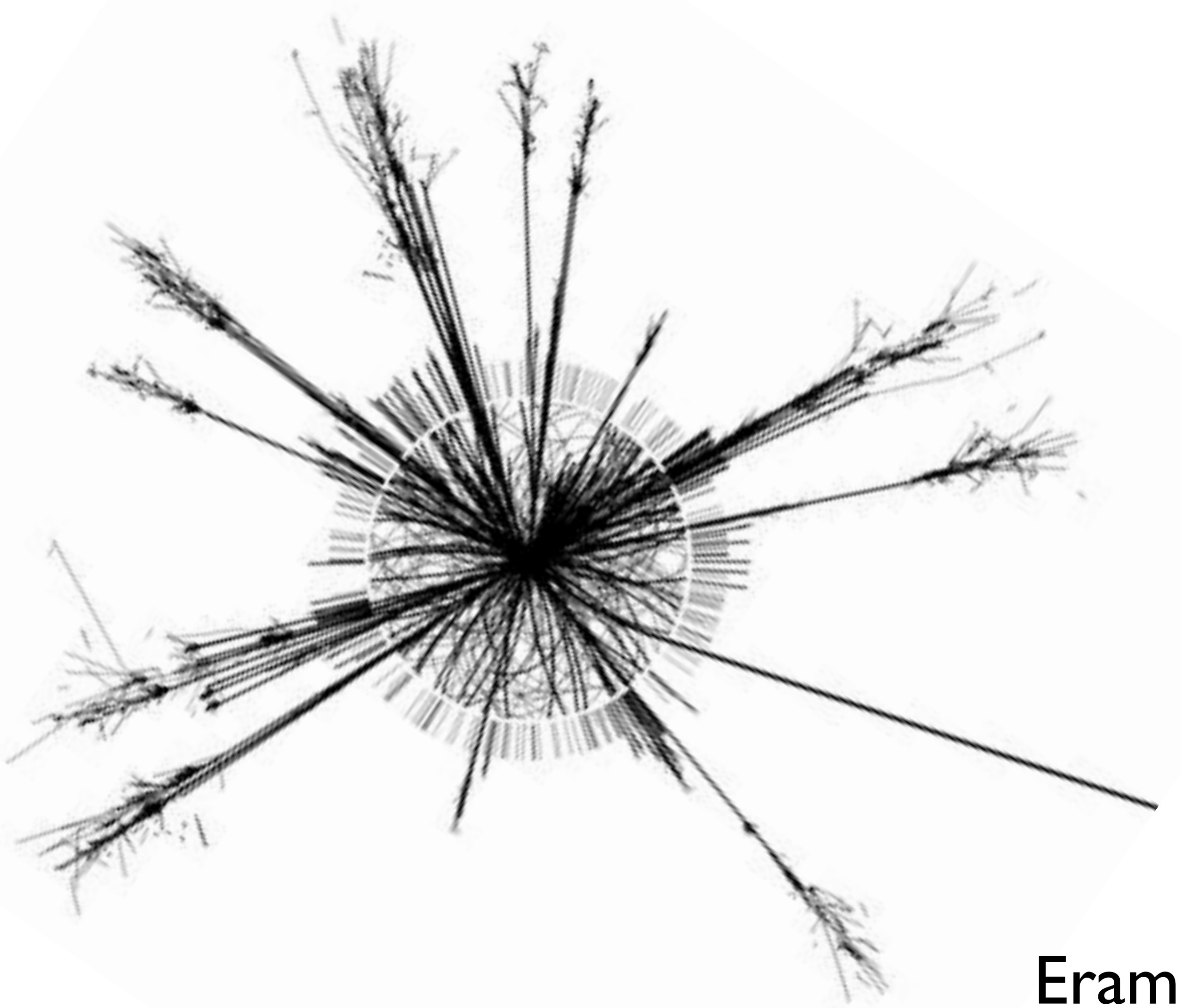
The Energy Frontier

Lecture 6

- Gravity at the TeV Scale
- Selected Results
- The Future Experiments



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20th March 2012

Outline

A Century of Particle Scattering 1911 - 2011
- scales and units
- overview of periodic table → atomic theory
- Rutherford scattering → birth of particle physics
- quantum mechanics - a quick overview
- particle physics and the Big Bang

A Particle Physicist's World - The Exchange Model
- quantum particles
- particle detectors
- the exchange model
- Feynman diagrams

The Standard Model of Particle Physics - I
- quantum numbers
- spin statistics
- symmetries and conservation principles
- the weak interaction
- particle accelerators

The Standard Model of Particle Physics - II
- perturbation theory & gauge theory
- QCD and QED successes of the SM
- solar neutrino problem

Beyond the Standard Model
- where the SM fails
- the Higgs boson
- the hierarchy problem
- supersymmetry

The Energy Frontier
- large extra dimensions
- selected new results
- future experiments

Supersymmetry

- 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: electro-weak + QCD
TOE = Theory of everything = GUT + quantum gravity
Expect this to occur 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, ħ, G

<u>units</u>
c → m s^{-1}
G → m^3 Kg^{-1} s^{-2}
ħ → 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

Dark Matter Candidates

Astronomical observation show that ~25% of universe is dark matter
It should be cold (i.e. non-relativistic) and stable (does not decay)
- Must be non-charged (or will interact with photons)
- Must be only weakly interacting (else Big Bang temperature fluctuations wouldn't seed galaxy formation)
- Cannot be neutrons - free neutrons decay
- Cannot be neutrinos - mass too small

The lightest SUSY particle (LSP) is a prime dark matter candidate!

Quantum Gravity

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!

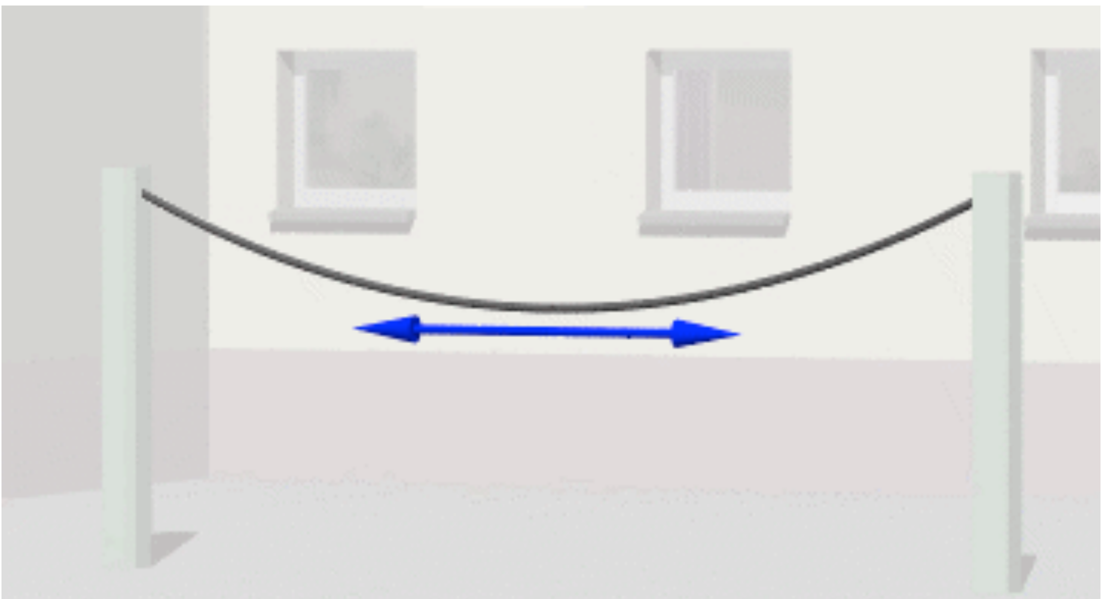
Some quantum gravity theories live in 10 or 11 dimensional space!
predict gravitons propagate in extra dimensions size of Planck length
(graviton = postulated force carrier of gravity)
Explains why gravity is 10^{23} times weaker than Weak force - gravity is diluted

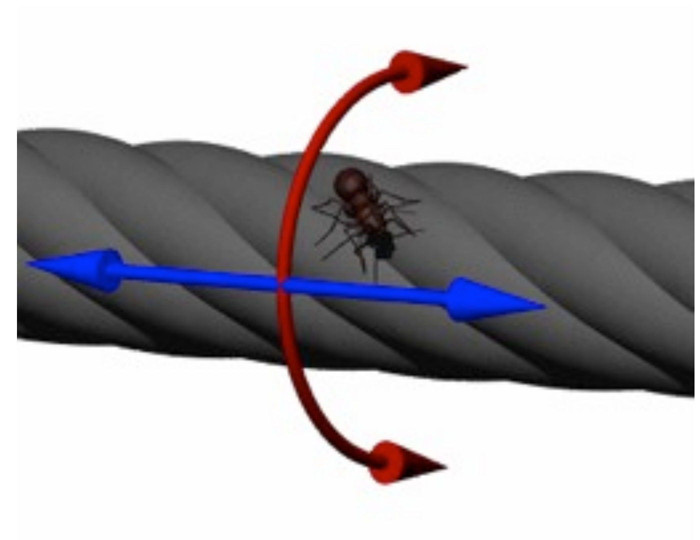
But: If extra dimensions "large" (~0.1mm) quantum gravity could be seen at TeV scale
Gravity has never been tested at such short distances!
LHC could open the possibility of creating mini-black holes & gravitons
laboratory for testing quantum gravity!!!

