Higgs Hands-On

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Fourth Lisbon mini-school on Particle/Astroparticle Physics

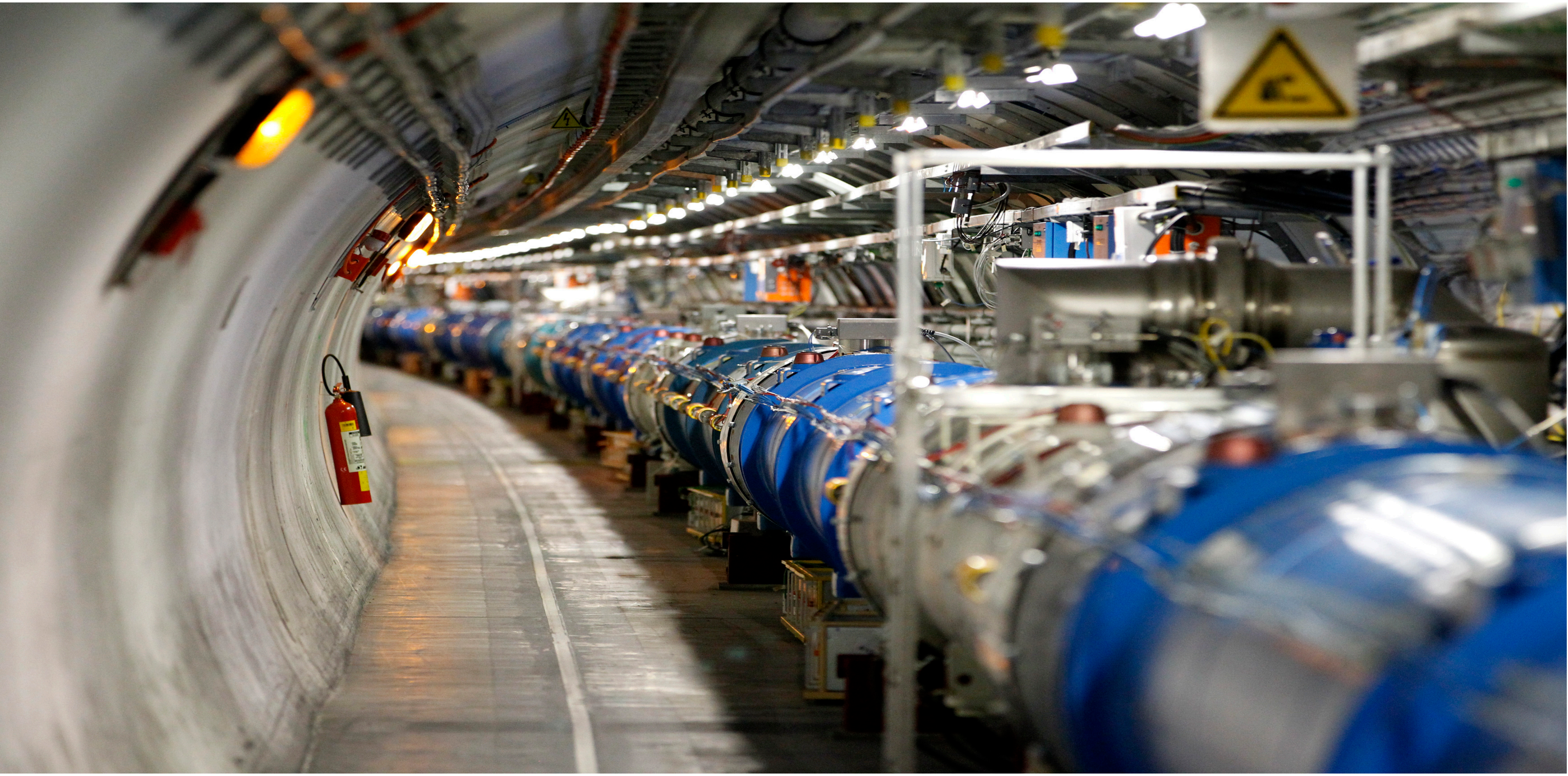
Costa da Caparica, February 2019

Cofinanciado por:

Summary of the exercise

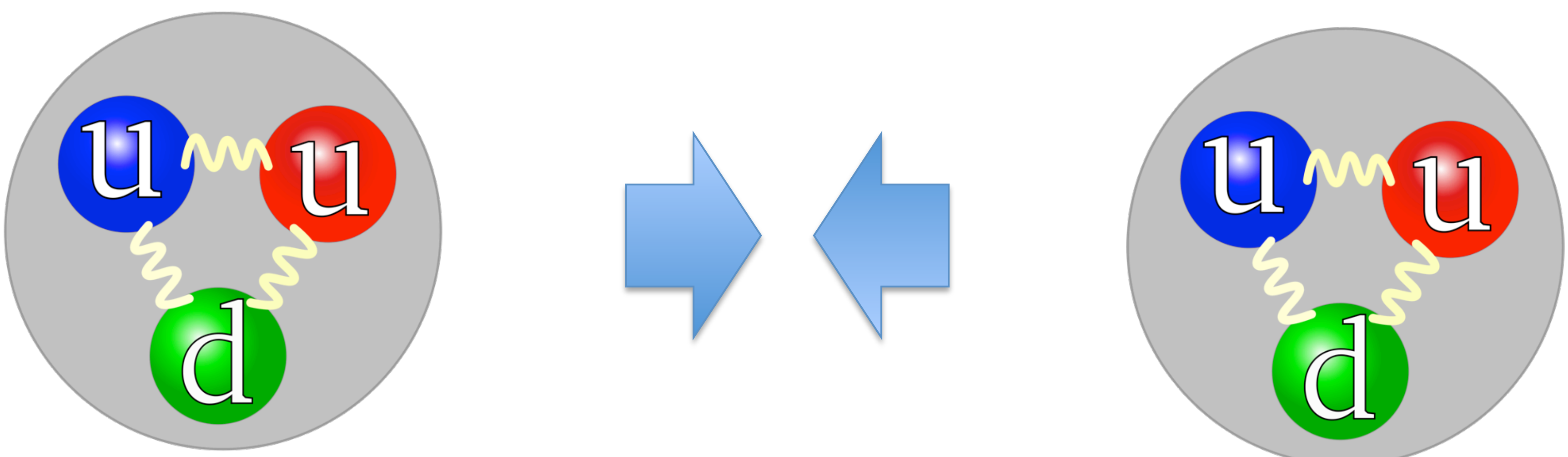
- We'll do an (extremely) simplified analysis of $H \rightarrow \gamma\,\gamma$ in run 2 of the LHC.
- We will:
  1. Set the stage:
     - Learn about the LHC and its experiments
  2. Look at the physics:
     - Understand the signal we're trying to find
  3. Run the analysis:

The LHC



1. The LHC: colliding beams

- At the LHC we collide **protons against protons**
  - Protons are used as “bags of quarks and gluons”
- Protons are made of 3 **valence** quarks, exchanging gluons, and a **sea** of **virtual** quark pairs
- The deeper we look (more energy, smaller distances) the more we see gluons and quarks from the sea
- Note:
  - Only a part ***x*** of the proton’s momentum intervenes in a collision
  - Generally $x_{\text{proton 1}} \neq x_{\text{proton 2}}$ => The collision reference frame is boosted



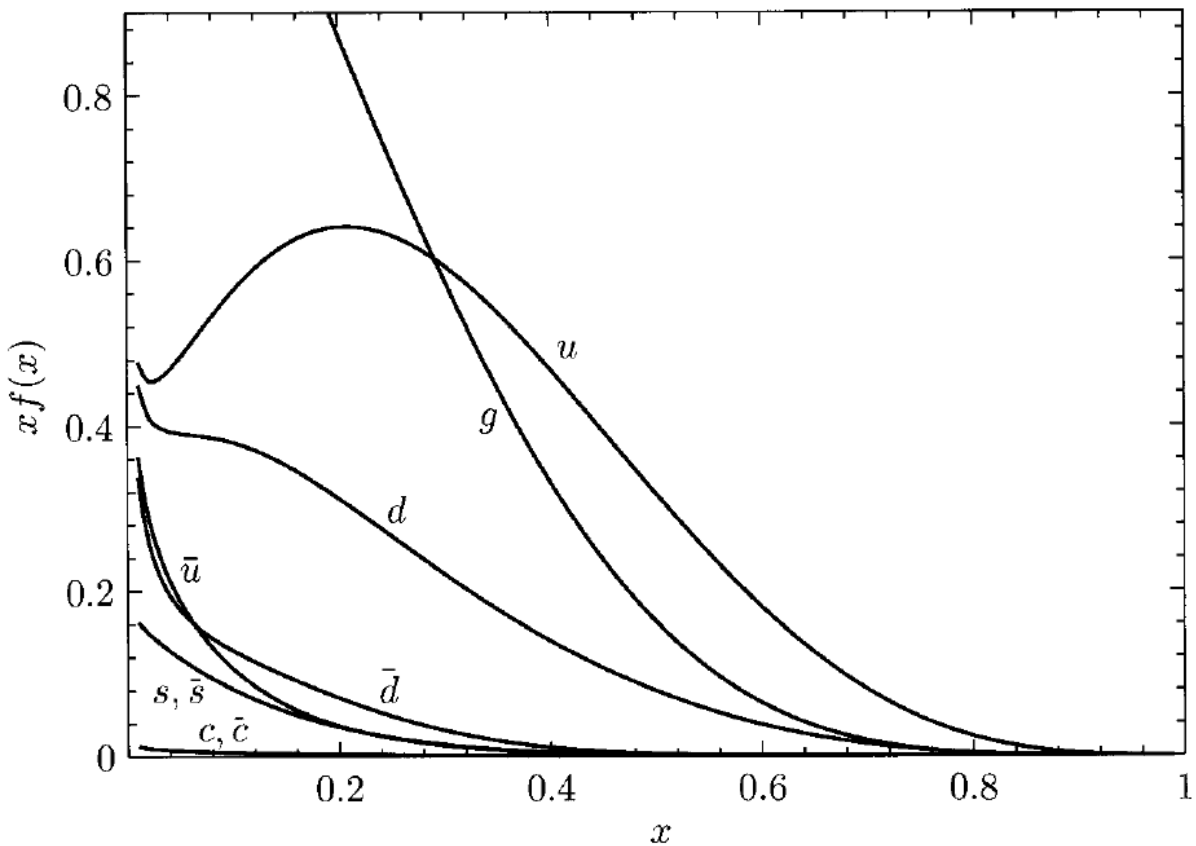
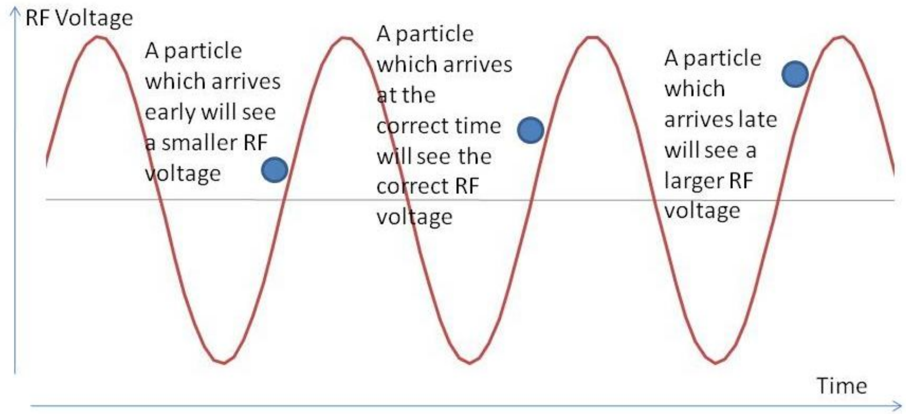


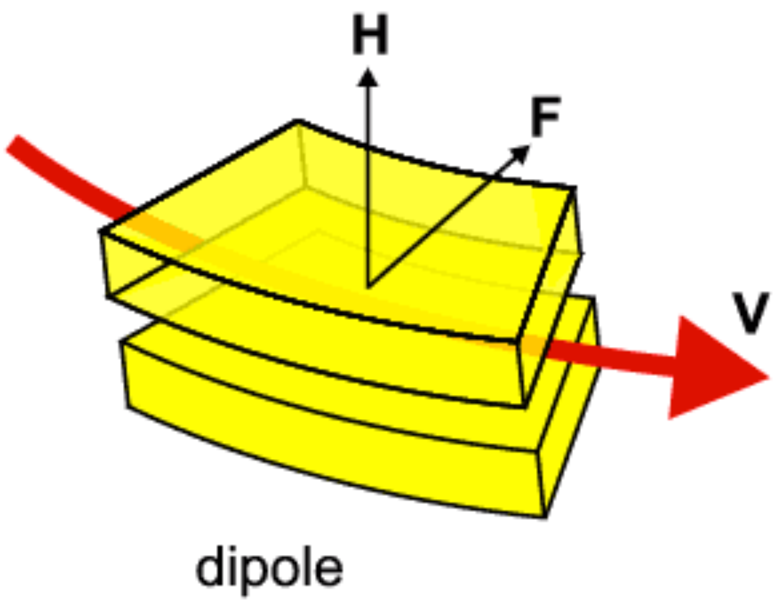
Figure 17.6. Parton distribution functions $xf_f(x)$ for quarks, antiquarks, and gluons in the proton, at $Q^2 = 4\ \mathrm{GeV}^2$. These distributions are obtained from a fit to deep inelastic scattering data performed by the CTEQ collaboration (CTEQ2L), described in J. Botts, et. al., *Phys. Lett.* **B304**, 159 (1993).

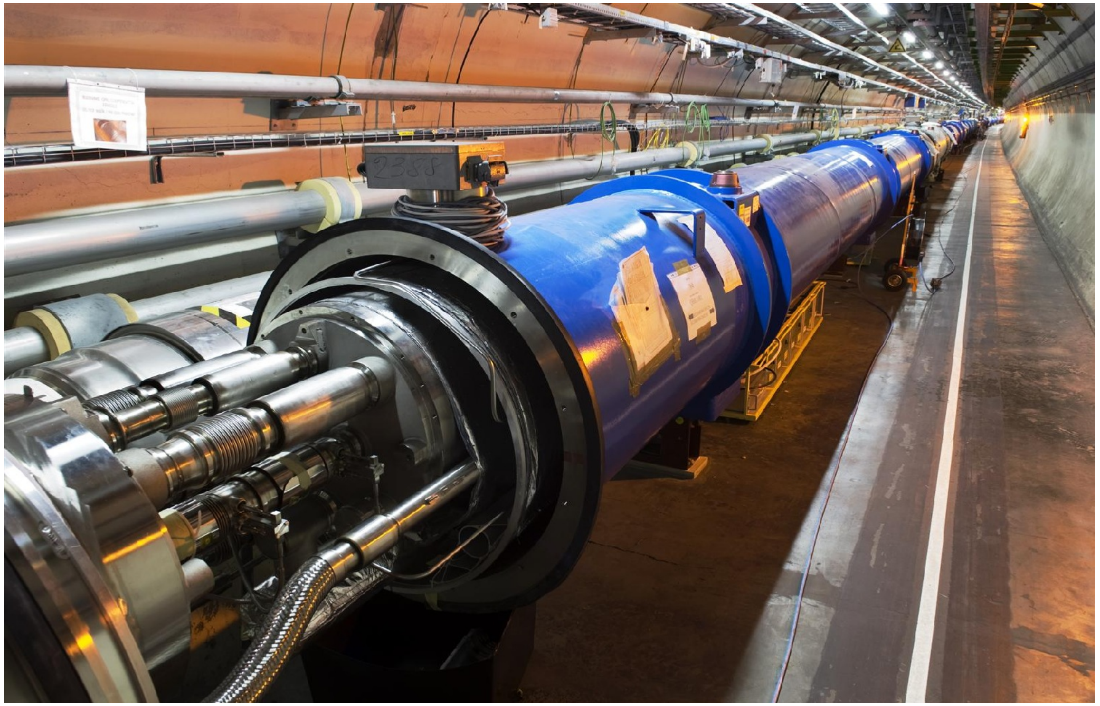
[see e.g

x
x
x

Colliding Beams

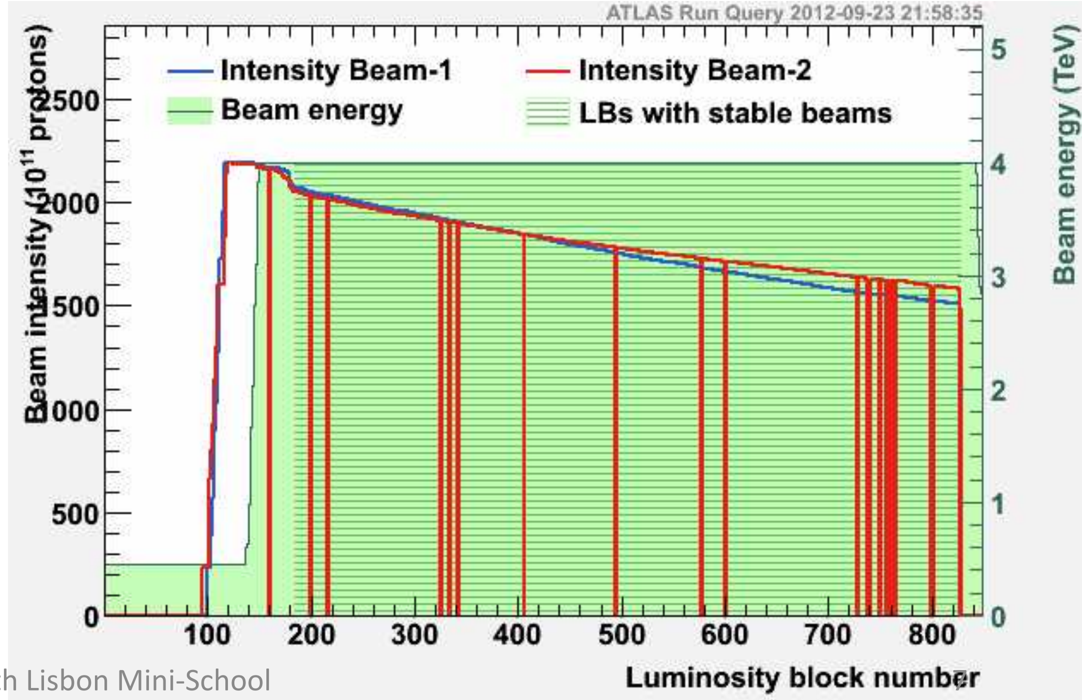






- Beam energy:
- 2802 bunches of 1.15×10^{11} protões
- 7TeV / proton (2015) = 7×10^{12} x 1.602×10^{-19} J
- Is 362 MJ per beam…
- Same as the kinetic energy of a 20,000 t aircraft carrier travelling at 12 knt (21.7 km/h)

