More Particle Physics, or A Tour of Standard Model in 50 minutes

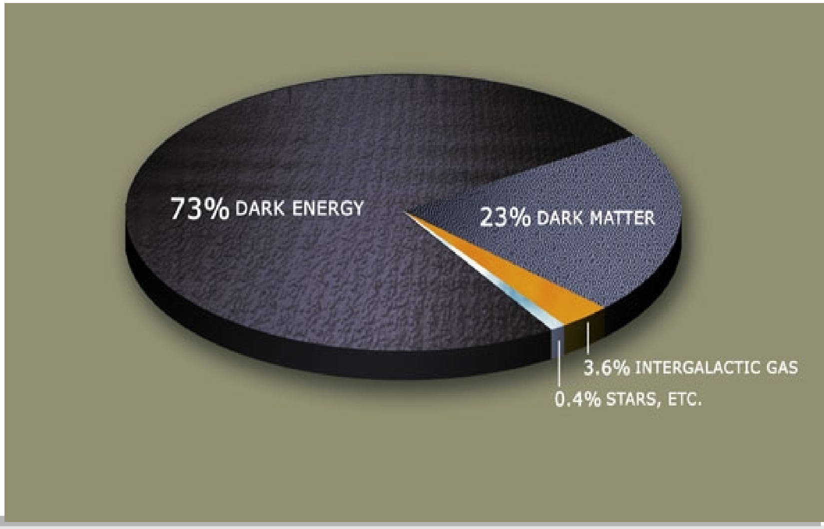
Petar Maksimovic

- A continuation of Jeremy's talk
- More theoretical than “Particle Fever”, less theoretical than Jared's talk on Tue.
- A good segue into experimental techniques – warm up for Andrei's talk on Wed.

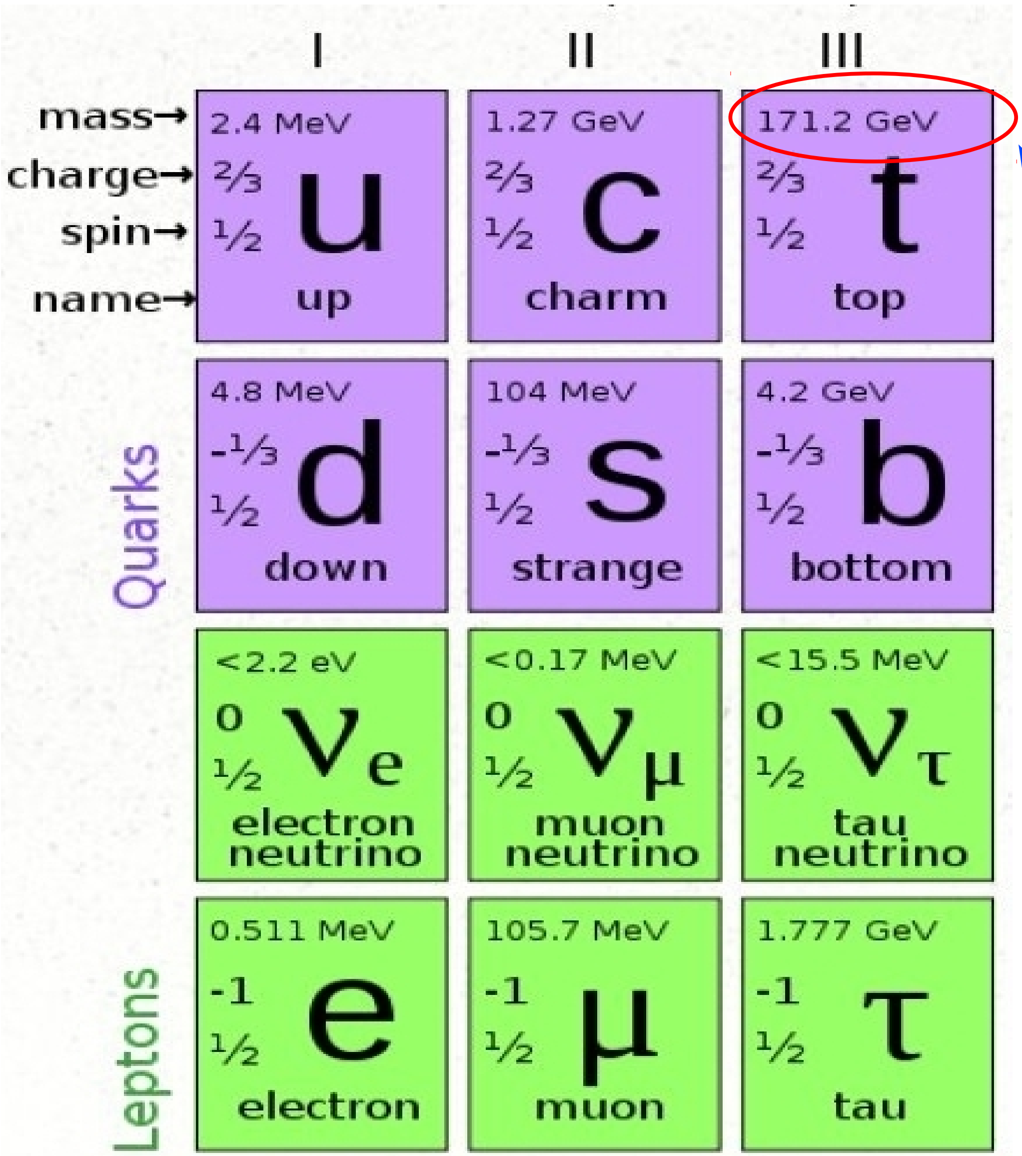
Questions

- 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



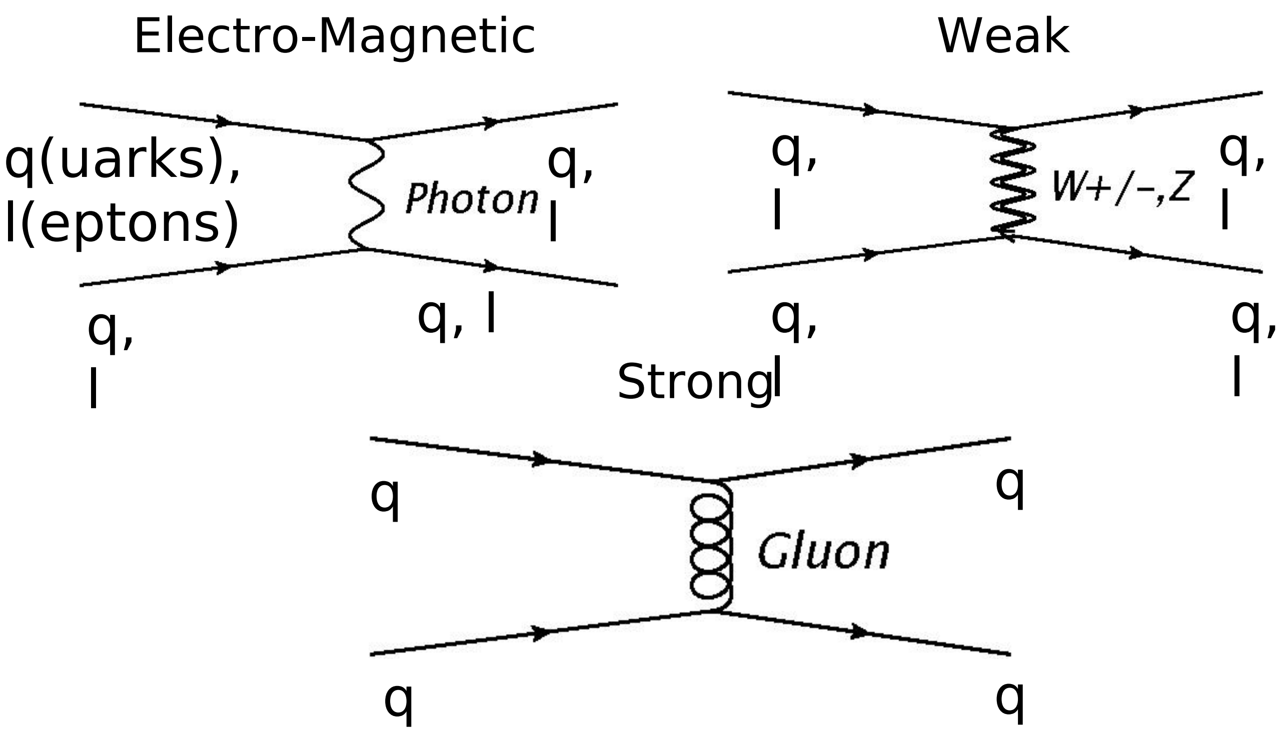
Three families of Standard Model

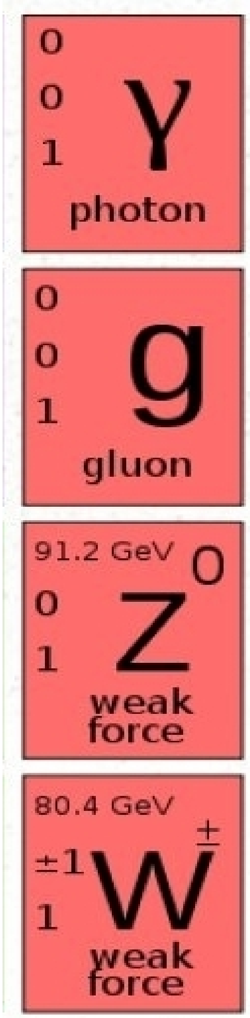


- All matter is composed of fermions = organized in three families of
  - 6 leptons
  - 6 quarks
  - masses are external parameters

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

Standard Model: Interactions

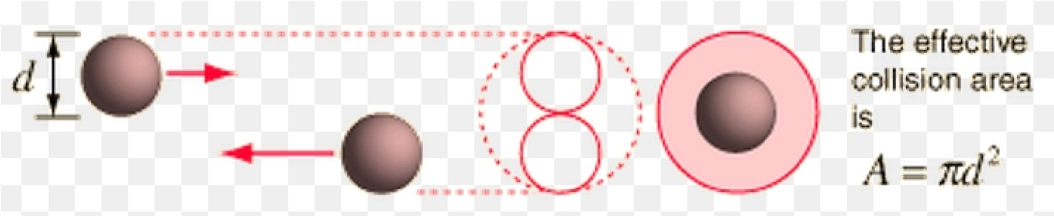




- Fermions with charge interact via Electromagnetic force
  - Quantum Electrodynamics (QED)
- Fermions with color (quarks) interact via Strong force
  - Quantum Chromodynamics (QCD)
- Fermions with weak isospin (all) interact via Weak force

Calculating things in Standard Model

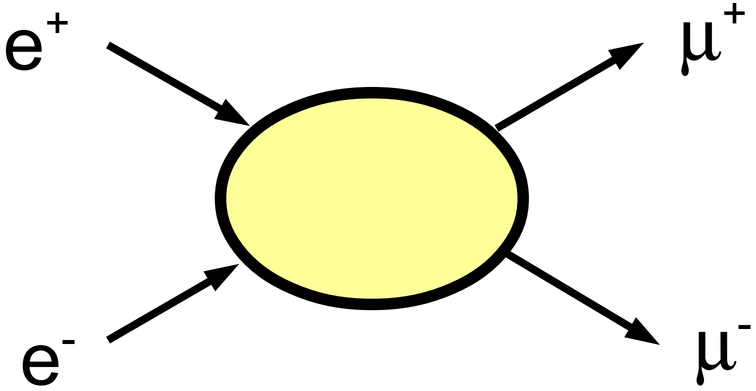
- Particles collide, different things can happen
  - Governed by Quantum Mechanics → probabilties
  - production rate ~ cross section * luminosity (flux)
- Cross section, classically:
  - effective area of collision



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

Quantum Electrodynamics (QED)

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



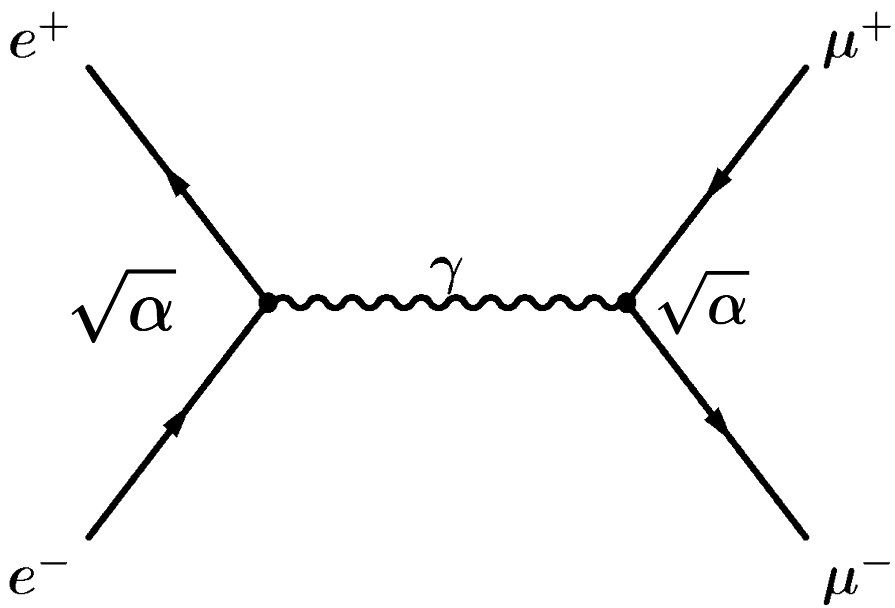
- Each term is represented with a pictogram, called a Feynman diagram
- Digression: Leibnitz formula for π:

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

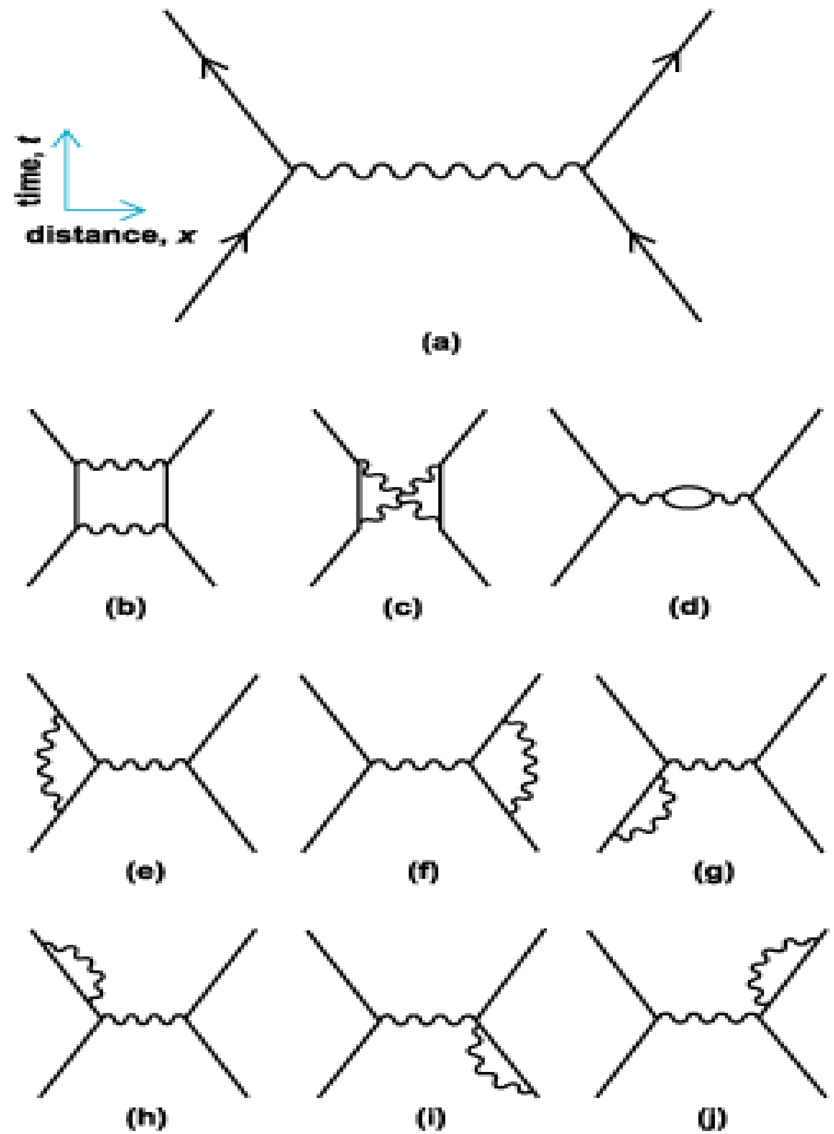
  - an example of a converging infinite series

Feynman series

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

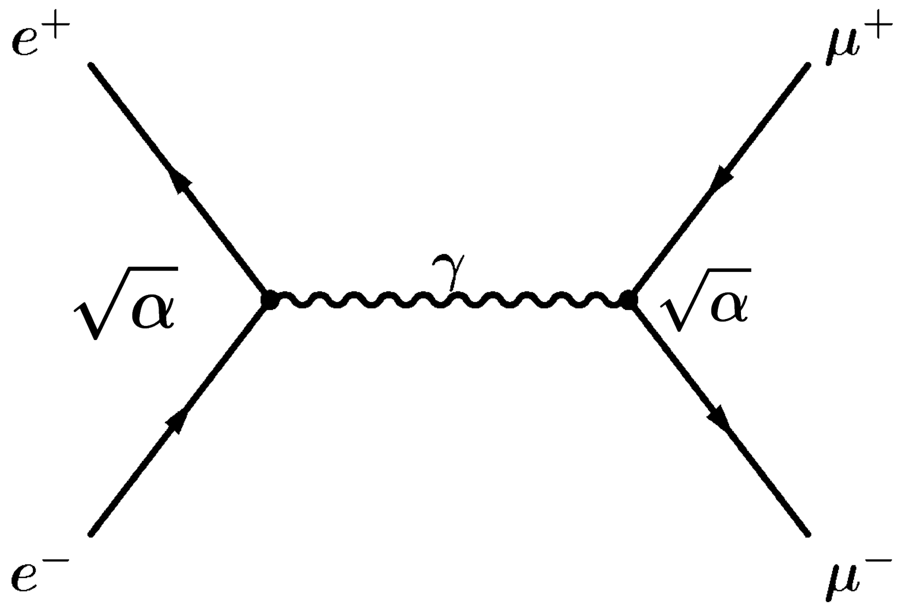


- At each vertex, coupling constant $\sqrt{\alpha}$
- $\alpha = \dfrac{1}{137}$ $\rightarrow$ converges rapidly!