Large Extra Dimensions

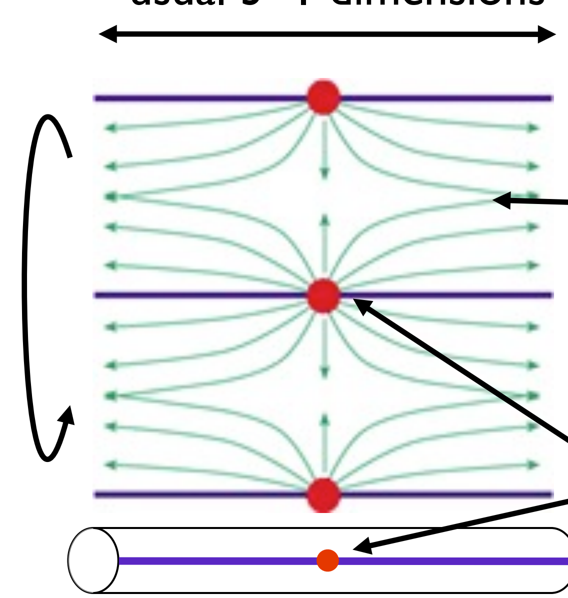
Why are the extra dims < 1 mm ?
gravity has only been tested down to this scale!

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





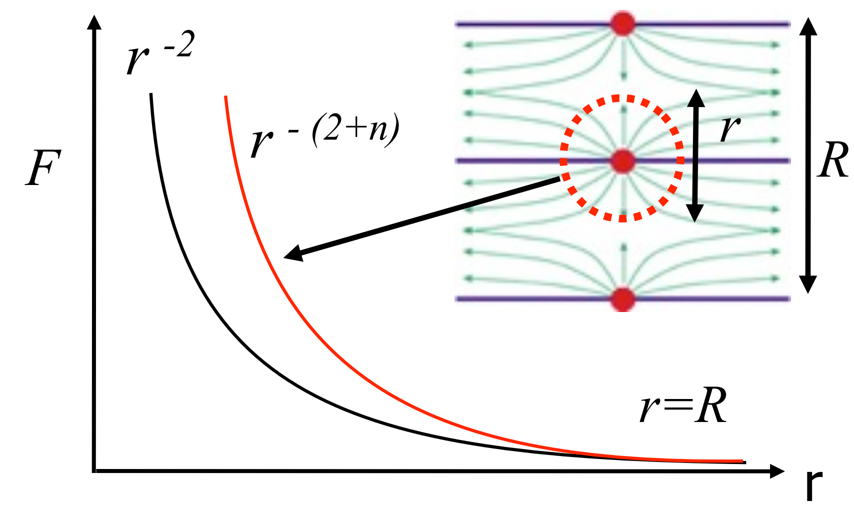
Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space



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

With extra dimensions gravity becomes modified

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



With n extra spatial dimensions each of size R

$$F = G_D \frac{m_1 m_2}{r^{2+n}}$$

$$F = \left(\frac{G_D}{R^n}\right)\frac{m_1 m_2}{r^2} \qquad \text{i.e} \qquad G = \frac{G_D}{R^n}$$

dilution due to volume of extra dimensions

For r much larger than R we recover Newtonian gravity

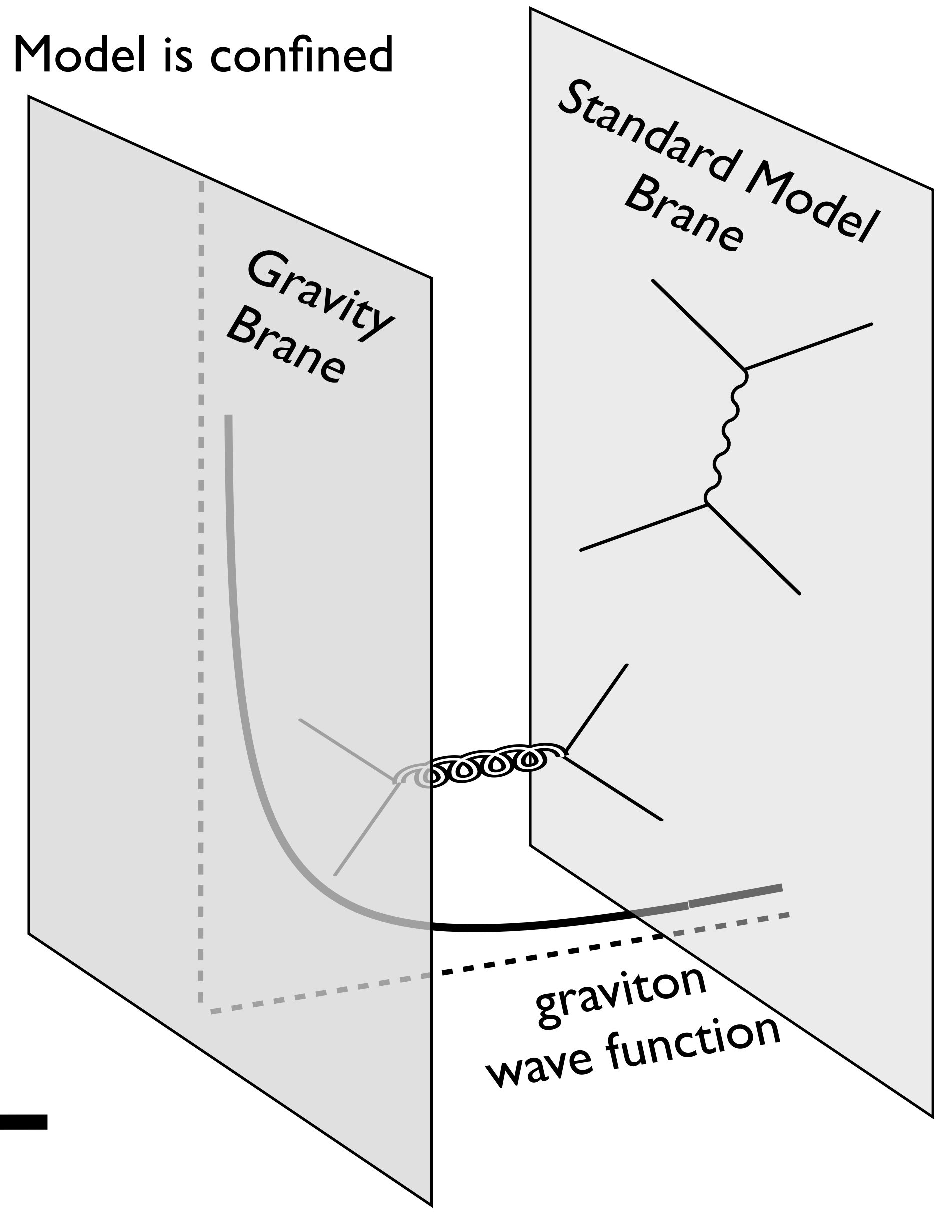
Planck scale: $M_P^2 = \dfrac{\hbar c}{G}$

In extra dimensions full scale of gravity M_D is given by $M_D^2 = \dfrac{\hbar c}{G_D} = \dfrac{M_P^2}{R^n}$ Thus M_D can be ~ 1 TeV when R^n is large

For n=1 and M_D=1 TeV then $R \sim 10^{16}$ m $\Rightarrow$ already excluded!

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



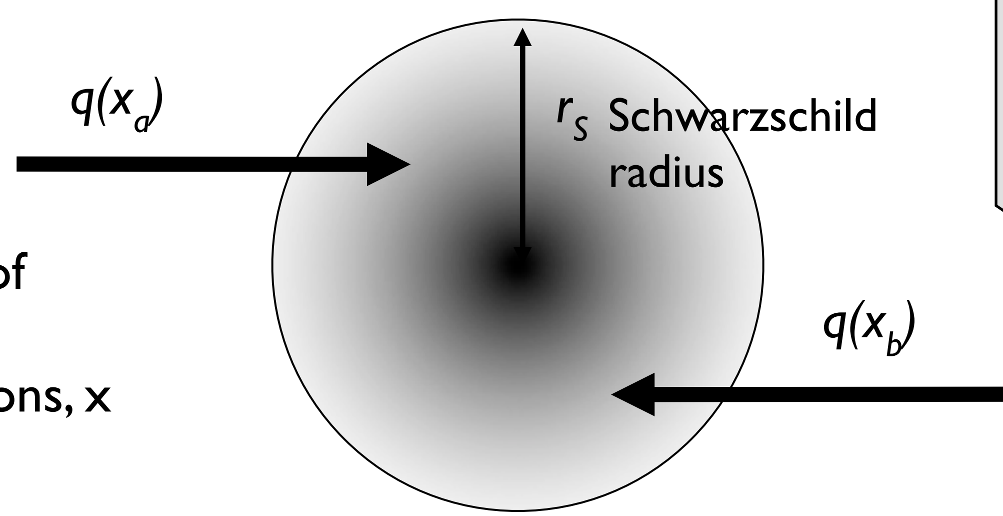
At high enough energy ADD models predict micro-blackhole production

