How models are tested at the LHC

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ATLAS

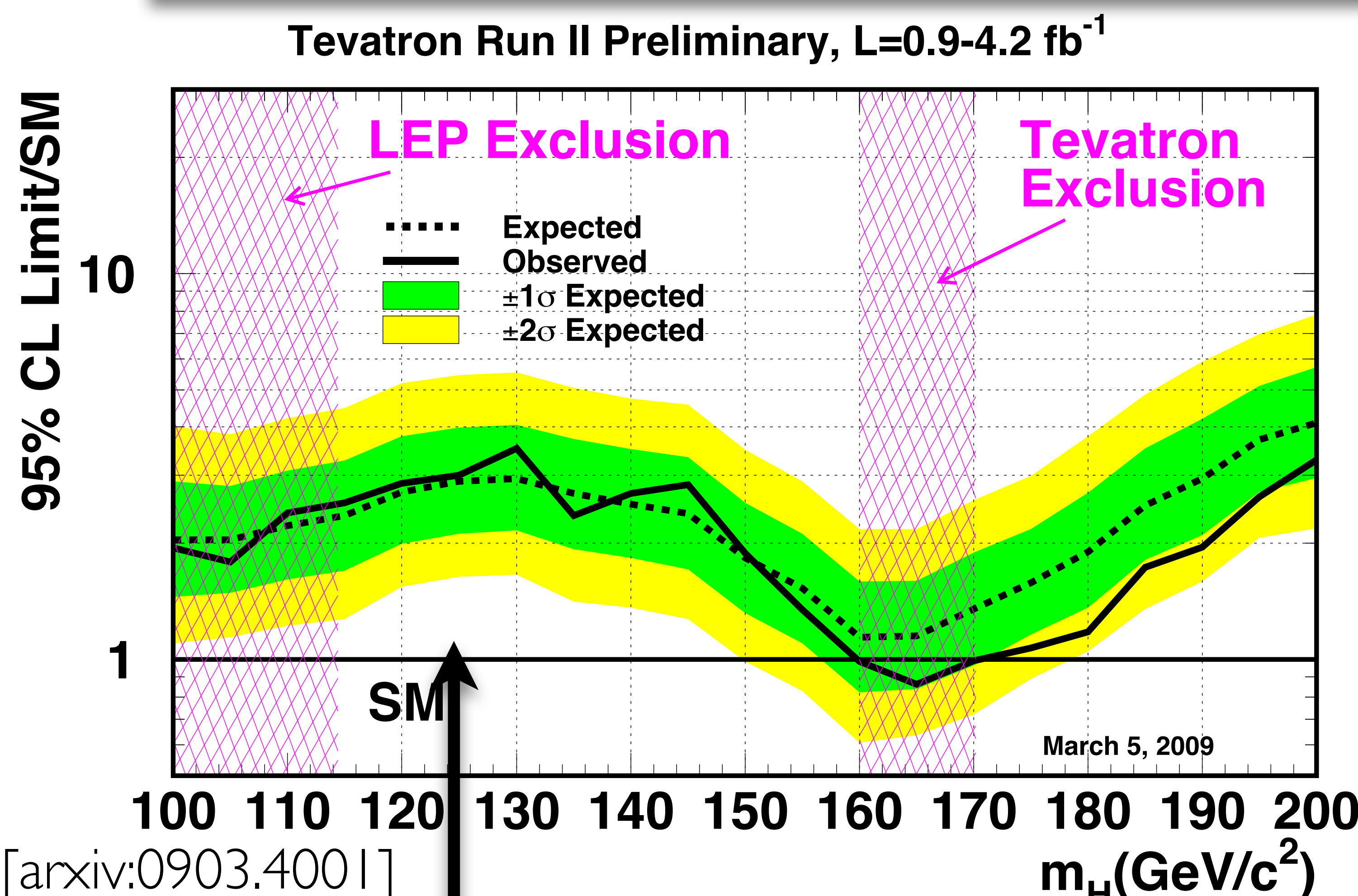
UNIVERSITY OF CALIFORNIA SANTA CRUZ

3rd International Summer School in Philosophy of Physics

July 21, 2015

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.



[arxiv:0903.4001]

Higgs was later found in 2012 by ATLAS and CMS with $m_{\mathrm{H}} \approx 125$ GeV

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]

Outline

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

$$\mathbf{SU(3)_C \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{Electroweak force}}}$$

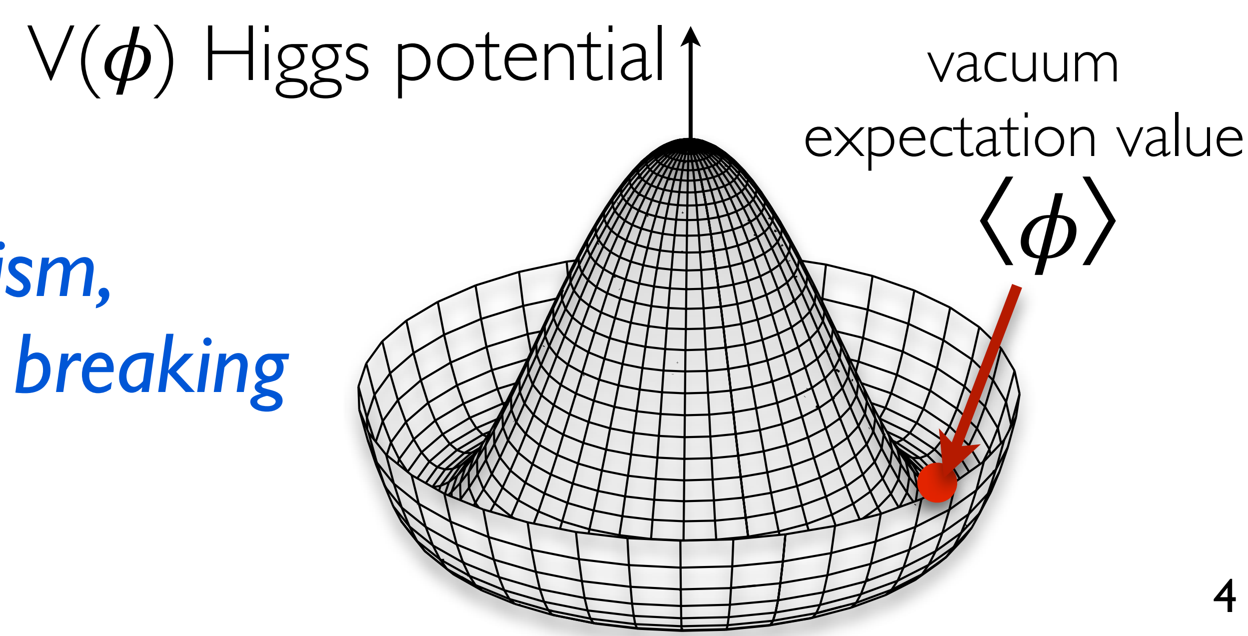
$\Downarrow$ **Strong force**

Electroweak force $\Downarrow$ *Higgs mechanism, EW symmetry breaking*

Electromagnetic + weak forces

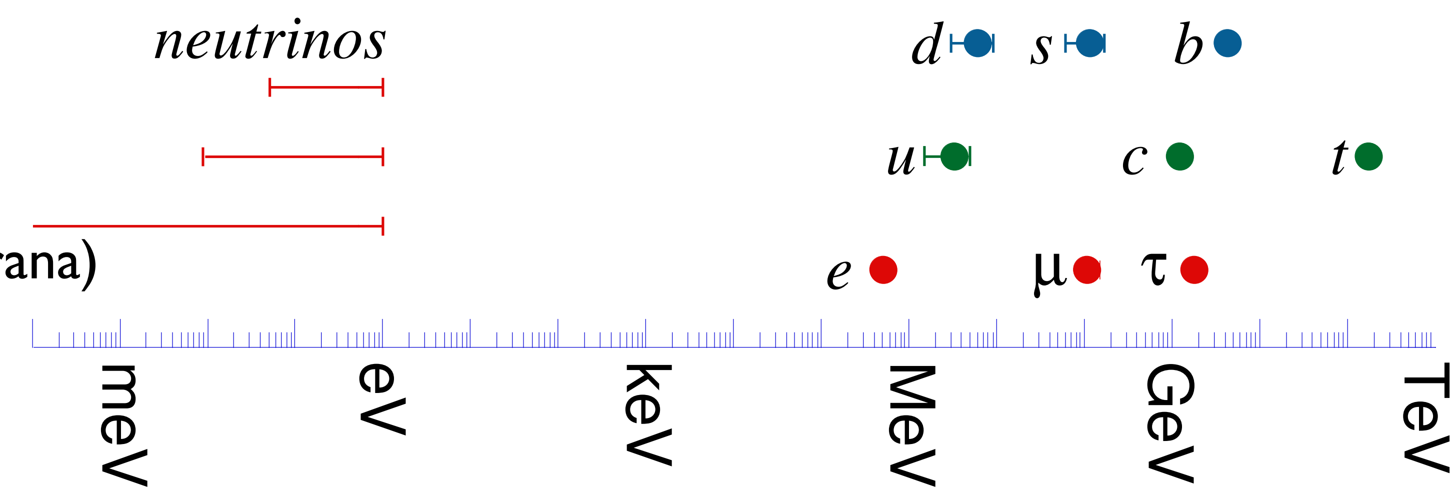
field content of the SM

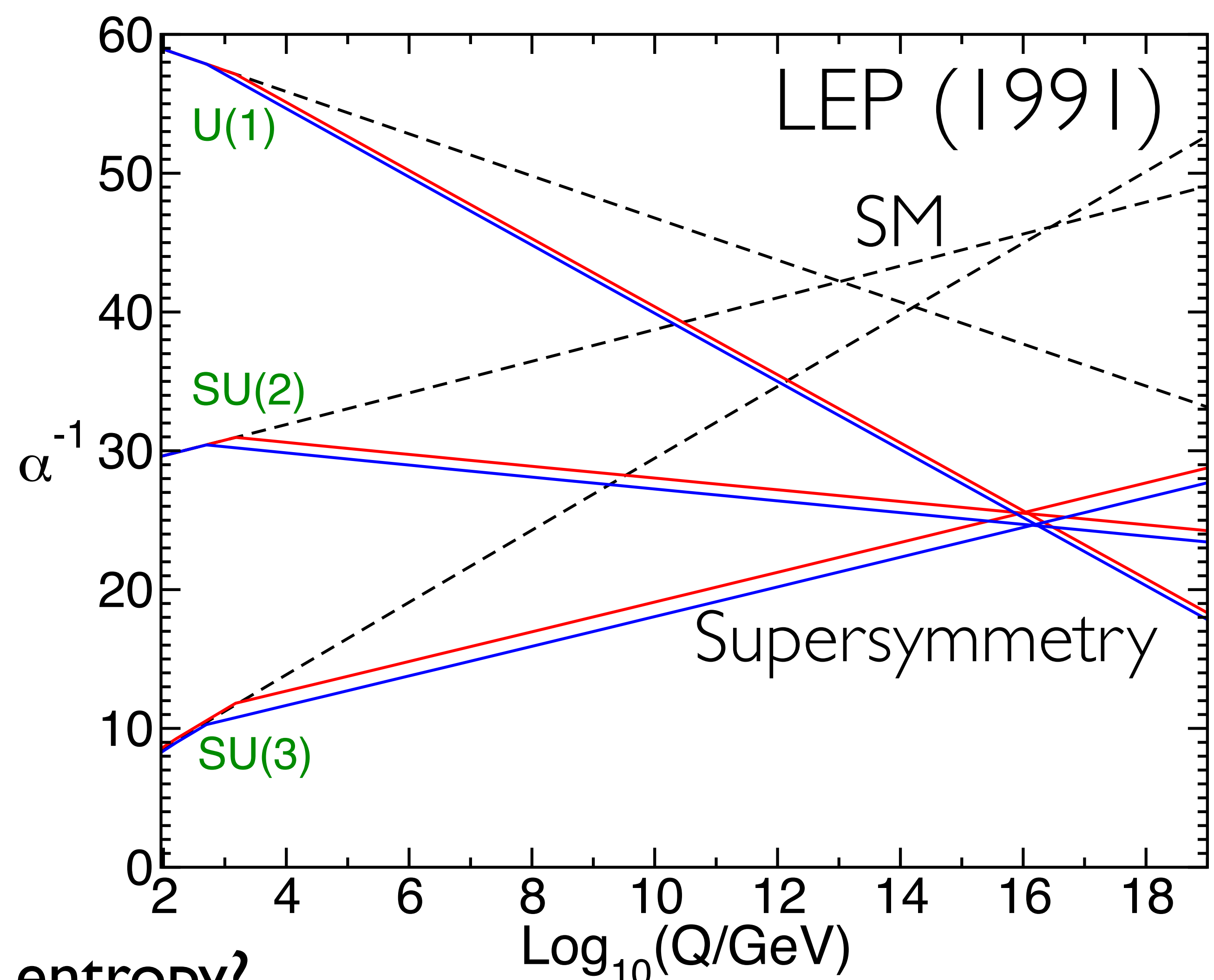
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	



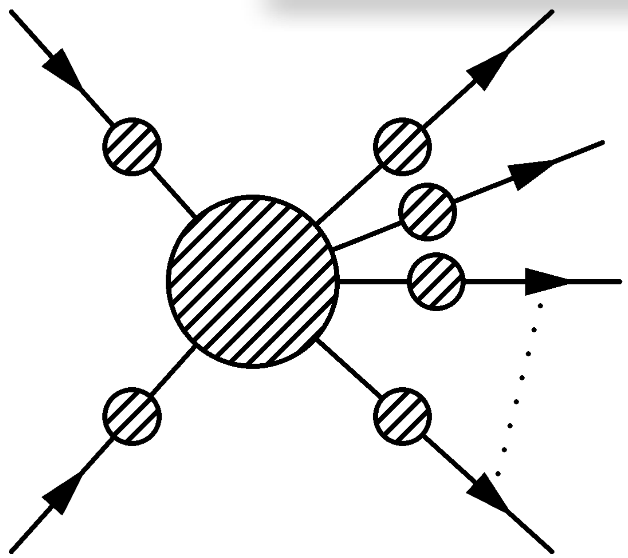
Unanswered problems in particle physics

- Ad hoc features
  - Why SU(3)xSU(2)xU(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_{Higgs} vs m_{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***.

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

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

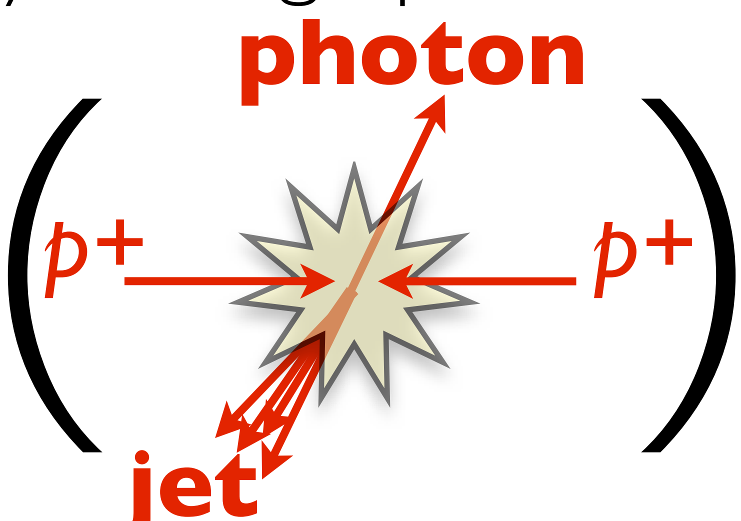
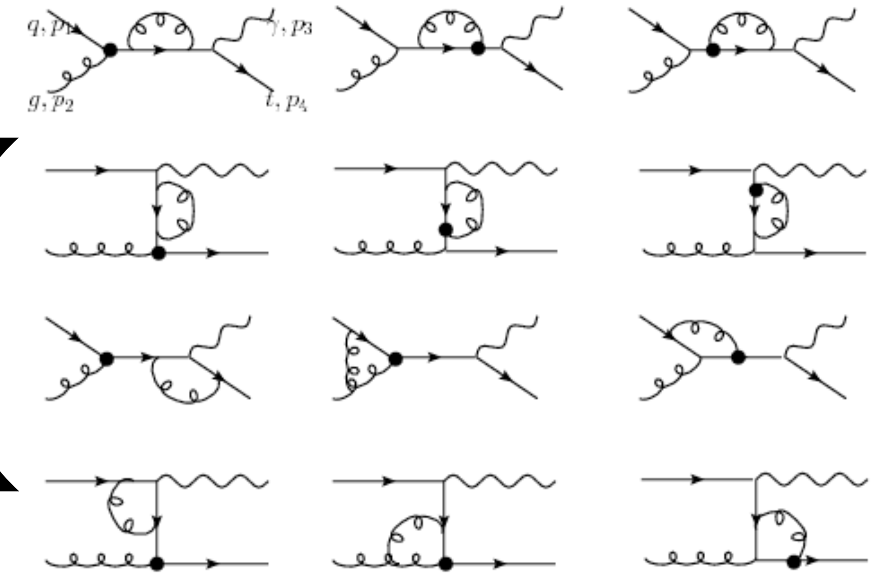
$$N = \int dt\, L \int d\sigma\, \varepsilon$$

