The Standard Model and Beyond

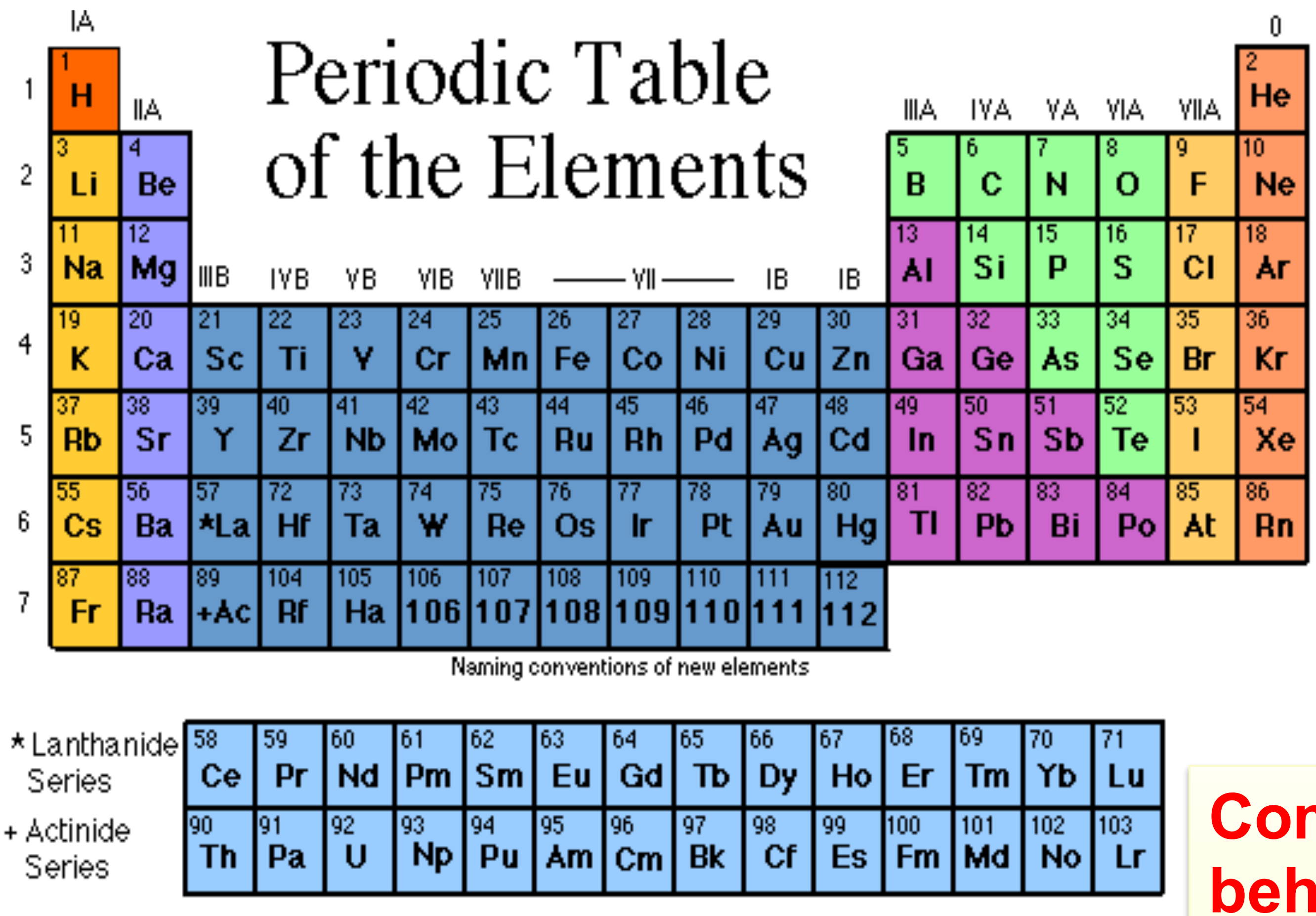
Paris Sphicas
CERN & University of Athens
CERN Accelerator School
Archamps, October 2019

- **The Standard Model of Particle Physics**
  - **What is everything made of?**
  - **And how do these things interact?**
  - **And how do they get their substance – mass?**
- **Looking for the Higgs**
  - **A new boson at ≈ 125 GeV!**
  - **Studying its properties**
- **Is this all there is to Nature?**
  - **Searching for New Physics; e.g. Supersymmetry?**
- **Outlook**

Nature…

What is everything made of?
And what is there in between?

What everything is made of



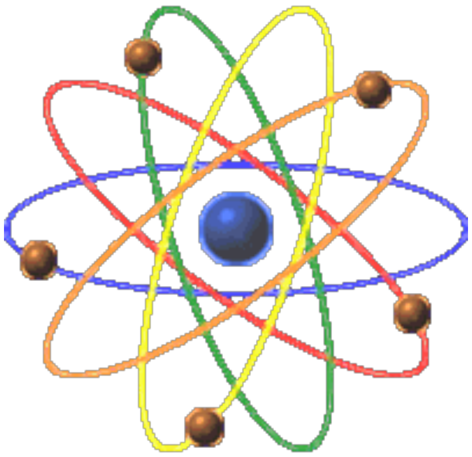
Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

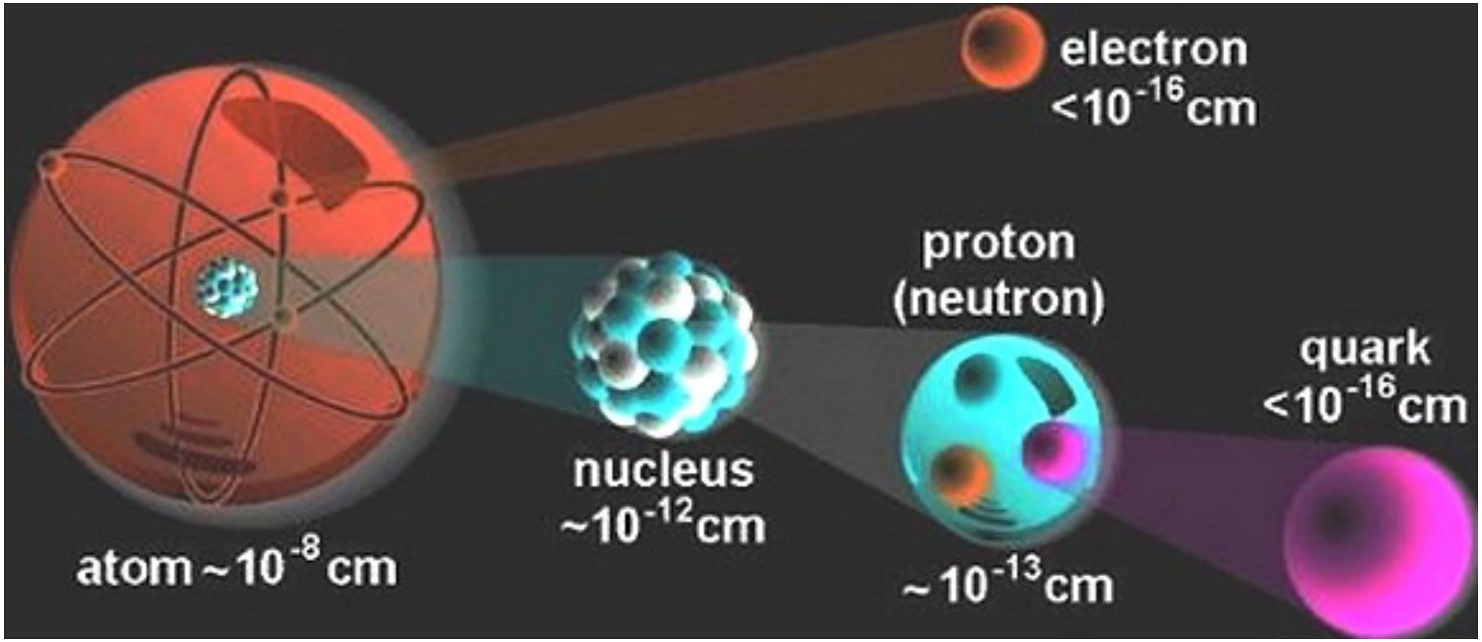
All elements are made of a-toms



Complexity of behavior: one parameter: the number of electrons!

Zooming (entering) into the atom

20^{st} century: everything is made of four particles (u, d, e, ν_e)*



These are pointlike!

* Plus two copies…

Forces...

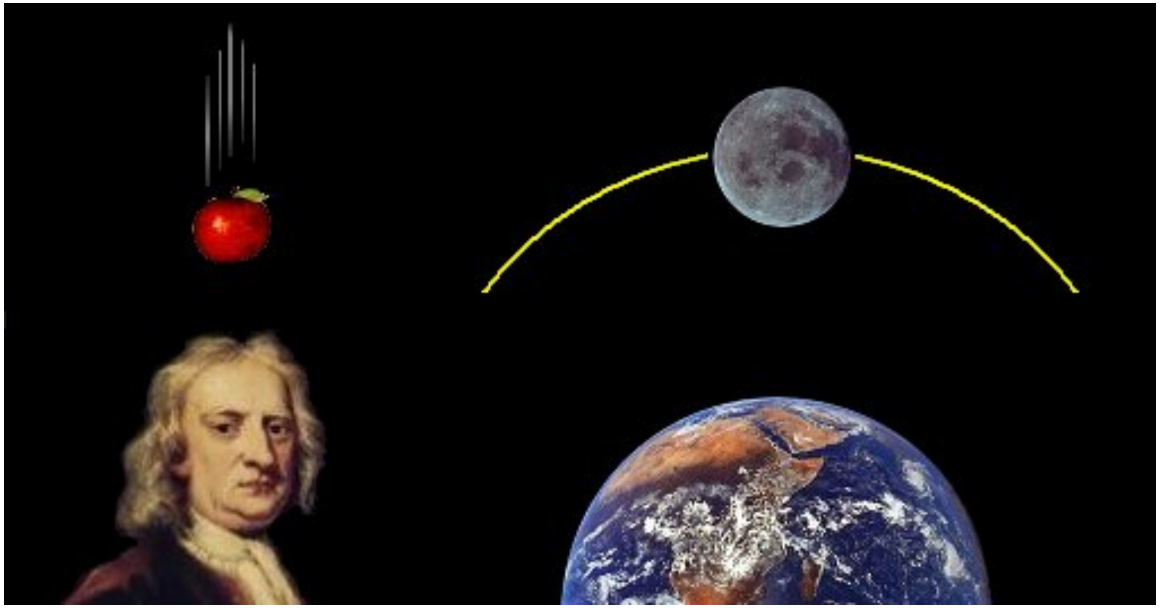
How does one particle “act” on another?

Do they have to “touch” each others, or can they act at a distance?

Nature and forces in the vacuum

Gravity :== action-at-a distance: separated objects, in the vacuum, act on each other!

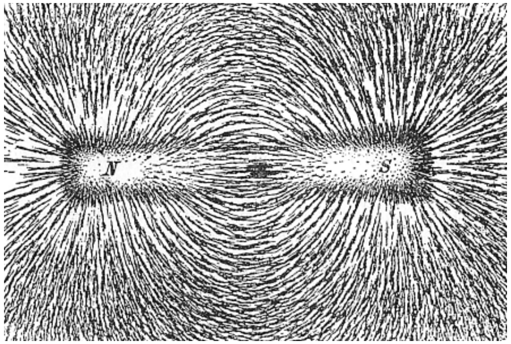
Mass: the "substance" of matter



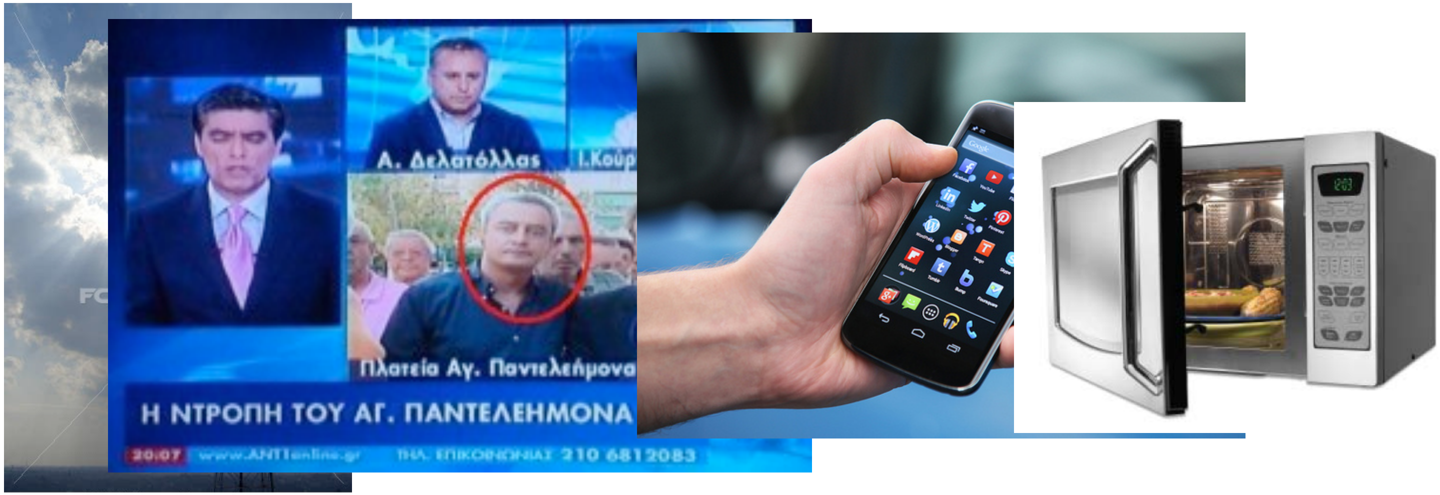
Bodies in the vacuum acting on each other!

Introduction of “fields”

Maxwell and electromagnetism: the concept of a field; charges generate fields which (can) permeate all of space… Other “charges” feel this field – and thus they feel a force.



Fields travel through matter and in the vacuum!



k0194407 www.fotosearch.com

20th century: two more forces at work

But nuclei are held together – against the electrostatic repulsion.

So there is yet another type of force!

It must be very, very strong.

But nuclei also "break"! Radioactivity! Neutrons become protons.

So there is yet another type of force!

And it is very, very weak.

There are, in total FOUR different forces in nature:

Gravity,
Electromagnetism,
Weak Force, Strong Force

FOUR???

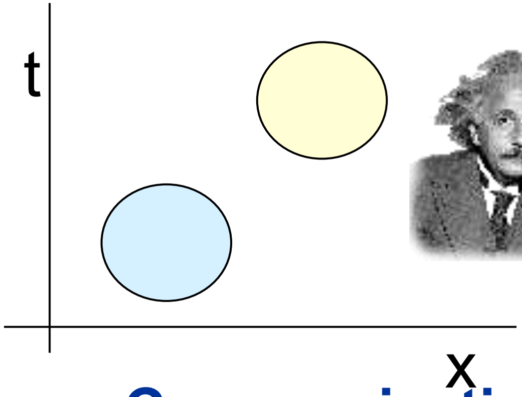
What makes them different?

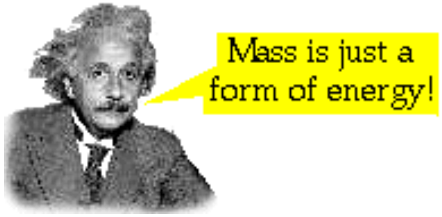
Are all of them "needed"?

Why not just one?

20th century physics: quantum mechanics and relativity

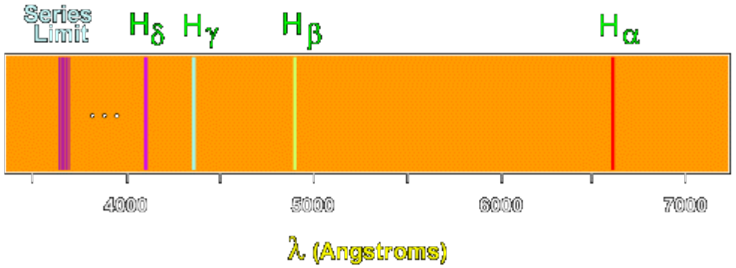
- **Relativity: action can only travel at speed c**
  - Localization





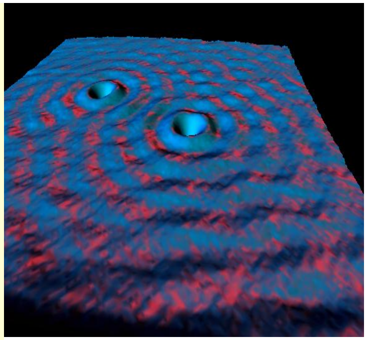
  - Communication between space-time points only as long as within light-cone
- **Thus: operators (that finally yield observables) are a function of x,t; i.e. they are fields**

- **Quantum Mechanics**
  - Dicretization
    - e.g. of absorption or emission



  - Wave-particle duality
    - demonstrated beyond all doubt:

Electron density waves are seen breaking around two atom-size defects on the surface of a copper crystal



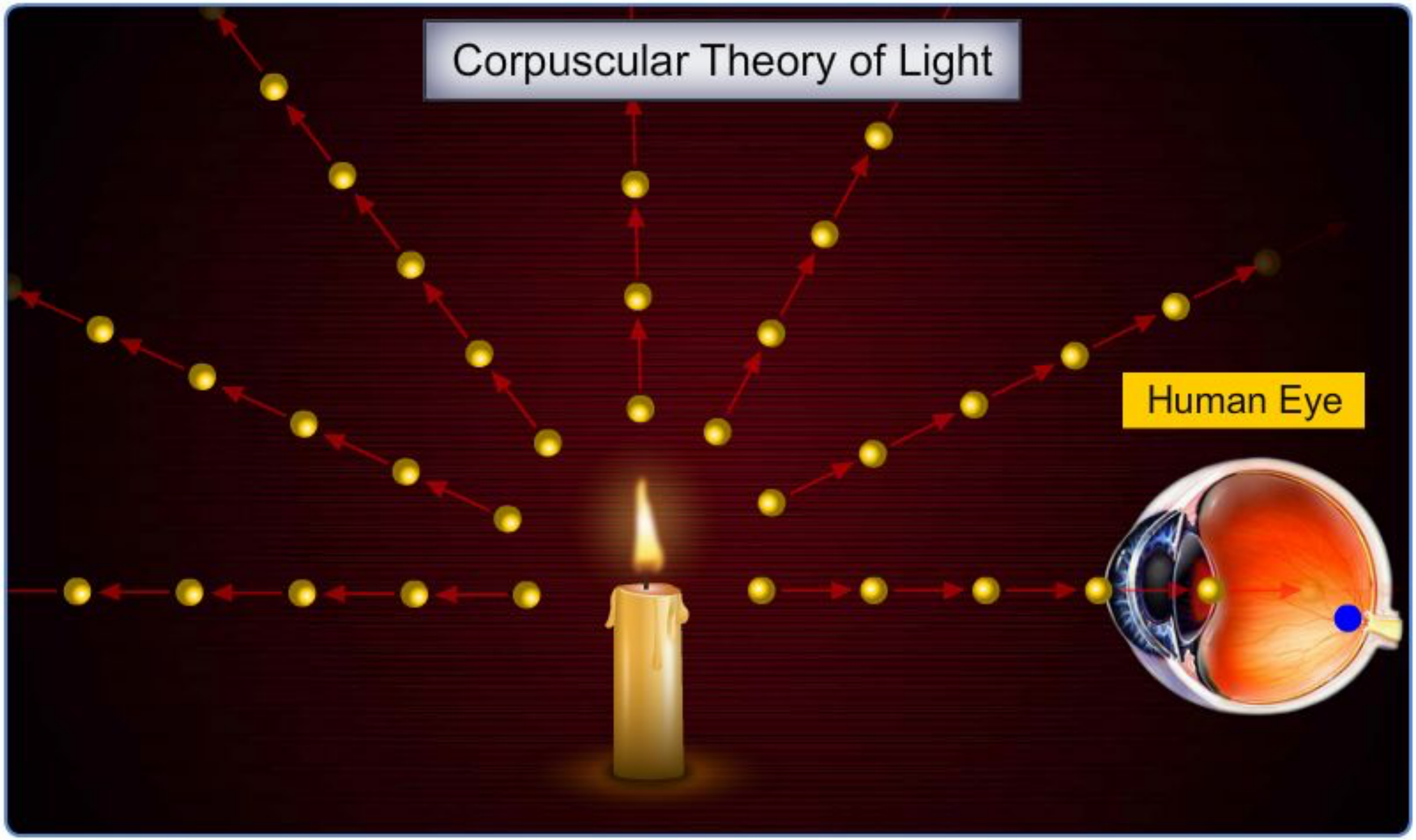
Classical Mechanics: light waves

- **Apparent continuity of light rays.**

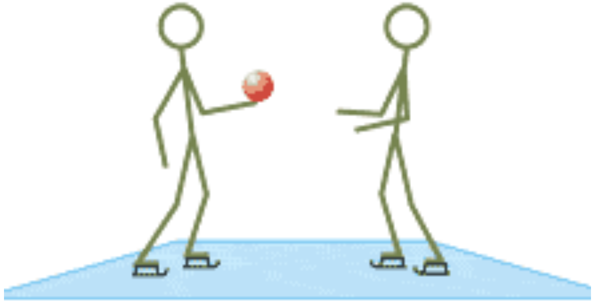
But: when “zooming in” on light...

