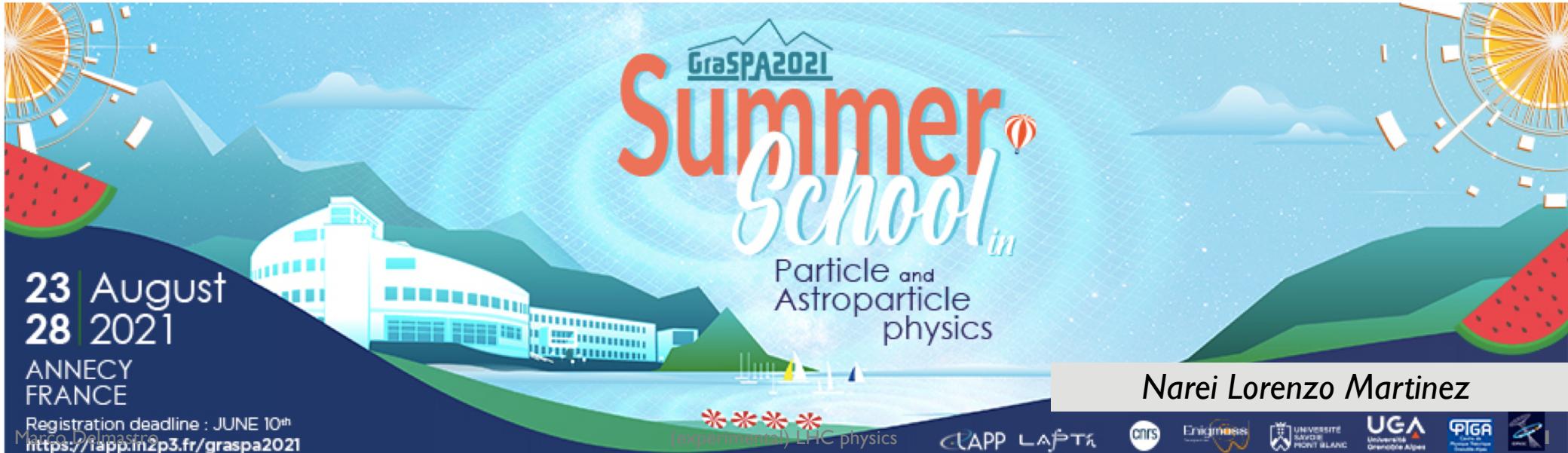


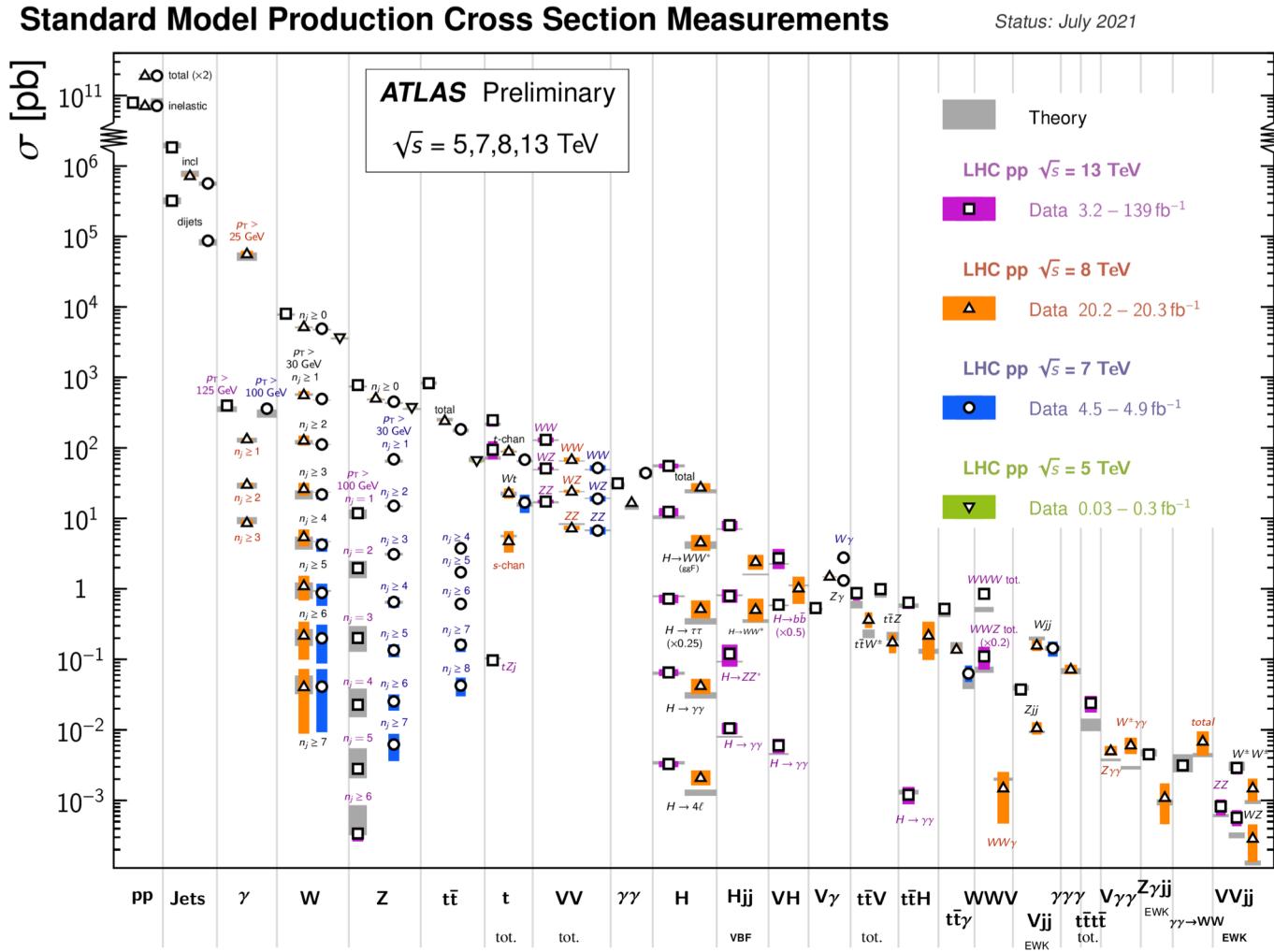
Experimental LHC physics – II

How to search for new phenomena



The Standard Model: the ultimate theory ?

- After a decade of measurements at LHC, the SM is becoming more and more consolidated (a few hint for new phenomena in heavy flavor physics though, see Diego's lectures)
- Process cross-section measured over 14 orders of magnitude, without any significant deviation from prediction !



However, many unanswered questions...

Why there are 3 families of particles? Are there more? Why is the top quark so heavy?

Why there's more matter than anti-matter?

How do neutrinos get mass?

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1947: Manchester University s strange quark	1977: Fermilab b bottom quark	1923: Washington University γ photon
1956: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
1897: Cavendish Laboratory e electron	1937: Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson
			2012: CERN H Higgs boson

How do we incorporate gravity?

What is Dark Matter?

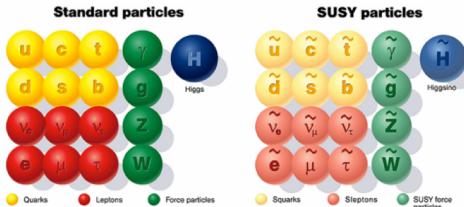
What is Dark Energy?

Are there more forces?

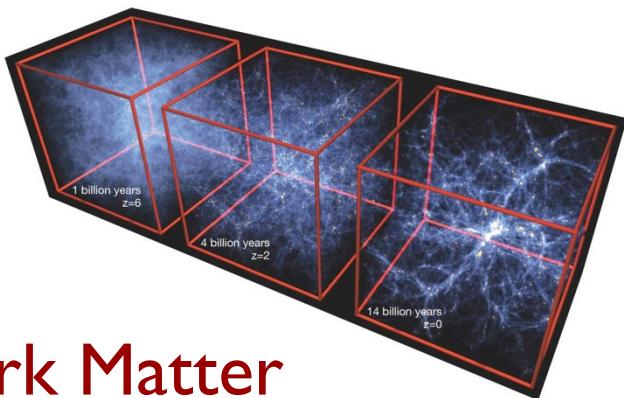
What keeps the Higgs mass so small?

... as many possible answers to probe!

Super-symmetry?

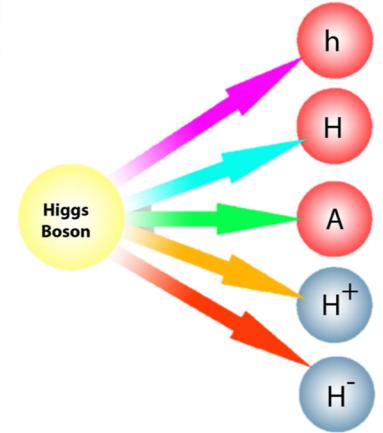


New heavy
bosons?



Dark Matter
particles?

Extended
Higgs sector?

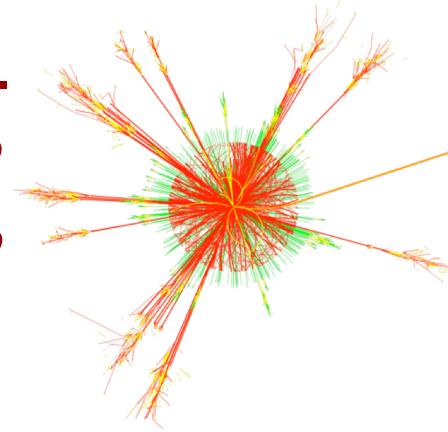


Composite
quark and
leptons?

u	c	t	g
up quark	charm quark	top quark	gluon
d	s	b	γ
down quark	strange quark	bottom quark	photon
ν_e	ν_μ	ν_τ	W
electron neutrino	muon neutrino	tau neutrino	W boson
e	μ	τ	Z
electron	muon	tau	Z boson

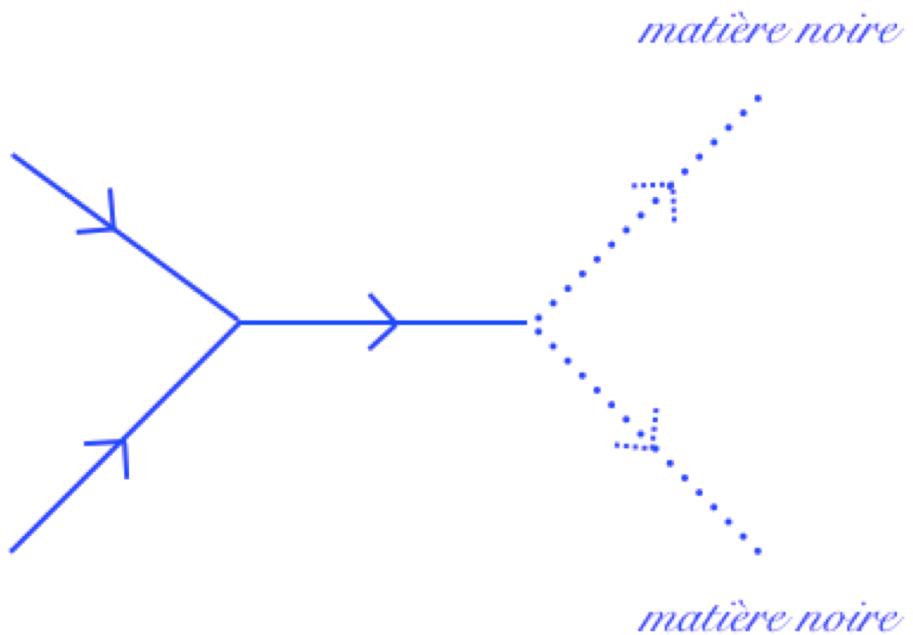
Any new theory
need to agree
with the SM!

Large extra-
dimensions?
Black holes?
Gravitons?



Direct vs indirect searches

Direct search to (e.g) dark matter



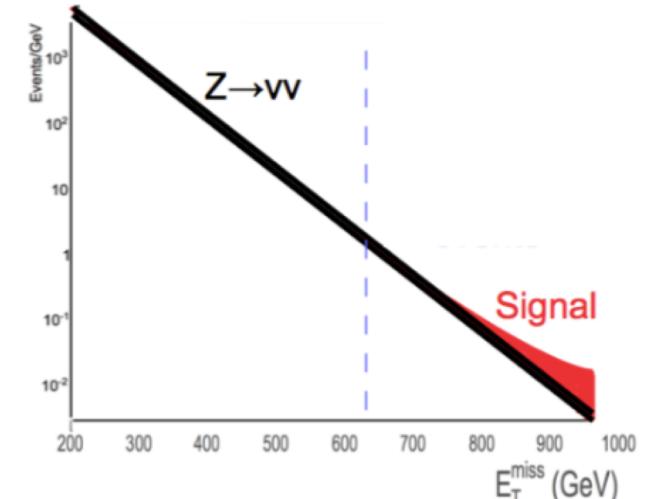
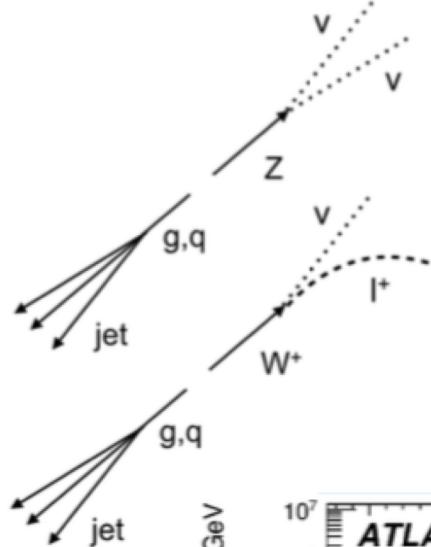
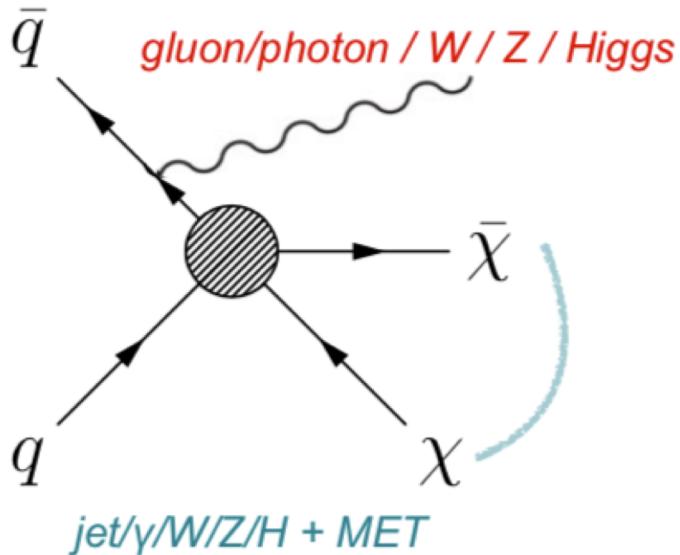
Indirect search to (e.g) dark matter



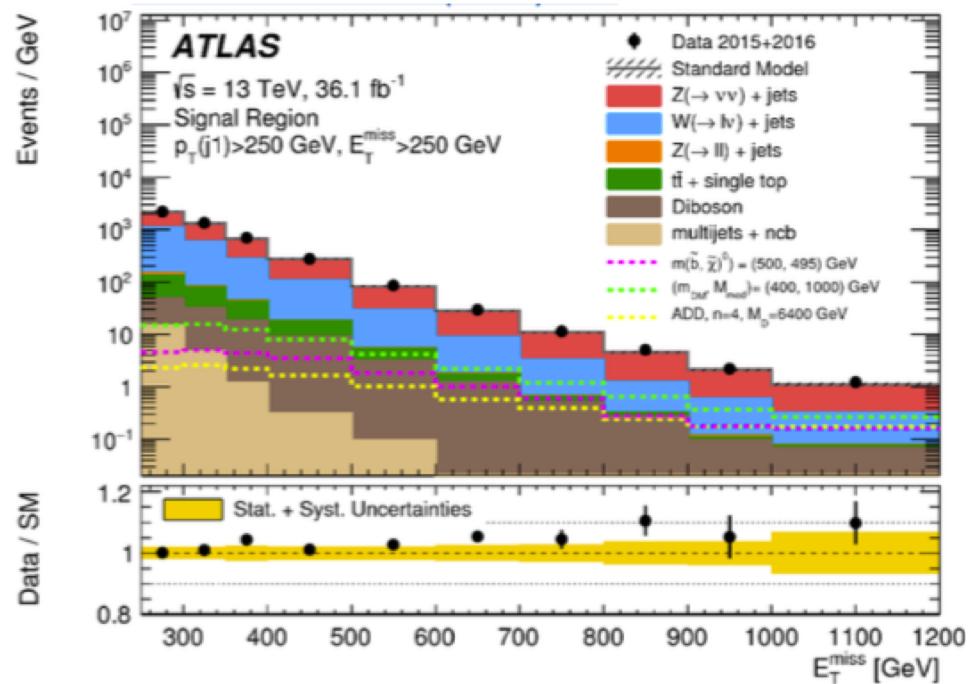
Missing energy in detector

High-energy behaviour of final state
particles modified

Example: Dark Matter searches at LHC



- Use missing energy shape to extract signal contribution
 - ✓ Similar shape for signal and background
 - ✓ Background modeling very important
- Main backgrounds
 - ✓ $Z(vv) + \text{jet}$
 - ✓ $W(lv) + \text{jet}$, where charged lepton is not reconstructed



Failure of direct searches for now...

Many reasons:

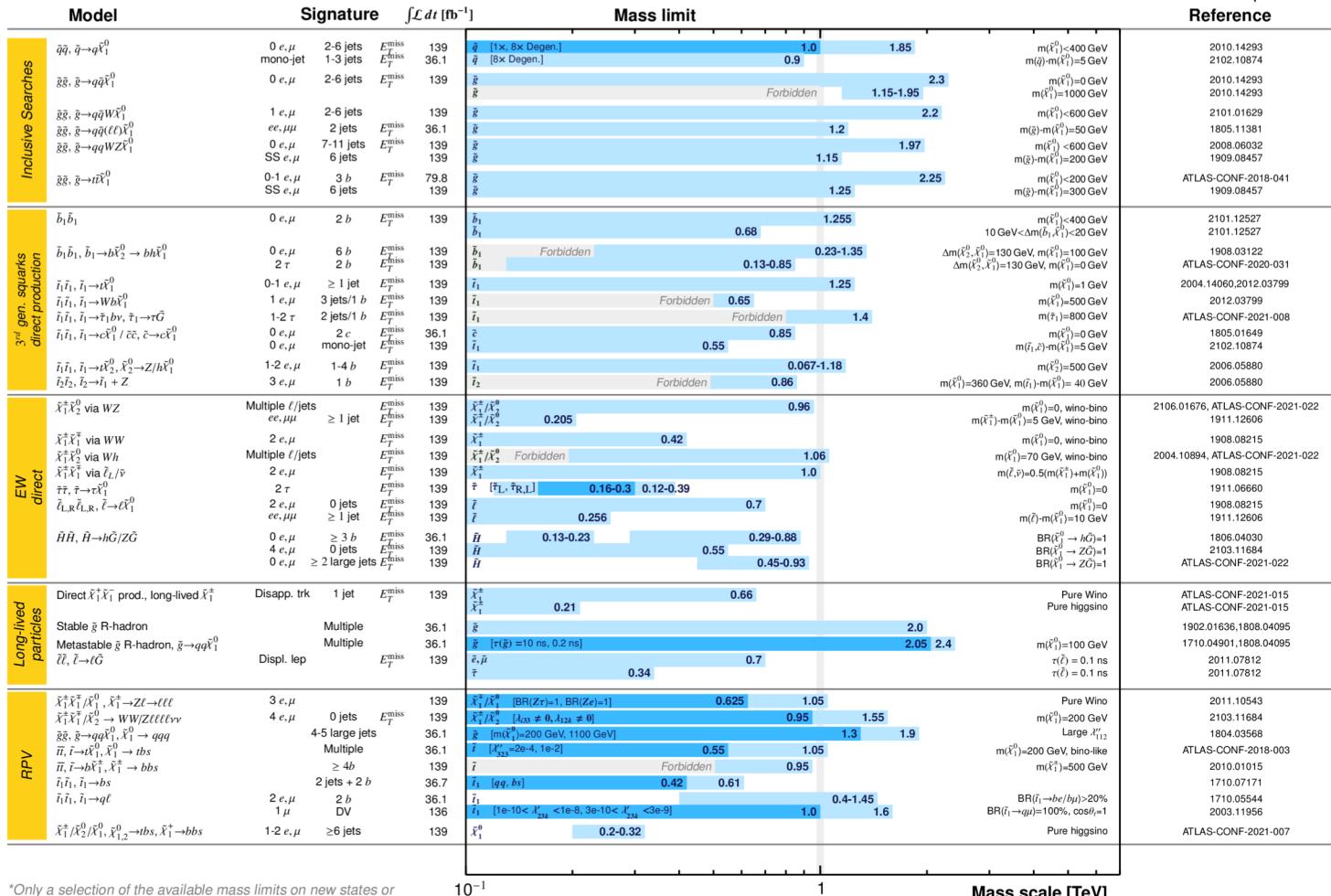
- Too large target masses ?
- Too small signal efficiency in LHC environment ?
- Signal outside acceptance ?

ATLAS SUSY Searches* - 95% CL Lower Limits

June 2021

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Failure of direct searches for now...

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

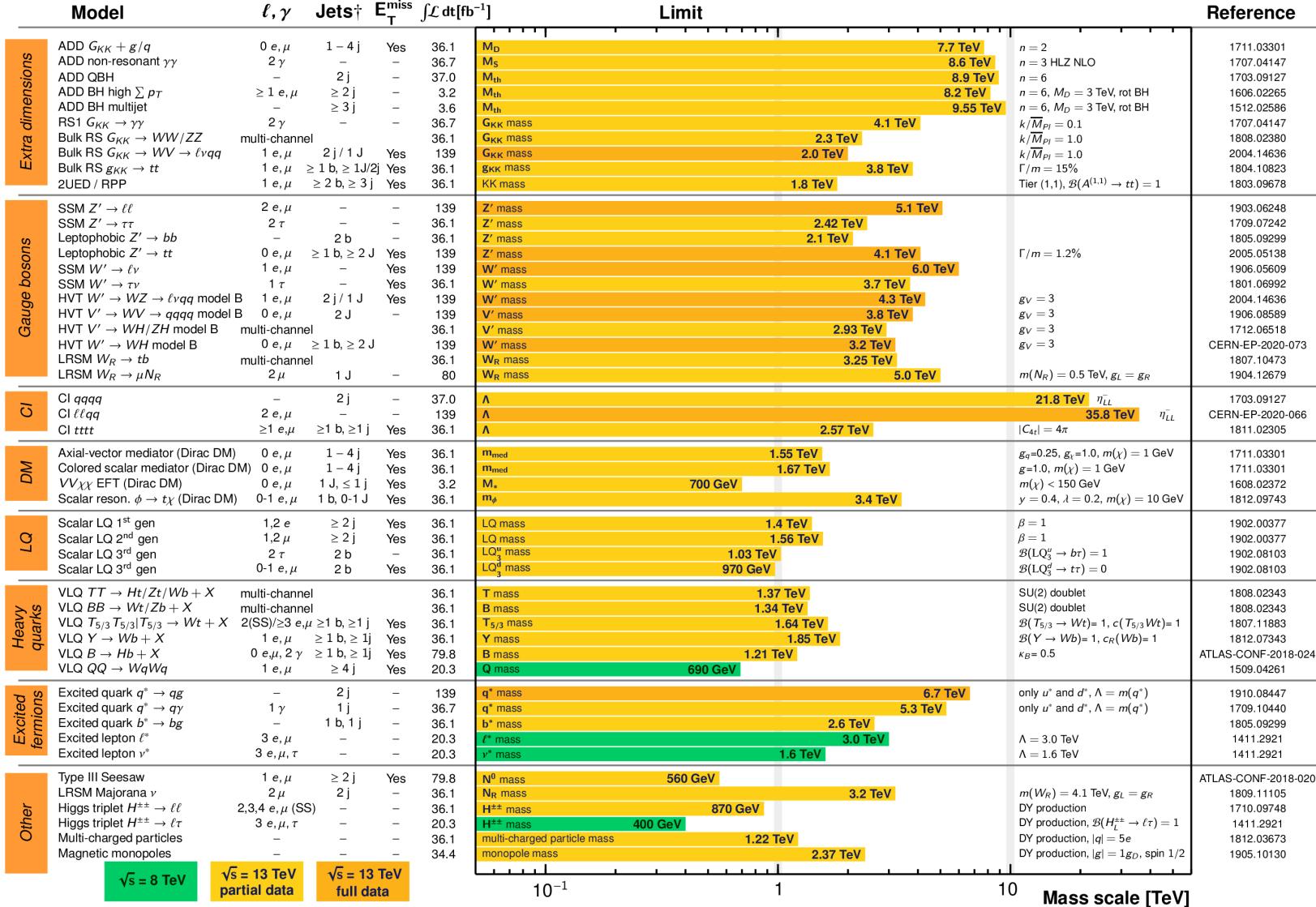
Status: May 2020

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Reference



*Only a selection of the available mass limits on new states or phenomena is shown.

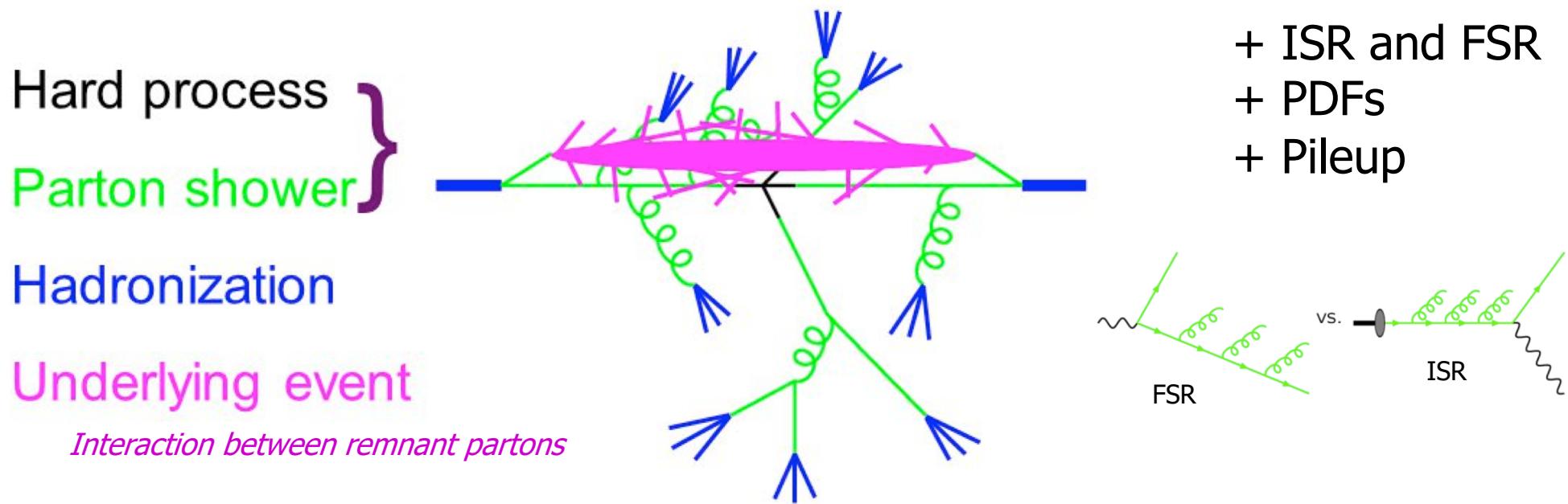
†Small-radius (large-radius) jets are denoted by the letter j (J).

