The Next 20 Years of the LHC

- The Standard Model
- LHC & ATLAS
- Results from Run 1
- Search for the Higgs Boson
- Cracks in the Standard Model
- Supersymmetry
- Quantum Gravity
- Status of Searches for New Physics
- LHC programme to 2035

#LHCnext20y

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School of Physics & Astronomy Public Lecture
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The Standard Model

Standard Model describes 3 of the 4 fundamental forces of nature with unprecedented accuracy
electromagnetic force / weak nuclear force / strong nuclear force

	Quarks						Leptons		
electric charge	+2/3			-1/3			-1	0	
Fermions spin = ½ constitute matter	u	u	u	d	d	d	e	ν_e	I
	c	c	c	s	s	s	μ	ν_μ	II
	t	t	t	b	b	b	τ	ν_τ	III

Bosons
spin = 0 / 1
transmit forces

g g g g g g g g — 8 gluons

propagate strong force

W Z γ — 3 electroweak bosons

electromagnetism & weak force unified into electroweak

propagate electroweak force

H — 1 Higgs boson

gravity is completely missing here!

gives fundamental particles a mass

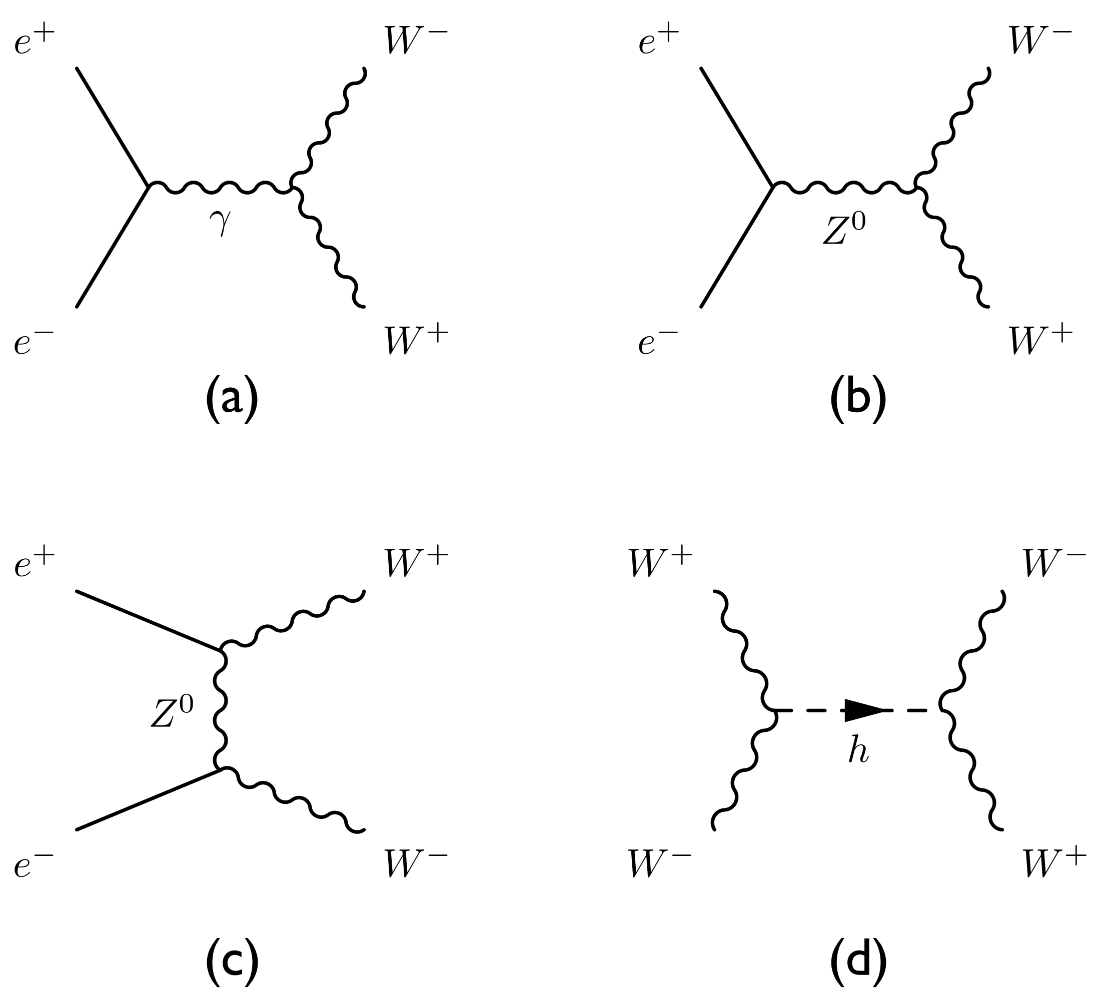
(what universe would look like with no Higgs boson)

The Higgs Boson

Higgs also saves the SM from some embarrassing predictions
Examine theoretically predicted energy dependence of scattering process $e^+e^- \rightarrow W^+W^-$

Processes (a) (b) and (c) become larger than total e^+e^- reaction rate! (probability greater than 100%)

Higgs-like particle is needed to cancel $e^+e^- \rightarrow W^+W^-$ theoretical inconsistency



Requires Standard Model Higgs to be <~1TeV

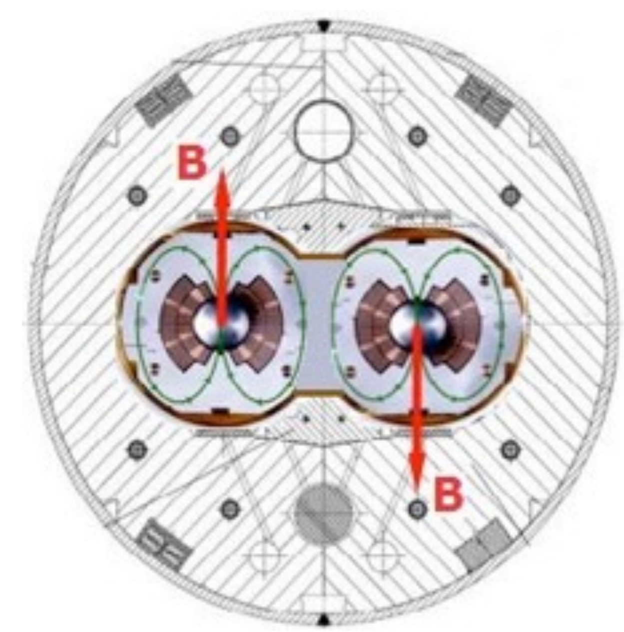
If Standard Model is correct we will find the Higgs at the LHC!

If Standard Model is wrong some new particle must do this job

win-win situation!

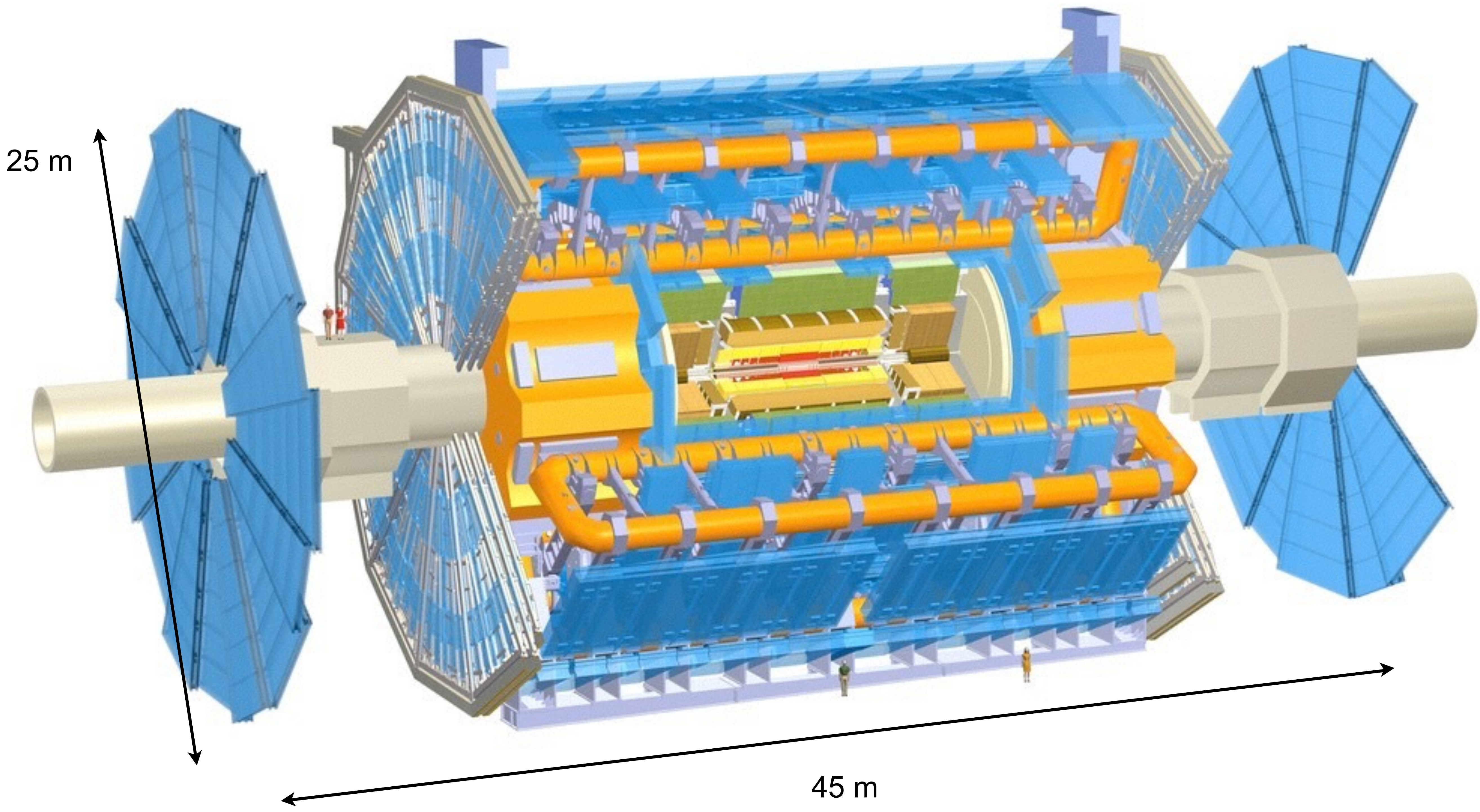
The Large Hadron Collider

27 km circumference tunnel in France / Switzerland - near Geneva
Highest energy accelerator in the world
Protons accelerated to 6,500 GeV = 99.9999991% speed of light
High vacuum
Super cold superconducting magnets to achieve strong magnetic fields
17,000 A current in magnets
Four experiments:
- Atlas
- CMS
- LHCb
- Alice



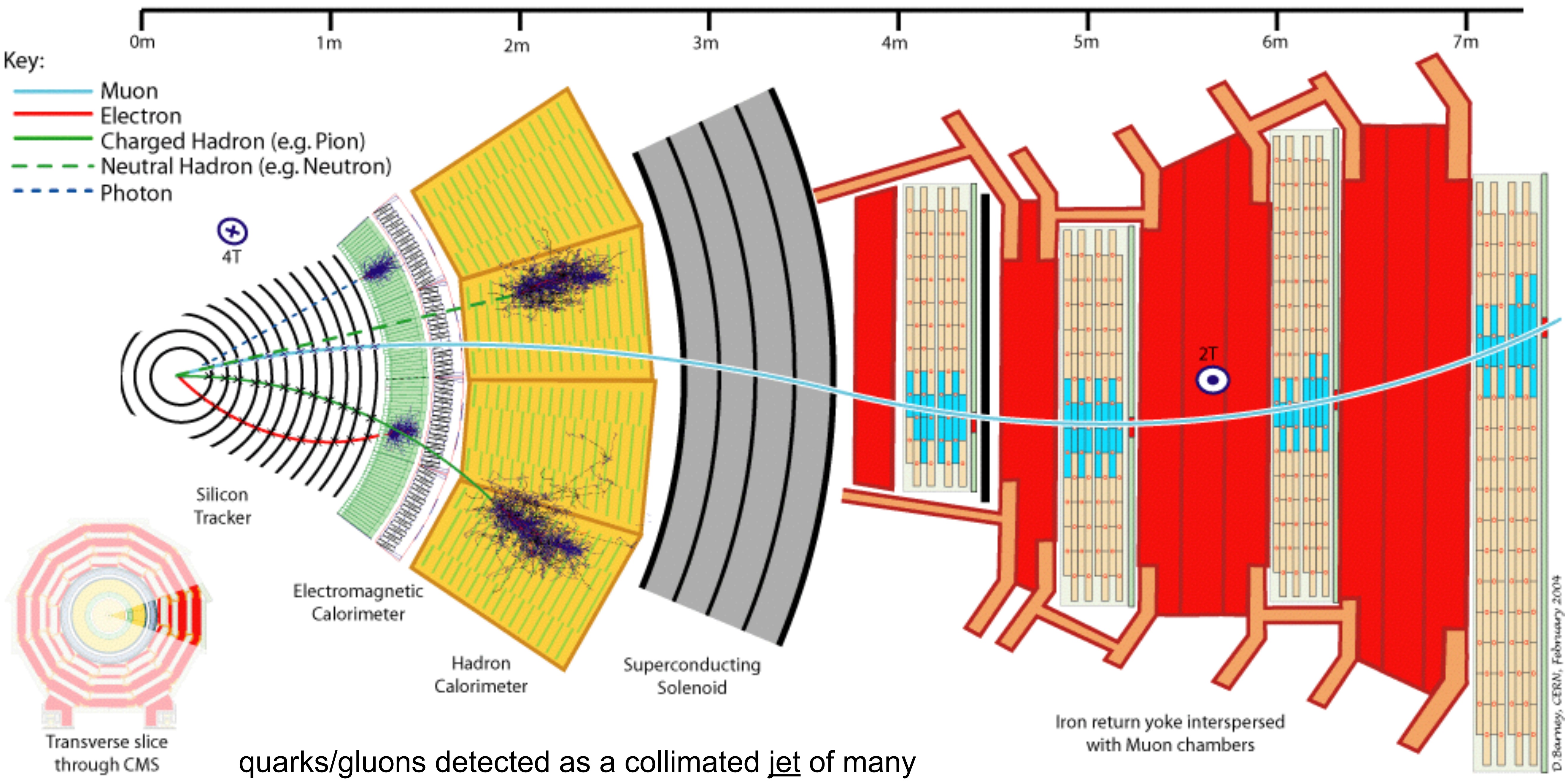
The ATLAS experiment at the LHC
3500 physicists
174 universities
38 countries

7000 tonnes
Mass of the Eiffel Tower
Half the size of Notre Dame
data rate: 20,000,000 Gb/s



Particle Signatures

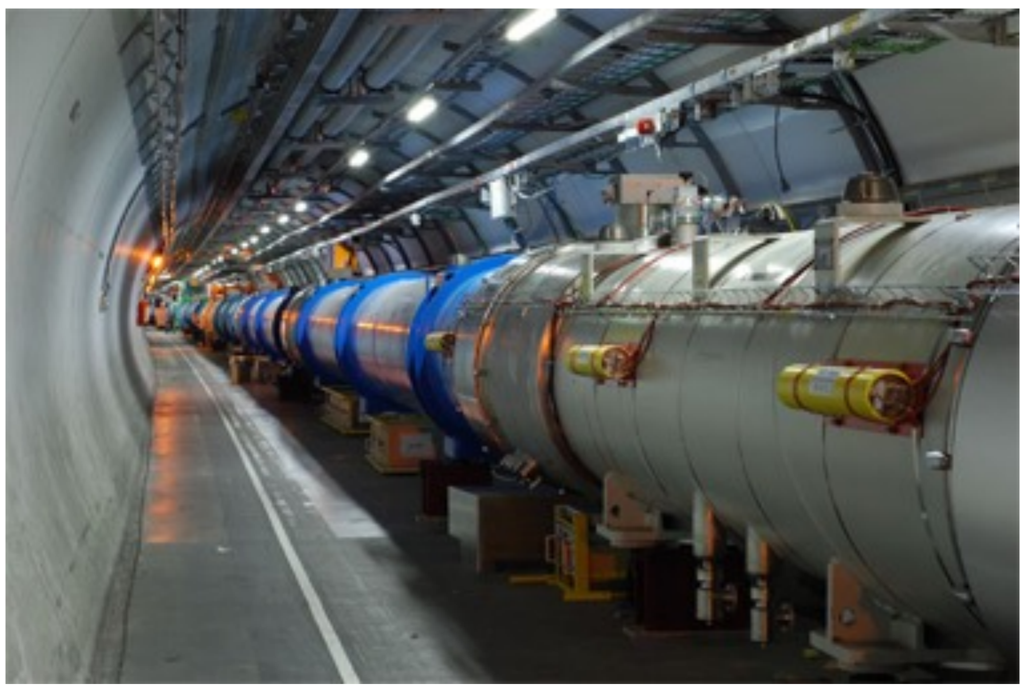
Large experiments needed to measure outgoing particles from collisions
Experiment consists of layered detectors each sensitive to different types of particle
Look for signatures of particle types



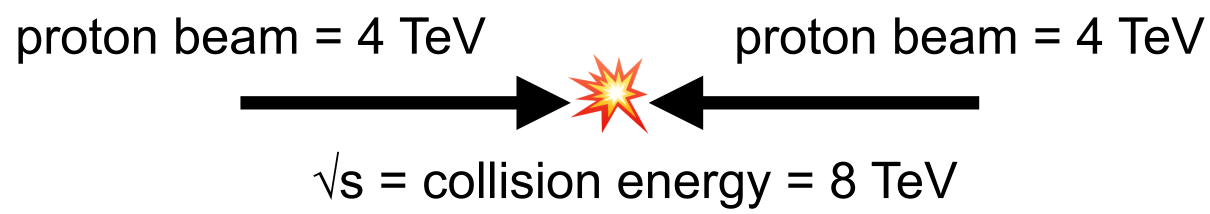
quarks/gluons detected as a collimated jet of many particles leaving energy in hadron calorimeter

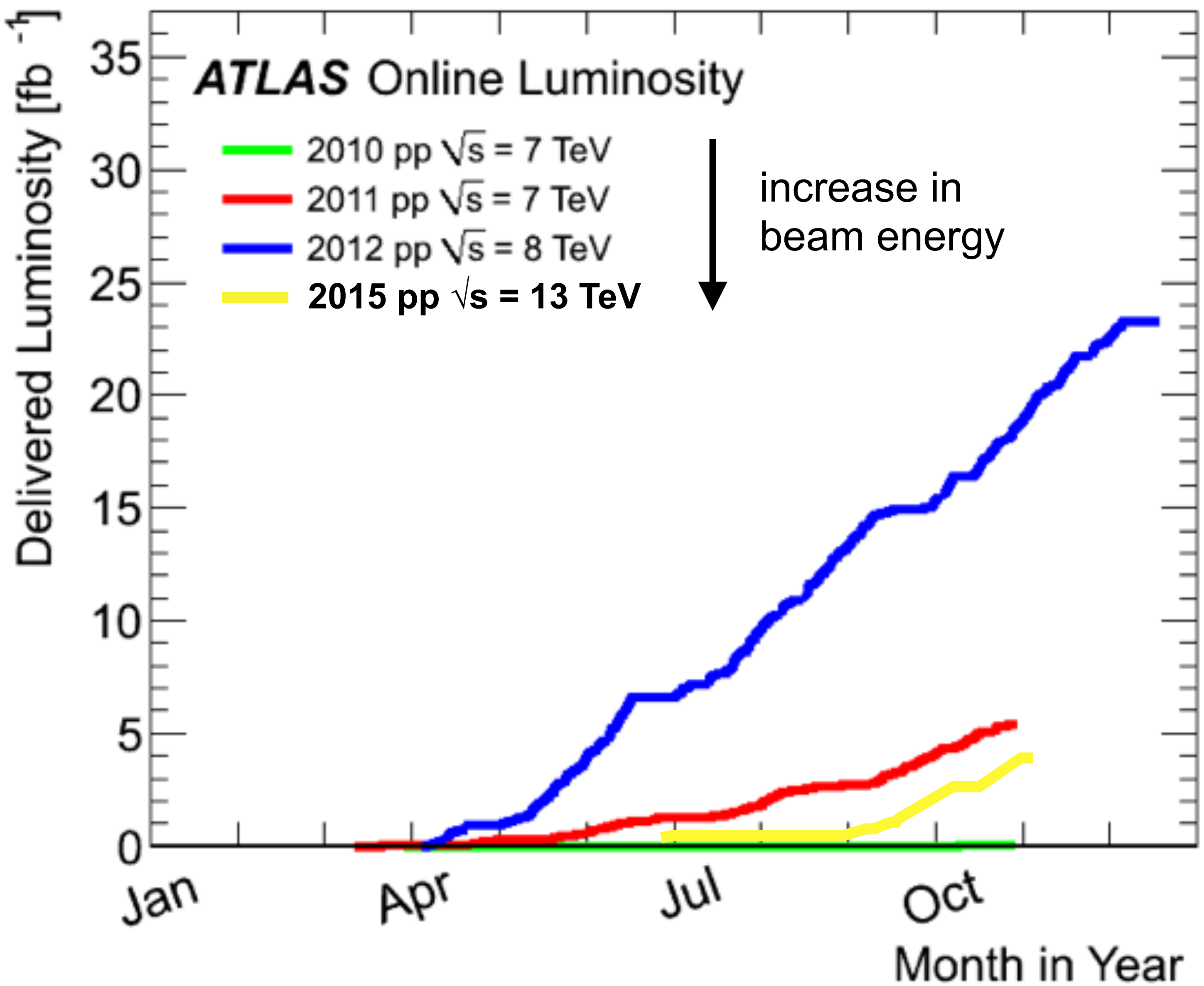
The LHC

High energy collisions equivalent to temperatures 100,000 times hotter than sun's core
High vacuum needed to avoid unwanted collisions with air molecules - less dense than solar system
1200 dipole magnets to bend the protons
Protons circulate 11,000 times per second
Generates up to 600 million collisions per second
LHC costs for material, construction, personnel (excluding experiments) = € 3, 000,000,000



The LHC Performance





Luminosity has strange units "inverse femtobarns" = Amount of data recorded

In 2015 LHC almost doubled beam energy
Luminosity was reduced compared to 2012
Carefully testing LHC machine's capability!

The LHC

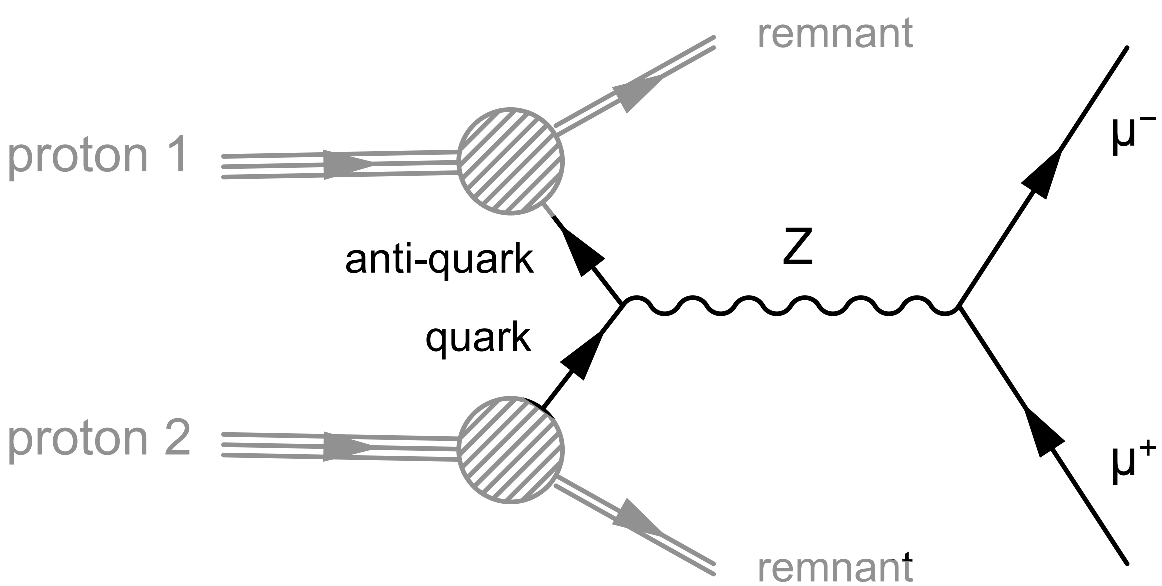
Why collide protons in LHC?
- easy to produce
- easy to accelerate (compared to electrons)
- are composite - bags of fundamental quarks and gluons

In reality the LHC is a quark / gluon collider

We measure reaction rates for different collision processes between quarks / gluons

Many different types of process occur

Compare measurement to predictions using Feynman diagrams

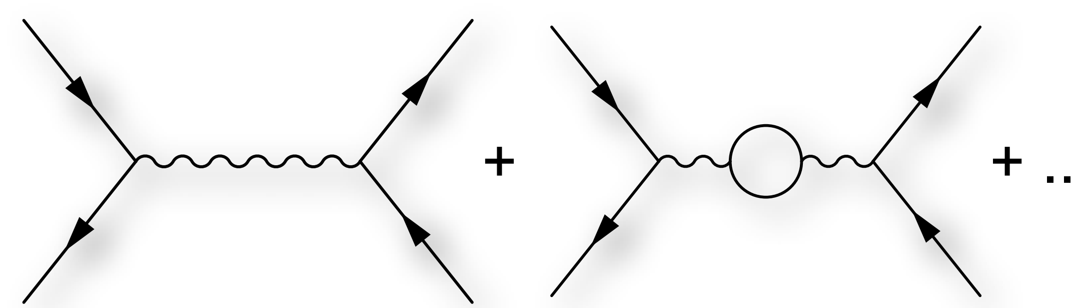


Momentum is transferred from quark pair to muon pair
$\Rightarrow$ Z has transmitted a force!

