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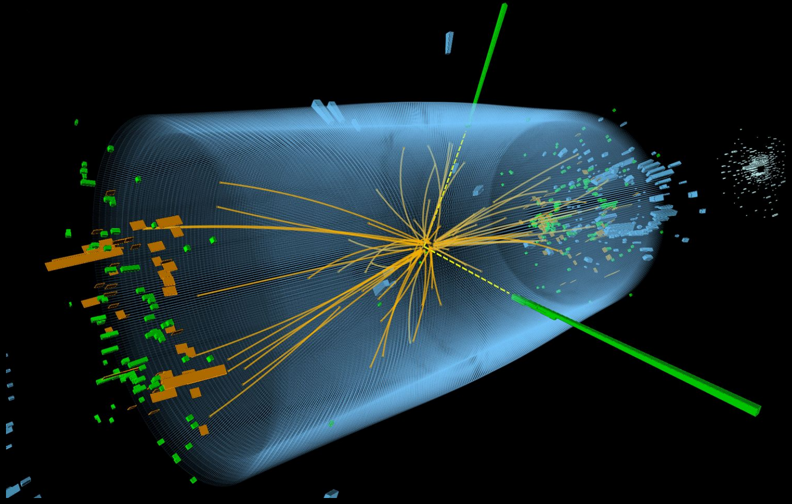
Particle Physics Phenomenology

