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Claude Bouchiat memorial session

Results from LHC

Louis FAYARD (IJCLab Orsay)

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Claude Bouchiat memorial session

I didn't know Claude Bouchiat well, but enough to have some idea of his personality. I wondered why he was not more often a member of thesis jurys at LAL Orsay.

I understood by attending an HDR in ~ 1990 where he was in the jury

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Claude Bouchiat memorial session

After a discussion with the youngster, he said something like *"enough discussion, write the Lagrangian on the blackboard"***.**

This threw a chill in the audience and destabilized the young

n physics, you had to either resign, which I did, or for Claude Bouchiat to be taken care of in a state body, in this case Les Poudr

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Claude Bouchiat memorial session

I knew Claude Bouchiat well, we were from the same class of 1953 at l'X.
At that time when leaving X to do research in physics, you had to either resign, which I did, or for Claude Bouchiat to be taken care of in a state body, in this case Les Poudres through the flair of Louis Michel.
Then I met and appreciated many times Claude Bouchiat in the context of physics

Jean-Marc Gaillard

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Claude Bouchiat memorial session

I knew Claude Bouchiat well. We had many exchanges on neutrino physics because he appreciated the discussions between experimenters and theoreticians.

I always see him enthusiastic and passionate, making movements, with his glasses which slipped on his nose and which he raised with a flick of his index finger. He was a valuable interlocutor for us as we prepared to publish the papers on neutral currents.

Jean-Pierre Vialle

g but a socialite. He didn't pay for words and knew his stuff. During a support session for the construction of the LHC at the CN

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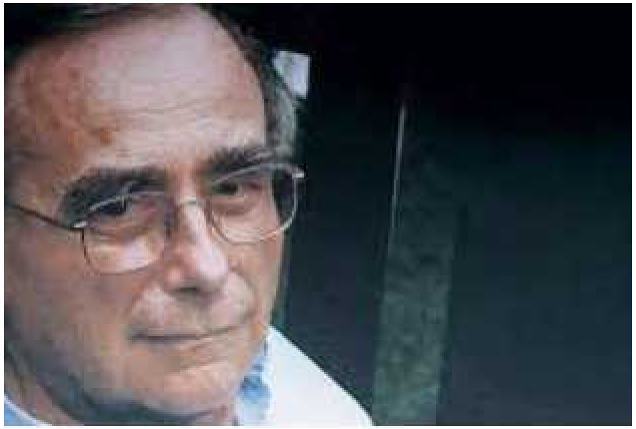
Claude Bouchiat memorial session

I had him as a teacher at the DEA in theoretical physics from 65-66 and that I, as such, really appreciated him. He was anything but a socialite. He didn't pay for words and knew his stuff.

During a support session for the construction of the LHC at the CNRS headquarters, quai Anatole France (the good times!), I remember that he glared at his neighbors ordering them to support this project unconditionally, and he was right even though we of LEP lamented Rubbia's haste to end LEP ...

Francois Richard

Claude Bouchiat memorial session



I had great esteem for Claude Bouchiat, like all experimenters I guess. His personality combined rigor, in-depth knowledge and a touch of irony almost permanent.

I don't know which region, probably of the South-West, he owed his accent, but his speeches could not be missed on this basis too

Jacques Haissinski

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He is one of the 4 people to whom I owe my desire to do research, with Louis Michel, Laurent Schwartz and Albert Messiah

Daniel Treille

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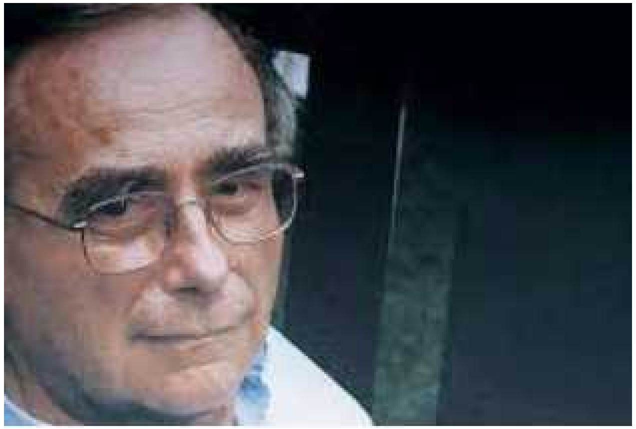
Claude Bouchiat memorial session



I got to know him a bit while the theory group was at Orsay, before going to ENS.
At the time there was a "second year" DEA course, in which he gave a course on the weak interactions, V-A, PCAC,… I remember that he insisted on the fact that writing a Lagrangian wasn't the most difficult. The most difficult being on the contrary to put all the numbers together to arrive at a lifetime or a cross section. It must have been in 1968. So he had the concern for the comparison between experience and theory

Daniel Fournier

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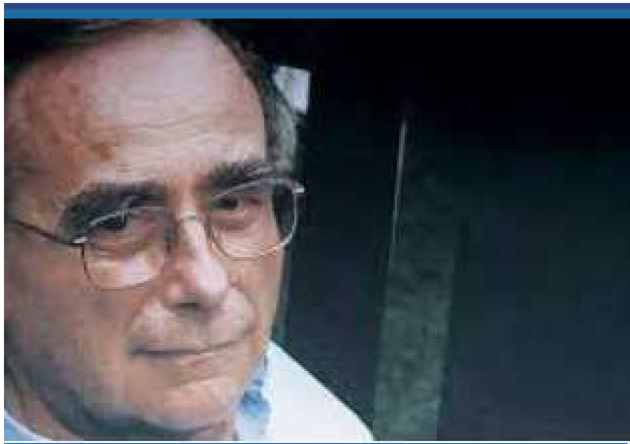
Claude Bouchiat memorial session

I have the image of a man always on the move, passionate, and it was better not to contradict him !

In this case, an avalanche of acerbic comments was triggered

Anne-Marie Lutz



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Claude Bouchiat memorial session

I have always taken very seriously the comments and advice of Claude each time I had the privilege of meeting him. For me a very great physicist, and perhaps too humble to assert himself as it should have been ***I have always taken very seriously the comments and advice of Claude each time I had the privilege of meeting him. For me a very great physicist, and perhaps too humble to assert himself as it should have been***

Eduardo de Rafael

The precise wording of a_μ(HVP), what is now called the dispersive HVP evaluation of a_μ, was first given by Claude Bouchiat and my thesis advisor Louis Michel in 1961.[20]

20. I remember Claude Bouchiat discussing this on the blackboard with Louis Michel in Louis's office sixty years ago, but I could not understand a word of it at that time! Claude Bouchiat and Louis Michel, "La Résonance dans la diffusion méson π— méson π et le moment magnétique anormal du méson μ," *Journal de Physique et le Radium* 22, no. 2 (1961): 121–21, doi:10.1051/jphysrad:01961002202012101. ↩

The title "Results from LHC" is a bit misleading

I will focus on (** some**) « high p_T physics » (i.e ATLAS and CMS)

Not completely forgetting the rest !

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

Nothing is believed as strongly as that we know the least

Montaigne, Essais

Two main results at the LHC

1 The (BE)H boson has been discovered and its properties are well measured (to be discussed later) as expected

2 No (*statistically significant*) new physics has been found

tremendous resilience of the Standard Model **Costas Bachas**

I will discuss more 'measurements' than searches

- ♪ ***Historical introduction and setting the stage***
  - ***Spontaneous Symmetry Breaking***
  - ***LHC and (mainly) ATLAS and CMS***
  - ***H(125) discovery***
- ♪ ***Results from Run 1 & Run 2 (& start of Run 3) (up to now) :***
  - ***mainly H(125)***
  - ***other physics (precision, searches)***
- ♪ ***Future of LHC , Run 3 , HL-LHC***
- ♪ ***Conclusions***
- ♪ ***Backup***

- ♪ ***Historical introduction and setting the stage***
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- ♪ ***Backup***

Spontaneous Symmetry breaking *(Baker-Glashow)*

The Electroweak Theory *(Salam)*

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, Gell-Mann Levy, NJL

1961 Schwinger

1962 Anderson

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

1967 Weinberg, Salam Faddeev, Popov

1970 Glashow, Iliopoulos,

Maiani, 't Hooft, Veltman, BRST…..

re

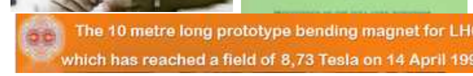
(A

1973 Neutral Currents dis

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

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

1984 Spiro, Repellin, …



1989 August 19

beginning

1992 LOI of 'lar

1994 TP of ATL

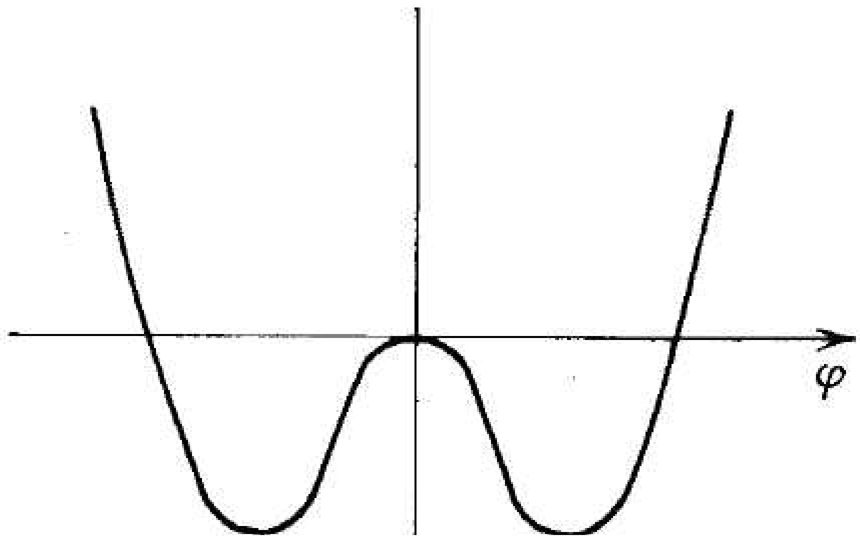
1995 discovery o

1996 approval o

1998

approval o ICE)

1999 ATLAS Ph P data ended in 2000



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

2006

2008 CMS Physi

2010 ATLAS Ex

2012 start-up at

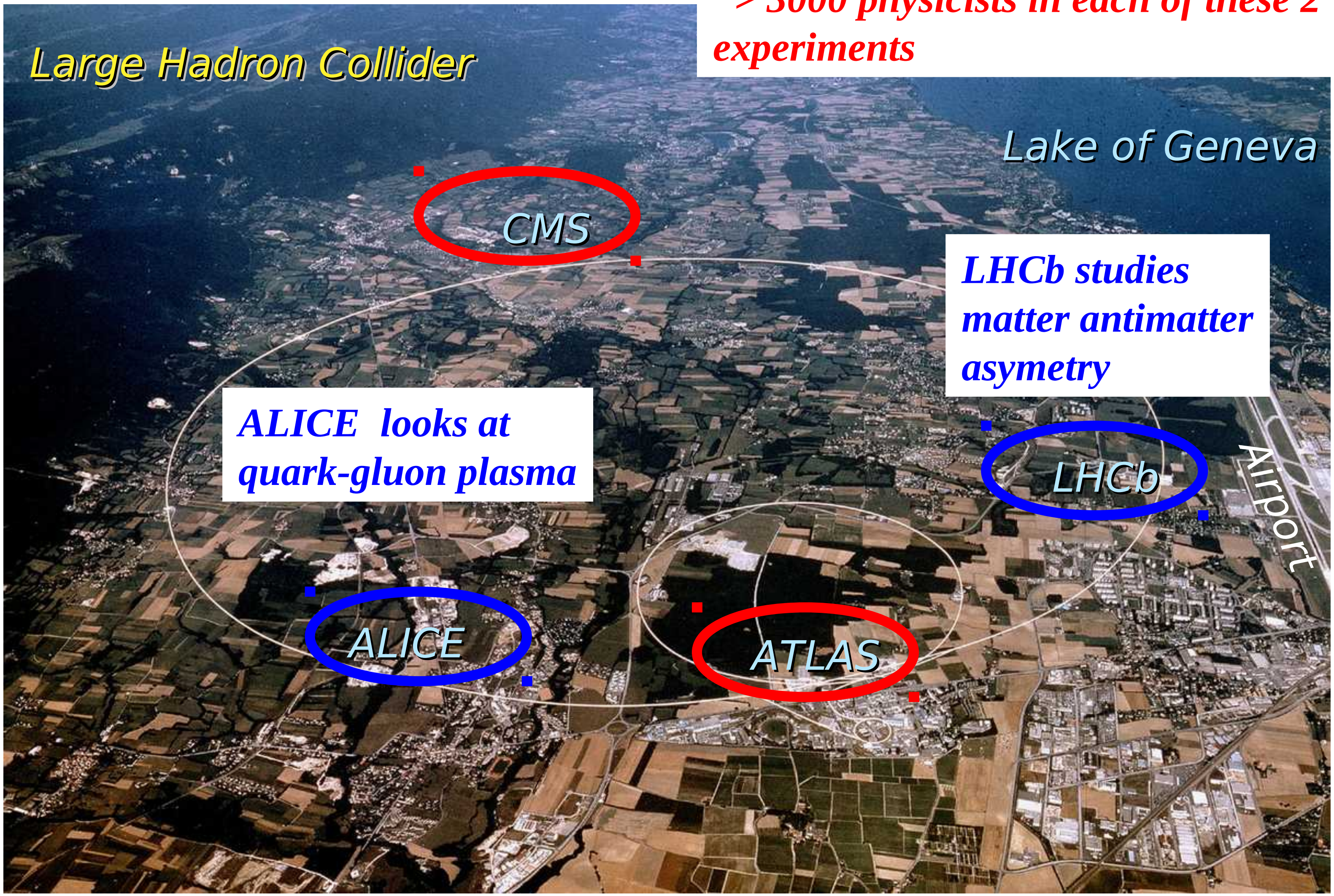
4th July discovery of boson (m ~ 125 GeV) Tevatron data ended in Sept 2011 (~10 fb^{-1})

2013

2014 boson like properties Nobel prize to Englert and Higgs

► Experiments at LHC

ATLAS & CMS study
(Brout-Englert-)Higgs boson+ (beyond?)
Standard Model in general :
> 3000 physicists in each of these 2 experiments



ALICE looks at quark-gluon plasma

LHCb studies matter antimatter asymetry

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 : 7 TeV integrated luminosity ~ 5 fb^{-1}
13th december 2011 : first 'signal' around 126 GeV

September 2011 :
end of Tevatron
data taking

2012

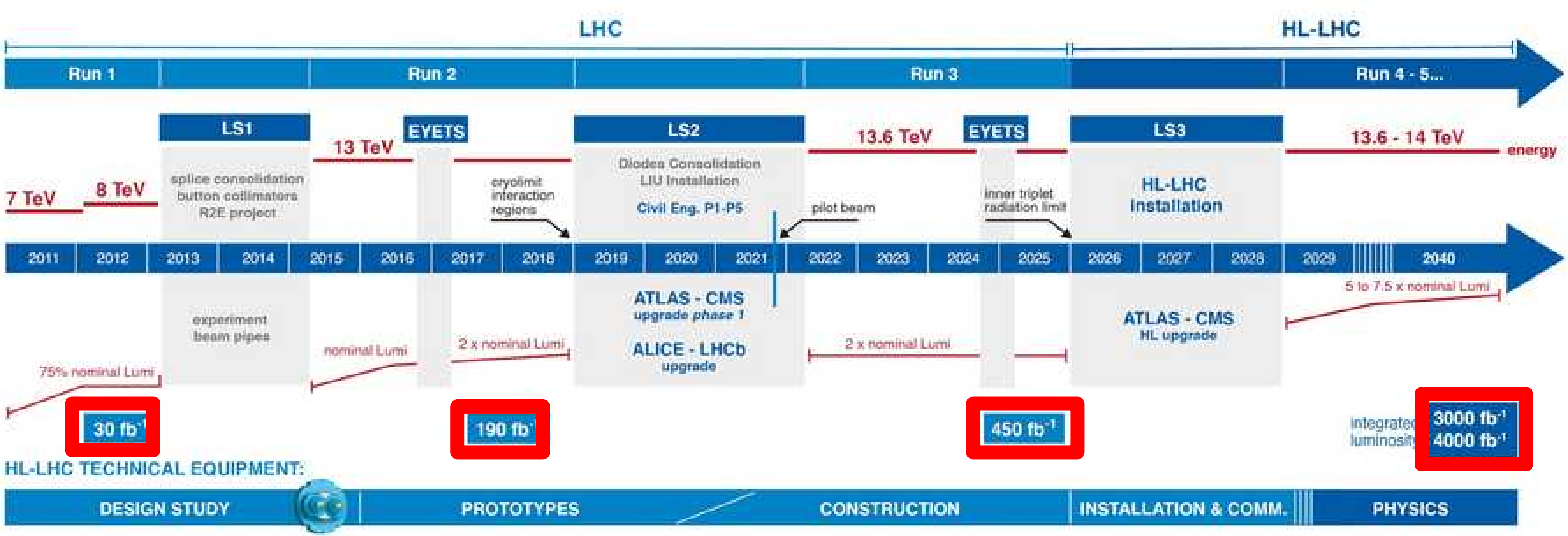
march 2012 : start again at 8 TeV
(50 ns between bunches)
4th July 2012 : evidence for a new boson
(8 TeV integrated luminosity ~ 6 fb^{-1})

2013

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

end of Run-1

LHC / HL-LHC Plan



Englert –Higgs Nobel prize

now

(B-E)-H boson discovery

These luminosities are for ATLAS and CMS

For LHCb ~ 3 (9) fb^{-1}
end of Run 1 (2)

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

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

At LHC there are ~ 2454 BCID (Bunch Crossing ID)
a BCID is a couple of 2 bunches of protons (each with ~ 1.5 10^{11} p)

$$L = L_{BCID}.\kappa_b = \frac{N_p^2 \kappa_b f_{rev}}{4\pi\sigma_x\sigma_y} F$$

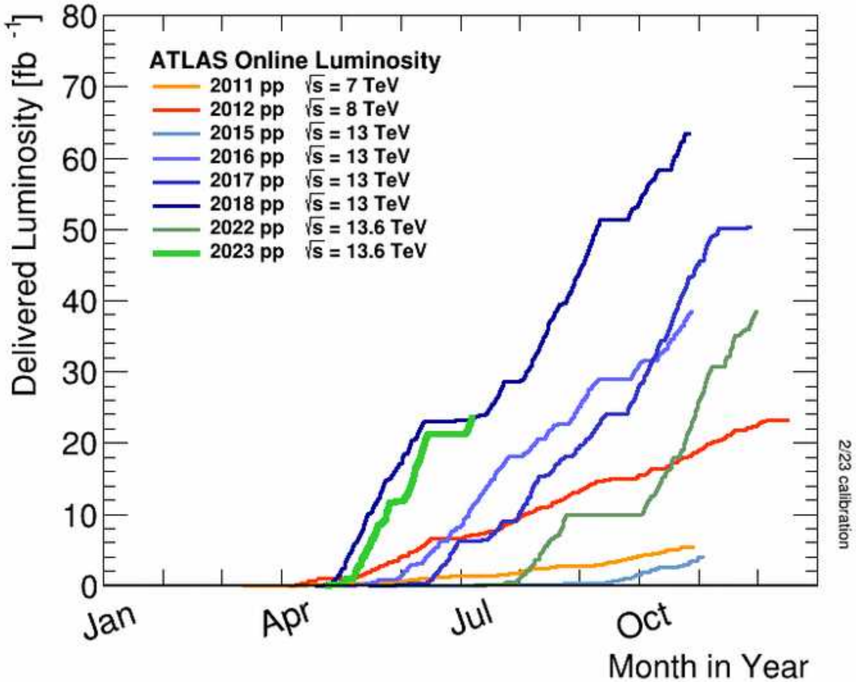
κ_b is the number of bunches per beam

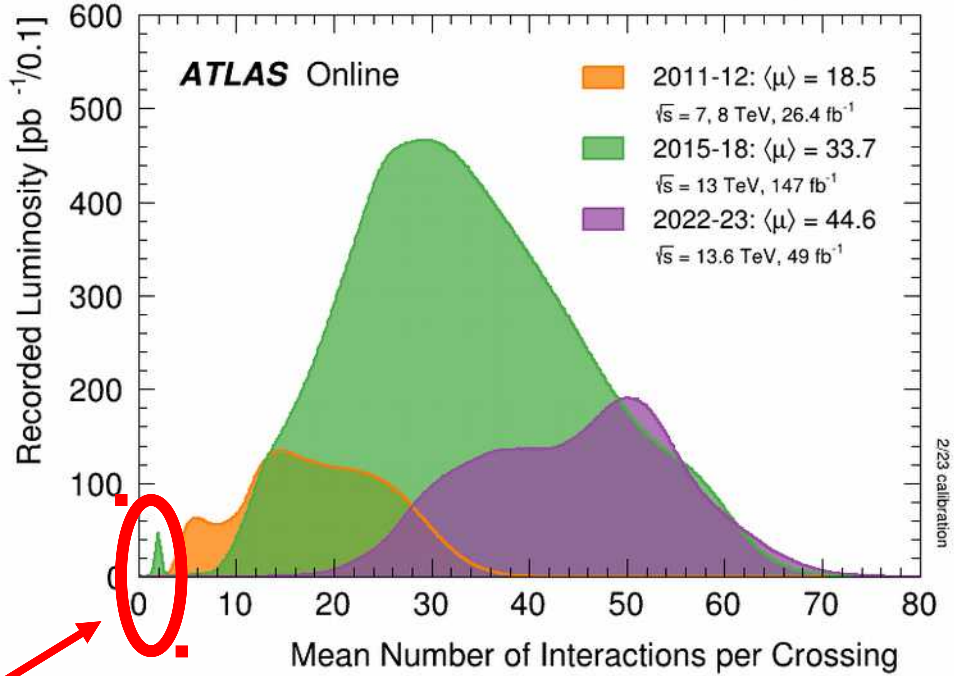
The average number of the in-time interactions per bunch crossing

$$\mu_{BCID} = \frac{L_{BCID}.\sigma_{inel}}{f_{rev}}$$

Important number : L ~ 2 10^{34} cm^{-2} s^{-1} μ_{BCID} ~ 60

pile-up





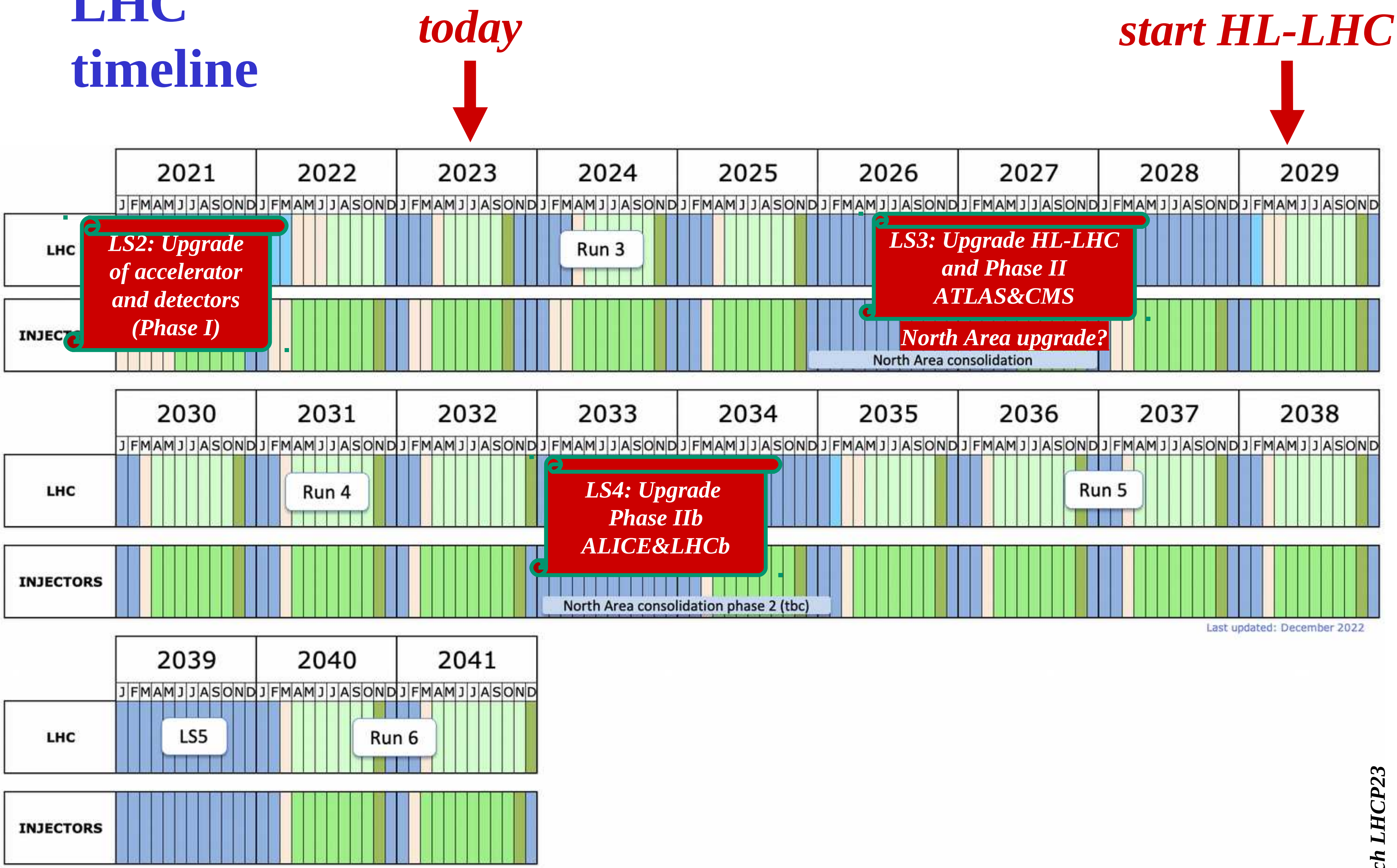
low μ data for precision measurements

and we have now a μ 2.5 times larger !

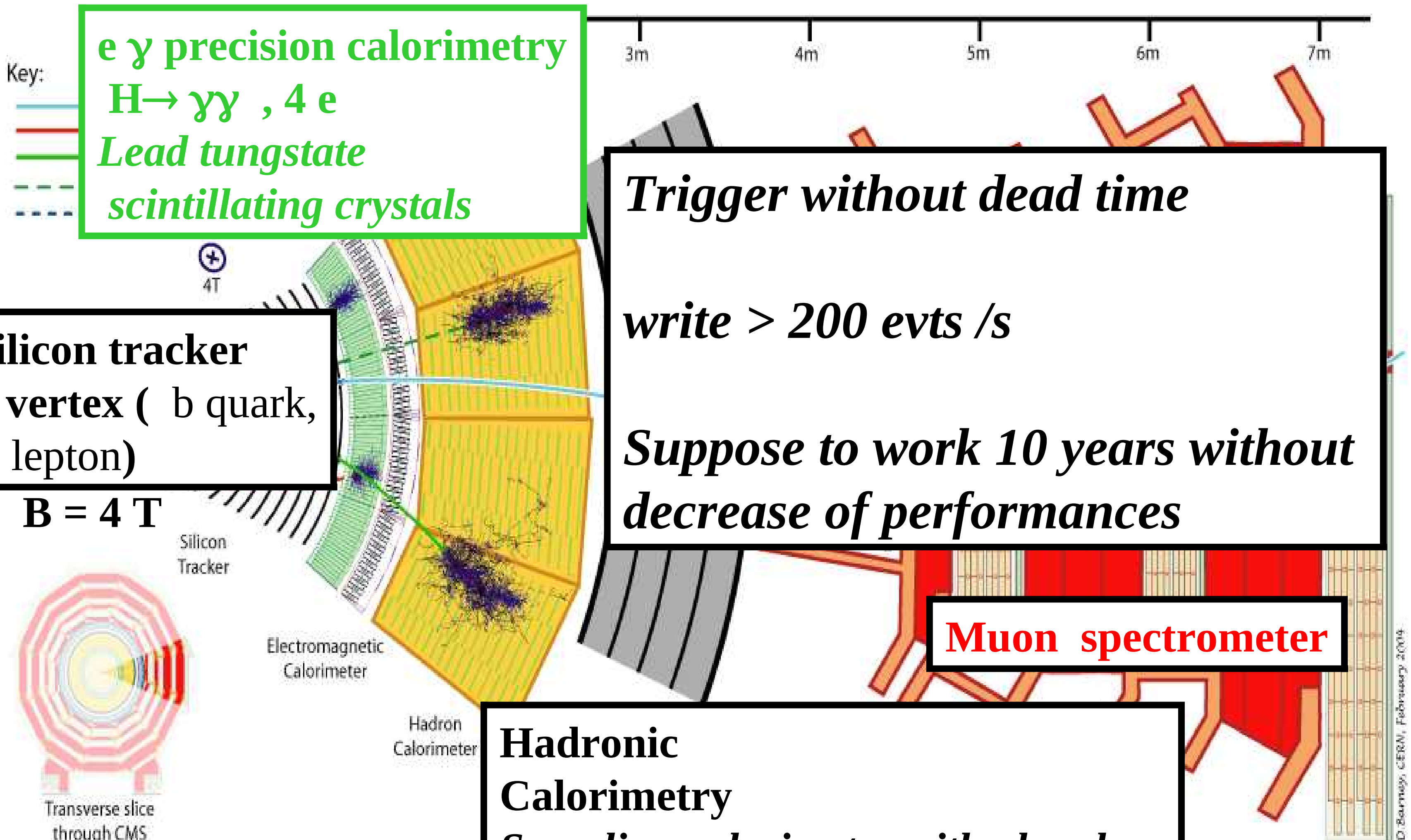
High μ means high luminosity !

But also aging of detectors !
Or just change of response with time !

LHC timeline



CMS = (*Compact Muon Solenoid)*



e γ precision calorimetry
H→ γγ , 4 e
Lead tungstate
scintillating crystals

Trigger without dead time

write > 200 evts /s

Suppose to work 10 years without decrease of performances

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

B = 4 T

Muon spectrometer

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

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

High level quality control !

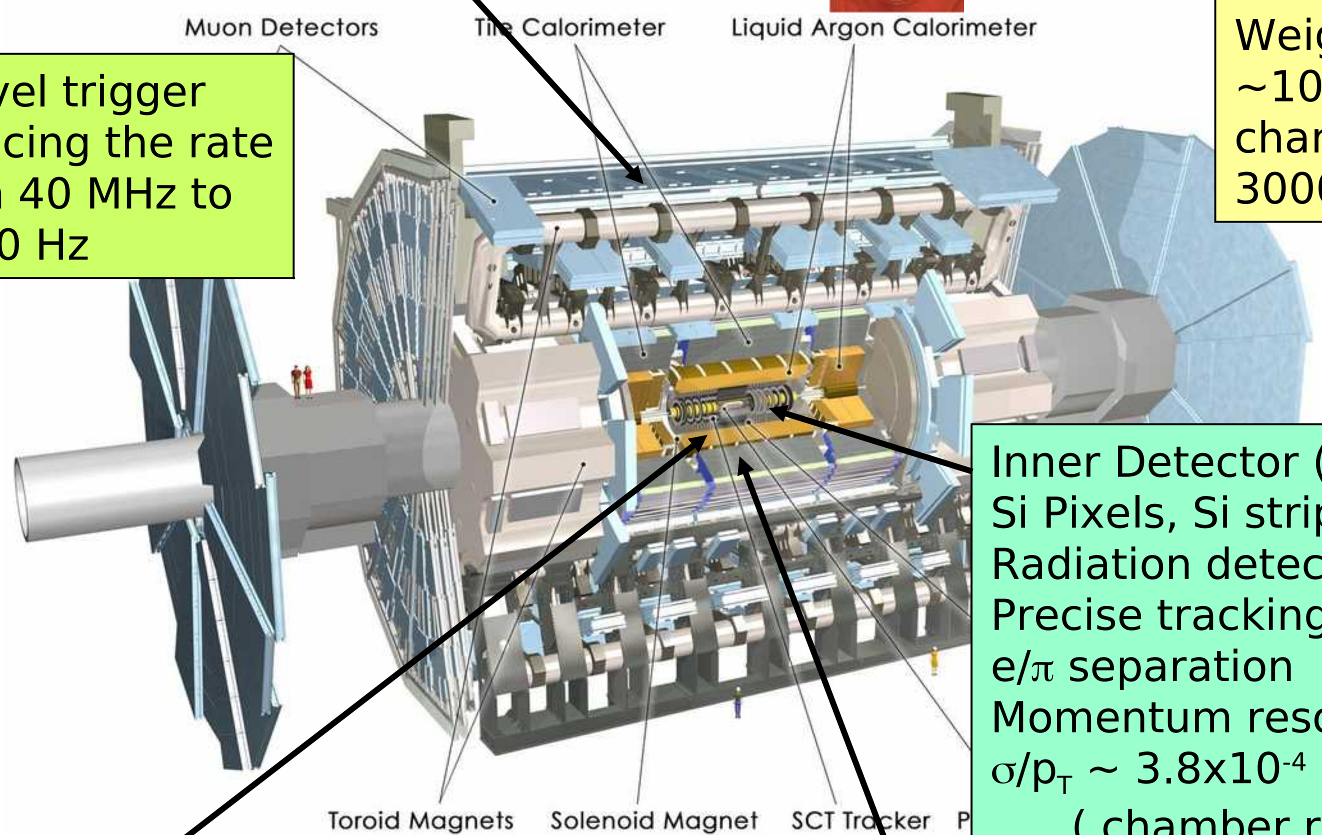
on Spectrometer ($|\eta|<2.7$) : air-core toroids (B ~ 0.5 / 1T in barrel/ end-cap) with gas-based
on chambers Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 Te

MarcVirchaux
(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



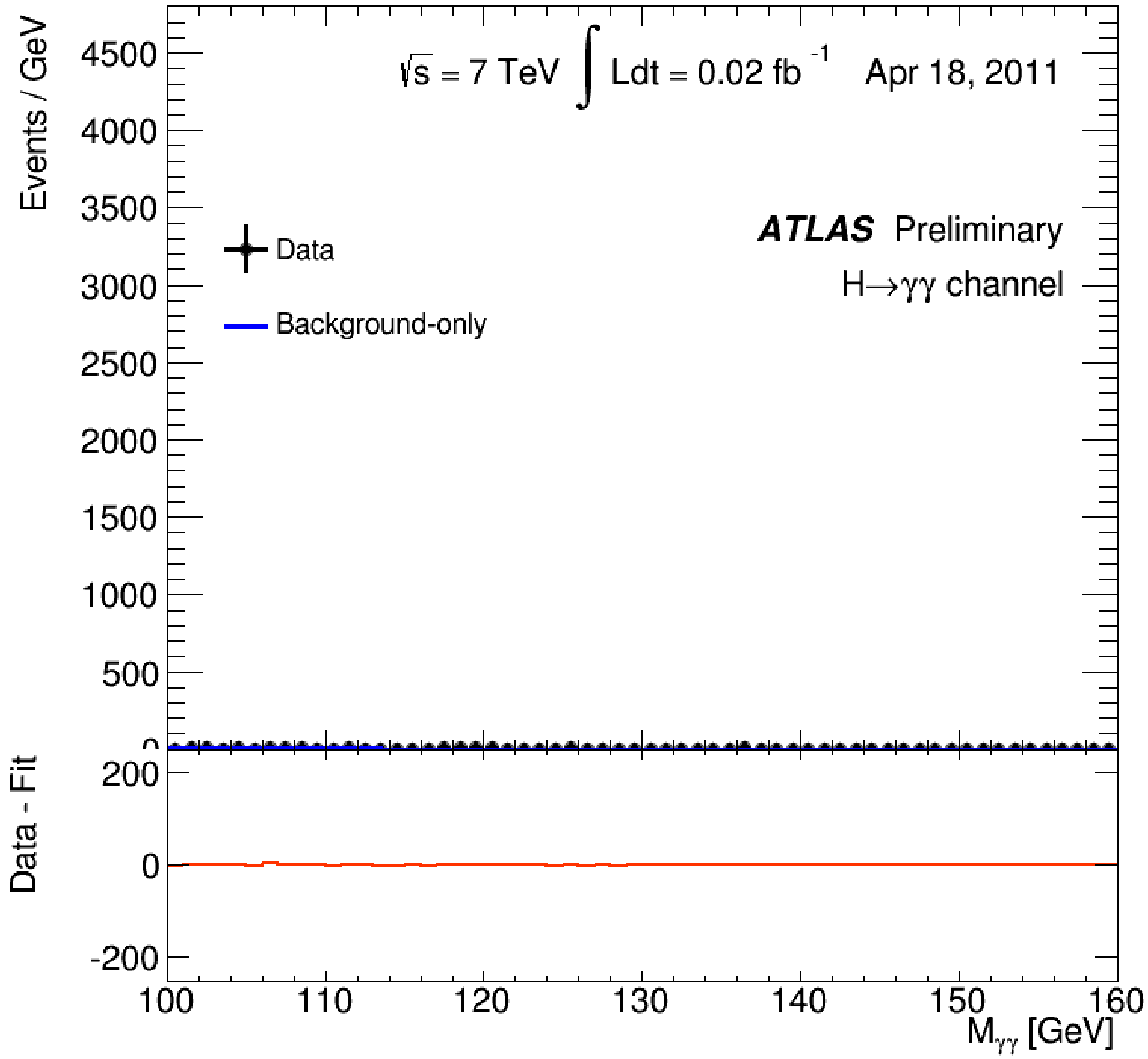
© F.Gianotti

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)

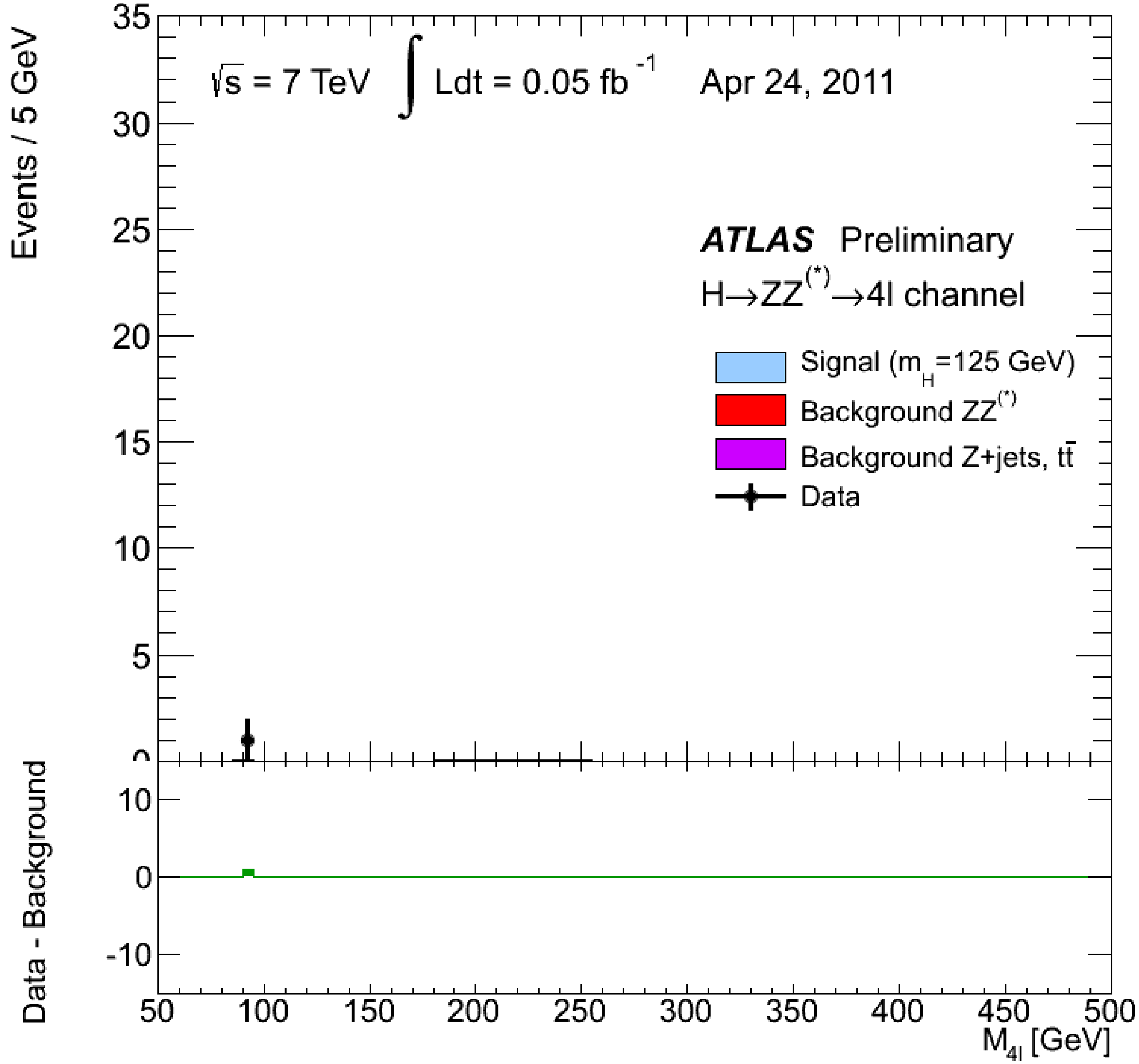
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measureme
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

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: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

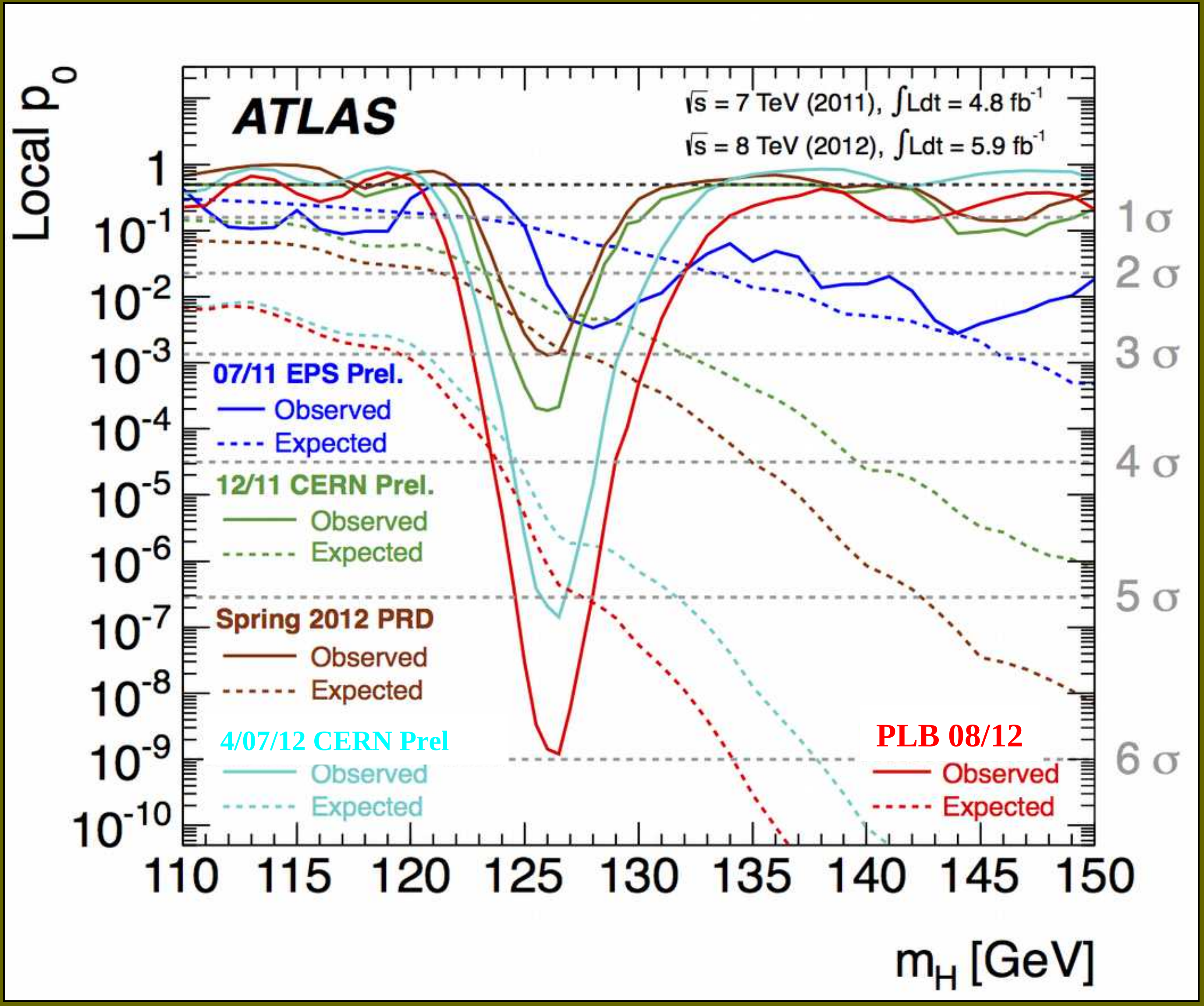


Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
Data
Background-only
ATLAS Preliminary
H→γγ channel
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]



Events / 5 GeV
35
30
25
20
15
10
5
0
√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
10
0
-10
50
100
150
200
250
300
350
400
450
500
M4l [GeV]

