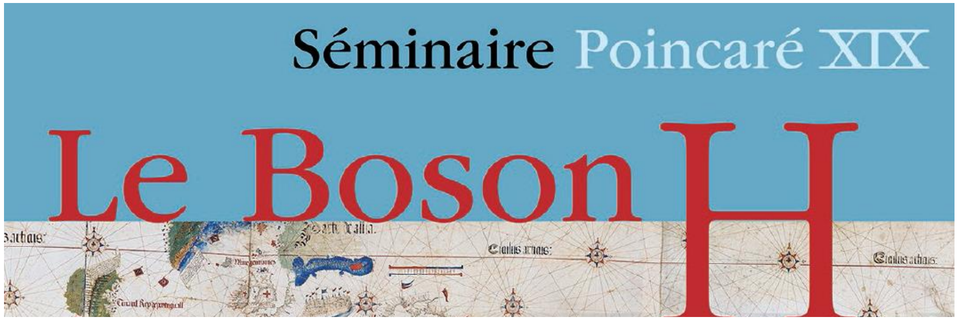


Future searches on scalar boson(s)

Louis Fayard (LAL Orsay)

- ♥ ***Historical introduction of the boson and of the LHC reminder (see François and Yves)***

- ♥ ***Future facilities (for future searches)***

- ♥ ***New physics in the scalar sector (see Pierre and Abdelhak)***

- ♥ ***Conclusion***

- ♥ ***Backup***

Rien n'est cru si fermement que ce que l'on sait le moins

Nothing is believed more strongly that which we know the least

Montaigne , Essais

- ***Historical introduction of the boson and of the LHC reminder (see François and Yves)***

- ***Future facilities (for future searches)***

- ***New physics in the scalar sector (see Pierre and Abdelhak)***

- ***Conclusion***

- ***Backup***

Spontaneous Symmetry breaking

The Brout-Englert-Higgs mechanism

The LHC

in a

1950 Ginzburg-Landau (Meissner-Ochsenfeld effect → London penetration length ~ W mass
→ Pippard coherence length ~ H mass)

1959 Nambu

1960 Goldstone

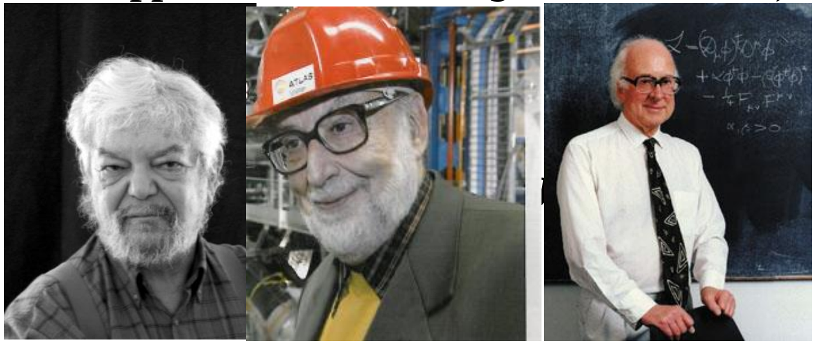
1961 Schwinger

1962 Anderson

1964 Brout, Englert, Higgs, Guralnik,Hagen,Kibble

1967 Weinberg, Salam Faddeev,Popov

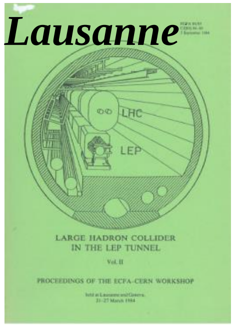
1970 Glashow, Iliopoulos,
Maiani, 't Hooft, Veltman…..



1983 Rubbia, van der Mee[r] discovery of W and Z at CERN

1984 Repellin. …

Lausanne



1989 construction
beginning of

1992 LOI of 'larg

1994 TP of ATLA[S]

1995 discovery of

1996 approval of [L]

1998

approval of [t] [C]E)

1999 ATLAS Phys

2006 CMS Physic

2008 ATLAS Exp

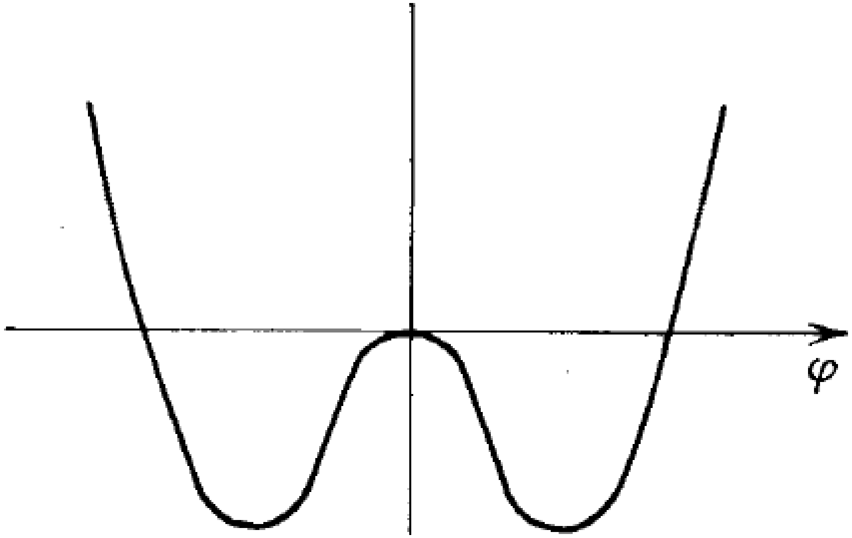
2010 start-up at 3

2012 4th July discovery of boson

boson like properties Nobel prize to Englert and Higgs

2014

particles of mass $\sqrt{-2\mu_0^2}$



$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4$$

2008

10th september 2008 : first beams around
19th september 2008 : incident

14 months of major repairs and consolidation
New Quench Protection system

2009

20th november 2009 : first beams around (again)
december 2009 : collisions at 2.36 TeV cms

January 2010 : decided scenario 2010-11 7 TeV cms
instead of 14 TeV

2010

30th march 2010 : first collisions at 7 TeV cms
august 2010 : luminosity of 10^{31} cm^{-2} s^{-1}

2011

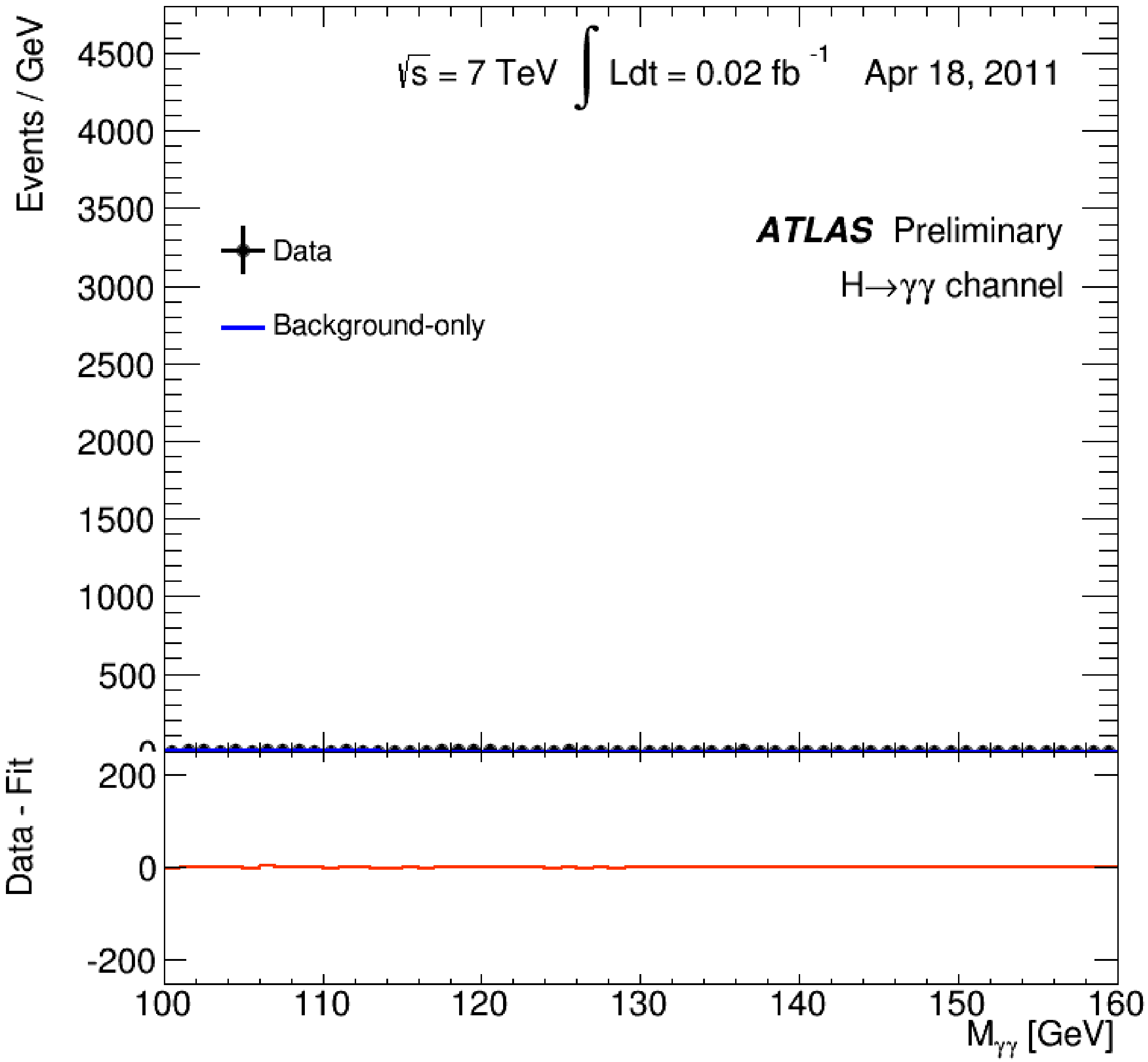
may 2011 : luminosity > 10^{33} cm^{-2} s^{-1}
november 2011 : integrated luminosity ~ 5 fb^{-1}
13^{th} december 2011 : first ‘signal’ around 126 GeV

2012

march 2012 : start again at 8 TeV
(50 ns between bunches)
4^{th} July 2012 : evidence for a new boson
(integrated luminosity ~ 6 fb^{-1})

2013

(Standard-Model) boson-like properties
peak luminosity 7 10^{33} cm^{-2} s^{-1}
integrated luminosity ~ 5+ 20 fb^{-1}



Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
Data
Background-only
ATLAS Preliminary
H→γγ channel
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

Two important results at the LHC

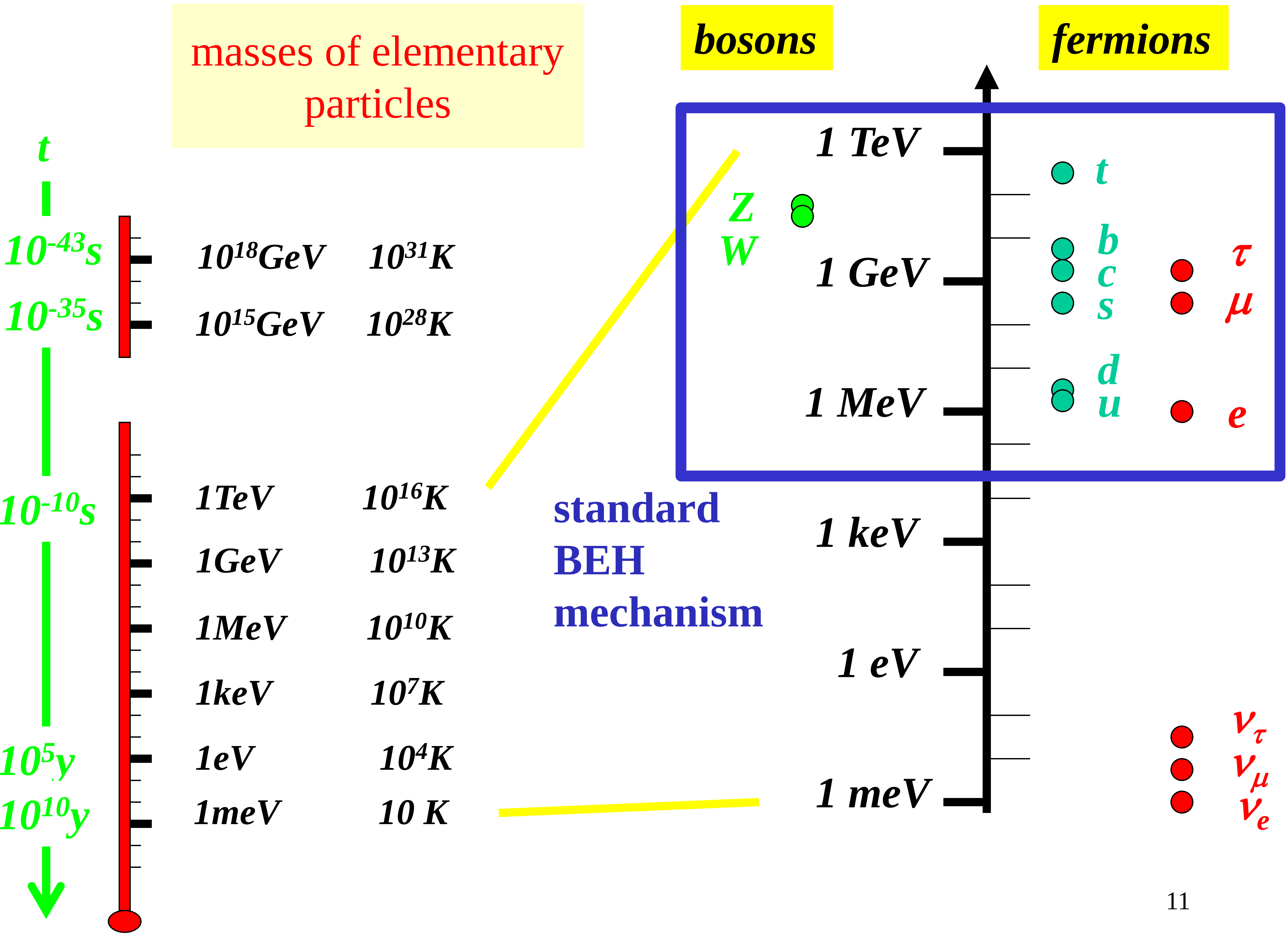
The discovery of the BEH boson ,
with properties close
to what was predicted by
the Standard Model

No new physics !

We hope to find new physics in the scalar sector either by looking at deviations of the properties (w.r.t SM properties) of the (already discovered) BEH boson , or by looking

at new bosons (using or not the already discovered boson)

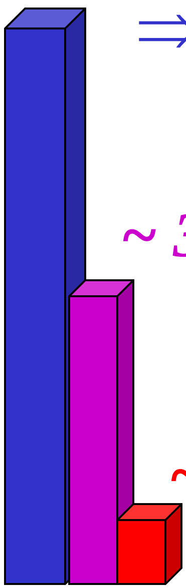
The SM (with a BEH boson) is NOT the ultimate theory (neutrino masses , dark matter , baryon-antibaryon asymetry , unification between electroweak theory and strong interation, … not explained)


masses of elementary particles
bosons
fermions
t
10^{-43}s
10^{-35}s
10^{-10}s
10^{5}y
10^{10}y
10^{18}GeV 10^{31}K
10^{15}GeV 10^{28}K
1TeV 10^{16}K
1GeV 10^{13}K
1MeV 10^{10}K
1keV 10^{7}K
1eV 10^{4}K
1meV 10 K
standard
BEH
mechanism
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Z
W
t
b
c
s
d
u
τ
μ
e
ν_τ
ν_μ
ν_e

A lot of things are not known !   SM not ultimate theory

Energy of Universe

~ 65 % of dark energy (vacuum energy)
⇒ expansion of Universe accelerating



~ 30 % of dark matter (not yet observed) ⇒ rotation of galaxies

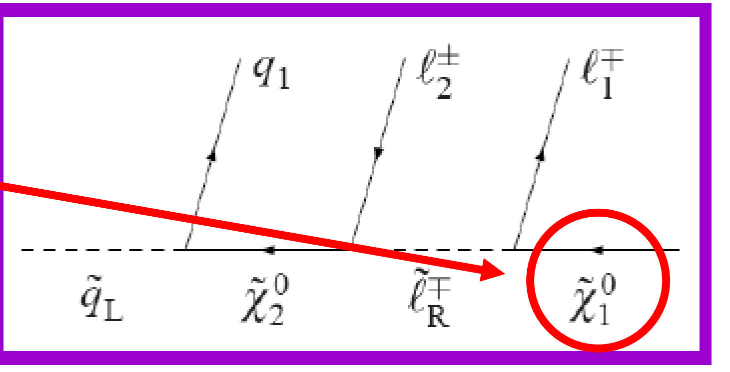
~ 5 % of "known" matter

Hierarchy problem
$m_H << m_{Planck}$

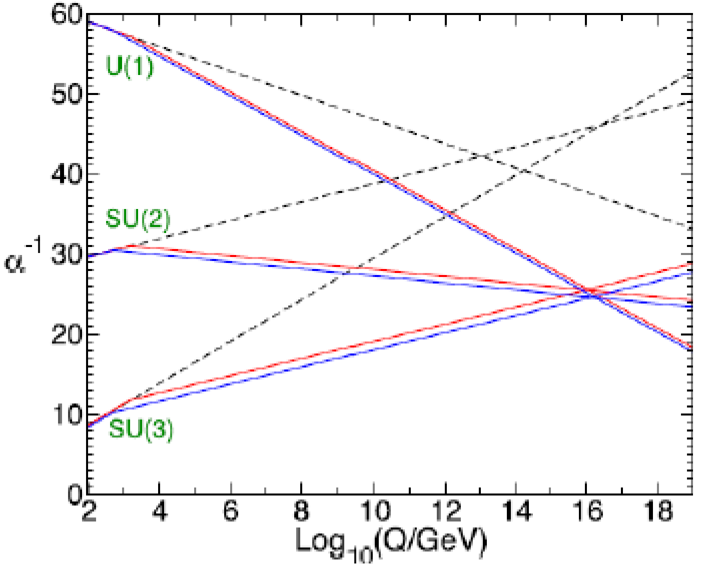
Connection with gravity

Supersymmetry (SUSY) is a popular candidate in order to 'explain' this

- ***Multiplies by ~2 the number of particles***
- ***Allows the stabilisation of the Higgs mass***
- ***Local SUSY incorporates gravity***
- ***Gives a natural candidate to dark matter : the LSP***



In addition better unification



MSSM

5 Higgs bosons
(3 neutrals A,H,h and 2 charged H±)

couplings to down part of doublets (b , τ, μ) enhanced at high tan(β)

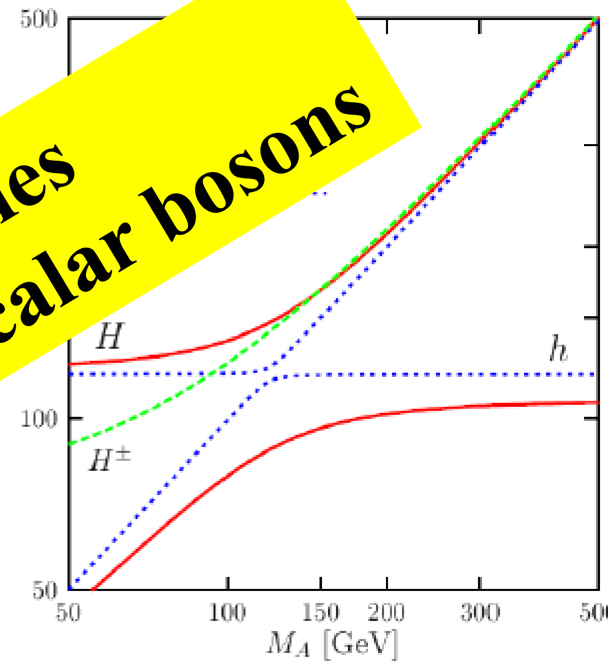
D.Rainwater hep-ph/0702124

Φ	$\frac{g_{\Phi u\bar{u}}}{g_f}$	$\frac{g_{\Phi d\bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
h	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$	$-\frac{1}{2}i\cos(\beta-\alpha)$
H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}i\sin(\beta -$ [illegible]
A	$-i\gamma_5\cot\beta$	$i\gamma_5\cot\beta$	$\boxed{0}$	[illegible]
h	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$-$ [illegible]
H	$-\frac{\sin\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta -$ [illegible]	[illegible]
A	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$	[illegible]	[illegible]

MSSM { (rows 4–6)

Type I (upper) [illegible] HDMs

There are other models/theories predicting even more new scalar bosons

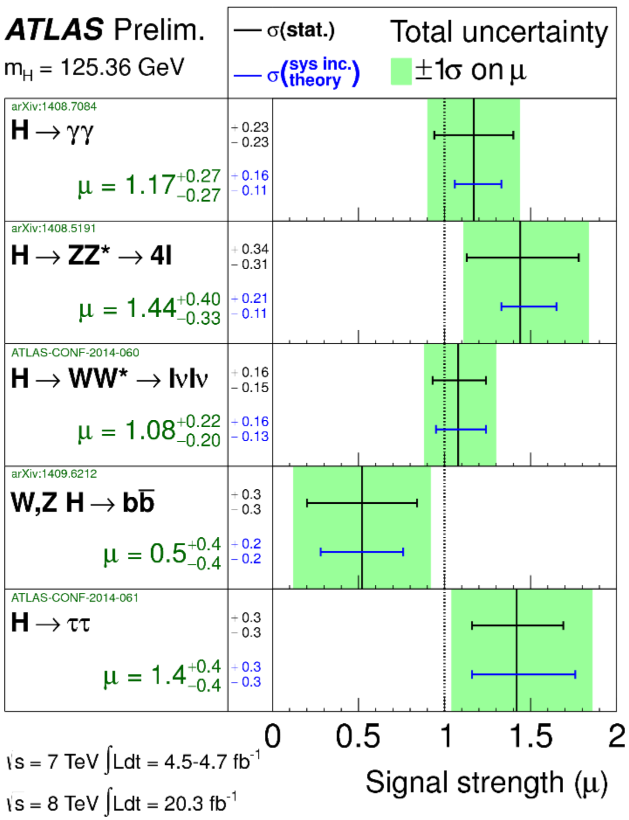


at LO I[illegible] [illegible]gs sector depends of 2 parameters M_A tan(β)
(= v2/v[illegible] at NLO more SUSY parameters

A (0^-) does not give ZZ and WW)

LHC results of run 1 (see Yves)

$$\mu = \sigma / \sigma_{\mathrm{SM}}$$

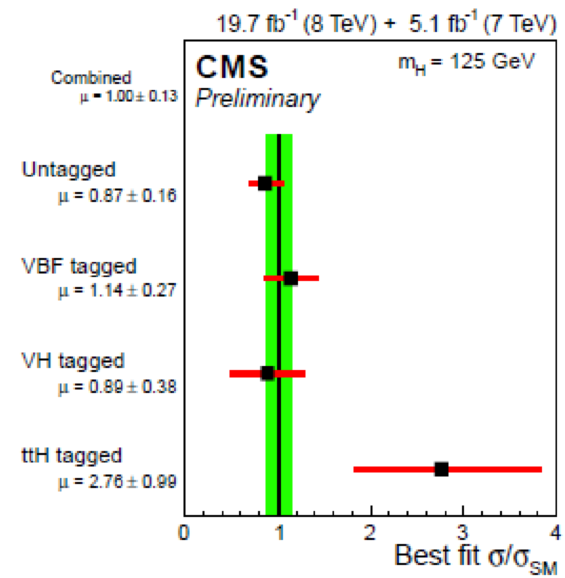


sensitive to

several decay modes

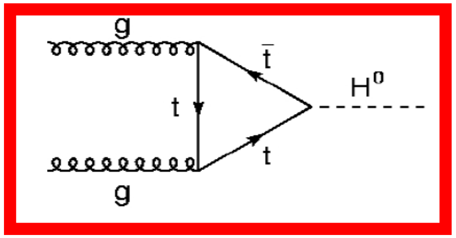
←

several production modes →

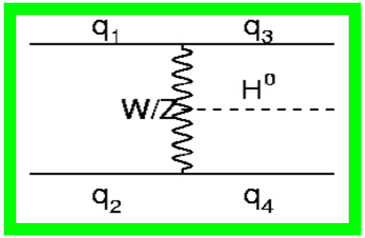


$$1.00 \pm 0.09\,(\text{stat.})\,{}^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

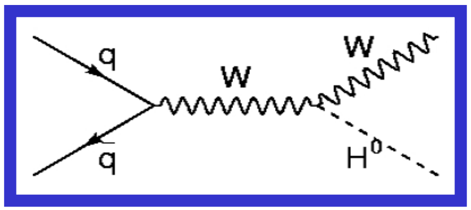
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/ATLAS_HIGGS_mu_Summary/ATLAS_HIGGS_mu_Summary_201410.png



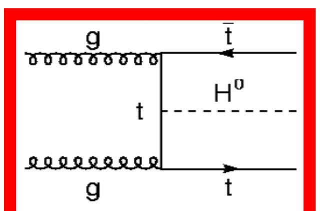
GF ***H → WW , ZZ , γγ , bb, ττ***



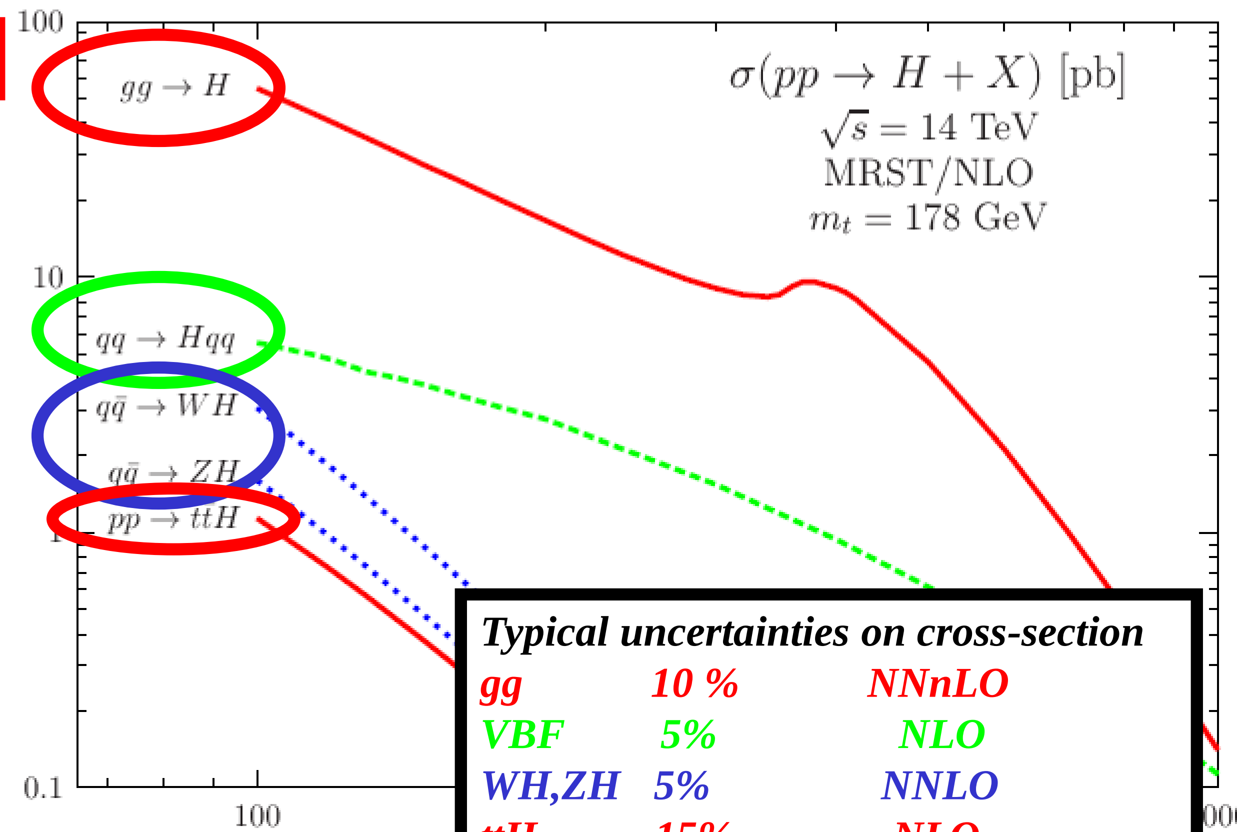
VBF ***H → WW, ZZ , γγ , ττ***



H → WW, γγ, bb



H → WW, γγ, bb

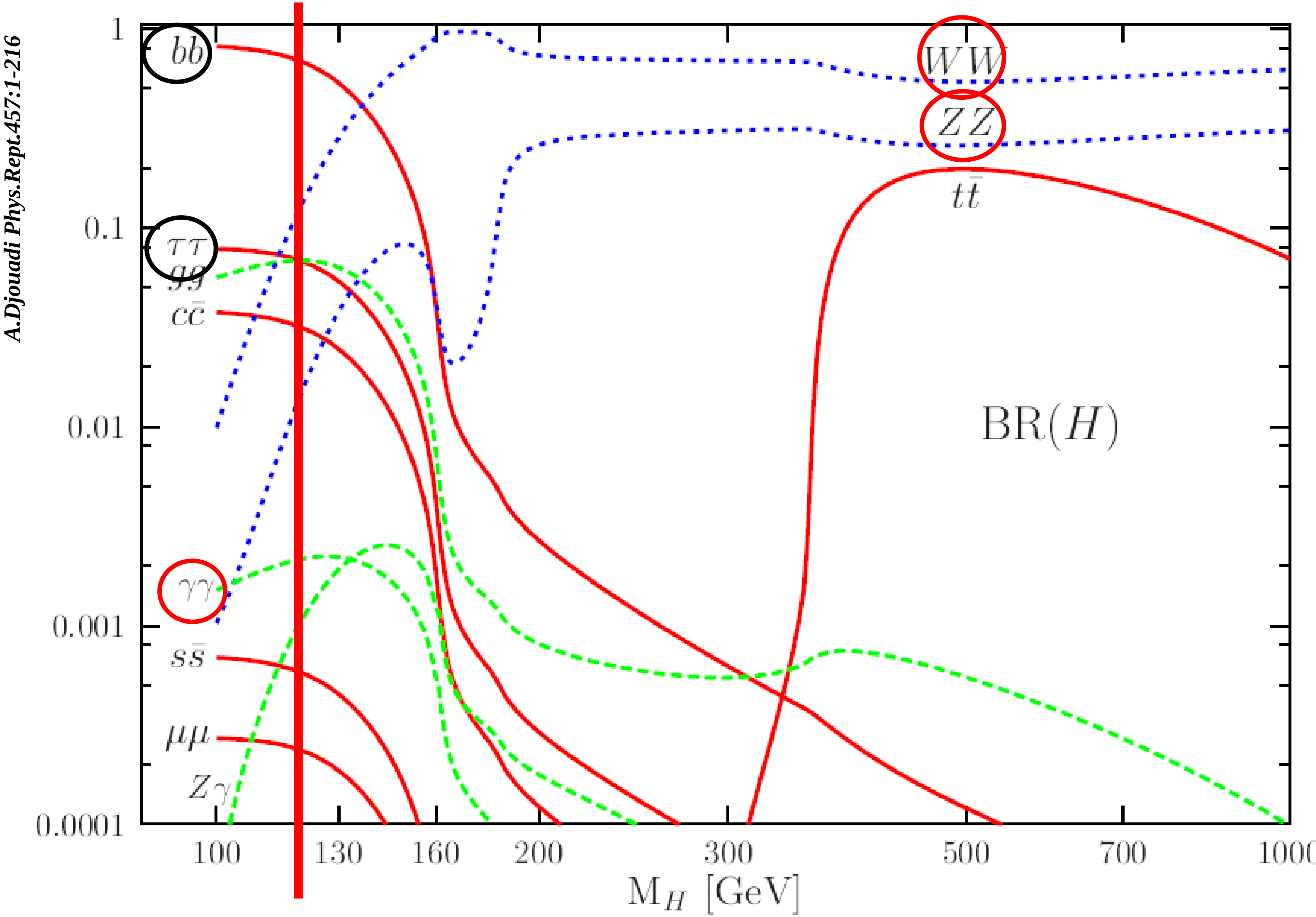


Typical uncertainties on cross-section

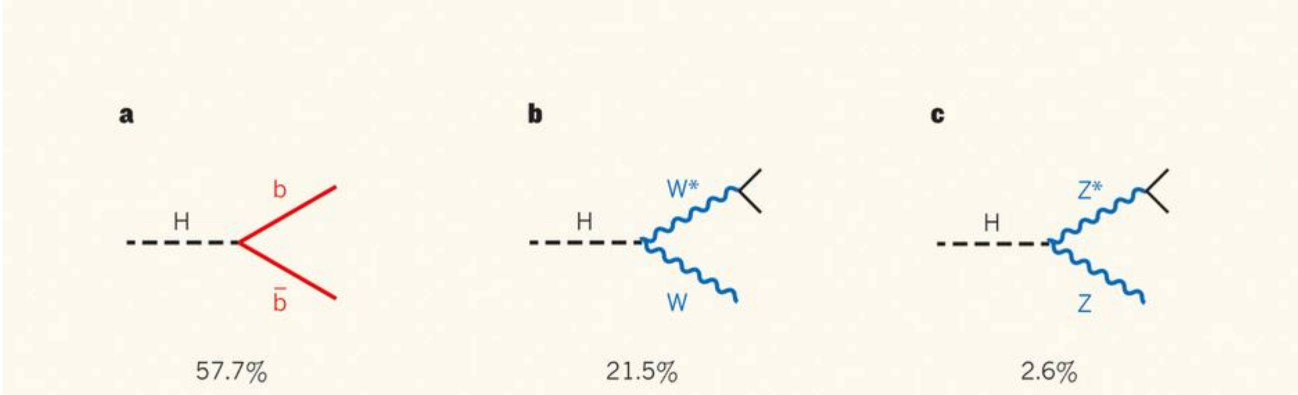
gg	*10 %*	*NNnLO*
VBF	*5%*	*NLO*
WH,ZH	*5%*	*NNLO*
ttH	*15%*	*NLO*

