Triggering at the LHC:

Too much data is a **good** thing

About me and about this talk

I teach and do research on the ATLAS experiment (@ CERN) just down the road at NIU. Similar to work on the CMS experiment here at Fermilab

This talk is meant to be interactive. I'm happy to be interrupted!

No knowledge of physics required, and not much math. At most, just looking at big and small numbers and maybe some multiplication (if that's OK?)

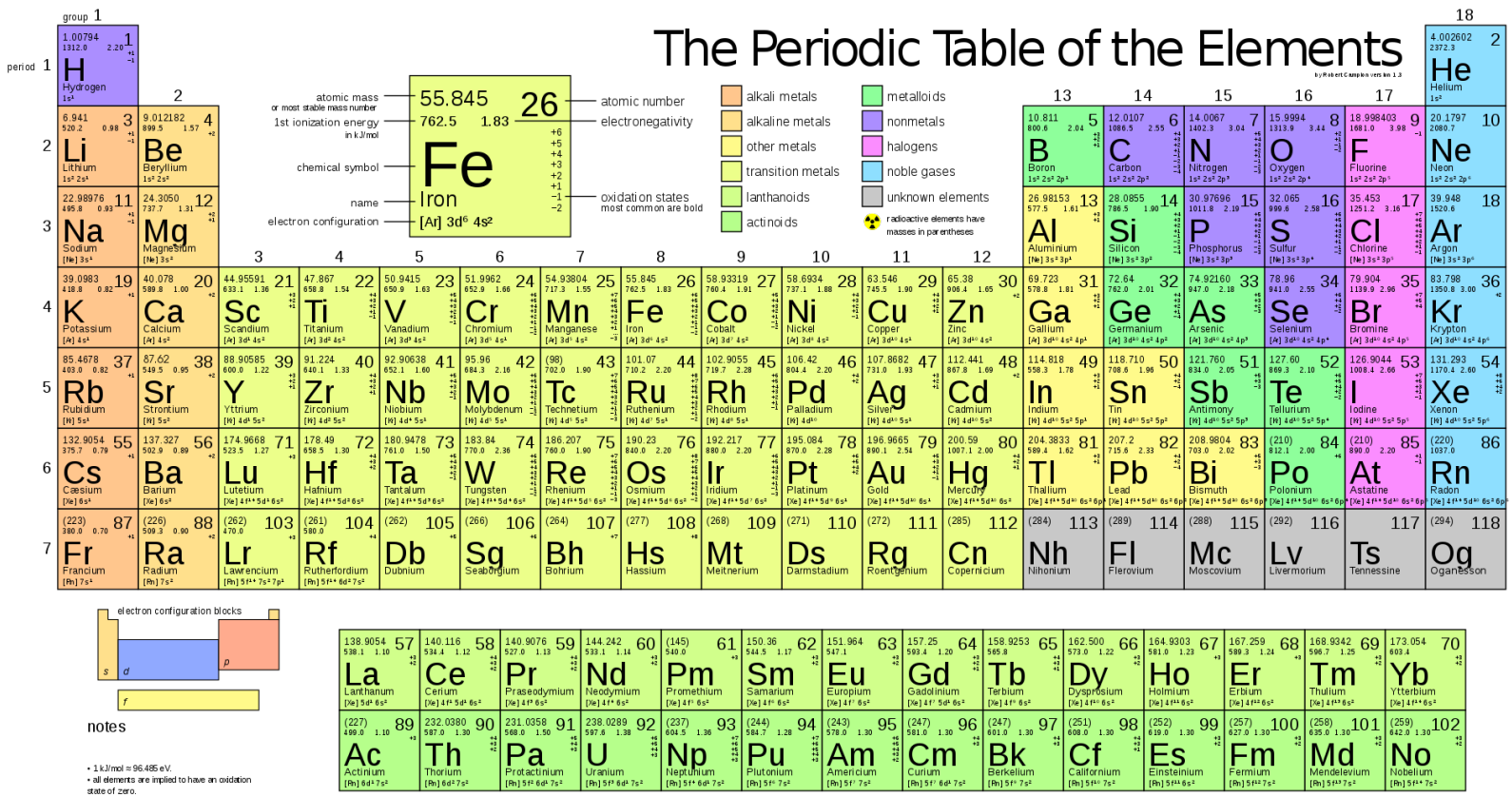
A (short) history of particle physics

Ancient Greeks (atomists): Everything in the world can be broken down into basic building blocks of matter (atoms) that we might call “fundamental particles” these days

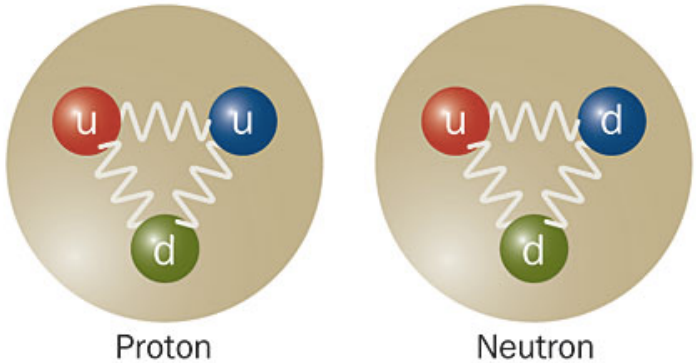
Democritus: “Nothing exists except atoms and empty space, everything else is opinion.”

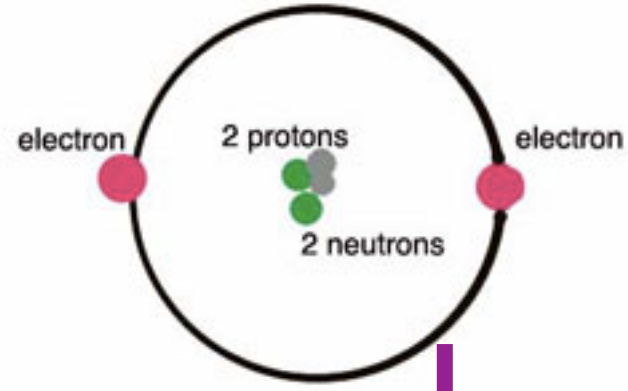
Atoms: the fundamental building blocks of nature?

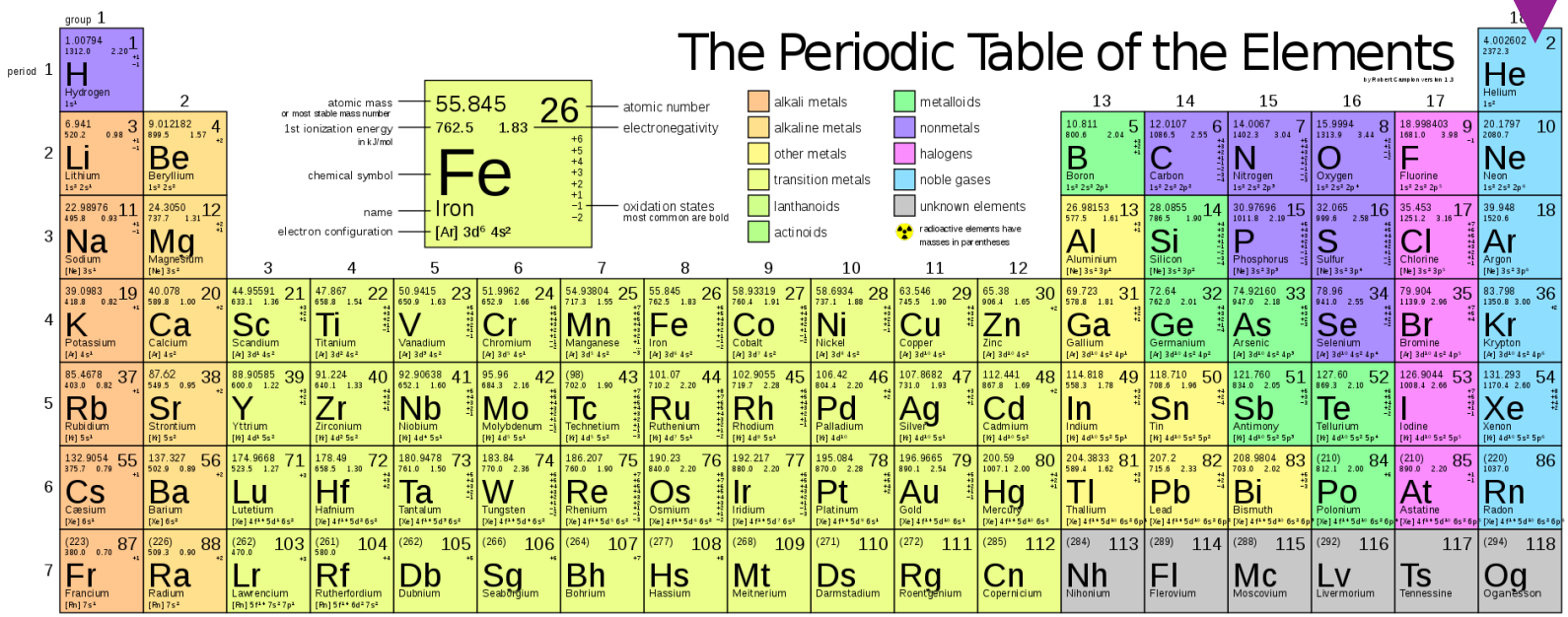
All of matter (chemistry) can be broken down into combinations of the various elements. Are these the **fundamental** building blocks of nature? (You might guess the answer)

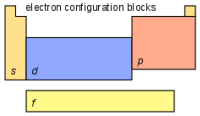


Atoms: Not fundamental objects!









notes

- 1 kJ/mol ≈ 96.485 eV.
- all elements are implied to have an oxidation state of zero.

How do we study the makeup of an object?

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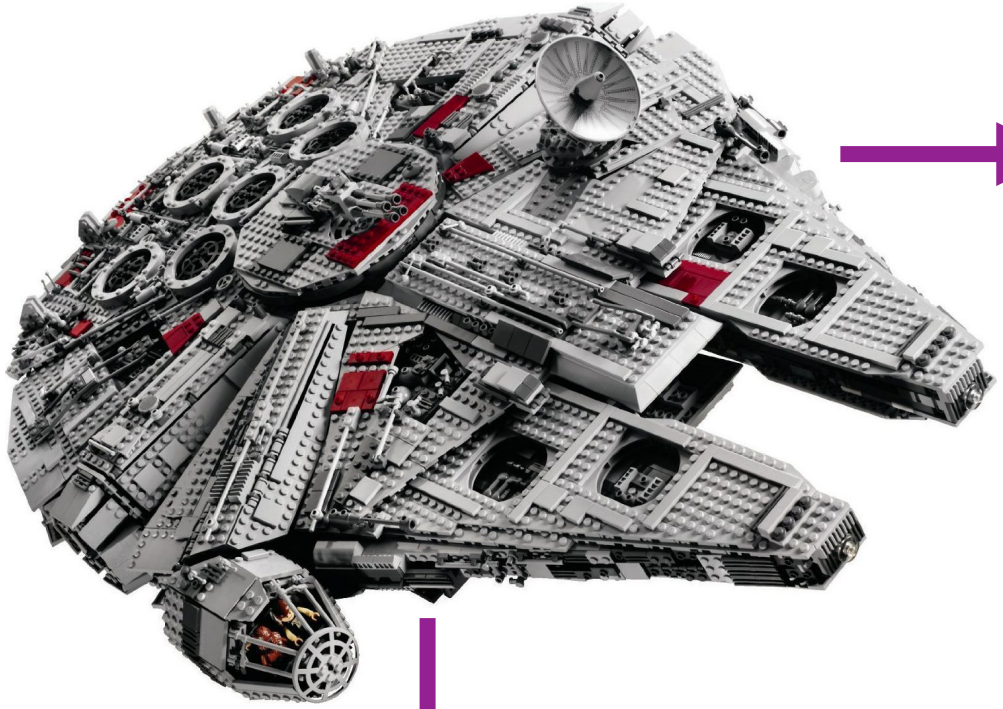
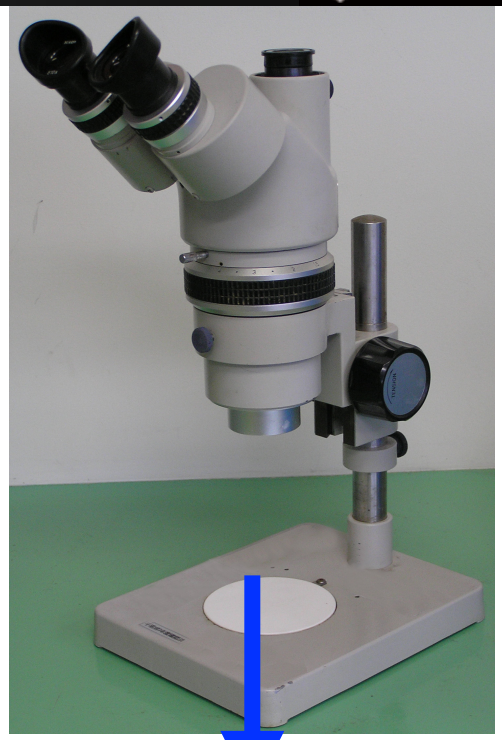


How do we study the makeup of a smaller object?

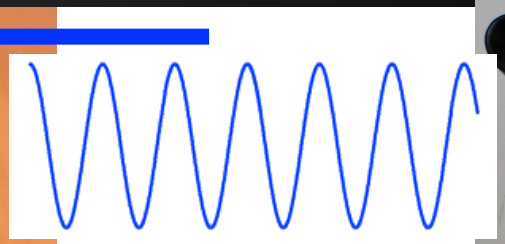
How do we study the makeup of a smaller object?

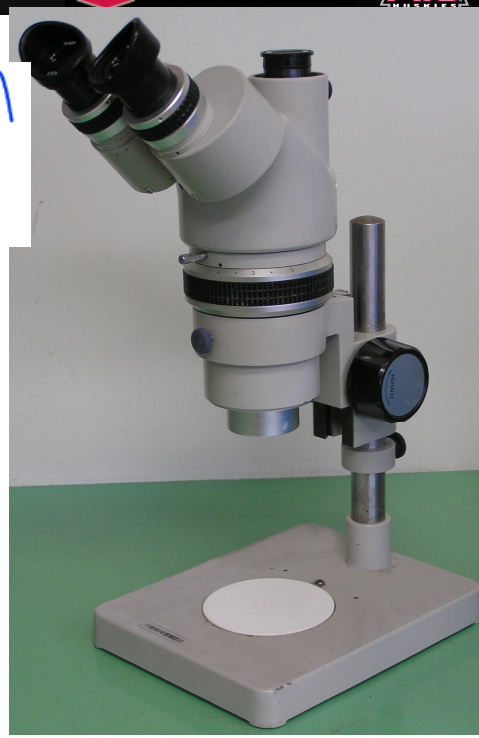
How to look for even smaller things?

How to look for even smaller things?



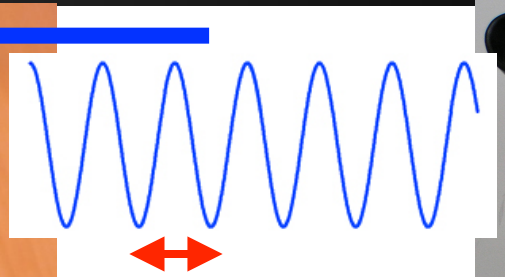
How does the microscope work?

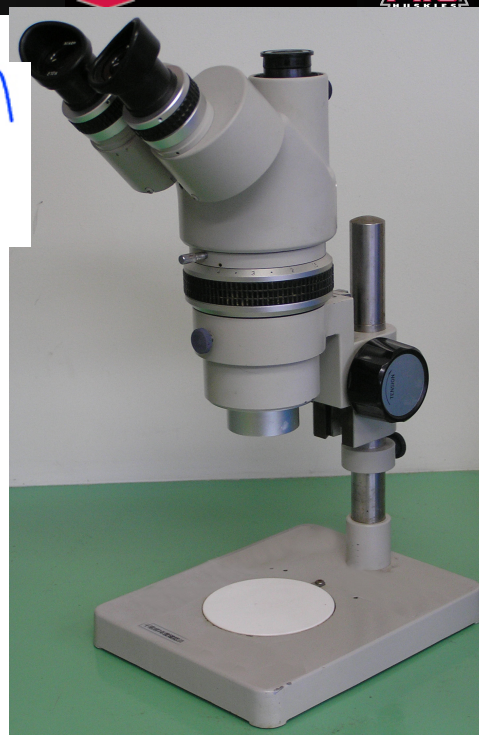




Shine light on an object. It bounces back and hits a sensor (your eye is a type of sensor)

How does the microscope work?

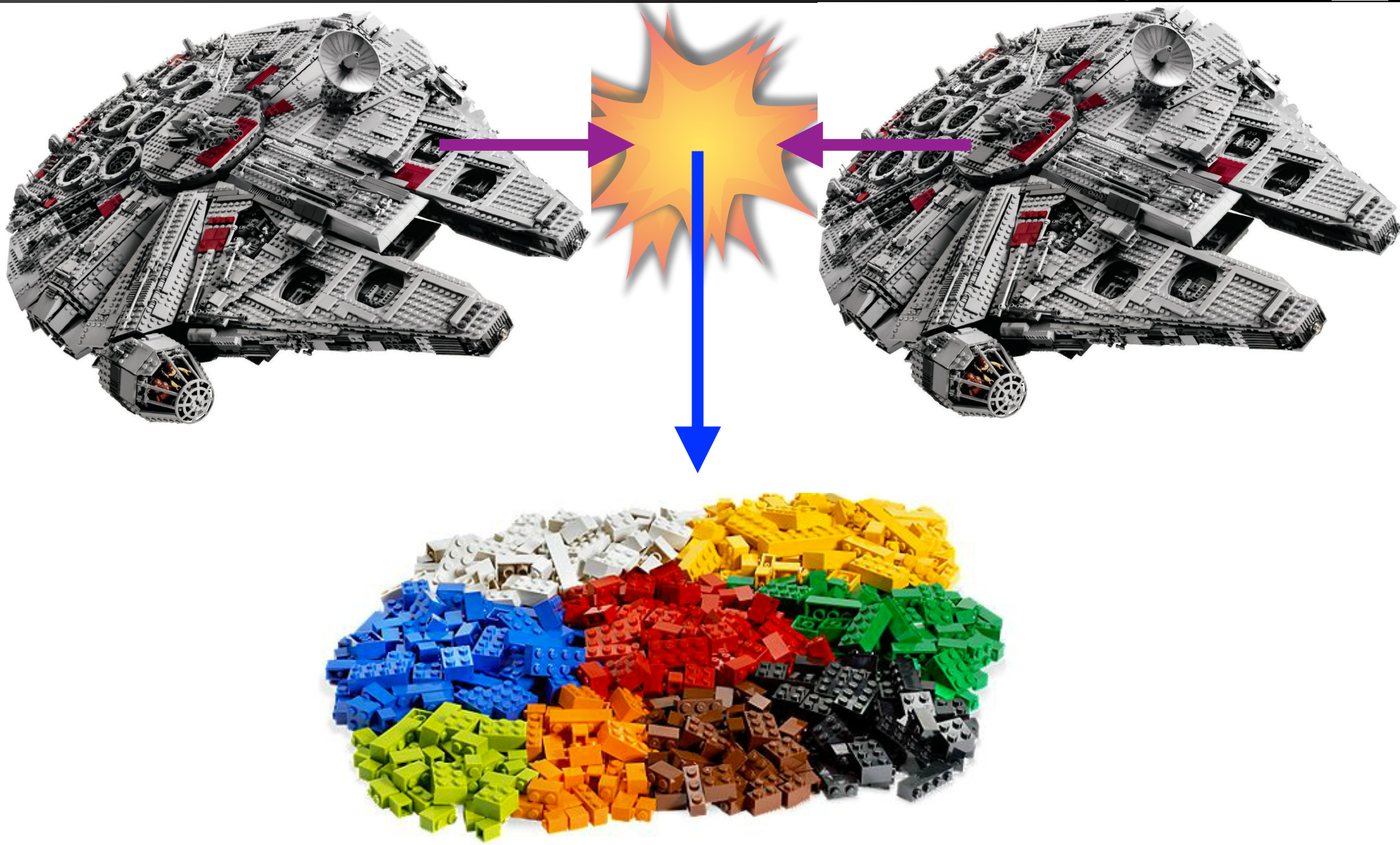




BUT … we can't distinguish things smaller than the **oscillations** (physicists would say "**wavelength**") of the light wave that we use.

Our approach stops working for really really small things!

So we get back to the previous approach



Smash things together and watch what comes out!

What sort of objects might we smash together?

