Search for an Excited Bottom Quark (b*)

GBO Presentation
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10/24/18

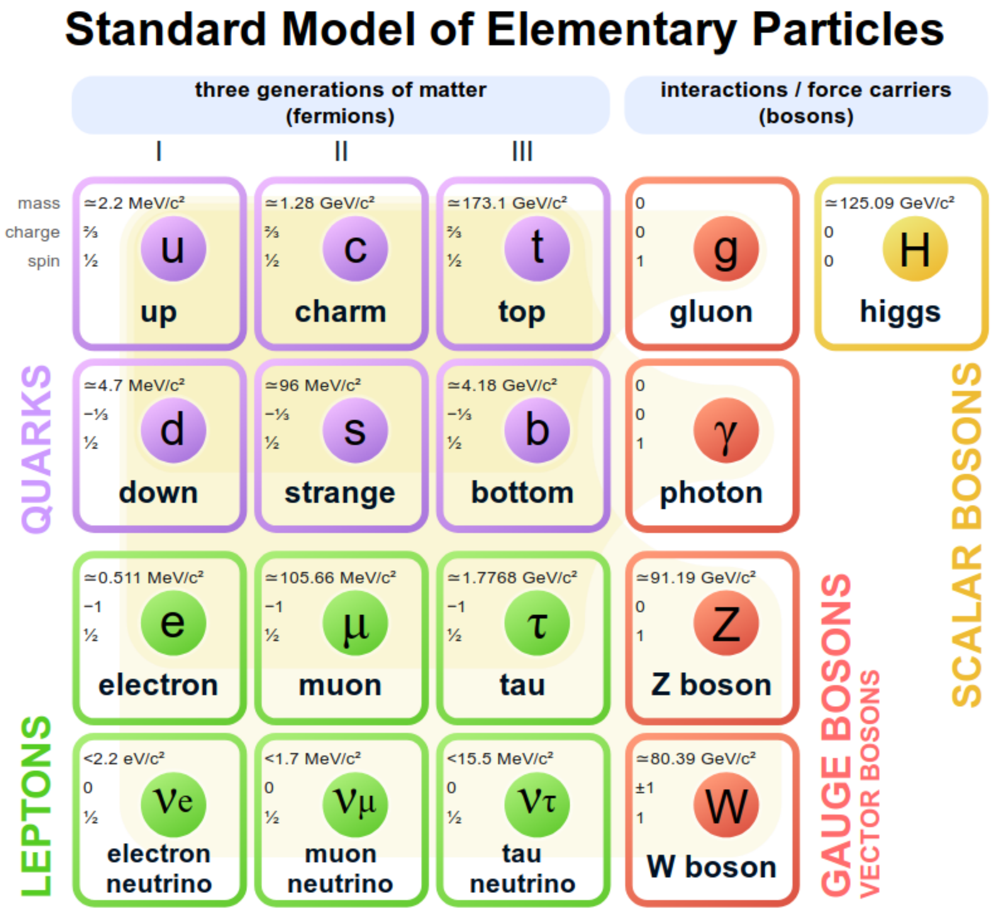
A Review of the Standard Model

- A quantum theory for 3 out of 4 forces and the particles that interact with them
- In excellent agreement with experiments

Does not explain everything!

- Dark Matter/Energy
- The Hierarchy Problem
- Matter/antimatter asymmetry

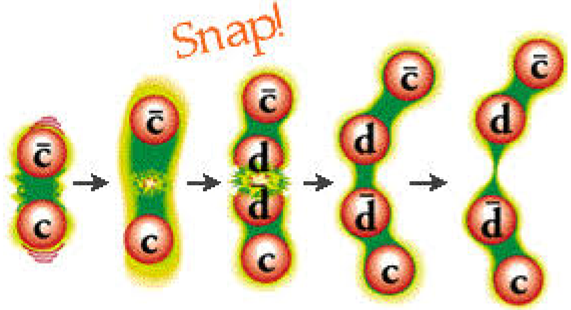
Gives motivation for Beyond Standard Model (BSM) physics!



https://en.wikipedia.org/wiki/Standard_Model

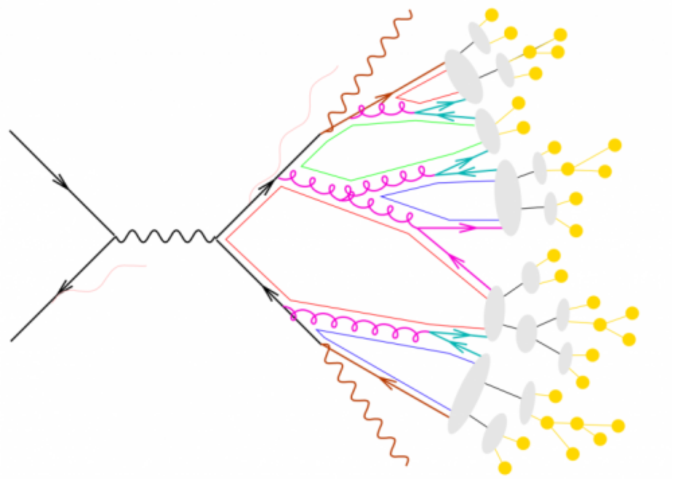
Hadronic Decays

- *Hadrons* are particles made up of quarks and gluons
  - Quarks exist in color neutral groups of 2 or 3
- Splitting hadrons results in creating more quarks
  - Strong force increases with distance
  - Energy to break strong force bond → new quarks
- Searching for an *all-hadronic* decay
  - *Hadronization* - hadrons keep splitting and forming new color neutral groupings



The Role of Hadronization

- Hadronization results in particle showers
  - Can be clustered into objects called *jets*
- At high momentum, smaller jets *merge* into *fat jets*
  - Sub-jets are identifiable and can be used to differentiate uniformly distributed fat jets with *pronged* fat jets



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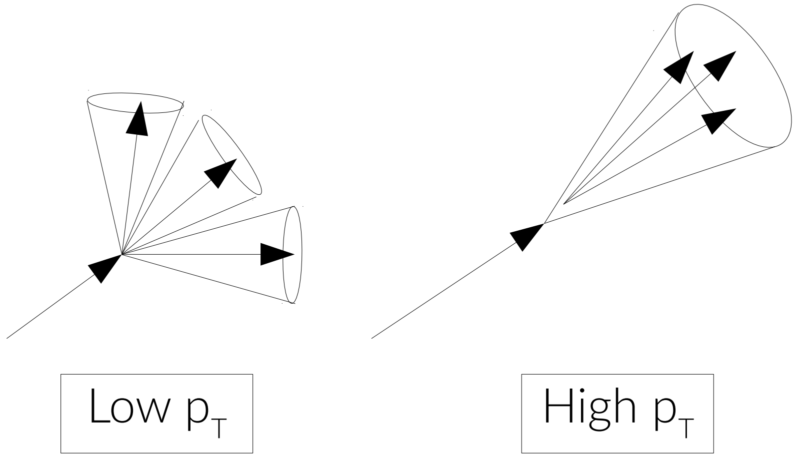


What Does an Analysis/Search Do?

Revisit the Rutherford Gold Foil experiment

- Measured number of events as a function of angle
- Observed discrepancy with expectation

Modern particle experimentalists do the same thing!

