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

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University of Chicago

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

Constituents *(Matter Particles)* **Spin = 1/2**

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:

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

Interactions Dictated by principles of symmetry **Spin = 1**

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

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

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

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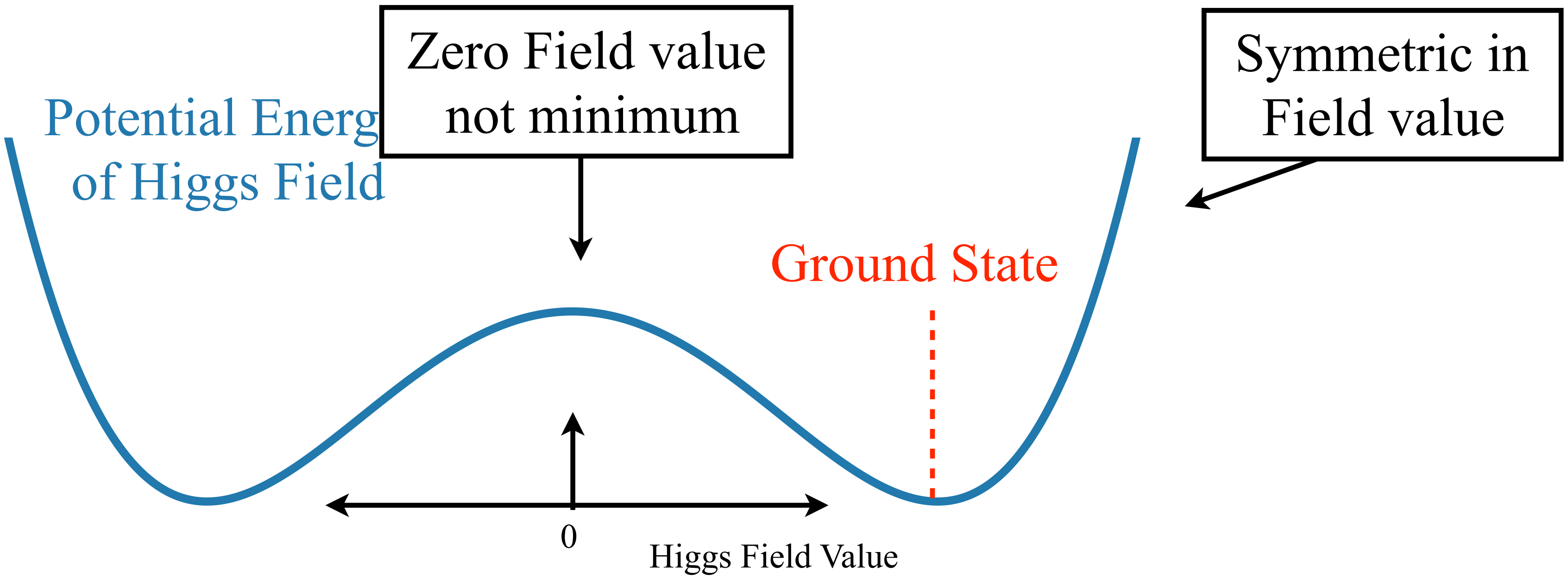
Consistent theory of electromagnetic, weak and strong forces ...
... provided <u>**massless**</u> *Matter* and *Force Carriers*

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

Last Time: *The Higgs Field*

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



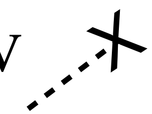
Ground state (vacuum of Universe) filled will Higgs field
Leads to particle masses: Energy cost to displace Higgs Field / $E=mc^2$
Additional particle predicted by the theory:
Generally Expected / Needed for Logical Consistency!

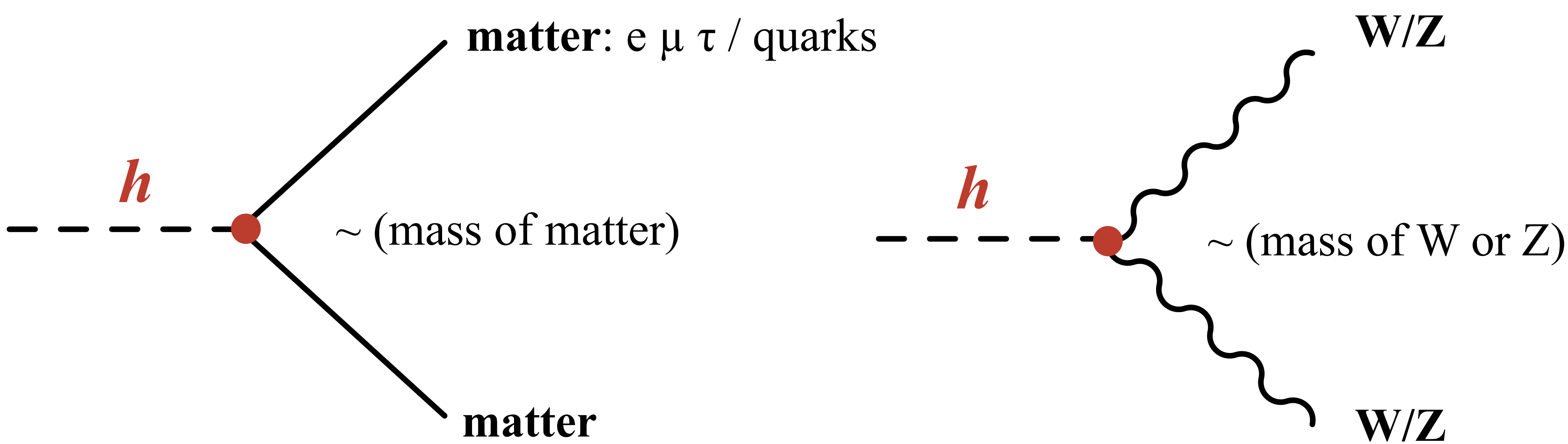
<u>Higgs boson:</u> H **Spin = 0**

Last Time: *The Higgs Boson*

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

Higgs is excitations of v-condensate

⇒ 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

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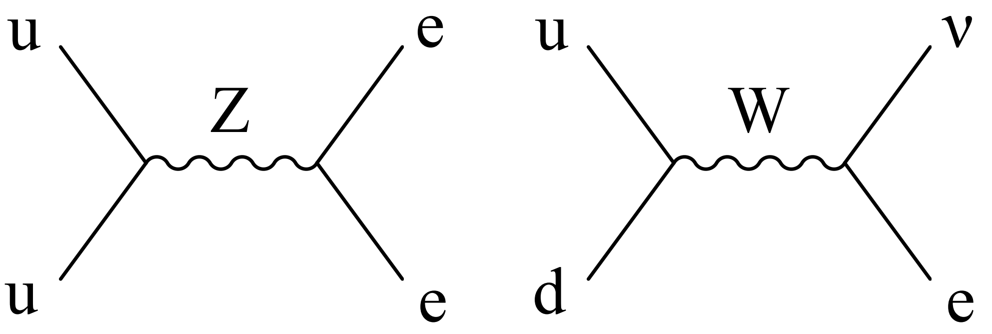

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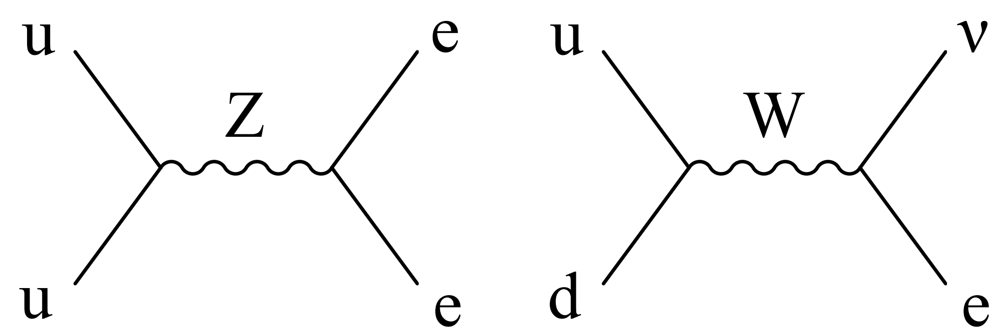
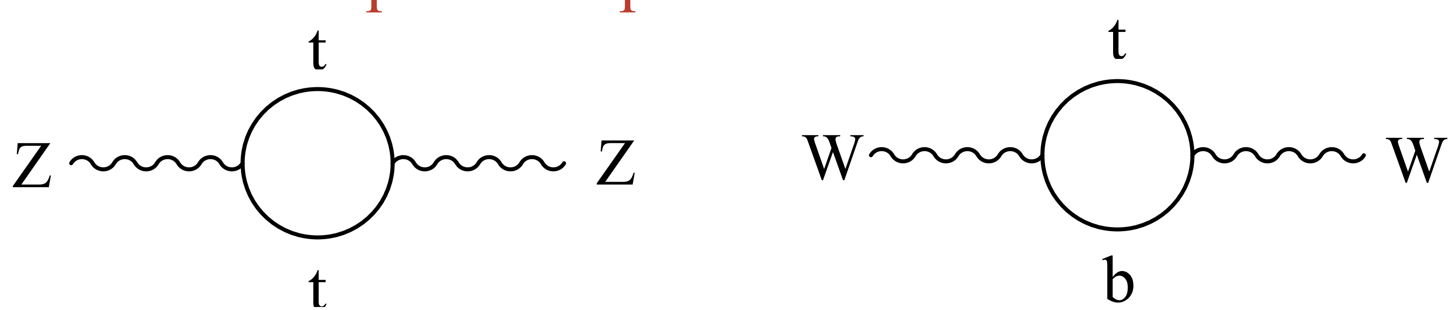


Early 90s: W/Z used to predict top mass



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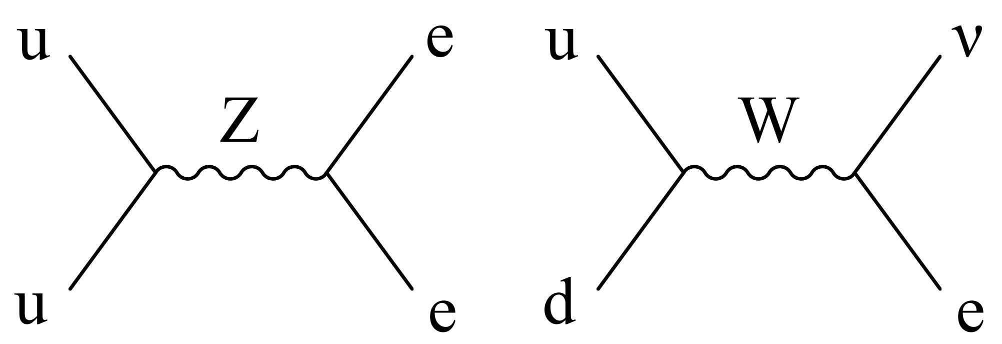

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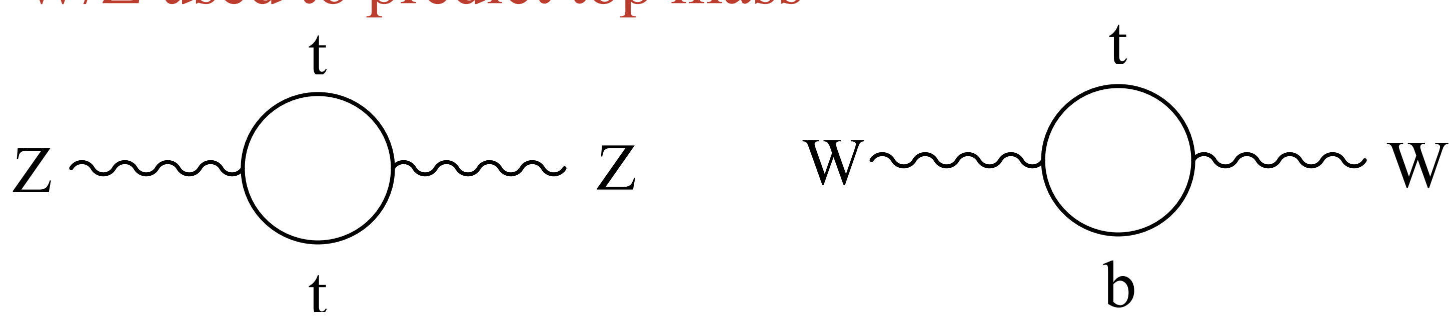

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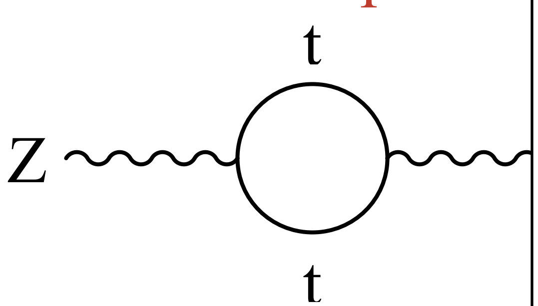

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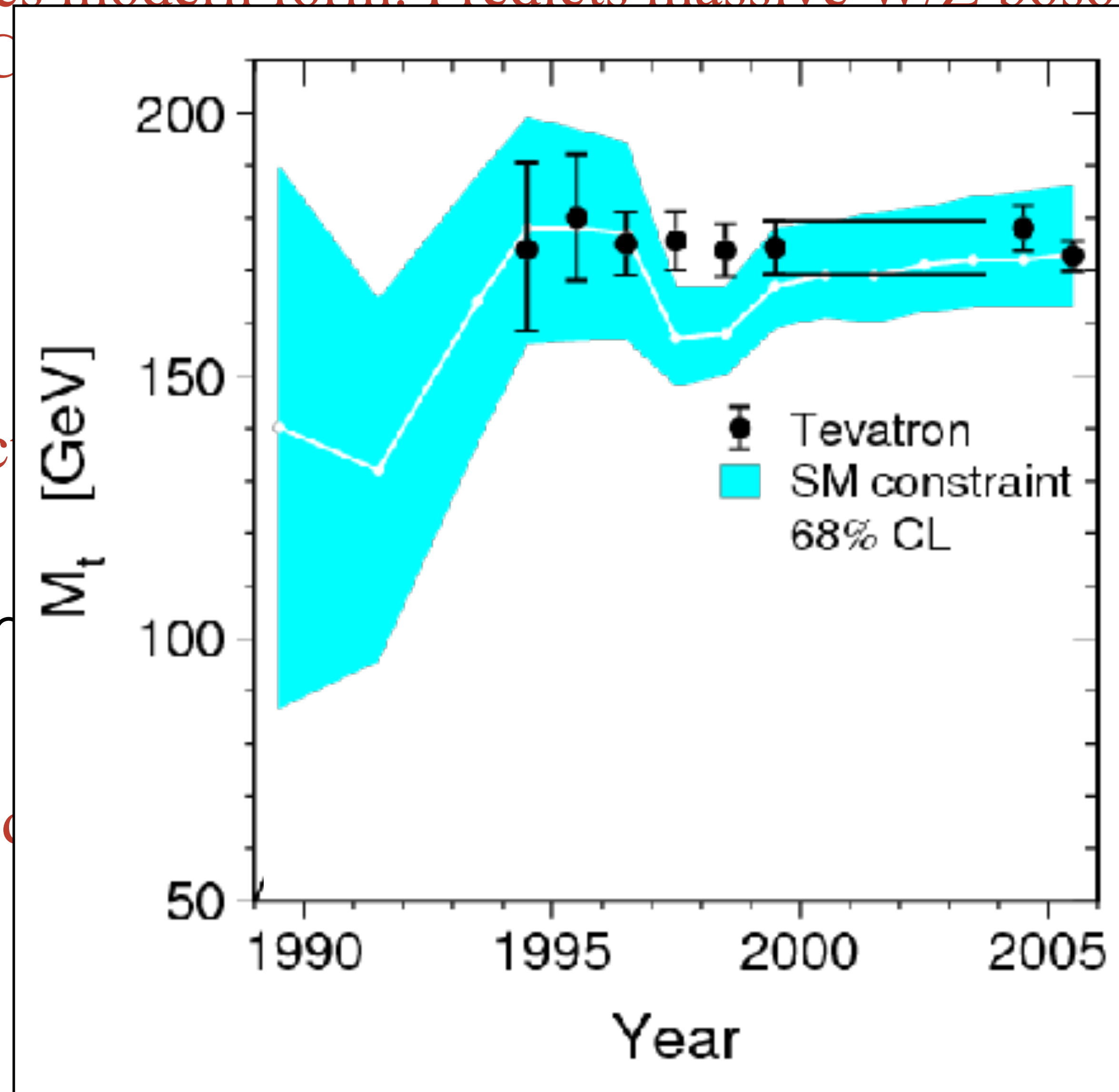

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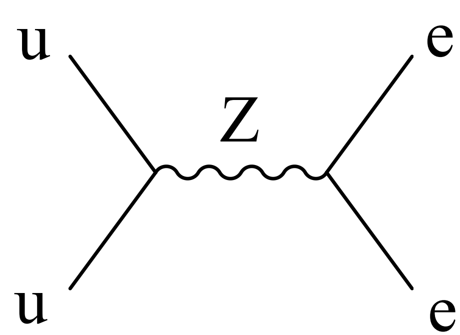

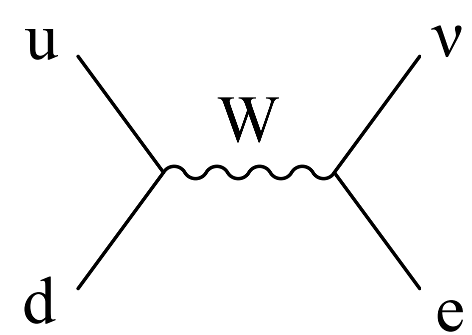

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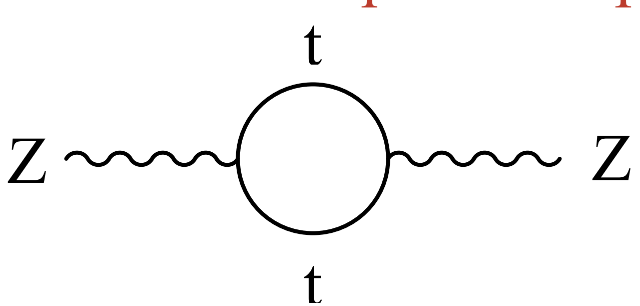

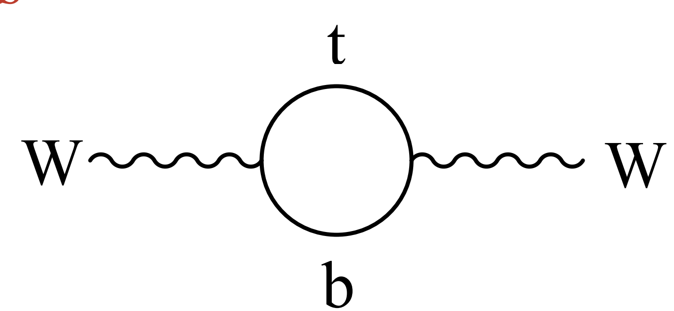

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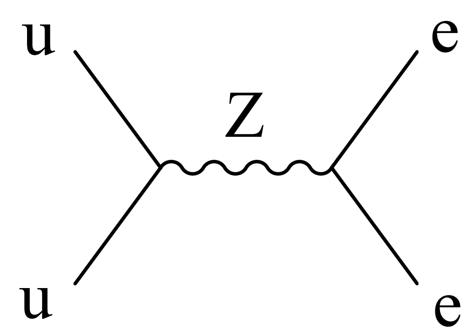

