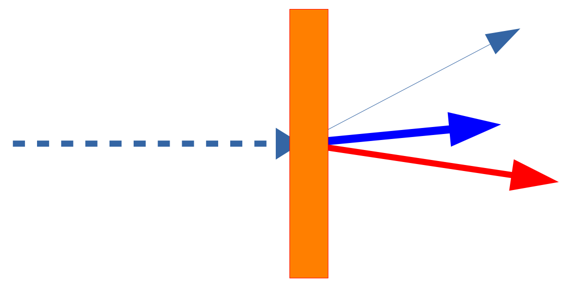
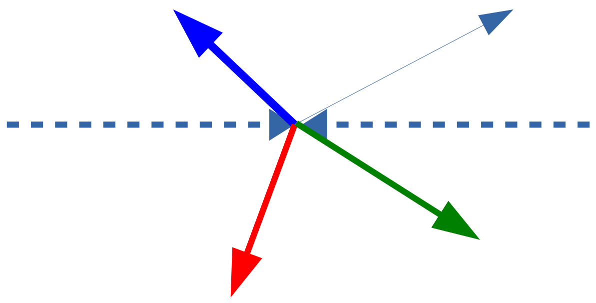
# PH4154
# Nuclear and Particle Physics

*Demystifying experiments*

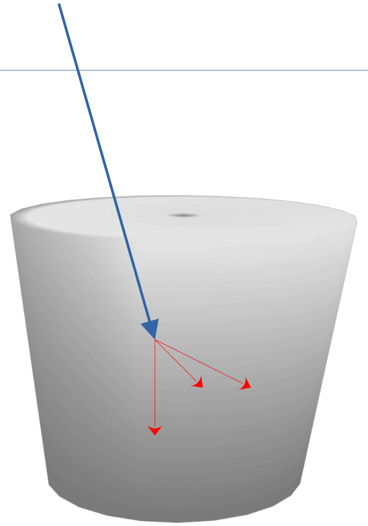
# Accelerators/Colliders



Fixed target



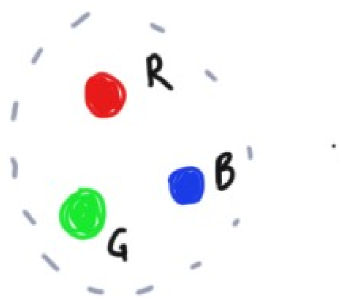
Collisions



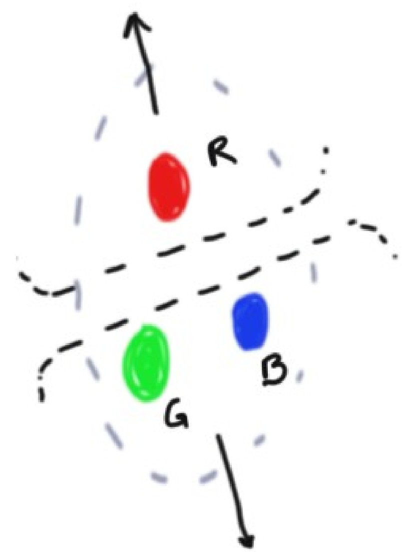
Neutrino/DM

- What particles should I collide? At what energy?
- What particles will be ejected? How do I identify them? What are their properties and how do I measure them?

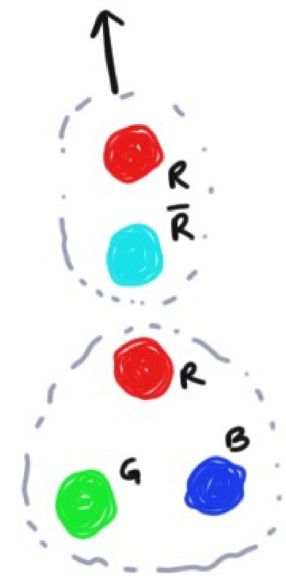
# Hadronization




Say you have a hadron (proton). And say you have infinite force at your disposal to grab one quark and try to pull it apart.




The strong force resists you… the more you pull the $q_R$ apart, the more the strong force increases and resists you… you keep pulling (putting in energy) the strong force keeps resisting.




Eventually, its energetically more favorable for a $q$-$\bar{q}$ pair to be created out of the energy… and what you are left in your hand is one more hadron than you started with.

# Hadronization: experimentally

A colored particle (quark and gluon) that is produced, cannot exist/escape by itself. Part of the production energy/momentum is used to produce additional quark/antiquark pairs – which then form hadrons. It is the hadrons that exist/escape from the collision.

Proton-proton collision

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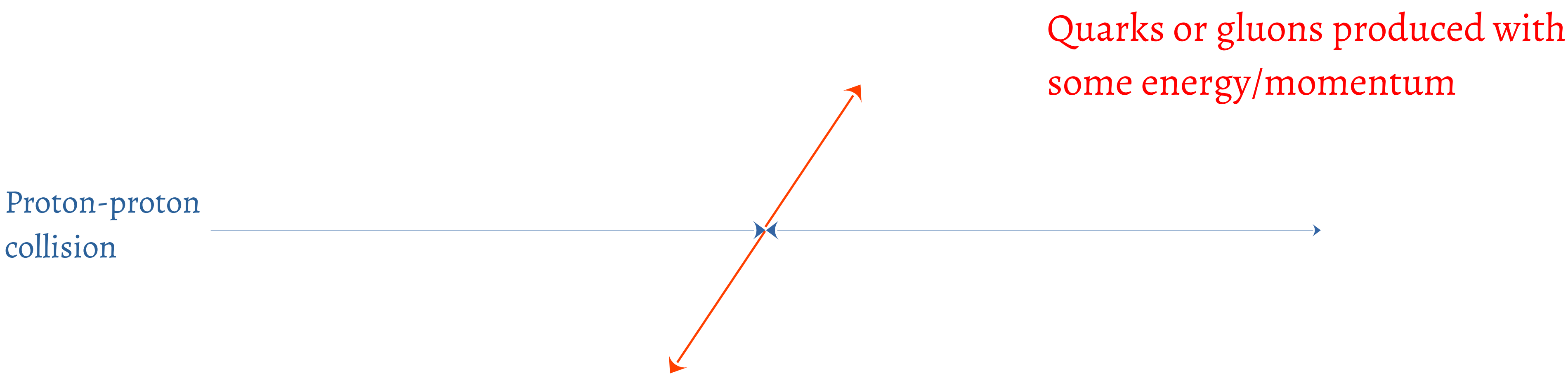

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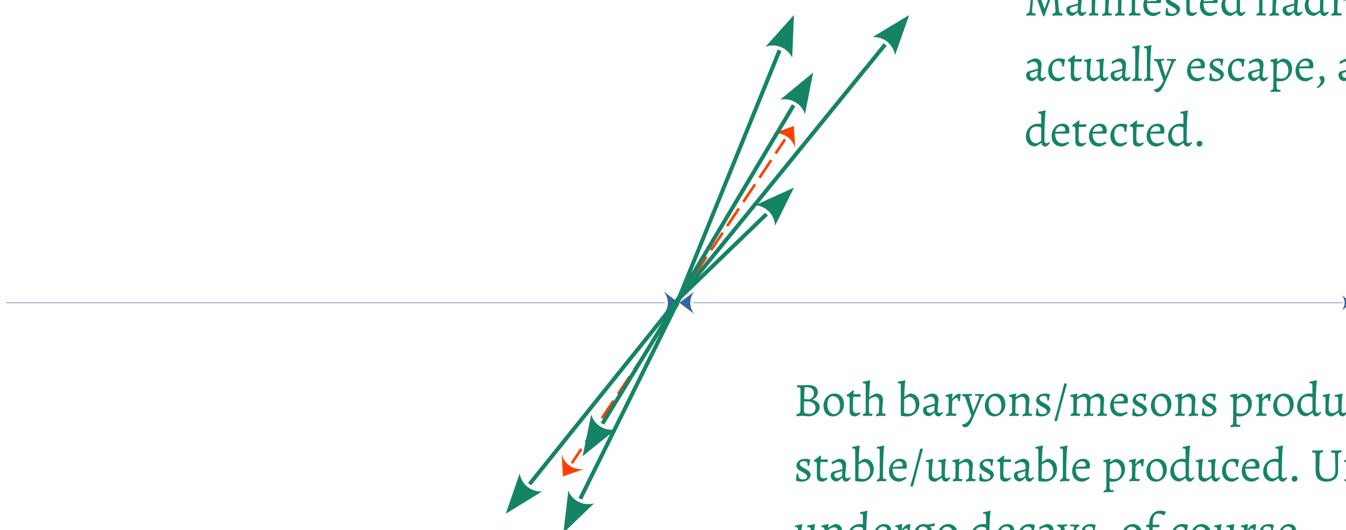
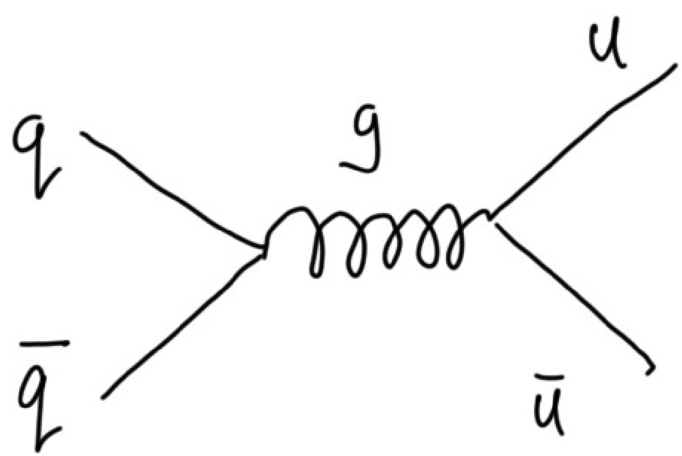
Manifested hadrons are what actually escape, and will be detected.

