ZE STANDARD MODEL (ELECTROWEAK SECTOR)

Georges Aad (CPPM)

JJC2014 - 2014-12-09

Disclaimer

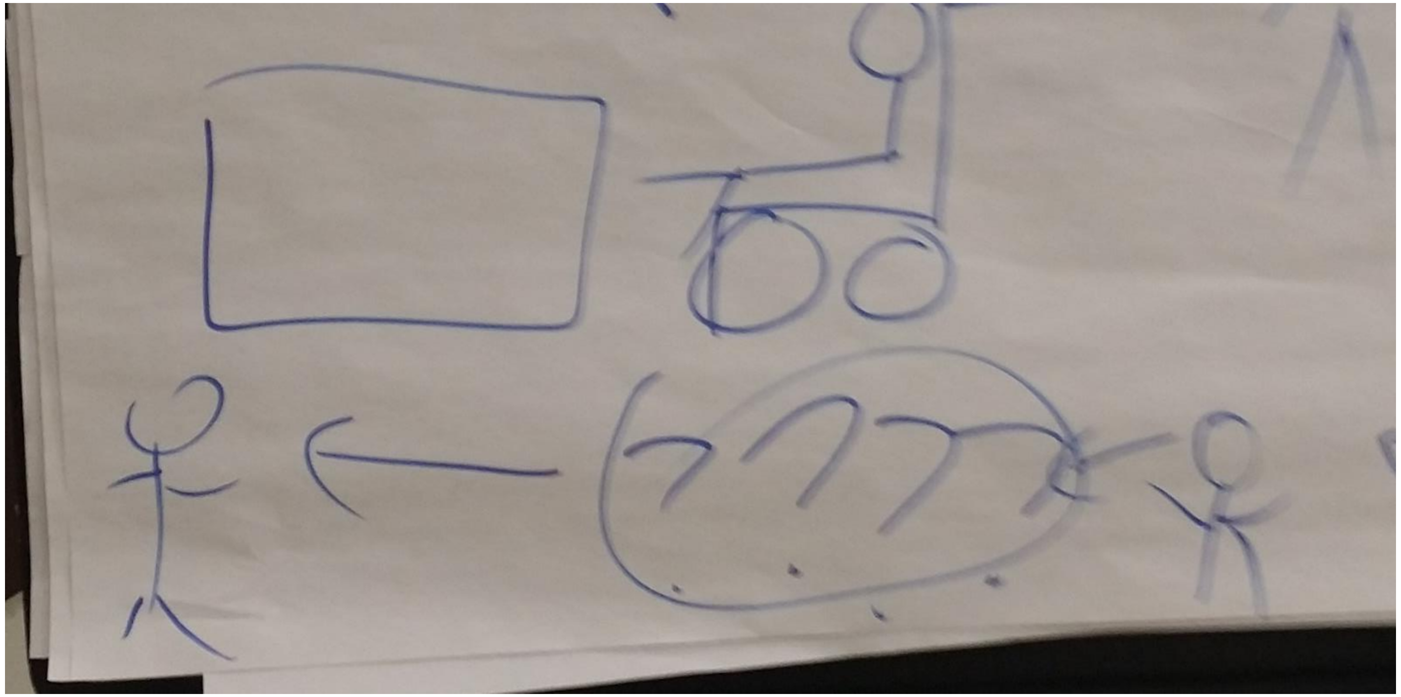
This is a totally biased introduction to the SM

I will concentrate on things I know and/or I work ON

ZE GAME

THE BAD REPUTATION

- I will talk for 40 minutes
- Then we will have 5 minutes of questions
  - From both sides !!
  - Priority for people in front of their laptops



Sorry I have a reputation to maintain

ZE USUAL

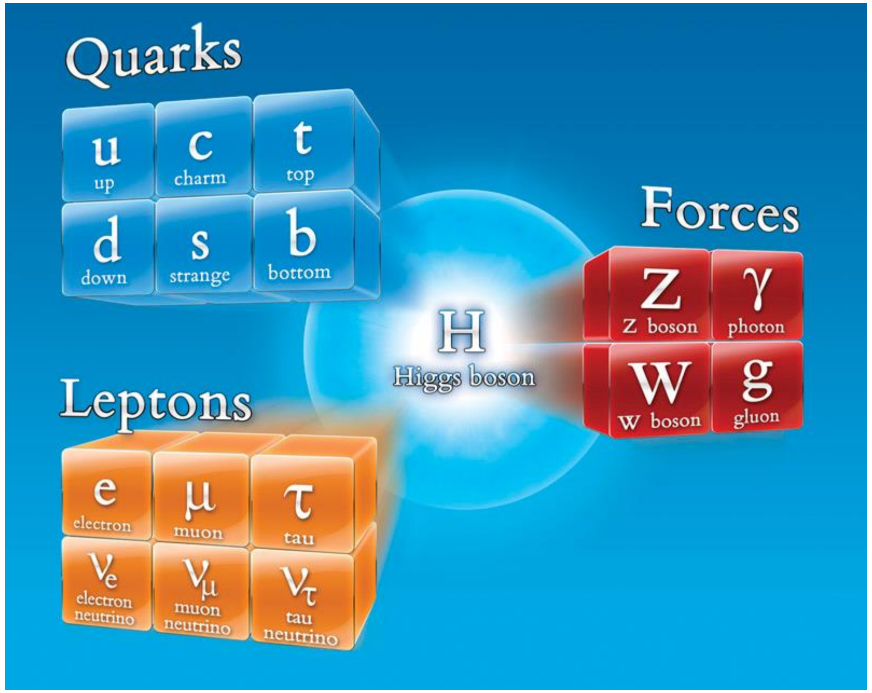
THE SM (REMINDER)

- Gauge invariance under $SU(3)_C \times SU(2)_L \times SU(1)_Y$

$$\mathcal{L}_D = \overline{\Psi} \not{D} \Psi \qquad \mathcal{L}_{\mathcal{M}} = \frac{1}{2g} F_{\mu\nu} F^{\mu\nu}$$

Covariant derivative including interaction terms

No mass terms for bosons



- The group representation determines the interaction form:
  - Leptons: SU(3) singlets → do not interact strongly
  - Quarks: SU(3) triplets → interact with gluons

- Parity violation → Separation of left and right SU(2) representations:
  - Left fermions: SU(2) doublets → interact weakly
  - Right fermions: SU(2) singlets → do not interact with the W boson
  - No mass terms for fermions

WHY THE HIGGS

SM solution to the mass problem

Add scalar field with spontaneous symmetry breaking

W, Z boson masses

Add Yukawa couplings

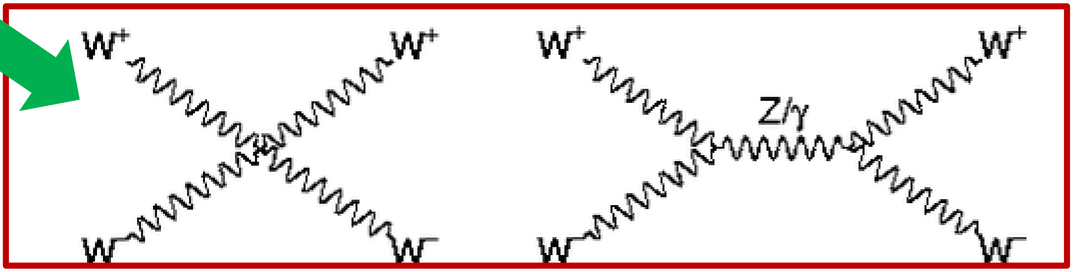
Fermion masses

Also good for other problems

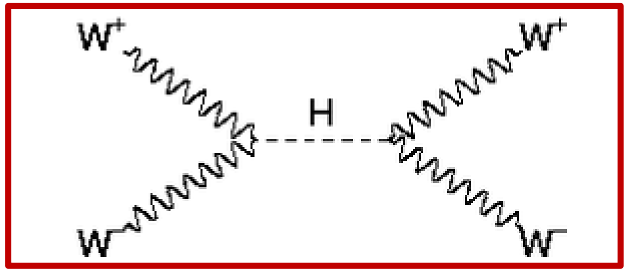
e.g.

Breaks unitarity → Probability > 1

Atelier



Regularized by the H



ZE PAST

THE VERY NEAR PAST

Yesterday night …

I'm tired …

And still only have the historical context …

So I decide to steal it from C. Ochando (JJC 2012)

Thanks Christophe

1961: electroweak unification SU(2)xU(1)
(Glashow)

1962: Neutrino μ
(Lederman, Schwartz, Steinberger)

1964: Quark Model (u, d, s)
(Gell-Mann, Zweig)

1964: BEH mechanism

1967: « A model of leptons »
(Weinberg, Salam)

1970: GIM mechanism
(need a fourth quark!)

1972: 3 generations of quarks !
(Kobayashi, Maskawa)

1973: Discovery of Neutral Current
(Gargamelle, CERN)

1973: Asymptotic Freedom
(Politzer, Gross, Wilczek)

1974: Charm Quark
(J/ψ: Richter, Ting)

1975: The Standard Model, a quantum field theory based on the local gauge invariance $SU(3)_C xSU(2)_L xU(1)_Y$ was in place

1975: Tau Lepton
(Perl)

A few remaining things at that time:
- Observed the vector bosons
- Reveal the third family
- + origin of family, grand unification, etc…

1961: electroweak unification SU(2)xU(1)
(Glashow)

1962: Neutrino μ
(Lederman, Schwartz, Steinberger)

1964: Quark Model (u, d, s)
(Gell-Mann, Zweig)

1964: BEH mechanism

1967: « A model of leptons »
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1973: Asymptotic Freedom
(Politzer, Gross, Wilczek)

1974: Charm Quark
(J/ψ: Richter, Ting)

1983 Découverte des
Bosons Z & W – UA1 UA2 CERN
SppS (ppbar, sqrt(s)=540 GeV)

1975: Tau Lepton
(Perl)

ECFA meeting in Lausanne – 1984:
Fondations pour le Large Hadron Collider

1977: Quark Bottom
(Υ)

LHC Workshop in Aachen – 1989:
Fondations pour les expériences LHC

Tunnel du SSC
en chantier: 1987-1993
(87 km, 40 TeV)

... LEP, SLC, Tevatron, HERA, b-factory

ZE INSTRUMENTS

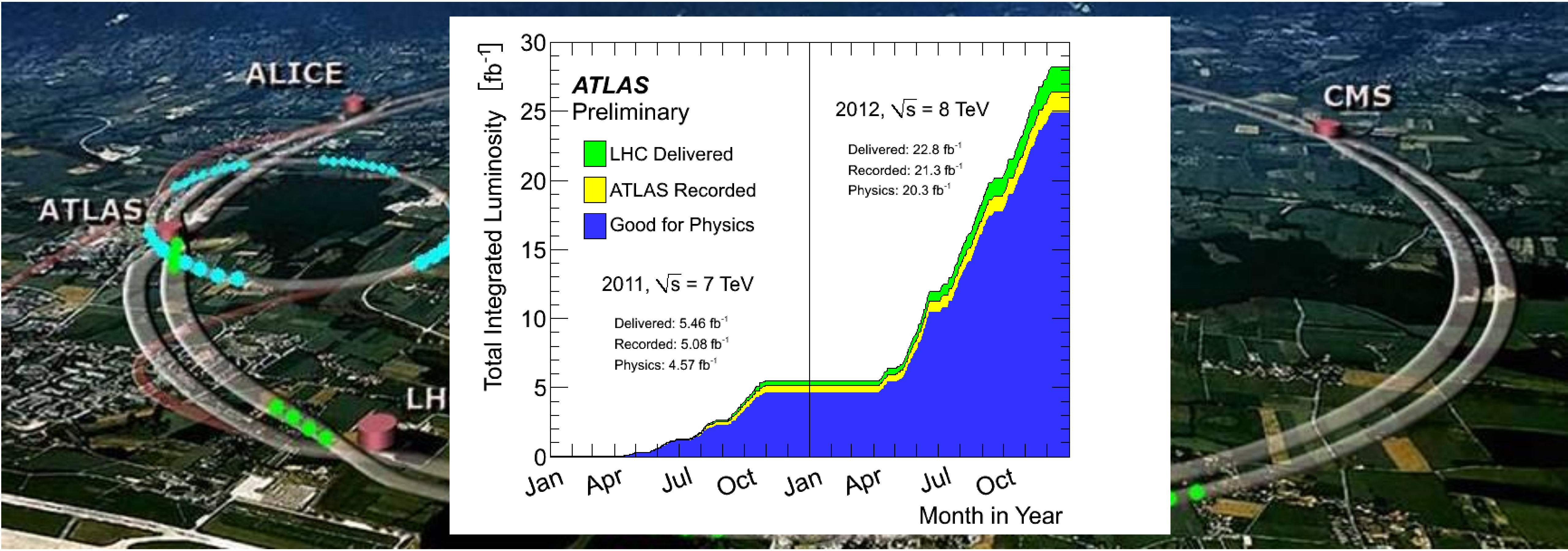
ONLY THE CURRENT ONES

THE LHC

PP collisions at 14 TeV (design energy)

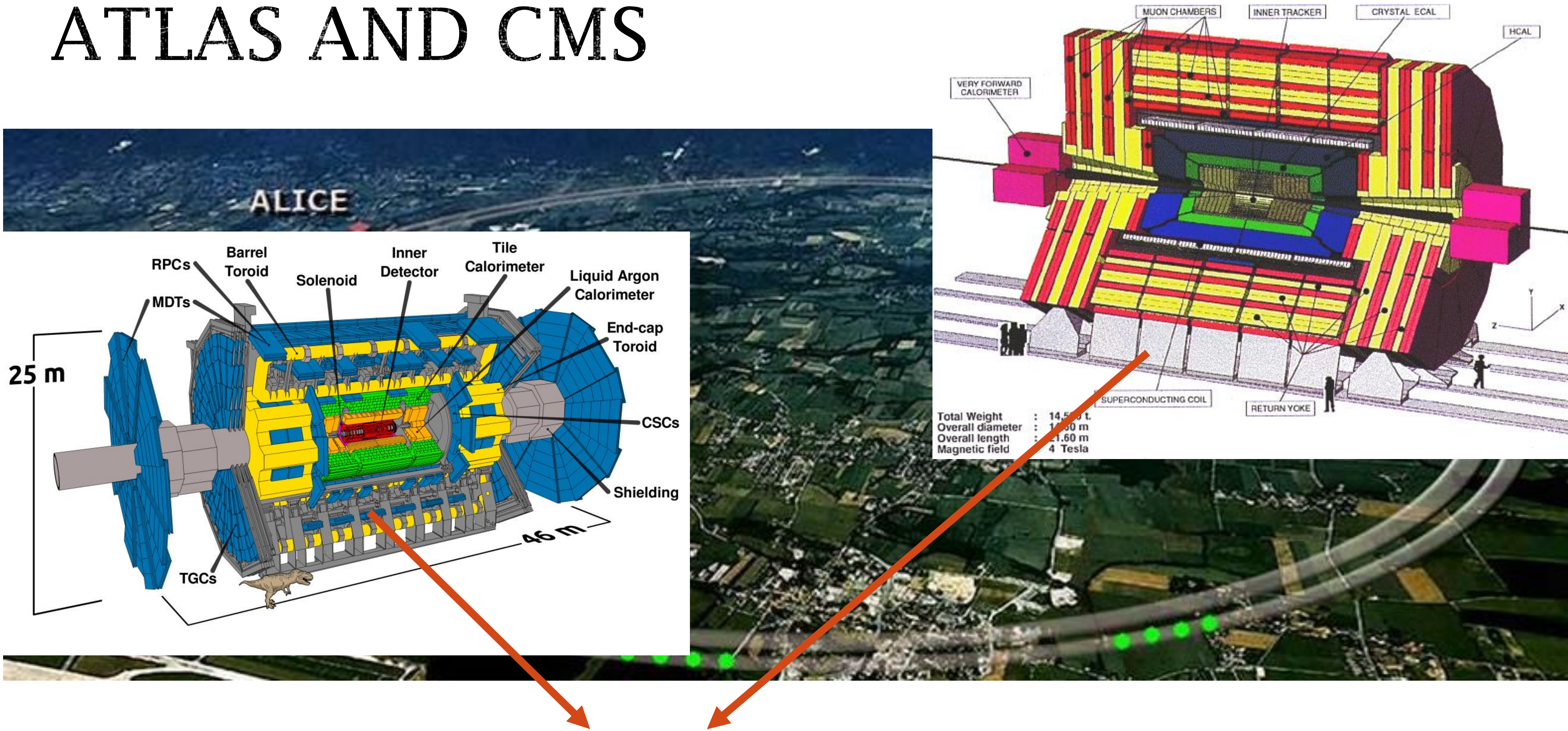
THE LHC

Very successful run at 7 (8) TeV in 2011 (2012)



Restart in 2015 at 13(ich) TeV

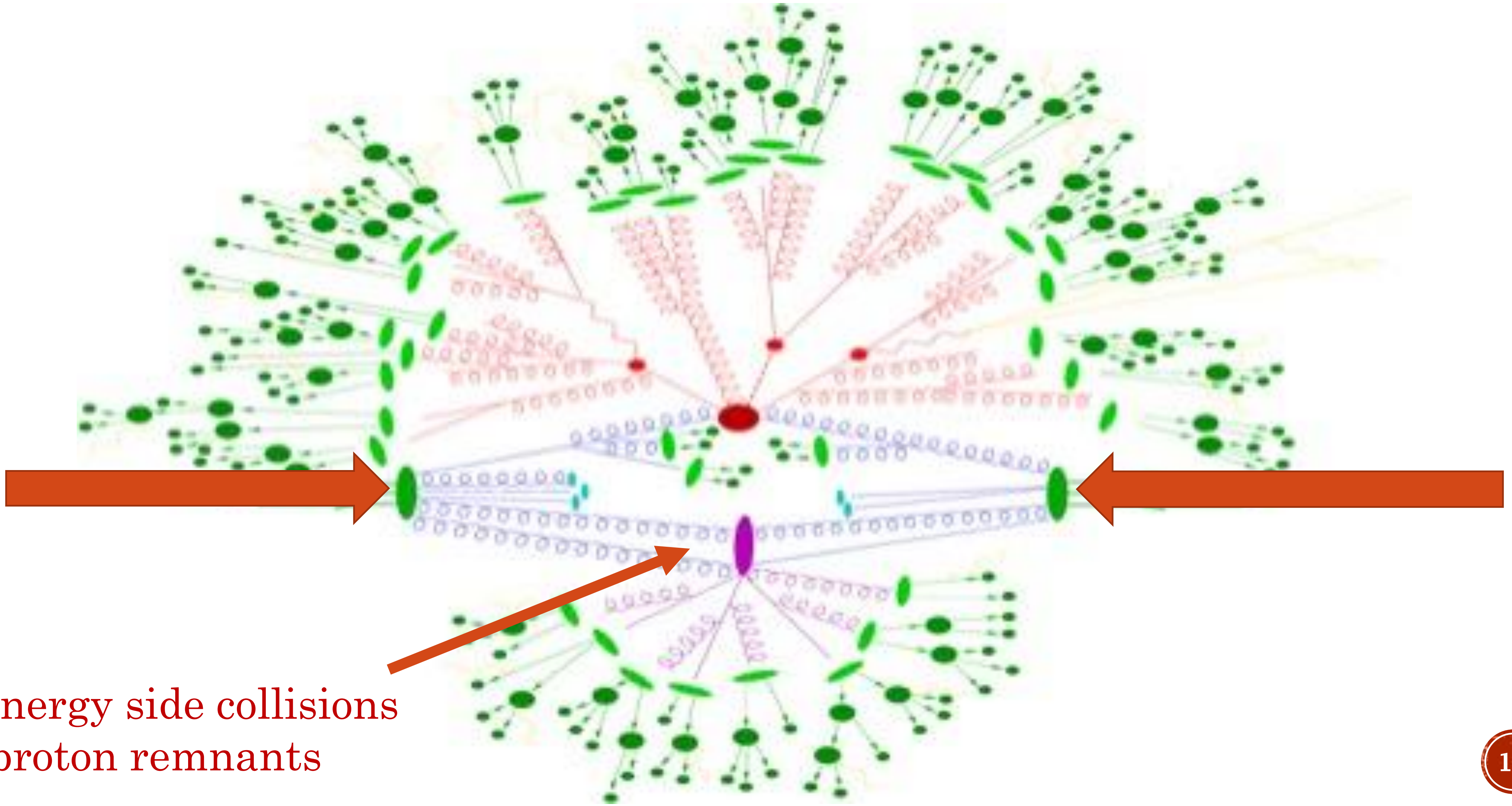
ATLAS AND CMS



Non-specialized detectors: broad range of physics
Same concept, different technologies