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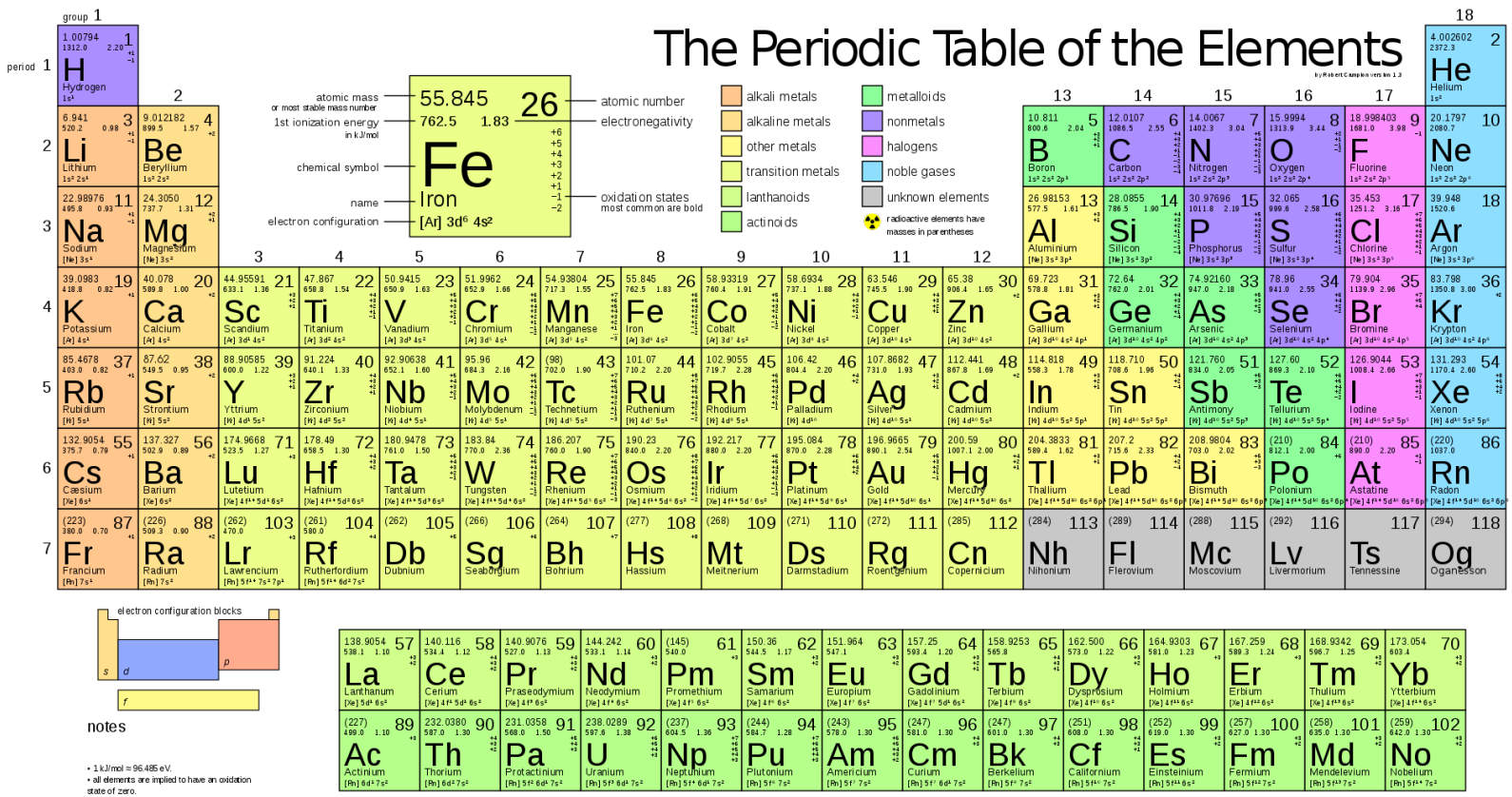
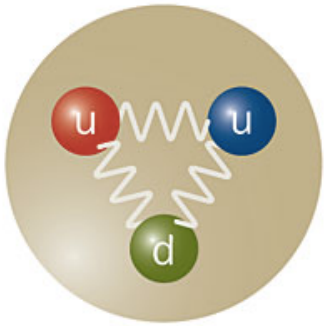
Requirements

- Small (otherwise collisions too messy!)
- Has electric charge (accelerate to high energies!)
- Abundant (want easy access!)

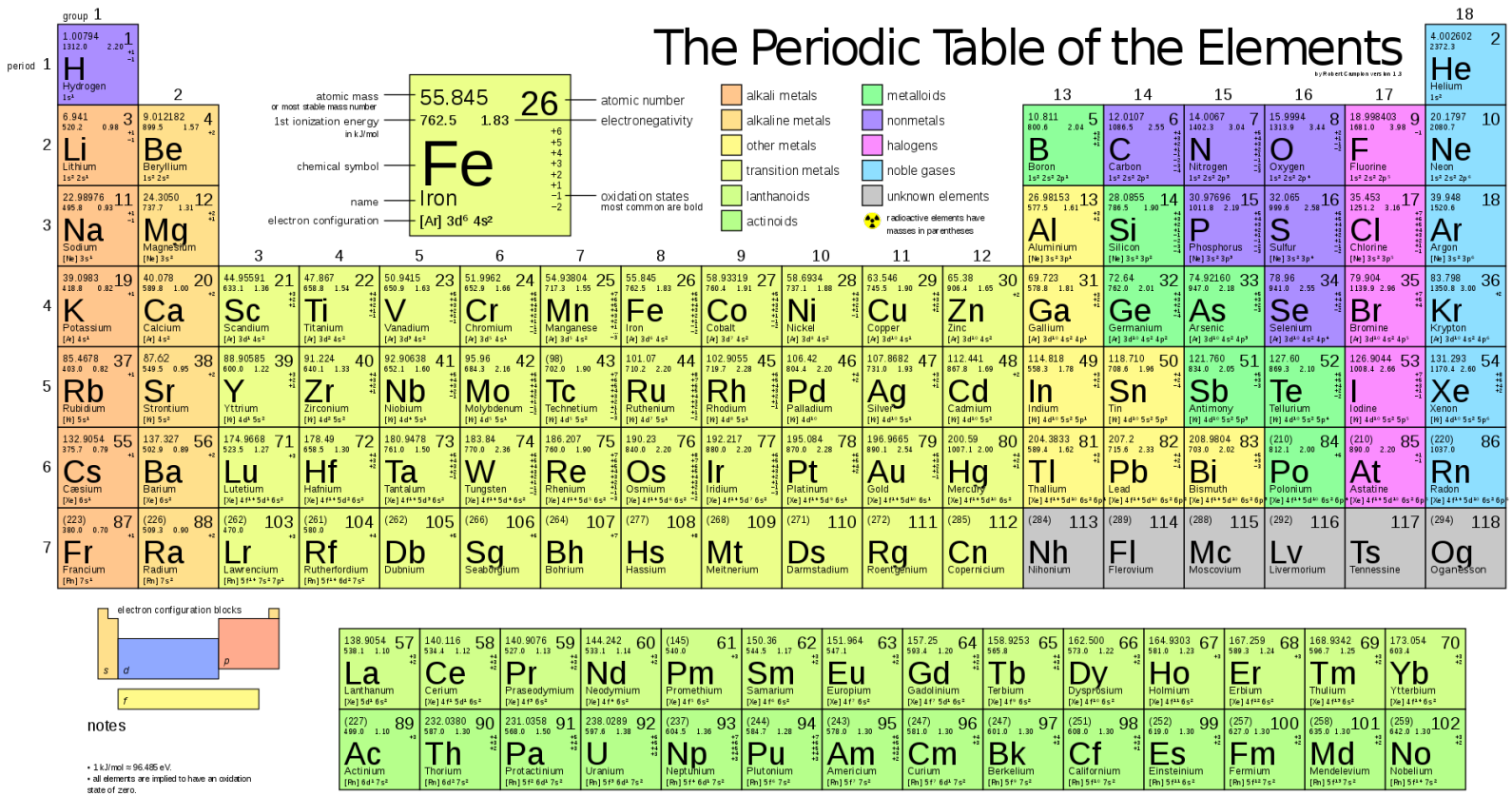


What sort of objects might we smash together?

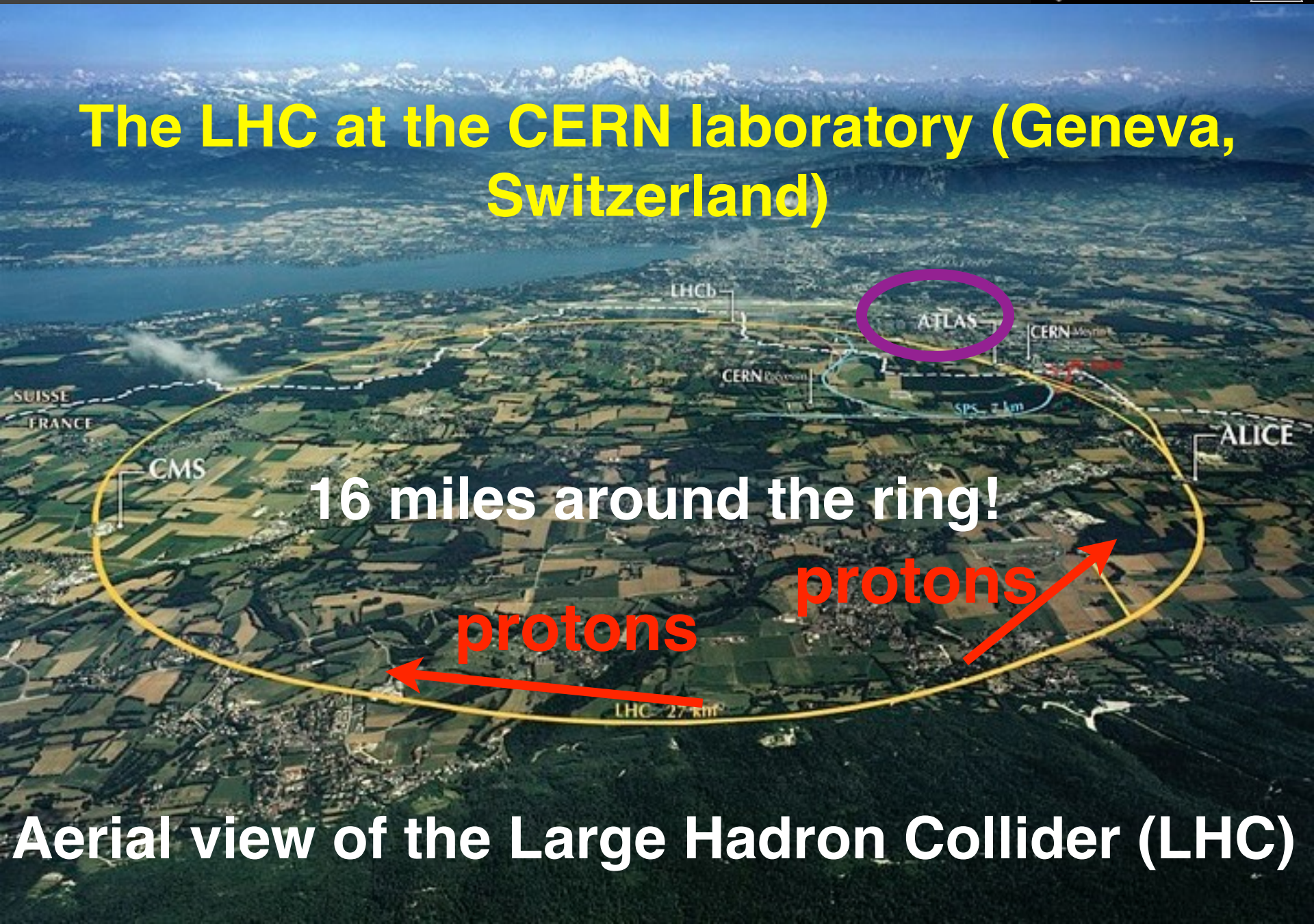


Proton

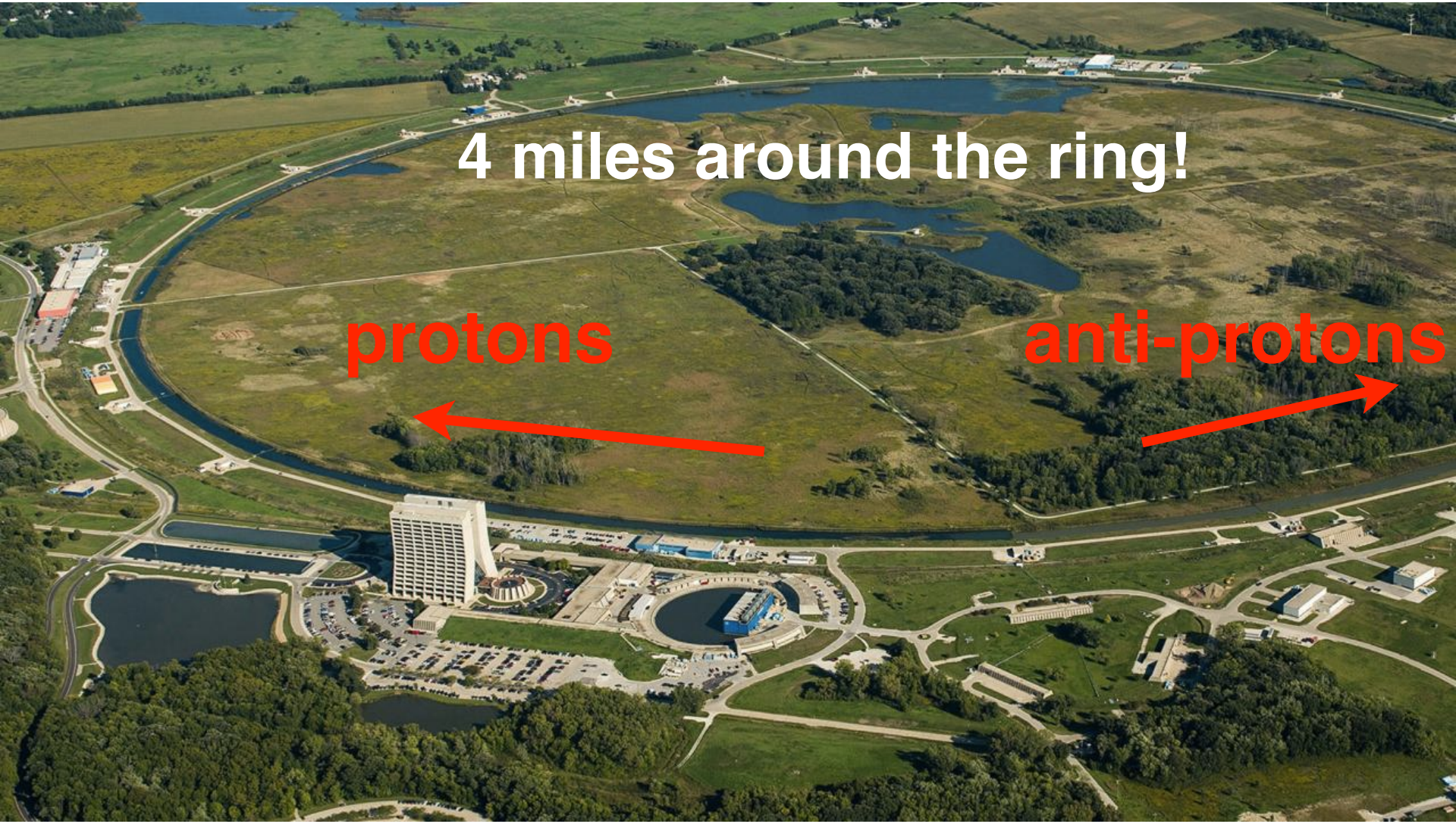
- Small (otherwise collisions too messy!)
- Has electric charge (accelerate to high energies!)
- Abundant (want easy access!)



A big machine

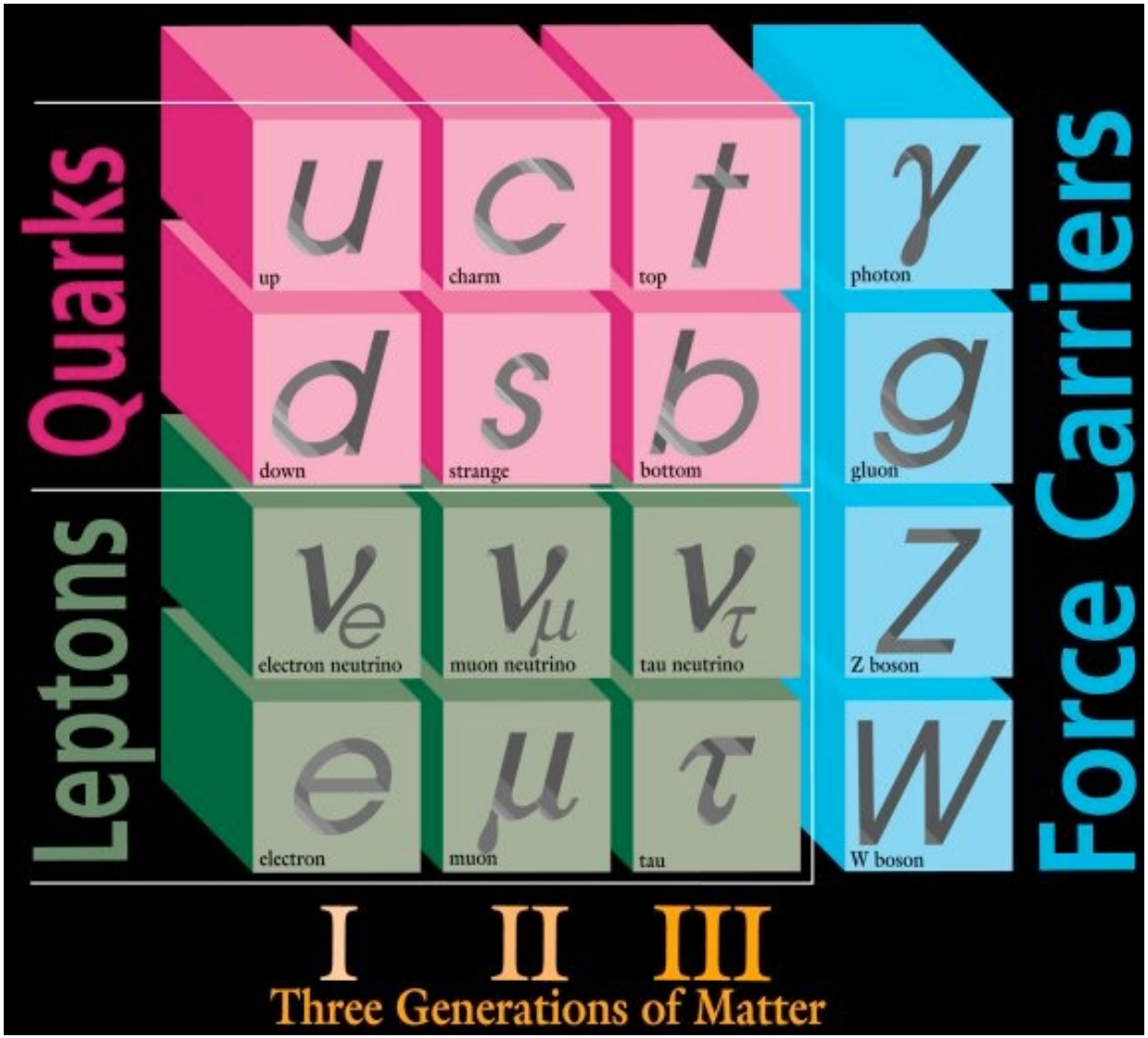


The LHC follows up on the Tevatron at Fermilab

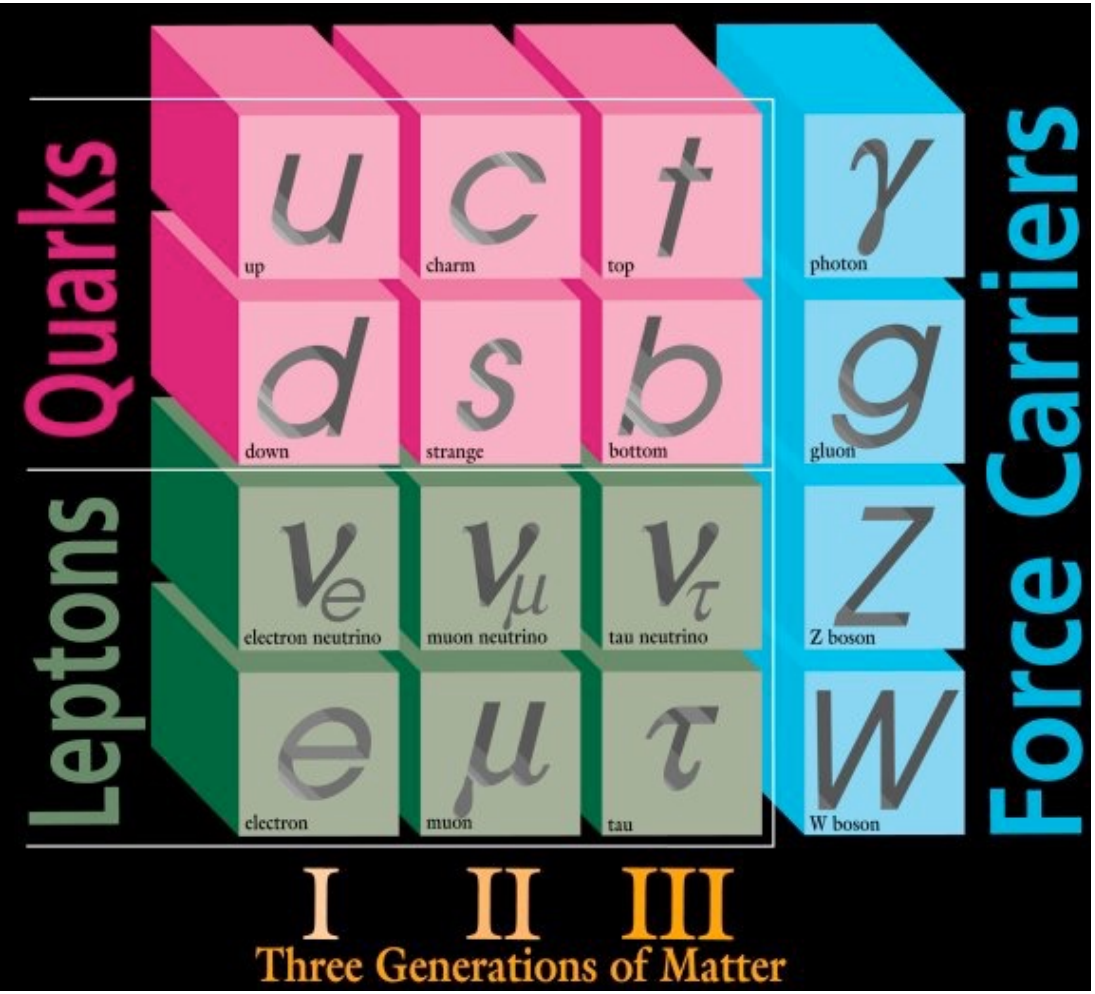


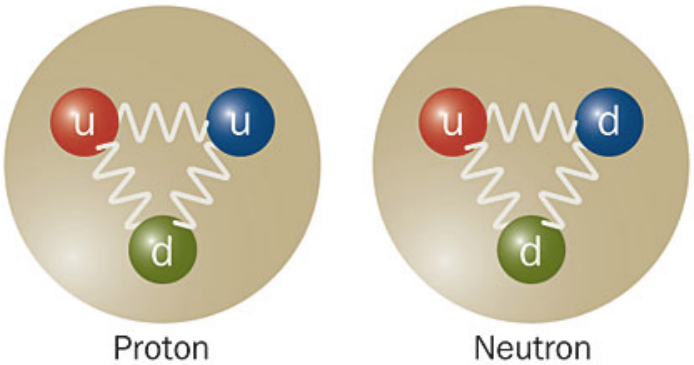
What do we know in particle physics?