Lecture III

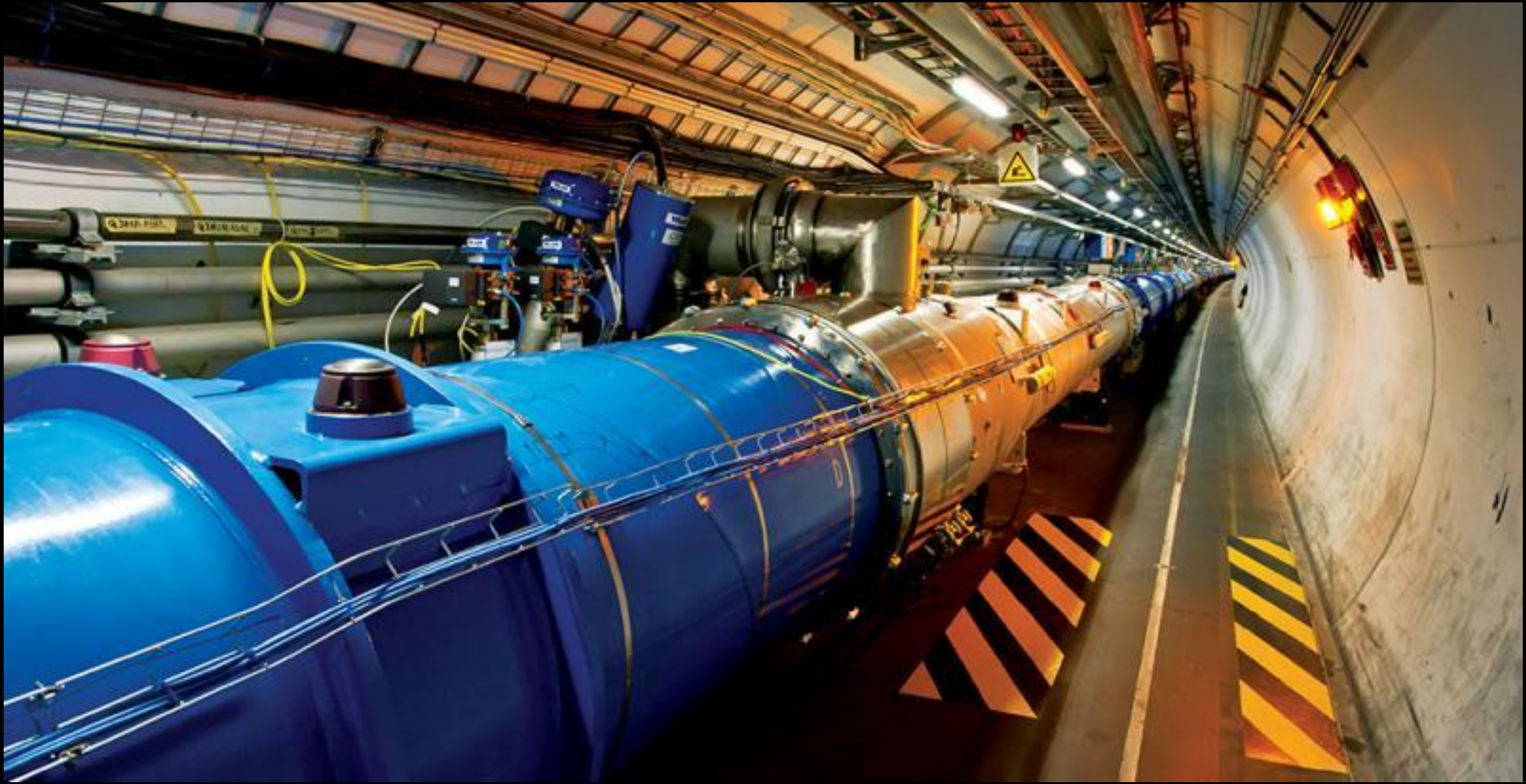
LHC Phenomenology

Giovanna Cottin

Mini Curso, Universidad de La Serena
December 2019

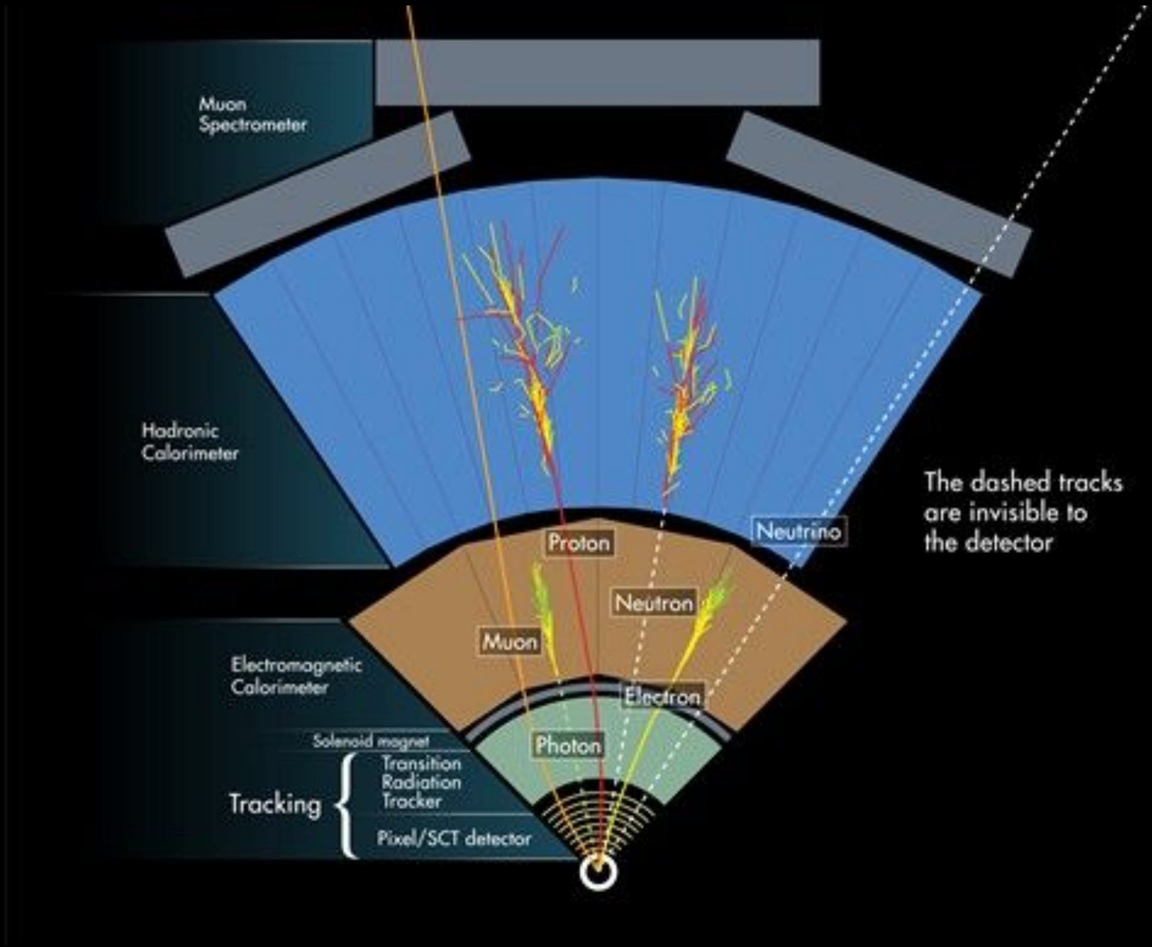


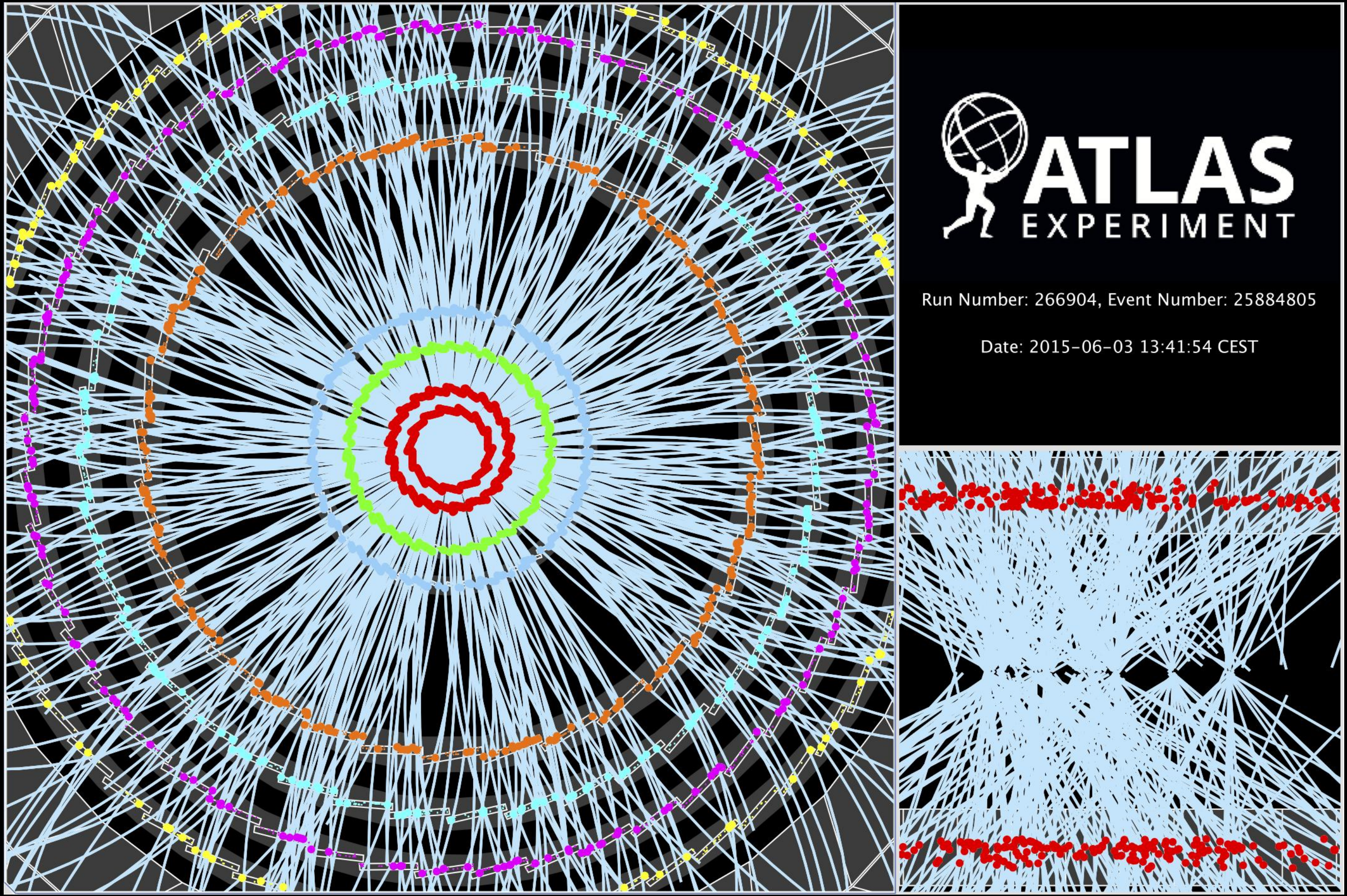
@ CERN, CMS



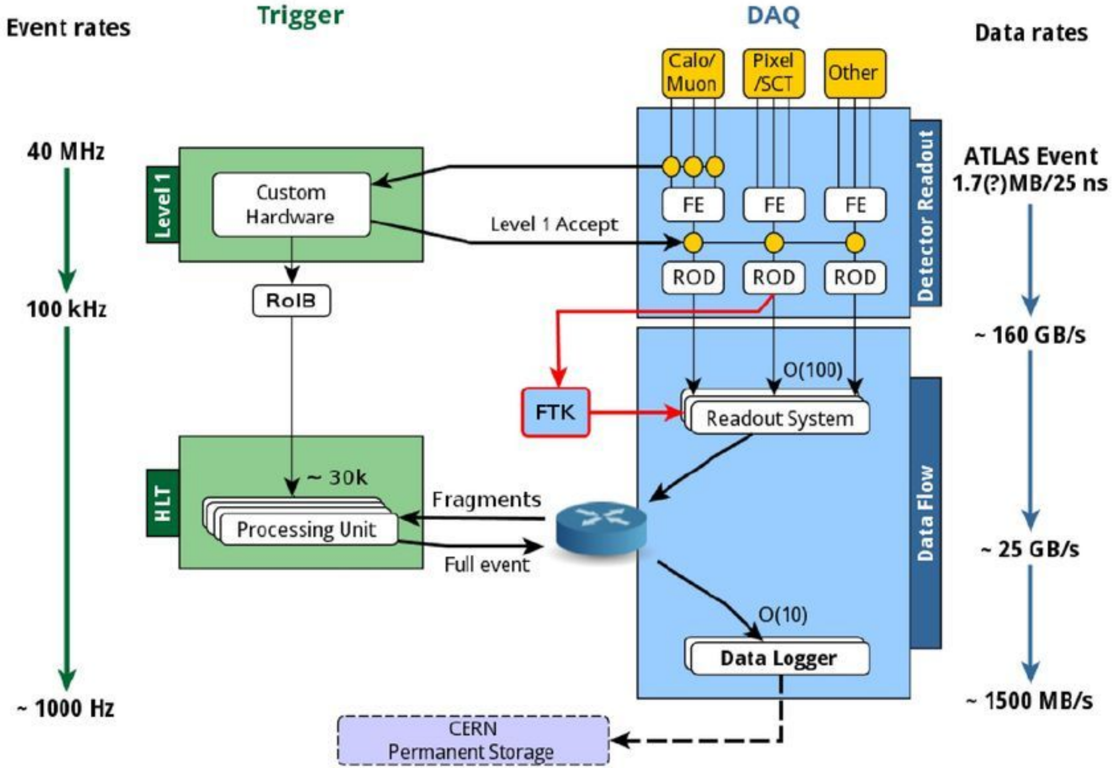
LHC@CERN

How ATLAS detects particles?

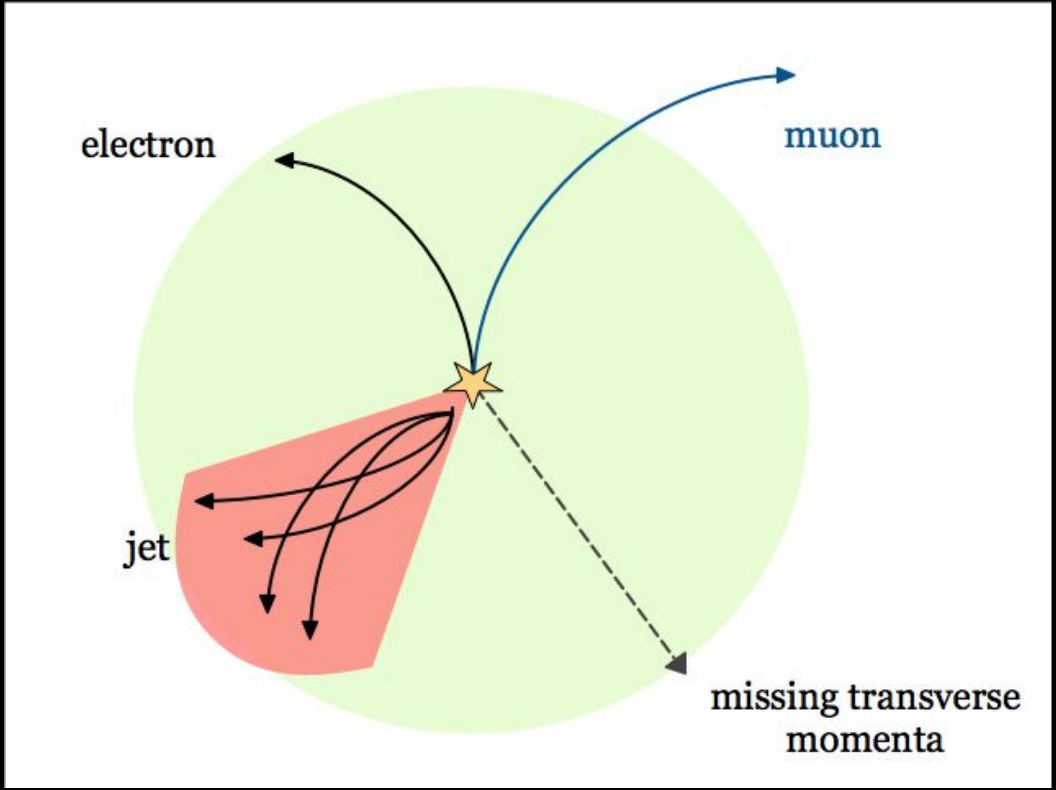



ATLAS
EXPERIMENT
Run Number: 266904, Event Number: 25884805
Date: 2015-06-03 13:41:54 CEST

ATLAS Trigger in Run 2 & 3



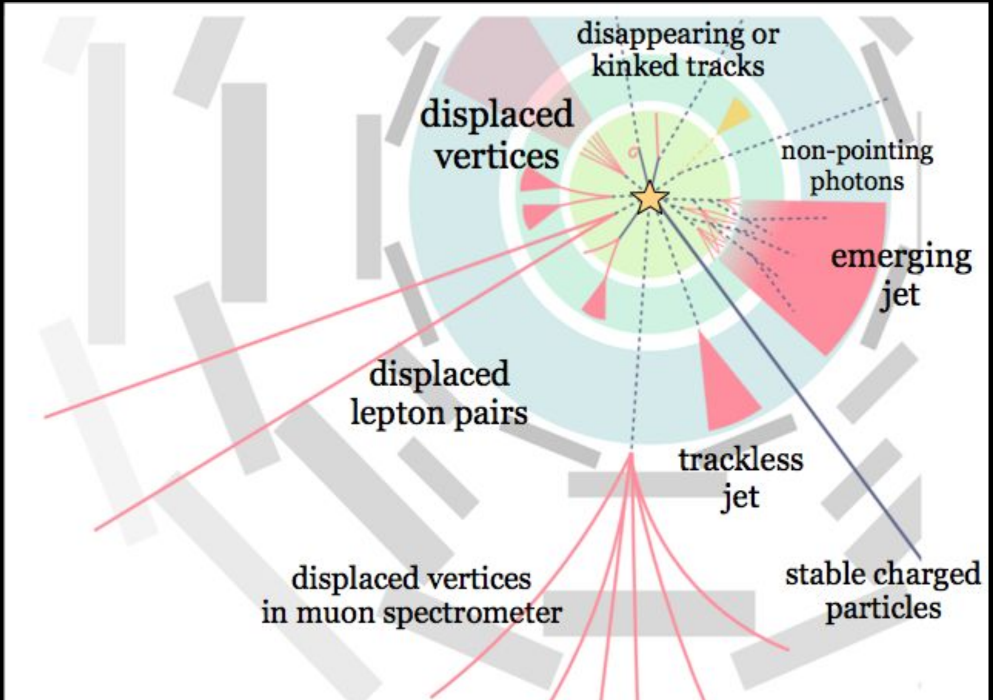
Reconstruction of Physics Objects inside experiments



Can also have long-lived decays and reconstruction of different objects!

Searches can target specific lifetimes using different parts of the detector.

Detection usually requires special triggers and reconstruction.



Source: Adapted from Heather Russel

Electrons or Muons?

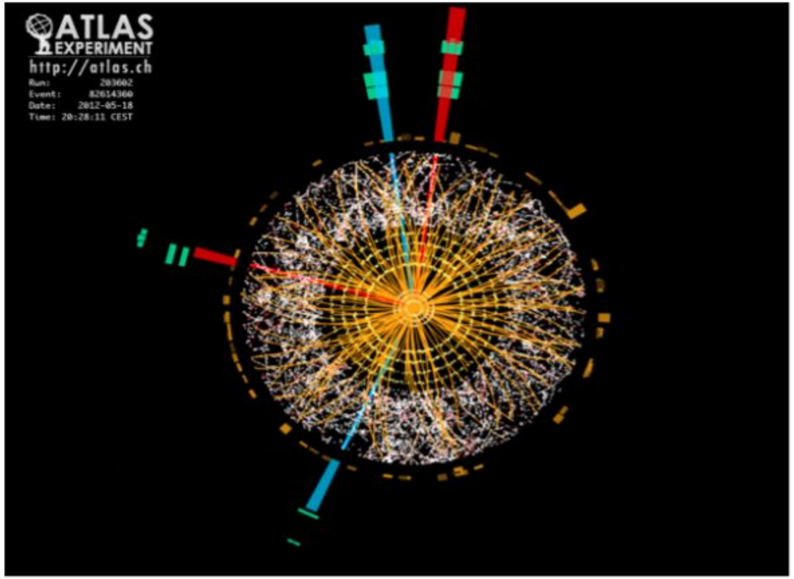
- An electron for a theorist is…

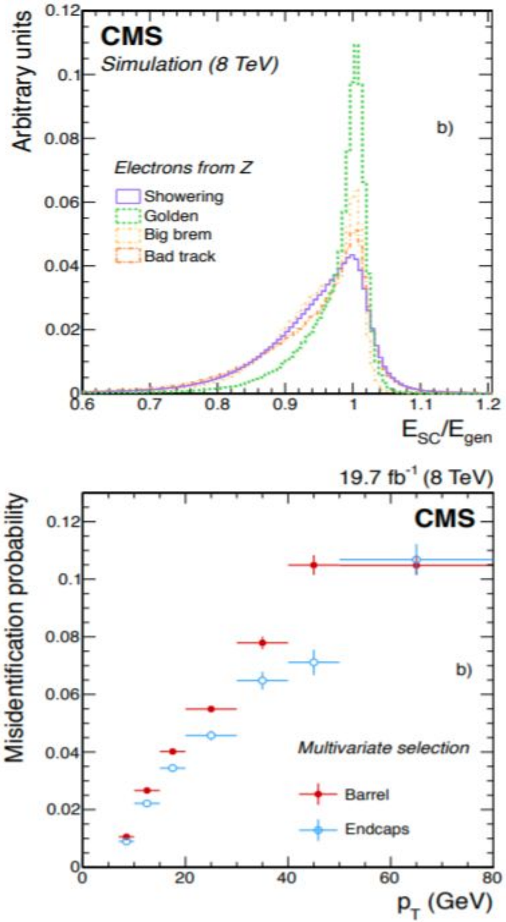
$$i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - M_{\psi}\bar{\psi}\psi + \ldots$$


```
<event>
 7      1 +5.2334007e-03 9.71984100e+00 7.81860800e-03 1.80002300e-01
       11 -1    0    0    0    0 +0.0000000000e+00 +0.0000000000e+00 +5.2899999753e+00 5.2900000000e+00 5.1100000000e-04 0.0000e+00 -1.0000e+00
      -11 -1    0    0    0    0 -0.0000000000e+00 -0.0000000000e+00 -5.2899999753e+00 5.2900000000e+00 5.1100000000e-04 0.0000e+00 1.0000e+00
       53  2    1    2    0    0 +5.5866191369e-01 +1.0939486250e-01 -6.3851596435e-01 8.6015871005e-01 9.0000000000e-02 5.3195e+00 0.0000e+00
       15  1    1    2    0    0 +3.8268104252e+00 -1.7634617467e+00 +1.0448486207e+00 4.6908115505e+00 1.7770000000e+00 1.9129e-01 -1.0000e+00
      -15  1    1    2    0    0 -4.3854723389e+00 +1.6540668842e+00 -4.0633265639e-01 5.0290297394e+00 1.7770000000e+00 0.0000e+00 1.0000e+00
       11  1    3    3    0    0 +6.3686707127e-02 -1.7129106352e-03 -1.1310323059e-01 1.2981345315e-01 5.1100000000e-04 0.0000e+00 -1.0000e+00
      -11  1    3    3    0    0 +4.9497520656e-01 +1.1110777314e-01 -5.2541273376e-01 7.3034525690e-01 5.1100000000e-04 0.0000e+00 -1.0000e+00
<mgrwt>
<rscale>  0 0.97198413E+01</rscale>
<asrwt>0</asrwt>
<pdfrwt beam="1">  1       11 0.10000000E+01 0.97198413E+01</pdfrwt>
<pdfrwt beam="2">  1      -11 0.10000000E+01 0.97198413E+01</pdfrwt>
<totfact> 0.10000000E+01</totfact>
</mgrwt>
</event>
```


