

How to search for “New Physics” at the LHC

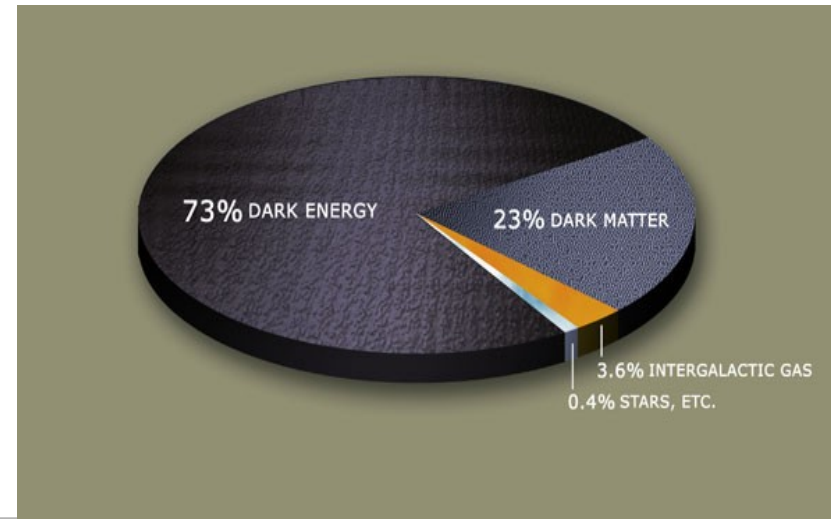
Petar Maksimovic

- “New Physics” = what is not Standard Model
- a.k.a. “Beyond Standard Model” Physics (BSM)

Questions

- What is the World made of?
- What is the nature of mass, energy, space & time?
- Are there new forces of nature?
- Are the known forces just manifestations of one fundamental interaction?
- What is the nature of dark matter and dark energy?
- Why is universe dominated by matter?

Particle physics attempts to answer these questions



Three families of Standard Model

	I	II	III
mass→	2.4 MeV	1.27 GeV	171.2 GeV
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name→	u up	c charm	t top
Quarks	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	d down	s strange	b bottom
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV
	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	0.511 MeV	105.7 MeV	1.777 GeV
	-1	-1	-1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	e electron	μ muon	τ tau

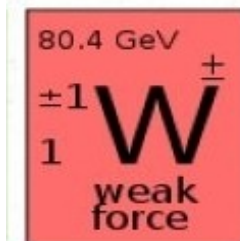
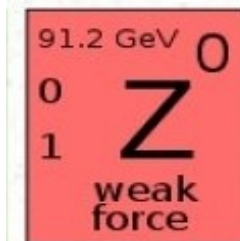
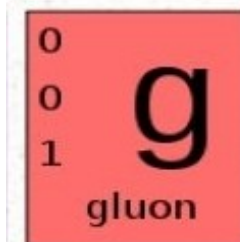
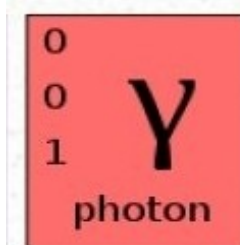
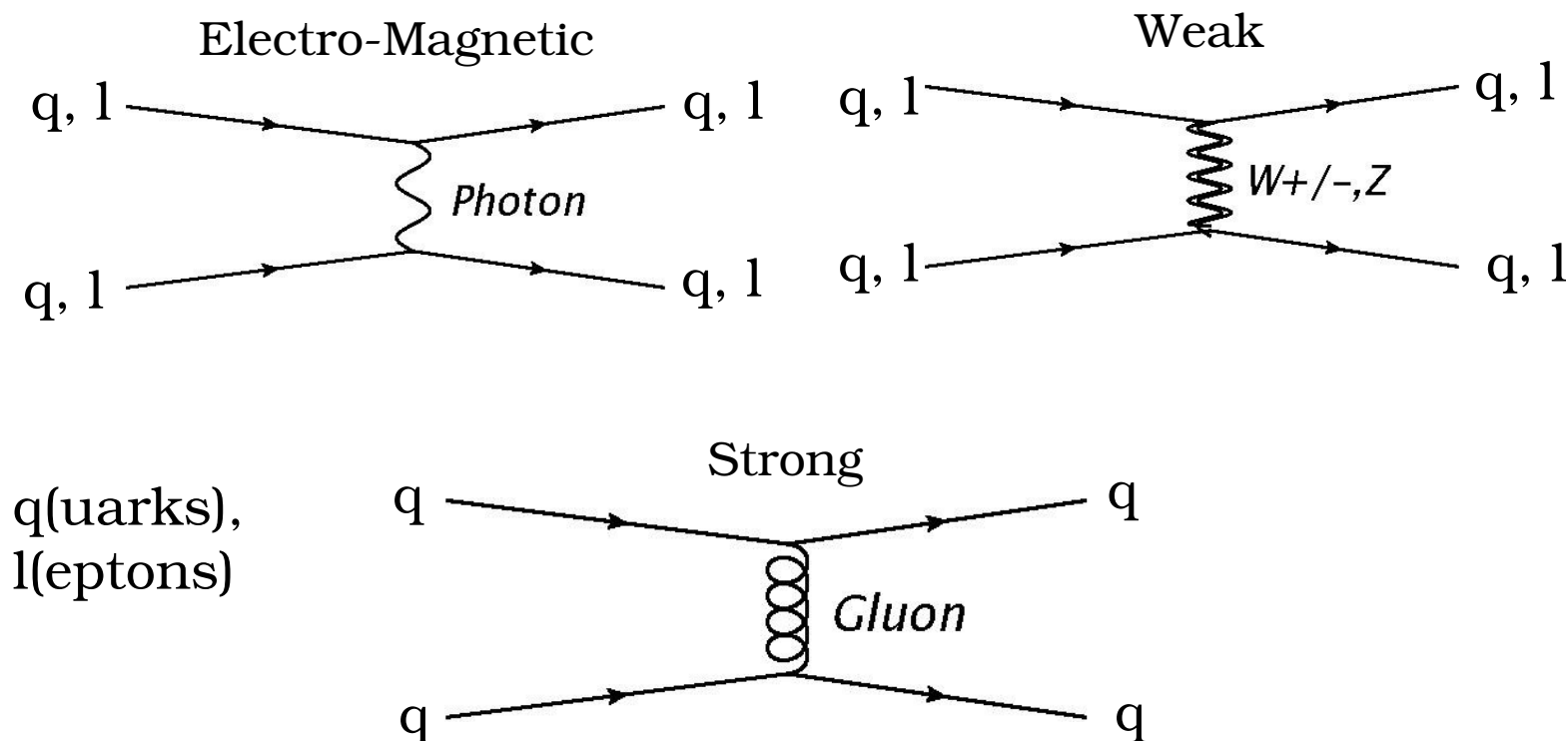
- All matter is composed of fermions = organized in three families of

- 6 leptons
- 6 quarks
- masses are external parameters

==> we don't know why top quark is so heavy!

- Three forces:
 - Electromagnetic
 - Weak
 - Strong
- No Gravity!

Standard Model: Interactions



- Fermions with charge interact via Electromagnetic force
 - Quantum Electrodynamics (QED)
- Fermions with color (quarks) interact via Strong force
 - Quantum Chromodynamics (QCD)
- Fermions with weak isospin (all) interact via Weak force

Calculating things in Standard Model

- Particles collide, different things can happen
 - governed by Quantum Mechanics → probabilities
 - production rate $\sim$ cross section * luminosity (flux)
- Cross section, classically:
 - effective area of collision



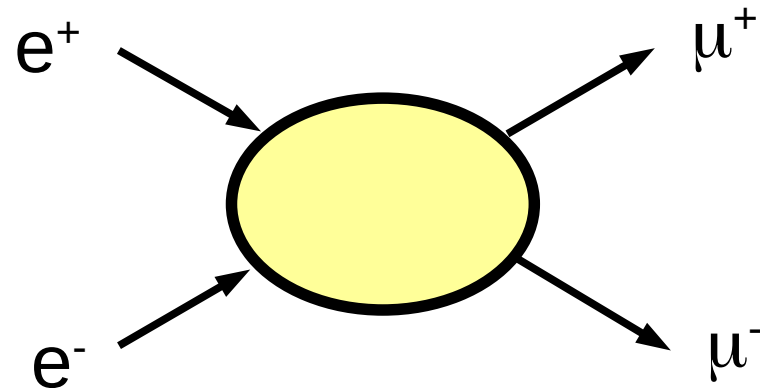
- (a bit more complicated for $1/r^2$ field, e.g. Rutherford scattering)
- Cross section, Quantum-Mechanically:
 - rate $\sim \sigma \sim |\mathcal{M}|^2 \times (\text{phase space})$ (“Fermi's golden rule”)
 - $\mathcal{M}$ = Quantum-Mechanical amplitude

Quantum Electrodynamics (QED)

- Consider $e^+ e^- \rightarrow \mu^+ \mu^-$

- Probability $\sim |\mathcal{M}|^2$

- $\mathcal{M}$ is calculated as infinite series of terms
(usually ever smaller)



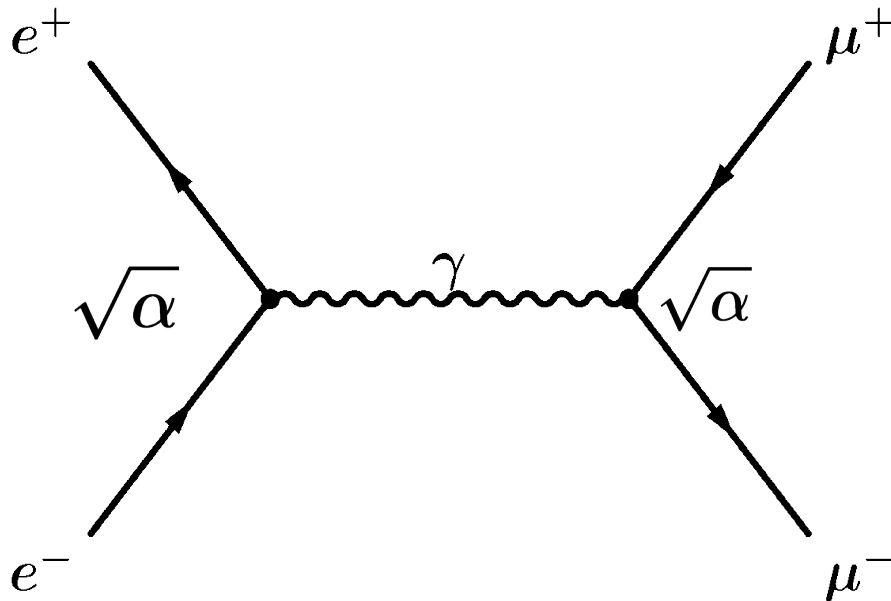
- Each term is represented with a pictogram, called a Feynman diagram
- Digression: Leibnitz formula for π :

$$\pi = 4 \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} = 4 - \frac{4}{3} + \frac{4}{5} - \frac{4}{7} + \frac{4}{9} - \dots$$

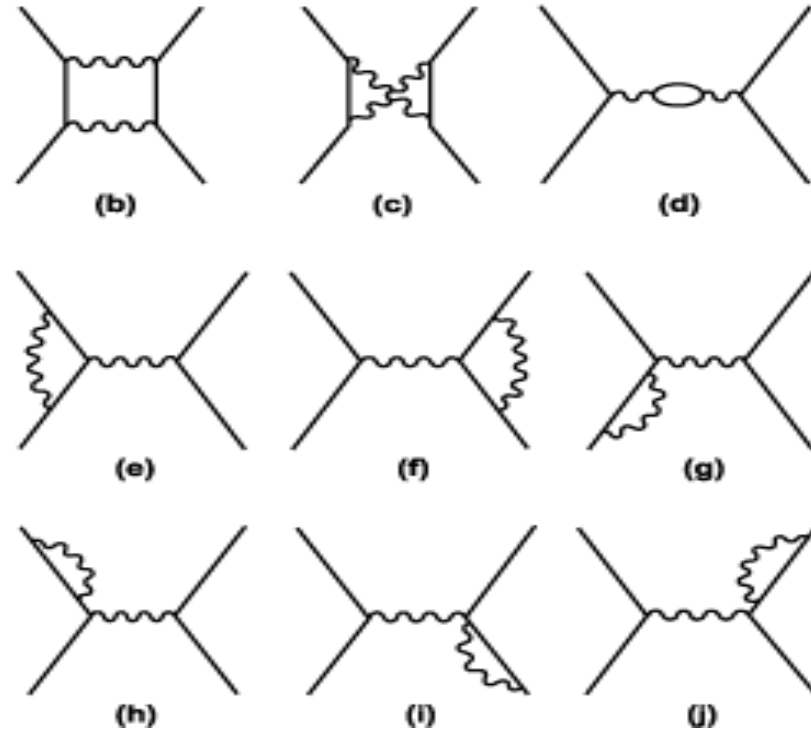
- an example of a converging infinite series

Feynman series

- Incoming particles: e^+, e^-
- Outgoing particles: μ^+, μ^-

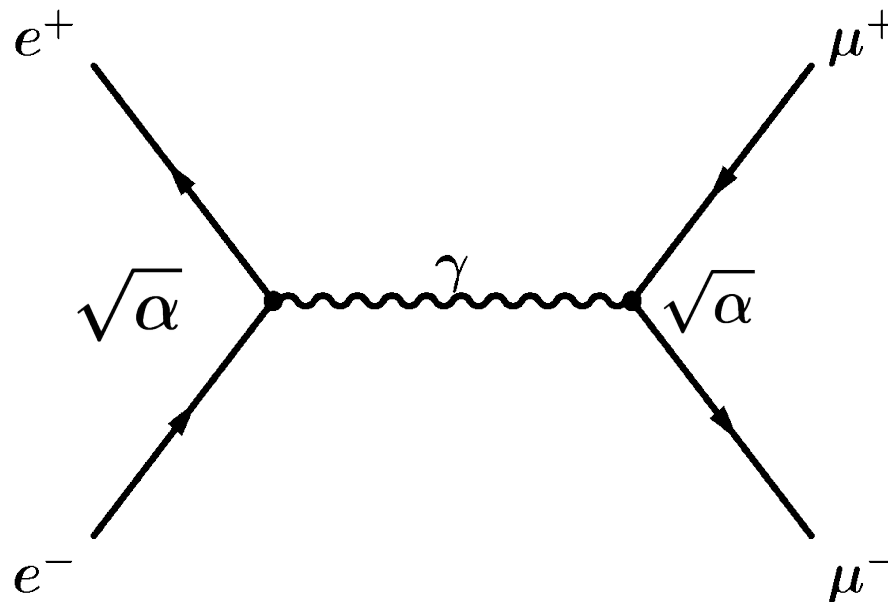


- At each vertex, coupling constant $\sqrt{\alpha}$
- $\alpha = \frac{1}{137} \rightarrow$ converges rapidly!



Virtual particles

- Photon in the middle can violate conservation of energy-momentum – it's virtual.

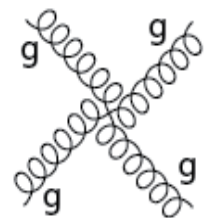
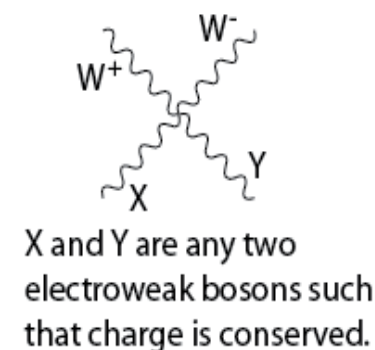
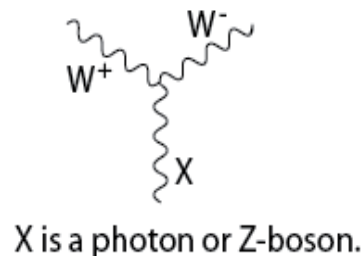
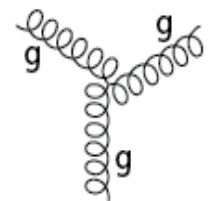
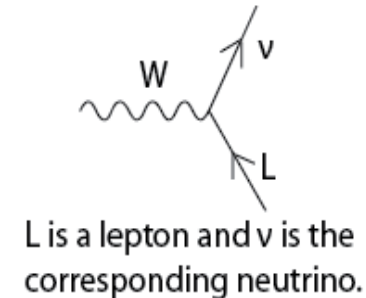
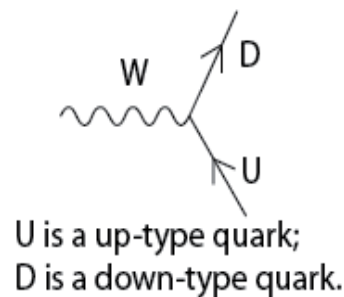
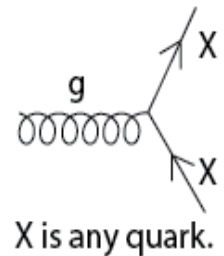
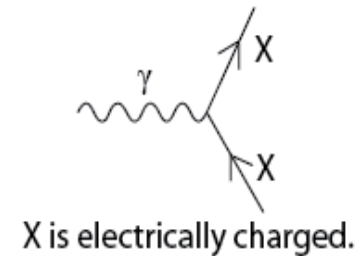
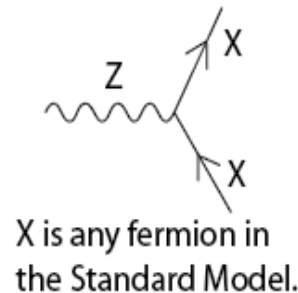


- Heisenberg Uncertainty Principle $\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$
- So it's OK to borrow energy for a very short period of time

Feynman rules

- All we need to know are the building blocks
 - lines = particles
 - vertices = how they interact!
- Build all possible diagrams for the same in/out lines
- Translate to formulas
- Sum first N terms
- Square it and... done!

Standard Model Interactions (Forces Mediated by Gauge Bosons)



Weak interactions

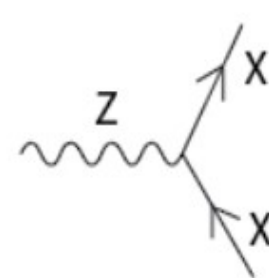
- “Quark flavor” = which type of quark it is (top, bottom, strange...)



U is a up-type quark;
D is a down-type quark.

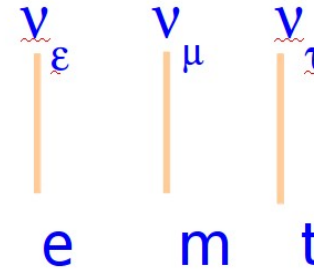
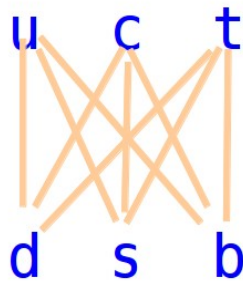


L is a lepton and ν is the
corresponding neutrino.



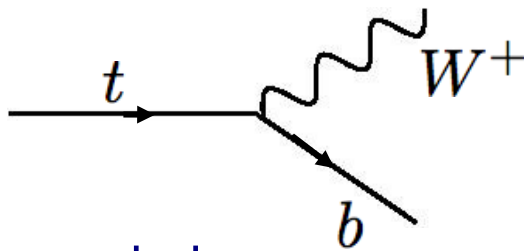
X is any fermion in
the Standard Model.

