How and Why to go Beyond the Discovery of the Higgs Boson

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http://hep.uchicago.edu/~johnda/ComptonLectures.html

Lecture Outline

April 1st: **Newton's dream & 20th Century Revolution**

April 8th: **Mission Barely Possible: QM + SR**

April 15th: **The Standard Model**

April 22nd: **Importance of the Higgs**

April 29th: **Guest Lecture**

May 6th: ***The Cannon and the Camera***

May 13th: **The Discovery of the Higgs Boson**

May 20th: **Problems with the Standard Model**

May 27th: **Memorial Day: No Lecture**

June 3rd: **Going beyond the Higgs: What comes next ?**

Reminder: *The Standard Model*

Description fundamental constituents of Universe and their interactions
Triumph of the 20th century
Quantum Field Theory: Combines principles of Q.M. & Relativity

Spin = 1/2

Constituents *(Matter Particles)*

Leptons:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Spin = 1

Interactions Dictated by principles of symmetry

QFT $\Rightarrow$ Particle associated w/each interaction *(Force Carriers)*

$$\gamma \qquad W \qquad Z \qquad g$$

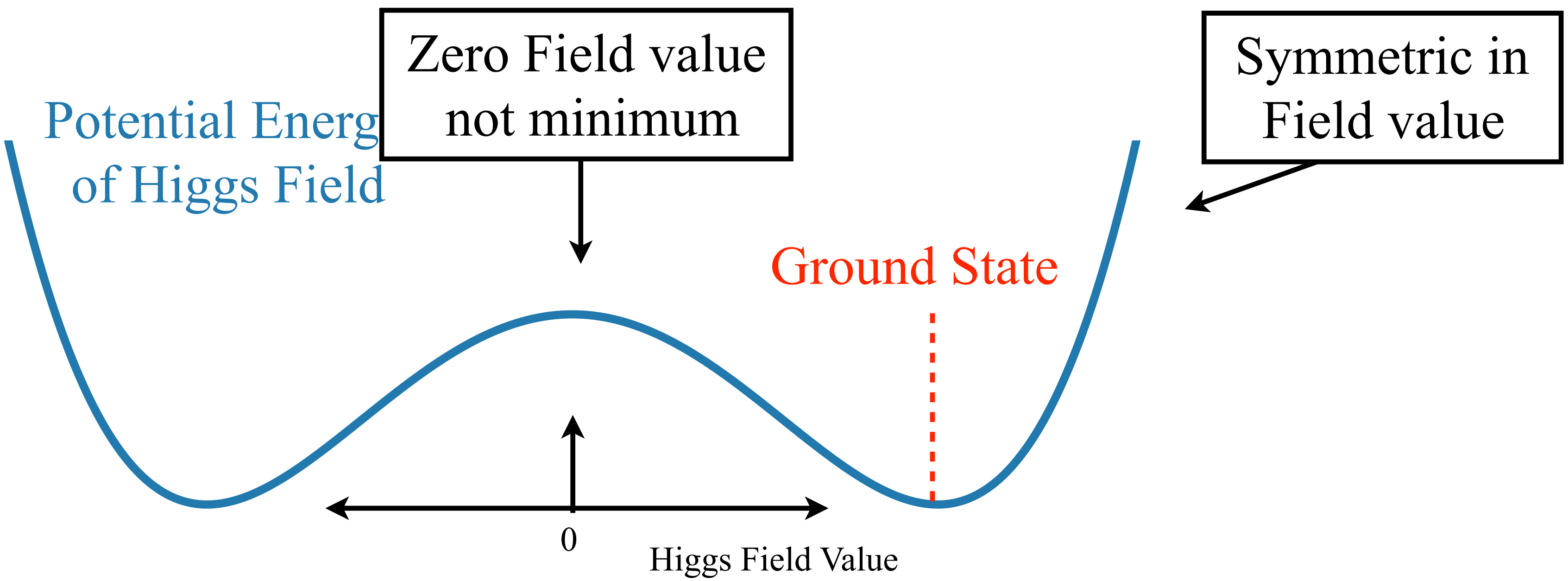
Consistent theory of electromagnetic, weak and strong forces ...

... provided **massless** *Matter* and *Force Carriers*

Serious problem: matter and W, Z carriers have Mass !

Last Time: *The Higgs Feild*

New field (Higgs Field) added to the theory
Allows massive particles while preserve mathematical consistency
Works using trick: "Spontaneously Symmetry Breaking"



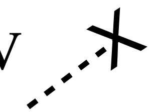
Ground state (vacuum of Universe) filled will Higgs field
 Leads to particle masses: Energy cost to displace Higgs Field / $E=mc_2$
Additional particle predicted by the theory.

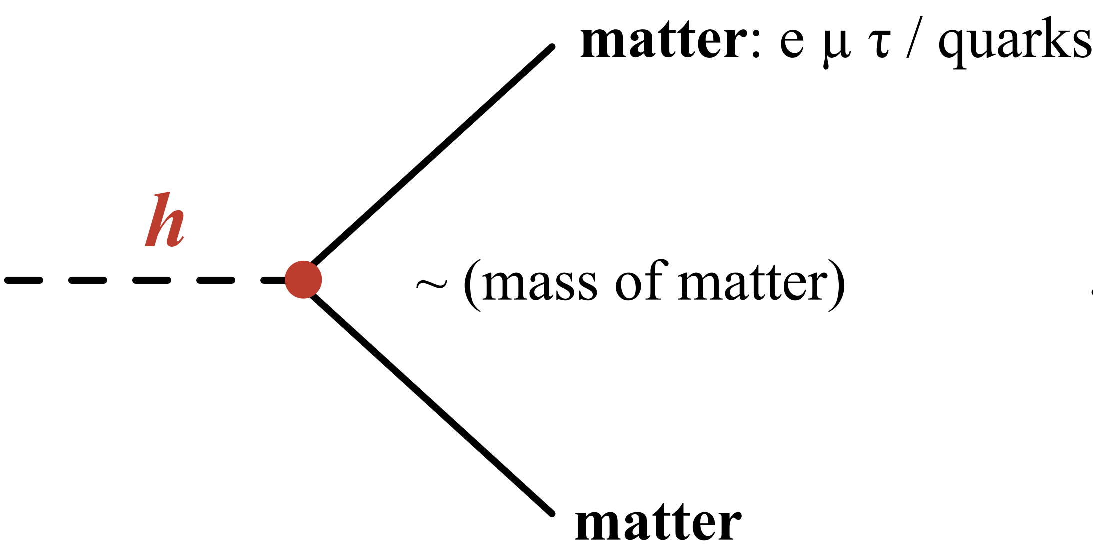
<u>Higgs boson:</u> H **Spin = 0**

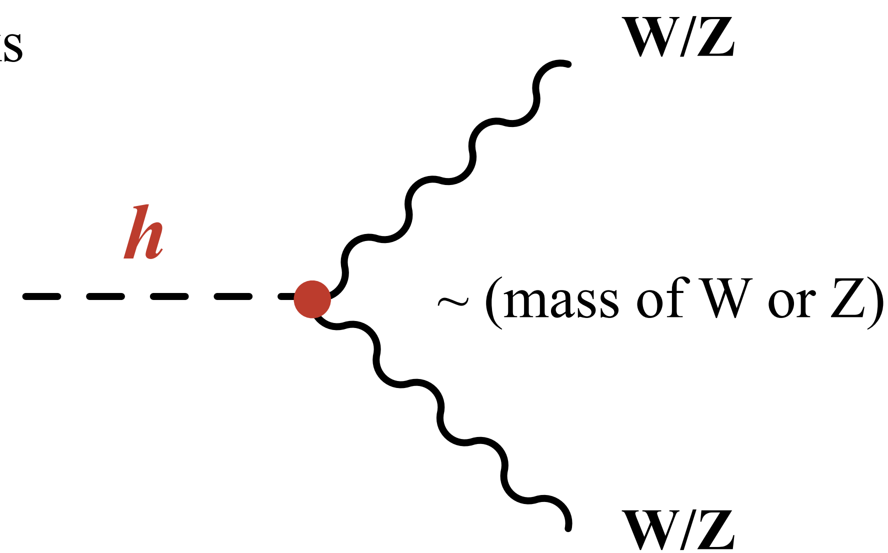
Last Time: *The Higgs Boson*

What do we know about the Higgs Particle: ***A Lot***

Higgs is excitations of v-condensate

$\Rightarrow$ Couples to matter / W/Z just like v 





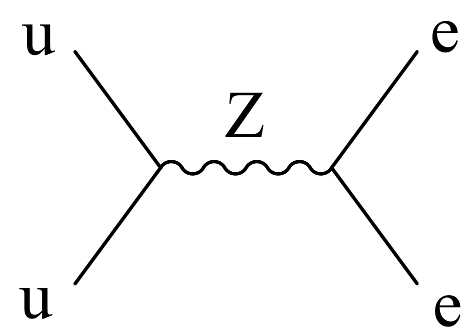
Spin: 0 ~~1/2~~ ~~1~~ ~~3/2~~ ~~2~~

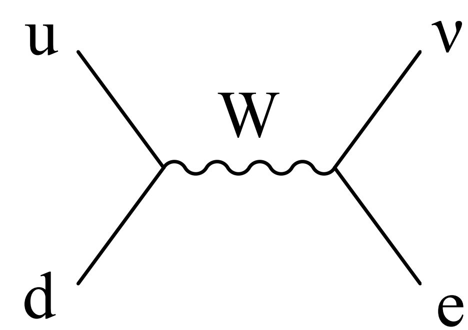
Only thing we don't (*didn't!*) know is the value of mH

History of Prediction and Discovery

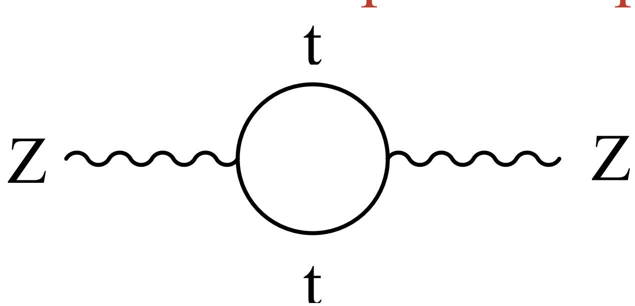
Late 60s: Standard Model takes modern form. Predicts massive W/Z bosons

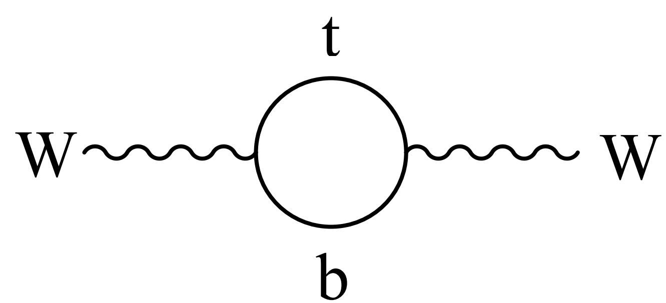
1983: W/Z discovered at CERN:





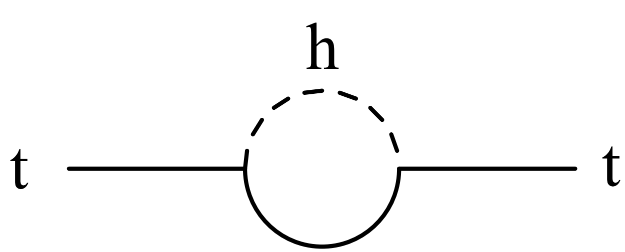
Early 90s: W/Z used to predict top mass

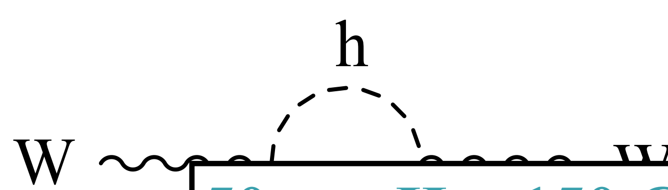




1995: top quark discovered at fermilab

2000s: W/top quark and used to predict the higgs:



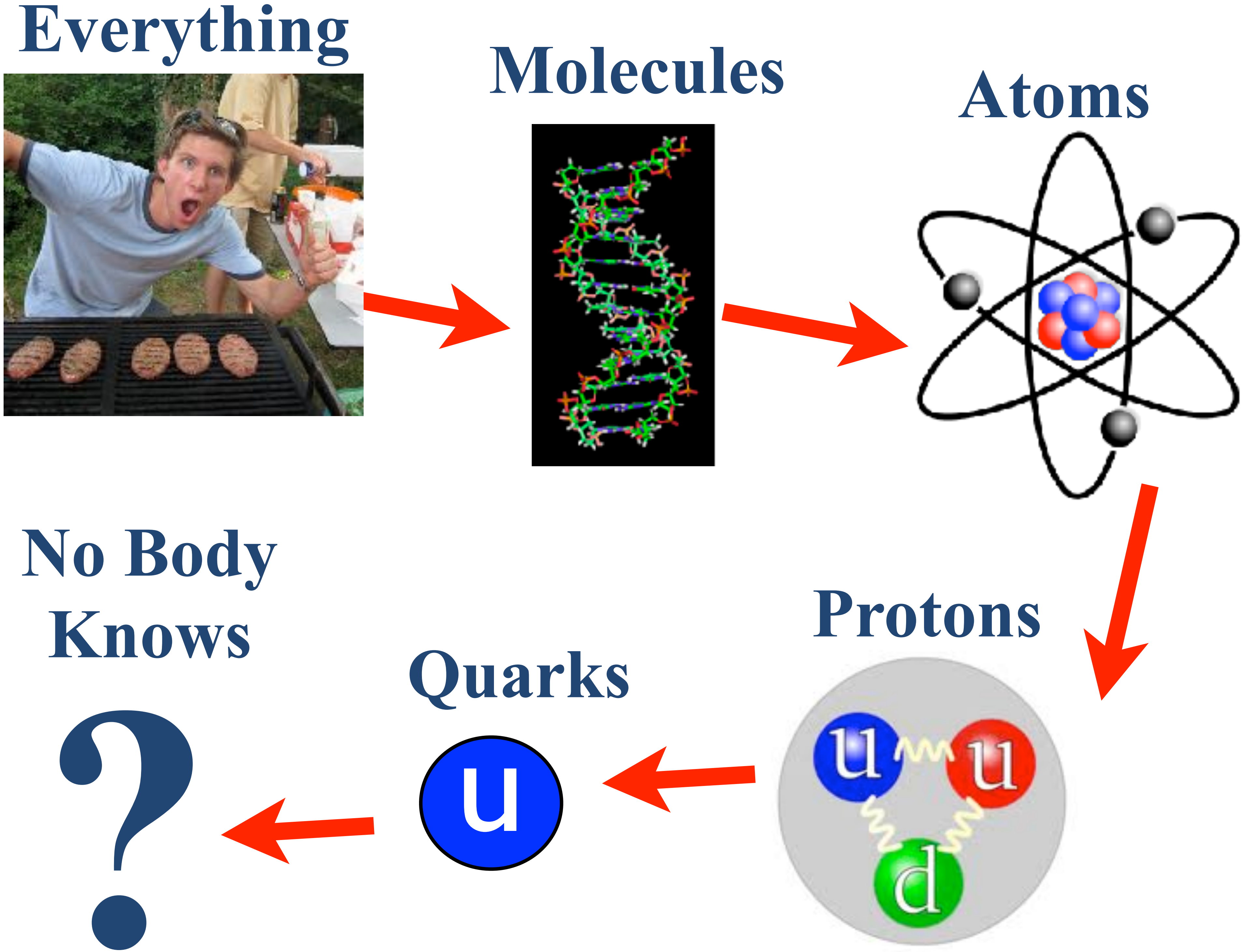


50 < mH < 150 GeV (95%)

Today’s Lecture

The Cannon and the Camera

Particle Physics for 3rd Graders


Everything
Molecules
Atoms
Protons
u
u
d
Quarks
u
No Body
Knows
?

What's in the Lunch Box ?

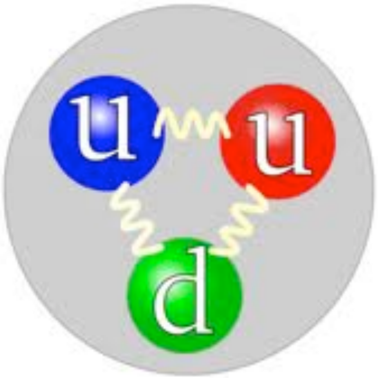
Look inside.

No Fun!

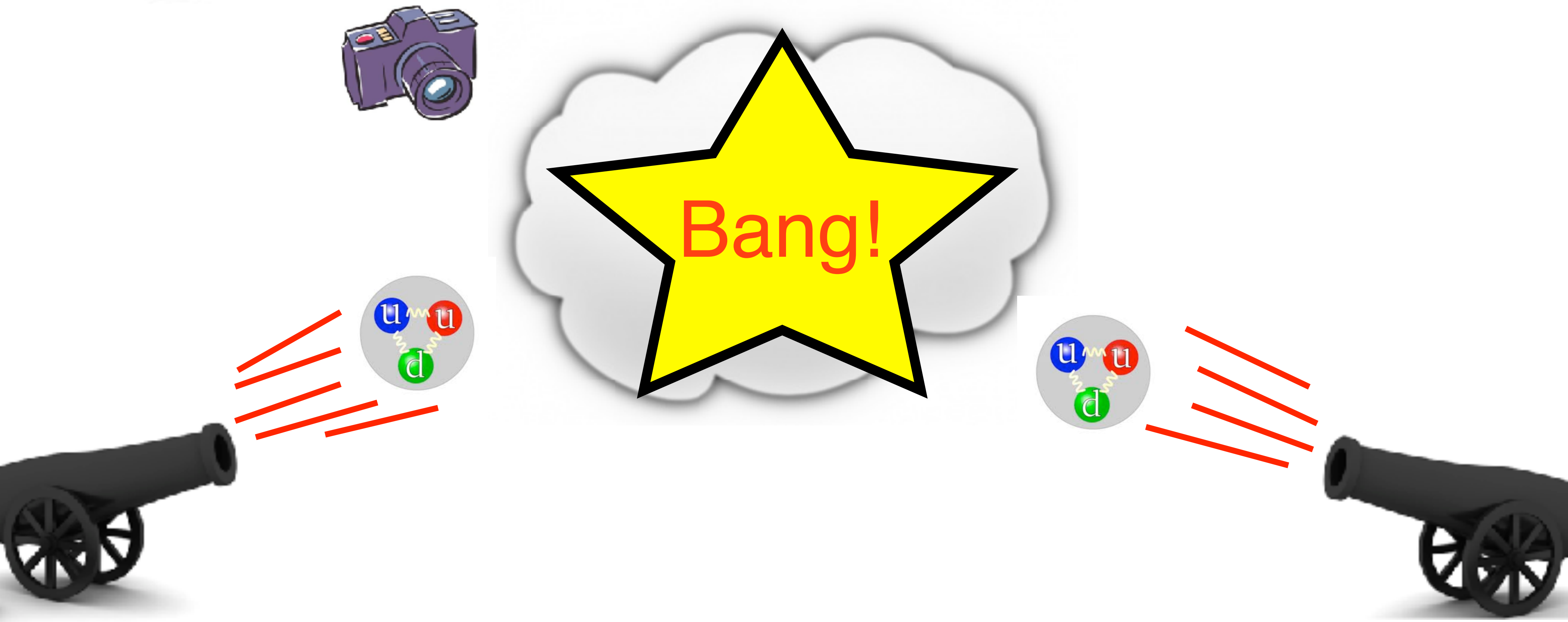
What's in the Lunch Box ?

What's in the Proton ?

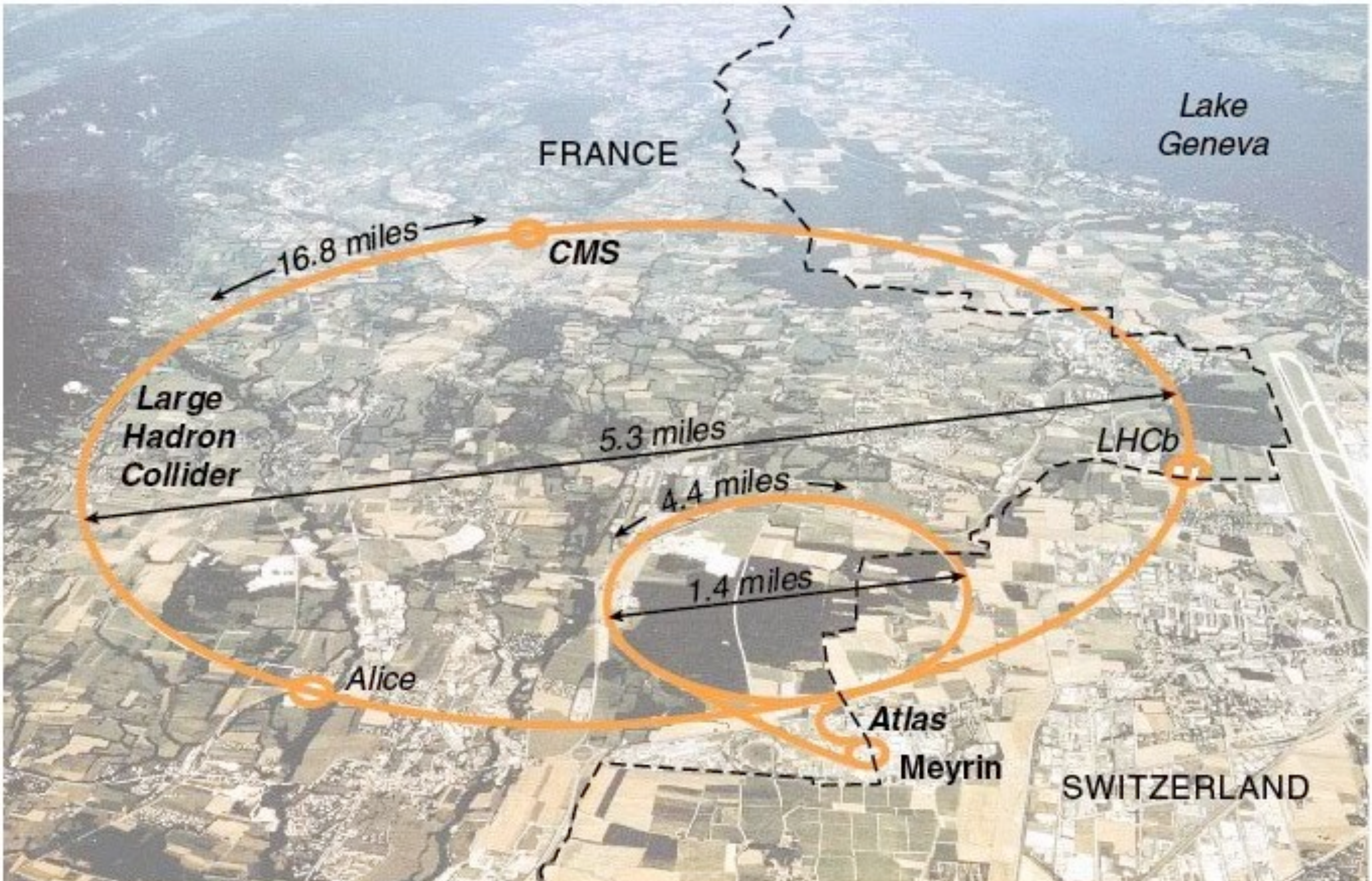
Protons are Too
small to look inside.