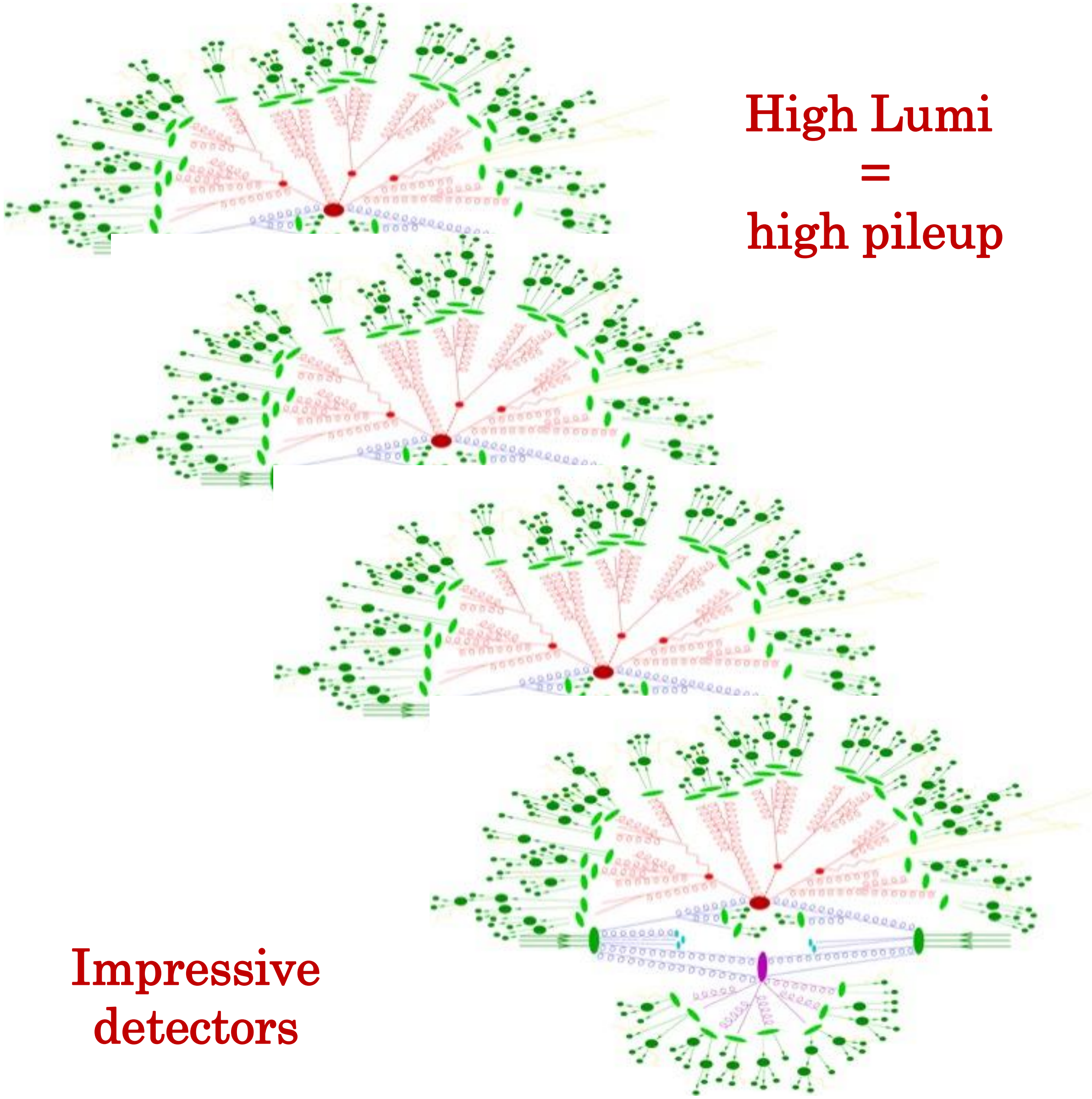
THE DIRTY BOOM

Protons not elementary particles
Mostly gluon-gluon collisions



Low energy side collisions
from proton remnants

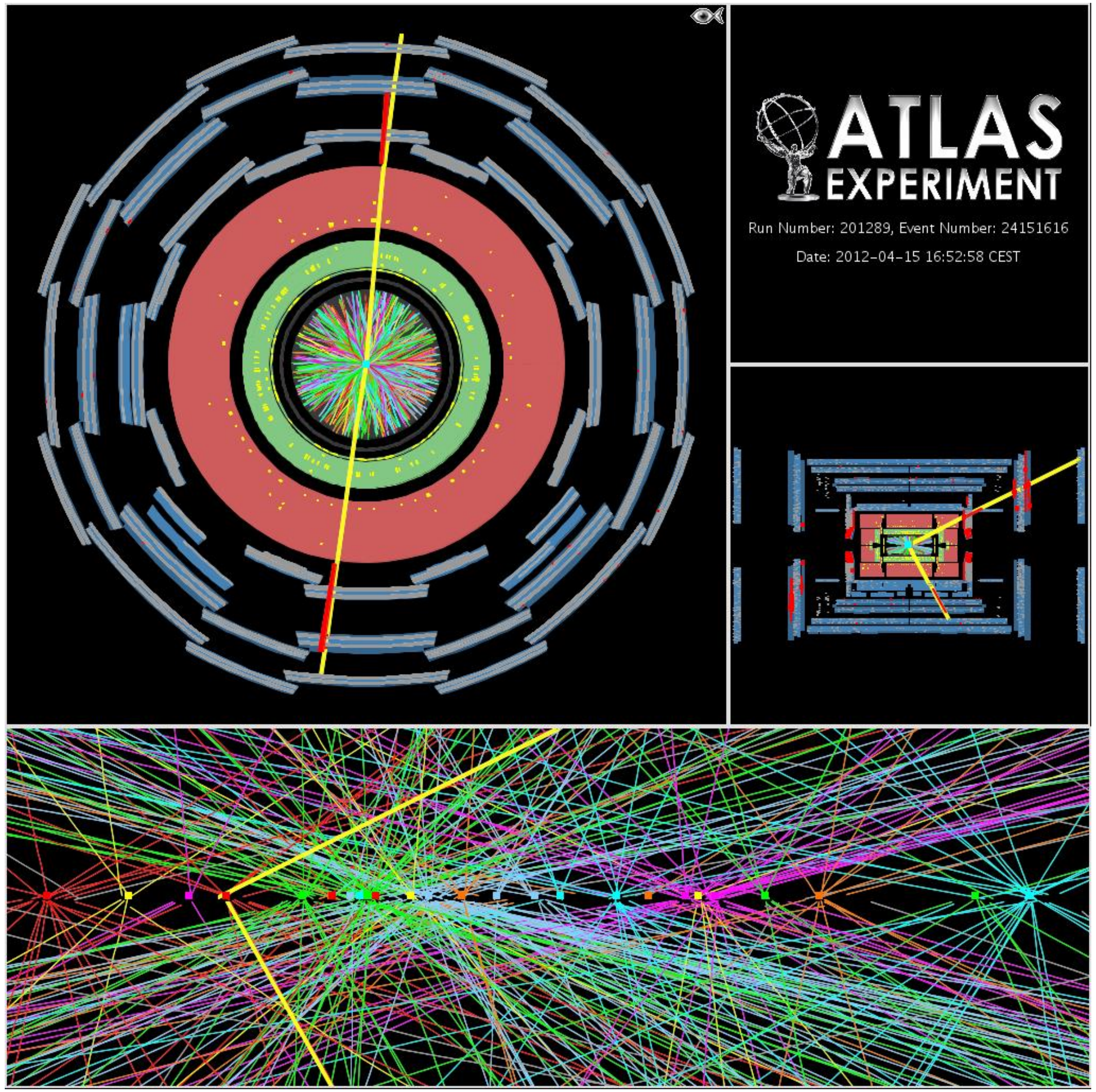
IT IS ACTUALLY DIRTIER



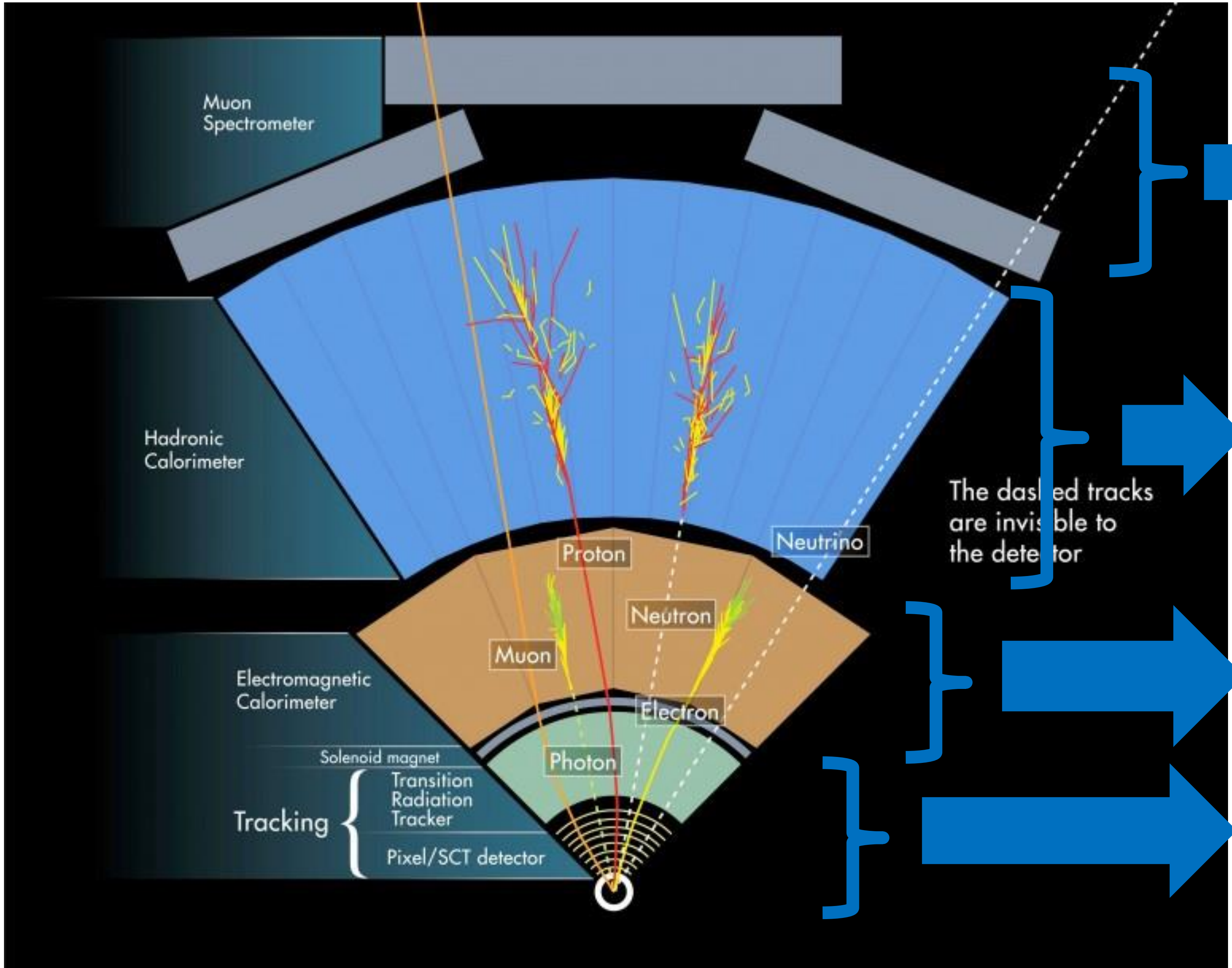
High Lumi
=
high pileup

Impressive
detectors

20 collisions !!



THE DETECTION



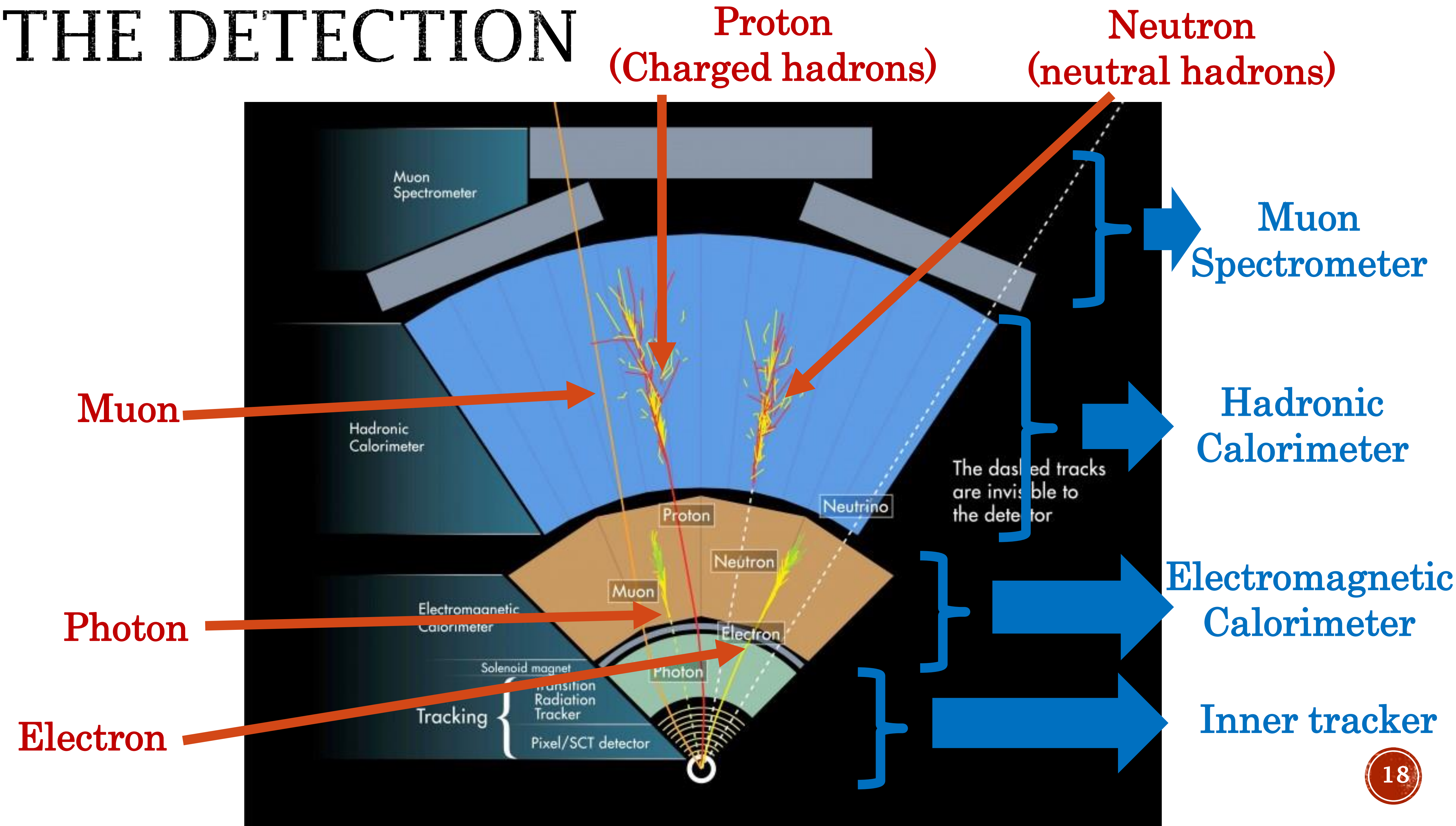
Muon Spectrometer

Hadronic Calorimeter

Electromagnetic Calorimeter

Inner tracker

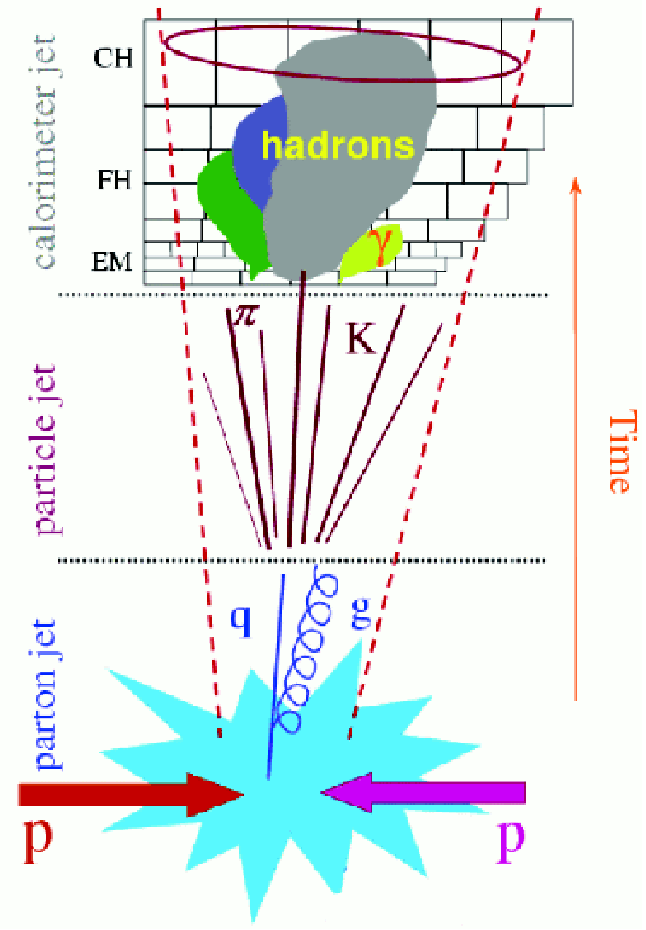
THE DETECTION



THE HARDER DETECTION

We do not detect quarks/gluons

We detect jets



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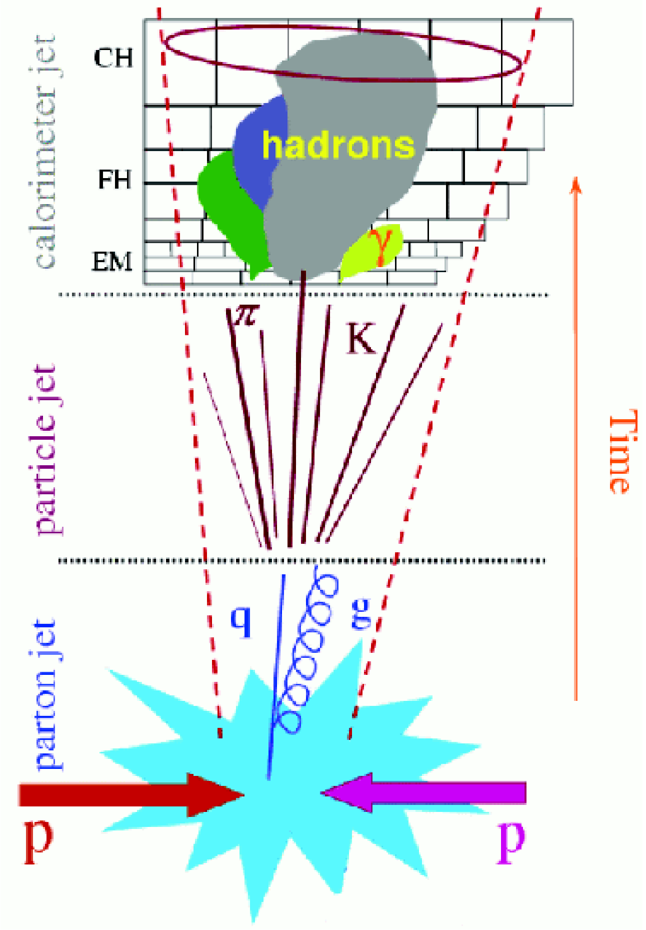
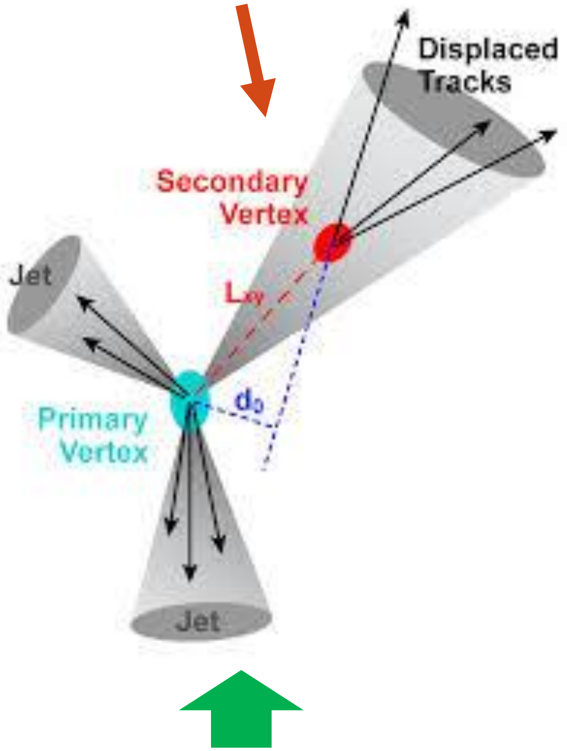


We can identify b-jets

B-hadrons fly before decaying



Royer's talk

THE HARDER DETECTION

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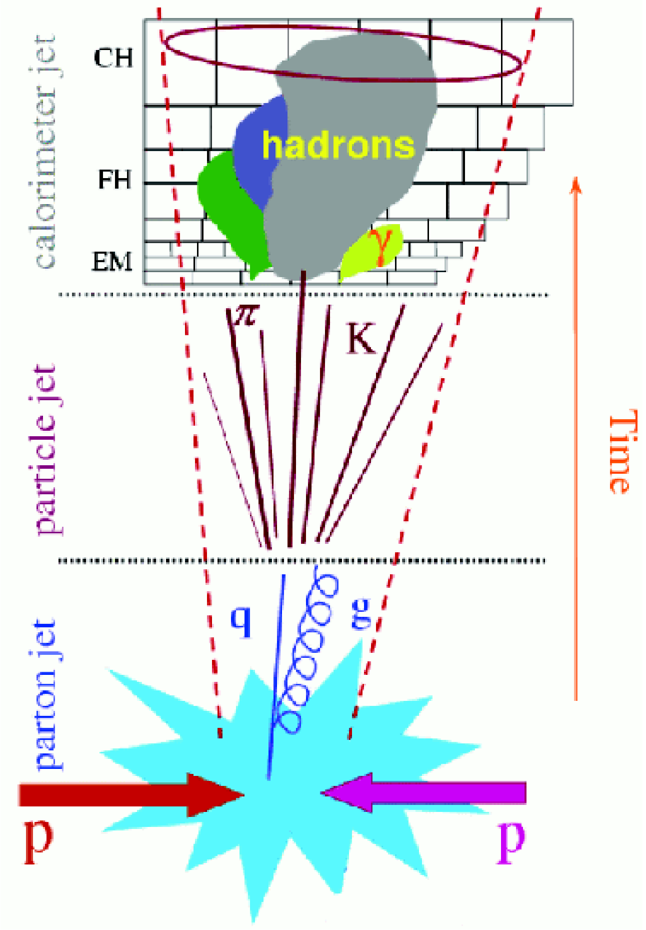

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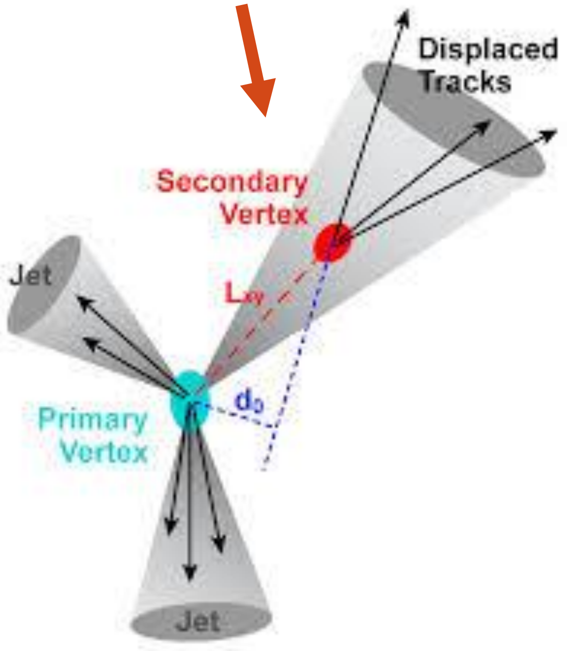
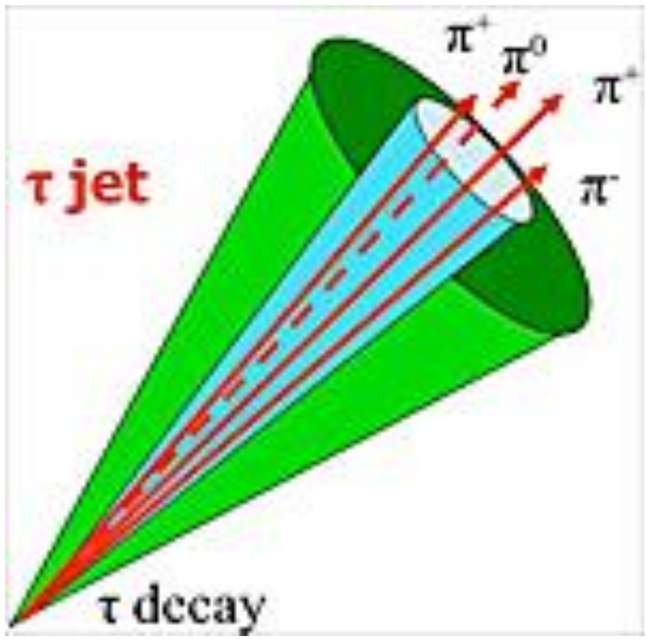


Royer's talk

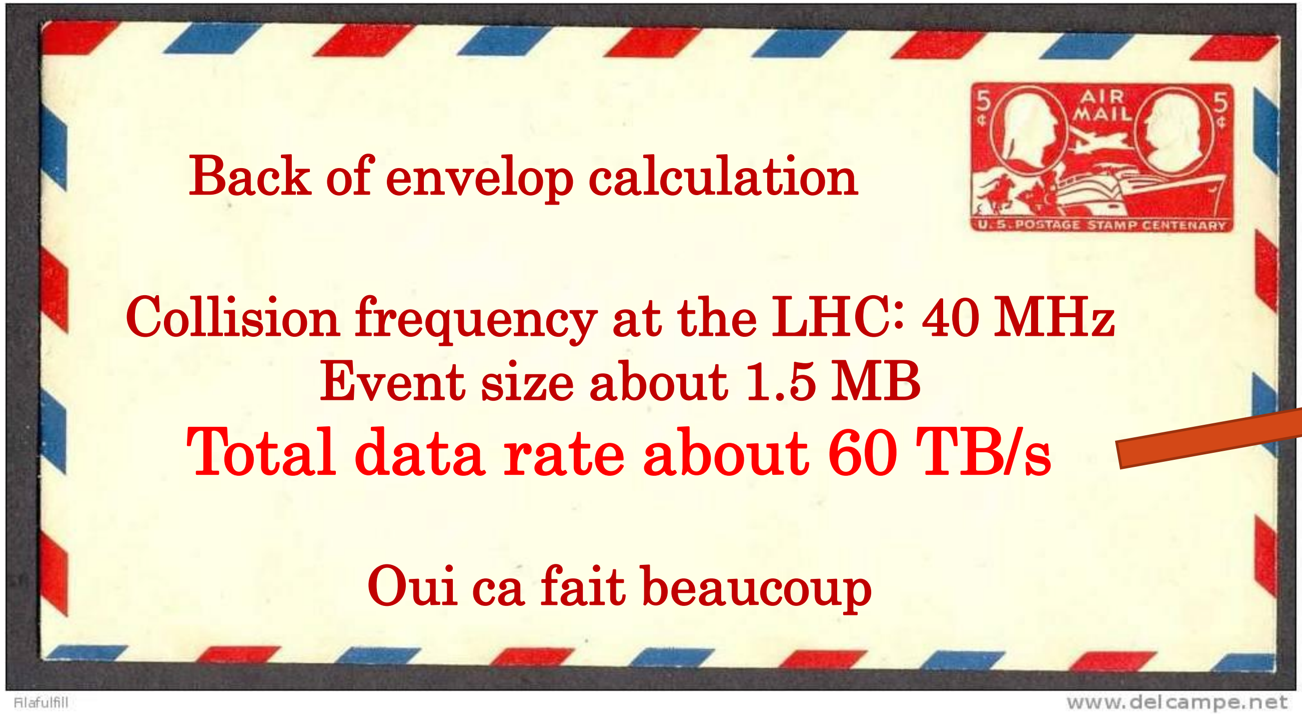
taus decay to hadrons and form jets
Usually narrower jets with less tracks



Mohamad's talk

TRIGGER

Simon's talk



Back of envelop calculation

Collision frequency at the LHC: 40 MHz
Event size about 1.5 MB
Total data rate about 60 TB/s

Oui ca fait beaucoup

O(10000) DVD/s

Vary fast treatment to identify
potentially interesting events
Uses hardware then software stages
Reduce the trigger rate to O(1KHz)