Indirect searches: precision area

- Indirect searches possible only if good precision reached in measurements
- Precision limited by
 - ✓ Precision of the prediction (MC generation)
 - ✓ Large background contamination
 - ✓ Limited reconstruction resolution in detectors
 - ✓ Limited amount of event collected (rare processes)
 - ✓ LHC collected luminosity precision
- Main focus of current LHC measurements: precision !
- In the following: main data analysis steps

Step 0: Simulations

- Monte Carlo tools used to predict final state of collisions
- Structure of simulation



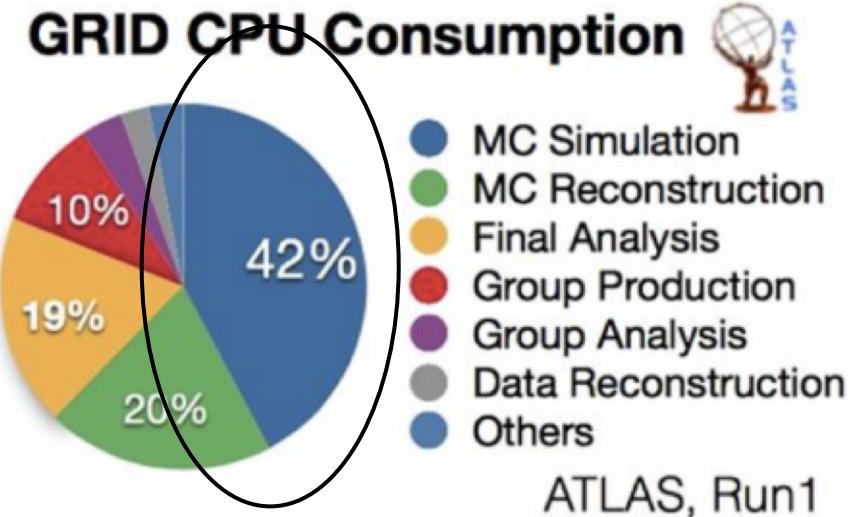
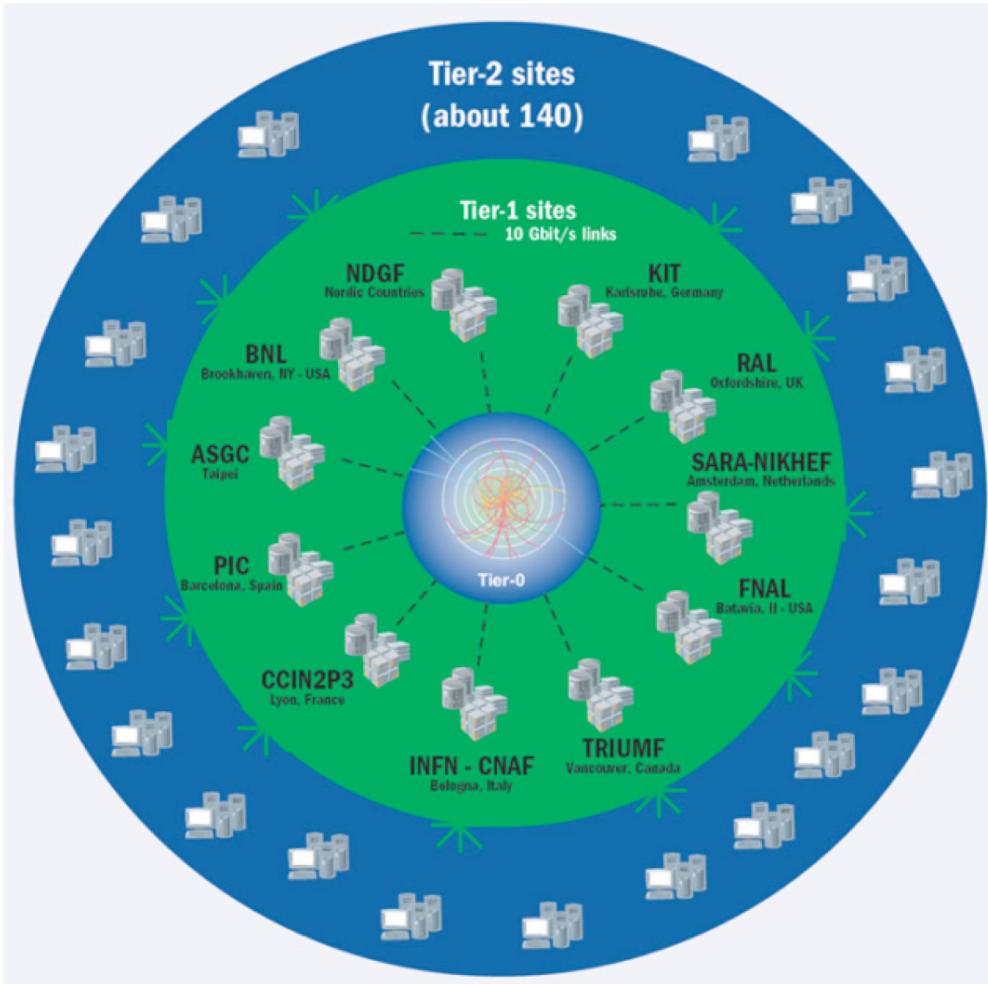
- Many assumptions need to be done, in many parts of the simulation process !!!
 - ✓ Not a unique Monte Carlo simulation, but several of them are used
 - ✓ **Their comparison allows to derive the “modelling systematic uncertainties”**

Worldwide LHC Computing Grid

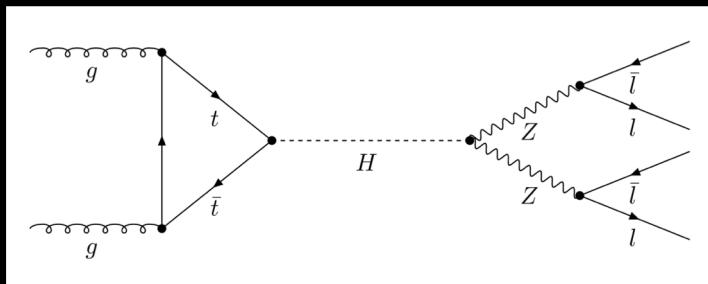
Data replicated over several sites

~20 millions of files transferred each day at 10 Go/s

About 2 millions job per day (data analysis, MC production, ...)

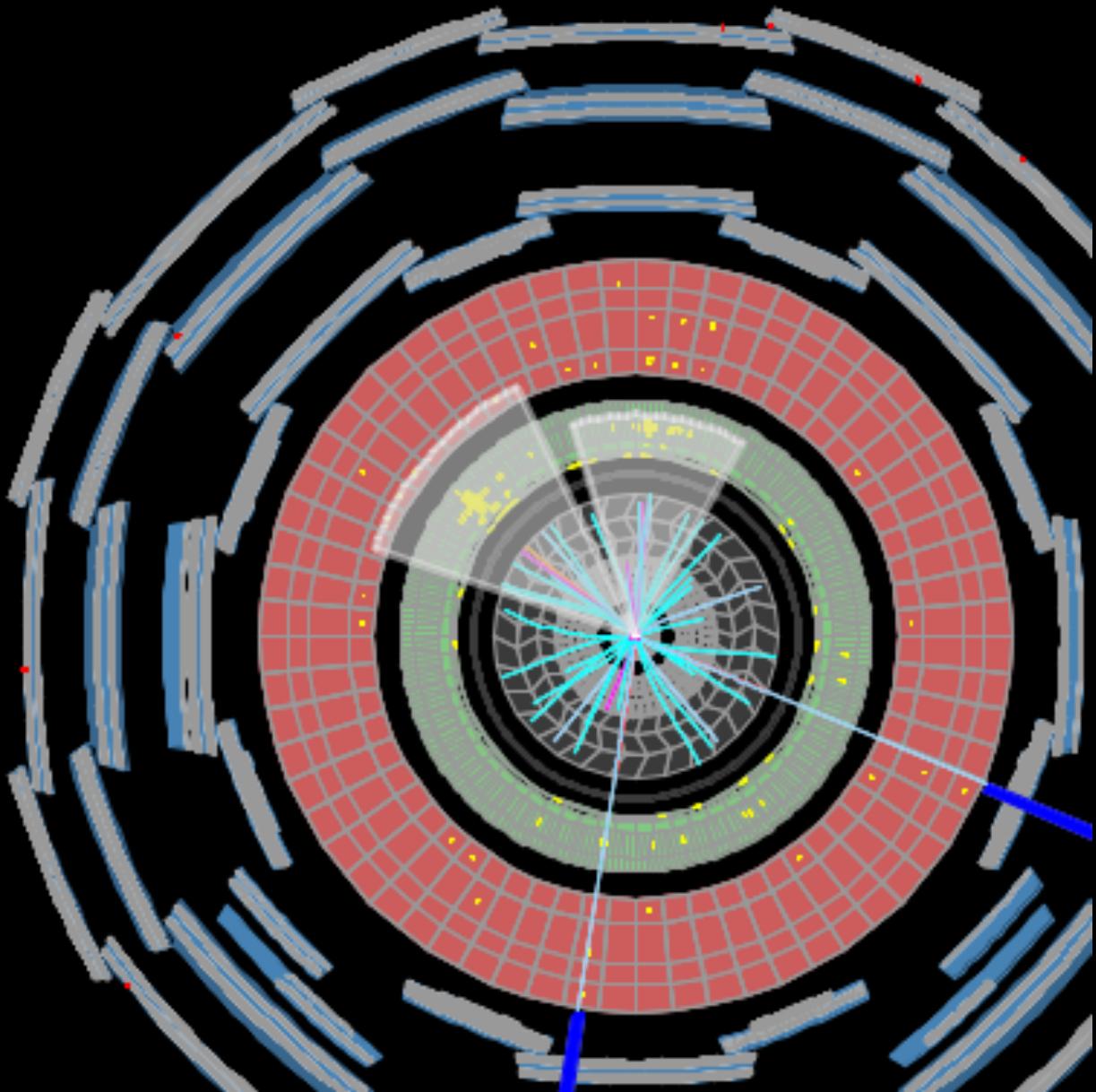


Step I: find events with the right ingredients



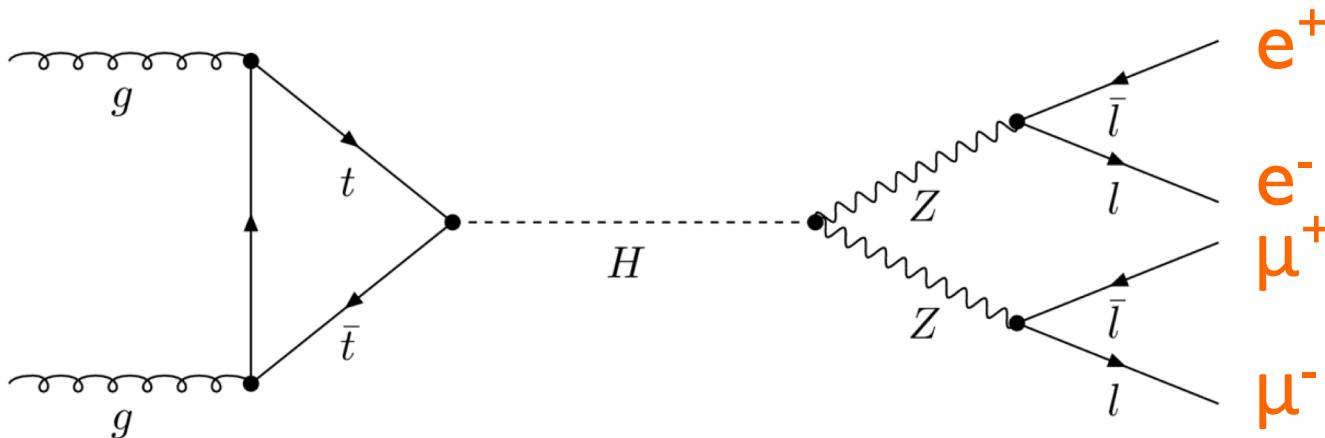
We are looking for $e^+e^- \mu^+\mu^- \dots$

Is this event ok?



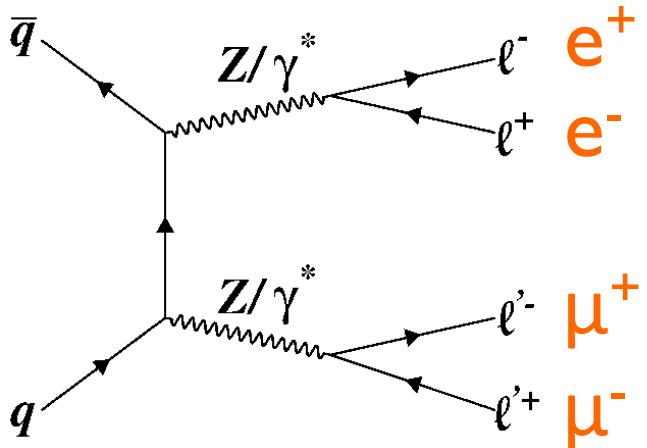
(experimental) LHC physics

Signal and background



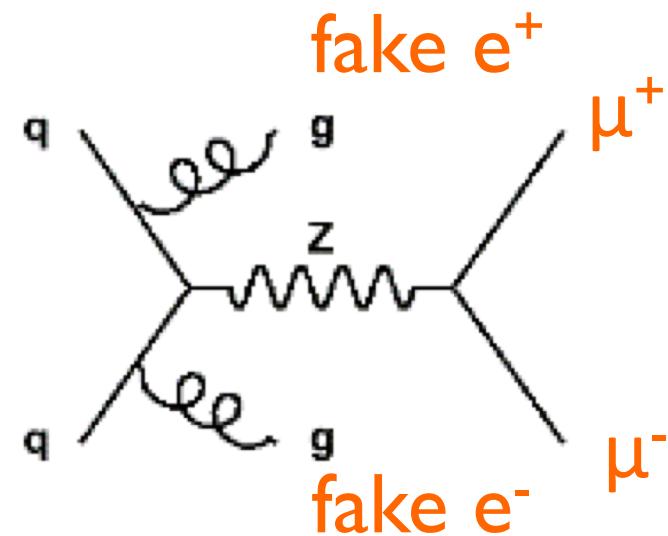
Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



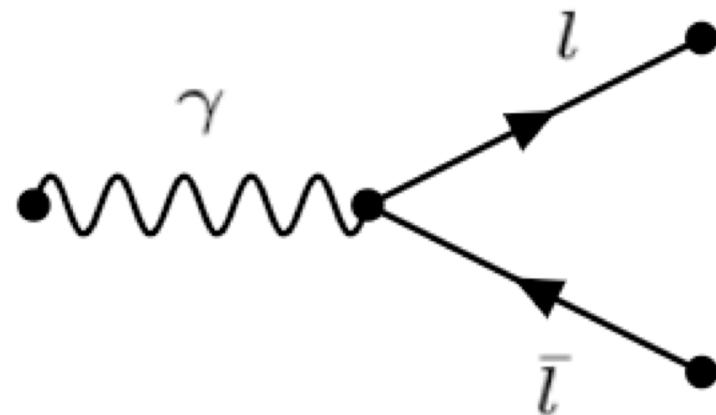
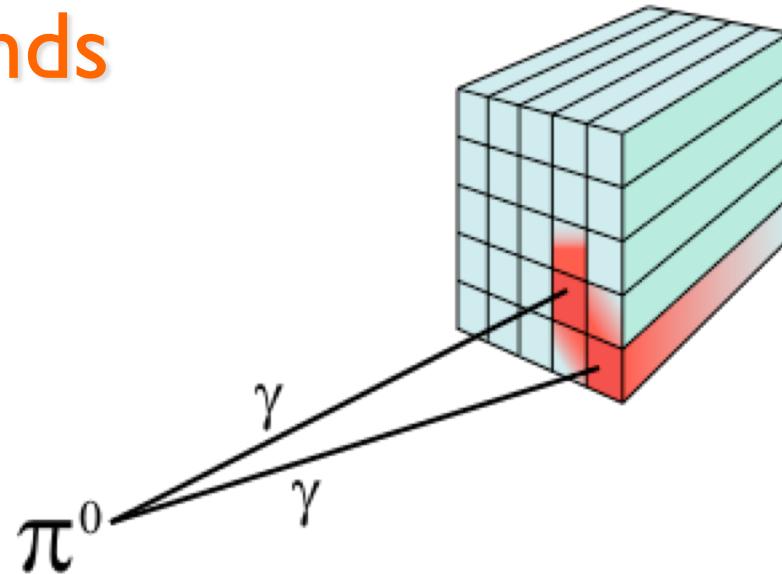
Reducible background

The final state looks like the same, but some of the particle fakes what you are looking for



Fake/Reducible backgrounds

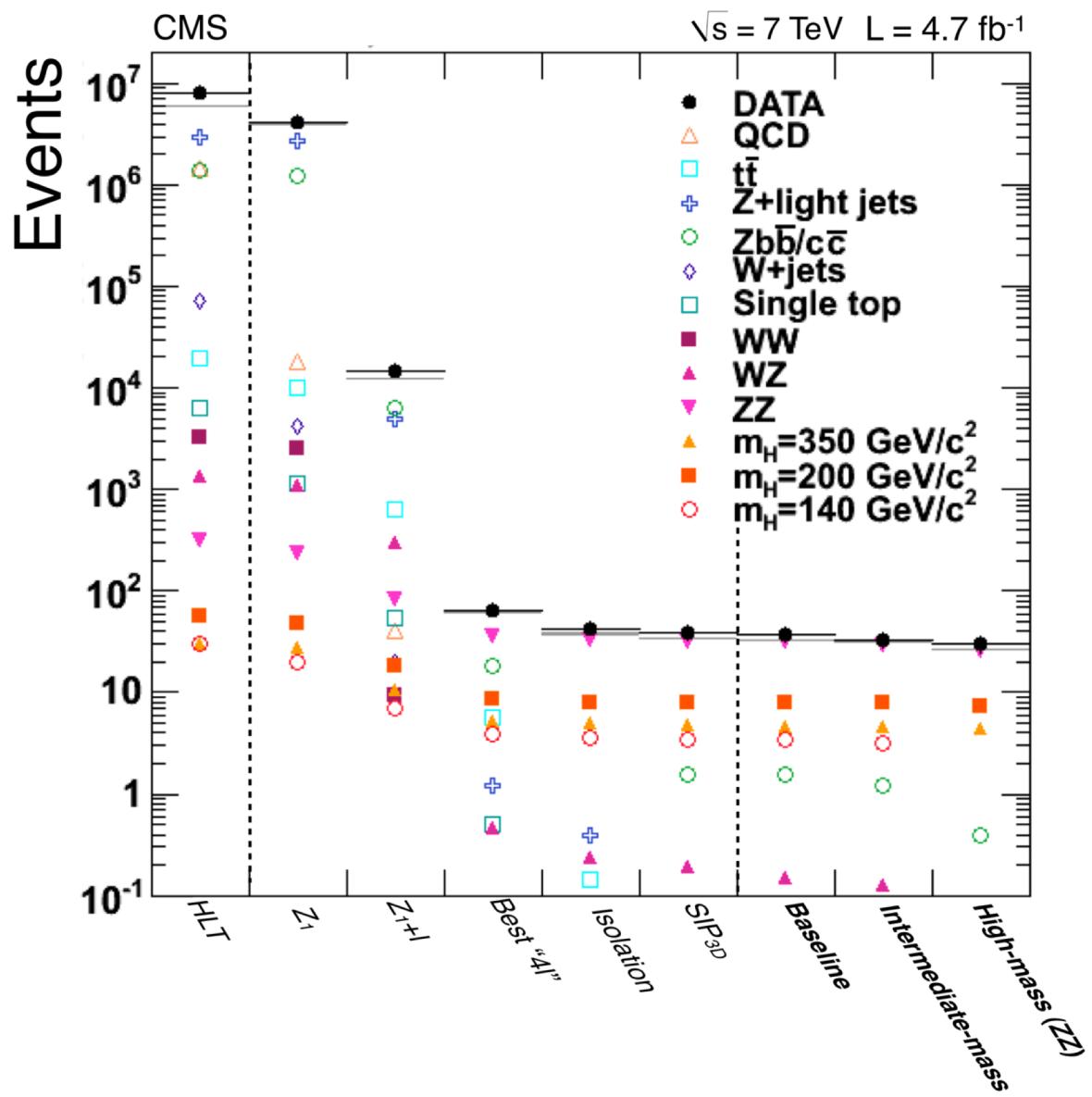
- Examples:
 - ✓ pion seen as a photon (due to its decay to two collimated photons)
 - ✓ Photon seen as an electron (due to missing one of the arms of the photon conversion to e+e- pair)
- **Fake backgrounds are mostly due to limited detector precision !**



Loose some signal, suppress backgrounds...

- Selections based on **particle** properties to reduce reducible background
 - ✓ Shower shapes, track properties, ...
- Selections based on **event** properties to distinguish signal from background
 - ✓ Particle kinematics, decay kinematics, event shape, ...
- Try to keep signal while reducing background!
 - ✓ Increase S/B...

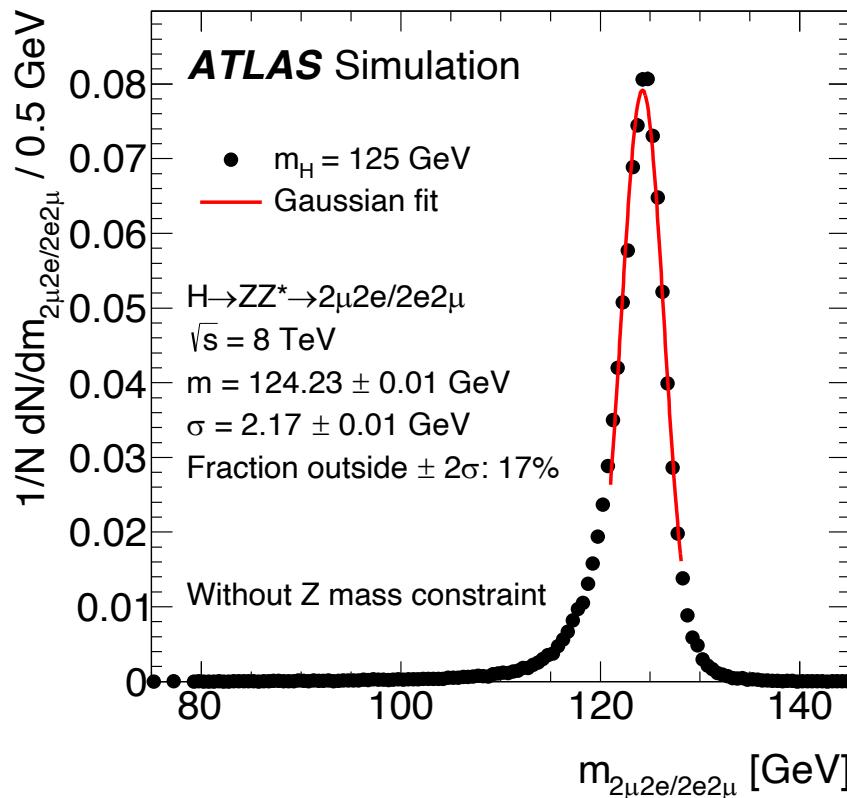
S/Bⁱⁿ = 0.00001
S/B^{fin} ~ 1 !!



Step 2: reconstruct properties of initial particle

- We have 4 particles...
 - ✓ ... with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles

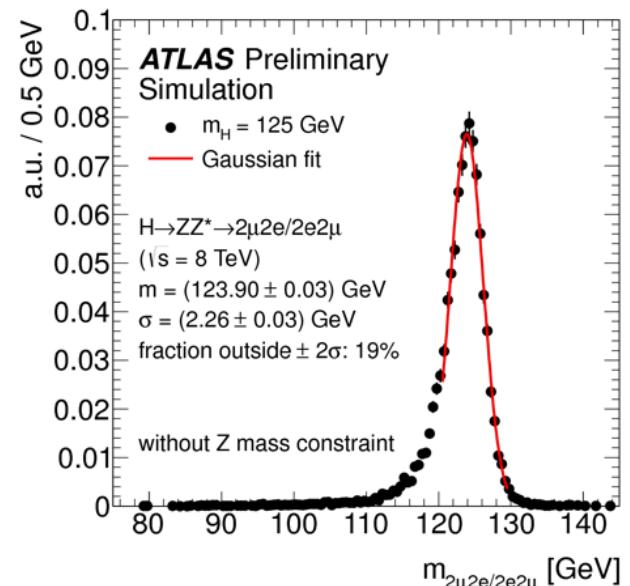
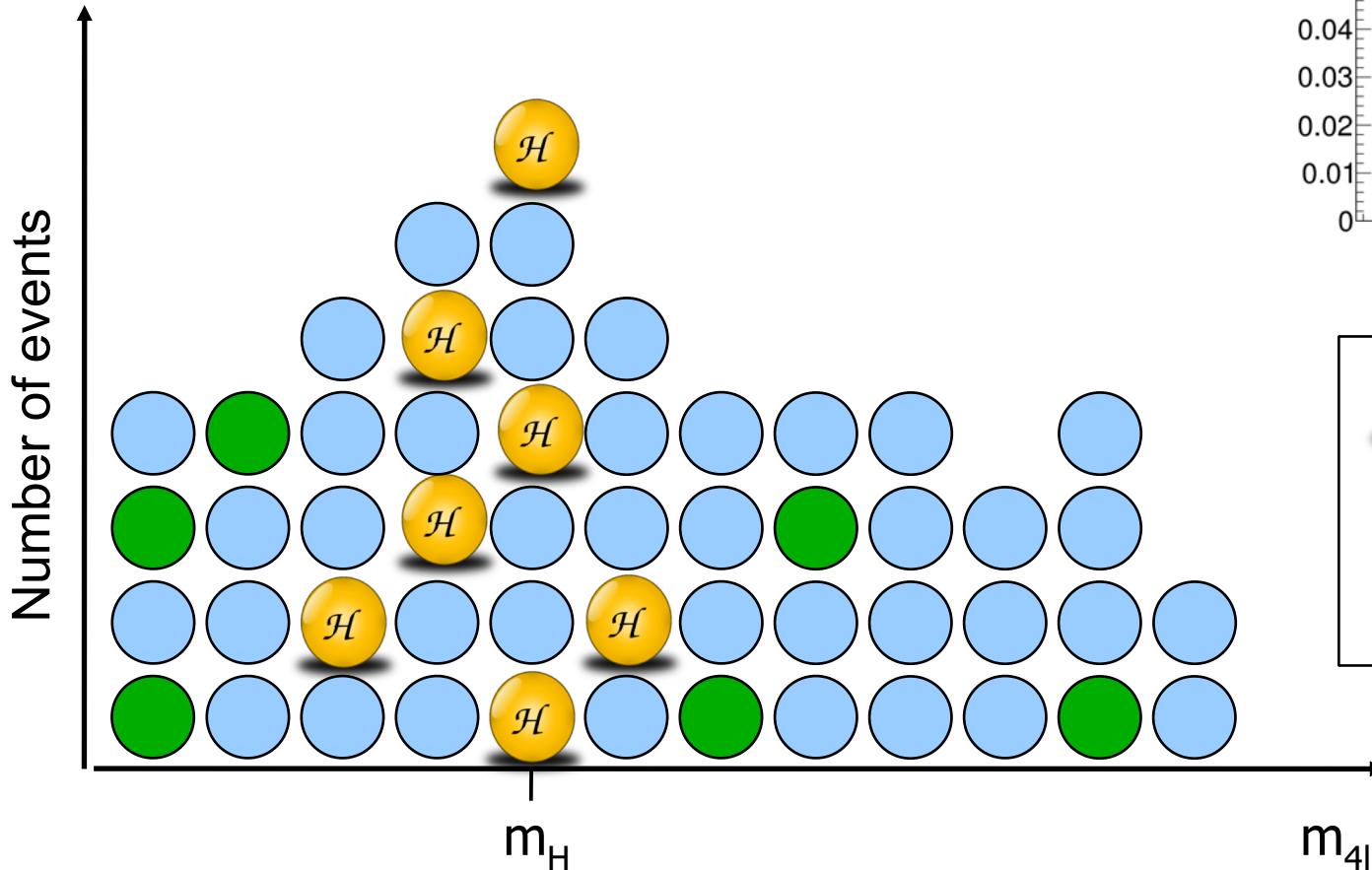
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