SMASH THEM!!!



The Worlds Biggest Cannon



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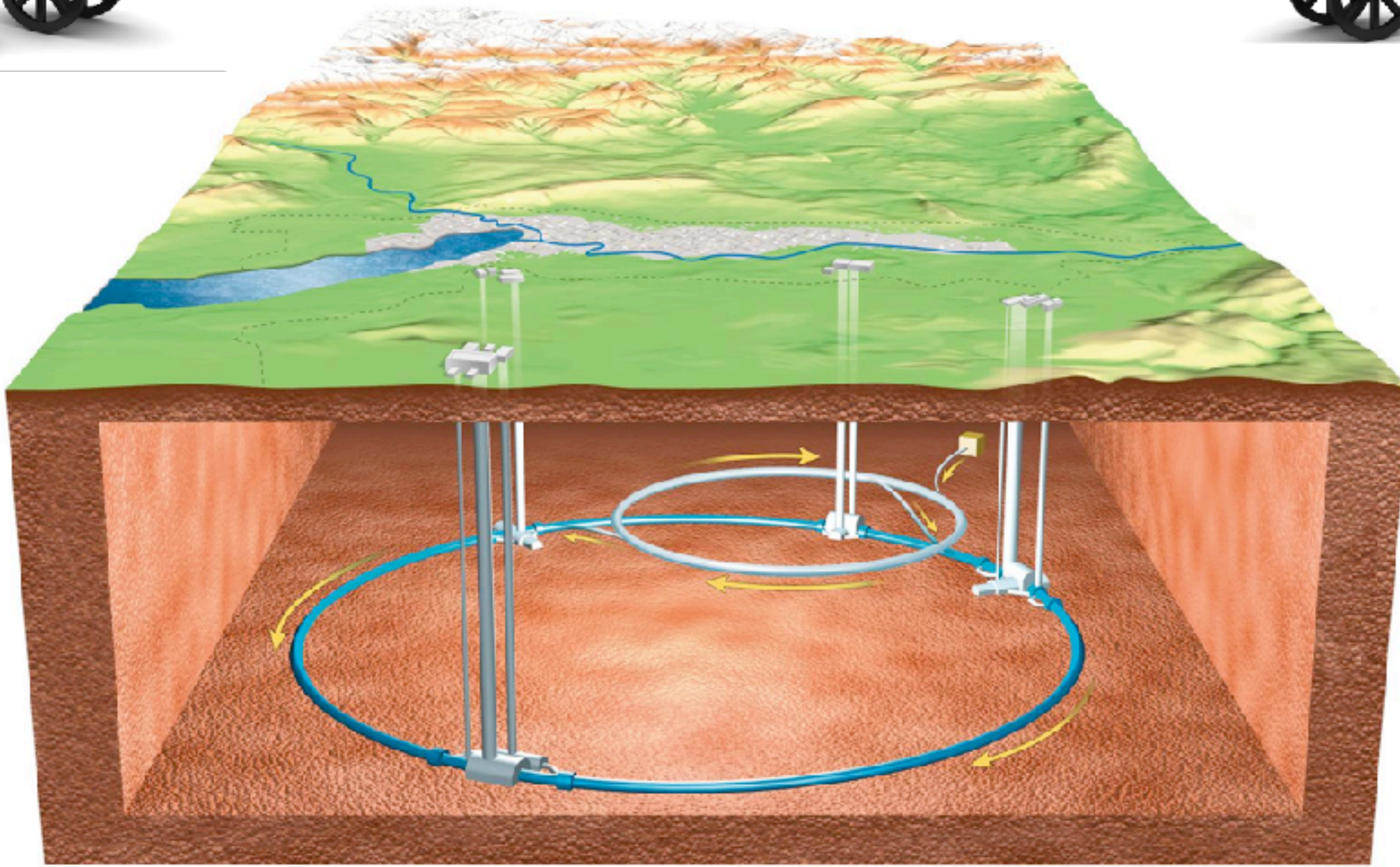
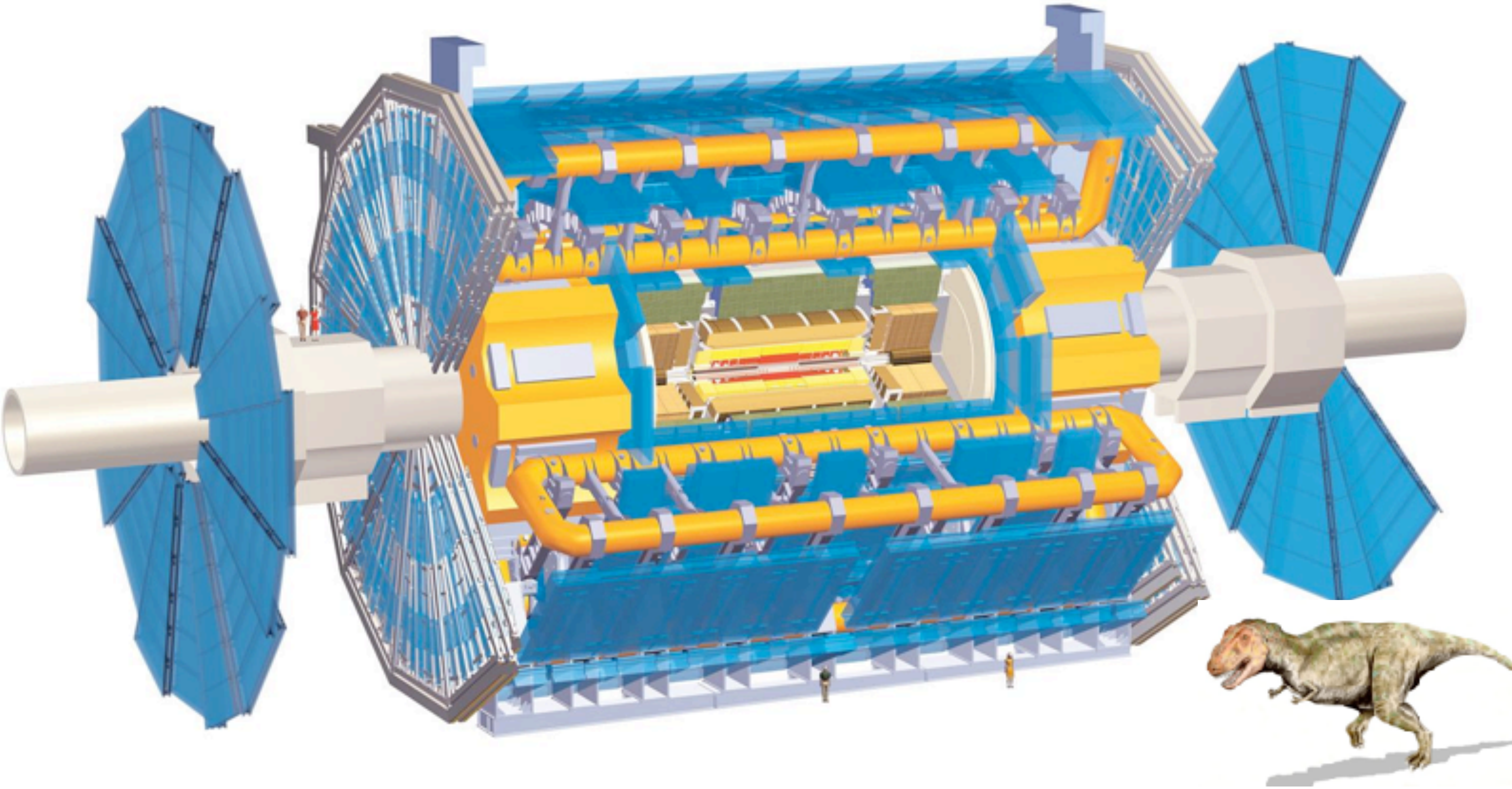


Really Big Camera!!!



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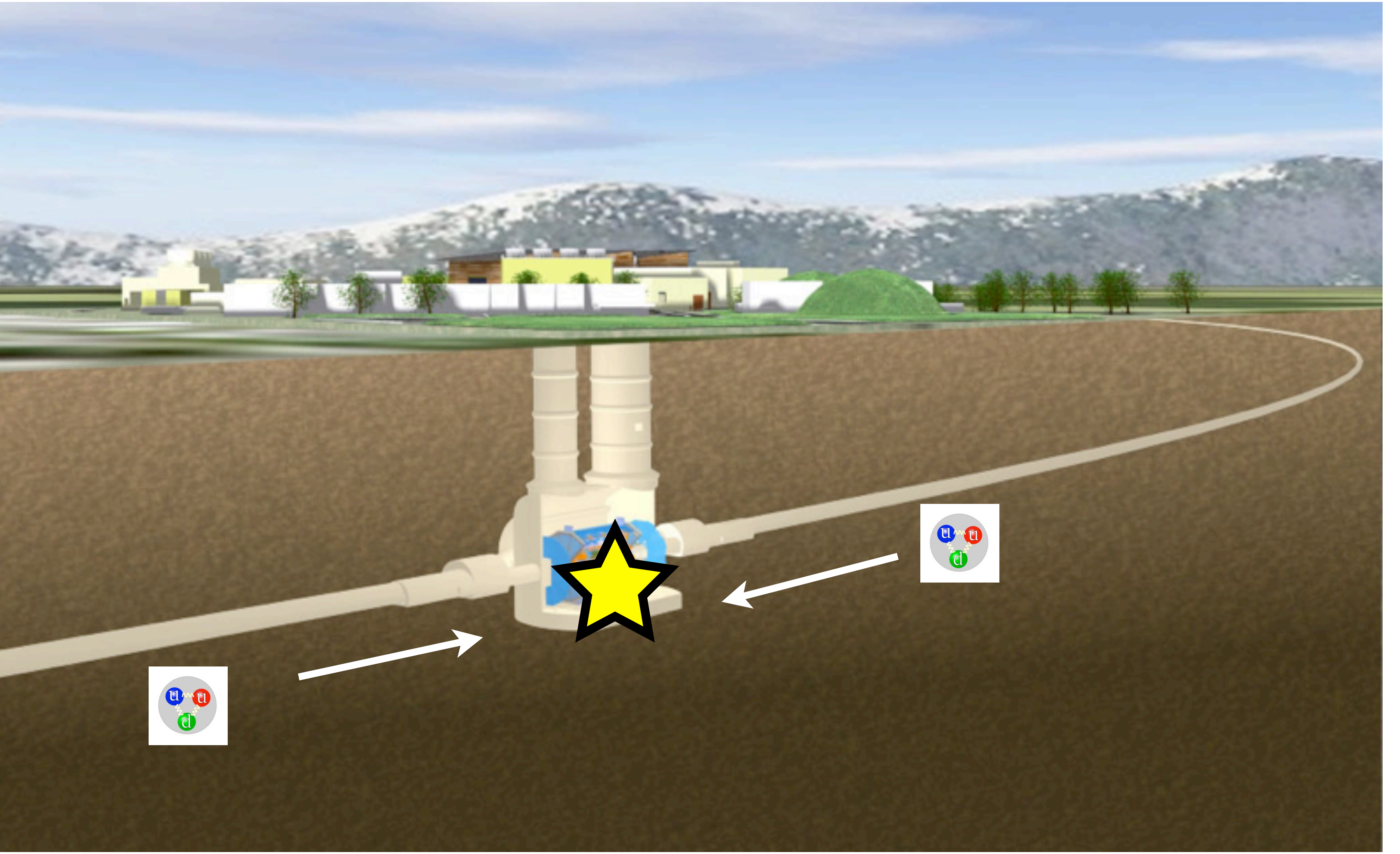
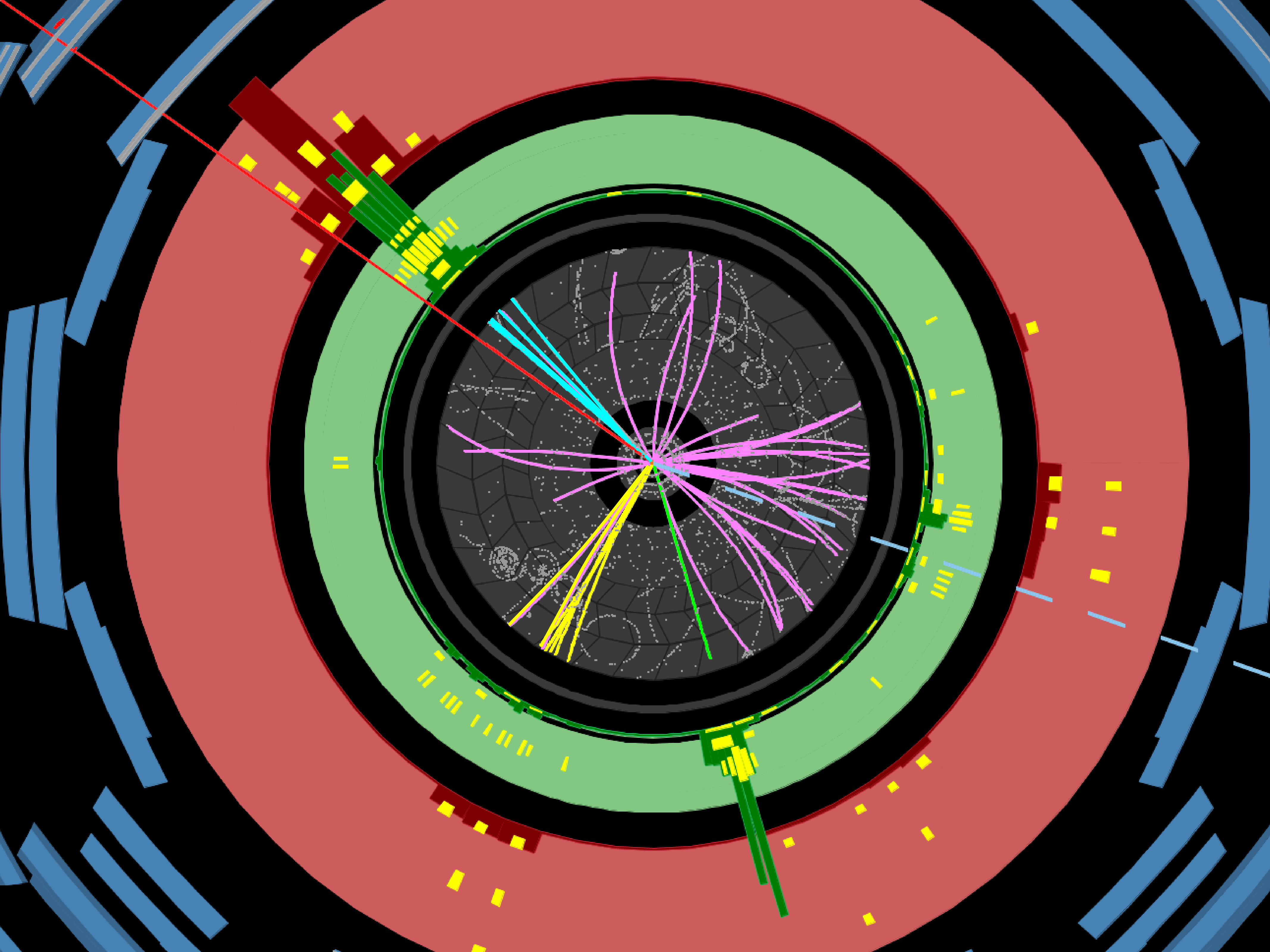




