How to search for “New Physics” at the LHC

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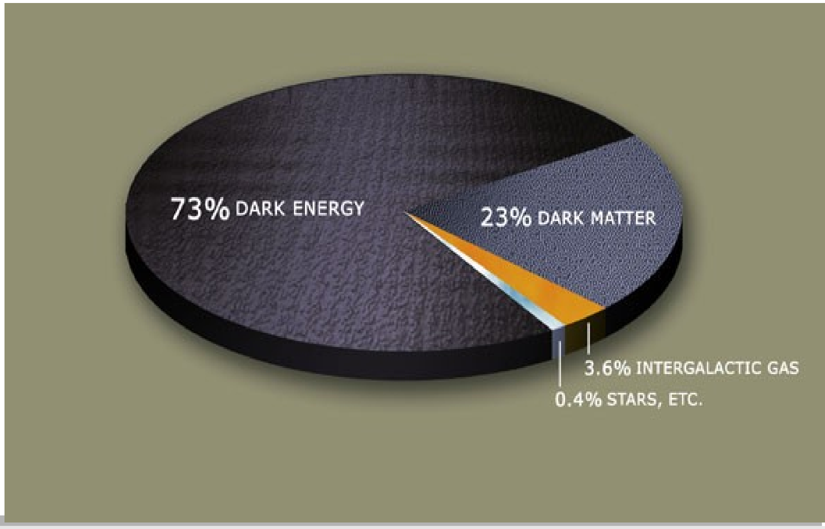
- “New Physics” = what is not Standard Model
- a.k.a. “Beyond Standard Model” Physics (BSM)

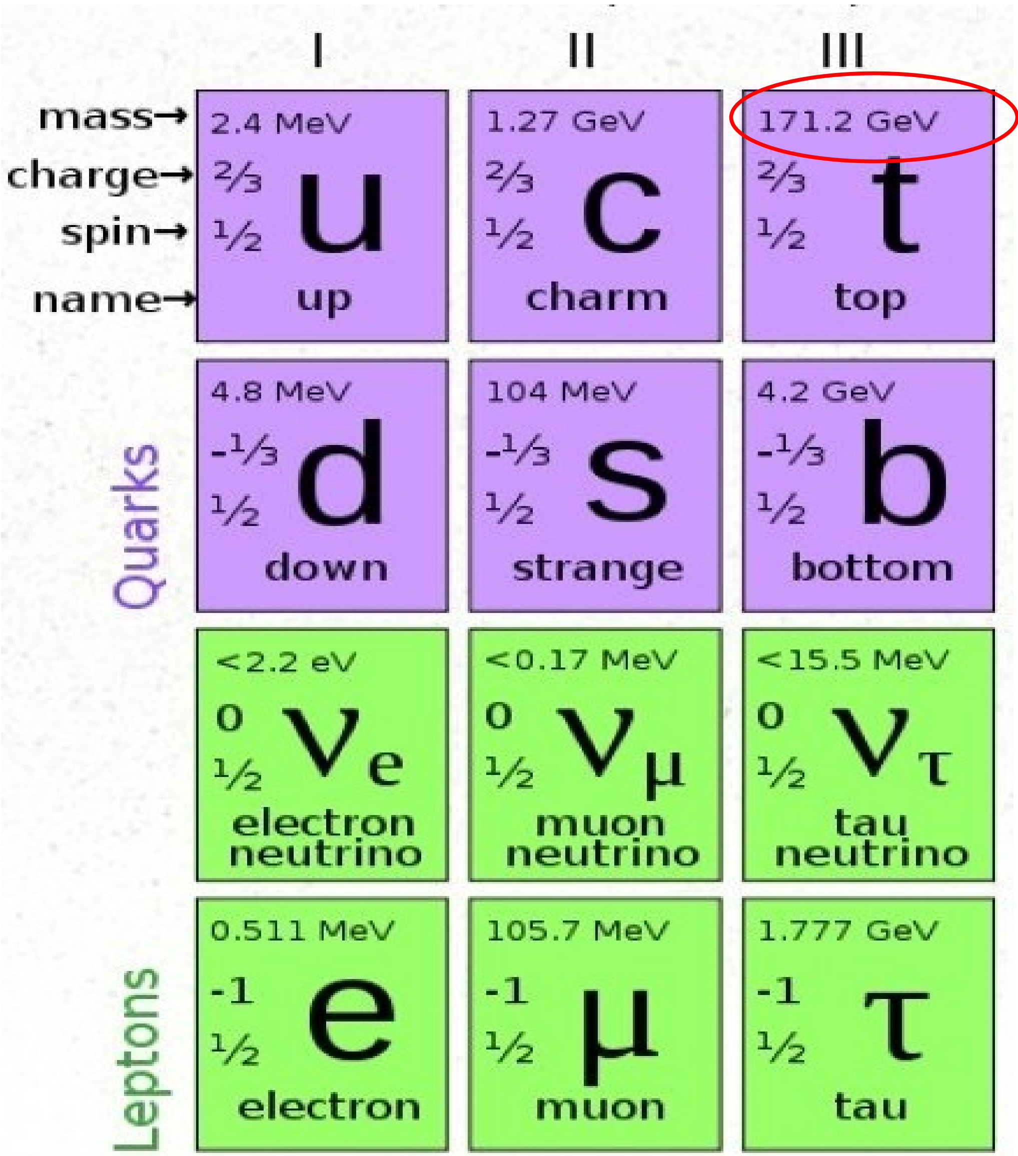
Questions

- 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

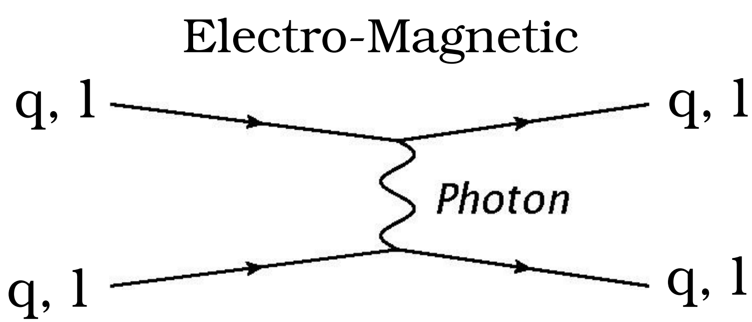
Three families of Standard Model

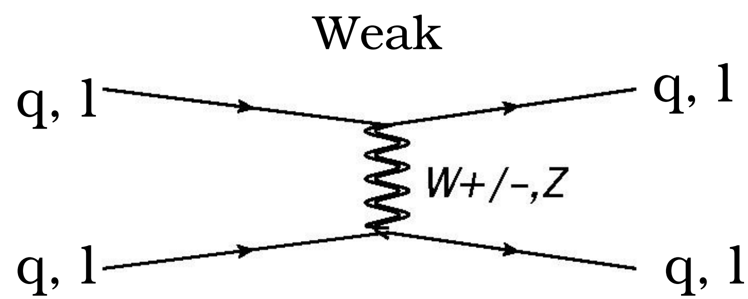


- All matter is composed of fermions = organized in three families of
  - 6 leptons
  - 6 quarks
  - masses are external parameters

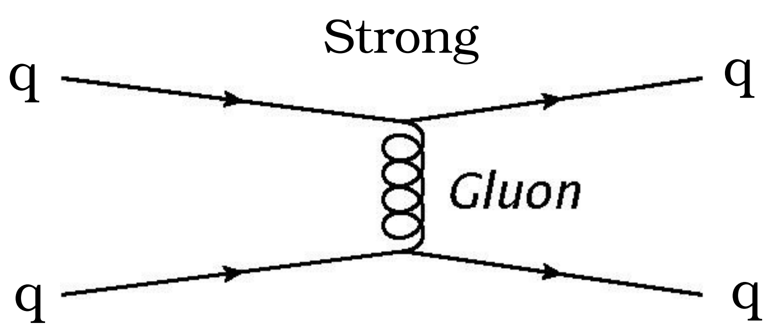
    ==> we don't know why top quark is so heavy!
- Three forces:
  - Electromagnetic
  - Weak
  - Strong
- No Gravity!

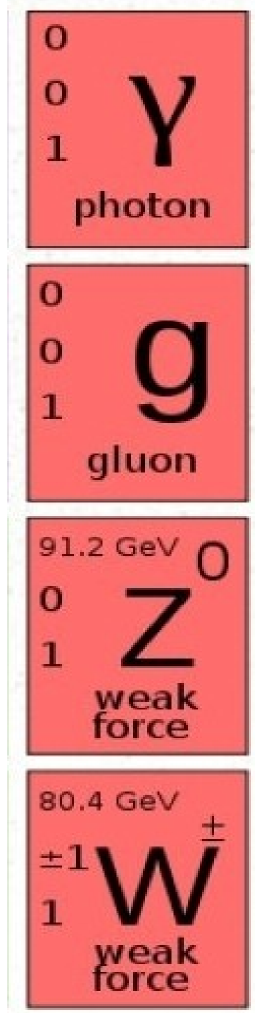
Standard Model: Interactions





q(uarks),
l(eptons)

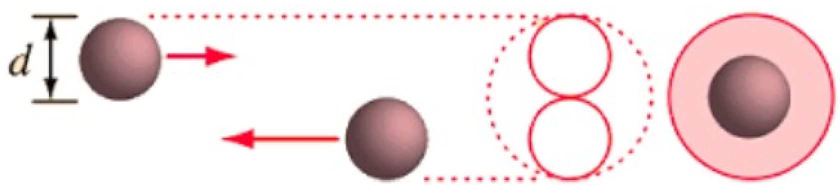




- Fermions with charge interact via Electromagnetic force
  - Quantum Electrodynamics (QED)
- Fermions with color (quarks) interact via Strong force
  - Quantum Chromodynamics (QCD)
- Fermions with weak isospin (all) interact via Weak force

Calculating things in Standard Model

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



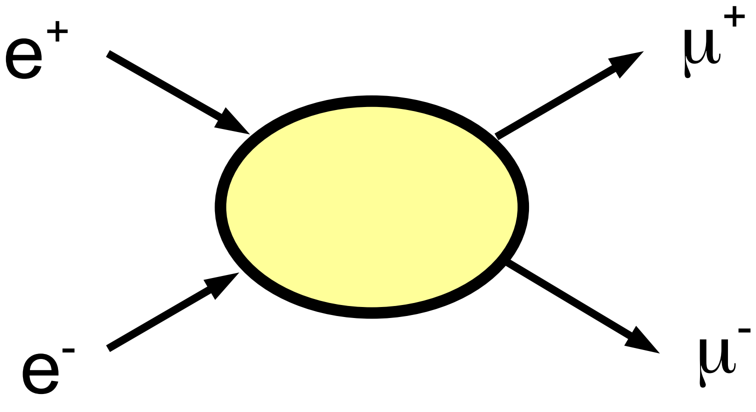
Effective area of the collision is

$A = \pi d^2$

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

Quantum Electrodynamics (QED)

- Consider $e^+e^- \rightarrow \mu^+\mu^-$
- Probability ~ $|\mathcal{M}|^2$
- $\mathcal{M}$ is calculated as infinite series of terms
  (usually ever smaller)



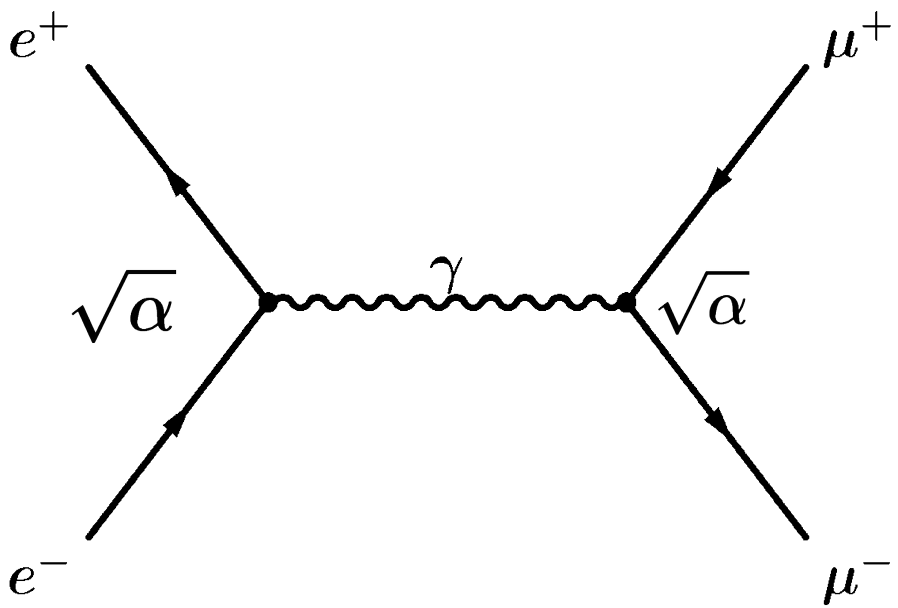
- Each term is represented with a pictogram, called a Feynman diagram
- Digression: Leibnitz formula for π:

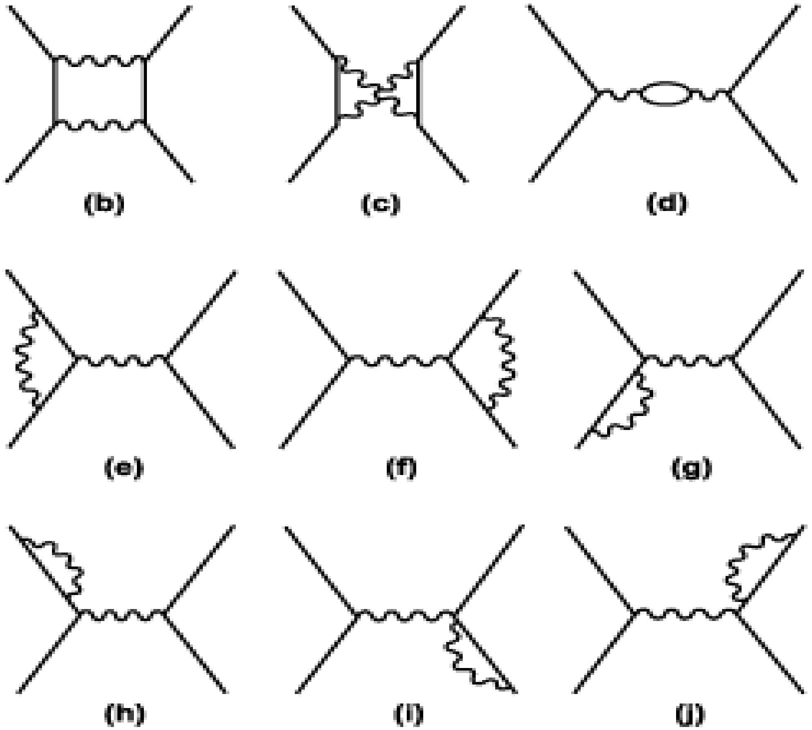
$$\pi = 4\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1} = 4 - \frac{4}{3} + \frac{4}{5} - \frac{4}{7} + \frac{4}{9} - \cdots$$

  - an example of a converging infinite series

Feynman series

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

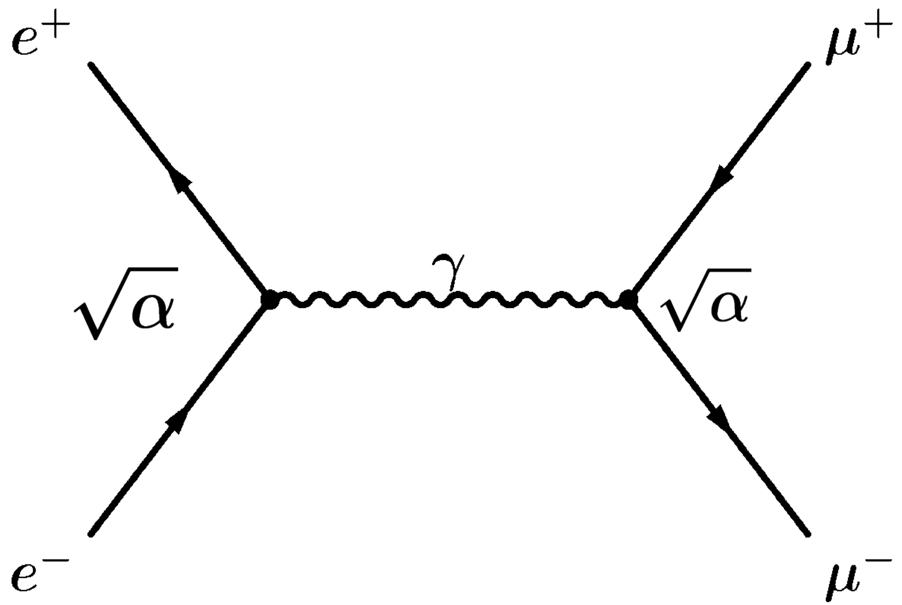




- At each vertex, coupling constant $\sqrt{\alpha}$
- $\alpha = \frac{1}{137}$ $\rightarrow$ converges rapidly!