- Count events as a function of variables
- Compare binned distributions
- Difference is in the size of the phase space

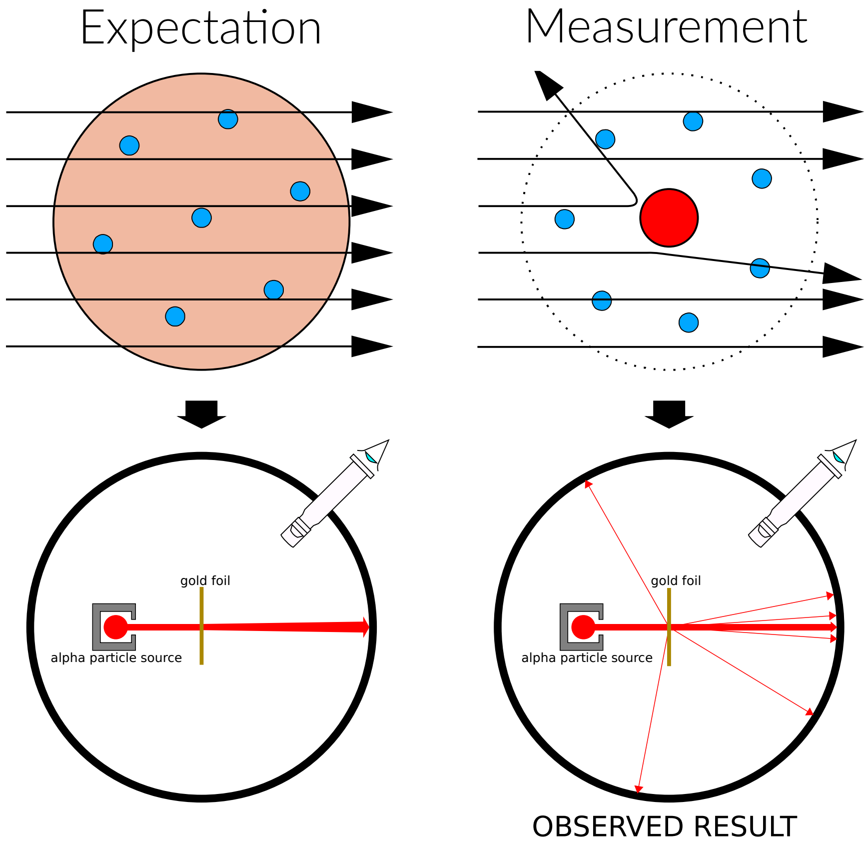
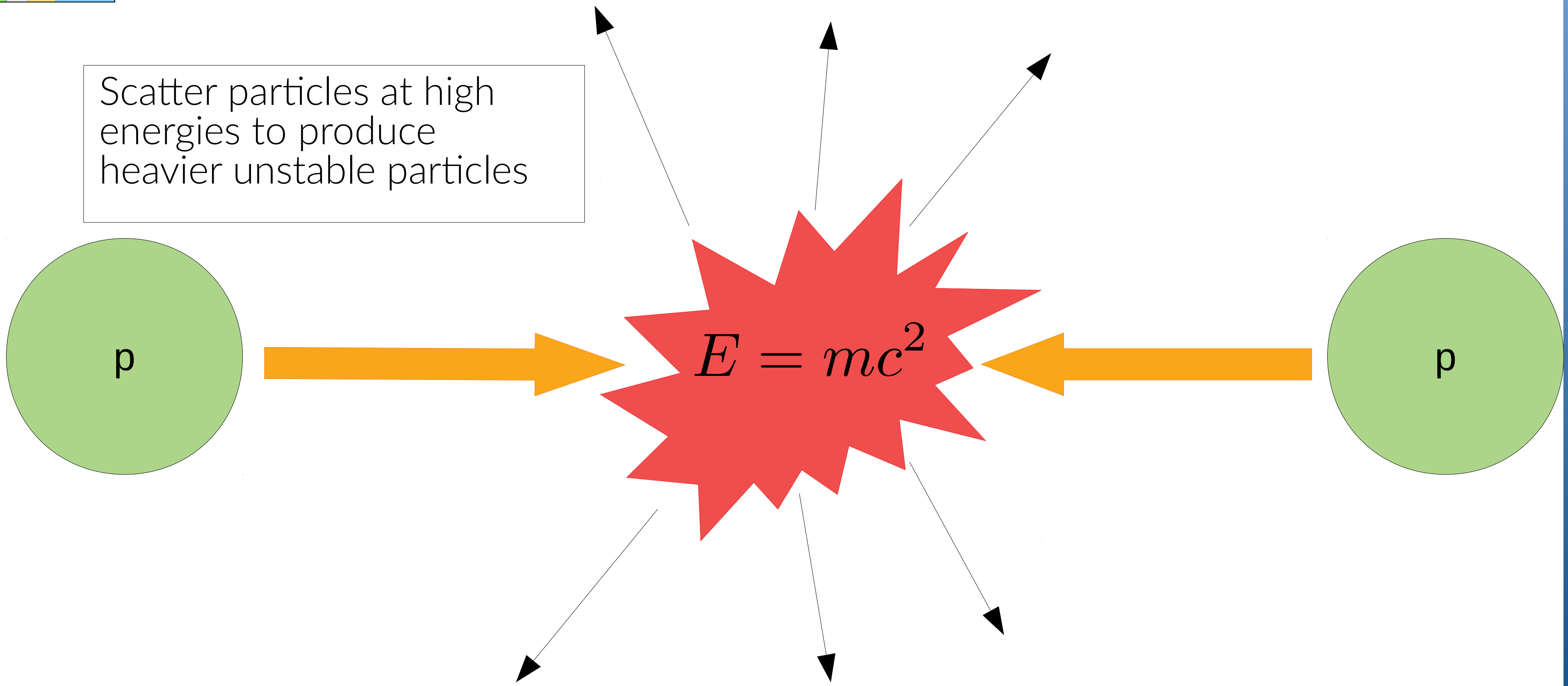


Image from https://en.wikipedia.org/wiki/Geiger%E2%80%93Marsden_experiment

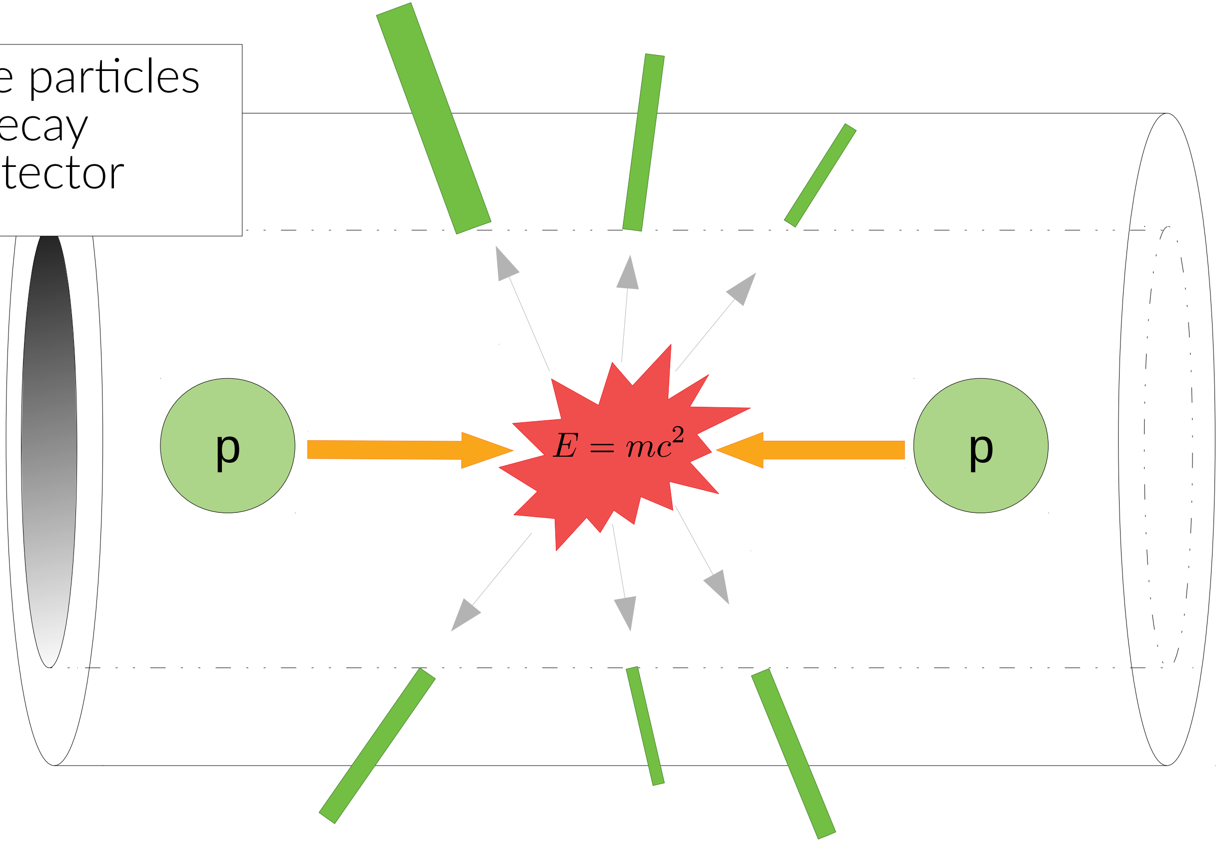
How can we find BSM physics?

Scatter particles at high energies to produce heavier unstable particles



How can we find BSM physics?