- W boson couples up-type quarks to down-type quarks
(quarks)



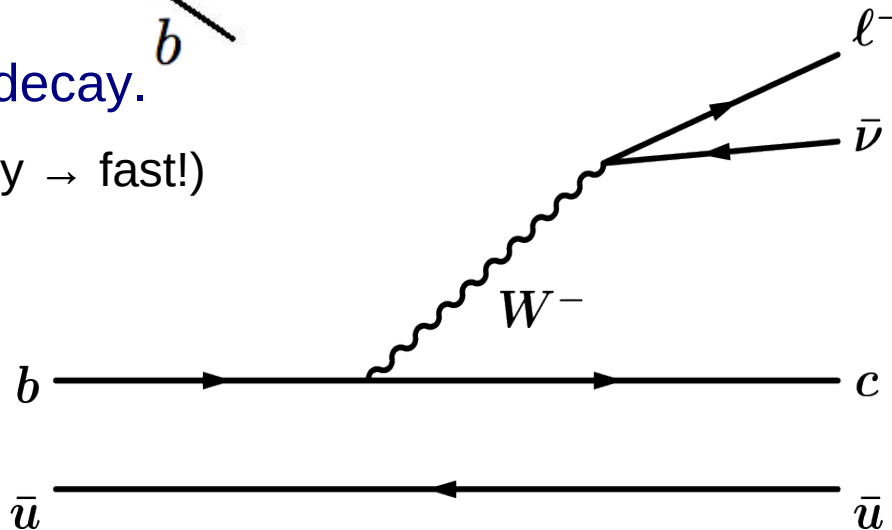
Examples of decays via weak interaction

- W bosons couple up-type and down-type fermions
 - couple quarks across families
 - couplings are external parameters too



Top quark decay.

(Top is heavy $\rightarrow$ fast!)



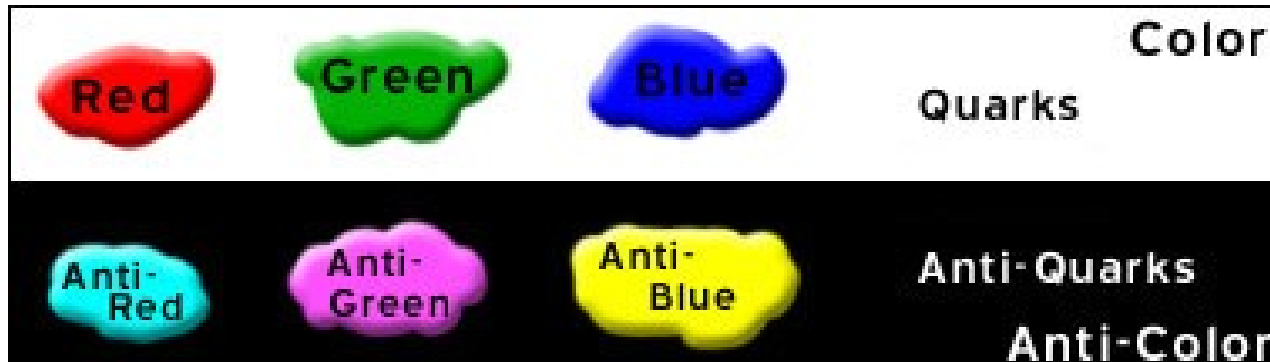
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charge $\rightarrow$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
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name $\rightarrow$	u up	c charm	t top
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom
	<2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau
Leptons			

Decay of B meson
into lepton + neutrino
+ D meson

(W is virtual $\rightarrow$ slow!)

Quantum Chromo-Dynamics (QCD)

- Strong force (QCD): quarks carry color, interact via (8) gluons:



Quarks carry a color



Anti-quarks carry an anti-color

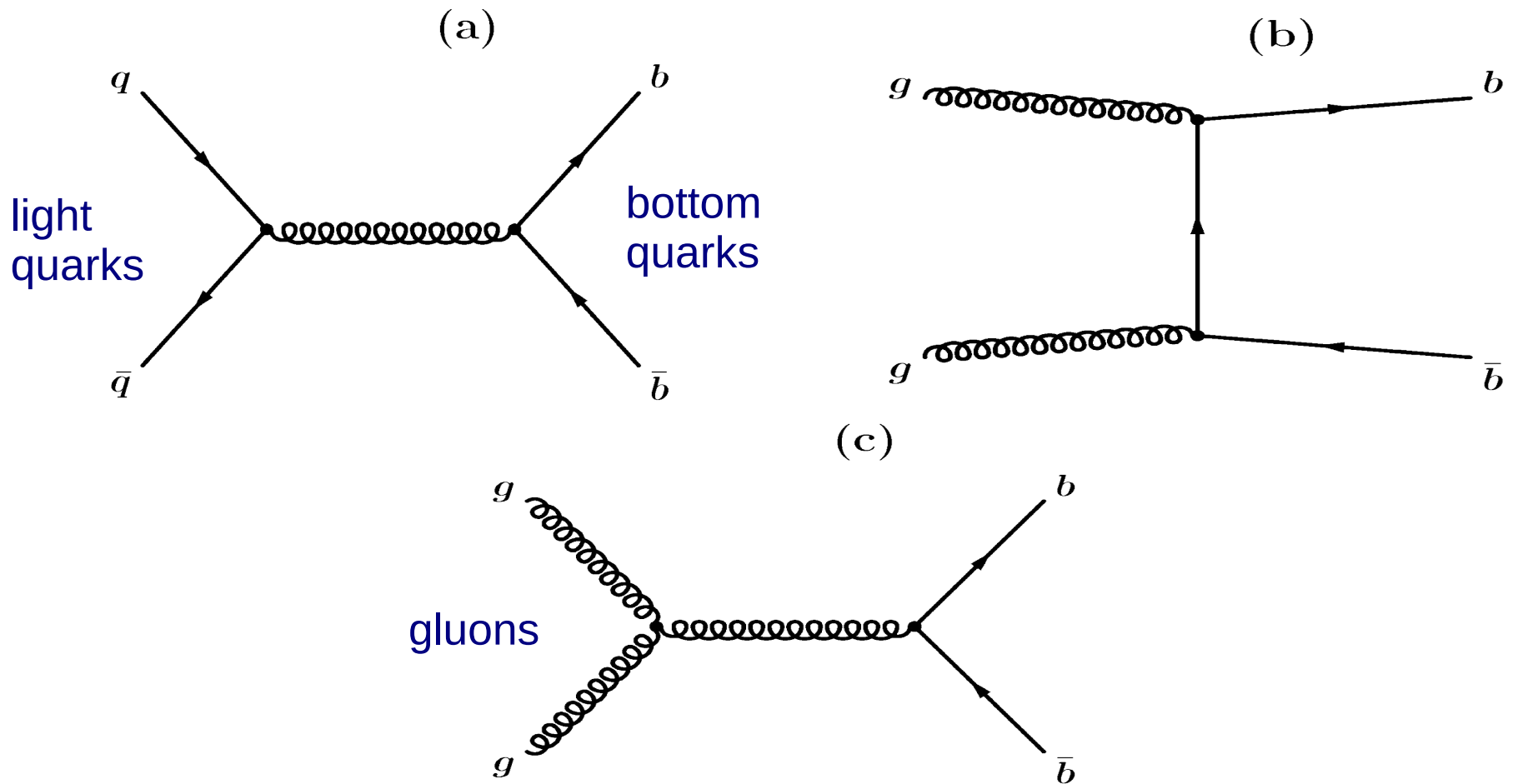


Gluons carry a color and an anti-color

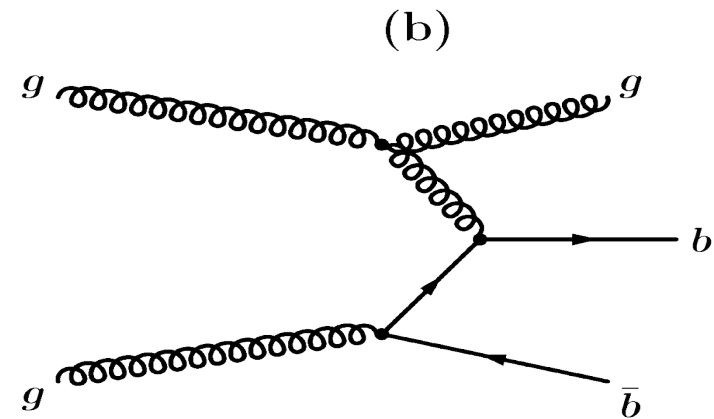
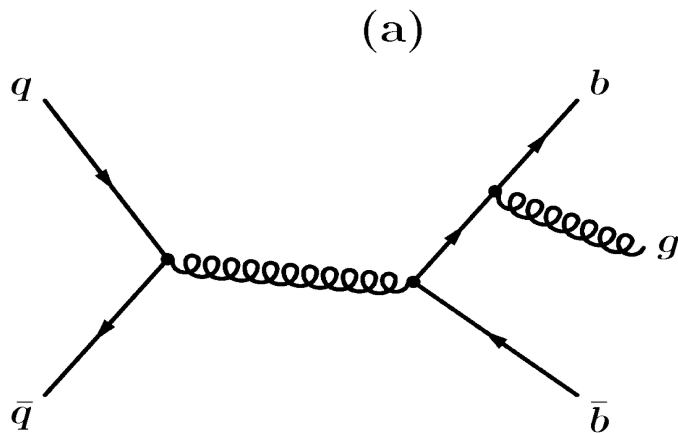
- But strong force is different from E&M:
 - gluons couple to each other
 - coupling constant $\alpha_s \sim 1$
 - (at low energies, it actually depends on the energy)

QCD

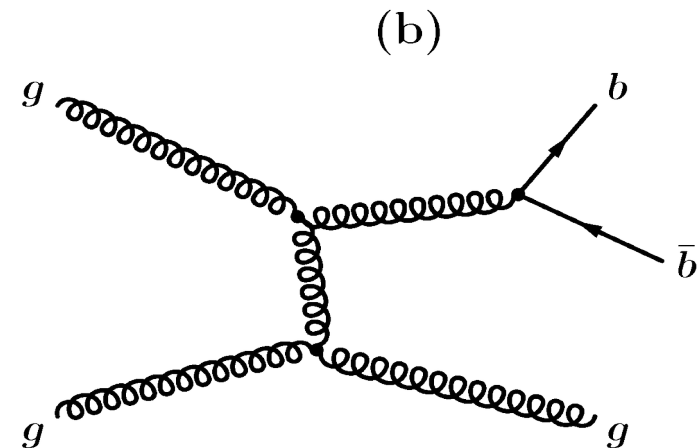
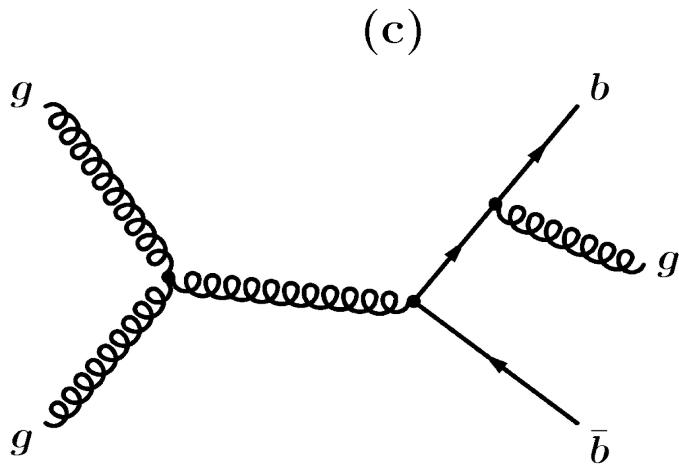
- Example: production of a pair of bottom quarks ($b\bar{b}$)



QCD

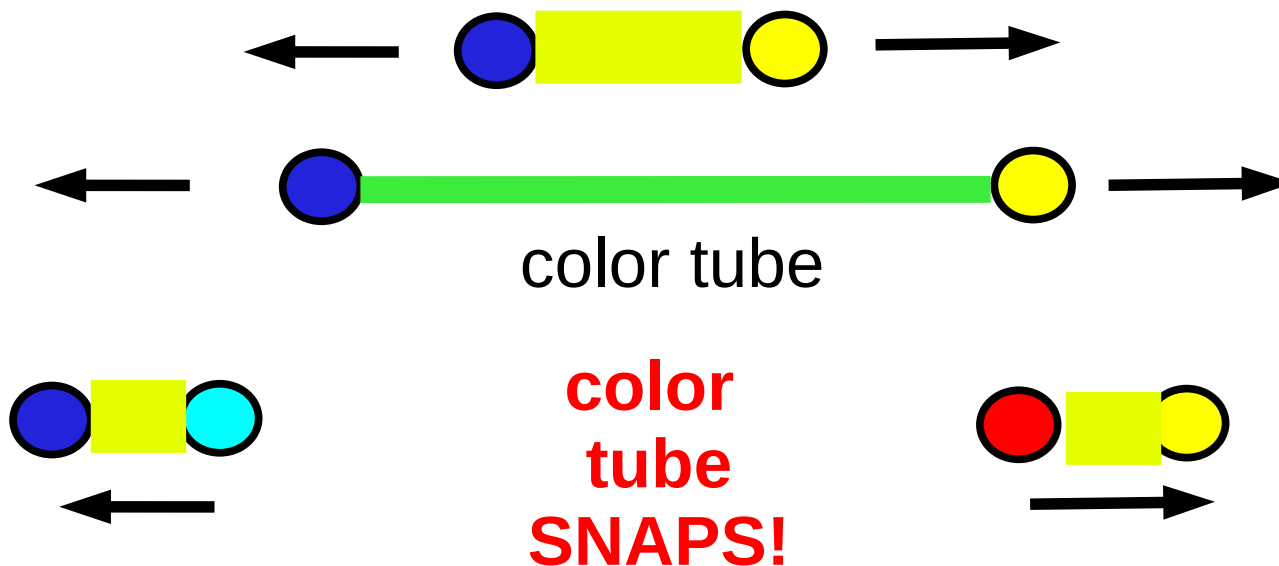


Adding more vertices with low energy gluons does not make amplitudes smaller!



QCD: hadronization

- Consider hadronic decay $W^+ \rightarrow u\bar{d}$
- As quarks move apart with high energy, color tube between them stretches, energy density rises

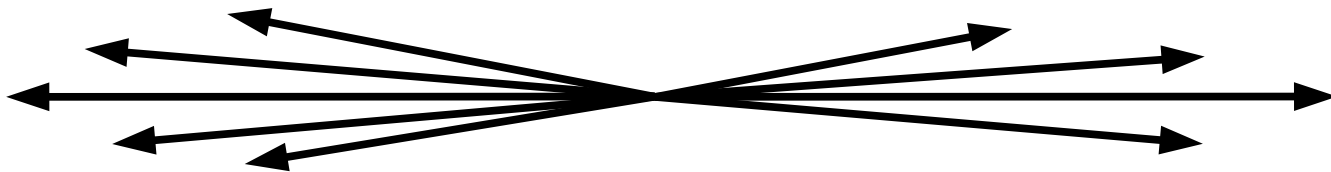


QCD: all quarks & gluons end up as jets

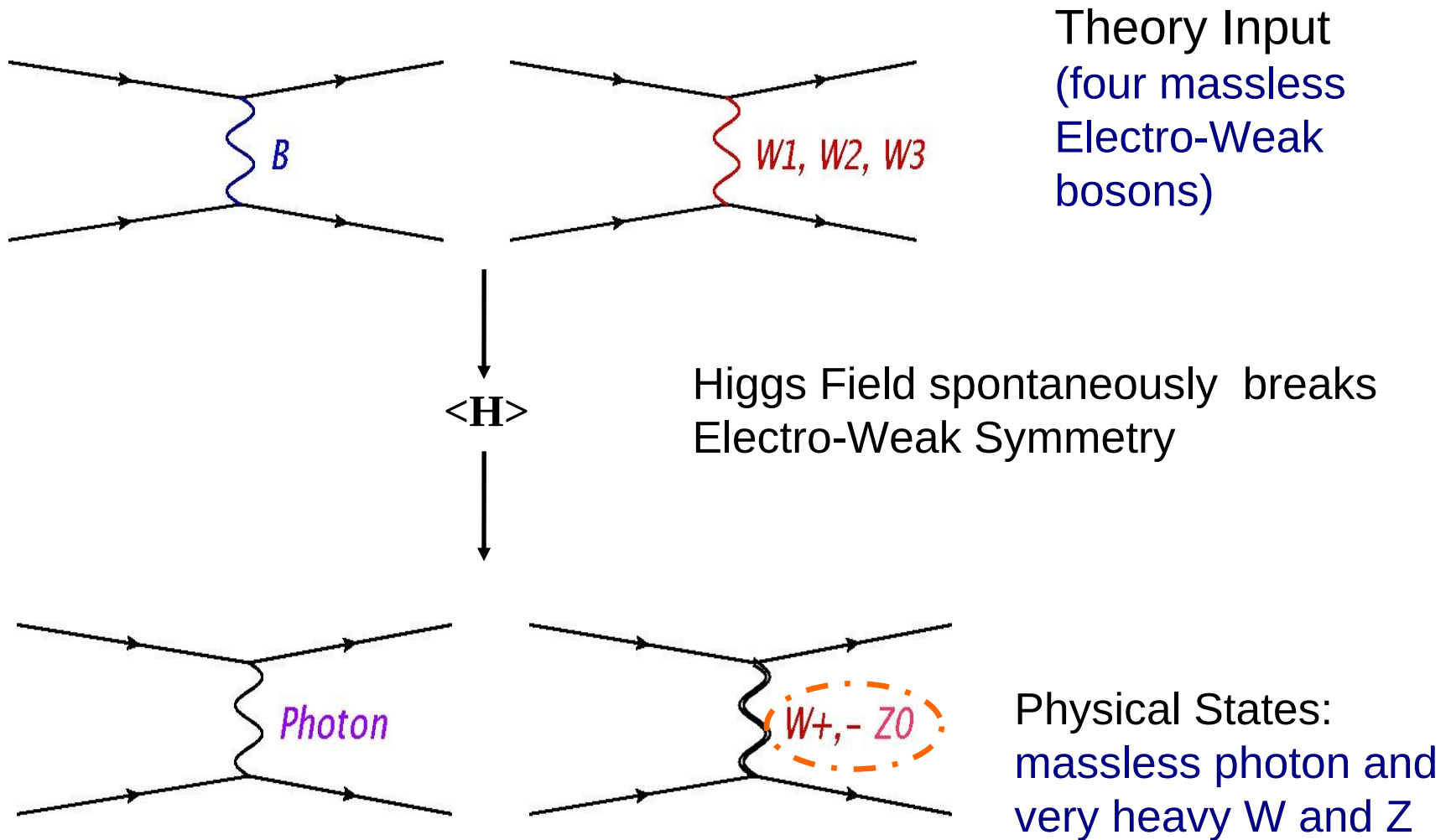
- Quarks still have unequal energies so more quark-antiquark pairs keep being created