- All in a beam ≈ 16 µm thick
- Typical runs last ≈ 12 hours
- Intensity decreases from losses and collisions
- Then re-inject, accelerate, and collide again

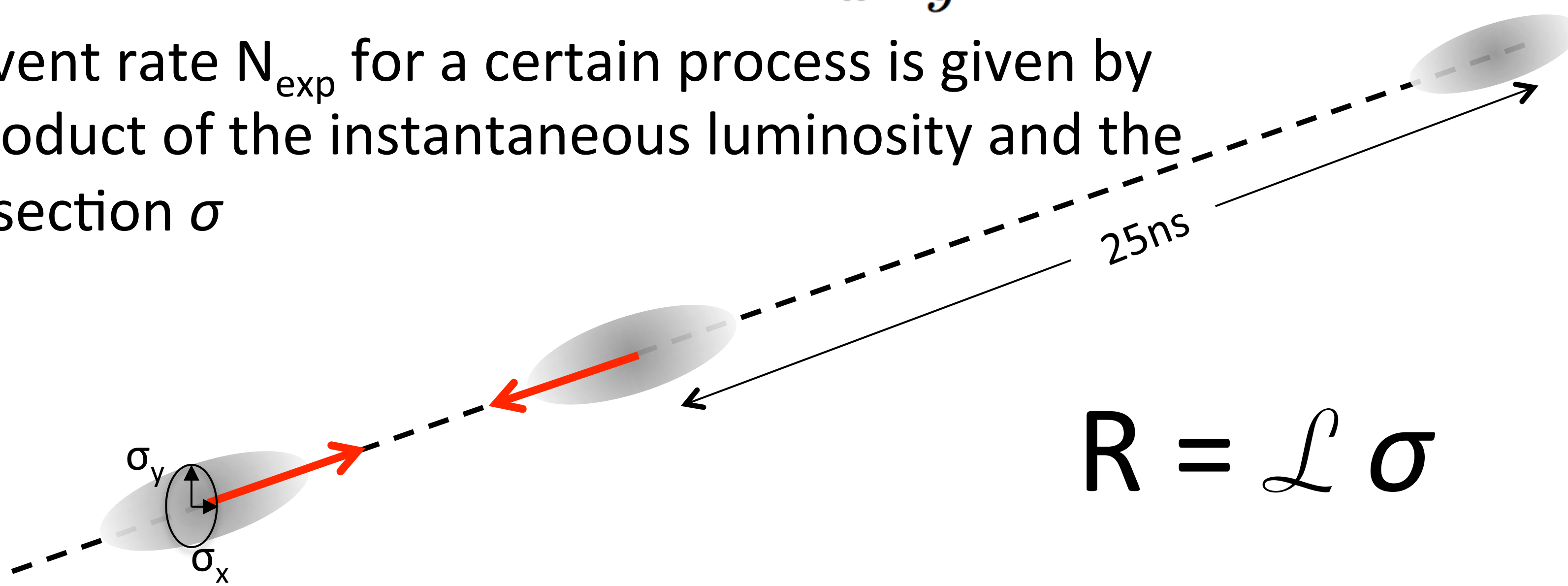


1. The LHC: Luminosity

- The **instantaneous luminosity** measures the rate of interactions
- If we collide, with a frequence *f*, two “bunches” with width σ_x and σ_y (rms) containing n_1 and n_2 protons, the luminosity is:

$$\mathcal{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

- The event rate N_{exp} for a certain process is given by the product of the instantaneous luminosity and the cross section σ



$$R = \mathcal{L}\,\sigma$$

1. The LHC: luminosity

- The instantaneous luminosity has inverse area units, usually: **[cm^{-2} s^{-1}]**

$$\mathscr{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

- The integrated luminosity is expressed in **inverse cross section units**
  - Why does this make sense?

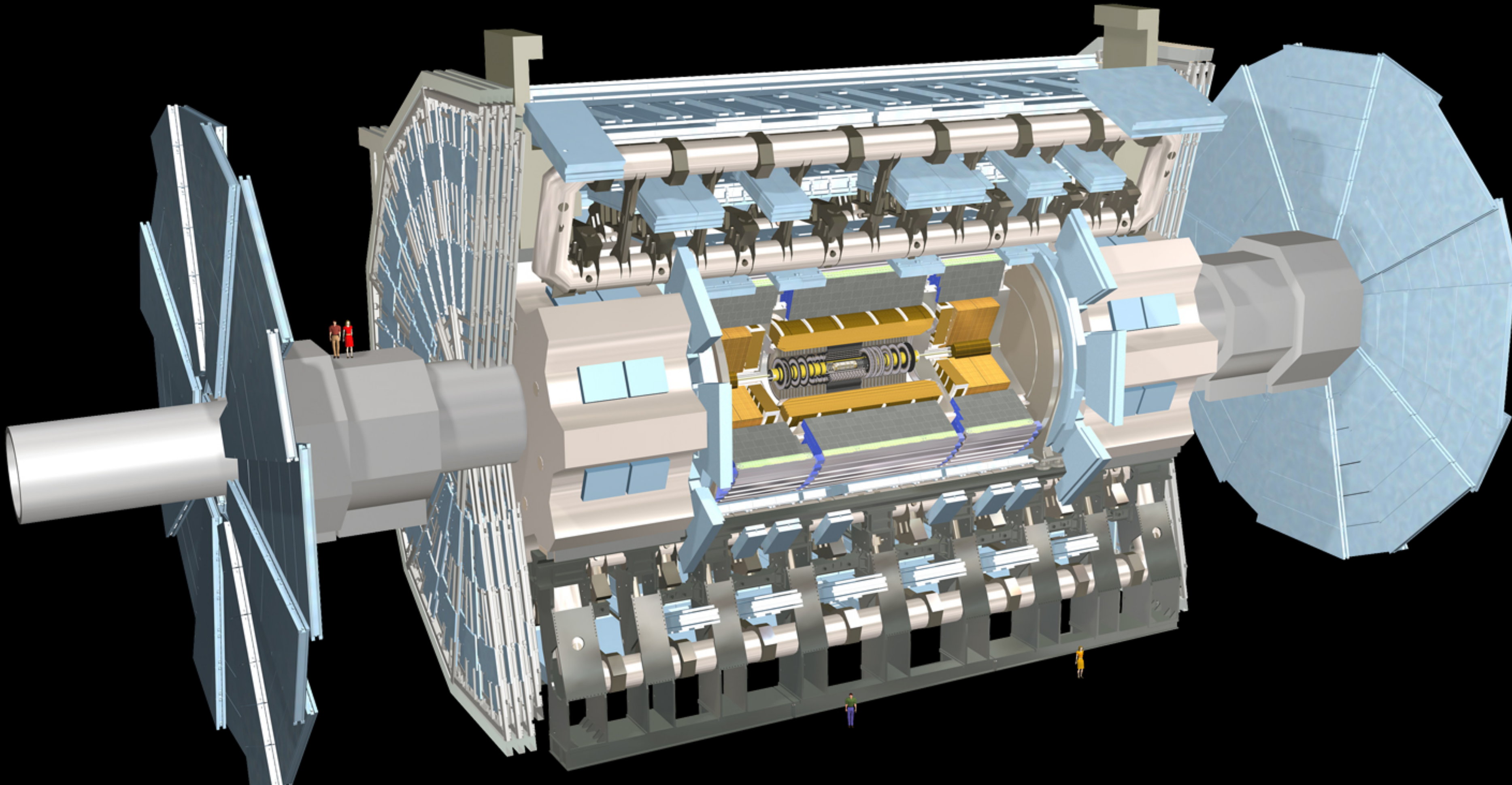
$$N_{exp} = \sigma_{exp} \times \int \mathscr{L}(t)dt$$

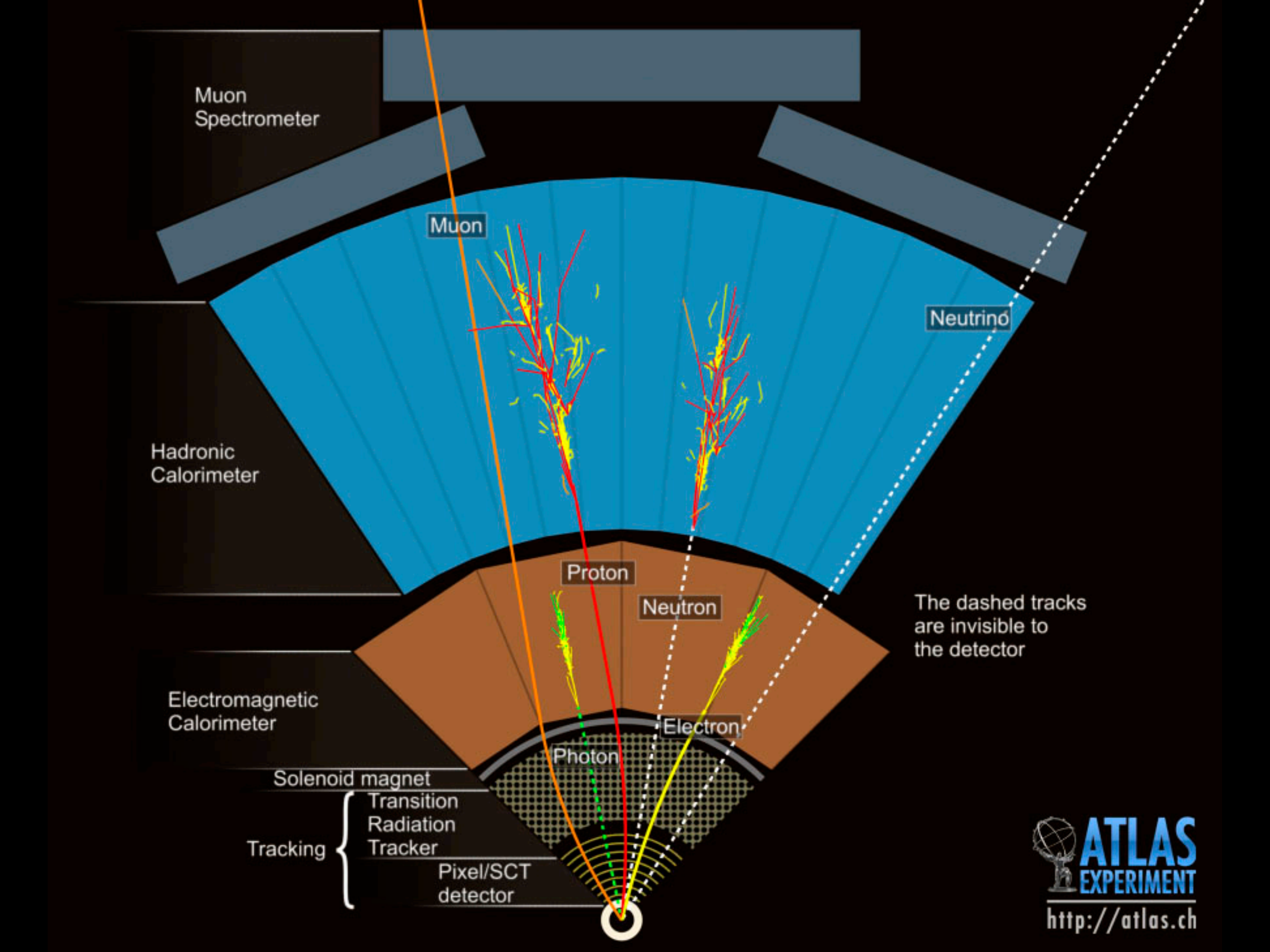
- In Run 1 we accumulated **≈25 fb^{-1}** per experiment at **√s = 7 / 8 TeV**
- In Run 2 (2015-2018) we got **≈150 fb^{-1}** at **13 TeV** per experiment

Note:

1fb^{-1} (1x10^{-15}/fb) has 1000 times more data than 1pb^{-1} (1x10^{-12}/fb)

1. The LHC: Experiments

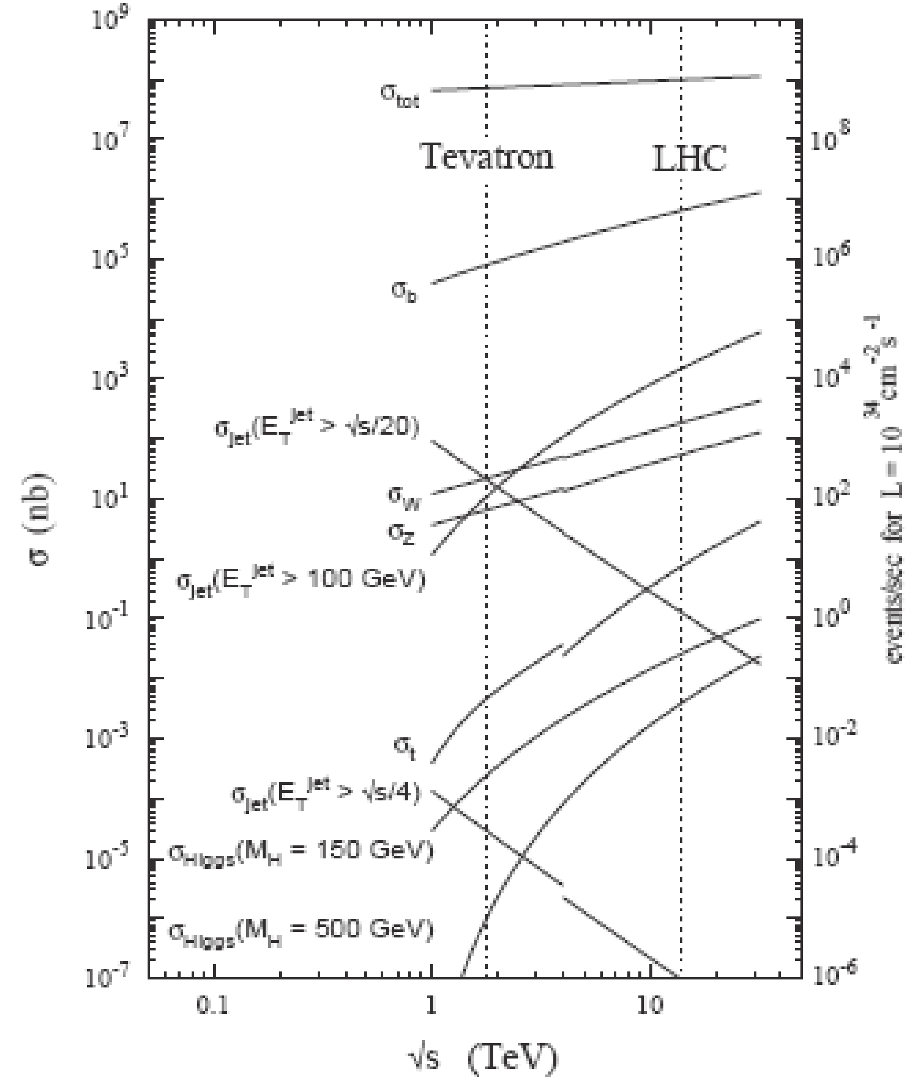



Muon Spectrometer
Muon
Hadronic Calorimeter
Neutrino
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

1. The LHC: trigger

- 25 ns bunch crossing
  - Means 40 million crossings per second
  - Each collision ≈1.5MBytes
  - Means > 60TB per second
- Impossible to keep all these data
  - And unnecessary!
  - Most collisions are boring (>99.99%)
- Use the trigger system to keep only 1 collision for every 40 000
  - But need to decide quickly in real time (in 2.5µs for the first trigger level!!)
- In our exercise we'll consider that the trigger selects events containing 2 photons with:

  $p_T > 35$GeV and $|\eta|<2.5$



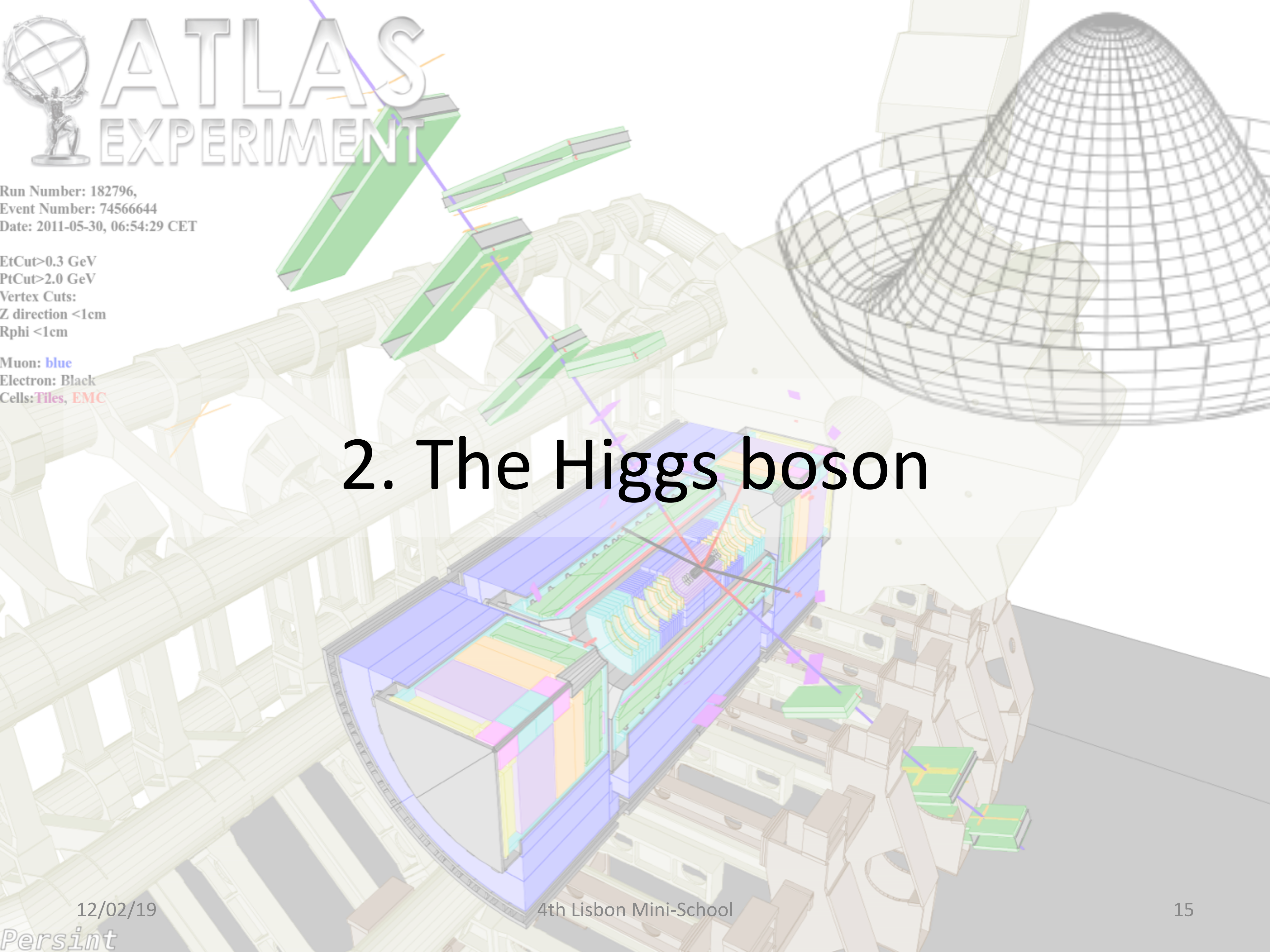
1. The LHC: the full picture

1. The LHC: TEST

- At the LHC, proton bunches collide every 25ns
- Each bunch has 10^{11} protons and a radius of 11.1μm (rms)
- The LHC has a circumference of 27 km

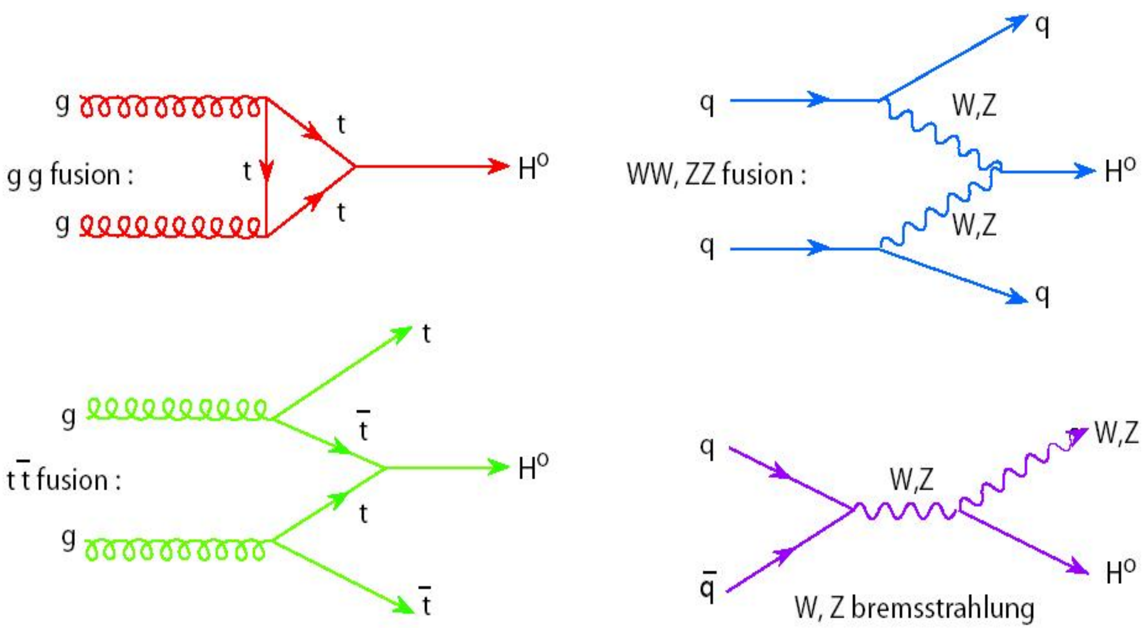
1. What is the instantaneous luminosity measured by the CMS experiment?
2. If the inclusive cross section for Z boson production is 28nb, how many are produced per second in ATLAS?
3. In $20fb^{-1}$, how many Higgs bosons were produzidos during LHC run 1 if the inclusive cross section is 20pb?
4. How many proton bunches fit in the LHC?

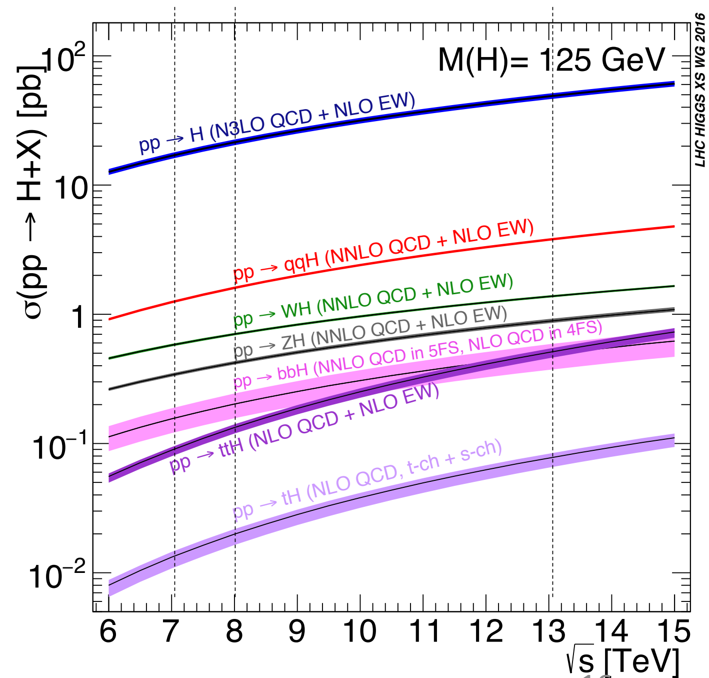
2. The Higgs boson



2. The Higgs boson at the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels
- Enormous amount of progress since discovery 6 years ago!





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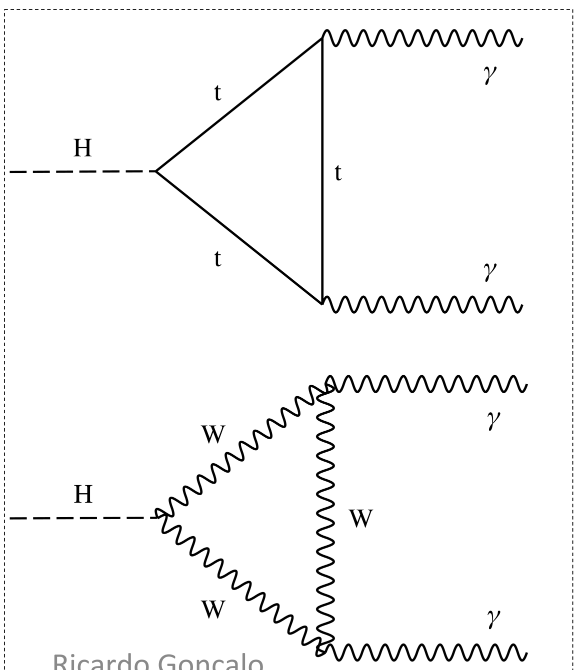
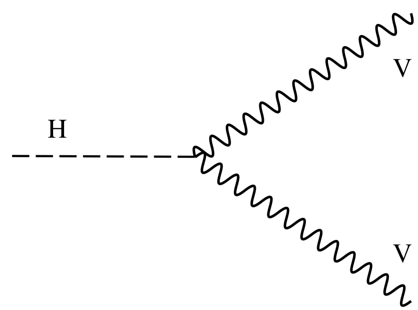
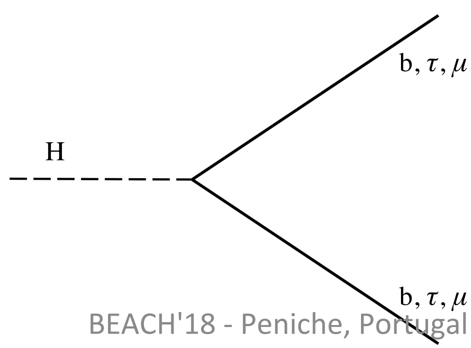
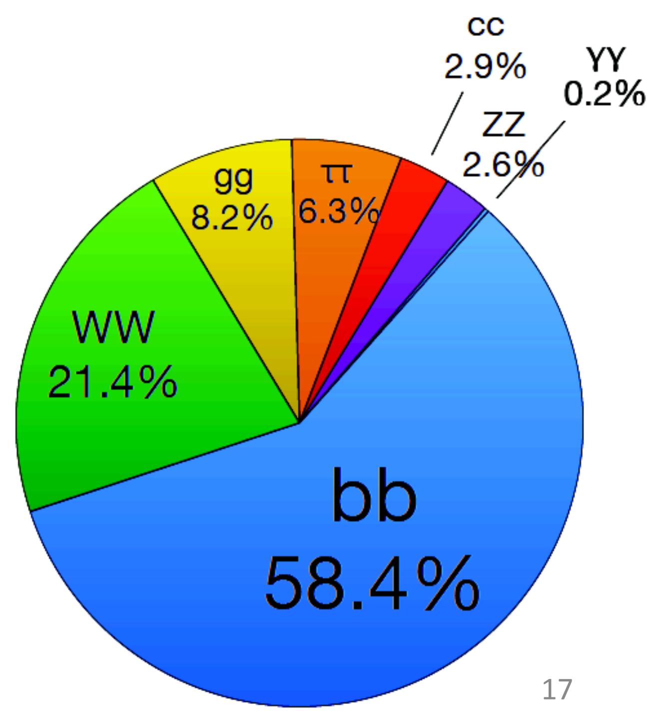
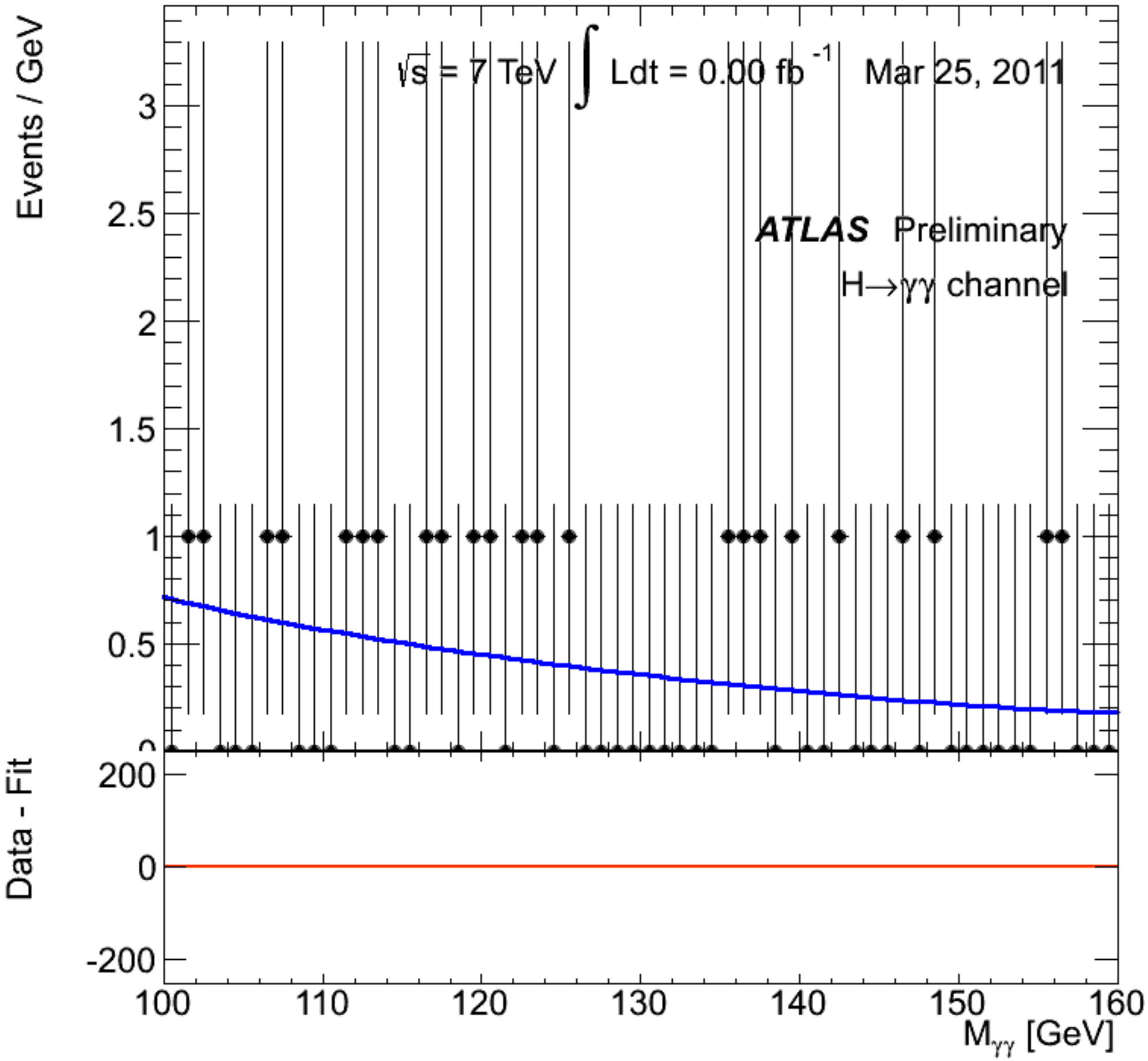








2012: Descoberta do bosão de Higgs: H->$\gamma\gamma$

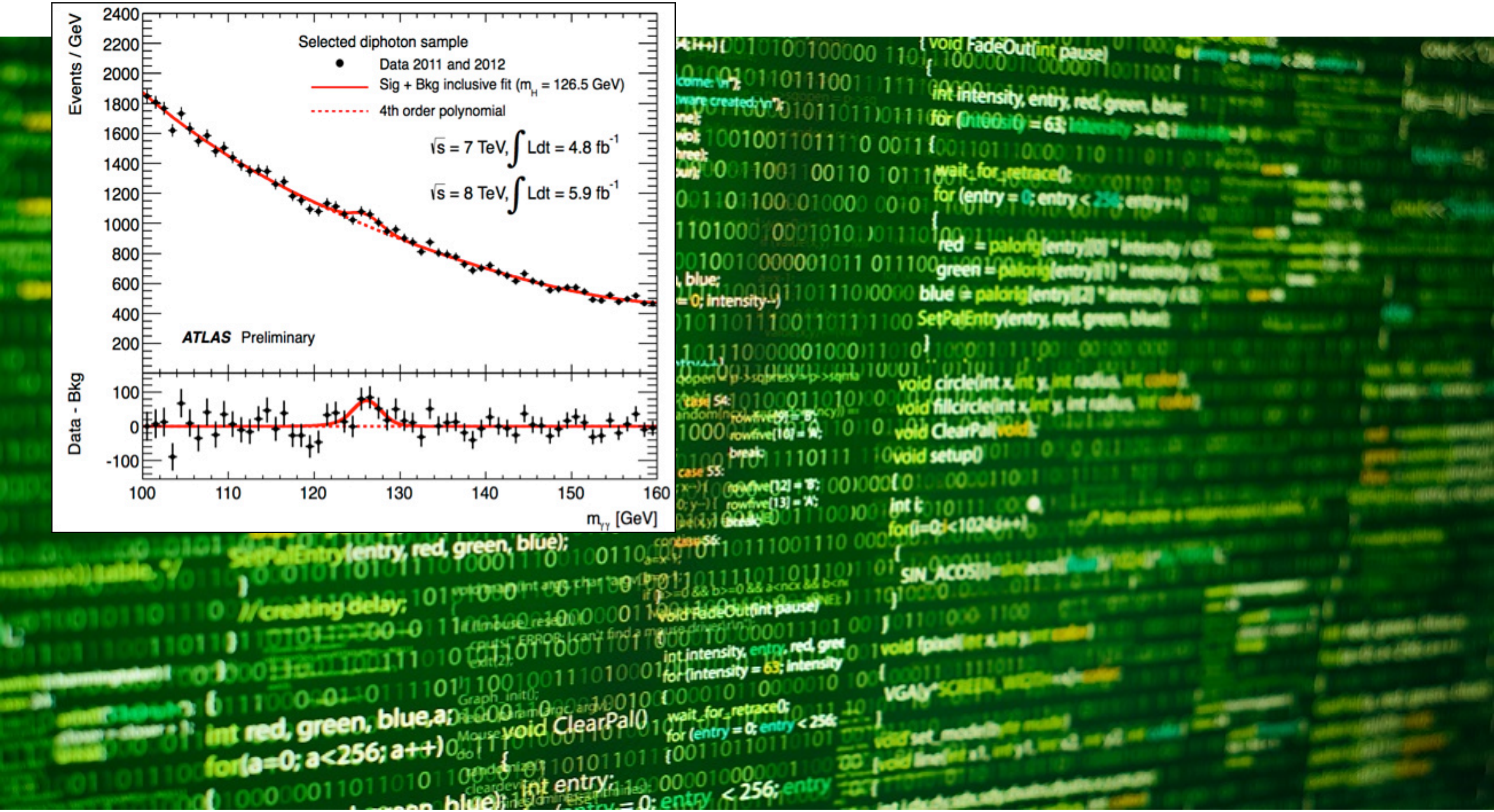


2. The Higgs: TEST

- The centre of mass energy during the LHC run 2 is 13TeV
- The calculated Higgs production cross section is 51.01pb
- The Higgs Branching Ratio to 2 photons is $2.28\text{x}10^{-3}$