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

Black hole mass:

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

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



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

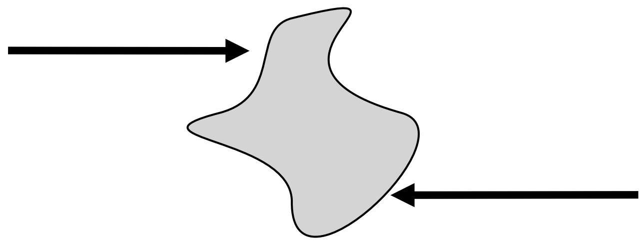
With extra dimensions:

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

r_S increased by factor R^n

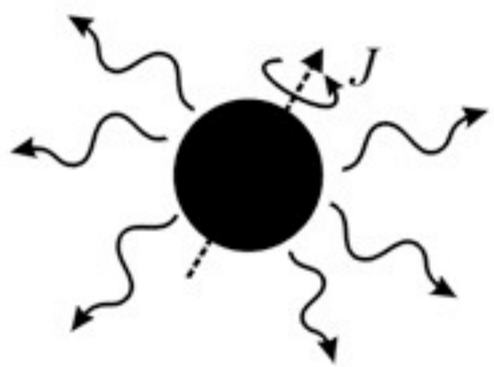
r_S = 1 cm for Earth

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

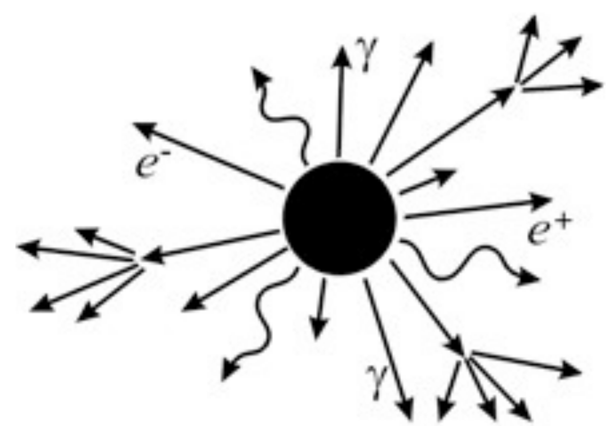


Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

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 quanta

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

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

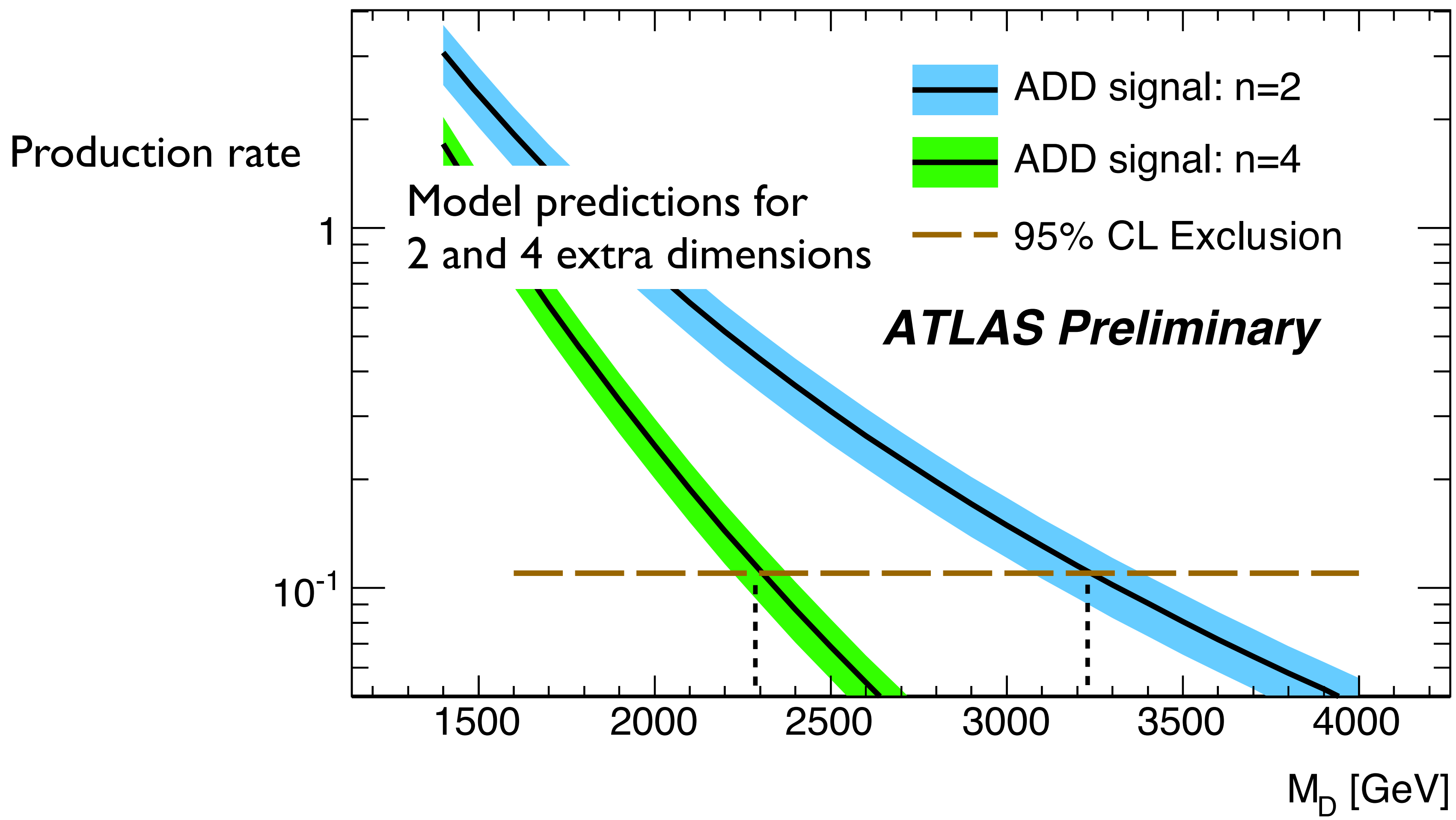
If you observe the Loch for 24 hours and see nothing, then either:
- 'Nessie' doesn't exist
- your camera has poor efficiency for spotting animals (larger than 2m long)
- it exists but comes to the surface less than once per day

In physics searches usually 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

You need to carefully consider your detector's efficiency in observing similar topology collisions

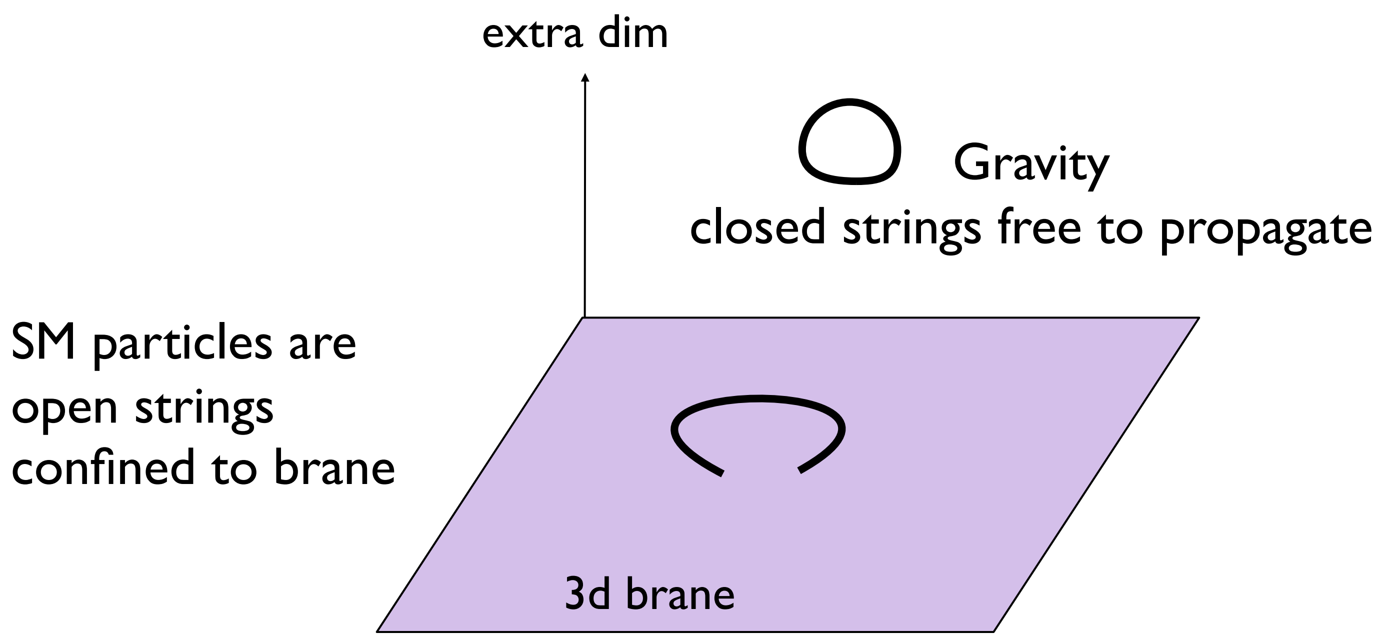
We found nothing so far...