Virtual particles

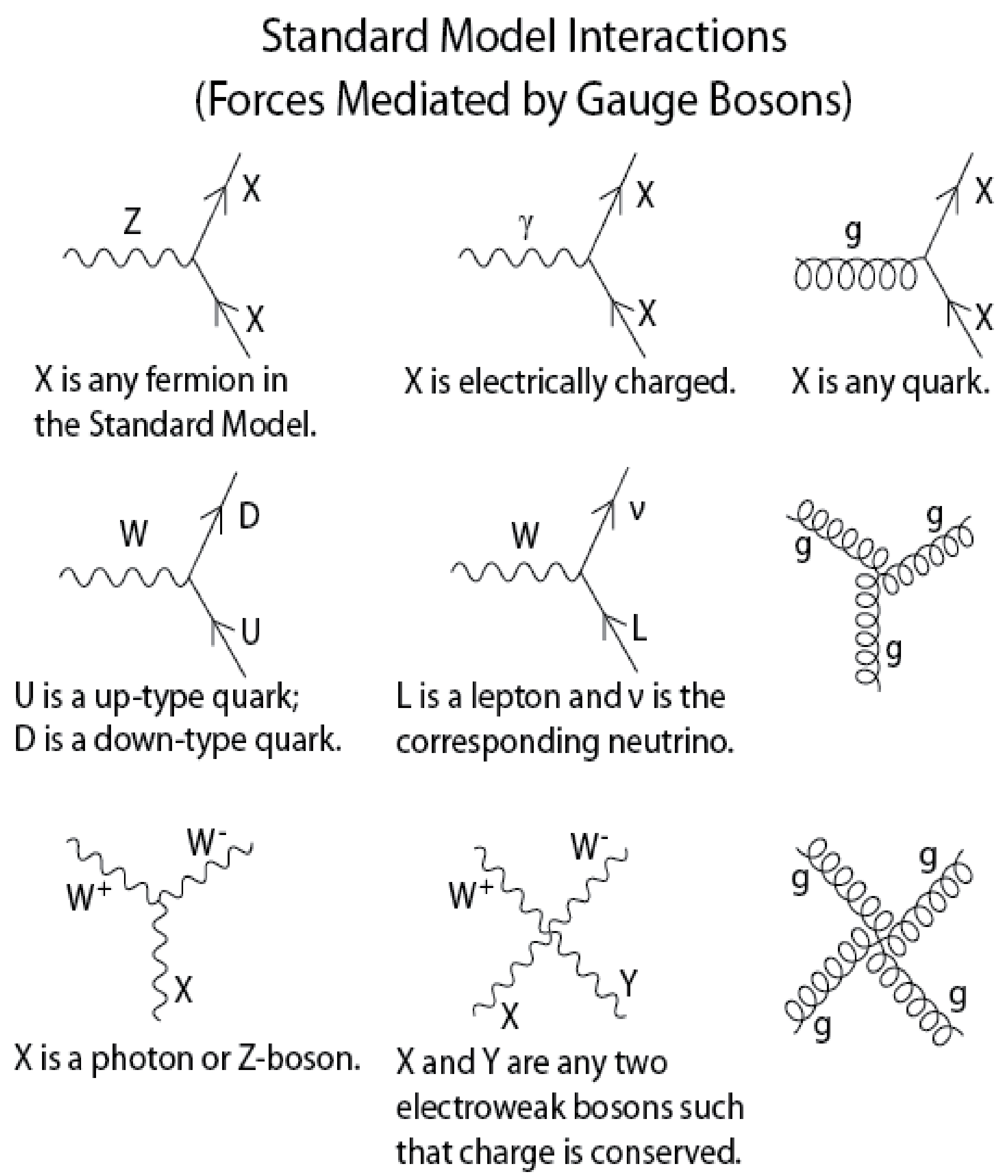
- Photon in the middle can violate conservation of energy-momentum – it's *virtual*.



- 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

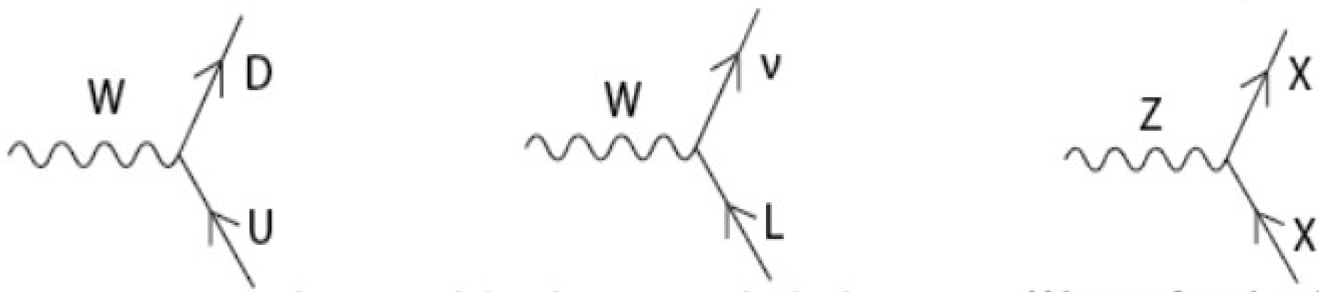
Feynman rules

- 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!



Weak interactions

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

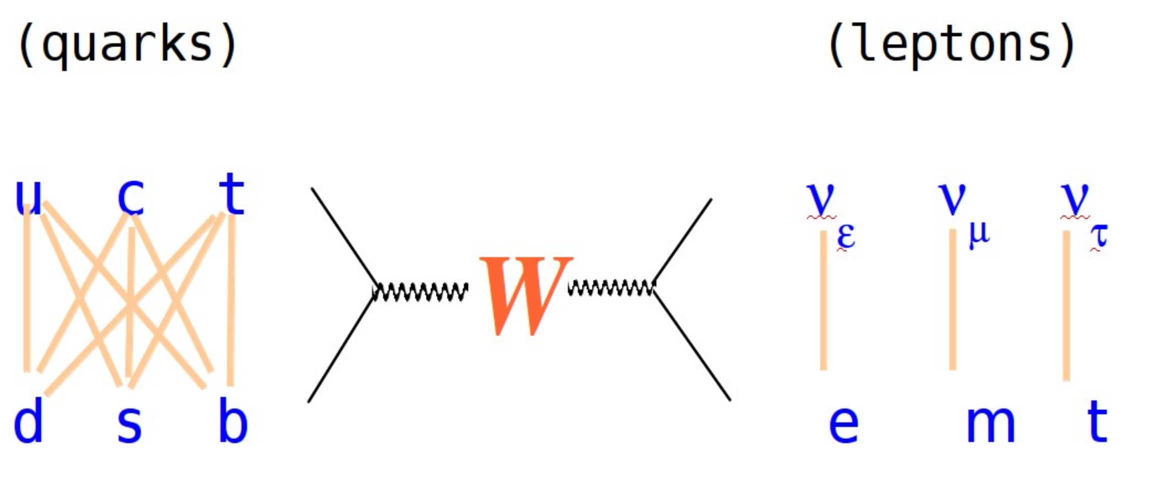


U is a up-type quark; D is a down-type quark.

L is a lepton and ν is the corresponding neutrino.

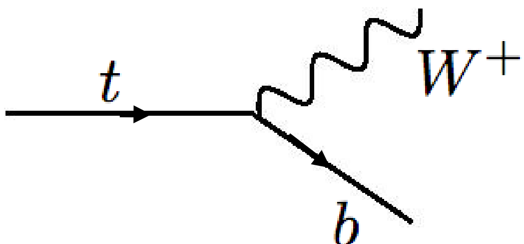
X is any fermion in the Standard Model.

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



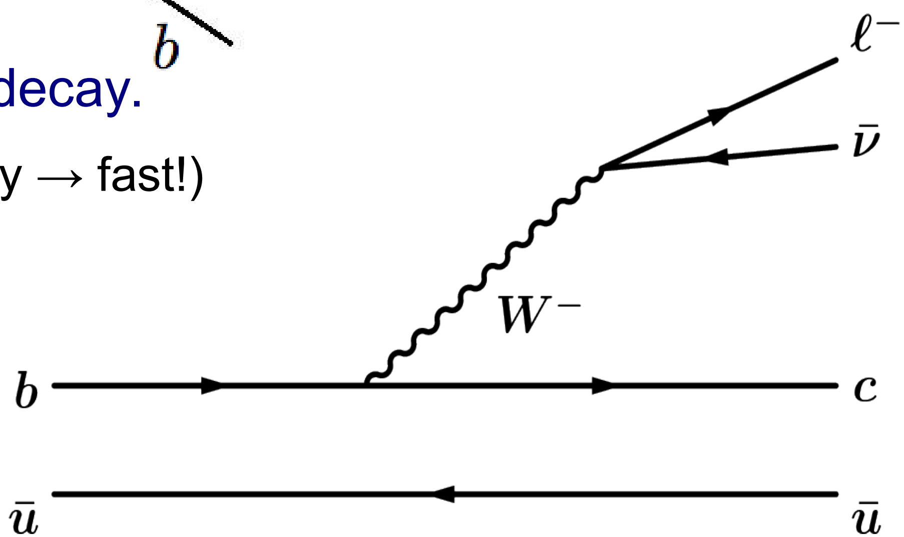
Examples of decays via weak interaction

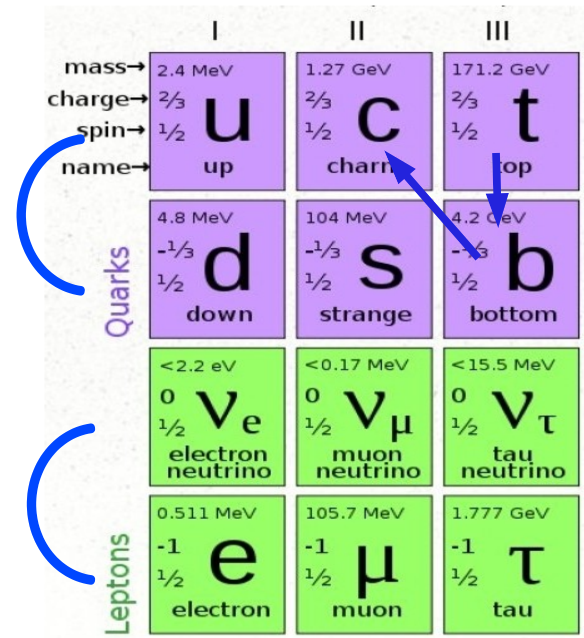
- W bosons couple up-type and down-type fermions
  - couple quarks across families
  - couplings are external parameters too



Top quark decay.

(Top is heavy → fast!)



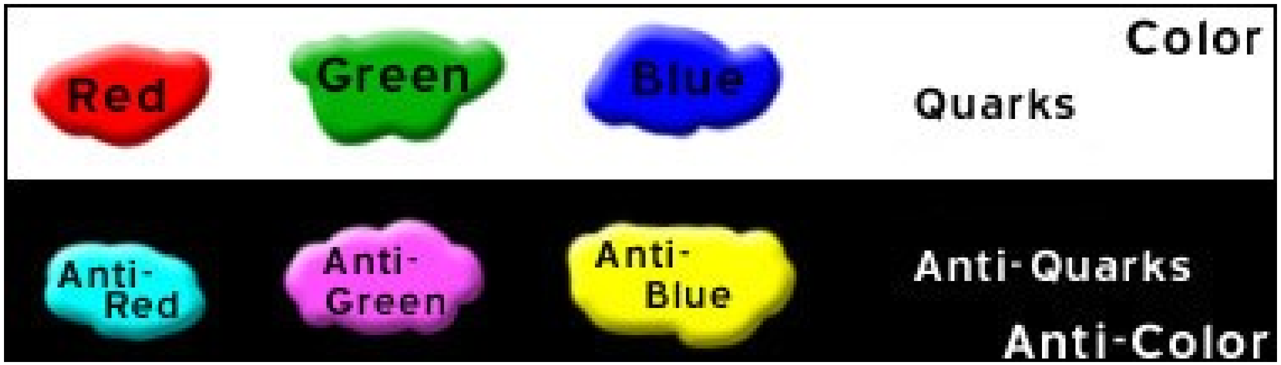


Decay of B meson into lepton + neutrino + D meson

(W is virtual → slow!)

Quantum Chromo-Dynamics (QCD)

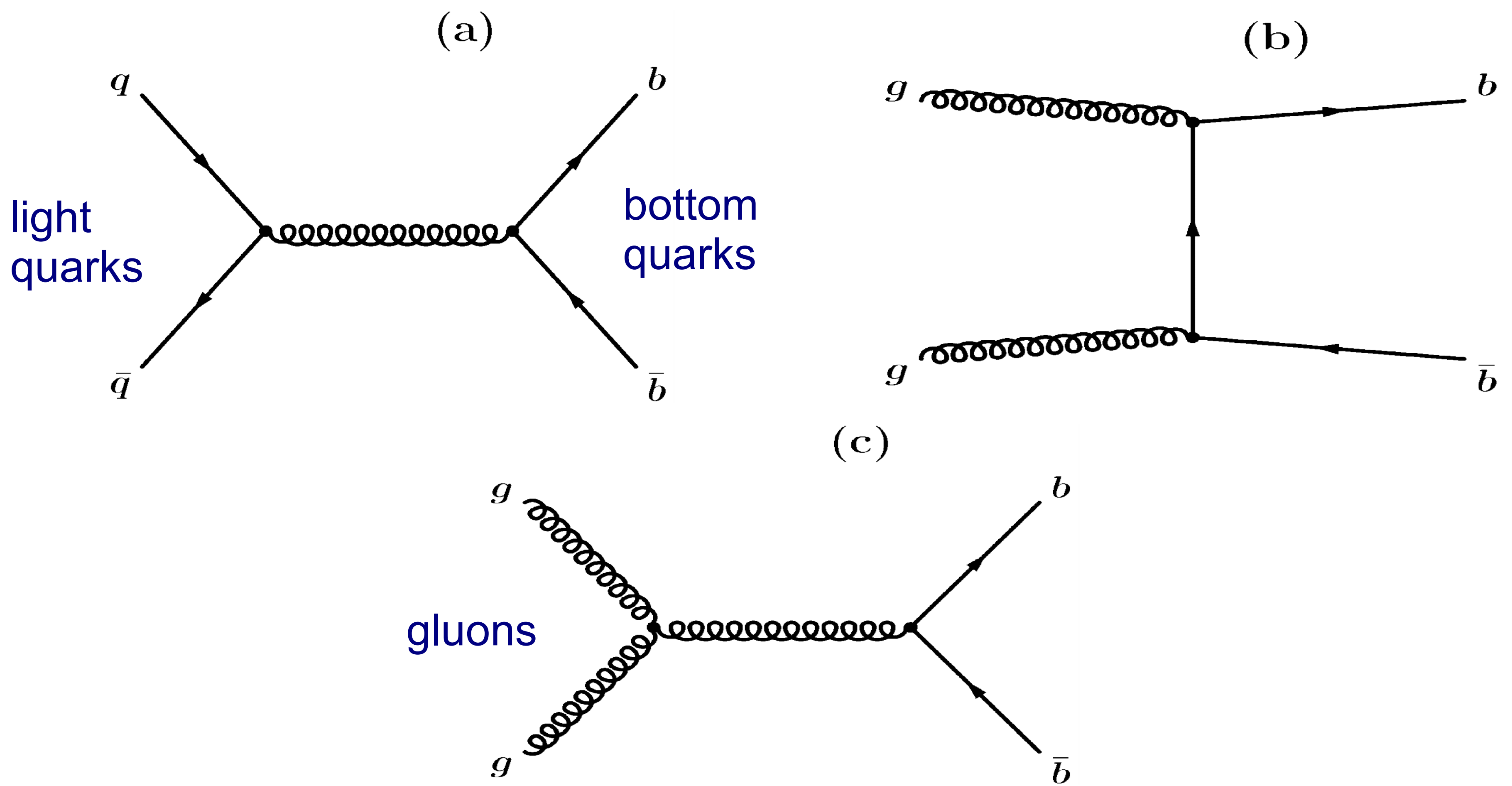
- Strong force (QCD): quarks carry color, interact via (8) gluons:



- 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)

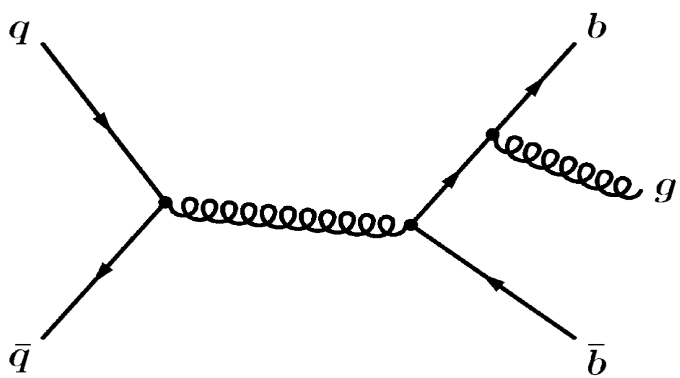
QCD

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

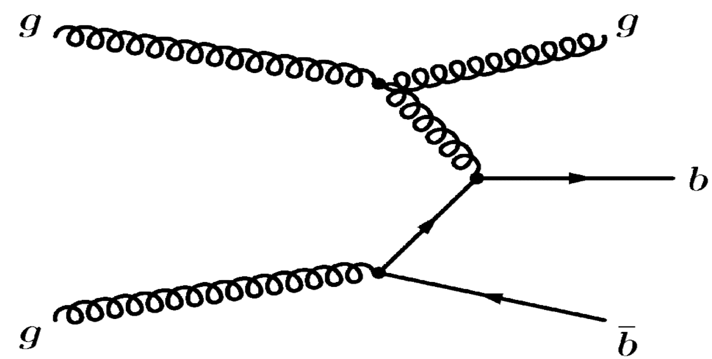


QCD

(a)

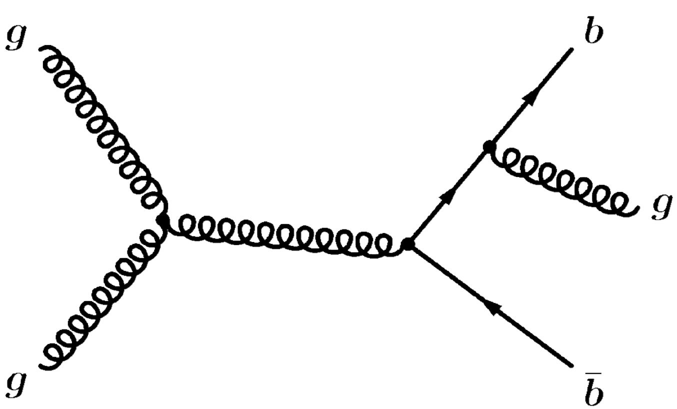


(b)

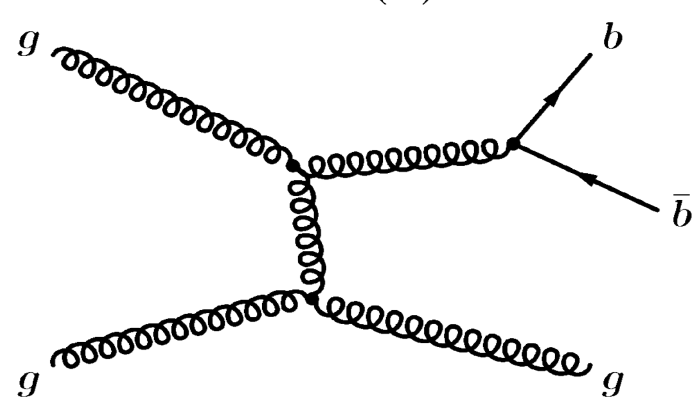


Adding more vertices with *low energy* gluons does not make amplitudes smaller!