Quantum Mechanics: discreteness

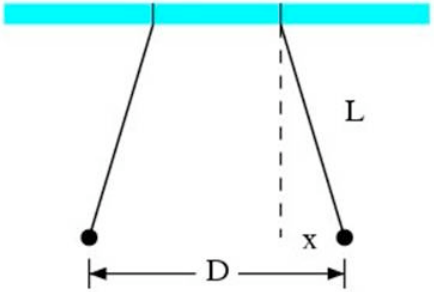
- **"Zooming in" on light… Light "comes" in discrete units → corpuscules → particles!**



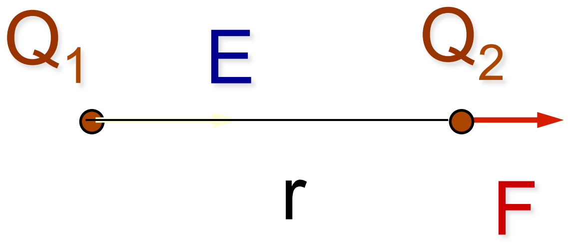
Theory of Relativity + Quantum Mechanics: New picture of a force:



Force is the exchange of particles

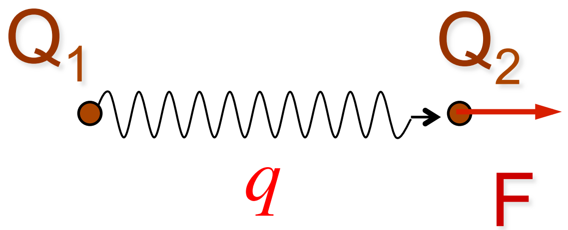


Classical and Quantum picture of “force”



Classical Field E(r)

$$\vec{F} = \vec{E}(r)\cdot Q_2 = \frac{Q_1}{r^2}\hat{r}\cdot Q_2 = \frac{Q_1 Q_2}{r^2}\hat{r}$$

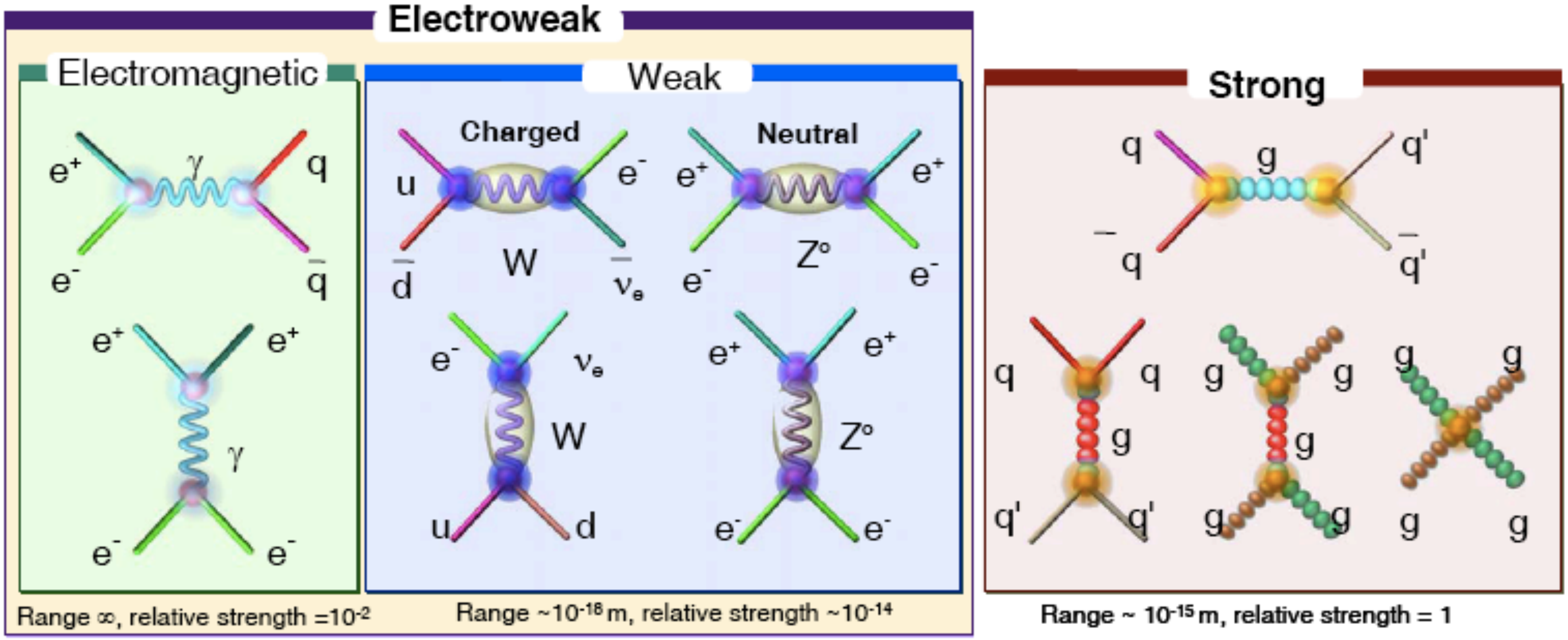


Exchange of a virtual particle of momentum q:

$$qr \approx \hbar \Rightarrow q \approx \frac{\hbar}{r} \Rightarrow q \approx \frac{\hbar}{ct} \Rightarrow \frac{dq}{dt} \approx \frac{\hbar}{ct^2} \Rightarrow \frac{dq}{dt} \approx \frac{\hbar c}{r^2}$$

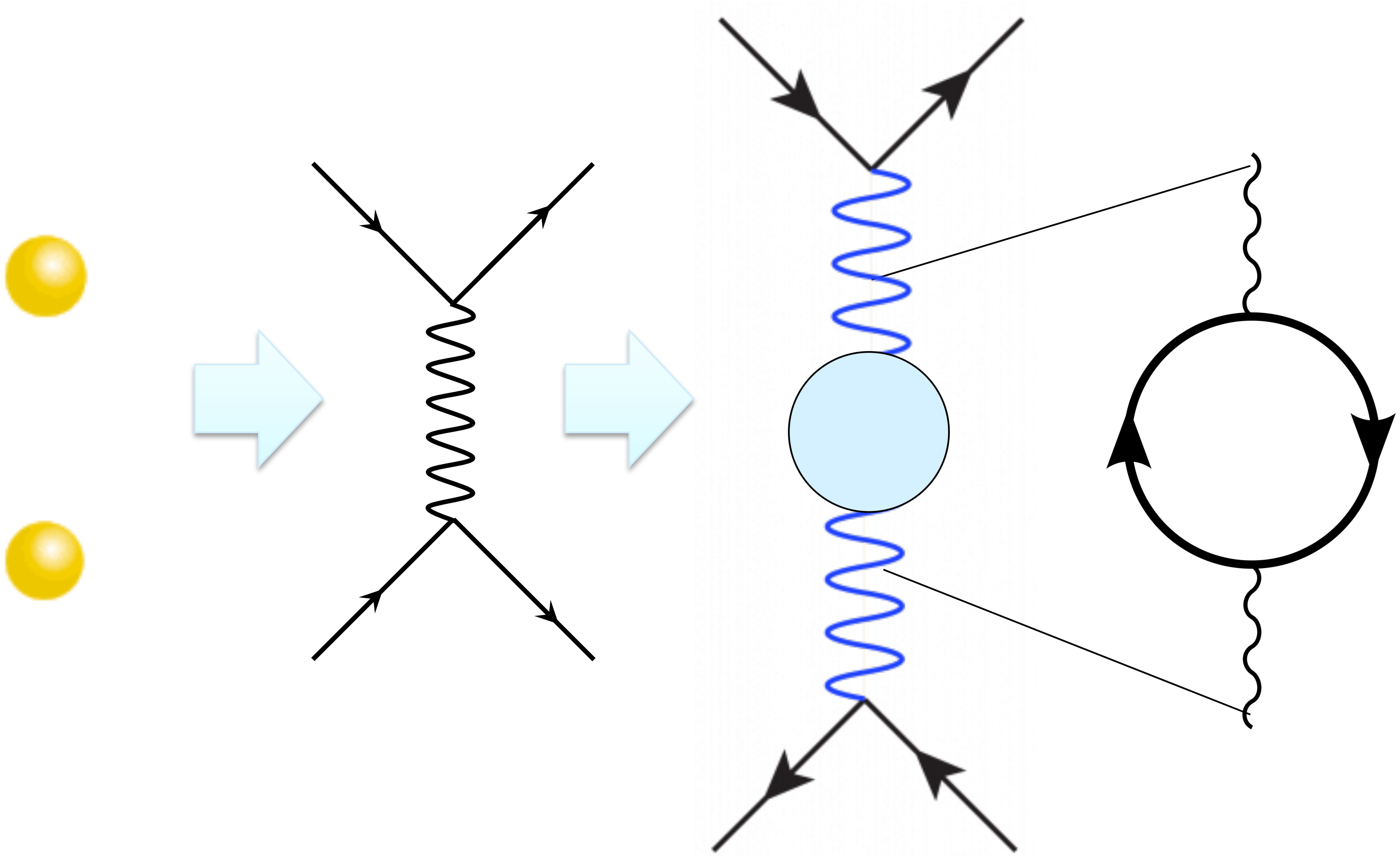
Standard Model of Particle Physics

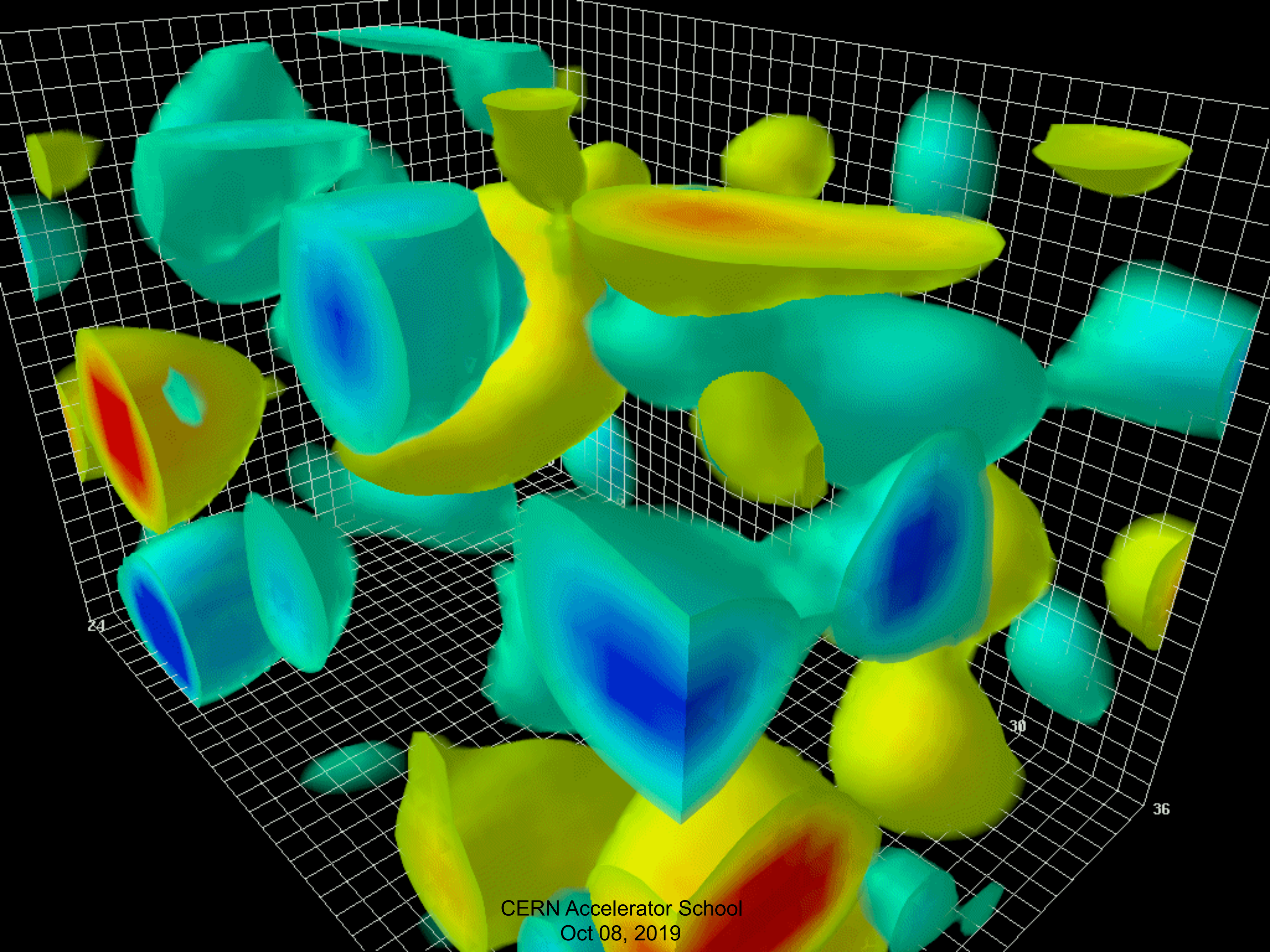
- Quantum Field theory: matter particles (spin-1/2) interact via the exchange of force particles (spin-1)



- Interactions → need charges. Which should be conserved. Implies some new symmetry…
  - Internal symmetry (SU(3)xSU(2)xU(1)) → massless bosons

And the vacuum is now full




24
30
36

Brout-Englert-Higgs mechanism: there is a new field that permeates all of space. It fills up the “vacuum”.

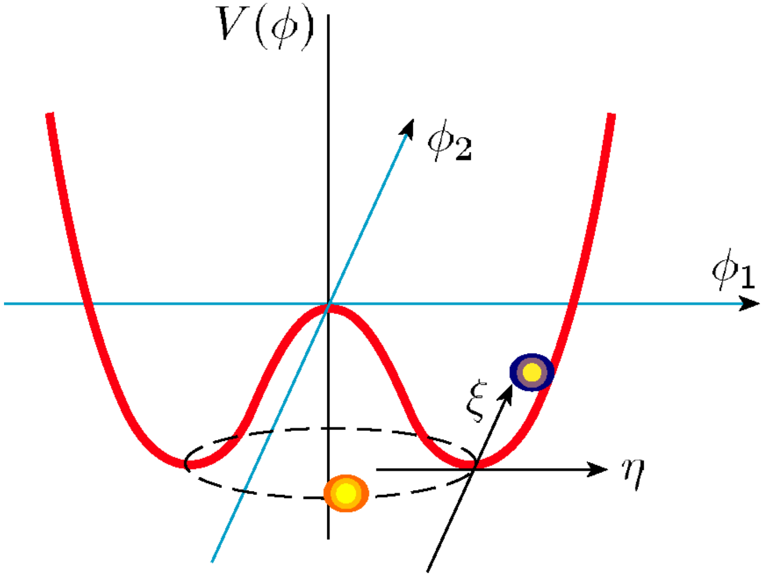
Particles travel (“swim”)
through it –
so they feel resistance

Inertia...

They acquire mass!

The Higgs Mechanism: mathematics

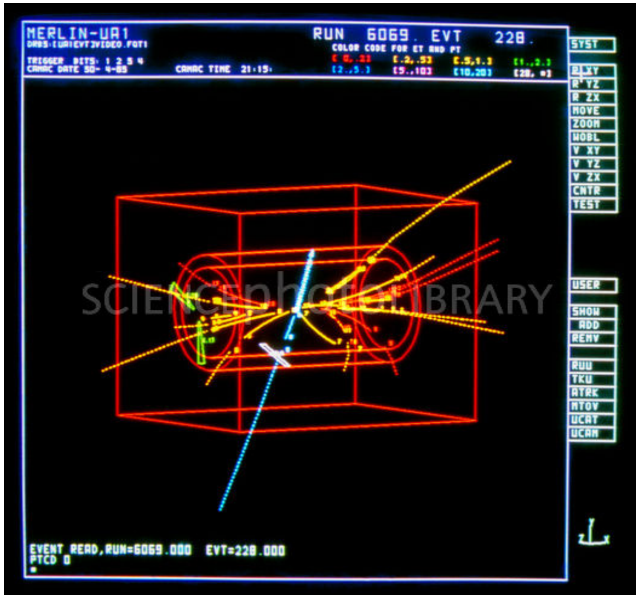
- With two independent (complex) fields (4 DoFs)
- Two "motions" in the potential
  - One on the plane; "massless" mode that is lost (once a direction is chosen). Each degree of freedom appears as additional degree of freedom of a gauge boson
    - Extra polarization state
    - The boson becomes massive!
  - One up/down on potential; massive
    - Higgs boson; for which theory predicts everything, except one parameter: its mass!

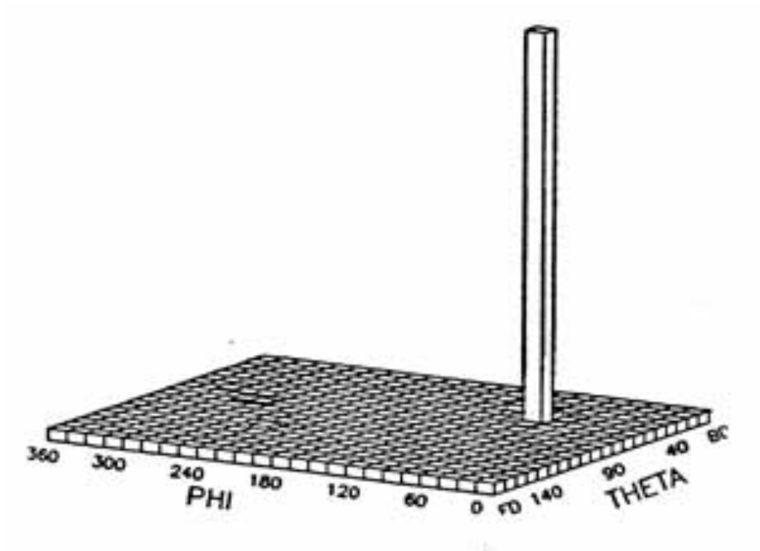


Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.

W and Z discovery

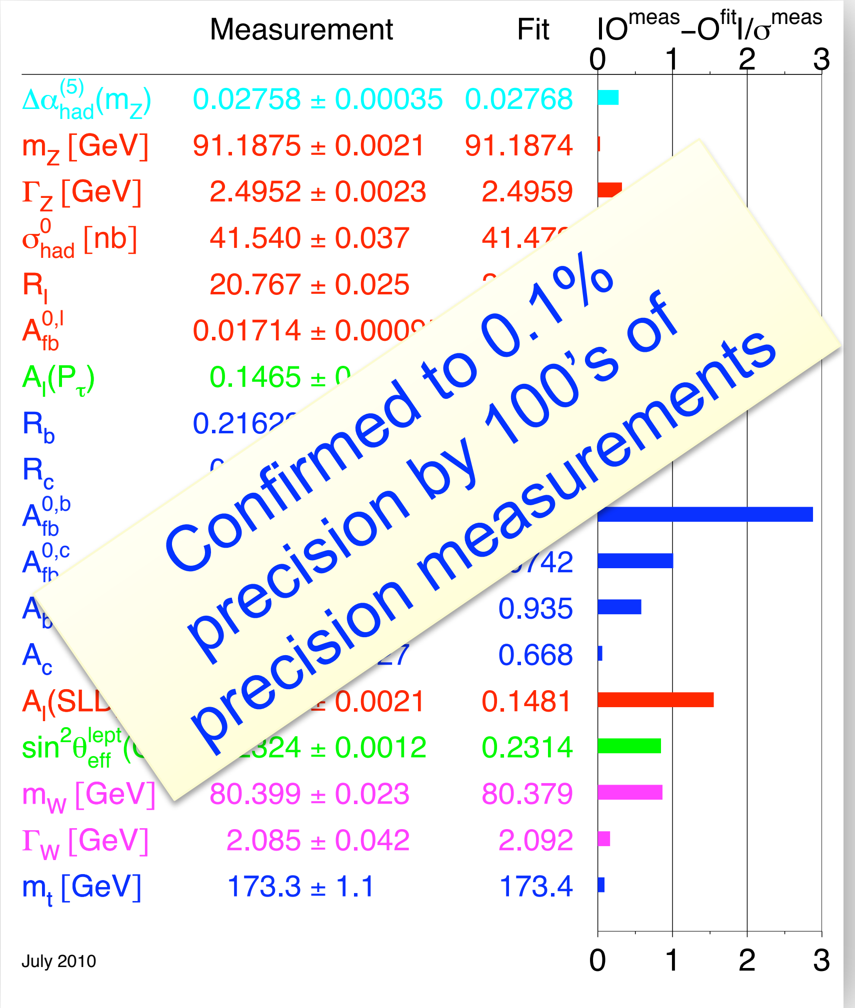
- In 1983, the *W* and *Z* particles were discovered at CERN (UA1 and UA2)
  - 1984 Nobel Prize to Simon van der Meer and Carlo Rubbia





- *Sneak preview:* at that point, the Higgs boson became the last important missing piece of SM!

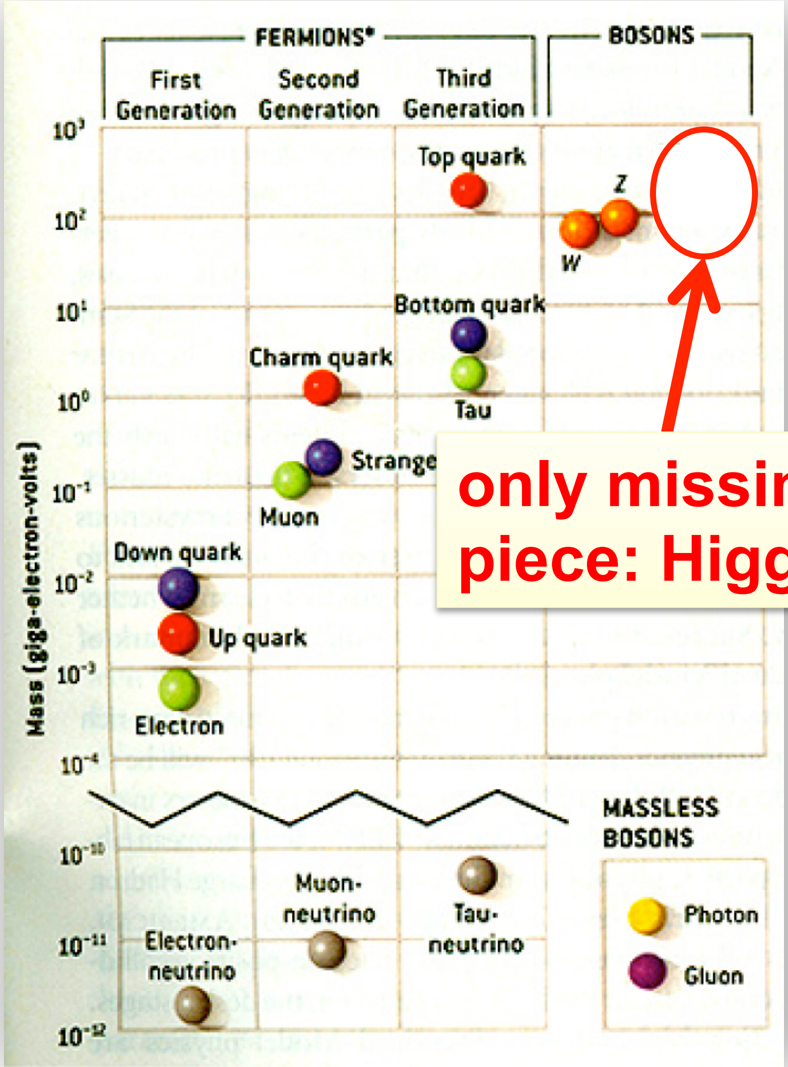
The Standard Model up until 2012



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.47	
R_l	20.767 ± 0.025		
$A_{fb}^{0,l}$	0.01714 ± 0.000		
$A_l(P_\tau)$	0.1465 ± 0		
R_b	0.2162		
R_c			
$A_{fb}^{0,b}$			
$A_{fb}^{0,c}$		742	
A_b		0.935	
A_c	27	0.668	
A_l(SL	0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}$(	324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.3 ± 1.1	173.4	