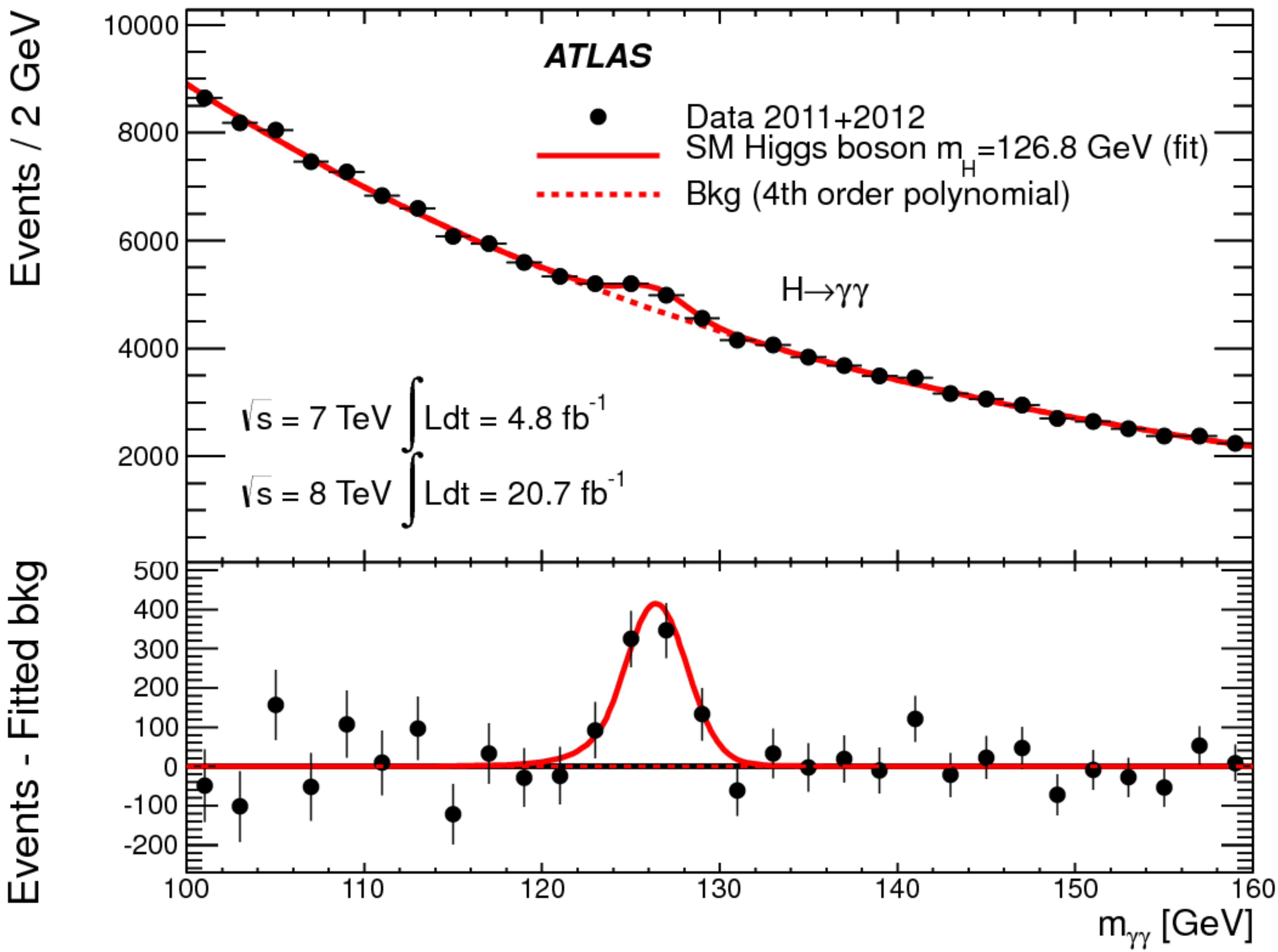
1. How many Higgs bosons do we expect to be produced in an integrated luminosity of 10.0 fb^{-1} at the LHC?
2. How many of those will decay into 2 photons?
3. What do you expect the photon spectrum will look like in approximate terms?
4. Why does the Higgs decay mostly to a b-quark pair?

3. Running the analysis



3. Running the analysis

1. Look at sensitive **observables**
2. Apply **selection cuts**
3. Take a background template from a **control region**
4. Fit the signal+bacground to extract **signal strength**
5. If time allows: extend the search to heavier Higgses


ATLAS
Data 2011+2012
SM Higgs boson m_H=126.8 GeV (fit)
Bkg (4th order polynomial)
H→γγ
√s = 7 TeV ∫Ldt = 4.8 fb^-1
√s = 8 TeV ∫Ldt = 20.7 fb^-1
Events / 2 GeV
Events - Fitted bkg
m_γγ [GeV]
10000
8000
6000
4000
2000
500
400
300
200
100
0
-100
-200
100
110
120
130
140
150
160

2. Explore the H→γγ signal

- Go to the `Monte Carlo` directory :

```
> cd Exercise/MC/
```

- Start a ROOT session opening file H0.root and use .ls

```
> root H0.root
root [1] .ls
TFile**         ../SecondSet/data/data50.root
 TFile*         ../SecondSet/data/data50.root
  KEY: TTree  T;1  event Tree
  KEY: TH1F   h_Nph;1  Number of photons
  KEY: TH1F   h_Njet;1 Number of jets
  KEY: TH1F   h_Mgg;1  Inv.mass of 2 lead photons
```

- TBrowser -> starts an interactive browser; use it to look at the file contents

```
root [2] TBrowser

root [3] T->Print()
******************************************************************************
*Tree    :T         : event Tree                                             *
*Entries :     2312 : Total =          218315 bytes  File  Size =     153299 *
*        :          : Tree compression factor =   1.40                       *
******************************************************************************
*Br    1 :Nph       : Nph/I                                                  *
*Entries :     2312 : Total  Size=       9781 bytes  File Size  =        238 *
```

2. Explore the H➞γγ signal

- Plot the transverse momenta of the photons

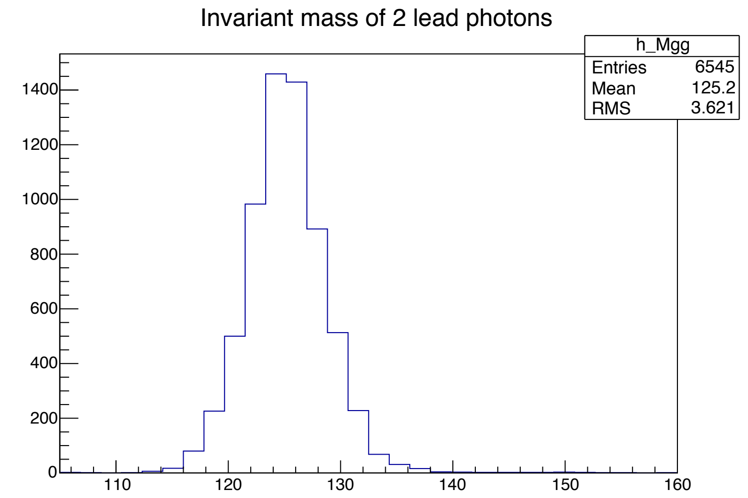
```
root [19] T->Draw("ph_pT")
```

- Or

```
root [20] T->Draw("ph_pT","ph_pT<200")
```

- Variables:
  - Nph: number of photons
  - ph_pT: photon p_T (from photon 0 to photon Nph-1)
  - ph_eta: photon $\eta = -\ln \tan \theta/2$ (pseudorapidity)
  - ph_phi: photon polar angle
  - Njet: number of jets
  - j_pT: jet p_T (from jet 0 to jet Nph-1)
  - j_eta: jet $\eta = -\ln \tan \theta/2$ (pseudorapidity)
  - j_phi: jet polar angle

2. Explore the H→γγ signal



- For more complicated things use a macro..
- Go to directory root/

```
> cd ../root/
> root
root [0] .x analyze.C
…
analyzed 141070 events
wrote histograms to file pyhistos.root
root [1] TFile *f = TFile::Open("histograms.root")
root [2] .ls
TFile**      histograms.root
 TFile*      histograms.root
  KEY: TH1F  h_Mgg;1 Invariant mass of 2 lead photons
  KEY: TH1F  h_MggH;1    Invariant mass of 2 lead photons
root [3] h_Mgg->Draw()
Info in <TCanvas::MakeDefCanvas>:  created default TCanvas with name c1
```

- Look at other variables to get a feeling for the signal…

3. The analysis: data

- Inside directory `Exercise/` there are 4 directories:
- `data/`: contains data events ($\sqrt{s}$ = 13TeV)
  - Trigger cuts: 2 photons with p_T > 35GeV and $|\eta|$<2.5
  - 383019 events in 150 root files
  - Integrated luminosity: 11.5fb^{-1}
- `backgr/`: contains a sample of background events
  - Integrated luminosity: 432pb^{-1}
  - 11596 events
  - Sideband: $M_{\gamma\gamma}$ < 120GeV
- `MC/`: contains simulated $H\longrightarrow\gamma\gamma$ events (m_H = 125 GeV)
  - 10 000 simulated; 6545 passed the trigger
  - Equivalent integrated luminosity: 156fb^{-1}
- `root/`: contains ROOT macros for analysis and plotting
  - `analysis.C`and `analysis.h` contain the analysis code
  - `analyze.C` steers the analysis code and has the list of data/MC files
  - `plot.C` plots the histograms created in the analysis

3. The analysis: the code

- File analysis.C ontains the important bits of the analysis:
  - In method Begin(), instantiate histograms (declared in analysis.h):
    - h_Mgg = new TH1F("h_Mgg","Invariant mass of 2 lead photons",30,90,190.);
    - h_MggH = new TH1F("h_MggH","Di-photon invariant mass after cuts",30,90,190.);
    - …etc
- In method analysis::Process(), select events with at least 2 photons and calculate the invariant mass of the two leading photons:

```
float Mgg
    = sqrt(2*ph_pT[0]*ph_pT[1]*(cosh(ph_eta[0]-ph_eta[1]) - cos(dPhi)));
```

- Then apply cuts to refine the selection and put the values in histograms

```
if ( ph_pT[0] > 40. && fabs(ph_eta[0]) < 2.37 &&
     ph_pT[1] > 30. && fabs(ph_eta[1]) < 2.37 ) {
      h_MggH->Fill(Mgg);
      h_dPhiH->Fill(dPhi);
…
```

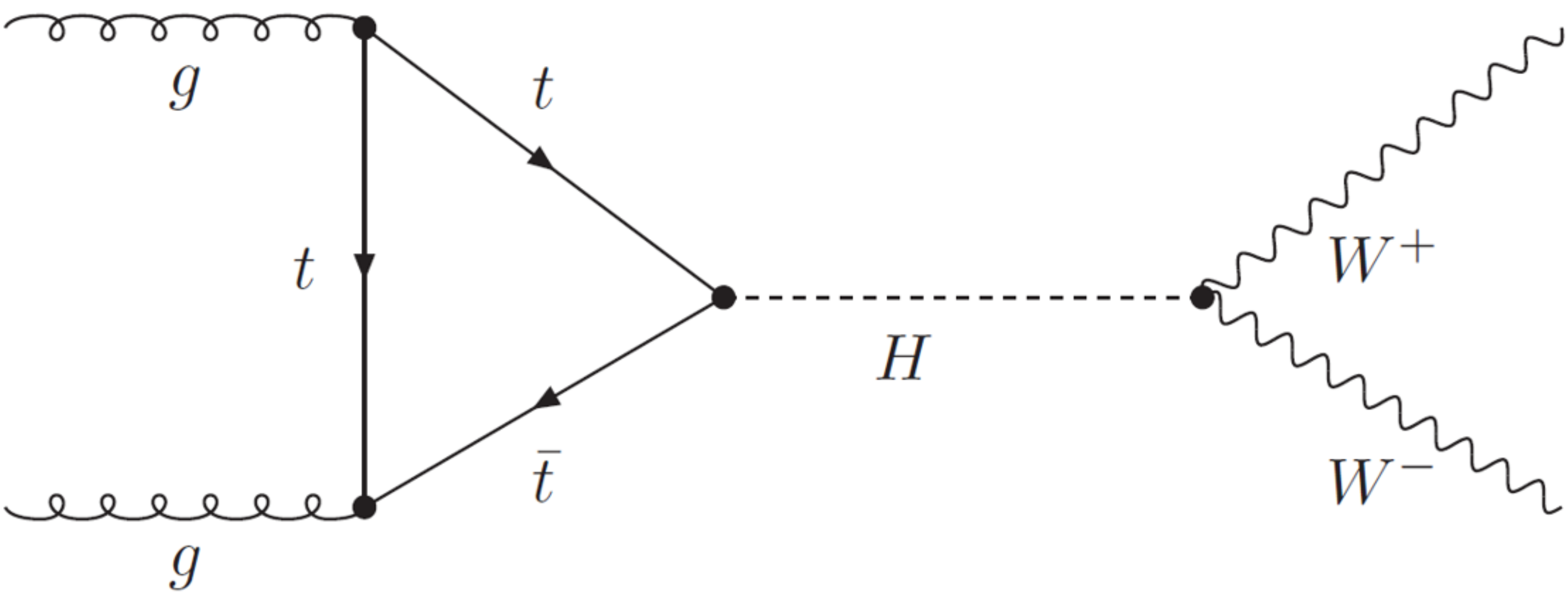
- Run the analysis code on simulated signal, on the background sample and on the data
  - To steer the analysis edit file `analyze.C` and change variable `dataType`
  - `// add each root file into chain of TTrees - only one in this case`
  - `int dataType = 0; // 0 = signal MC; 1 = background data; other = data`
  - Rename the output file `histograms.root` into:
    - `MChistos.root`
    - `backgrhistos.root`
    - `datahistos.root`

3. Run the analysis

1. In ROOT, execute macro `plot.C`
   - Needs files `MChistos.root, backgrhistos.root, datahistos.root` to be present
   - You'll be guided through the various plots which will serve to illustrate aspects of a real analysis
   - Look at observables in the data after the trigger selection and after analysis cuts
   - A pure background sample can sometimes be taken from from a control region like a sideband; this can help study the background
2. Now go back to refine the analysis and try to optimize the selection
   - E.g. try to estimate signal and background in the signal mass peak and change cuts to maximize S/√B
3. If time allows: extend the search to heavier Higgses – any surprises?