These production cross sections have to be used with the decays ***bb , ττ , WW , ZZ , γγ***

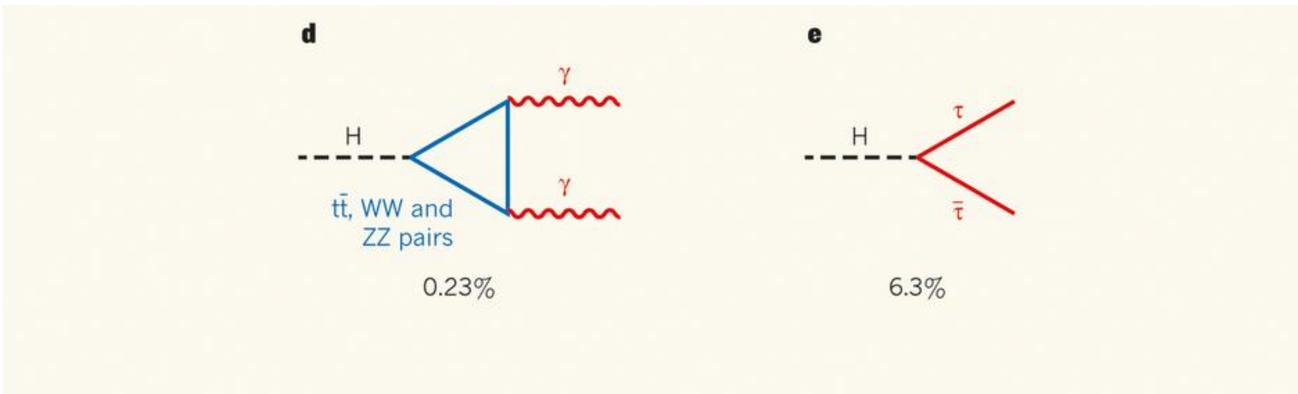
channels with good mass resolution



A.Djouadi Phys.Rept.457:1-216
1
0.1
0.01
0.001
0.0001
$b\bar{b}$
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$s\bar{s}$
$\mu\mu$
$Z\gamma$
WW
ZZ
$t\bar{t}$
BR(H)
100
130
160
200
300
500
700
1000
M_H [GeV]



values of the couplings can be modified in extensions of the SM



relative modifications of direct and loop-induced couplings depend of BSM models :

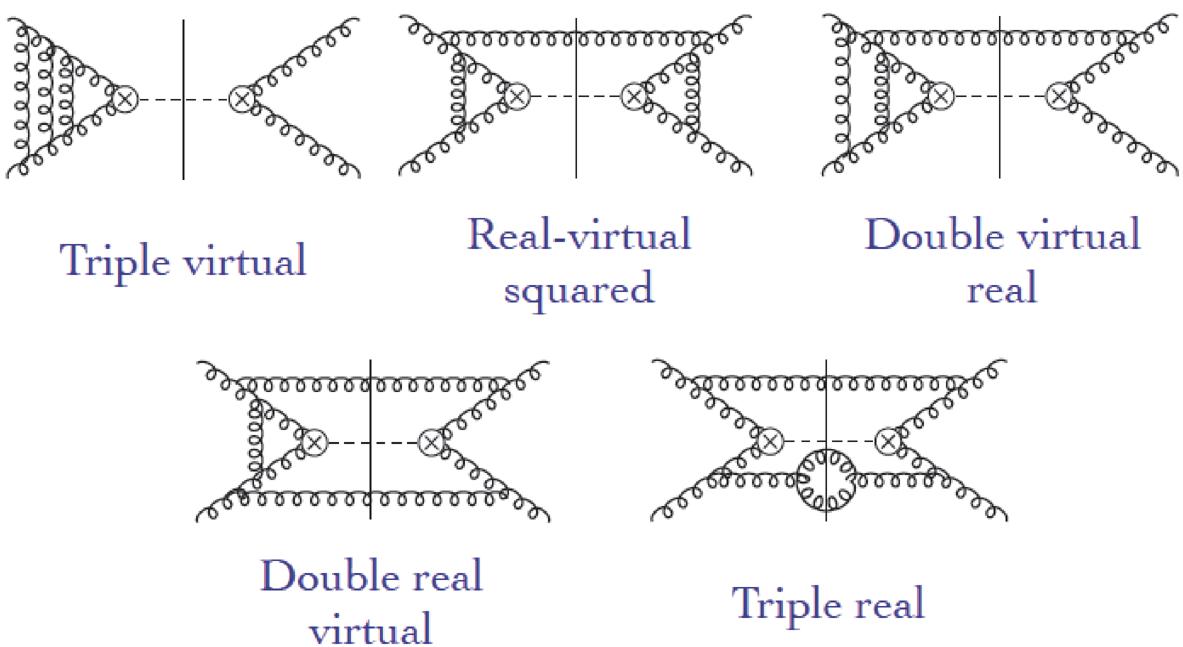
- in 'composite models' couplings to $\gamma\gamma$ are protected by global symetries and deviations are therefore smaller ,

- in MSSM loop-induced deviations are larger

$$1.00 \pm 0.09\,(\text{stat.})\,{}^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

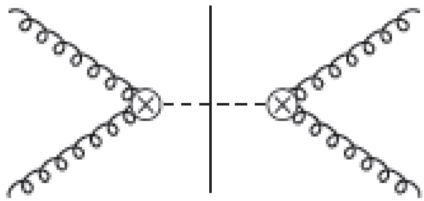
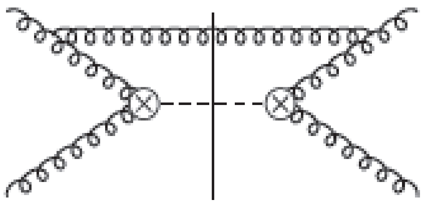
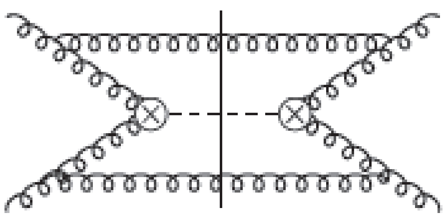
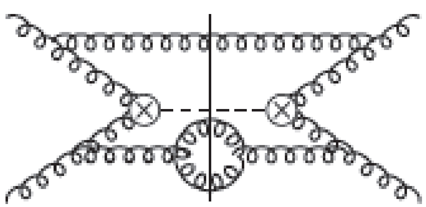
Importance of theoretical errors at the LHC
but they should decrease (soon) !

- At N3LO, there are five contributions:



C.Duhr

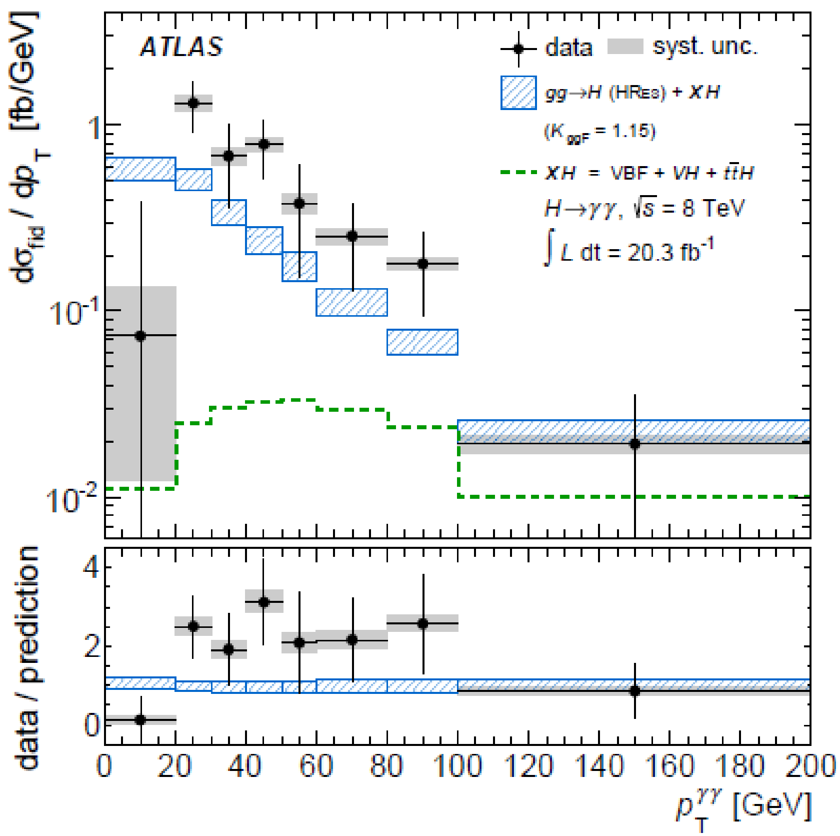
Growth in complexity for real emission

LO		1 diagram	1 integral
NLO		10 diagrams	1 integral
NNLO		381 diagrams	18 integrals
N3LO		26565 diagrams	~500 integrals

CMS PAS HIG-14-005

Search for lepton flavor violating decays

A slight excess of signal events with a significance of 2.5σ is observed.



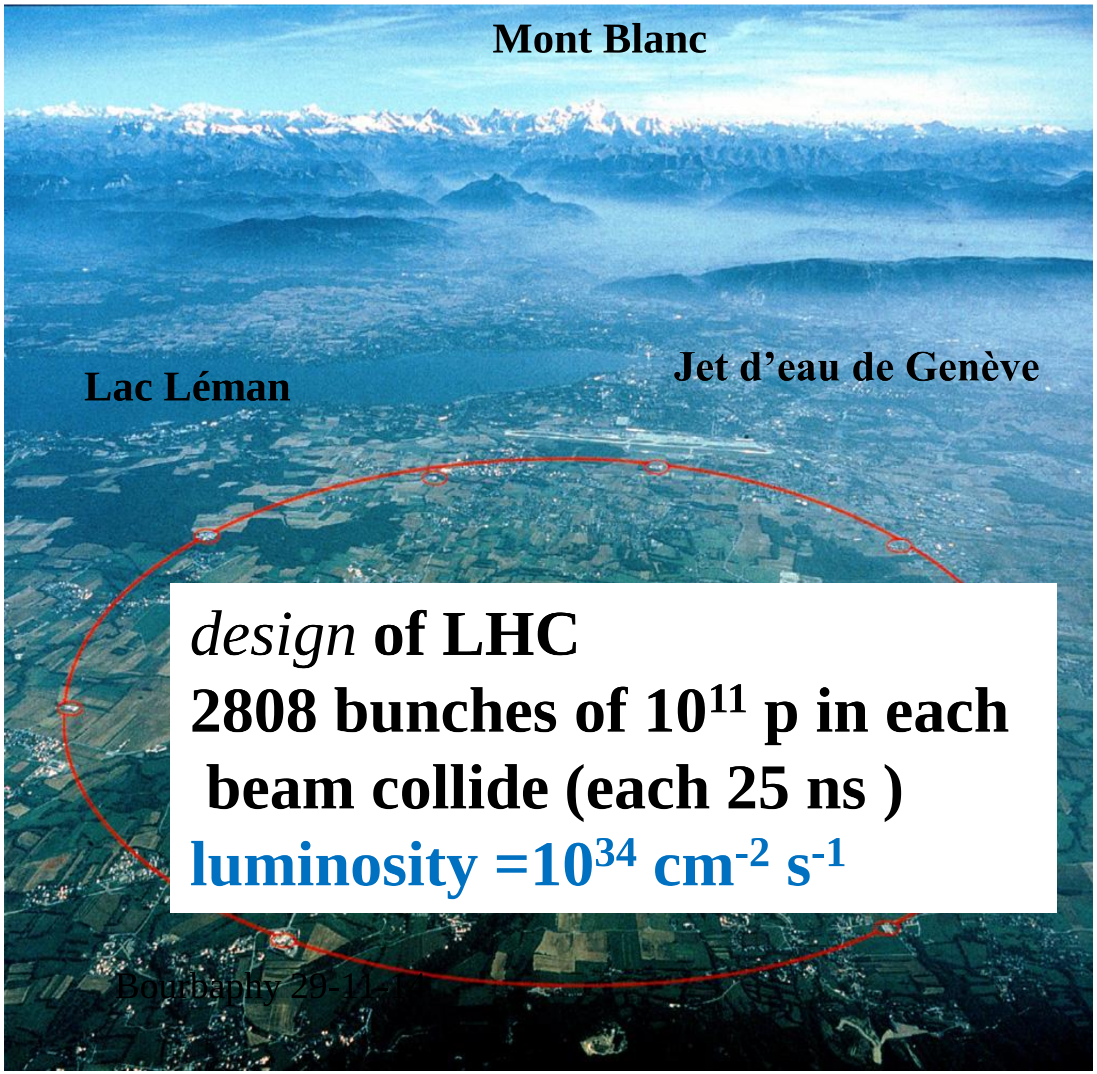
JHEP 1409 (2014) 112

Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV with ATLAS

however several small tensions with the (current) data

► The LHC

The LHC is a (mainly) pp superconducting collider of 27 km long in a tunnel ~ 100 m underground close to Geneva (tunnel already used by LEP) which should work with a *design* centre-of-mass energy of 14 TeV



design **of LHC**
2808 bunches of 10^{11} p in each beam collide (each 25 ns)
luminosity $=10^{34}$ cm^{-2} s^{-1}

CERN
(Centre Europeen de Recherche (sub)Nucleaire)

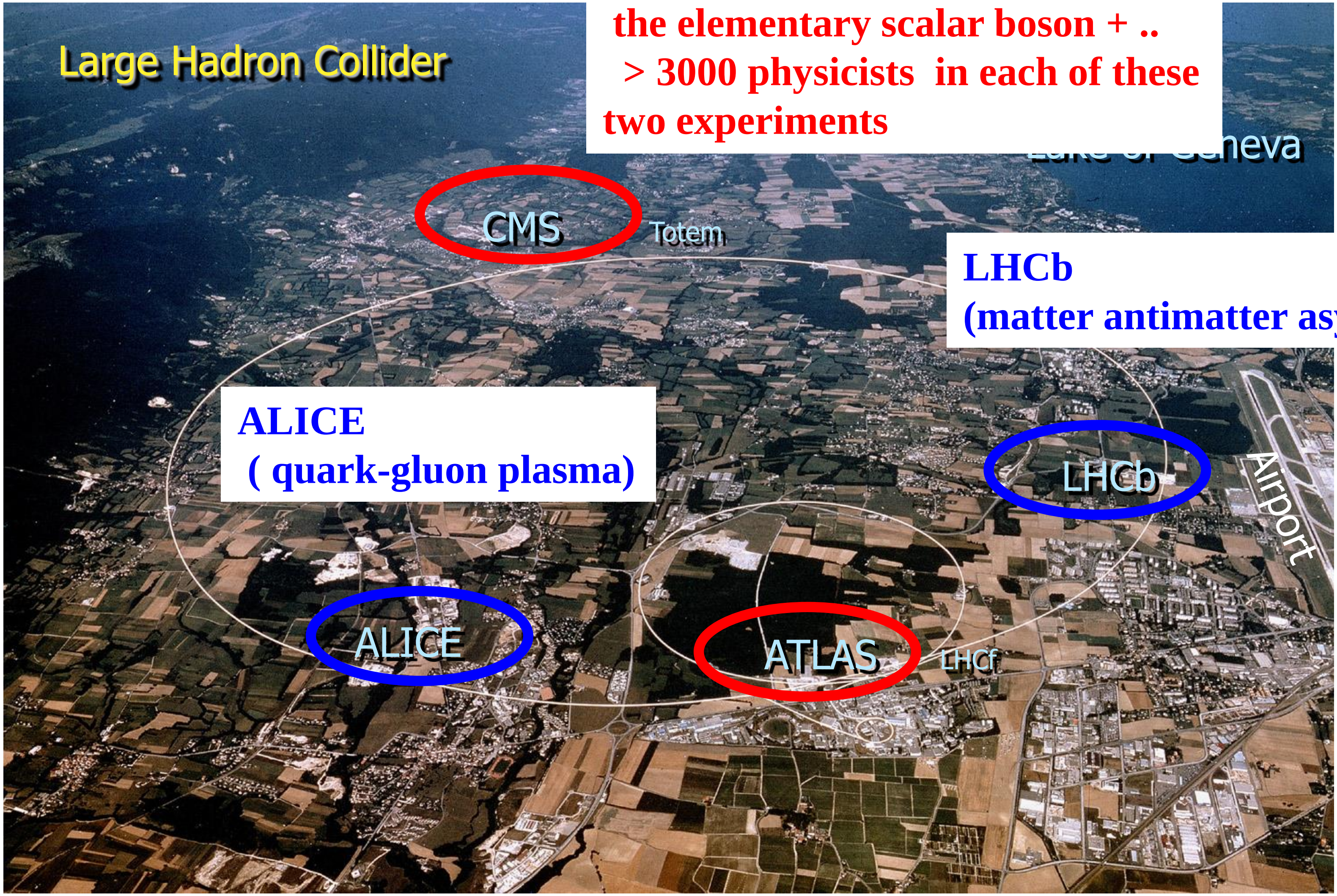
in fact world center

experiments at the LHC

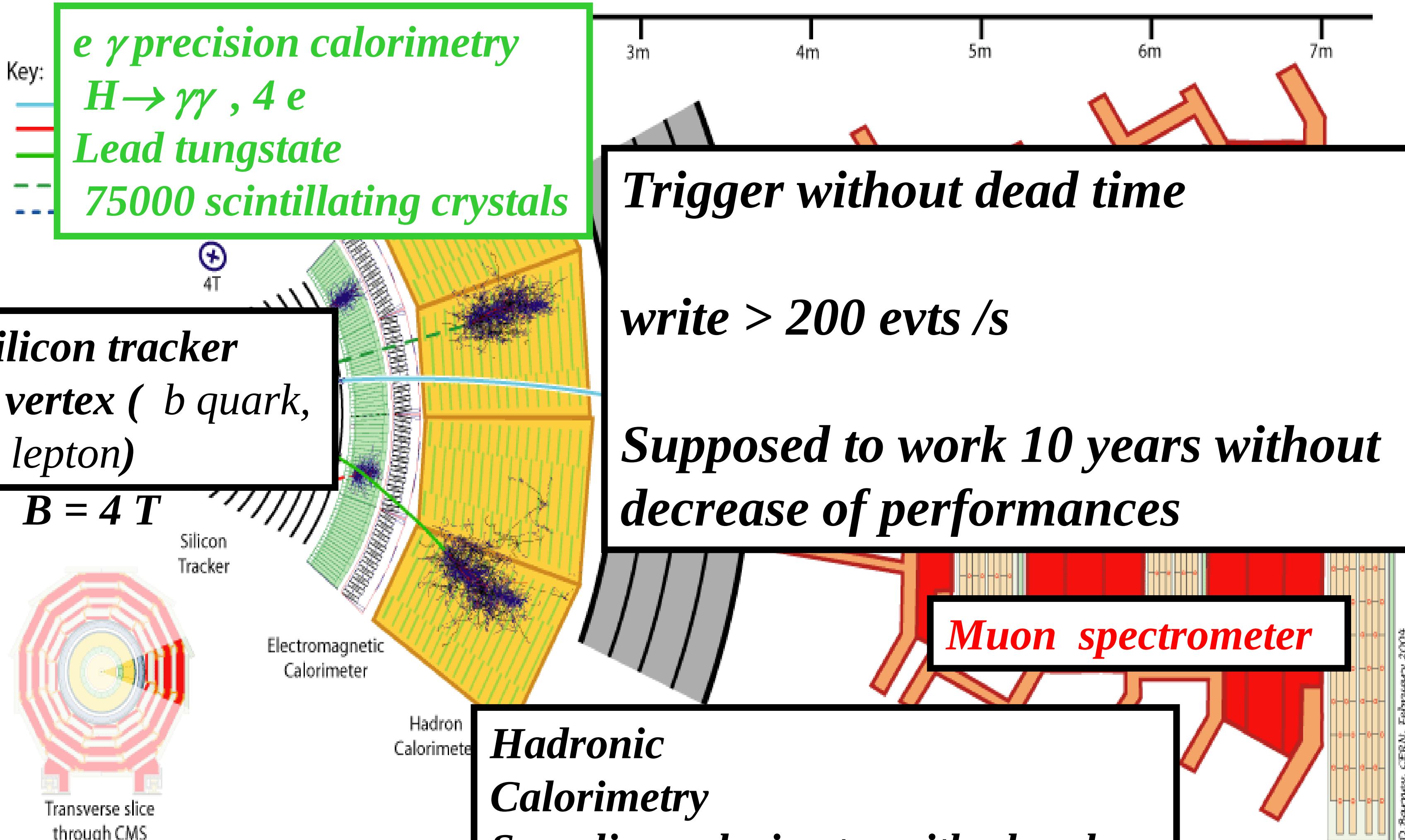
ATLAS and CMS look for
the elementary scalar boson + ..
> 3000 physicists in each of these two experiments

LHCb
(matter antimatter asymmetry)

ALICE
(quark-gluon plasma)



Example of CMS = (Compact Muon Solenoid)



e γ precision calorimetry
$H \rightarrow \gamma\gamma$, 4 e
Lead tungstate
75000 scintillating crystals

Trigger without dead time

write > 200 evts /s

Supposed to work 10 years without decrease of performances

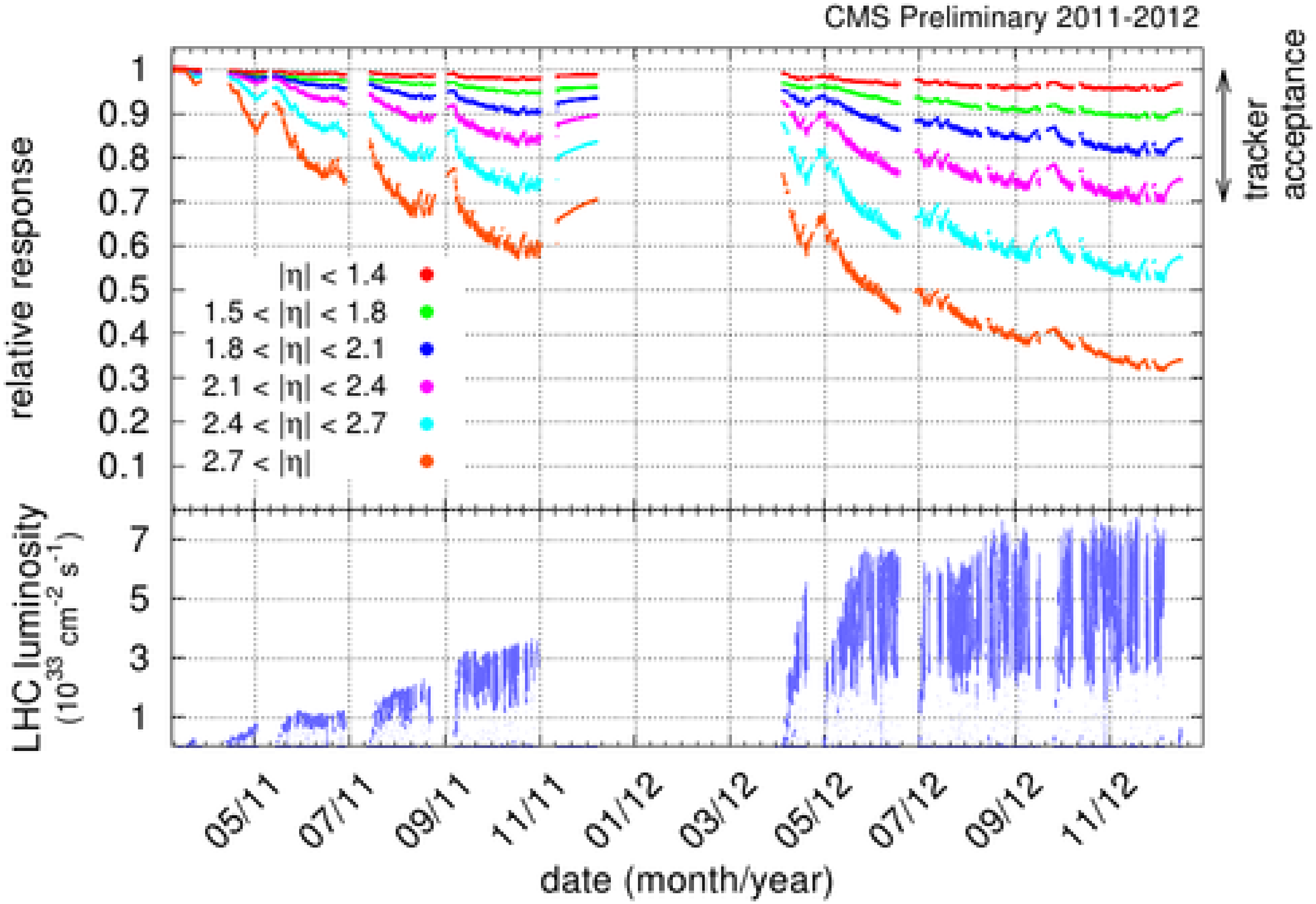
Silicon tracker
+ vertex (*b quark,*
τ lepton)

B = 4 T

Muon spectrometer

Hadronic Calorimetry
Sampling calorimeter with absorber (brass) and plastic scintillators
Jets and $E_T$miss

« 4 π » detector
up to η=5
(from θ = 1.35°)



CMS-DP-2013/007

history of relative response

High level quality control !

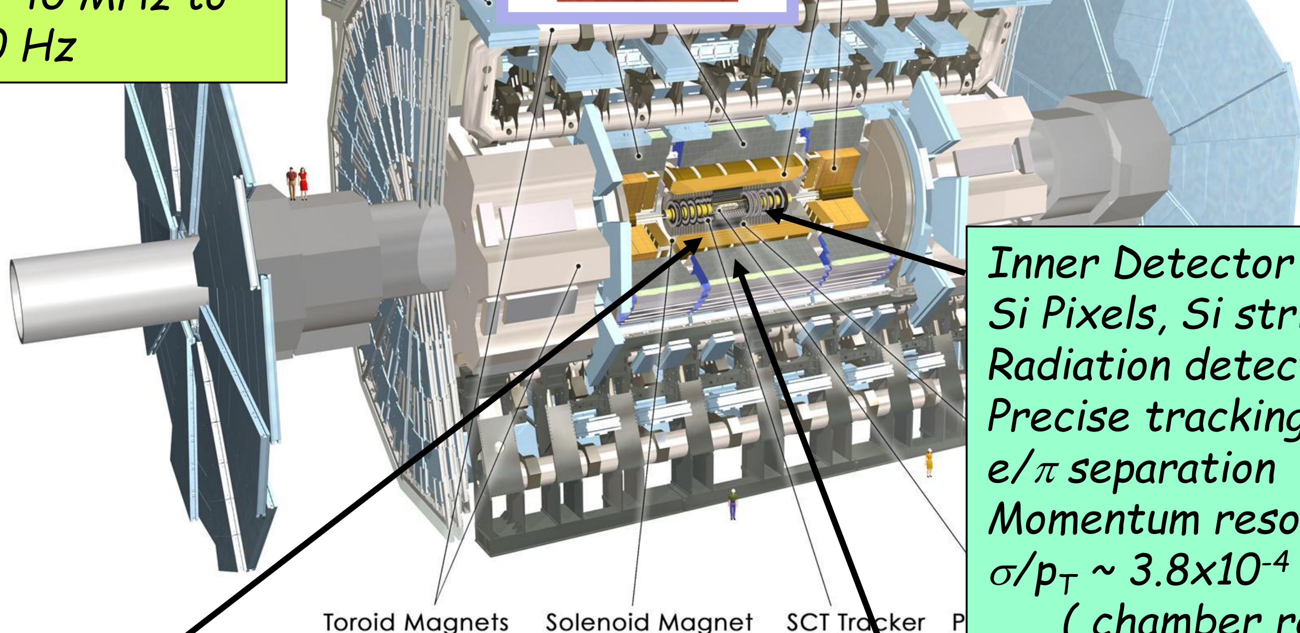
Muon Spectrometer ($|\eta|<2.7$) : air-core toroids (B ~ 0.5 / 1T in barrel/ end-cap) with gas-based muon chambers Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Marc Virchaux (1953-2004)

ATLAS detector

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



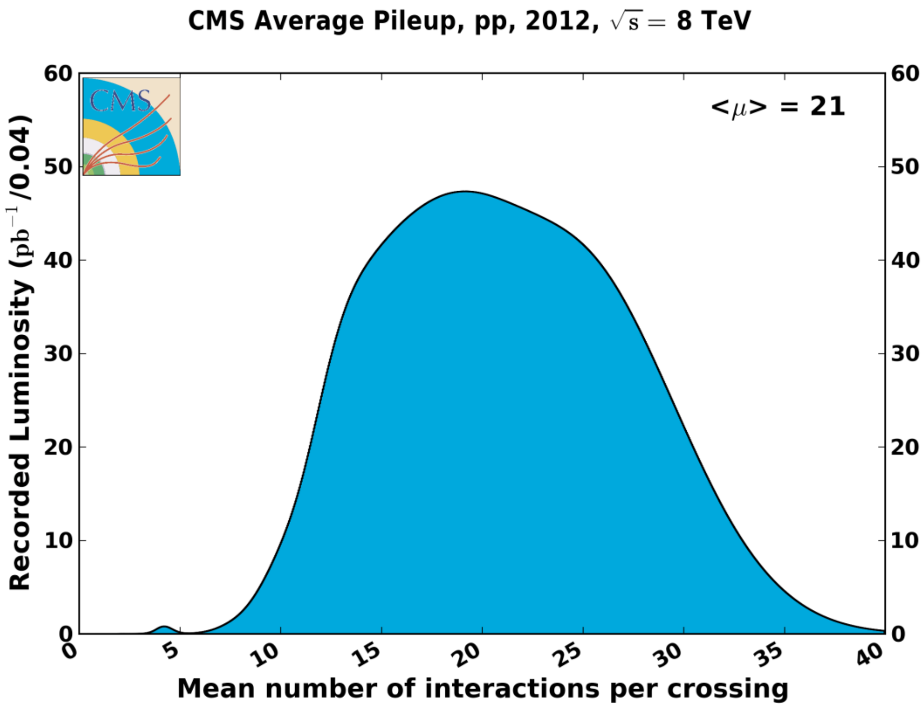
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$
(chamber resolution $\oplus$ MS)