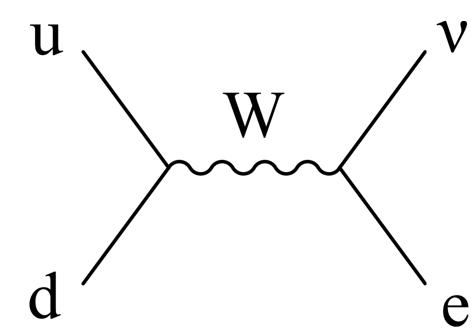

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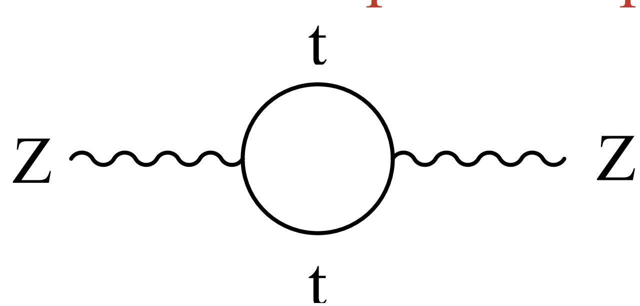

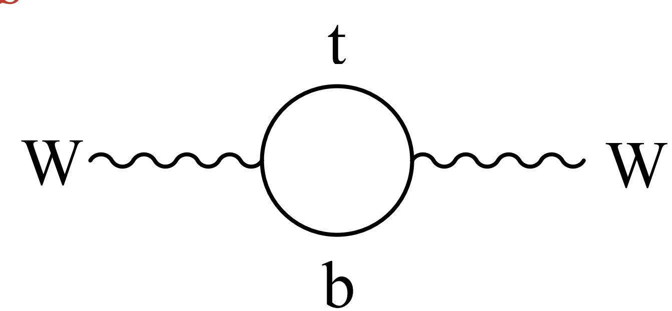

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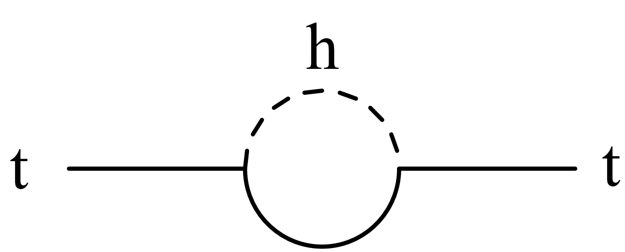

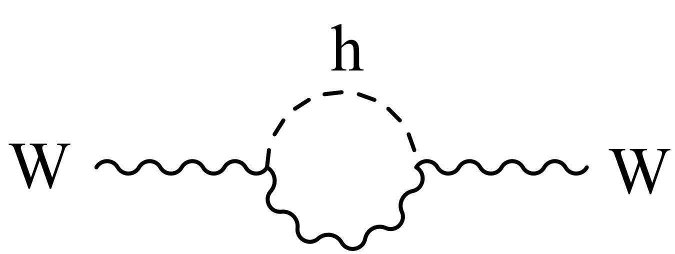

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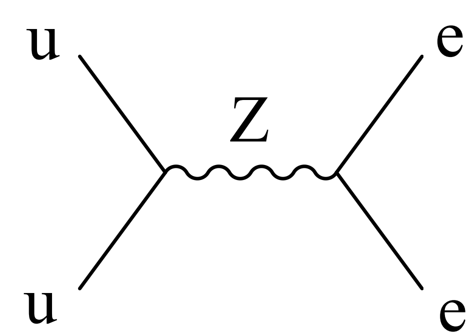

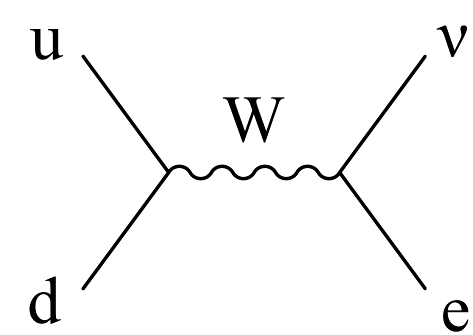

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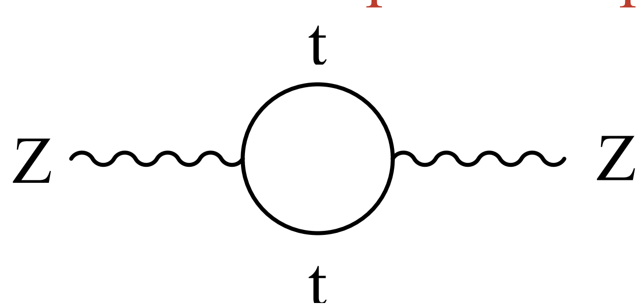

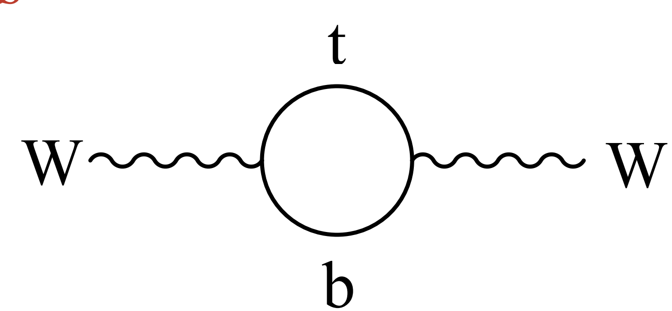

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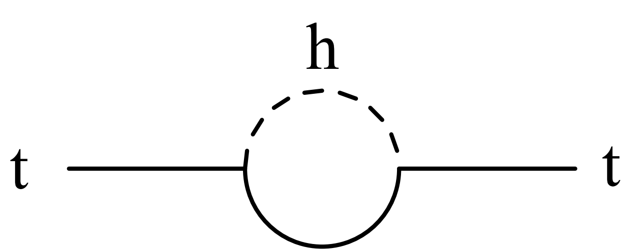

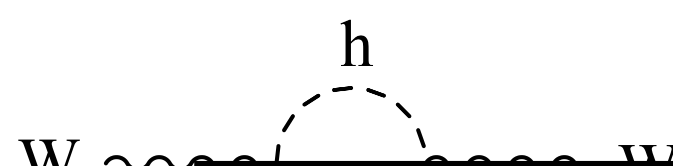

50 < mH < 150 GeV (95%)

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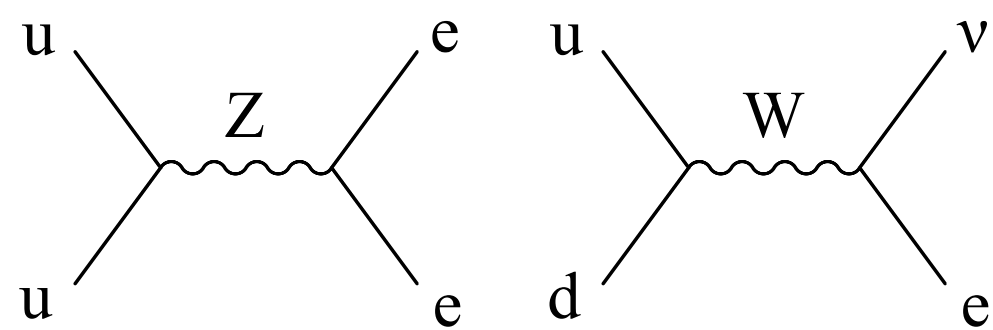
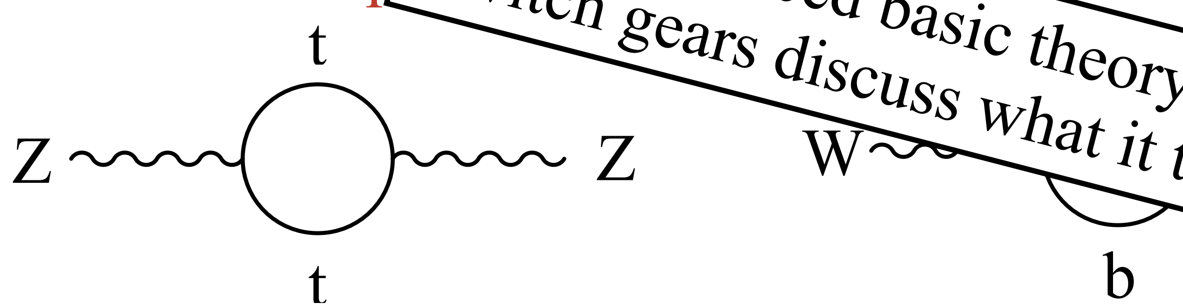


Early 90s: W/Z used to p



Now introduced basic theory.
Switch gears discuss what it takes to test it.

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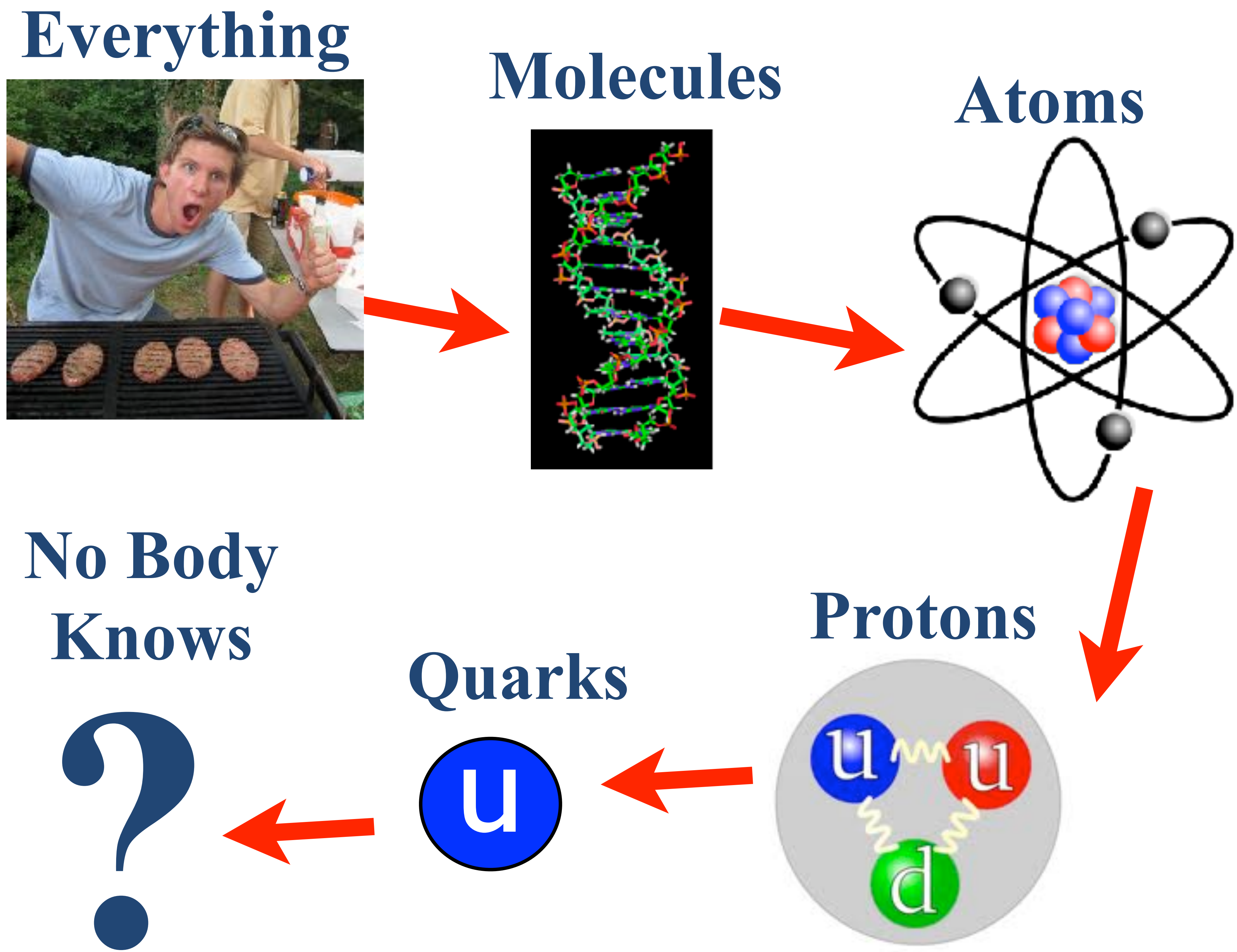
Today's Lecture

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 ?

What's in the Lunch Box ?

Look inside.

No Fun!

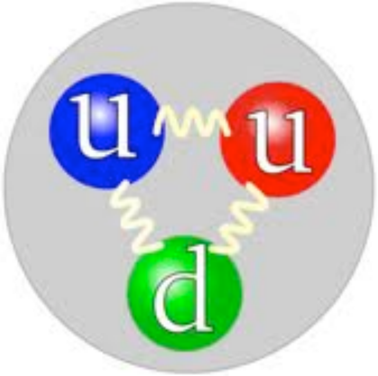
What's in the Lunch Box ?

SMASH THEM!!!

What's in the Lunch Box ?

What's in the Proton ?

Protons are Too
small to look inside.



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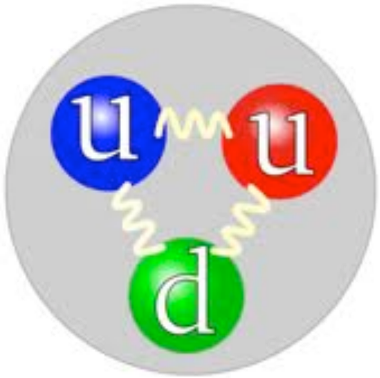

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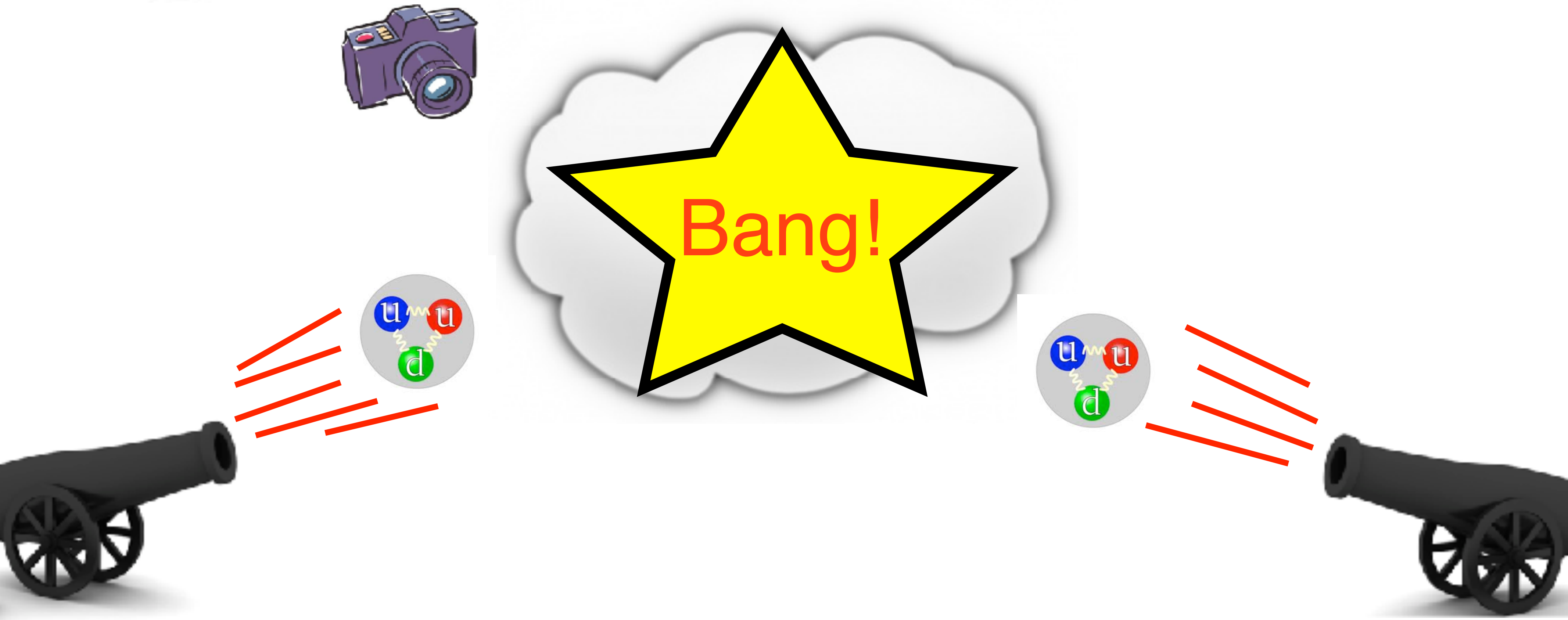

The Worlds Biggest Cannon

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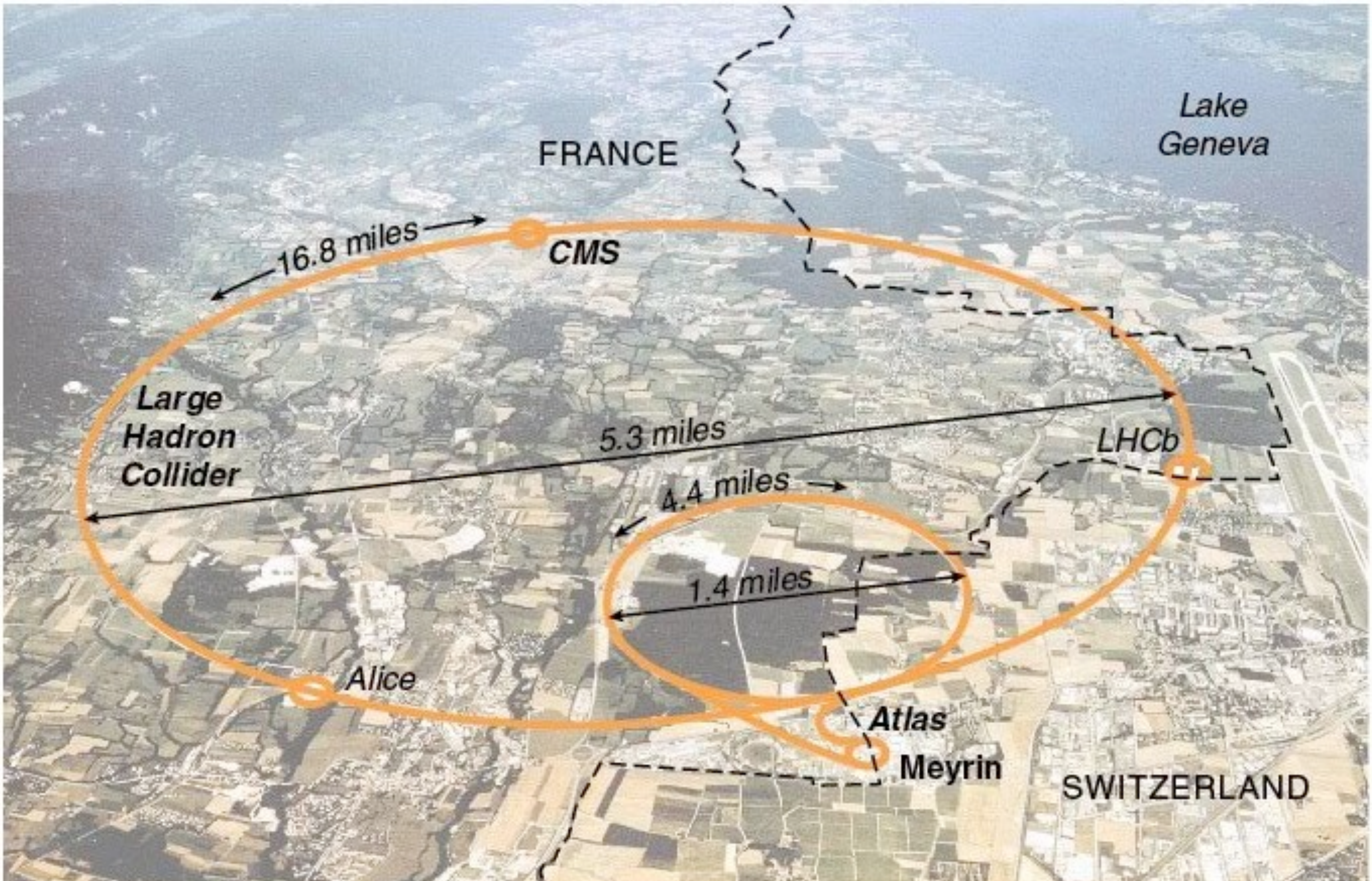