This is the reconstructed simulated signal

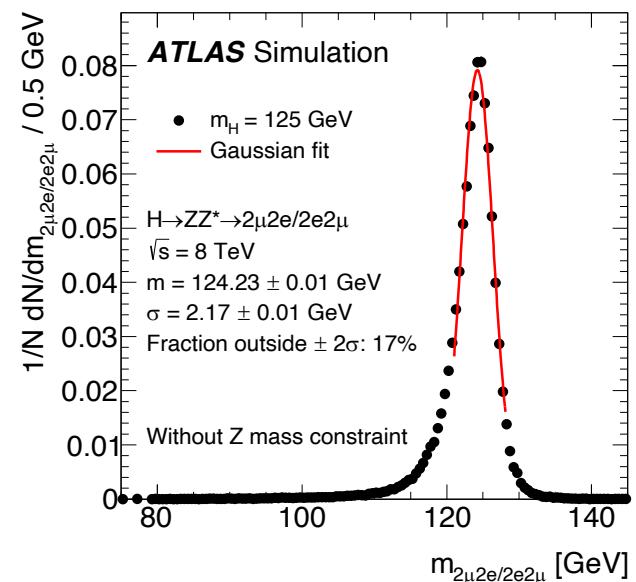
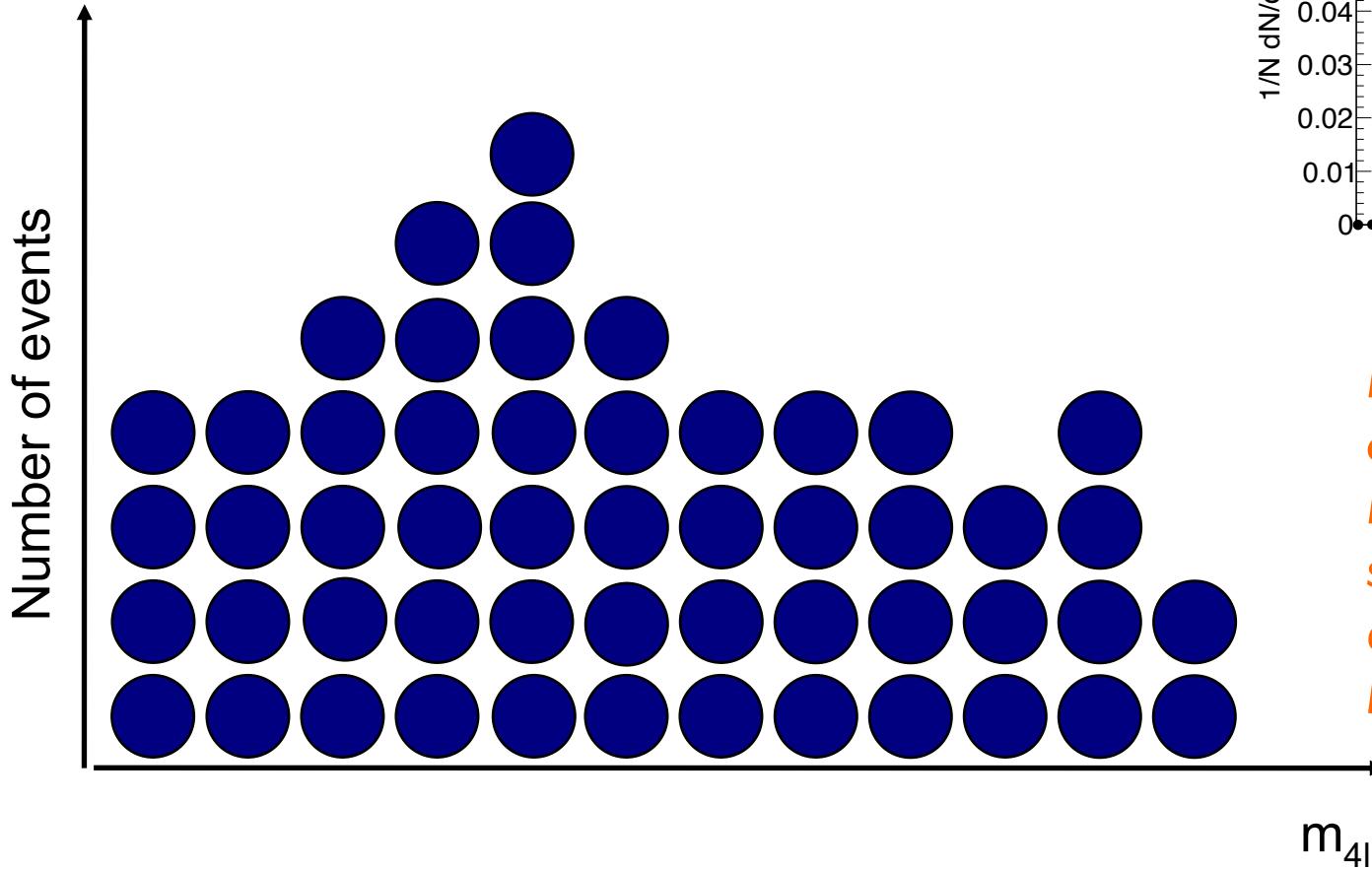
Step 3: Extract signal from background

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



Step 3: Extract signal from background

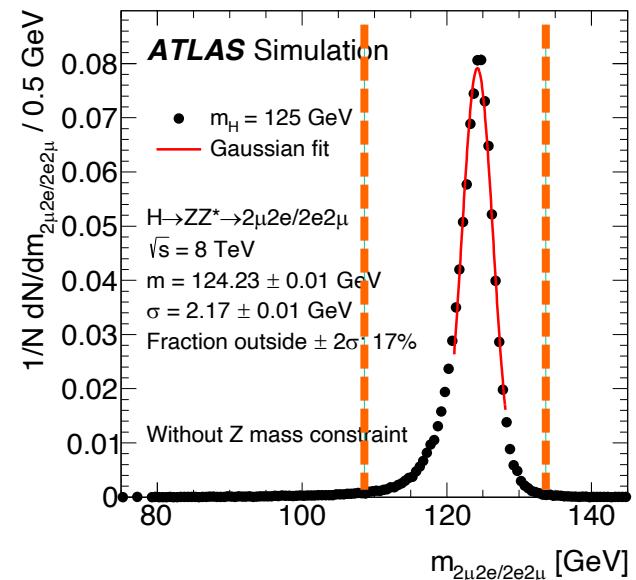
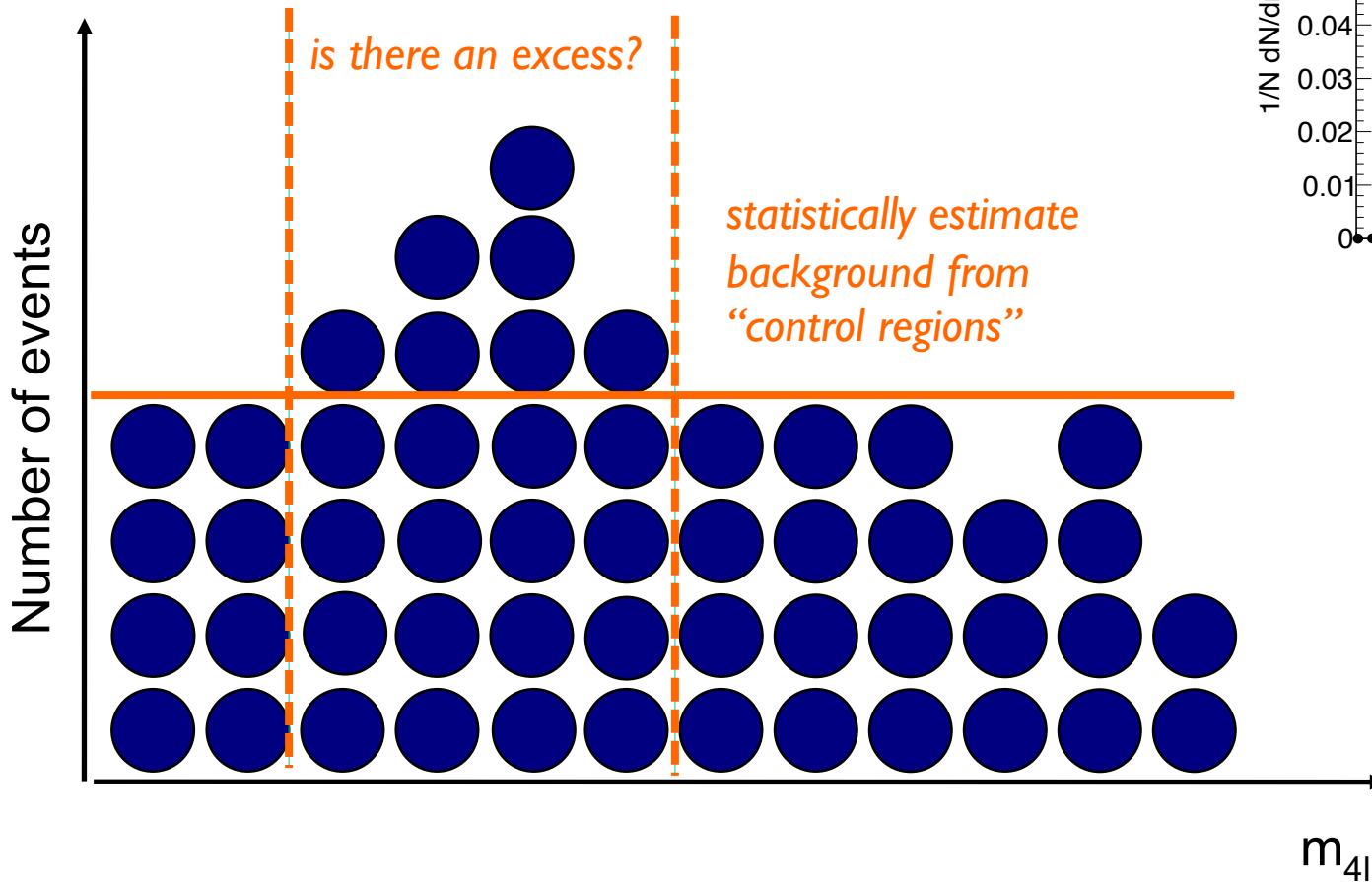
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



*Events in real life do not come with a label!
No way to distinguish signal from background on an event-by-event basis...*

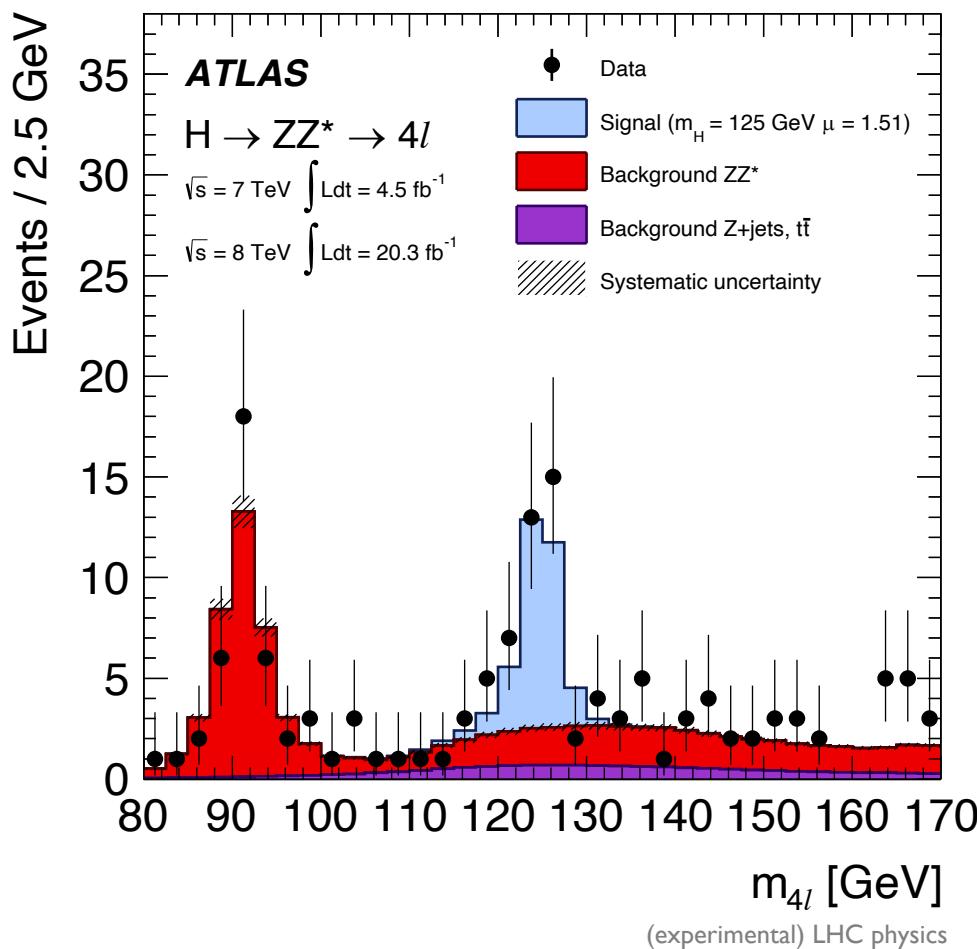
Step 3: Extract signal from background

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



Step 3: Extract signal from background

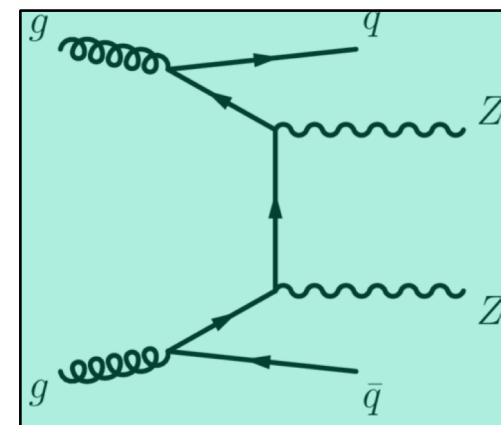
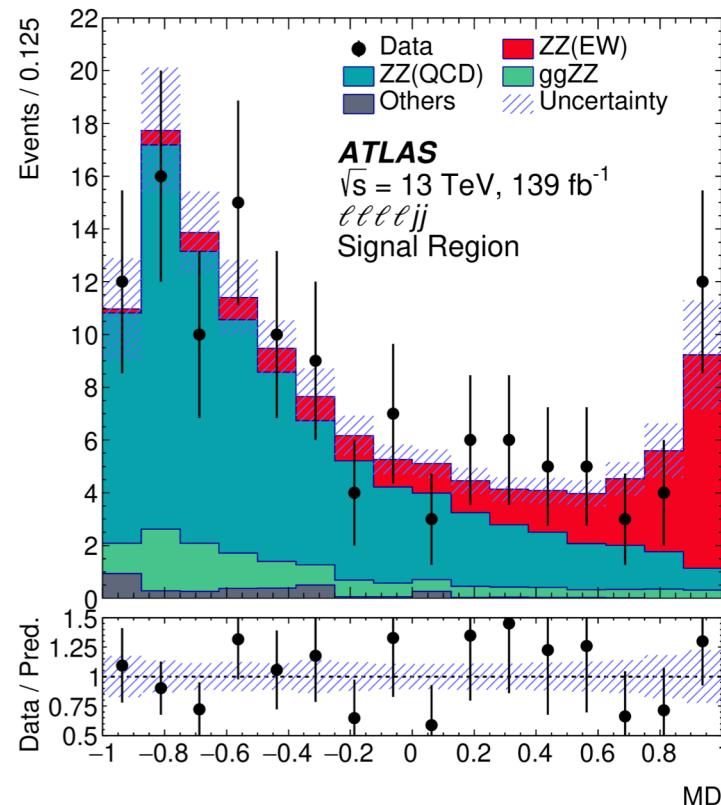
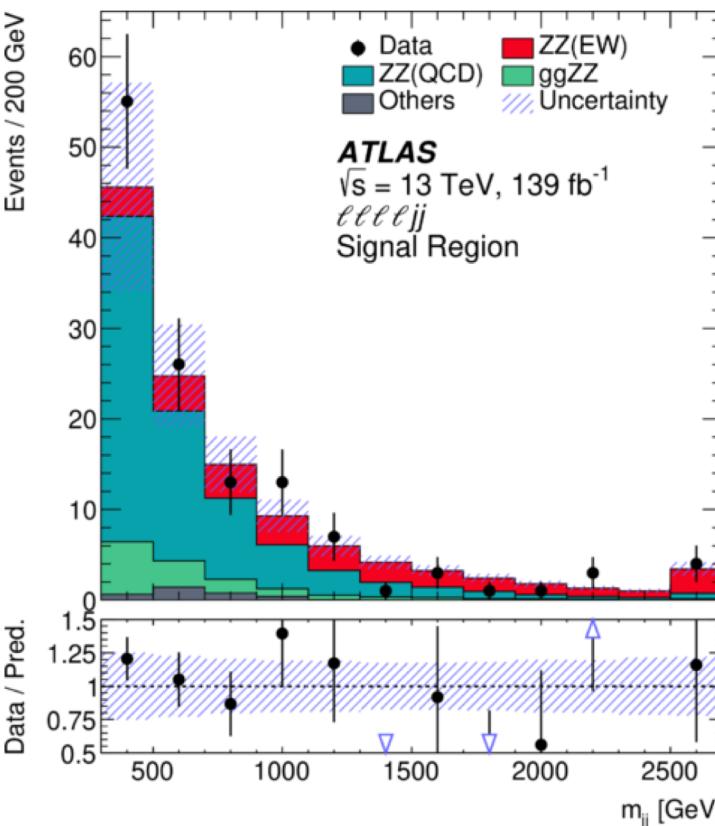
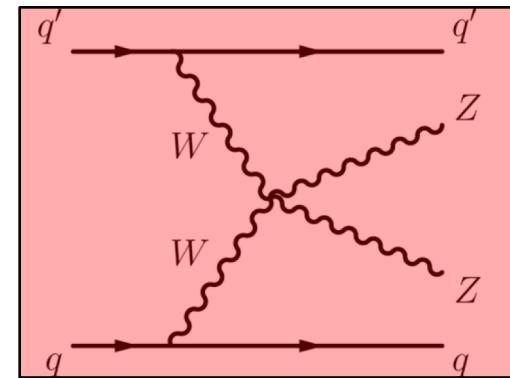
- Background gets estimated...
 - ✓ ... from simulation (normalized to data)
 - ✓ ... directly from data (“control regions”, enriched in background events)

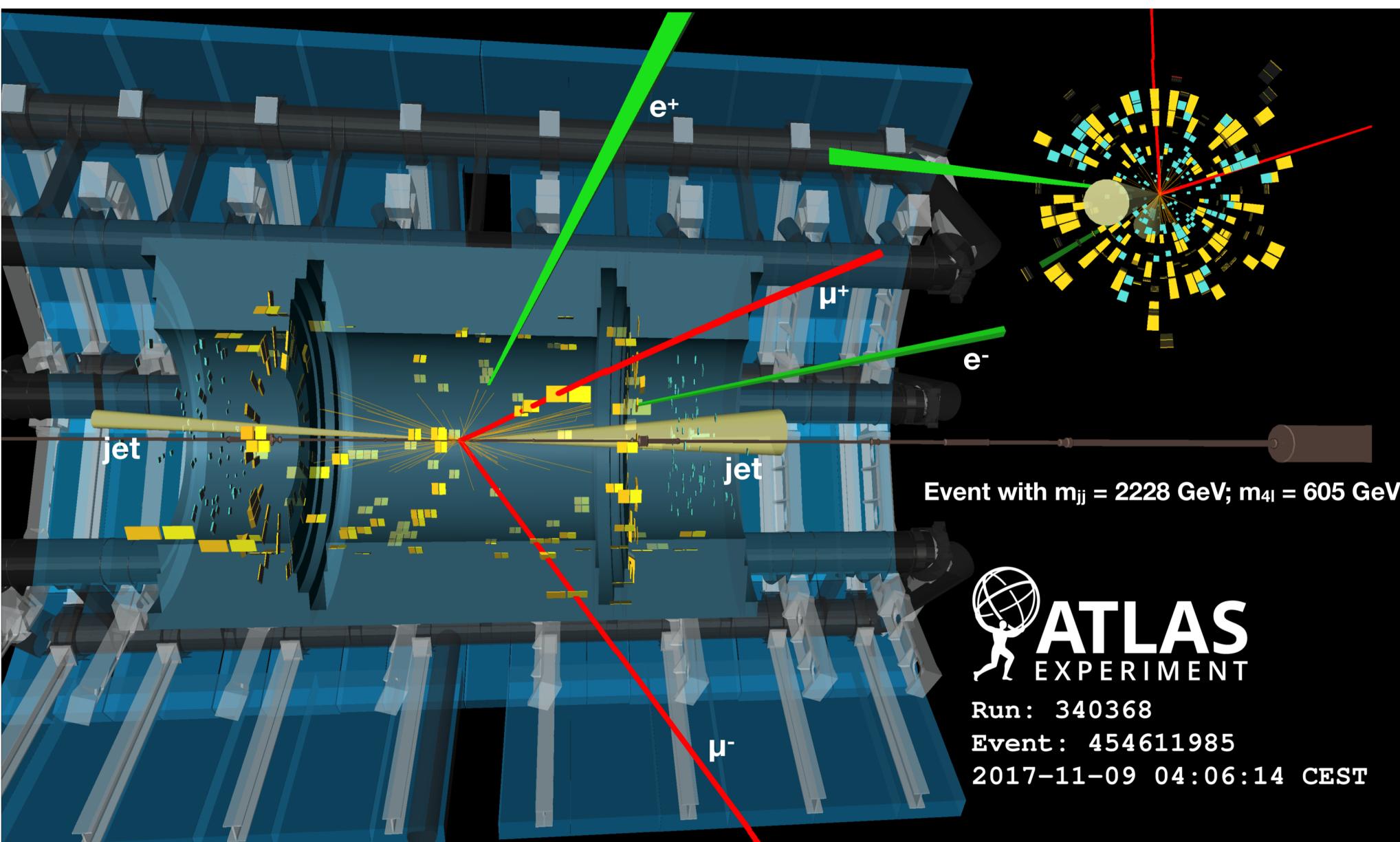


A region in which events fail to pass one of the selection criteria is highly enriched in a given type of reducible background

Machine learning to distinguish signal

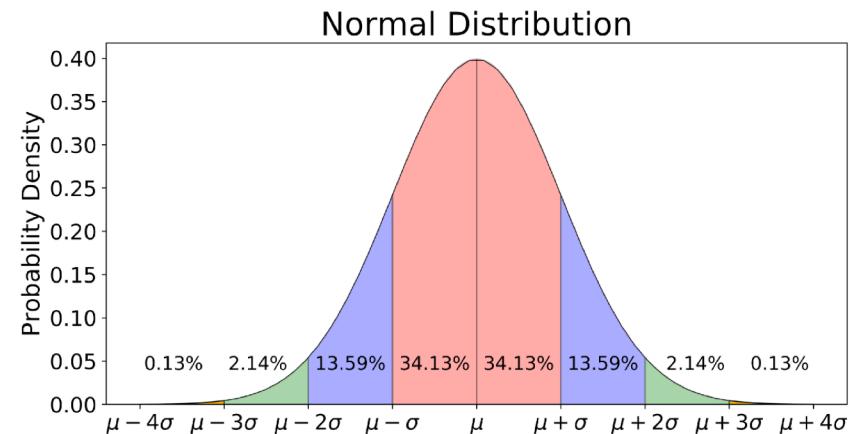
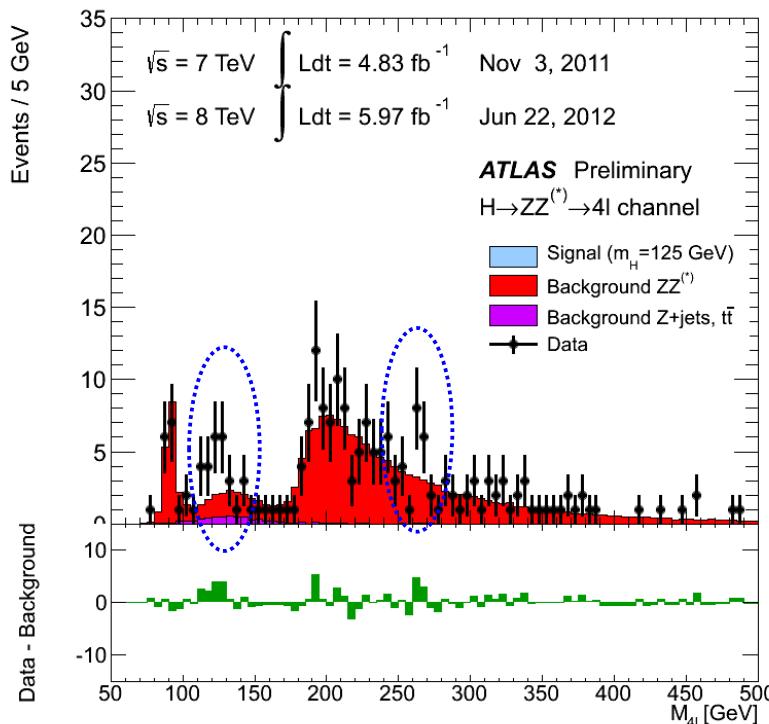
- Sometimes simple selection cuts are not sufficient
 - ✓ E.g in the Vector Boson Scattering process $q\bar{q} \rightarrow ZZq\bar{q}$
 - ✓ Very large irreducible background (order of magnitude larger than signal)
- Multivariate discriminant based on event kinematic helps !





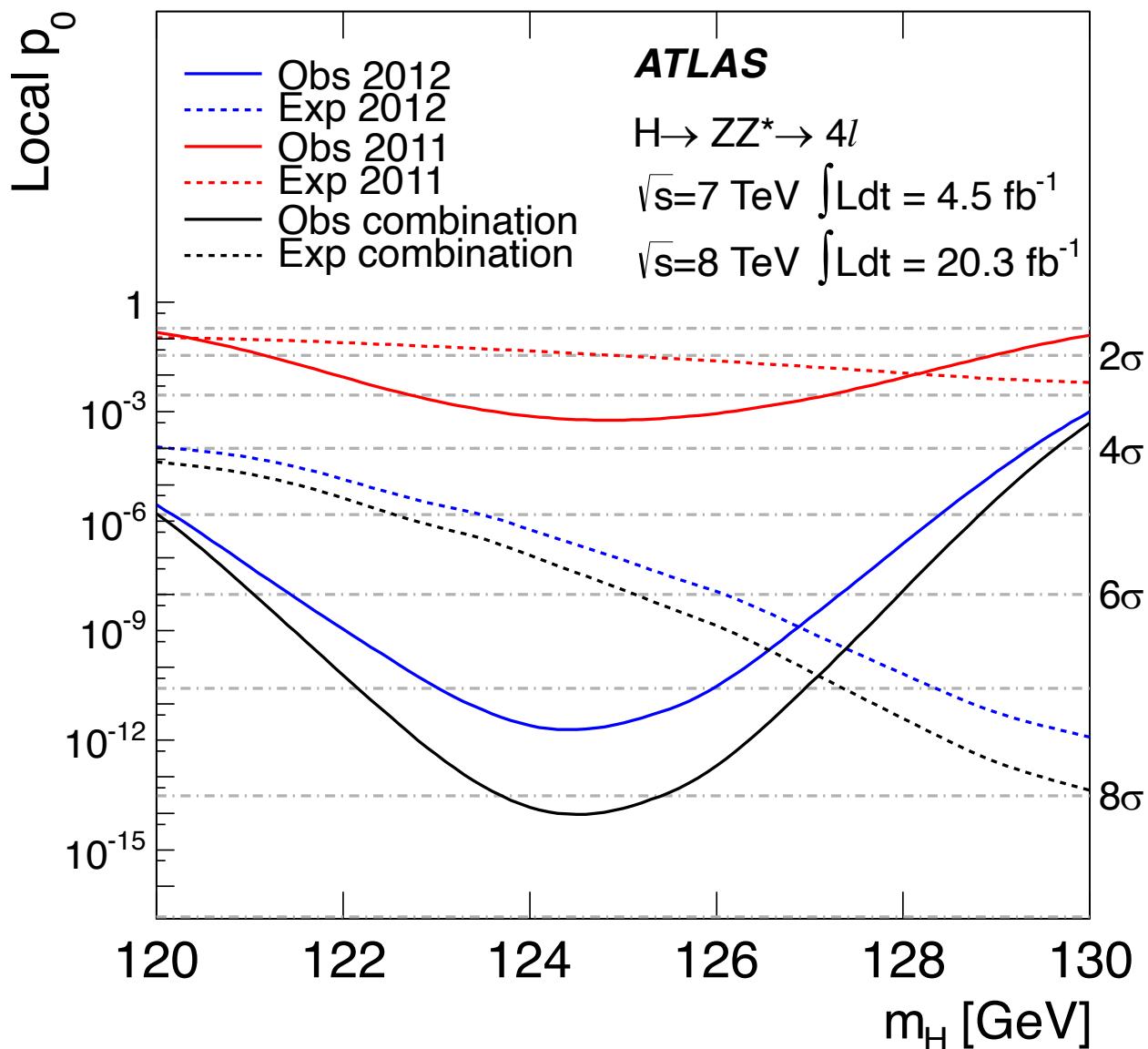
Step 4: How significant is an excess?