Detect unstable particles by examining decay products via detector

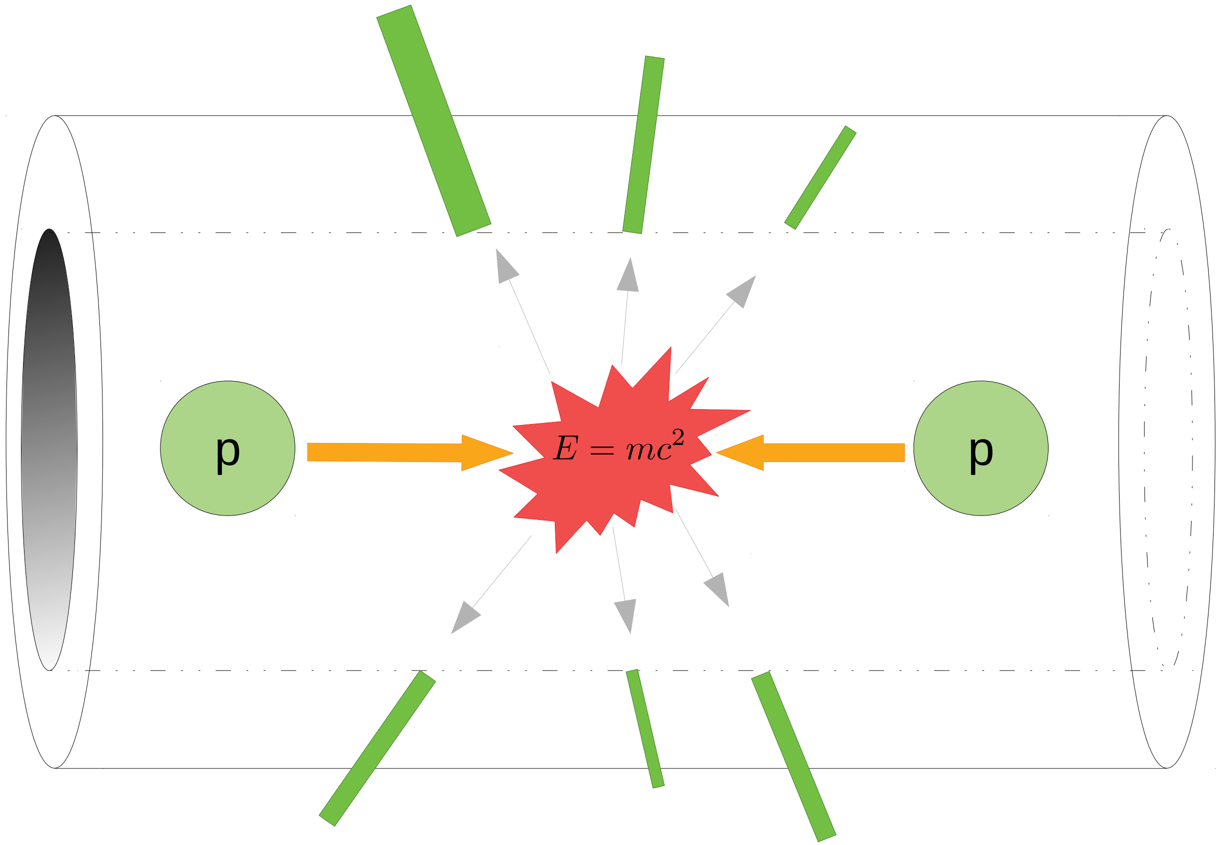


The Large Hadron Collider (LHC)

Collides bunches of protons every 25 ns
- Center of mass energy 13 TeV

- 26 kilometers long
- 150 meters underground

The Compact Muon Solenoid (CMS)



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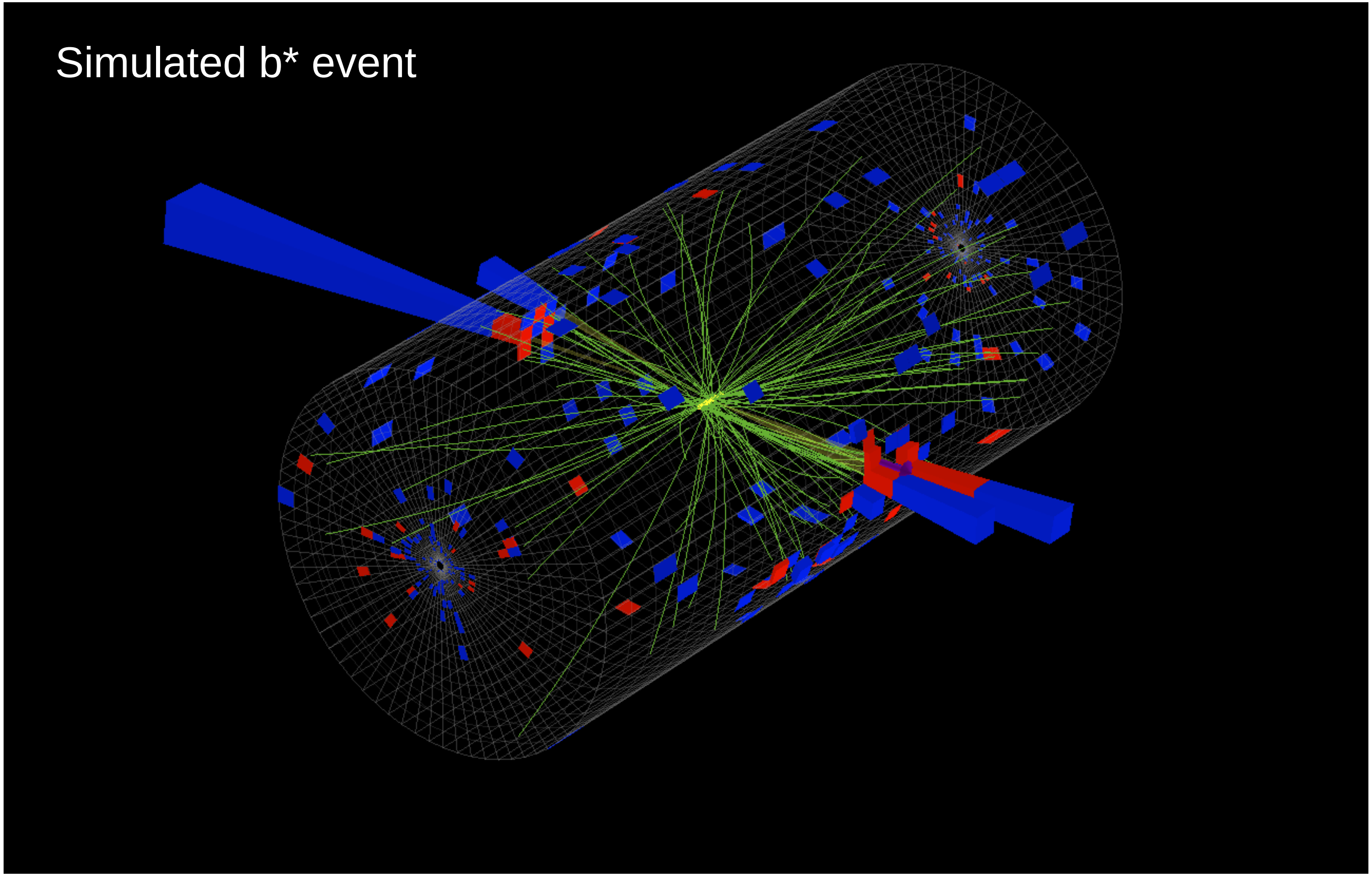
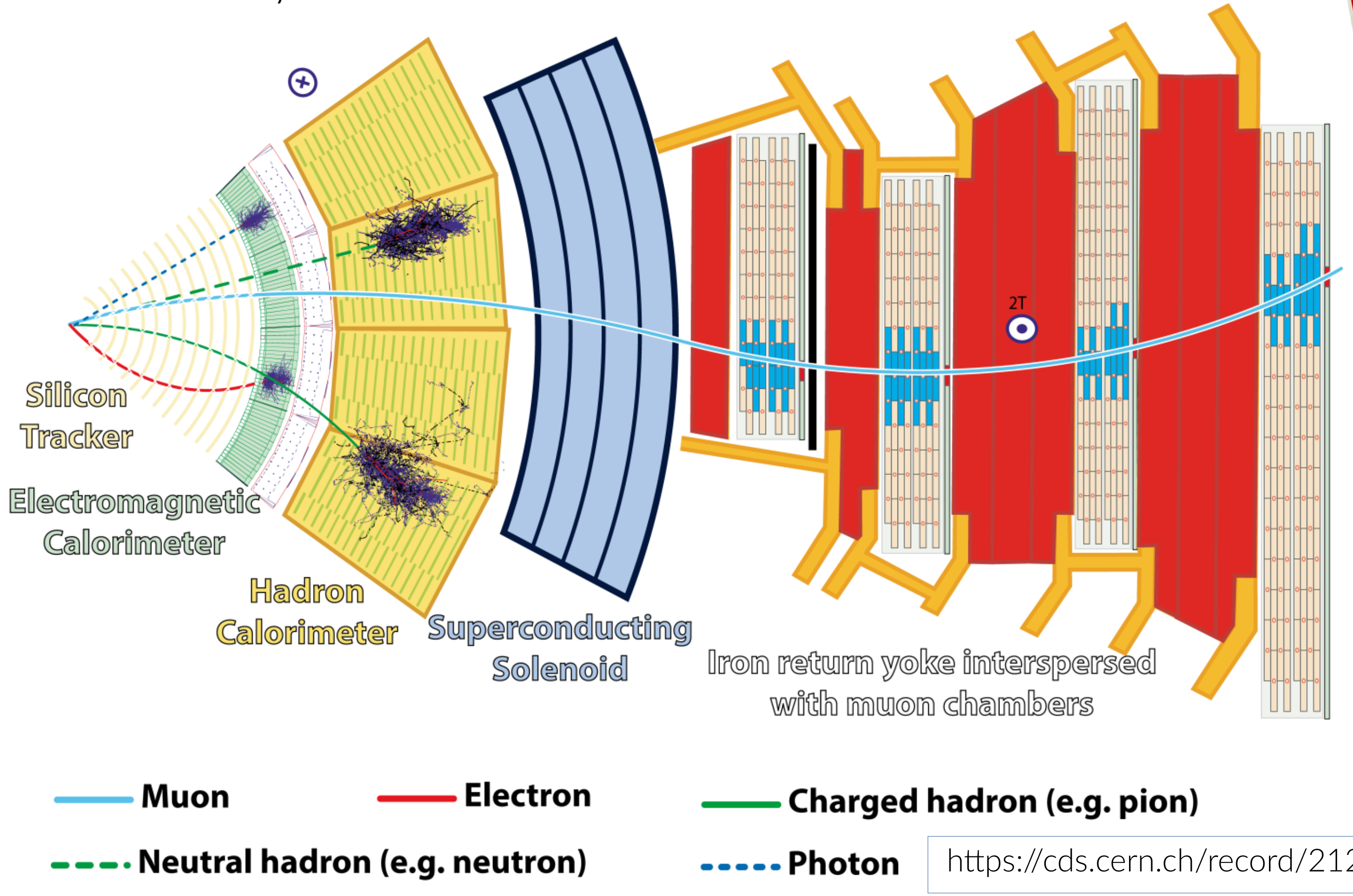


