How to search for “New Physics” at the LHC

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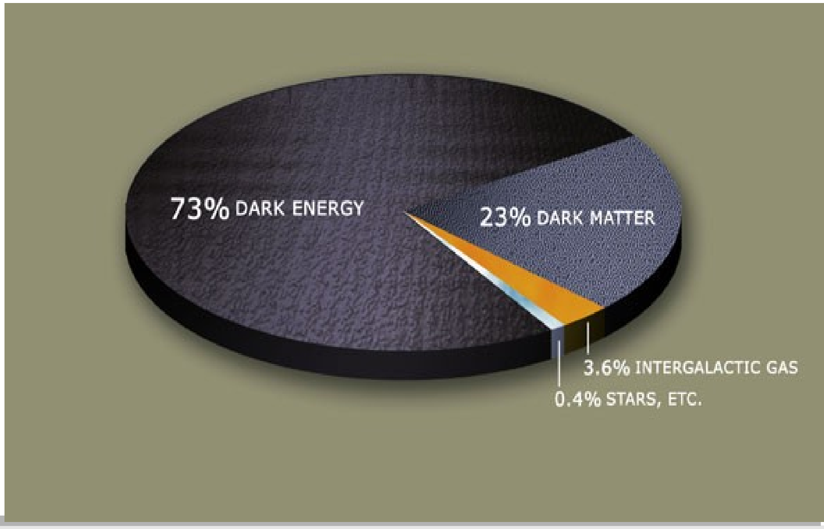
- “New Physics” = what is not Standard Model
- a.k.a. “Beyond Standard Model” Physics (BSM)

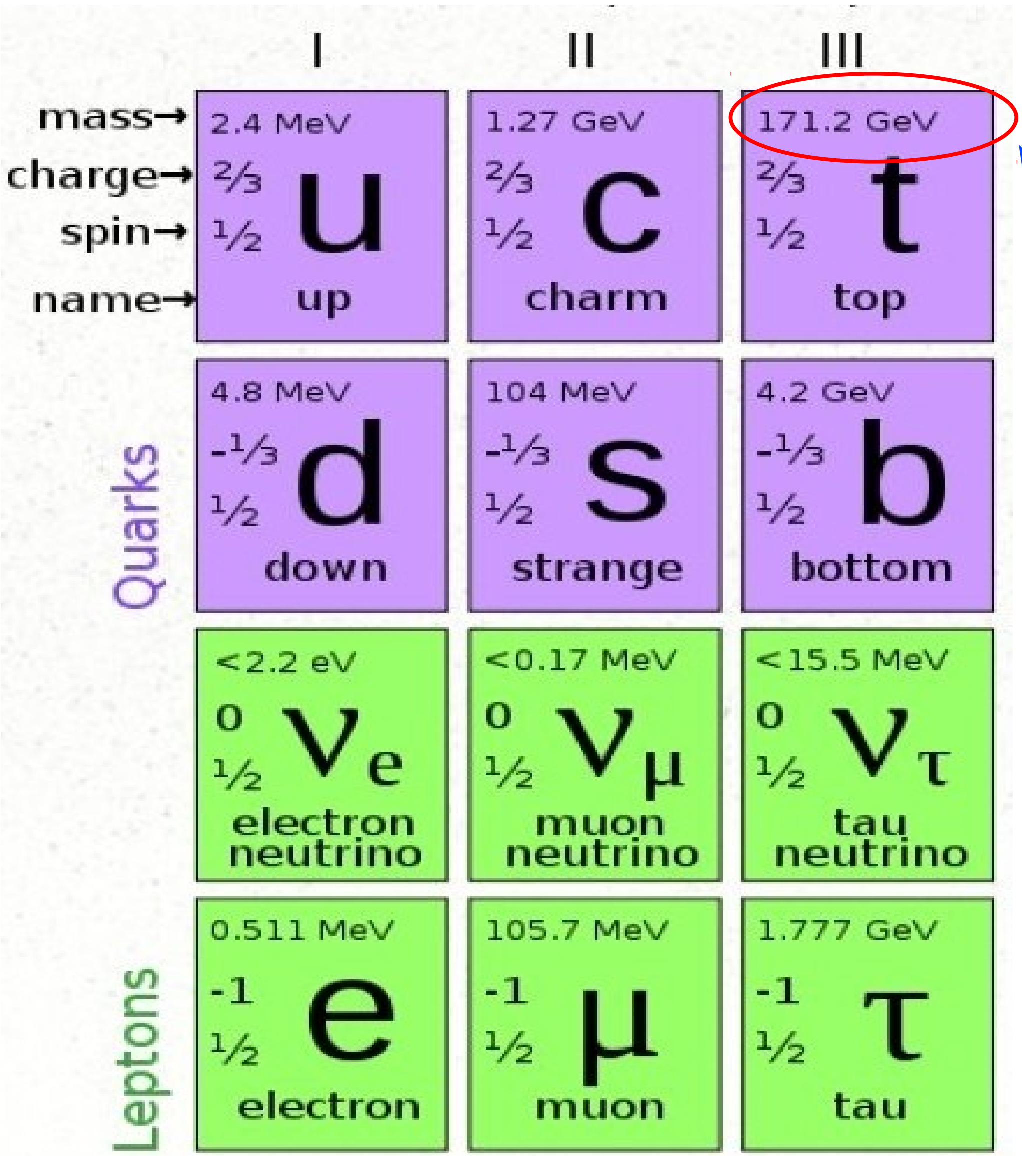
Questions

- 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

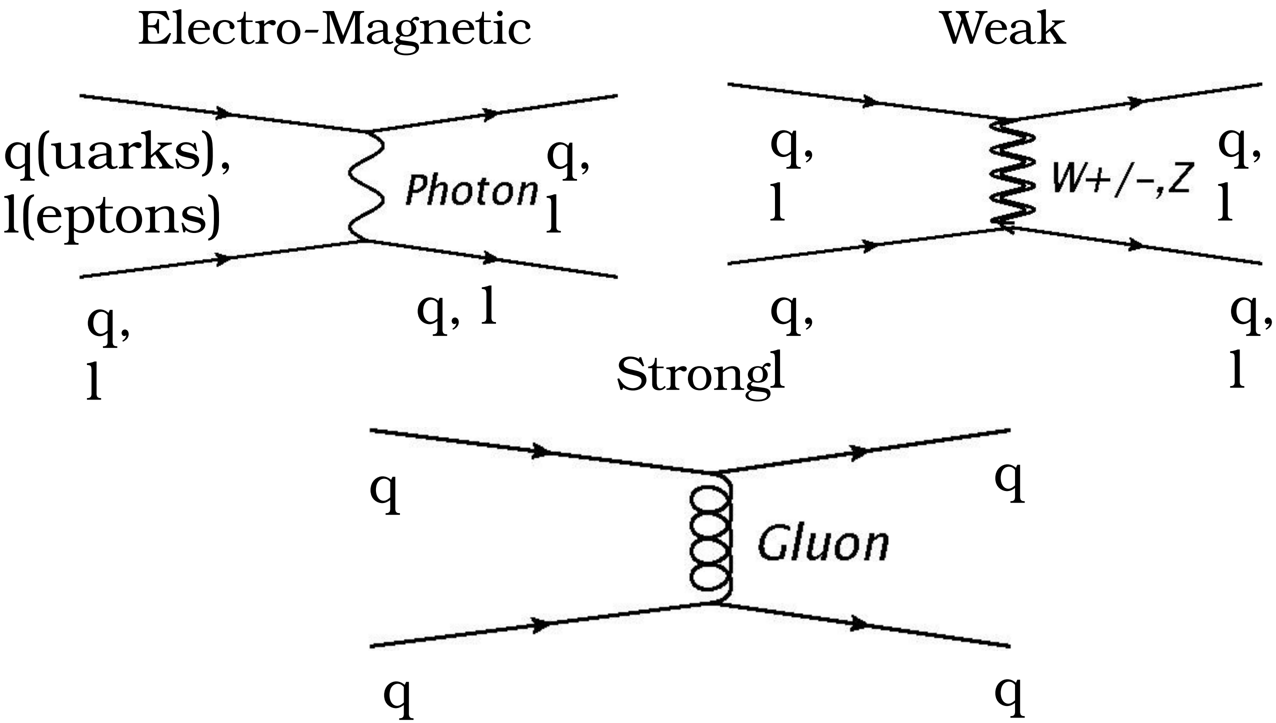
Three families of Standard Model



- 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!

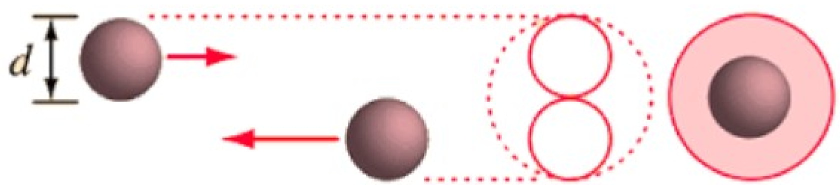
Standard Model: Interactions



- 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

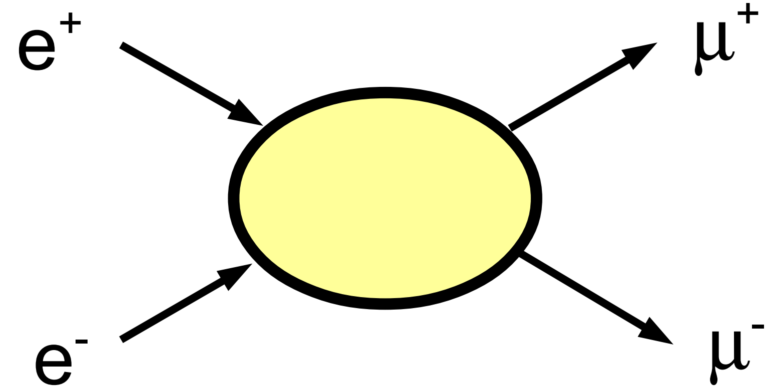
Calculating things in Standard Model

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



  - (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)



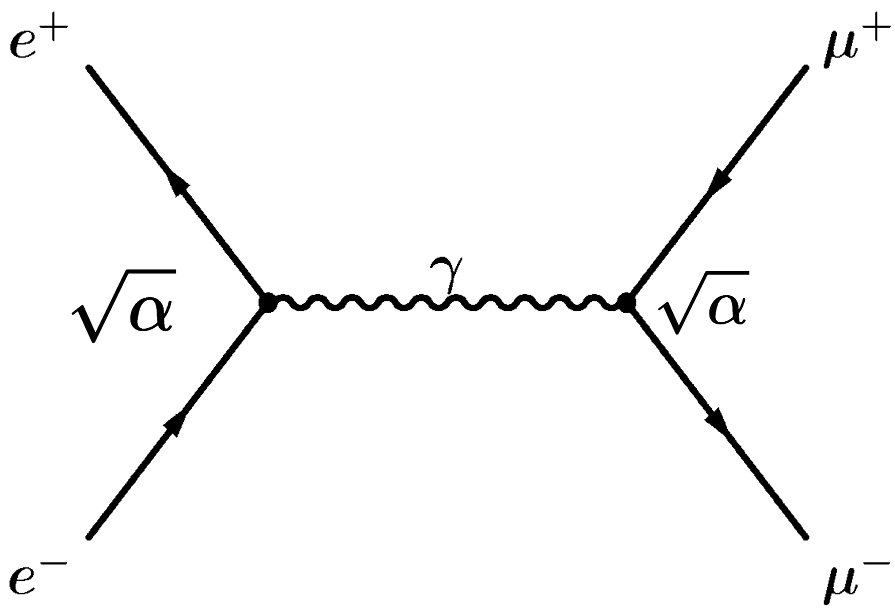
- Consider $e^+e^- \rightarrow \mu^+\mu^-$
- Probability ~ $|\mathcal{M}|^2$
- $\mathcal{M}$ is calculated as infinite series of terms
  (usually ever smaller)
- Each term is represented with a pictogram, called a Feynman diagram
- Digression: Leibnitz formula for π:

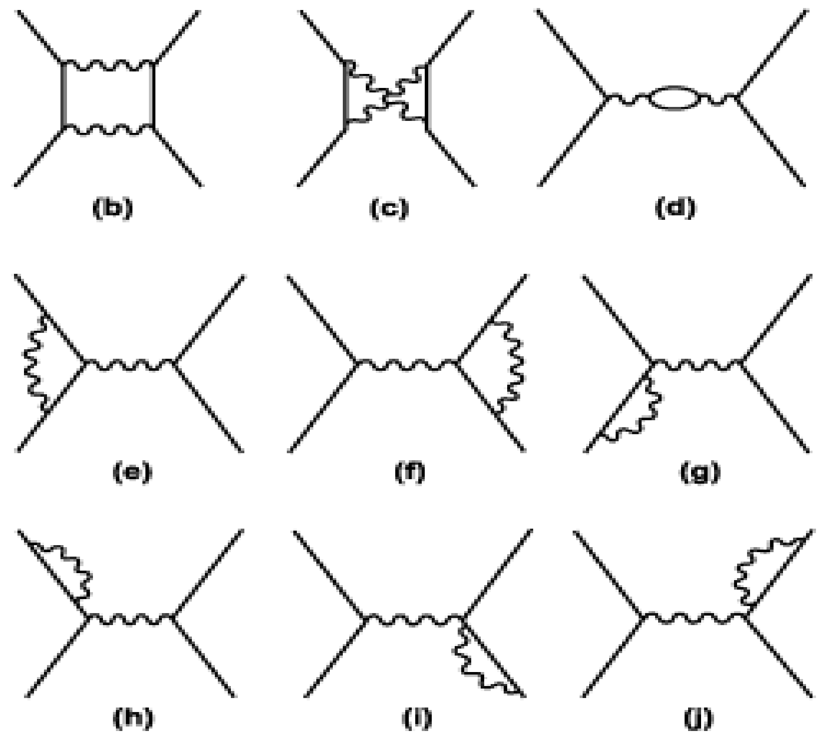
$$\pi = 4\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1} = 4 - \frac{4}{3} + \frac{4}{5} - \frac{4}{7} + \frac{4}{9} - \cdots$$

  - an example of a converging infinite series

Feynman series

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

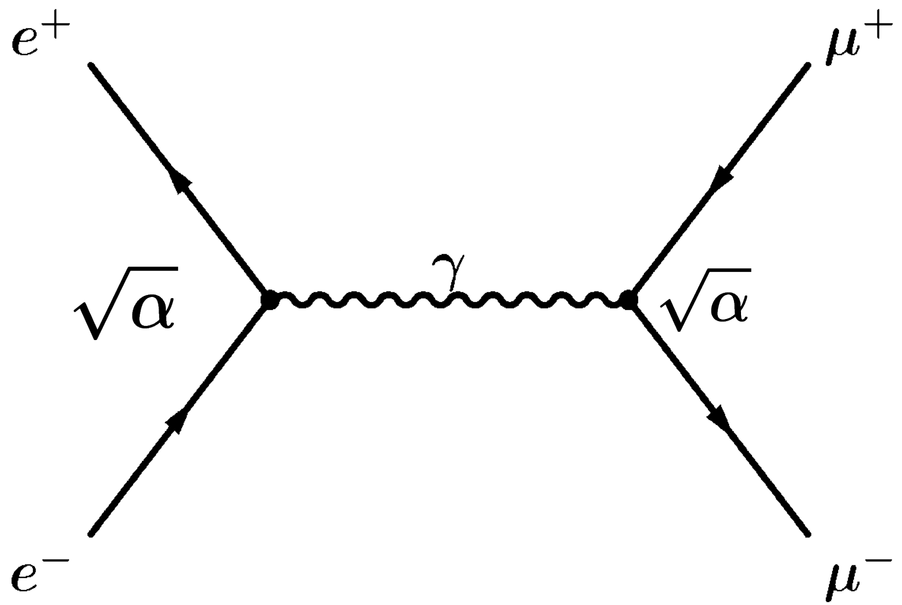




- At each vertex, coupling constant $\sqrt{\alpha}$
- $\alpha = \frac{1}{137}$ $\rightarrow$ converges rapidly!