Feynman Diagram is an equation
Allows calculation of reaction rate

Feynman diagram pieces

→	fermion (quark or lepton)
wavy line	boson (W, Z, photon)
curly line	gluon
- - - - - - - - -	Higgs boson
•	vertex: coupling of boson to fermion = strength of interaction α



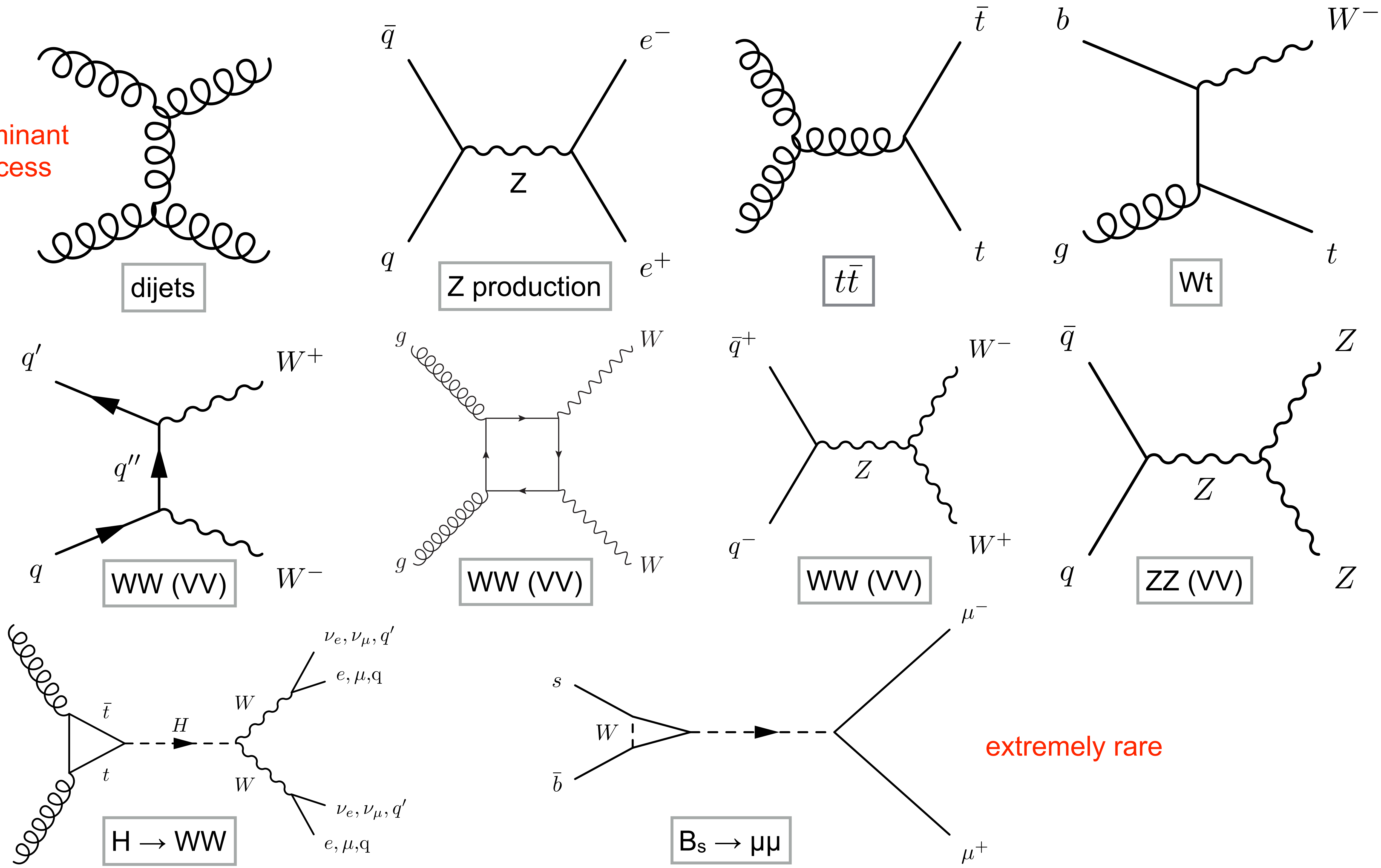
More complicated loop diagrams also contribute
→ quantum fluctuations

Complex diagrams have more vertices
→ smaller contributions

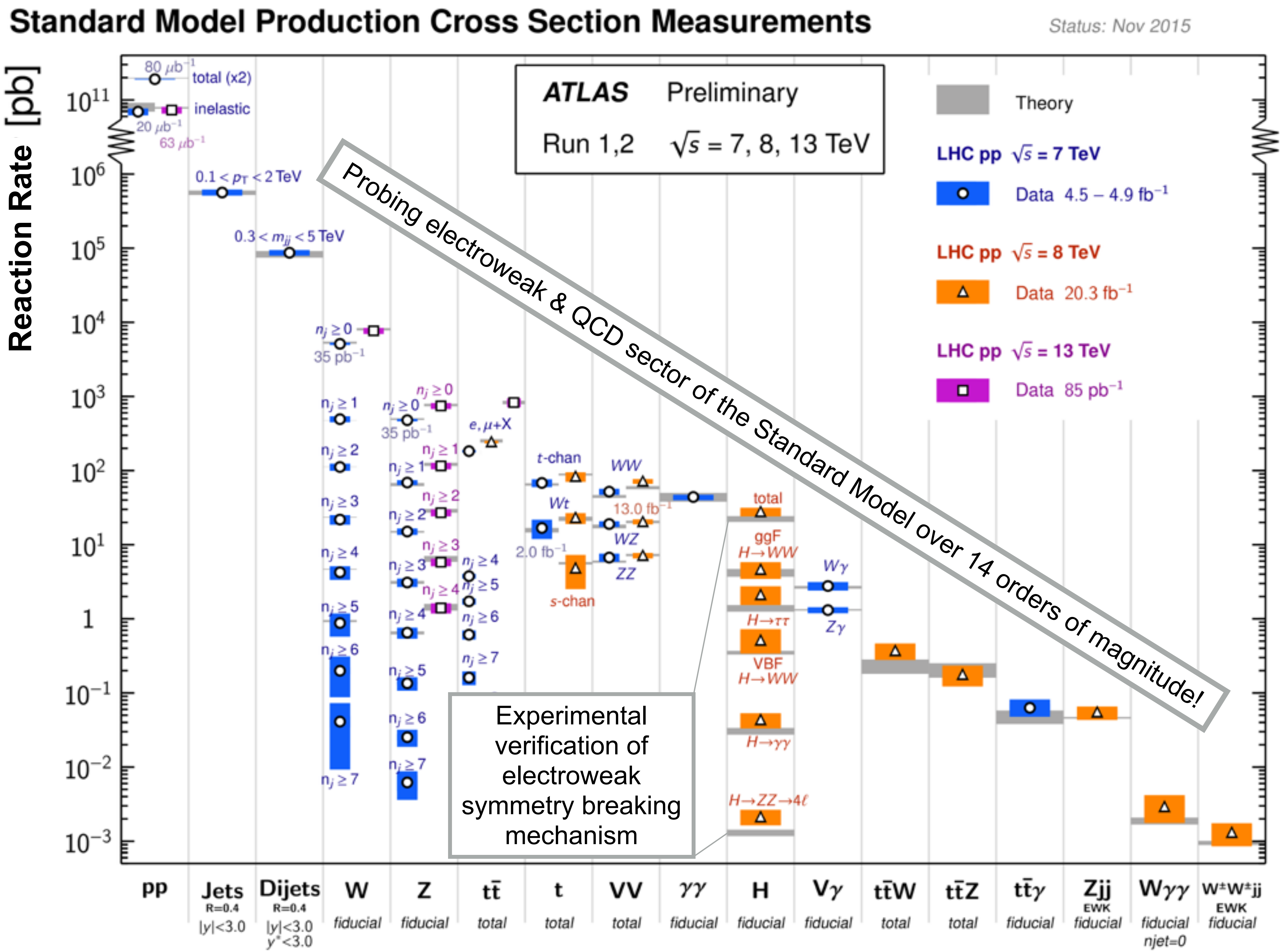
The LHC

Examples of processes / Feynman diagrams measured at the LHC and compared to theory calculations
Approximately ordered in decreasing reaction rate (see next page)

dominant process

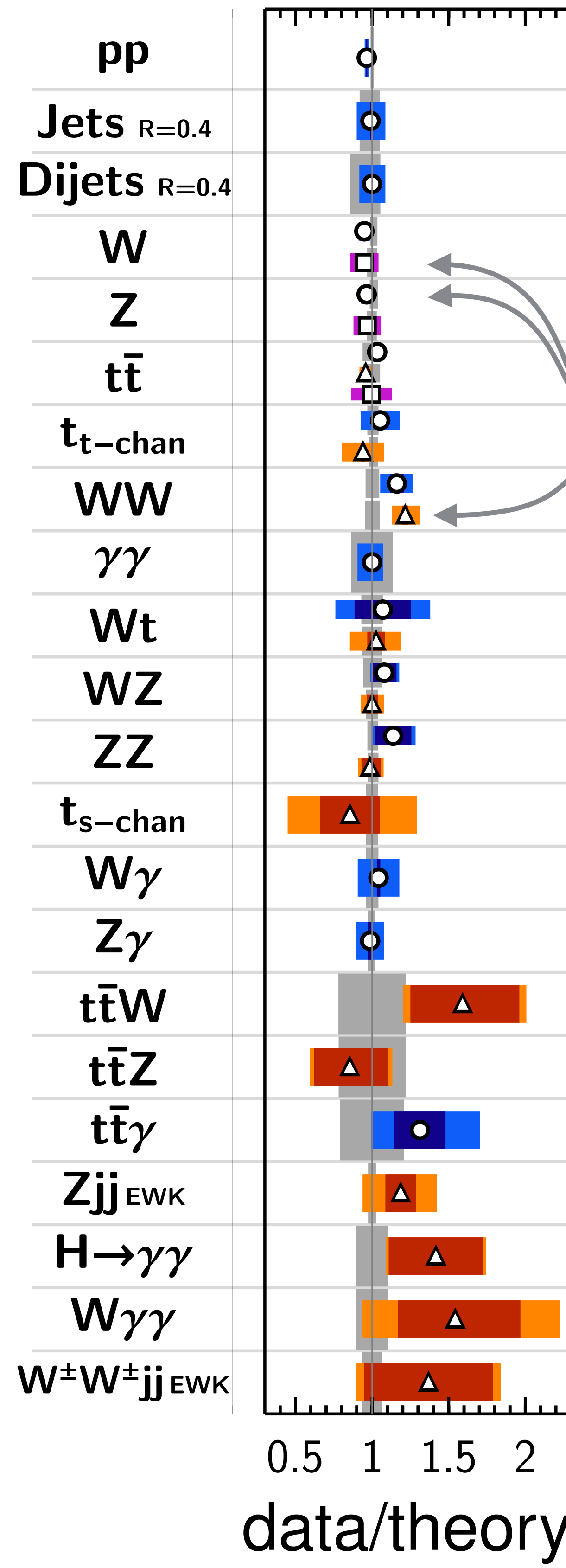


extremely rare


Standard Model Production Cross Section Measurements
Status: Nov 2015
Reaction Rate [pb]
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 85 pb⁻¹
Probing electroweak & QCD sector of the Standard Model over 14 orders of magnitude!
Experimental verification of electroweak symmetry breaking mechanism
total (x2)
inelastic
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
e, μ+X
t-chan
Wt
s-chan
WW
WZ
ZZ
total
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
pp
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ total
t total
VV total
γγ fiducial
H fiducial
Vγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial

Ratio of measurement to prediction
Everything is consistent with unity

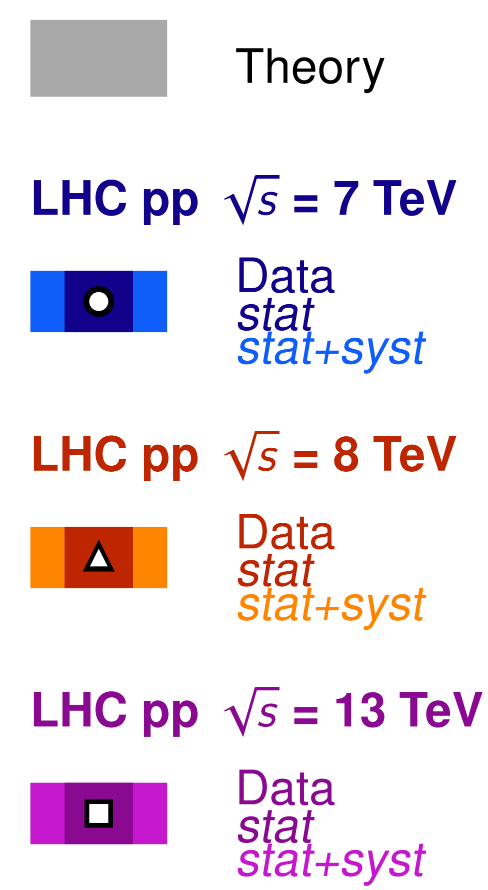
→ Data and theory agree!
(within their uncertainties)



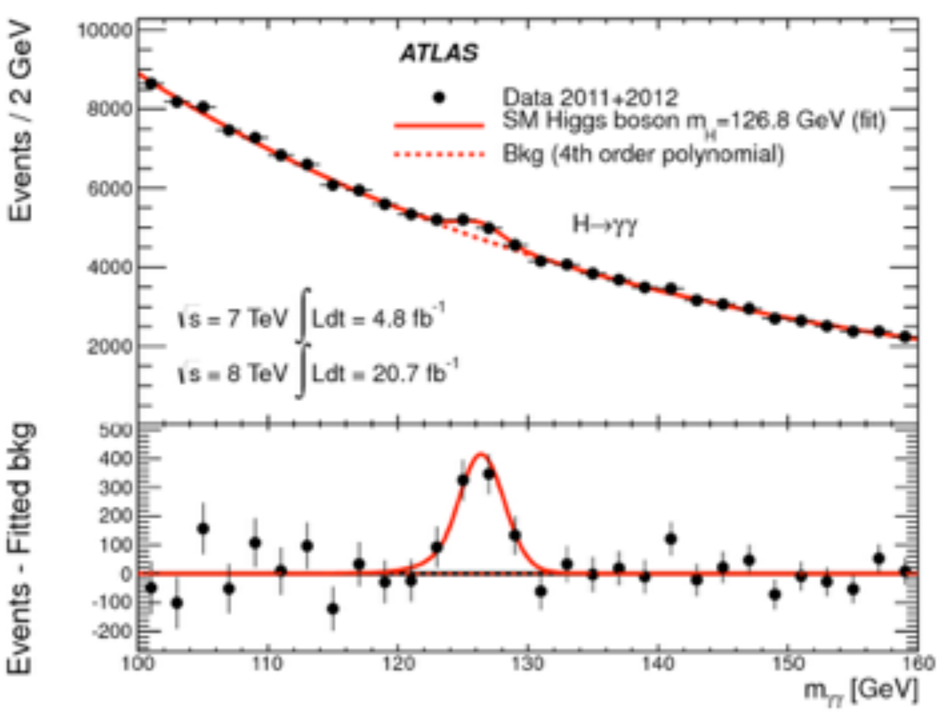
ATLAS Preliminary

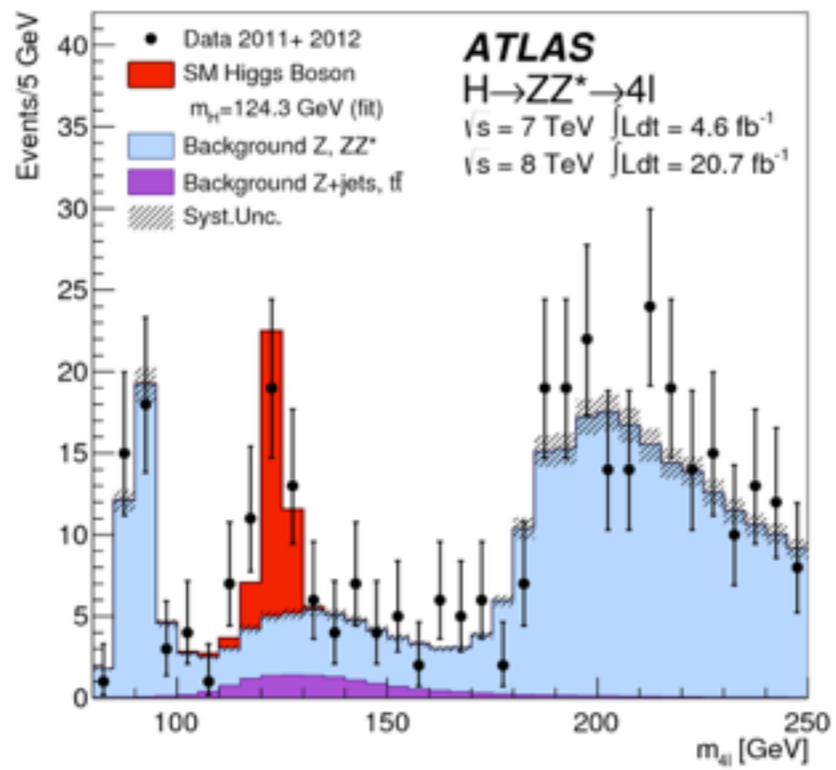
Run 1,2 $\sqrt{s}$ = 7, 8, 13 TeV

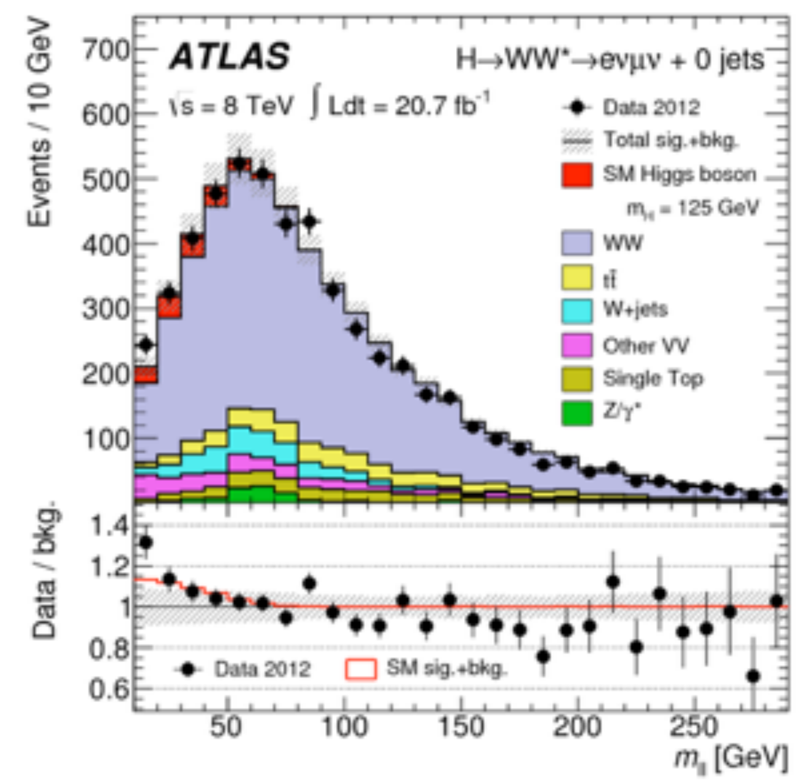
I personally was involved in some of these measurements with my PhD students



Higgs Hunting



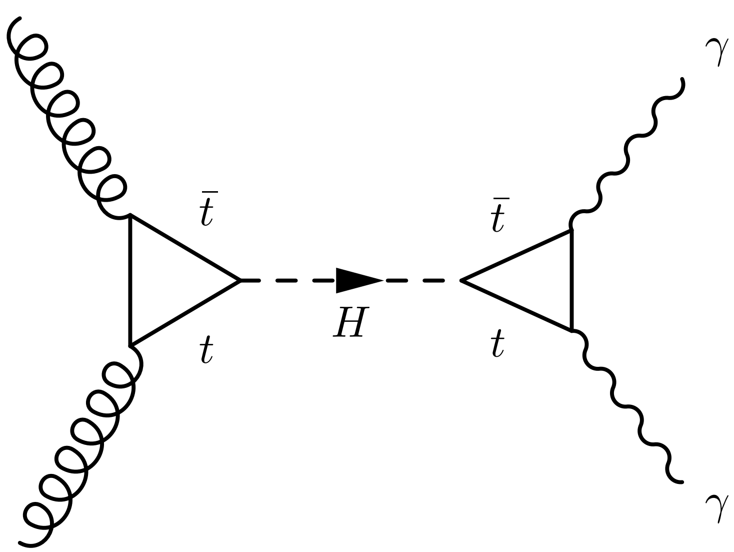


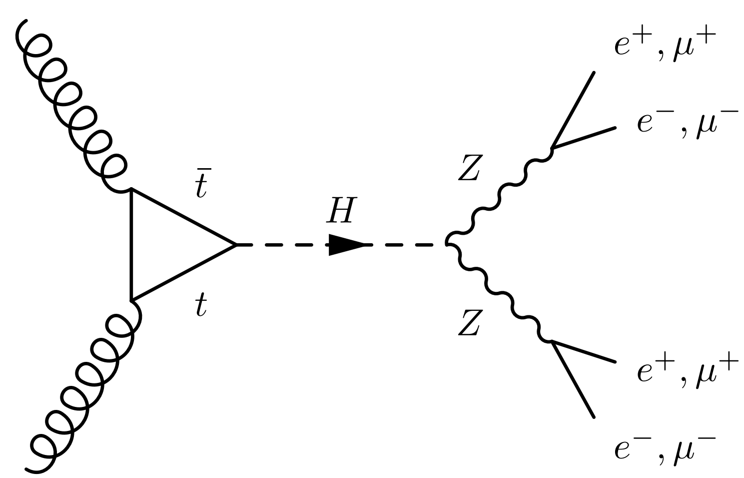


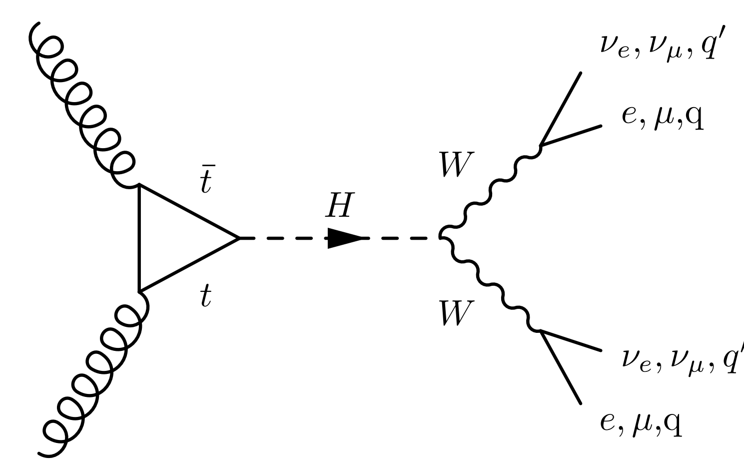
clear peak, low background, but low rate too