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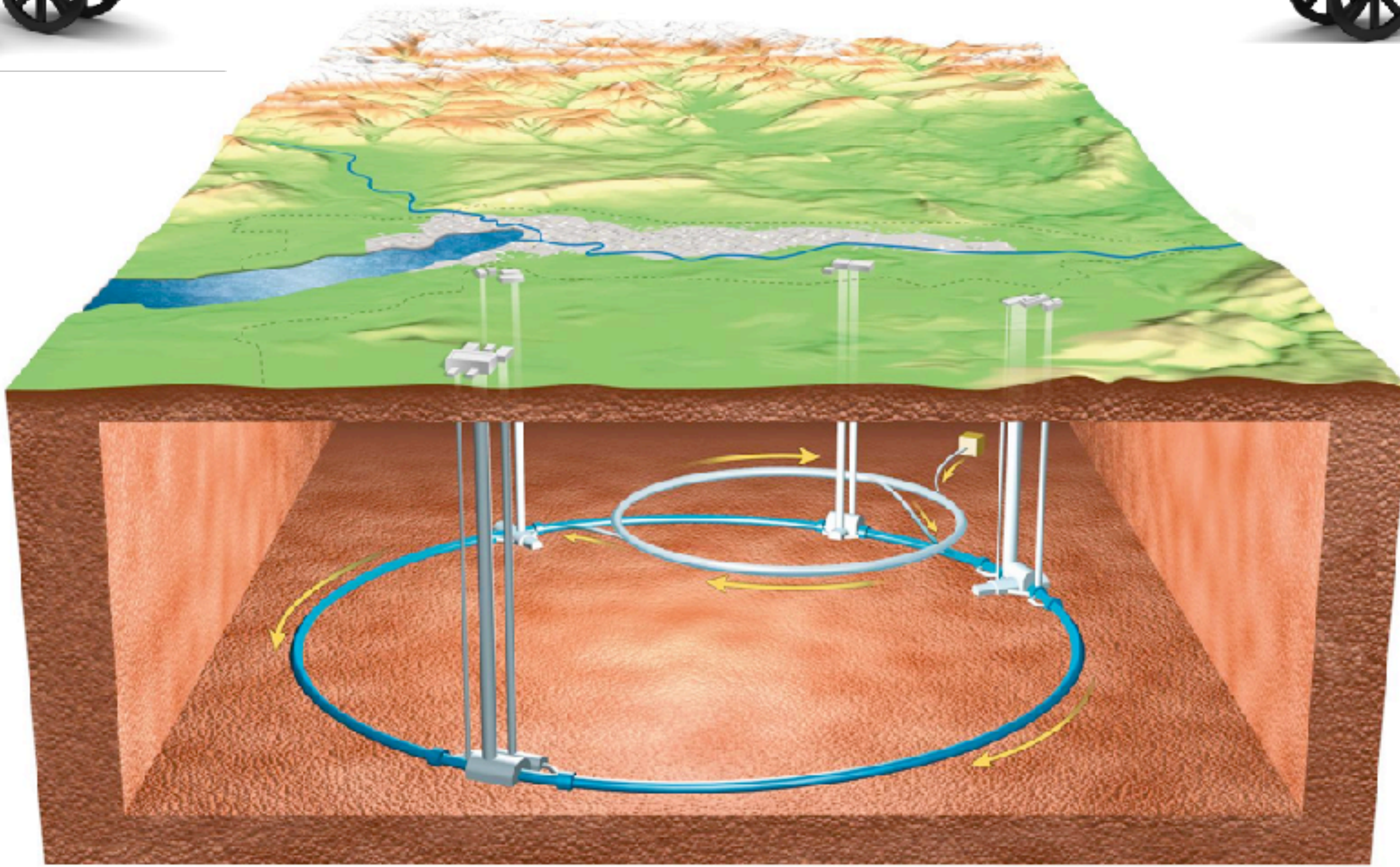
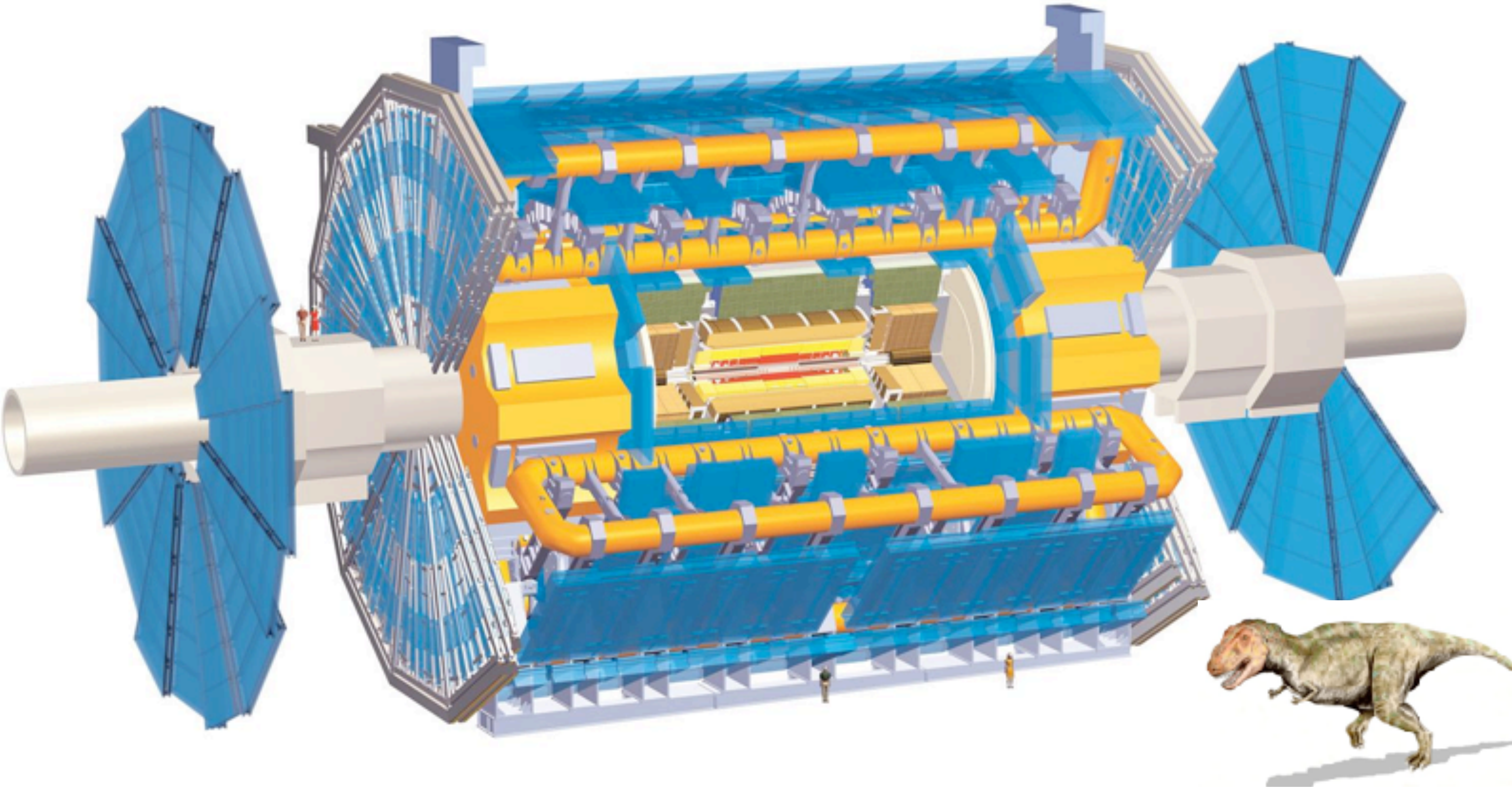


Really Big Camera!!!



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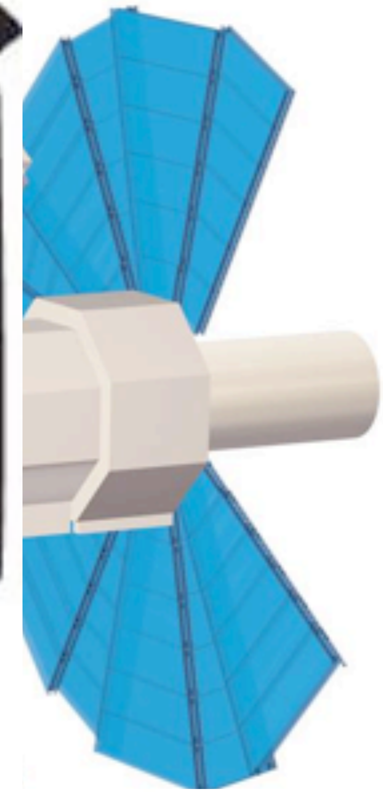

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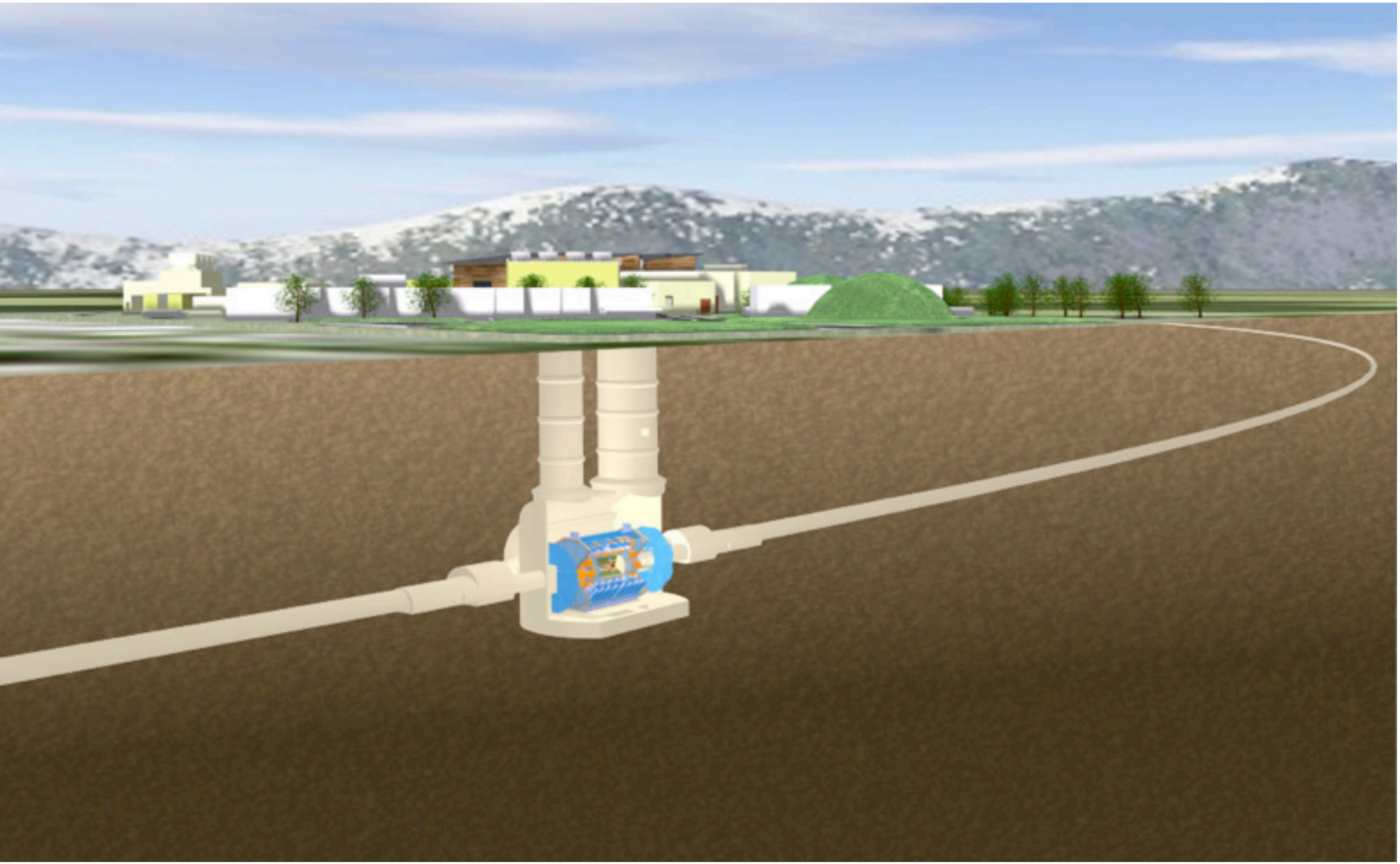

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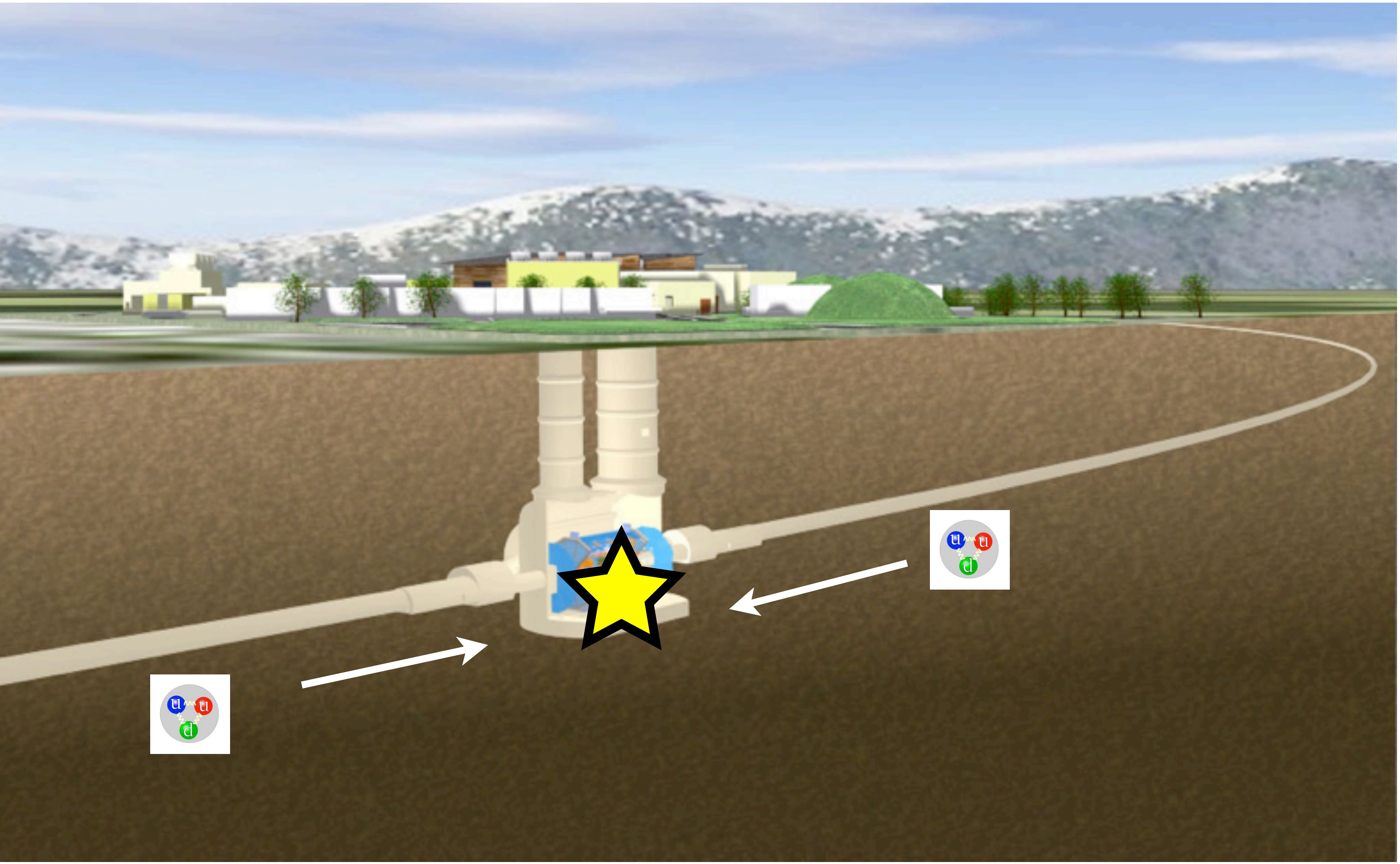

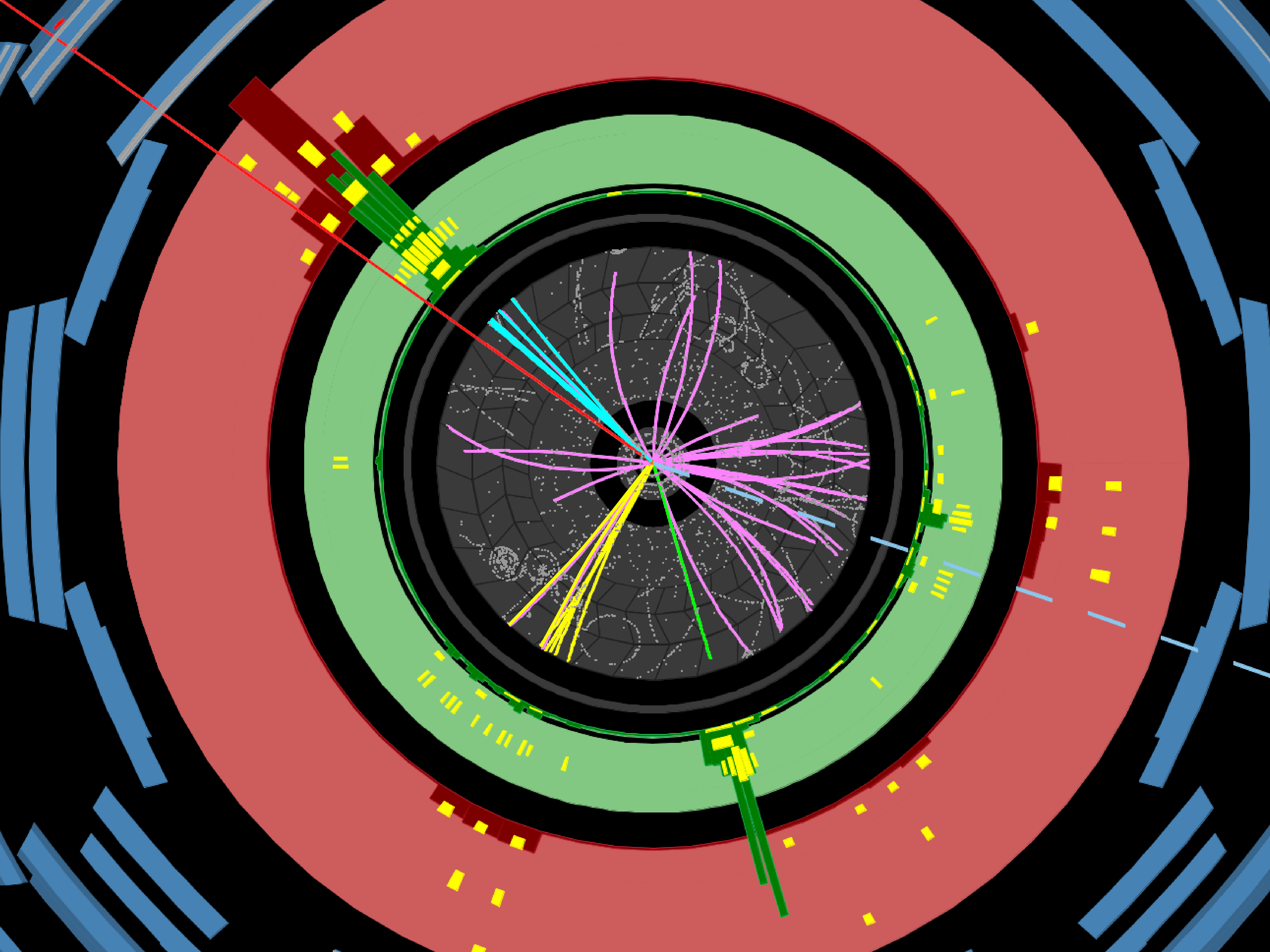

3rd Grade Explanation is Essentially Correct

Some Caveats:

- More sophisticated analog to "what are quarks made of ?"
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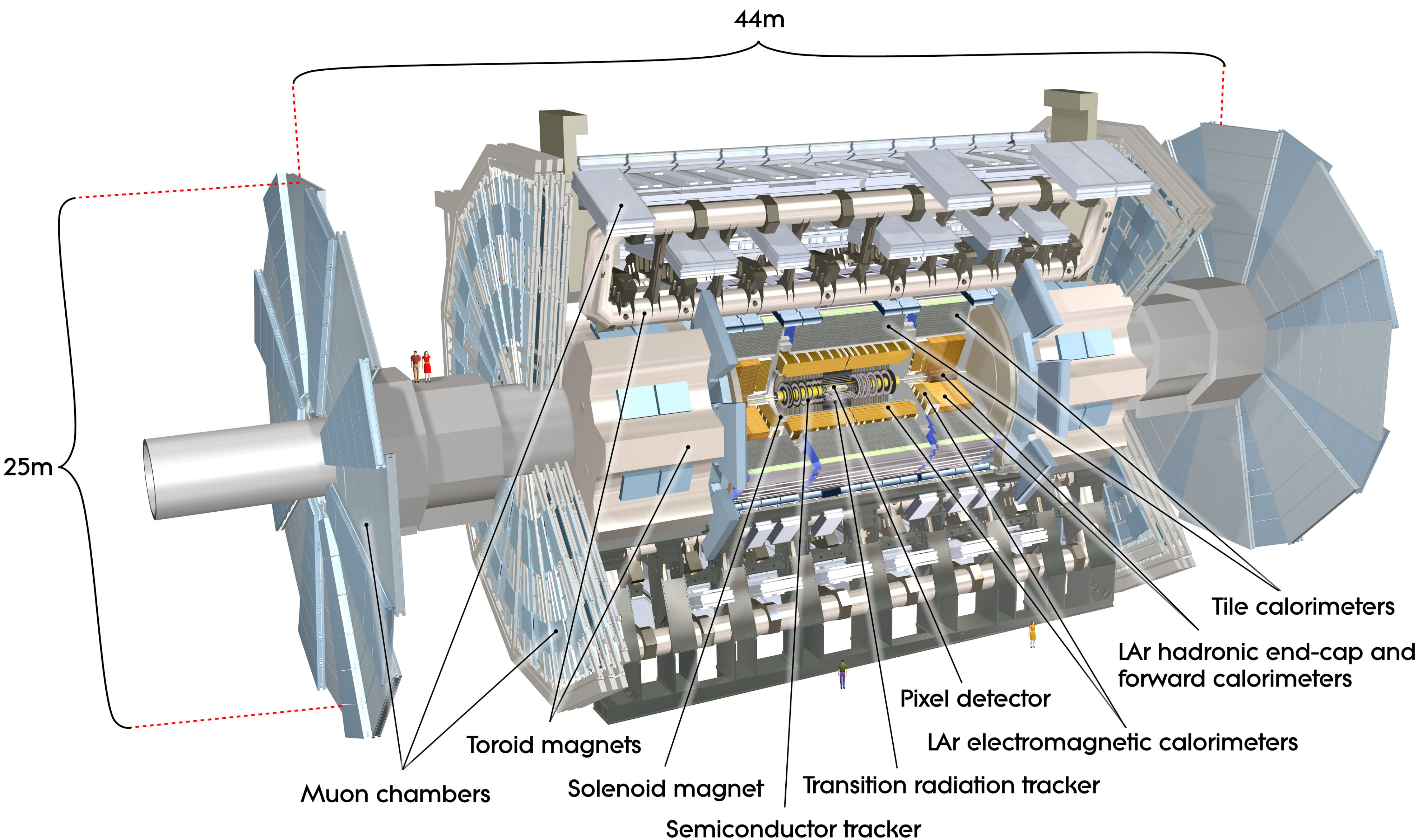
Rest of lecture:

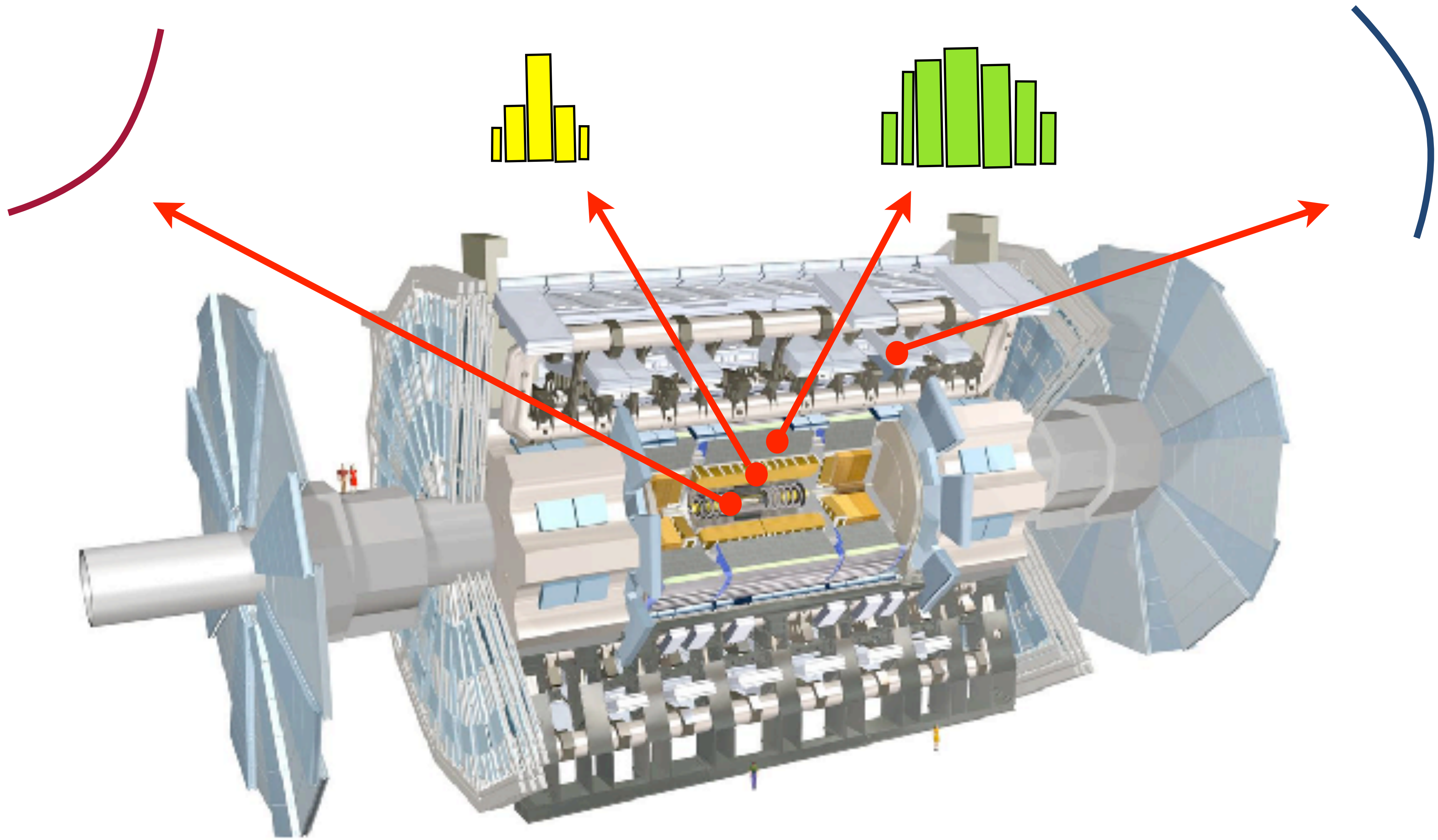
- Refine basic notions of camera and cannon
- Discuss challenges in collecting/analyzing pictures
- Talk about how we use picture to test SM

A Toroidal LHC ApparatuS



The Basic Outputs:

Inner Tracking System | Electro-Magnetic Calorimeter | Hadronic Calorimeter | Muon Tracking System

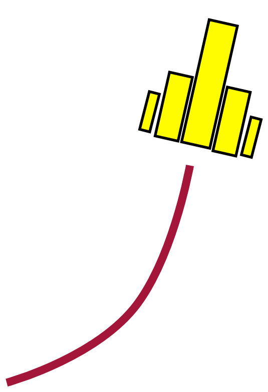


A lot of work goes into making/understanding these basic outputs.

ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b

ν_e ν_μ ν_τ u c t

e μ τ d s b



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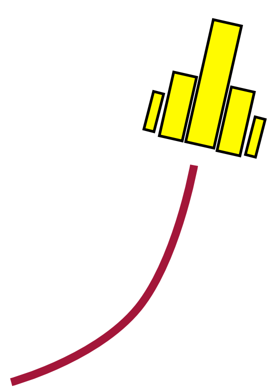
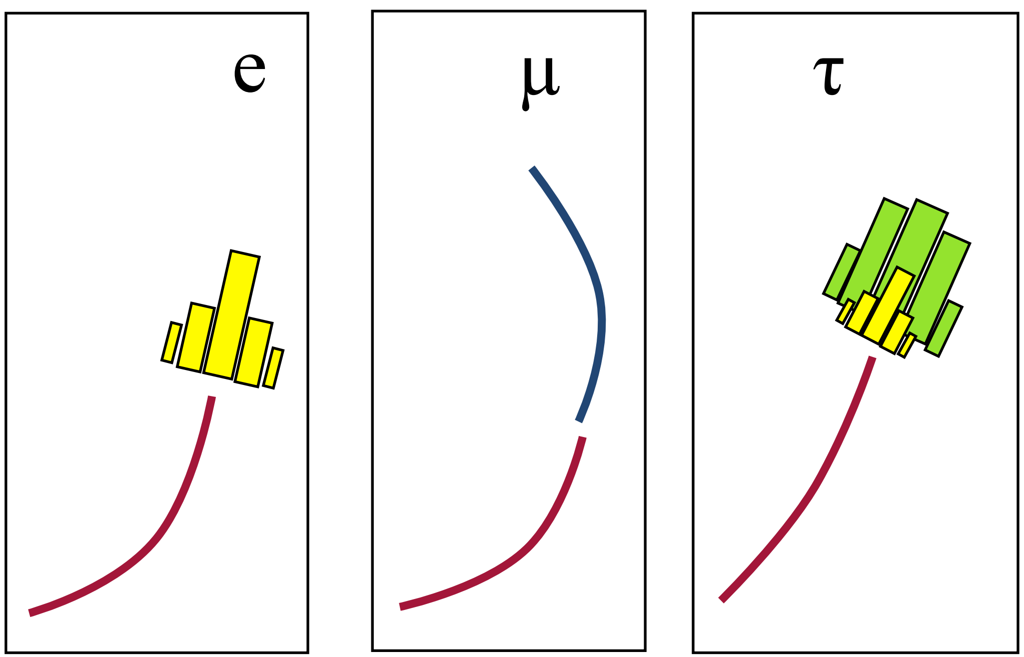
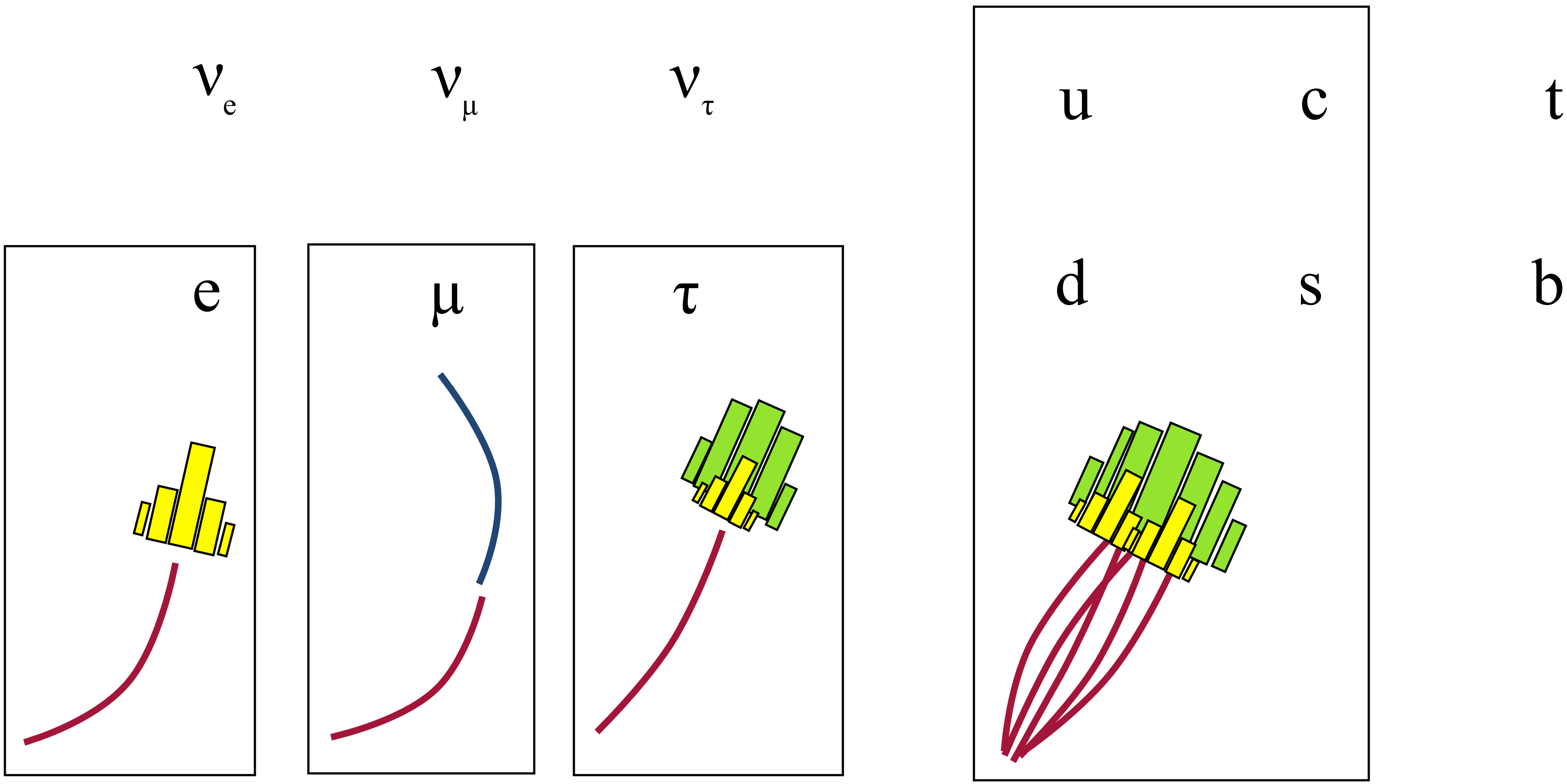