Virtual particles

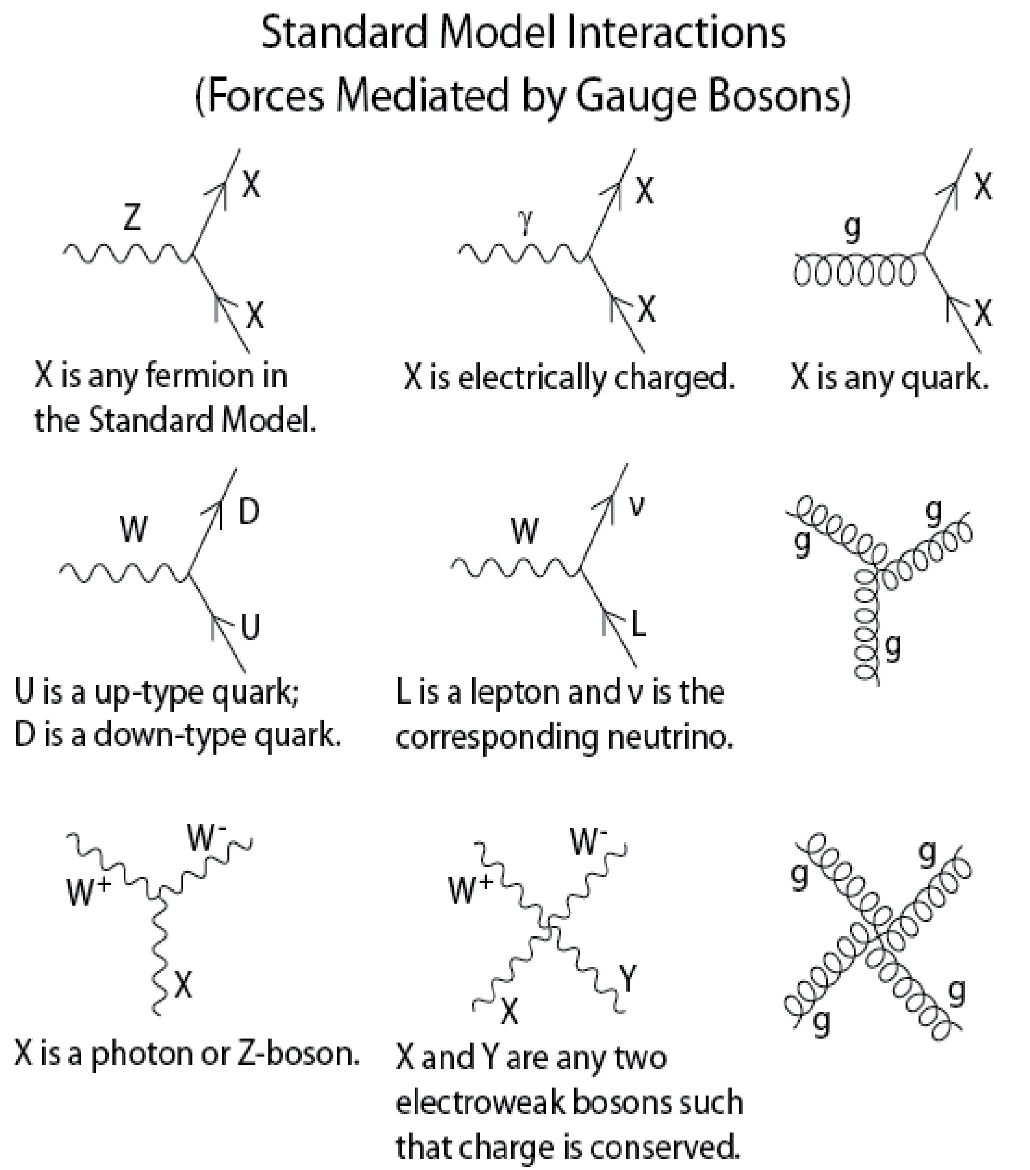
- Photon in the middle can violate conservation of energy-momentum – it's *virtual*.



- 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

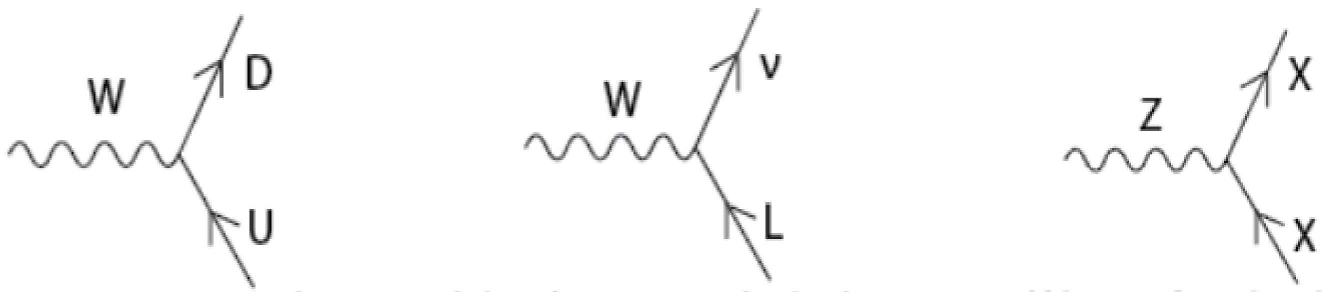
Feynman rules

- 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!



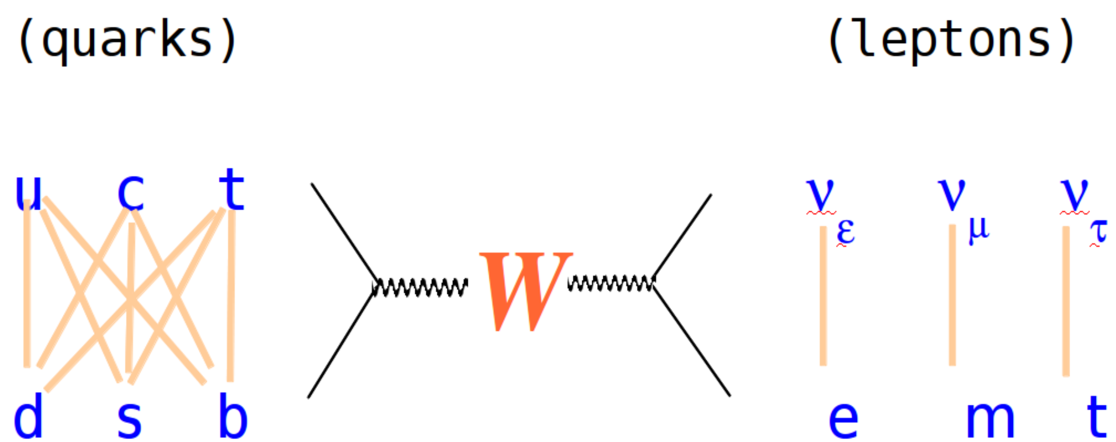
Weak interactions

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



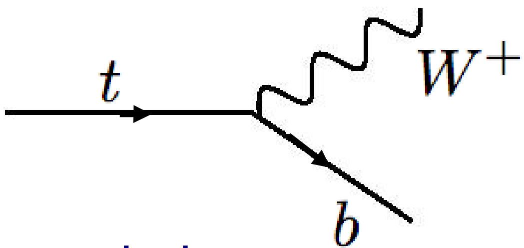
U is a up-type quark; D is a down-type quark. | L is a lepton and ν is the corresponding neutrino. | X is any fermion in the Standard Model.

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



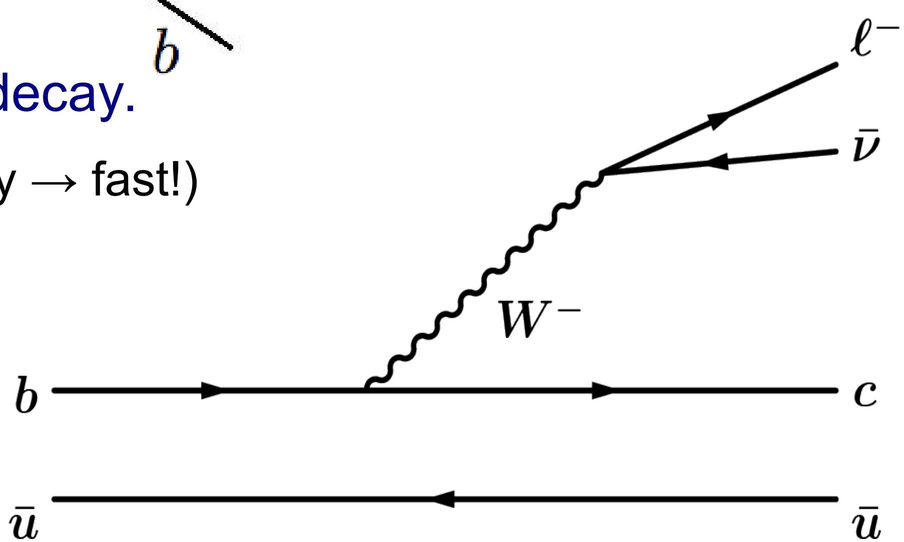
Examples of decays via weak interaction

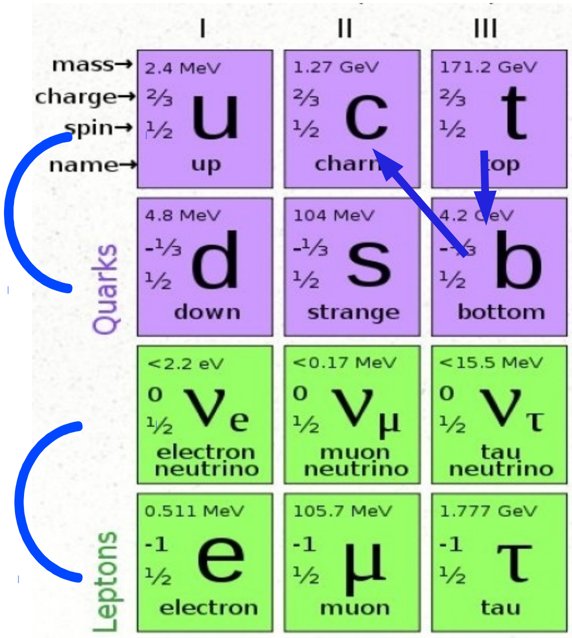
- W bosons couple up-type and down-type fermions
  - couple quarks across families
  - couplings are external parameters too



Top quark decay.

(Top is heavy → fast!)



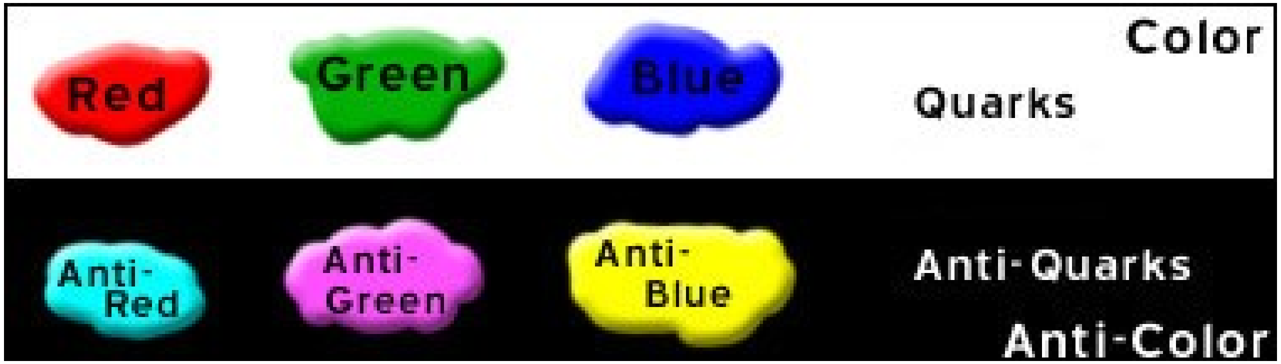


Decay of B meson into lepton + neutrino + D meson

(W is virtual → slow!)

Quantum Chromo-Dynamics (QCD)

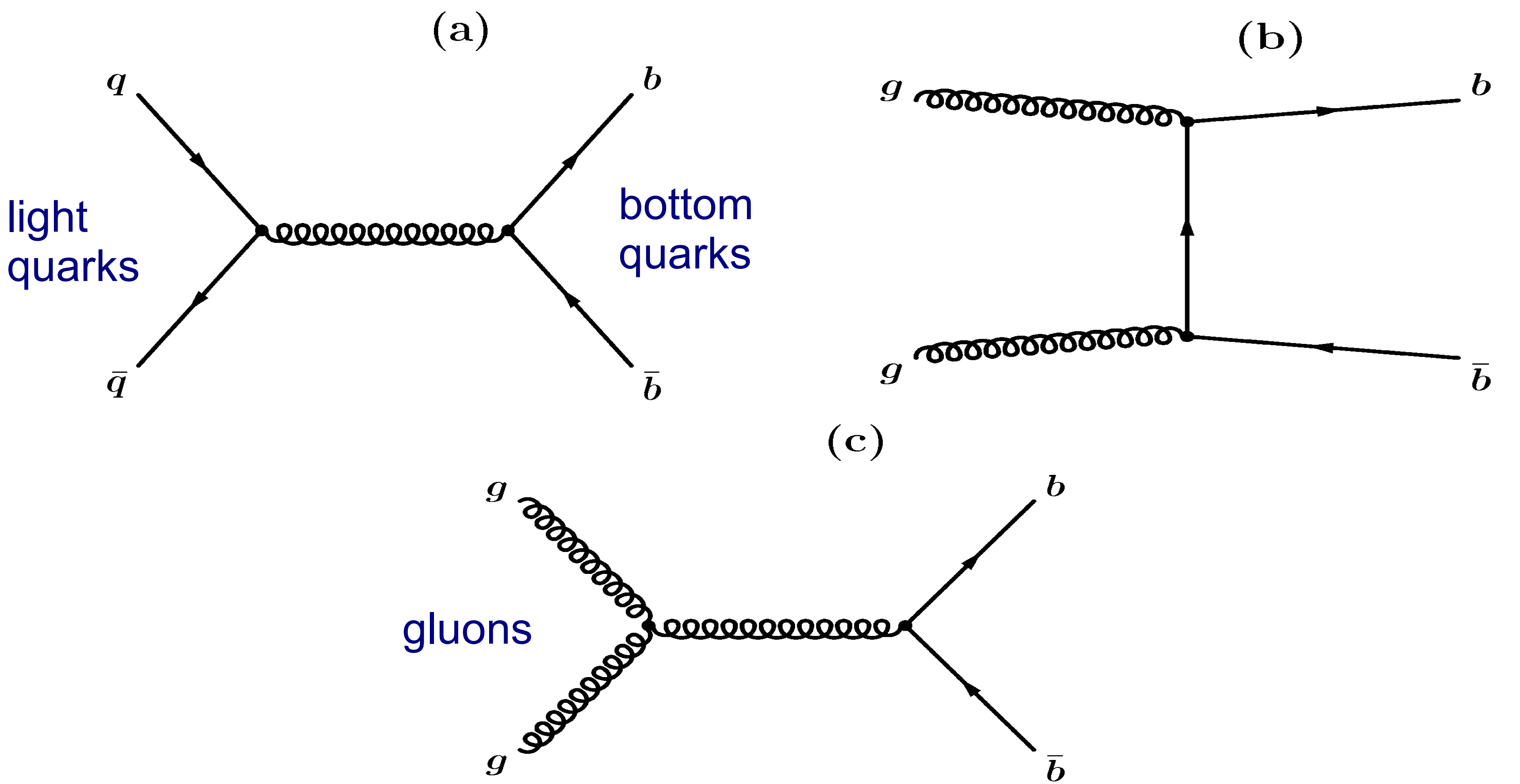
- Strong force (QCD): quarks carry color, interact via (8) gluons:



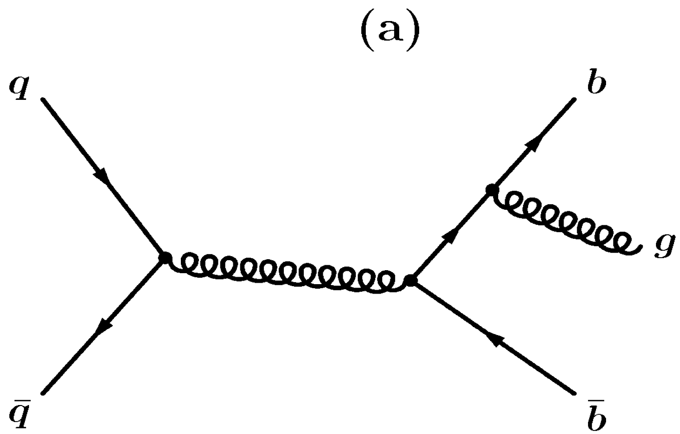
- But strong force is different from E&M:
  - gluons couple to each other
  - coupling constant $\alpha_s \sim 1$
  - (at low energies, it actually depends on the energy)

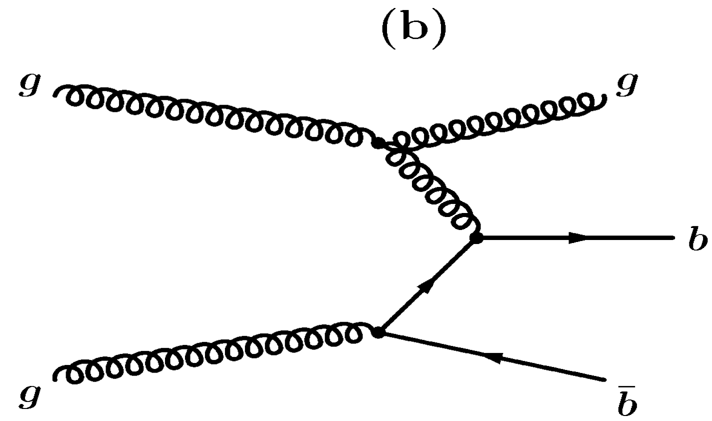
QCD

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

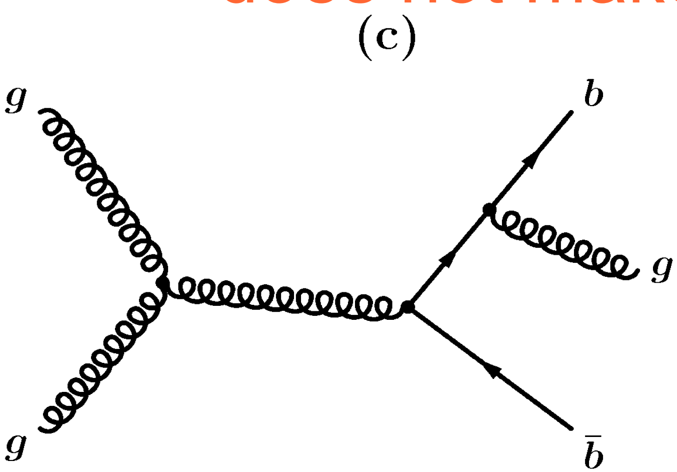


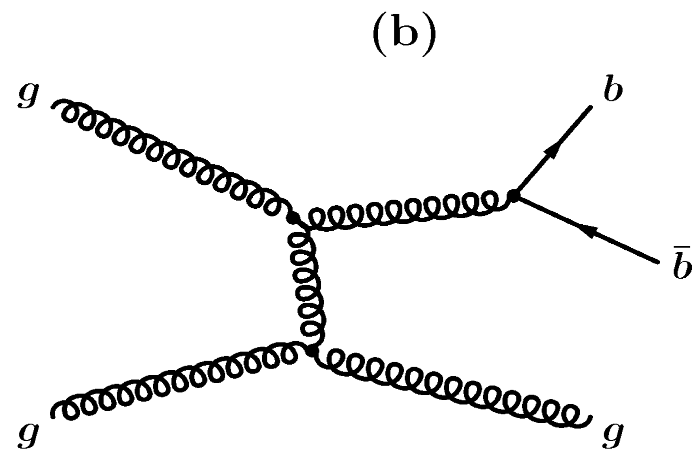
QCD





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





Running coupling constant

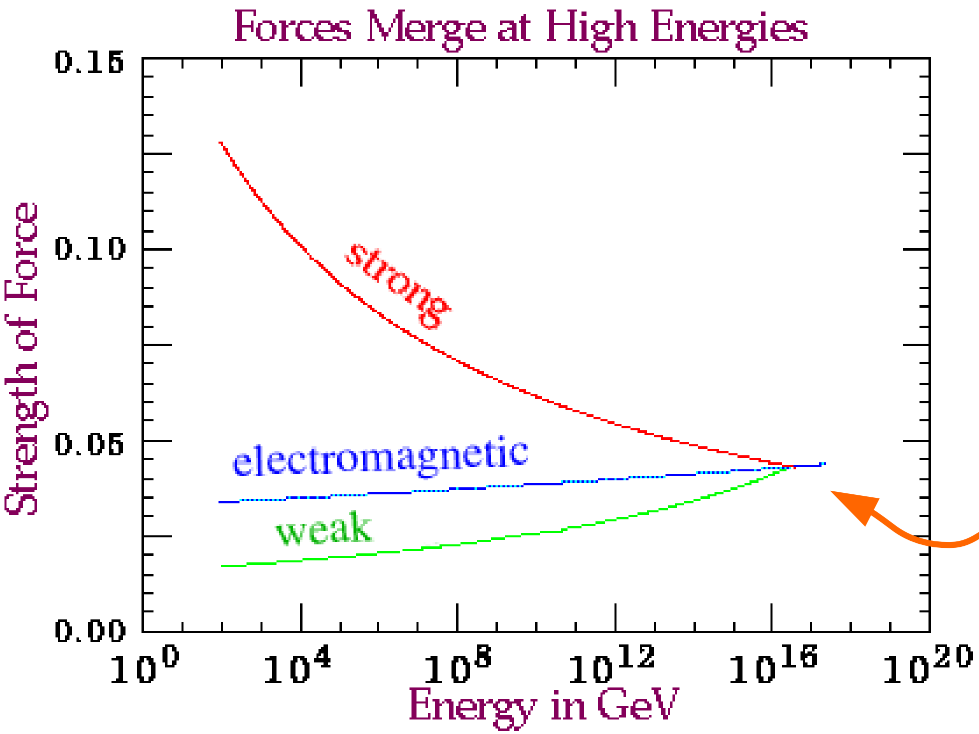
- Making low-energy, virtual gluons is `cheap'
  - $\alpha_s \sim 1$, so adding vertices with gluons causes no suppression
- This + gluons couple to each other ==> $\alpha_s \neq \text{const.}$
- α_s changes with energy $\rightarrow$ `α_s runs'

$\Longrightarrow$ "Asymptotic freedom"

- a curious behavior that the stronger the probe, the more free the quarks feel
- stronger probe $\rightarrow$ larger α_s $\rightarrow$ smaller interaction ...

- Another consequence: color field (carried by gluons) between colore objects is localized – *i.e.* appears as a `color tube'.

Aside: Grand Unified Theories



- All three coupling constants converge at ~ same energy...

Electromagnetic and Weak force are both facets of the same original "electroweak" force.

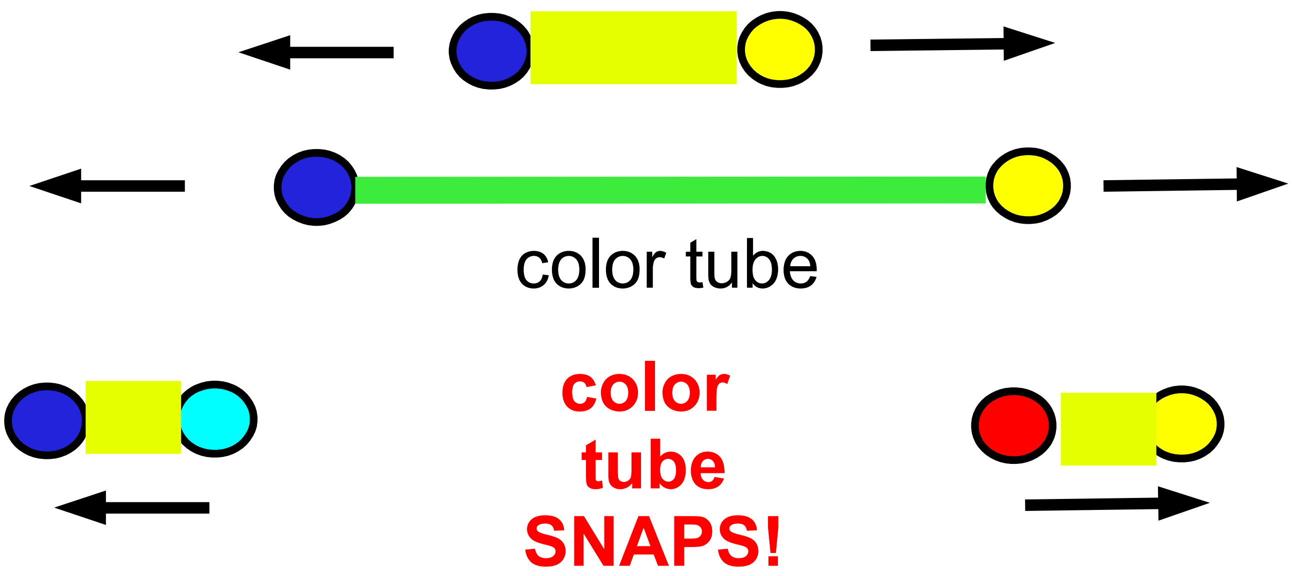
Broken by Higgs mechanism

QCD might have been a part of that too

– except we don't know how exactly...

QCD: hadronization

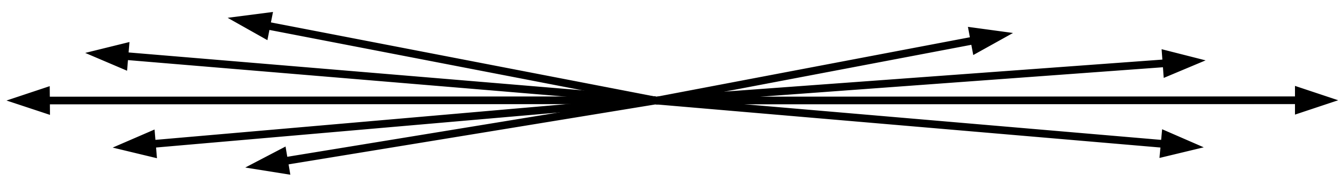
- Consider hadronic decay $W^+ \rightarrow u\bar{d}$
- As quarks move apart with high energy, color tube between them stretches, energy density rises



QCD: all quarks & gluons end up as jets

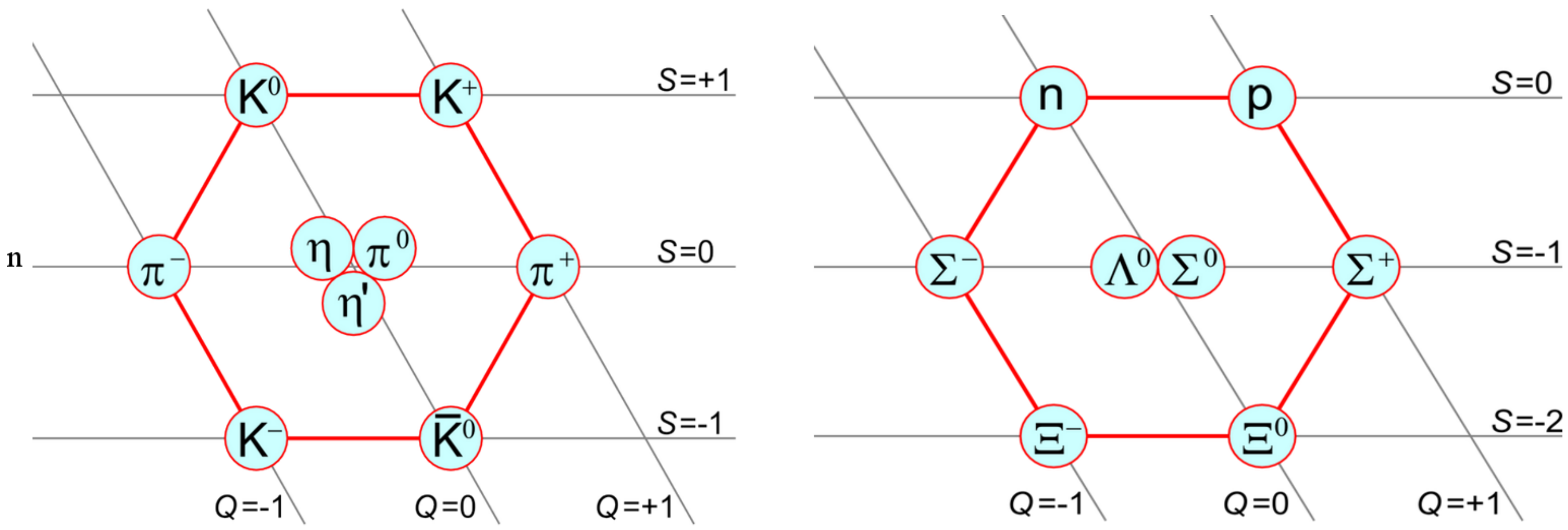
- Quarks still have unequal energies so more quark-antiquark pairs keep being created

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

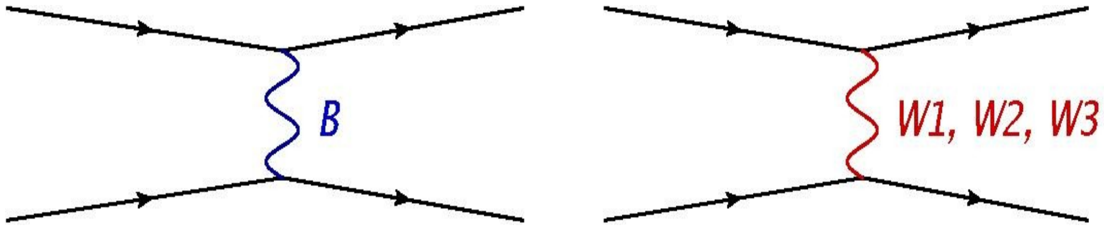


QCD: no open color!