subtle 'bump' on top of large background

small excess, large background, high rate

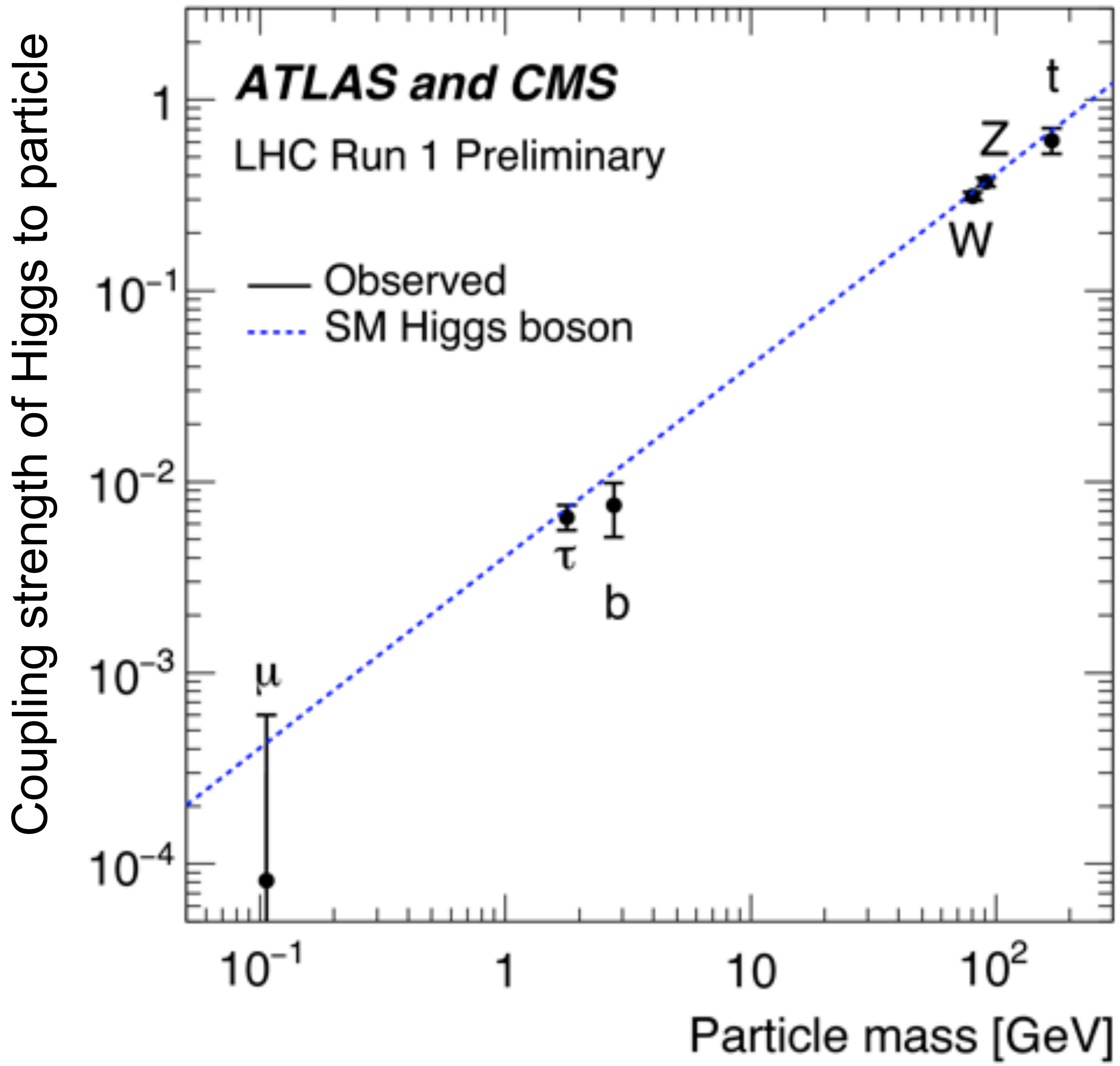


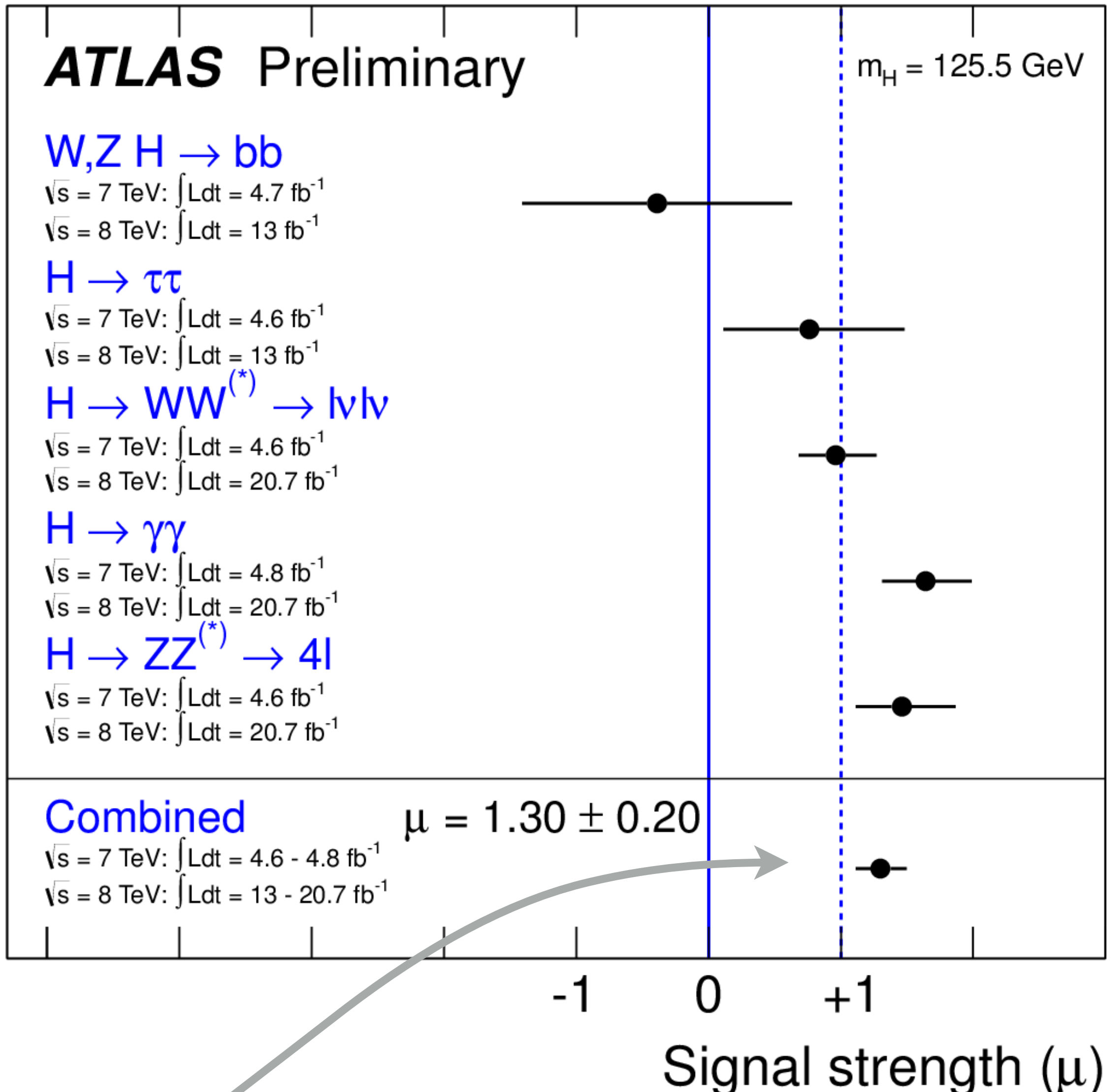




Is the Higgs coupling to particles ∝ mass?

Is the Higgs being produced at the expected rate?

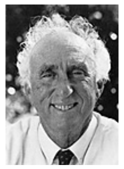


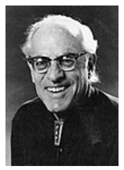


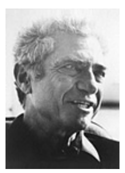
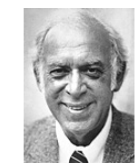
The Higgs particle is being produced
at about the predicted Standard Model rate

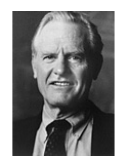
Have we found it ? yes!
We still need to measure all of it's properties
Are there more Higgs-like particles ? Any signs of new physics??

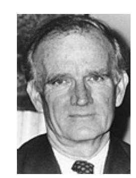
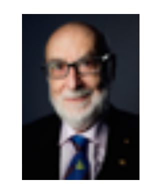
The Standard Model

 Perl
 Gross
 Rubbia
 van der Meer

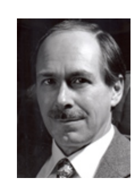
 Reines
 Lederman
 Gell-man
 Cronin

 Steinberger
 Feynman
 Glashow
 Taylor
 Friedman

 Hofstadter
 Schwinger
 Kendall
 Veltman
 Higgs

 Politzer
 Ting
 Alvarez
 Fitch
 Englert

 Schwarz
 Richter
 Weinberg
 Yang

 Wilczek
 Salam
 Lee
 t'Hooft

2013 Nobel prize for
Peter Higgs
François Englert

31 Nobel prizes awarded for the Standard Model !

The Problematic Standard Model

$$
\begin{gathered}
-\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(\bar q_i^\sigma \gamma^\mu q_j^\sigma)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac12 \partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - \frac12\partial_\mu H\partial_\mu H - \\
\frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac12\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 + \frac12(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)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_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^-] - \\
\frac18 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)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 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)] + \frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac12 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_wMA_\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_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac14 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^-] - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar d_j^\lambda(\gamma\partial + \\
m_d^\lambda)d_j^\lambda + igs_wA_\mu[-(\bar e^\lambda\gamma e^\lambda) + \frac23(\bar u_j^\lambda\gamma u_j^\lambda) - \frac13(\bar d_j^\lambda\gamma d_j^\lambda)] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+ \\
\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar u_j^\lambda\gamma^\mu(\frac43 s_w^2 - 1 - \gamma^5)u_j^\lambda) + \\
(\bar d_j^\lambda\gamma^\mu(1 - \frac83 s_w^2 - \gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u_j^\lambda\gamma^\mu(1+ \\
\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u_j^\lambda)] + \\
\frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + \\
i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + m_u^\lambda(\bar u_j^\lambda C_{\lambda\kappa}(1+ \\
\gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa] - \\
\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda) - \frac g2\frac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d_j^\lambda\gamma^5 d_j^\lambda) + \\
\bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + \\
igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) + \\
igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + \\
igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) - \\
\frac12 gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \\
\bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \\
\bar X^0X^+\phi^-] + \frac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]
\end{gathered}
$$

The Standard Model works beautifully!
Describes all experimental data!

But it's incomplete
Many things have to be inserted by hand
Leaves many questions unanswered

The Problematic Standard Model

A good theory has few parameters
to explain many phenomena
e.g. Newtonian gravity has 1 parameter G
to describe all planetary motions!

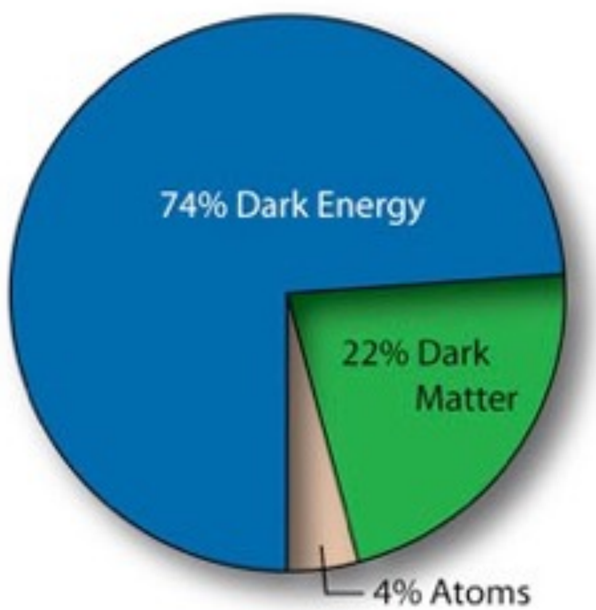
$$F = G\frac{m_1 m_2}{r^2}$$

The Standard Model has 22 parameters to be measured:
- 6 quark masses
- 3 charged leptons masses
- 3 couplings α_1 , α_2 , α_3 for 3 forces
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (1 predicted from other EW params)
- 1 Higgs mass

We feel this is too much for a fundamental theory
(but better than 105 params of supersymmetry)

We have no idea what 96% of the universe is!
unknown form of dark energy (74% of universe's mass!)
unknown form of dark matter (22% of universe's mass!)

Two gas clouds collide
Clouds slow down
Dark matter passes through



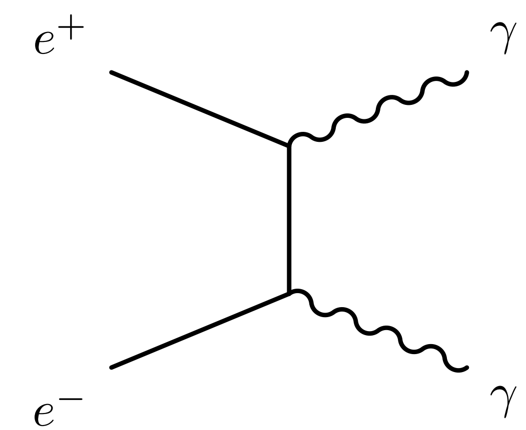
No treatment of gravity in the Standard Model...
In a symmetric theory gauge bosons are massless
Higgs mechanism explains EW symmetry breaking
→ EW bosons acquire mass

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

We know quantum gravity effects must play a role at
the Planck scale i.e. energy ~ 10^{19} GeV

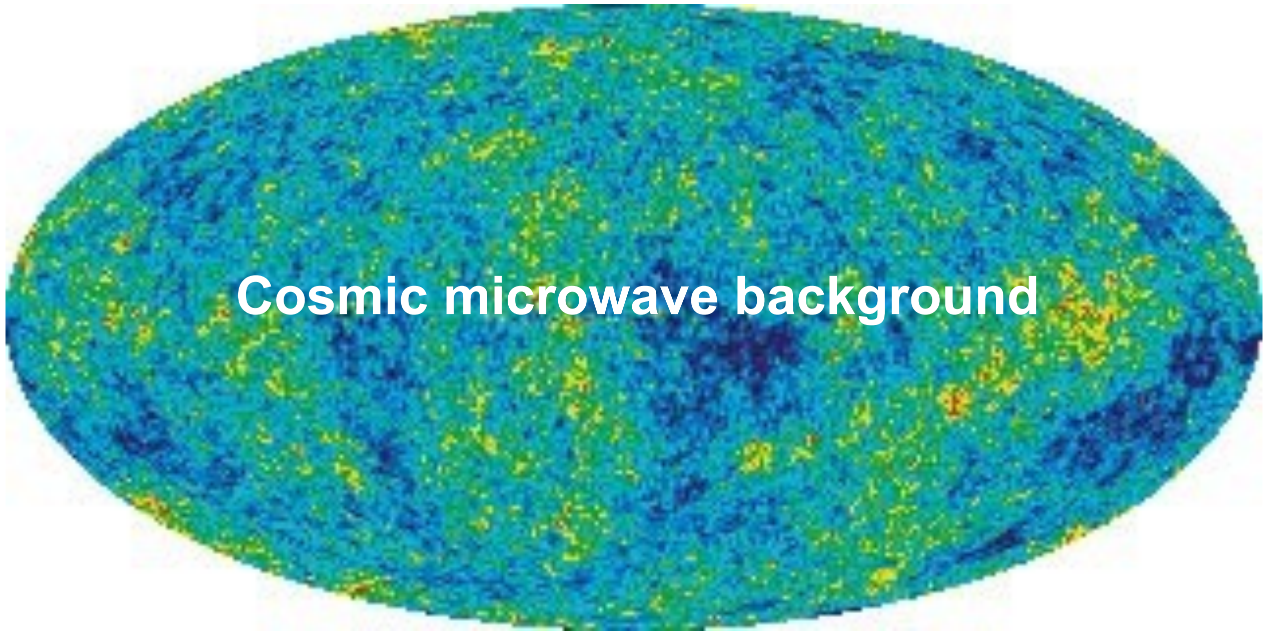
Standard Model is lacking:
- why 3 generations of particles?
- why do particles have the masses they do?
- no consideration of gravity on quantum level...

$e^+ e^-$ annihilation



In the Standard Model matter and anti-matter produced in equal quantities
- In the Big Bang: for every quark, one anti-quark is also produced
- As universe cools expect all particles and anti-particles to annihilate
- ⇒ soon after big bang all matter will have annihilated to photons

We should not exist!
For every proton/neutron/electron in universe there are 10^9 photons (CMB - cosmic microwave background)
Thus matter/anti-matter asymmetry must be $1:10^9$
We cannot see where this asymmetry lies...



(Actually SM can account for only 1000th of this asymmetry)

The Hierarchy Problem

Planck mass = regime of quantum gravity (see later)

- Why is gravity ~10^{33} weaker than EW interactions?
- Why is m_H Higgs mass (125 GeV) so much smaller than Λ Planck mass (10^{19} GeV)?

Leads to fine tuning problem:
Corrections to Higgs mass rapidly diverge up to 10^{19} GeV

contribution to the mass from quantum loop fluctuations

physical Higgs mass = bare mass + "loops" $m_H^2 = m_0^2 + \Delta m_H^2$

For Higgs field we get:

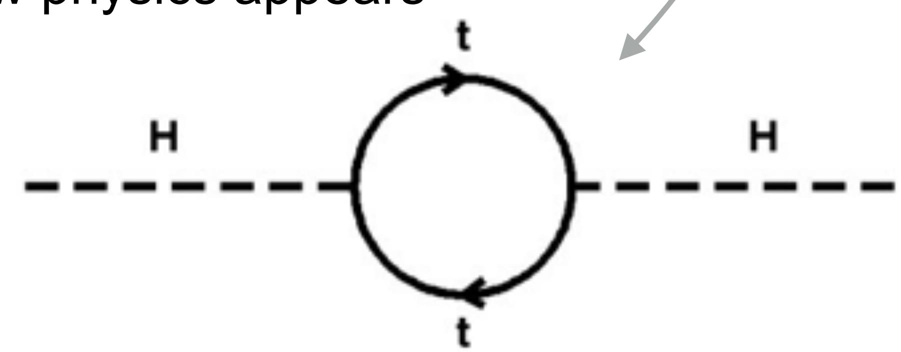
Λ is the energy up to which the SM is valid
... or the energy at which new physics appears

top quark loop: $\Delta m_H^2 = -a\Lambda^2$

W/Z boson loop: $\Delta m_H^2 = +b\Lambda^2$

Higgs loop: $\Delta m_H^2 = +c\Lambda^2$

a,b,c are couplings of particles to Higgs



top quark loop contributing to Higgs mass

If Λ^2 ~ $(10^{19}$ GeV$)^2$ and m_H^2 ~ (100 GeV$)^2$

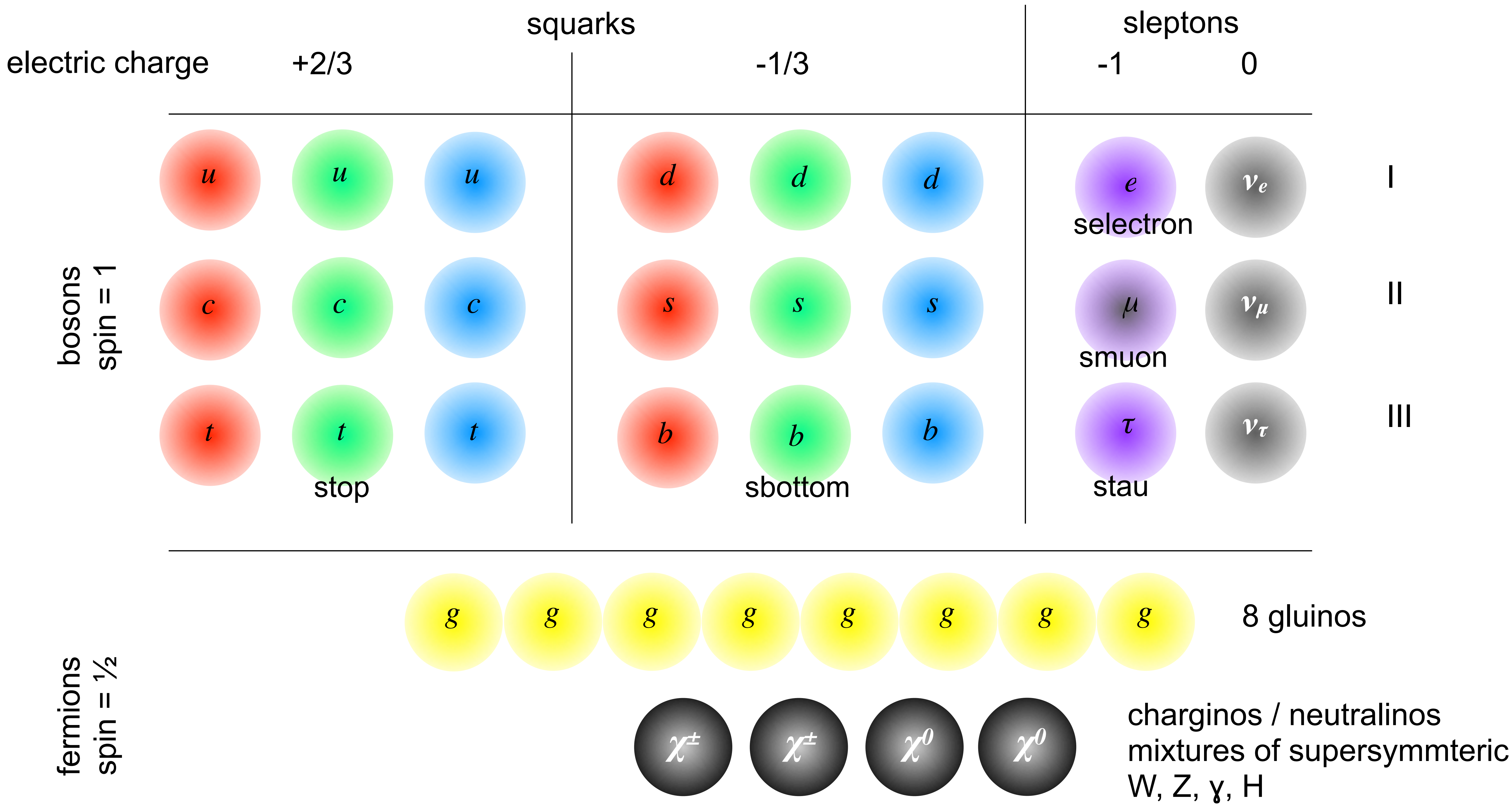
$$m_H^2 = m_0^2 + (-a + b + c)\Lambda^2$$

$$m_H^2 = m_0^2 + (-a + b + c) \cdot 10^{38} \approx 100^2$$

If SM is valid to energy scale Λ (i.e. no new physics from 10^3 GeV − 10^{19} GeV)
incredible fine tuning required between bare mass and the corrections
to maintain ~ 100 GeV Higgs mass

Supersymmetry

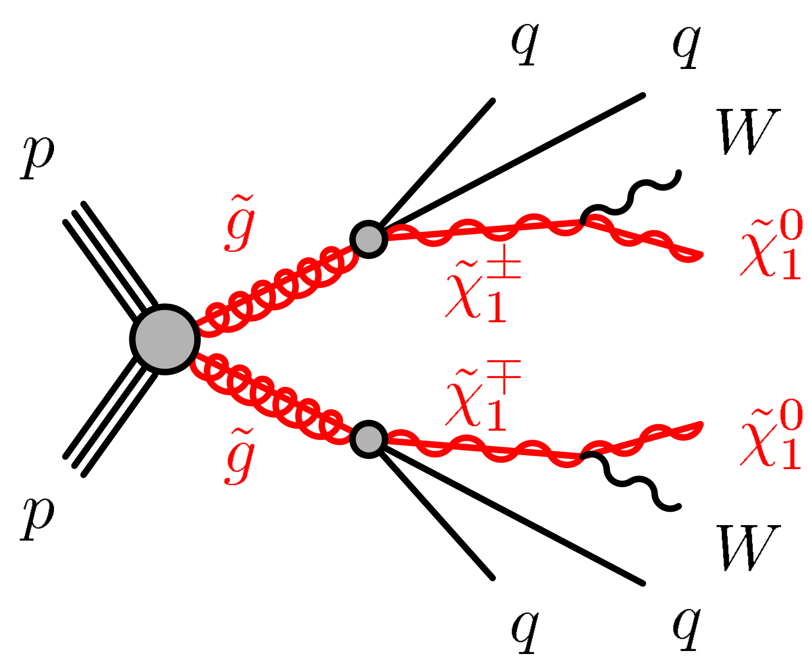
Every Standard Model particle gets a supersymmetric partner sparticle with opposite spin



None of these has been observed

105 new parameters required by theory - So why bother??

Astronomers observations show Dark Matter is:
- probably a particle
- electrically neutral (does not interact with photons)
- cold (non-relativistic)
- stable (does not decay to anything else)
- weakly interacting (else galaxies won't form)
- cannot be neutrons (they're unstable)
- cannot be neutrinos (mass too small)



In LHC pp collision SUSY sparticles could be produced

In some models only sparticle & anti-sparticle pairs can be formed

This means the lightest neutralino cannot decay into ordinary SM particle

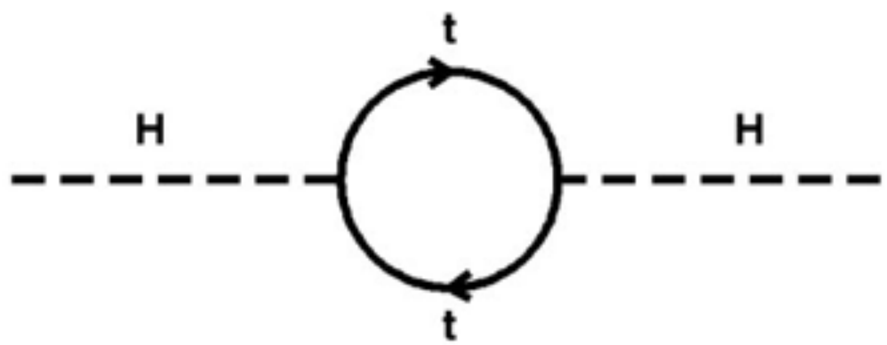
It is stable!

This Lightest Supersymmetric Particle (LSP) could be Dark Matter!