$$= \left(\int dt\, L \right) A\, C\, \sigma$$

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

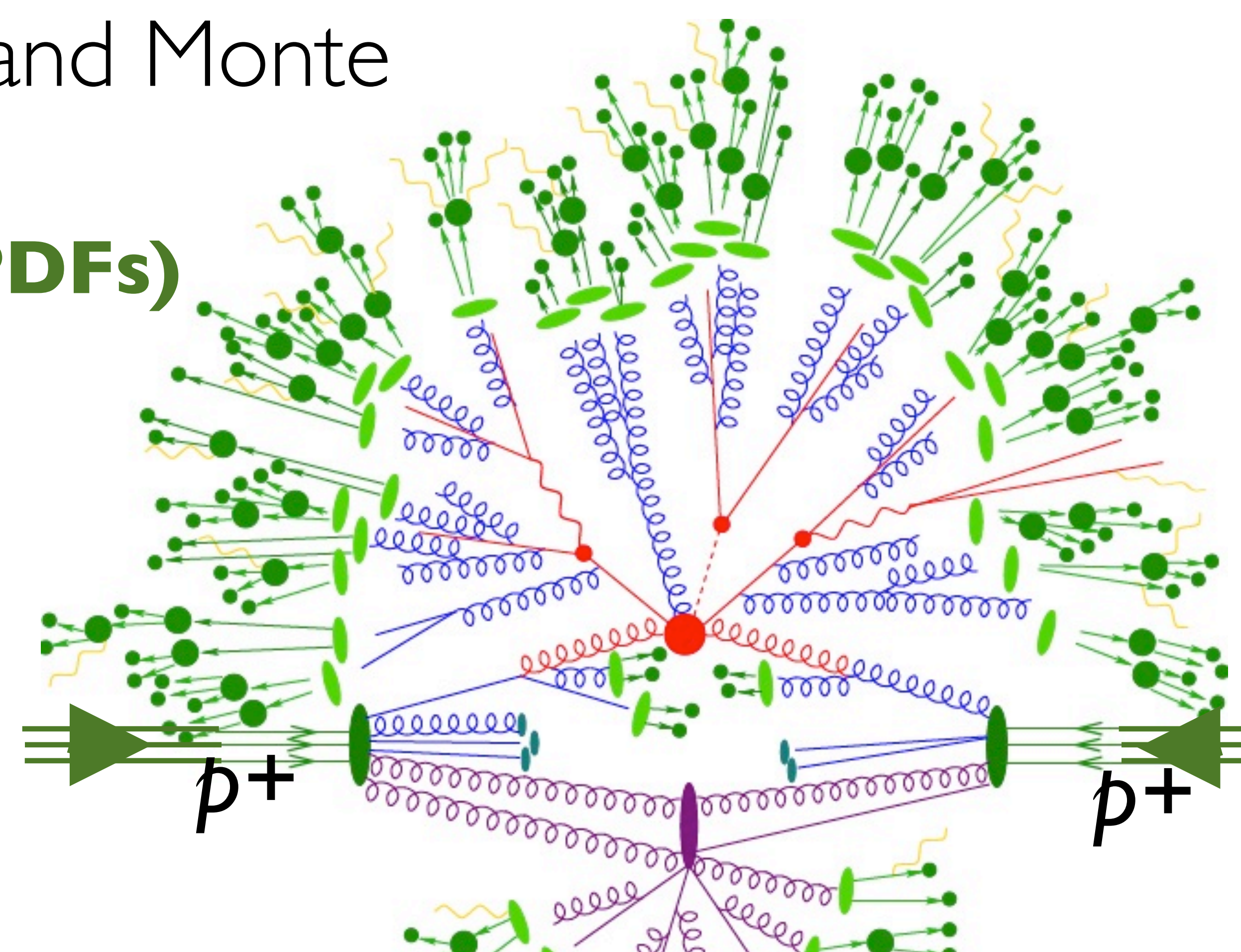
Matrix element

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

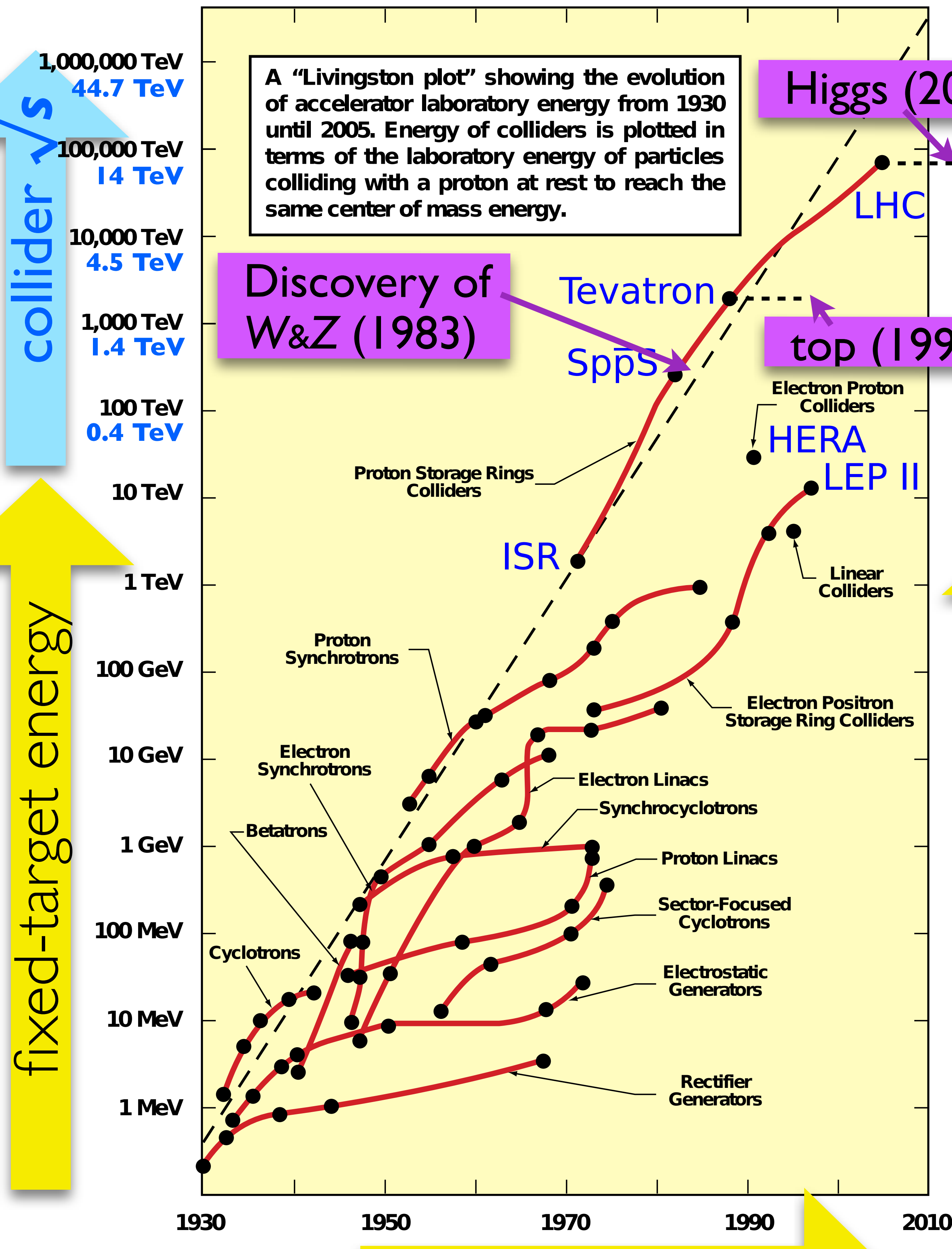
$|\mathcal{M}|^2 \Big($  $\Big) = \Big|\sum \Big($  $\Big)\Big|^2$

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

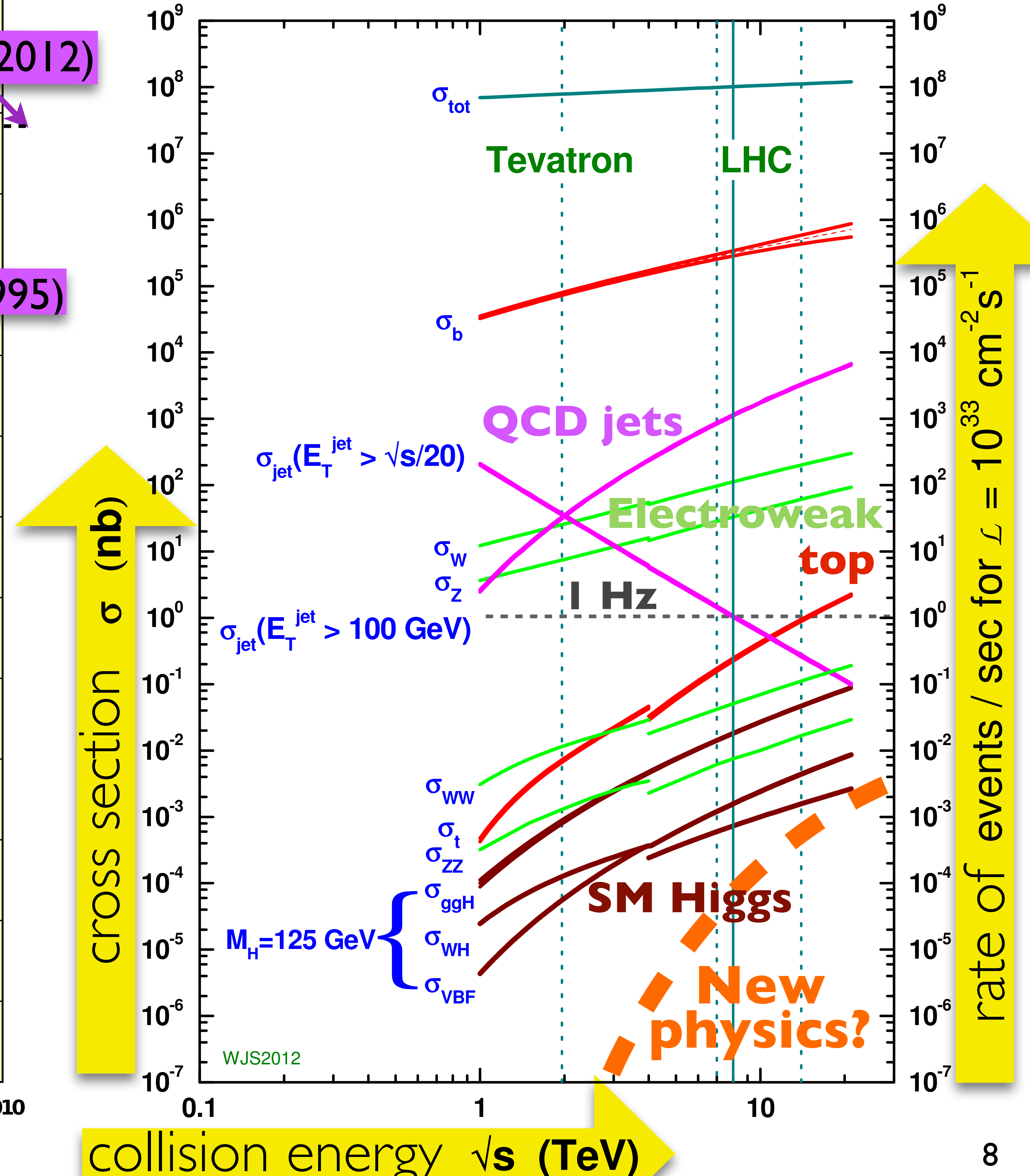
- **"Parton Distribution Functions" (PDFs)**
- **"Hard-scatter" matrix element generator**
- **"Parton shower", Bremsstrahlung, Initial/final-state radiation**
- **"Hadronization"**



We need high energies



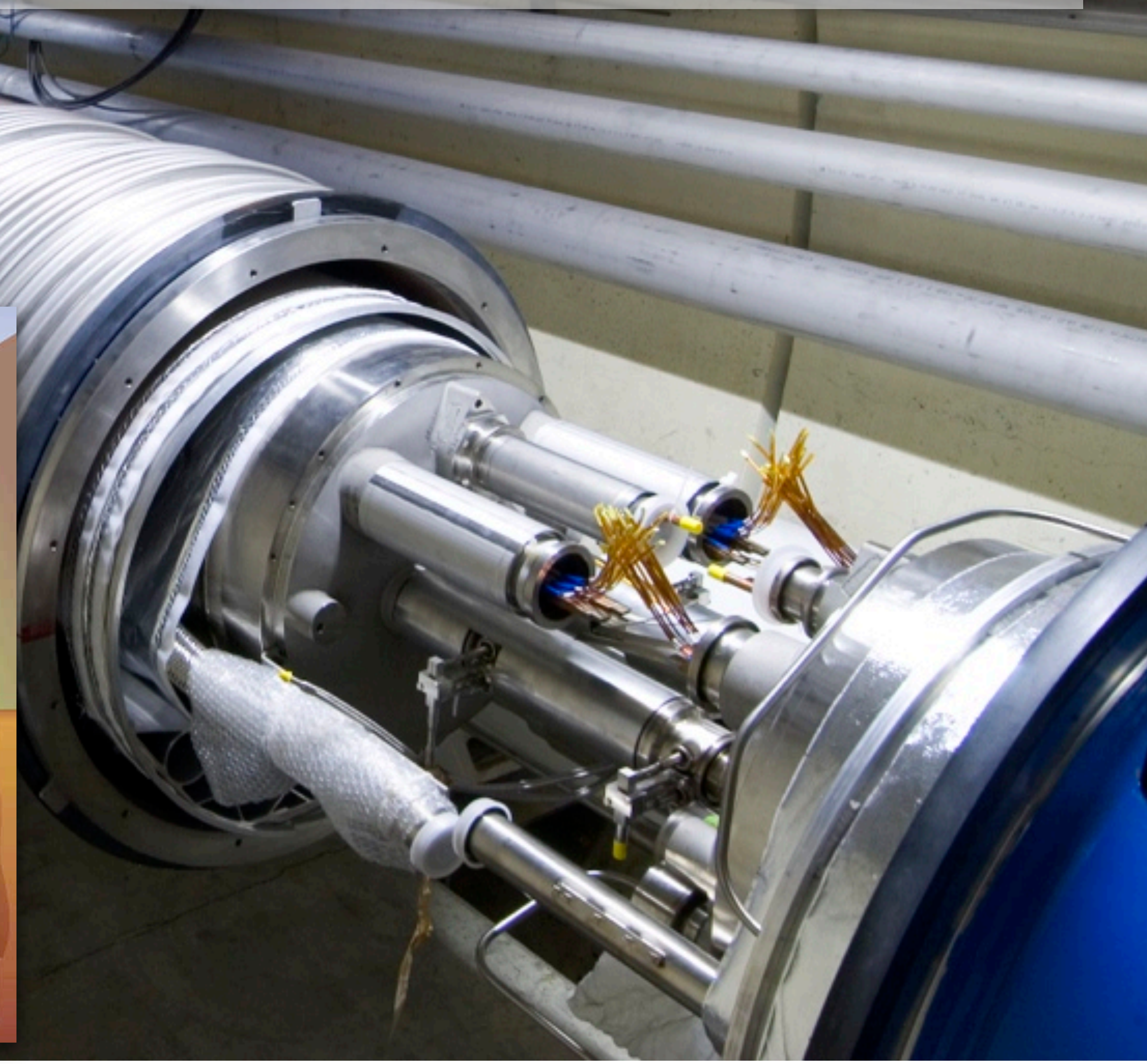
proton - (anti)proton cross sections

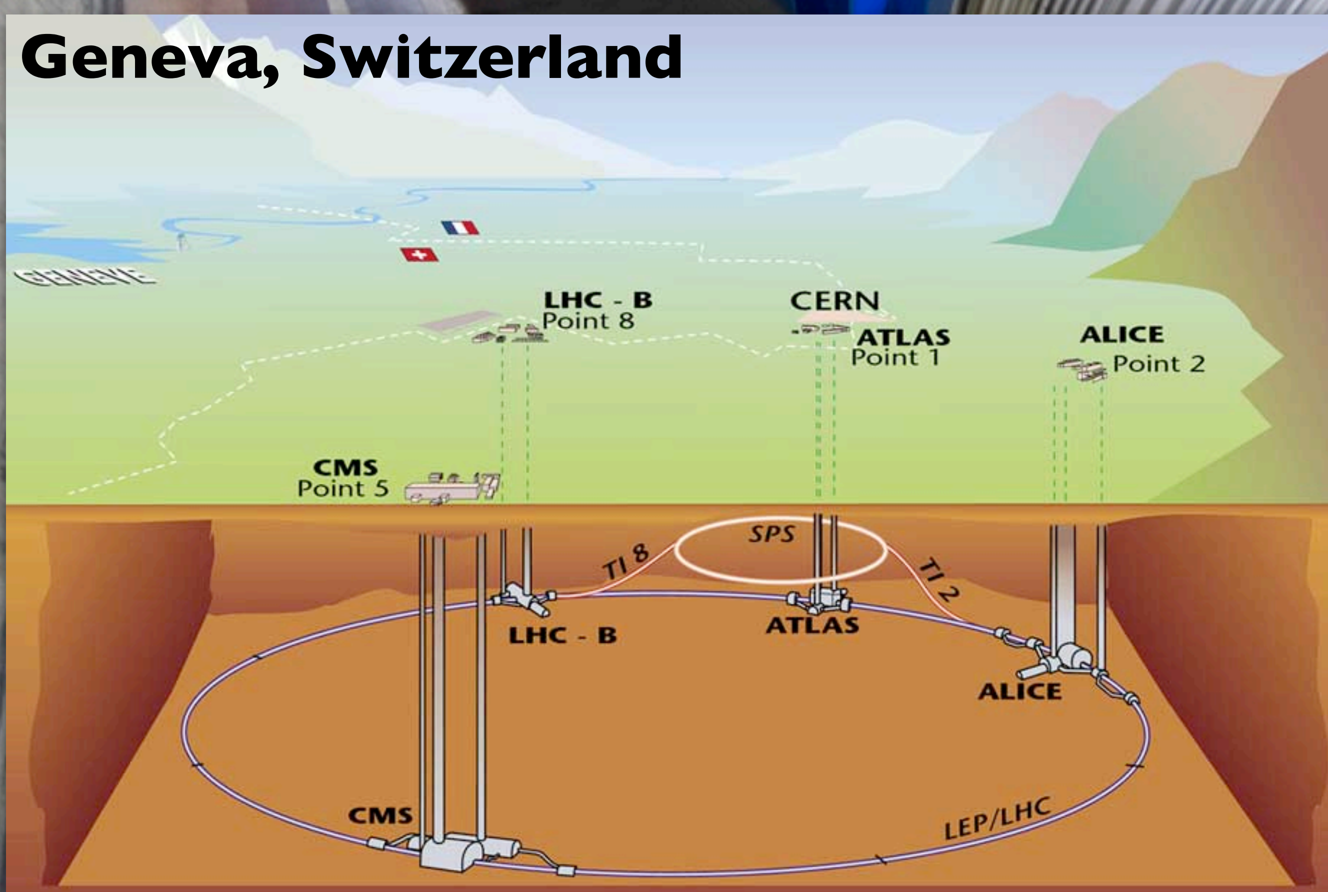


Large Hadron Collider

- p-p collisions at $\sqrt{s}$ = 7-13 TeV
- inst. luminosity = 10^{32}-10^{34} $cm^{-2}s^{-1}$
- 27 km circumference
- 1232 dipoles: 15 m , 8.3 T
- 100 tons liquid He, 1.9 K