- p_0 : probability that the excess is due to a background fluctuation
- Significance: $Z \sim \frac{S}{\sqrt{B}}$ $p_0 = 1 - \text{Erf} \left(\frac{Z}{\sqrt{2}} \right)$
- Convention:
 - 3σ is an **evidence** ($p_0 = 0.27\%$)
 - 5σ is a **discovery** ($p_0 = 5.7 \cdot 10^{-7}$) -> ~ 1 chance over 1 million

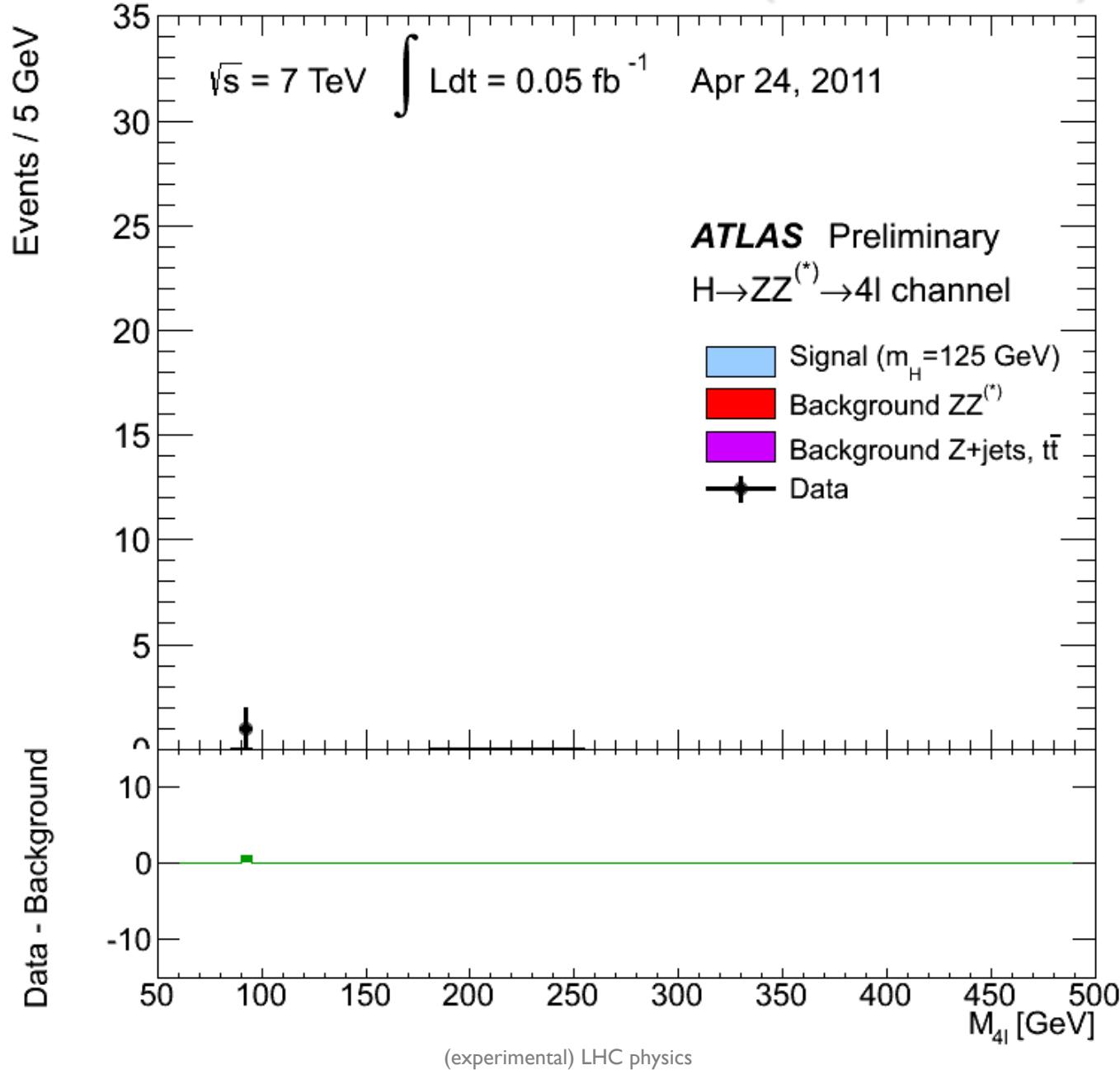


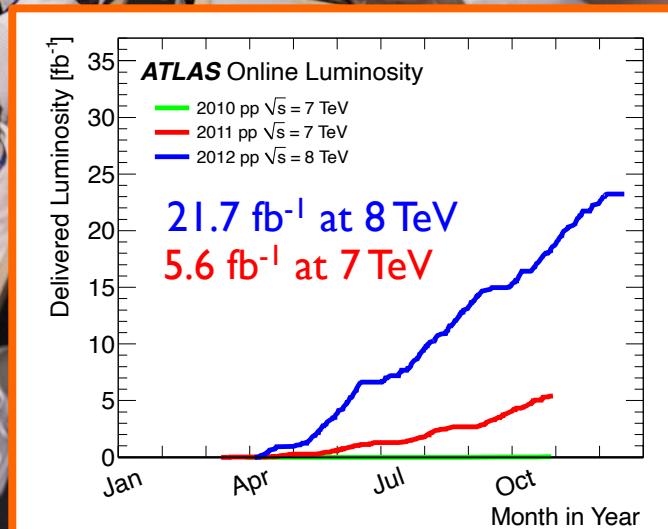
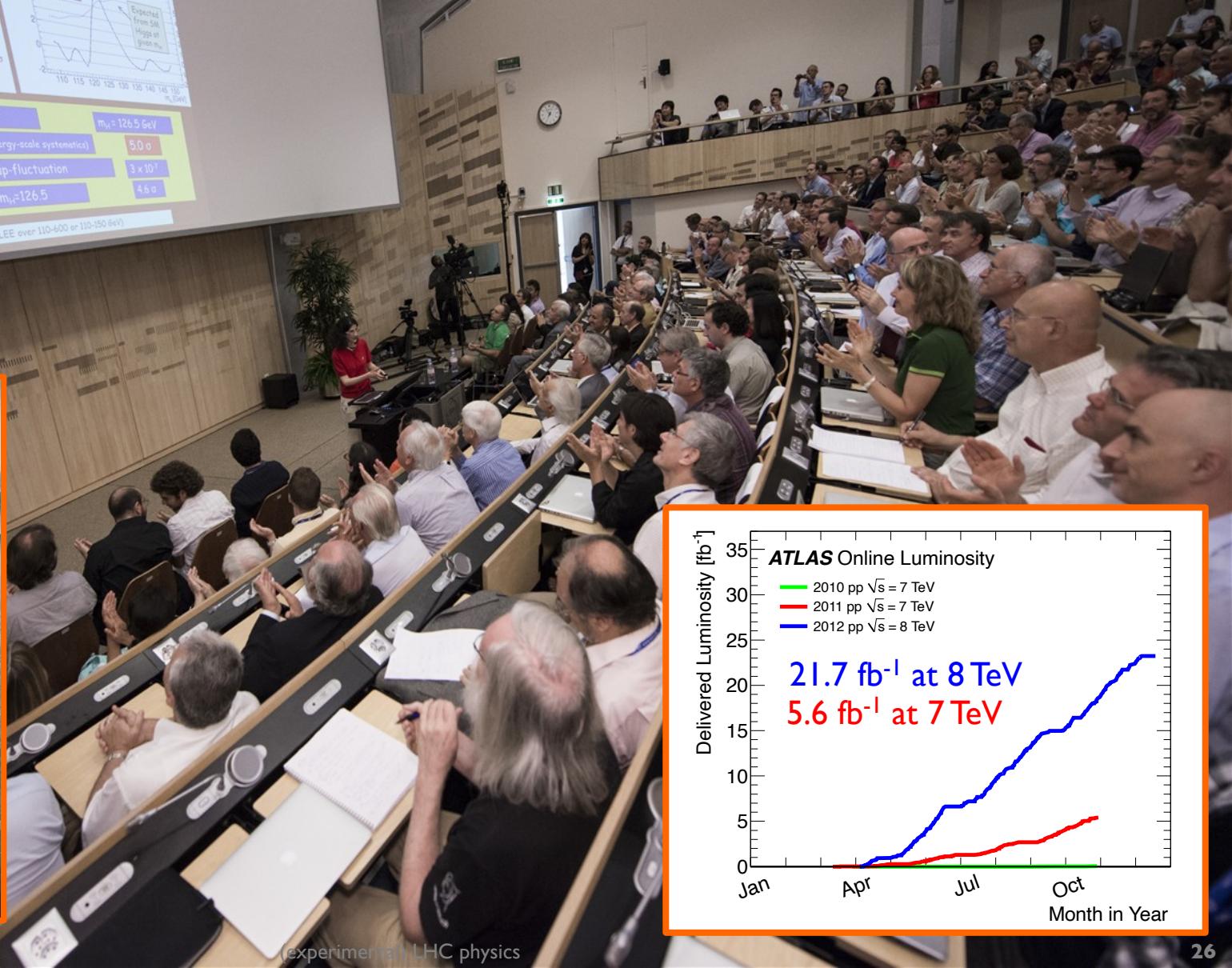
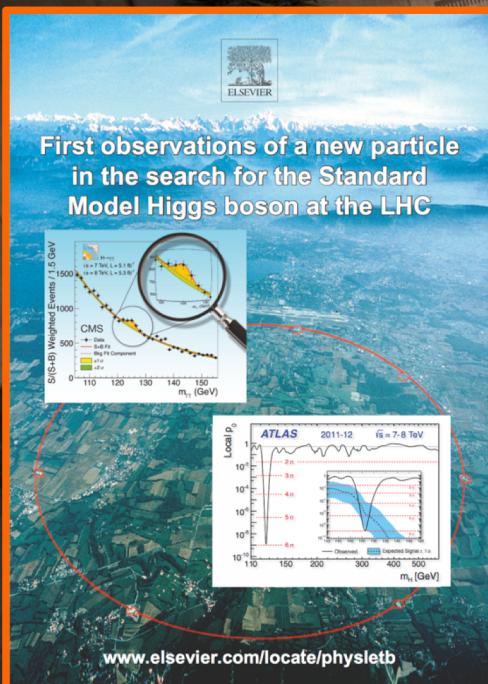
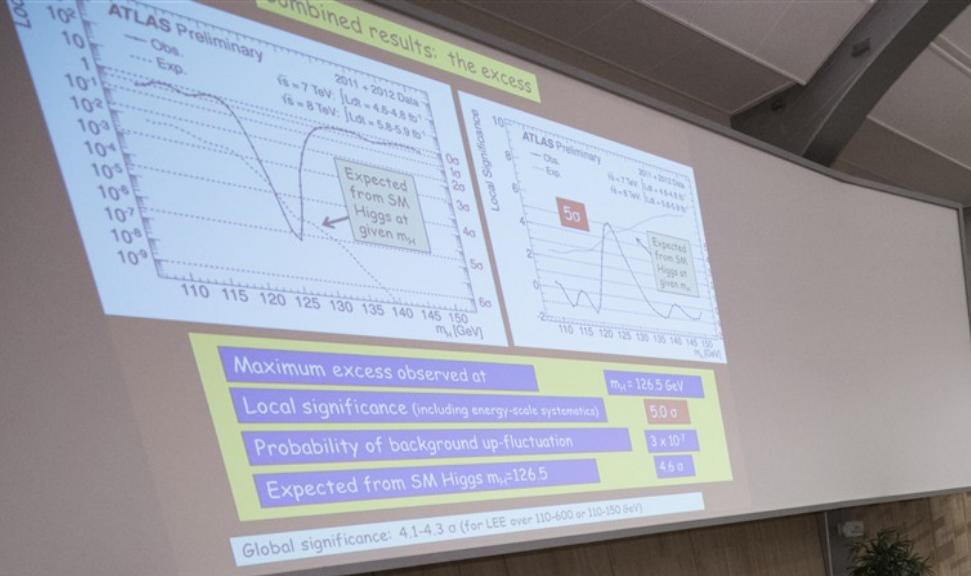
But in general, more complex estimate of signal significance via the use of a **likelihood functions** integrating all correlations and systematic uncertainties

Step 4: How significant is an excess?



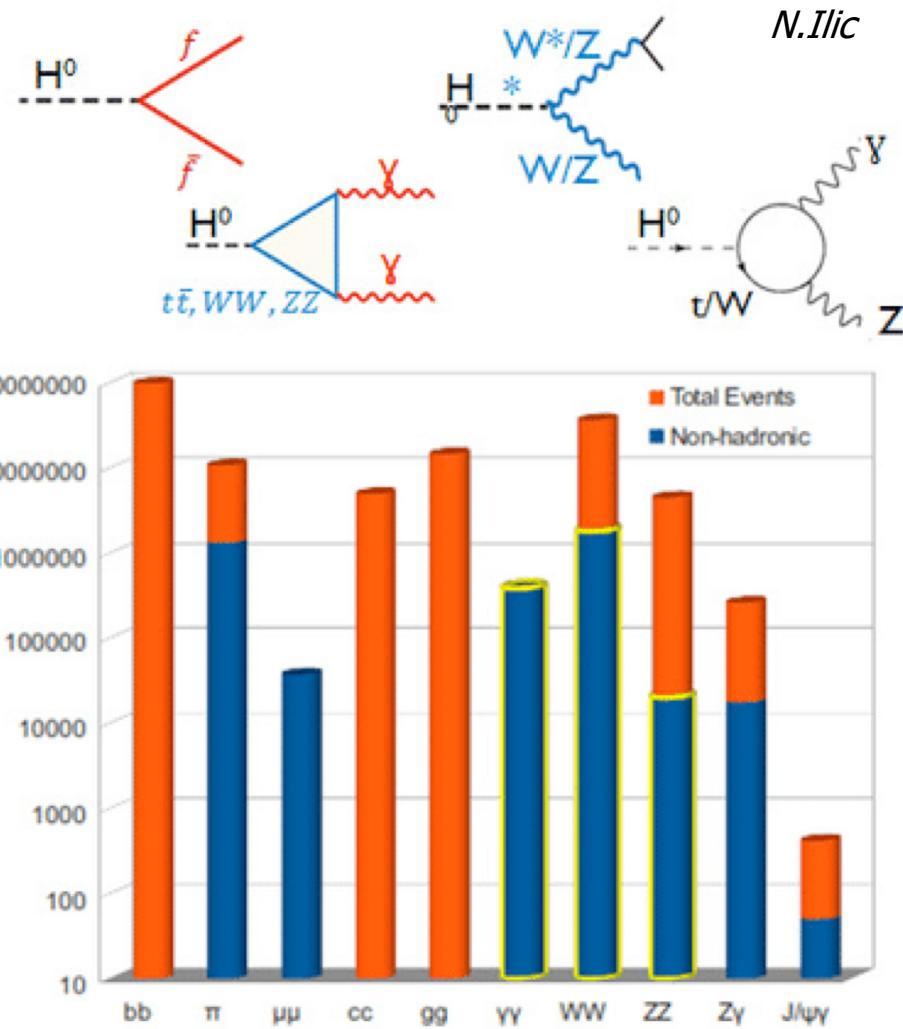
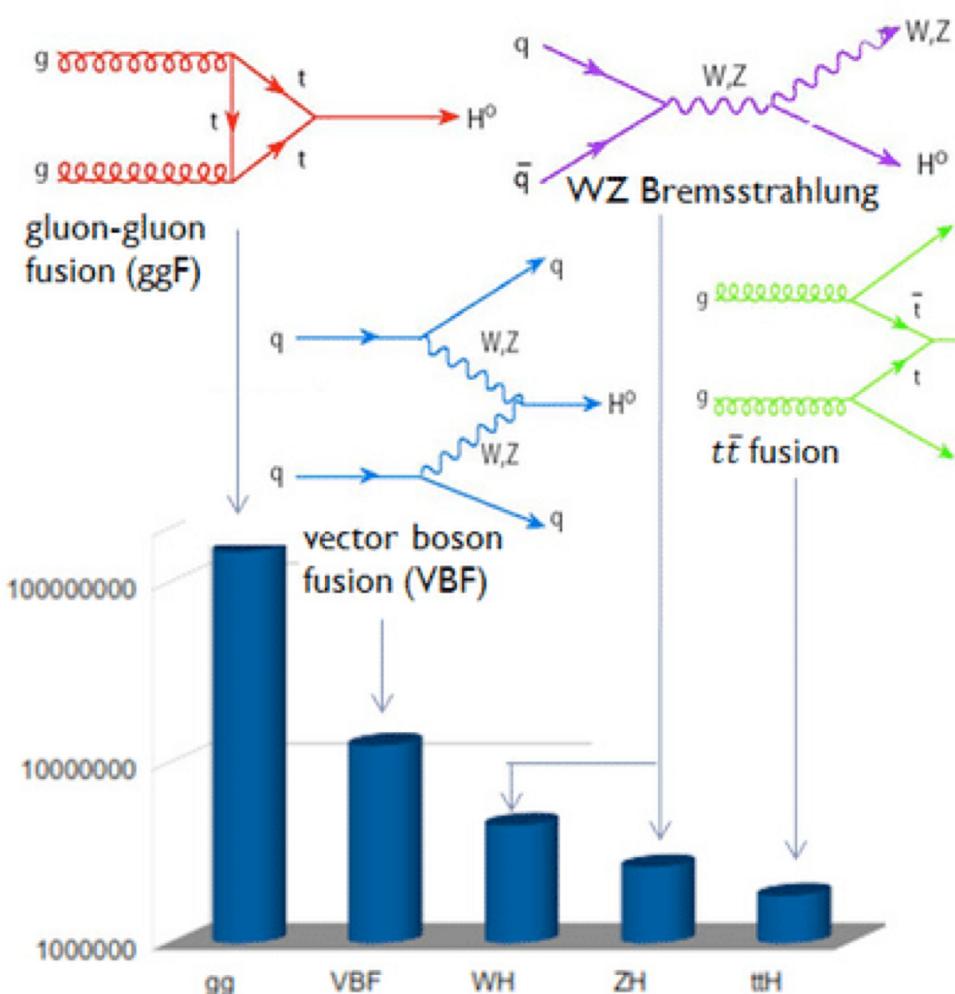
Significance increase with data (and time!)





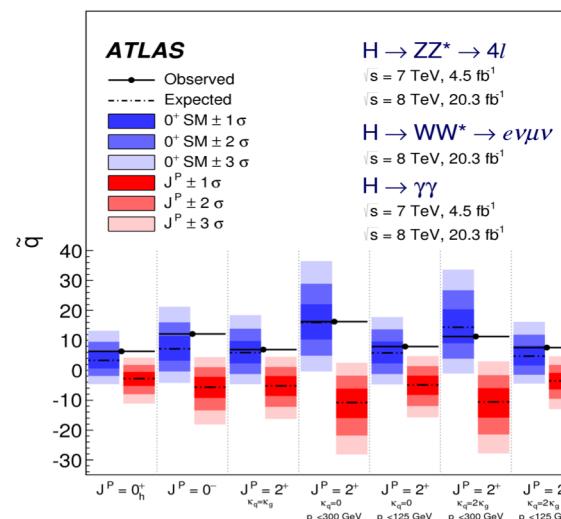
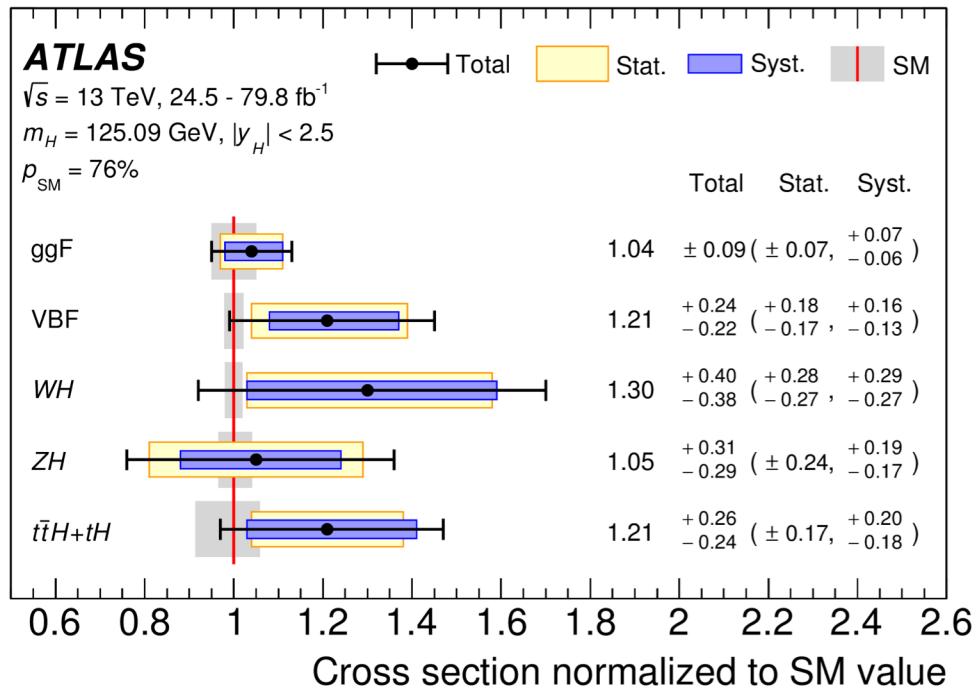
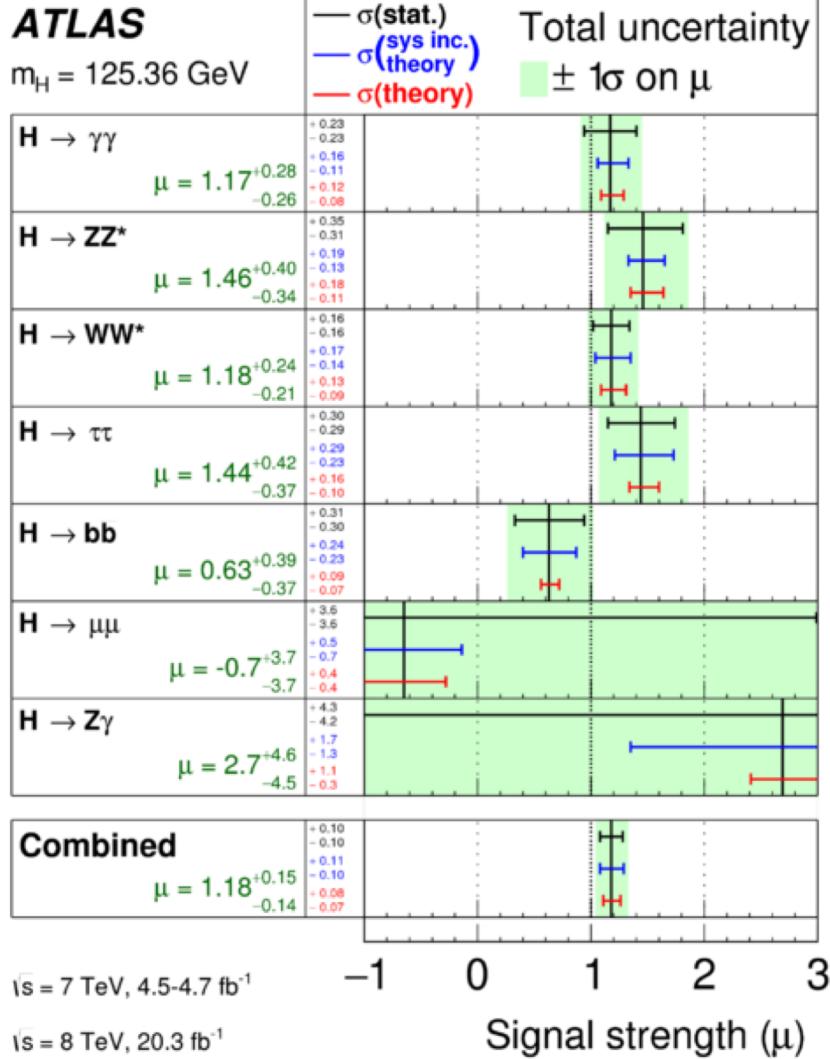
Example of current questions/measurements

- Is this the Higgs boson or a Higgs boson ?