July 2010

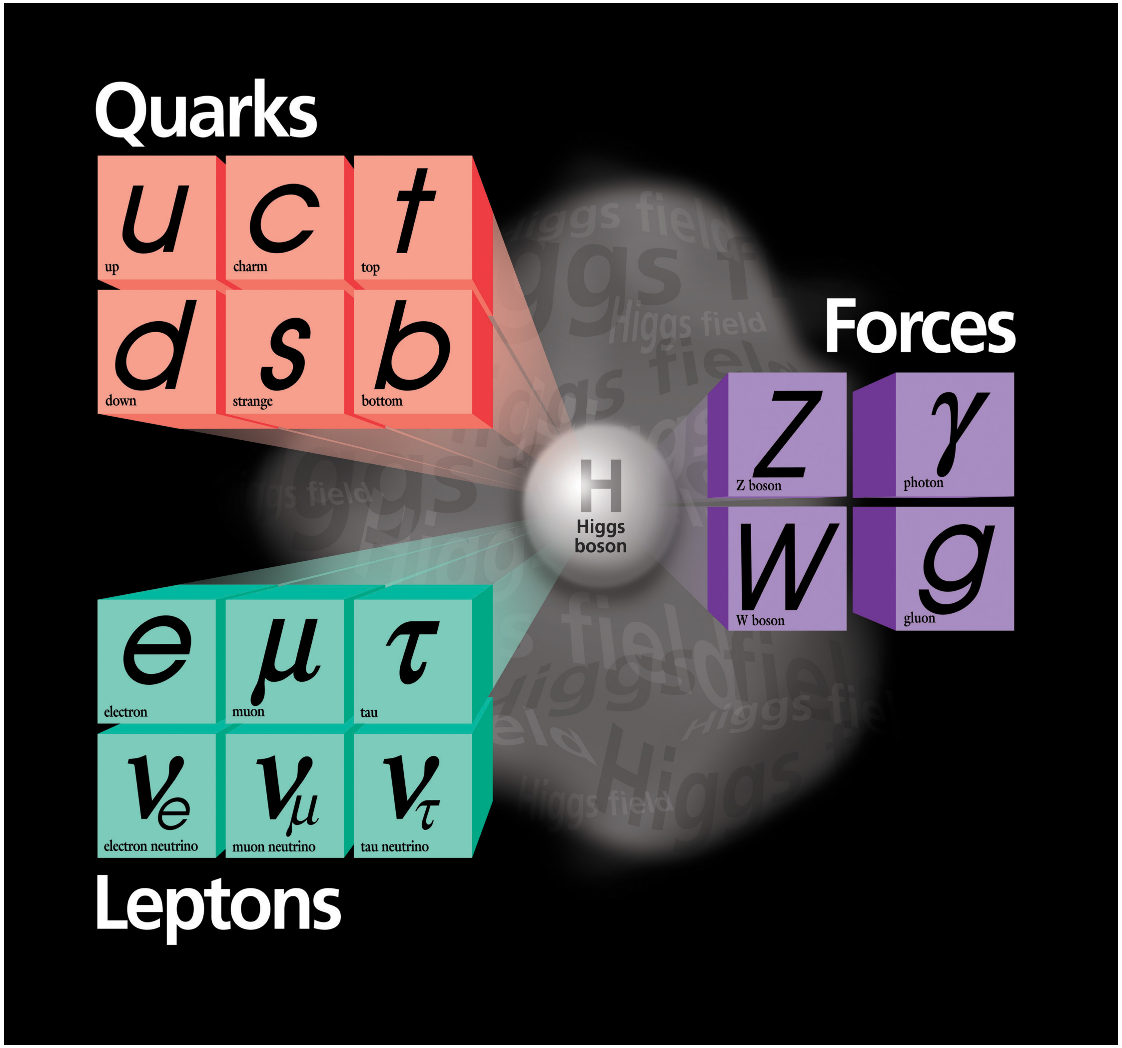
Confirmed to 0.1% precision by 100's of precision measurements



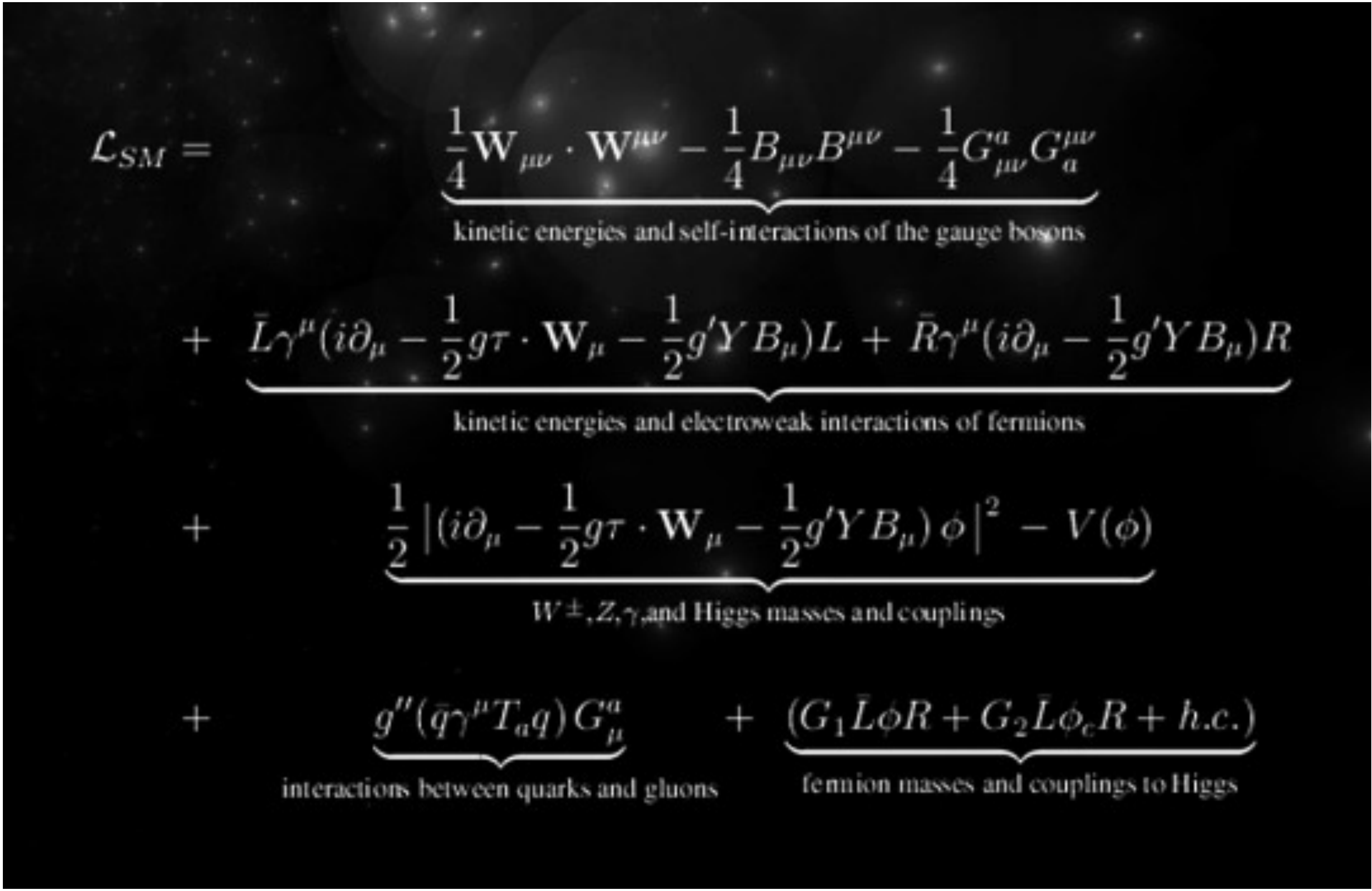
only missing piece: Higgs

Summary: the “Standard Model”

Matter particles



Force particles



$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})L + \bar{R}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu})R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})\,\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma,\text{and Higgs masses and couplings}}$$

$$+ \underbrace{g''(\bar{q}\gamma^{\mu}T_{a}q)\,G^{a}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$

$$-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$

$$\frac{1}{2}ig_s^2(q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + G^a\partial^2 G^a + g_s f^{abc}\partial_\mu G^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$

$$\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$

$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$

$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$

$$W_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W_\mu - W_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W_\mu W^+_\nu W_\nu +$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W_\mu) - 2A_\mu Z^0_\mu W^+_\nu W_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi] -$$

$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi - W_\mu\phi^+) +$$

$$igs_w MA_\mu(W^+_\mu\phi - W_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi - \phi\partial_\mu\phi^+) +$$

$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi - W_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi +$$

New field, the BEH field

- But, like any other field, in quantum mechanics, there much be a particle that corresponds to it!
  - The Higgs boson!
- Why can’t we just observe it if “it’s everywhere”, “in the vacuum”?
  - Because we need to supply the energy needed to produce it ($E=mc^2$)
  - Theory dictated that its mass could be as high as 1 TeV (10^{12} eV! Or 1000 times the proton!)

LHC($t_0+\Delta t=3$yrs):

Foundations established
a “tour de force” of SM measurements

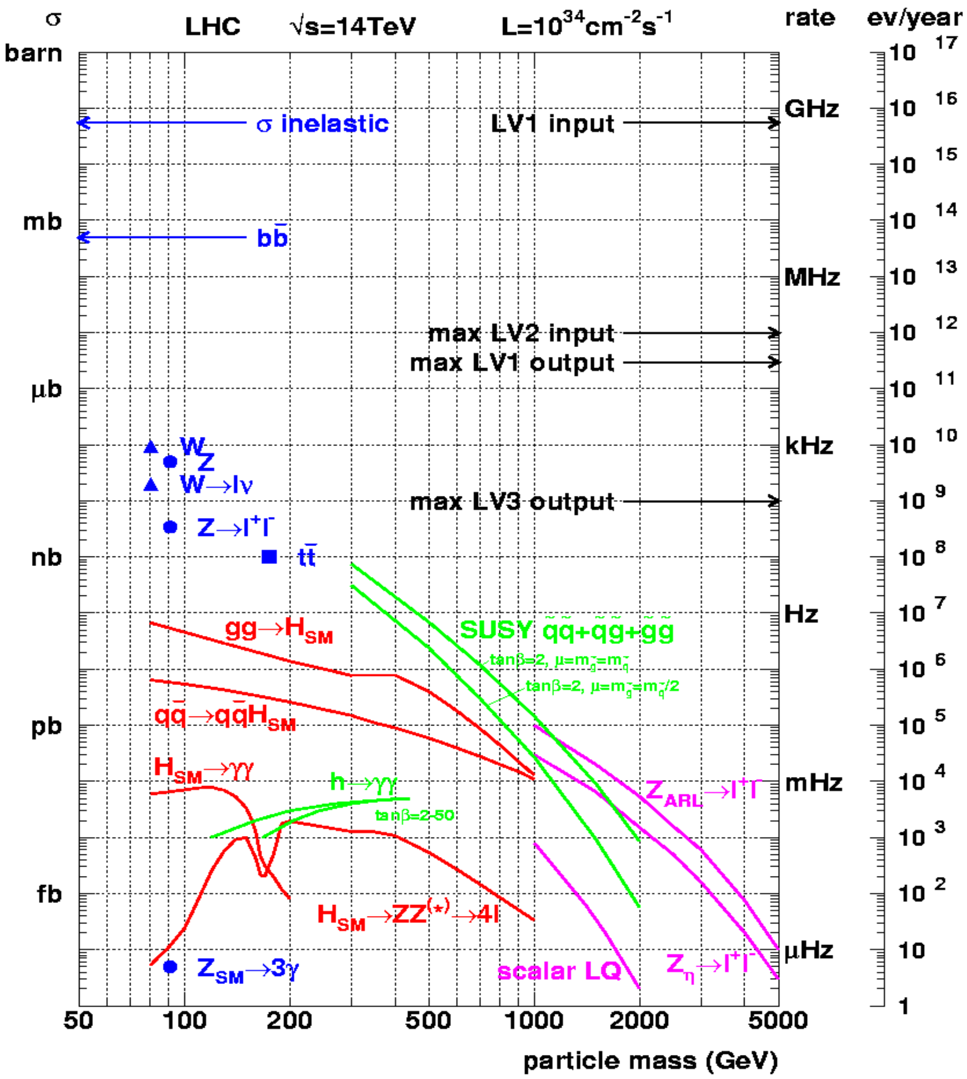
and, of course,
the hunt for the Higgs boson…

The LHC: signals much smaller than “bkg”

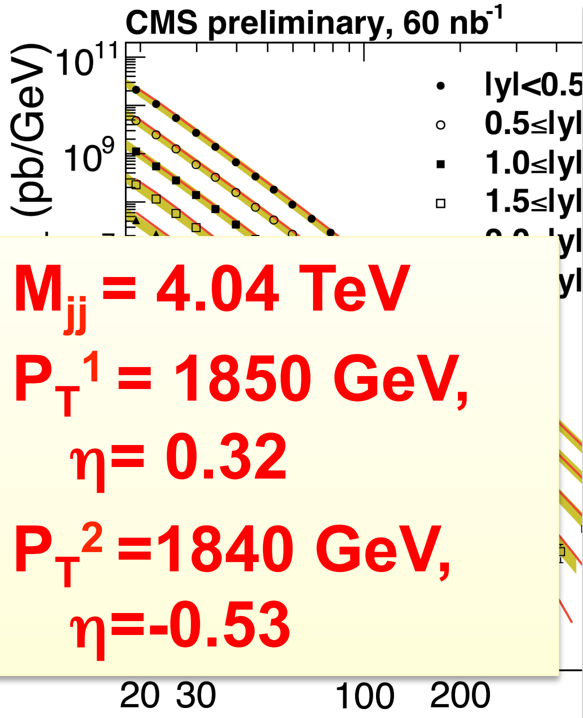
- **General event properties**

- **Heavy flavor physics**
- **Standard Model physics**
  - QCD jets
  - EWK physics
  - Top quark

