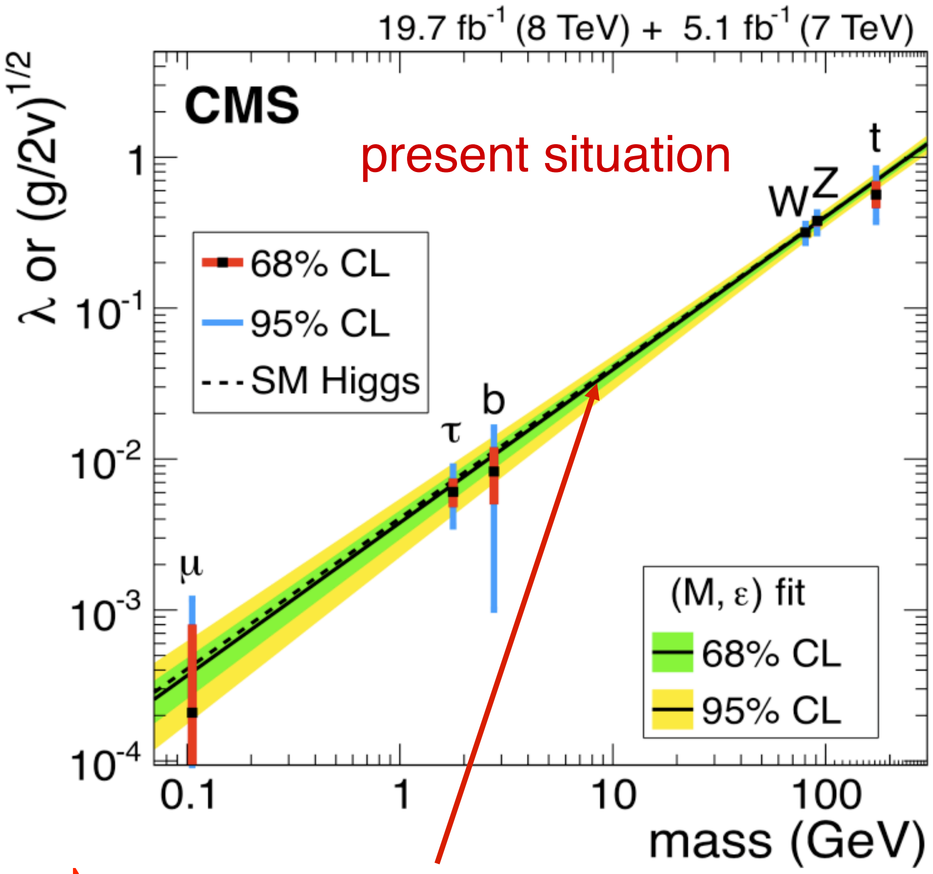
WH → lν + bb



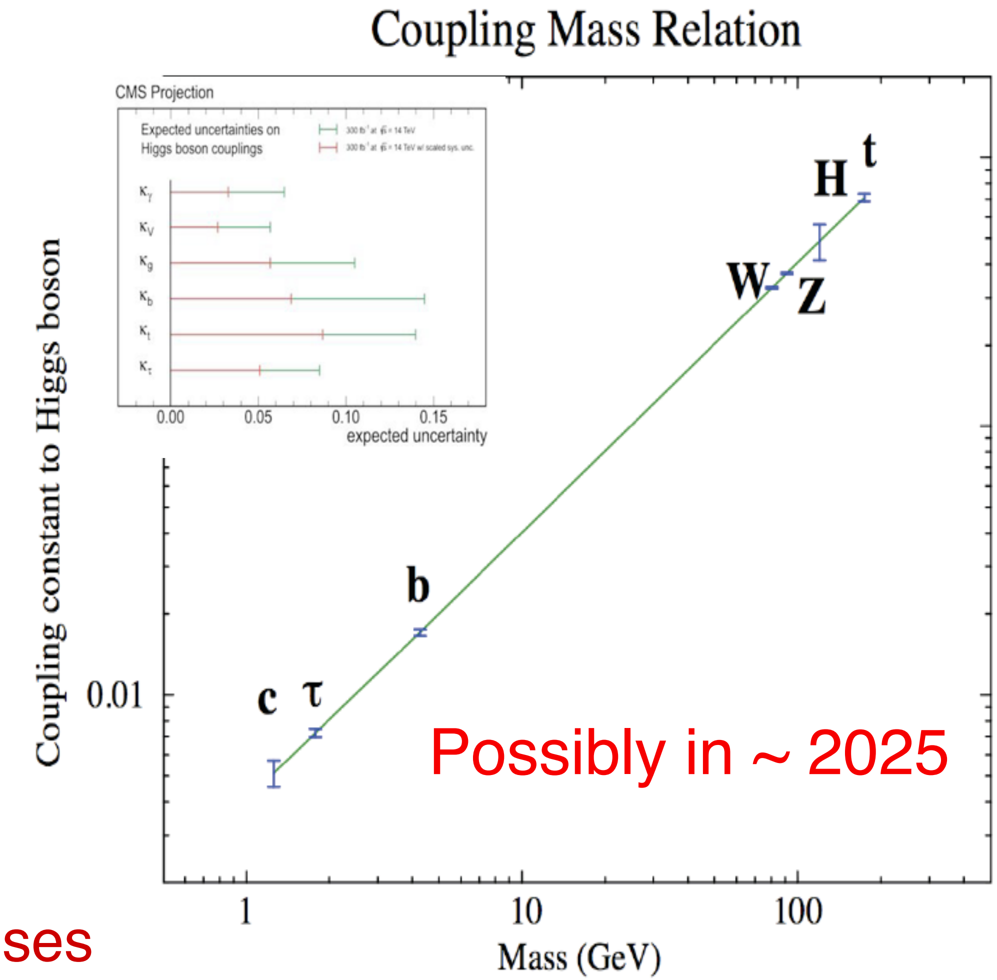
CMS has reached a 5.6σ observation of the H→bb decay, with signal strength μ = 1.04 ± 0.20

- Combination of several production channels, dominated by VH(bb)
- Result contained in HIG-18-016, arXiv:XXXX.XXXXX submitted to PRL

Higgs couplings, the key prediction of the theory, present situation and expectations for LHC by about 2025



present situation



Possibly in ~ 2025

Higgs couplings ∝ particle masses

We need precise measurements of properties looking for small deviations to clarify/understand the exact nature of the observed Higgs boson; for ex. in the decoupling limit of the MSSM the h is very much SM-like! Is it really elementary?

Higgs couplings - why is precision needed….I

New physics affects the Higgs couplings:

SUSY
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$
for tanβ = 5

Composite Higgs
$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

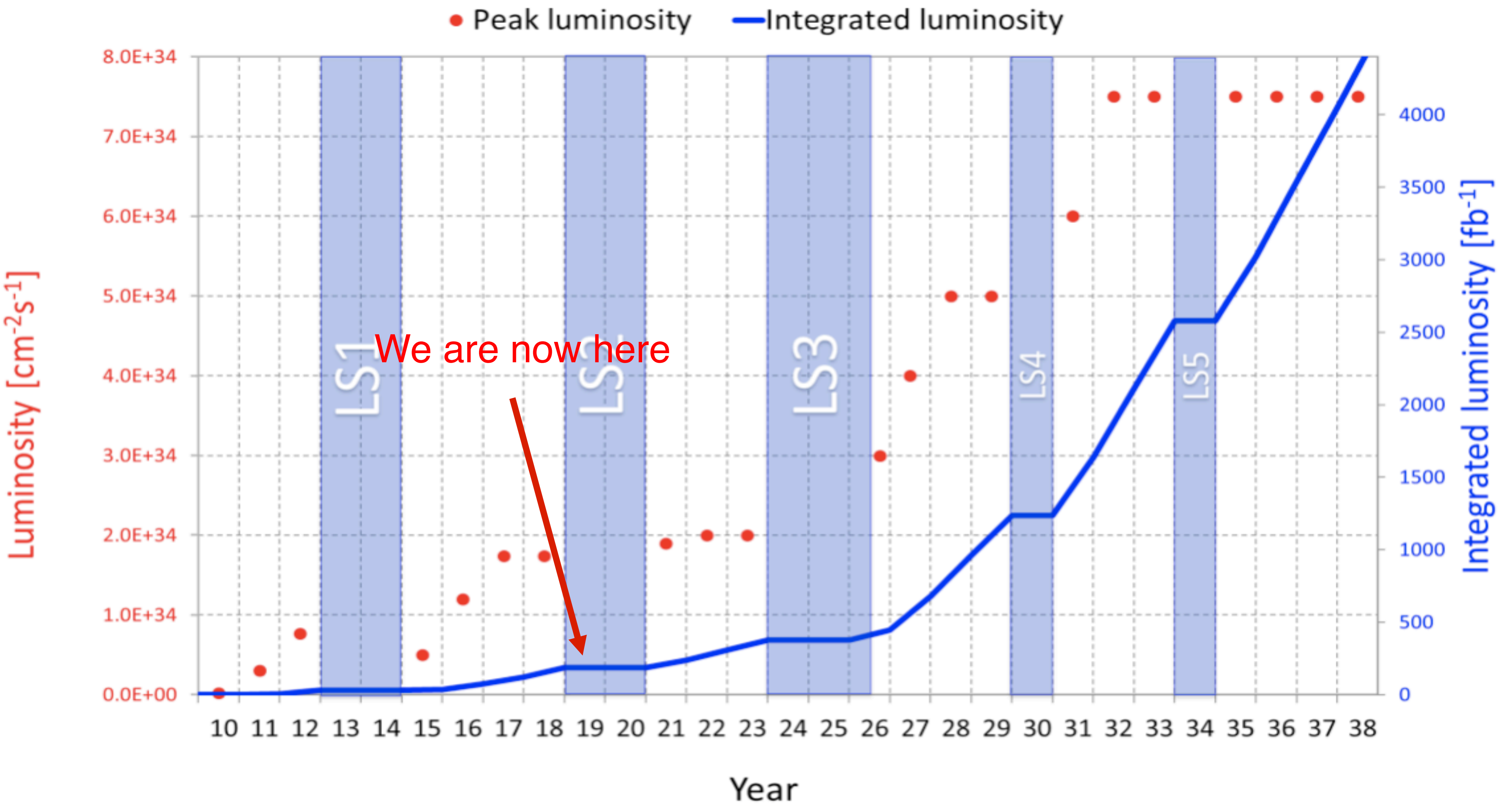
Top partners
$$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$$

Other models may give up to 5% deviations with respect to the Standard Model

➡ Sensitivity to “TeV” new physics needs per-cent to sub-per-cent accuracy on couplings for 5 sigma evidence/discovery