With thanks to B. Shuve

- An electron for an experimentalist is…





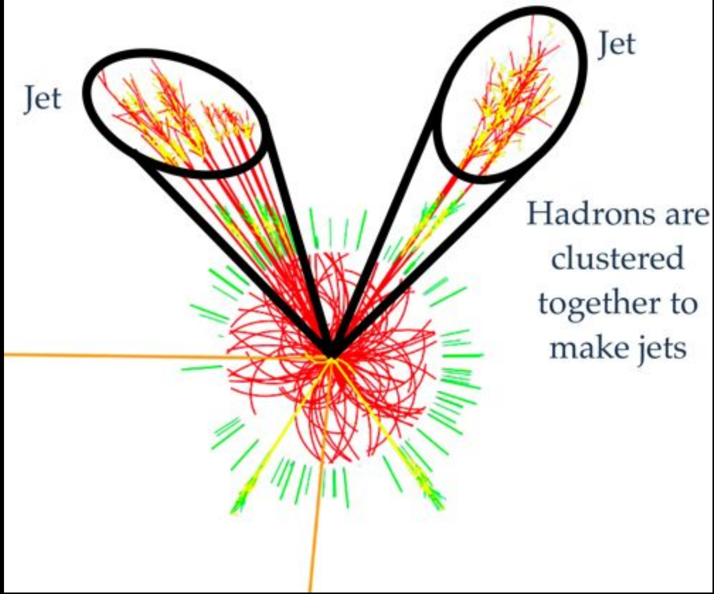
CMS, 1502.02701 [JINST]

37

With thanks to B. Shuve

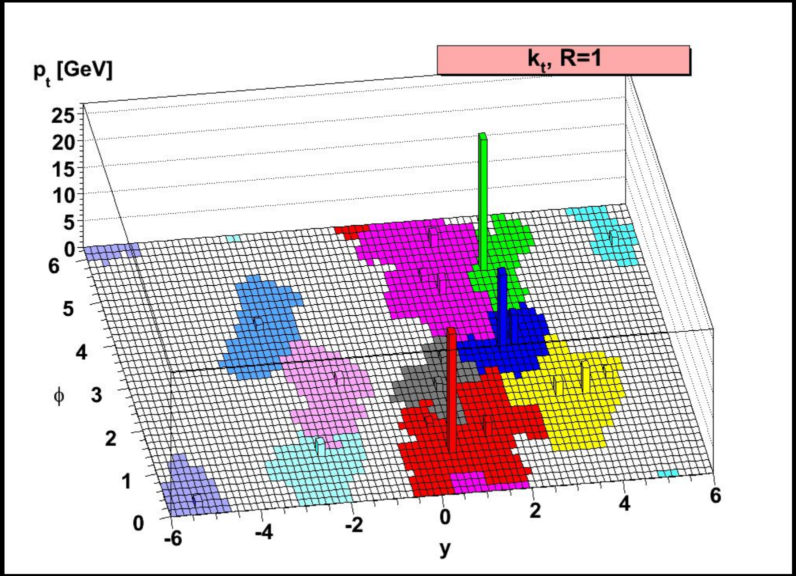
Jets?

What's a jet?



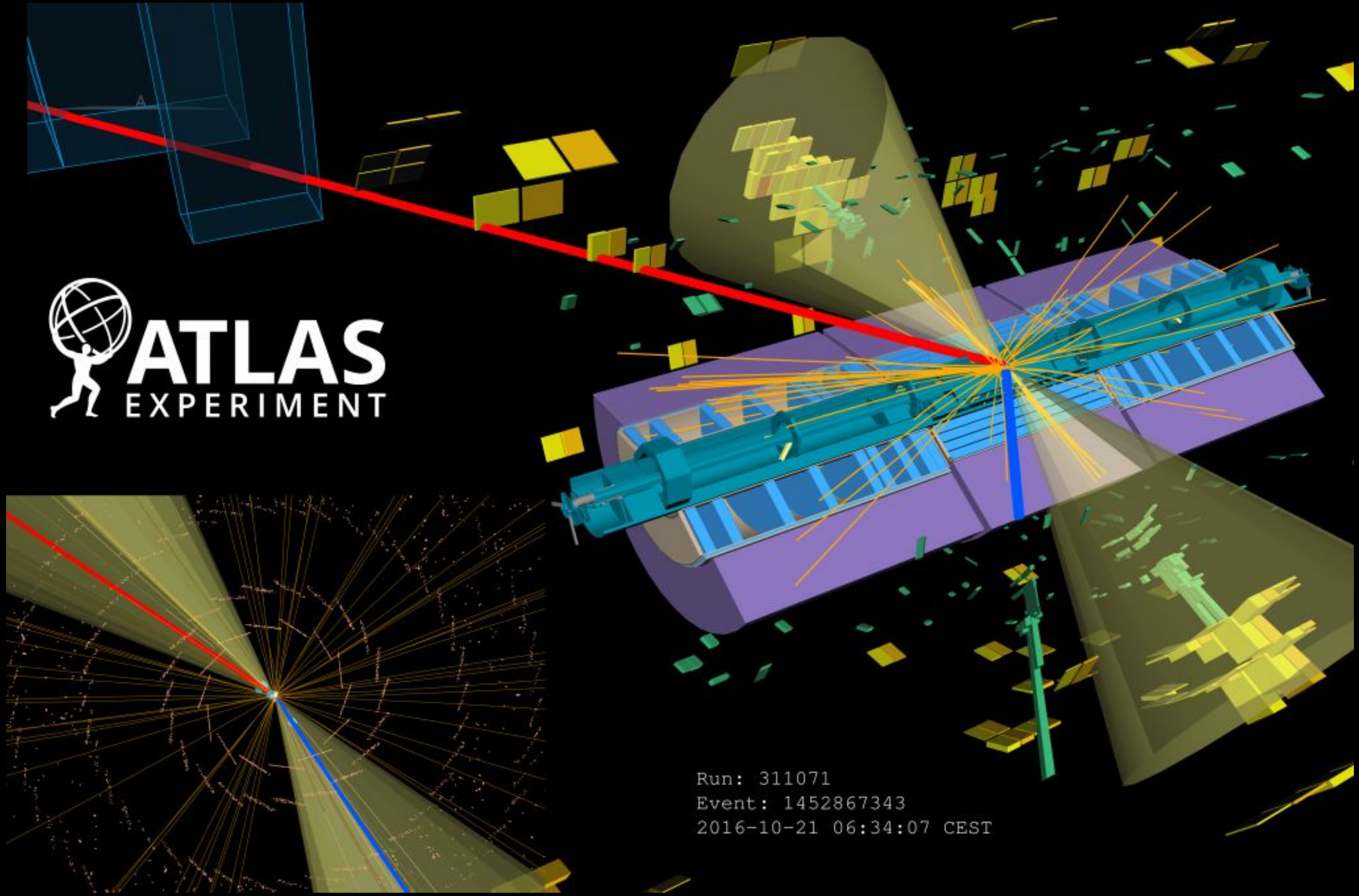
Source @quantumdiaries

Several jet clustering algorithms widely used (anti-kt, Cambridge/Aachen)

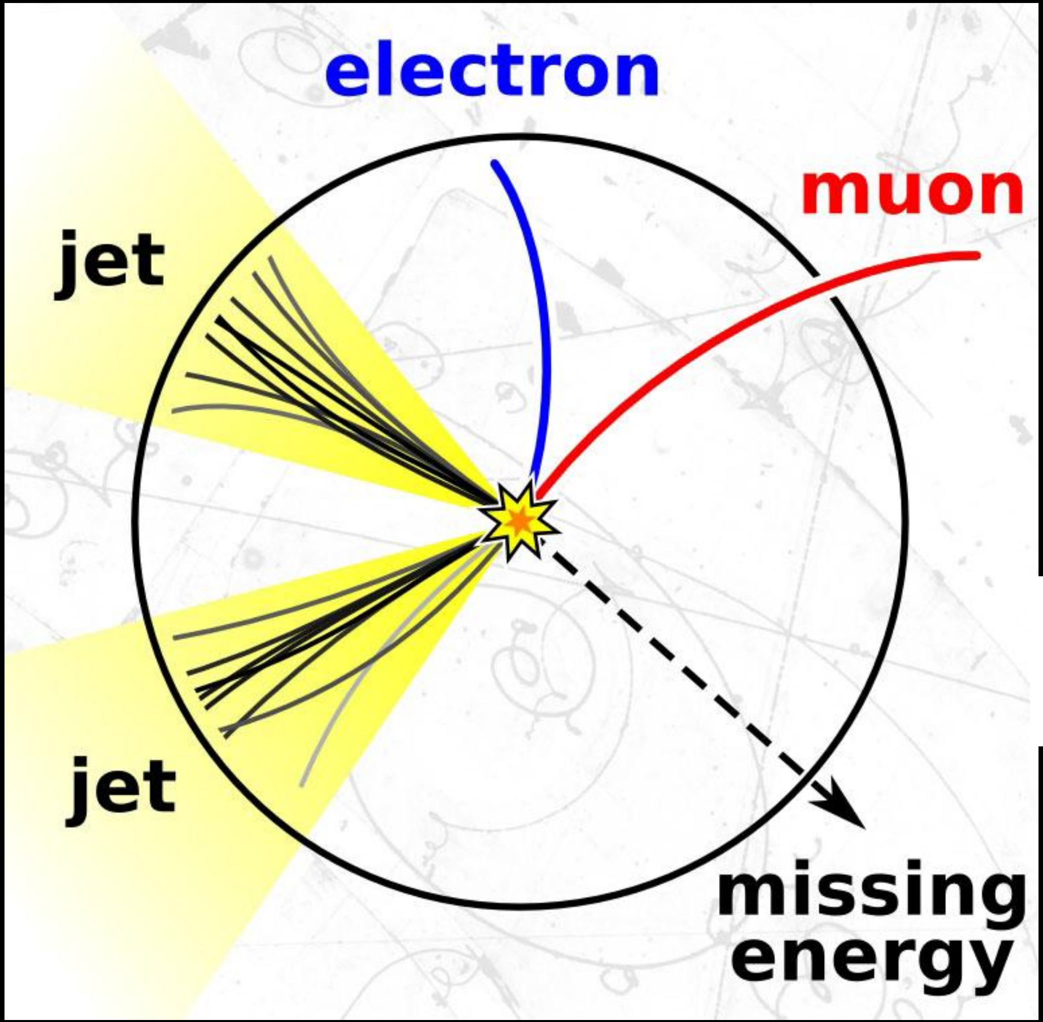


Source M. Cacciari et al, *The anti-kt jet clustering algorithm*, arXiv:0802.1189