- **Higgs physics**
- **Searches for SUSY**
- **Searches for ‘exotica’**



Jets



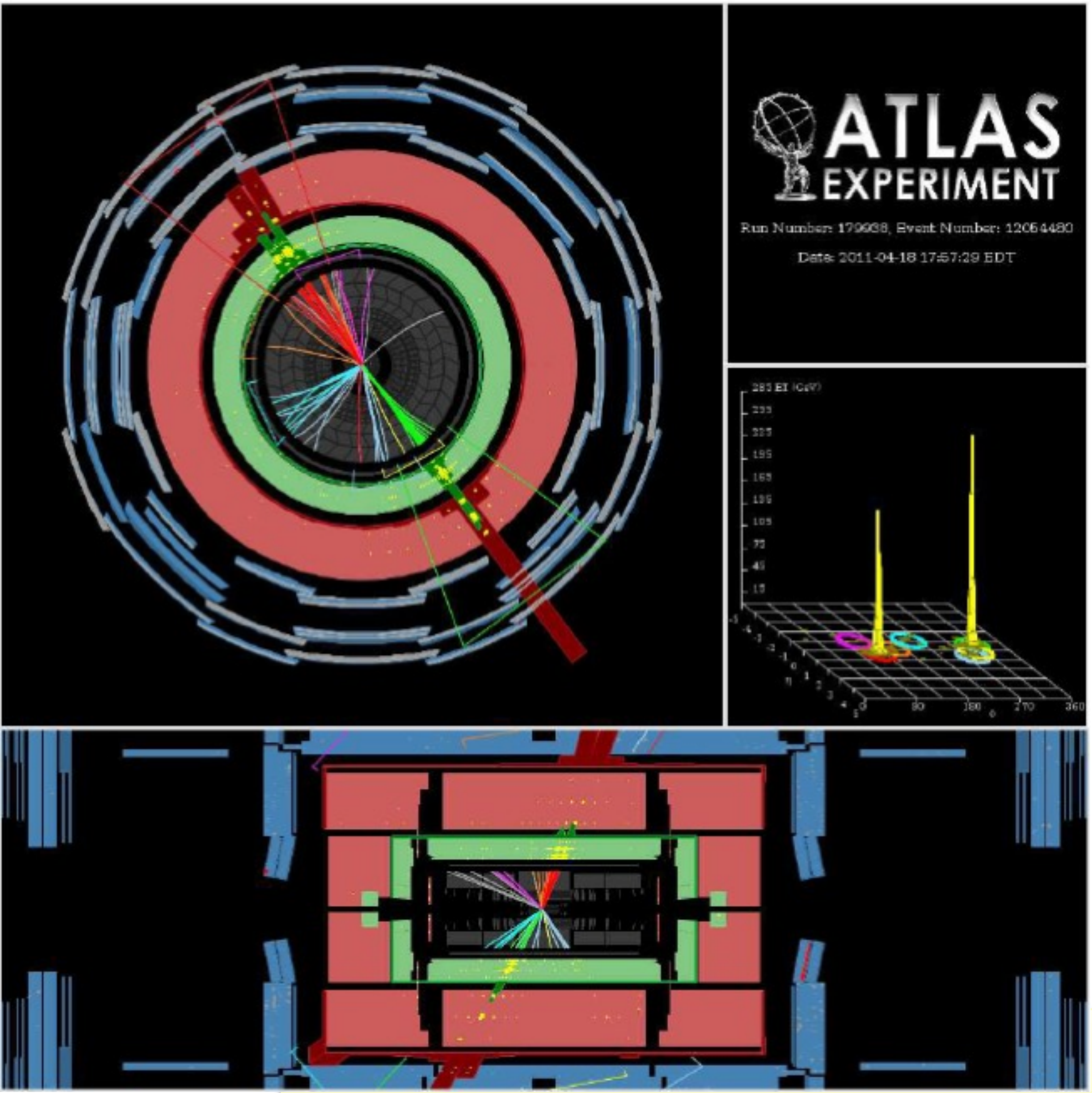
M_{jj} = 4.04 TeV

P_T^1 = 1850 GeV,

η= 0.32

P_T^2 =1840 GeV,

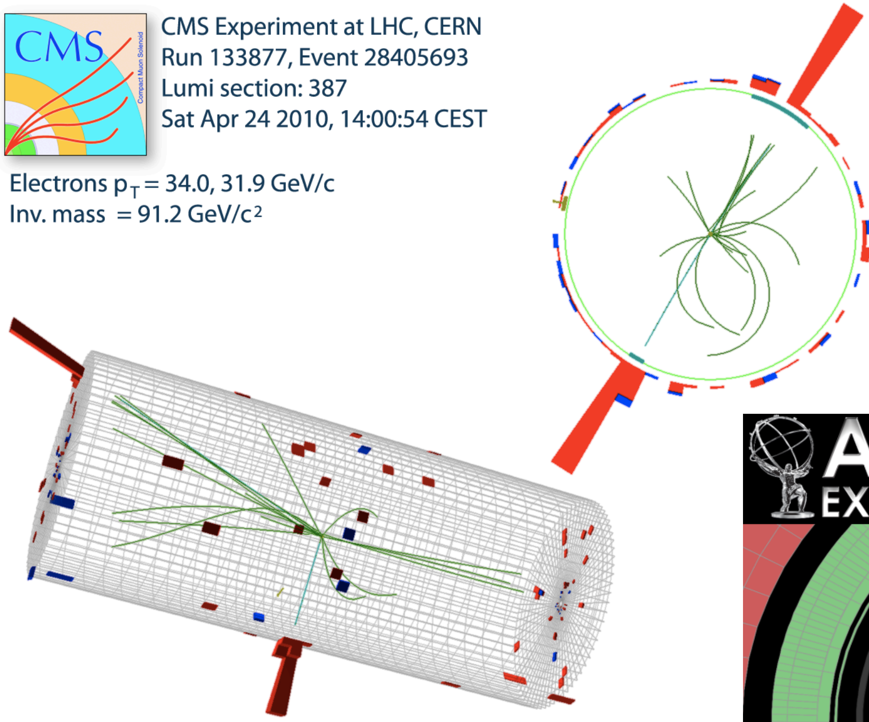
η=-0.53



- To probe the hard s
  - The hard scatter: jet

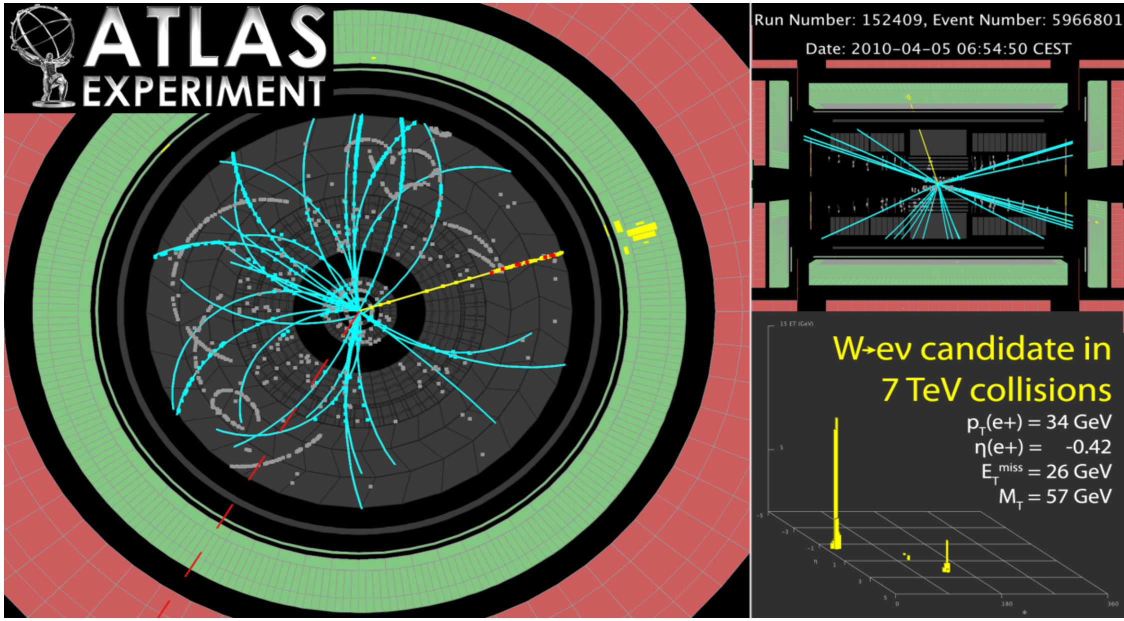
W/Z at 7 TeV: (still) clean & beautiful

Z → electron + positron



Electrons p_T = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/c^2

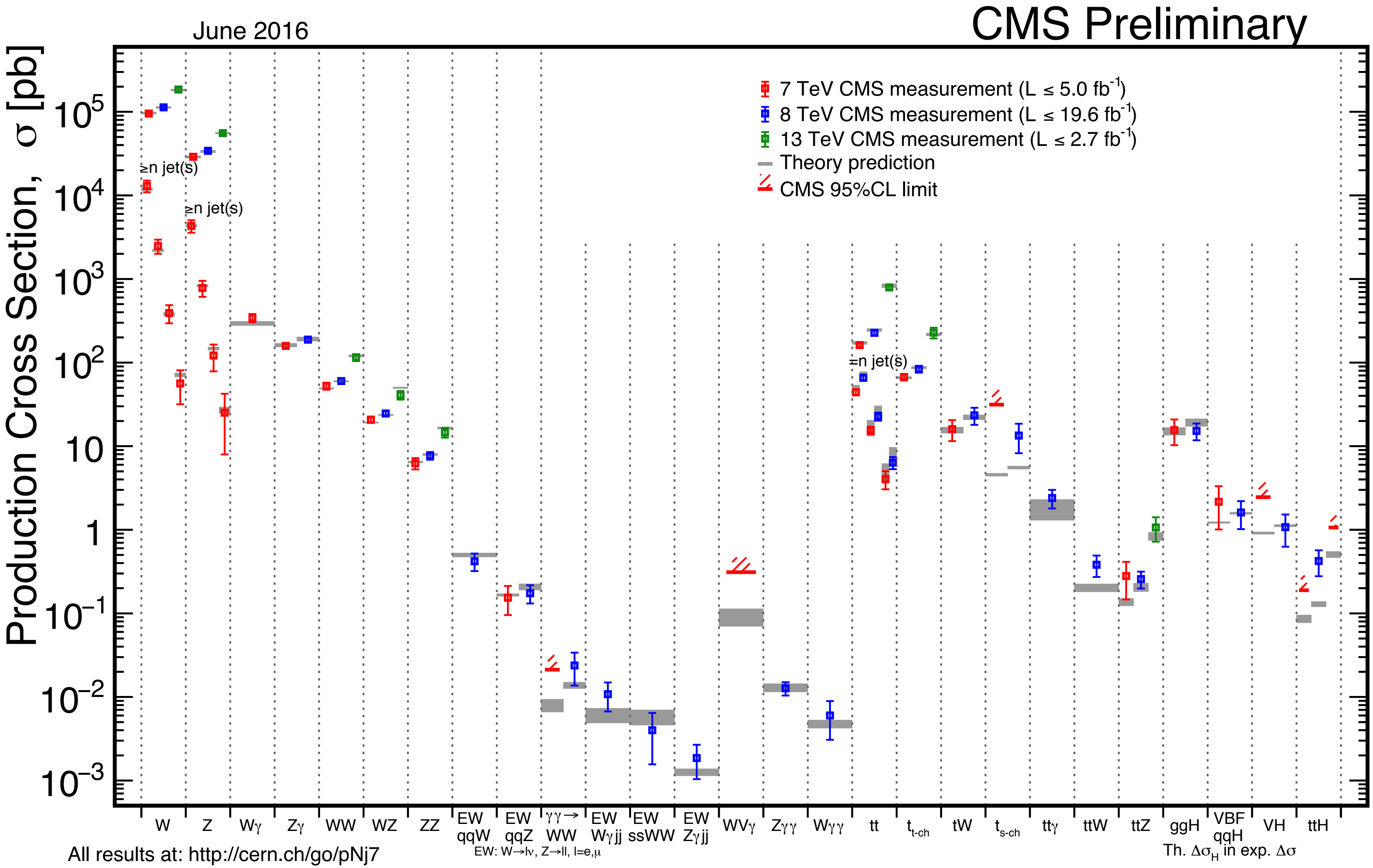
W → electron + neutrino



W→eν candidate in 7 TeV collisions

$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

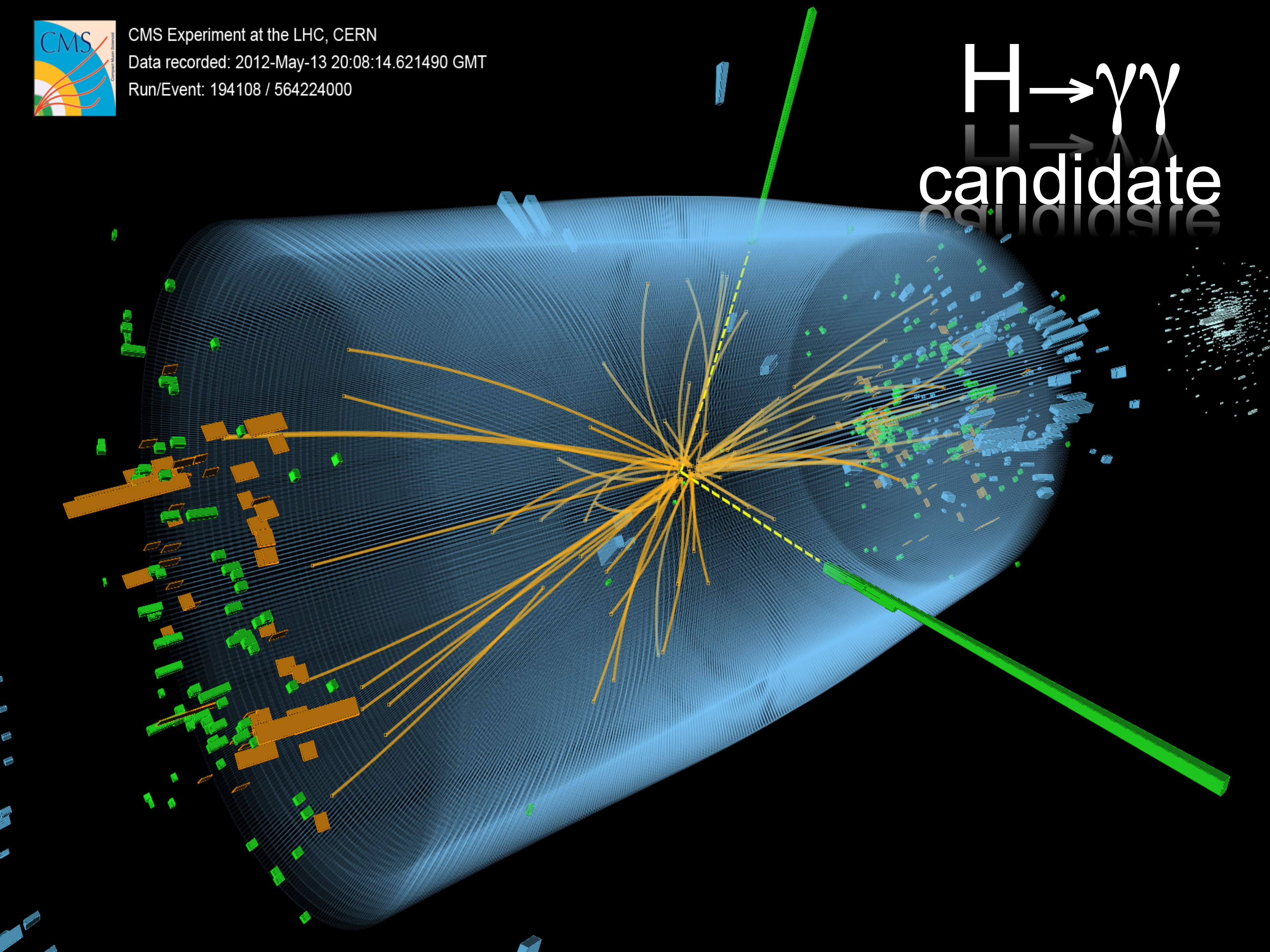
Standard Model Measurements



What about the Higgs boson?

Some “signatures”

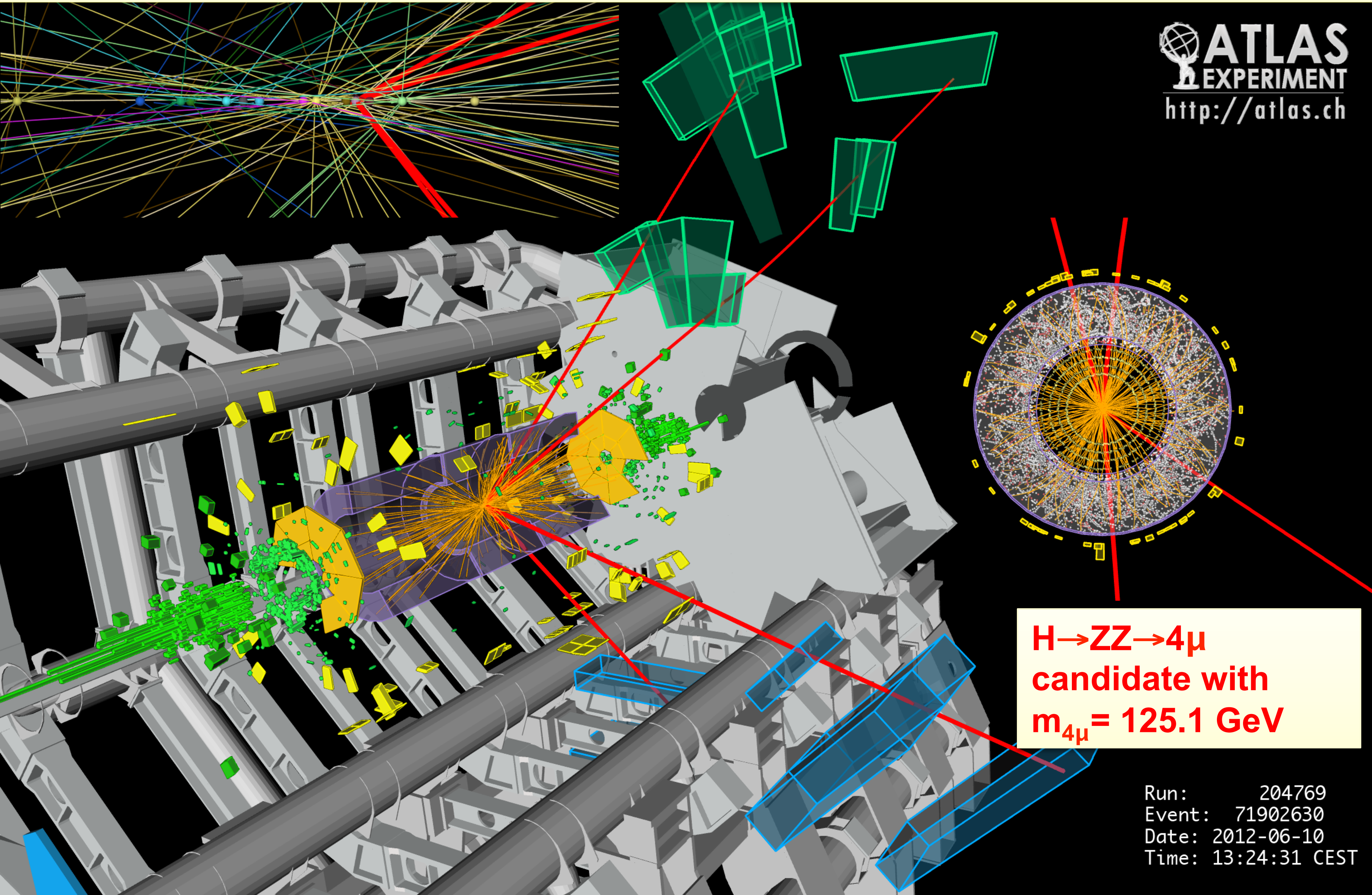
$H \to \gamma\gamma$ candidate



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

$p_T(\mu)$= 36, 48, 26, 72 GeV; m_{12}= 86.3 GeV, m_{34}= 31.6 GeV

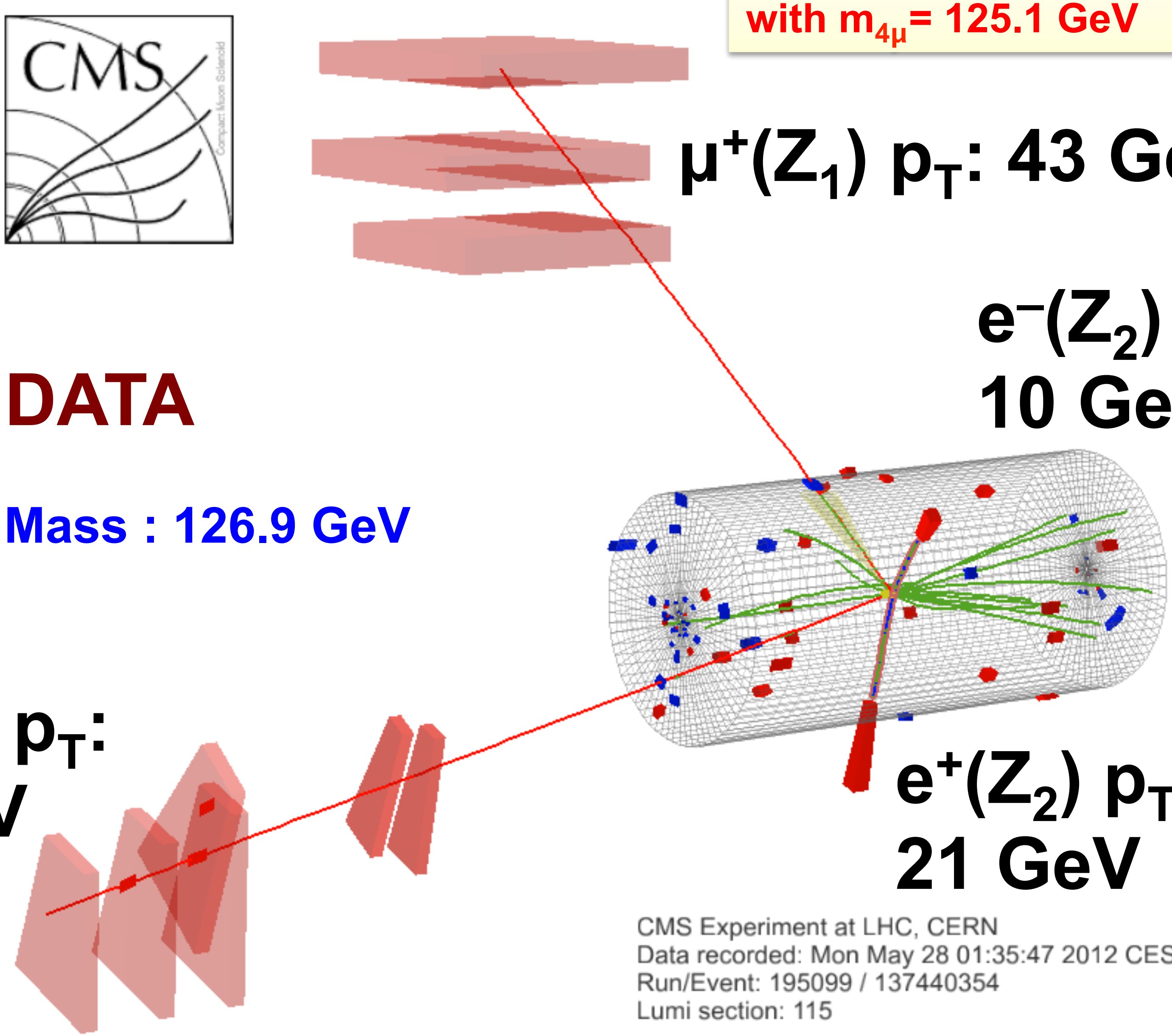
15 reconstructed vertices



H→ZZ→4μ candidate with $m_{4\mu}$= 125.1 GeV

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

H→ZZ→μμee candidate with $m_{4\mu}$= 125.1 GeV



$\mu^{+}(Z_1)$ p_T: 43 GeV

$e^{-}(Z_2)$ p_T: 10 GeV

8 TeV DATA

4-lepton Mass : 126.9 GeV

$m^{-}(Z_1)$ p_T: 24 GeV

$e^{+}(Z_2)$ p_T: 21 GeV

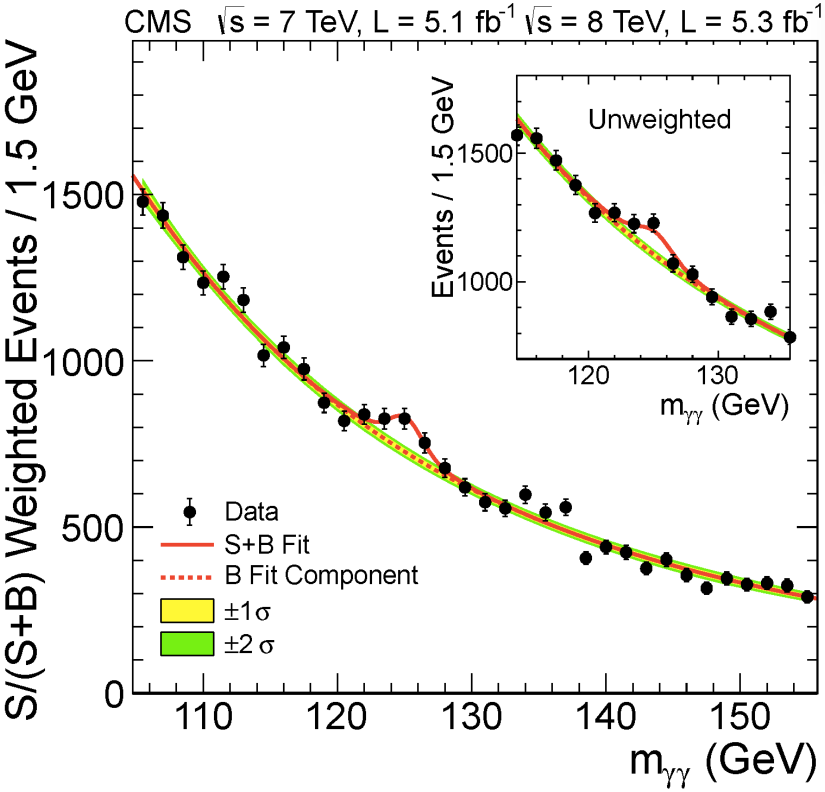
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

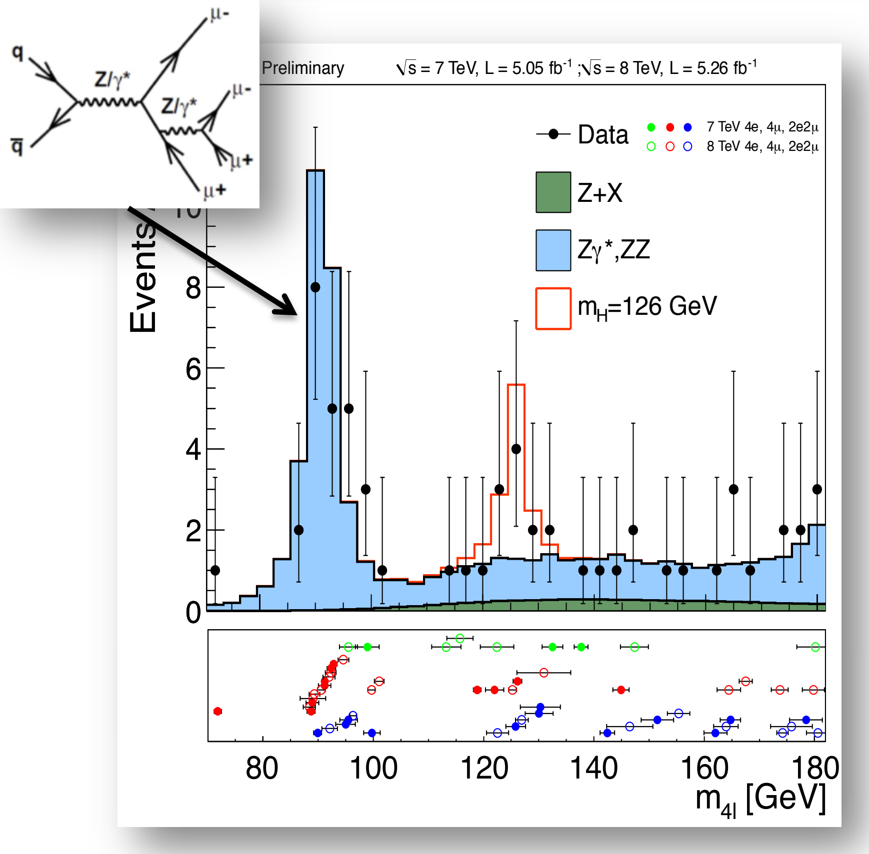
Are these events “significant”?

Discovery of a new boson

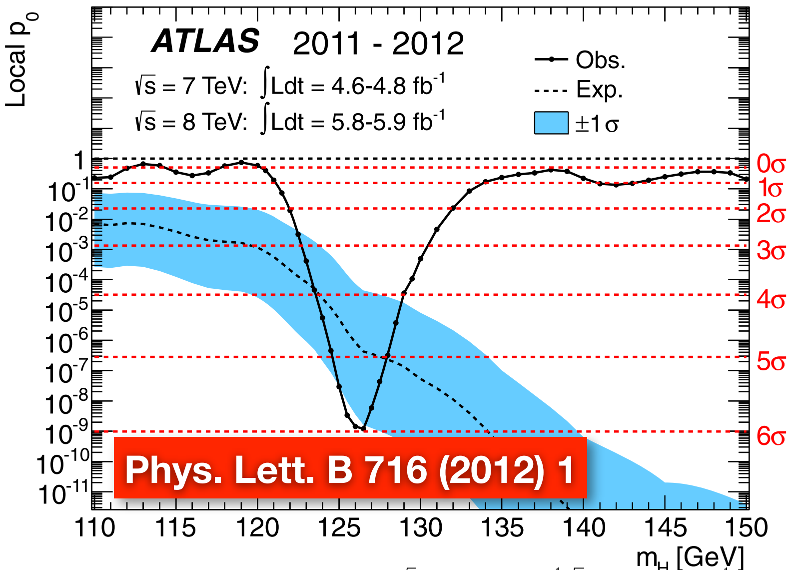
Mass peaks: H(?)→γγ & H(?)→ZZ→4leptons

Despite the low branching fraction to the final state, the mass resolution of these two channels enables the siting of a “peak”. The ZZ peak has a Z calibration as well(!)

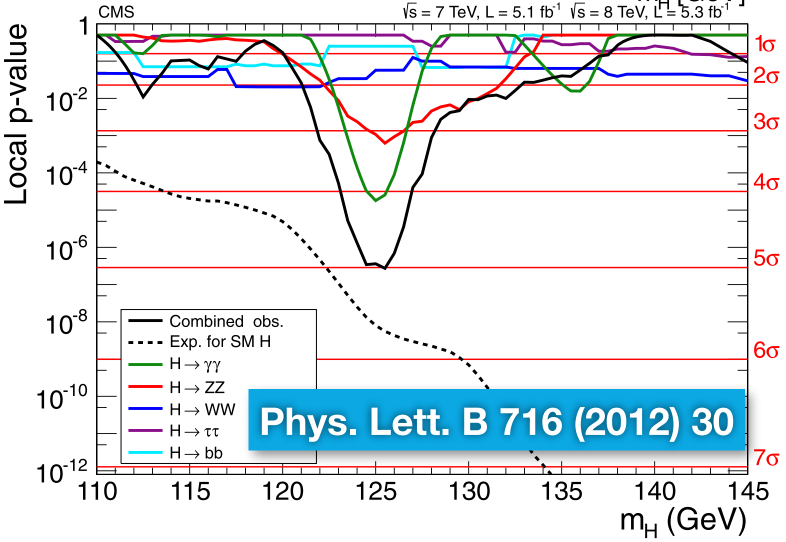




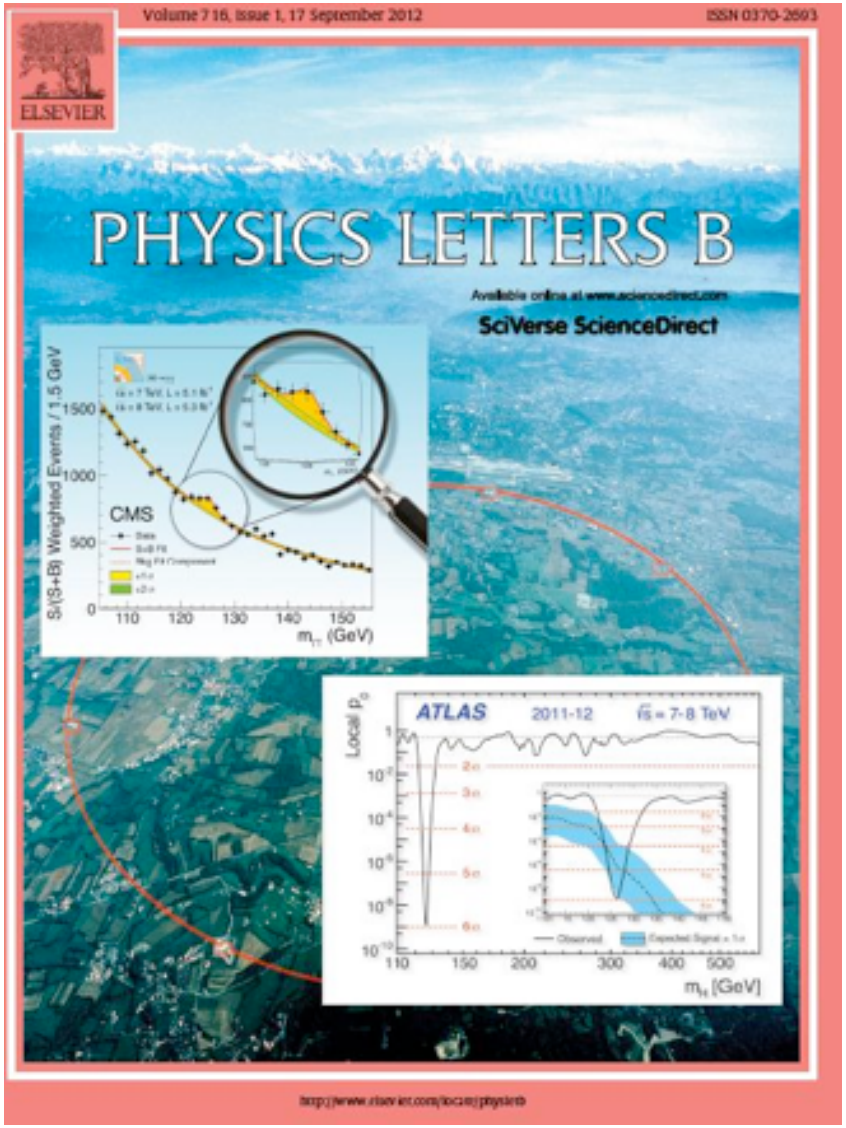
Putting it all together…



Phys. Lett. B 716 (2012) 1



Phys. Lett. B 716 (2012) 30



Volume 716, issue 1, 17 September 2012

ISSN 0370-2693

ELSEVIER

PHYSICS LETTERS B

Available online at www.sciencedirect.com

SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

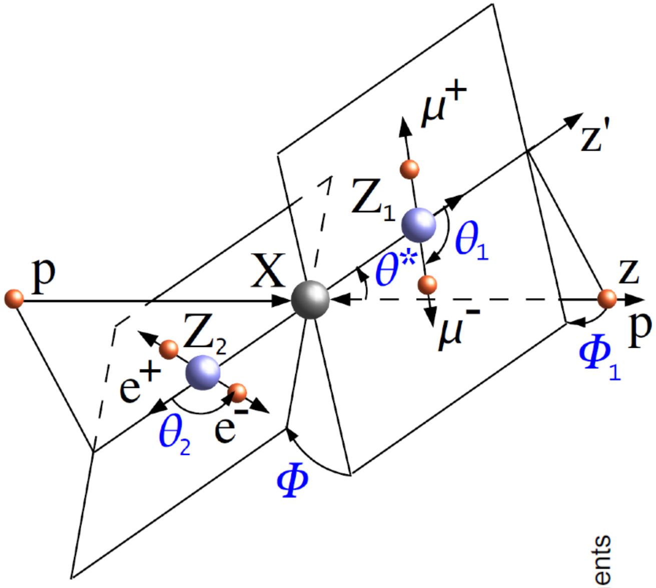
And thus was born, on July 4th 2012, “a new boson with mass ~126 GeV”:

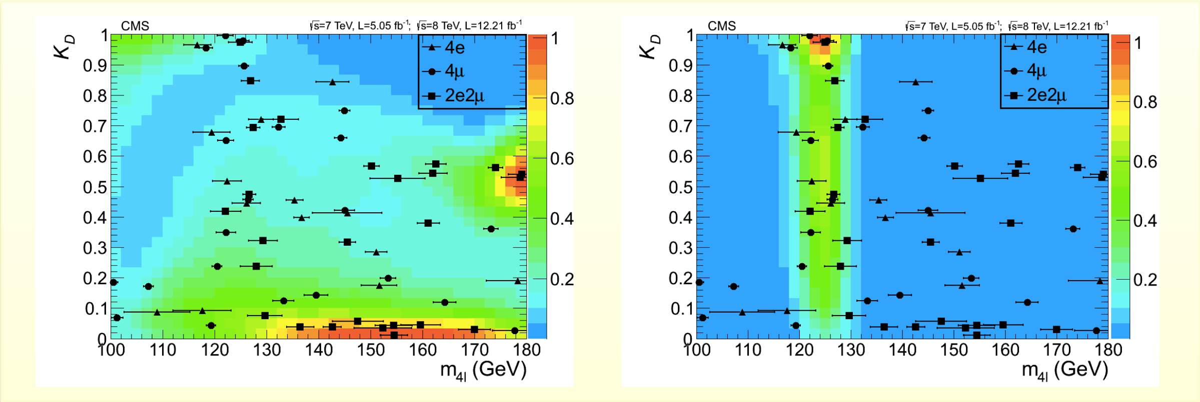
it decayed to two bosons
(two γ; two Z; two W)

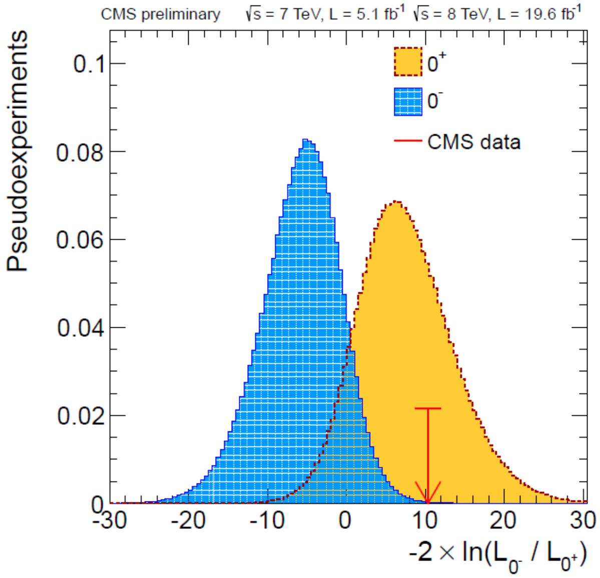
It is not spin-1: it decays to two photons (Landau-Yang theorem)

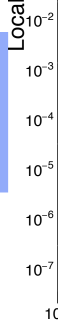
It is either spin-0 or spin-2 (could also be higher spin, but this is really disfavored)

H→ZZ→4leptons: angular analysis



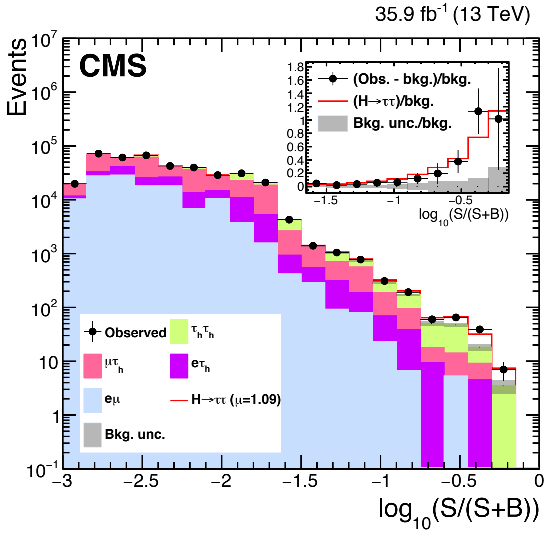


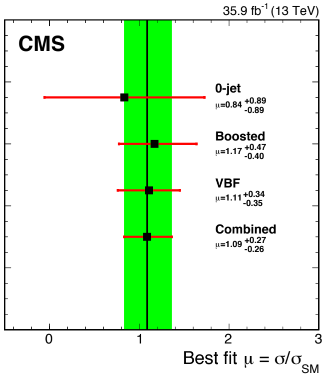




EWSB/H sector: coupling to fermions

H→ττ: established



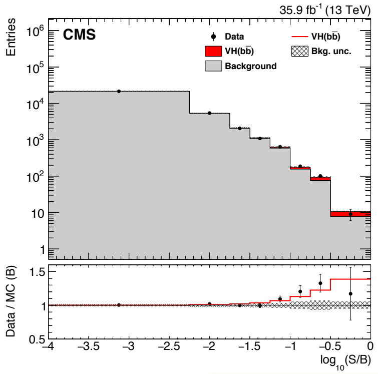


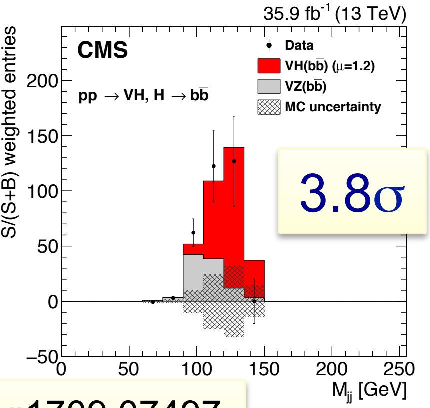
$$\mu = 1.09^{+0.27}_{-0.26} \quad (4.9\sigma)$$

Comb. 7+8+13 TeV:

$$\mu = 0.98 \pm 0.18 \quad (5.9\sigma)$$

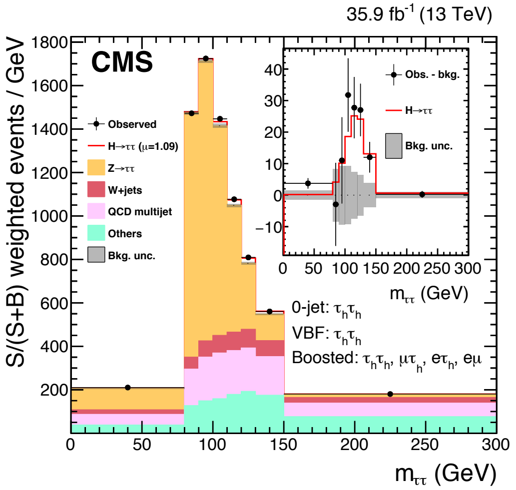
H→bb: evidence (>3σ)

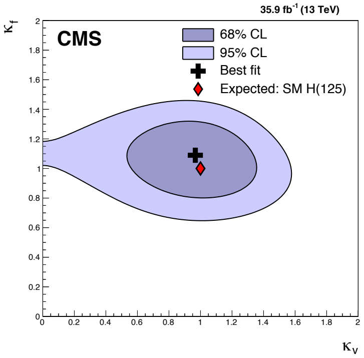


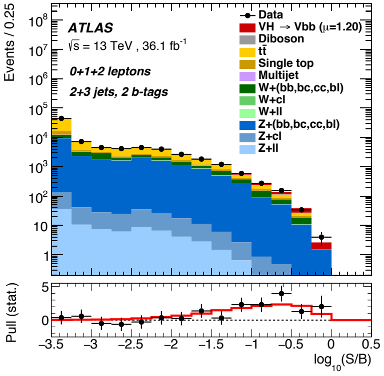


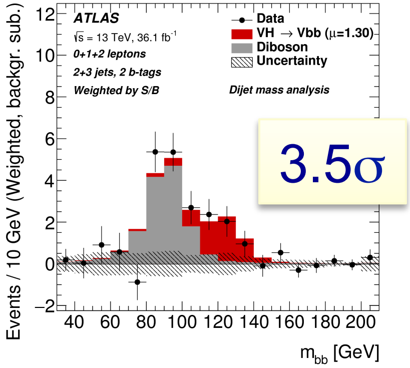
3.8σ

CMS arXiv:1709.07497





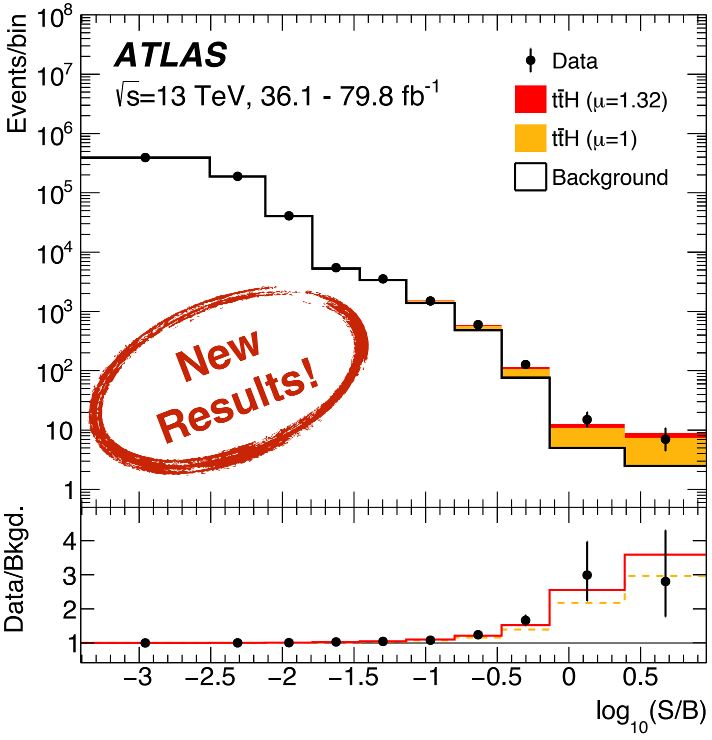


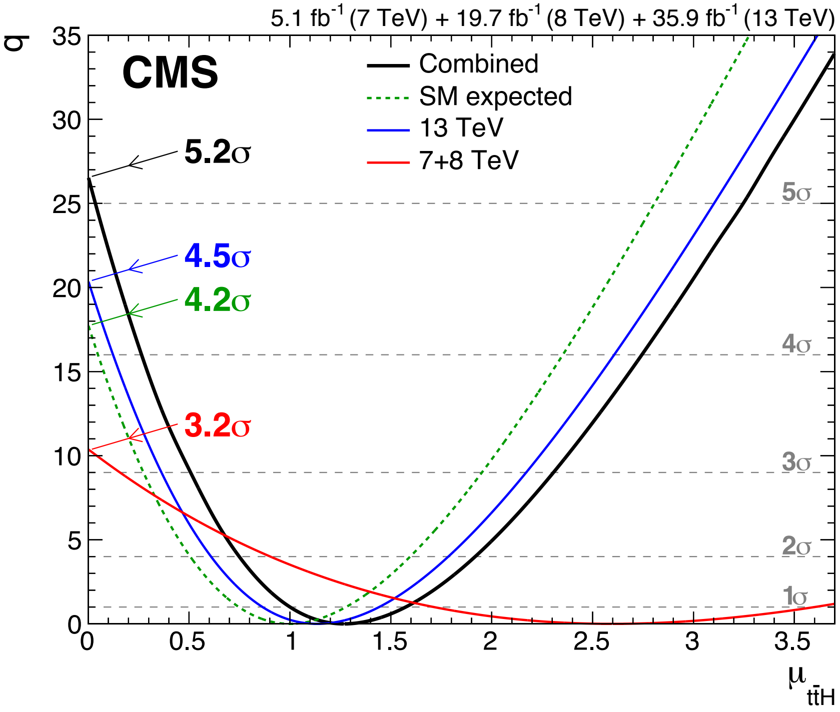


3.5σ

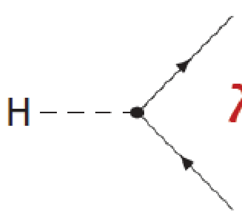
ATLAS arXiv:1708.03299

Top-Higgs “Yukawa” coupling

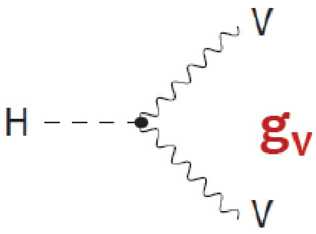




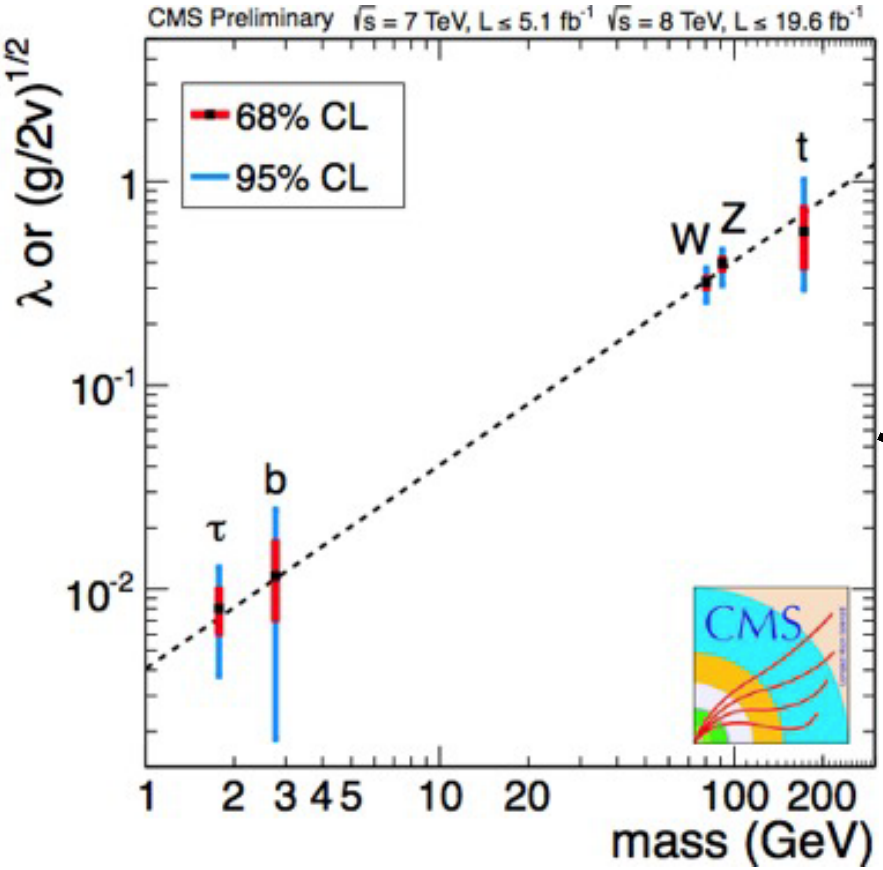
It couples to Mass!



$\lambda_f = m_f / v$



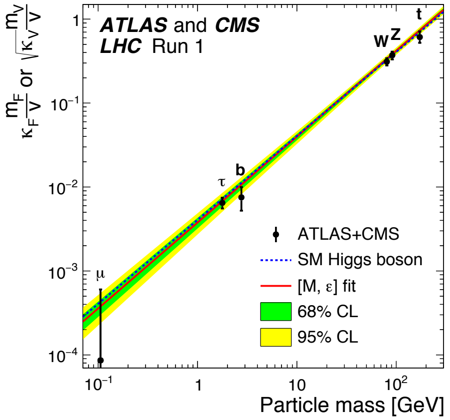
$g_V = 2\, m_V^2 / v$



And has SPIN 0(!)

It's a Higgs boson!

(a) $J^P=0^+$ **(b)**



Is it *the* Higgs?
→ establish production and decay (AMAP)

SM: EWSB/Higgs sector

Higgs couplings to fermions (τ, b and t)

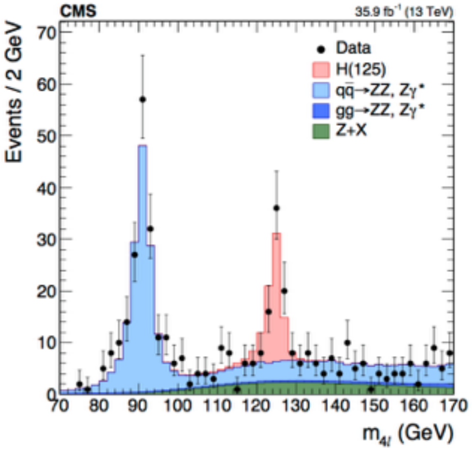
Couplings to 2nd-gen fermions

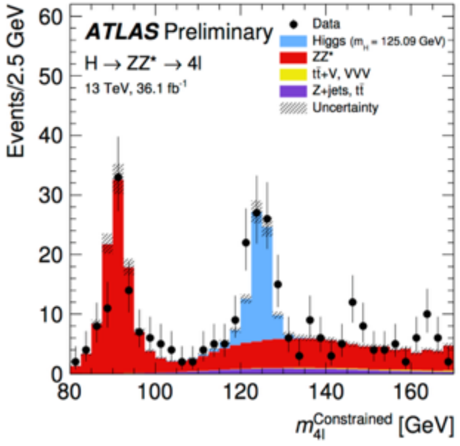
Measurements enabled by high stats

H self-coupling; long-term future

EWSB/H sector: increasing statistics

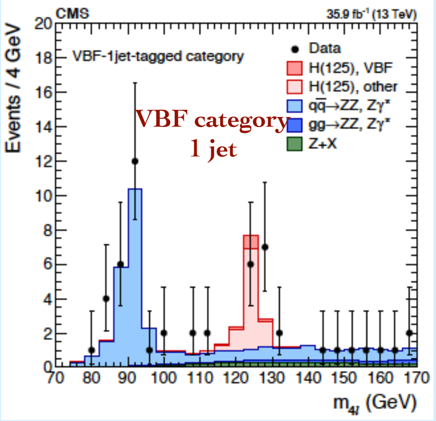
- **With increased stats: Observation channels → measurement channels**

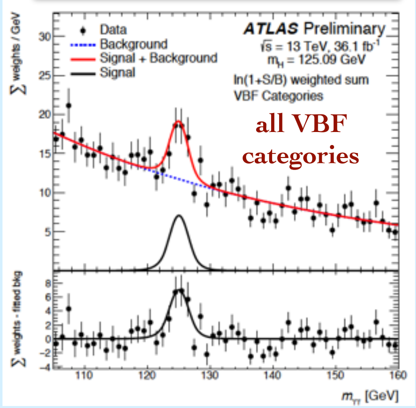




CMS-HIG-16-041

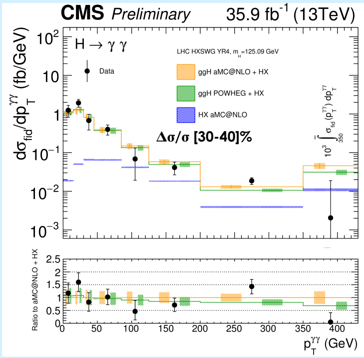
ATLAS 1708.03299

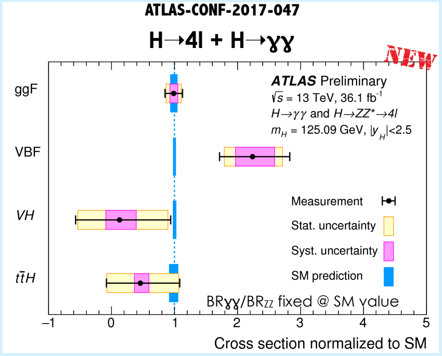




σ/σ_{SM}=1.2±0.2

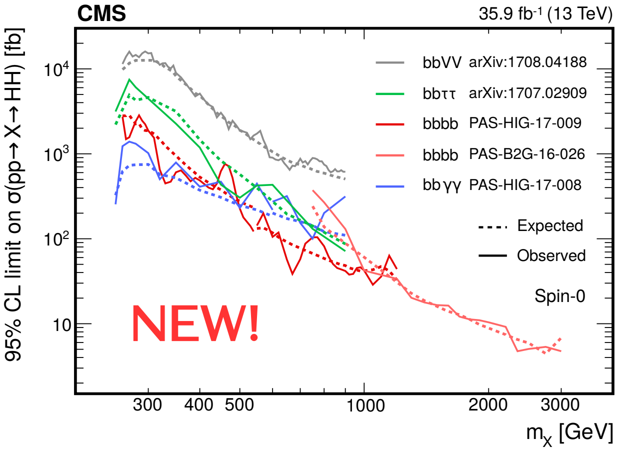
VBF clearly seen

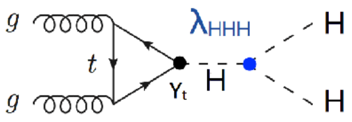


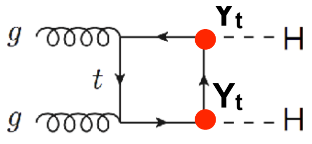


SM EWSB/H sector: for the future

HH; today, within 20xSM
→ need HL-LHC







Final state	ATLAS	CMS
$b\bar{b}\gamma\gamma$	177 (162)	19 (16)
$b\bar{b}\tau\tau$		30 (25)
$b\bar{b}b\bar{b}$	29 (38)	342 (308)
$b\bar{b}WW^*$		79 (89)
$\gamma\gamma WW^*$	750 (386)	

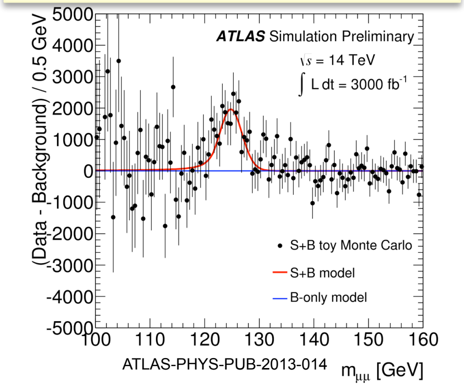
2015 (2.3-3.2 fb^{-1})

2015+2016 (13.3 fb^{-1})

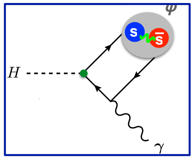
2016 (35.9 fb^{-1})

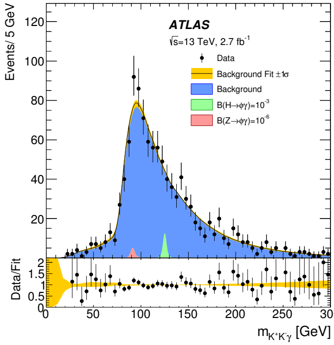
S. Wertz,
Higgs Coupling 2017

H→μμ @ HL-LHC:
7σ (/exp)



Rare decays…





ATLAS-CONF-2017-057

Process	σ/σ$_{SM}$ (95% CL)
H→Zγ (ATLAS) 36fb^{-1}@ 13 TeV	<6.6
H→Zγ (CMS) Run1	<9
H→γ*γ (CMS) Run1	<7.7
H→J/Ψγ (ATLAS) Run1	<540
H→J/Ψγ (CMS) Run1	<540
H→ργ (ATLAS) 36 fb-1 @ 13 TeV	<52
H→φγ (ATLAS) 36 fb-1 @ 13 TeV	<208
H→ee (CMS) Run1	<~10^5

Run1 🟨

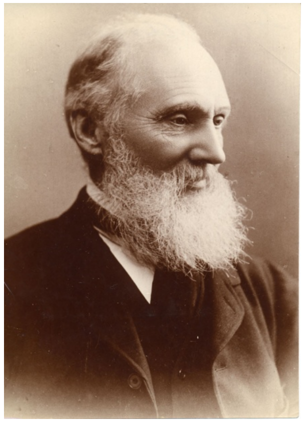
Run2 **36 fb^{-1}**

So is this it?