Evolution of the excess with time

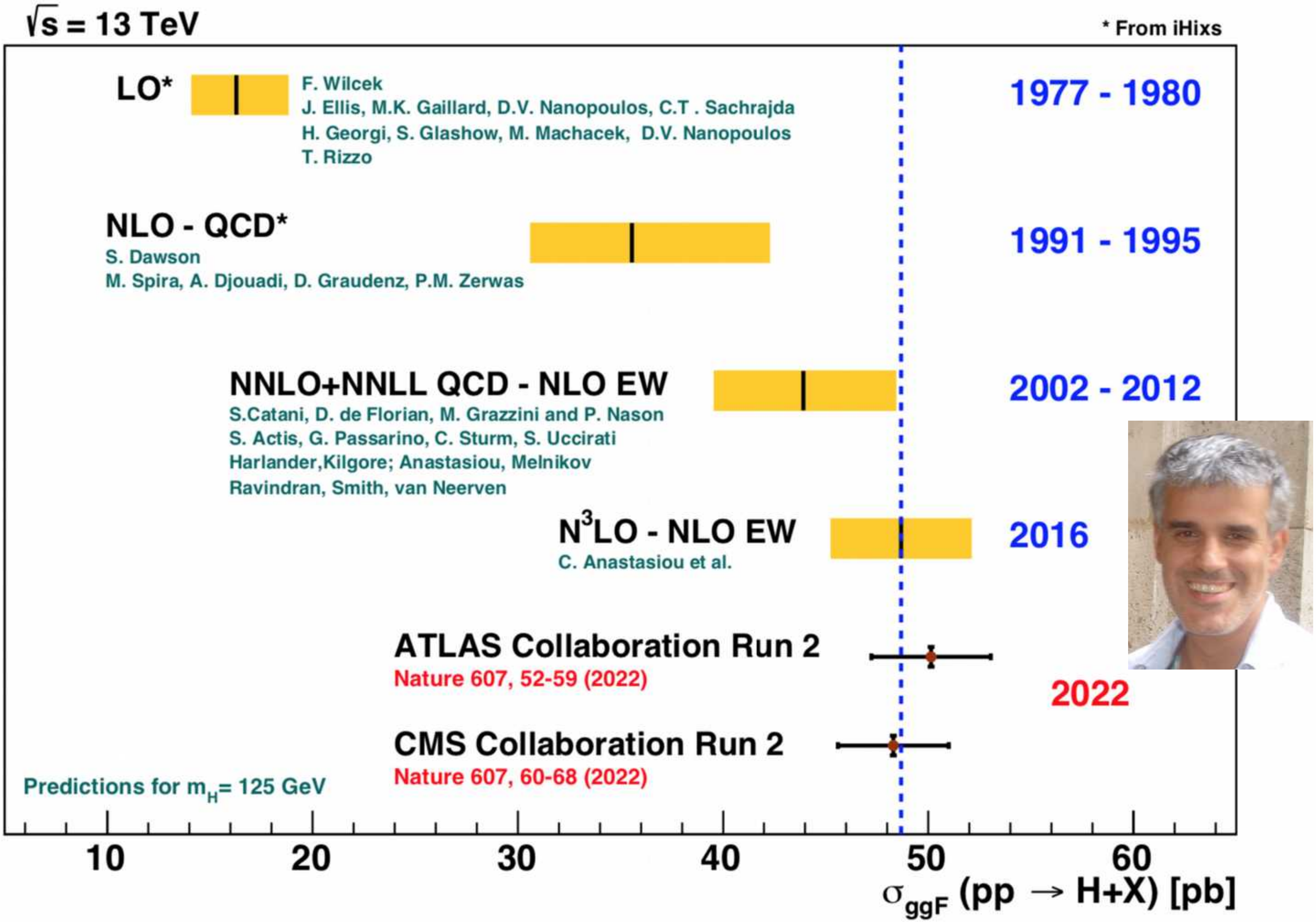


p_0= probability that the background fluctuates more than the observed excess

Theory

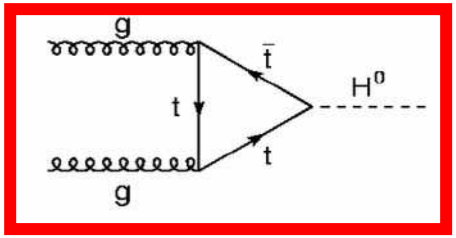
I will say very few things

- → ***H phenomenology really started in 1976***
- → ***1977 (Lee, Quigg, Thacker)*** ***either m_H<800 GeV or perturbative unitarity violated around 3 TeV ⇒ « no-lose » theorem (LHC had to find the H or something else at an accessible scale)***
- → ***1991 SUSY mH < mZ + (< 40 GeV with radiative corrections)***
- → ***A lot of QCD theory improvements***

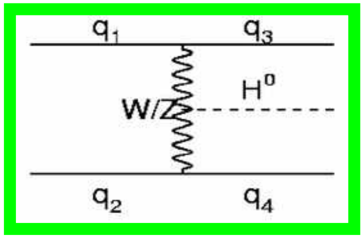

√s = 13 TeV
* From iHixs
LO*
F. Wilcek
J. Ellis, M.K. Gaillard, D.V. Nanopoulos, C.T . Sachrajda
H. Georgi, S. Glashow, M. Machacek, D.V. Nanopoulos
T. Rizzo
1977 - 1980
NLO - QCD*
S. Dawson
M. Spira, A. Djouadi, D. Graudenz, P.M. Zerwas
1991 - 1995
NNLO+NNLL QCD - NLO EW
S.Catani, D. de Florian, M. Grazzini and P. Nason
S. Actis, G. Passarino, C. Sturm, S. Uccirati
Harlander,Kilgore; Anastasiou, Melnikov
Ravindran, Smith, van Neerven
2002 - 2012
N^{3}LO - NLO EW
C. Anastasiou et al.
2016
ATLAS Collaboration Run 2
Nature 607, 52-59 (2022)
CMS Collaboration Run 2
Nature 607, 60-68 (2022)
2022
Predictions for m_H= 125 GeV
10
20
30
40
50
60
σ_{ggF} (pp → H+X) [pb]

The SM BEH boson

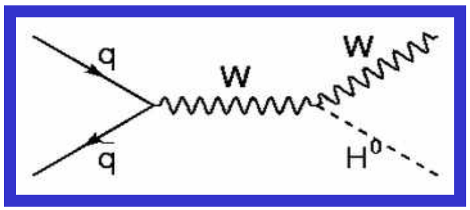
A.Djouadi Phys.Rept.457:1-216



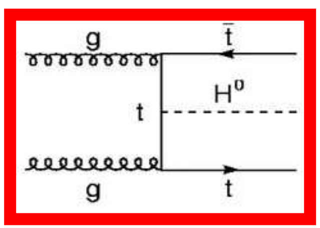
GF *H → WW , ZZ , γγ , (bb),ττ*



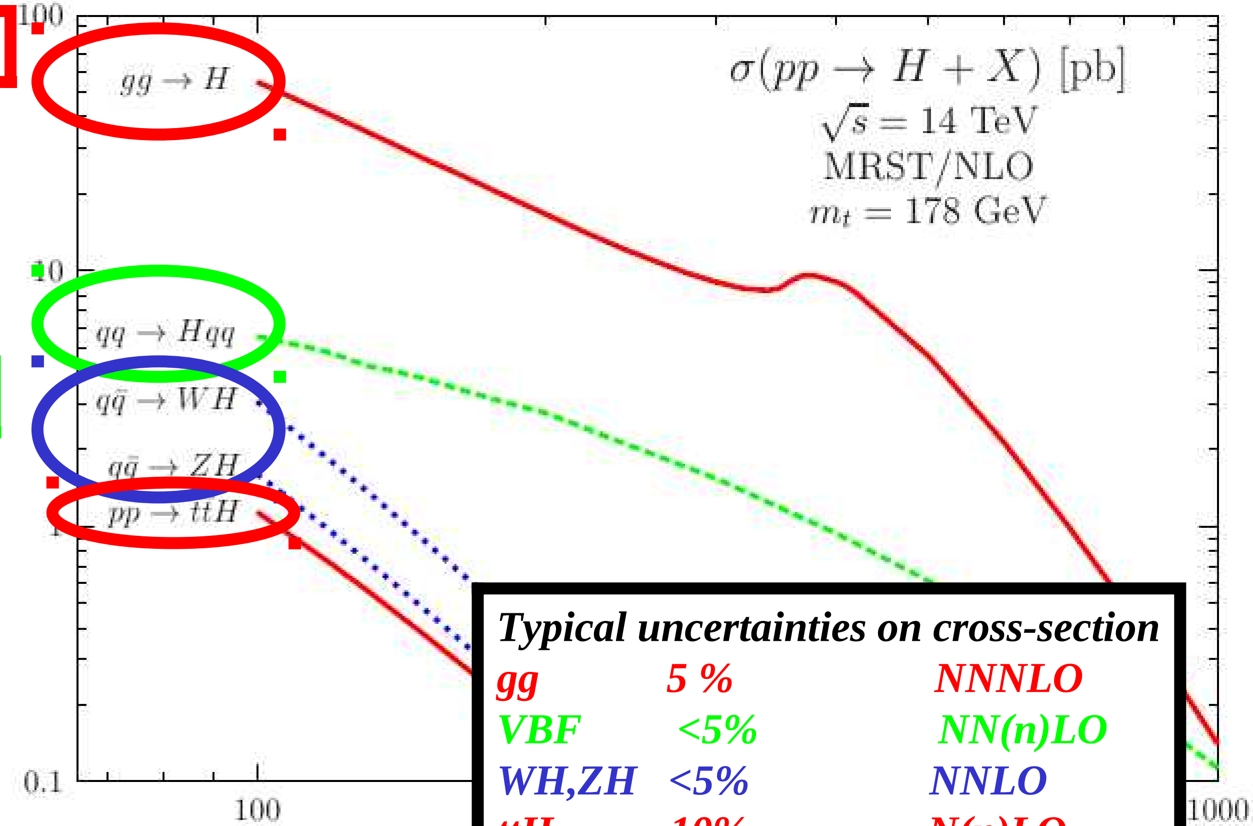
VBF *H → WW, ZZ , γγ , bb, ττ*



WH, ZH *H → WW, γγ, bb*



ttH *H → WW, γγ, ττ, ZZ, bb*



Typical uncertainties on cross-section

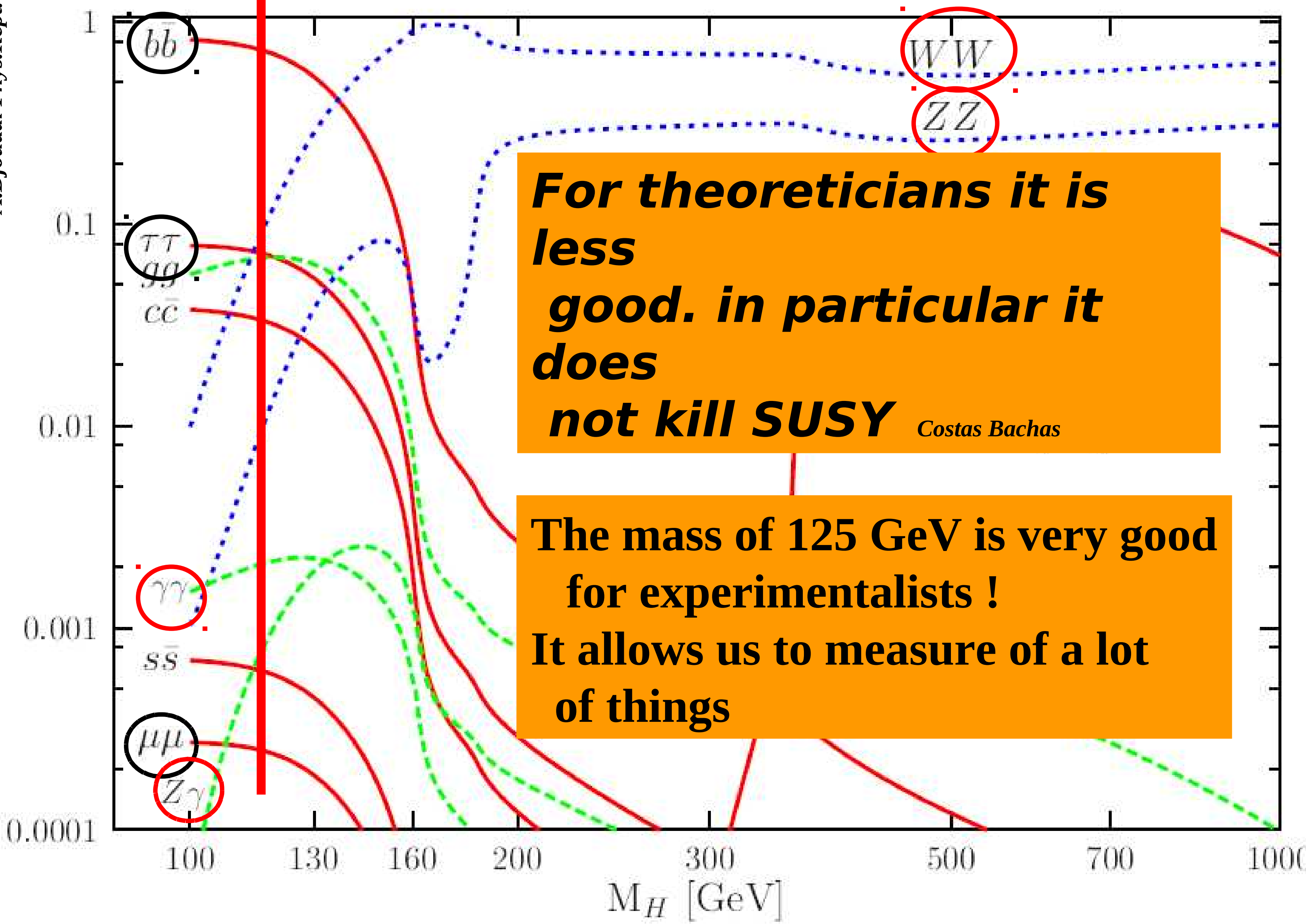
gg	5 %	NNNLO
VBF	<5%	NN(n)LO
WH,ZH	<5%	NNLO
ttH	10%	N(n)LO

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

channels with good mass resolution

The SM BEH boson

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



For theoreticians it is less good. in particular it does not kill SUSY *Costas Bachas*

The mass of 125 GeV is very good for experimentalists !
It allows us to measure of a lot of things

♪ *Historical introduction and setting the stage*

Spontaneous Symmetry Breaking

LHC and (mainly) ATLAS and CMS

H(125) discovery

♪ ***Results from Run 1 & Run 2 (& start of Run 3) (up to now) :***

- ***mainly H(125)***
- ***other physics (precision, searches)***

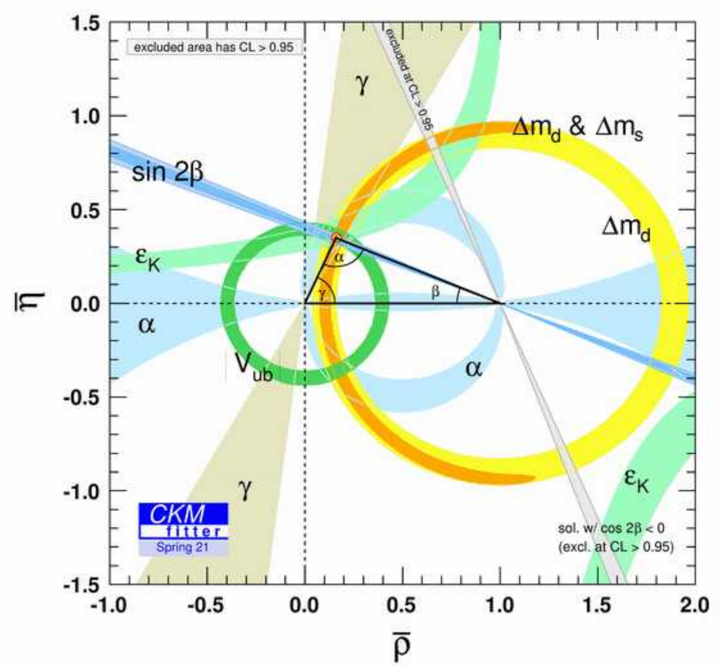
♪ *Future of LHC , Run 3 , HL-LHC*

♪ *Conclusions*

♪ *Backup*

A lot of LHC results are not discussed !

- *heavy ions*
- *di-bosons*
- *first observation of detection of ν produced at LHC (FASER , SND@LHC)*
- *a lot of SM results ..*
- *CP violation mesurements*
- *a lot of exotic and other things !!!*
- *exotic particles*



see

for the most recent results

♪ *Historical introduction and setting the stage*

Spontaneous Symmetry Breaking

LHC and (mainly) ATLAS and CMS

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♪ ***Results from Run 1 & Run 2 (& start of Run 3) (up to now) :***

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♪ *Backup*

The SM BEH boson executive summary

11 years after the discovery we have now a much clearer picture of the BEH boson properties

♠ It is spin 0 and its interactions with bosons are mainly CP-even

♠ We know its mass with close to 0.1% accuracy

BEH boson couples to mass ➔ couplings to be measured

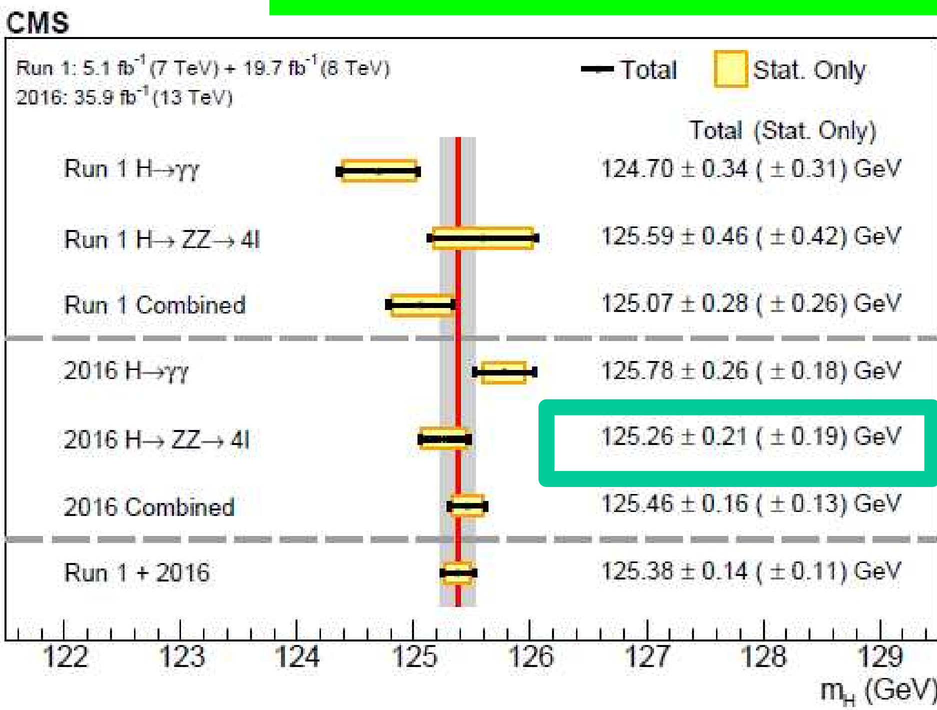
► Observation of all main production modes (ggF, VBF, VH, ttH)

Increasing precision in all measurements

► bosonic sector : inclusive measurement at ~10% precision
differential measurements probing extended phase space with increasing accuracy

► fermionic sector : 3rd generation (τ, t, b) established with uncertainties approaching ~ 20% level . Most promising channel for 2nd generation is $H \rightarrow \mu\mu$

The SM BEH boson The H mass



Phys.Lett.B 805 (2020) 135425

uncertainty on mass close to 0.1 %

Remember ATLAS has an uncertainty on W mass of 19 MeV *Eur.Phys.J. C78 (2018) no.2, 110*

note that $\Delta m_H = 0.1$ GeV $\rightarrow \Delta(BR(H\rightarrow ZZ)) / BR(H\rightarrow ZZ) \sim 1\%$

At longer term uncertainty will be dominated by 4l

(for $H\rightarrow \gamma\gamma$: need to extrapolate from e to γ !)

ATLAS

($H\rightarrow ZZ^*$ Run1+Run2 @ 139 fb^{-1})

$m_H = 124.94 \pm 0.18$ GeV

arXiv:2207.00320

Some definitions

1

definition of μ (signal strength)

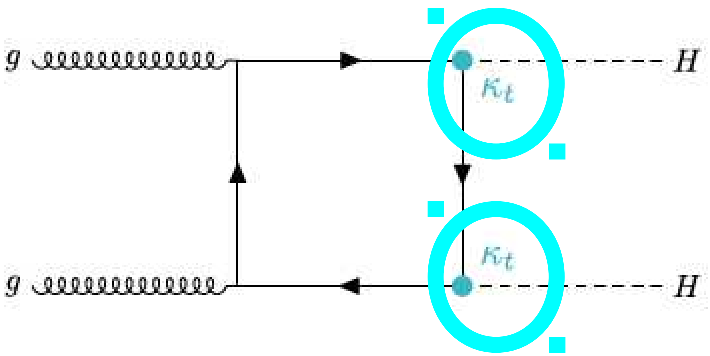
$$\mu = (\sigma \,.\, BR) \,/\, (\sigma \,.\, BR)_{SM}$$

called ***signal strength***

2

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}.$$

(coupling modifiers)



The Higgs boson Width

©C.Arcangeletti LHCP2023

Nature Physics **18**, 1329–1334 (2022)
arXiv:2304.01532v1

SM Higgs width Γ_H=4.1 MeV → experimental resolution O(1-2 GeV)

⇒ no direct measurement

Indirect measurement from the ratio of the on-shell/off-shell Higgs boson production

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

$$\Longrightarrow \frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV @68% C. L.

CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV @68% C. L.

First evidence of **off-shell** Higgs boson production

ATLAS: $\mu_{\text{off-shell}} = 1.1 \pm 0.6$ (3.3 σ)

CMS: $\mu_{\text{off-shell}} = 0.74^{+0.56}_{-0.38}$ (3.6 σ)

The Higgs boson invisible decays

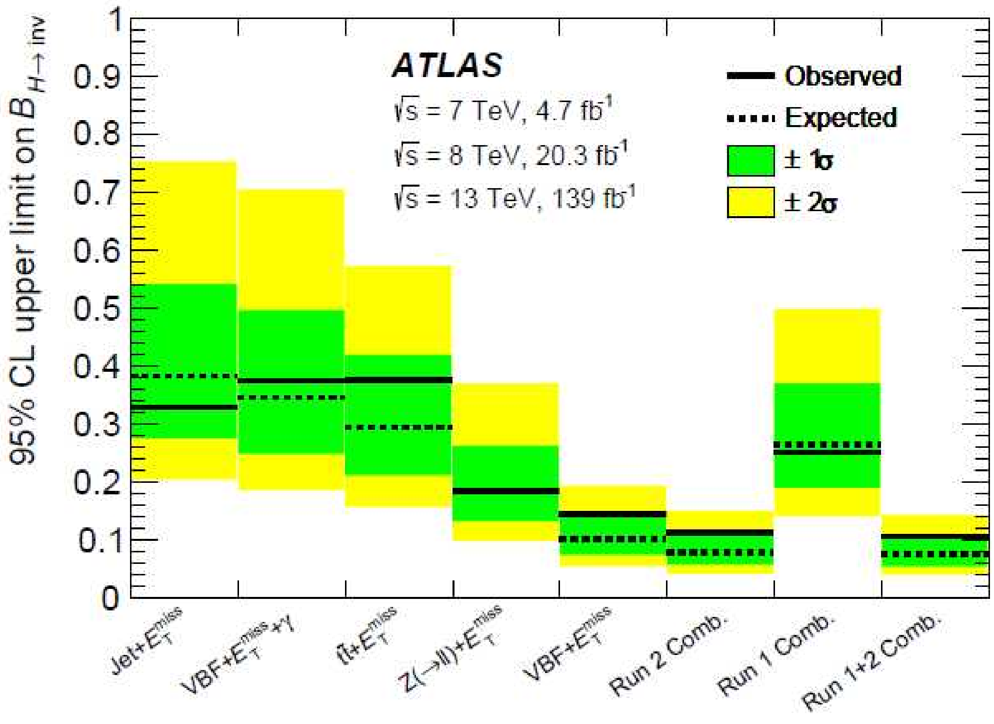
©C.Arcangeletti LHCP2023

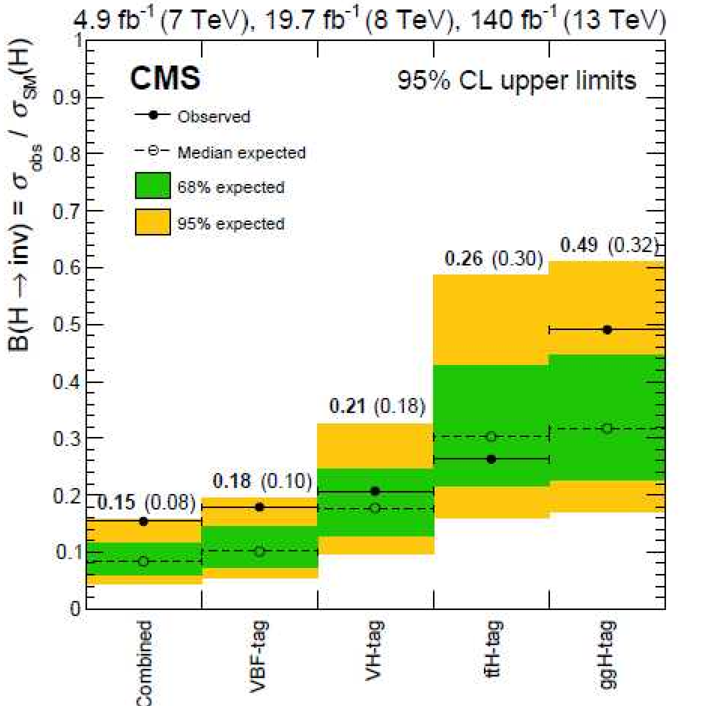
- Probe possible Higgs decay in WIMPs (Dark Matter candidates)
  - Presence of missing transverse momentum (E_T^{miss}) in the interaction

- SM expectation BR(H→inv) = 0.1% (given by ZZ*→4ν)

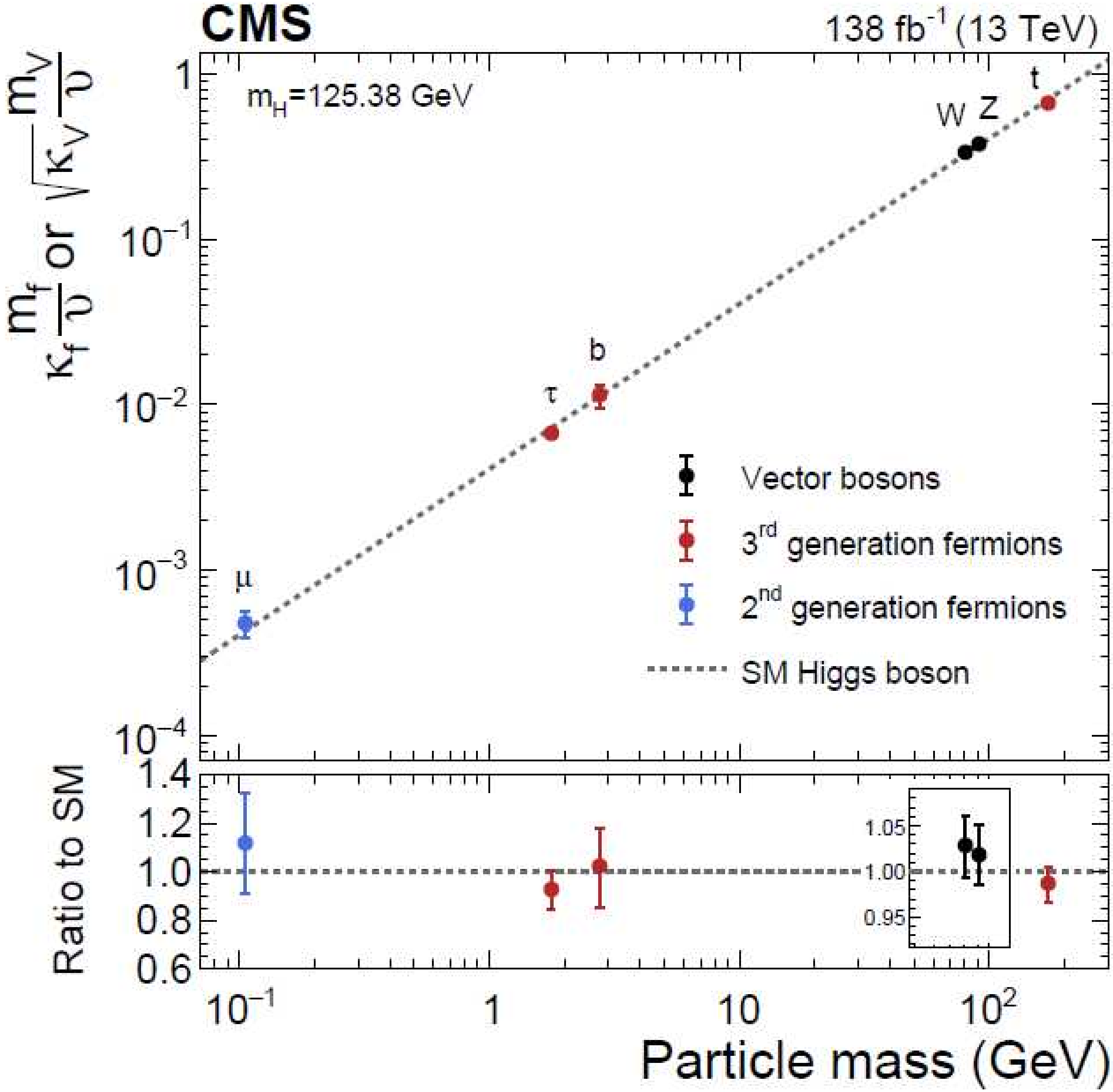
ATLAS: BR(H→inv)< 0.107 at 95% CL (0.077 expected) arXiv:2301.10731

CMS: BR(H→inv)< 0.15 at 95% CL (0.08 expected) arXiv:2303.01214



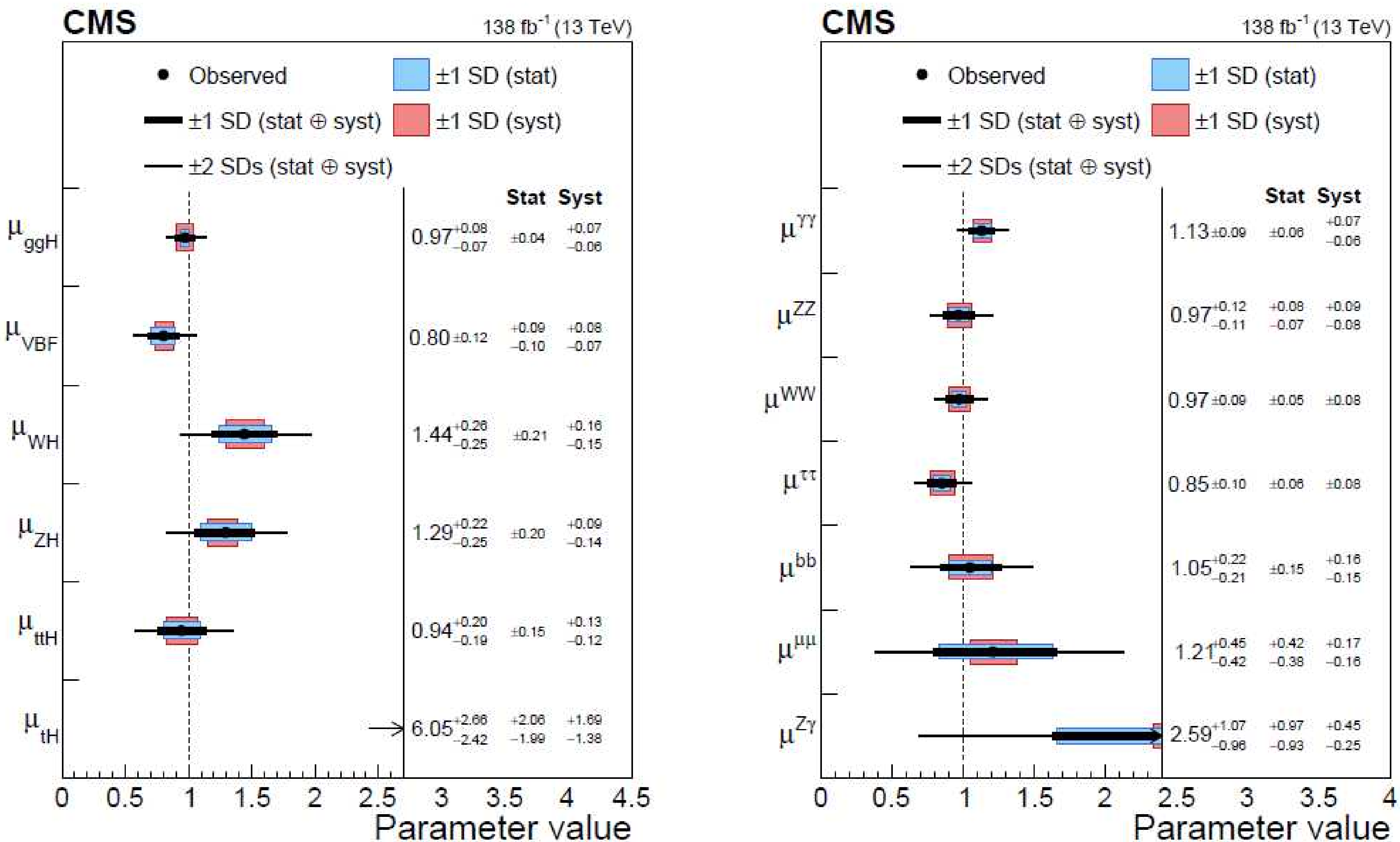


Nature 607 (2022) 7917, 60-68



Nature 607 (2022) 7917, 60-68

A lot of H couplings measurements !



The SM BEH boson $H \to Z\gamma$

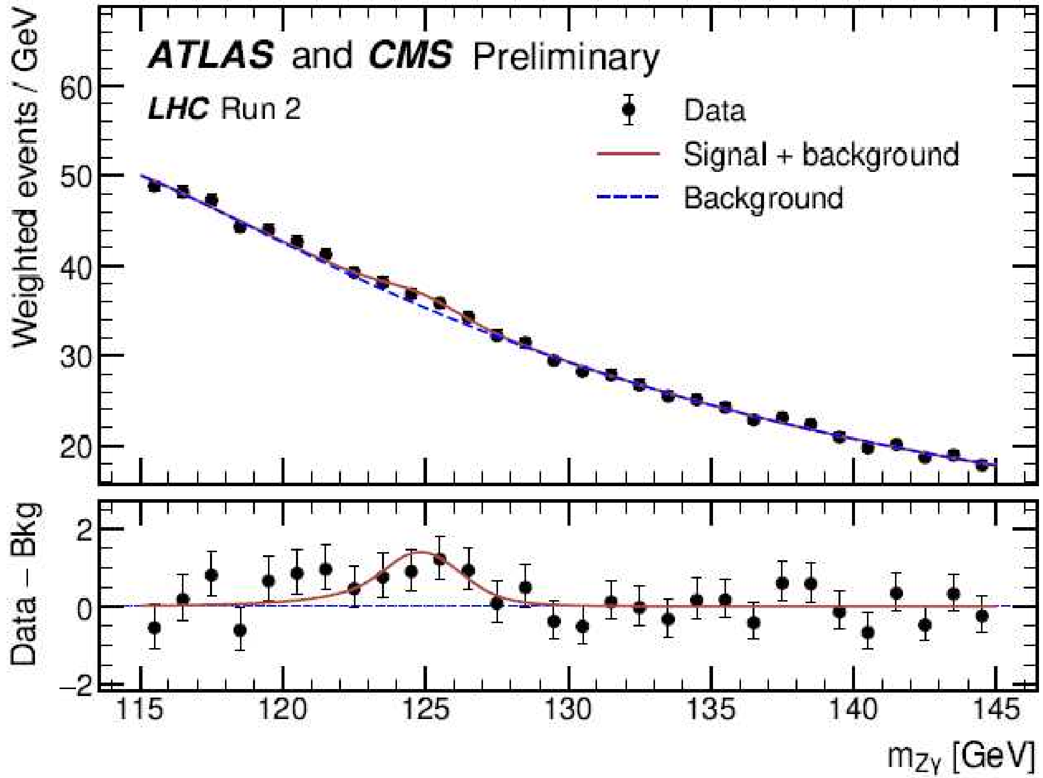
ATLAS-CONF-2023-025
CMS-PAS-HIG-23-002

Combination effort between ATLAS and CMS

$\mu_{sig} = 2.2 \pm 0.7$,

3.4σ

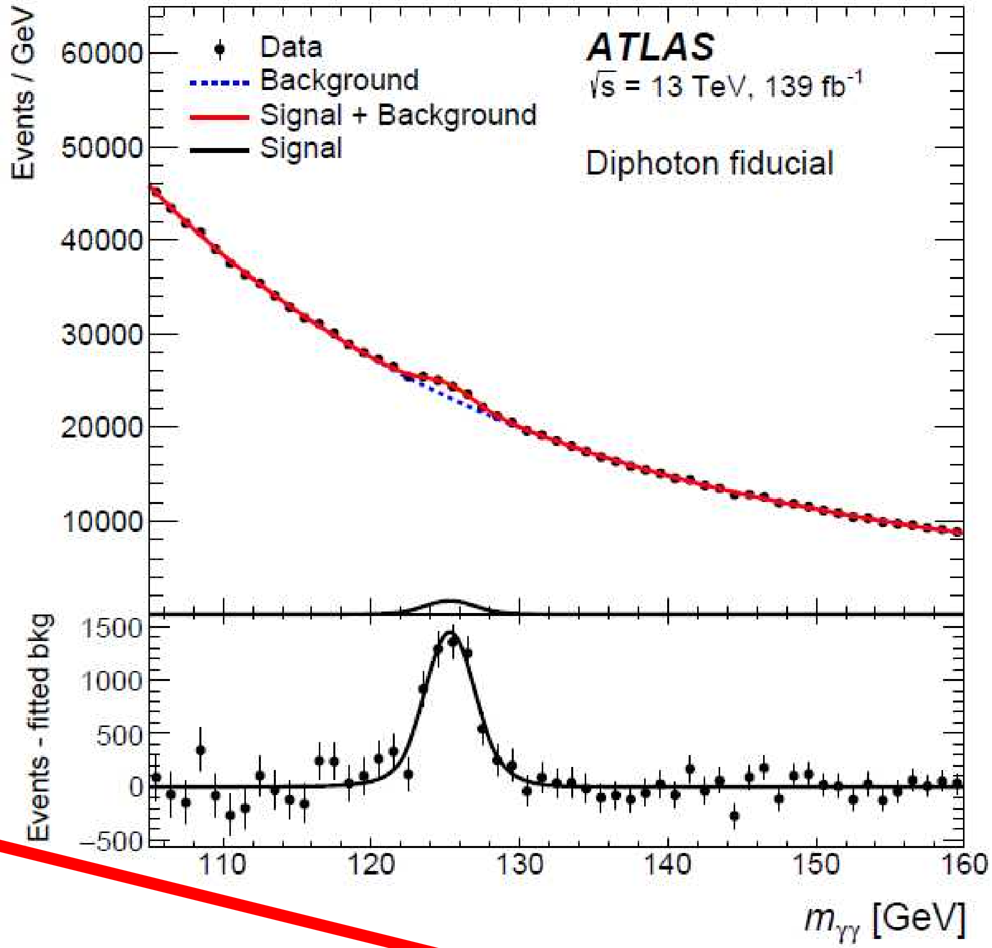
SM compatibility: $1.9\ \sigma$



The SM BEH boson $H \to \gamma\gamma$

Full Run-2

JHEP 08 (2022) 027

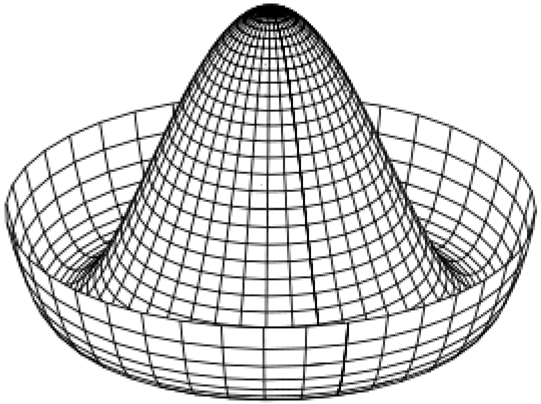


syst (background modelling + energy resolution + …. = stat !

$$\sigma_{\text{fid}} = 67 \pm 5\,(\text{stat.}) \pm 4\,(\text{sys.})\ \text{fb} = 67 \pm 6\ \text{fb}$$

64.2 ± 3.4 fb = prediction

Search for a pair of BEH bosons



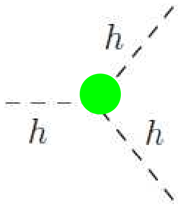
After discovering the Higgs boson, the ultimate probe of the Standard Model is to fully measure the Higgs potential.

$\Phi \rightarrow v + h$

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

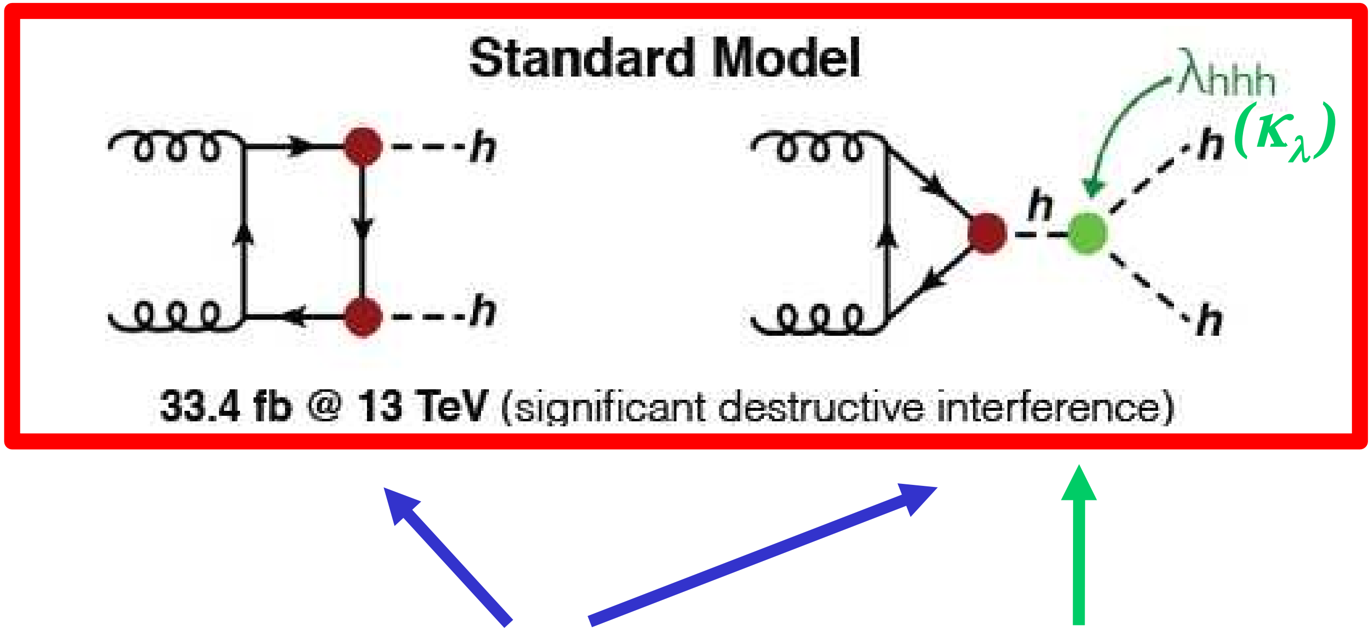
mass term $\frac{1}{2} m_h^2 h^2$

self coupling terms



Higgs potential maybe related to EW baryogenesis

Search for a pair of BEH bosons

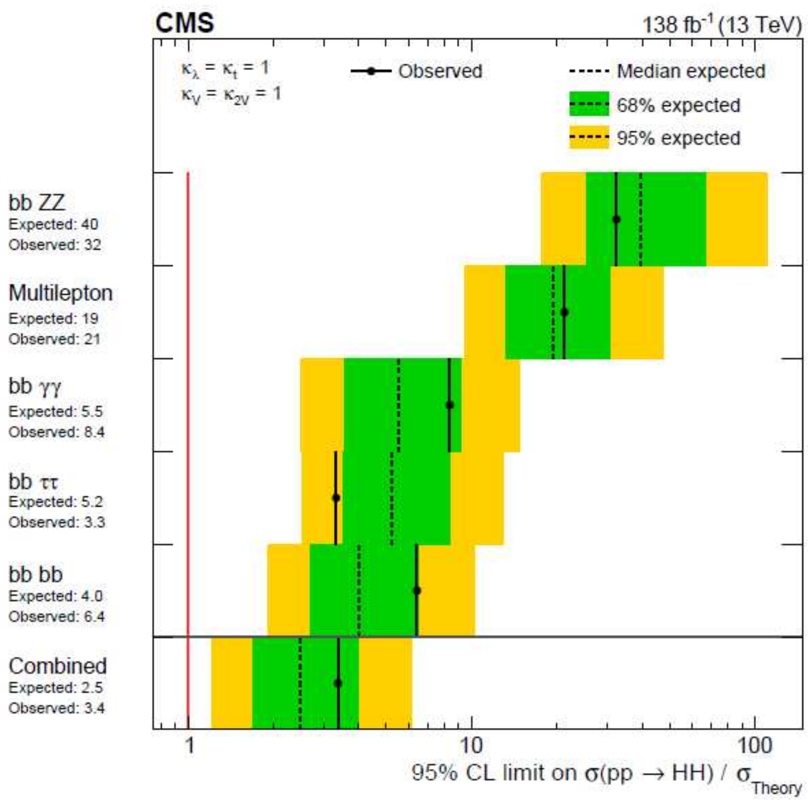


2 steps : measure h pairs μ_{hh} measure κ_λ

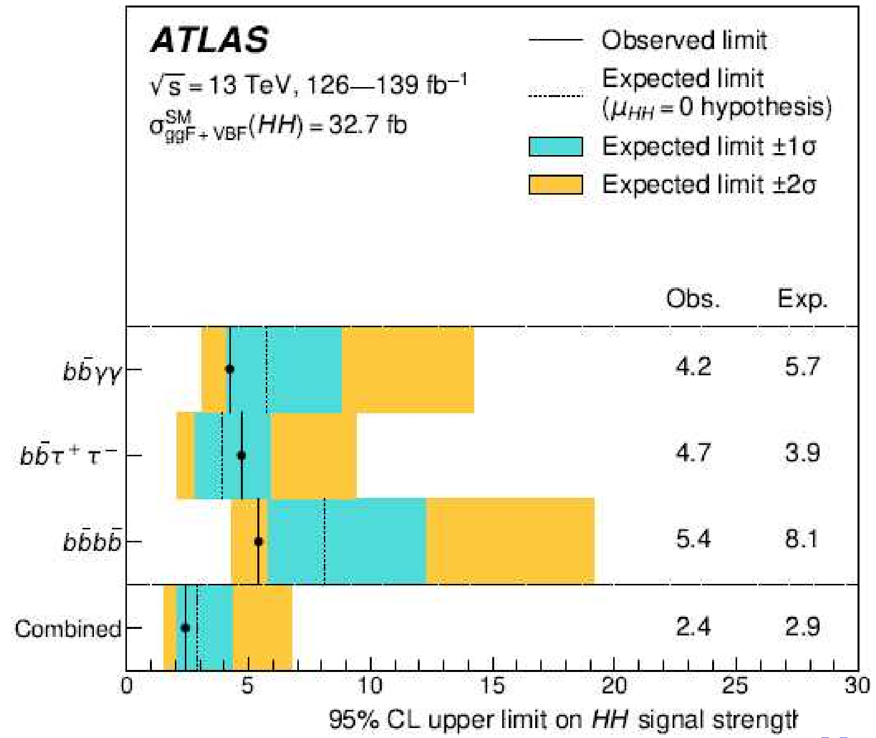
Search for a pair of BEH bosons

Nature 607 (2022) 7917, 60-68

Phys.Lett.B 843 (2023) 137745



μ_{hh}



μ_{hh}

ATLAS: combination HH+H

$-0.4 < \kappa_\lambda < 6.3$ @ 95 % C.L.