Proton-proton collision



Both baryons/mesons produced, both stable/unstable produced. Unstable hadrons undergo decays, of course.
(Different ways to hadronize 'same' initial state)

# Hadronization



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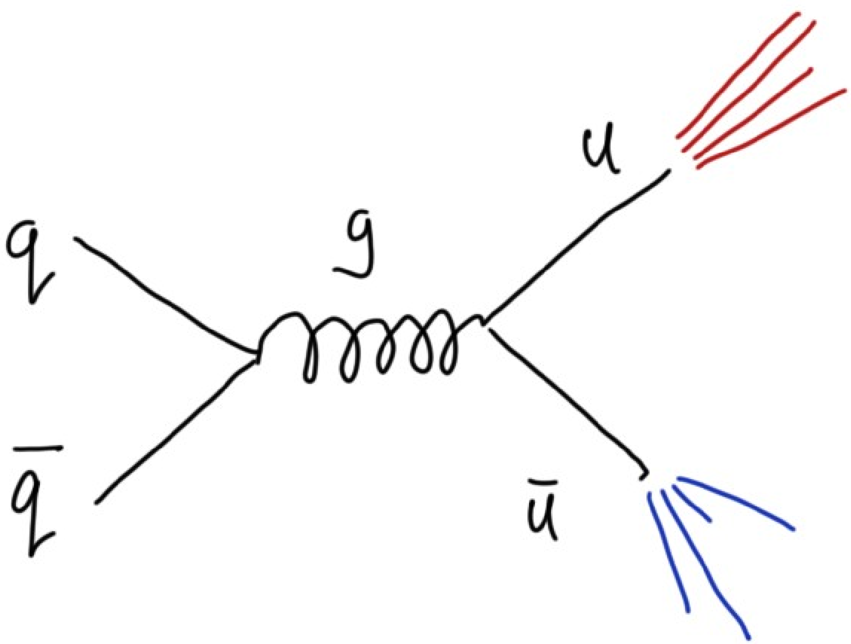

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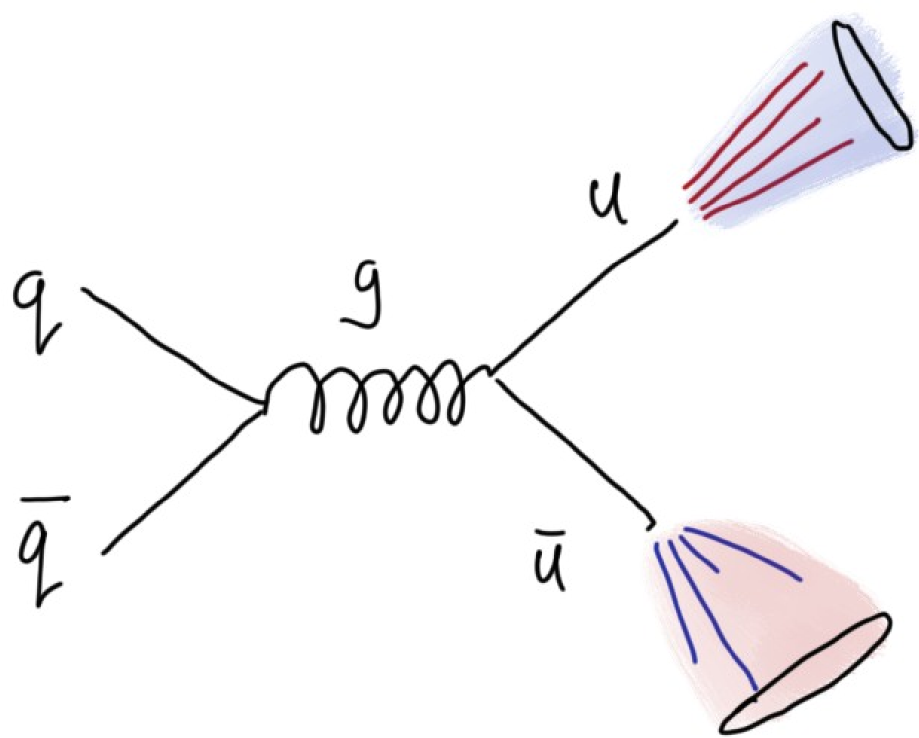



We *cluster* the produced hadrons into a single logical unit called a “jet”

This jet is now treated as a single object, with its own energy and momentum.

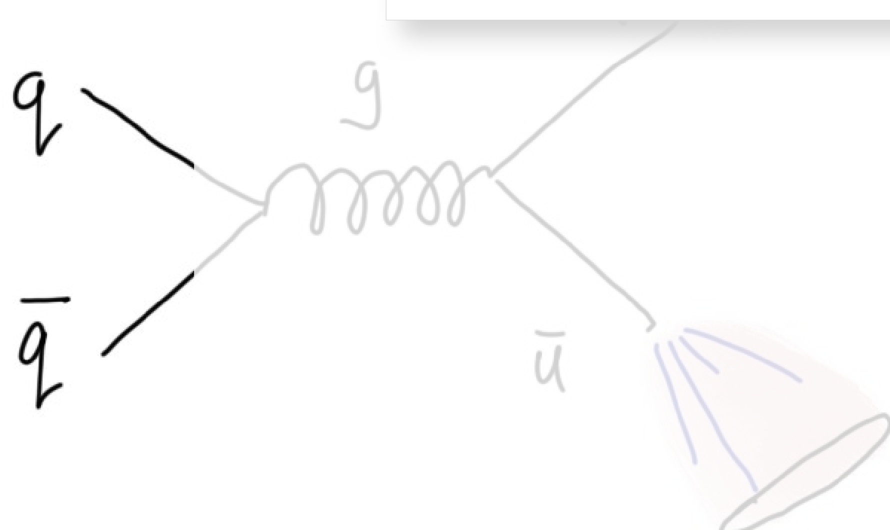
# On the incoming side

We can't just start with quarks.

We start with hadrons (i.e. protons!)

oduced hadrons into a
called a "jet"

This jet is now treated as a single object, with its own energy and momentum.



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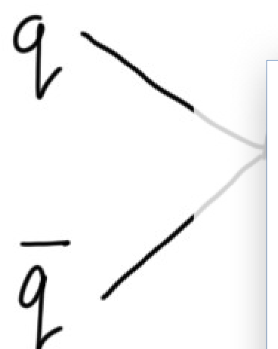
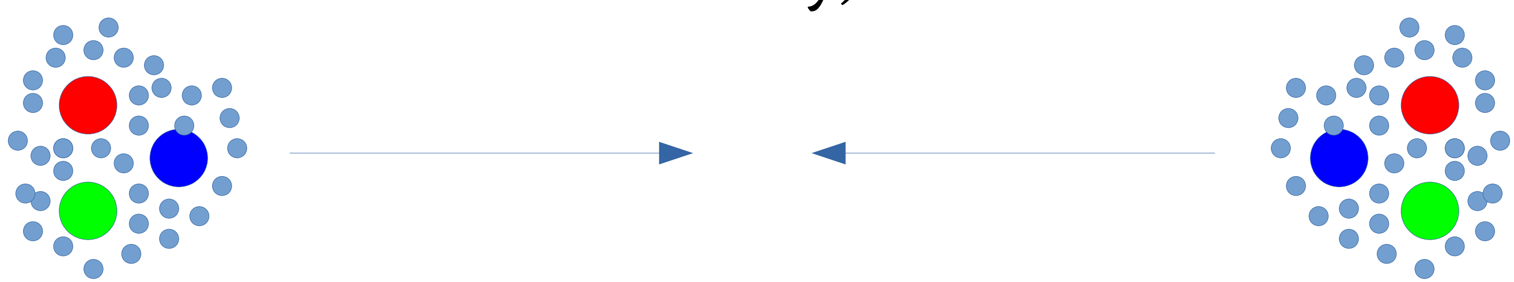



Actually,



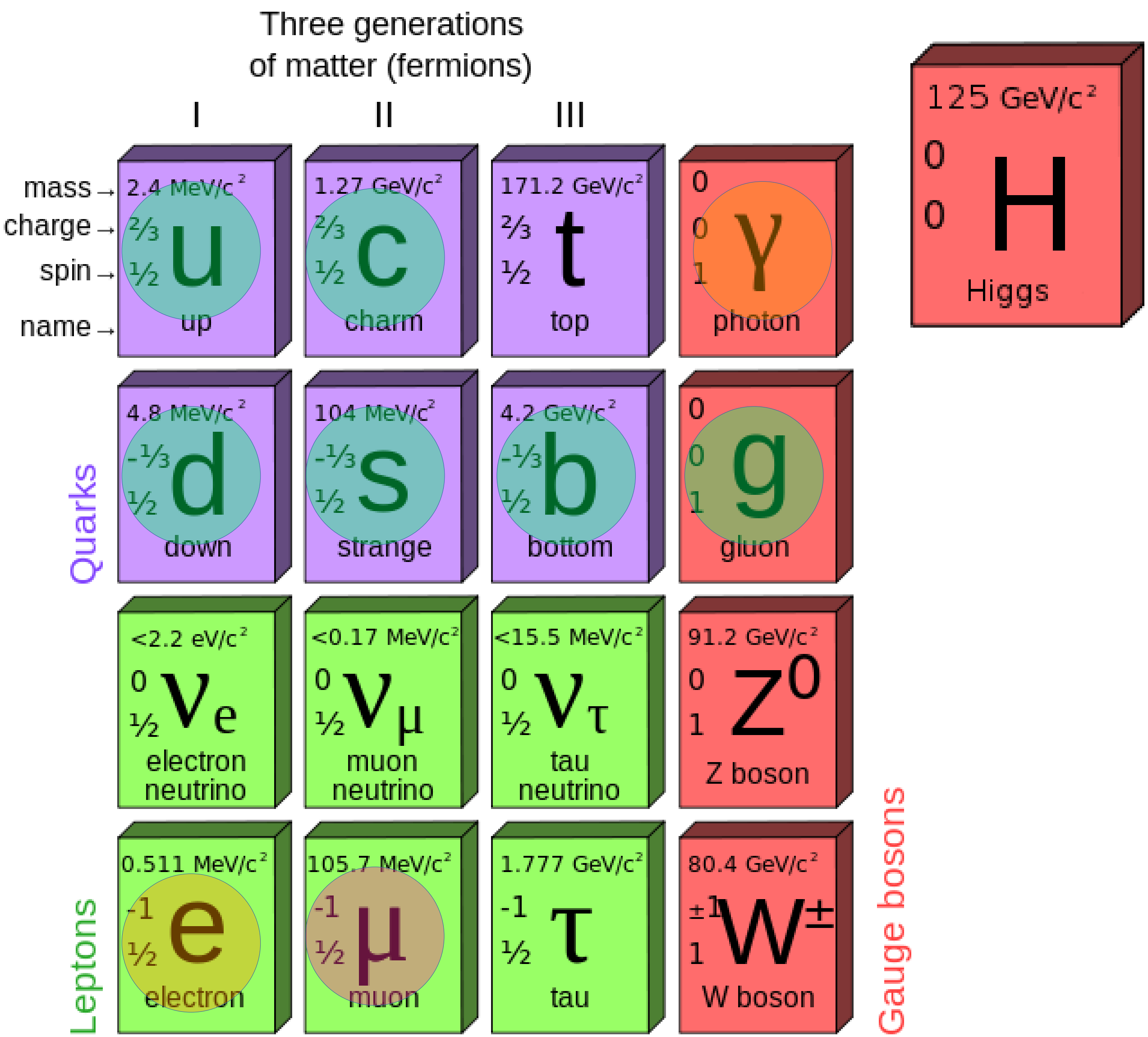
# Some relevant properties

| Name | Mass | Approx. Travel distance |
|---|---|---|
| e | 0.51 MeV | stable |
| $\gamma$ | 0 | stable |
| $\mu$ | 105 MeV | 6250 m |
| $\tau$ | 1.8 GeV | 50 $\mu$m |
| $\pi^{\pm}$ | 140 MeV | 56 m |
| n | 939 MeV | $10^{11}$ m |
| W | 80.4 GeV | $10^{-19}$ m |
| Z | 91.2 GeV | $10^{-19}$ m |

Some particles can be detected directly, some will decay – so we must infer their presence.