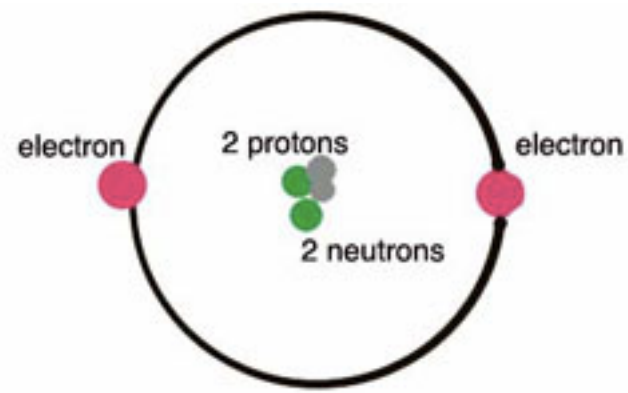
We have a periodic table, too…



Quarks, electrons and atoms

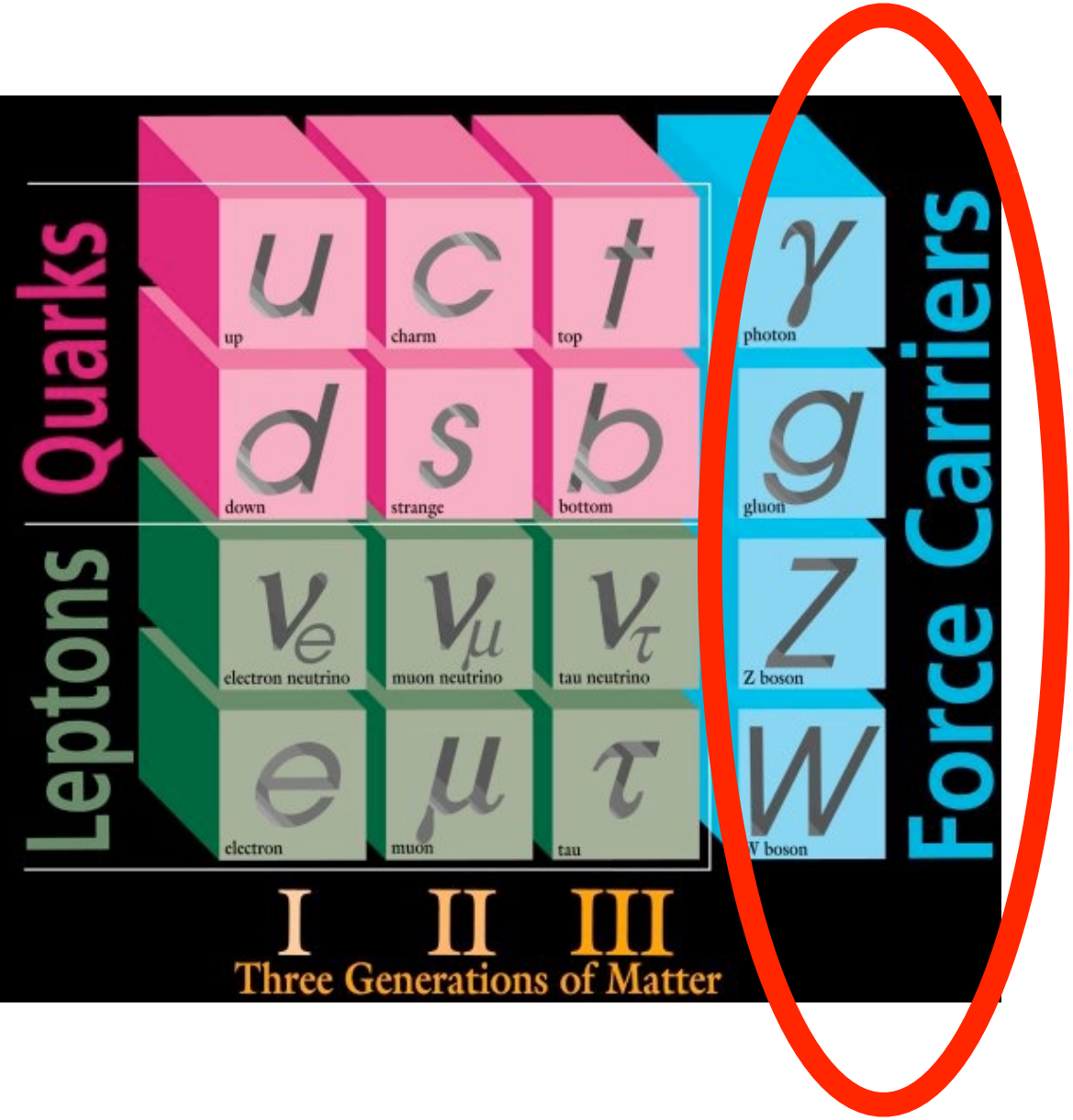






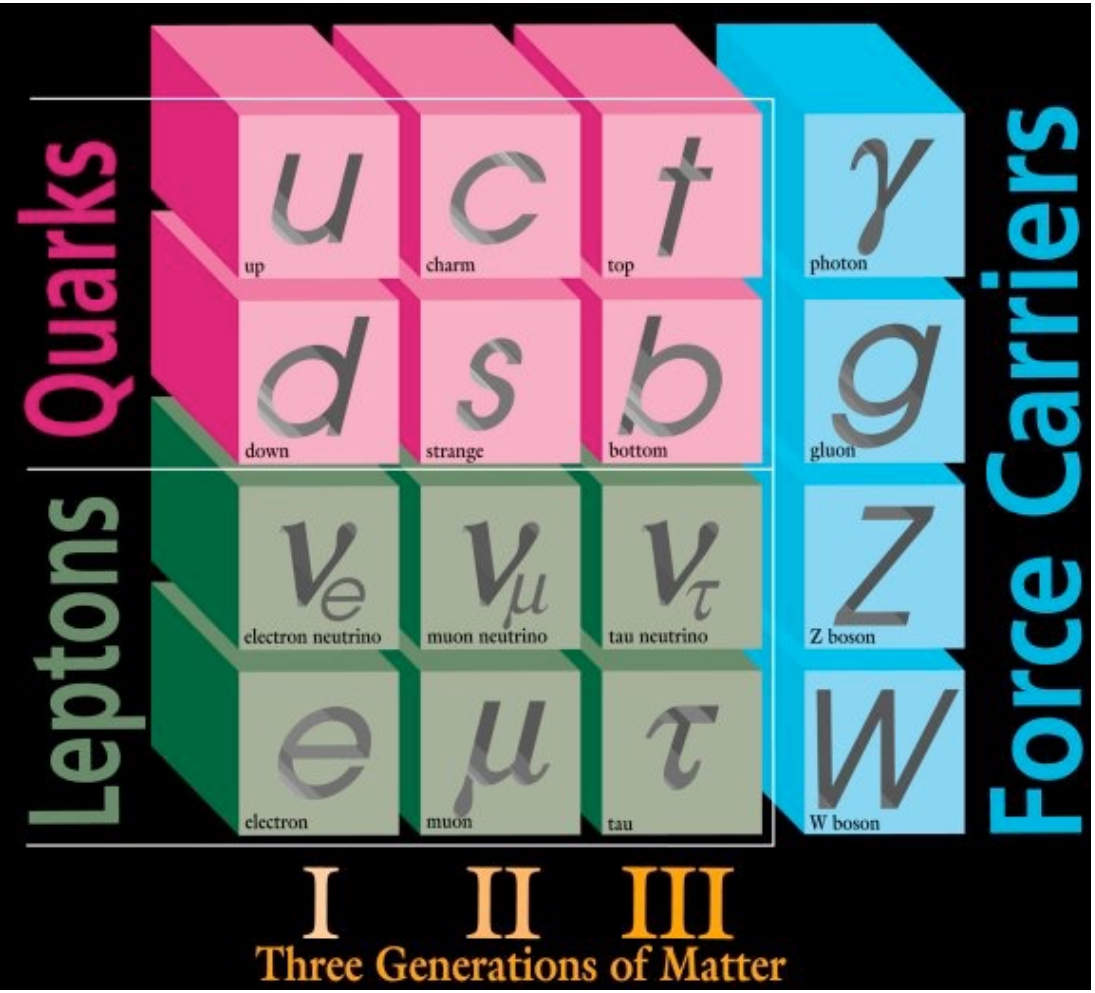
Helium atom

Our table



Our table also describes the interactions between matter

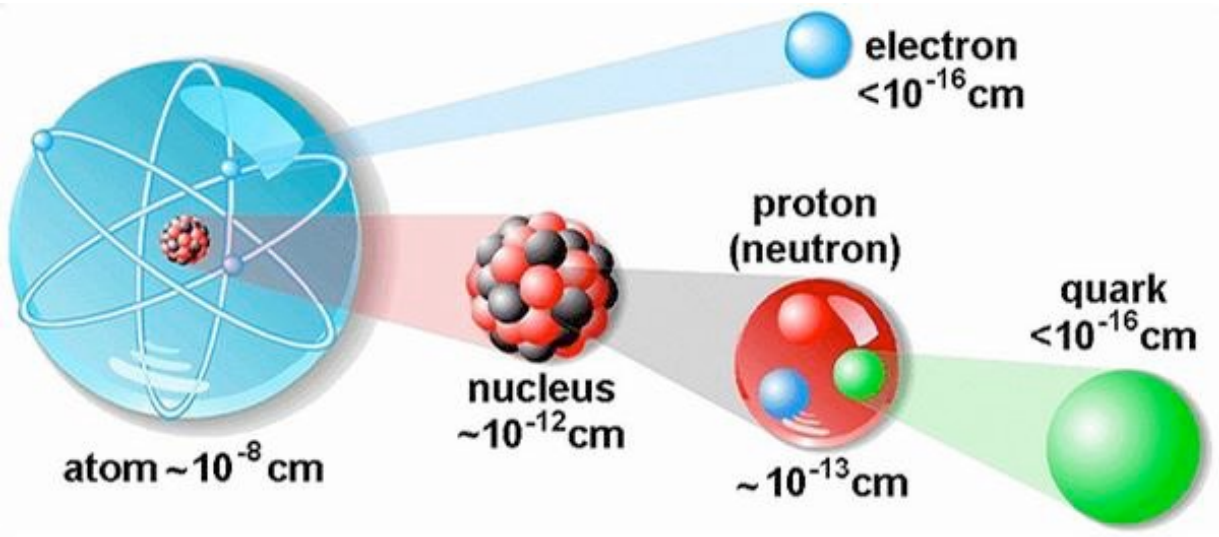
Missing piece of the puzzle



You might have heard about the last missing piece of the table

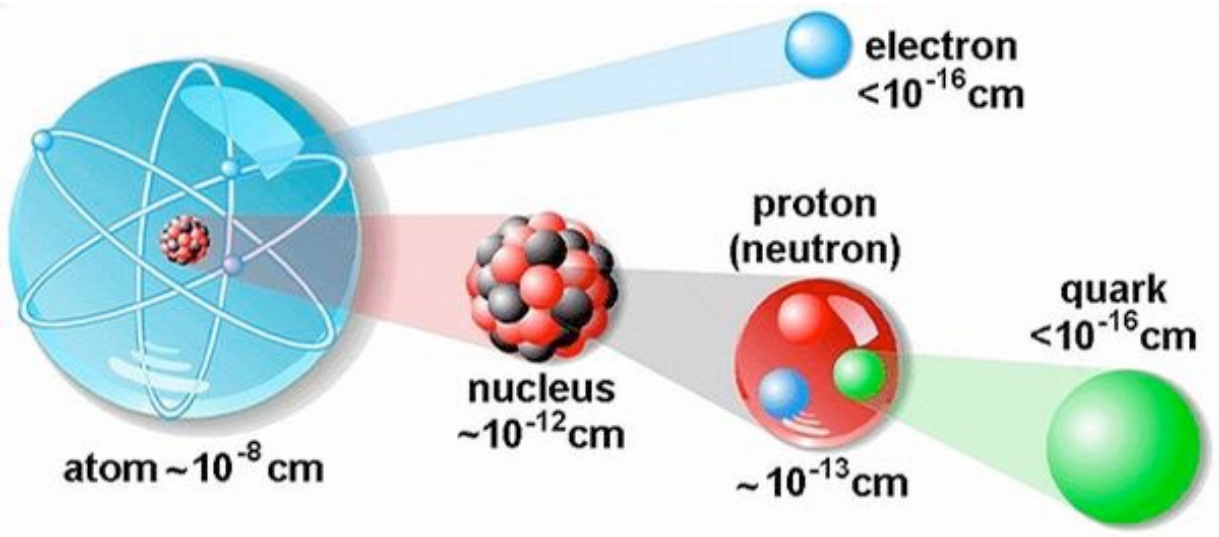
How I view what we try to study at the LHC....

baseball
$\sim 10^{+1}$ cm



Who here knows something about scientific notation and how to view these numbers?

How I view what we try to study at the LHC....



baseball

$\sim 10^{+1}$ cm = 10 cm

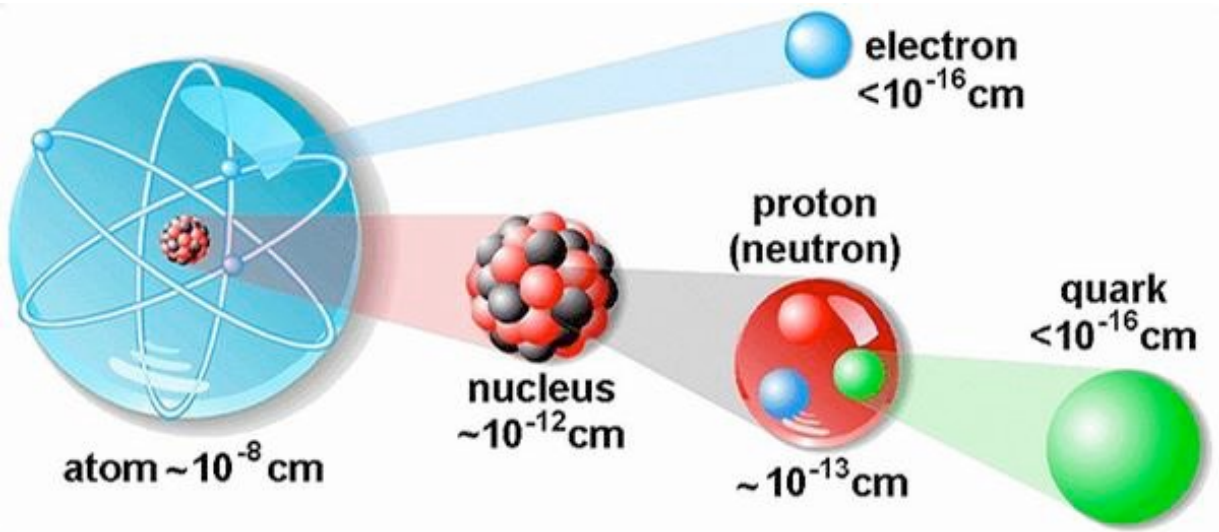
1 with 1 zero after it

Who here knows something about scientific notation and how to view these numbers?

How I view what we try to study at the LHC....

baseball

$\sim 10^{+1}$ cm



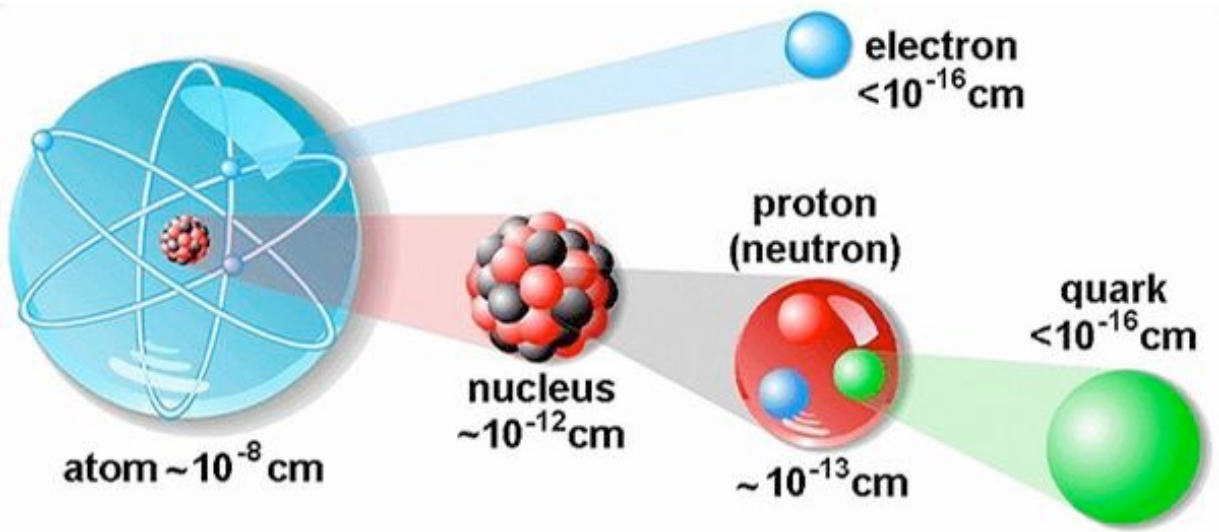
~0.00000001 cm

1 with 8 zeros before it

Who here knows something about scientific notation and how to view these numbers?

How I view what we try to study at the LHC....

baseball
$\sim 10^{+1}$ cm

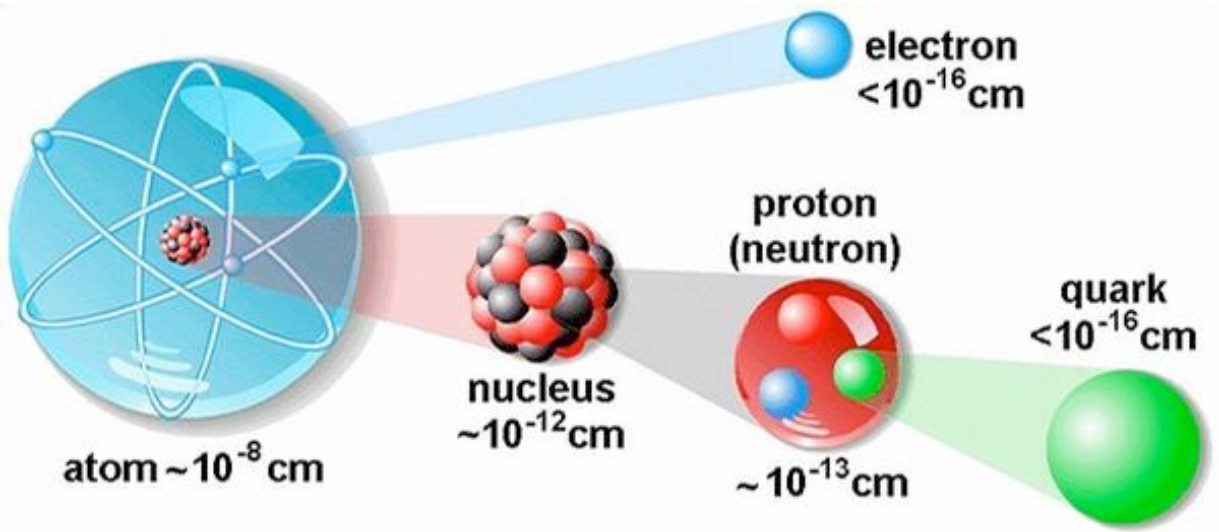


~0.00000001 cm

Question: How much bigger is a baseball than a quark?