3rd Grade Explanation is Essentially Correct

Some Caveats:

- More sophisticated analog to "what are quarks made of ?"
- What comes out of the lunch box is there to begin with…

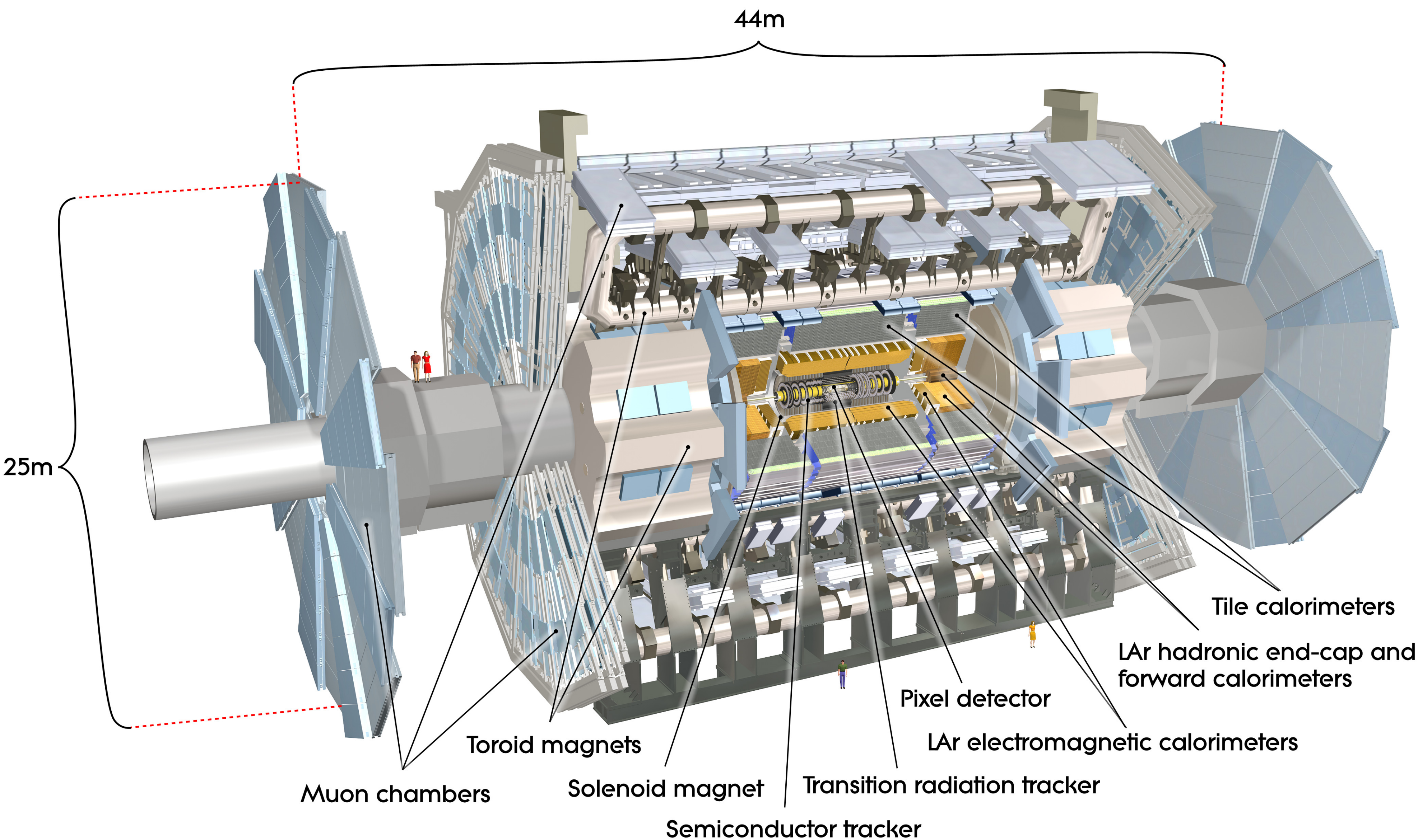
However, basic concepts/methods something that anyone understands

One of the great things about this business !

Rest of lecture:

- Refine basic notions of camera and cannon
- Discuss challenges in collecting/analyzing pictures
- Talk about how we use picture to compare to test SM

A Toroidal LHC ApparatuS



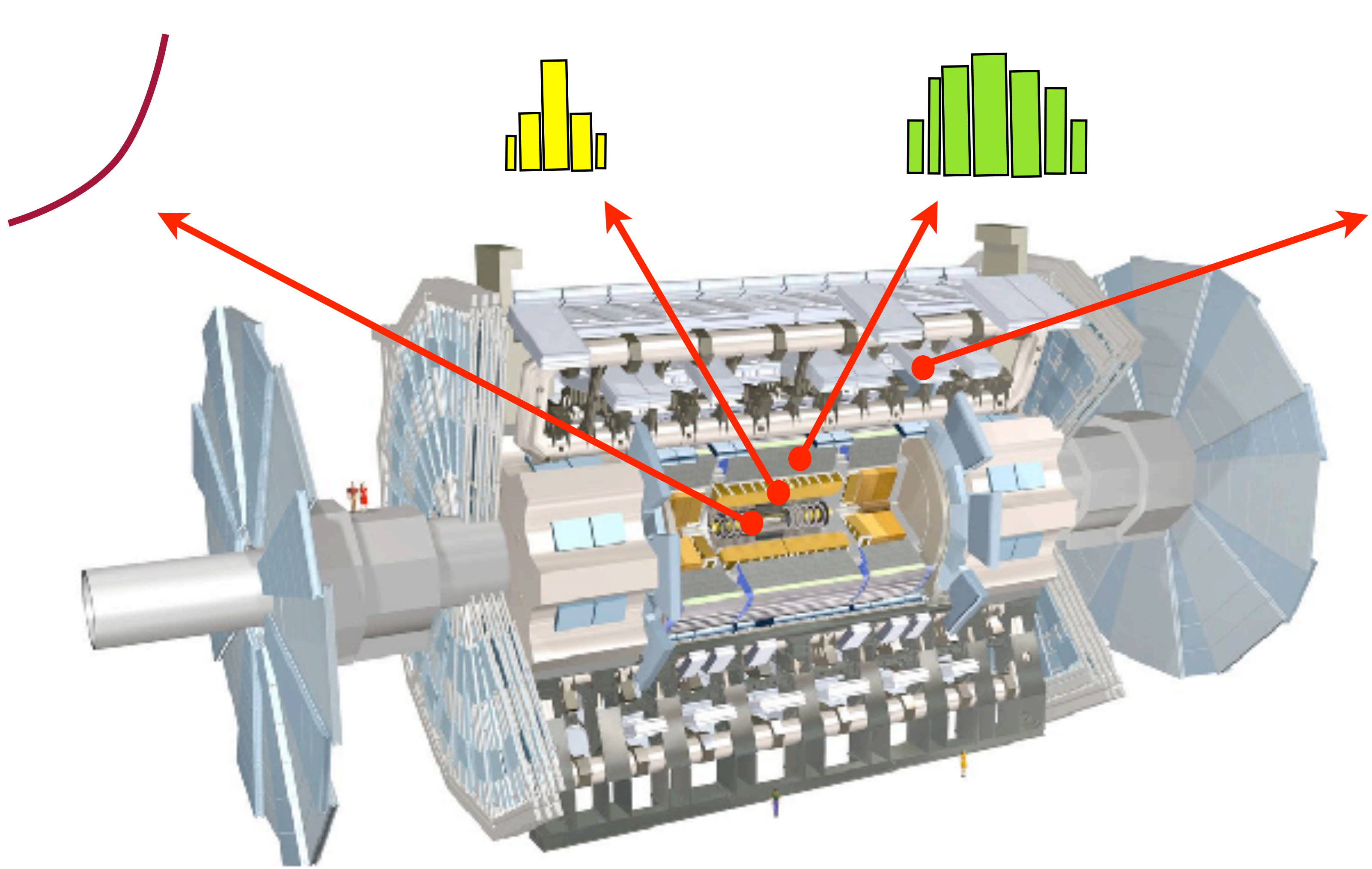
The Basic Outputs:

Inner Tracking System

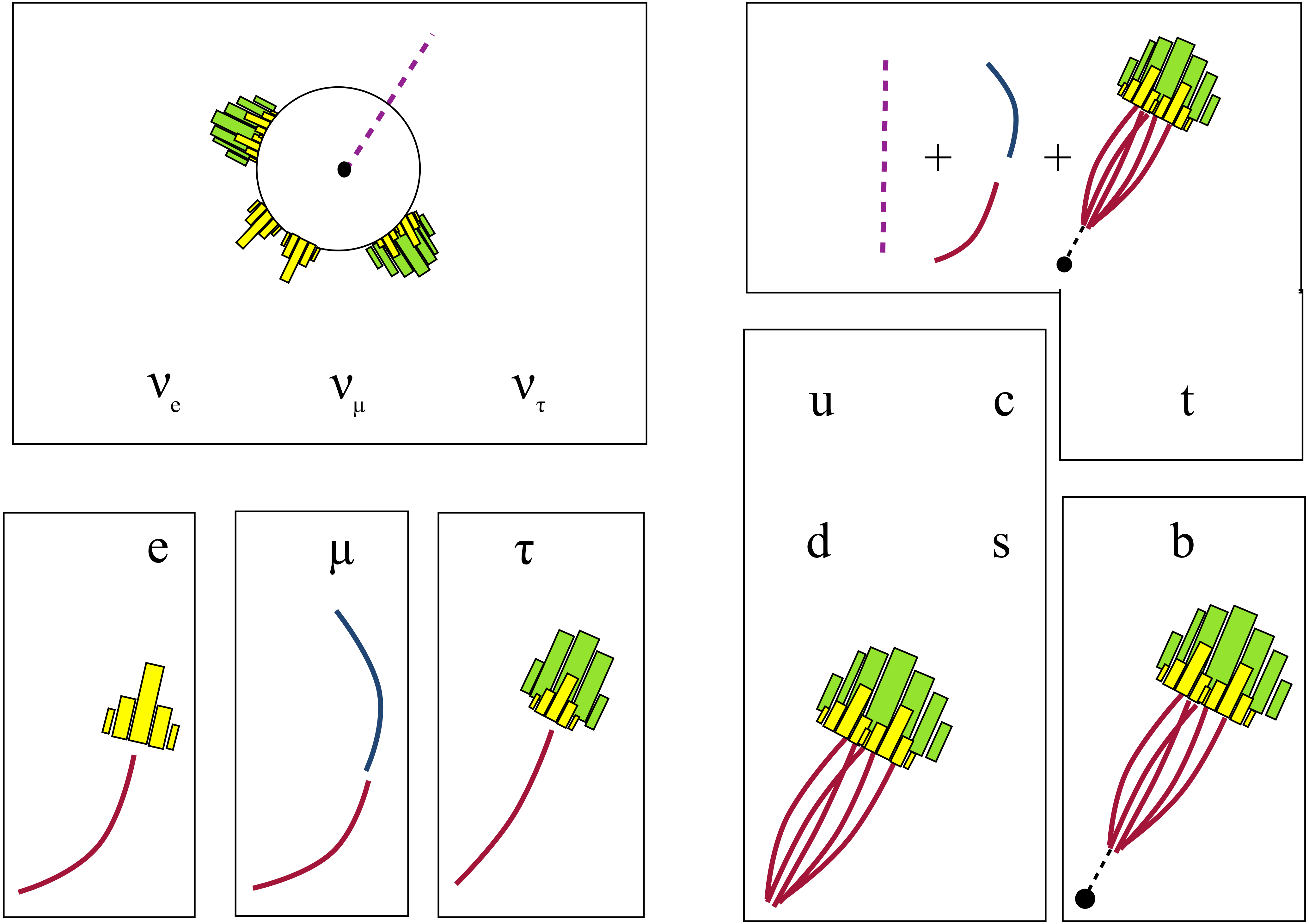
Electro-Magnetic Calorimeter

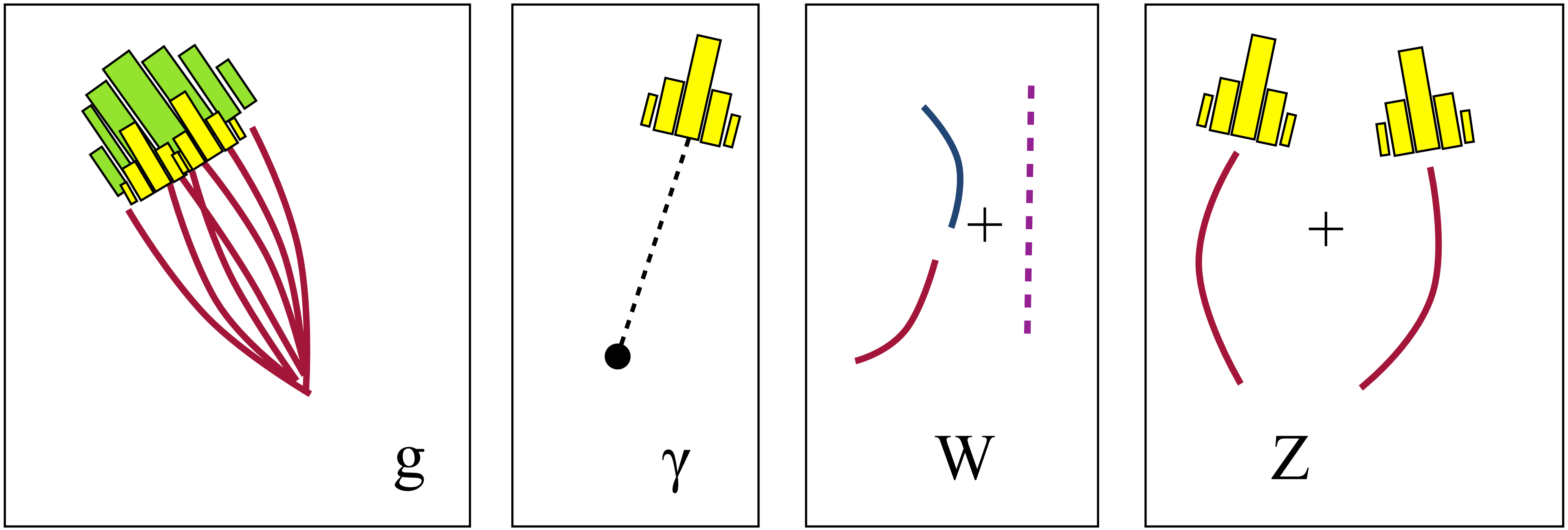
Hadronic Calorimeter

Muon Tracking System



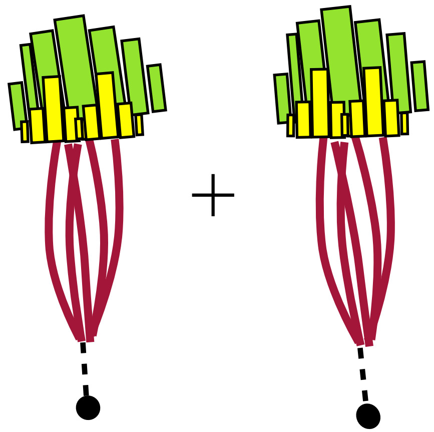
A lot of work goes into making/understanding these basic outputs.