**For any particle that will live 50m or longer.... A collider experiment will detect it directly, and thus we can think of it as stable for a collider experiment.**

# List of particles




Stable

Stable in this context

Hadronize

# Quick exercise

$$u\bar{u} \to t\bar{t}$$

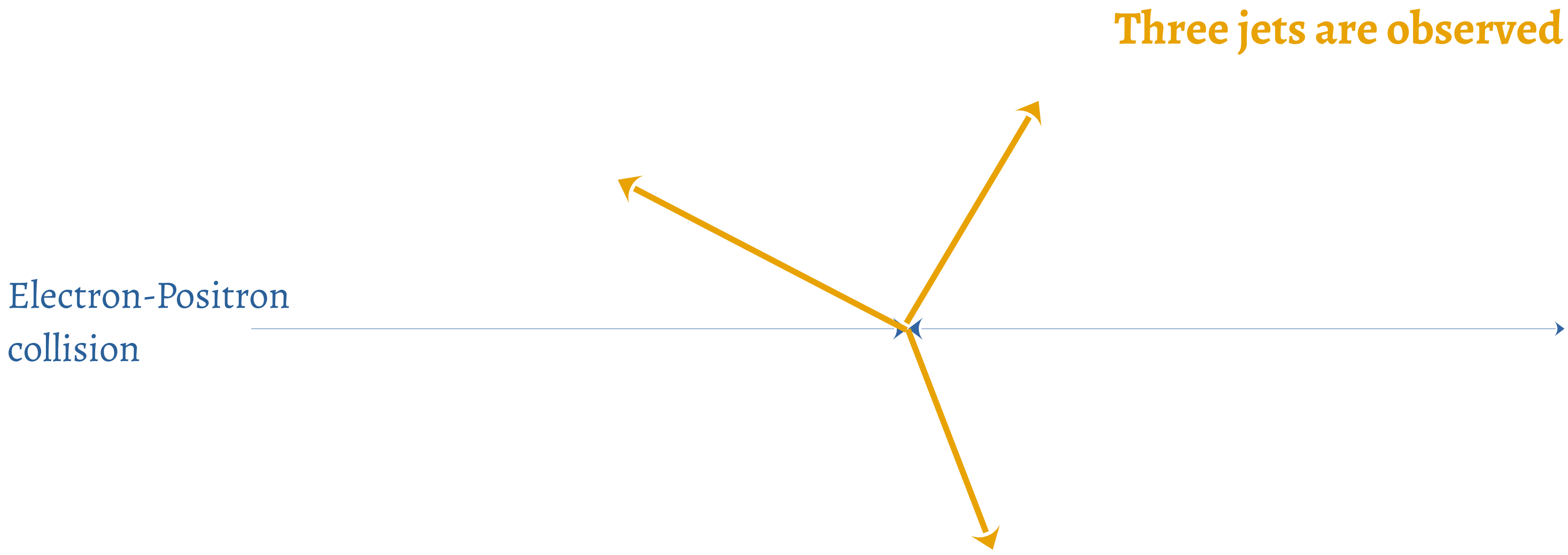
What are the ultimate possible particles?

How many minimum jets will be produced?

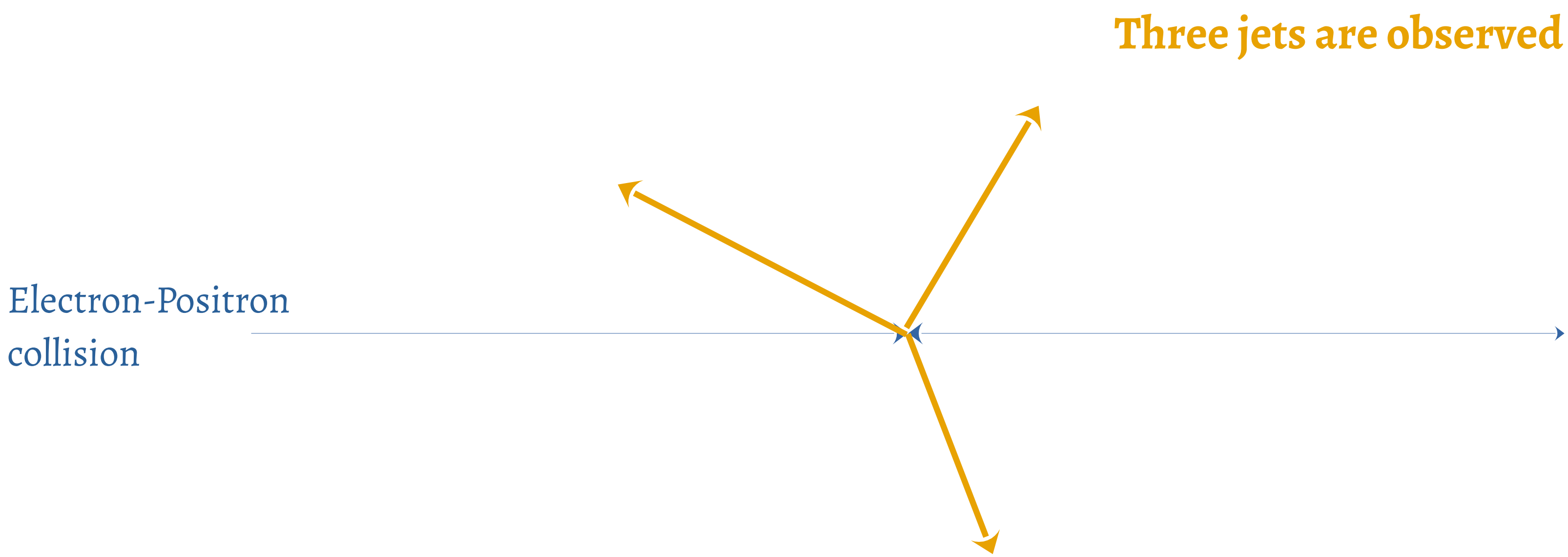
How many maximum jets can be produced?

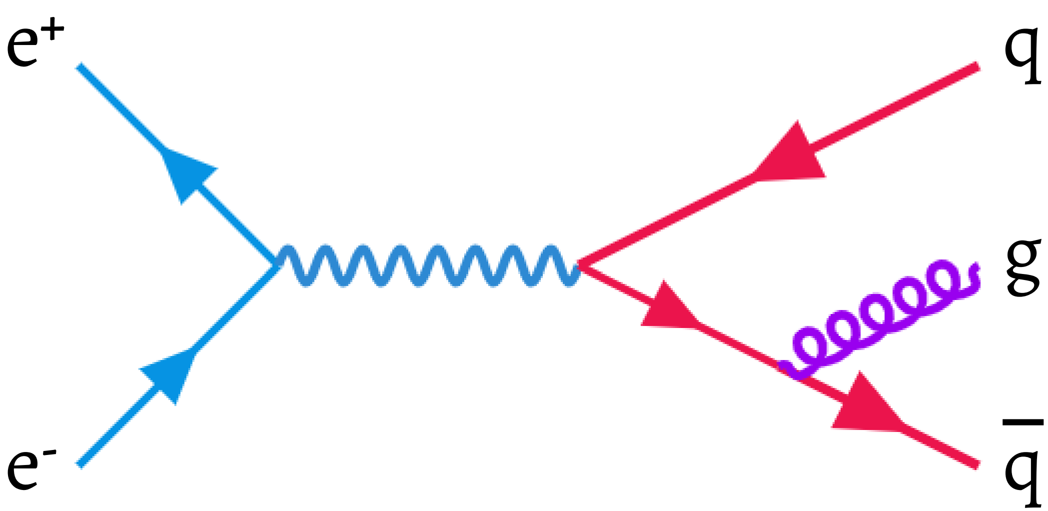
Given a million "events" of $u\bar{u} \to t\bar{t}$, how many of those will have $\geq 4$ jets

# How?



# Discovery of gluons



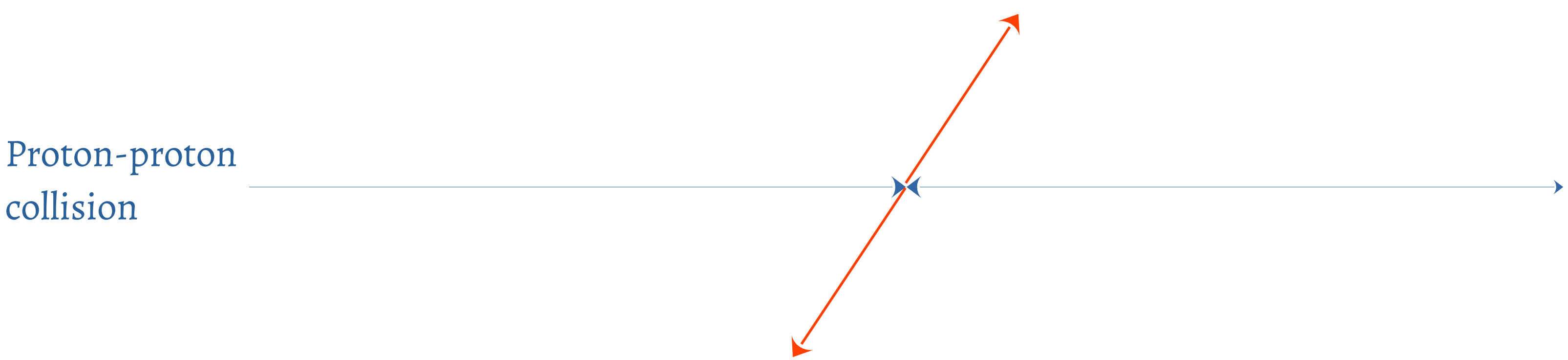

"The discovery of the gluon"

John Ellis

https://arxiv.org/abs/1409.4232

# Detectors: collider

Let's say we collide proton-proton. What is the information about the resultant collision that we are interested in?