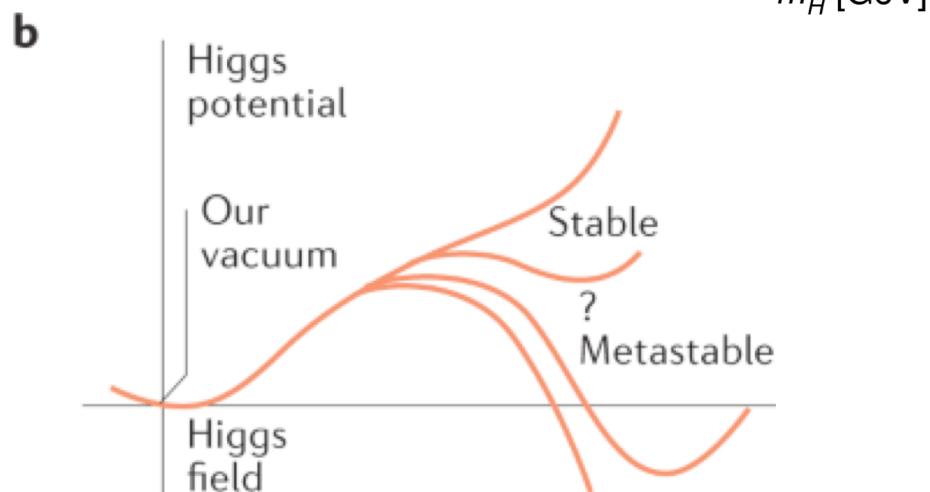
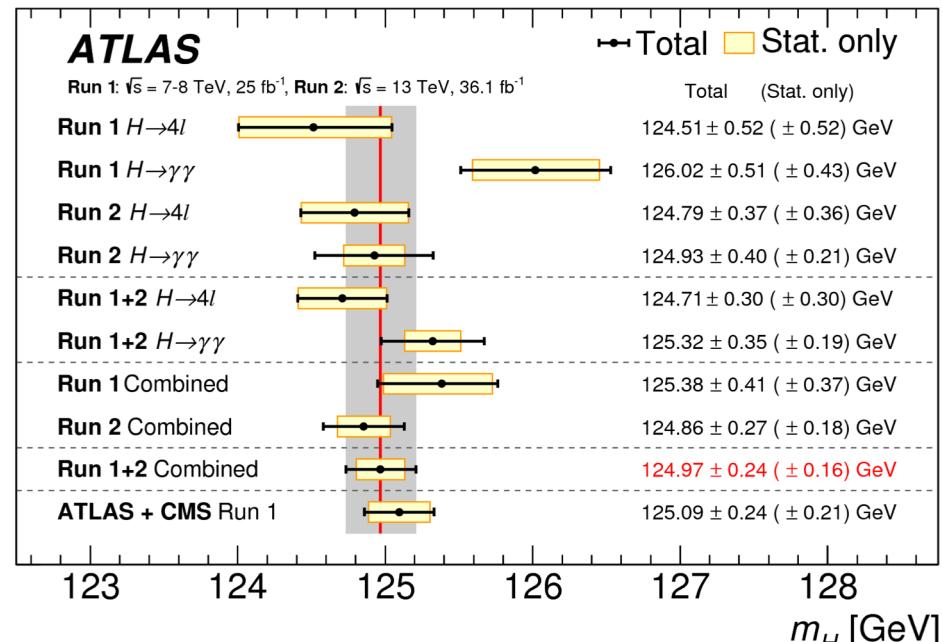
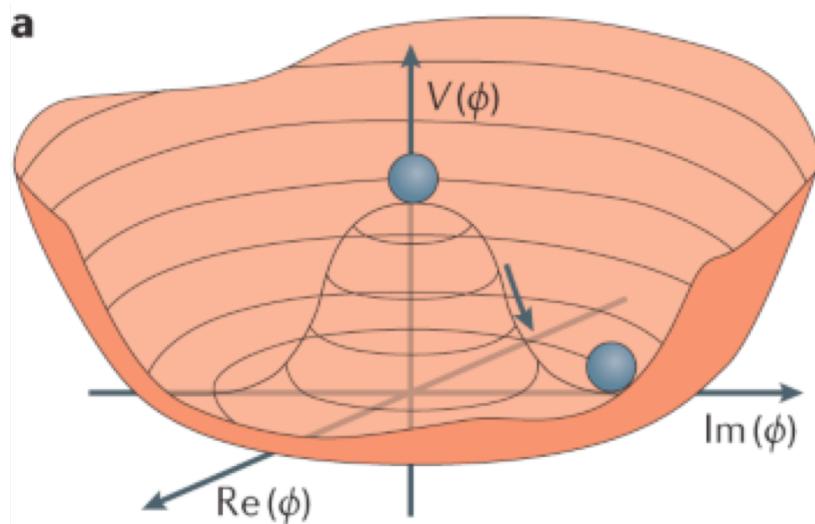
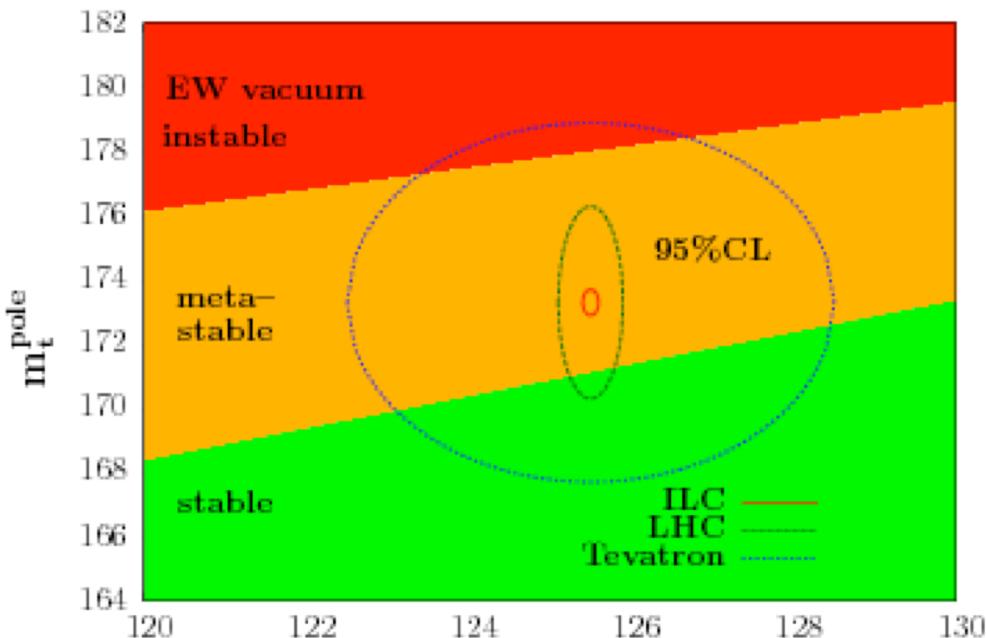
Example of current questions/measurements

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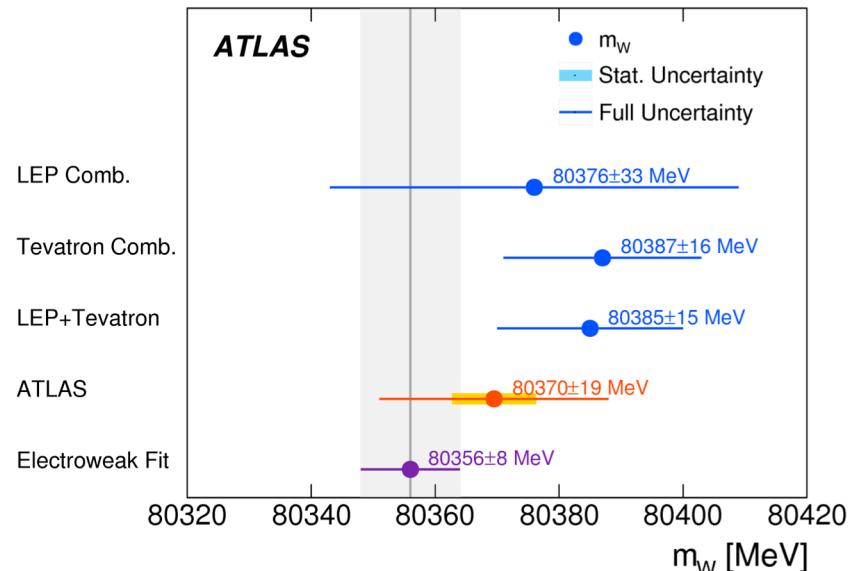
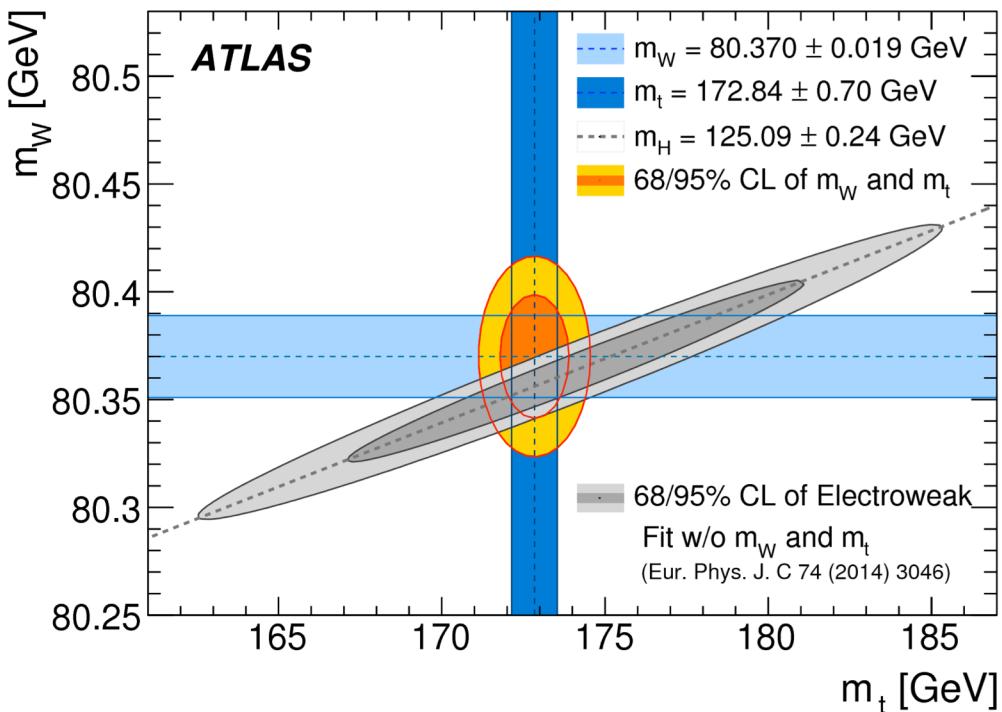
Example of current questions/measurements

- Are we in a stable or metastable universe ?

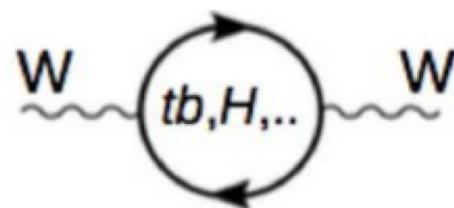


Example of current questions/measurements

- Is the standard Model fully consistent ?

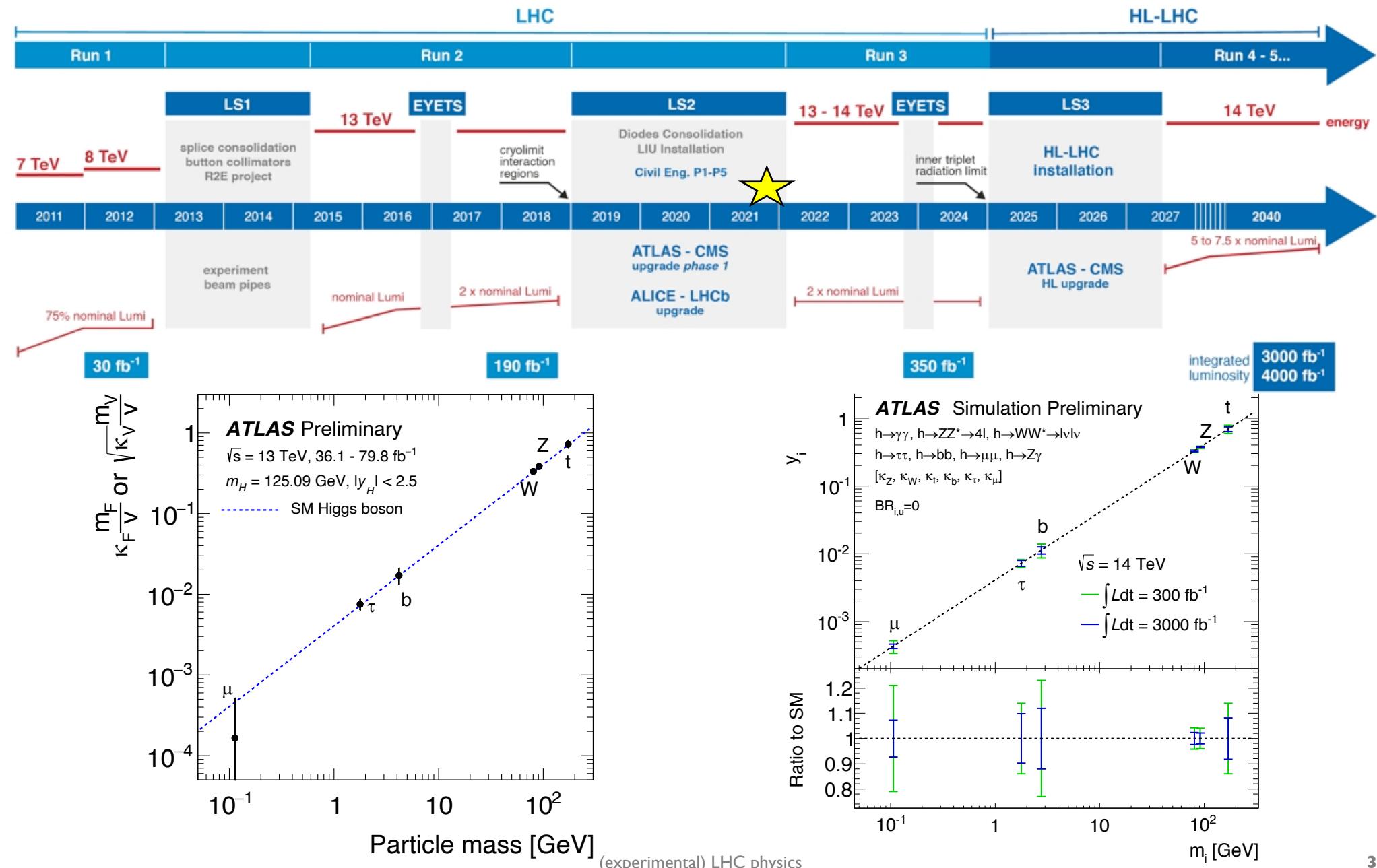


$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r),$$



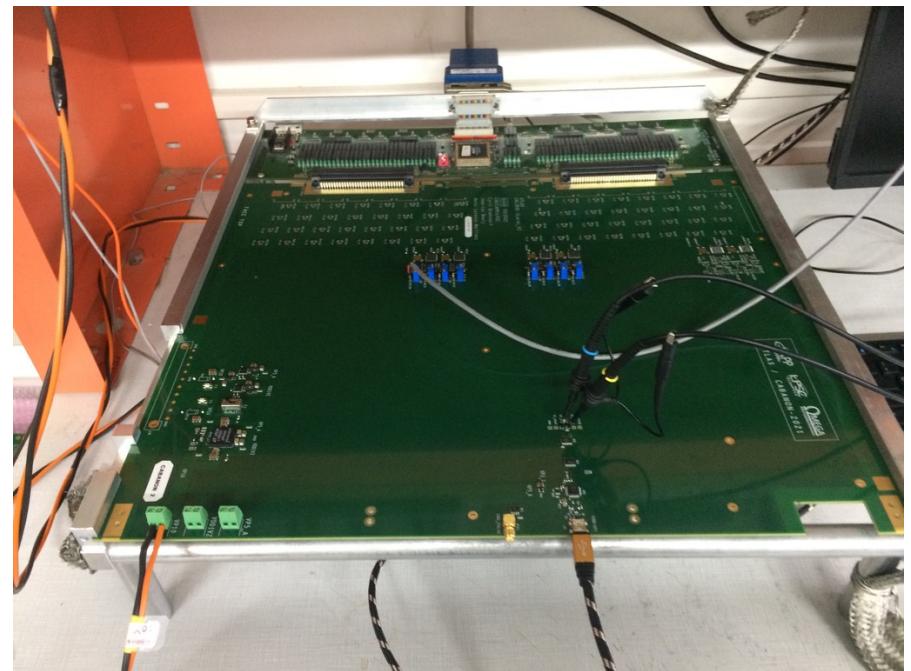
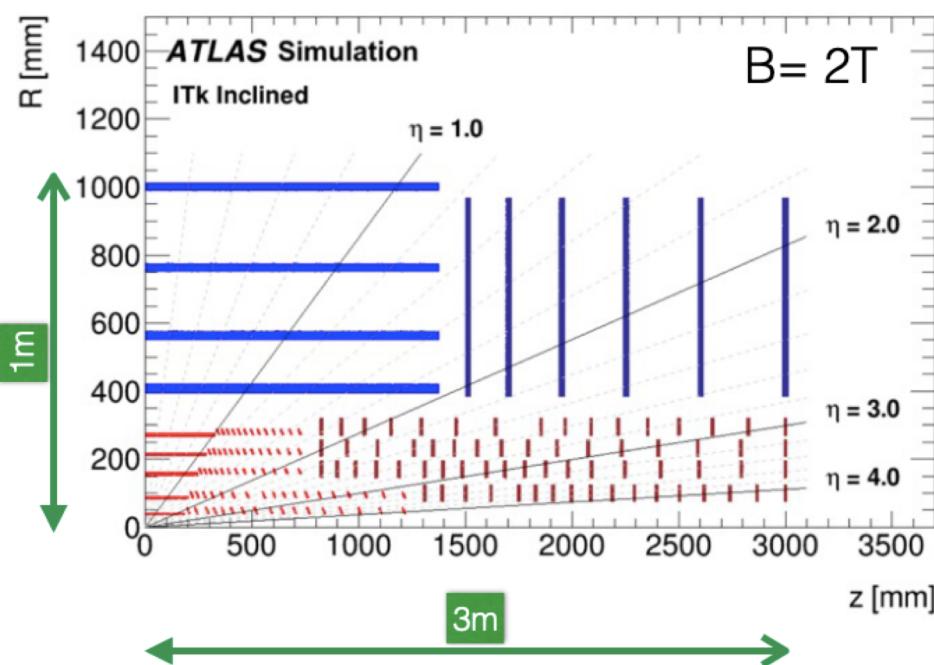
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T - p_T^ℓ , W^\pm , e - μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

The LHC will run for a long time...

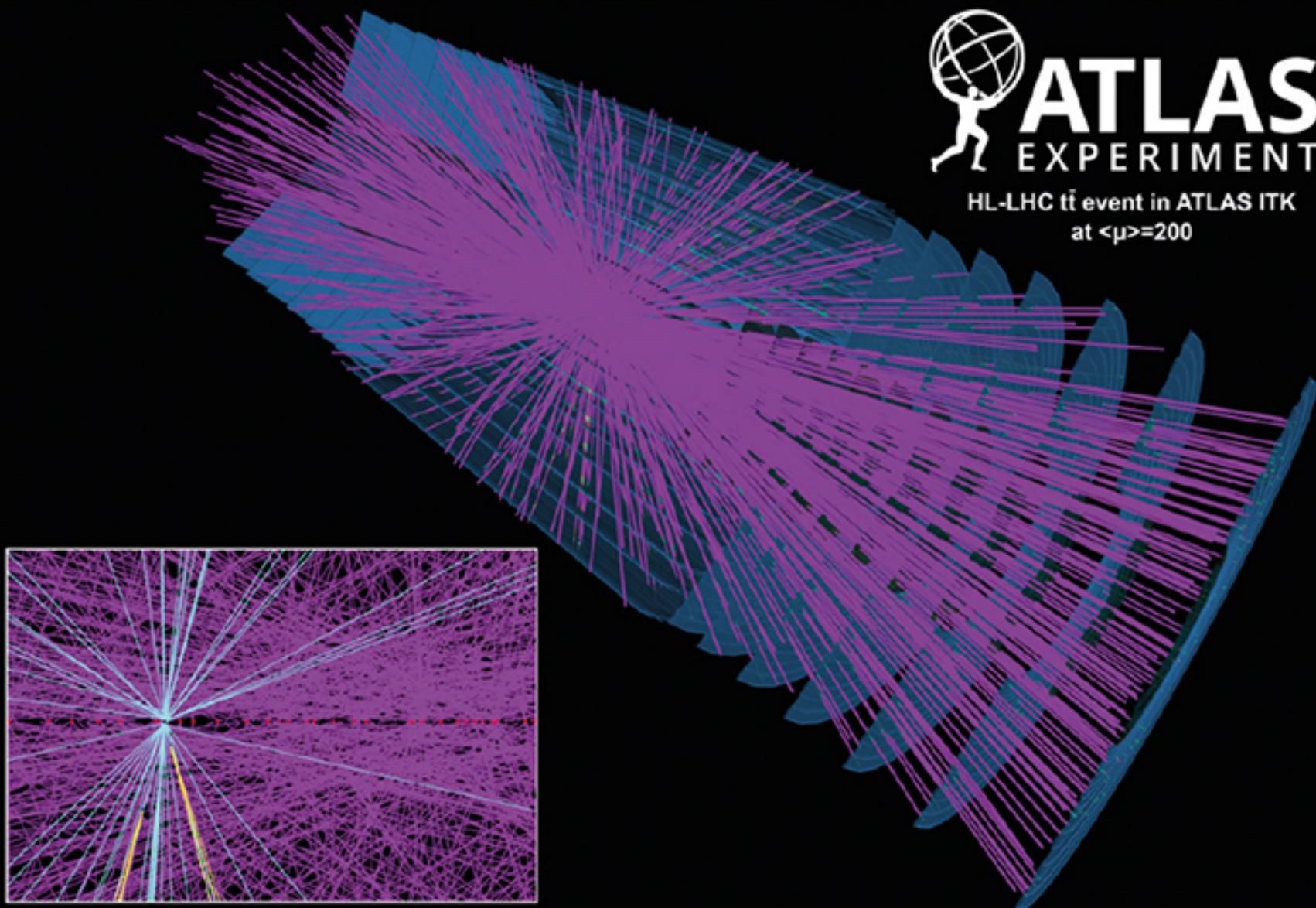


Detector upgrade for HL-LHC

- Extended eta coverage for trackers
- Improved granularity calorimeter (CMS)
- Electronic chain need to be changed (e.g hard radiation level)



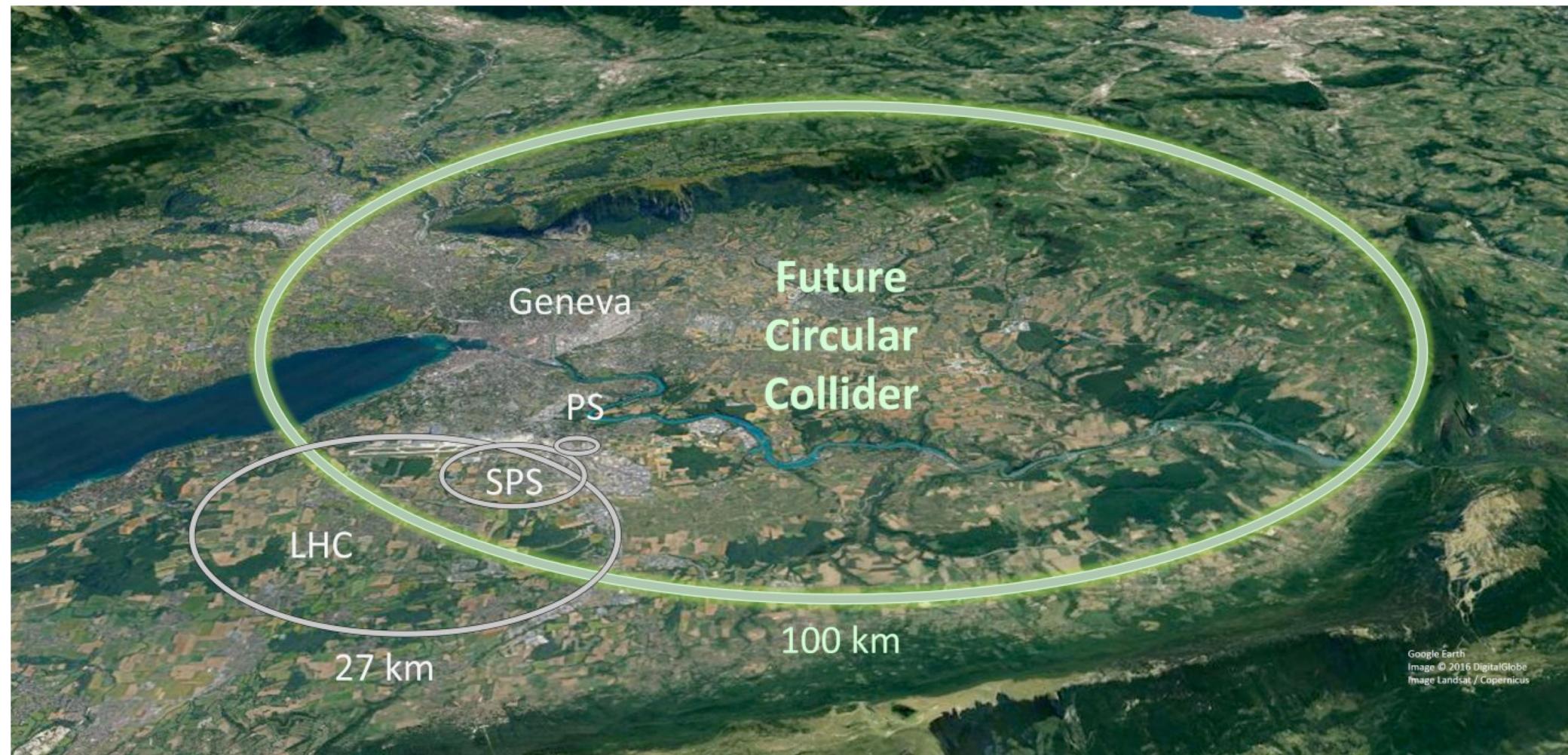
HL-LHC $t\bar{t}$ event in ATLAS ITK



ATLAS
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle \mu \rangle = 200$

And for the second half of the century ...

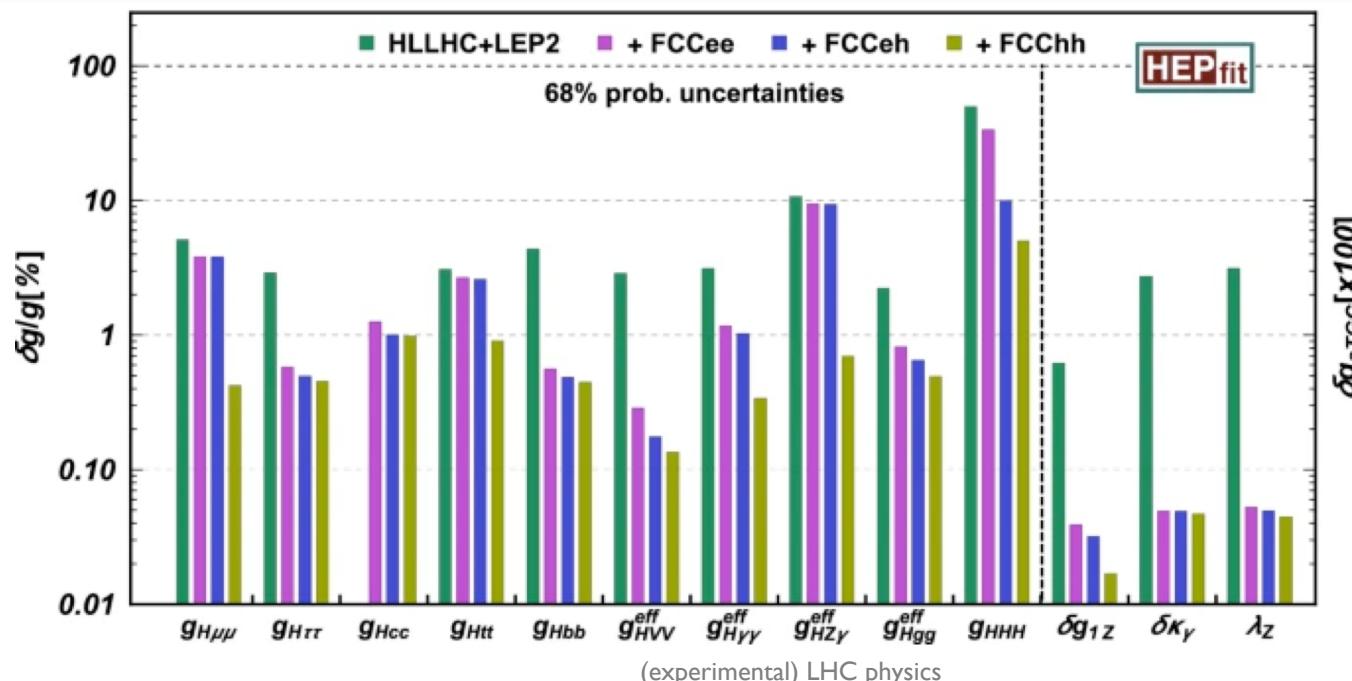
- FCC
 - FCC-hh P-p collisions -> 100 TeV, 20 ab-1
 - FCC-ee (ee- collisions)
 - CFF-eh (e-p collisions)



And for the second half of the century ...

- FCC
 - FCC-hh P-p collisions $\rightarrow 100 \text{ TeV}, 20 \text{ ab}^{-1}$
 - FCC-ee (ee- collisions)
 - CFF-eh (e-p collisions)

Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340–350	0.2	t <bar>t threshold scan</bar>
FCC-ee-tt(2)	4	365	1.5	10^6 t <bar>t events</bar>



And for the second half of the century ...