Virtual particles

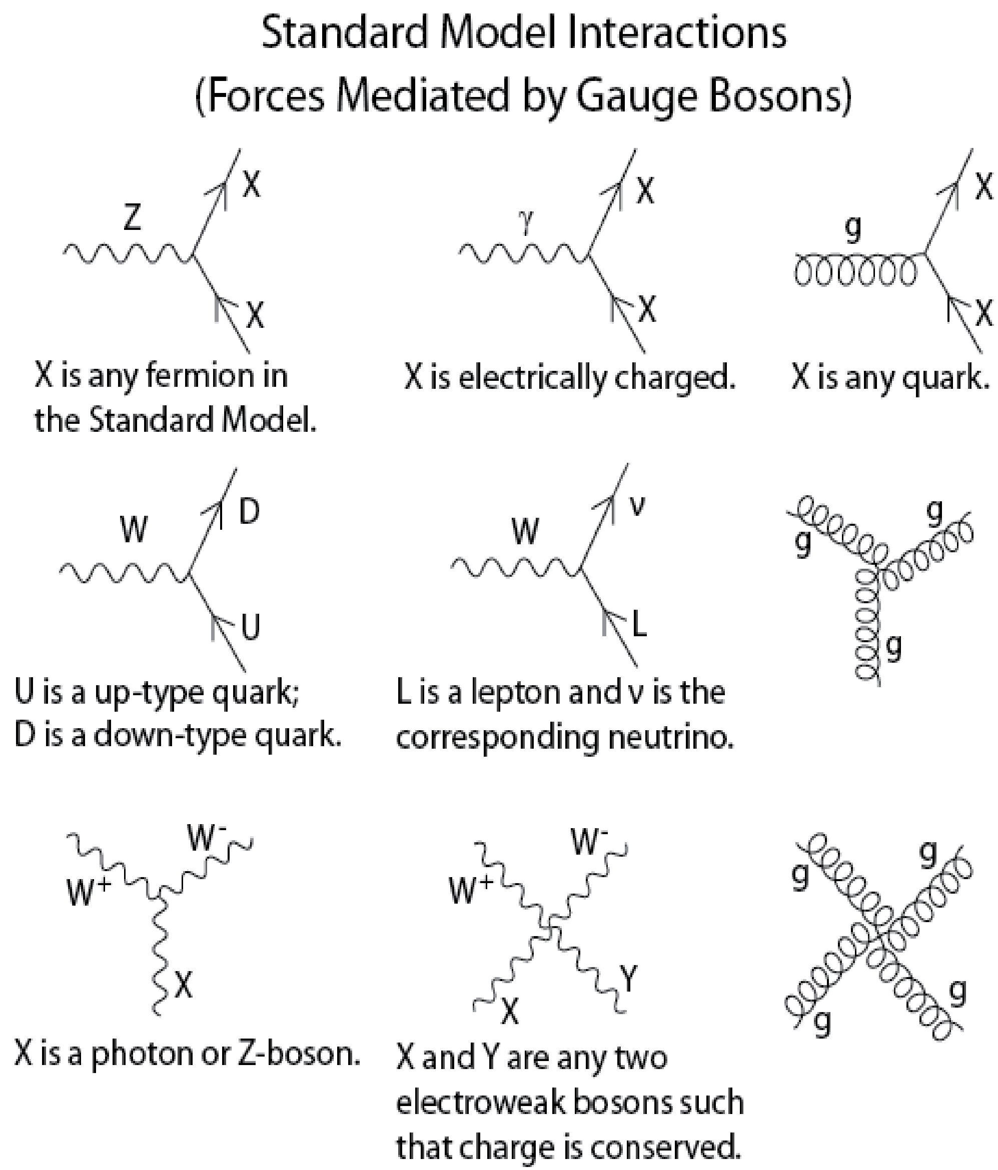
- Photon in the middle can violate conservation of energy-momentum – it's *virtual*.



- 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

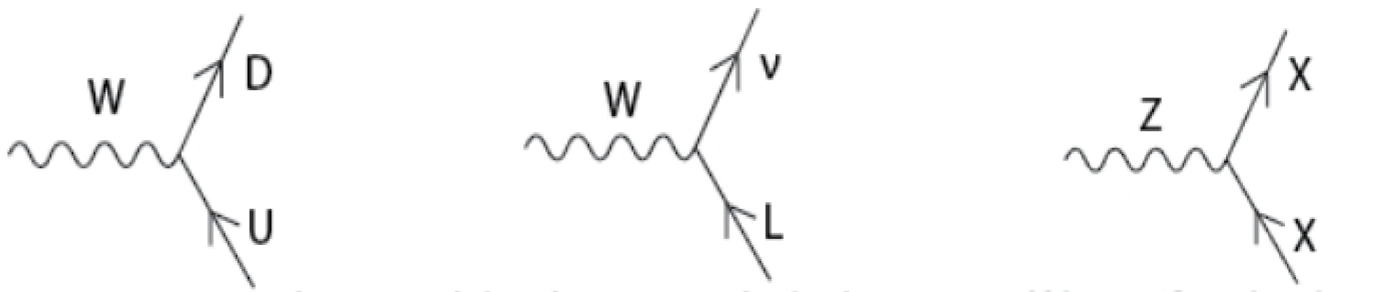
Feynman rules

- So all I 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...)

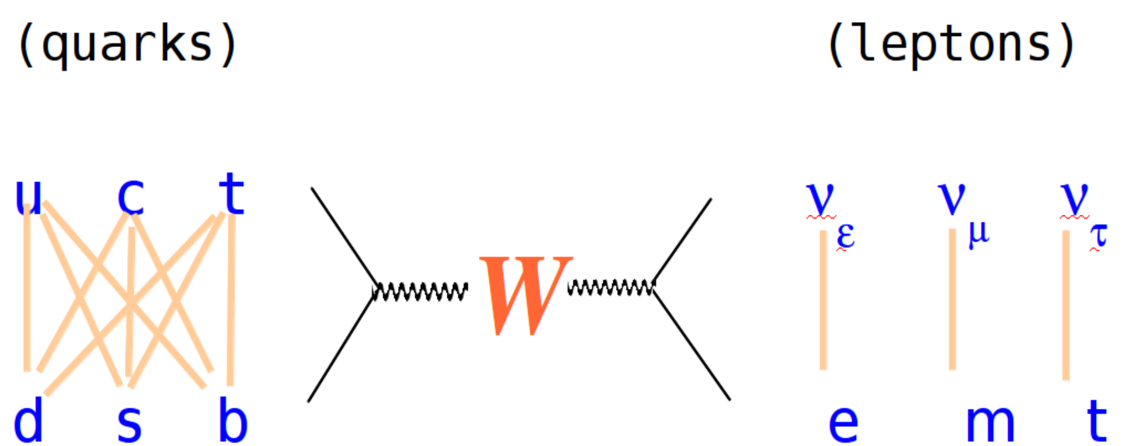


U is a up-type quark; D is a down-type quark.

L is a lepton and ν is the corresponding neutrino.

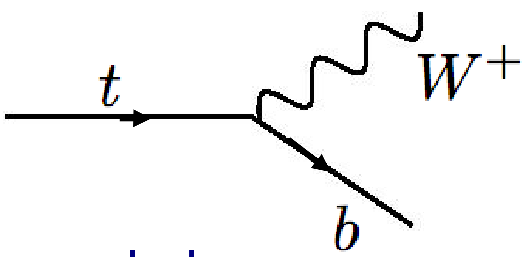
X is any fermion in the Standard Model.

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



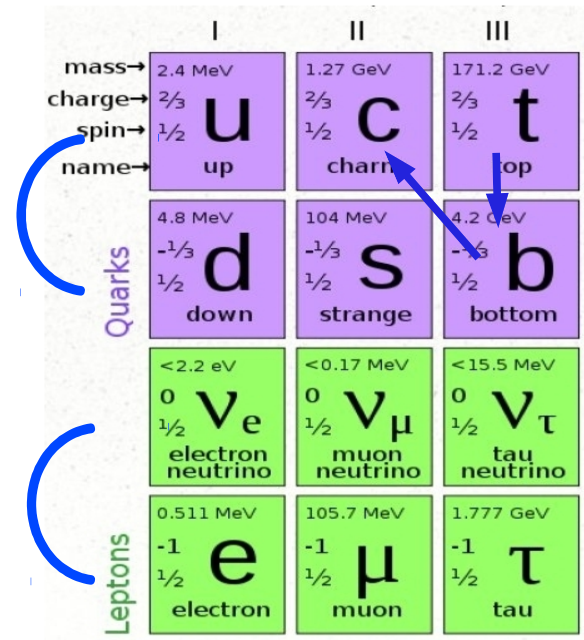
Examples of decays via weak interaction

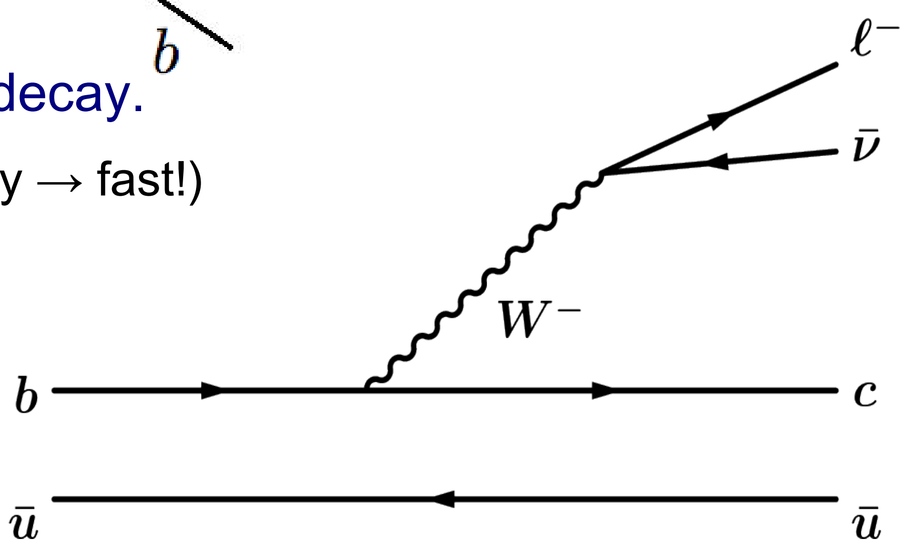
- W bosons couple up-type and down-type fermions
  - couple quarks across families
  - couplings are external parameters too



Top quark decay.

(Top is heavy → fast!)

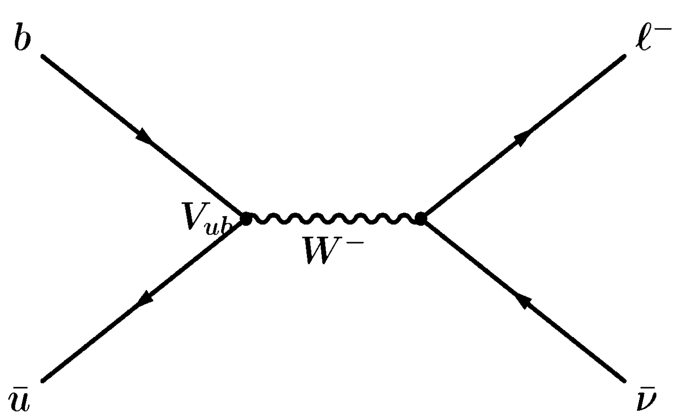


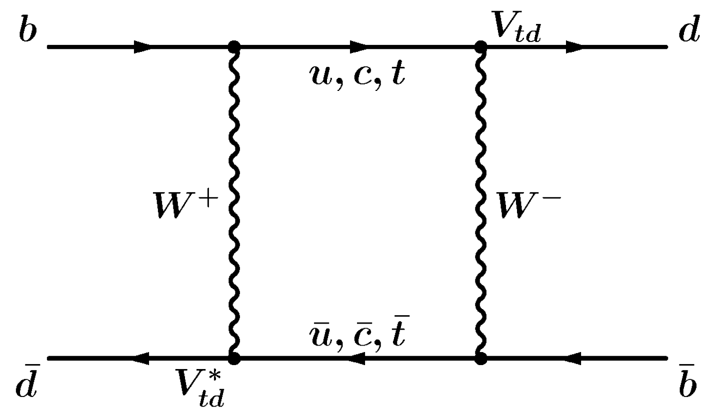


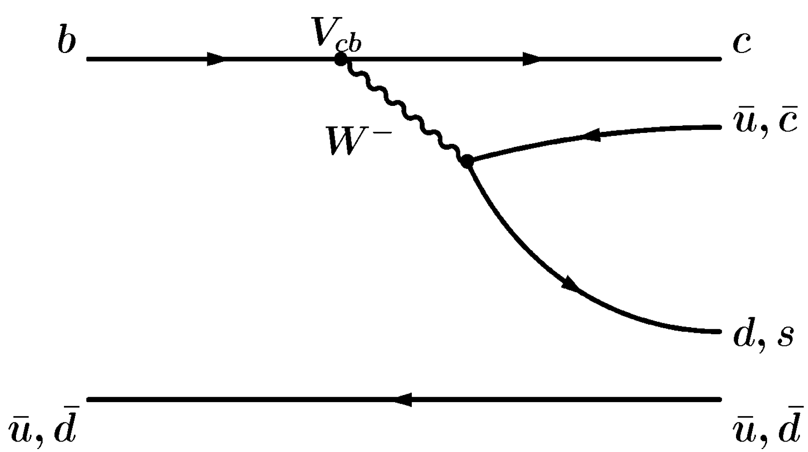
Decay of B meson into lepton + neutrino + D meson

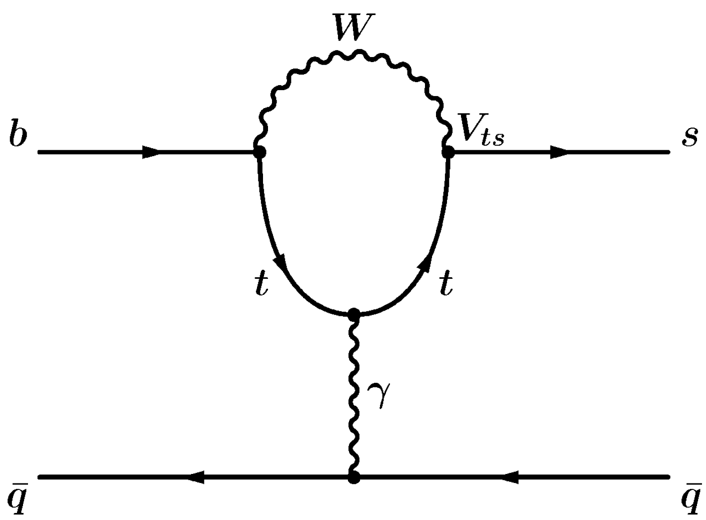
(W is virtual → slow!)