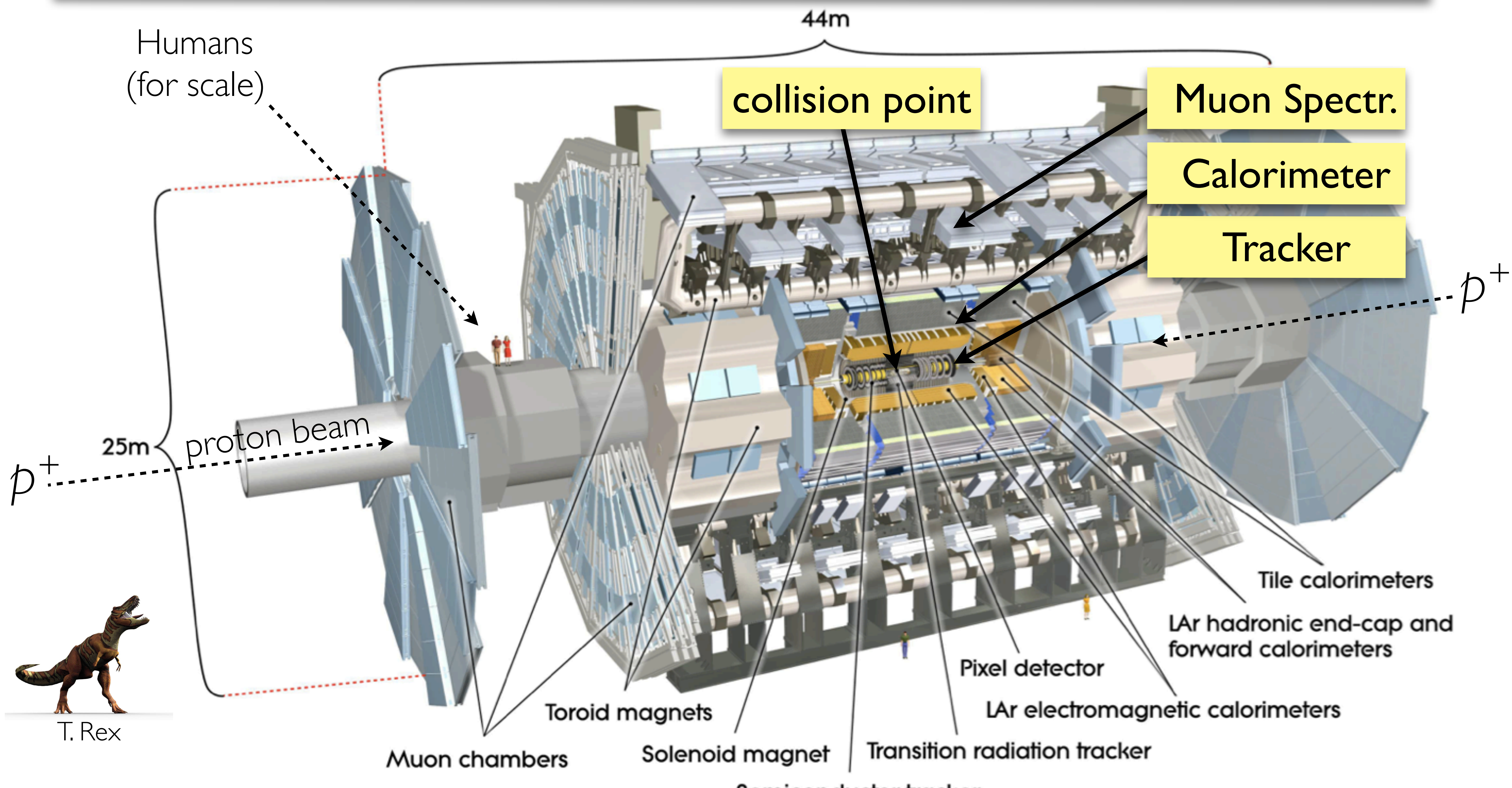
- ~10^{11} protons / bunch
- ~1000 bunches/ beam
- 20 MHz , 50 ns bunch spacing
- 1-40 interactions / crossing
- ~0.5 × 10^9 interactions / sec



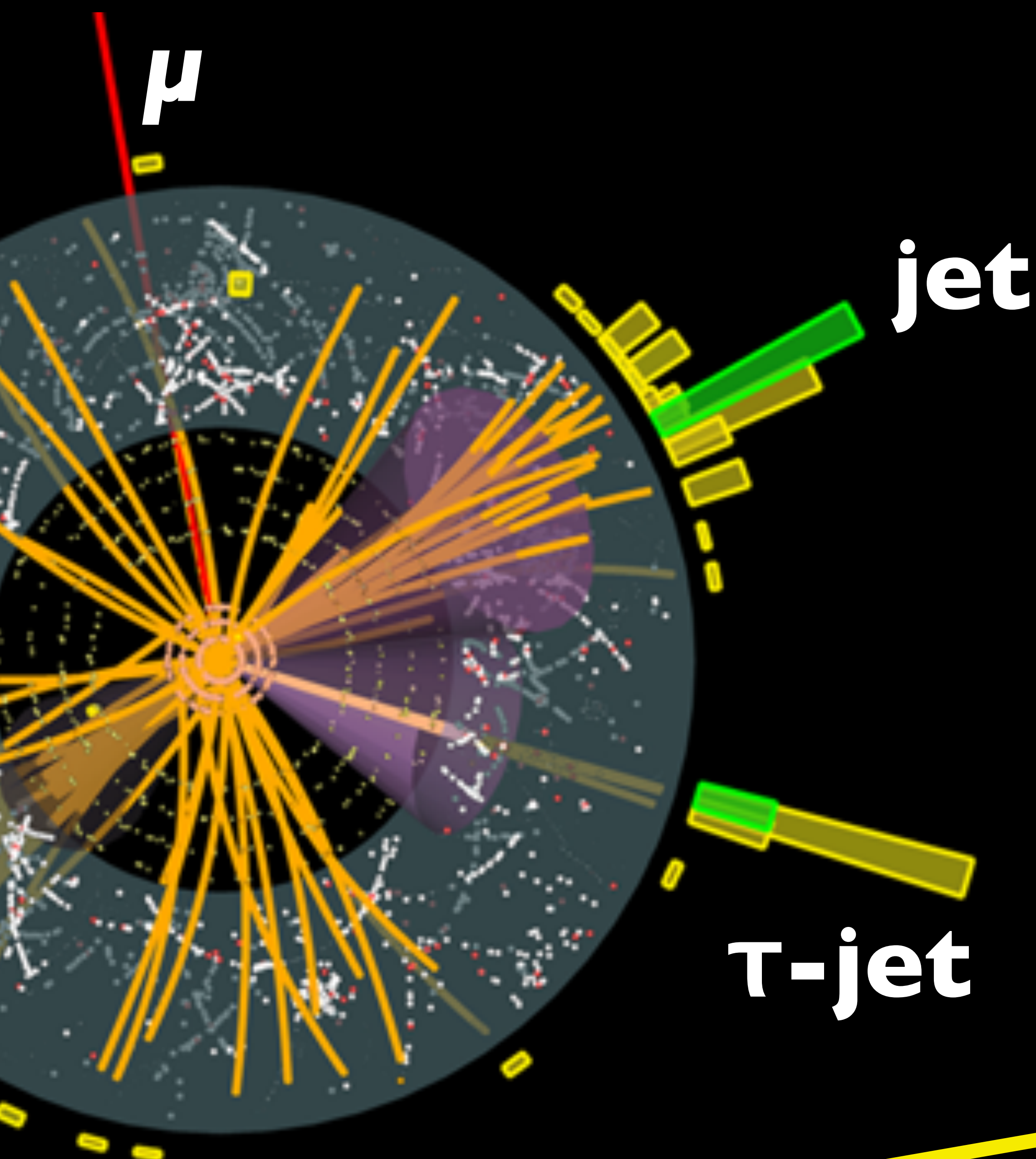


ATLAS Detector

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?



(main objects)

- muons
- electrons & photons
- jets of hadrons
- τ- and *b*-tagged jets
- missing energy

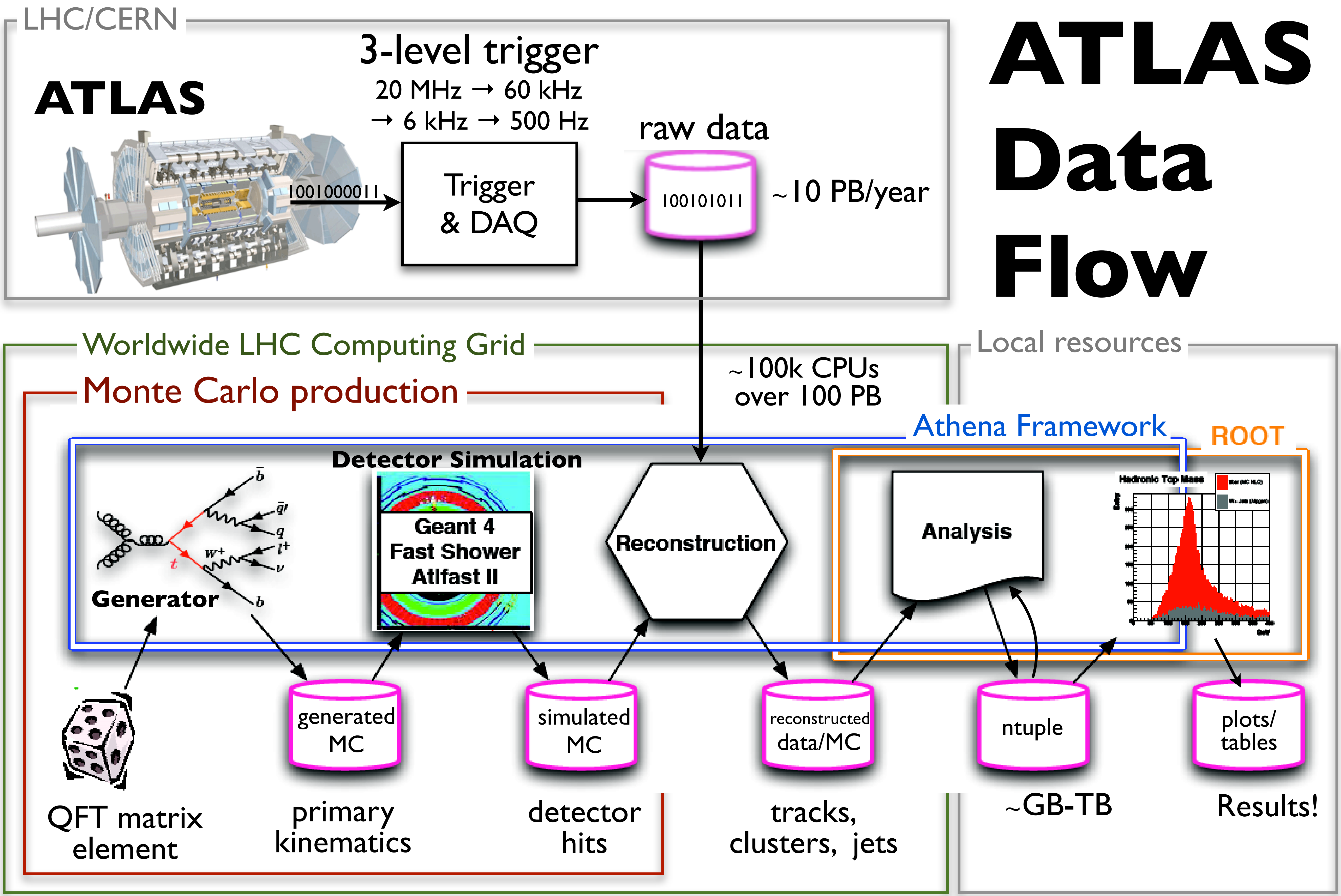
How do we search?

ATLAS Physics Groups

SM	**Higgs**	**SUSY**	**Exotics**
W, *Z*, top,...	*H*→γγ, *ZZ*, *WW*, ...	*l*+jets,γ+jets, ...	*Z'*,*W'*, ...

Currently ATLAS has published 410+ papers

ATLAS Data Flow

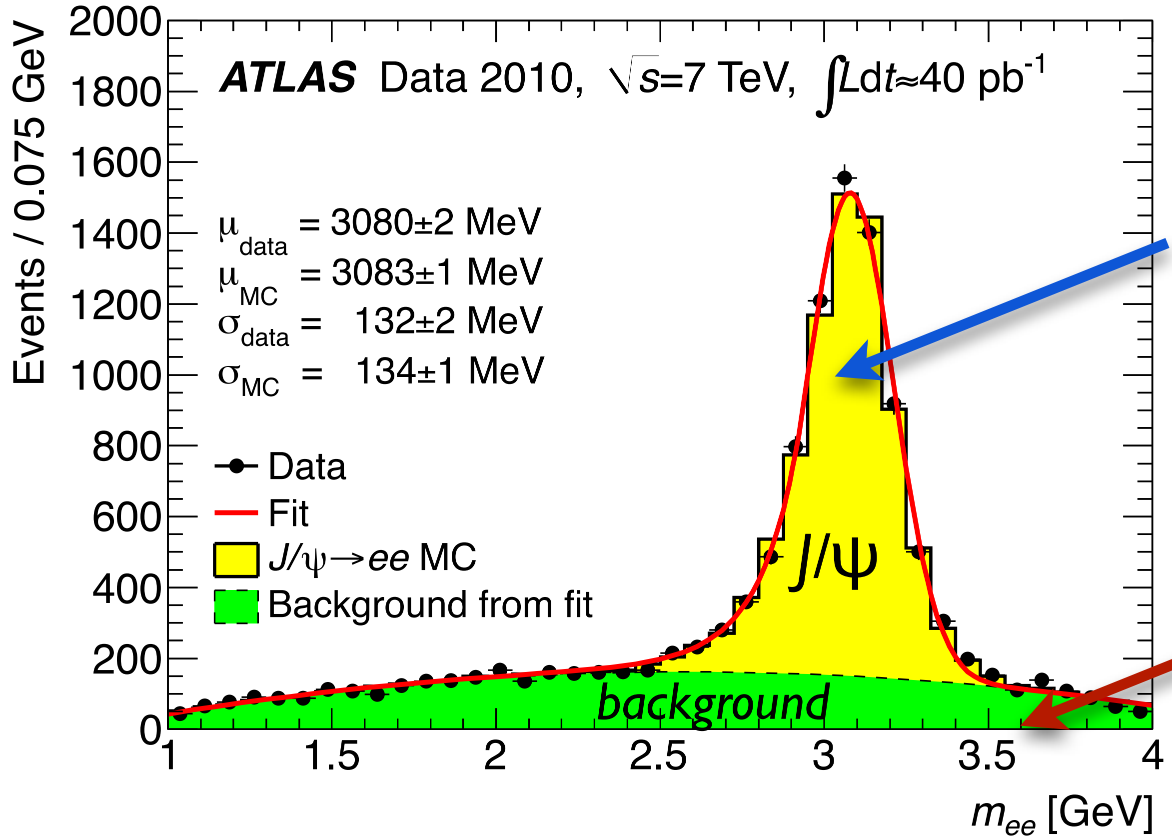


Building a model

$$\underbrace{N(\text{expected})}_{} = \underbrace{N(\text{correct-ID})}_{} + \underbrace{N(\text{fake})}_{}$$

- ***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

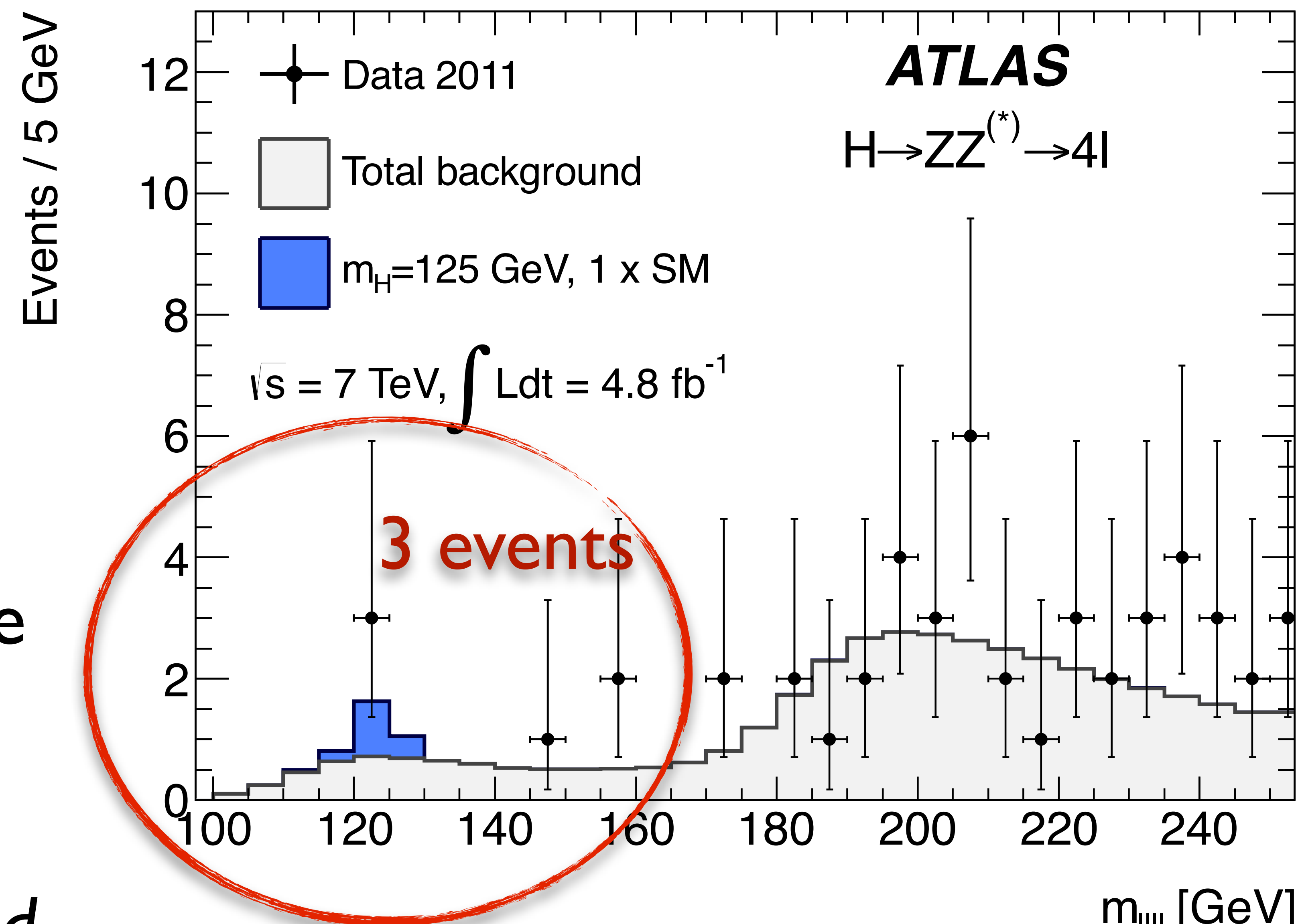
Data-driven
side-band fit

[arxiv:1110.3174]

Is this significant?