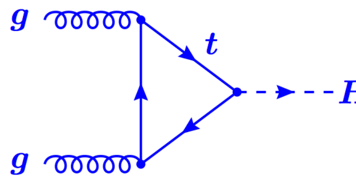
Now let's try an interactive analysis

http://opendata.atlas.cern/visualisations/analyser-js.php

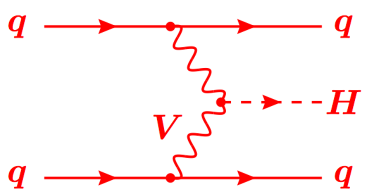


$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

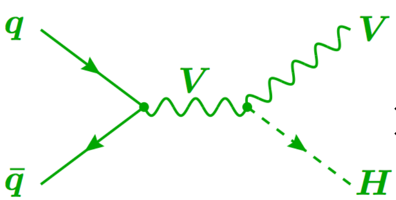
Production



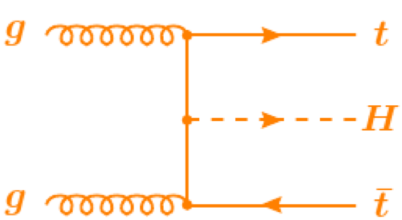
$\times \kappa_g$



$\times \kappa_{W/Z}$



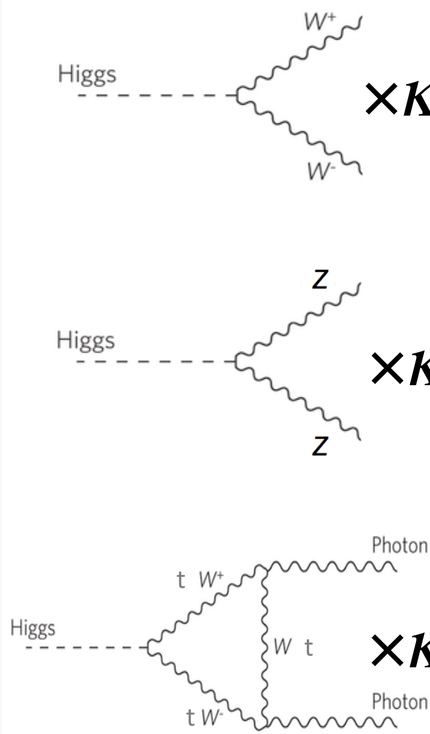
$\times \kappa_{W/Z}$



$\times \kappa_t$

$\times$

Decay



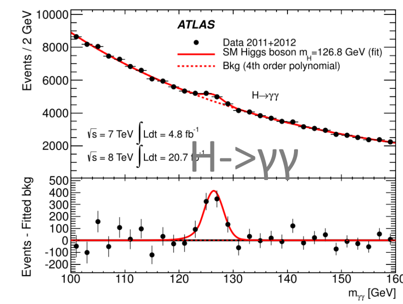
$\times \kappa_W$

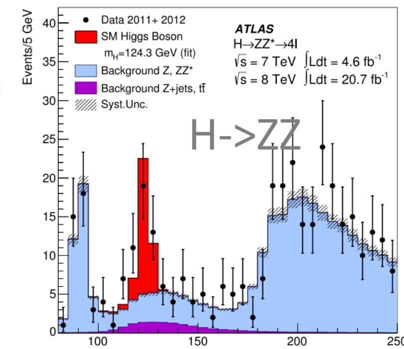
$\times \kappa_Z$

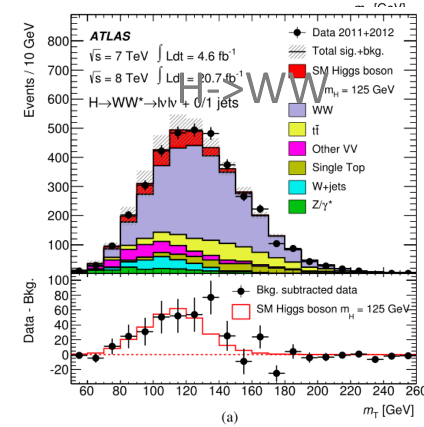
$\times \kappa_\gamma$

FIT

Backgrounds +



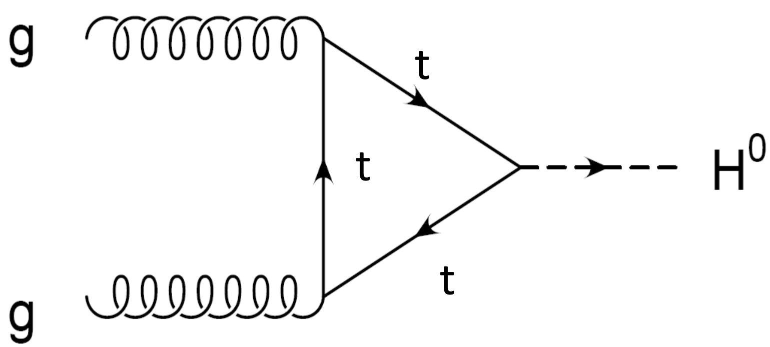


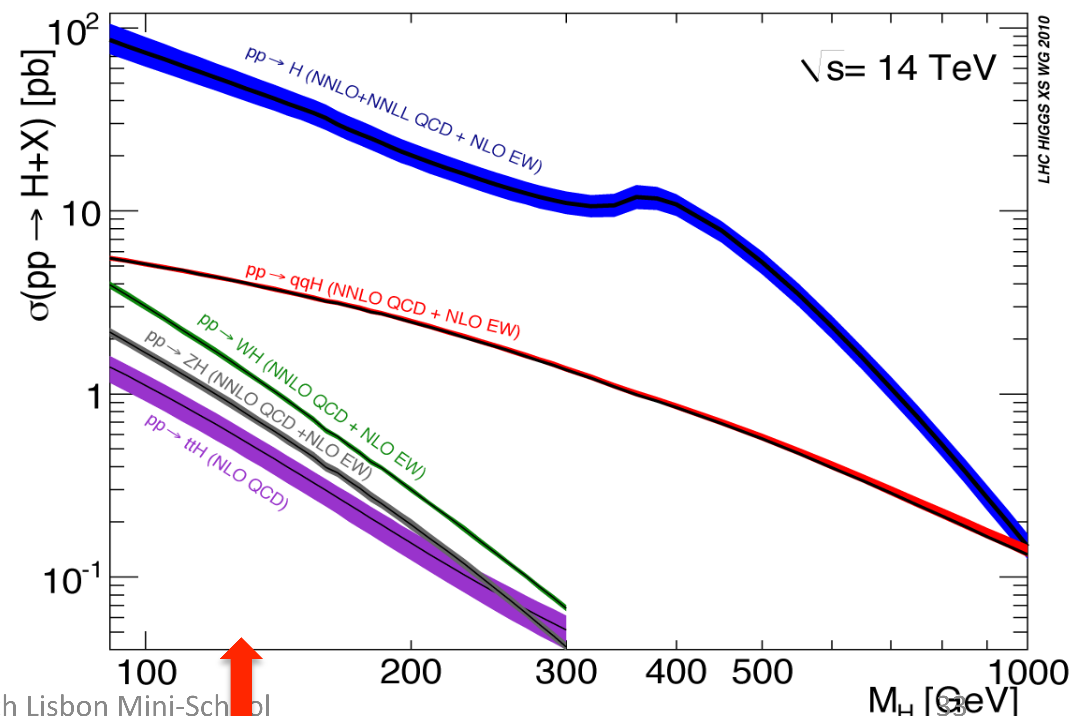


Questions???
jgoncalo@lip.pt

2. The Higgs at the LHC: production

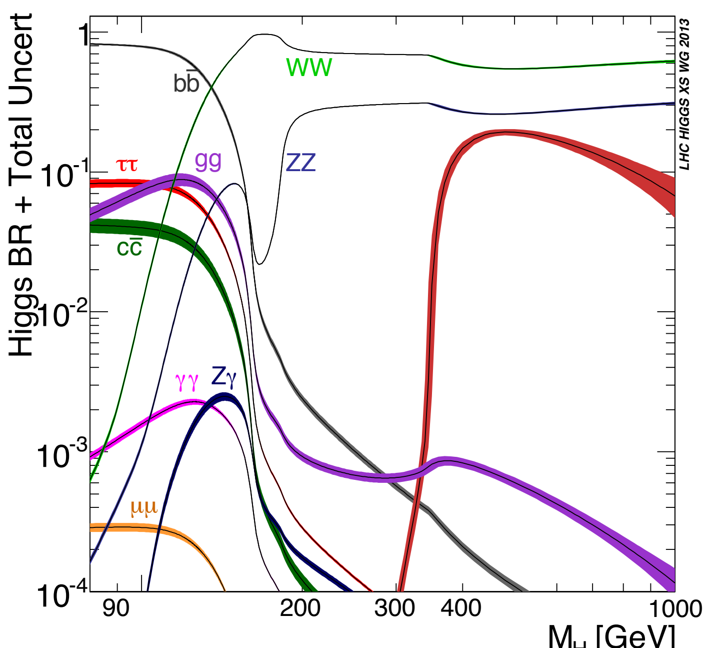
- The Higgs couples to particles with mass:
  - Fermions or weak bosons, but not (directly) gluons or photons
  - But there are many gluons in our beams …
- Largest cross section is “gluon fusion”
  - Loop is dominated by the massive virtual top quarks

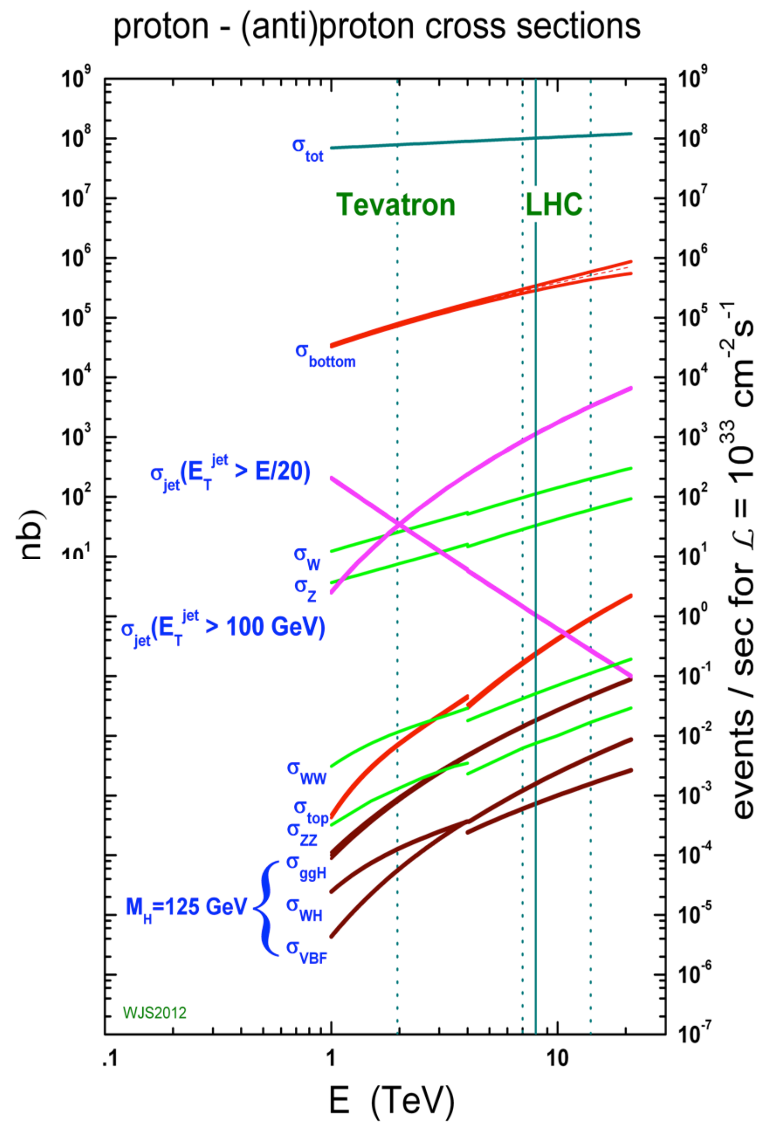




2. The Higgs at the LHC: decay

- With the mass of m_H = 125 GeV, the Higgs boson decays mostly to b quarks
- But it is basically impossible to separate this signal from the b-quark production background (10^6 times more frequent!...)
- H⟶γγ decays through W- and top-dominated loop





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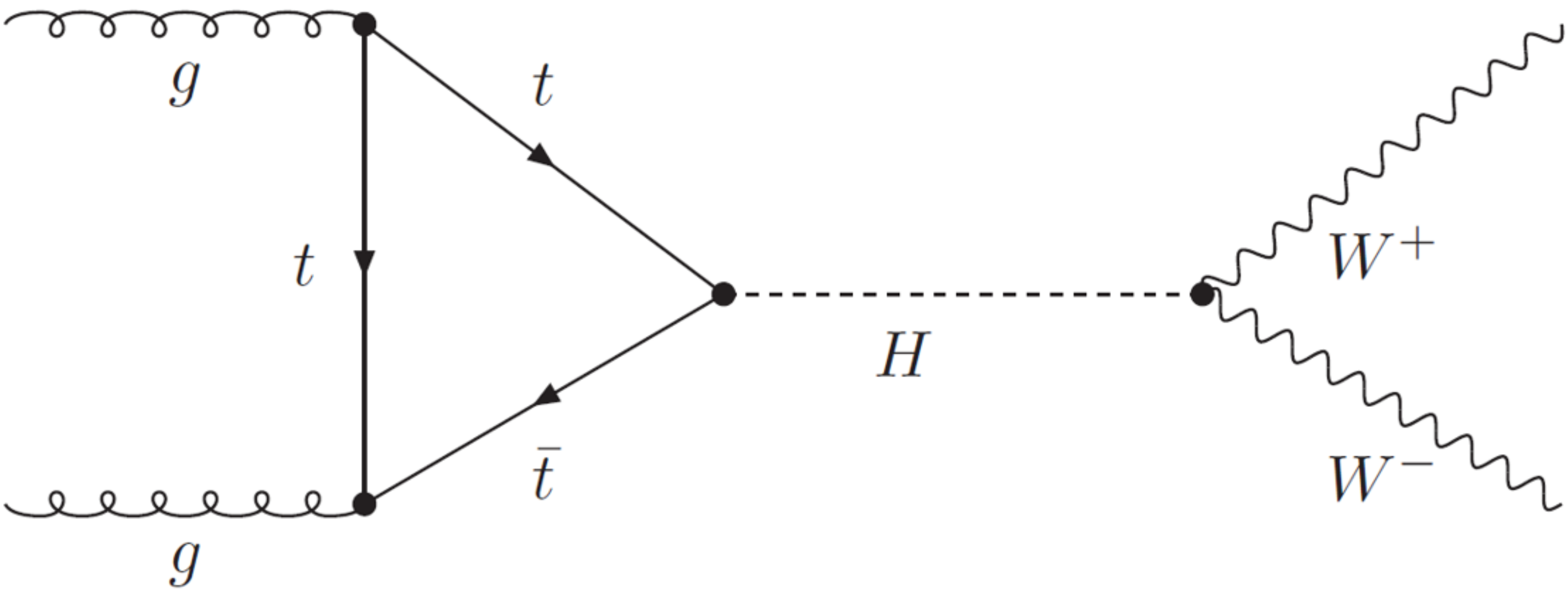
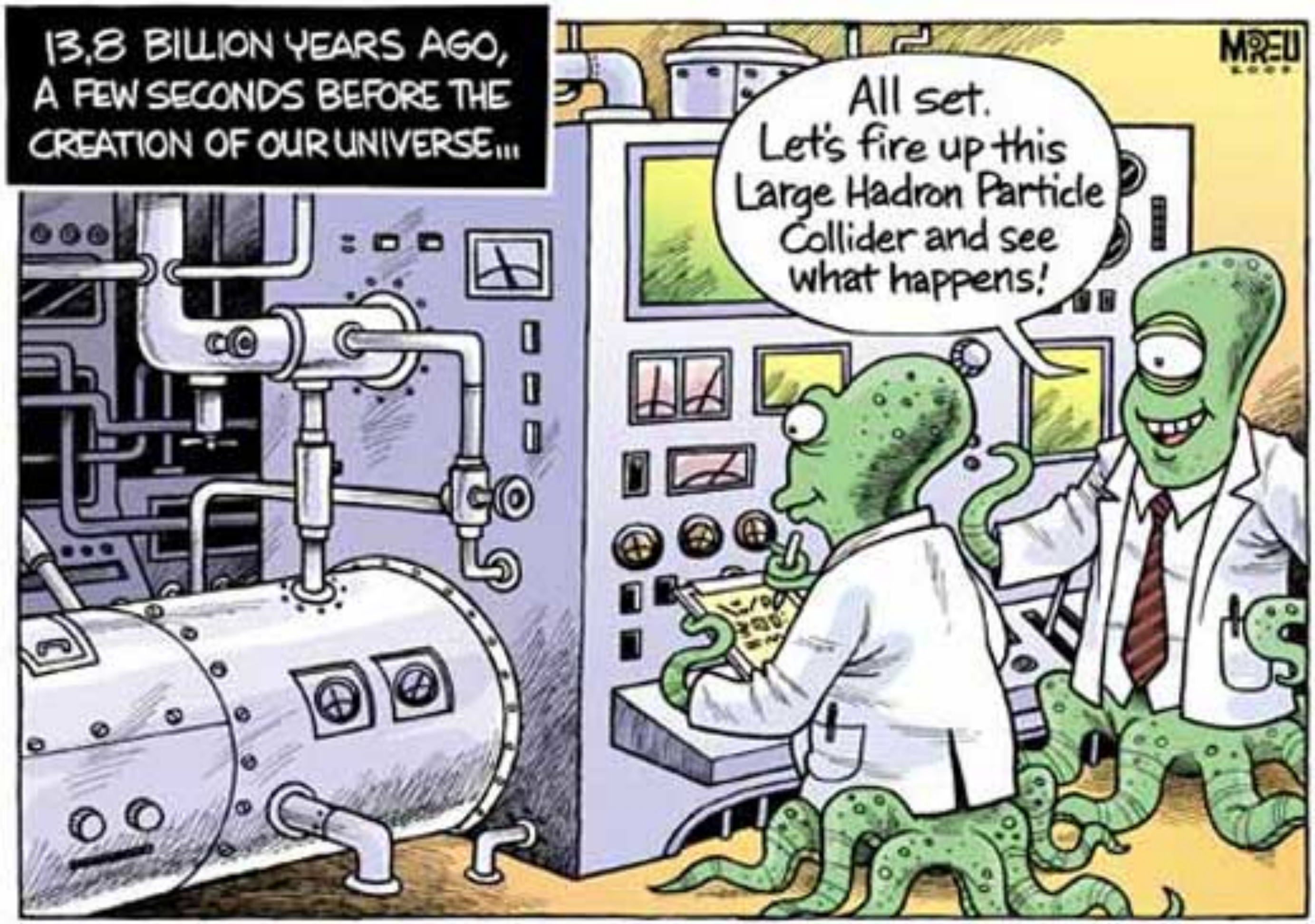
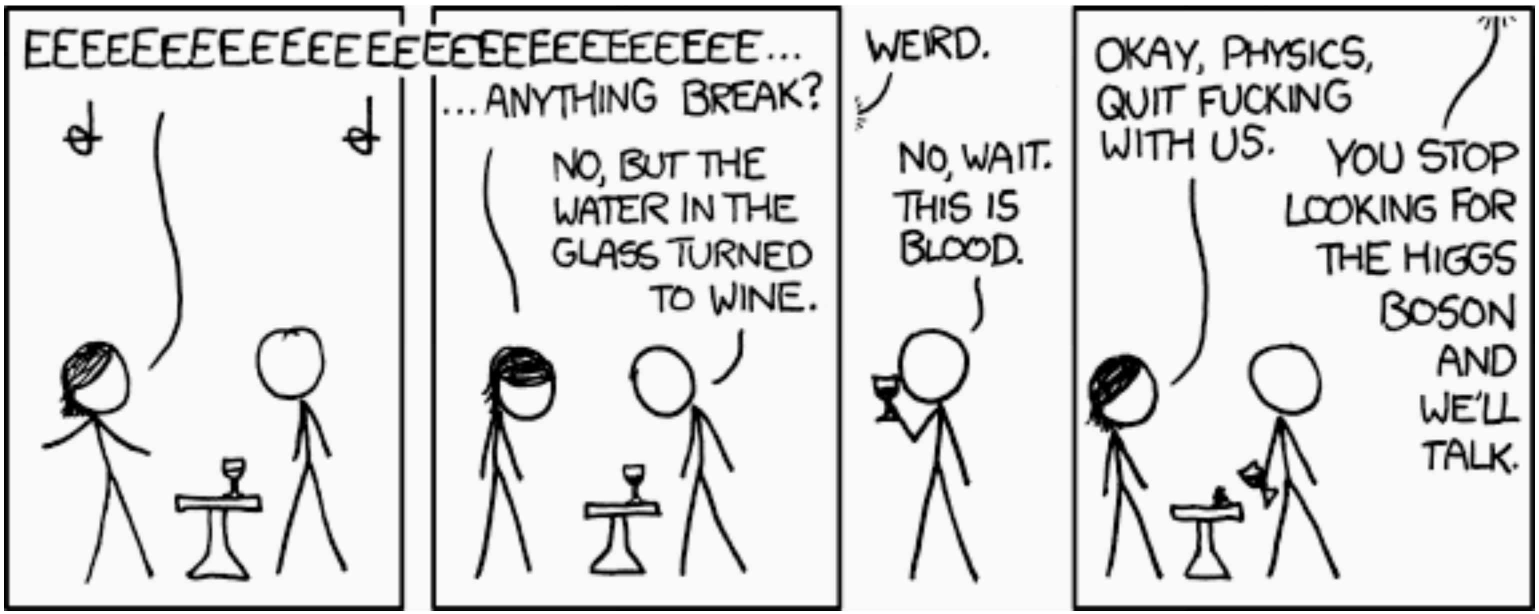