Exclude masses below 2.27 TeV for n=4

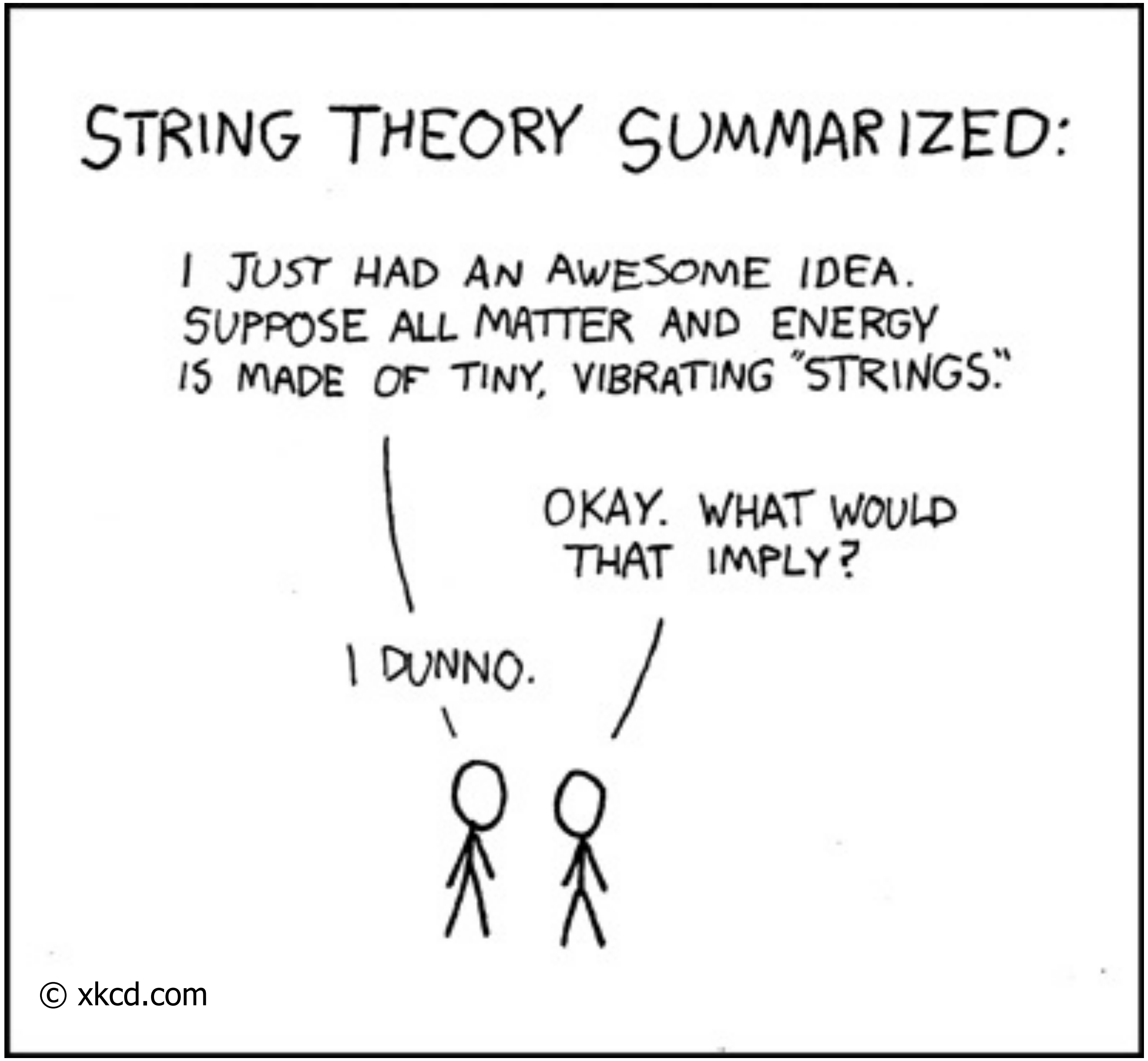
Exclude masses below 3.22 TeV for n=2

True theory of quantum gravity does not exist
String theory may fill that gap



String theory may be candidate theory for quantum gravity
Requires 6-7 extra spatial dimensions

Problem: string theory is unable to make testable predictions - operates only at the Planck scale


STRING THEORY SUMMARIZED:
I JUST HAD AN AWESOME IDEA. SUPPOSE ALL MATTER AND ENERGY IS MADE OF TINY, VIBRATING "STRINGS."
OKAY. WHAT WOULD THAT IMPLY?
I DUNNO.
© xkcd.com

Colliders At The Electroweak Scale

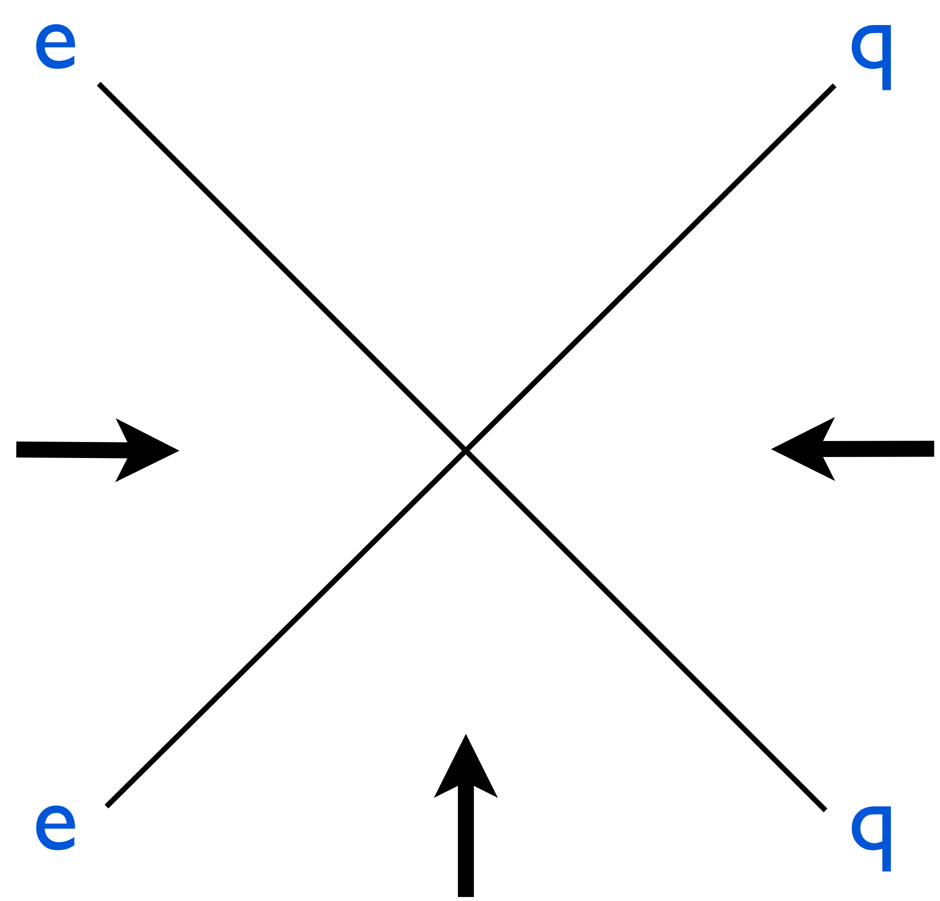
We have learnt a lot from the synergy between different colliders

Precision electroweak measurements LEP/SLD

M_Z

α

etc...



LHC / Tevatron

m_{top}

Higgs

new physics

HERA

Precision QCD

electroweak couplings

quark / gluon dynamics

What are we looking for ?

$e+e$ $e+\mu$ $e+\mu+2b+2\nu$ $e+2\mu+\nu$ $\mu+j+\nu$ $\mu+\mu$

$e+j$ $e+\mu+j$ $e+2\tau+2b+3\nu$

$2e+3j$ $3e+3\nu+j$ $2\mu+2\tau+j$ $2\mu+2b$

$e+\tau+2j$ $e+2\tau+\nu+j$ $\mu+\tau+2b$ $2\mu+2j+2\nu$

$\tau+\tau$

$e+2j+\nu$ $2e+\tau+2\nu+2j$ $2\tau+2b$ $2\tau+2j+\nu$ $2b+4j$

$\gamma+e+\nu$ $\gamma+\mu+\nu+2j$ $\gamma+\tau+\nu$ $e+\mu+\tau+3\nu$ $4j+\nu$ $2b+2\nu$

$\gamma+\gamma$ $\gamma+c+\nu$ $\gamma+2e+\nu$ $\gamma+b+2j$ $2b+2j$

$\gamma+\nu$ $2\gamma+2j$ $2\gamma+2\mu+3j$ $j+j$ $j+\nu$

What are we looking for ?