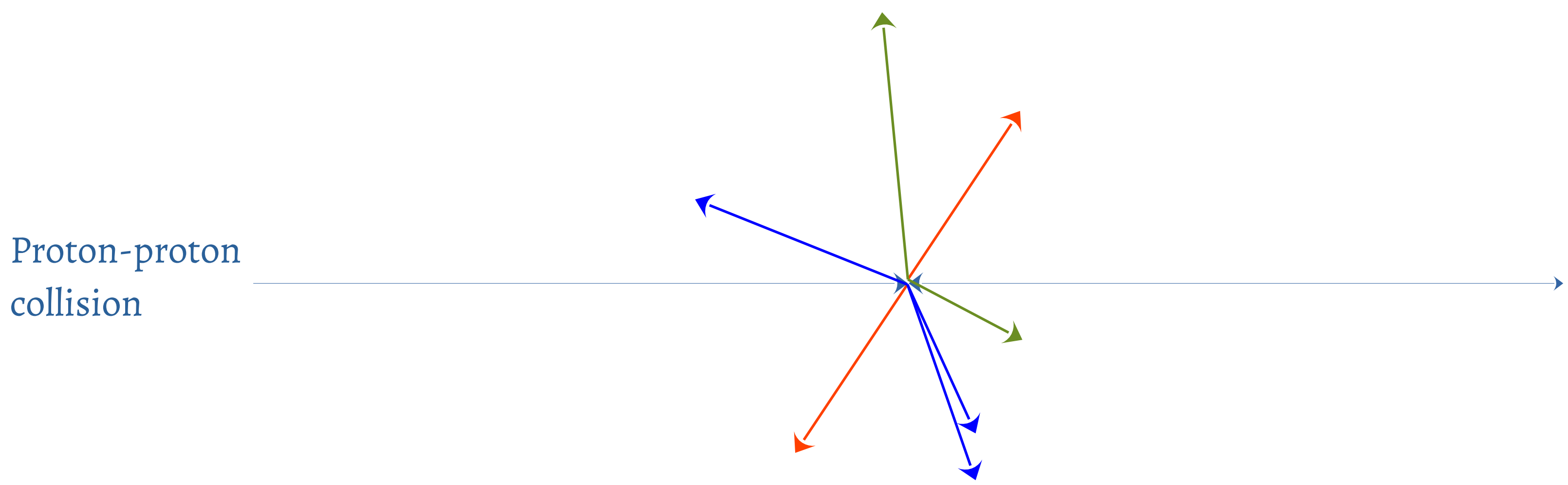
# Detectors: collider

Let's say we collide proton-proton. What is the information about the resultant collision that we are interested in?

(i) what particles are produced and how many? (electrons, muons, jets, etc.)

(ii) the energy and momentum of these particles....

(iii) some details about the interactions with material....



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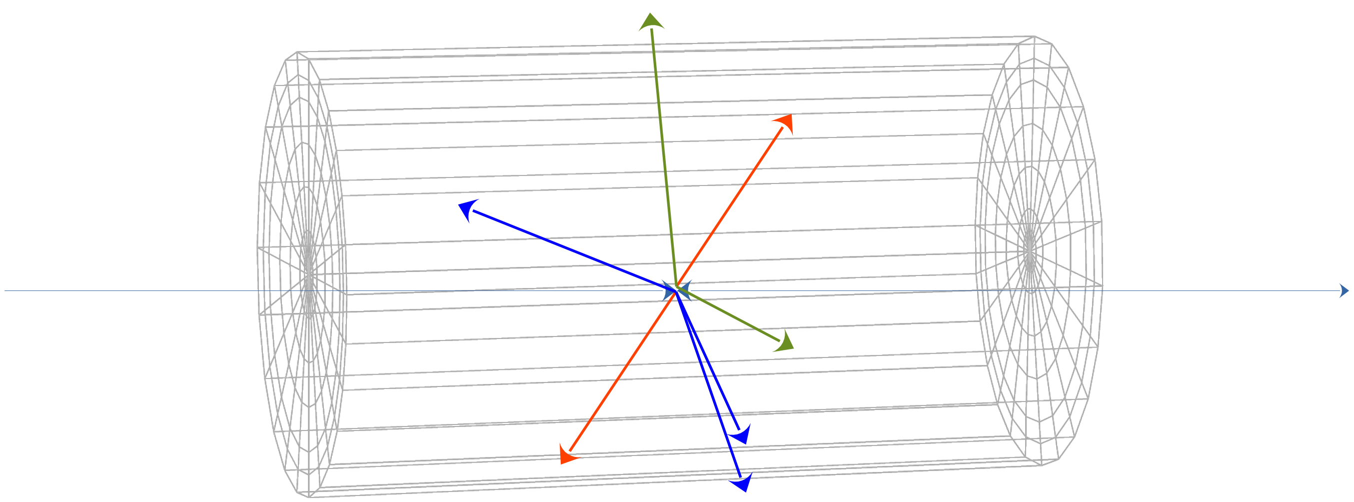
Proton-proton collision



# Design of Modern Multipurpose Detector at a collider

Tracker: detects charged particles.
Measures momentum, and sign of charge.

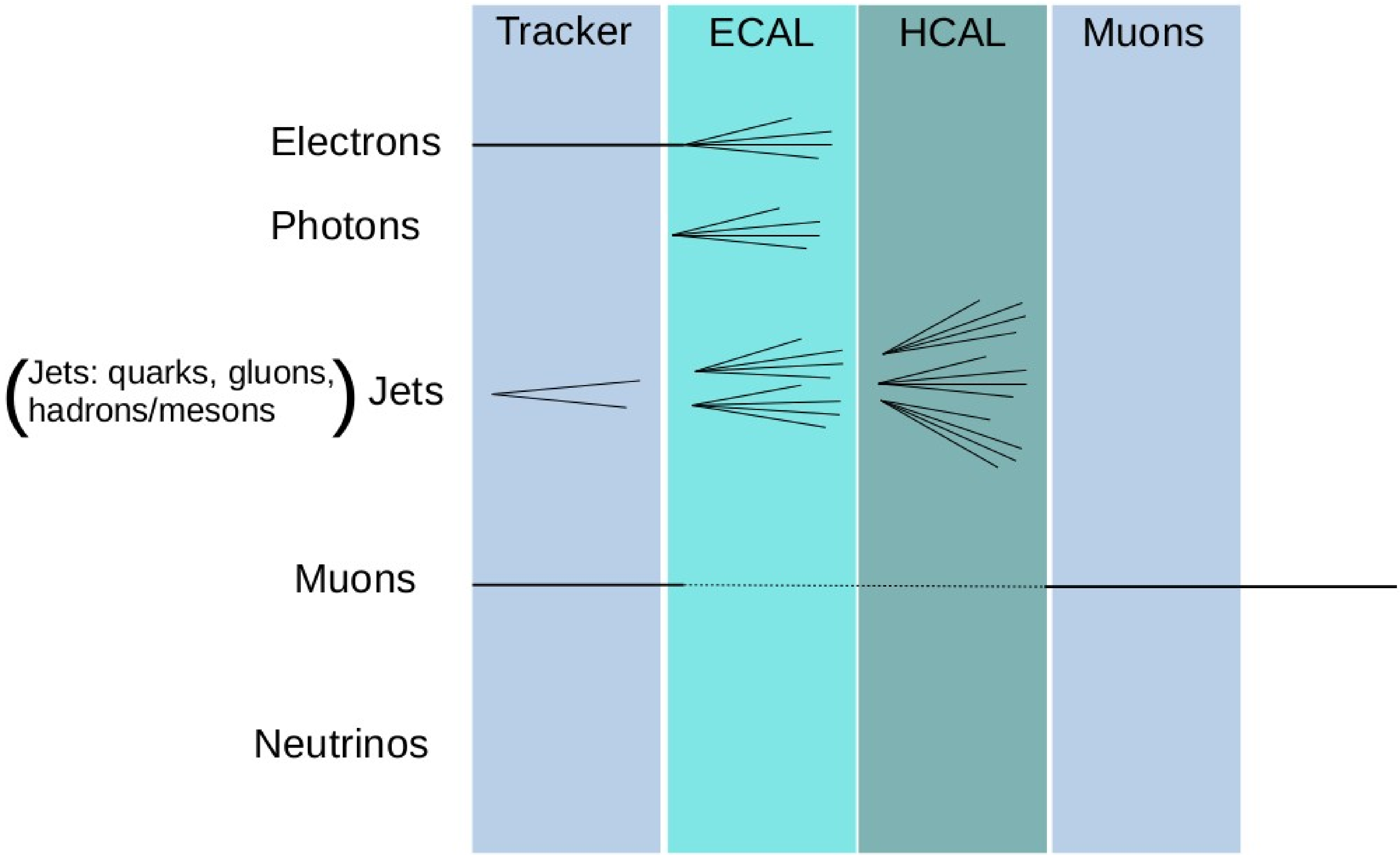
Calorimeter: detects all particles (except $\nu$). Measures energy of the particles.

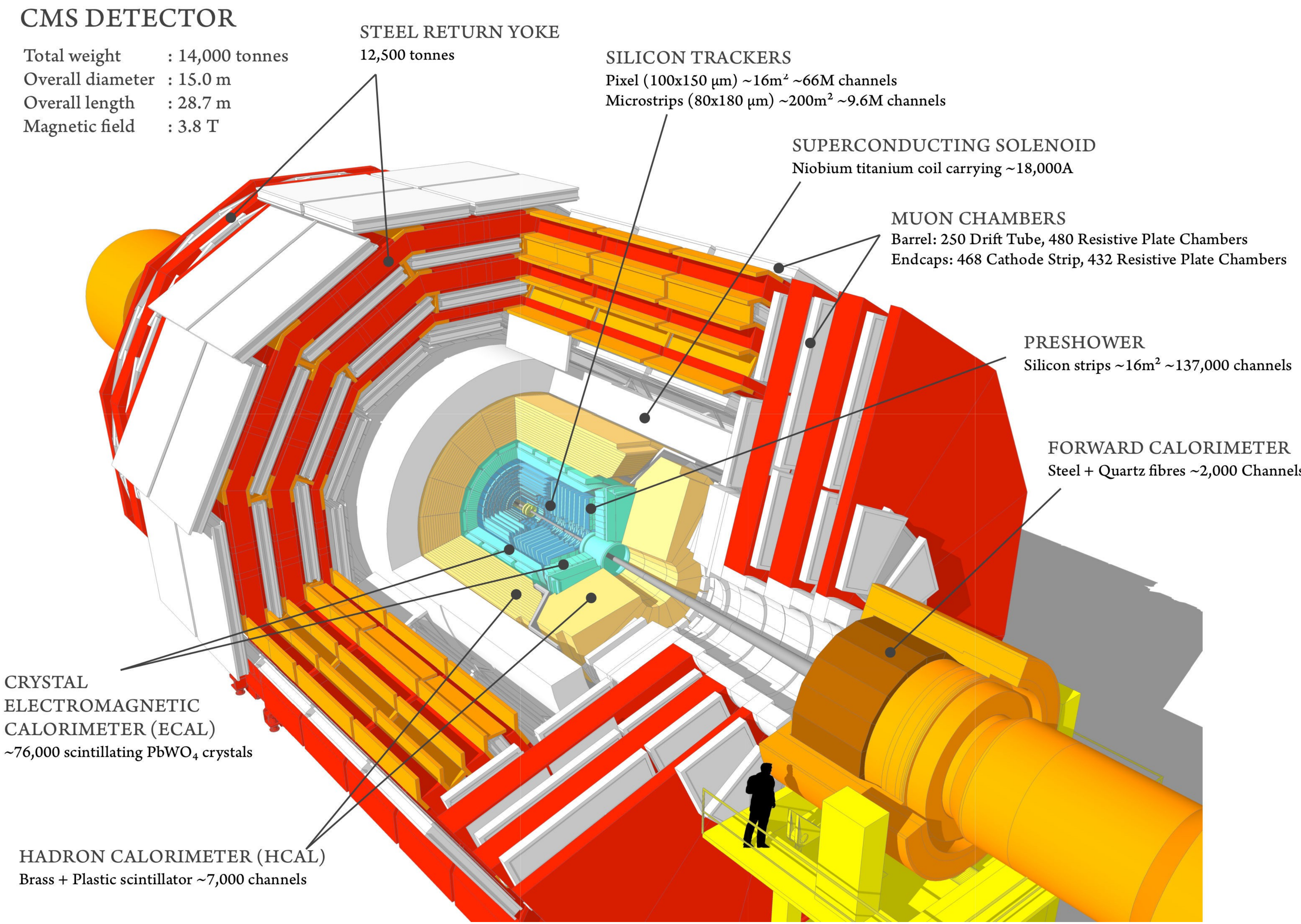
- Electromagnetic ($e,\gamma$)
- Hadronic (hadrons)