CMS combination HH

$-1.24 < \kappa_\lambda < 6.49$ @ 95 % C.L.

♪ Historical introduction and setting the stage

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LHC and (mainly) ATLAS and CMS

H(125) discovery

♪ Results from Run 1 & Run 2 (& start of Run 3) (up to now) :

- ***mainly H(125)***
- ***other physics (precision, searches)***

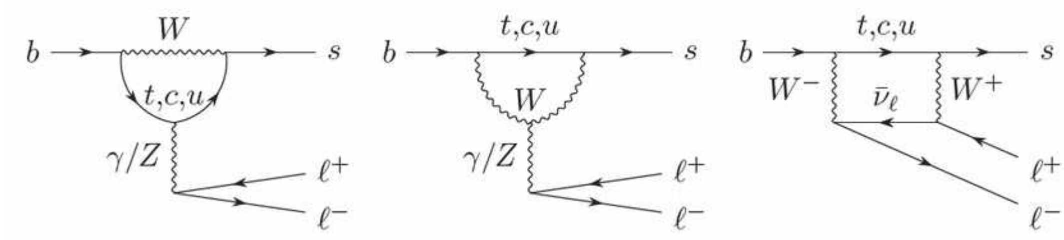
♪ Future of LHC , Run 3 , HL-LHC

♪ Conclusions

♪ Backup

Test of lepton universality in $b \to s\ell^+\ell^-$ decays

arXiv:2212.09152v1 arXiv:2212.09153v1



full runs 1 and 2

- e and μ acceptance very different in LHCb, unique backgrounds only for electrons
- Exploit normalisation via J/ψ

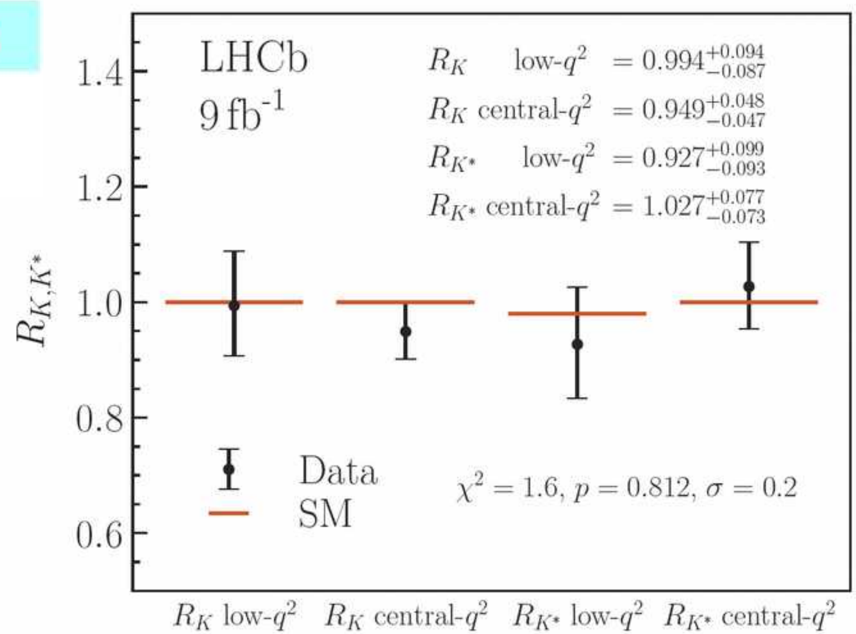
$$R_{(K,K^*)} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to e^+e^-))}$$

Results consistent with SM predictions

Shift wrt to previous R(K) central-q^2

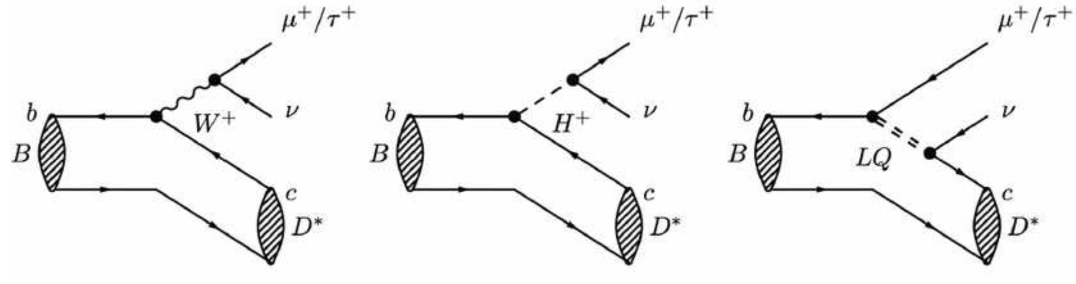
Nature Physics 18 (2022) 277

- ➡ tighter electron PID reduce hadronic backgrounds
- ➡ modelling of the remaining contribution
- ➡ statistical component (small)



Charged $b \to c\ell\nu$ transitions
lepton universality μ τ

arXiv:2302.02886v1
arXiv:2305.01463v1



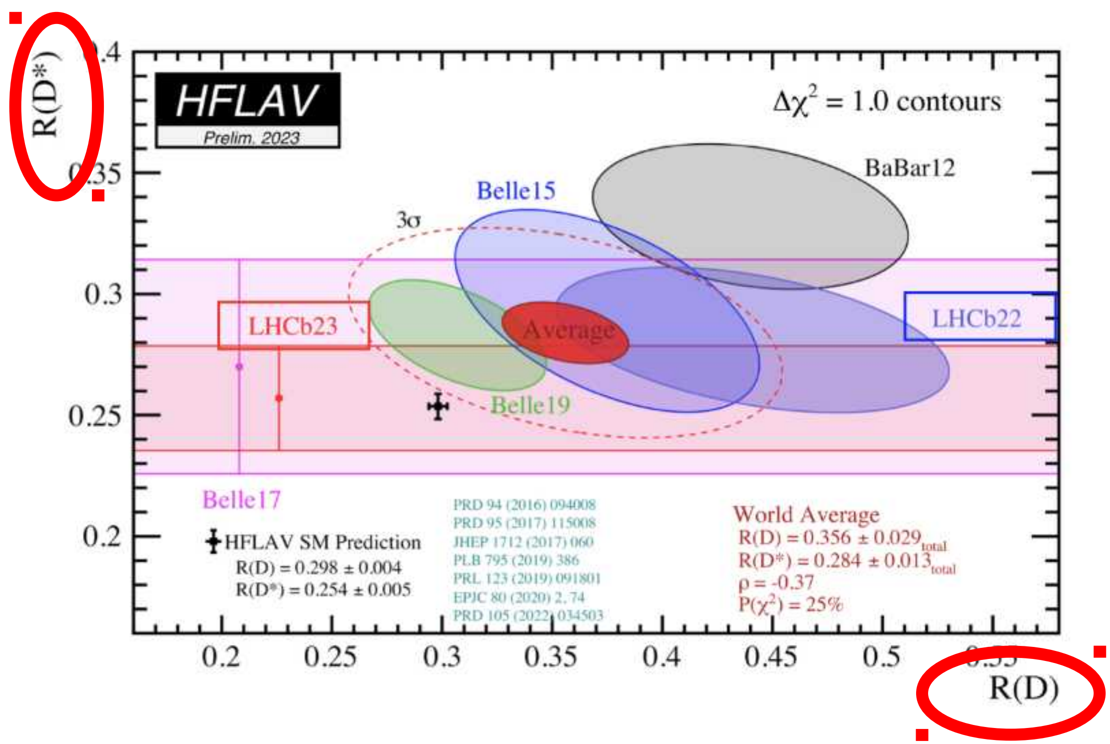
$$\mathscr{R}(H_c) = \frac{\mathscr{B}(H_b \to H_c \tau \nu_\tau)}{\mathscr{B}(H_b \to H_c \mu \nu_\mu)}$$

$H_b = B^0, B_s^0, B^+, B_c^+, \Lambda_b^0$

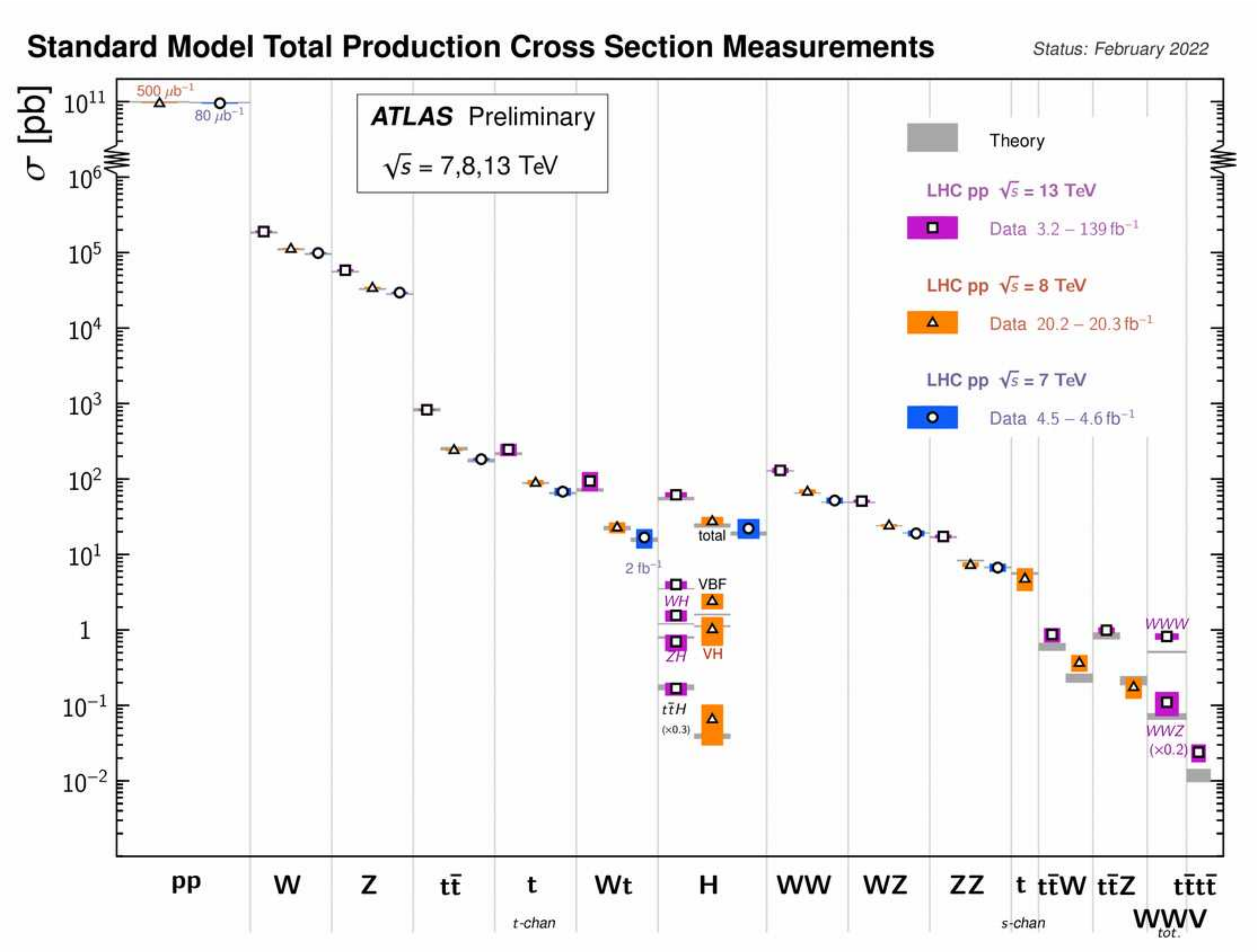
$H_c = D^0, D^{*(0,+)}, D^+, D_s^+, \Lambda_c^+, J/\psi$

Two modes being studied by LHCb: muonic and hadronic taus

a persisting tension with SM ~ 3.1 σ



ATLAS and CMS SM results

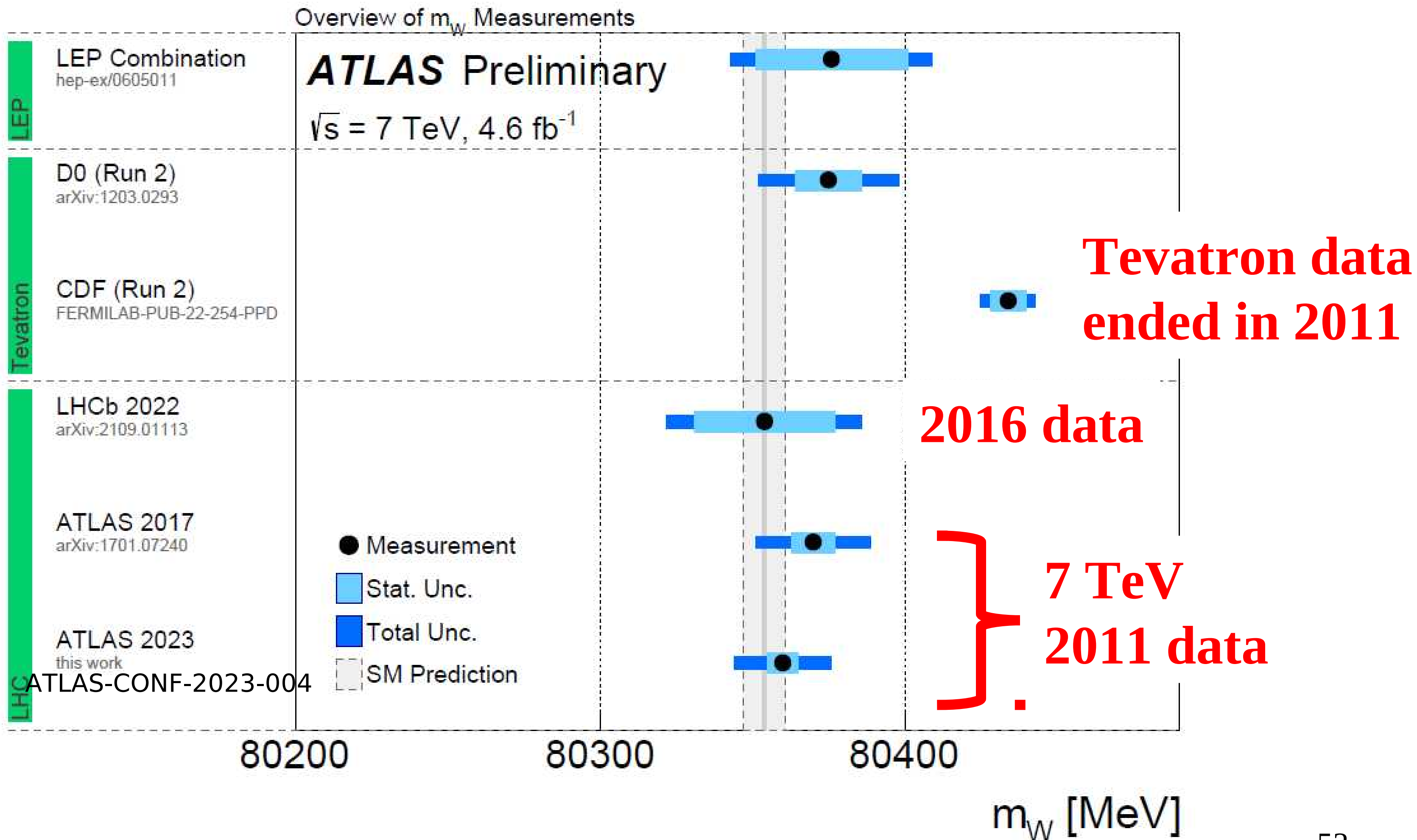


Very good agreement between SM and theory

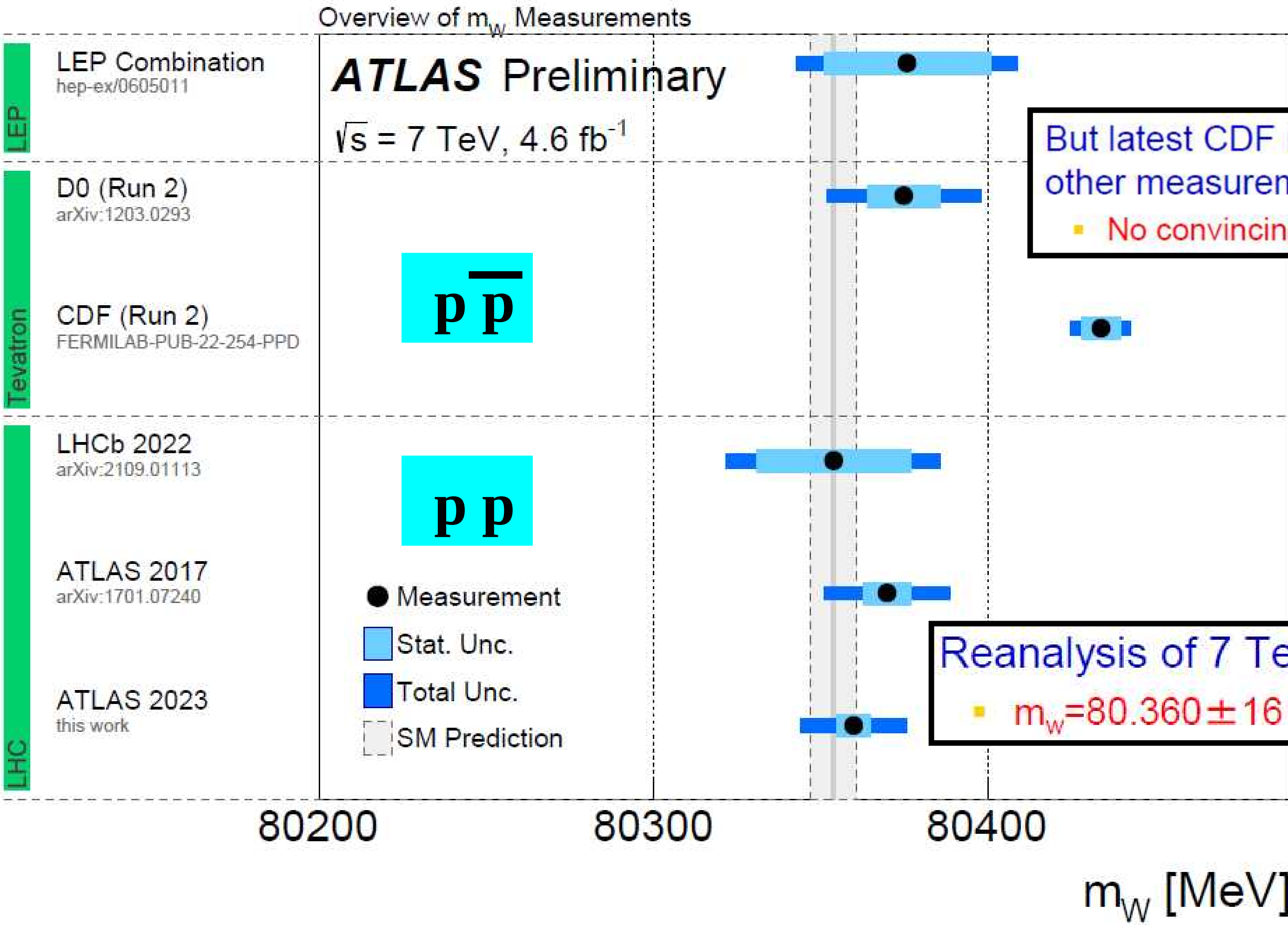
W mass m_W

One wants to have measurements with uncertainties close to the results of the EW fit $m_W = 80354 \pm 7$ ***MeV***

arXiv:1803.01853



W mass m_W



But latest CDF m_W strongly disagrees with other measurements and with SM

- No convincing explanation so far

Reanalysis of 7 TeV data, updated PDFs

- m_W=80.360±16 MeV

arXiv:1701.07240

W mass m_W

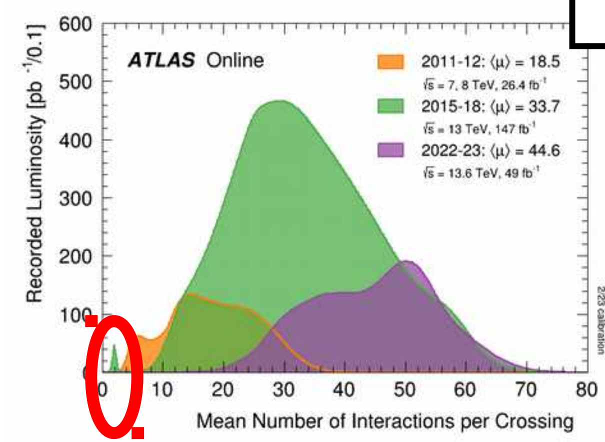
a lot of systematic uncertainties !

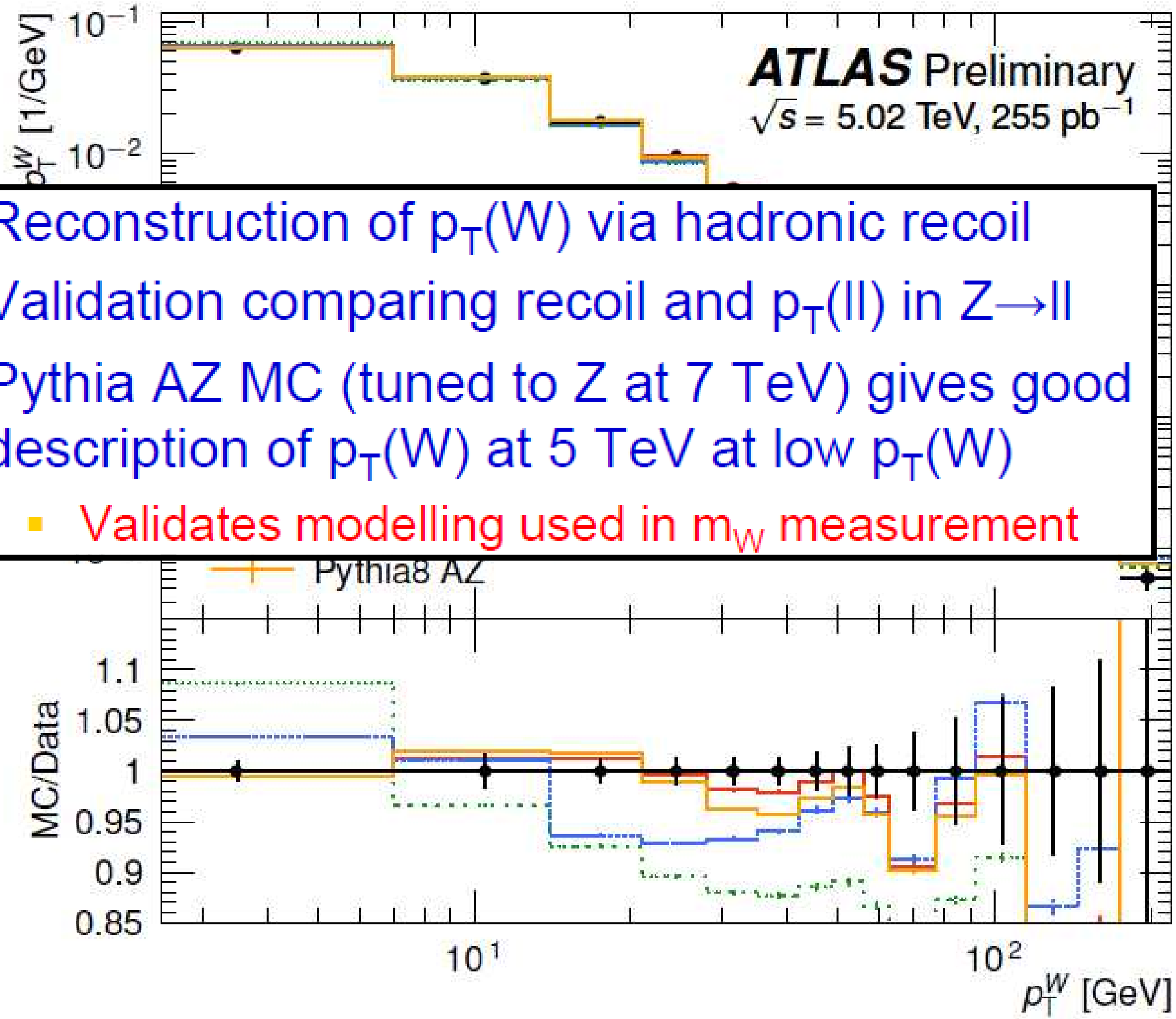
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Improvement : new direct measurement of $p_T(W)$ with low pileup samples at $\sqrt{s}$=5 and 13 TeV

ATLAS-CONF-2023-028

- Reconstruction of $p_T(W)$ via hadronic recoil
- Validation comparing recoil and $p_T(ll)$ in $Z\rightarrow ll$
- Pythia AZ MC (tuned to Z at 7 TeV) gives good description of $p_T(W)$ at 5 TeV at low $p_T(W)$
  - Validates modelling used in m_W measurement

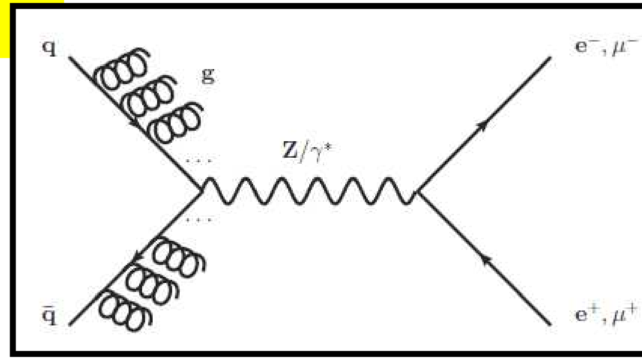


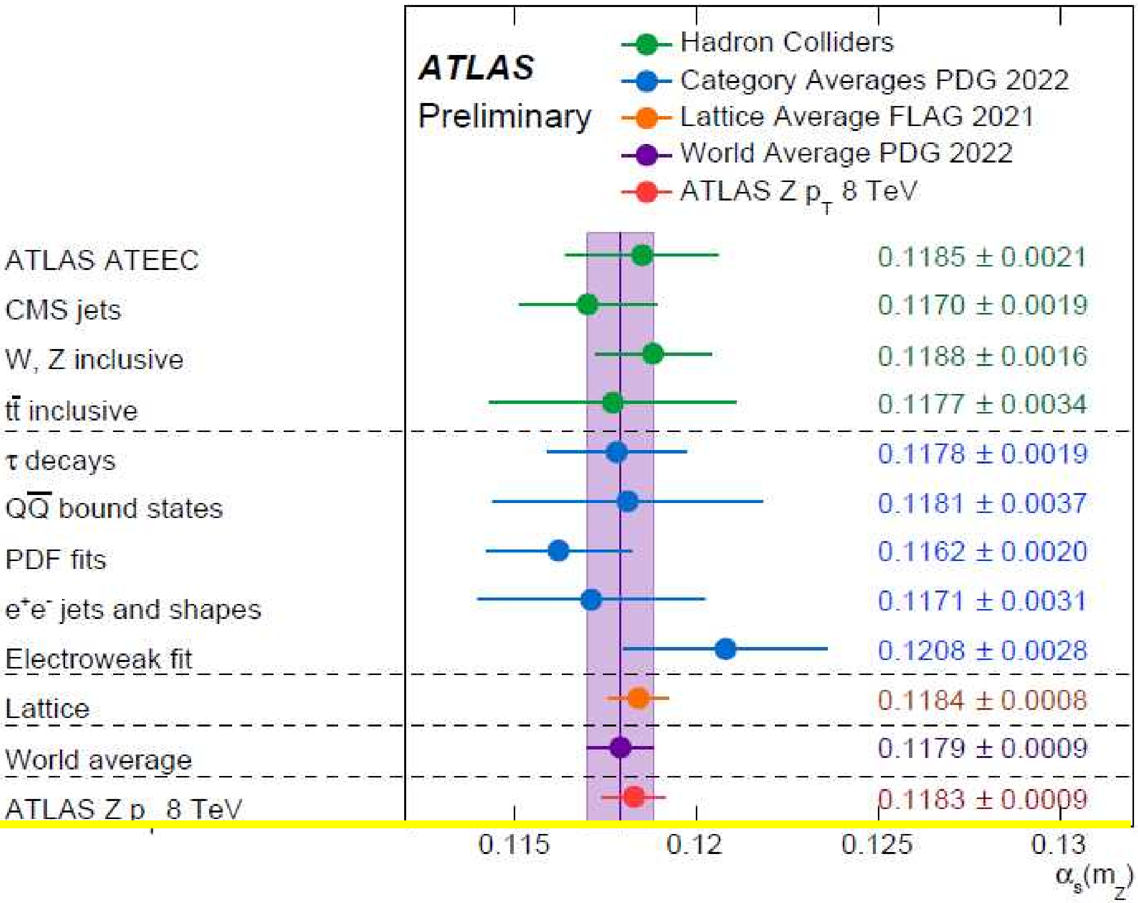


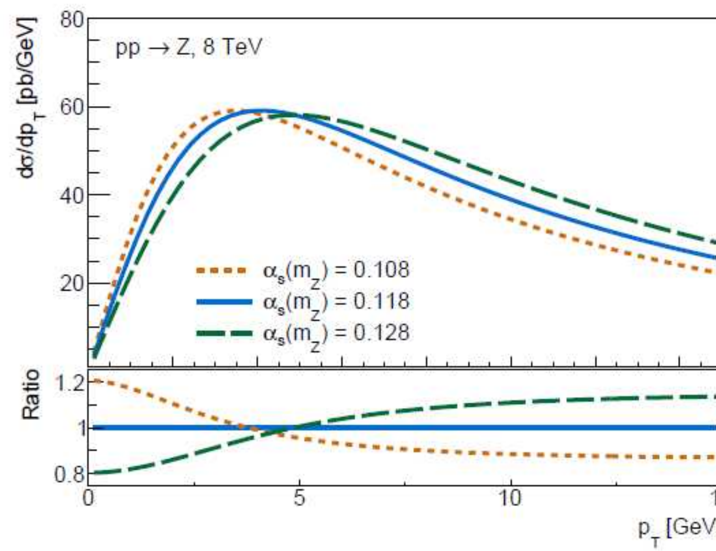
Measurement of α_s with Z bosons at 8 TeV

ATLAS-CONF-2023-01

Using Z-boson p_T distribution in full phase space of decay leptons, ATLAS has provided the most precise experimental determination of $\alpha_s(m_Z)$







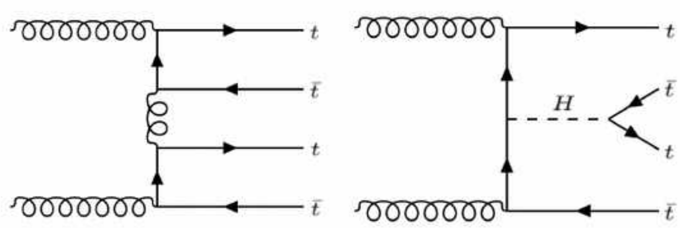
ATLAS and CMS observe simultaneous production of four top quarks

arXiv:2303.15061

IS PAS TOP-22-01

4 top quark production observed by ATLAS+CMS

Highest-threshold SM process



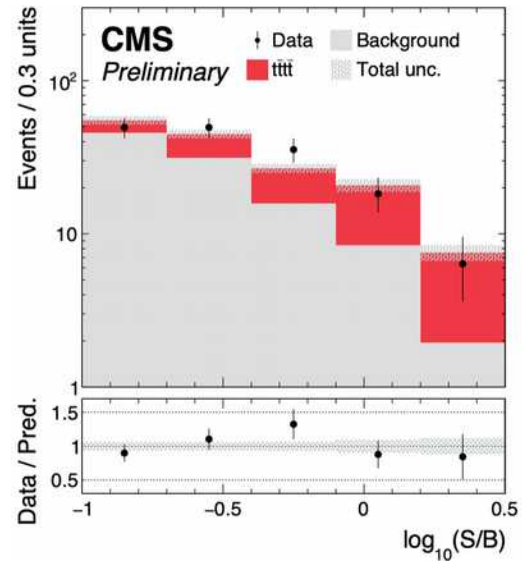
2nd generation full Run-2 analysis from both expts.

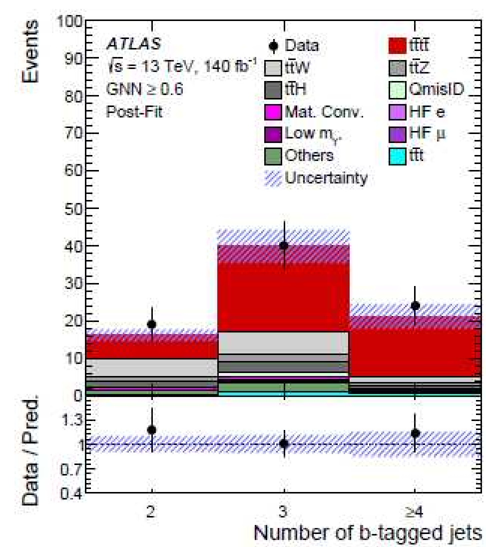
Focused on 2 same-sign leptons or 3+ leptons and large jet and b-jet multiplicity

Optimised selections, greater use of machine learning

	Obs	Exp	σ (fb)
ATLAS	6.1	4.3	$22.5^{+6.6}_{-5.5}$
CMS	5.6	4.9	$17.9^{+4.4}_{-4.0}$

Slight upward fluctuation on SM σ=12.0±2.4 fb





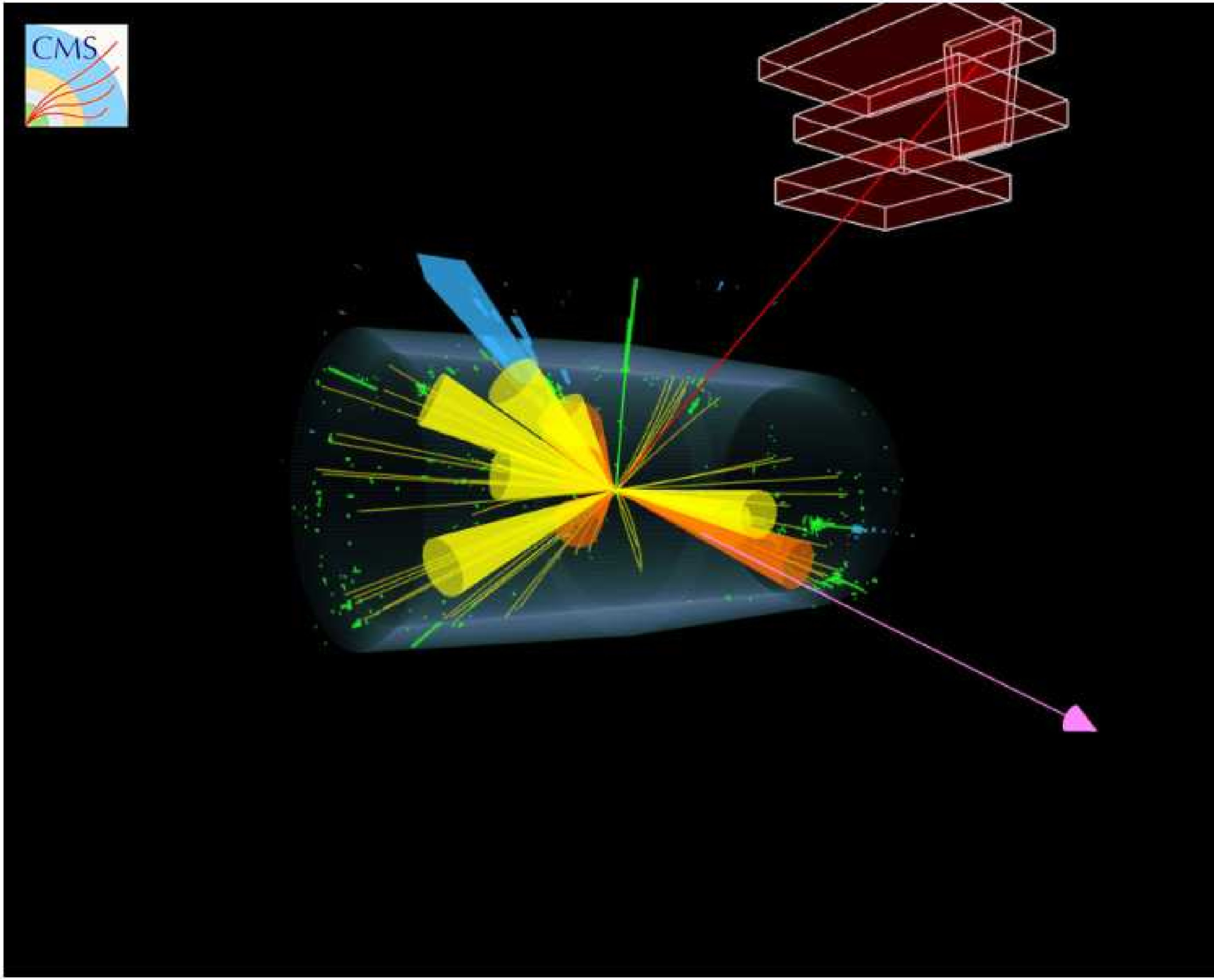
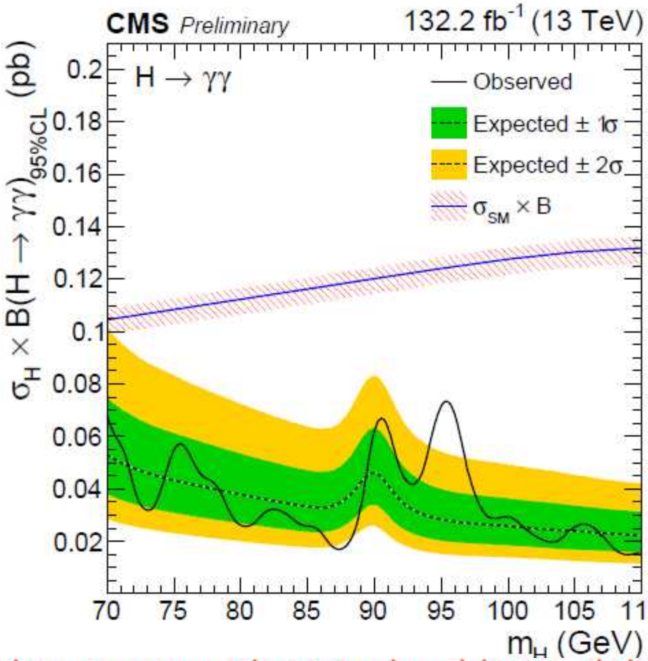


Figure 1: A four-top event candidate. Two W bosons decayed to leptons (an electron in green and a muon in red) and neutrinos, while the other two decayed to quarks that lead to jets (showers of strongly interacting particles). The jets identified as originating from b quarks are highlighted in orange. The missing transverse energy from the neutrinos is represented by the magenta line. You can view (zoom/rotate) the interactive event display on this separate page.

CMS PAS TOP-22-01

https://cms.cern/news/cms-observes-four-top-quark-production

Searches ATLAS CMS low mass γγ



CMS PAS HIG-20-002

- Modest excess with ~2.9σ local (1.3σ global) significance at $m_{\gamma\gamma}$=95.4 GeV, more data needed to conclude!

similar excess than previous analysis (with much less L)

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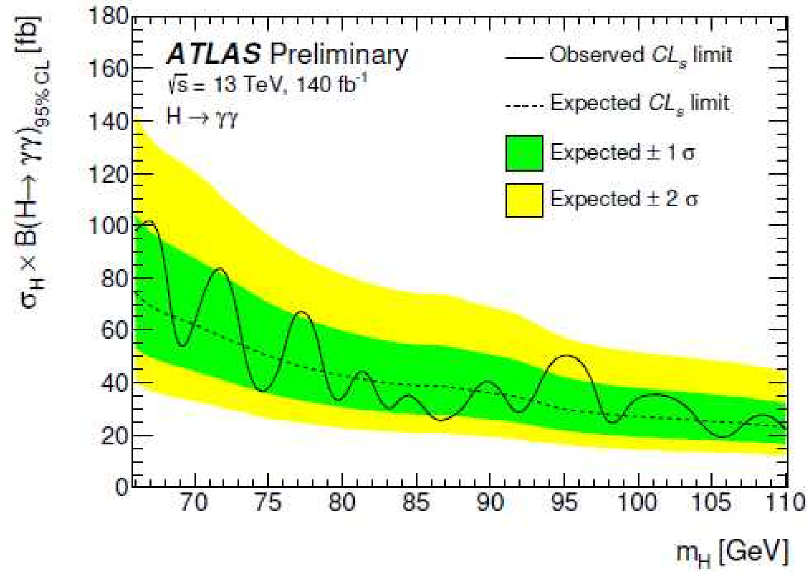
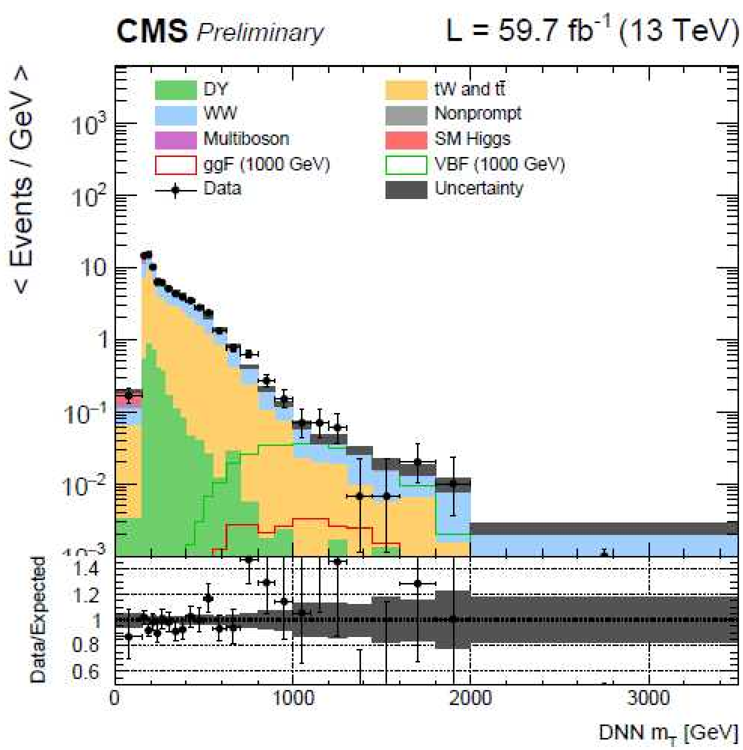
ATLAS-CONF-2023-035



For the model-dependent search, the largest deviation is observed for a mass of 95.4 GeV, corresponding to a local significance of 1.7σ.

souvenirs from LEP

Searches CMS high mass resonances decaying into W+W-



an effort should be made by the other experiment to validate or invalidate the excesses of the f irst

CMS PAS HIG-20-016

Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

Scenario	Mass [GeV]	ggF cross sec. [pb]	VBF cross sec. [pb]	Local signi. [σ]	Global signi. [σ]
SM f_{VBF}	800	0.16	0.057	3.2	1.7 ± 0.2
$f_{VBF} = 1$	650	0.0	0.16	3.8	2.6 ± 0.2
$f_{VBF} = 0$	950	0.19	0.0	2.6	0.4 ± 0.6
floating f_{VBF}	650	2.9×10^{-6}	0.16	3.8	2.4 ± 0.2

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- mainly H(125)
- other physics (precision, searches)

♪ **Future of LHC , Run 3 , HL-LHC**

♪ Conclusions

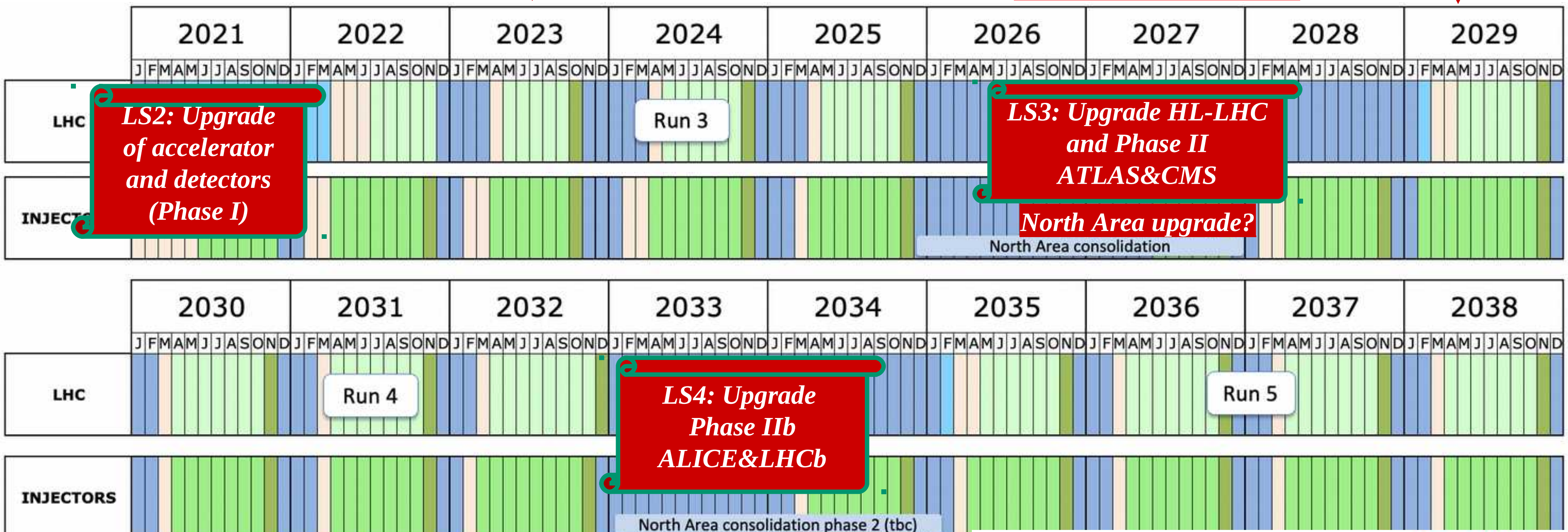
♪ Backup

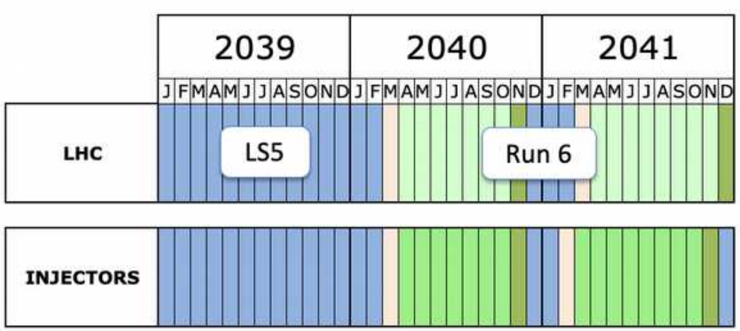
LHC timeline

today

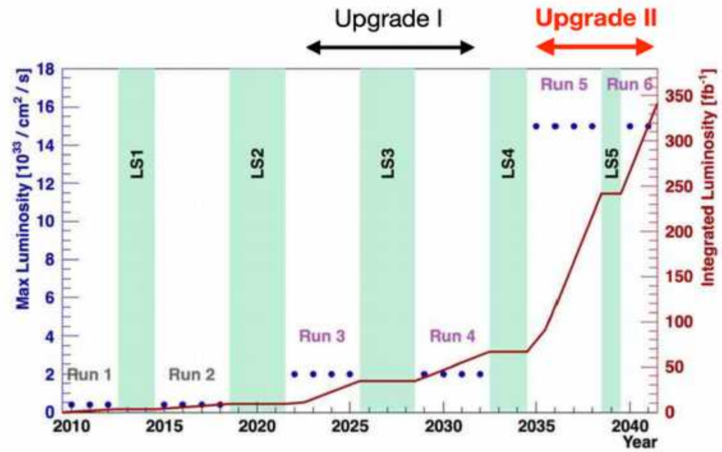
start HL-LHC

~ 450 fb^{-1}

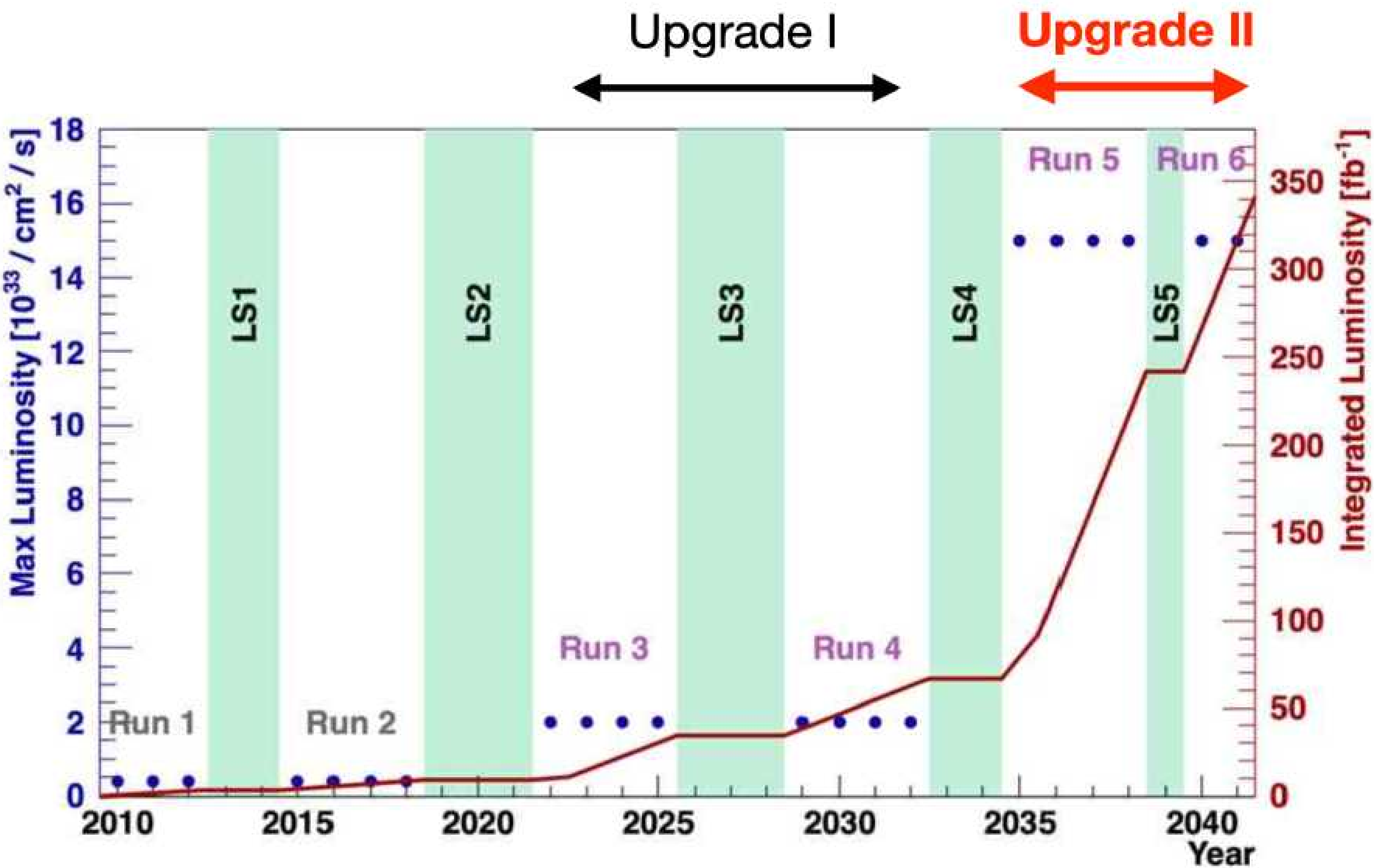




LHCb



~ 3000 to 4000 fb^{-1}

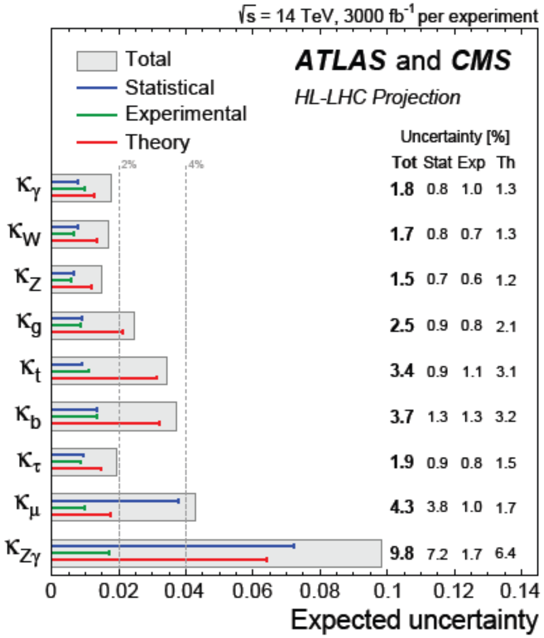


Upgrade I
Upgrade II
Max Luminosity [10^33 / cm^2 / s]
Integrated Luminosity [fb^-1]
Run 1
Run 2
Run 3
Run 4
Run 5
Run 6
LS1
LS2
LS3
LS4
LS5
Year
2010
2015
2020
2025
2030
2035
2040
0
2
4
6
8
10
12
14
16
18
50
100
150
200
250
300
350

It is very hard to predict, especially the future.