Higgs boson

spin-2 gravitons G

$\mu+\mu$ $\tilde{l}^{\pm}$

χ_1^0 e+e e+μ e+μ+2b+2ν e+2μ+ν μ+j+ν Axigluon

e+j e+μ+j e+2τ+2b+3ν b' $\tilde{g}$ 2μ+2b

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

W' e+τ+2j e+2τ+ν+j μ+τ+2b 2μ+2j+2ν

KK particle τ+τ Z' q^*

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

$\overline{LQ}$ e+μ+τ+3ν CMLLPs 2b+2ν

γ+e+ν γ+μ+ν+2j γ+τ+ν SUSY 4j+ν

R-hadrons γ+2e+ν 2b+2j $\chi_1^{\pm}$

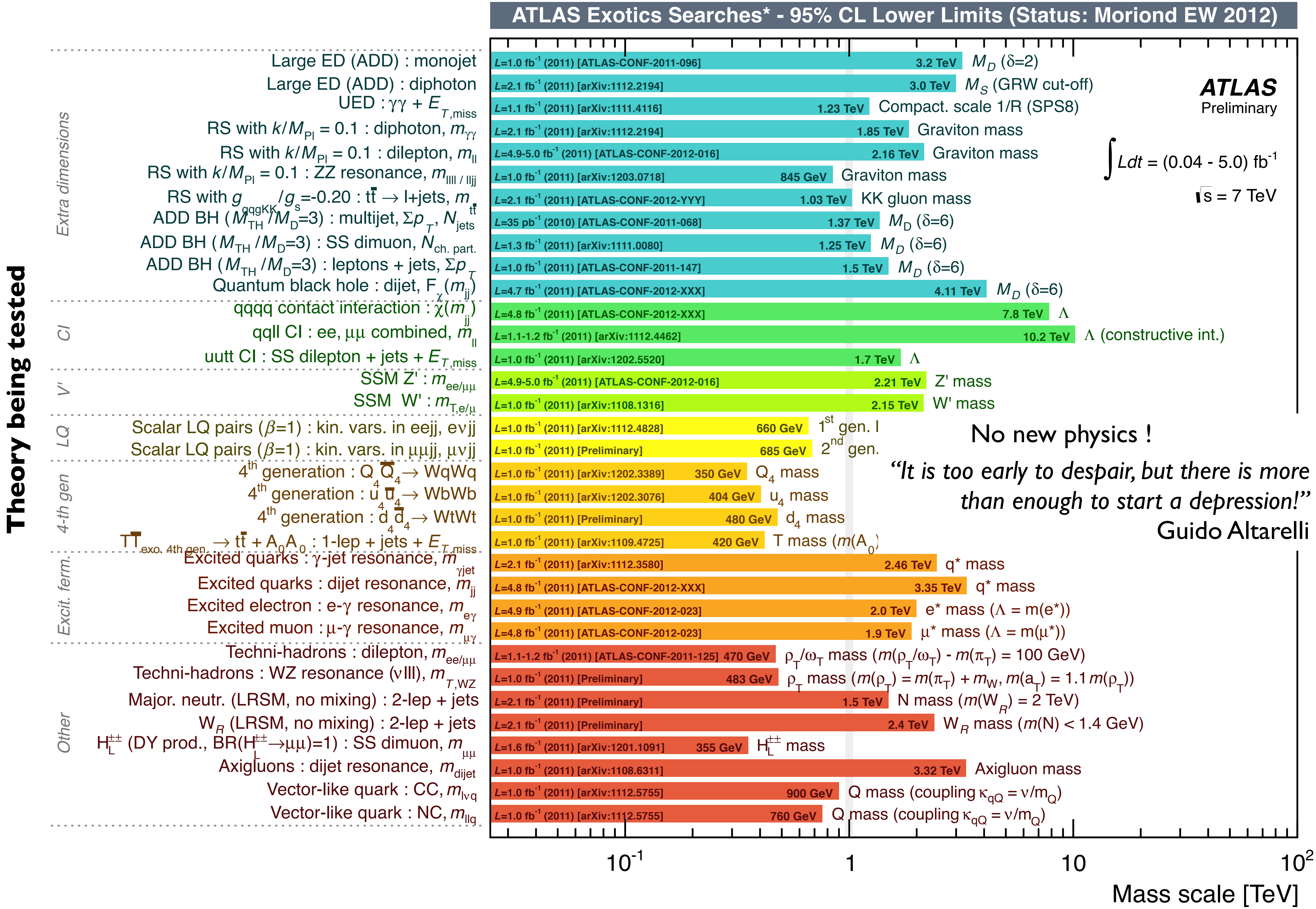
γ+γ $\tilde{\nu}$ γ+c+ν γ+b+2j

Coloron j+ν

γ+ν E_6 diquark 2γ+2j 2γ+2μ+3j j+j

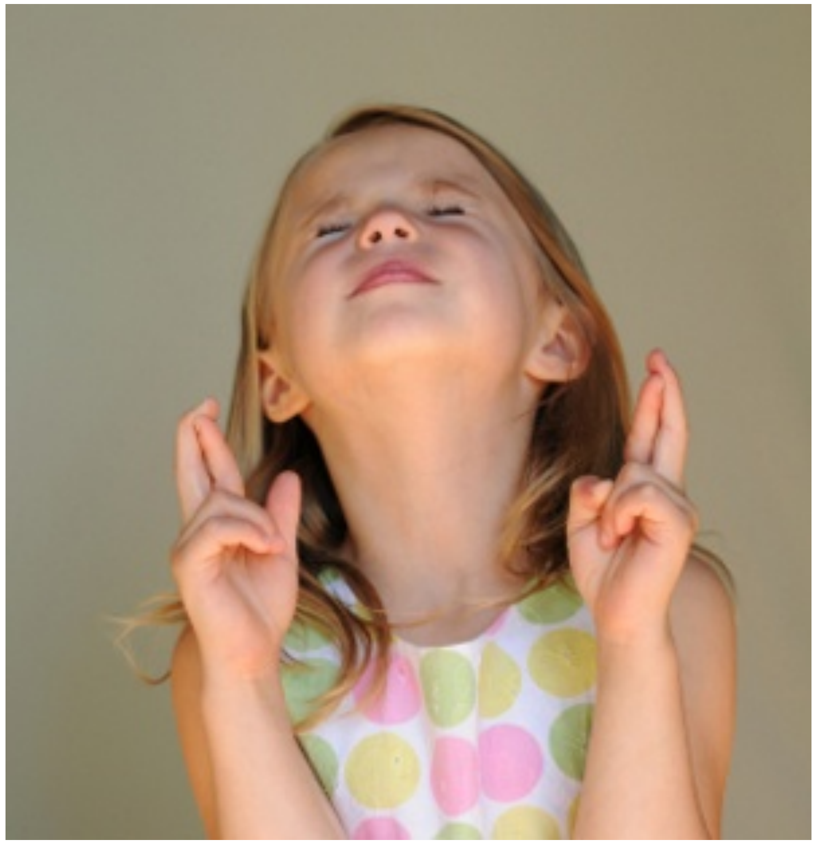
E_6 GUT model

Results of ATLAS searches for new physics



No new physics !

"It is too early to despair, but there is more than enough to start a depression!"
Guido Altarelli