How I view what we try to study at the LHC....

baseball
$\sim 10^{+1}$ cm

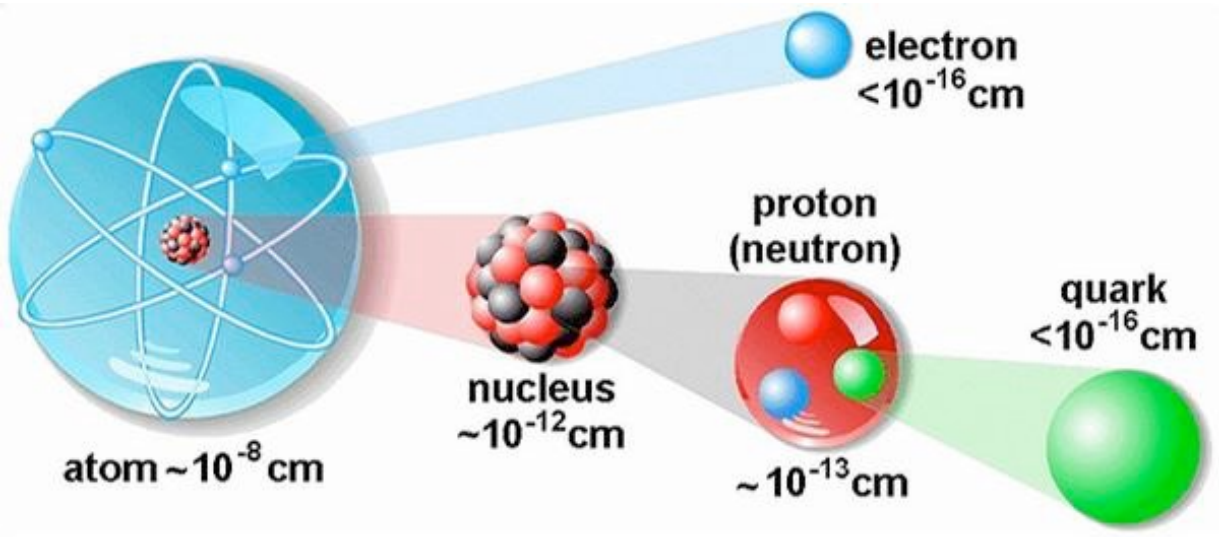


~0.00000001 cm

Question: How much bigger is a baseball than a quark? 10^{+1} cm vs 10^{-16} cm. Difference between +1 and -16 is … 17

How I view what we try to study at the LHC....

baseball
$\sim 10^{+1}$ cm



(How much bigger is a baseball than a quark?)

at least 10^{17} =

100,000,000,000,000,000x as large

Life as a particle physicist at CERN

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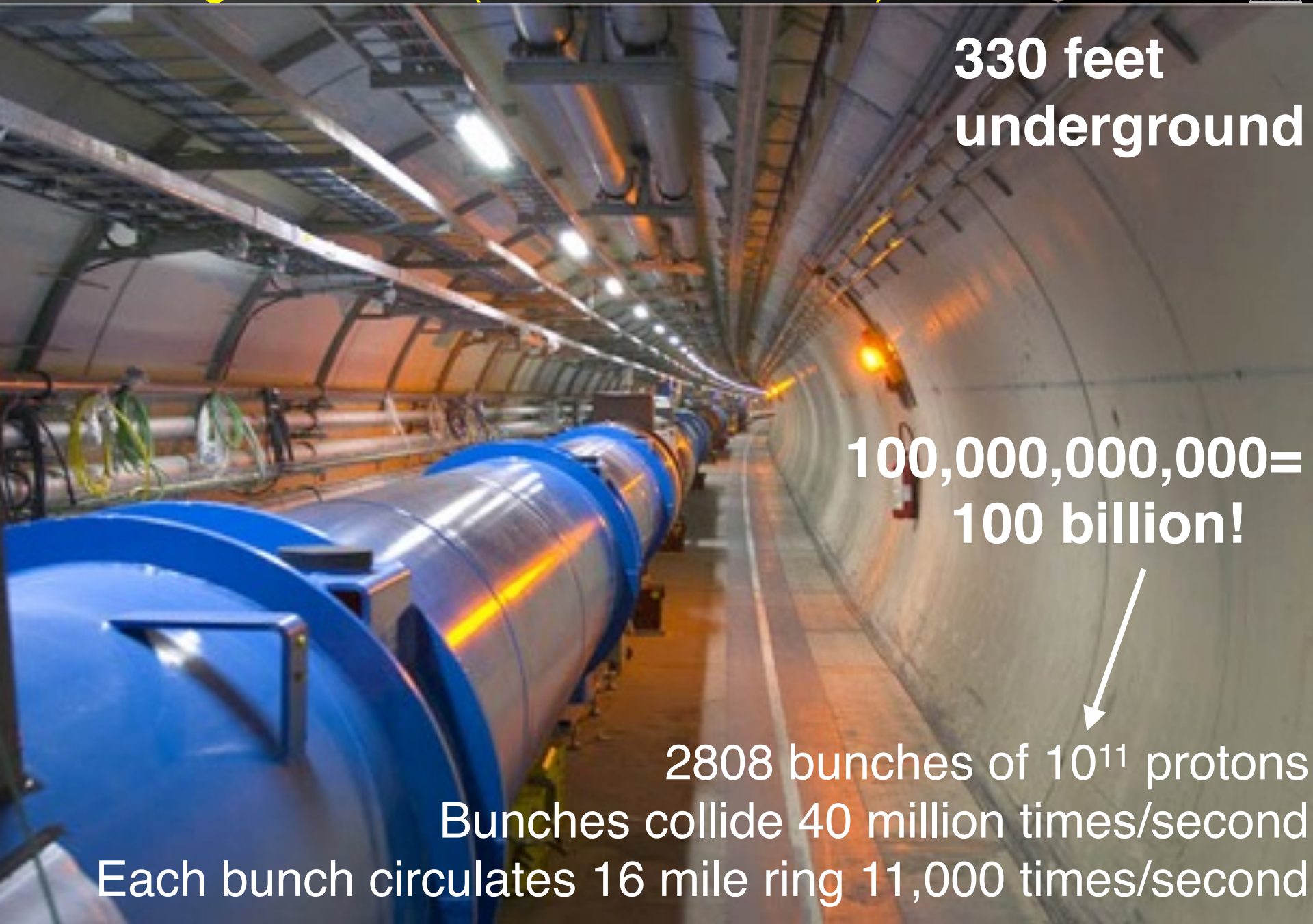
Producing collisions (inside of the LHC)



330 feet underground

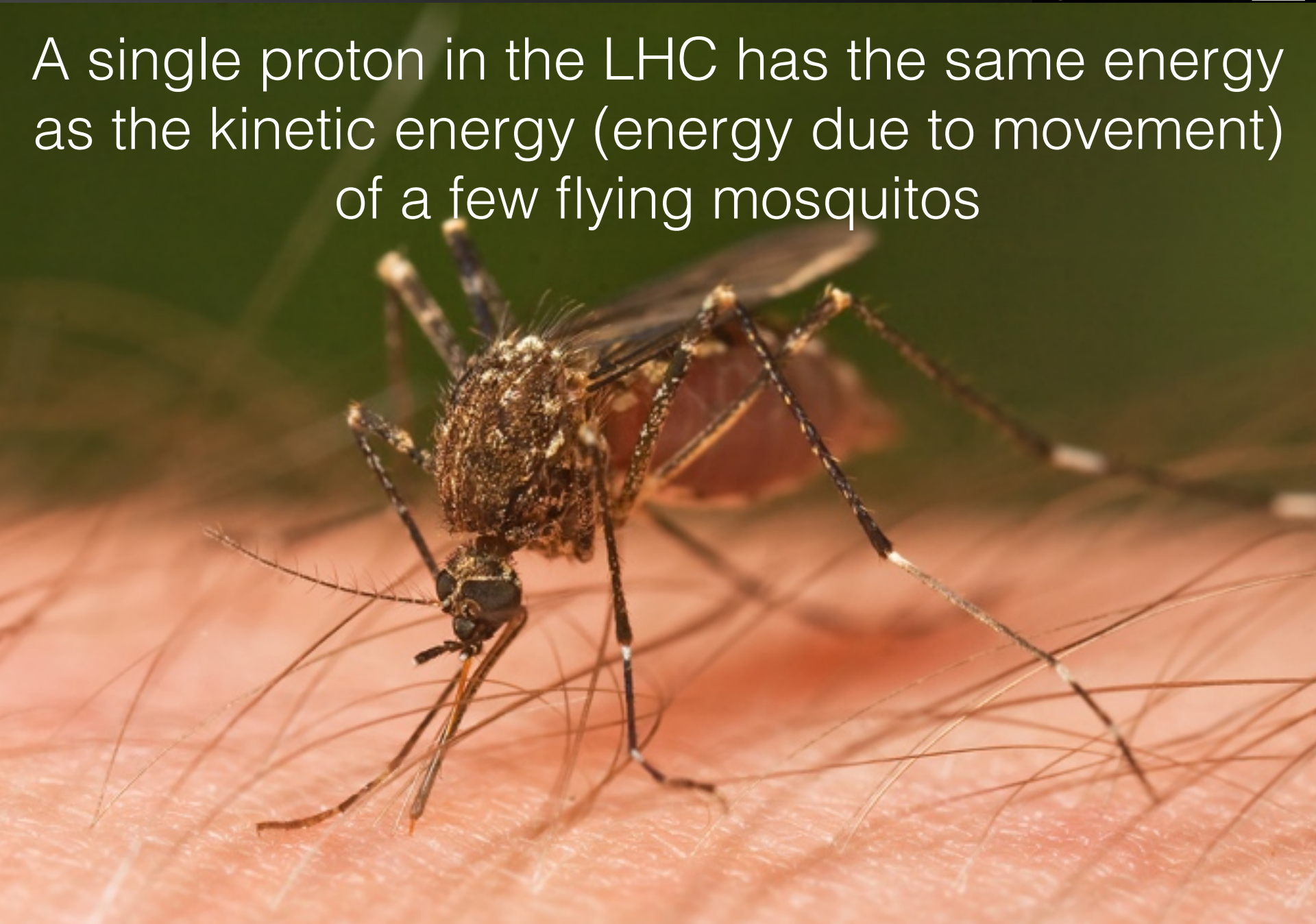
100,000,000,000= 100 billion!

2808 bunches of 10^{11} protons

Bunches collide 40 million times/second

Each bunch circulates 16 mile ring 11,000 times/second

From small numbers



A single proton in the LHC has the same energy as the kinetic energy (energy due to movement) of a few flying mosquitos

To big numbers

The entire LHC beam has the same energy as the kinetic energy of a fully loaded 747 at takeoff speed

To really big numbers

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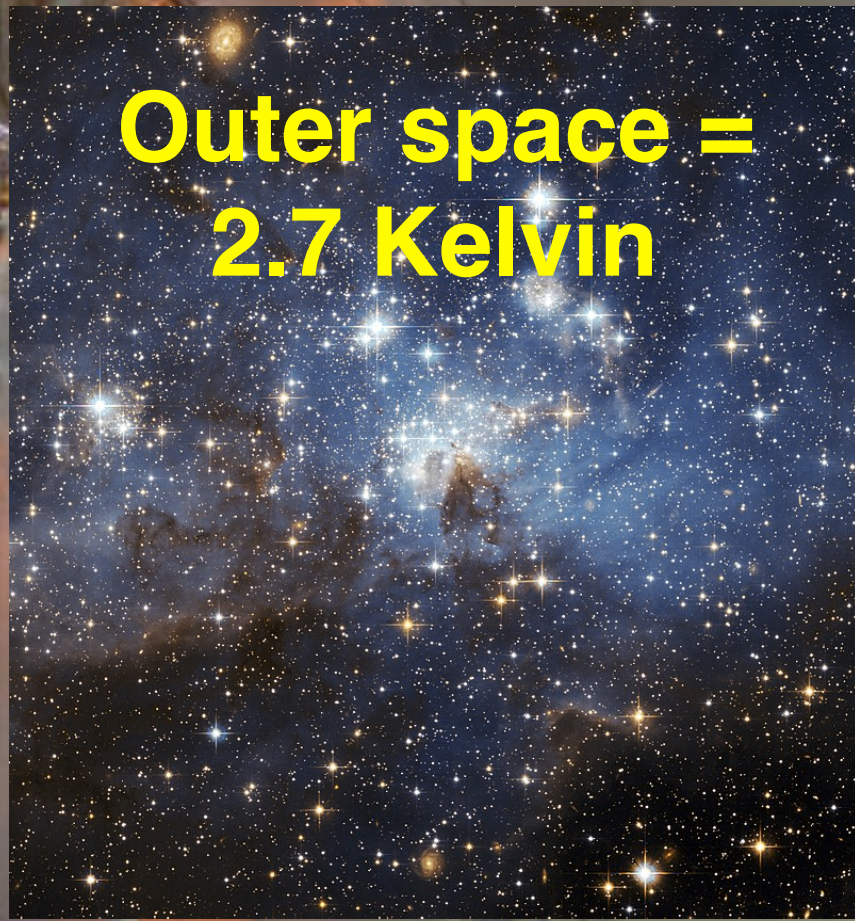
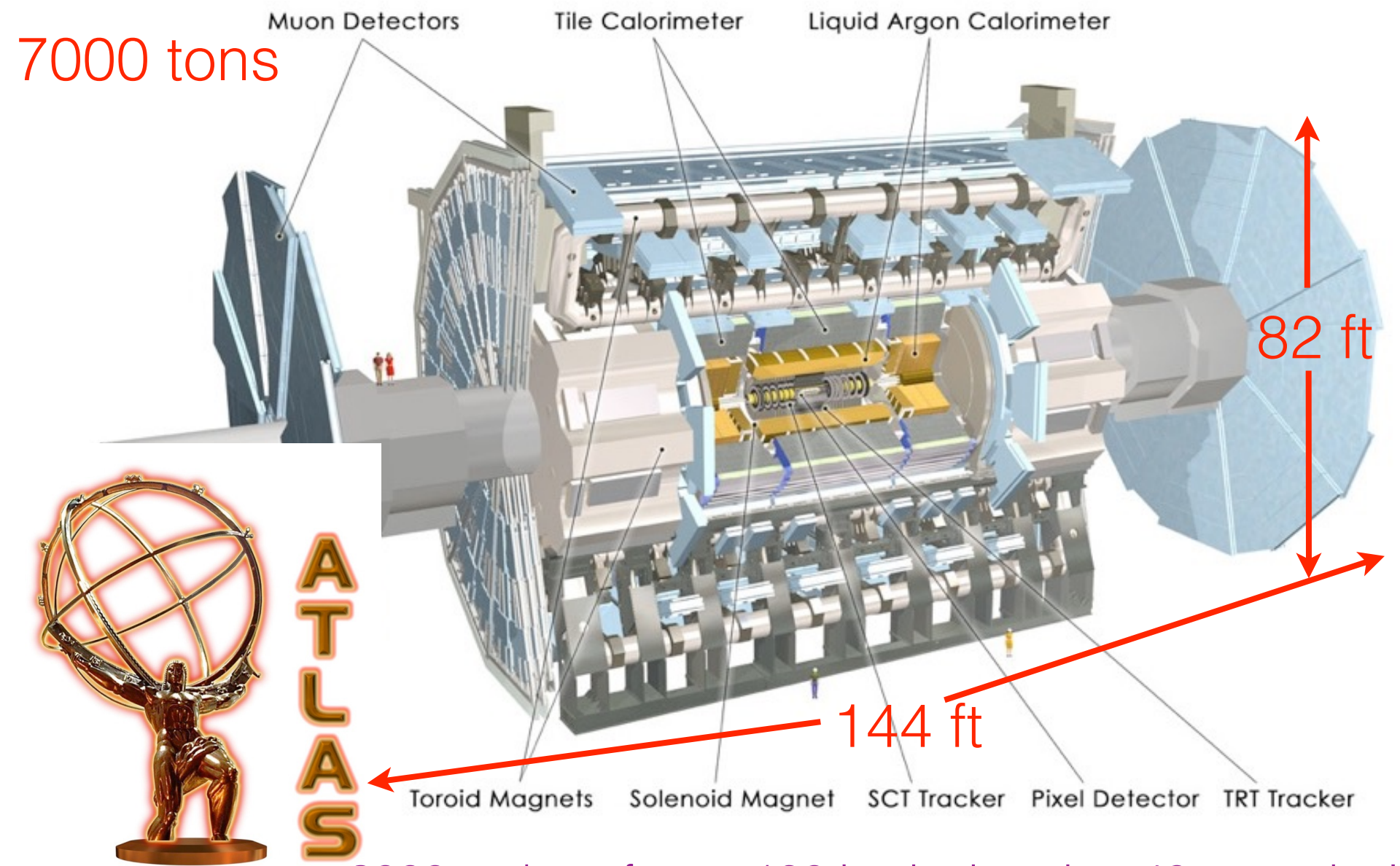
And the total stored energy in the LHC's 1200 superconducting (1.9 Kelvin) magnets is the same as the kinetic energy of that 747 at cruising speed

How cold is 1.9 Kelvin? Any ideas?

To really big numbers



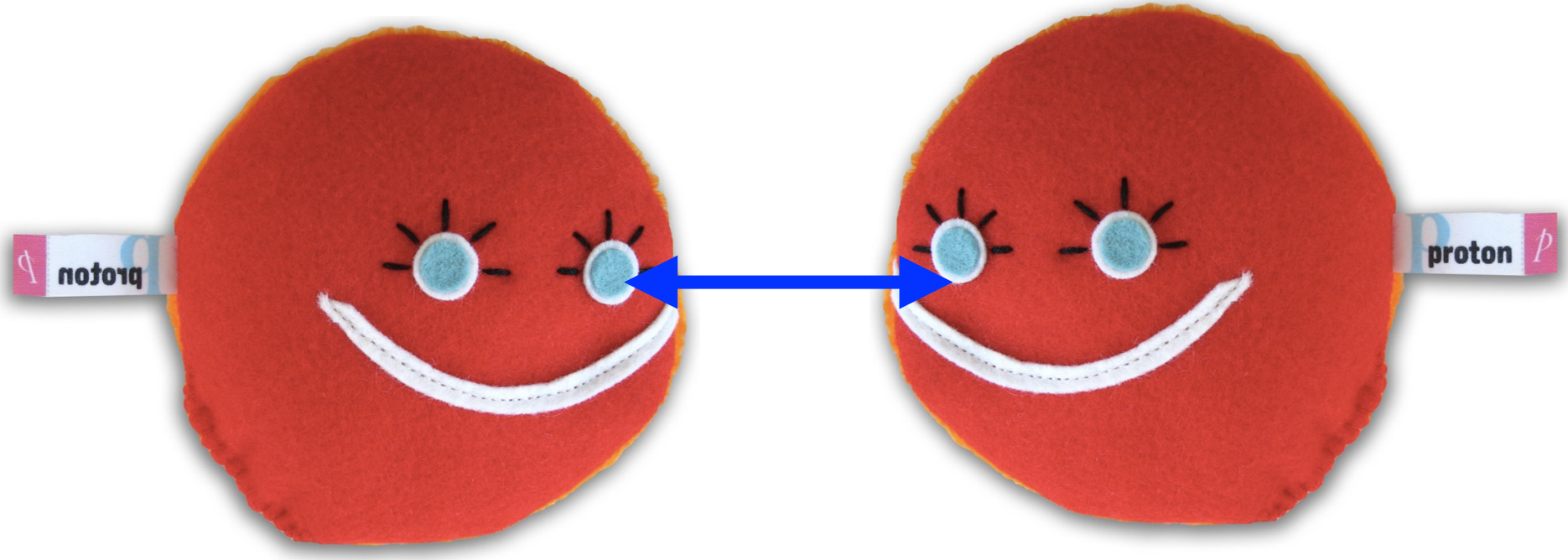
A picture of my experiment (ATLAS)



3000 authors from ~180 institutions in ~40 countries!