In a world of an SM Higgs, is there any room for new physics?

Learning from history

- **With the discovery of the Higgs boson, the Standard Model (SM) is now complete**
  - **The SM provides a remarkably accurate description of experiments with and without high-energy accelerators.**
- **With the physics of the very small [thought to be] understood at energy scales of ≥ 100 GeV, the situation is reminiscent of previous times in history when our knowledge of nature was deemed to be "complete".**

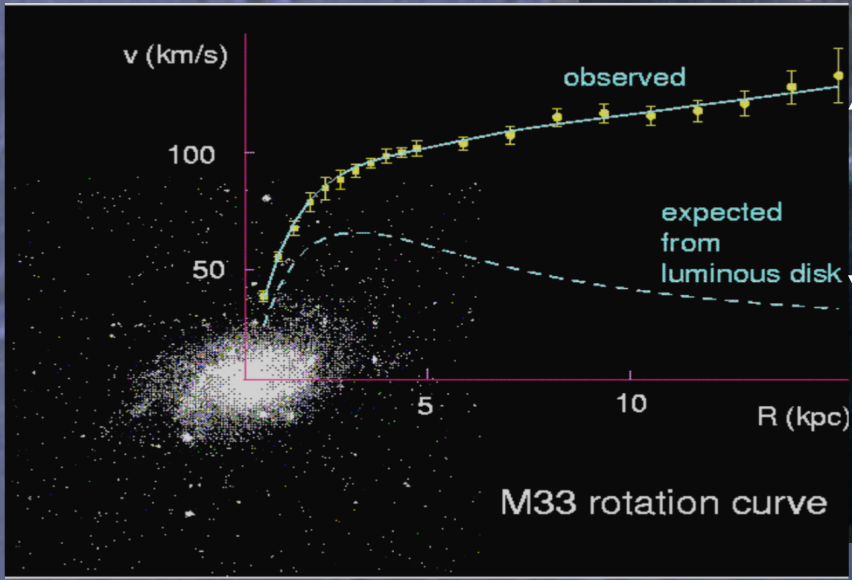


Lord Kelvin (1900):
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

1905-1920: Relativity, Quantum mechanics

Dark matter in the universe

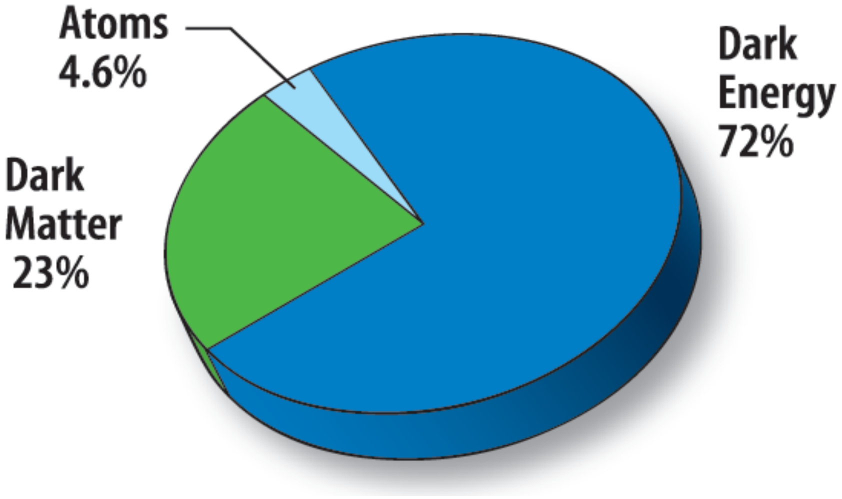
Hubble: we have probed the universe to distances of 13,5 billion years



M33 rotation curve

Dark (invisible) matter!

Dark Matter



Perhaps the biggest mystery in nature (as we speak)

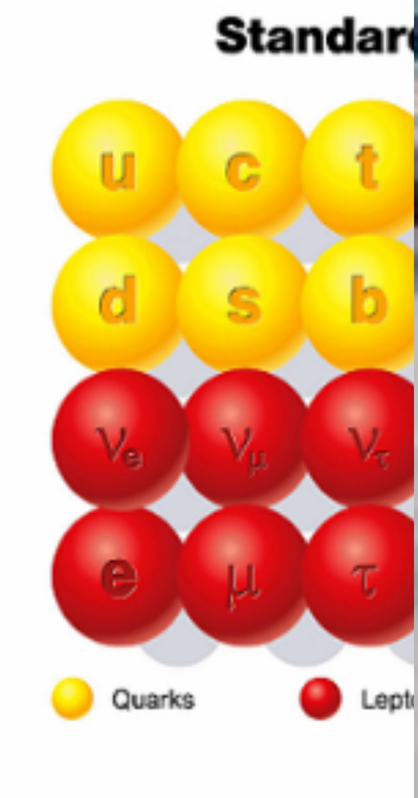
New type of matter?
New forces?
New dimensions?

And now that the Higgs is found: questions

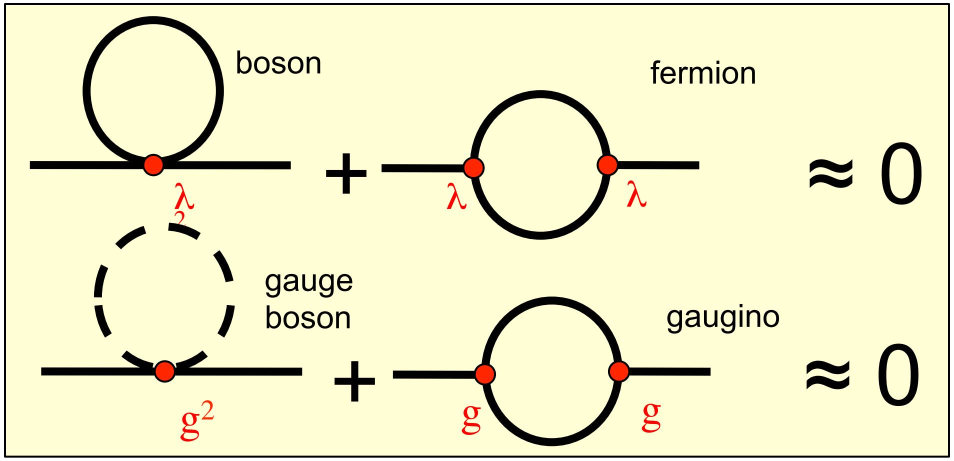
- **Foremost: how can its mass be anything “small”?**
  - It should resist itself (since it couples to mass, it should couple to itself as well). A cascade/avalanche…
  - Its mass should be almost infinite!
- **Where is all this vacuum energy?**
  - We would expect a tremendous energy density, >Googol (10^{100}) times larger than observed! (“Cosmological constant too small”)
  - Size of the universe if the Higgs was there (ALONE): a football (soccer ball)

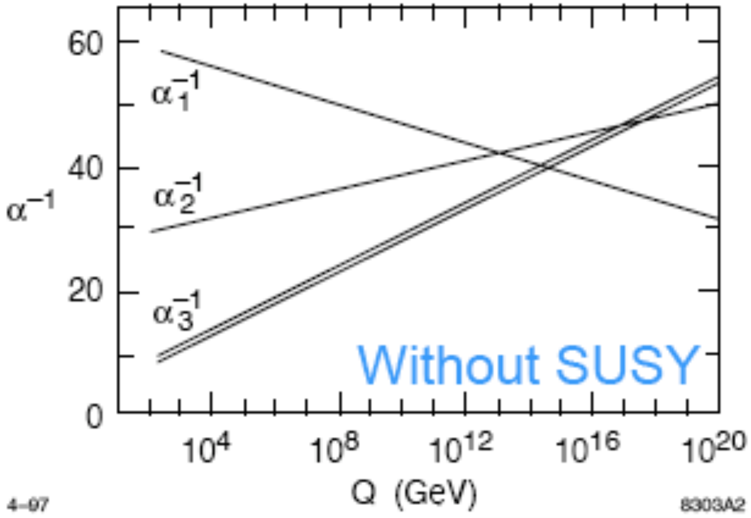
S)

- **SUSY (super ry particle in the SM, there -½ difference**



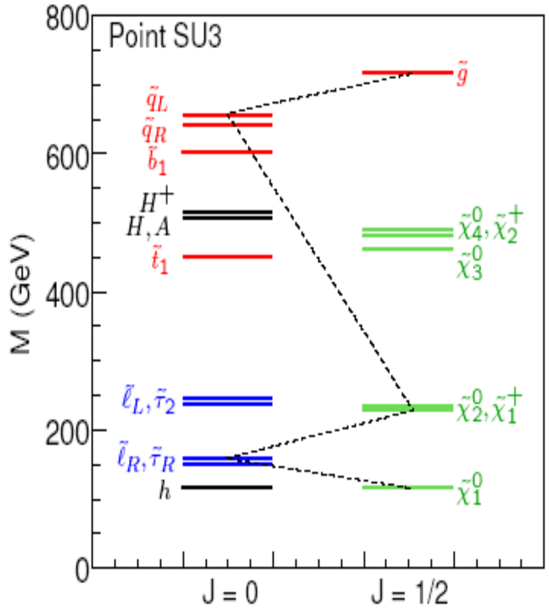
Higgs (mass) is natural ?!



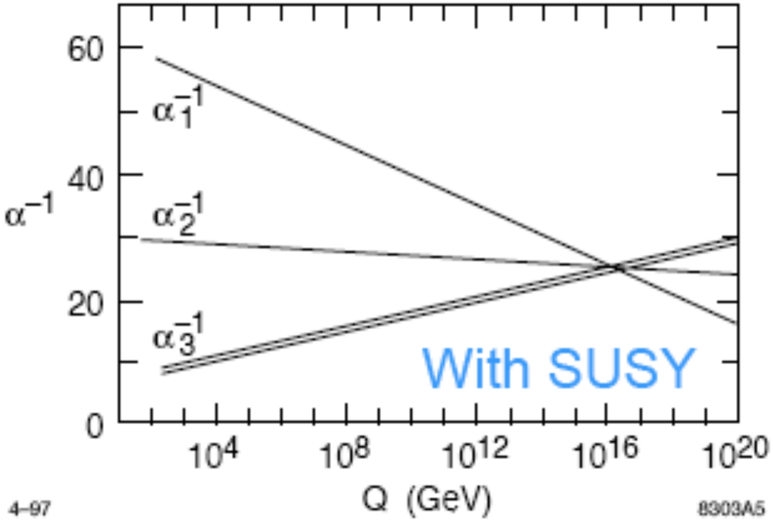


A super(b) symmetry!

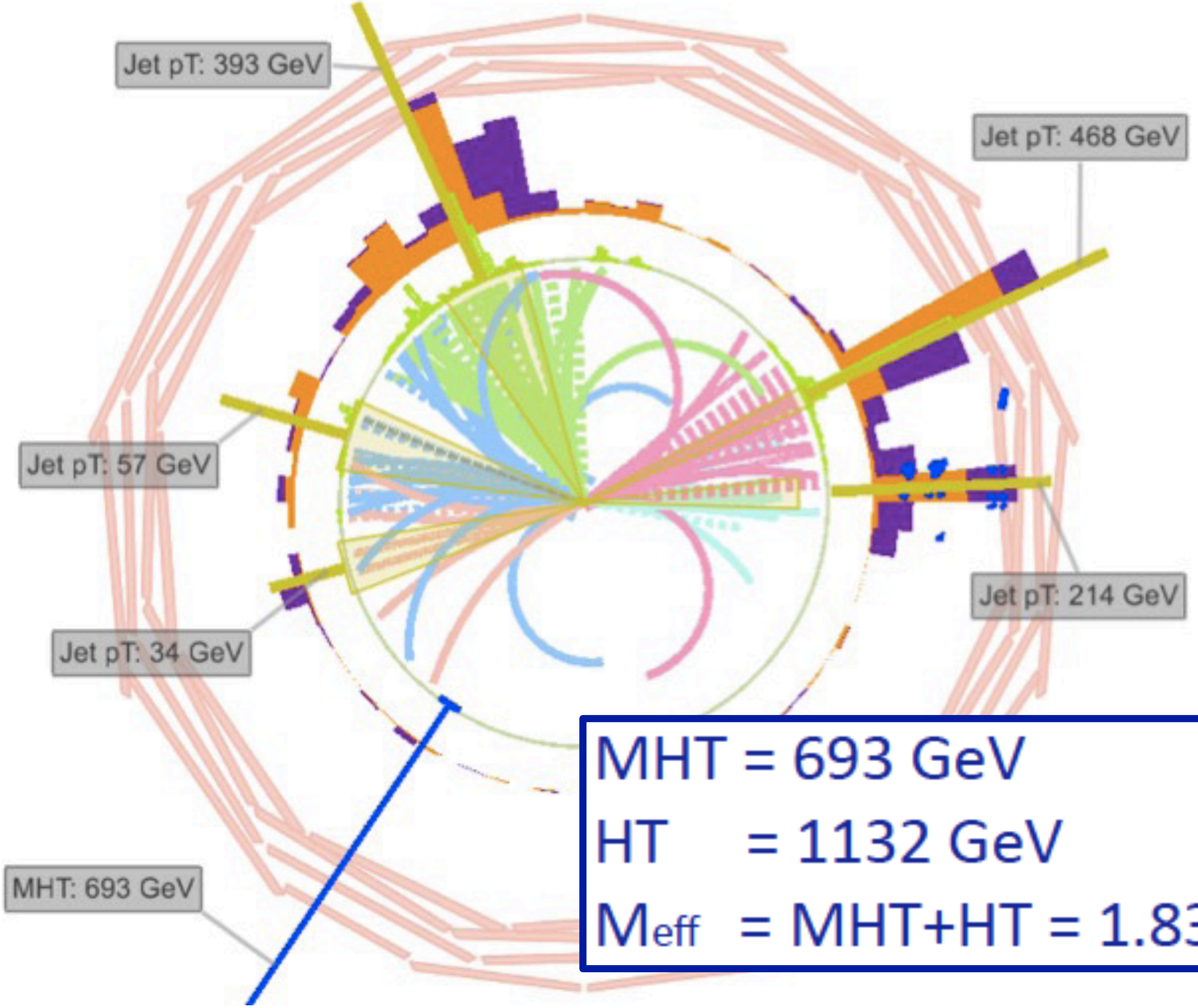
Grand Unifier?



Dark Matter candidate



SUSY? What it could look [looks?] like



MHT = 693 GeV

HT = 1132 GeV

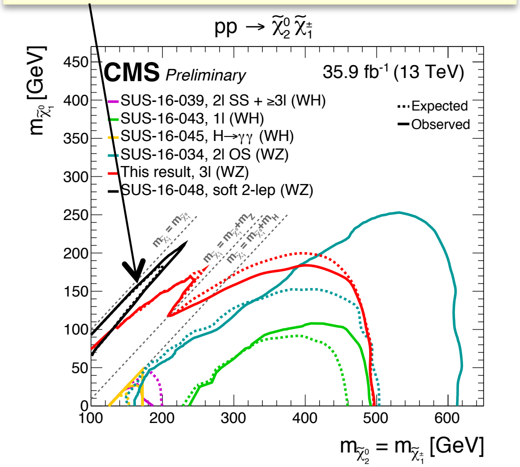
M_{eff} = MHT+HT = 1.83 TeV

Supersymmetry

- The LHC has placed very severe constraints on Supersymmetry
  - In fact, the more “constrained” models of SUSY are now almost excluded (M>~2 TeV)
  - So, is it dead? [it seems the press loves to declare this…]
- There is a lot of room still left. But if SUSY is the answer to the “naturalness” problem, then there must exist light colored particles
  - Leading hypothesis: a relatively light (~TeV) top squark (partner of the top quark)
  - Second-to-leading: compressed spectra

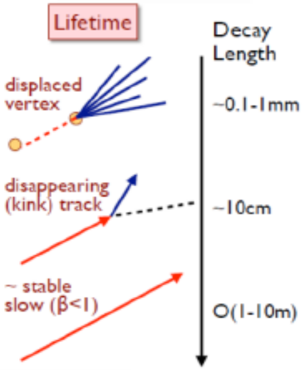
Supersymmetry: what to do next

Compressed spectra



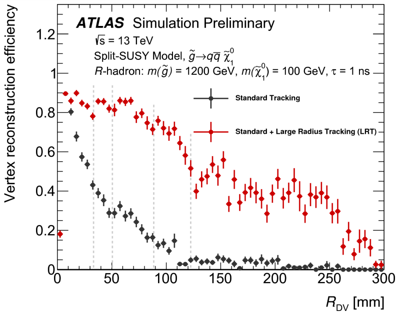
Long Lifetimes

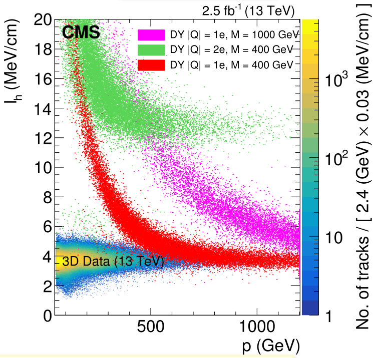
- Small couplings: RPV decays, dark sector coupling
- Small Δm: almost degenerate NLSP heavy messenger: Z', split SUSY
- Hidden valleys…



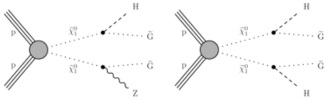
Dedicated (re)tracking

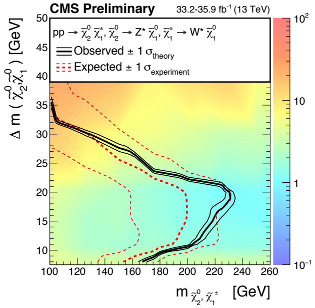
dE/dx

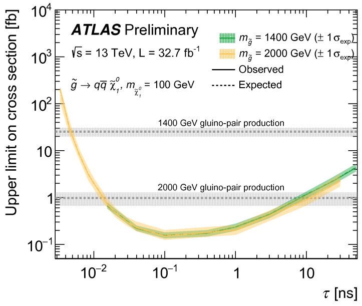




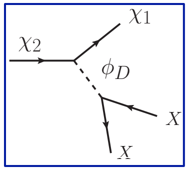
We will always have Higgsinos… μ term must be ~O(M_H)







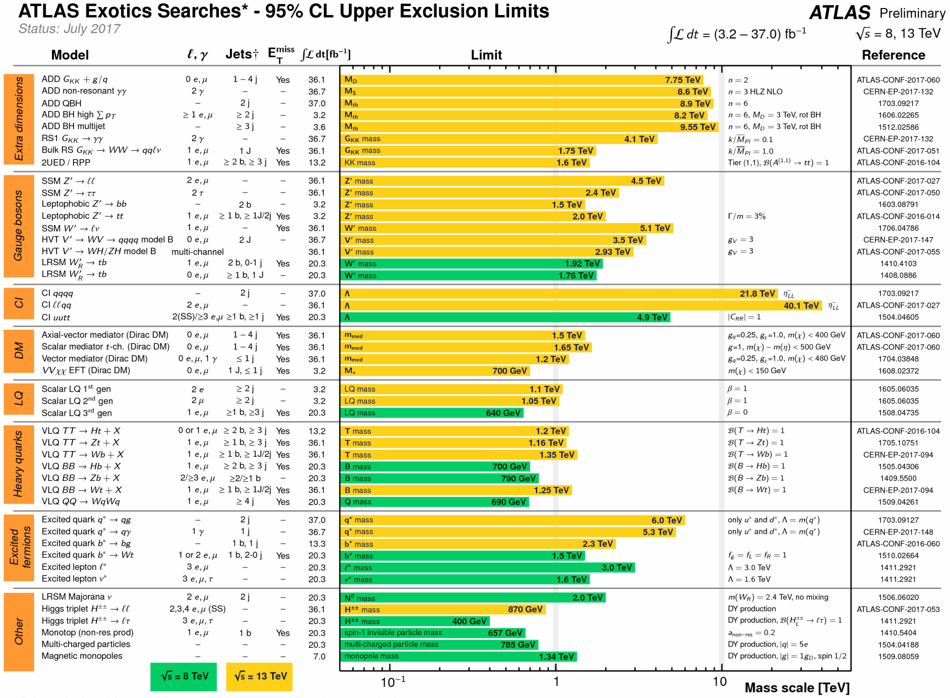
What is really needed: Systematic study of all SUSY and DM space under long-τ hypothesis



CERN LLP Workshop

arXiv:1704.06515

Non-SUSY BSM: vast, simply vast…



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$

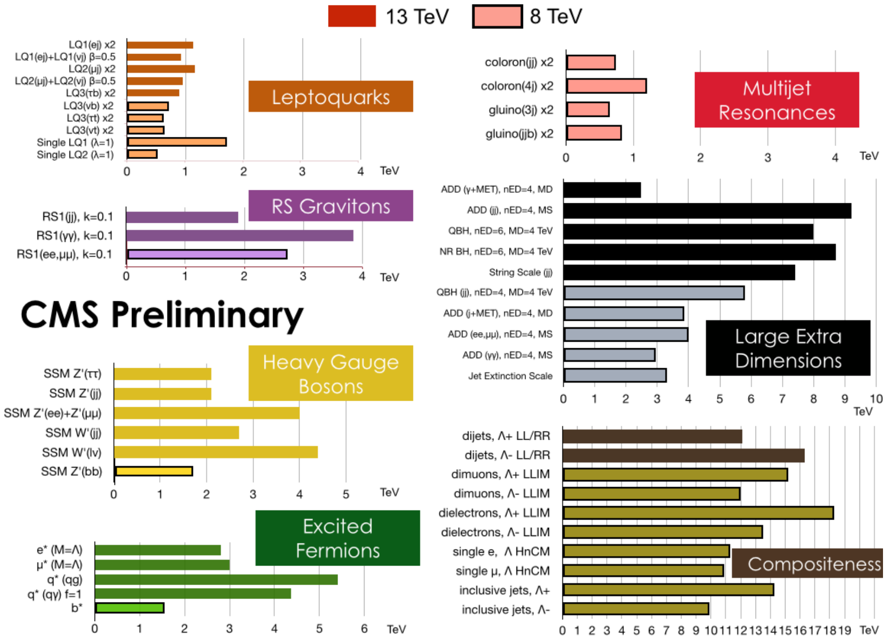
$\sqrt{s} = 8,\ 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1 - 4$ j	Yes	36.1	🟨 M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	🟨 V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.1 TeV η_{LL}^-		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1 - 4$ j	Yes	36.1	🟨 m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Scalar mediator t-ch. (Dirac DM)	$0\ e, \mu$	$1 - 4$ j	Yes	36.1	🟨 m_{med} 1.65 TeV	g=1, $m(\chi) - m(\eta) < 500$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu, 1\ \gamma$	≤ 1 j	Yes	36.1	🟨 m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

*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).