Mostly events with leptons/photons
Or objects at very high energy

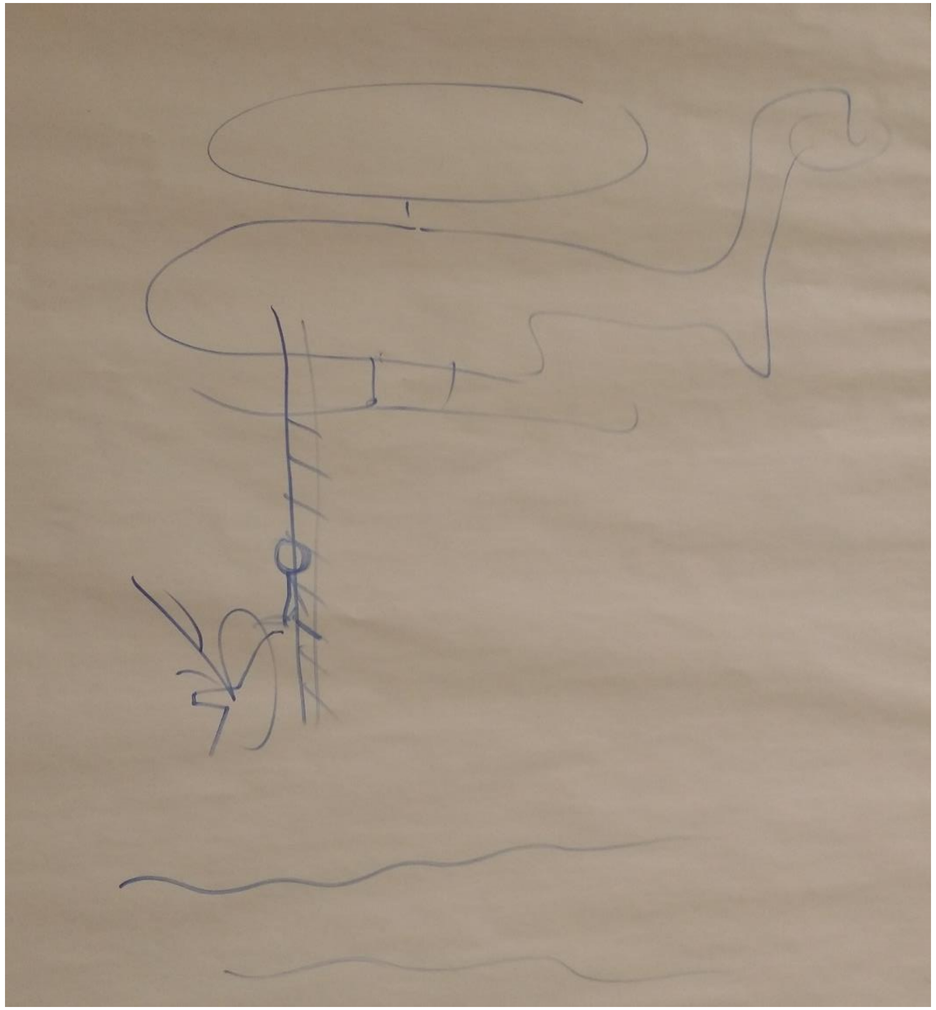
THE MAGIC OF MVA

Yesterday night I started to believe in
Neural Networks

I want to share my experience with you

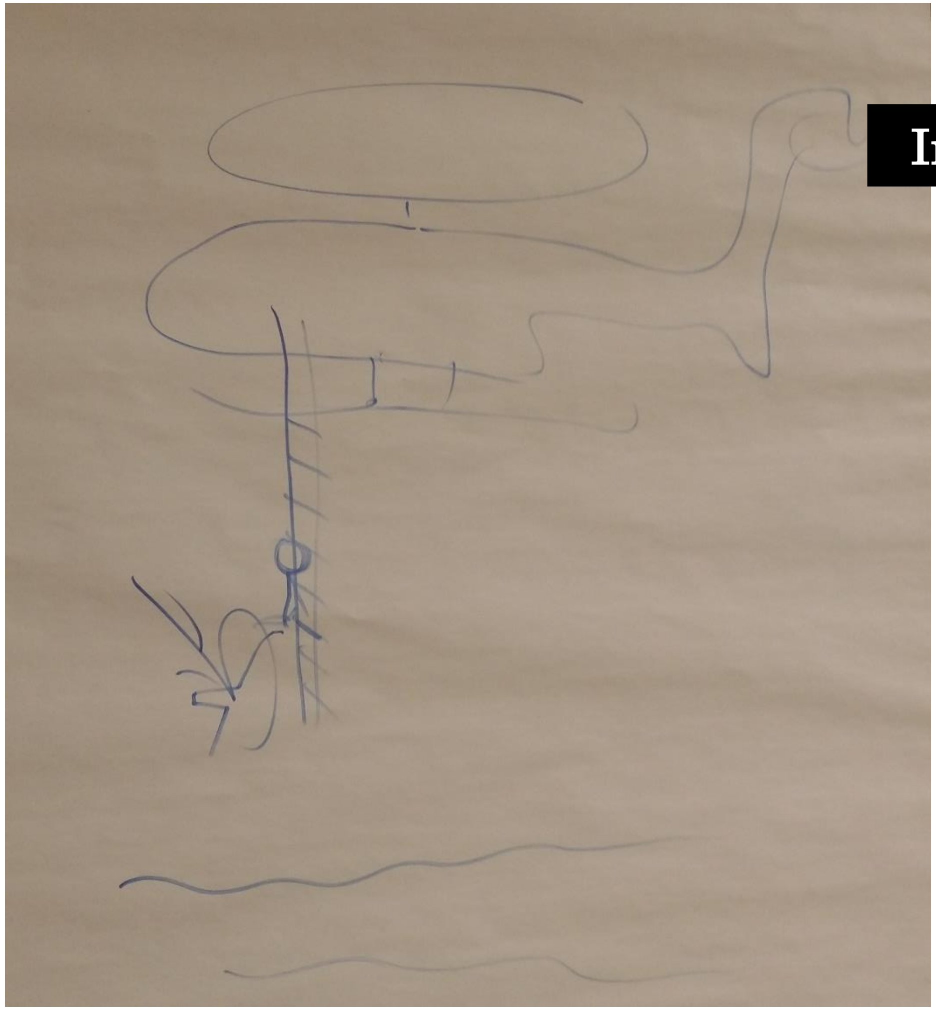
THE MAGIC OF MVA

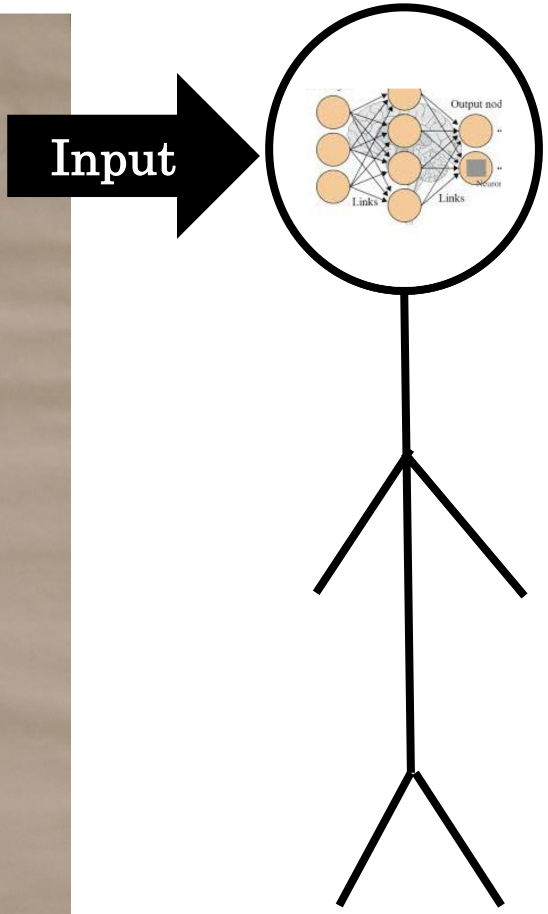
The raw data



THE MAGIC OF MVA

The raw data ➡ Trained Neural Network

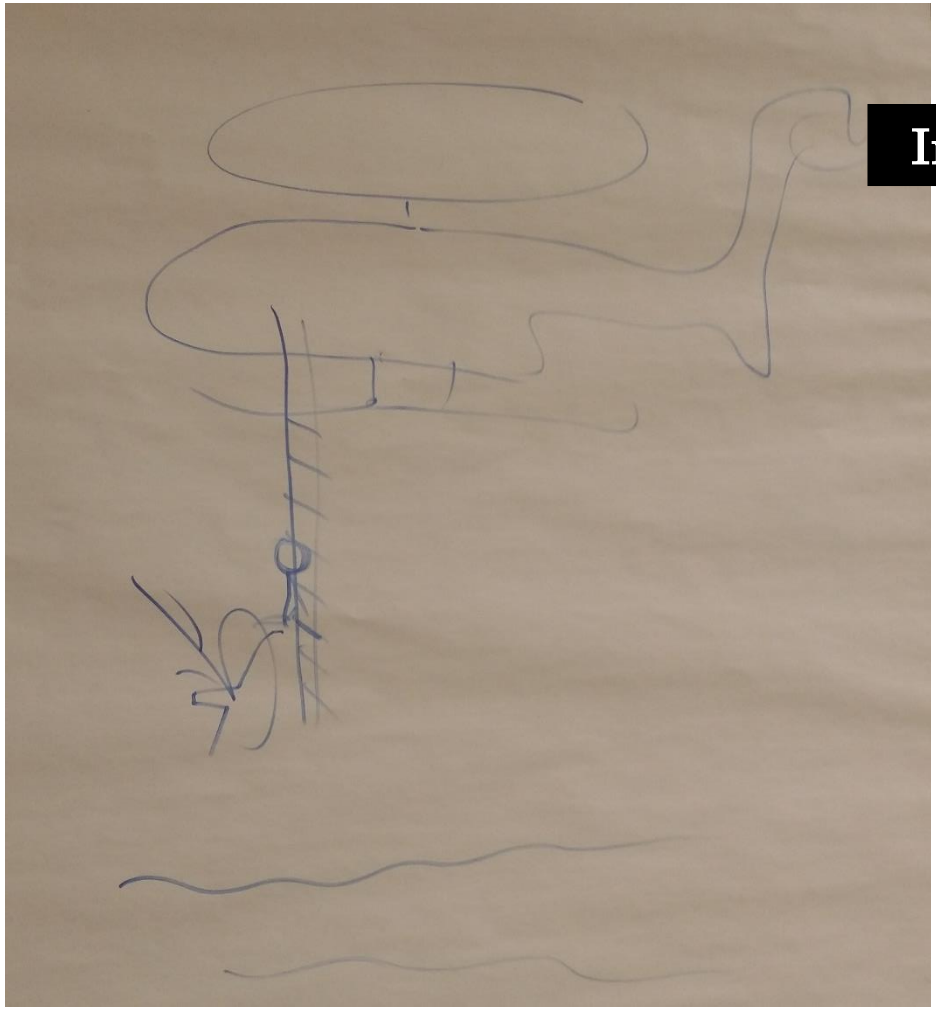


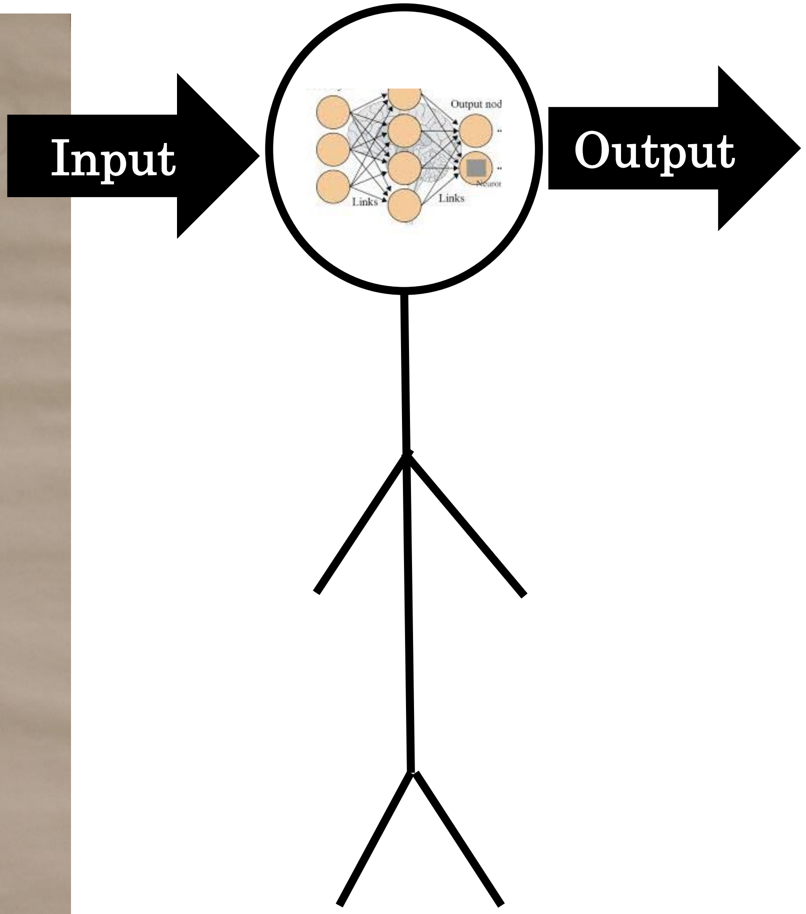


Student

THE MAGIC OF MVA

The raw data ➡ Trained Neural Network ➡ The NN output





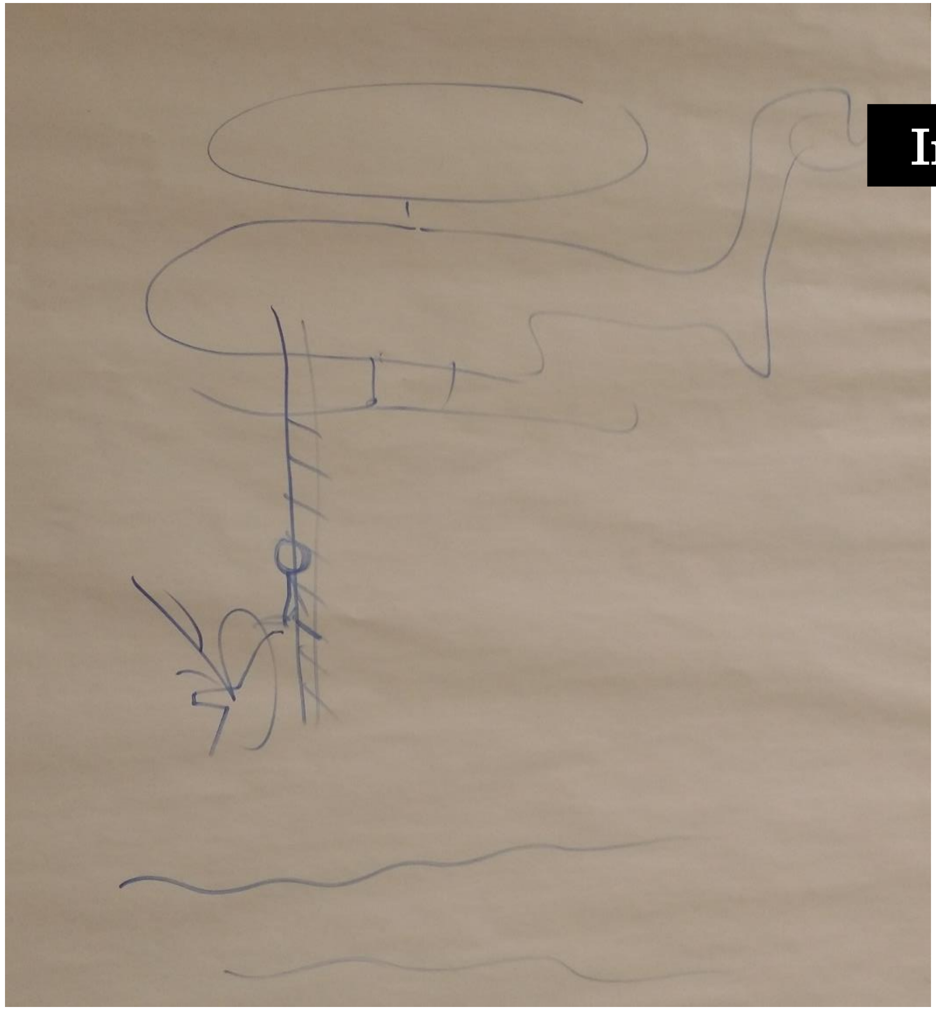
Student

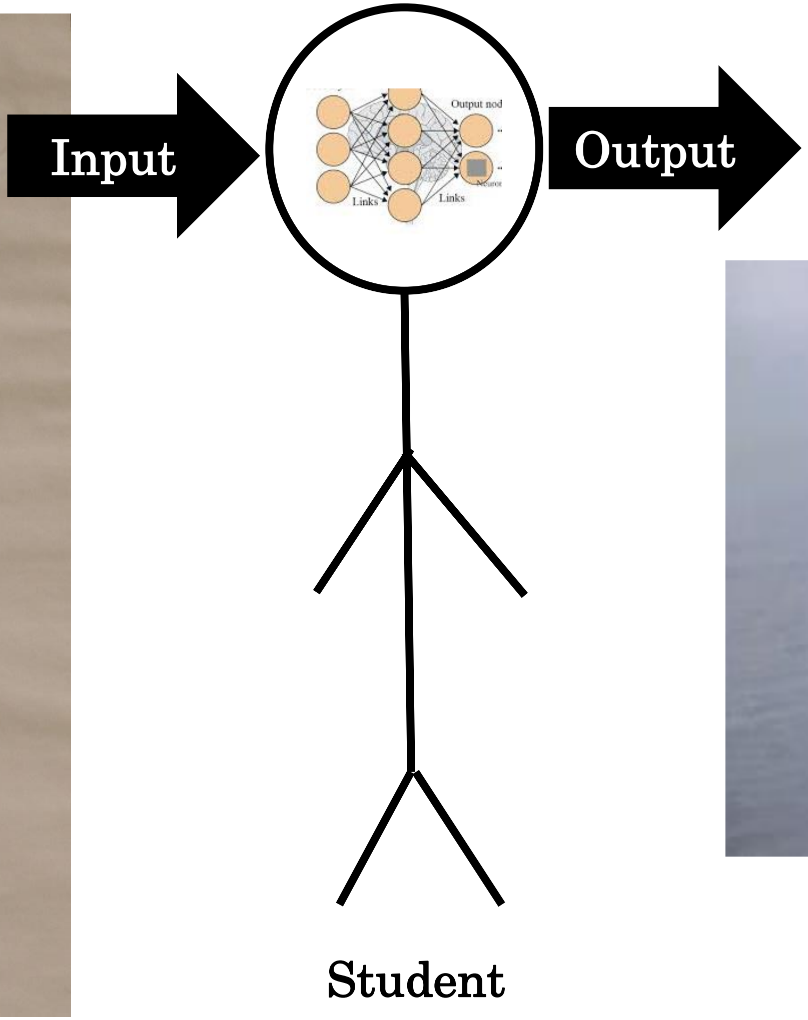
Batman and Robin

MAGIC NO!!

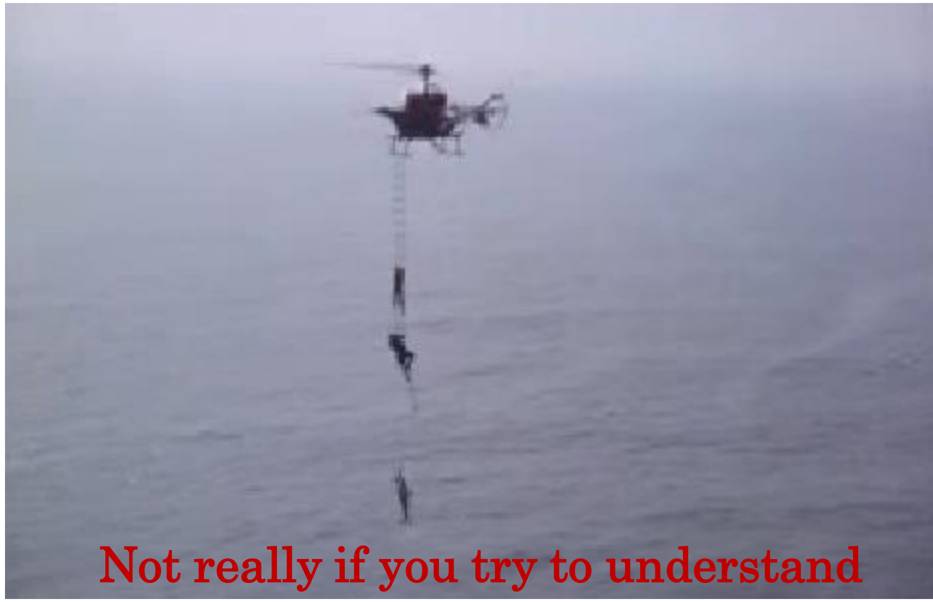
THE MAGIC OF MVA

The raw data ➡ Trained Neural Network ➡ The NN output





Batman and Robin

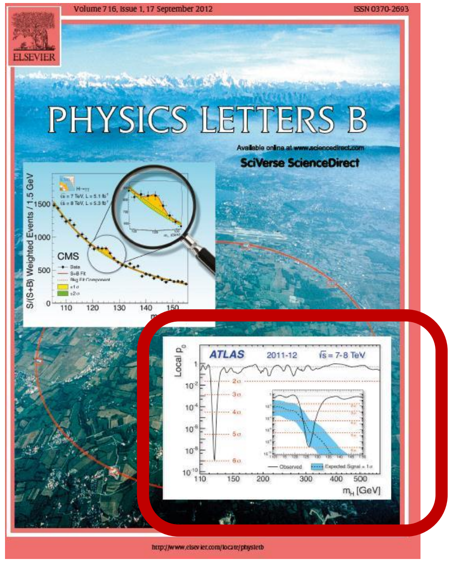


No not him
THE BOSON

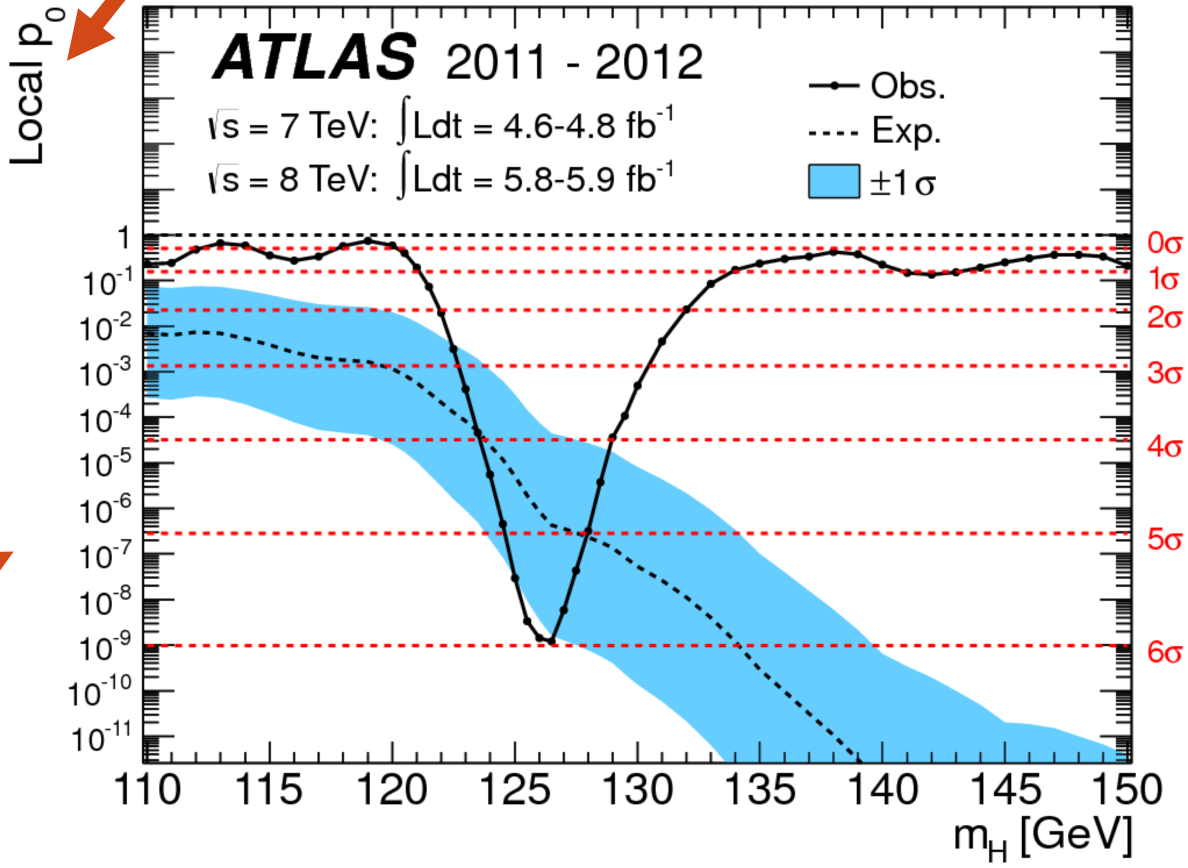
ZE HIGGS

THE HIGGS DISCOVERY

July 2012 at ICHEP



Probability that background fluctuates and looks like observed data



THE NOBEL PRIZE

Englert and Higgs got the Physics Nobel Prize in 2013

Some experimentalists were not happy!!

THE LUCKY NAME

And here it is in the PDG

$\boxed{H^0}$ $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

A combination of the results from ATLAS and CMS, where a recent unpublished result from CMS is used, yields an average value of 125.6±0.3 GeV, see the review on "Status of Higgs Boson Physics."

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.7±0.4 OUR AVERAGE				
$125.5 \pm 0.2 ^{+0.5}_{-0.6}$	[1,2] AAD	13AK	ATLS	pp, 7 and 8 TeV
$125.8 \pm 0.4 \pm 0.4$	[1,3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV

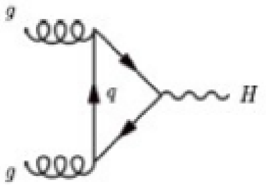
Life is not always fair!