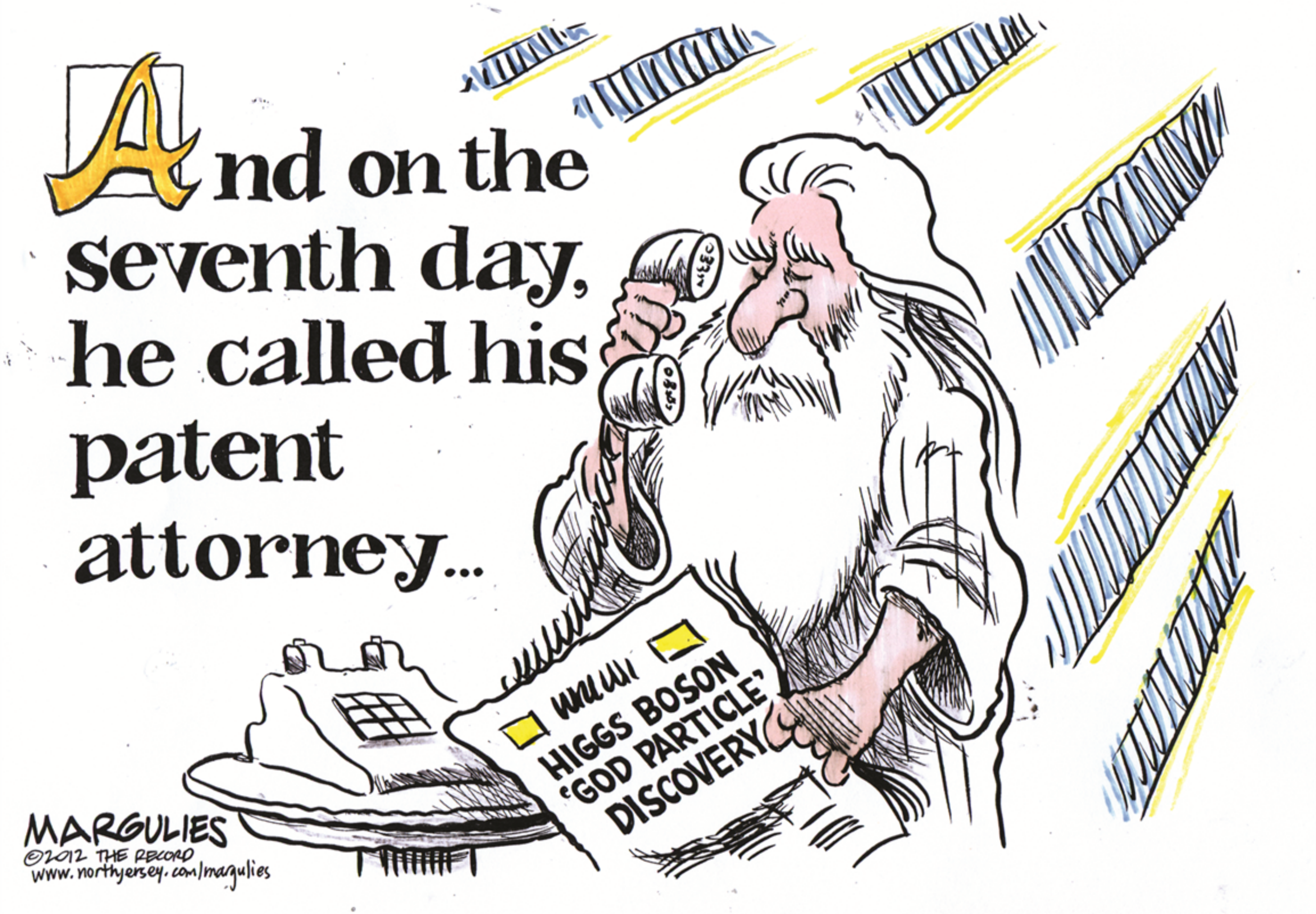
The Higgs boson discovery in cartoons...

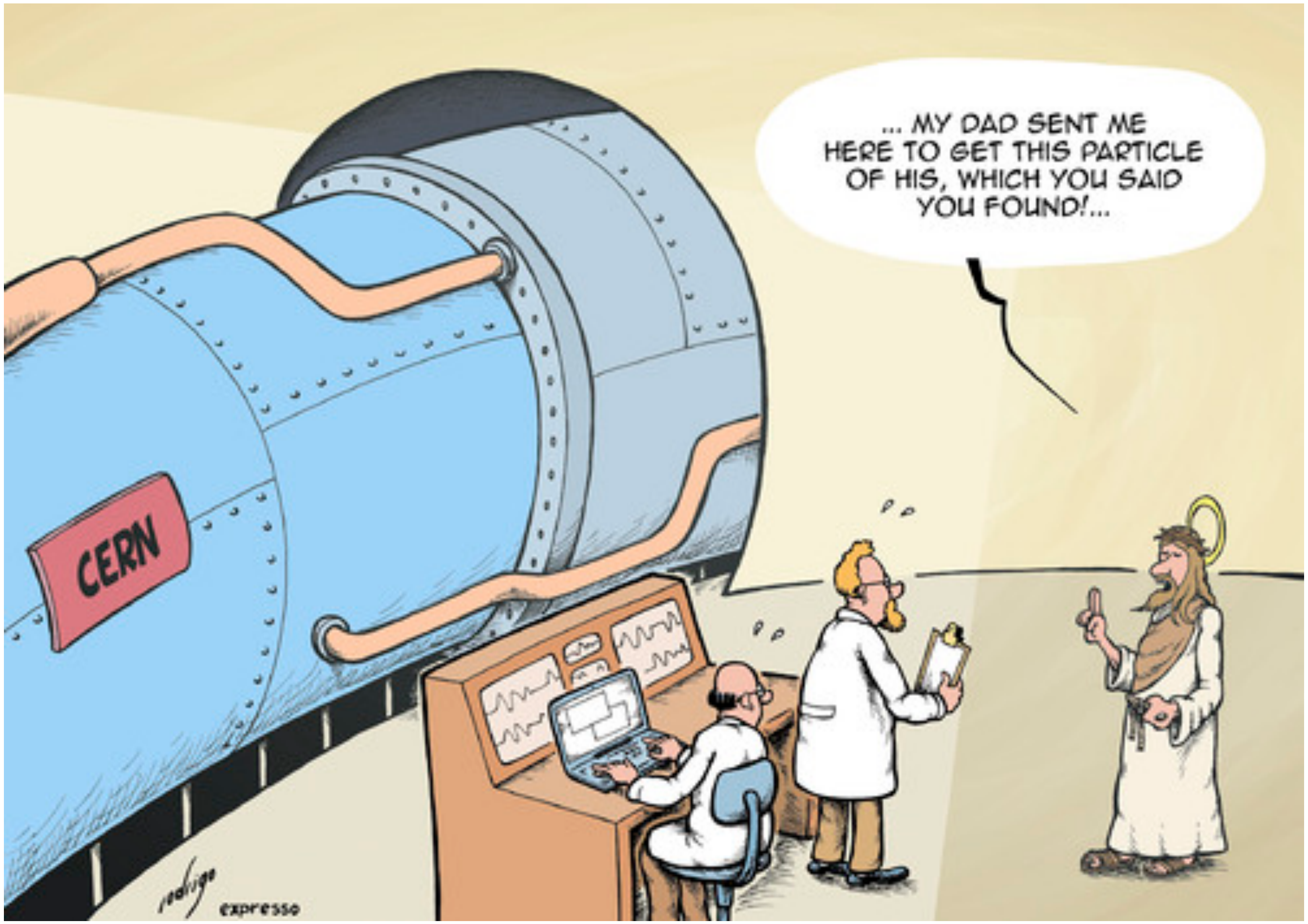


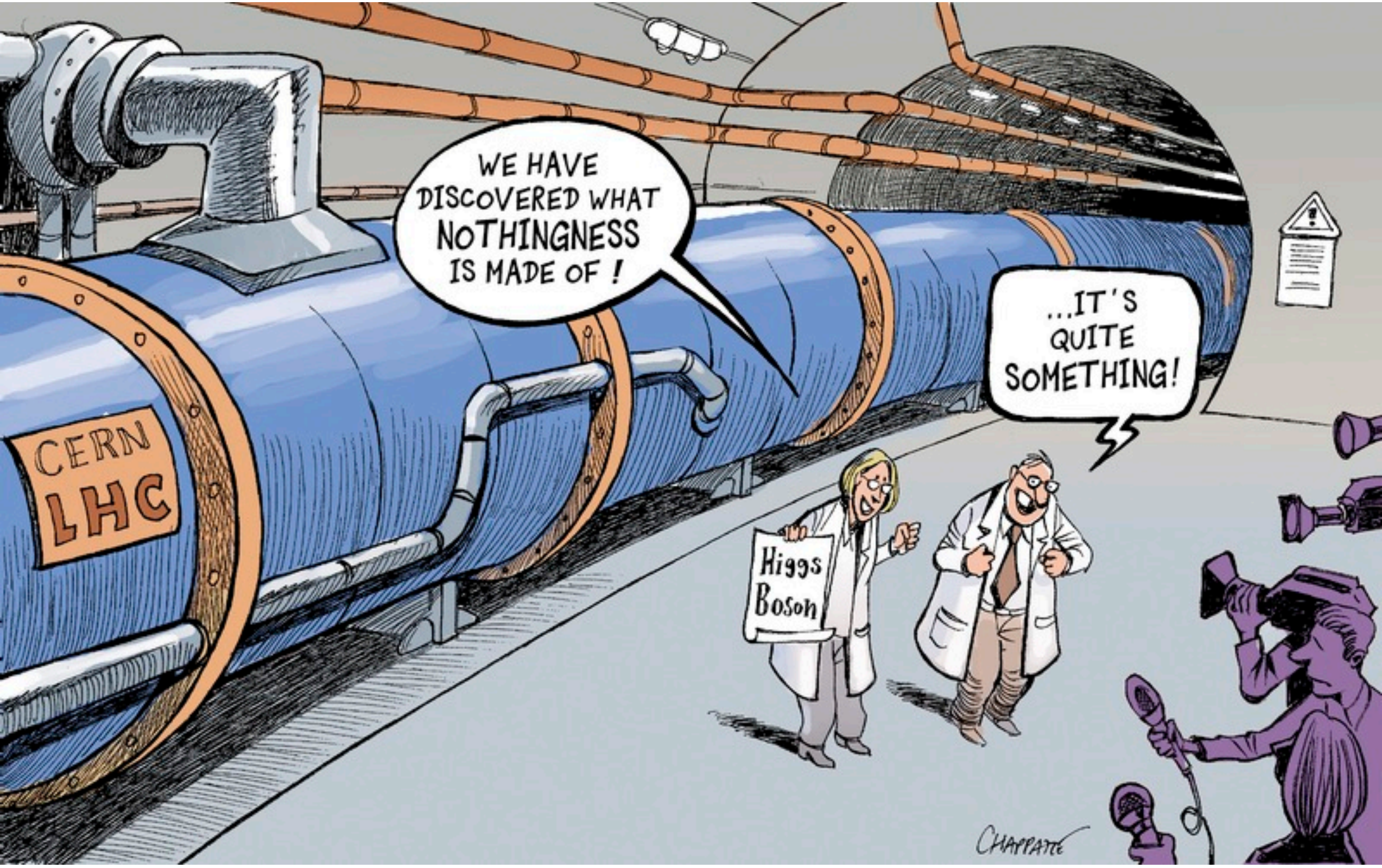

EEEEEEEEEEEEEEEEEEEEEEEEEEE...
...ANYTHING BREAK?
NO, BUT THE WATER IN THE GLASS TURNED TO WINE.
WEIRD.
NO, WAIT. THIS IS BLOOD.
OKAY, PHYSICS, QUIT FUCKING WITH US.
YOU STOP LOOKING FOR THE HIGGS BOSON AND WE'LL TALK.

Nigel finds the Higgs boson.

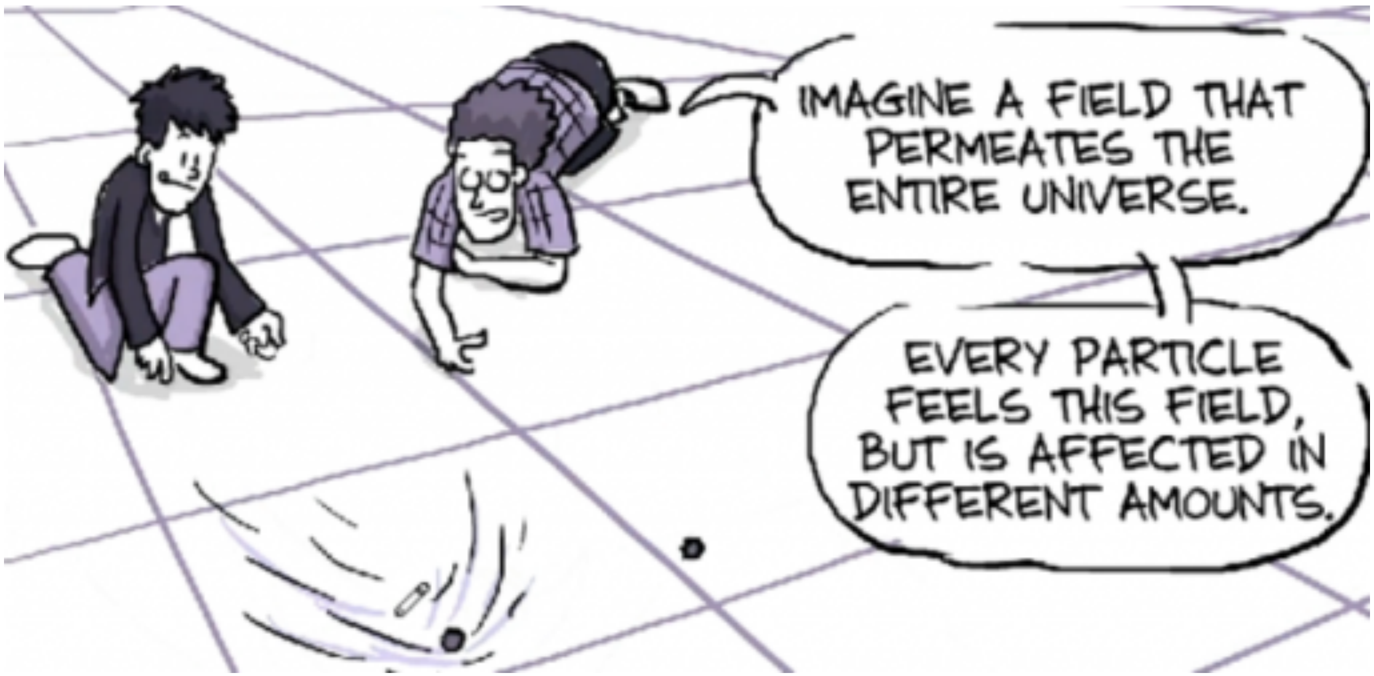
"Run! I've discovered the Higgs bison."

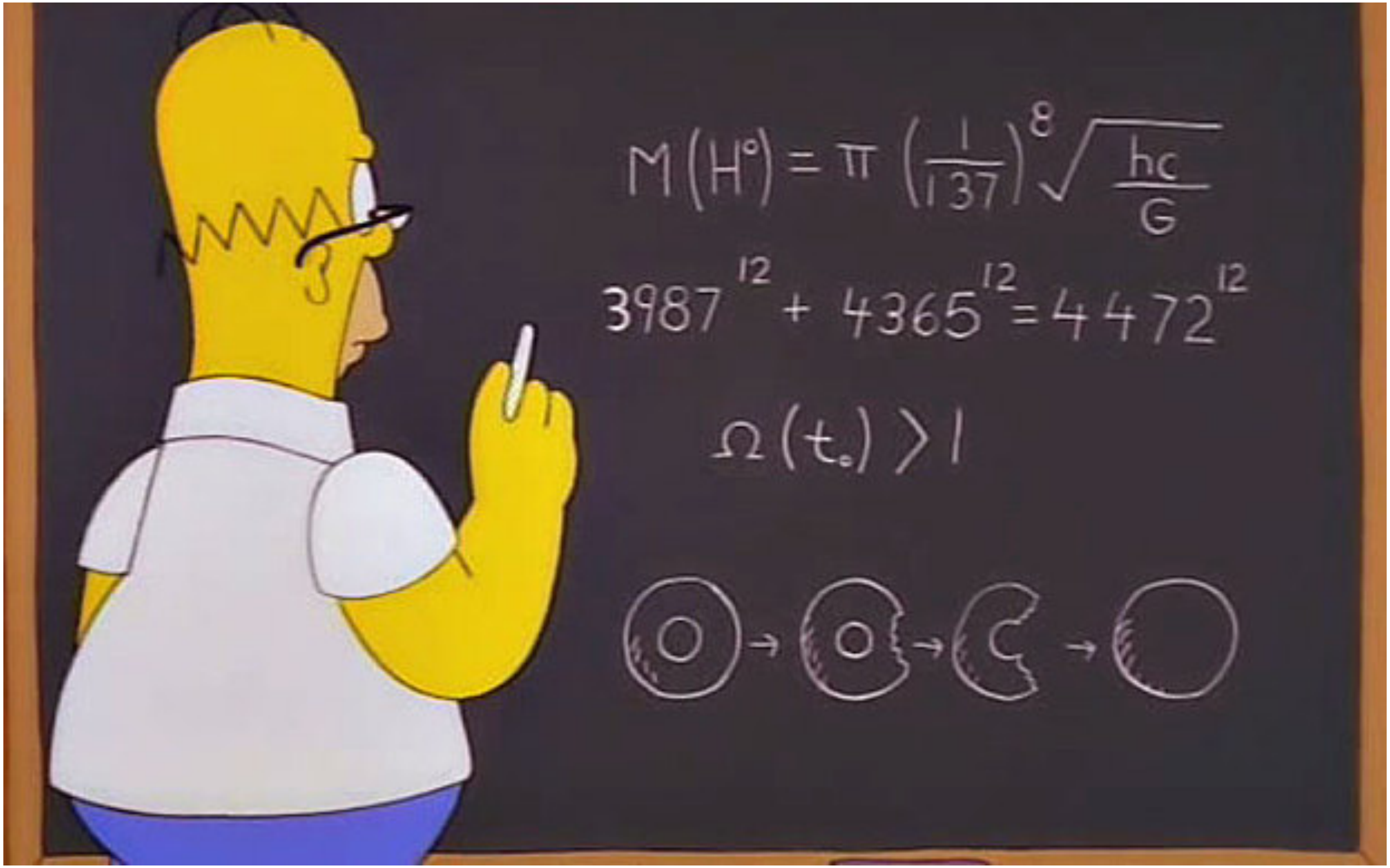

And on the seventh day, he called his patent attorney...
HIGGS BOSON 'GOD PARTICLE' DISCOVERY
MARGULIES
©2012 THE RECORD
www.northjersey.com/margulies