(c)

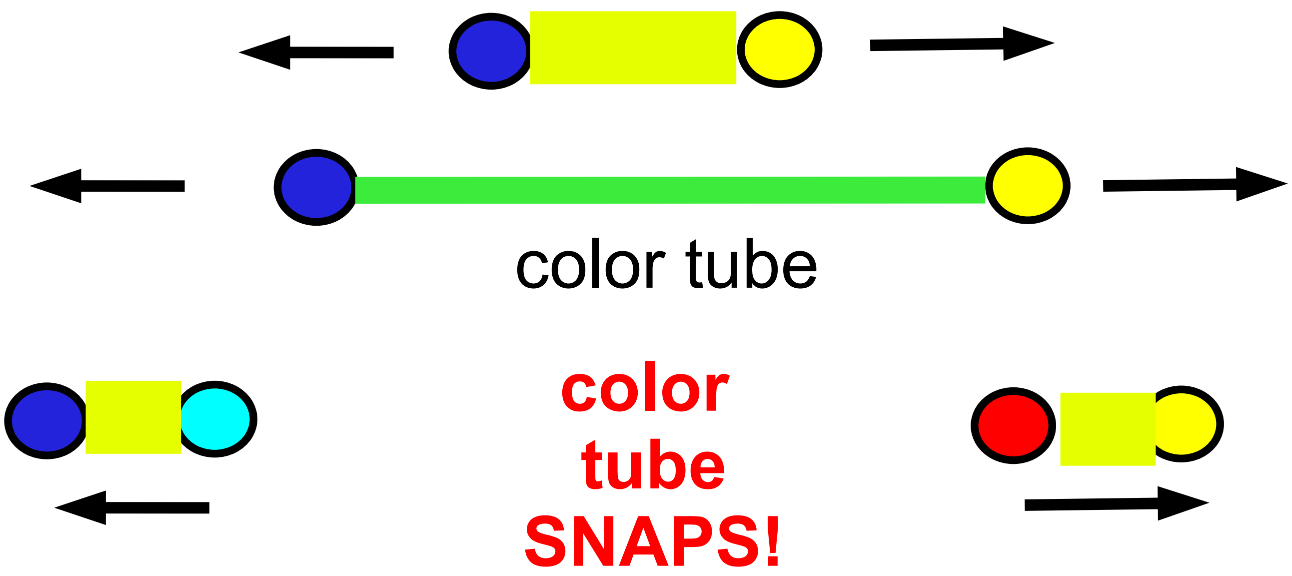


(b)



QCD: hadronization

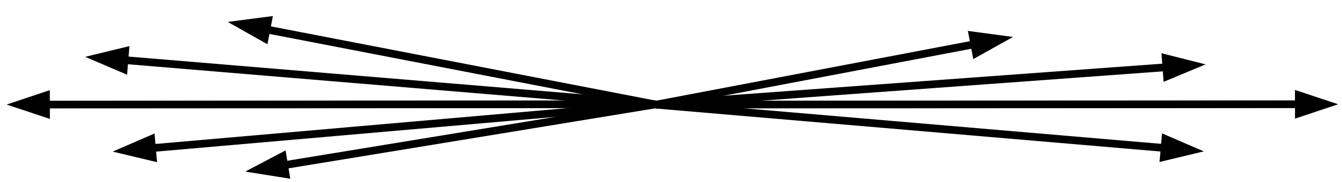
- Consider hadronic decay $W^+ \to u\bar{d}$
- As quarks move apart with high energy, color tube between them stretches, energy density rises



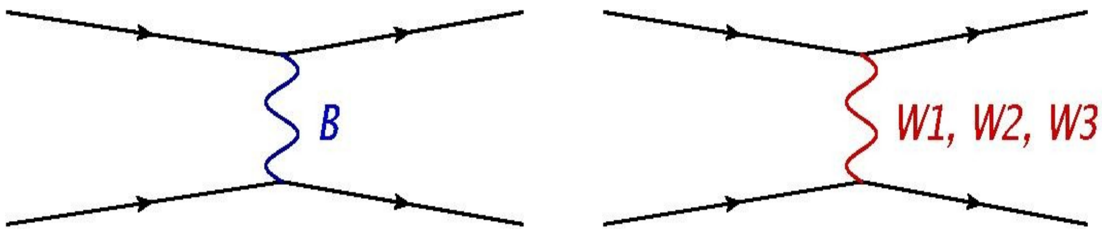
QCD: all quarks & gluons end up as jets

- 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':**



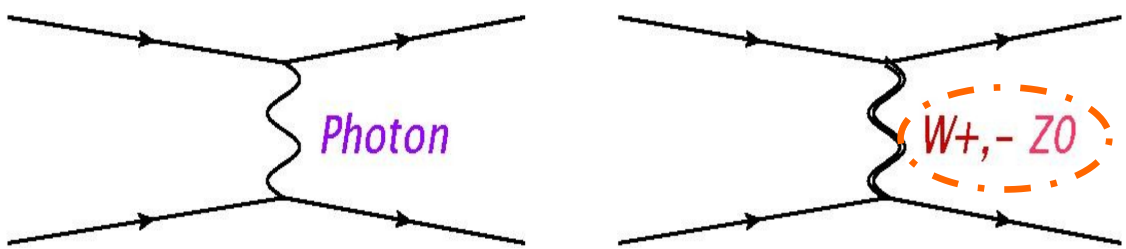
Electro-Weak symmetry breaking



Theory Input
(four massless Electro-Weak bosons)

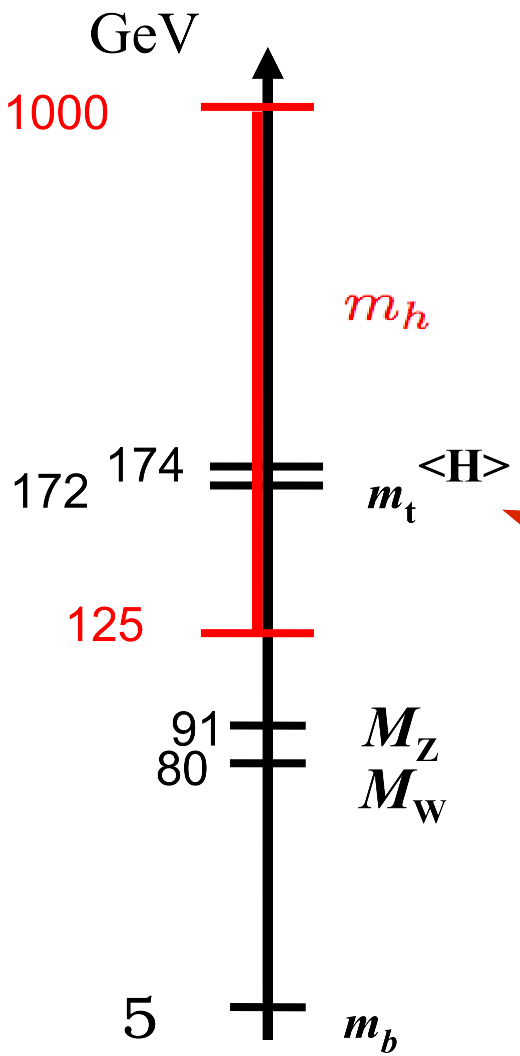
<H>

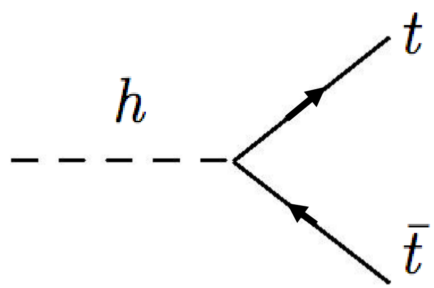
Higgs Field spontaneously breaks Electro-Weak Symmetry



Physical States:
massless photon and very heavy W and Z

Weak scale physics





- Higgs field pervades all space
  - fermions are interacting with it and acquire mass.
  - mass ~ strength of coupling to Higgs!

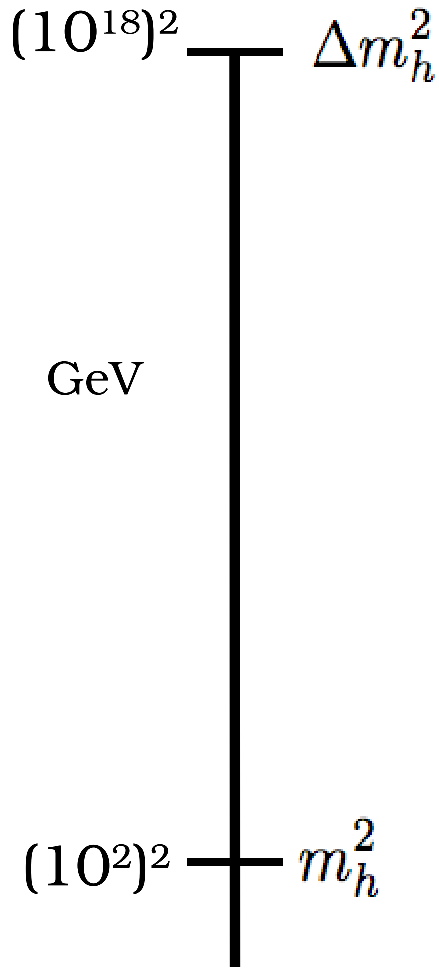
$\Longrightarrow$ Higgs have by far the strongest coupling to the top!

- Higgs vacuum expectation value is ~ top mass!?

- Higgs has been observed!

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

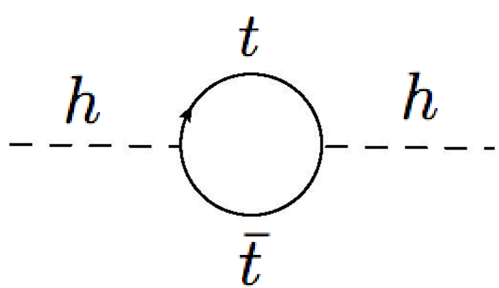
Hierarchy Problem



- When fundamental parameters (couplings or masses) are vastly different from measured values

- Quantum corrections to Higgs boson mass have contributions from virtual top quarks:

$$\Delta m_h^2 = \cdots +$$

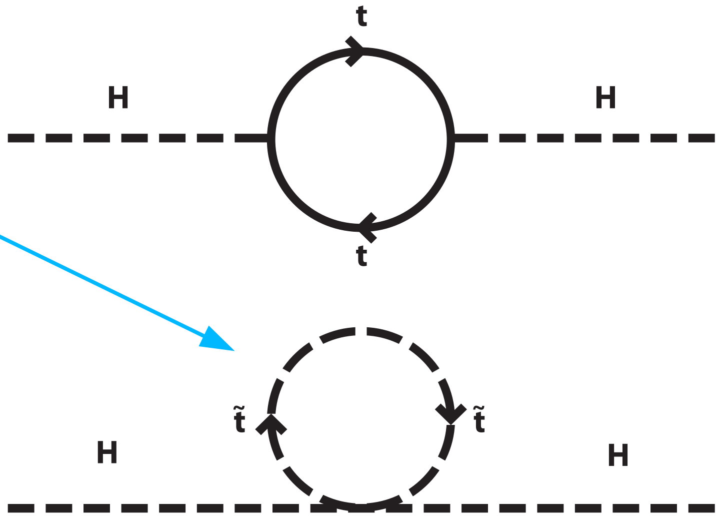


$$+ \cdots$$

- Correction is many orders of magnitude larger!

New Physics solutions to Hierarchy Problem

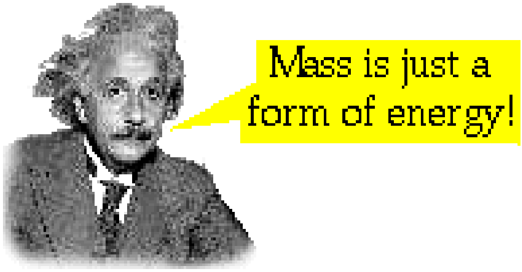
- Supersymmetry (SUSY)
  - add new particles (`super-partners') to cancel terms
  - many SUSY models result in *enhanced top quark production*



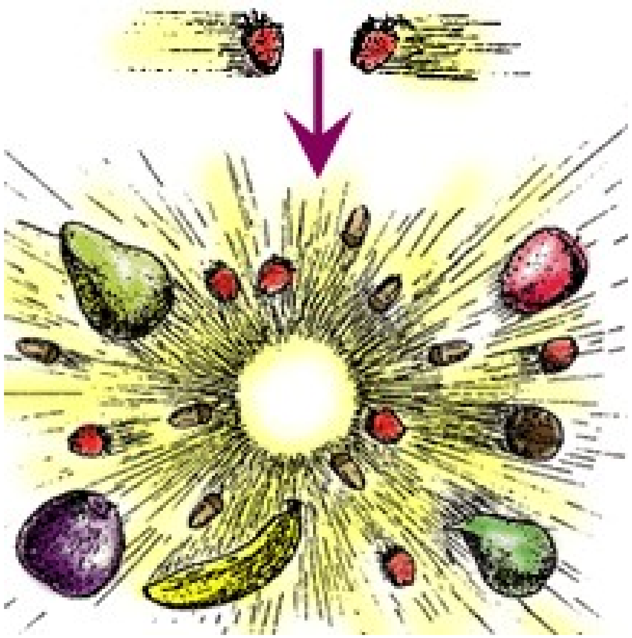
- Strongly Coupled Models:
  - Electro-Weak symmetry broken using a different mechanism
  - technicolor, topcolor, top condensates, extra dimensions (large: Arkani-Hamed, Dimopoulos & Dvali, warped: Randall & Sundrum)
  - *possible new particles (mass ~ TeV) with large coupling to top quarks!*

Collider Physics

- Plan: smash protons head on and turn their kinetic energy into those heavy particles!

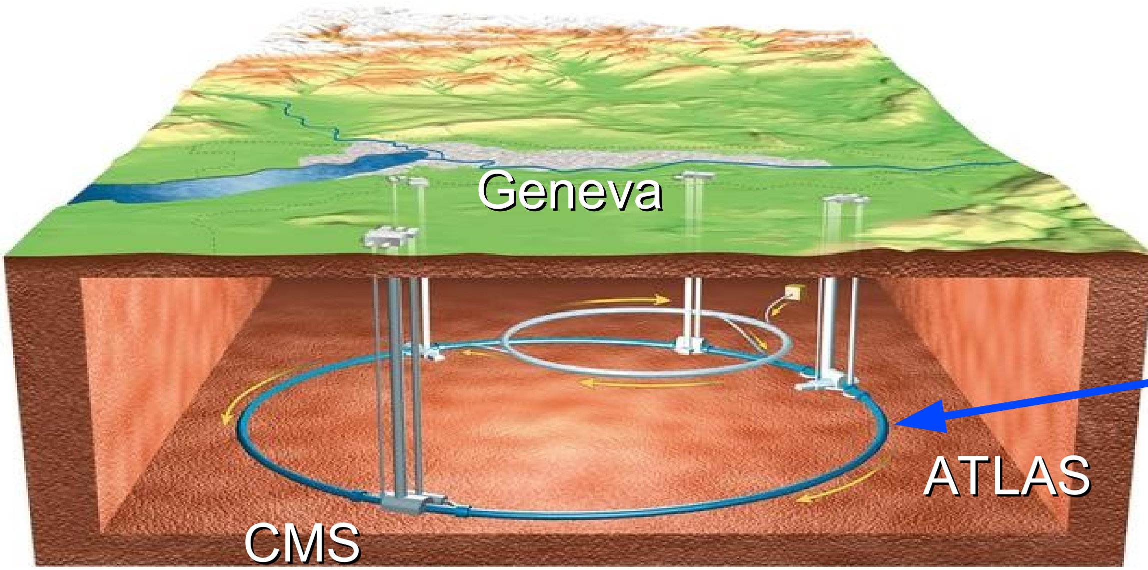


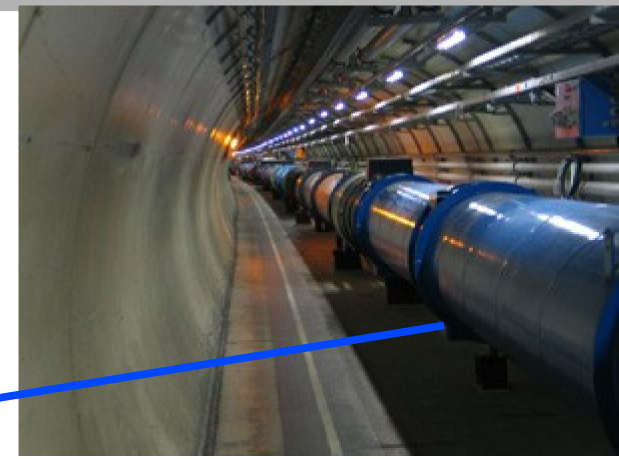
- Very heavy fruits (e.g. watermelons = top quarks) show up with very low probability

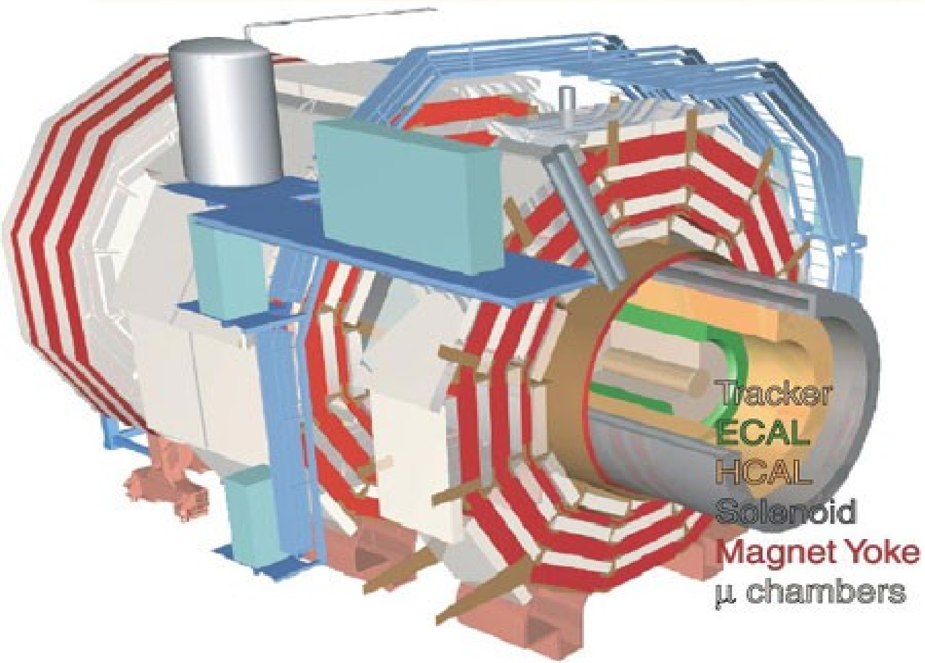


- Watermelons (top quarks)
  - appear briefly, but
  - decay immediately to lots of `debris' (other fruits = particles)
- Experimental issues:
  - how to detect this `debris'?
  - which collisions need to be saved for posterity?