In this case gluino pair is created
Each decays to two quarks, W and a stable neutralino
Search for this experimental signature in ATLAS

Hierarchy Problem

Why is Higgs mass (~1 TeV) so much smaller than the Planck scale (10^{19} GeV)?
Such calculations need to take account virtual fluctuations



Higgs interacts with all spin ½ particle-antiparticle pairs in the vacuum

Higgs mass quantum corrections diverge up to 10^{19} GeV
If SM valid up to Planck scale then incredible fine-tuning of cancellations is needed to ensure ~1 TeV Higgs mass
Seems unnatural
Only a problem for the Higgs (only SM particle with spin 0)

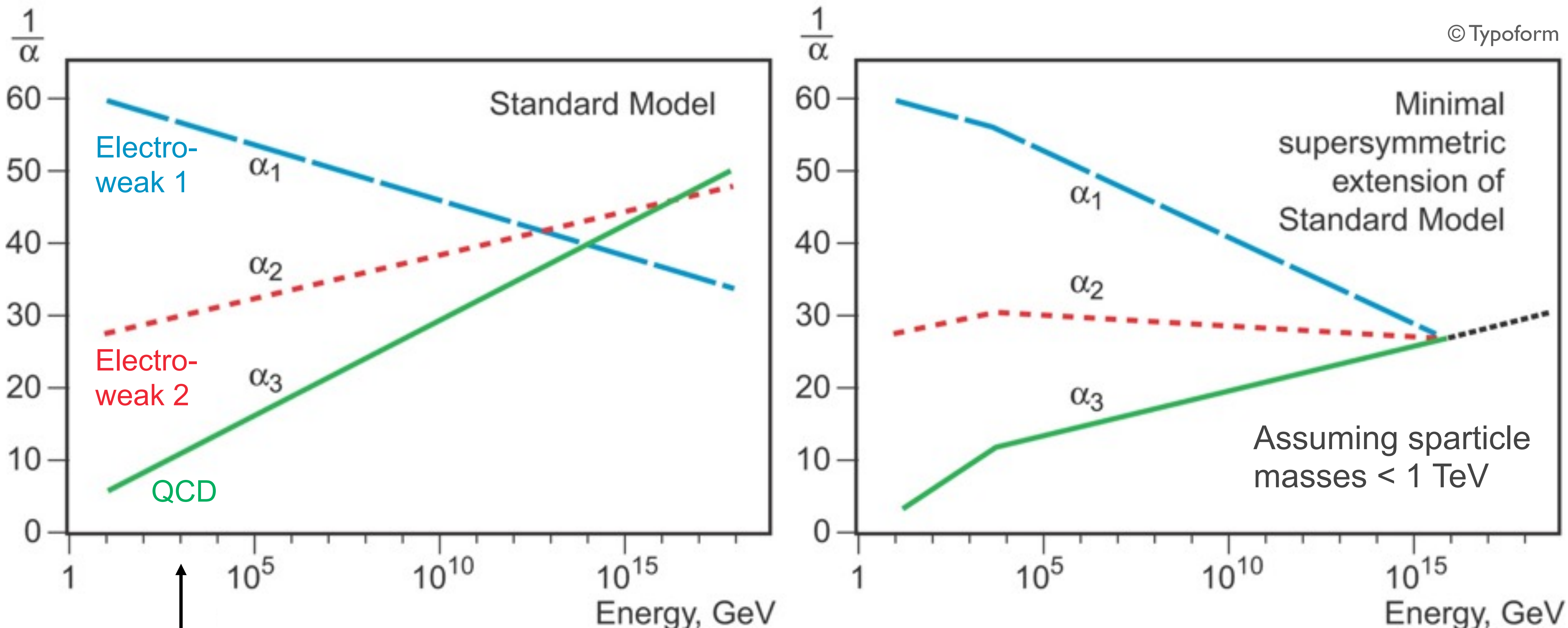
New SUSY sparticles (e.g. stop squark) contribute and cancel identically

Higgs interaction with spin 0 sparticle cancels SM quantum corrections above

GUT Unification

Another of SUSY's charms:

Three force couplings extrapolated to Planck scale do not intersect

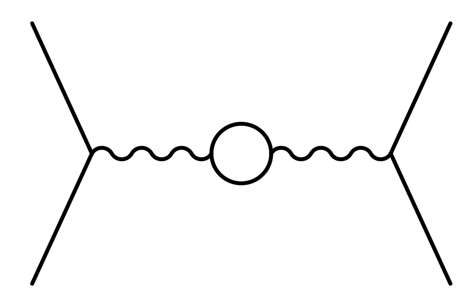


Current measurements
at 1000 GeV

16 orders of magnitude extrapolation!
Involves including all particle loops

New SUSY particles = different loops
= different extrapolation

Incorporating SUSY into extrapolation causes
couplings to coincide below Planck scale!
Forces are unified ?!



Supersymmetry & Quantum Gravity

- Naturally extends to quantum gravity
- Provides a candidate for dark matter
- SUSY solves hierarchy problem
- Brings about GUT unification of couplings
- Some general assumptions can reduce 105 parameters to 5

What are GUTs?
Grand unified theories: electroweak + QCD
TOE = Theory of everything = GUT + quantum gravity

Occurs at energy scales when couplings reach strength of gravity

Construct a quantity with dimensions of energy or length
from constants of relativity, quantum mechanics & gravity: $c, \hbar, G$

Quantity	Symbol	unit
speed of light	c	m s^{-1}
Gravitational constant	G	m^3 Kg^{-1} s^{-2}
Planck constant	$\hbar$	Kg m^{-2} s^{-1}

$$E_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} = 10^{19}\ \text{GeV}$$

Planck energy

$$L_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}} = 10^{-35}\ \text{m}$$

Planck length

$$T_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^5}} = 10^{-44}\ \text{s}$$

Planck time

This exercise <u>very roughly</u> tells us what energy or length scale we need to see effects of quantum gravity

These are all equivalent: experiments probing the Planck energy, also probe distances of Planck length

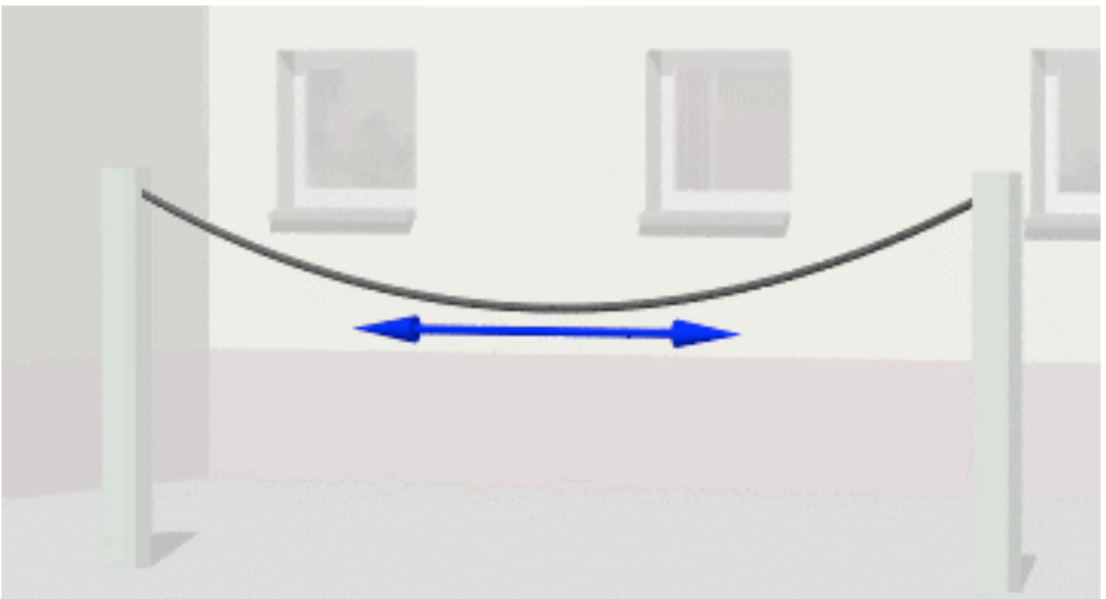
10^{19} GeV = 10,000,000,000,000,000,000 GeV   No chance to build a collider at this energy!

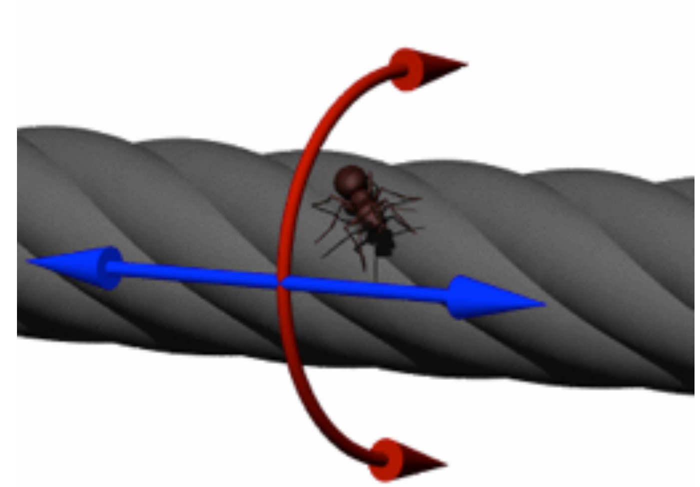
10^{-35} m = 0.000 000 000 000 000 000 000 000 000 000 000 001 m

Large Extra Dimensions

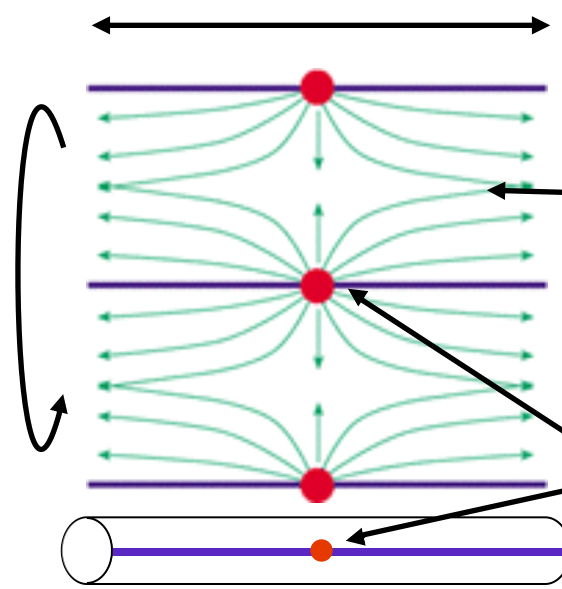
Extra spatial dimensions of size < 1 mm could exist
gravity has only been tested down to this scale!

Where are the extra dimensions?
curled up (compactified) and finite
only visible at small scales / high energies





Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space



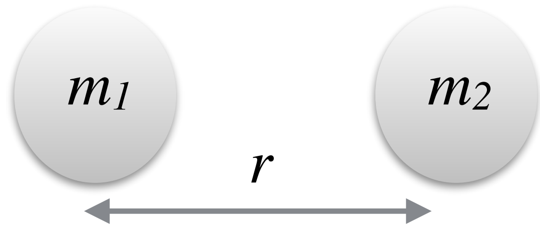
This is the ADD model of extra dimensions
Proposed in 1998 by Arkani-Hamed, Dimopoulos and Dvali

Large Extra Dimensions

With extra dimensions gravity becomes modified

Newton's law: $F = G\frac{m_1 m_2}{r^2}$

Force F between two masses m_1 and m_2 distance r apart
G is Gravitational constant



With n extra spatial dimensions each of size R then $F = G_D \frac{m_1 m_2}{r^{2+n}}$

G_D is higher dimensional Gravitational constant

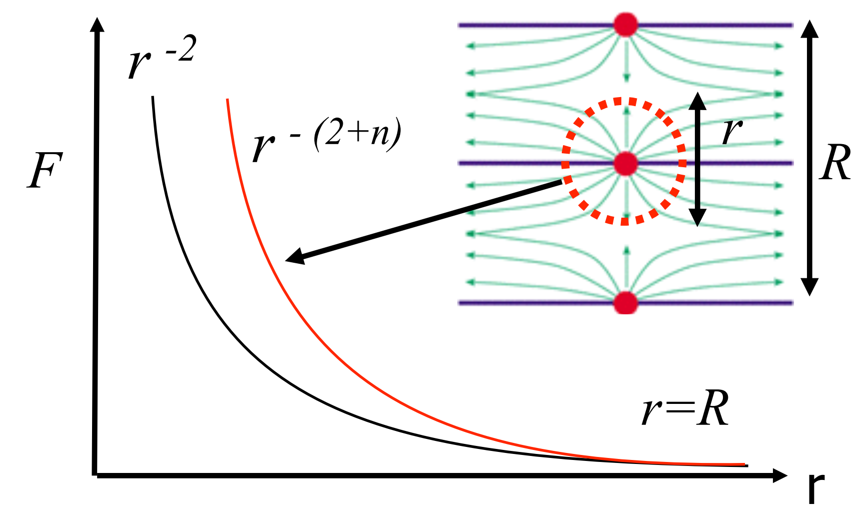
$$F = \left(\frac{G_D}{R^n}\right)\frac{m_1 m_2}{r^2}$$

i.e $G = \frac{G_D}{R^n}$

For r much larger than R we recover Newtonian gravity

dilution due to volume of extra dimensions

Planck scale: $M_P^2 = \frac{\hbar c}{G}$



In extra dimensions full scale of gravity M_D is given by $M_D^2 = \frac{\hbar c}{G_D} = \frac{M_P^2}{R^n}$

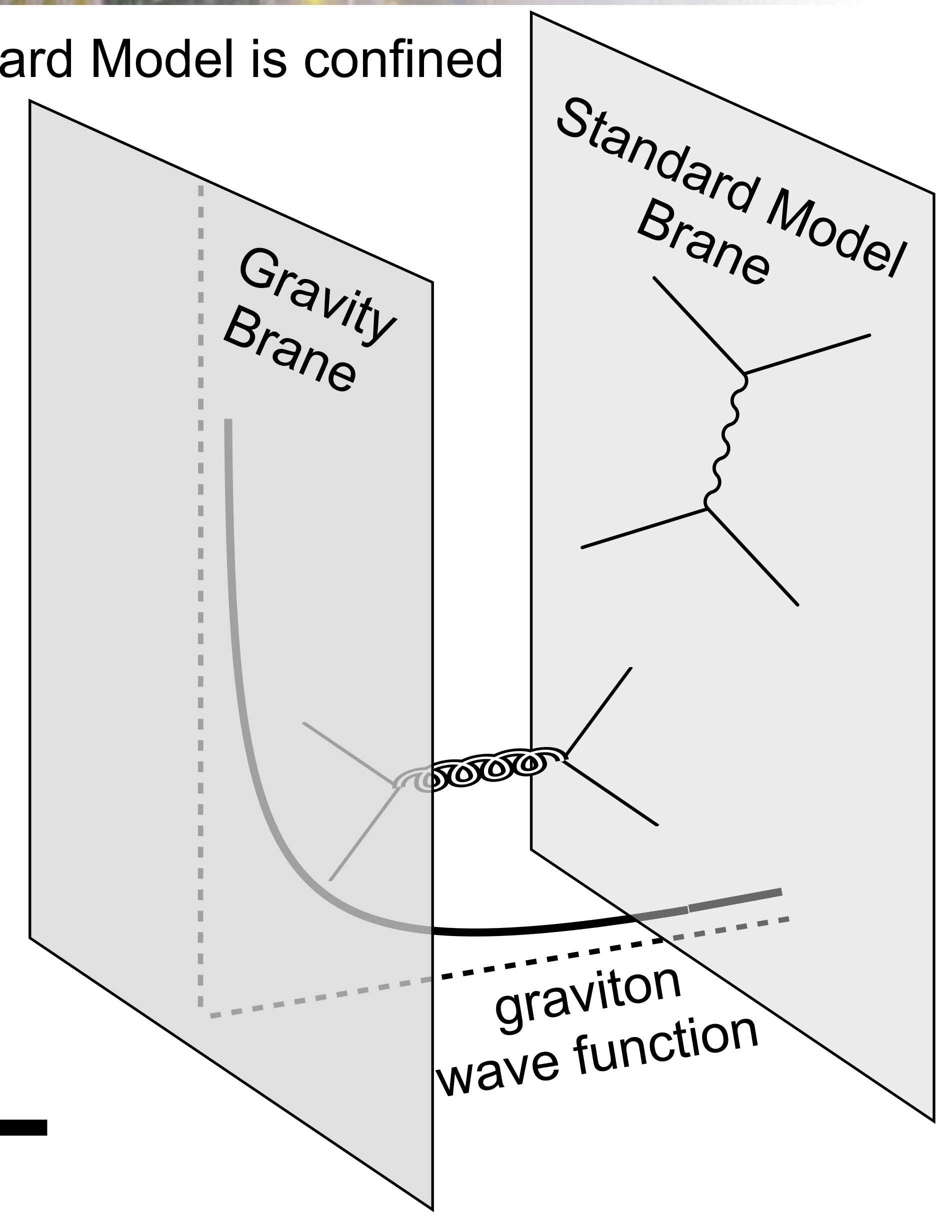
Thus M_D can be ~ 1 TeV when R^n is large

LHC could open the possibility of creating mini-black holes & gravitons
laboratory for testing quantum gravity!!!

Large Extra Dimensions

In the Randall-Sundrum model the Standard Model is confined to a “low energy” brane

Gravity propagates in 1 higher dimension linked to a “high energy” brane
Gravity is weakly interacting at low energy
... and interacts strongly on the high energy brane

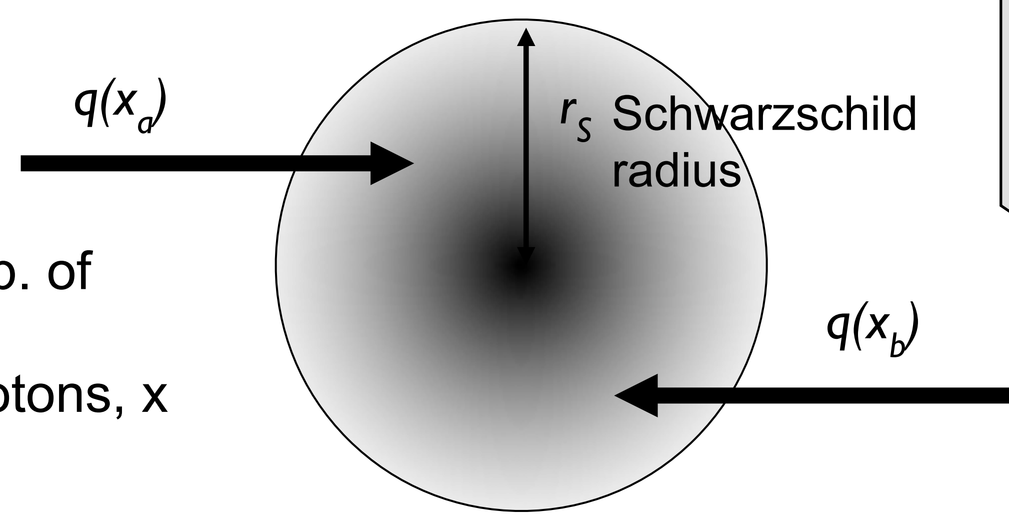


At high enough energy ADD models predict micro-blackhole production

Black hole forms when quarks collide with separation < $2r_S$

Black hole mass:

$$M_{BH} = E_{\text{LHC}}\sqrt{x_a} \cdot \sqrt{x_b}$$



Depends on LHC energy & prob. of finding quarks carrying high momentum fractions of both protons, x

For “normal” objects $r_s = \dfrac{2GM}{c^2}$

With extra dimensions:

$$r_s = \frac{2GR^n M_{BH}}{c^2}$$

r_S increased by factor R^n

r_S = 1 cm for Earth

Should observe continuous mass spectrum of BHs
$M > M_D$

Exotic Physics Searches

√s=7 TeV

√s=8 TeV

Black Holes
Gravitons
Quantum Gravity

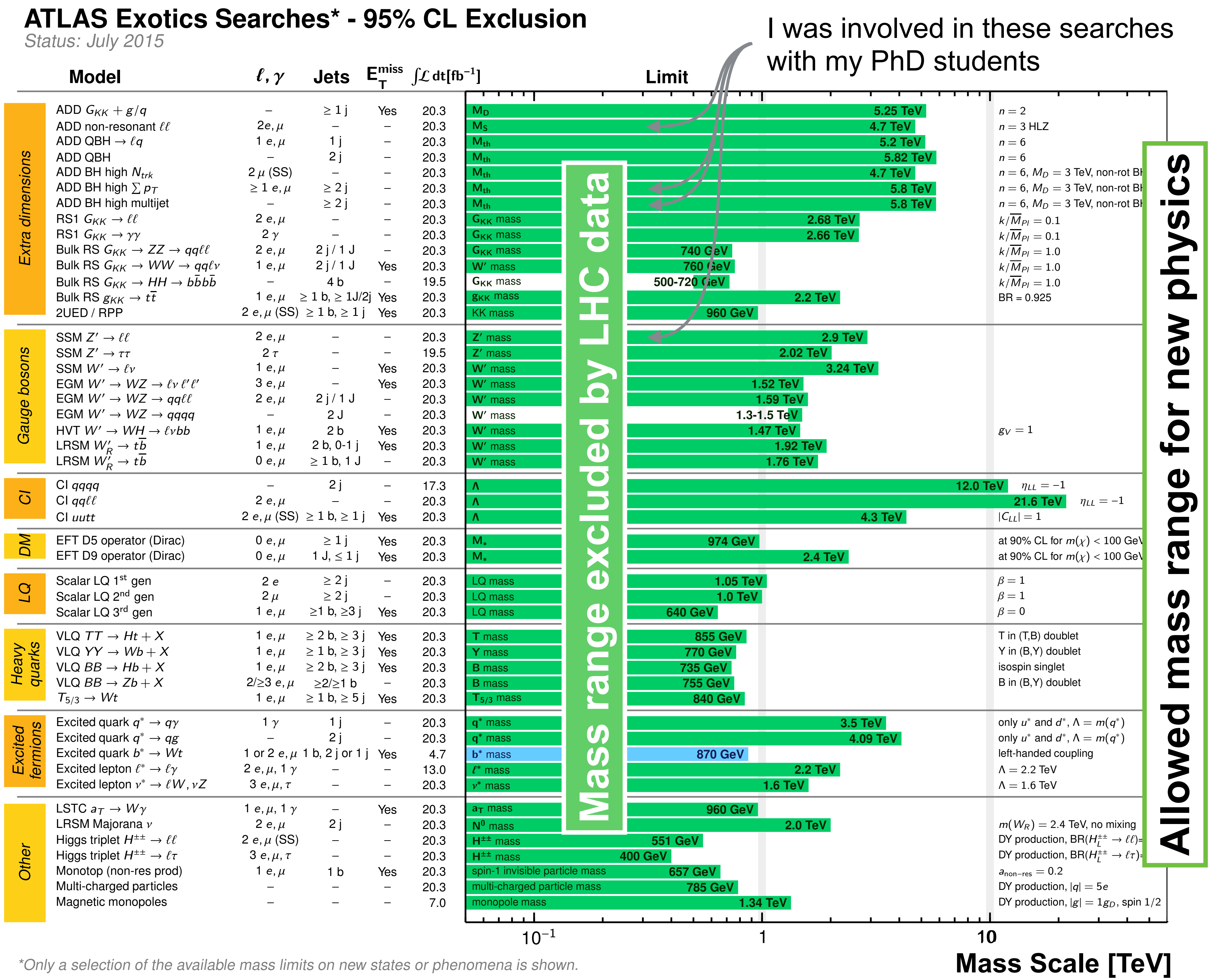
New heavier
W and Z bosons

Dark Matter

4th Generation
Quarks

Composite Leptons
and Quarks

Anything Else!