The Compact Muon Solenoid (CMS)

Build in layers like an onion



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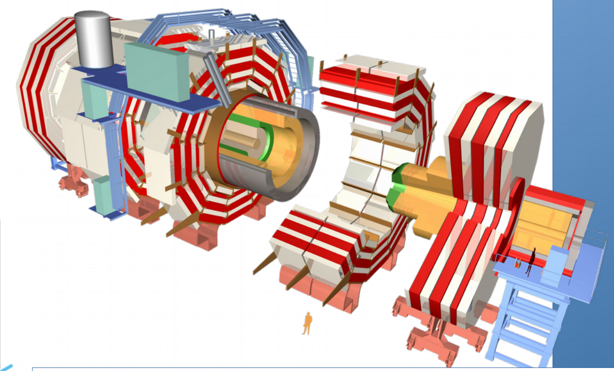
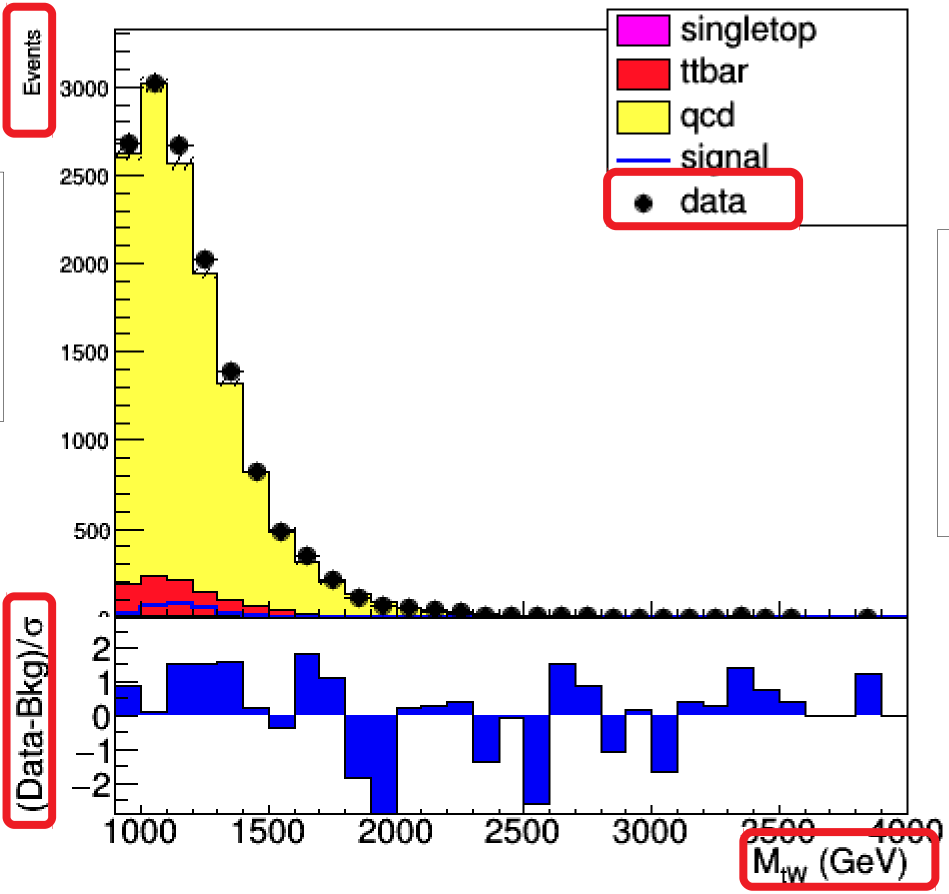


http://ippog.org/resources/2011/cms-detector-3d-image

Combination of layers used to identify particles

How Do We Count?

Events per bin
- X-axis variable is only one dimension of the bin!



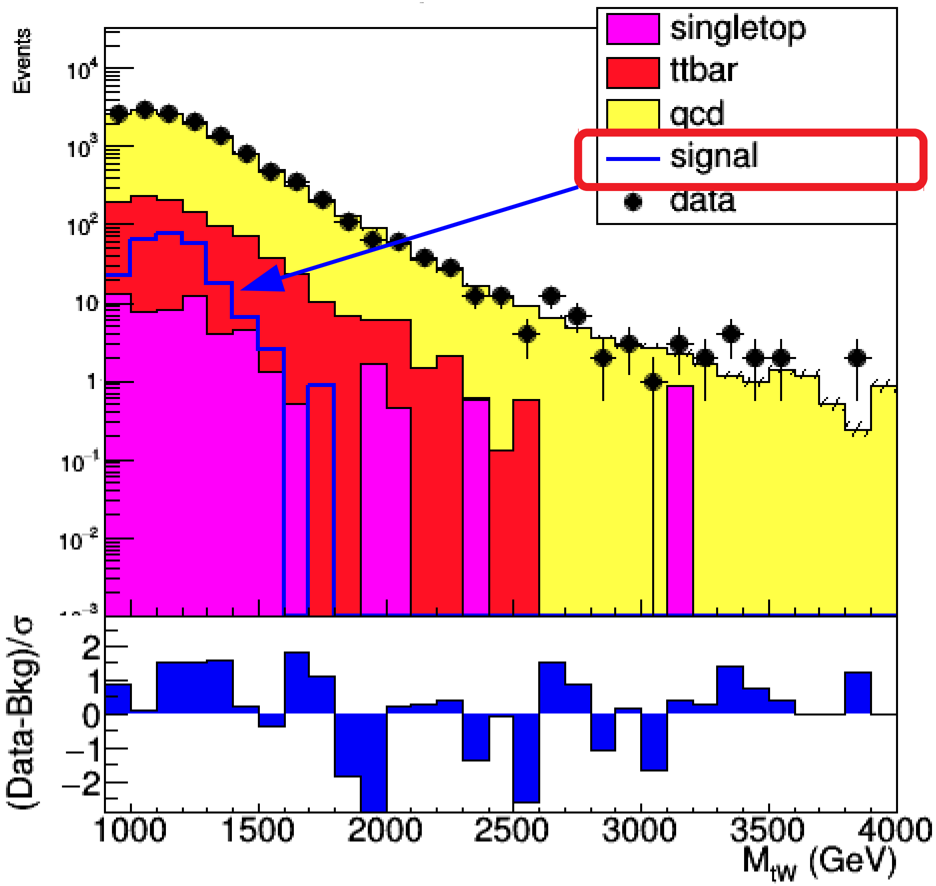
Invariant mass of “tW” pair
- *Resonance mass*
- Backgrounds are smooth
- Signals are “peaky”
- *Bump hunt*

“Pull”
- Easy way to view deviations from expectation

What Is The Signal?