ν_e
ν_μ
ν_τ
u
c
t
d
s
b
e
μ
τ

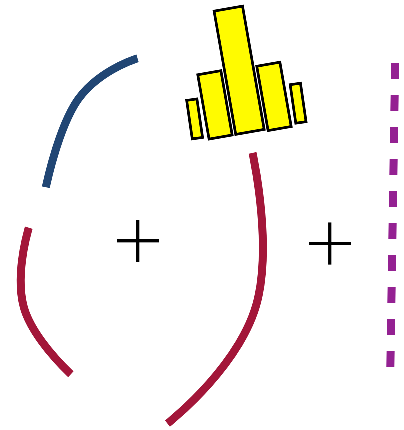

g
γ
+
W
+
Z

Higgs decays

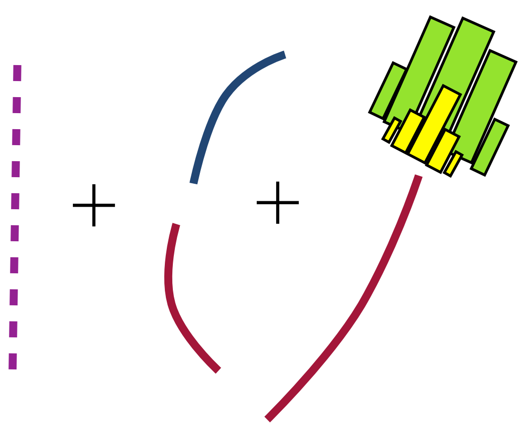
$H \rightarrow bb$: **~60%**



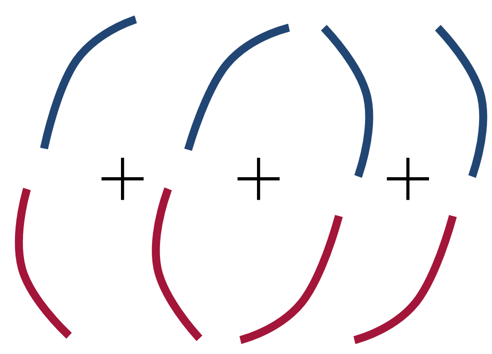
$H \rightarrow WW$: ~20%



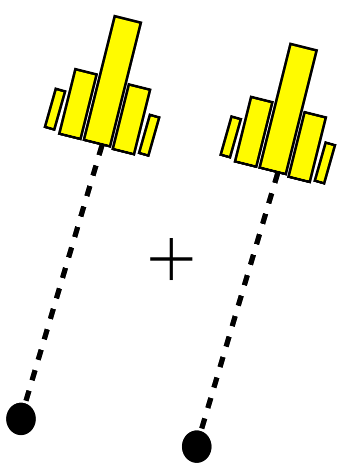
$H \rightarrow \tau\tau$: ~5%

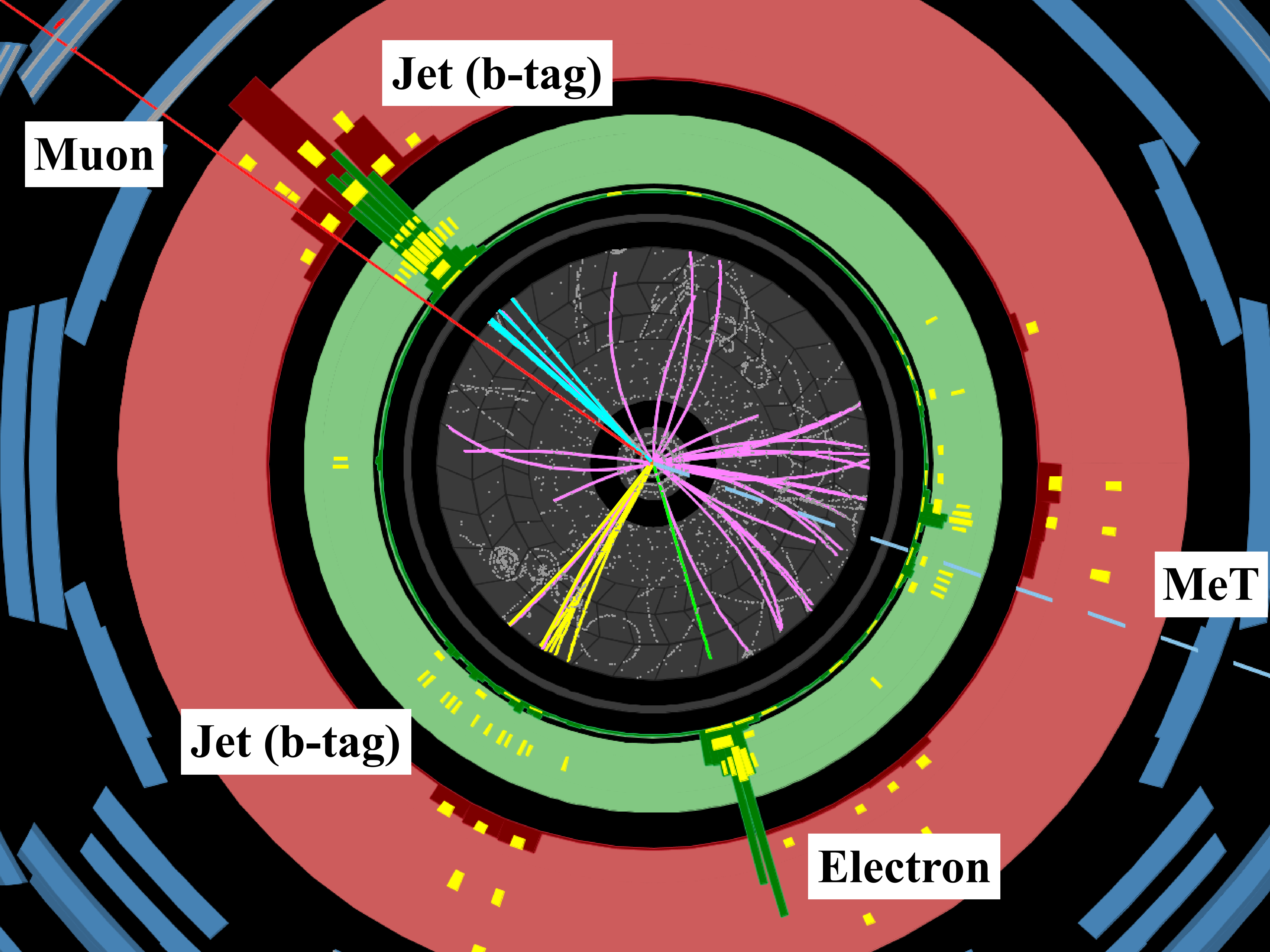


$H \rightarrow ZZ$: ~2%



$H \rightarrow \gamma\gamma$: 0.2%





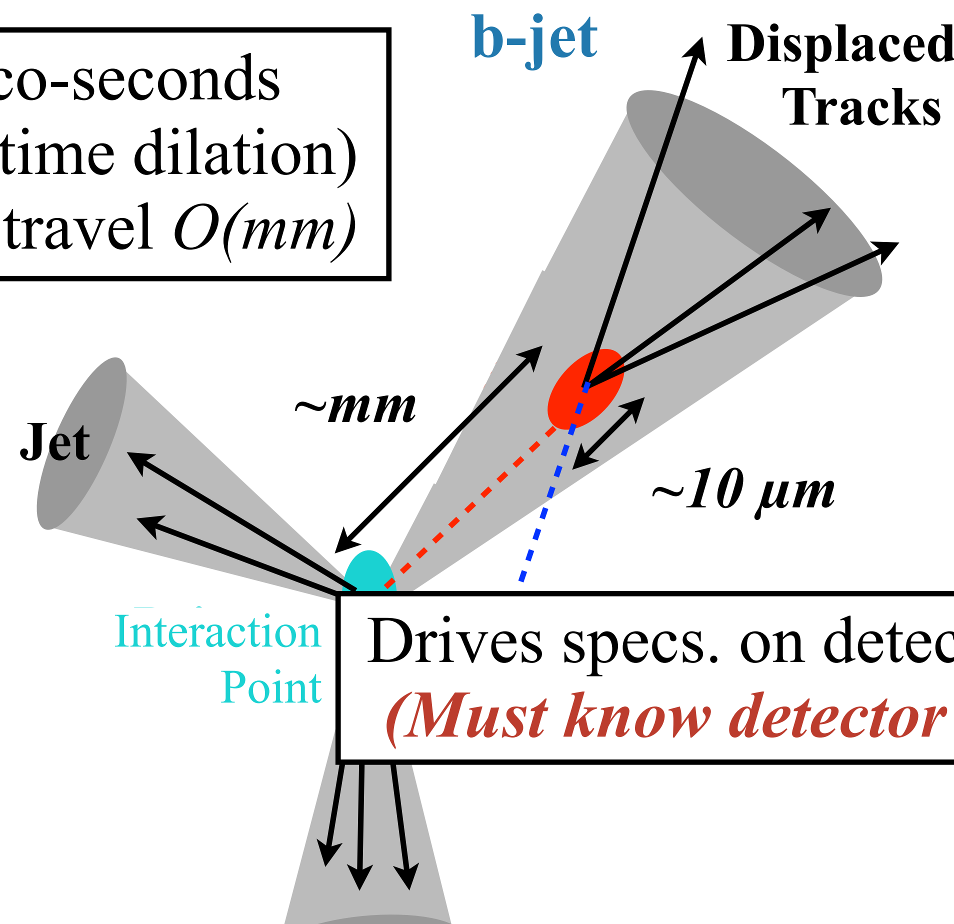
Jet (b-tag)
Muon
MeT
Jet (b-tag)
Electron

Experimental Challenges

b-jet Identification *(b-Tagging)*

Critical as b-jet ubiquitous in Higgs final states.

- b-lifetimes ~pico-seconds
- Typical speed (time dilation) ⇒ travel *O(mm)*



Drives specs. on detector resolution
(Must know detector positions to ~μm)

Detectors size apartment buildings, measure to accuracy of something barely visible to human eye. ***Major cost driver***

Triggering

- LHC provides orders of magnitude more collisions than can save to disk
    - Can only keep 1 out of 40,000 events / Discarded data lost forever
- Interesting physics is incredibly rare.
    ~1 Higgs per billion events

Triggering:
Process of selecting which collisions to save for further analysis.

Triggering in ATLAS:

- Custom Electronics + Commodity CPU
- Fast processing of images (micro-seconds / seconds)
- Events rate from 40 MHz → 1kHz.
- Data rate from 80 TBs **(!)** → 2 GB/s

Another major cost driver

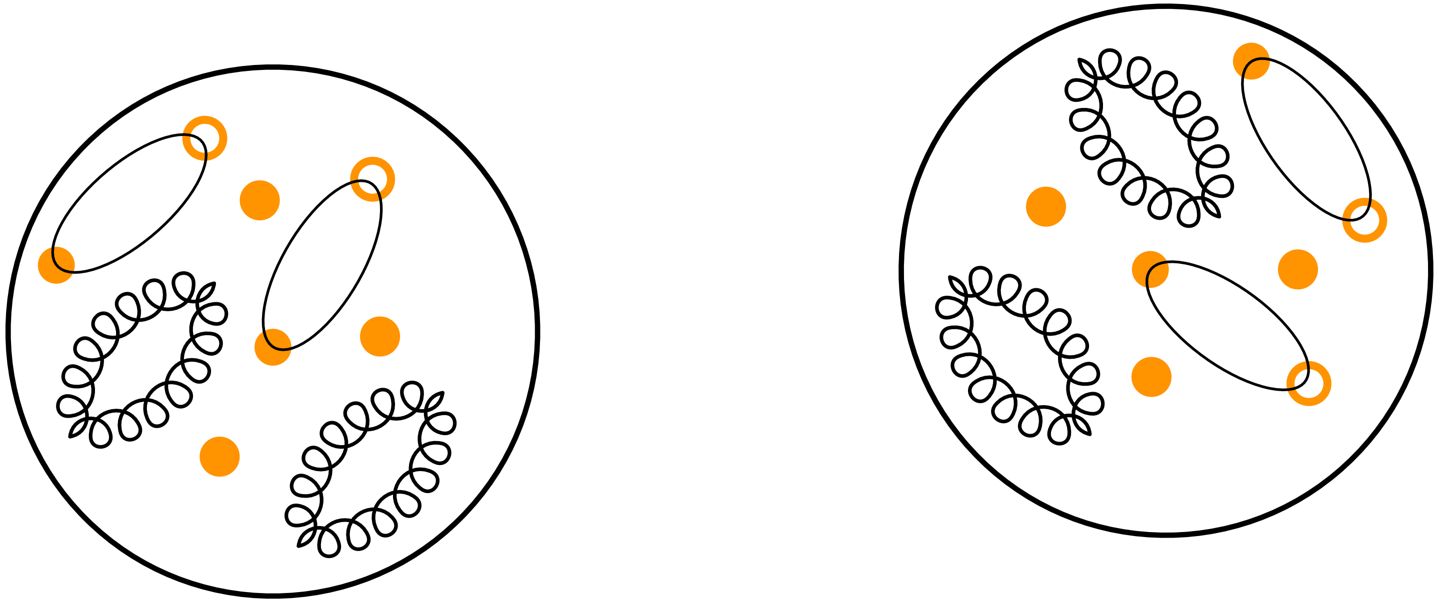
The Cannon

Most of the time protons miss one another:

Cant aim with enough precision to ensure a direct hit each time

Need to collide bunches of tightly packed protons to ensure hit

LHC: 10^11 protons per bunch



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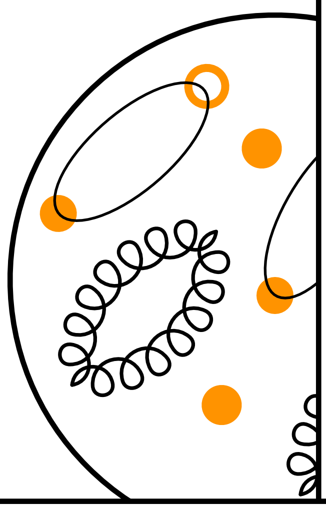
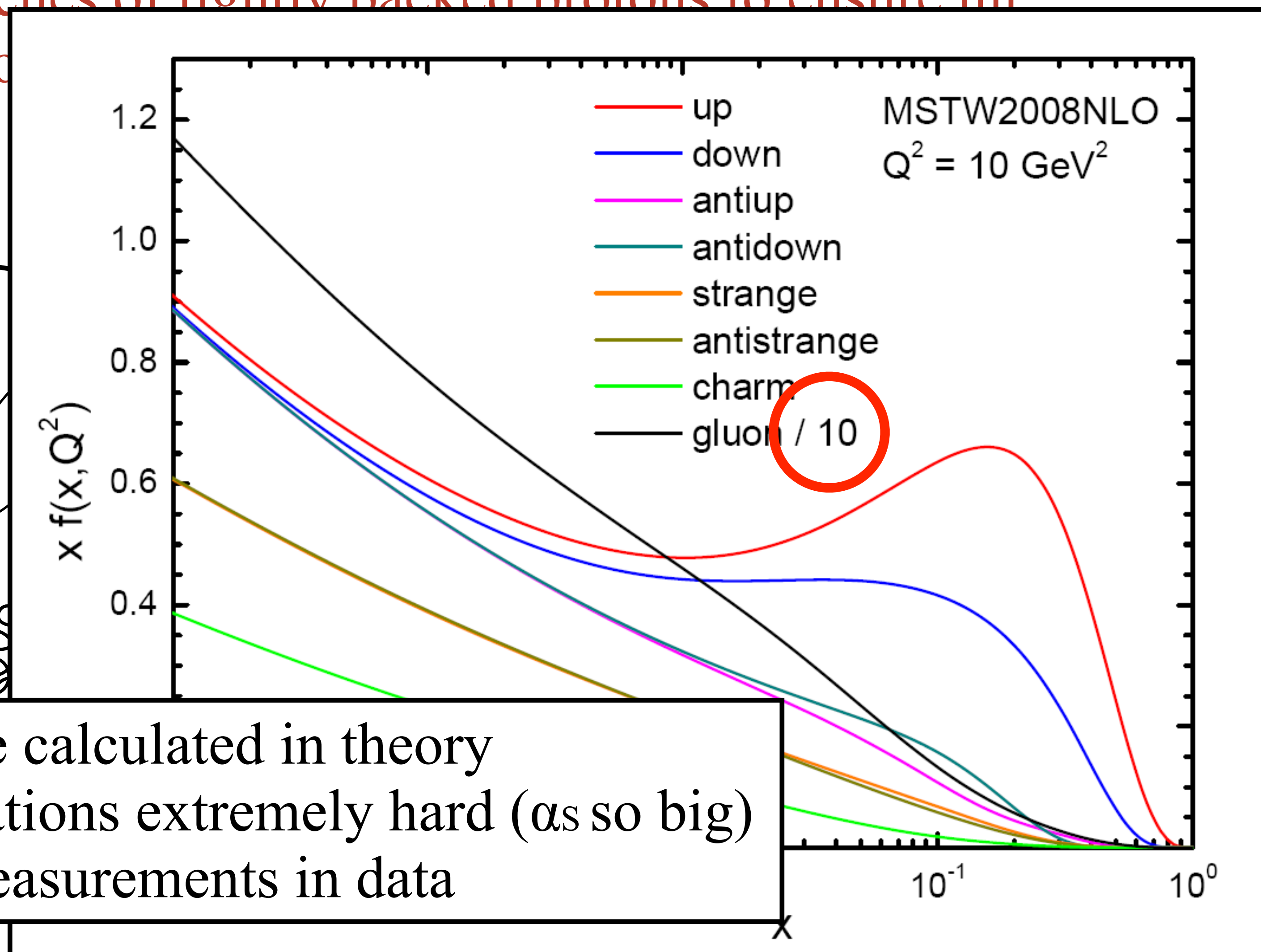