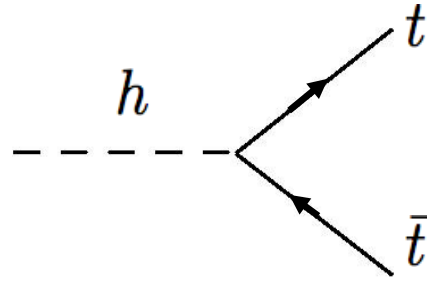
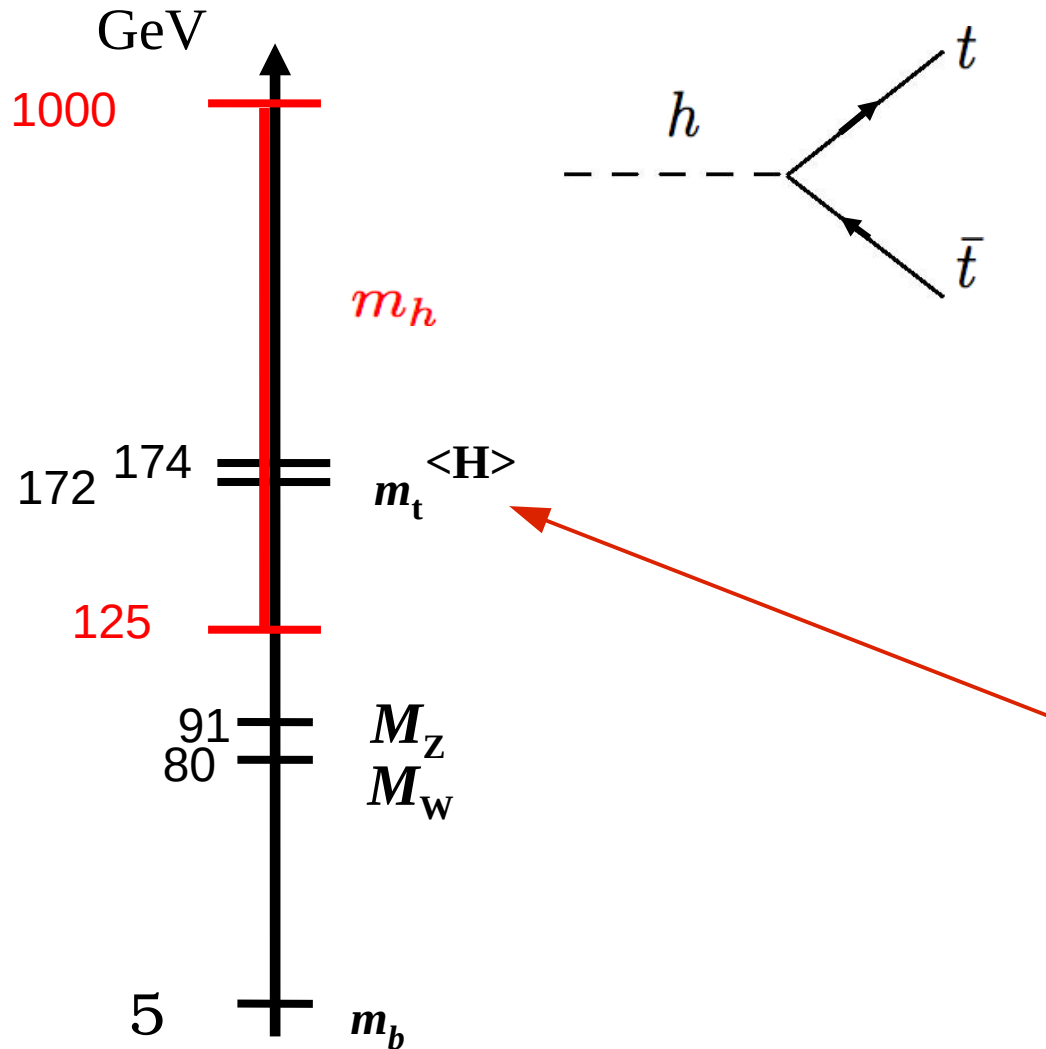
- So, every quark or gluon creates a stream of collinear particles called a 'jet':



Electro-Weak symmetry breaking



Weak scale physics

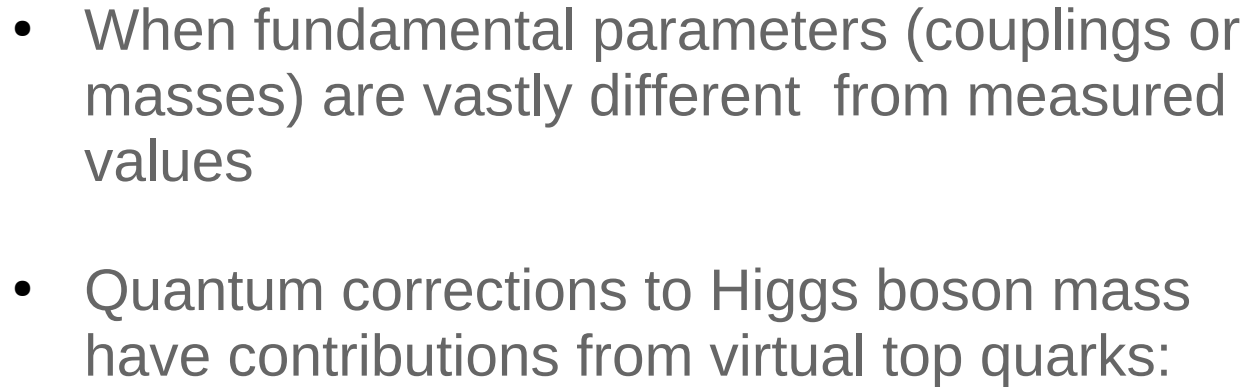


- Higgs field pervades all space
 - fermions are interacting with it and acquire mass.
 - mass $\sim$ strength of coupling to Higgs!
- $\Rightarrow$ Higgs have by far the strongest coupling to the top!

- Higgs vacuum expectation value is $\sim$ top mass!?

- Higgs has been observed!

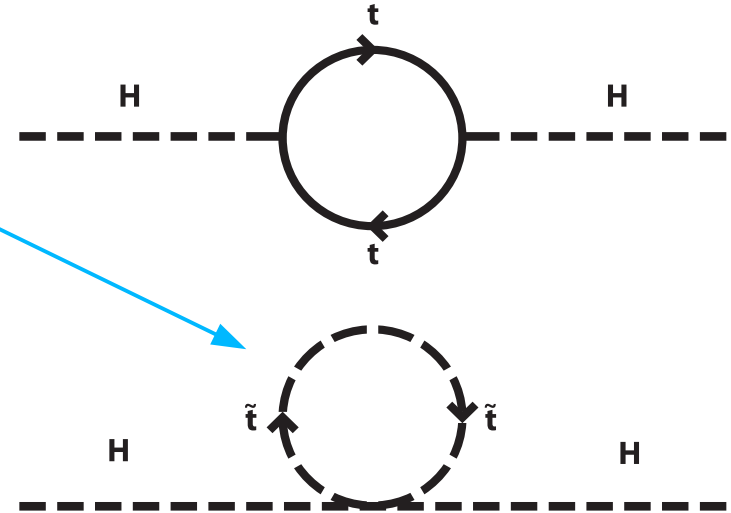
$$m_H = 125 \text{ GeV}$$



- Correction is many orders of magnitude larger!

New Physics solutions to Hierarchy Problem

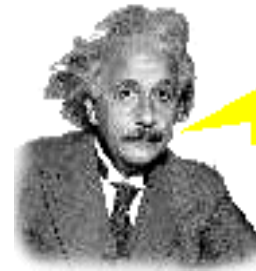
- Supersymmetry (SUSY)
 - add new particles ('super-partners') to cancel terms
 - many SUSY models result in enhanced top quark production



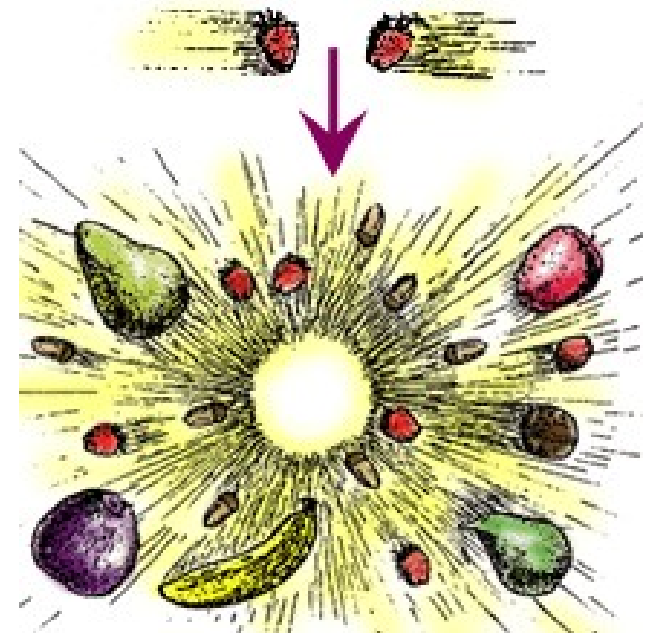
- Strongly Coupled Models:
 - Electro-Weak symmetry broken using a different mechanism
 - technicolor, topcolor, top condensates, extra dimensions
(large: Arkani-Hamed, Dimopoulos & Dvali, warped: Randall & Sundrum)
 - possible new particles (mass $\sim$ TeV) with large coupling to top quarks!

Collider Physics

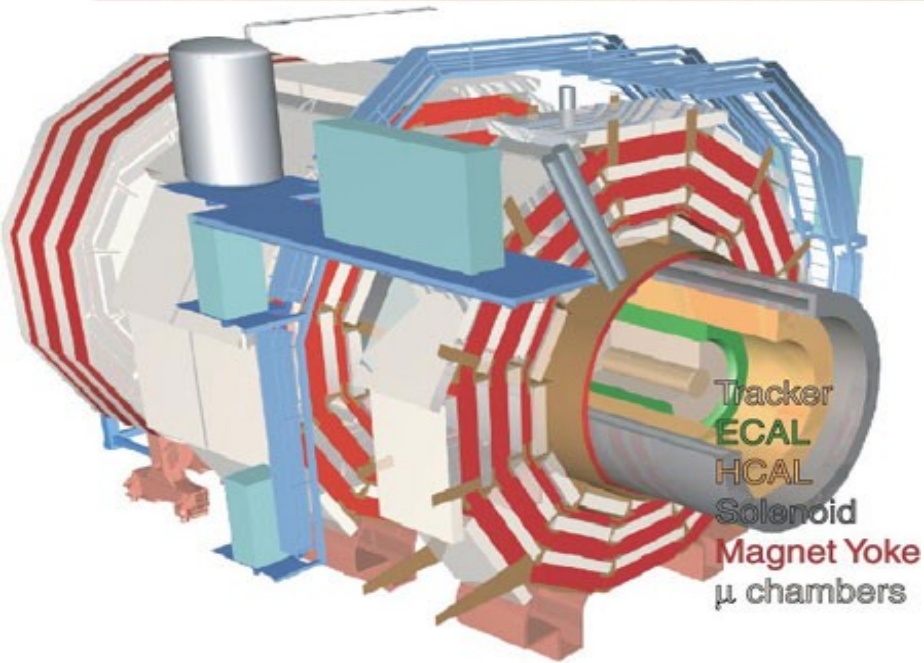
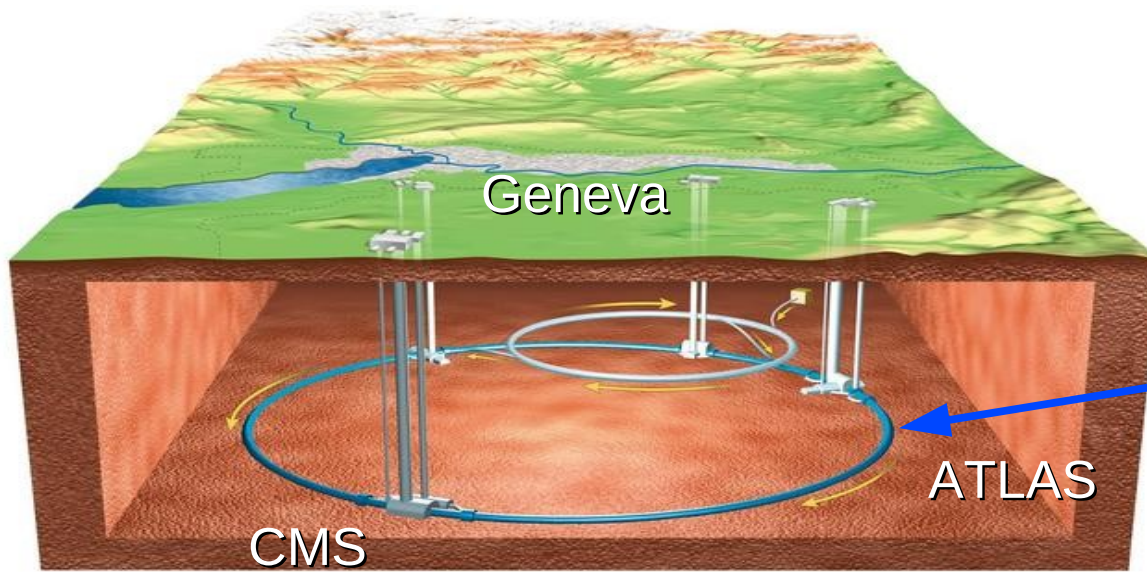
- Plan: smash protons head on and turn their kinetic energy into those heavy particles!
- Very heavy fruits (e.g. watermelons = top quarks) show up with very low probability
- Watermelons (top quarks)
 - appear briefly, but
 - decay immediately to lots of 'debris' (other fruits = particles)
- Experimental issues:
 - how to detect this 'debris'?
 - which collisions need to be saved for posterity?



Mass is just a form of energy!

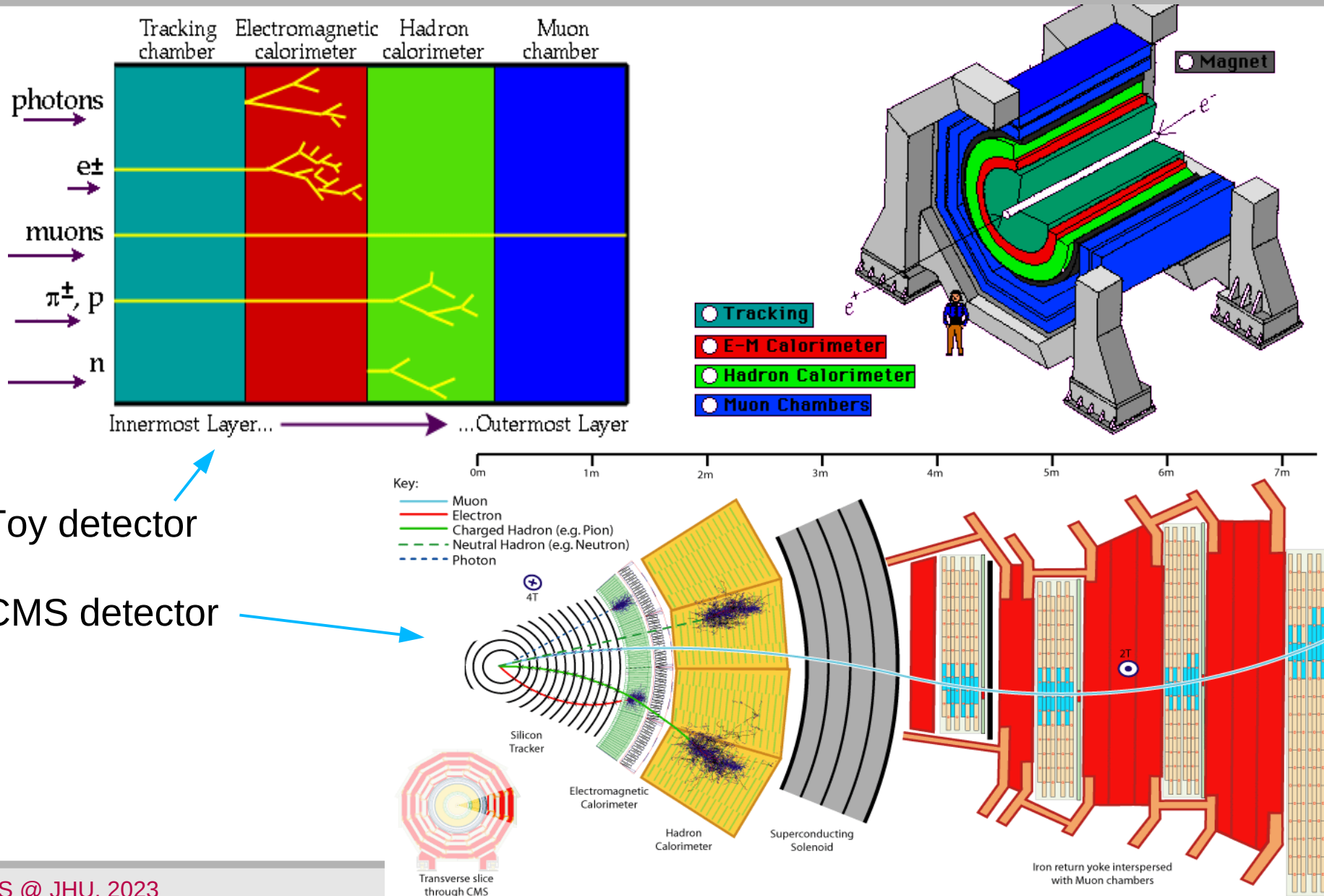


LHC and CMS Detector



- Five stories tall
("Like a 5-story swiss watch")

