The Particle World: an introduction to particle physics

CERN summer student lectures 2019

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What particle physics describes

What we know (and what we don't)

The Standard Model: matter; forces; Higgs.

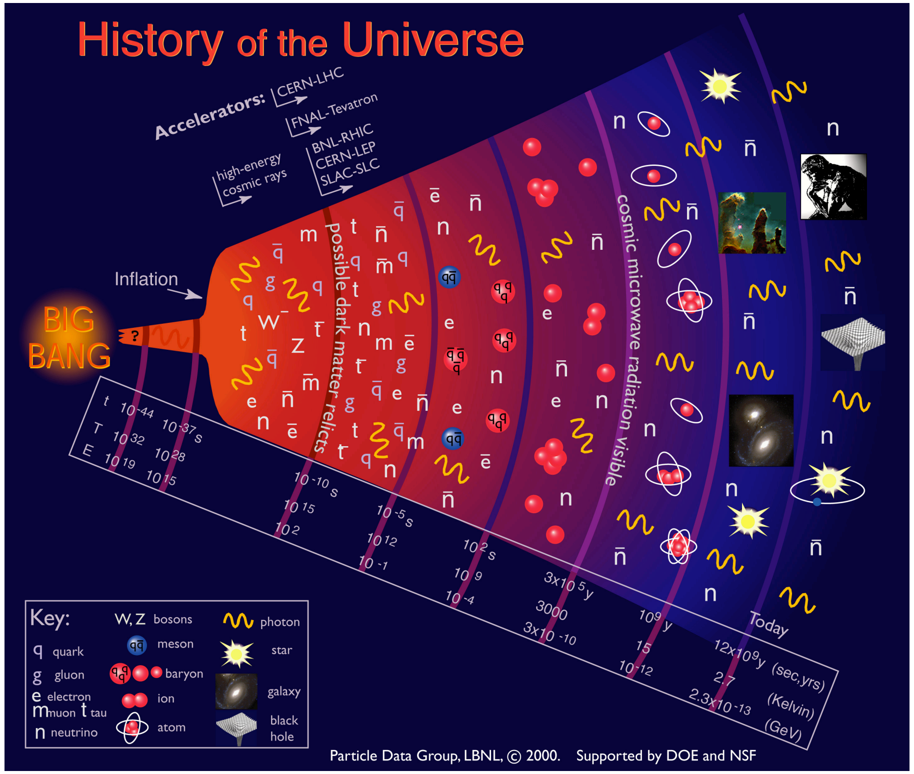
Experiments; performing research

Outstanding questions and mysteries …

…… in three lectures!

The universe

BIG BANG



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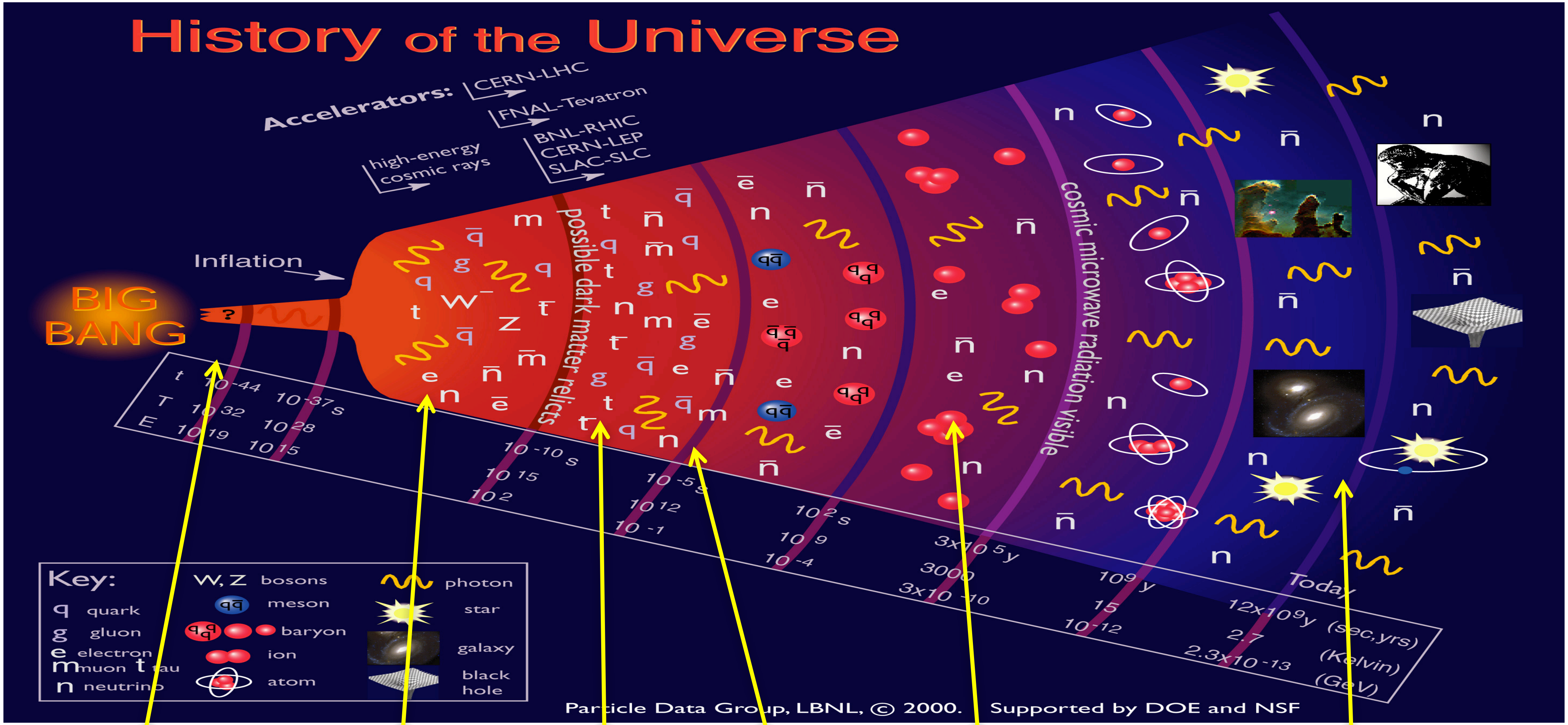


Cosmology
22/7/19

Cosmic rays

LHC

Quark/gluon plasma
Heavy ions 18/7/19

Nuclear physics
29/7/19

Astrophysics

Plus ....
Antimatter 1/8/19
Astroparticle physics 18/7/19

aside: units

Our scale	
Length	**m**
Mass	**kg**
Time	**s**
Energy	**kg m^2 s^{-2}**

Particle Physics	
Length	**fm**
Mass	**eV/c^2**
Time	**s**
Energy	**eV**

Convert

1 eV = 1.6 x 10^{-19} J

1 GeV = 10^9 eV

1 TeV = 10^3 GeV

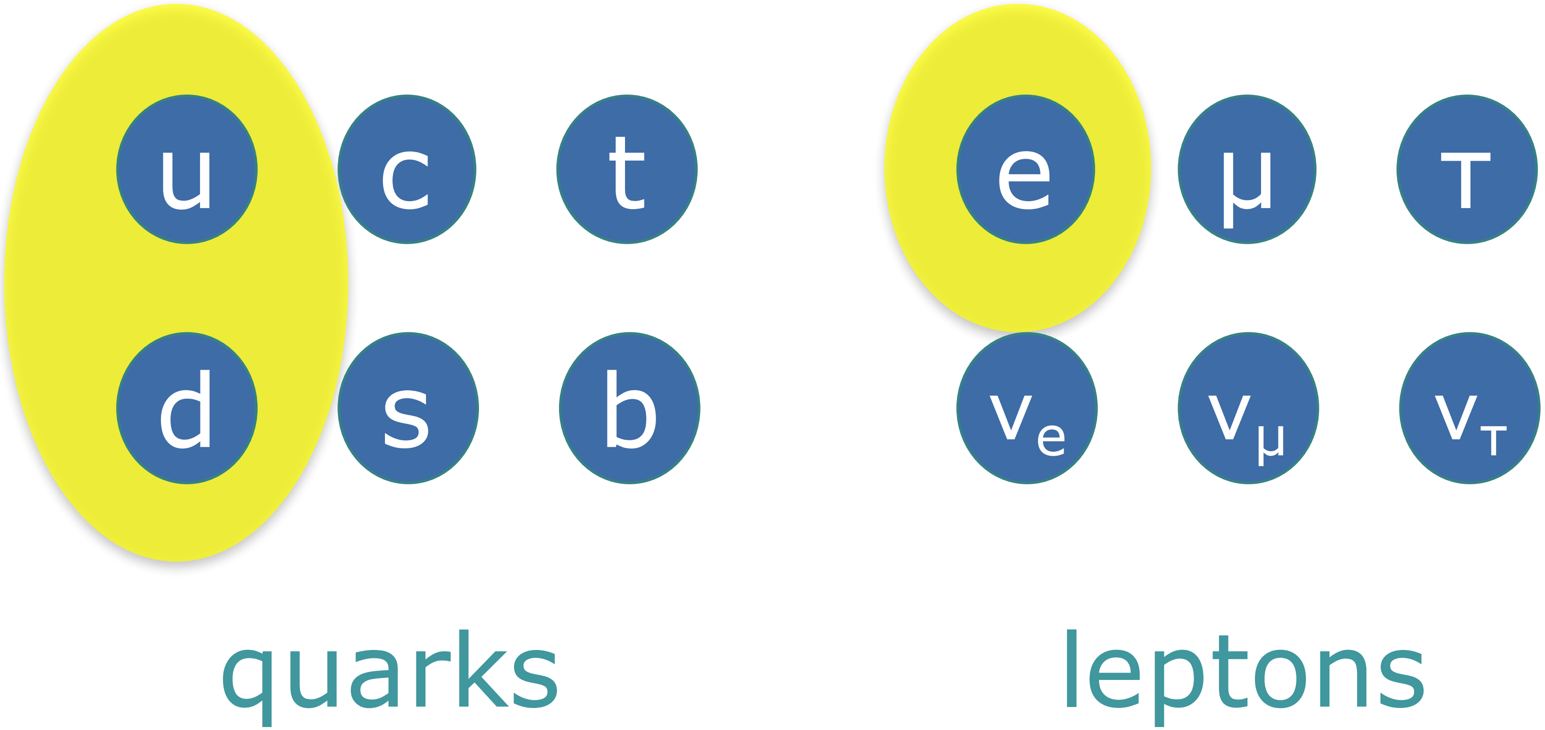
1 fm = 10^{-15} m

Note: often set $\hbar = c = 1$

u	c	t	e	μ	τ
d	s	b	ν_e	ν_μ	ν_τ

quarks

leptons



u,d proposed 1960s, discovered ~1968

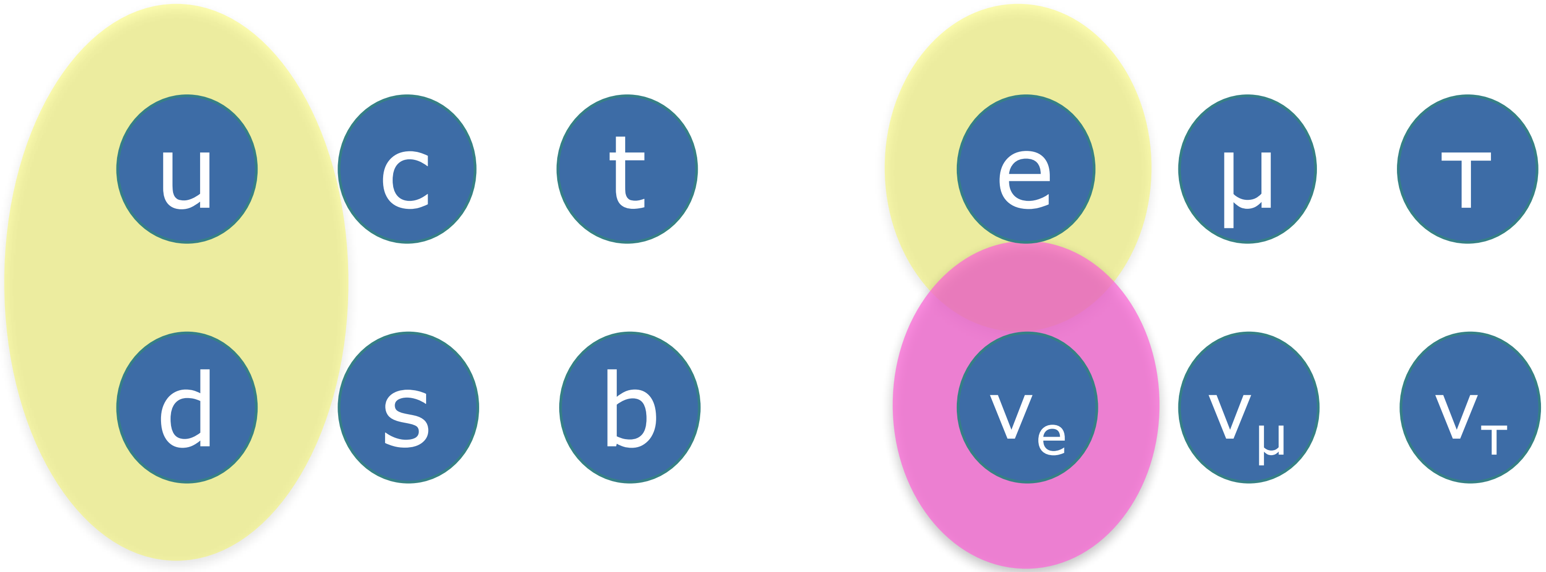
e discovered 1897

1900

2000

1897
Electron
J.J. Thomson, *Philosophical magazine* **44**:293

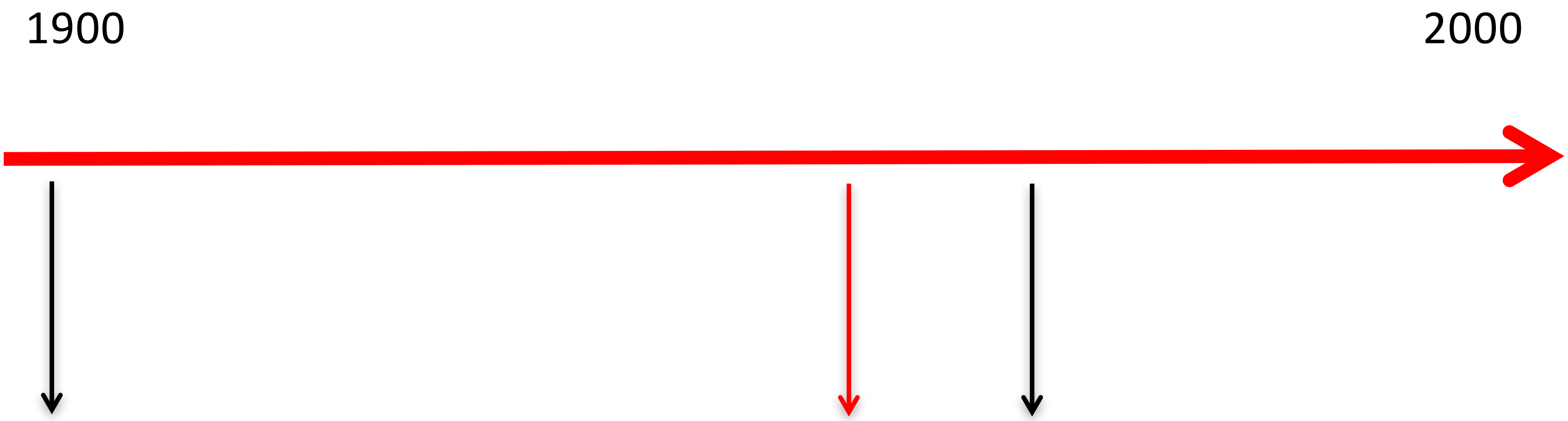
1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235



quarks

leptons

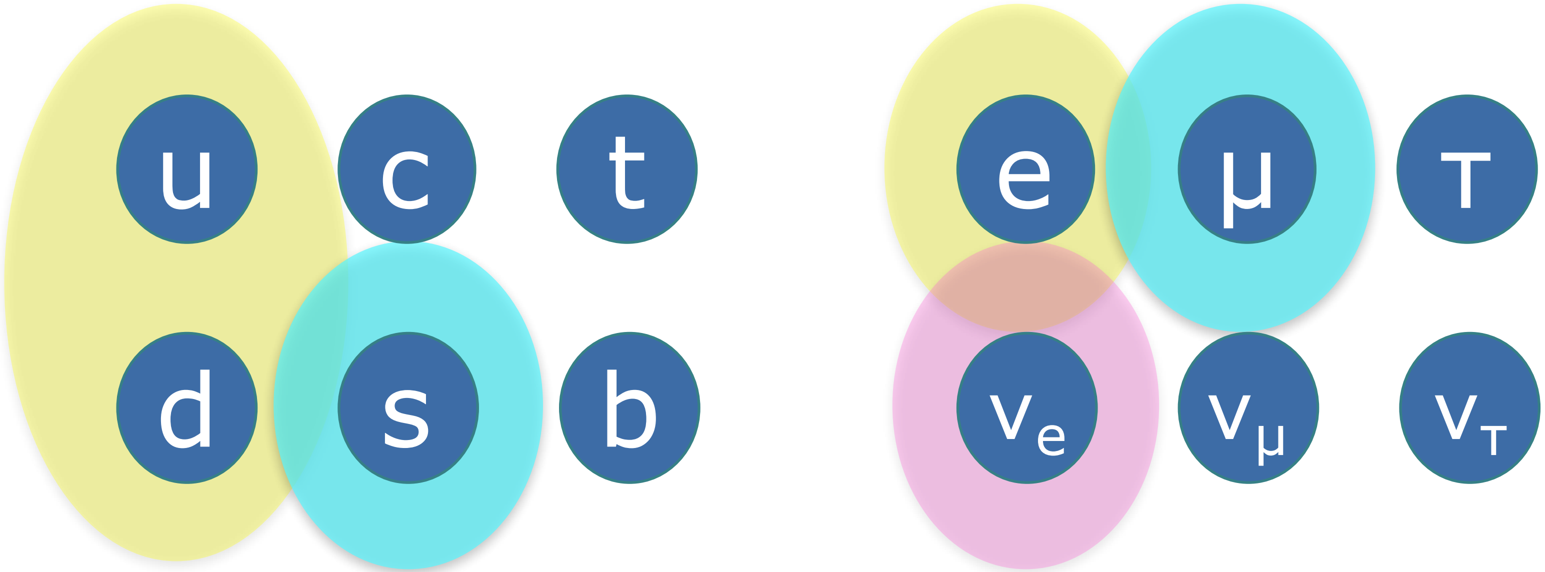
Radioactive decay (inferred 1930s, seen 1956)



1956

Electron neutrino

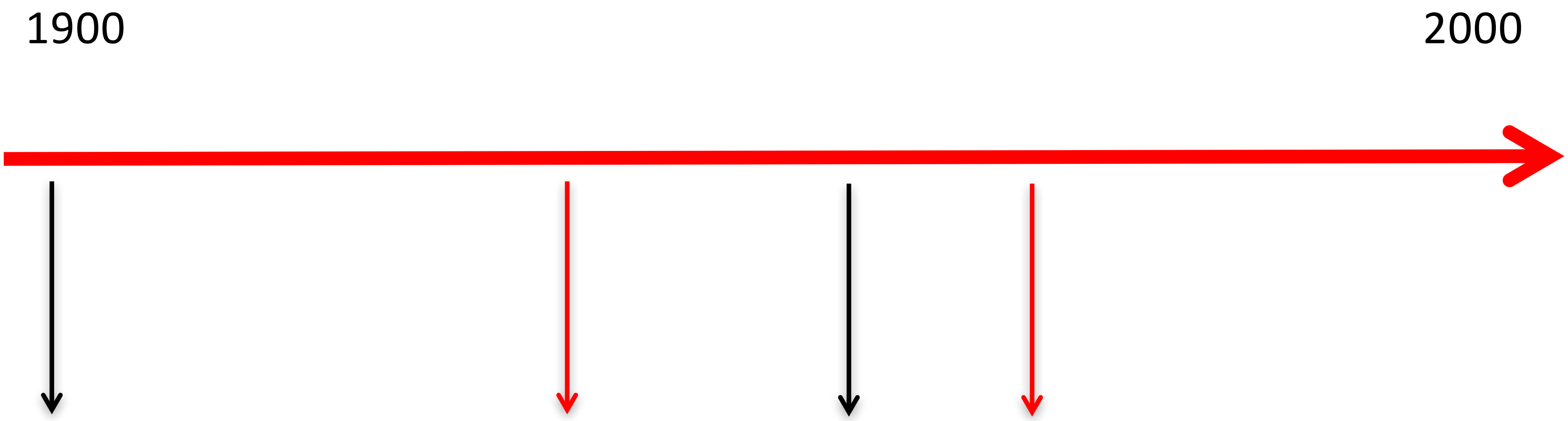
F. Reines, C.L. Cowan, *Nature* **178** (4531): 446



quarks

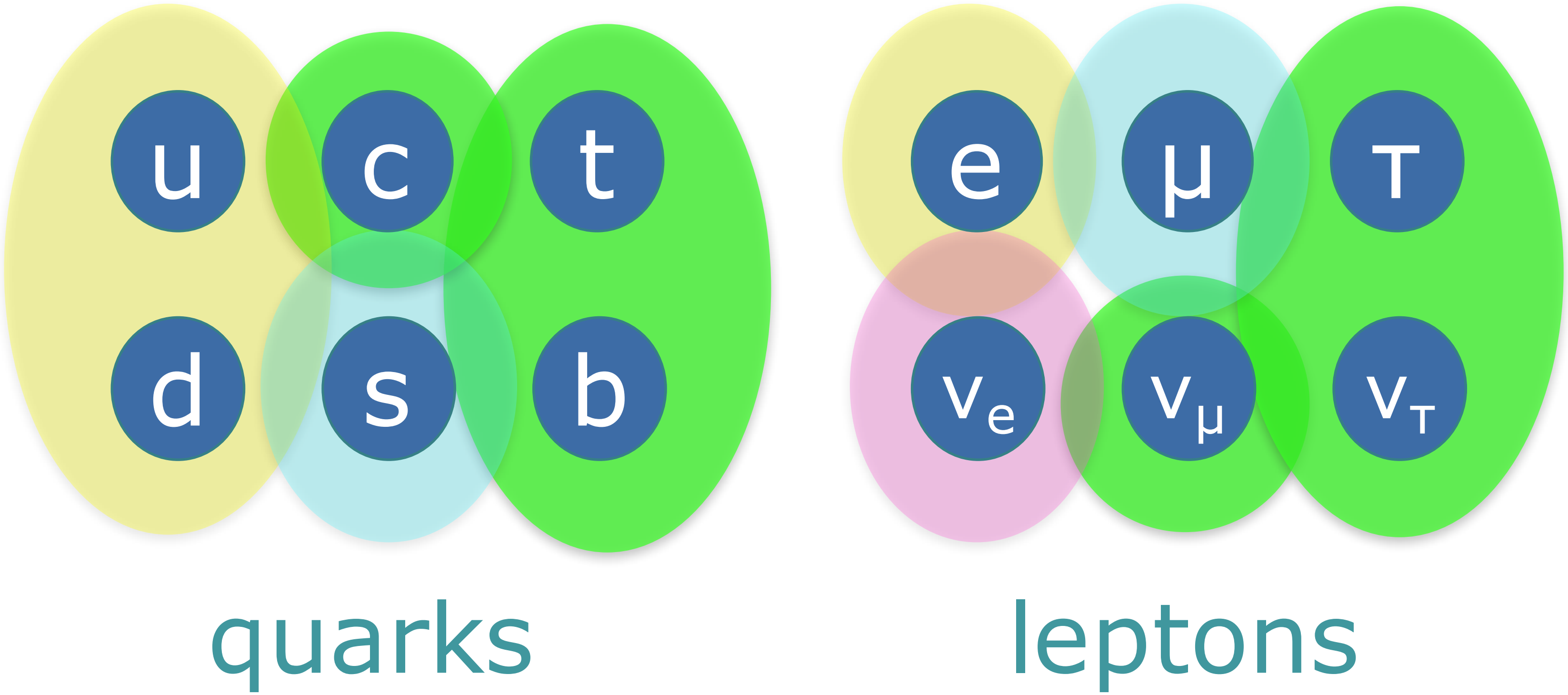
leptons

Cosmic ray experiments (1930s, 1940s)