Tracker: detects charged particles.
Meant for muons

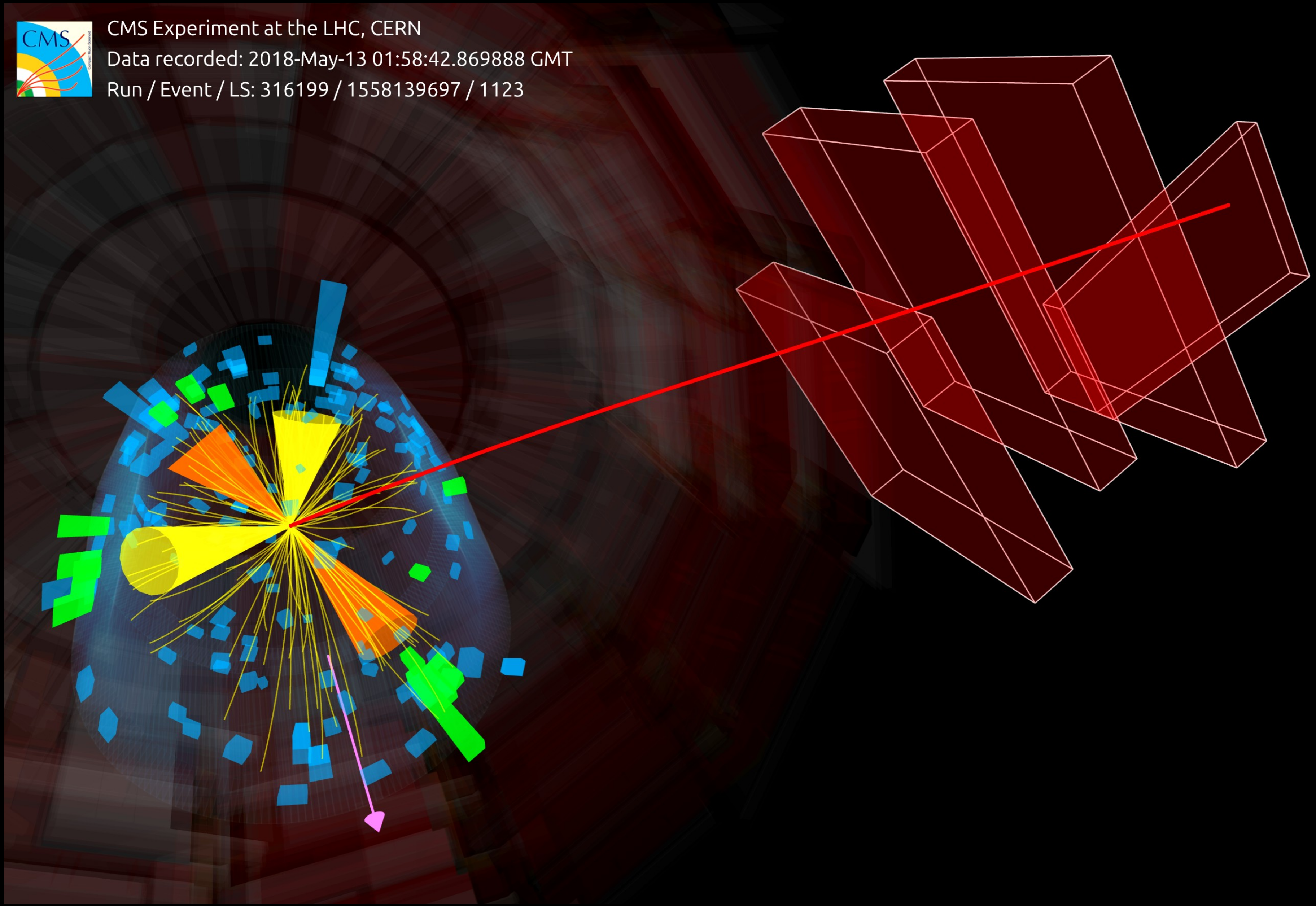
Radially outwards

# Design of Modern Multipurpose Detector at a collider





CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels




An event consistent with production of a top quark pair decaying semileptonically. Each top quark decays into a W boson and a b quark. The b-tagged jets are represented by the orange cones. One W boson decays to a muon (the red line) and a neutrino (not seen) and the other decays to jets (represented by the yellow cones).

# Reconstruction and Identification

A detector, typically responds with an electric/electronic reaction to some stimulus.

That is… if a particle interacts with detector, you get some current pulse.

Treat the current pulse as binary (fired or not) or as a continuous response (amount of current $\propto$ some property like energy of particle)

# Reconstruction and Identification

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*Think Camera.*
*Incoming photons generate currents in pixels. These are turned into intensities. You see a visual representation of pixels with r,g,b intensities.*
*YOU look at this representation and decide what it is.*

*Vast software needed.*

E Px Py Pz other information

$N_e$

Ele1

Ele2

$N_{mu}$

Mu1

Mu2

Mu3

$N_{jets}$

Jet1

Jet2

Jet3

Jet4

.

.

.

1 event or 1 collision

We have many such collisions

E Px Py Pz other information

$N_e$

Ele1

Ele2

$N_{mu}$

Mu1

Mu2

Mu3

$N_{jets}$

Jet1

Jet2

Jet3

Jet4

.

.

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This is the LHC data.

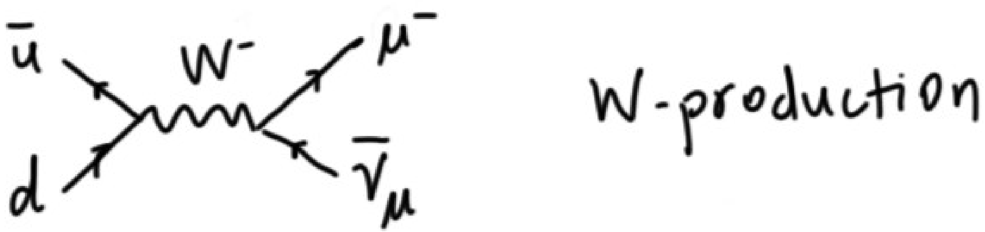
# Use the data to answer questions

Measurements

- Cross section
- Mass
- Other properties

Searches

# Cross section



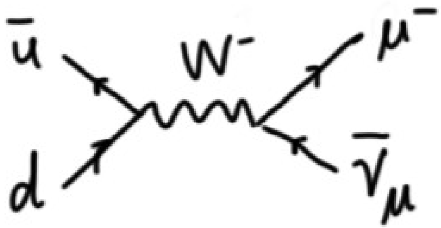

Associated with each Feynman diagram, we can calculate a rate… this rate is the **cross section** of that particular process taking place.

This rate, for a particular diagram depends on the 4-vectors of the incoming particles, and is typically integrated over the possible 4-vectors of all outgoing particles.

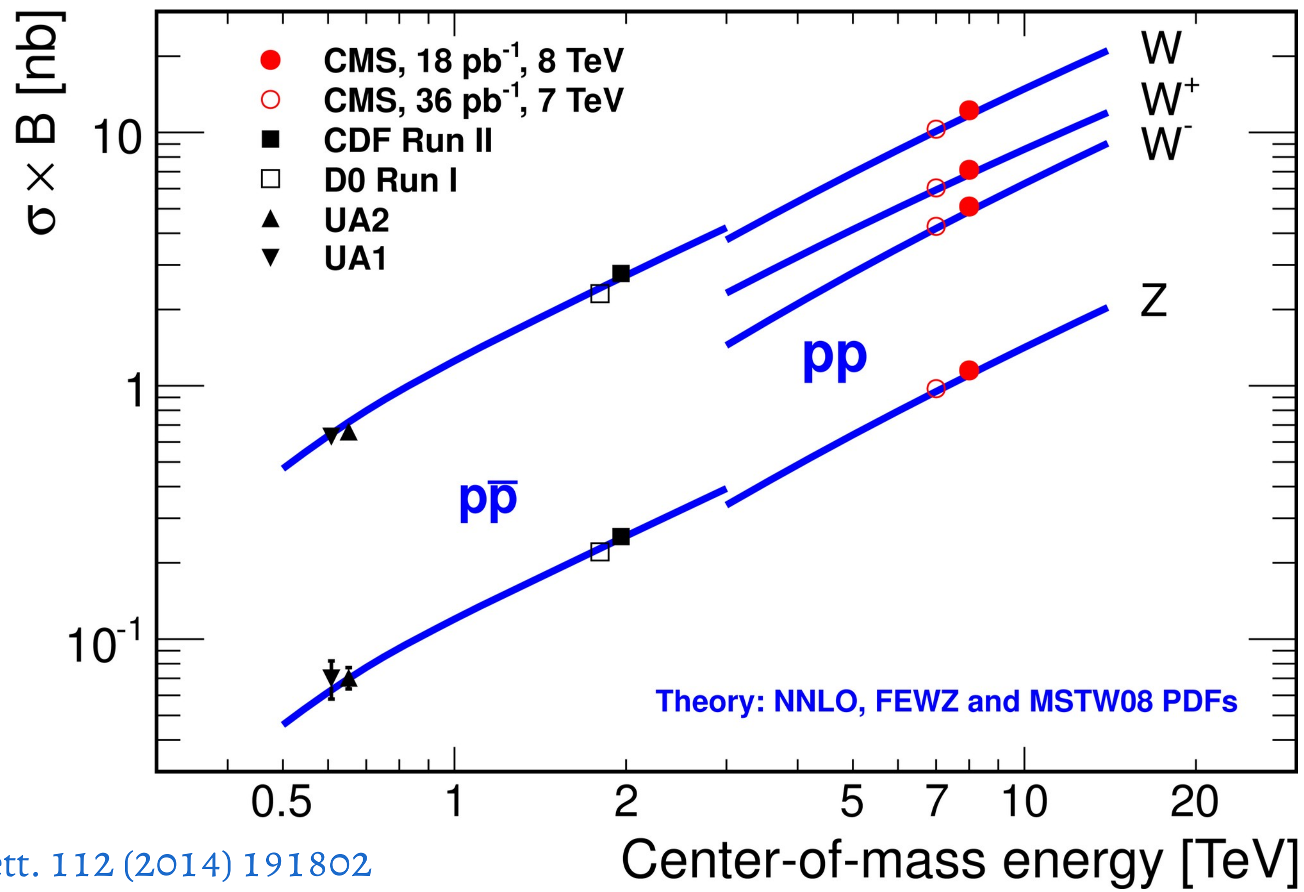
In other words…. We specify a collision energy, and ask for a cross section for a given process.