Statistical (and philosophical) questions:

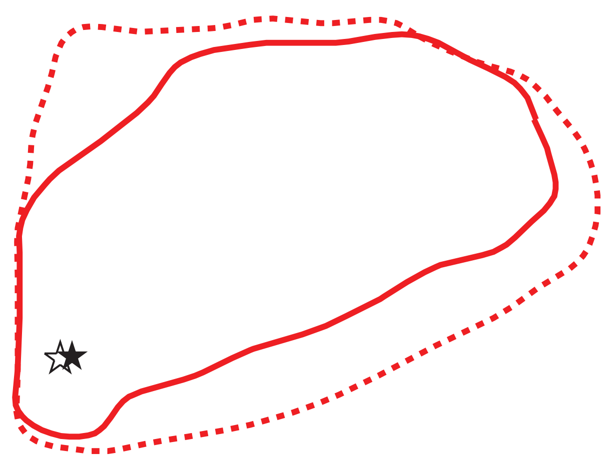
- How can we be precise and rigorous about how confident we are that a model is wrong?
  - ***Hypothesis testing***
- How can we calculate the best-fit estimate of some parameter?
  - ***Point estimation*** *and* ***confidence intervals***



Has a local p_0 of ≈ 2%

Confidence Intervals

- 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 ≈95% *coverage*).
  - They can be one-sided exclusions, *e.g.* $m(Z')$ > 2.0 TeV at 95% CL
  - Two-sided measurements, *e.g.* m_H = 125.1 ± 0.2 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):

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

data, #expected, events n, observable

$$\mathbf{f}(\mathcal{D}|\nu, \alpha) = \mathrm{Pois}(n|\nu) \prod_{e=1}^{n} f(x_e|\alpha) \quad = \quad L(\alpha)$$

histograms

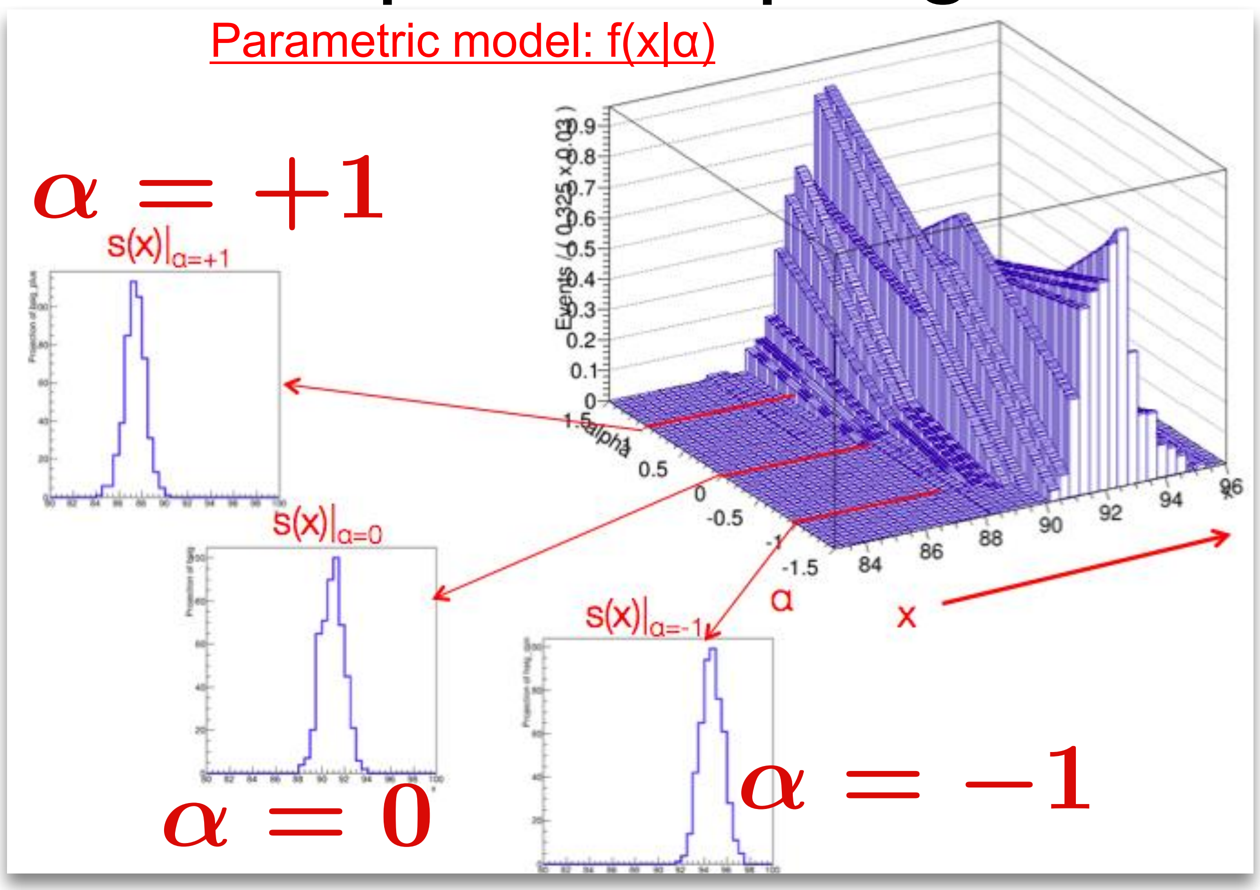
"Likelihood"

function of params with data fixed

$\{\alpha\}$ parameters include:

1. parameters of interest $\{\mu\}$:
   - e.g. Higgs mass (m_H) and signal strength (μ)
     μ=0 no signal, μ=1 nominal signal
2. nuisance parameters $\{\theta\}$:
   systematic uncertainties to be "profiled" away by maximizing L for a given μ.
   - e.g. luminosity uncert., jet-energy scale, electron energy scale, electron identification efficiency, etc.

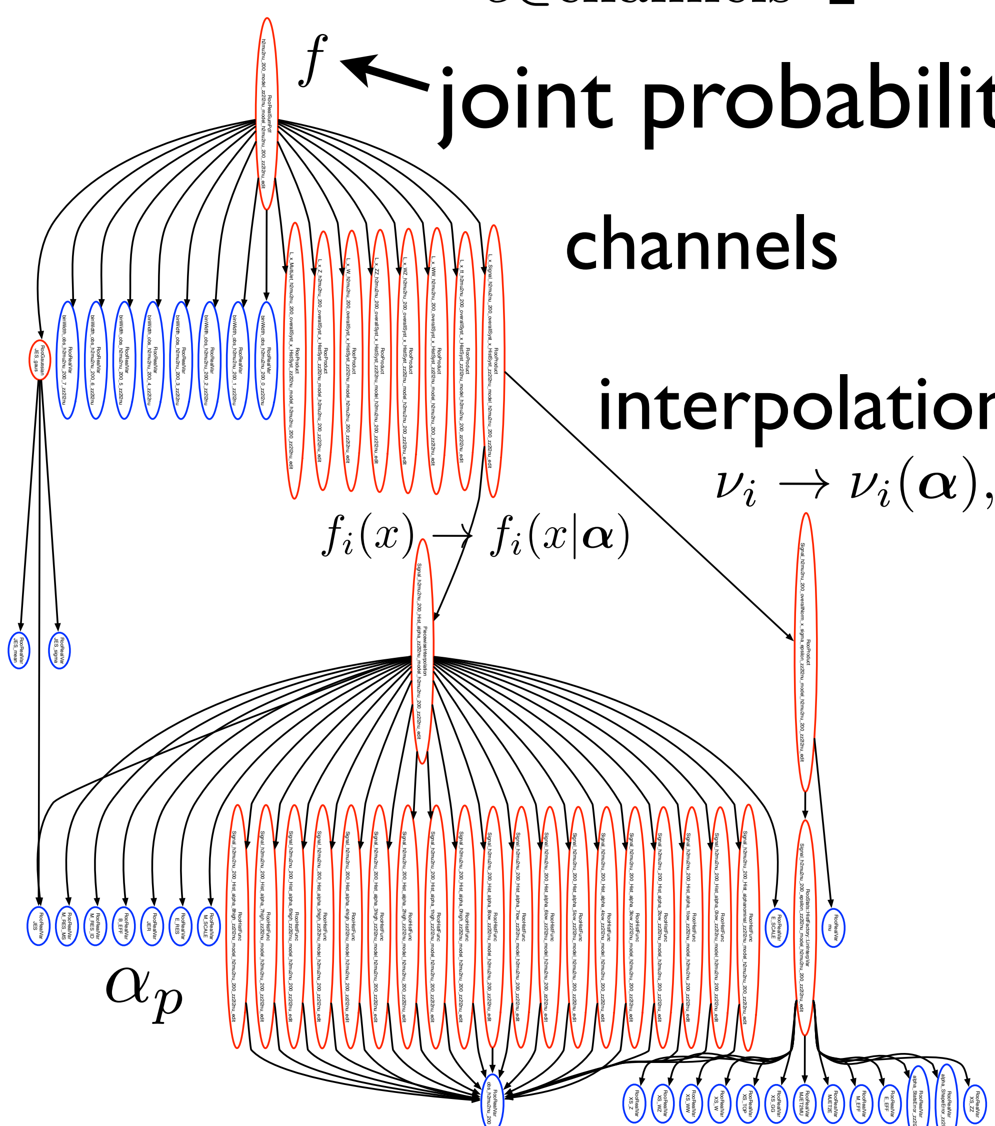
template morphing



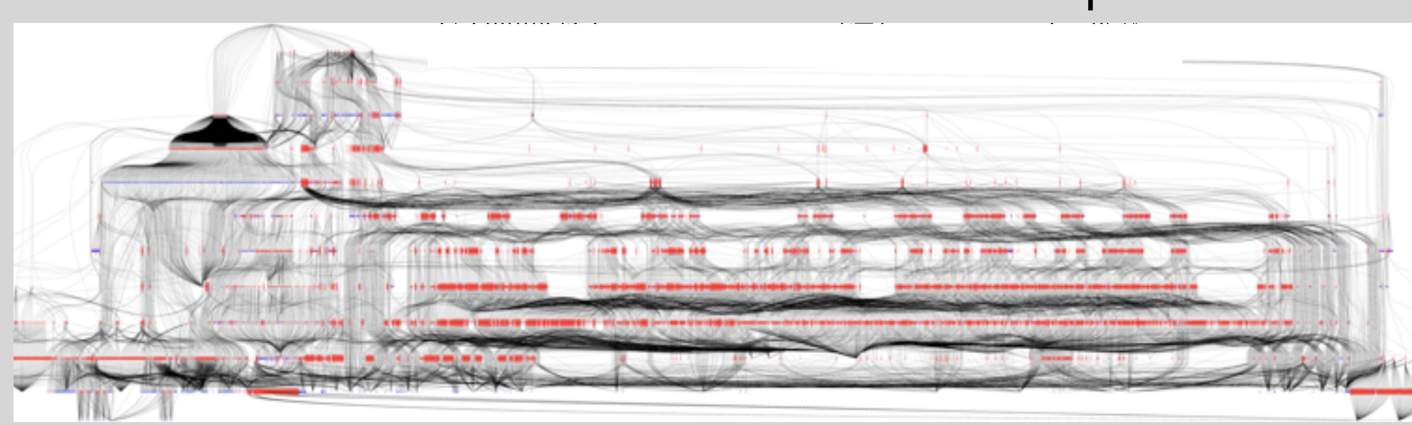
Statistical model

General probability model with many channels and constraints:

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



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



[arxiv:1503.07622, https://indico.cern.ch/event/243641/]

Statistical point estimation

"Profiling"

Calculate the profile likelihood ratio:

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

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

$\hat{}$ = Maximum Likelihood Estimates

$\hat{\hat{}}$ = MLE for given μ

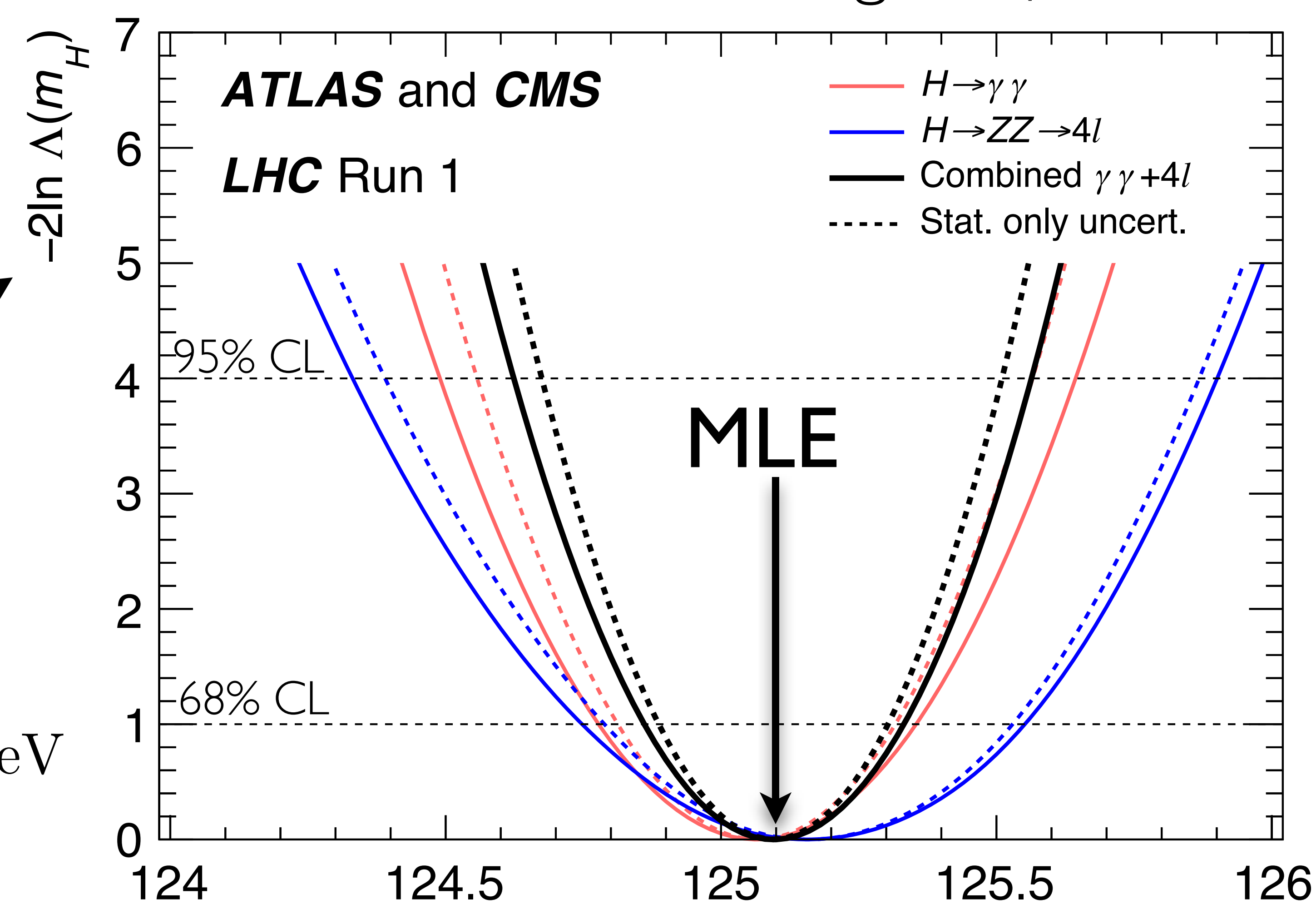
Maximum Likelihood Estimate

Maximize $\lambda(\mu)$

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

e.g. Best-fit Higgs mass

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

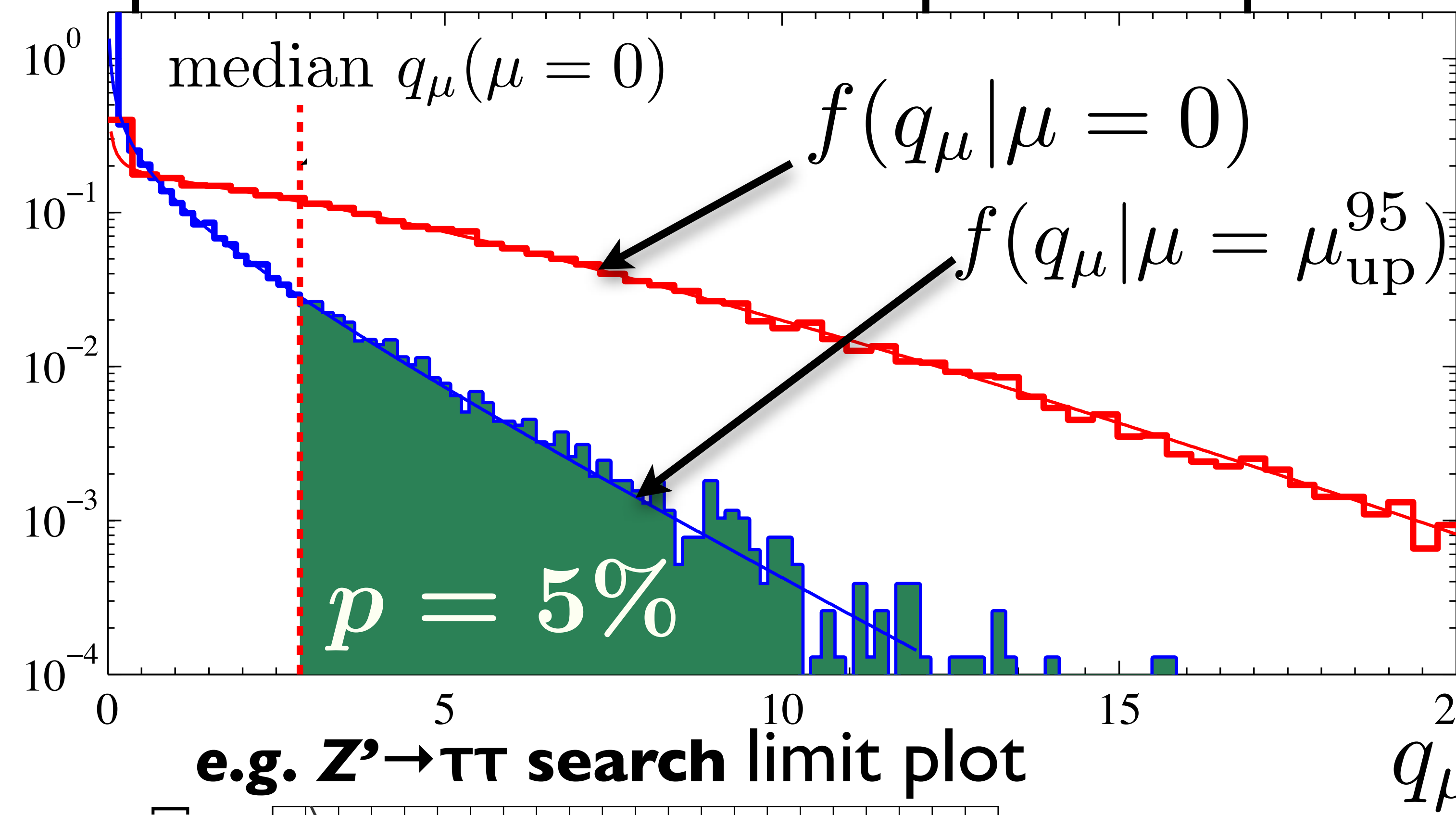


[arxiv:1503.07622, 1503.07589]