If you tried to smash two protons together

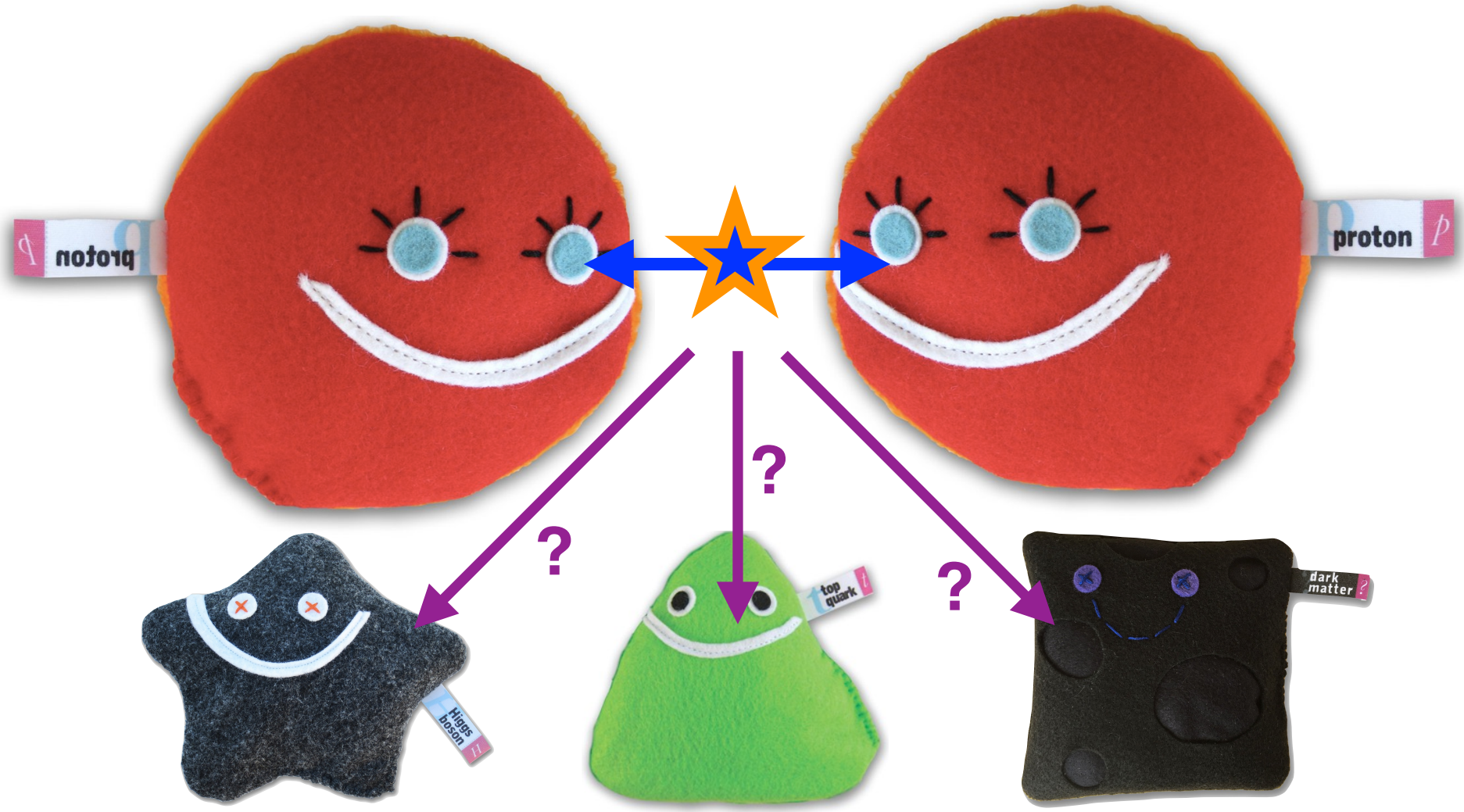
What do you think would be most likely to occur?



If you tried to smash two protons together

You would almost definitely miss

If the protons somehow did smash together, what would you most likely get out?



If you did manage to smash them together

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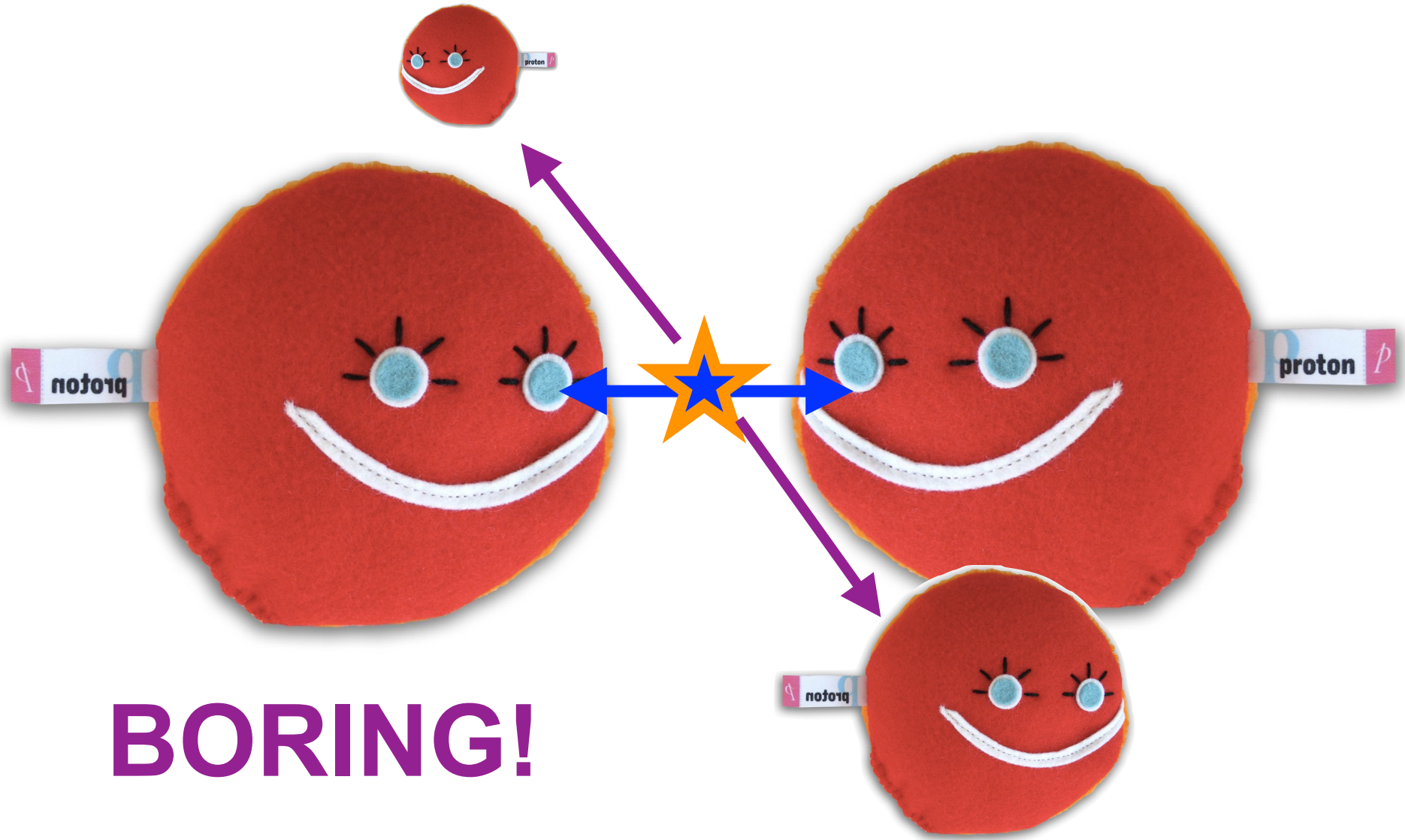
The most likely thing that happens is that the protons barely glance off each other

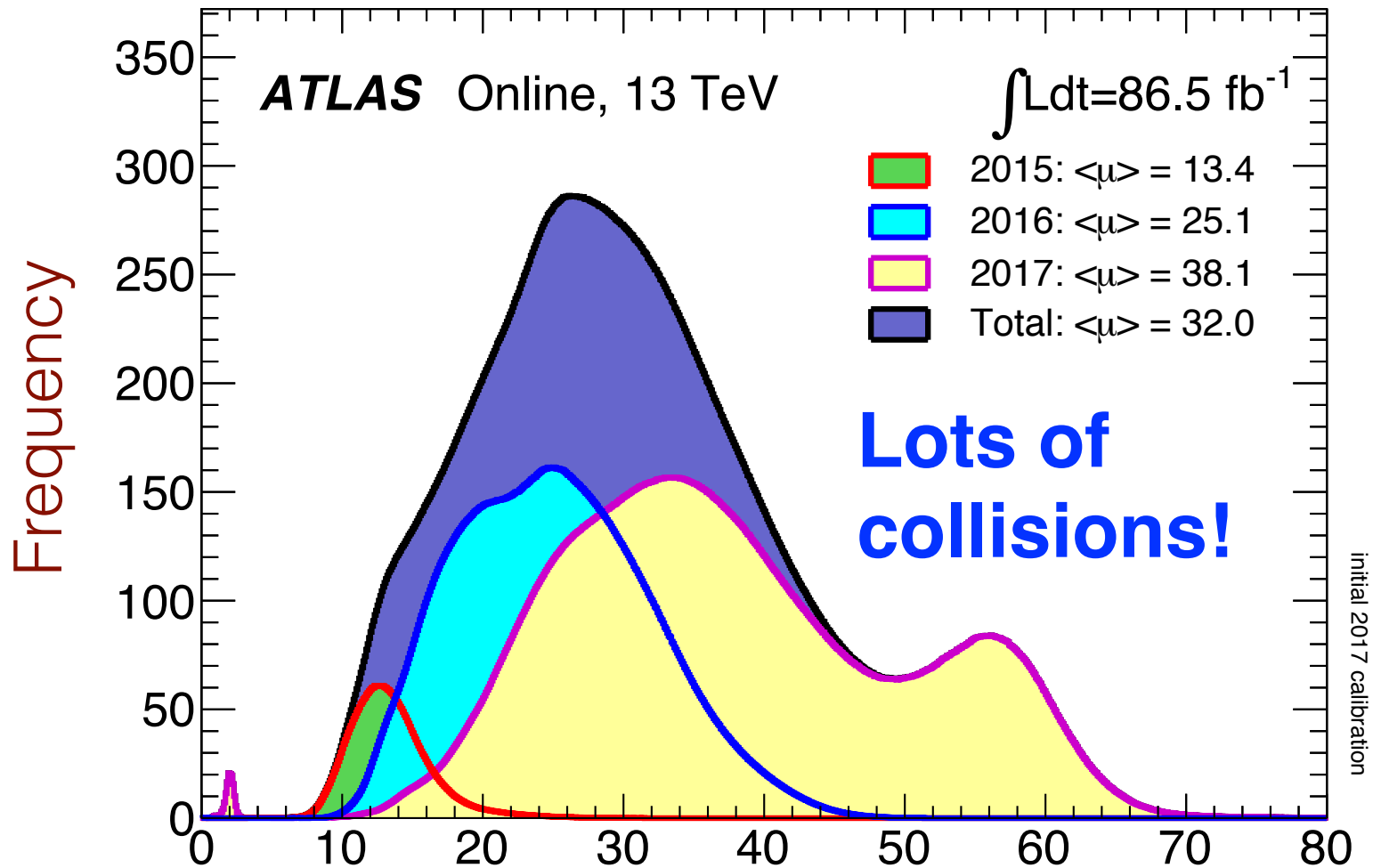


BORING!

A related question

In every "bunch crossing" inside ATLAS (occurring 40 million times a second!), how many proton-proton pairs smash together, on average?

Pileup in collisions



Average number of proton-proton collisions in a crossing of bunches

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

What sort of physics are we looking for?

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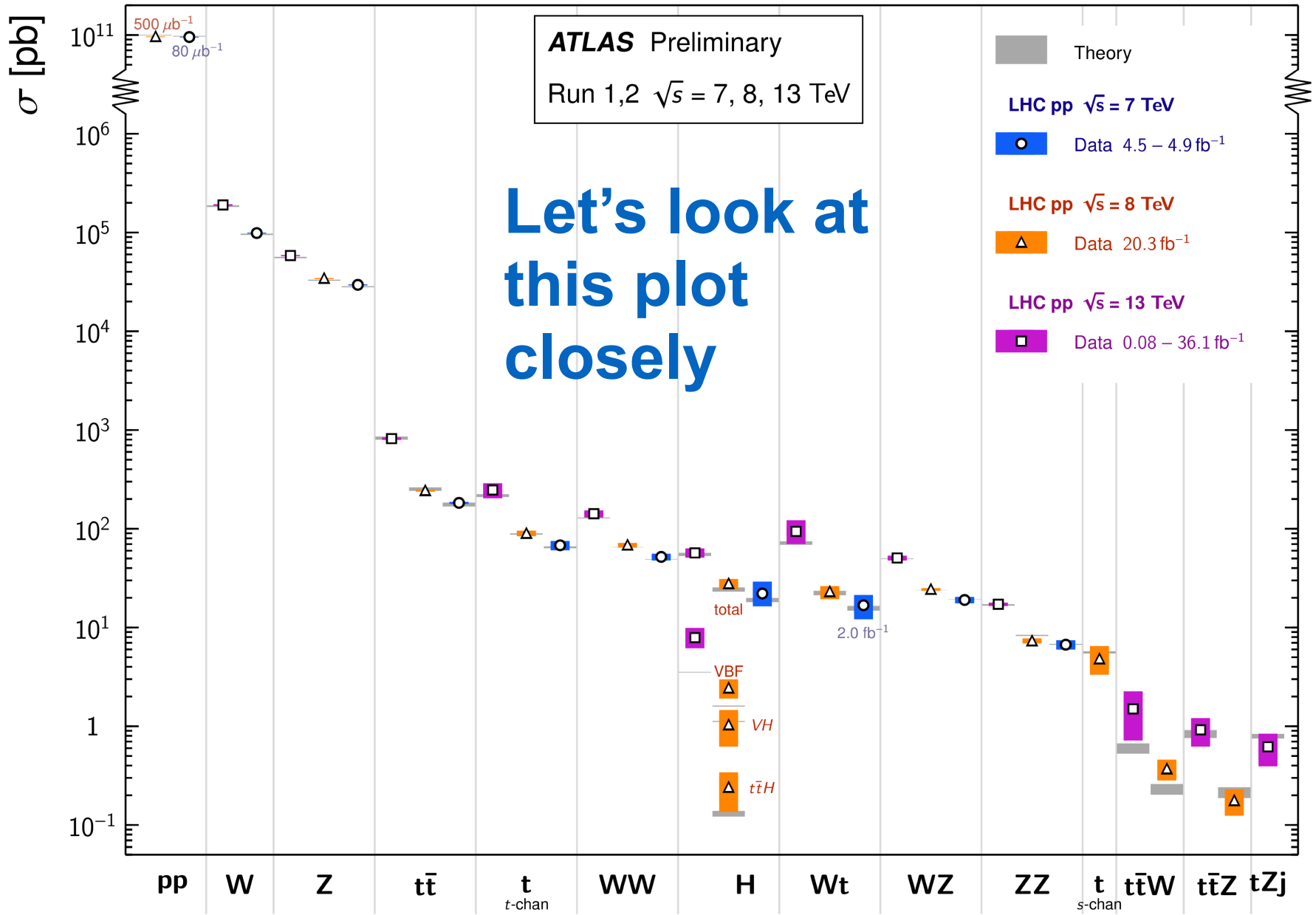
Needles in a haystack

Needles in a haystack

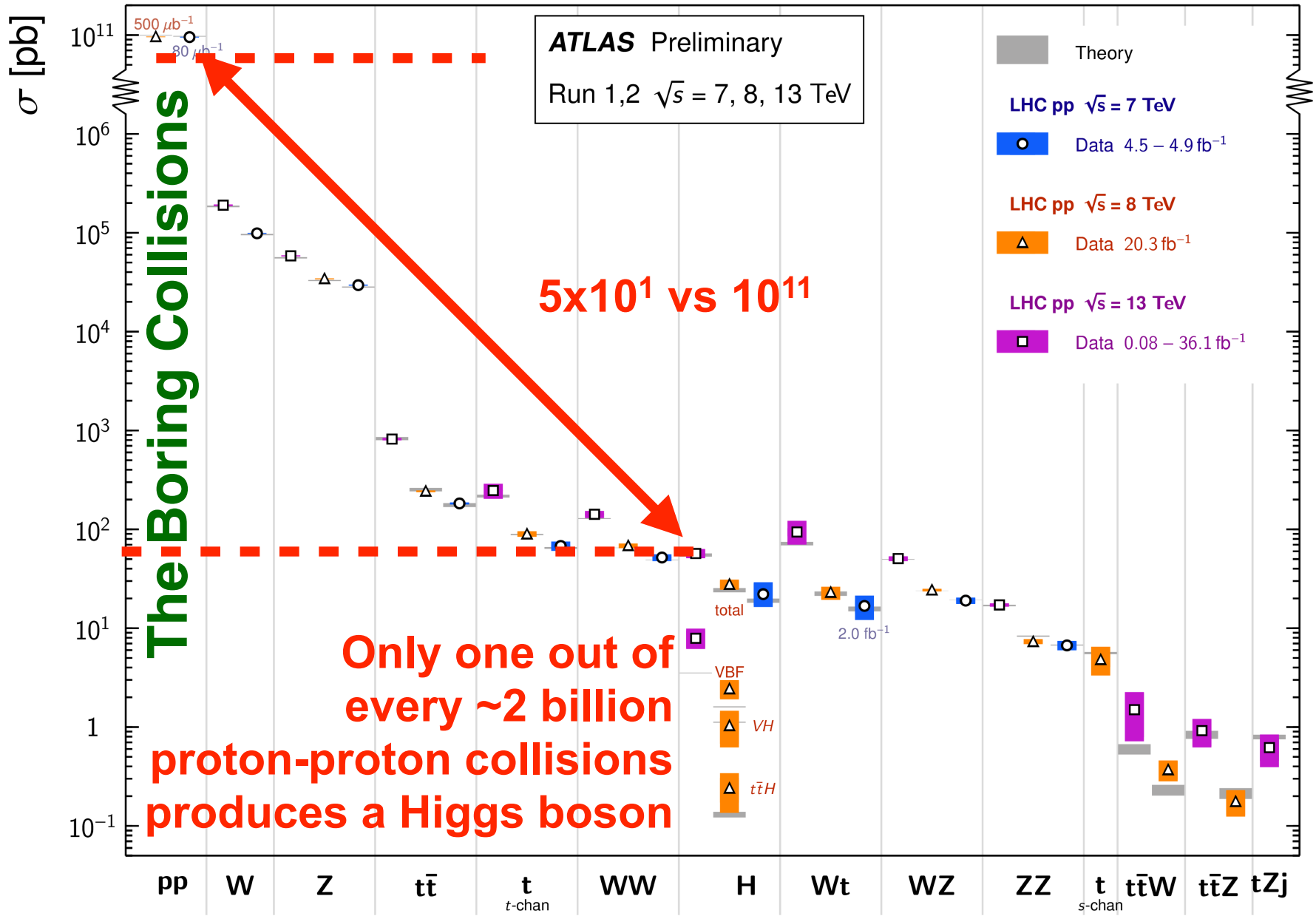
Needles in a haystack



Let's look at this plot closely

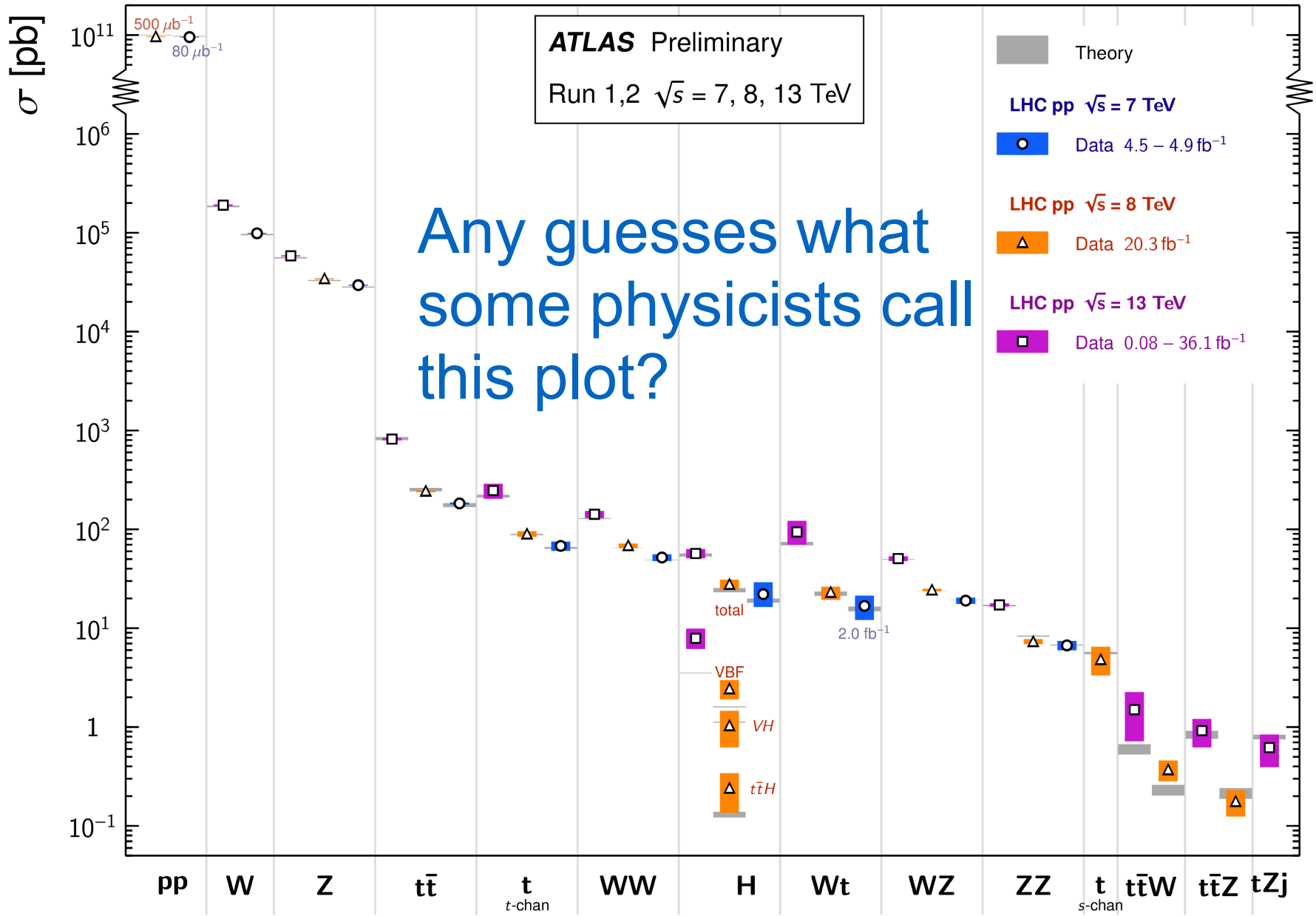
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Needles in a haystack