This *cross section, can also be measured experimentally* using the data. Comparison with results allows us to modify our theory and our understanding.

# Cross section

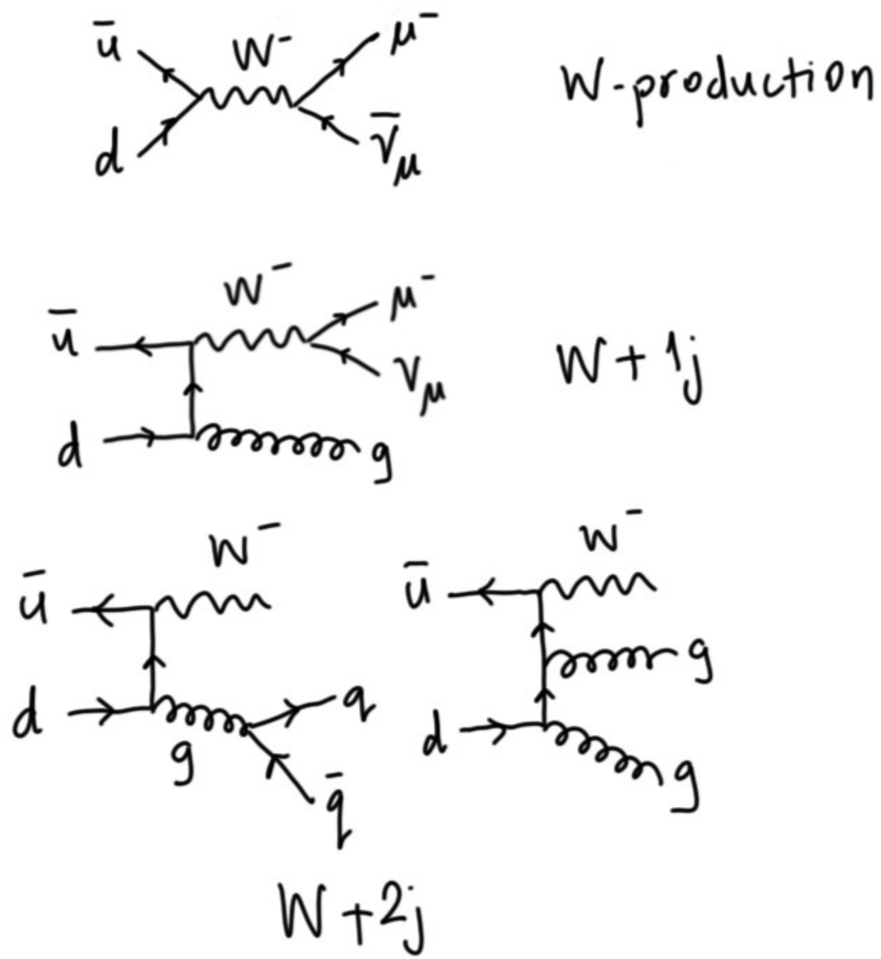


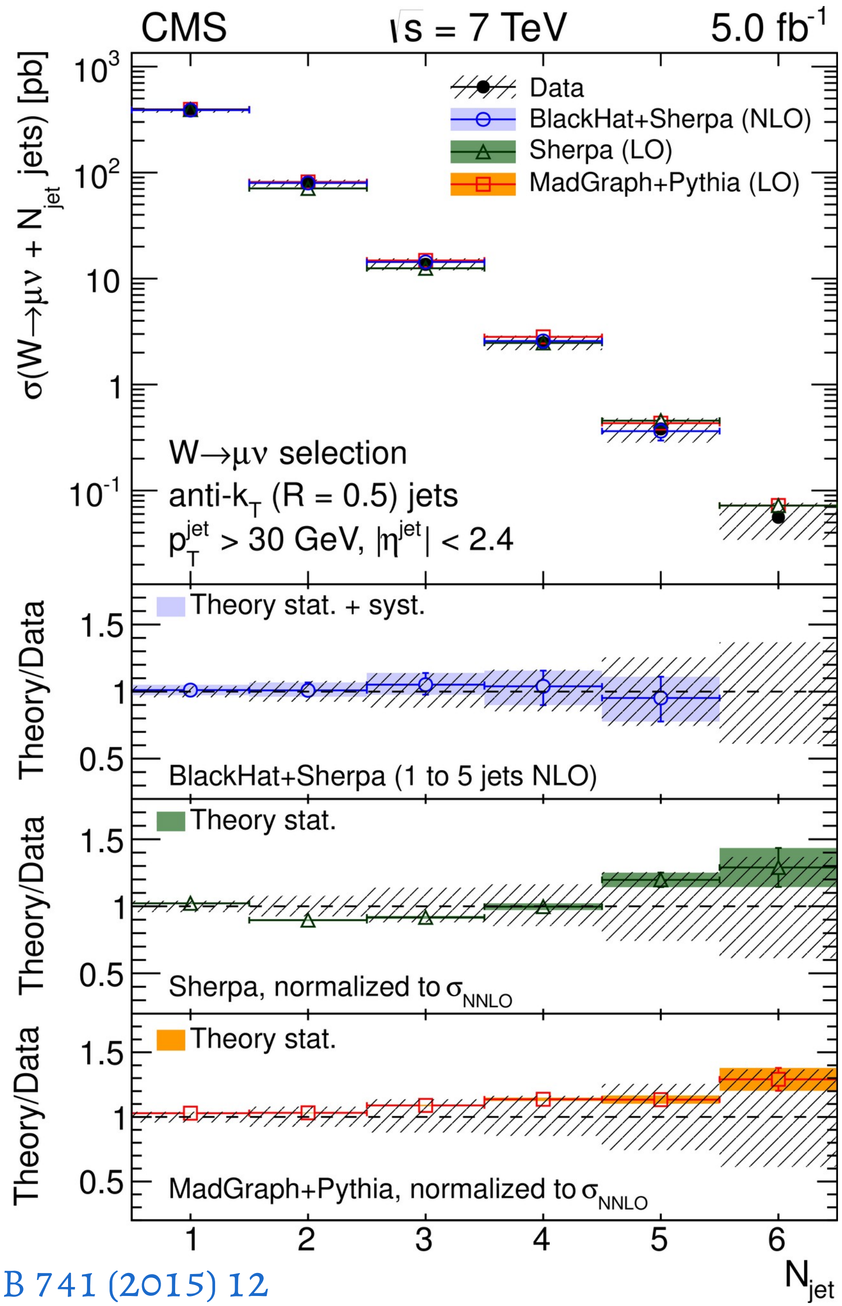

W-production




Phys. Rev. Lett. 112 (2014) 191802

# Cross section



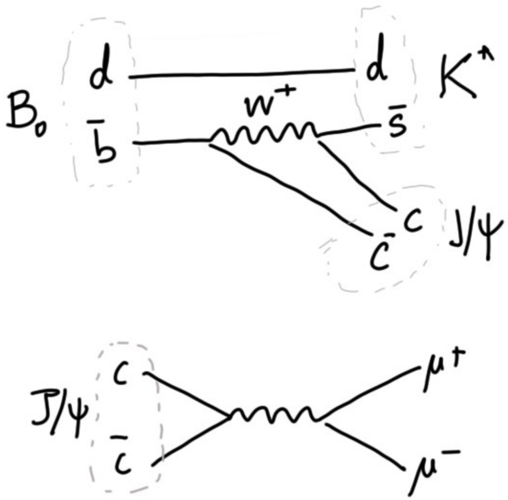



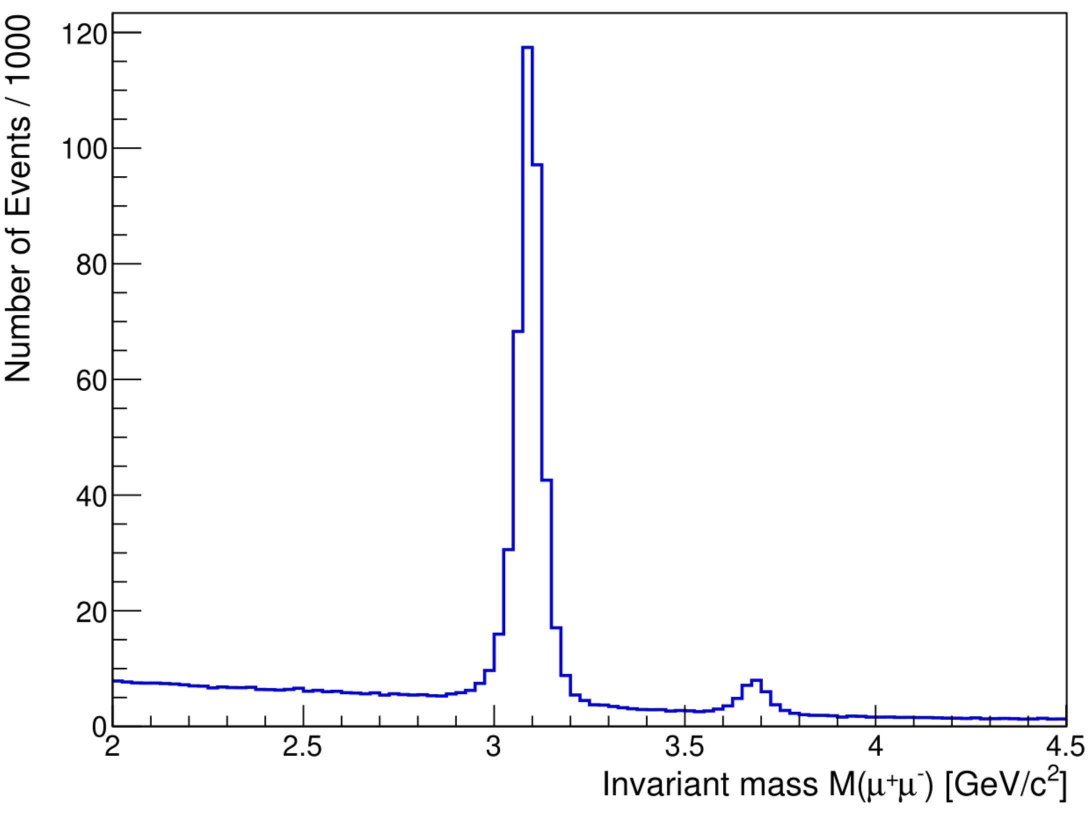

Phys. Lett. B 741 (2015) 12

# Mass

Consider the decay

$B^{\circ} \rightarrow J/\Psi\ \ K^{*}$ with the subsequent decay $J/\Psi \rightarrow \mu^{+}\mu^{-}$