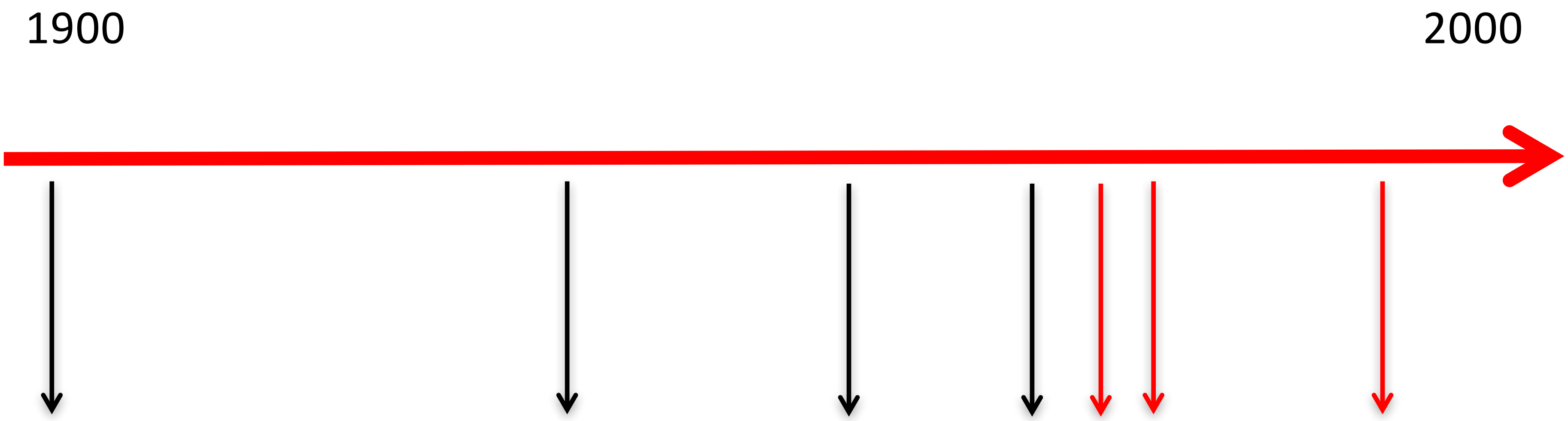


1937
Muon
S.H. Neddermeyer, C.D. Anderson,
Physical Review **51** (10): 884

1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235



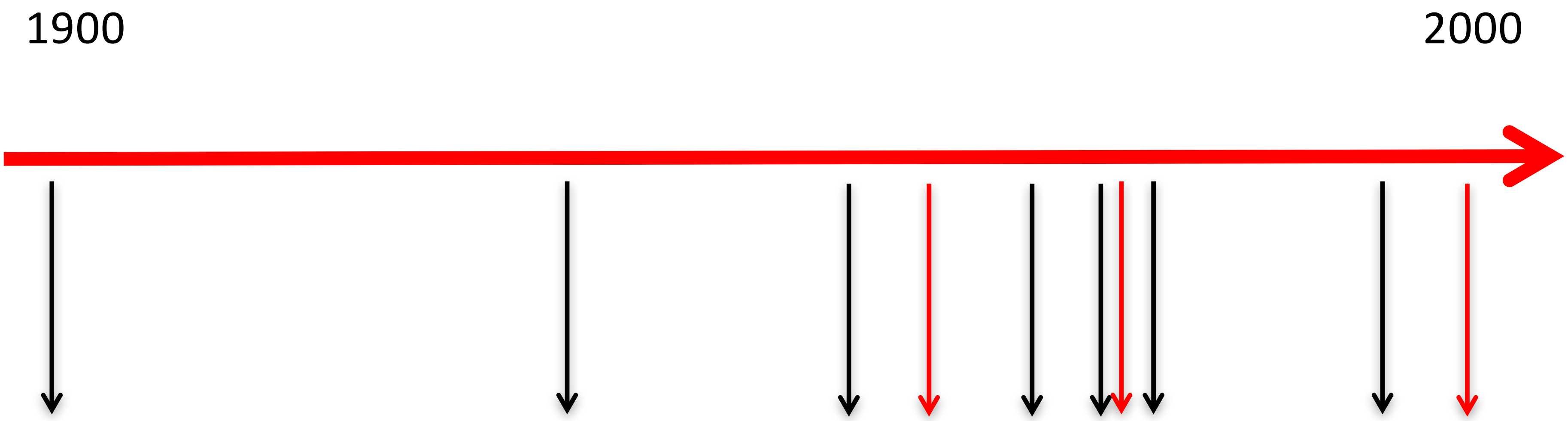
Collider experiments (1960s -)



1974
Charm quarks
J.J. Aubert *et al.* *Physical Review Letters* **33** (23): 1404
J.-E. Augustin *et al.* *Physical Review Letters* **33** (23): 1406

1977
Bottom quarks
S.W. Herb *et al.* *Physical Review Letters* **39** (5): 252.

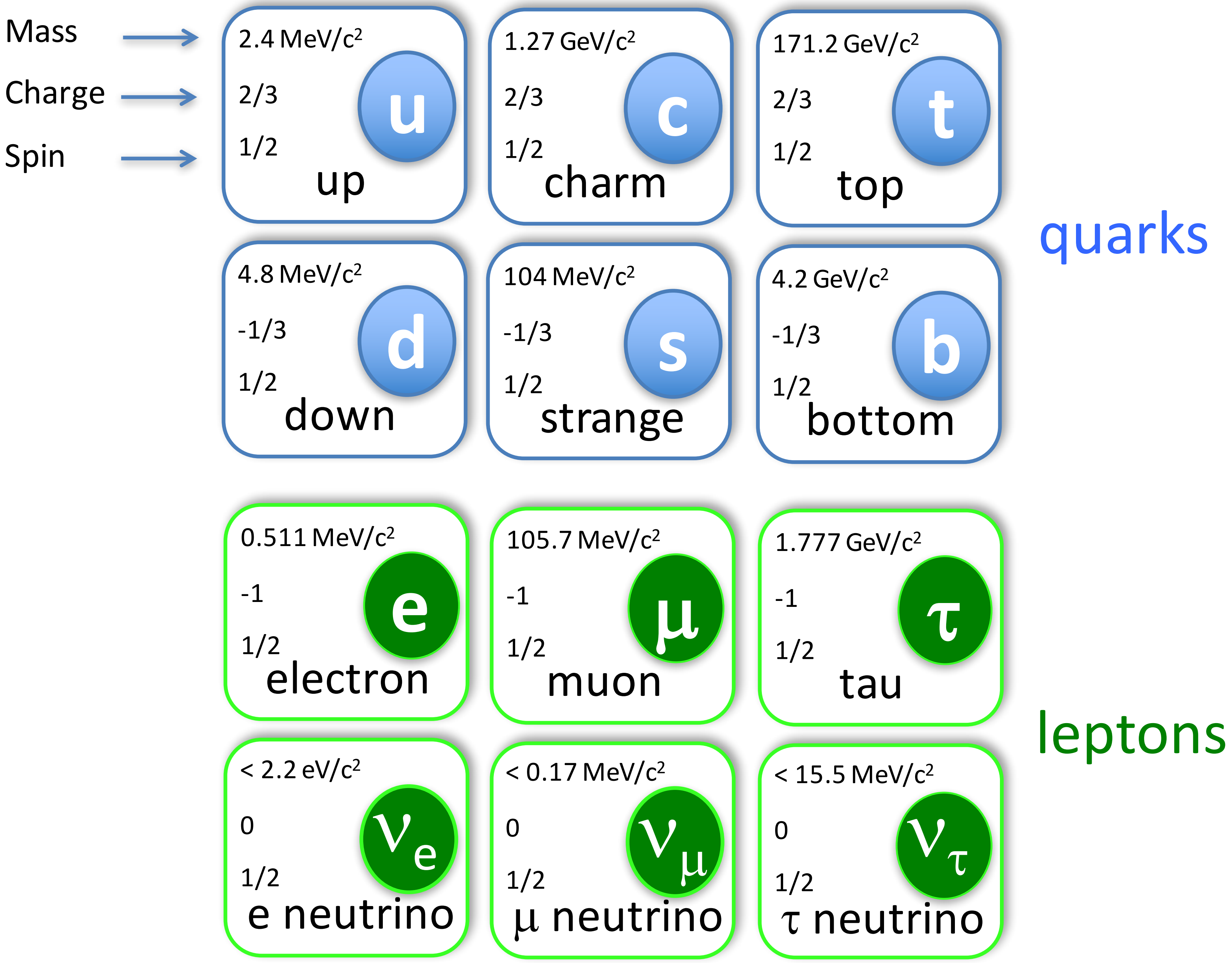
1995
Top quarks
F. Abe *et al.* (CDF collaboration) *Physical Review Letters* **74** (14): 2626–2631.
S. Arabuchi *et al.* (D0 collaboration) *Physical Review Letters* **74** (14): 2632–2637.



1962
Muon neutrino
G. Danby *et al.* *Physical Review Letters* **9** (1):36

1975
Tau lepton
M.L. Perl *et al.* *Physical Review Letters* **35** (22): 1489.

2000
Tau neutrino
K. Kodama *et al.* (DONUT Collaboration),
Physics Letters B **504** (3): 218.



Mass →

Charge →

Spin →

2.4 MeV/c^2 2/3 1/2 u up	1.27 GeV/c^2 2/3 1/2 c charm	171.2 GeV/c^2 2/3 1/2 t top	quarks
4.8 MeV/c^2 -1/3 1/2 d down	104 MeV/c^2 -1/3 1/2 s strange	4.2 GeV/c^2 -1/3 1/2 b bottom	
0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	leptons
< 2.2 eV/c^2 0 1/2 ν_e e neutrino	< 0.17 MeV/c^2 0 1/2 ν_μ μ neutrino	< 15.5 MeV/c^2 0 1/2 ν_τ τ neutrino	

And … antimatter

Einstein's equation of motion*: $E^2 = p^2c^2 + m^2c^4$

Two energy solutions for the same mass;

- Matter
- Antimatter

Every fermion has an antimatter version.

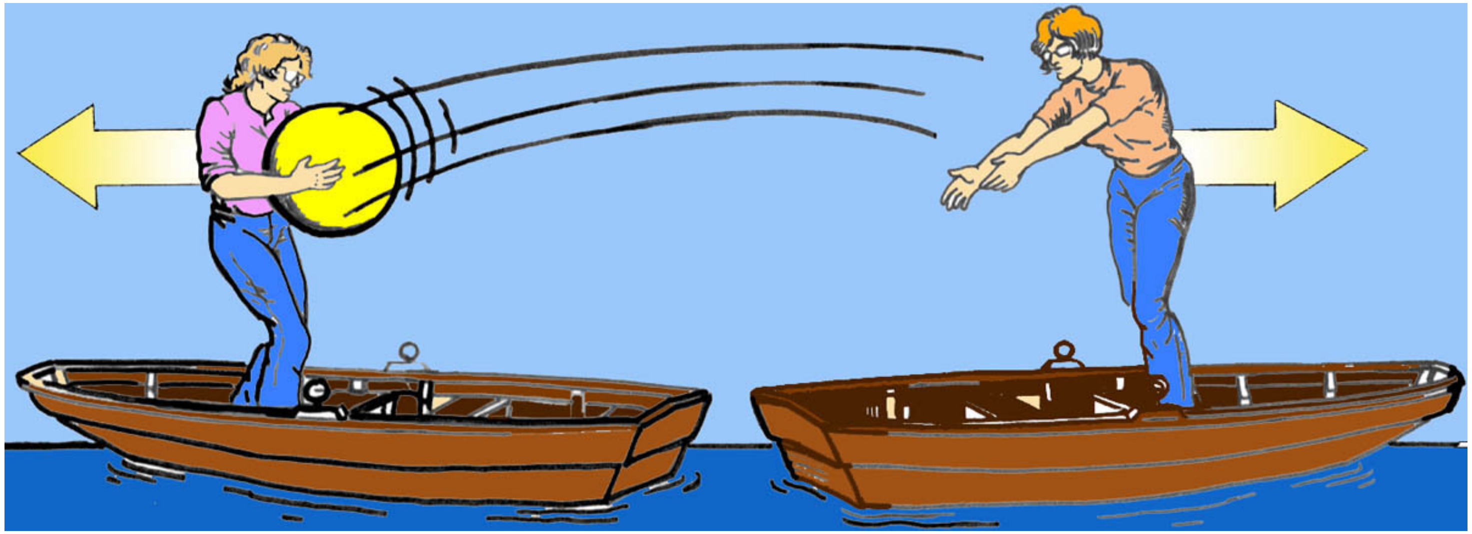
Same mass, opposite charge

eg. antiquark $\bar{q}$, antimuon μ^+, antineutrino $\bar{\nu}$

*(and others, more famously Dirac)

Matter is held together by forces;

- mediated by force carrying particles (bosons; spin 1)



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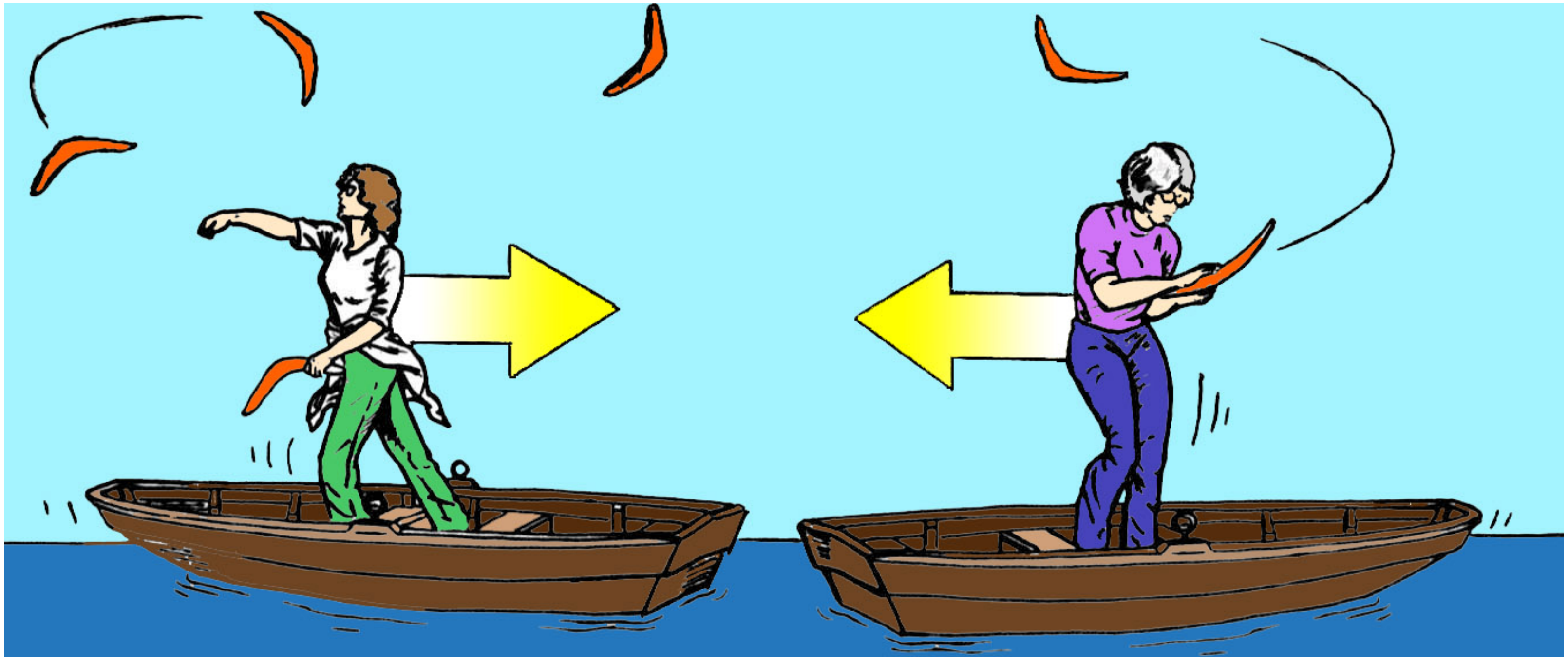
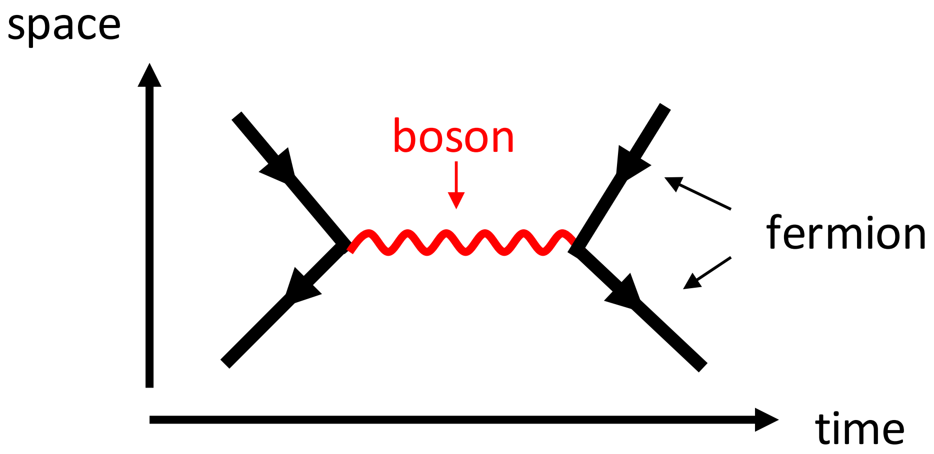


Aside: Feynman diagrams

“tree” level

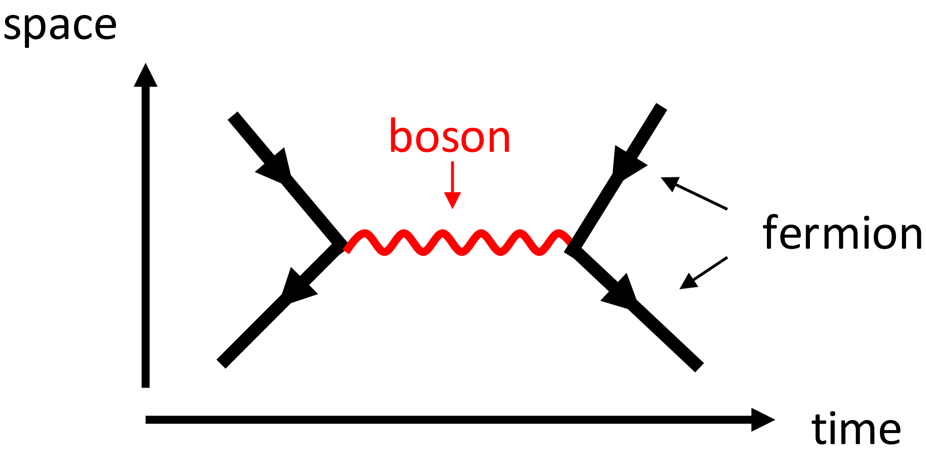
Lowest order



Aside: Feynman diagrams

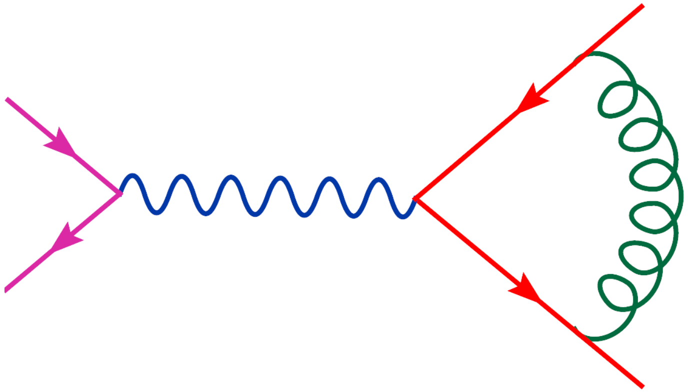
“tree” level

Lowest order



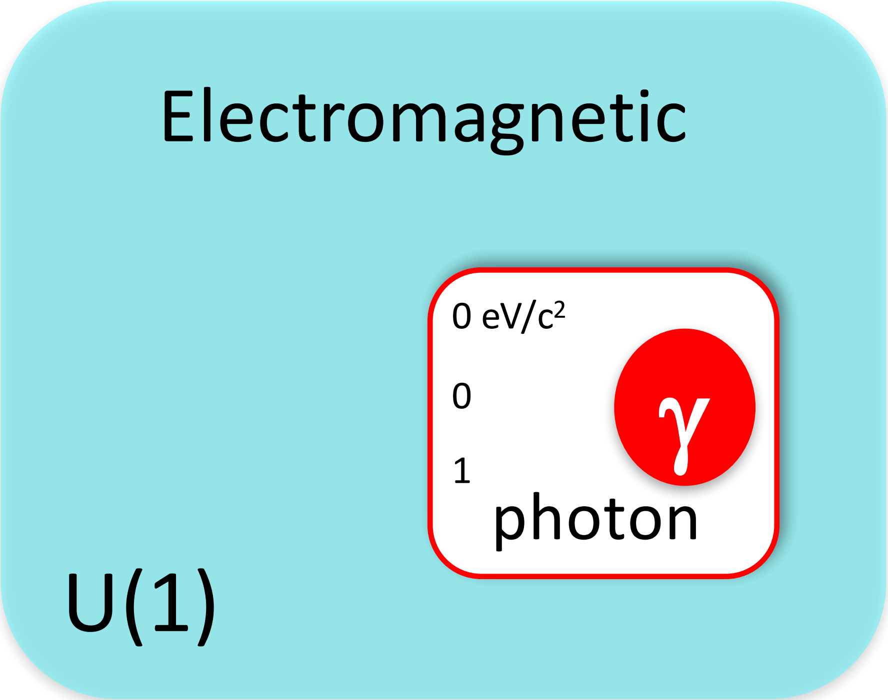
Higher orders possible

Loops



Matter is held together by forces;

- mediated by force carrying particles (bosons; spin 1)
- **3 forces considered in particle physics**



Electromagnetic

0 eV/c^2

0

1

photon

U(1)

Electromagnetic

0 eV/c^2
0
1
γ
photon

U(1)

Weak

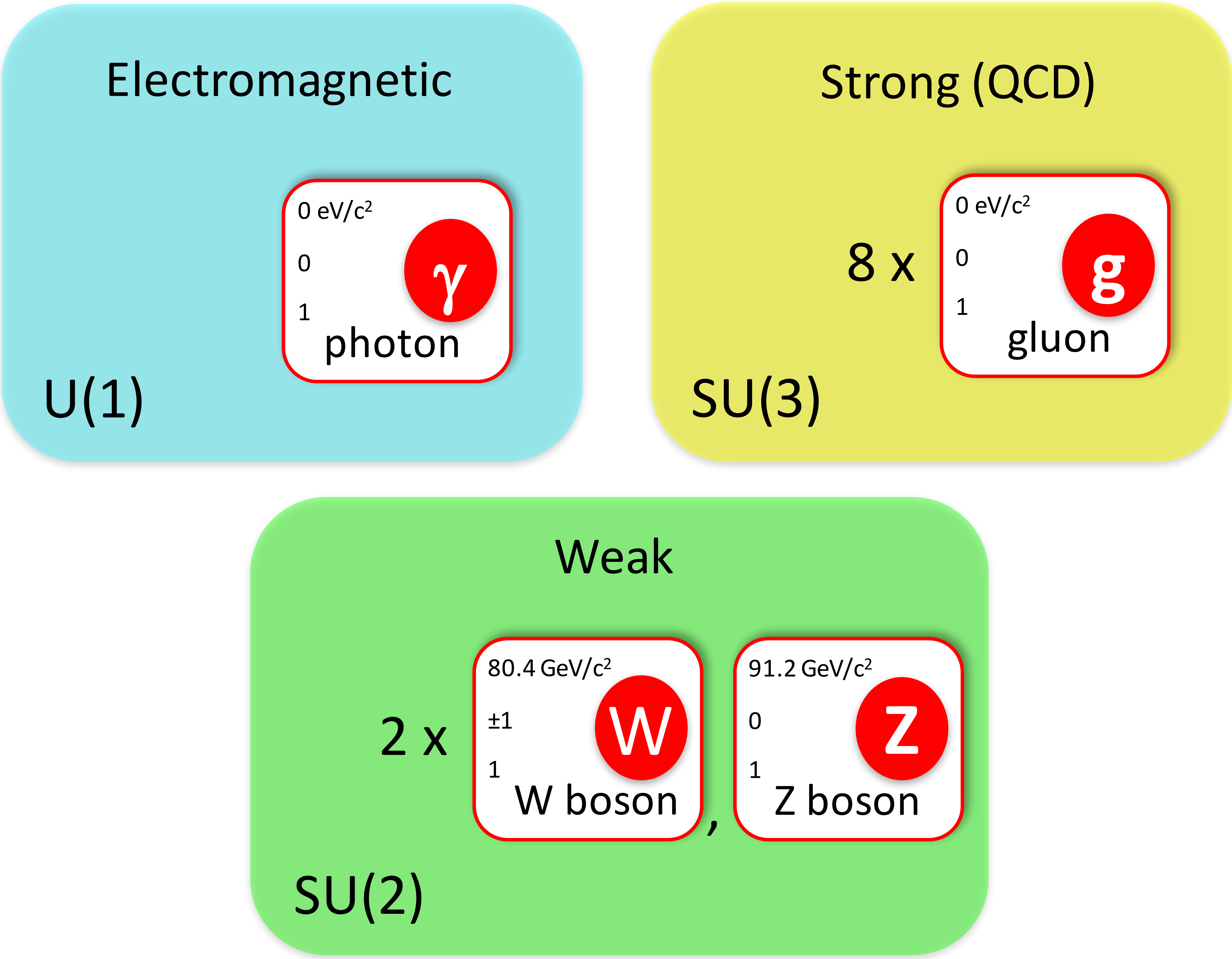
2 x

80.4 GeV/c^2
±1
1
W
W boson

,

91.2 GeV/c^2
0
1
Z
Z boson

SU(2)



Electromagnetic

0 eV/c^2

0

1

γ

photon

U(1)

Strong (QCD)

8 x

0 eV/c^2

0

1

g

gluon

SU(3)

Weak

2 x

80.4 GeV/c^2

±1

1

W

W boson

,

91.2 GeV/c^2

0

1

Z

Z boson

SU(2)

Electromagnetic

0 eV/c^2
0
1
γ
photon

U(1)

Strong (QCD)

8 x

0 eV/c^2
0
1
g
gluon

SU(3)

Weak

2 x

80.4 GeV/c^2
±1
1
W
W boson

,

91.2 GeV/c^2
0
1
Z
Z boson

SU(2)

Note:
No gravity!!