LHC and CMS Detector

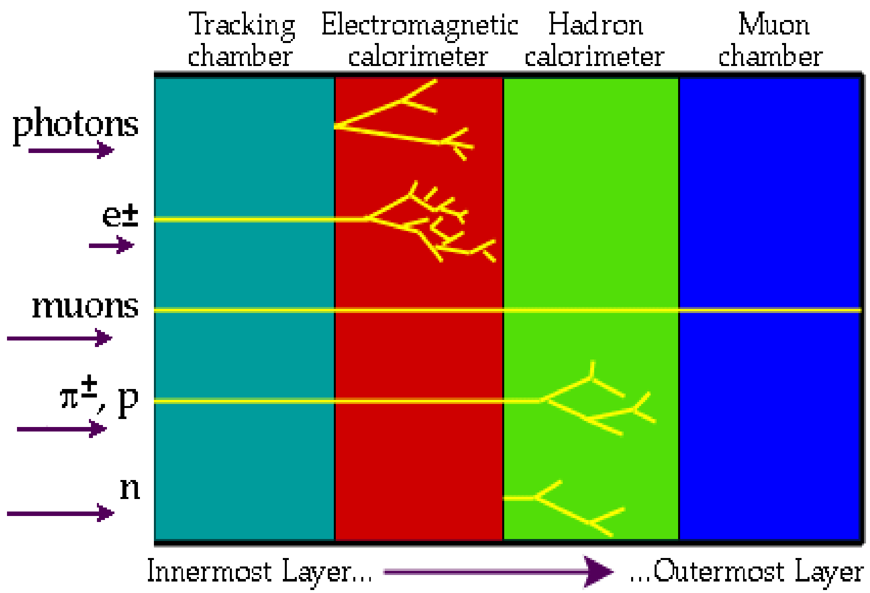


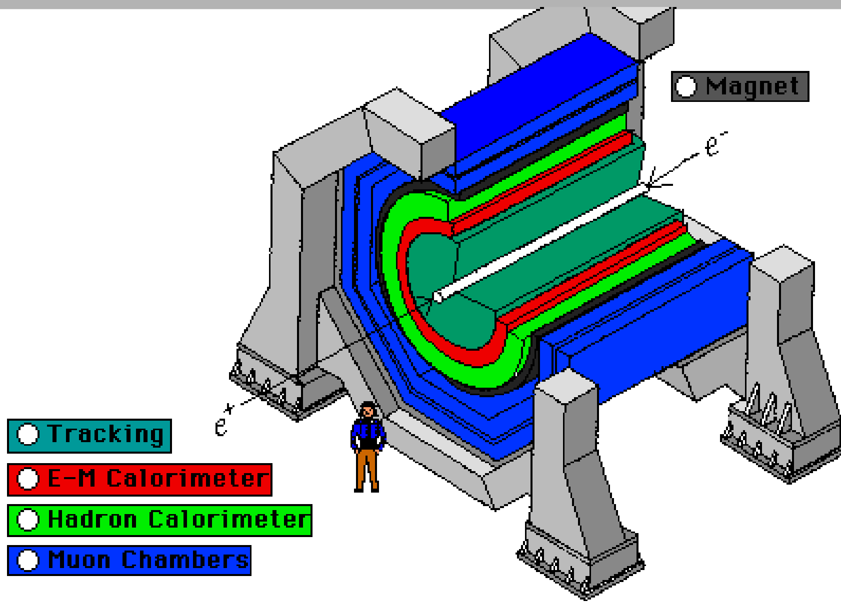




- Five stories tall
  ("Like a 5-story swiss watch")

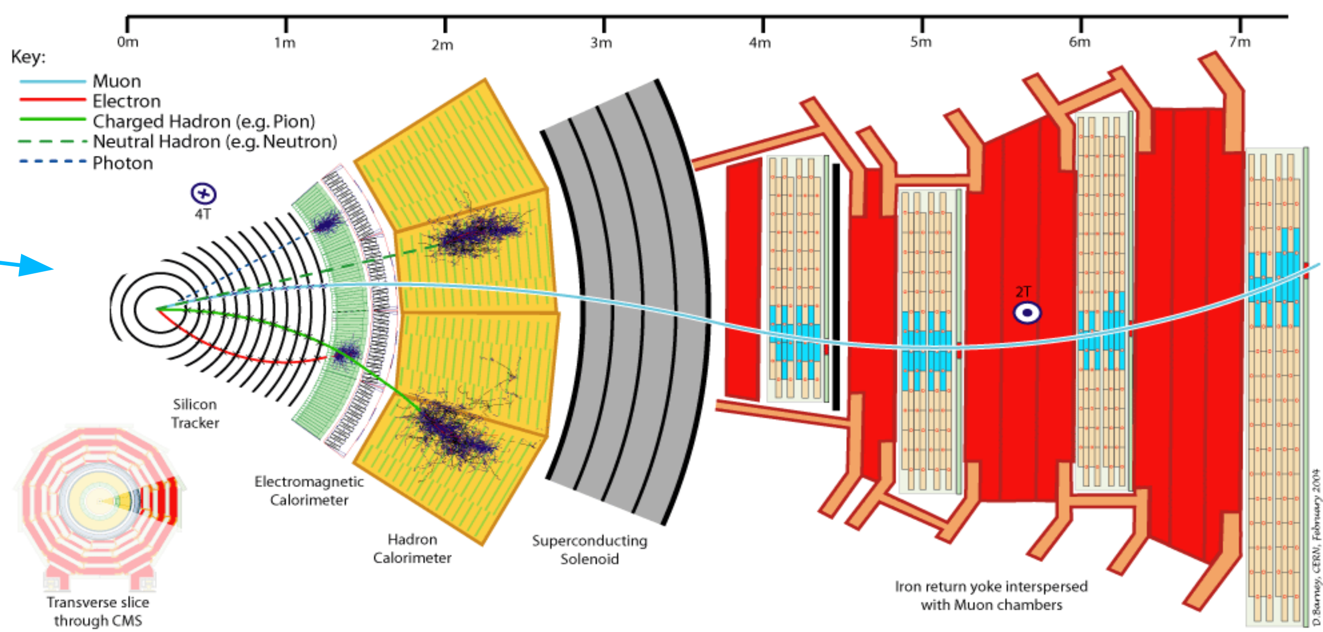
Collider detectors





Toy detector

CMS detector



The CMS Detector

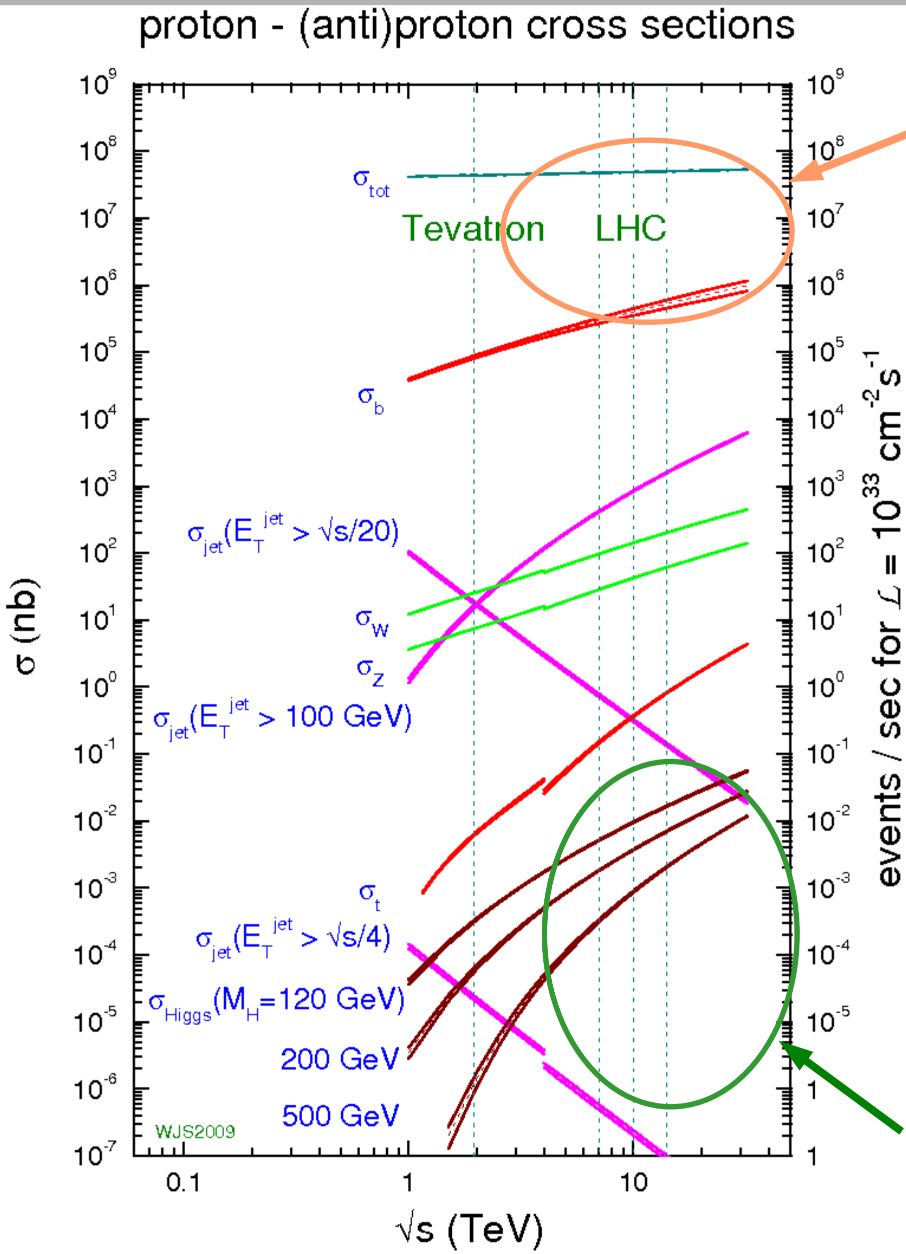
Total weight 12500 T

Diameter 15 m

Length 22 m

Magnetic field 4 T

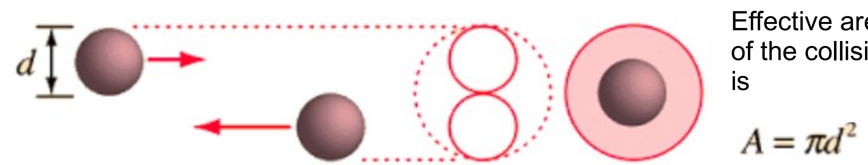
LHC production cross-sections at a glance



uninteresting

new particles

- Cross section measured in barns (area)



Effective area of the collision is

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

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*

Primary Dataset
(on trigger bits)

Secondary Dataset

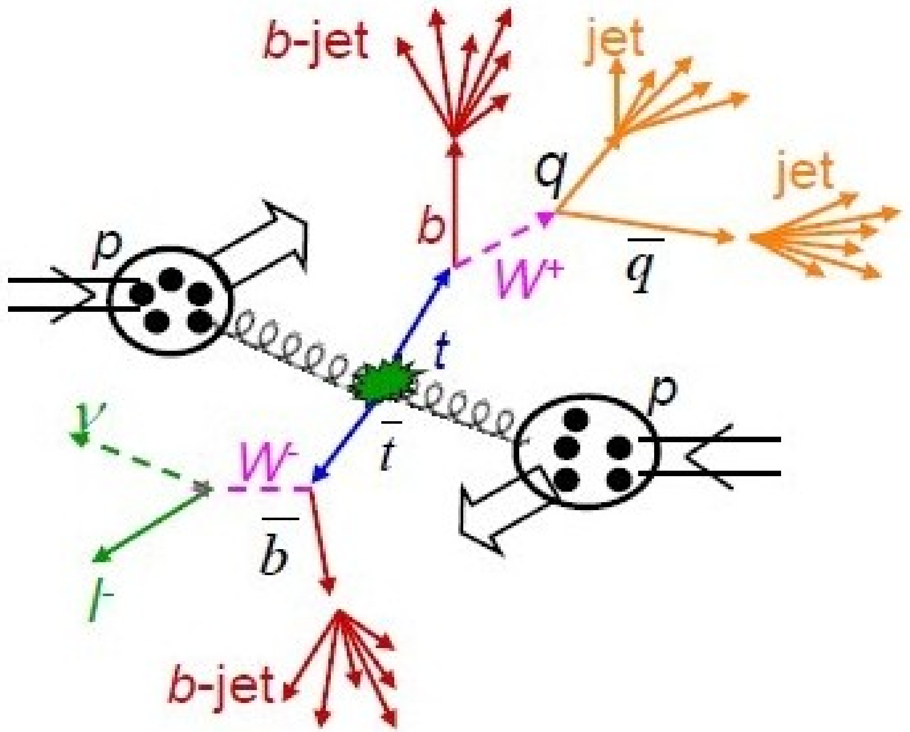
Group Skim
(e.g. Higgs group)

Final Sample
(interactive analysis)

(Also need to drop unneeded parts of each event)

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)

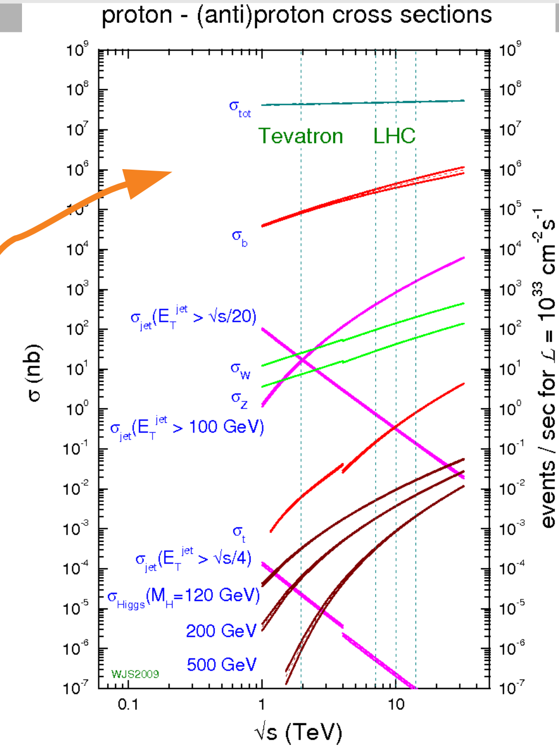


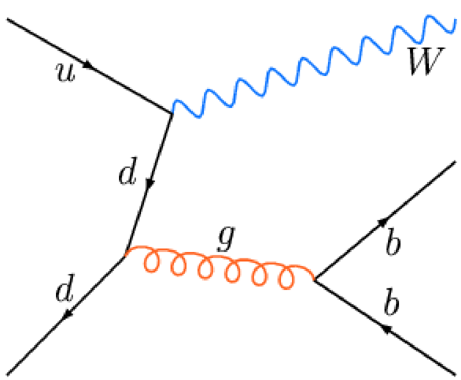
- Most other analyses built from same building blocks!

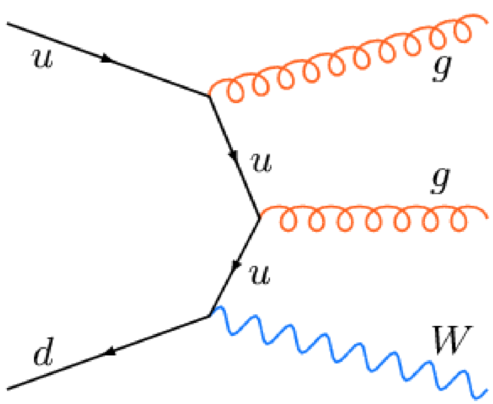
  ==> $t\bar{t}$ events are a perfect tool for physics commissioning!