ν_e ν_μ ν_τ u c t



d s b



νe
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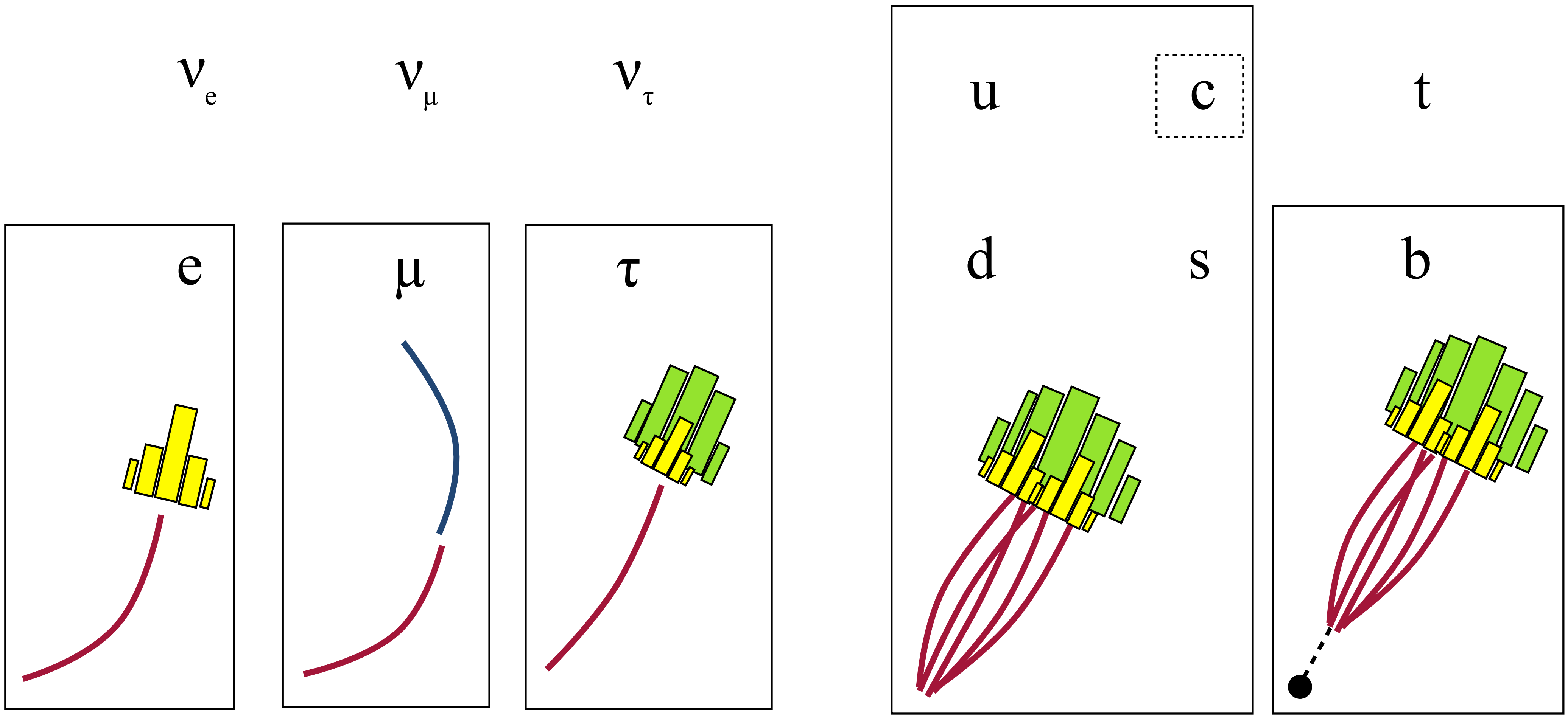
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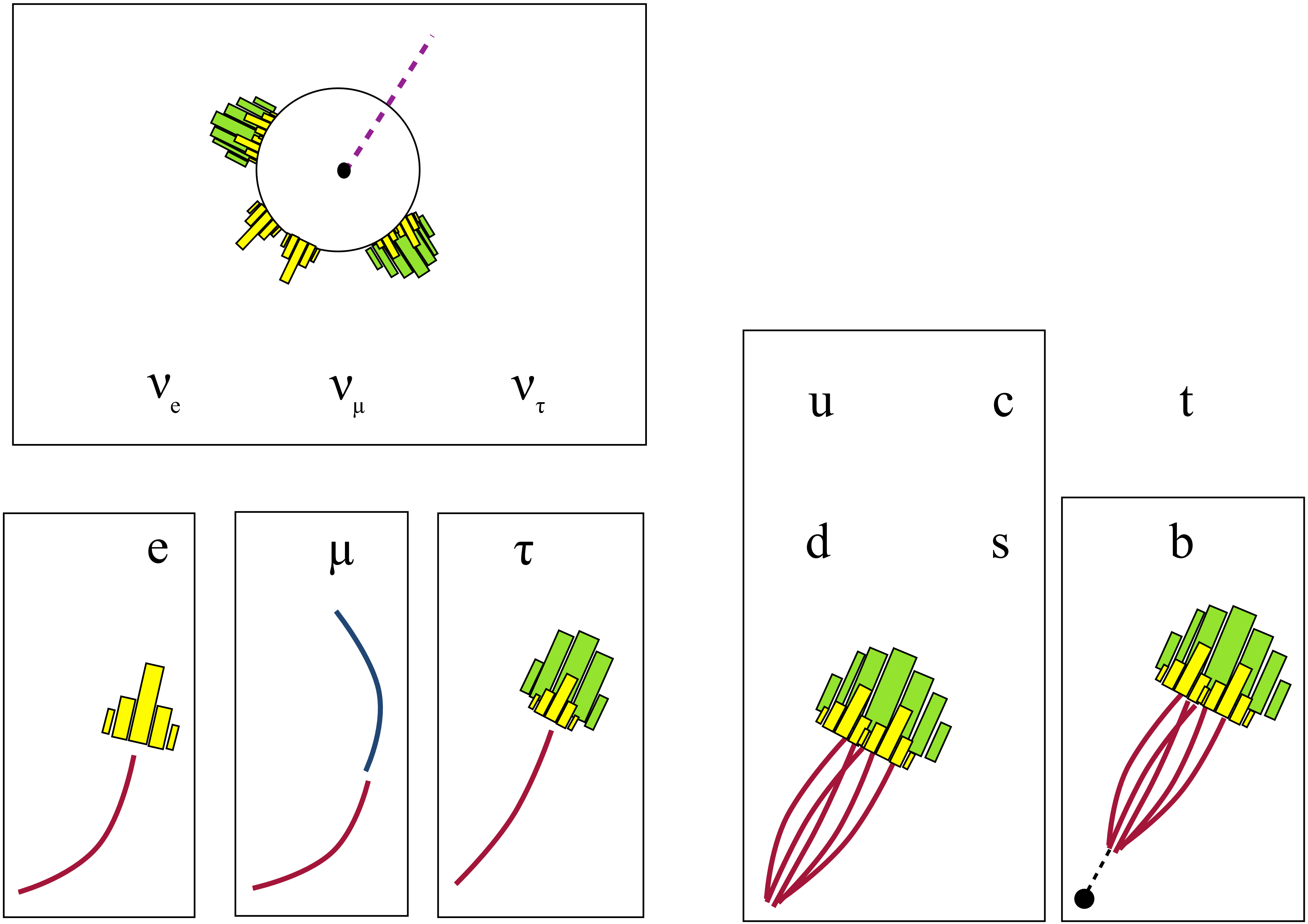
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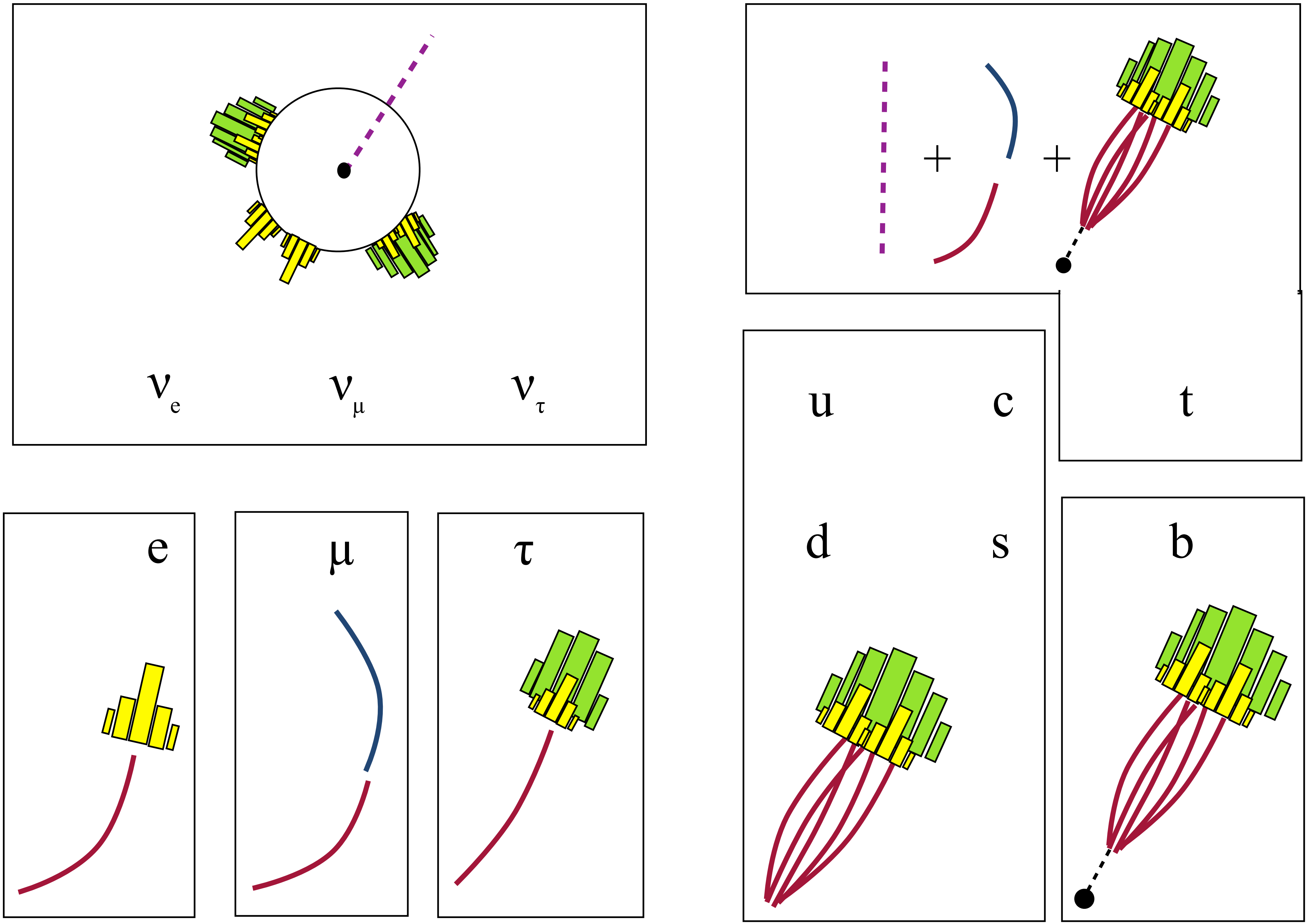

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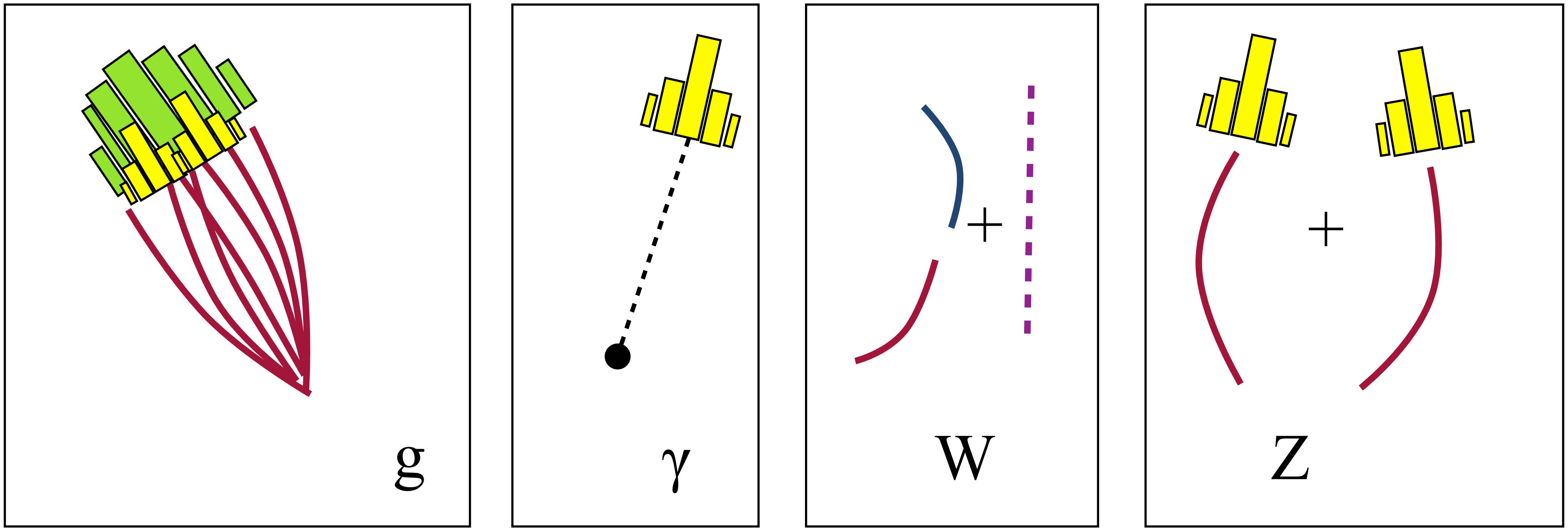
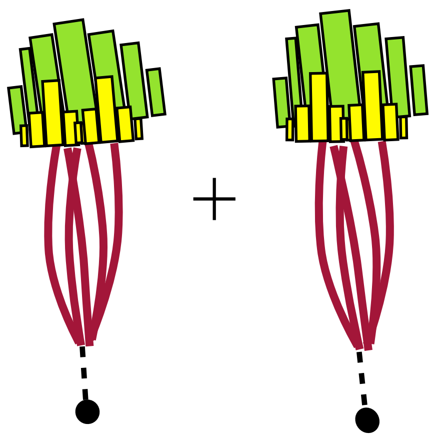
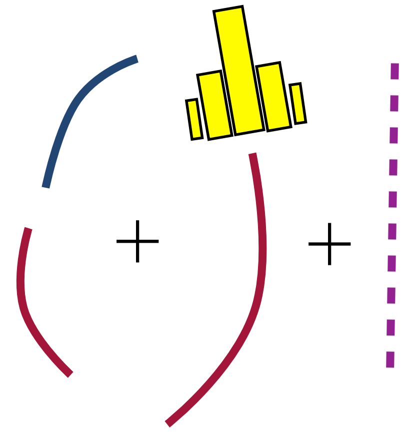

g
γ
W
+
Z
+

Higgs decays

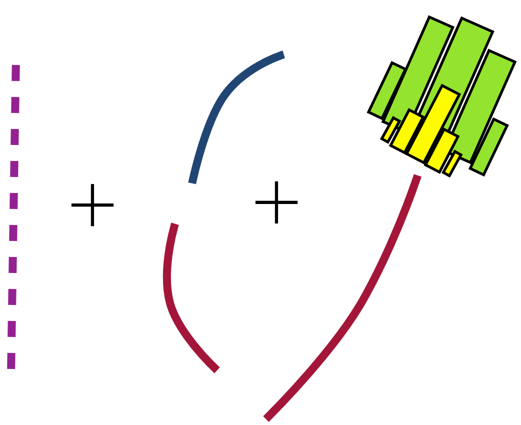
$H \rightarrow bb$: ~60%



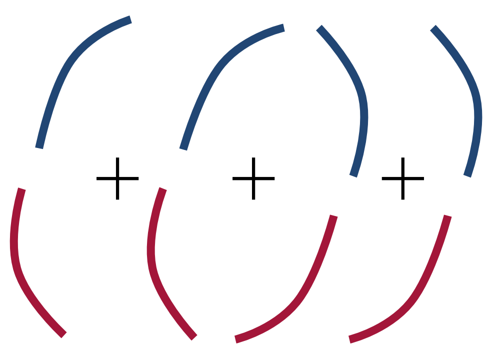
$H \rightarrow WW$: ~20%



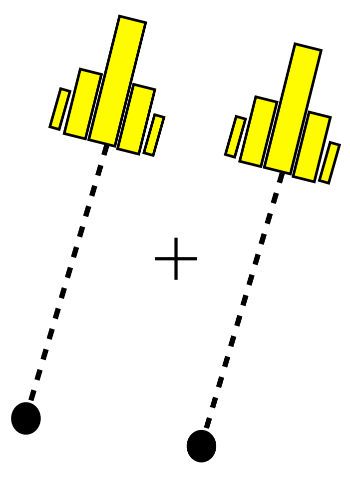
$H \rightarrow \tau\tau$: ~5%

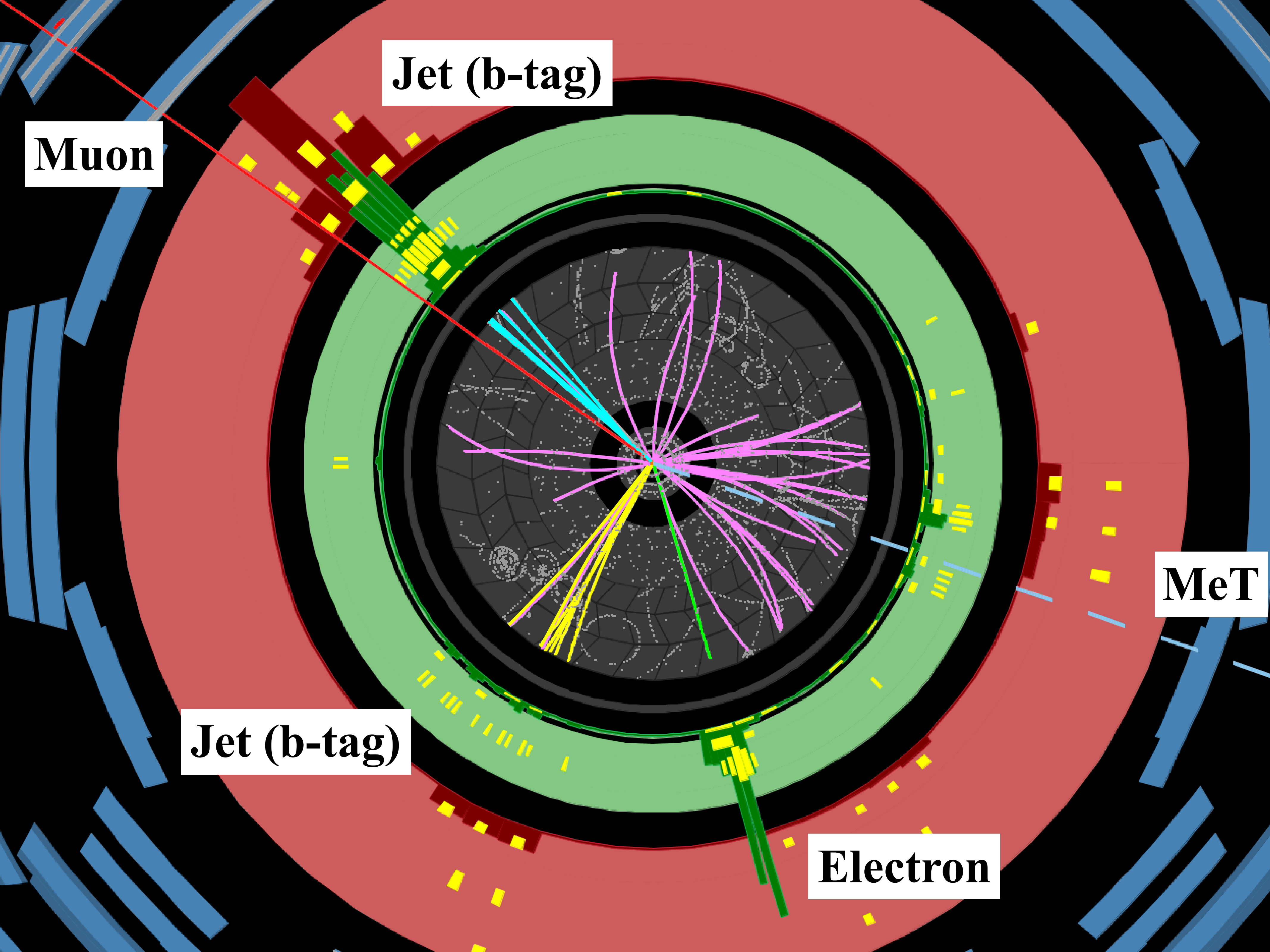


$H \rightarrow ZZ$: ~2%



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

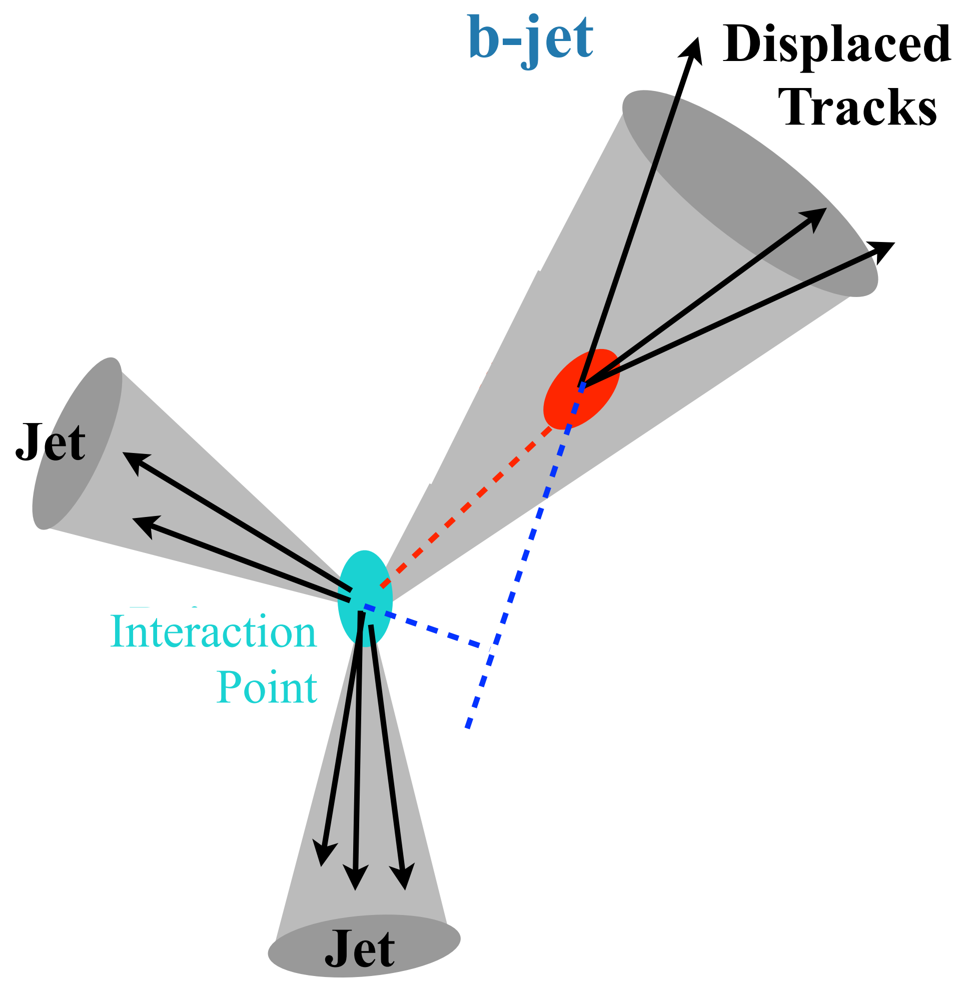



Jet (b-tag)
Muon
MeT
Jet (b-tag)
Electron

Experimental Challenges

b-jet Identification *(b-Tagging)*

Critical as b-jet ubiquitous in Higgs final states.