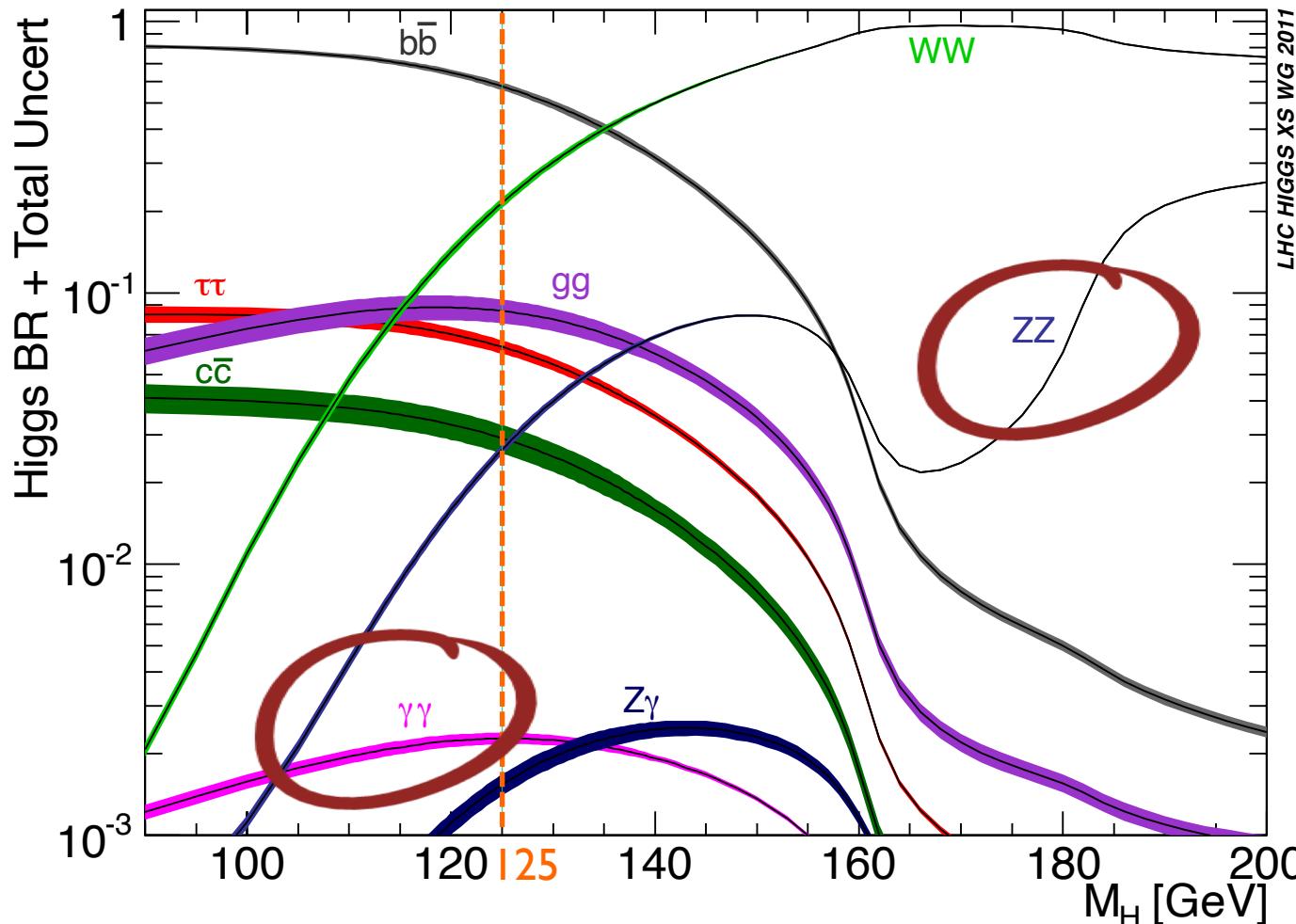
- HE-LHC:

- ✓ 27 TeV p-p collisions,
3 times the luminosity
of HL-LHC.
- ✓ Reuse LHC
underground
infrastructure
- ✓ 20 years
- ✓ Need 16 T FCC-type
magnets

Parameter	Unit	FCC-hh	HE-LHC	(HL-)LHC
Centre-of-mass energy	TeV	100	27	14
Injection energy	TeV	3.3	1.3 (0.9, 0.45)	0.45
Peak arc dipole field	T	16	16	8.33
Circumference	km	97.8	26.7	26.7
Straight-section length	m	1400	528	528
Beam current	A	0.5	1.12	(1.12) 0.58
Bunch population	10^{11}	1.0	2.2	(2.2) 1.15
Number of bunches/beam	–	10400	2808	(2760) 2808
RF voltage	MV	32	16	(16) 16
RMS bunch length	mm	~80	90	(90) 75.5
Longitudinal emittance ($4\pi\sigma_z\sigma_E$)	eVs	~8	4.2	2.5
Bunch spacing	ns	25	25	25
Norm. transv. rms emittance	μm	2.2	2.5	(2.5) 3.75
IP beta function $\beta_{x,y}^*$	m	1.1	0.3	0.45
Initial rms IP beam size $\sigma_{x,y}^*$	μm	6.7	3.5	9.0
Half crossing angle	μrad	37	100	(250) 142.5
Peak luminosity per IP	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	5	30	16
Peak no. of events/crossing	–	170	1000	460
RMS luminous region	mm	53	49	57
Stored energy/beam	GJ	8.4	1.4	(0.7) 0.36
SR power/beam	kW	2400	100	(7.3) 3.6
Transv. emittance damping time	h	1.1	3.6	25.8
No. of high-luminosity IPs	–	2	2	(2) 2
Initial proton burn-off time	h	17	3.4	(15) 40
Allocated physics time/year	days	160	160	160 (160)
Average turnaround time	h	5	4	4 (5)
Optimum run time	h	11.6	3.7	(18–13) ~10
Accelerator availability	–	70%	70%	75% (80%) 71%
Nominal luminosity per day	fb^{-1}	2.0	8.0	4.5 (1.9) 0.4
Luminosity per year (160 days)	fb^{-1}	>250	>1000	500 (350) 55

Additional information

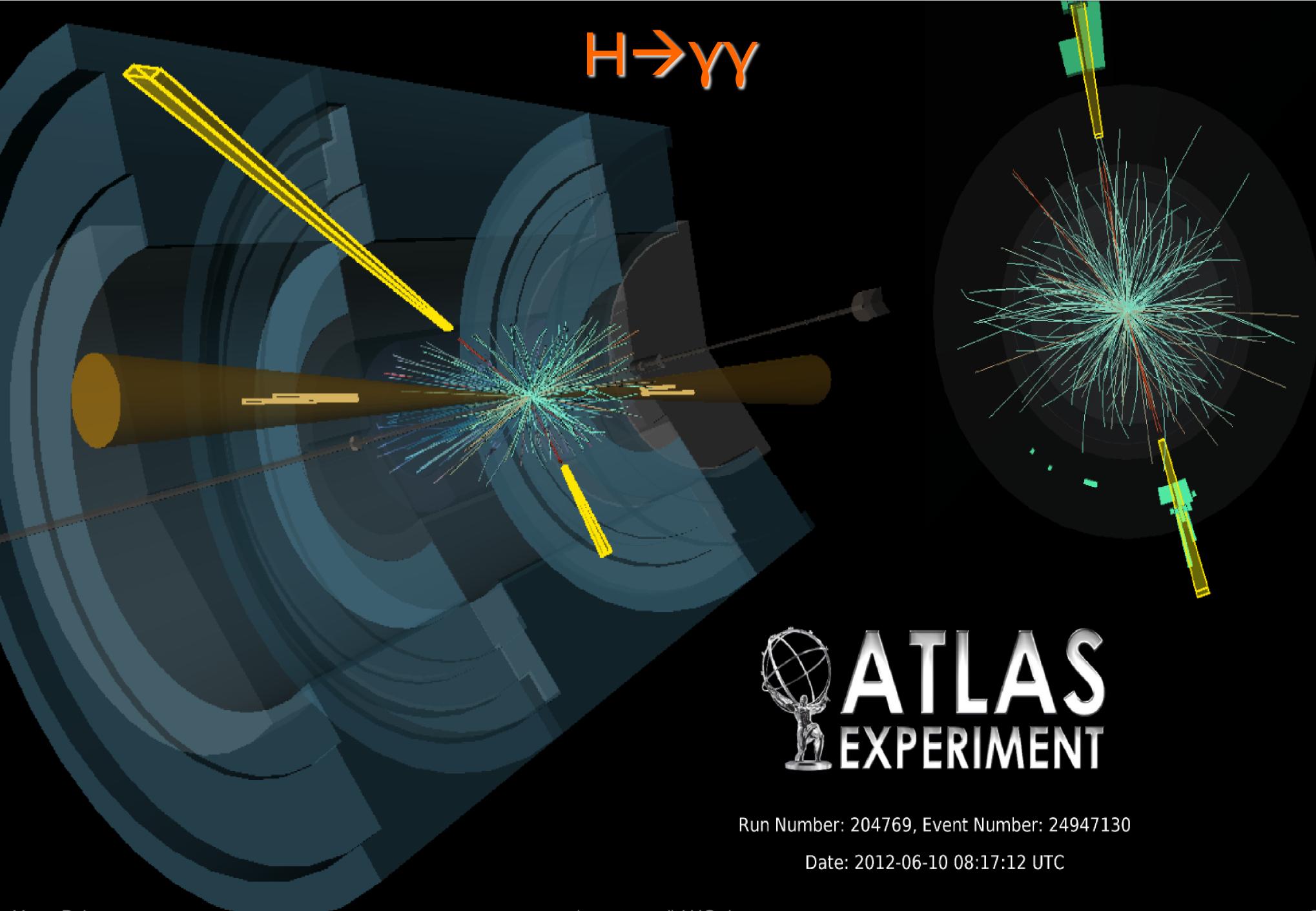
Standard Model Higgs decays



decay	SM BR [%] $m_H = 125.09$ GeV
$H \rightarrow b\bar{b}$	58.1
$H \rightarrow WW$	21.5
$H \rightarrow \tau\tau$	6.26
$H \rightarrow ZZ$	2.64
$H \rightarrow \gamma\gamma$	0.23

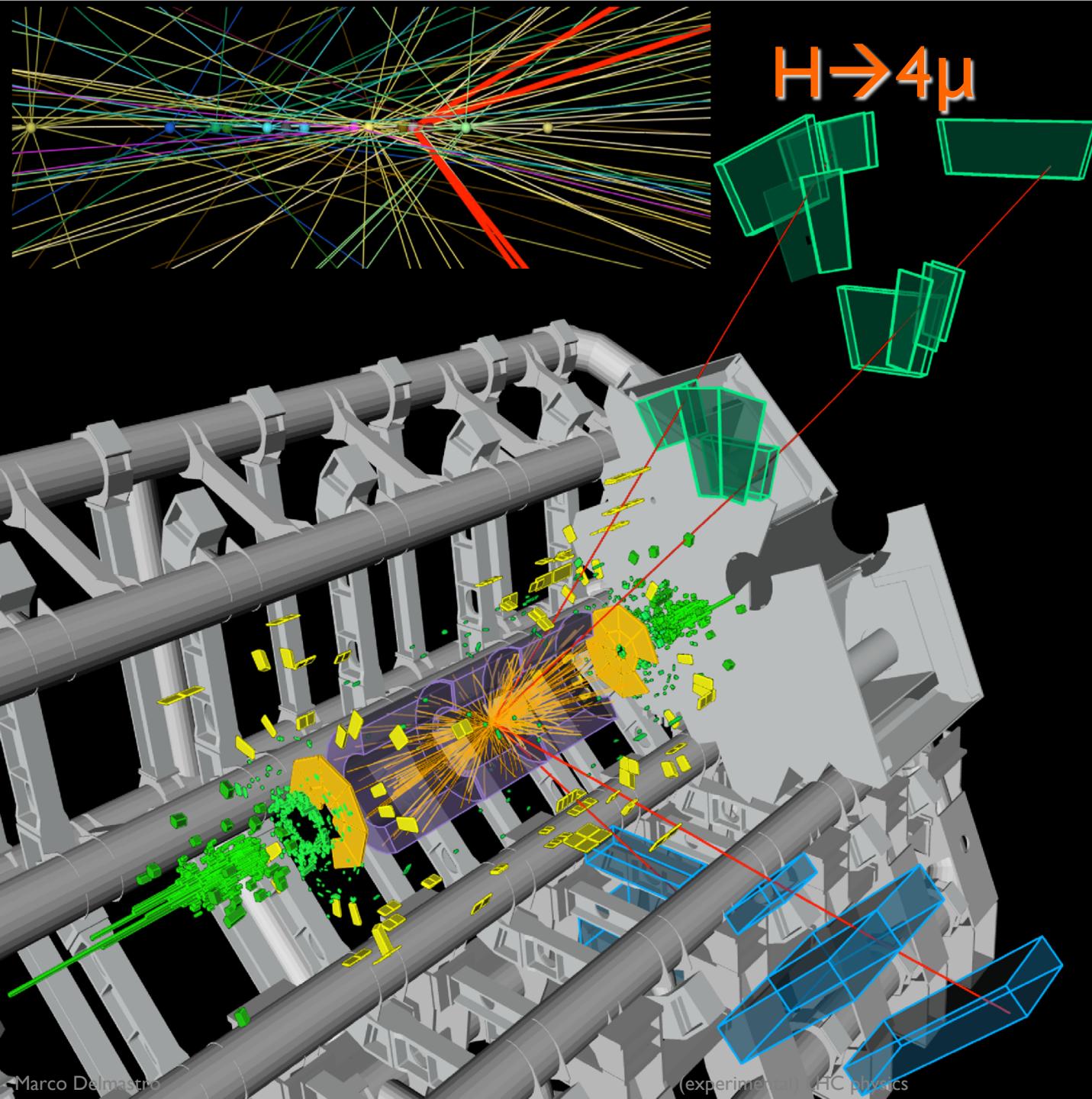
- 1 Higgs every 10 s
- 1 $H \rightarrow \gamma\gamma$ every 1.5 h
- 1 $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e$ or μ) every 2 days

$H \rightarrow \gamma\gamma$

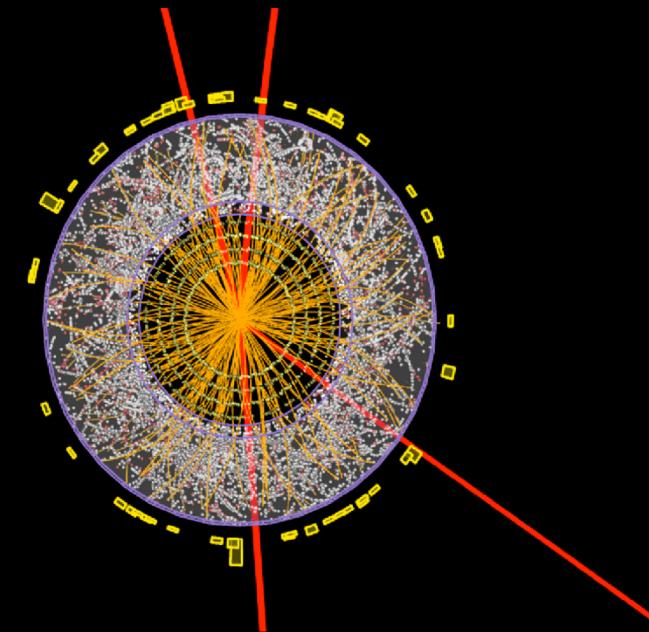


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Date: 2012-06-10 08:17:12 UTC

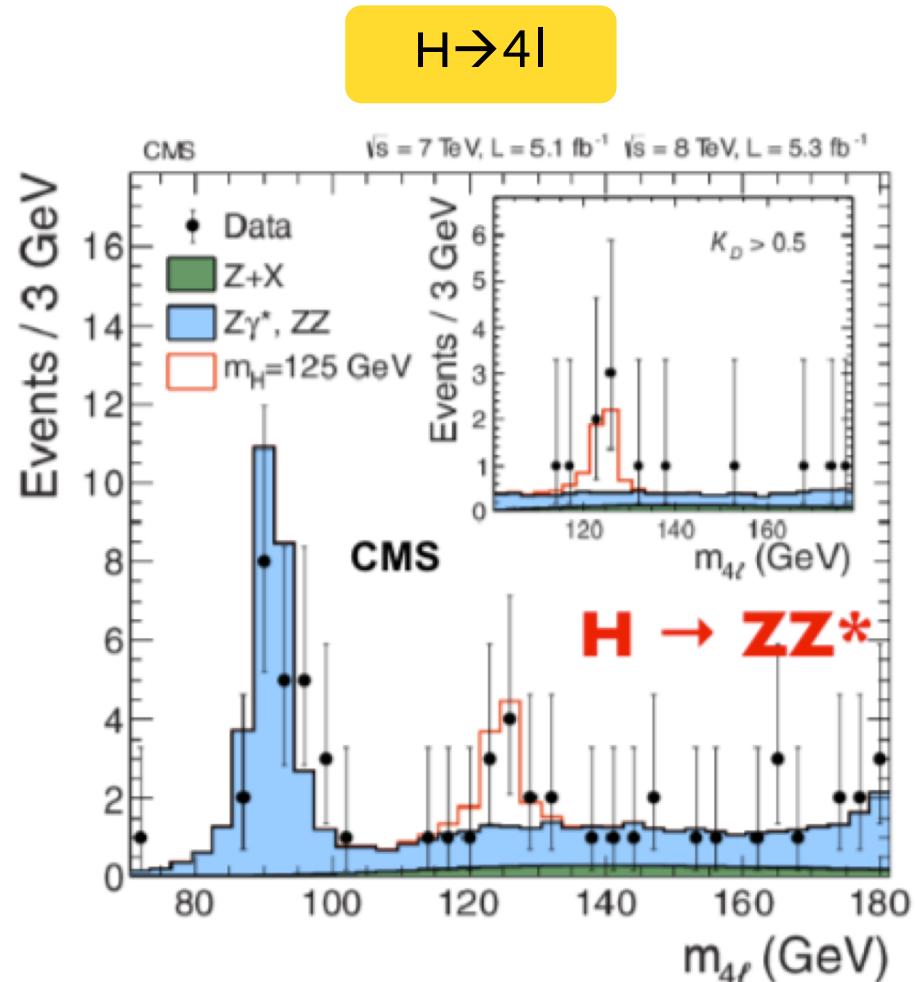
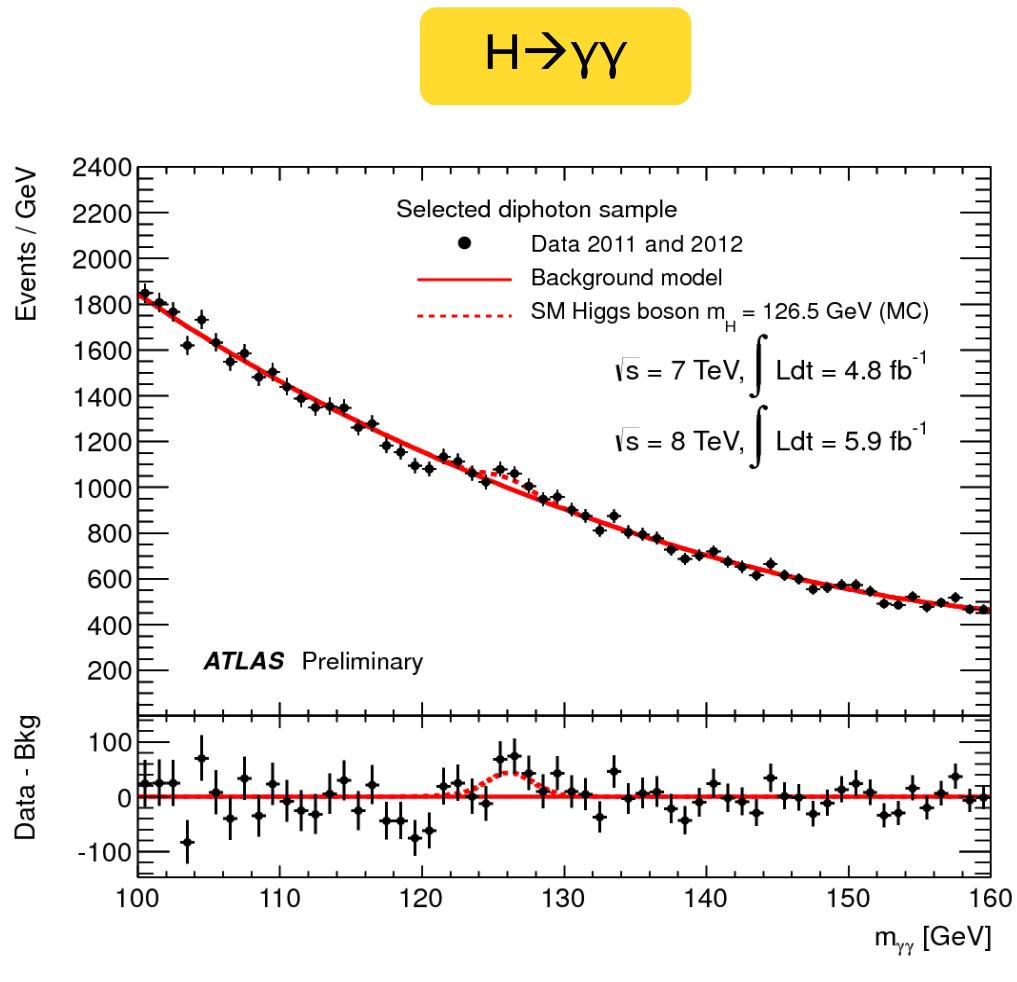


(experimental) ATLAS physics



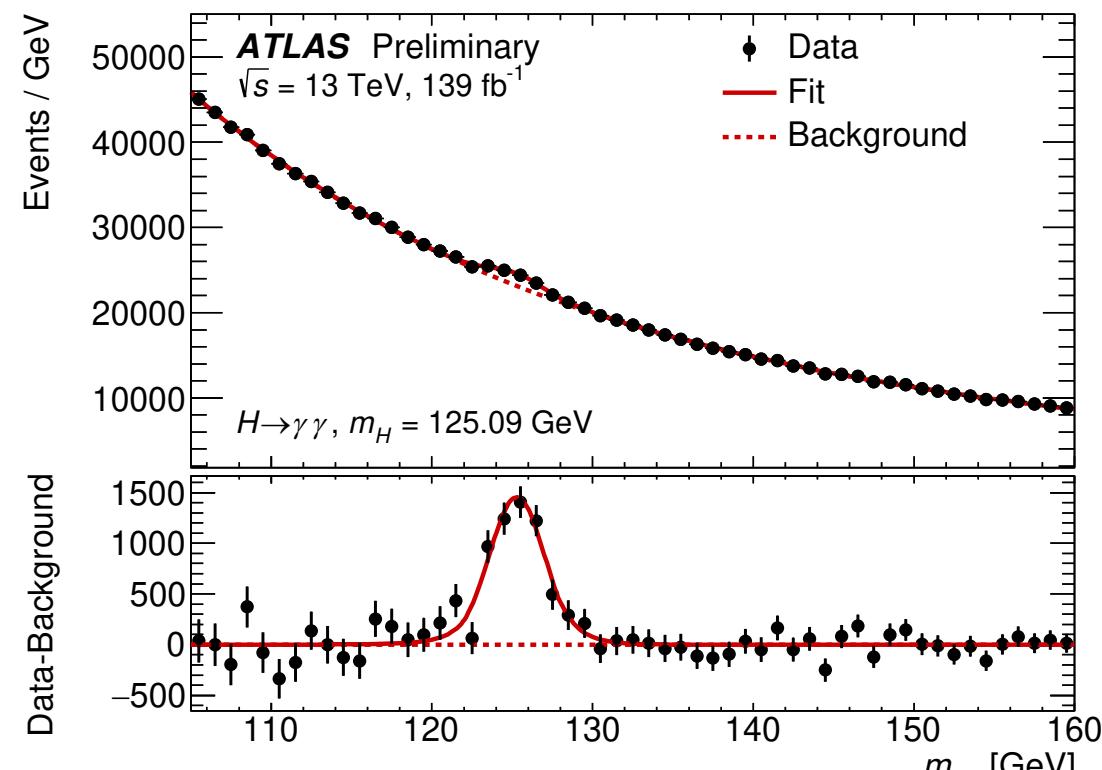
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs signals on July 4th 2012

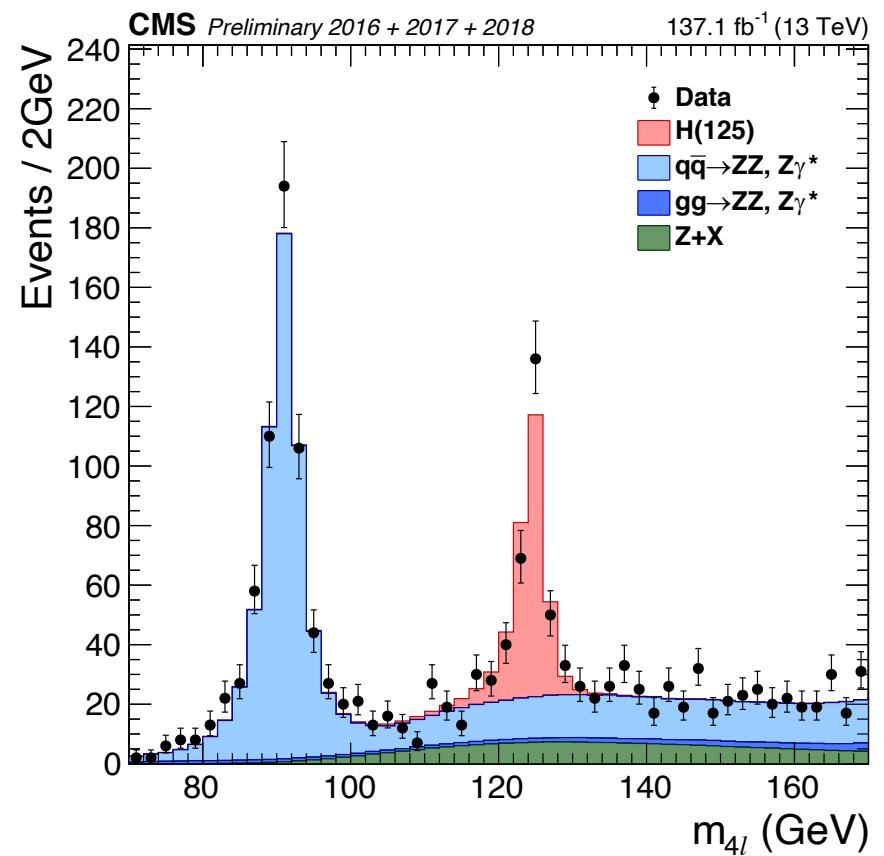


Higgs signals with the latest 13 TeV data...