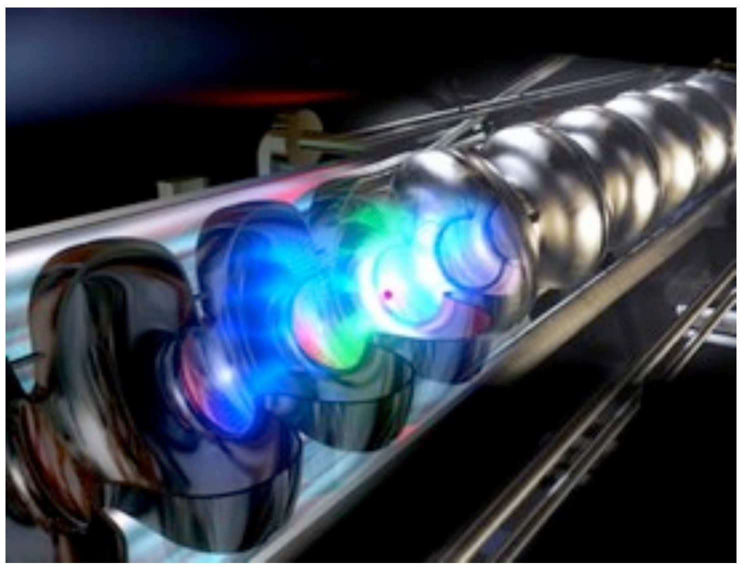


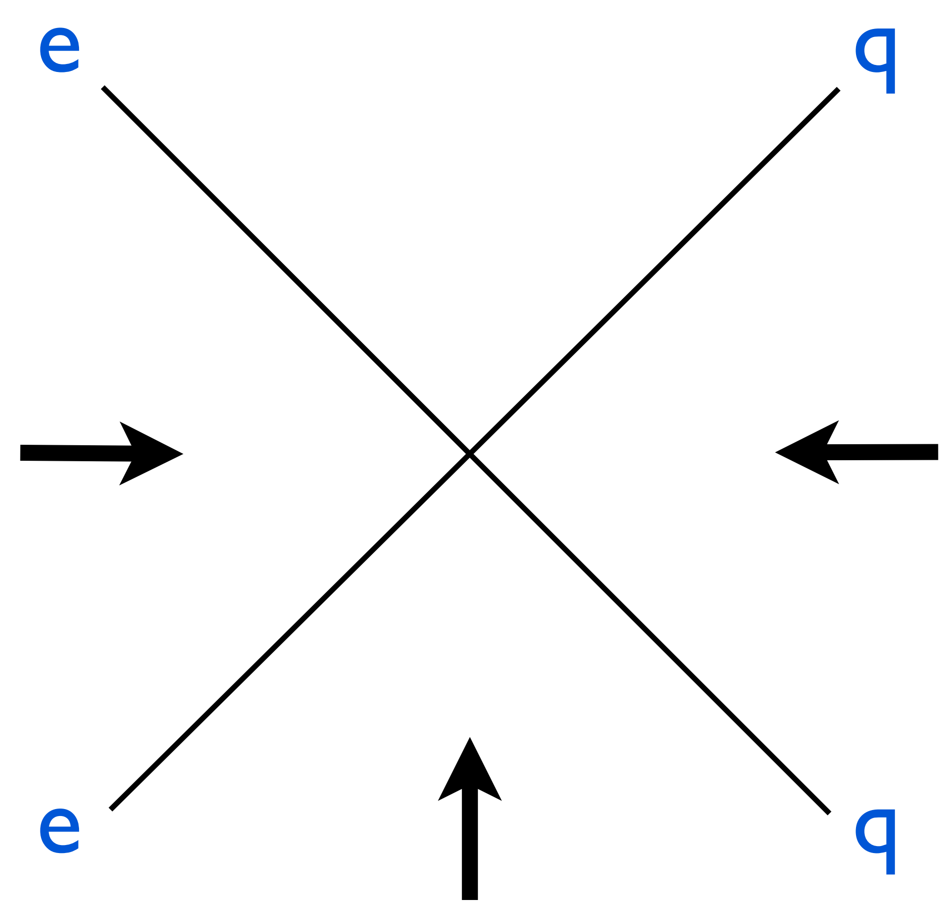

Beyond the LHC ?

Colliders At The Energy Frontier

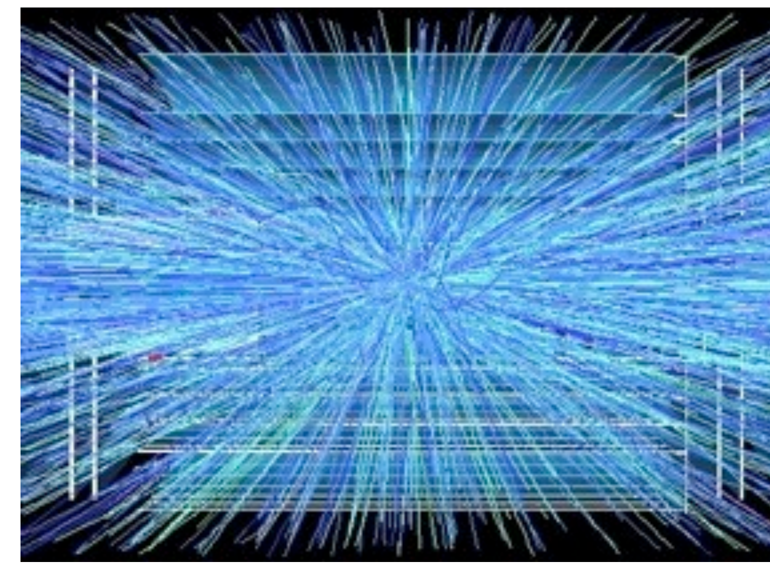
LHC data will guide us in the future...

International Linear Collider - ILC
Compact Linear Collider - CLIC



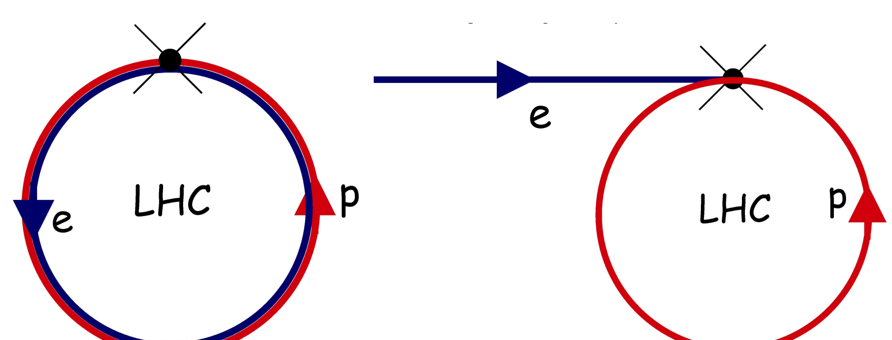


High Luminosity LHC
High Energy LHC



LHeC

Large Hadron electron Collider

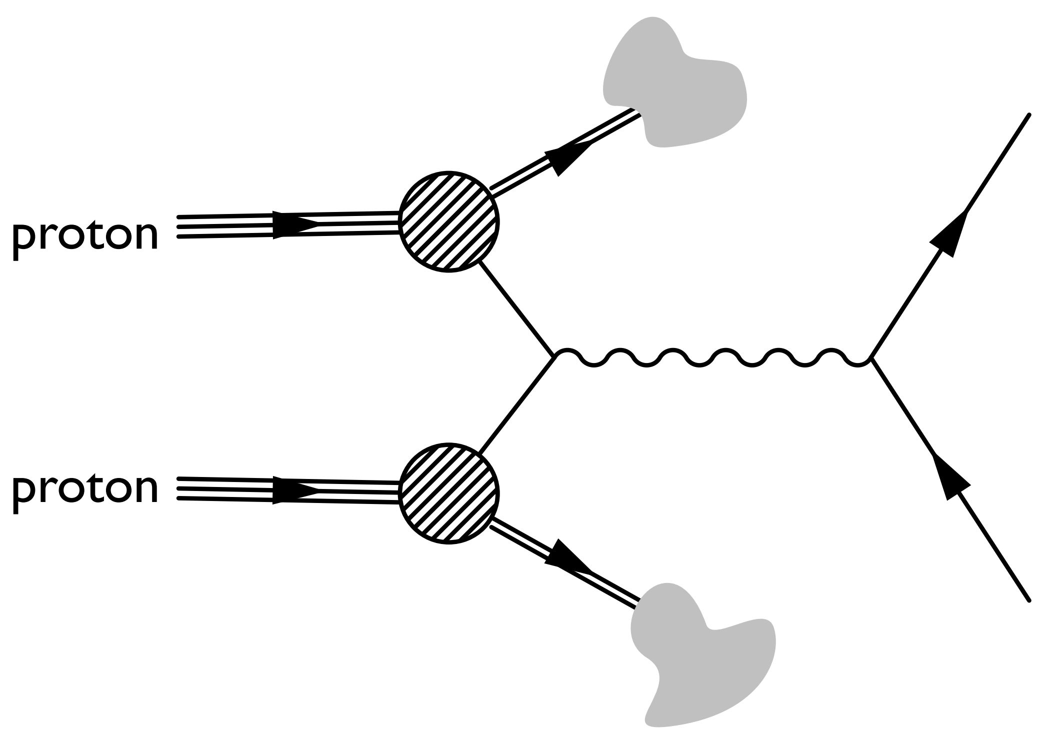


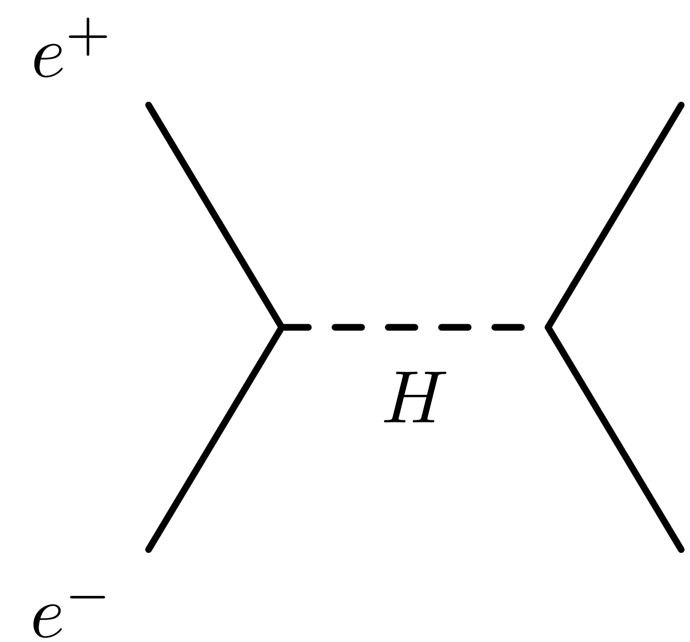
Many other experiments planned

- Neutrino interactions at high intensity
- Proton decay experiments
- Very high energy cosmic ray showers
- Double beta decay experiments
- Muon colliders
- ...