N.Bohr

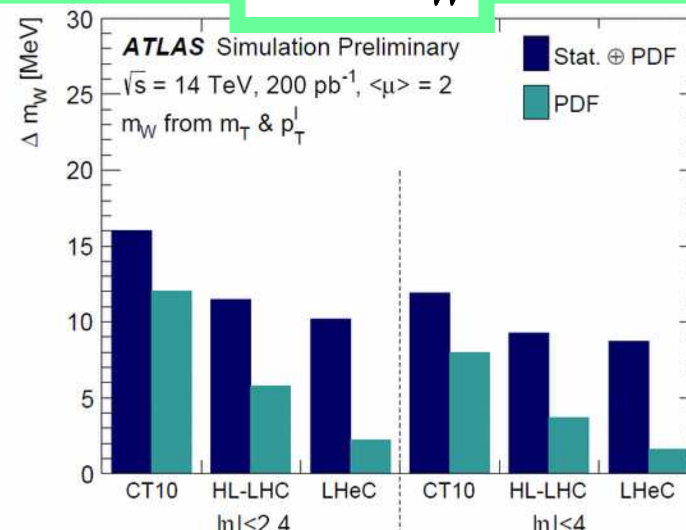
arXiv:1902.00134



$$\kappa_j^2 = \sigma_j / \sigma_j^{SM}$$

H

Δ m_W



ATL-PHYS-PUB-2018-026

will require special runs

Sensitivity to hh direct search

50% uncertainty on $\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{SM}}$

self coupling normalized to SM

3000 fb^{-1}

arXiv:1905.03764

HH

- ♪ *Historical introduction and setting the stage*
  - *Spontaneous Symmetry Breaking*
  - *LHC and (mainly) ATLAS and CMS*
  - *H(125) discovery*
- ♪ *Results from Run 1 & Run 2 (& start of Run 3) (up to now) :*
  - *mainly H(125)*
  - *other physics (precision, searches)*
- ♪ *Future of LHC , Run 3 , HL-LHC*
- ♪ ***Conclusions***
- ♪ *Backup*

- ***Fantastic Run-2 dataset , thanks to the outstanding performance of the LHC***

- ***During Run-3 emphasis on precision***

- ***< 5% of the data that will be delivered by HL-LHC are analysed $\Rightarrow$ a lot to do !***

Thank you for your attention

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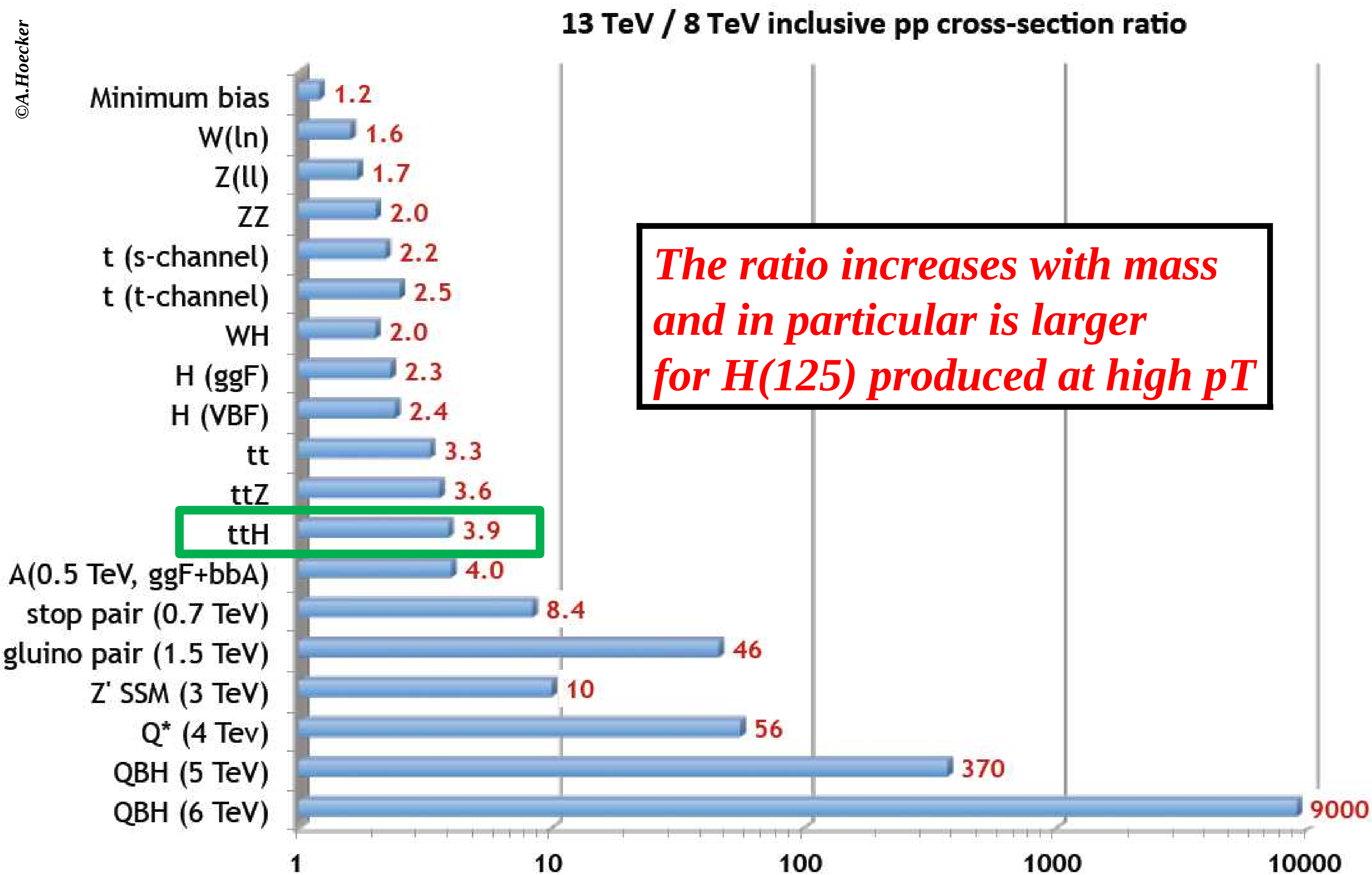
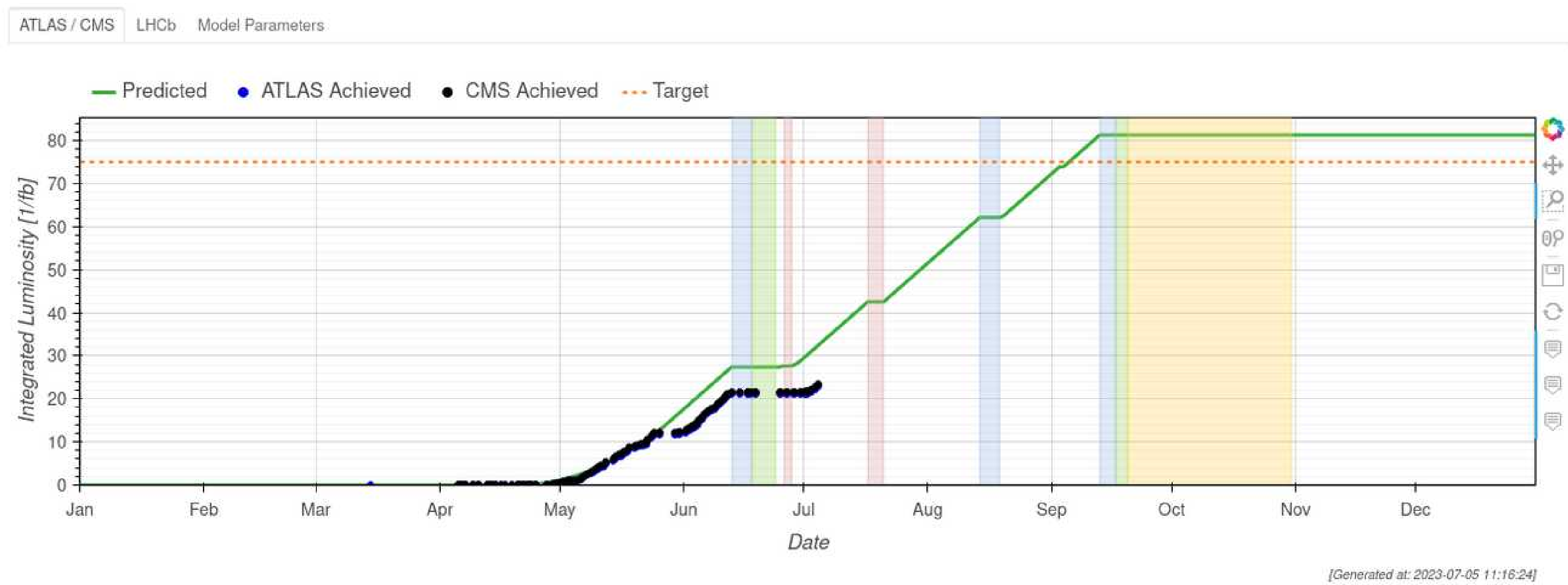
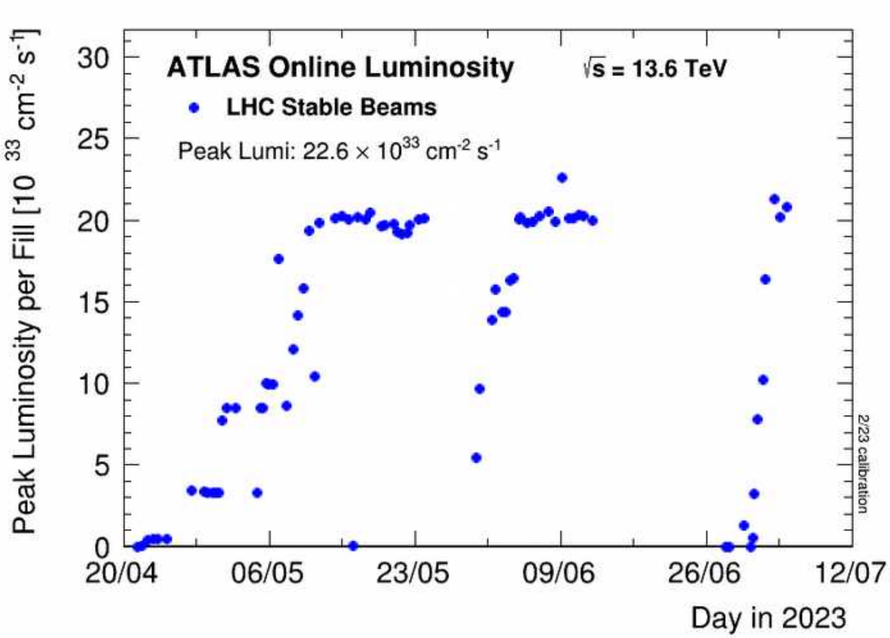
♪ ***Backup***

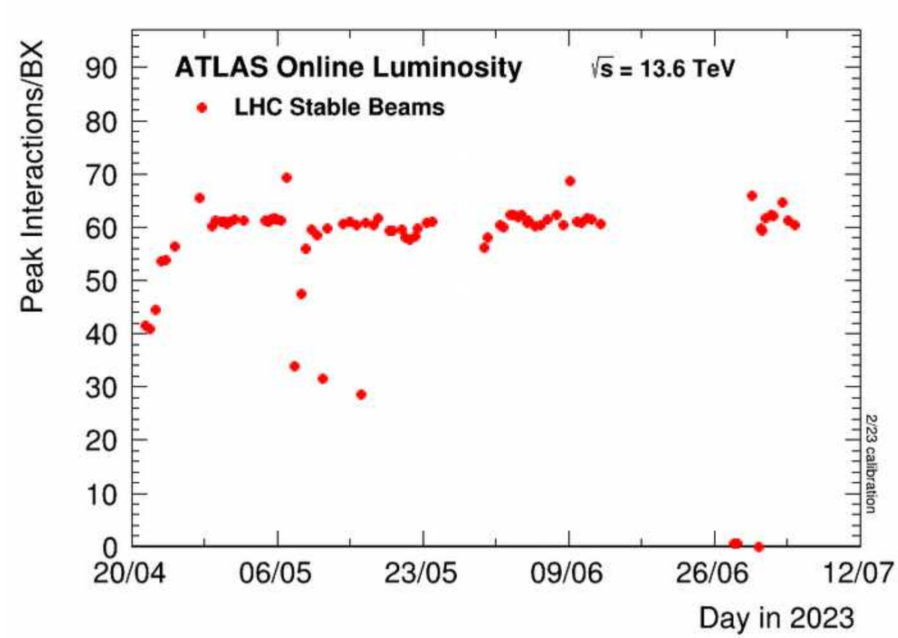

13 TeV / 8 TeV inclusive pp cross-section ratio
Minimum bias 1.2
W(ln) 1.6
Z(ll) 1.7
ZZ 2.0
t (s-channel) 2.2
t (t-channel) 2.5
WH 2.0
H (ggF) 2.3
H (VBF) 2.4
tt 3.3
ttZ 3.6
ttH 3.9
A(0.5 TeV, ggF+bbA) 4.0
stop pair (0.7 TeV) 8.4
gluino pair (1.5 TeV) 46
Z' SSM (3 TeV) 10
Q* (4 Tev) 56
QBH (5 TeV) 370
QBH (6 TeV) 9000
1
10
100
1000
10000
The ratio increases with mass
and in particular is larger
for H(125) produced at high pT

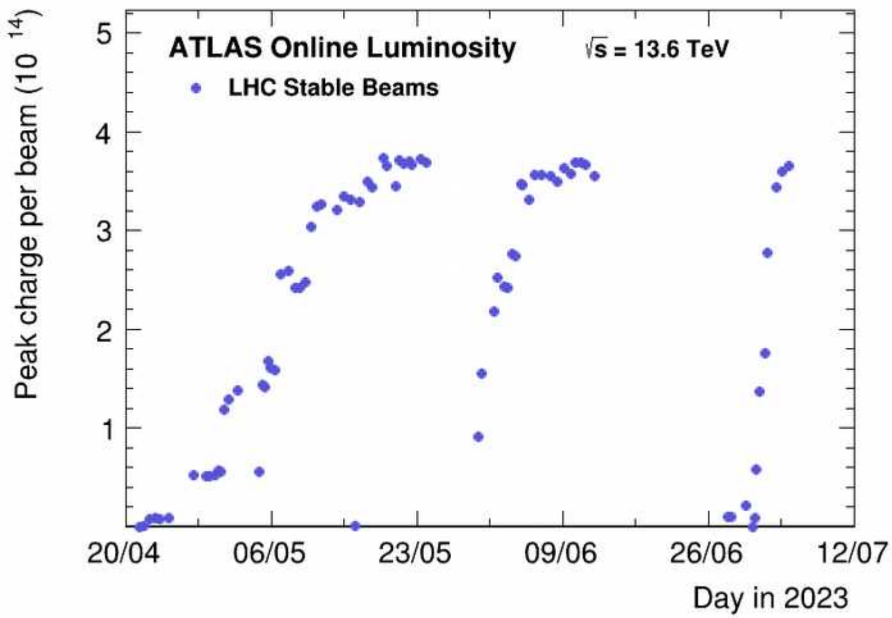
LHC 2023 Statistics

Schedule, Predicted and Achieved Luminosity

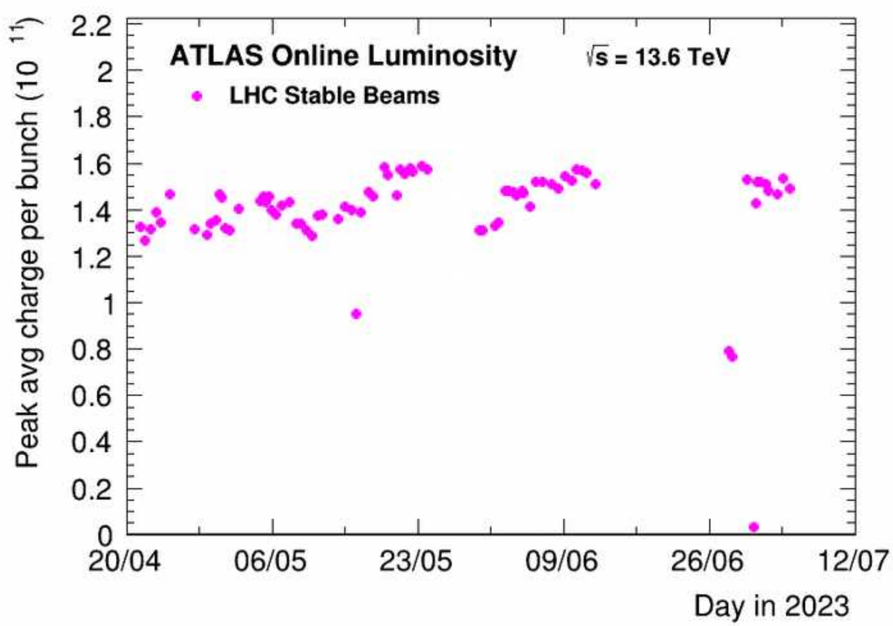



ATLAS Online Luminosity
√s = 13.6 TeV
LHC Stable Beams
Peak Lumi: 22.6 × 10^33 cm^-2 s^-1
Peak Luminosity per Fill [10^33 cm^-2 s^-1]
Day in 2023
2/23 calibration


ATLAS Online Luminosity
√s = 13.6 TeV
LHC Stable Beams
Peak Interactions/BX
Day in 2023
2/23 calibration

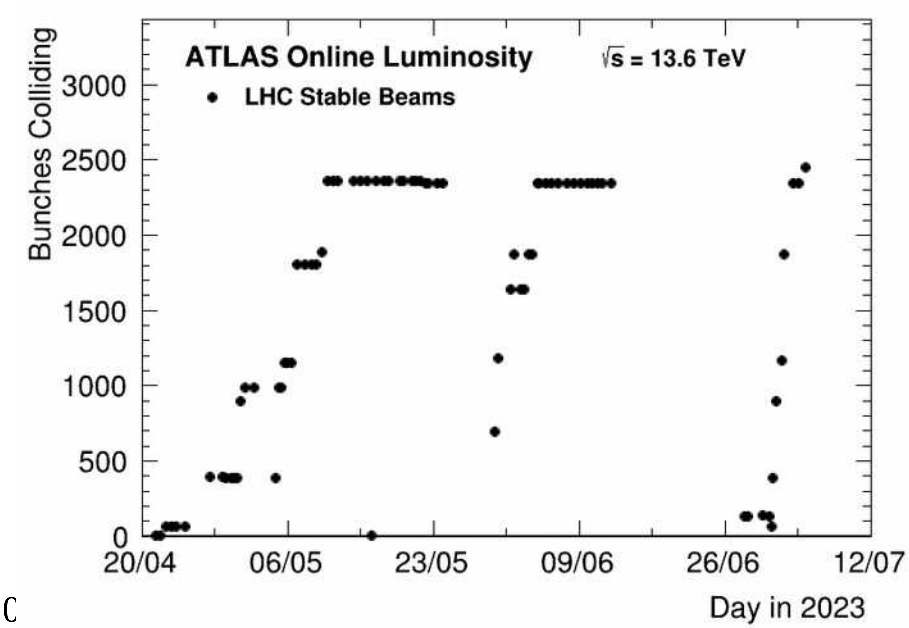


ATLAS Online Luminosity
√s = 13.6 TeV
LHC Stable Beams
Peak charge per beam (10 14)
5
4
3
2
1
20/04
06/05
23/05
09/06
26/06
12/07
Day in 2023

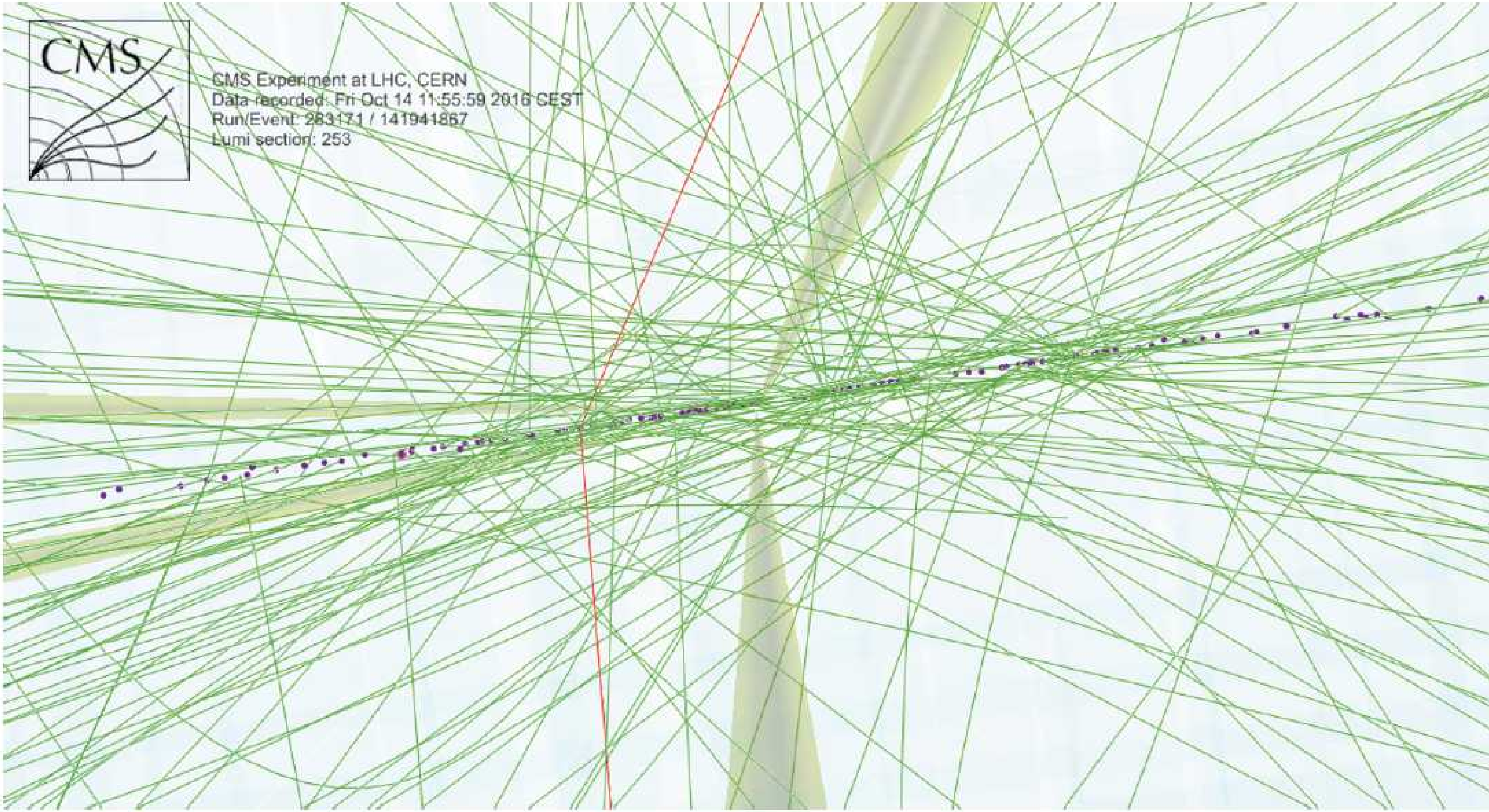


ATLAS Online Luminosity
√s = 13.6 TeV
LHC Stable Beams
Peak avg charge per bunch (10 11)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
20/04
06/05
23/05
09/06
26/06
12/07
Day in 2023

0



ATLAS Online Luminosity
√s = 13.6 TeV
LHC Stable Beams
Bunches Colliding
3000
2500
2000
1500
1000
500
0
20/04
06/05
23/05
09/06
26/06
12/07
Day in 2023



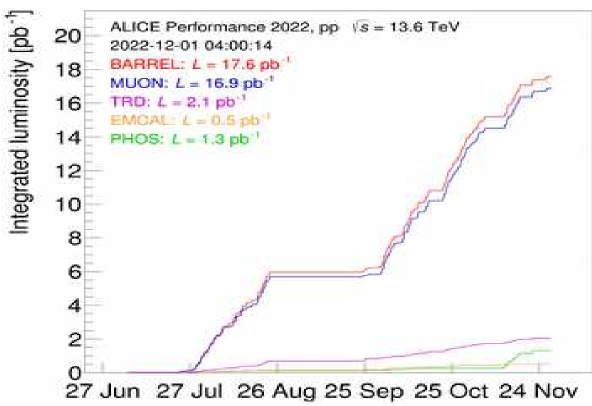
Z+jets event in high PU data recorded in 2016, with 103 number of vertices, tracks of $p_T > 1.5$ GeV are shown.

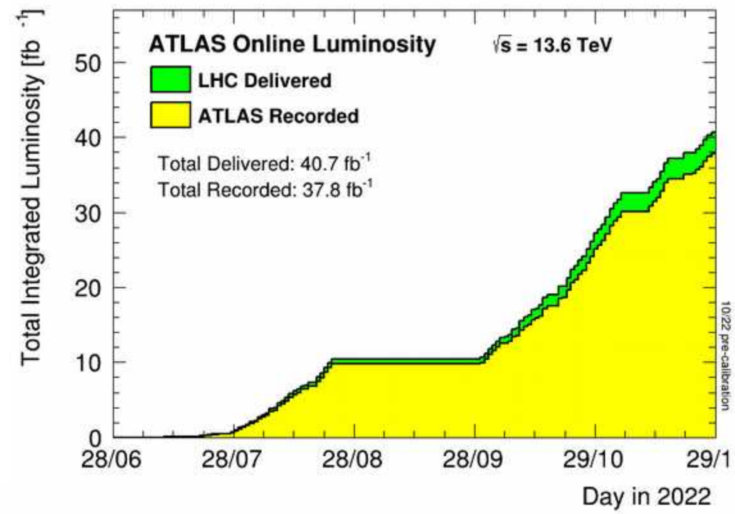
Successful LHC Run 2022

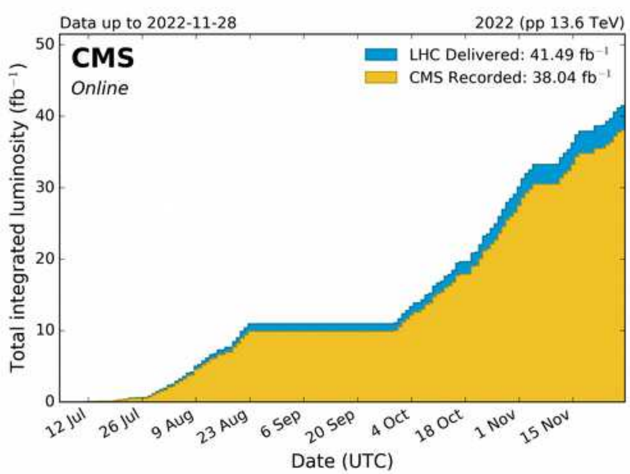
About 40 fb^{-1} pp luminosity delivered to ATLAS & CMS

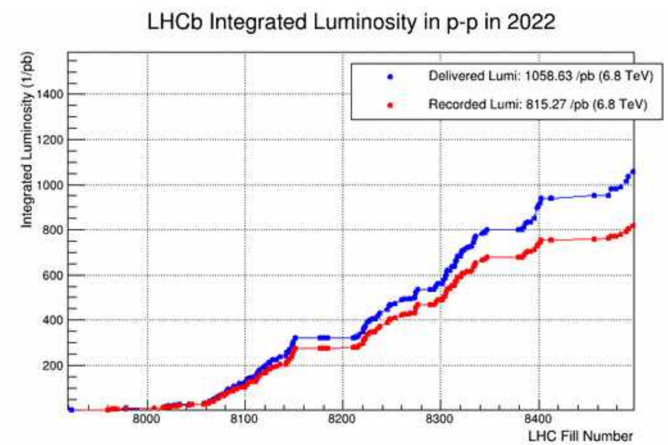
Note:

- ***only pp run in 2022***
- ***HI to be compensated in 2023***

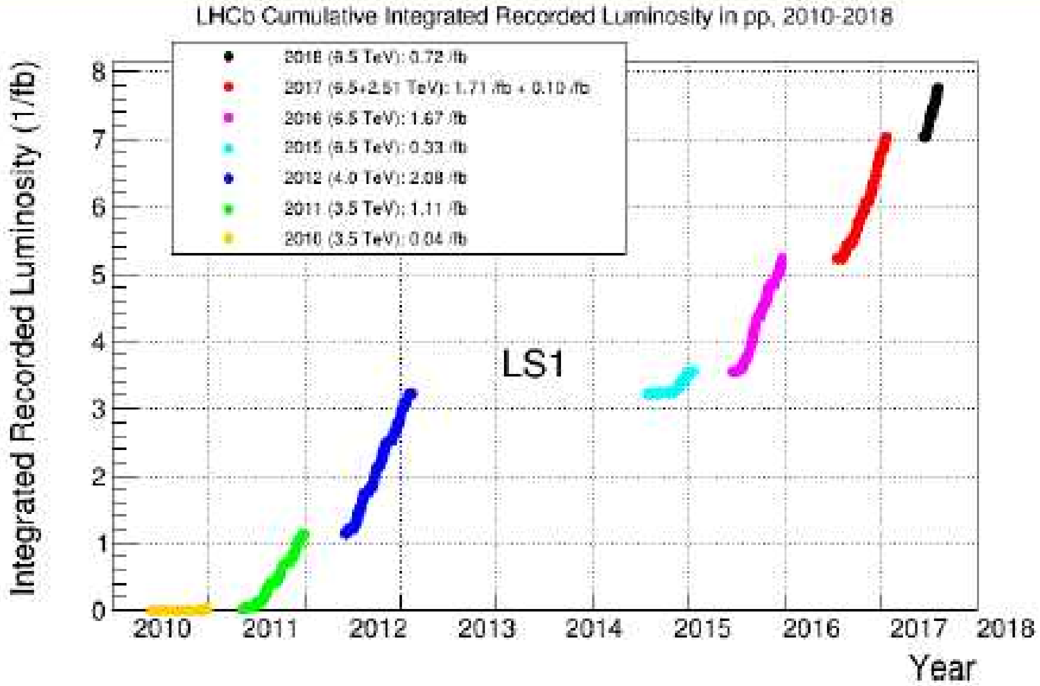




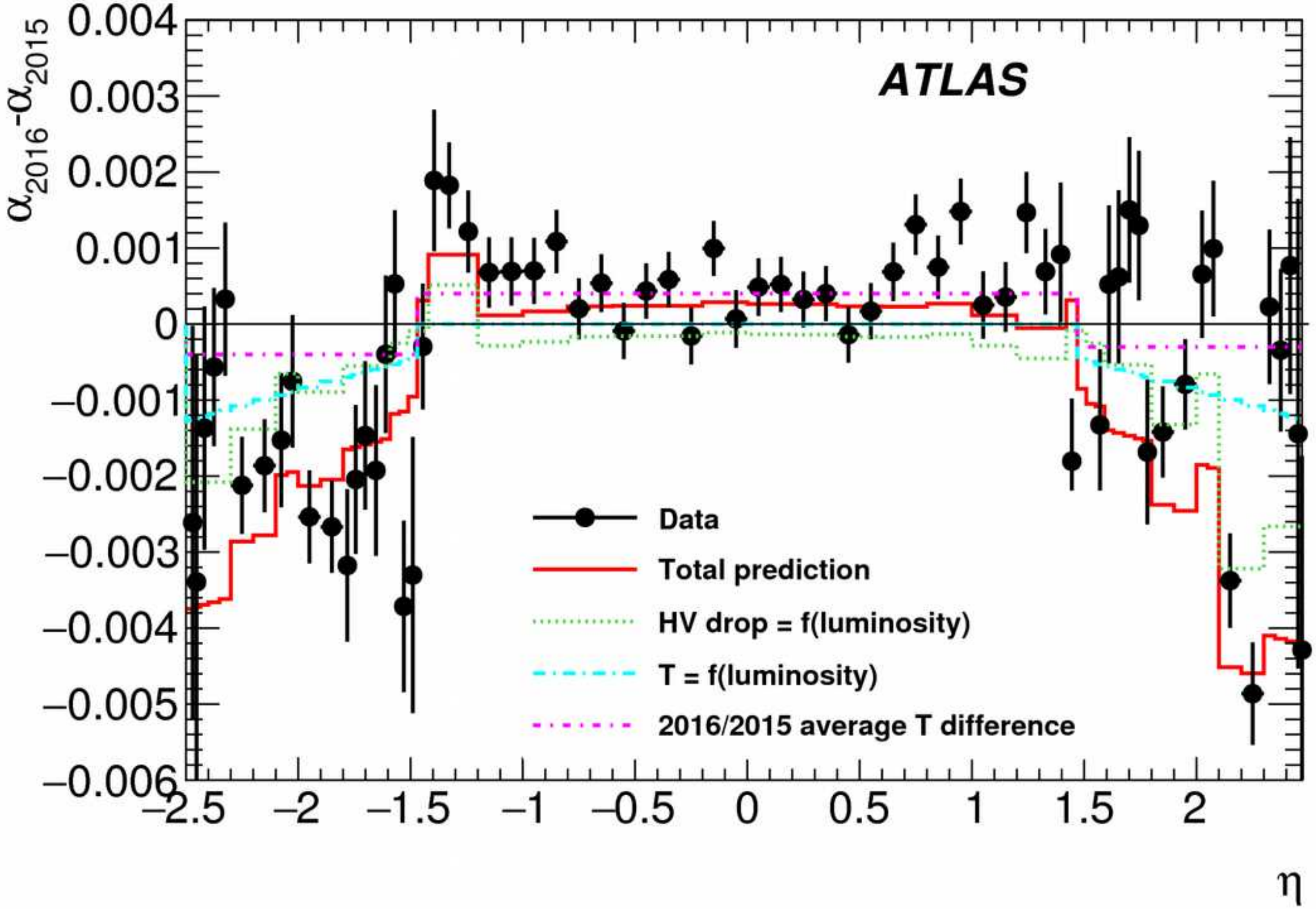




LHCb experiment

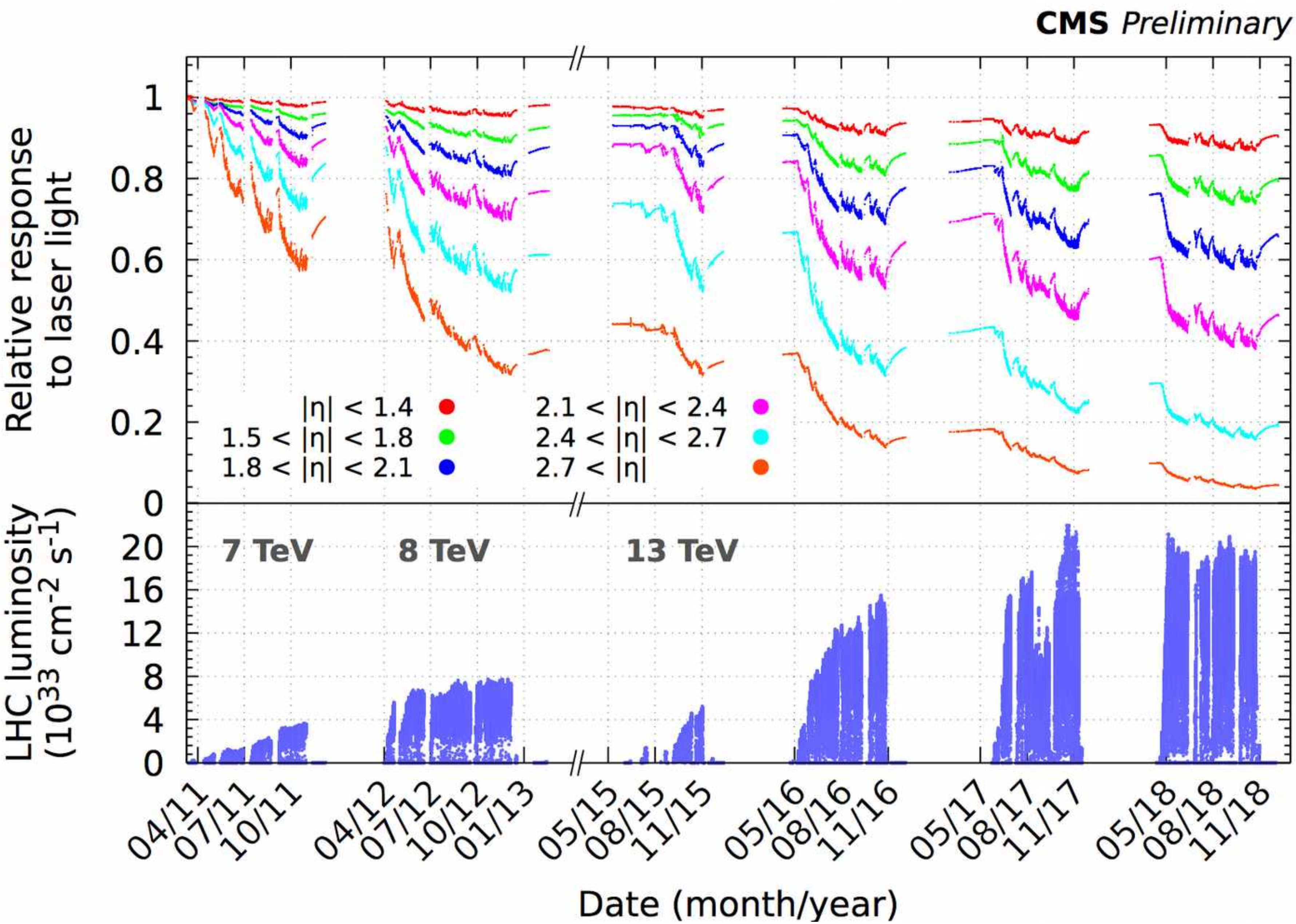


Period	Integrated luminosity	$\sqrt{s}$	Number of $b\bar{b}$
Run1 2011-2012	$3.2\,\text{fb}^{-1}$	7-8 TeV	2.5×10^{11}
Run2 2015-2016	$2.0\,\text{fb}^{-1}$	13 TeV	2.9×10^{11}
Run2 2017-2018	$3.9\,\text{fb}^{-1}$	13 TeV	5.7×10^{11}



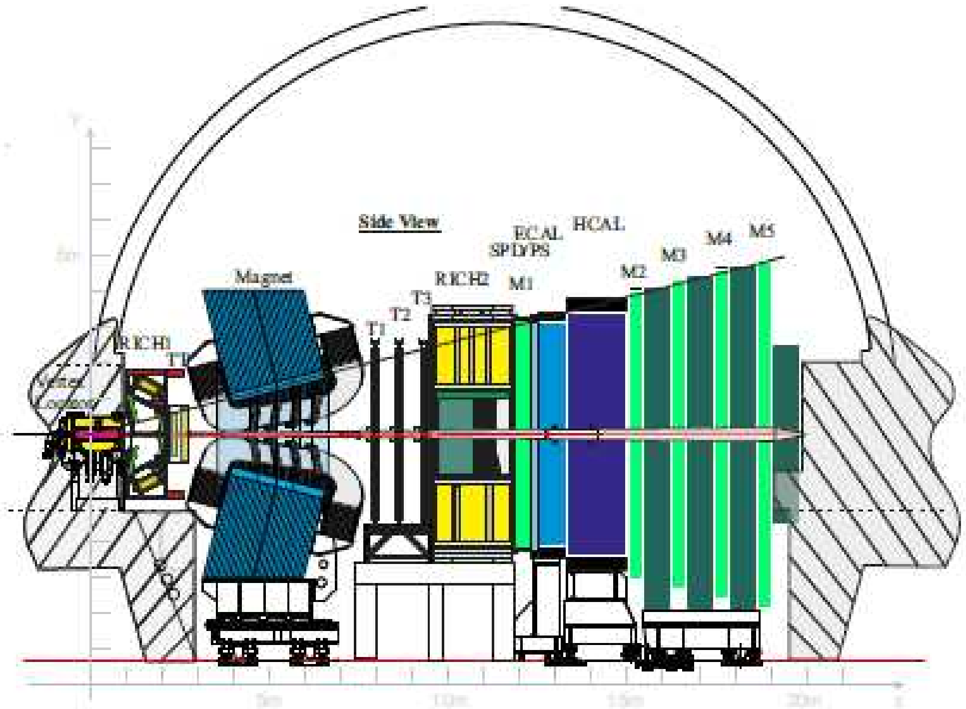
JINST 14 (2019) no.03, P03017

Comparison between the energy scale corrections derived from $Z \to ee$ events in 2015 and 2016 as a function of η. *The difference of the energy scales measured in the data are compared with predictions taking into account the luminosity-induced high-voltage reduction and LAr temperature changes as well as the small overall difference in LAr temperature between 2015 and 2016*