CMS Exotica Physics Group Summary – ICHEP, 2016

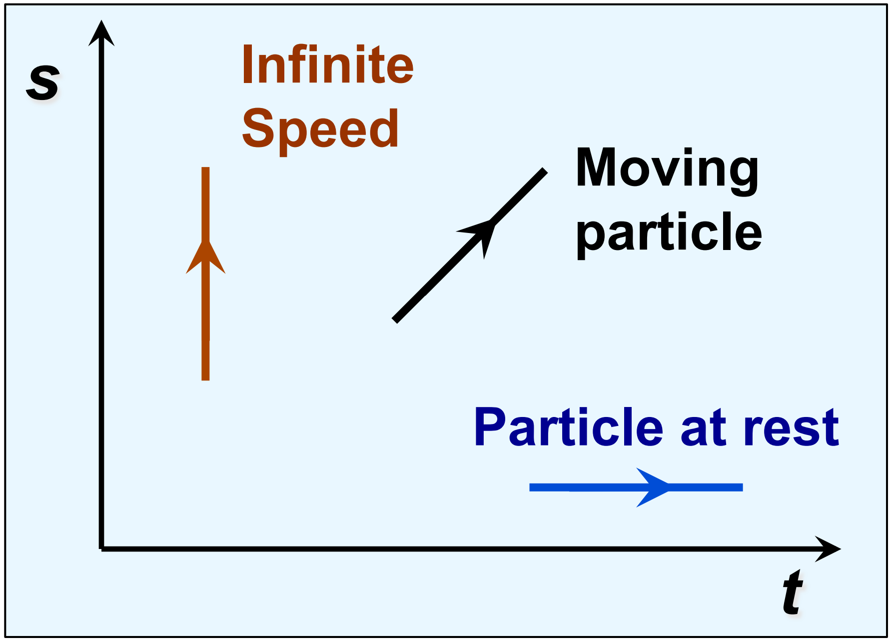
Summary

Summary

- The Standard Model of particle physics is actually much more: it's the Standard Theory of particle physics
    - An elegant description of "interactions", based on Quantum Field Theory (special relativity and quantum mechanics)
    - For decades, it had only one missing element the Higgs boson
- LHC and experiments: a 20-year "Odyssey"
    - And we found a Higgs boson at 125 GeV! Is it the very Higgs boson of the SM?
    - Now need to study the Higgs boson in detail!
- Still, huge reasons to believe in new physics
    - Dark Matter; the finiteness of the Higgs; history!
    - There is still plenty of room where SUSY and other new physics may be hiding
- Stay tuned! The best may well be ahead!

Force = exchange of particle

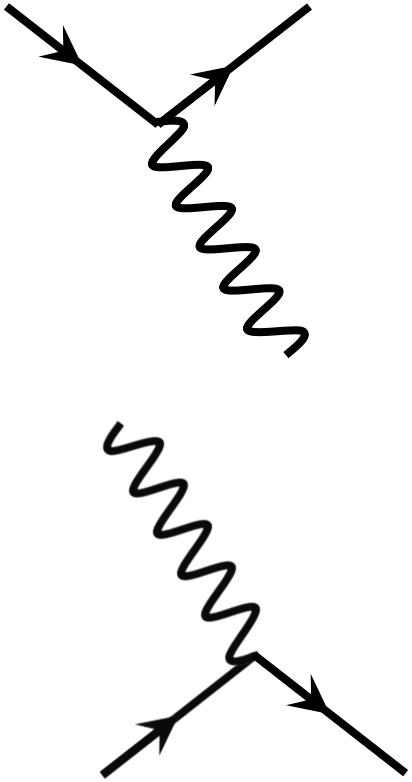
- The most basic process: a fermion (matter particle) emits/absorbs a boson (force particle)



Infinite Speed

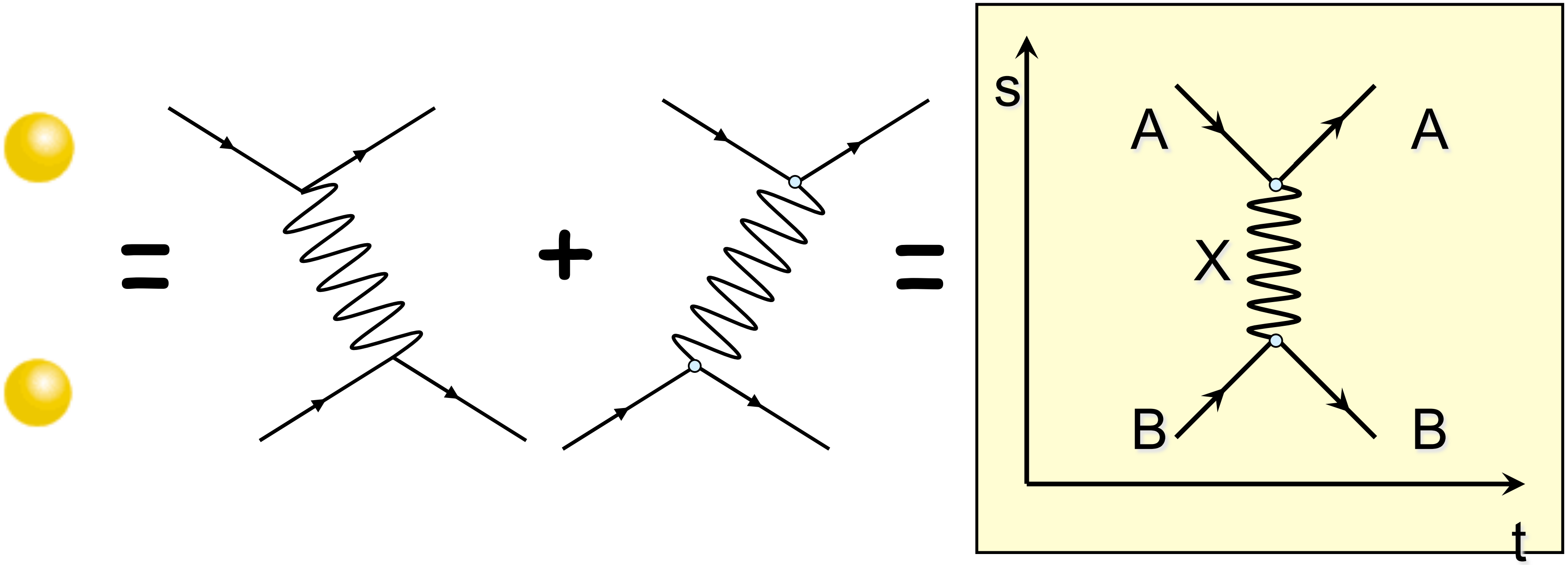
Moving particle

Particle at rest



Feynman diagrams (I)

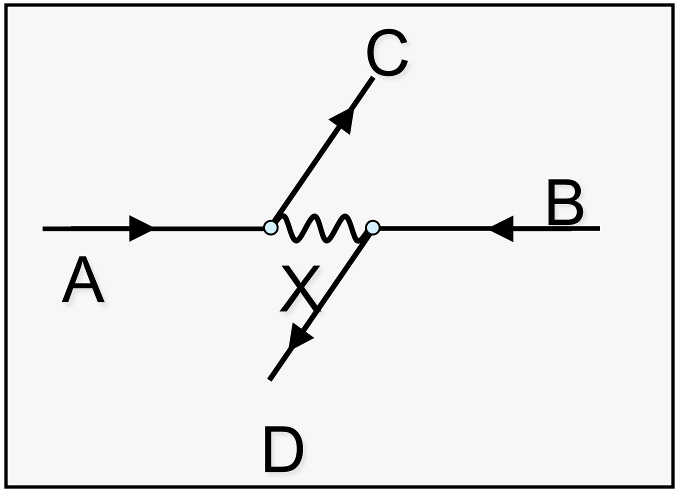
- **Have to draw all possibilities**
  - We do not know whether X was emitted by A and absorbed by B or the opposite
  - So: X is drawn vertically [though it does not have infinite v]



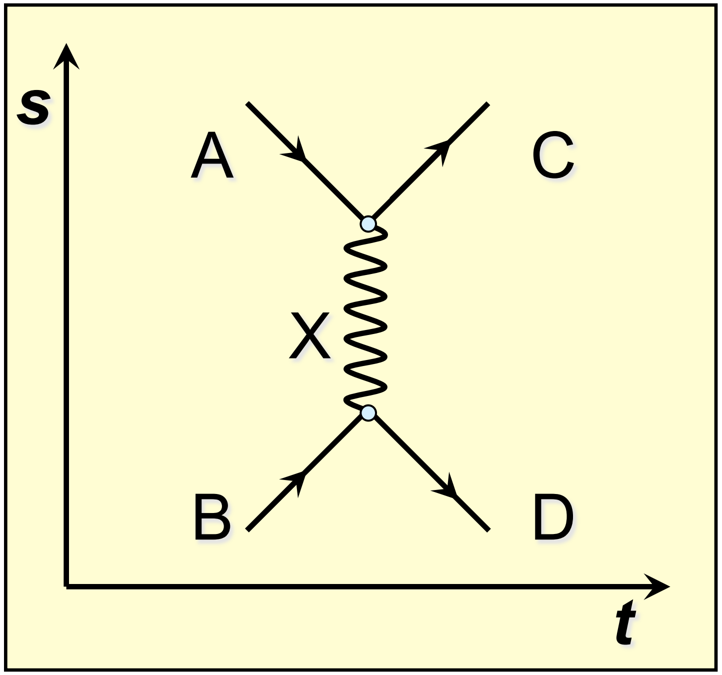
Feynman diagrams (II)

Exchange Diagrams

- Particle A scatters off of particle B by exchanging intermediate particle X. If X is a photon, then the final particles C and D are the same as A and B.



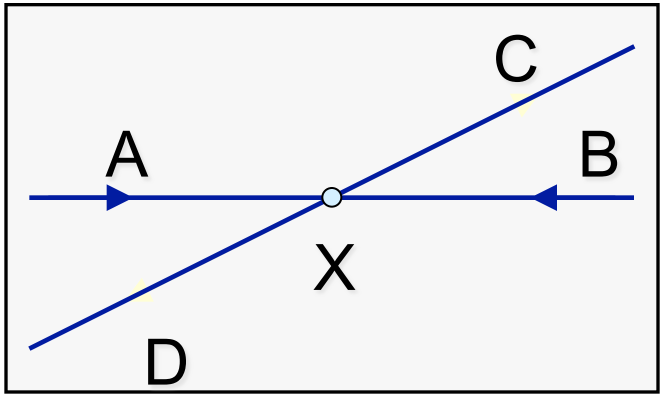
The interaction, as seen in the laboratory frame



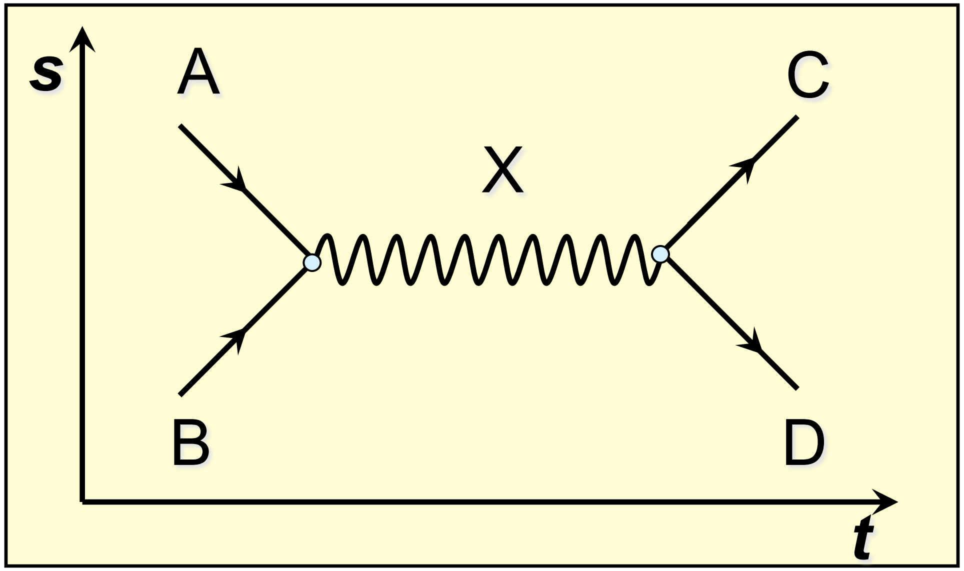
Schematic representation of the collision in terms of a Feynman diagram.

Feynman diagrams (III)

- **Annihilation and Creation (Formation) diagrams**
  - **Incoming particles A and B collide, forming an intermediate particle X, which in turn decays into particles C and D**



The interaction, as seen in the laboratory frame



Schematic representation of the collision in terms of a Feynman diagram. Note that vertices conserve charge/momentum

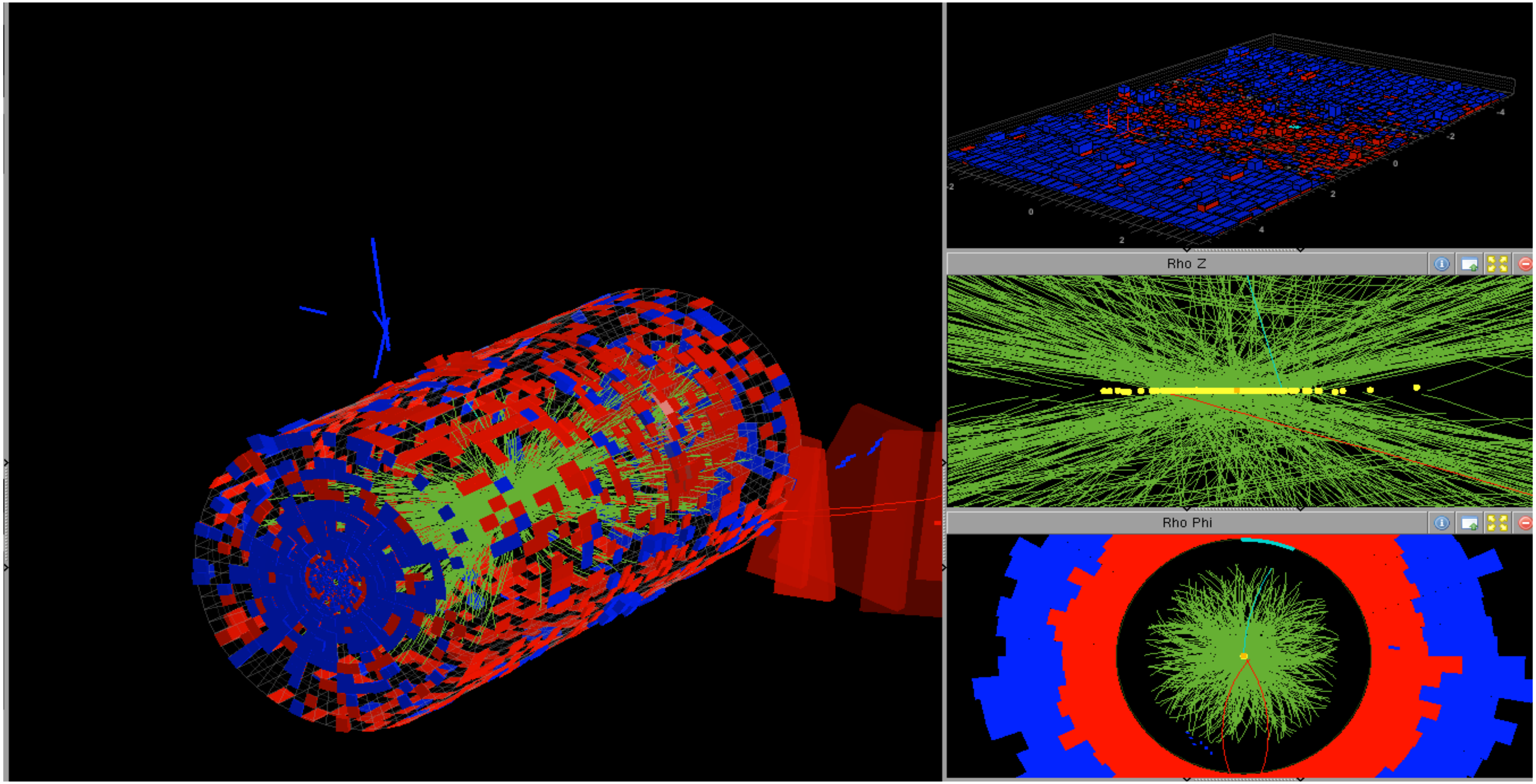
Summary

- The Standard Model of particle physics is actually much more: it's the Standard Theory of particle physics
  - An elegant description of "interactions", based on Quantum Field Theory (special relativity and quantum mechanics)
  - One tricky issue: symmetry breaking. Needed a truly new mechanism – BEH? There should be a left-over boson
    - For decades: missing element – the Higgs boson
- A new boson with mass 125 GeV has been found
  - We are probing its properties. It IS A Higgs boson! Is it THE SM Higgs boson? Need to study it in more detail.
- Even if this turns out to be the very Higgs boson of the Standard Model, there are huge reasons to believe that new physics is within reach;
  - A gigantic amount of work on searches for SUSY, extra dimensions, etc…; Null so far, but, the best has yet to come!

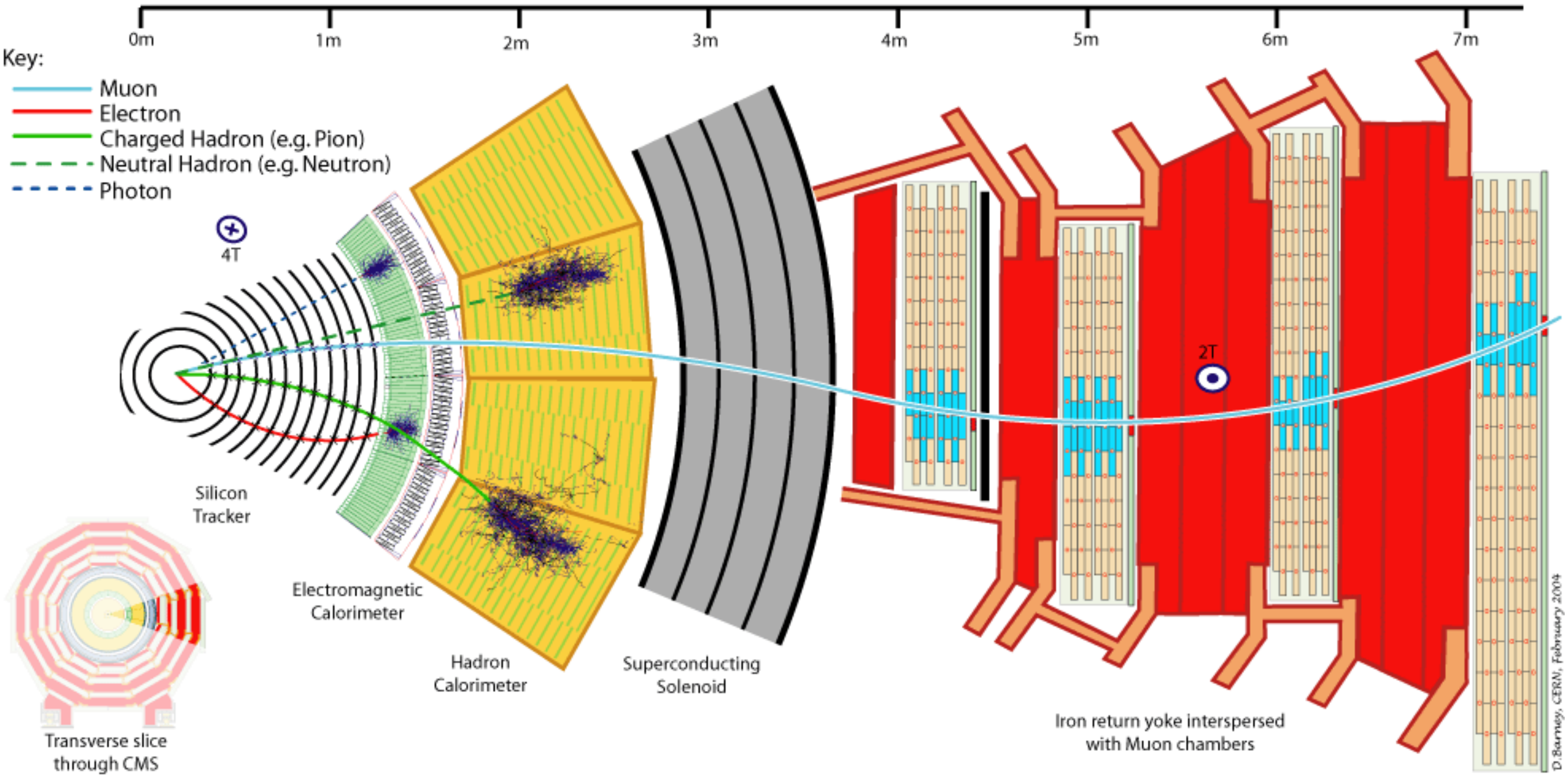
Backups

Going beyond design conditions

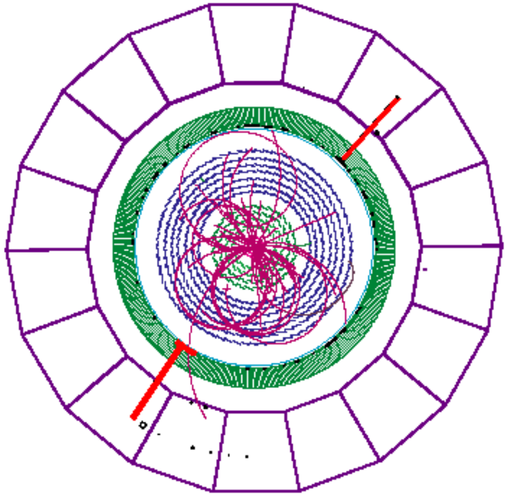
CMS event with 78 reconstructed vertices and 2 muons…