Supersymmetry Searches

√s=7 TeV

√s=8 TeV

General searches

stop / sbottom indirect production

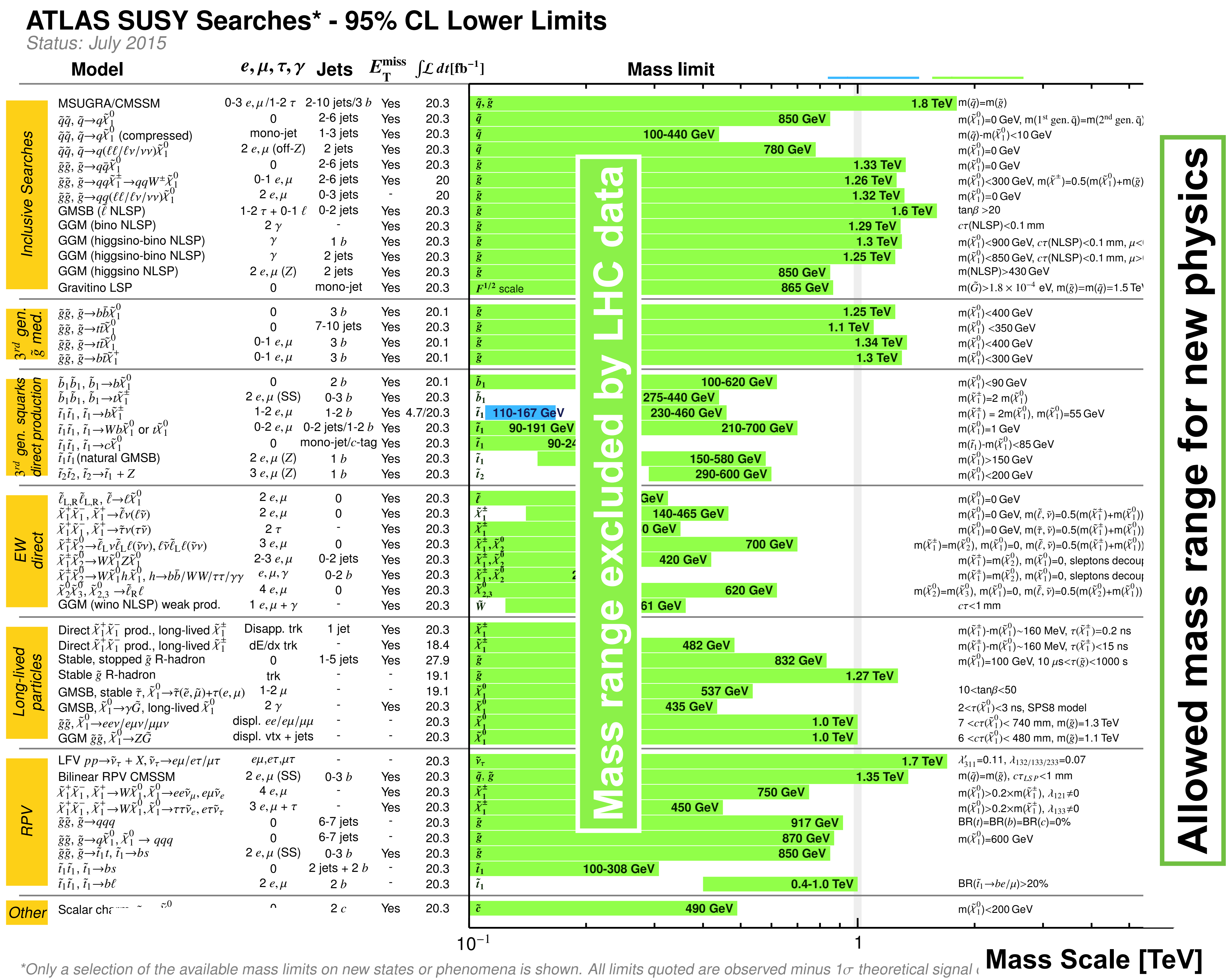
stop / sbottom direct production

slepton / chargino

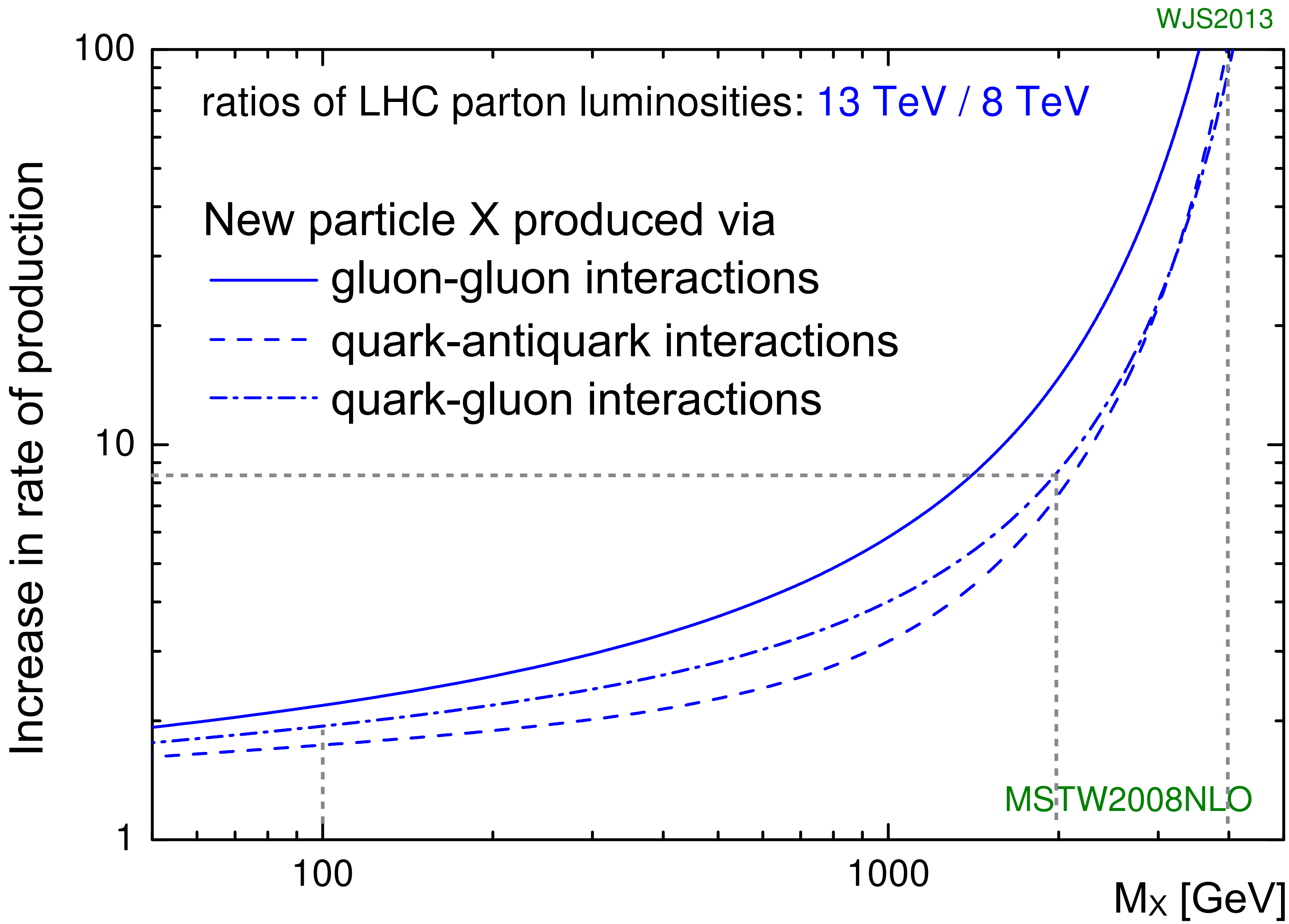
Long lived / stable sparticles

Composite Leptons and Quarks

Anything Else!



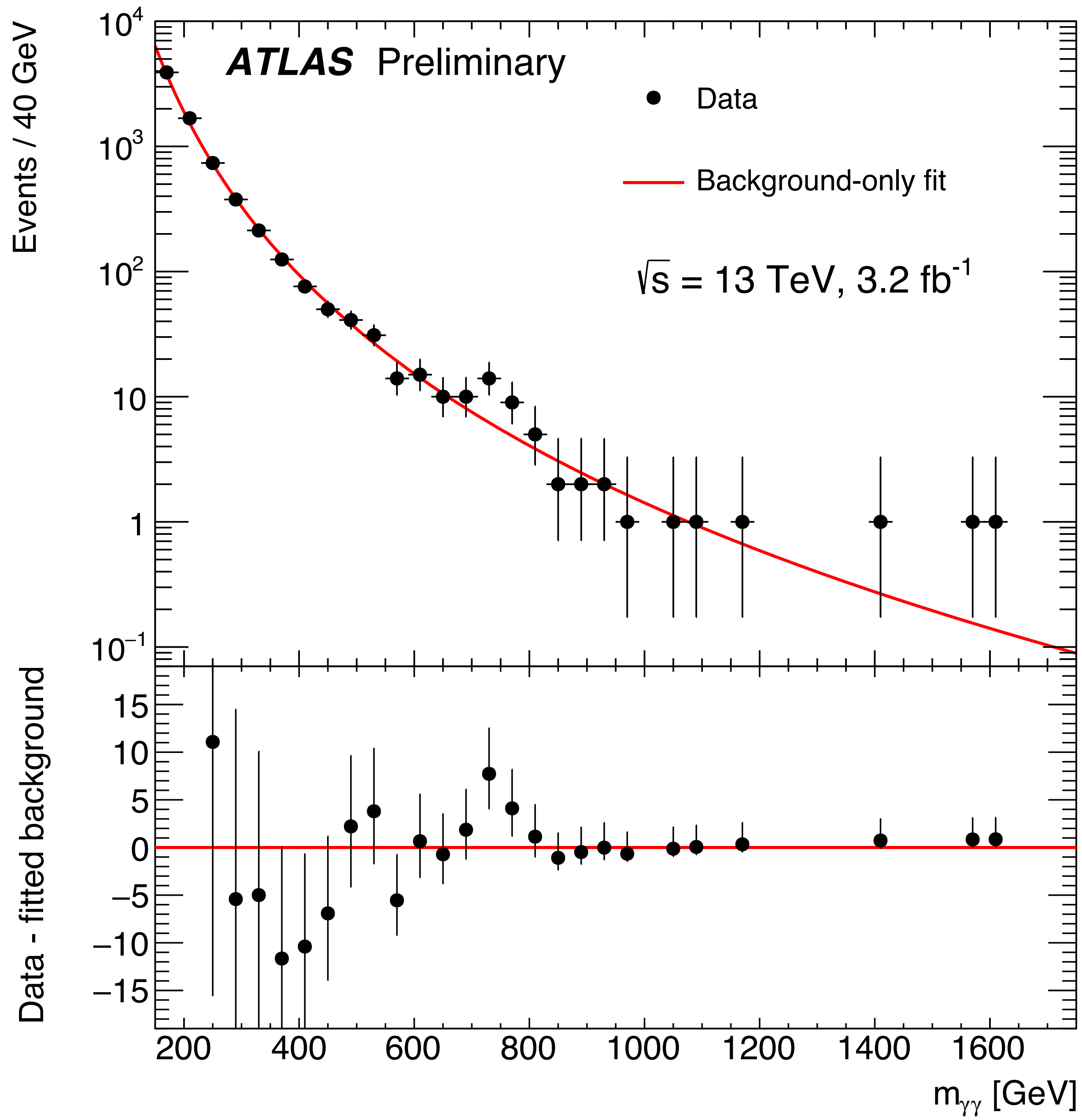
Effect of increasing the collision energy from 8 TeV to 13 TeV



factor 2 increase in production rate for new particle with mass M_X = 0.1 TeV
factor 10 increase in production rate for new particle with mass M_X = 2 TeV
factor 100 increase in production rate for new particle with mass M_X = 4 TeV

A Hint of Something New?

15th December 2015 ATLAS released first tranche of new results using run 2 data

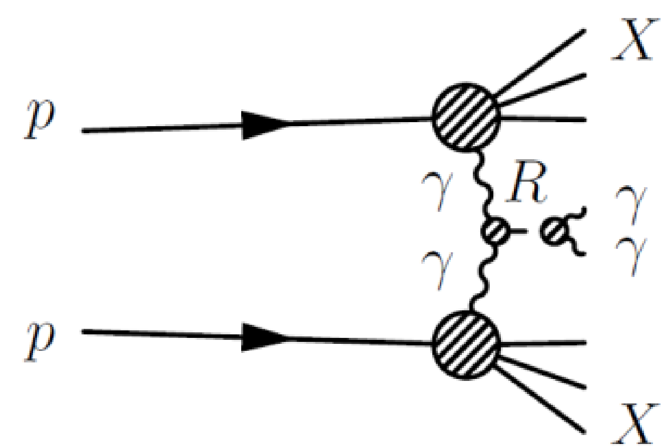


Using 2015 data only

Analysis searching for new particle decaying to 2 photons

Small deviation at mass of ~ 750 GeV

Significance ~ 2 standard deviations probability of fluctuation ~ 5%



Same odds as throwing 4 heads in a row

Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS collaboration. Dec 15, 2015.

ATLAS-CONF-2015-081

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

CERN Document Server ; Link to Fulltext

Detailed record - Cited by 221 records 100+

!!!

What are we looking for ?

e+e
e+μ
e+μ+2b+2ν
e+2μ+ν
μ+j+ν
μ+μ
e+j
e+μ+j
e+2τ+2b+3ν
2e+3j
3e+3ν+j
2μ+2τ+j
2μ+2b
e+τ+2j
e+2τ+ν+j
μ+τ+2b
2μ+2j+2ν
τ+τ
e+2j+ν
2e+τ+2ν+2j
2τ+2b
2τ+2j+ν
2b+4j
γ+e+ν
γ+μ+ν+2j
γ+τ+ν
e+μ+τ+3ν
4j+ν
2b+2ν
γ+γ
γ+c+ν
γ+2e+ν
γ+b+2j
2b+2j
γ+ν
2γ+2j
2γ+2μ+3j
j+j
j+ν

What are we looking for ?

Higgs boson

spin-2 gravitons G

χ_1^0 e+e e+μ e+μ+2b+2ν e+2μ+ν μ+μ $\tilde{l}^{\pm}$

e+j μ+j+ν Axigluon

e+μ+j e+2τ+2b+3ν b' $\tilde{g}$

2e+3j t' 3e+3ν+j $\tilde{\tau}$ 2μ+2τ+j 2μ+2b $\tilde{t}_1$

e+τ+2j e+2τ+ν+j 2μ+2j+2ν

W' KK particle τ+τ Z' μ+τ+2b q^*

$\tilde{q}$ e+2j+ν 2e+τ+2ν+2j 2τ+2b 2τ+2j+ν LQ 2b+4j

$\overline{LQ}$ CMLLPs

γ+e+ν γ+μ+ν+2j e+μ+τ+3ν 2b+2ν

γ+τ+ν SUSY 4j+ν

R-hadrons γ+2e+ν 2b+2j

γ+γ $\tilde{\nu}$ γ+c+ν $\chi_1^{\pm}$

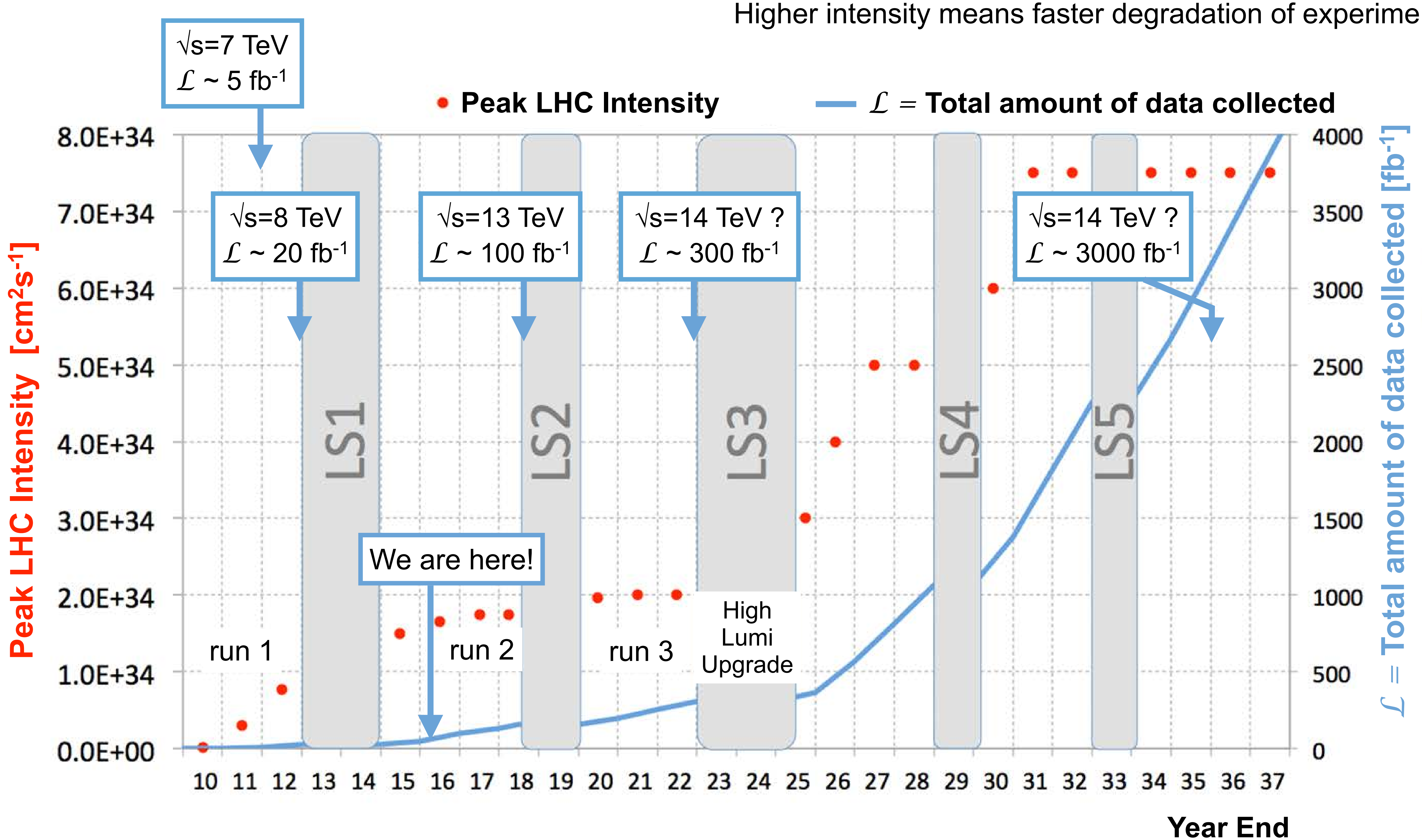
Coloron γ+b+2j j+ν

γ+ν E_6 diquark 2γ+2j 2γ+2μ+3j j+j

E_6 GUT model

LHC Schedule to 2035

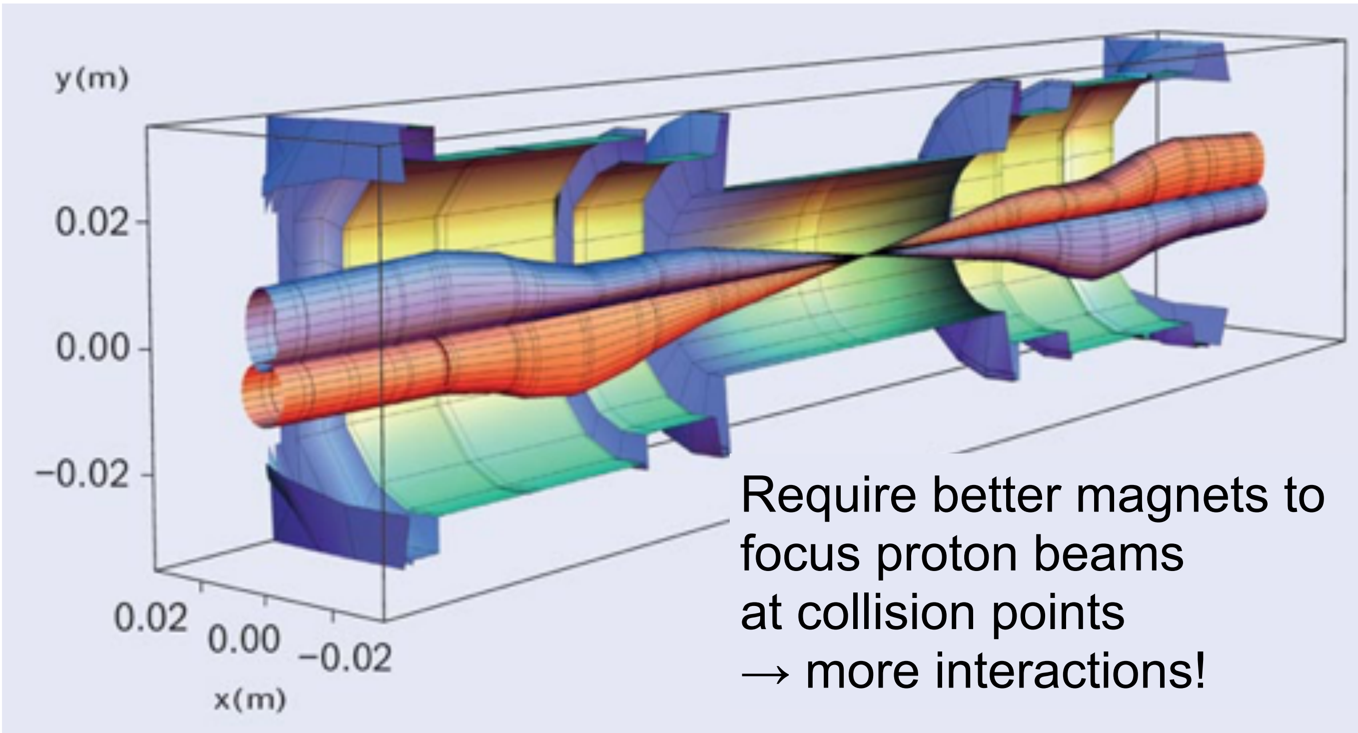
Large increases in intensity
Requires significant changes to LHC magnets
Higher intensity means faster degradation of experiments



LS = Long Shutdown for repairs and upgrades

LHC High Luminosity Upgrade

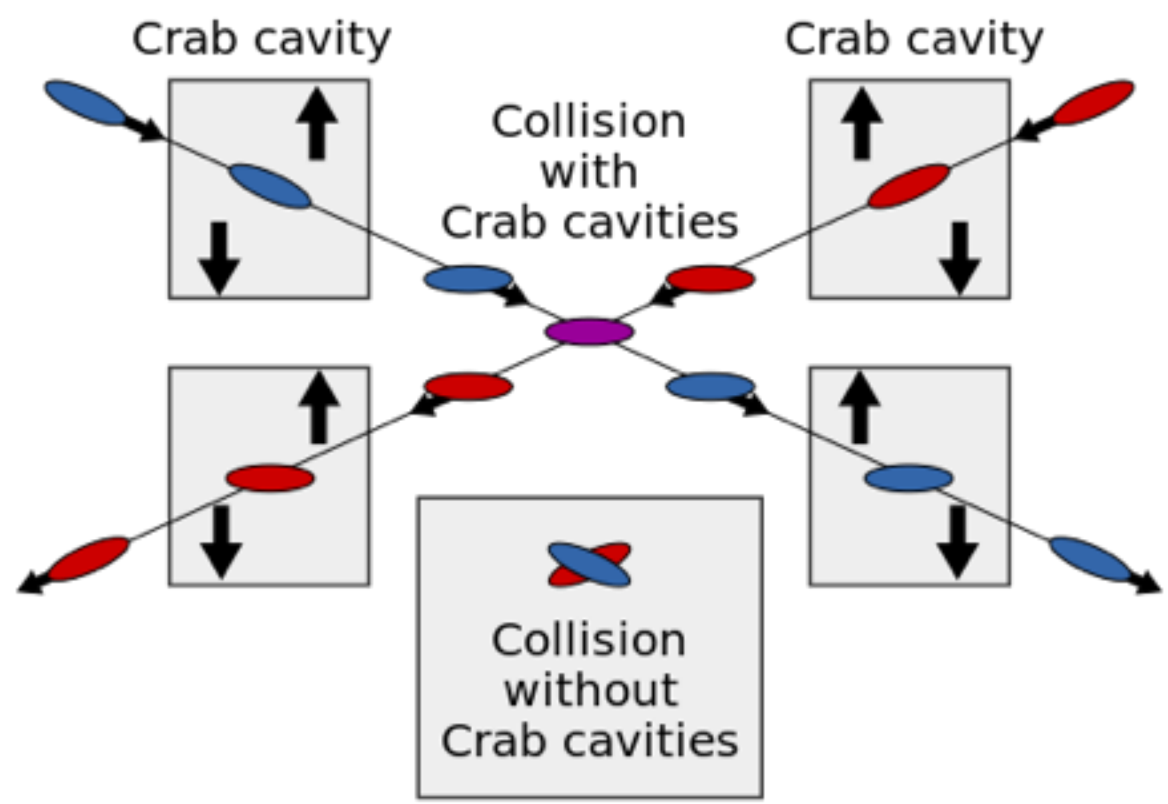
In 2023 LHC will shutdown for 2 years
Upgrade machine / magnets to provide more data (luminosity)
Magnets accelerate, bend and focus the beams

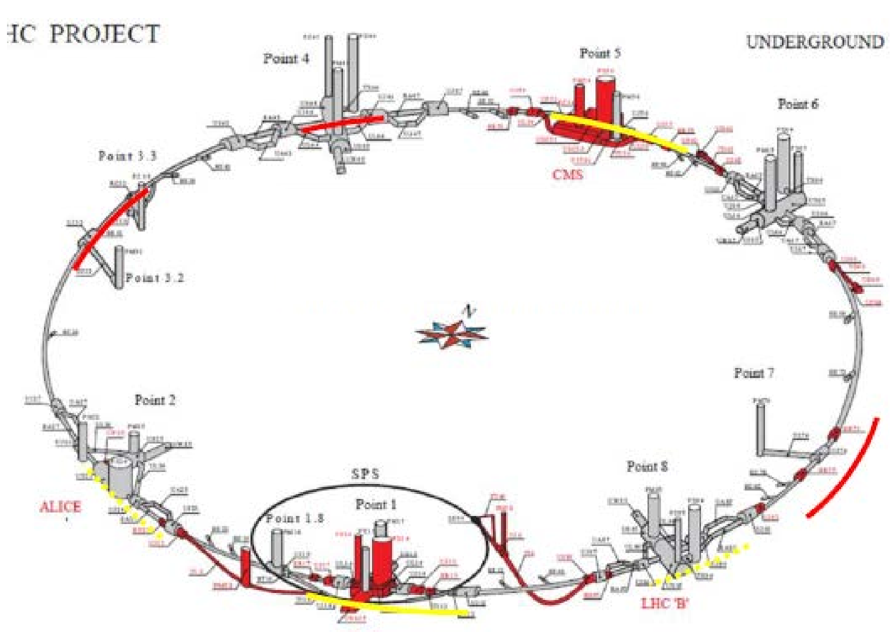


Require better magnets to
focus proton beams
at collision points
→ more interactions!