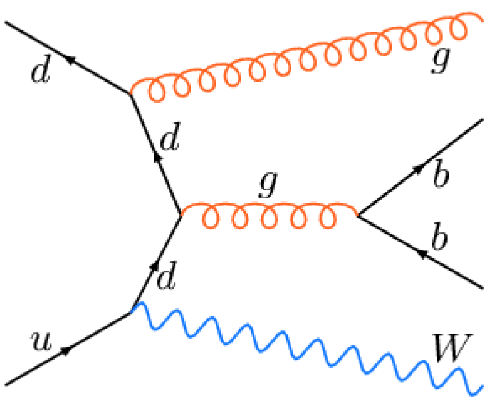
Reconstructing $t\bar{t}$: backgrounds

- 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 $t\bar{t}$ → **Signal (S)**
  - however, our selection is imperfect ==> some events in data will be something else → **Background (B)**



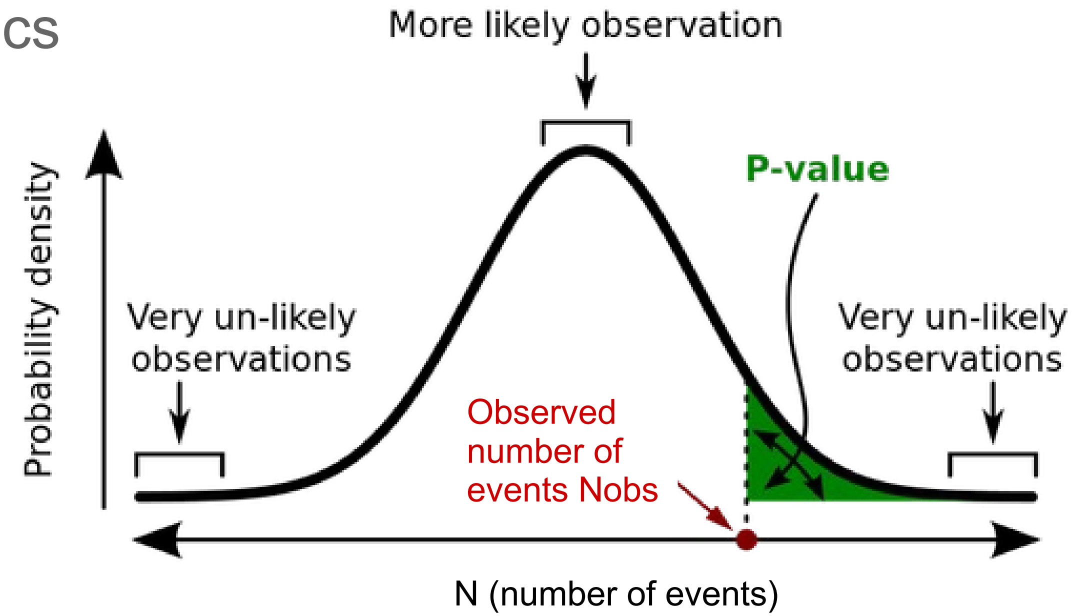






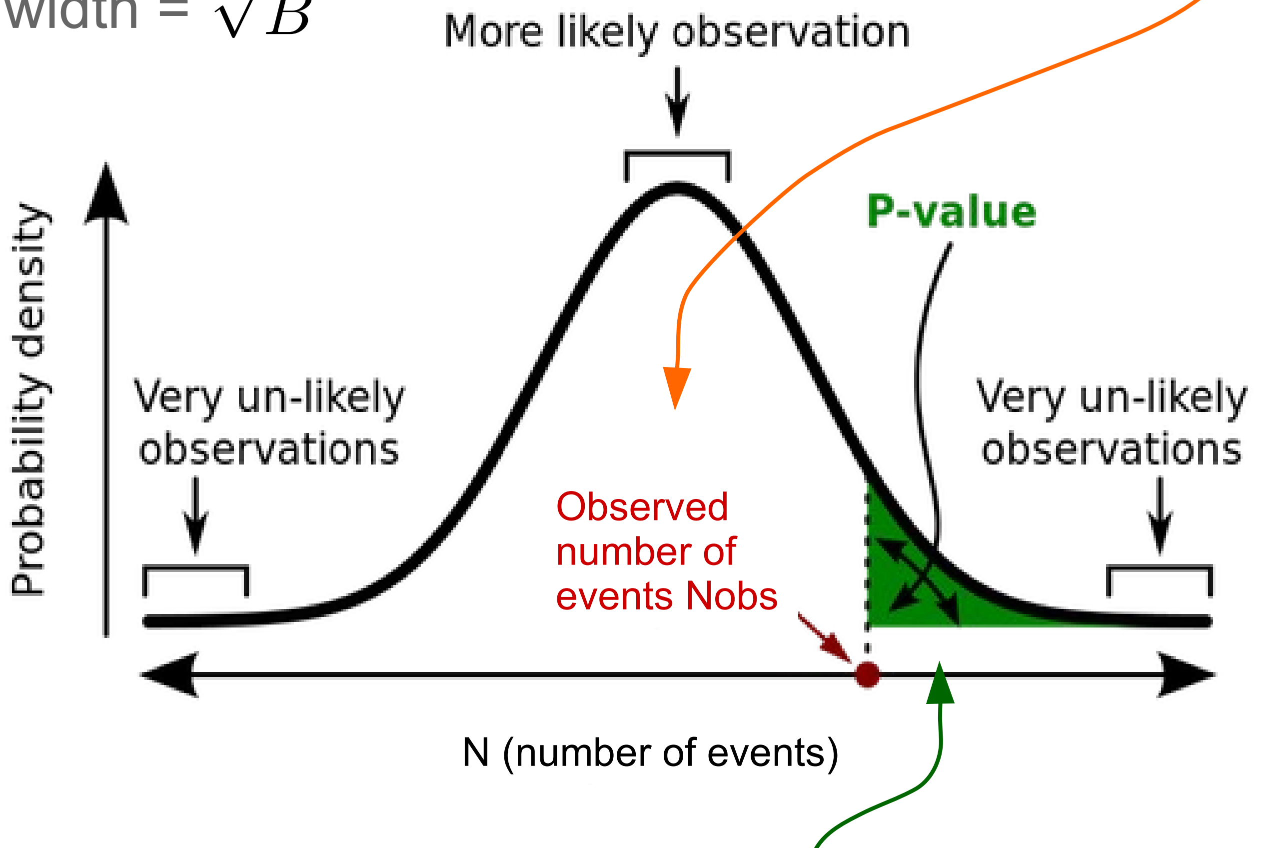
An anatomy of a search for New Physics

- Observe N_{obs} evens: $N_{\rm obs} = S + B$
- Need a separate measurement to estimate $B \pm \delta B$ (error)
- We then have two options
  - only SM = no New Physics ("null hypothesis", H0)
  - there is New Physics ("alternative hypothesis", H1)
- Discovering New Physics = ruling out H0.



An anatomy of a search for New Physics

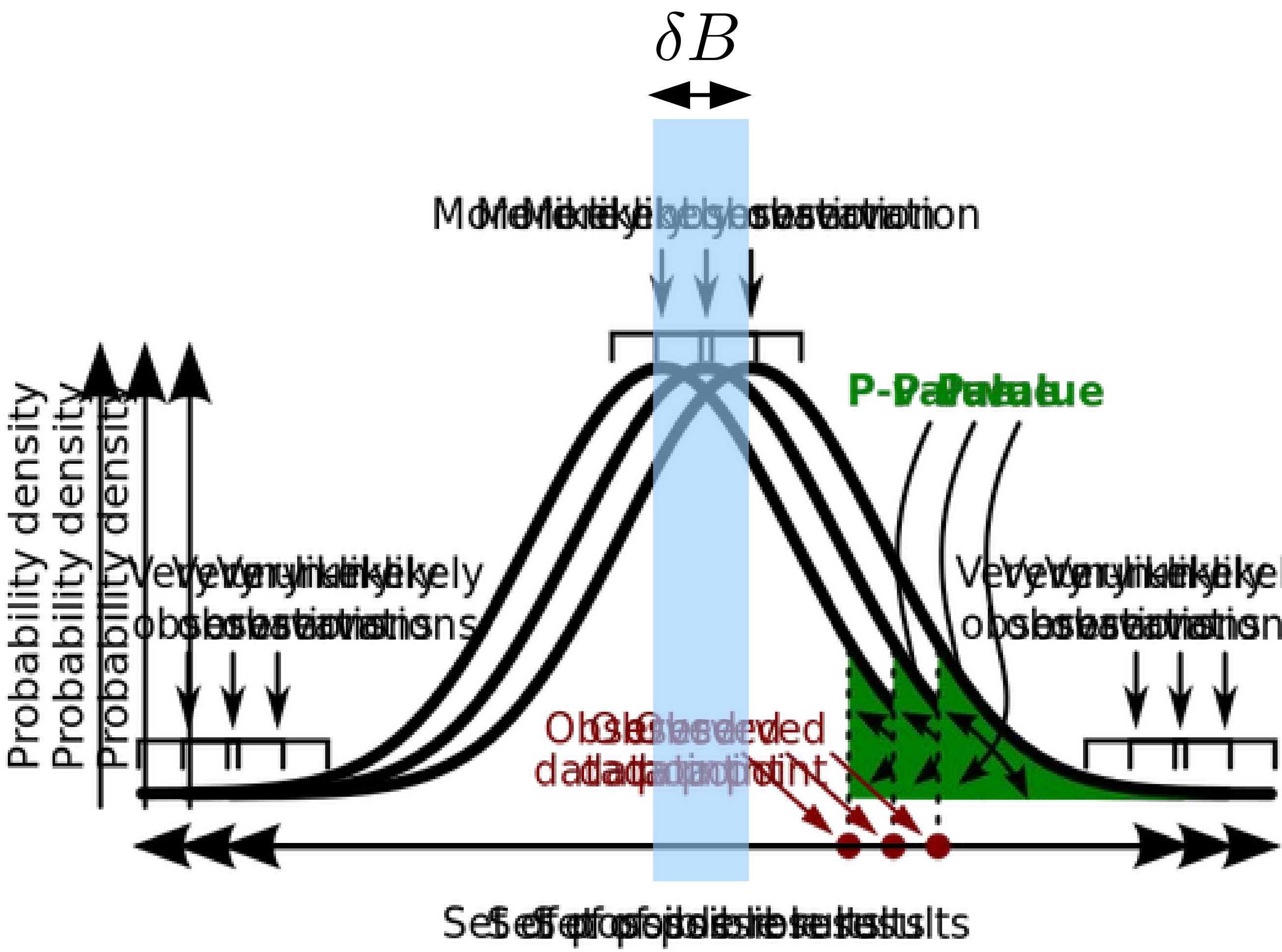
- Center of SM Gaussian = # of background events, B .
- Its width = $\sqrt{B}$



- 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 → decreases P-value.



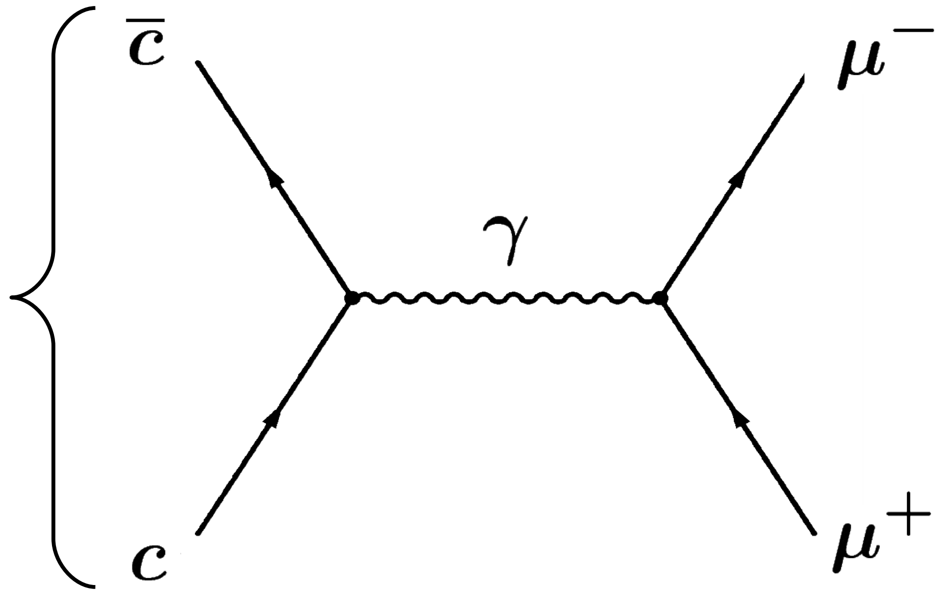
An anatomy of a search for New Physics

- 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):

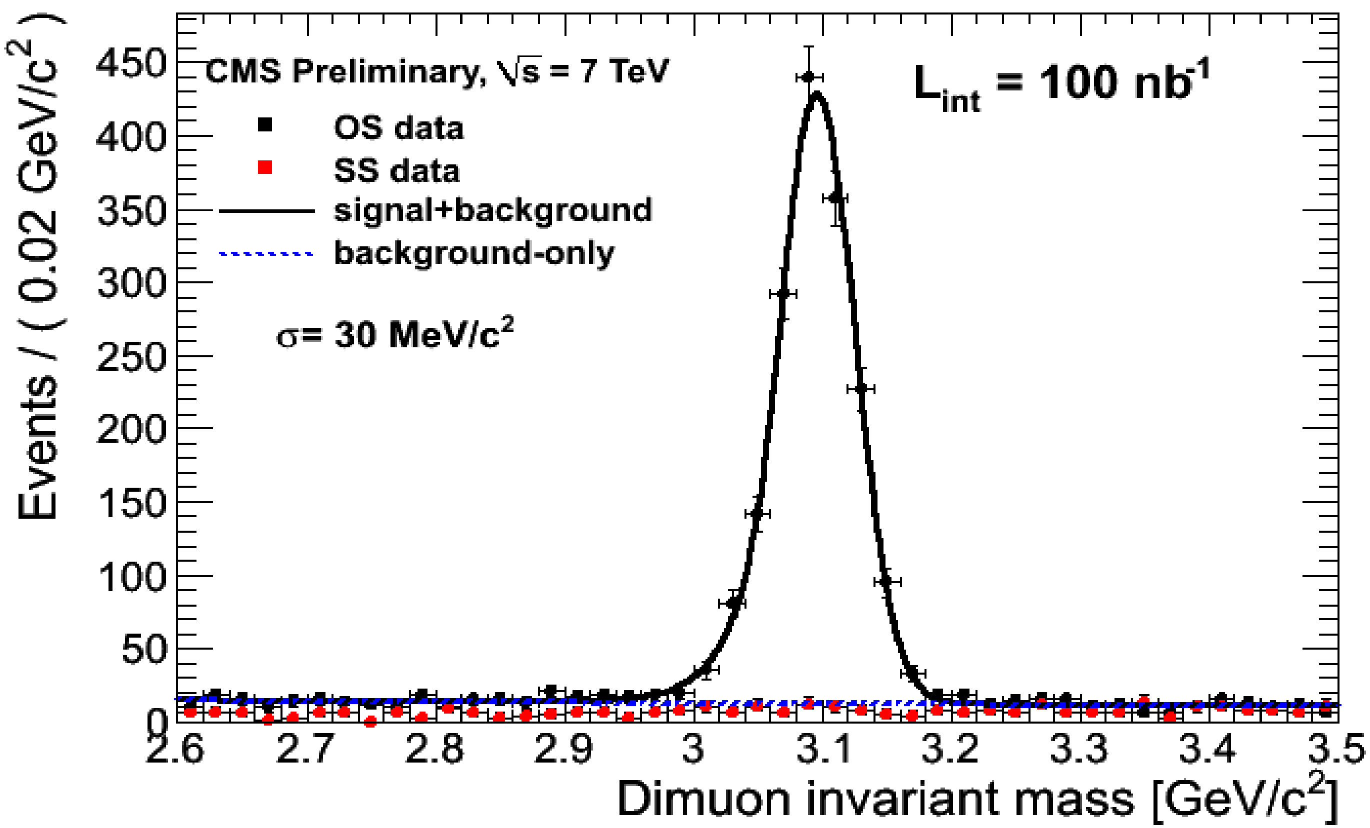
$J/\psi =$



==> rate of this decay is `slow' enough that width is narrow

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

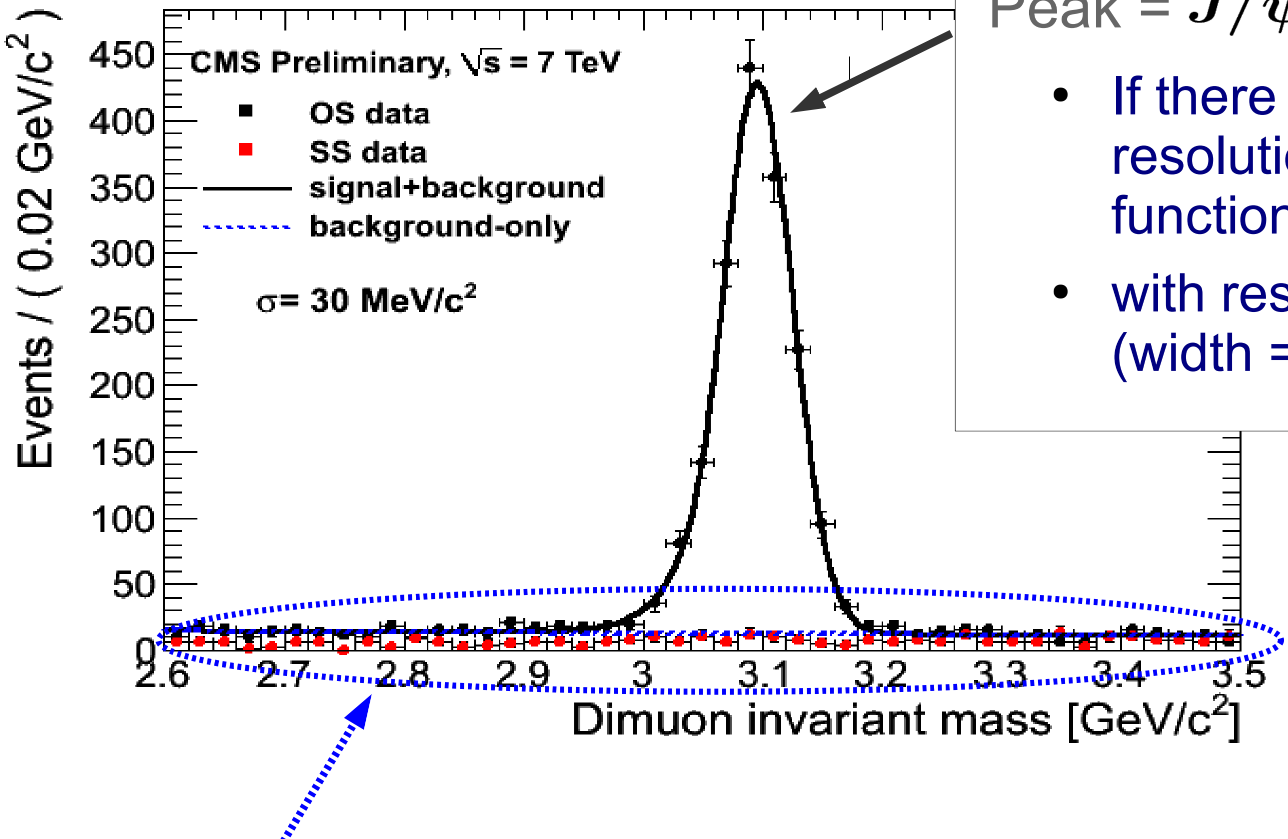
- consider pairs of oppositely charged muons
- add their 4-vectors, create a 4-vector of a J/ψ `candidate'
- plot distribution of invariant mass: $mc^2 = \sqrt{E^2 - p^2c^2}$



$$E = E_1 + E_2$$

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

Anatomy of a `mass plot'