More weak decays



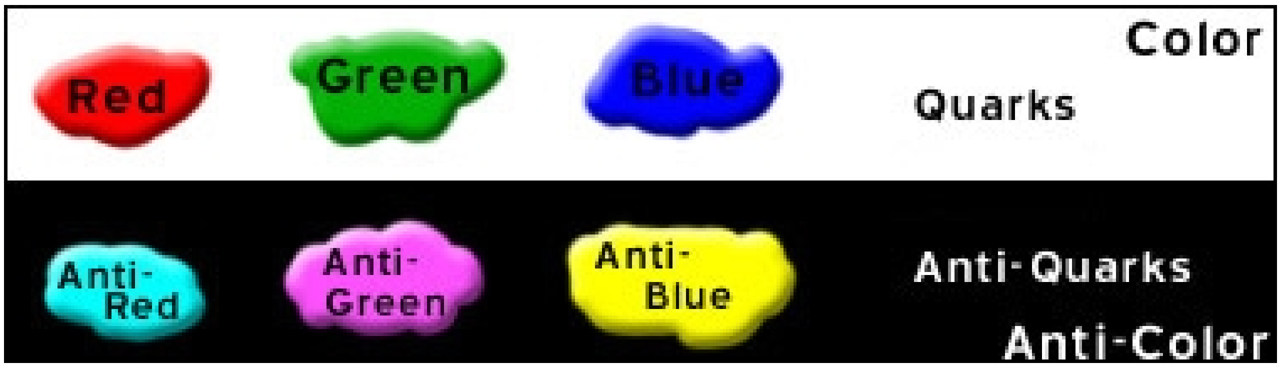






Quantum Chromo-Dynamics (QCD)

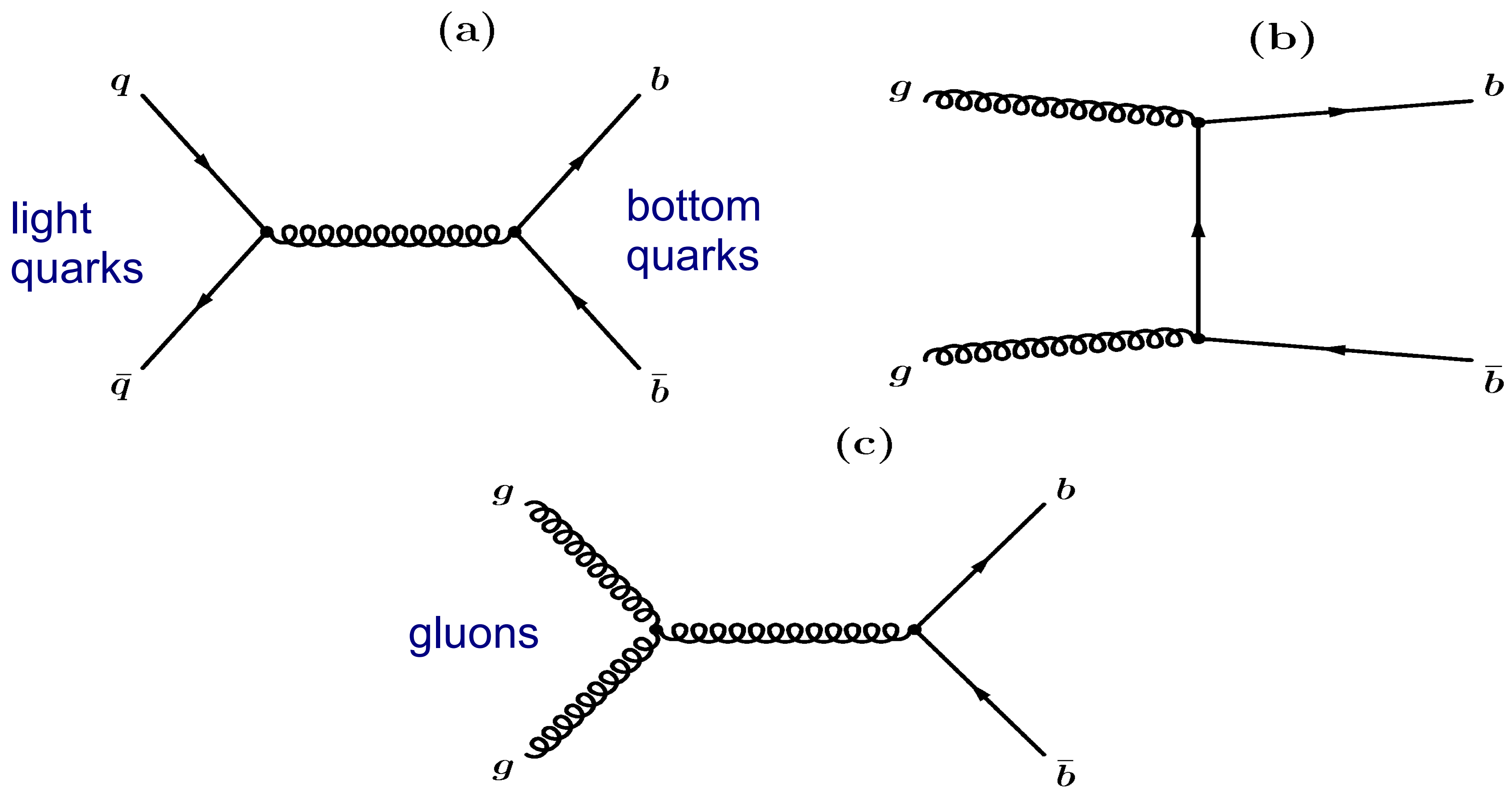
- Strong force (QCD): quarks carry color, interact via (8) gluons:



- 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)

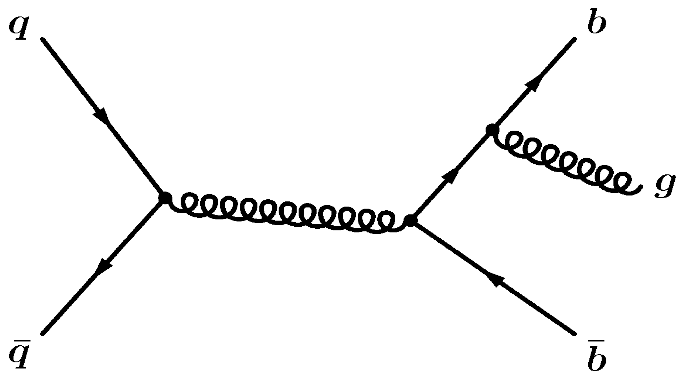
QCD

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

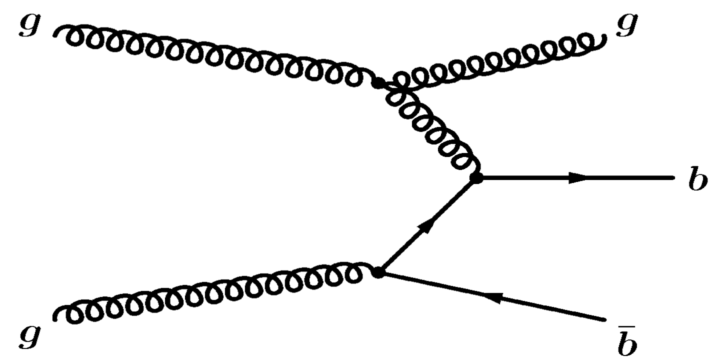


QCD

(a)

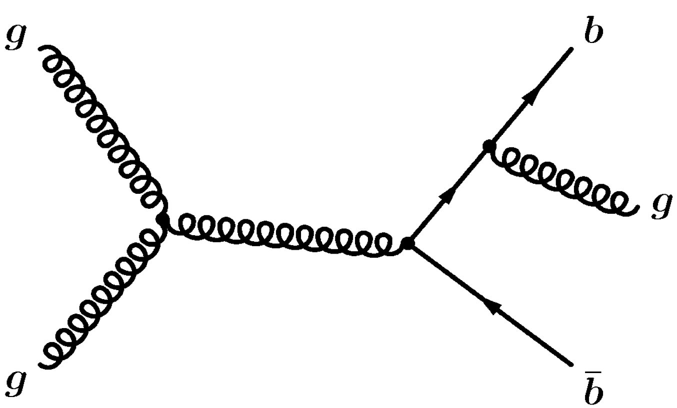


(b)

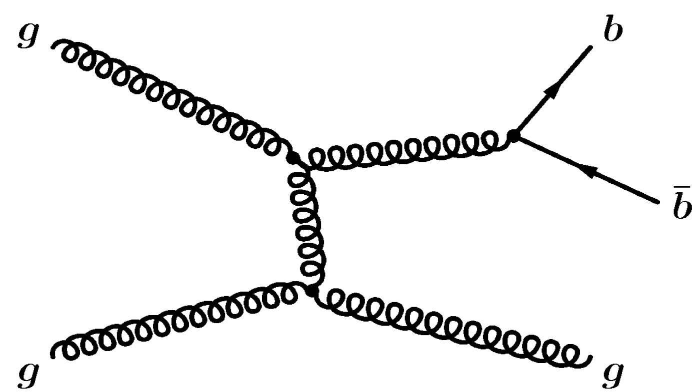


Adding more vertices with *low energy* gluons does not make amplitudes smaller!

(c)



(b)



Running coupling constant

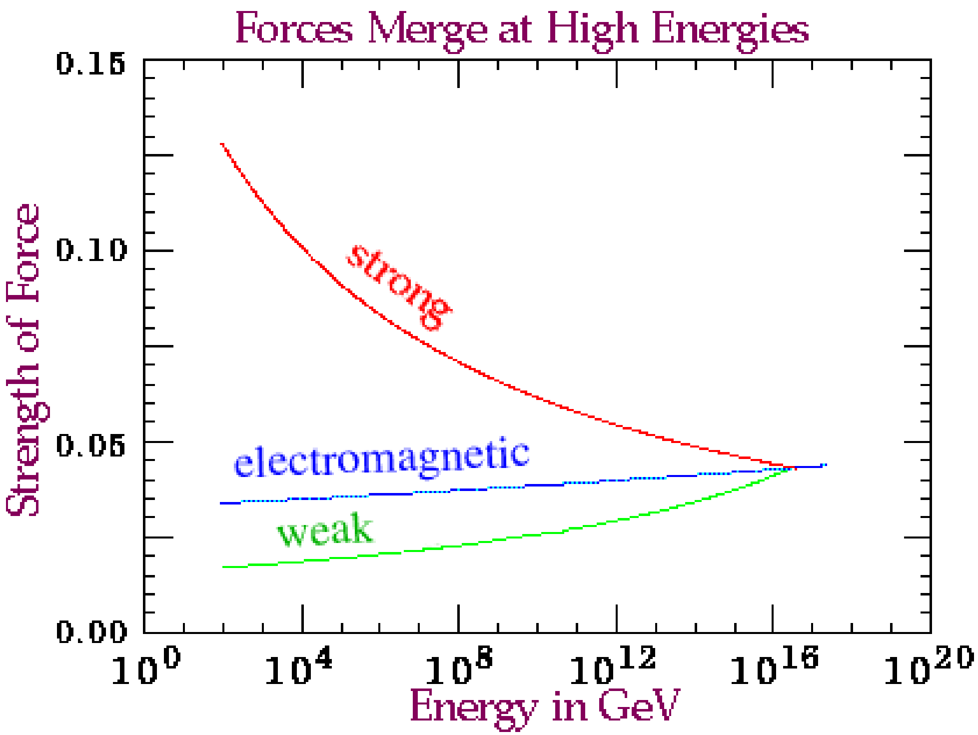
- Making low-energy, virtual gluons is `cheap'
  - $\alpha_s \sim 1$, so adding vertices with gluons causes no suppression
- This + gluons couple to each other ==> $\alpha_s \neq \text{const.}$
- α_s changes with energy $\rightarrow$ `α_s runs'

$\Longrightarrow$ “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



Electromagnetic and Weak force are both facets of the same original “electrweak” force.

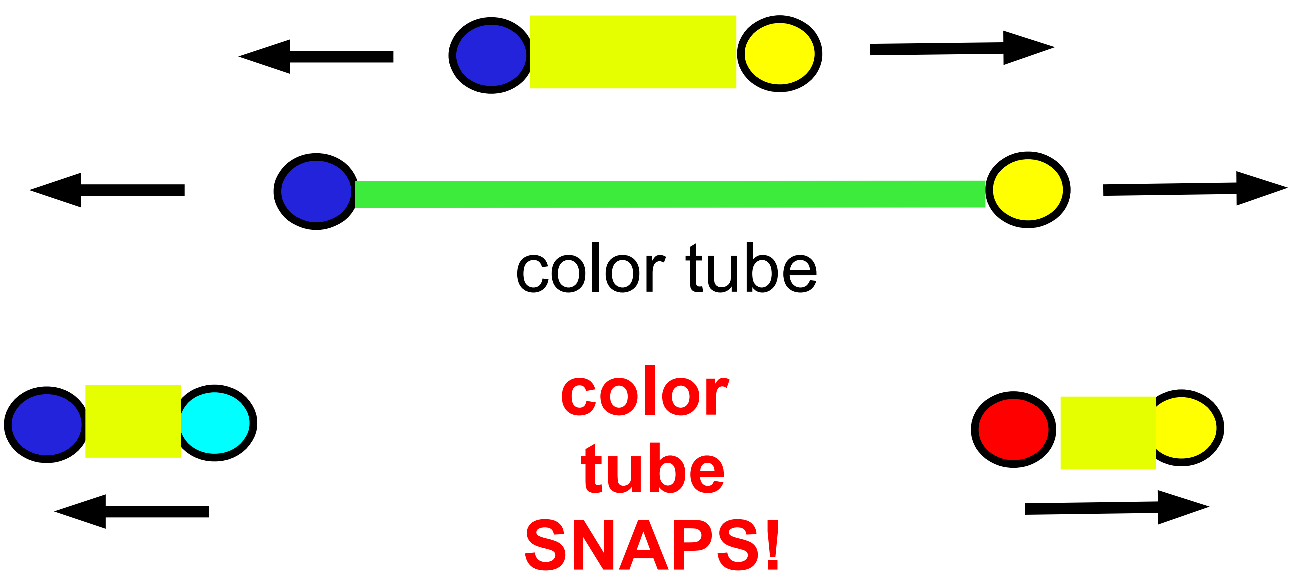
Broken by Higgs mechanism

But, it seems that the QCD was a part of that too – except we don't know how exactly...

- Current data suggest that all three coupling constants coverge at the same energy...

QCD: hadronization

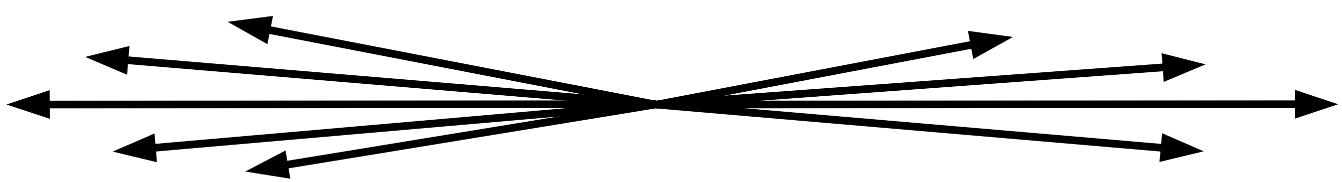
- Consider hadronic decay $W^+ \rightarrow u\bar{d}$
- As quarks move apart with high energy, color tube between them stretches, energy density rises



QCD: all quarks & gluons end up as jets

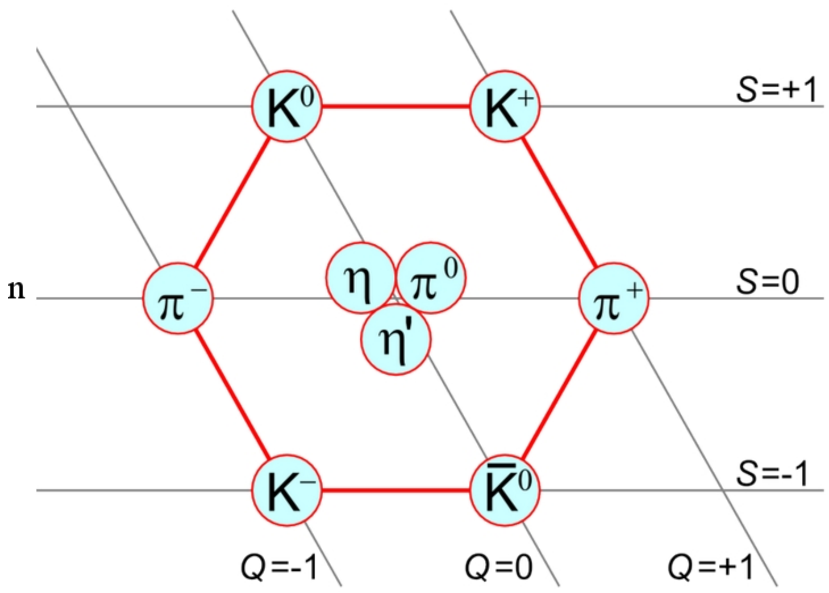
- Quarks still have unequal energies so more quark-antiquark pairs keep being created

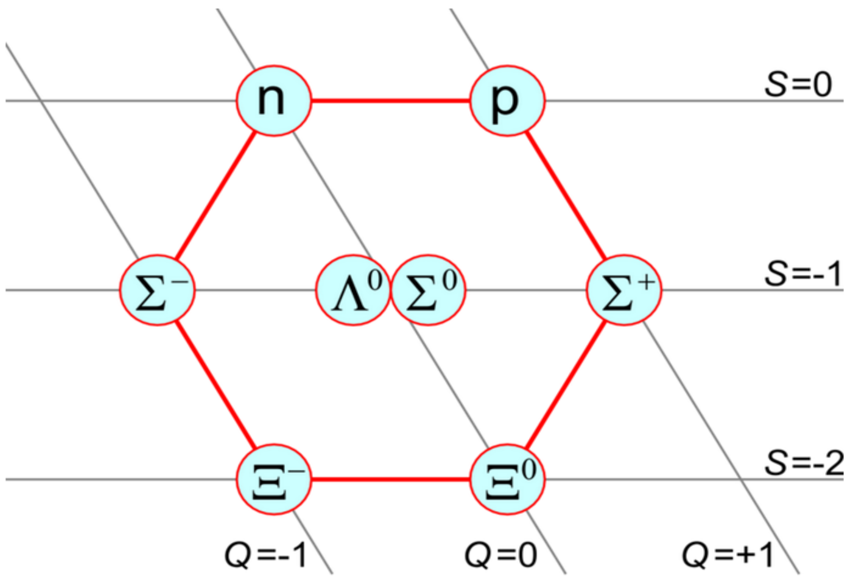
- So, every quark or gluon creates a stream of collinear particles called a **`jet':**



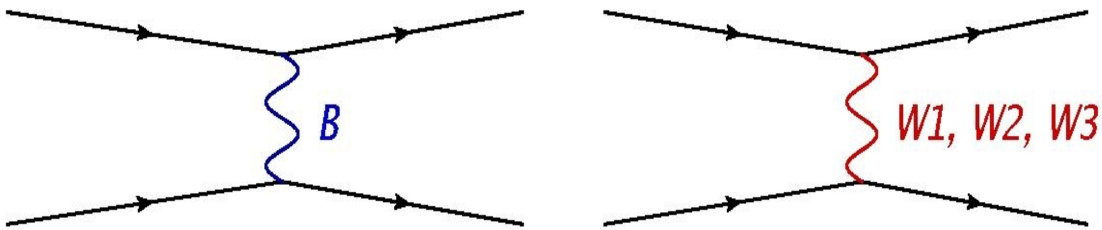
QCD: no open color!