A jet is defined by a clustering algorithm, which *is* an example of unsupervised Machine Learning
And they do have a physical meaning ! Can be given as image to a CNN


ATLAS
EXPERIMENT
Run: 311071
Event: 1452867343
2016-10-21 06:34:07 CEST

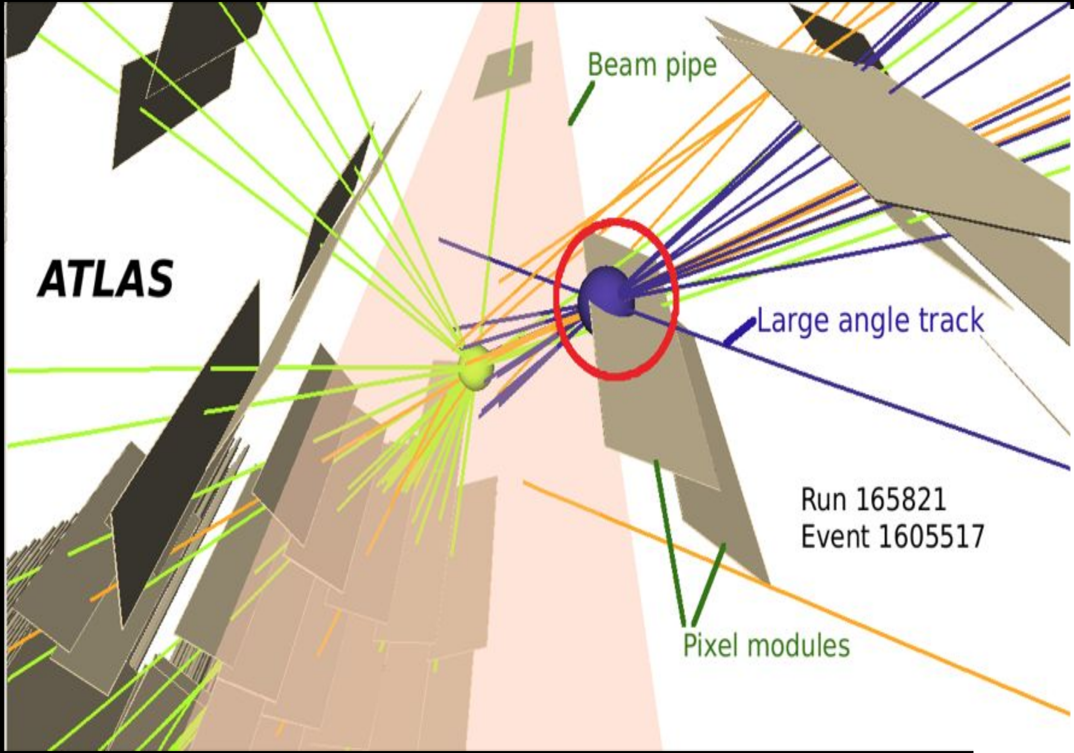
MET?

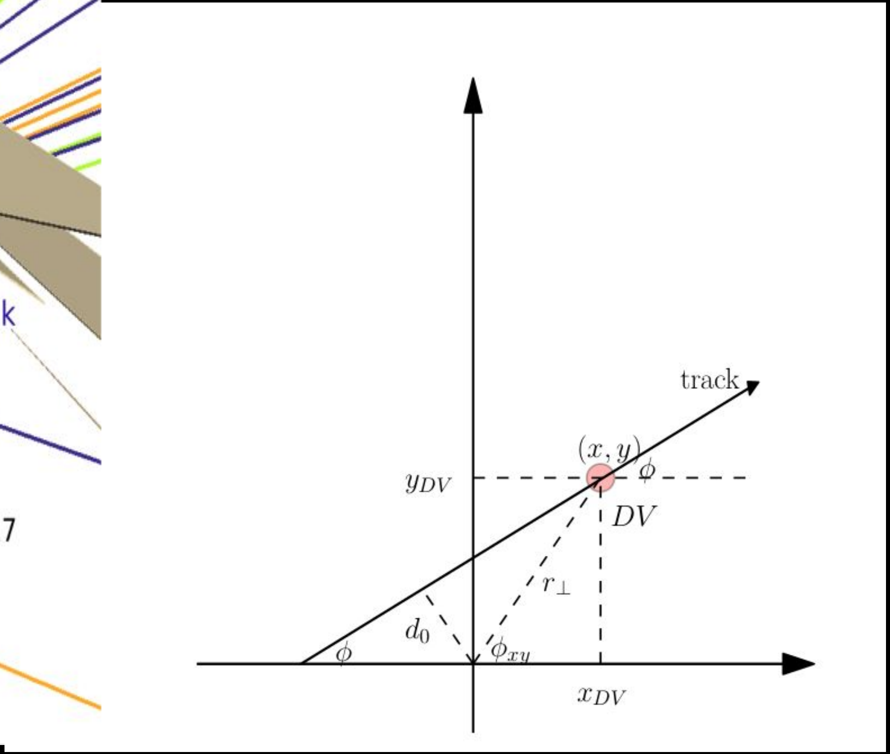


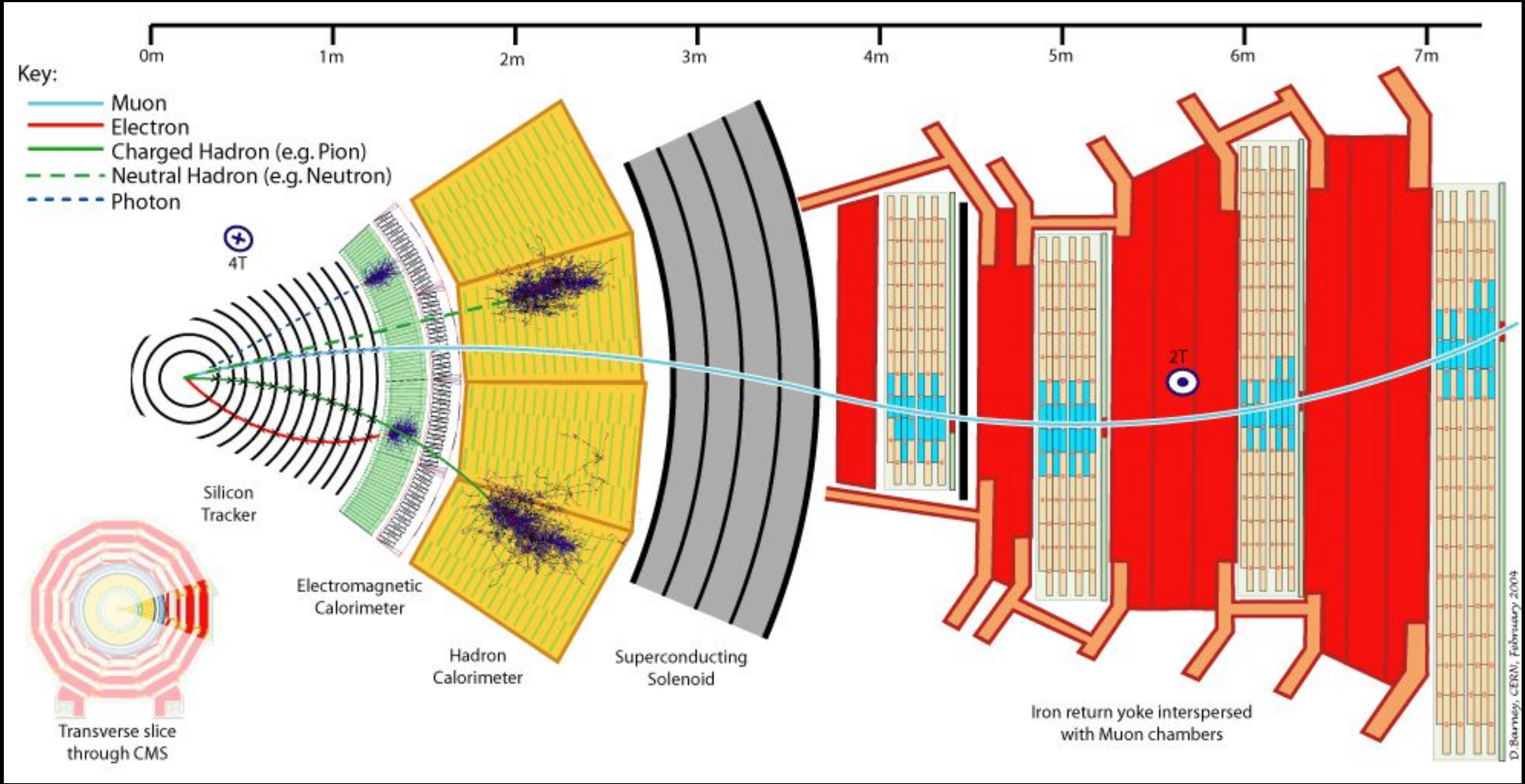
" To see nothing, you have to understand everything "

$$\vec{p}_T^{\,\text{miss}} = -\sum_{\text{visible particles}} \vec{p}_T = \sum_{\text{invisible particles}} \vec{p}_T$$

Just tracks or displaced vertices?

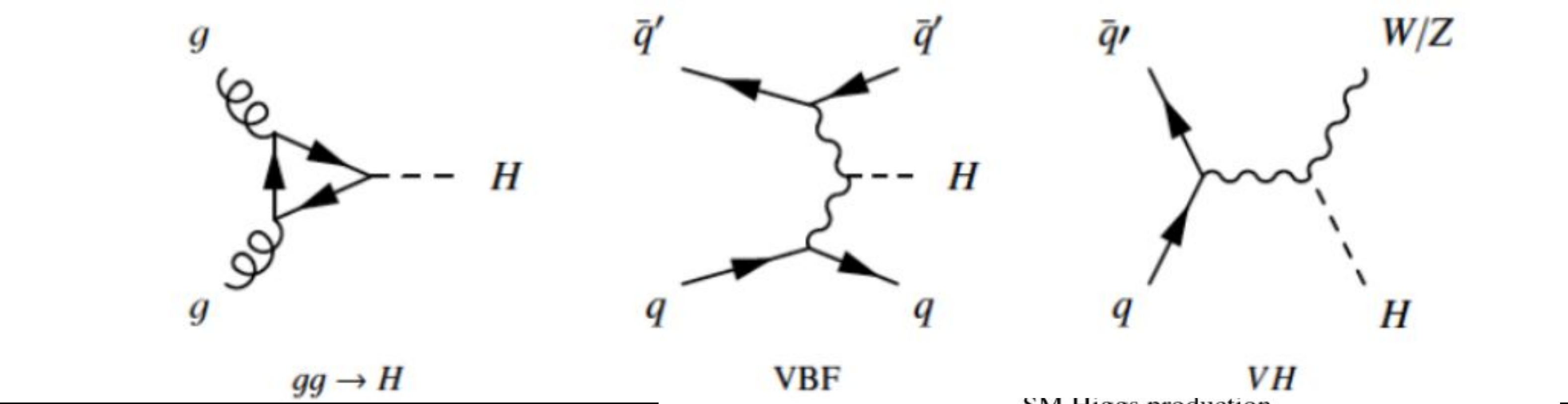




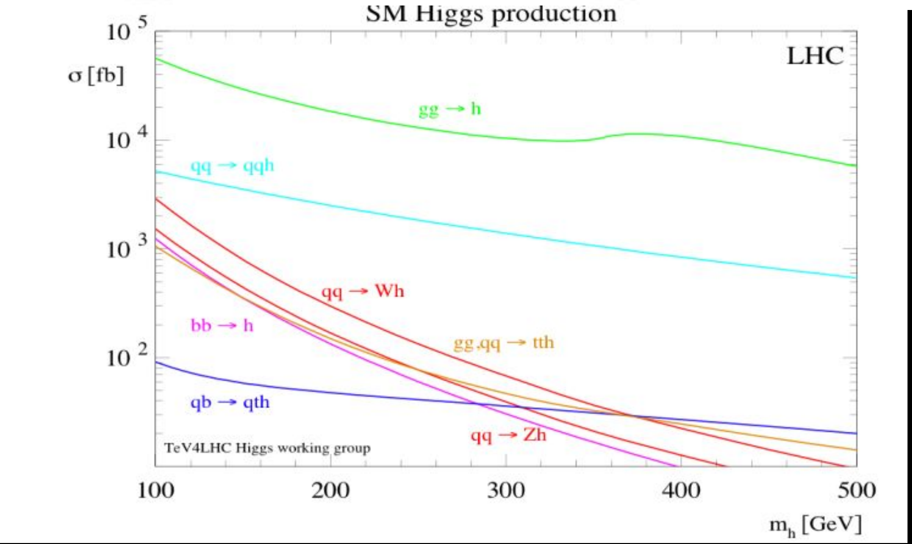

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Example: How to identify a Higgs boson @ LHC?