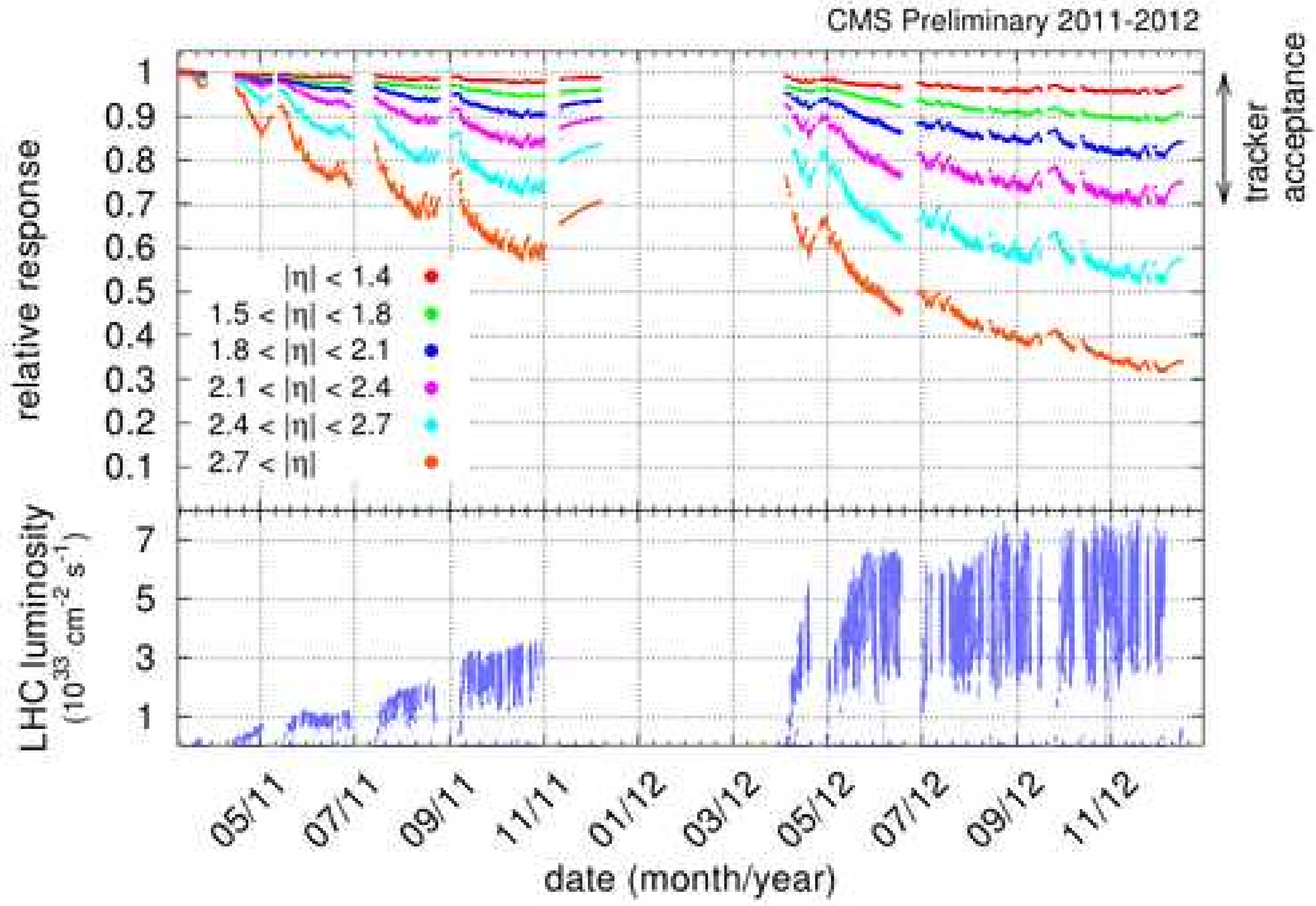
CMS-DP-2019/005

LHCb experiment



- Excellent vertex resolution (10 – 40 μm in xy-plane and **50 – 300 μm in z-axis**) τ^+ lifetime resolution 0.4 ps
- Particle identification efficiencies ~97% for μ, e and ~3% pion misidentification, good separation between π, K, p

[JINST 3 (2008) S08005, Int. J. Mod. Phys. **A30**, 1530022 (2015)]

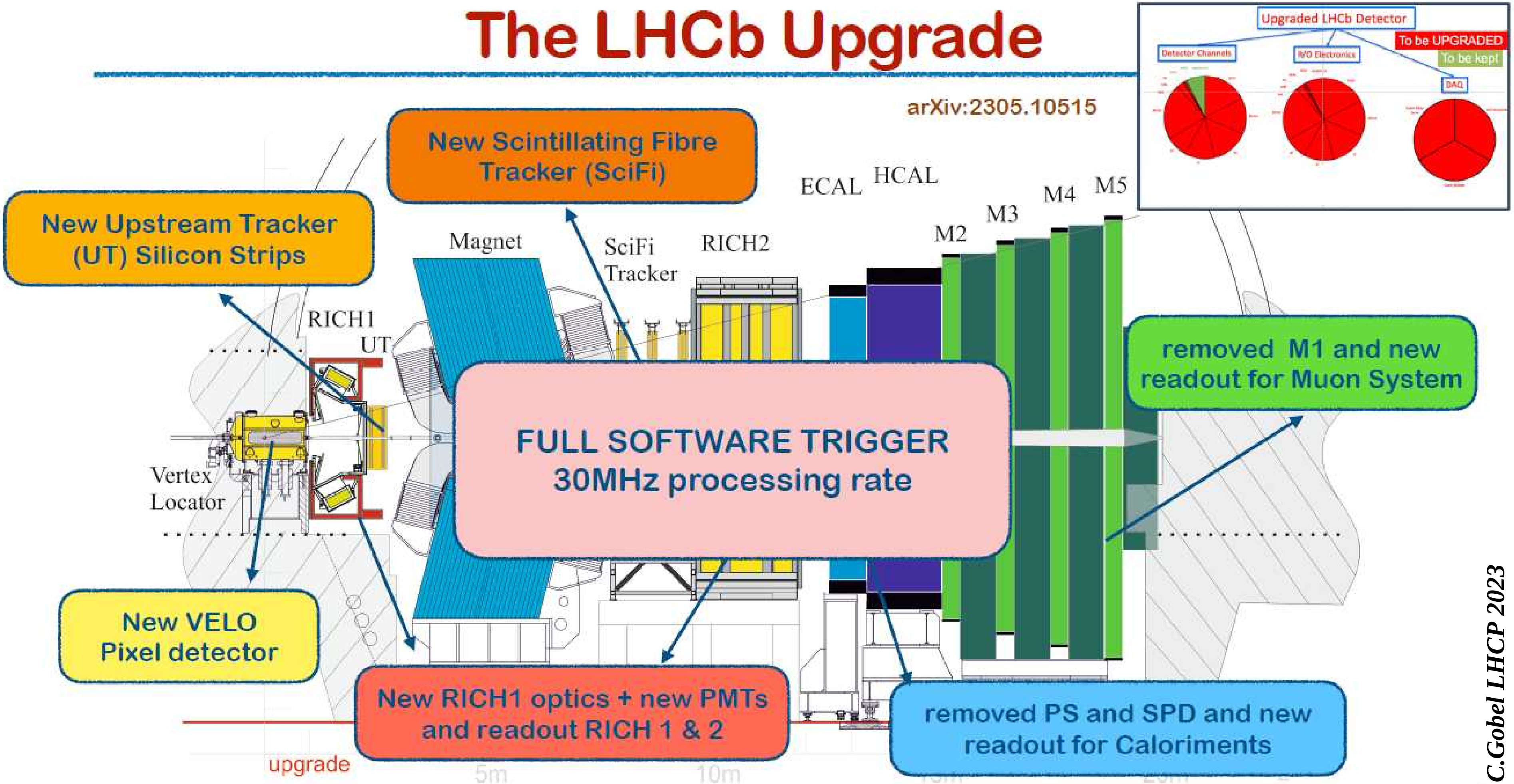


CMS-DP-2013/007

history of relative response

The LHCb Upgrade

arXiv:2305.10515

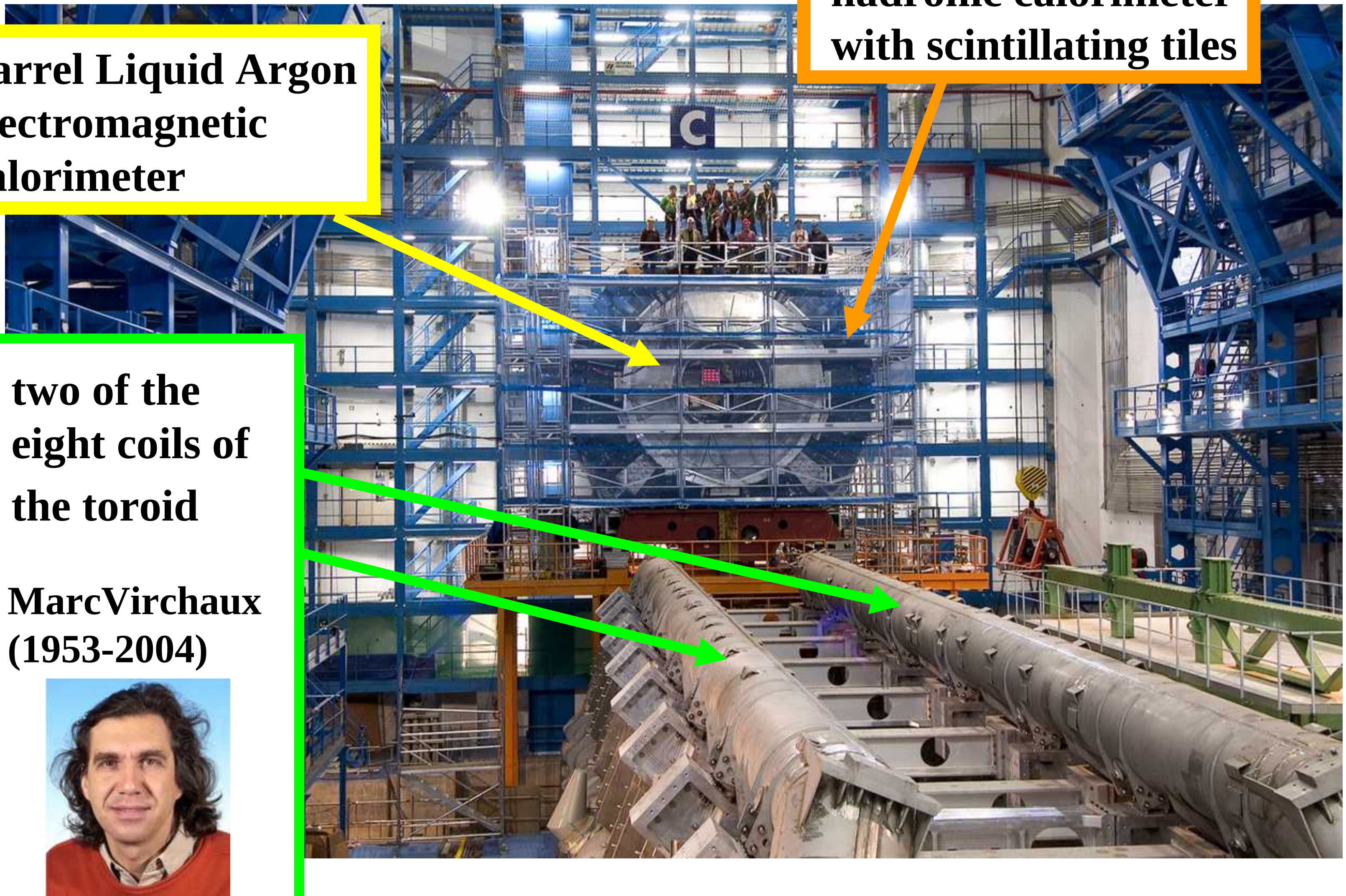


C.Gobel LHCP 2023

CMS EM calorimeter more than 75000 cristals of $PbW0_4$

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

ATLAS end of 2004

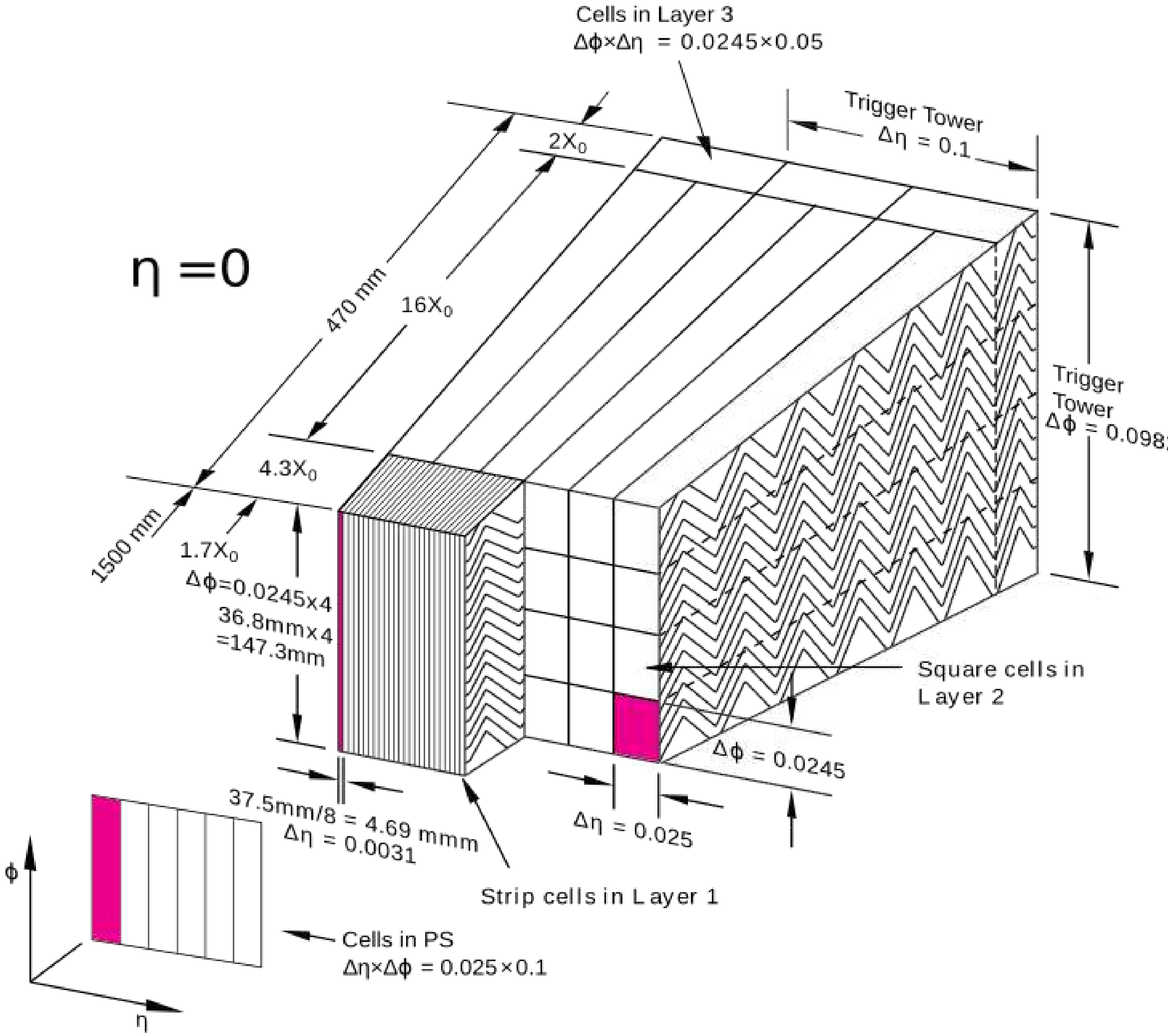


barrel Liquid Argon electromagnetic calorimeter

hadronic calorimeter with scintillating tiles

two of the eight coils of the toroid

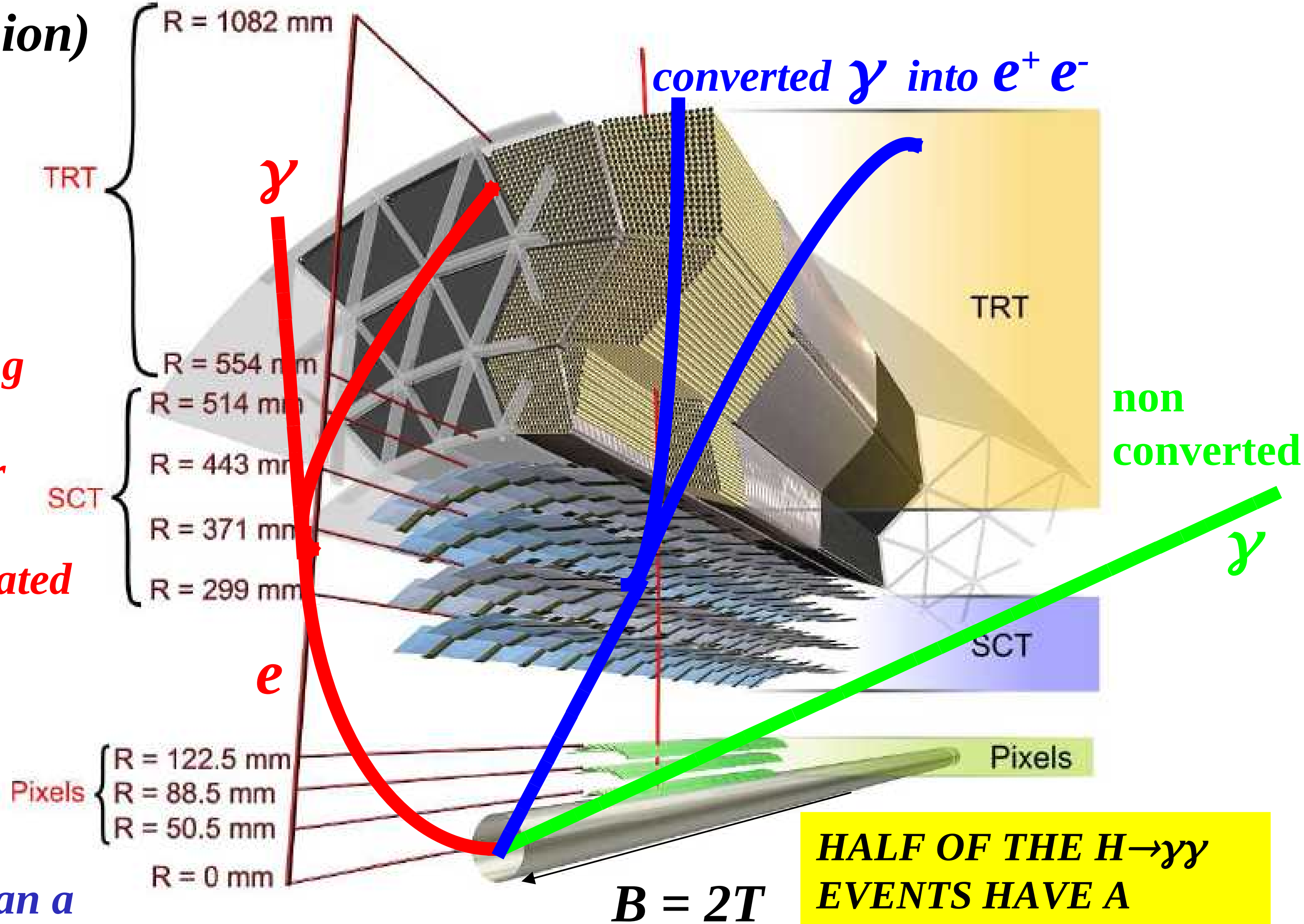
MarcVirchaux (1953-2004)



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

ATLAS inner detector (run 1 version)

Outside are installed the calorimeters and the muon detector

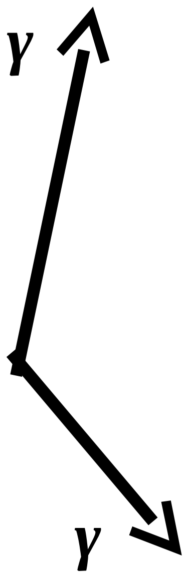


electrons can do some bremsstrahlung in the Inner Detector ⇒response more complicated

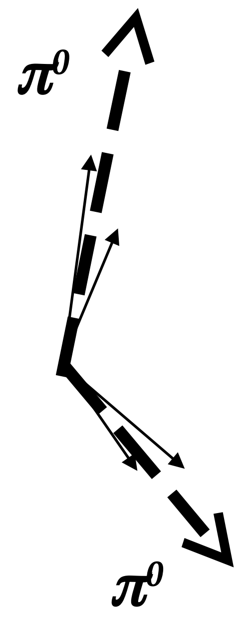
photons can convert ⇒more complicated than a non converted photon

HALF OF THE $H \to \gamma\gamma$ EVENTS HAVE A CONVERTED PHOTON

Example of $H \to \gamma\gamma$



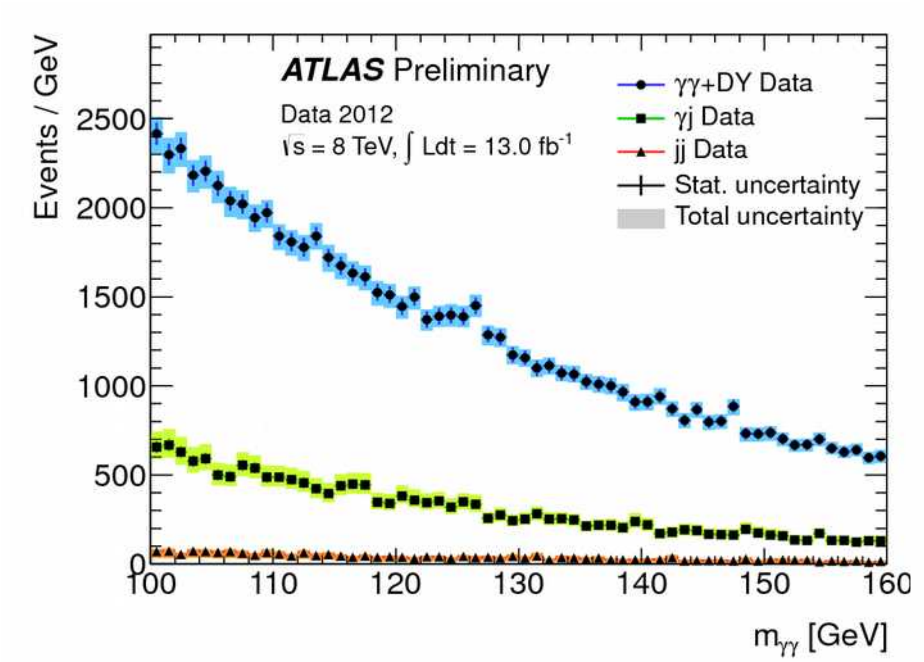
signal

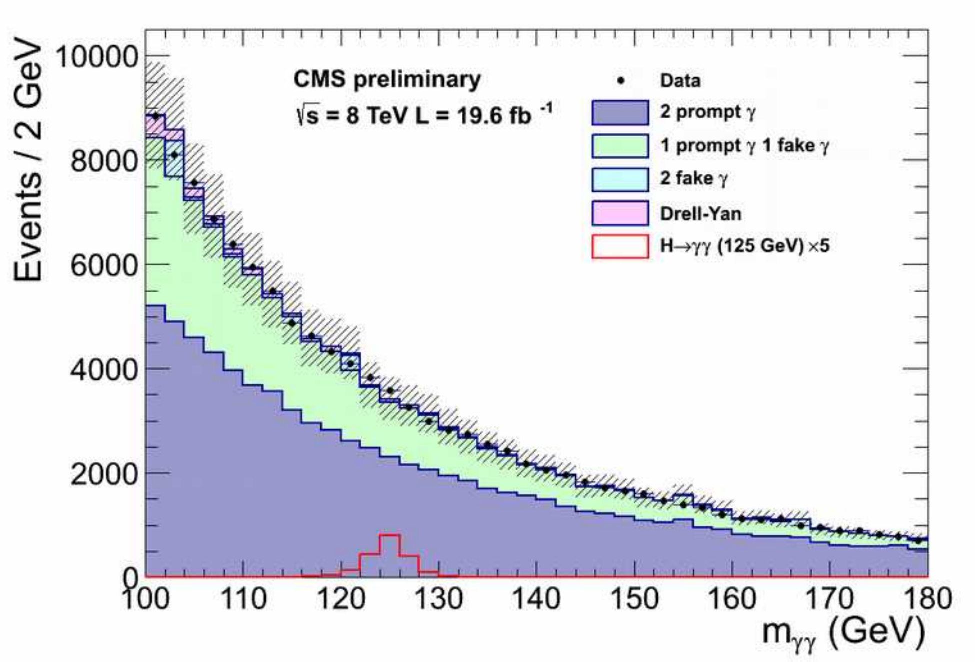


background

angle between the 2 γ of a π^0

$$\sim \frac{2\, m(\pi^0)}{p_T(\pi^0)}$$





large (non photon) background

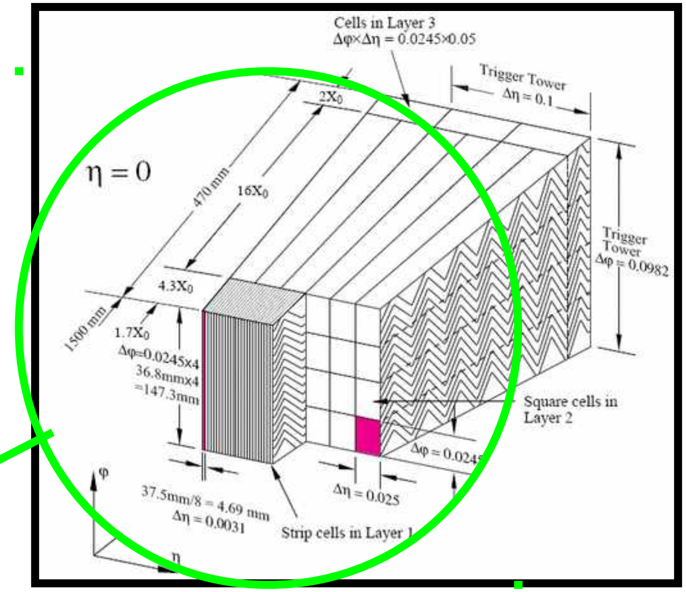
(before any cuts , more than 10^6 times larger than $\gamma\gamma$ background)

dominated by jets fragmenting mainly into π^0 's

background 'photon candidates' coming from jets are less isolated than real photons

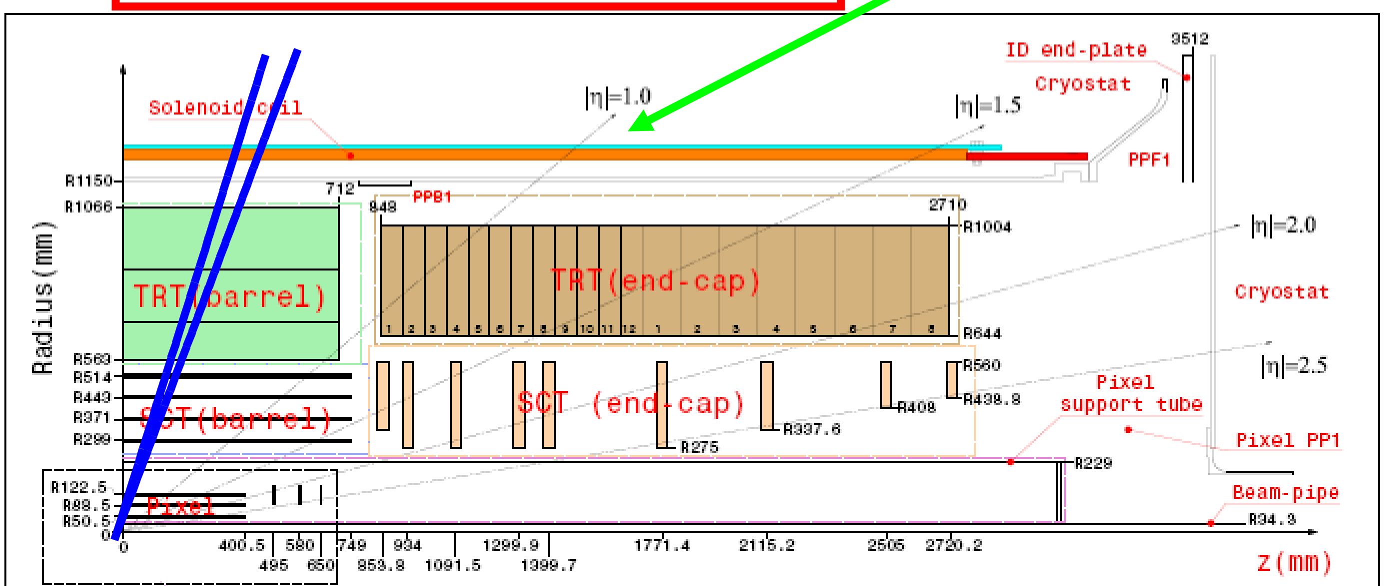
♦ *good jet rejection essential (to reduce γj and jj backgrounds)*

The granularity of the electromagnetic ATLAS detector is very useful to reject the π^0 bakground



opening of photons coming from a π^0 (p_T = 50 GeV)

$\Delta R > .006 \sim 2\ m(\pi^0)/p_T(\pi^0)$



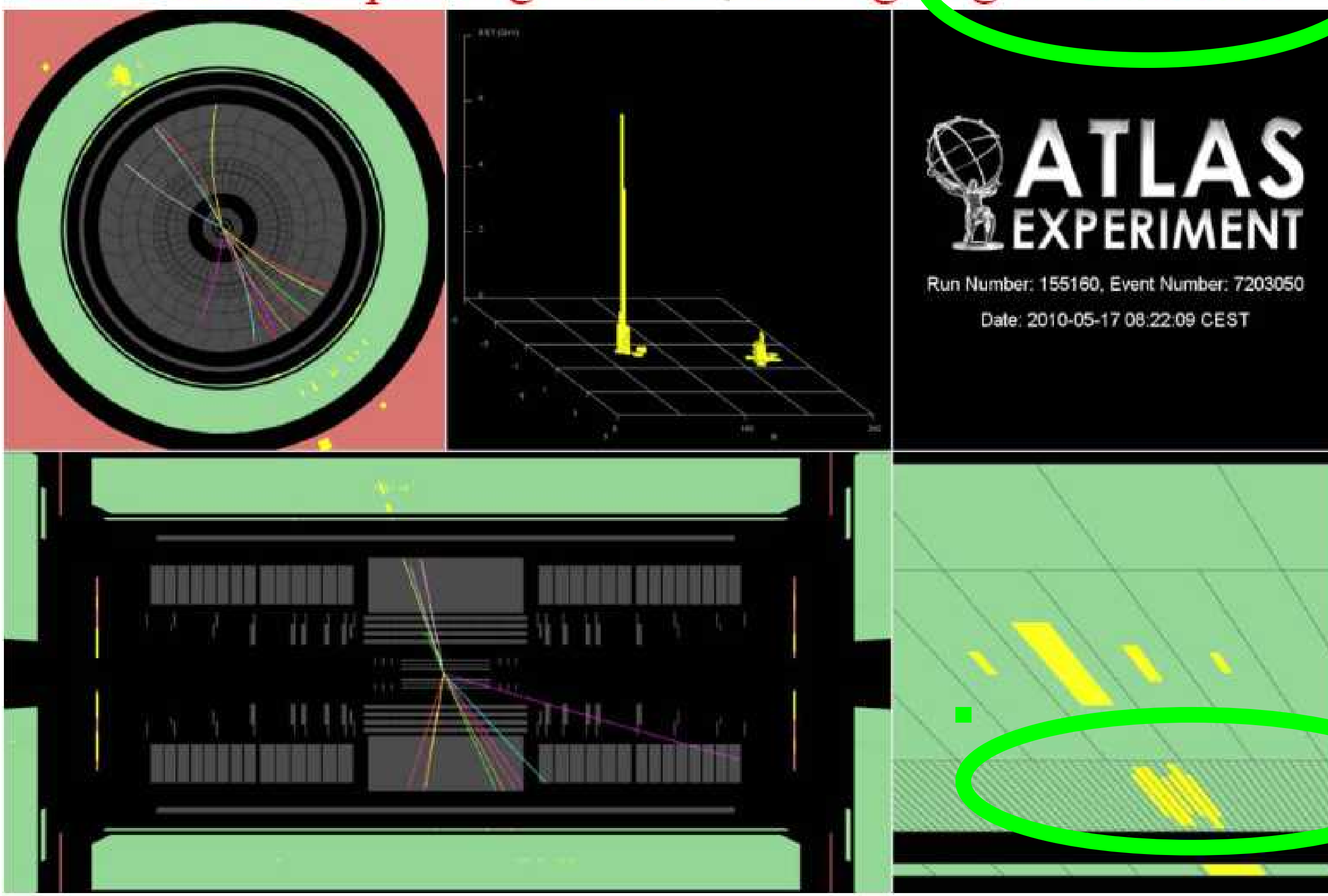
granularity of 1st sampling of calorimeter

$\Delta\eta \sim .003$

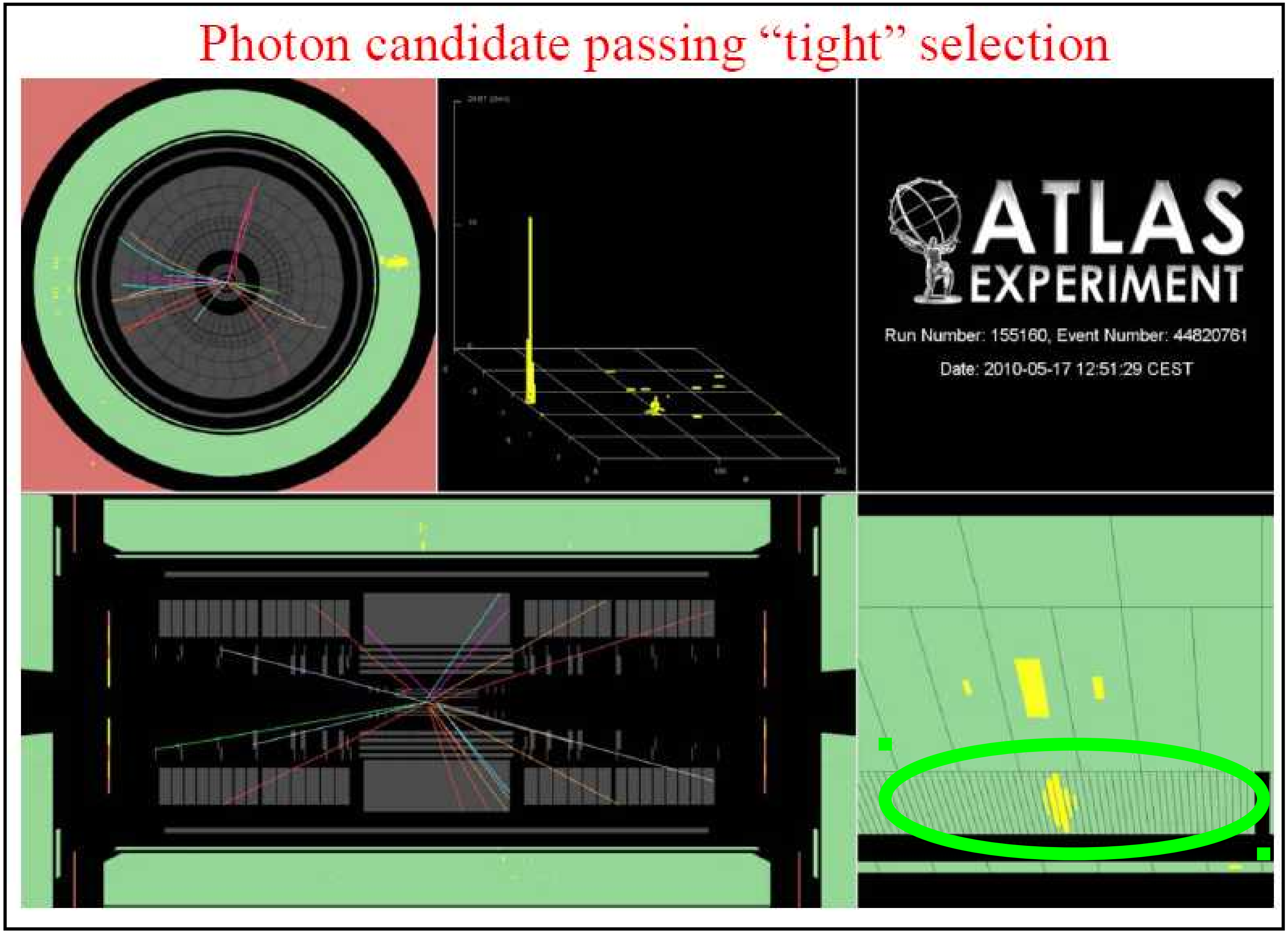
Photon identification with shower shapes

reminder: opening angle between the two photons of a π^0 of p_T =50 GeV ***is > 0.006***
to be compared with size of strip calo 1[st]***sampling ~0.003***

π^0 candidate passing "loose", failing "tight" selection



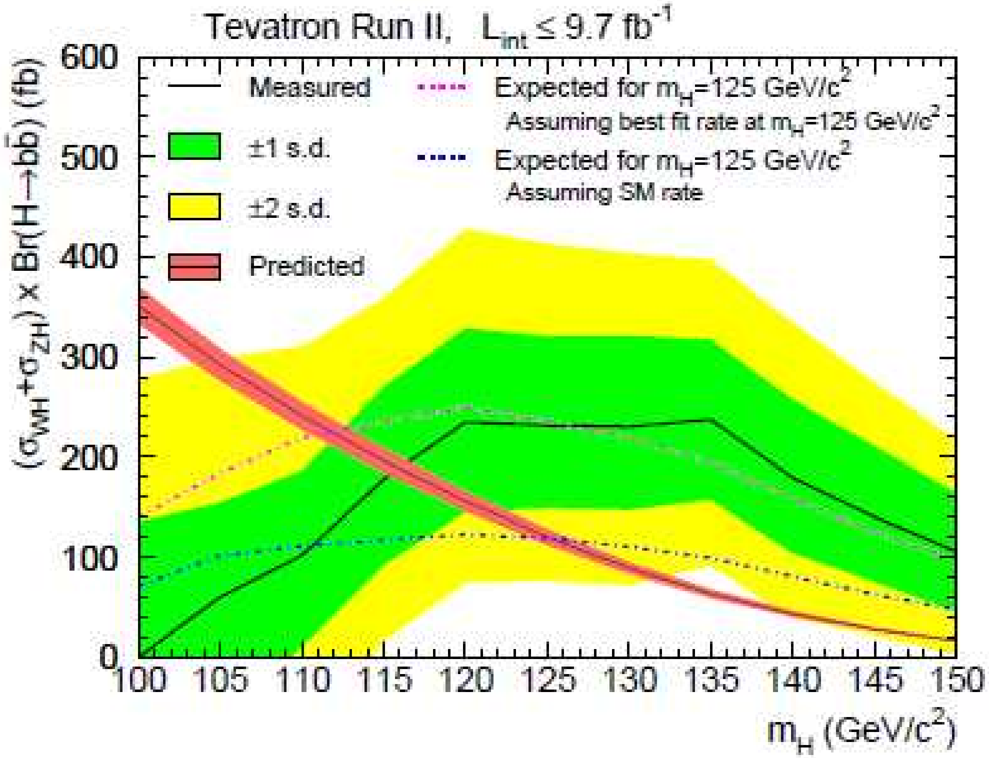
tight selection uses mainly calo 1st sampling



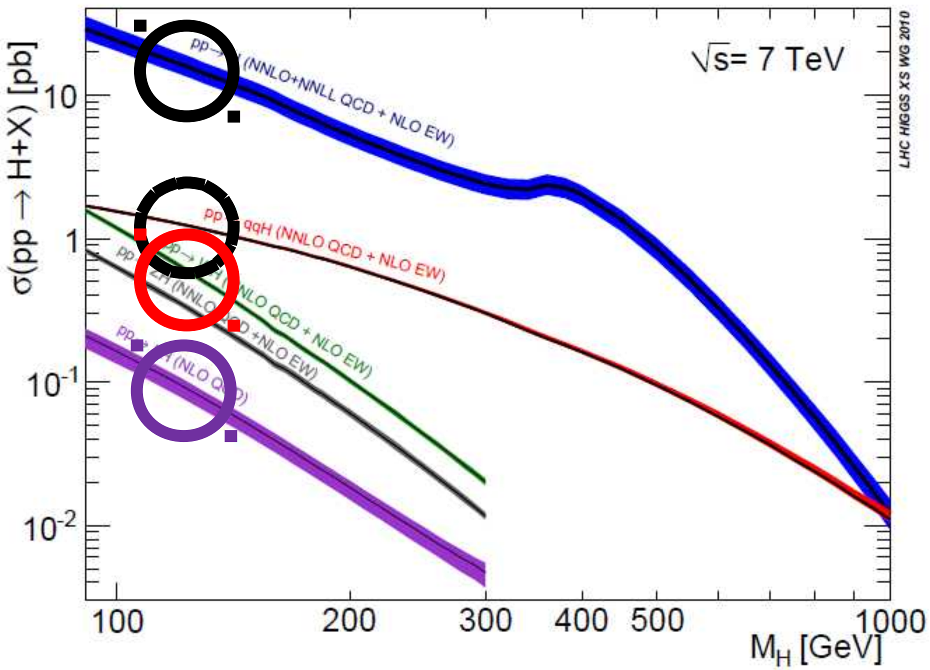
Nice shape in first sampling of EM calorimeter

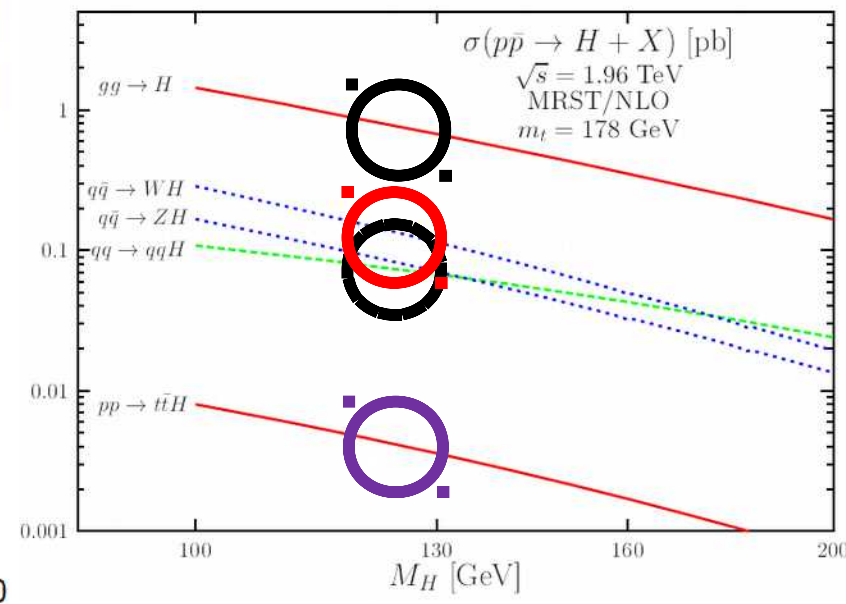
(Tevatron data (proton –antiproton √s =1.96 TeV) ended in september 2011)

CDF and D0 (at Tevatron) have paved the way and brought sophistication and maturity into Higgs boson searches at hadron colliders



We combine searches by the CDF and D0 Collaborations for the associated production of a Higgs boson with a W or Z boson and subsequent decay of the Higgs boson to a bottom-antibottom quark pair. The data, originating from Fermilab Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, correspond to integrated luminosities of up to 9.7 fb^{-1}. The searches are conducted for a Higgs boson with mass in the range 100–150 GeV/c^2. We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 120 and 135 GeV/c^2. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations. We interpret this as evidence for the presence of a new particle consistent with the standard model Higgs boson, which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair.





comparison between LHC and Tevatron :

gg cross section at least 10 × higher at LHC

backgrounds to WW , ZZ , γγ are q qbar annihilation

(Remember Tevatron was a p pbar collider)

→ S/B better in these channels at LHC than at Tevatron

however it is worse in associated modes ⚠

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid **2T** 4 magnets Calorimeters in field-free region	Solenoid **4T** 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\mathrm{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\mathrm{x}10^{-4}\, p_T \oplus 0.005$
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

S.Dawson 4th July 2022

First Study of the Higgs, 1976

- The beginning of Higgs phenomenology

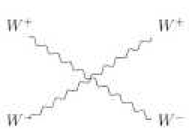
> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A Phenomenological Profile of the Higgs Boson
John R. Ellis (CERN), Mary K. Gaillard (CERN and Orsay, LPT), Dimitri V. Nanopoulos (CERN) (Oct, 1975)
Published in: Nucl.Phys.B 106 (1976) 292

S. Dawson, BNL

Unitarity, 1977

- We did know something about the Higgs mass
- Either M_H < 800 GeV or perturbative unitarity violated around 3 TeV



Cross sections grow with energy without Higgs

- Led to the powerful idea of a "no-lose" theorem
- "The LHC had to find a Higgs or something else at an accessible scale"

Weak Interactions at Very High-Energies: The Role of the Higgs Boson Mass
Benjamin W. Lee (Fermilab), C. Quigg (Fermilab), H.B. Thacker (Fermilab) (Mar, 1977)
Published in: Phys.Rev.D 16 (1977) 1519

The Strength of Weak Interactions at Very High-Energies and the Higgs Boson Mass
Benjamin W. Lee (Fermilab), C. Quigg (Fermilab), H.B. Thacker (Fermilab) (Feb, 1977)
Published in: Phys.Rev.Lett. 38 (1977) 883-885

Theorists and SUSY prefer low mass boson

$m_h < m_Z$ at lowest order . But was realized that this prediction is subject to important radiative corrections that could push m_h up to ~130 GeV in simple supersymmetric models

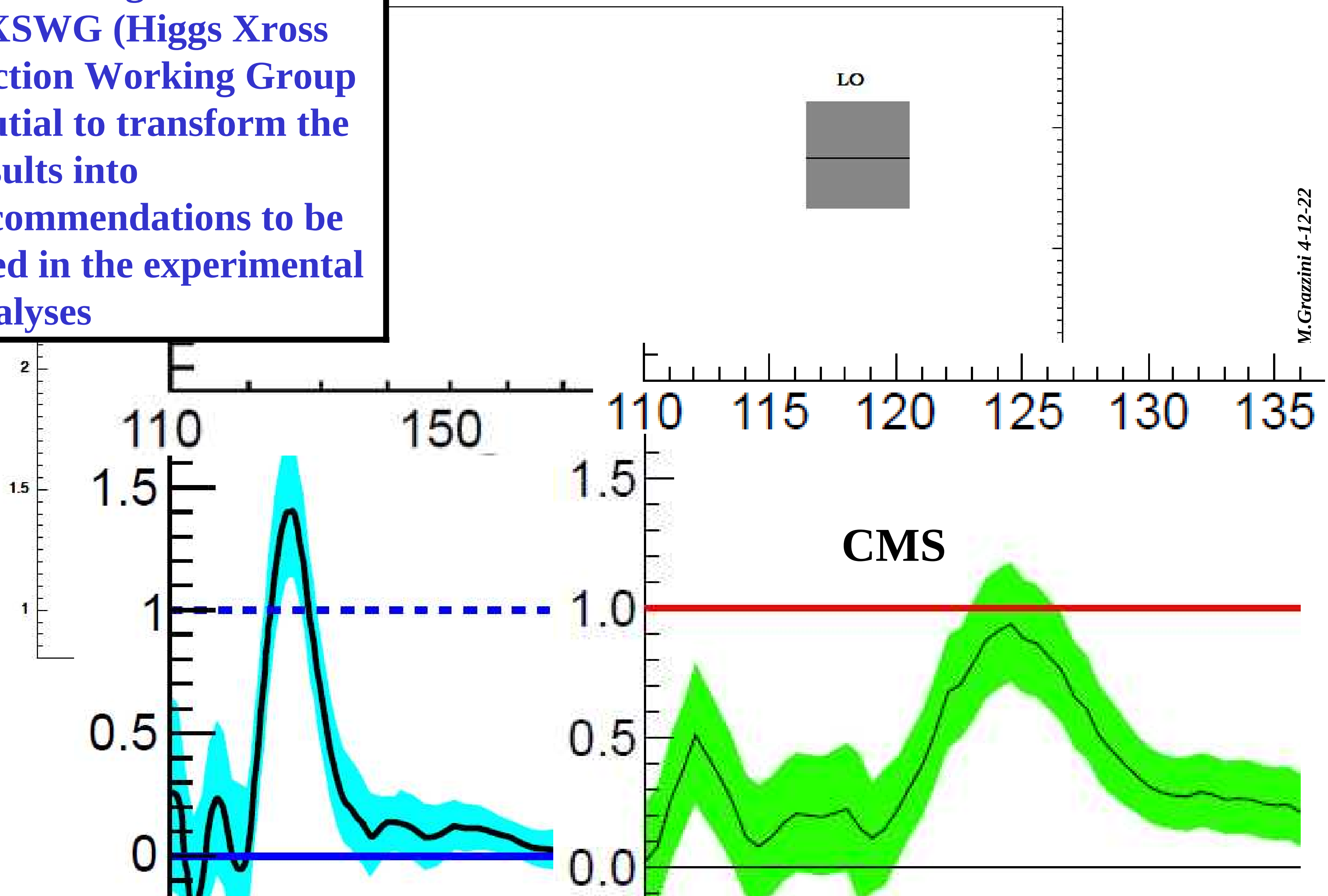
Y. Okada, M. Yamaguchi and T. Yanagida, *Upper bound of the lightest Higgs boson mass in the minimal supersymmetric standard model*, Prog. Theor. Phys. **85** (1991) 1.