- 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

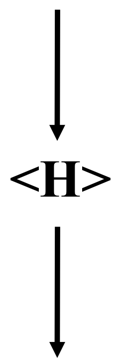




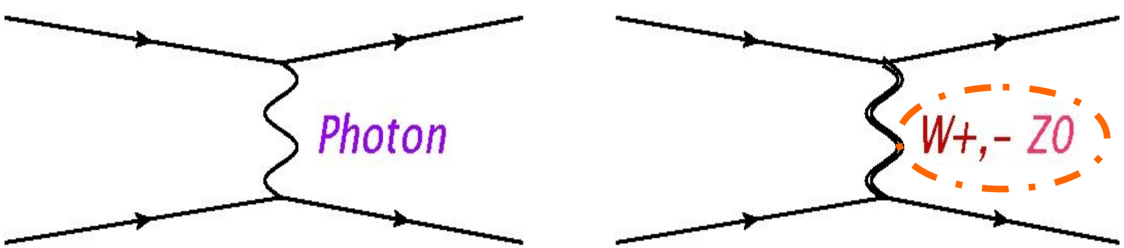
Electro-Weak symmetry breaking



Theory Input
(four massless Electro-Weak bosons)

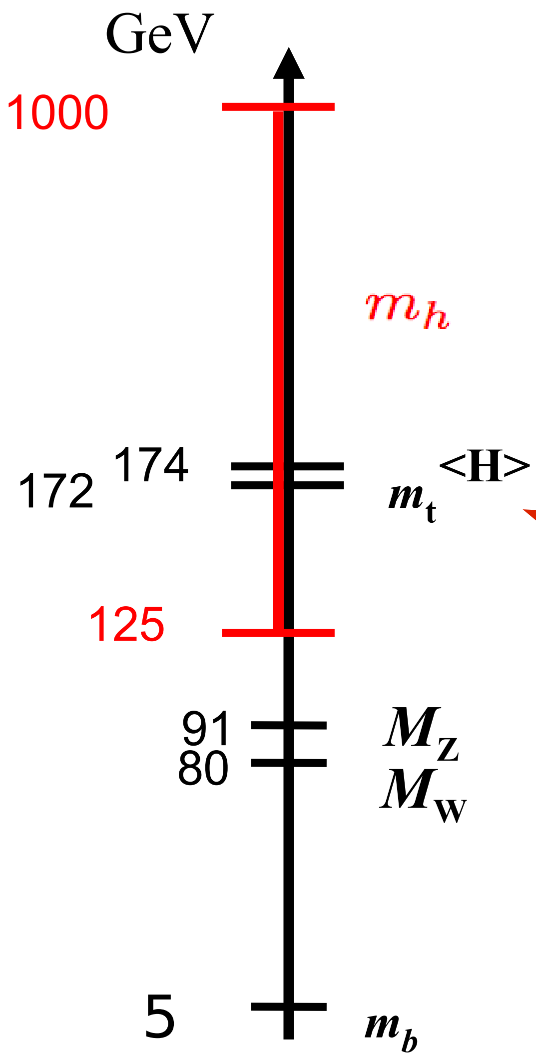


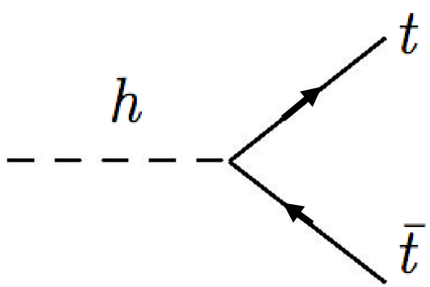
Higgs Field spontaneously breaks Electro-Weak Symmetry



Physical States:
massless photon and very heavy W and Z

Weak scale physics





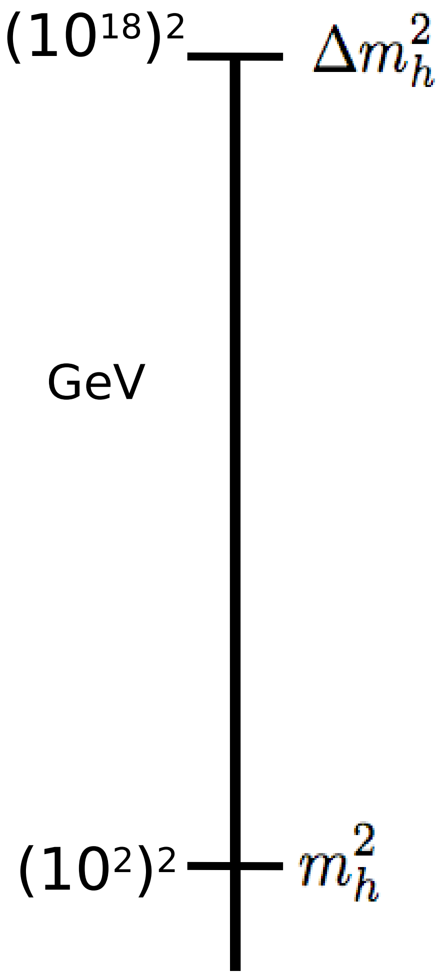
- Higgs field pervades all space
  - fermions are interacting with it and acquire mass.
  - mass ~ strength of coupling to Higgs!

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

- Higgs vacuum expectation value is ~ top mass!
- Higgs has been observed!

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

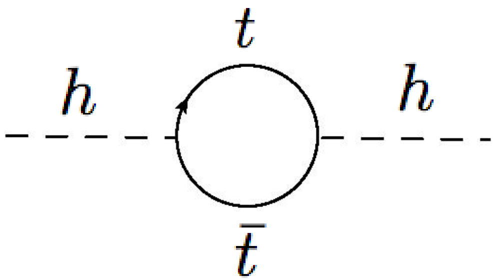
Hierarchy Problem



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

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

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

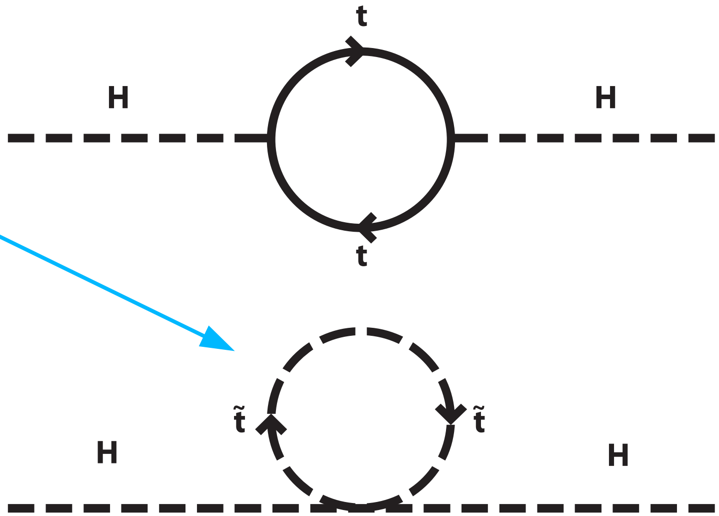


$$+ \cdots$$

- Correction is many orders of magnitude larger!

New Physics solutions to Hierarchy Problem

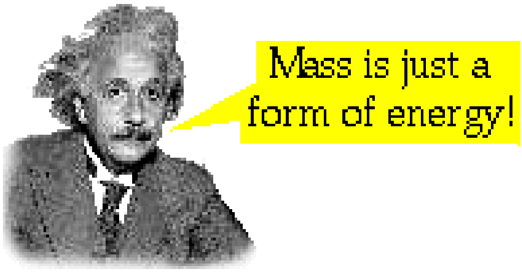
- Supersymmetry (SUSY)
  - add new particles (`super-partners') to cancel terms
  - many SUSY models result in *enhanced top quark production*

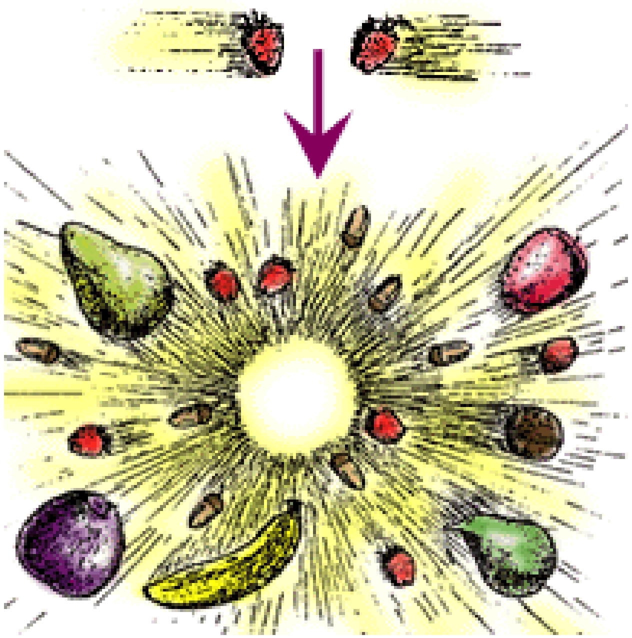


- Strongly Coupled Models:
  - Electro-Weak symmetry broken using a different mechanism
  - technicolor, topcolor, top condensates, extra dimensions (large: Arkani-Hamed, Dimopoulos & Dvali, warped: Randall & Sundrum)
  - *possible new particles (mass ~ TeV) with large coupling to top quarks!*

Collider Physics

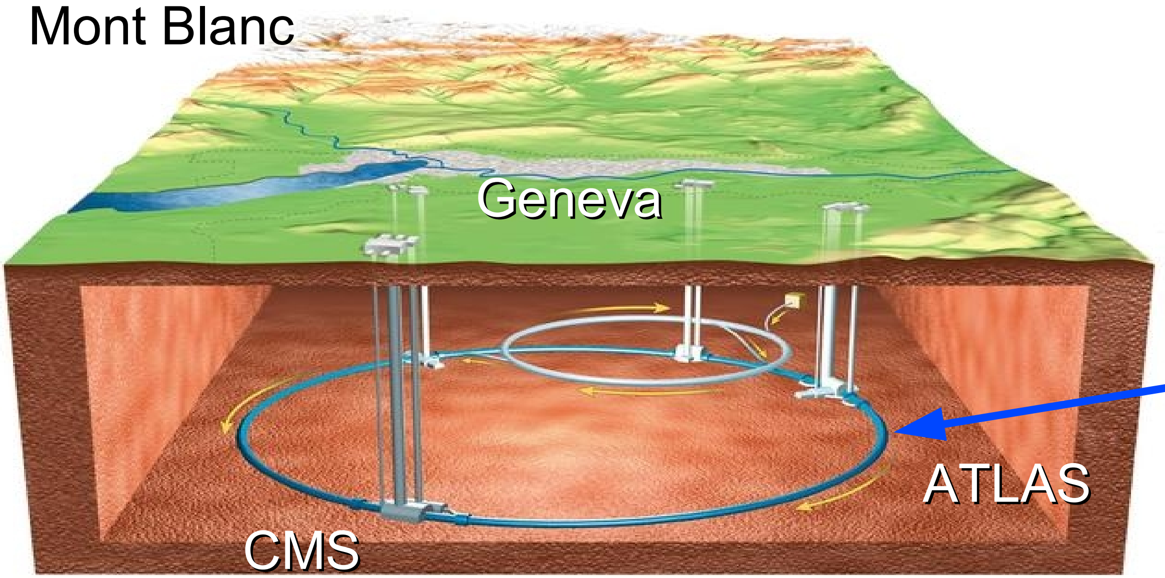
- Plan: smash protons head on and turn their kinetic energy into those heavy particles!

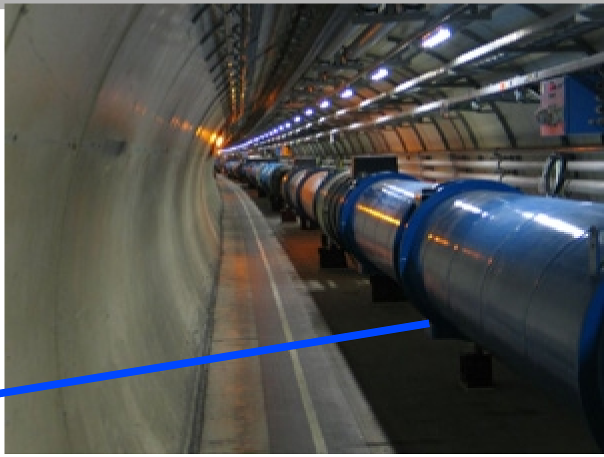


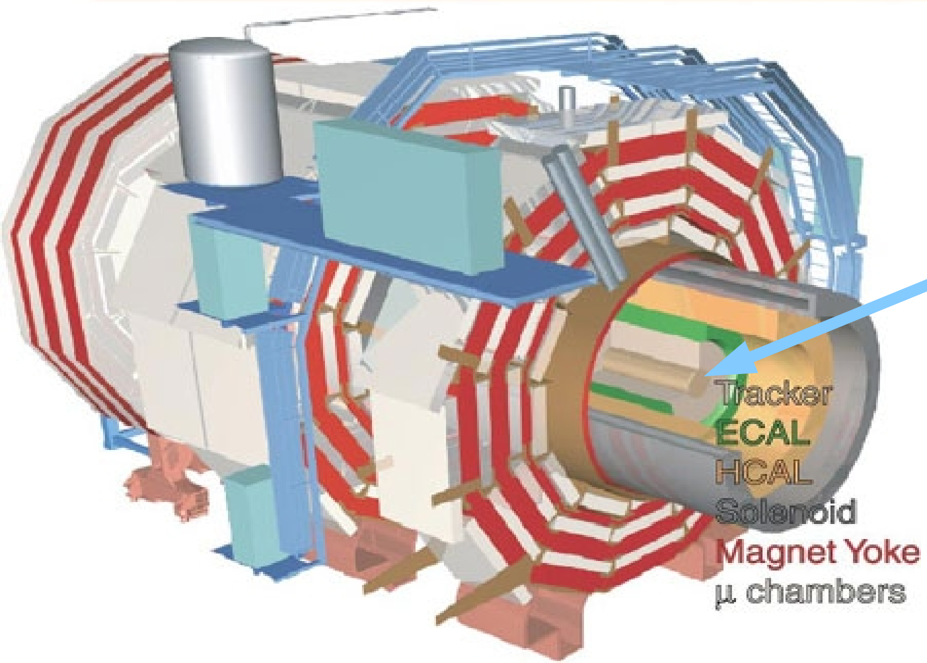


- Very heavy fruits (e.g. watermelons = top quarks) show up with very low probability
- Watermelons (top quarks)
  - appear briefly, but
  - decay immediately to lots of `debris' (other fruits = particles)
- Experimental issues:
  - how to detect this `debris'?
  - which collisions need to be saved for posterity?

LHC and CMS Detector

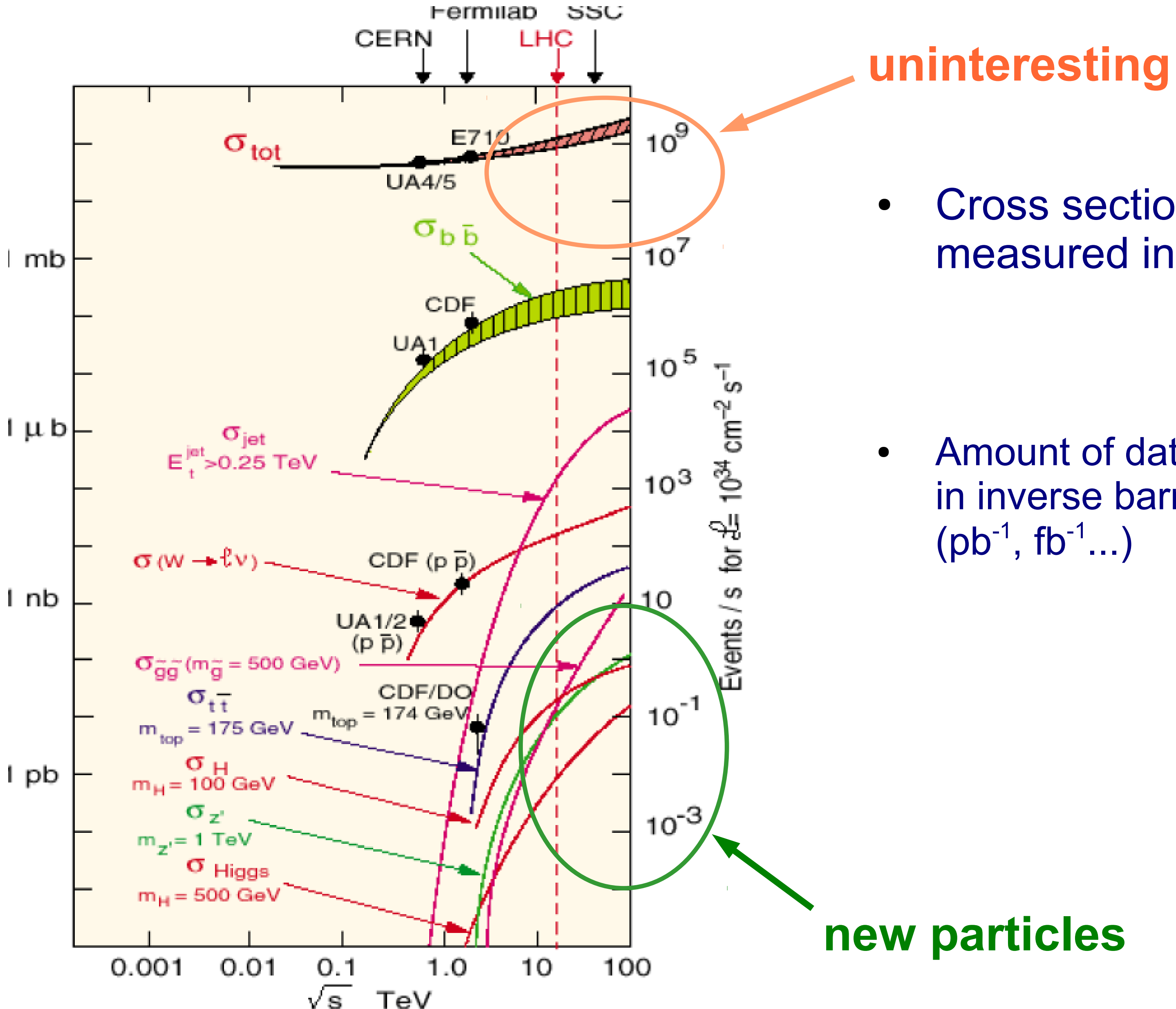






- Five stories tall
- Excellent tracking
  - Pixel detector ~ 66 million channels
- The only problem: it has a lot of material
  - fake electrons from $\gamma \to e^+e^-$

LHC production cross-sections at a glance



- Cross section measured in barns

- 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 will produce particles we want to find

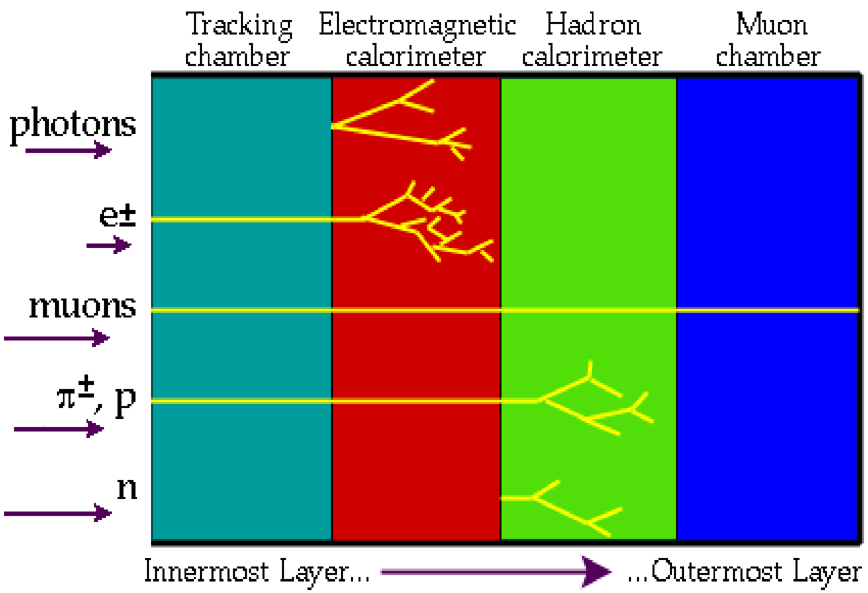
  ==> sample of these collisions is "Signal"
  - many other possibilities, overwhelming majority is *completely unintresting*!