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)

EM force

Electric charge (1)

Massless photon

Weak force

Weak charge (2)

Massive $W^{\pm}$,Z

Strong force

Colour charge (3)

8 massless gluons

Value unknown/
not predicted

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^{\pm}$,Z	8 massless gluons
Coupling g	Coupling g_W	Coupling g_s

Value unknown/
not predicted

EM force

Abelian

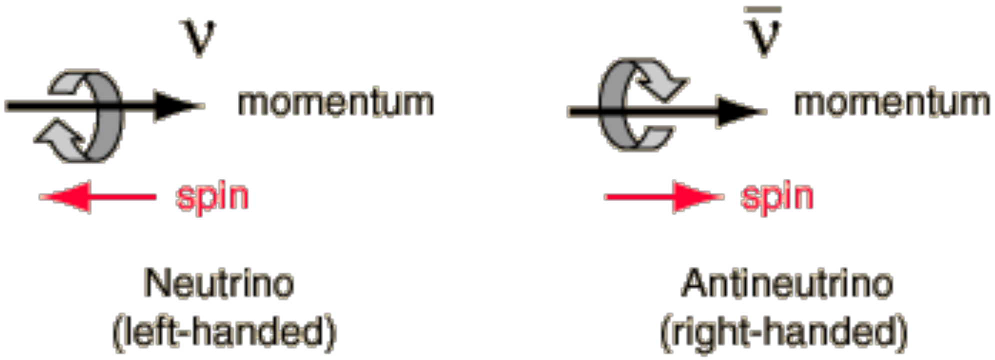
Weak force

Non-abelian

Strong force

Non-abelian

Value unknown/
not predicted



(in massless limit)

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

Strong force

Non-abelian

Only quarks couple

Value unknown/
not predicted

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

Strong force

Non-abelian

Only quarks couple

Value unknown/
not predicted

Where do the differences come from?

EM force

Electric charge (1)

Massless photon

Weak force

Weak charge (2)

Massive $W^{\pm}$,Z

Strong force

Colour charge (3)

8 massless gluons

Value unknown/
not predicted

Massive gauge bosons are a problem

Standard Model equations have a very particular form.

- (local) gauge invariance* imposed
- satisfied if we derive equations treating matter and forces together, and if **bosons are massless**.

Massive gauge bosons require a gauge-invariant fix-up to our theory.

=> Higgs mechanism

* See your Standard Model course.

Higgs

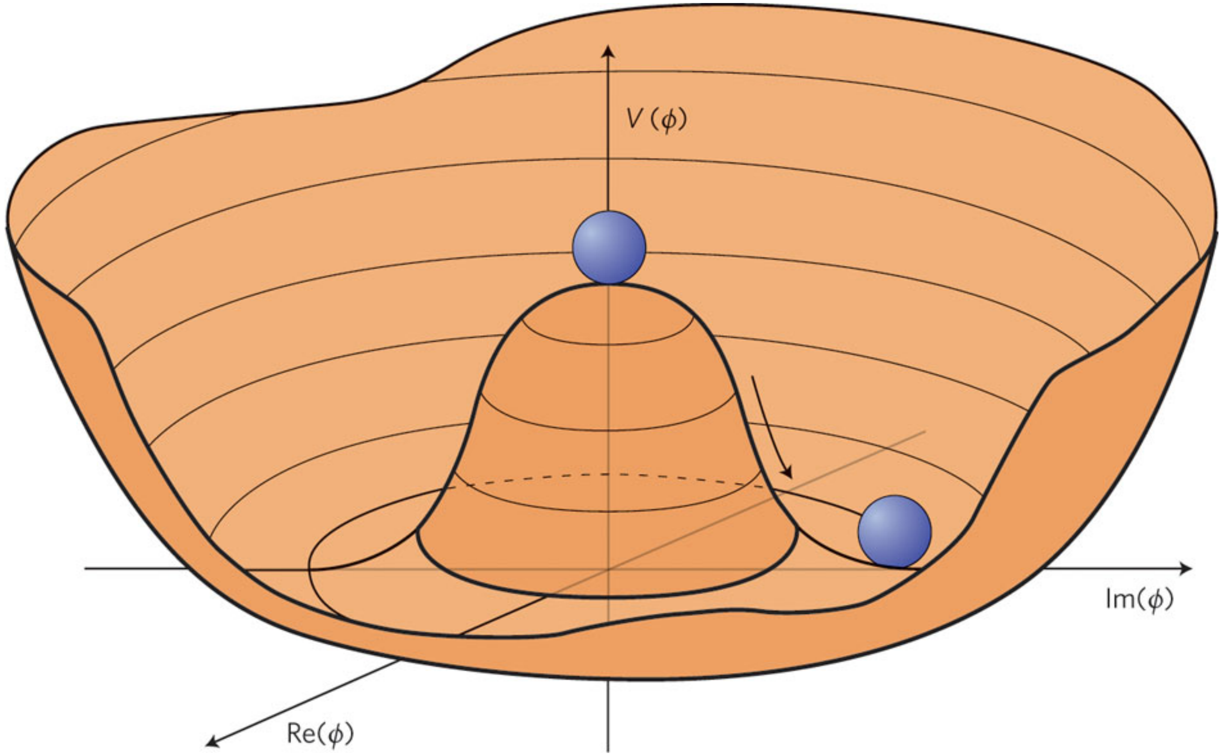
Introduce Higgs field ϕ:

Complex doublet (but 1d case shown here to get idea)

$V(\phi) = -0.5\mu^2|\phi|^2 + \lambda|\phi|^4$

Shape of potential:

- $\mu^2 < 0$
- $\lambda > 0$



Higgs

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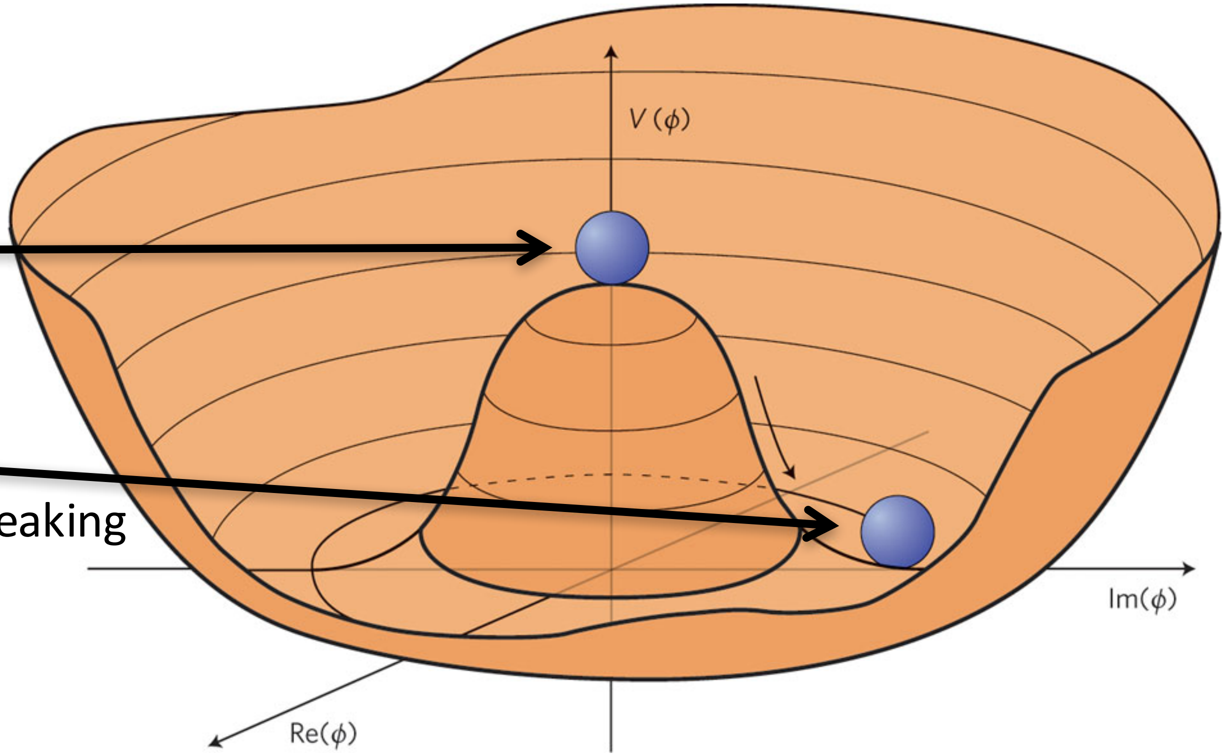


Big Bang
Massless bosons

Shortly (~10^{-12} s) after
Spontaneous symmetry breaking
Bosons acquire mass
(nb. fermions too)

Higgs

Introduce Higgs field :

Couples to particles to give mass (amount ~ coupling strength)

Higgs

Introduce Higgs field :

Couples to particles to give mass (amount ~ coupling strength)

Complex doublet has **4 free parameters**

- 3 absorbed into W+, W-, Z boson mass
    - W+, W-, Z, γ admixtures of original weak, em massless bosons.
- 1 manifested as a massive Higgs boson (m_H)

Connection between weak and electromagnetic forces

Higgs

Introduce Higgs field :

Couples to particles to give mass (amount ~ coupling strength)

Complex doublet has 4 free parameters

3 absorbed into W+, W-, Z boson mass

W+, W-, Z, γ admixtures of original weak, em massless bosons.

1 manifested as a massive Higgs boson (m_H)

(note: Higgs field gives mass to fermions by a different mechanism)

Yukawa coupling; yet to be fully tested.

- No deep explanation; motivated by simplicity.

Higgs

Introduce Higgs field :

After symmetry breaking, Higgs sector properties are:

- spinless Higgs boson (m_H)
- vacuum expectation value (mean field value) (v)

Consequences:

Weak and electromagnetic forces connected

Massive Z is mixture of massless em + weak bosons

Relates Mw, Mz and weak, electromagnetic couplings:

$\tan \theta_W = g_W / g$

$M_W = M_Z \cos \theta_W$


1
A | B | C | D | E
Conference Rooms
Salles de conférences
07:30:38
A
Main Amphitheatre
06:00
Latest update in the search for the Higgs boson
13:00
maintenance
E
Council Chamber
01:00
DG-CO meeting

July 4th 2012

126 GeV/c^2

0

0

H

Higgs

The Economist

JULY 7TH–13TH 2012

Economist.com

In praise of charter schools

Britain's banking scandal spreads

Volkswagen overtakes the rest

A power struggle at the Vatican

When Lonesome George met Nora

A giant leap for science

Finding the Higgs boson

~7 years later .. you are here

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^{\pm}$,Z	8 massless gluons
Coupling $\mathbf{g}$	**Coupling** $\mathbf{g_W}$	**Coupling** $\mathbf{g_s}$

Value unknown/
not predicted

Force Strengths:

Quantified by "**coupling constants**" $\alpha = \frac{g^2}{4\pi}$

Strong: $\alpha_s \sim 1$

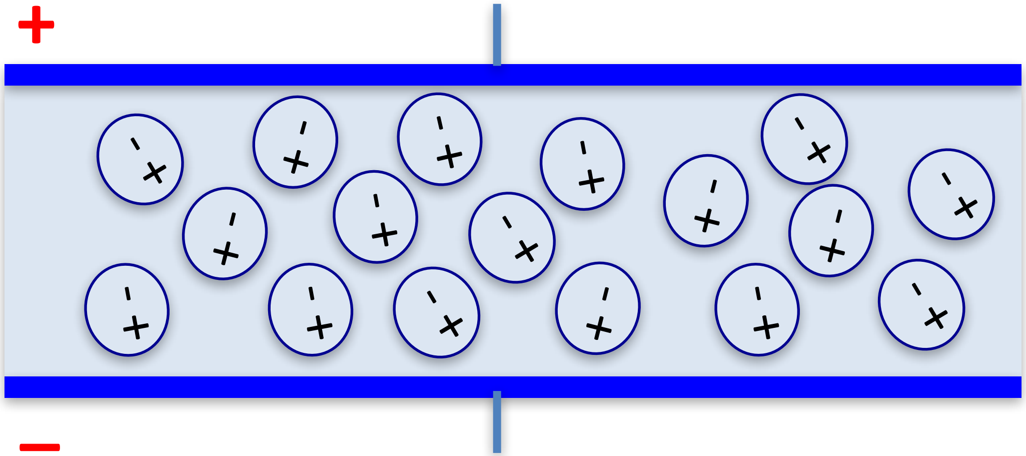
Electromagnetic: $\alpha_{em} \sim 1/137$

Weak: $\alpha_W \sim 10^{-6}$

Gravity: $\alpha_g \sim 10^{-40}$

(note: low energy/large distance scale values. Coupling strength changes with energy)

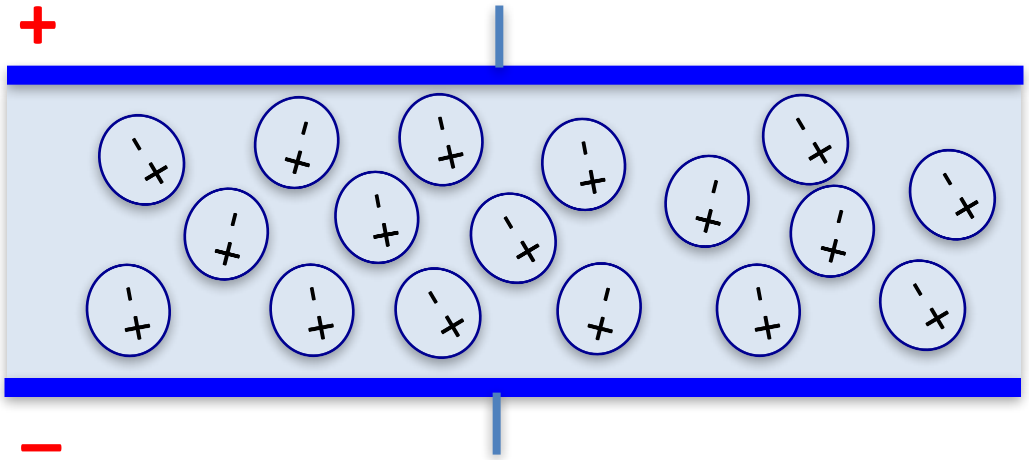
Running couplings

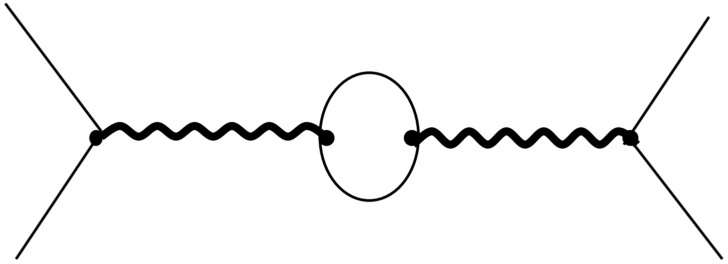


Parallel plate capacitor

Dielectric reduces apparent charge on plates (polarisation)

Screening of charge.



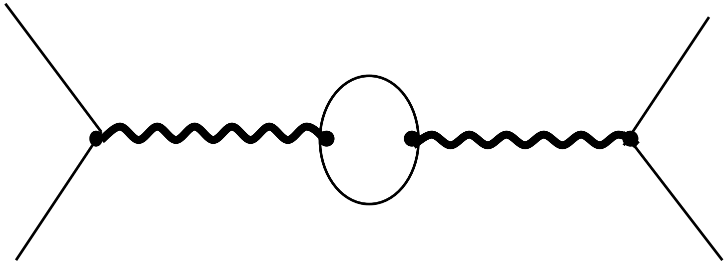


Screening of charge by **vacuum polarisation**;

High E ⇒smaller distances ⇒see more charge

Coupling increases with E

Non-Abelian effects

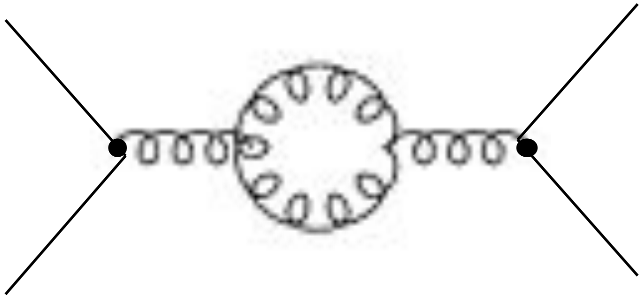


Screening of charge by vacuum polarisation;

High E ⇒smaller distances ⇒see more charge

Coupling increases with E

+



Non-abelian forces also include these “extra” charge loops

Net effect: **coupling decreases with E**

Note:

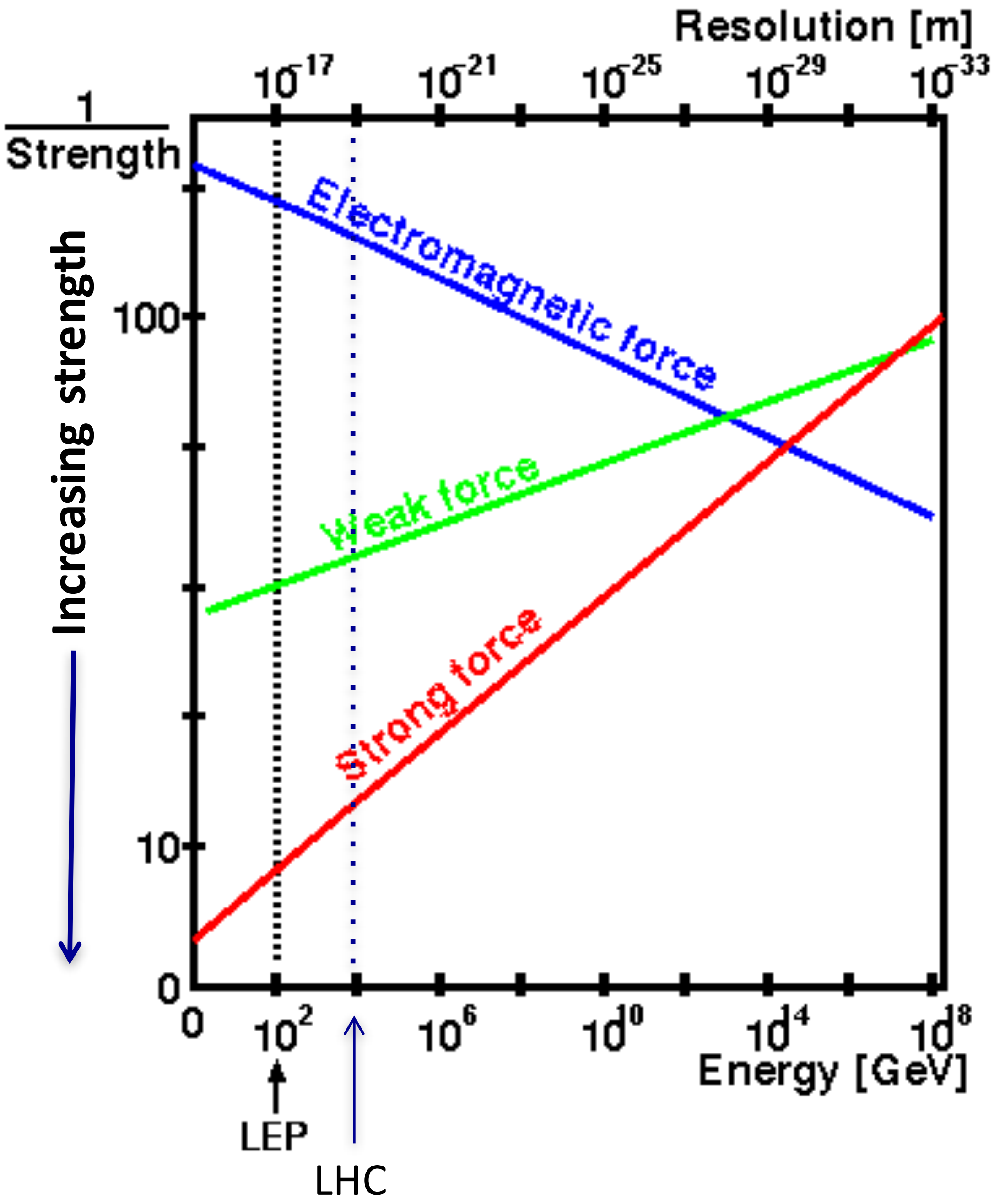
1/coupling plotted.

1/em falls with E.

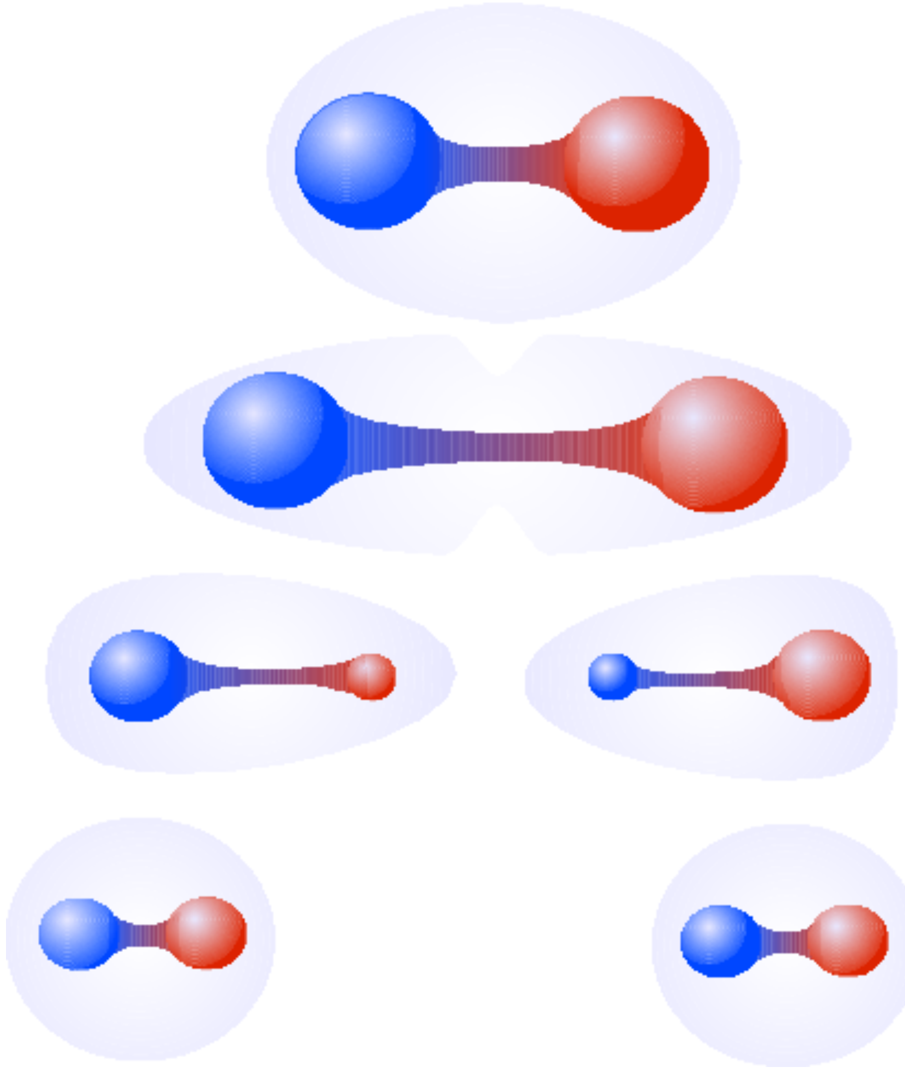
1/weak rises with E.