$H \rightarrow \gamma\gamma$

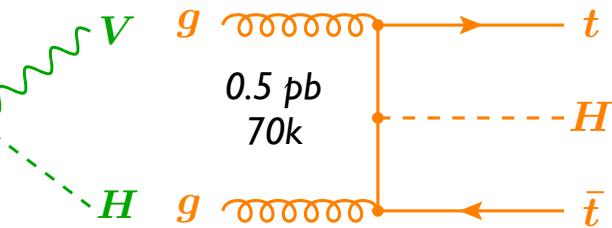
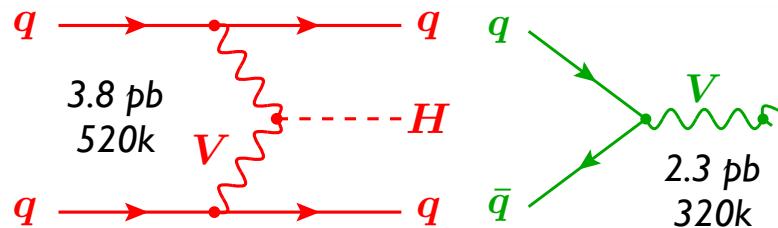
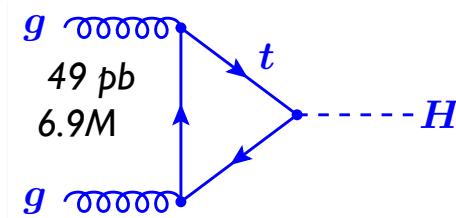


$H \rightarrow 4l$



Probing Higgs couplings at the LHC

$\sigma[\text{pb}] @ 13 \text{ TeV}$
 $\# \text{Higgs produced in } 140 \text{ fb}^{-1}$
 in one experiment

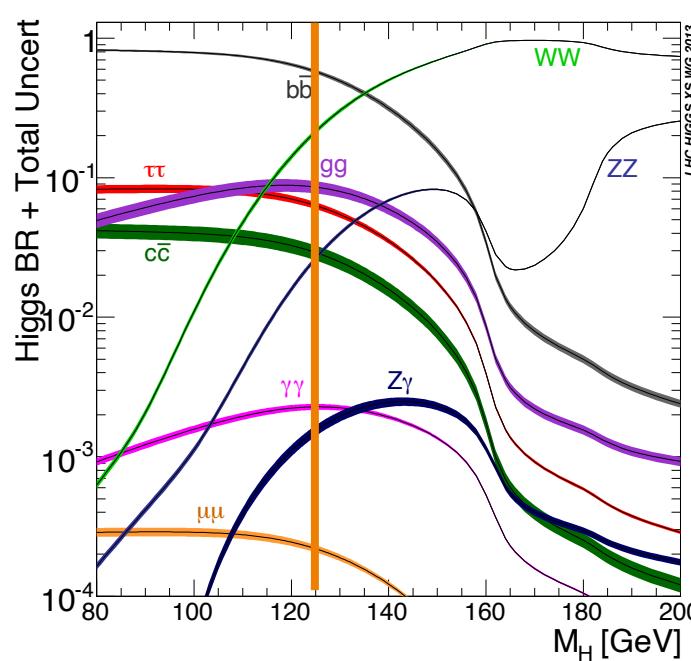
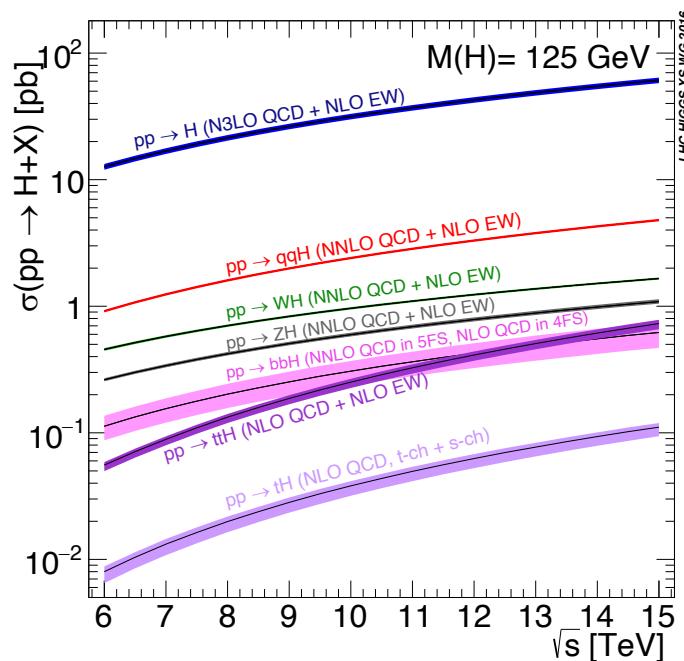


gluon-gluon fusion:
main production mode at
LHC

Vector Boson Fusion
2 well-separated forward
jets

VH
tag W and Z
boson decays

ttH
tag 2 top quarks

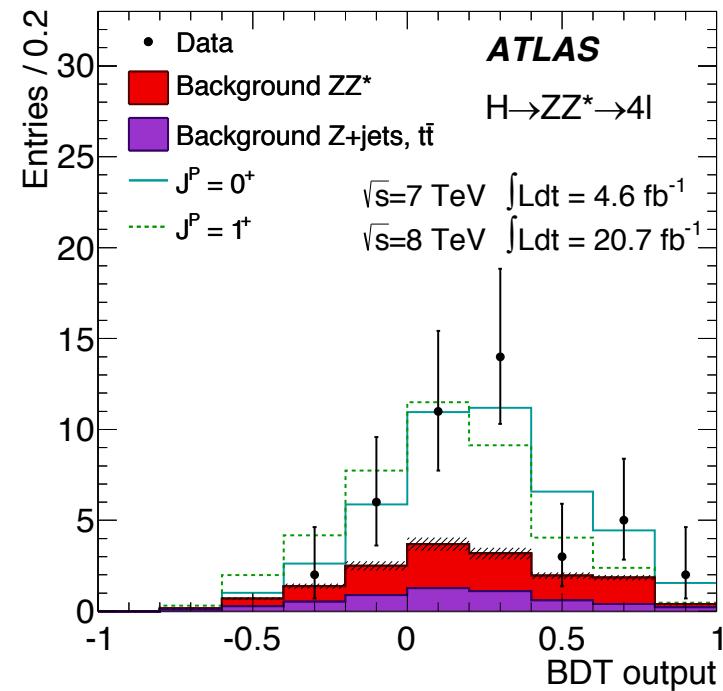
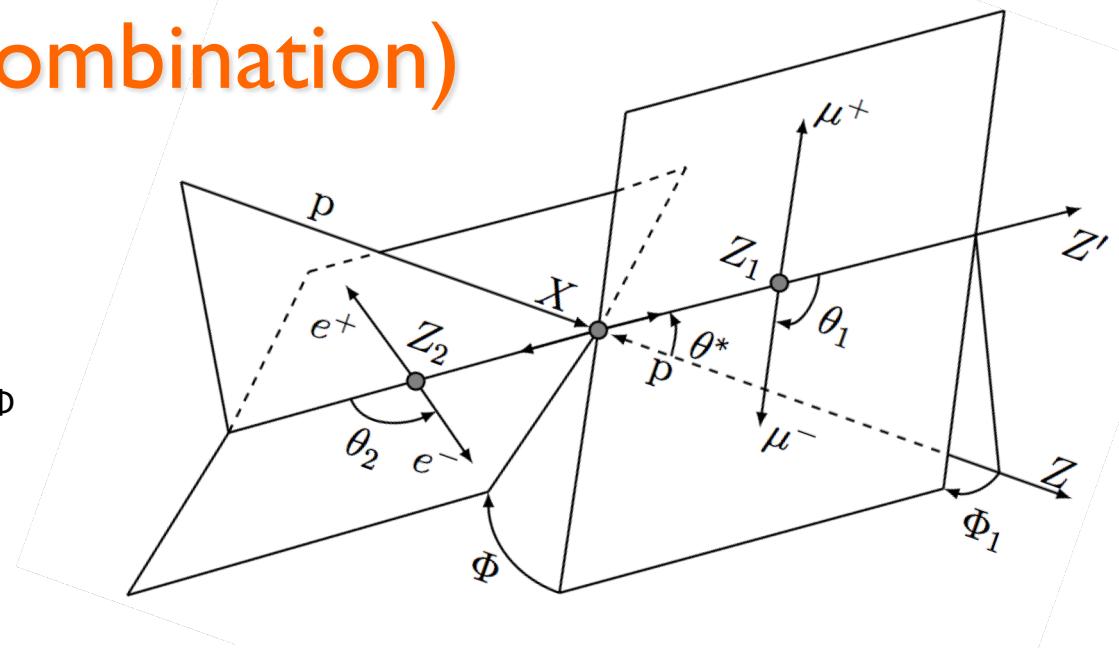
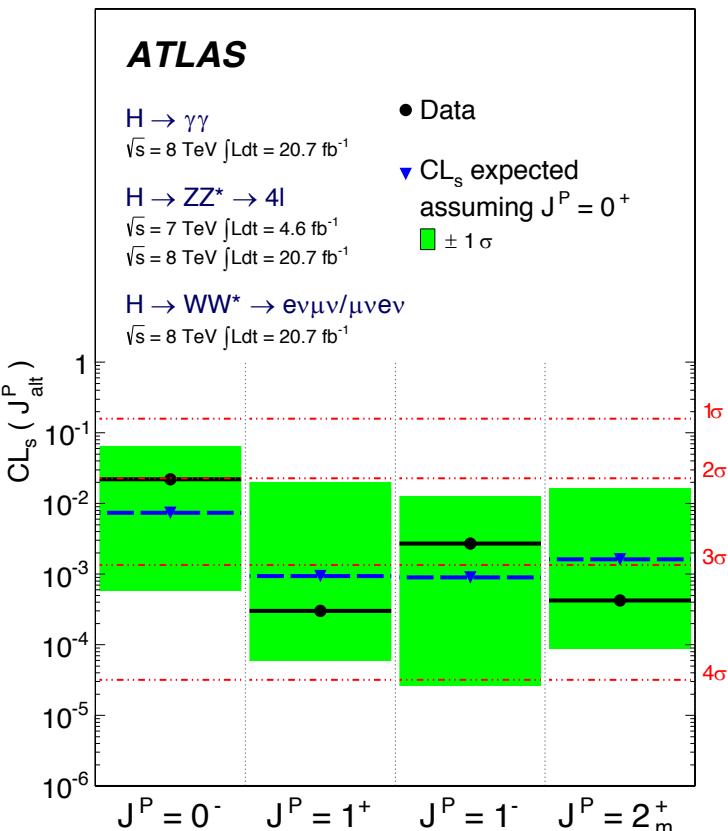


decay	SM BR [%]
$H \rightarrow bb$	58.1
$H \rightarrow WW$	21.5
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$H \rightarrow ZZ$	2.64
$H \rightarrow \gamma\gamma$	0.23

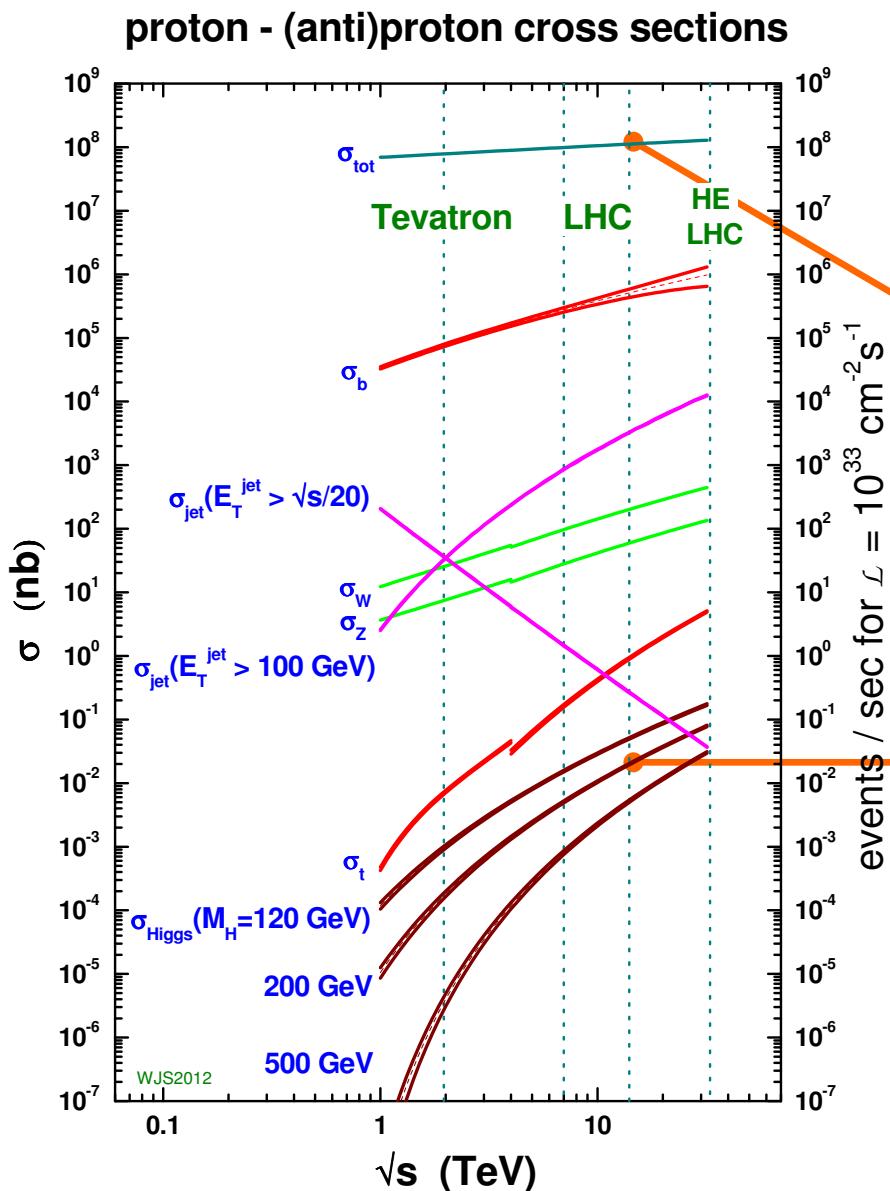
$m_H = 125.09 \text{ GeV}$

Spin with $H \rightarrow 4l$ (& combination)

- Sensitive variables combined in BDT score
 - ✓ Intermediate boson masses: m_{Z_1} , m_{Z_2}
 - ✓ Z_1 production angle: θ^*
 - ✓ Z_1 decay plane angle: Φ_1
 - ✓ Angle between the Z_1 and Z_2 decay planes: Φ
 - ✓ Decay angles of negative leptons: θ_1 , θ_2



Interesting processes are rare!



$$1 \text{ nb} = 10^{-33} \text{ cm}^2$$

$$\sigma_{\text{tot}}(13 \text{ TeV}) = 10^8 \text{ nb}$$

$$\sigma_H(13 \text{ TeV}) = 0.05 \text{ nb}$$

$$\text{LHC instantaneous luminosity } \mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

inelastic $p\bar{p}$ collisions

10^9 events/s

$\sim 10^{10}$

10^{-1} events/s

$\sim 1 \text{ Higgs boson}$
every 2 seconds

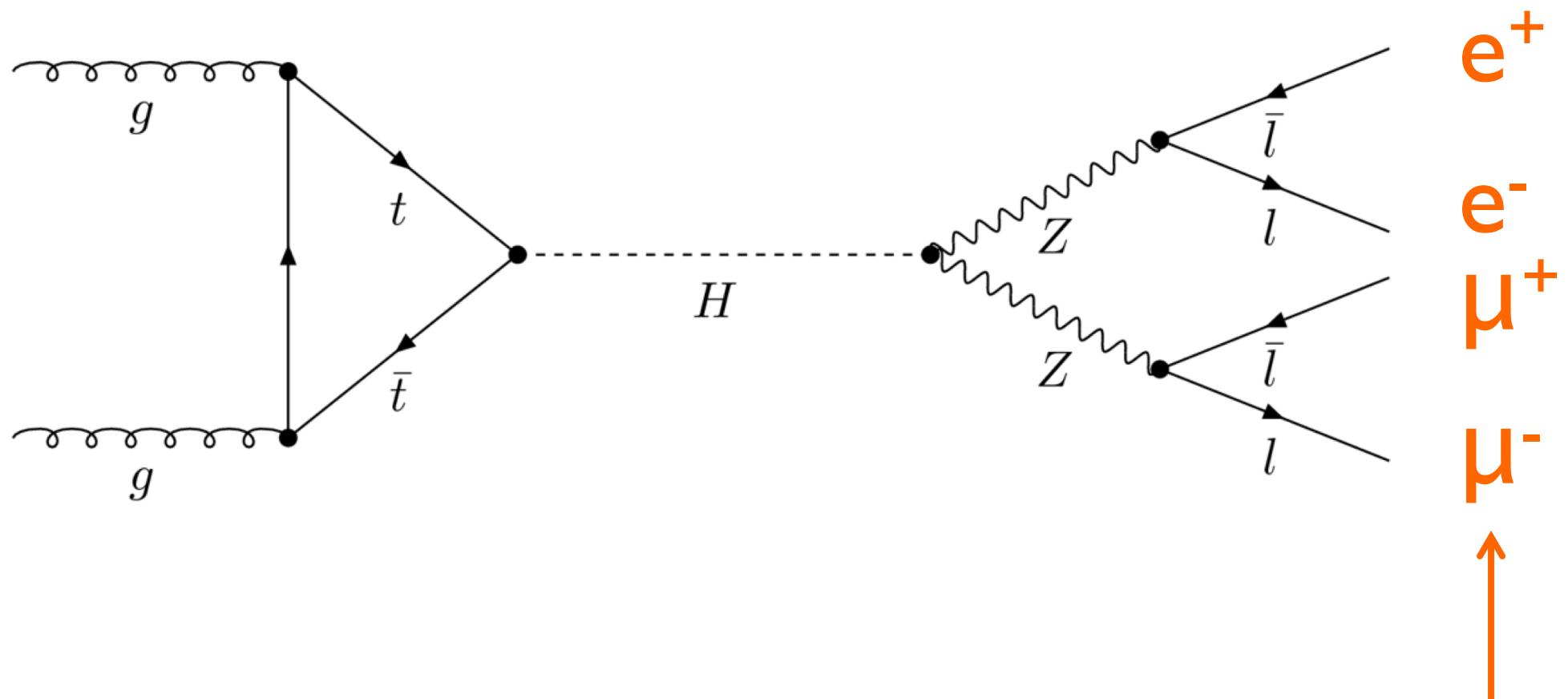
$[m_H \sim 125 \text{ GeV}]$

$0.2\% H \rightarrow \gamma\gamma$

$1.5\% H \rightarrow ZZ$



There is no Higgs-boson detector!

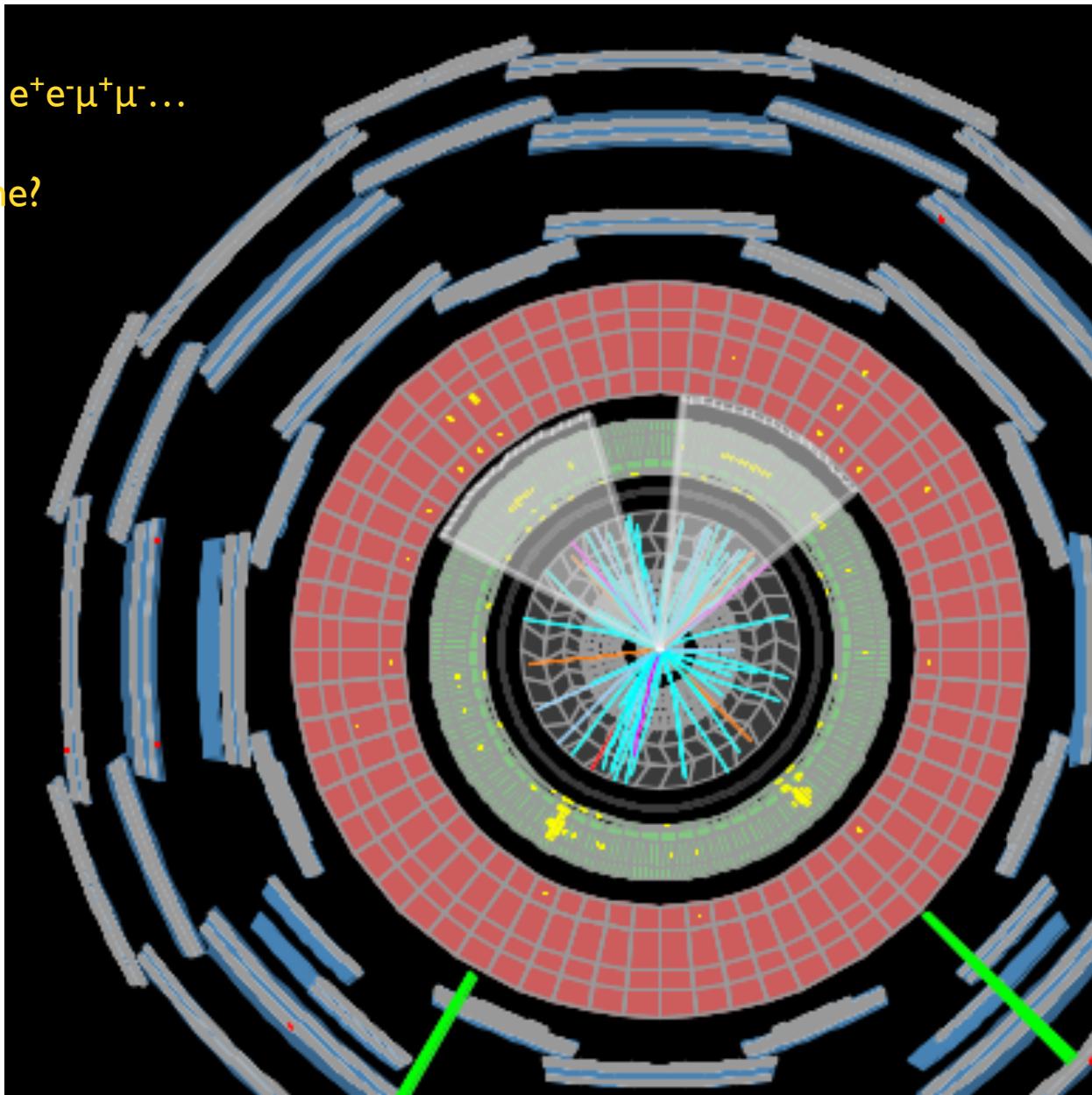


this is what we are looking for...

Step I: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-...$

What about this one?

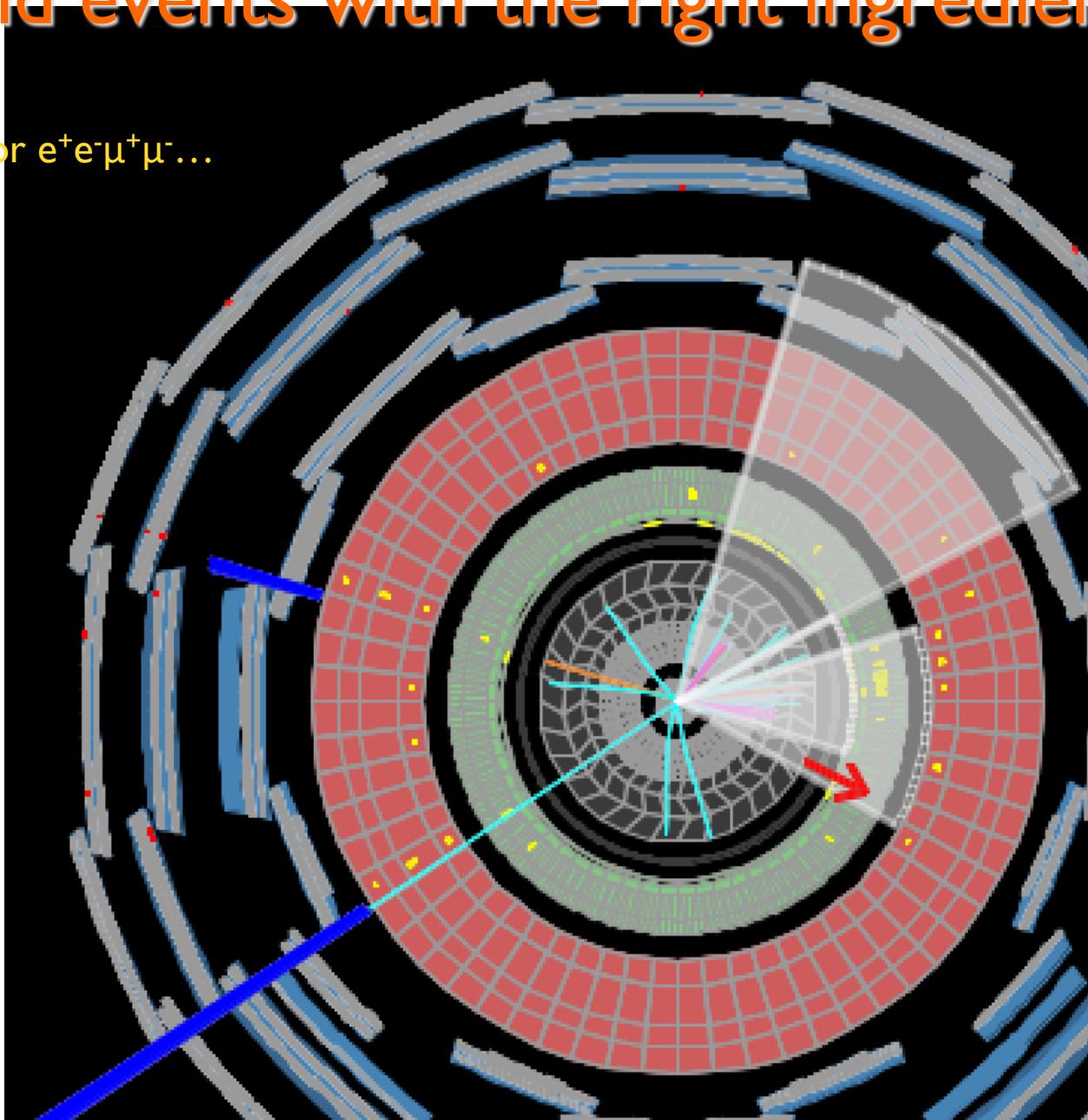


(experimental) LHC physics

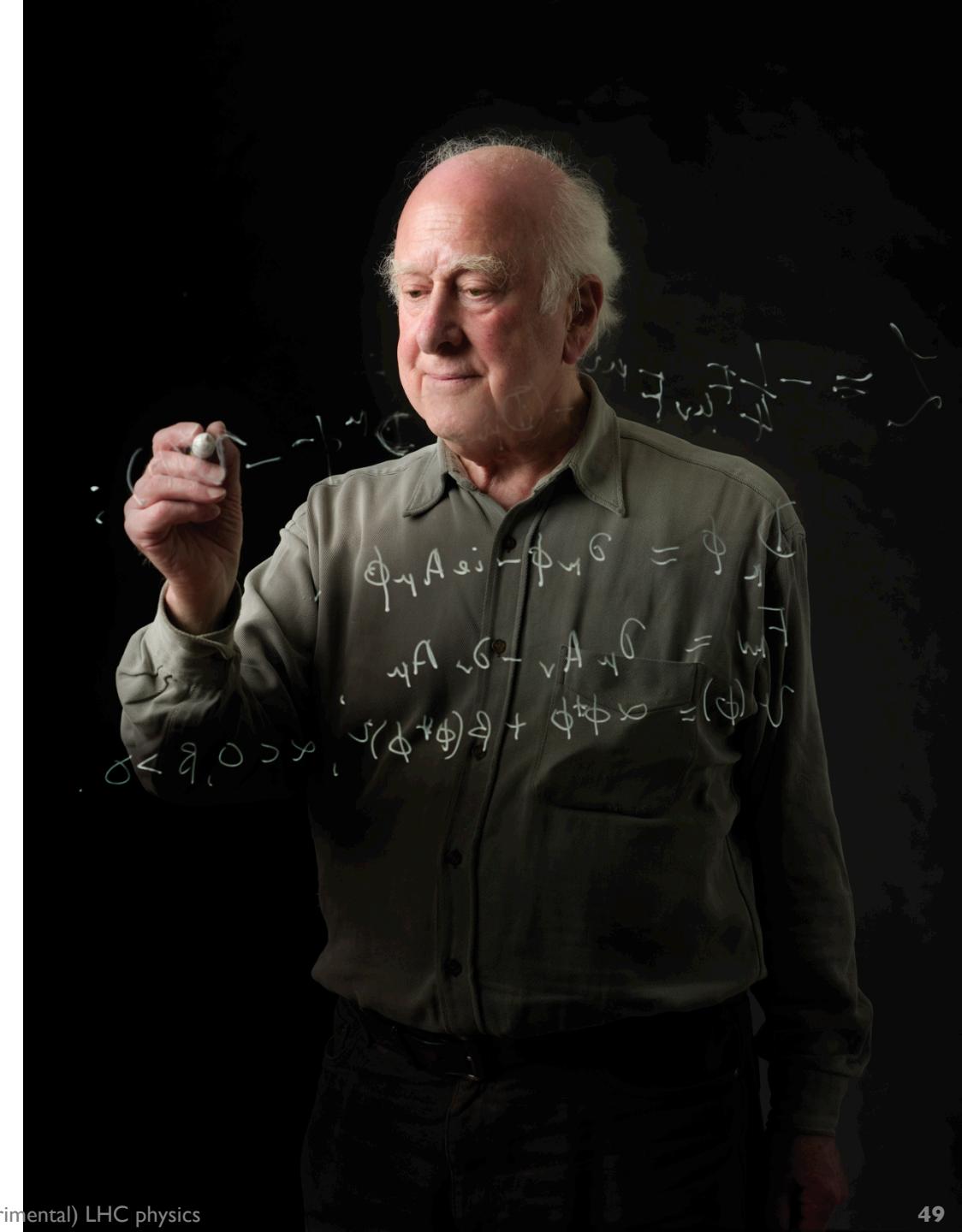
Step I: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^- \dots$

And this one?



is it the Higgs boson?