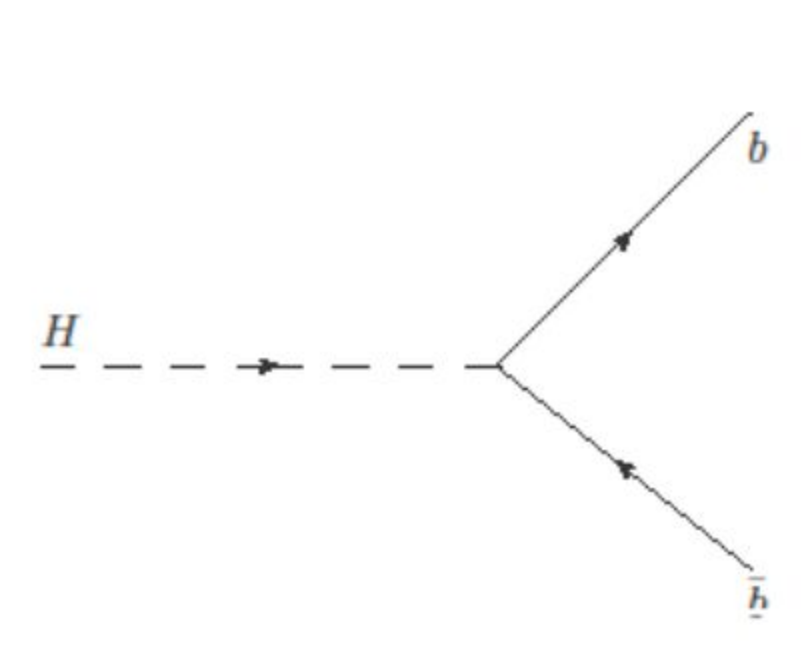
Production

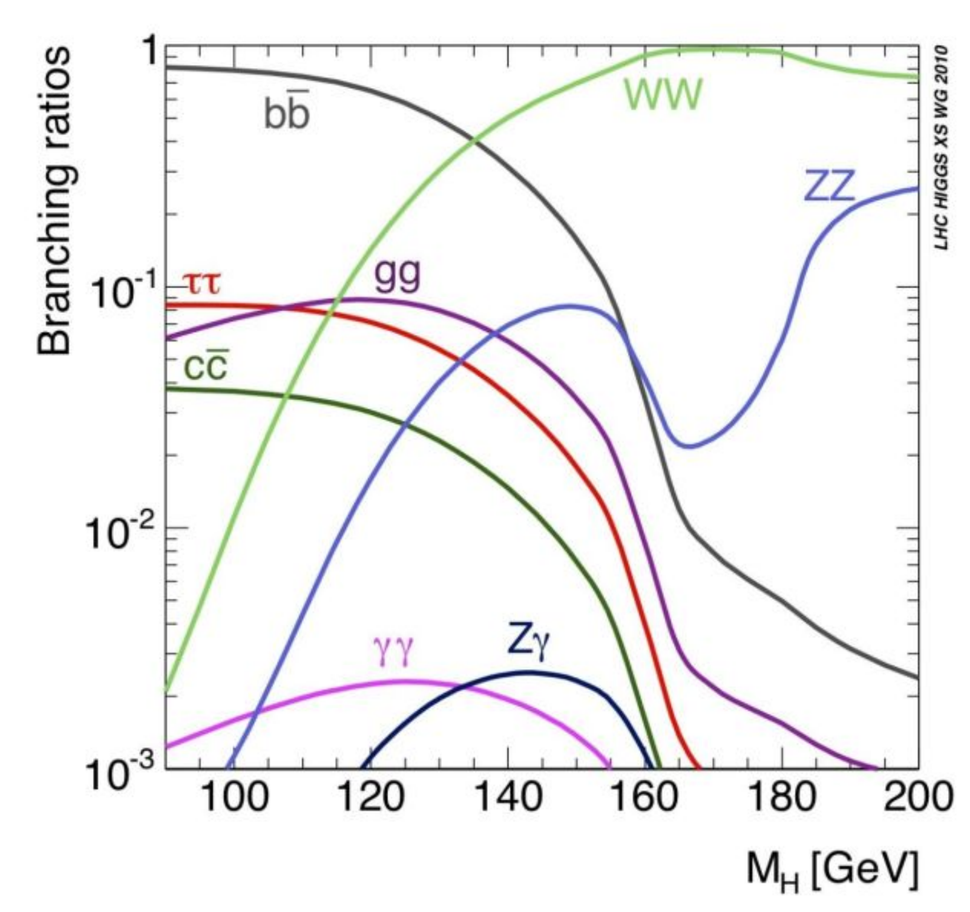


Seleccionamos los eventos con el Trigger (i.e Vector Boson Fusion o VBF, requiring at least two jets with MET > X GeV)



Decay

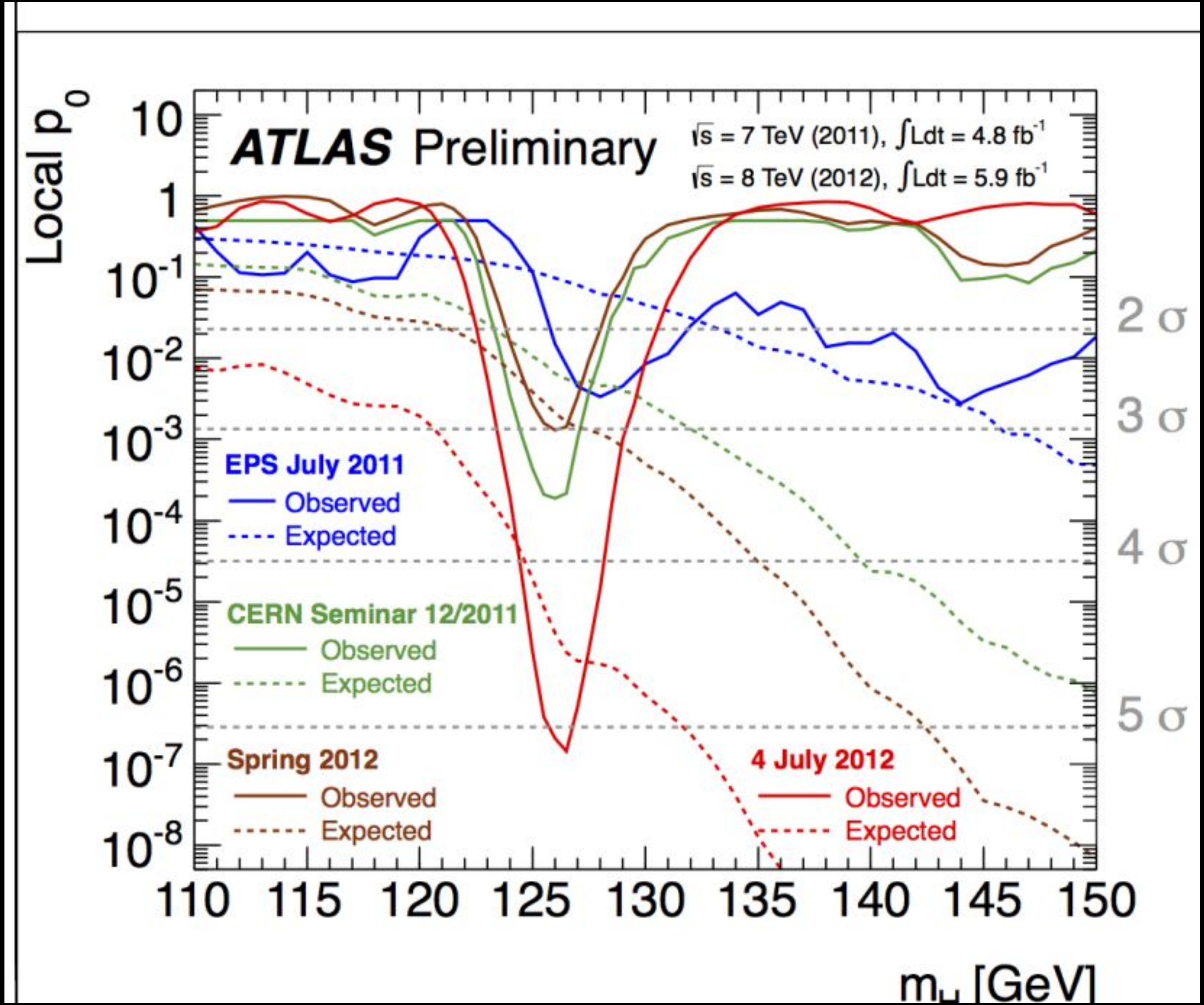


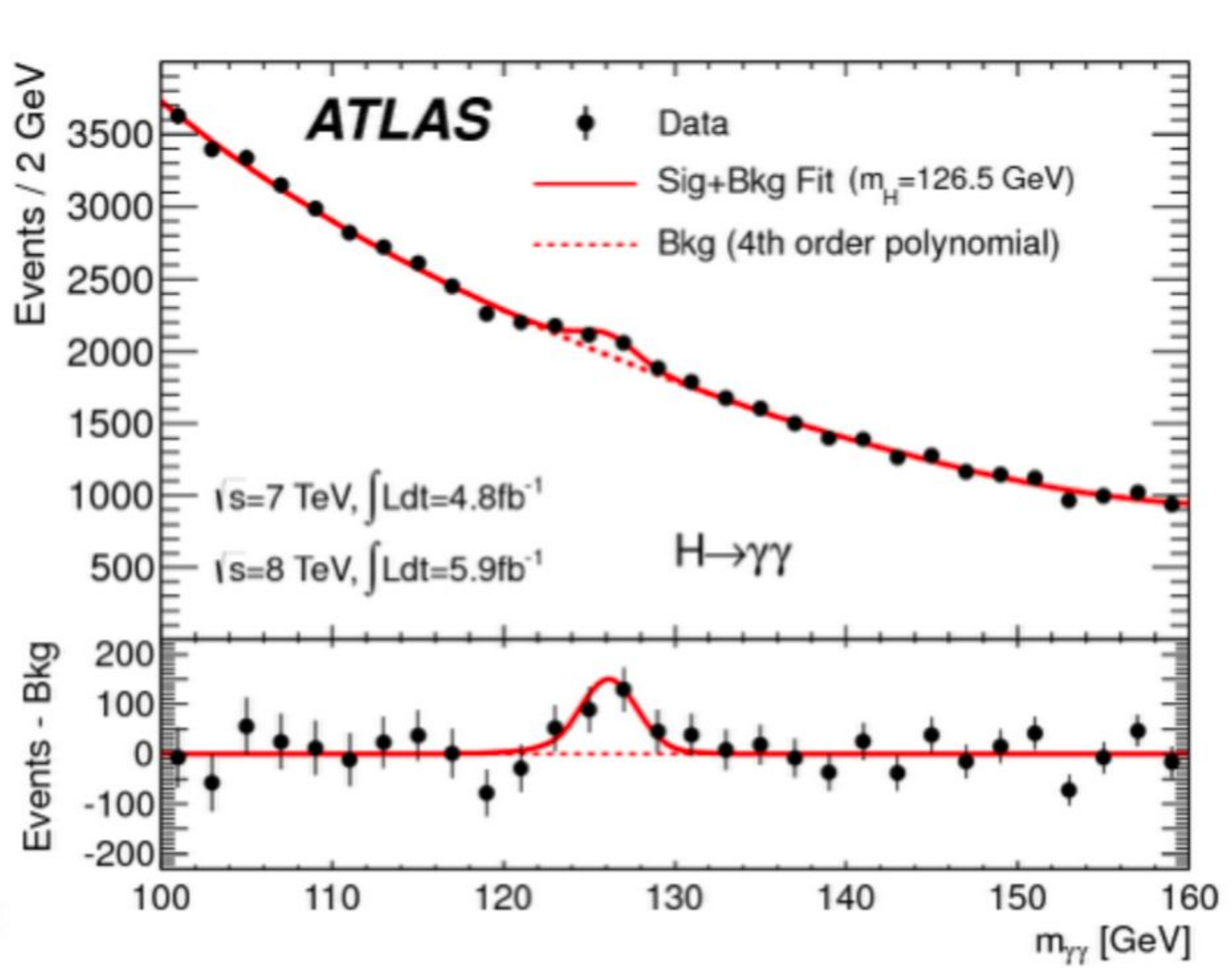


Luego de producir un Higgs detectamos sus decaimientos (i.e reconstruimos los fotones, leptones (del Z decay) o “jets”)