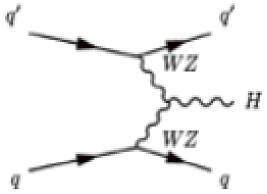
Thanks to my grand-grand parents

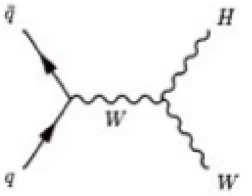
THE HIGGS (125GEV) AT 8TEV LHC

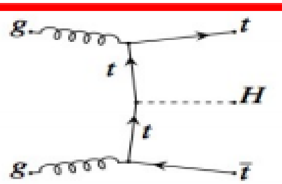
The Higgs couples to the mass

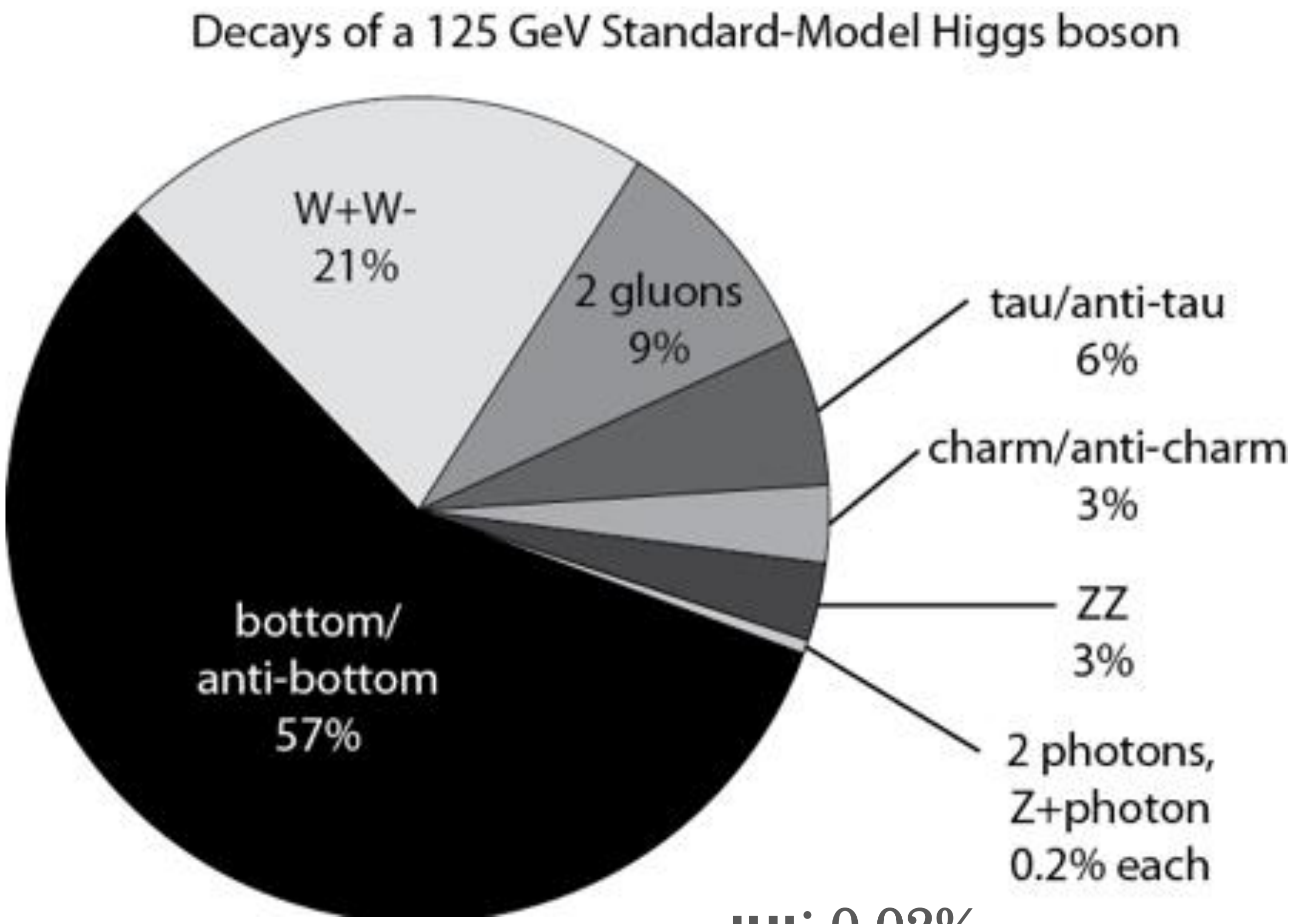
Production cross sections

ggH 19.27 pb  86%

qqH 1.58 pb  7%

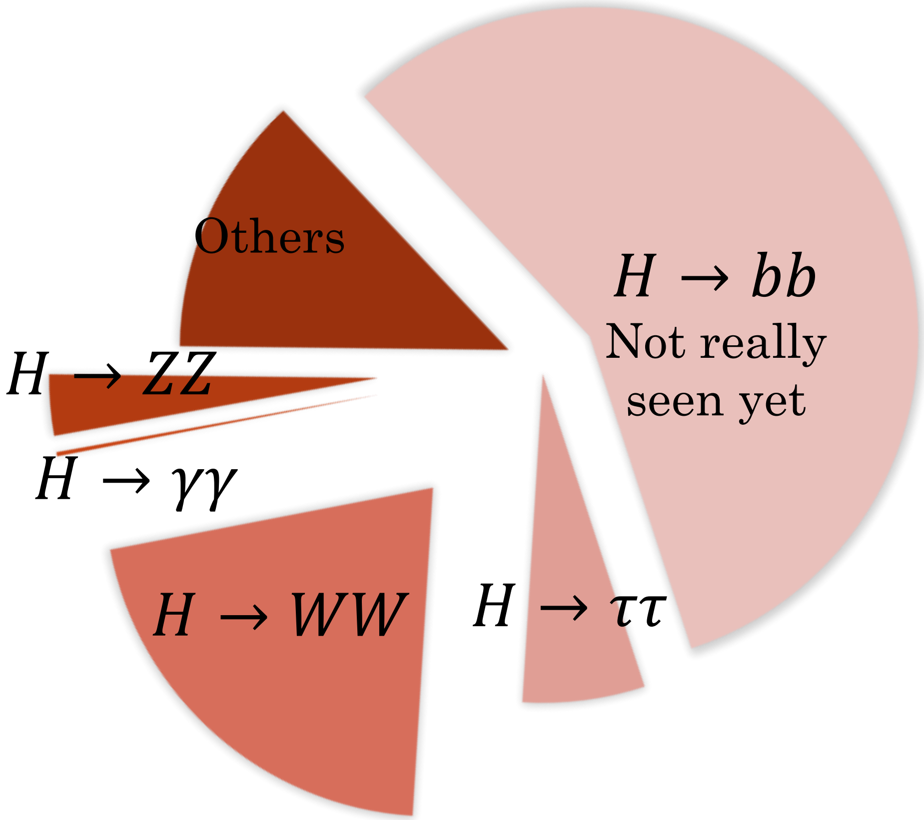
WH+ZH 1.12 pb  5%

ttH+bbH 0.33 pb  1.5%



μμ: 0.02%

THE HIGGS DETECTION CHANNELS

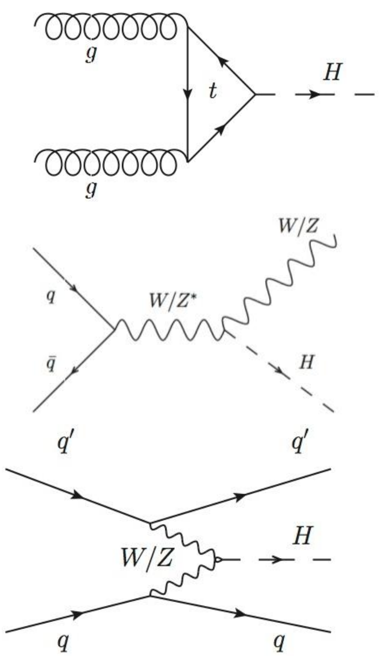


We used to mainly separate decay channels

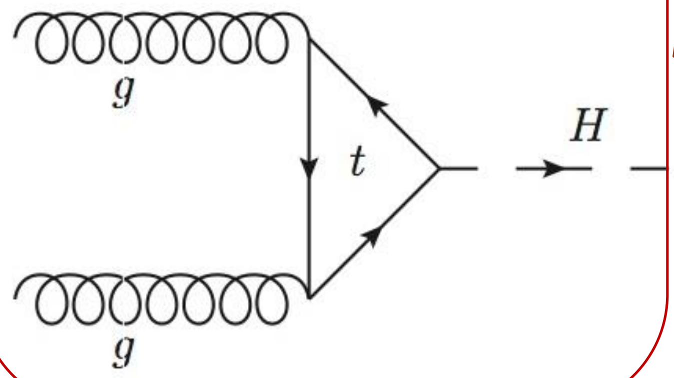
$\to$ Choose best production mode (background considerations)

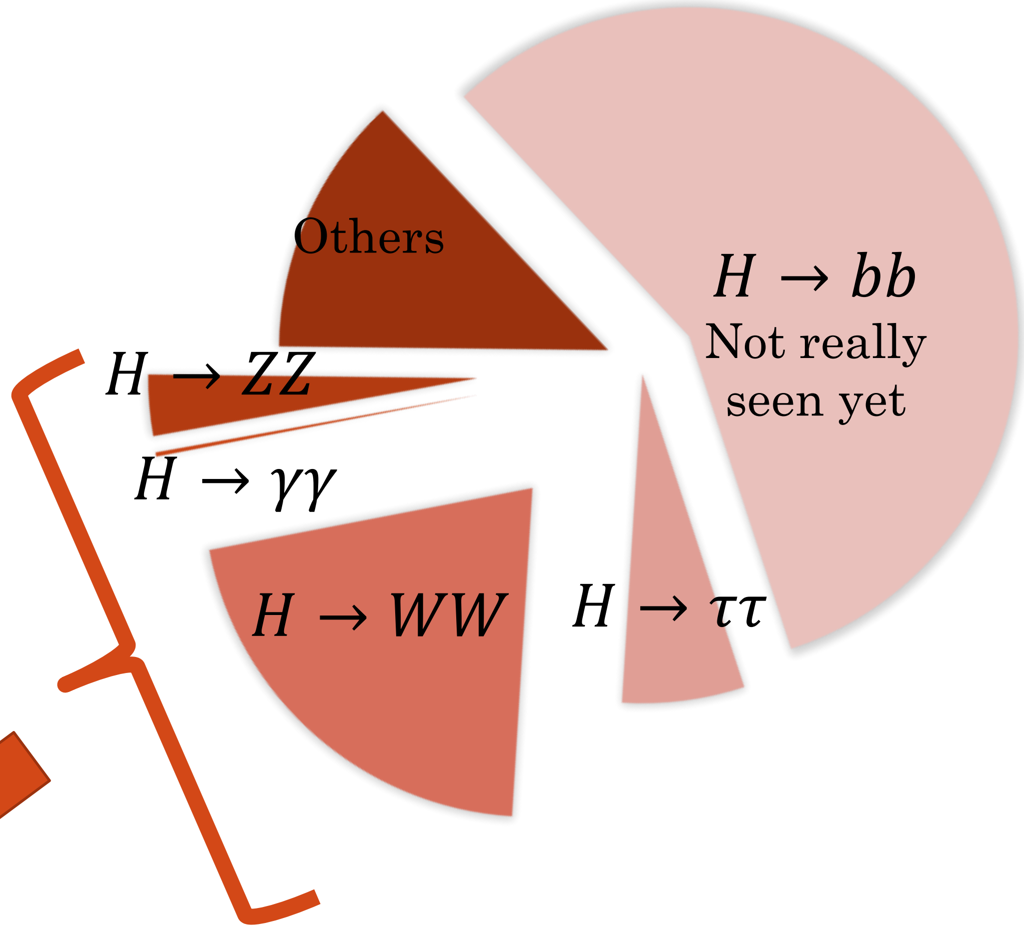
But need/start to separate also production modes

THE HIGGS CHANNELS

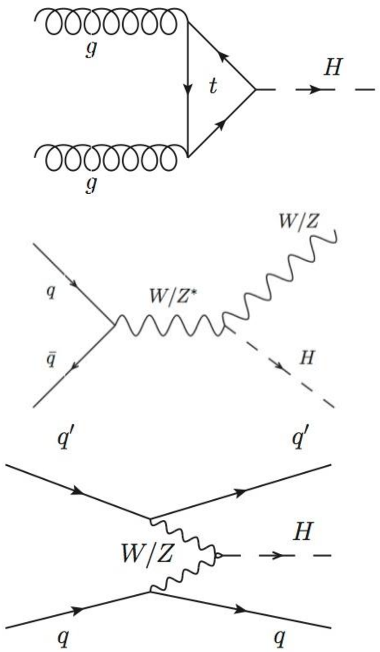


Mainly ggF

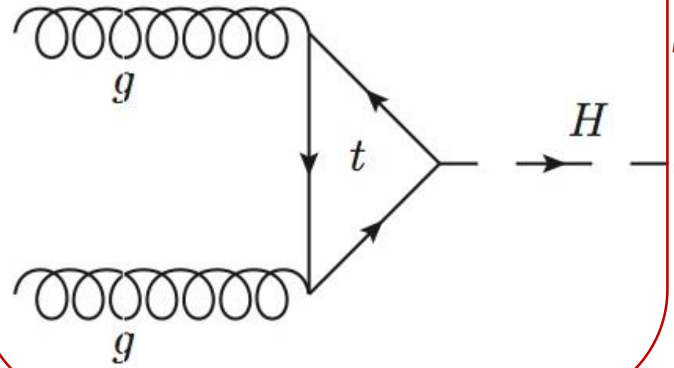


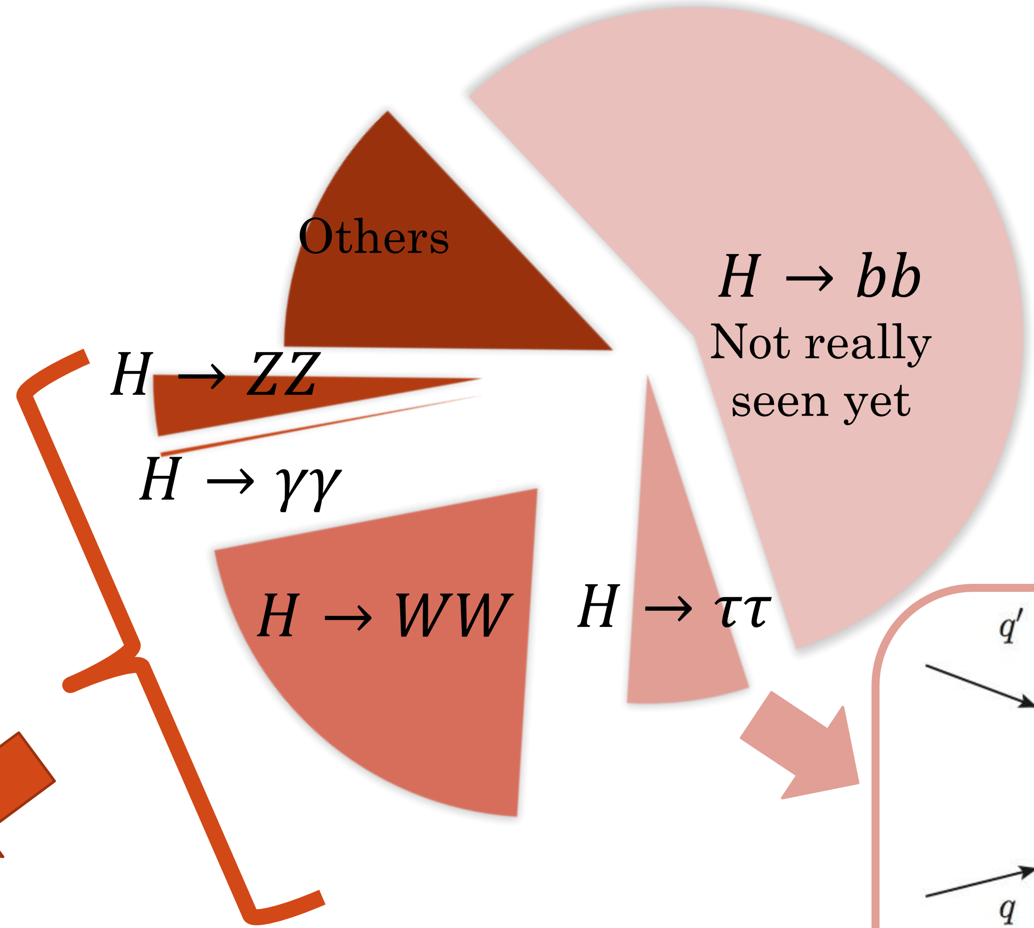


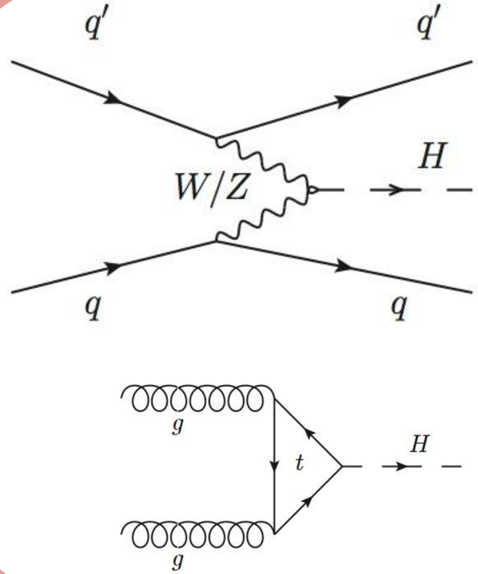
THE HIGGS CHANNELS



Mainly ggF

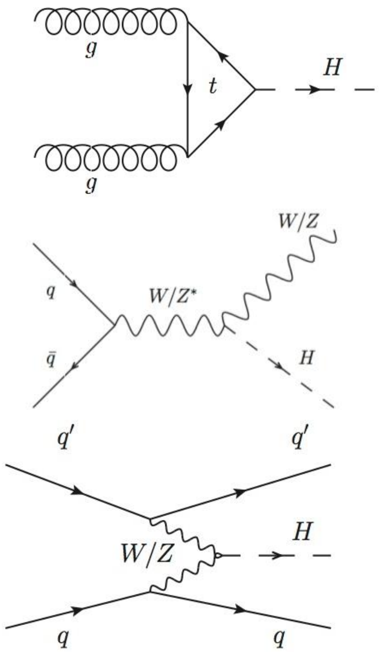




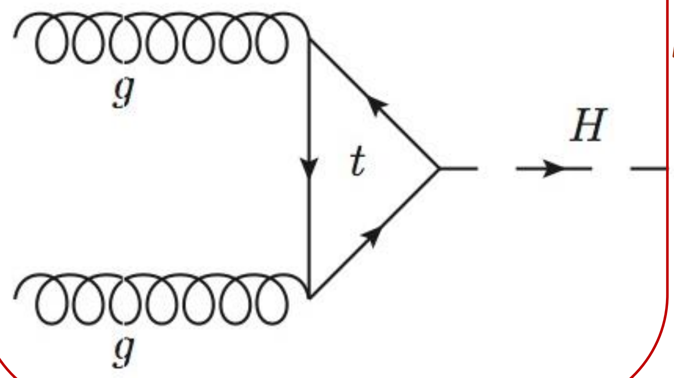


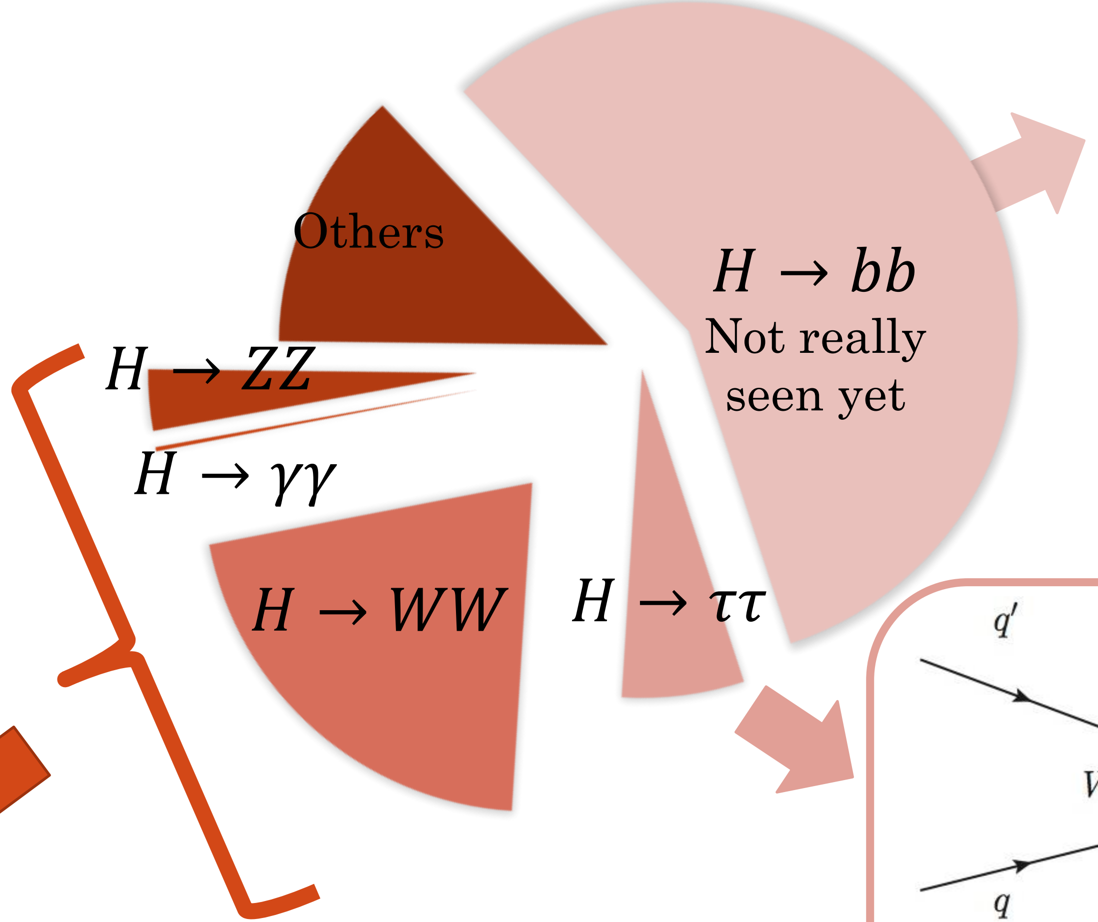
Main one

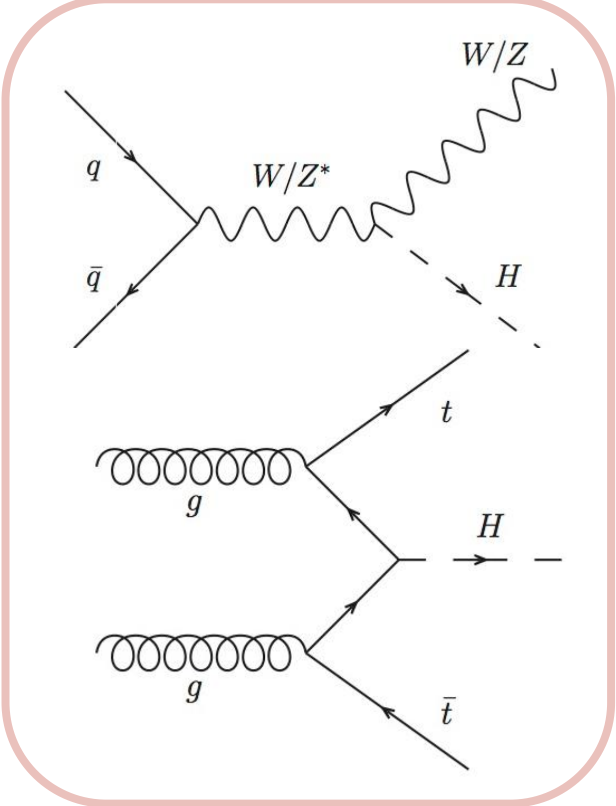
THE HIGGS CHANNELS

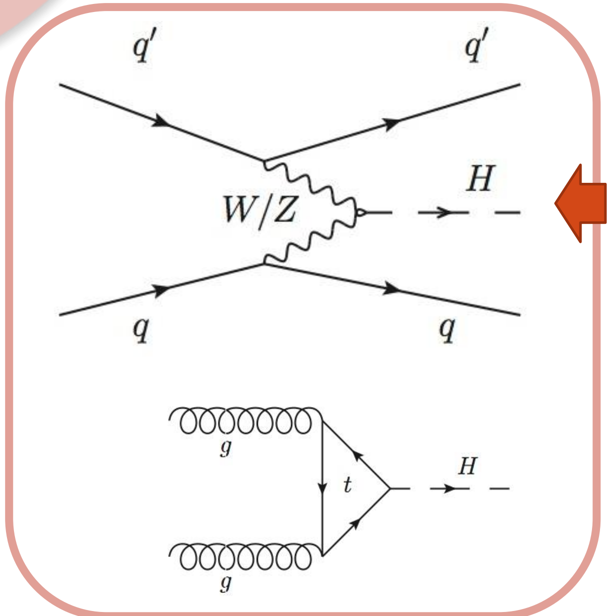


Mainly ggF







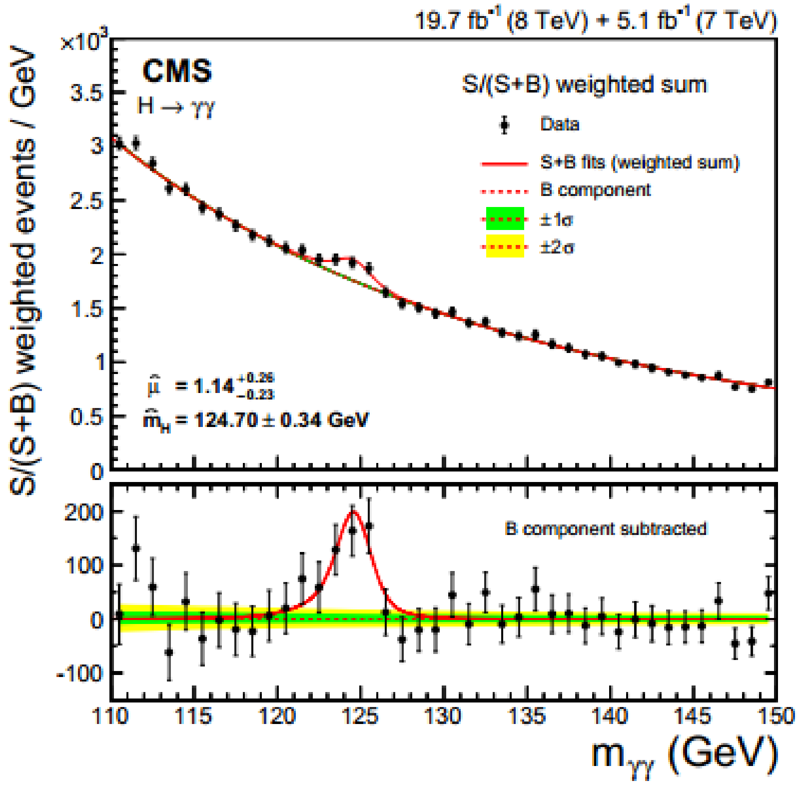


Main one

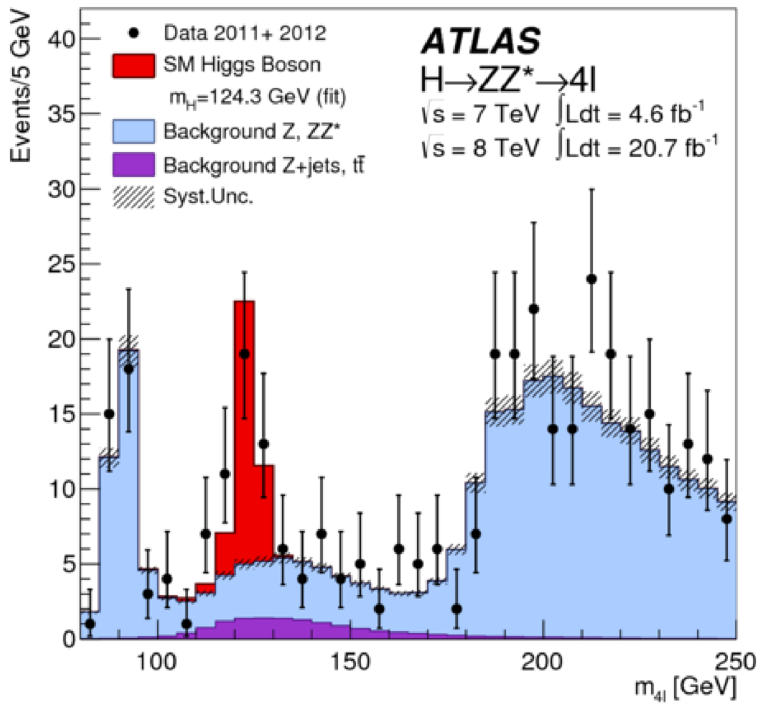
THE GOLDEN(ISH) CHANNELS

Simon's talk

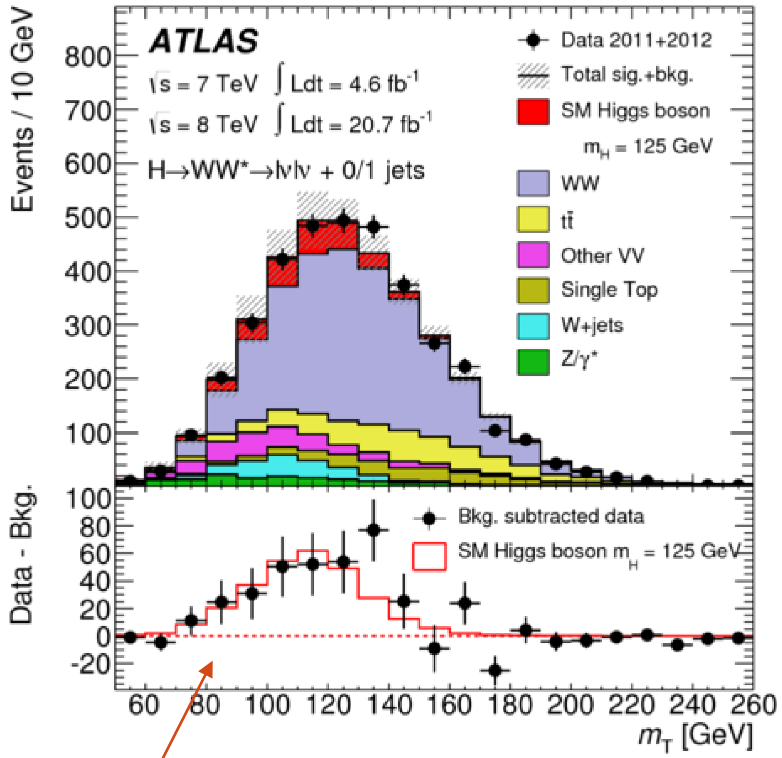
$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ \rightarrow 4\ell$