1/strong rises with E.

(note: weak force isnt as weak as it appears, this is intrinsic strength. Apparent strength is diluted by W mass)



Implications: QCD



Force grows with distance.

Confinement

- No free quarks
- Colourless hadrons
  - Baryons (3 q)
  - Mesons (q anti-q)
  - Tetraquarks? (2q 2anti-q)
  - Pentaquarks? …?

Hadronisation

- jets

Quantum Electrodynamics: QED

Quantum Chromodynamics: QCD

Quantum Electrodynamics: QED

Electric charge → Atoms → Molecules

Quantum Chromodynamics: QCD

Colour charge → Baryons → Nucleus

Quantum Electrodynamics: QED

Electric charge → Atoms → Molecules

Interaction of electric charges and photons

Quantum Chromodynamics: QCD

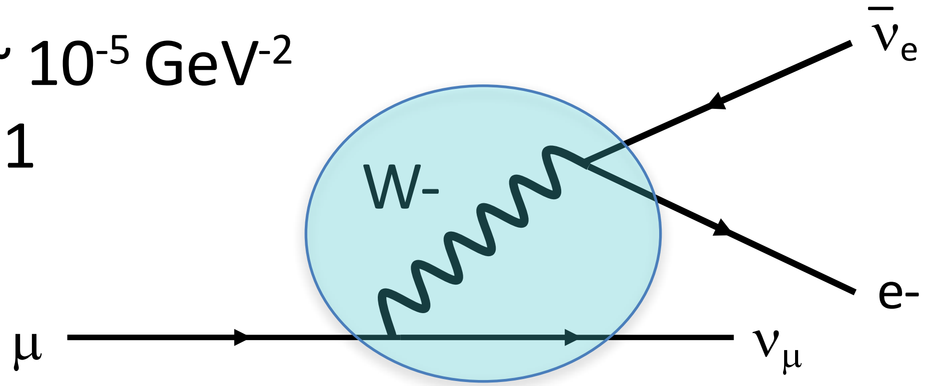
Colour charge → Baryons → Nucleus

Interaction of colour charges and gluons

Different forces, but **similar** (mathematical) structure/behaviour

Weak force vs. EM, QCD?

Muon decay:
Strength of weak force ~ G_F ~ 10^{-5} GeV^{-2}
cf. strength of em force ~ 0.01



W boson **massive**
Factor involved in boson exchange ~ $1/(E^2+M^2)$ (hence units)
Strength of weak force = em force if M~ 30 GeV (M$_W$~80 GeV)

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

Strong force

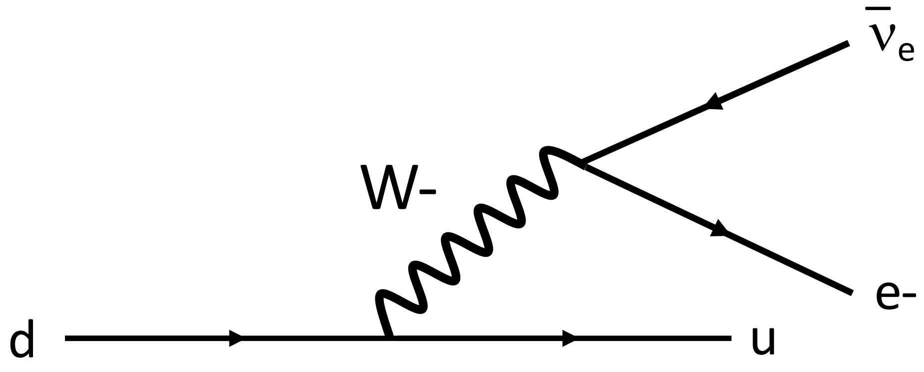
Non-abelian

Only quarks couple

Value unknown/ not predicted

Weak force interactions

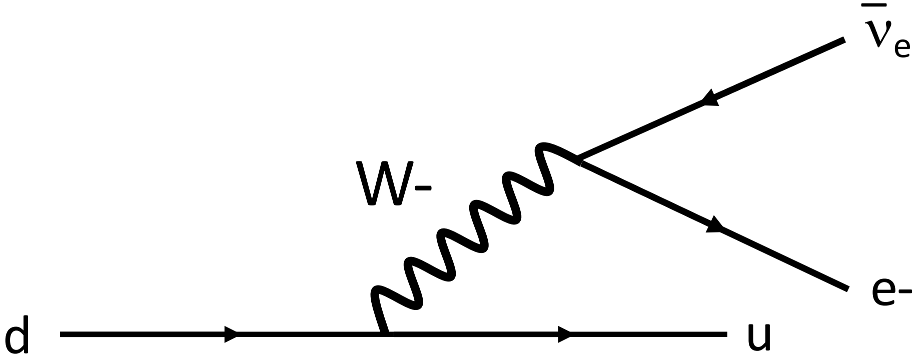
W couples to:
Upper and lower members of a fermion generation.
L- (R-) handed (anti)particles



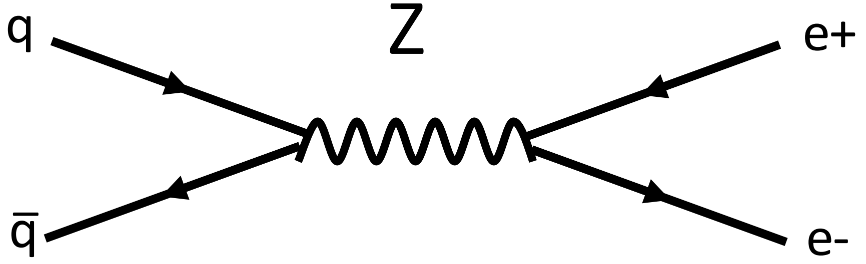
(observed, not predicted behaviour)

Weak force interactions

W couples to:
Upper and lower members of a fermion generation.
L- (R-) handed (anti)particles



Z couples to:
Matter and antimatter versions of a fermion.
Complicated mix of L-, R- particles.



“vector, axial couplings”; Higgs mechanism.

EM force

Abelian

Only charged particles couple

Weak force

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

Strong force

Non-abelian

Only quarks couple

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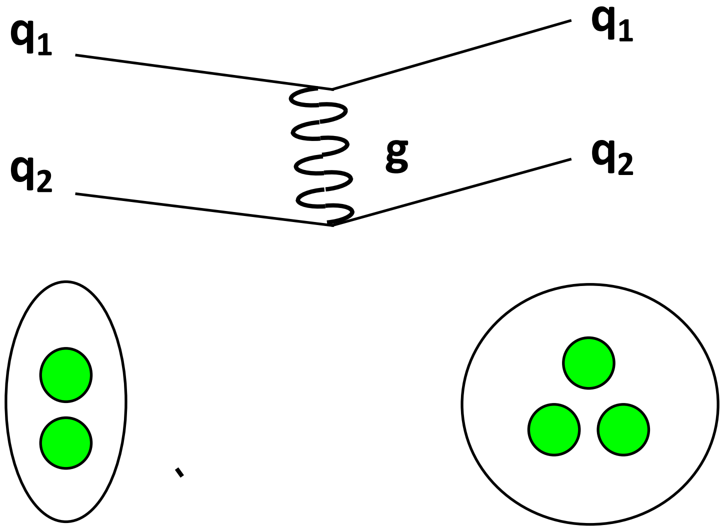
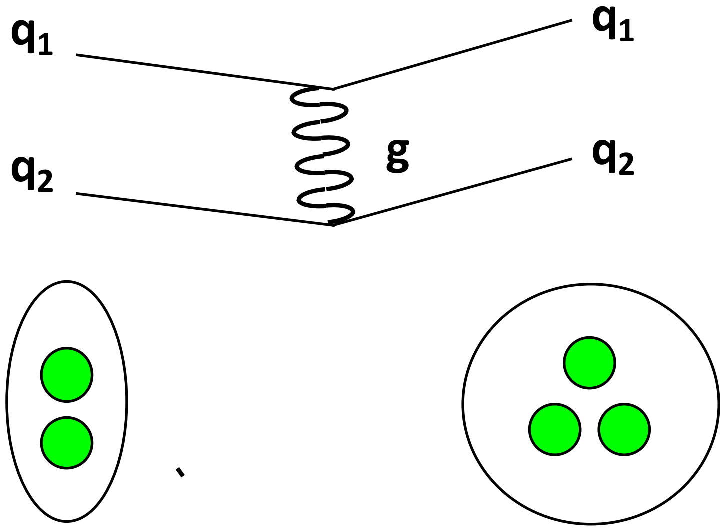
Weak vs. mass quark eigenstates

Mass eigenstates of quarks form hadrons



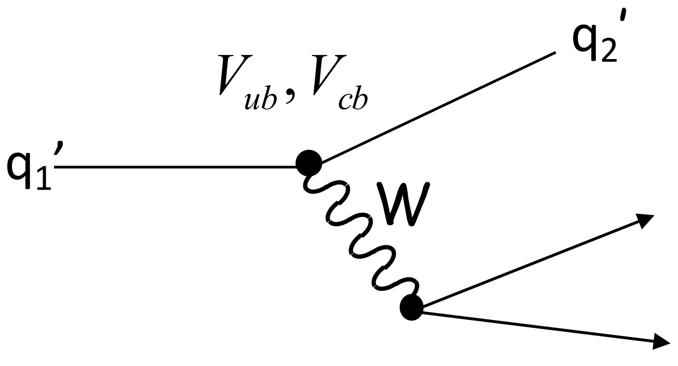
Weak vs. mass quark eigenstates

Mass eigenstates of quarks form hadrons



W couples to weak quark eigenstates q’

q’ admixture of q and vice versa



Quark mixing

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak, mass eigenstates related by mixing matrix in SM (3x3 matrix)

Mixing matrix is unitary (inverse = complex conjugate)

CKM matrix

CKM matrix (1973 – before charm! Predicted 3rd generation)

Elements describe every weak quark transition

SM does not predict existence of or values for matrix elements (couplings of W to quarks).

Input by experimental data

$$V_{CKM} = \begin{matrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{matrix}$$

CP violation

C = charge operator
P = parity operator

CP operation changes particle q to antiparticle $\bar{q}$ (and vice versa)
CP **violation** if q→q’ rate different to q’→q ie. $V_{qq'} \neq V^{*}_{qq'}$

CP violation observed in weak decays.

Note:

- **SM does not predict** CP violation.
- **SM does not explain** CP violation.
- CP violation **must be added** to SM.

CP violation

- Need 3 generations of quarks to introduce CP violation into theory

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} \qquad\qquad & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mixing matrix is 3x3.

Unitarity constraints $\Rightarrow$ 4 independent parameters

3 angles quantify mixing between (1,3) (2,3) (1,2) generations, **1 complex phase** (mechanism for introducing CP)

Aside: neutrino CP violation, mixing

- Similar framework adopted for neutrinos (PMNS matrix). Weak (v_e, v_μ, v_τ) related to mass eigenstates (v_1 etc):

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{pmatrix} \quad & \quad & \quad \\ & & \\ & & \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

3 angles quantify mixing between (1,3) (2,3) (1,2) generations, **1 complex phase** (mechanism for introducing CP)

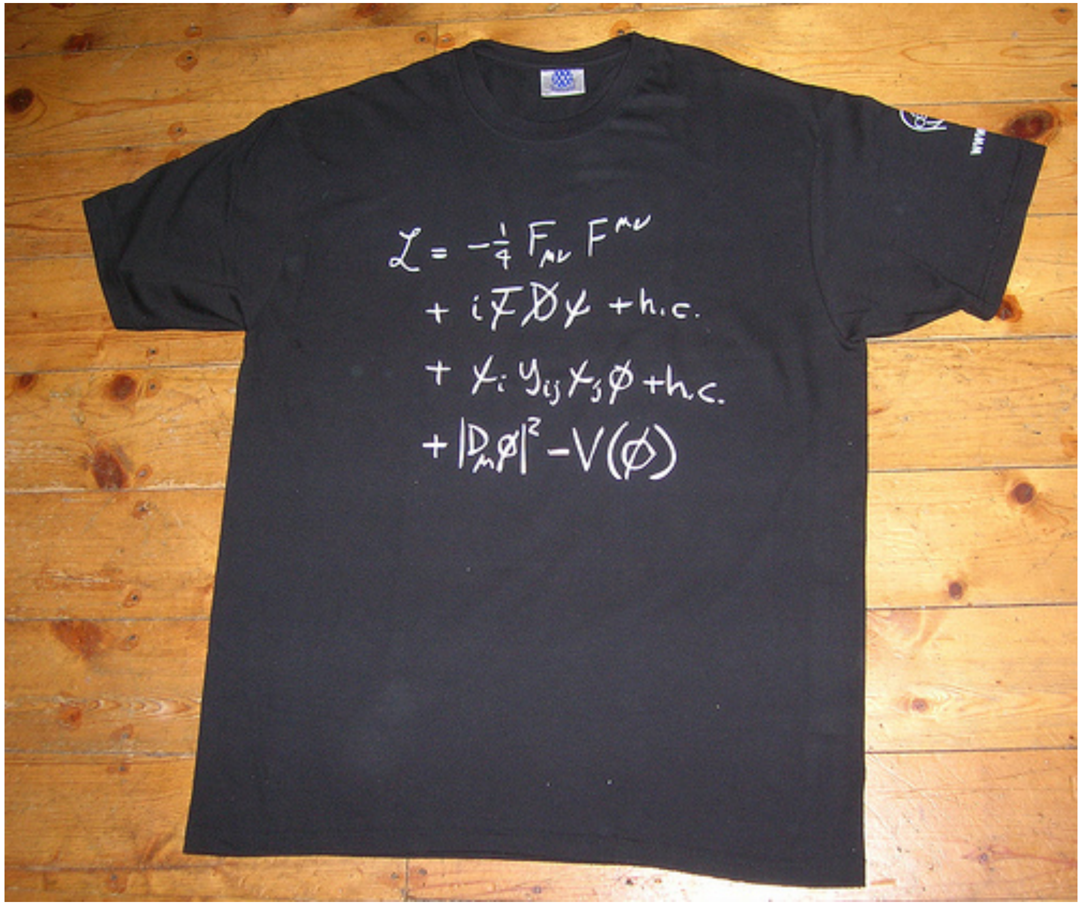
Note: parameters investigated in dedicated neutrino experiments

Standard Model

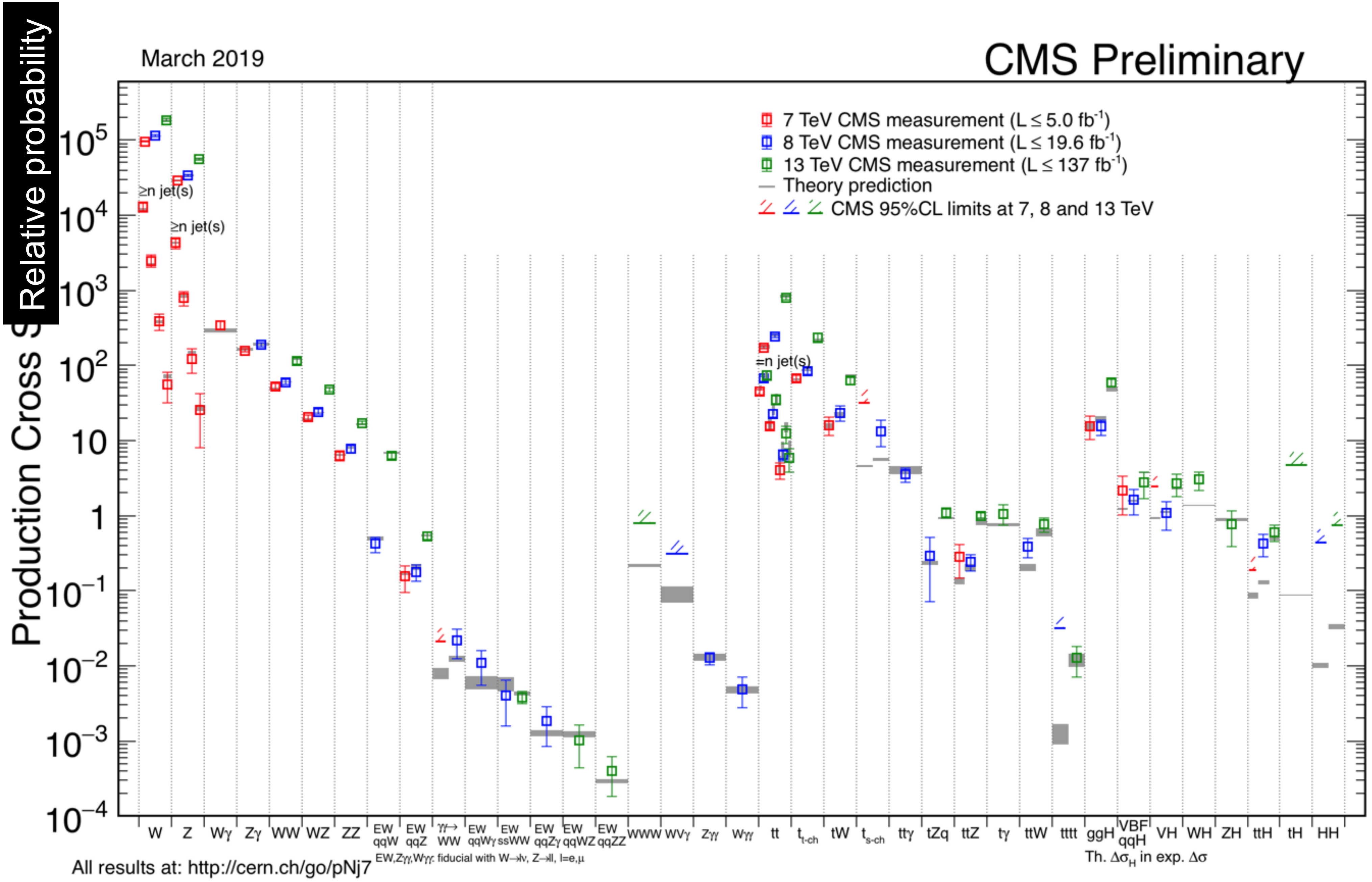
Standard Model (SM)

Quantum field theory based on lagrangians

We use the SM to predict experimental observations



Standard Model 15/7/19
HEP theory concepts 8/7/19


Relative probability
March 2019
CMS Preliminary
Production Cross S
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 137 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW qqWγ
EW ssWW
EW qqZγ
EW qqWZ
EW qqZZ
WWW
WVγ
Zγγ
Wγγ
tt
t_t-ch
tW
t_s-ch
ttγ
tZq
ttZ
tγ
ttW
tttt
ggH
VBF qqH
VH
WH
ZH
ttH
tH
HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

Successes

Consistent with experiment

No deviations seen

Predictions (eg Higgs) proven

Holes

Incomplete (eg. no gravity)

Few explanations

Many ad-hoc additions to fit experimental data

Successes

Consistent with experiment

No deviations seen

Predictions (eg Higgs) proven

Holes

Incomplete (eg. no gravity)

Few explanations

Many ad-hoc additions to fit experimental data

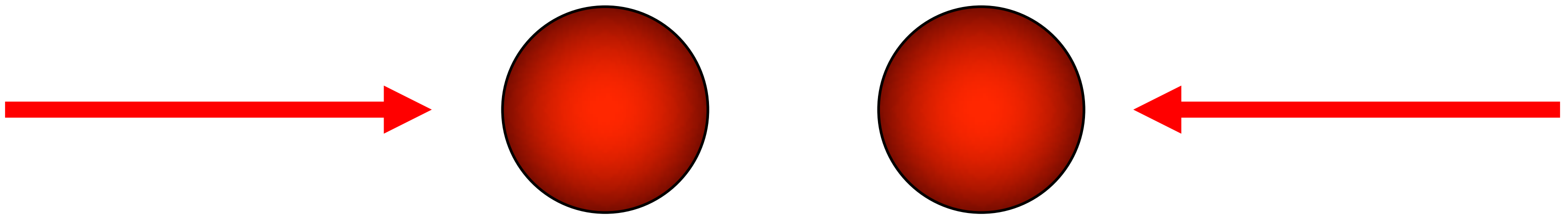
Need to find a breakdown to move forward.

Need experiments.

Experiments.

Particle accelerators

Beams of charged particles accelerated by electromagnetic force*.



Centre of mass energy: $\sqrt{s} = \sqrt{\left(\sum_i E_i^2 - \sum_i p_i^2\right)}$

* Note: also used as sources; cosmic rays, neutrinos from nuclear reactors.

Linear

No bremsstrahlung

Long (for high energy)

“one shot” accelerator

Circular

Bremsstrahlung

Strong magnets needed to maintain circular beam path

Long beam lifetime; many revolutions, many collisions.