simulation of proton beams merging & separating inside ATLAS

Protons collide in ‘bunches’ every 25ns
Can gain luminosity by rotating bunches
Use superconducting ‘crab cavities’



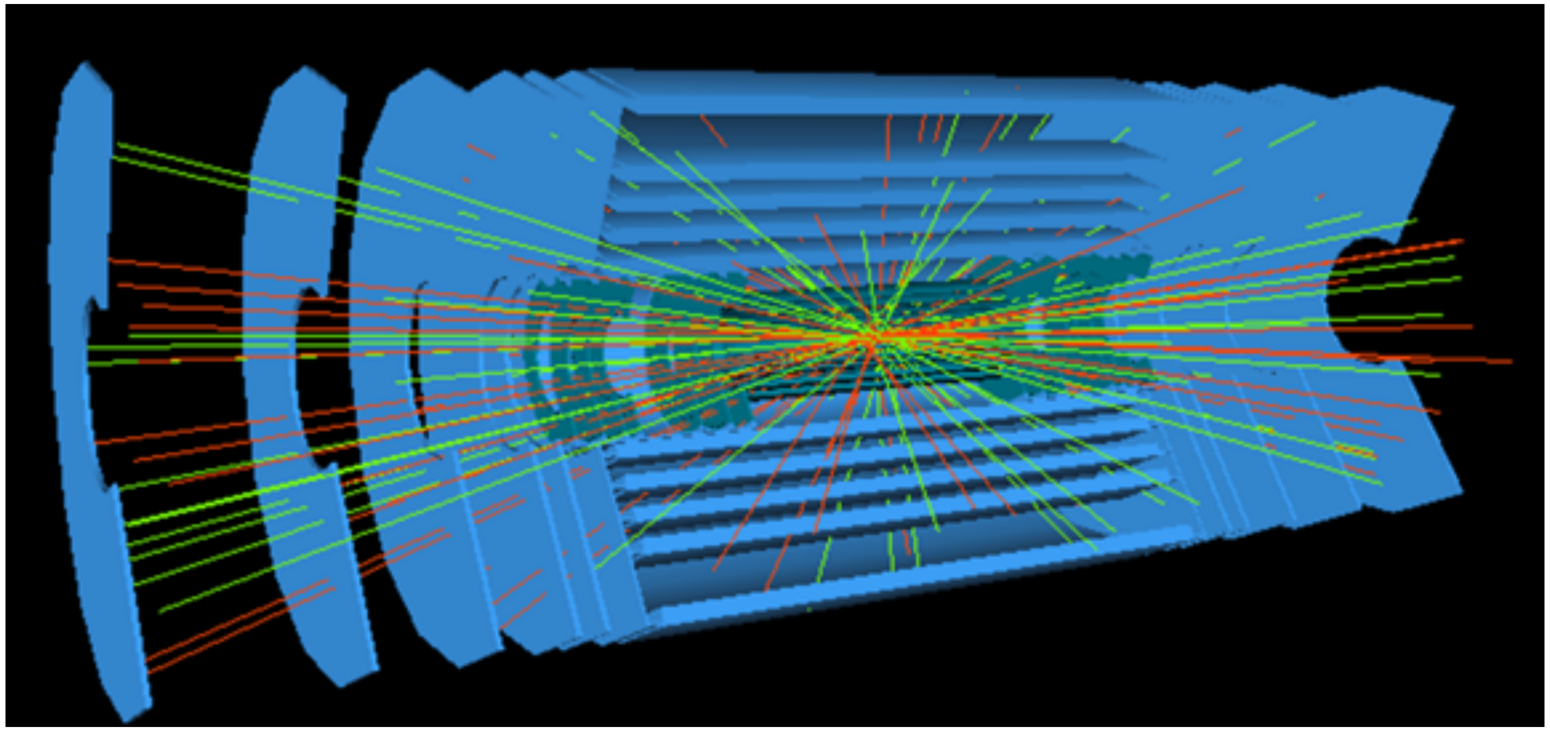


New high performance
superconducting magnets
needed all around LHC ring
Magnetic field 8T → 12 T

Upgrade cryogenics systems
to keep magnets cold

ATLAS High Luminosity Upgrade

ATLAS detector in Run-2

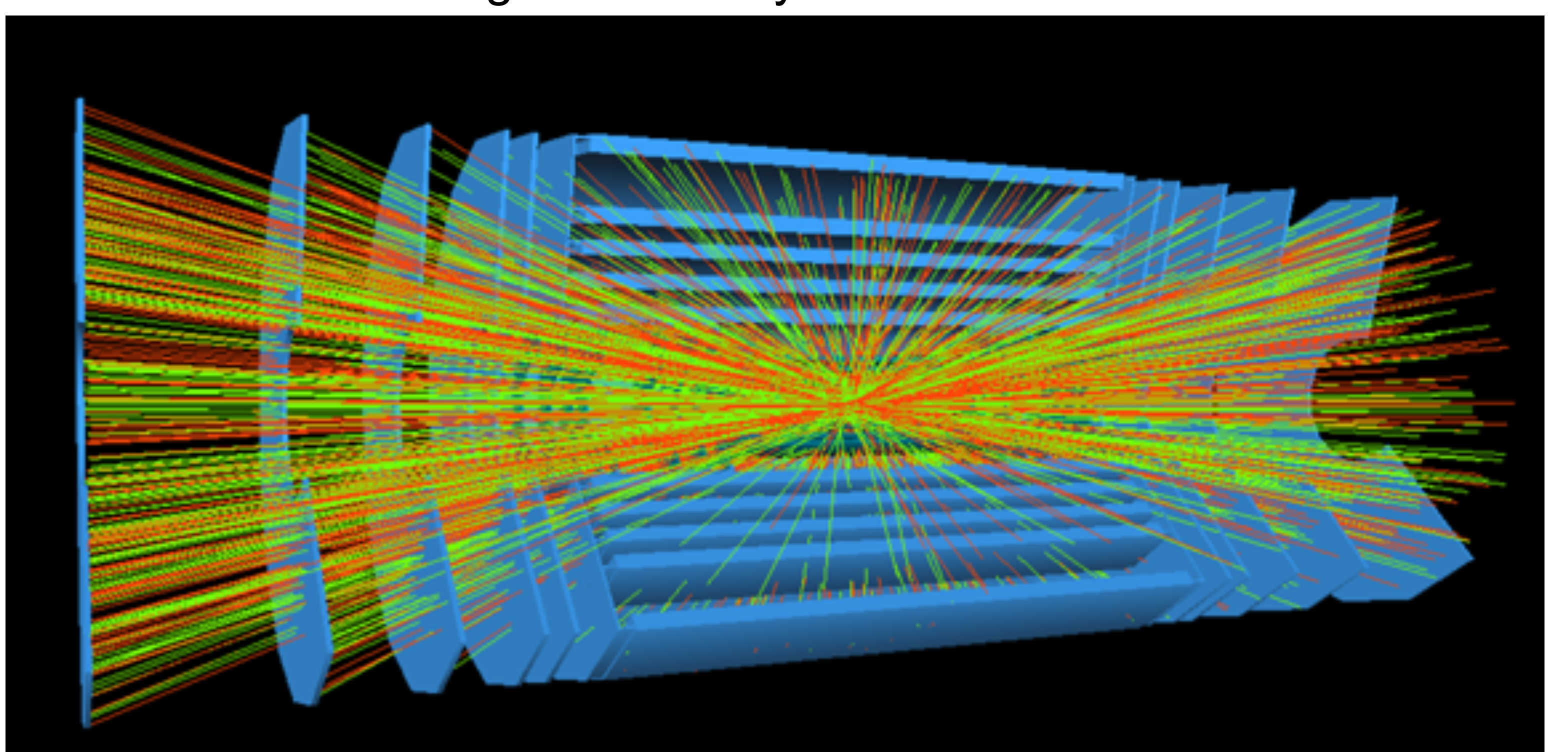


Current LHC operation yields typically 23 overlapping collisions every 25ns

Large flux of particles in 10 years of operation causes damage to detector

example: silicon wafer crystal structure is deformed and electrical properties degraded

ATLAS detector in High Luminosity run



Future LHC operation will yield typically 200 overlapping collisions every 25ns !!!

ATLAS will entirely replace inner tracker in 2023

Upgrade ‘trigger electronics’ to select interesting collision events online to record to disk for offline analysis

Queen Mary group strongly involved in both efforts

Summary & Conclusions

- Run 2 restarts in April - expect 100 fb^{-1} by 2018 (five times more data than now)
- By 2023 we will have 300 fb^{-1} — allows us to search for rarer processes
- Many new physics models still to be tested
- Experimental data is the final arbiter of truth!
- Some models appear contrived....
- ... but nature is weird (who could have predicted quantum mechanics?)
- Nevertheless, we should continue to look because we can!
- The ‘holy grail’ of quantum gravity may be experimentally within reach
- Plenty more work to be done

The Game is On!

Backup

The Standard Model- Quarks & Leptons

quarks interact through all three quantum forces:
- electromagnetism
- weak force
- strong force

quark	symbol	mass MeV/c²	electric charge	weak charge	colour charge	spin
down	d	2	−⅓	yes	yes	½
up	u	5	+⅔	yes	yes	½
strange	s	100	−⅓	yes	yes	½
charm	c	1300	+⅔	yes	yes	½
bottom	b	4300	−⅓	yes	yes	½
top	t	173000	+⅔	yes	yes	½

← quark flavour →

all matter particle (quark and leptons) have spin ½

lepton	symbol	mass MeV/c²	electric charge	weak charge	colour charge	spin
electron	e	0.5	-1	yes	no	½
electron neutrino	ν_e	$<10^{-5}$	0	yes	no	½
muon	μ	106	-1	yes	no	½
muon neutrino	ν_μ	$<10^{-1}$	0	yes	no	½
tau	τ	1780	-1	yes	no	½
tau neutrino	ν_τ	<0.3	0	yes	no	½

← lepton flavour →

leptons interact through one or two quantum forces only:
- weak force
- electromagnetism (not neutrinos)

The values of the weak charge and colour charge are known but not important for our discussion

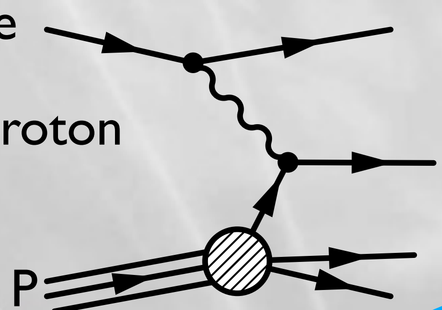
The Standard Model - Bosons

	boson	symbol	mass MeV/c²	electric charge	weak charge	colour charge	spin	
← gauge bosons →	photon	γ	0	0	no	no	1	
	$W^{\pm}$	W	80400	−⅓	yes	no	1	all force carrying particles have spin 1
	Z	Z	91200	+⅔	yes	no	1	
	gluons	g	0	0	no	yes	1	
	Higgs	h	125000	0	no	no	0	

- photon cannot interact with itself (electric charge = 0)
- W/Z bosons can interact with each other (they have weak charge)
- W bosons can interact with photons (they have electric charge)
- gluons can interact with each other (they have colour charge)

- Aside from mass, the higgs boson has the quantum numbers of the vacuum i.e. all zero!

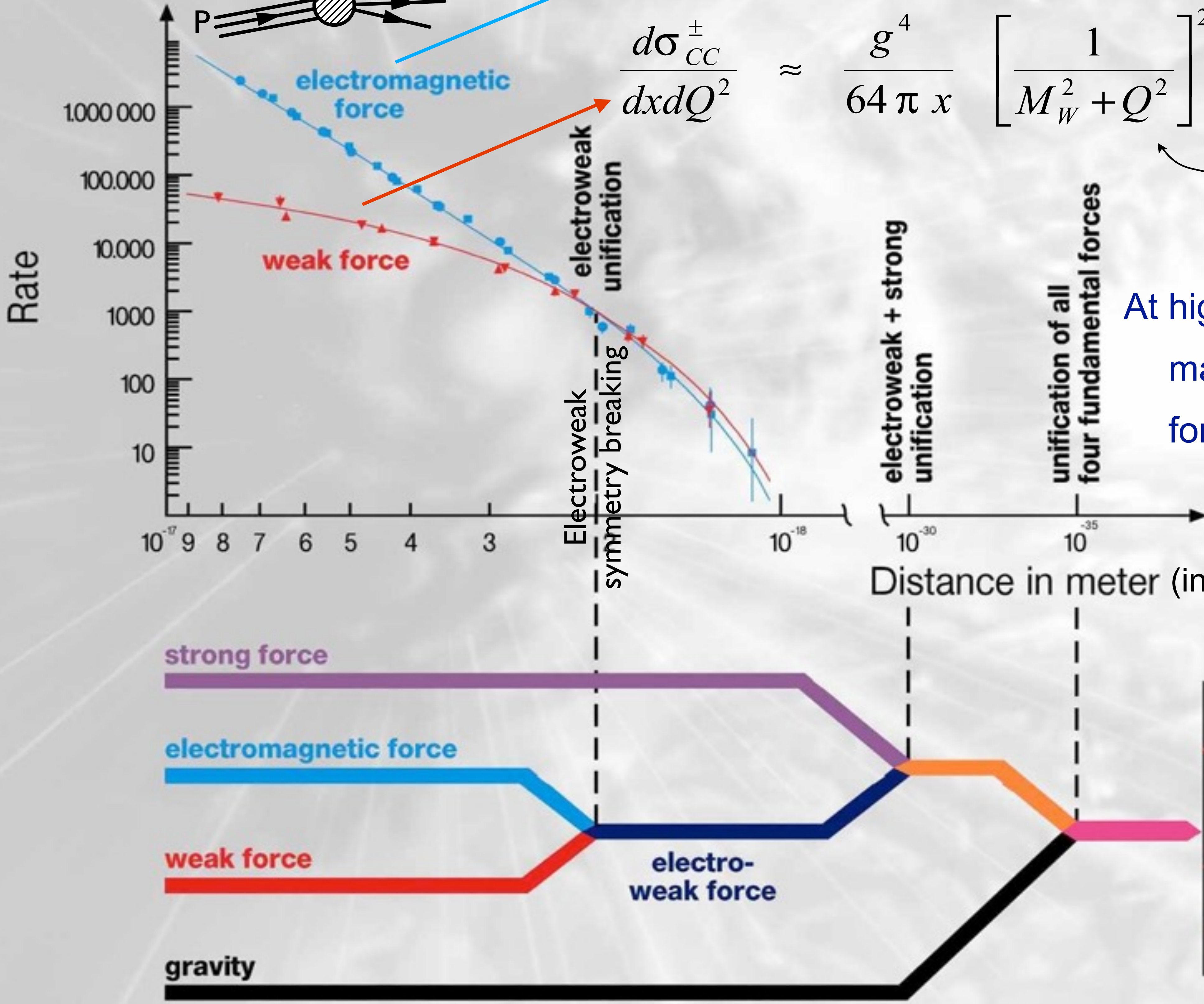
electron - proton scattering



$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi\, x} \left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3\right]$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{g^4}{64\,\pi\, x} \left[\frac{1}{M_W^2 + Q^2}\right]^2 \left[Y_+ \tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm}\right]$$

propagator term



At high energy /momentum(Q):

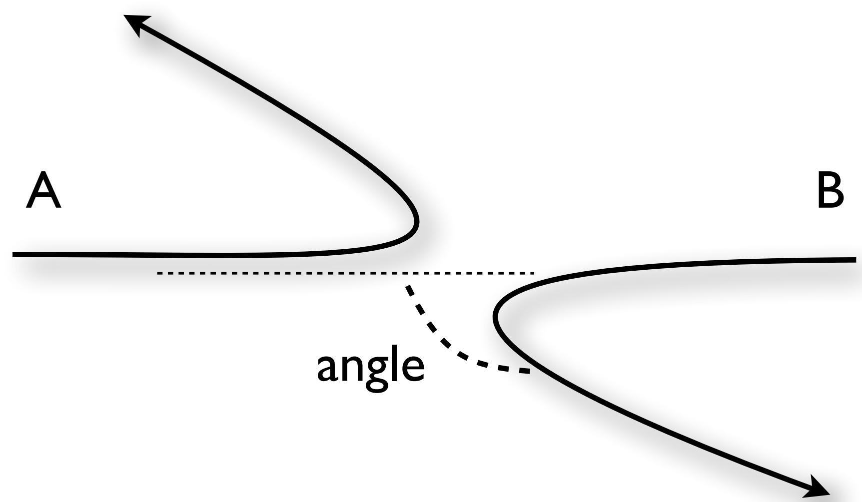
masses M_W & M_Z are small

forces are ~ equal

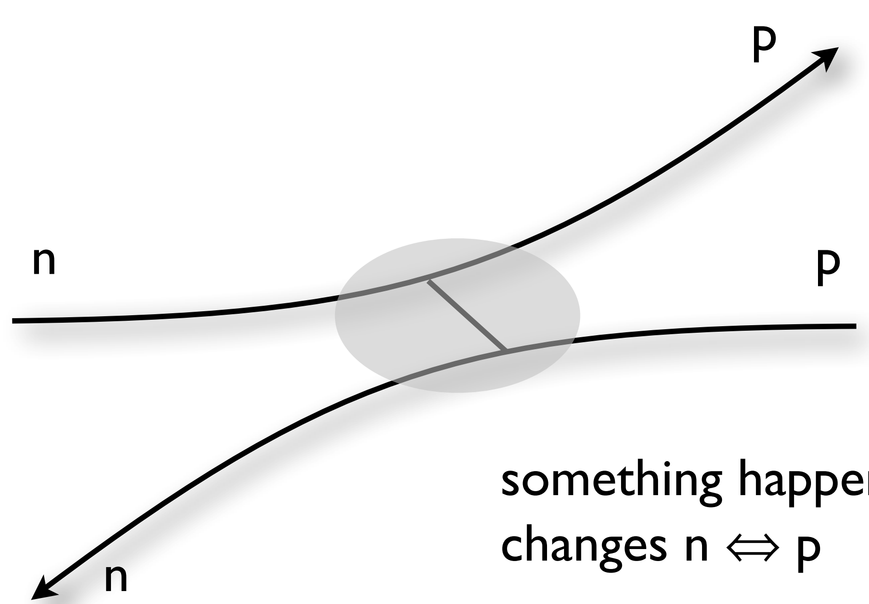
big bang

Aim to unify all forces

The Exchange Model



Momentum is transferred between particles A and B

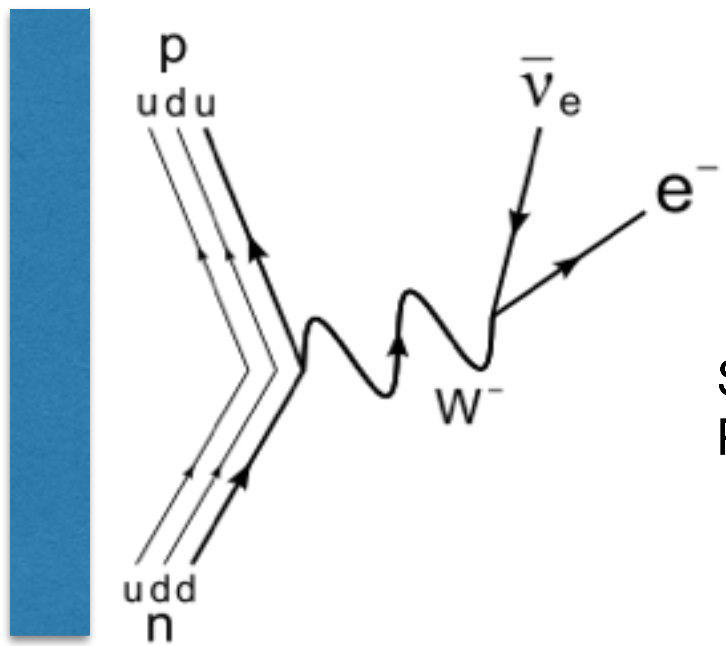


In some cases particles can even exchange identity!

The interaction must:
- exchange momentum
- exchange electric charge?

The Exchange Model

Weak force is responsible for β decay
quarks emit heavy W particle which decays



An exchange particle is forbidden
violates energy-momentum conservation

Particle cannot emit anything in its own rest-frame

Saved by the Heisenberg Uncertainty Principle:

$$\Delta E \Delta t > h$$

Small energy ΔE can be 'borrowed' for a time Δt = h / ΔE !

This process is an interaction - it is the expression of a force of nature
Newton: force = rate of change of momentum (F=ma)

What can we predict about the exchange particle?

ΔE is 'used' to produce the particle with mass - what is it?
Weak force acts in β decay - has a range of 10^{-3} fm
Assume it travels at light speed c - how long does it live for?
$c\Delta t = 10^{-3}$ fm & $\Delta E = mc^2$

$$mc^2 \approx \frac{hc}{c\Delta t}$$

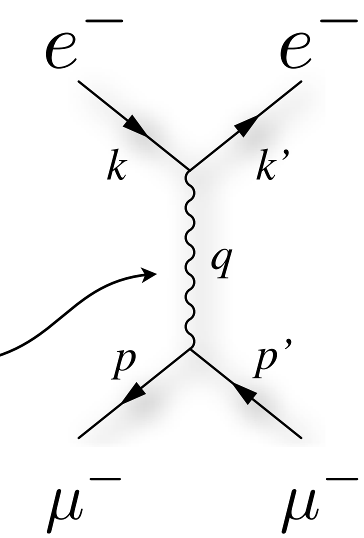
So m = 100,000 MeV/c^2
100 times proton mass!

But we don't understand why W,Z are heavy and photon is massless! ....

Feynman Diagrams

in case you don't believe me...

$$|M_{fi}|^2 = \frac{e^4}{q^4}\frac{1}{4}\sum_{spin}\{[\bar{u}(k')\gamma^{\mu}u(k)]\,[\bar{u}(k')\gamma^{\nu}u(k)]^*\}\{[\bar{u}(p')\gamma_{\mu}u(p)]\,\{[\bar{u}(p')\gamma_{\nu}u(p)]^*\}$$



note the photon propagator

k, k' = incoming , outgoing electron momentum
p, p' = incoming , outgoing muon momentum
q = momentum transfer
e = strength of electromagnetic interaction (electric charge)

electron charge

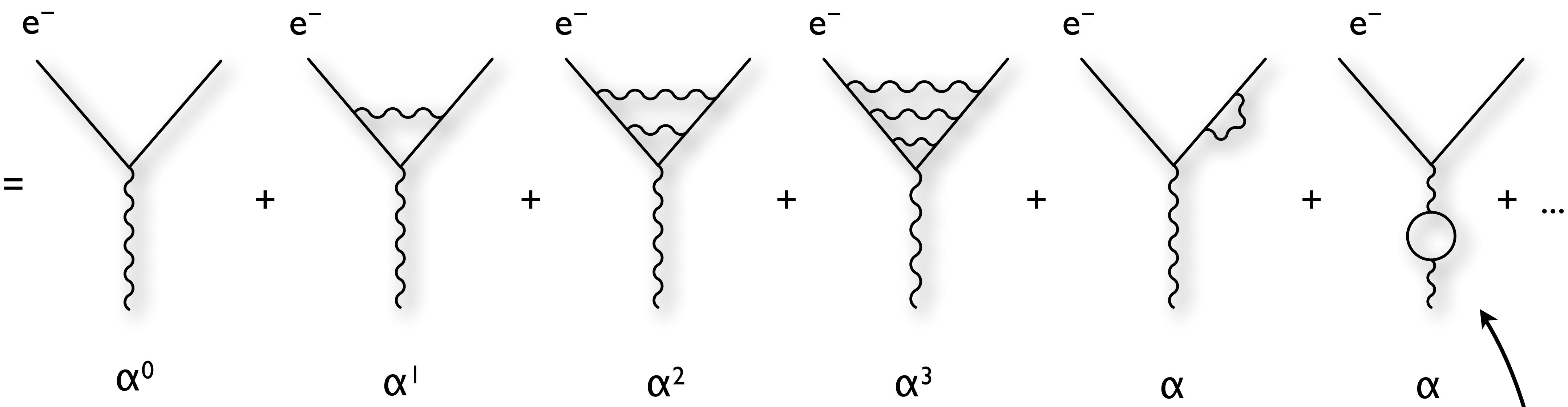
For electromagnetism α_{EM} = 1/137 ~ e^2
Small enough for perturbation theory to work

For strong interaction α_S ~ 0.1
Perturbation theory works but need to calc more diagrams for precision - difficult!
For QCD it took 10 years to calculate second order diagrams!

Reminder from last week:
Quantum fluctuations affect all reaction rate measurements
Effects are subtle but measurable
Consider e⁻ scattering process:

e.g. Higgs converts into <u>all</u> possible fermion/anti-fermion pairs and back again:
$e^+e^-, \mu^+\mu^-, u\bar{u}, s\bar{s}...$

$e^- + H \rightarrow e^-$ =



Measure electron scattering off Higgs

(ignore missing lower part of diagram!)