Collider detectors



The CMS Detector

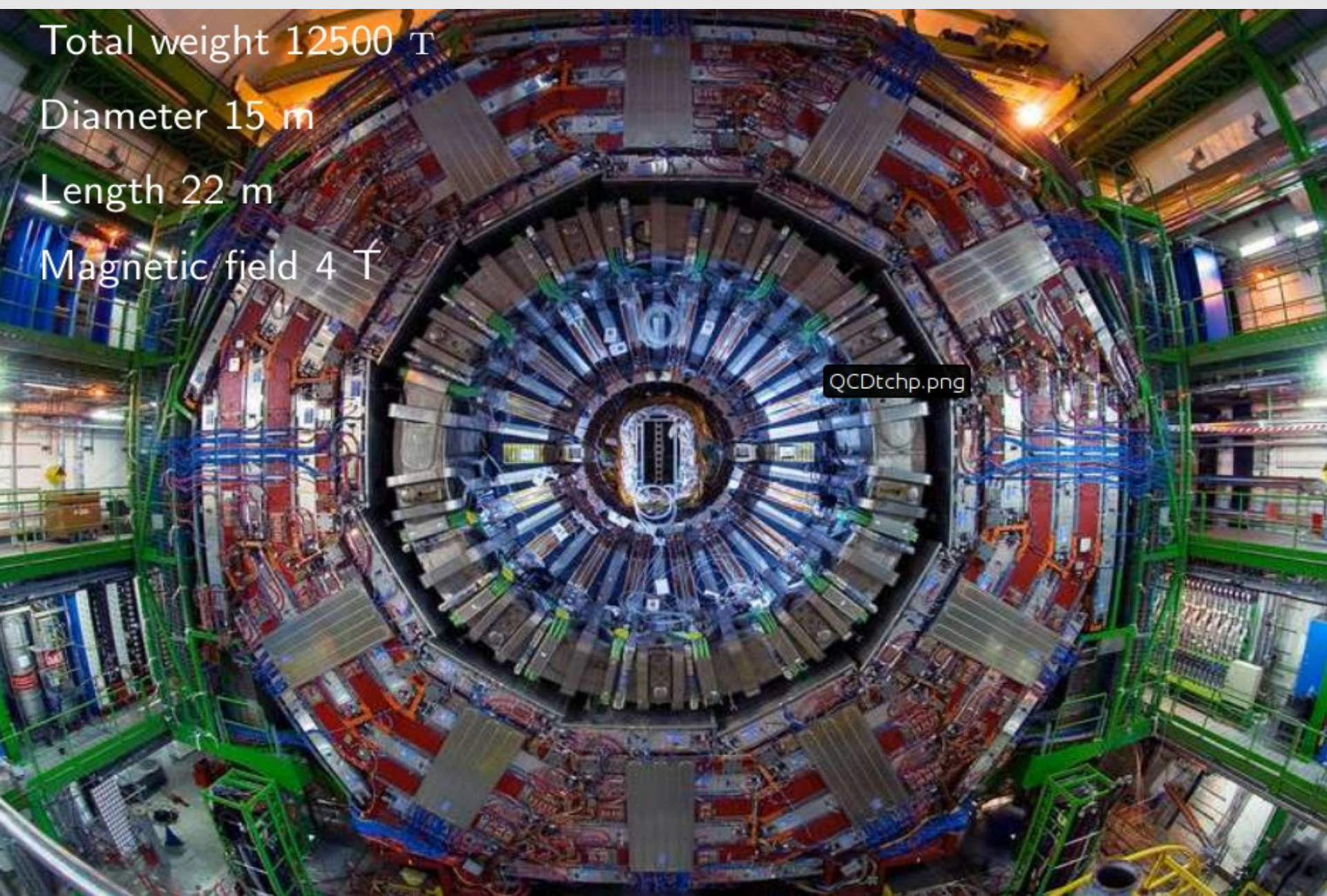
Total weight 12500 T

Diameter 15 m

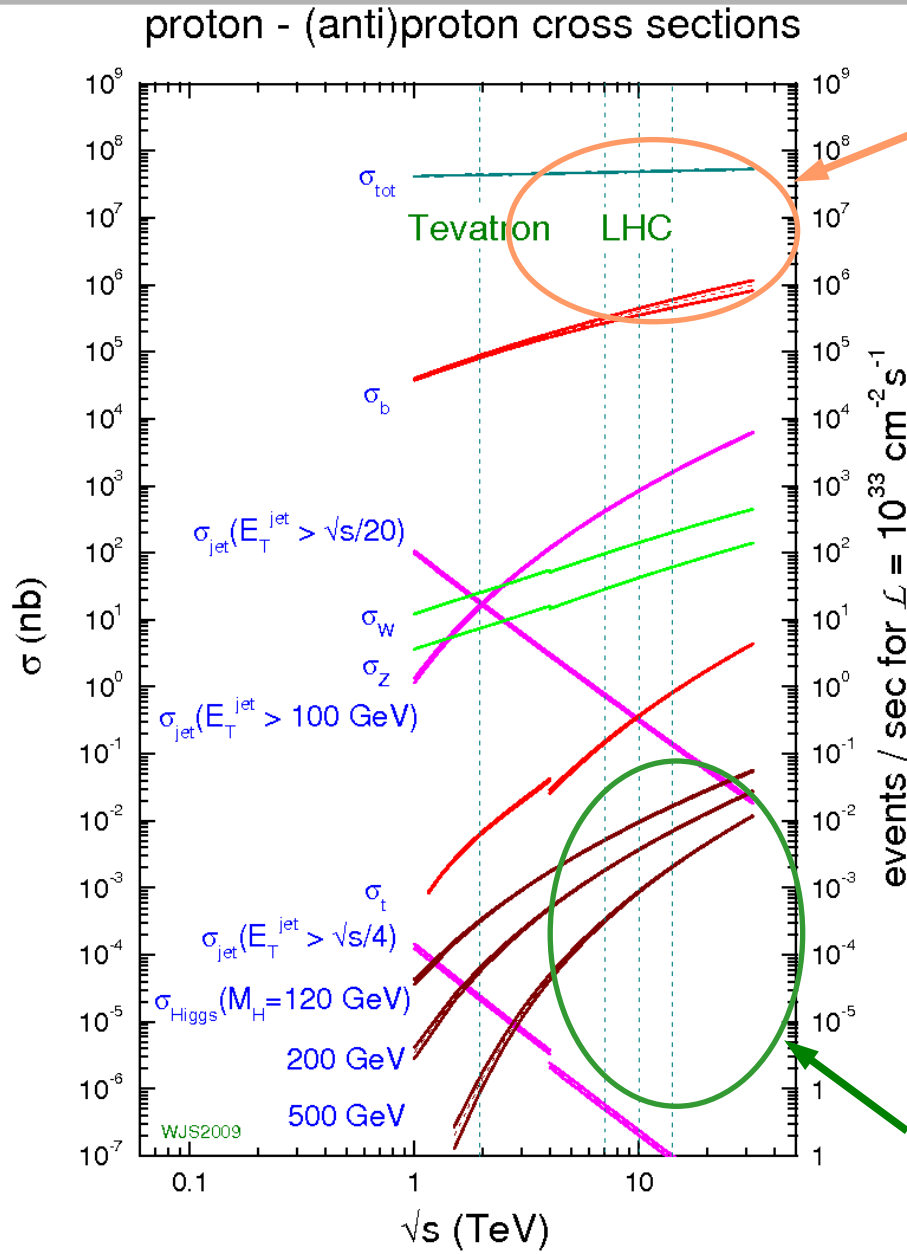
Length 22 m

Magnetic field 4 T

QCDtchp.png

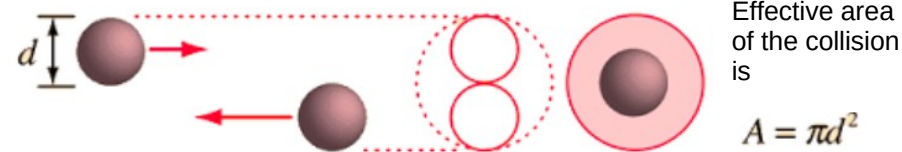


LHC production cross-sections at a glance



uninteresting

- Cross section measured in barns (area)



- Amount of data measured in inverse barns (pb^{-1} , fb^{-1} ...)

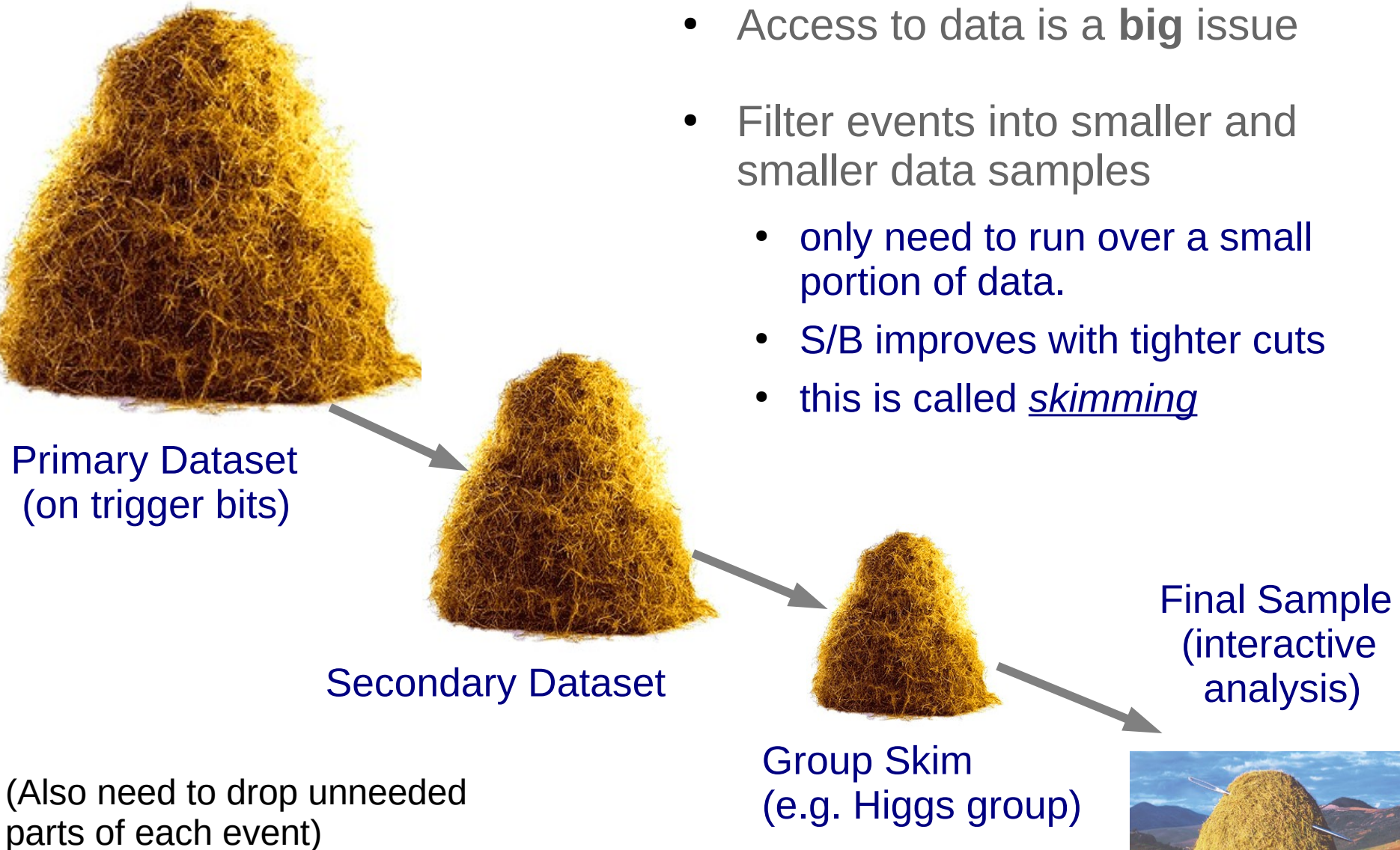
new particles

HEP Analysis in a Nutshell

- Each collision is independent from any other
- Governed by Quantum Mechanics
 - some (very rare) collisions may produce particles from BSM theory
==> sample of these collisions is “Signal”
 - decays of other Standard Model particles
==> sample of such collisions is “Background”
- We need to dig these jewels from the mounds of dirt!
- Filter events, maximize $\text{Signal} / \sqrt{\text{Background}}$
- Special for HEP: most of this filtering is done during data taking!

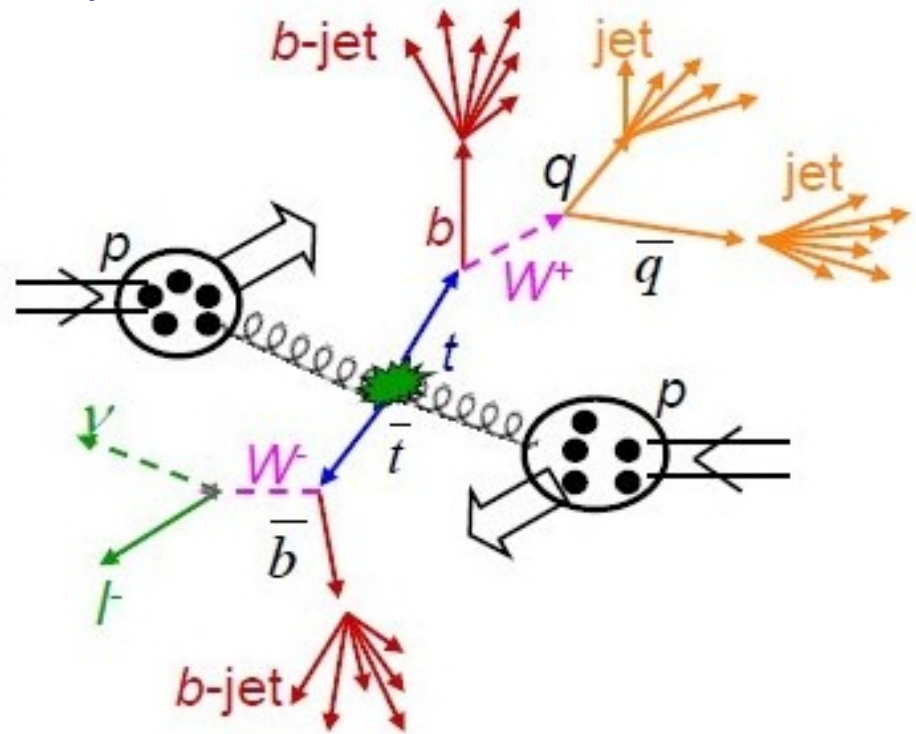
Data flow from detector to analysis

- Access to data is a **big** issue
- Filter events into smaller and smaller data samples
 - only need to run over a small portion of data.
 - S/B improves with tighter cuts
 - this is called skimming



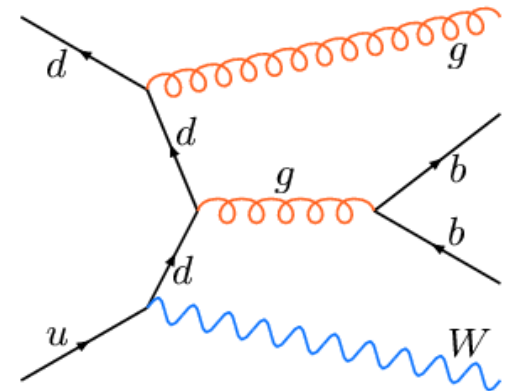
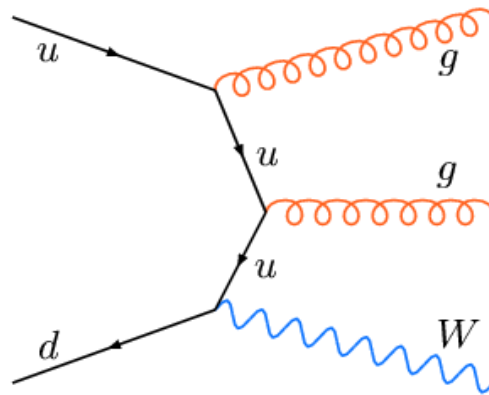
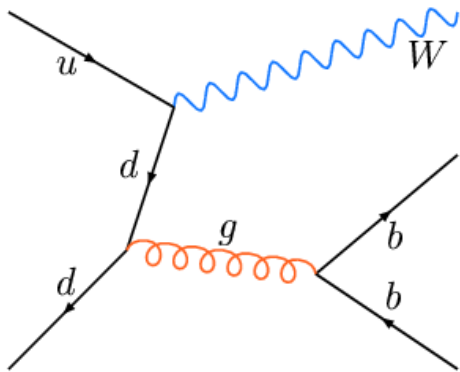
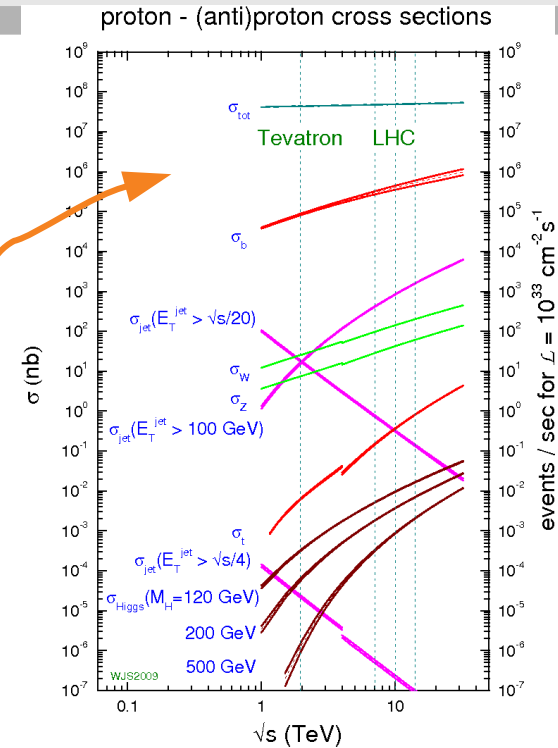
Example: $t\bar{t}$ event reconstruction

- An event with two top quarks (Standard Model production of $t\bar{t}$, or from some new particle $X \rightarrow t\bar{t}$)
- We need to reconstruct:
 - electrons
 - muons
 - missing energy
 - jets
 - (and identify those with b-quarks)
- Most other analyses built from same building blocks!
 $\Rightarrow t\bar{t}$ events are a perfect tool for physics commissioning!



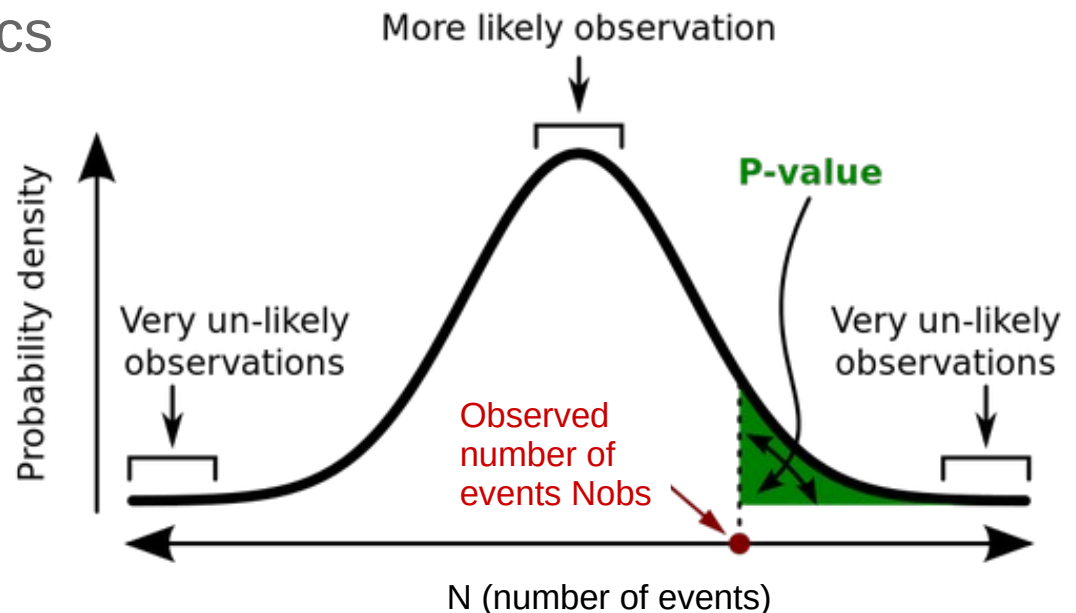
Reconstructing $t\bar{t}$: backgrounds

- Orders of magnitude more 'junk' than $t\bar{t}$
- Select a teeny subset of events which 'look very much like two top quarks'
 - many of them will indeed be $t\bar{t} \rightarrow$ **Signal (S)**
 - however, our **selection is imperfect**
 $\Rightarrow$ some events in data will be something else $\rightarrow$ **Background (B)**