Protons vs. electrons

Accelerators 8/7/19, 9/7/19, 31/7/19
Medical physics 29/7/19

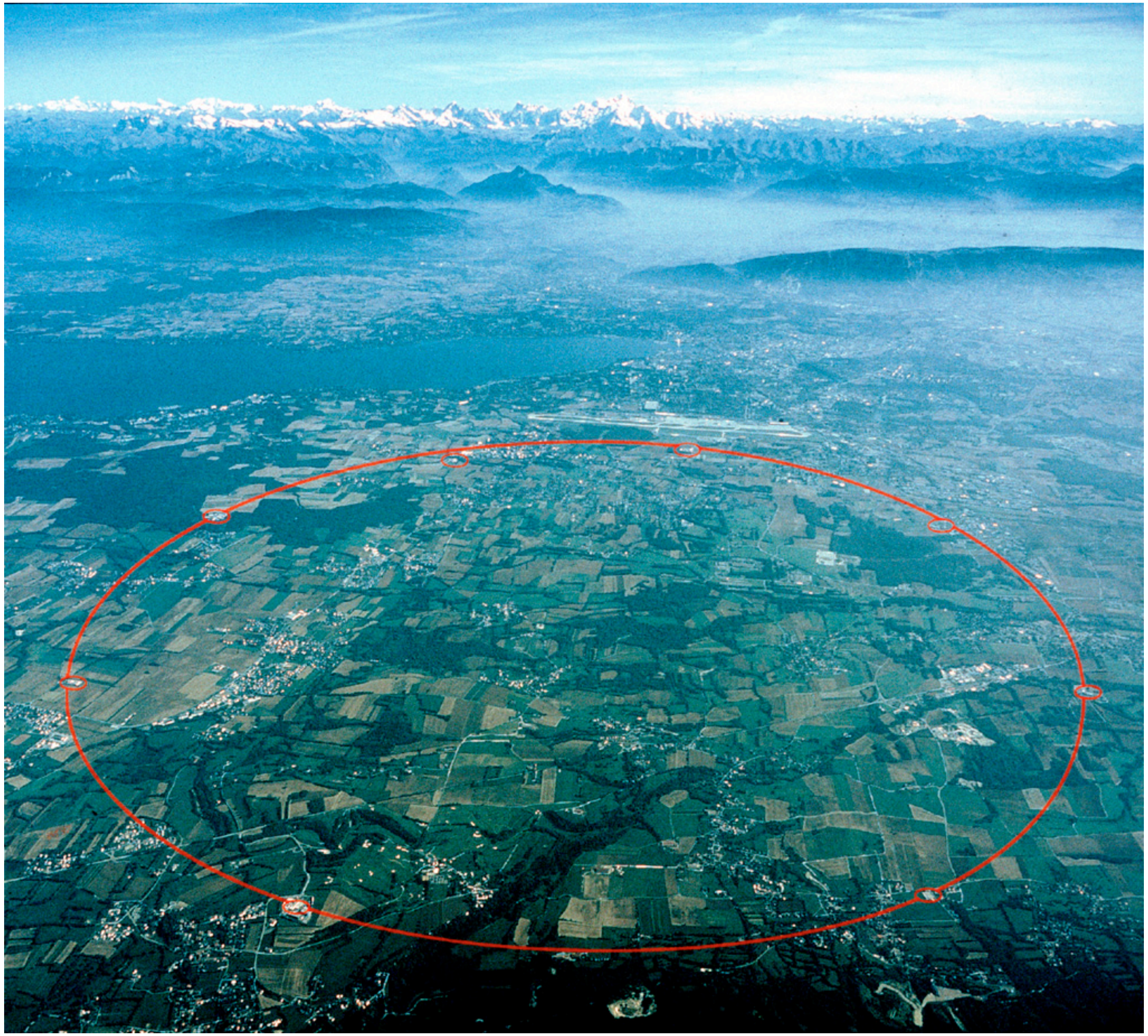
LHC:

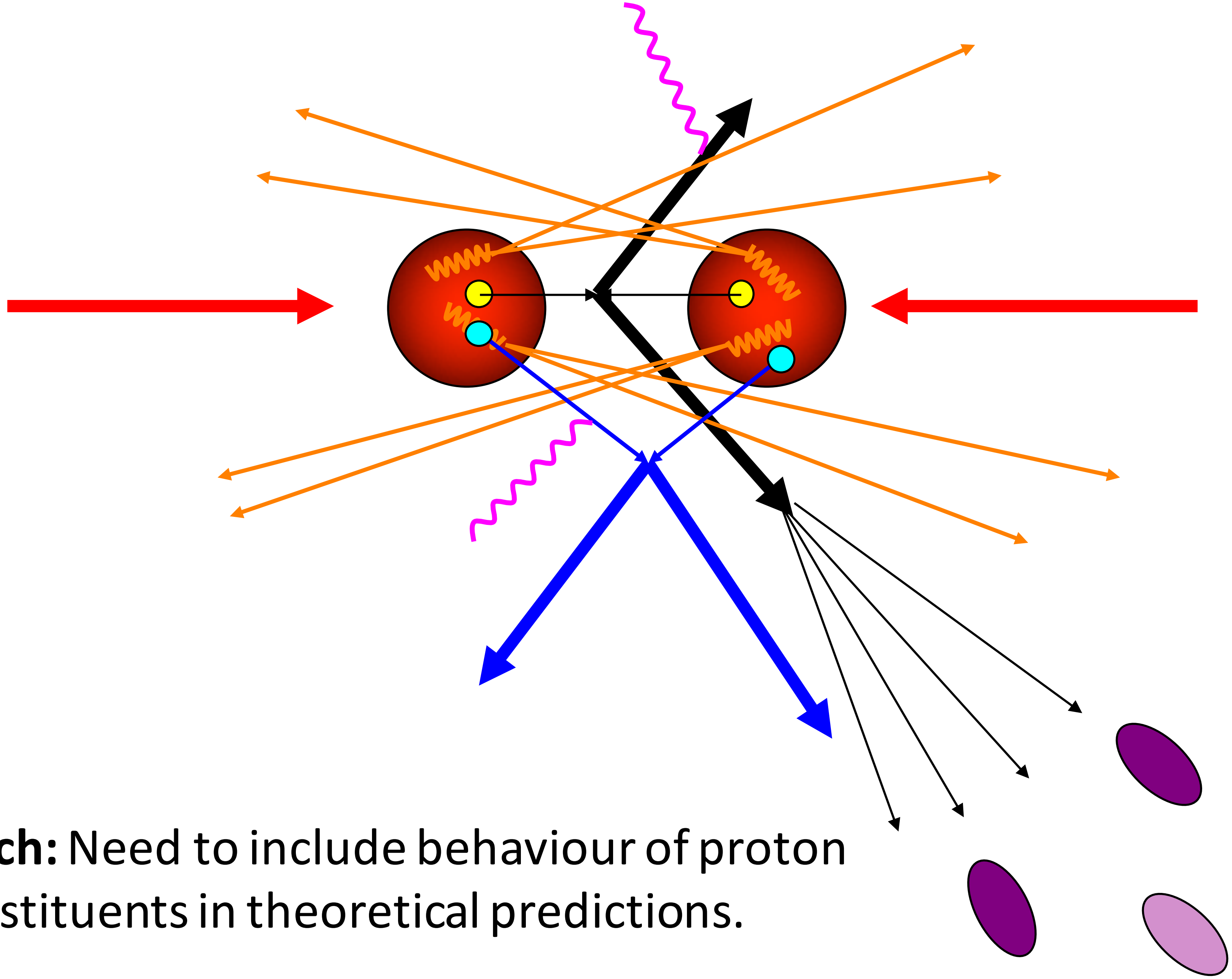
High energy ($\sqrt{s}$=14 TeV)

Circular

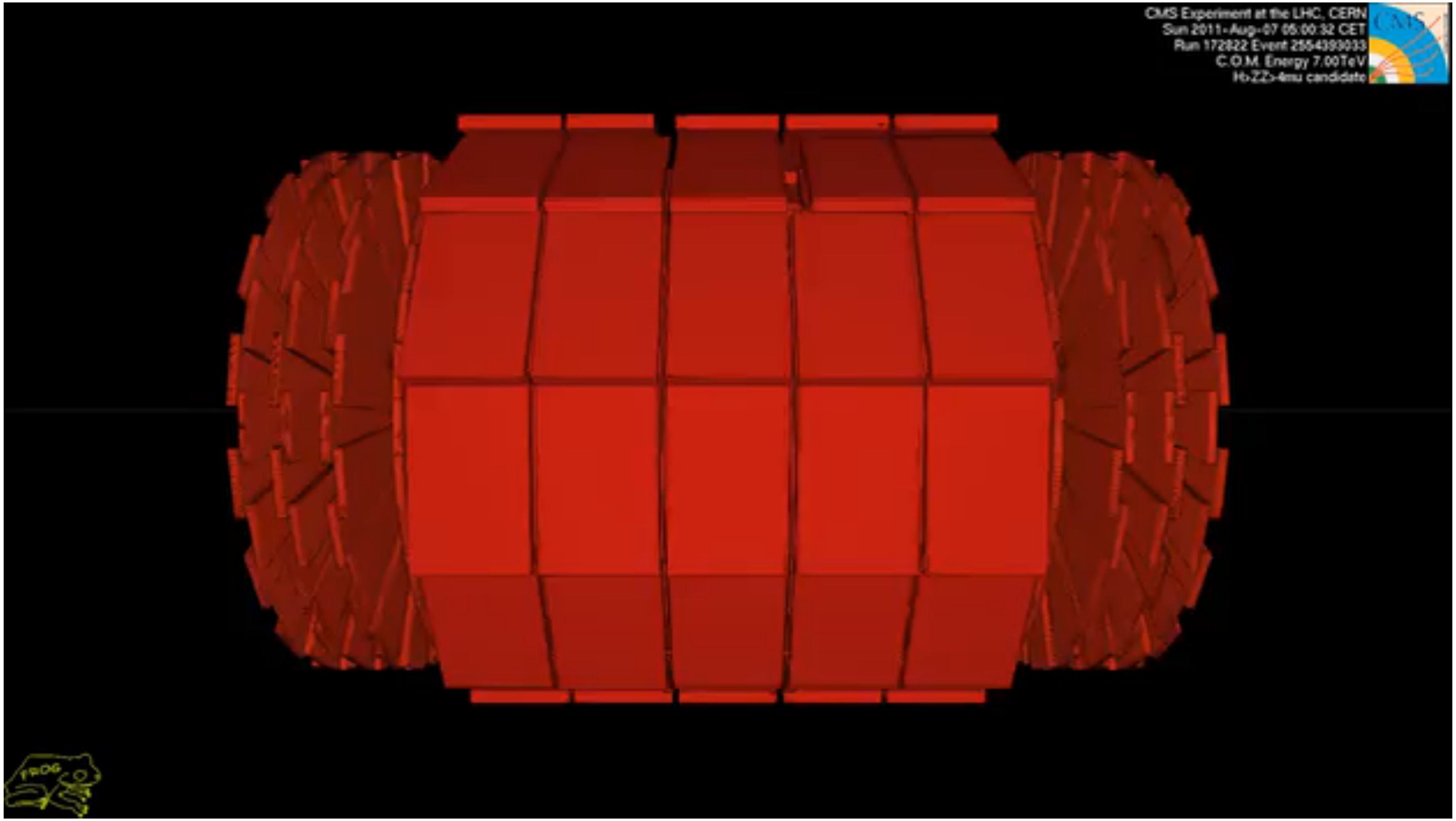
Proton beams

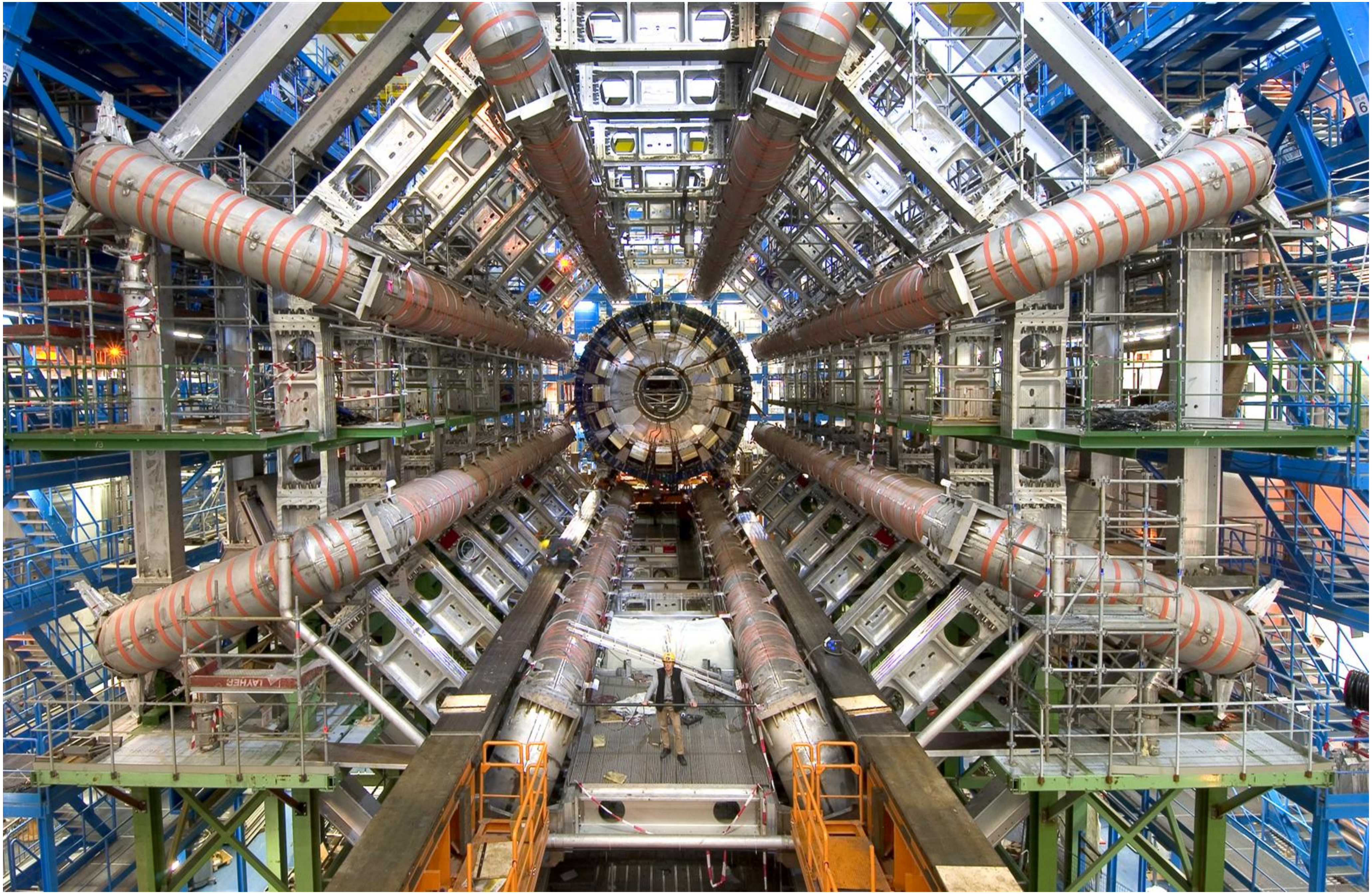
Up to 10^8 collisions/s

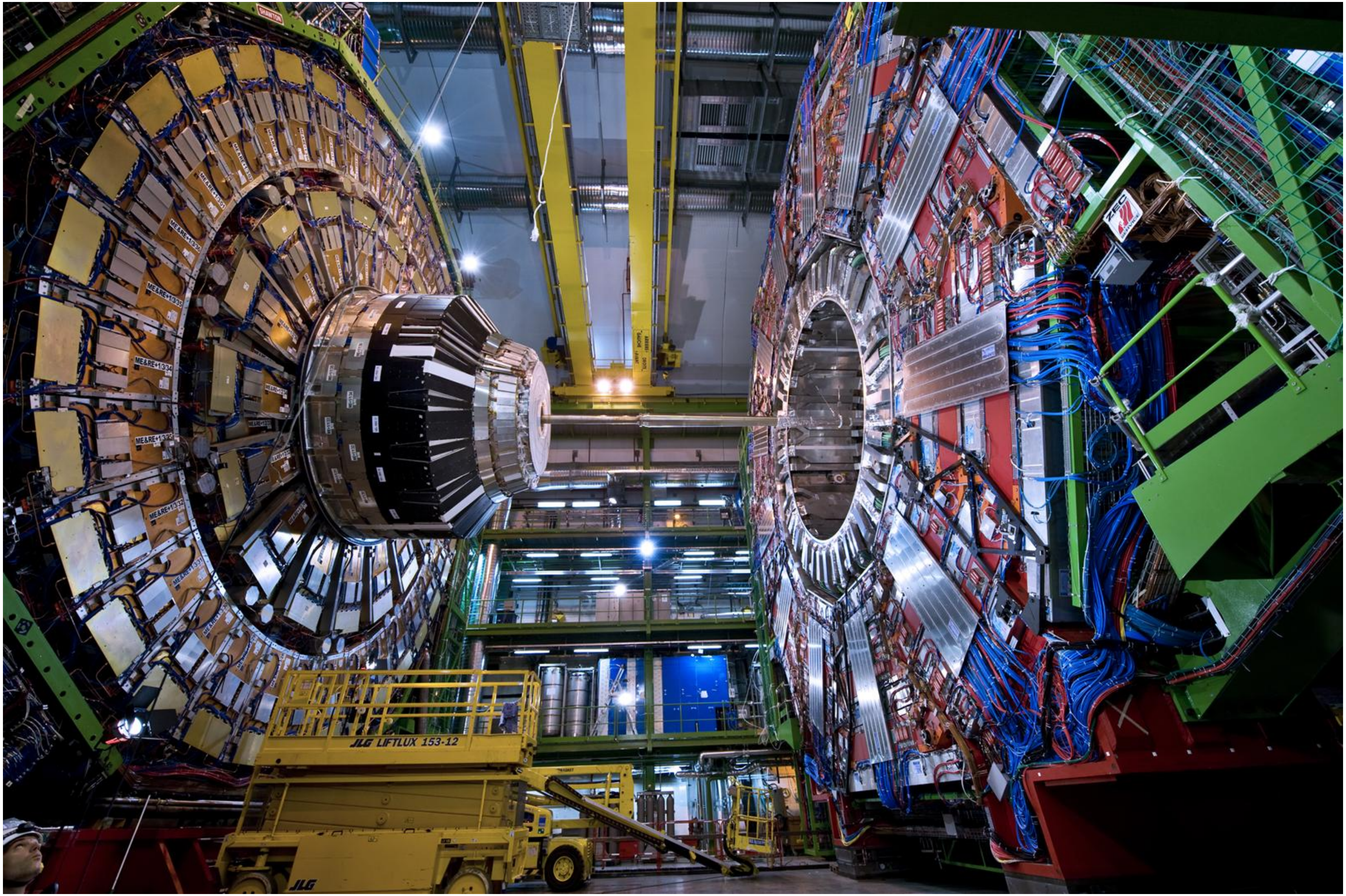




Catch: Need to include behaviour of proton constituents in theoretical predictions.


CMS Experiment at the LHC, CERN
Sun 2011-Aug-07 05:00:32 CET
Run 172822 Event 2554393033
C.O.M. Energy 7.00TeV
H>ZZ>4mu candidate
FROG




ME&RE+1/3/33
ME&RE+1/3/34
ME&RE+1/3/35
ME&RE+1/3/32
JLG LIFTLUX 153-12
JLG

(and ALICE, LHCb, Moedal, LHCf, TOTEM….)

(**px,py,pz**,m)

↑

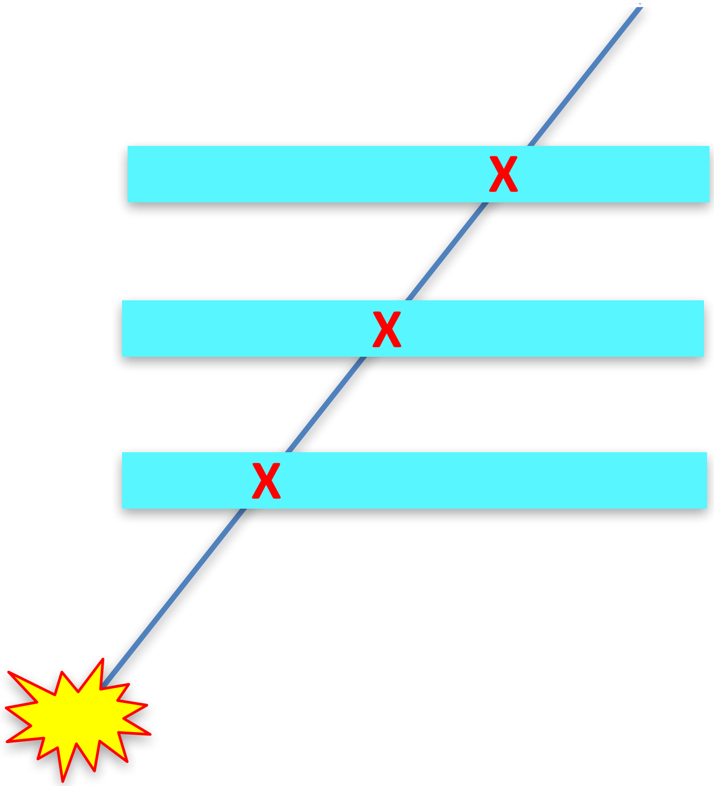
(x,y,z)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



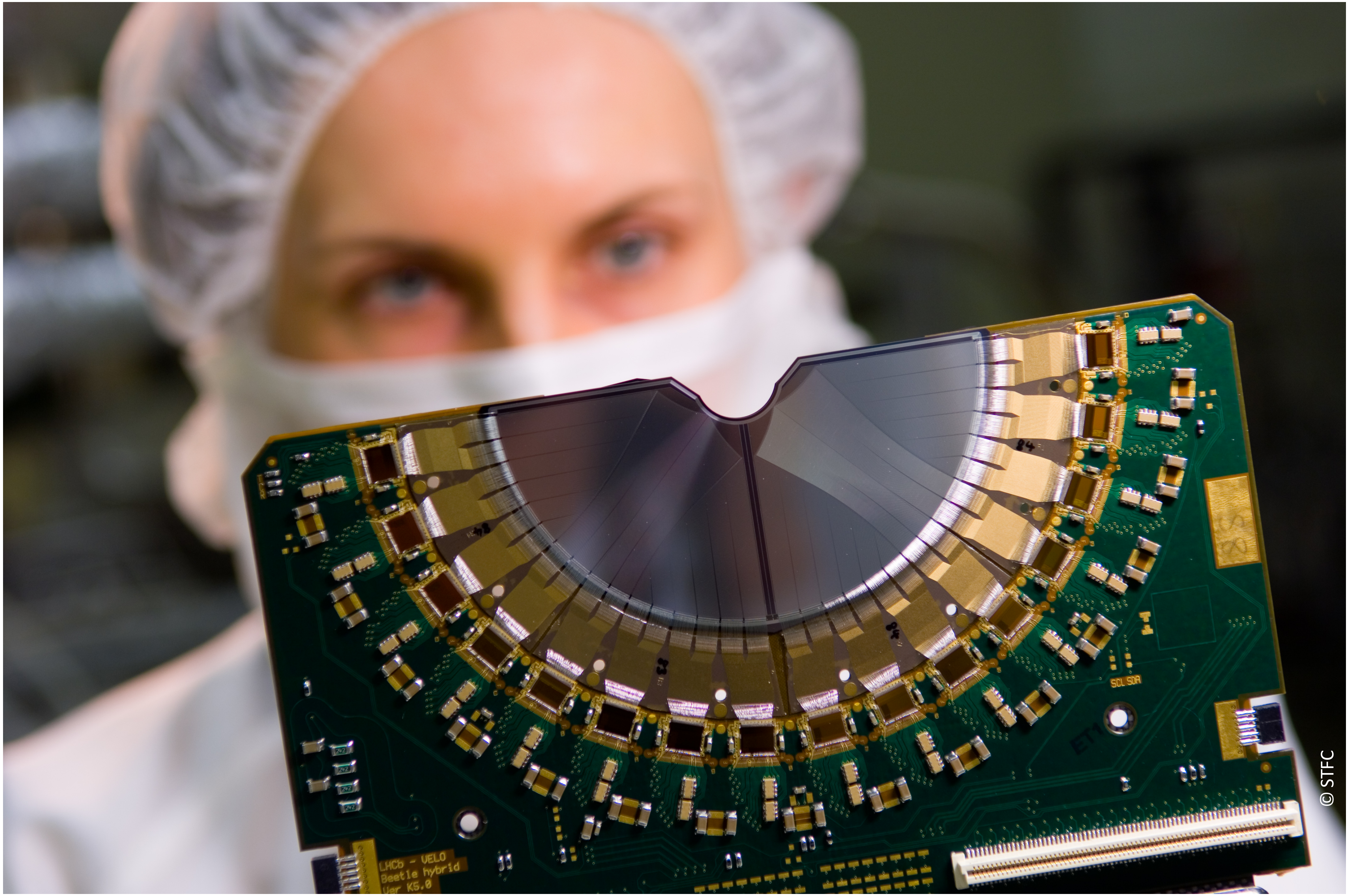
Tracking detectors

Charged particles

Location:

- Ionisation (gas)
- e/hole (silicon)

Detectors 2/7/19
Electronics/TDAQ 9/7/19



© STFC

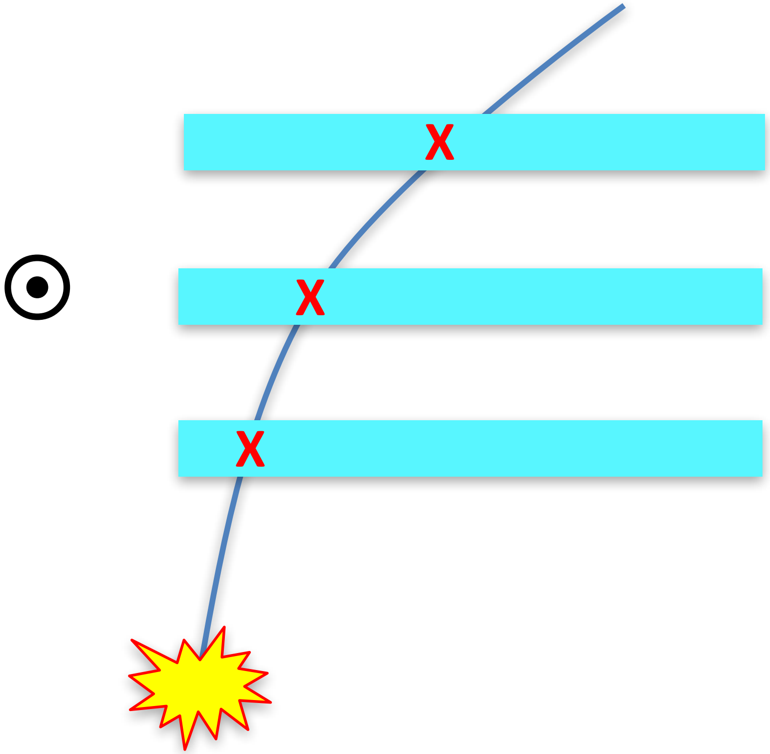
(**px,py,pz**,m)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Magnetic field