J. R. Ellis, G. Ridolfi and F. Zwirner, *Radiative corrections to the masses of supersymmetric Higgs bosons*, Phys. Lett. B **257** (1991) 83; H. E. Haber and R. Hempfling, *Can the mass of the lightest Higgs boson of the minimal supersymmetric model be larger than m(Z)?*

…or signal strength

discovery papers (2012)

Do not forget the HXSWG (Higgs Xross Section Working Group crutial to transform the results into recommendations to be used in the experimental analyses



♪ *Historical introduction and setting the stage*

Spontaneous Symmetry Breaking

LHC and (mainly) ATLAS and CMS

H(125) discovery

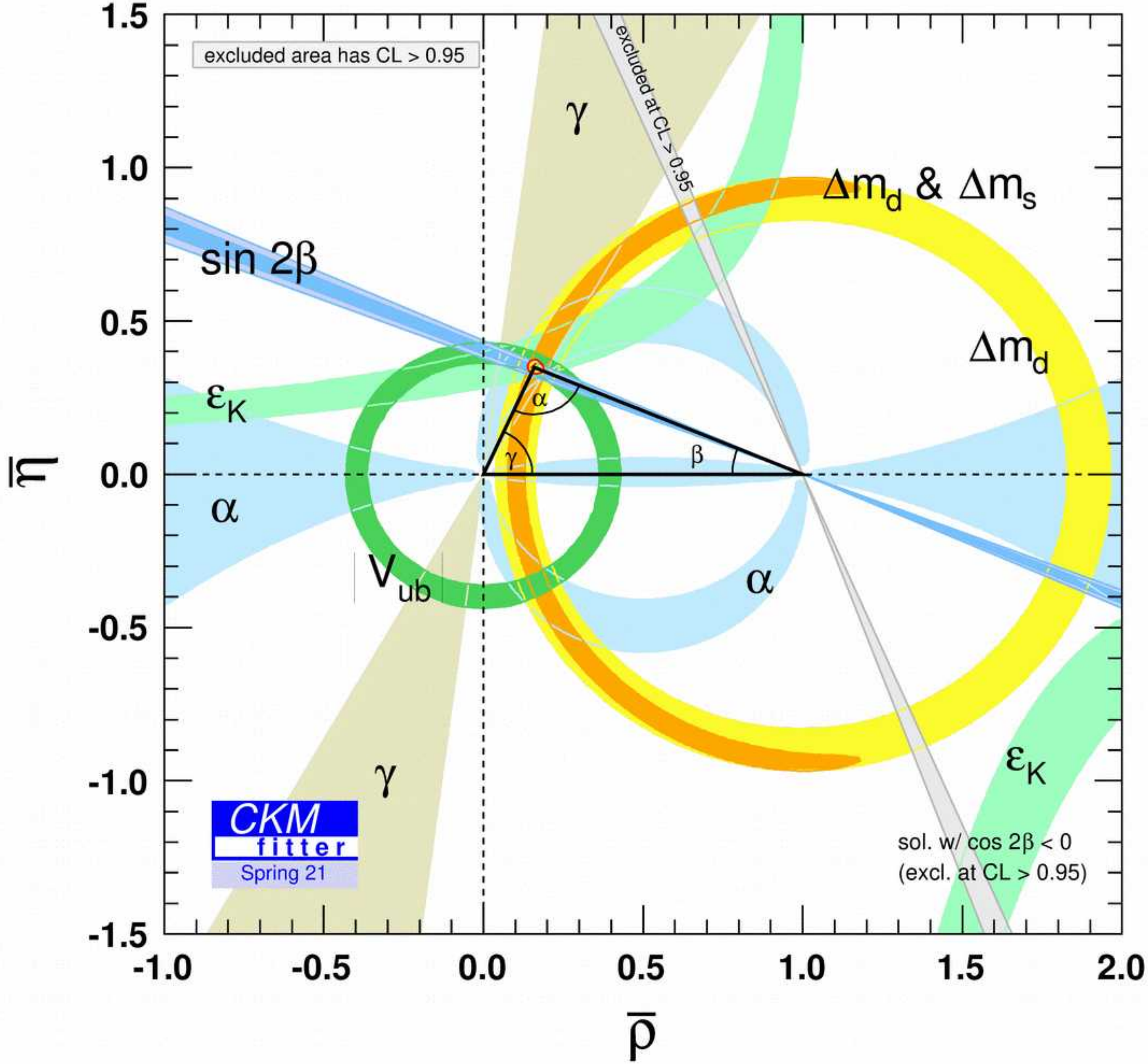
♪ ***Results from Run 1 & Run 2 (& start of Run 3) (up to now) :***

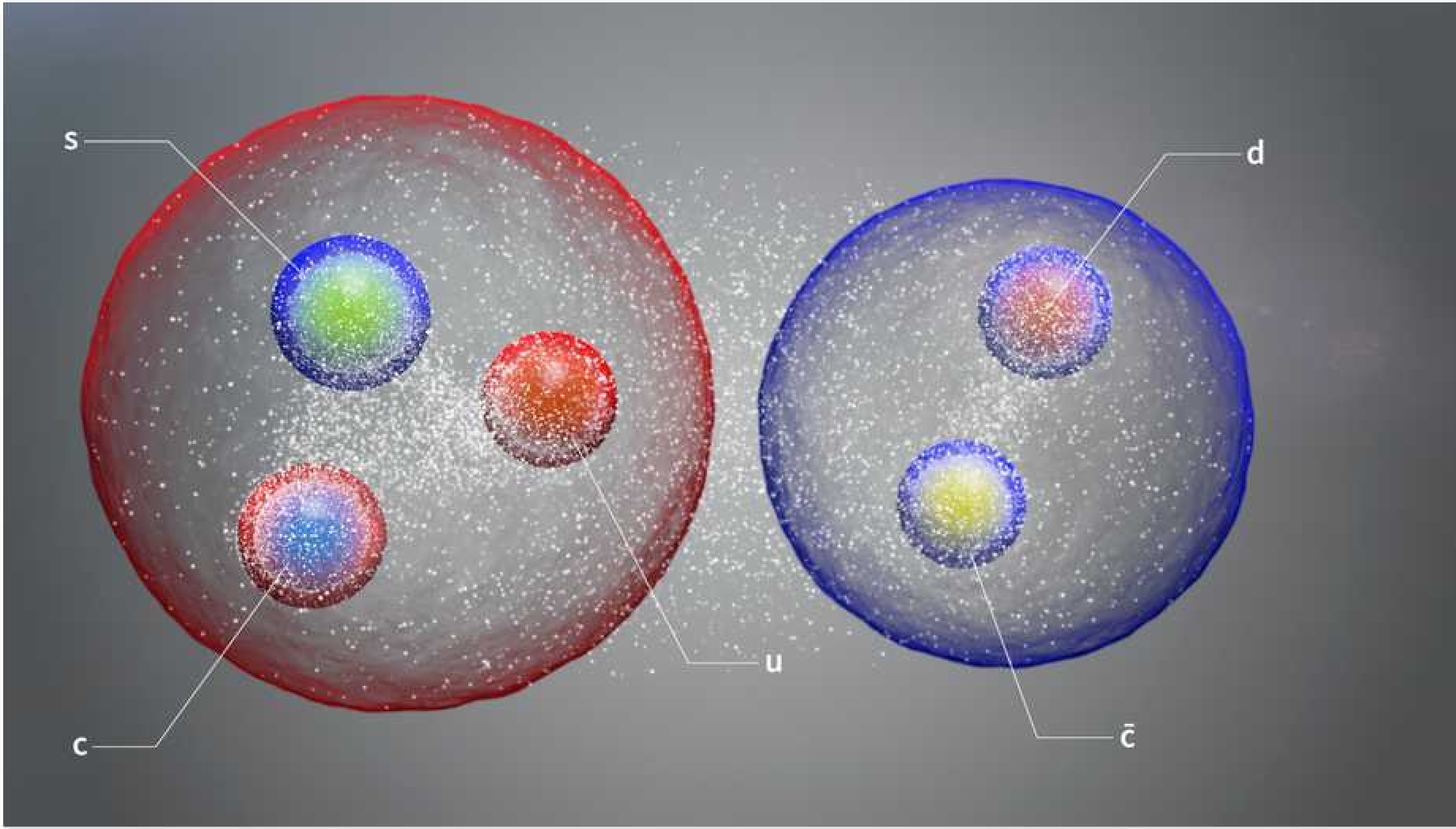
- ***mainly H(125)***
- ***other physics (precision, searches)***

♪ *Future of LHC , Run 3 , HL-LHC*

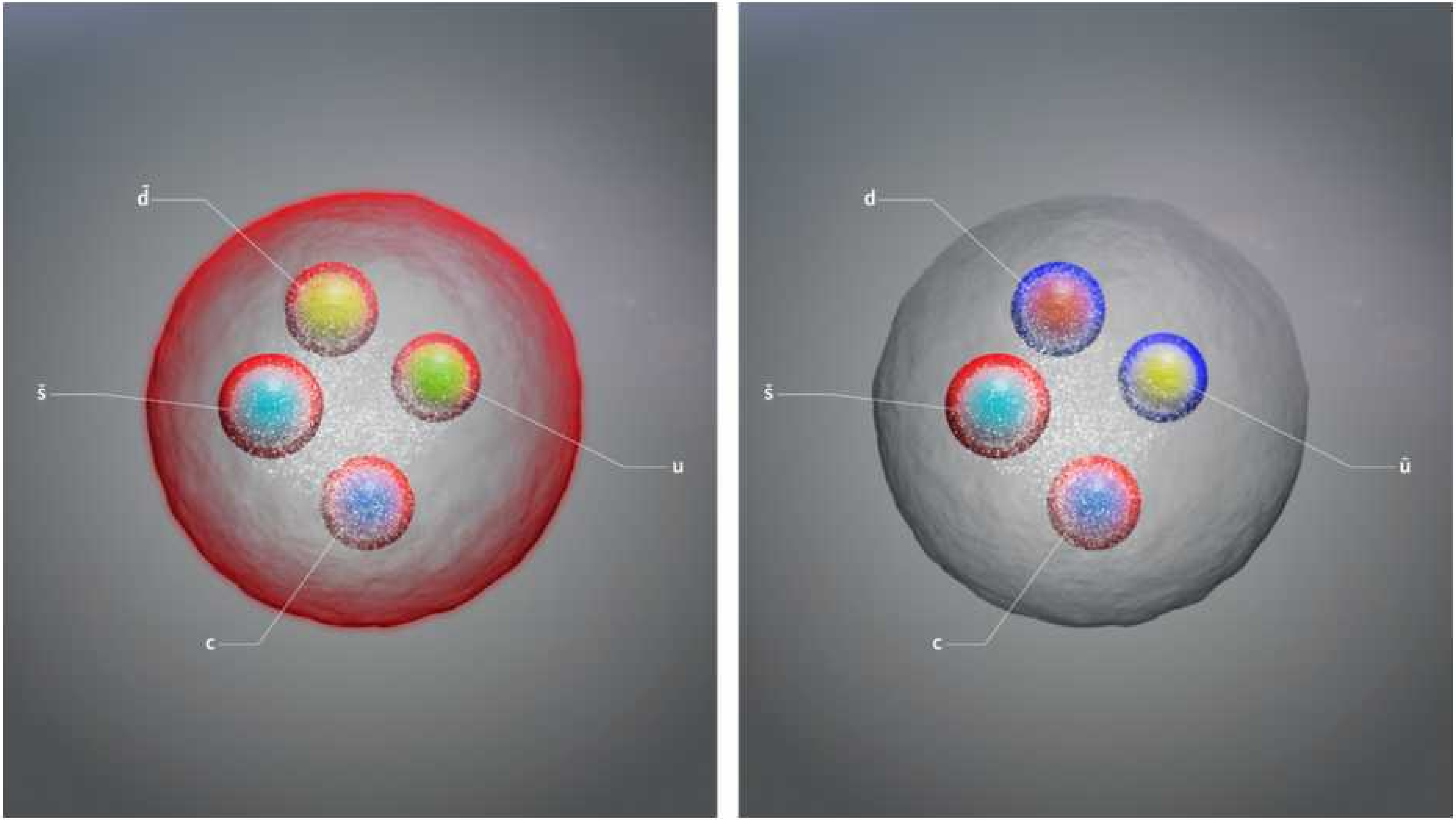
♪ *Conclusions*

♪ *Backup*


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
V_{ub}
α
γ
ε_K
CKM
fitter
Spring 21
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

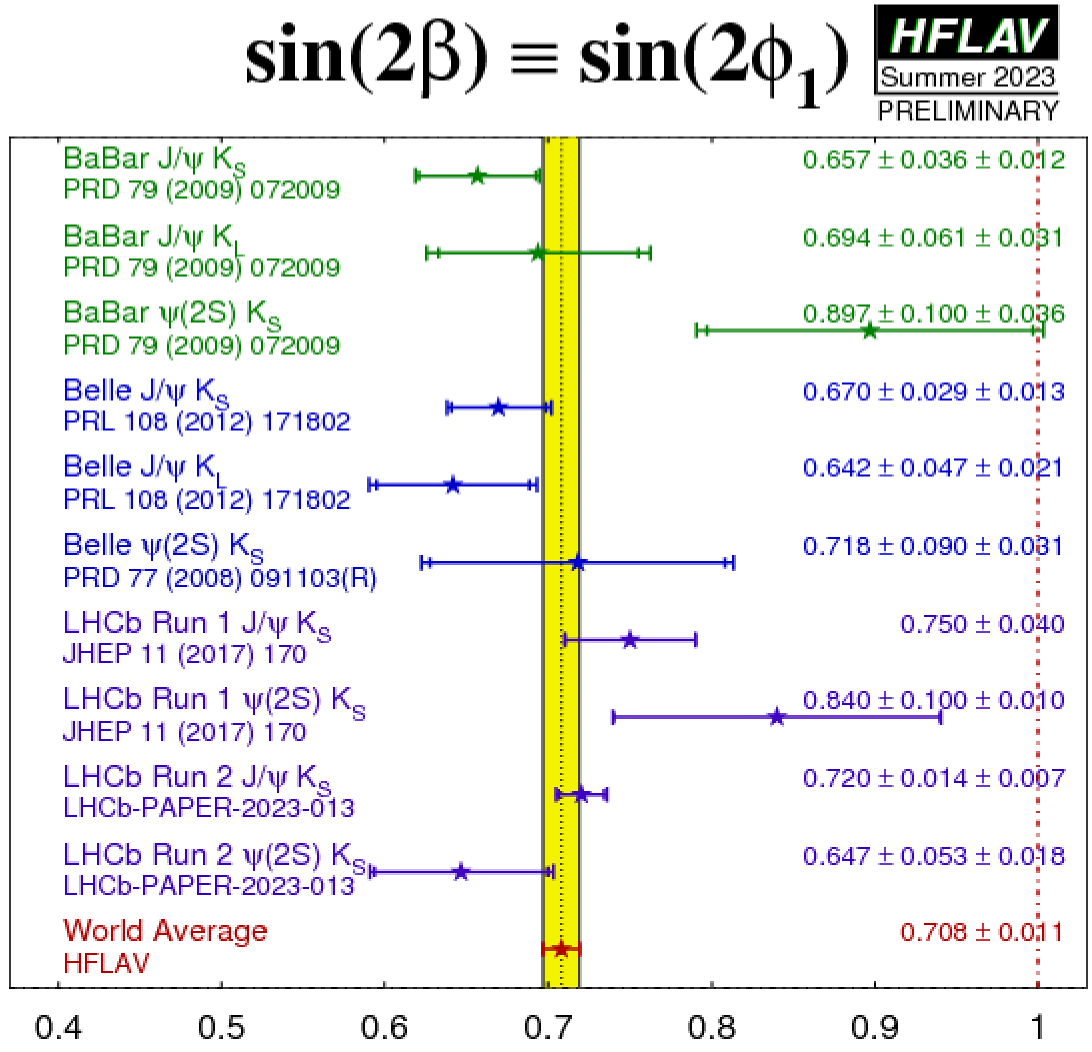


The new pentaquark, illustrated here as a pair of standard hadrons loosely bound in a molecule-like structure, is made up of a charm quark and a charm antiquark and an up, a down and a strange quark (Image: CERN) *https://home.cern/news/news/physics/lhcb-discovers-three-new-exotic-particles*



The two new tetraquarks, illustrated here as single units of tightly bound quarks. One of the particles is composed of a charm quark, a strange antiquark and an up quark and a down antiquark (left), and the other is made up of a charm quark, a strange antiquark and an up antiquark and down quark (right) (Image: CERN)

$\sin(2\beta) \equiv \sin(2\phi_1)$



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Spontaneous Symmetry Breaking

LHC and (mainly) ATLAS and CMS

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♪ ***Results from Run 1 & Run 2 (& start of Run 3) (up to now) :***

- ***mainly H(125)***
- *other physics (precision, searches)*

♪ *Future of LHC , Run 3 , HL-LHC*

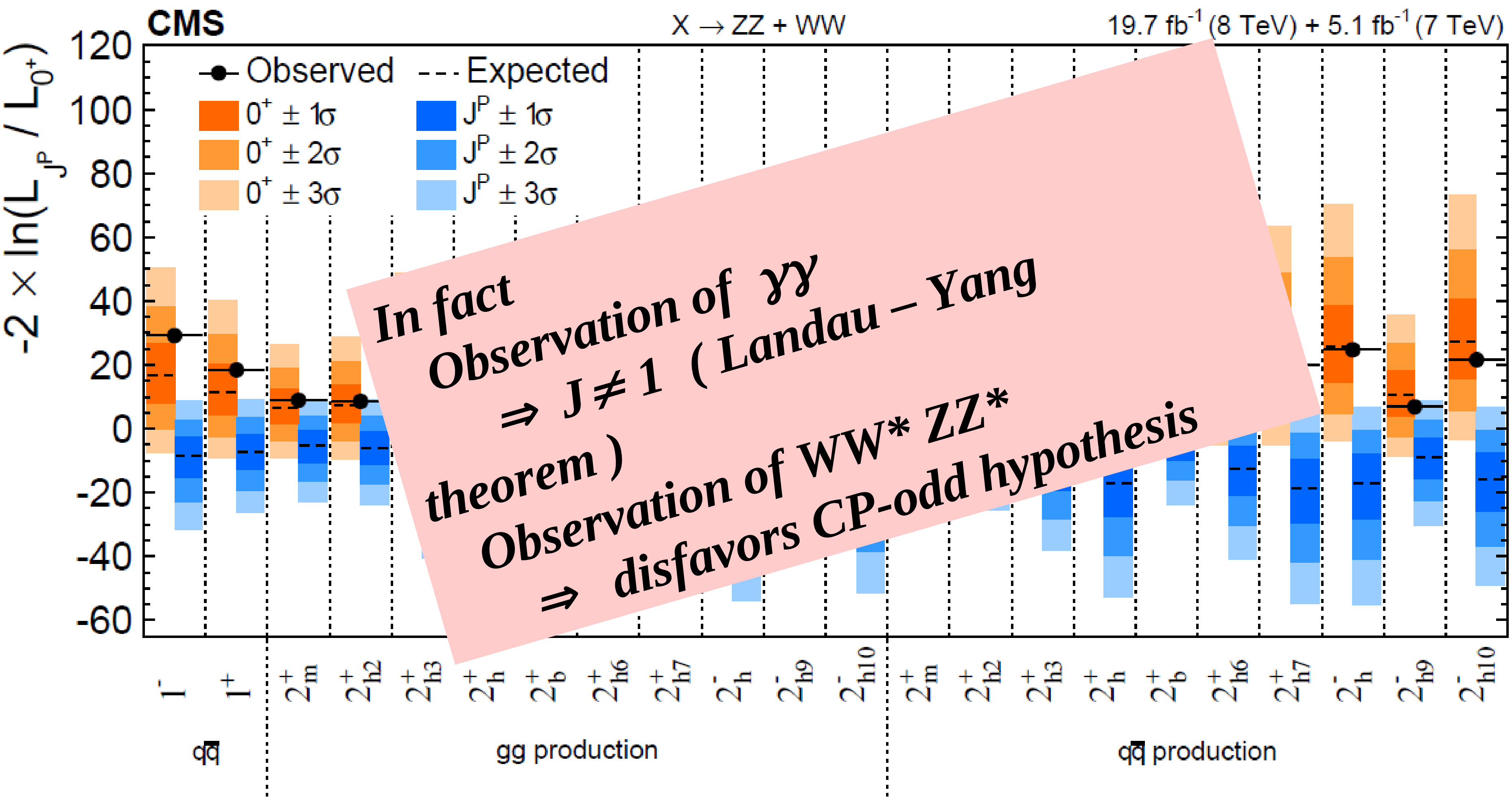
♪ *Conclusions*

♪ *Backup*

Exotic spin scenarios excluded

Phys.Rev. D92 (2015) 1, 012004   arXiv:1411.3441

→ go to anomalous spin 0 couplings and CP



In fact

Observation of $\gamma\gamma$

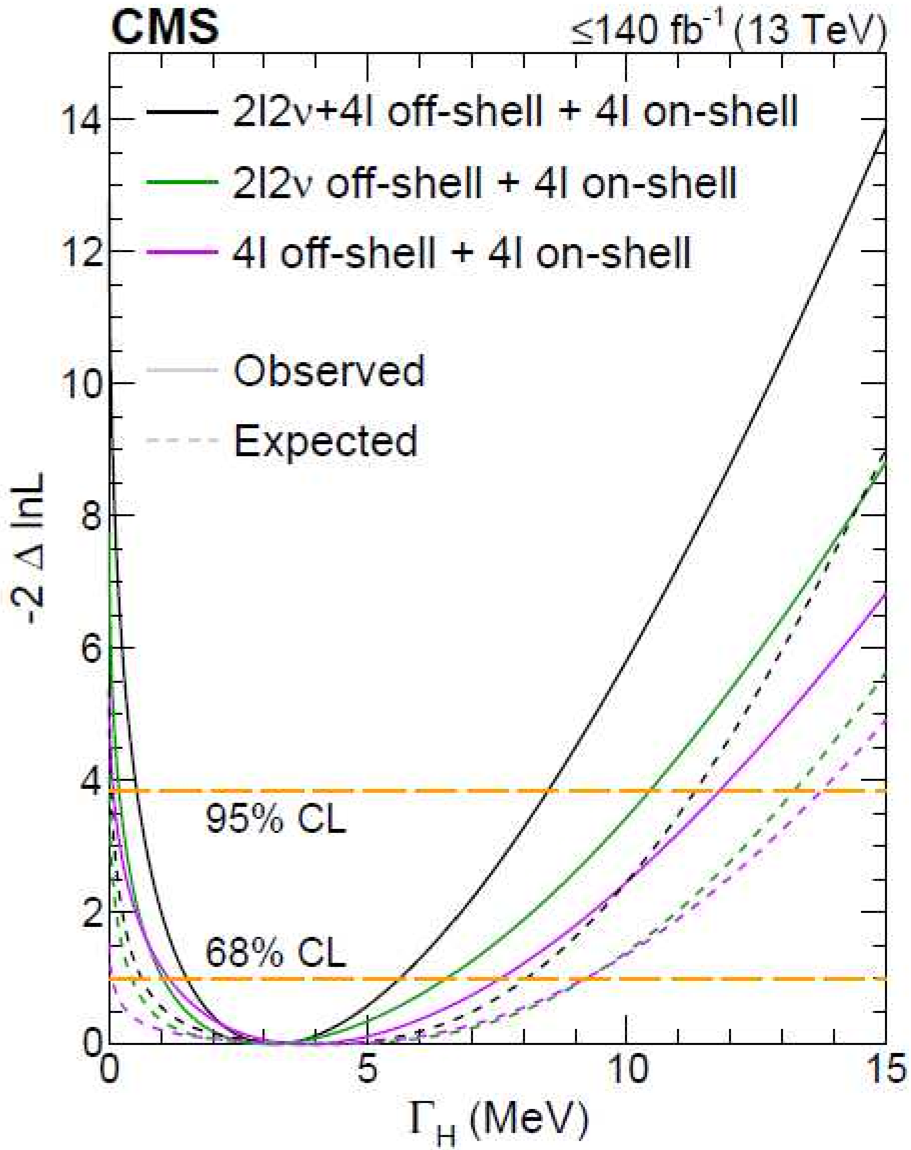
$\Rightarrow J \neq 1$ (Landau – Yang theorem)

Observation of WW ZZ**

$\Rightarrow$ disfavors CP-odd hypothesis

The Higgs boson Width

Nature Physics 18, 1329–1334 (2022)



The Higgs boson invisible decays

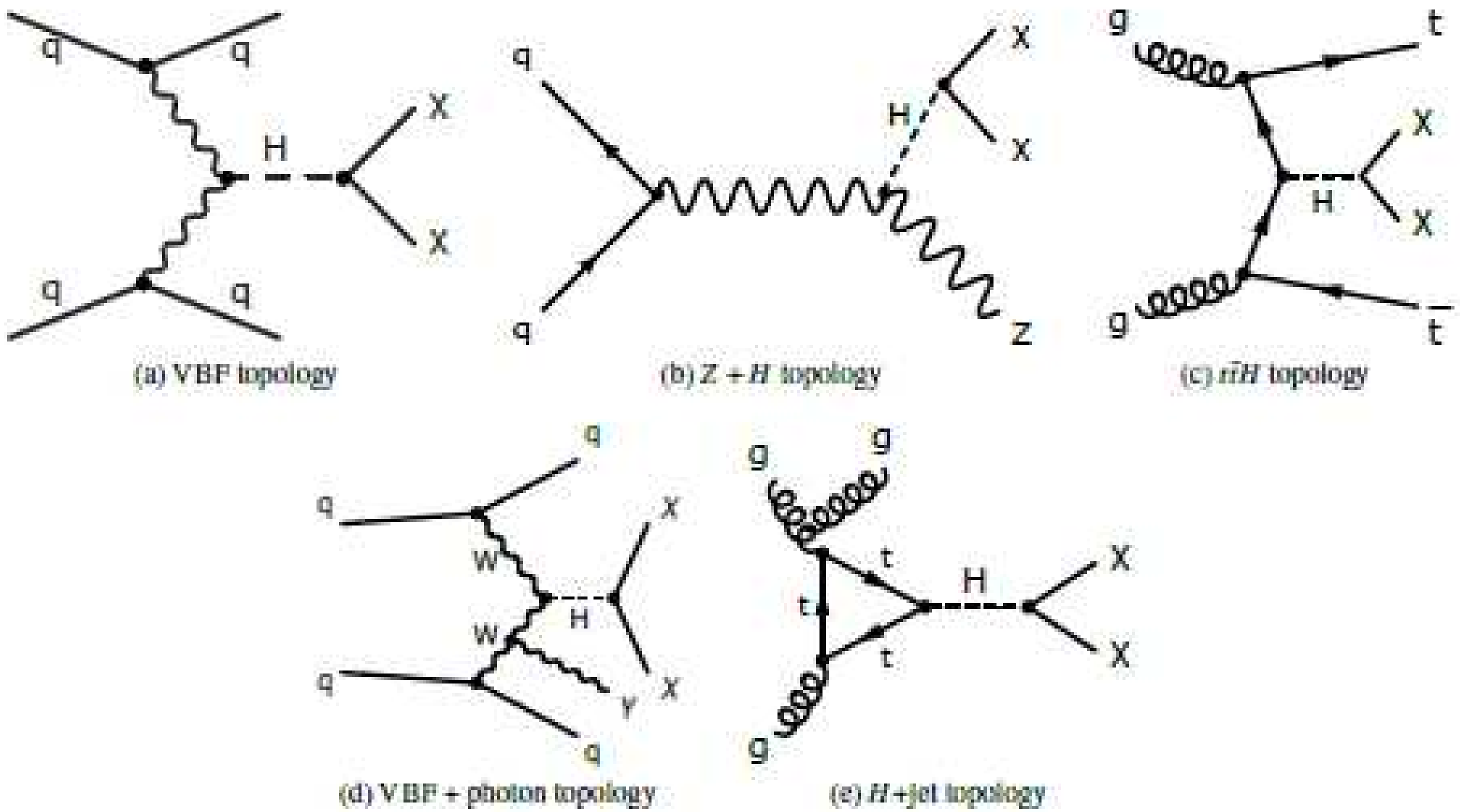


Figure 1: Diagrams illustrating the Higgs boson production mode targetted for the Run 2 searches.

arXiv:2301.10731v1

The Higgs boson invisible decays

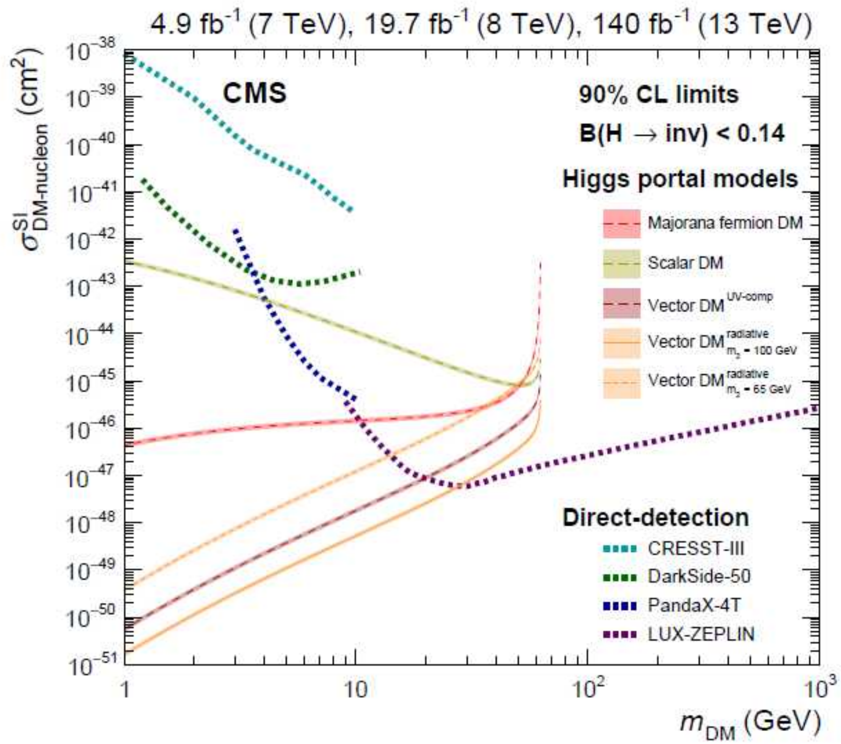
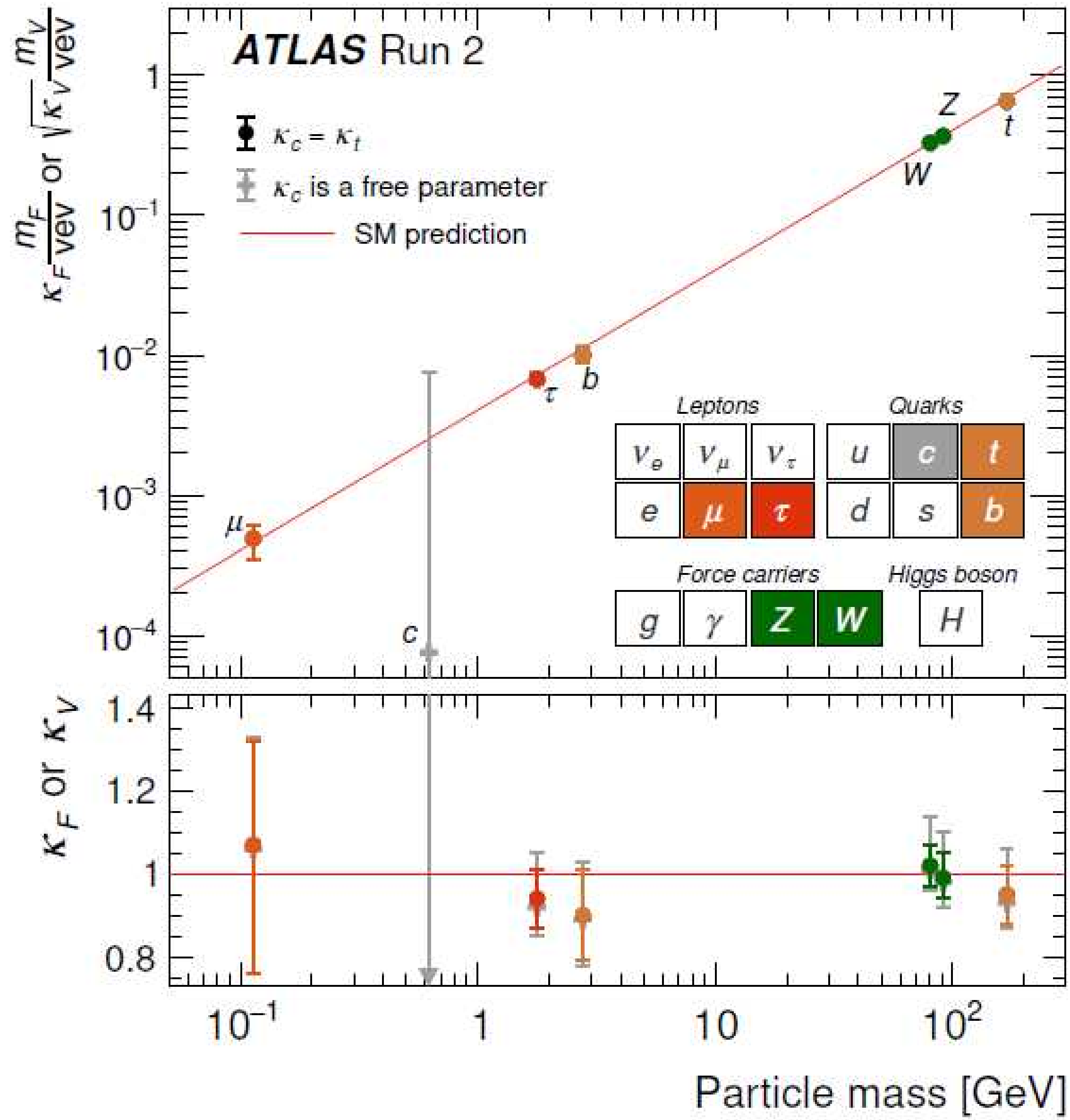


Figure 8: Upper limits on $\sigma^{\mathrm{SI}}_{\mathrm{DM\text{-}nucleon}}$ as a function of DM candidate mass m_{DM}. Results are presented for a fermion (red) and scalar (yellow) DM candidate. In addition, a vector DM candidate is studied using two UV-comp approaches, the first denoted Vector DM$^{\mathrm{UV\text{-}comp}}$ [20] (burgundy), and the second a radiative portal version denoted Vector DM$^{\mathrm{radiative}}_{m_2}$ [23] (orange) with a dark Higgs boson mass of $m_2 = 65$ and 100 GeV. Uncertainties are derived from Refs. [19, 99, 100]. Results are compared to direct-detection searches from CRESST-III [95] (truncated at $m_{\mathrm{DM}} > 1$ GeV), DarkSide-50 [96], PandaX-4T [97] and LUX-ZEPLIN [98].

$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^{2} \cdot \kappa_{\gamma}^{2}}{\kappa_{\mathrm{H}}^{2}}$$

arXiv:1307.1347v2



Phys.Lett.B 843 (2023) 137745

JHEP 08 (2022) 027

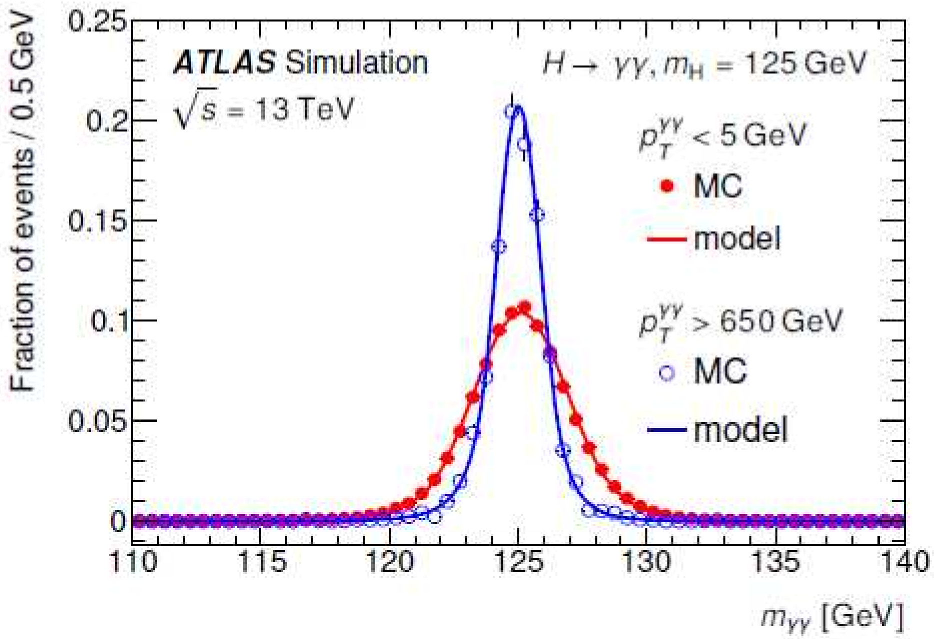


Figure 2: Signal $m_{\gamma\gamma}$ model in the lowest and highest $p_T^{\gamma\gamma}$ bins considered. The two fitted models (solid curves) are compared with the $m_{\gamma\gamma}$ distributions of the signal MC events in the lowest (filled markers) and highest (open markers) $p_T^{\gamma\gamma}$ bins. The resolution, evaluated as half the width of the narrowest interval containing 68.3% of the simulated events, varies between 1.0 GeV and 1.9 GeV.

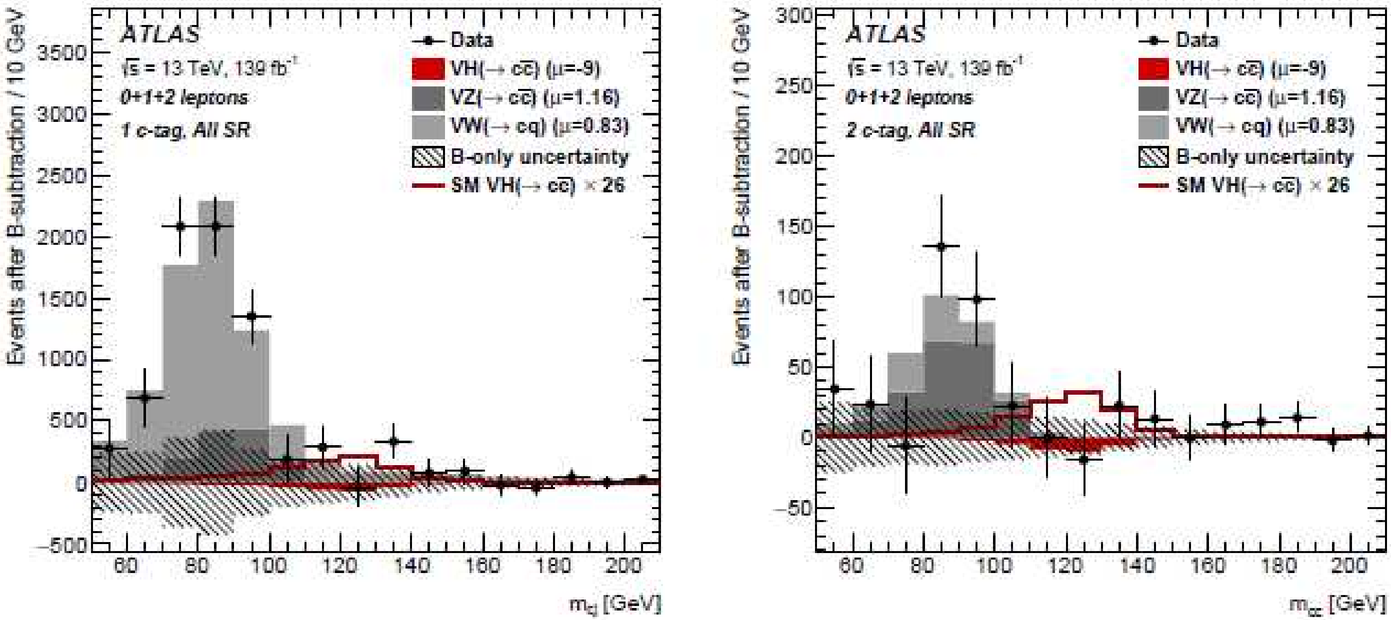
The SM BEH boson $H \to cc$

Eur.Phys.J.C 82 (2022) 717

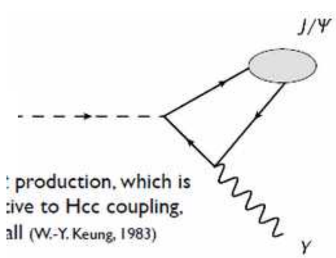
$H \to cc$

in mode V H

$|\kappa_c| < 8.5\ (12.4)$



also $H \to J/\psi\, \gamma$



constraint on charm coupling through H p_T distribution

($gg \to H$ and $cc \to H$)

ATLAS-CONF-2019-029

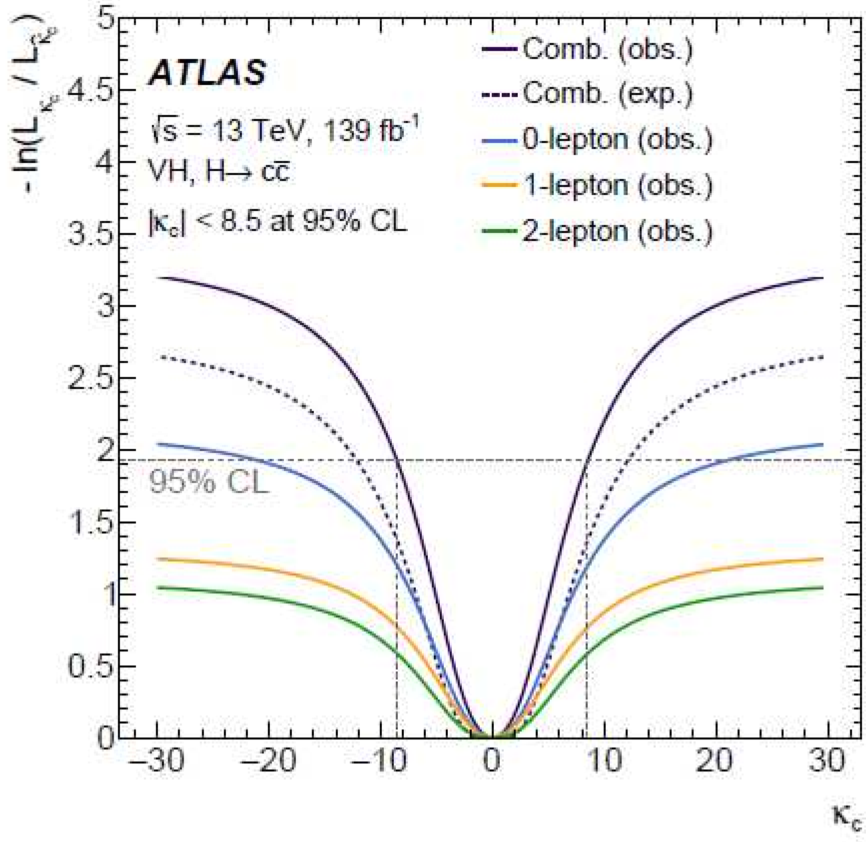
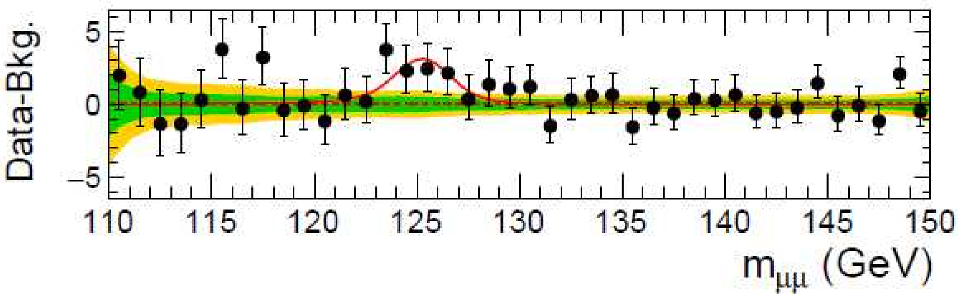


Figure 4: Expected and observed values of the negative profile log-likelihood ratio as a function of κ_c. The single-channel likelihoods are obtained using a five-POI fit, in which each channel has a separate $VH(\to c\bar{c})$ parameter of interest. The order of the lines in the plot matches the order of the lines in the legend.