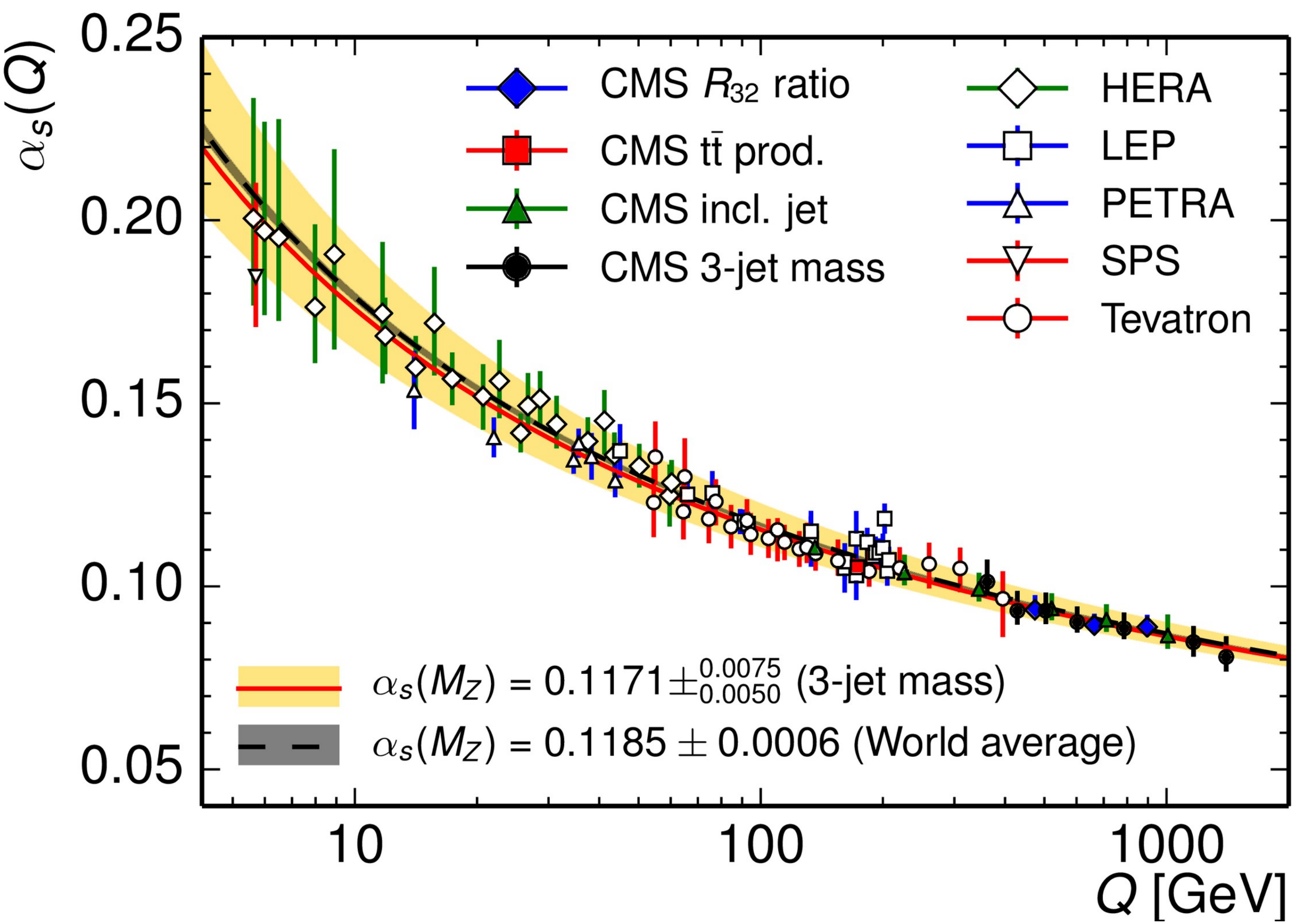

Conservation of 4-momenta tells us that

$p(\mu^{+}) + p(\mu^{-}) = p(J/\Psi)$

Taking the norm on both sides

$|p(\mu^{+}) + p(\mu^{-})| = |p(J/\Psi)| = m(J/\Psi)$

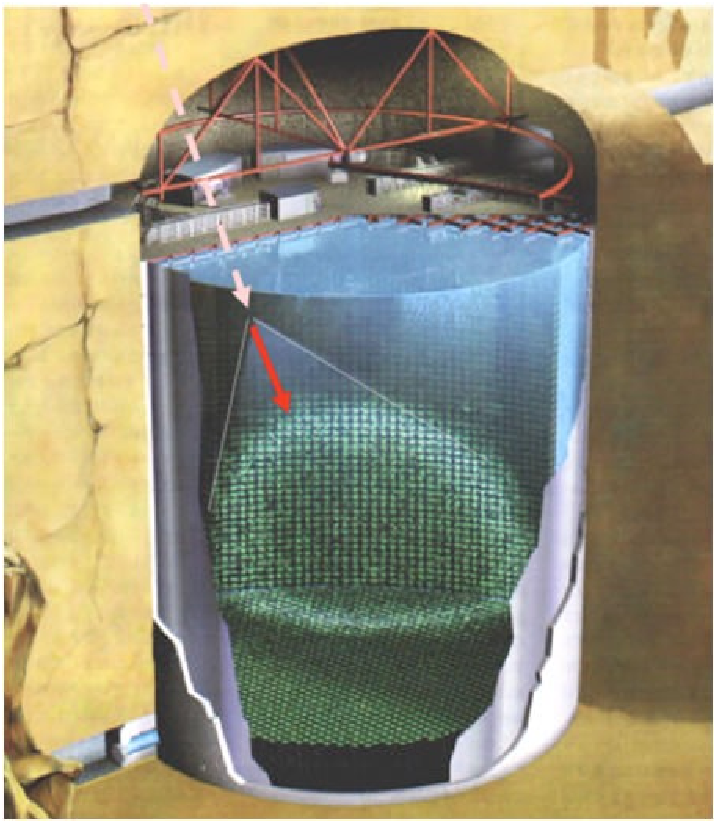
# $\alpha_s$

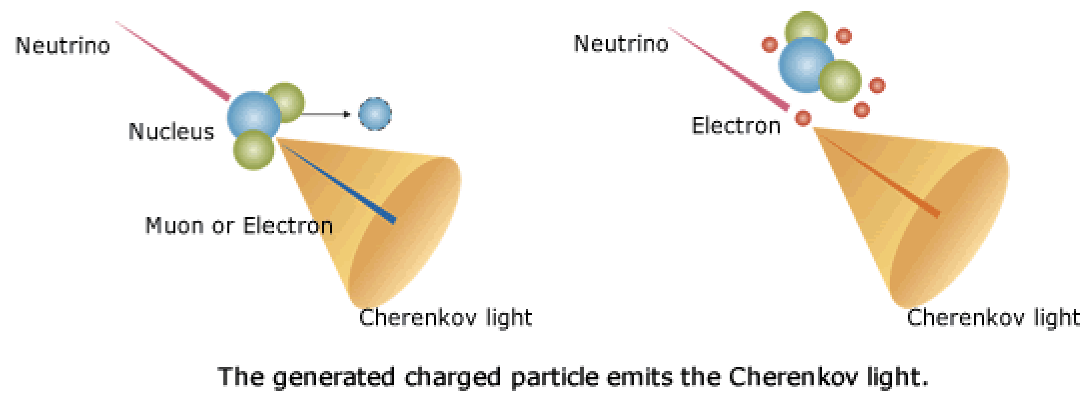



Measurement of the inclusive 3-jet production differential cross section in proton-proton collisions at 7 TeV
and determination of the strong coupling constant in the TeV range Eur. Phys. J. C 75 (2015) 186

# Neutrinos at neutrino detectors

Consider the Super-K experiment
(Super-Kamioka Neutrino Detection Experiment)
Uses 50K tons of ultrapure water and detects Cherenkov light.