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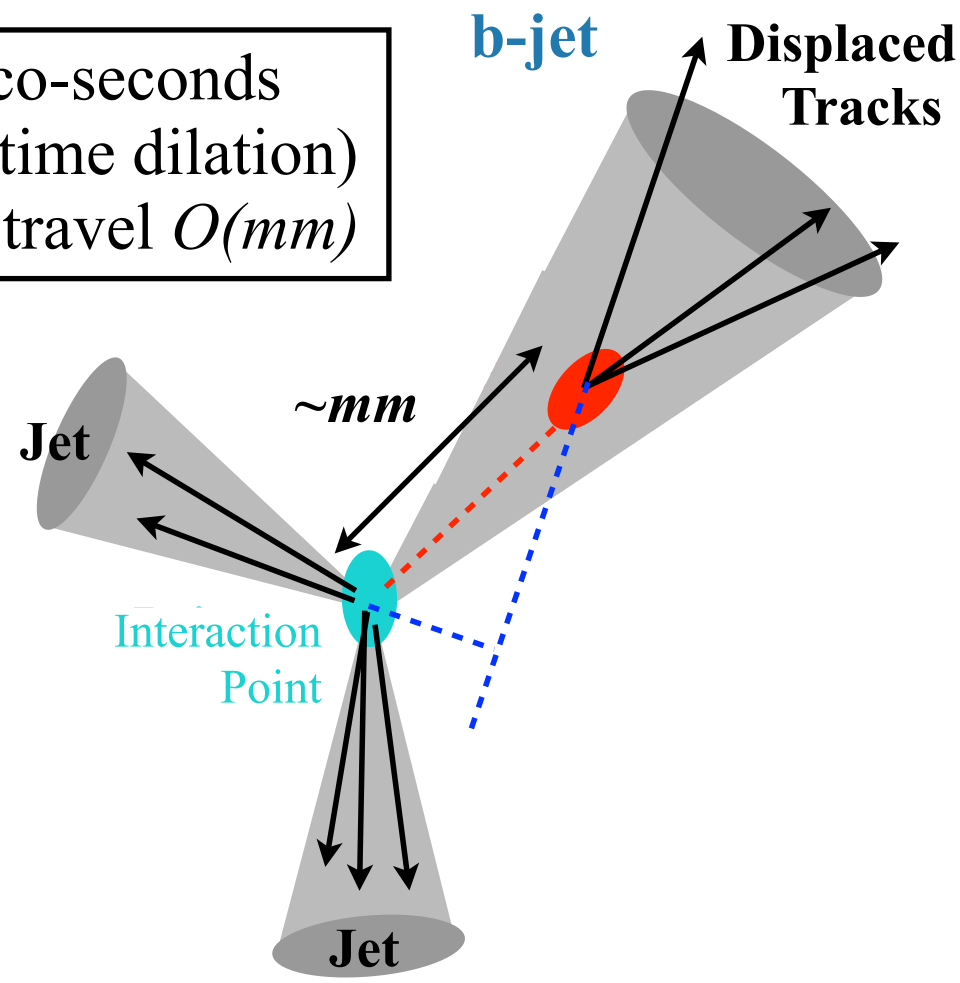
- Typical speed (time dilation) ⇒ travel *O(mm)*



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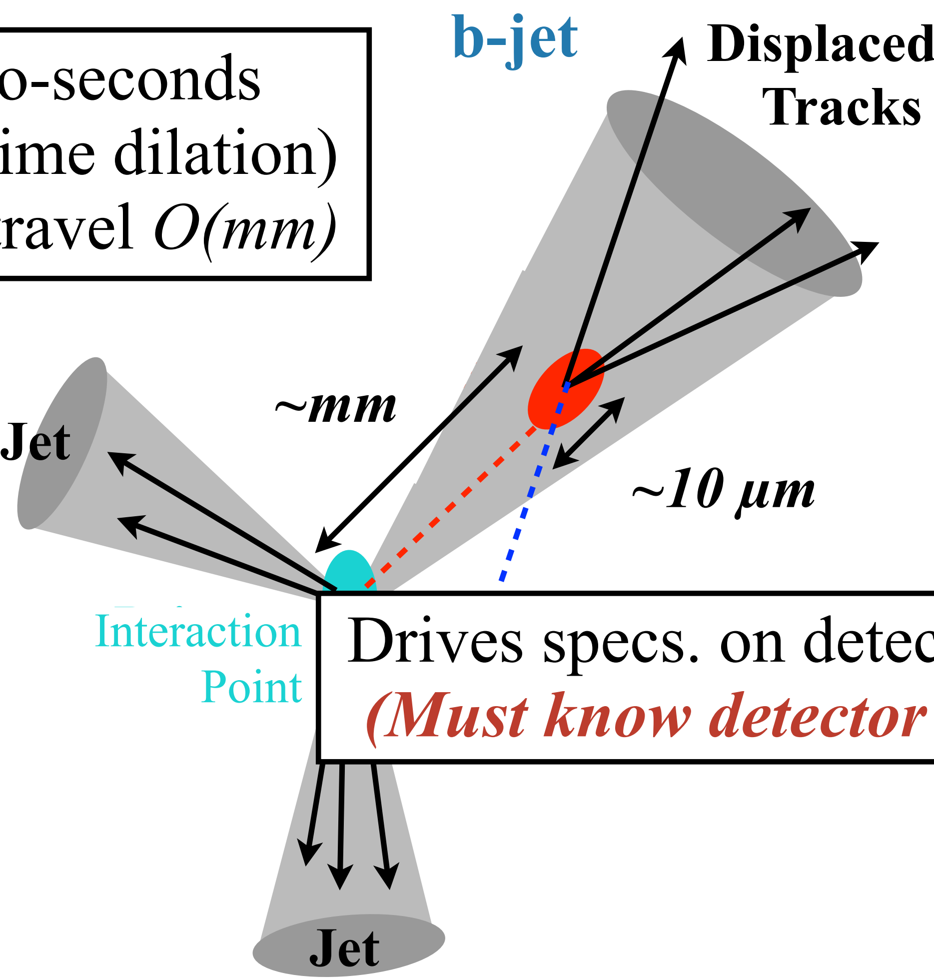

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(Must know detector positions to ~μm)

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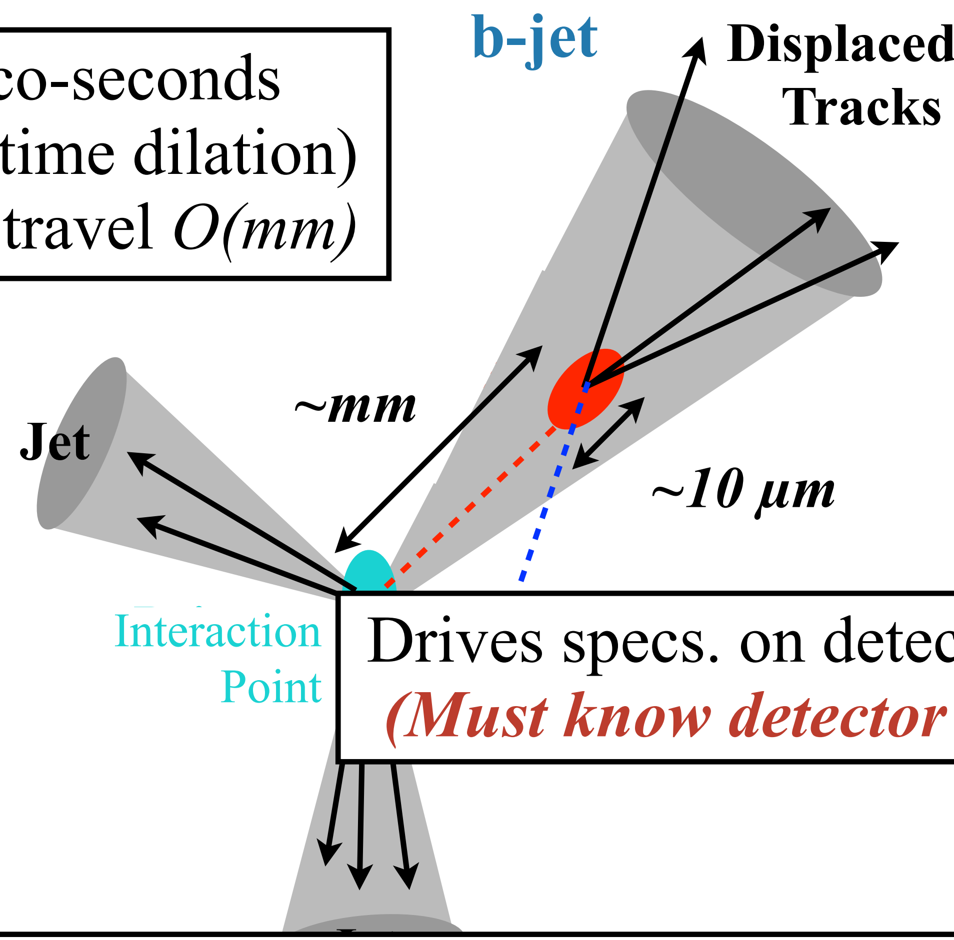

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Detectors size apartment buildings, measure to accuracy of something barely visible to human eye. ***Major cost driver***

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- LHC provides orders of magnitude more collisions than can save to disk

- Interesting physics is incredibly rare.

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- Fast processing of images (micro-seconds / seconds)
- Events rate from 40 MHz → 1kHz.
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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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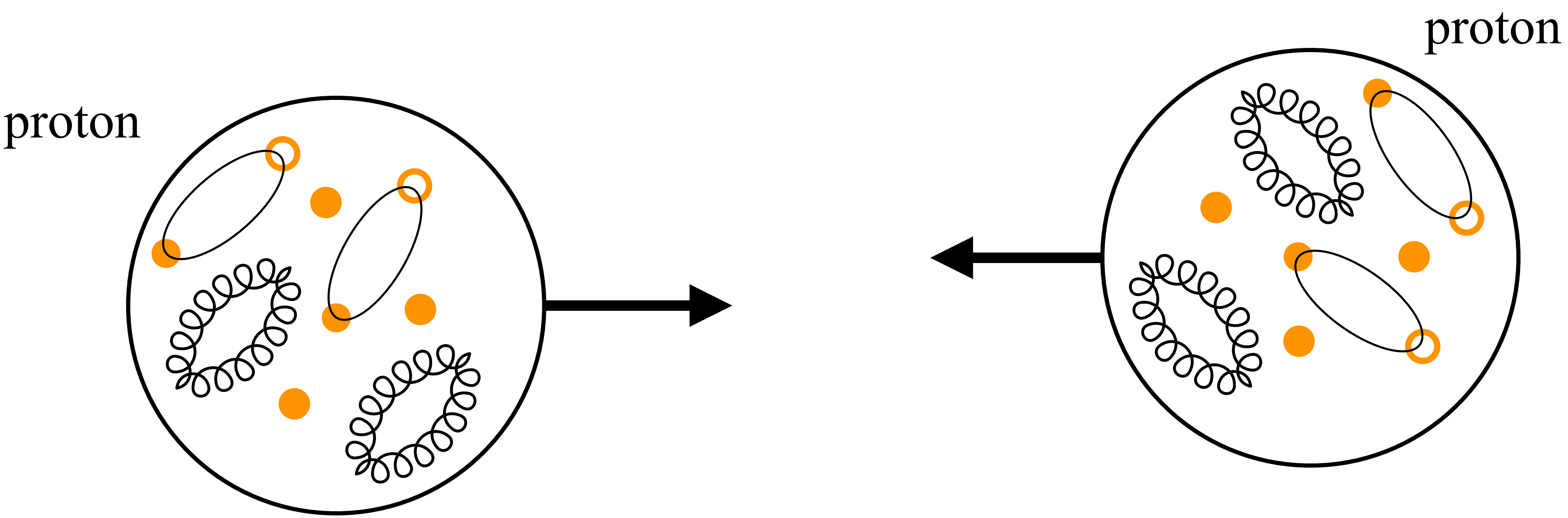

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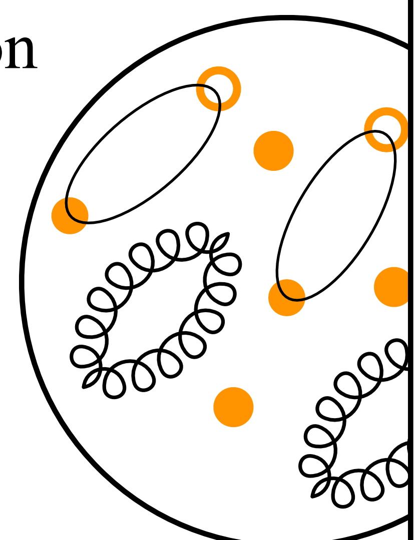
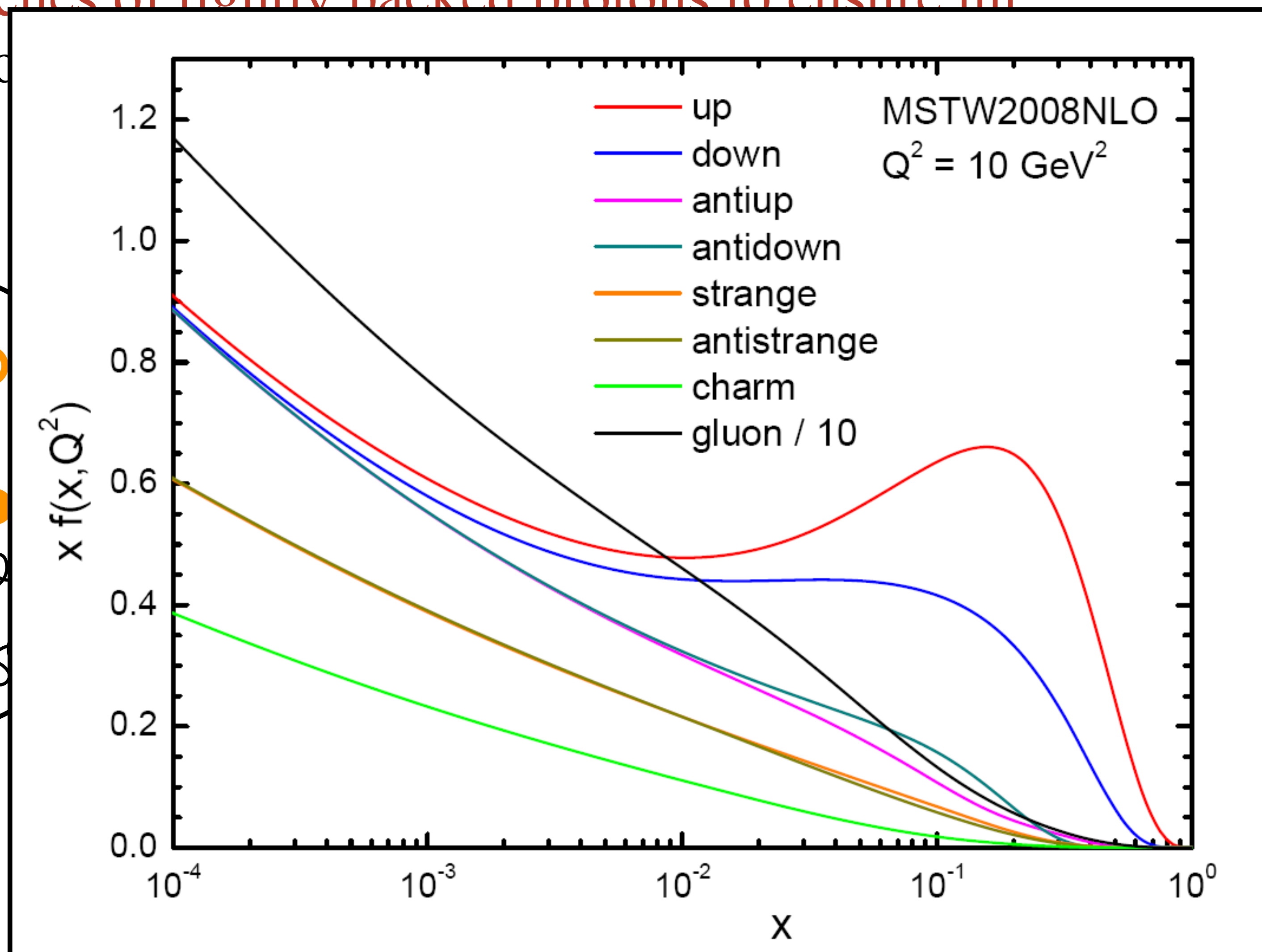
n

proton





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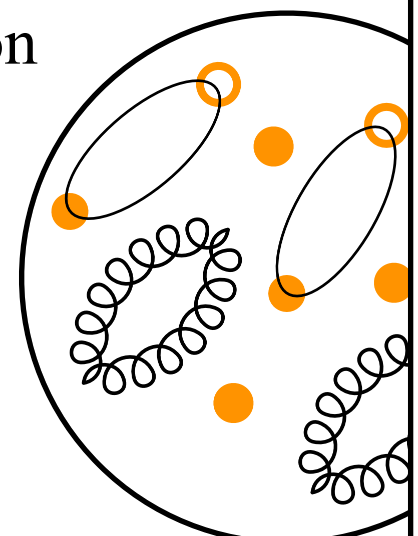