Spin!

What's a particle spin?

*“An amount of rotation
that is somehow
quantized”*

An electron has always
an angular momentum of $\frac{1}{2} \hbar$
either in its direction of travel ($+\frac{1}{2} \hbar$)
or opposite to it ($-\frac{1}{2} \hbar$)

$$\hbar = 1.0545 \times 10^{-34} \text{ m}^2 \text{ kg / s}$$

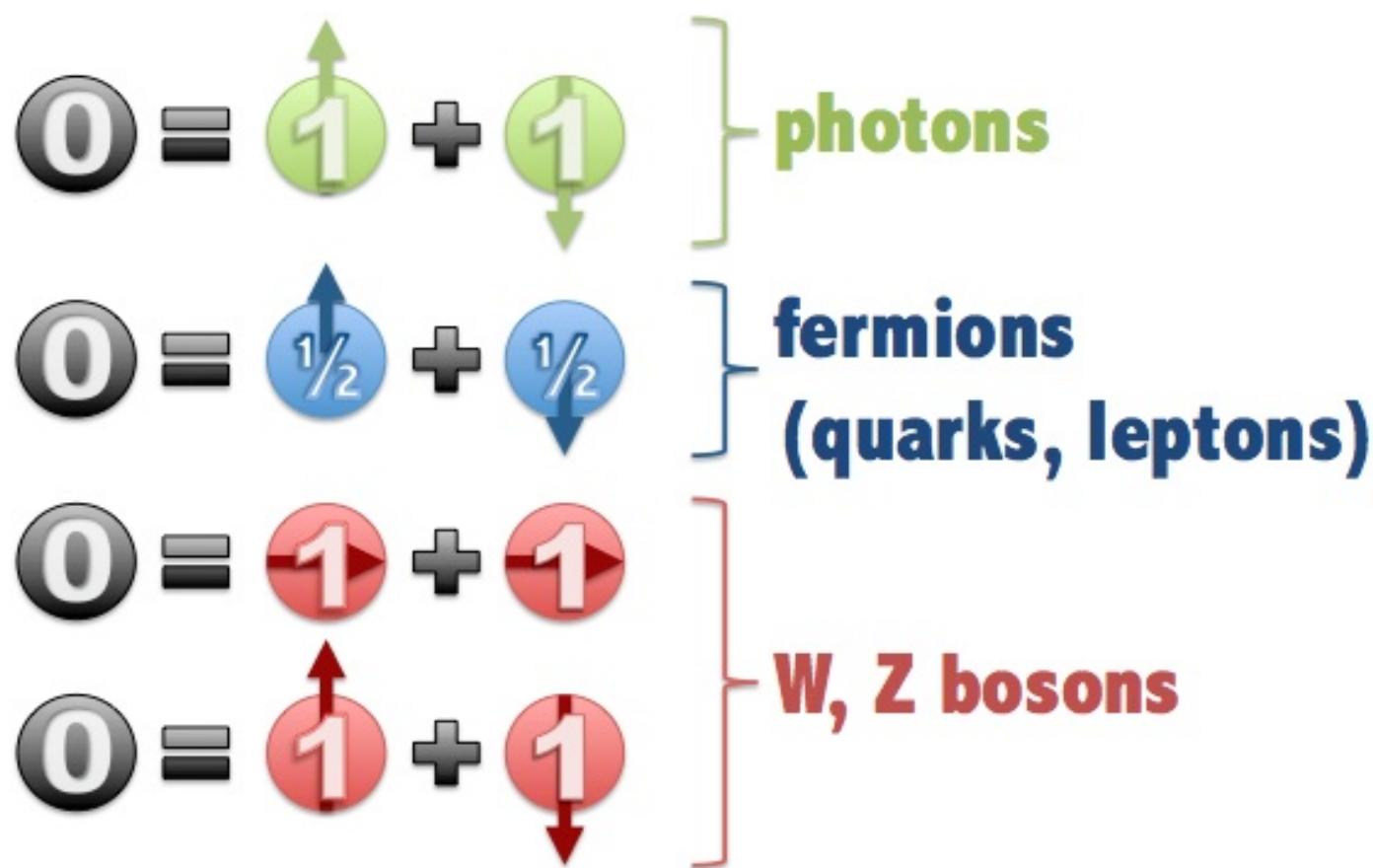
What spin do particles have?

 **fermions**
(quarks, leptons)
spin = +1/2, -1/2

 **massive bosons**
(W, Z bosons)
spin = +1, 0, -1

 **massless bosons**
(photon, gluon)
spin = +1, -1

What can a spin 0 particle decay to?



What can a spin 1 particle decay to?

$$\begin{aligned} \textcircled{\textbf{1}} &\neq \textcircled{\textcolor{lightgreen}{1}} + \textcircled{\textcolor{lightgreen}{1}} & \} &\textcolor{lightgreen}{\text{photons}} \\ \textcircled{\textbf{1}} &= \textcircled{\textcolor{blue}{1/2}} + \textcircled{\textcolor{blue}{1/2}} & \} &\textcolor{blue}{\text{fermions}} \\ \textcircled{\textbf{1}} &= \textcircled{\textcolor{red}{1}} + \textcircled{\textcolor{red}{1}} & \} &\textcolor{red}{\text{W, Z bosons}} \end{aligned}$$

What can a spin 2 particle decay to?

$$2 = \text{ } \begin{matrix} \uparrow \\ 1 \end{matrix} + \text{ } \begin{matrix} \uparrow \\ 1 \end{matrix} \quad \} \text{ photons}$$

$$2 \neq \text{ } \begin{matrix} 1/2 \\ \uparrow \end{matrix} + \text{ } \begin{matrix} 1/2 \\ \uparrow \end{matrix} \quad \} \text{ fermions}$$

$$2 = \text{ } \begin{matrix} \uparrow \\ 1 \end{matrix} + \text{ } \begin{matrix} \uparrow \\ 1 \end{matrix} \quad \} \text{ W, Z bosons}$$

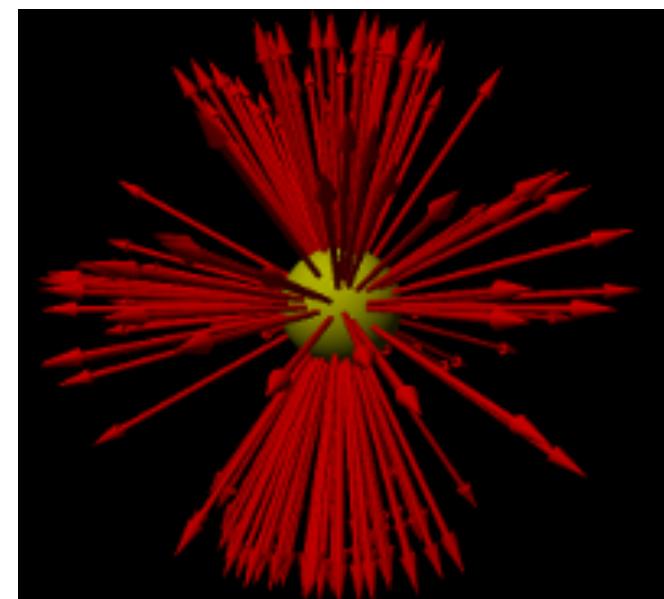
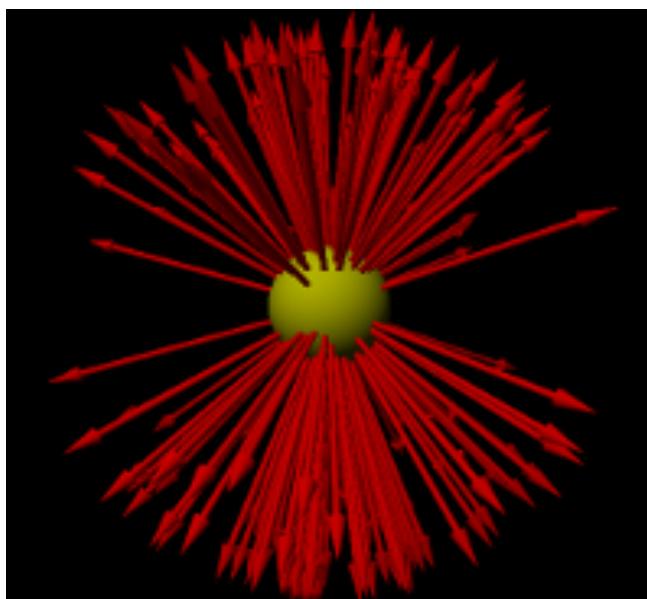
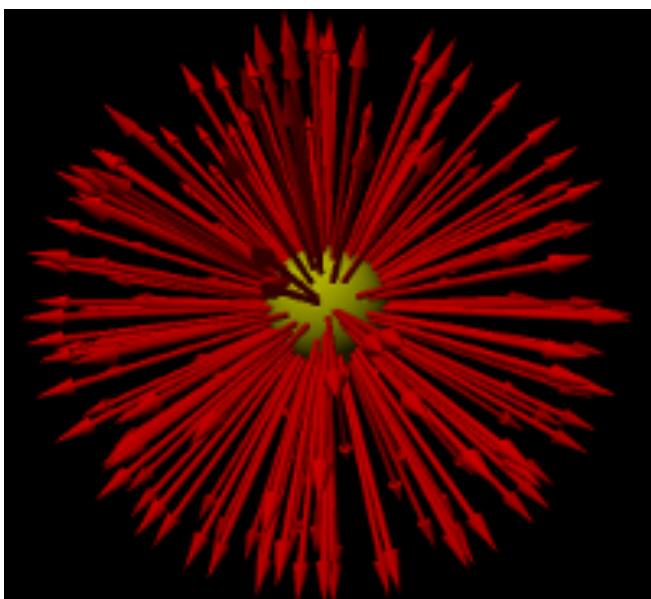
$$2 = \text{ } \begin{matrix} \uparrow \\ 1/2 \end{matrix} + \text{ } \begin{matrix} \uparrow \\ 1/2 \end{matrix} + \text{ } \begin{matrix} \uparrow \\ 1 \end{matrix} \quad \} \text{ b quarks+gluon}$$

$$2 \neq \text{ } \begin{matrix} 1/2 \\ \uparrow \end{matrix} + \text{ } \begin{matrix} 1/2 \\ \uparrow \end{matrix} \quad \} \text{ } \tau \text{ leptons}$$

So, what spin has our Higgs-like particle?

Spin of particle	$\gamma\gamma$	ZZ^*
Spin 0		
Spin 1		
Spin 2		

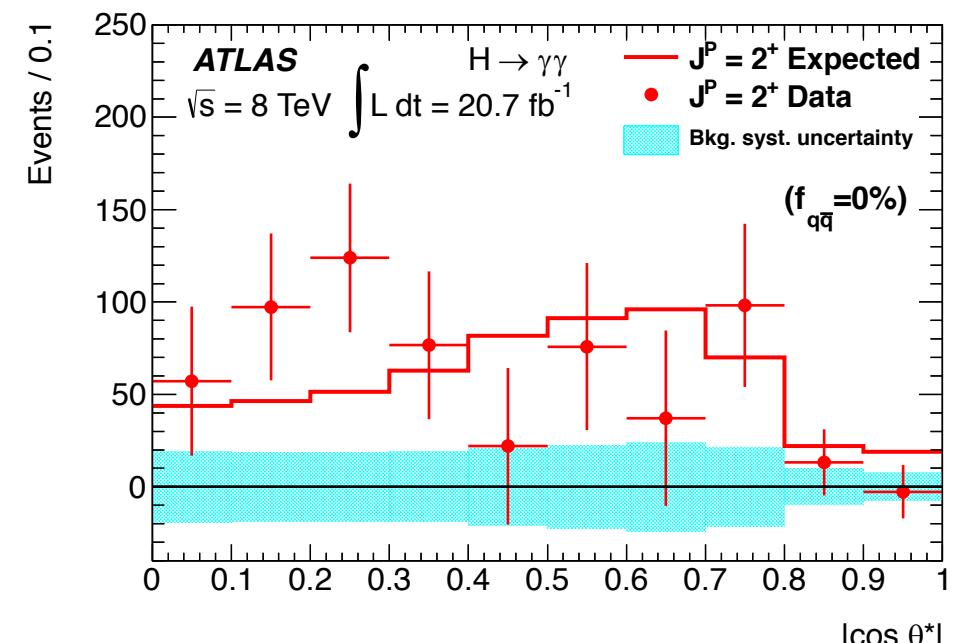
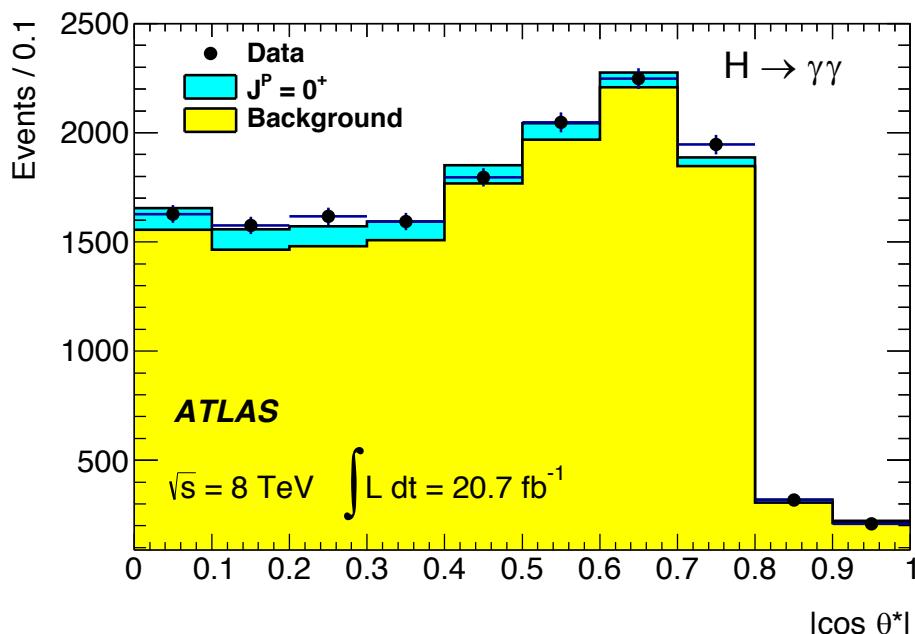
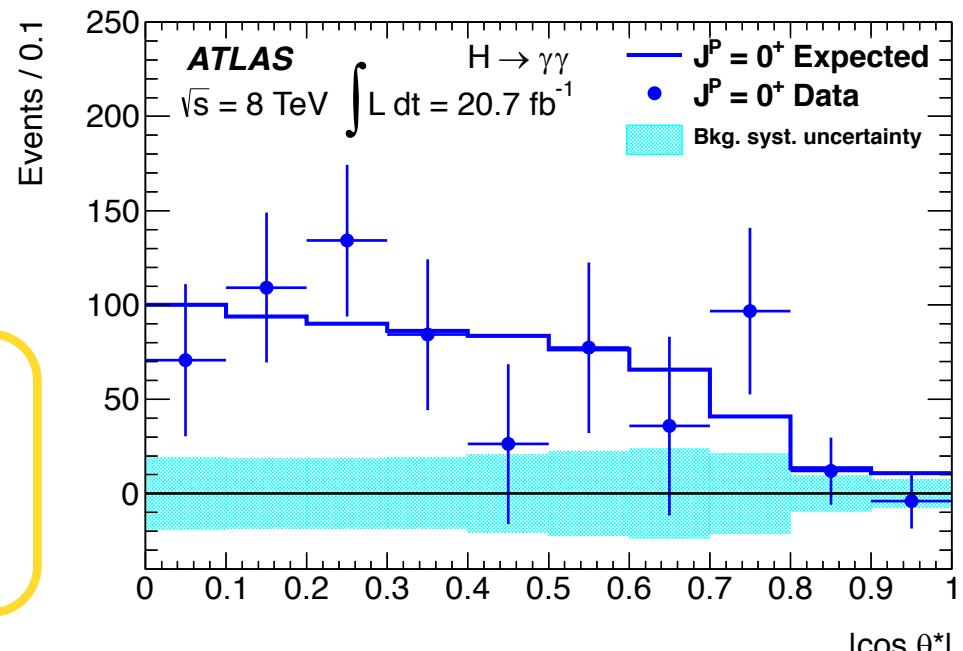
How can we recognize spin?



Spin with $H \rightarrow \gamma\gamma$

$\gamma\gamma$ polar angle ϑ^* with respect to Z-axis in Colin-Sopper frame

$$\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + (p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



The Higgs boson or a Higgs boson?

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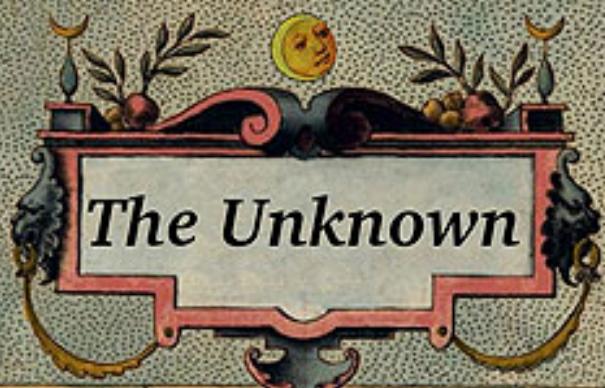
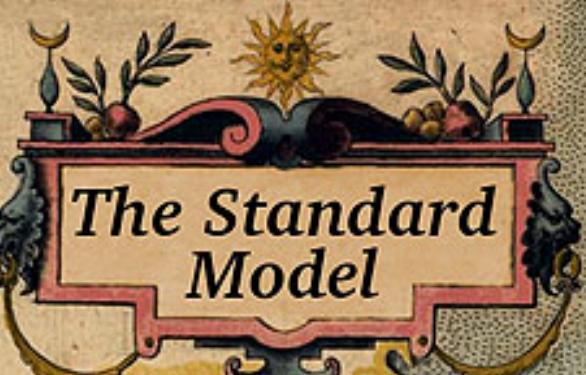
New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN¹'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Beyond the SM

dragons!

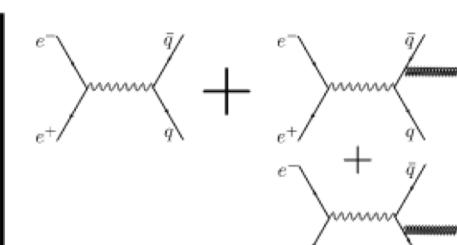
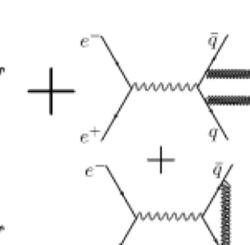
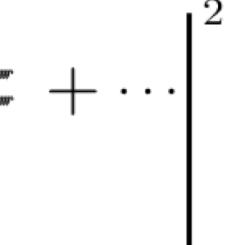


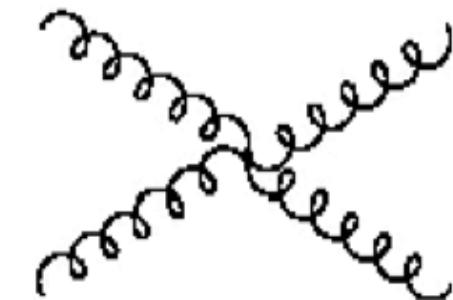
A few words about hadronic particles

• Principle of asymptotic freedom

- ✓ At short distances strong interactions are weak
 - Quarks and gluons are essentially free particles
 - Perturbative regime (can calculate!)
- ✓ At large distances, higher-order diagrams dominate
 - Interaction is very strong
 - Perturbative regime fails, have to resort to effective models

$$|\mathcal{M}|^2 = \left| e^- \begin{array}{c} \diagdown \\ \text{---} \\ \diagup \end{array} \bar{q} + e^- \begin{array}{c} \diagdown \\ \text{---} \\ \diagup \end{array} \bar{q} + e^- \begin{array}{c} \diagdown \\ \text{---} \\ \diagup \end{array} \bar{q} + \dots \right|^2$$

 +  + 
+ 

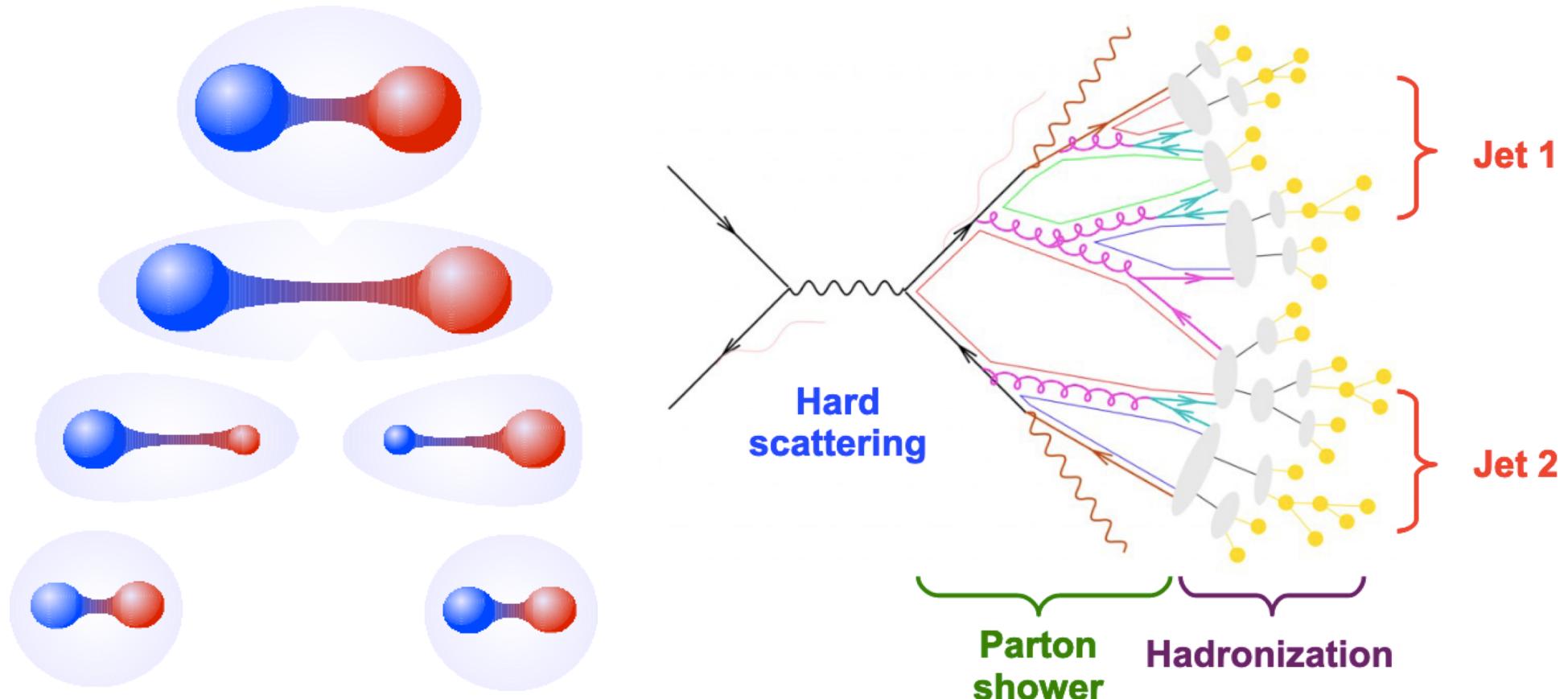


quark-quark effective potential

$$V_s = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

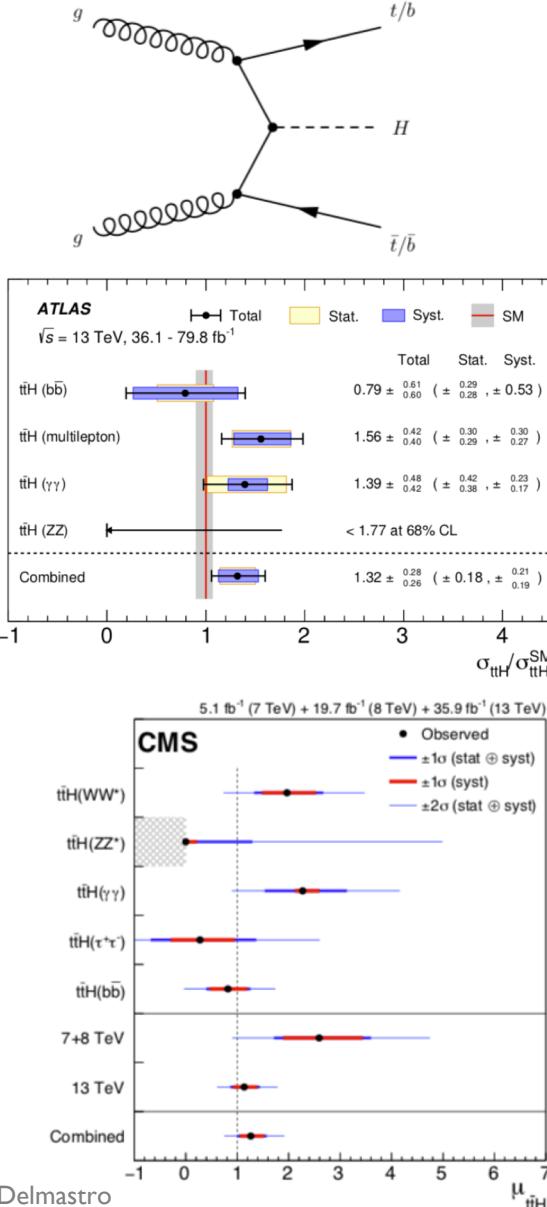
single gluon confinement
exchange

Confinement, hadronization, jets

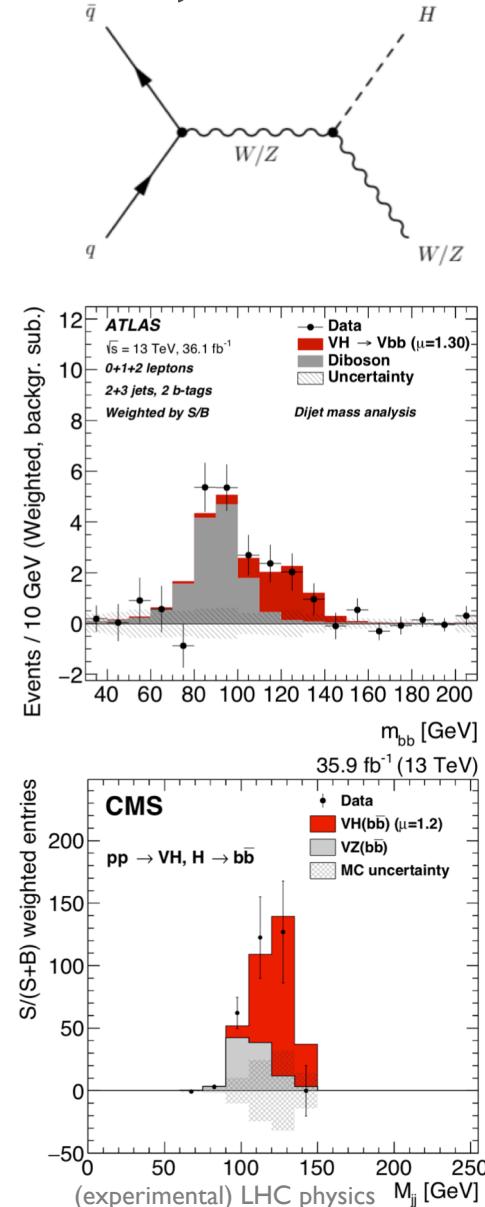


The Higgs boson definitively couples to fermions!

$t\bar{t}H$



$VH, H \rightarrow bb$



$H \rightarrow \tau\tau$