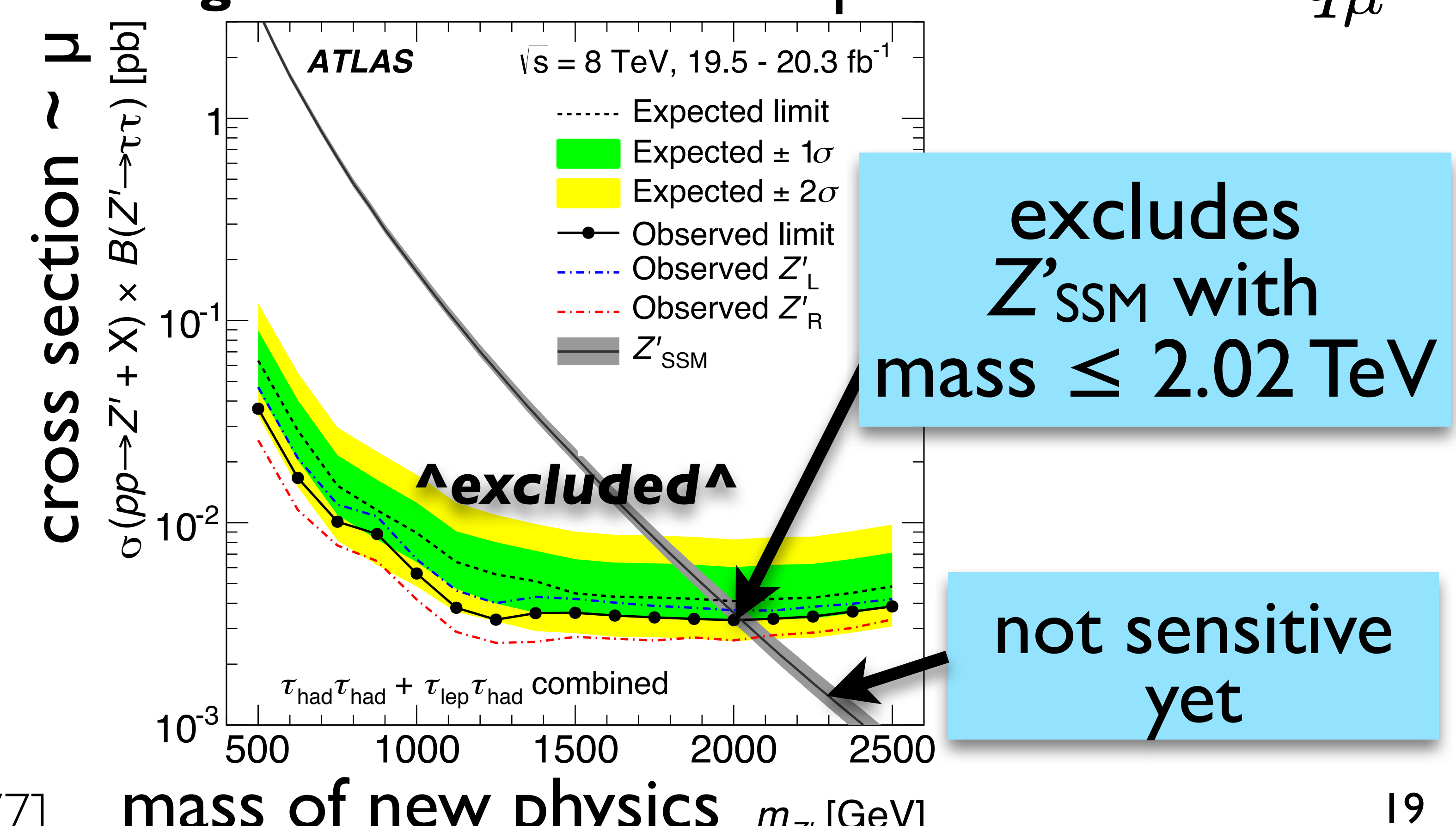
Statistical hypothesis tests (upper limits)

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

Sample the test statistic with pseudo experiments



e.g. Z'→ττ search limit plot



mass of new physics

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$ = m(c)	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})$>1.8 × 10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV; 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV; 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1   **Mass scale [TeV]**

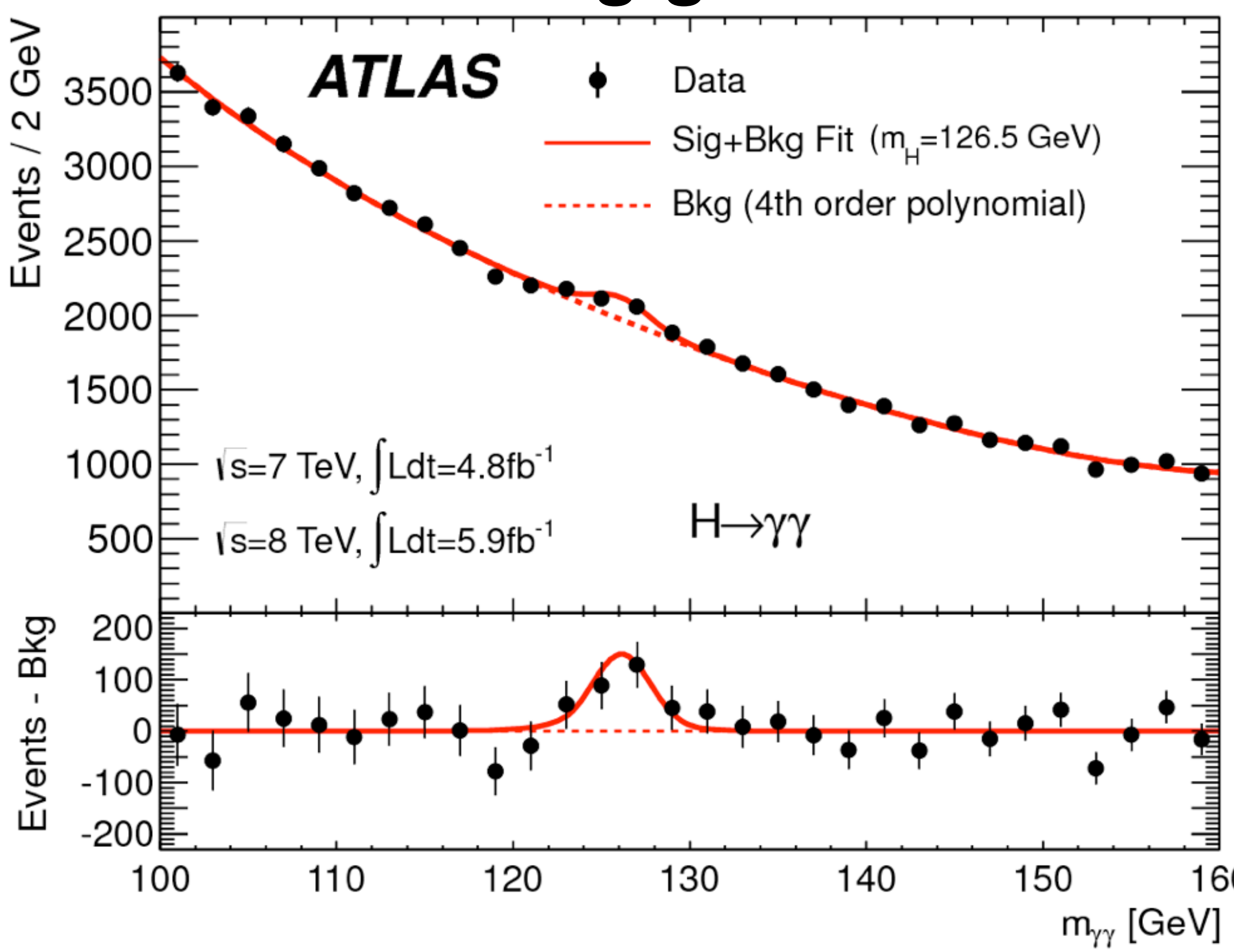
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


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
July 5 cover of the New York Times:
“Physicists Find Elusive Particle Seen as Key to the Universe”
The New York Times
Late Edition
NEW YORK, THURSDAY, JULY 5, 2012
ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX
SHIFT RENEWS CRITICISM
Move Aligns Him With Conservative Voices Within His Party
Physicists Find Elusive Particle Seen as Key to Universe

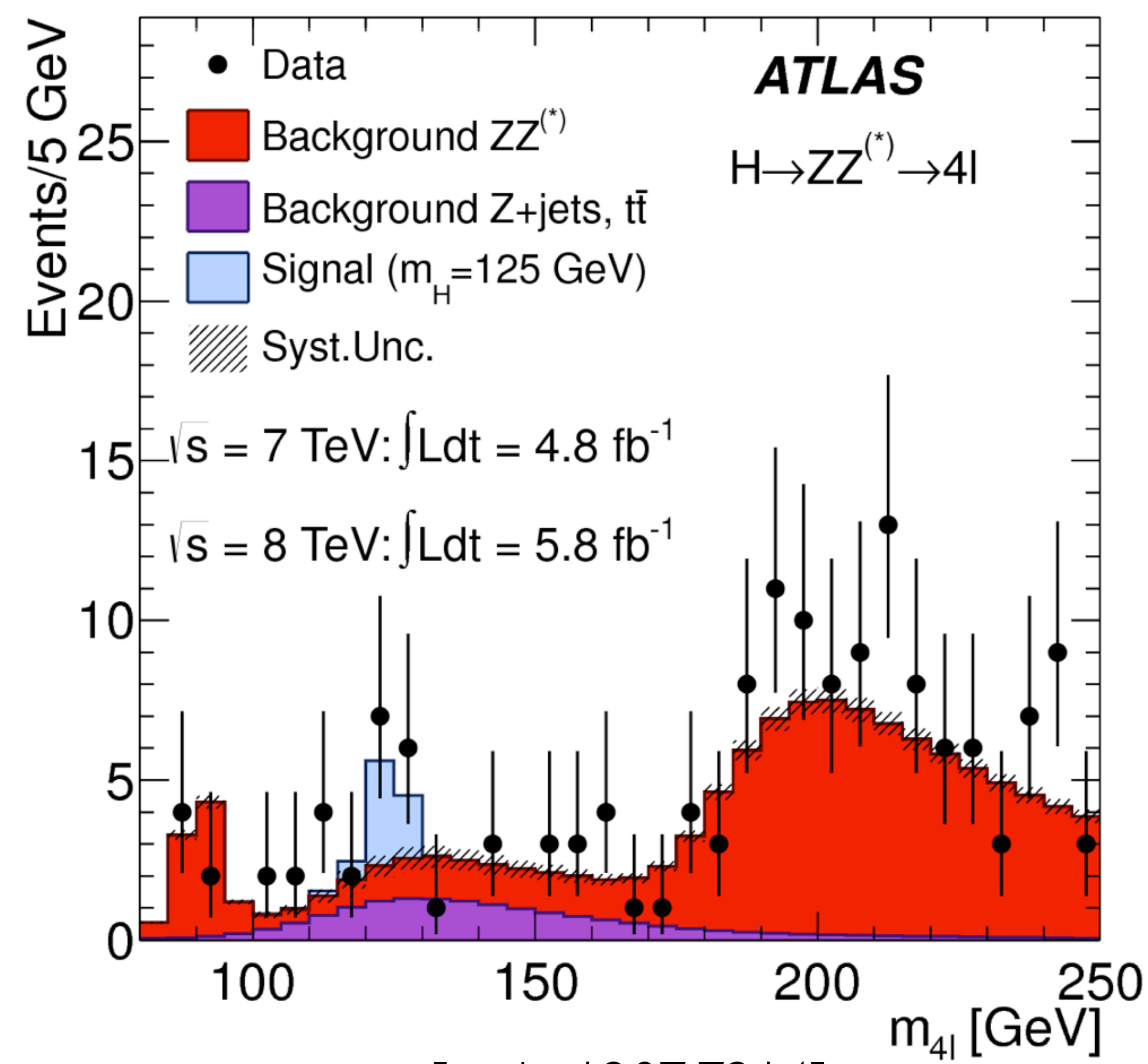
Higgs mass bumps

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

$H \to \gamma\gamma$



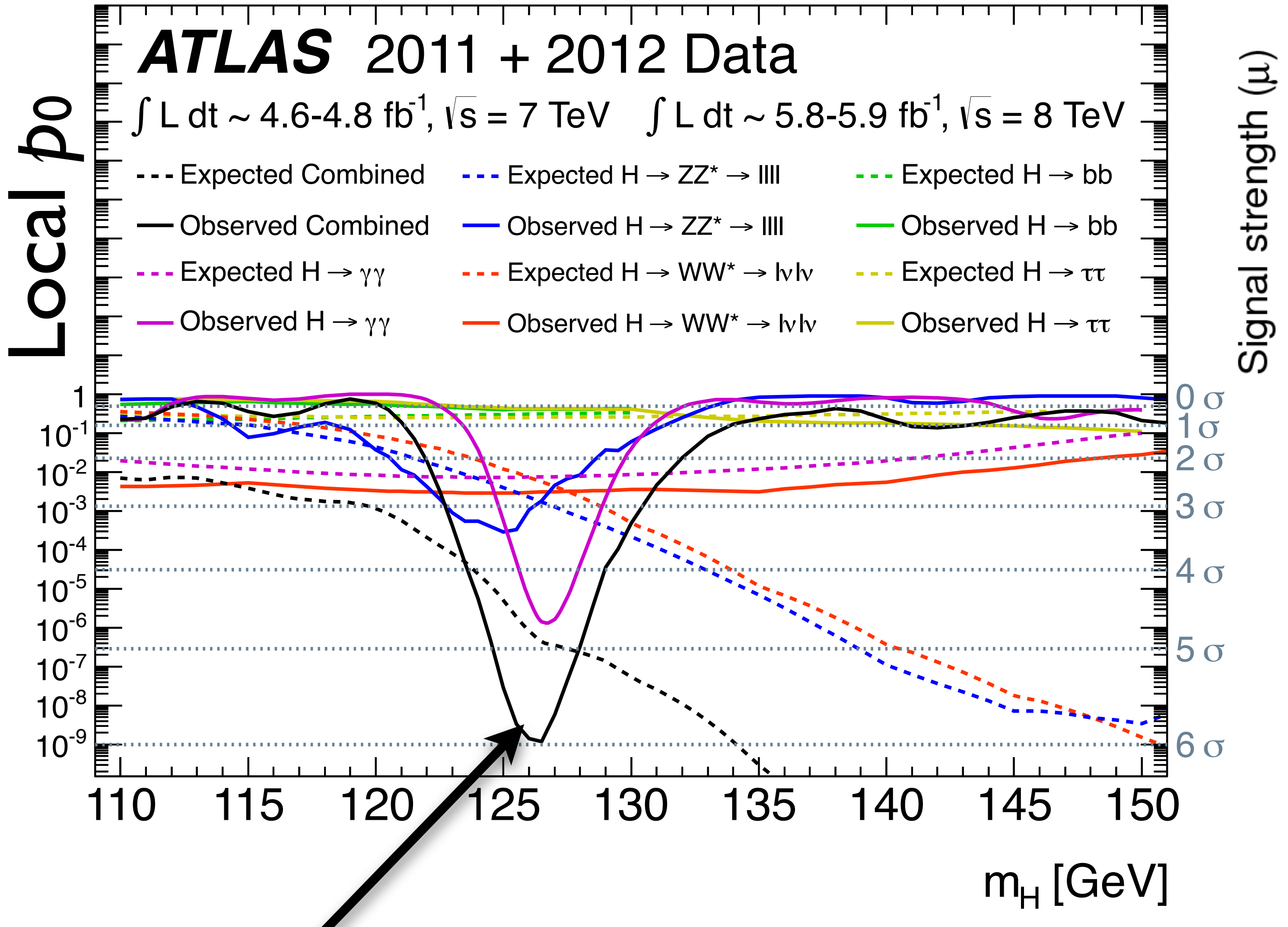
$H \to ZZ \to 4l$



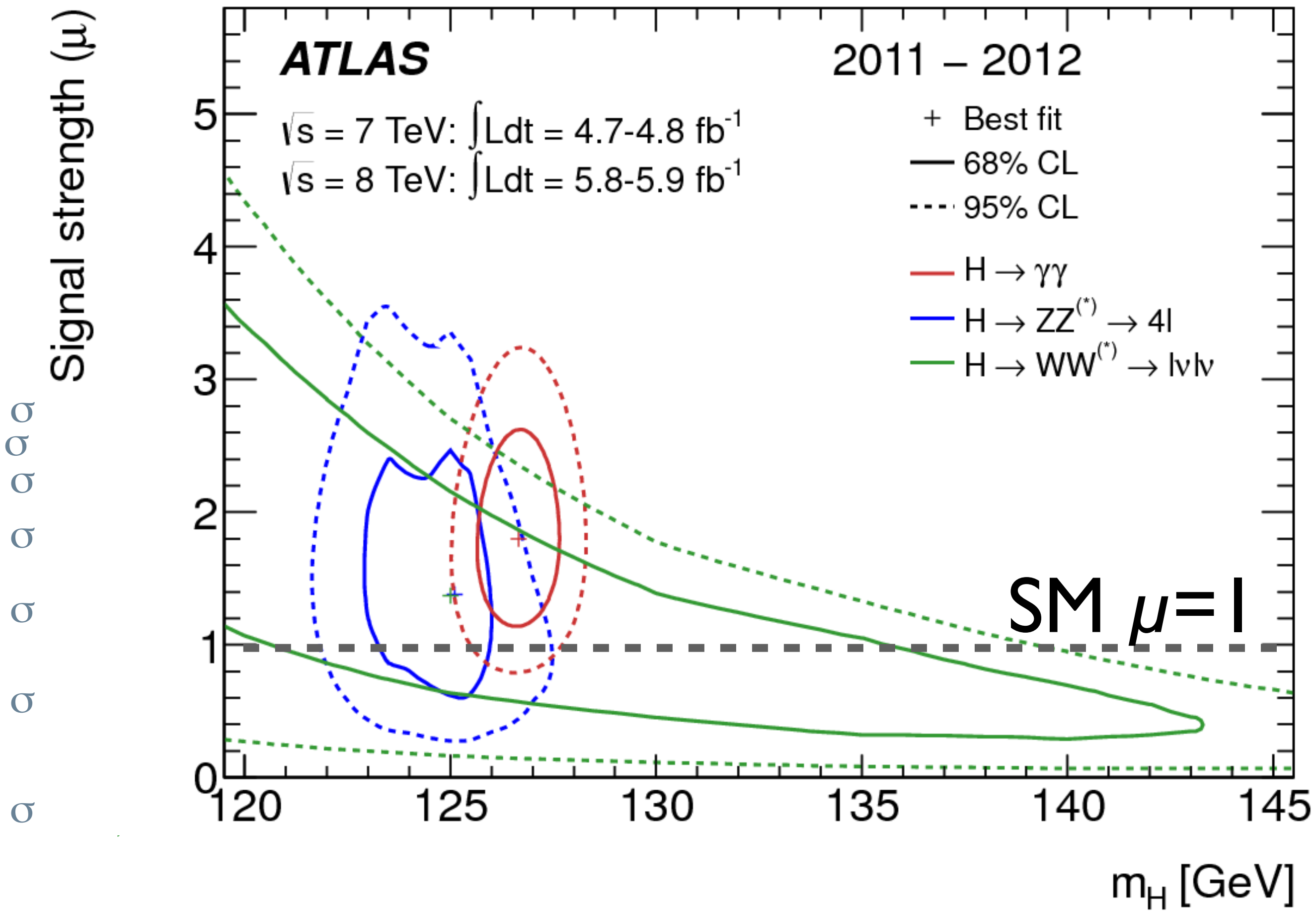
[arxiv: 1207.7214]