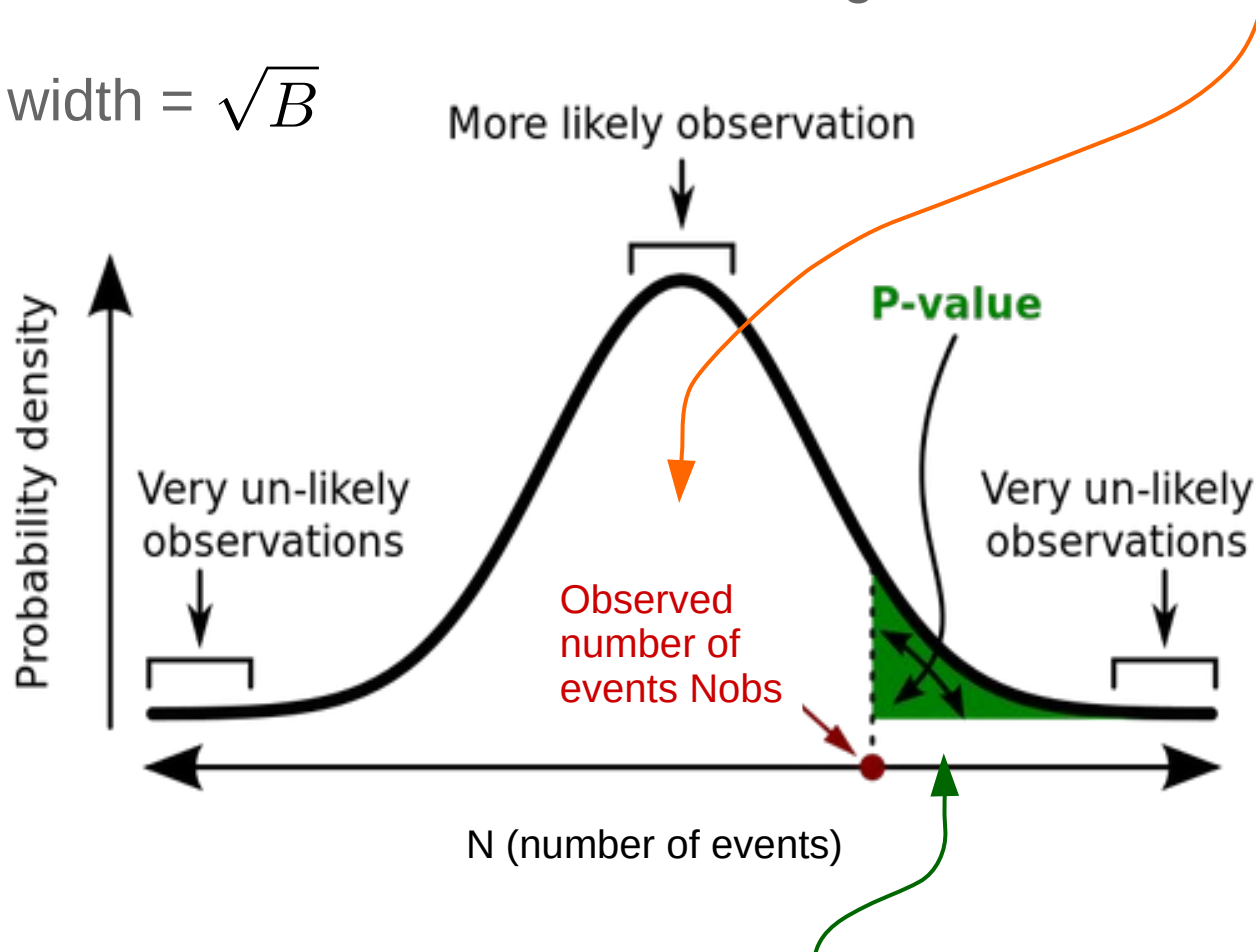
An anatomy of a search for New Physics

- Observe N_{obs} events: $N_{\text{obs}} = S + B$
- Need a separate measurement to estimate $B \pm \delta B$ (error)
- We then have two options
 - only SM = no New Physics (“null hypothesis”, H_0)
 - there is New Physics (“alternative hypothesis”, H_1)
- Discovering New Physics
= ruling out H_0 .



An anatomy of a search for New Physics

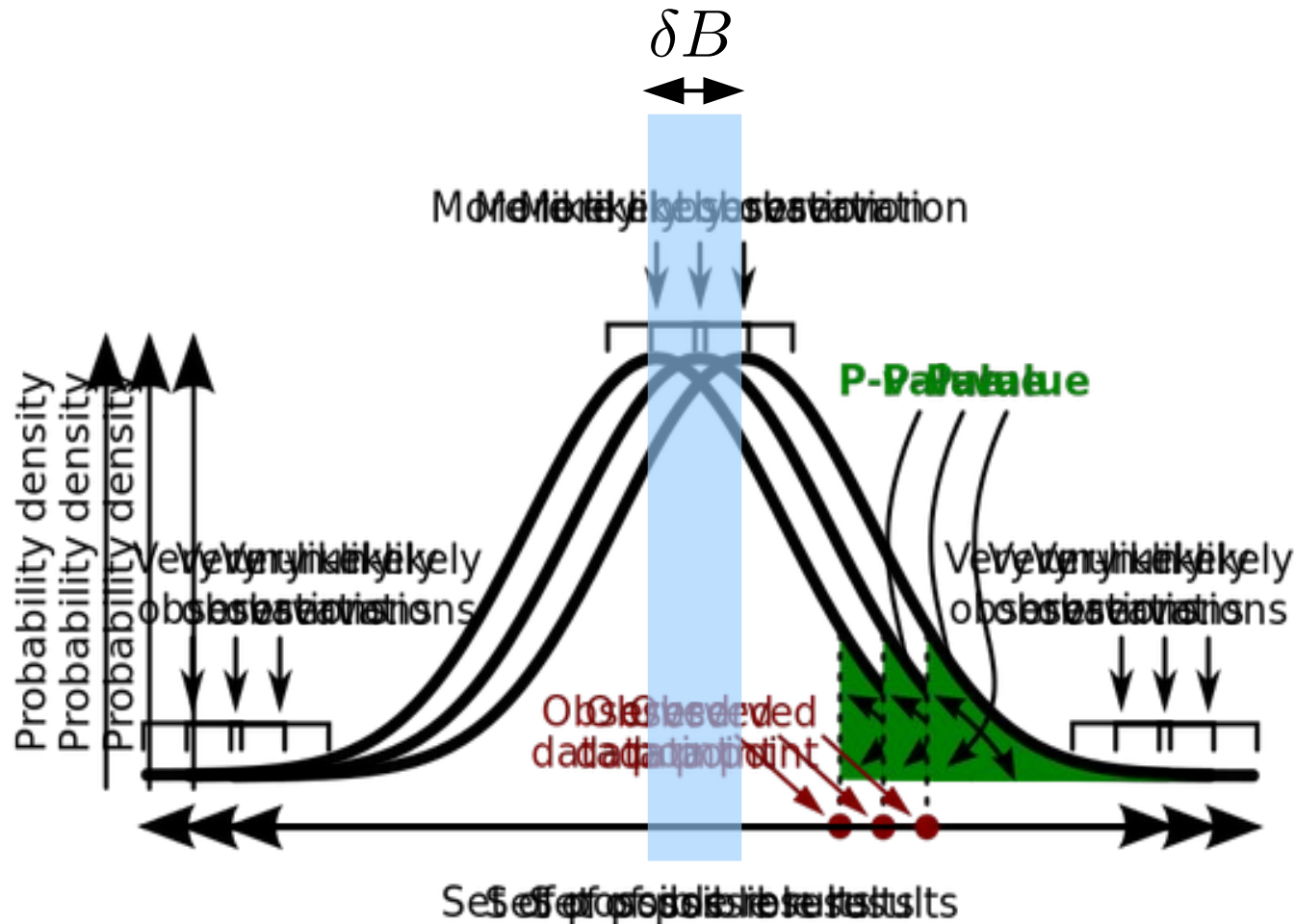
- Center of SM Gaussian = # of background events, B .
- Its width = $\sqrt{B}$



- Observation is “significant” if **P-value** is small. (Not likely from SM.)

An anatomy of a search for New Physics

- Uncertainty on background, δB , smears true position of the SM Gaussian $\rightarrow$ decreases P-value.

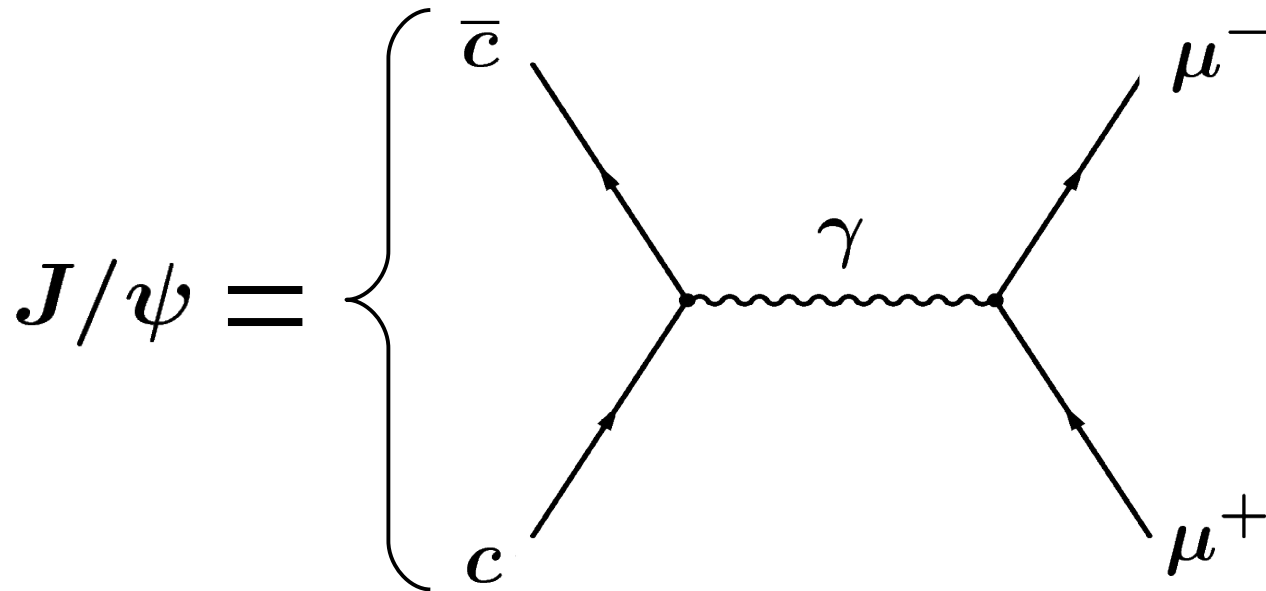


An anatomy of a search for New Physics

- In order to convert the observation to production cross-section, we also need to know “signal efficiency”, ϵ_S .
- = probability that BSM signal event passes selection
- Need also to minimize $\delta\epsilon_S$
- To summarize, we want to
 - pass as much S as we can (high efficiency)
 - kill as much B as we can
 - measure B well (small δB)
 - know ϵ_S precisely (small $\delta\epsilon_S$)

Reconstructing $J/\psi \rightarrow \mu^+ \mu^-$

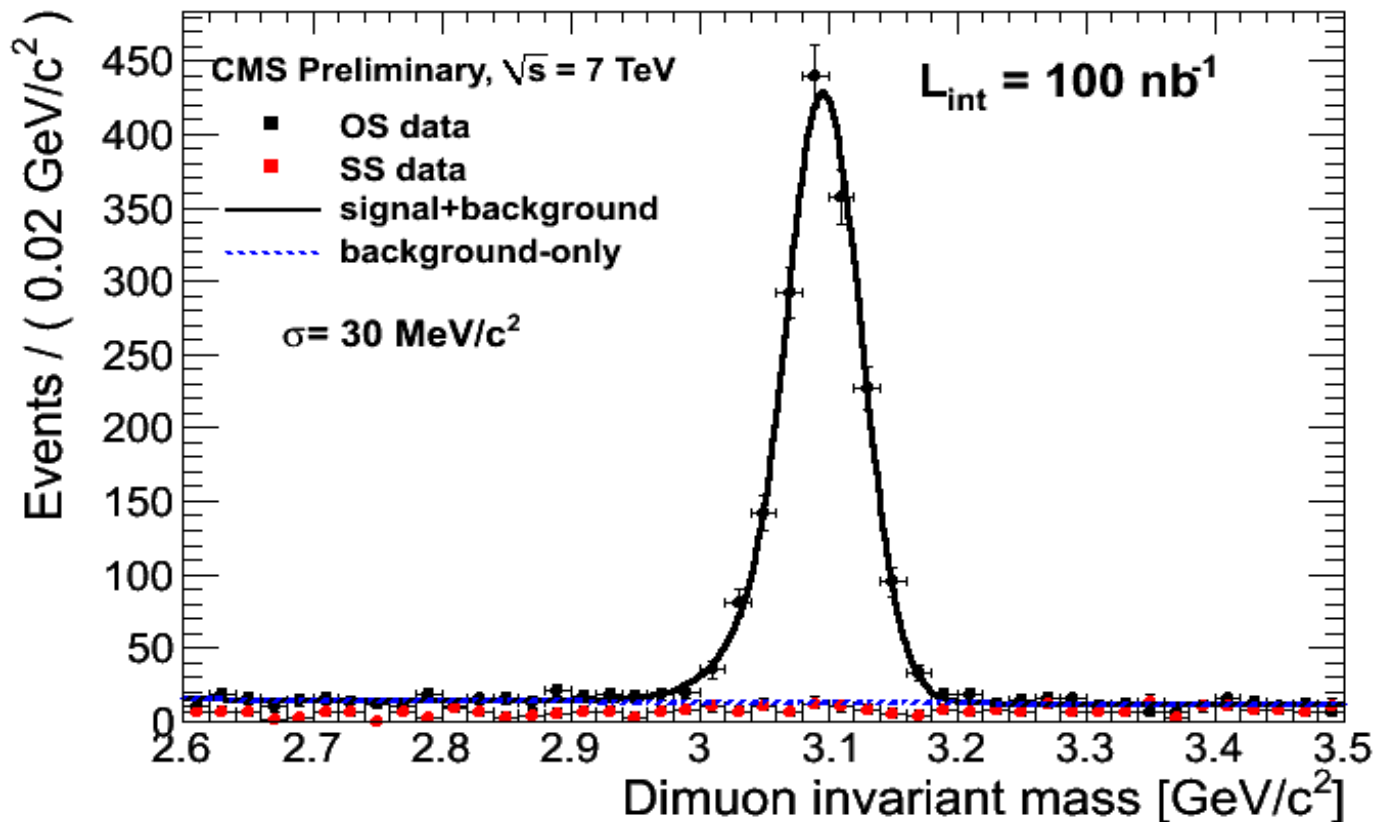
- J/ψ meson is a bound state of $c\bar{c}$
- decays electromagnetically (photon as a force carrier):



$\Rightarrow$ rate of this decay is 'slow' enough that width is narrow

Reconstructing $J/\psi \rightarrow \mu^+ \mu^-$

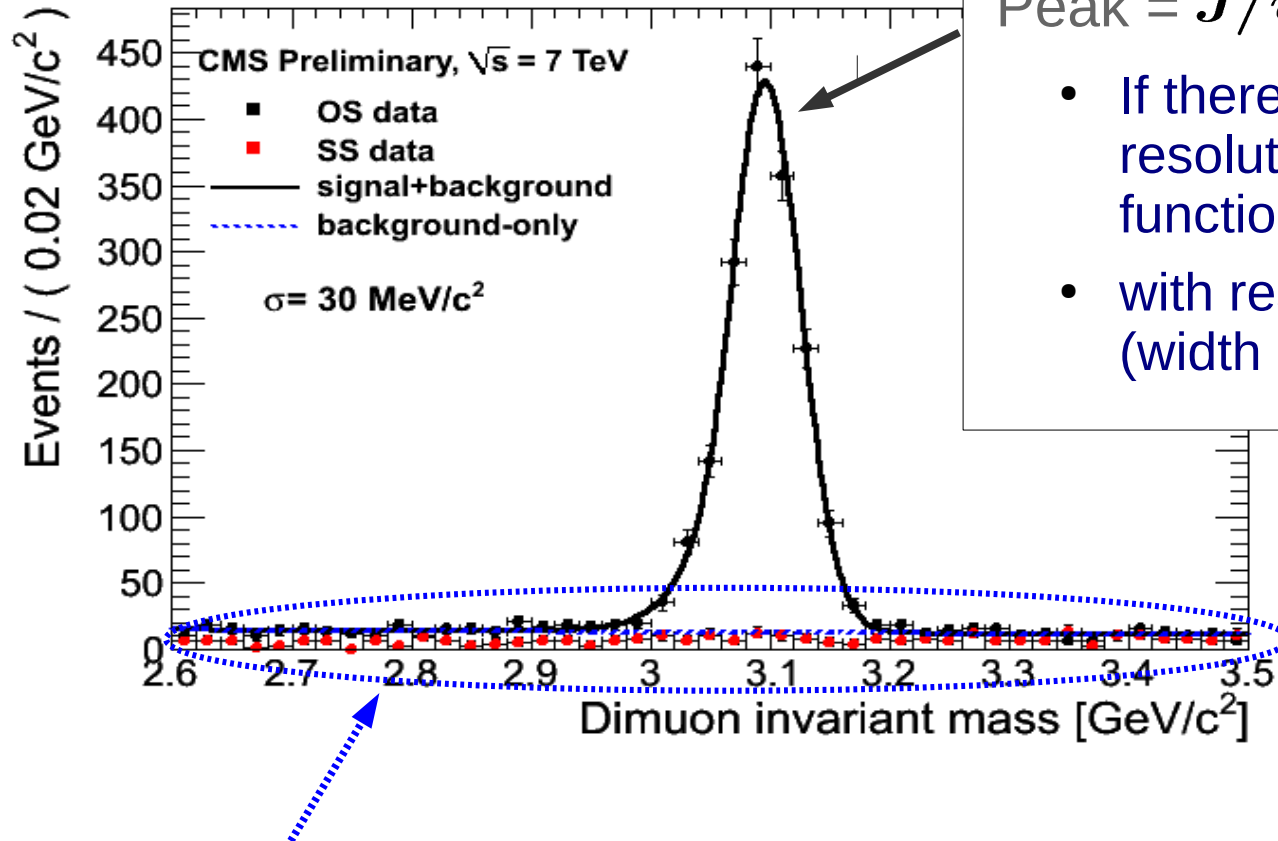
- consider pairs of oppositely charged muons
- add their 4-vectors, create a 4-vector of a J/ψ 'candidate'
- plot distribution of invariant mass: $mc^2 = \sqrt{E^2 - p^2 c^2}$



$$E = E_1 + E_2$$

$$\vec{p} = \vec{p}_1 + \vec{p}_2$$

Anatomy of a 'mass plot'