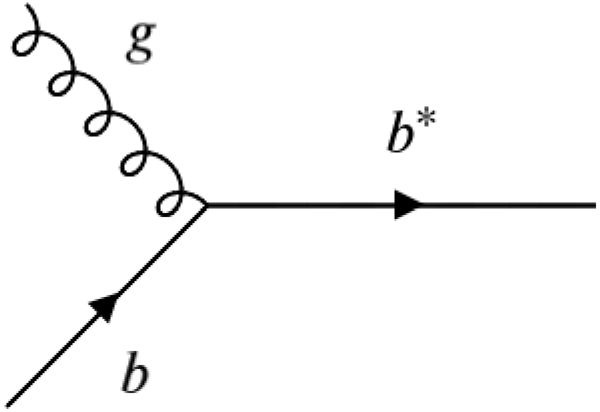
Mass of BSM particles is unknown

- Requires simulating separate samples at different particle masses
- 1200 GeV excited b signal sample shown here



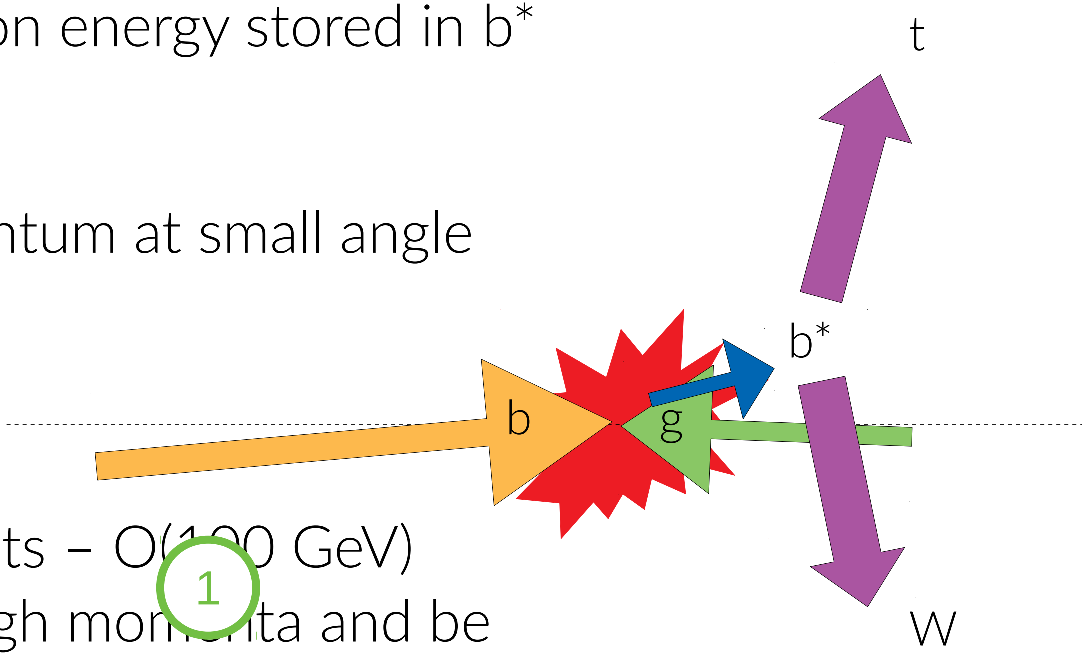
What is an excited b quark (b*)?

- Standard Model assumes that quarks are elementary
  - Theoretical motivation for b* contests this
  - Proposes that a b quark can be excited by a gluon
- Existence of a b* would imply that quarks are not elementary!



What would a b* “look” like?

- Very heavy b* (> 1 TeV)
  - Large portion of collision energy stored in b* mass
- Nearly head-on scatter
  - b* will have low momentum at small angle from beamline



- Much lighter decay products – O(100 GeV)
  - Top and W will have high momenta and be back-to-back

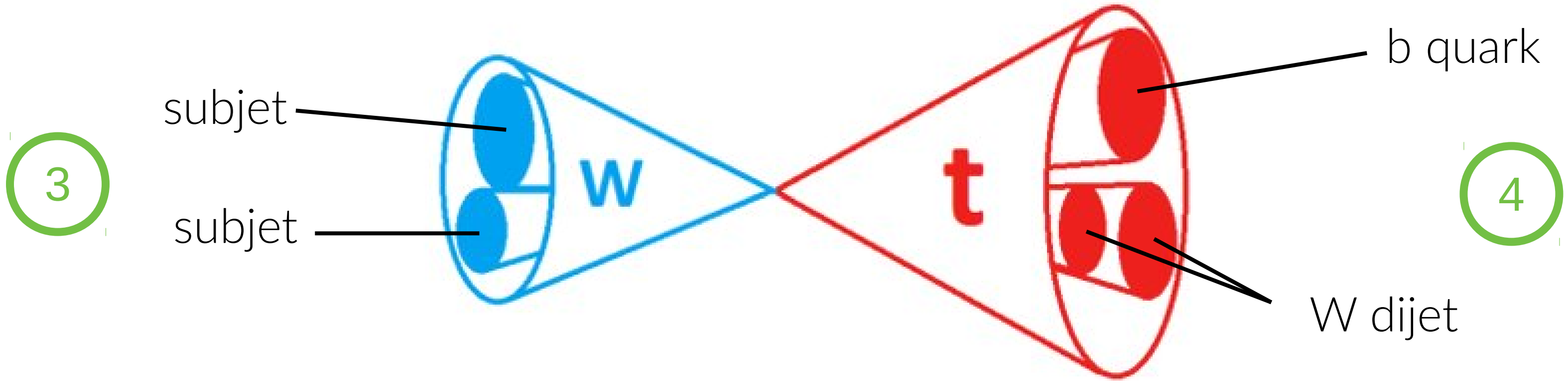
What would a b* “look” like?

$W \rightarrow qq$ (68%)

$t \rightarrow W{+}b$ (96%)

$\downarrow$

$W \rightarrow qq$ (68%)



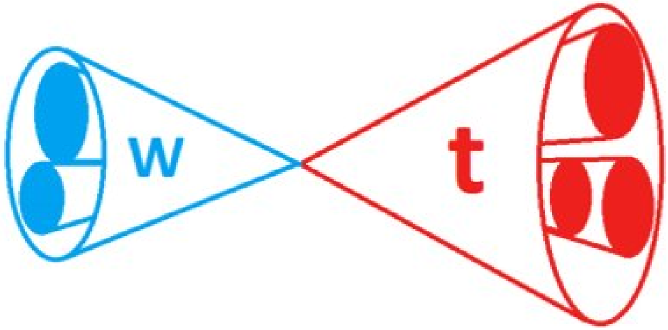
Use *N-subjetiness* to differentiate jets with 1, 2, or 3 subjets

How is signal isolated?