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

Daniel Fournier

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

L = Luminosity = $0.8\ 10^{34}$ [$cm^{-2}\ s^{-1}$]



pile up will increase at higher energy → experiments request 25 ns** (instead of 50 ns) **operation in 2015

M. Lamont, IPAC'13

♥ *Historical introduction of the boson and of the LHC reminder (see François and Yves)*

♥ ***Future facilities (for future searches)***

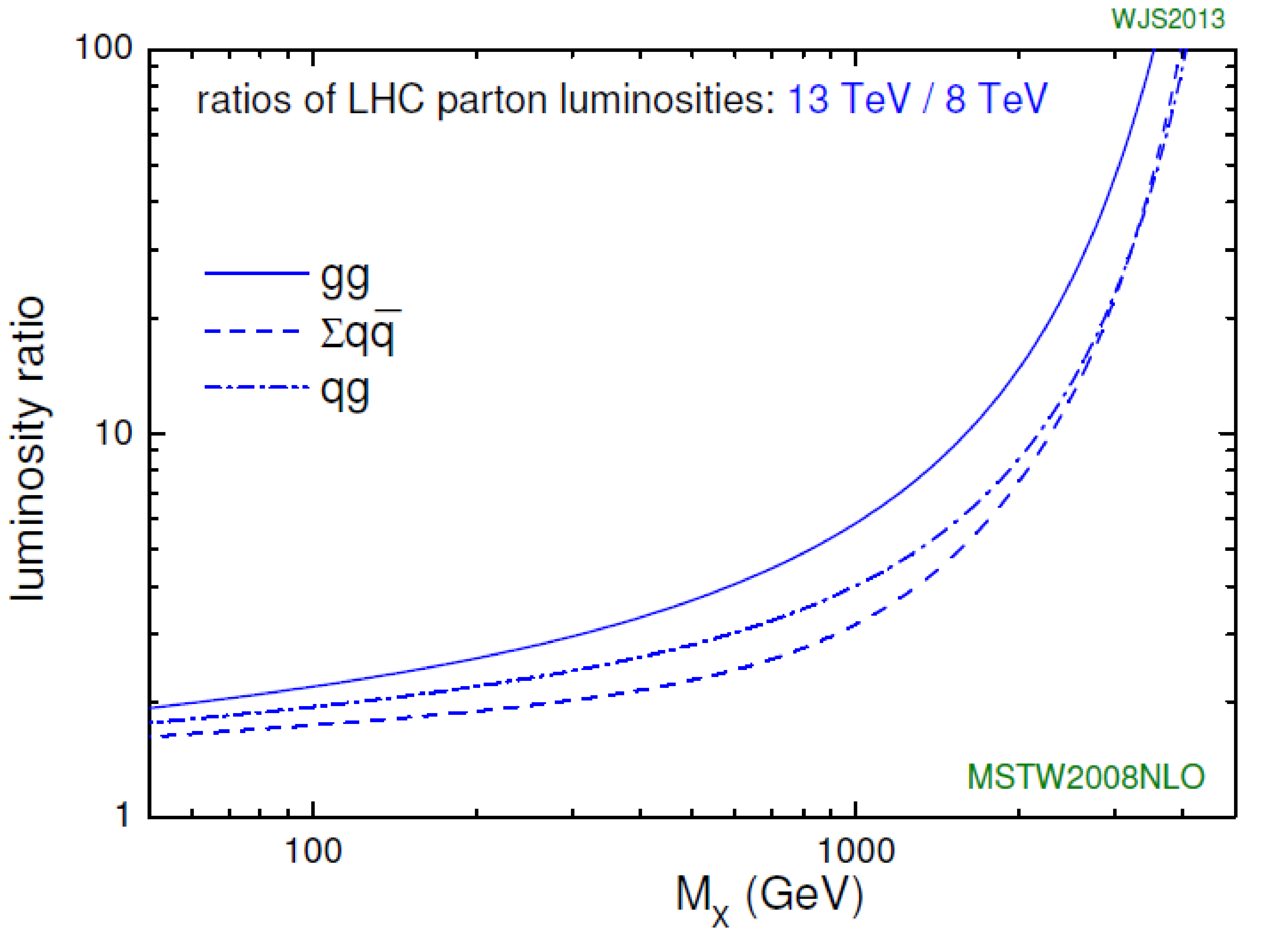
♥ *New physics in the scalar sector (see Pierre and Abdelhak)*

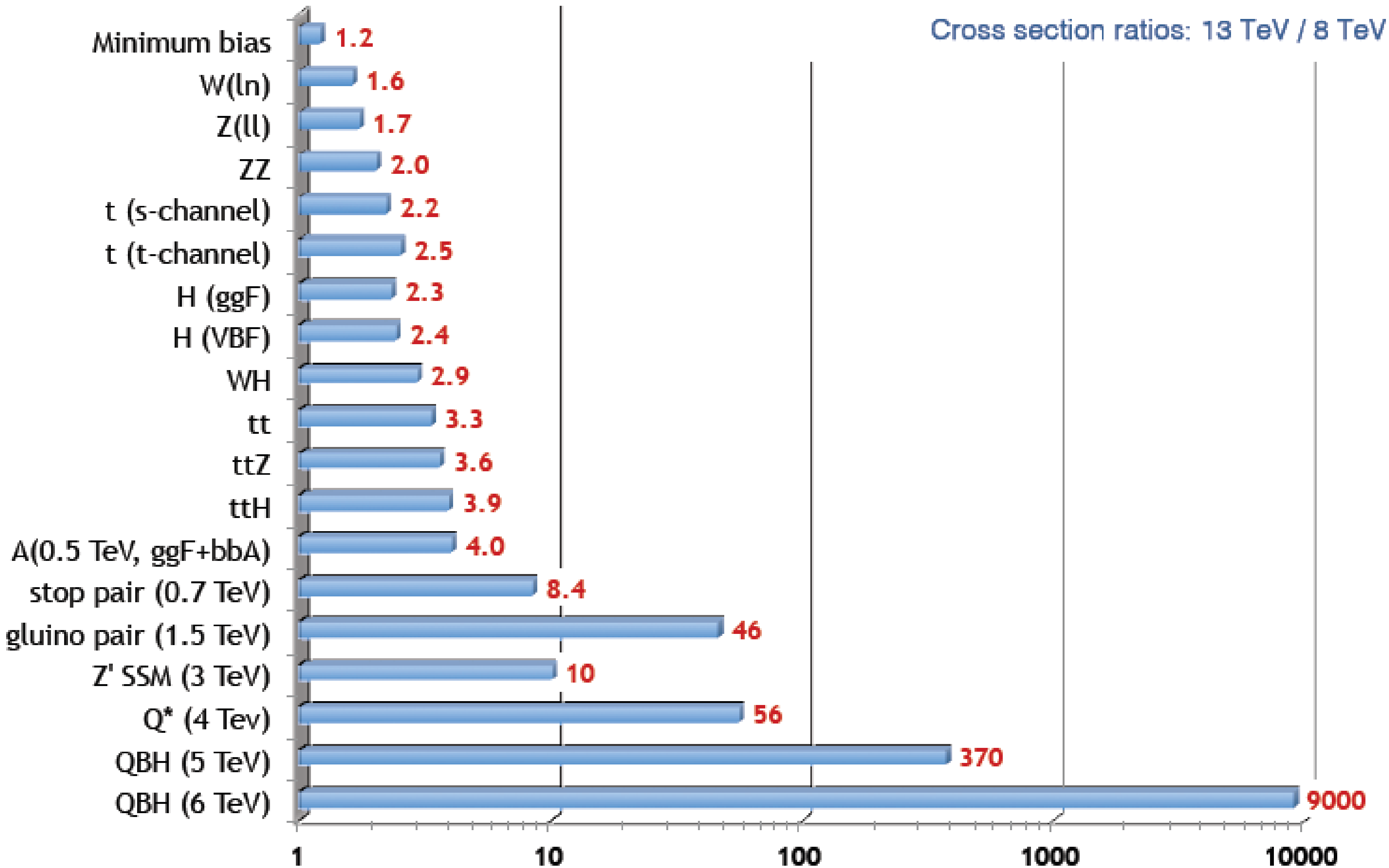
♥ *Conclusion*

♥ *Backup*

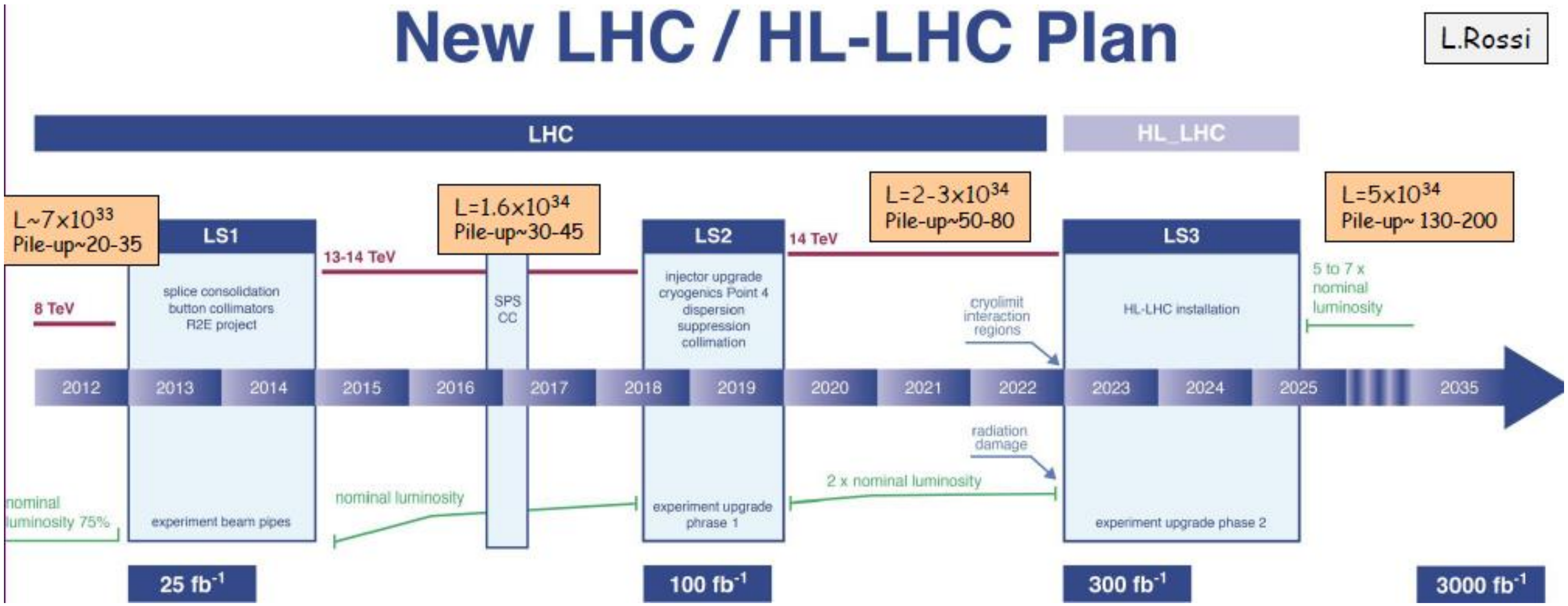
Short term future (improvements of LHC)

(upgraded) LHC may be the only machine in the next 20 years


WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
Σqq̄
qg
MSTW2008NLO
luminosity ratio
1
10
100
100
1000
M_X (GeV)

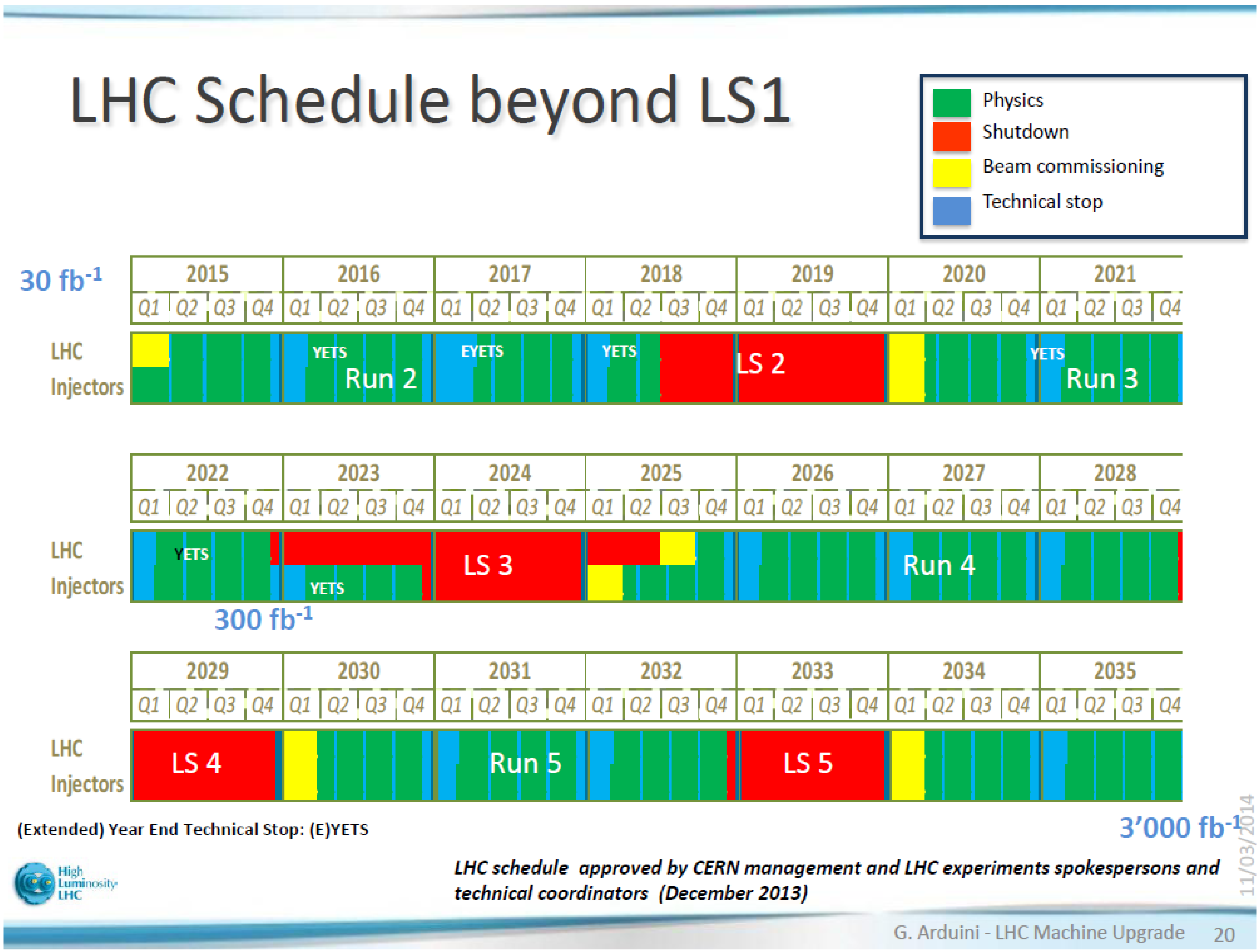

Cross section ratios: 13 TeV / 8 TeV
Minimum bias 1.2
W(ln) 1.6
Z(ll) 1.7
ZZ 2.0
t (s-channel) 2.2
t (t-channel) 2.5
H (ggF) 2.3
H (VBF) 2.4
WH 2.9
tt 3.3
ttZ 3.6
ttH 3.9
A(0.5 TeV, ggF+bbA) 4.0
stop pair (0.7 TeV) 8.4
gluino pair (1.5 TeV) 46
Z' SSM (3 TeV) 10
Q* (4 Tev) 56
QBH (5 TeV) 370
QBH (6 TeV) 9000
1
10
100
1000
10000

The LHC will start again soon

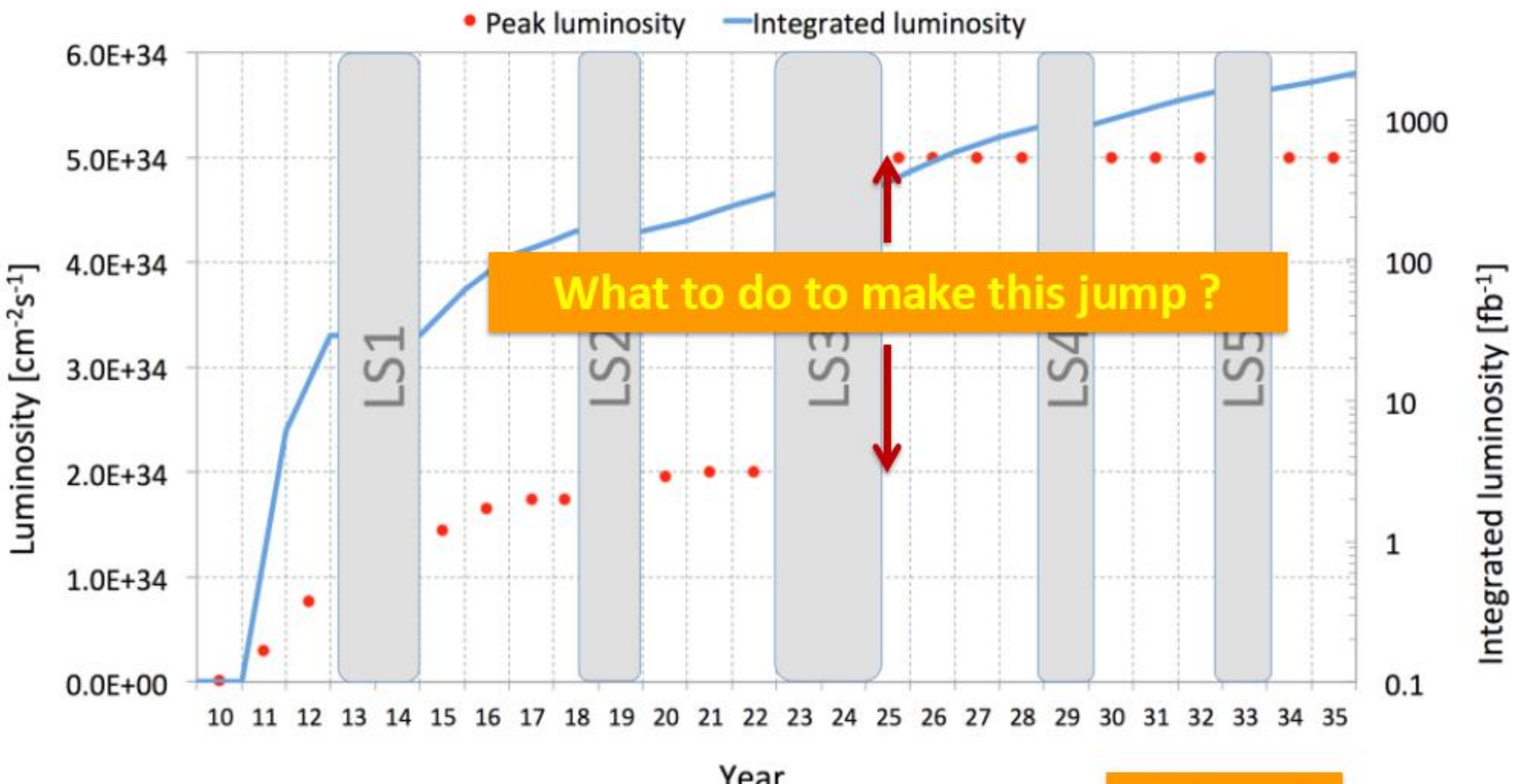


Next 20 years !

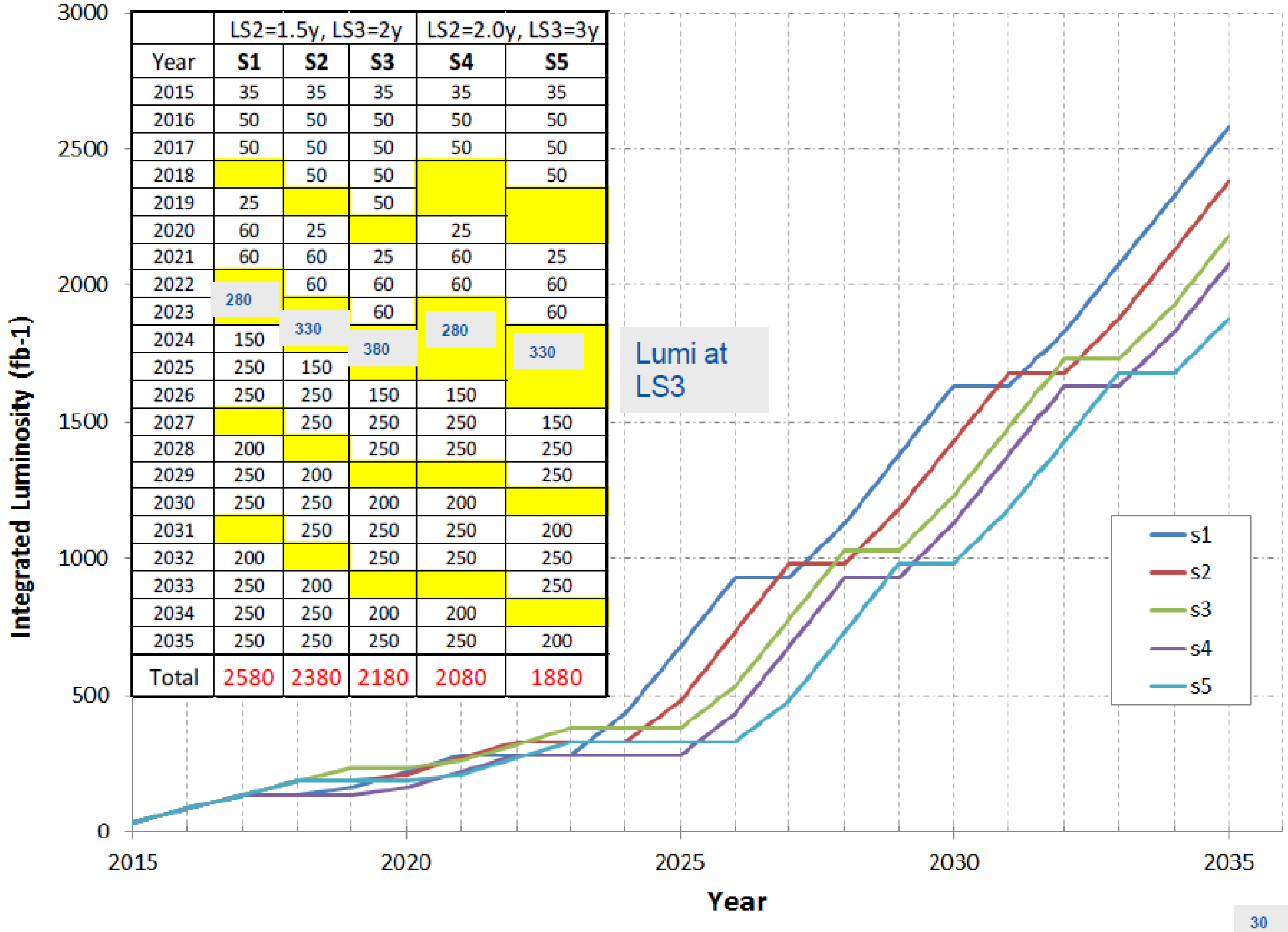
© Arduini



Why an LHC Upgrade?



M. Lamont

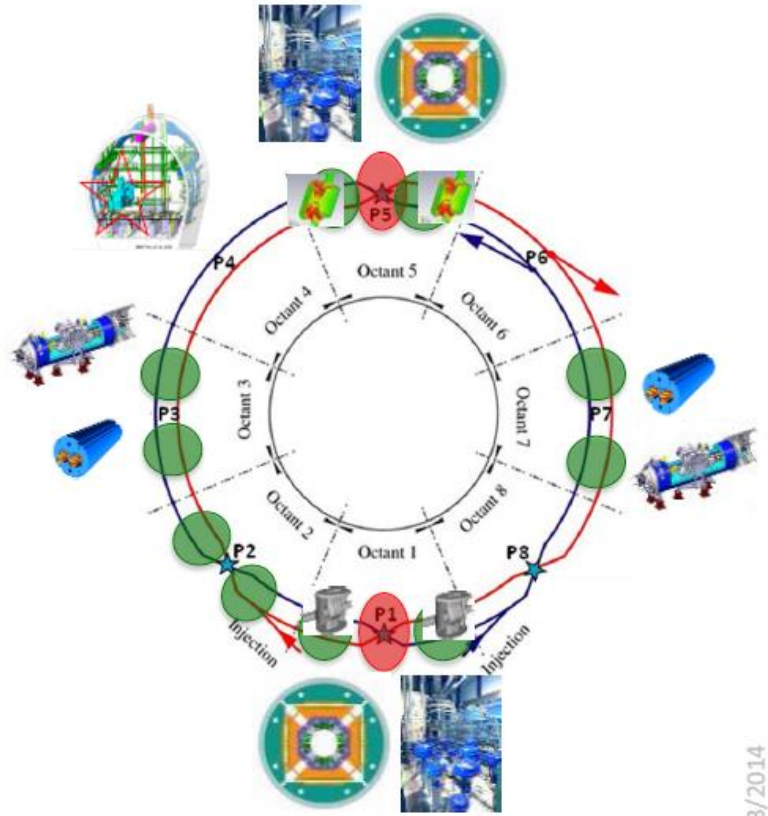


	LS2=1.5y, LS3=2y			LS2=2.0y, LS3=3y	
Year	**S1**	**S2**	**S3**	**S4**	**S5**
2015	35	35	35	35	35
2016	50	50	50	50	50
2017	50	50	50	50	50
2018		50	50		50
2019	25		50		
2020	60	25		25	
2021	60	60	25	60	25
2022		60	60	60	60
2023	280		60		60
2024	150	330	380	280	
2025	250	150			330
2026	250	250	150	150	
2027		250	250	250	150
2028	200		250	250	250
2029	250	200			250
2030	250	250	200	200	
2031		250	250	250	200
2032	200		250	250	250
2033	250	200			250
2034	250	250	200	200	
2035	250	250	250	250	200
Total	2580	2380	2180	2080	1880

Hardware for the Upgrade

cost (machines)
850 MCHF

- Main modifications:
  - New high field/larger aperture interaction region magnets
  - Cryo-collimators and high field 11 T dipoles in dispersion suppressors
  - Crab Cavities to take advantage of the small β*
  - New collimators (lower impedance)
  - Additional cryo plants (P1, P4, P5)
  - SC links to allow power converters to be moved to surface



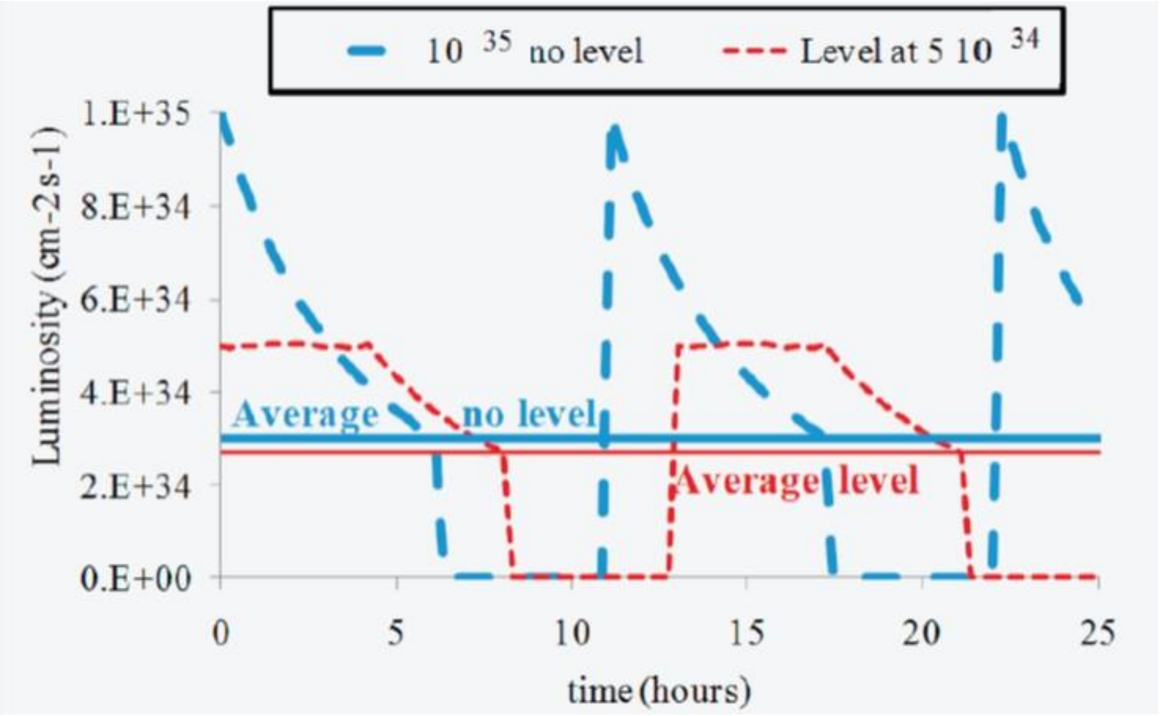
High Luminosity LHC

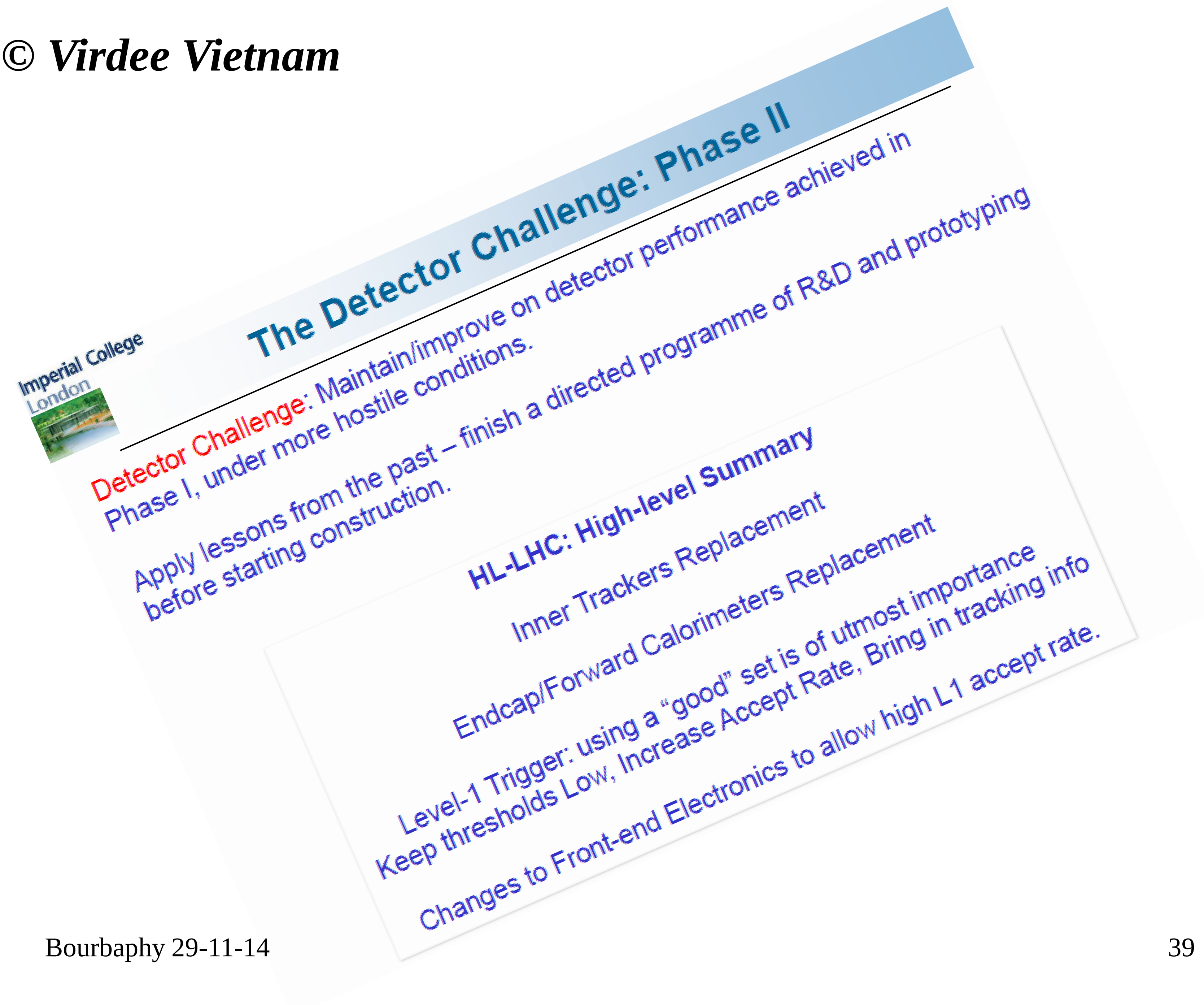
11/03/2014

G. Arduini - LHC Machine Upgrade 32

cost (detectors) ~ 500 MCHF

Luminosity levelling




Imperial College London
The Detector Challenge: Phase II
Detector Challenge: Maintain/improve on detector performance achieved in Phase I, under more hostile conditions.
Apply lessons from the past – finish a directed programme of R&D and prototyping before starting construction.
HL-LHC: High-level Summary
Inner Trackers Replacement
Endcap/Forward Calorimeters Replacement
Level-1 Trigger: using a "good" set is of utmost importance
Keep thresholds Low, Increase Accept Rate, Bring in tracking info
Changes to Front-end Electronics to allow high L1 accept rate.