- So it seems Nature does not allow open color – everything needs to be color neutral (= color + anti-color)
- Mesons = quark + antiquark, and Baryons = three quarks



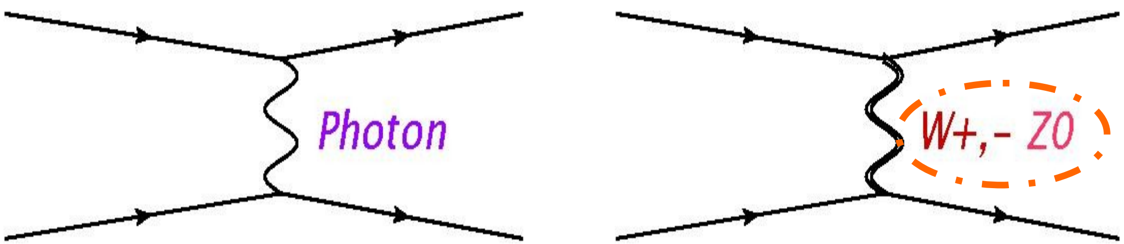
Electro-Weak symmetry breaking



Theory Input
(four massless Electro-Weak bosons)

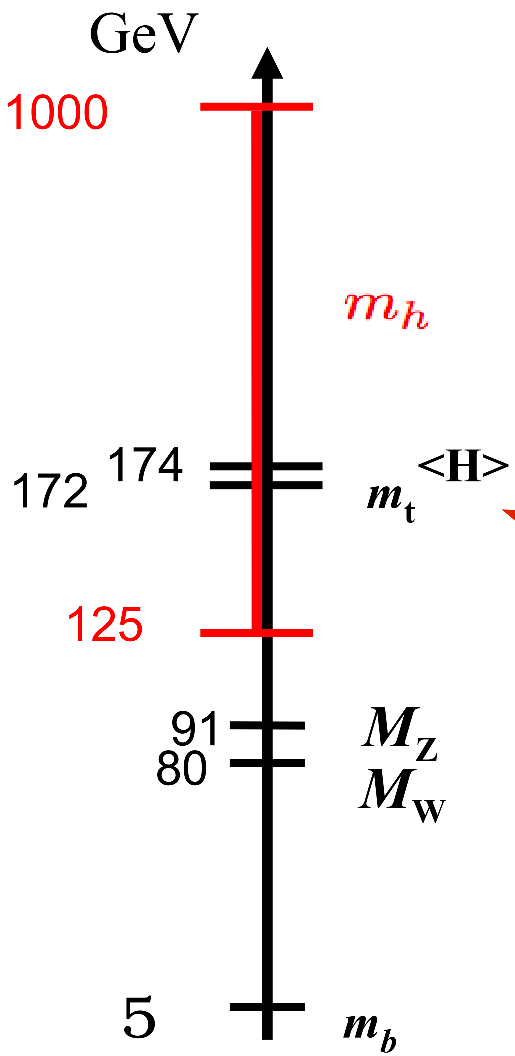
<H>

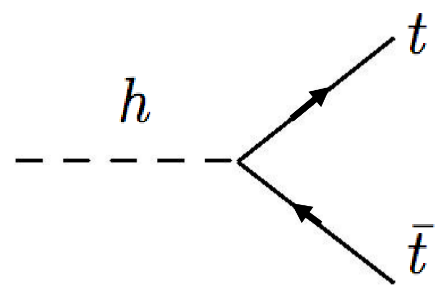
Higgs Field spontaneously breaks Electro-Weak Symmetry



Physical States:
massless photon and very heavy W and Z

Weak scale physics



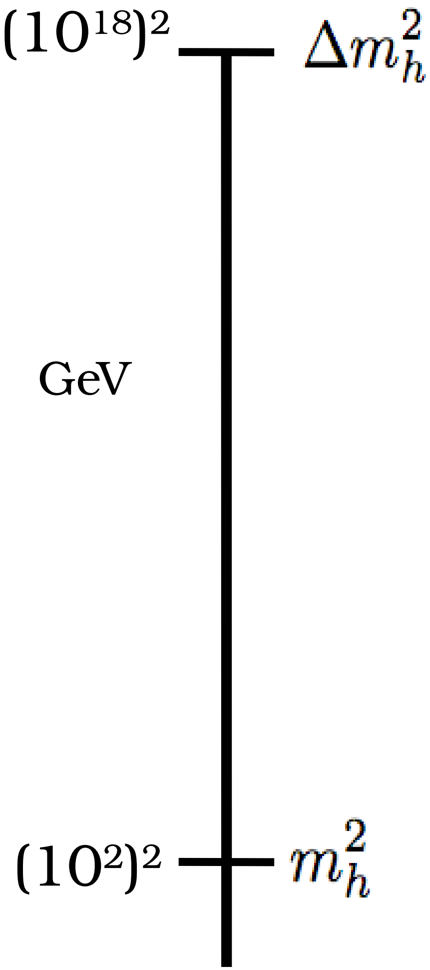


- Higgs field pervades all space
  - fermions are interacting with it and acquire mass.
  - mass ~ strength of coupling to Higgs!

  $\Longrightarrow$ Higgs have by far the strongest coupling to the top!
- Higgs vacuum expectation value is ~ top mass!?
- Higgs has been observed!

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

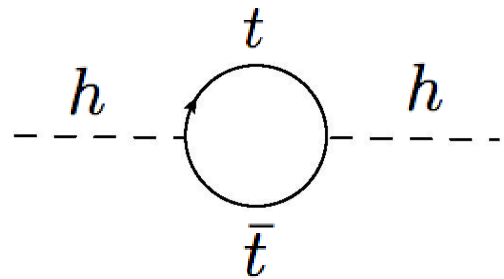
Hierarchy Problem



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

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

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

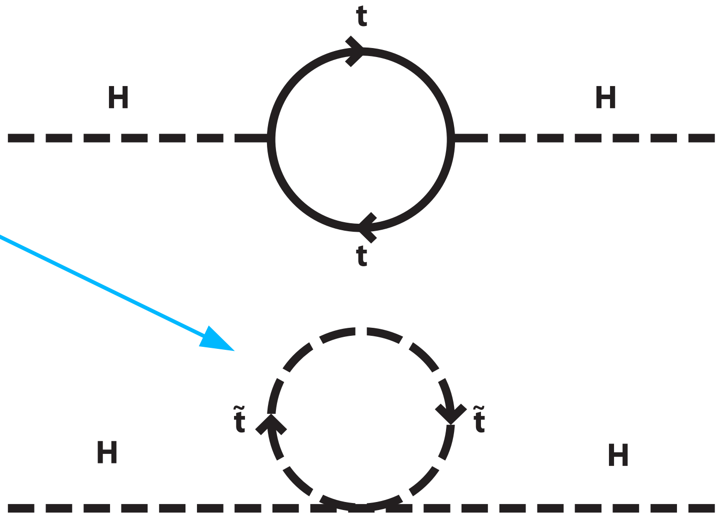


$$+ \cdots$$

- Correction is many orders of magnitude larger!

New Physics solutions to Hierarchy Problem

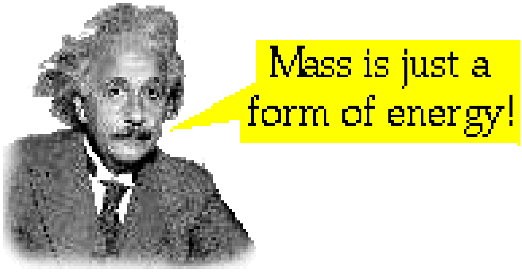
- Supersymmetry (SUSY)
  - add new particles (`super-partners') to cancel terms
  - many SUSY models result in *enhanced top quark production*



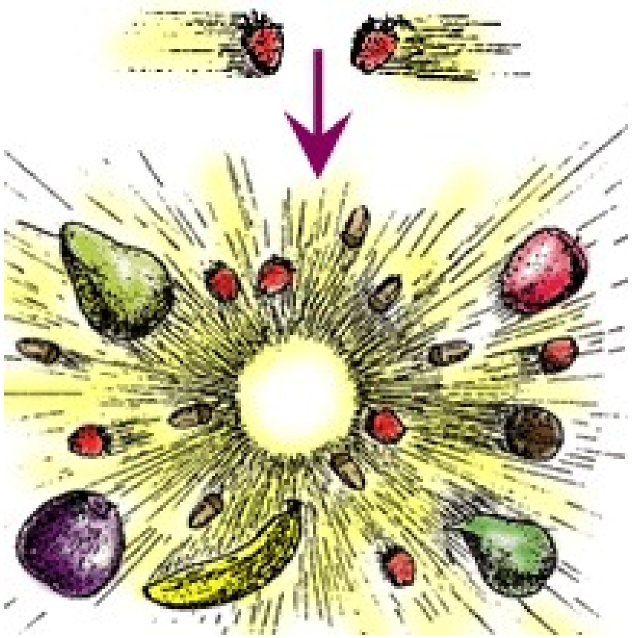
- Strongly Coupled Models:
  - Electro-Weak symmetry broken using a different mechanism
  - technicolor, topcolor, top condensates, extra dimensions (large: Arkani-Hamed, Dimopoulos & Dvali, warped: Randall & Sundrum)
  - *possible new particles (mass ~ TeV) with large coupling to top quarks!*

Collider Physics

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

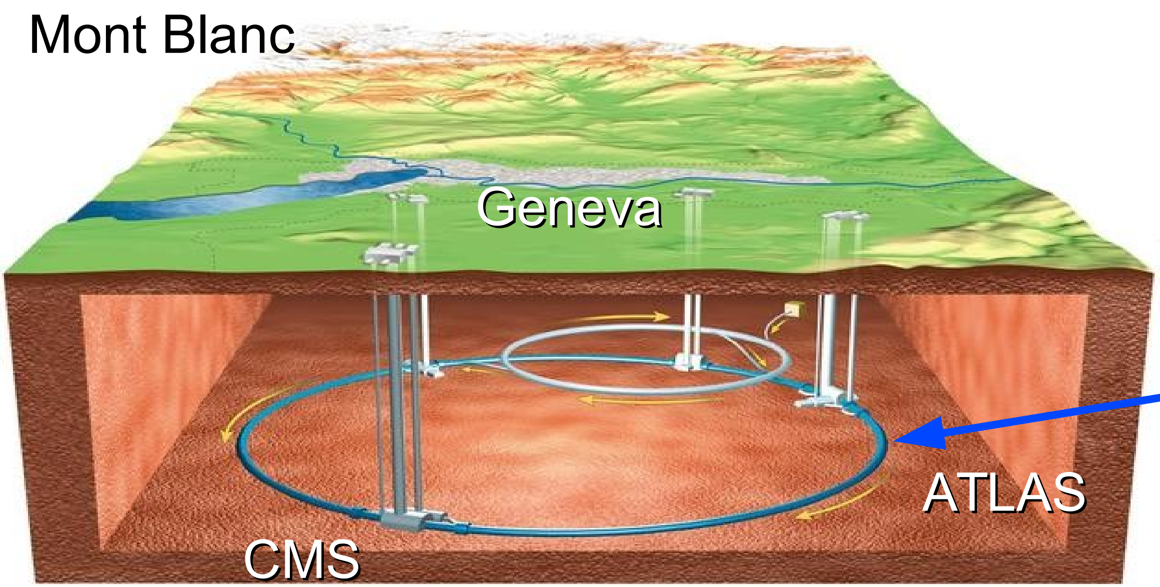


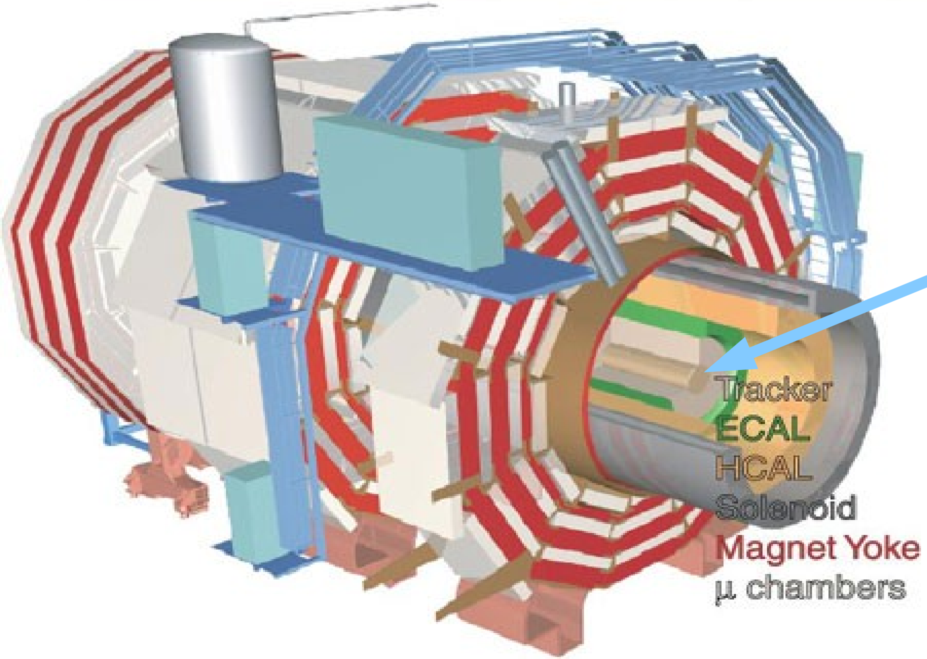
- Very heavy fruits (e.g. watermelons = top quarks) show up with very low probability



- 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?

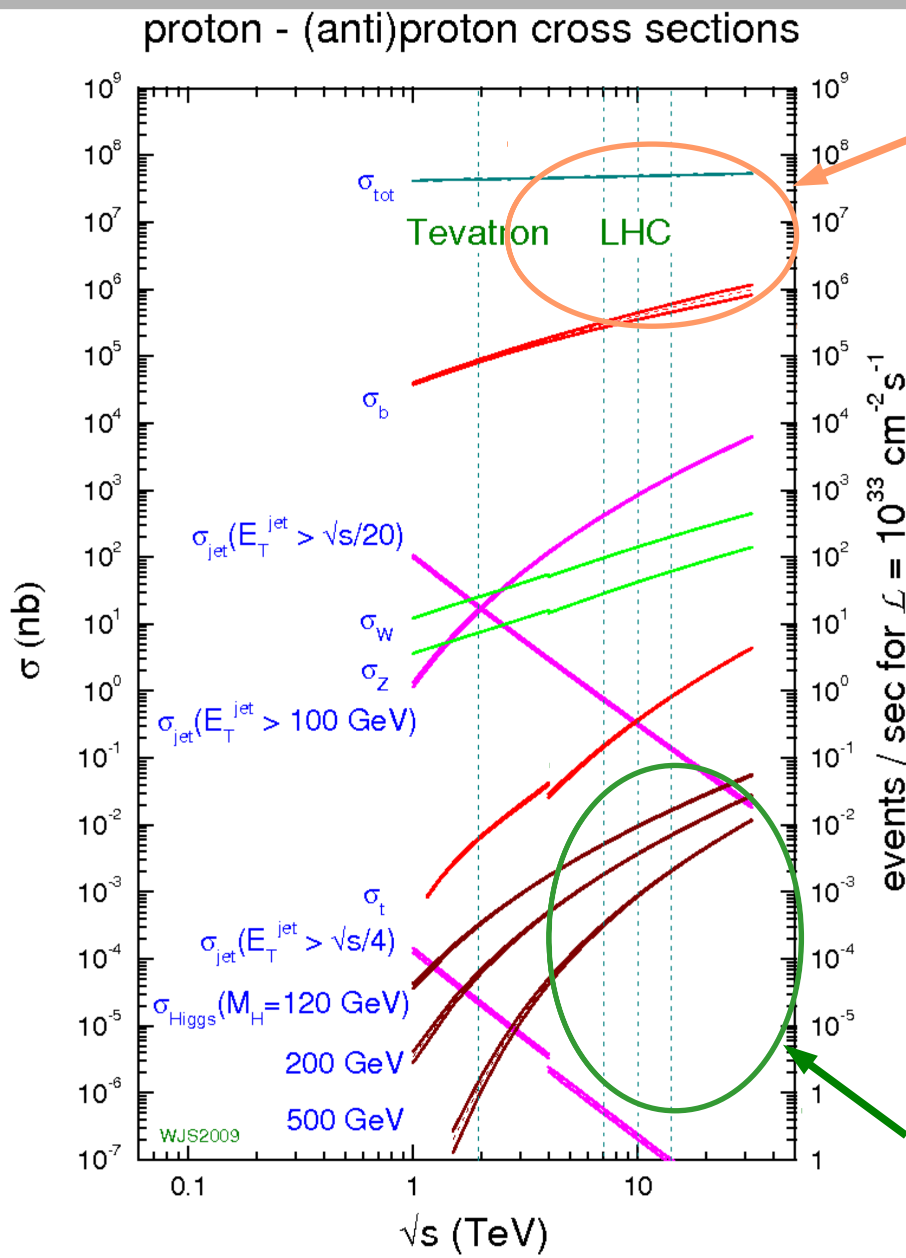
LHC and CMS Detector





- Five stories tall
- Excellent tracking
    - Pixel detector ~ 66 million channels
- The only problem: it has a lot of material
    - fake electrons from $\gamma \rightarrow e^+e^-$

