

# How models are tested at the LHC

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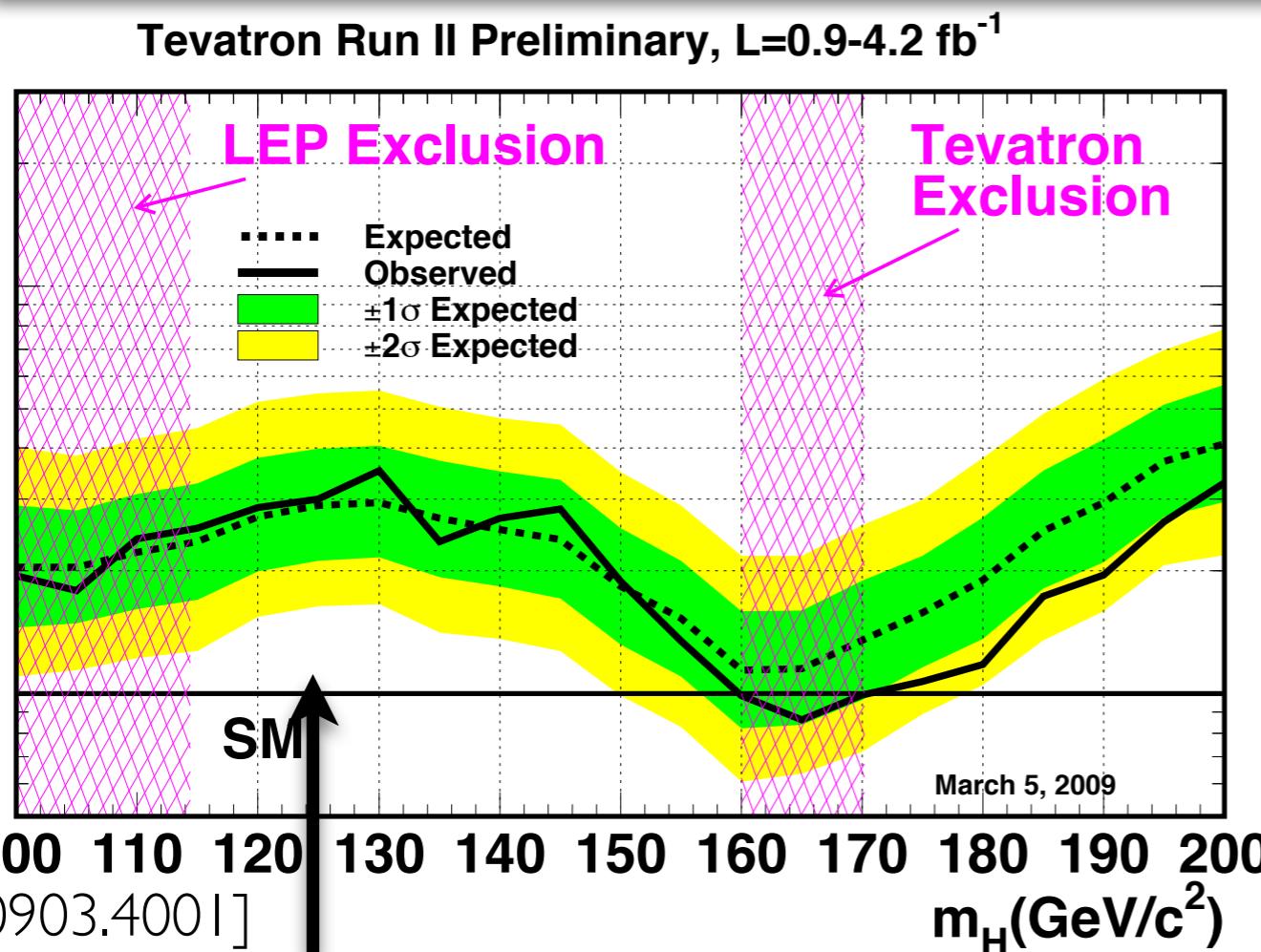
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UNIVERSITY OF CALIFORNIA  
**SANTA CRUZ**

# My main goal of this talk

I want to facilitate an appreciation for statistical confidence intervals like below, and try to touch ground with how LHC physicists go from collecting and reducing data to performing a statistical test.



Lot's of important details glossed over. Great pedagogical documents on statistics:

- ▶ Cranmer, K. "Practical Statistics for the LHC". [arxiv:1503.07622]
- ▶ Cowan, G. (1998). *Statistical Data Analysis*.
- ▶ ATLAS Higgs Combination [arxiv:1207.0319]
- ▶ Cranmer et al. [arxiv:1007.1727]

Higgs was later found in 2012 by  
ATLAS and CMS with  $m_H \approx 125 \text{ GeV}$

# Outline

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1. Introduce the Standard Model, some issues, and some ideas beyond it.
2. Cram together some scattering theory.
3. Introduce the LHC and ATLAS.
4. Discuss reconstruction and model building in HEP.
5. Cram some lessons in statistical hypothesis testing.  
e.g. searches for new physics and the Higgs discovery.
6. Try to make some provocative comments and summarize.

# The Standard Model

- In QFT, **fields** are actually what is fundamental, and particles are quantized and often localized excitations in the fields.
- **Gauge symmetries** determine the character of the forces between fermion fields through exchanging gauge bosons.
- Bosons and chiral fermions develop mass terms that still preserve the gauge symmetries of the Lagrangian through the **Higgs mechanism**.
- The SM gauge group is

$$\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$$

**Strong force**

**Electroweak force**

**Higgs mechanism,  
EW symmetry breaking**

**Electromagnetic  
+ weak forces**

field content of the SM

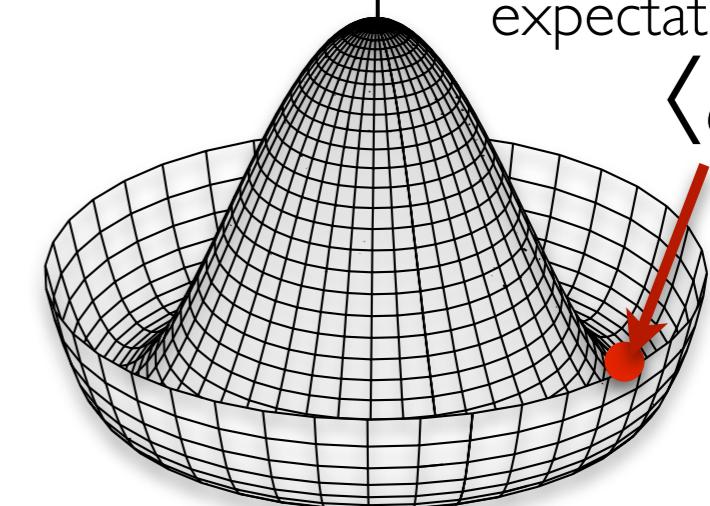
	Fermions			Bosons
Quarks	$u$ up	$c$ charm	$t$ top	$\gamma$ photon
	$d$ down	$s$ strange	$b$ bottom	$Z$ Z boson
Leptons	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	$W$ W boson
	e electron	$\mu$ muon	$\tau$ tau	$g$ gluon

Higgs boson

$V(\phi)$  Higgs potential

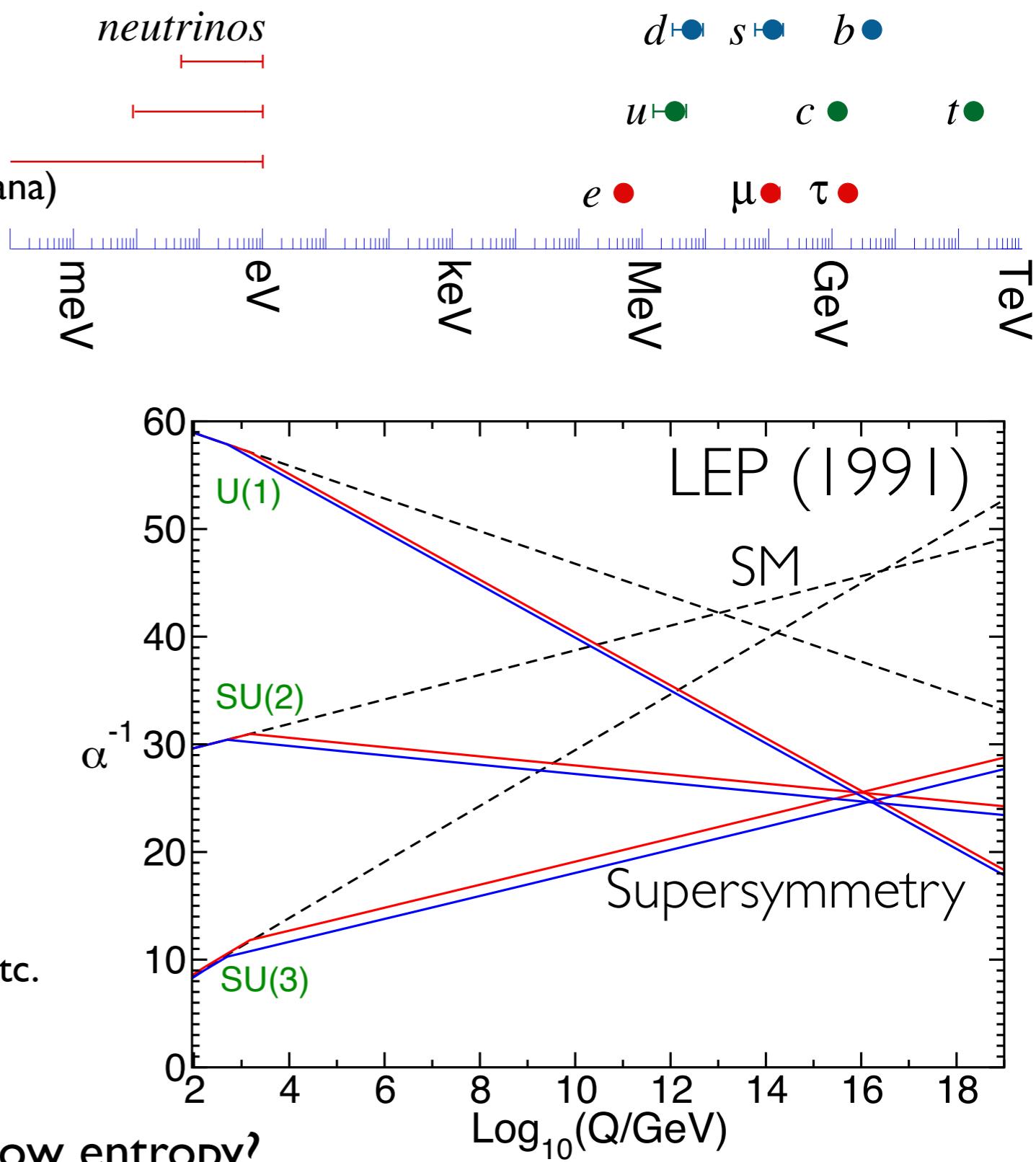
vacuum expectation value

$\langle\phi\rangle$

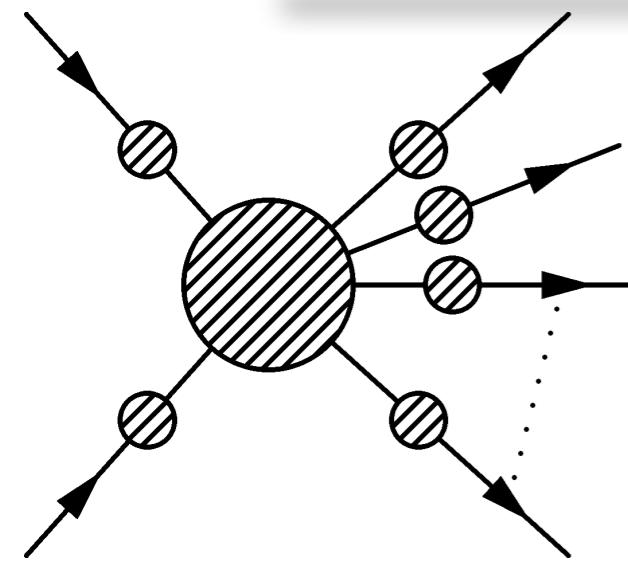


# Unanswered problems in particle physics

- Ad hoc features
  - ▶ Why  $SU(3) \times SU(2) \times U(1)$  ?
  - ▶ Neutrino mixing and masses (Dirac or Majorana)
  - ▶ Matter-antimatter asymmetry
  - ▶ Strong CP-problem
- Dark matter and dark energy
  - ▶ 5% SM, 27% dark matter, 68% dark energy
- Hierarchy problem(s)
  - ▶  $m_{\text{Higgs}} \text{ vs } m_{\text{Planck}}$ ,
  - ▶ quark masses range:  $10^5$ , leptons:  $10^9$
- Fine-tuning:
  - ▶ EW-scale, flatness problem, vacuum stability, etc.
- Unification? Supersymmetry?
- Why did the early universe have such low entropy?



# Scattering cross sections



At colliders, it can be shown that the differential rate of any given process factors as

$$dN = \varepsilon L dt d\sigma$$

= (efficiency) (luminosity) d(time) d(cross section)

QFT shows that the **cross section** can be calculated in terms of a **matrix element**.

$$d\sigma = \prod_f \left( \frac{d^3 p_f}{(2\pi)^3 2 E_f} \right) \frac{|\mathcal{M}|^2}{4 E_1 E_2 |v_1 - v_2|} (2\pi)^4 \delta^4(p_1 + p_2 - \sum_f p_f)$$

The number of expected events can be calculated by integrating the differential cross section over the running of the experiment.

$$N = \int dt L \int d\sigma \varepsilon$$
$$= \left( \int dt L \right) A C \sigma$$

= (integrated luminosity) (acceptance) (efficiency) (cross section)

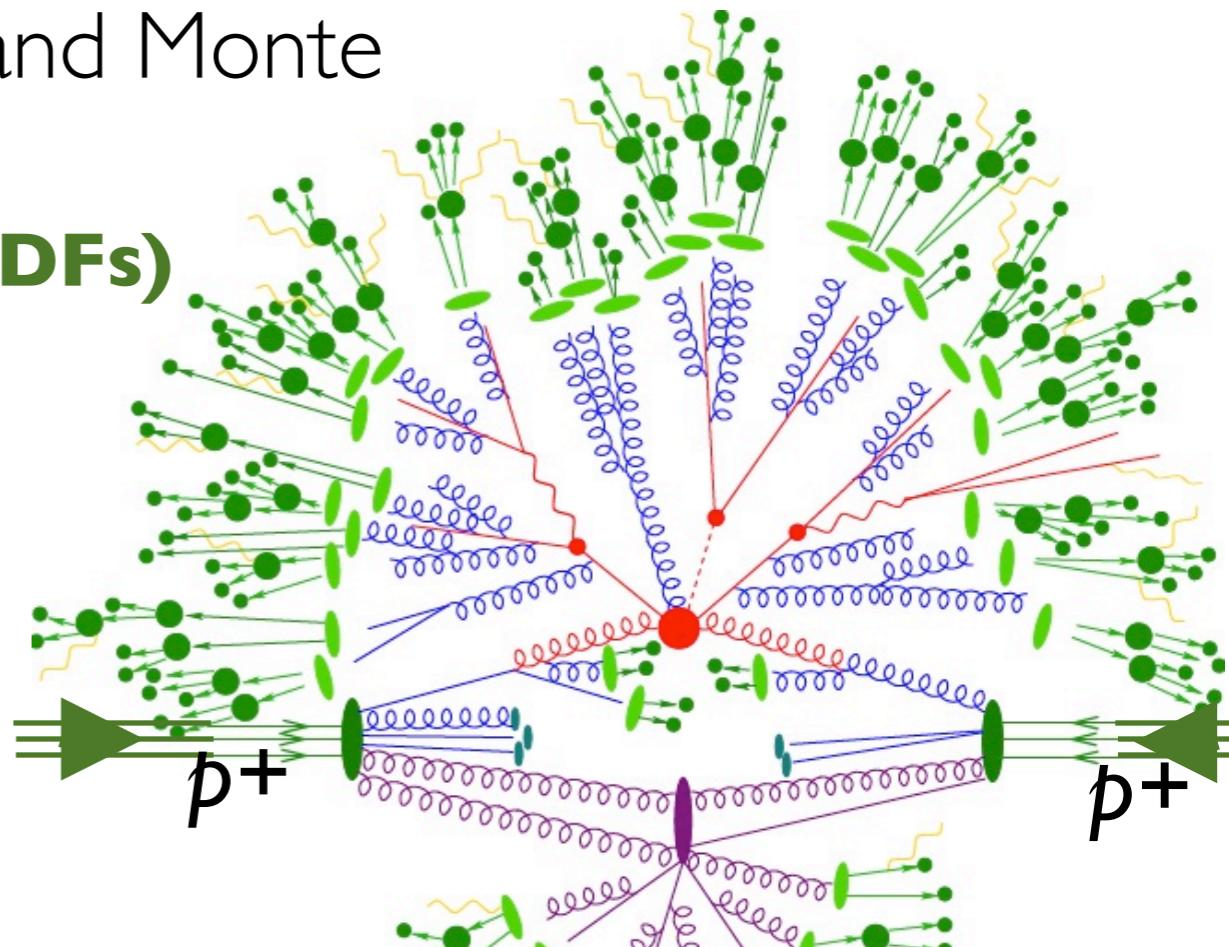
# Matrix element

Hard-scatter matrix elements are calculated from a perturbative sum of Feynman graphs.