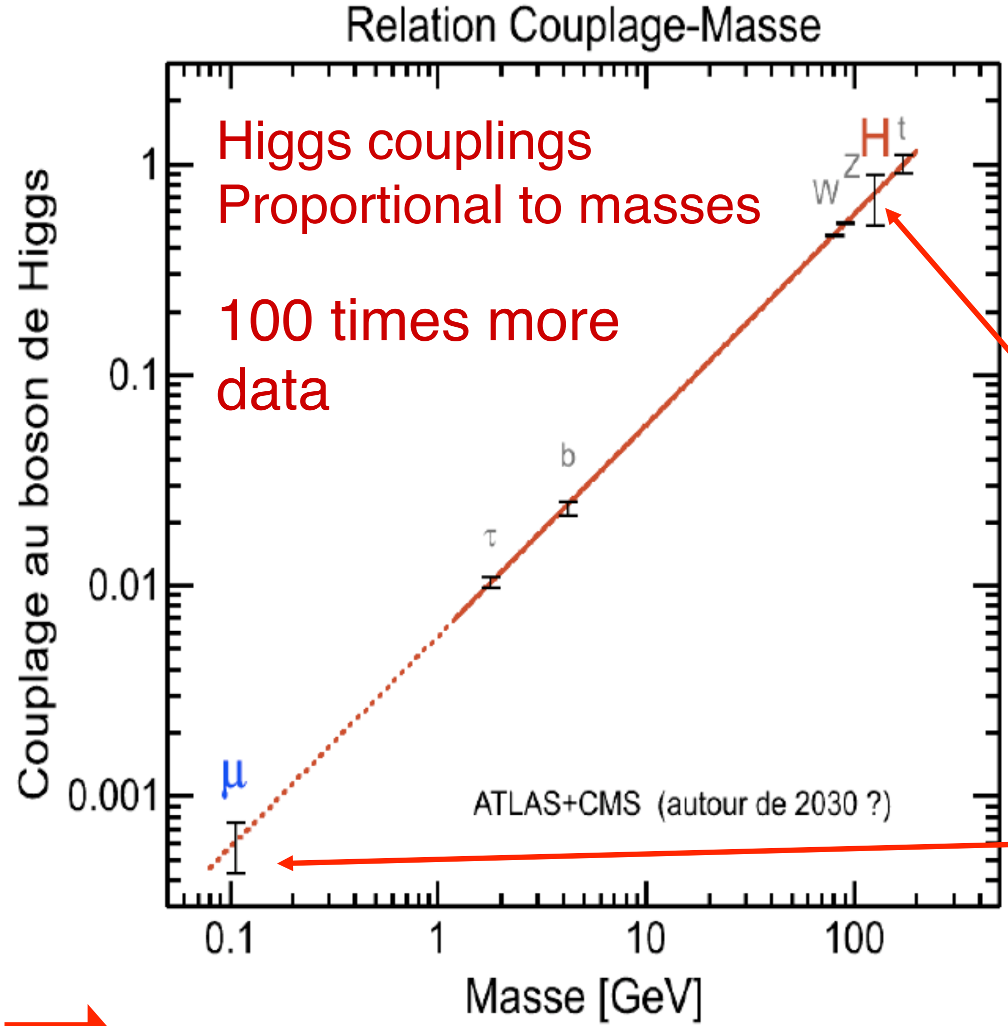
Evolution of LHC luminosity till 2038

- october 2018 HL-LHC workshop -



We are now here

Higgs couplings - future up to HL-LHC and 3000fb^{-1}



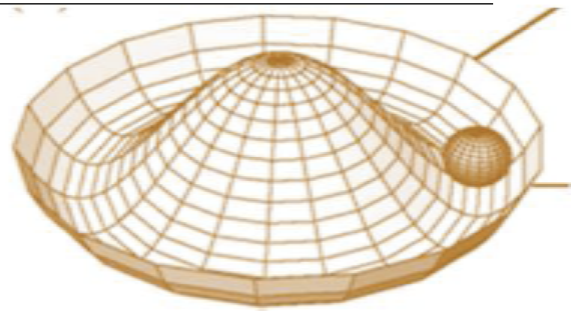
Higgs couplings
Proportional to masses

100 times more data

$g_{Hff} = m_f/v$

$g_{HHH} = 3m_H^2/v$

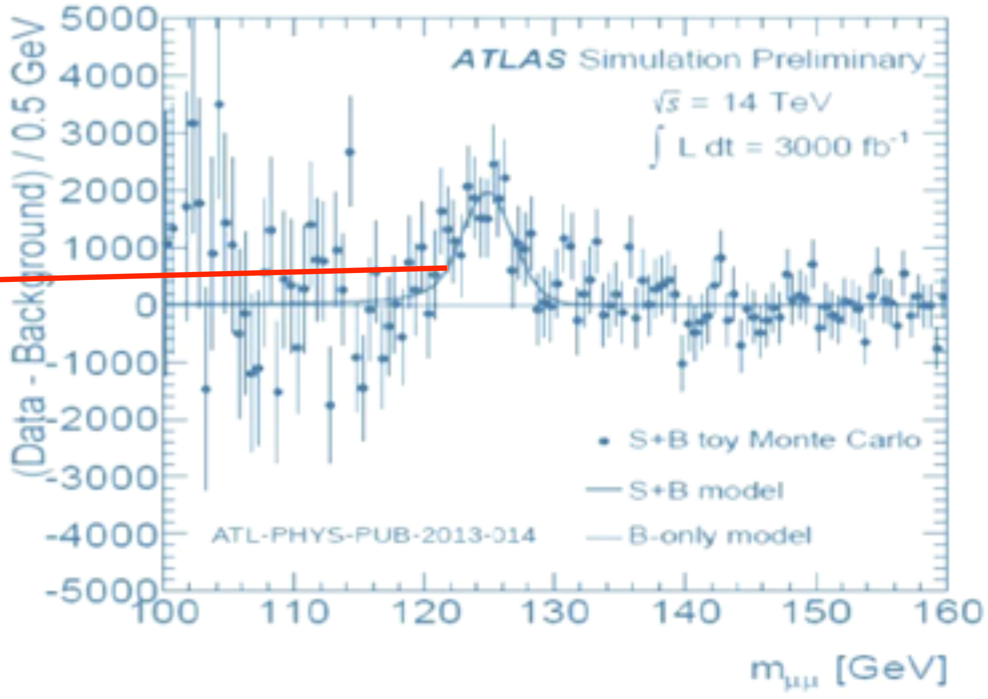
$g_{HVV} = 2m_V^2/v$



$v = (-\mu^2/\lambda)^{???} = 246$

Γεζ

Higgs self-coupling and Higgs potential

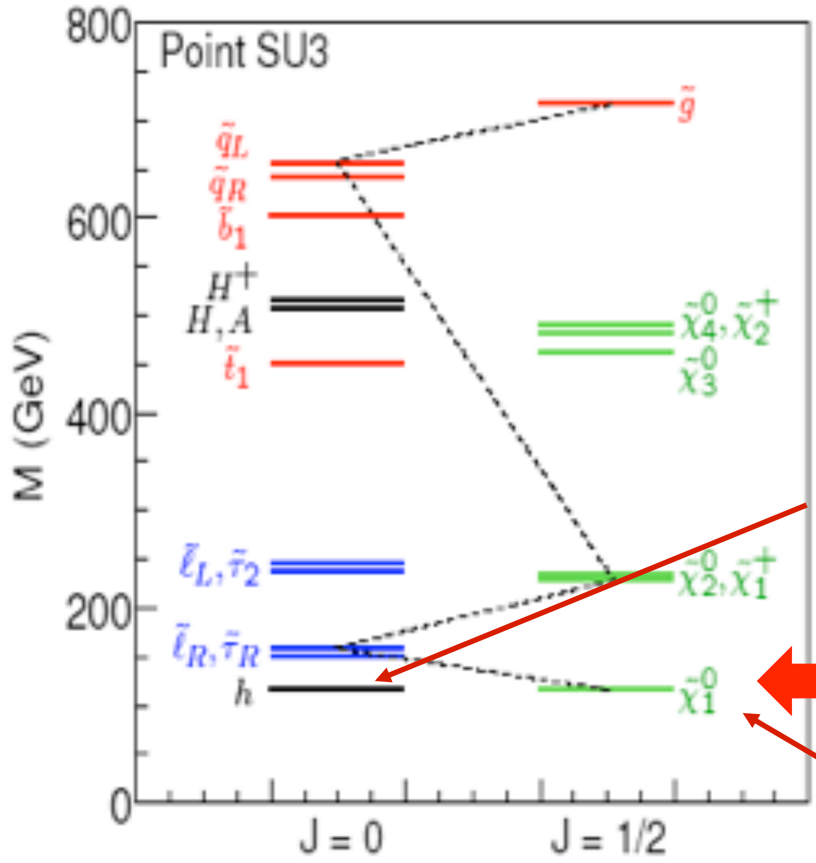


With 3000fb^{-1} data at 13 TeV (by ~ 2025) couplings to 8 particles, including coupling to muons

Looking further for physics beyond the Standard Model

- SUSY
- DM…..

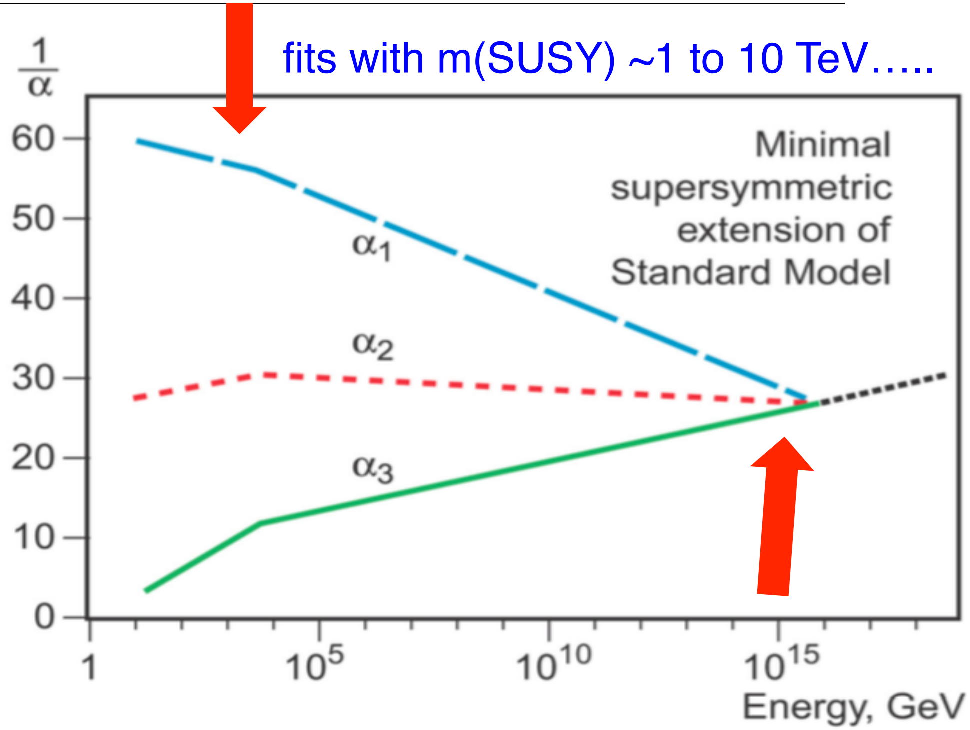
SUSY - could solve a number of problems at ew scale……..

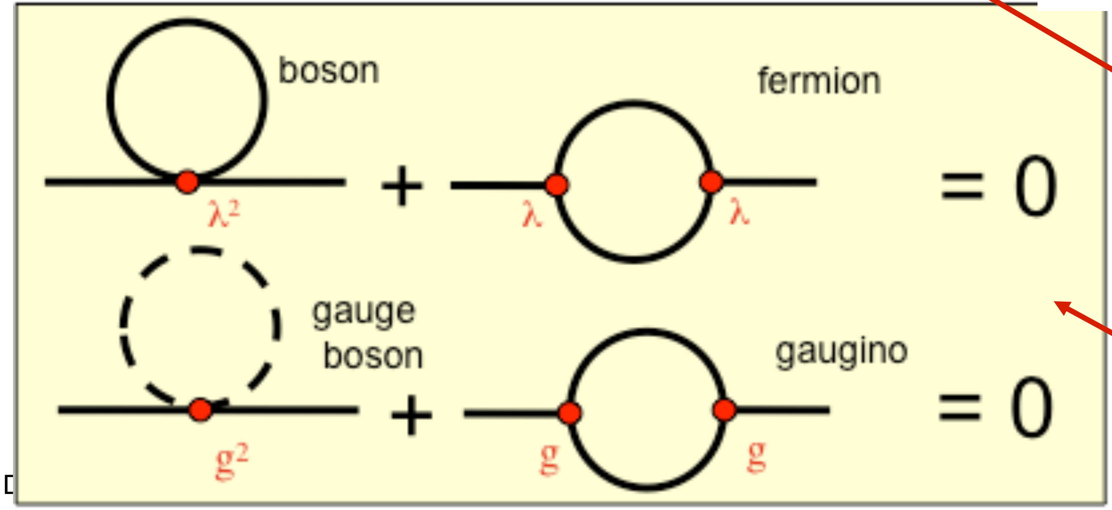


Present Higgs?

LSP

fits with m(SUSY) ~1 to 10 TeV…..



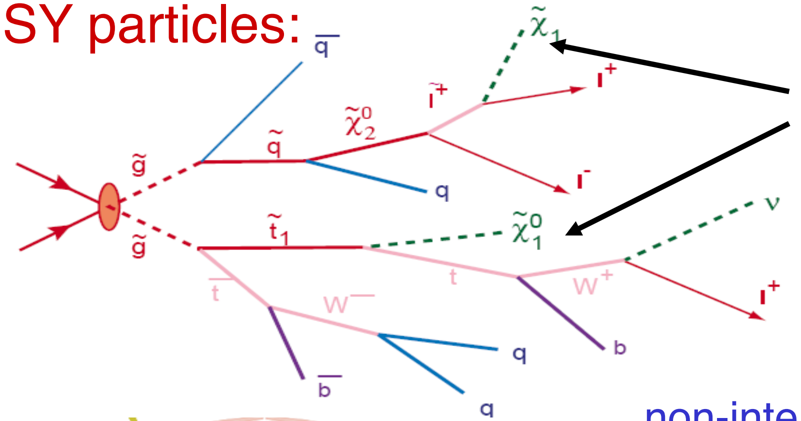


Possibly the DM particle….

Stabilizes Higgs boson mass

DM – could SUSY and the LHC bring the solution? SUSY search in jets + missing-E_t channel

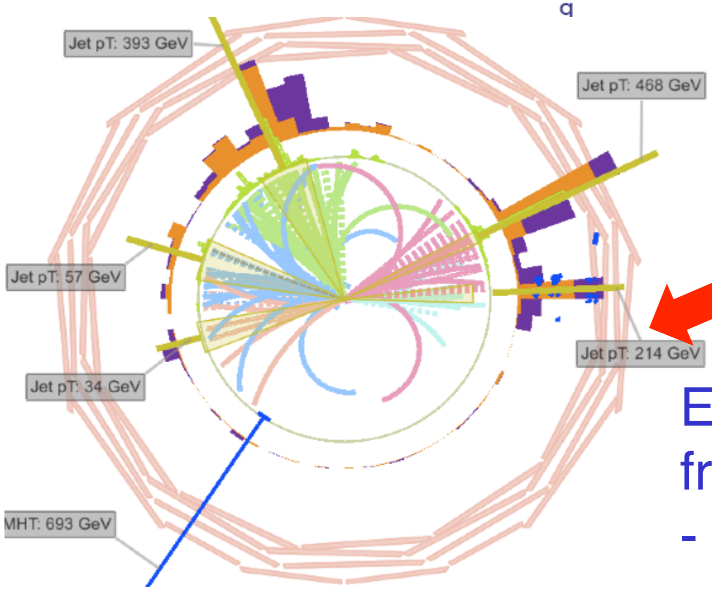
Proton-proton collision at the LHC producing a pair of SUSY particles:



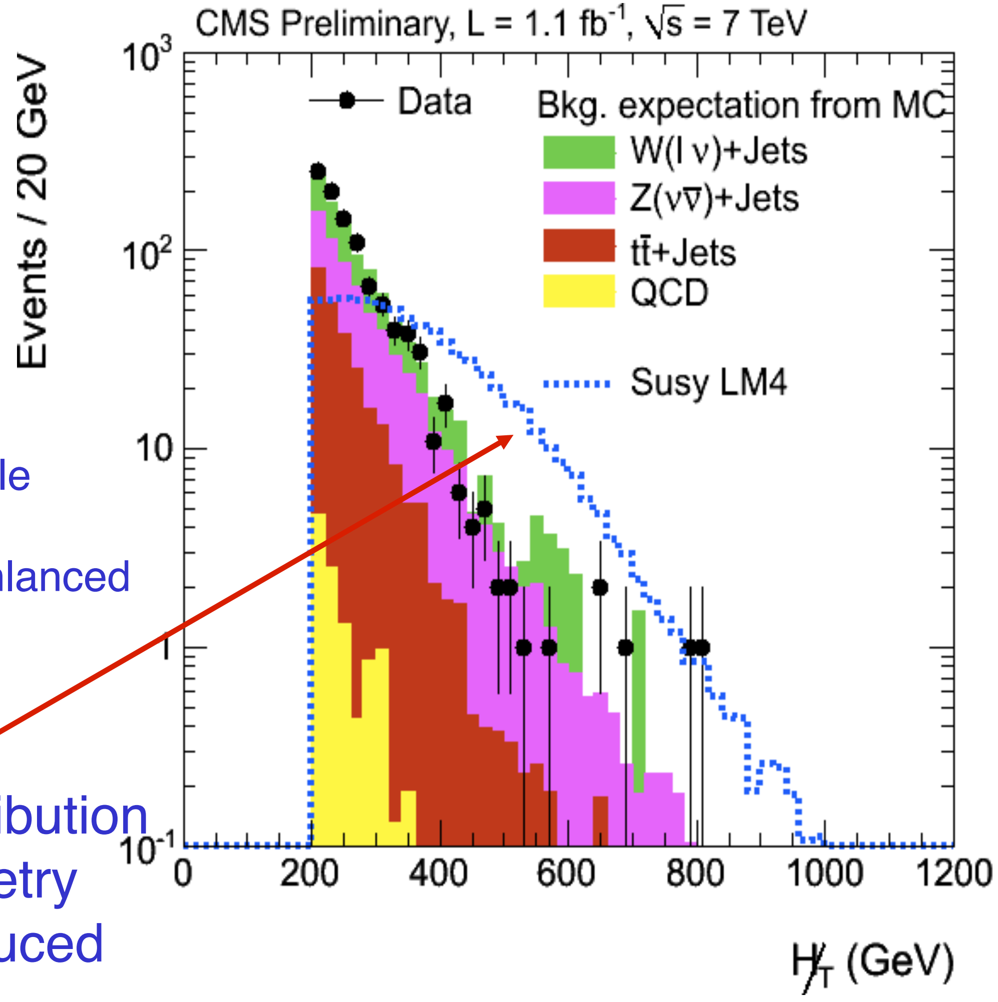
LSP

non-interacting "escaping" particle

resulting in unbanlanced events



Missing transverse energy

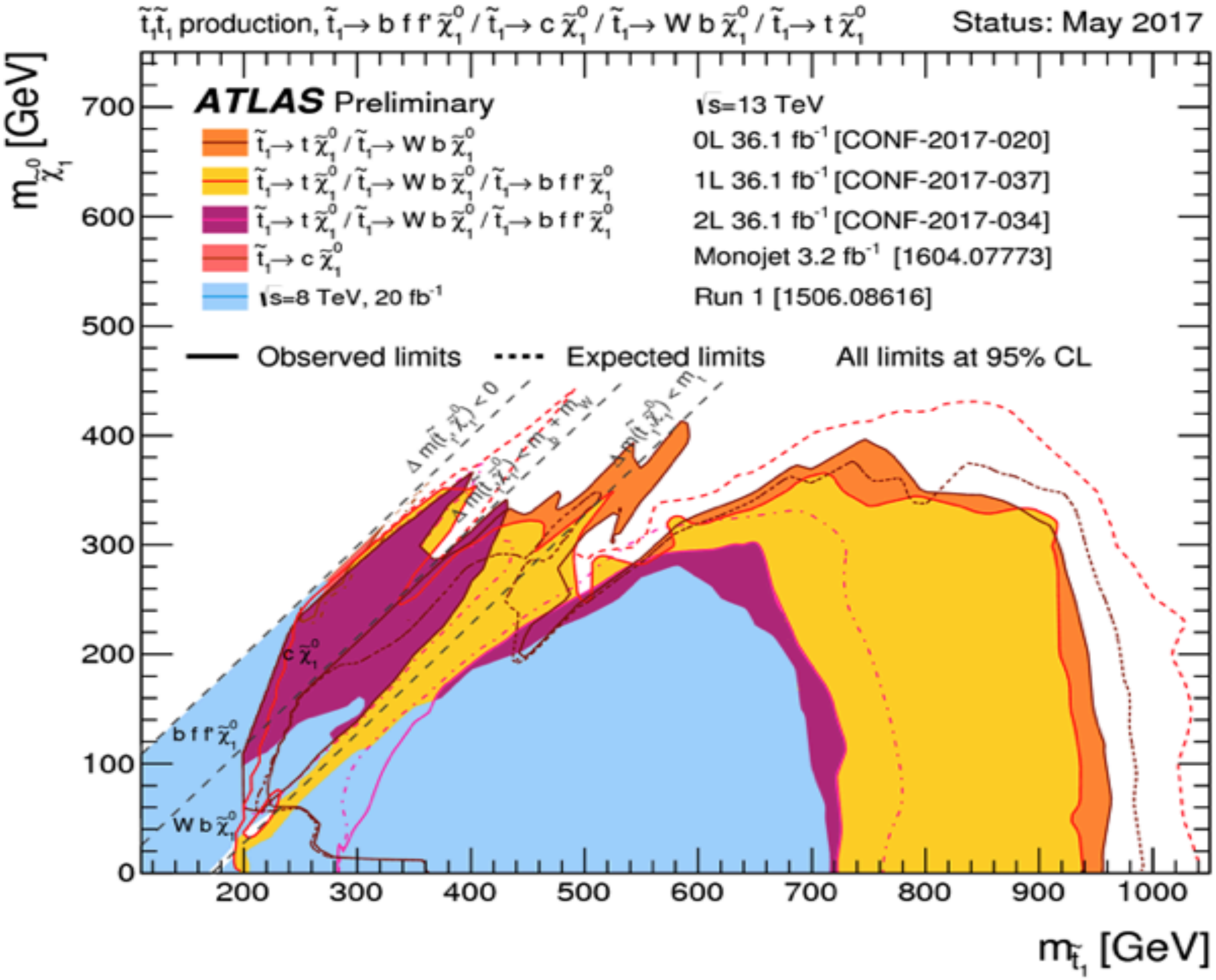


Expected contribution from supersymetry
- if it were produced

Nothing has yet been observed at the LHC….
insuficient statistics or energy?

D. Denegri; Istanbul, Turkey, Iran-Turkey conf. on LHC, June 2019

Stop searches, ATLAS

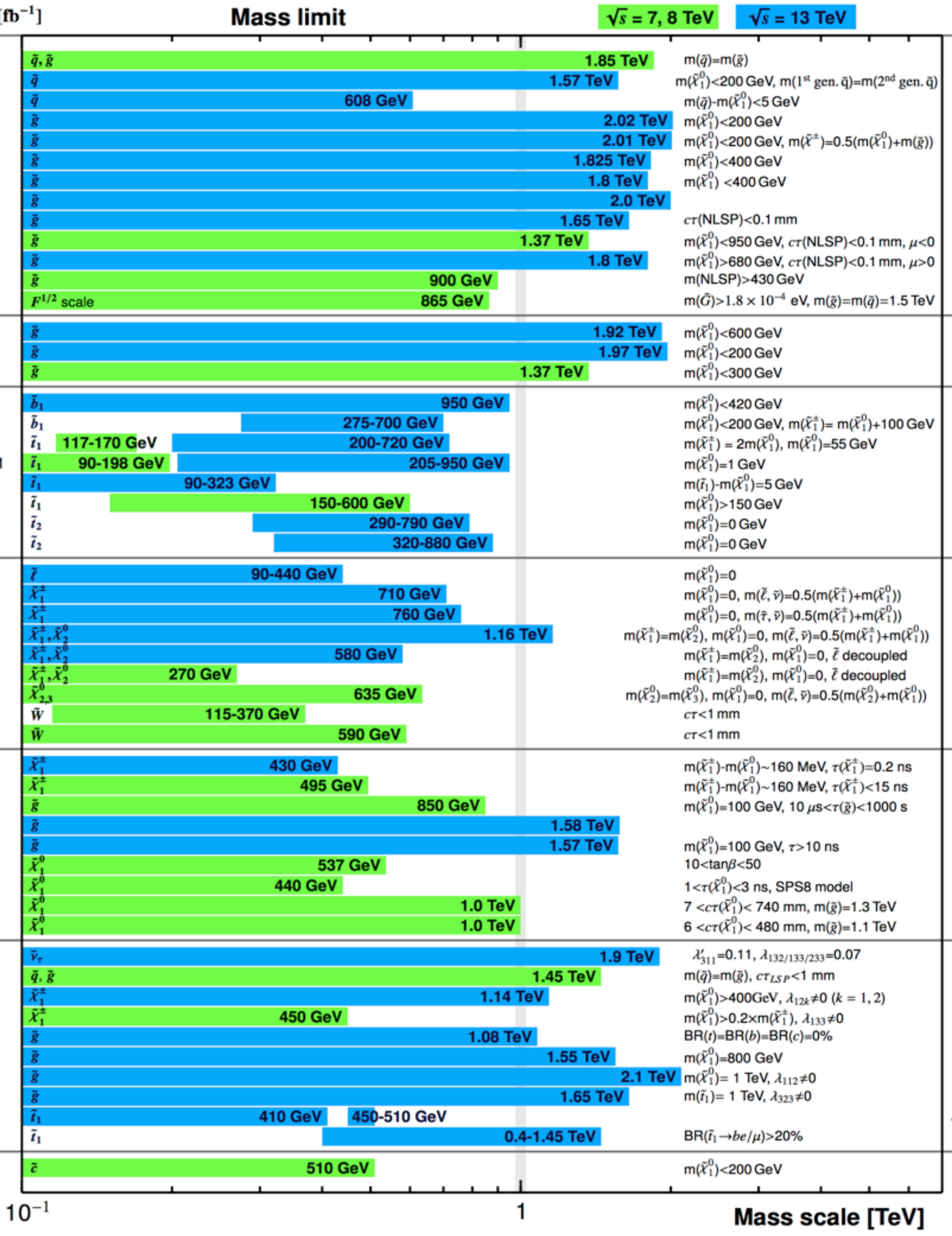


$m(t_1) > 950$ GeV

ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV



🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	🟩 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$	🟦 1.57 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	🟦 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.02 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.01 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	36.1	$\tilde{g}$	🟦 1.825 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$	🟦 1.8 TeV	m($\tilde{\chi}^0_1$) <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$	🟦 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$	🟦 1.8 TeV	m($\tilde{\chi}^0_1$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	$\tilde{g}$	🟦 1.92 TeV	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$	🟦 1.97 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	36.1	$\tilde{b}_1$	🟦 950 GeV	m($\tilde{\chi}^0_1$)<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	🟦 275-700 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)= m($\tilde{\chi}^0_1$)+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}^\pm_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	🟩 90-198 GeV 🟦 205-950 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	$\tilde{t}_1$	🟦 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	🟩 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	🟦 290-790 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$	🟦 320-880 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$	🟦 90-440 GeV	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	$\tilde{\chi}^\pm_1$	🟦 710 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^\pm_1$	🟦 760 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	🟦 1.16 TeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	🟦 580 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	🟩 270 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$	🟩 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	$\tilde{W}$	🟩 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^\pm_1$	🟦 430 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^\pm_1$	🟩 495 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	🟩 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	🟦 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$	🟩 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$	🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$	🟩 1.0 TeV	6 <$c\tau$($\tilde{\chi}^0_1$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}^\pm_1$	🟦 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$	🟩 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	🟦 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	🟦 1.55 TeV	m($\tilde{\chi}^0_1$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 2.1 TeV	m($\tilde{\chi}^0_1$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$	🟦 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$	🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$	🟩 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

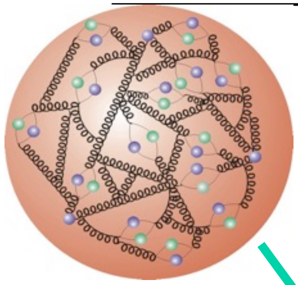
**Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

CERN - the longer term plans…. (~ 2035 till ~ 2060)

ILC - CLIC - FCC

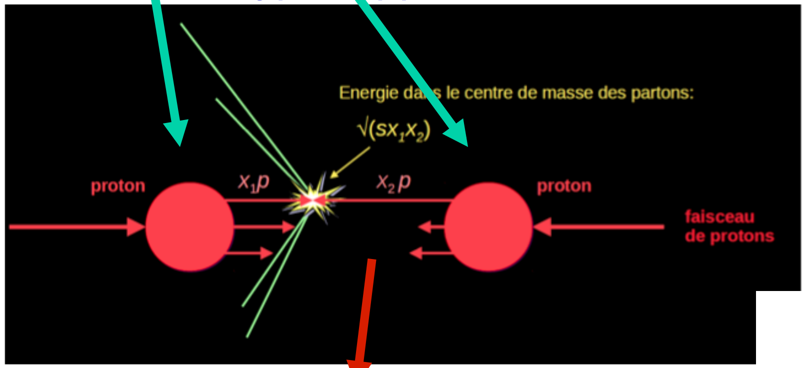
and the international competition….

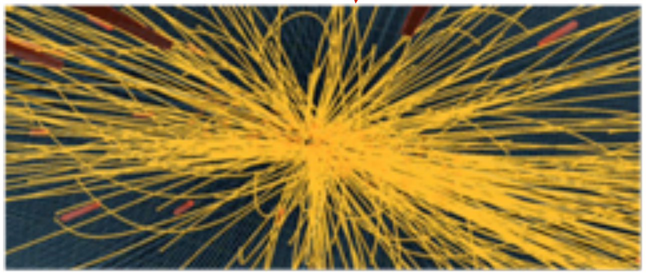
Higgs production at e^+e^- colliders, simple, clean final states in contrast to pp collisions

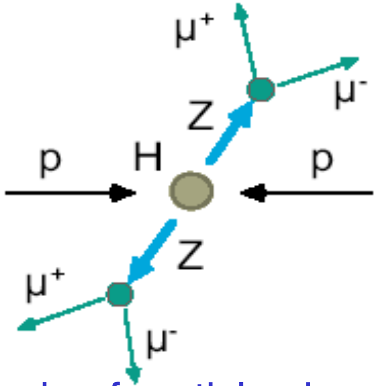


The proton is a complex system,
with three 'valence' quarks,
a 'sea' of quark-antiquark pairs
and a multitude of gluons

Typical pp collisions:

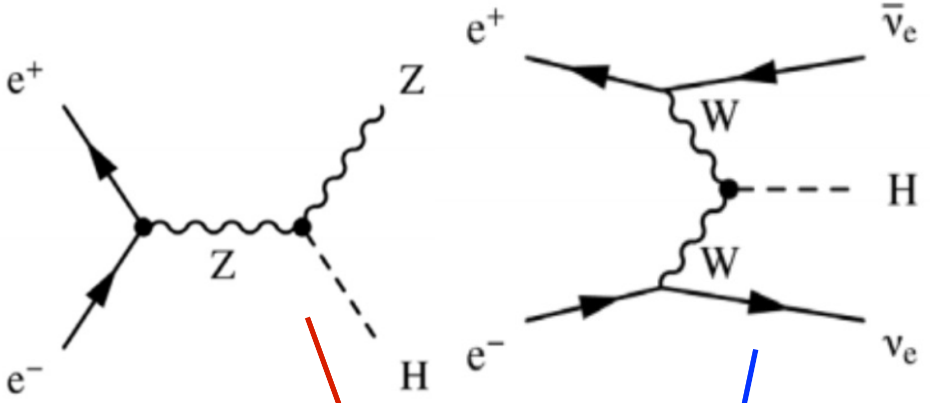


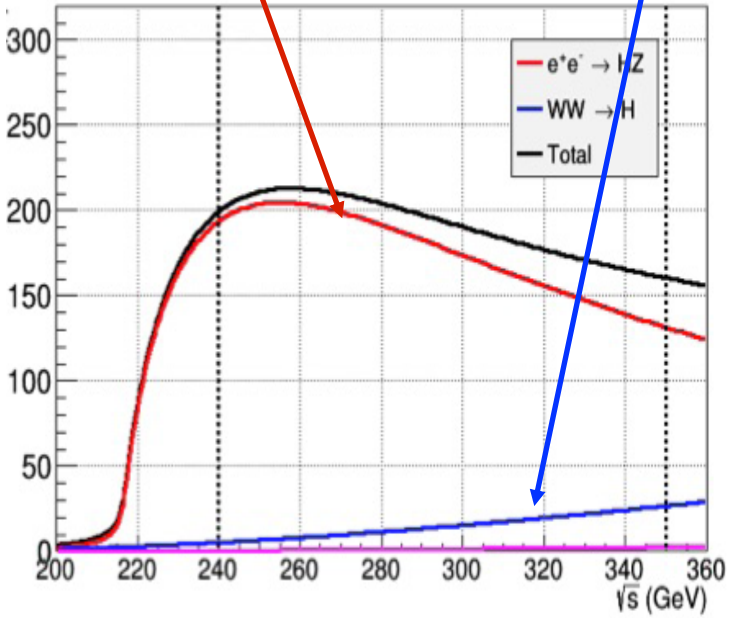


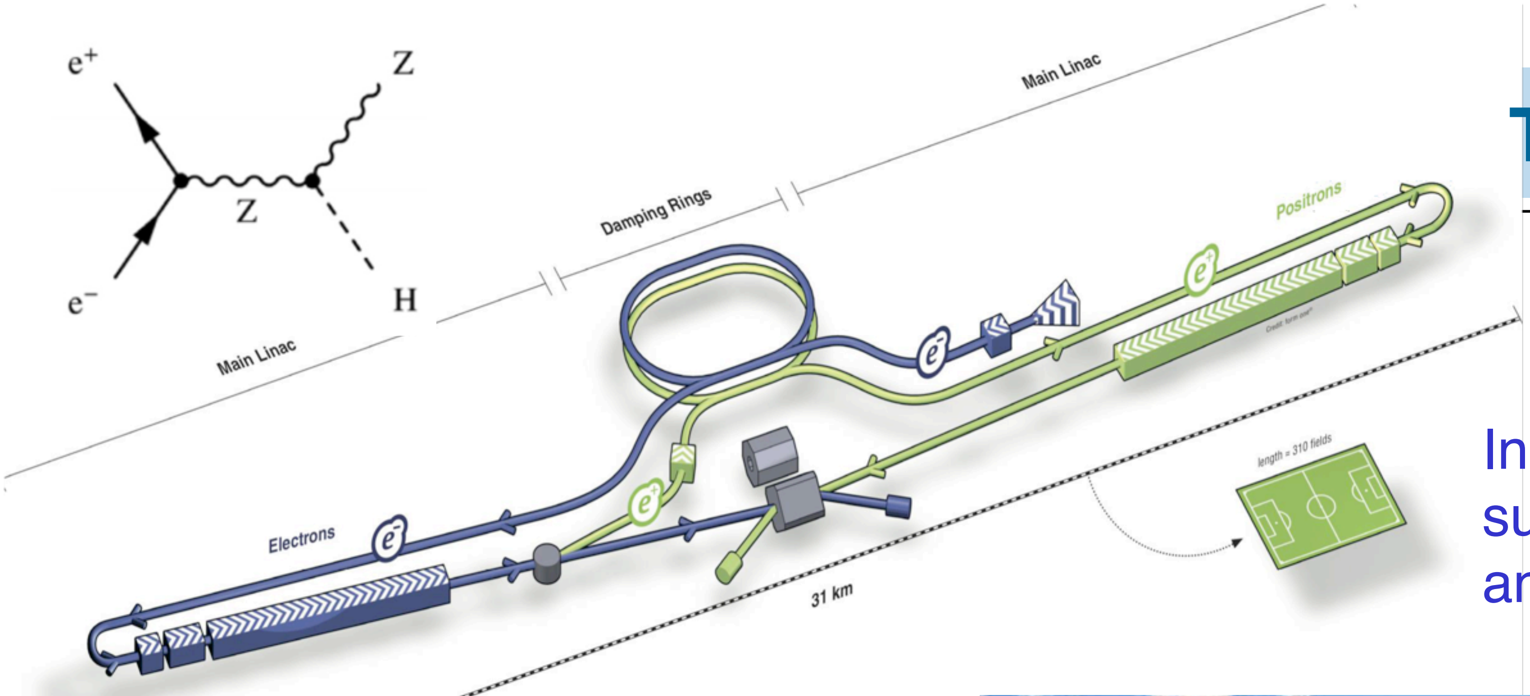


In proton-proton collisions a multitude of particles in the final state, thus Higgs was searched initially in particularly simple final states!

e+e- collisions leading to Higgs production:
Simple and clean final states

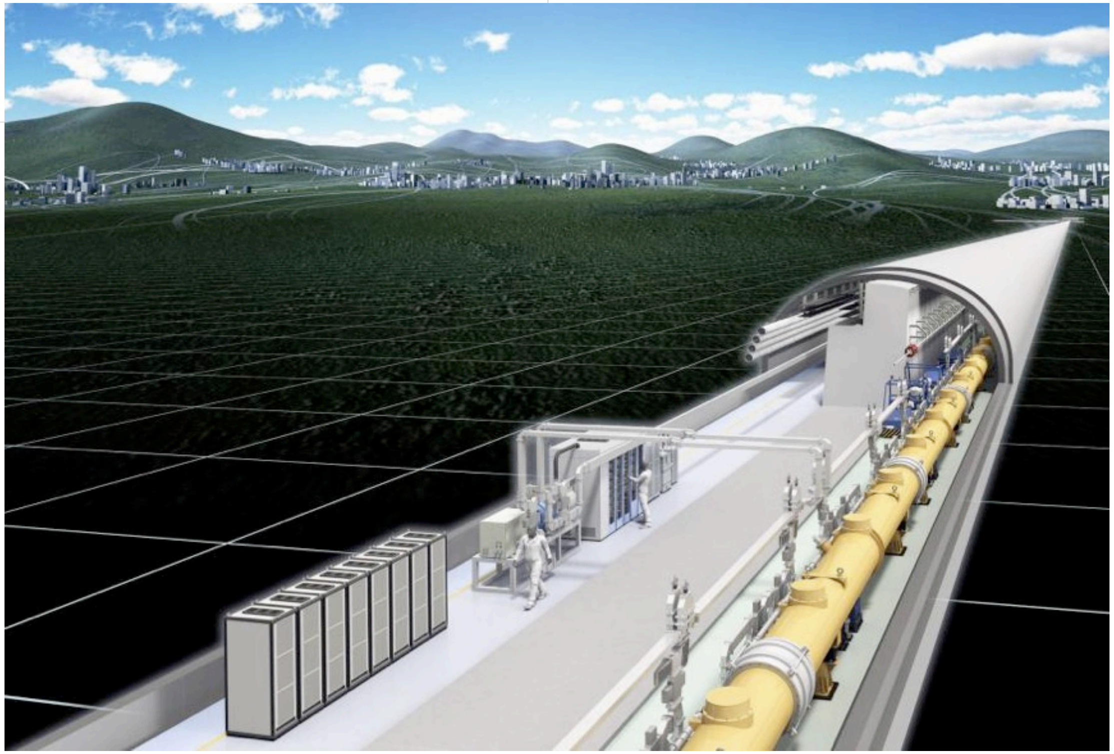






The ILC project

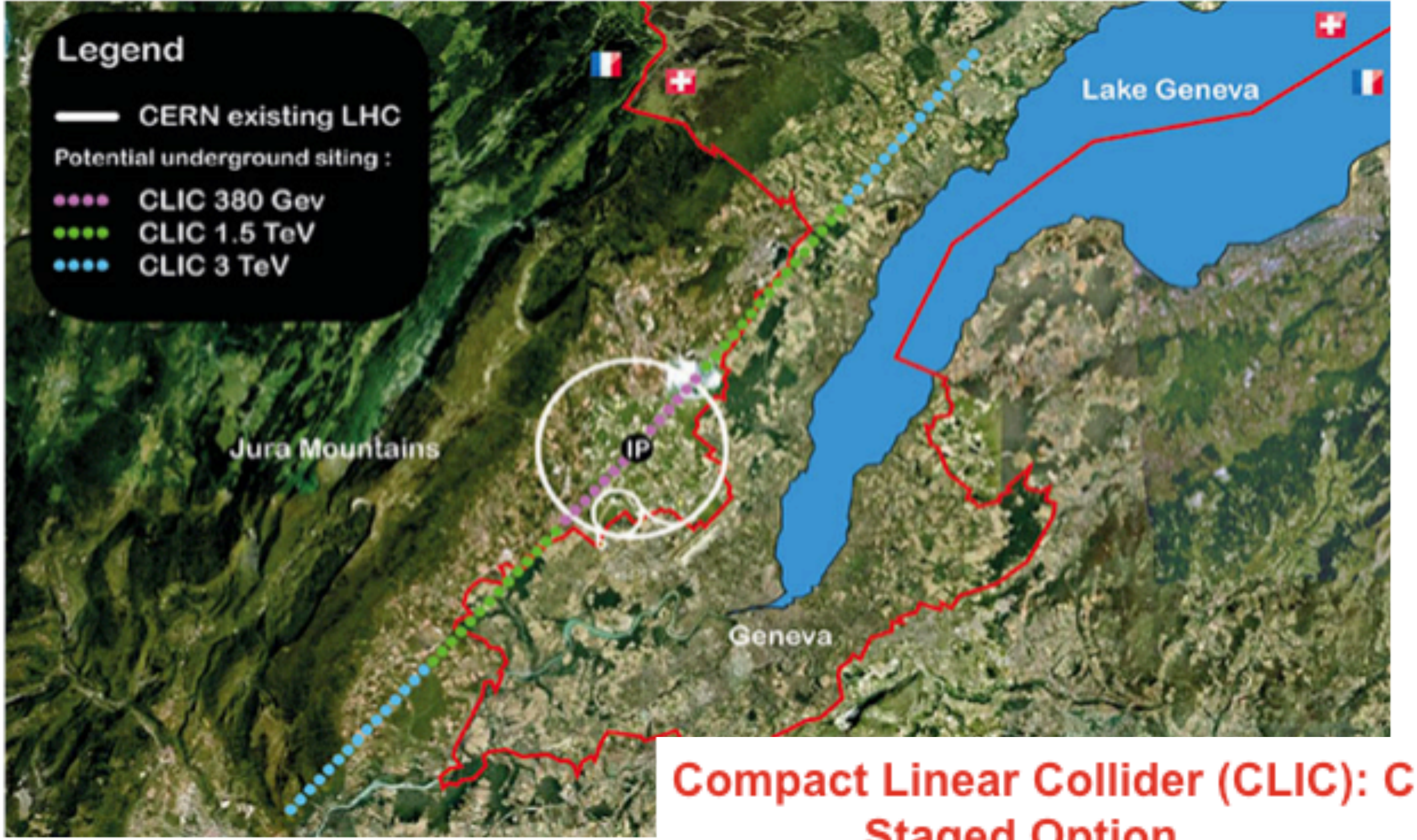
Initially at 250 GeV
subsequently 500 GeV
and ultimately 800 GeV



ILC project technically almost ready to go, machine for detailled Higgs production, but new direct discovery potential somewhat limited….

➡ Japan willing to put up half the price…..price about 7 GCHF

Compact Linear Collider CLIC - CERN



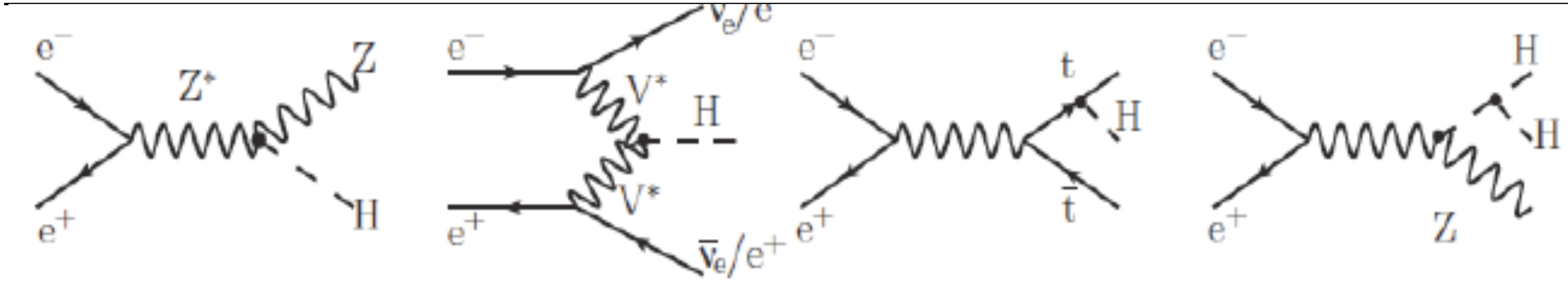
Compact Linear Collider (CLIC): CERN
Staged Option