LHC production cross-sections at a glance



uninteresting

new particles

- Cross section measured in barns (area)

- 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

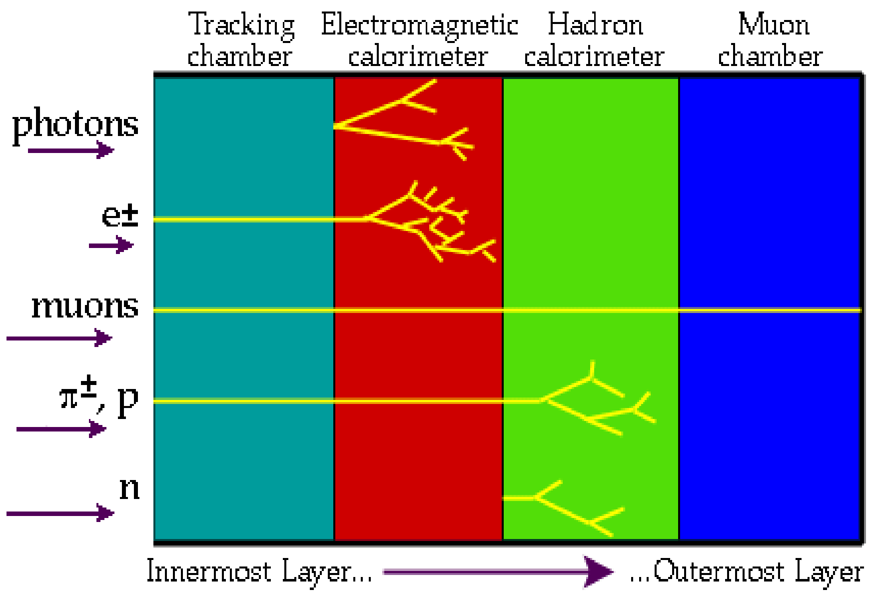
Group Skim
(e.g. Higgs group)

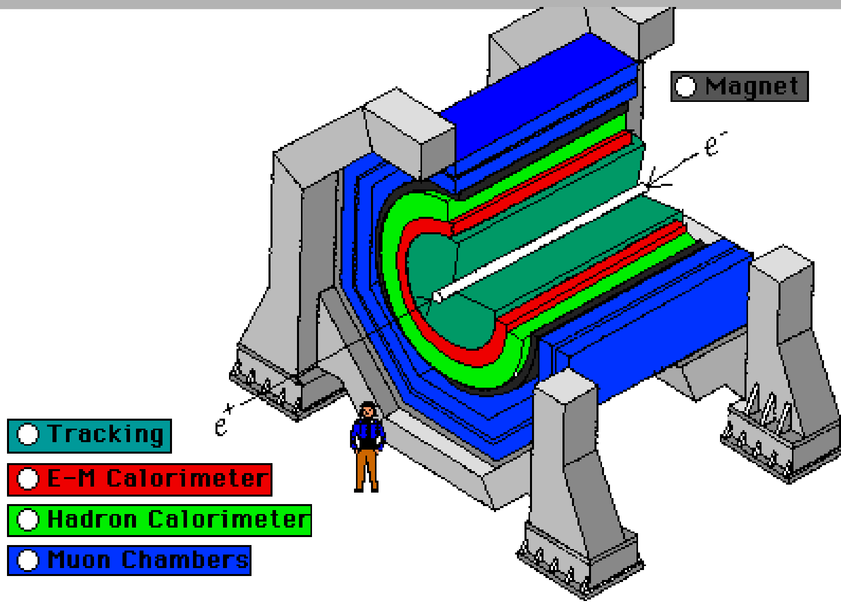
Final Sample
(interactive analysis)

(Also need to drop unneeded parts of each event)

The CMS Detector

Collider detectors

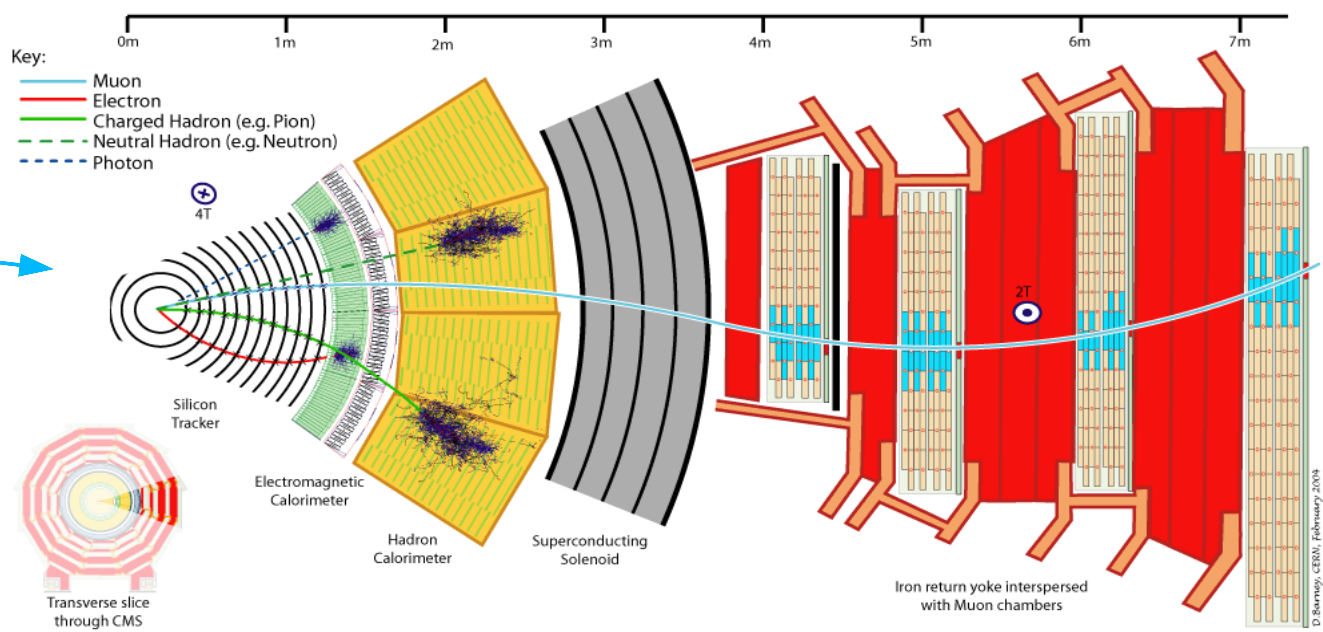




Toy detector

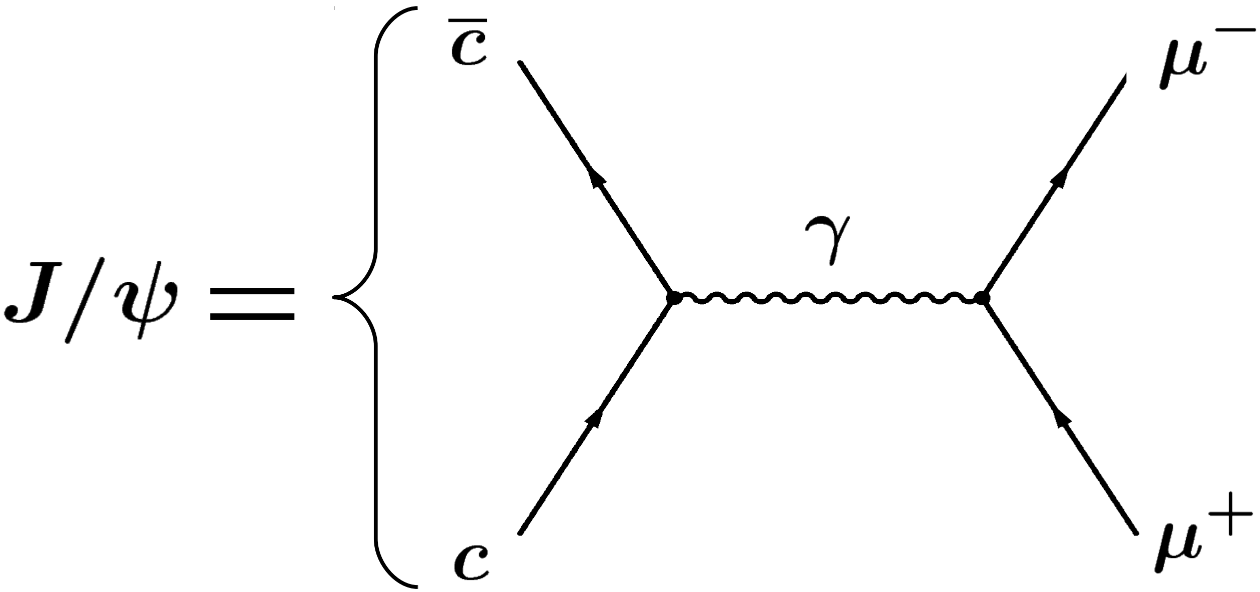
CMS detector

(CDF follows identical principles but it's smaller)



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

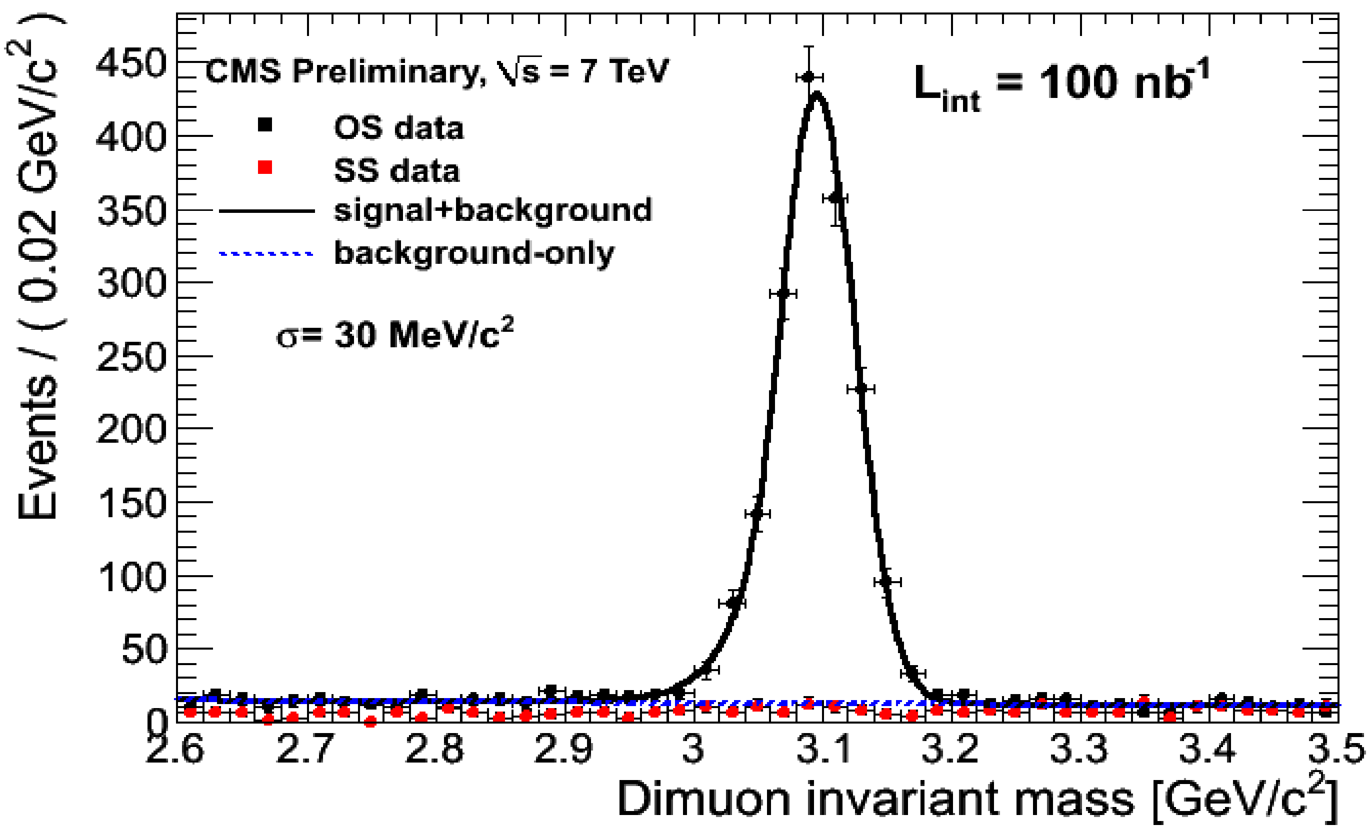
- J/ψ meson is a bound state of $c\bar{c}$
- decays electromagnetically (photon as a force carrier):



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

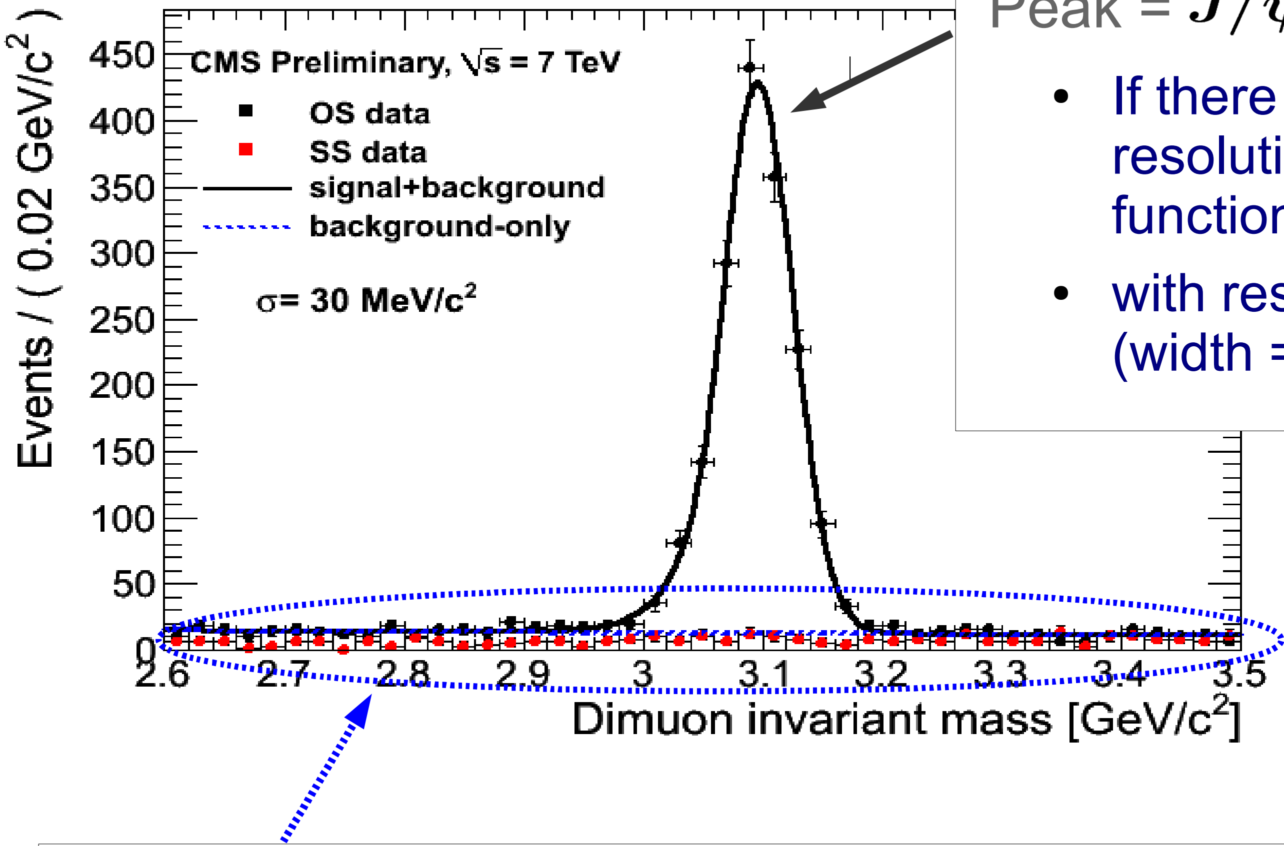
Reconstructing $J/\psi \rightarrow \mu^+\mu^-$