$H \rightarrow WW \rightarrow ll\nu\nu$



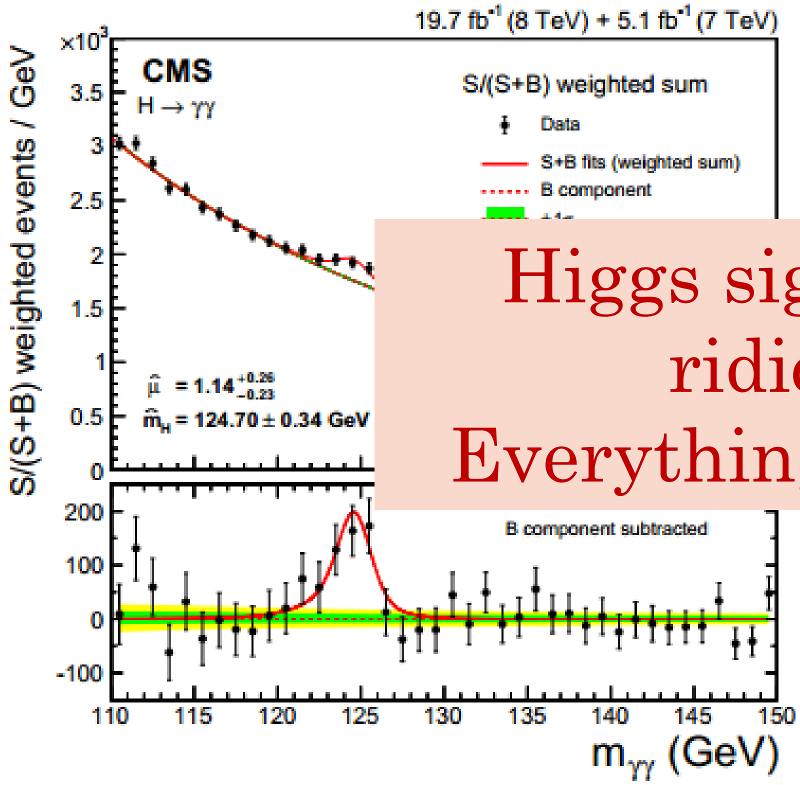
ATLAS: $m_H = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})$ GeV

CMS: $m_H = 125.03\ ^{+0.26}_{-0.27}\ (\text{stat})\ ^{+0.13}_{-0.15}\ (\text{syst})$ GeV

Not so golden

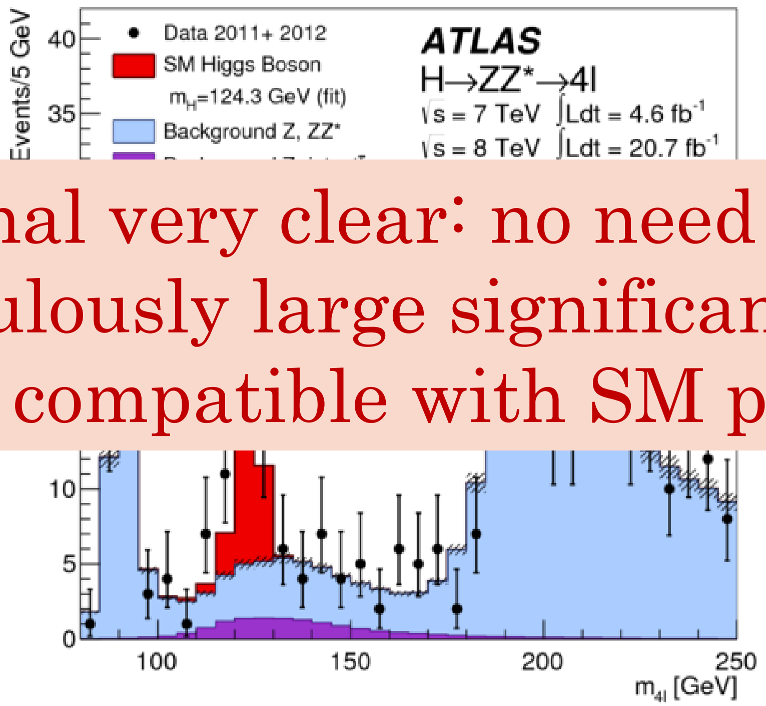
THE GOLDEN(ISH) CHANNELS

$H \to \gamma\gamma$

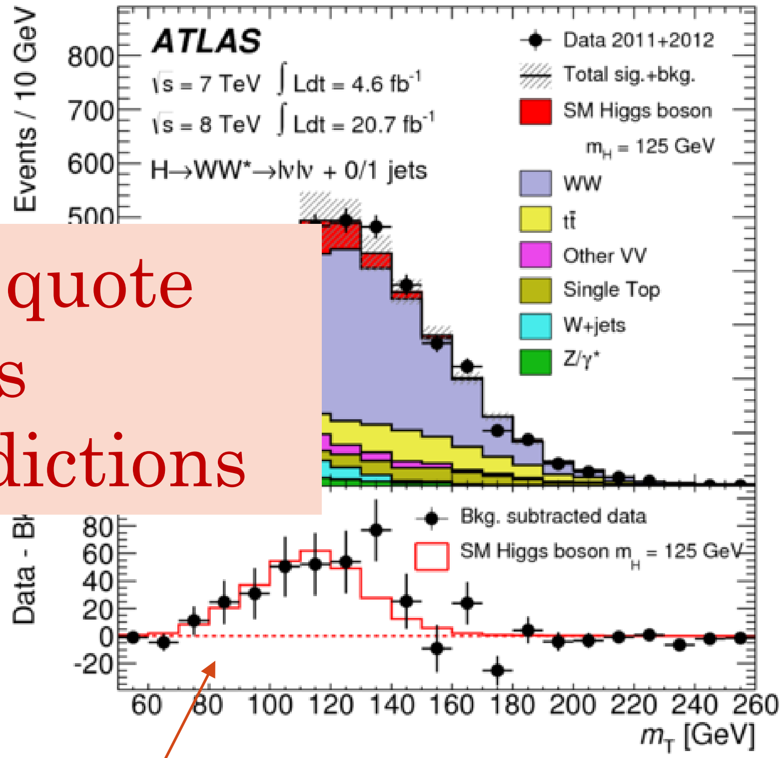


Simon's talk

$H \to ZZ \to 4\ell$



$H \to WW \to ll\nu\nu$



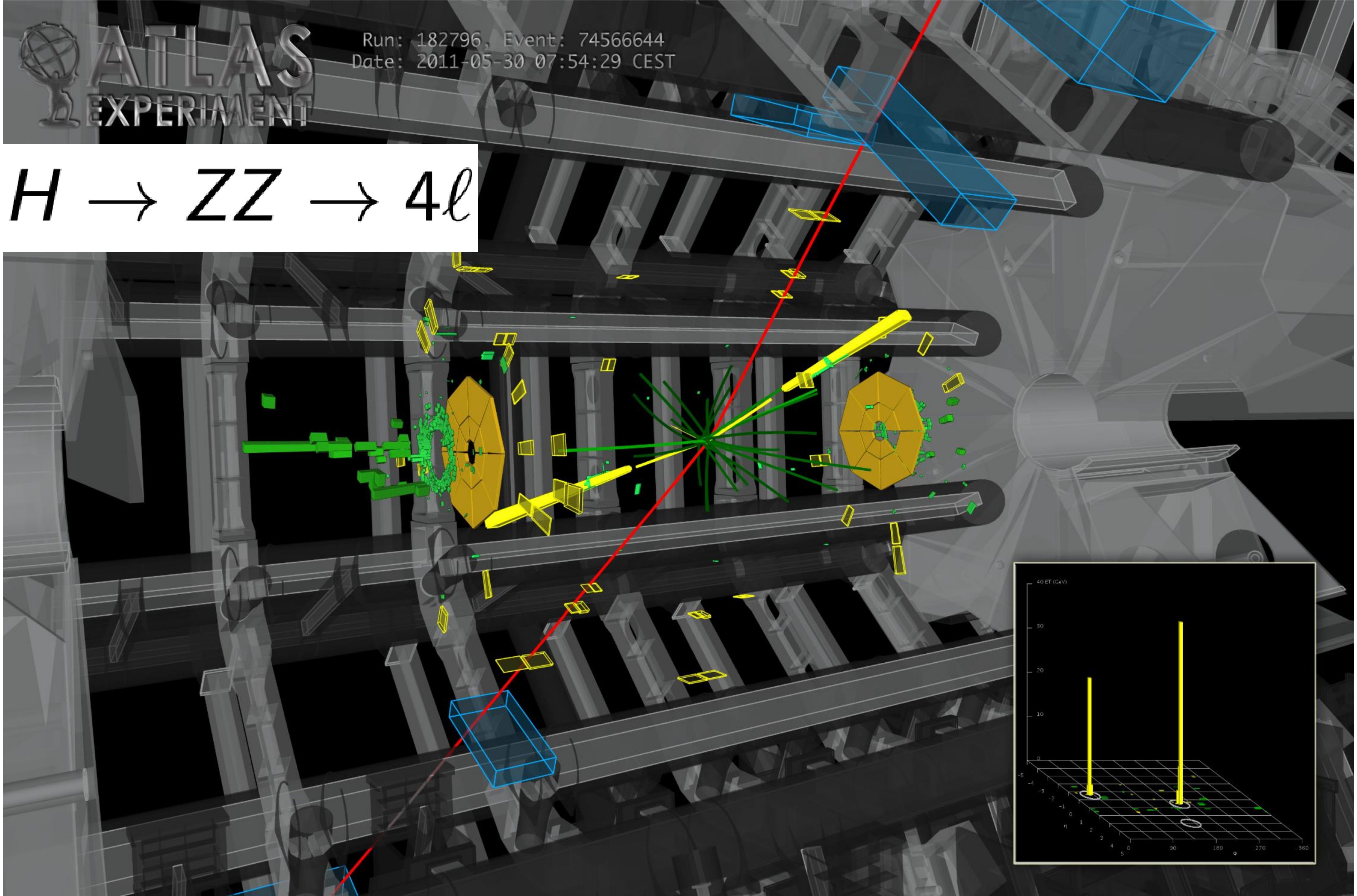
Higgs signal very clear: no need to quote ridiculously large significances

Everything compatible with SM predictions

Not so golden

ATLAS:	$m_H = 125.36 \pm 0.37$ (stat) ± 0.18 (syst) GeV
CMS:	$m_H = 125.03\ ^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (syst) GeV

$H \to ZZ \to 4\ell$

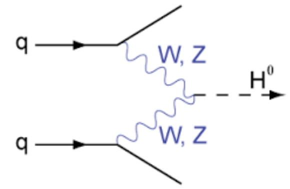


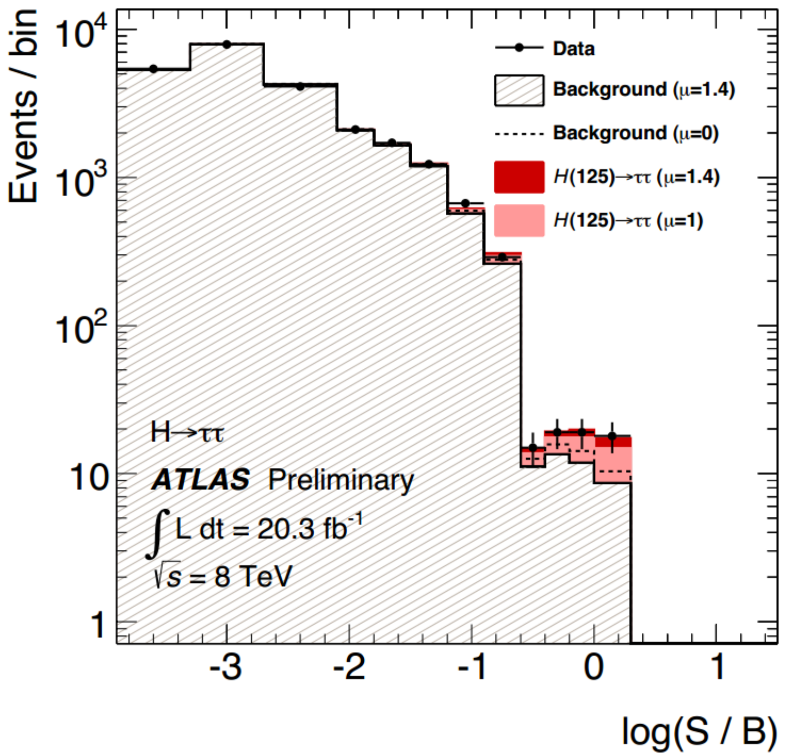
THE HARD CHANNELS

Mohamad's talk

$H \to \tau\tau$

Mainly VBF production





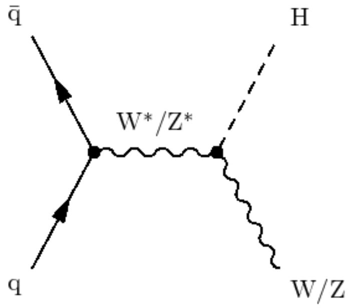
ATLAS : 4.1 σ observed

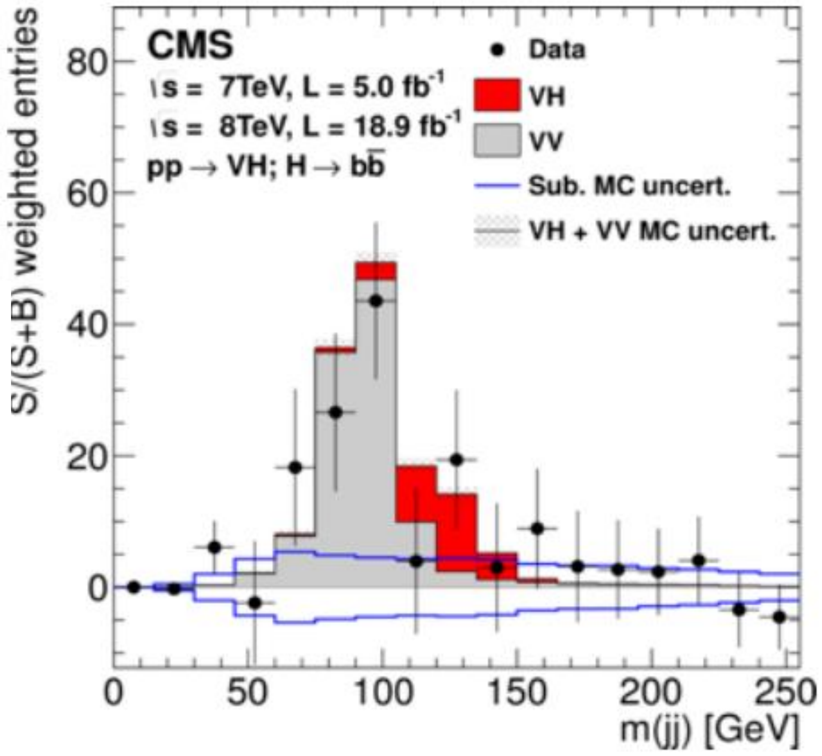
CMS : 3.2 σ observed

Carlo's talk

$H \to bb$

W/Z + H production





ATLAS : 1.4 σ observed

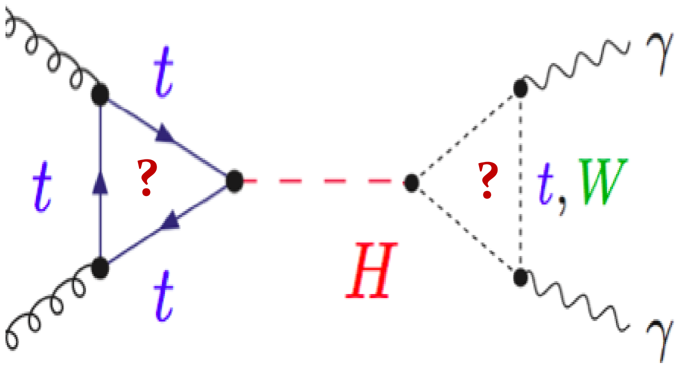
CMS : 2.1 σ observed

THE CHANNEL THAT I LOVE

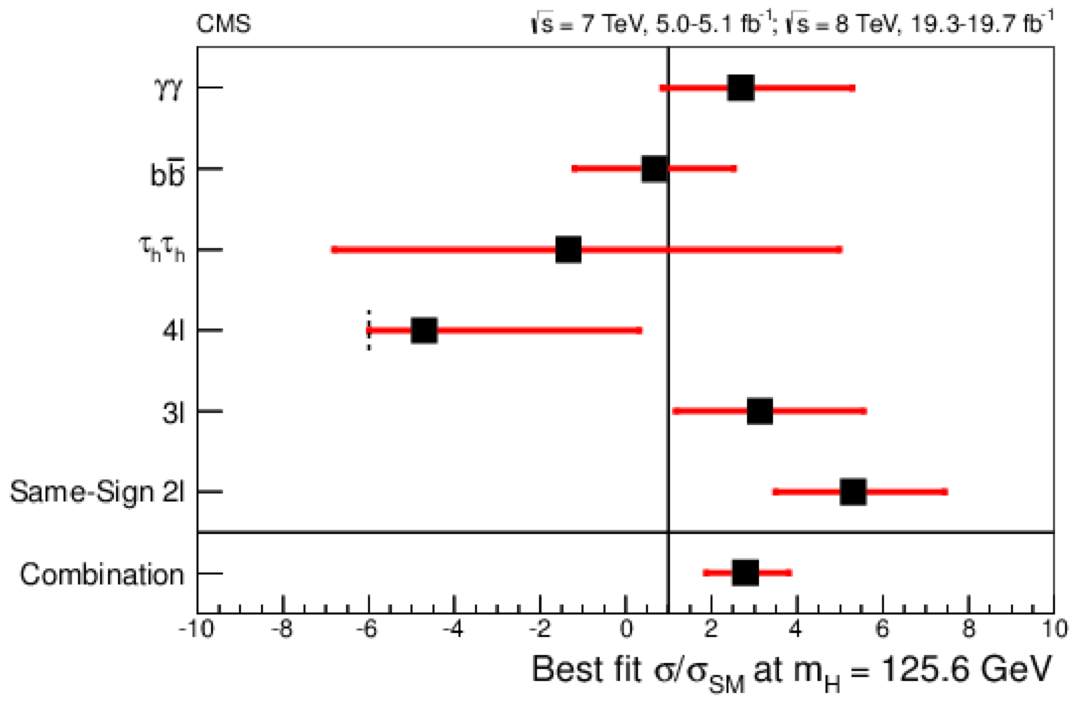
Royer's talk

Top-Higgs coupling largest in the SM

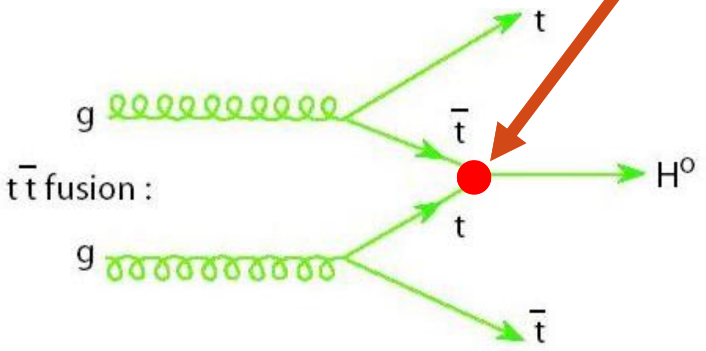
Fundamental to verify the discovered boson nature



Already constrained indirectly in loops



Only way to directly assess the top Yukawa coupling at the LHC



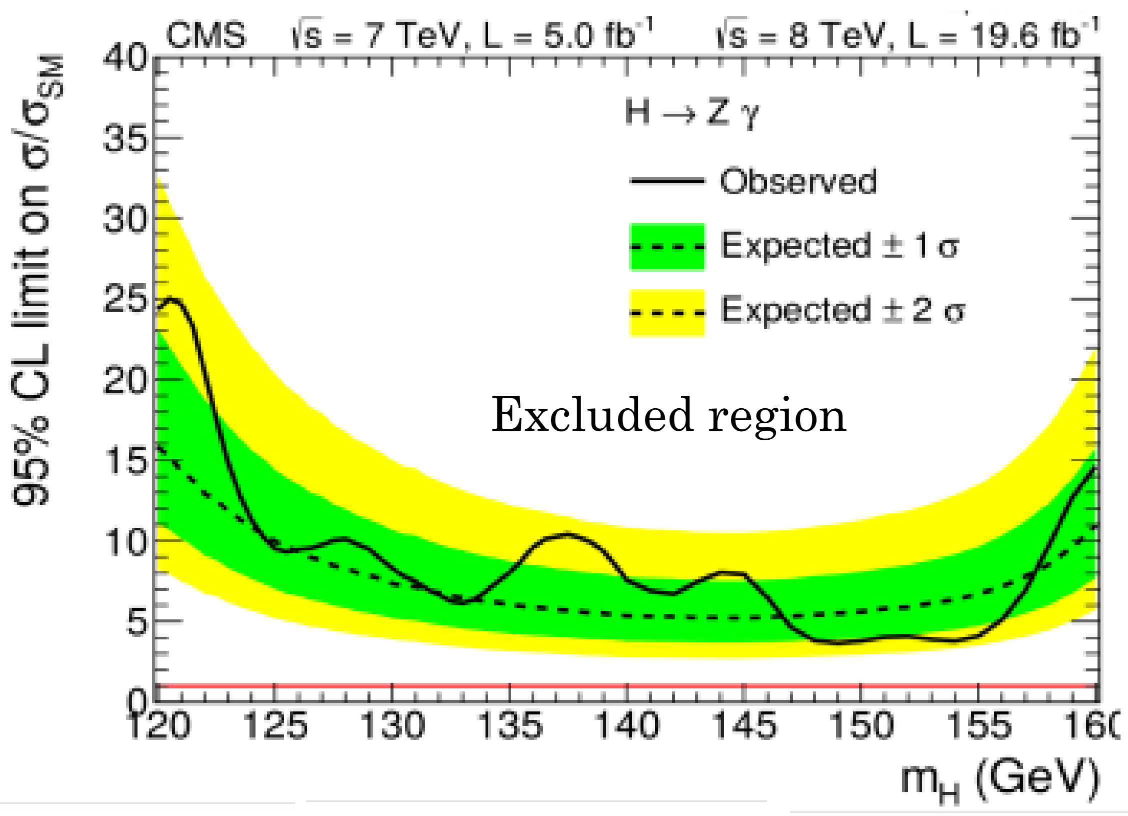
CMS: 3.4σ (1.2 excepted)

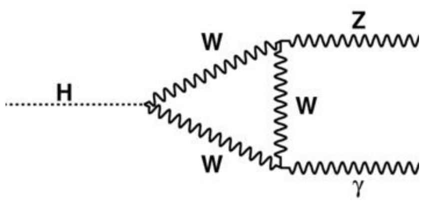
→2.0σ deviation from SM+higgs

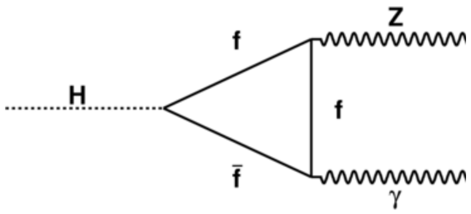
ATLAS: 1.5σ (1.2 expected)