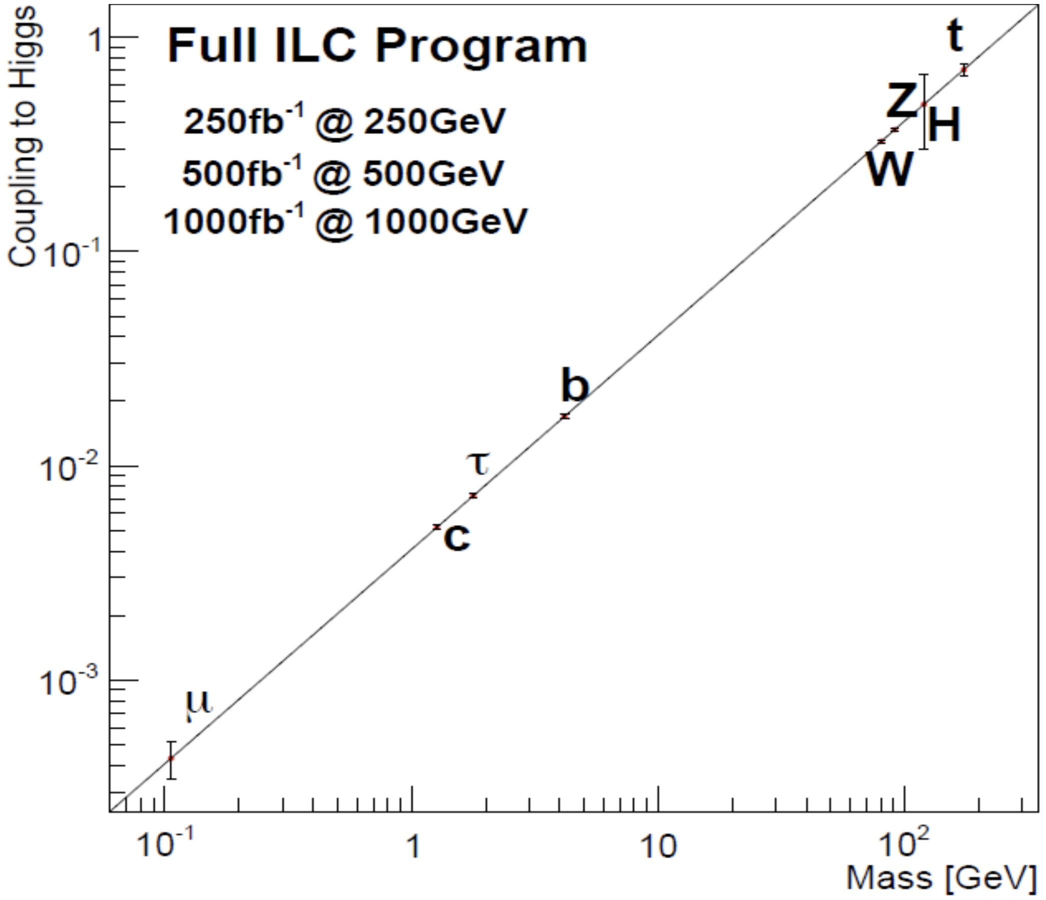
e−e+, √s: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

price of order 10 GCHF

D. Denegri; Istanbul, Turkey, Iran-Turkey conf. on LHC, June 2019

Higgs at ILC…..expected precision on couplings

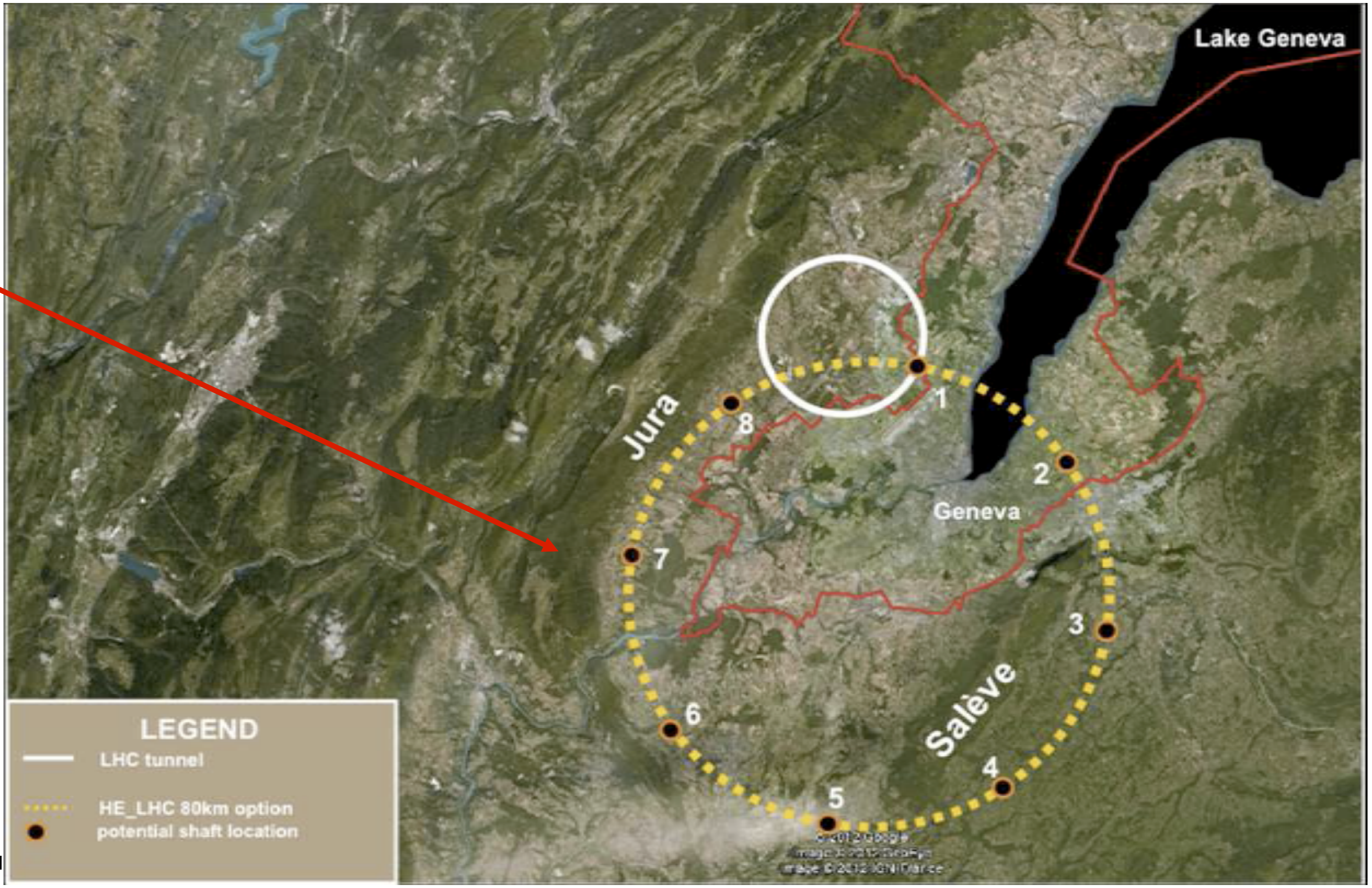




Possible long-term future (beyond ~2035/40) - the FCC project (ee, pp, ep, Pb-Pb)

An Ultra Large Collider to reach 100 TeV in pp mode, an order of magnitude larger then LHC, with an e^+e^- initial phase at ~350 GeV, and potential for e-p and Pb-Pb. Projects at the technology frontier at level of design studies and generating requiring/motivating ambitious R&D efforts

An 80-100 km tunnel encompassing all of the Geneva area….



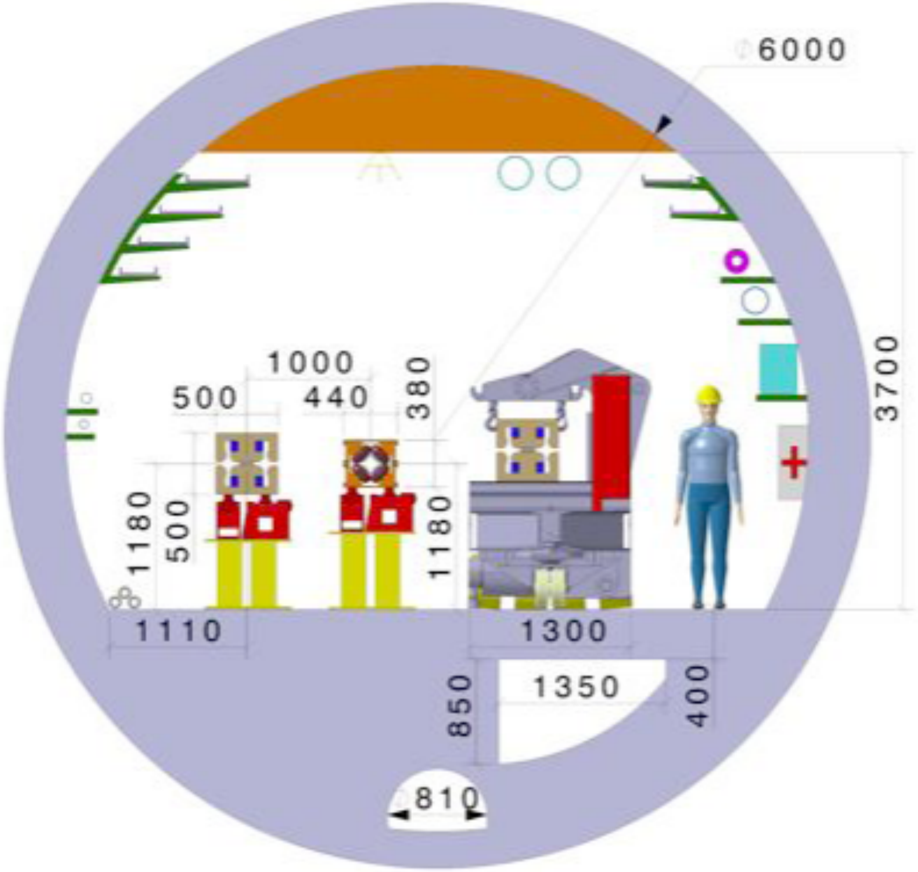
- China is proposing to built it in China, first the ee phase, but help needed for the proton-proton phase.

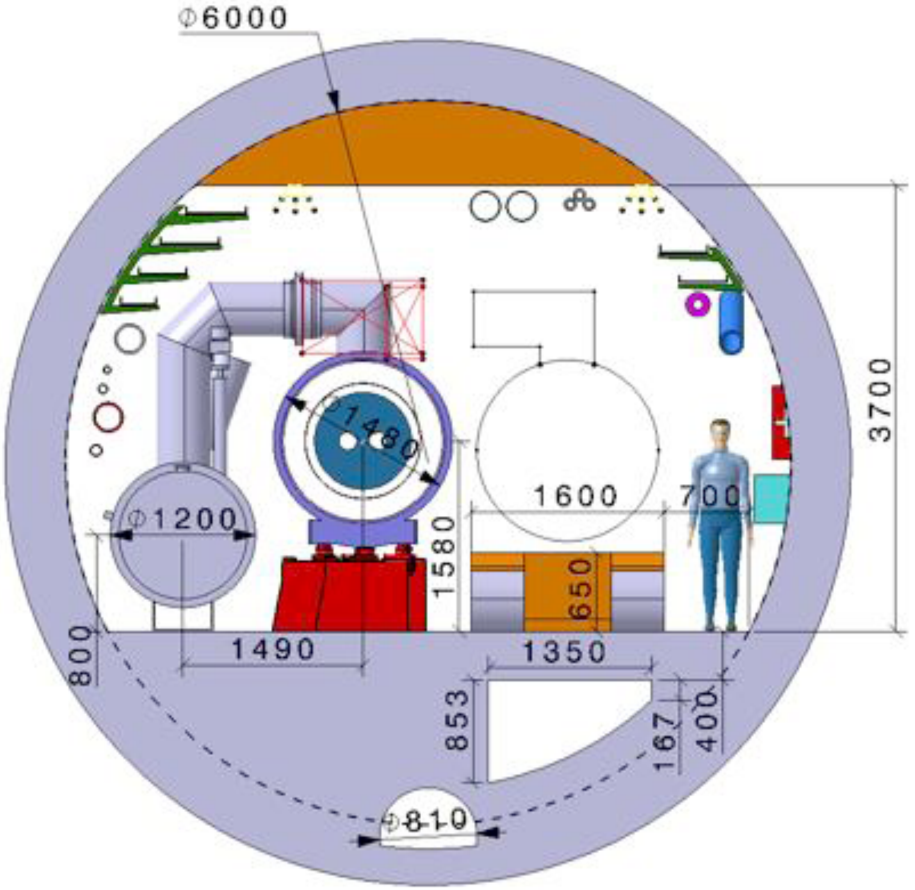
price of order 15 GCHF

FCC ee and hh tunnel instalations

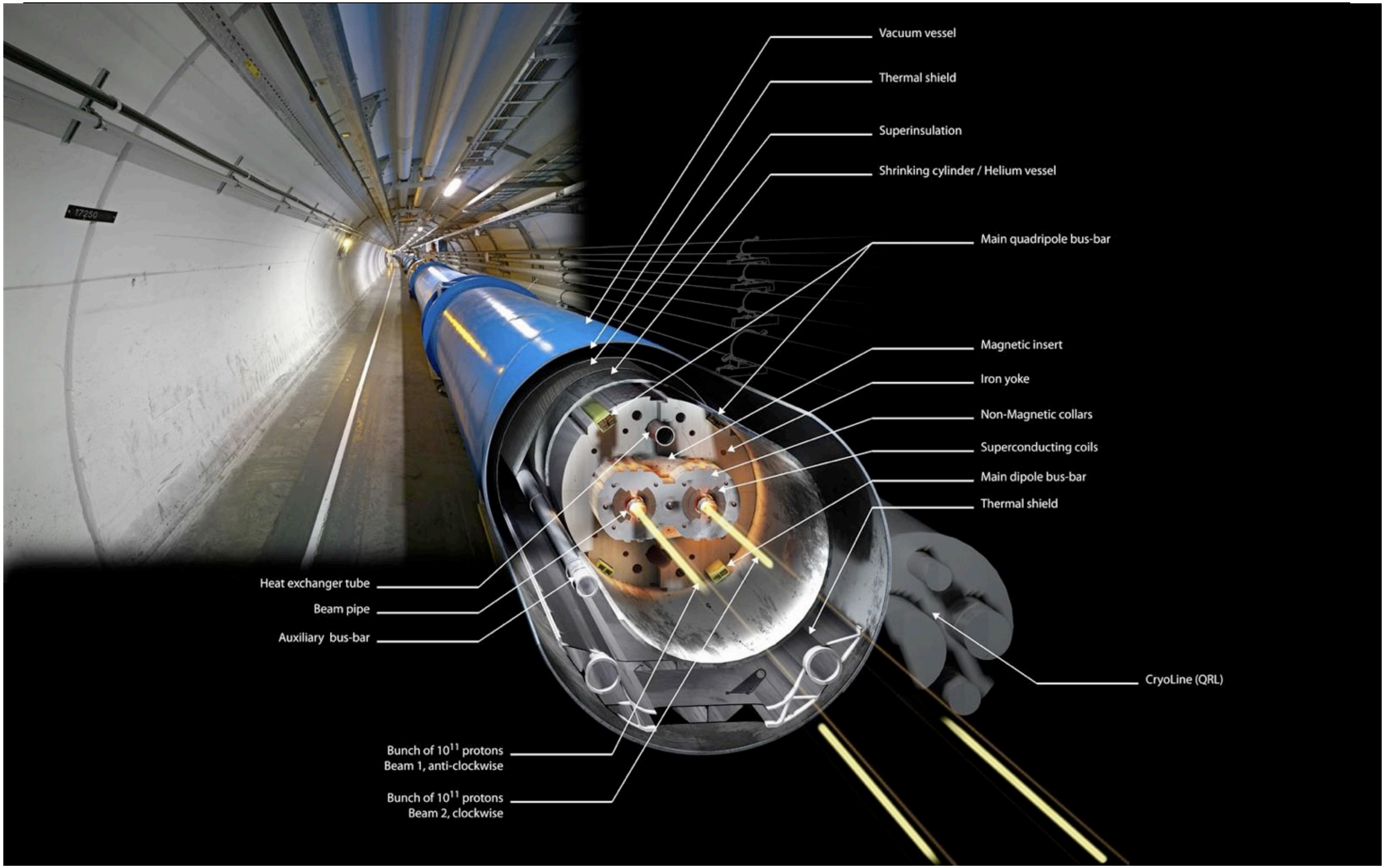
FCC-ee FCC-hh

new 5.5 m inner diameter



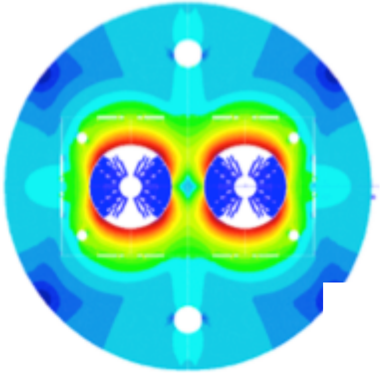


LHC magnets - key of the LHC project…..