- 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

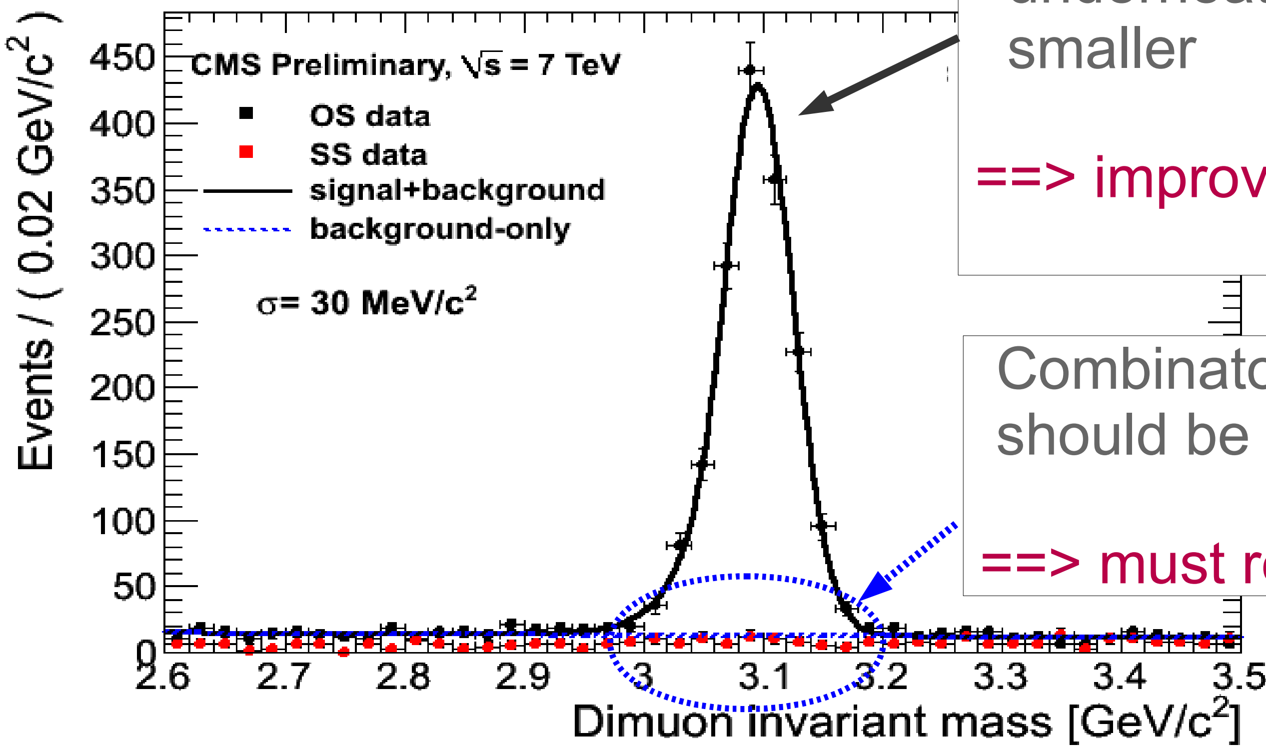
- If there were no detector resolution, it would be delta function (a vertical line)
- with resolution, it's a Gaussian (width = resolution)

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

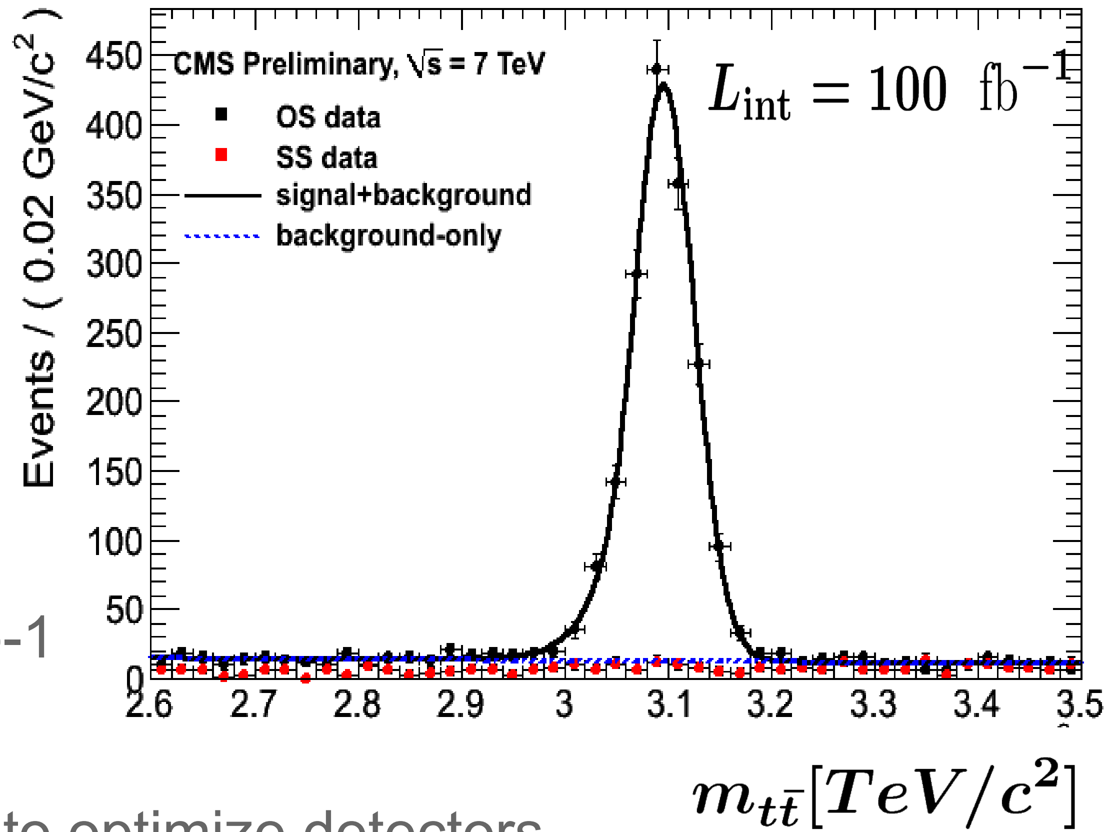
==> improve detector resolution

Combinatorial background: should be as low as possible

==> must reduce fake rate

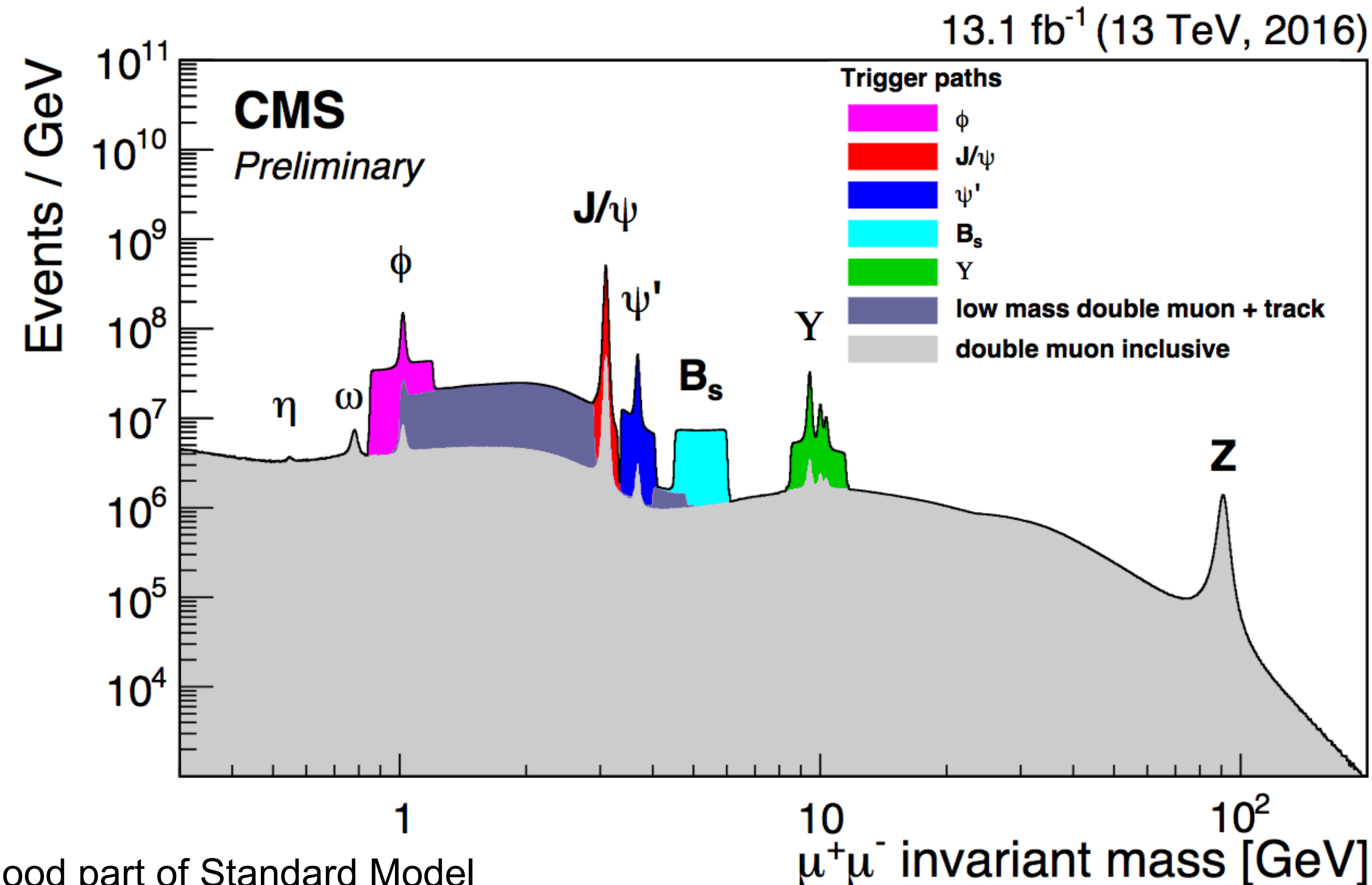
Digression #3: bump hunting

- 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 **<u>"bump hunting"</u>** – the easiest way to find new physics

Two-muon resonances

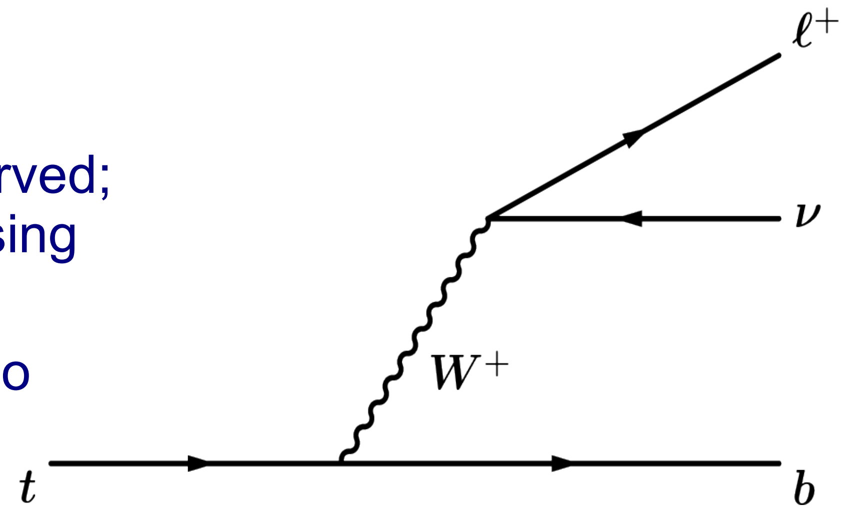


(A good part of Standard Model
in a single plot!)

Example: reconstructing top quarks

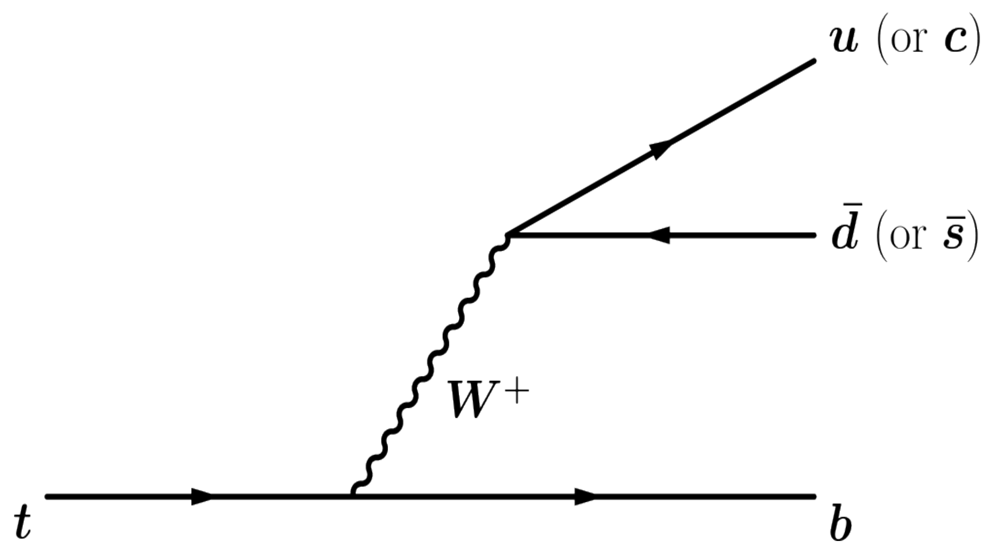
"Semileptonic" decay:

- neutrinos can't be directly observed; partially reconstructed via "missing transverse energy" (MET)
- look at `isolated' lepton – with no other particles around it



"Hadronic" decay:

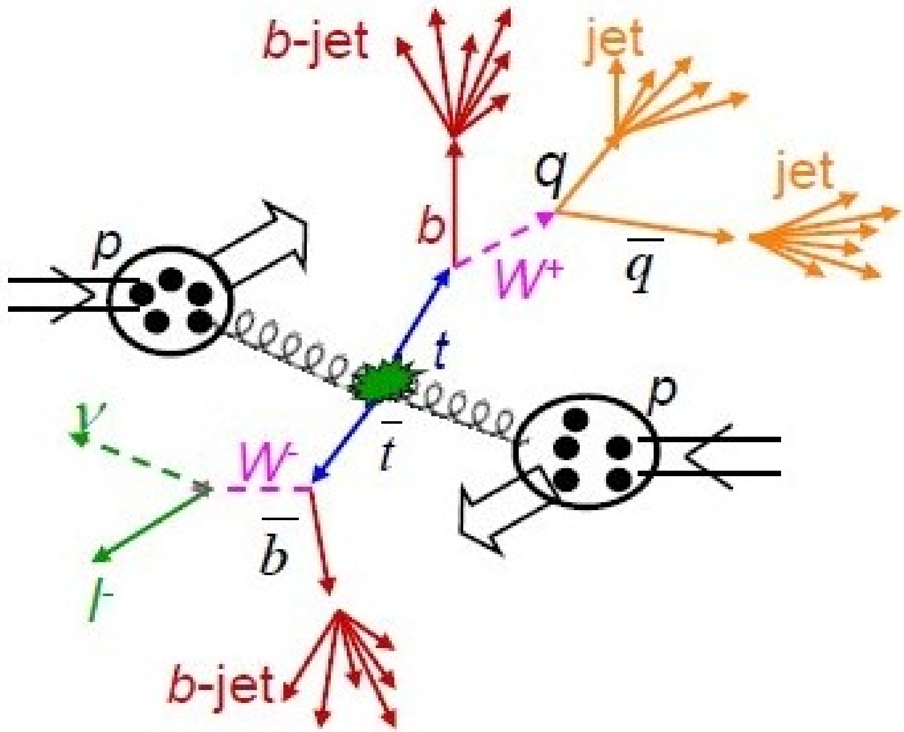
- more complicated, since quarks can't be free



Building blocks of $t\bar{t}$ 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)

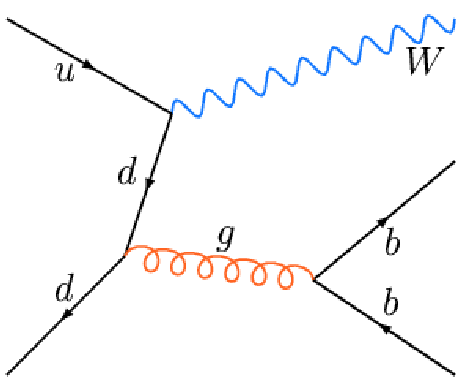


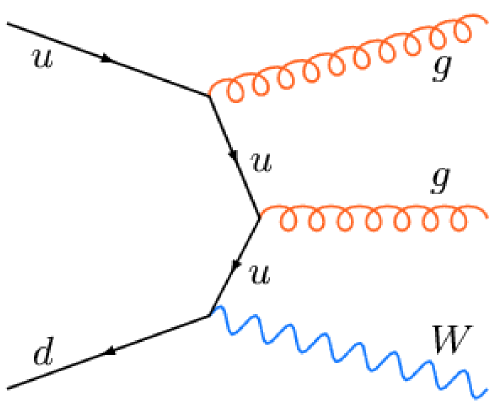
- Most other analyses built from same building blocks!