P0 is the probability (under the assumption of the hypothesis we want to test, H0 in this case “background only” or no Higgs) to find data with at least as much incompatibility with H0 as the data actually found

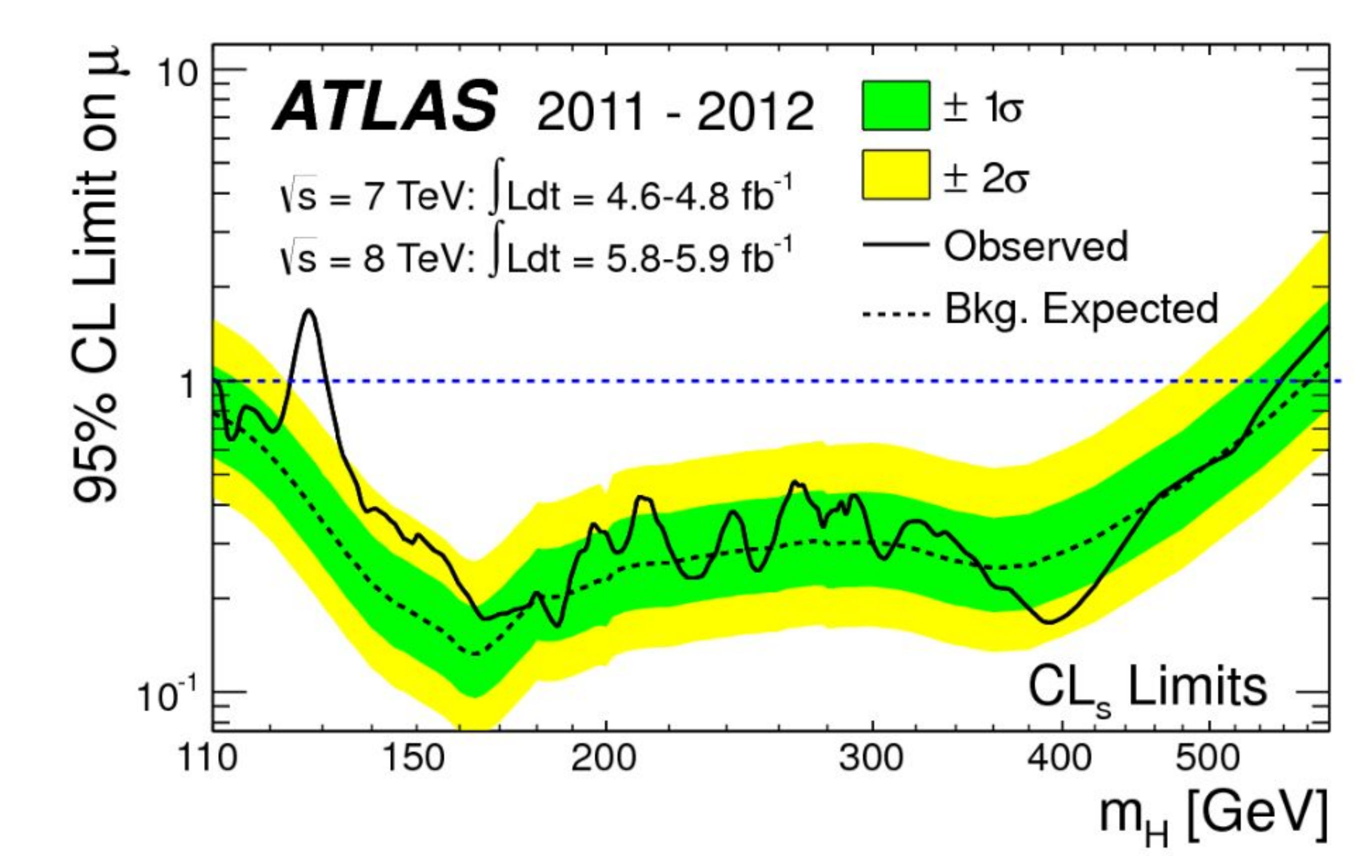
Large p—values indicate good agreement of the data with the background-only hypothesis, while small values favors the signal-plus-background hypothesis




ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
$H\rightarrow\gamma\gamma$
Events / 2 GeV
3500
3000
2500
2000
1500
1000
500
Events - Bkg
200
100
0
-100
-200
100
110
120
130
140
150
160
$m_{\gamma\gamma}$ [GeV]

$s\mu + b$ is defined, such that if $\mu = 0$ indicates an expected measurement of background-only, while $\mu = 1$ corresponds to the signal-plus-background model.

Solid line above yellow line are Higgs candidates !

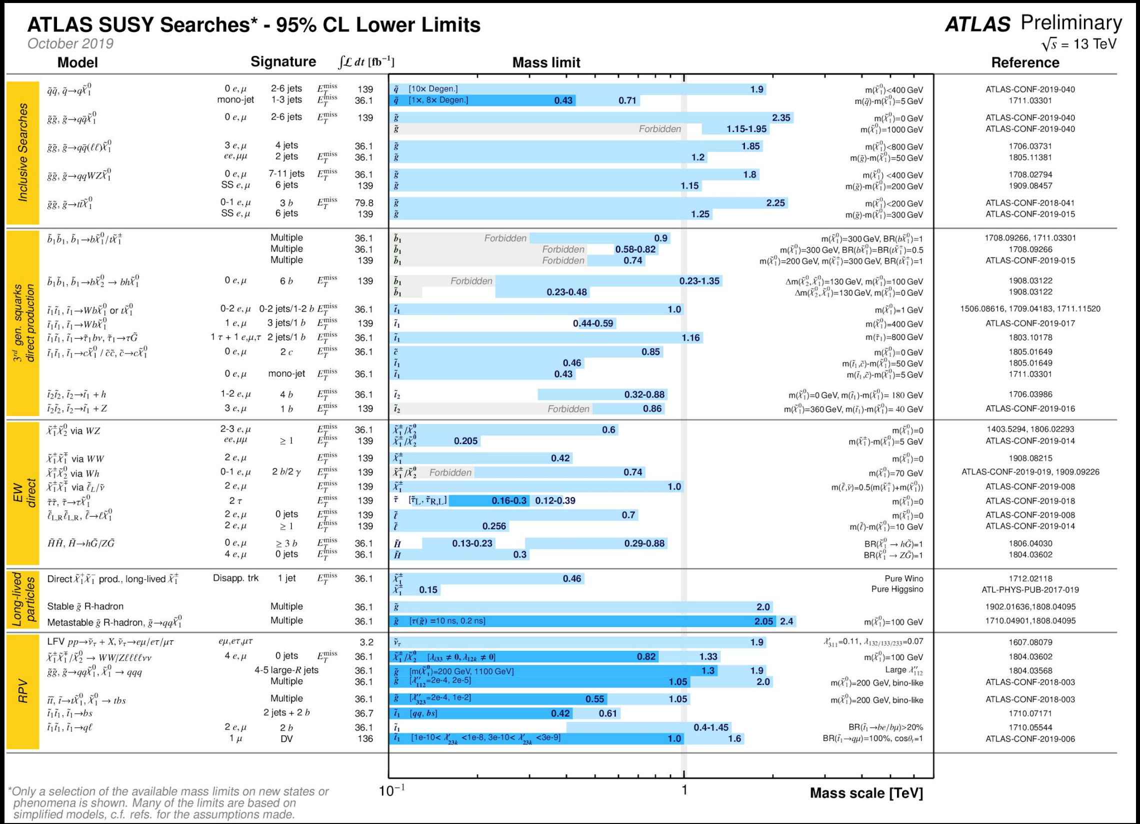


Coffee??

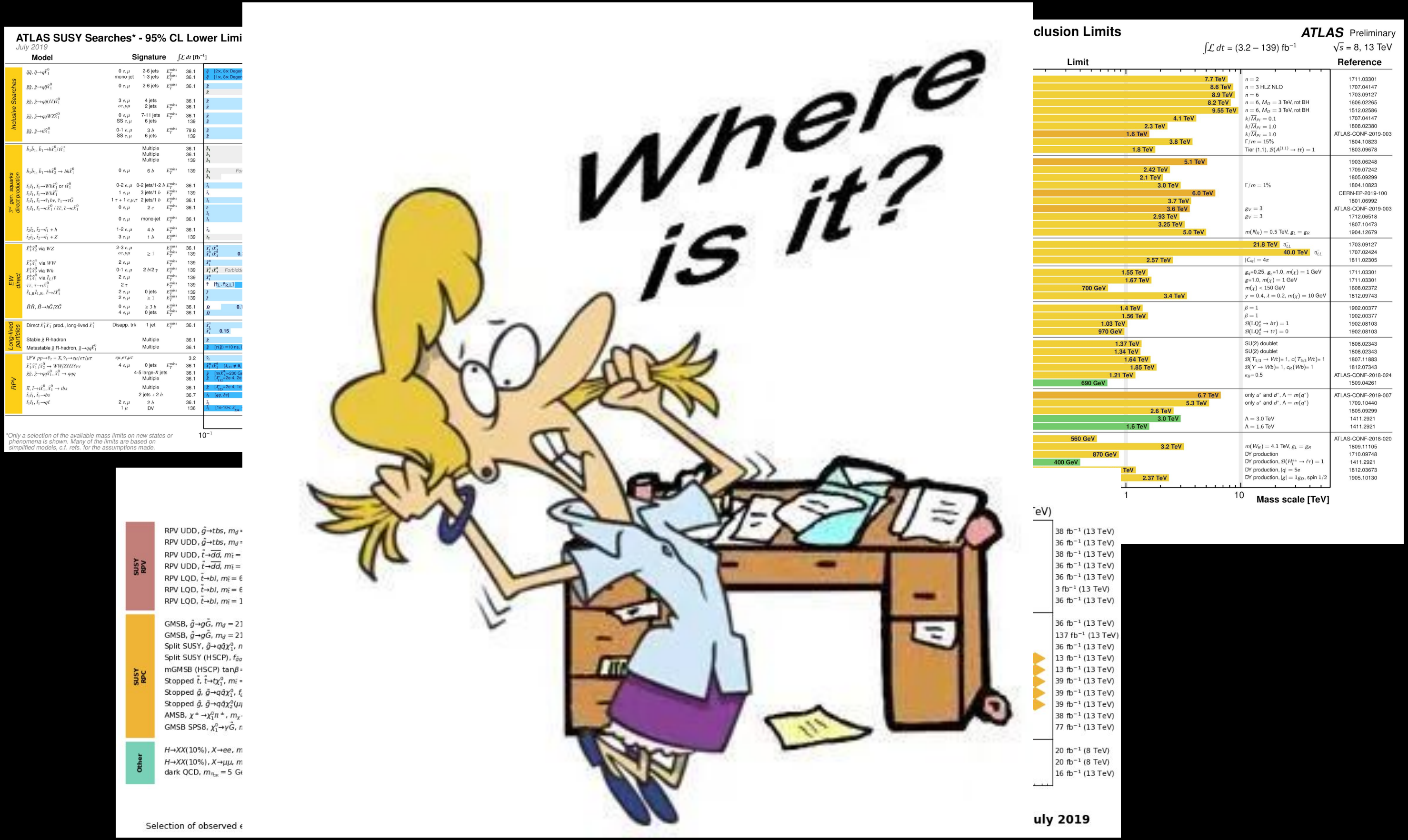
Many Experimental Results From the LHC Experiments besides Higgs !