An infinite number of diagrams contribute to this scattering process
Result is finite due to cancellations

Precision measurements are weakly sensitive to existence of new particles modifying "loop corrections"
Particle masses also affected by such quantum fluctuations
Particles have <u>fixed</u> mass, but experimentally measured mass = "bare" mass + quantum loop effects

$$m_H^2 = m_0^2 + \Delta m_H^2$$

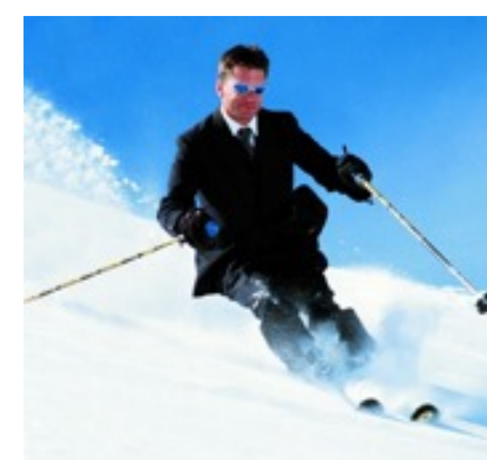
quantum loop fluctuations affect a "bare" particle mass resulting in different but experimentally measurable mass

Particle with strong Higgs interaction is slowed down
Imagine walking with boots on snow
Appear to have large mass

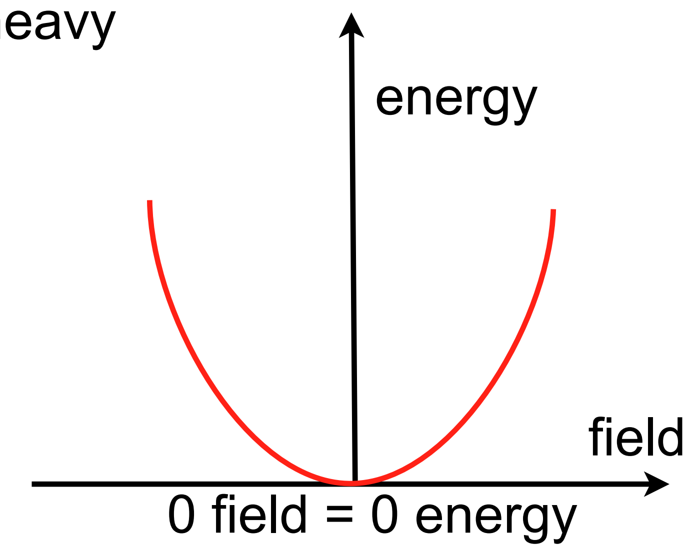
Particle with moderate Higgs interaction travels faster
Like walking with snow shoes
Has moderate mass

Higgs particle appears as a snow-flake

Particle with no Higgs interaction travels at speed of light
⇒ massless particle



Higgs boson required to explain why $W^{\pm}$ and Z^0 bosons are very heavy
And why the photon is massless
In a symmetric theory all force particles should be massless

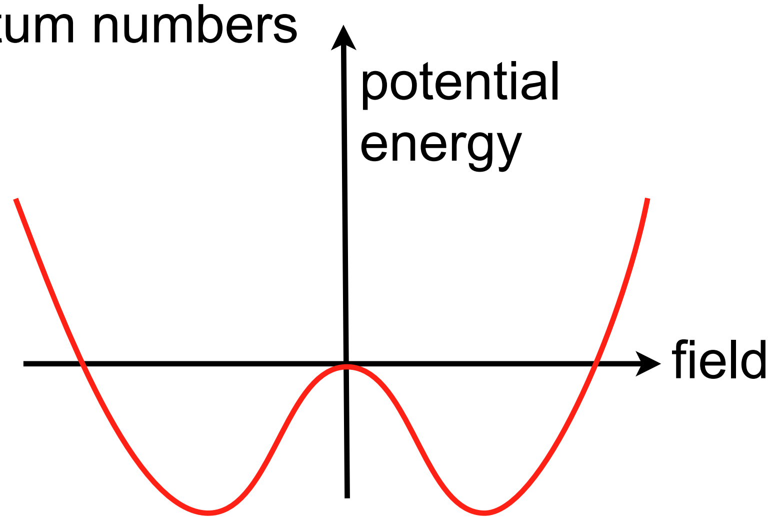


Usually fields have zero energy when field is zero: energy $\propto$ field^2

In quantum field theory all particles are described as oscillations in a field
Electrons are oscillations of the 'electron field' etc...
Oscillations are the particle wave functions

Higgs particle is a particle of the vacuum:
Has zero for all quantum numbers
- no charge
- no colour
- no spin

It just has mass!



At the Big Bang: field = zero
As universe cooled Higgs field 'collapsed' to minimum energy

Higgs field has minimum energy when field is non-zero

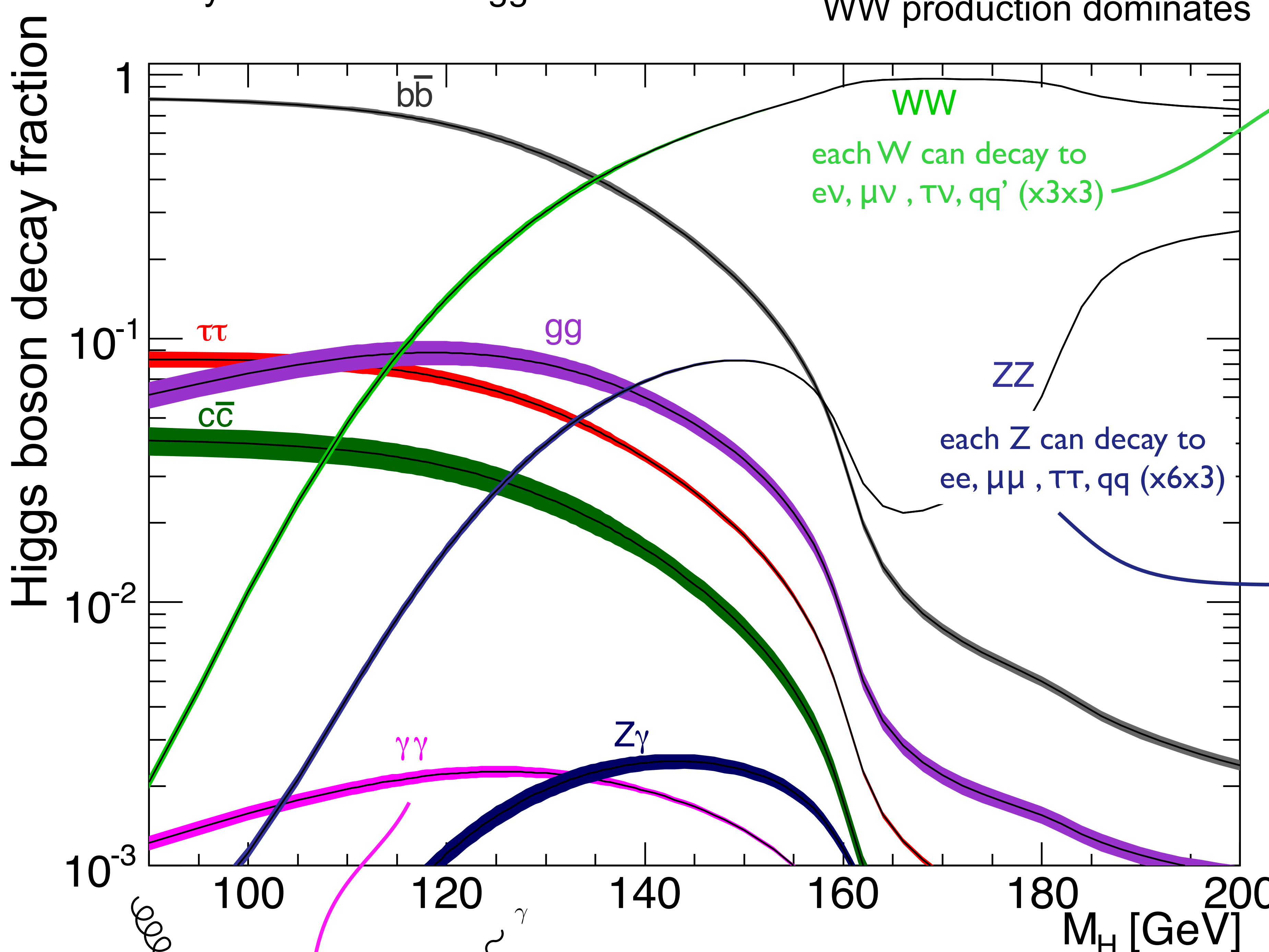
In vacuum of empty space energy is at minimum so Higgs field is non-zero
⇒ Higgs particles are everywhere!

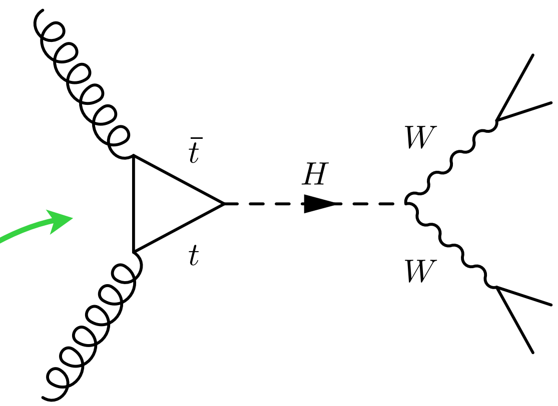
Any particles interacting with Higgs field acquire mass - Higgs particles slow them down

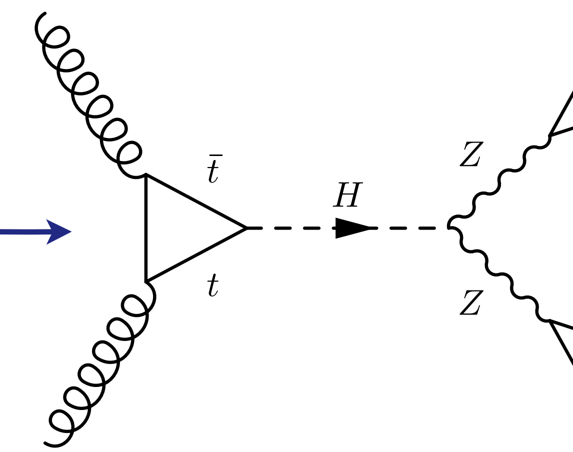
Higgs Hunting

Decay modes of the Higgs vs mass

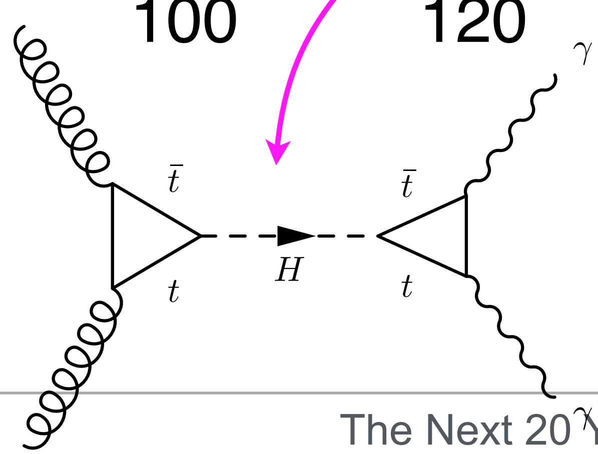
For $m_H > 2m_W$ then WW production dominates



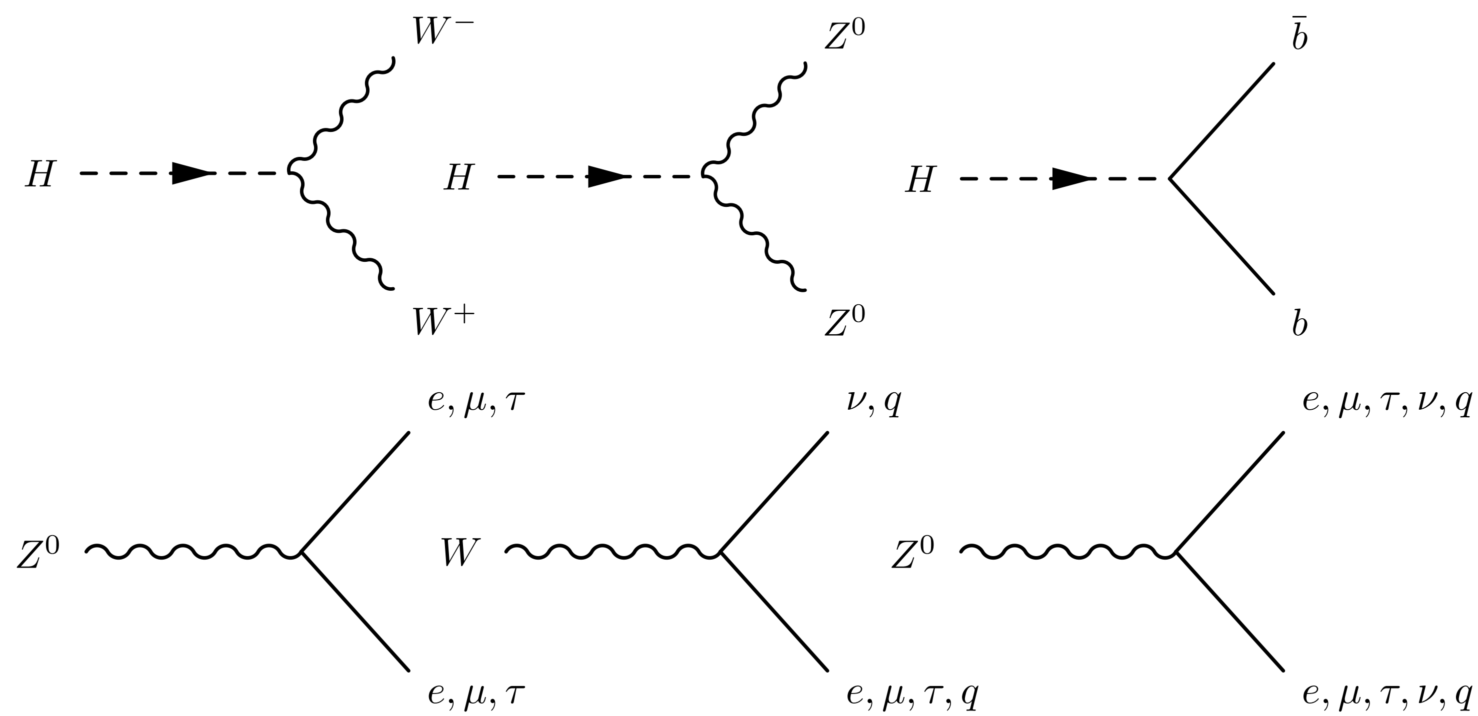




For $m_H > 2m_Z$ then ZZ production increases



Many possible Higgs decay modes/channels:



W/Z can further decay to many combinations of fermions

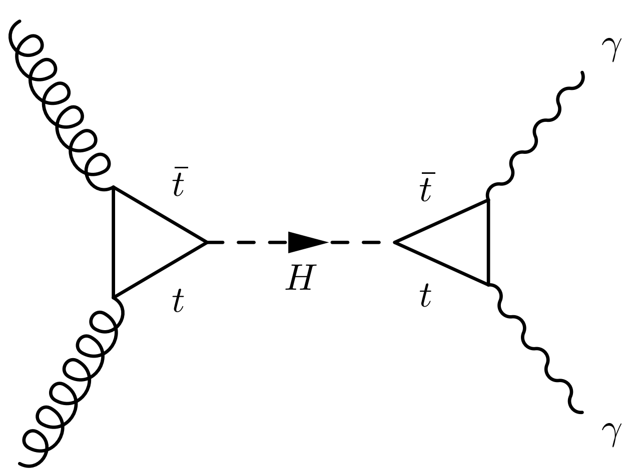
H→ ZZ
- ZZ → llll (4 lepton golden mode)
- ZZ → llνν (good for high mass Higgs)
- ZZ → llbb (good at high mass)

H→ WW
- WW→ lνlν (most sensitive)
- WW → lνqq (highest rate)

H→ γγ
- Rare, best for low mass Higgs high background

H→ττ
- Rare, good at low mass, low background

H→ bb
- Useful but difficult to identify b quarks

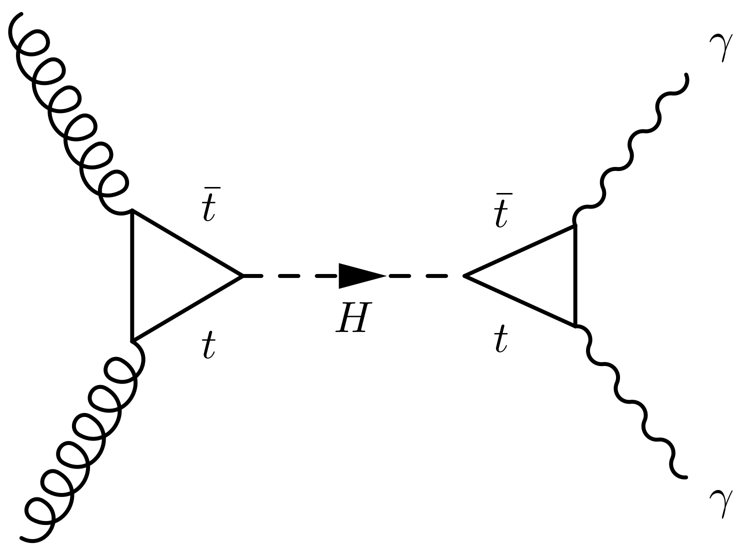


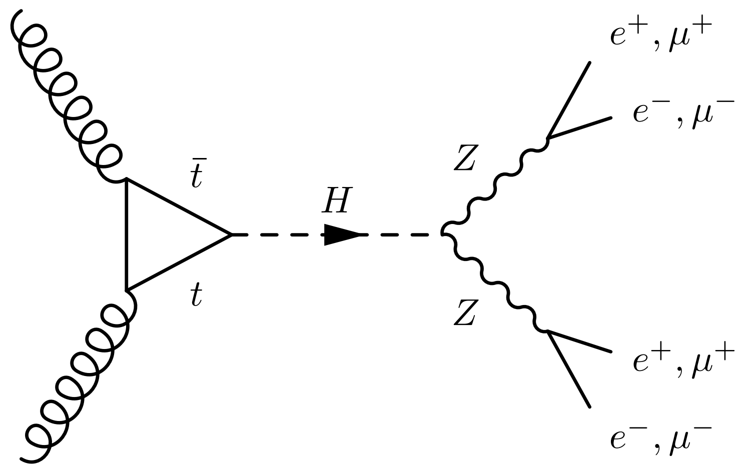
At LHC Higgs is produced via a loop

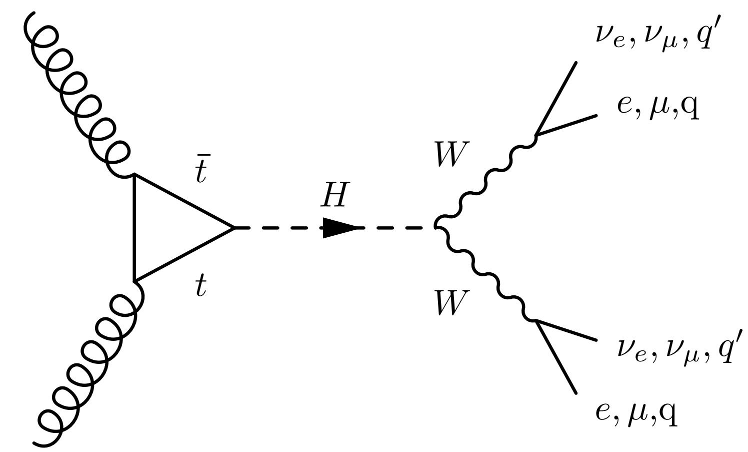
Each mode has different:
- sensitivity depending on mass range
- production rate
- contributions from background processes

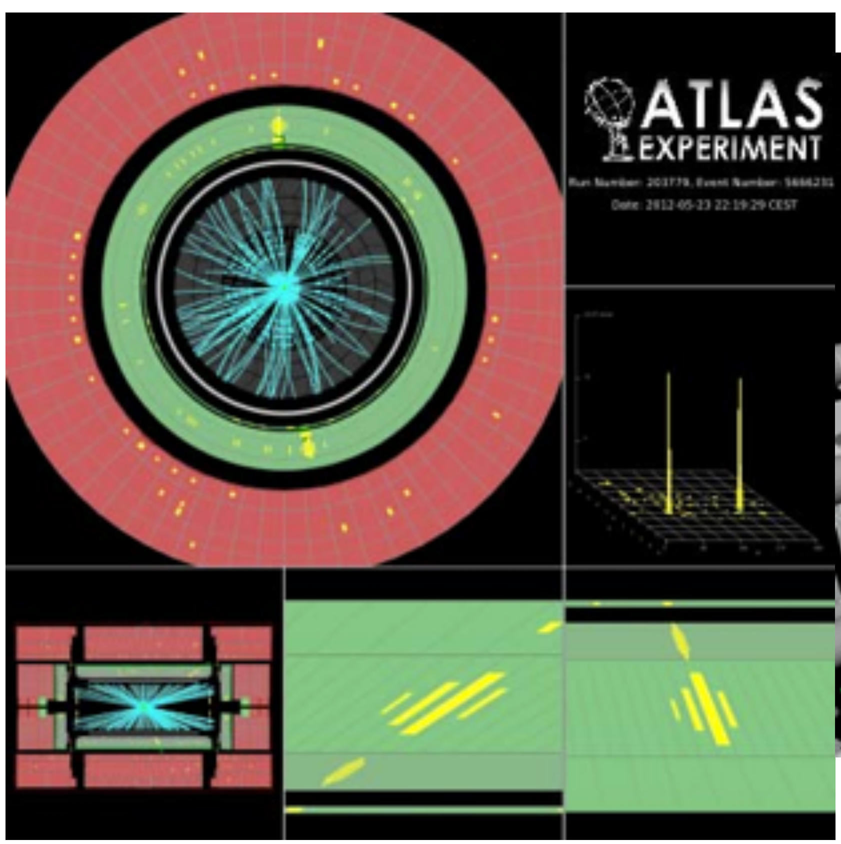
All modes need to be studied together!