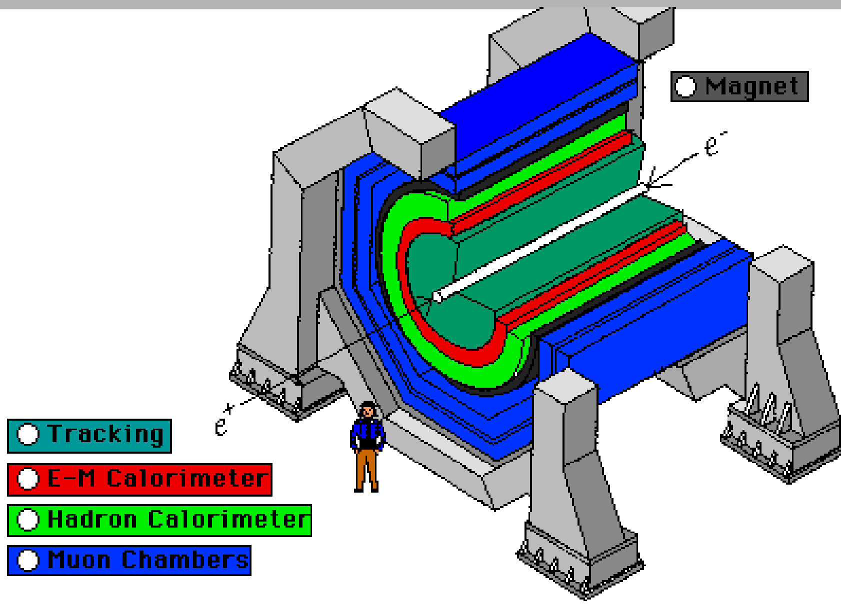
  ==> sample of such collisions is "Background"

- We need to dig these jewels from the mounds of dirt!
- Plan: filter events, maximize $\mathrm{Signal}/\sqrt{\mathrm{Background}}$
- Special for HEP: most of this filtering is done *during* data taking!

The CMS Detector

Collider detectors

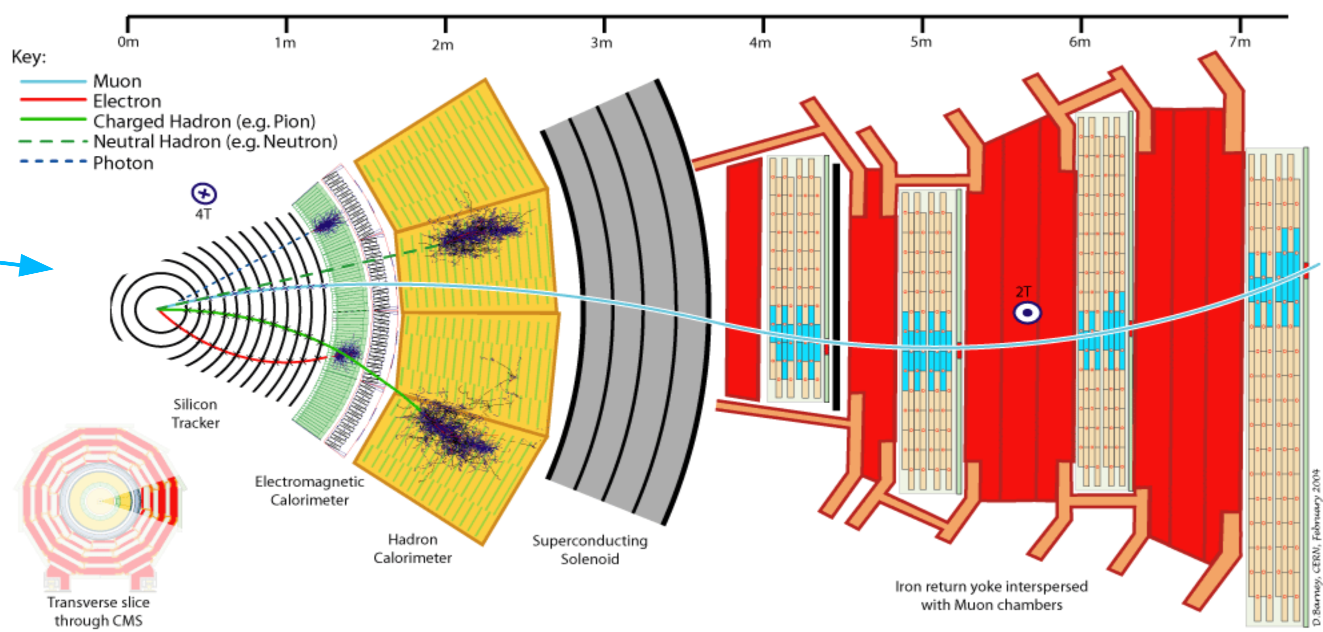




Toy detector

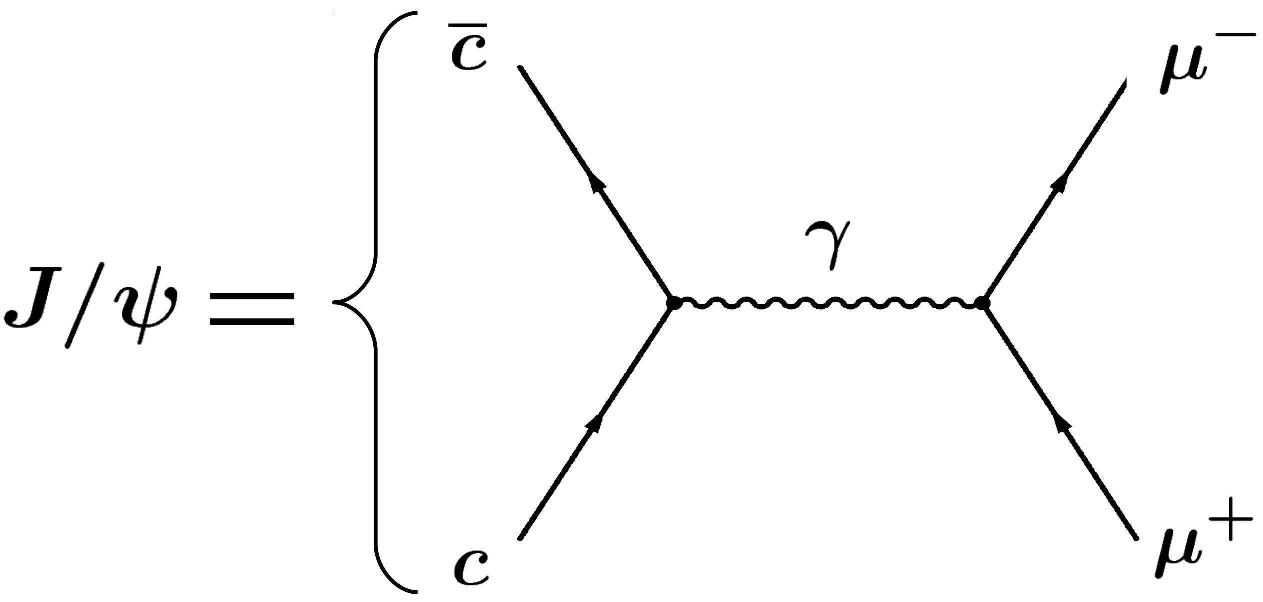
CMS detector

(CDF follows identical principles but it's smaller)



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

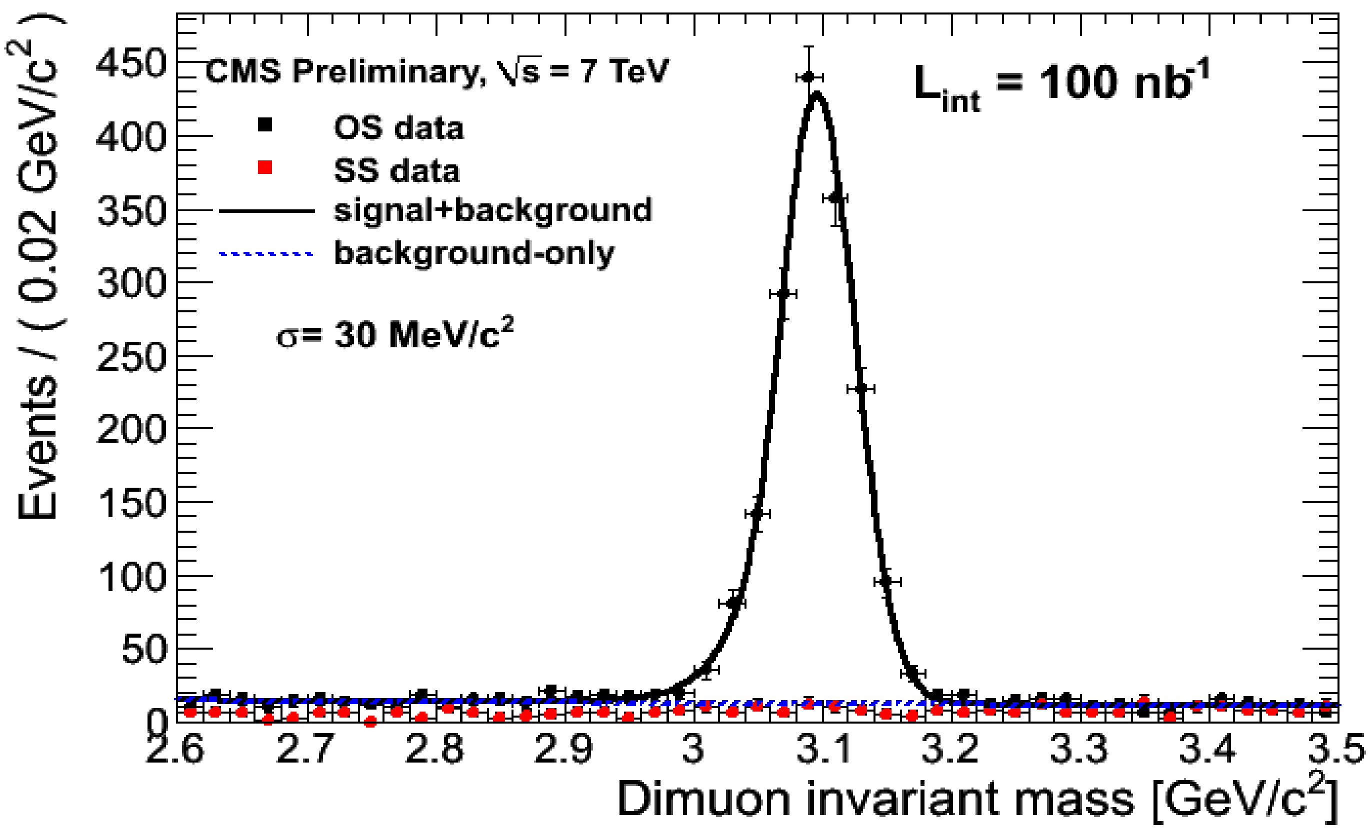
- J/ψ meson is a bound state of $c\bar{c}$
- decays electromagnetically (photon as a force carrier):



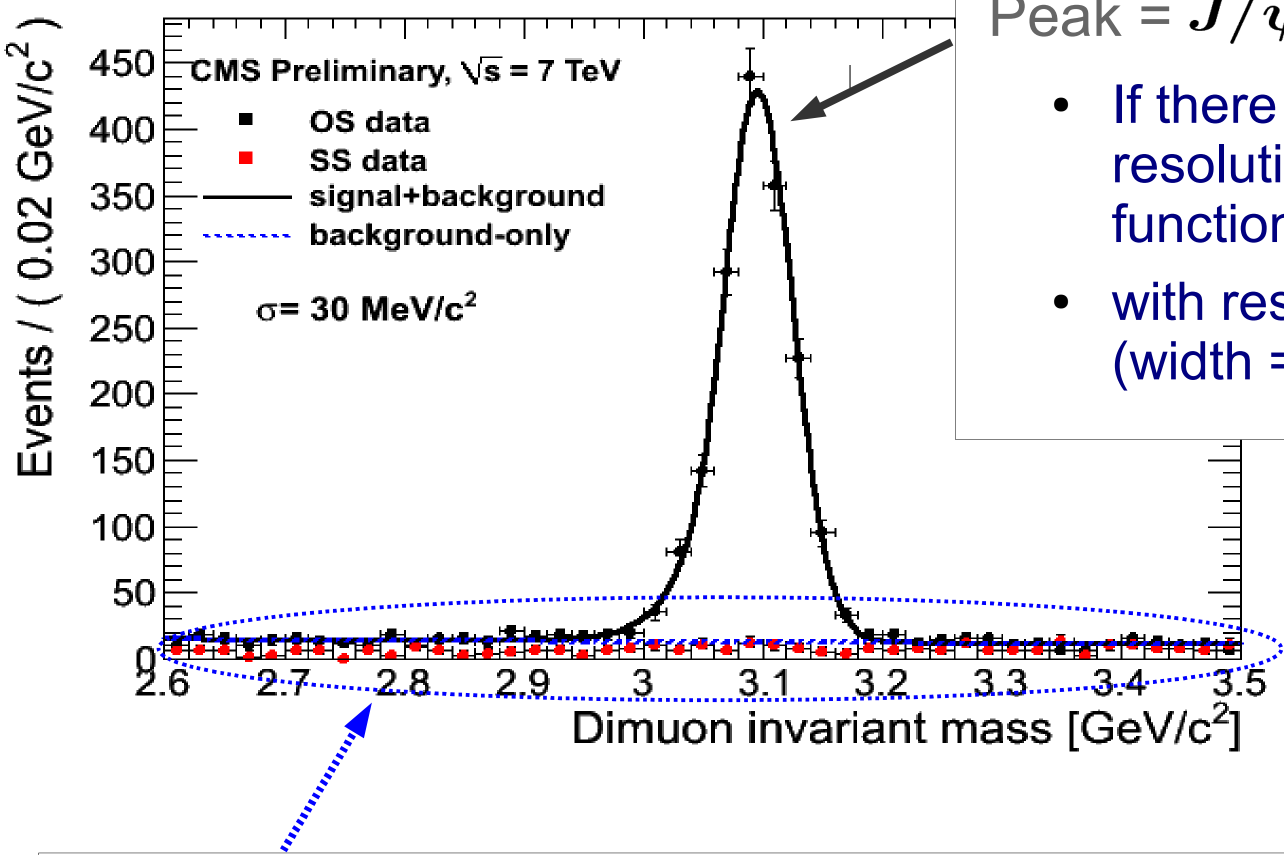
==> rate of this decay is `slow' enough that width is narrow

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: $mc^2 = \sqrt{E^2 - p^2c^2}$



Anatomy of a `mass plot'