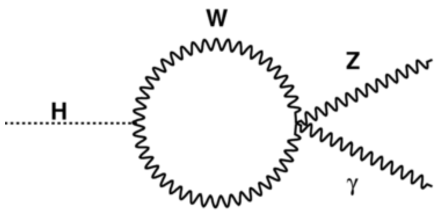
THE VERY HARD CHANNELS

$H \to Z\gamma$

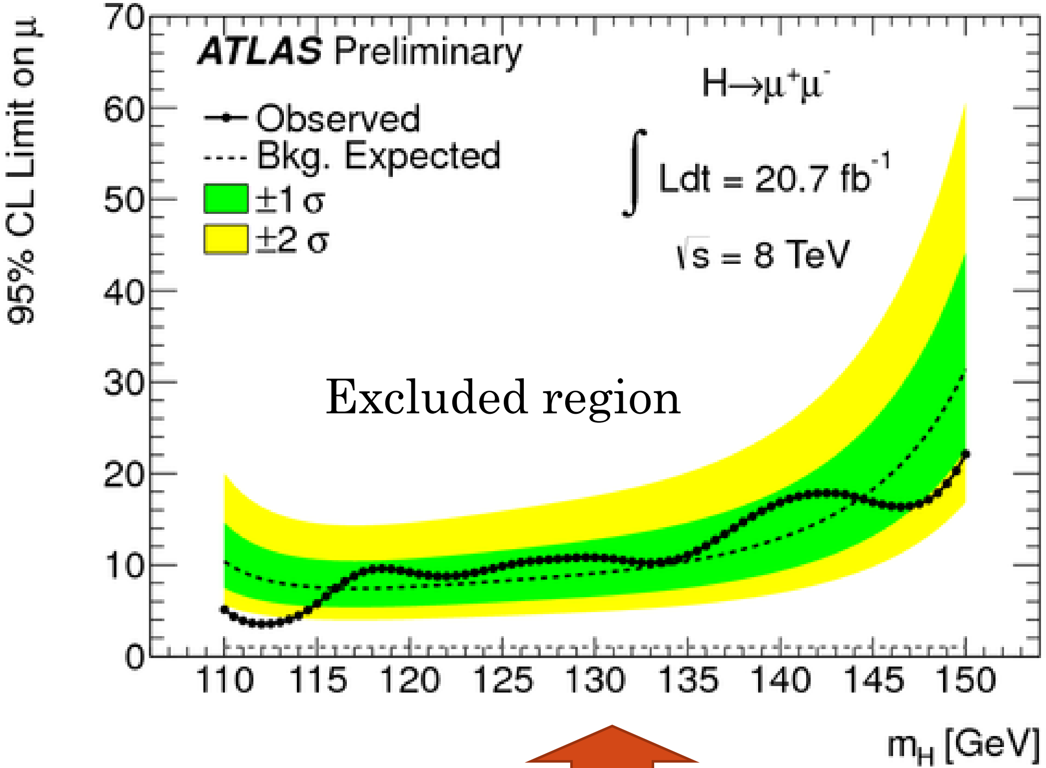








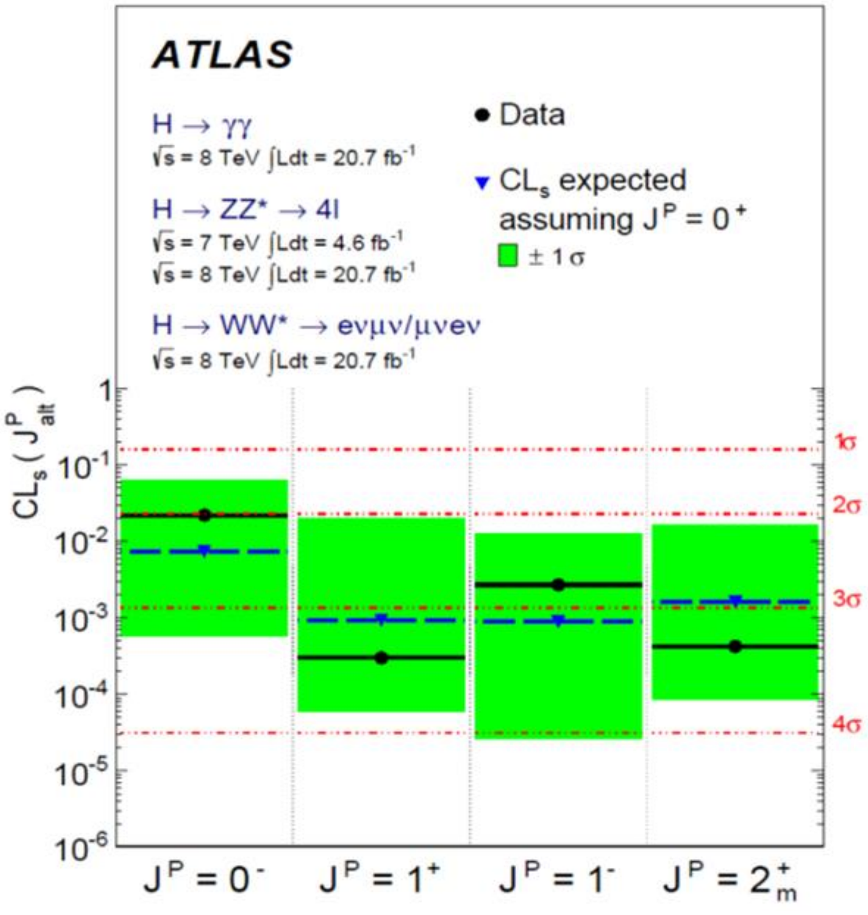
$H \to \mu\mu$

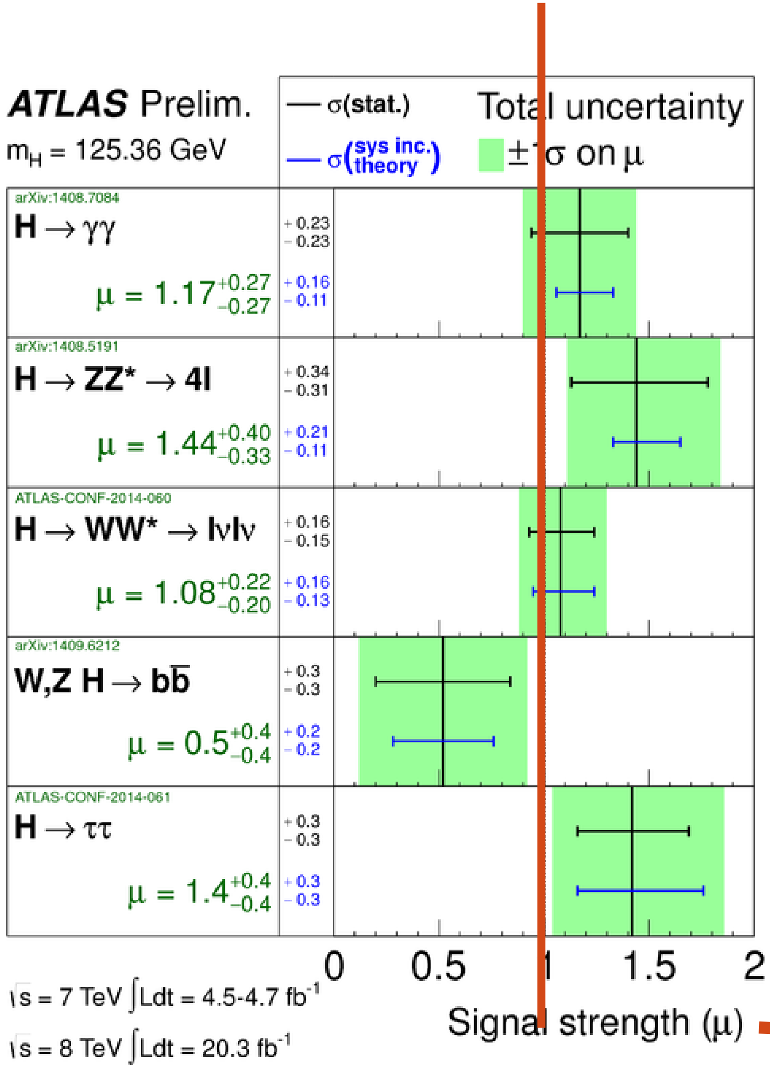


Excludes universal couplings of the Higgs boson

ZE NOW

THE HIGGS PROPERTIES





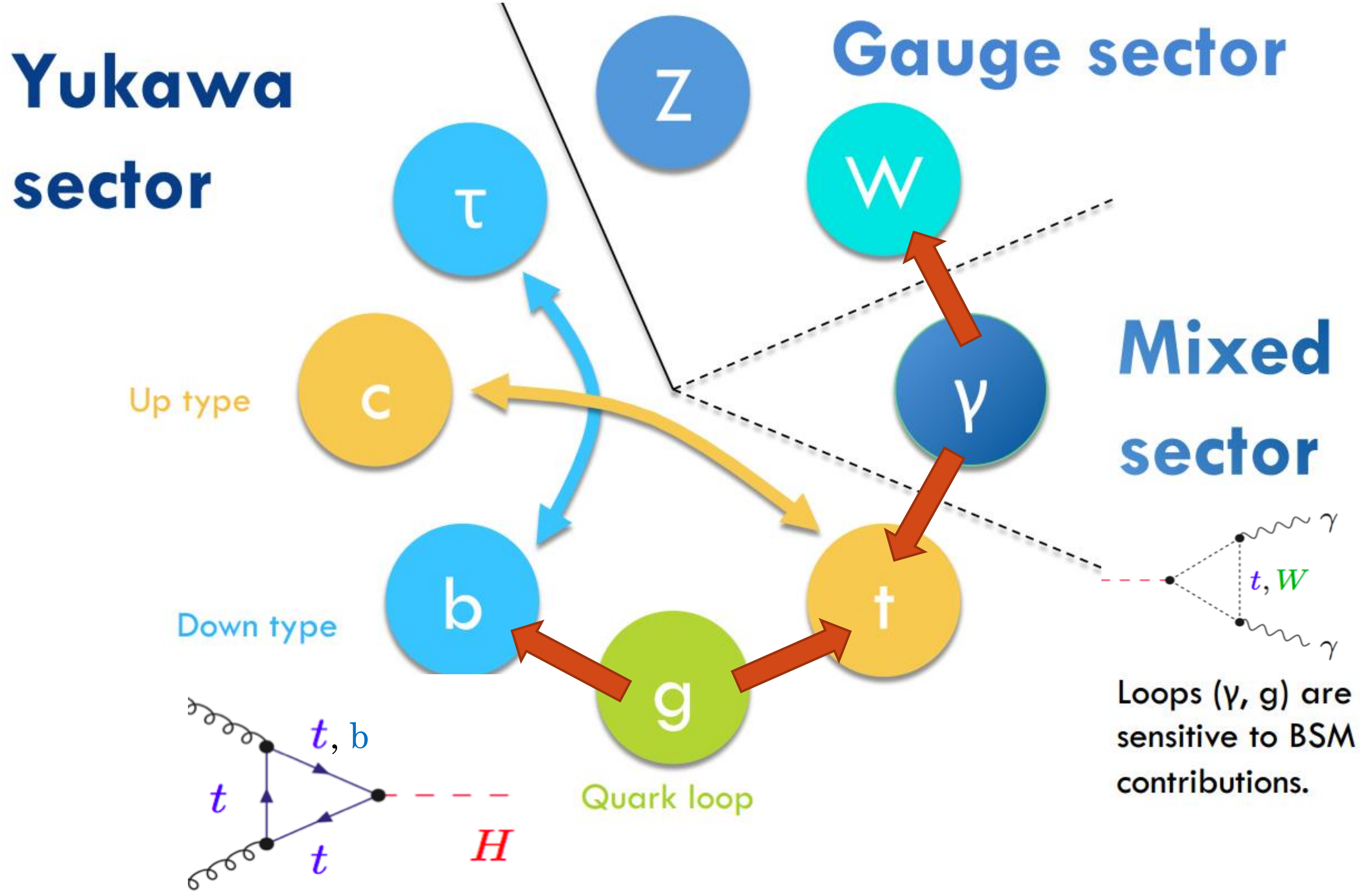
$$\frac{\sigma}{\sigma_{SM}}$$

It pretty much looks like a $J^P=0^+$

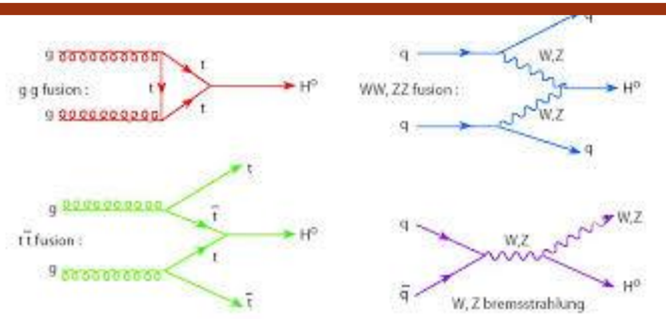
Cross sections compatible with SM predictions

THE "WHAT WE CAN TEST NOW"

- Current data can't constrain all parameters simultaneously
- We have to chose what we test
  - Leave only few parameters free in the fit
- What we test:
  - Custodial symmetry (W vs Z)
  - Fermions(Yukawa) vs Bosons (EW)
  - Lepton vs quarks
  - Up-type vs down-type fermions
  - BSM in the loop
  - Decay to invisible new particles