Images: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

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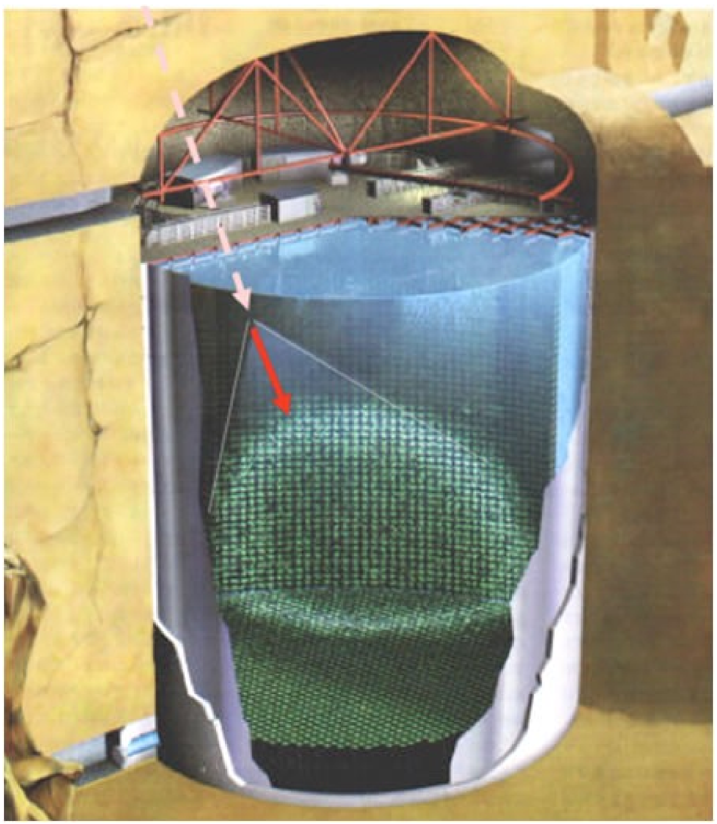
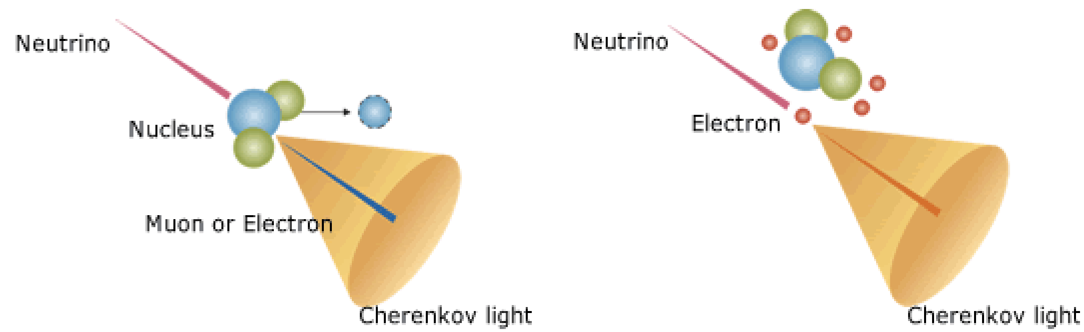
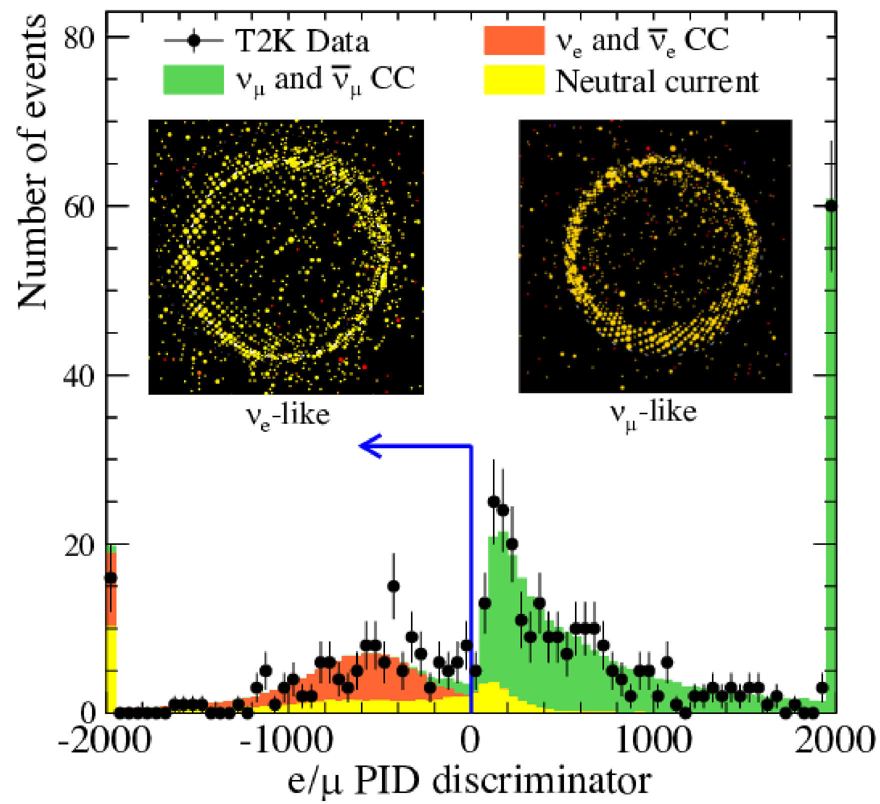





The generated charged particle emits the Cherenkov light.

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Nature 580, 339-344 (2020)

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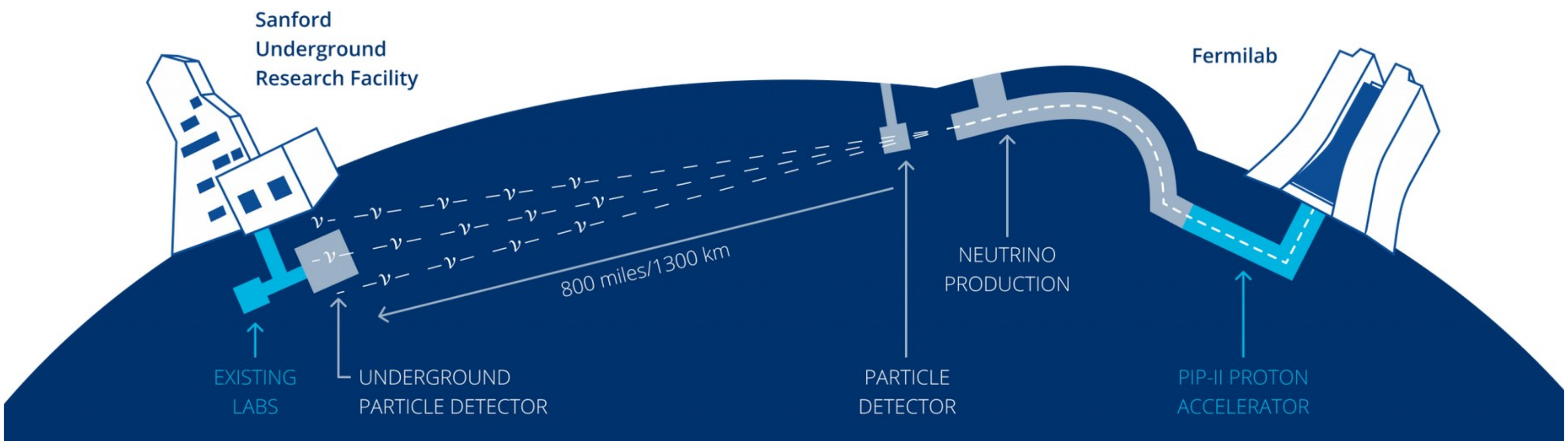
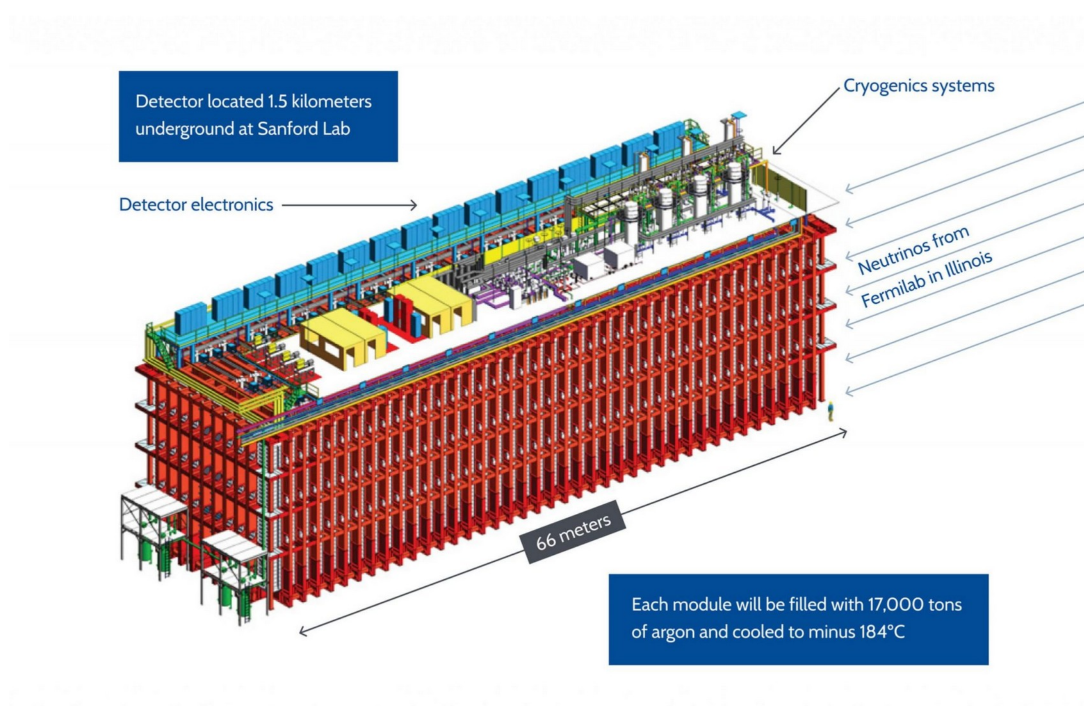



Consider the DUNE experiment
(Deep Underground Neutrino Experiment)
70k tons of Liquid-Argon




https://lbnf-dune.fnal.gov/

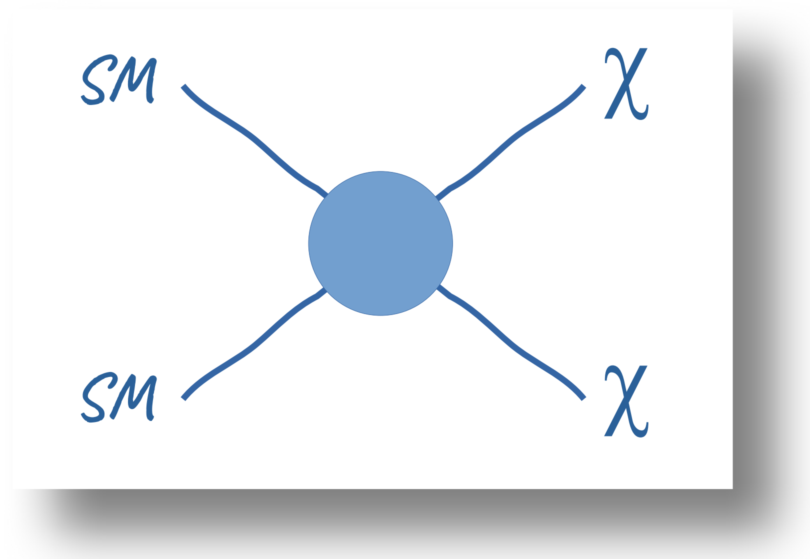
# Dark Matter Searches

Detect dark matter annihilation

Break it

Detect dark matter scattering from regular matter

Shake it




Make it

Produce dark matter in colliders