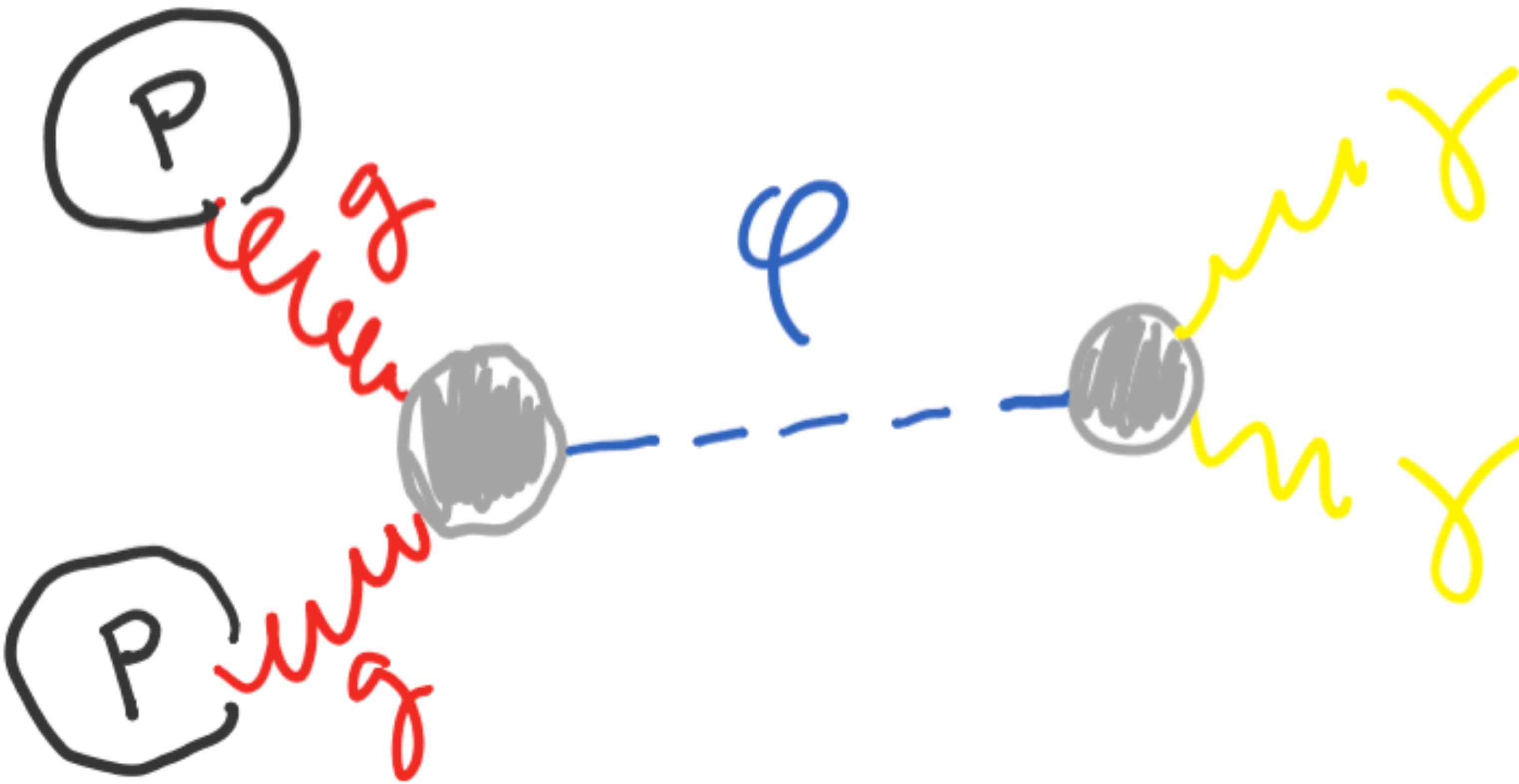

... MY DAD SENT ME HERE TO GET THIS PARTICLE OF HIS, WHICH YOU SAID YOU FOUND!...
CERN
expresso

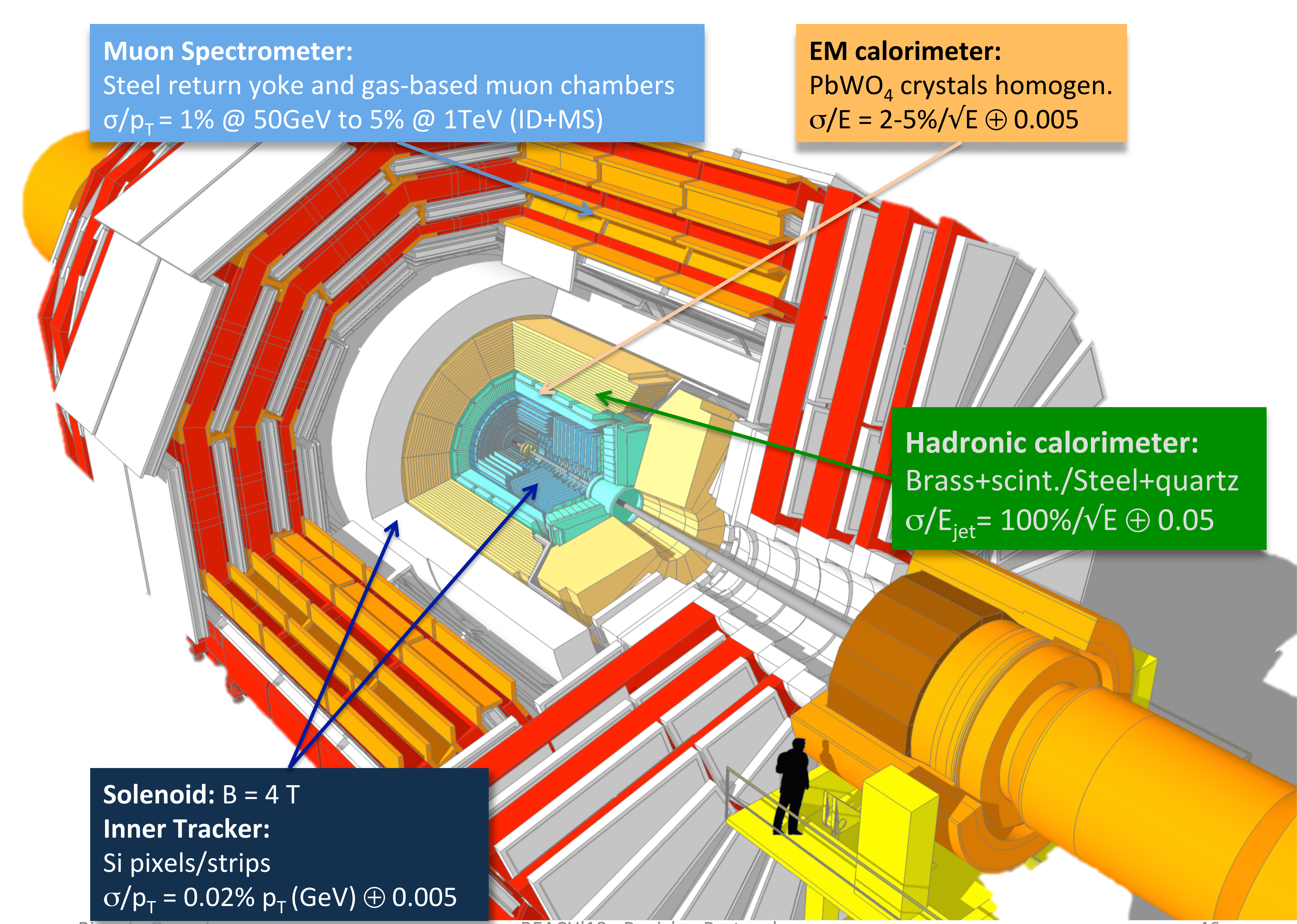


WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN
LHC
Higgs Boson
CHAPPATTE


IMAGINE A FIELD THAT PERMEATES THE ENTIRE UNIVERSE.
EVERY PARTICLE FEELS THIS FIELD, BUT IS AFFECTED IN DIFFERENT AMOUNTS.


$M(H^\circ) = \pi \left(\frac{1}{137}\right)^8 \sqrt{\frac{hc}{G}}$
$3987^{12} + 4365^{12} = 4472^{12}$
$\Omega(t_\circ) > 1$

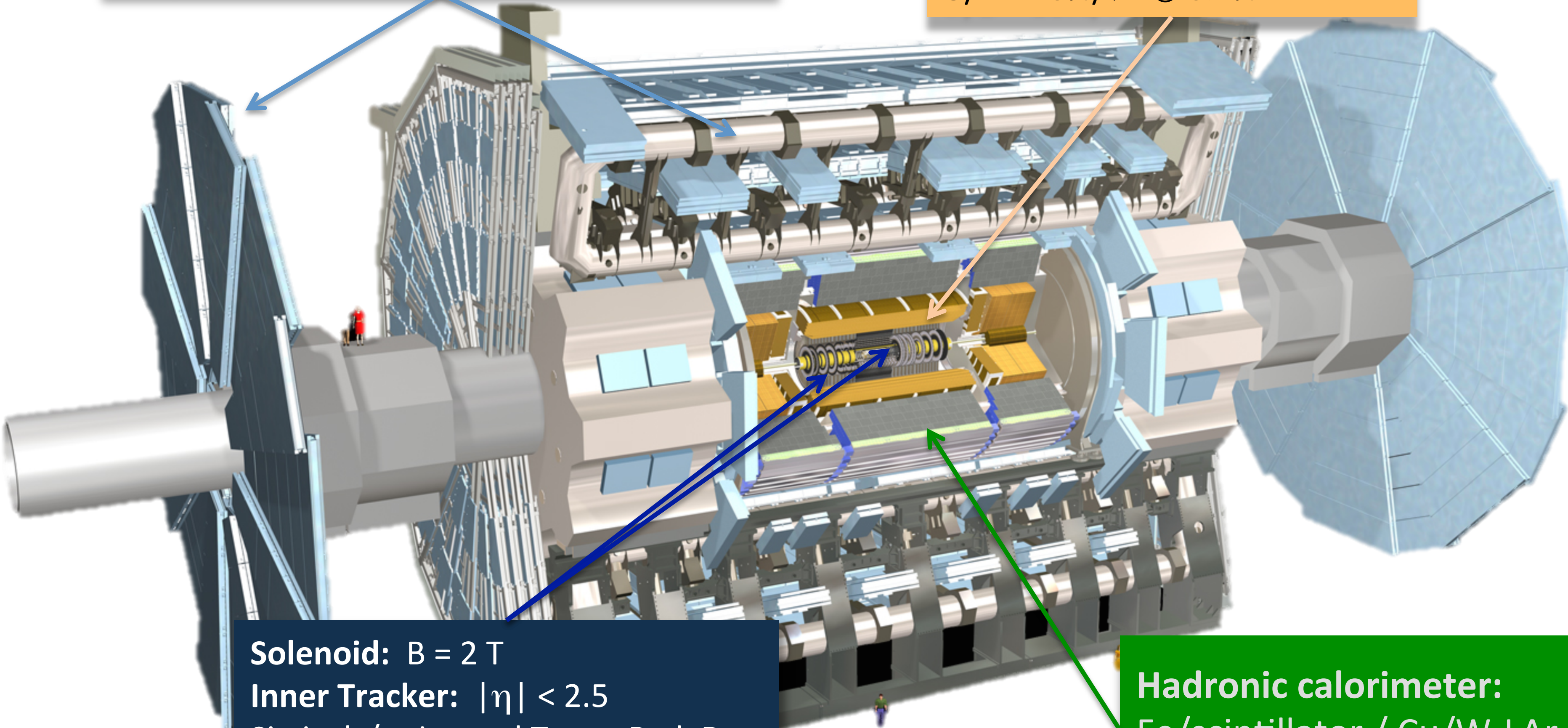

P
P
g
g
φ
γ
γ


Muon Spectrometer:
Steel return yoke and gas-based muon chambers
σ/p_T = 1% @ 50GeV to 5% @ 1TeV (ID+MS)
EM calorimeter:
$PbWO_4$ crystals homogen.
$\sigma/E = 2\text{-}5\%/\sqrt{E} \oplus 0.005$
Hadronic calorimeter:
Brass+scint./Steel+quartz
$\sigma/E_{jet} = 100\%/\sqrt{E} \oplus 0.05$
Solenoid: B = 4 T
Inner Tracker:
Si pixels/strips
$\sigma/p_T = 0.02\%\ p_T\,(\text{GeV}) \oplus 0.005$

1. The LHC: Experiments

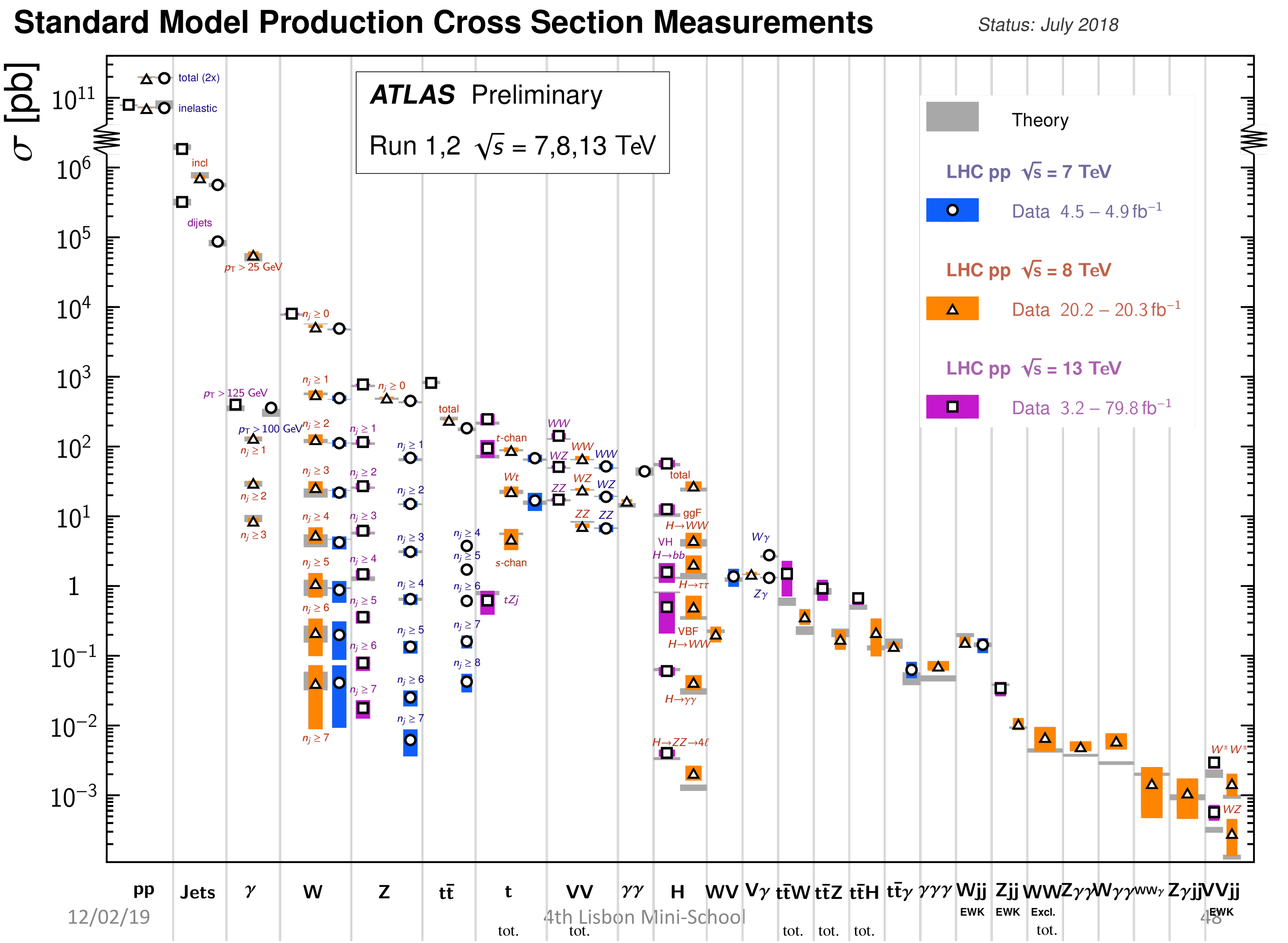
Muon Spectrometer: |η| < 2.7
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: |η| < 2.5 (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