Relate track curvature, B to p.

$$p = 0.3Br$$

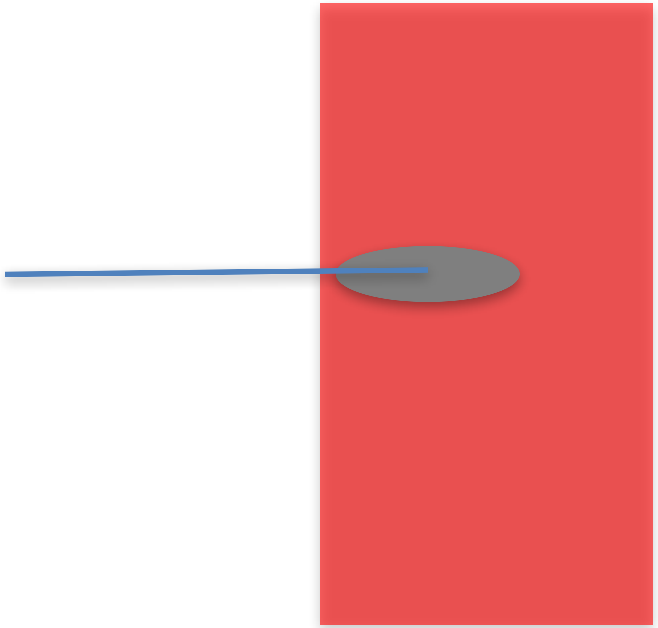
(px,py,pz,m)

Reconstruct path

Reconstruct momentum

Measure energy

Identify type



Calorimeters
Charged + neutral particles
Two types:
    Electromagnetic
    Hadronic
Absorb + measure energy

(px,py,pz,**m**)

Reconstruct path

Reconstruct momentum

Measure energy

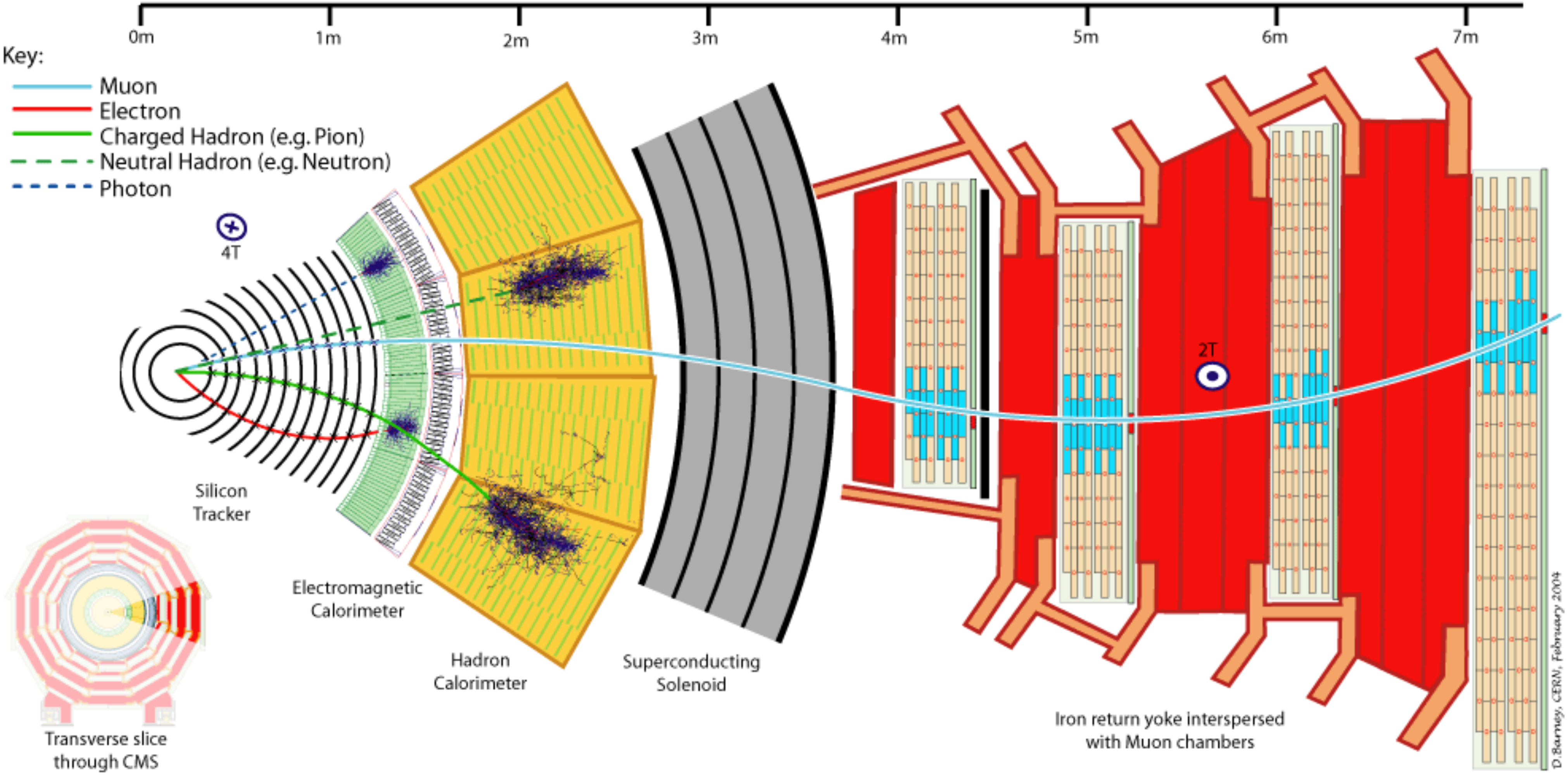
Identify type

Location of absorption:
- Calorimeters
- Muon chambers

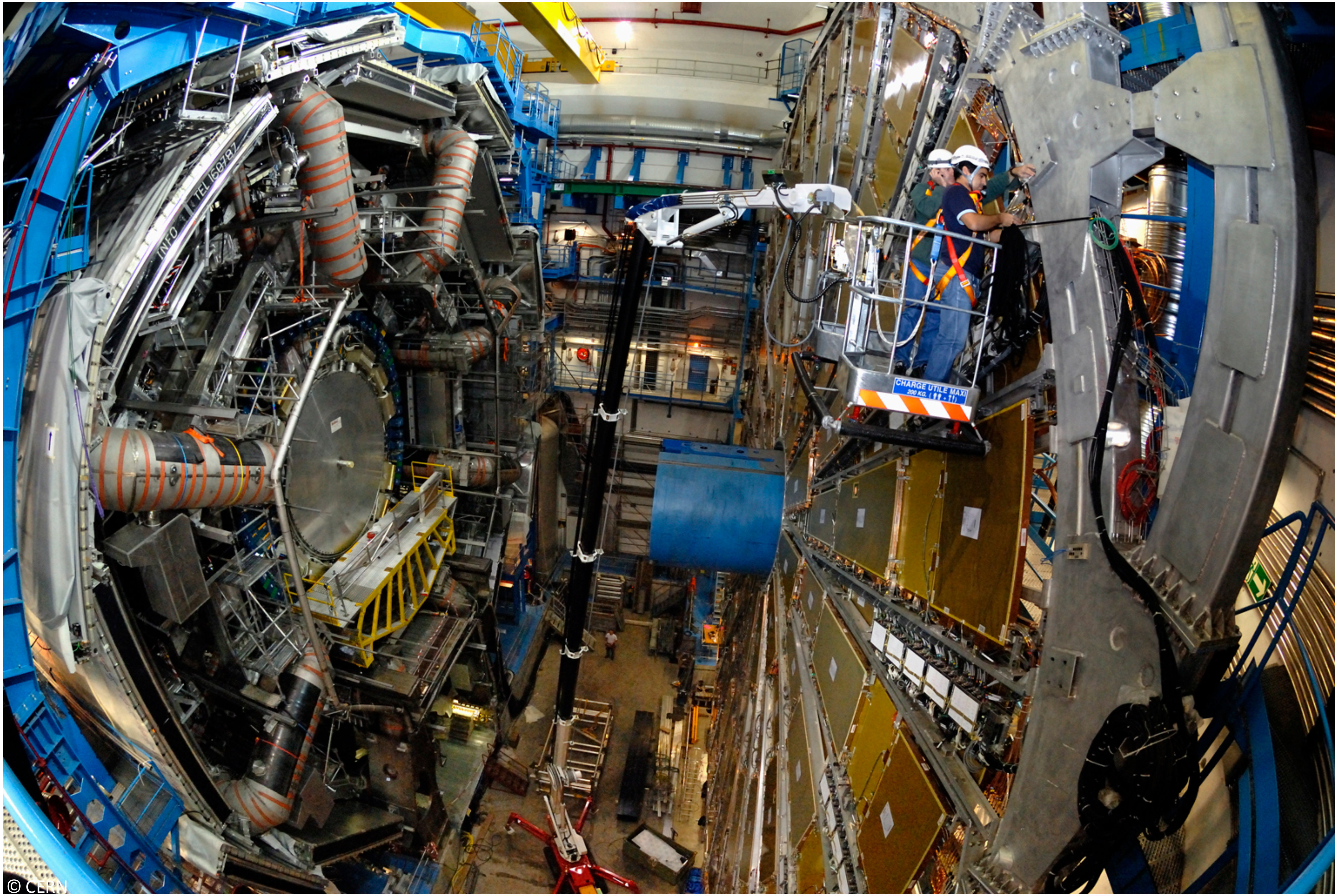
Cerenkov detectors (**v**)
- Add momentum -> m

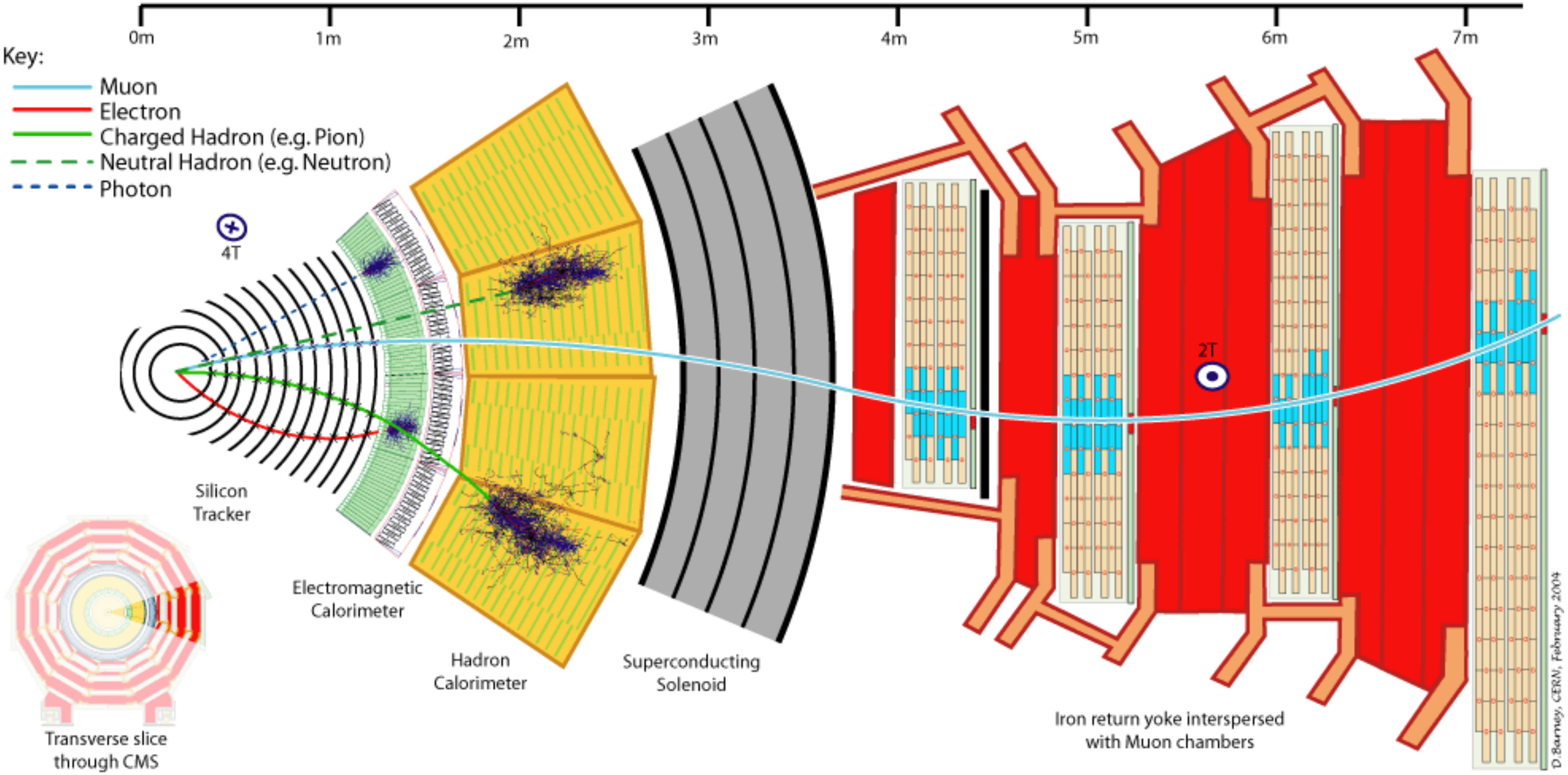
Transition radiation (γ)
- Add energy -> m

Time-of-flight (comparative m)



D.Barney, CERN, February 2004

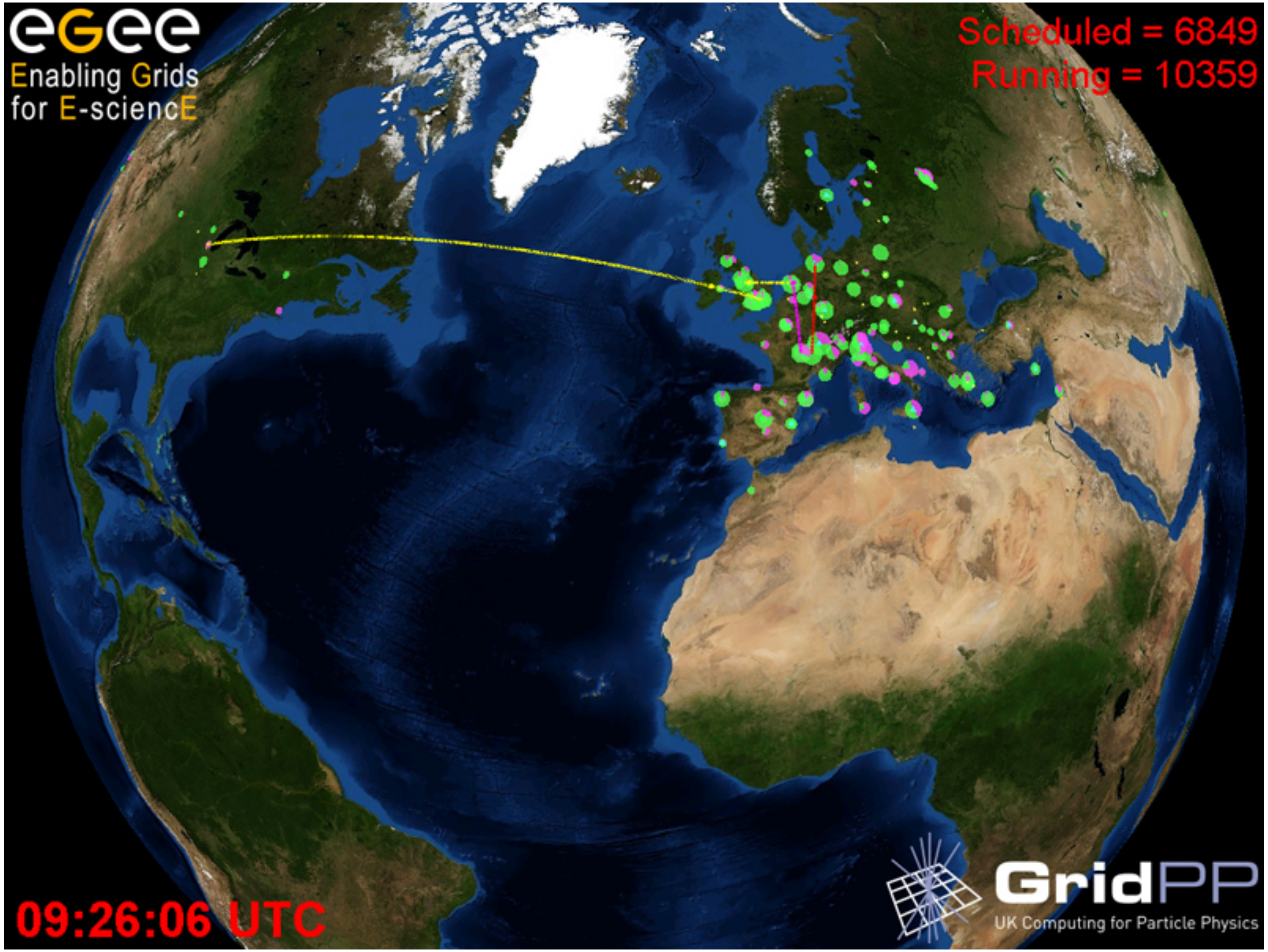

INFO TEL 160787
CHARGE UTILE MAXI
200 KG. (1 + 1)



Identify particles by characteristic signatures in experiment

Add computers: calculate particle paths and energies

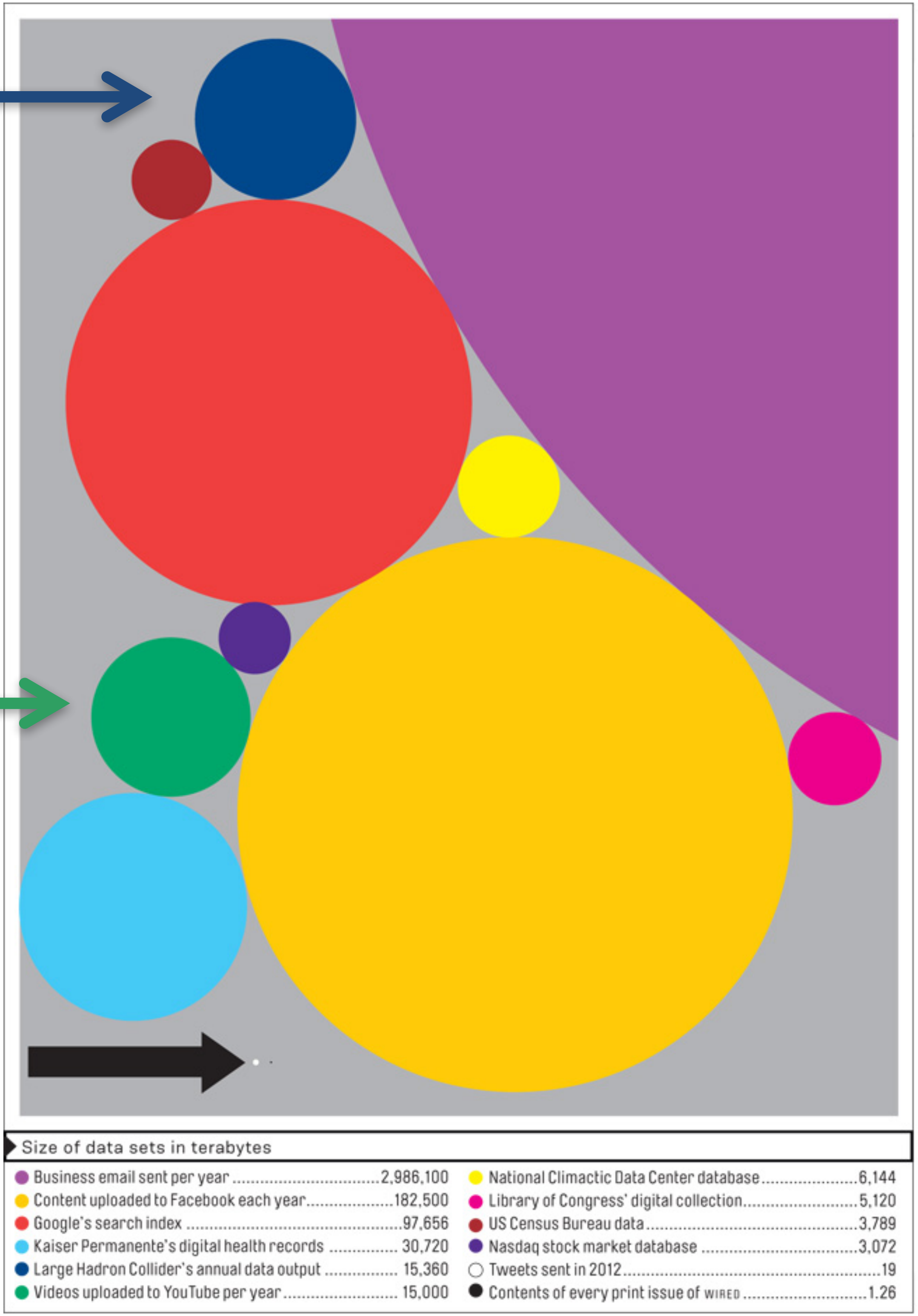
Add theory: infer what fundamental process happened


egee
Enabling Grids for E-sciencE
Scheduled = 6849
Running = 10359
GridPP
UK Computing for Particle Physics
09:26:06 UTC

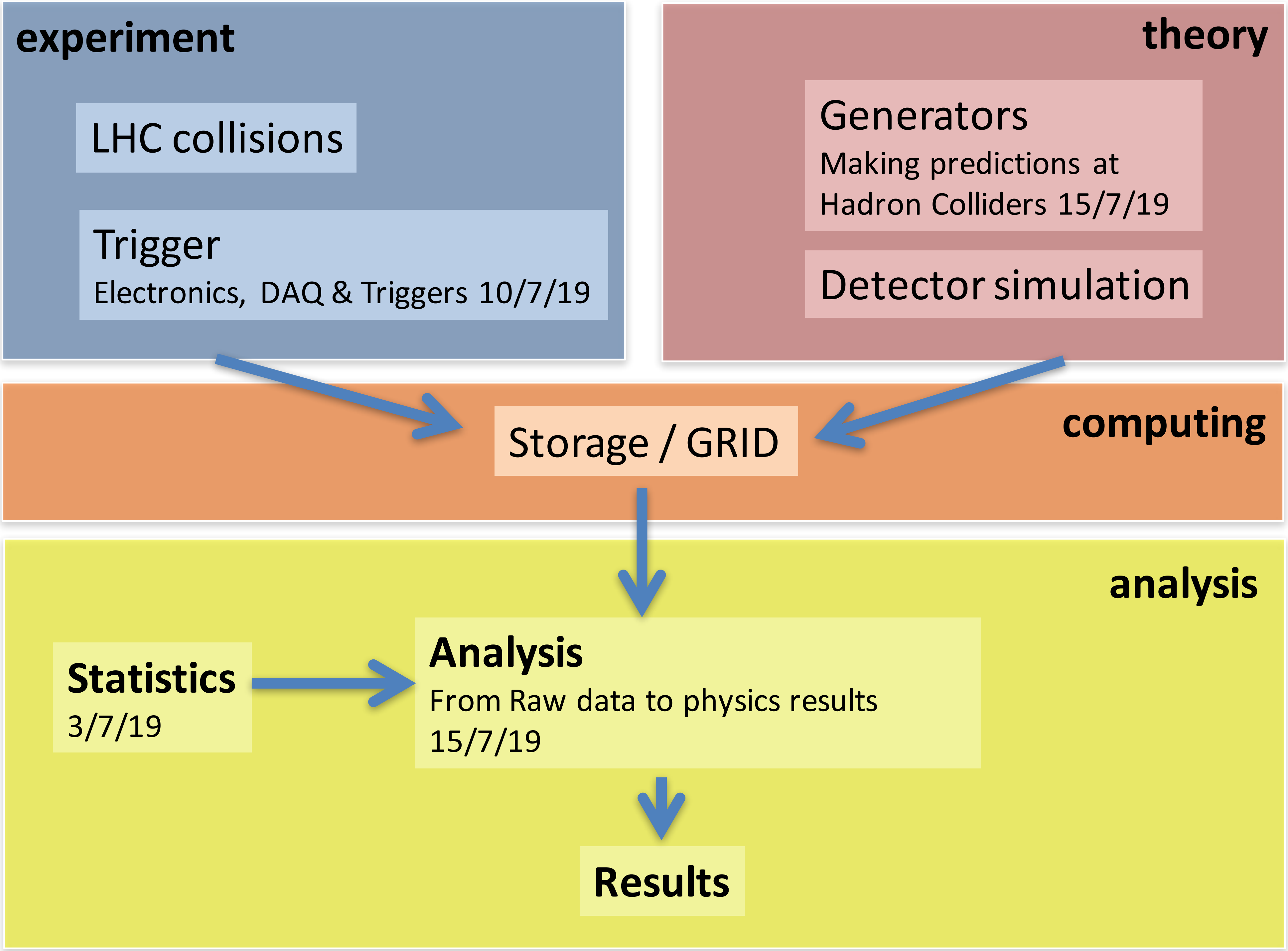
Big data …….