Peak = J/ψ itself

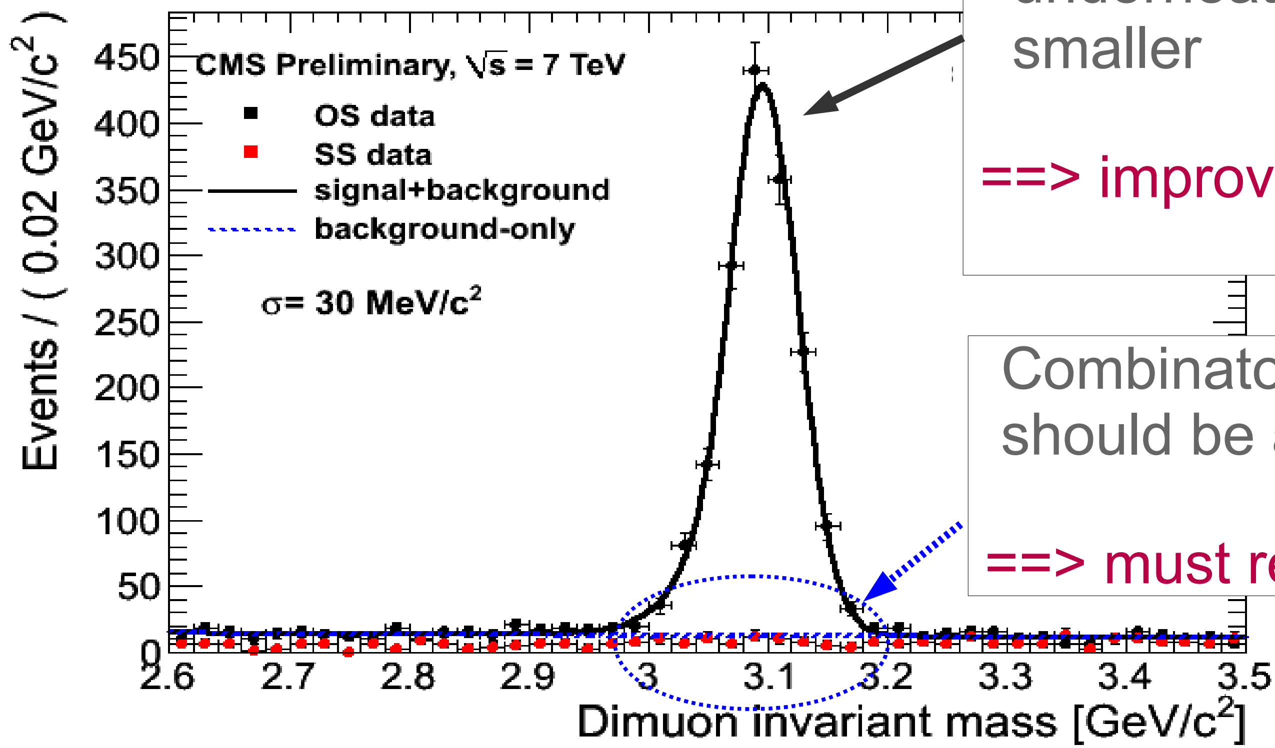
- If there were no detector resolution, it would be delta function (vertical line)
- with resolution, it's a Gaussian (width = resolution)

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

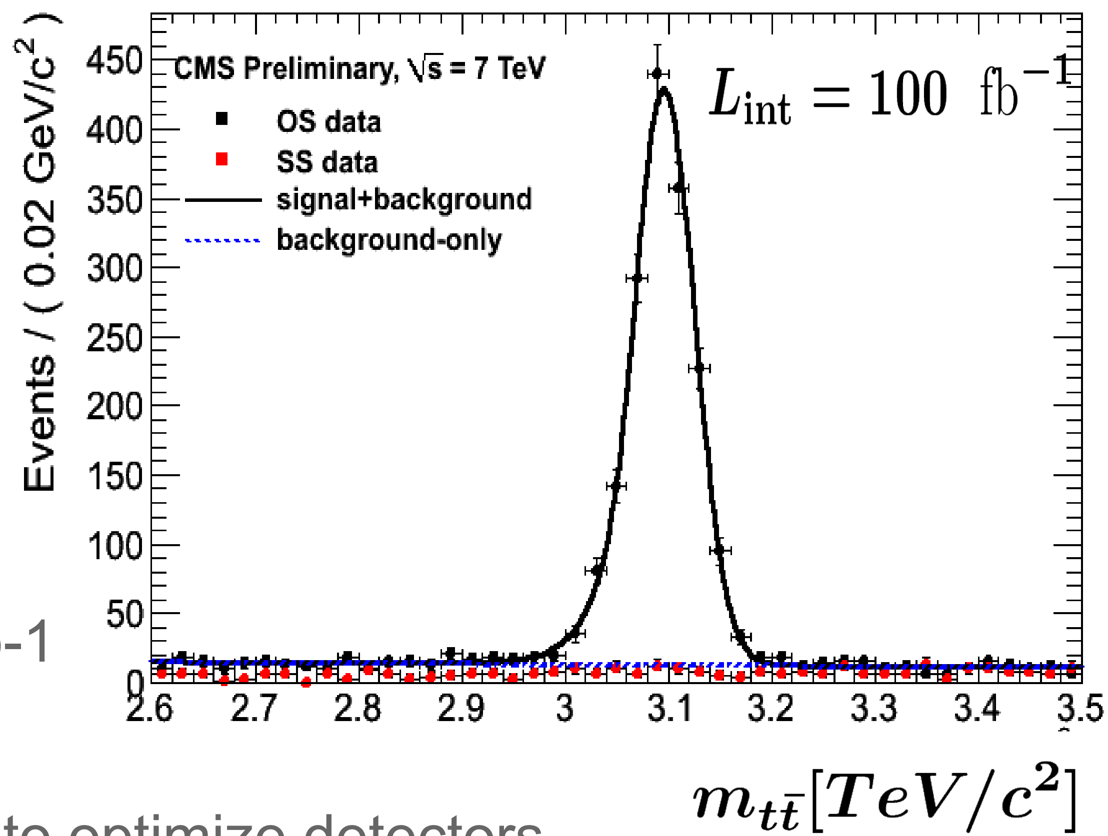
==> improve detector resolution

Combinatorial background: should be as low as possible

==> must reduce fake rate

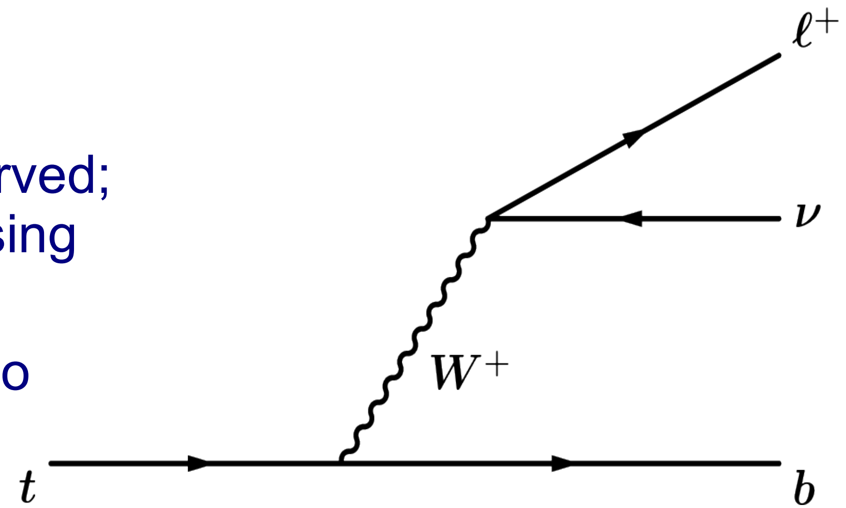
Digression #3: bump hunting

- Hypothetical scenario:



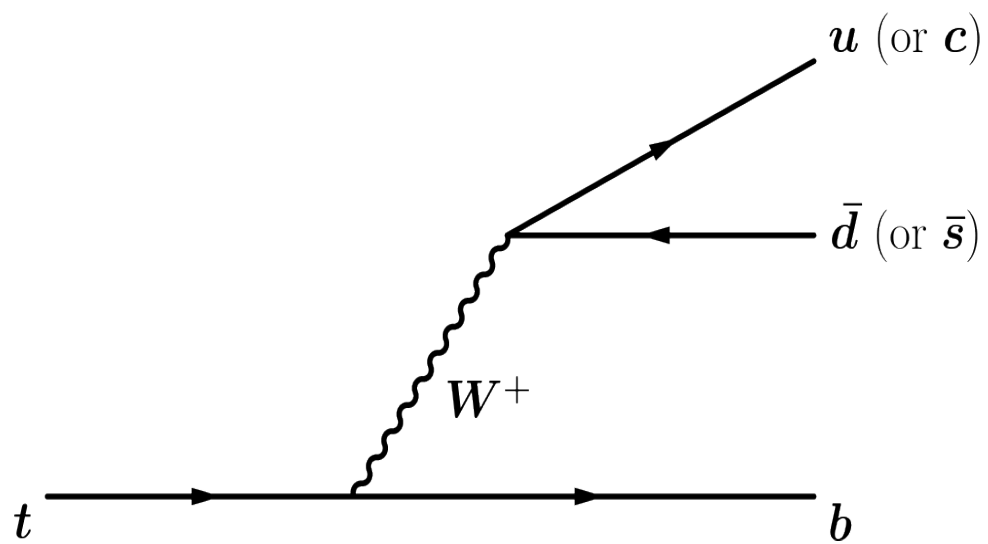
- Say, a 3.1 TeV resonance, after 100 fb-1 of data
- Logic is identical: want to optimize detectors so that the peaks ("bumps") are narrow, on small background.
- This is **"bump hunting"** – the easiest way to find new physics

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

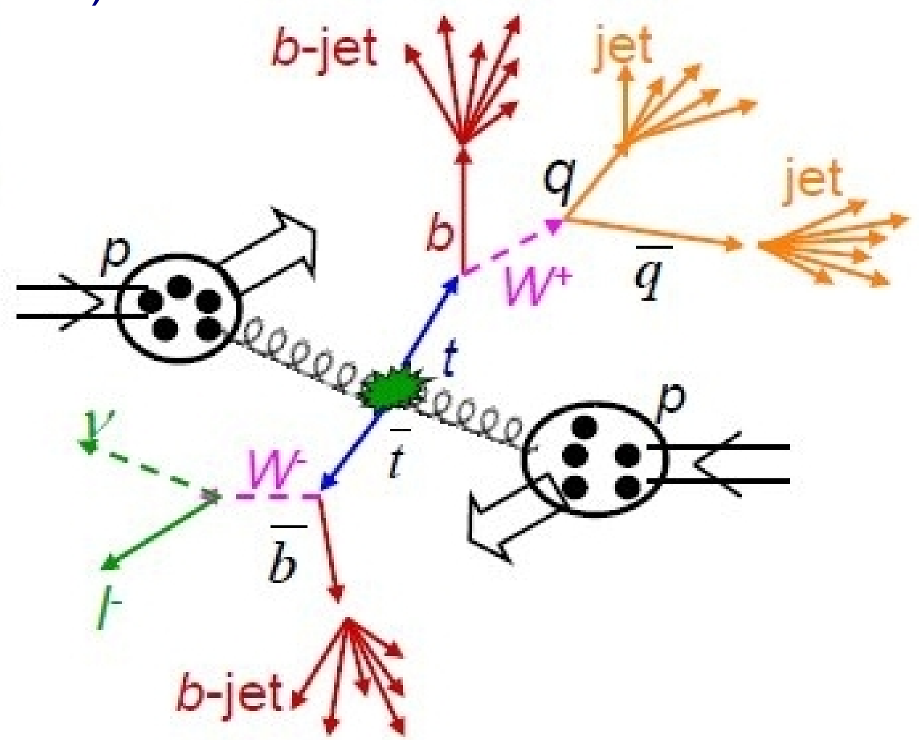


"Hadronic" decay:

- 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)

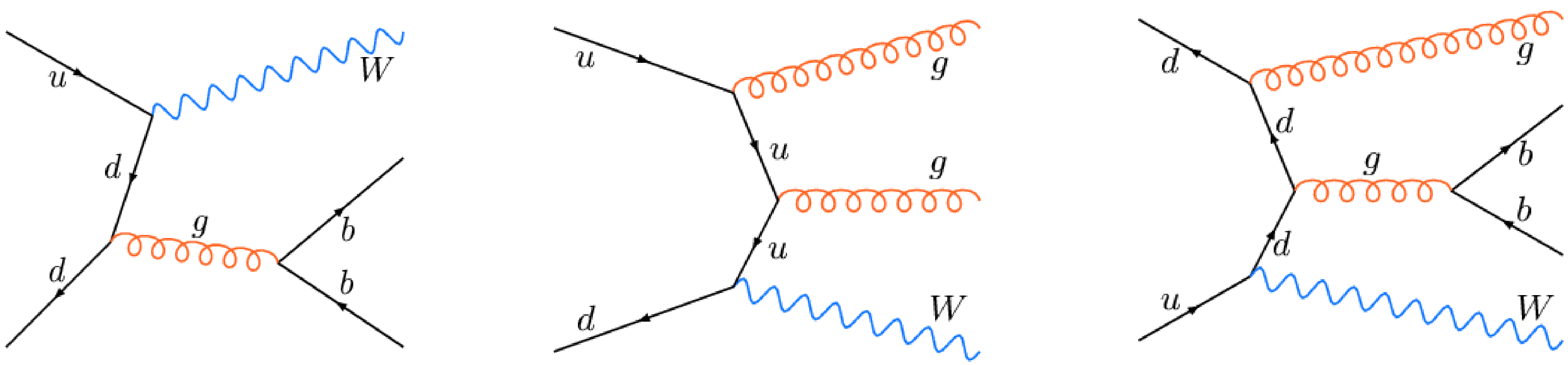


- Most other analyses built from same building blocks!

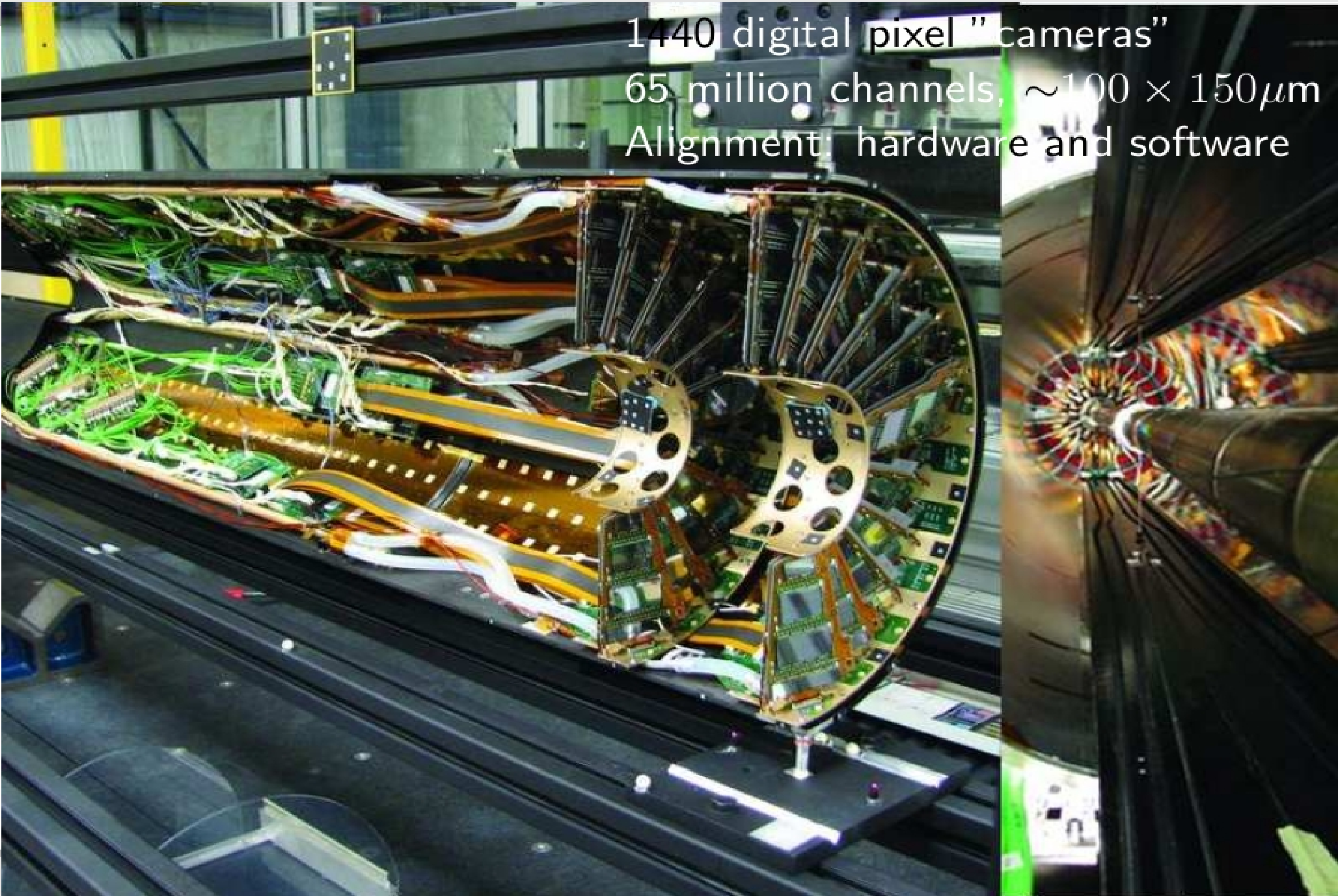
  ==> $t\bar{t}$ events are a perfect tool for physics commissioning!

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 → **Background**
  - seek to maximize $\mathrm{Signal}/\sqrt{\mathrm{Background}}$
  - *must also know how much Background we have left-over*!