Can in principle be calculated in theory

In practice, calculations extremely hard (α_S so big)

So extract from measurements in data

What We Measure

Probability for process to happen given in terms of an area: *Cross-section*

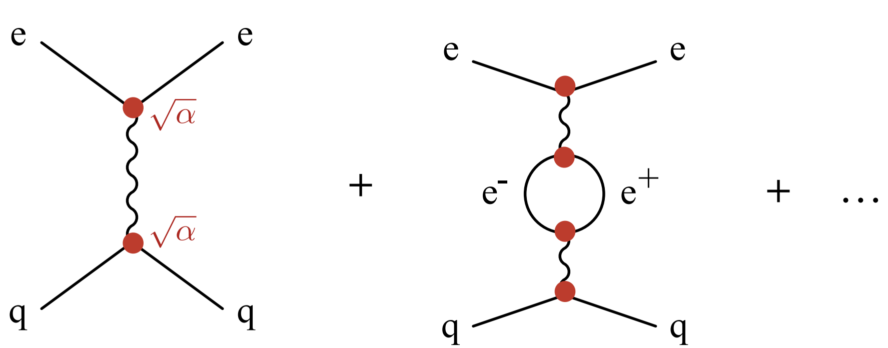
Event Rate = Cross-Section × Particle Flux

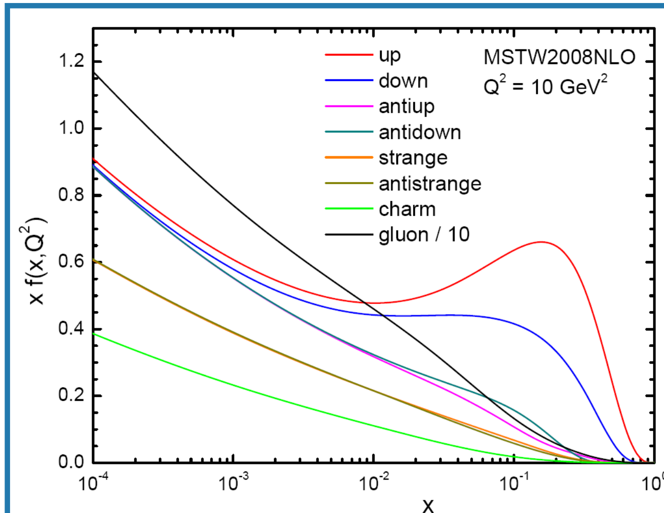
- Rate certain pictures (Directly measured) → Event Rate
- Infer "Cross Section" Units area / Probability → Cross-Section
- Known input from LHC Protons /area / time → Particle Flux

Cross-Section (σ) can be calculated from theory

$$\sigma \sim \int |\psi(x_1, x_2)|^2 f(x_1) f(x_2)$$

$\psi =$





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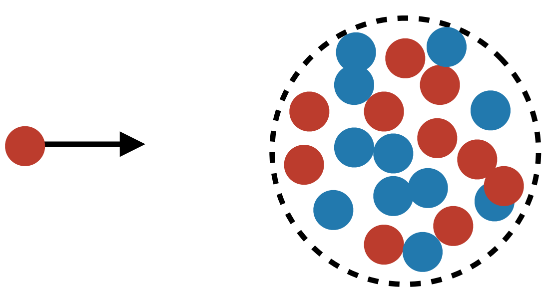
Protons /area / time

<u>Cross-Section (σ) can be calculated from theory</u>

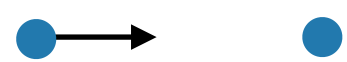
$$\sigma \sim \int |\psi(x_1, x_2)|^2 f(x_1) f(x_2)$$

Quote σ (areas) in funny units: *barns*

1 barn = cross section for neutron to interact with Uranium *(E. Fermi)*



238 (n+p)



σ(n,U(238)) ~ 1 barn ~ (238)^2/3 × σ(p,p)

σ(p,p) ~ 0.03 barn (30 milli-barn) ~ GeV^-2

What We Measure

Count pictures ("*Events*")

Compare events selected w/particular signature to prediction from theory

SM Prediction:

$$N^{\text{Signal}}_{\text{Events}} = \sigma \times \mathcal{L}$$

Probability of process to happen (SM calculation) → σ

Size of the dataset (Total number of events) → $\mathcal{L}$

Measurement:

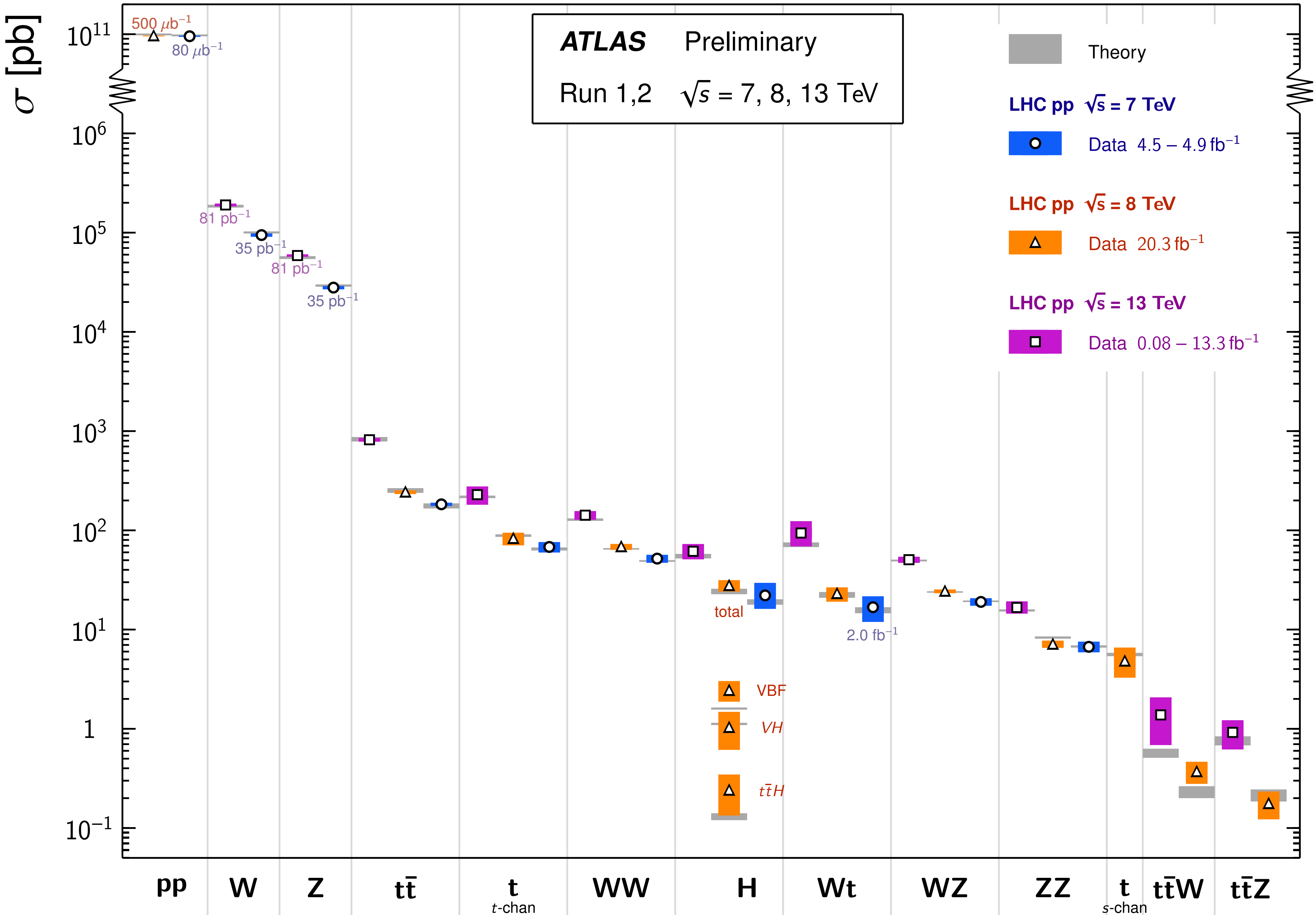
$$N^{\text{Observed}}_{\text{Events}} = N^{\text{Signal}}_{\text{Events}} + N^{\text{Background}}_{\text{Events}}$$

Report measured probabilities σ "*cross sections*" / Compare directly to theory

$$\sigma_{\text{Measured}} = \frac{N^{\text{Observed}}_{\text{Events}} - N^{\text{Background}}_{\text{Events}}}{\mathcal{L}}$$