The SM BEH boson $H \rightarrow \mu\mu$

JHEP 01 (2021) 148

3.0 σ (2.5 σ) 7+8+13 TeV

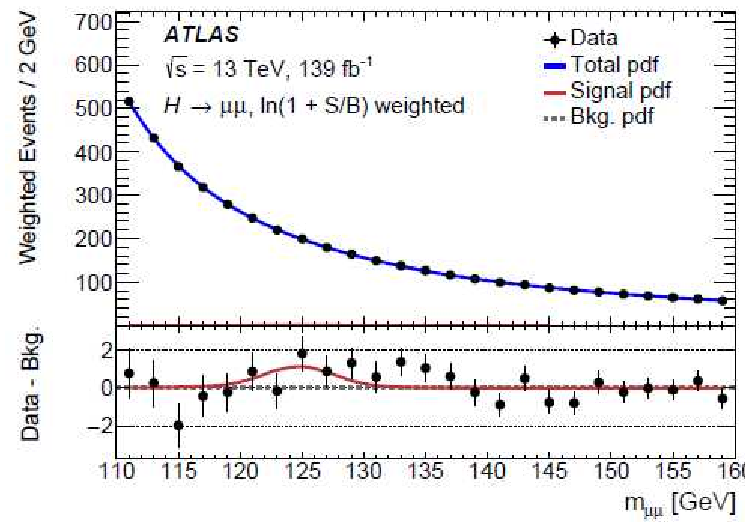


$$\mu = 1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}$$

CMS

Phys.Lett.B 812 (2021) 135980

2.0σ (1.7σ)



$$\mu = 1.2 \pm 0.6$$

ATLAS

The SM BEH boson $H \to Z\gamma$

Phys. Lett. B 809 (2020) 135754

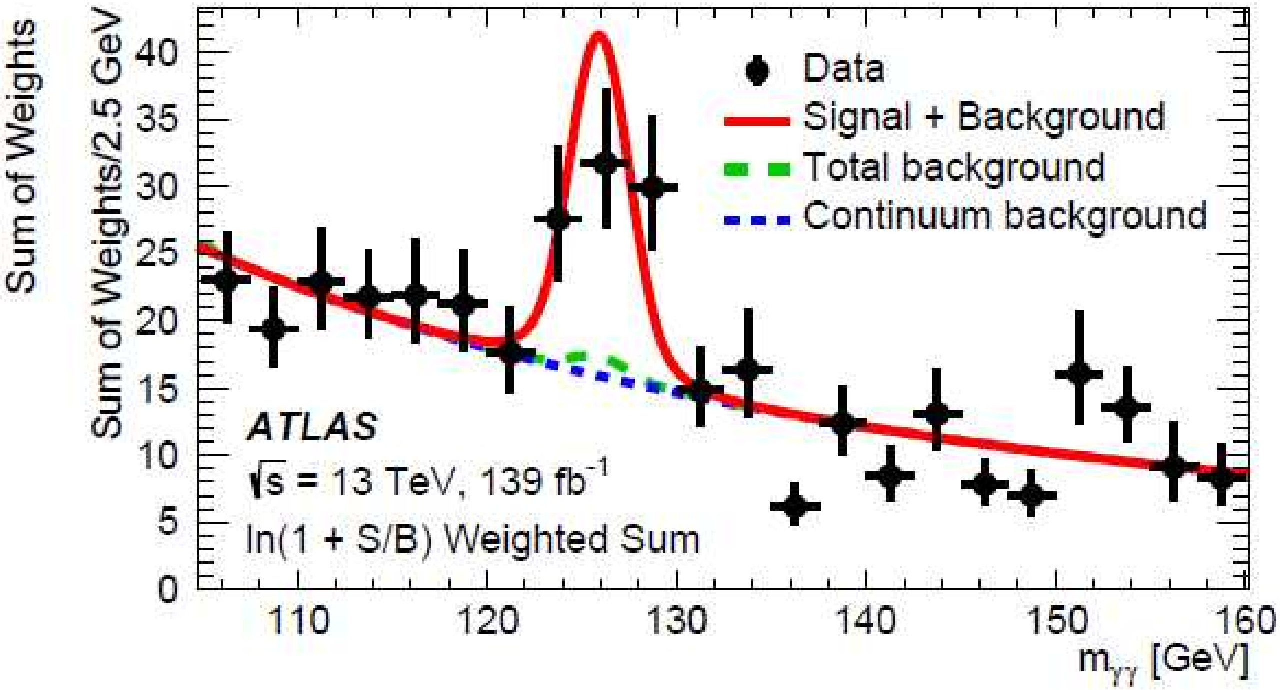
ATLAS: $\mu_{sig} = 2.0 \pm 1.0$, local significance 2.2(1.2) σ

CMS: $\mu_{sig} = 2.4 \pm 0.9$, local significance 2.7(1.2) σ

JHEP 05 (2023) 233

The SM BEH boson $t\,t\,H \quad H \rightarrow \gamma\,\gamma$

Phys.Rev.Lett. 125 (2020) 6, 061802

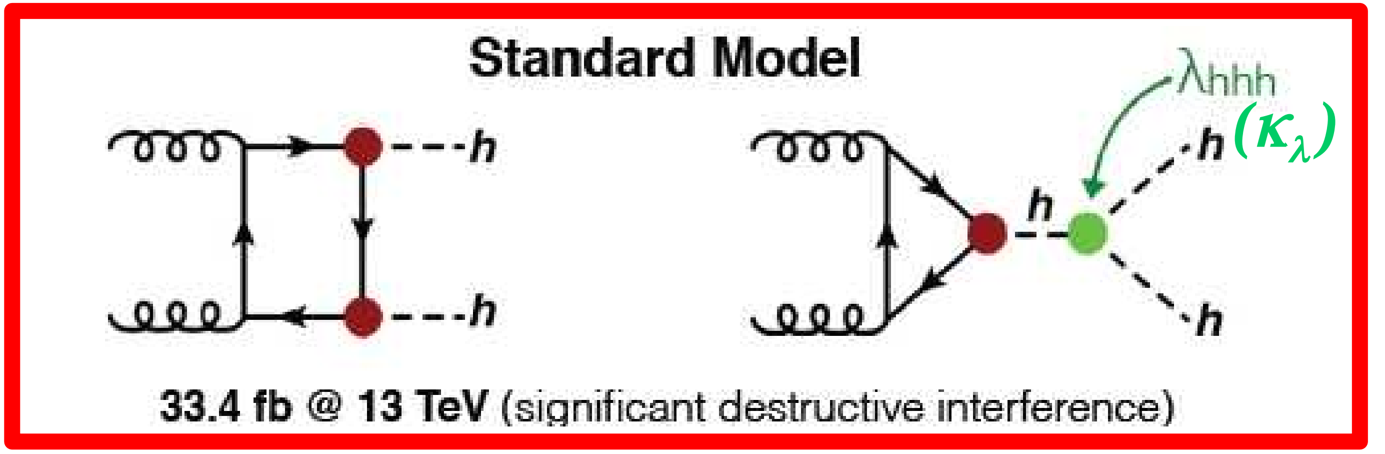


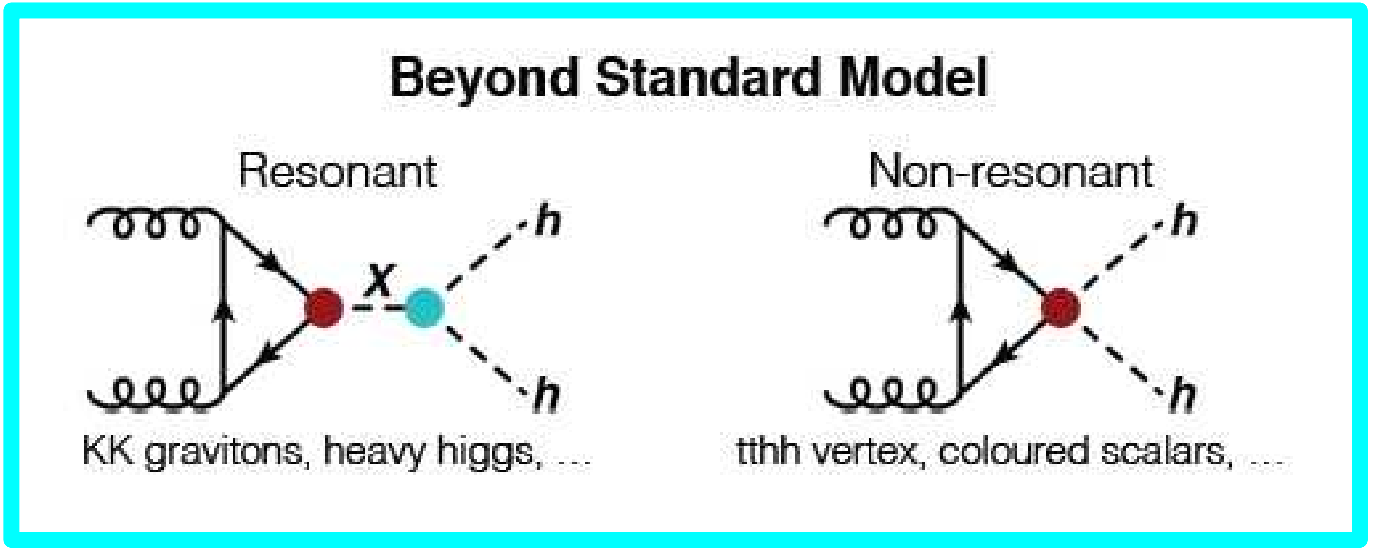
Assuming a CP-even coupling, the $t\bar{t}H$ process is observed with a significance of 5.2 standard deviations

4.4 expected

contraints on CP admixture

3 Search for a pair of BEH bosons





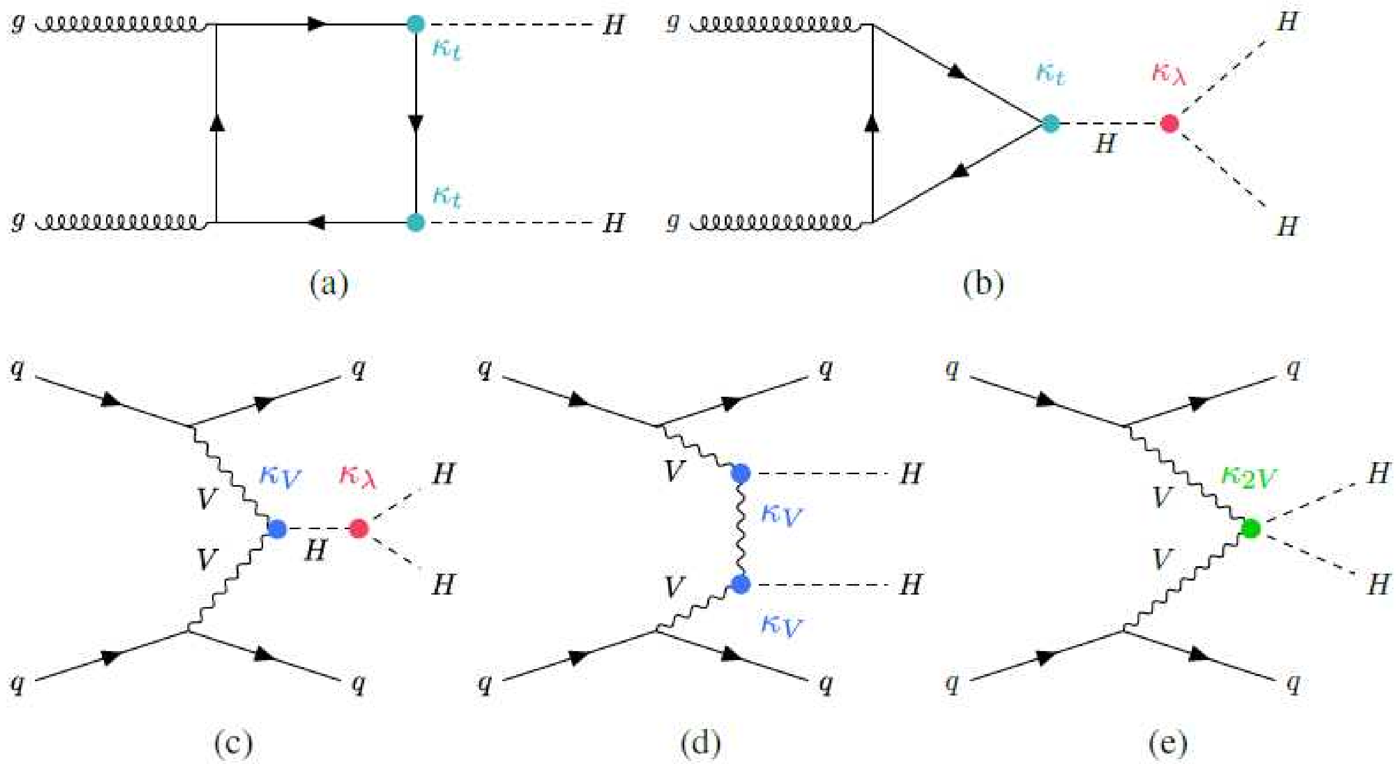


Figure 1: Examples of leading-order Feynman diagrams for Higgs boson pair production: for ggF production, diagram (a) is proportional to the square of the top-quark Yukawa coupling, while diagram (b) is proportional to the product of the top-quark Yukawa coupling and the Higgs boson self-coupling. For VBF production, diagram (c) is proportional to the product of the coupling of the Higgs boson to the vector bosons and the self-coupling, diagram (d) to the square of the coupling to the vector bosons, and diagram (e) to the interaction between two vectors bosons and two Higgs bosons.

Phys.Lett.B 843 (2023) 137745

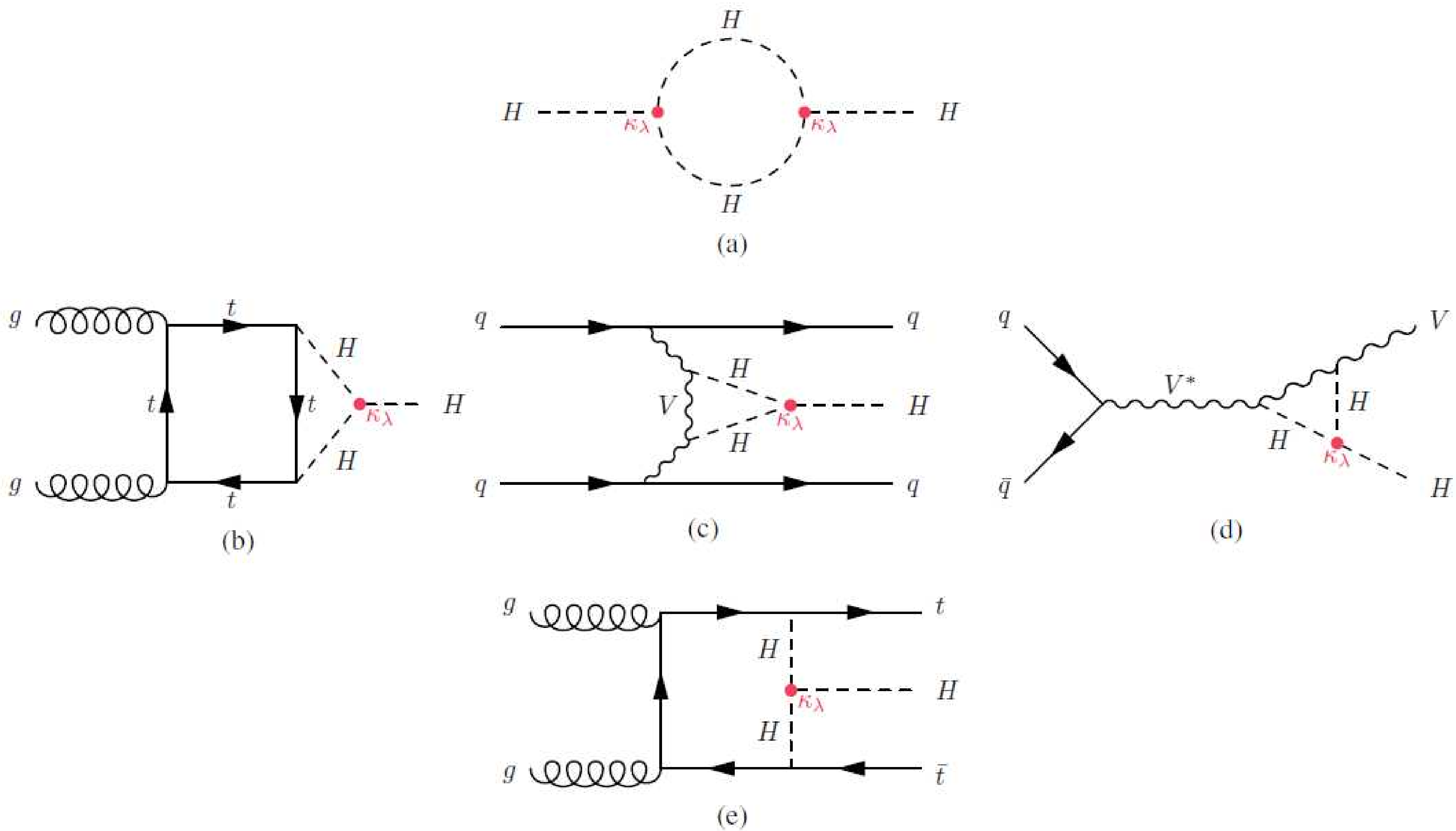


Figure 2: Examples of one-loop λ_{HHH}-dependent diagrams for (a) the Higgs boson self-energy, and for single-Higgs production in the (b) ggF, (c) VBF, (d) VH, and (e) $t\bar{t}H$ modes. The self-coupling vertex is indicated by the filled circle.

Phys.Lett.B 843 (2023) 137745

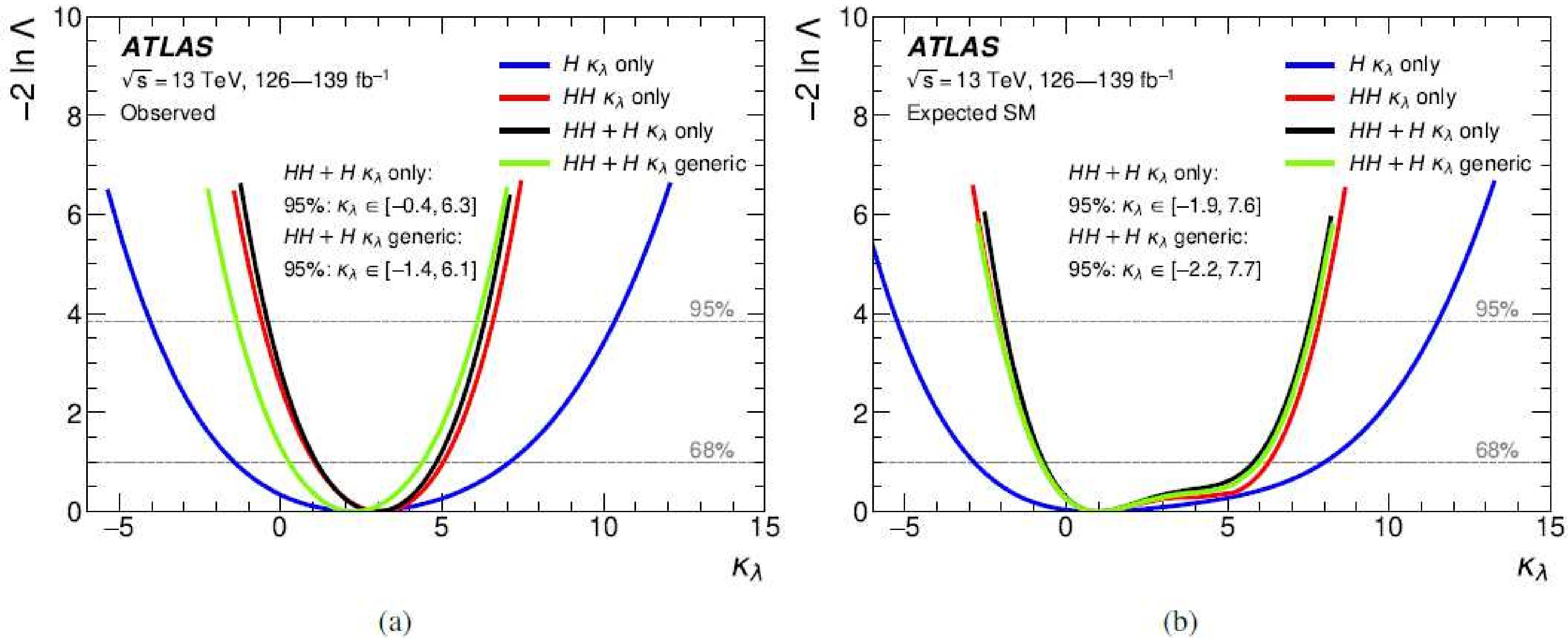


Figure 5: Observed (a) and expected (b) values of the test statistic ($-2 \ln \Lambda$), as a function of the κ_λ parameter for the single-Higgs (blue) and double-Higgs (red) analyses, and their combination (black) derived from the combined single-Higgs and double-Higgs analyses, with all other coupling modifiers fixed to unity. The combined result for the generic model (free floating κ_t, κ_b, κ_V and κ_τ) is also superimposed (green curve). The observed best-fit value of κ_λ for the generic model is shifted slightly relative to the other models because of its correlation with the best-fit values of the κ_b, κ_t and κ_τ parameters, which are slightly below, but compatible with unity.

Phys.Lett.B 843 (2023) 137745

- ♪ *Historical introduction and setting the stage*
  - *Spontaneous Symmetry Breaking*
  - *LHC and (mainly) ATLAS and CMS*
  - *H(125) discovery*
- ♪ ***Results from Run 1 & Run 2 (& start of Run 3) (up to now) :***
  - *mainly H(125)*
  - ***other physics (precision, searches)***
- ♪ *Future of LHC , Run 3 , HL-LHC*
- ♪ *Conclusions*
- ♪ *Backup*

EW precision measurements

W mass m_W

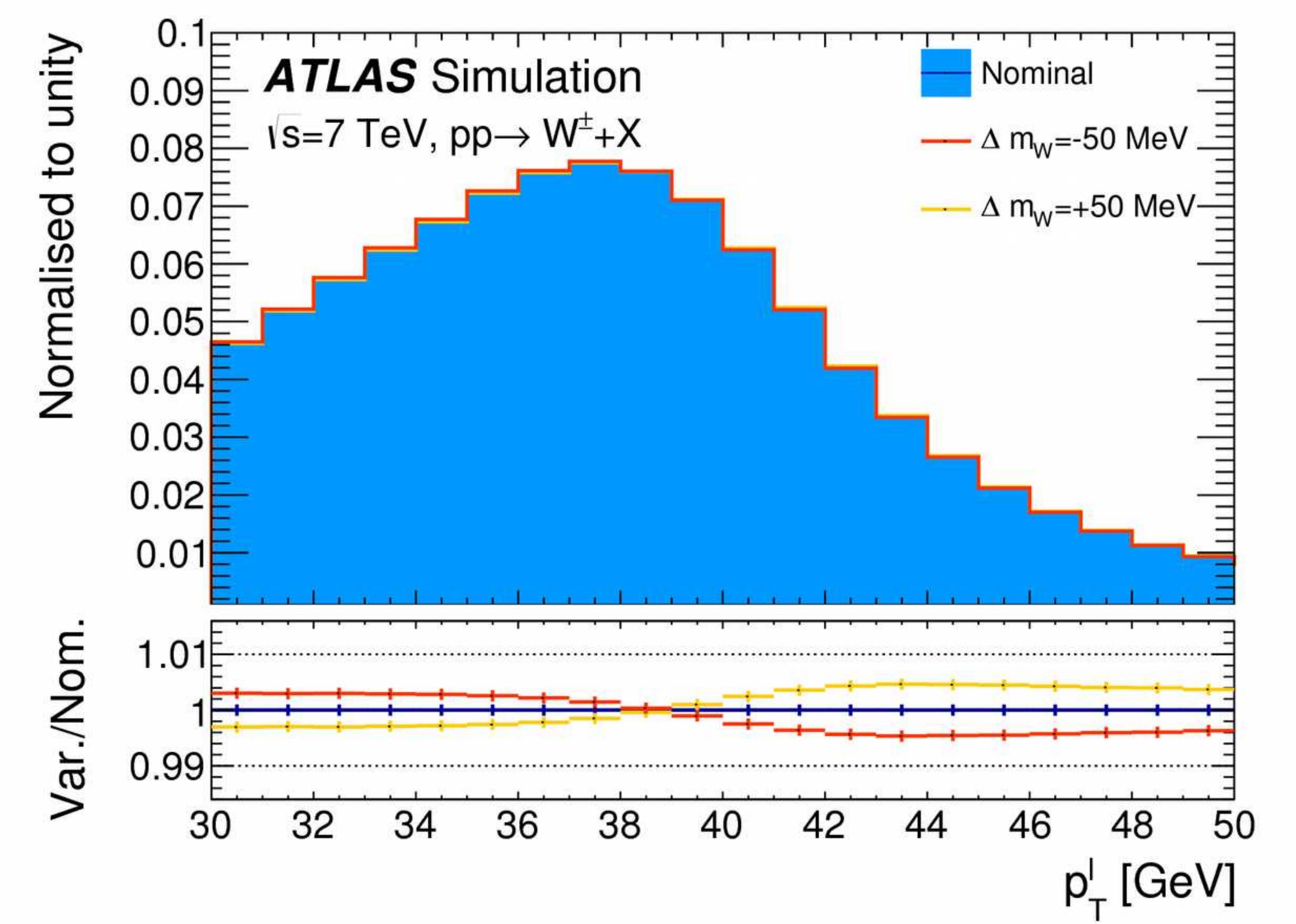
arXiv:1701.07240

$$m_W = 80369.5 \pm 6.8\,\text{MeV(stat.)} \pm 10.6\,\text{MeV(exp. syst.)} \pm 13.6\,\text{MeV(mod. syst.)}$$
$$= 80369.5 \pm 18.5\,\text{MeV},$$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

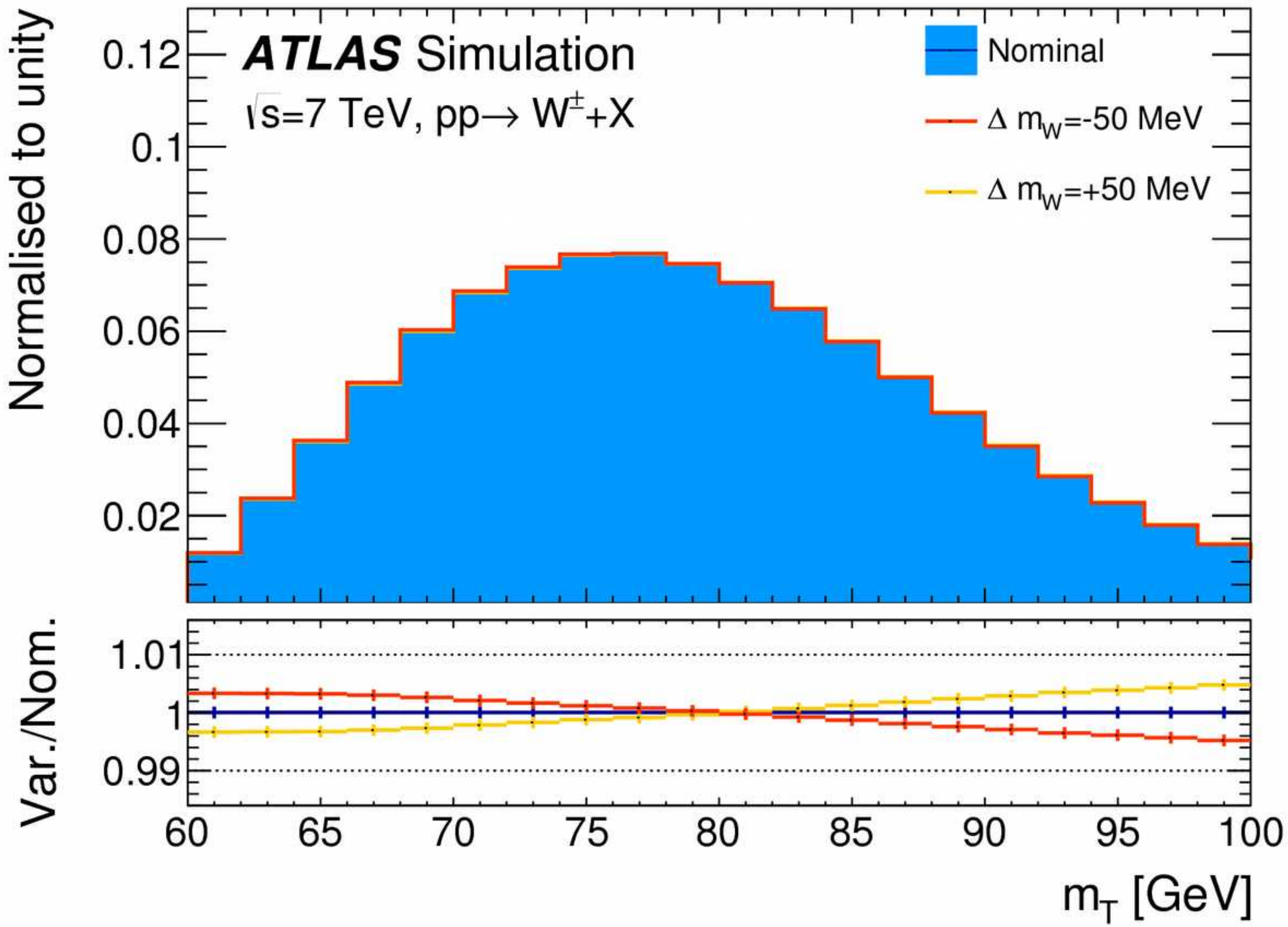
EW precision measurements

W mass m_W



EW precision measurements

W mass m_W



EW precision measurements
W mass m_W LHCb

muon p_T based m_W measurement by LHCb *2016 dataset 1.7 fb $^{-1}$*

M.Vesterinen CERN seminar 29 June 2021

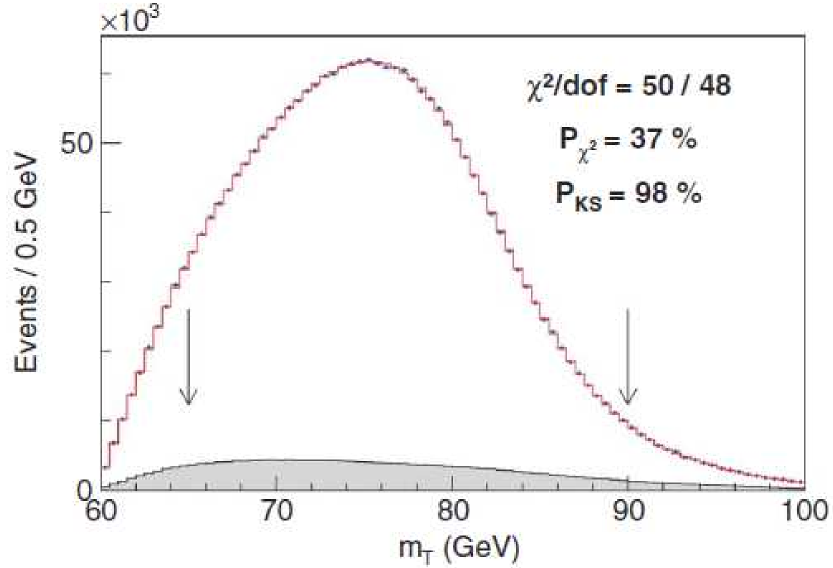
JHEP 01 (2022) 036

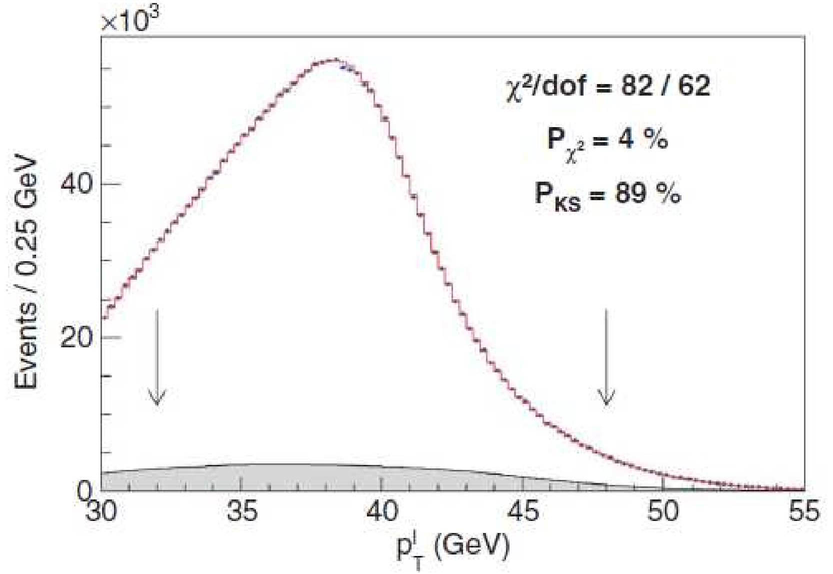
$$m_W = 80354 \pm 23_{\mathrm{stat}} \pm 10_{\mathrm{exp}} \pm 17_{\mathrm{theory}} \pm 9_{\mathrm{PDF}}\ \mathrm{MeV}$$

Source	Size [MeV]	
Parton distribution functions	9	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	17	
Transverse momentum model	11	Envelope from five different models
Angular coefficients	10	"Uncorrelated" 31 point scale variation
QED FSR model	7	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5	Test with POWHEGew
Experimental total	10	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Momentum scale and resolution modelling	7	
Muon ID, trigger and tracking efficiency	6	
Isolation efficiency	4	
QCD background	2	
Statistical	23	
Total	32	

EW precision measurements

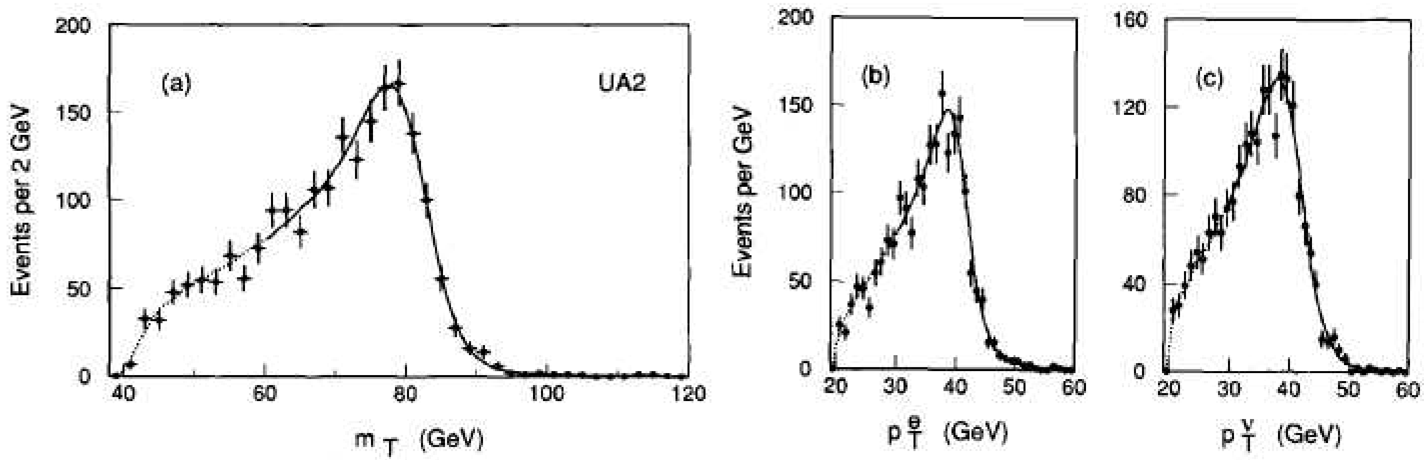
W mass m_W LHCb





muon channel

EW precision measurements
W mass m_W UA2'



The size (in MeV) of the systematic uncertainties in measuring m_W and m_Z.

	$\delta m_W(m_T)$	$\delta m_W(p_T^e)$	$\delta m_W(p_T^\nu)$	δm_Z(central)	$\delta m_Z(p_T$-con)
structure function	85	135	105	–	–
electron energy resolution	75	100	75	35	35
neutrino scale	70	–	140	–	–
p_T^W and p_T^{had}	60	120	90	–	–
underlying event	30	50	–	50	50
fitting procedure	30	40	40	–	–
radiative decays	30	50	20	50	50
electron efficiency versus p_T^e	30	40	30	–	–
$u_\parallel$ effect	25	95	350	–	–
p_T constraint	–	–	–	–	100
total systematic uncertainties	160	240	420	80	130

Physics Letters B 276 (1992) 354–364

EW precision measurements
W mass m_W CDF

Table 1. Individual fit results and uncertainties for the M_W measurements. The fit ranges are 65 to 90 GeV for the m_T fit and 32 to 48 GeV for the p_T^ℓ and p_T^ν fits. The χ^2 of the fit is computed from the expected statistical uncertainties on the data points. The bottom row shows the combination of the six fit results by means of the best linear unbiased estimator (66).

Distribution	*W* boson mass (MeV)	χ^2/dof
$m_T(e, \nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^\ell(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^\nu(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu, \nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^\ell(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^\nu(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

CDF Collaboration *et al.*, *Science* **376**, 170–176 (2022)

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

arXiv:2212.09153v1

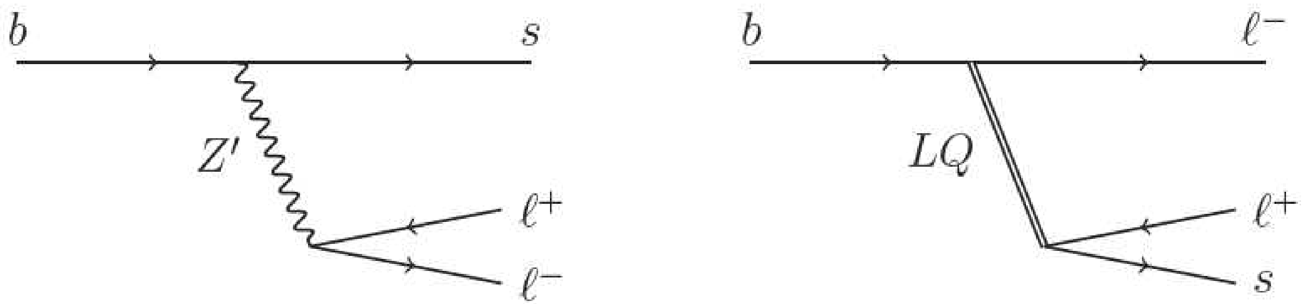


Figure 2: Examples of Feynman diagrams for $b \to s\ell^+\ell^-$ decays beyond the SM. Potential contributions from new heavy Z' gauge bosons are shown on the left, contributions from leptoquarks (LQ) on the right.

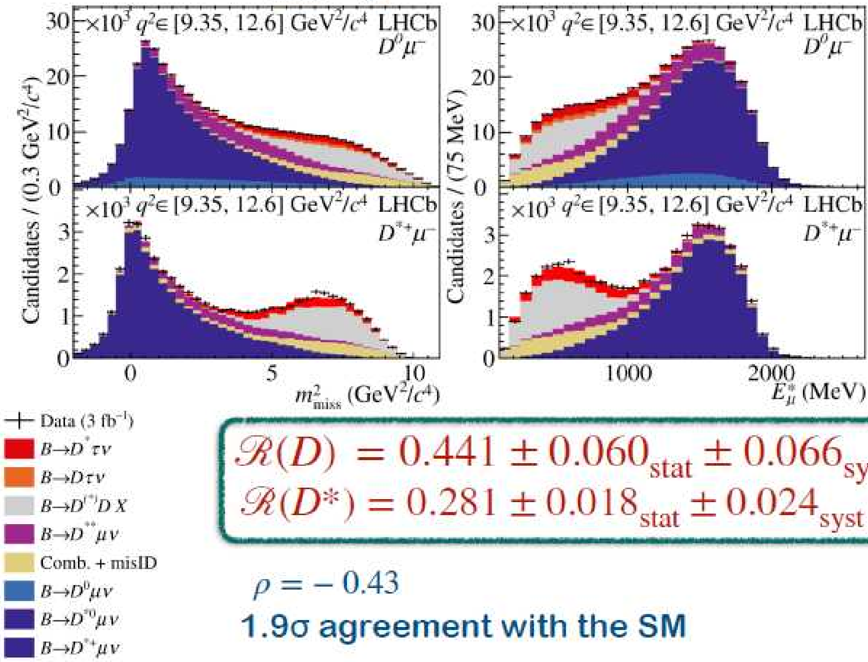
New $\mathcal{R}$(D) and $\mathcal{R}$(D*) results!