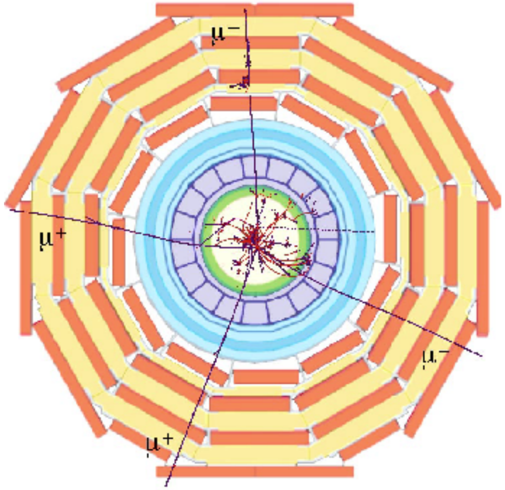


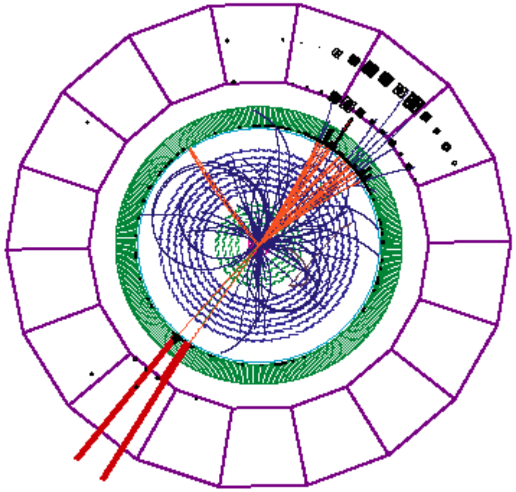
Particle detection/identification in CMS

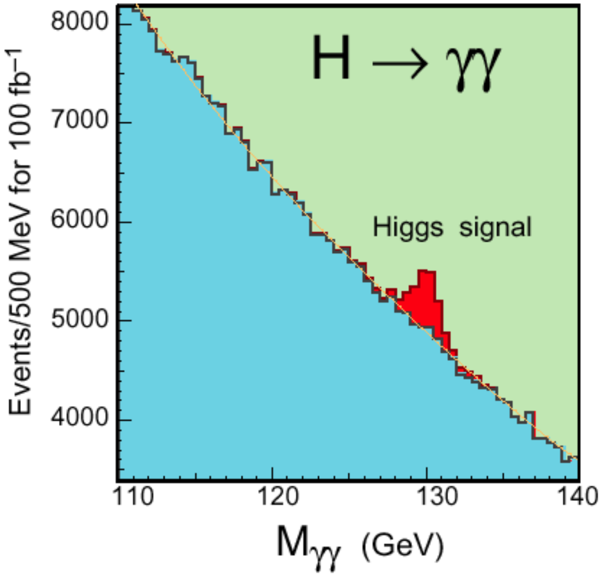


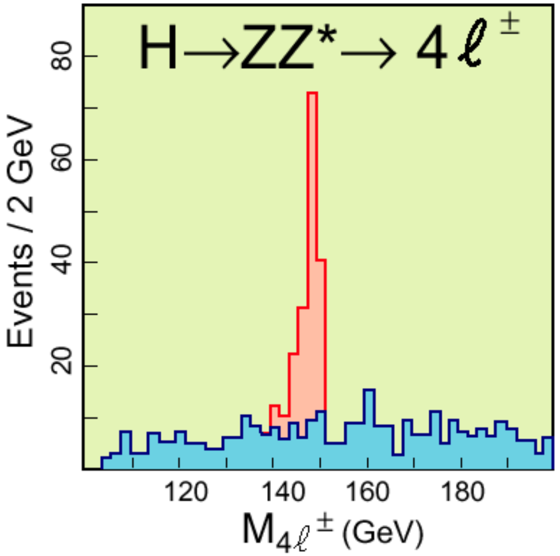
The (SM) Higgs in the detector

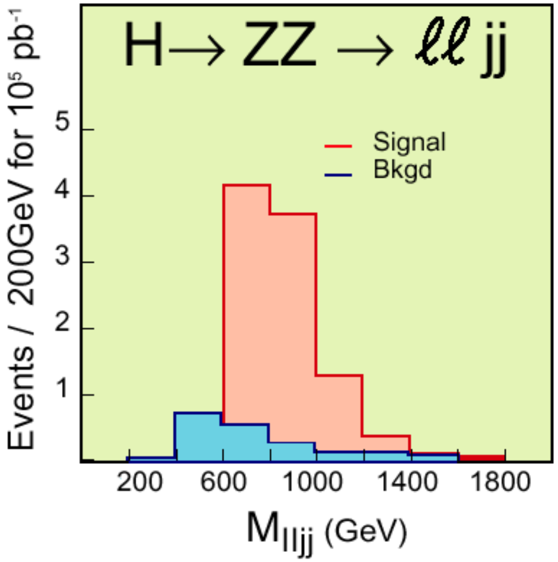




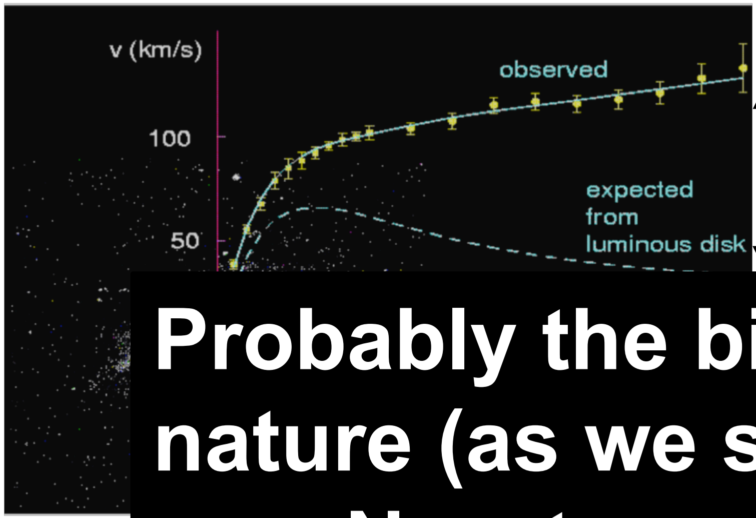








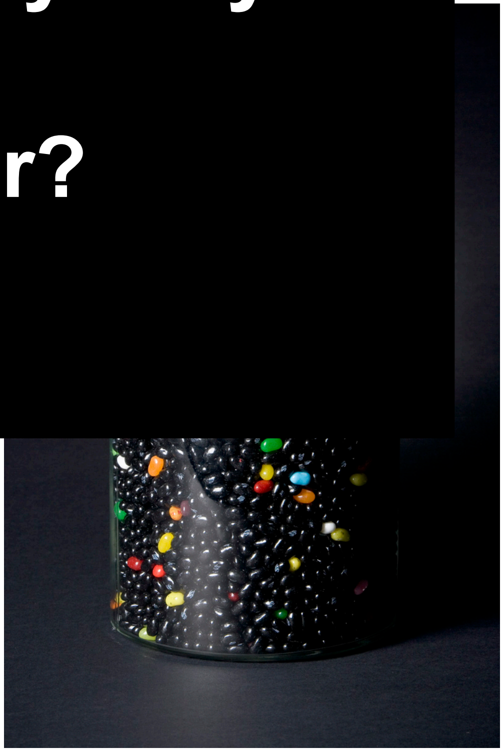
Dark matter



Dark (invisible) matter!

Probably the biggest mystery in nature (as we speak)

- New type of matter?
- New forces?
- New dimensions?

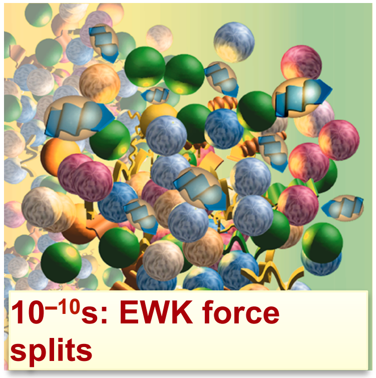


The A word: anthropic [aka “accident”*]

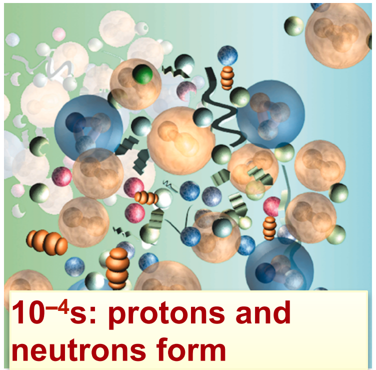
- **Extreme fine-tuning (ETF) of parameters: no problem!**

10^{-43}s

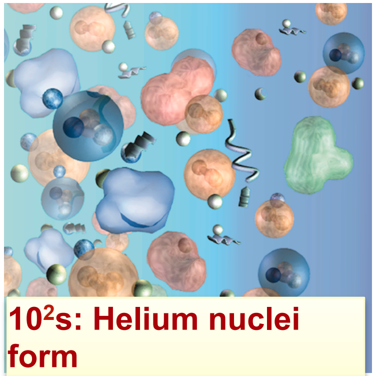
10^{-35}s: inflation ceases, GUT breaks



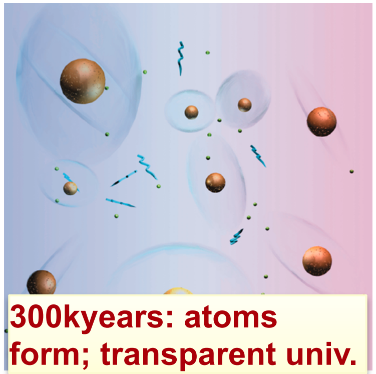
10^{-10}s: EWK force splits



10^{-4}s: protons and neutrons form

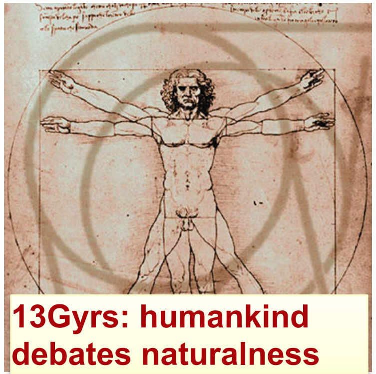


10^{2}s: Helium nuclei form



300kyears: atoms form; transparent univ.

1Gyrs: glaxies form



13Gyrs: humankind debates naturalness

- **Of the 10^{500} possible ways of making a universe, we live in the one that has this cancellation – so as to ensure that we end up with a “livable” universe as we know it**

*Oxford dictionary: an unfortunate incident that happens unexpectedly and unintentionally, typically resulting in damage or injury

Supersymmetry: TO“AE” at the Weak Scale

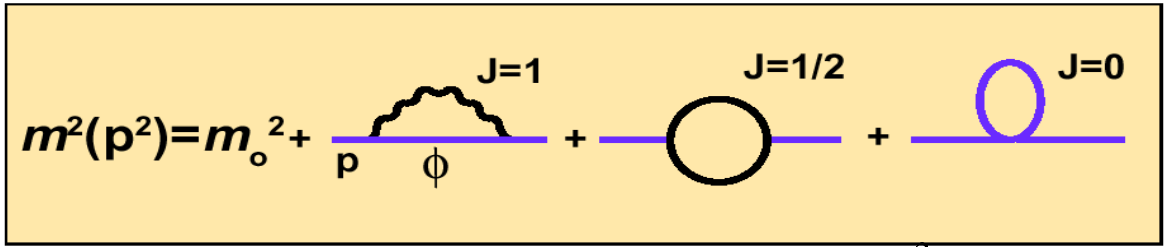
- SUSY is a broken symmetry!
- SUSY partners do not have the same mass as their Standard Model counterparts.
  - Though they are the same in (essentially) every other aspect.

- Make/keep the mass split at ~TeV and nature’s choice of the Higgs boson mass is… “natural”

The magic of the Higgs boson mass

P.A.M Dirac

- **Quantum Mechanics: ultimate destructor of small numbers (in nature) not protected by some symmetry (thus “law”)**
- **Higgs boson: the ultimate example.**



$$m^2\left(p^2\right) = m^2\left(\Lambda^2\right) + Cg^2\int_{p^2}^{\Lambda^2} dk^2$$

  - If no new physics up to Planck scale, then $\Lambda \sim 10^{19}$ GeV
  - m^2 = 123456789012345678901234567543218901**2** –
    123456789012345678901234567543217313**6** = 15876 GeV^2

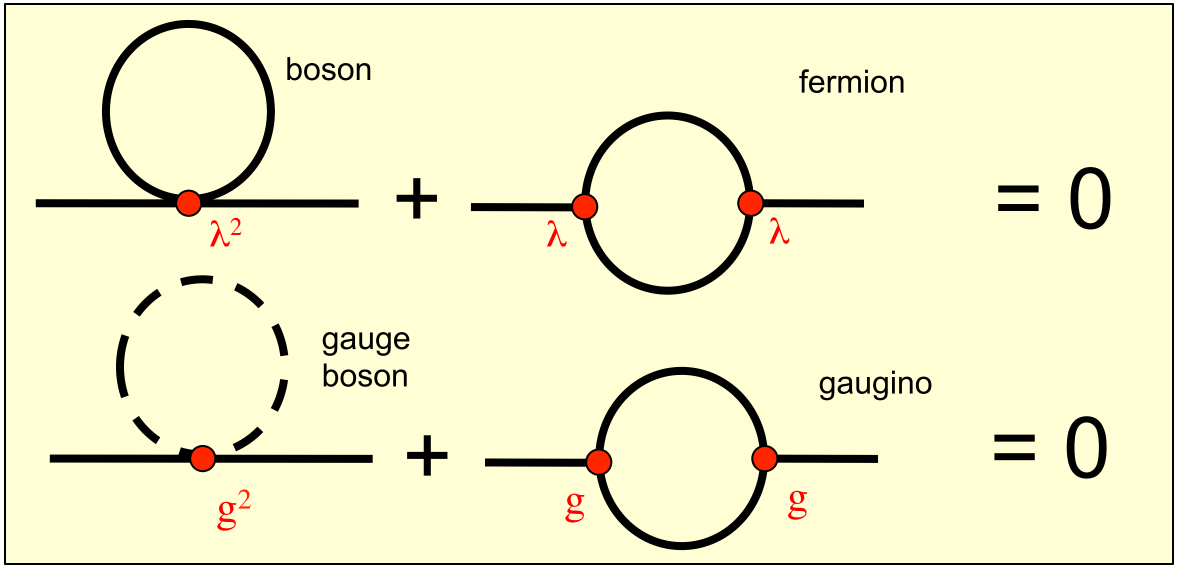
- **Two possible explanations for this:**

  (a) The A word (b) New Physics

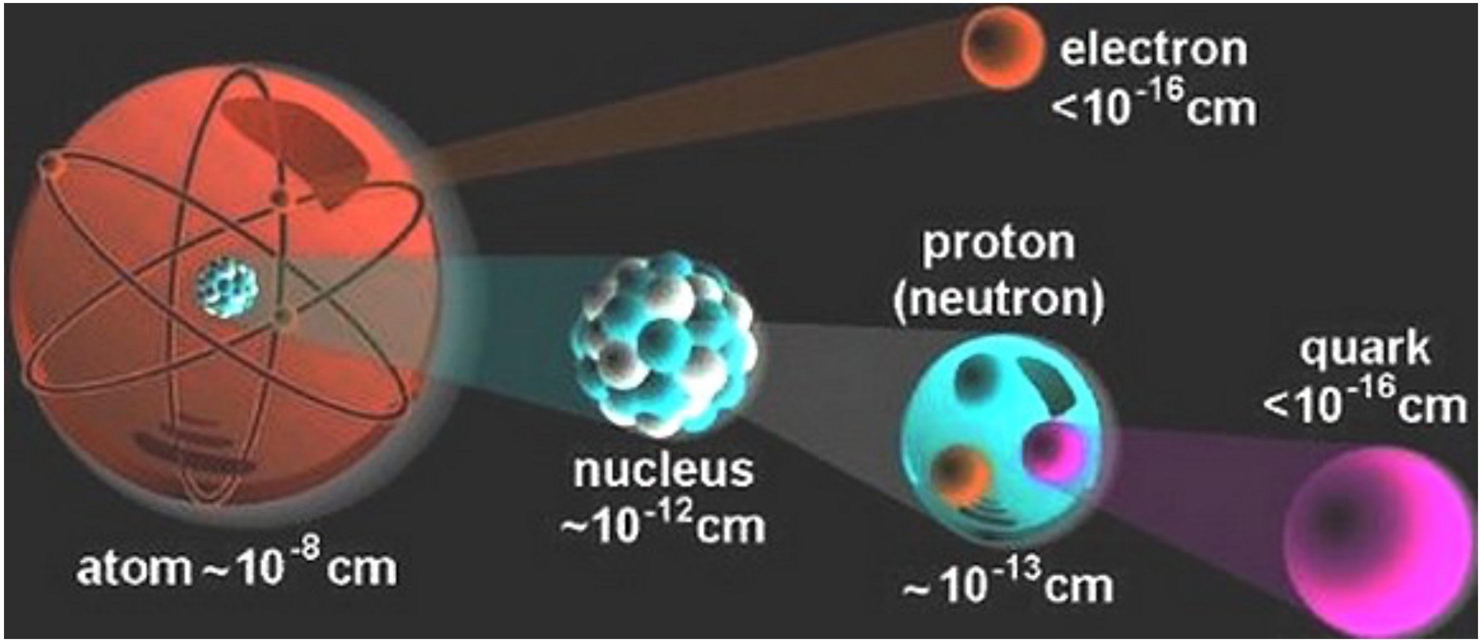
The NP word(s): this is no accident

- **Strong dependence of Physics(Λ_{EWK}) on Physics(Λ_{PL})?**
  - It's like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)

- **No way. There must be some physics that cancels these huge corrections. A straightforward way:**



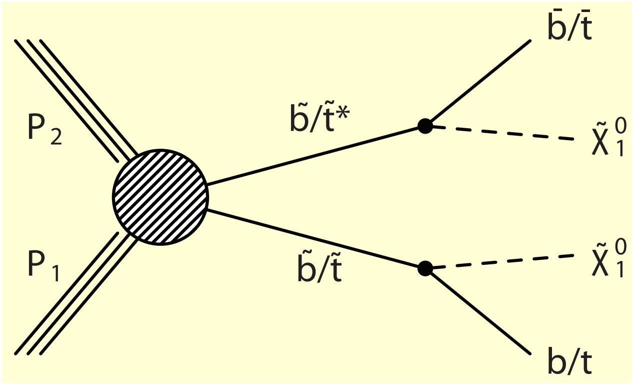
20^{st} century: everything is made of four particles (u, d, e, ν_e)*

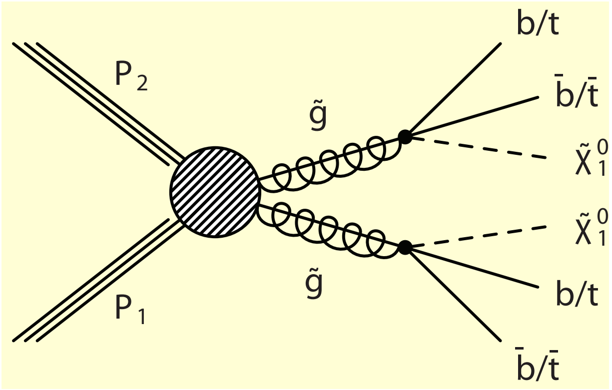


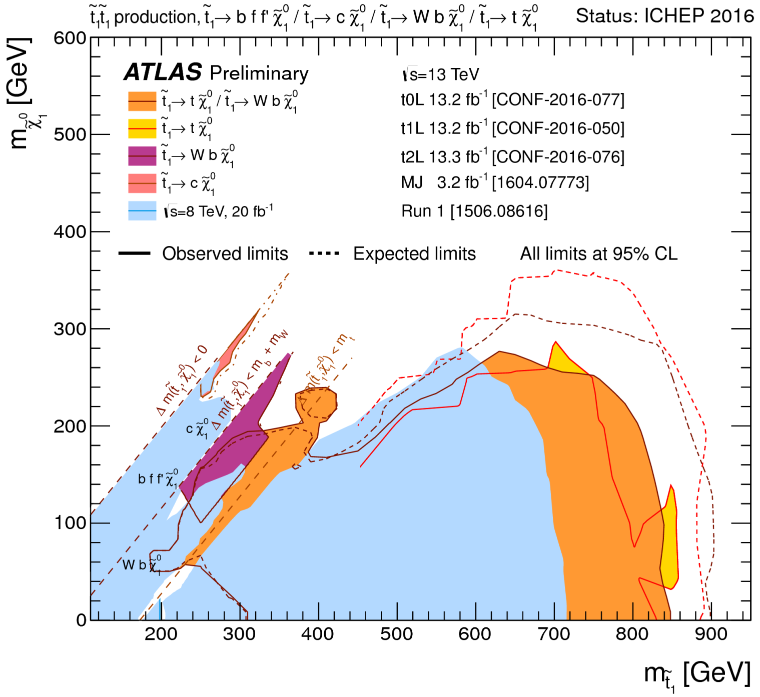
These are pointlike!

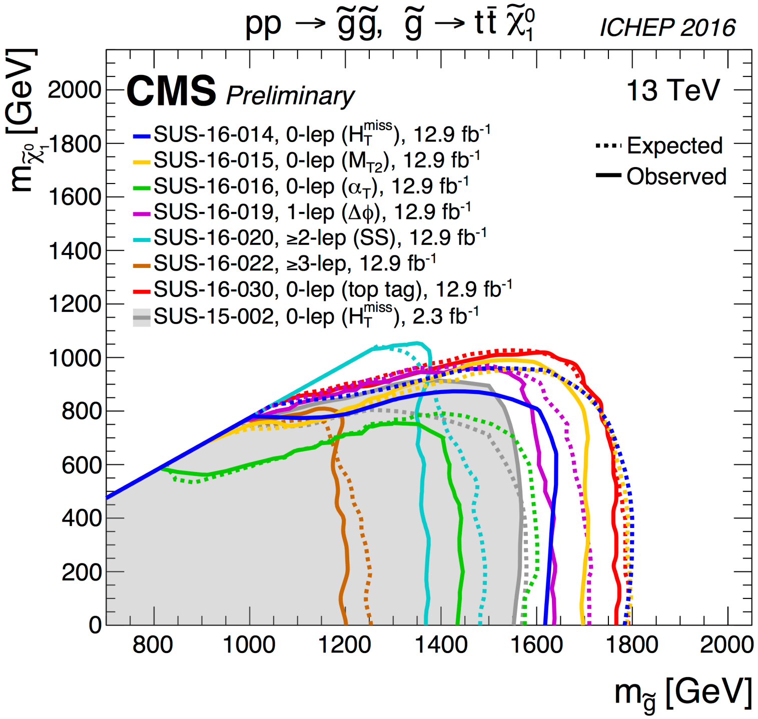
The problem: the background

SUSY: searching for the top squark









Outlook
(LHC at 13-14 TeV & at very high luminosity)
&
Summary

And the vacuum is now full