The Silicon Pixel Detector



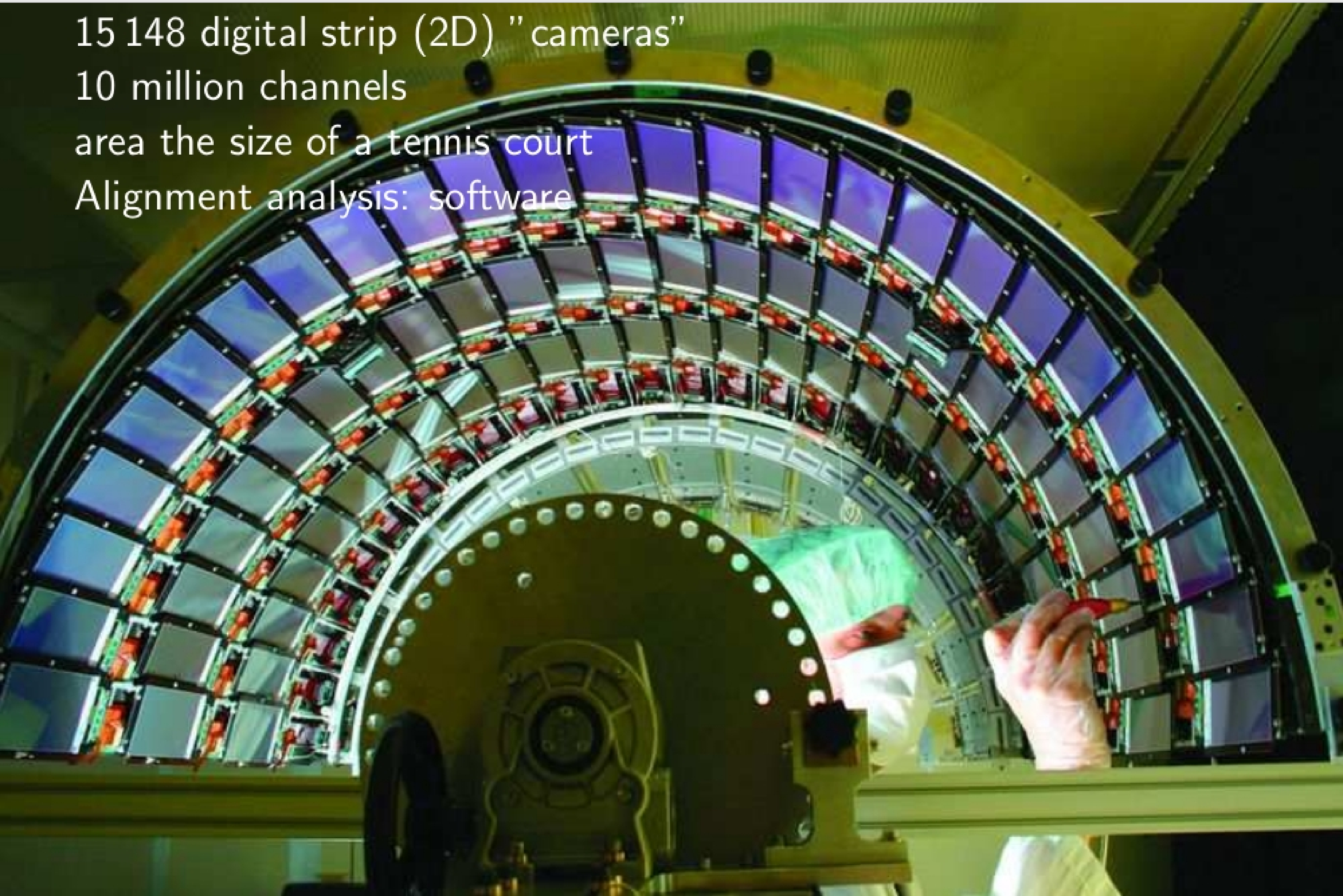
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"

10 million channels

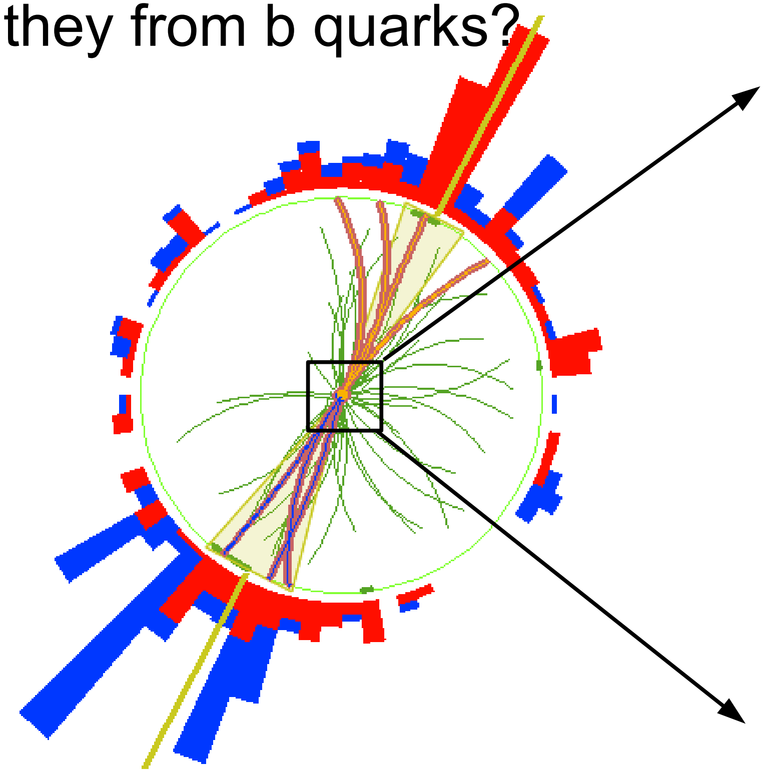
area the size of a tennis court

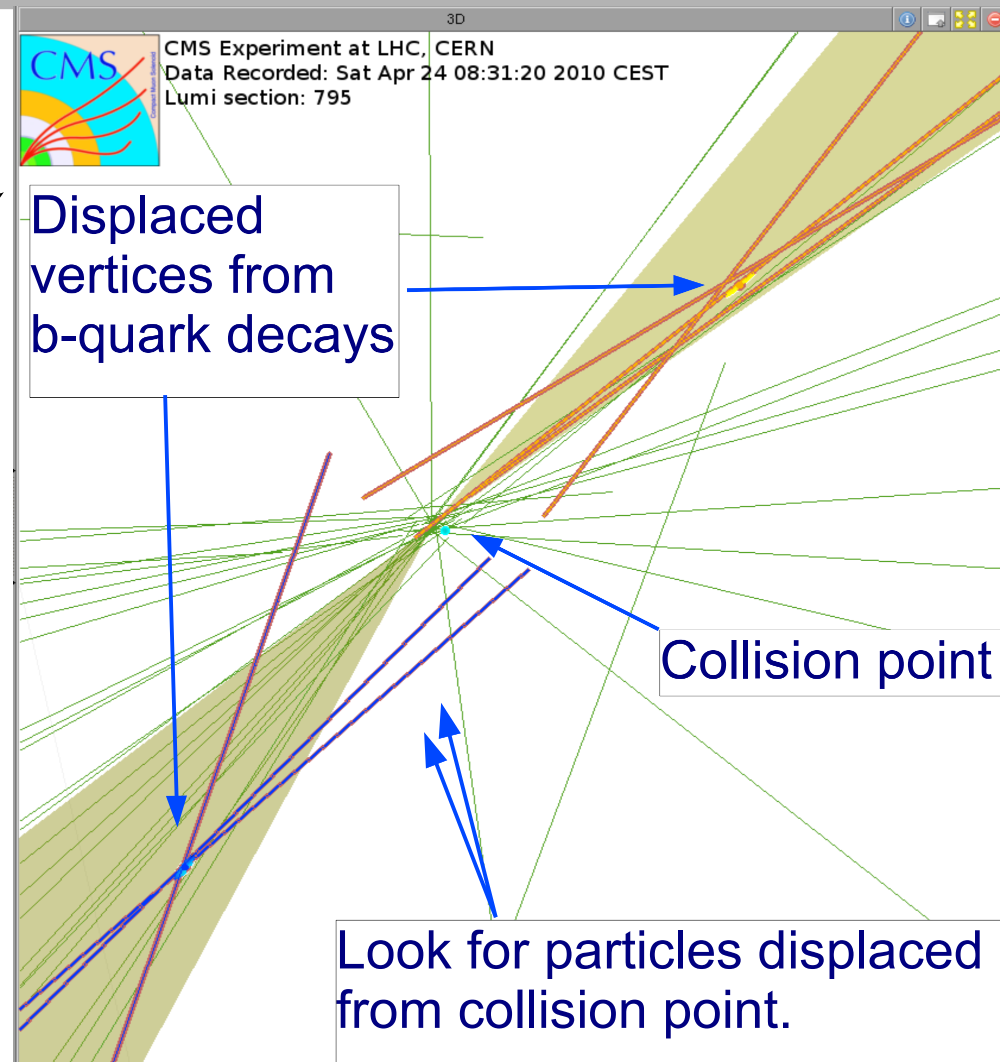
Alignment analysis: software



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

Event with two jets:
are they from b quarks?





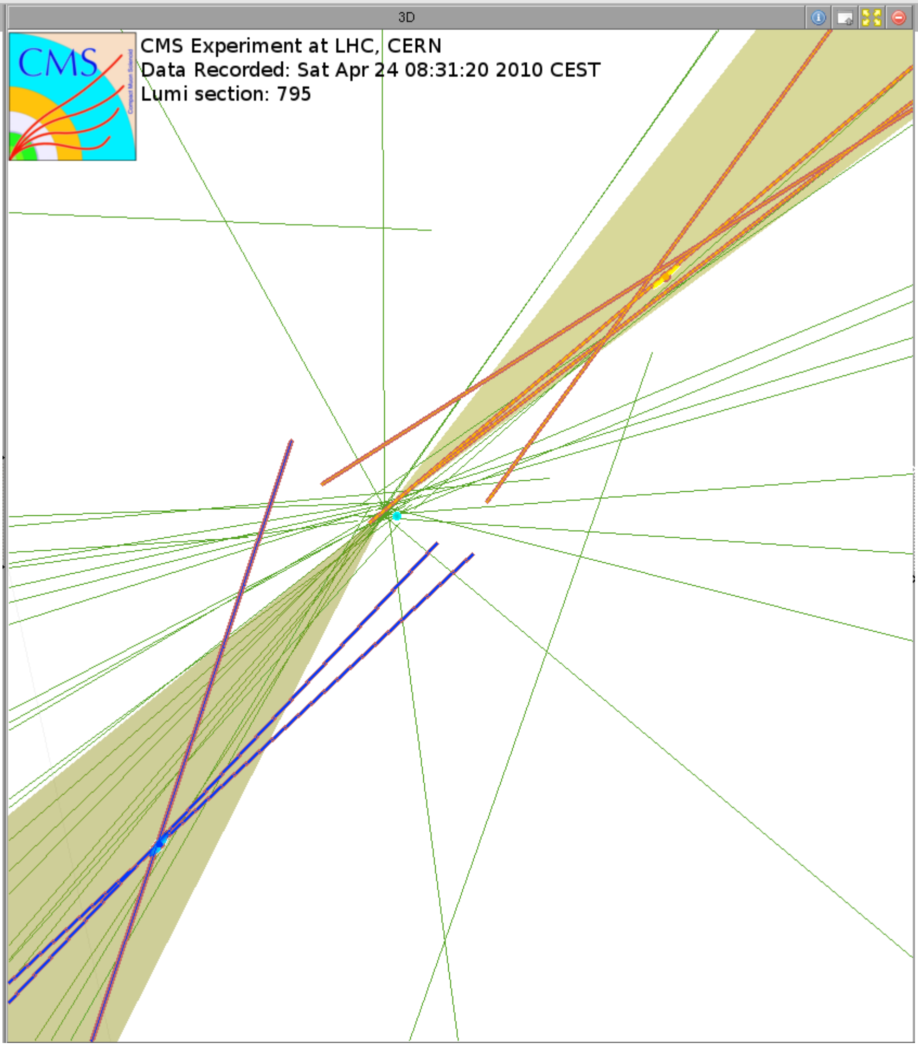
Displaced vertices from b-quark decays

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: where we are now

- LHC physics program has only started!
- Already collected ~ 20 fb-1 of data at 8 TeV.
- CMS and ATLAS detector performance is excellent
- All the physics objects are in good shape
  - including top-jets, W/Z-jets, Higgs-jets...
- Finishing re-discovery of the Standard Model
  - found the Higgs boson! :)
  - no sight of Beyond SM physics jet :(
- Looking forward to LHC running at 13 TeV in 2015!
  - plug the holes in searches
  - get ready for the onslaught of new data

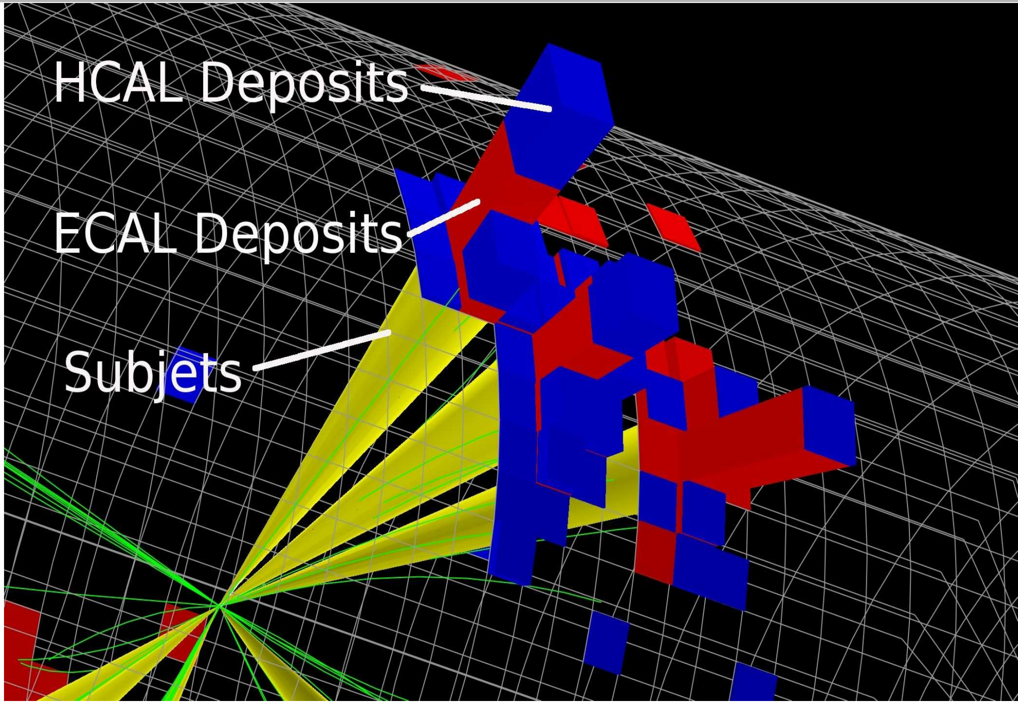
BACKUP

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

e+Jets candidate event on July 18

Event passes all cuts:

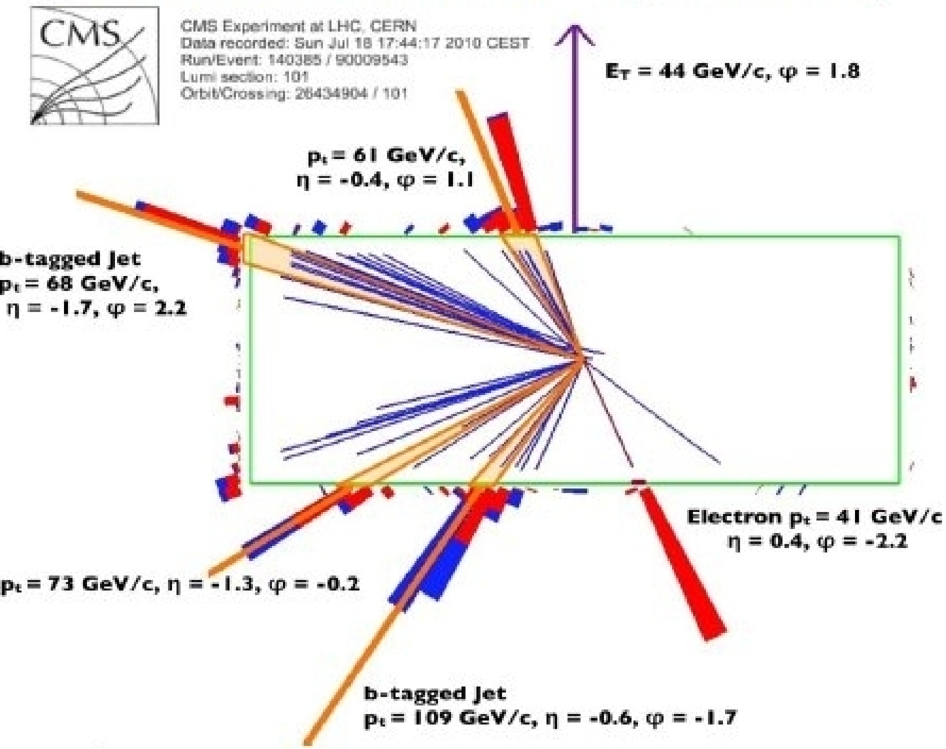
1 high-momentum electron

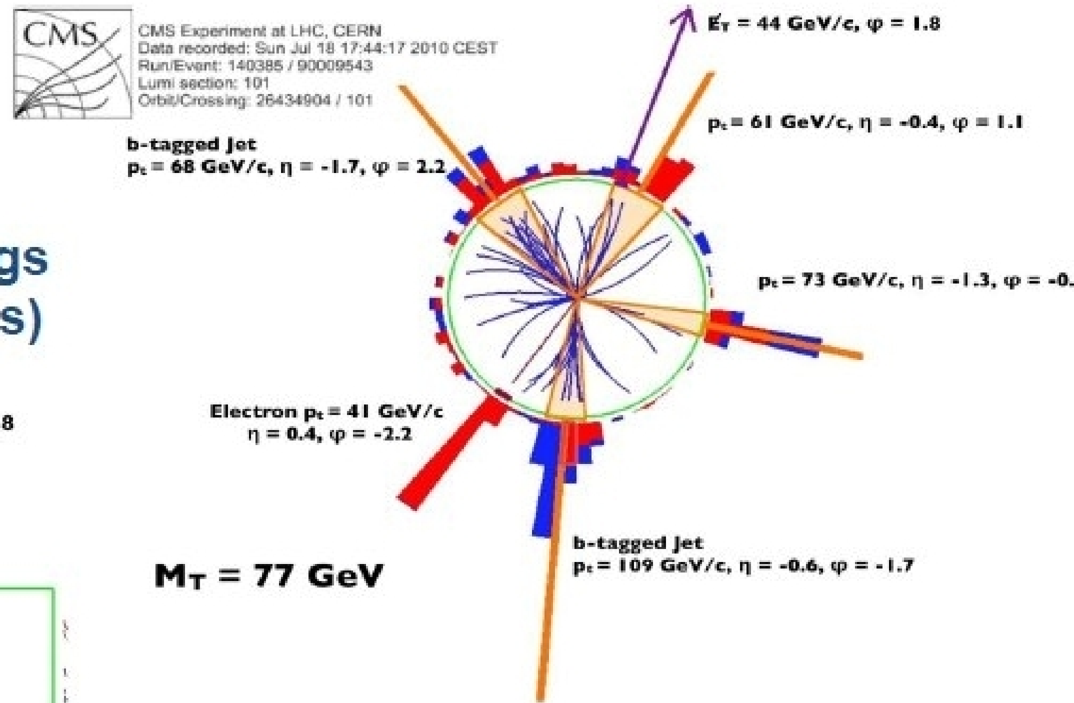
significant MET ≈ 44 GeV

4 high-p_T jets,

two of which with good/clear *b*-tags

(with reconstructed 2nd ary vertices)