Peak = J/ψ itself

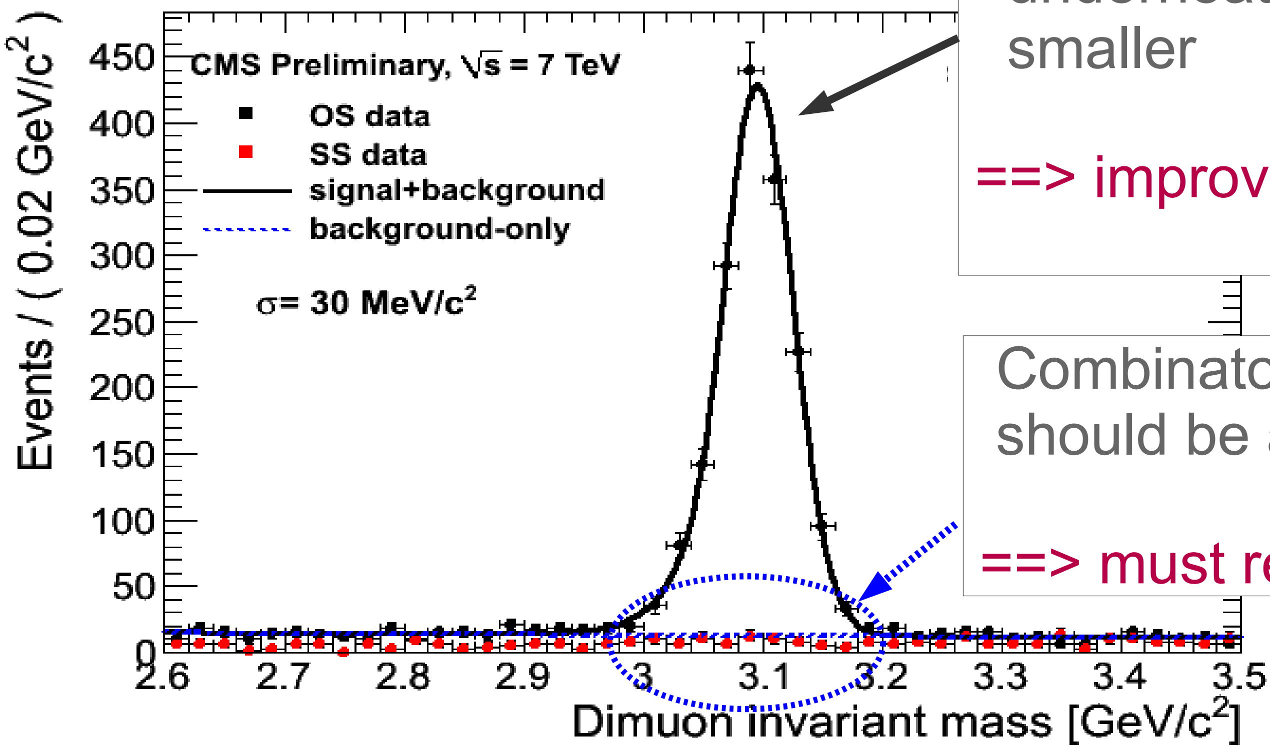
- If there were no detector resolution, it would be delta function (a vertical line)
- with resolution, it's a Gaussian (width = resolution)

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

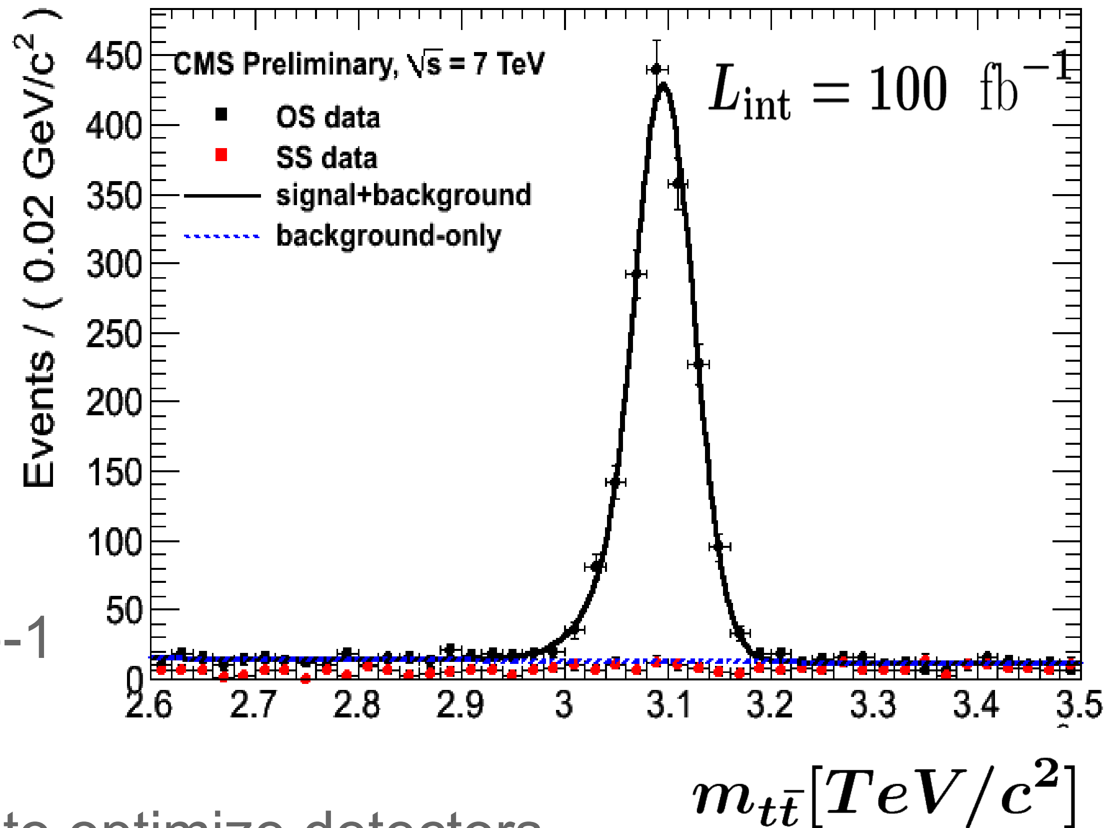
==> improve detector resolution

Combinatorial background: should be as low as possible

==> must reduce fake rate

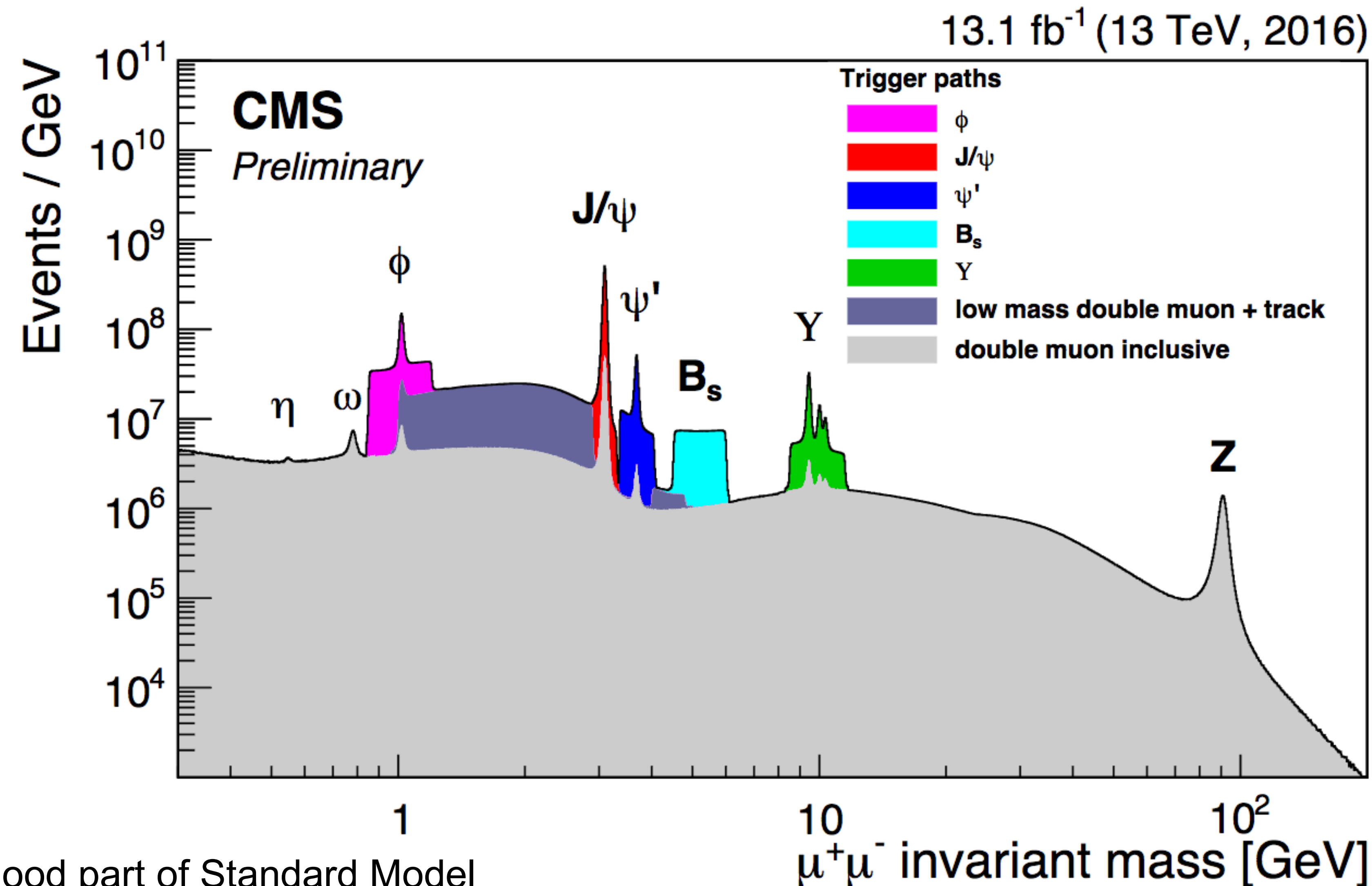
Digression #3: bump hunting

- Hypothetical scenario:



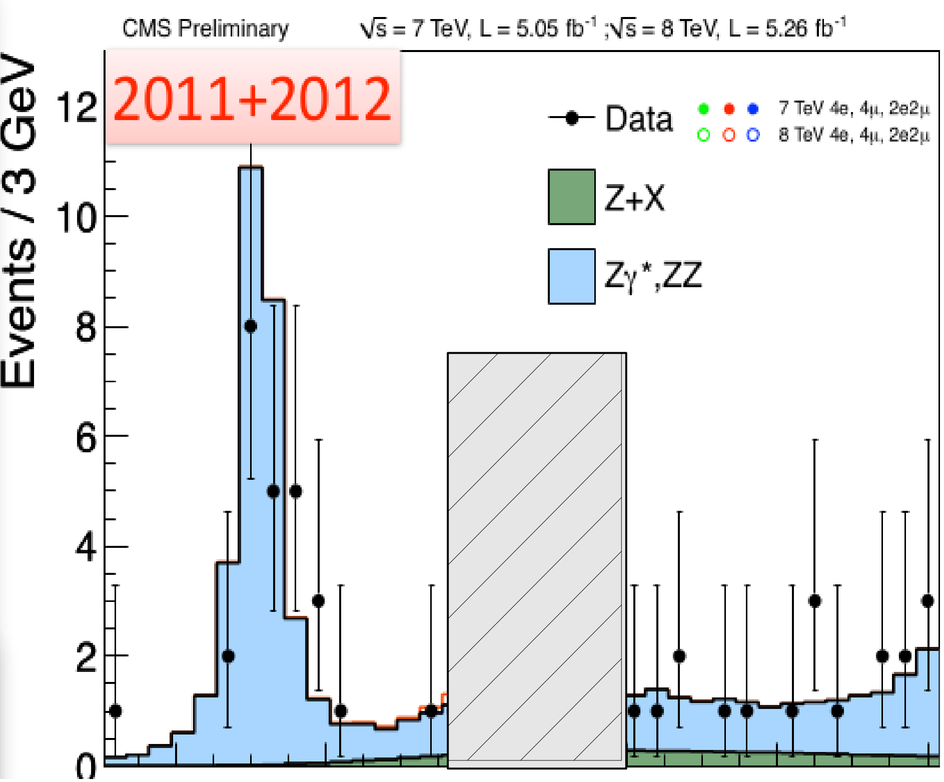
- Say, a 3.1 TeV resonance, after 100 fb-1 of data
- Logic is identical: want to optimize detectors so that the peaks ("bumps") are narrow, on small background.
- This is **"bump hunting"** – the easiest way to find new physics

Two-muon resonances



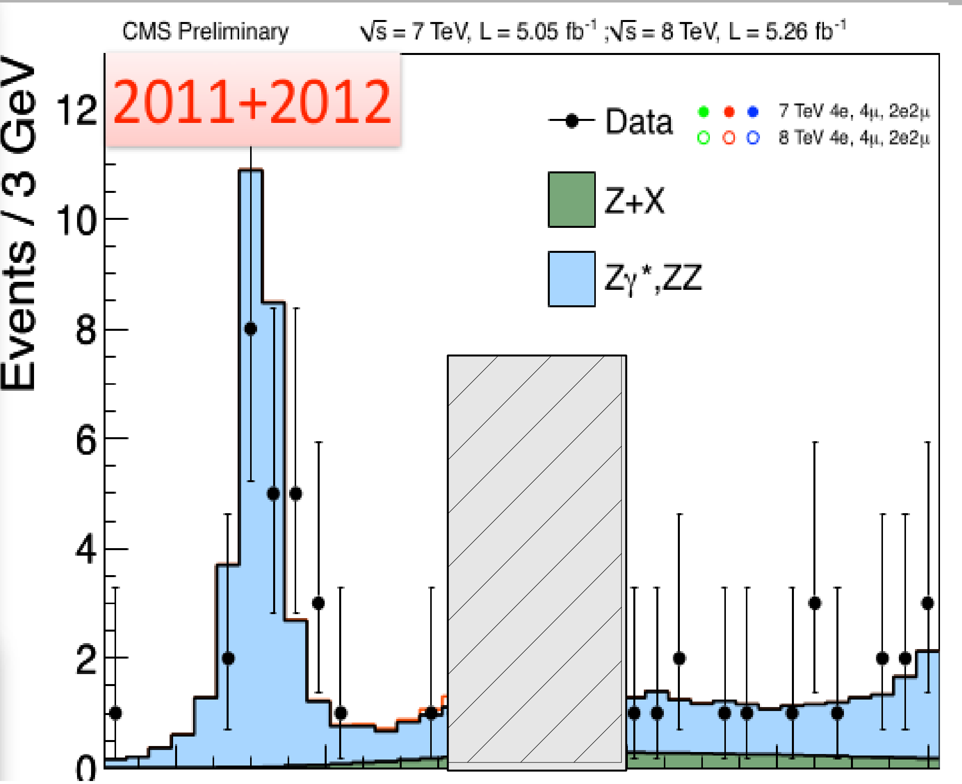
(A good part of Standard Model in a single plot!)

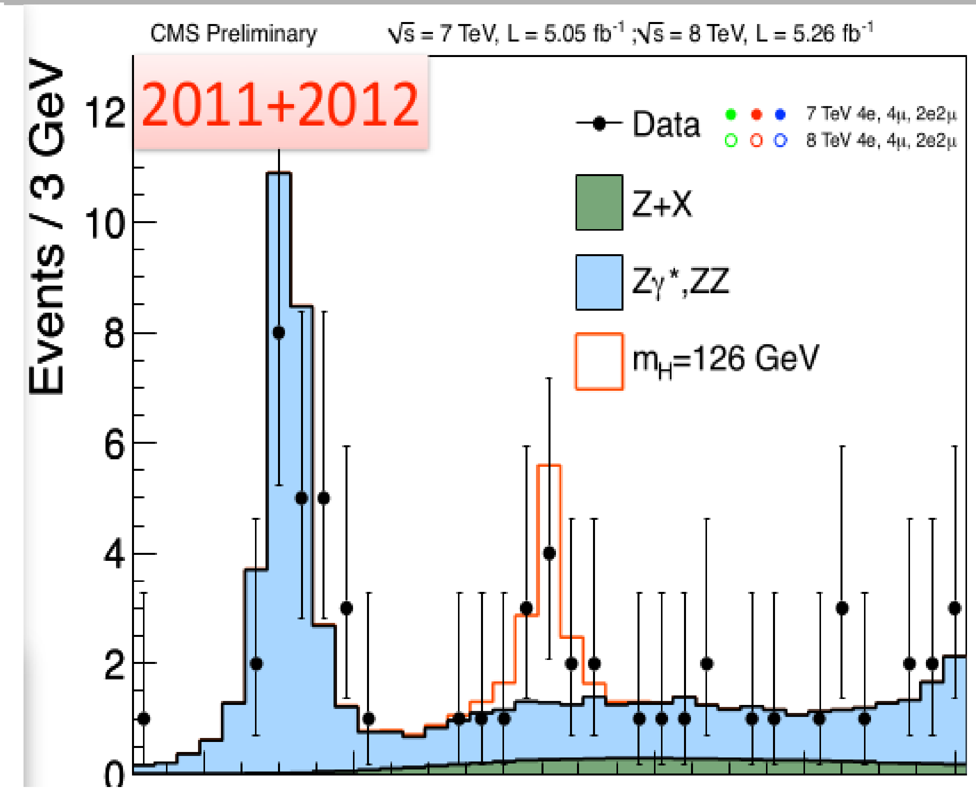
Higgs search: $H \rightarrow ZZ^* \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$