https://twiki.cern.ch/twiki/bin/view/AtlasPublic
http://cms-results.web.cern.ch/cms-results/public-results/publications/
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

Common Benchmarks and Models are defined, including Supersymmetric Models, Dark Matter Models, Dark Portals and Neutrinos

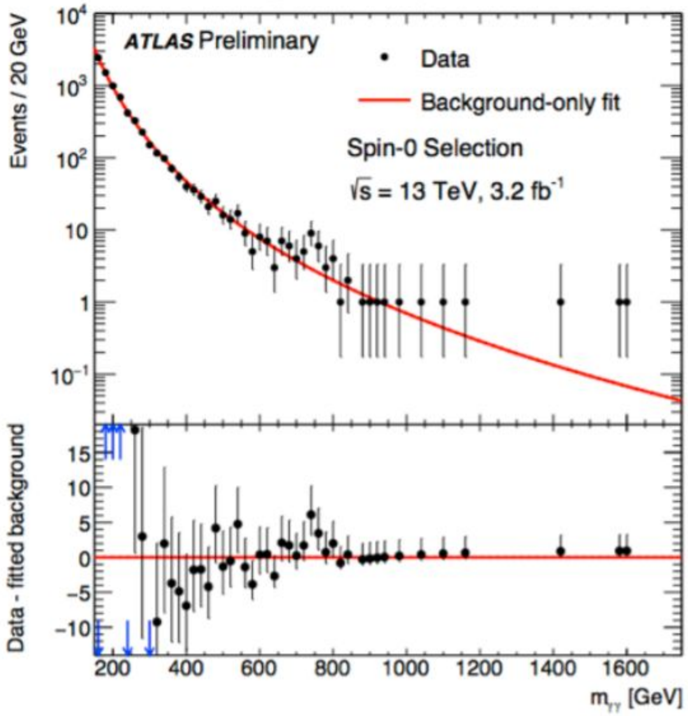


Many Searches, but where is the new physics?



No new physics yet … we got excited a few years back !

A new boson ???



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

Sort by: earliest date | desc. | times cited
Display results: 25 results | single list

HEP 116 records found 1 - 25 jump to record: 1 Search took 0.

1. **Composite Models for the 750 GeV Diphoton Excess**
(166) Keisuke Harigaya, Yasunori Nomura (LBNL, Berkeley & UC, Berkeley). Dec 15, 2015. 6 pp.
Published in **Phys.Lett. B754 (2016) 151-156**
UCB-PTH-15-15
DOI: 10.1016/j.physletb.2016.01.026
e-Print: **arXiv:1512.04850 [hep-ph] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service ; Link to Article from SCOAP3
Detailed record - Cited by 166 records

2. **Scenarii for interpretations of the LHC diphoton excess: two Higgs doublets and vector-like quarks**
(160) Andrei Angelescu, Abdelhak Djouadi, Grégory Moreau (Orsay, LPT). Dec 15, 2015. 7 pp.
Published in **Phys.Lett. B756 (2016) 126-132**
LPT-ORSAY-15-99
DOI: 10.1016/j.physletb.2016.02.064
e-Print: **arXiv:1512.04921 [hep-ph] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 160 records

3. **Singlet Scalar Resonances and the Diphoton Excess**
(159) Samuel D. McDermott, Patrick Meade, Harikrishnan Ramani (YITP, Stony Brook). Dec 16, 2015. 5 pp.
Published in **Phys.Lett. B755 (2016) 353-357**
YITP-SB-15-47
DOI: 10.1016/j.physletb.2016.02.033
e-Print: **arXiv:1512.05326 [hep-ph] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

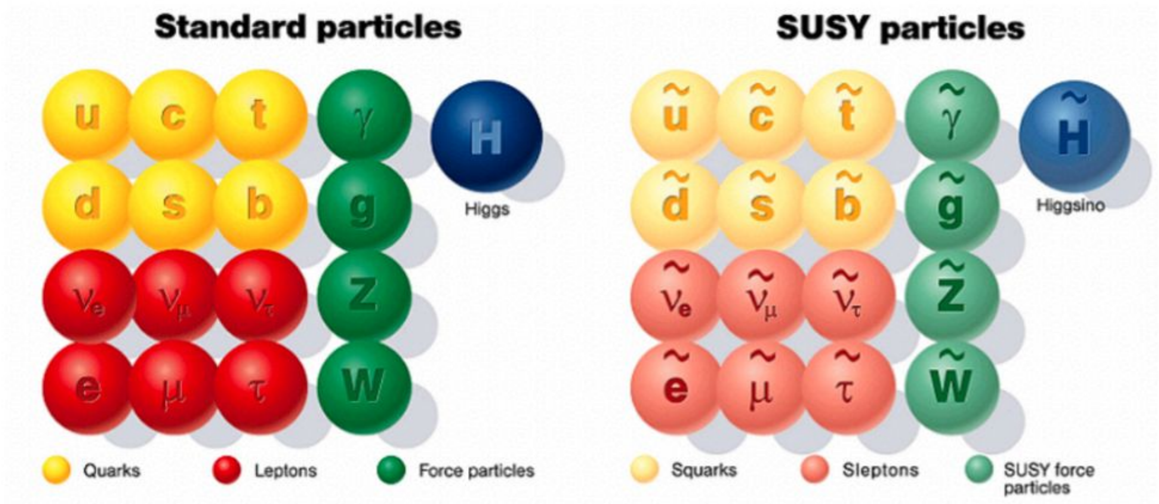
More than a 100 theoretical interpretations in the literature already !

Looking for Beyond the Standard Model Physics (BSM)

Example from SUSY Searches

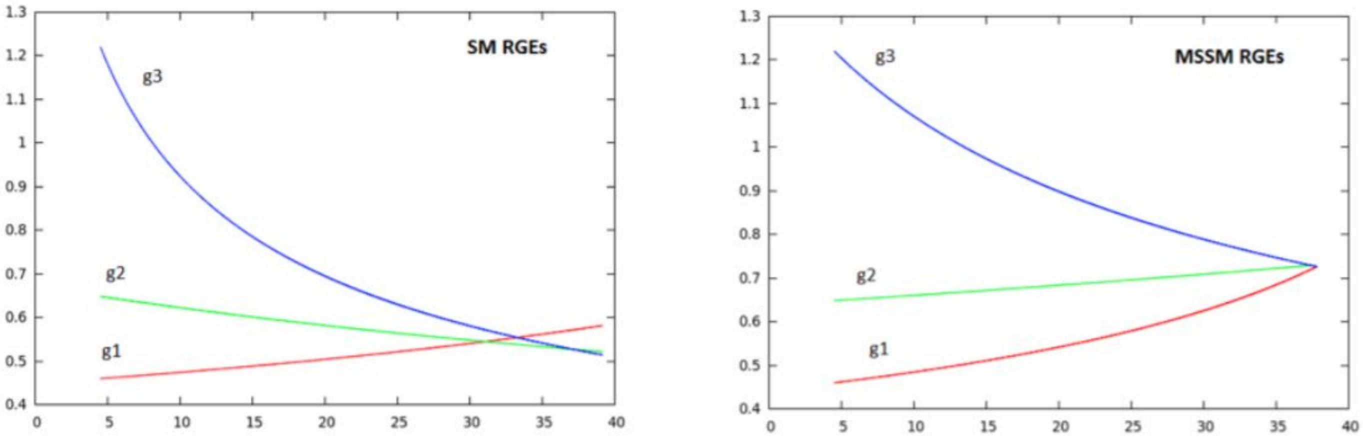
All known elementary particles are bosons or fermions
Fermions have half-integer spin
Bosons have integer spin

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle \quad ; \quad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$



Why is Supersymmetry so attractive?

* We have unification of three of the four known forces in nature
* We have a Dark Matter candidate
* We can explain neutrino masses
* Elegance, simplicity, and all other prejudices

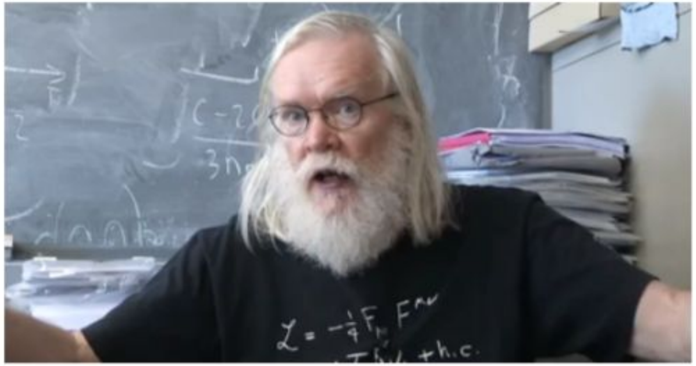


Running gauge couplings for the Standard Model and the MSSM. We see gauge unification in the MSSM at $M_{GUT} \sim 10^{16}$ GeV

If not found, it would be the first time in history that symmetry has failed as a guiding principle to construct new theories. This is one of the reasons it has been looked for so hard and for so many years !

Some physicist really believe in SUSY!

But there is no experimental evidence so far

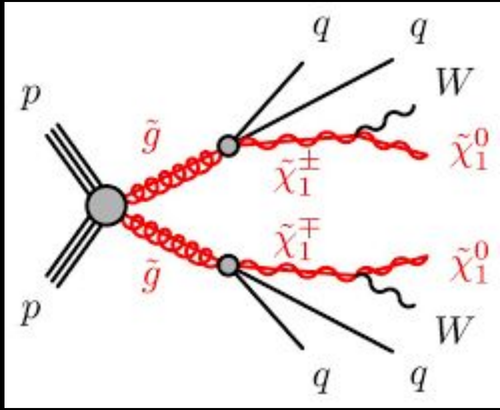


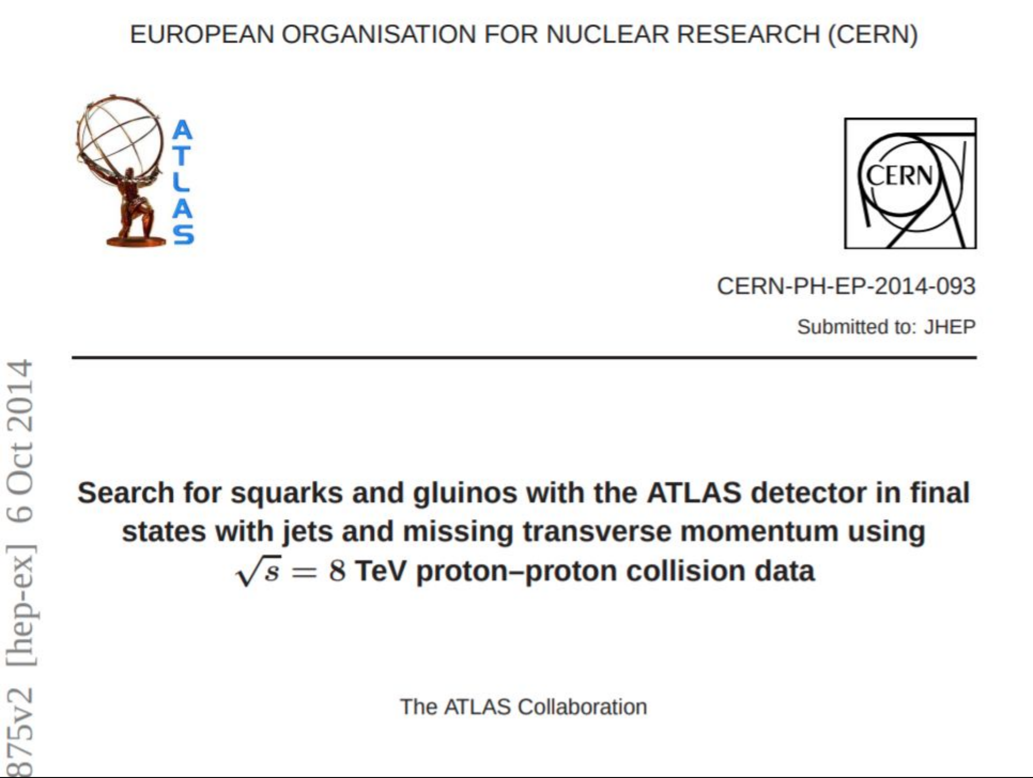
Source : https://www.youtube.com/watch?v=bq1z6zFmcgM