- Kinematics
  - p_T(top) > 400 GeV
  - p_T(W) > 400 GeV
  - Central

1

2

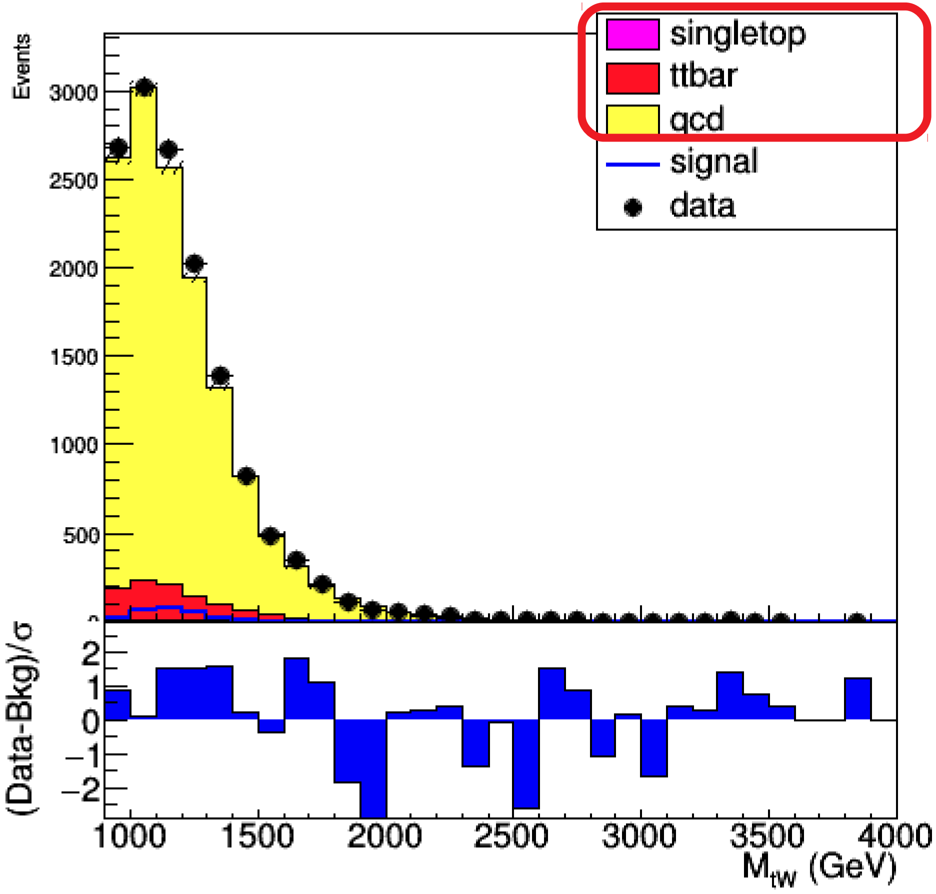


- Standard CMS “tagging” algorithms to identify candidate top and W jets
  - Mass
  - Jet Substructure
  - b-tag

3 4

The tagging of the W is inverted to define the selection for the closure tests shown today

How Are Backgrounds Estimated?

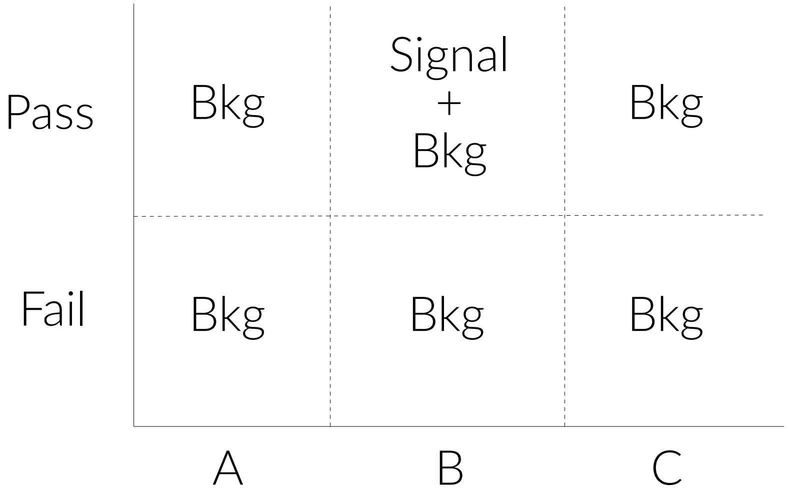


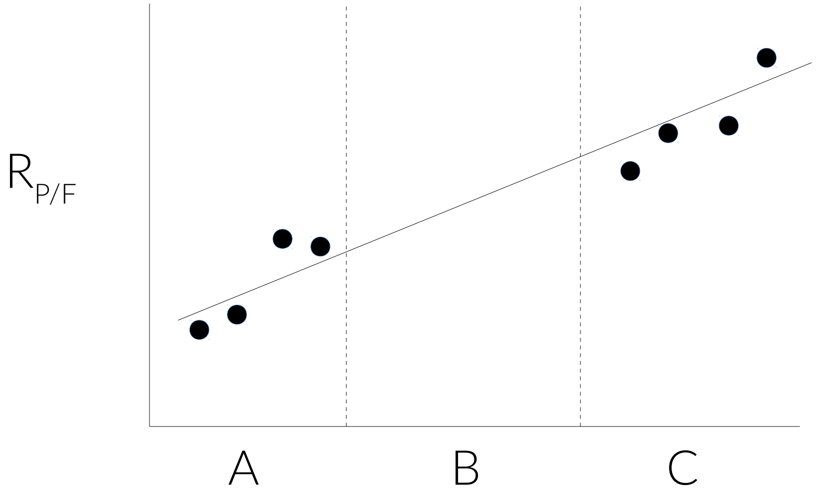
Backgrounds

- Dominated by QCD multijet
  - Poorly modeled with Monte Carlo simulation
  - Estimate with data driven method instead
- $t\bar{t}$ and single top
  - Modeled using Monte Carlo plus any recommended corrections

Data Driven Technique for QCD

- Built on a simple idea of transfer functions
- If the background over the following space is smooth…