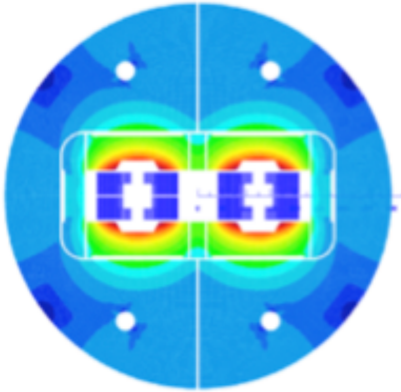
World-wide 16 Tesla dipole design activities and options - for FCC-pp

Cos-theta



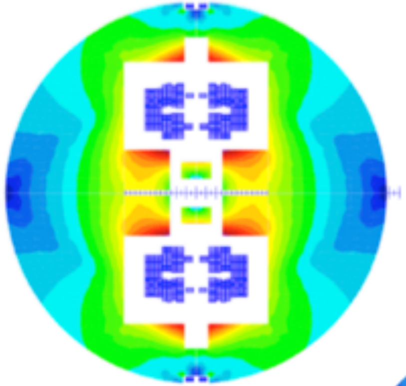
INFN

Blocks



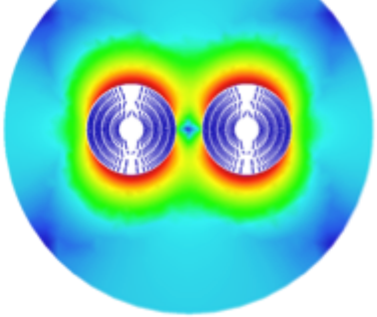
CEA

Common coils



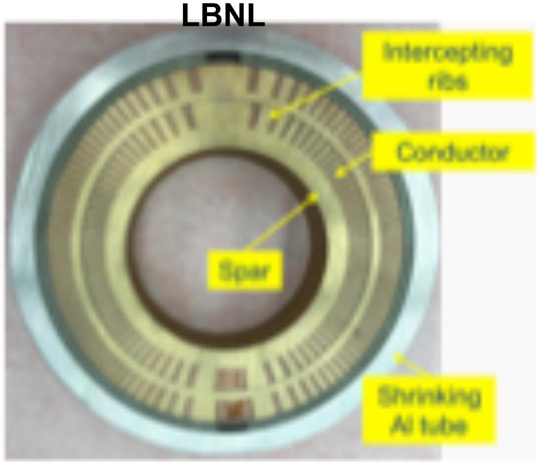
CIEMAT

Canted
Cos-theta

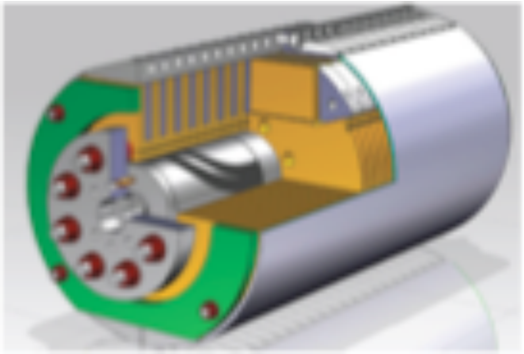


PSI

LBNL



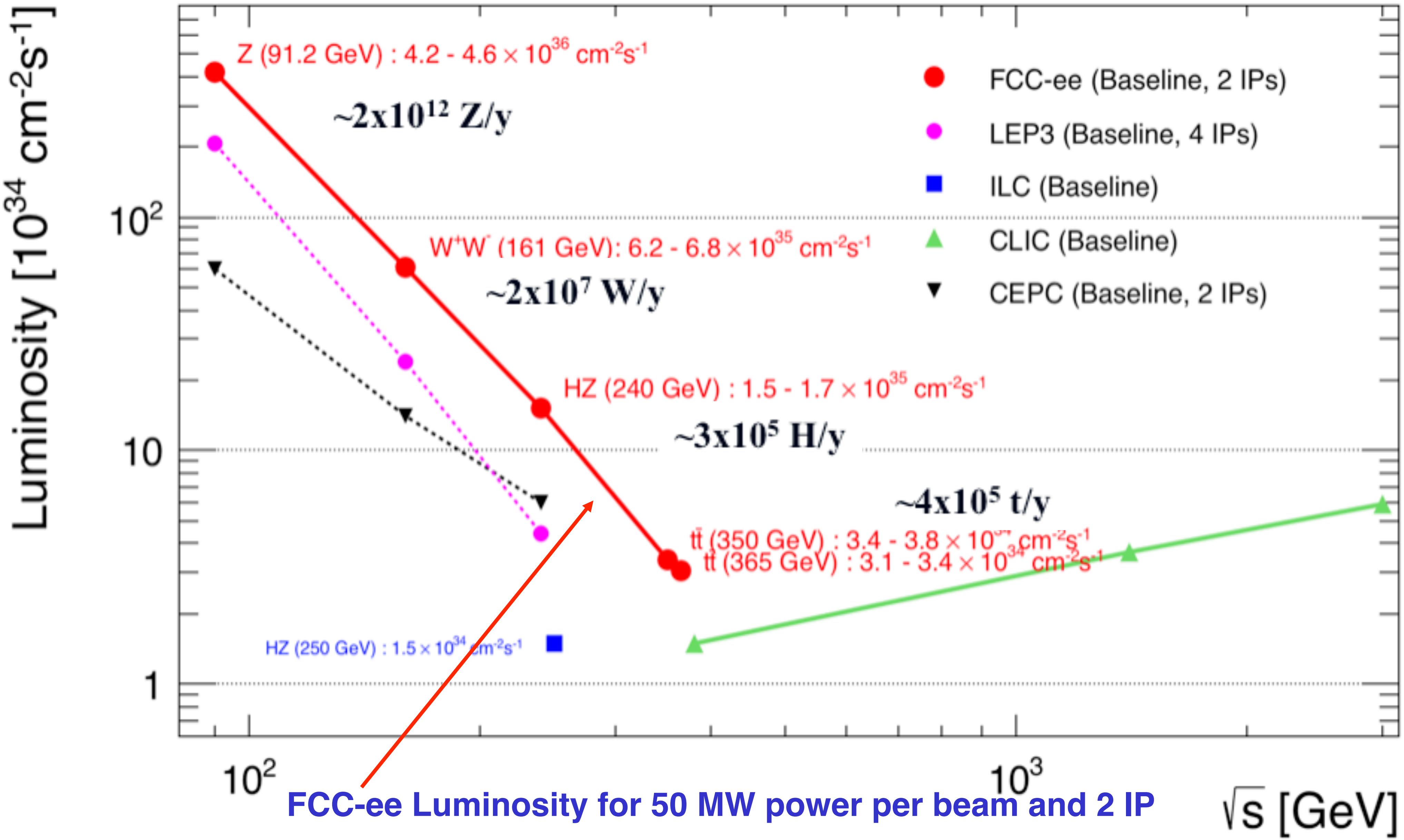
FNAL



Short model magnets (1.5 m lengths) will be built from 2018 – 2022

Russian 16 T magnet program launched by BINP recently.

Electron-positron colliders, ILC, CLIC, FCC-ee perspectives

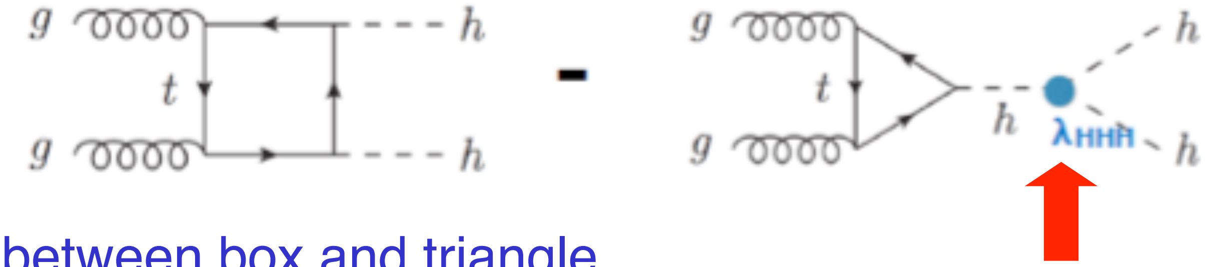


FCC-ee Luminosity for 50 MW power per beam and 2 IP

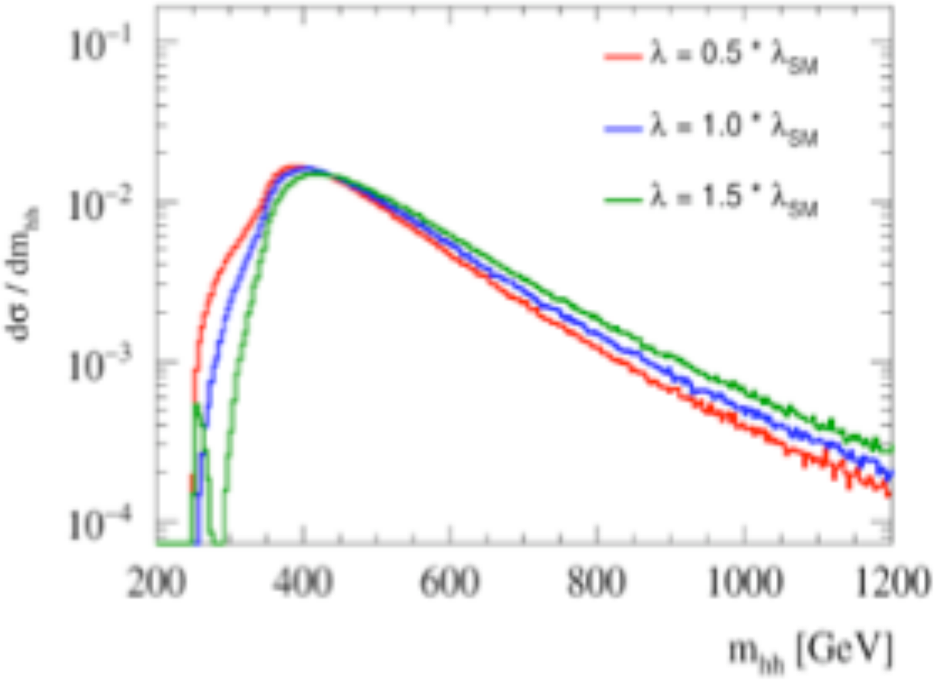
FCC-hh: Higgs self coupling at 100 TeV

σ(100 TeV)/σ(14 TeV) ≈ 40 x factor 10 for luminosity

gluon fusion:



Negative interference between box and triangle
Sensitivity to λ from low M_{HH} region



Mode	Sensivity : δK_λ(Stat) with 30 ab^{-1}
HH → $bb\gamma\gamma$	3.5%
HHj → bbbbj + $bb\tau\tau$j	10-30%
HH → bb4l	20-30%
HH → bbWW→ bblvjj	40%

FCC--hh is the machine for the H self coupling

$\delta k_\lambda / k_\lambda$ <3.5%

Unification of fundamental interactions, past and future possibilities, perspectives…

10^{-35} m
10^{19} GeV

10^{-32} m
10^{16} GeV

10^{-18} m
10^{2} GeV

10^{-16} m
1 GeV

10^{-15} m
1 Mev

10^{-10} m
10 eV

?

Quantum Gravity

Super Unification

Grand Unification

SUSY ?