Standard Model Total Production Cross Section Measurements

Status: August 2016

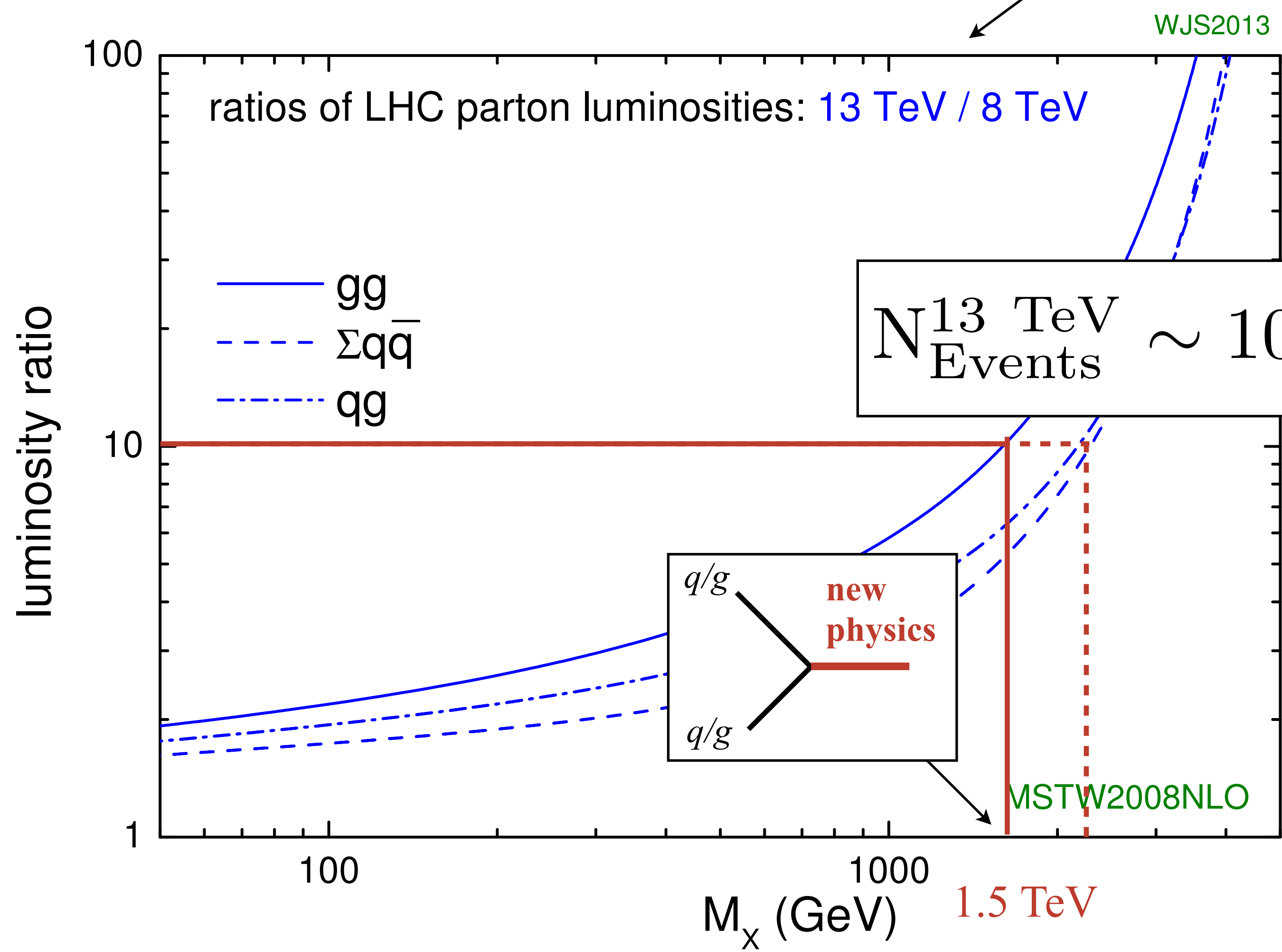


Advantage of Higher Energy

$$N_{\text{Events}} = \sigma \times \mathcal{L}$$

$$\frac{N_{\text{Events}}^{13\ \text{TeV}}}{N_{\text{Events}}^{8\ \text{TeV}}} = \frac{\sigma^{13\ \text{TeV}}}{\sigma^{8\ \text{TeV}}} \times \frac{\mathcal{L}^{13\ \text{TeV}}}{\mathcal{L}^{8\ \text{TeV}}}$$

Now ~ 10
(linear w/dataset size)



$$N_{\text{Events}}^{13\ \text{TeV}} \sim 100 \times N_{\text{Events}}^{8\ \text{TeV}}$$

Advantage of Higher Energy

$$\mathrm{N}_{\mathrm{Events}} = \sigma \times \mathcal{L}$$

$$\frac{\mathrm{N}^{13\ \mathrm{TeV}}_{\mathrm{Events}}}{\mathrm{N}^{8\ \mathrm{TeV}}_{\mathrm{Events}}} = \frac{\sigma^{13\ \mathrm{TeV}}}{\sigma^{8\ \mathrm{TeV}}} \times \frac{\mathcal{L}^{13\ \mathrm{TeV}}}{\mathcal{L}^{8\ \mathrm{TeV}}}$$

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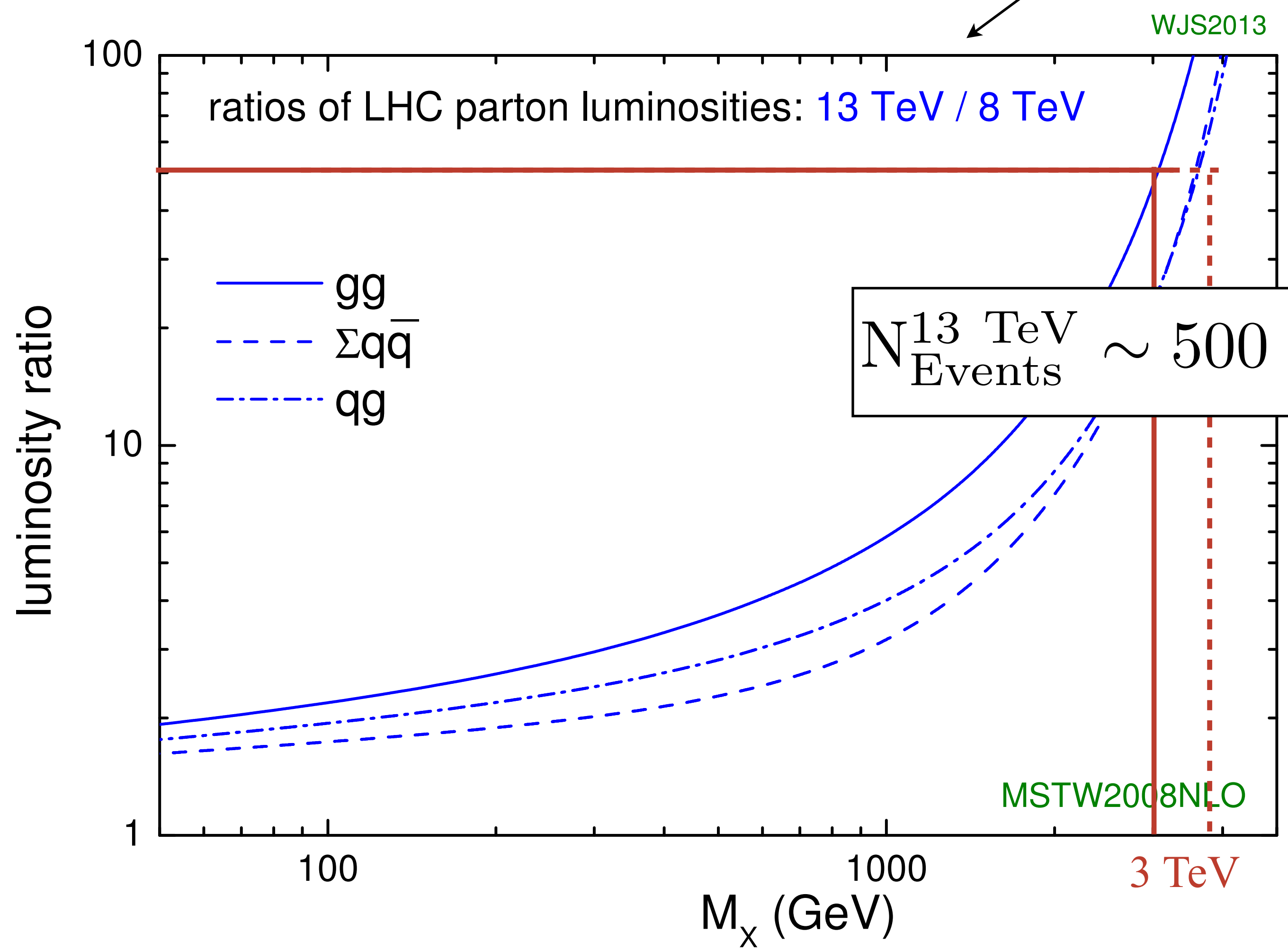
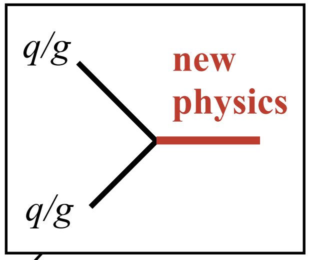


$$\mathrm{N}^{13\ \mathrm{TeV}}_{\mathrm{Events}} \sim 500 \times \mathrm{N}^{8\ \mathrm{TeV}}_{\mathrm{Events}}$$



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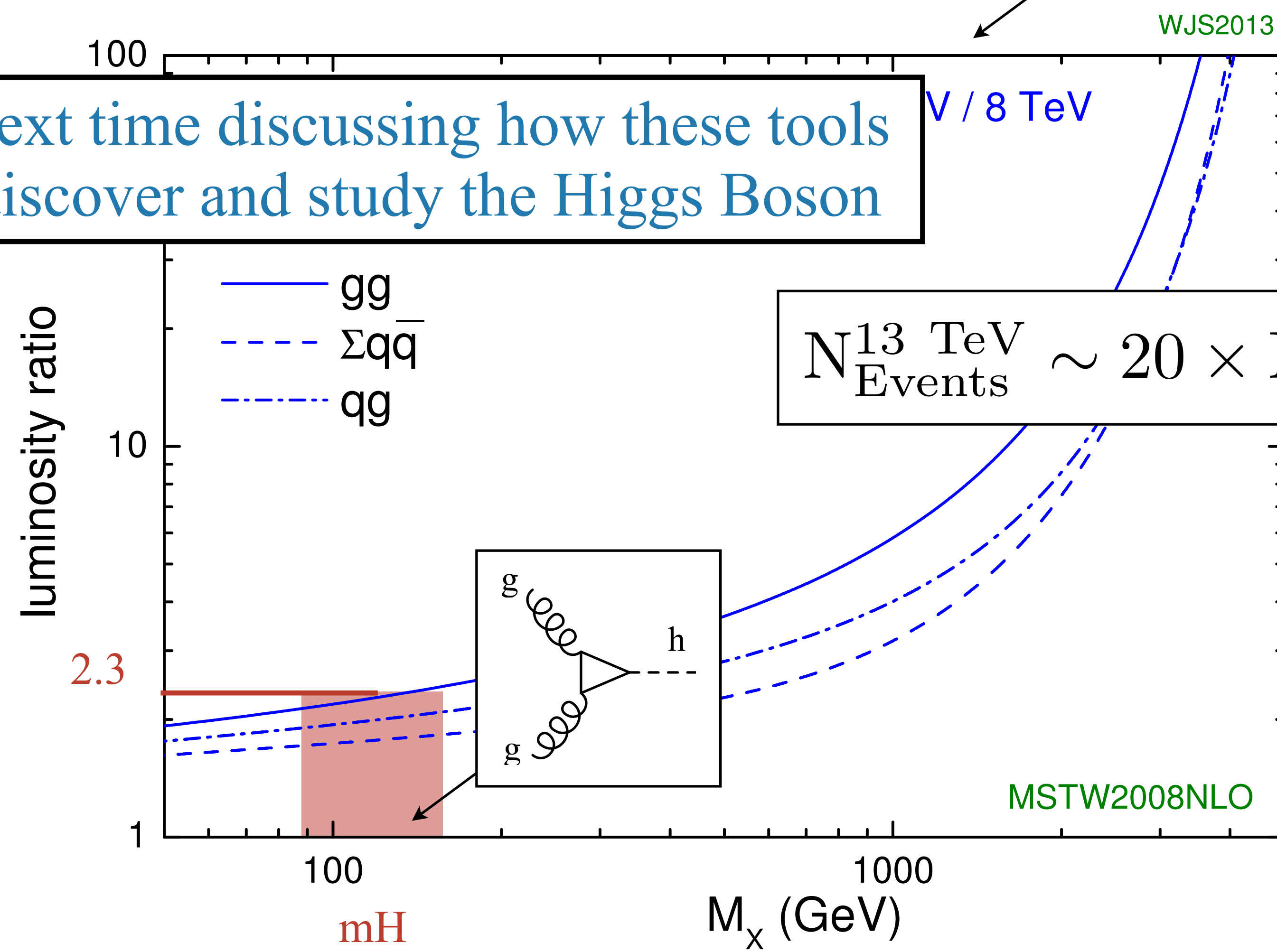
Now ~ 10

(linear w/dataset size)



$$N^{13\ \text{TeV}}_{\text{Events}} \sim 20 \times N^{8\ \text{TeV}}_{\text{Events}}$$

Pick up next time discussing how these tools used to discover and study the Higgs Boson