Peak = J/ψ itself

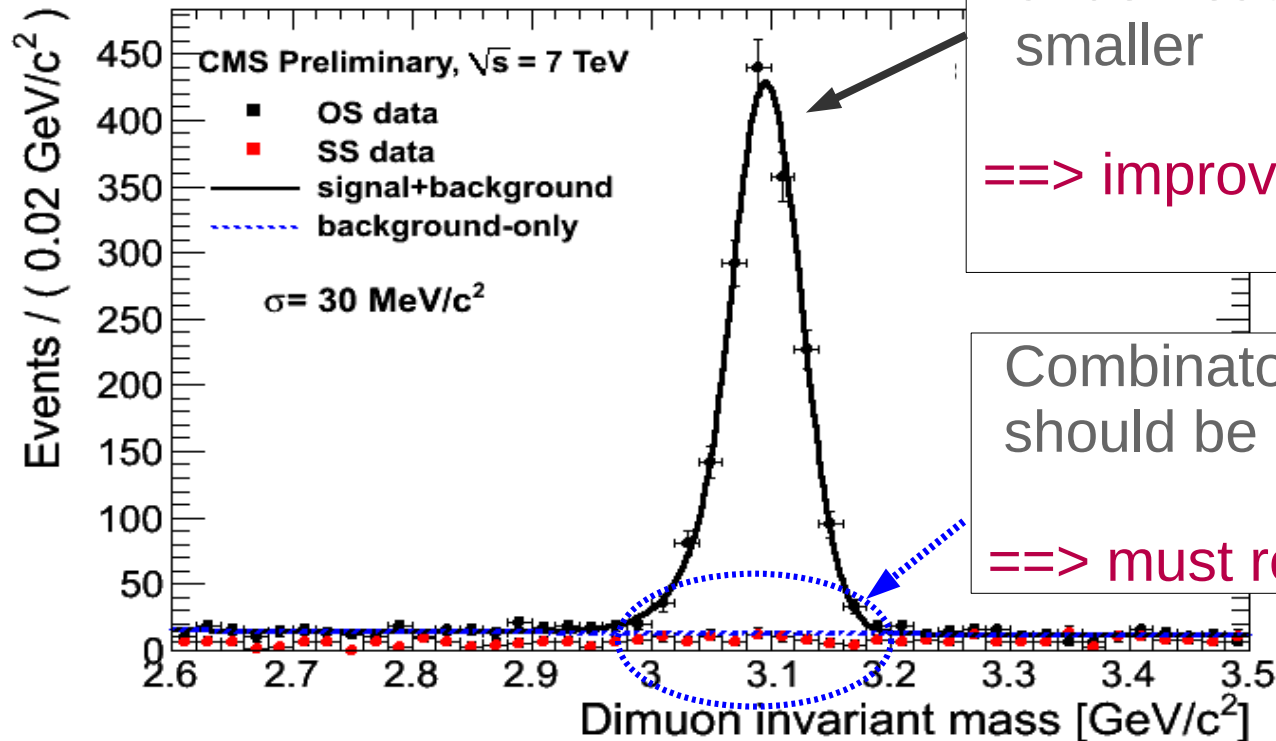
- If there were no detector resolution, it would be delta function (a vertical line)
- with resolution, it's a Gaussian (width = resolution)

Flat shape = 'combinatorial' background

- there are fake muons (false positives in muon reconstruction)
- they are random ==> pairs have almost uniformly distributed mass

Digression #2: Detector Design Demystified

- Recall: we want to maximize $\text{Signal} / \sqrt{\text{Background}}$



Signal: narrower is better ==> background underneath the peak will be smaller

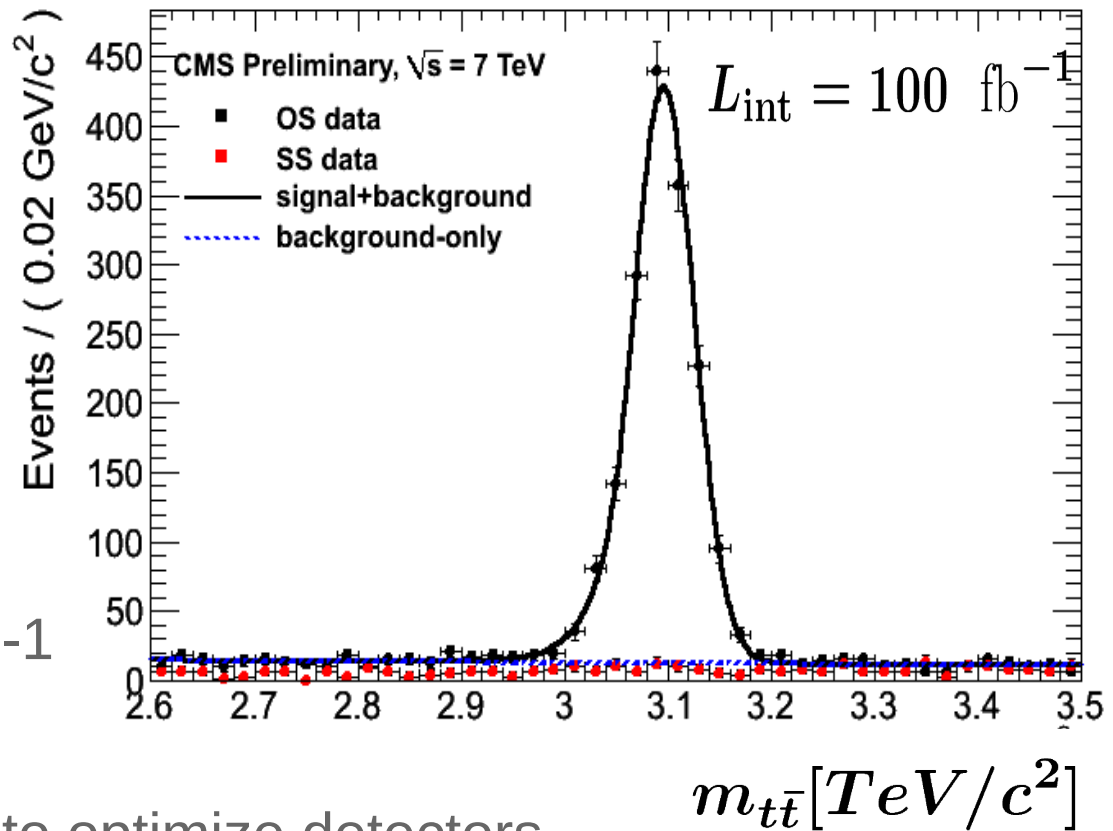
==> improve detector resolution

Combinatorial background: should be as low as possible

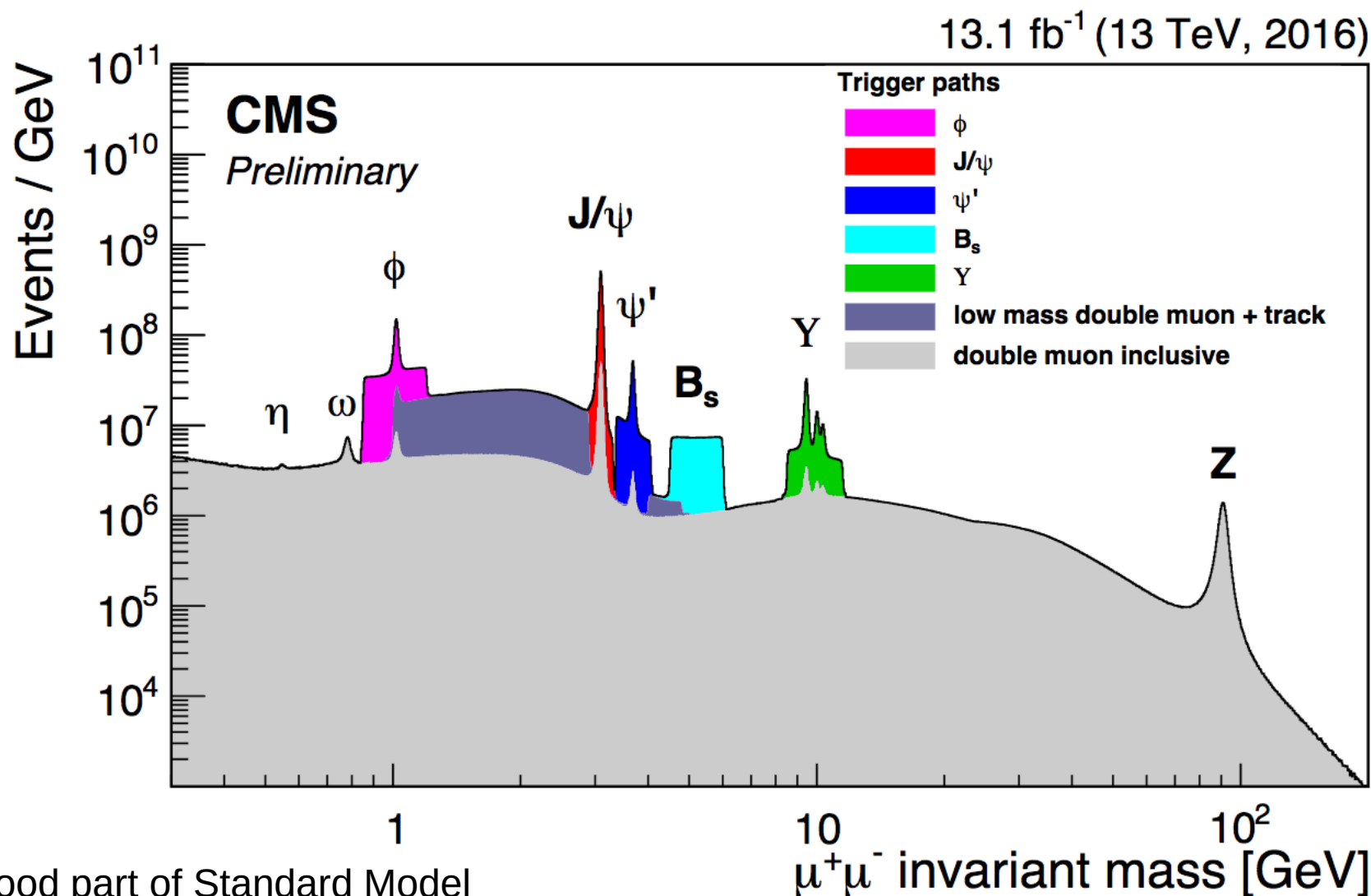
==> must reduce fake rate

Digression #3: bump hunting

- Hypothetical scenario:
- Say, a 3.1 TeV resonance, after 100 fb⁻¹ of data
- Logic is identical: want to optimize detectors so that the peaks (“bumps”) are narrow, on small background.
- This is “bump hunting” – the easiest way to find new physics

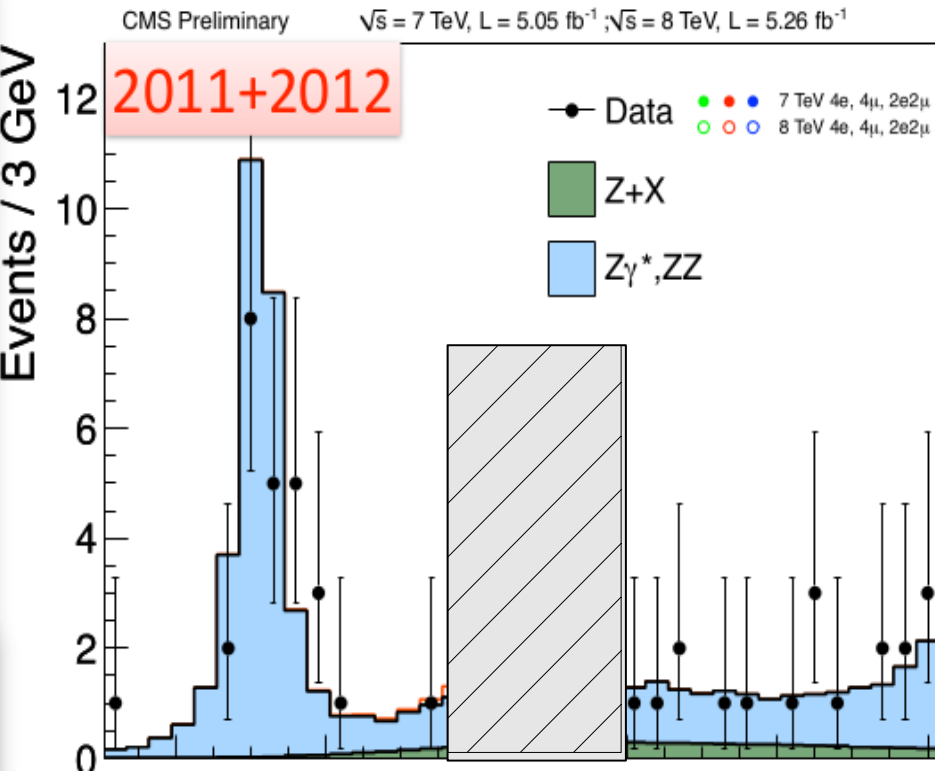


Two-muon resonances



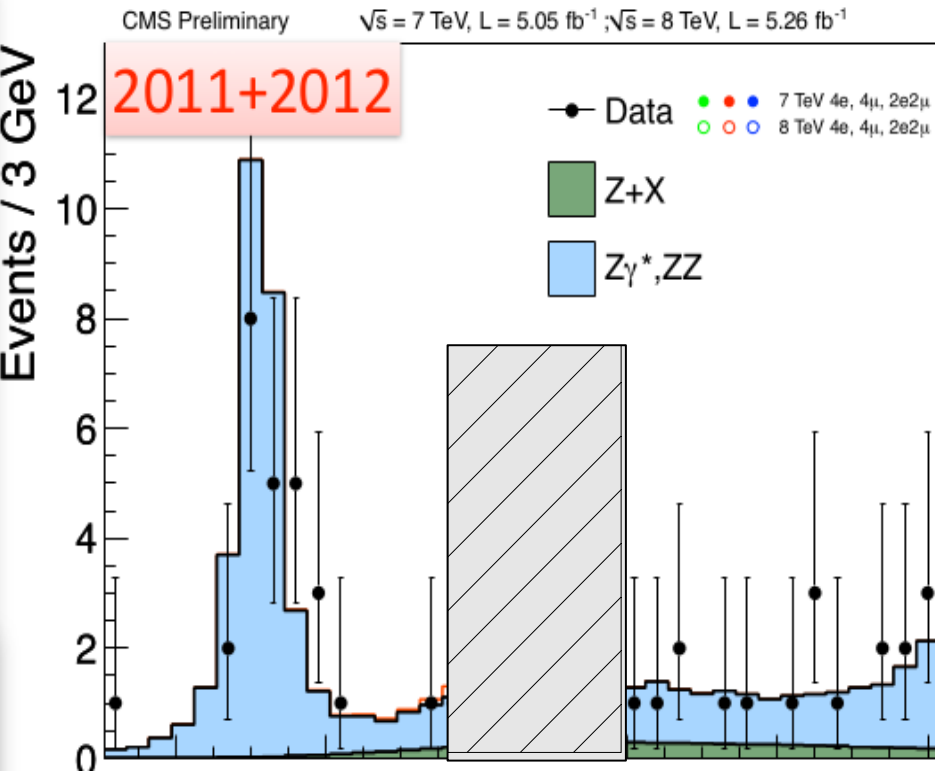
(A good part of Standard Model
in a single plot!)

Higgs search: $H \rightarrow ZZ^* \rightarrow (\mu^+ \mu^-)(\mu^+ \mu^-)$

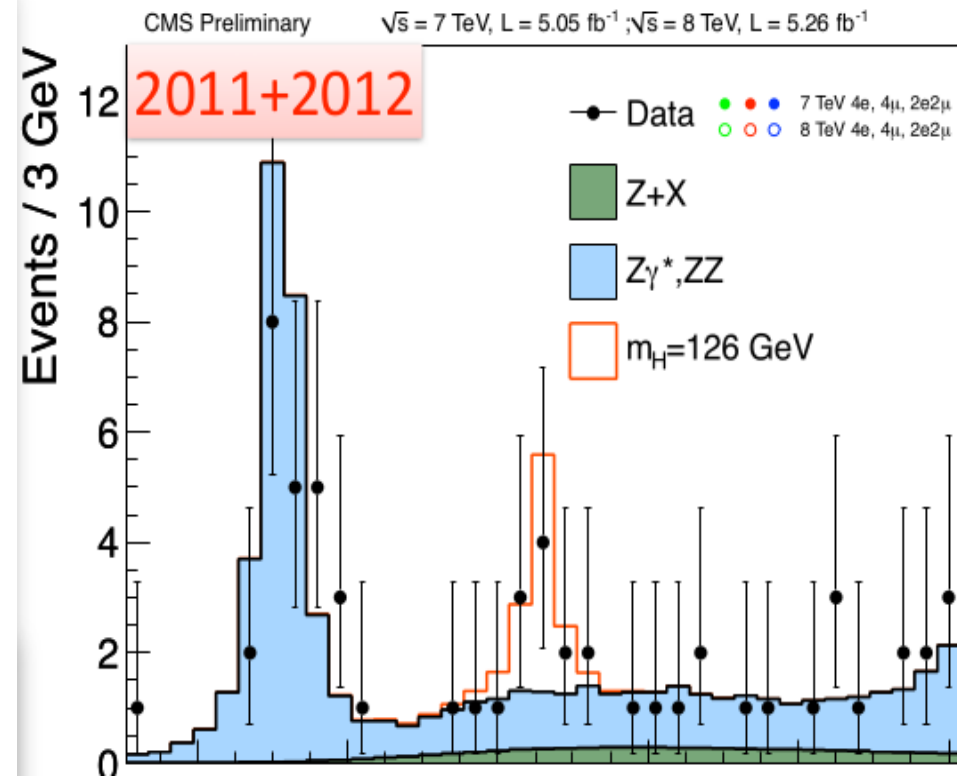


- Light blue: Standard Model
- Possible Higgs location is **blinded** (to avoid human bias)

Higgs search: $H \rightarrow ZZ^* \rightarrow (\mu^+ \mu^-)(\mu^+ \mu^-)$

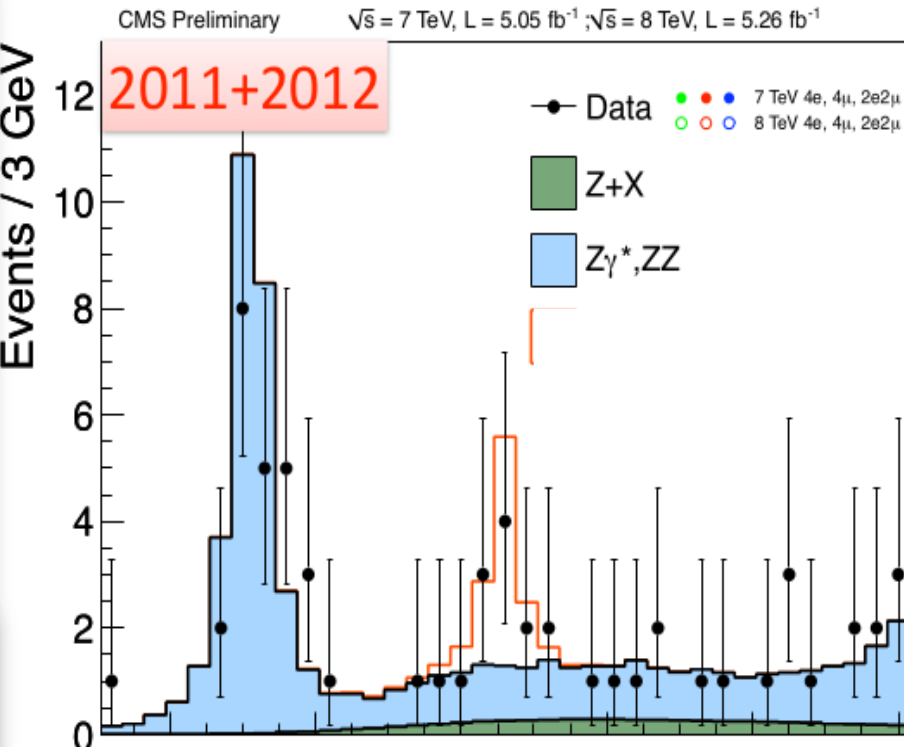


- Light blue: Standard Model
- Possible Higgs location is **blinded** (to avoid human bias)

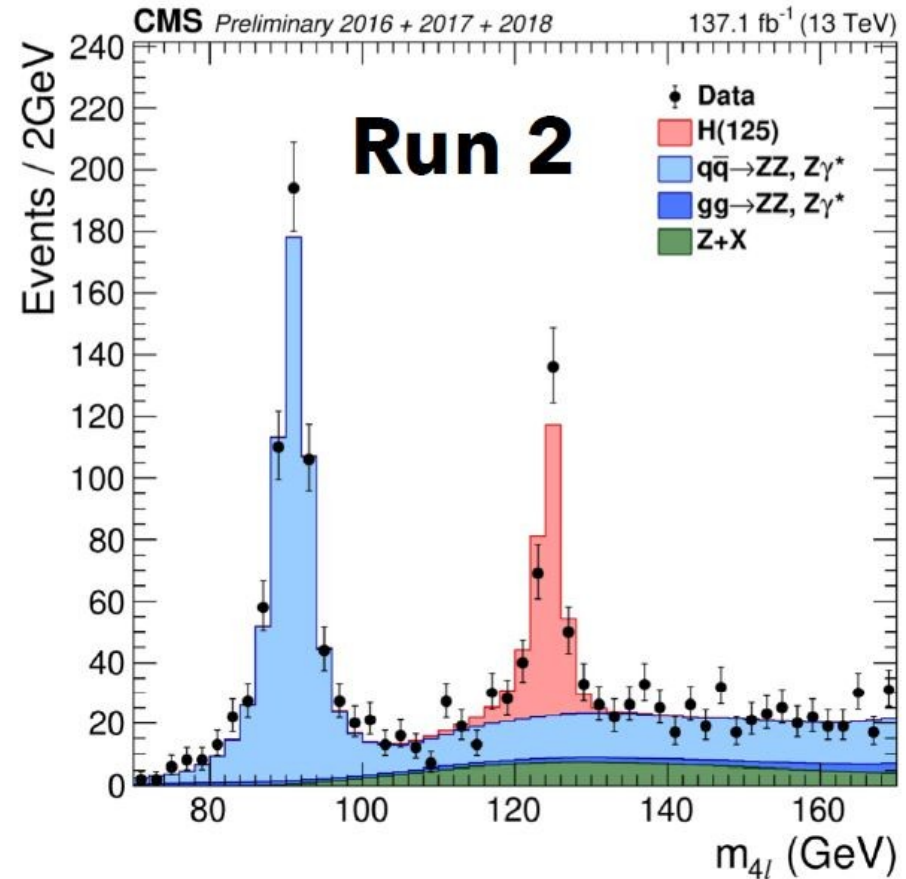


- Unblind and...excess over SM!
- In multiple channels at the **same** place – significant!