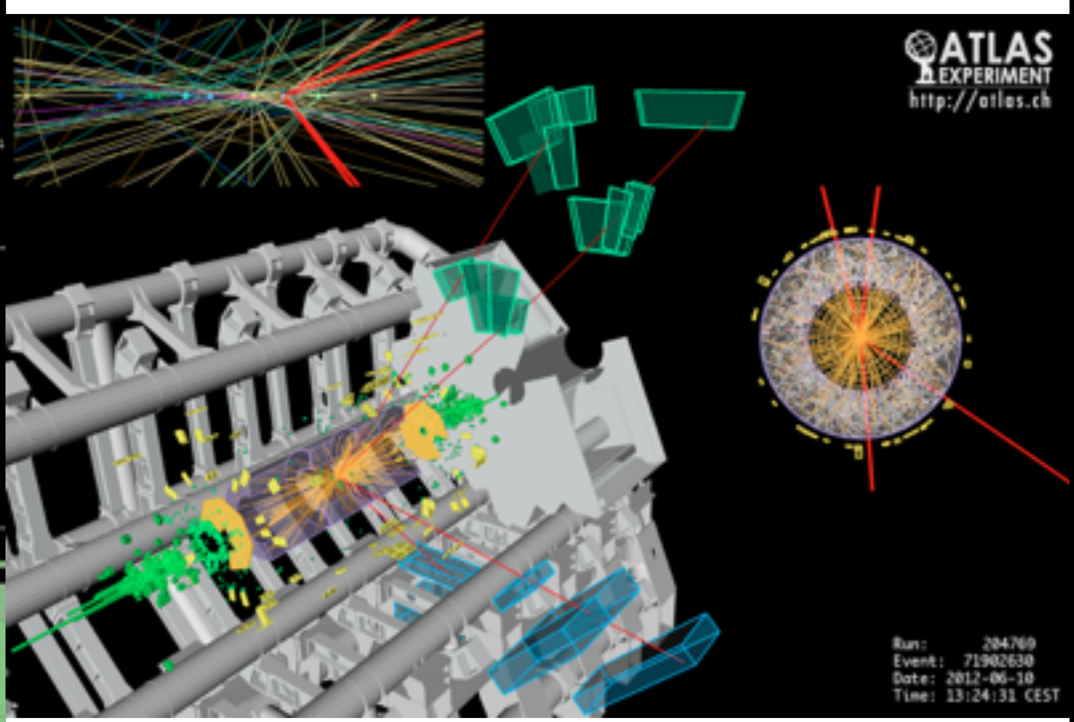
Higgs Hunting

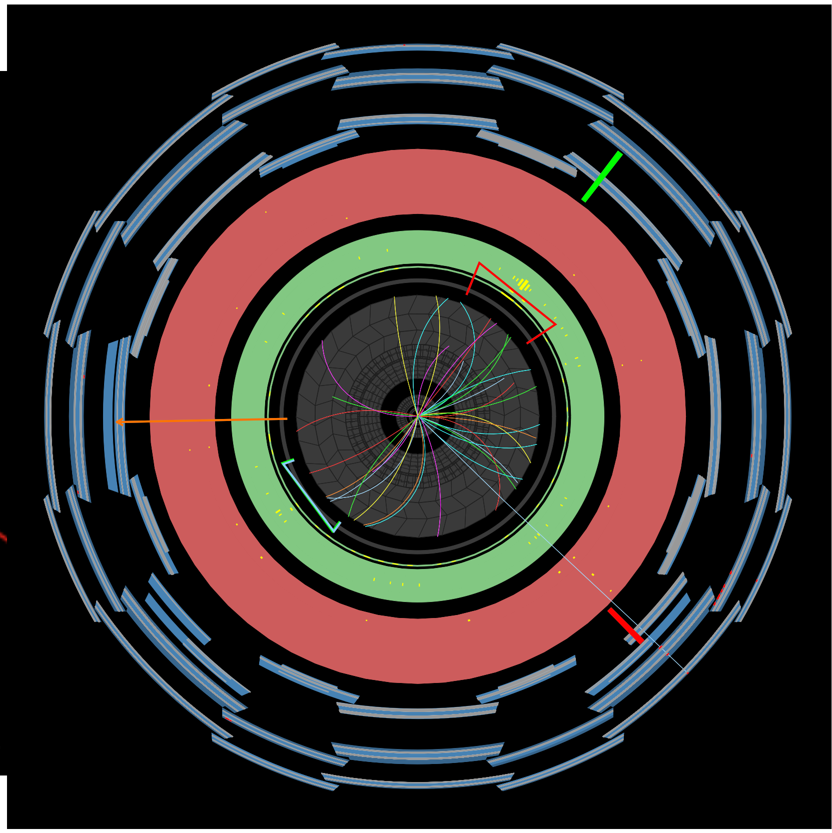






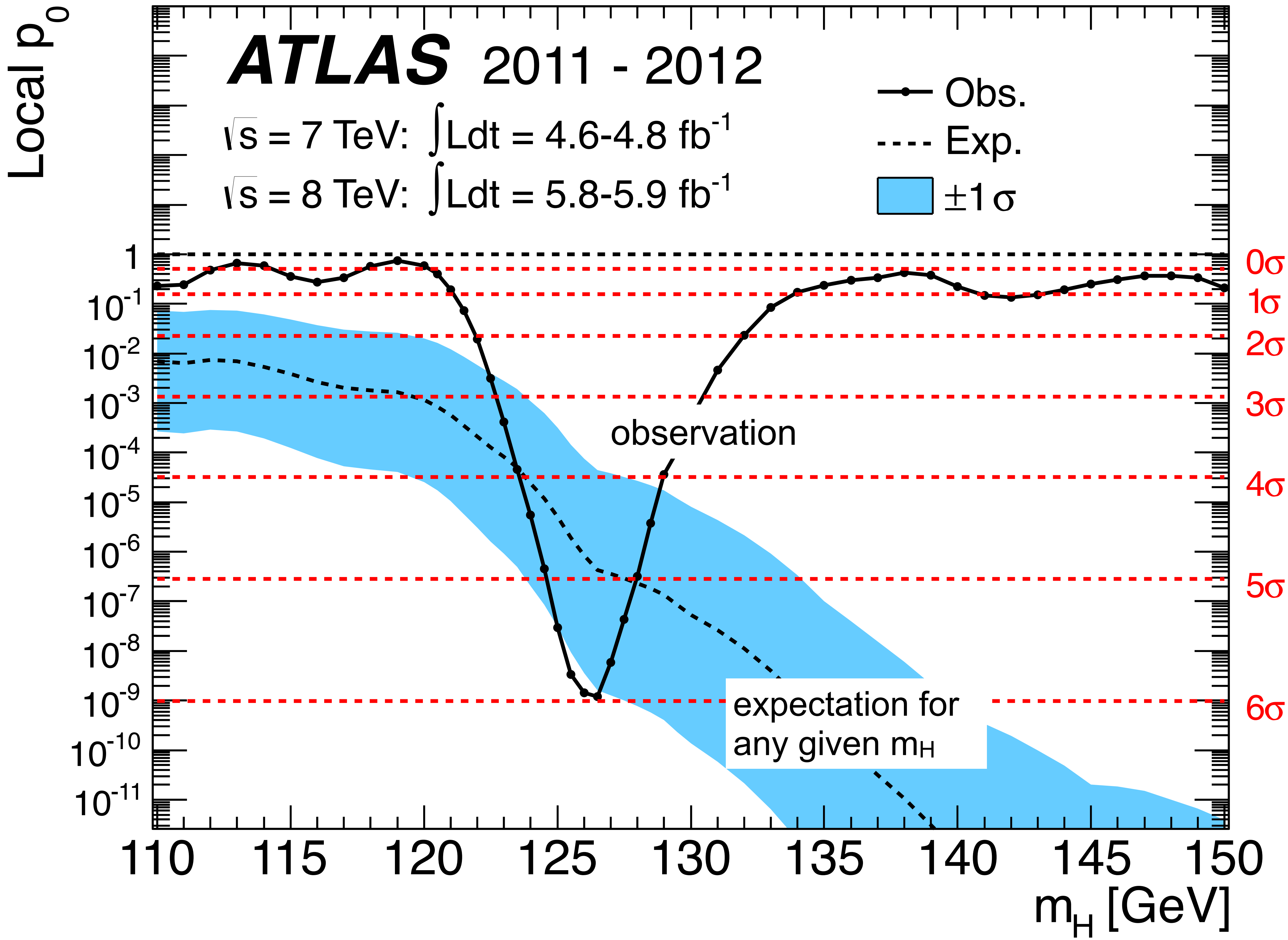






Higgs Hunting: Probability of Chance Fluctuation

Probability of “no Higgs” hypothesis
fluctuating to mimic Higgs signal

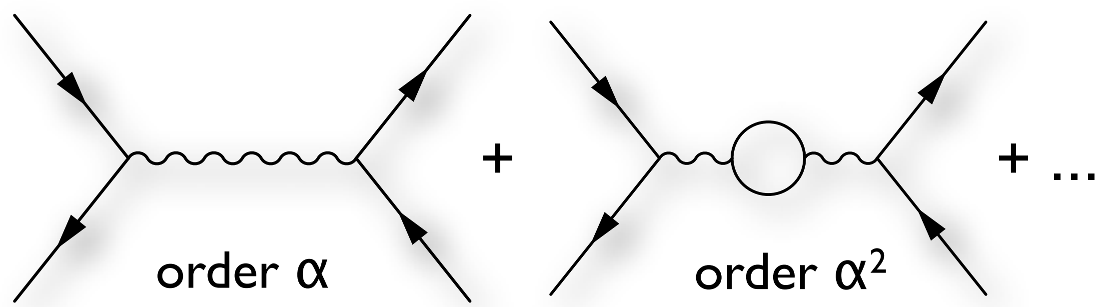


Feynman Diagrams

Transition due to the exchange of a gauge boson
Exchanges momentum & quantum numbers
Strength of the interaction is parameterised by couplings α
One α for each fundamental force

Draw all possible Feynman diagrams for your experiment:

M_{fi} = sum of transitions of initial state ψ_i to final state ψ_f



Simplest interaction is single boson exchange

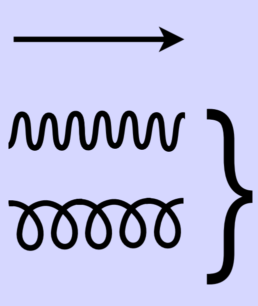
More complicated loop diagrams also contribute

Potentially infinite series of diagrams for 2 → 2 scattering process

For each diagram calculate the transition amplitude
Add all transition amplitudes
Square the result to get the reaction rate

If perturbation is small i.e. α < 1 then contributions from extra loop diagrams is suppressed

Feynman Rules: start from left side



Write a free particle wave function for each particle

$$\psi = Ae^{i(kx-\omega t)}$$

Multiply by an exchanged boson write $\frac{1}{q^2-m^2}$ for particle of momentum q and mass m

For each vertex multiply by coupling $\sqrt{\alpha}$ = e

The propagator - transfers momentum further a boson is from it's mass *m* the more suppressed the interaction

reaction rate / probability $\propto |M_{fi}|^2$

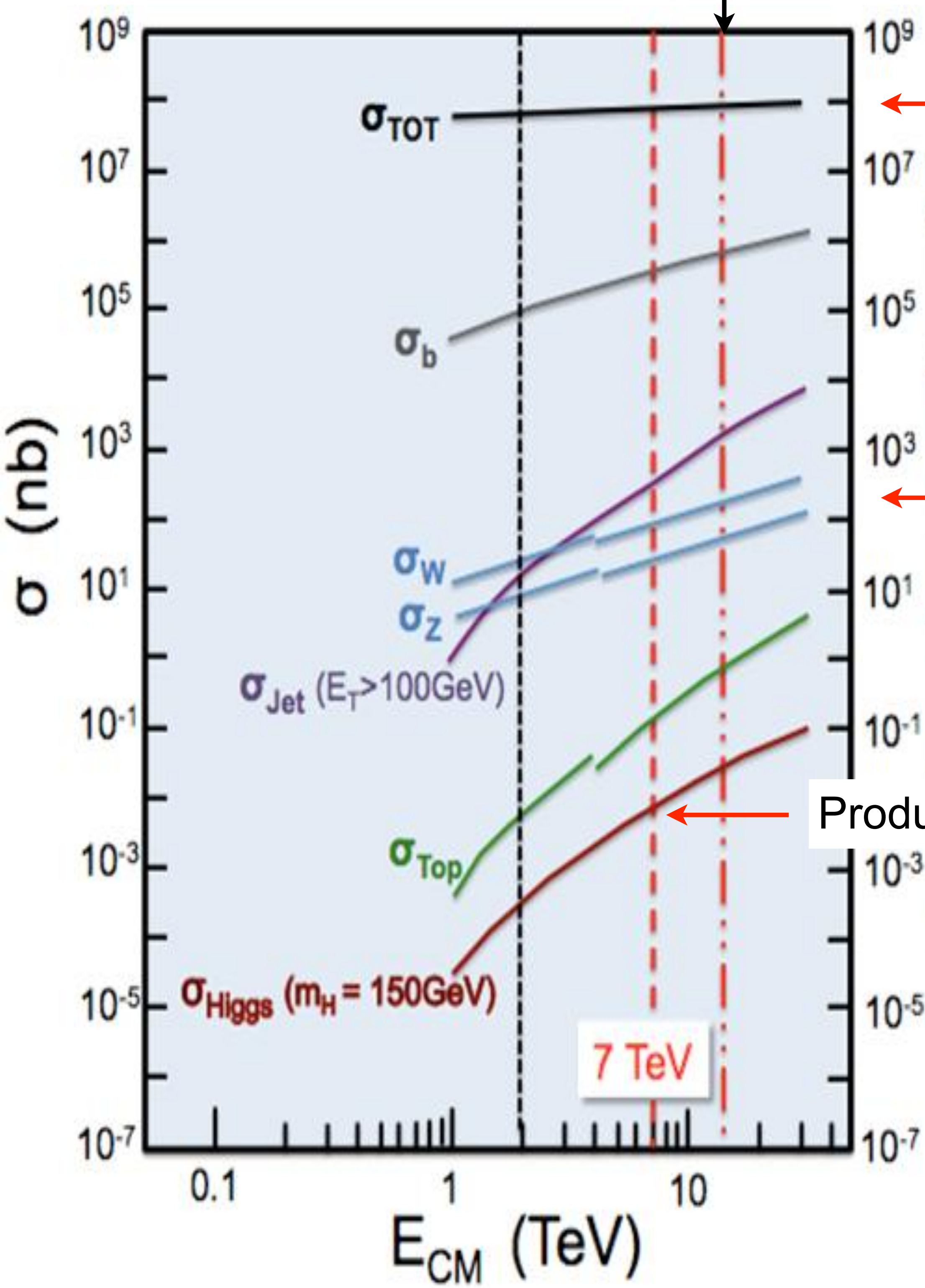
$$|M_{fi}|^2 = \frac{e^4}{q^4}\frac{1}{4}\sum_{spin}\{[\bar{u}(k')\gamma^\mu u(k)]\,[\bar{u}(k')\gamma^\nu u(k)]^*\}\{[\bar{u}(p')\gamma_\mu u(p)]\,\{[\bar{u}(p')\gamma_\nu u(p)]^*\}$$

Higgs Hunting

σ = reaction rate

current LHC operating energy

Number of events (i.e. collisions) per second



Total rate of data produced by LHC:
100,000,000 events/second

Huge event rates
New physics swamped!
Need to filter events 1:10^7 online

Maximum recording rate of ATLAS experiment:
200 events/second

Production rate of 125 GeV Higgs: 0.01 events/second

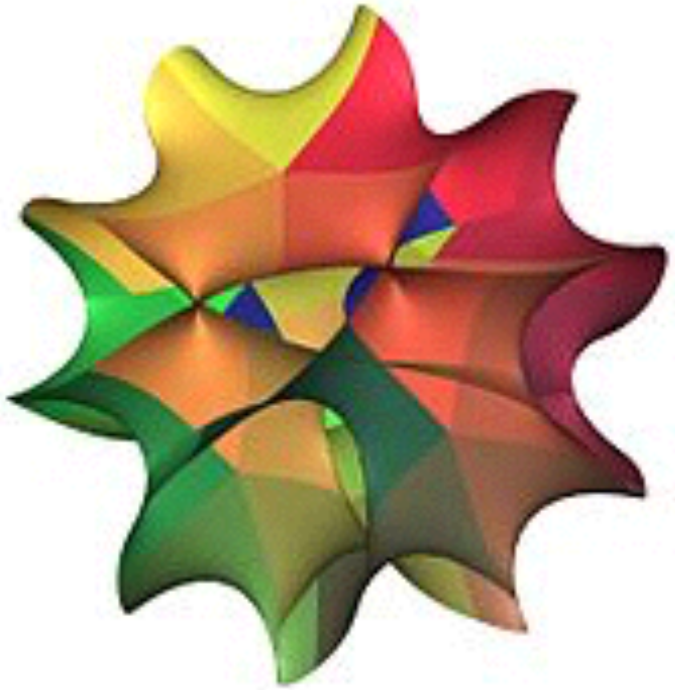
Like trying to find a cheap plumber from entire human population in 2 μs

Supersymmetry is a particular form of string theory
String theory aims to describe physics of Planck scale - domain of quantum gravity
Impossible to reach in any collider!

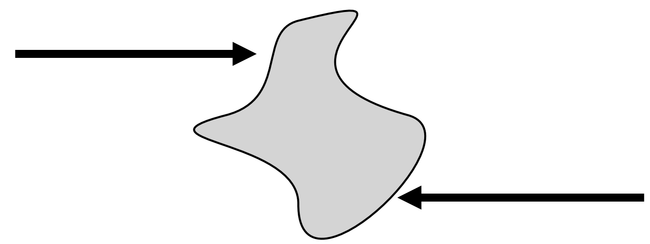
Some quantum gravity theories live in 10 or 11 dimensional space!
  predict gravitons propagate in extra dimensions size of Planck length
  (graviton = postulated force carrier of gravity)
Explains why gravity is 10^{23} times weaker than Weak force - gravity is diluted

But: If extra dimensions “large” (~0.1mm) quantum gravity could be seen at TeV scale
Gravity has never been tested at such short distances!
LHC could open the possibility of creating mini-black holes & gravitons
  laboratory for testing quantum gravity!!!

11 dimensional space
projected into 2d

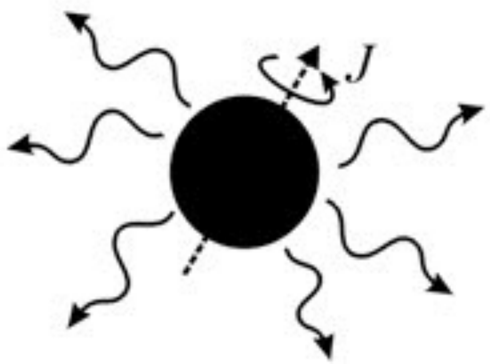


Tragic Life of a Micro-Black Hole

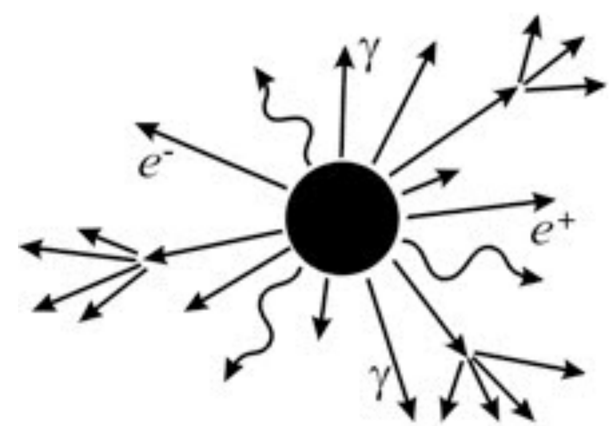


Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

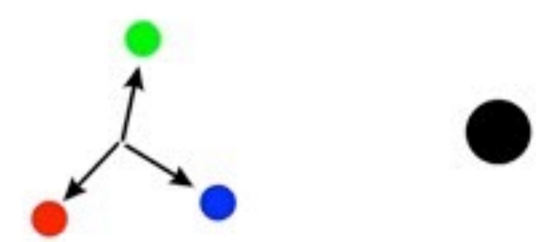
Extremely short lifetime ~ 10^{-25} s



Balding
Energy lost as BH settles into 'hairless' state

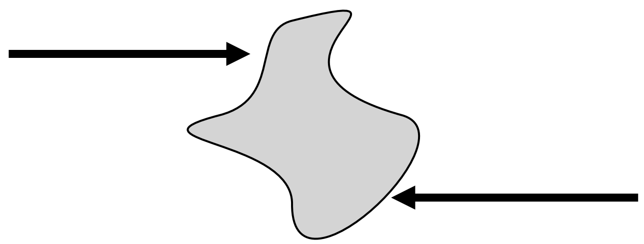


Evaporation
Thermal Hawking radiation in form of SM particles & gravitons
Greybody factors give emission probabilities for all particles



Plank Phase
For $M_{BH} \sim M_D$ unknown quantum gravity effects dominates. BH left as stable remnant or final burst of particles **????**

Tragic Life of a Micro-Black Hole



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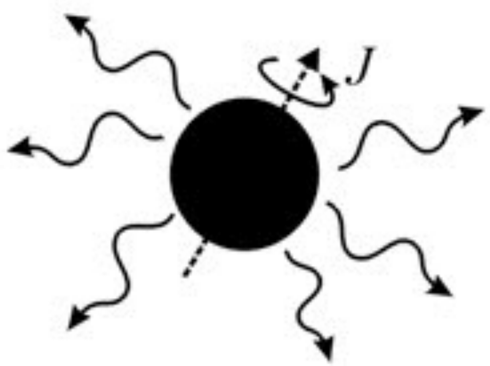

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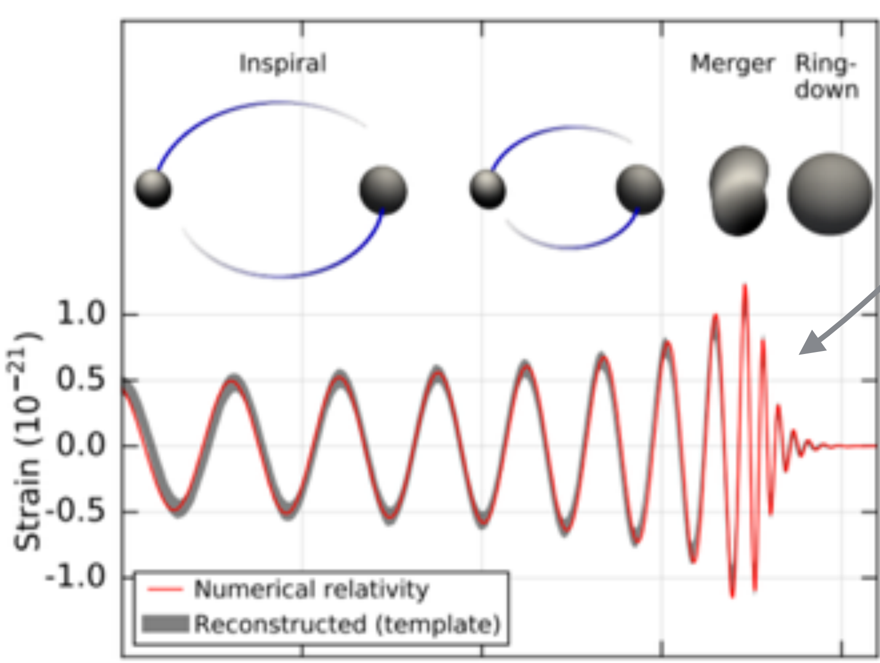

On Feb 11th 2016 the LIGO experiment announced discovery of gravitational waves

They observed two astrophysical black holes collide & merge 410 Mpc away (1 billion light years!)

Waveform of the gravity wave tells us about dynamics of the system

Ringdown is high frequency part of waveform

In this step irregularly shaped merged black hole sheds energy and stabilises

This is equivalent to 'balding phase' of a microscopic black hole

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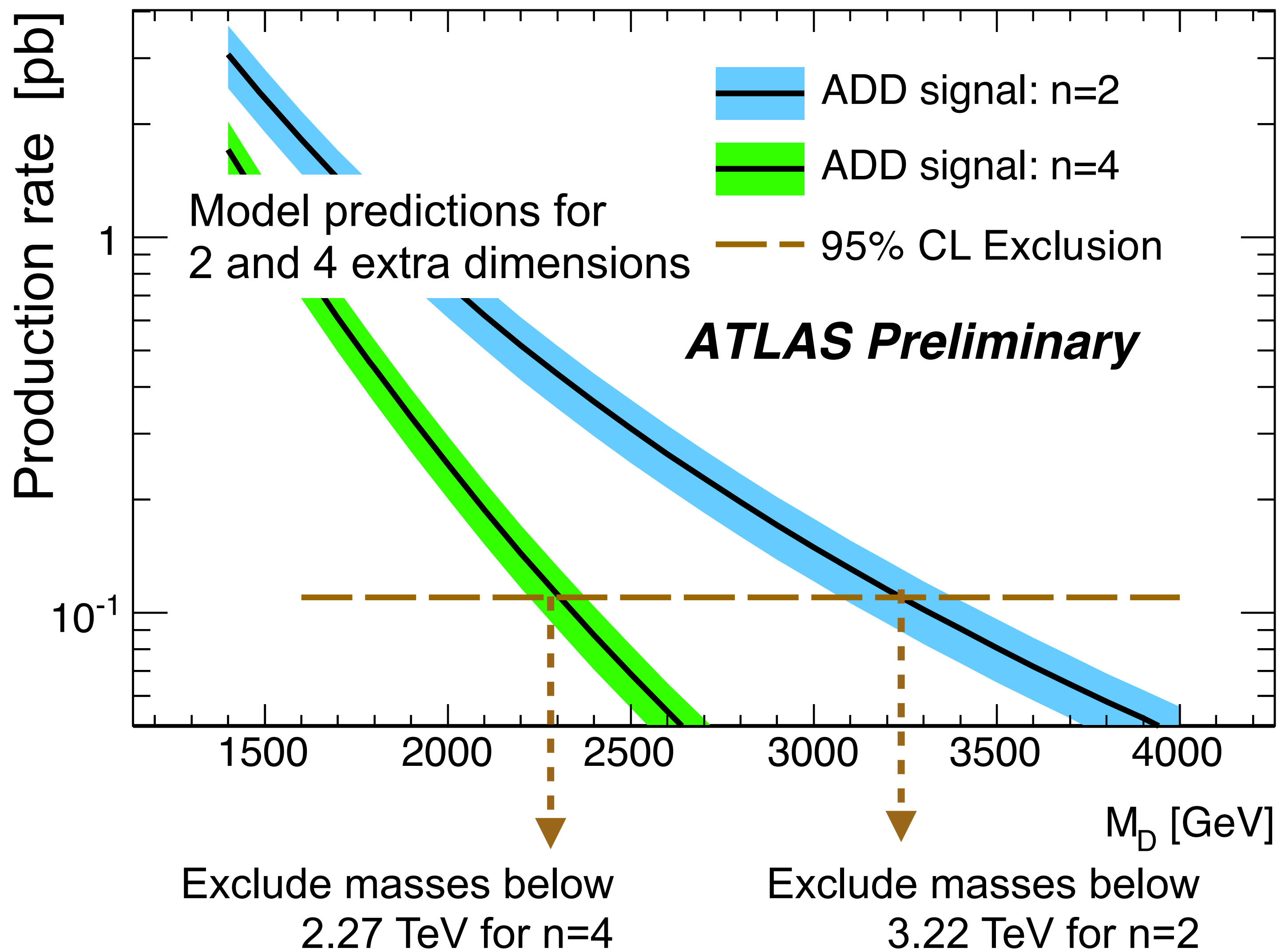
Searching for new physics is like searching for the Loch Ness Monster:

If you observe the Loch for 24 hours and see nothing, then either:

a) Nessie doesn't exist
b) camera has poor efficiency for spotting animals (larger than 2m long)
c) Nessie exists but comes to the surface less than once per day

Must exclude (b) and (c) before we can conclude (a) !



In searches a model predicts a reaction rate

If you observe no such reaction rate (i.e. zero collisions) then you can calculate upper limit on allowable reaction rate

Carefully consider your detector's efficiency in observing similar collisions

Do you understand background processes that mimic the signal you're looking for?

We found nothing so far...

Pile-up

Particle trajectories from single bunch crossing
25 collisions occurred all overlapping
ATLAS can reconstruct 25 separate interaction points
Only 1 collision is interesting - has much higher energy particles than other collisions