Long term future (linear and circular colliders)

Obviously final decisions will wait for (more) results from LHC …

proton colliders , circular , allow to go to very high energy , technological challenges : magnets

electron colliders , circular (large synchrotron radiation power ~ $1/m^4$) or linear , allow a well defined centre of mass energy between constituents

+ *muon colliders , e-p colliders (LHeC), photon colliders*
plasma-based particle acceleration not described here

e+e- colliders : remind Synchrotron Radiation Power ~ E_{beam}^4

ILC : two single-beam linac with superconducting RF accelerating cavities ~ 40 MV/m √s ~ .25 – 1 TeV

CLIC : two double beam linac : the low energy , high current drive beam powers ~100 MV/m RF cavities in main linac √s ~3 TeV

Circular e+e- colliders : FCC-ee : 80 km circular ring ,

e+e- collider (** *could have also L3 √s ~240 GeV in LHC tunnel* ***)

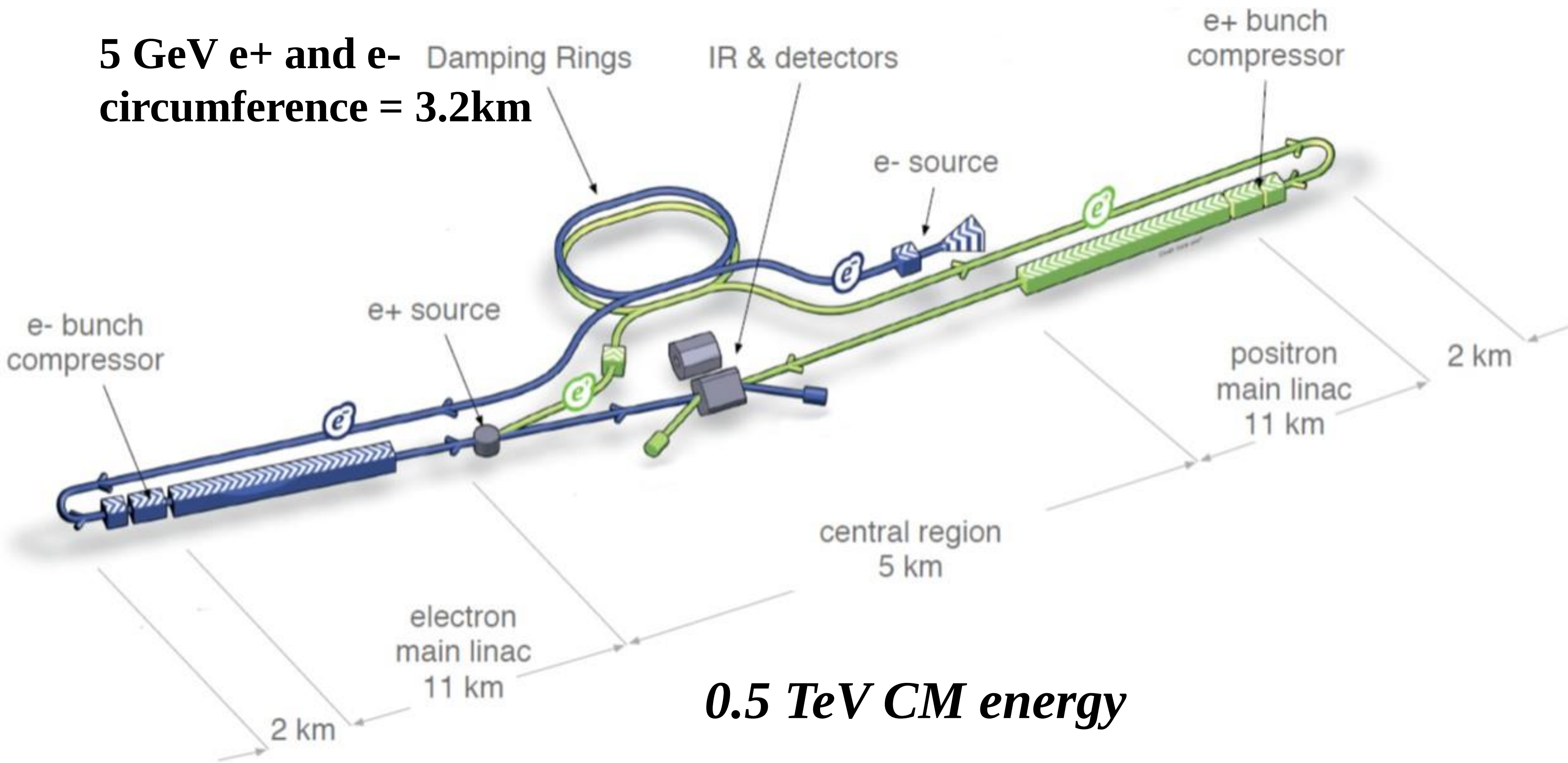
requires two ring scheme in order to have a lot of bunches and continuous injection (tested at B factories) .. see also CepC

FCC-pp (could go up to √s=100 TeV)

The International Linear Collider (ILC)

Linear e+ e- collider , based on superconducting radio-frequency accelerating technology.

5 GeV e+ and e- circumference = 3.2km



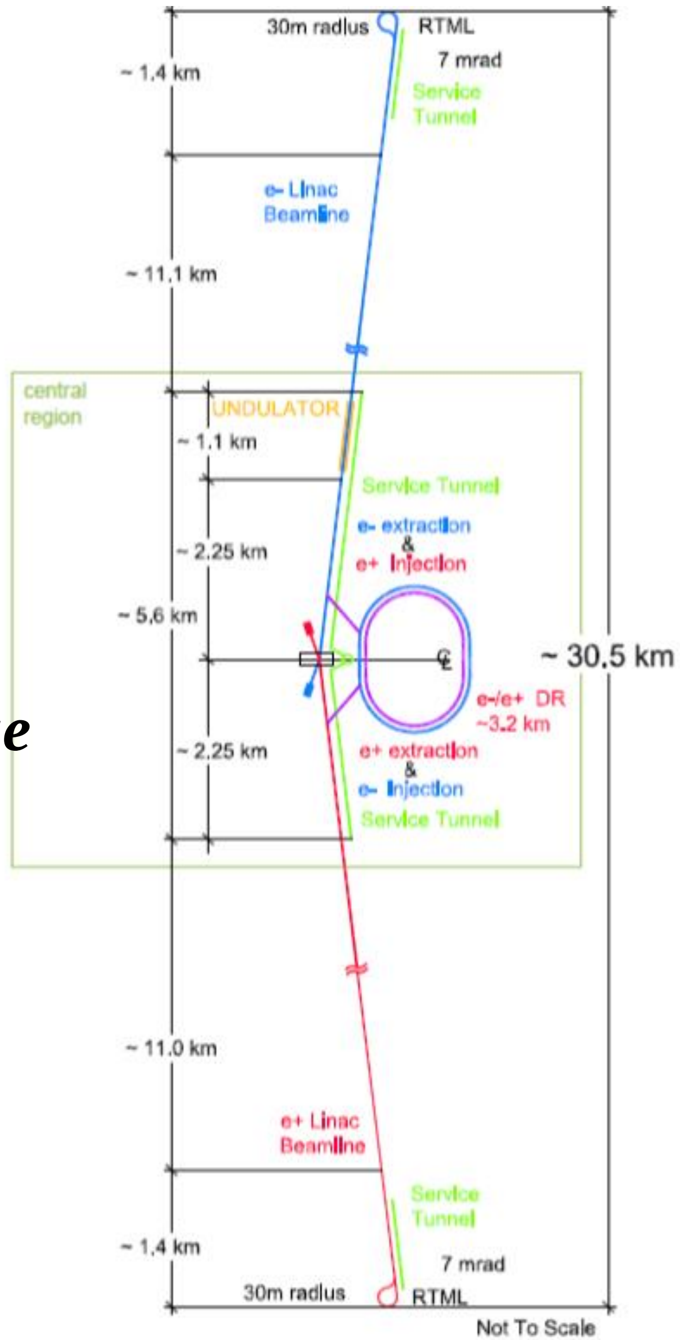
0.5 TeV CM energy

$\sqrt{s}$ = 0.5 TeV

(1.3 GHz) superconducting cavities with a pulse length of 1.6 ms
40 MV/m

separation between bunches in a pulse ~ 0.5 μs

rate of pulses ~ 5 Hz

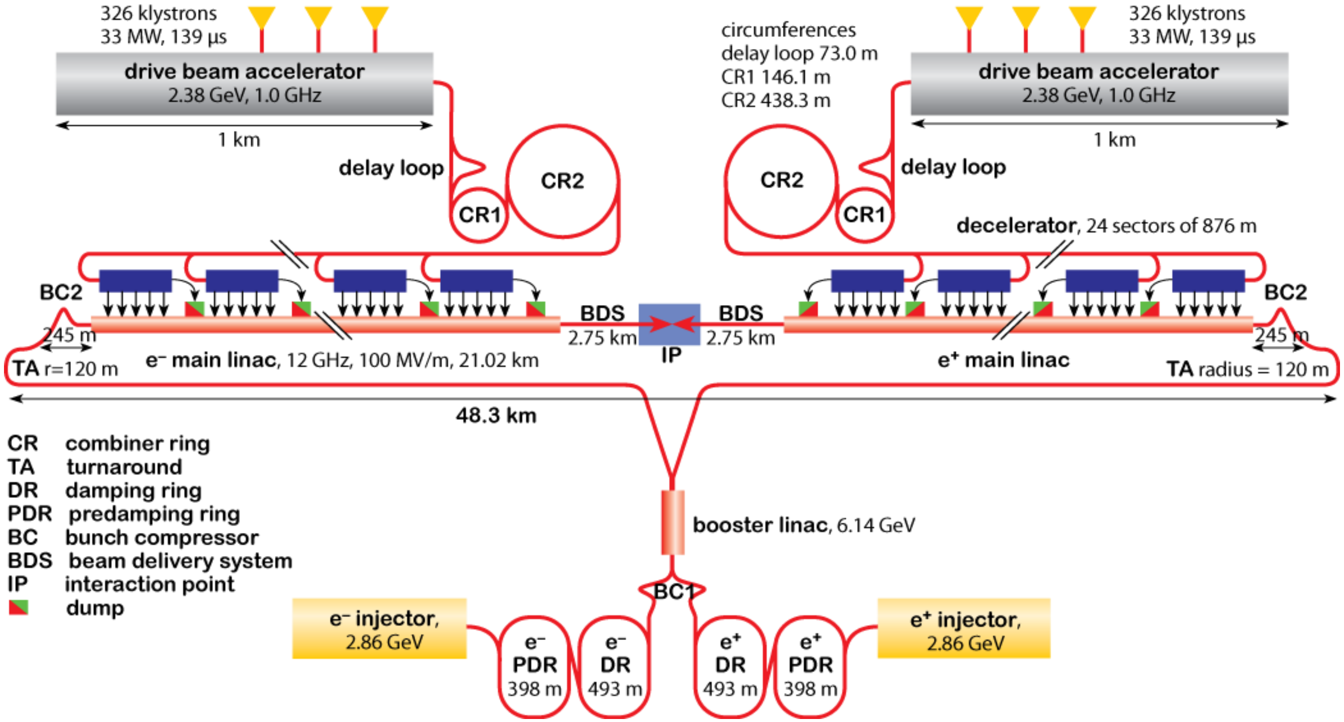


			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current **within pulse (~ 1 ms)**	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ $cm^{-2}s^{-1}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

almost 20 years of R&D

Synergy with XFEL (X-ray Free Electron Laser at DESY)

Compact LInear Collider CLIC



pulse rate : 50 Hz
350 bunches
(each 0.5 ns)
in a pulse

High gradient normal-conducting accelerating structure
RF power for the colliding beams extracted from a high current drive beam

CLIC

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Center-of-mass energy	$\sqrt{s}$	GeV	350	1400	3000
Integrated luminosity	$\mathscr{L}_{\text{int}}$	ab^{-1}	0.5	1.5	2.0

4-5 years of operation 200 days/year 50% efficiency

Description [units]	**500 GeV**	**3 TeV**
Total (peak 1%) luminosity	$2.3\ (1.4)\times10^{34}$	$5.9\ (2.0)\times10^{34}$
Total site length [km]	13.0	48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	50	
Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m]	2.4/25	0.66/20
Hor./vert. IP beam size [nm]	202/2.3	40/1
Beamstrahlung photons/electron	1.3	2.2
Hadronic events/crossing at IP	0.3	3.2
Coherent pairs at IP	200	6.8×10^8

3 TeV CLIC

	Power [MW]	Days	Energy [TWh]
Nominal operation mode	582	177	2.47
Fault-induced downtime	60	44	0.06
Programmed stops	60	144	0.21
Energy consumption per year			2.74

Note : 1 year of CERN with LHC at 4+4 TeV
1.26 TWh

Will add 0.1 TWh at 6.5+6.5 or 7+7 TeV

Future Circular Colliders

CERN is considering a design study of post-LHC particle circular accelerator , with emphasis on pp and e+e- high energy frontier machines

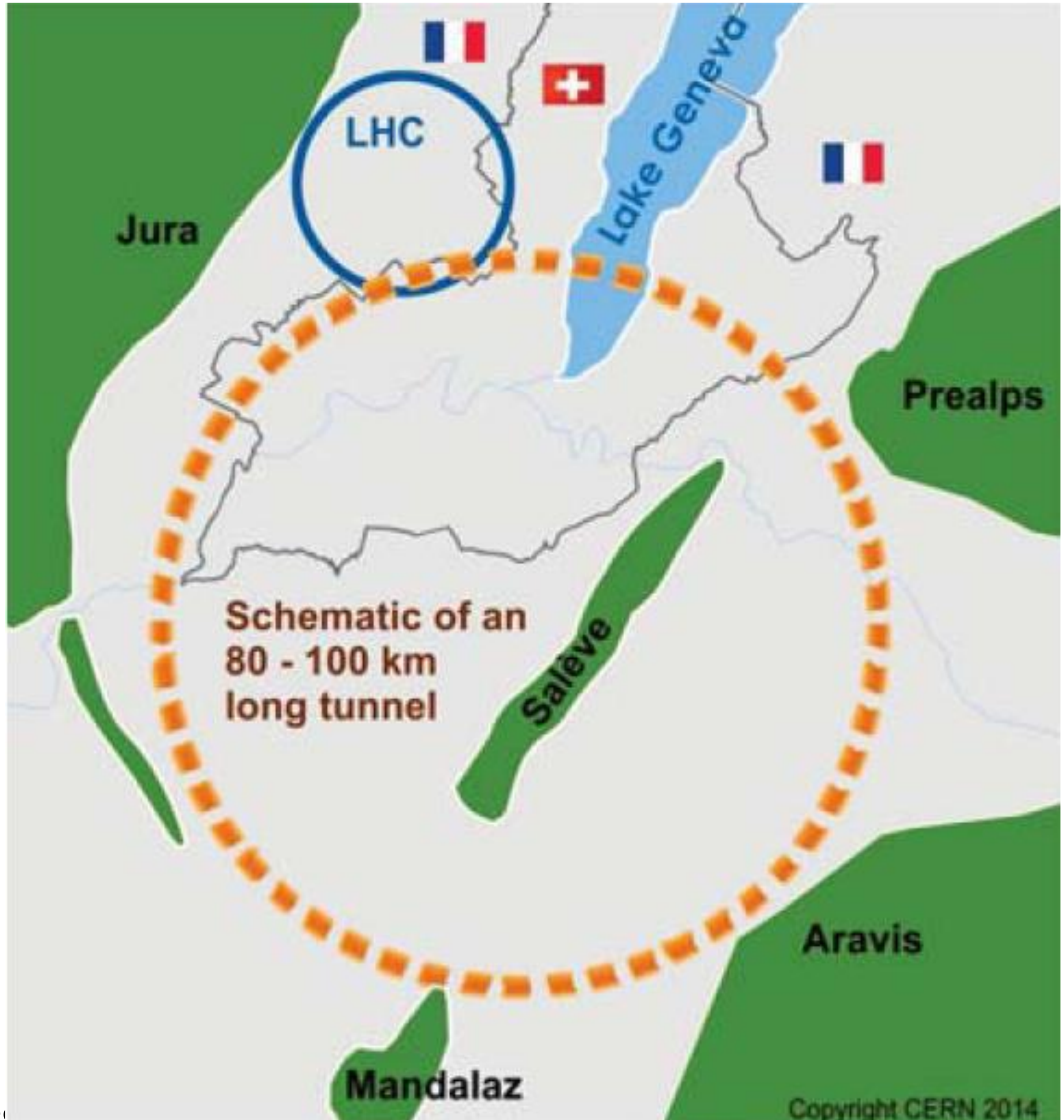
Circular design also considered in China (CepC , SppC)

pp colliders :

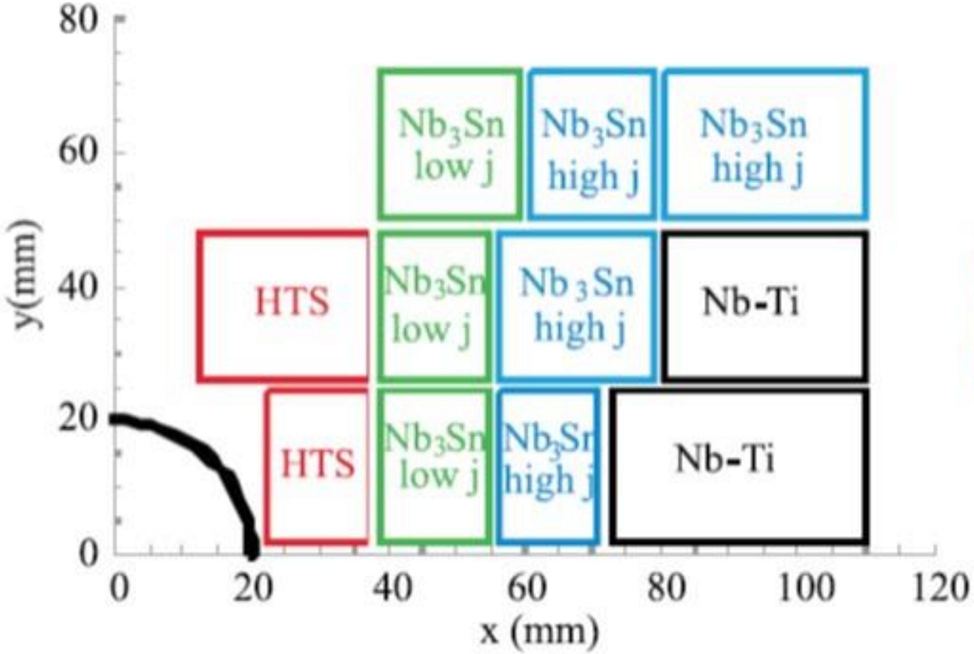
LHC circumference = 27 km B = 8.3 T $\sqrt{s}$ =14 TeV

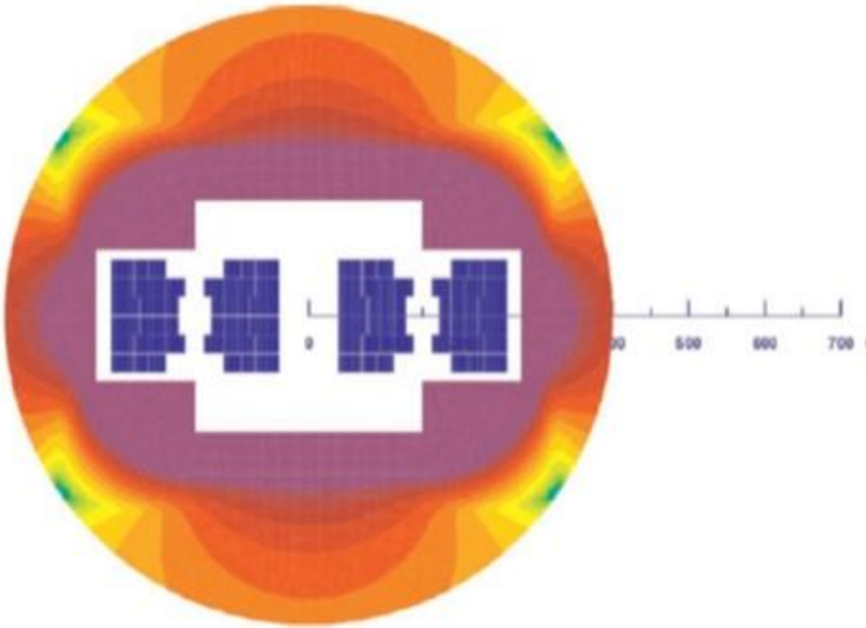
100 km 20 T 125 TeV

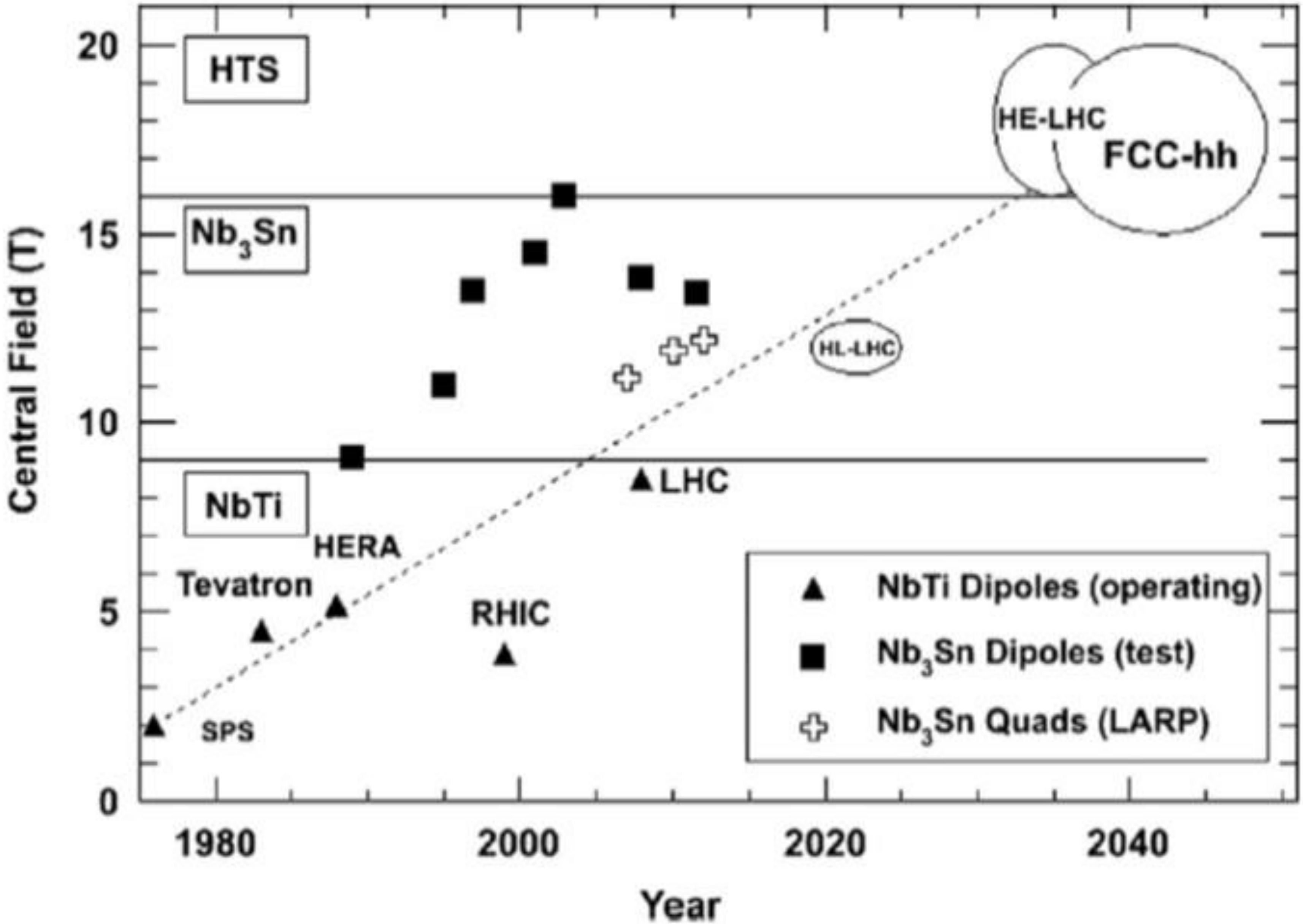
technological challenge


LHC
Lake Geneva
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandalaz
Copyright CERN 2014

Magnet 'design'







Magnet fields

Very high luminosity e+ e- colliders considered

FCC-ee High luminosity

→ short beam lifetime

→ top-up injection , operating the collider at constant magnetic field and with almost constant beam current (tested at KEKB and PEP-II B factories)

→ Requires a full-energy injector

The FCC-ee collider is a double ring with separate beam-pipes for the e+ and e- beams

→ allows a large number of bunches

→ 3 rings

parameter	LHC (pp) design	FCC-hh	LEP2 achieved	FCC-ee (TLEP) Z	Z (cr. w.)	W	H	$t\bar{t}$	CepC
species	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-
E_{beam} [GeV]	7,000	50,000	104	45.5	45	80	120	175	120
circumf. [km]	26.7	100	26.7	100	100	100	100	100	54
current [mA]	584	500	3.0	1450	1431	152	30	6.6	16.6
no. of bunches, n_b	2808	10600	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	1.15	1.0	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ϵ_x [nm]	0.5	0.04	22	29	0.14	3.3	0.94	2	6.8
ϵ_y [pm]	500	41	250	60	1	7	2	2	20
β_x^* [m]	0.55	1.1	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β_y^* [mm]	550	1100	50	1	1	1	1	1	1.2
σ_x^* [μm]	16.7	6.8	162	121	8	26	22	45	74
σ_y^* [μm]	16.7	6.8	3.5	0.25	0.032	0.13	0.044	0.045	0.16
θ_c [mrad]	0.285	0.074	0	0	30	0	0	0	0
f_{rf} [MHz]	400	400	352	800	300	800	800	800	700
V_{rf} [GV]	0.016	>0.020	3.5	2.5	0.54	4	5.5	11	6.87
α_c [10^{-5}]	32	11	14	18	2	2	0.5	0.5	4.15
$\delta_{\mathrm{rms}}^{\mathrm{SR}}$ [%]	—	—	0.16	0.04	0.04	0.07	0.10	0.14	0.13
$\sigma_{z,\mathrm{rms}}^{\mathrm{SR}}$ [mm]	—	—	11.5	1.64	1.9	1.01	0.81	1.16	2.3
$\delta_{\mathrm{rms}}^{\mathrm{tot}}$ [%]	0.003	0.004	0.16	0.06	0.12	0.09	0.14	0.19	0.16
$\sigma_{z,\mathrm{rms}}^{\mathrm{tot}}$ [mm]	75.5	80	11.5	2.56	6.4	1.49	1.17	1.49	2.7
F_{hg}	1.0	1.0	0.99	0.64	0.94	0.79	0.80	0.73	0.61
$\tau_{\|\|}$ [turns]	10^9	10^7	31	1320	1338	243	72	23	40
ξ_x/IP	0.0033	0.005	0.04	0.031	0.032	0.060	0.093	0.092	0.103
ξ_y/IP	0.0033	0.005	0.06	0.030	0.175	0.059	0.093	0.092	0.074
no. of IPs, n_{IP}	3 (4)	2 (4)	4	4	4	4	4	4	2
L/IP [10^{34}/cm^2/s]	1	5	0.01	28	219	12	6	1.7	1.8
τ_{beam} [min]	2760	1146	300	287	38	72	30	23	57
P_{SR}/beam [MW]	0.0036	2.4	11	50	50	50	50	50	50
energy / beam [MJ]	392	8400	0.03	22	22	4	1	0.4	0.3

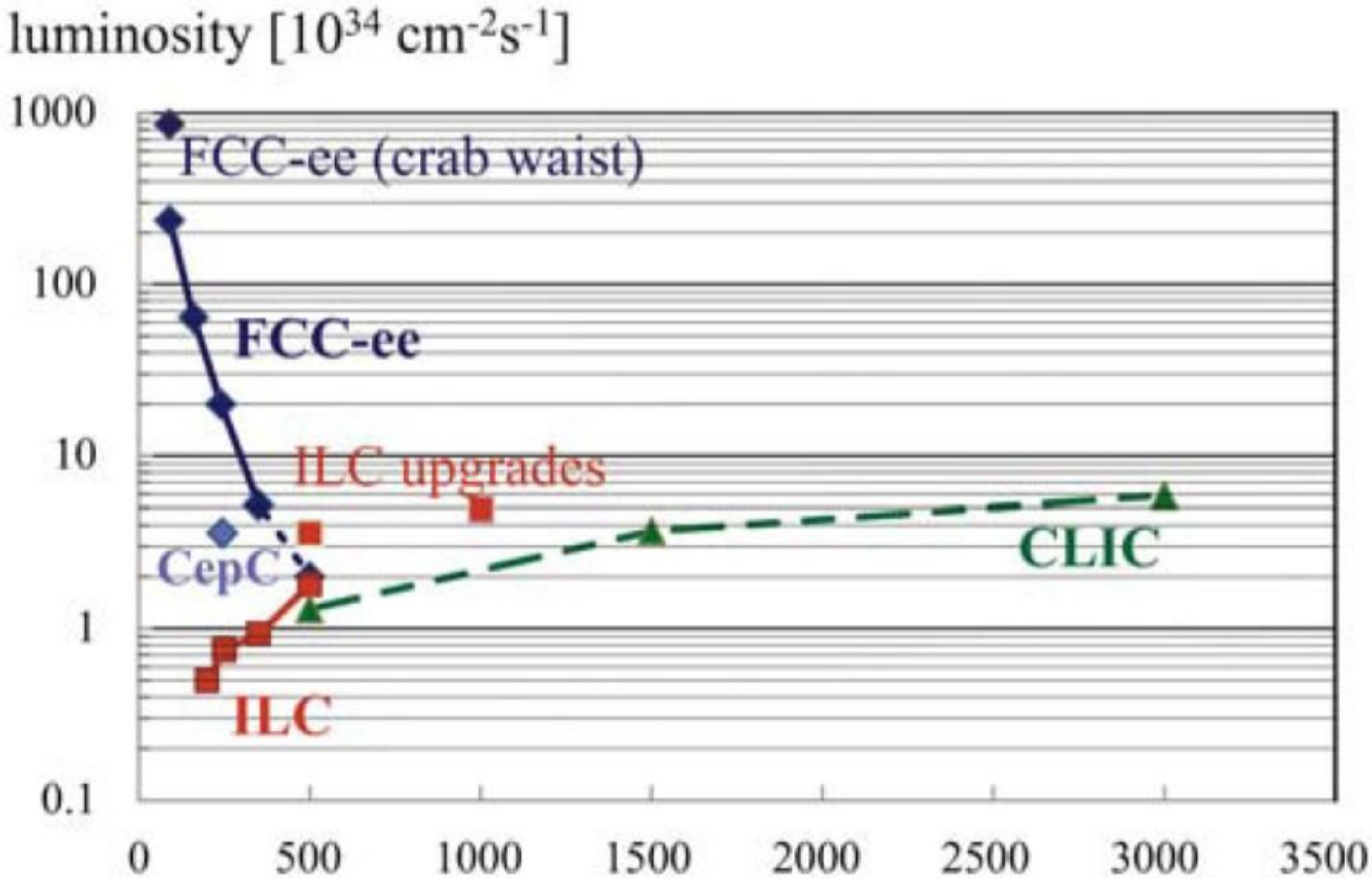
current ~ $1/(E_{\mathrm{beam}})^4$

large number of bunches

Constant P_{SR}

100 MW $P_{SR} \rightarrow$ 300 MW total for FCC-ee

comparison of luminosity of various colliders



FCC-ee and CepC values are summed over 4 and 2 IPs

♥ ***Historical introduction of the boson and of the LHC reminder (see François and Yves)***