Higgs search: $H \rightarrow ZZ^* \rightarrow (\mu^+ \mu^-)(\mu^+ \mu^-)$



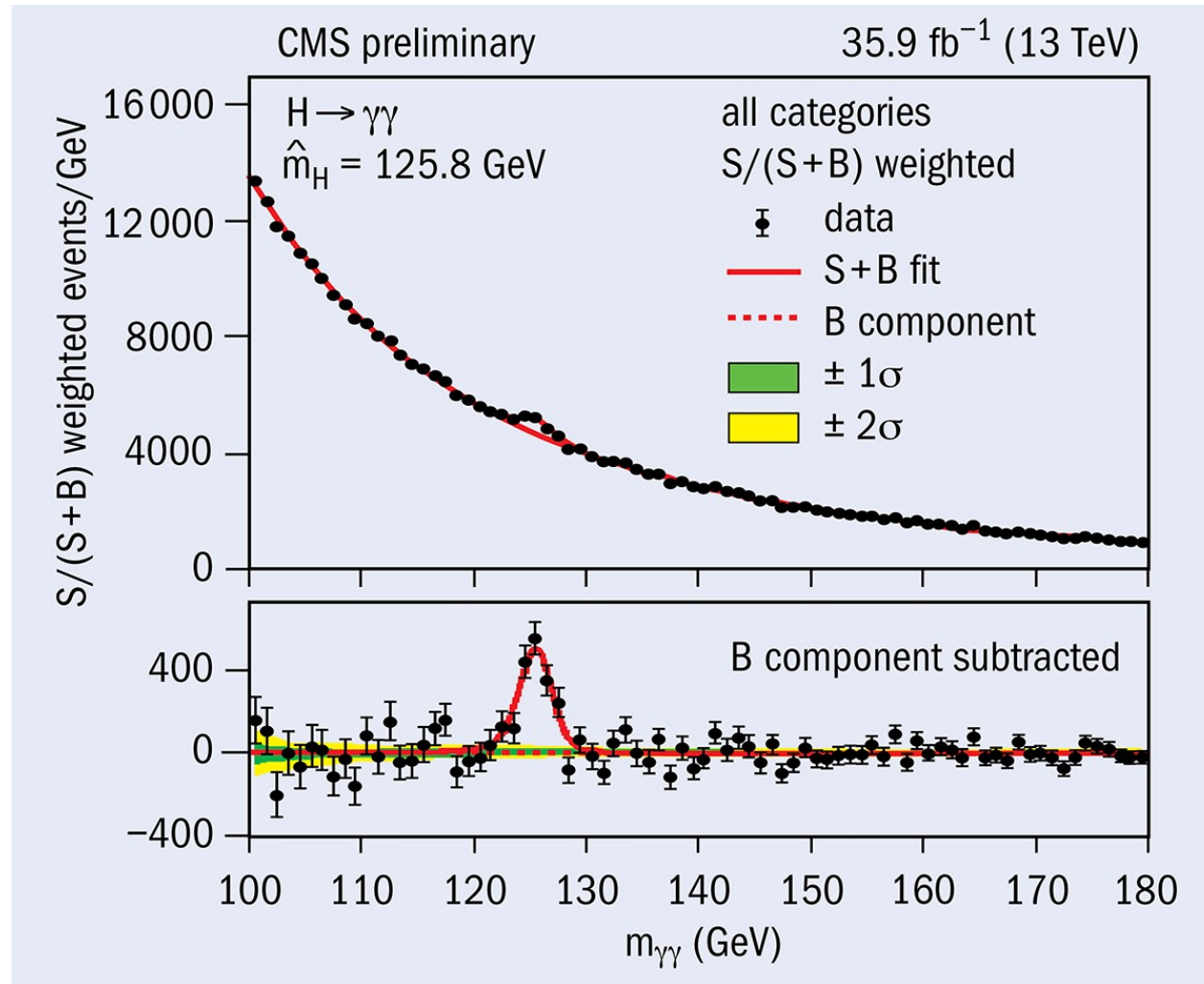
- Light blue: Standard Model
- At the time of discovery



- How it looks like today
 - (~ 20x more data)

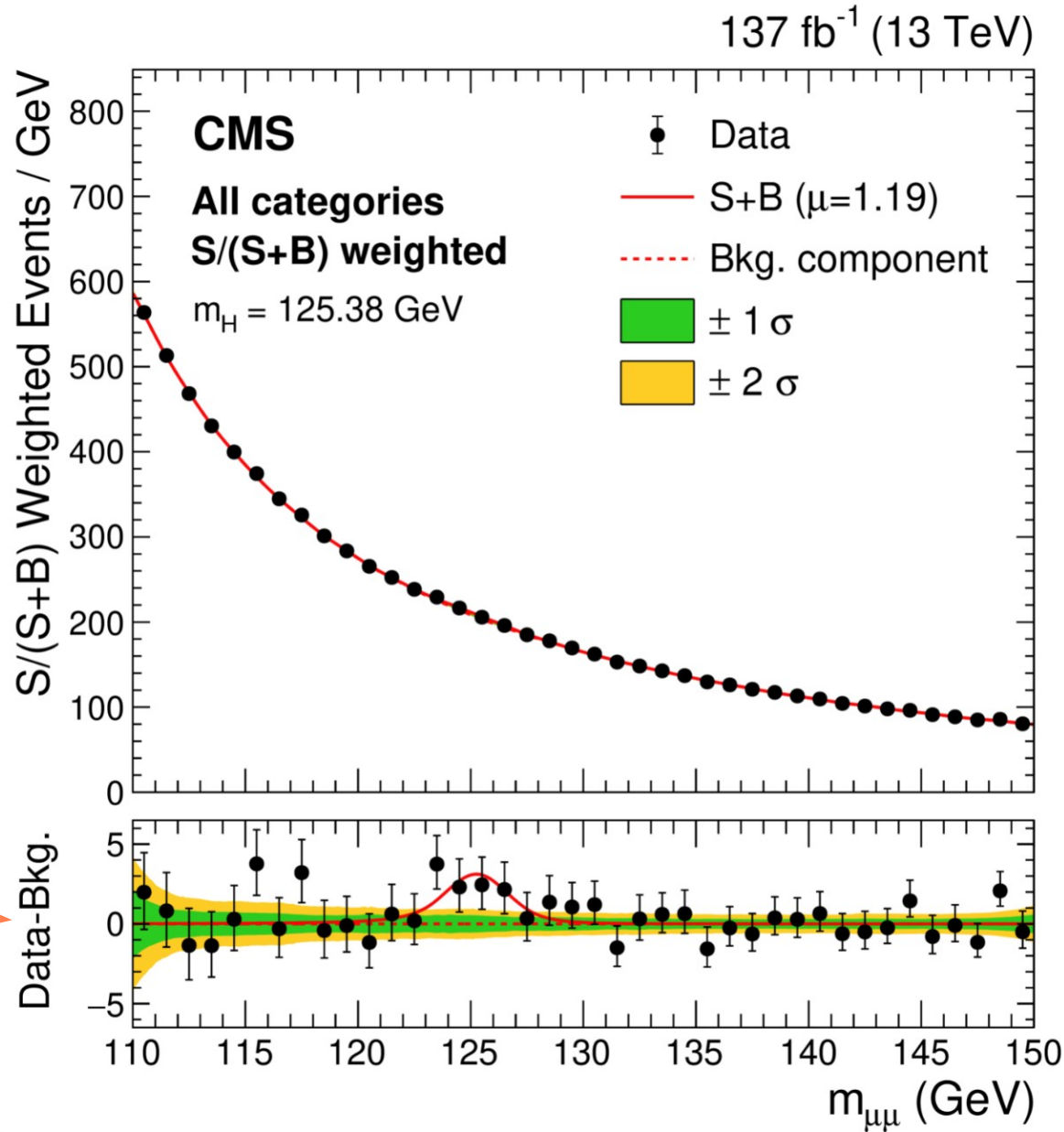
More examples of a 'bump hunt'

- $H \rightarrow \gamma\gamma$ channel
- More background
- Still smooth, falling shape

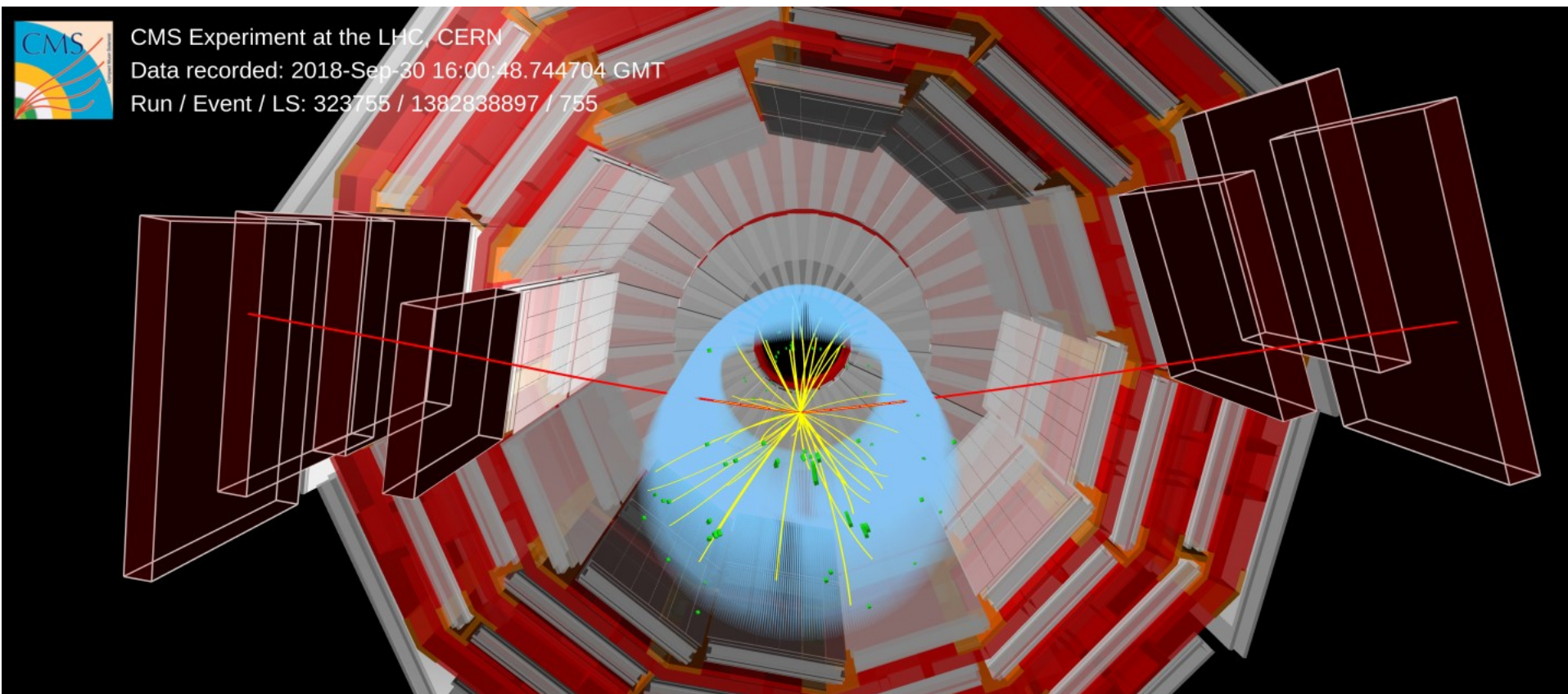


Now back to two muons!

- $H \rightarrow \mu^+ \mu^-$
(sum of several search channels)
- Background is again a smooth, falling shape
- Only way to see signal is to subtract the background shape from data

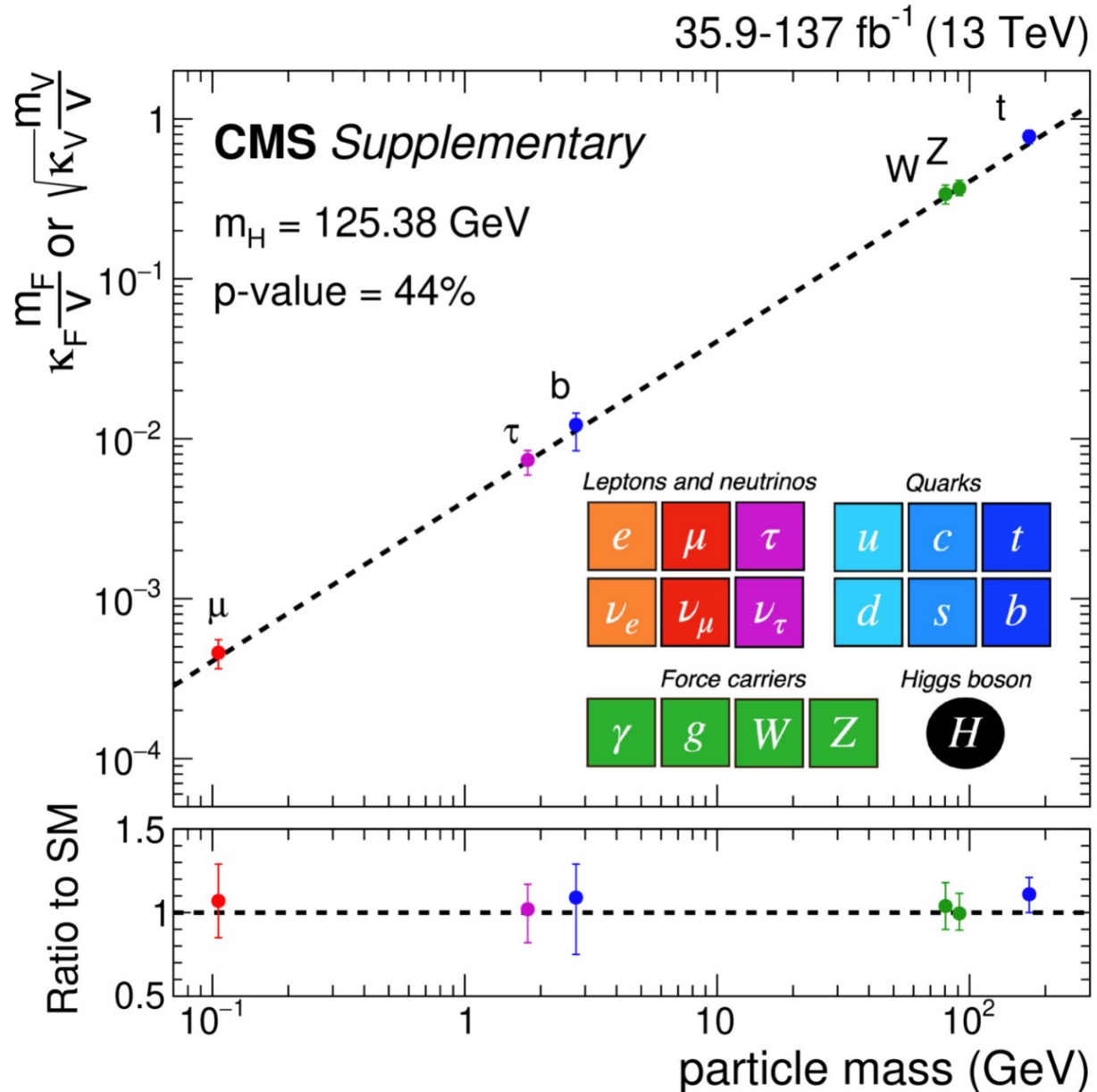


Higgs to two muons event



This is how we learn about the world

- Observe Higgs decays to various particles
- Use this to measure how strongly Higgs couples to them
- Validates Standard Model!