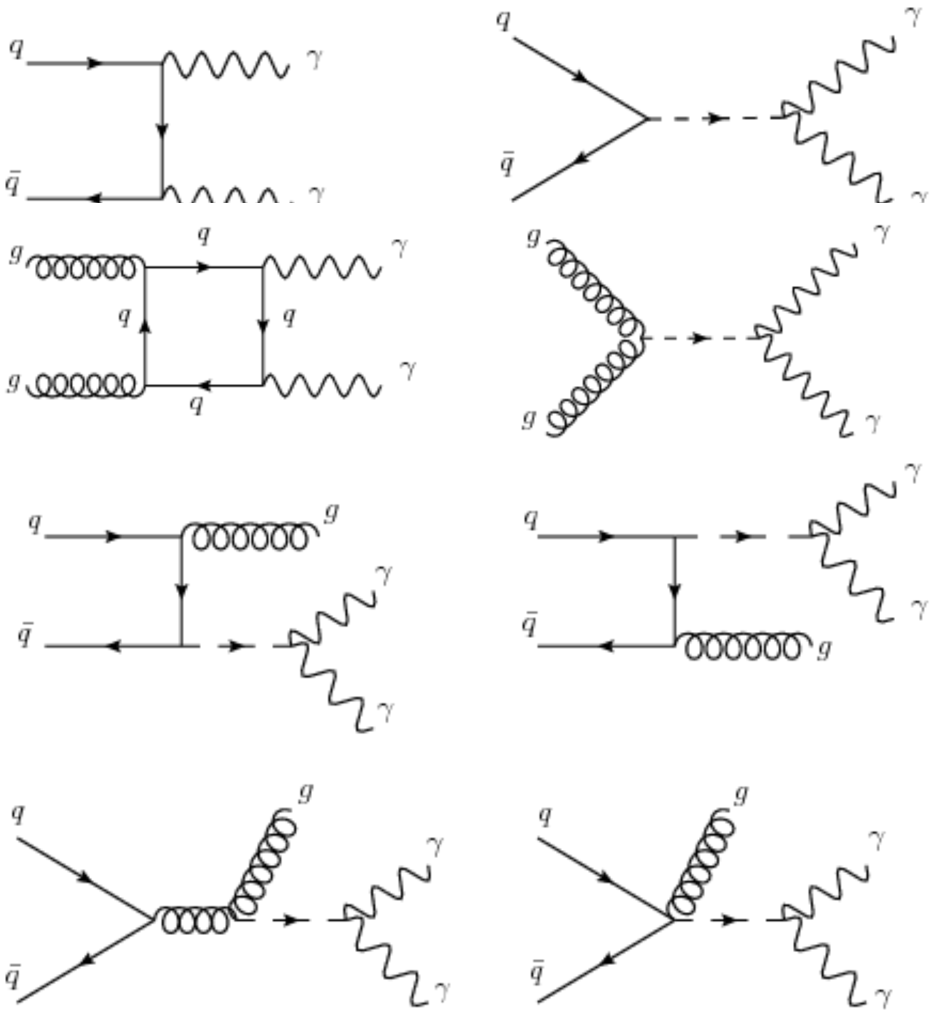


Solenoid: B = 2 T
Inner Tracker: |η| < 2.5
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\mathrm{GeV}) \oplus 1\%$

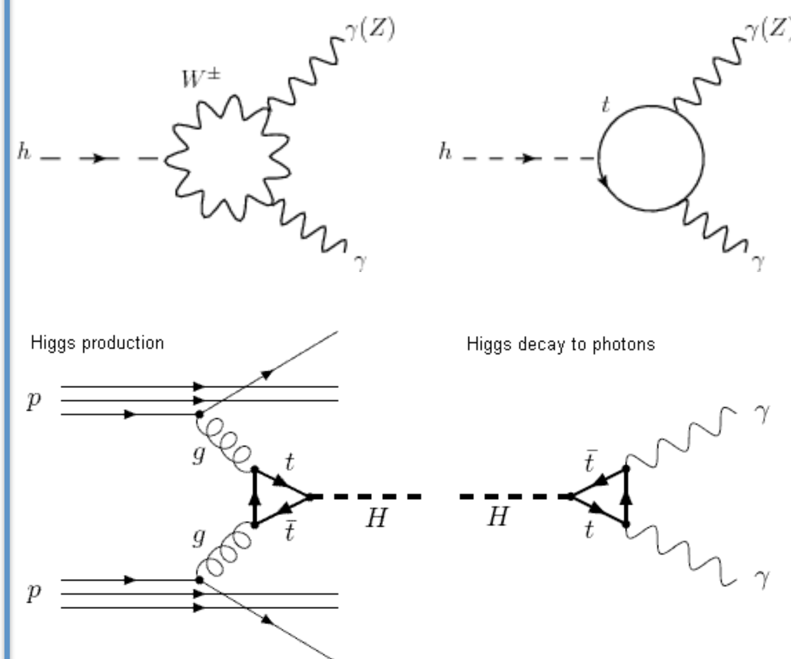
Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$


Standard Model Production Cross Section Measurements
Status: July 2018
σ [pb]
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
total (2x)
inelastic
incl
dijets
pT > 25 GeV
pT > 125 GeV
pT > 100 GeV
total
t-chan
Wt
s-chan
tZj
ggF
H→WW
VH
H→bb
H→ττ
VBF
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
W±W±
WZ
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj
Zjj
WW
Zγγ
Wγγ
WWγ
Zγjj
VVjj
EWK
Excl.
tot.

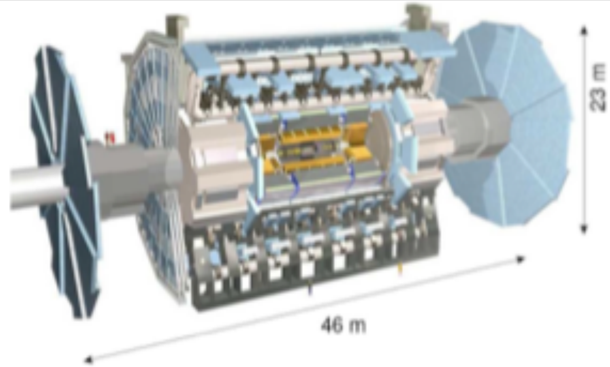
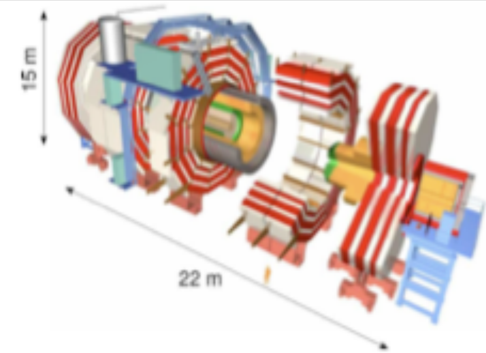
Quantum Mechanics Strikes Back!



- Background, signal, and their interference!

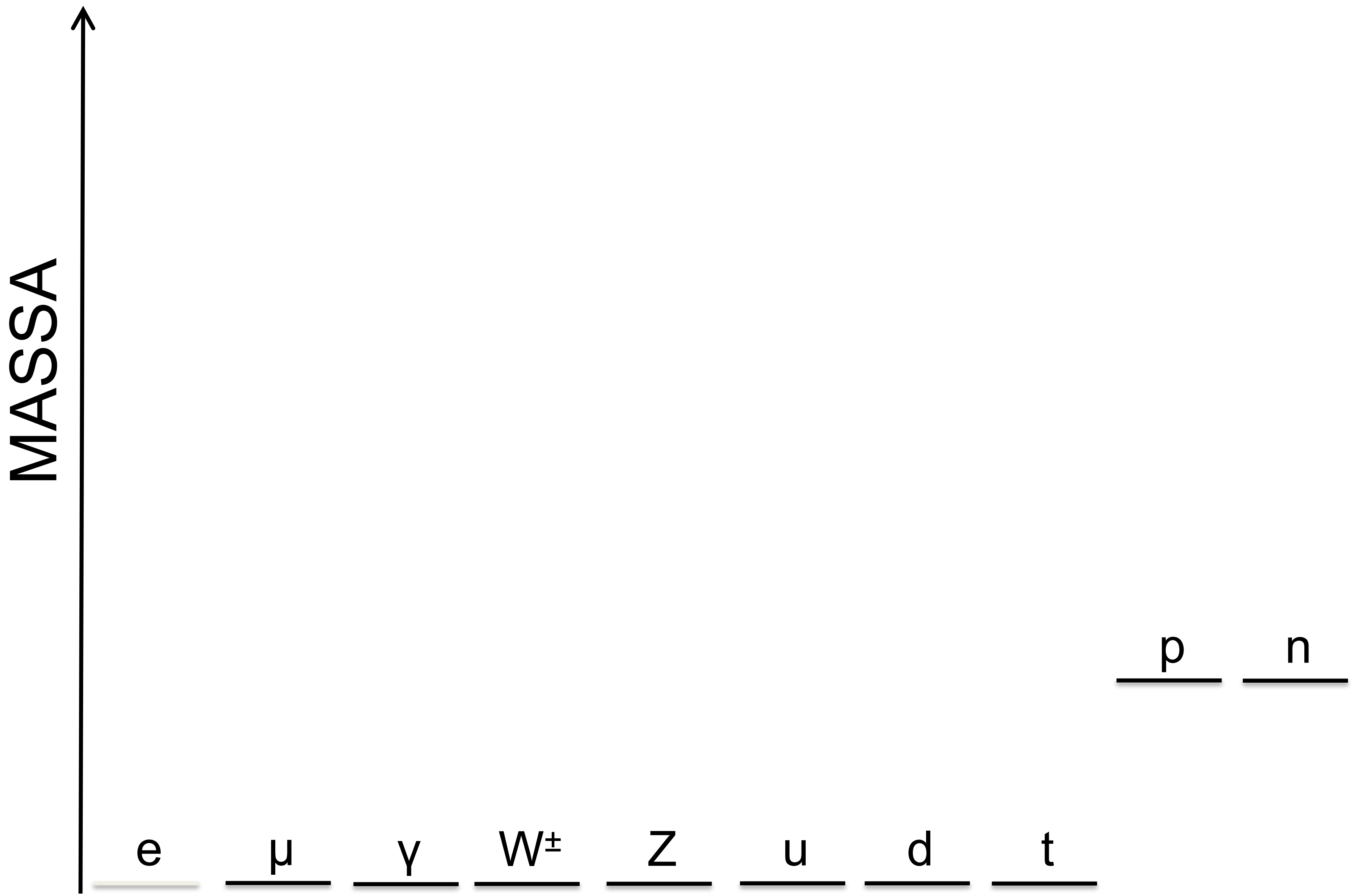


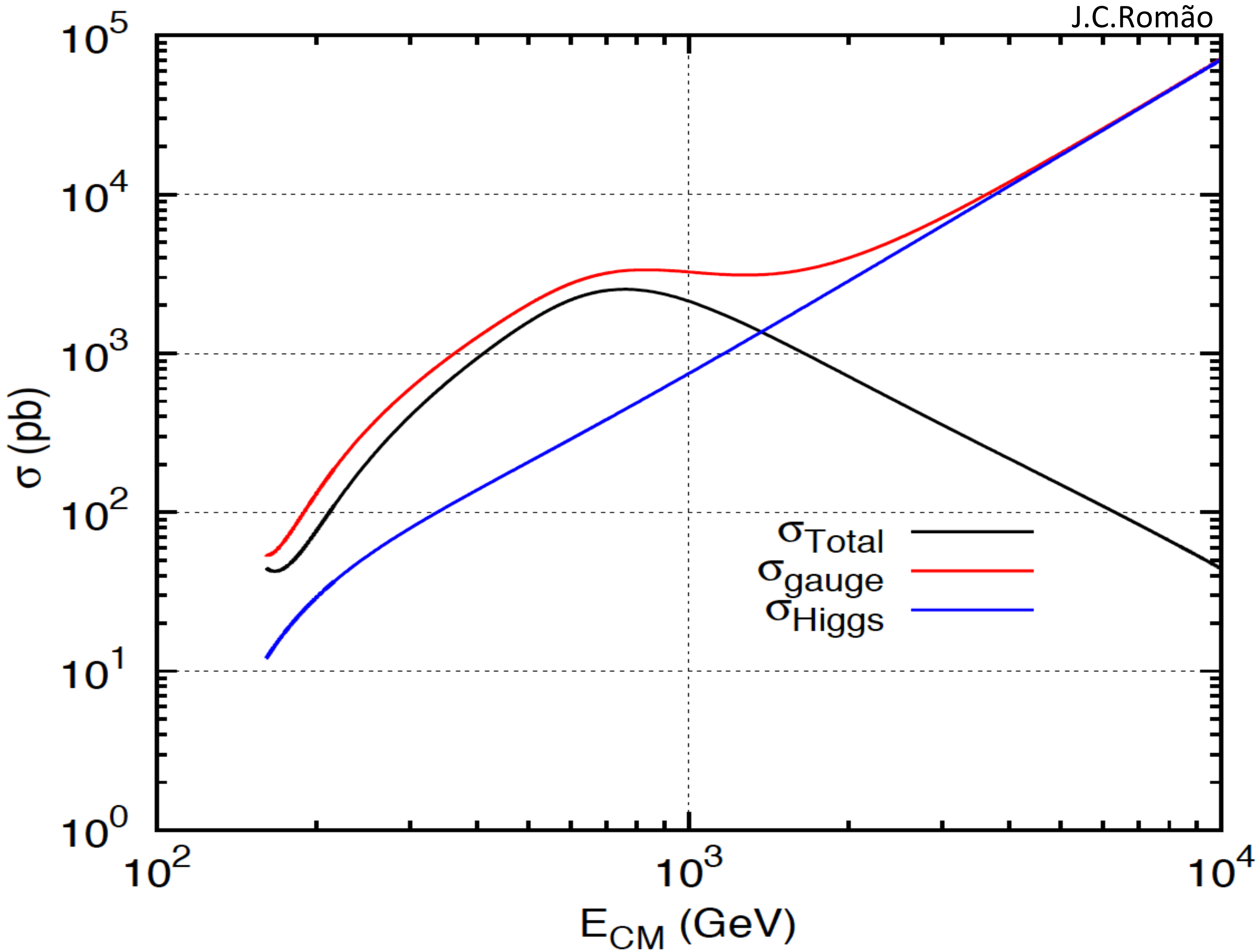
The ATLAS and CMS Detectors In a Nutshell

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\%$ (at 50 GeV) $\sim 11\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Agora os problemas...

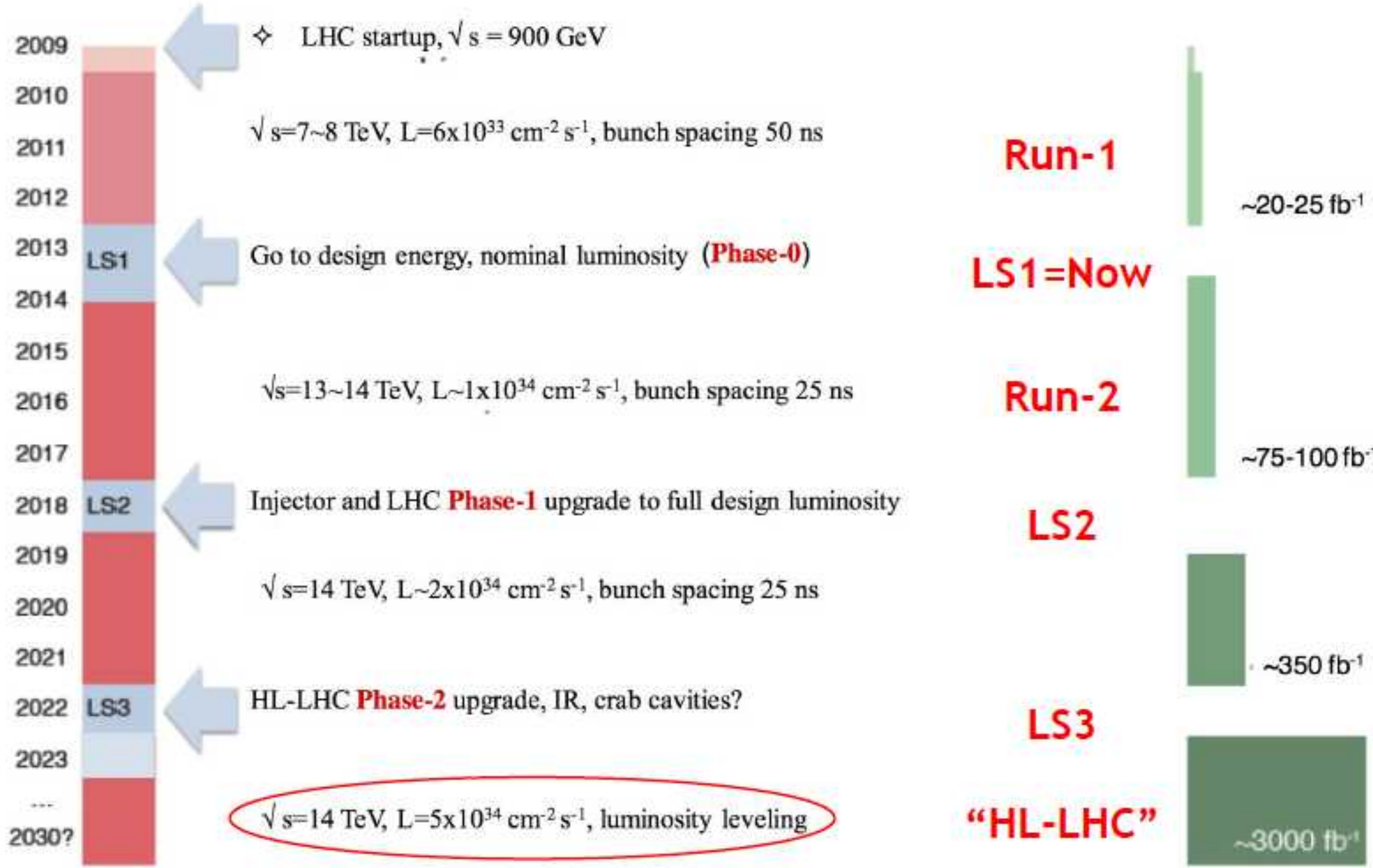
Isto não devia funcionar!…





J.C.Romão
10^5
10^4
10^3
10^2
10^1
10^0
σ (pb)
10^2
10^3
10^4
E_{CM} (GeV)
σ_{Total}
σ_{gauge}
σ_{Higgs}

The landscape in the next decade(s)



D Charlton / Birmingham - 12 August 2013, ICISE inauguration, Quy Nhon, Vietnam 43