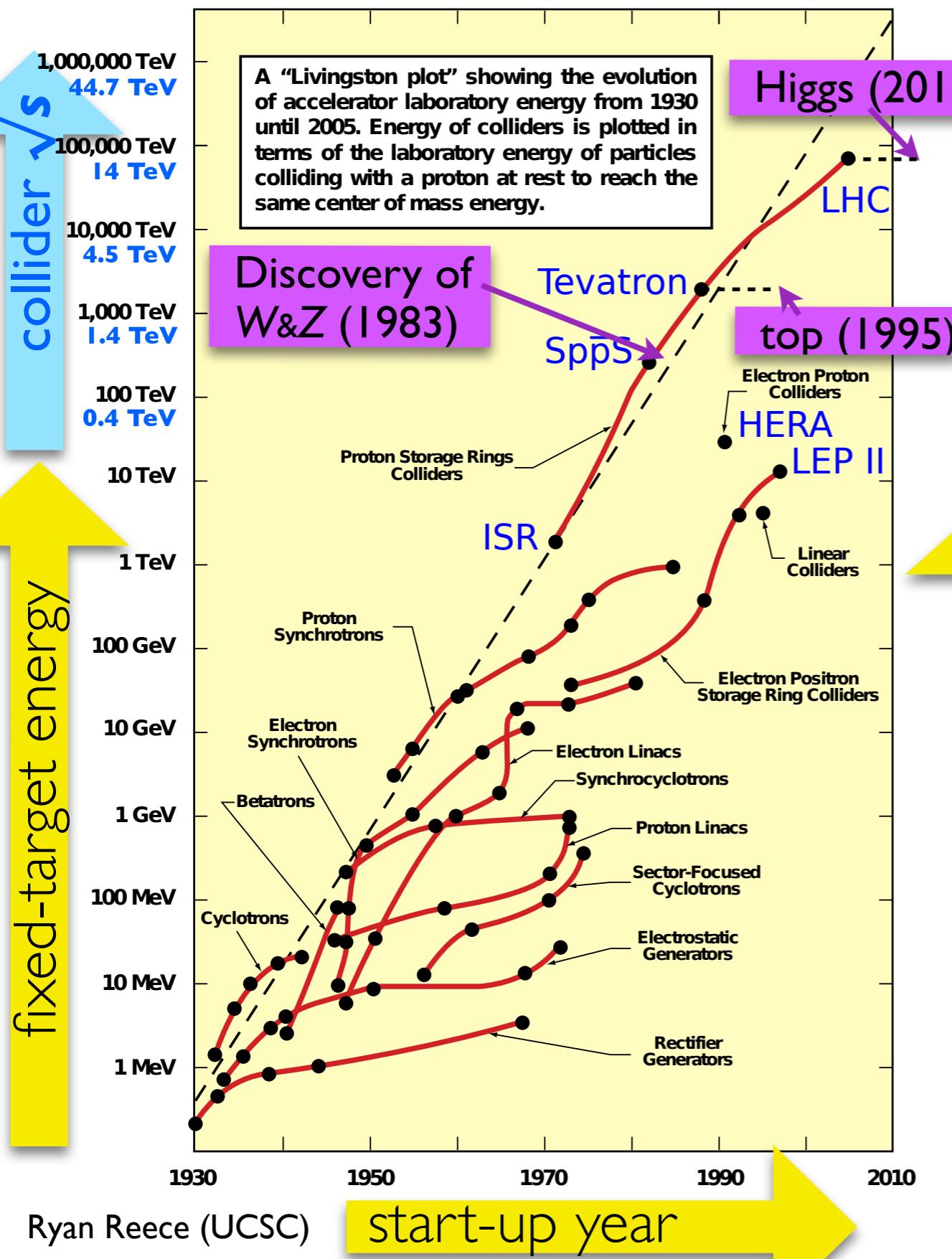
$$|\mathcal{M}|^2 \left( p^+ \xrightarrow{\text{jet}} \text{jet} \xrightarrow{\text{photon}} p^+ \right) = \left| \sum \left( \begin{array}{c} \text{Feynman graphs} \\ \text{with loop} \end{array} \right) \right|^2$$

The strong force further complicates things by confining quarks in hadrons. Theorists and Monte Carlo simulations factor the problem:

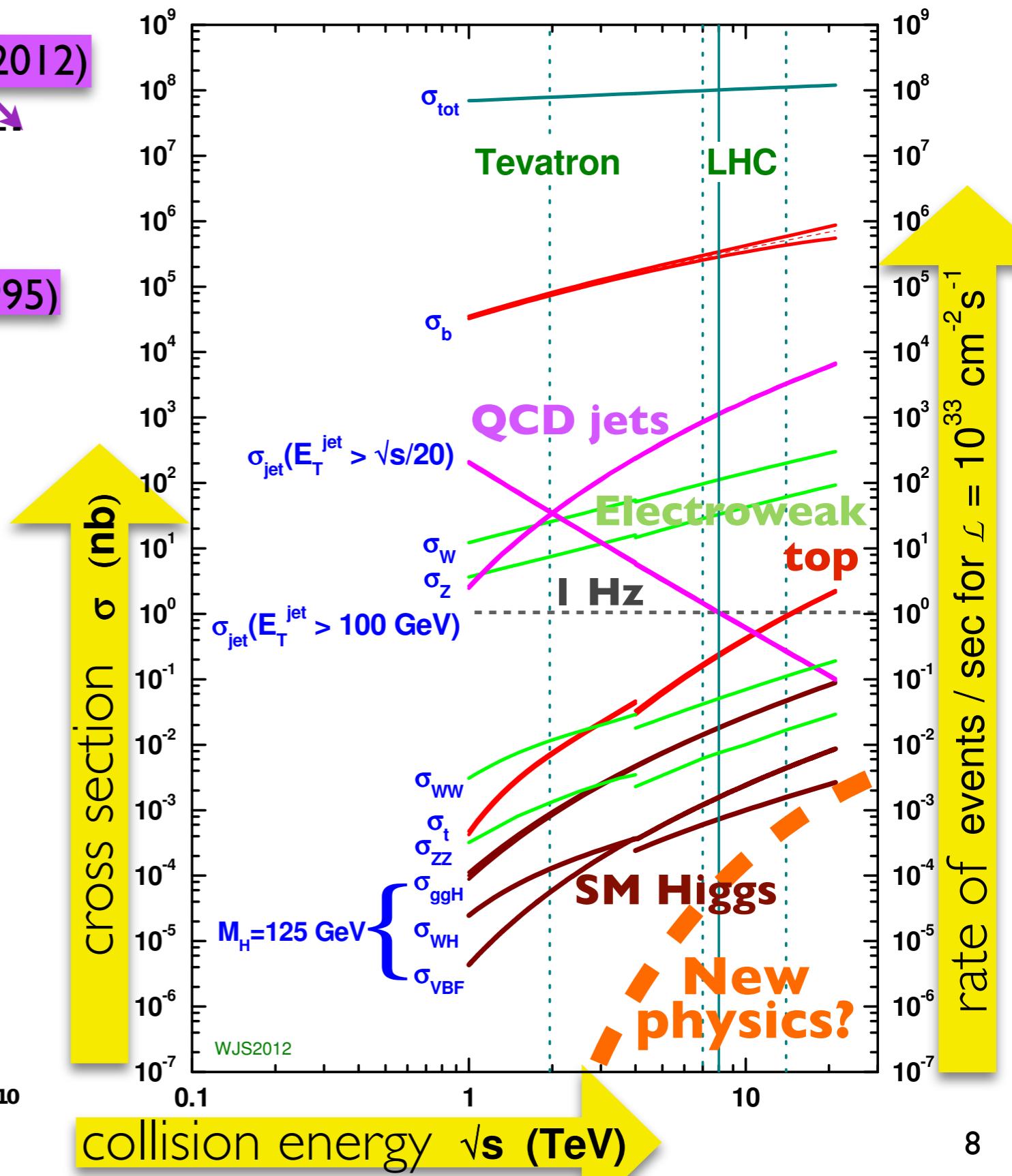
- “**Parton Distribution Functions**” (**PDFs**)
- “**Hard-scatter**” **matrix element generator**
- “**Parton shower**”, **Bremsstrahlung**, **Initial/final-state radiation**
- “**Hadronization**”



# We need high energies



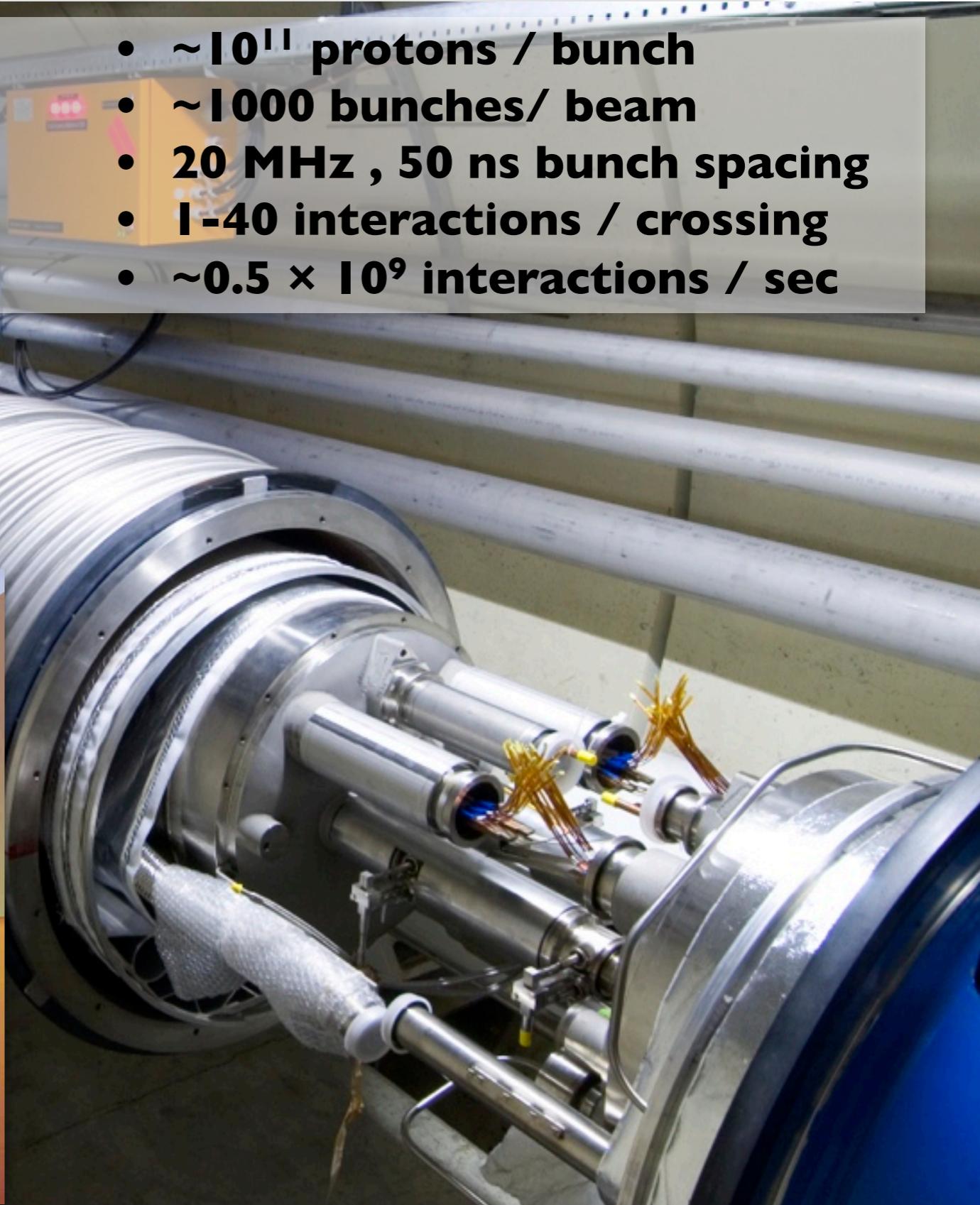
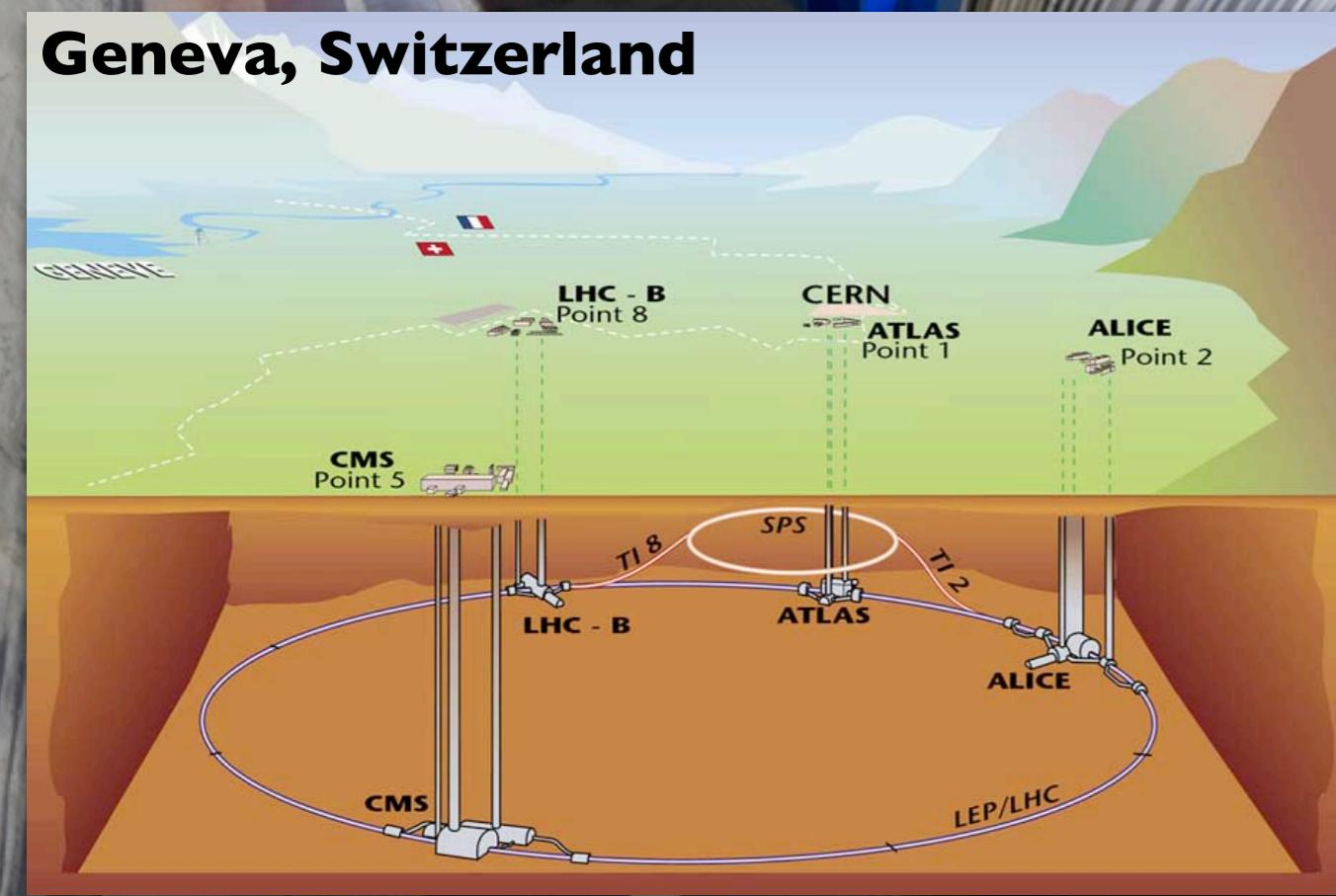
proton - (anti)proton cross sections



# Large Hadron Collider

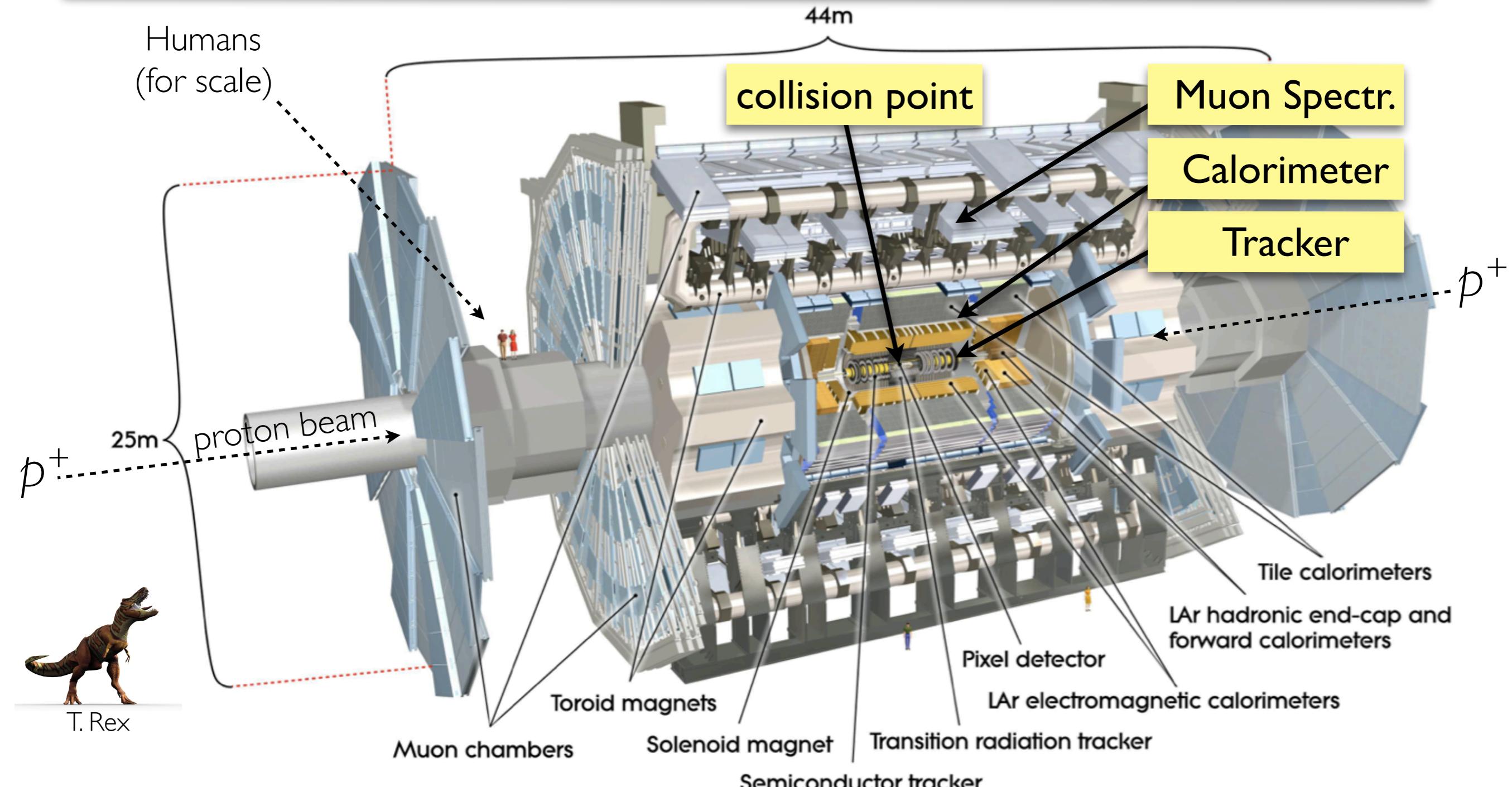
- p-p collisions at  $\sqrt{s} = 7\text{-}13 \text{ TeV}$
- inst. luminosity =  $10^{32}\text{-}10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- 27 km circumference
- 1232 dipoles: 15 m , 8.3 T
- 100 tons liquid He, 1.9 K
- $\sim 10^{11}$  protons / bunch
- $\sim 1000$  bunches/ beam
- 20 MHz , 50 ns bunch spacing
- 1-40 interactions / crossing
- $\sim 0.5 \times 10^9$  interactions / sec