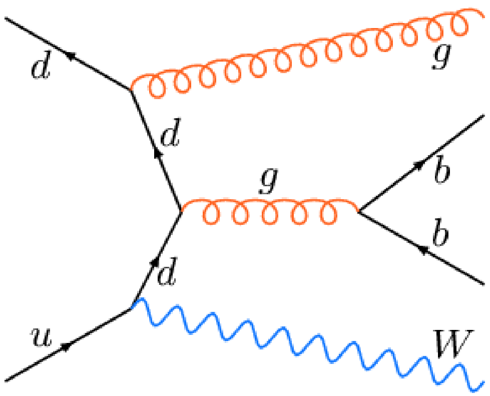
  ==> $t\bar{t}$ events are a perfect tool for physics commissioning!

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 $t\bar{t}$ $\rightarrow$ **Signal**
  - however, our selection is imperfect ==> some events in data will be something else $\rightarrow$ **Background**
  - seek to maximize $\mathrm{Signal}/\sqrt{\mathrm{Background}}$
  - *must also know how much Background we have left-over*!

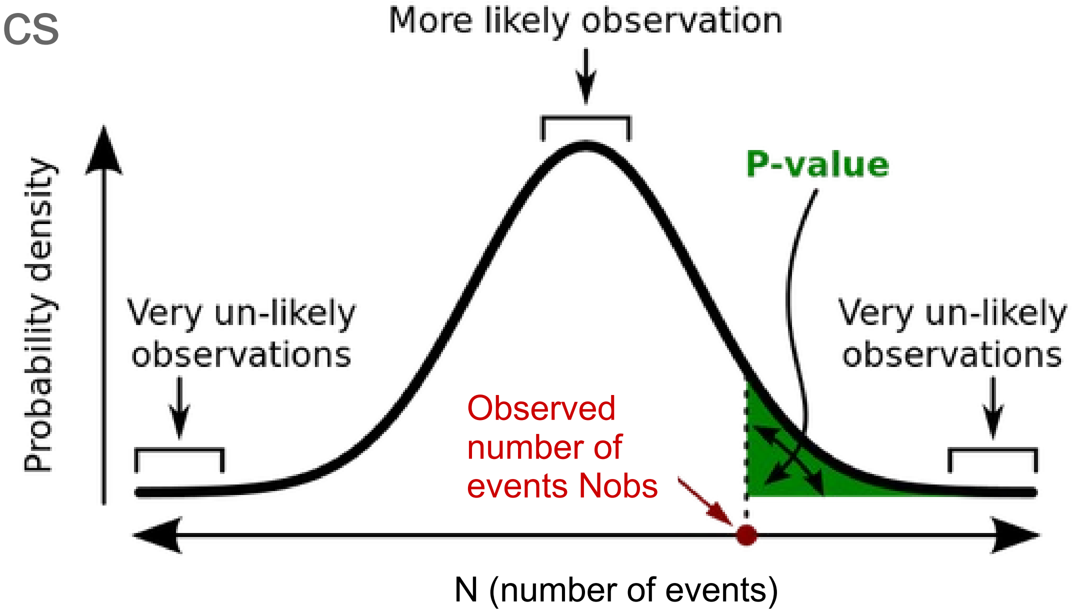






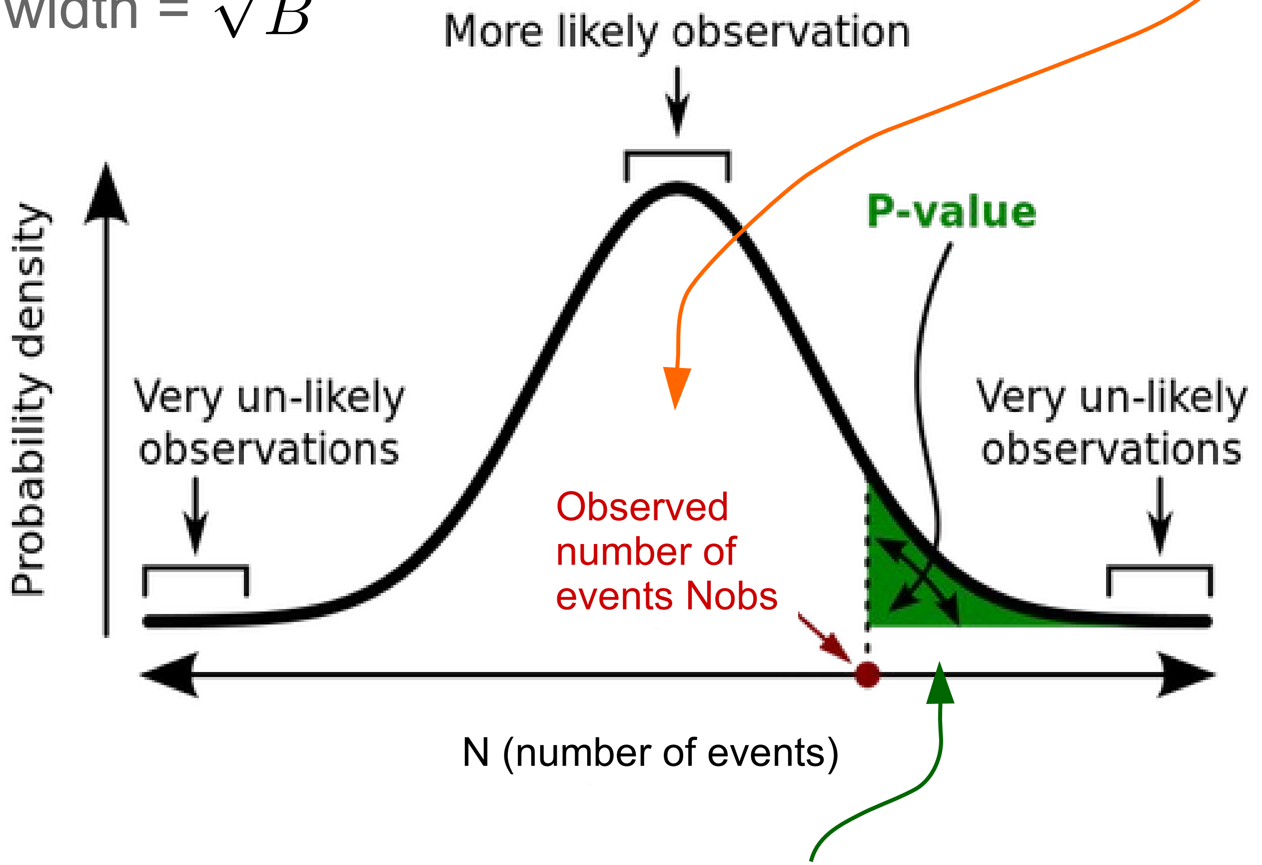
An anatomy of a search for New Physics

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



An anatomy of a search for New Physics

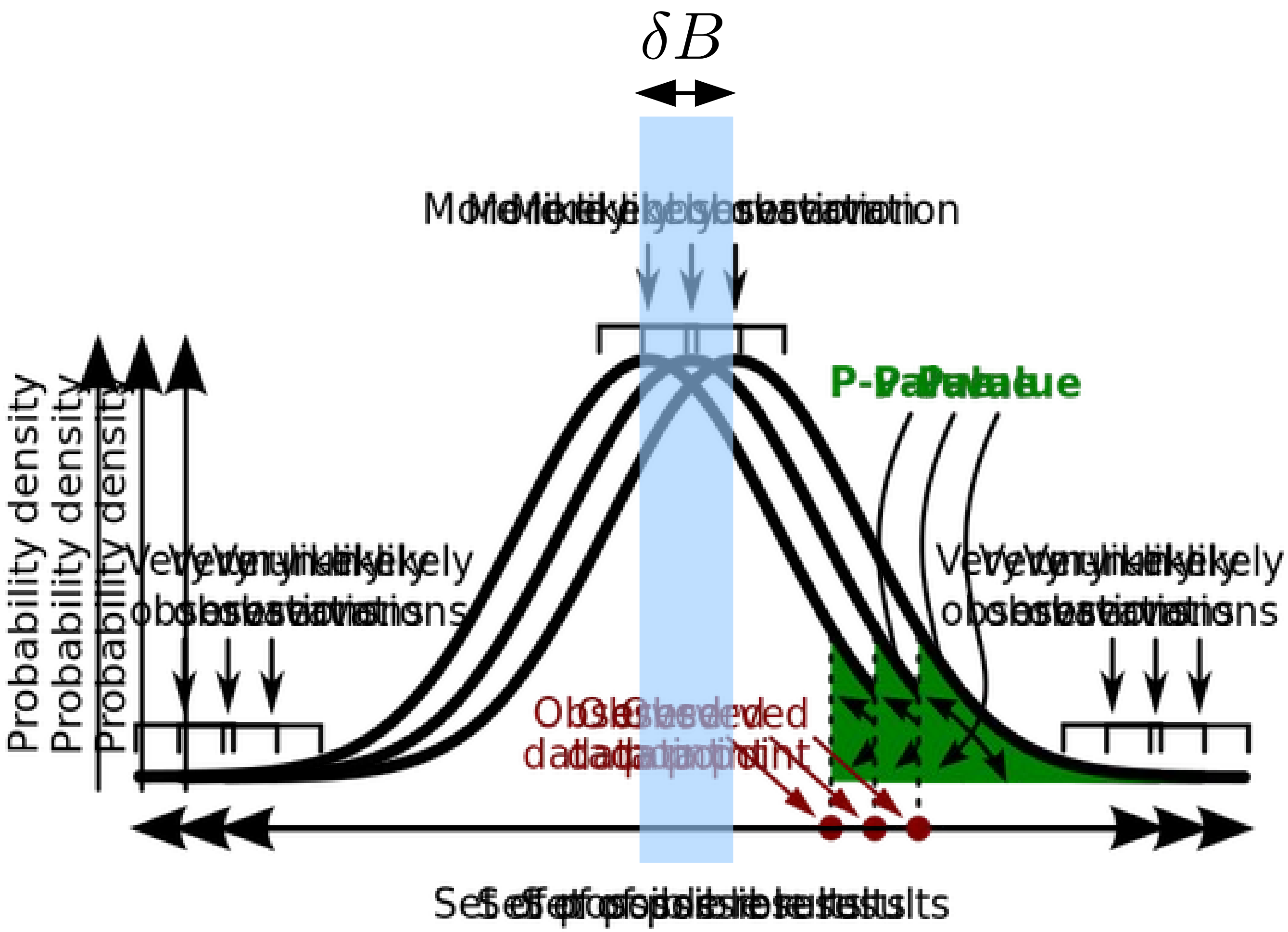
- Center of SM Gaussian = # of background events, B .
- Its width = $\sqrt{B}$



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

An anatomy of a search for New Physics

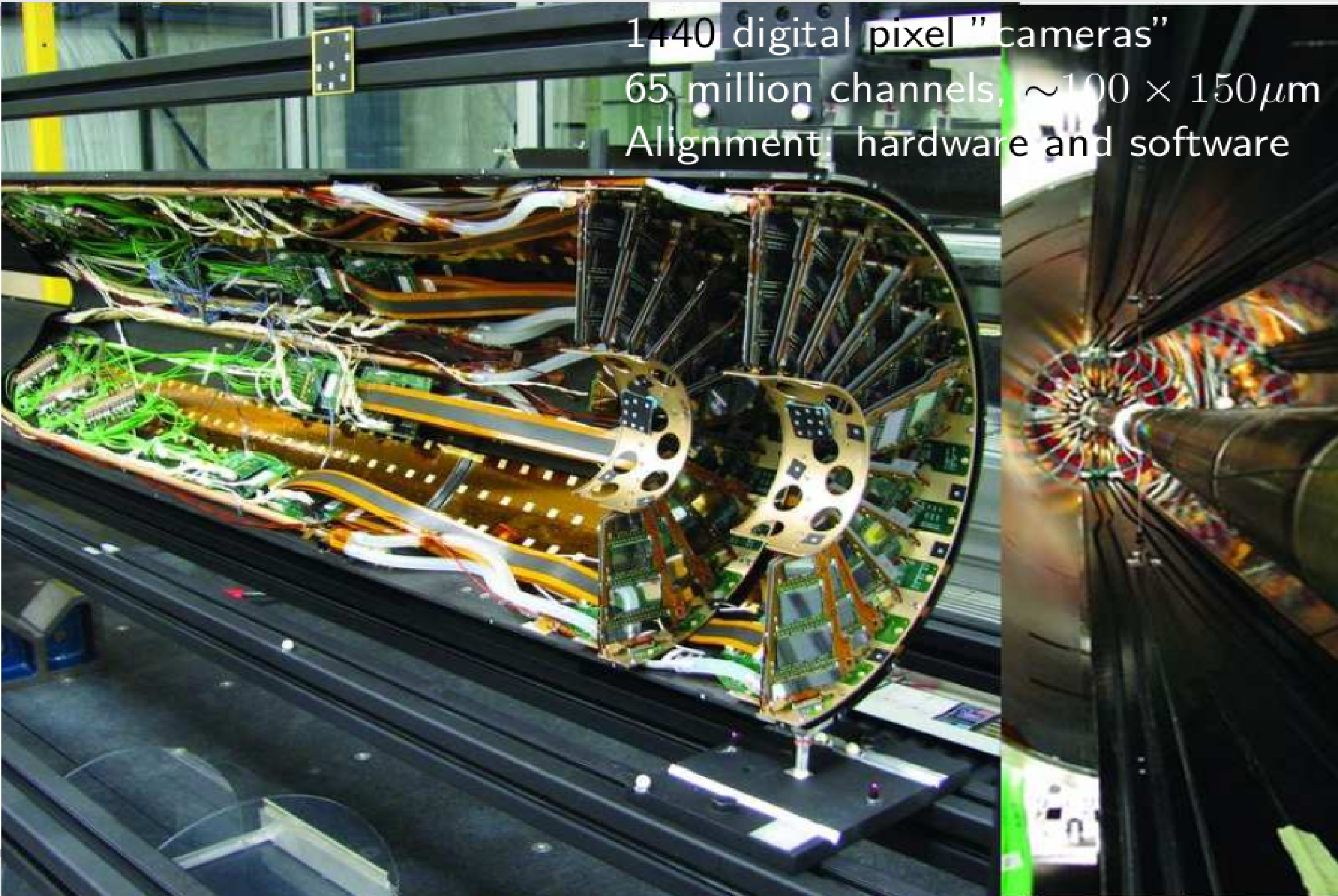
- Uncertainty on background, δB, smears true position of the SM Gaussian → decreases P-value.