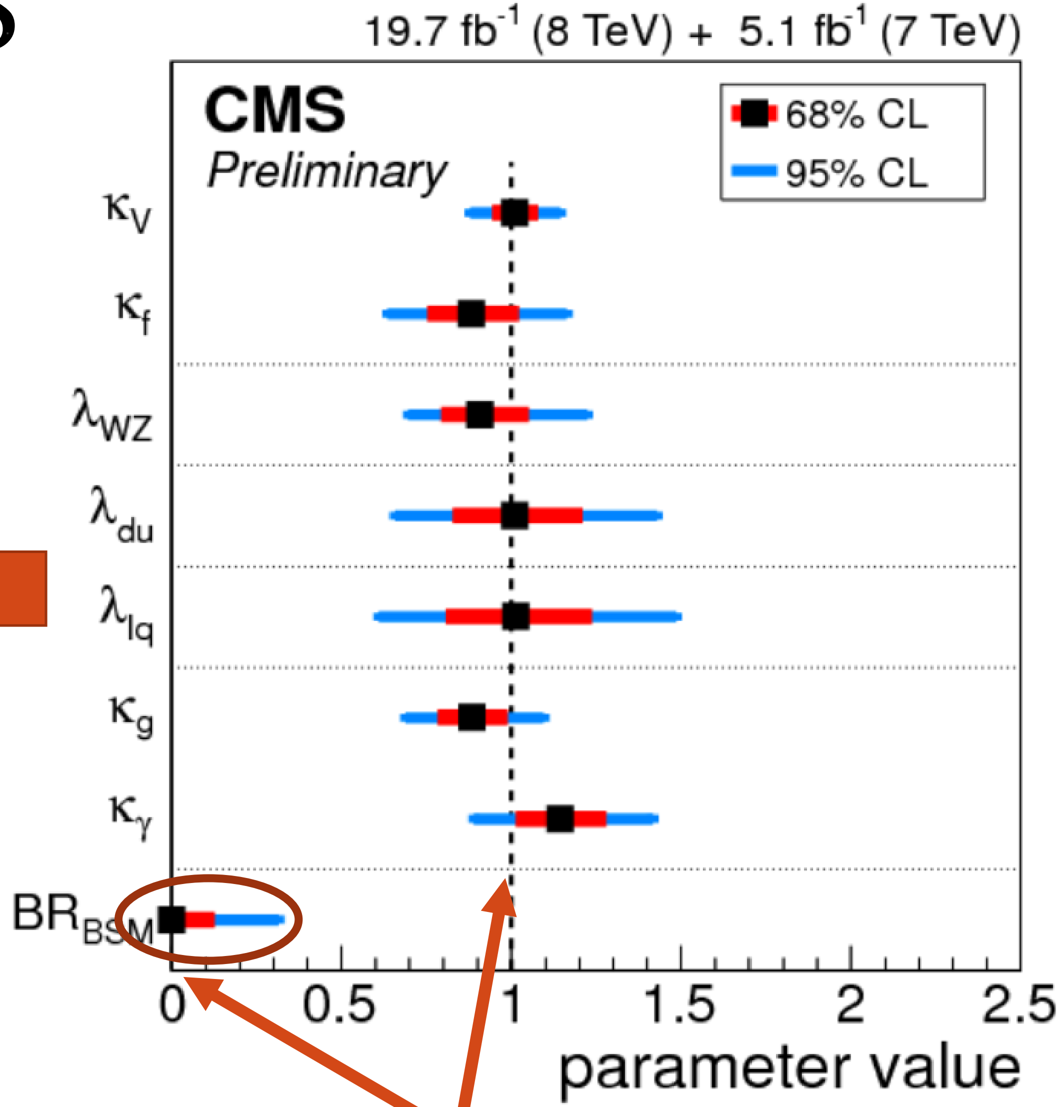
THE HIGGS COUPLINGS



Decay channels

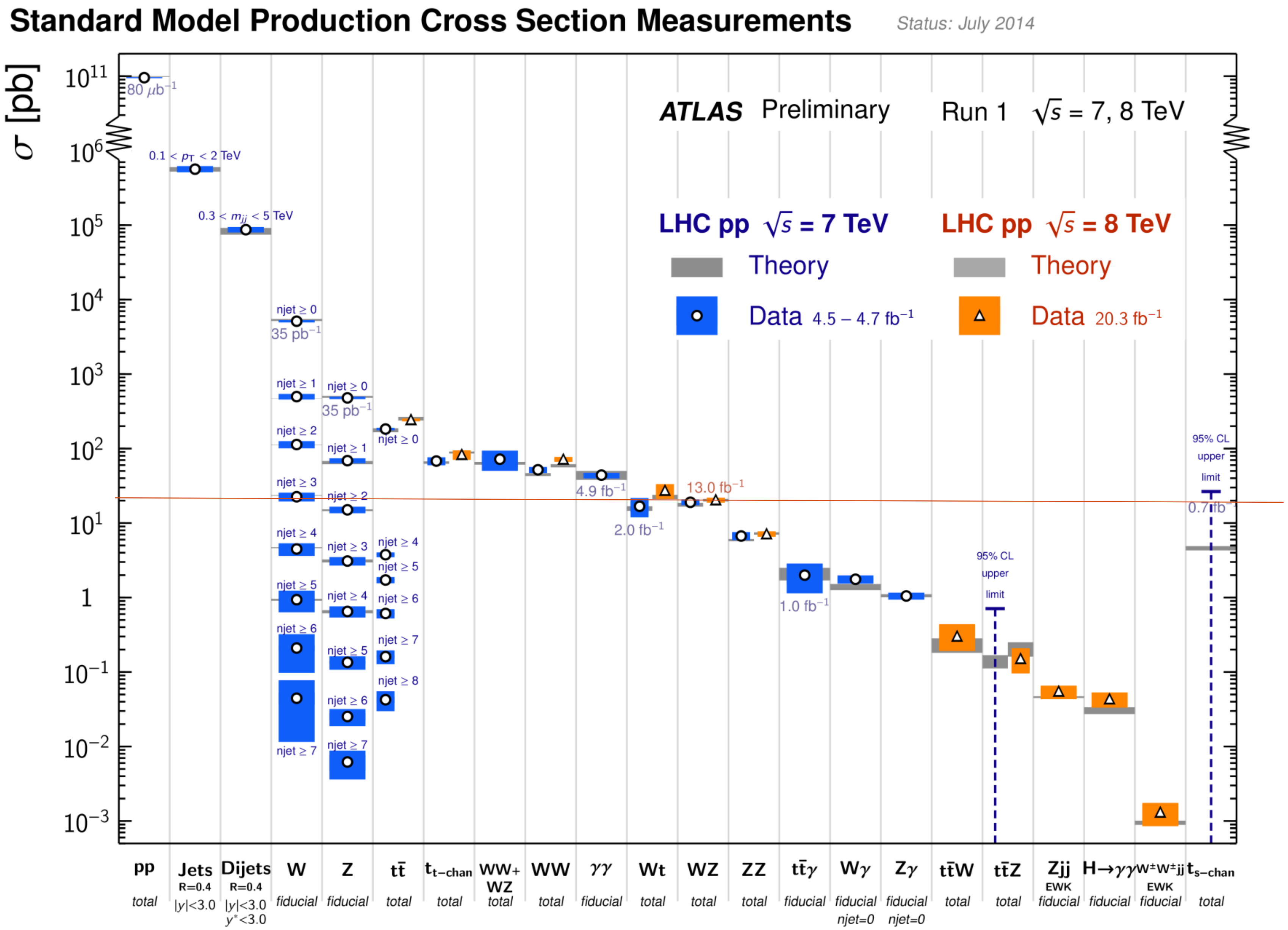
Coupling deviations with respect to SM

You can ask me latter about there meaning



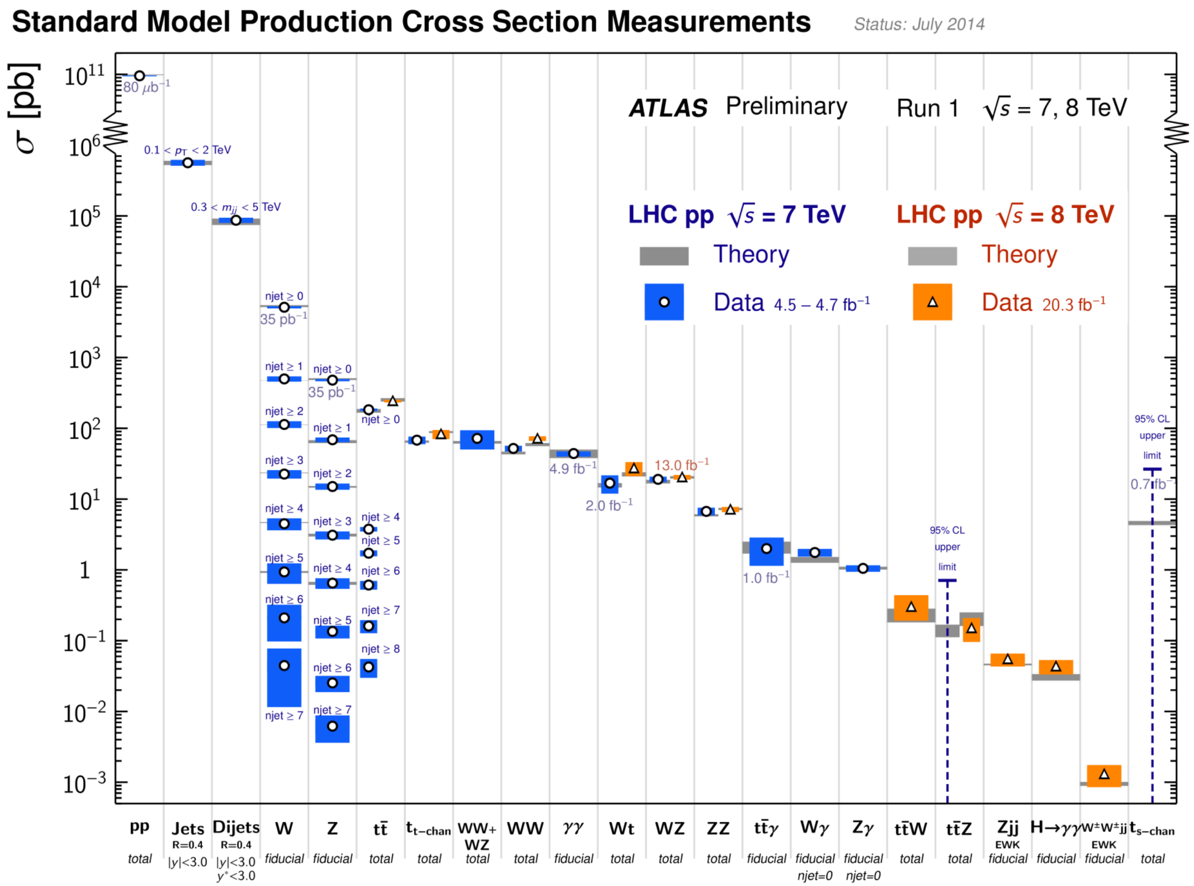
SM

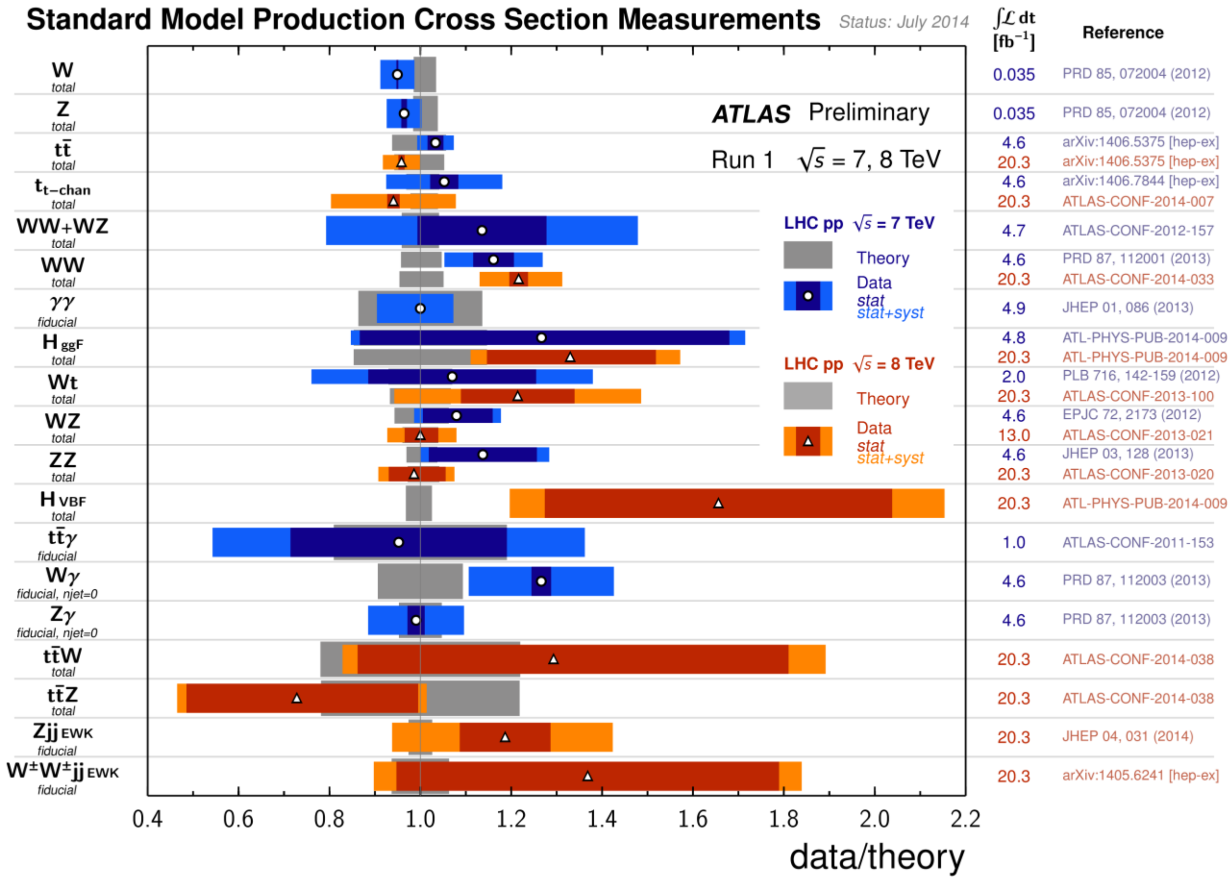
THE IMPRESSIVE SM



Higgs cross section

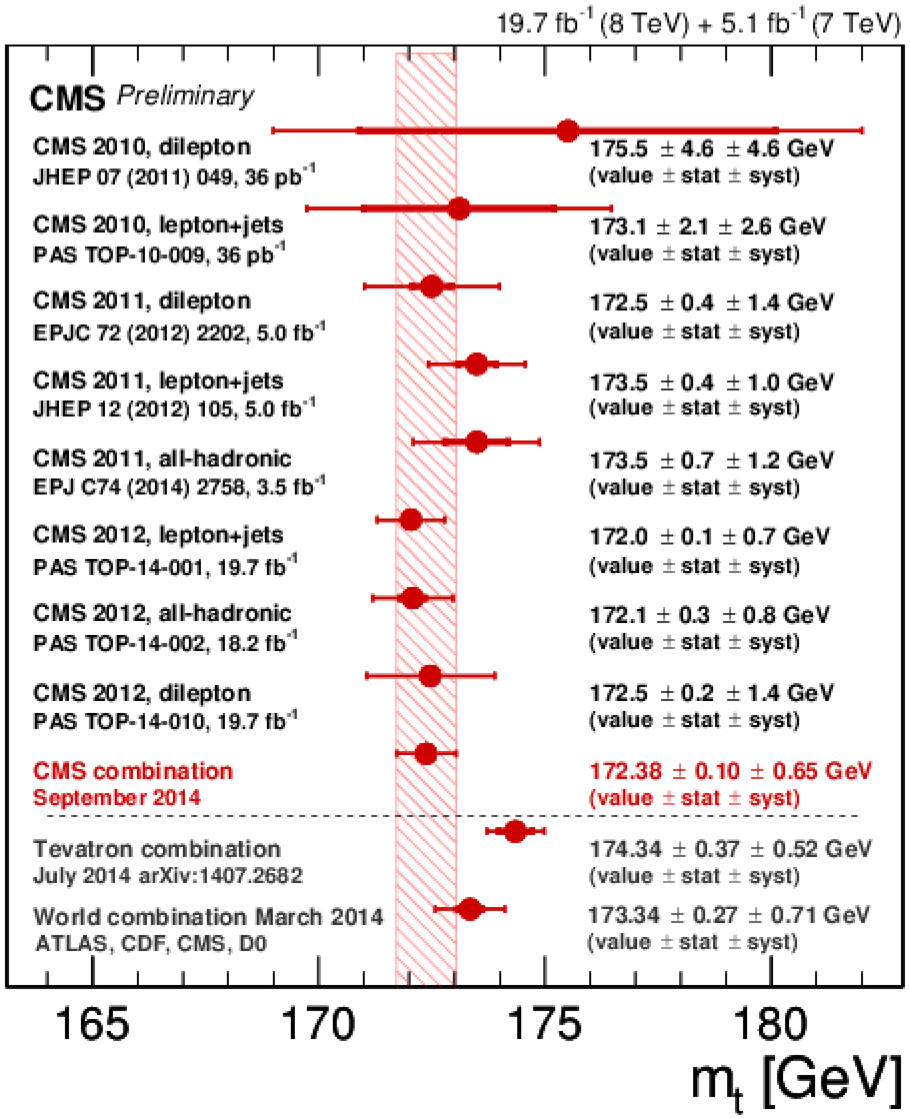
THE IMPRESSIVE SM



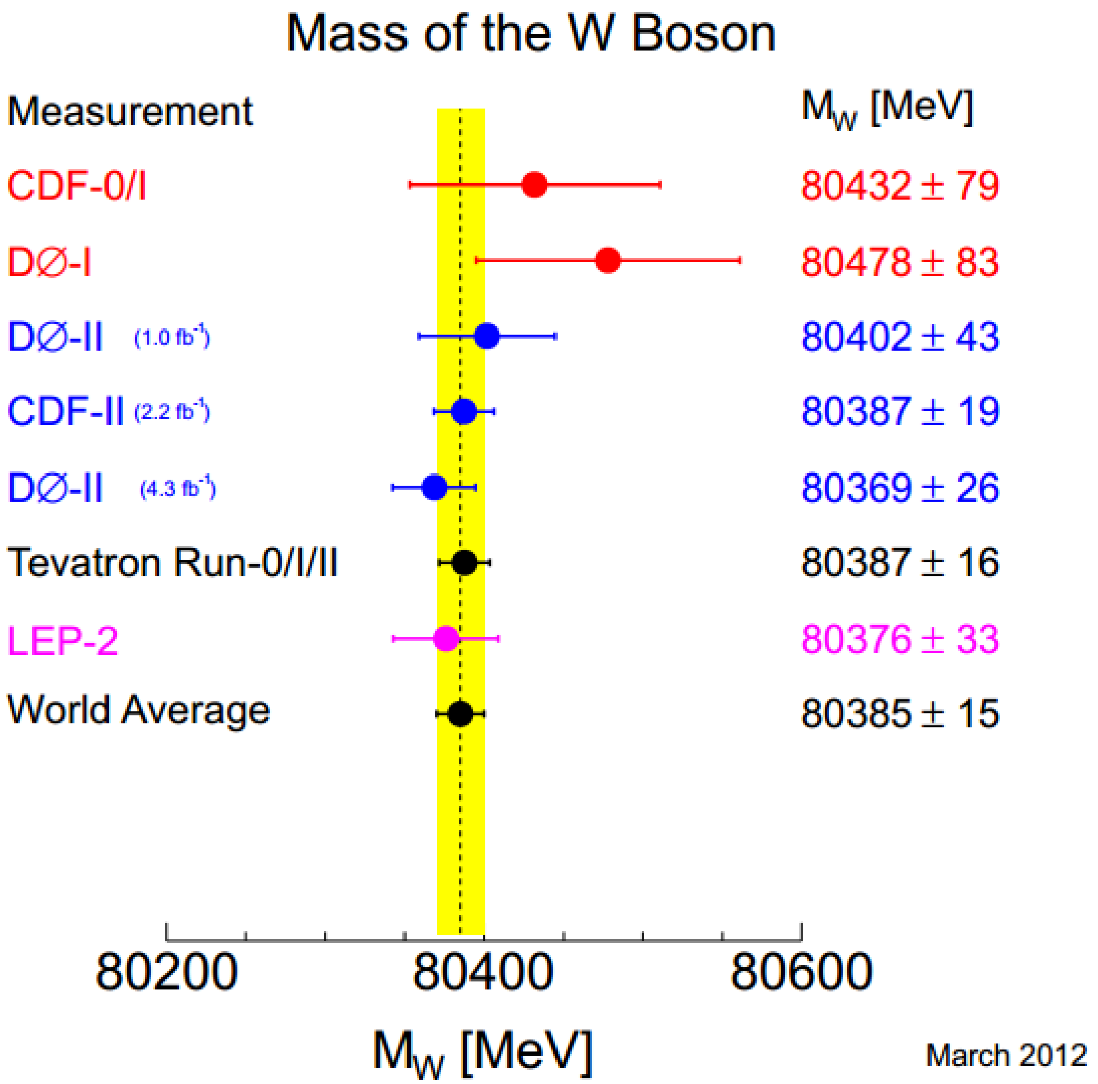


It is not all about the Higgs
Many many other measurements

THE FUNDAMENTALS (WILL GET BACK TO THIS)

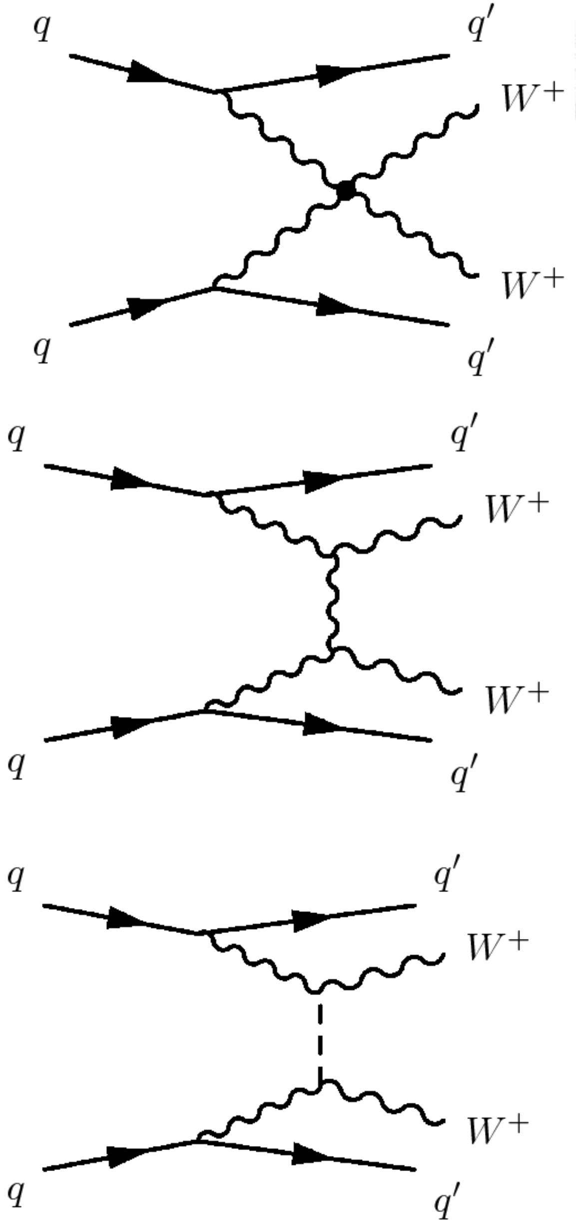


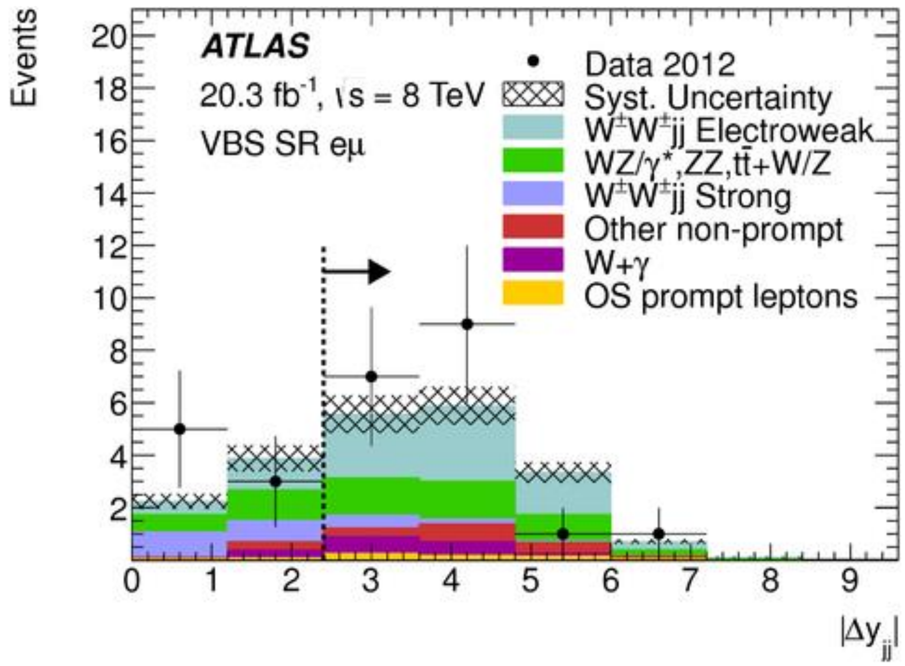
Top mass: experimental precision reaching theory uncertainties

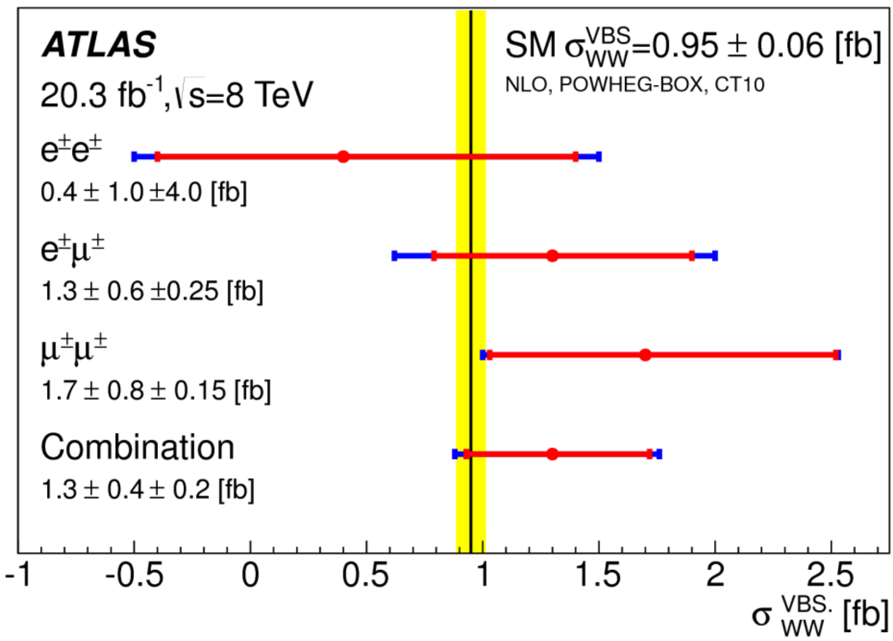


W mass: Tevatron still rules

OTHER IMPORTANT MEASUREMENTS







Electroweak production observed with 3.6σ

Cross section compatible with SM predictions (large errors)

Very interesting for LHC run II
Tightly connected to the Higgs sector

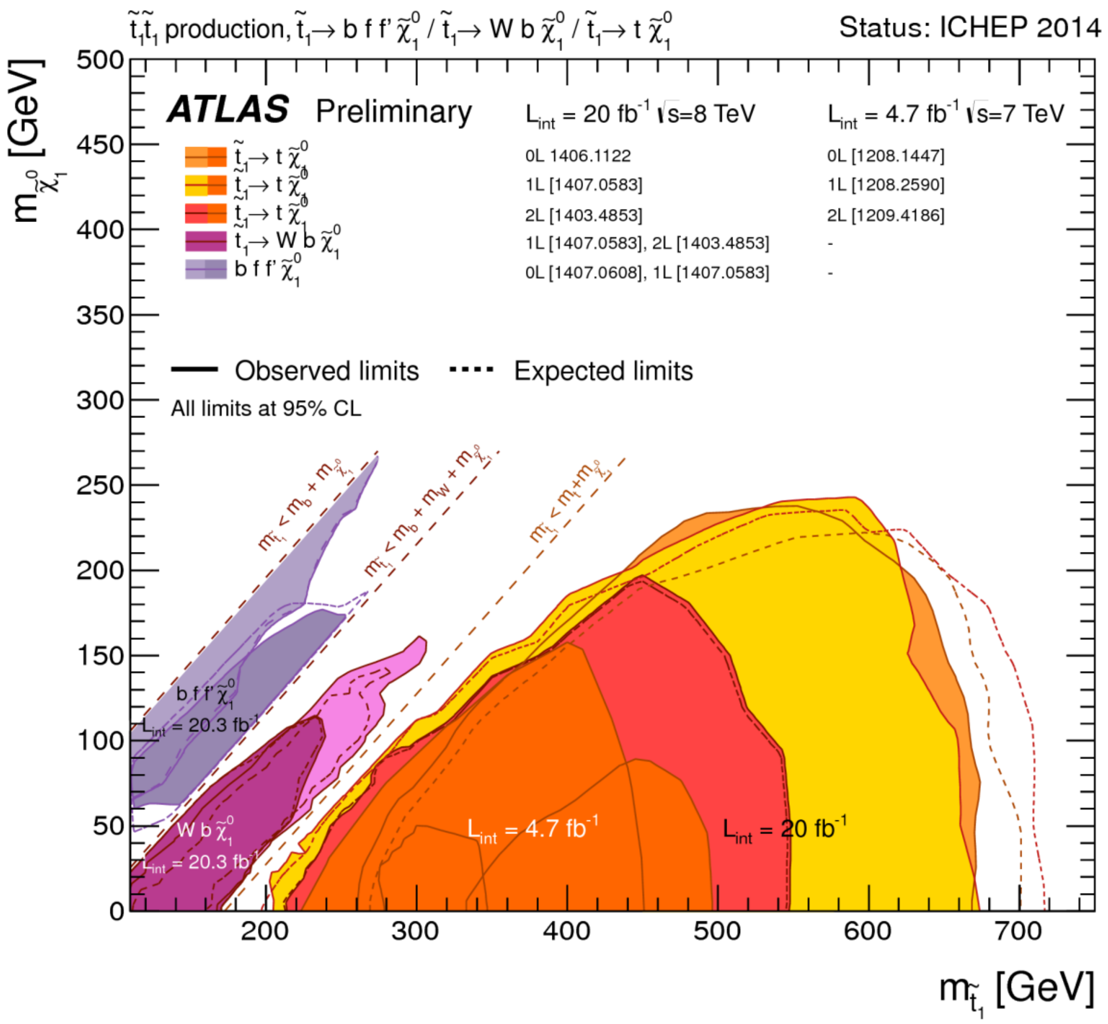
SM subject for the Atelier

THE THINGS WE DID NOT FIND (YET)

Well this will be discussed in details in the BSM session
But just to put things into perspective

THE THINGS WE DID NOT FIND (YET)

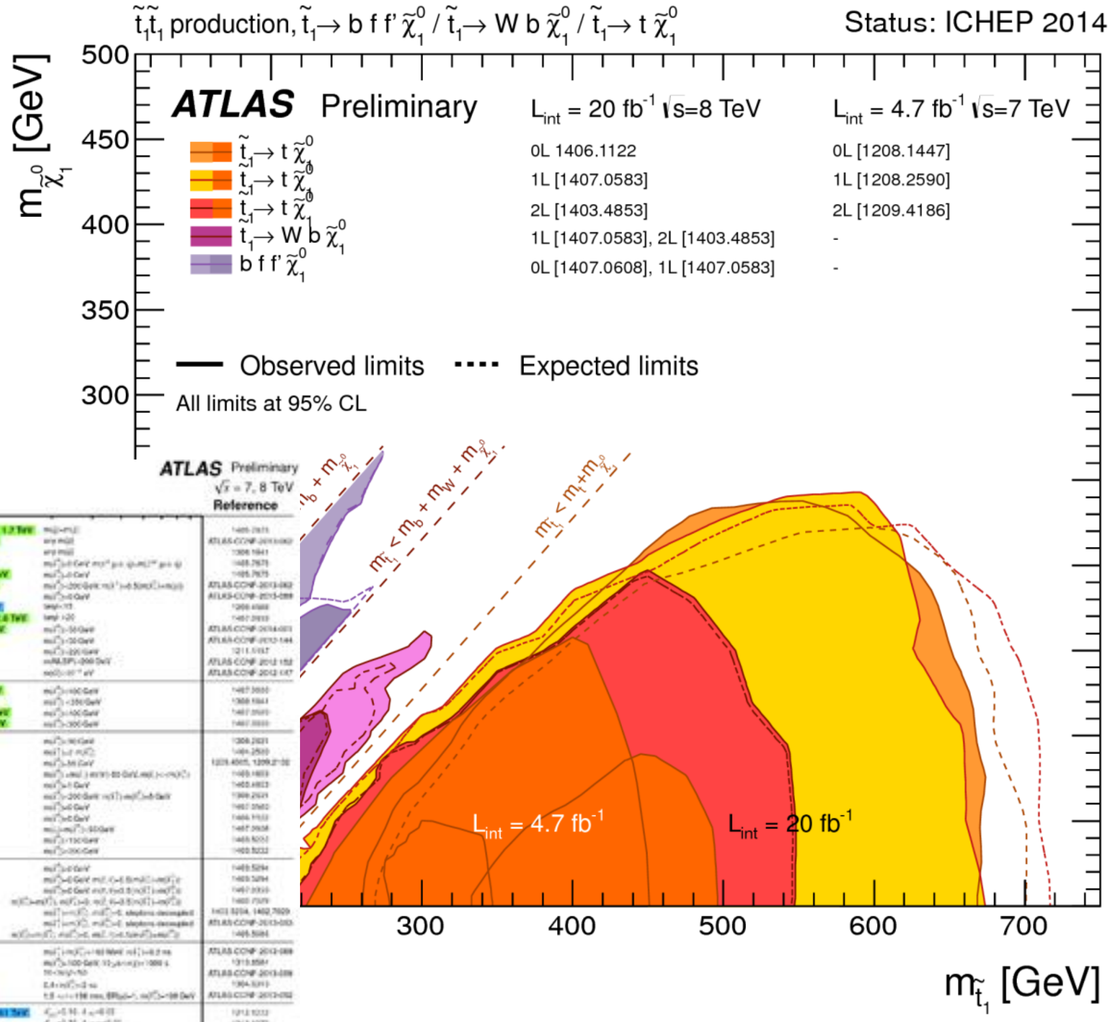
LIMITS

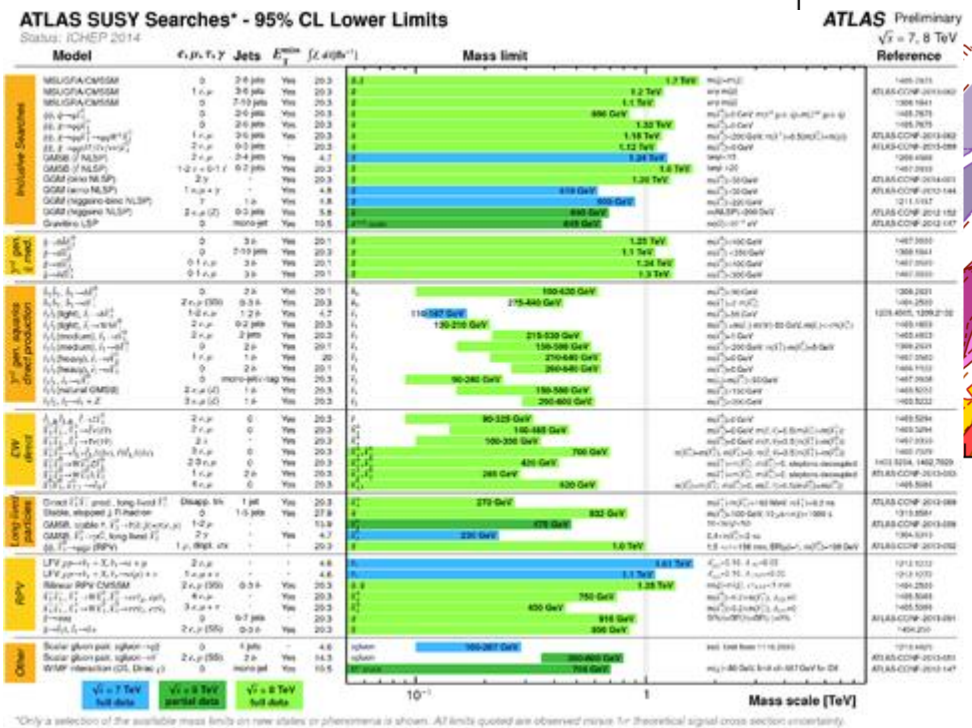


THE THINGS WE DID NOT FIND (YET)

LIMITS

LIMITS



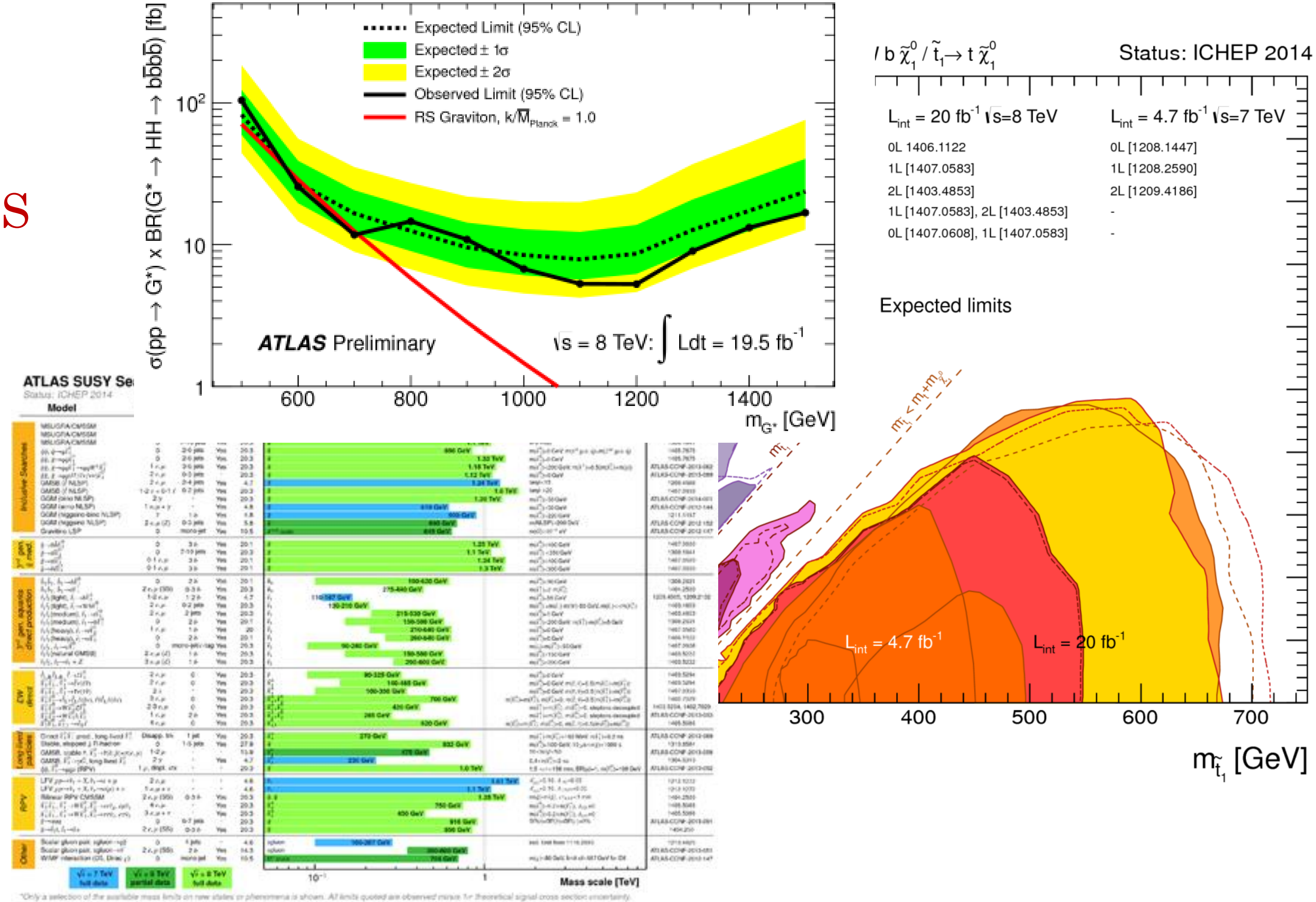


THE THINGS WE DID NOT FIND (YET)

LIMITS

LIMITS

LIMITS



THE THINGS WE DID NOT FIND (YET)