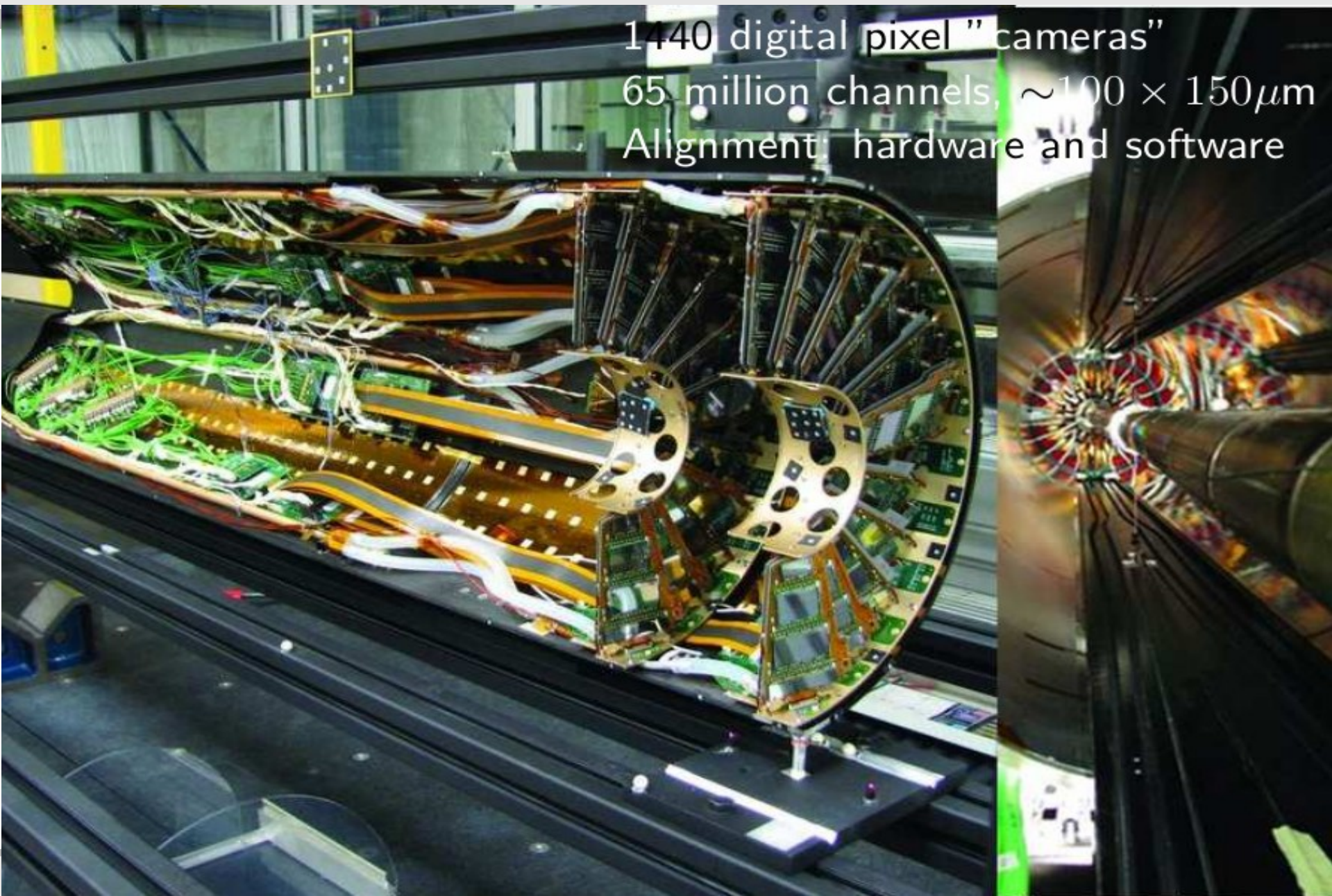


Summary

- Standard Model is the most precisely tested theory in science
- And yet... We know it's not the whole story
- SM is an approximation of a deeper theory
 - many many candidates
 - experimentally no evidence yet
- To search for signal of beyond-SM theory:
 - maximize # of signal events that pass cuts
 - minimize # of background events that pass cuts
 - estimate amount of background events that remain
 - minimize uncertainties of both background and possible signal

BACKUP

The Silicon Pixel Detector



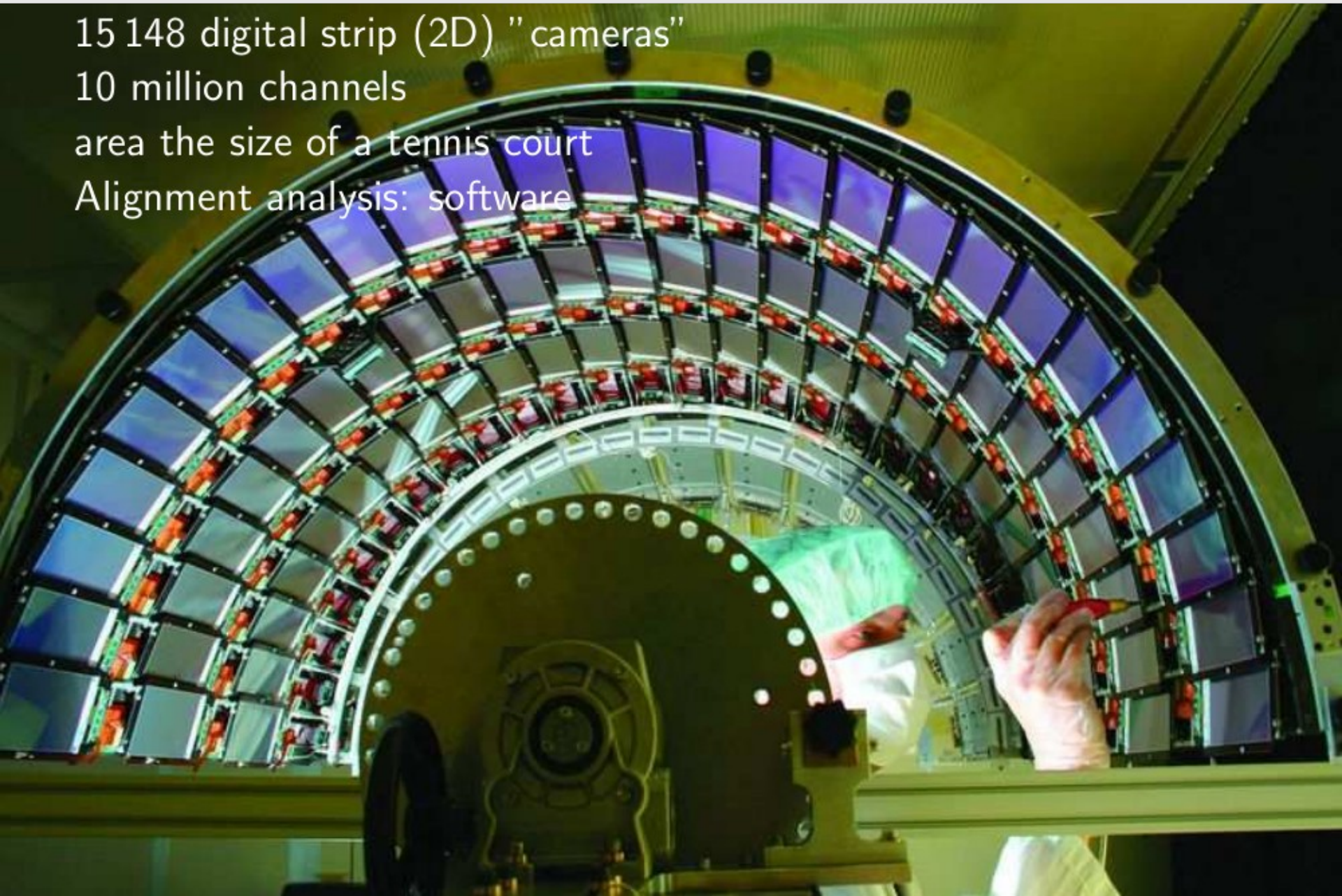
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"

10 million channels

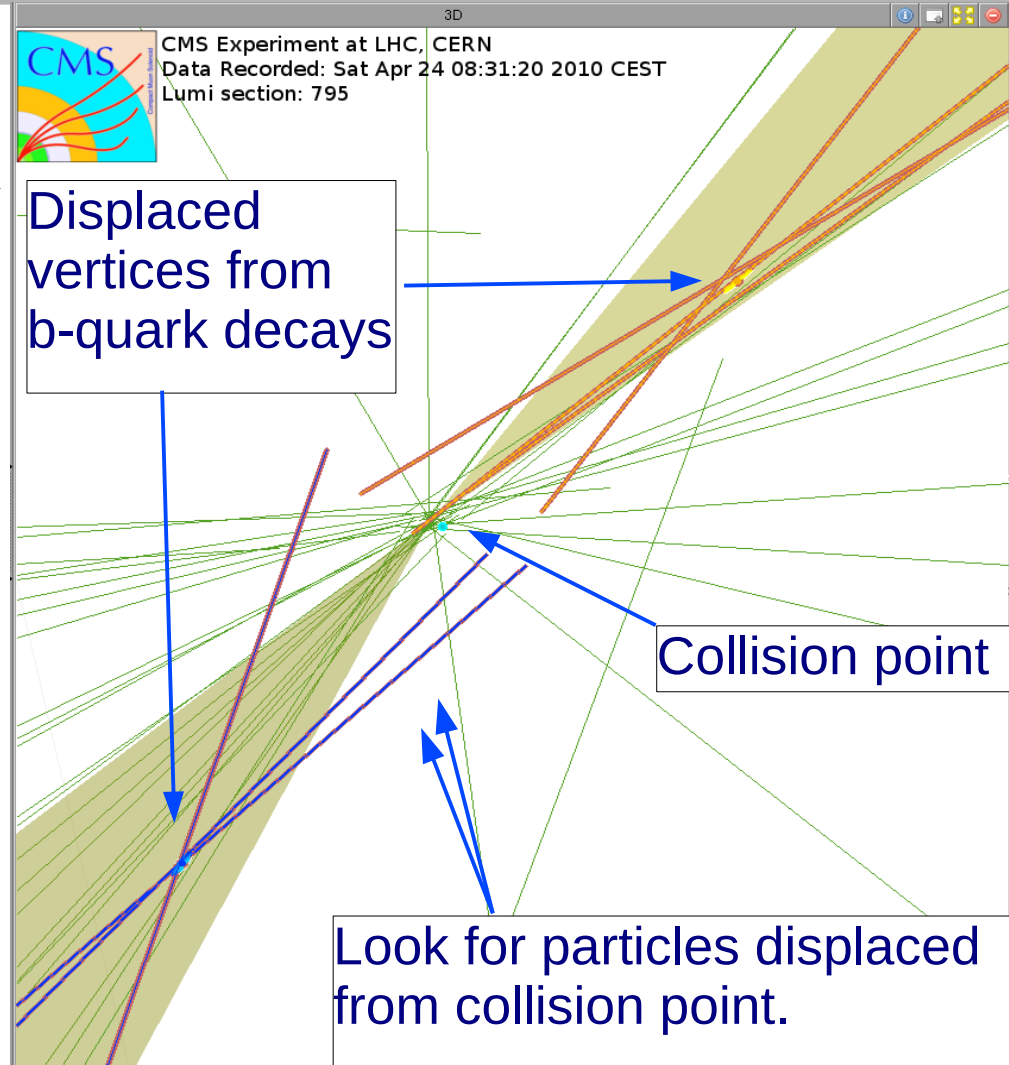
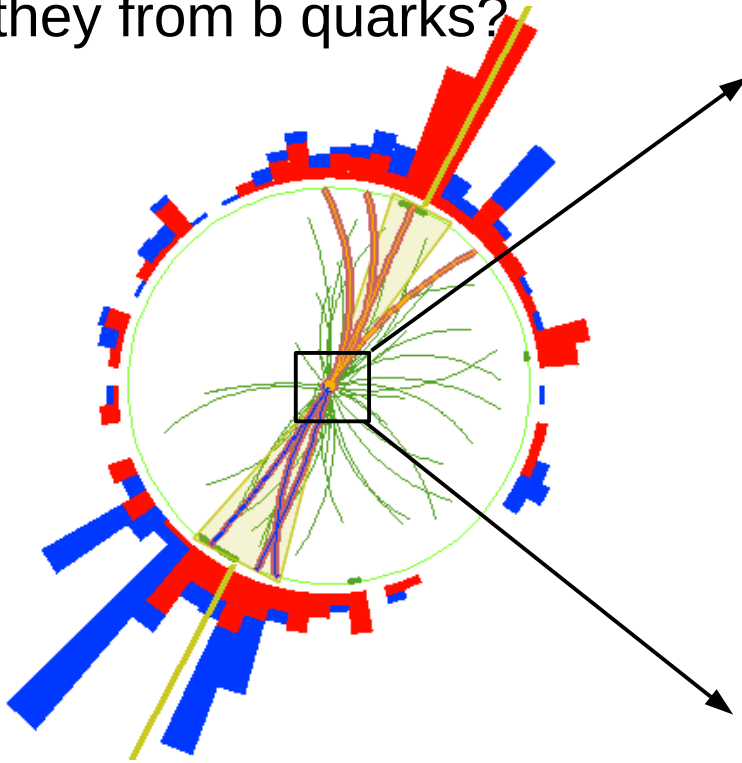
area the size of a tennis court

Alignment analysis: software

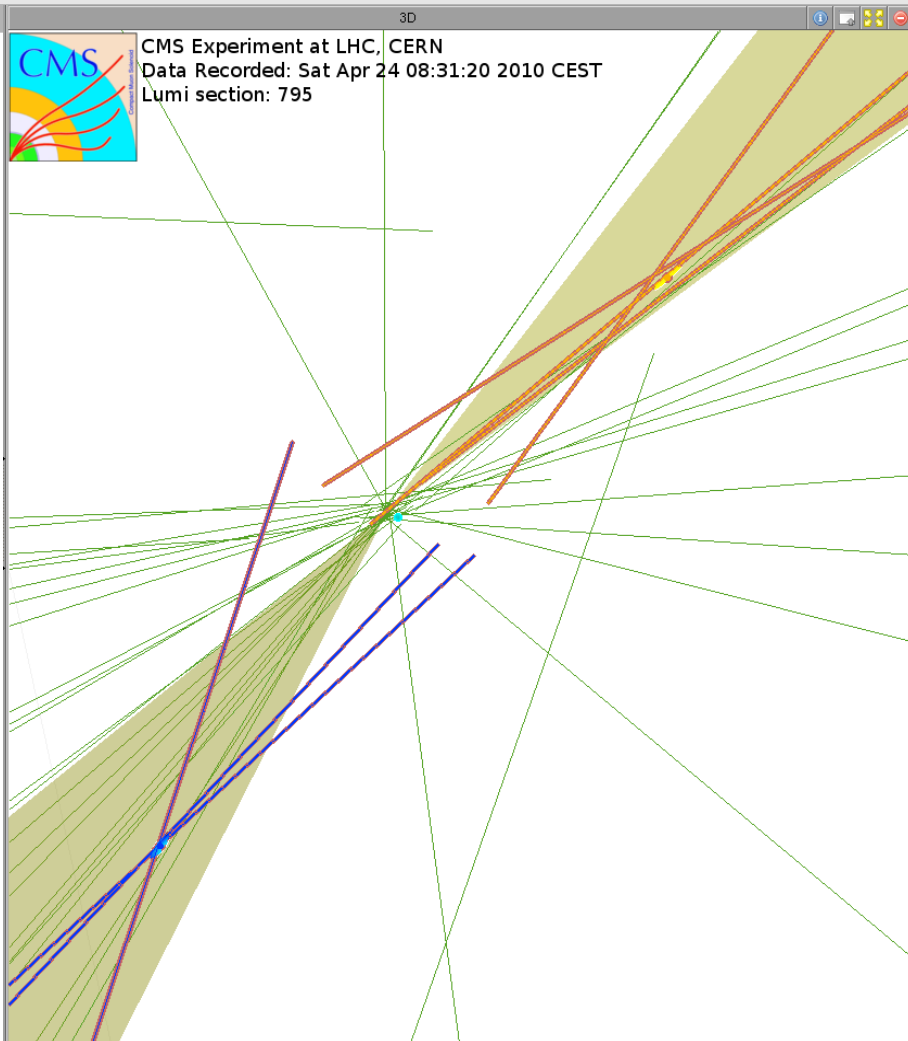


Finding jets with b-quarks: 'b-tagging'

Event with two jets:
are they from b quarks?



Finding jets with b-quarks: 'b-tagging'



Efficiency:

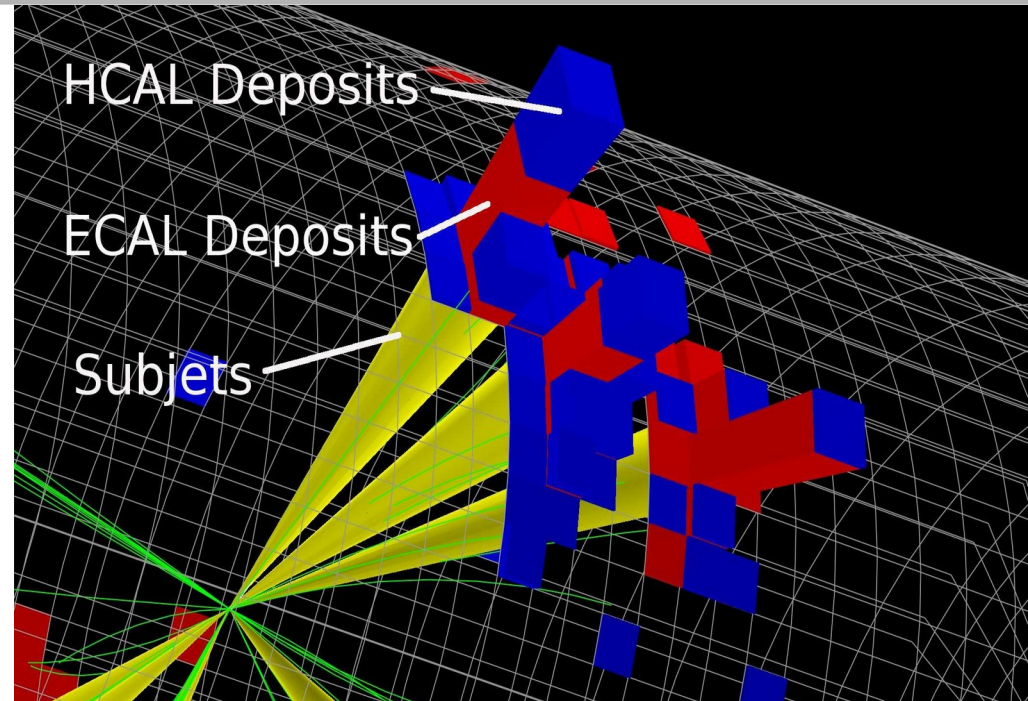
- only ~ 50% of jets with b-quarks are 'b-tagged'

Purity:

- occasional problems with reconstruction of tracks of charged particles.
- b-tagging may makes a false positive
 - a jet without a true displaced vertex is falsely identified as a "b-tag"
 - called "mis-tag"
 - rate ~ 0.1%

Top-tagging: jet substructure

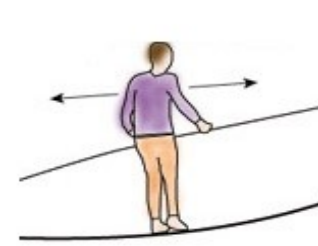
- Decay products of a very energetic top form a single 'top jet'
- Plan:
 - decompose jets into "subjects"
 - dedicated jet clustering + apply extra selection
→ *top-tagging!*
- This is a hot topic:
 - Butterworth et al : Boosted Higgs (hep-ph/0201098)
 - Kaplan et al: Boosted top (0806.0848)



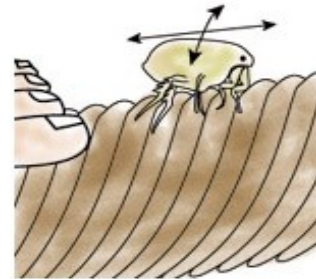
- Blue: hadronic calorimeter
- Red: electromagnetic calor.
- Yellow: found subjets

More questions

- Are there hidden additional dimensions of space and time?
 - large or small, flat or curved...?
- Are there new forces of nature?
- Are all forces manifestations of one fundamental interaction?
 - E-M and Weak force were one at the beginning of the universe
- Can the Standard Model explain baryon-antibaryon asymmetry in the Universe?
- What is the dark matter of the universe?
 - good candidate: heavy but inert particles from new theories
 - those particles can be produced at the LHC!
(manifest themselves as missing energy!)



An acrobat can only move in one dimension along a rope..



...but a flea can move in two dimensions.