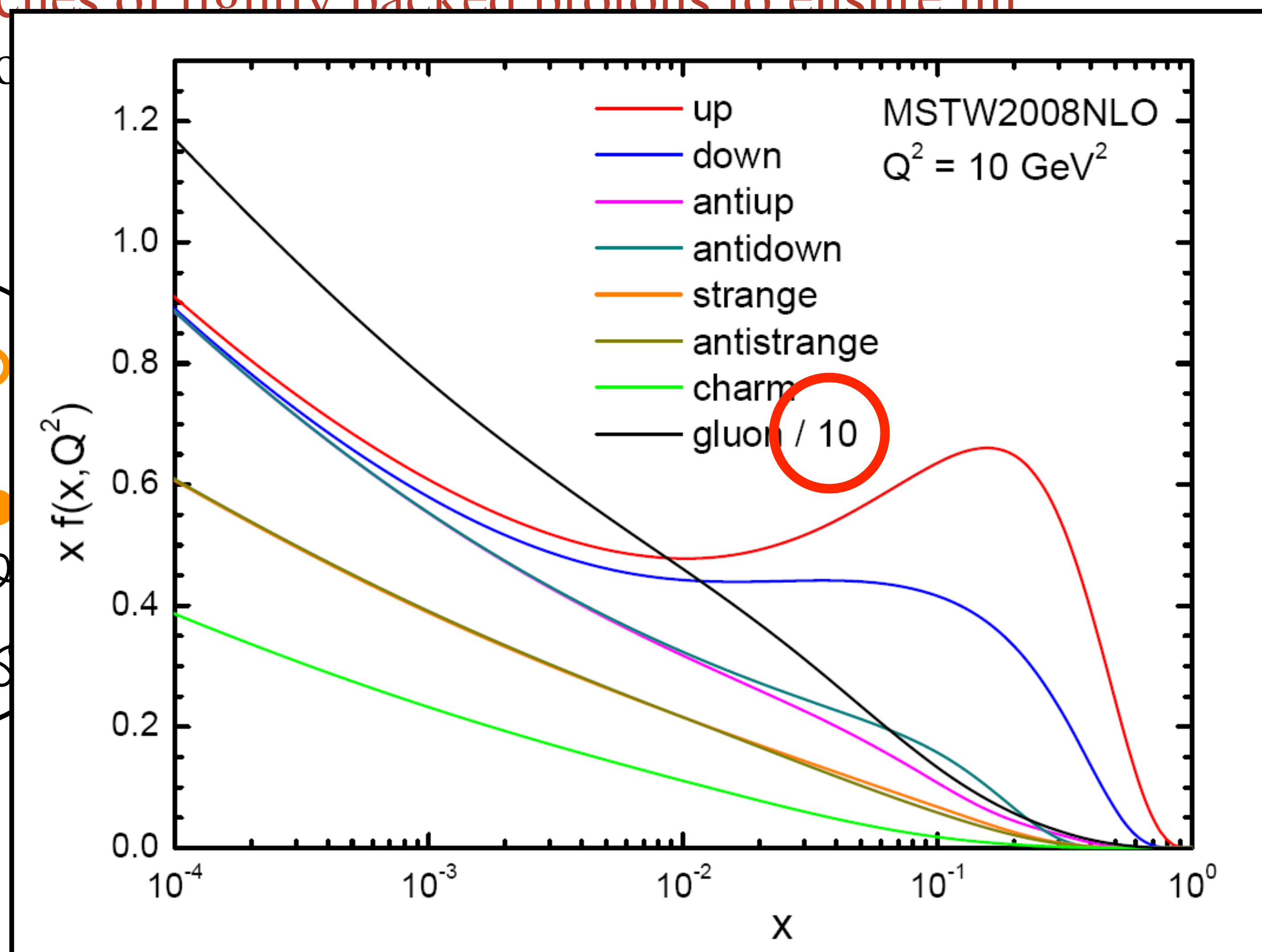

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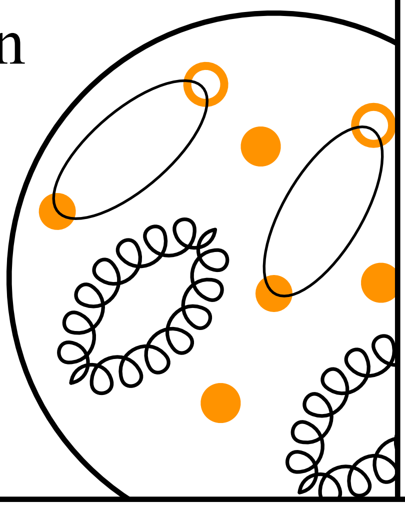

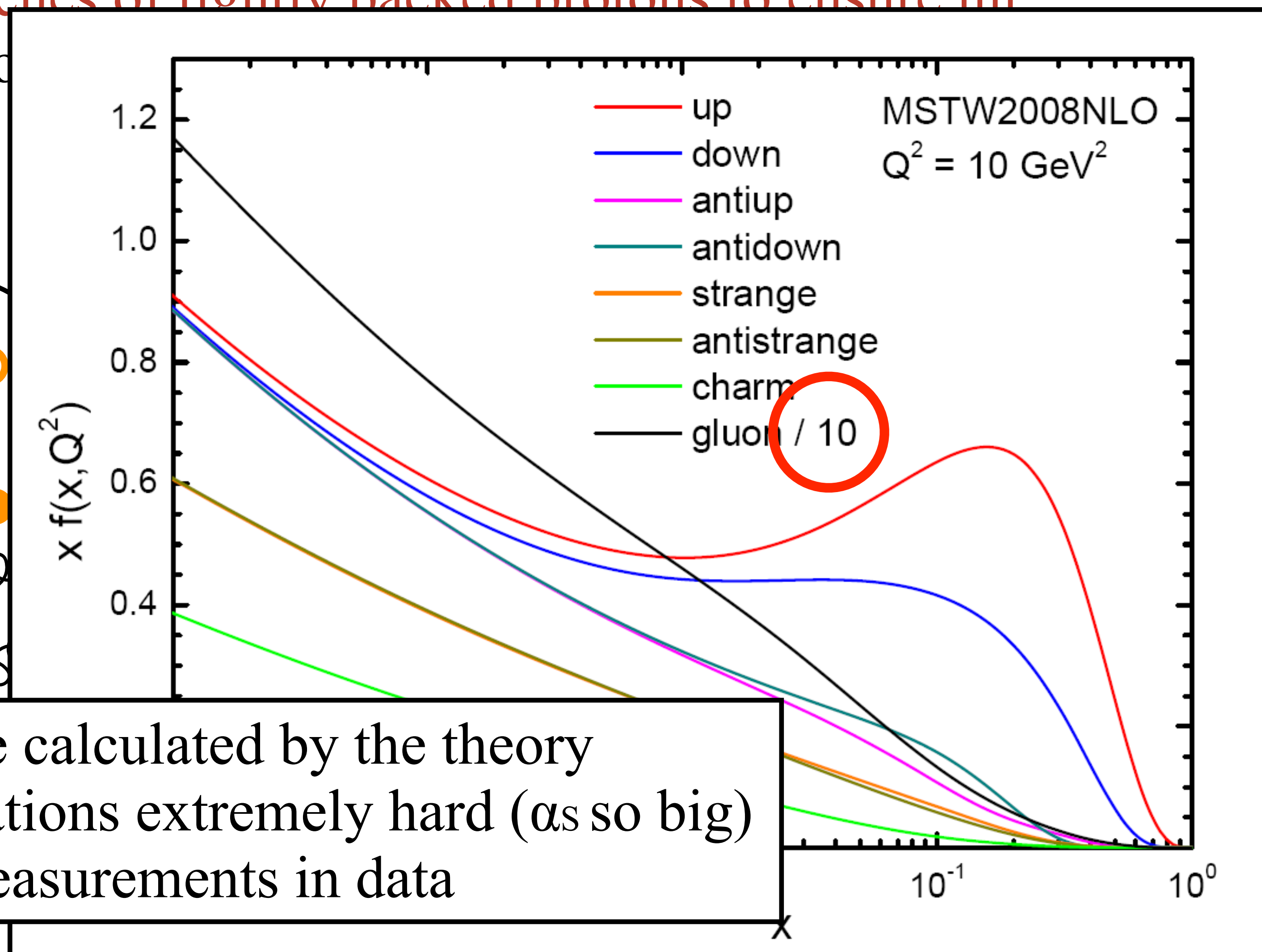

Can in principle be calculated by the theory

In practice, calculations extremely hard (αs so big)

So extract from measurements in data

What We Measure

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

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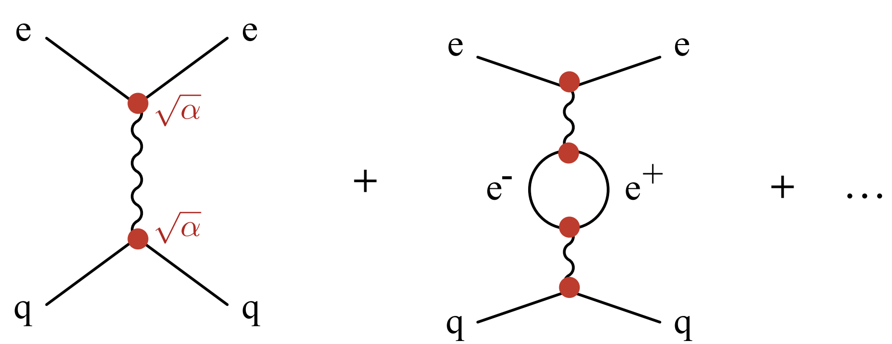

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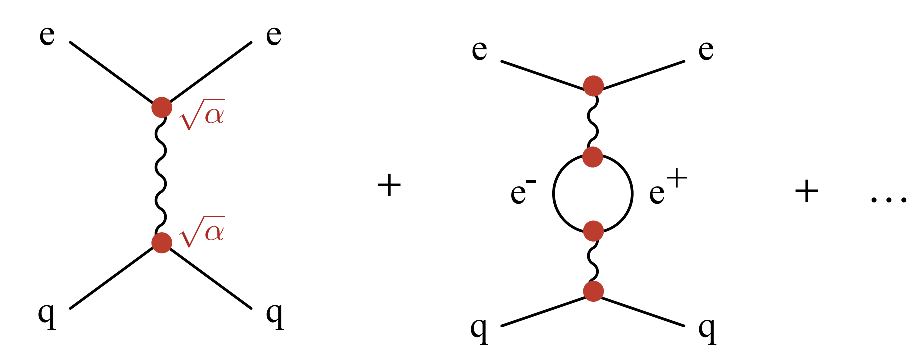

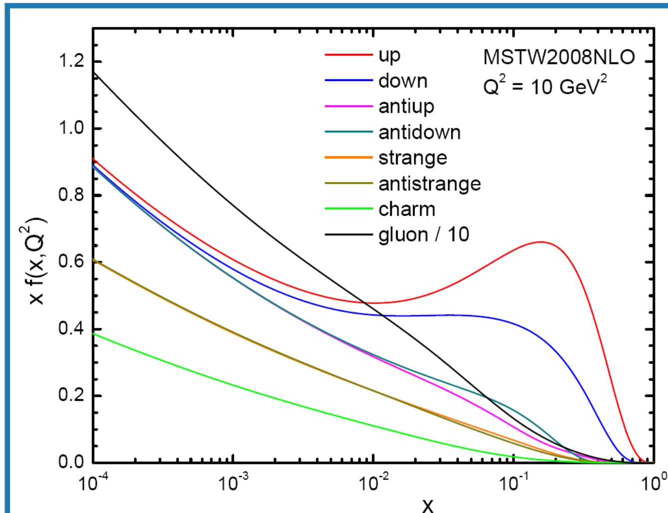

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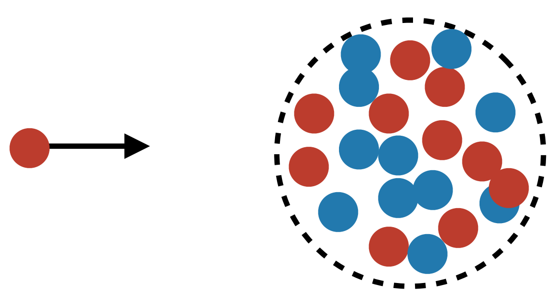

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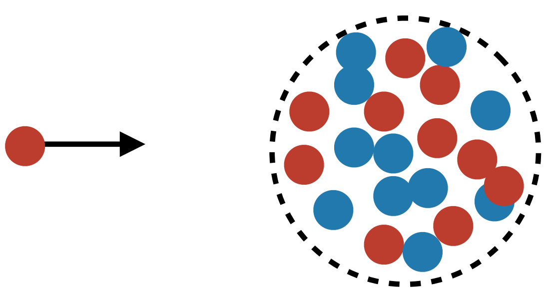

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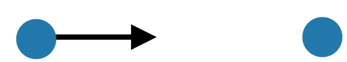

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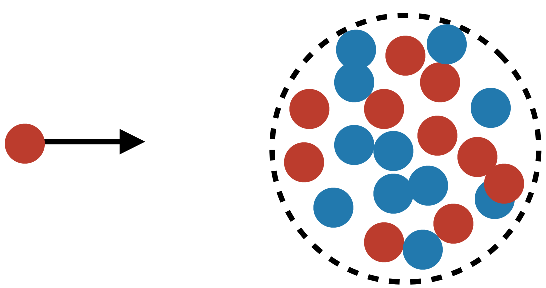

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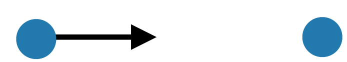

$$\sigma(\mathrm{n} \rightarrow \mathrm{U}^{238}) \sim 1 \text{ barn}$$

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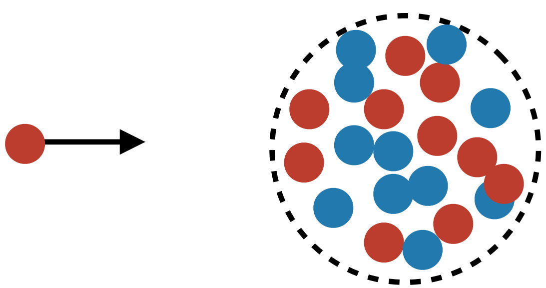

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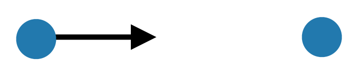

$$\sigma(\mathrm{n} \to \mathrm{U}^{238}) \sim 1 \text{ barn} \sim (238)^{2/3} \times \sigma(\mathrm{p},\mathrm{p})$$

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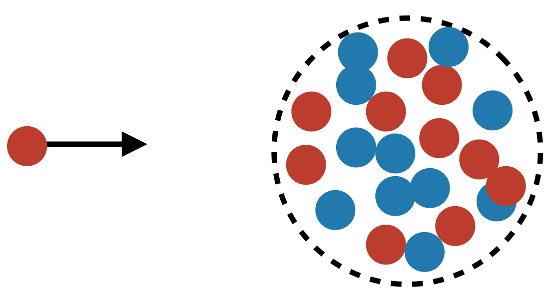

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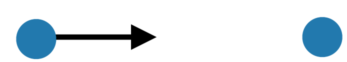

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$$\Longrightarrow \sigma(\mathrm{p} \to \mathrm{p}) \sim 0.03 \text{ barn (30 millibarn)}$$

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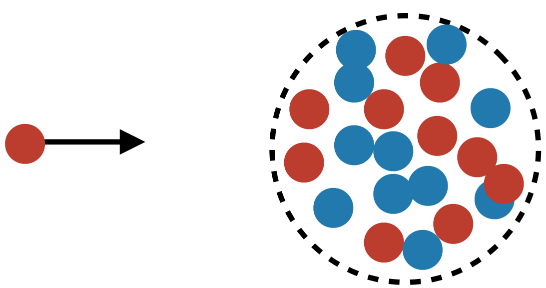

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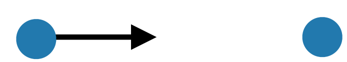

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Count pictures ("*Events*")
Compare events selected w/particular signature to prediction from theory

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) → $\mathcal{L}$

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

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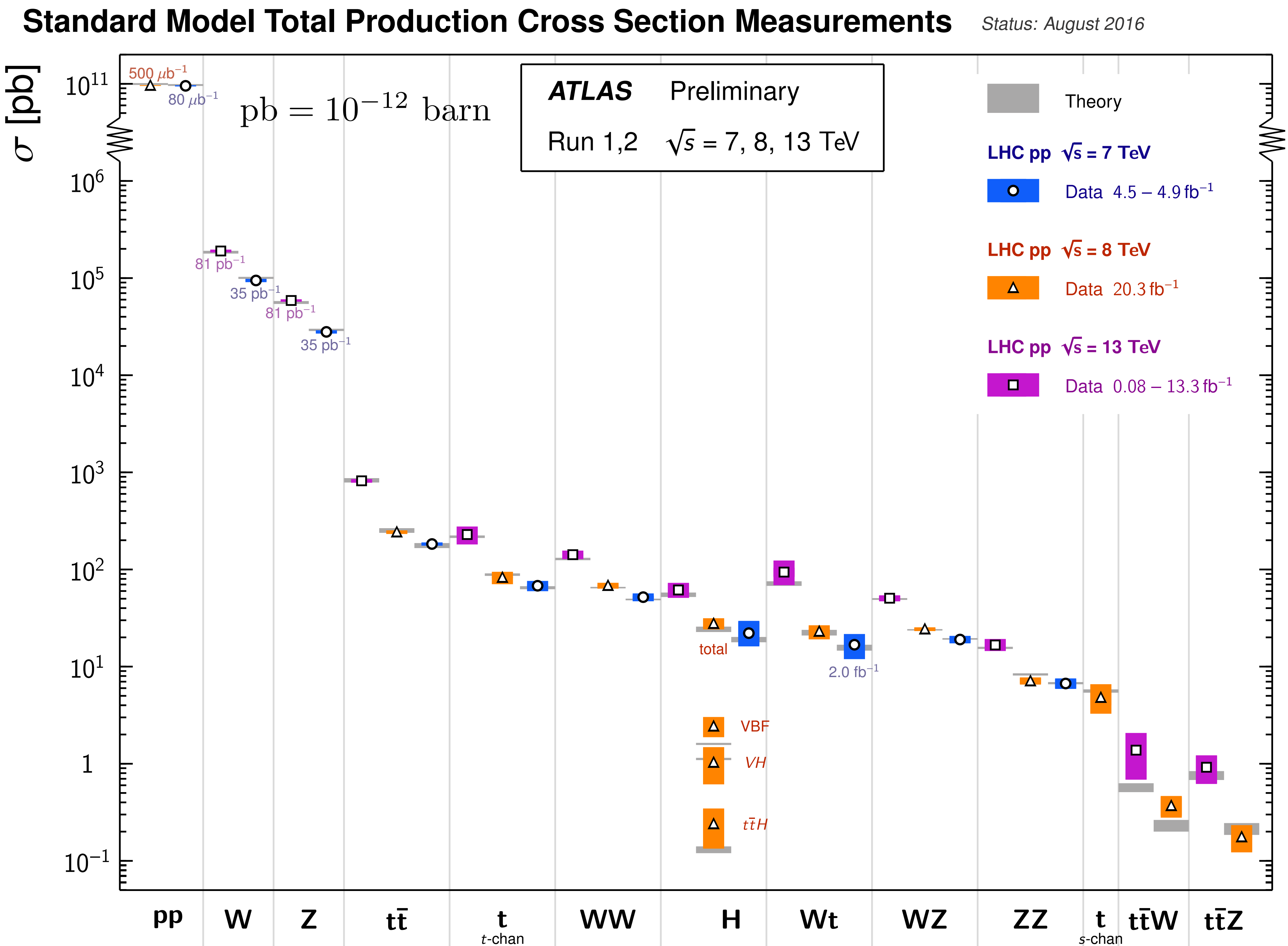
Report measured probabilities *(cross sections)* / Compare directly to theory

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


Standard Model Total Production Cross Section Measurements
Status: August 2016
σ [pb]
pb = 10^−12 barn
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb^−1
LHC pp √s = 8 TeV
Data 20.3 fb^−1
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb^−1
500 μb^−1
80 μb^−1
81 pb^−1
35 pb^−1
81 pb^−1
35 pb^−1
total
2.0 fb^−1
VBF
VH
tt̄H
10^11
10^6
10^5
10^4
10^3
10^2
10^1
1
10^−1
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
tt̄W
tt̄Z

Advantage of Higher Energy

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

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

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Now ~ 10

(linear w/dataset size)