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

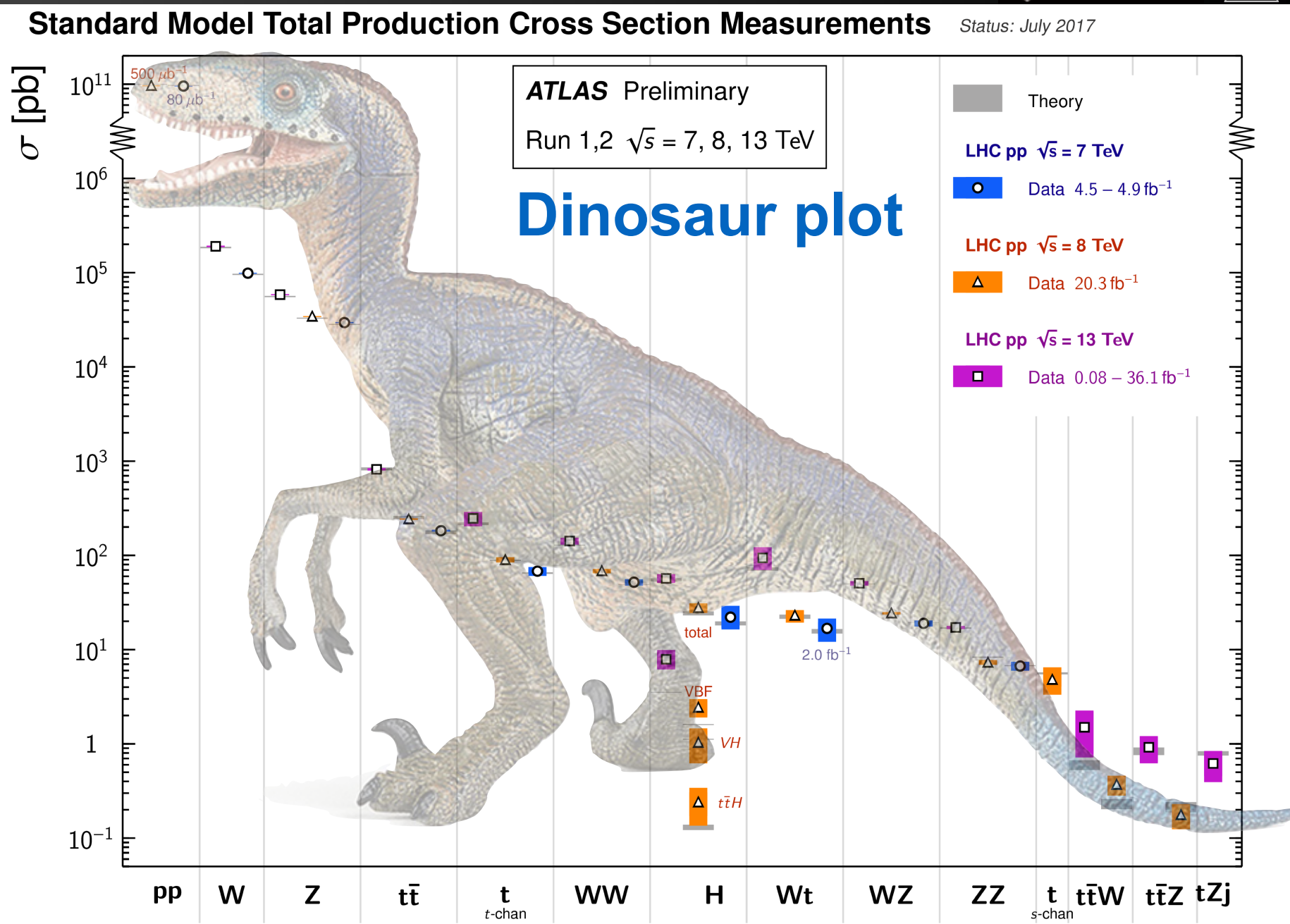
Needles in a haystack



Any guesses what some physicists call this plot?

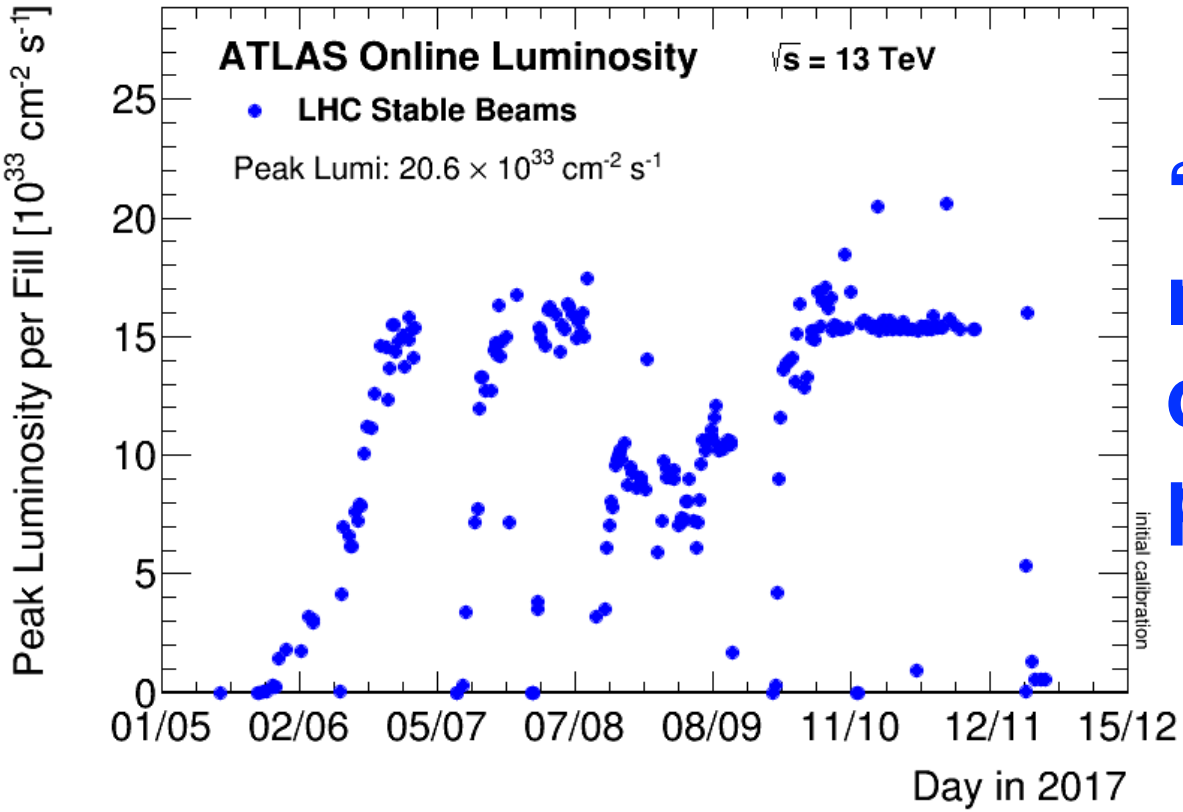
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Needles in a haystack



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Luminosity

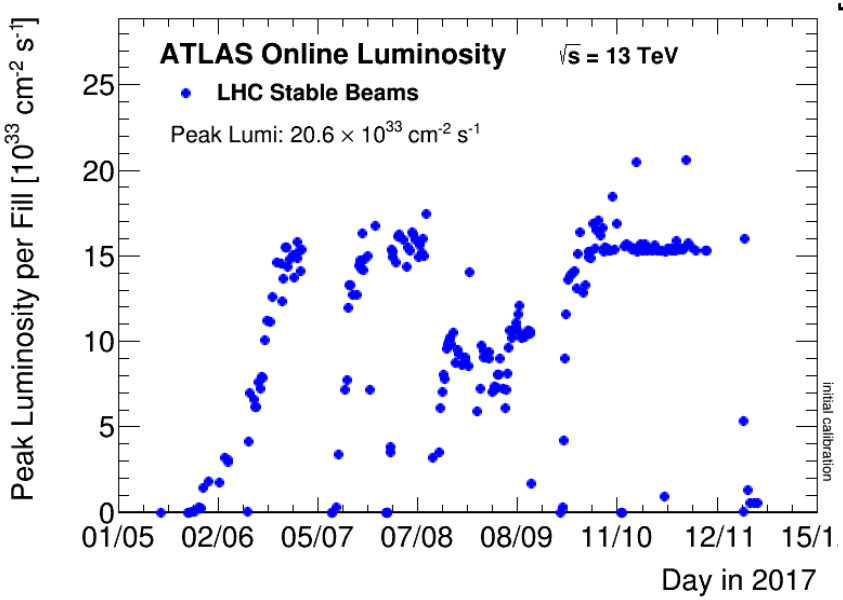


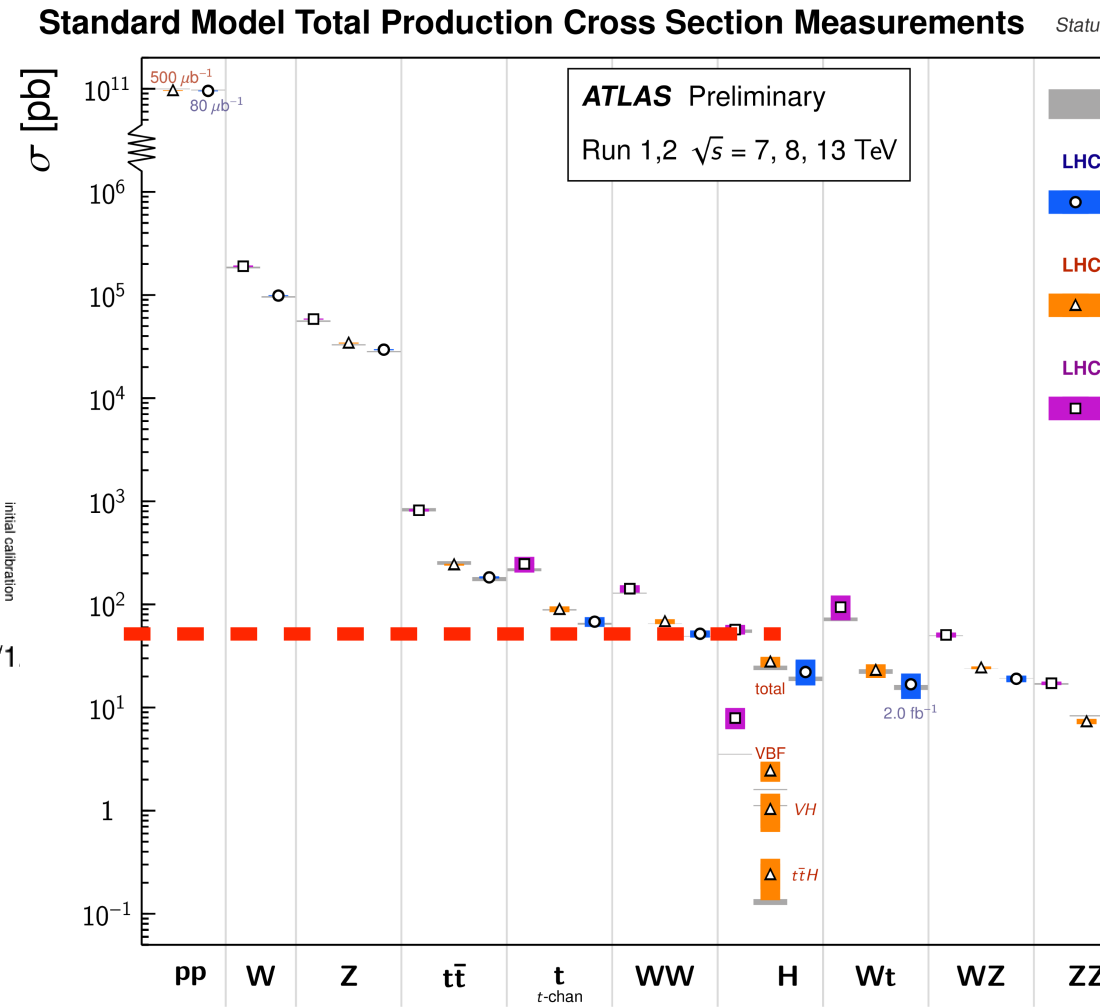
"Luminosity" is a measure of how often pairs of protons collide

Highest luminosity ~20x10^{33} cm^{-2} s^{-1}

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Time to multiply to numbers





Peak luminosity
~20x10^{33} cm^{-2} s^{-1}
x 5x10^{-35} cm^{2} = …

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Higgs boson production

At peak running conditions, the LHC produces a Higgs boson at each experiment every second! Which brings us to another question…

Another interesting question

How many of the 40 million bunch crossings ("events") a second are we capable of recording, on average?

How to record data?

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40 million crossings/second must be reduced to ~1000/second

1.5 GB/s data recording rate

(40 million collisions/ second: recording rate would be ~50 TB/s)

Is that OK?

Northern Illinois University

We can only keep ~1 out of every 40,000 crossings of protons! Aren't we wasting any data?

If you've been paying attention, you know why this is OK…

How to decide which events to record?

Several options

A good task for graduate students?

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Perhaps if there's good … incentive?

Another option

Northern Illinois University

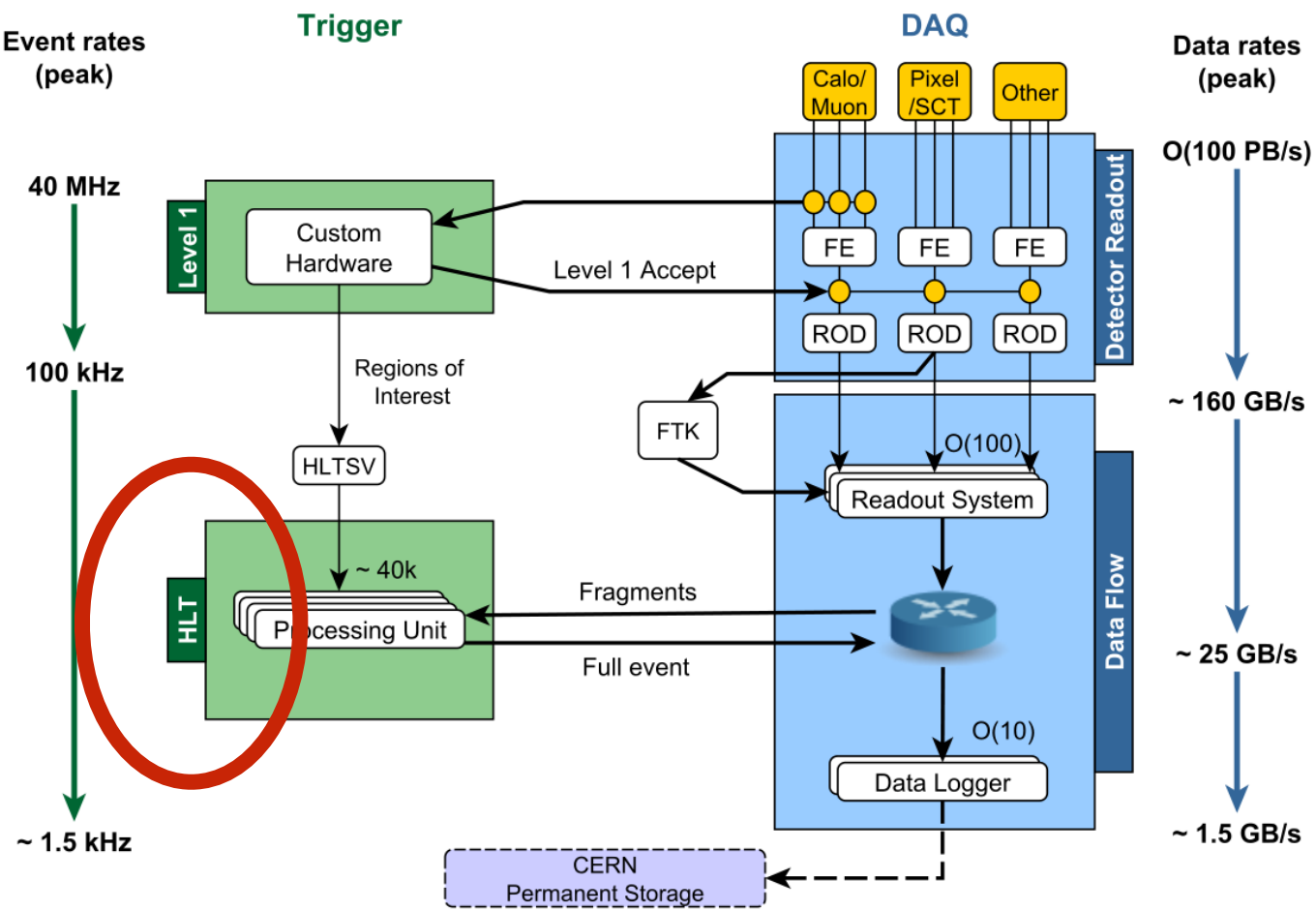
Use a **trigger system** to rapidly decide which crossings of protons to keep, and which to reject

Custom hardware ("**Level 1**") first asks simple questions about what is observed in the detector to reduce the rate from 40 million crossings/second to 100,000 crossings/second

Example Level 1 trigger questions

- Is there a set of objects in the detector roughly consistent with an electron or photon of a given energy?
- Do we see a muon with a minimum momentum?
- Is there something in the detector consistent with a muon and an electron?
- If I loosely sum up the energy in the detector, do I find missing momentum indicating a neutrino or something similar?

The Trigger and DAQ system



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsDAQ

High Level Trigger (HLT) is a massive computer farm that determines what happened in events passing the Level 1 trigger

Example HLT questions

- After further consideration, does the electron that Level 1 saw still look like a real electron?
- What is the momentum of the muon that caused the event to pass Level 1?
- Are there any objects that look like decays from a tau?
- With more precise calibration, if I sum up the energy in the detector, do I still see something that looks like an energetic neutrino got produced?

Trigger menu

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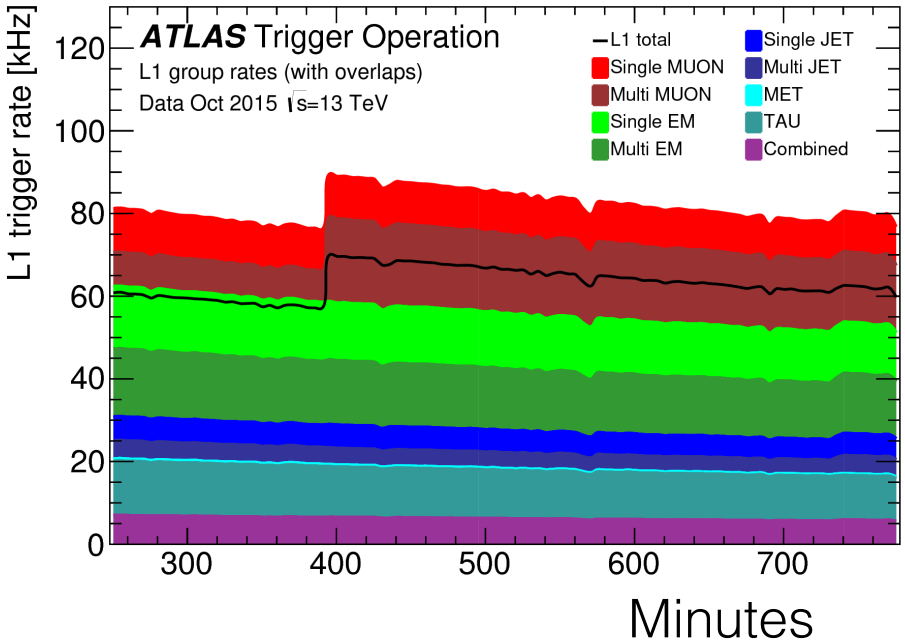
There are lot of ways that the trigger can “fire”. Lots of physics to look for! We refer to the set of ways that we decide to record events as the **trigger menu**

Maybe something like this?

The trigger menu

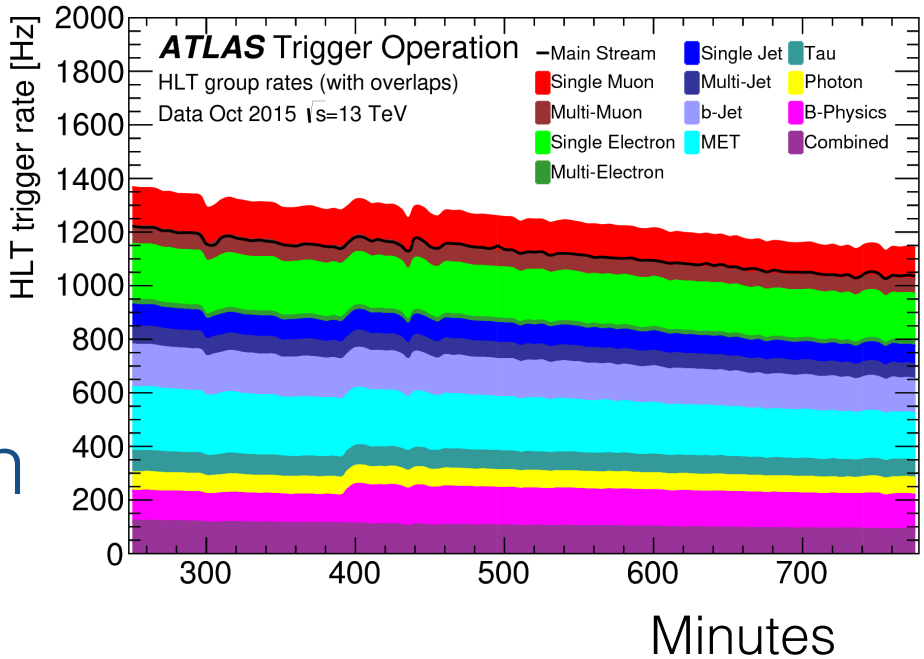


Note overlaps - total not equal to sum!