♥ ***Future facilities (for future searches)***

♥ ***New physics in the scalar sector (see Pierre and Abdelhak)***

♥ ***Conclusion***

♥ ***Backup***

First , study of the properties of the already discovered BEH boson

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

measured directly by experiments

scale factors (κ's)

obtained by fits of different measurements

$$g_{Hff} = \kappa_f \cdot g_{Hff}^{\mathrm{SM}} = \kappa_f \cdot \frac{m_f}{v}$$

$$g_{HVV} = \kappa_V \cdot g_{HVV}^{\mathrm{SM}} = \kappa_V \cdot \frac{2m_V^2}{v}$$

$$\sigma \times \mathrm{BR}(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Γ_H

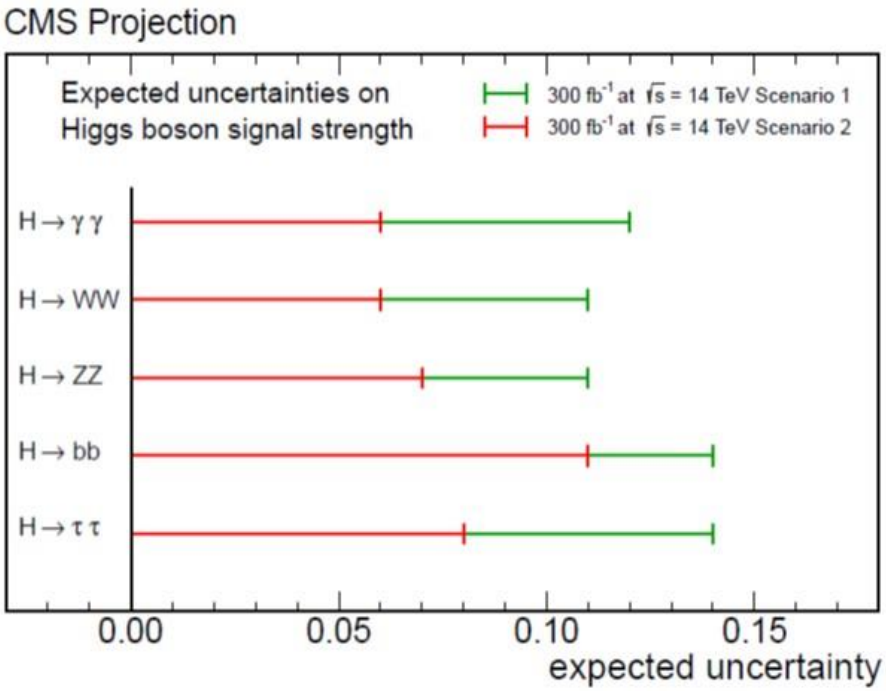
Generic size of Higgs coupling modifications from the Standard Model values

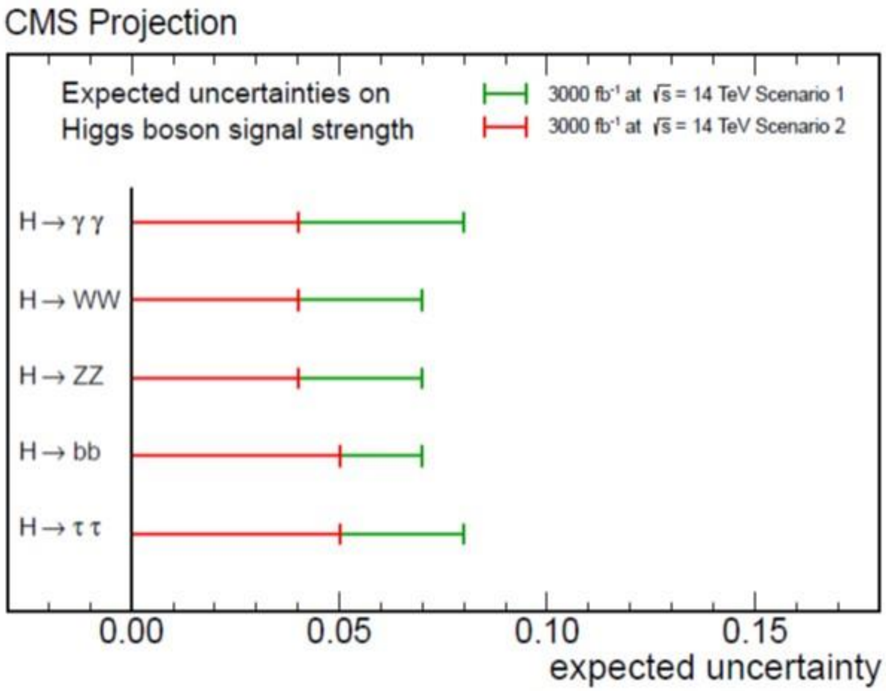
$$M \sim 1\ TeV$$

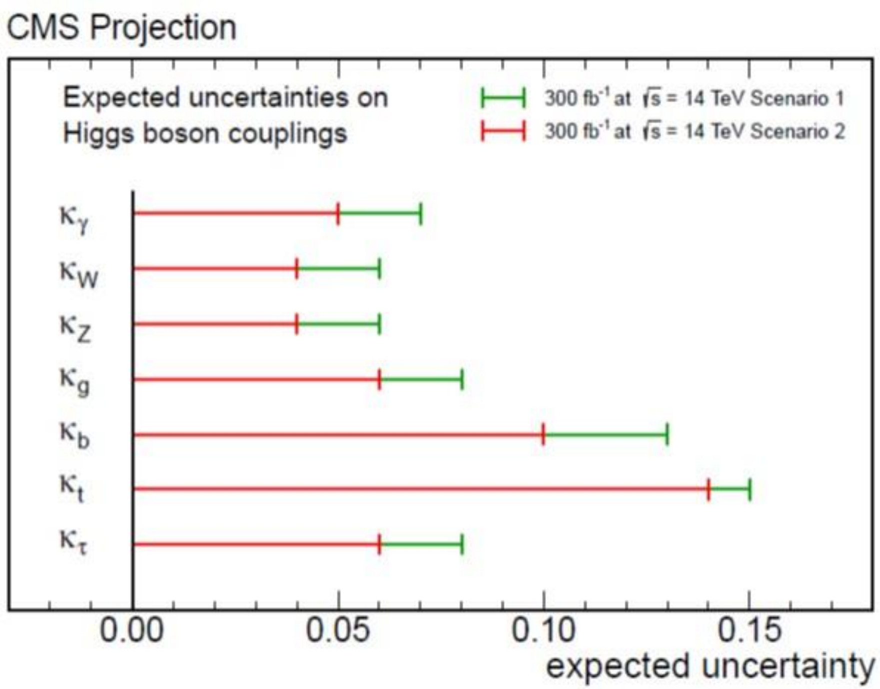
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

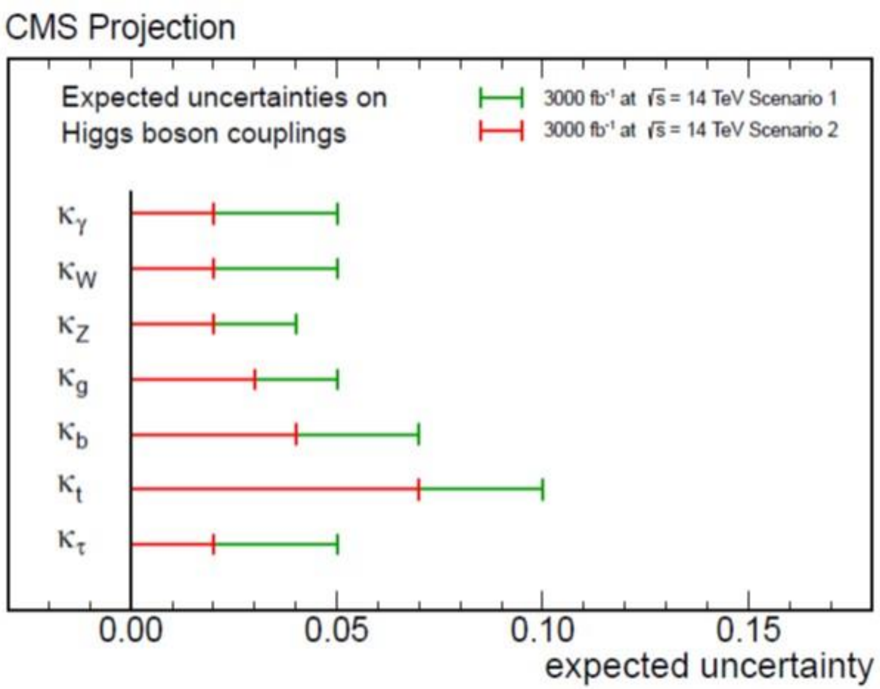
Expectations from HL-LHC

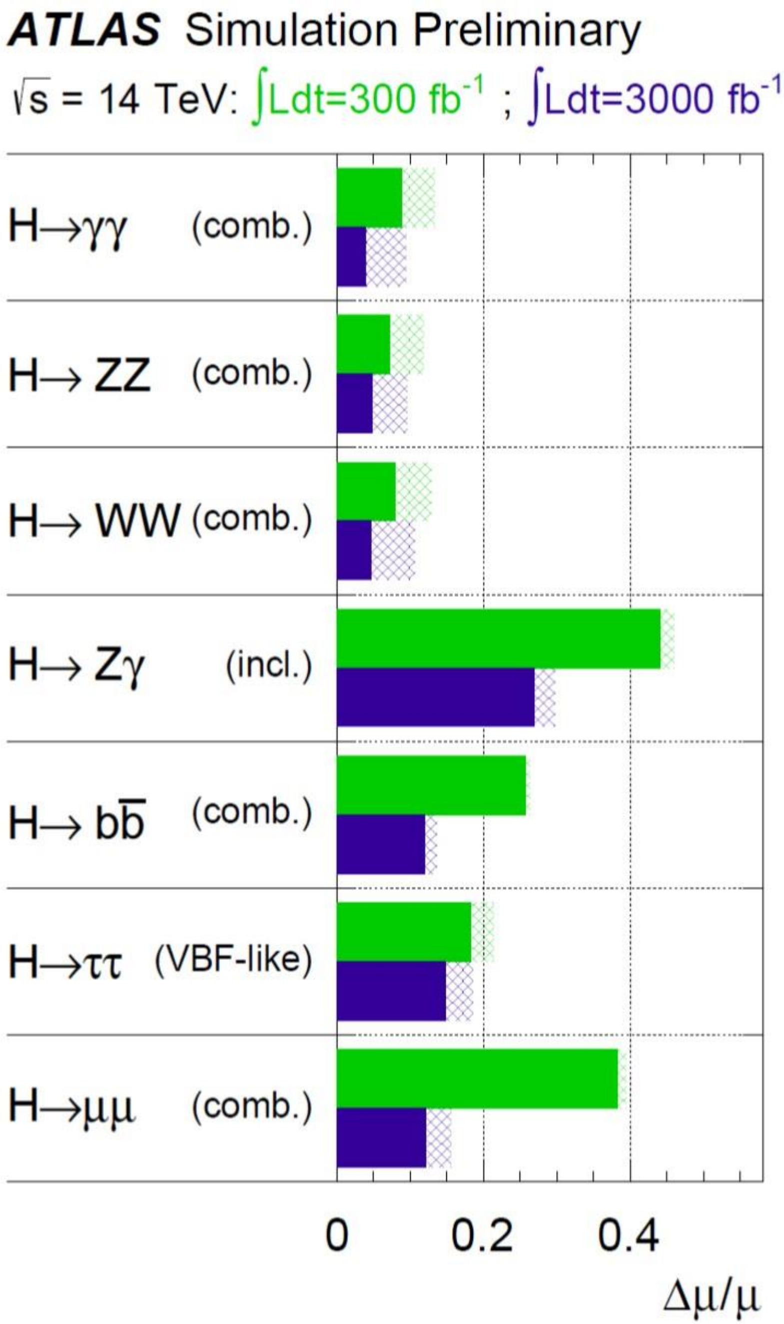
300 fb^{-1} ~ 2025 ***3000 fb^{-1} ~ 2035***

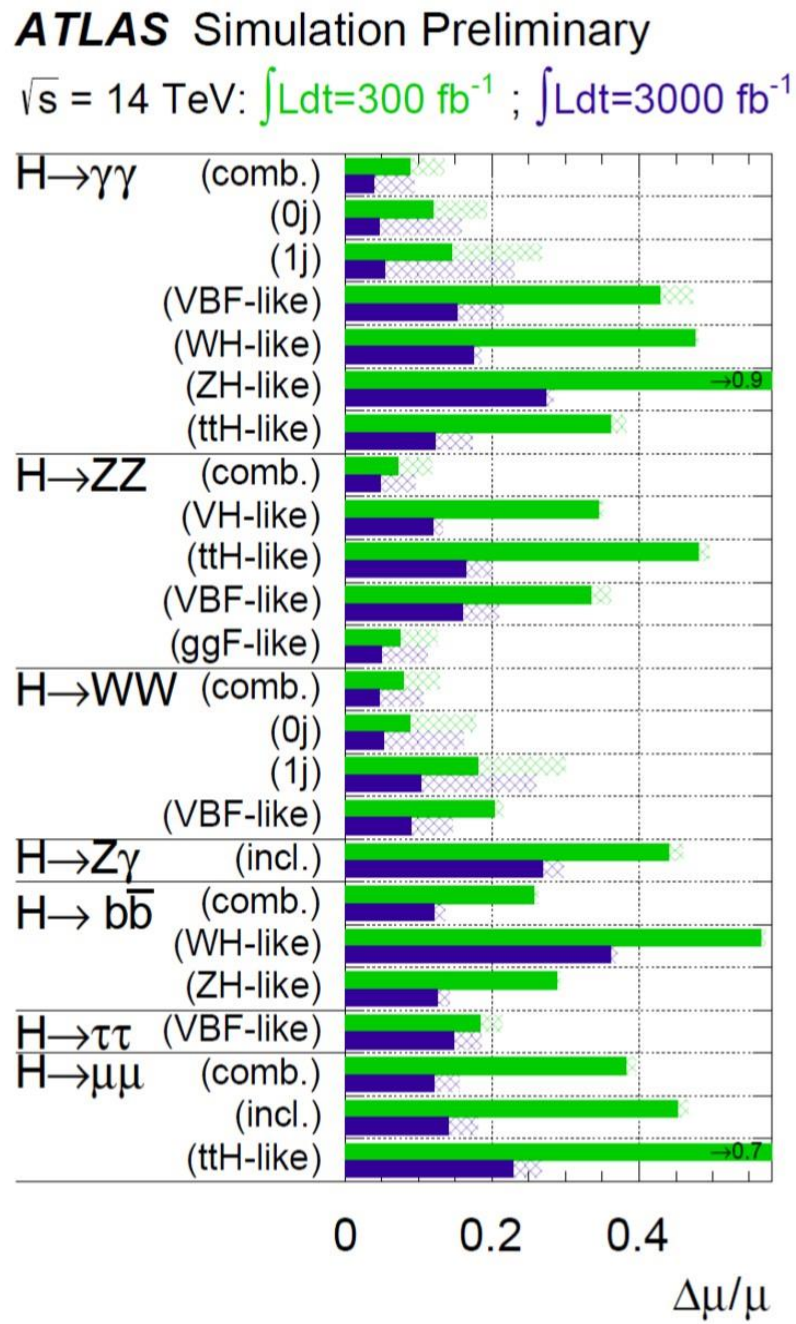





CMS Projection
Expected uncertainties on
Higgs boson couplings
300 fb-1 at √s = 14 TeV Scenario 1
300 fb-1 at √s = 14 TeV Scenario 2
κγ
κW
κZ
κg
κb
κt
κτ
0.00
0.05
0.10
0.15
expected uncertainty

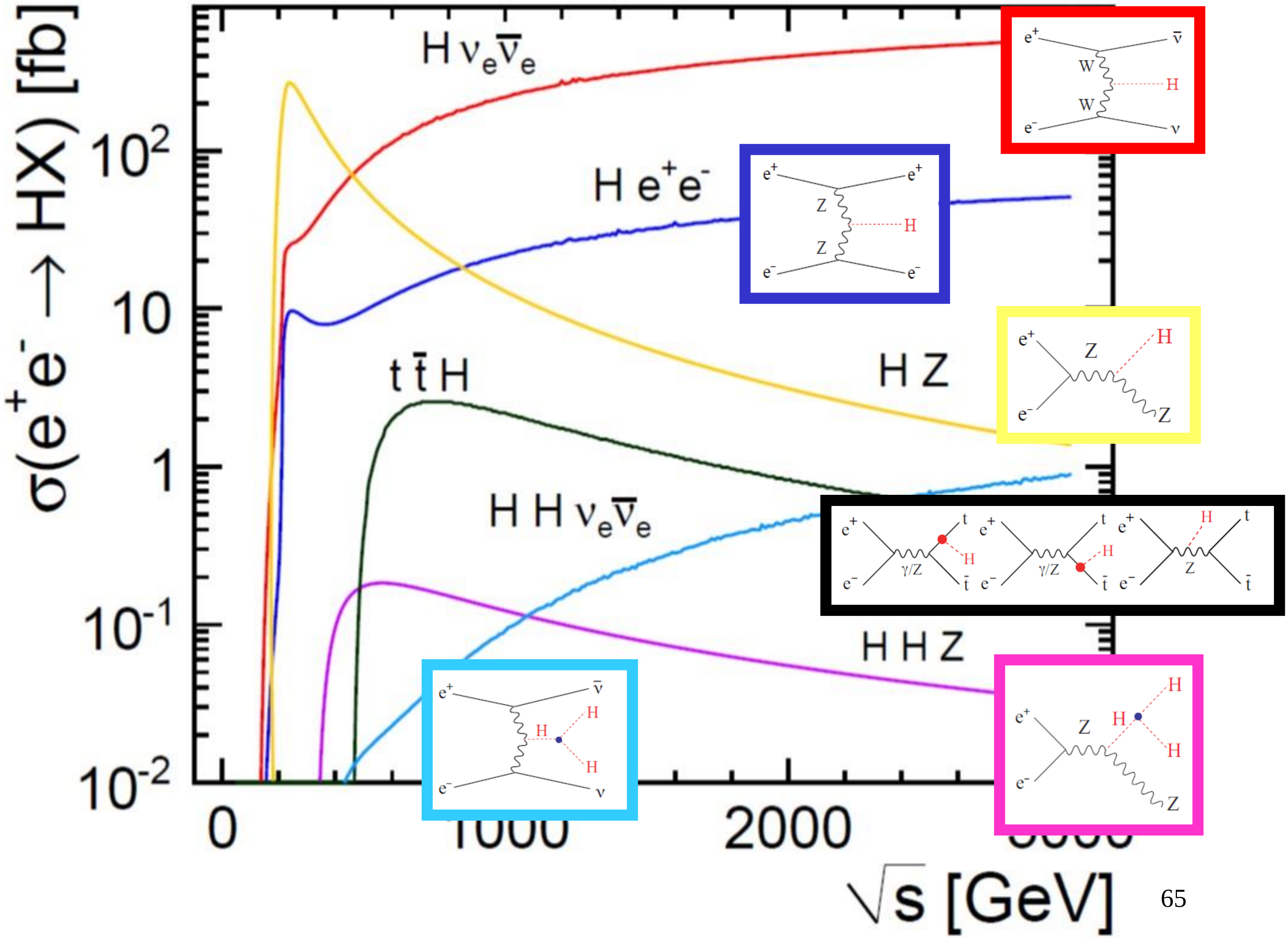

CMS Projection
Expected uncertainties on
Higgs boson couplings
3000 fb-1 at √s = 14 TeV Scenario 1
3000 fb-1 at √s = 14 TeV Scenario 2
κγ
κW
κZ
κg
κb
κt
κτ
0.00
0.05
0.10
0.15
expected uncertainty

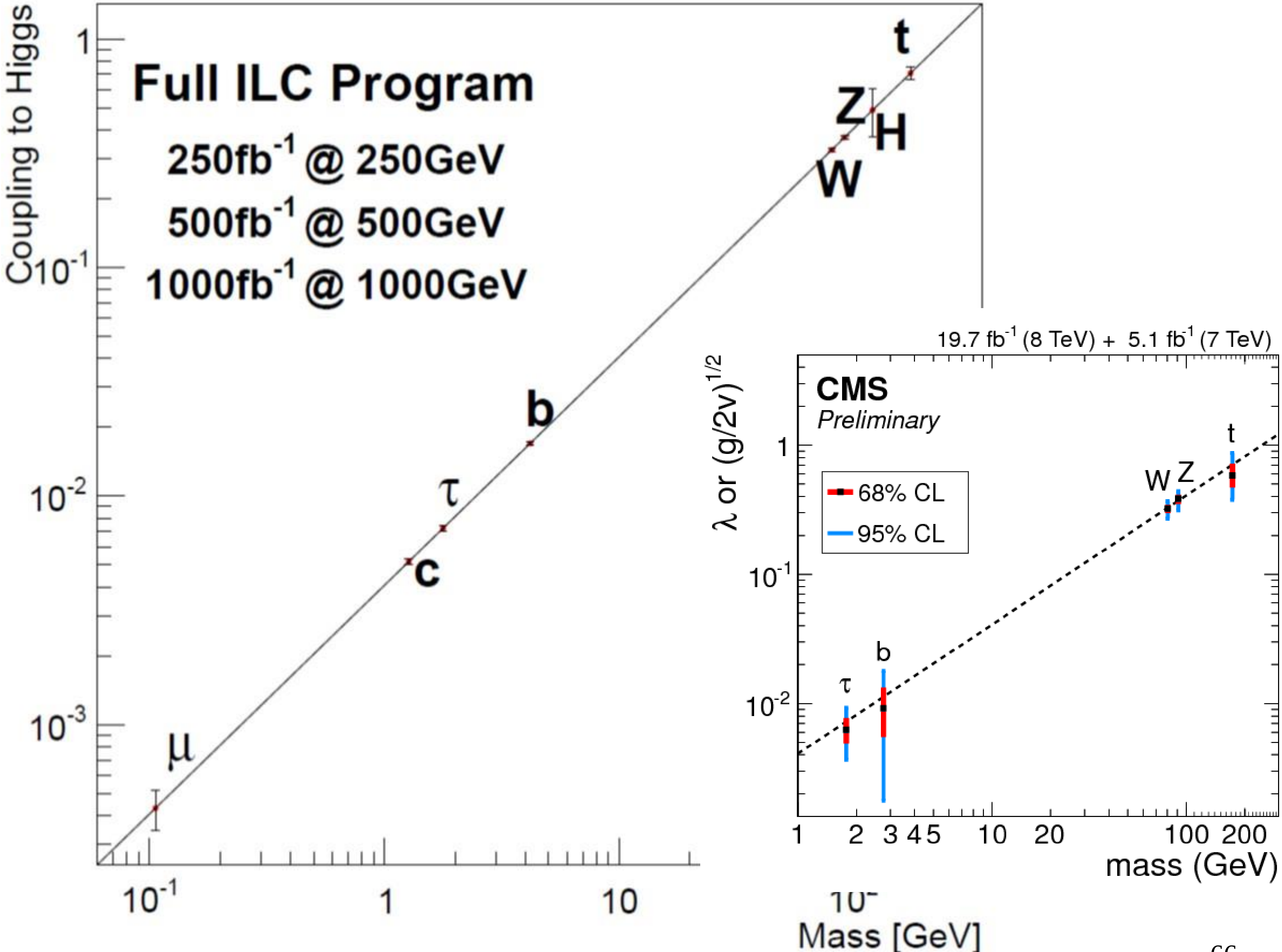

ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
H→γγ (comb.)
H→ ZZ (comb.)
H→ WW (comb.)
H→ Zγ (incl.)
H→ bb̄ (comb.)
H→ττ (VBF-like)
H→μμ (comb.)
0
0.2
0.4
Δμ/μ


ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
H→γγ (comb.)
(0j)
(1j)
(VBF-like)
(WH-like)
(ZH-like)
(ttH-like)
H→ZZ (comb.)
(VH-like)
(ttH-like)
(VBF-like)
(ggF-like)
H→WW (comb.)
(0j)
(1j)
(VBF-like)
H→Zγ (incl.)
H→ bb̄ (comb.)
(WH-like)
(ZH-like)
H→ττ (VBF-like)
H→μμ (comb.)
(incl.)
(ttH-like)
→0.9
→0.7
0
0.2
0.4
Δμ/μ

Increase of cross section with $\sqrt{s}$

Process	σ (14 TeV)	R (33)	R (40)	R (60)	R (80)	R (100)
$gg \to H$	50.4 pb	3.5	4.6	7.8	11	15
$qq \to qqH$	4.40 pb	3.8	5.2	9.3	14	19
$q\bar{q} \to WH$	1.63 pb	2.9	3.6	5.7	7.7	10
$q\bar{q} \to ZH$	0.90 pb	3.3	4.2	6.8	10	13
$pp \to HH$	33.8 fb	6.1	8.8	18	29	42
$pp \to ttH$	0.62 pb	7.3	11	24	41	61


$\sigma(e^+e^- \to HX)$ [fb]
$\sqrt{s}$ [GeV]
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000
$H\nu_e\bar{\nu}_e$
$H e^+e^-$
$t\bar{t}H$
HZ
$HH\nu_e\bar{\nu}_e$
HHZ
e^+ $\bar{\nu}$ W H W e^- ν
e^+ e^+ Z H Z e^- e^-
e^+ Z H e^- Z
e^+ t H γ/Z e^- $\bar{t}$
e^+ t H γ/Z e^- $\bar{t}$
e^+ H t Z e^- $\bar{t}$
e^+ $\bar{\nu}$ H H H e^- ν
e^+ Z H H H e^- Z


Full ILC Program
250fb-1 @ 250GeV
500fb-1 @ 500GeV
1000fb-1 @ 1000GeV
Coupling to Higgs
1
10-1
10-2
10-3
t
Z
H
W
b
τ
c
μ
10-1
1
10
Mass [GeV]
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
λ or (g/2v)1/2
68% CL
95% CL
1
10-1
10-2
t
W
Z
b
τ
1
2
3
4
5
10
20
100
200
mass (GeV)

Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7 %
$\mu^+\mu^-$	–	–	–	16 %
self	–	–	104%	26 %
BR(invis.)	$< 9\%$	< 0.44 %	< 0.30 %	< 0.26 %
$\Gamma_T(h)$	20.3%	4.8 %	1.6 %	1.2 %

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

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

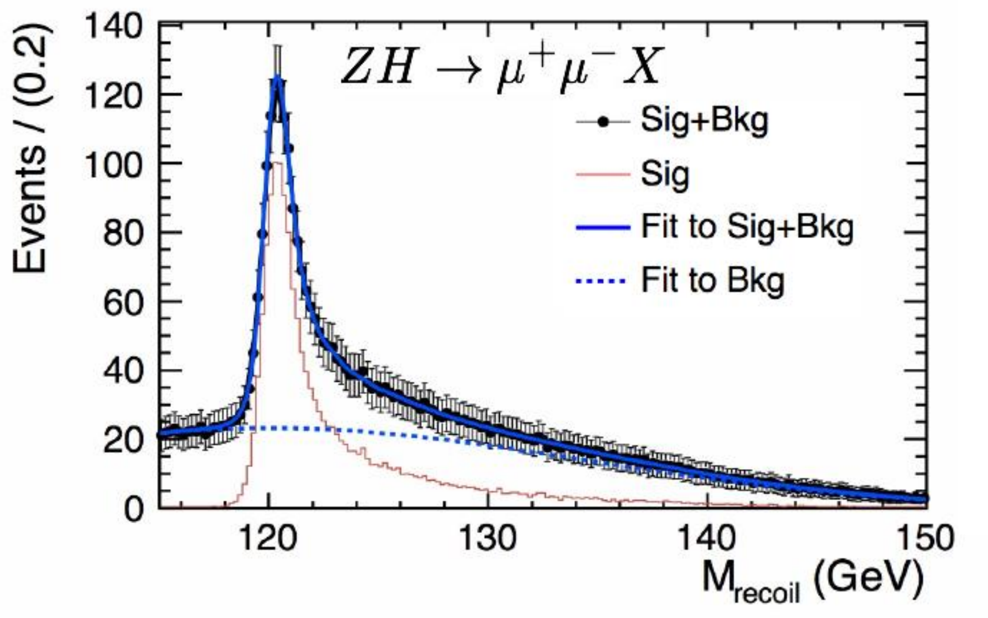
width (and mass) of (already discovered) BEH boson

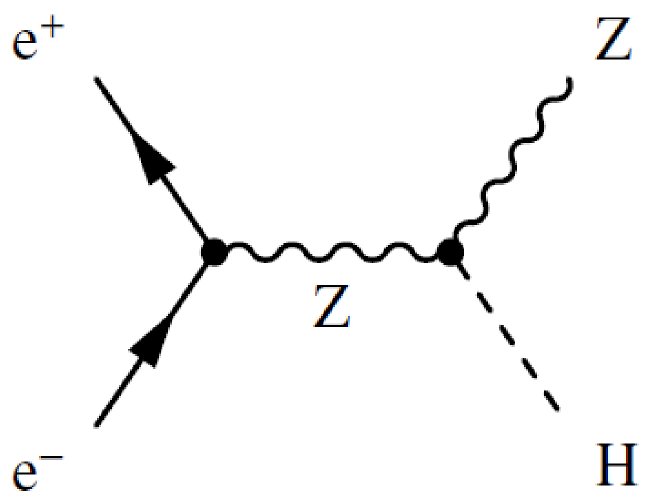
measuring the width is a clear way to search for new physics

measurement precisions

Facility	LHC	HL-LHC	ILC500	ILC1000
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500/1000
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	250+500	250+500+1000
m_H (MeV)	100	50	32	32
Γ_H	–	–	5.0%	4.6%

ILC1000-up	CLIC	TLEP (4 IP)
250/500/1000	350/1400/3000	240/350
1150+1600+2500‡	500+1500+2000	10,000+2600
15	33	7
2.5%	8.4%	1.0%





recoil mass

absolute measurement of the Bosonstrahlung cross section

regardless of the H decay mode

$\Rightarrow$ ***equally valid if H decays to invisible final states***

$\sigma(m) < 50$ ***MeV***

$\Rightarrow$ ***model-independent measurement of*** g_{HZZ}

The total boson width can be determined with an error of ~ few % using formulae like this

$$\Gamma(H) = \Gamma(H \rightarrow ZZ) \; / \; Br(H \rightarrow ZZ)$$

Obtained from direct HZZ couplings (g_{HZZ})