Higgs Confidence

Inconsistent with background only



Consistent with SM Higgs



- Local $p_0 = 1.7\times10^{-9}$, corresponding to 5.9σ
- Particle physics has a conservative traditional threshold of significance for claiming discovery of $5\sigma \Rightarrow p_0 = 2.9\times10^{-7}$

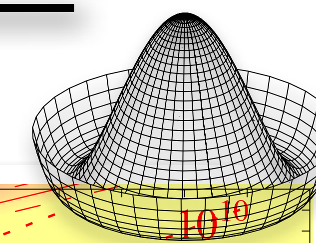
$= 1$ in 3.5 million

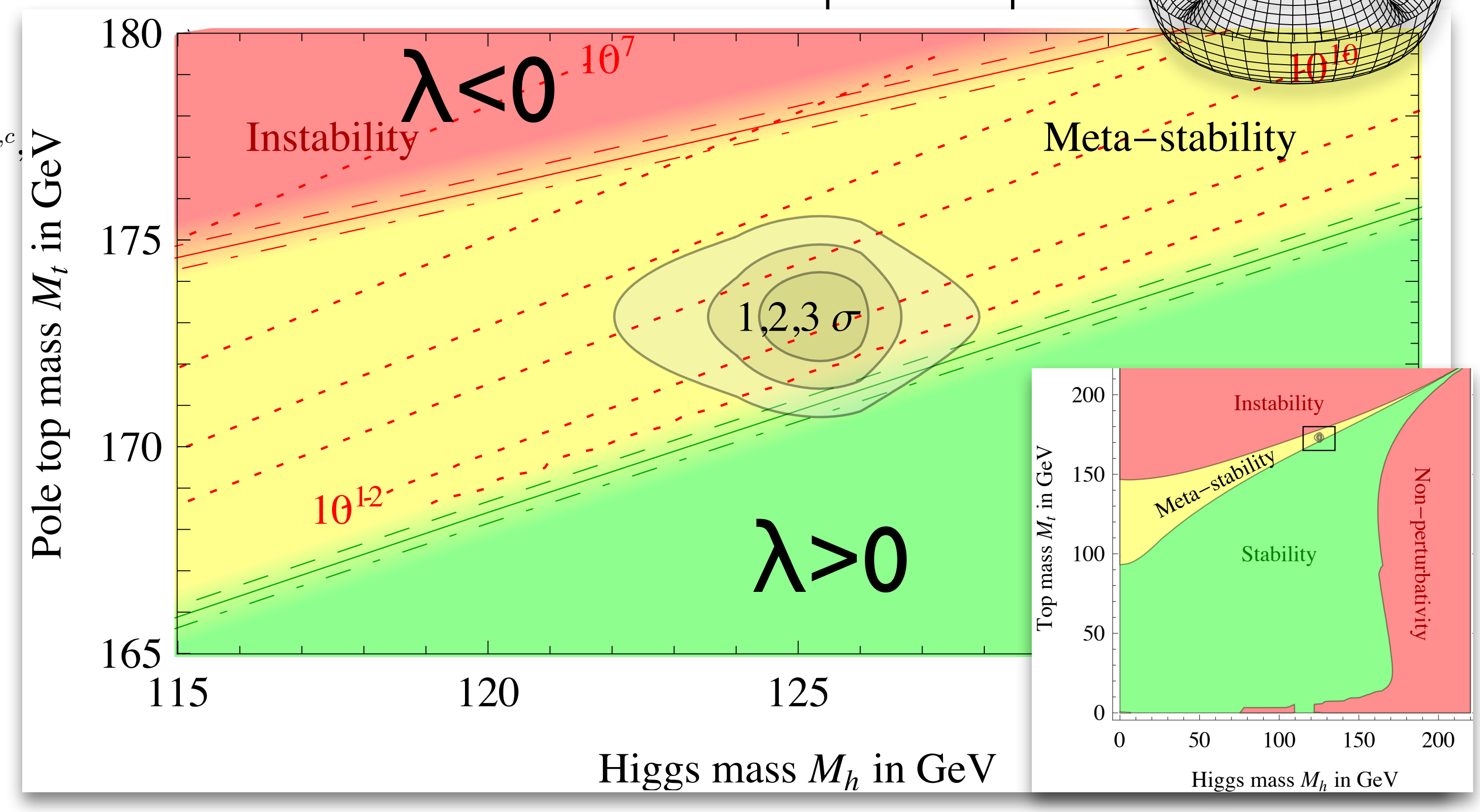
Naturalness or multiverse?

Higgs mass and vacuum stability in the Standard Model at NNLO

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

$$V(\Phi) = \mu^2\,\Phi^\dagger\,\Phi + \lambda\,\left|\Phi^\dagger\,\Phi\right|^2$$



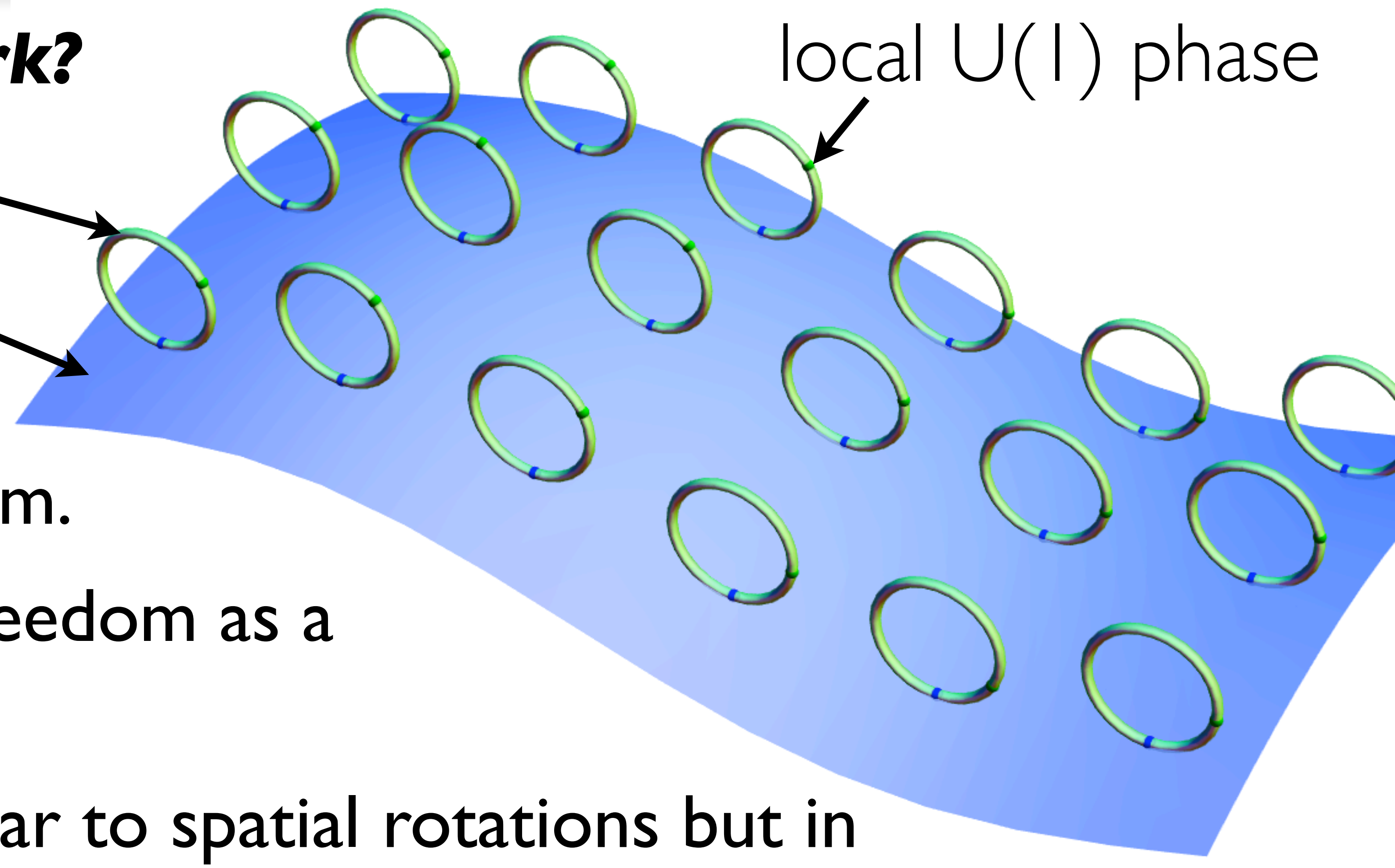


"If the LHC finds Higgs couplings deviating from the SM prediction and new degrees of freedom at the TeV scale, then the most important question will be to see if a consistent and natural (in the technical sense) explanation of EW breaking emerges from experimental data. But if the LHC discovers that 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."

[arxiv: 1205.6497]

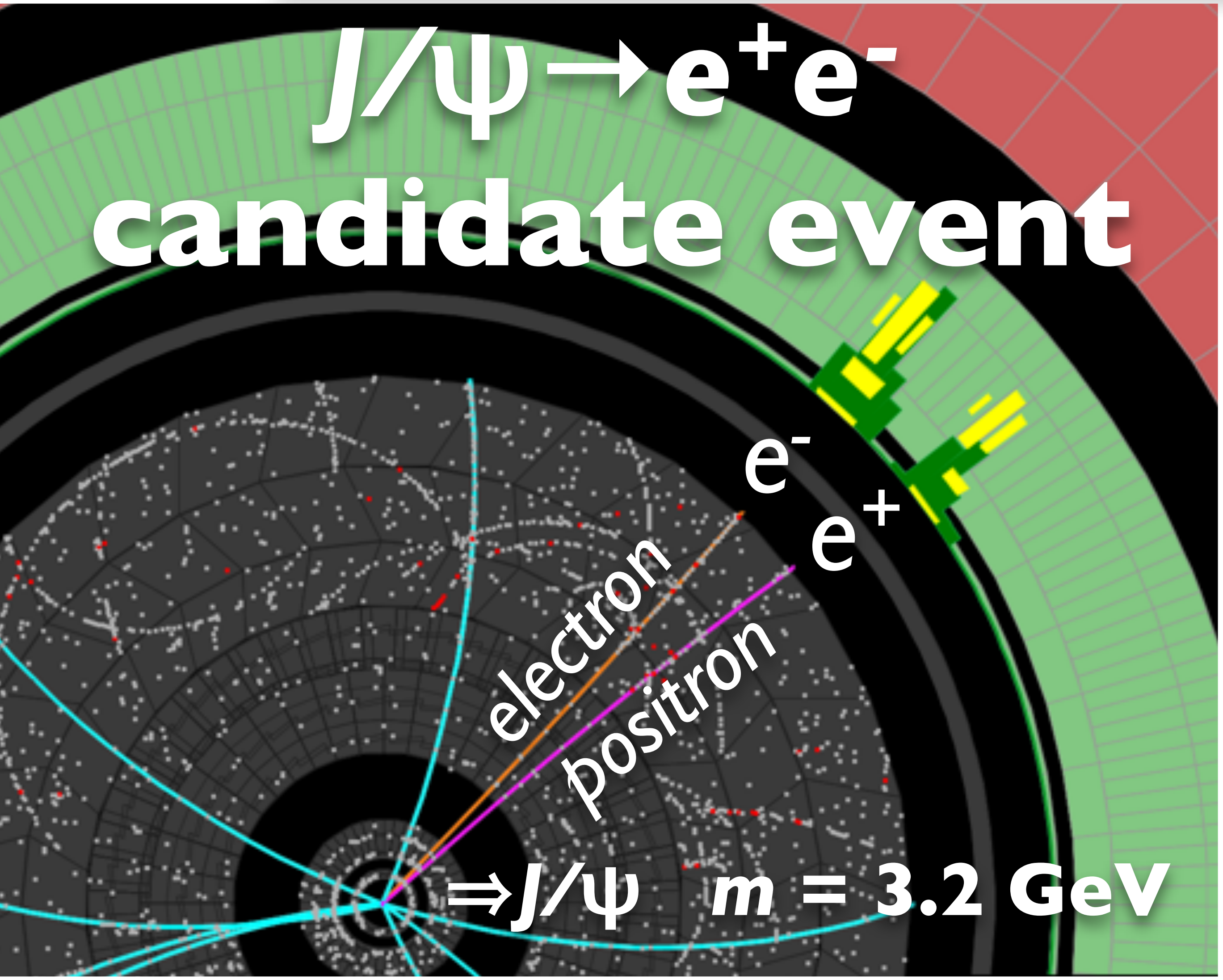
Gauge invariance is deep!

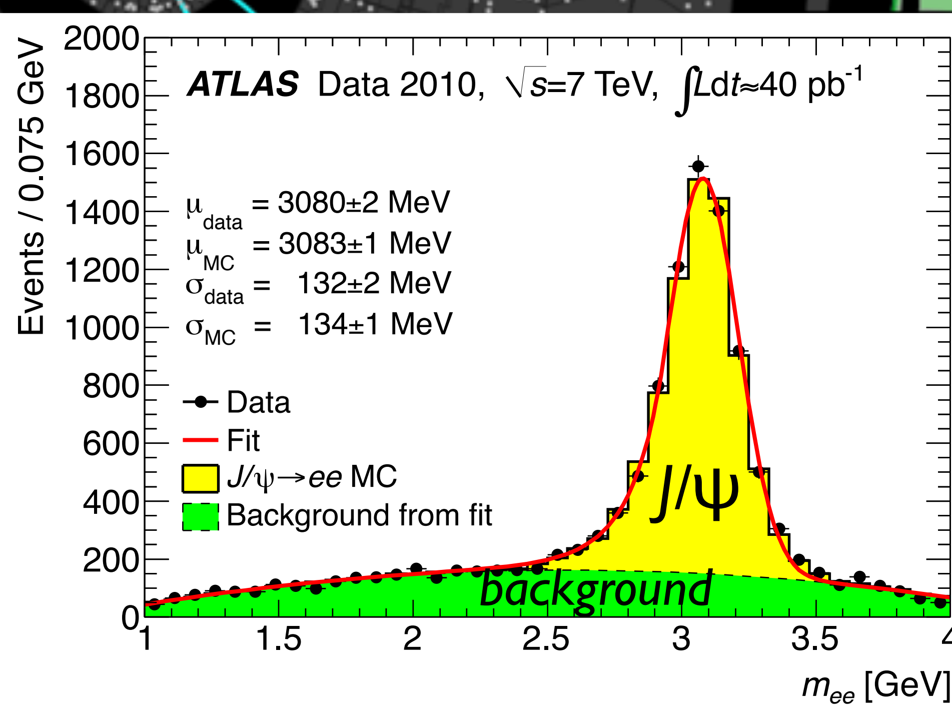
Why do gauge theories work?



- 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?