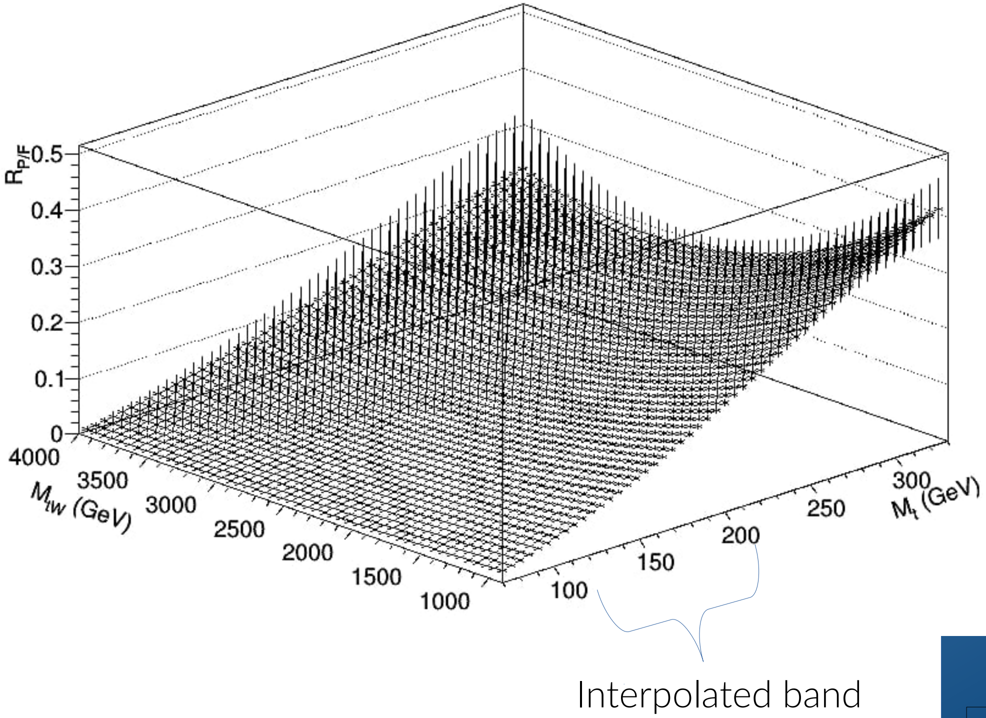




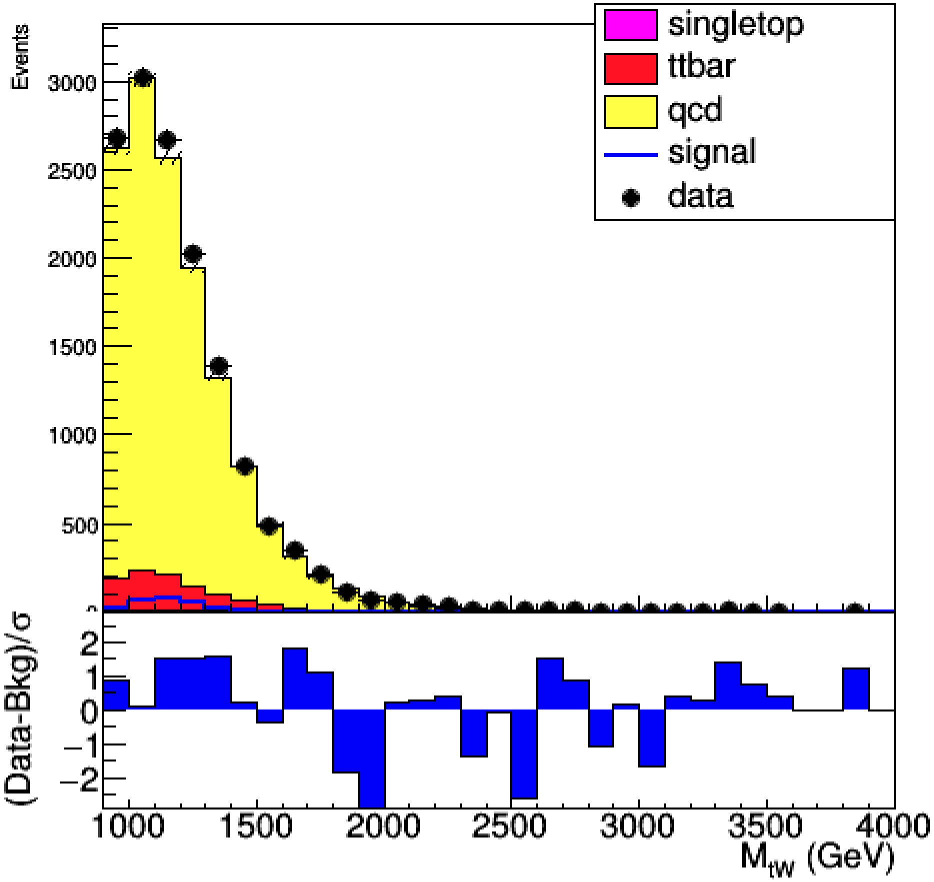
$$fail_B * R_{P/F} = pass_B$$

2D Alphabet

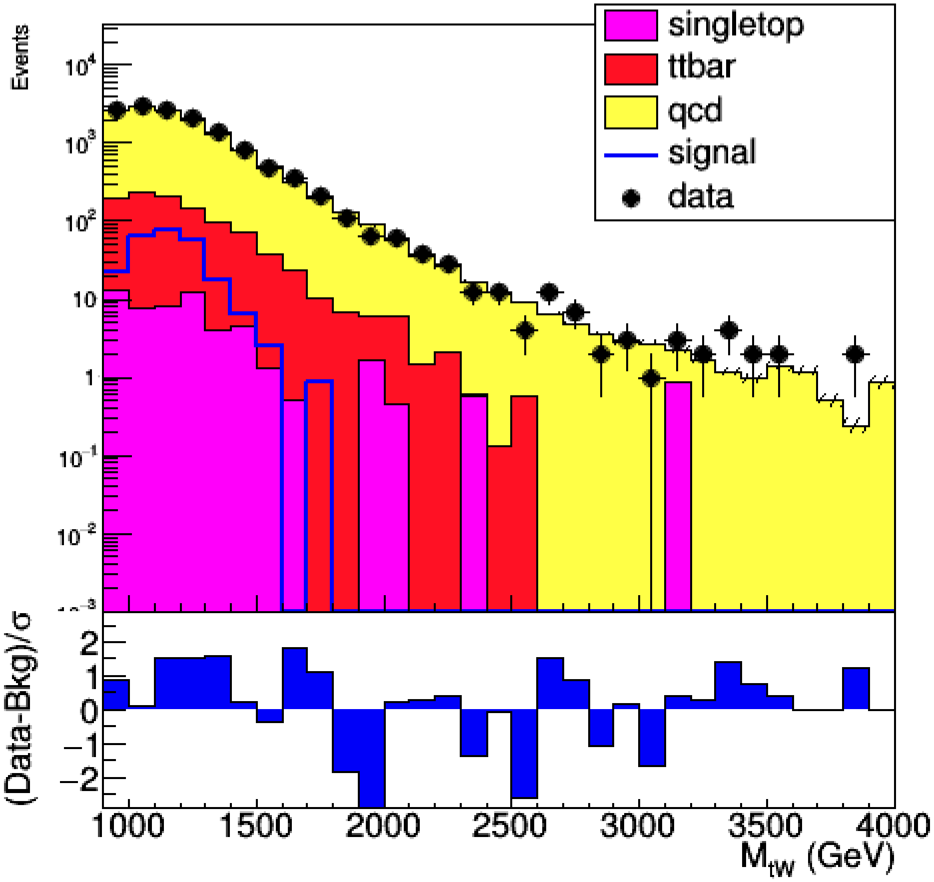
- Perform algorithm on previous slide **in 2D** to estimate QCD
  - M_{tW} vs M_{top} where the top mass signal band is interpolated by the surface
- Perform maximum likelihood fit for total background estimate
- Float
  - Failing QCD
  - 2D $R_{P/F}$ polynomial coefficients
  - Effect of systematic uncertainties



Revisiting



singletop
ttbar
qcd
signal
data
Events
(Data-Bkg)/σ
M_{tw} (GeV)



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Final Thoughts

- Work on $b^* \rightarrow tW$ all hadronic search is wrapping up
  - Combining results with a semi-leptonic (top) channel
- Performing some final improvements
  - Deep learning algorithm for top tagging
  - Adding 2017 data
- 2D Alphabet has been a success
  - I've written it to be generic and flexible for re-use
    - Semi-leptonic (W) channel up next along with others!

Thank You!

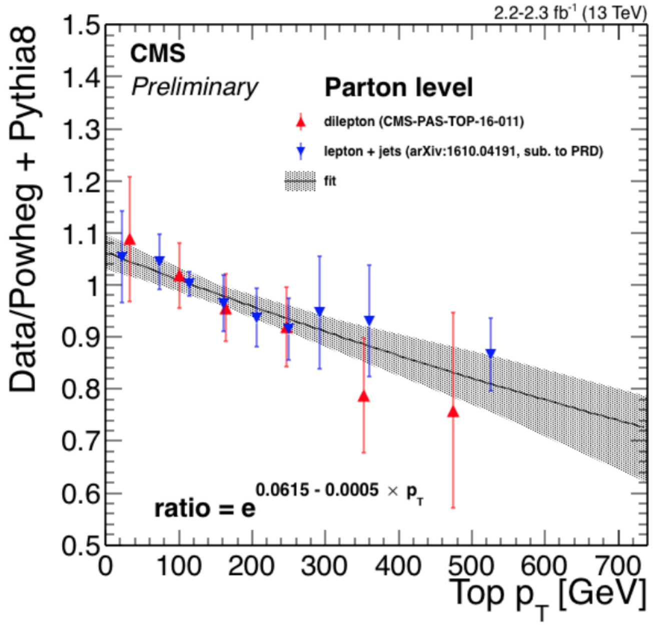
Backup

2D Alphabet

- Maximum likelihood fit is performed for a **total** background estimate
- Fit additionally considers **normalization *and* shape** based uncertainty templates for all MC
  - Allows single top and $t\bar{t}$ distributions to **morph**!
- **Simultaneously fit** a $t\bar{t}$ enriched region (**$M_{t\bar{t}}$ vs M_{top}**), $t\bar{t}$ can be further corrected to match the data
  - Known that top quarks in data are observed to be softer than MC predicts (means more events at lower resonance mass)
    - Source unknown
    - An official correction is recommended but only valid for low p_T

$t\bar{t}$ Estimation

- Use official correction as a starting point
  - Use uncertainty in correction to create the up/down 2D templates
  - Can show fit is isolating these templates to perform the morphing!
- Single top treated in the same manner