The LHC will discover the Higgs or new physics!
We need to characterise the new particle(s) - determine its quantum numbers / couplings

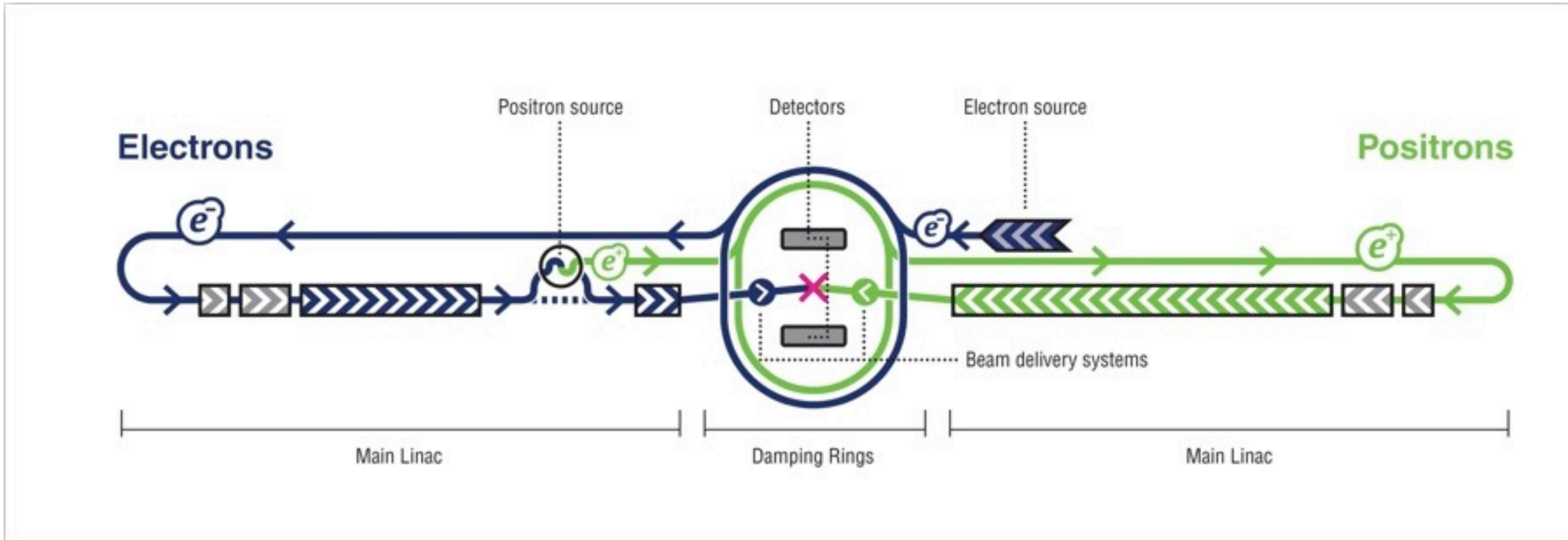
Proton colliders can be built at higher energy than electron colliders
Excellent for producing new high mass particles
But... need to contend with extremely large backgrounds - reactions that mimic new physics
Background arises from extremely high rate quark/gluon collisions

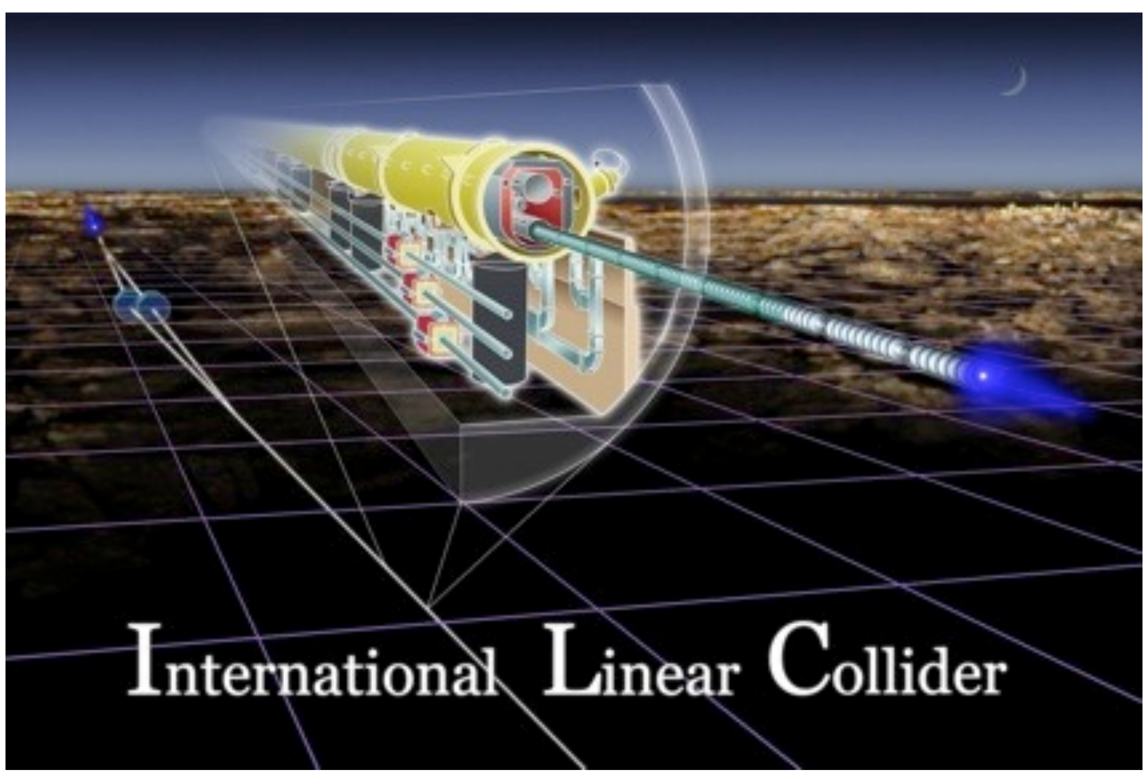




Build proton colliders to discover new things

Build lepton colliders to make precision measurements





<u>ILC and CLIC</u>
Two competing technologies for e^+e^- collider
Projects are in R&D phase

CLIC	ILC
energy: 1 − 3 TeV	energy: 0.5 − 1 TeV
length: 13 - 48 km	length: 30 - 50 km

Tune energy to produce many Higgs particles - Higgs factory!
Allow precision study of Higgs parameters
Low backgrounds - no messy quarks!

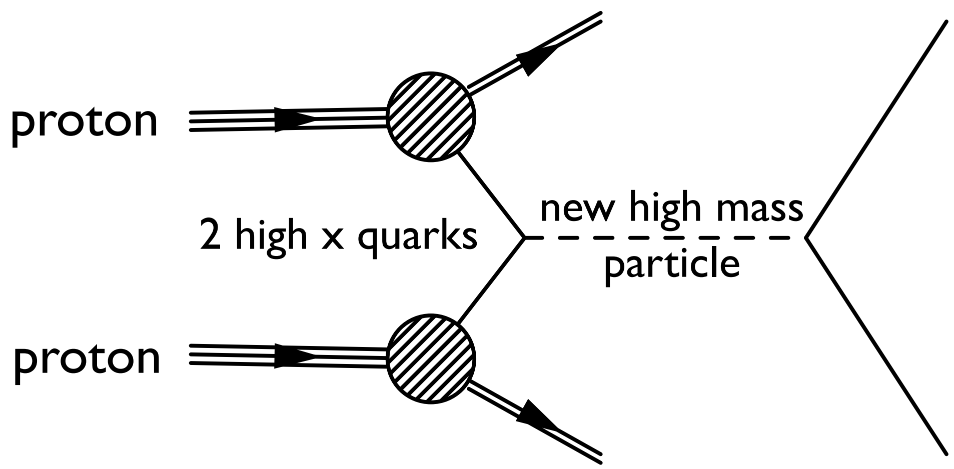
Project not yet approved - only R&D phase funded