Geneva, Switzerland

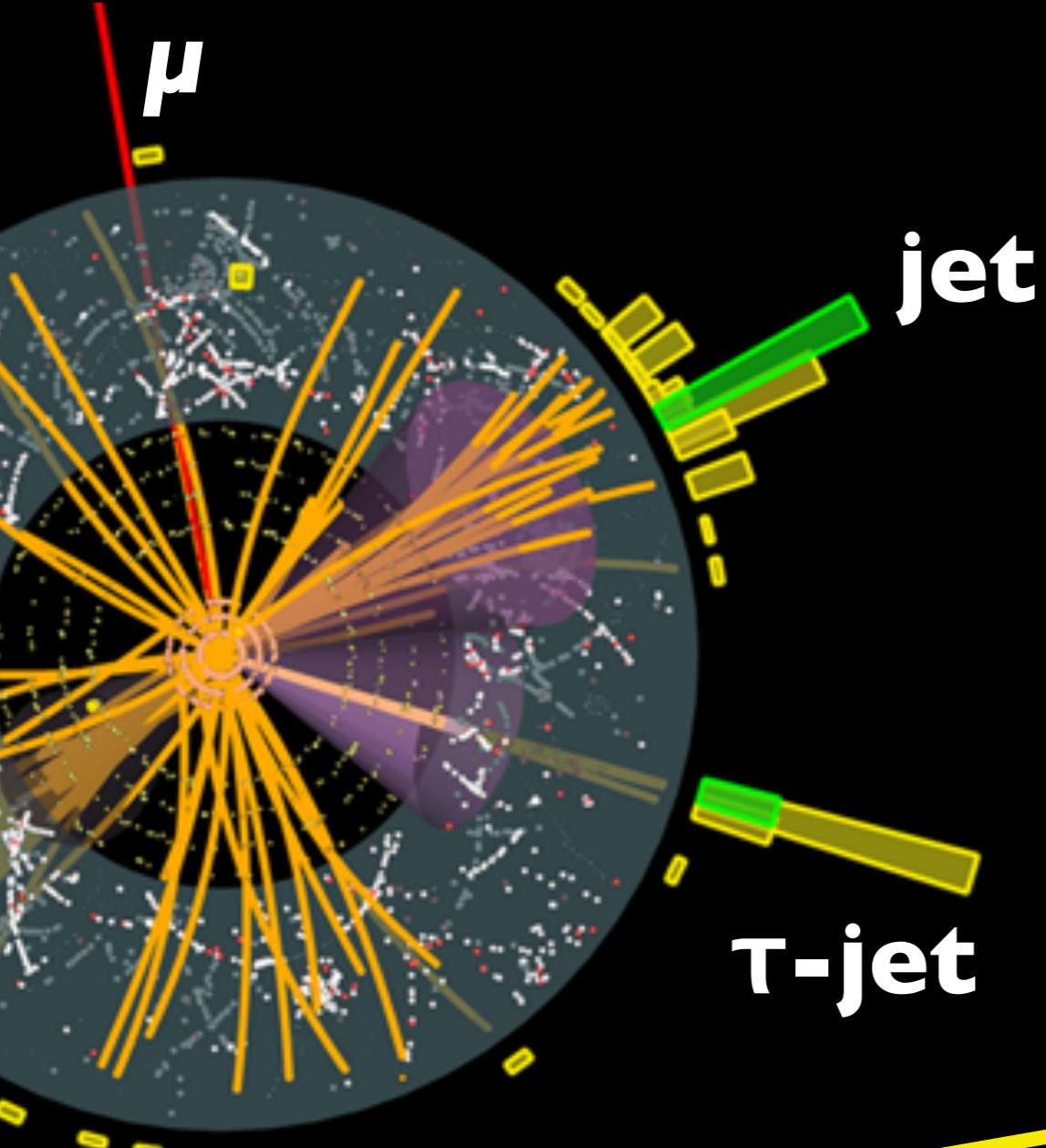


# ATLAS Detector

ATLAS is a 7 story tall, 100 megapixel “camera”, taking 3-D pictures of proton-proton collisions 20 million times per second, saving 10 million GB of data per year, using a world-wide computing grid with over 100,000 CPUs. The collaboration involves more than 3000 scientists and engineers.



# What do we reconstruct?



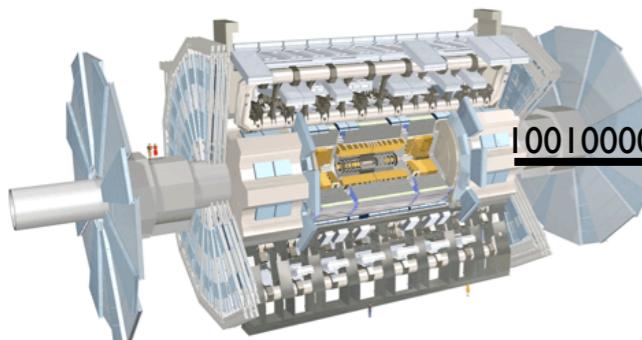
- muons (main objects)
- electrons & photons
- jets of hadrons
- $\tau$ - and  $b$ -tagged jets
- missing energy

## How do we search?

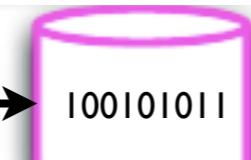
### ATLAS Physics Groups



Currently ATLAS has published 410+ papers

**ATLAS****3-level trigger**
 $20 \text{ MHz} \rightarrow 60 \text{ kHz}$   
 $\rightarrow 6 \text{ kHz} \rightarrow 500 \text{ Hz}$ 


raw data

 $\sim 10 \text{ PB/year}$ 

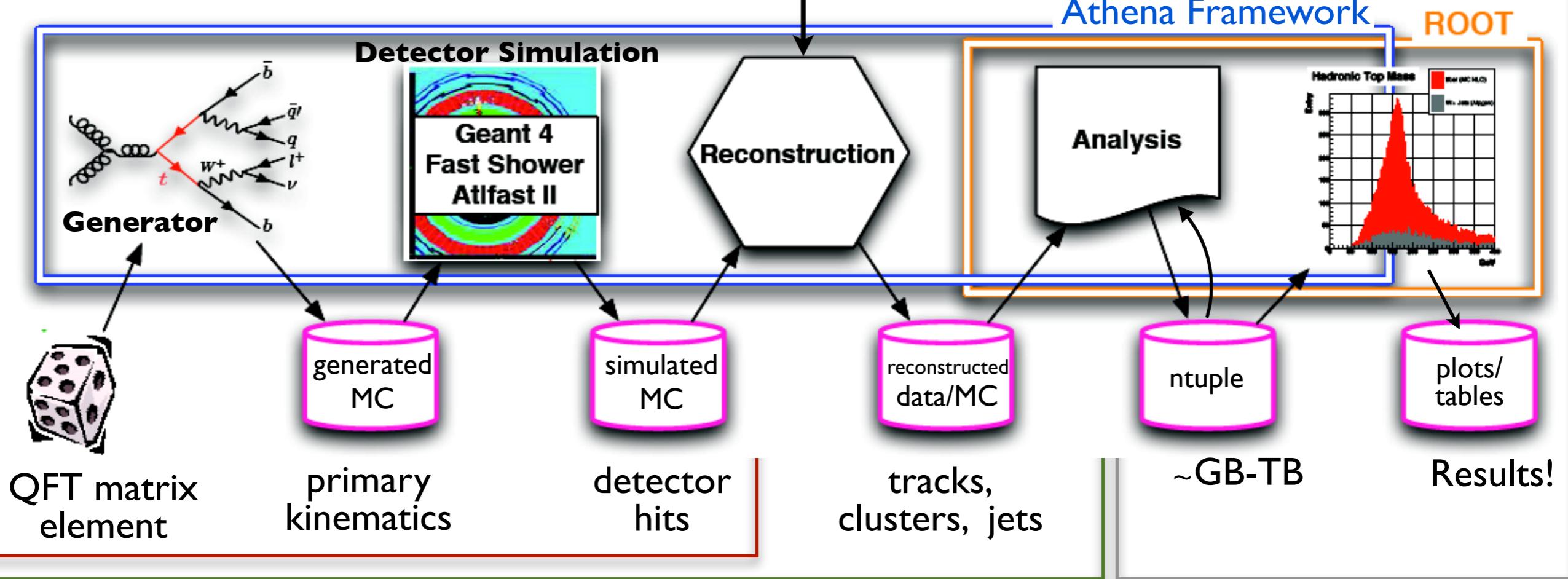
# ATLAS

## Data Flow

Worldwide LHC Computing Grid

Monte Carlo production

Local resources

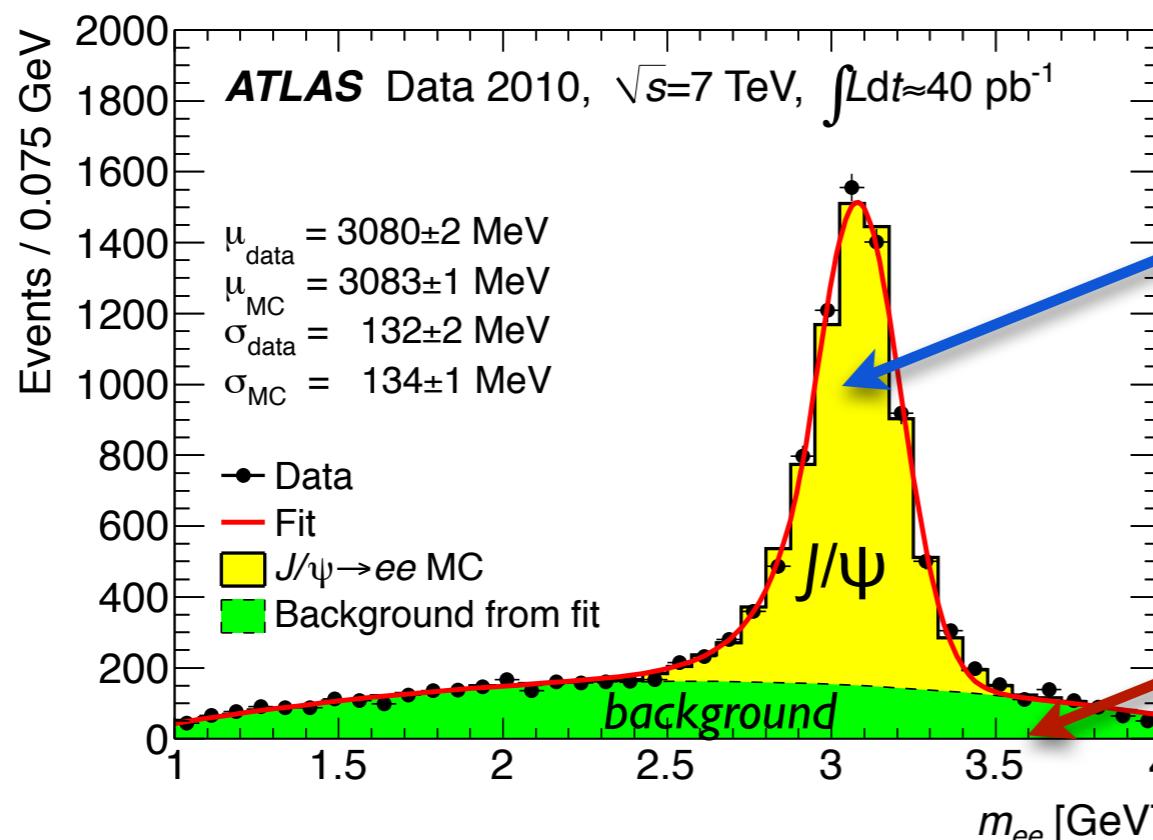


# Building a model

$$N(\text{expected}) = \underbrace{N(\text{correct-ID})}_{\text{Bottom-up}} + \underbrace{N(\text{fake})}_{\text{Top-down, "data-driven"}}$$

- **Bottom-up**
- well-identified objects have scale factors from control regions
- estimated with detailed Monte Carlo simulation

- **Top-down, “data-driven”**
- various magic with data depending on the analysis and your creativity
- side-band fit
- fake-factor method



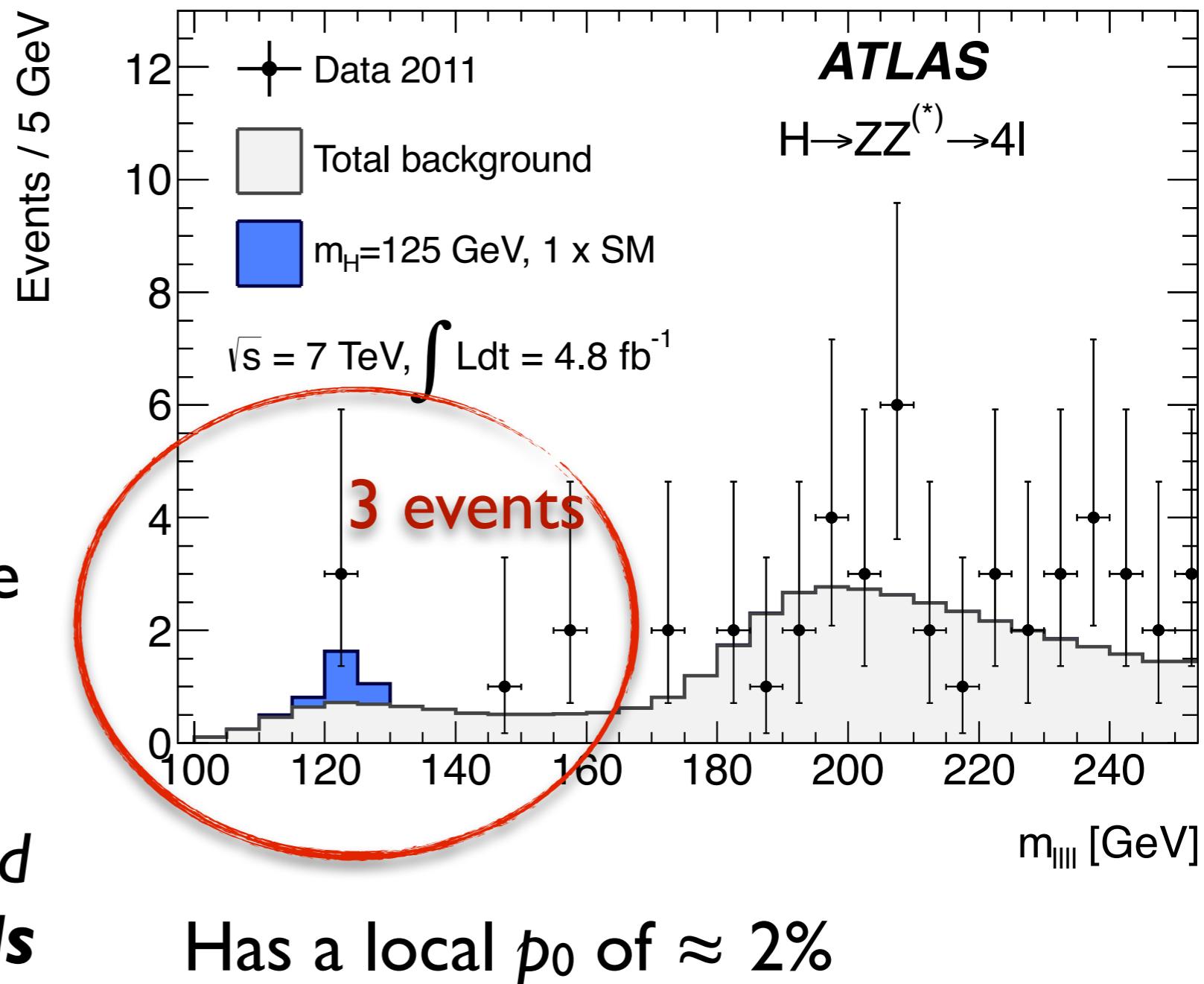
**Bottom-up**  
Monte Carlo

**Data-driven**  
side-band fit

# Is this significant?

## Statistical (and philosophical) questions:

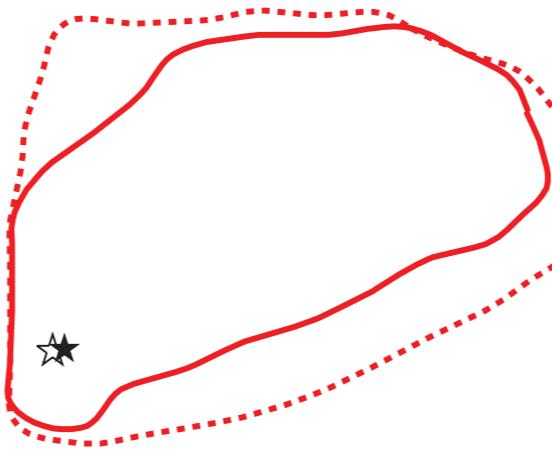
- How can we be precise and rigorous about how confident we are that a model is wrong?
  - ▶ **Hypothesis testing**
- How can we calculate the best-fit estimate of some parameter?
  - ▶ **Point estimation and confidence intervals**



# Confidence Intervals

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- A **frequentist confidence interval** is constructed such that, given the model, if the experiment were repeated, each time creating an interval, 95% (or other CL) of the intervals would contain the true population parameter (i.e. the interval has  $\approx 95\%$  coverage).
  - ▶ They can be one-sided exclusions, e.g.  $m(Z') > 2.0 \text{ TeV}$  at 95% CL
  - ▶ Two-sided measurements, e.g.  $m_H = 125.1 \pm 0.2 \text{ GeV}$  at 68% CL
  - ▶ Contours in 2 or more parameters
- This **is not the same** as saying “There is a 95% probability that the true parameter is in my interval”. Any probability assigned to a parameter strictly involves a Bayesian prior probability.