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 $\delta\epsilon_S$)

The Silicon Pixel Detector



1440 digital pixel "cameras"

65 million channels, $\sim 100 \times 150 \mu m$

Alignment: hardware and software

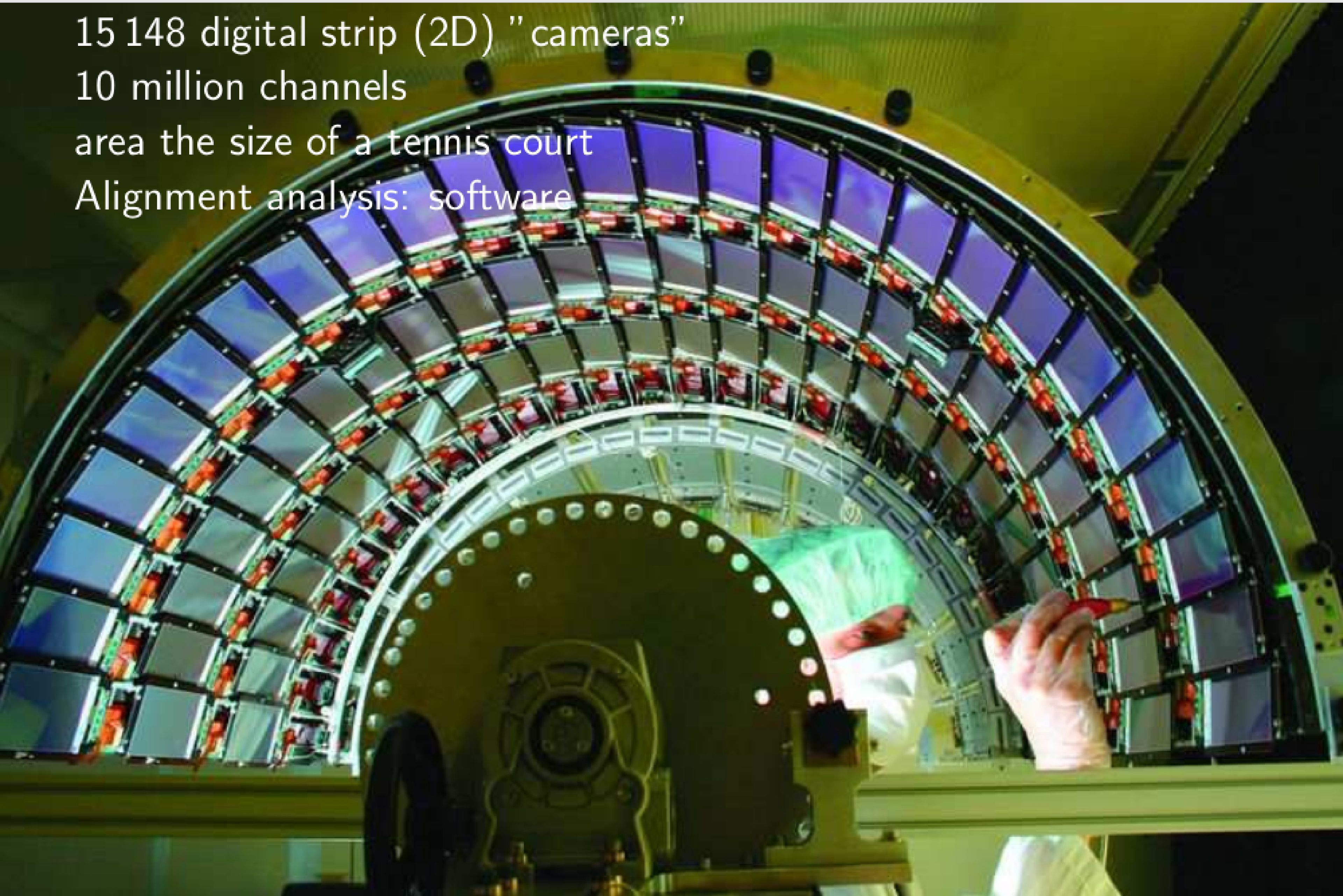
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"

10 million channels

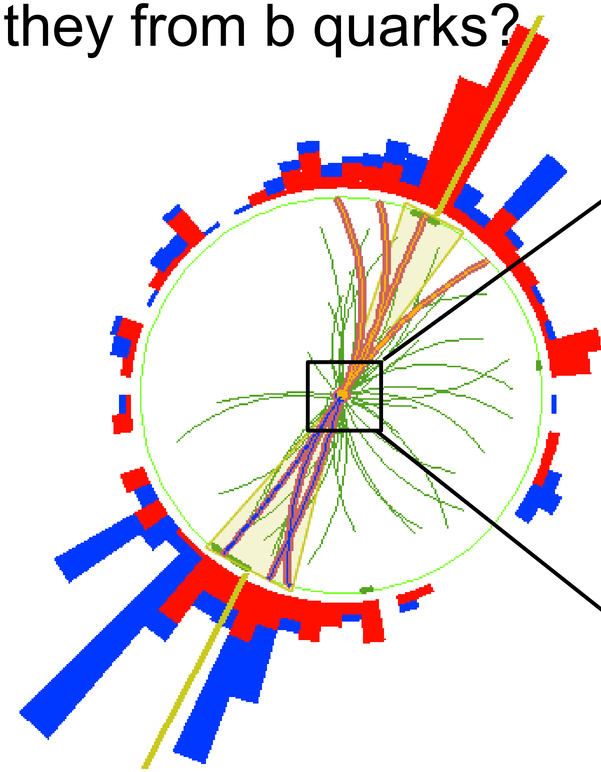
area the size of a tennis court

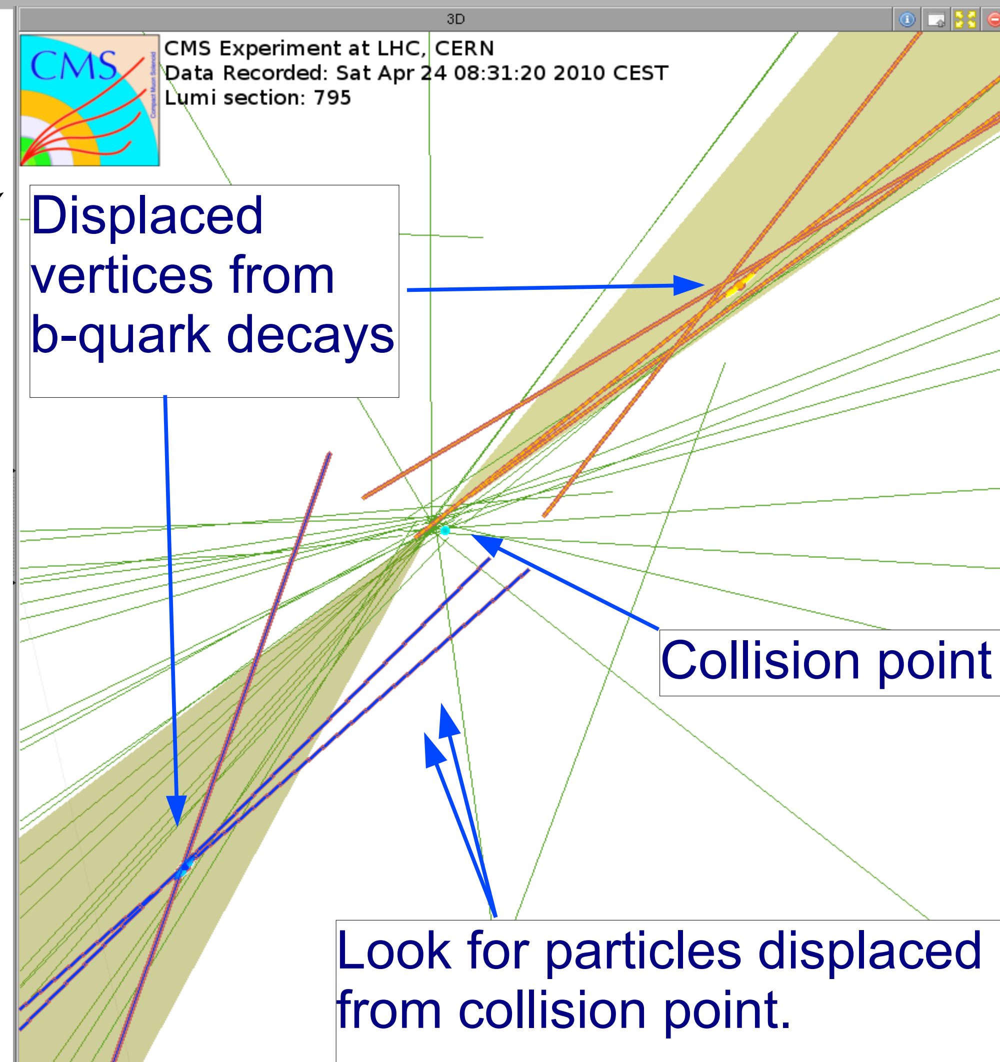
Alignment analysis: software



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

Event with two jets:
are they from b quarks?





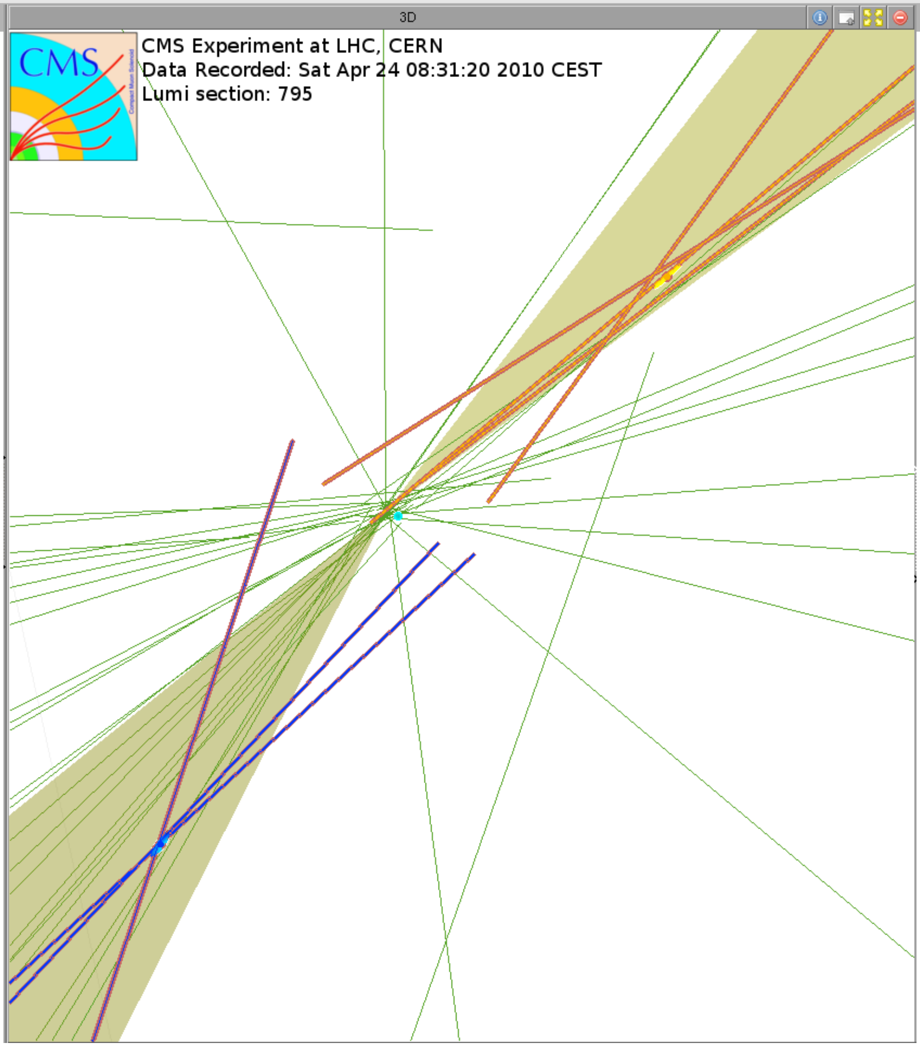
Displaced vertices from b-quark decays

Collision point

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%

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

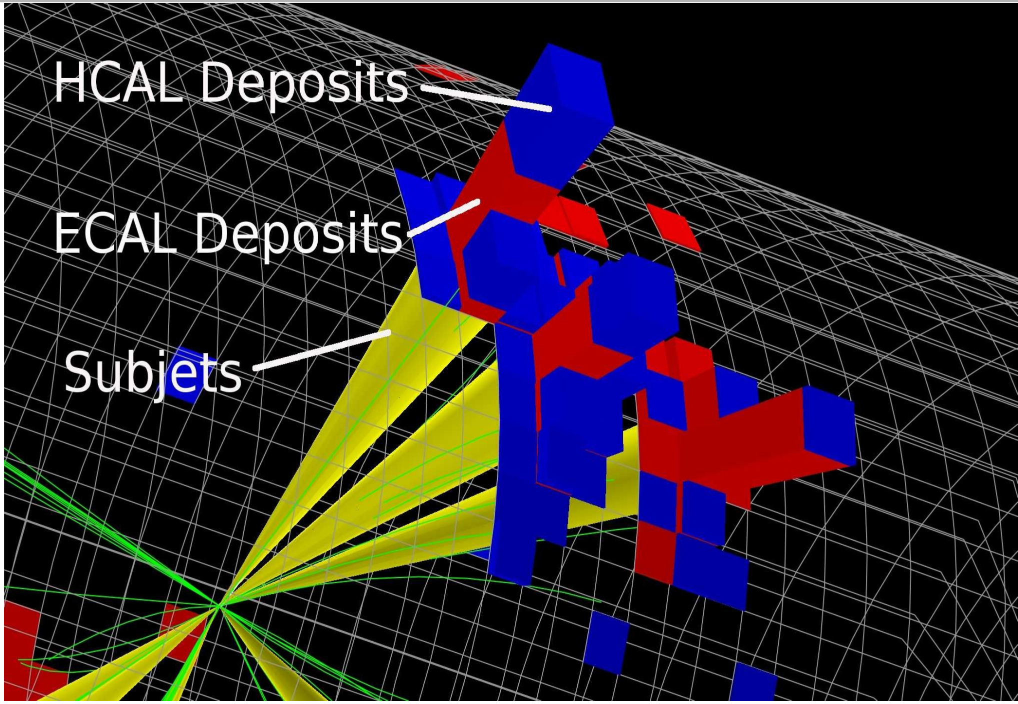
BACKUP

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

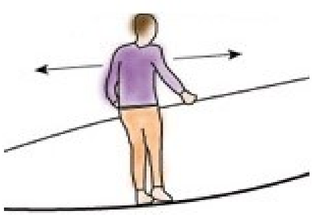
    → *top-tagging!*
- This is a hot topic:
  - Butterworth et al : Boosted Higgs (hep-ph/0201098)
  - Kaplan et al: Boosted top (0806.0848)



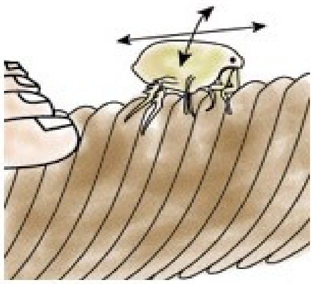
- Blue: hadronic calorimeter
- Red: electromagnetic calor.
- Yellow: found subjets

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*!)