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

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

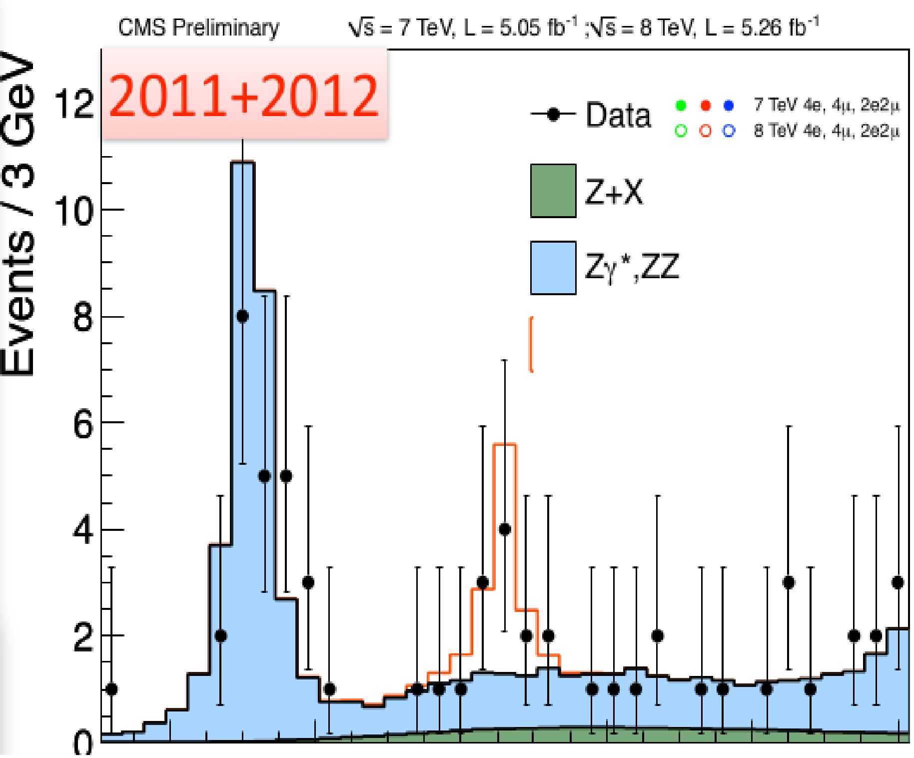


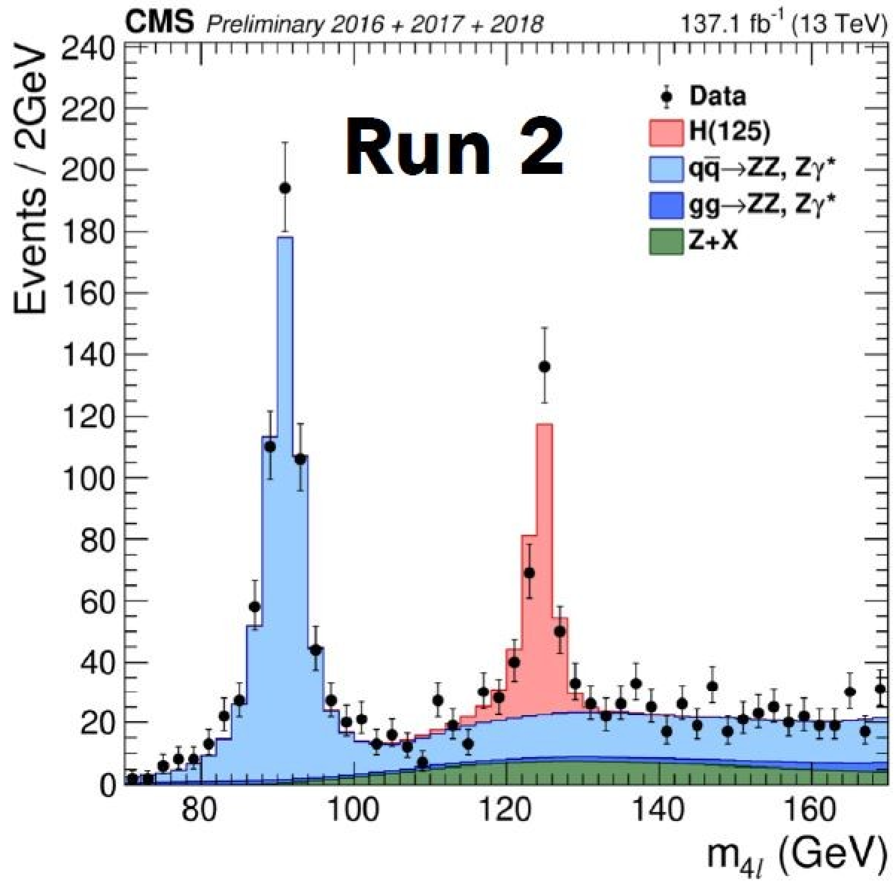


- Light blue: Standard Model
- Possible Higgs location is **blinded** (to avoid human bias)

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

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

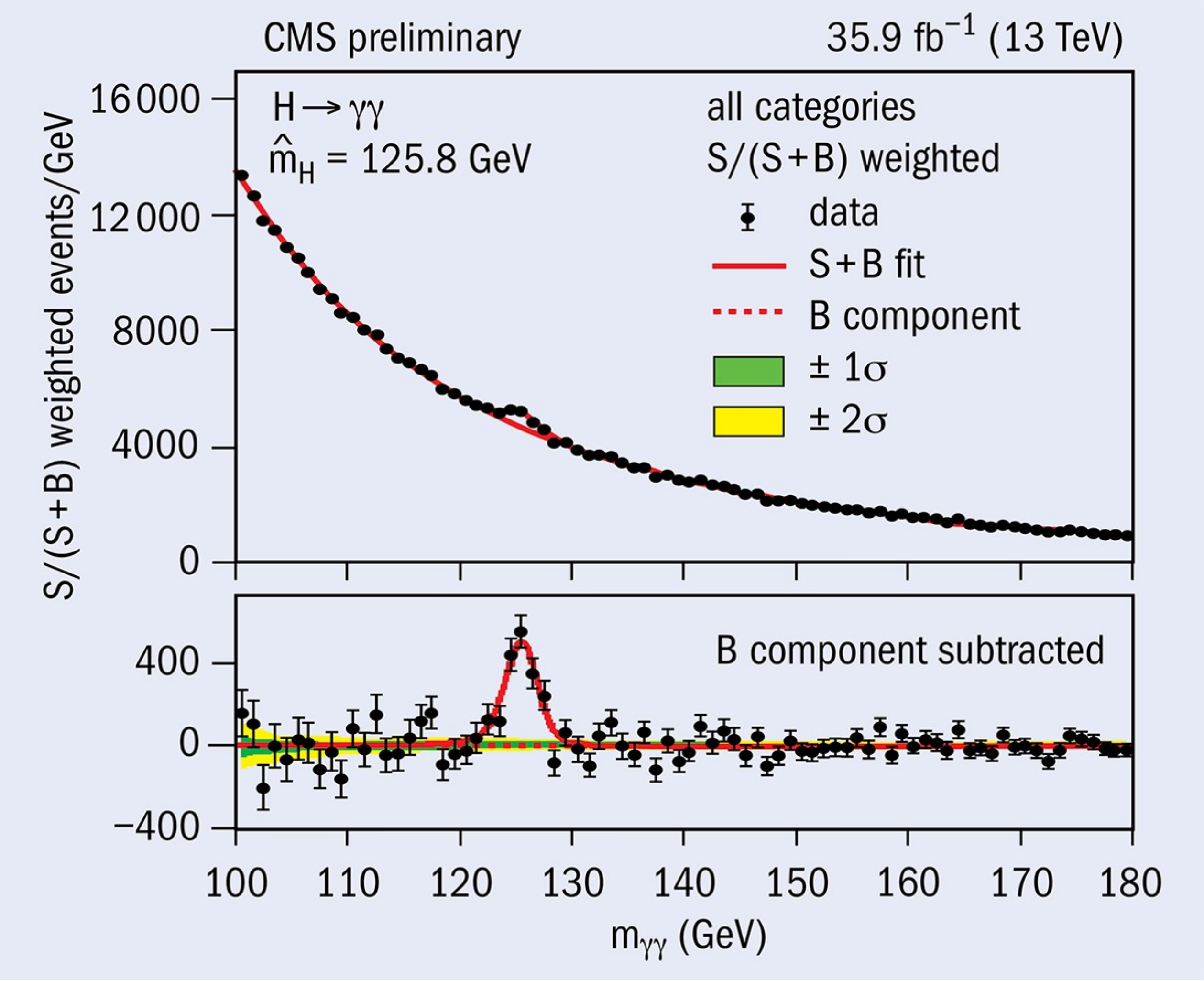




- Light blue: Standard Model
- At the time of discovery
- How it looks like today
  - (~ 20x more data)

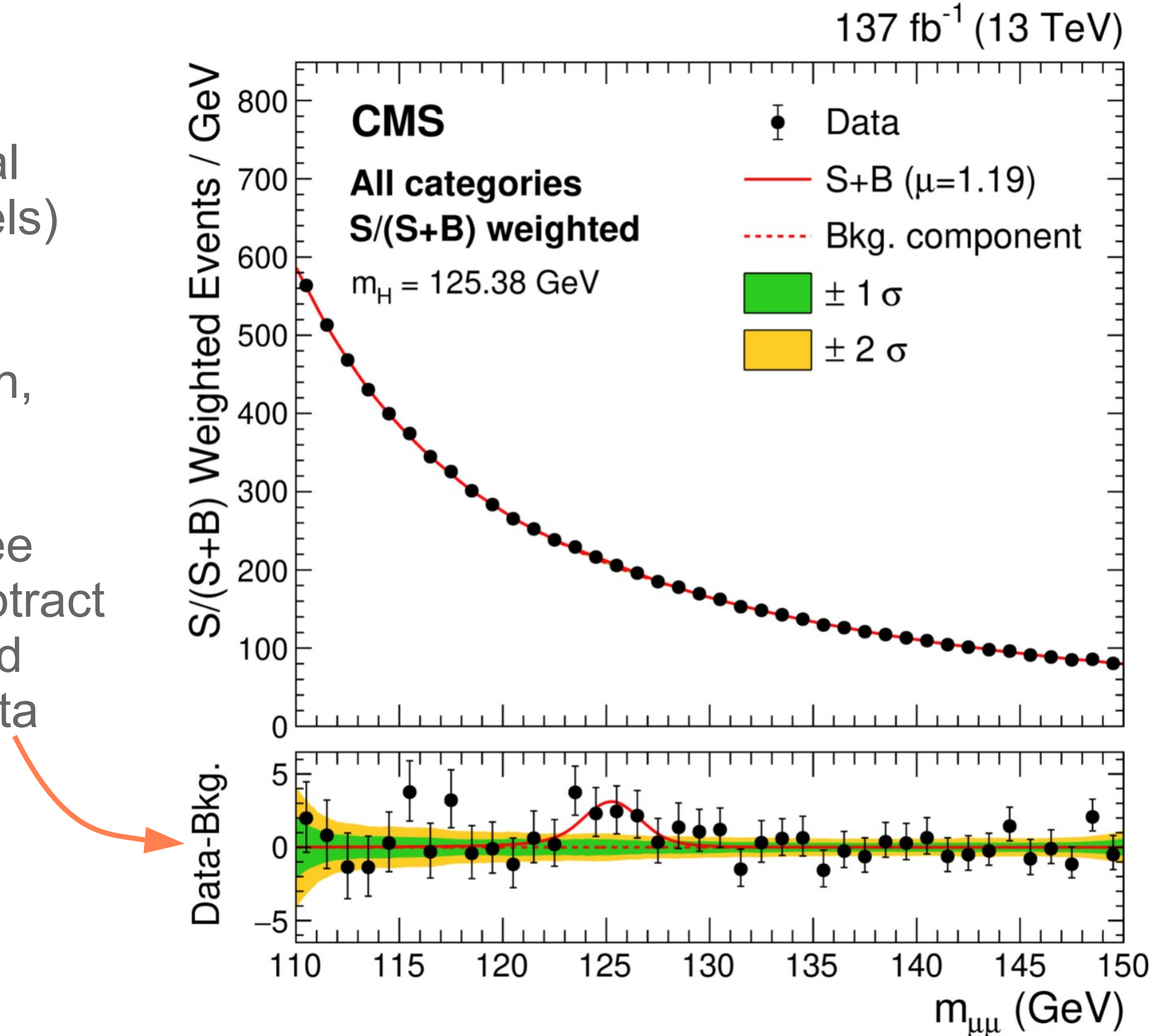
More examples of a `bump hunt'

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

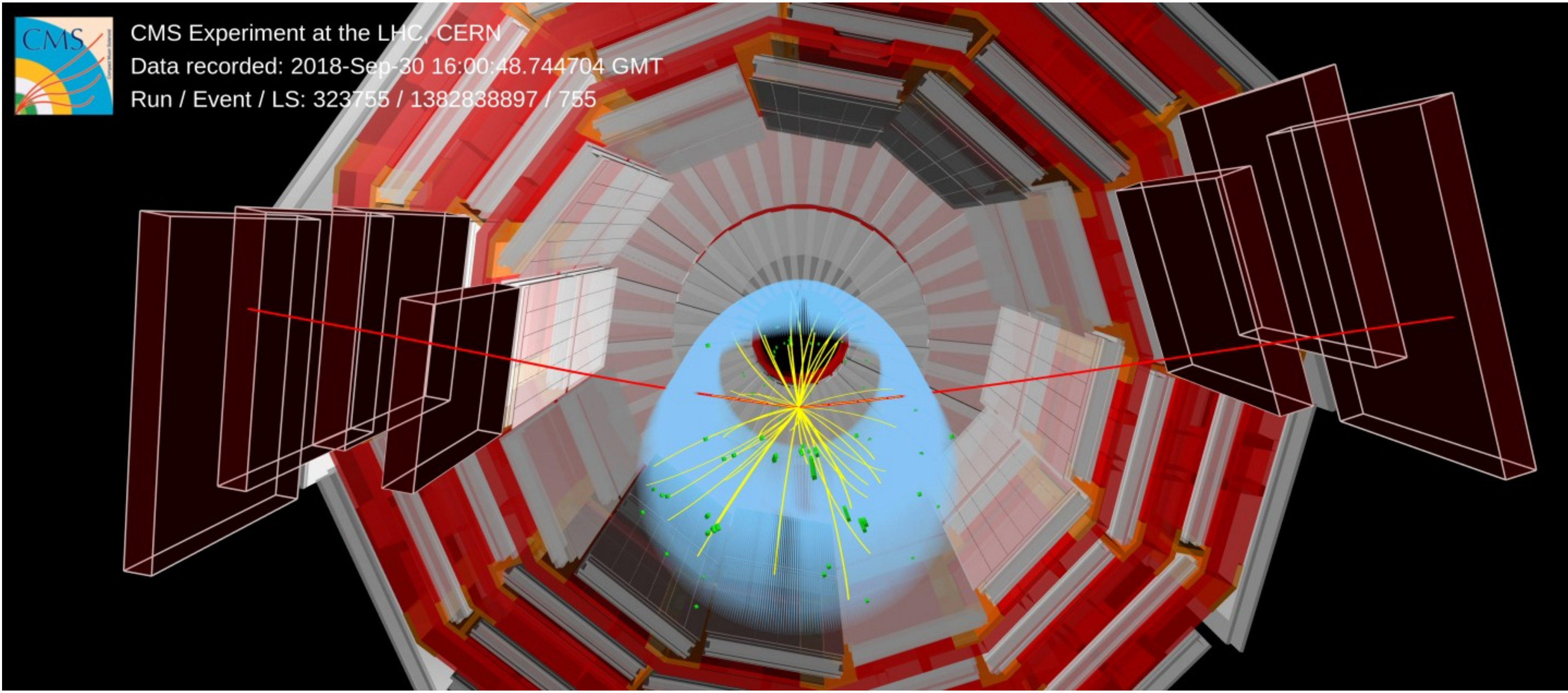


Now back to two muons!

- $H \to \mu^+\mu^-$ (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

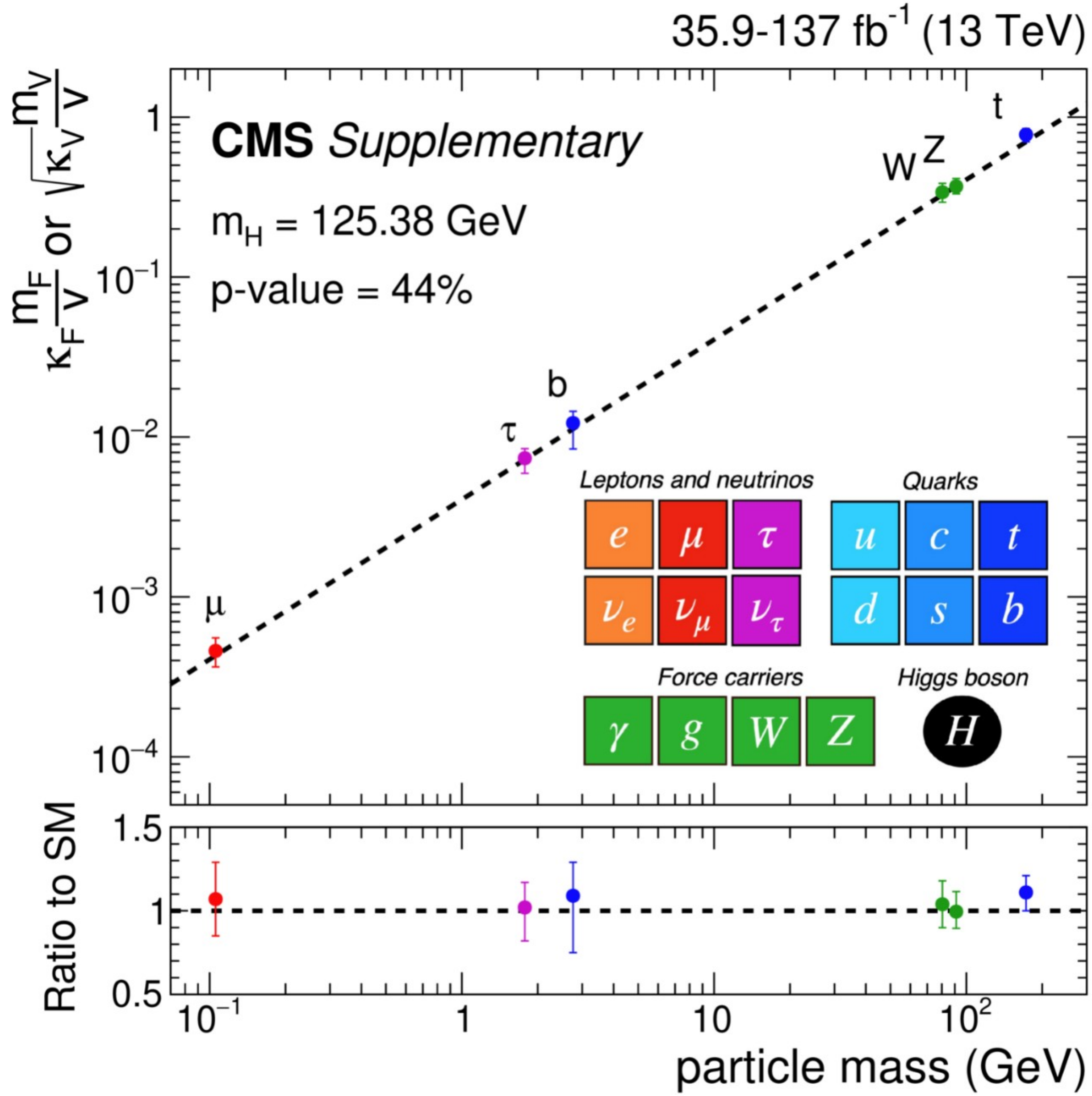


Higgs to two muons event



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!