# Statistical model

“Marked Poisson” Probability model (PDF):

$$\mathcal{D} = \{x_1, \dots, x_n\}$$

data      #expected  
↓      ↓  
 $f(\mathcal{D}|\nu, \alpha) = \text{Pois}(n|\nu) \prod_{e=1}^n f(x_e|\alpha)$

events      observable  
 $\downarrow$   
 $n$   
 $f(x_e|\alpha)$   
 $e=1$  histograms

“Likelihood”  
 $L(\alpha)$   
function of params  
with data fixed

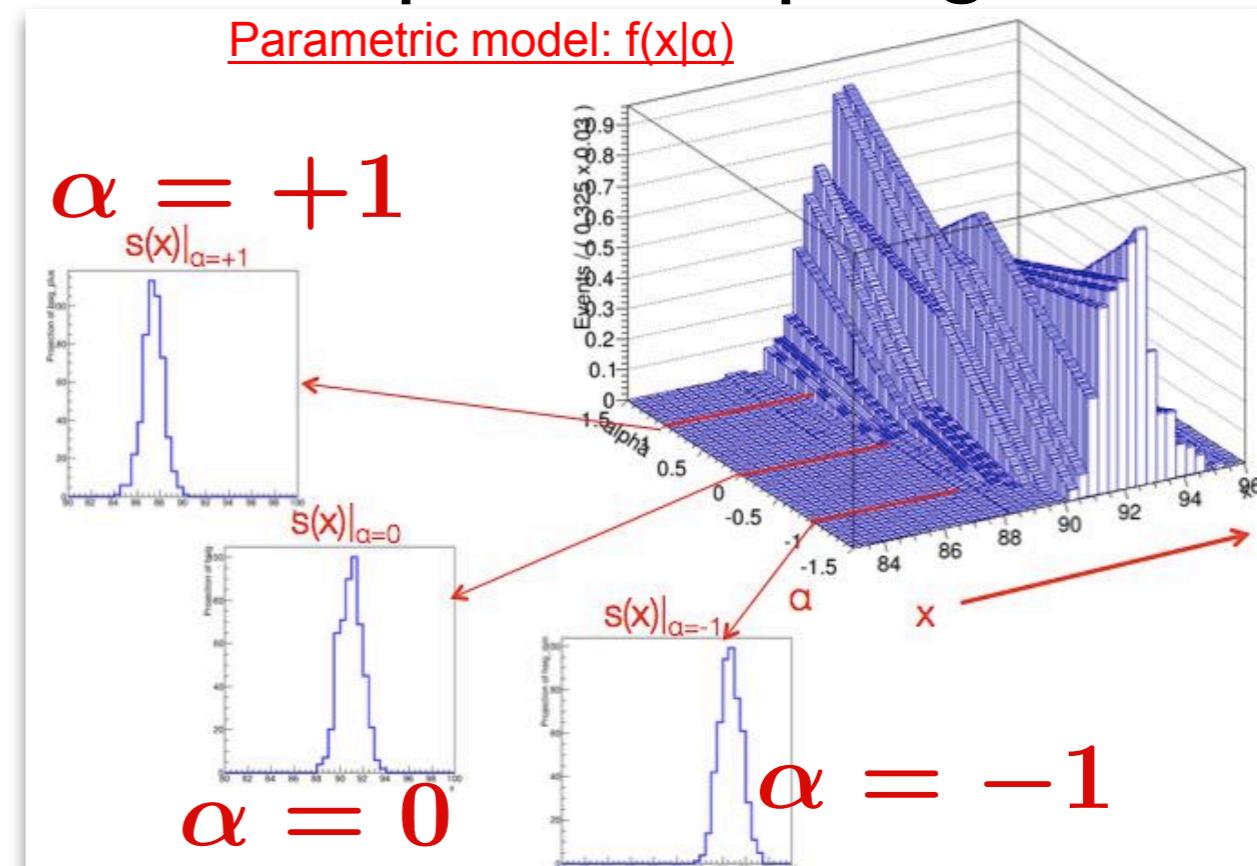
{ $\alpha$ } parameters include:

1. parameters of interest { $\mu$ }:

- e.g. Higgs mass ( $m_H$ ) and signal strength ( $\mu$ )  
 $\mu=0$  no signal,  $\mu=1$  nominal signal

template morphing

Parametric model:  $f(x|\alpha)$



2. nuisance parameters { $\theta$ }:

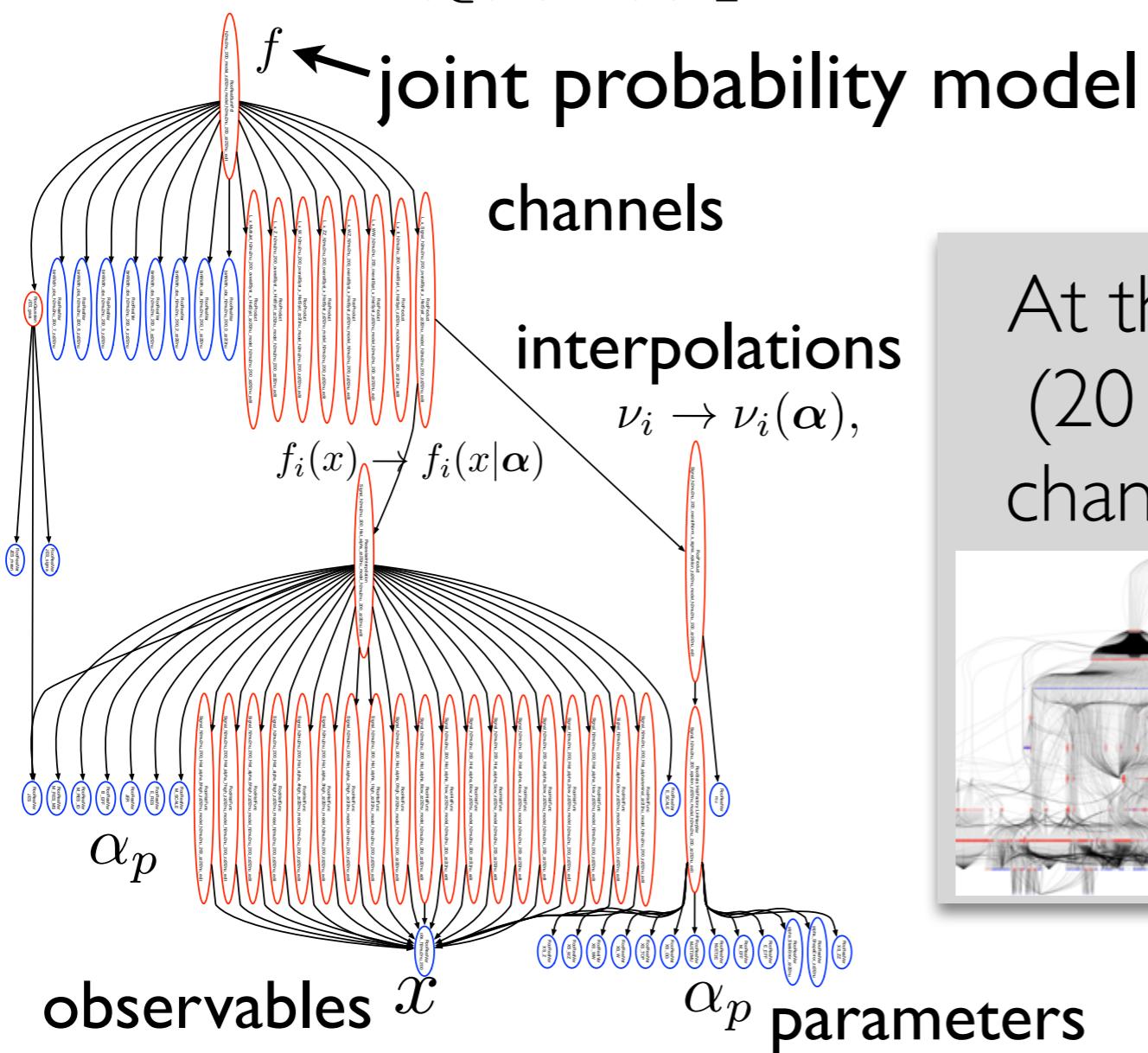
systematic uncertainties to be “profiled” away by maximizing  $L$  for a given  $\mu$ .

- e.g. luminosity uncert., jet-energy scale, electron energy scale, electron identification efficiency, etc.

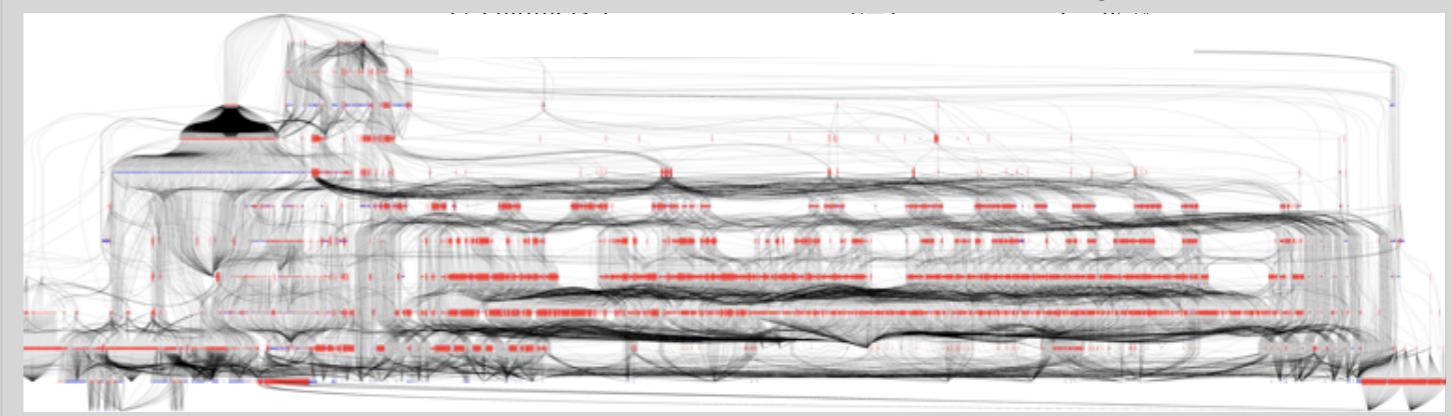
# Statistical model

General probability model with many channels and constraints:

$$f_{\text{tot}}(\mathcal{D}_{\text{sim}}, \mathcal{G} | \alpha) = \prod_{c \in \text{channels}} \left[ \text{Pois}(n_c | \nu_c(\alpha)) \prod_{e=1}^{n_c} f_c(x_{ce} | \alpha) \right] \cdot \prod_{p \in \mathbb{S}} f_p(a_p | \alpha_p)$$



At the time of the Higgs discovery (2012) combined model had 100 channels & 500+ nuisance params.



# Statistical point estimation

“Profiling”

Calculate the profile likelihood ratio:

Similar to the Likelihood, but does not depend on the nuisance parameters.

$$\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}$$

$\hat{\phantom{x}}$  = Maximum Likelihood Estimates  
 $\hat{\phantom{x}}$  = MLE for given  $\mu$

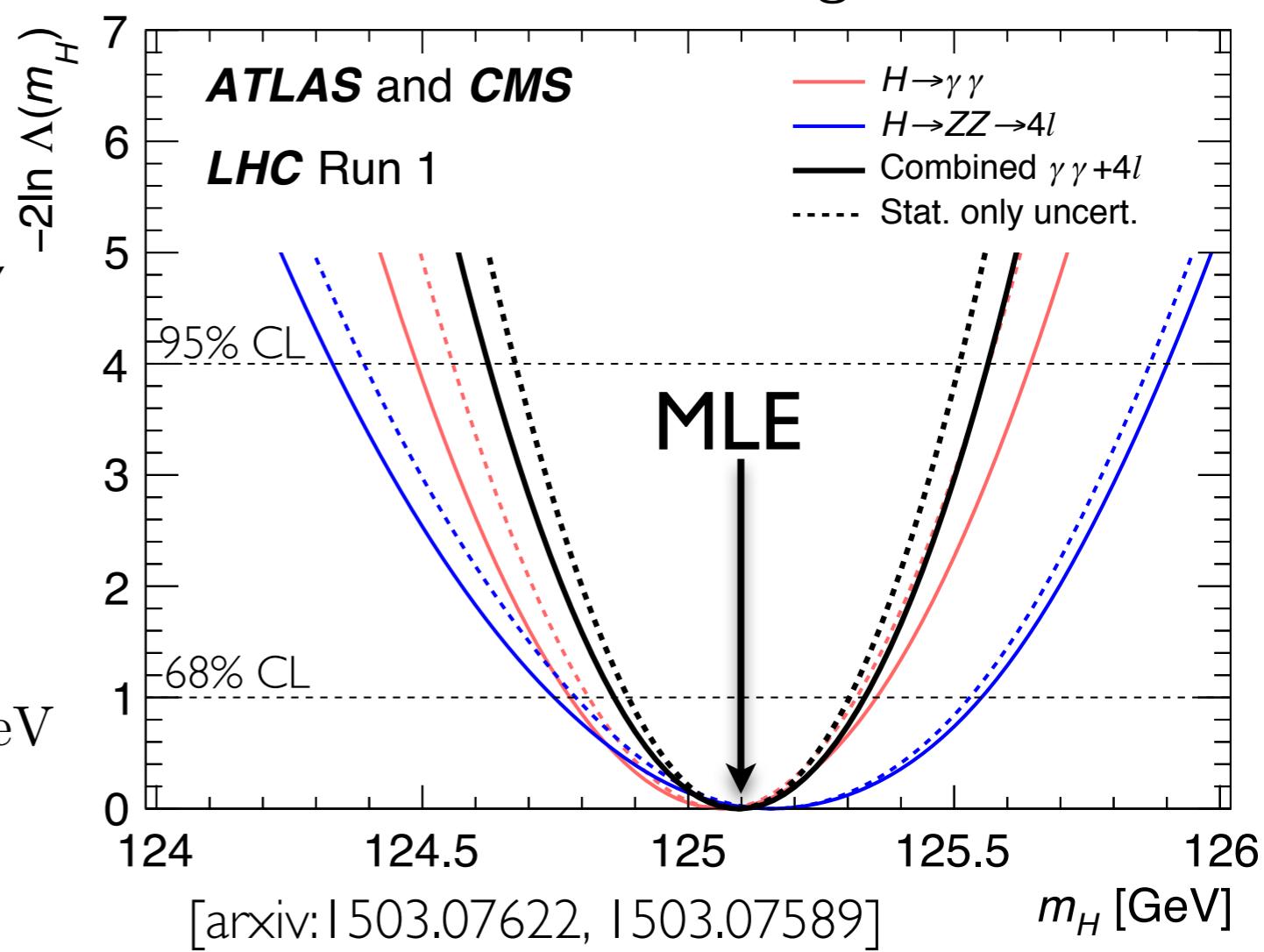
## Maximum Likelihood Estimate

Maximize  $\lambda(\mu)$

$\Rightarrow$  minimize  $-2\ln \lambda(\mu)$

e.g. Best-fit Higgs mass

$m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV}$

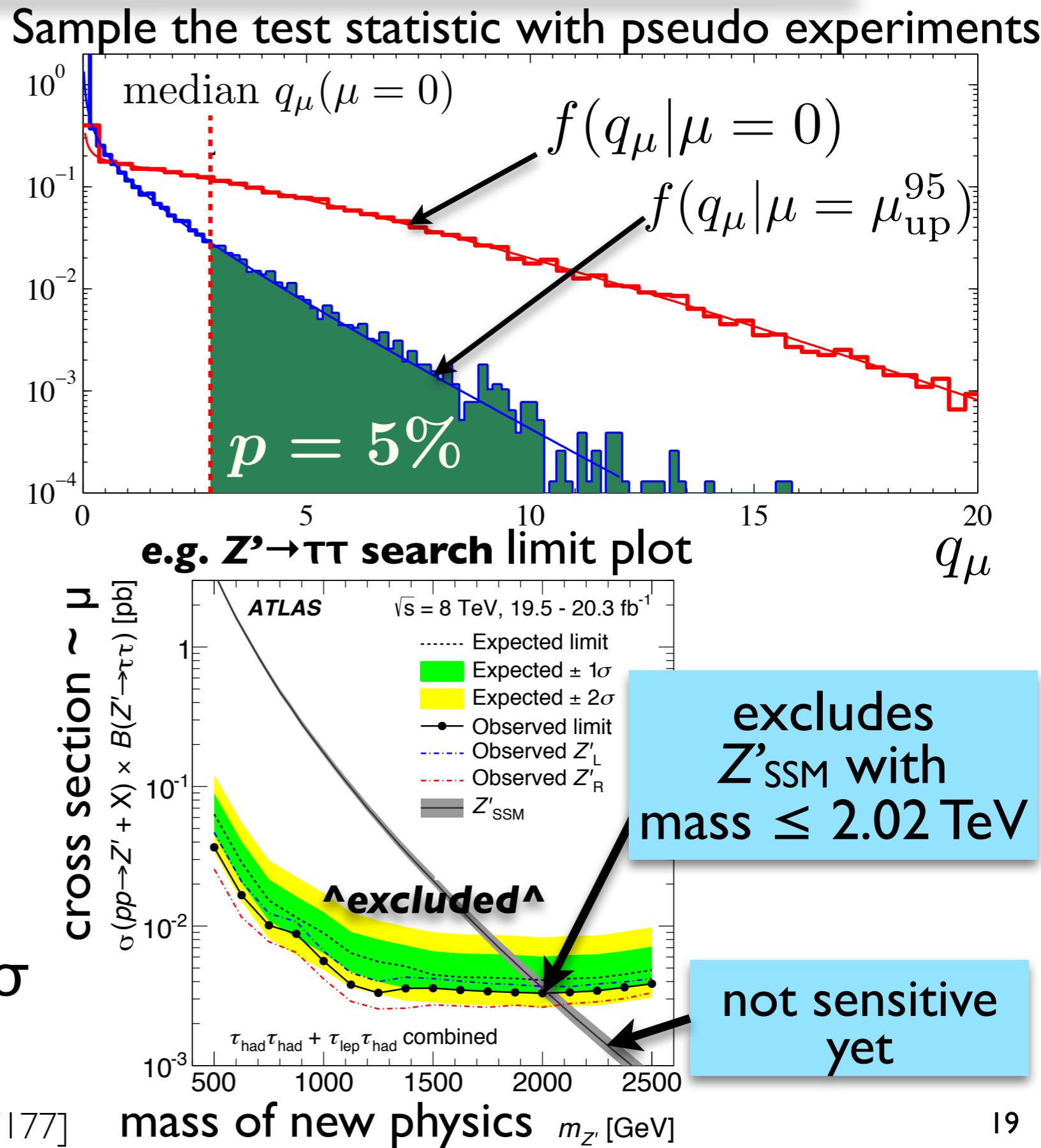


[arxiv:1503.07622, 1503.07589]