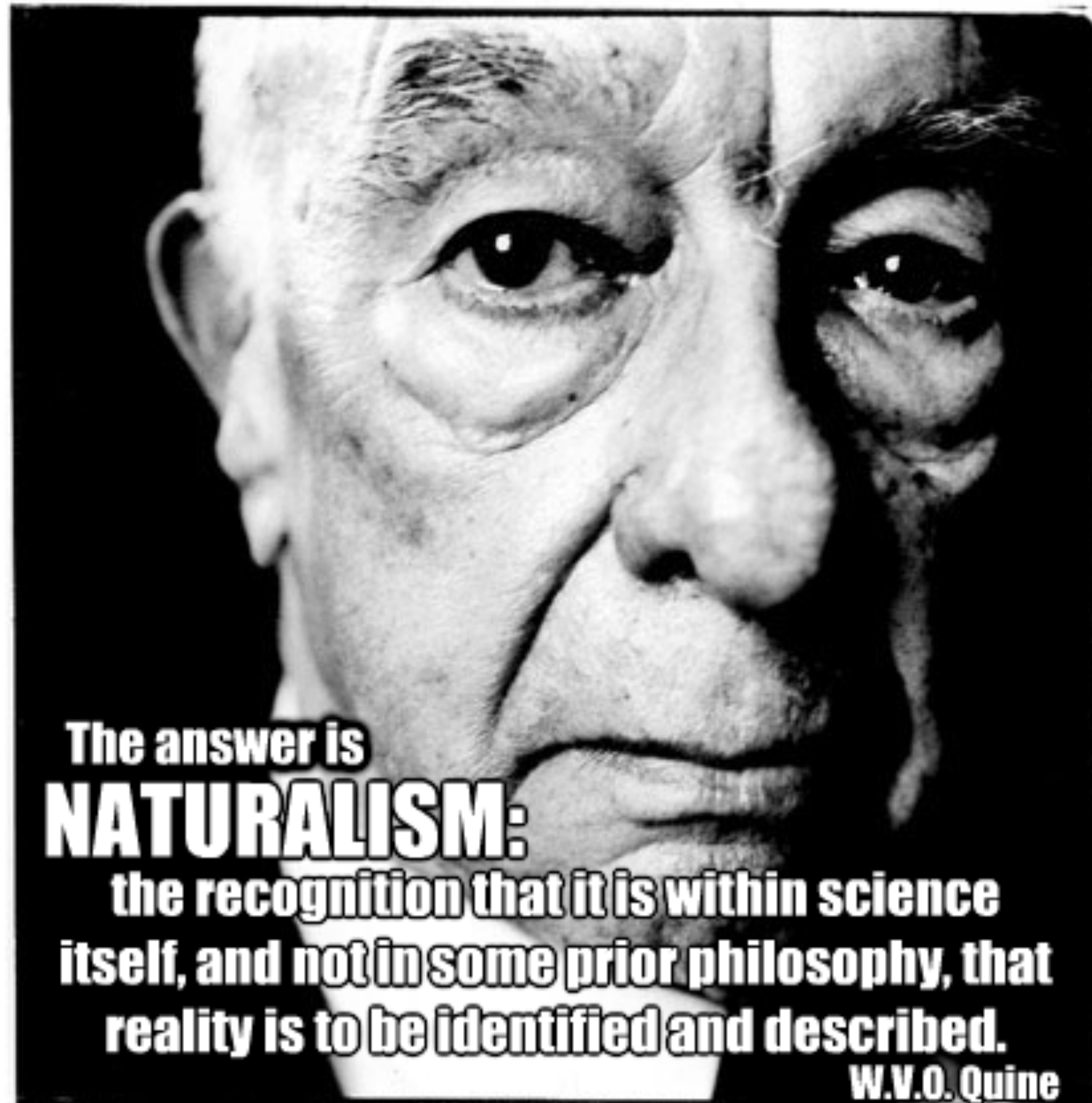
- An excitation in a ***Dirac spinor field*** representation of SU(2)xU(1), the *"Platonic electron"*.
- ***A software object*** with a reconstructed track and calorimeter deposit, passing some selection cuts, the *"pragmatist electron"*.
- ***A set of voltages*** and timings read-out from the detector,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

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

Summary

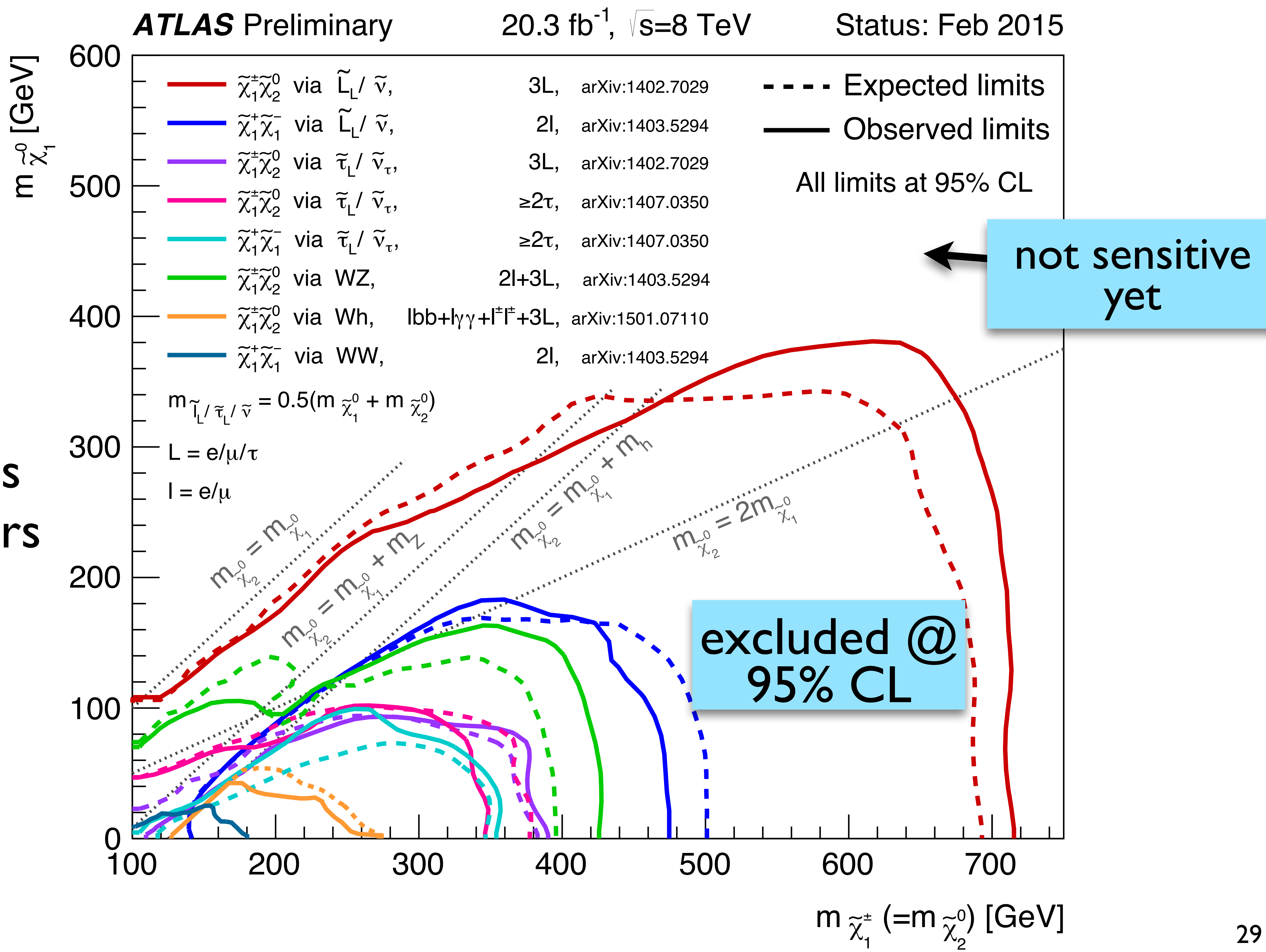
- Particle physics probes very deep questions about what the world is made of, how it works, and how it got here.
- While this school is specifically about ontology, I also want to emphasize that ***physics has a profound epistemology grounded in statistical significance***.
- Physicists have learned 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

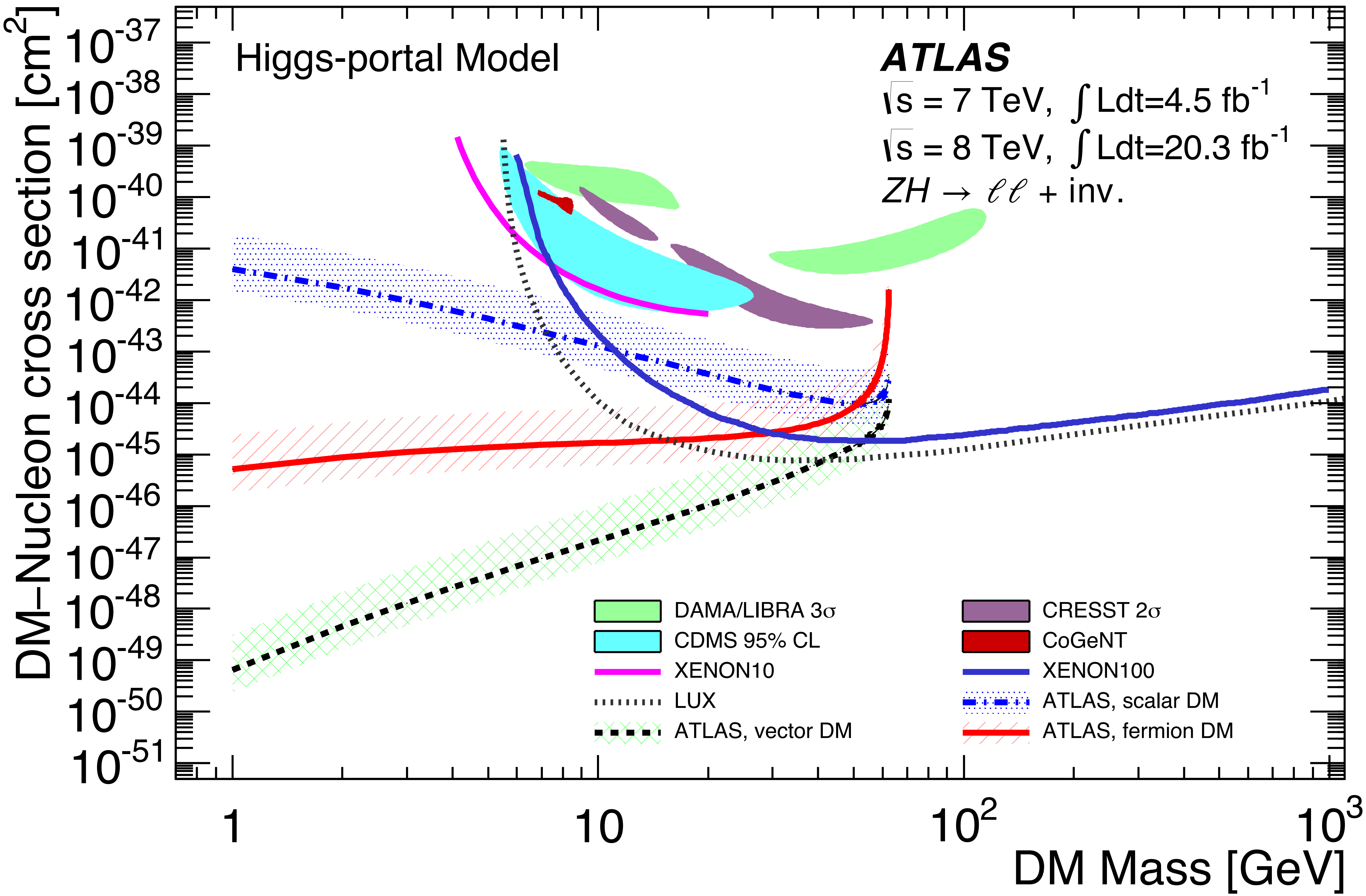


SUSY chargino-neutralino exclusions

Scan in two mass parameters



Higgs-portal to Dark Matter?

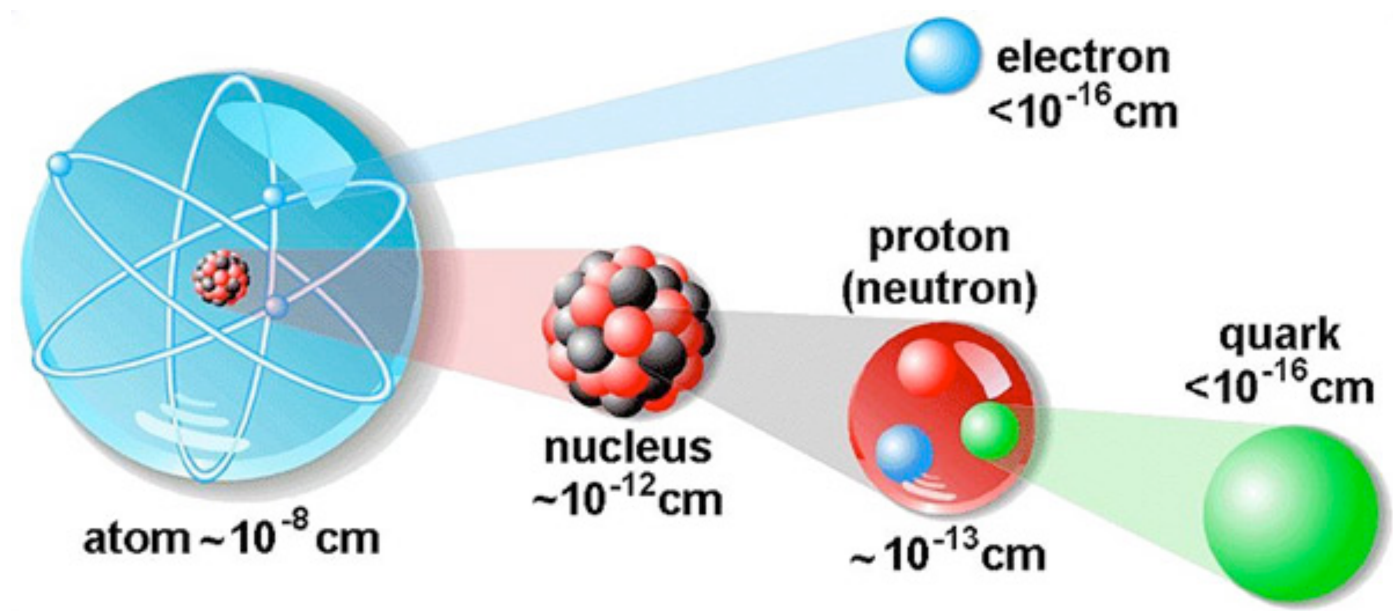


[arxiv:1402.3244]

Particle Physics

Fundamental questions of particle physics:

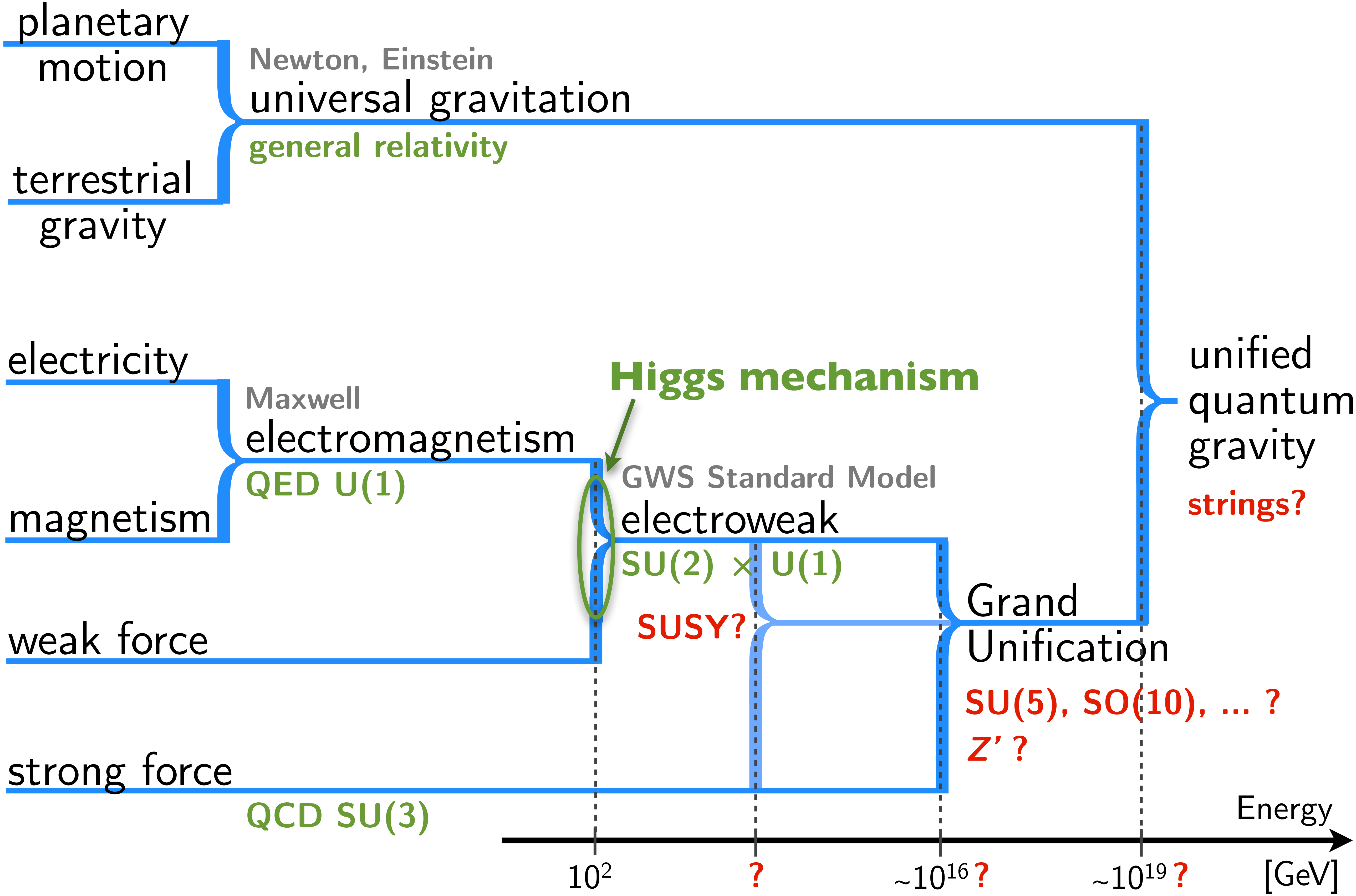
1. ***What is matter?***
2. ***How does it interact?***



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

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

Wave function

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

- Superposition principle

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

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

$$\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_E$$

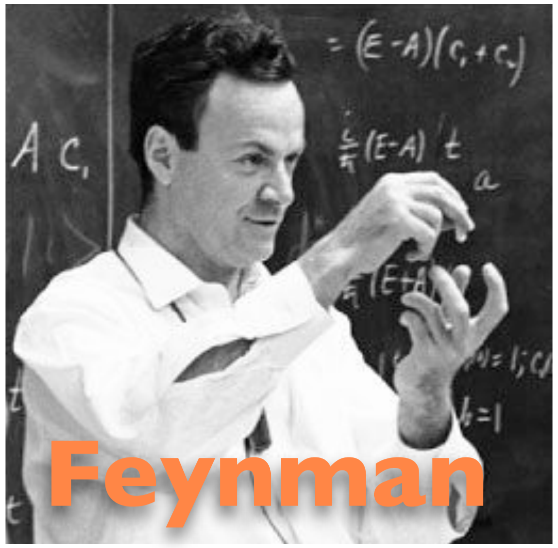
$$|\alpha\rangle \otimes |\psi\rangle \longrightarrow |\alpha\rangle \otimes |\psi;\alpha\rangle$$