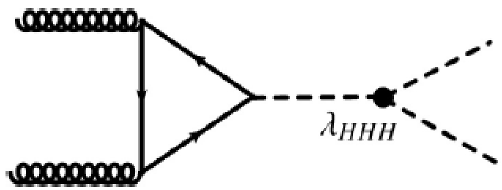
Directly measured

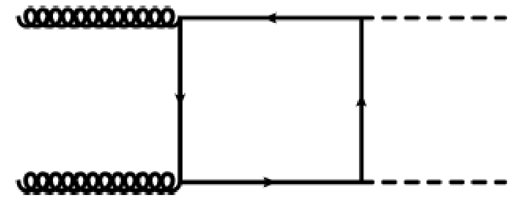
Double H production and self coupling

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger\Phi)^2 \qquad v = \sqrt{\mu^2/\lambda} \simeq 246 \text{ GeV}, \qquad m_H = \sqrt{2\lambda}\, v \simeq 125 \text{ GeV}$$

$$\Delta\mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{HHH}}{3!} H^3 - \frac{g_{HHHH}}{4!} H^4 \qquad \boxed{g_{HHH} = 6\lambda v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6\lambda = \frac{3m_H^2}{v^2}}$$

hadron colliders





ATL-PHYS-PUB-2014-019

3000 fb^{-1} of 14 TeV proton-proton collisions

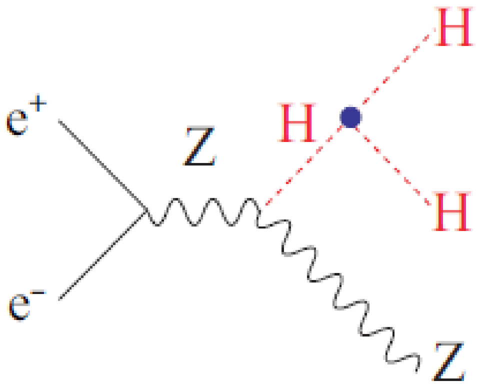
$$H(\to \gamma\gamma)H(\to b\bar{b})$$

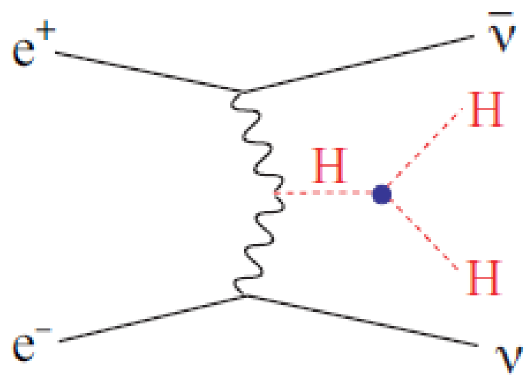
yield of around 8 events is obtained for the Standard Model scenario, corresponding to a signal significance of 1.3 σ.

very challenging

e+e- study of triple H coupling

$$e^+e^- \rightarrow ZHH \quad e^+e^- \rightarrow \nu_e\bar{\nu}_e HH$$





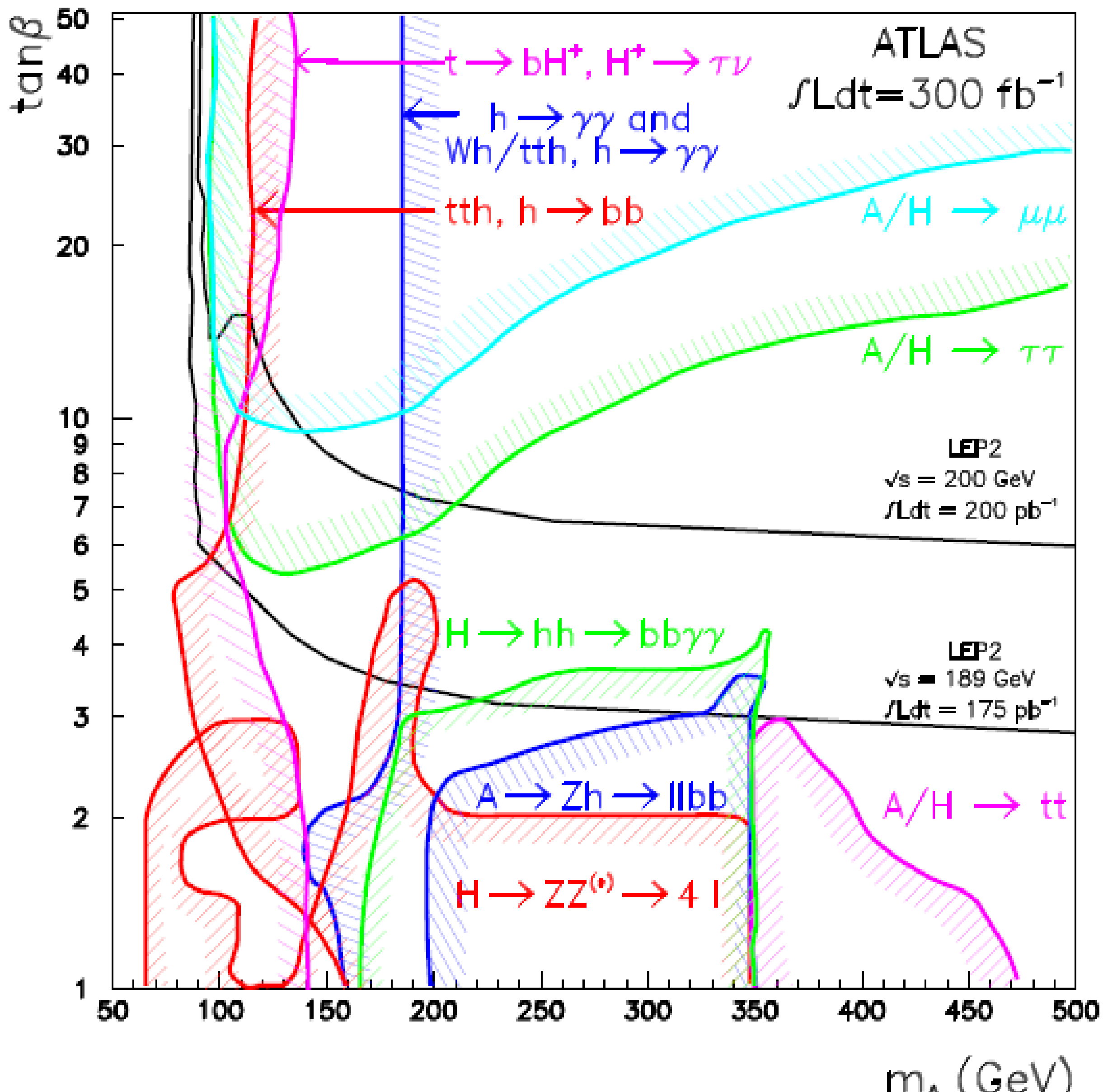
	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

Additional bosons

Was already studied a long time ago

A/H→ ττ, tt
A → Zh
H→hh

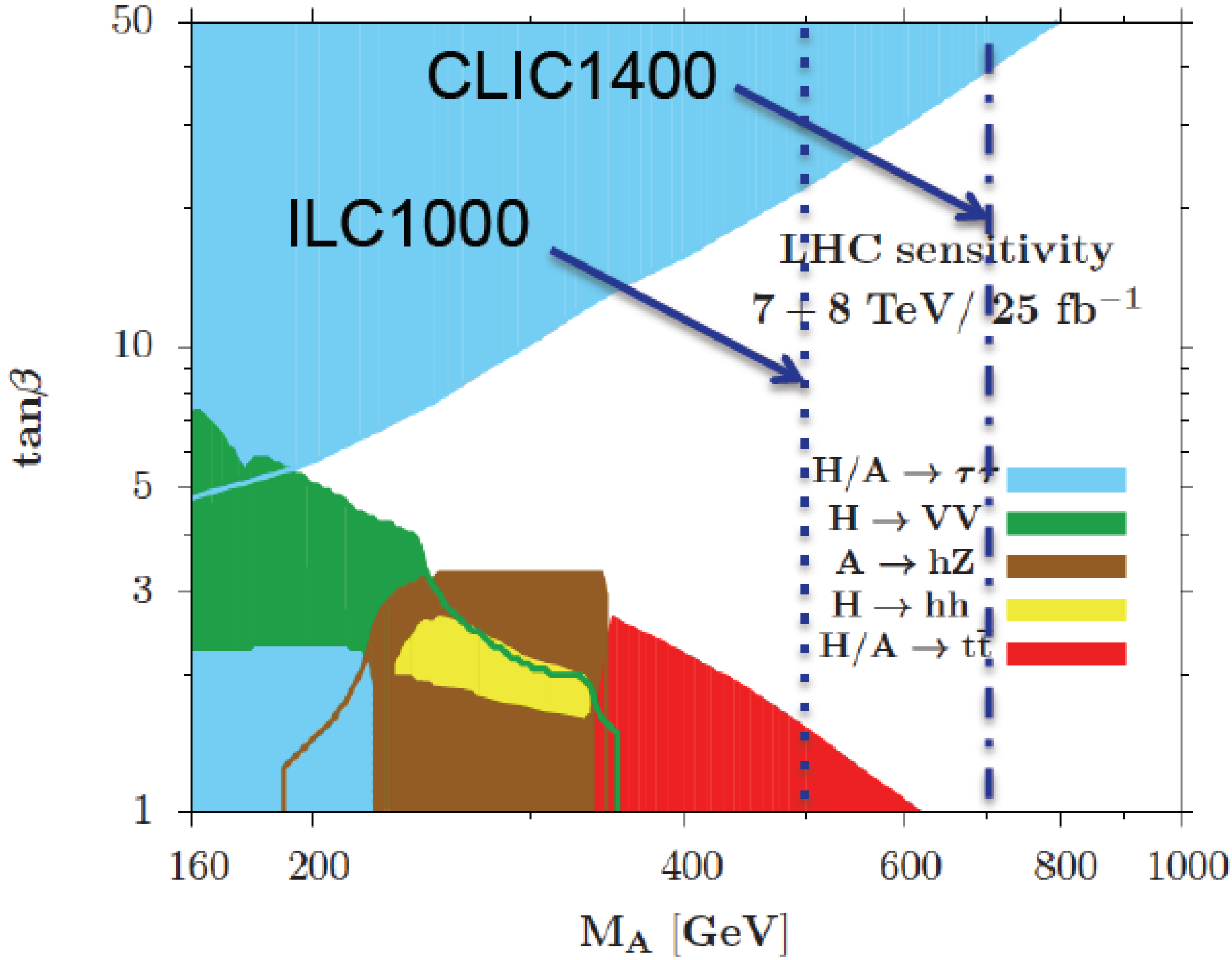
ATLAS TDR



discovery potential for heavy H bosons increase a lot for FCC-hh

e+ e- machines

$$M_{H^+} < \sqrt{s}/2, \qquad M_{H^0} + M_{A^0} < \sqrt{s}.$$



♥ *Historical introduction of the boson and of the LHC reminder (see François and Yves)*

♥ *Future facilities (for future searches)*

♥ *New physics in the scalar sector (see Pierre and Abdelhak)*

♥ ***Conclusion***

♥ *Backup*

A very large program in the scalar sector
(*and elsewhere !* ***) to be done with HL-LHC***
and future e+ e- colliders
(and future pp colliders)

and CP violation was not discussed
and also WW scattering at high mass …

finally some publicity

Journée "Futur de la Physique des particules"

vendredi 23 janvier 2015 de 10:00 à 17:00 (Europe/Paris)
à LPNHE (Amphithéâtre Georges Charpak)

10:00 - 10:30 La physique du H et la physique BSM 30'
10:30 - 11:00 La physique des neutrinos 30'
11:00 - 11:30 Le scénario standardissimo 30'
11:30 - 12:00 Le programme LHC-HL 30'
12:00 - 12:20 Les 60 ans du CERN 20'
12:20 - 13:30 déjeuner
13:30 - 14:00 La physique des saveurs 30'
14:00 - 14:30 le projet ILC 30'
14:30 - 15:00 Design study FCC 30'
15:00 - 15:30 Accélérateurs futurs : les défis à relever 30'
15:30 - 17:00 Table Ronde 1h30'

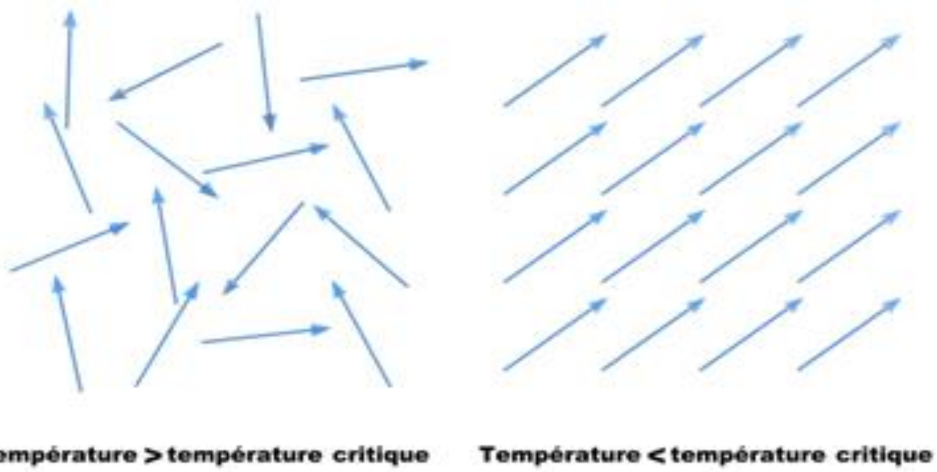
SOCIÉTÉ FRANÇAISE DE PHYSIQUE

- ♥ ***Historical introduction of the boson and of the LHC reminder (see François and Yves)***
- ♥ ***Future facilities (for future searches)***
- ♥ ***New physics in the scalar sector (see Pierre and Abdelhak)***
- ♥ ***Conclusion***
- ♥ ***Backup***

Brisure spontanée de symétrie = mot clef !

exemple : ferromagnétisme

pout $T < T_C$ les dipoles sont alignés dans une direction (arbitraire)

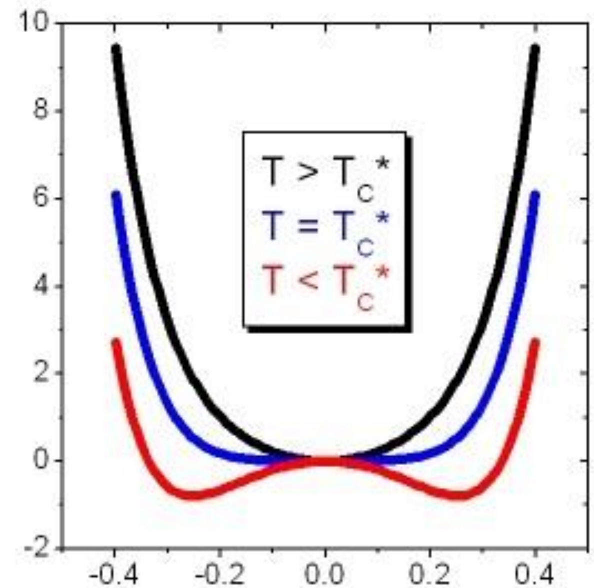


L'etat fondamental brise la symétrie des lois physiques

(Superfluidité et) supraconductivité : transition de phase vers une condensation de Bose-Einstein

Pour T < T_C le champ magnetique ne rentre pas a l'interieur d'un materiau supraconducteur (effet Meissner – Ochsenfeld)

V = potentiel

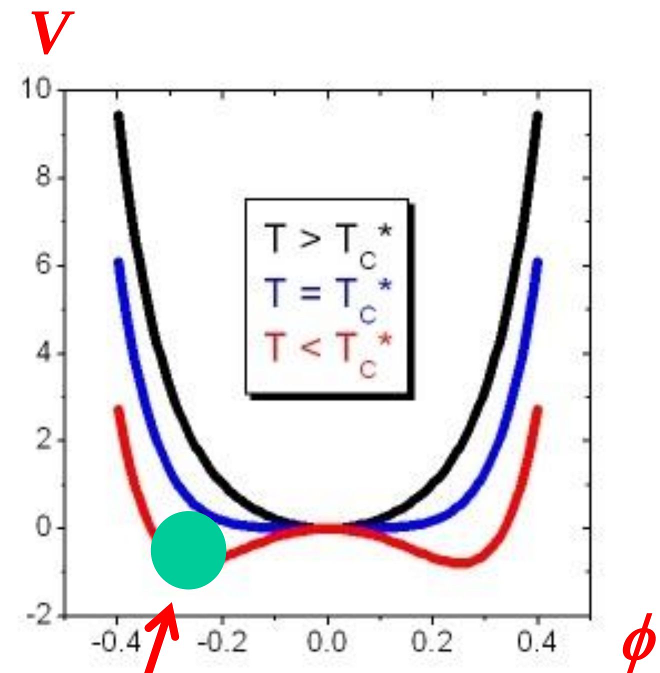


paramètre d'ordre
(lié au condensat de Bose Einstein)

$\Rightarrow$ Le photon acquiert une masse (dans le supraconducteur)

De facon analogue a la supraconductivité mais de facon plus profonde on suppose que l'Univers est rempli du champ de BEH ϕ

Le potentiel (aux énergies nous intéressant) a une forme de chapeau mexicain et le vide correspond à une valeur non nulle de ϕ



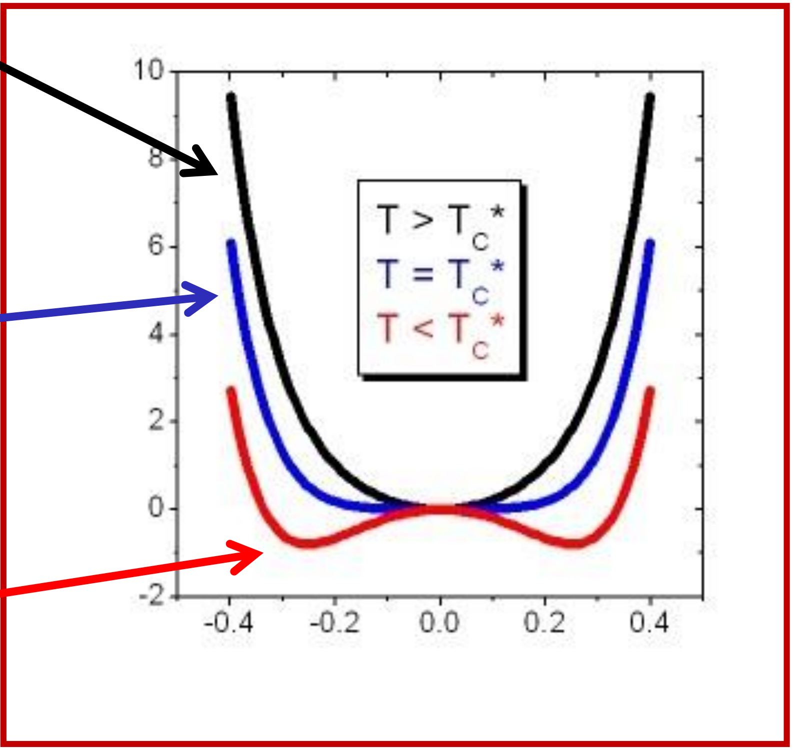
A ce moment les bosons faibles (W et Z) prennent une masse

La masse du boson de BEH est liée aux oscillations de ϕ dans le vide (au minimum)

Mass of the 4 scalar bosons positive
W and Z mass = 0
fermion masses =0

10^{-10} s

Mass of one scalar (BEH) boson positive
W and Z mass positive
fermion have their masses



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.[7,8] We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons φ_A which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reasonable.

(1) Lest the simplicity of the argument be shrouded in a cloud of indices, we first consider a one-parameter Abelian group, representing, for example, the phase transformation of a charged boson; we then present the generalization to an arbitrary compact Lie group.

The interaction between the φ and the A_μ fields is

$$H_{\text{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \tag{1}$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$.

We shall assume that the application of the theorem of Goldstone, Salam, and Weinberg[7] is straightforward and thus that the propagator of the field φ_2, which is "orthogonal" to φ_1, has a pole at $q=0$ which is not isolated.

We calculate the vacuum polarization loop $\Pi_{\mu\nu}$ for the field A_μ in lowest order perturbation theory about the self-consistent vacuum. We take into consideration only the broken-symmetry diagrams (Fig. 1). The conventional terms do not lead to a mass in this approximation if gauge invariance is carefully maintained. One evaluates directly

$$\Pi_{\mu\nu}(q)=(2\pi)^4 ie^2[g_{\mu\nu}\langle\varphi_1\rangle^2-(q_\mu q_\nu/q^2)\langle\varphi_1\rangle^2]. \quad (2)$$

Here we have used for the propagator of φ_2 the value $[i/(2\pi)^4]/q^2$; the fact that the renormalization constant is 1 is consistent with our approximation.[9] We then note that Eq. (2) both maintains gauge invariance ($\Pi_{\mu\nu}q_\nu=0$) and causes the A_μ field to acquire a mass

$$\mu^2=e^2\langle\varphi_1\rangle^2. \quad (3)$$

We have not yet constructed a proof in arbitrary order; however, the similar appearance of higher order graphs leads one to surmise the general truth of the theorem.

Consider now, in general, a set of boson-field operators φ_A (which we may always choose to be Hermitian) and the associated Yang-Mills field $A_{a,\mu}$. The Lagrangian is invariant under the transformation[10]

$$\delta\varphi_A=\textstyle\sum_{a,A}\epsilon_a(x)T_{a,AB}\varphi_{B'}$$
$$\delta A_{a,\mu}=\textstyle\sum_{c,b}\epsilon_c(x)c_{acb}A_{b,\mu}+\partial_\mu\epsilon_a(x), \quad (4)$$

where c_{abc} are the structure constants of a compact Lie group and $T_{a,AB}$ the antisymmetric generators of the group in the representation defined by the φ_B.

Suppose that in the vacuum $\langle\varphi_{B'}\rangle\neq 0$ for some B'. Then the propagator of $\sum_{A,B'}T_{a,AB'}\varphi_A$

(a) (b)

FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\to(2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) $\to -(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

$\times\langle\varphi_{B'}\rangle$ is, in the lowest order,

$$\left[\frac{i}{(2\pi)^4}\right]\sum_{A,B',C'}\frac{T_{a,AB'}\langle\varphi_{B'}\rangle T_{a,AC'}\langle\varphi_{C'}\rangle}{q^2}$$
$$=\left[\frac{-i}{(2\pi)^4}\right]\frac{(\langle\varphi\rangle T_a T_a\langle\varphi\rangle)}{q^2}.$$

With λ the coupling constant of the Yang-Mills field, the same calculation as before yields

$$\Pi_{\mu\nu}{}^a(q)=-i(2\pi)^4\lambda^2(\langle\varphi\rangle T_a T_a\langle\varphi\rangle)$$
$$\times[g_{\mu\nu}-q_\mu q_\nu/q^2],$$

giving a value for the mass

$$\mu_a{}^2=-(\langle\varphi\rangle T_a T_a\langle\varphi\rangle). \quad (6)$$

(2) Consider the interaction Hamiltonian

$$H_{\text{int}}=-\eta\bar\psi\gamma_\mu\gamma_5\psi B_\mu-\epsilon\bar\psi\gamma_\mu\psi A_\mu, \quad (7)$$

where A_μ and B_μ are vector and pseudovector gauge fields. The vector field causes attraction whereas the pseudovector leads to repulsion between particle and antiparticle. For a suitable choice of ϵ and η there exists, as in Johnson's model,[11] a broken-symmetry solution corresponding to an arbitrary mass m for the ψ field fixing the scale of the problem. Thus the fermion propagator $S(p)$ is

$$S^{-1}(p)=\gamma p-\Sigma(p)=\gamma p[1-\Sigma_2(p^2)]-\Sigma_1(p^2), \quad (8)$$

with

$$\Sigma_1(p^2)\neq 0$$

and

$$m[1-\Sigma_2(m^2)]-\Sigma_1(m^2)=0.$$

We define the gauage-invariant current $J_\mu{}^5$ by using Johnson's method[12]:

$$J_\mu{}^5=-\eta\lim_{\xi\to 0}\bar\psi'(x+\xi)\gamma_\mu\gamma_5\psi'(x),$$

$$\psi'(x)=\exp[-i\textstyle\int_{-\infty}^x\eta B_\mu(y)dy^\mu\gamma_5]\psi(x). \quad (9)$$

This gives for the polarization tensor of the pseudovector field

$$\Pi_{\mu\nu}{}^5(q) = \eta^2 \frac{i}{(2\pi)^4} \int \mathrm{Tr}\{S(p-\tfrac{1}{2}q)\Gamma_{\nu 5}(p-\tfrac{1}{2}q; p+\tfrac{1}{2}q) \times S(p+\tfrac{1}{2}q)\gamma_\mu\gamma_5 - S(p)[\partial S^{-1}(p)/\partial p_\nu]S(p)\gamma_\mu\} d^4p, \quad (10)$$

where the vertex function $\Gamma_{\nu 5} = \gamma_\nu\gamma_5 + \Lambda_{\nu 5}$ satisfies the Ward identity[5]

$$q_\nu \Lambda_{\nu 5}(p-\tfrac{1}{2}q; p+\tfrac{1}{2}q) = \Sigma(p-\tfrac{1}{2}q)\gamma_5 + \gamma_5\Sigma(p+\tfrac{1}{2}q), \quad (11)$$

which for low q reads

$$q_\nu\Gamma_{\nu 5} = q_\nu\gamma_\nu\gamma_5[1-\Sigma_2] + 2\Sigma_1\gamma_5 - 2(q_\nu p_\nu)(\gamma_\lambda p_\lambda)(\partial\Sigma_2/\partial p^2)\gamma_5. \quad (12)$$

The singularity in the longitudinal $\Gamma_{\nu 5}$ vertex due to the broken-symmetry term $2\Sigma_1\gamma_5$ in the Ward identity leads to a nonvanishing gauge-invariant $\Pi_{\mu\nu}{}^5(q)$ in the limit $q \to 0$, while the usual spurious "photon mass" drops because of the second term in (10). The mass of the pseudovector field is roughly $\eta^2 m^2$ as can be checked by inserting into (10) the lowest approximation for $\Gamma_{\nu 5}$ consistant with the Ward identity.

Thus, in this case the general feature of the phenomenological boson system survives. We would like to emphasize that here the symmetry is broken through the gauge fields themselves. One might hope that such a feature is quite general and is possibly instrumental in the realization of Sakurai's program.[3]

(3) We present below a simple argument which indicates why the gauge vector field need not have zero mass in the presence of broken symmetry. Let us recall that these fields were introduced in the first place in order to extend the symmetry group to transformations which were different at various space-time points. Thus one expects that when the group transformations become homogeneous in space-time, that is $q \to 0$, no dynamical manifestation of these fields should appear. This means that it should cost no energy to create a Yang-Mills quantum at $q = 0$ and thus the mass is zero. However, if we break gauge invariance of the first kind and still maintain gauge invariance of the second kind this reasoning is obviously incorrect. Indeed, in Fig. 1, one sees that the A_μ propagator connects to intermediate states, which are "rotated" vacua. This is seen most clearly by writing $\langle\varphi_1\rangle = \langle[Q\varphi_2]\rangle$ where Q is the group generator. This effect cannot vanish in the limit $q \to 0$.

---

*This work has been supported in part by the U. S. Air Force under grant No. AFEOAR 63-51 and monitored by the European Office of Aerospace Research.

[1]J. Schwinger, Phys. Rev. 125, 397 (1962).
[2]C. N. Yang and R. L. Mills, Phys. Rev. 96, 191 (1954).
[3]J. J. Sakurai, Ann. Phys. (N.Y.) 11, 1 (1960).
[4]Y. Nambu, Phys. Rev. Letters 4, 380 (1960).
[5]Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345 (1961).
[6]"Broken symmetry" has been extensively discussed by various authors in the Proceedings of the Seminar on Unified Theories of Elementary Particles, University of Rochester, Rochester, New York, 1963 (unpublished).
[7]J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).
[8]S. A. Bludman and A. Klein, Phys. Rev. 131, 2364 (1963).
[9]A. Klein, reference 6.
[10]R. Utiyama, Phys. Rev. 101, 1597 (1956).
[11]K. A. Johnson, reference 6.
[12]K. A. Johnson, reference 6.

Field Theories with «Superconductor» Solutions.

J. Goldstone
CERN - Geneva

(ricevuto l'8 Settembre 1960)

Plasmons, Gauge Invariance, and Mass

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Spontaneous Symmetry Breakdown without Massless Bosons*

Peter W. Higgs†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

Symmetry Breaking in Non-Abelian Gauge Theories*

T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 24 October 1966)

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

LEP/LIBRARY

ps

LEP Note 440
11.4.1983

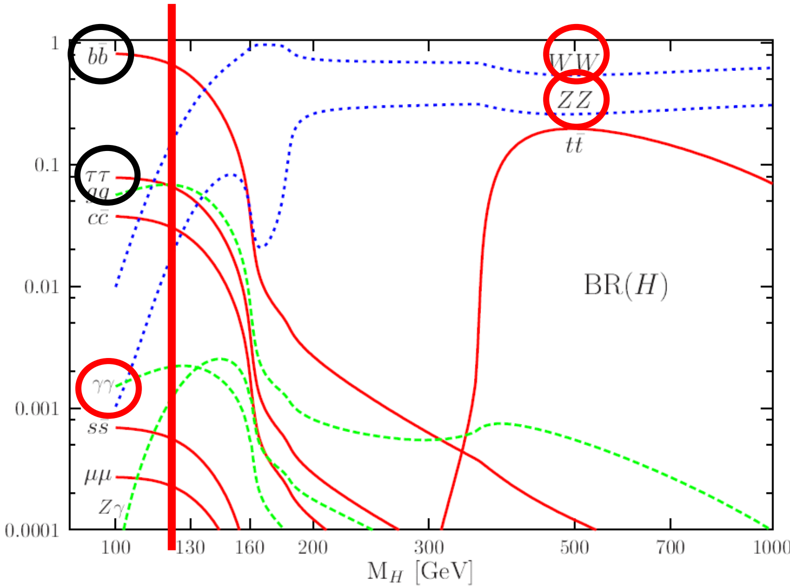
PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

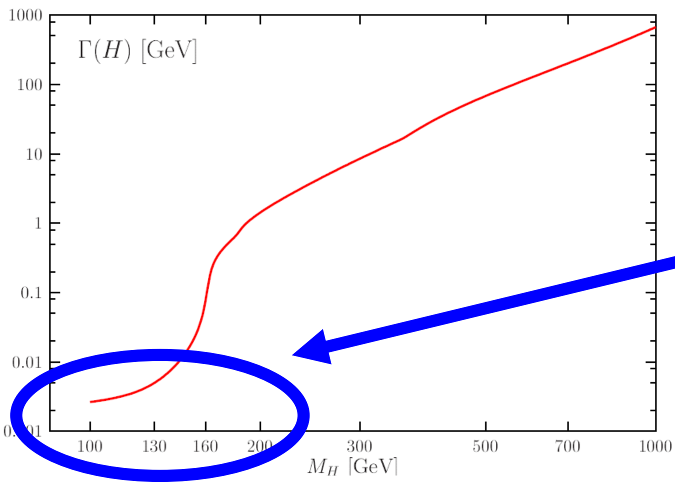
S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