$m_H$  [GeV]

# Statistical hypothesis tests (upper limits)

- Construct test statistic:  
$$q_\mu = -2\ln(\lambda(\mu))$$
- Analogous to a  $\chi^2$  dist., larger values of  $q_\mu$  indicate greater incompatibility.
- Throw pseudo experiments to find  $\mu_{\text{up}}^{95}$  which has a p-value of 5%.
- If this signal strength were there, only 5% of experiments would have higher  $q_\mu$ .  $\Rightarrow$  95% CL or  $2\sigma$



# ATLAS SUSY Searches\* - 95% CL Lower Limits

ATLAS Preliminary

Status: Feb 2015

$\sqrt{s} = 7, 8 \text{ TeV}$

Reference

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ <b>1.7 TeV</b>
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ <b>850 GeV</b>
	$\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	1 $\gamma$	0-1 jet	Yes	20.3	$\tilde{q}$ <b>250 GeV</b>
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ <b>1.33 TeV</b>
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$	1 $e, \mu$	3-6 jets	Yes	20	$\tilde{g}$ <b>1.2 TeV</b>
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\ell\nu/v\nu)\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	-	20	$\tilde{g}$ <b>1.32 TeV</b>
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	$\tilde{g}$ <b>1.6 TeV</b>
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}$ <b>1.28 TeV</b>
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ <b>619 GeV</b>
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	4.8	$\tilde{g}$ <b>900 GeV</b>
Gravitino LSP	GGM (higgsino NLSP)	2 $e, \mu (Z)$	0-3 jets	Yes	5.8	$\tilde{g}$ <b>690 GeV</b>
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2} \text{ scale}$ <b>865 GeV</b>
$3^{\text{rd}}$ gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$ <b>1.25 TeV</b>
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ <b>1.1 TeV</b>
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ <b>1.34 TeV</b>
	$\tilde{g} \rightarrow b\bar{t}\tilde{\chi}_1^\pm$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ <b>1.3 TeV</b>
$3^{\text{rd}}$ gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$ <b>100-620 GeV</b>
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$	2 $e, \mu (\text{SS})$	0-3 $b$	Yes	20.3	$\tilde{b}_1$ <b>275-440 GeV</b>
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	1-2 $e, \mu$	1-2 $b$	Yes	4.7	$\tilde{t}_1$ <b>110-167 GeV</b> <b>230-460 GeV</b>
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ <b>90-191 GeV</b> <b>215-530 GeV</b>
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$	1-2 $b$	Yes	20	$\tilde{t}_1$ <b>210-640 GeV</b>
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ <b>90-240 GeV</b>
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu (Z)$	1 $b$	Yes	20.3	$\tilde{t}_1$ <b>150-580 GeV</b>
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu (Z)$	1 $b$	Yes	20.3	$\tilde{t}_2$ <b>290-600 GeV</b>
EW direct	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$ <b>90-325 GeV</b>
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\ell}\nu(\ell\tilde{\nu})$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm$ <b>140-465 GeV</b>
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu})$	2 $\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ <b>100-350 GeV</b>
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ <b>700 GeV</b>
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ <b>420 GeV</b>
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ <b>250 GeV</b>
	$\tilde{\chi}_2^0\tilde{\chi}_3^0 \rightarrow \tilde{\ell}_R\ell$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ <b>620 GeV</b>
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ <b>270 GeV</b>
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ <b>832 GeV</b>
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ <b>1.27 TeV</b>
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$ <b>537 GeV</b>
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$ <b>435 GeV</b>
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV)	1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ <b>1.0 TeV</b>
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ <b>1.61 TeV</b>
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ <b>1.1 TeV</b>
	Bilinear RPV CMSSM	2 $e, \mu (\text{SS})$	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$ <b>1.35 TeV</b>
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ <b>750 GeV</b>
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ <b>450 GeV</b>
	$\tilde{g} \rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ <b>916 GeV</b>
Other	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	2 $e, \mu (\text{SS})$	0-3 $b$	Yes	20.3	$\tilde{g}$ <b>850 GeV</b>
	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 $c$	Yes	20.3	$\tilde{c}$ <b>490 GeV</b>

$\sqrt{s} = 7 \text{ TeV}$   
full data

$\sqrt{s} = 8 \text{ TeV}$   
partial data

$\sqrt{s} = 8 \text{ TeV}$   
full data

$10^{-1}$

1

Mass scale [TeV]

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.

**July 4, 2012**

# **CERN announces the discovery of a new particle by ATLAS and CMS, consistent with the Higgs boson**



**Fabiola Gianotti  
ATLAS Spokesperson**

**Joe Incandela  
CMS Spokesperson**



ROMNEY NOW SAYS  
HEALTH MANDATE  
BY OBAMA IS A TAX  
SHIFT REINFORCES CRITICISM  
More Aligns Him With  
Conservative Voices  
Within His Party

By JEREMY W. PETERS  
WOLFSBURG, A.G. — Mitt Romney declared on Wednesday that the Princeton Oberlin debate was a mistake in that it was “skilling his campaign’s characterization of the free ride aligning himself with the conservative voices in his party.”

Mr. Romney’s remarks, made in a hasty arranged interview

**Physicists Find Elusive Particle Seen as Key to Universe**

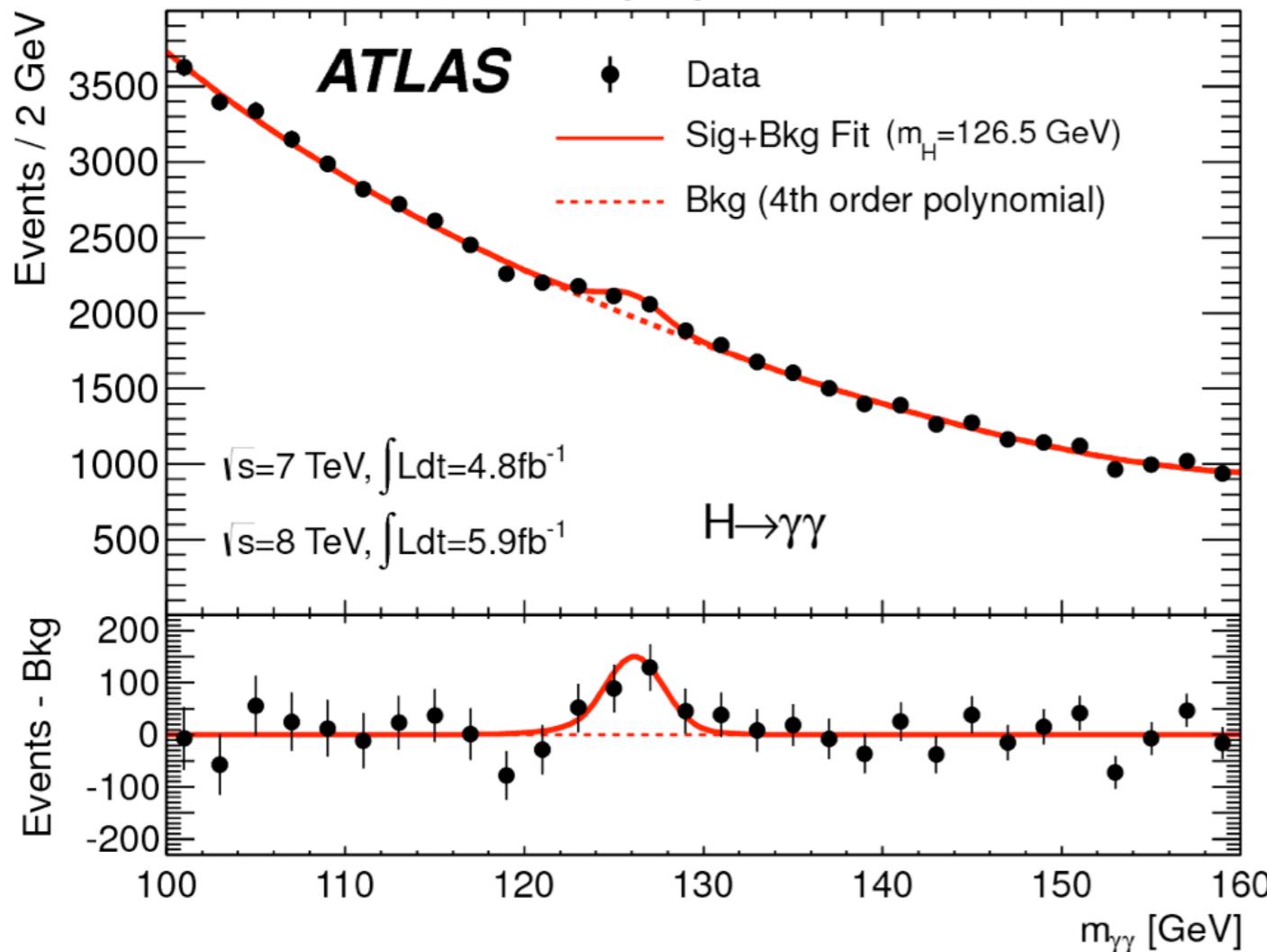
A smaller photograph showing a group of people in a lecture hall, possibly the same one from the main photo, clapping and cheering.

**July 5 cover of the New York Times:  
“Physicists Find Elusive Particle  
Seen as Key to the Universe”**

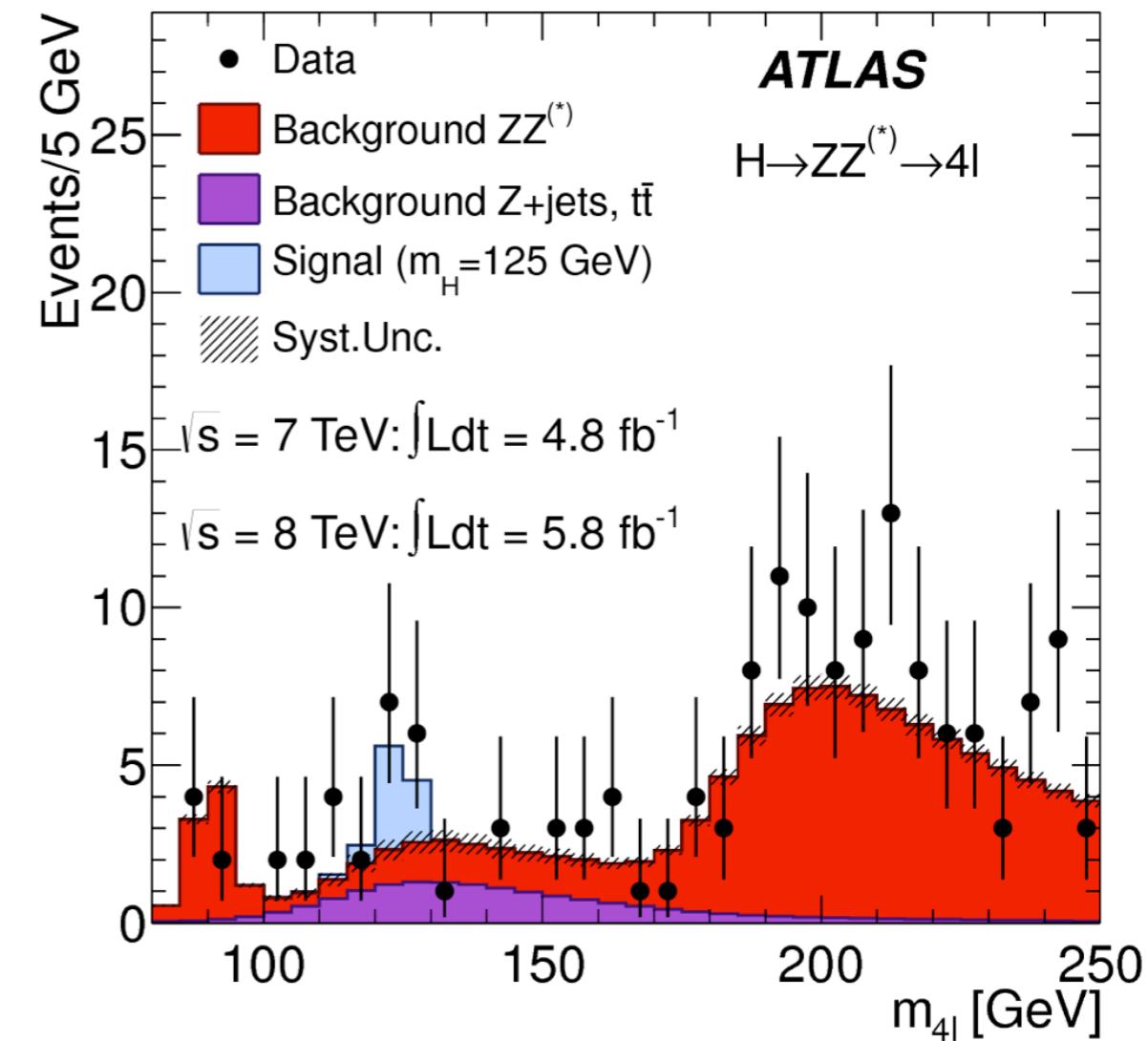
# Higgs mass bumps

- Two channels with precise mass measurements:  
 $H \rightarrow \gamma\gamma, H \rightarrow ZZ \rightarrow 4l$ .
- $H \rightarrow WW$  also observes a broad excess.