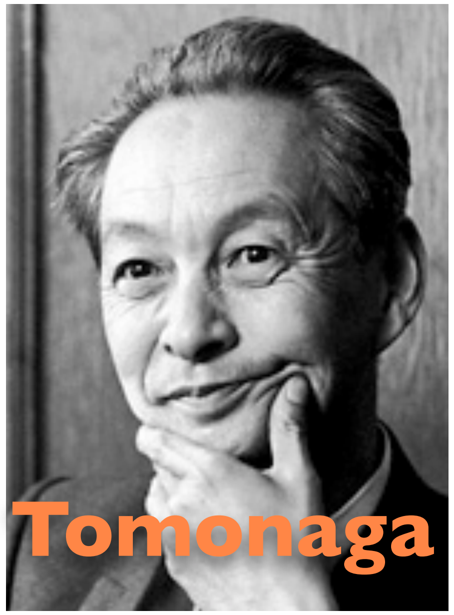
- Wigner's theorem

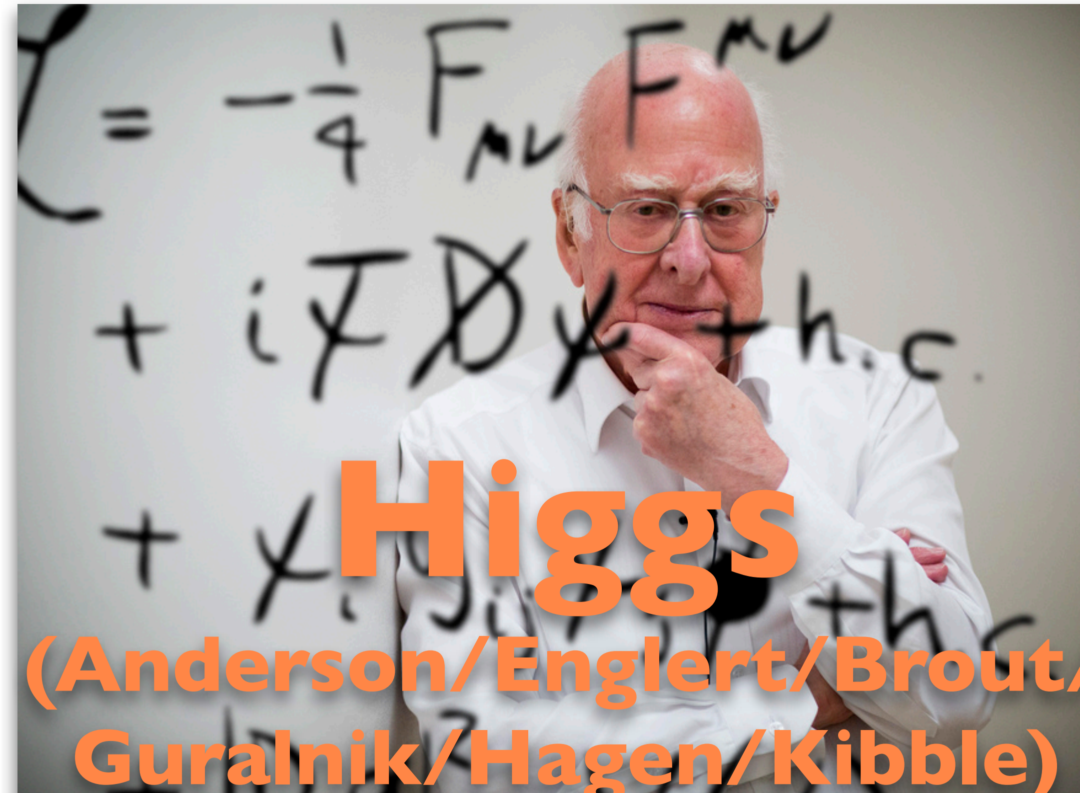
$$\hat{U}(x^\mu) = e^{-i\,\hat{P}_\mu\,x^\mu}$$

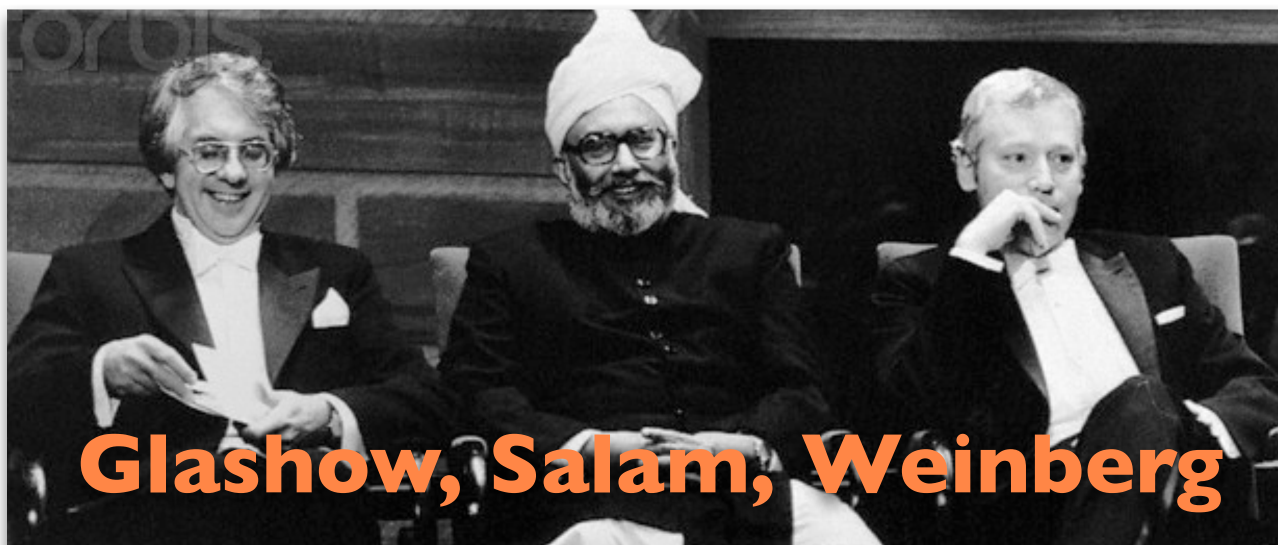
> The generators of the representation of a transformation in the Hilbert space are the operators representing the classical Noether's Charges that are conserved under that transformation.

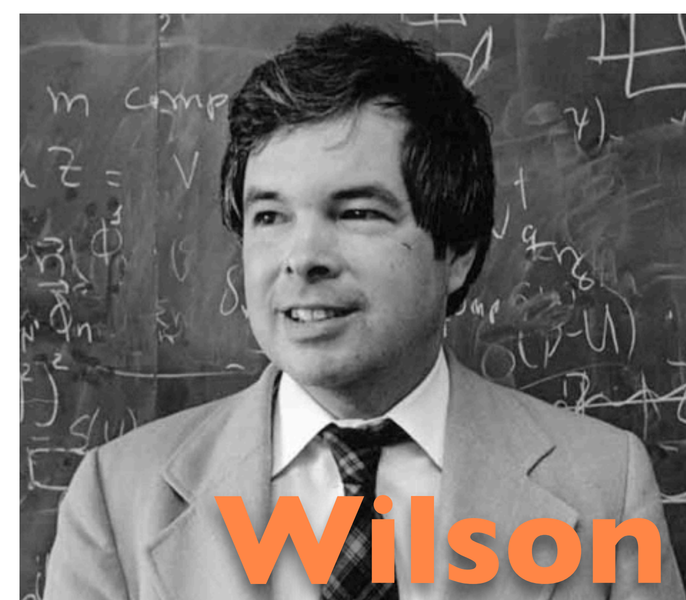
QFT & SM Heroes



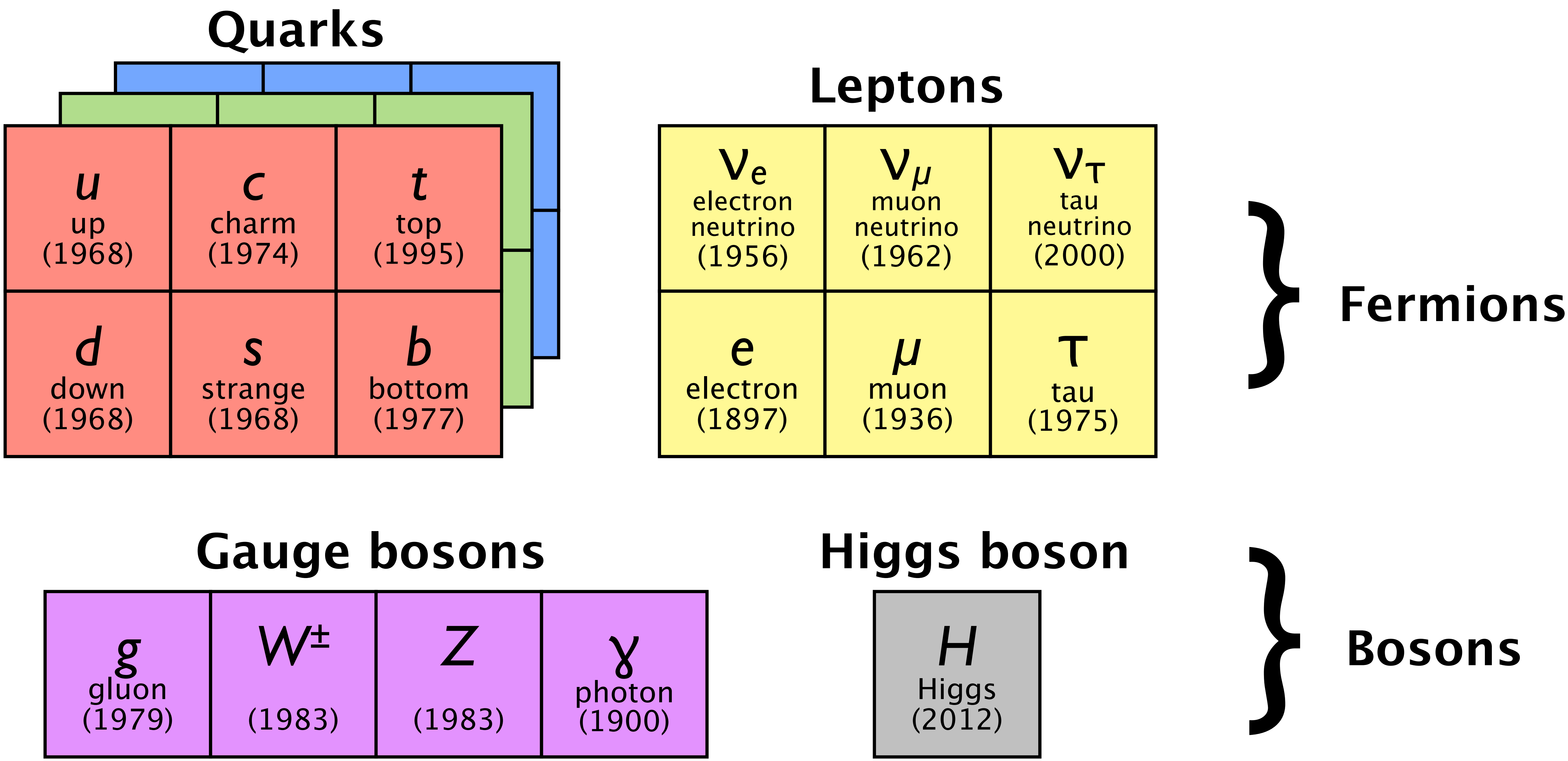








Discoveries in the SM



SM Lagrangian

kinetic energies and self-interactions of the gauge bosons

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

kinetic energies and electroweak interactions of the left-handed fermions

$$+\,\bar{L}_i\,\gamma^{\mu}\Big(i\,\partial_{\mu} - \frac{1}{2}\,g_1\,Y_{i\mathrm{L}}\,B_{\mu} - \frac{1}{2}\,g_2\,\sigma^{a}\,W^{a}_{\mu}\Big)L_i$$

kinetic energies and electroweak interactions of the right-handed fermions

$$+\,\bar{R}_i\,\gamma^{\mu}\Big(i\,\partial_{\mu} - \frac{1}{2}\,g_1\,Y_{i\mathrm{R}}\,B_{\mu}\Big)R_i$$

strong interactions between quarks and gluons

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

electroweak boson masses and Higgs couplings

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

fermion masses and Higgs couplings

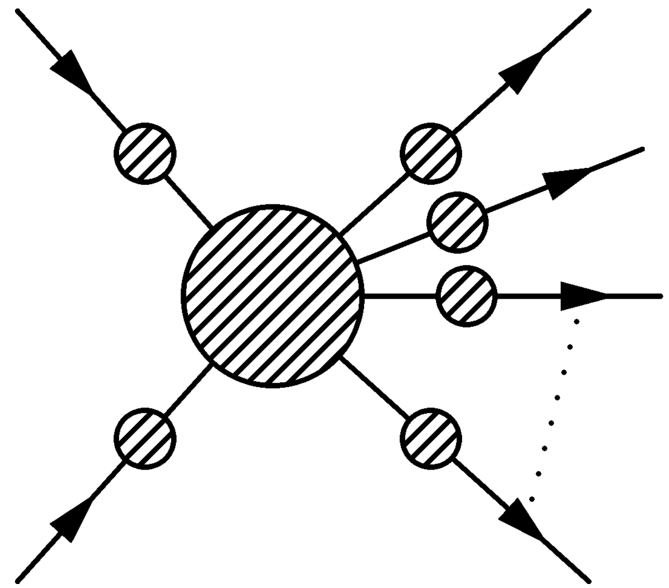
$$-\,\Big(y^{\mathrm{d}}_{k\ell}\,\bar{L}_k\,\Phi\,R_{\ell} + y^{\mathrm{u}}_{k\ell}\,\bar{R}_k\,\tilde{\Phi}\,L_{\ell} + h.c.\Big)\,.$$

LSZ Reduction Formula

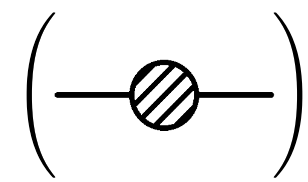
$$S_{fi} = \langle f|\hat{S}|i\rangle$$

$$= \tilde{G}^{(n)}(-p_f, \ldots, p_i) \prod_f \left(\tilde{G}^{(2)}(p_f)\right)^{-1} \prod_i \left(\tilde{G}^{(2)}(p_i)\right)^{-1}$$

$=$

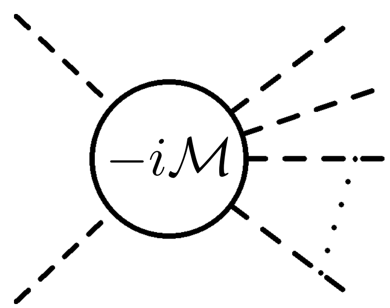


$\times \prod_{i,f}^{n}$



$^{-1}$

$=$



$$= -i\,\mathcal{M}\,(2\,\pi)^4\,\delta^4\left(\sum p_i - \sum p_f\right)\,,$$

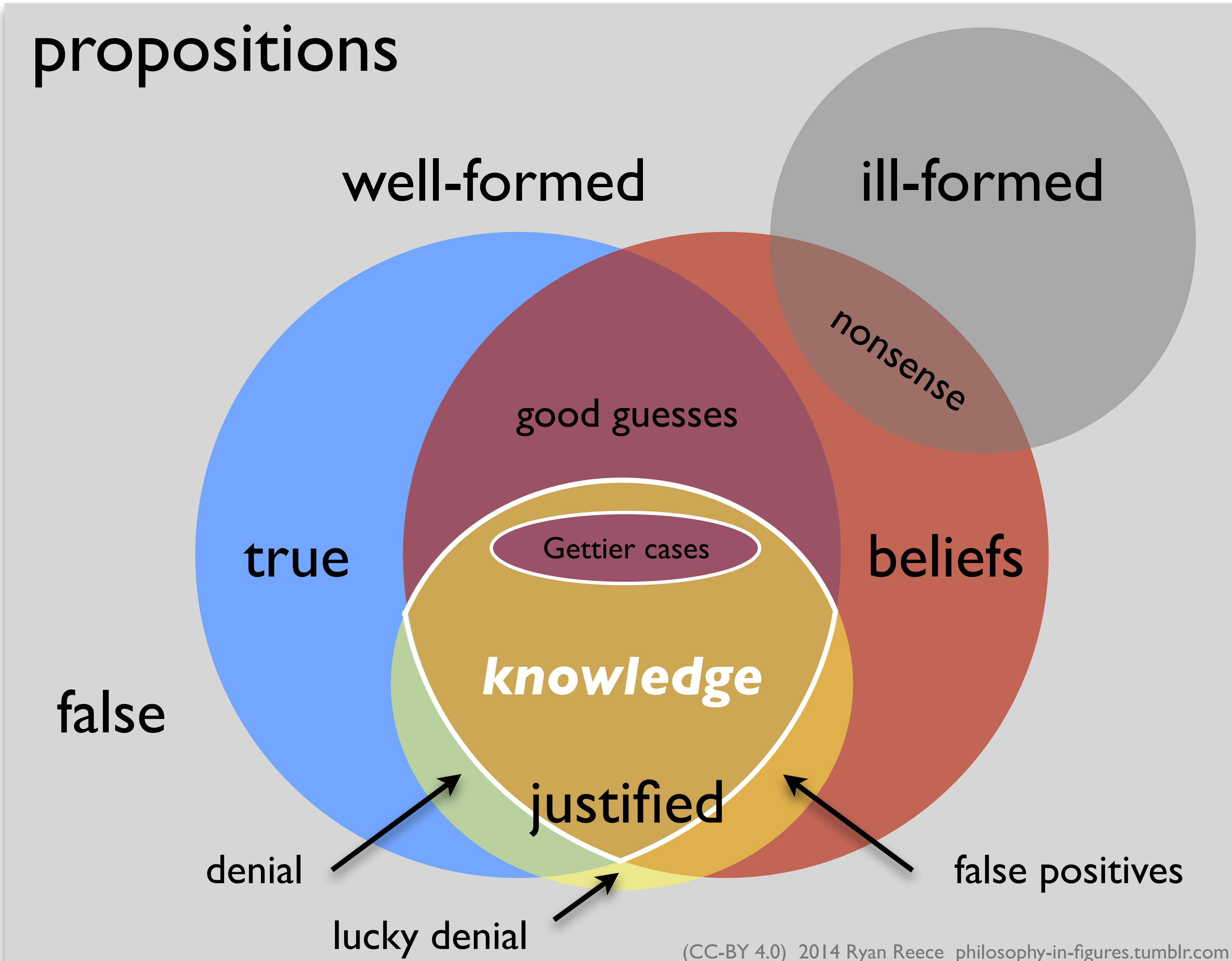
where $\tilde{G}^{(n)}$ denotes the momentum-space Fourier transform of the space-time n-point correlation function:

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

Indeterminacy of reference?

- 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 th SM.

Knowledge = JTB-G



philosophy of science