Prescale: Only save trigger every Xth event

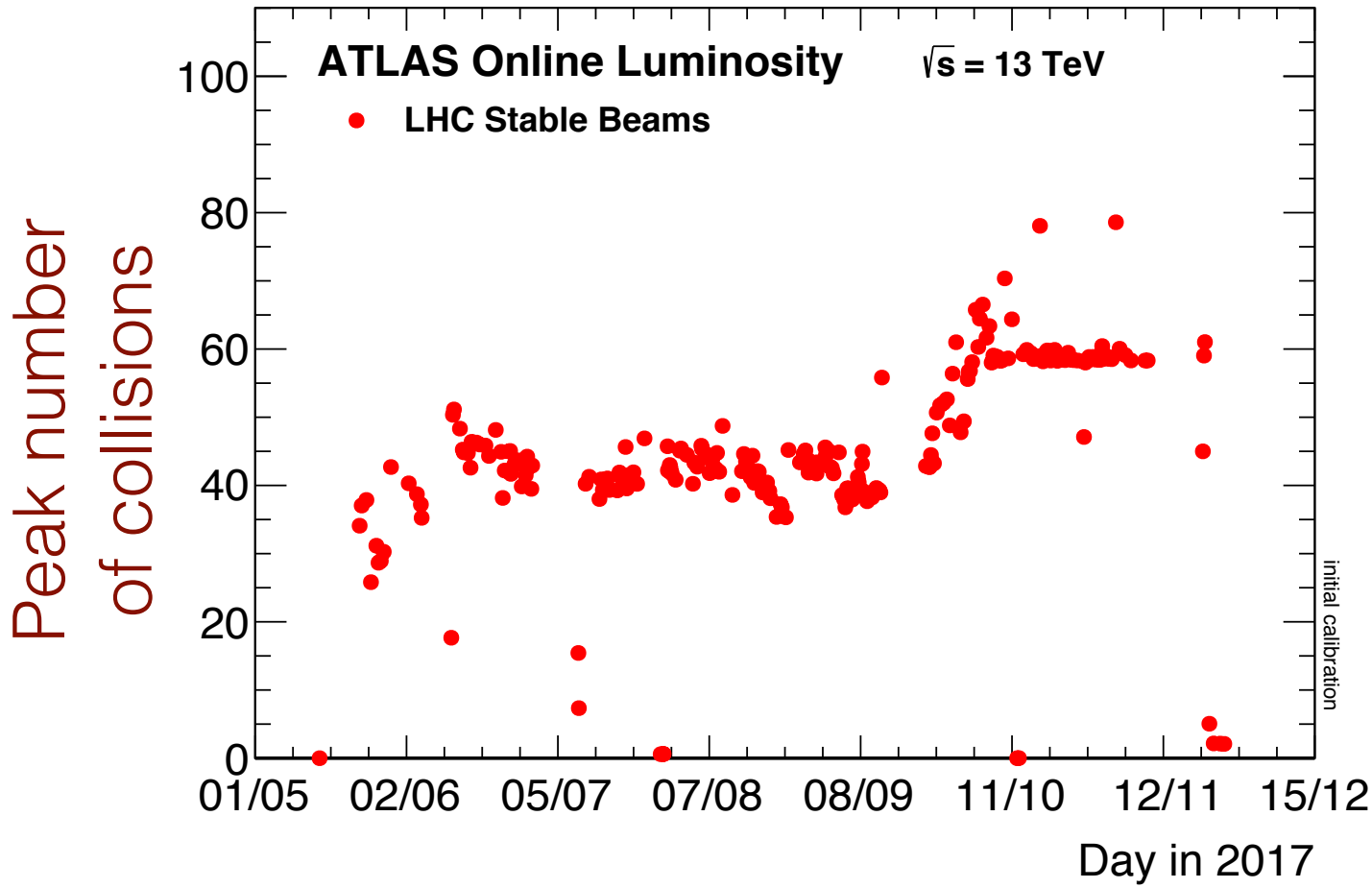
Some items have thresholds (only turn on at certain luminosity)

~1000 ways for a collision to pass the trigger



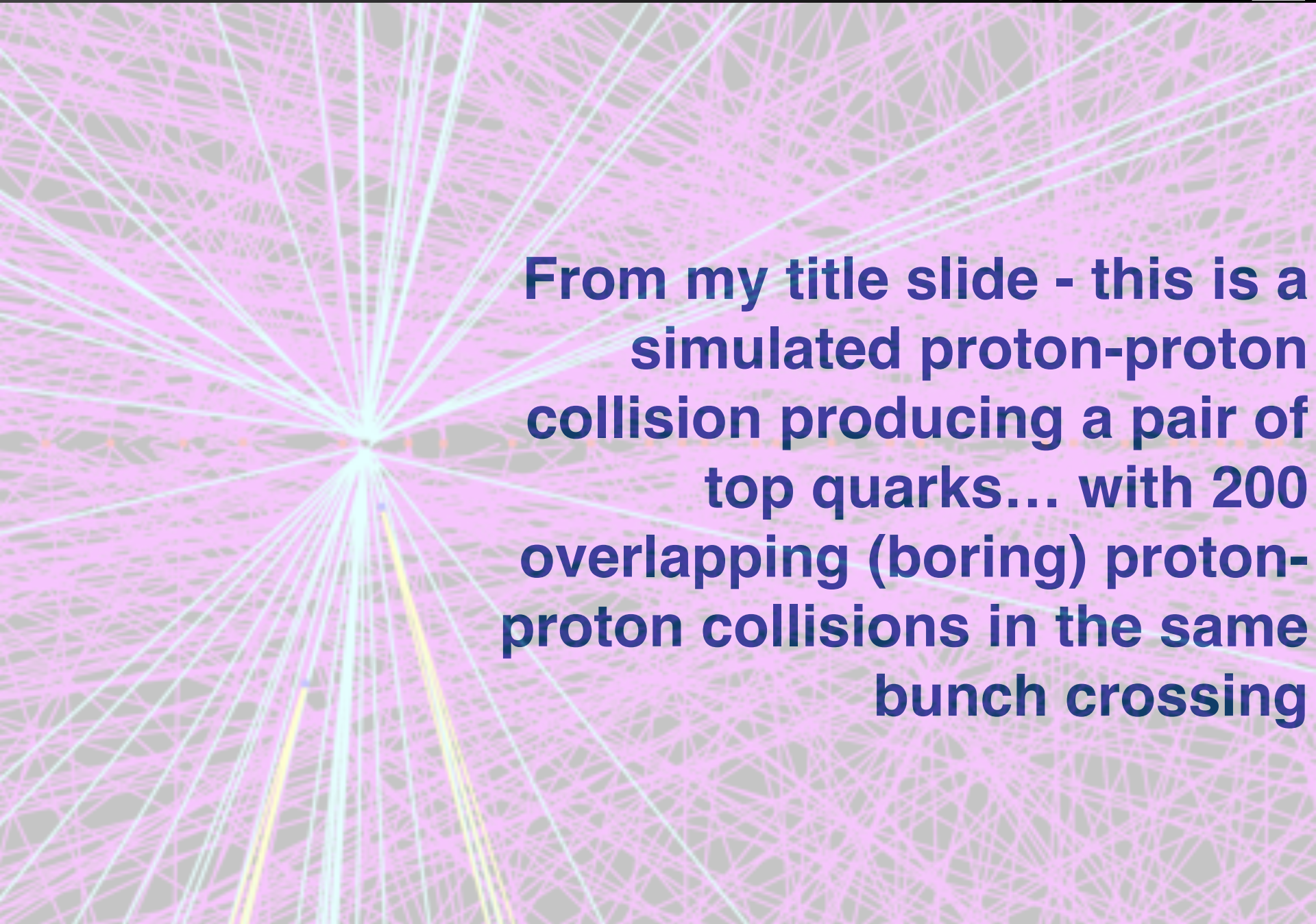
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TRIG-2016-01/

What about the future?



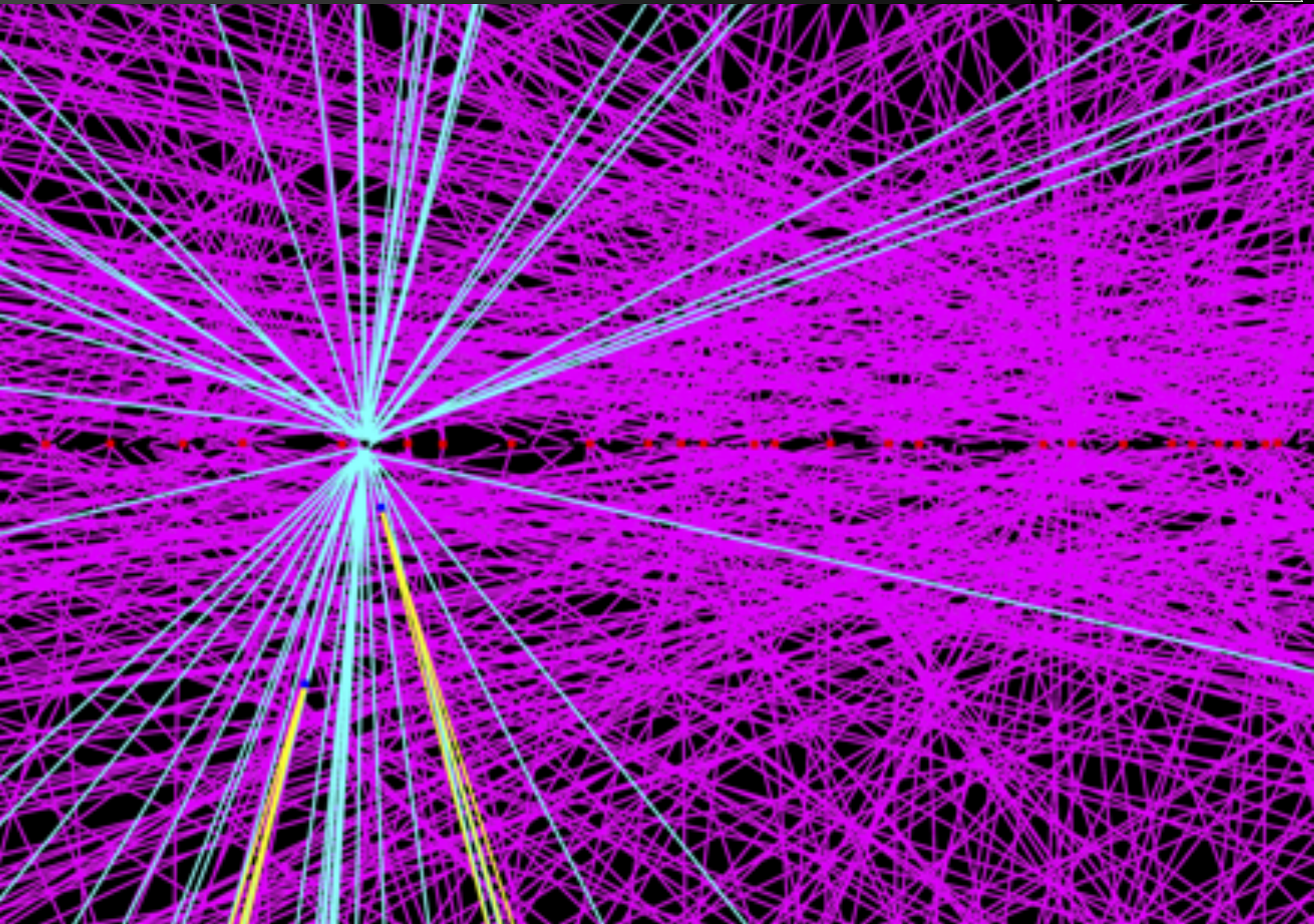
At peak, expected to reach 150-200 proton-protons collisions per bunch crossing at end of LHC running. Important to find rare things!

What will that look like?



From my title slide - this is a simulated proton-proton collision producing a pair of top quarks… with 200 overlapping (boring) proton-proton collisions in the same bunch crossing

What will that look like?

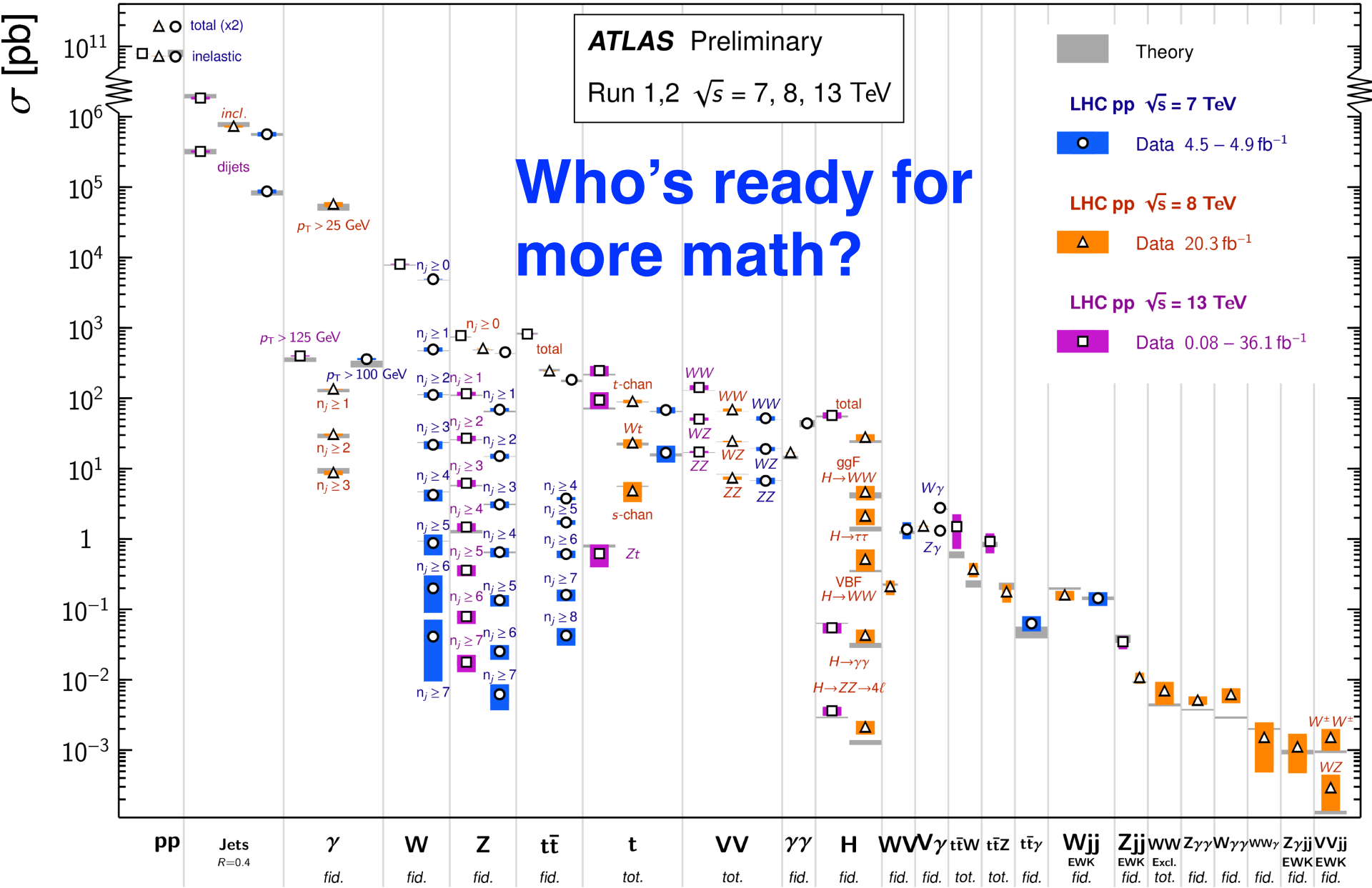


This will be challenging

So why do we want so many collisions?

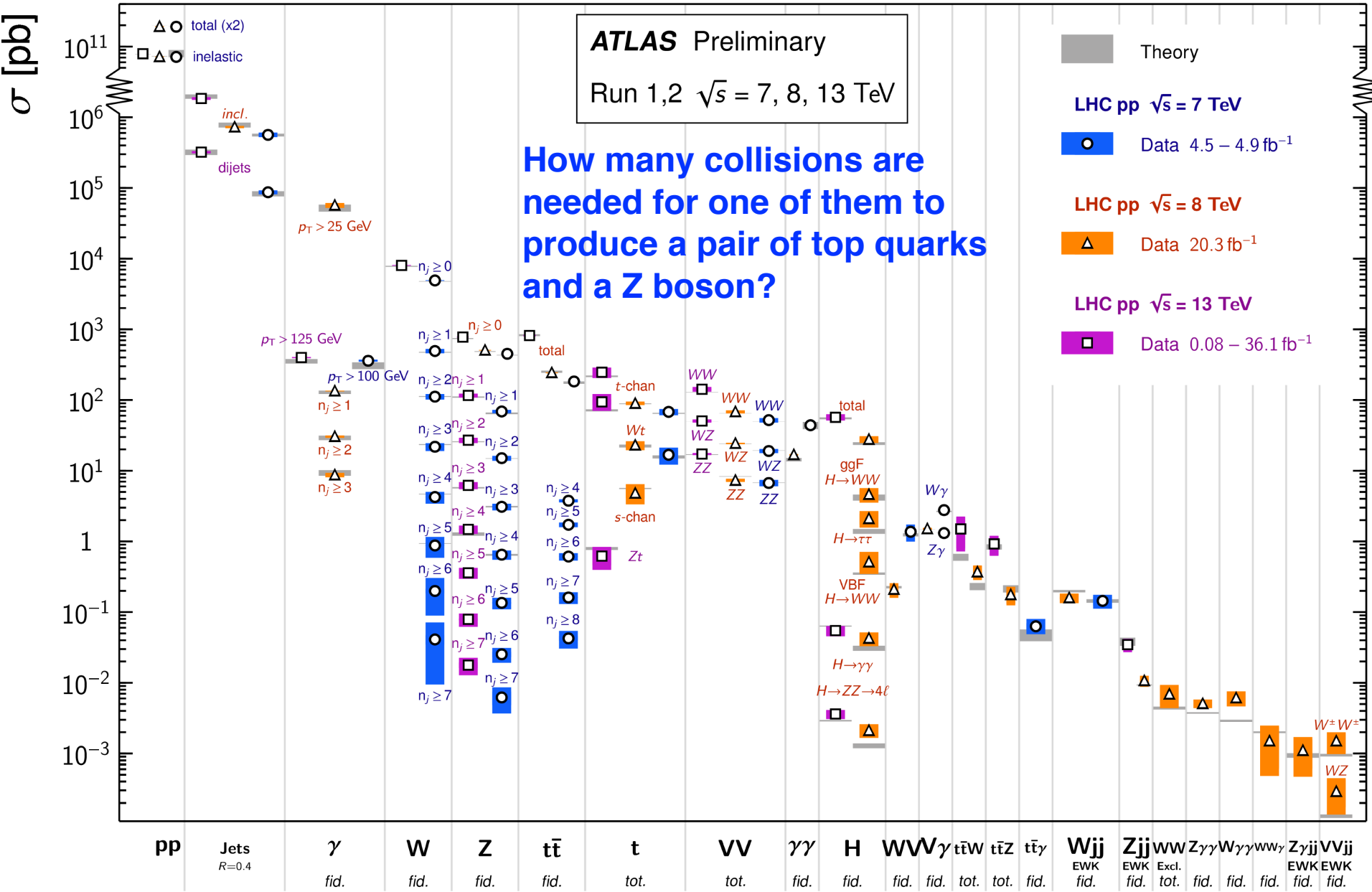
What we're looking for

Why do we want so many collisions?