**$H \rightarrow \gamma\gamma$**

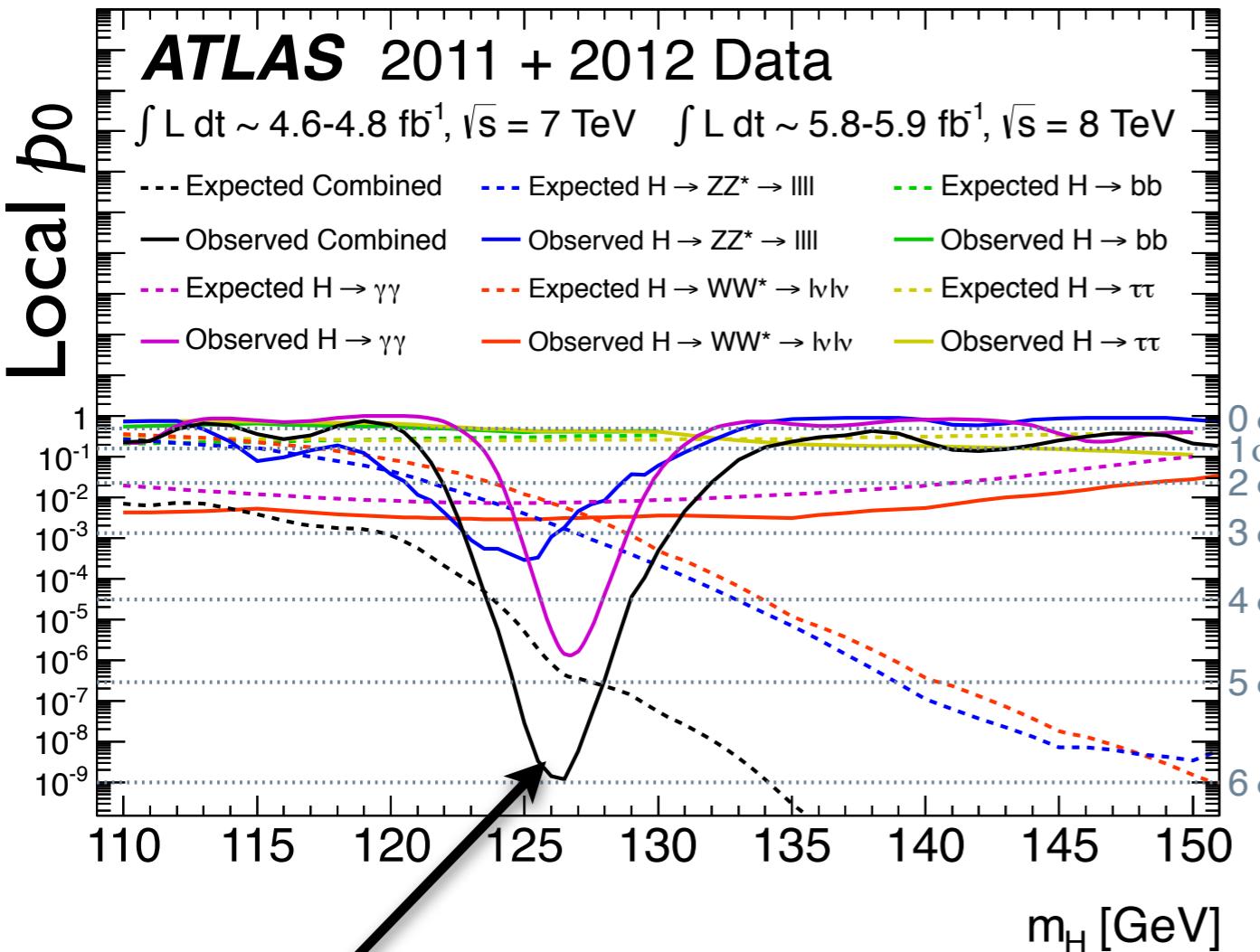


**$H \rightarrow ZZ \rightarrow 4l$**

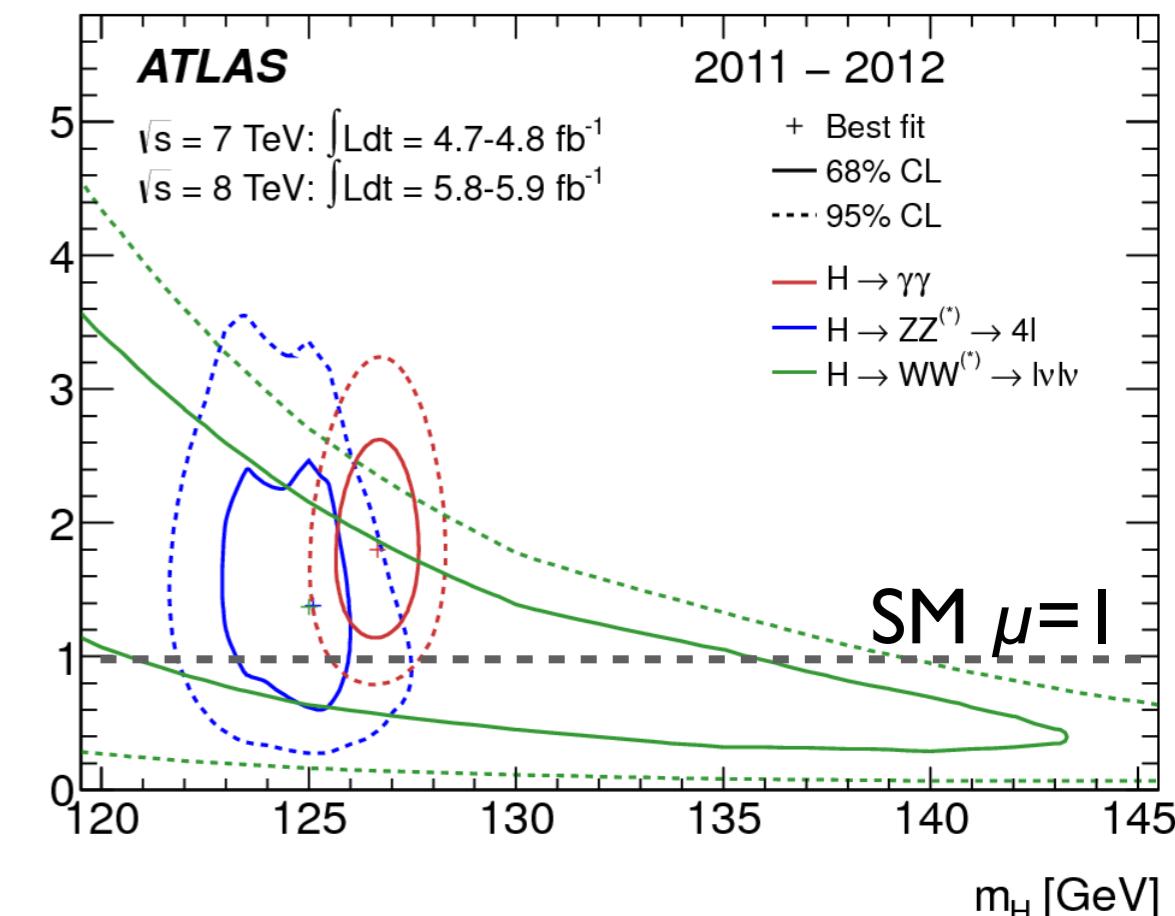


# Higgs Confidence

Inconsistent with background only



Consistent with SM Higgs



- Local  $p_0 = 1.7 \times 10^{-9}$ , corresponding to  $5.9\sigma$
- Particle physics has a conservative traditional threshold of significance for claiming discovery of  $5\sigma \Rightarrow p_0 = 2.9 \times 10^{-7}$

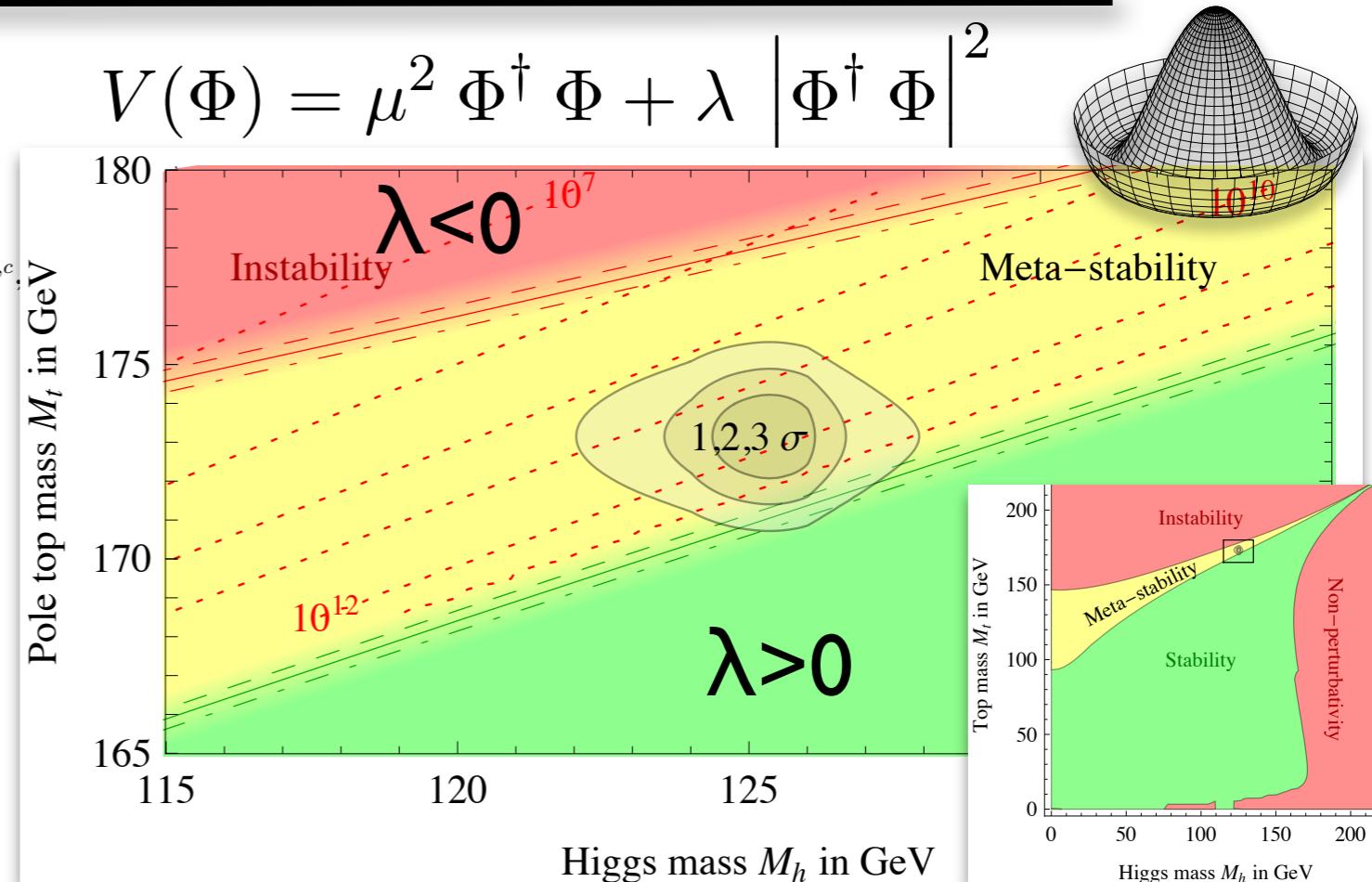
= 1 in 3.5 million

# Naturalness or multiverse?

## Higgs mass and vacuum stability in the Standard Model at NNLO

Giuseppe Degrassi<sup>a</sup>, Stefano Di Vita<sup>a</sup>, Joan Elias-Miró<sup>b</sup>, José R. Espinosa<sup>b,c</sup>,  
Gian F. Giudice<sup>d</sup>, Gino Isidori<sup>d,e</sup>, Alessandro Strumia<sup>g,h</sup>

“If the LHC finds Higgs couplings deviating from the SM prediction and new degrees of freedom at the TeV scale, then the most important question will be to see if a consistent and natural (in the technical sense) explanation of EW breaking emerges from experimental data. But if the LHC discovers that the Higgs boson is not accompanied by any new physics, then it will be much harder for theorists to unveil the underlying organizing principles of nature. The multiverse, although being a stimulating physical concept, is discouragingly difficult to test from an empirical point of view. The measurement of the Higgs mass may provide a precious handle to gather some indirect information.”



# Gauge invariance is deep!

## Why do gauge theories work?

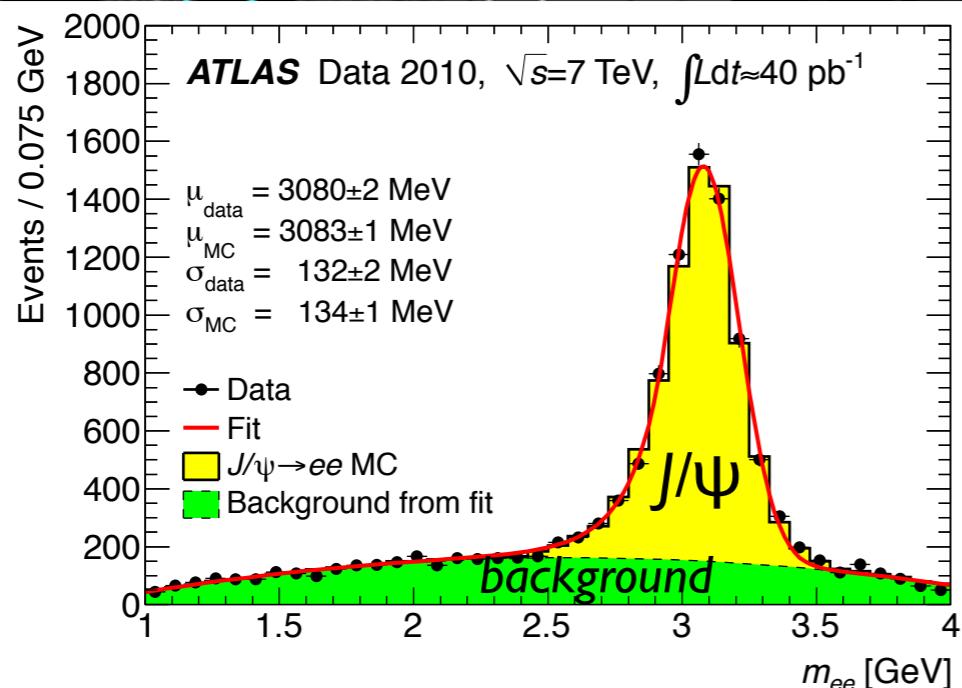
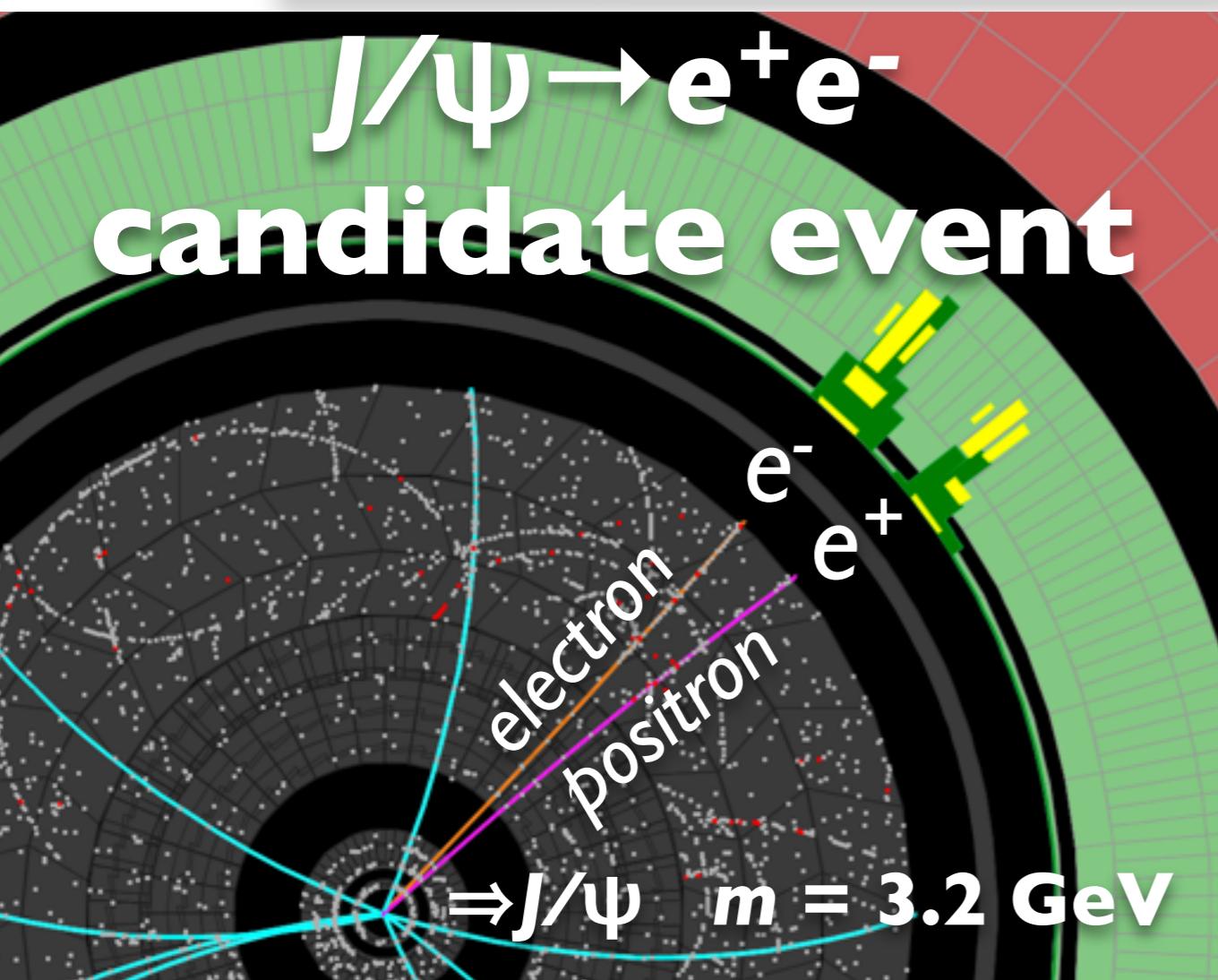
Internal gauge space

Spacetime

local  $U(1)$  phase

- Loyalty to the gauge principle motivated the Higgs mechanism.
- Some have described gauge freedom as a “redundancy of description”.
- But it is also a symmetry, similar to spatial rotations but in the *internal space of the field*.
- Can be rotated *locally*, independently at every spacetime point.
- What does it mean for the laws of nature to be describable by the continuous symmetries of Lie groups?
- What does it mean that the state of the universe can be represented as an element of a complex vector space, a Hilbert space?

# Real Patterns



## What is an electron?

- An excitation in a **Dirac spinor field** representation of  $SU(2)\times U(1)$ , the “Platonic electron”.
- A **software object** with a reconstructed track and calorimeter deposit, passing some selection cuts, the “pragmatist electron”.
- A **set of voltages** and timings read-out from the detector, the “Ramsified electron”.