LHC
15 360 TB/yr

Videos uploaded to YouTube
15 000 TB/yr



(http://www.wired.com/2013/04/bigdata/)



experiment

LHC collisions

Trigger
Electronics, DAQ & Triggers 10/7/19

theory

Generators
Making predictions at Hadron Colliders 15/7/19

Detector simulation

computing

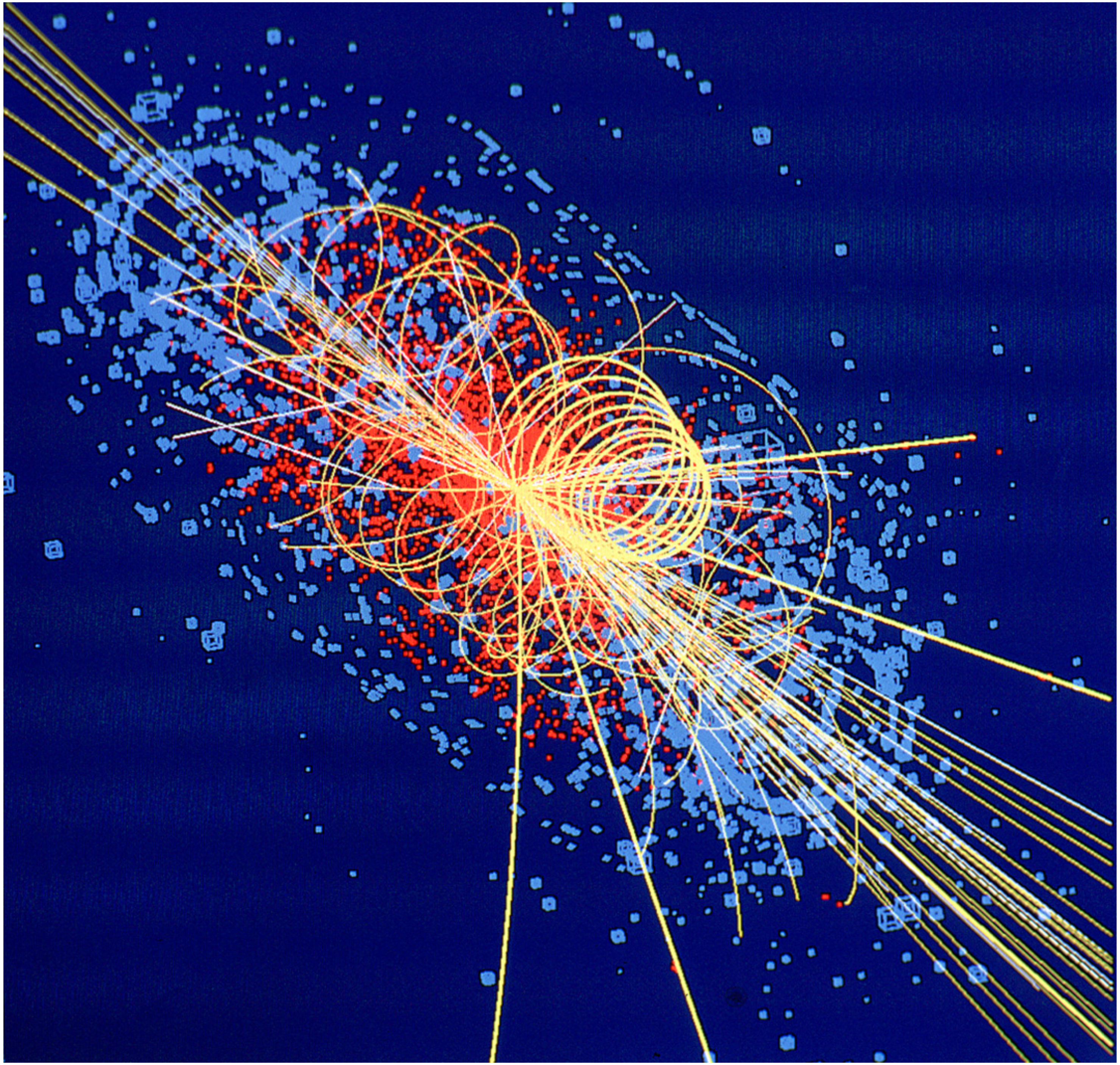
Storage / GRID

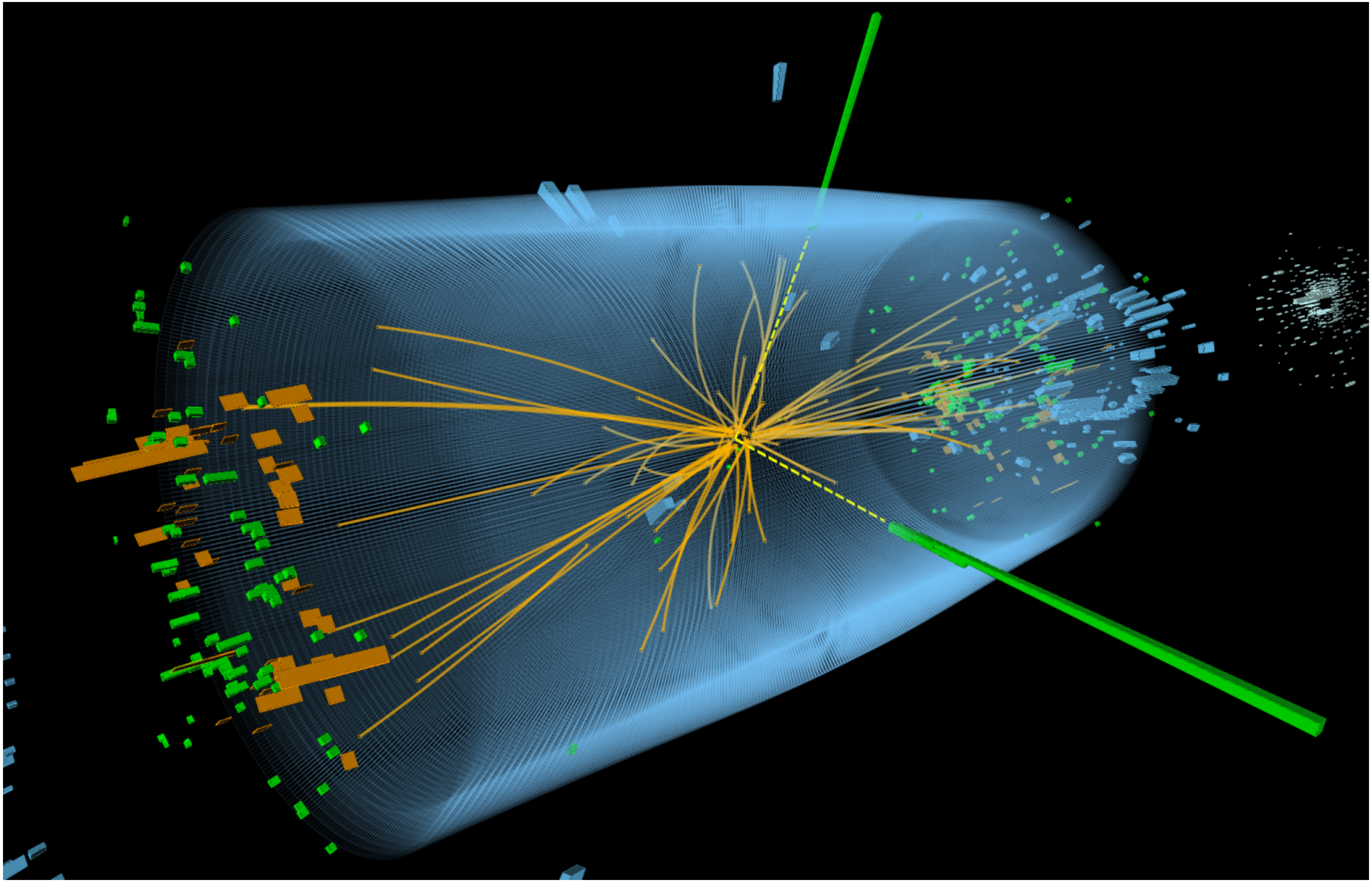
analysis

Statistics
3/7/19

Analysis
From Raw data to physics results
15/7/19

Results





Future facilities

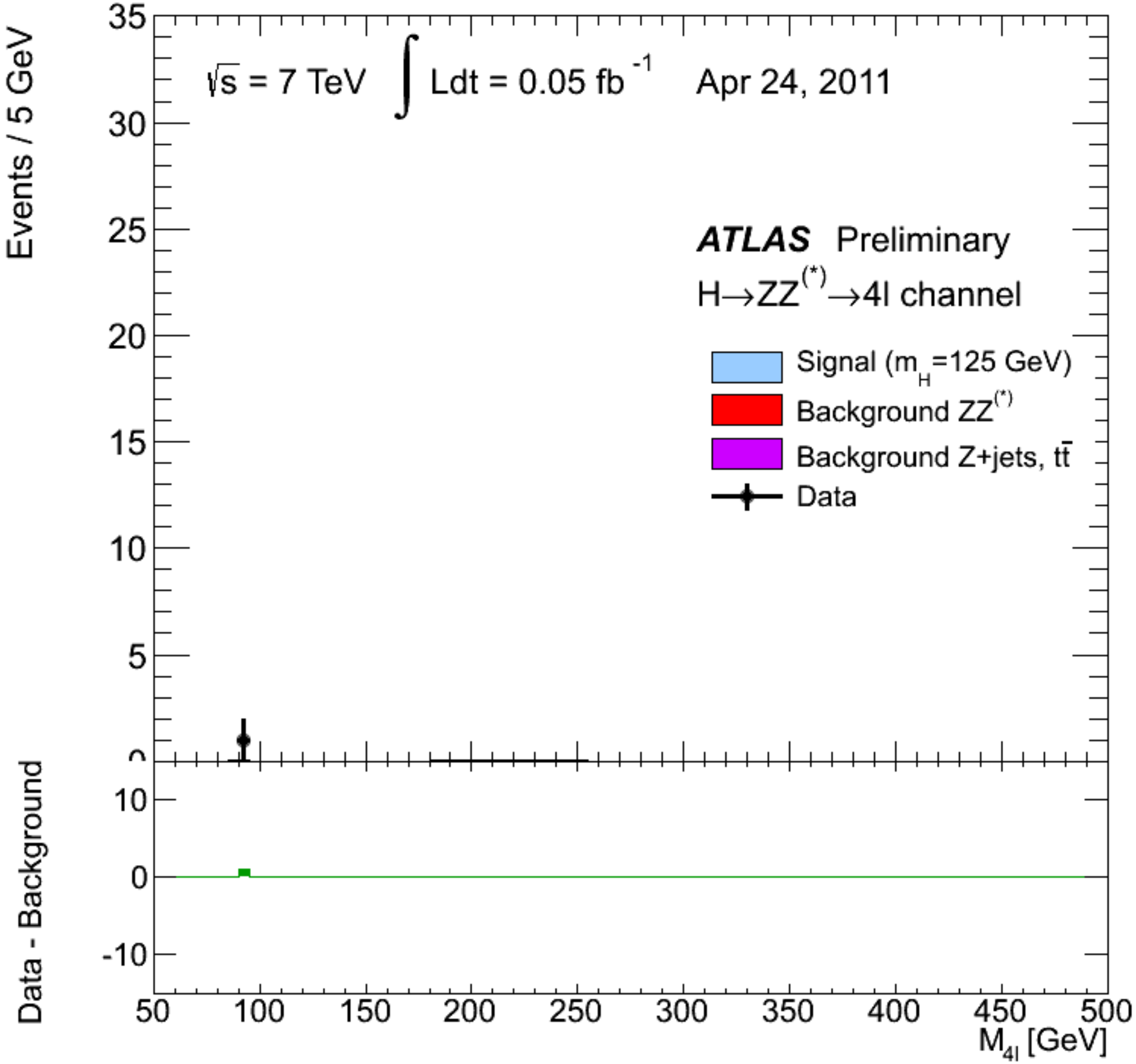
Too many open questions to stop here.

- New neutrino facility?
- New high energy machine?
- New linear collider?

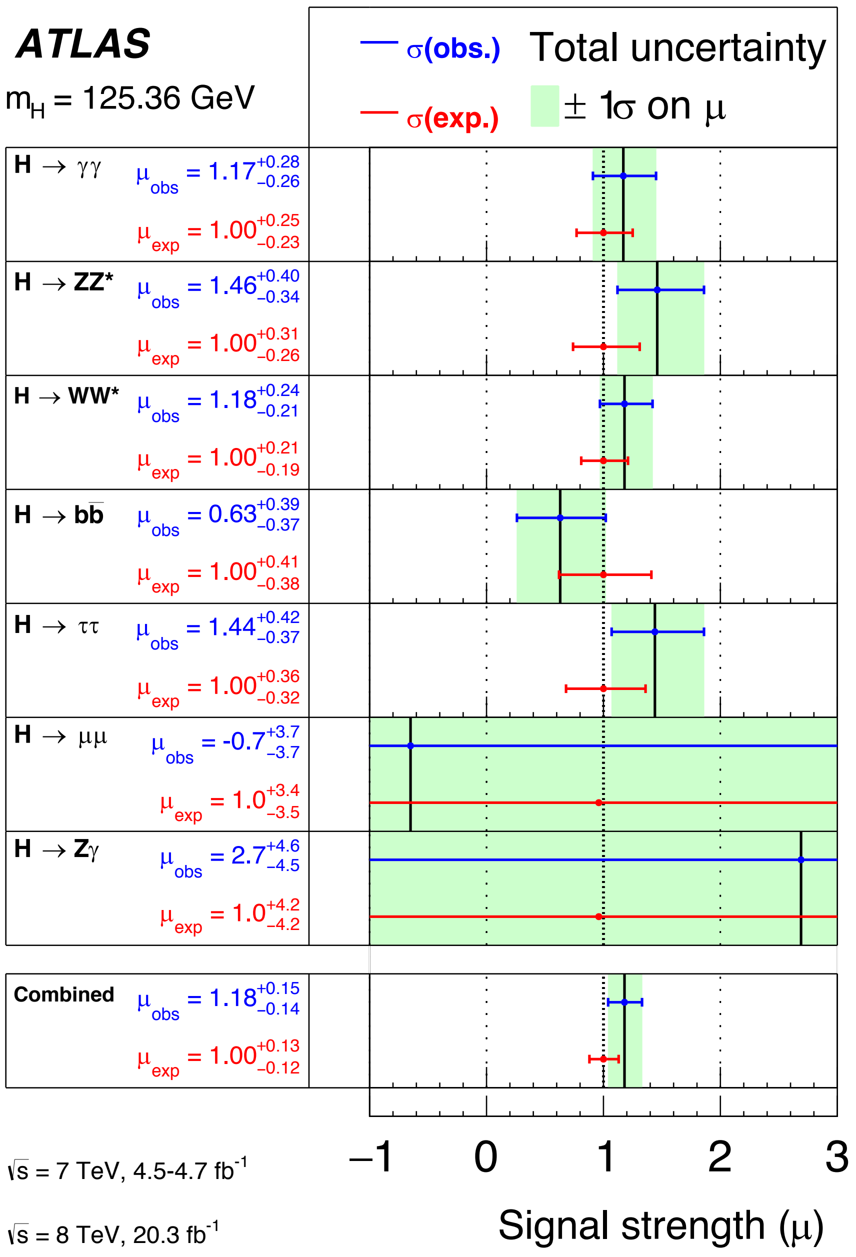
Physics at lepton colliders 31/7/19
Future collider projects 31/7/19

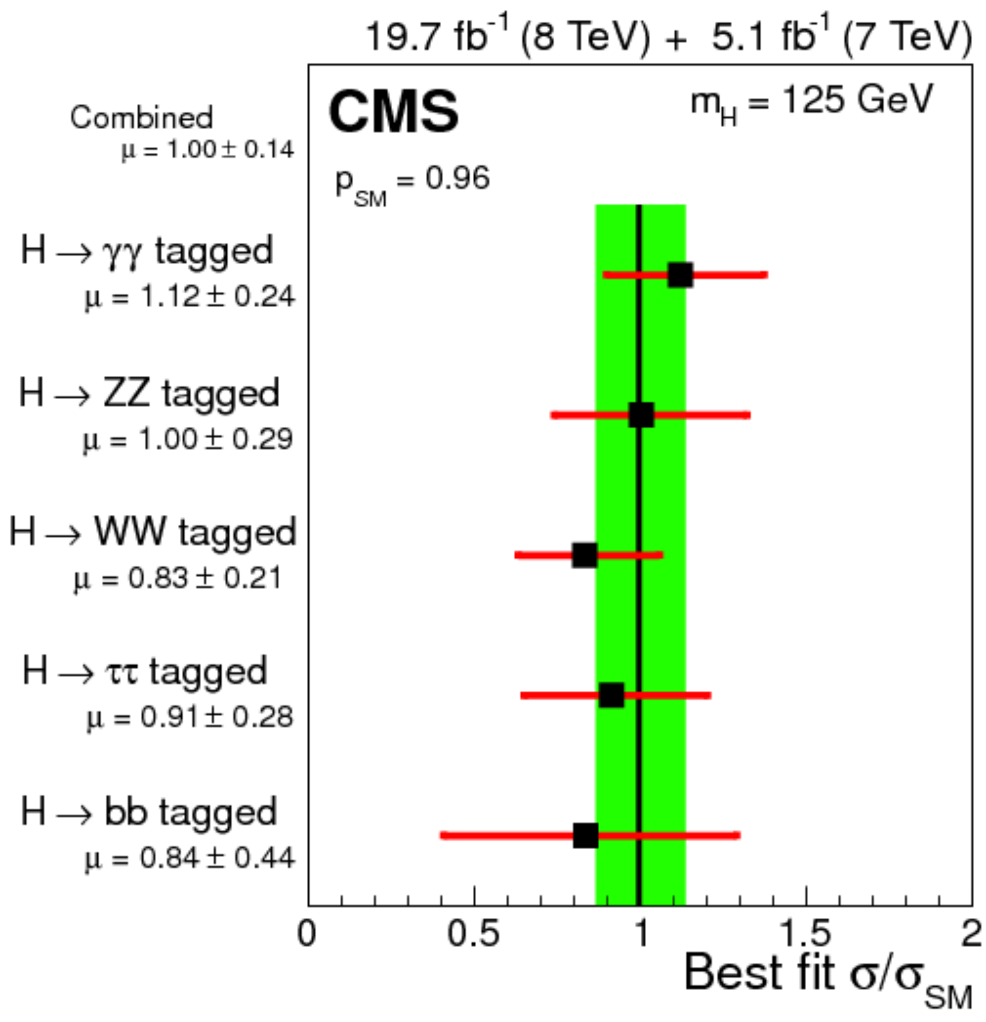
The known unknowns

- Higgs
- Gravity
- Antimatter
- Dark matter, dark energy
- A unified theory
- + unknown unknowns…..


$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.05 fb^{-1} Apr 24, 2011
ATLAS Preliminary
H→ZZ$^{(*)}$→4l channel
Signal (m_H=125 GeV)
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Events / 5 GeV
35
30
25
20
15
10
5
0
Data - Background
10
0
-10
50
100
150
200
250
300
350
400
450
500
M_{4l} [GeV]

A Higgs? The Higgs?





Gravity

Can’t describe it in SM

Can include it in string theory – not very testable (yet)

Large extra dimensions could be observed at LHC (no sign so far…)

?

CP violation

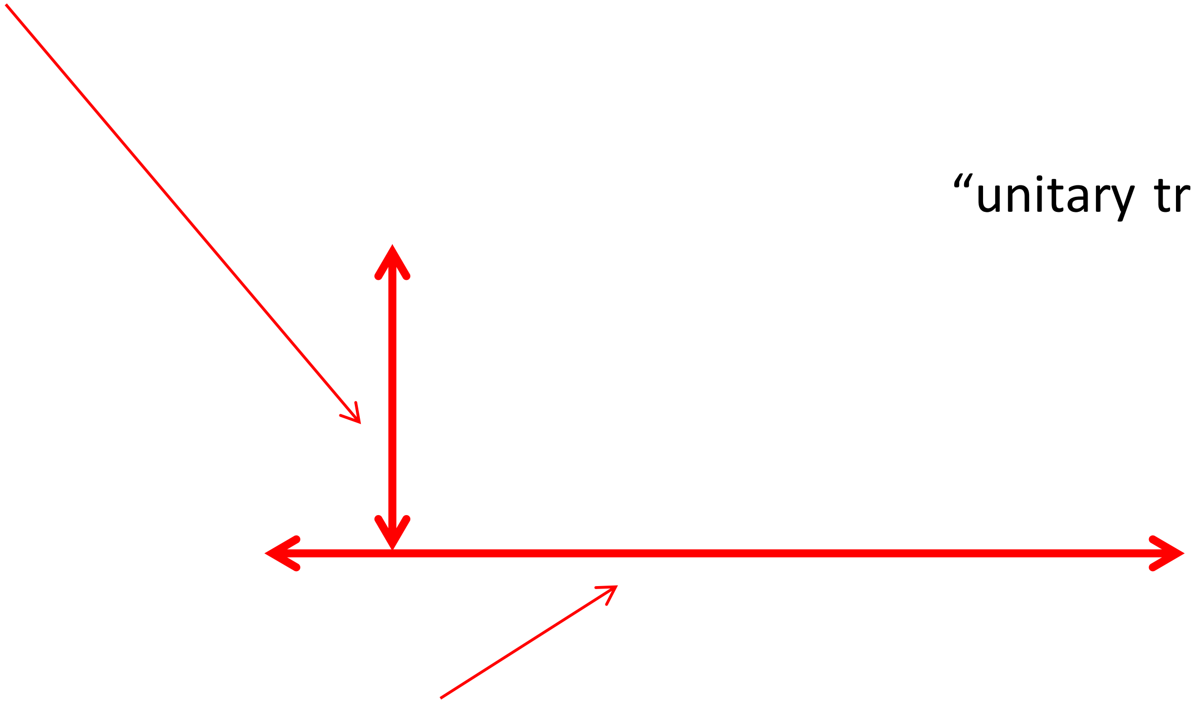
Consistent picture in SM but can we explain matter – antimatter asymmetry of the universe?

Does the answer lie in new physics?

?