A.Djouadi Phys.Rept.457:1-216



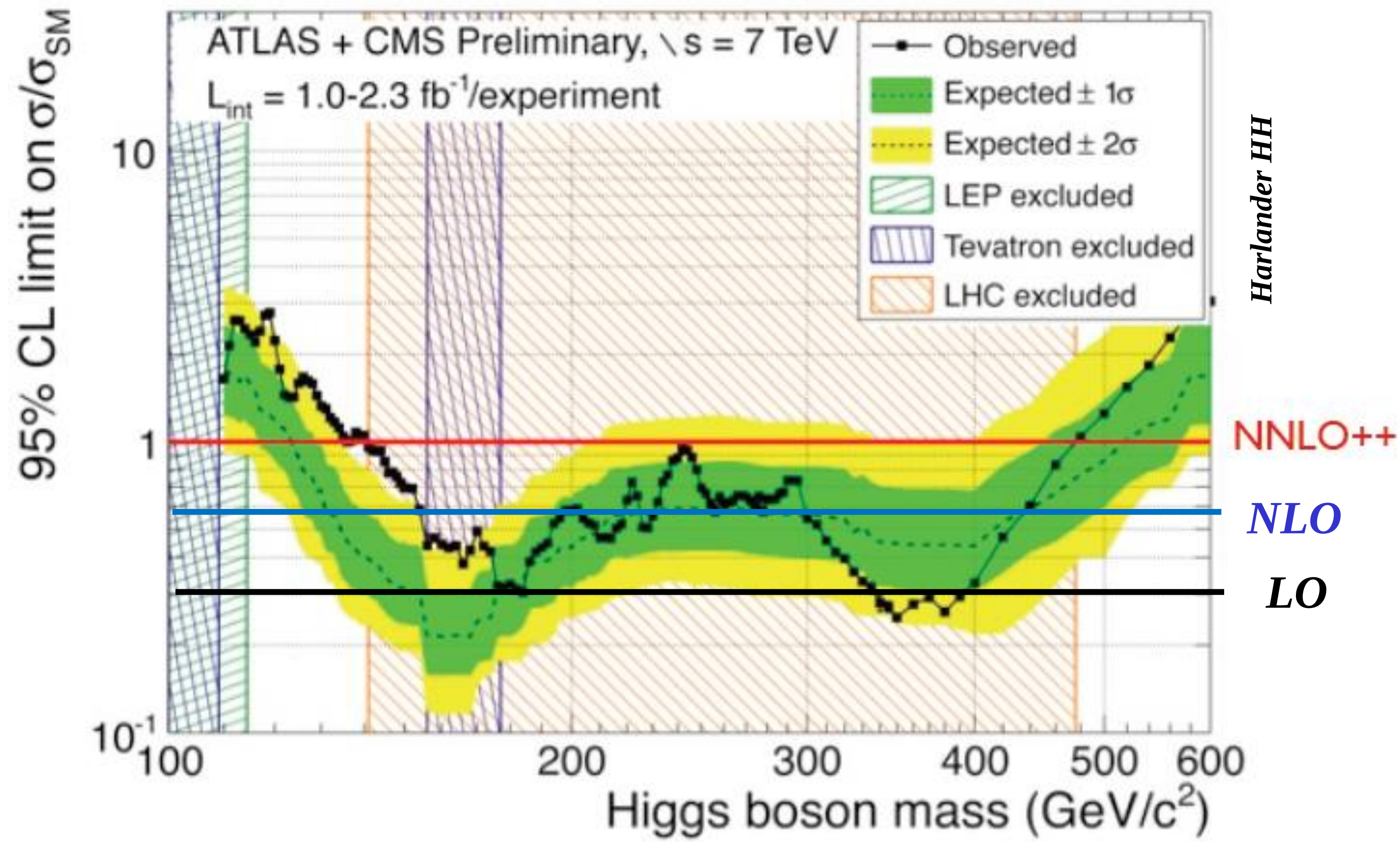


zone favored by** (pre-LHC) **data

For m_H ~ 125 GeV the width is about 4 MeV corresponding to ~ 10^{-22} s and ~100 fm

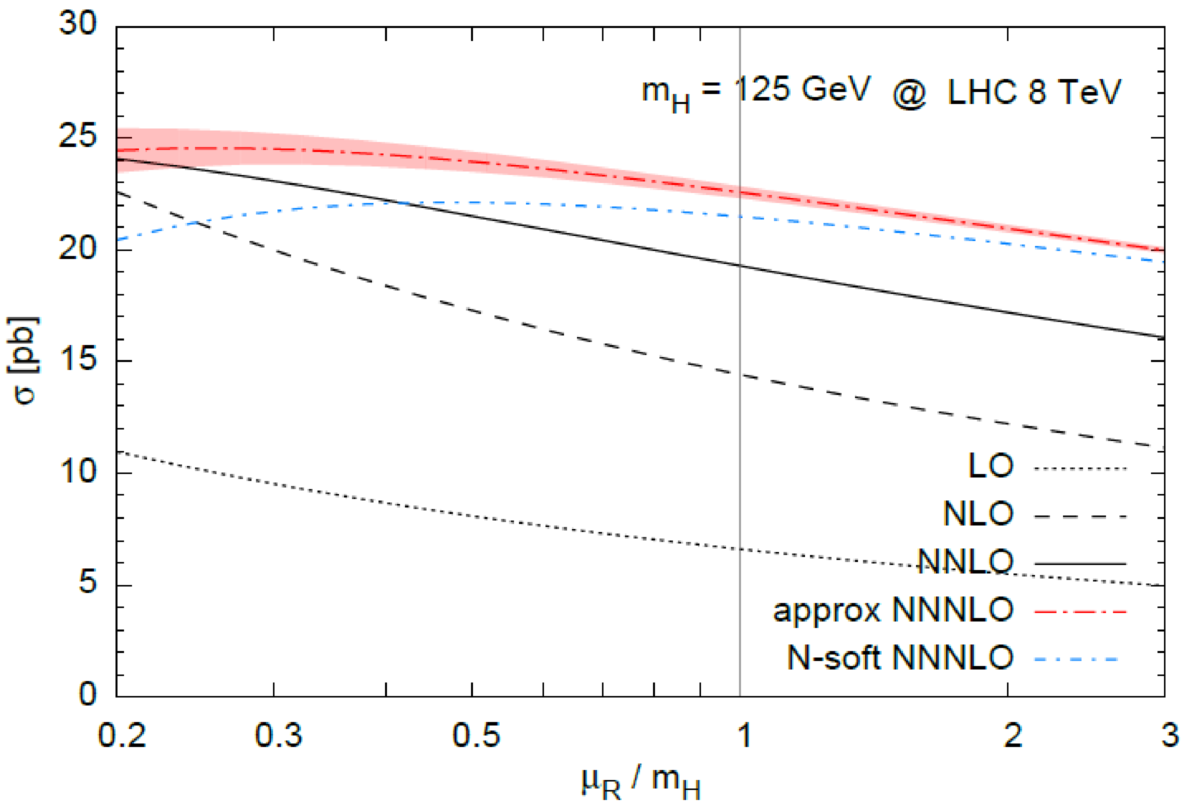
Width smaller than 'leptonic/γ resolution'

Importance of theory !



$\mu = \sigma / \sigma_{SM}$ ***SM = SM boson***

approximate NNNLO cross section computation

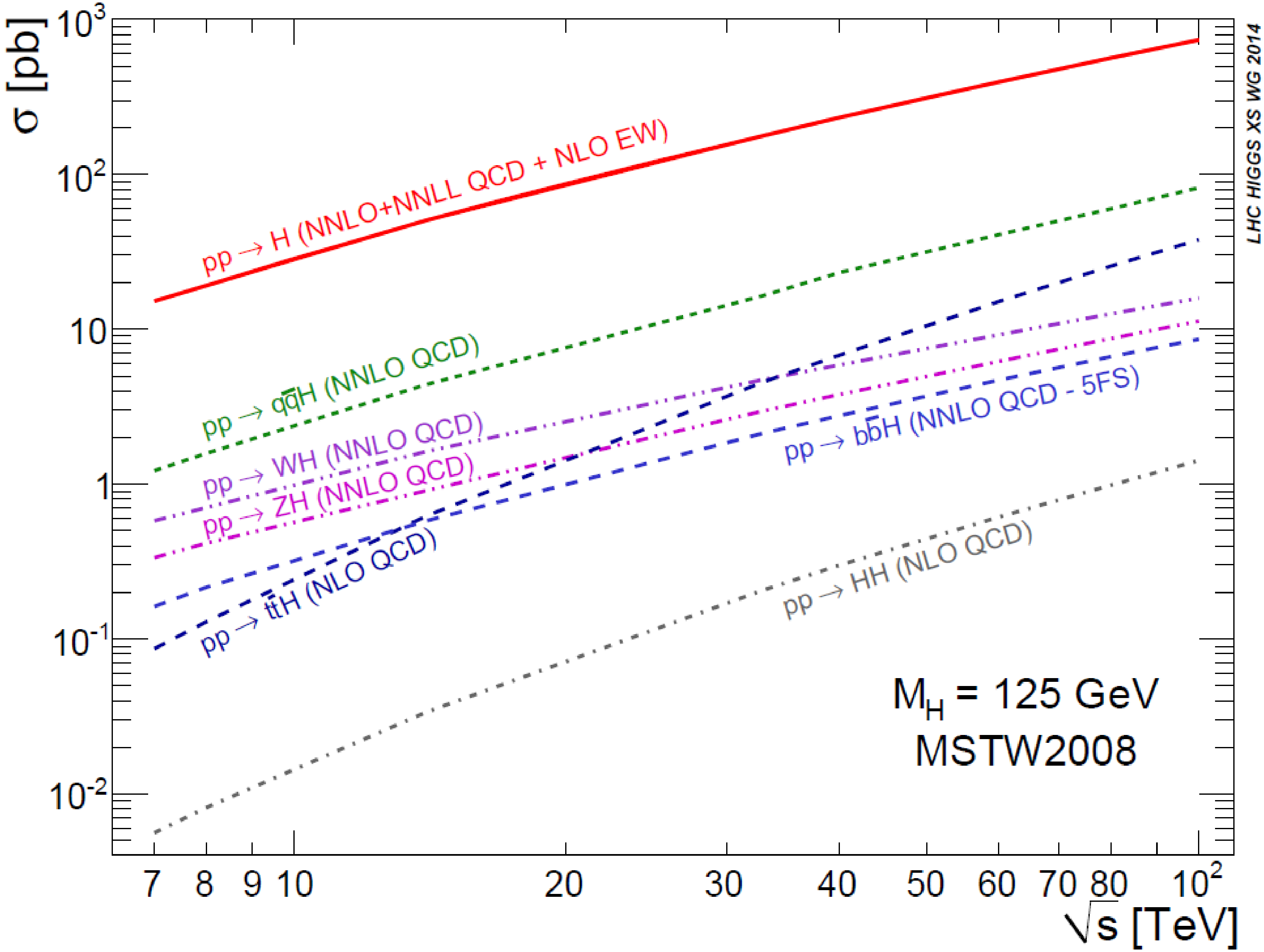


Nuclear Physics B 874 (2013) 746–772

Richard D. Ball [a], Marco Bonvini [b], Stefano Forte [c,*], Simone Marzani [d]
Giovanni Ridolfi [e]

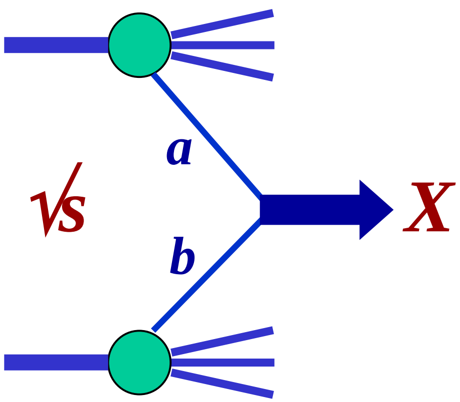
small(er) dependence w.r.t μ_R

'full' NNNLO H cross section computation soon by Anastasiou et al.


σ [pb]
10^3
10^2
10
1
10^{-1}
10^{-2}
7 8 9 10 20 30 40 50 60 70 80 10^2
$\sqrt{s}$ [TeV]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD)
pp → WH (NNLO QCD)
pp → ZH (NNLO QCD)
pp → ttH (NLO QCD)
pp → bbH (NNLO QCD - 5FS)
pp → HH (NLO QCD)
M_H = 125 GeV
MSTW2008
LHC HIGGS XS WG 2014

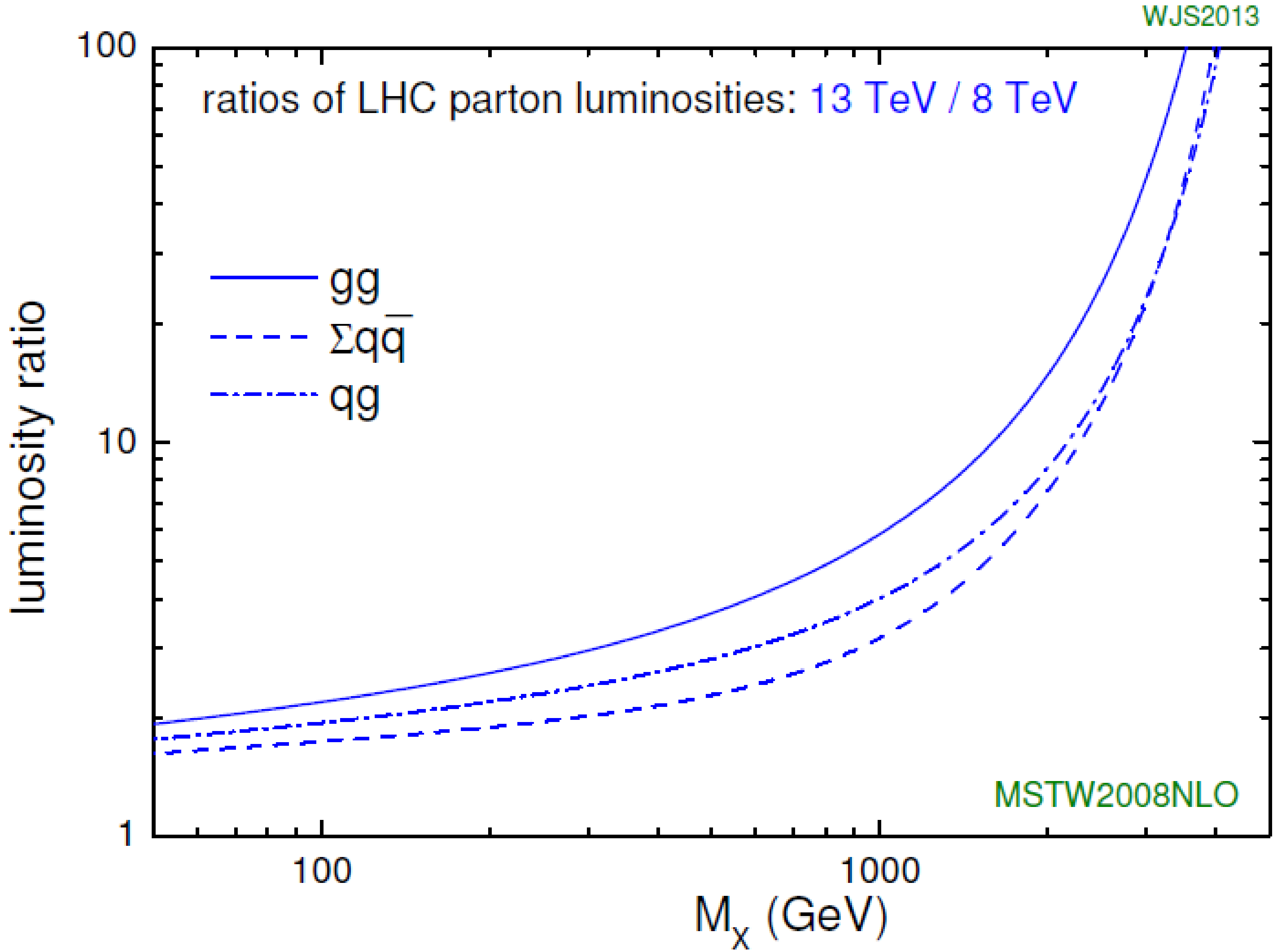
parton luminosity functions

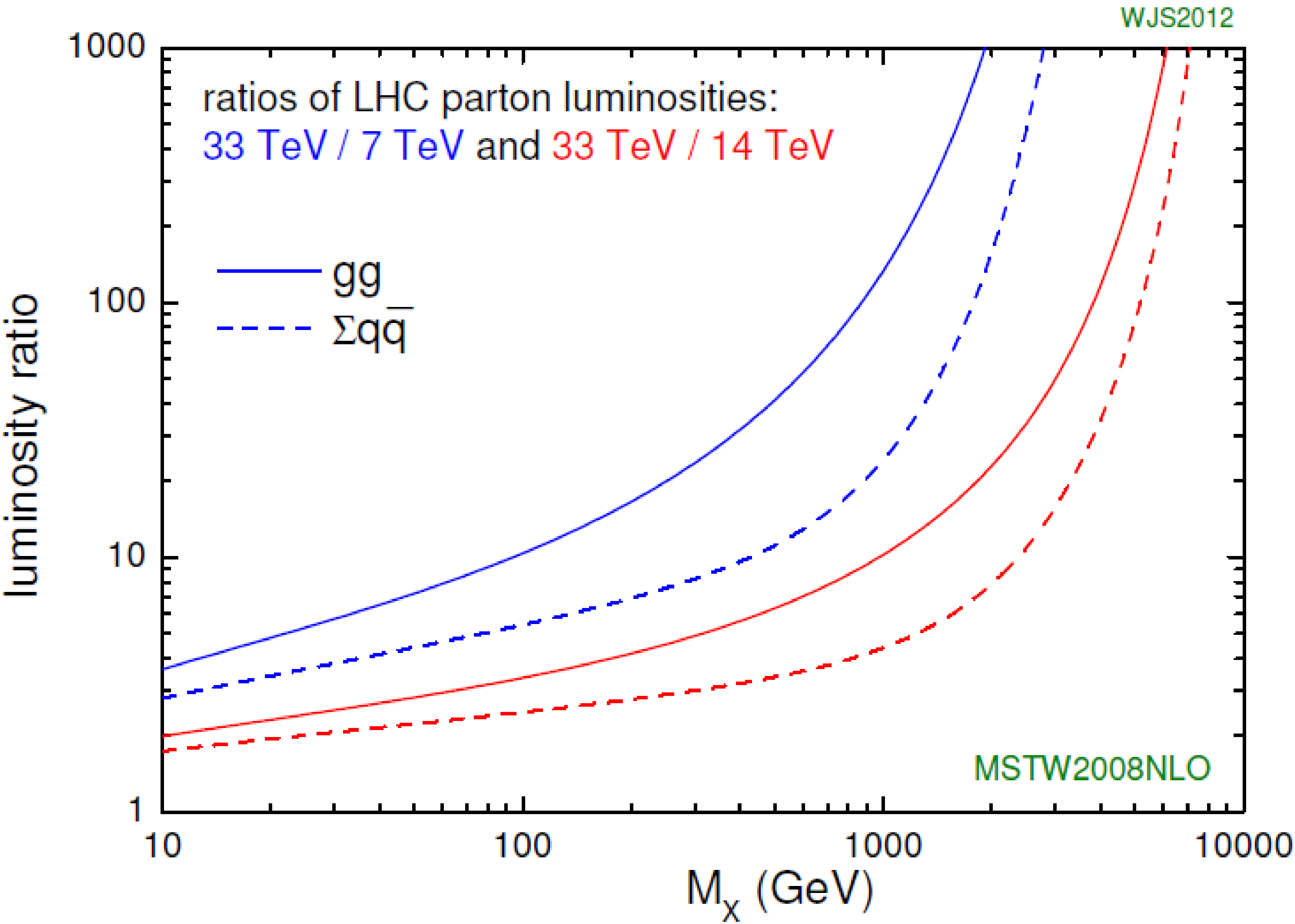
- ***a quick and easy way to assess the mass and collider energy dependence of production cross sections, and to compare different PDF sets***



$$
\begin{aligned}
\hat{\sigma}_{ab\to X} &= C_X \delta(\hat{s} - M_X^2) \\
\sigma_X &= \int_0^1 dx_a dx_b\, f_a(x_a, M_X^2) f_b(x_b, M_X^2)\, C_X\, \delta(x_a x_b - \tau) \\
&\equiv C_X \left[\frac{1}{s}\frac{\partial \mathcal{L}_{ab}}{\partial \tau}\right] \qquad (\tau = M_X^2/s) \\
\frac{\partial \mathcal{L}_{ab}}{\partial \tau} &= \int_0^1 dx_a dx_b\, f_a(x_a, M_X^2) f_b(x_b, M_X^2)\, \delta(x_a x_b - \tau)
\end{aligned}
$$

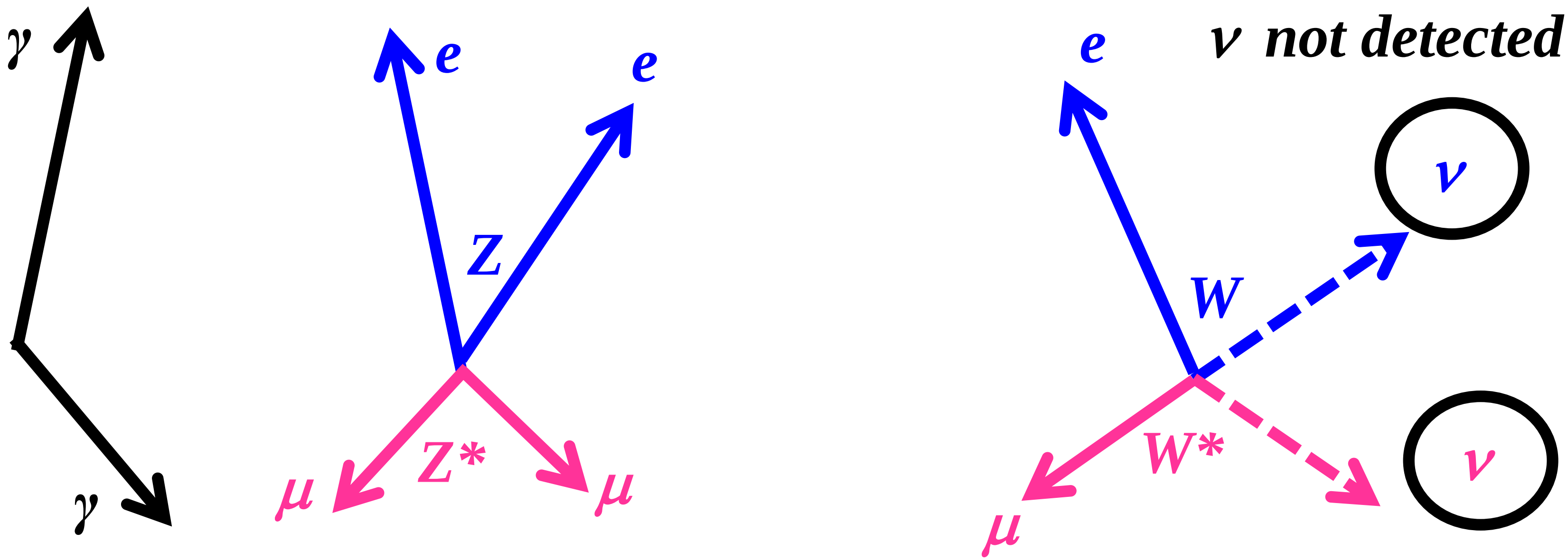
- ***i.e. all the mass and energy dependence is contained in the X-independent parton luminosity function in [ ]***
- ***useful combinations are*** $ab = gg, \sum_q q\bar{q}, \ldots$
- ***and also useful for assessing the uncertainty on cross sections due to uncertainties in the PDFs***


WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
Σqq̄
qg
luminosity ratio
100
10
1
100
1000
M_X (GeV)
MSTW2008NLO


WJS2012
ratios of LHC parton luminosities:
33 TeV / 7 TeV and 33 TeV / 14 TeV
gg
$\Sigma q\bar{q}$
MSTW2008NLO
luminosity ratio
M_X (GeV)
1000
100
10
1
10
100
1000
10000

Fundamental scalar (Higgs) boson searches have guided the conception, design and technological choices of ATLAS and CMS

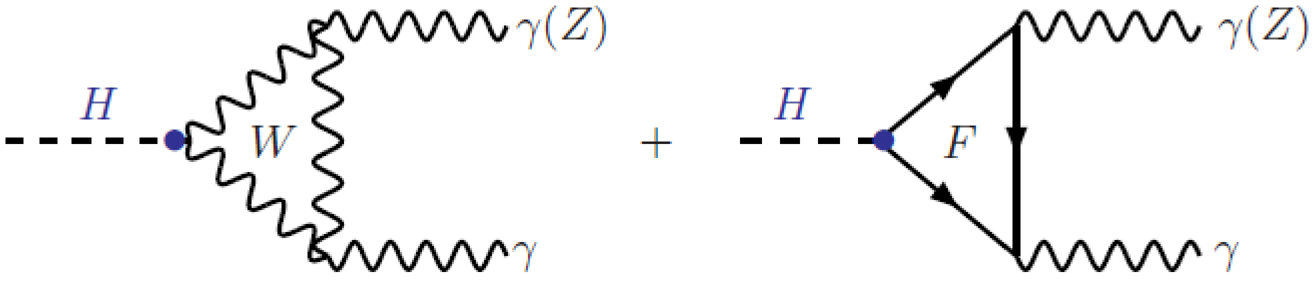
almost instantaneous decay



In these 2 cases the boson mass is computed reconstructing the invariant mass of the decay products

⇒ the mass resolution (and E and p) is very important in order to have a good significance S/√ B, **often** ∝ 1/√(resolution) **since the natural width of the boson is (*almost always*) negligible**

Scalar boson decays : example of $H \rightarrow \gamma\gamma$



Interference between

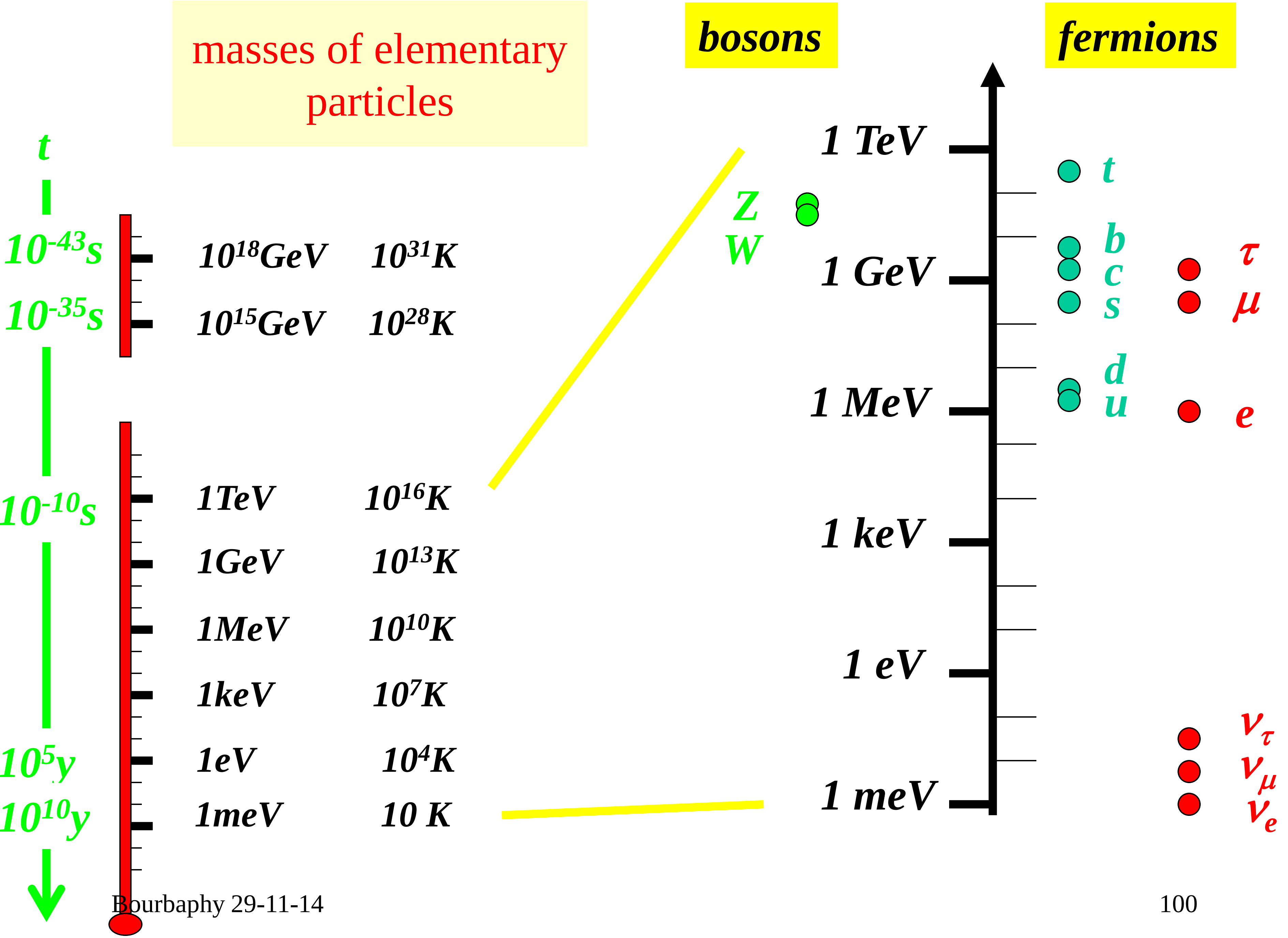
W loop ***top loop***

$$\Gamma\,(H \to \gamma\gamma) = \frac{G_\mu\,\alpha^2\,M_H^3}{128\,\sqrt{2}\,\pi^3}\left|\sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W)\right|^2$$

$\propto$ ***-.26*** ***+ 1.26***

A.Djouadi Phys.Rept.457:1-216

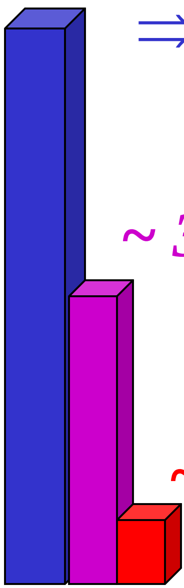
masses of elementary particles



A lot of things are not known ! SM not ultimate theory

Energy of Universe

~ 65 % of dark energy (vacuum energy) ⇒ expansion of Universe accelerating



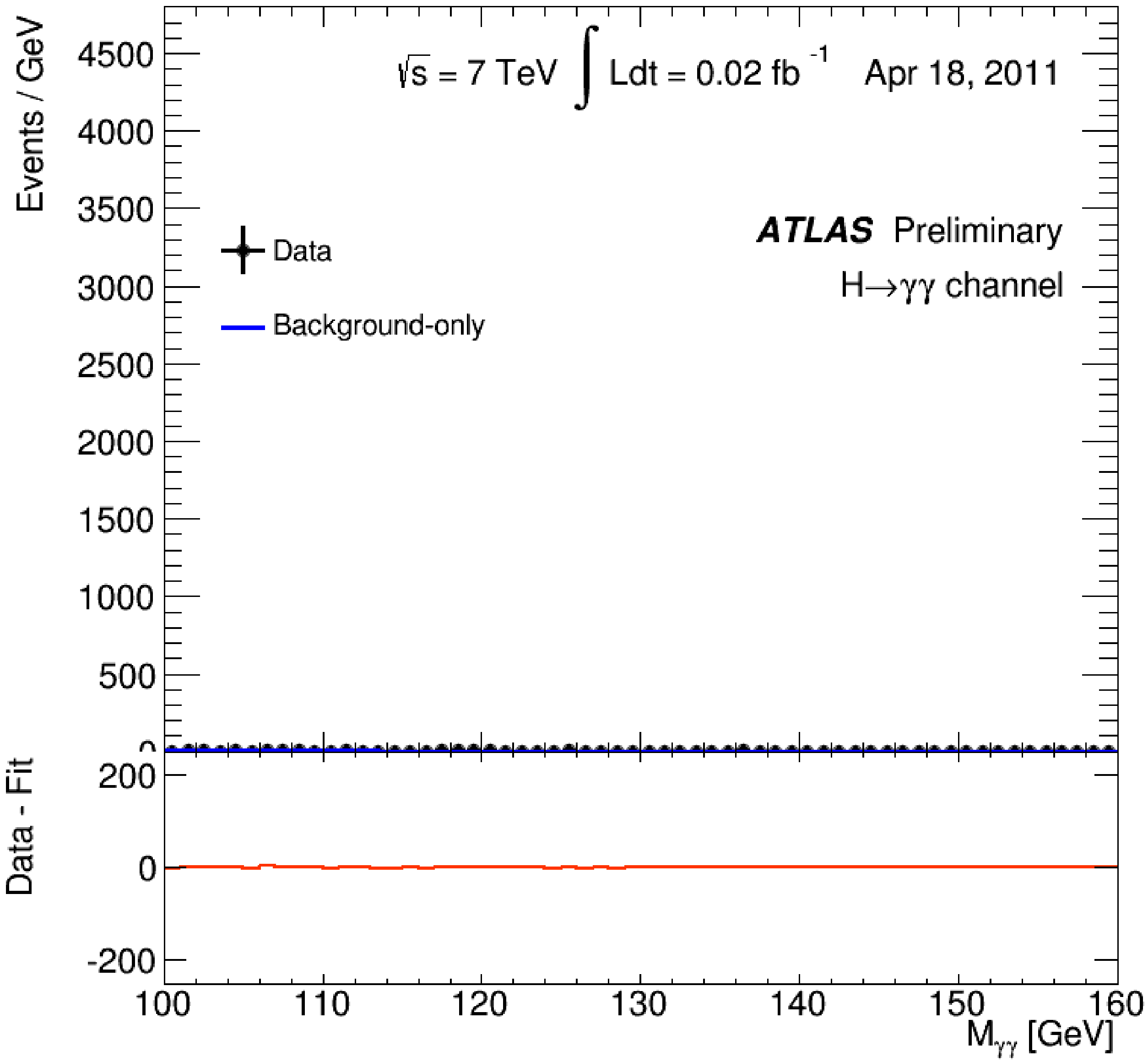
~ 30 % of dark matter (not yet observed) ⇒ rotation of galaxies