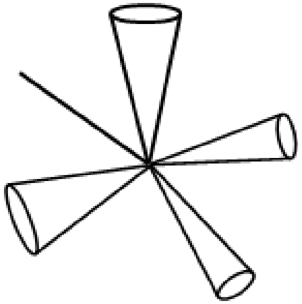
$m_T(W) \approx 77$ GeV/c^2

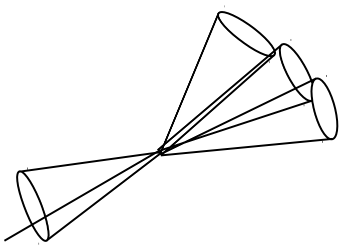
Mass of 2 untagged jets ≈ 102 GeV/c^2

m(jjj) ≈ 208, 232 GeV/c^2
(for the two 3-jet combinations)

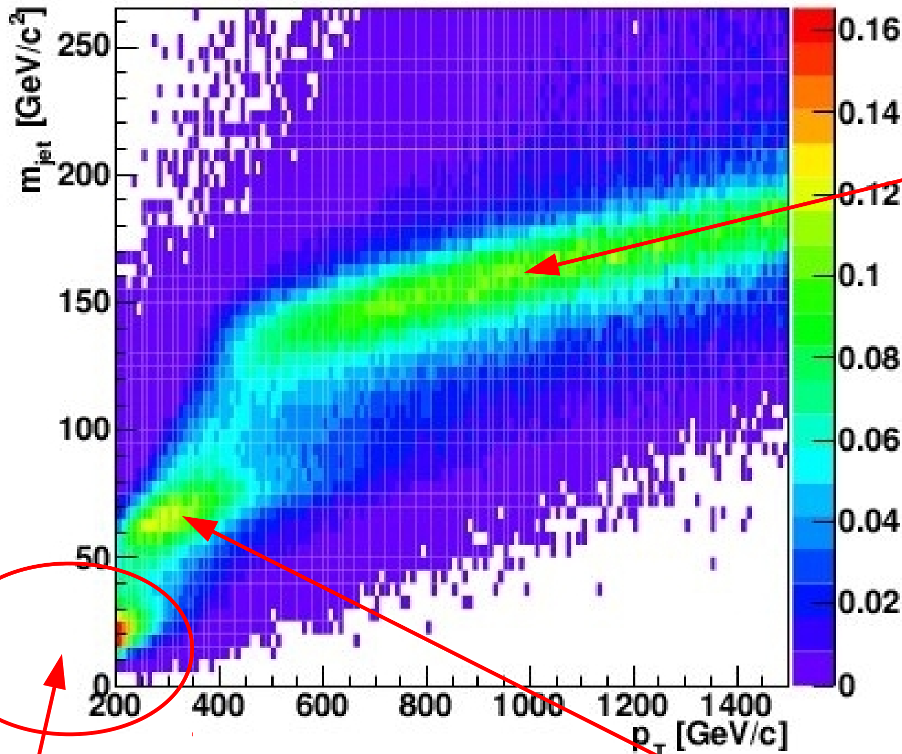
CMS: Searches for top pair resonances

- Look at invariant mass distribution of two top quarks, $m_{t\bar{t}}$
- New particles $X \rightarrow t\bar{t}$ would be **peaks** on Standard Model background
- Before us, CMS looked at events with leptonically decaying W boson
  - "Low mass": isotropic events like top cross section measurement
  - "High mass": energetic lepton + jet recoiling against another jet



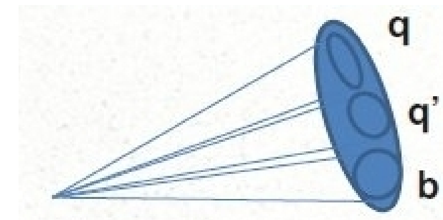


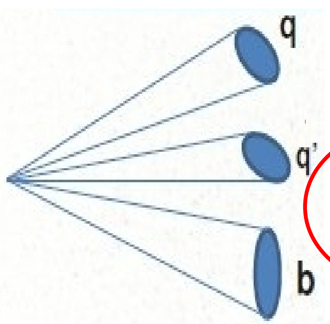
Three kinematic regions



High mass regime:

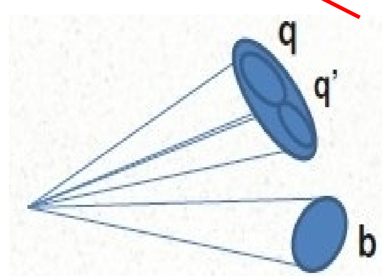
- fully merged
- JHU "Top-tagging"





Low mass regime:

- unmerged
- similar to top cross-section

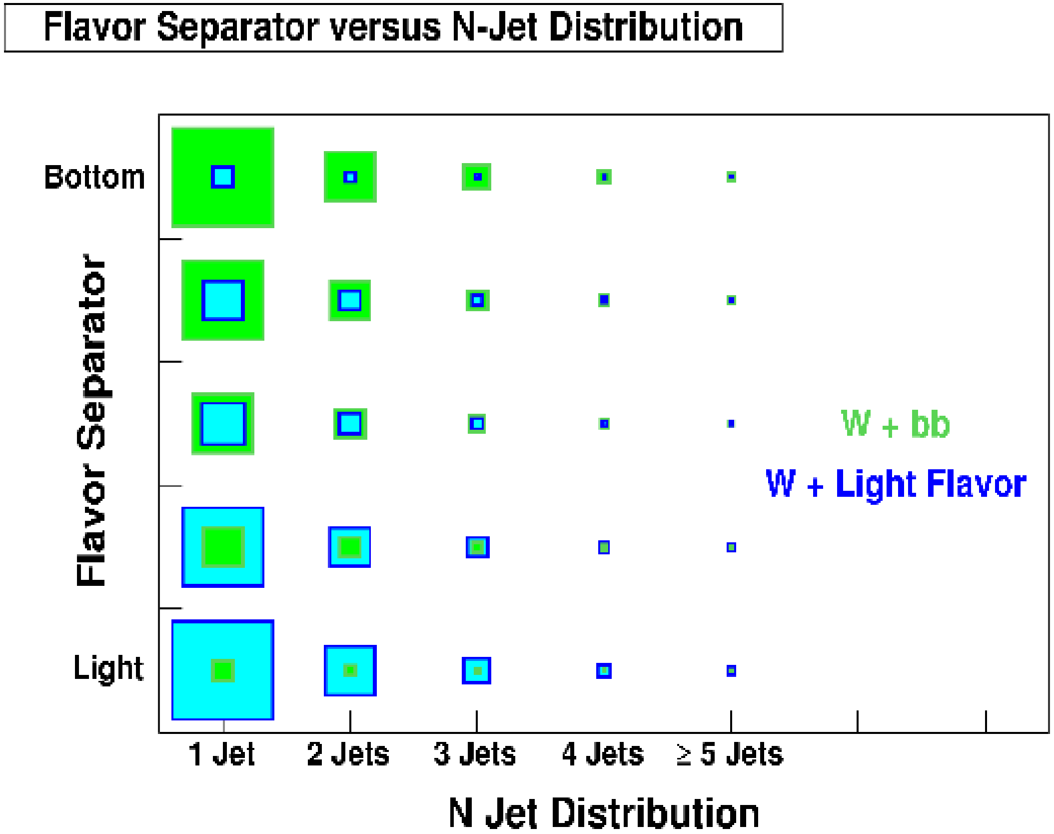


"Medium mass" regime:

- partially merged
- *topic of recent work*

Discriminating variables (2)

- top has 2 b-jets, use b-tagging
- combine various information into "flavor separator" (a neural net)
  - separates b-jets from c-jets from light flavor jets (u,d,s, or gluon)
  - uses mass of secondary vertex
- also use number of jets in the event
- flavor separator is different for W+bottom and W+light flavor jets



Data flow from detector to analysis

- We will be flooded with data – access to data is a **big** issue
- Must optimize: filter events into smaller and smaller data samples, so that you 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)

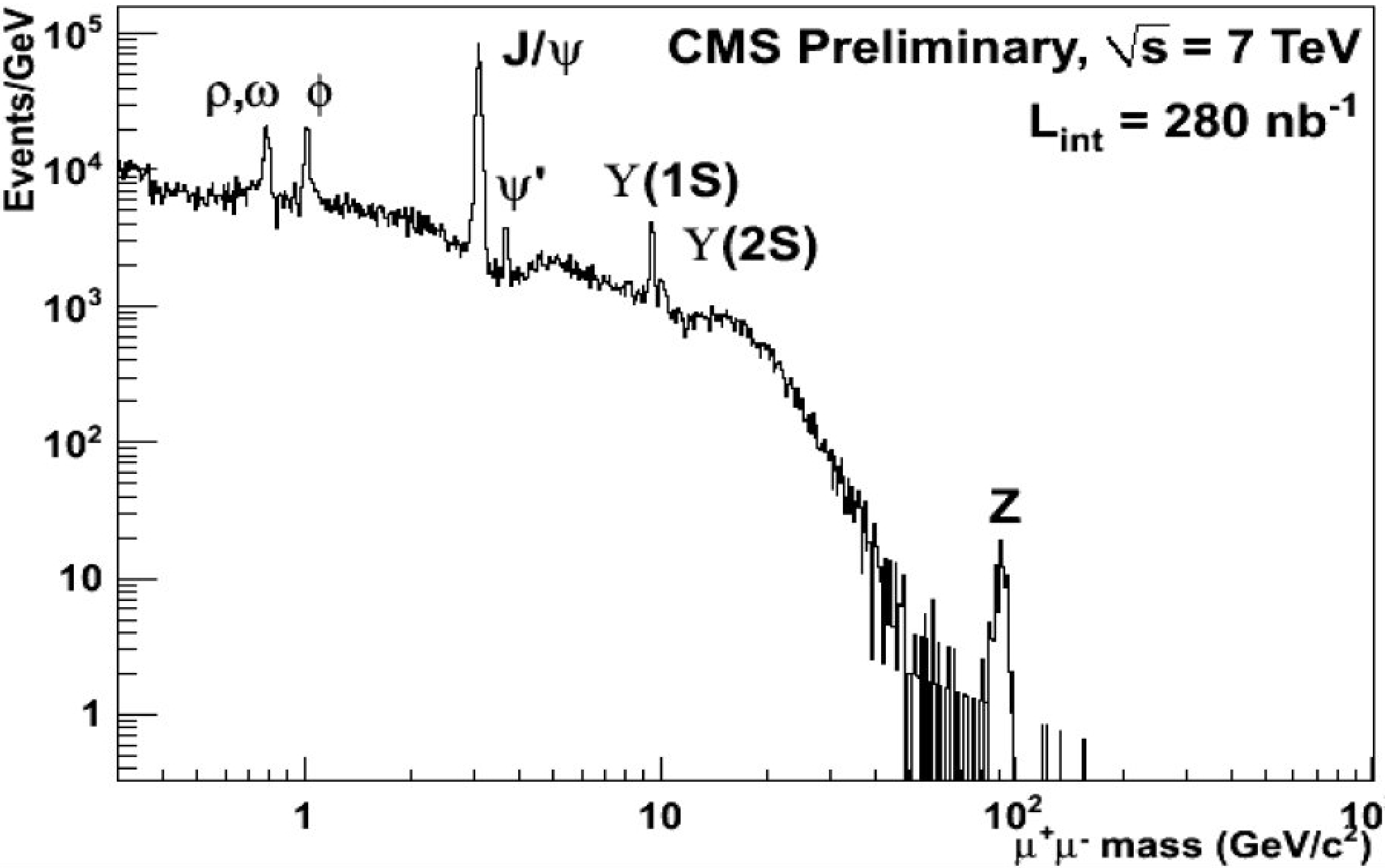
Secondary Dataset

Group Skim
(e.g. Higgs group)

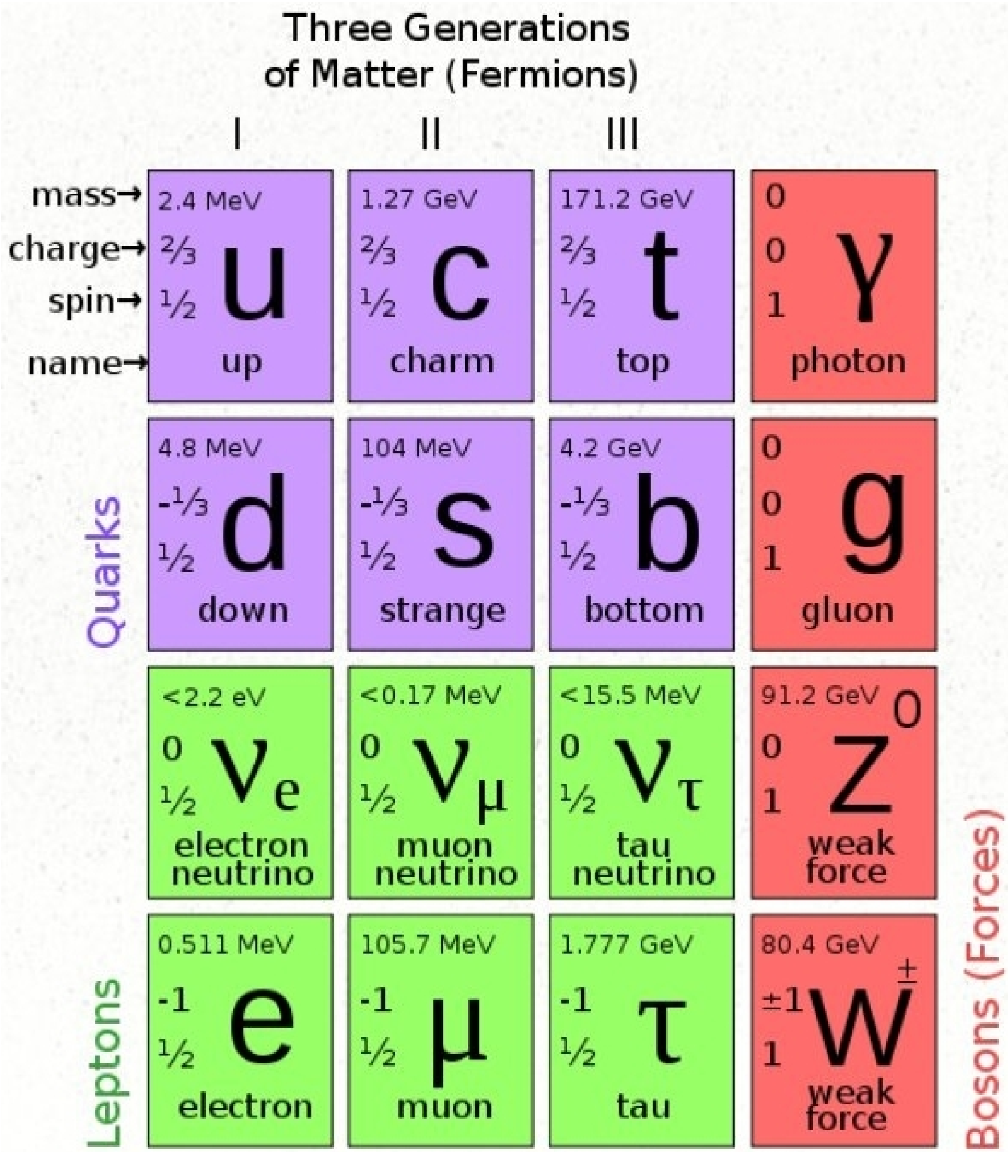
Final Sample
(interactive analysis)

(Also need to drop unneeded parts of each event – *slimming*, *thinning*)

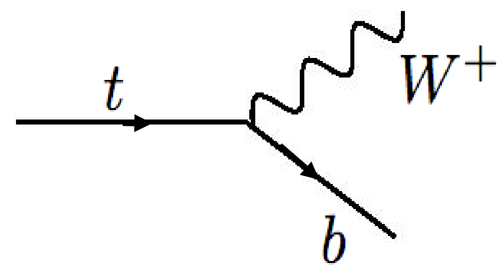
Two-muon resonances



Standard Model at a glance



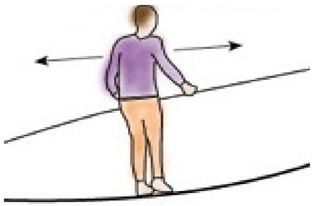
- fermions form matter
  - three families
- bosons carry interactions
- W couples within and across families



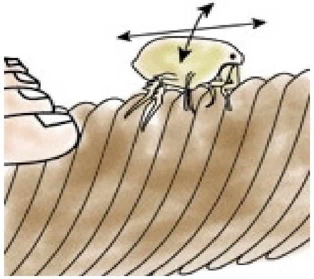
- however:
  - no Gravity
  - no Higgs yet

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*!)

Reconstructing events with two top quarks

- SM production of $t\bar{t}$, or from beyond-SM, *e.g.*, $X \rightarrow t\bar{t}$
- Depending on how W decays, there are three main options:
  - "dileptons":
    - two leptons (e or mu), two neutrinos, two b-jets
  - "lepton+jets":
    - one lepton (e or mu) + two b-jets + two W daughter jets (4 jets in total)
  - "all hadronic":
    - 2 b-jets + 4 W daughter jets