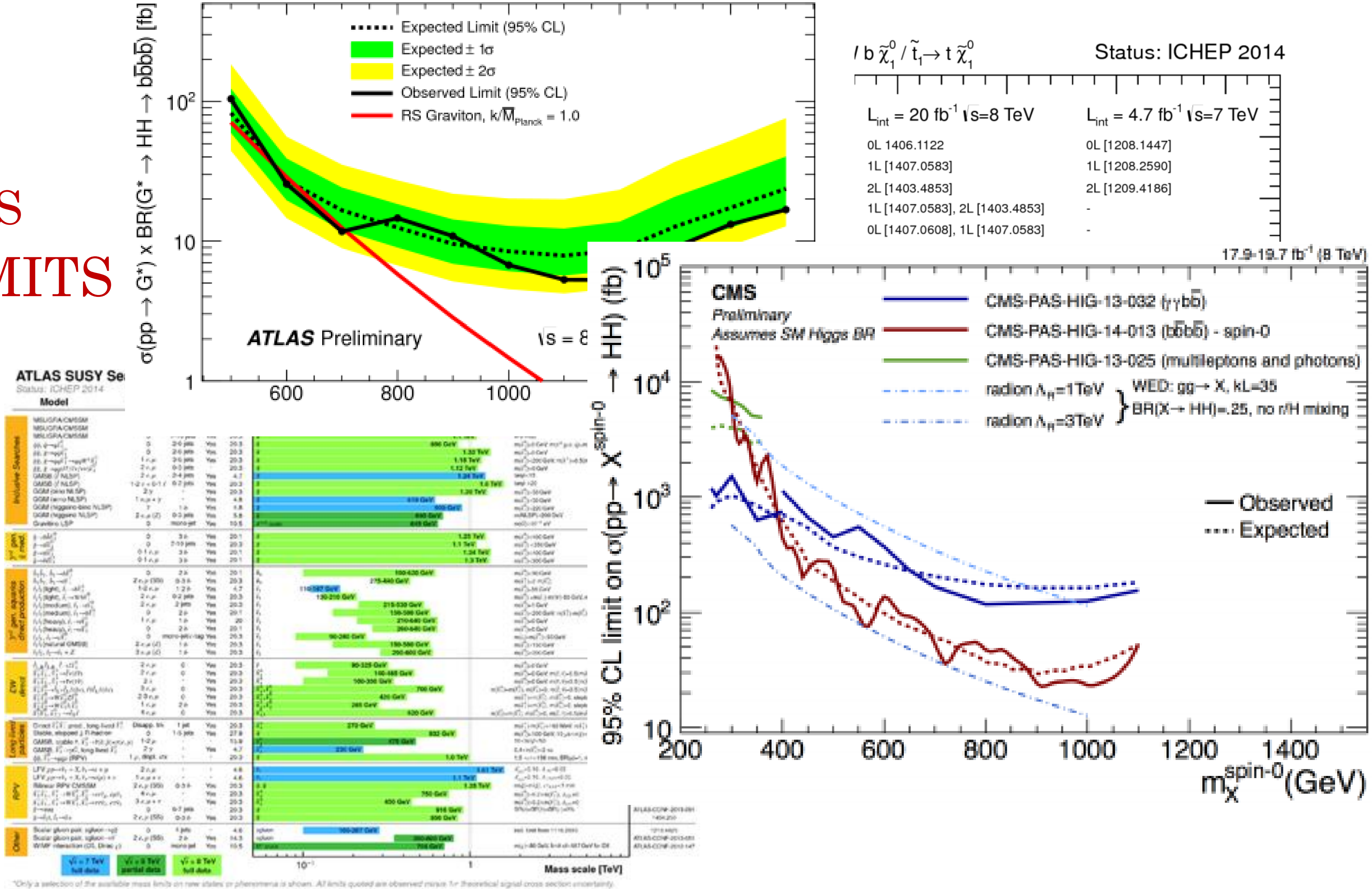
LIMITS

LIMITS

LIMITS

LIMITS

…



THE THINGS WE DID NOT FIND (YET)

LIMITS

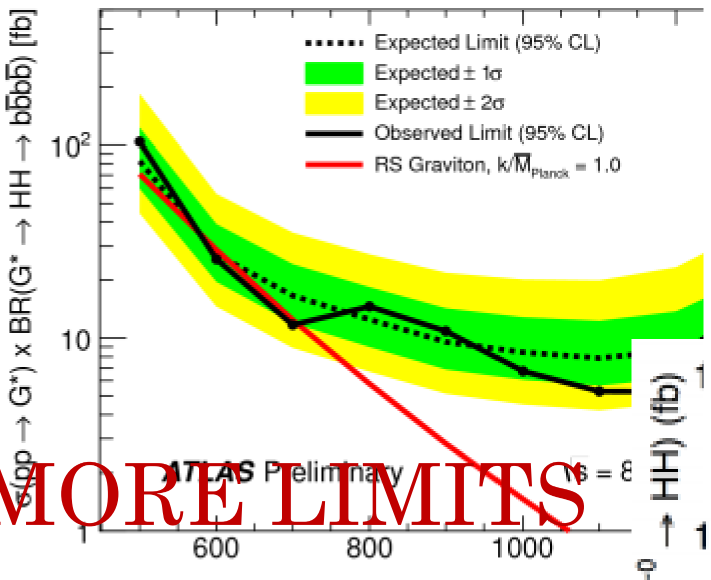
LIMITS

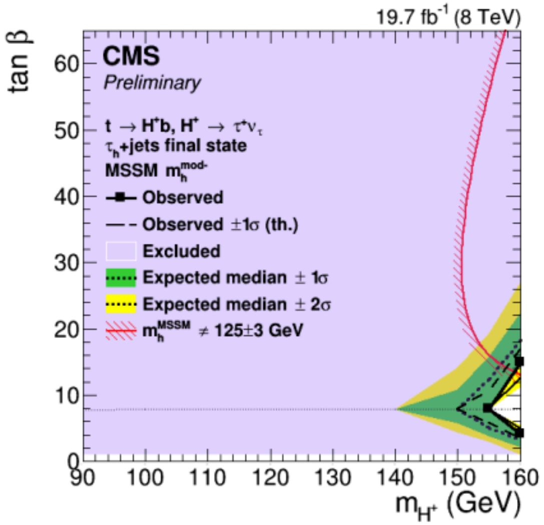
LIMITS

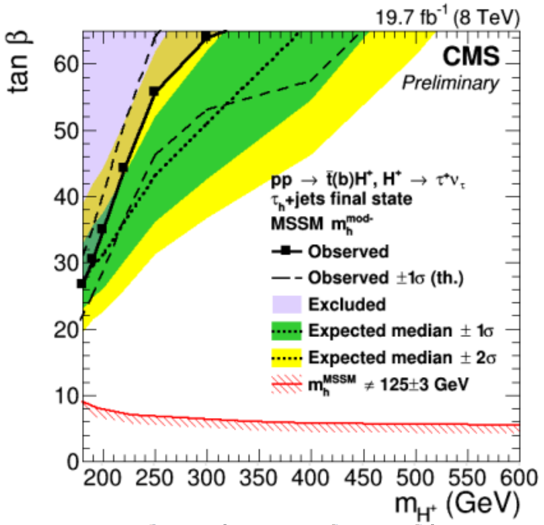
LIMITS

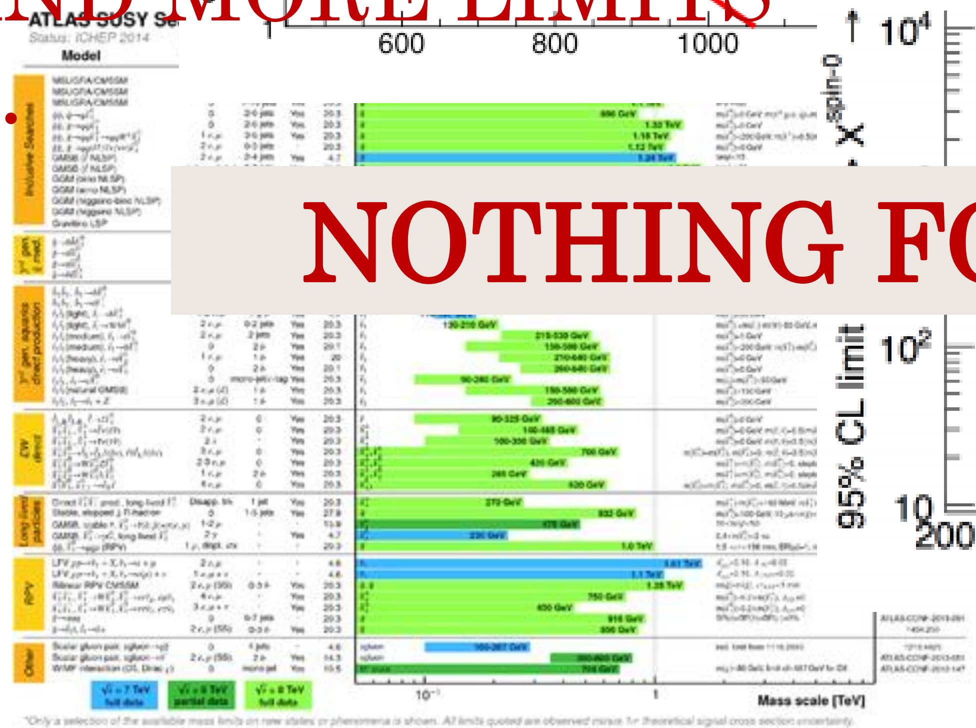
…AND MORE LIMITS

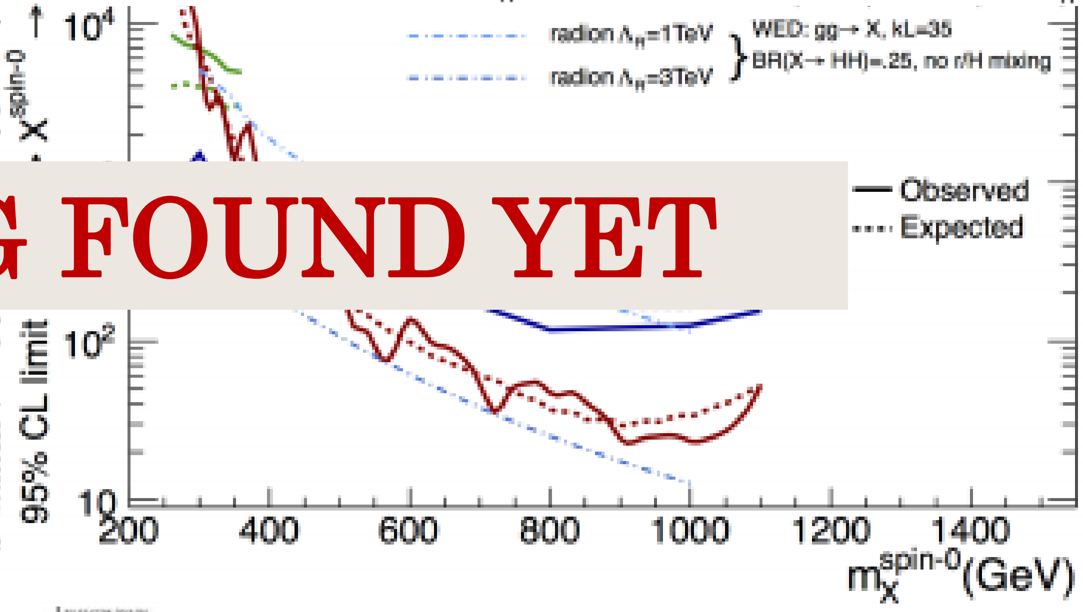
…





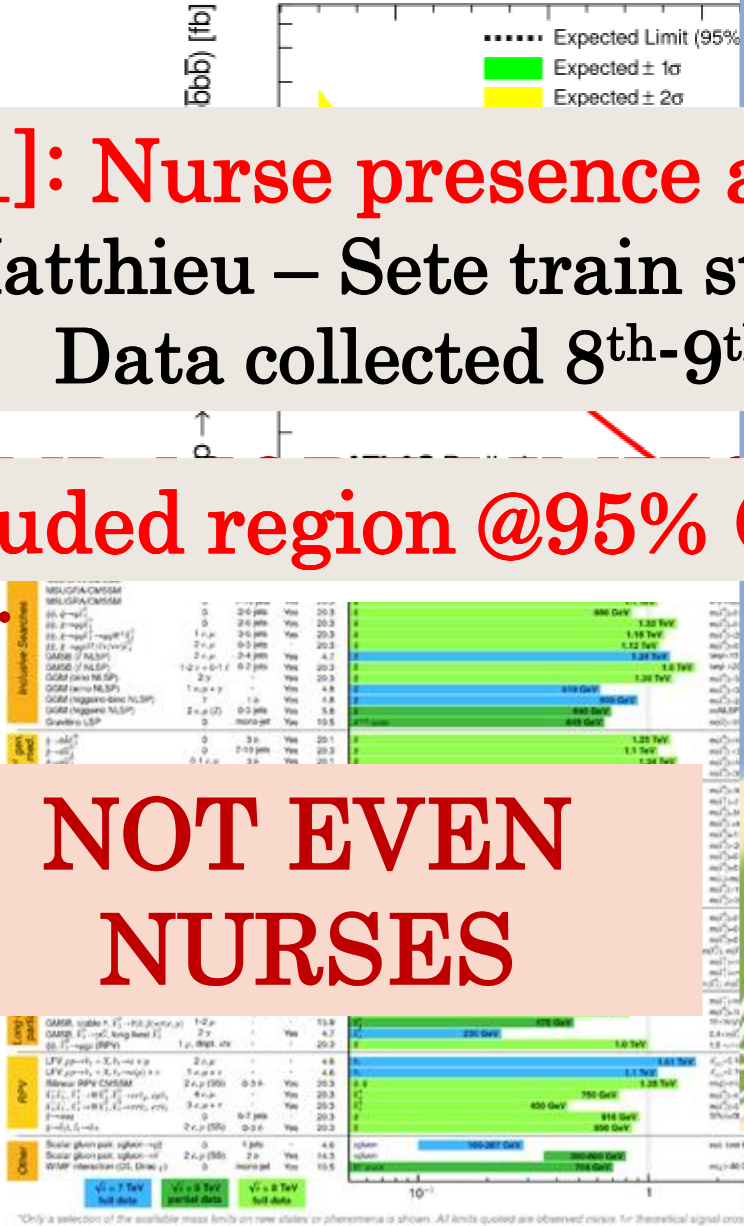






NOTHING FOUND YET

THE THINGS WE D



Model [1]: Nurse presence at the Lazaret

[1] Matthieu – Sete train station – Dec. 2014

Data collected 8th-9th Dec. 2014

Excluded region @95% CL

…

NOT EVEN NURSES

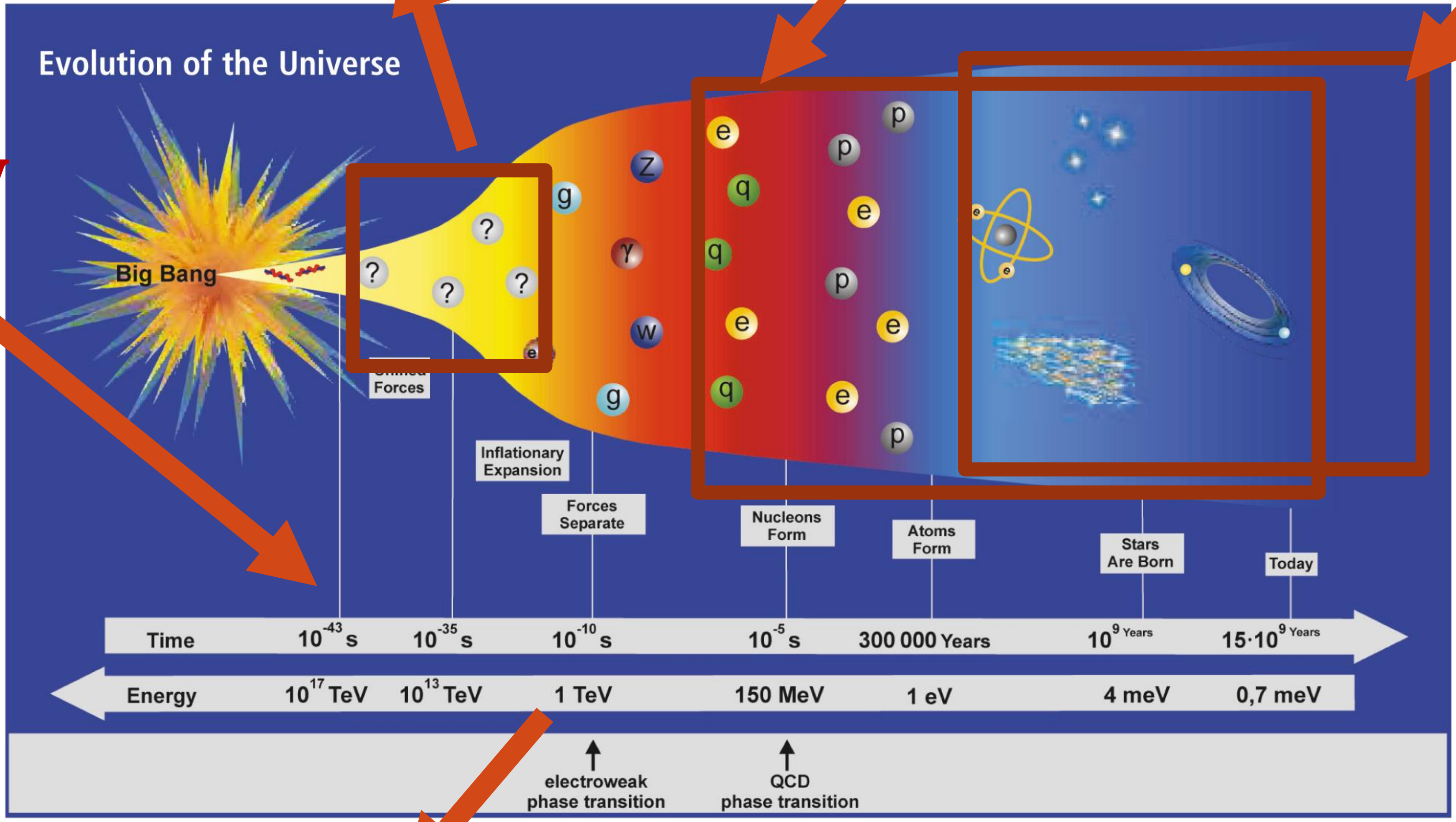
THE BIGGER PICTURE

New physics??

The SM rules!!

SM and GR rules!!

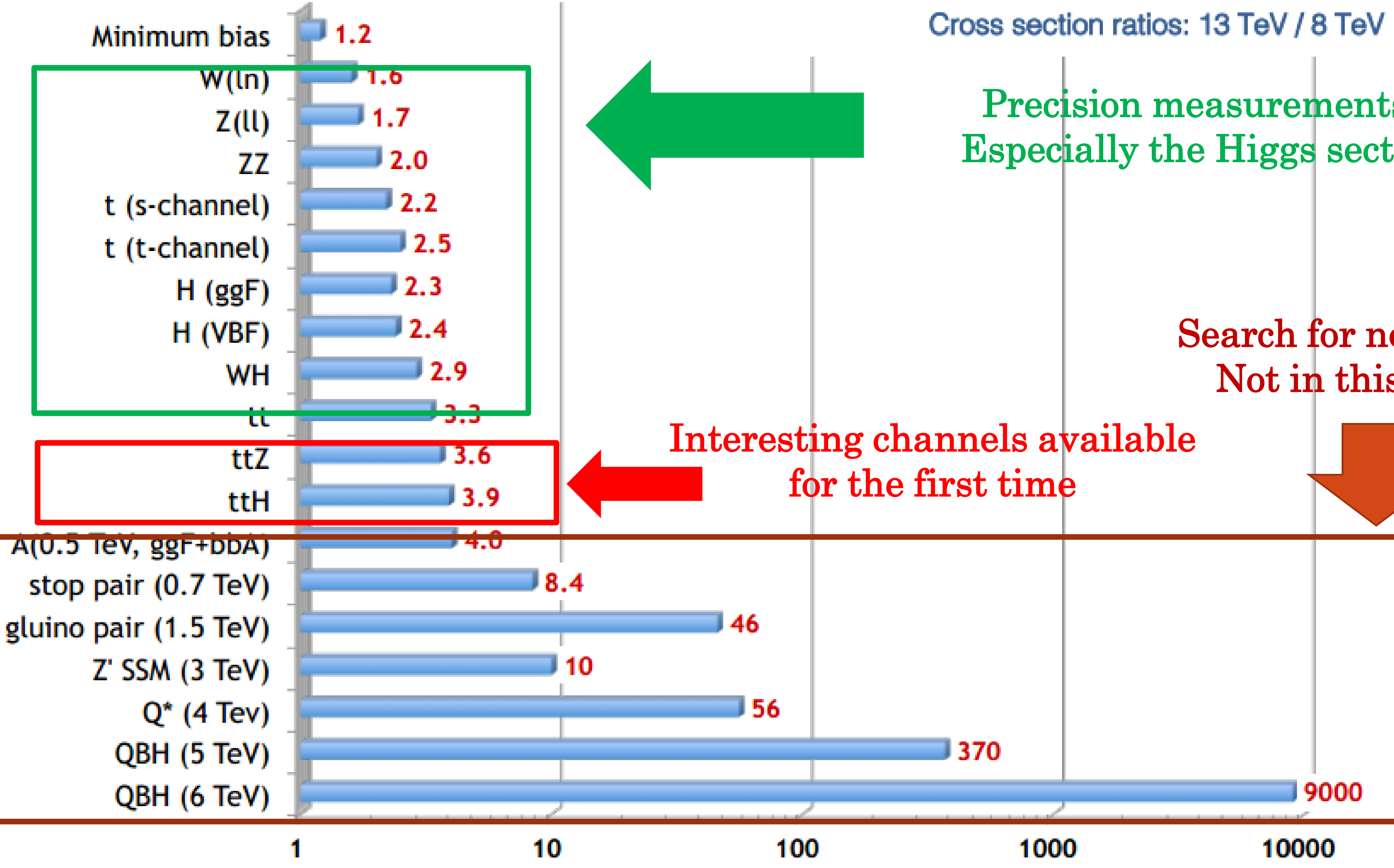
For sure new physics



LHC

ZE FUTURE

THE LHC @13 TEV

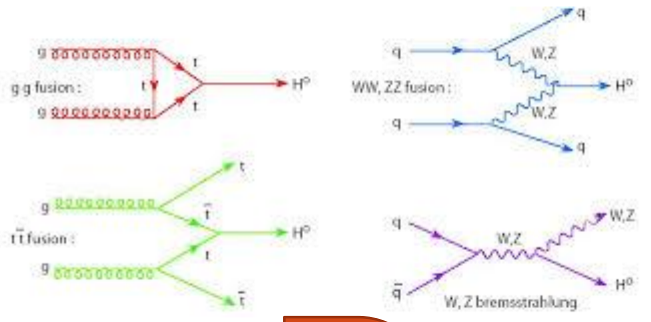


Precision measurements
Especially the Higgs sector

Interesting channels available
for the first time

Search for new physics
Not in this session

THE HIGGS @LHC RUN II



+ Decay

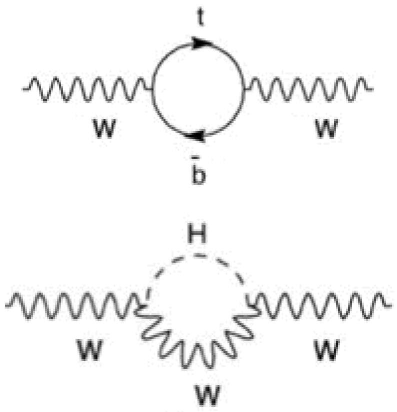
1. Access to H→bb (largest BR)
2. Access to ttH (largest coupling)
3. Separate individual production channels
4. Combine with other SM measurements in the electroweak sector
5. …

Best precision on couplings

Will be hard for many!!

Also confirm pure $J^P=0^+$ State
And better precision on the mass

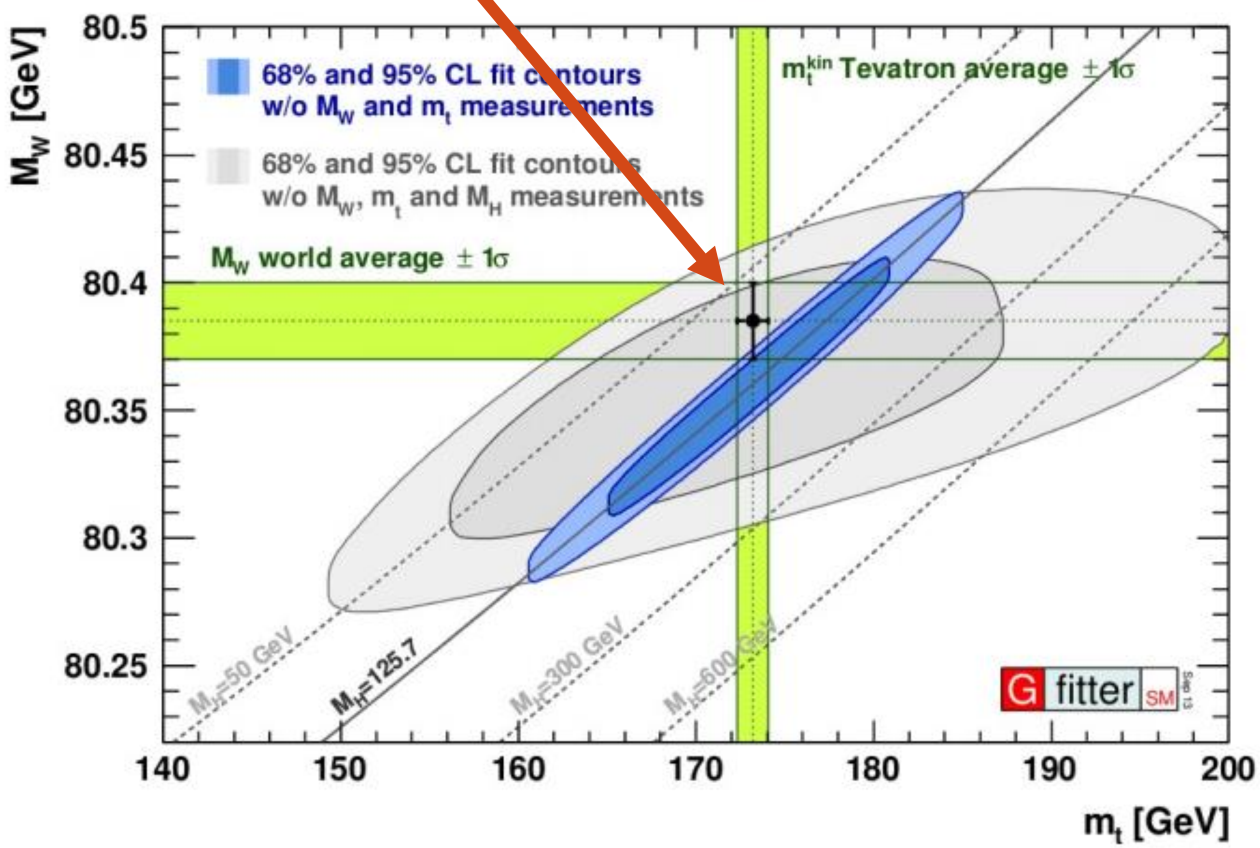
ELECTROWEAK TESTS



W, top and Higgs masses (and other parameters) related in the SM (~~quantum corrections~~)

Fits done in the past to indirectly determine the top and Higgs mass

Fluctuation or real effect?



Now can be used to test the internal consistency of the SM

- Higgs mass precision not so important
- top mass precision OK
- W mass very important
  - Should go to < 10 MeV at LHC

ZE CONCLUSION

THE CONCLUSION

Well, do I really need to?!?

THE SELF COUPLINGS