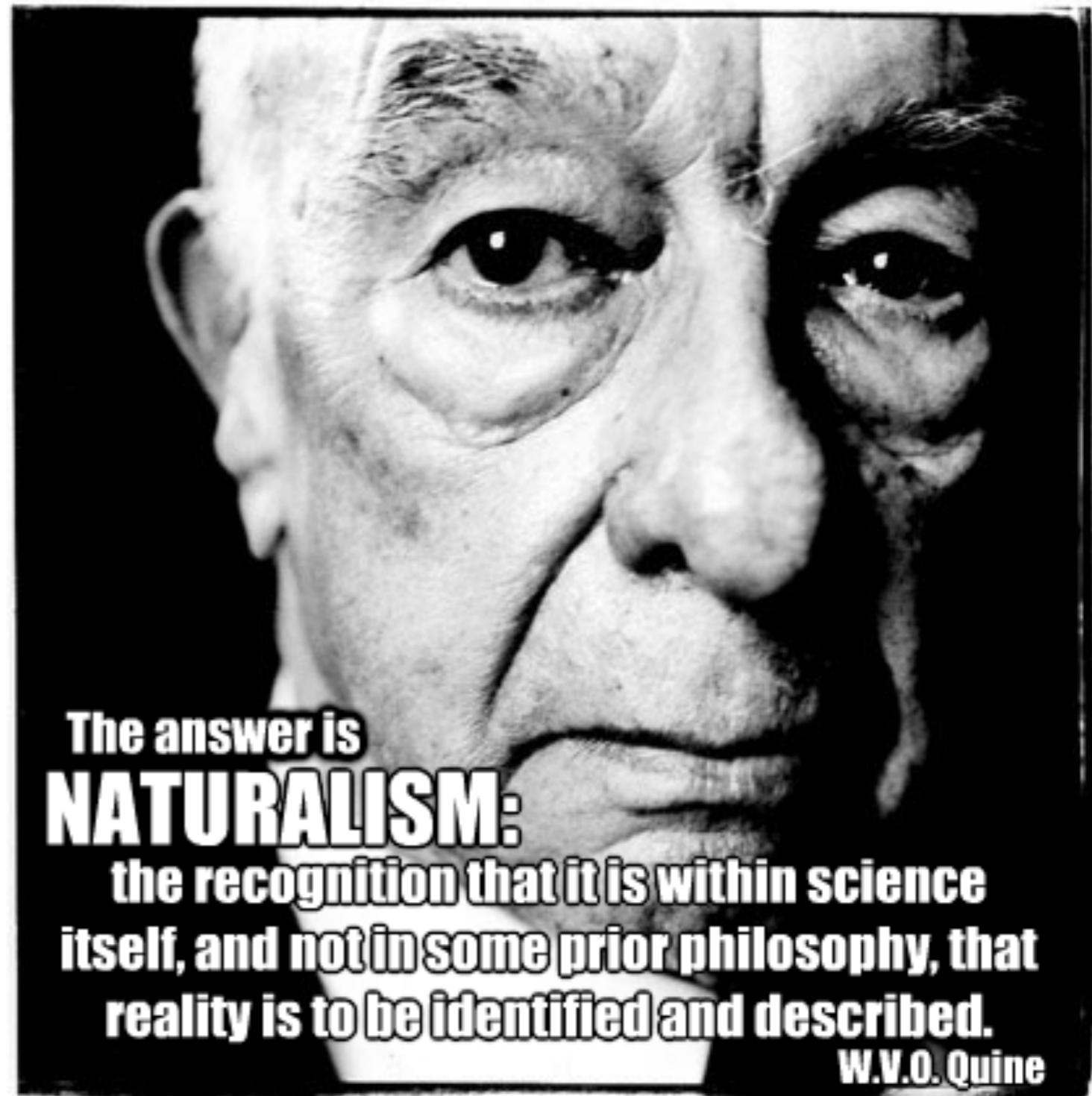
→ Reality has a hierarchy of onion layers, but it has **real patterns** (Dennett 1991).

# Summary

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- Particle physics probes very deep questions about what the world is made of, how it works, and how it got here.
- While this school is specifically about ontology, I also want to emphasize that ***physics has a profound epistemology grounded in statistical significance.***
- Physicists have learned to statistically justify their claims, and have often lead in developing statistical theory and methods.
  - **PhyStat** - Conference/Workshop with statisticians and LHC physicists (2002, 03, 05, 07, 11): <https://plone4.fnal.gov:4430/P0/phystat/>

# Back up slides

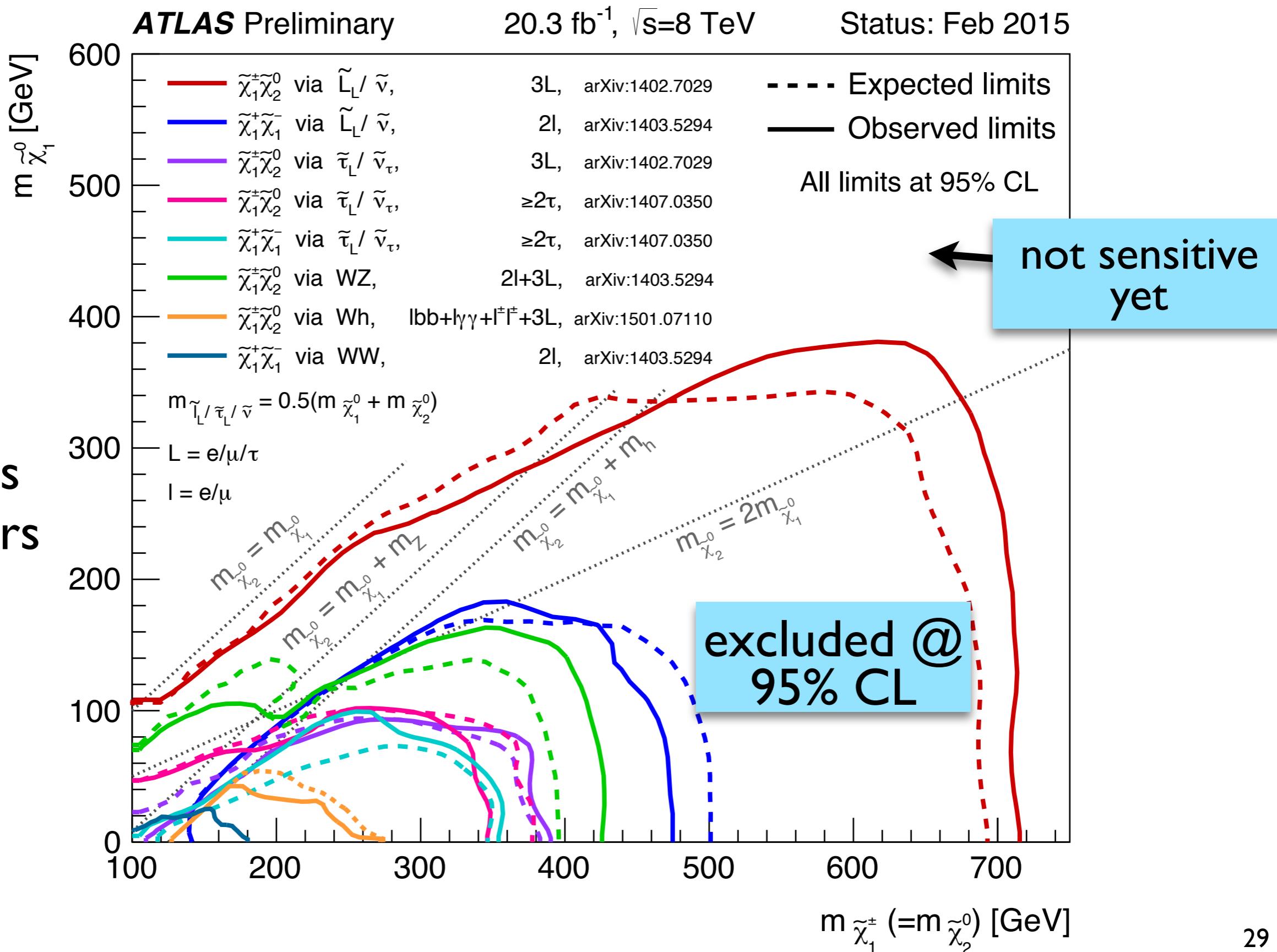


The answer is  
**NATURALISM:**  
the recognition that it is within science  
itself, and not in some prior philosophy, that  
reality is to be identified and described.

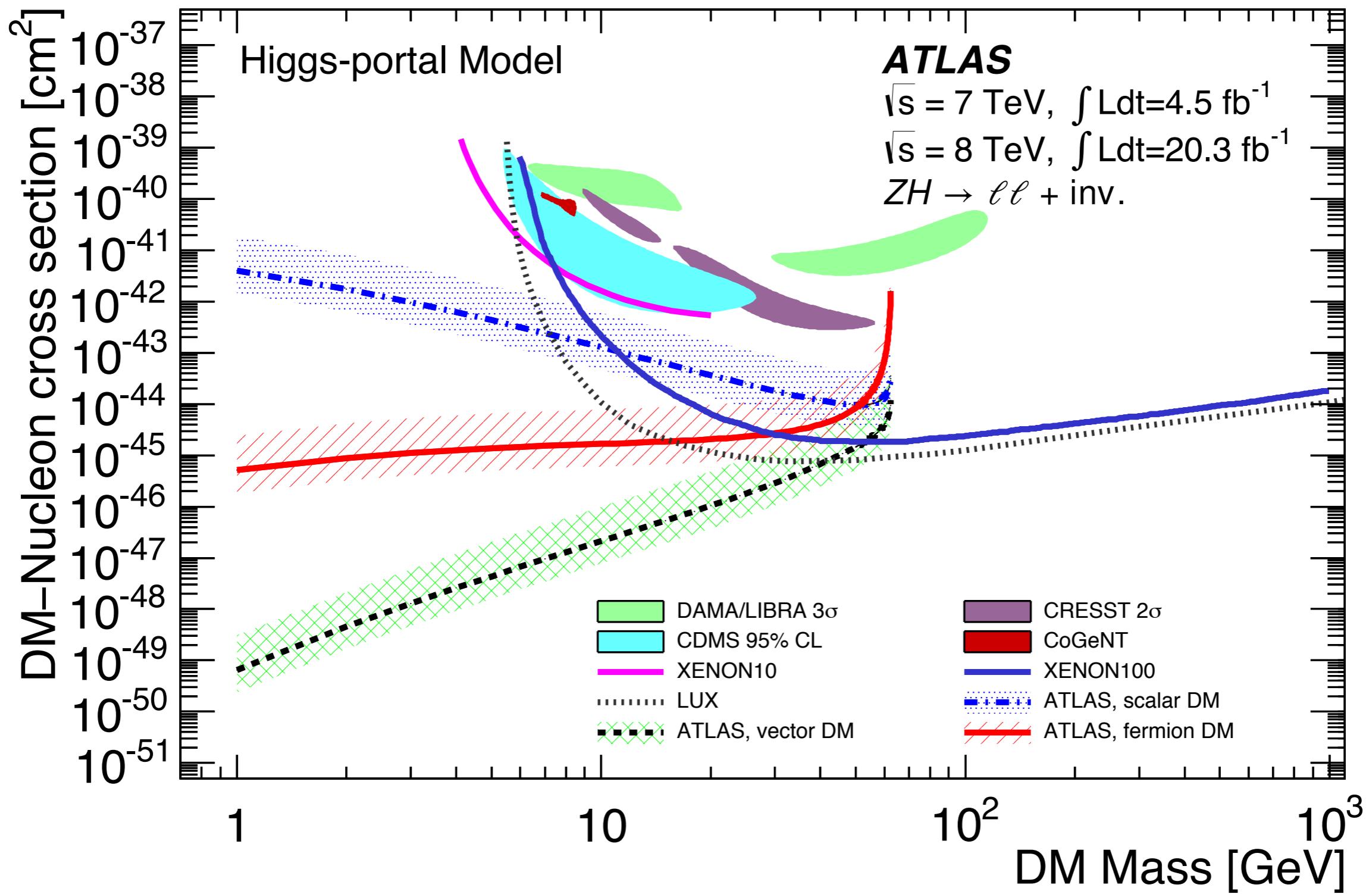
W.V.O. Quine

# SUSY chargino-neutralino exclusions

Scan in  
two mass  
parameters



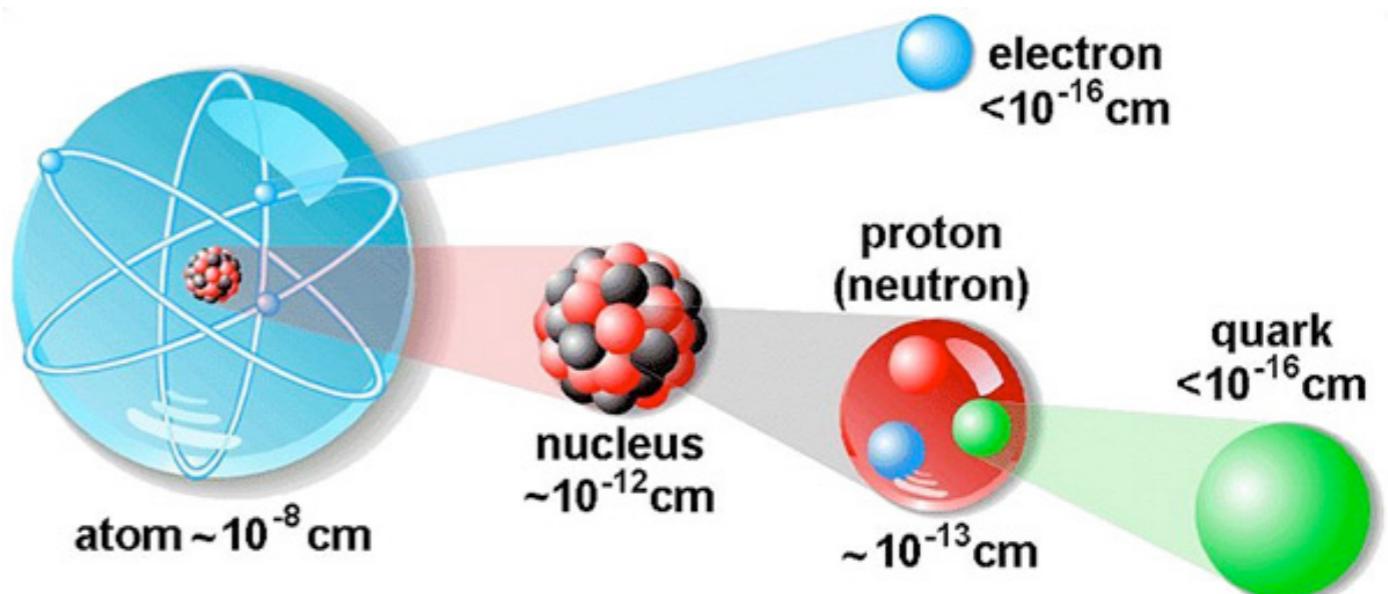
# Higgs-portal to Dark Matter?



# Particle Physics

Fundamental questions  
of particle physics:

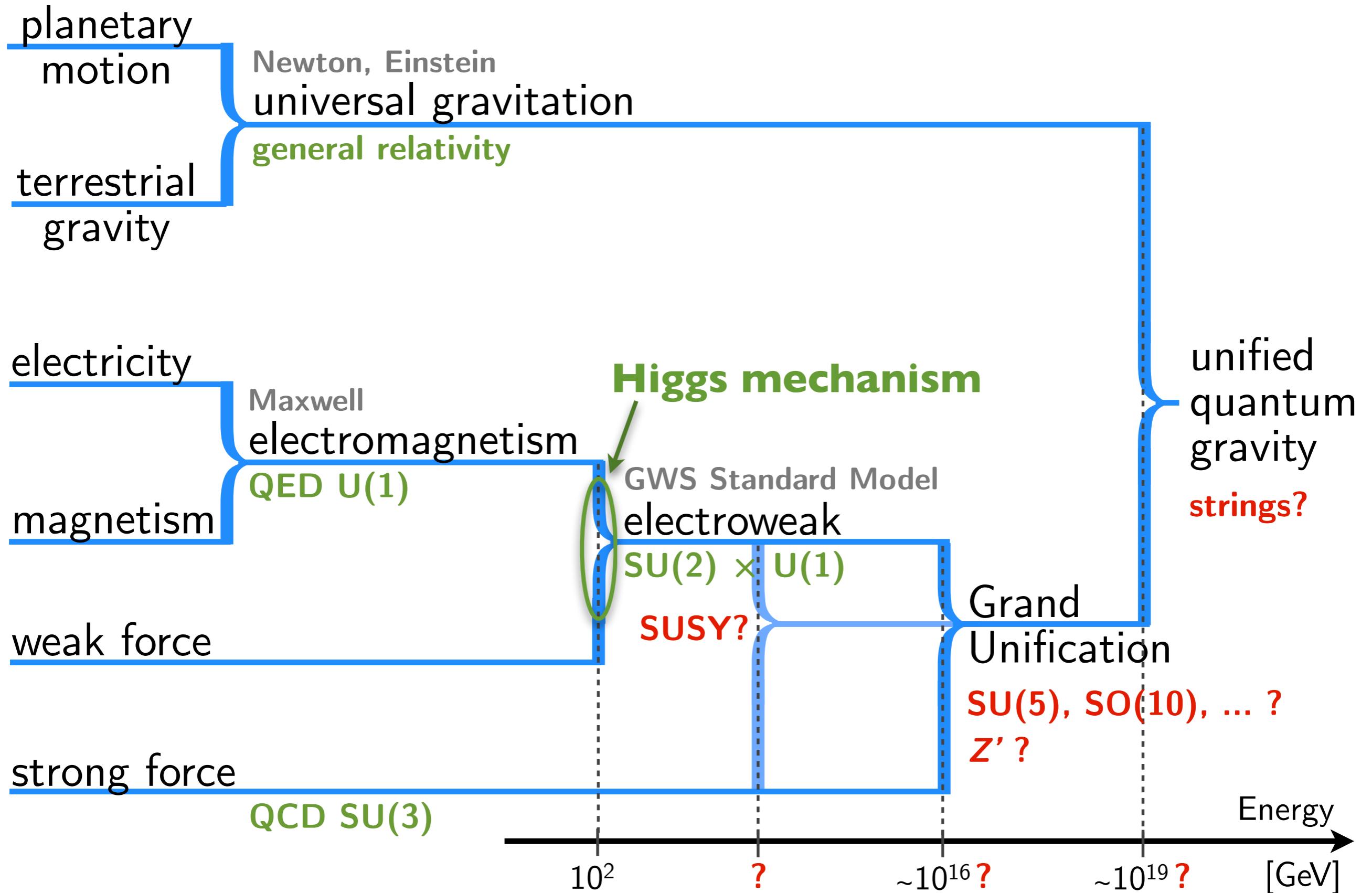
1. **What is matter?**
2. **How does it interact?**



Four fundamental forces at low energies:

1. Gravity - very weak, no complete quantum theory
2. Electromagnetism - binds atoms, chemistry
3. Strong force - nuclear range, binds nuclei
4. Weak force - nuclear range, radioactivity, solar fusion