Glashow, Weinberg, Salam, Rubbia

Electroweak Model

Standard model

QCD

QED

Electro magnetism

Maxwell

Magnetism

Long range

Electricity

Weak Theory

Fermi

Weak Force

Short range

Nuclear Force

Short range

We are now here

Universal Gravitation

Einstein, Newton

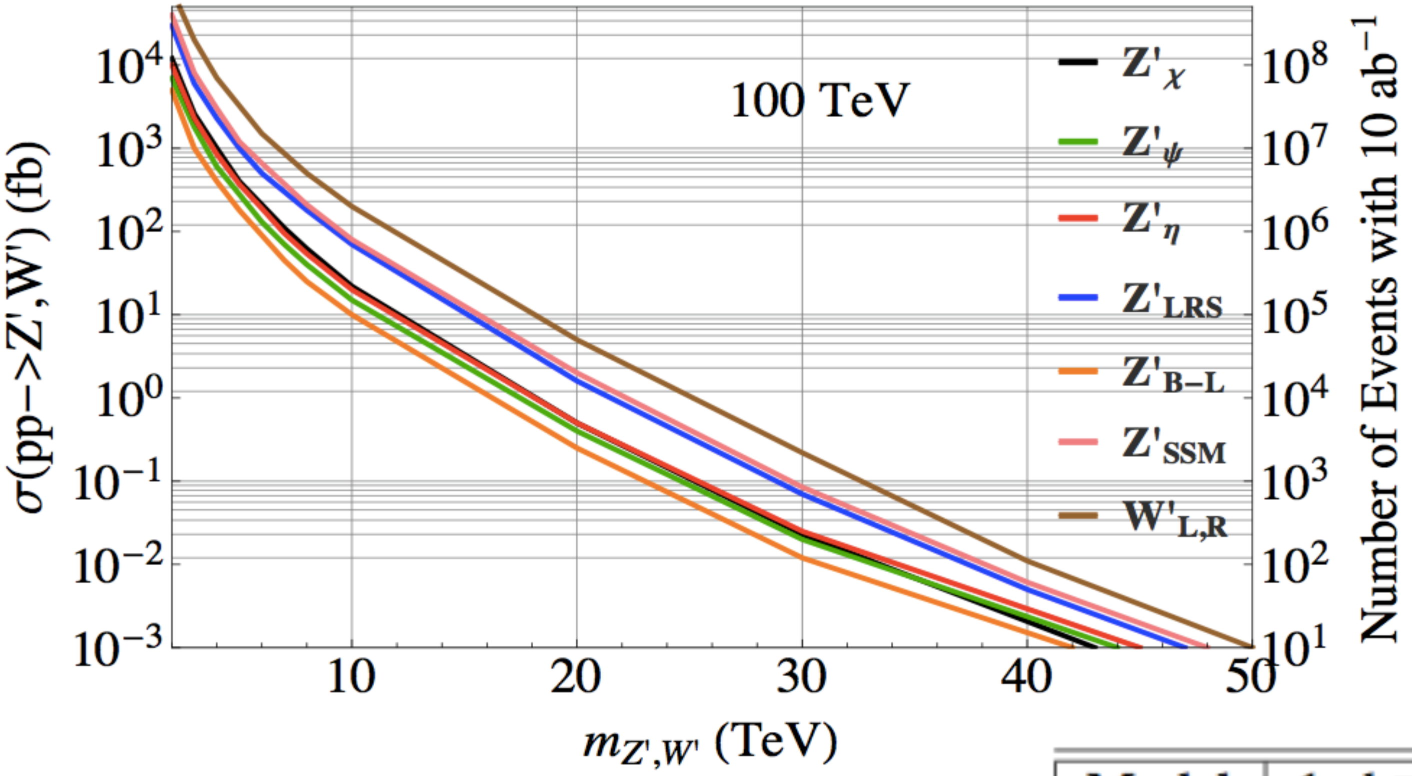
Kepler Celestial Gravity

Long range

Terrestrial

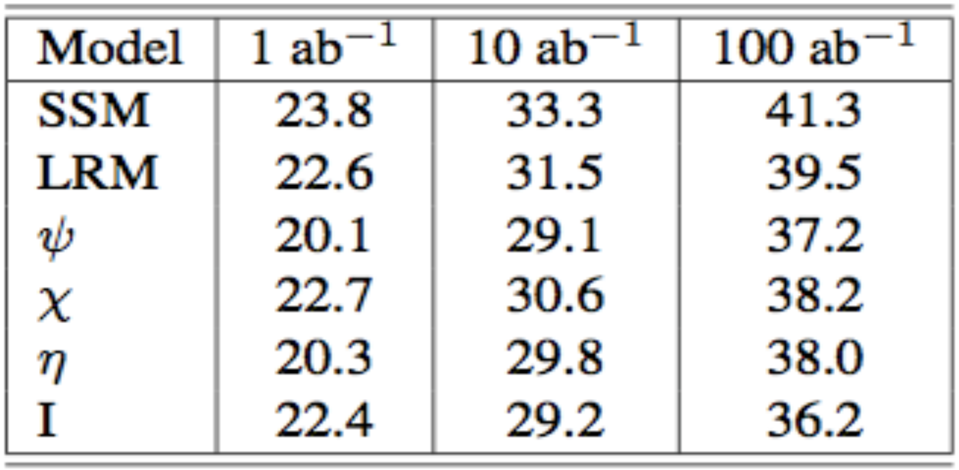
Galilei Gravity

New weak gauge interactions, Fcc-hh reach with 10 atob^{-1}



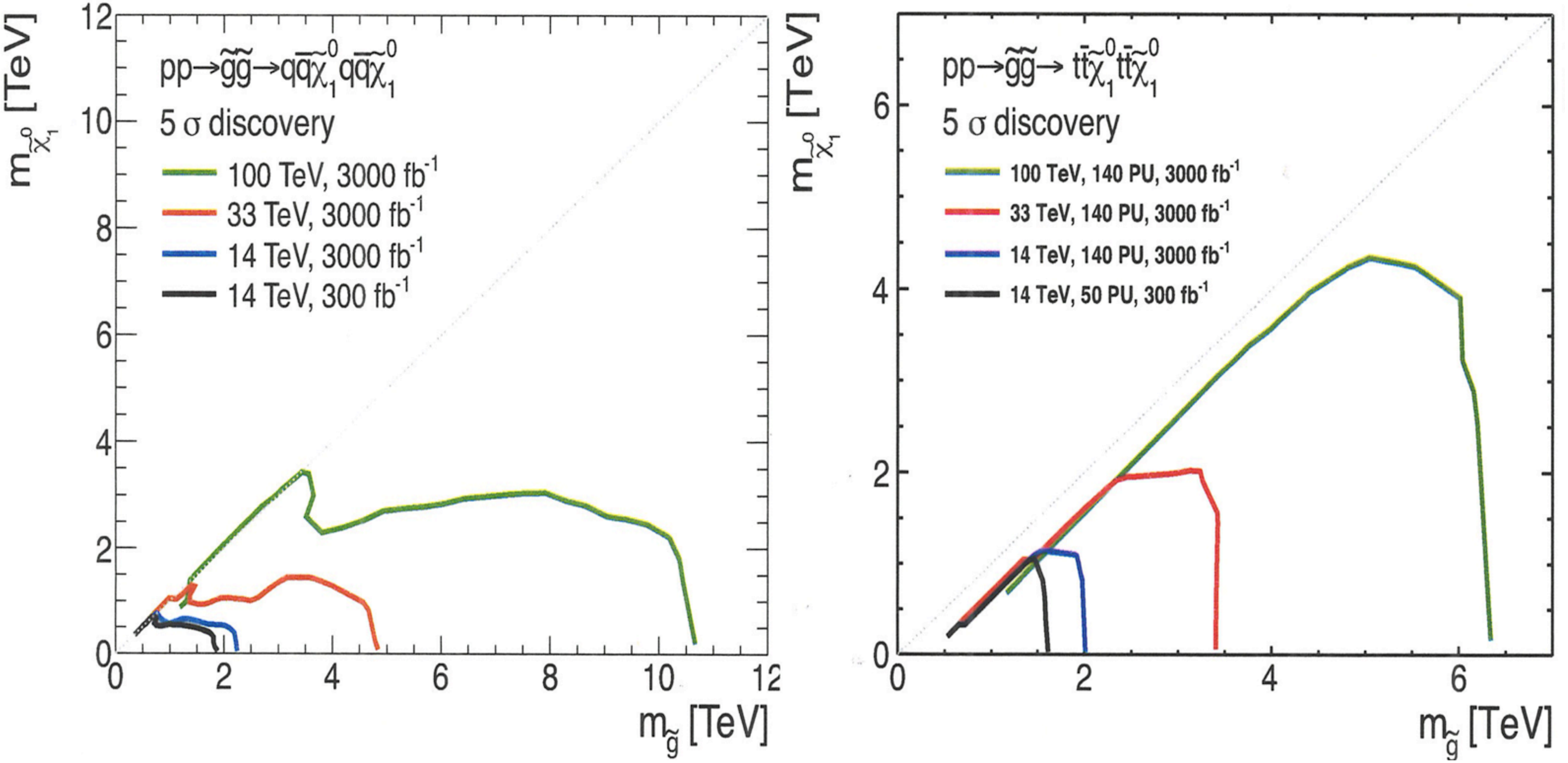
Depending on the Z' model reach up to 40-50 TeV

Discovery reach
T.Rizzo, arXiv:1403.5465



Model	1 ab^{-1}	10 ab^{-1}	100 ab^{-1}
SSM	23.8	33.3	41.3
LRM	22.6	31.5	39.5
ψ	20.1	29.1	37.2
χ	22.7	30.6	38.2
η	20.3	29.8	38.0
I	22.4	29.2	36.2

Expected gluino reaches at 33 and 100 TeV in FCC-hh machine with $3000\ fb^{-1}$



D. Denegri; Istanbul, Turkey, Iran-Turkey conf. on LHC, June 2019

Conclusions

The LHC is an incredible technological and scientific endeavor - on a world-wide scale

The four major experiments ATLAS, CMS, ALICE and LHCb are all operating very successfully. The physics harvest up to now is extraordinary, the Higgs, beautiful and detailed studies in EWK and QCD physics, rare decay modes, QGP studies etc

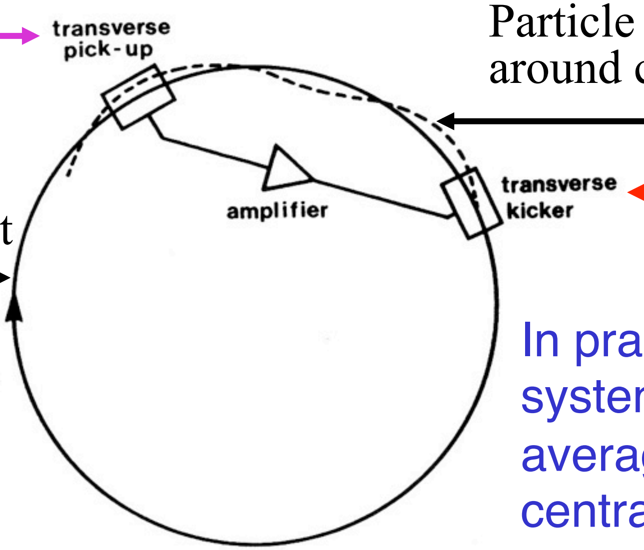
In 2015 LHC started operating at ~13 TeV; many technical challenges. Aims: clarification of the Higgs (i.e. is it THE Higgs boson or a A Higgs from an extentionn of the SM), looking for SUSY etc

The particle physics community is already working on long-term options/projects to take over in ~ 20-30 years from now

SPARES

Stochastic cooling (S. van der Meer)

Principle of operation: for ex. cooling in the horizontal plane:



Measure particle distance from central orbit

Particle oscillating around central orbit

Central orbit

kick particle onto central orbit

3.5 GeV/c large-aperture ring for antiproton storage and cooling

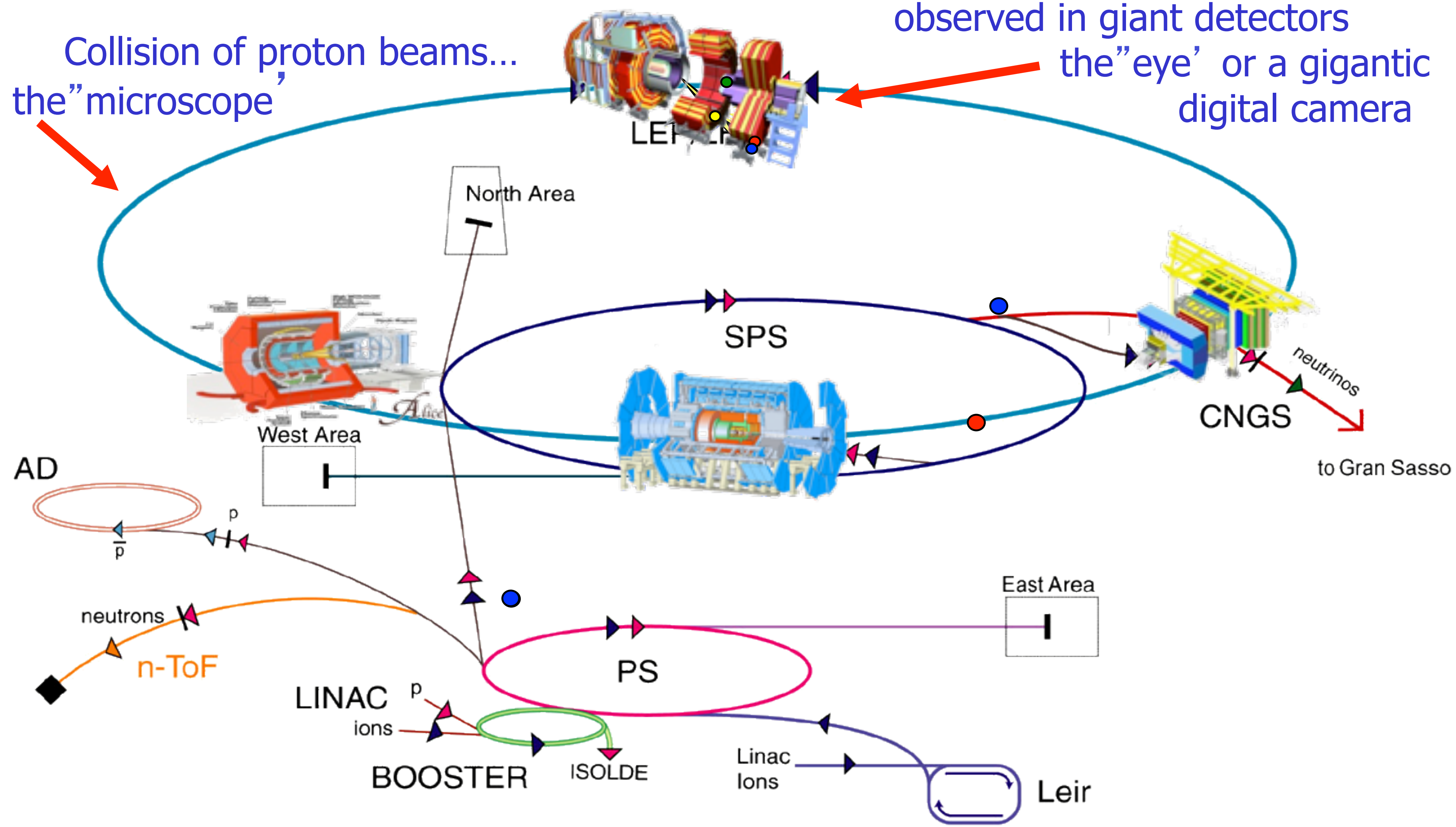
In practice, the pick-up system measures the average distance from central orbit of a group of particles

Independent pick-up – kicker systems to cool:

- horizontal motion
- vertical motion
- longitudinal motion (decrease of $\Delta p/p$)

- Antiproton production rate : 1 antiproton (at 3.5 GeV) per 10^6 incident protons of 26 GeV on target. About 10^{11} cooled antiprotons were accumulated per day; luminosity lifetime ~ one day

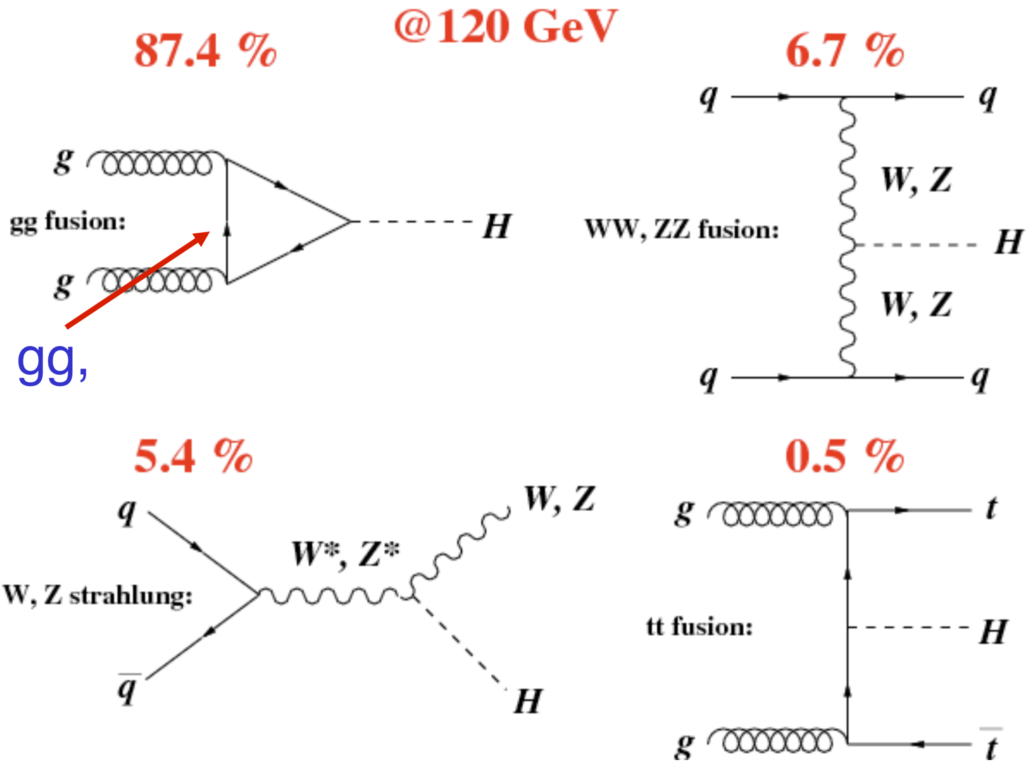
The Large Hadron Collider and experiments;
the sequence of accelerators - injectors



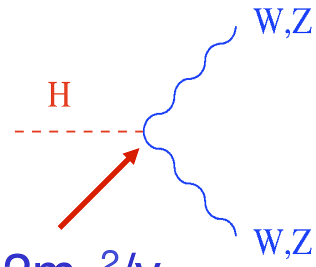
Collision of proton beams…
the”microscope’

observed in giant detectors
the”eye’ or a gigantic
digital camera

Higgs production mechanisms and decay modes

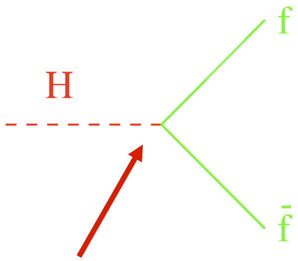


indirect coupling to gg,
top in the loop

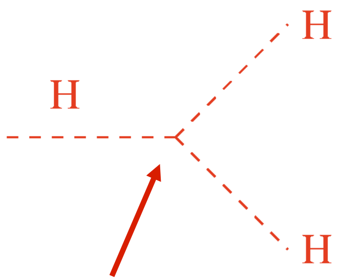


$g_{HVV} = 2m_V^2/v$

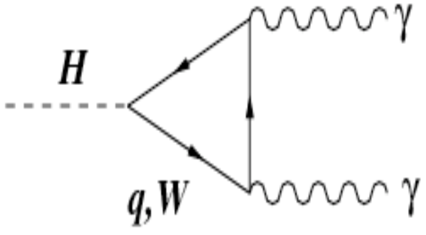
$g_{HWW} = g\ m_W$



$g_{Hff} = m_f/v$

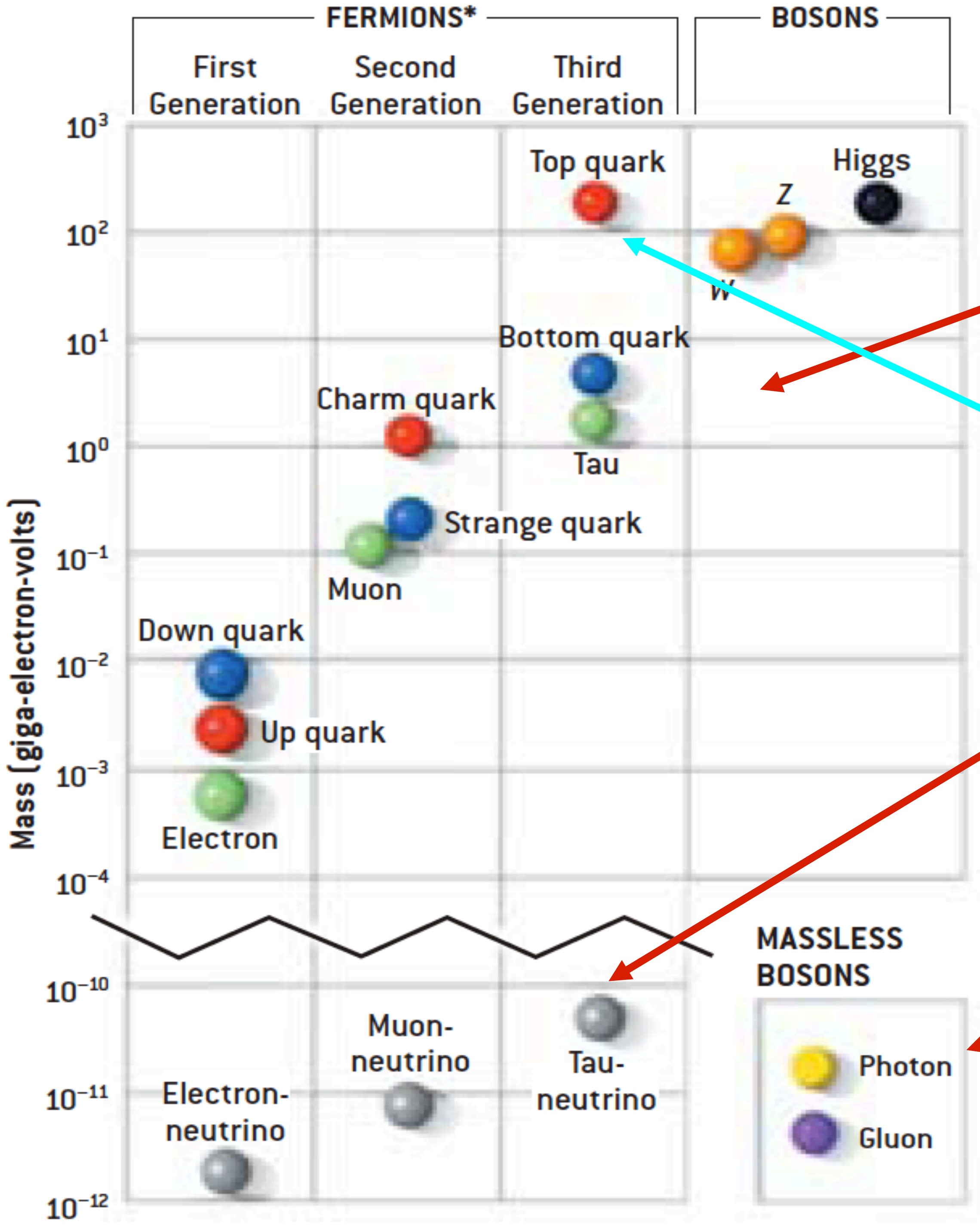


$g_{HHH} = 3m_H^2/v$



indirect coupling to γγ

Particle masses and the Higgs boson



Higgs boson responsible for the massesof W, Z, quarks, leptons

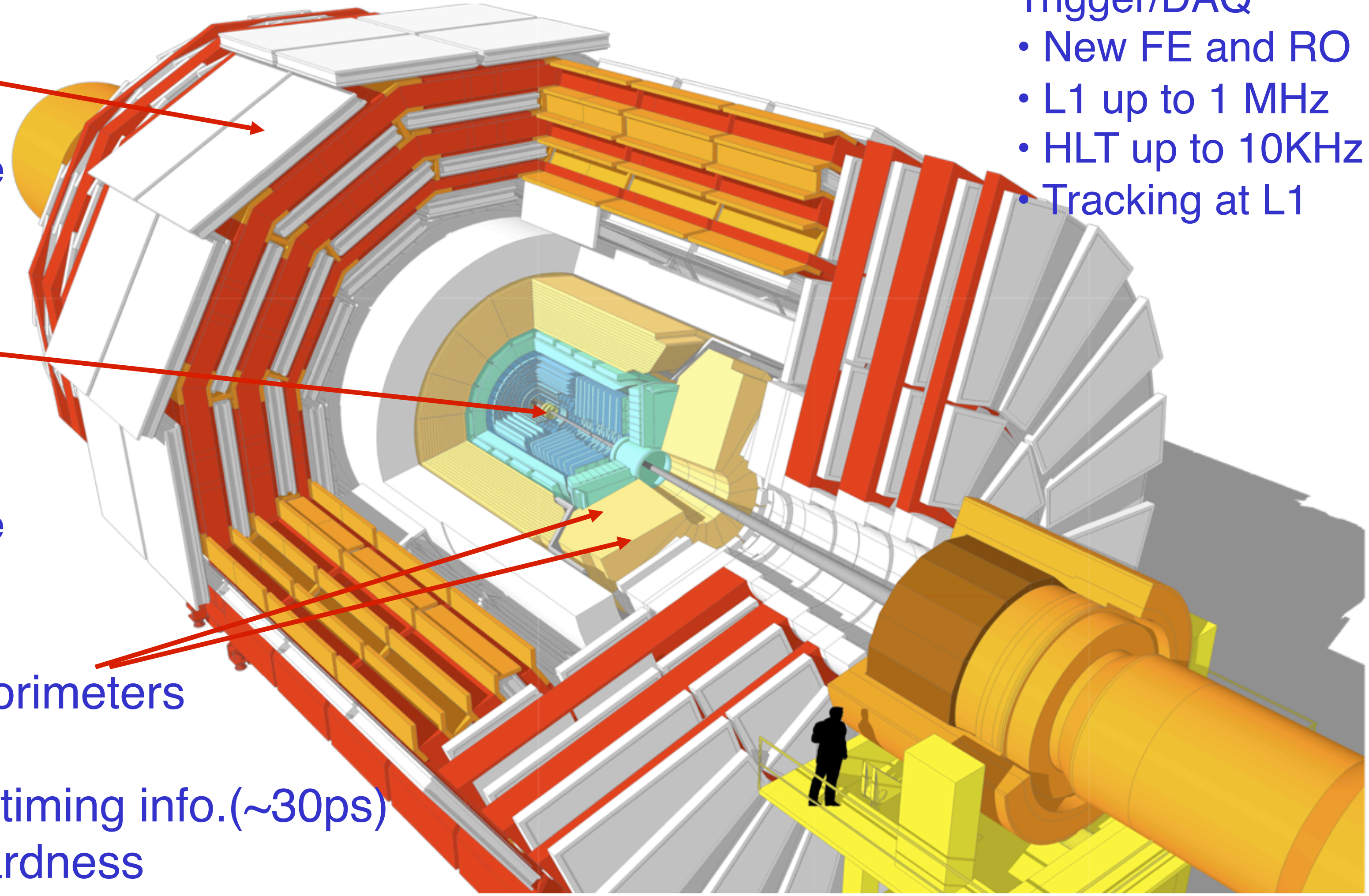
Top quark

the Higgs boson is not responsible for the neutrino masses in the SM!

…a problem for the future….

Mass-less particles/fields, not coupled to the Higgs boson field

CMS phase-2 upgrades to face the challenges of HL-LHC



Muon system
- GEM Glass RPCs
- Extended η coverage
- New DT minicrates

Tracker
- Higher granularity
- Less material
- Better pT resolution
- Extended η coverage
- Track trigger at L1

Replace endcap calorimeters
- Higher granularity
- 3D reconstruction, timing info.(~30ps)
- Higher radiation hardness

Trigger/DAQ
- New FE and RO
- L1 up to 1 MHz
- HLT up to 10KHz
- Tracking at L1

The CMS-Phase 2 (HL-LHC) upgrade is a major construction effort financial level is at 50% of the original CMS detector cost, ~ 300 MCHF

Linear colliders in competitiom

Competition of two concepts.

- Length determined by efficiency (gradient) of RF cavities.

- ILC – International Linear Collider, 0.5 TeV, based on Superconducting RF cavities (gradient 31.5 MV/m)
1st option Ecm = 250 GeV

- CLIC – Compact Linear Collider, developed by CLIC Collaboration (CERN), 0.5 -3 TeV , based on warm RF cavities at 12 GHz with very high el. gradient ~ 100 MV/m
1st option Ecm = 380 GeV

Competition but also cooperation:
CLIC + ILC >> Linear Collider Collaboration

ILC - International Linear Collider

QuickTime™ and a
decompressor
are needed to see this picture.

Collisions: Between electrons - positrons, in bunches of 5 nm
Energy: Up to 0.5 TeV with an option to upgrade to 1 TeV
Acceleration Technology: 16,000 superconducting accelerating cavities made of pure niobium
Length: Approximately 31 kilometres
Accelerating Gradient: 31.5 megavolts per metre

1.3 GHz superconducting cavities for ILC

Gradient 31.5 MV/m, restricted by quality of forming and welding techniques (surface roughness, impurities….) of bulk niobium

FCC-ee challenges

Deal with small beam life time

⇨ Top up scheme needed

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decompressor
are needed to see this picture.

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are needed to see this picture.

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FCC-hh parameters

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FCC-hh main cross sections