Antimatter 1/8/19
Flavour physics 29/7/19

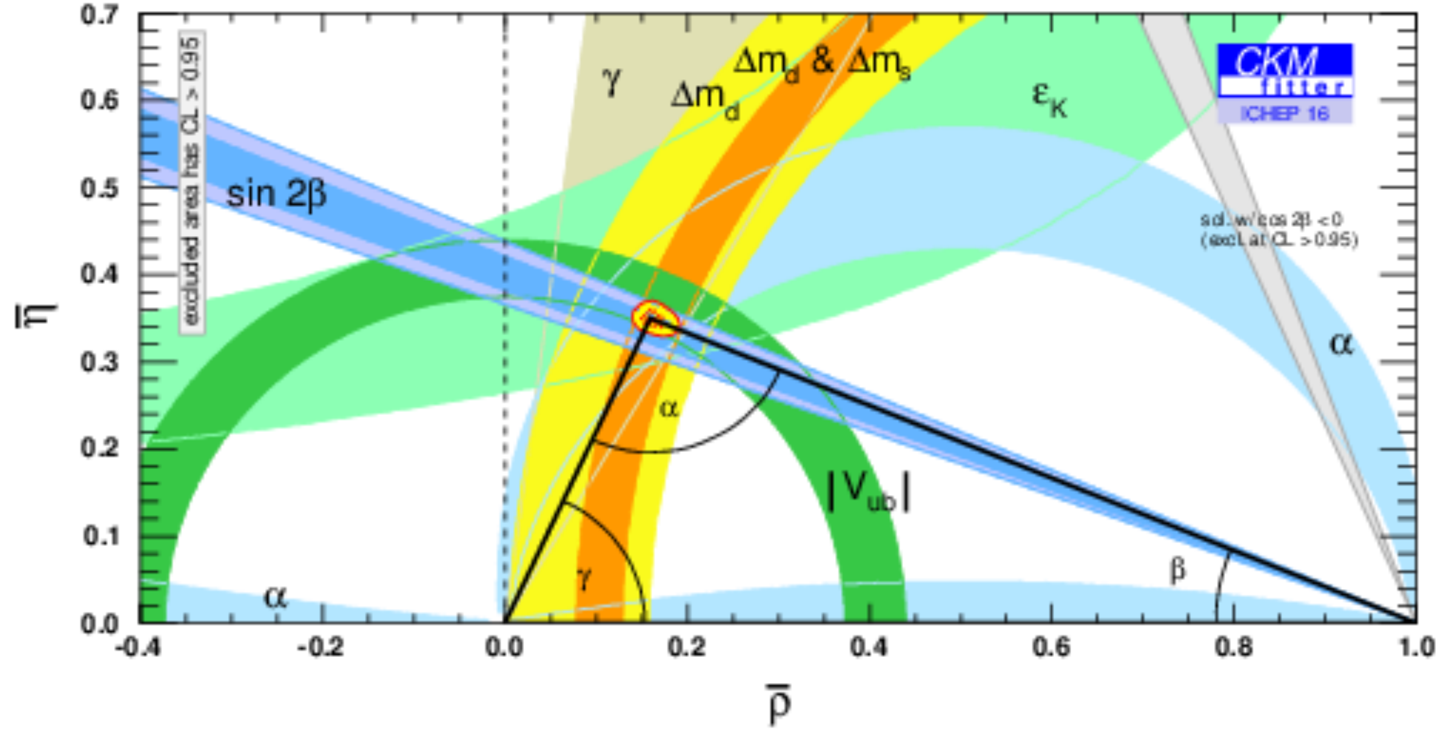
SM: 4 numbers



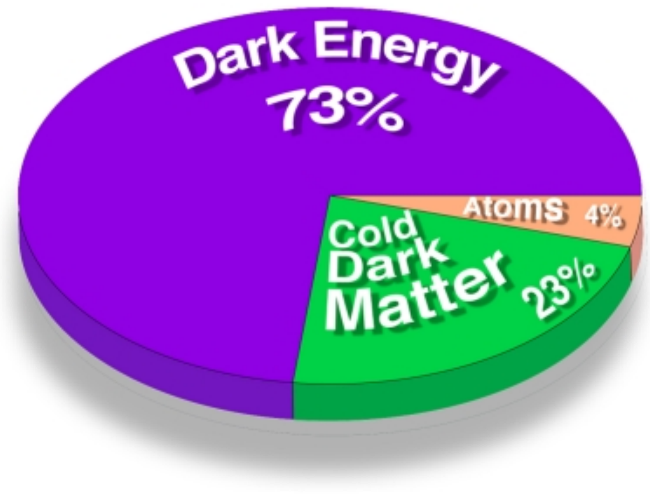
Measure of matter / antimatter difference (1)

“unitary triangle”

Measure of quark behaviour under the weak force (3)

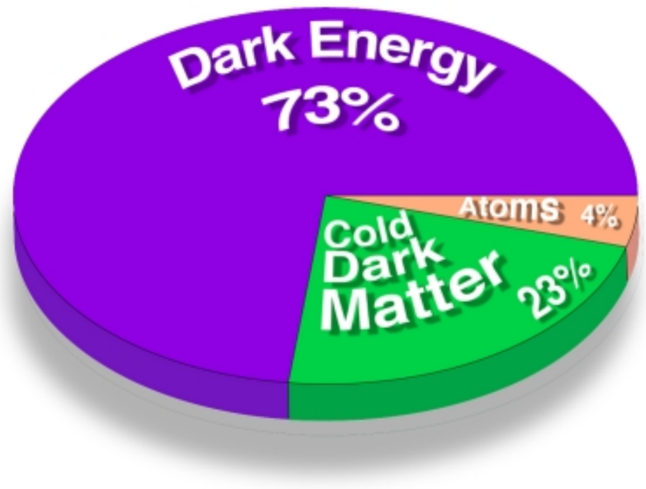

excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_d & Δm_s
ε_K
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
α
α
γ
β
|V_ub|
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

Dark stuff?



Source: Robert Kirshner
Source: NASA/WMAP Science Team

SM with electroweak and strong interactions only describes 4% of the universe

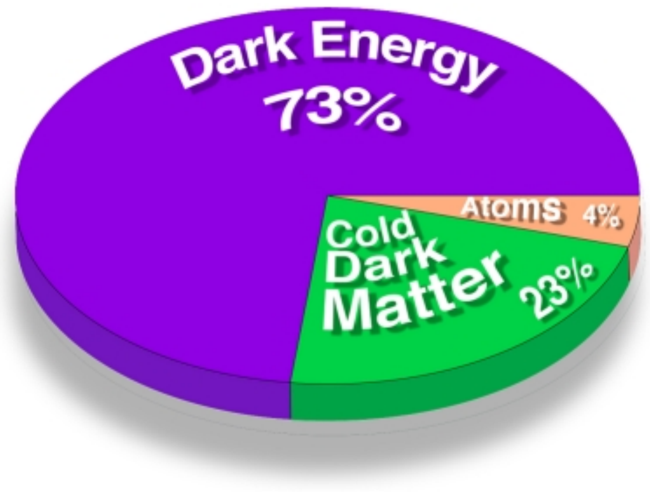


Source: Robert Kirshner
Source: NASA/WMAP Science Team

SM with electroweak and strong interactions only describes 4% of the universe

Dark energy:

?



Source: Robert Kirshner
Source: NASA/WMAP Science Team

SM with electroweak and strong interactions only describes 4% of the universe

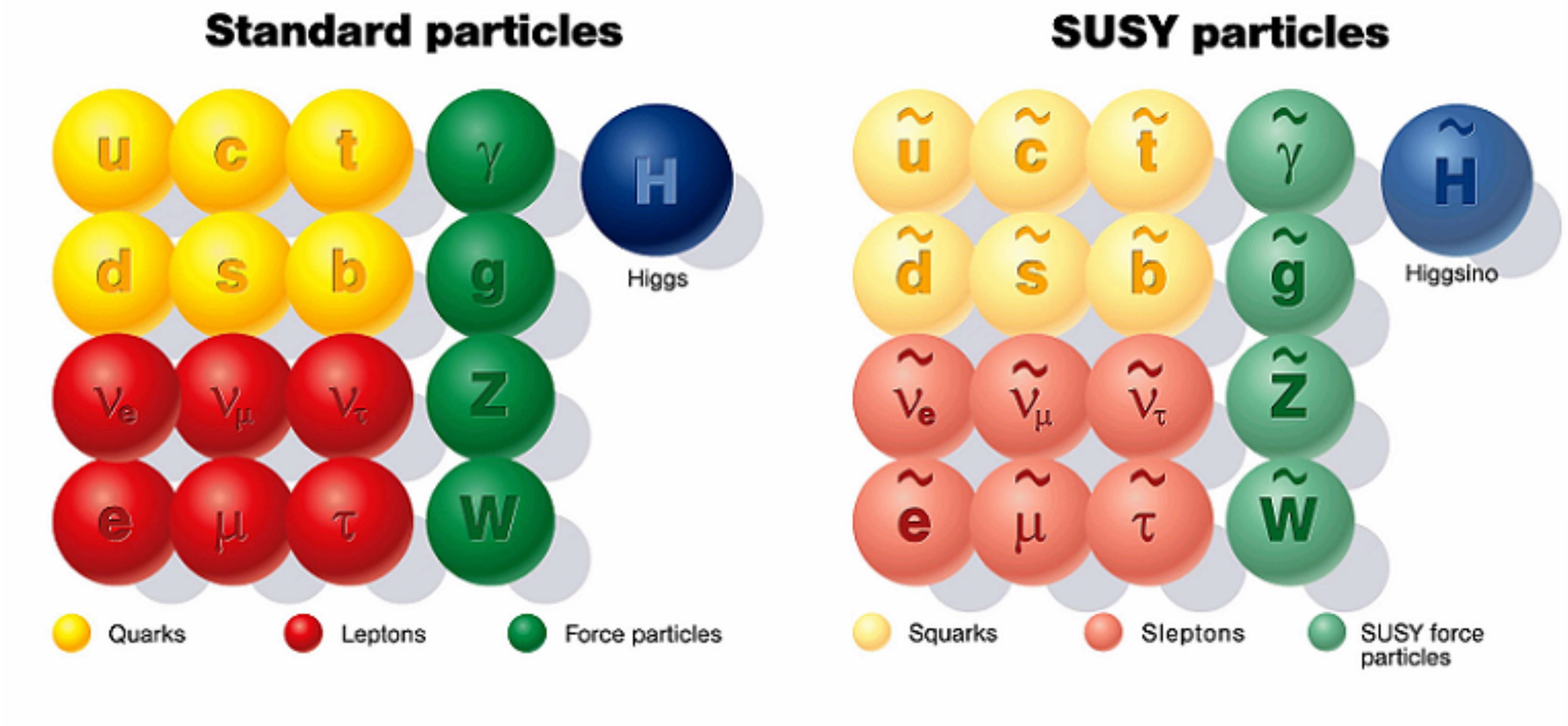
Dark energy:

?

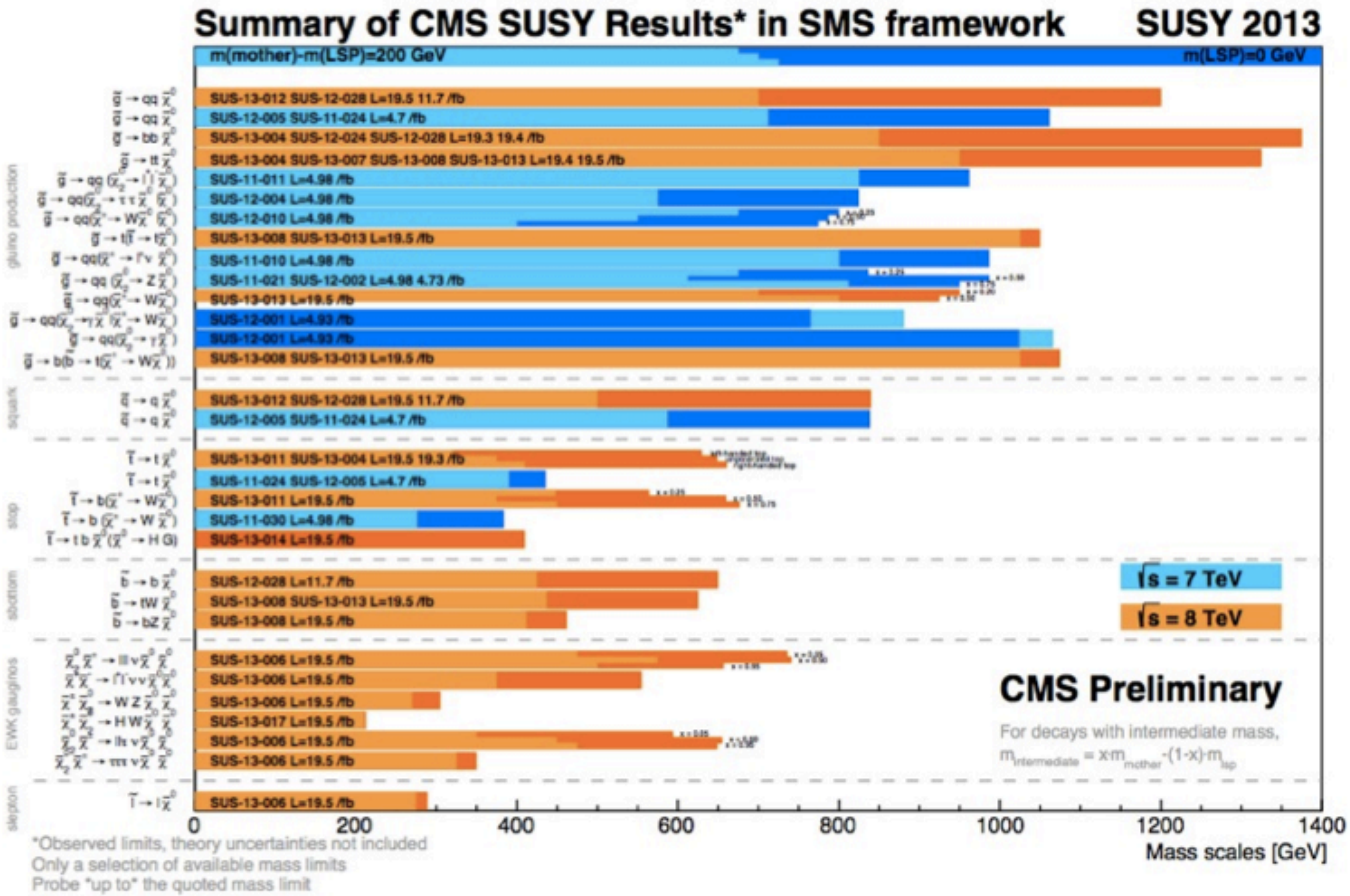
Dark matter?

Try Supersymmetry (SUSY).

Lightest supersymmetric particle is a dark matter candidate (massive and unobservable)


Standard particles
u
c
t
γ
H
d
s
b
g
Higgs
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
Quarks
Leptons
Force particles
SUSY particles
$\tilde{u}$
$\tilde{c}$
$\tilde{t}$
$\tilde{\gamma}$
$\tilde{H}$
$\tilde{d}$
$\tilde{s}$
$\tilde{b}$
$\tilde{g}$
Higgsino
$\tilde{\nu}_e$
$\tilde{\nu}_\mu$
$\tilde{\nu}_\tau$
$\tilde{Z}$
$\tilde{e}$
$\tilde{\mu}$
$\tilde{\tau}$
$\tilde{W}$
Squarks
Sleptons
SUSY force particles

The “we did not find SUSY” Plot



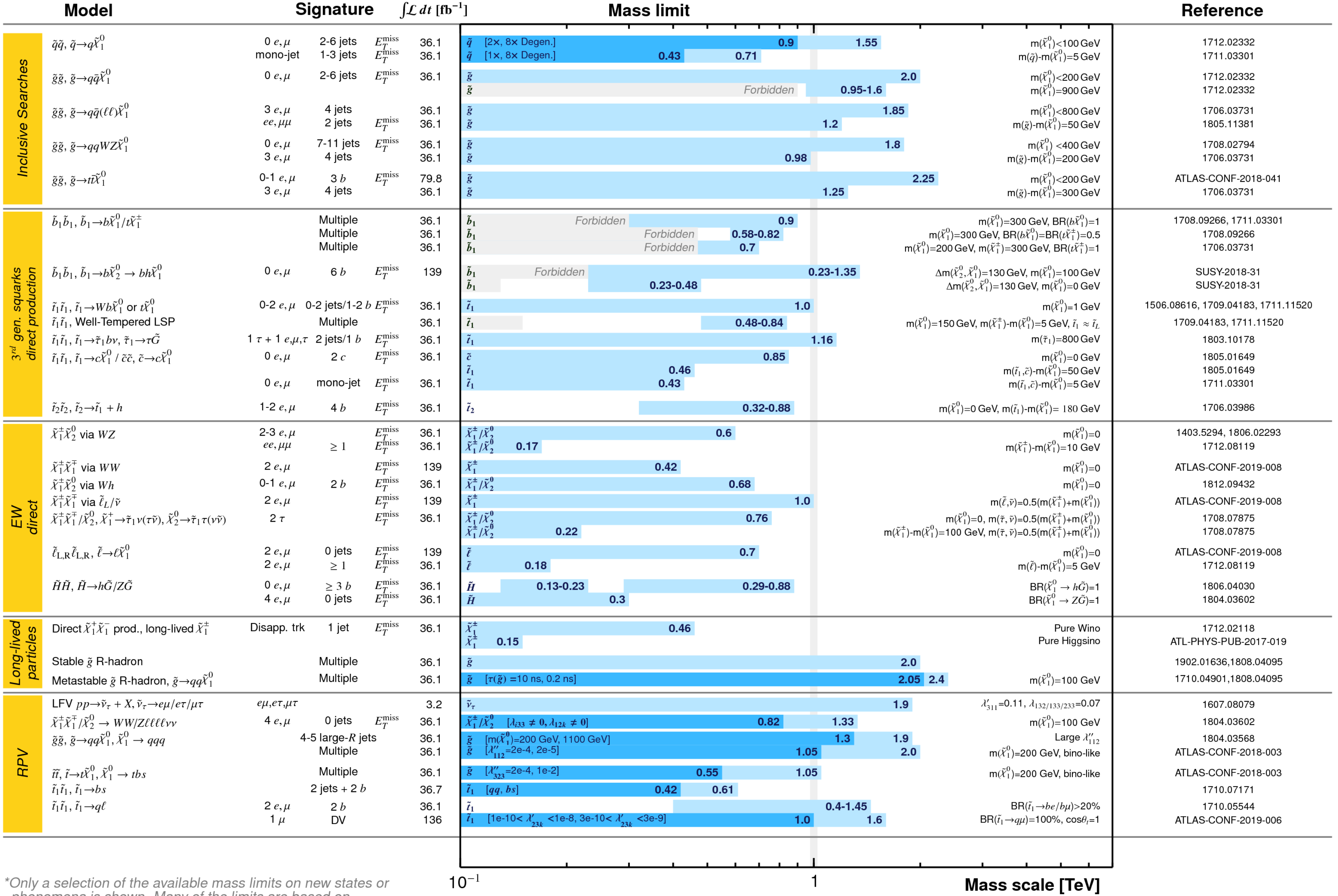
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

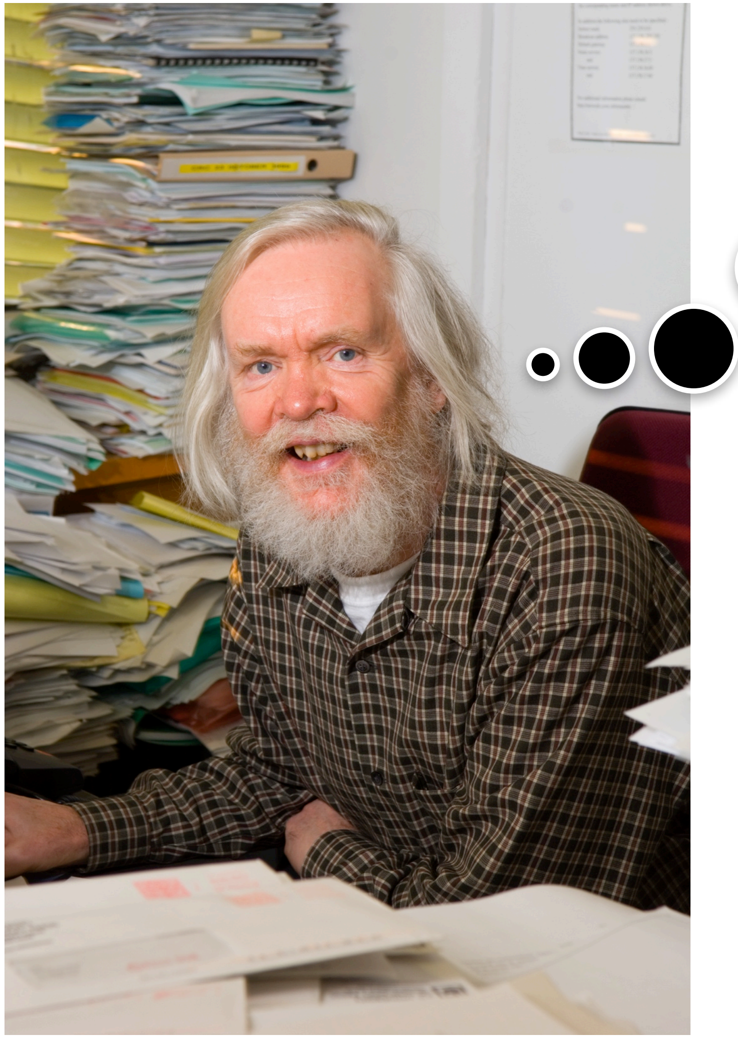
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int \mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets		36.1	$\tilde{g}$	0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		3 e,μ	4 jets		36.1	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$	0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$	0.42	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.68	m($\tilde{\chi}_1^0$)=0	1812.09432
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}_1\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\ell}$	0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

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



Absence of evidence is not necessarily evidence of absence..

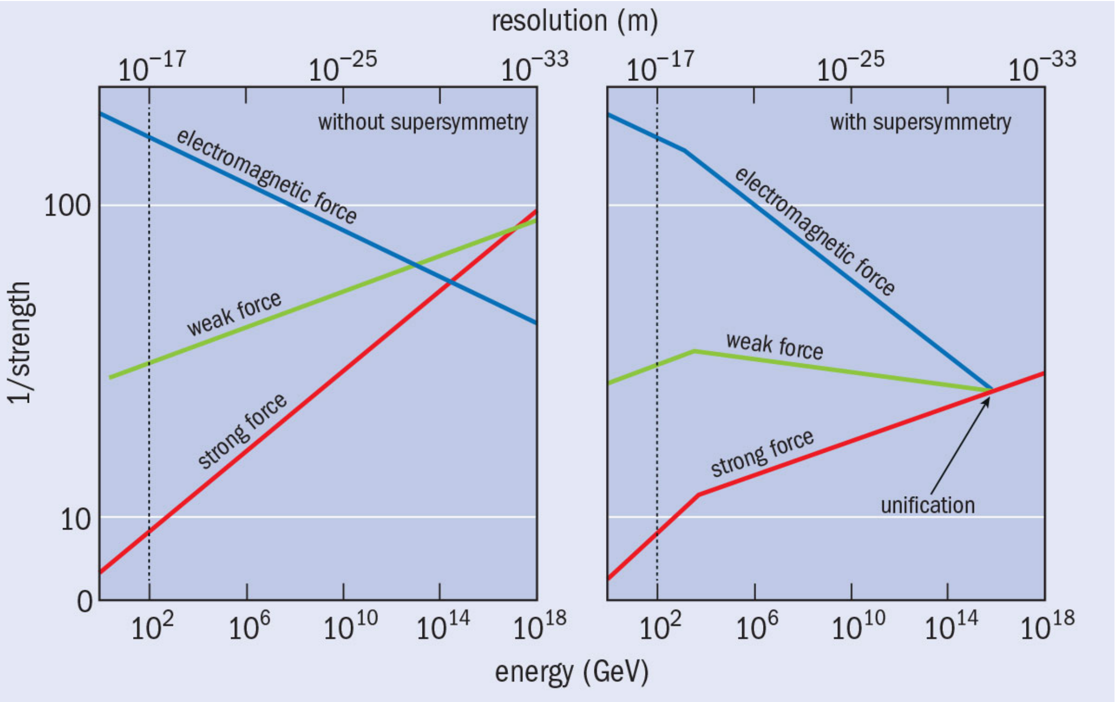
Professor John Ellis, SUSY enthusiast

Why 3 forces? 3 generations?

What if there is 1 force, which fractured at high energy to give what we see today?

Forces "run" with energy ….. and don't agree at high energy

New Physics (eg. SUSY) can modify their evolution to join up → unification?



Particles – why so many ingredients of matter?

Why are their masses so different?

?

Conclusions

Particle physics describes the smallest structures in the universe

Theory: the Standard Model

- Works fabulously well
- Is fabulously frustrating

Many big mysteries to solve.