# Unification?



# What is quantum mechanics?

- Hilbert spaces

$$\hat{H} \mid n \rangle = E_n \mid n \rangle$$

Wave function  
 $\langle x | n \rangle = \psi_n(x)$

- Superposition principle

$$|\psi\rangle = \sum_n a_n \mid n \rangle$$

Schrodinger Equation  
 $i\frac{\partial}{\partial t}\hat{U}(t) |\psi\rangle = \hat{H} \hat{U}(t) |\psi\rangle$

- Born rule

$$P(n) = |\langle n | \psi \rangle|^2 = |a_n|^2$$

Decoherence

- Wigner's theorem

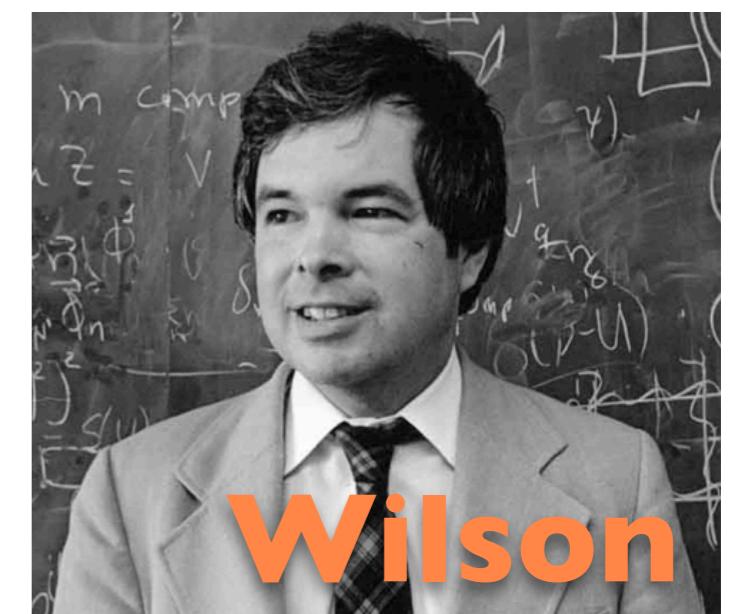
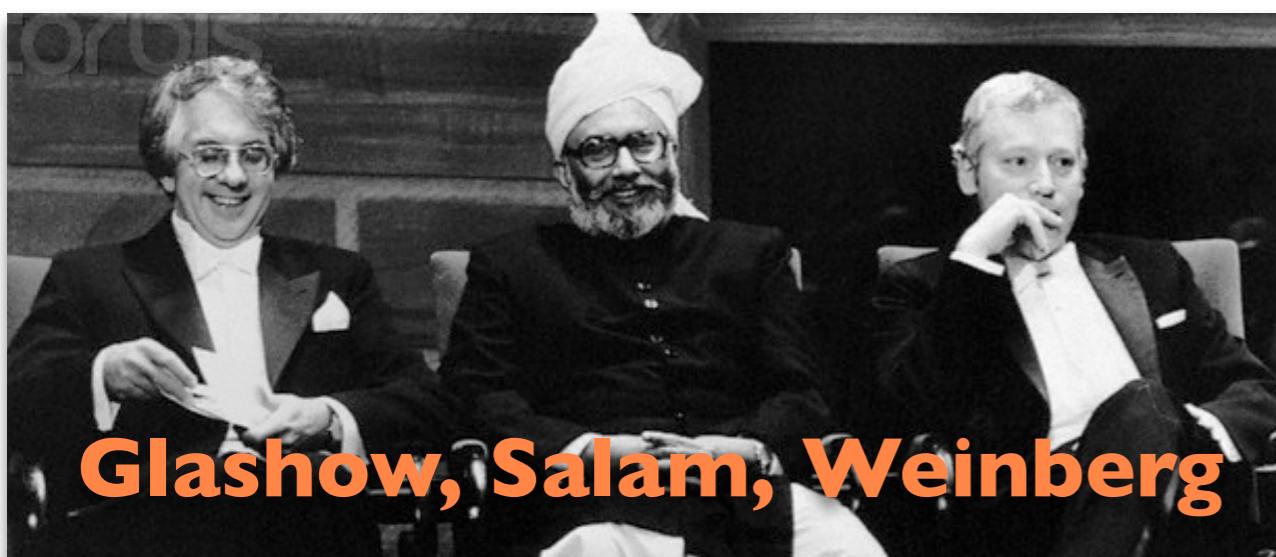
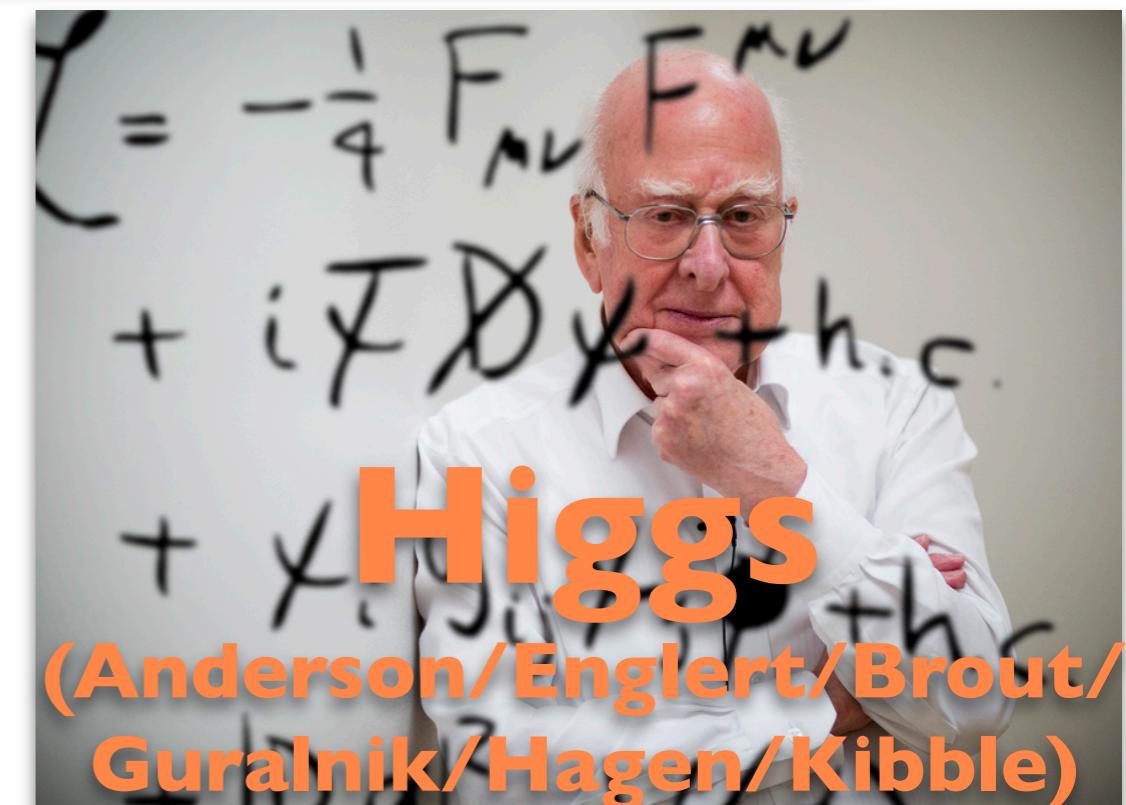
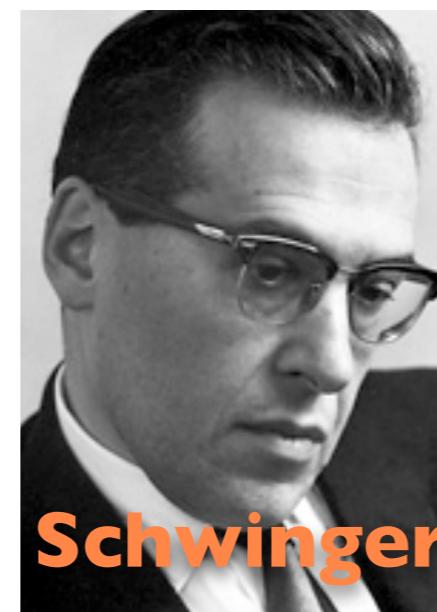
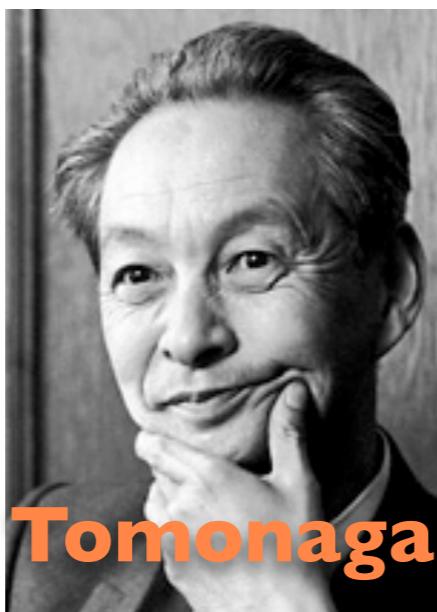
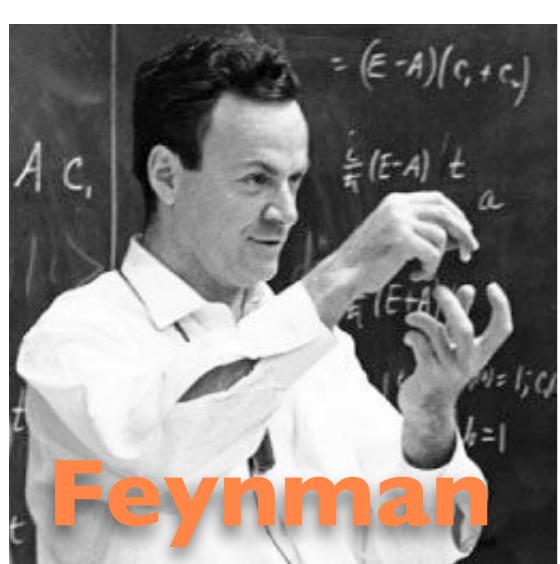
$$\hat{U}(x^\mu) = e^{-i \hat{P}_\mu x^\mu}$$

$$\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_E$$
$$|\alpha\rangle \otimes |\psi\rangle \longrightarrow |\alpha\rangle \otimes |\psi; \alpha\rangle$$

The generators of the representation of a transformation in the Hilbert space are the operators representing the classical Noether's Charges that are conserved under that transformation.

# **QFT & SM Heroes**

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# Discoveries in the SM

## Quarks

$u$ up (1968)	$c$ charm (1974)	$t$ top (1995)
$d$ down (1968)	$s$ strange (1968)	$b$ bottom (1977)

## Leptons

$\nu_e$ electron neutrino (1956)	$\nu_\mu$ muon neutrino (1962)	$\nu_\tau$ tau neutrino (2000)
$e$ electron (1897)	$\mu$ muon (1936)	$\tau$ tau (1975)

}

Fermions

## Gauge bosons

$g$ gluon (1979)	$W^\pm$ (1983)	$Z$ (1983)	$\gamma$ photon (1900)
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## Higgs boson

$H$ Higgs (2012)
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}

Bosons

# SM Lagrangian

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kinetic energies and self-interactions of the gauge bosons

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \text{tr} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} \text{tr} G_{\mu\nu}^\alpha G^{\alpha\mu\nu}$$

kinetic energies and electroweak interactions of the left-handed fermions

$$+ \bar{L}_i \gamma^\mu \left( i \partial_\mu - \frac{1}{2} g_1 Y_{i\text{L}} B_\mu - \frac{1}{2} g_2 \sigma^a W_\mu^a \right) L_i$$

kinetic energies and electroweak interactions of the right-handed fermions

$$+ \bar{R}_i \gamma^\mu \left( i \partial_\mu - \frac{1}{2} g_1 Y_{i\text{R}} B_\mu \right) R_i$$

strong interactions between quarks and gluons

$$+ \frac{i g_3}{2} \bar{Q}_j \gamma^\mu \lambda^\alpha G_\mu^\alpha Q_j$$

electroweak boson masses and Higgs couplings

$$+ \frac{1}{2} \left| \left( i \partial_\mu - \frac{1}{2} g_1 B_\mu - \frac{1}{2} g_2 \sigma^a W_\mu^a \right) \Phi \right|^2 - V(\Phi)$$

fermion masses and Higgs couplings

$$- \left( y_{k\ell}^{\text{d}} \bar{L}_k \Phi R_\ell + y_{k\ell}^{\text{u}} \bar{R}_k \tilde{\Phi} L_\ell + h.c. \right).$$

# LSZ Reduction Formula

---

$$\begin{aligned}
 S_{fi} &= \langle f | \hat{S} | i \rangle \\
 &= \tilde{G}^{(n)}(-p_f, \dots, p_i) \prod_f \left( \tilde{G}^{(2)}(p_f) \right)^{-1} \prod_i \left( \tilde{G}^{(2)}(p_i) \right)^{-1} \\
 &= \text{Diagram showing a central shaded circle connected to several other circles, which are then connected to external lines with arrows.} \times \prod_{i,f}^n \left( \text{Diagram of a shaded circle} \right)^{-1} \\
 &= \text{Diagram showing a central circle labeled } -i\mathcal{M} \text{ connected to dashed lines.} \\
 &= -i \mathcal{M} (2\pi)^4 \delta^4 \left( \sum p_i - \sum p_f \right),
 \end{aligned}$$

where  $\tilde{G}^{(n)}$  denotes the momentum-space Fourier transform of the space-time  $n$ -point correlation function:

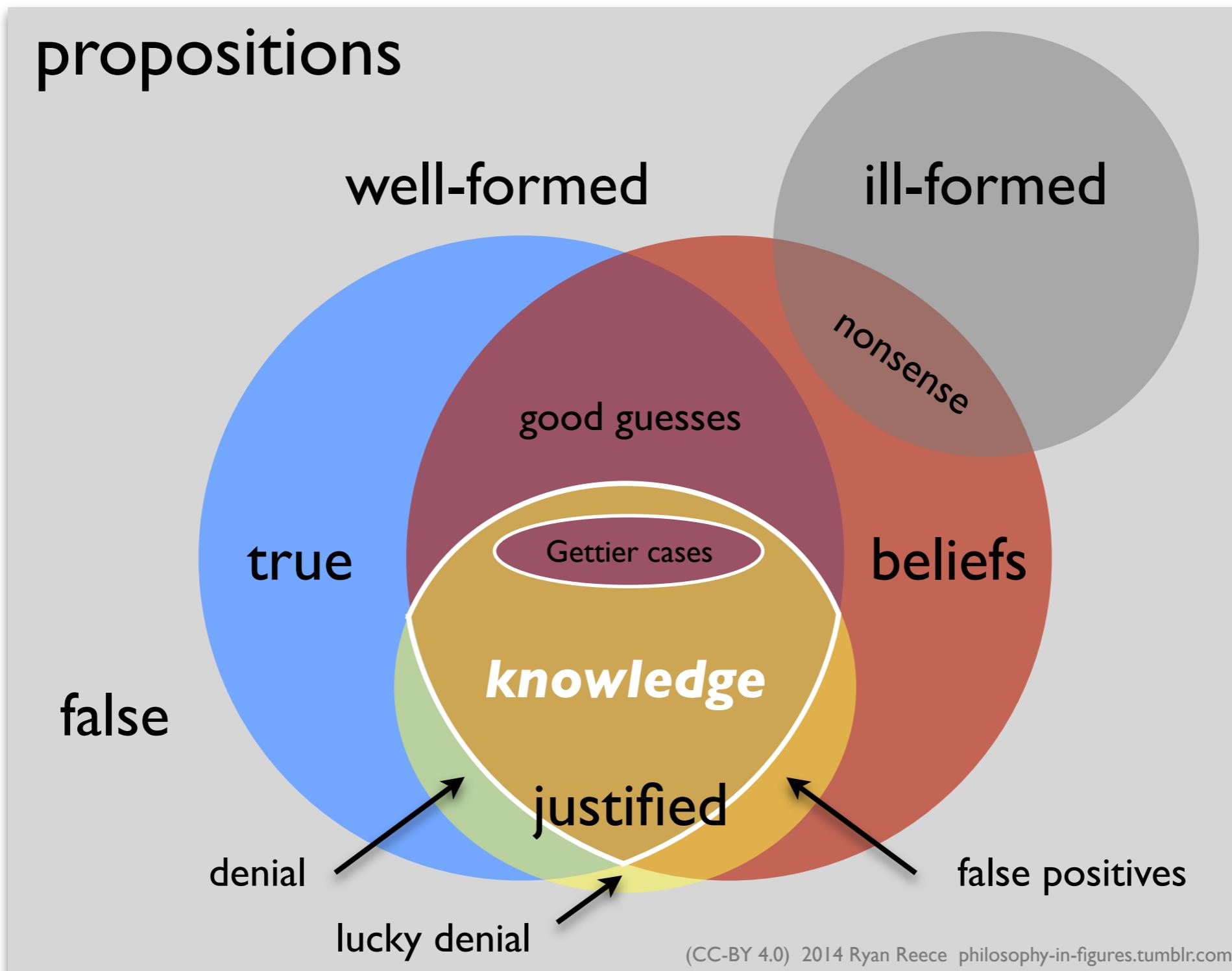
$$\tilde{G}^{(n)}(p_1, \dots, p_n) \equiv \prod_i^n \left[ \int \frac{d^4 p_i}{(2\pi)^4} e^{-i p_i \cdot x_i} \right] G^{(n)}(x_1, \dots, x_n).$$

# Indeterminacy of reference?

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- Button and Walsh. (2015). “Ideas and Results in Model Theory: Reference, Realism, Structure and Categoricity”. arxiv:1501.00472.
- Differing views on *categoricity*
- I doubt one could rename-away the Higgs field, for example, being the only scalar field in the SM.

# **Knowledge = JTB-G**



# philosophy of science