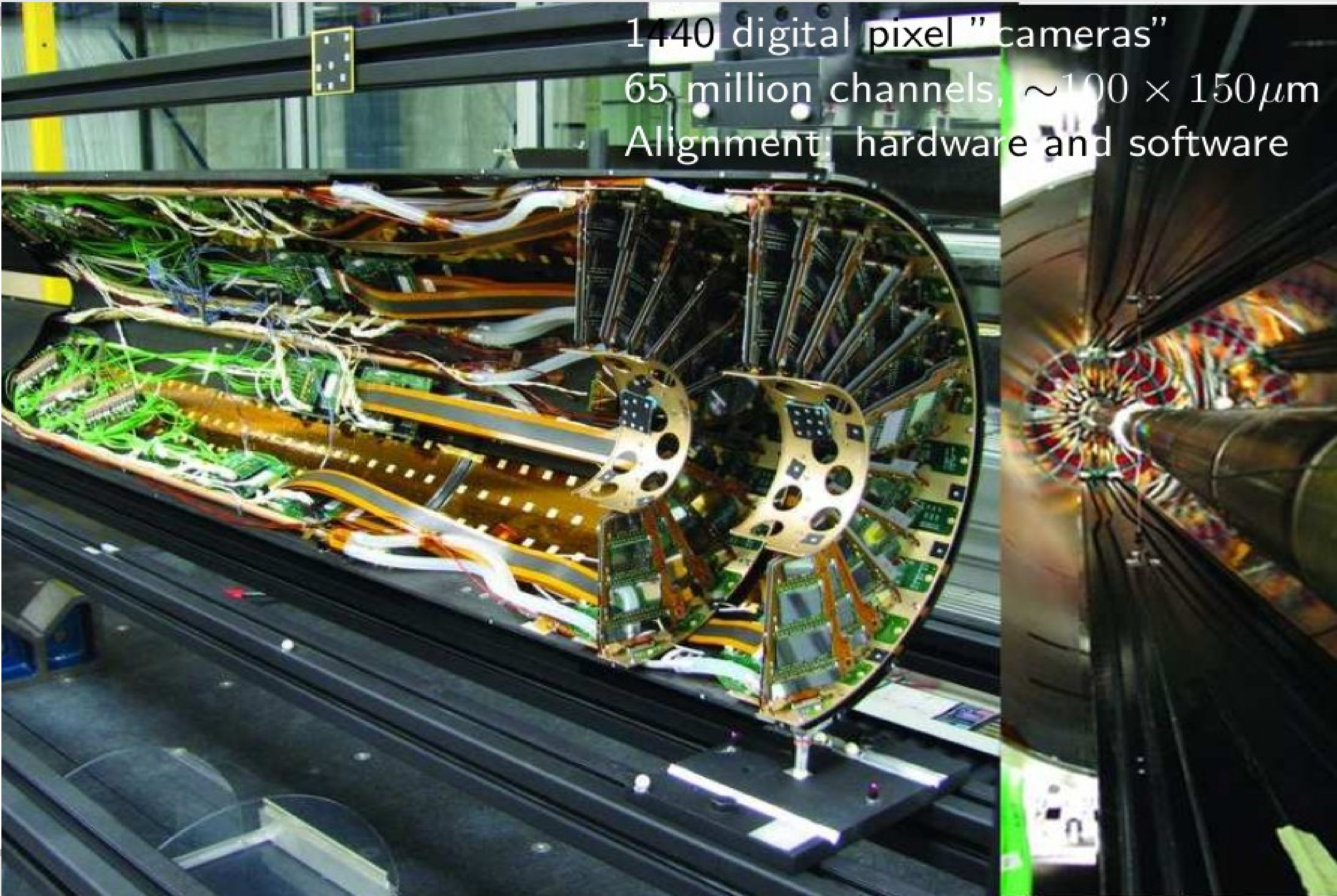


Summary

- 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



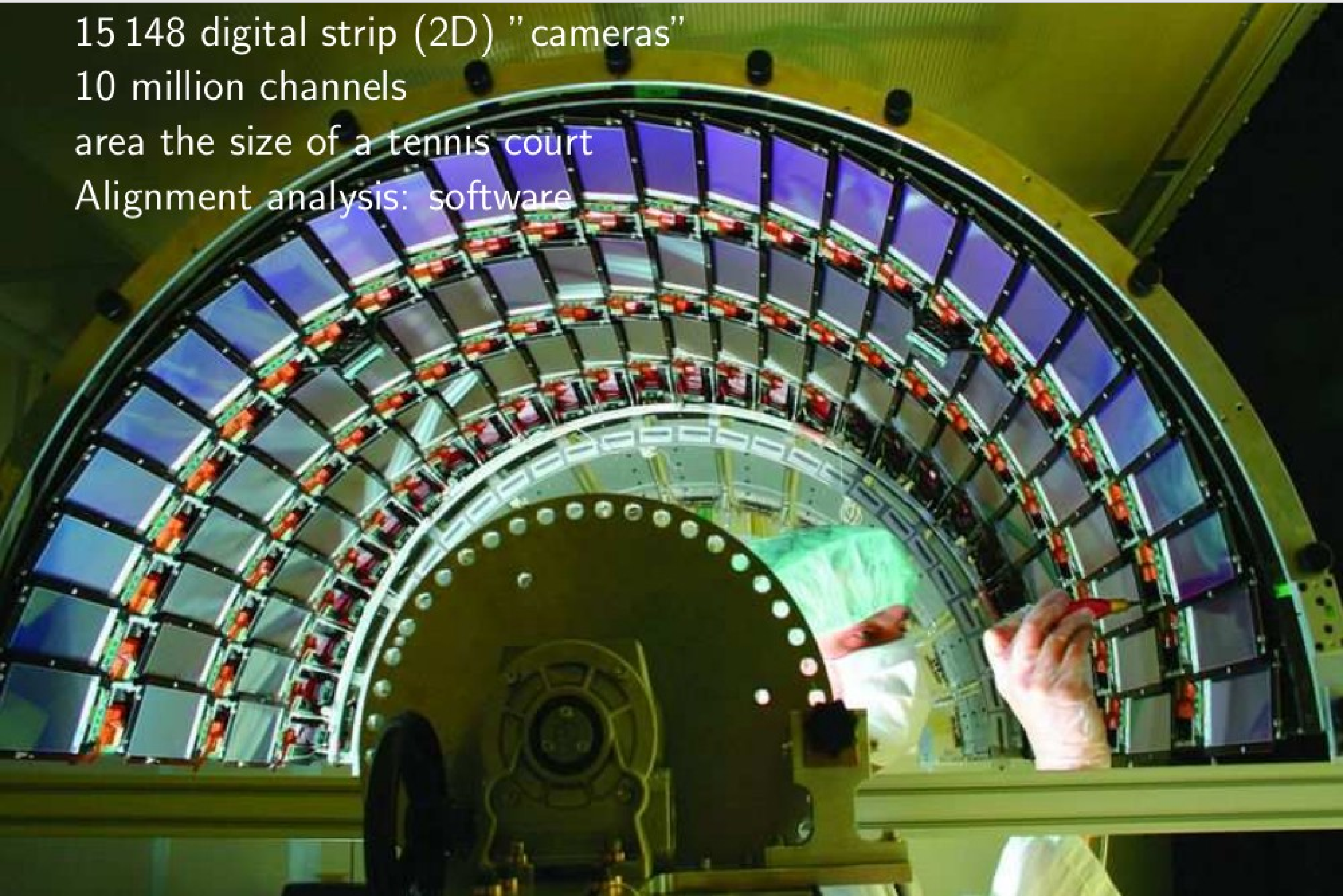
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"

10 million channels

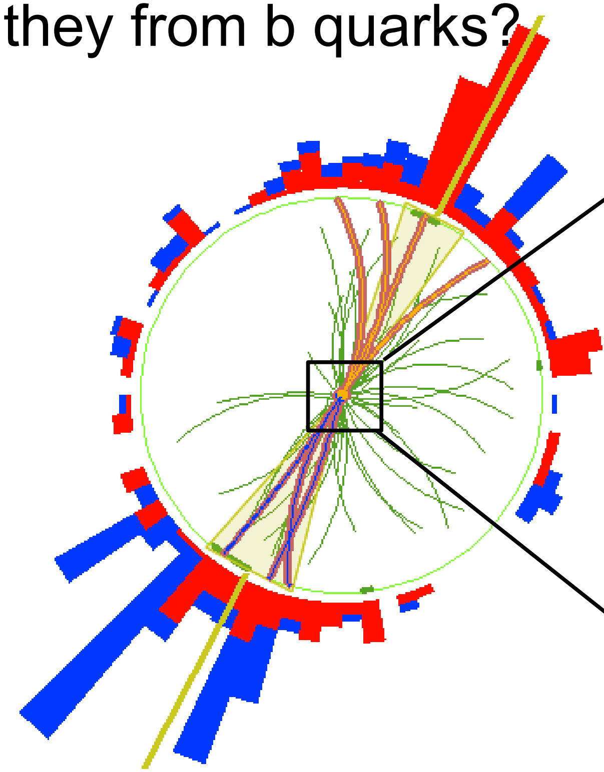
area the size of a tennis court

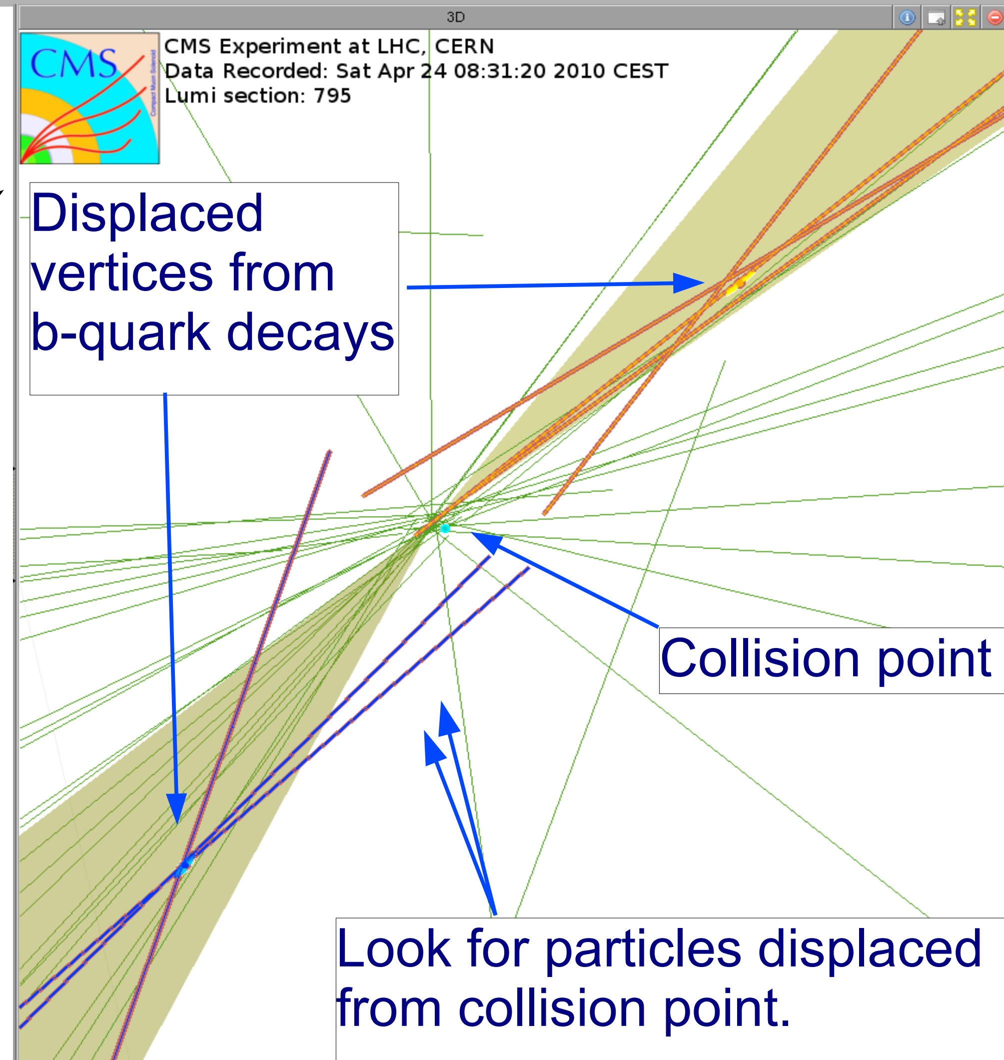
Alignment analysis: software



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

Event with two jets:
are they from b quarks?

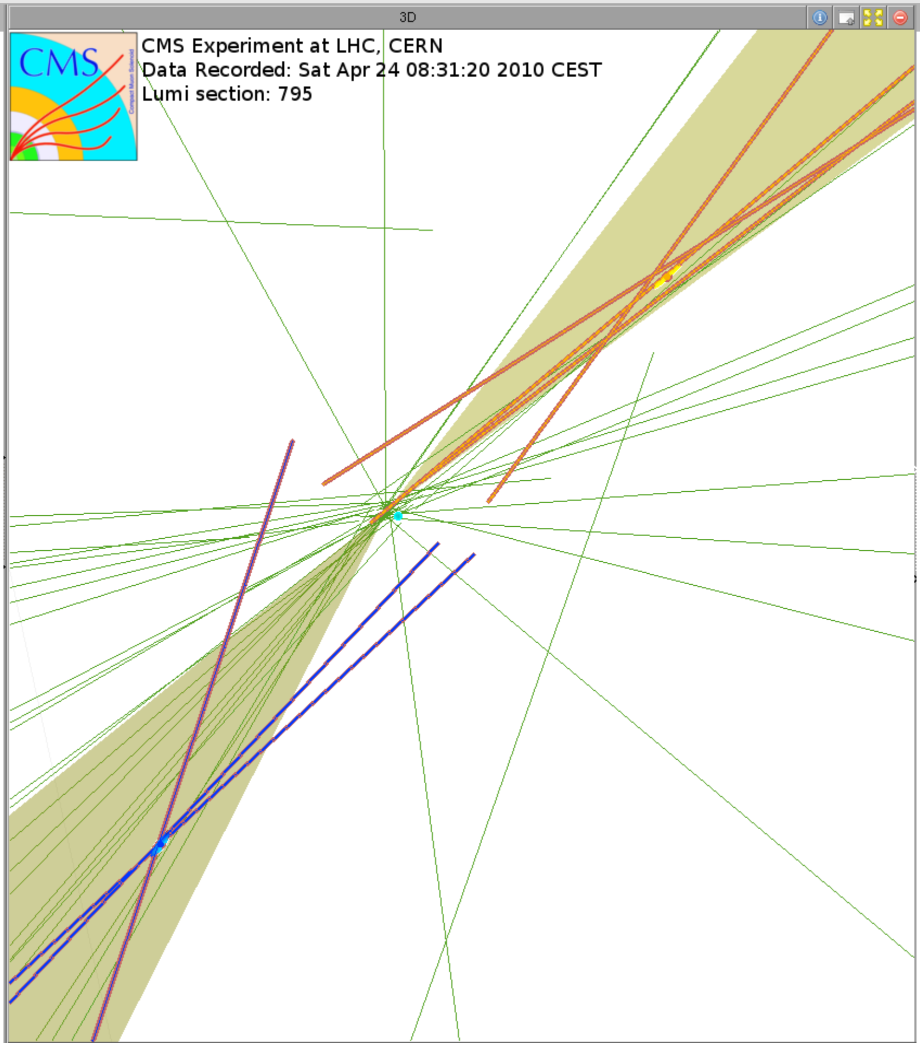




Look for particles displaced from collision point.

Need precision tracking of charged particles!

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



Efficiency:

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

Purity:

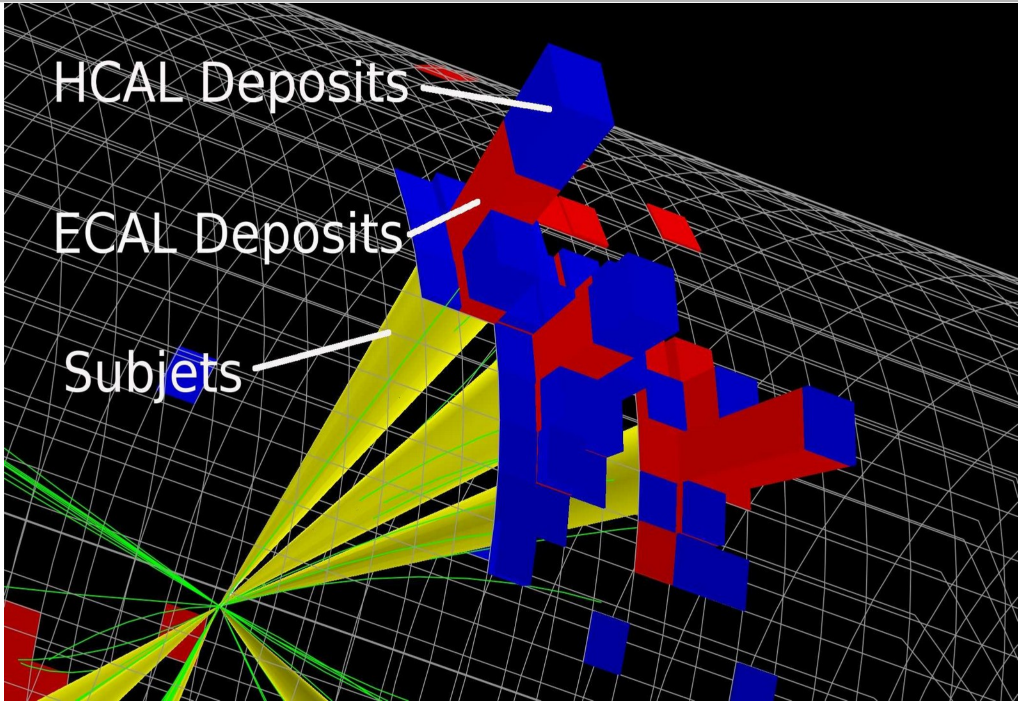
- occasional problems with reconstruction of tracks of charged particles.
- b-tagging may makes a false positive
  - a jet without a true displaced vertex is falsely identified as a "b-tag"
  - called "mis-tag"
  - rate ~ 0.1%

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

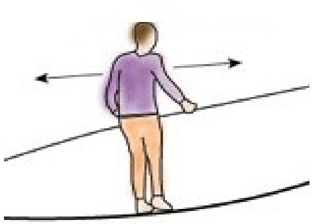
    → *top-tagging!*
- This is a hot topic:
  - Butterworth et al : Boosted Higgs (hep-ph/0201098)
  - Kaplan et al: Boosted top (0806.0848)



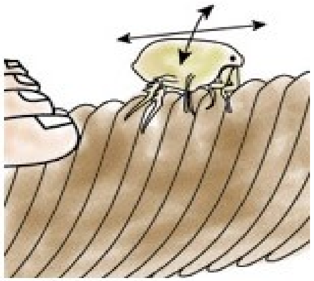
- Blue: hadronic calorimeter
- Red: electromagnetic calor.
- Yellow: found subjets

More questions

- Are there hidden additional dimensions of space and time?
  - large or small, flat or curved...?



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



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

- 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*!)