Advantage of Higher Energy

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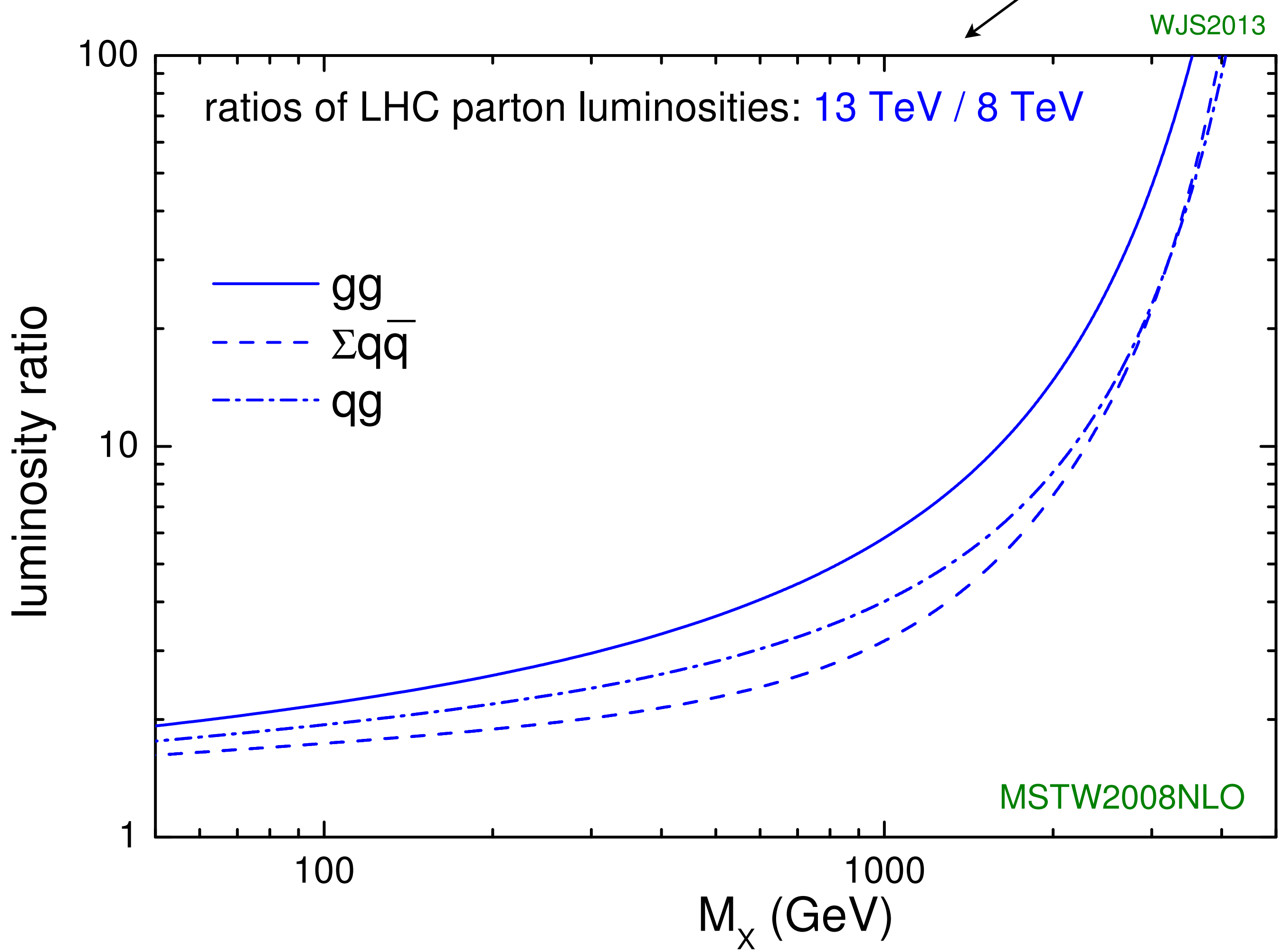

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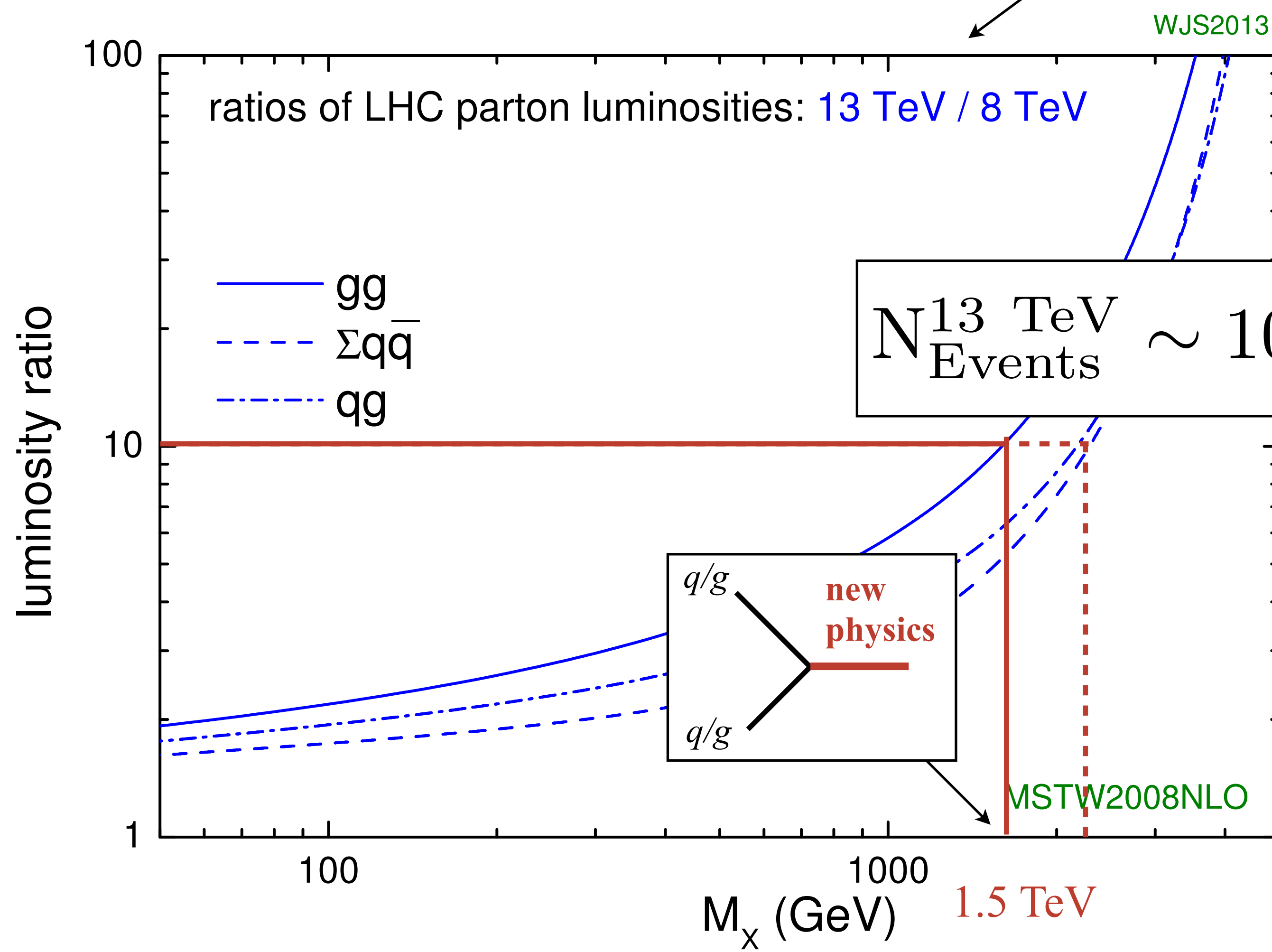

$$N^{13\ \text{TeV}}_{\text{Events}} \sim 100 \times N^{8\ \text{TeV}}_{\text{Events}}$$

Advantage of Higher Energy

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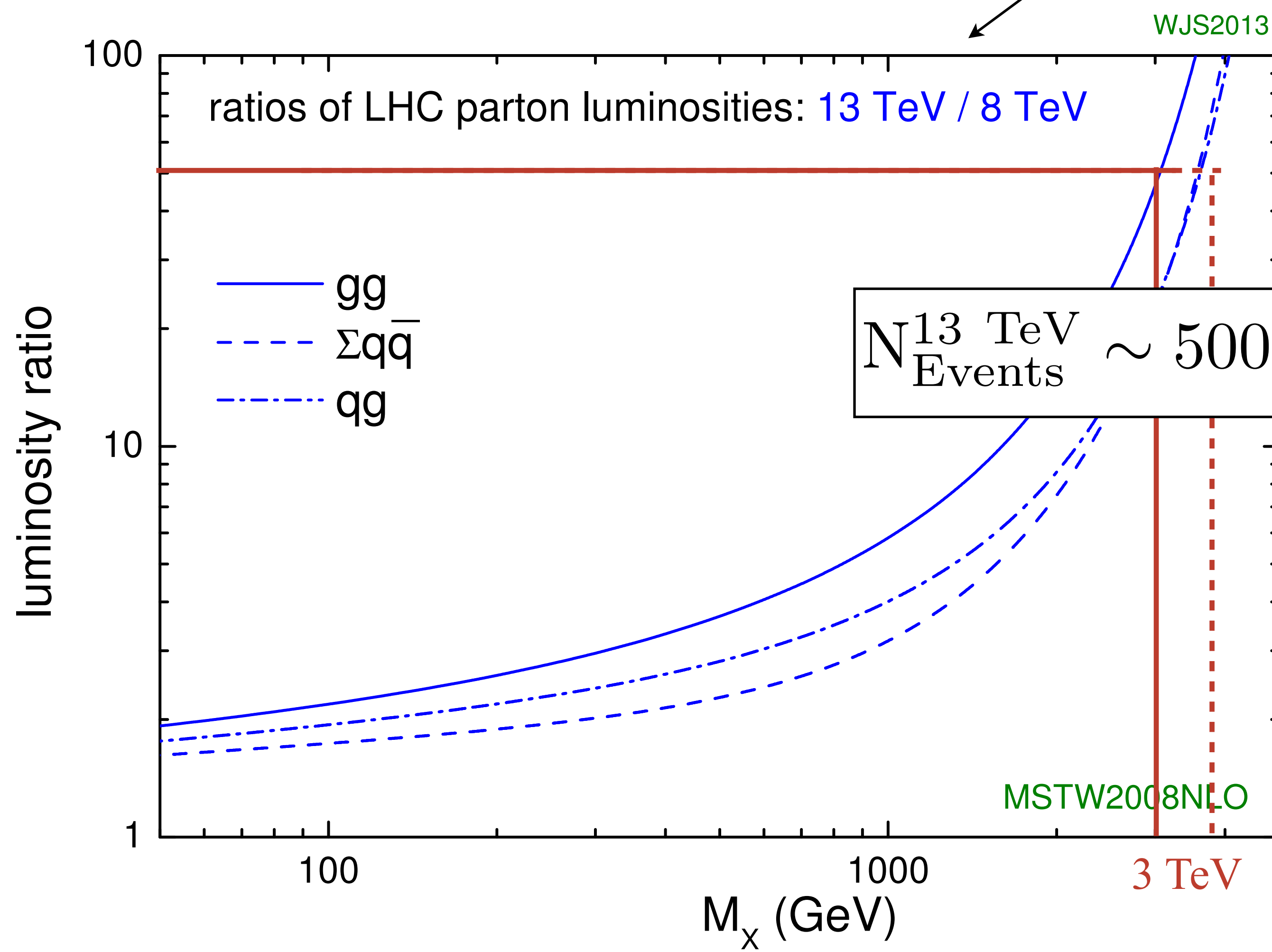
$$\frac{N^{13\ \text{TeV}}_{\text{Events}}}{N^{8\ \text{TeV}}_{\text{Events}}} = \frac{\sigma^{13\ \text{TeV}}}{\sigma^{8\ \text{TeV}}} \times \frac{\mathcal{L}^{13\ \text{TeV}}}{\mathcal{L}^{8\ \text{TeV}}}$$



Now ~ 10

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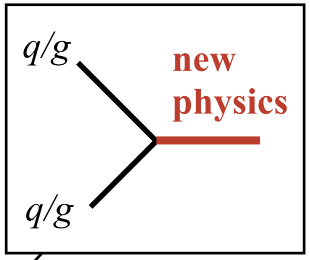
$$N^{13\ \text{TeV}}_{\text{Events}} \sim 500 \times N^{8\ \text{TeV}}_{\text{Events}}$$



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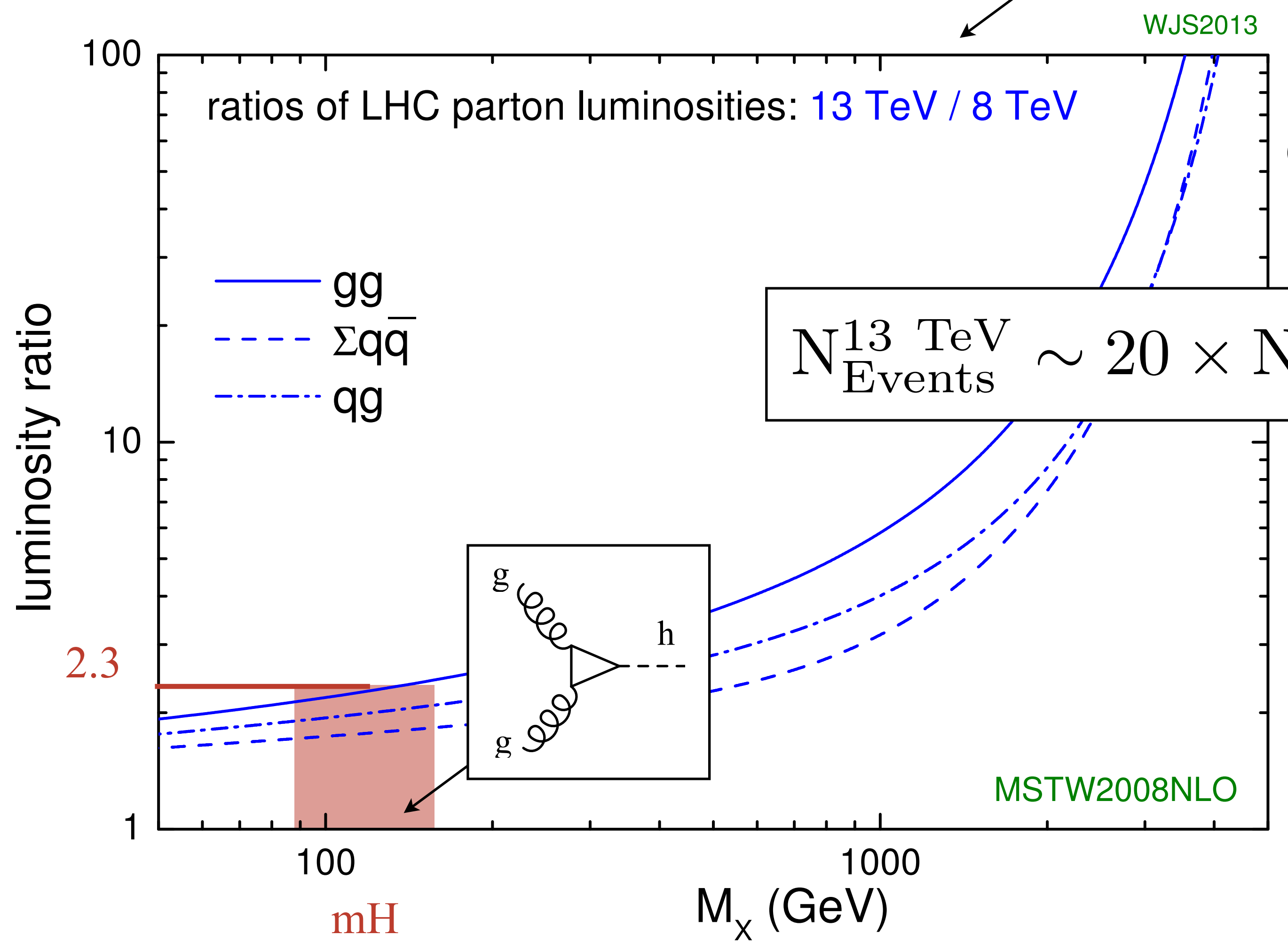
$$\frac{\mathrm{N^{13\ TeV}_{Events}}}{\mathrm{N^{8\ TeV}_{Events}}} = \frac{\sigma^{13\ \mathrm{TeV}}}{\sigma^{8\ \mathrm{TeV}}} \times \frac{\mathcal{L}^{13\ \mathrm{TeV}}}{\mathcal{L}^{8\ \mathrm{TeV}}}$$

Now ~ 10
(linear w/dataset size)



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

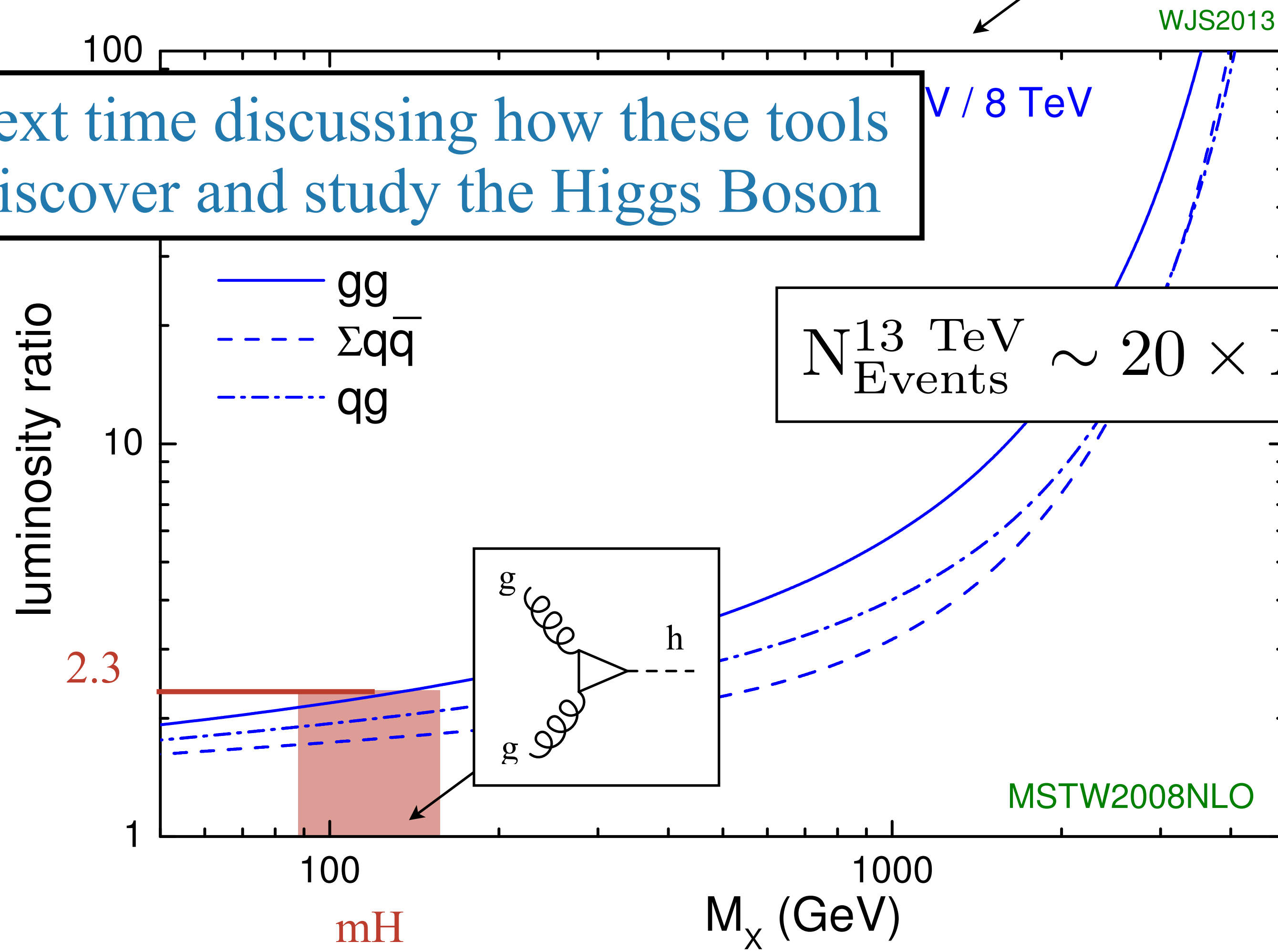
Advantage of Higher Energy

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

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

Now ~ 10

(linear w/dataset size)



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

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