Still run 1

Simultaneous analysis of $\mathcal{R}$(D) and $\mathcal{R}$(D*) from muonic decays

3D fit in $m^2_{\text{miss}}, E^*_\mu, q^2$

arXiv:2302.02886



$$\mathcal{R}(D) = 0.441 \pm 0.060_{\text{stat}} \pm 0.066_{\text{syst}}$$
$$\mathcal{R}(D^*) = 0.281 \pm 0.018_{\text{stat}} \pm 0.024_{\text{syst}}$$

$\rho = -0.43$

1.9σ agreement with the SM

run 2: 2015 & 2016

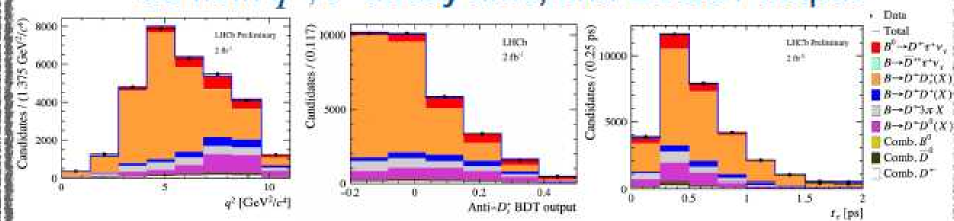
$\mathcal{R}$(D*) from hadronic decays

arXiv:2305.01463

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = \frac{N_{\text{sig}}}{N_{\text{norm}}}\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}\frac{1}{\mathcal{B}(\tau^+ \to 3\pi^\pm(\pi^0)\bar{\nu}_\tau)}$$

$$R(D^*) = \mathcal{K}(D^*)\left\{\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right\}_{\text{ext. input}}$$

3D fit in q^2, τ^+decay time, anti-Ds BDT output

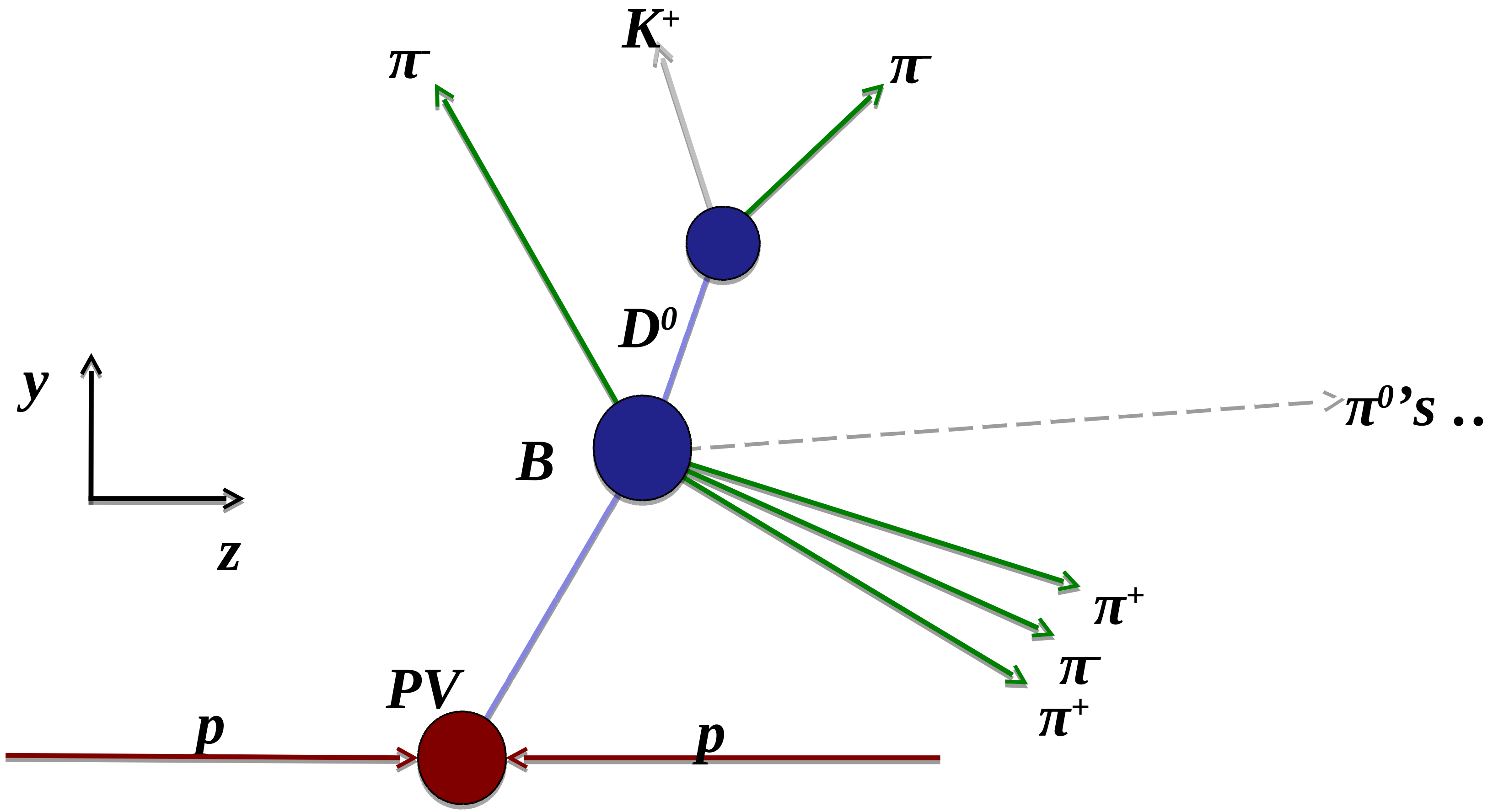


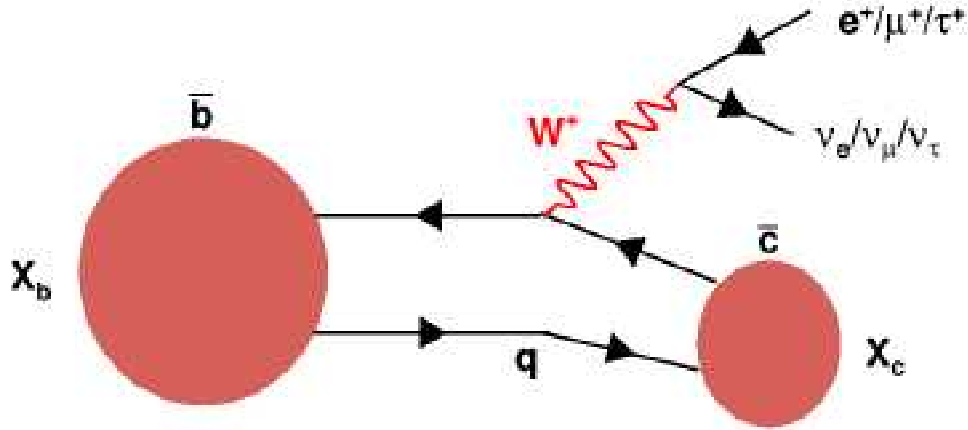
$$R(D^*) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$$

Combination with run 1 result:

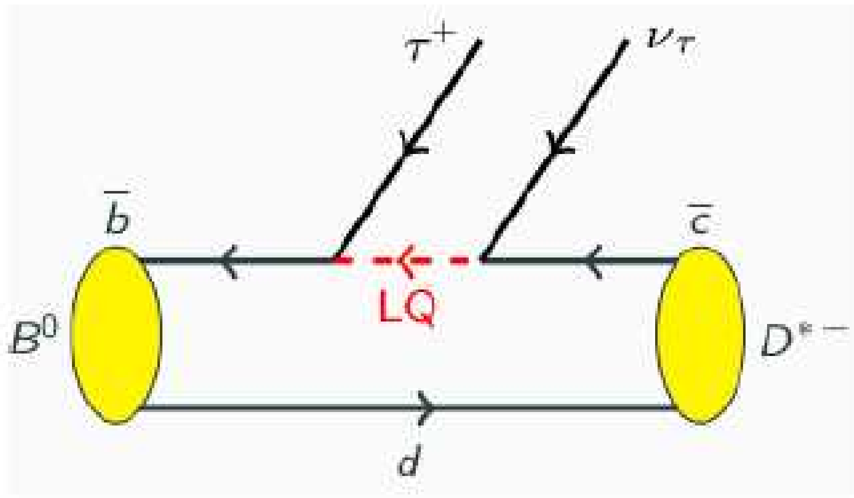
$$\mathcal{R}(D^*) = 0.257 \pm 0.012_{\text{stat}} \pm 0.014_{\text{syst}} \pm 0.012_{\text{ext}}$$

1.0σ agreement with the SM


K+
π−
π−
D0
y
π0's …
B
z
π+
π−
π+
PV
p
p



e+/μ+/τ+
W+
b̄
νe/νμ/ντ
c̄
Xb
q
Xc



τ+
ντ
b̄
c̄
LQ
B0
D*−
d

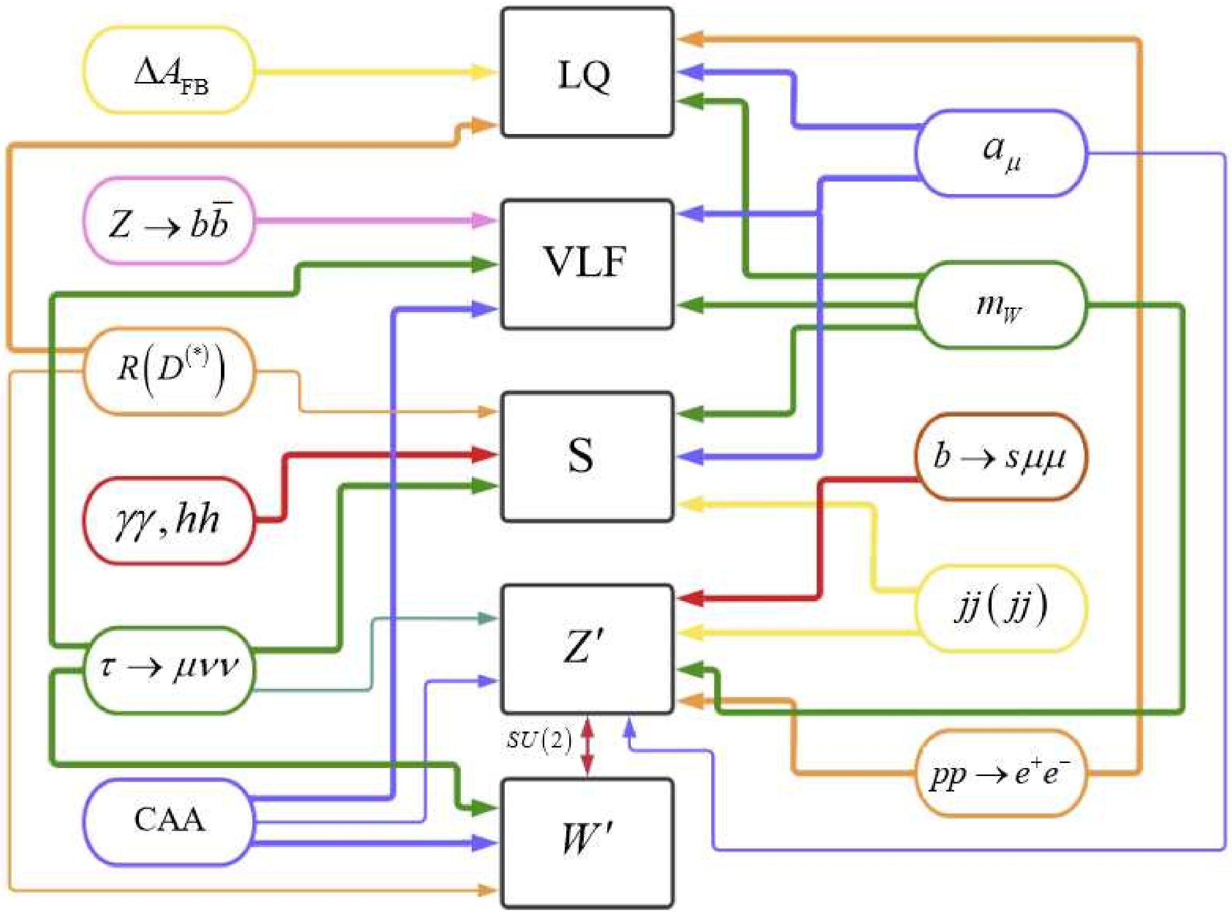


Figure 4: Summary of the anomalies together with the implications for extending the SM with new particles: Leptoquarks (LQ), vector-like fermions (VLF), electrically neutral scalars (S), neural gauge bosons (Z') and charged gauge bosons (W'). Thick lines indicate that full explanations are possible while thin lines mean that only a partial one is or that conflicts with other observables exist.

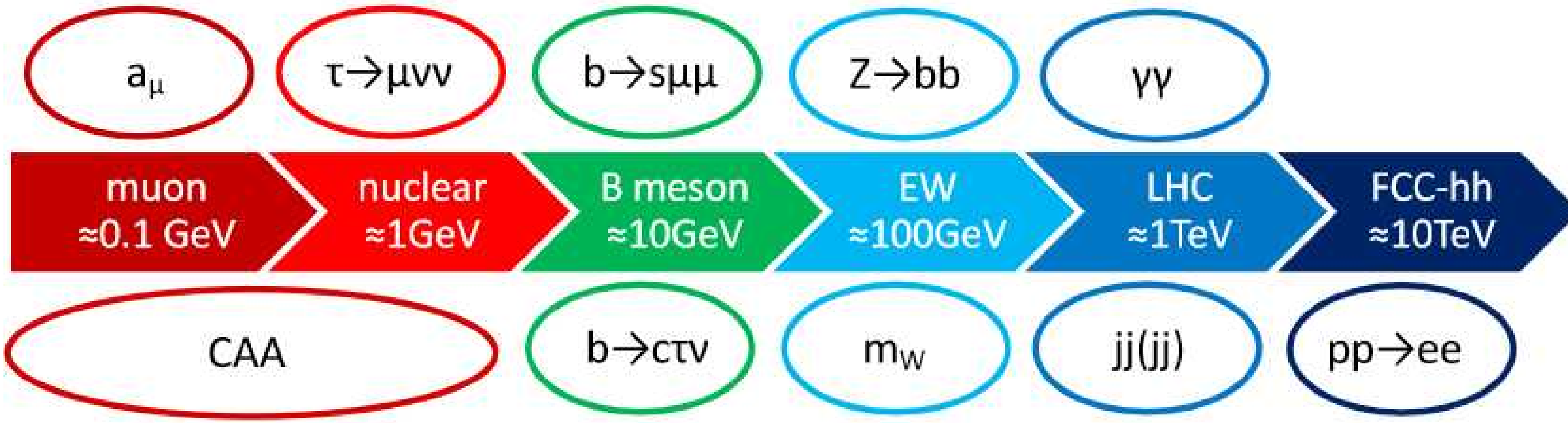


Figure 2: Compilation of various anomalies ordered according to the corresponding energy scale.

Searches ATLAS CMS low mass γγ

CMS PAS HIG-20-002

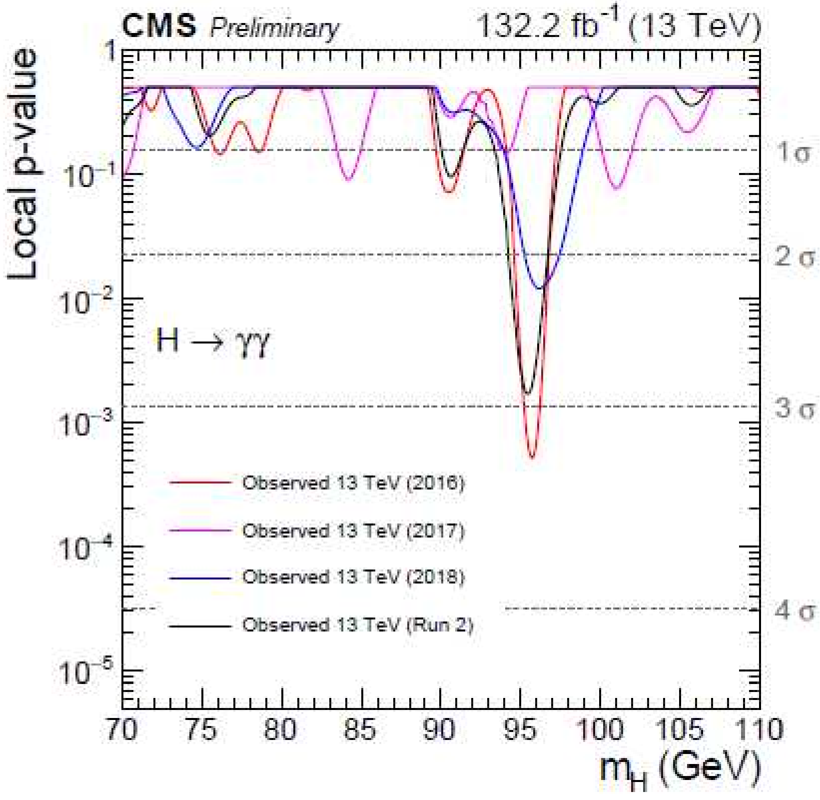


Figure 7: The observed local p-values for an additional SM-like Higgs boson as a function of m_{H}, from the analysis of the data from 2016, 2017, 2018, and their combination.

Searches ATLAS CMS low mass γγ

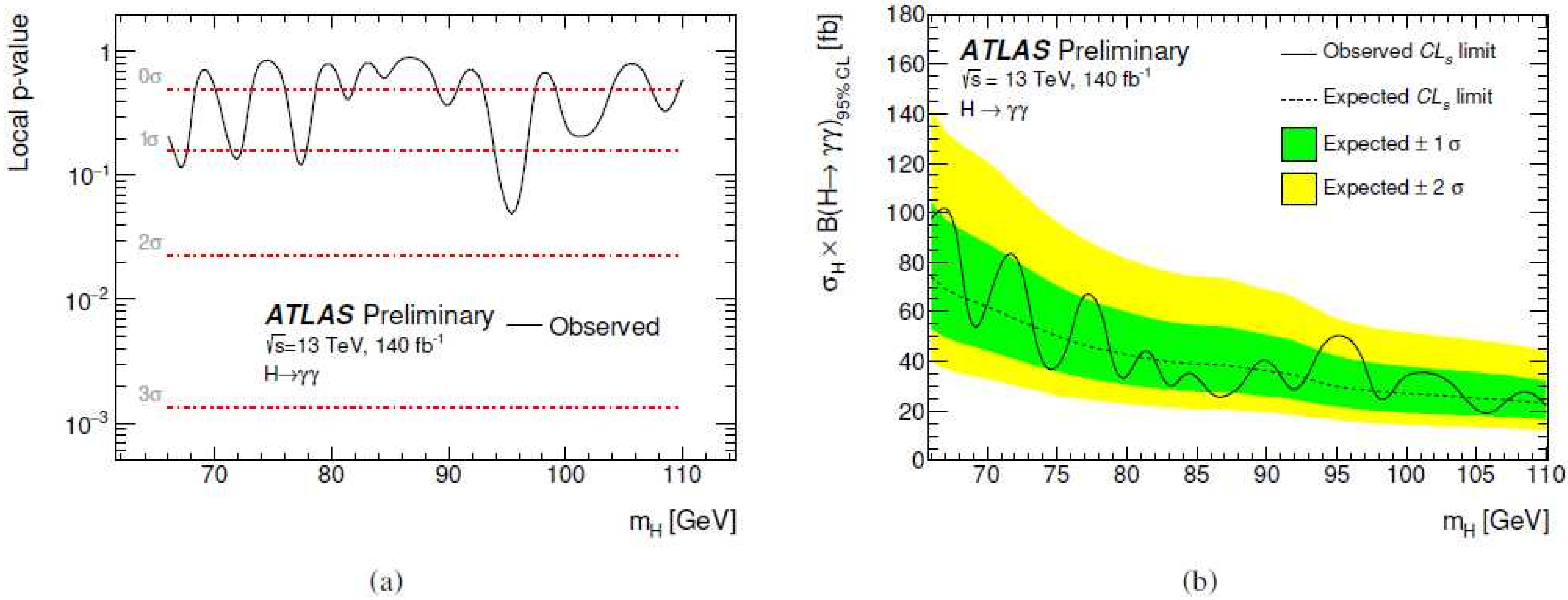


Figure 7: The (a) compatibility of the data, in the model-dependent search, in terms of local p-value (solid line), with the background-only hypothesis as a function of the assumed signal mass m_H. The dotted-dashed lines correspond to the standard deviation quantification σ. The (b) upper limit on the total cross-section times branching ratio $\mathcal{B}(H \to \gamma\gamma)$ as a function of m_H, where the solid (dashed) line corresponds to the observed (expected) limit and the green (yellow) band corresponds to one (two) standard deviation from the expectation.

ATLAS-CONF-2023-035

Searches ATLAS CMS low mass γγ

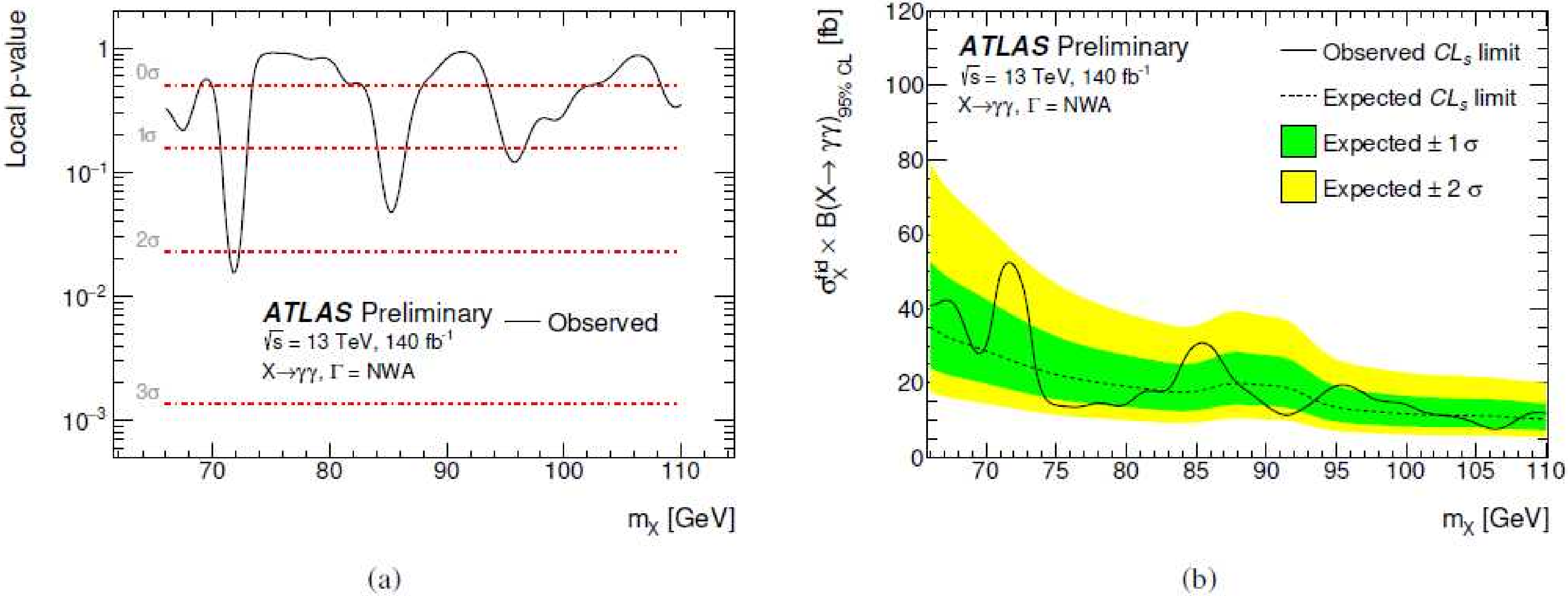


Figure 6: The (a) compatibility of the data, in the model-independent search, in terms of local p-value (solid line), with the background-only hypothesis as a function of the assumed signal mass m_X. The dotted-dashed lines correspond to the standard deviation quantification σ. The (b) upper limit on the fiducial cross-section times branching ratio $\mathcal{B}(X \to \gamma\gamma)$ as a function of m_X, where the solid (dashed) line corresponds to the observed (expected) limit and the green (yellow) band corresponds to one (two) standard deviation from the expectation.

ATLAS-CONF-2023-035

♪ *Historical introduction and setting the stage*

Spontaneous Symmetry Breaking

LHC and (mainly) ATLAS and CMS

H(125) discovery

♪ *Results from Run 1 & Run 2 (& start of Run 3) (up to now) :*

- *mainly H(125)*
- *other physics (precision, searches)*

♪ ***Future of LHC , Run 3 , HL-LHC***

♪ *Conclusions*

♪ *Backup*

Phase II upgrades

Upgrades of ATLAS & CMS to prepare for HL-LHC:

- ❑ Projects have made very good progress, moving from R&D and prototyping phase to (pre-)production

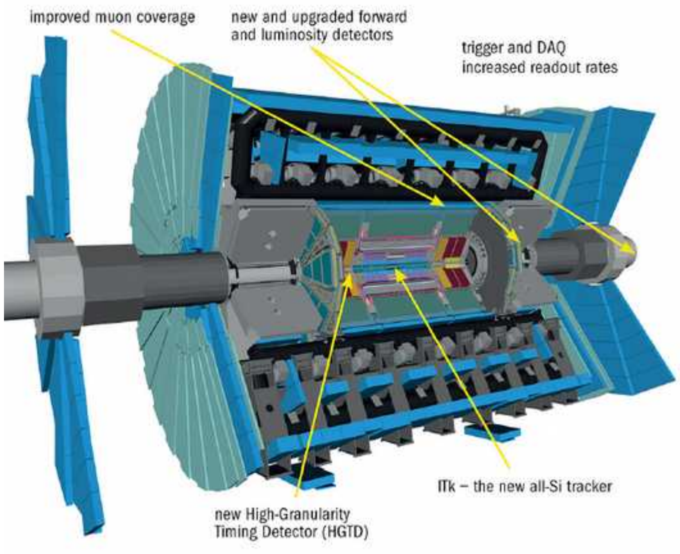
But there are challenges:

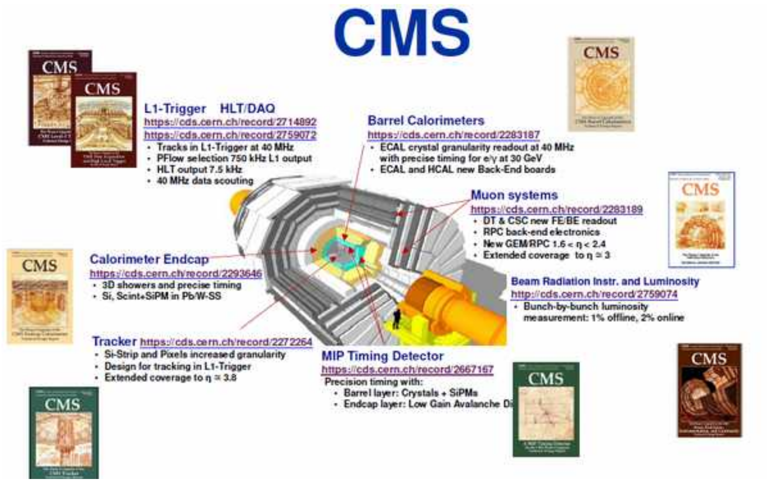
- ❑ Chip design and validation
- ❑ Some (sub)detectors very close to critical path
- ❑ Contributions from institutes in Russia (and Belarus):
  strong recommendation from the LHCC to develop plans to become as much as possible independent of (time-)critical in-kind contributions
- ❑ CMS HGCAL most exposed project

Mitigation:

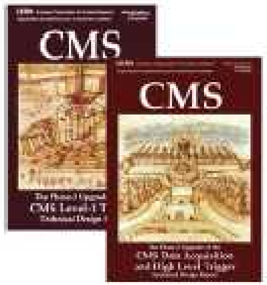
- ❑ Stronger engagement by all people and institutes in the collaborations
- ❑ Develop plans to speed up production phase

ATLAS





CMS



L1-Trigger HLT/DAQ

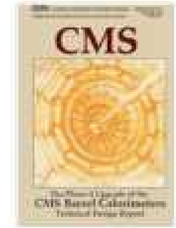
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072

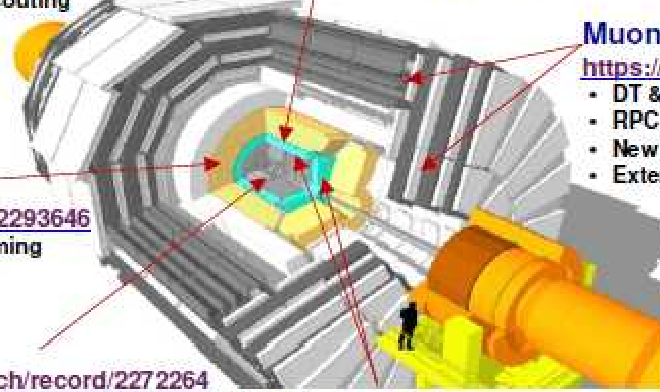
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters

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

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

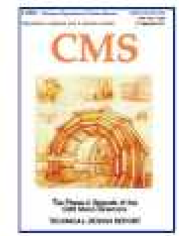




Muon systems

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

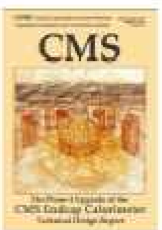
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap

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

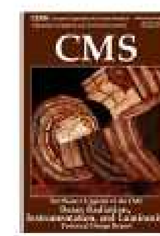
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Beam Radiation Instr. and Luminosity

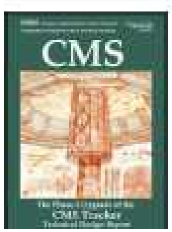
http://cds.cern.ch/record/2759074

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



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

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

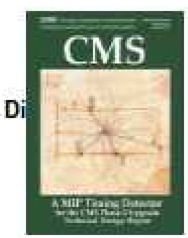


MIP Timing Detector

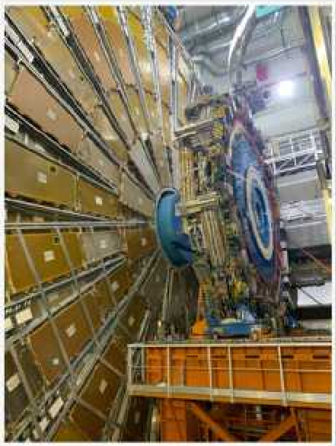
https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Di

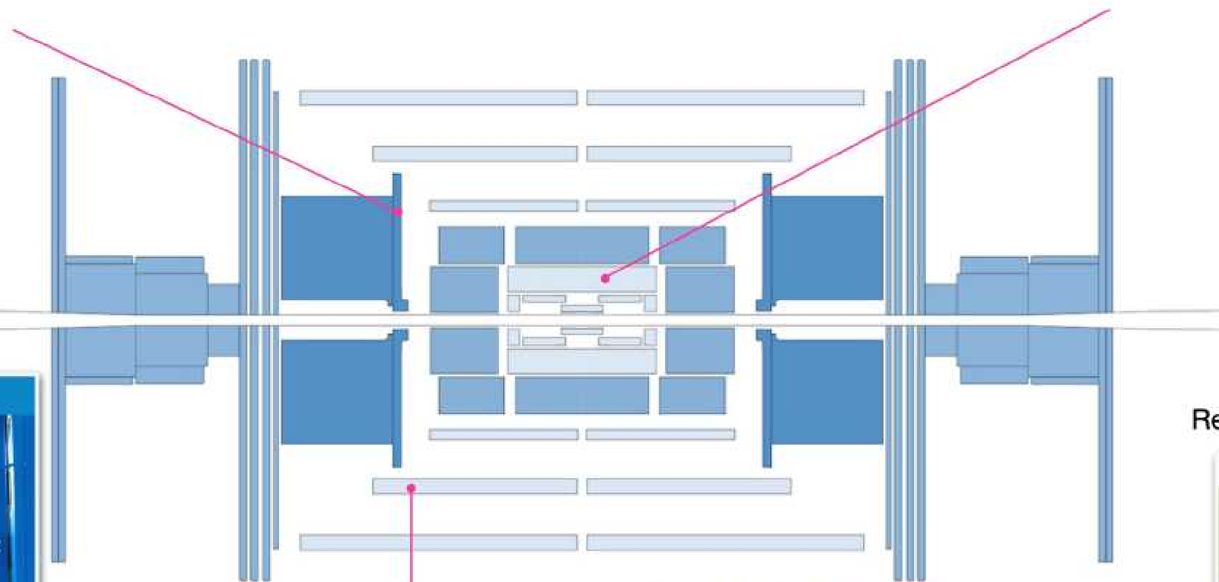


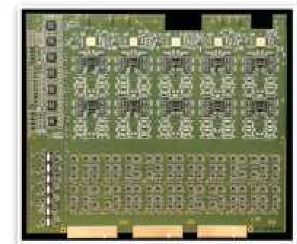
ATLAS Phase-I Upgrades for Run 3



Muon New Small Wheels
Precision tracking, identification and triggering

New LAr Calorimeter digital trigger electronic boards
Improved trigger granularity





AFP
Re-designed TOF detector

Trigger and Data Acquisition
Upgraded hardware, firmware and software for improved trigger and DAQ

TDAQ Upgrade briefing

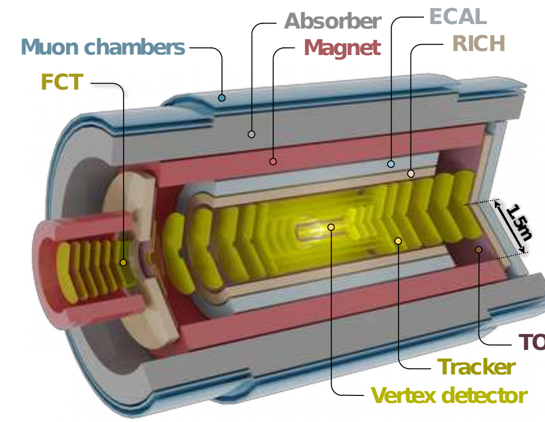
BIS78
New Muon chambers sMDT and new generation RPC (8 chambers installed)

Phase IIb Upgrades

Fully exploit HL-LHC for Heavy Ion & Flavour physics

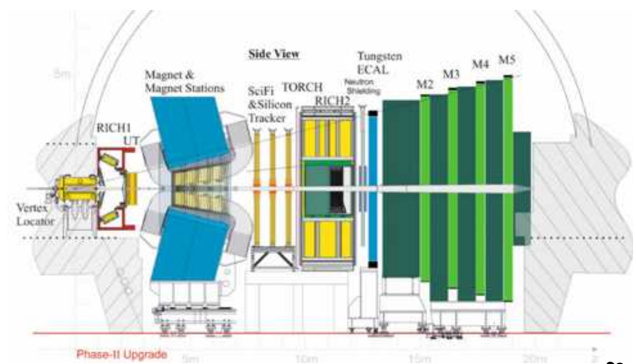
ALICE3:

- ❑ ***Tracking precision x 3: 10 µm at p_T = 200 MeV***
- ❑ ***Acceptance x 4.5: |η| < 4 (with particle ID)***
- ❑ ***A-A rate x 5 (pp x 25)***
- ❑ ***Excellent particle ID***



LHCb Upgrade II:

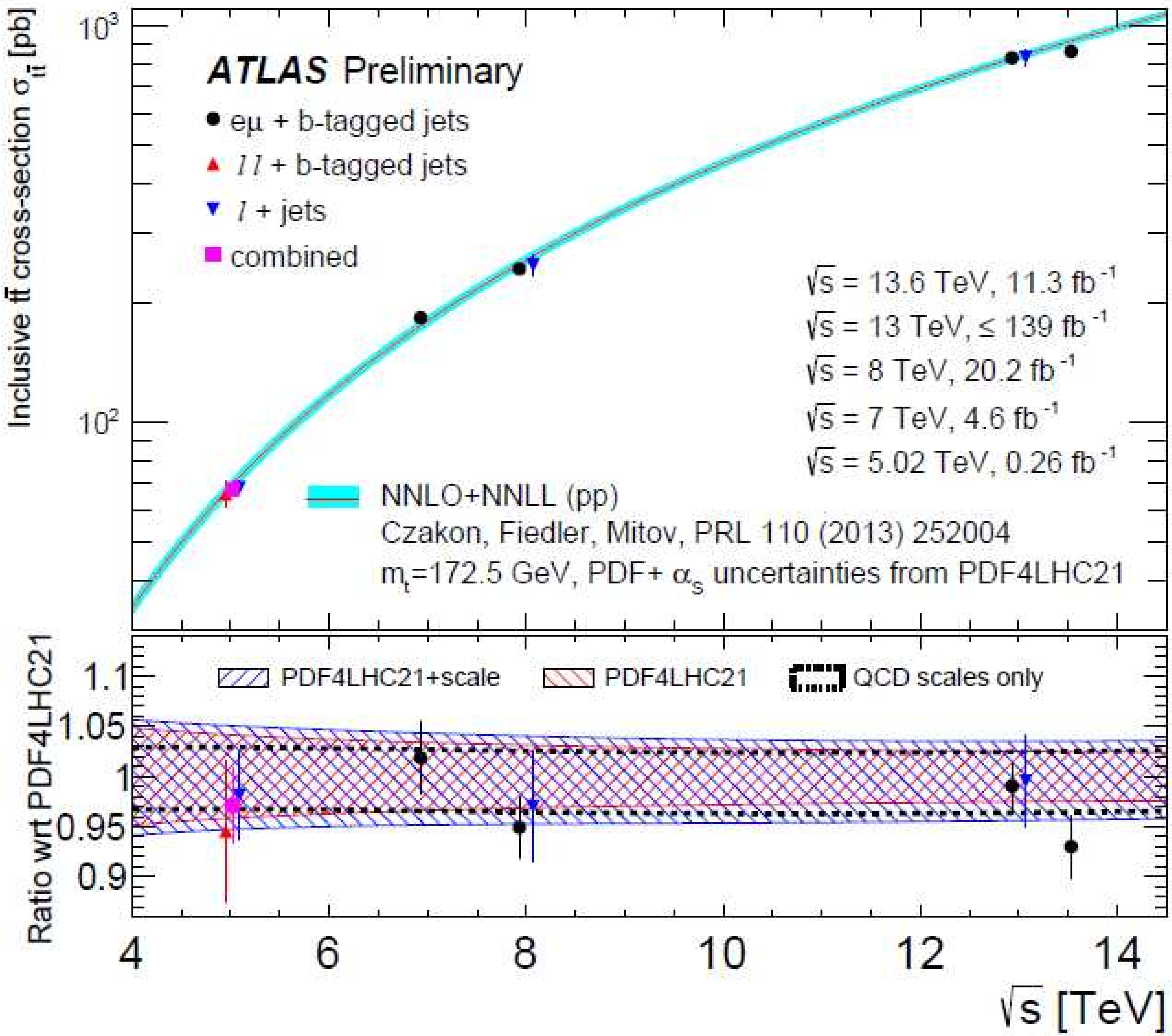
- ❑ ***Precision timing few tens of ps: Vertex Detector, RICH,ECAL, …***
- ❑ ***Tracker based on Scintillating Fibres with cryo-cooled SiPMs & first rad-hard CMOS tracker***



LHCC review for both projects started
Discussions with Funding Agencies ongoing (special RRBs)

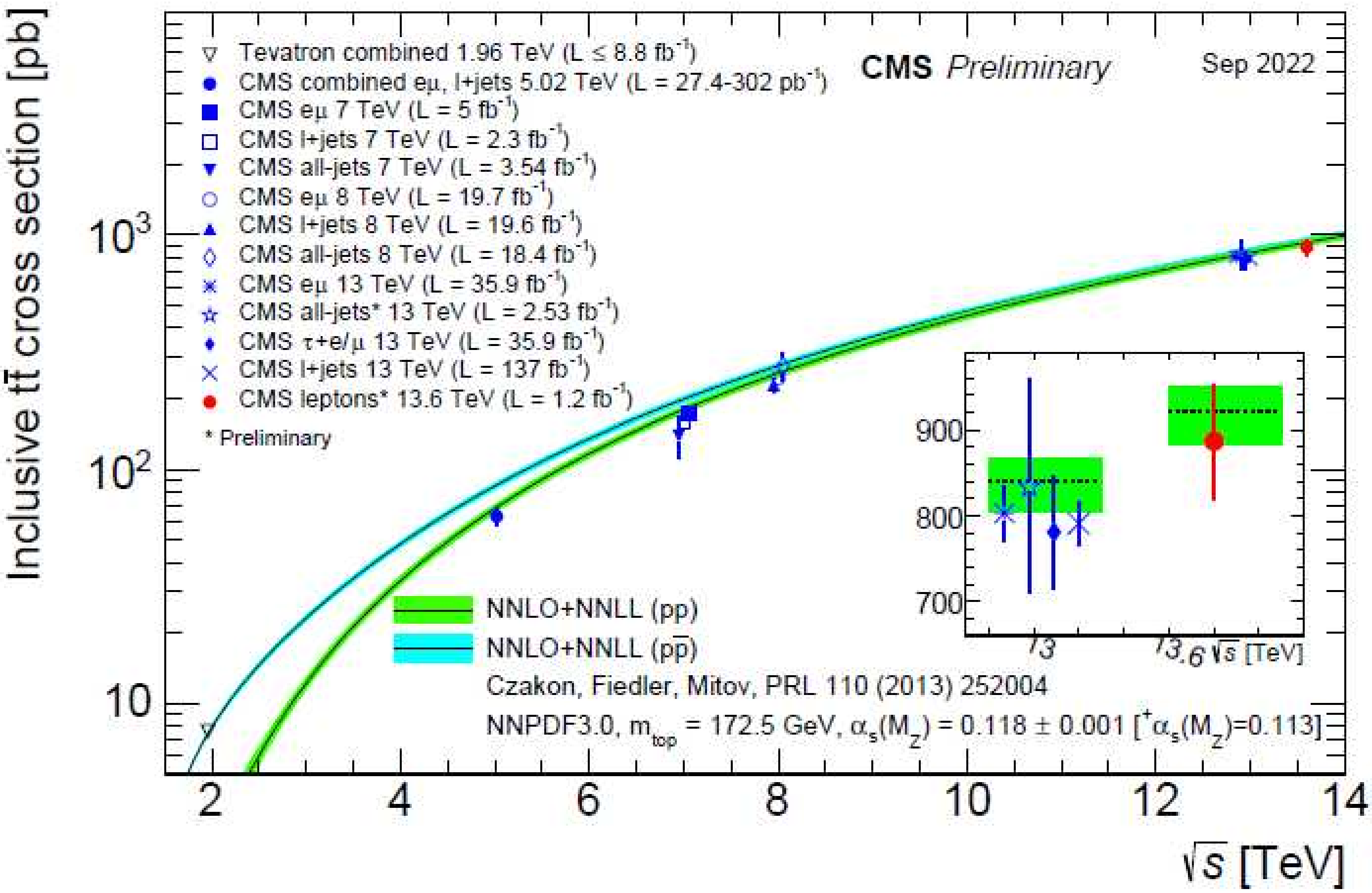
Innovative technologies relevant for future HEP experiments
Pathfinder towards future (accelerator) projects

13.6 TeV results



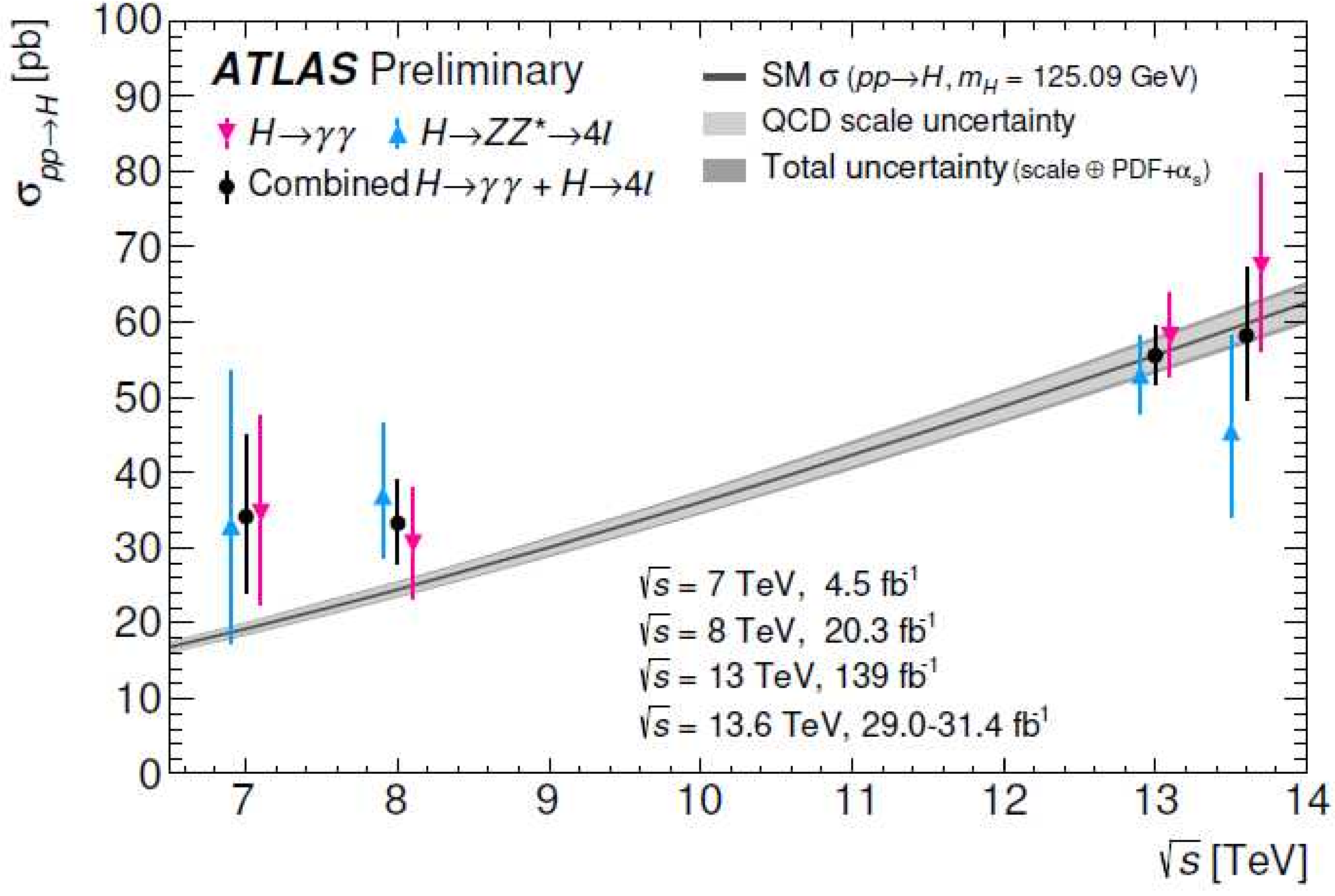
ATLAS-CONF-2023-006

13.6 TeV results



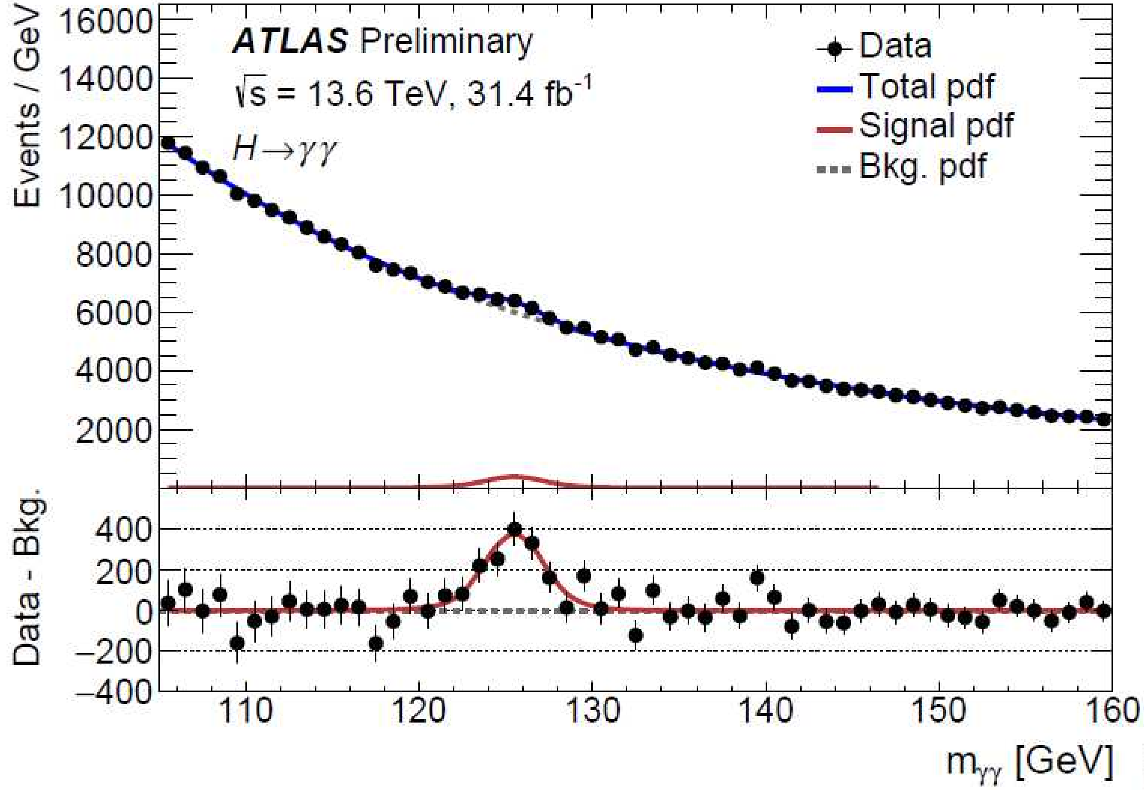
CMS PAS TOP-22-012

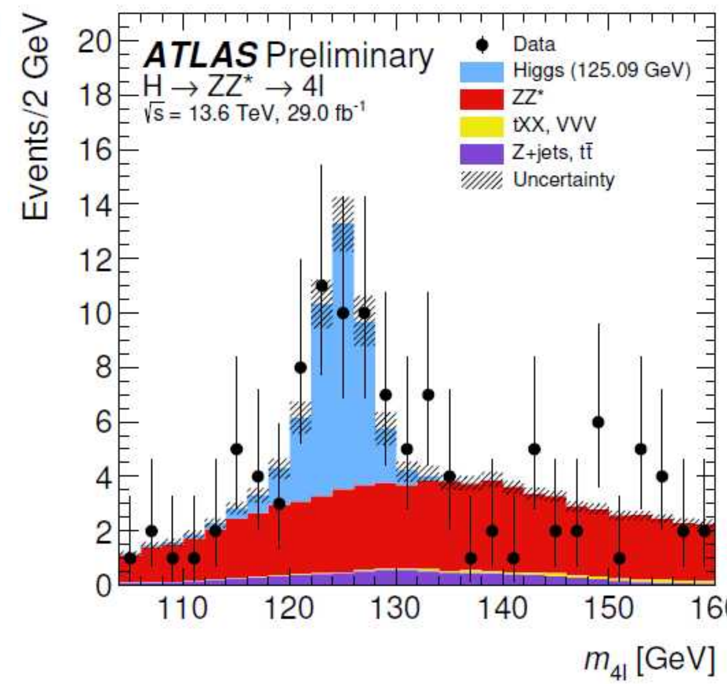
13.6 TeV results



ATLAS-CONF-2023-032

13.6 TeV results





ATLAS-CONF-2023-032

- ♪ *Historical introduction and setting the stage*
  - *Spontaneous Symmetry Breaking*
  - *LHC and (mainly) ATLAS and CMS*
  - *H(125) discovery*
- ♪ *Results from Run 1 & Run 2 (& start of Run 3) (up to now) :*
  - *mainly H(125)*
  - *other physics (precision, searches)*
- ♪ *Future of LHC , Run 3 , HL-LHC*
- ♪ ***Conclusions***
- ♪ *Backup*

♪ *Historical introduction and setting the stage*

Spontaneous Symmetry Breaking

LHC and (mainly) ATLAS and CMS

H(125) discovery

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(up to now) :

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♪ ***Backup***