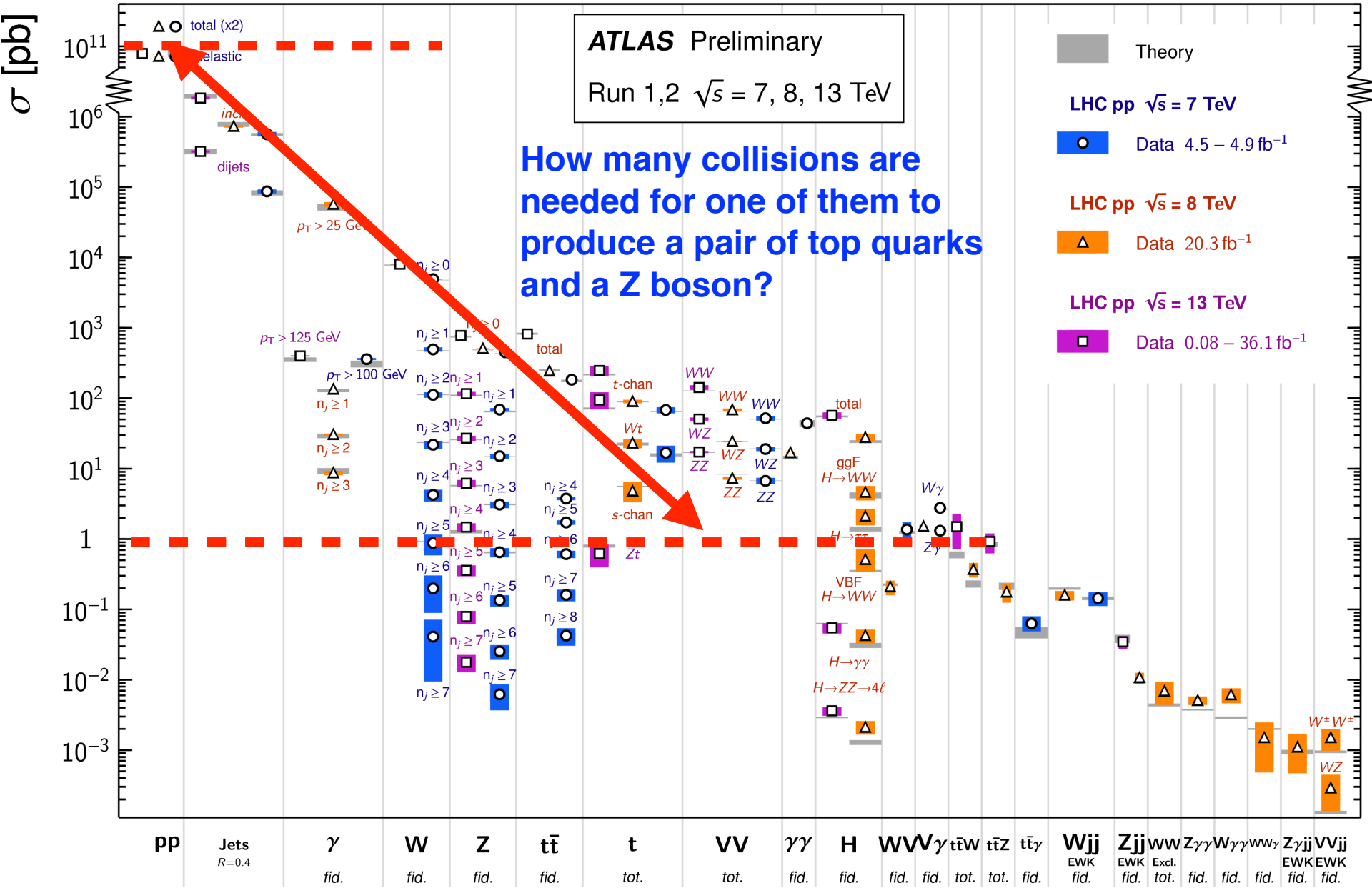


Northern Illinois University

Why do we want so many collisions?



Why do we want so many collisions?



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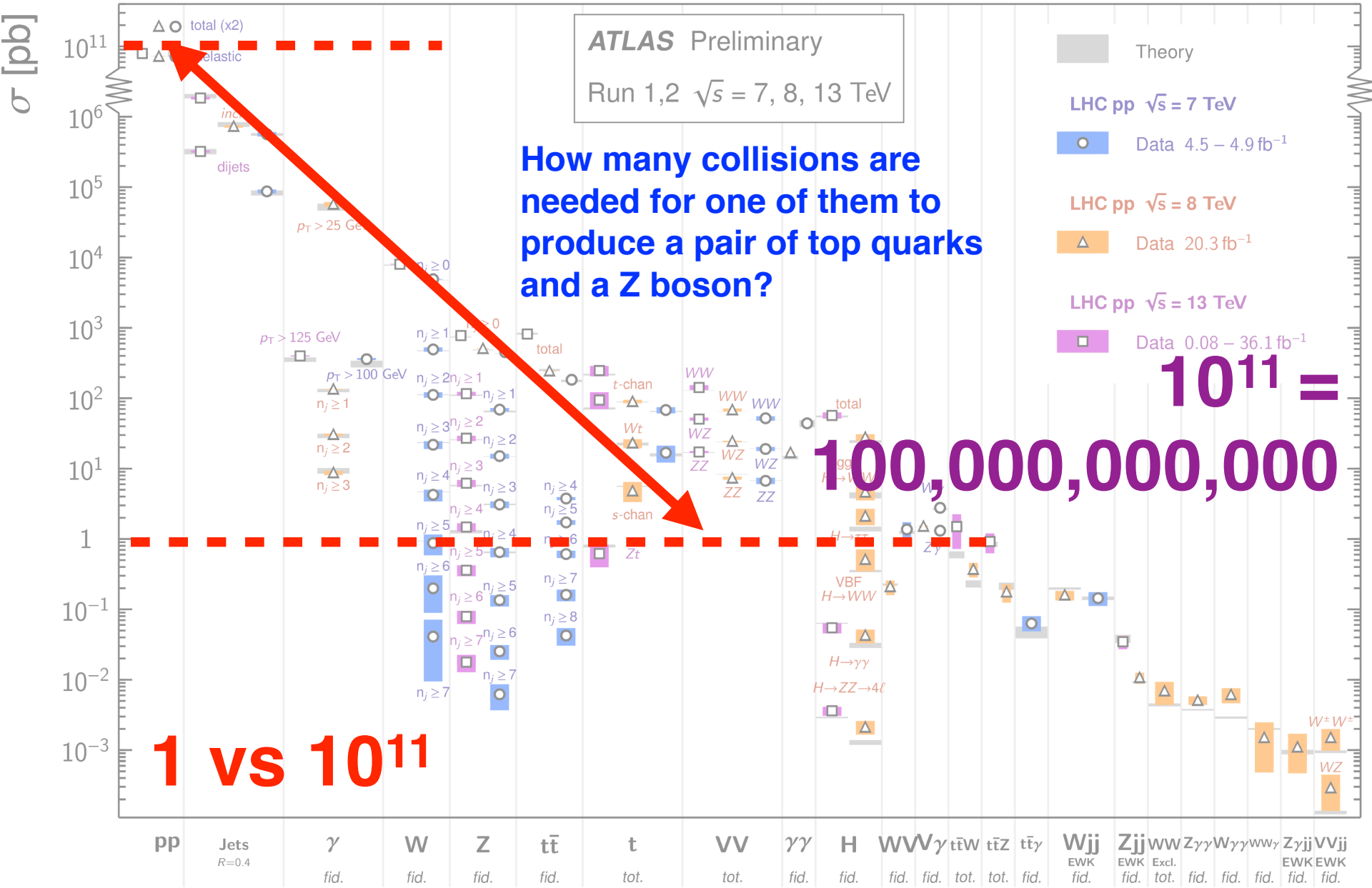
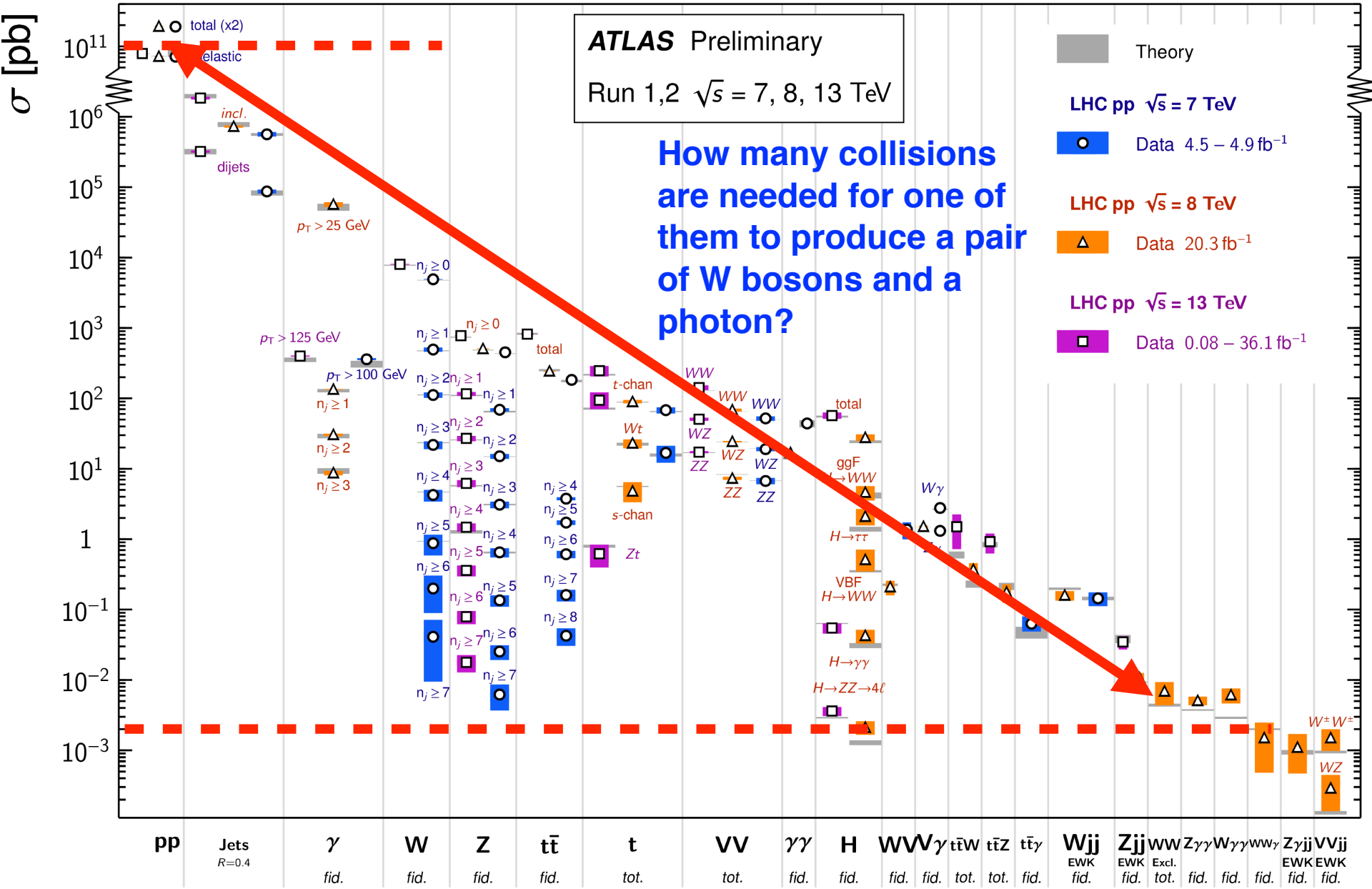
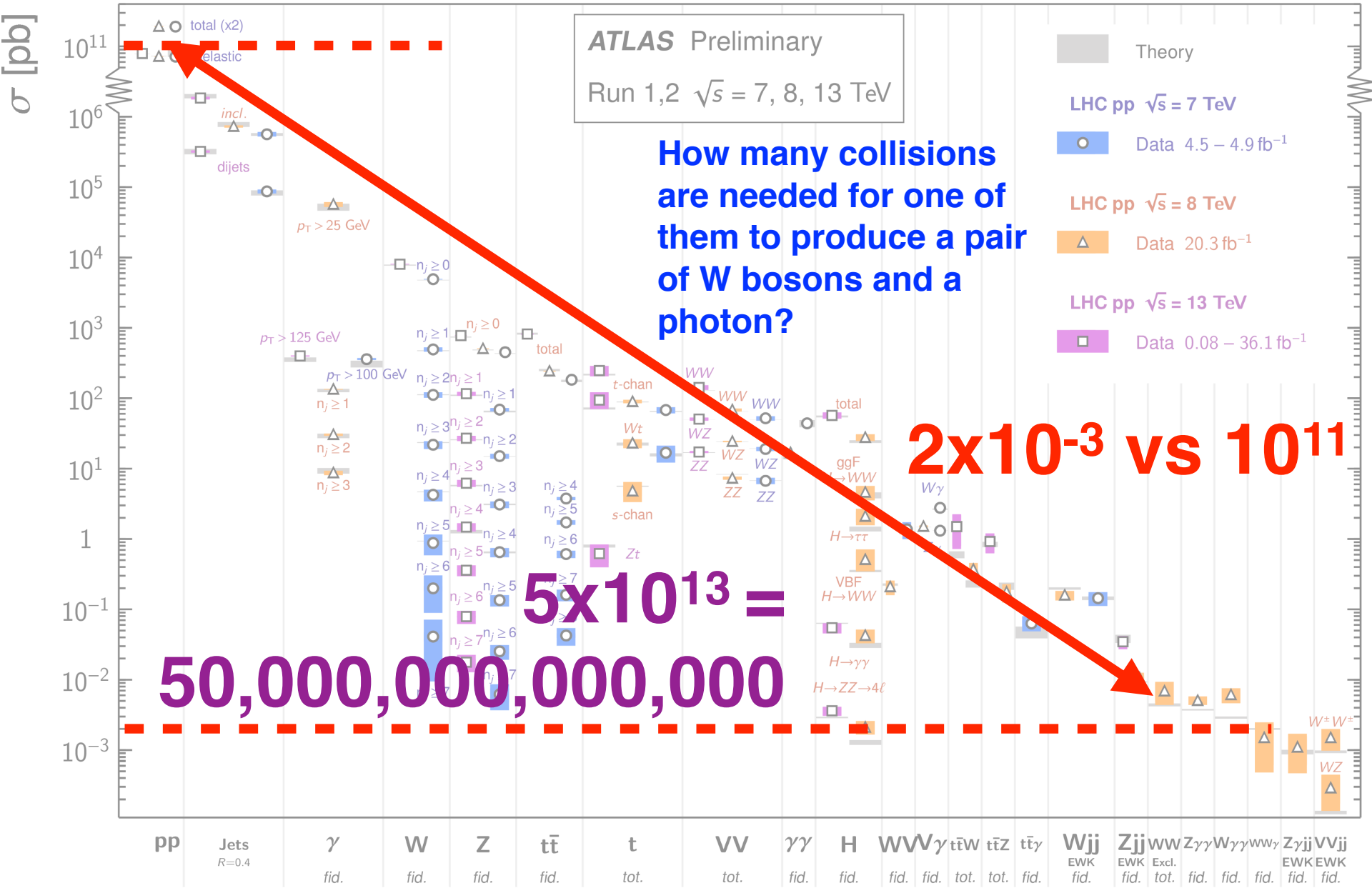


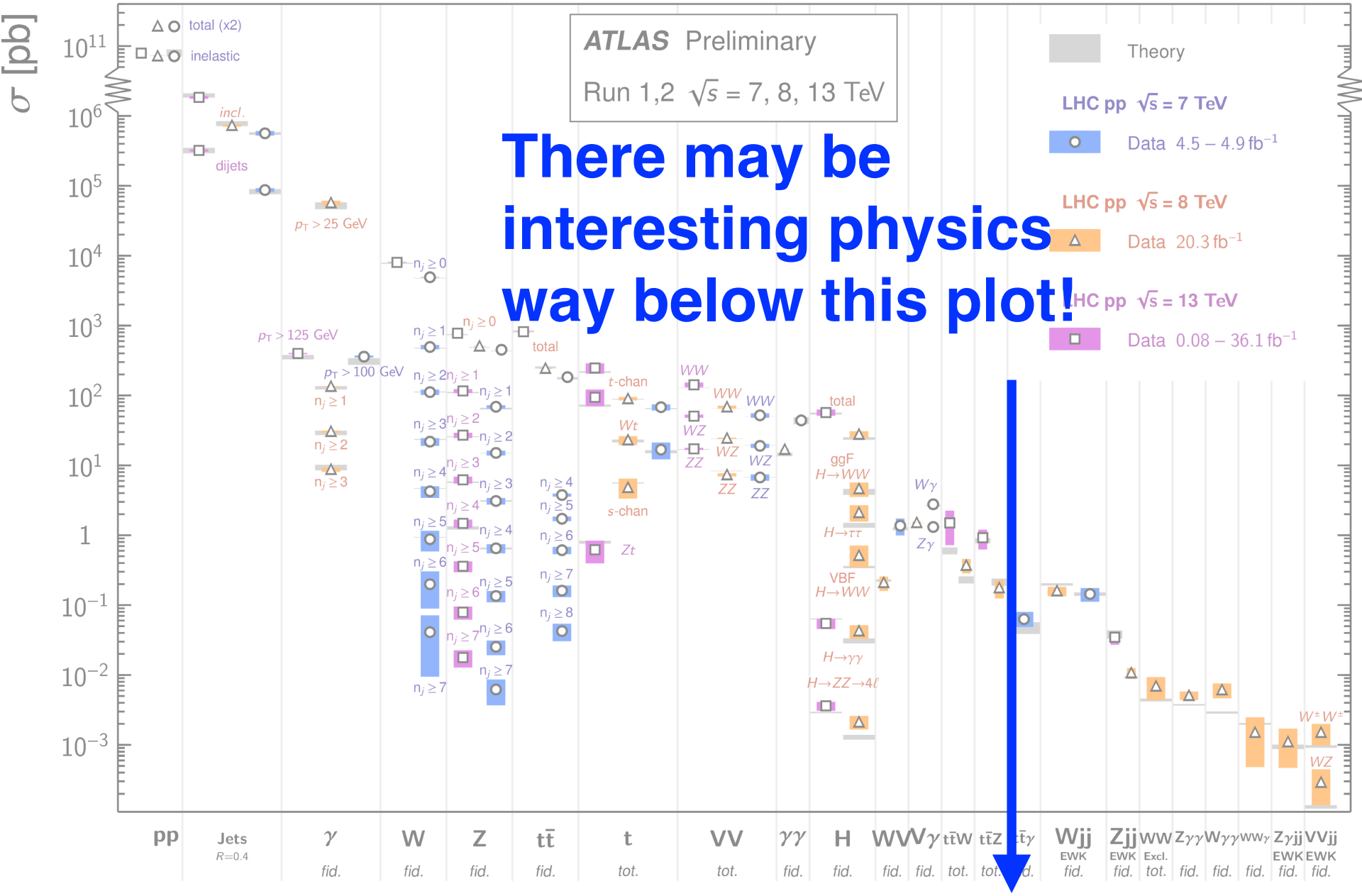
Why do we want so many collisions?



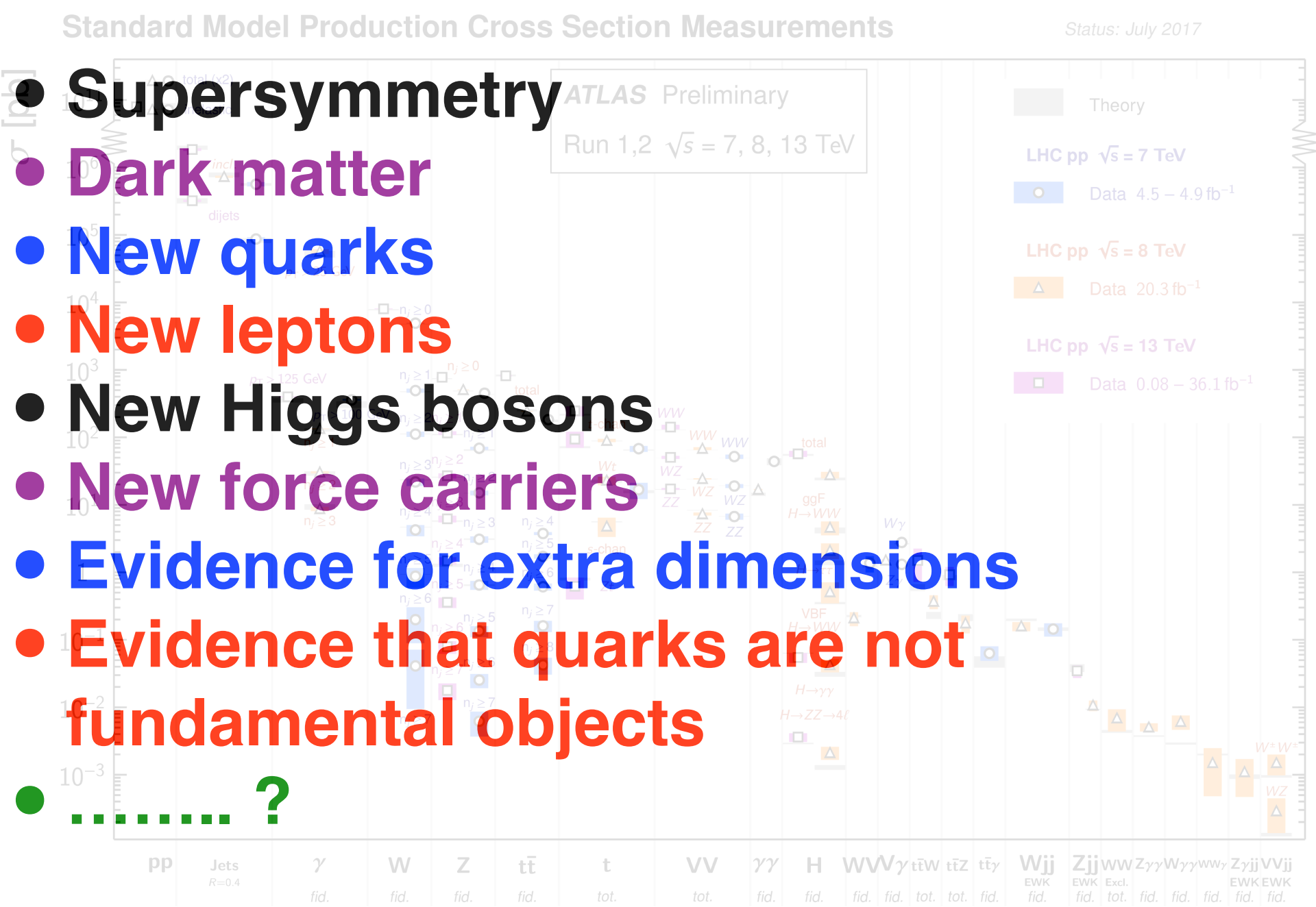
Why do we want so many collisions?



Why do we want so many collisions?



Those needles in a haystack



- Supersymmetry
- Dark matter
- New quarks
- New leptons
- New Higgs bosons
- New force carriers
- Evidence for extra dimensions
- Evidence that quarks are not fundamental objects
- …….. ?

Thanks!