Source : Source : ... 21992757248

A SUSY experimental analysis

Example paper https://arxiv.org/abs/1405.7875 the "0-lepton + 2-6 jets +MET" search





EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS

CERN

CERN-PH-EP-2014-093

Submitted to: JHEP

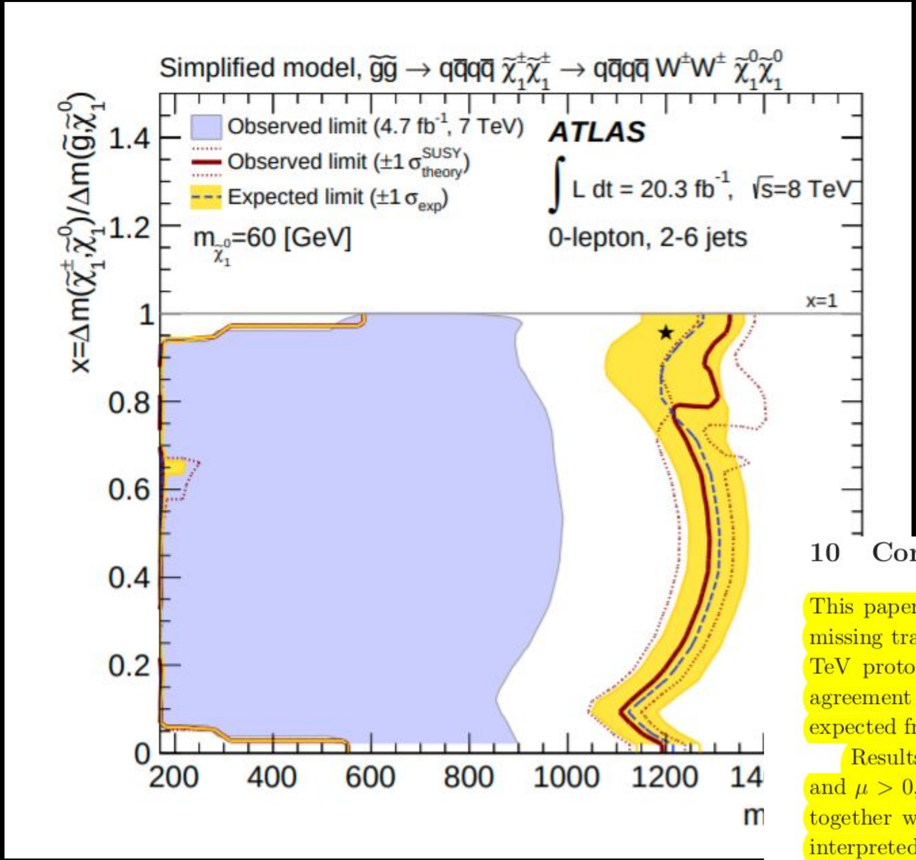
875v2 [hep-ex] 6 Oct 2014

Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s} = 8$ TeV proton–proton collision data

The ATLAS Collaboration

Analysis cuts, most are designed to suppress the SM backgrounds !

$\sqrt{s}$	8 TeV		13 TeV	
Signal Region	4jt-8	6jt-8	4jt-13	6jt-13
$p_T^{\mathrm{miss}}/\mathrm{GeV} >$	160	160	200	200
$p_T(j_1)/\mathrm{GeV} >$	130	130	200	200
$p_T(j_2)/\mathrm{GeV} >$	60	60	100	100
$p_T(j_3)/\mathrm{GeV} >$	60	60	100	100
$p_T(j_4)/\mathrm{GeV} >$	60	60	100	100
$p_T(j_5)/\mathrm{GeV} >$	-	60	-	50
$p_T(j_6)/\mathrm{GeV} >$	-	60	-	50
$\Delta\phi(\mathrm{jet}_{1,2,3}, \mathbf{p}_T^{\mathrm{miss}})_{min} >$	0.4			
$\Delta\phi(\mathrm{jet}_{j>3}, \mathbf{p}_T^{\mathrm{miss}})_{min} >$	0.2			
$p_T^{\mathrm{miss}}/m_{\mathrm{eff}}(N_j) >$	0.25		0.2	
$m_{\mathrm{eff}}(\mathrm{incl.})/\mathrm{GeV} >$	2200	1500	2200	2000
$\sigma_{95}^{\mathrm{obs}}$ (fb)	0.15	0.32	2.7	1.6

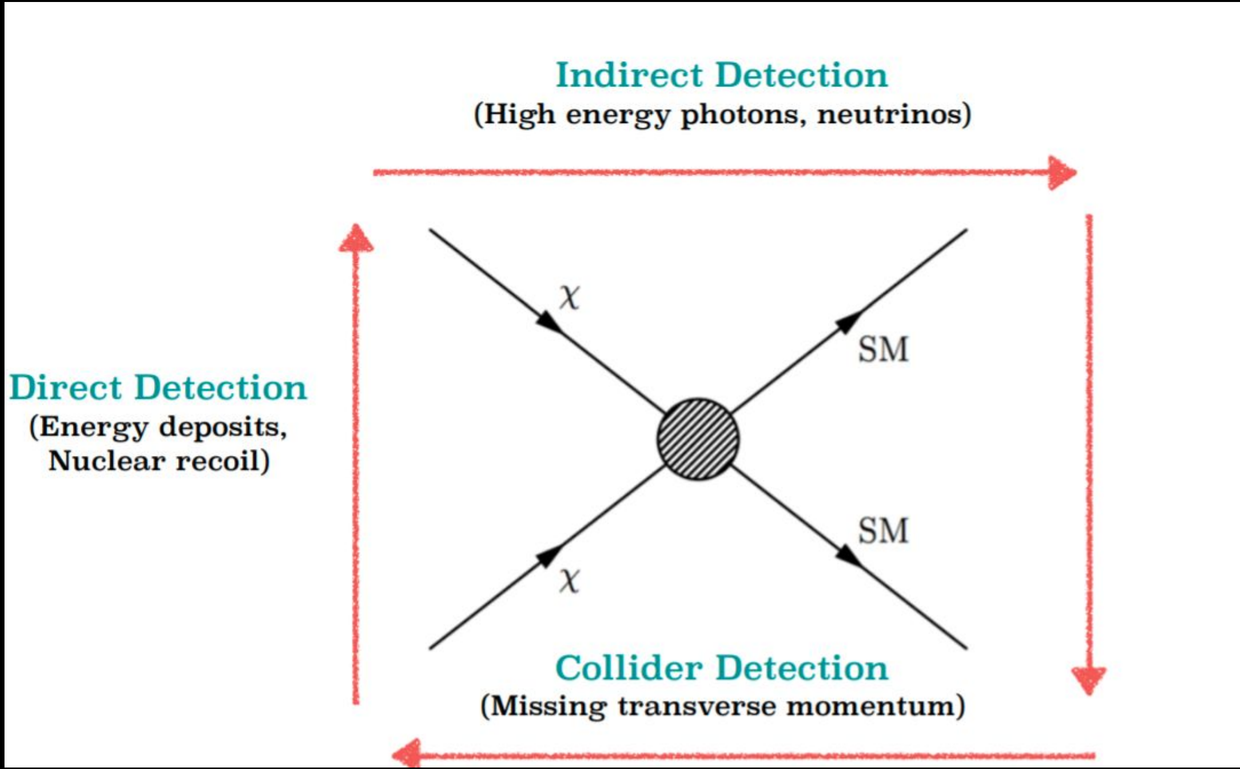


10 Conclusions

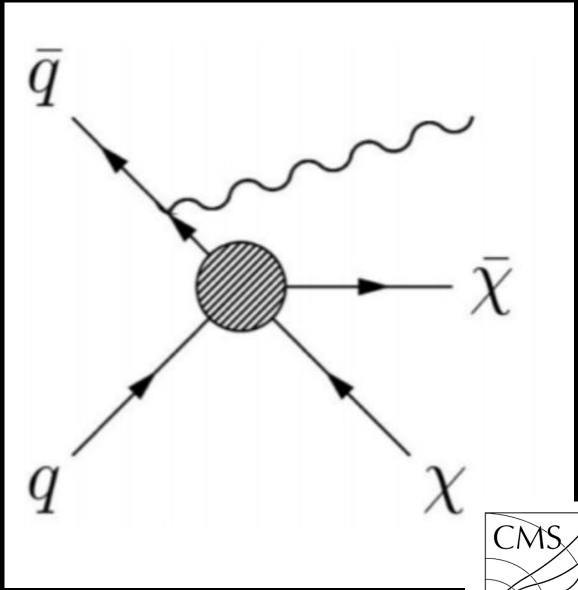
This paper reports a search for squarks and gluinos in final states containing high-p_T jets, large missing transverse momentum and no electrons or muons, based on a 20.3 fb^{-1} dataset of $\sqrt{s} = 8$ TeV proton–proton collisions recorded by the ATLAS experiment at the LHC in 2012. Good agreement is seen between the numbers of events observed in the data and the numbers of events expected from SM processes.

Results are interpreted in terms of mSUGRA/CMSSM models with $\tan\beta = 30$, $A_0 = -2m_0$ and $\mu > 0$, and in terms of simplified models with only light-flavour squarks, or gluinos, or both, together with a neutralino LSP, with the other SUSY particles decoupled. The results are also interpreted in terms of several other SUSY models. In the mSUGRA/CMSSM models, the 95% confidence level exclusion limit on $m_{1/2}$ is greater than 380 GeV for $m_0 < 6$ TeV and reaches 770 GeV for low m_0. Equal mass squarks and gluinos are excluded below 1700 GeV in this scenario. A lower limit of 1650 GeV for equal mass light-flavour squarks and gluinos is found for simplified MSSM models with a massless lightest neutralino. For a massless lightest neutralino, gluino masses below 1330 GeV are excluded at the 95% confidence level in a simplified model with only gluinos

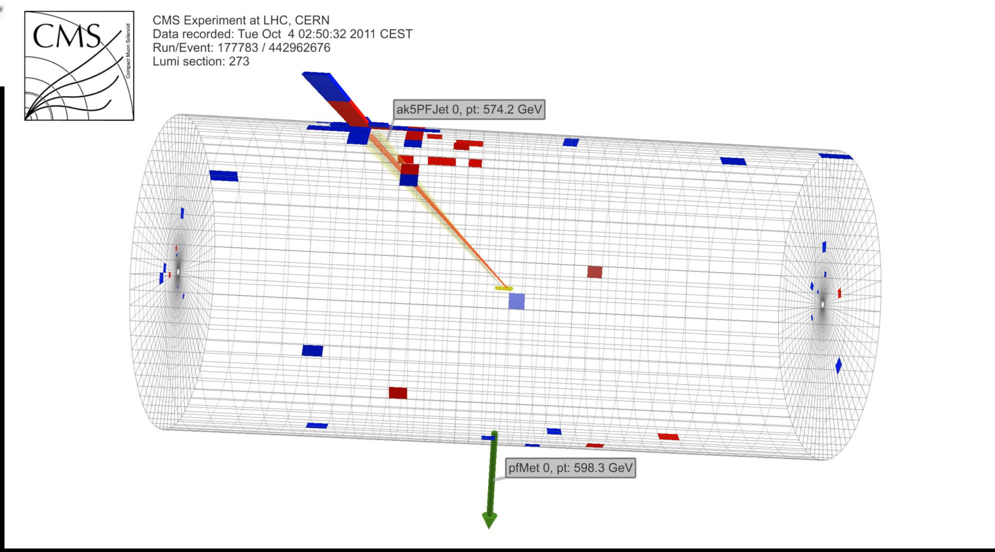
Example from Dark Matter Searches



“Monojet” type of searches @ Colliders



We trigger on events with “initial state radiation” and basically look for pp->”nothing”!



Some common challenges experimentalist deal with

Que tan bien se entiende el detector y el software que afecta las mediciones?

Que tan bien se entiende el background del Standard Model?

Si se observa un exceso, confiamos en las systematic uncertainties y en la significancia?

Si como teoricos/fenomenologos nos interesa probar un determinado modelo, como utilizamos los resultados del experimento? Como extrapolamos esos resultados a otros modelos?