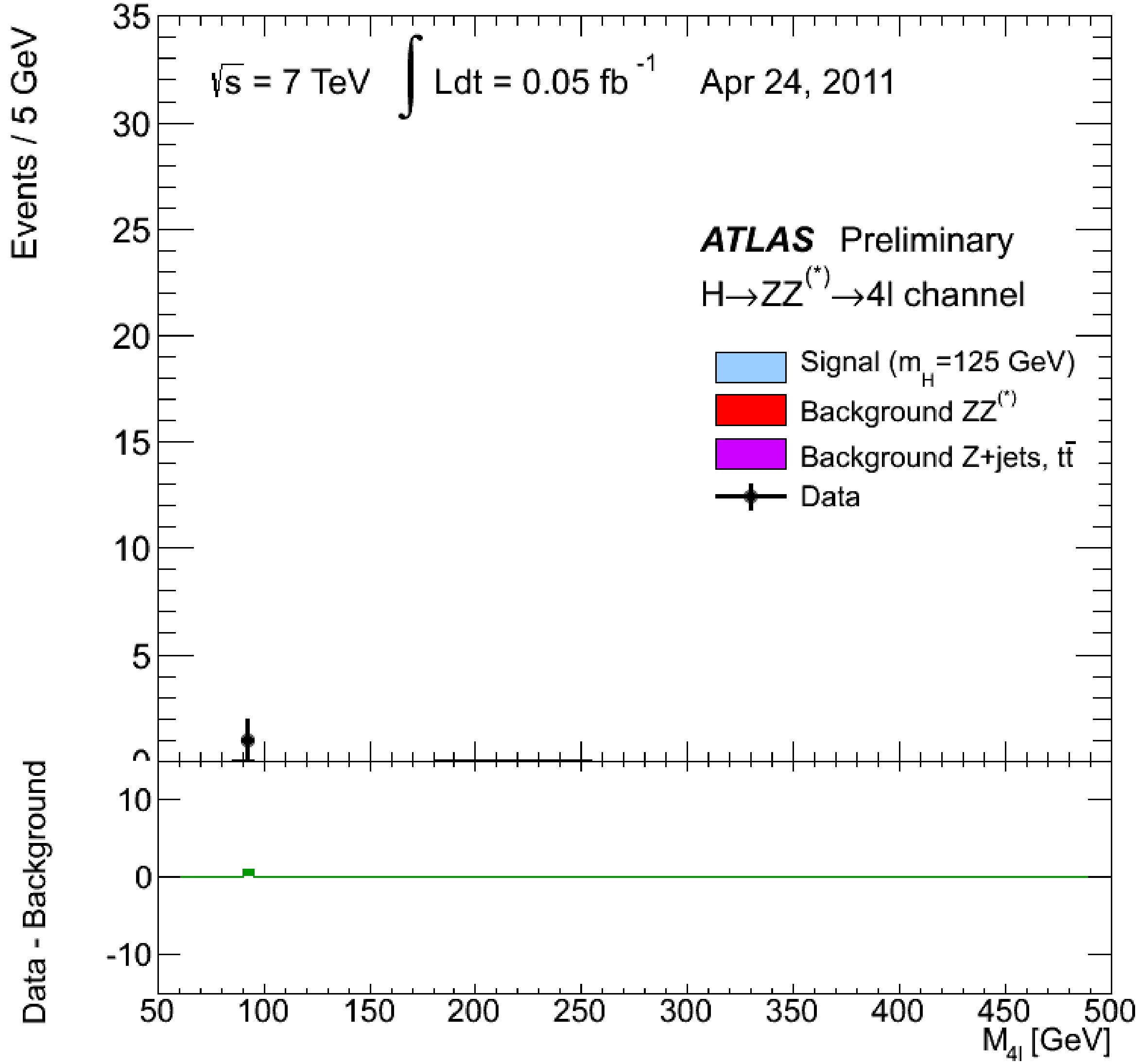
~ 5 % of "known" matter

Hierarchy problem

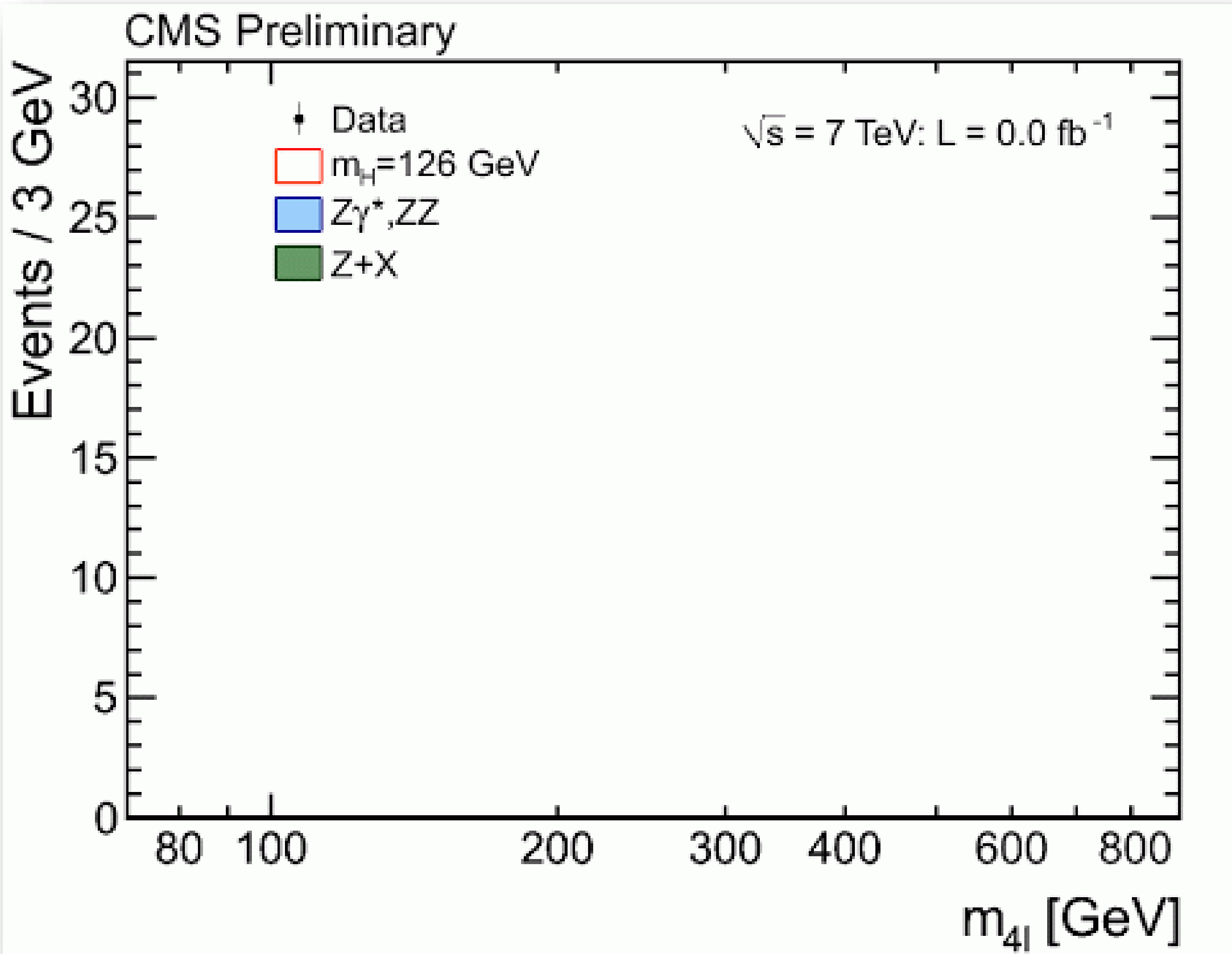
$m_H << m_{Planck}$

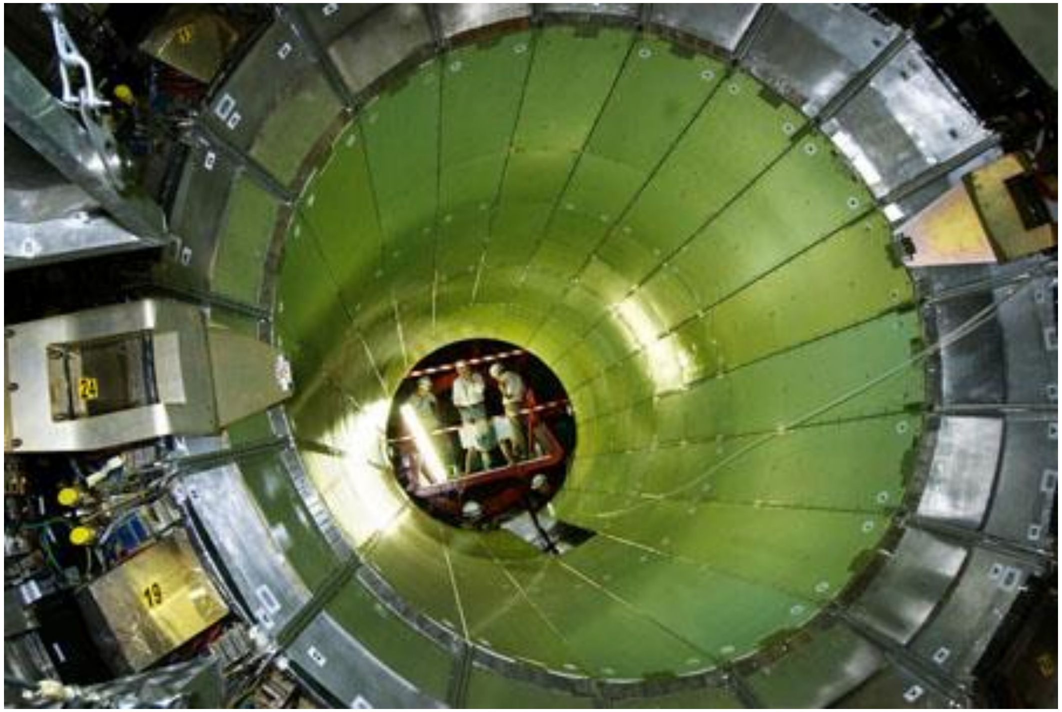
Connection with gravity


Events / GeV
√s = 7 TeV ∫Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
M γγ [GeV]



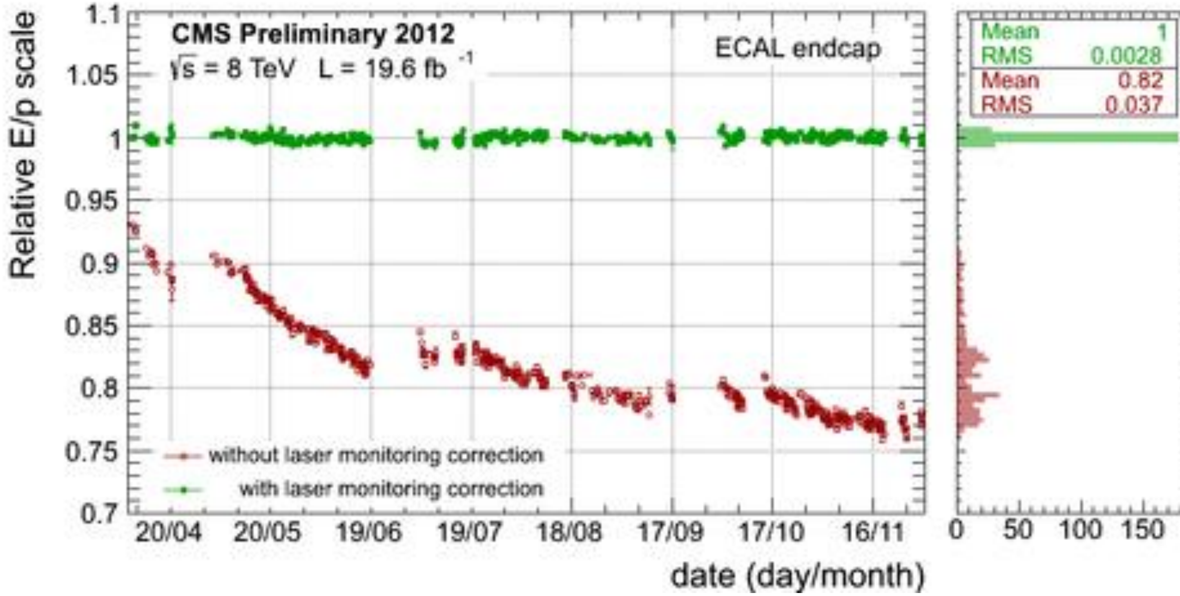
√s = 7 TeV ∫ Ldt = 0.05 fb^-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]


CMS Preliminary
Events / 3 GeV
30
25
20
15
10
5
0
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
√s = 7 TeV: L = 0.0 fb^-1
80
100
200
300
400
600
800
m_4l [GeV]



CMS EM calorimeter more than 75000 crystals of $PbW0_4$

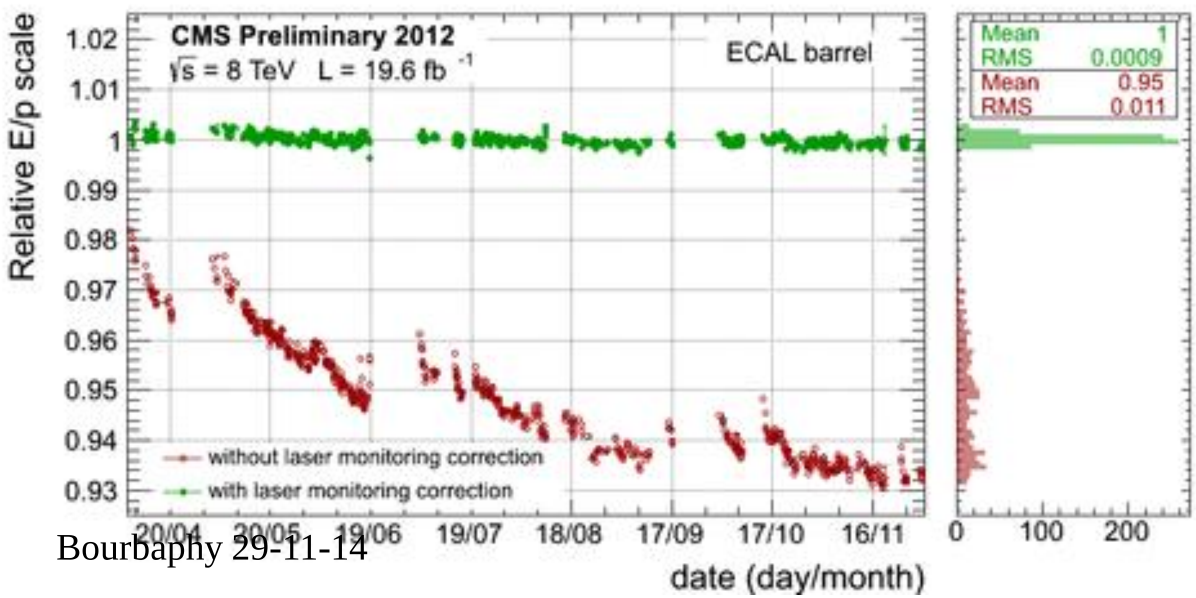
$$\sigma(E)/E = 3\%/\sqrt{E_{GeV}} \oplus 0.7\ \%$$

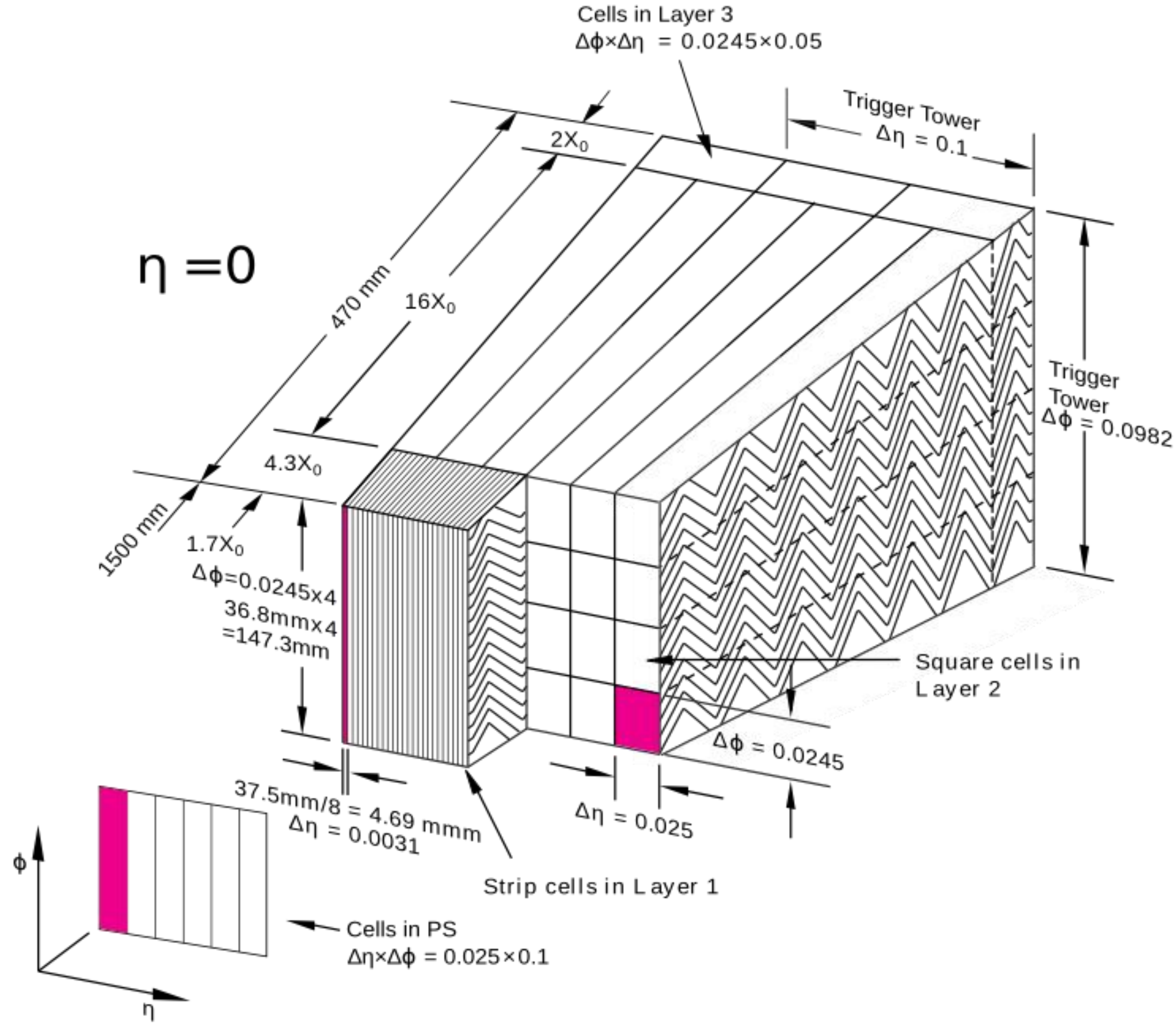


E/p history

correction
to normal
response

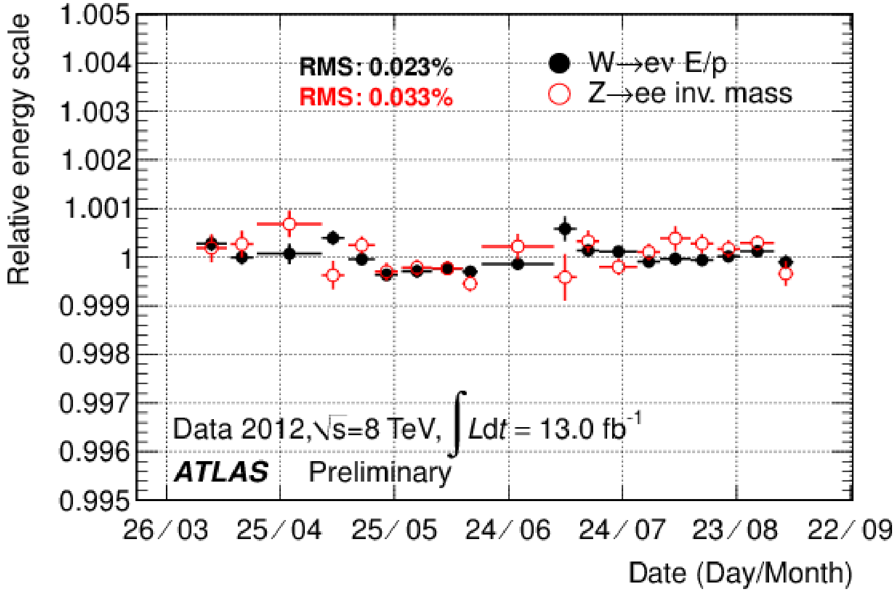
CMS-DP-2013/007





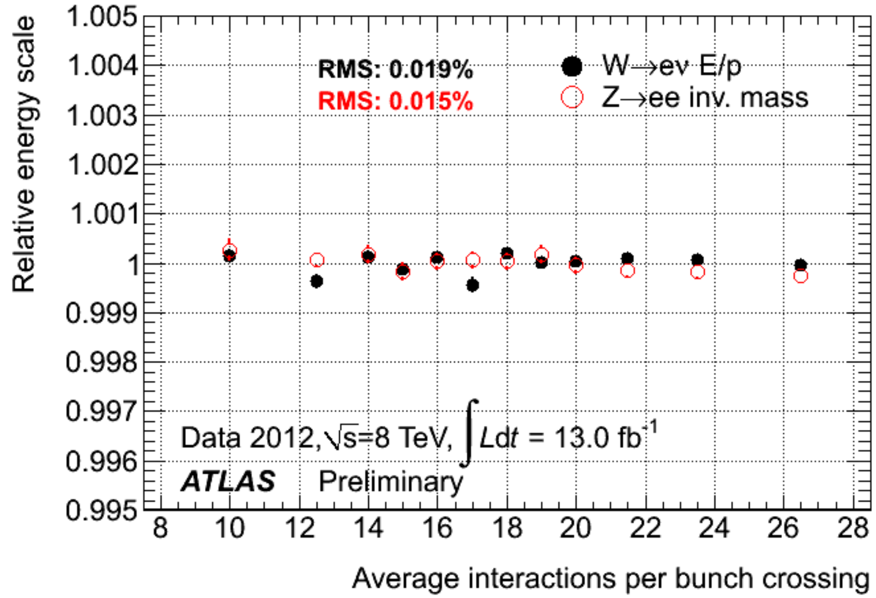
presampler and longitudinal segmentation of the EM
(** Liquid Argon **) accordion calorimeter

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121106/ATL-COM-PHYS-2012-1593/index.html

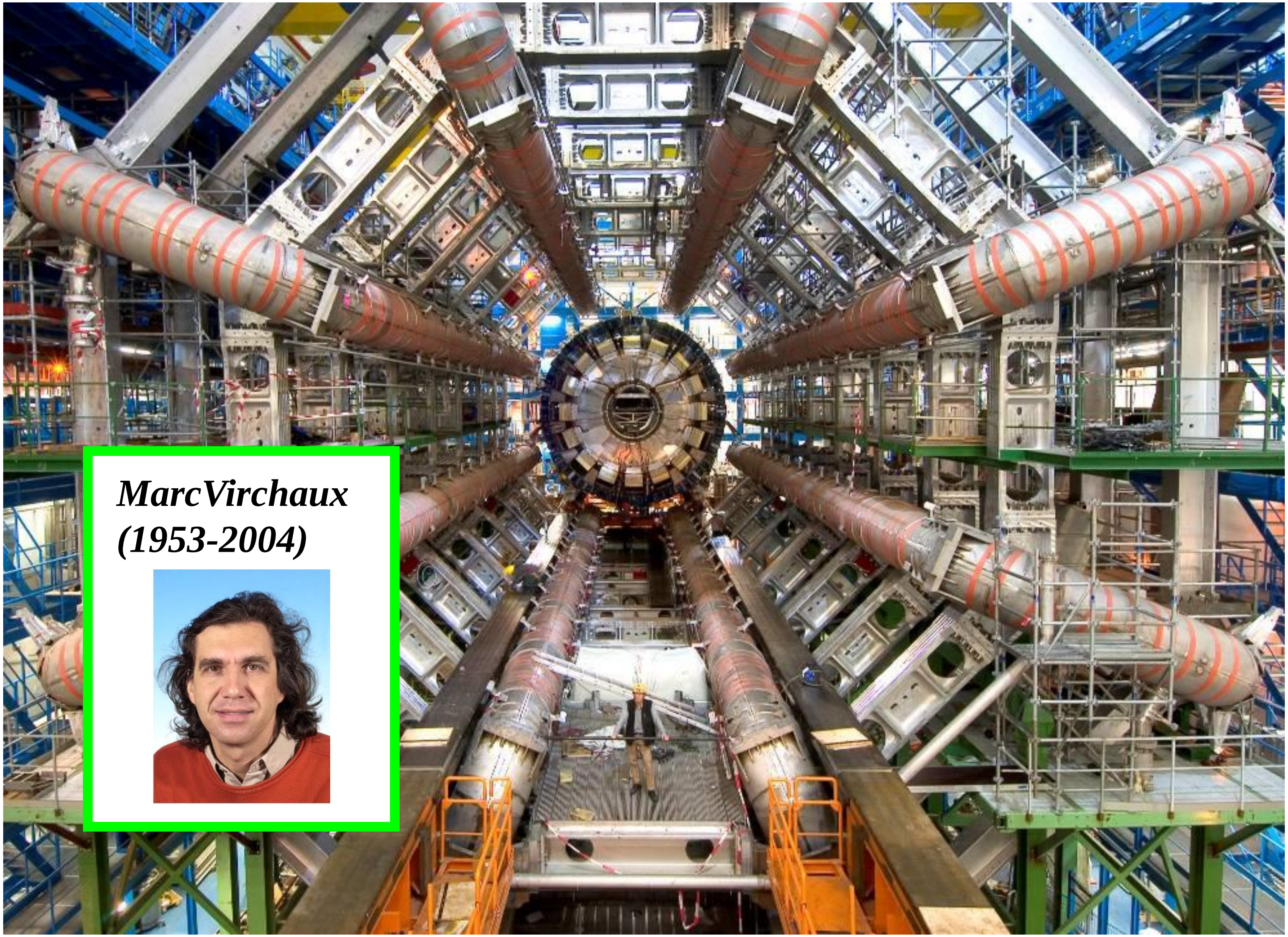


very good stability

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121129/ATL-COM-PHYS-2012-1668/index.html



Le toroide supraconducteur d'ATLAS (A Toroidal LHC ApparatuS)



	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

***luminosity* is a property of beams**

event rate [events s^{-1}]
= luminosity [nb^{-1} s^{-1}] * cross section [nb]

$$L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*}$$

Number of protons in A bunch

Number of bunches in collision

energy

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} E}{m_p 4\pi \beta^* \epsilon} F$$

Transverse size of the beams

Important parameters

(instantaneous) luminosity

LHC : currently

peak luminosity is $7\ 10^{33}$ cm^{-2} s^{-1}

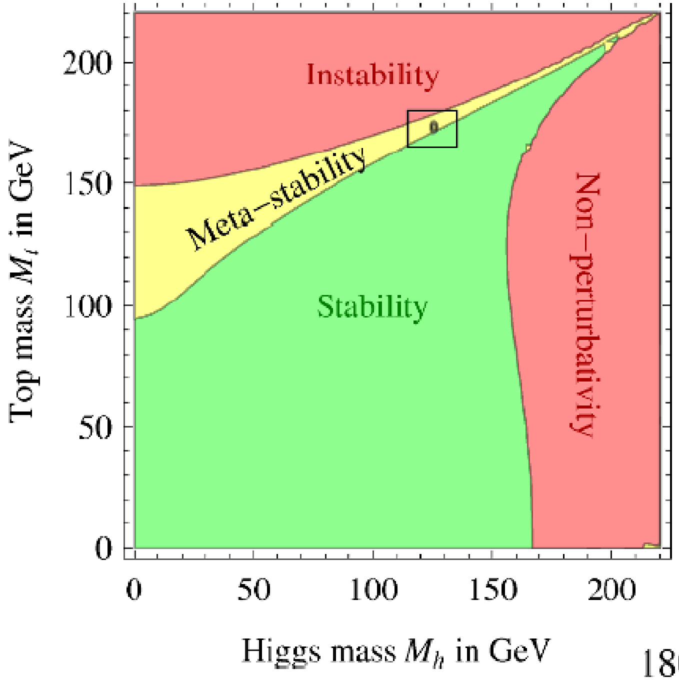
other unit = nb^{-1} s^{-1}

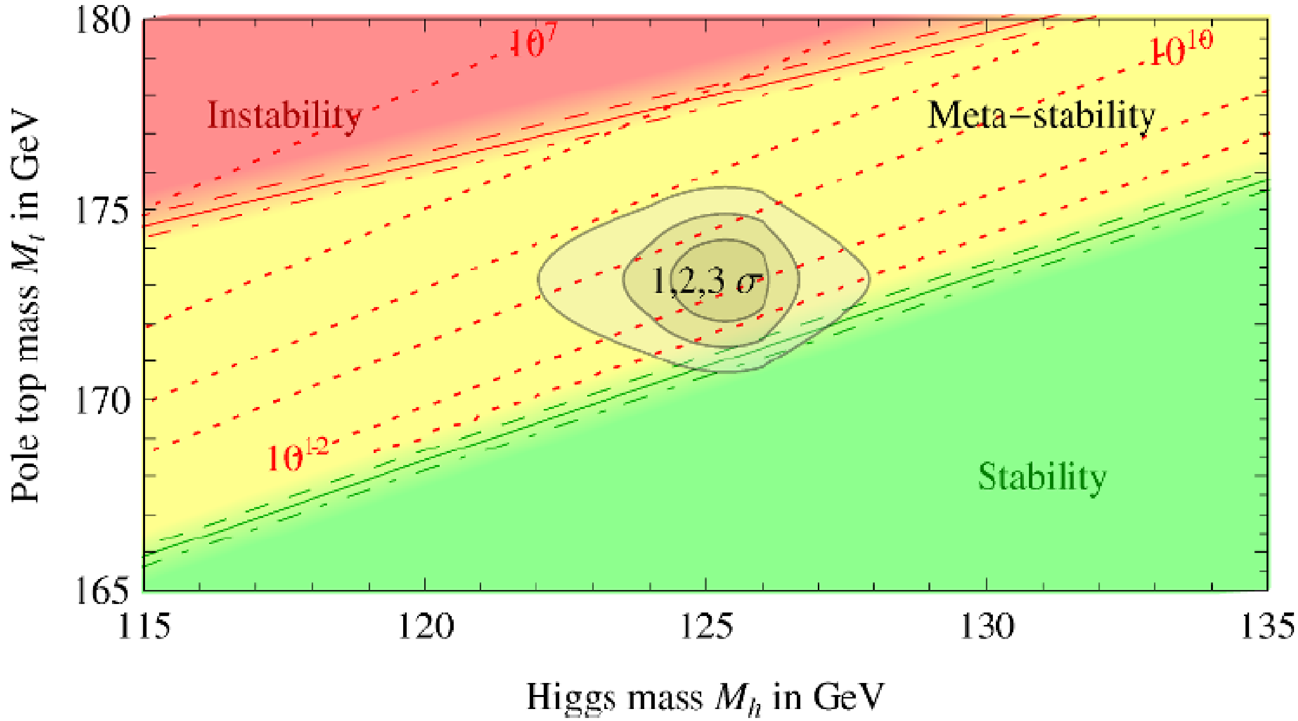
Integrated luminosity

for ATLAS and CMS each

it was ~ 5 fb^{-1} at $\sqrt{s}$ = 7 TeV and ~ 20 fb^{-1} at $\sqrt{s}$ = 8 TeV

Notion of pile-up : in a bunch-crossing , in addition to the 'nice' event there are additional p-p interactions (~35 for $7\ 10^{33}$ cm^{-2} s^{-1}) which make the 'nice' event more complicated to analyze





Bourbaphy 29-11-14