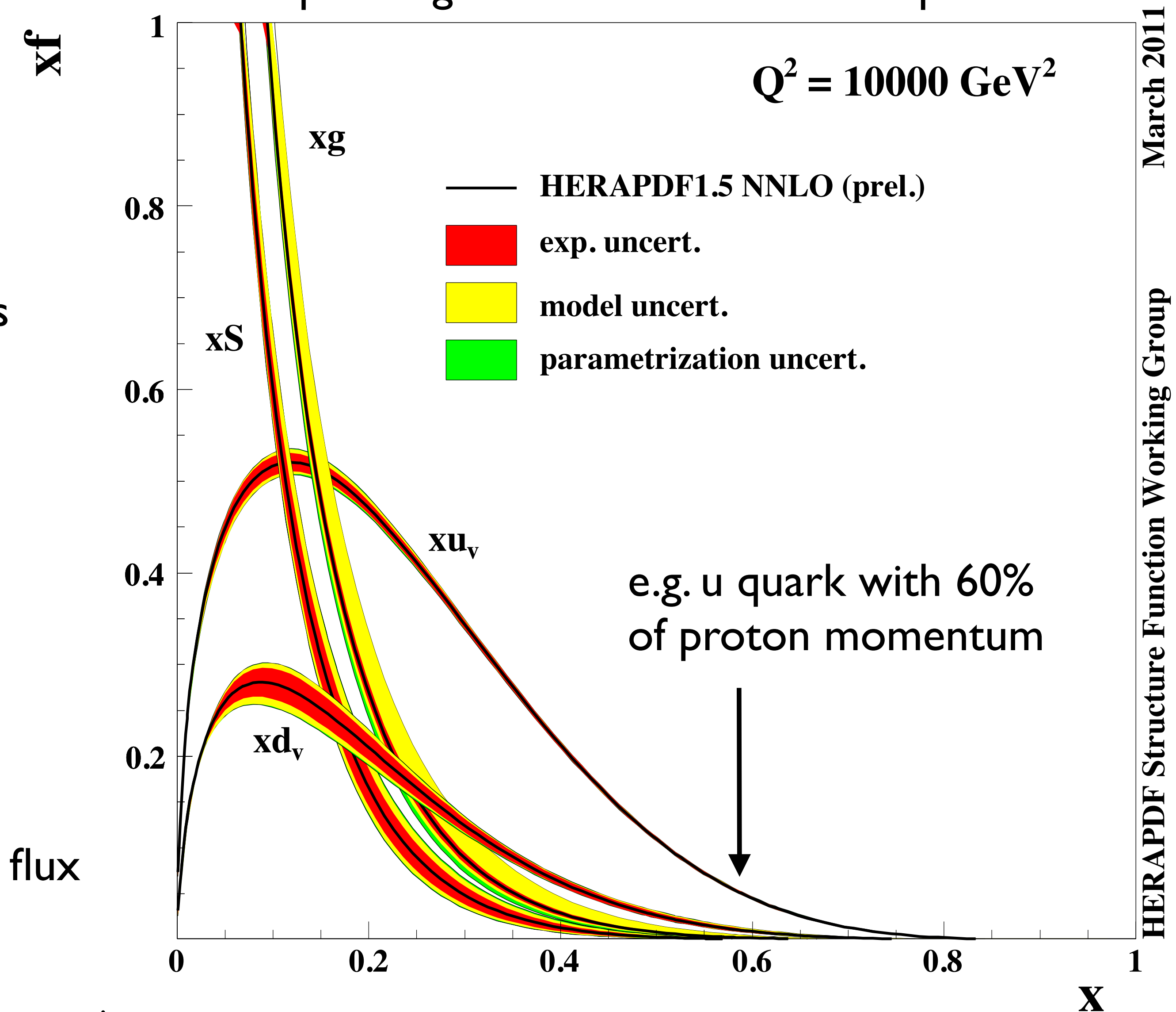
Colliders At The Energy Frontier

Parton density functions map out momentum of quark / gluon constituents in the proton

<u>High luminosity LHC</u>
Project approved & funded
Expect to start operation ~ 2022
super-LHC will provide 10 times more data

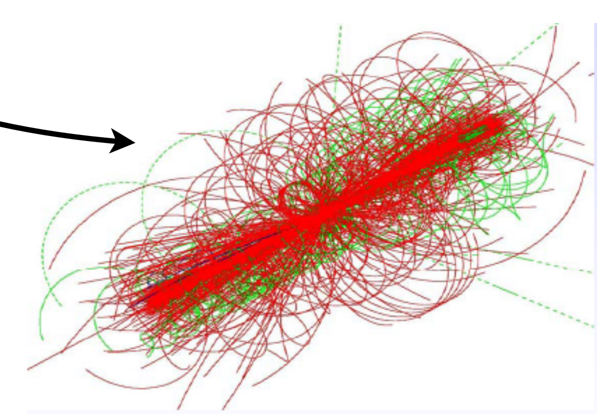
Small probability to collide two quarks at very high x
Need high x collisions to form highest mass new particles



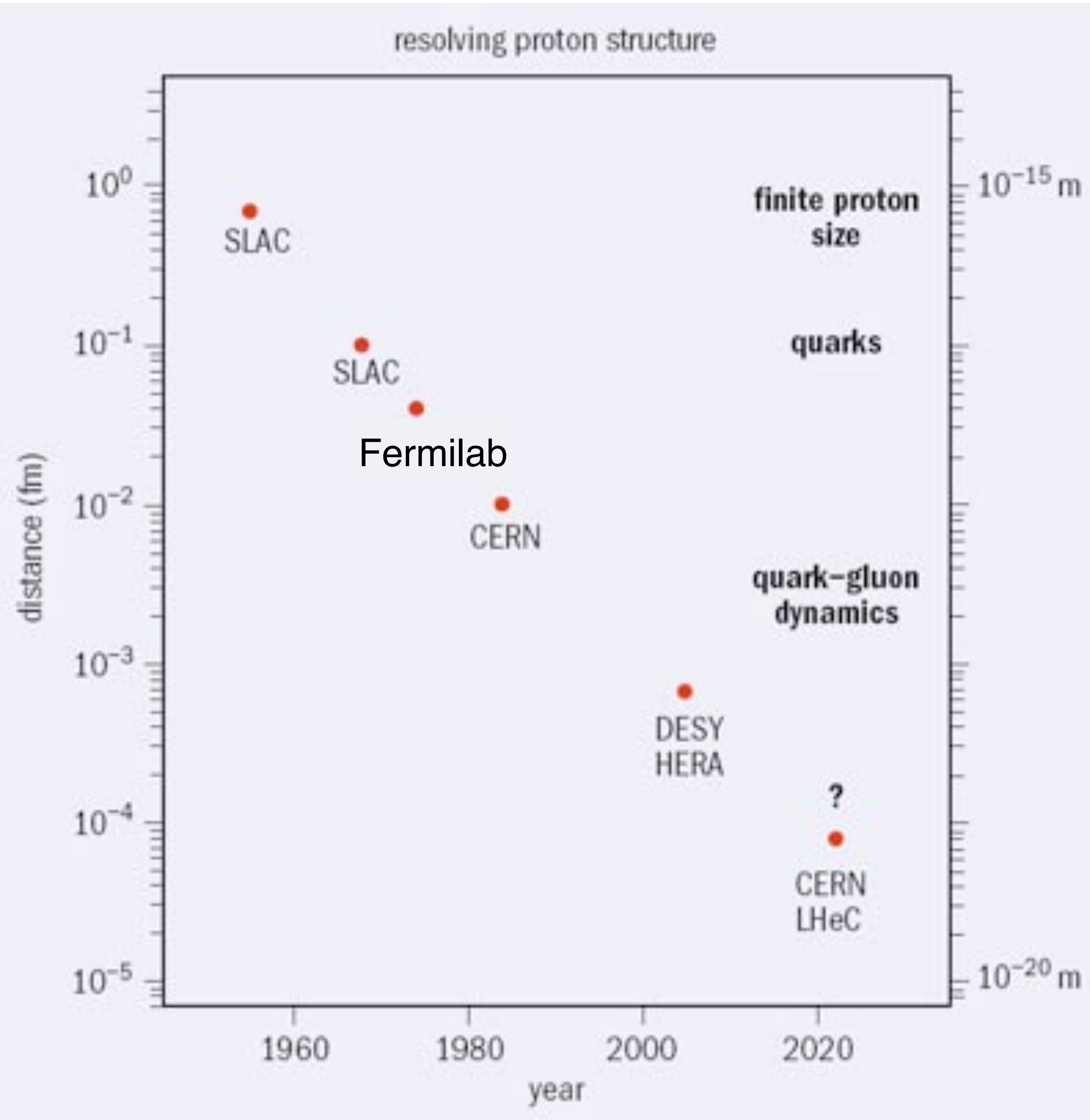


x = fraction of proton's momentum carried by quark / gluon

LHC will deteriorate from 10 years high intensity particle flux
Need to be upgrade experiments / magnets
Profit from new technology
At high intensity expect more than 400 simultaneous collisions!



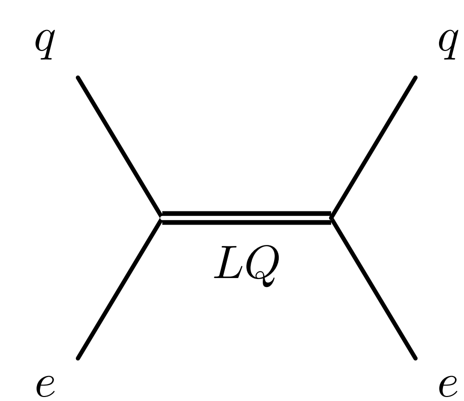
<u>High energy LHC</u>
Under discussion - no firm plans
Potential to double beam energy to 16.5 TeV per beam
Timescale approx. 2030



<u>LHeC</u>

Simultaneous operation of LHC and LHeC
Install electron ring accelerator into LHC tunnel
... or ...
Linear electron accelerator to intersect LHC beam
Electron energy = 60 - 170 GeV

Precision QCD machine
Lower backgrounds
Probe proton structure at highest energy
Constrains proton structure
→ will help LHC discovery potential
Lepto-quark discovery machine
Access LQ quantum numbers



Project at conceptual design phase
Could start operation with HL-LHC phase 2022
Currently unfunded

Past decades saw precision studies of 5% of
our Universe − Discovery of the Standard Model

The LHC is delivering high quality data

We are just at the beginning of exploring
95% of the Universe