Jet Clustering

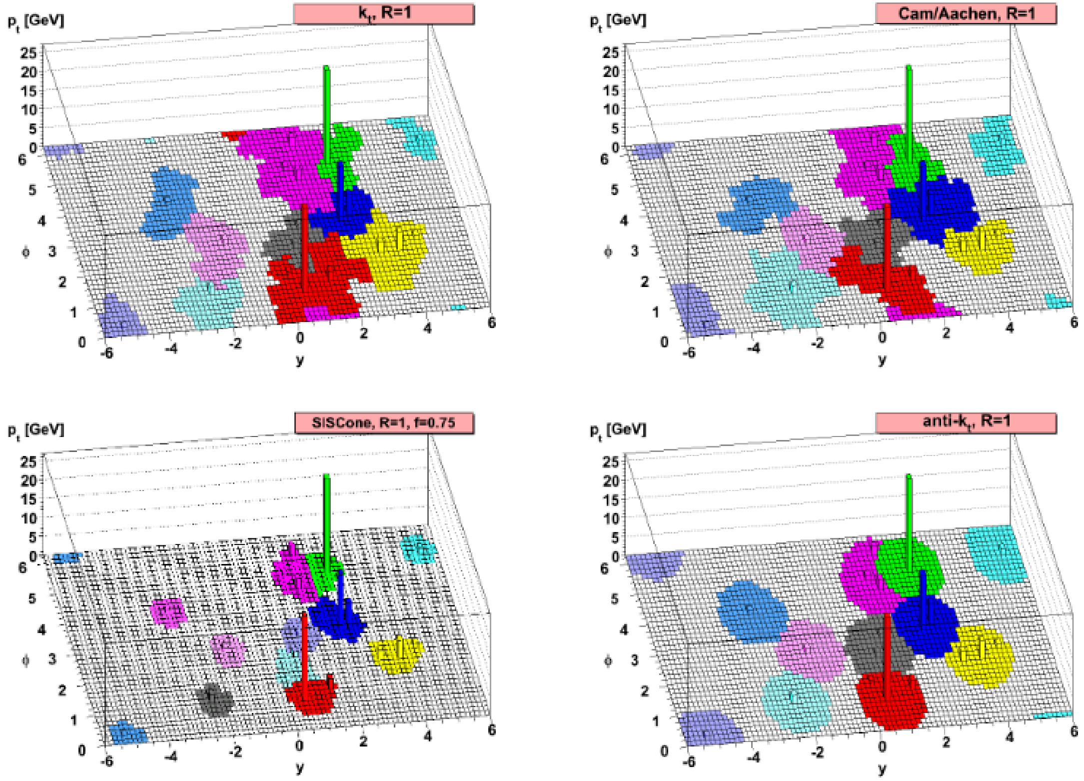
- k_t, p=1
- Anti-k_t, p=-1
- CA, p=0

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$R = \sqrt{\eta^2 + \phi^2}$$



Start with hardest particles

- If $d_{iB} < d_{ij}$, call *i* a jet and remove it from list
- If $d_{iB} > d_{ij}$, cluster *i* and *j*

N-subjetiness

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} min(\Delta R_{1,k}, \Delta R_{2,k}, ...\Delta R_{N,k})$$

Normalization factor so that $0 < \tau_N < 1$

$$d_0 = \sum_k p_{T,k} R_0$$

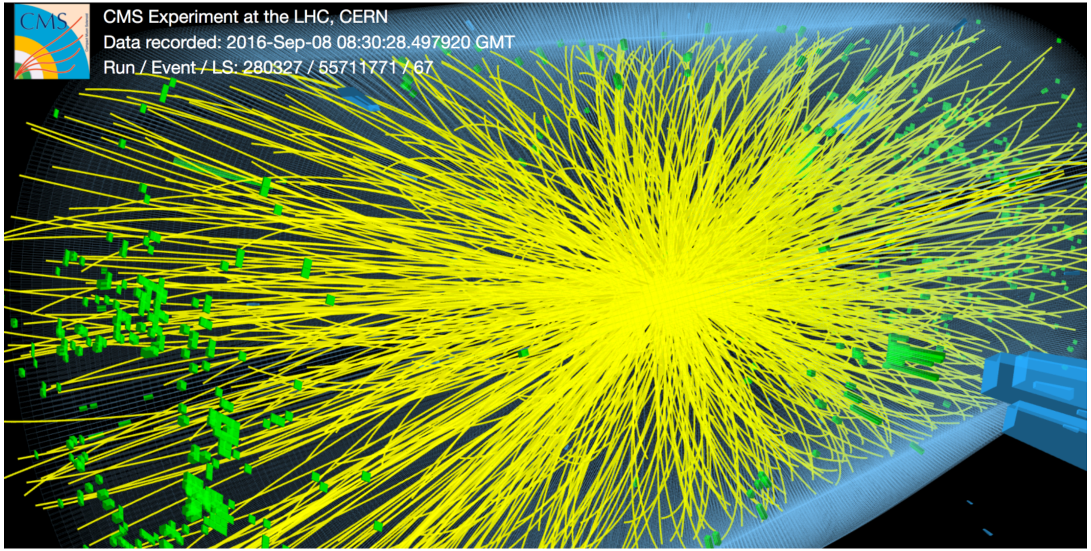
$R_0 = 0.8$ for fat jets

Angular separation between constituent *k* and candidate subjet *N*

Take ratio τ_N/τ_M to determine if jet is more *N* like than *M* like

Data Taking

- The LHC collides <u>bunches</u> of protons
  - Several scattering events in every crossing makes for messy events with lots of *pileup*



https://cds.cern.ch/record/2241144

Event with 86 reconstructed vertices

Data Taking

- Bunch crossings every 25 nanoseconds
  - Not enough throughput to write all data!
  - *Triggers* used to decide which information to write to tape
- Data processed in several layers to go from 1s and 0s to values of interest for researchers

Detector Coordinates

- X-Y plane defines Φ and r
- r-Z plane defines θ

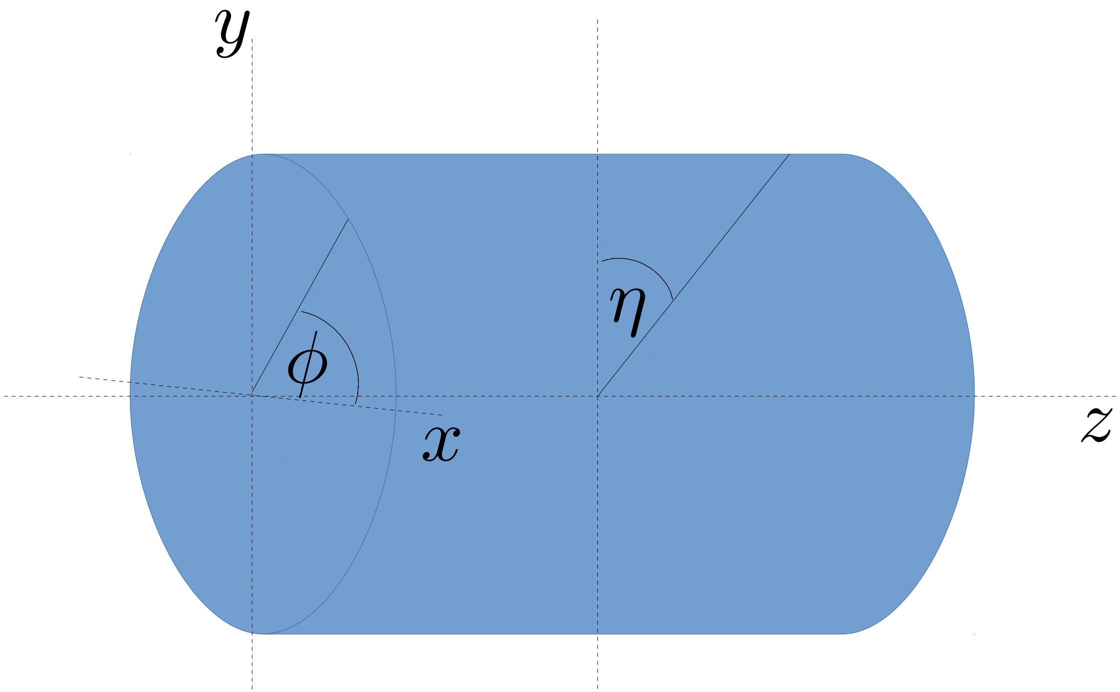
Pseudorapidity

$$\eta = -\ln \tan(\theta/2)$$

Rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c}$$

Equivalent in limit E ≈ |p|



- Particle production approximately constant as a function of η/y
- Differences in η/y are Lorentz invariant

PUPPI

PUPPI+Softdrop

The Higgs Mechanism

CKM Matrix

Jet Energy Corrections

Systematic Uncertainties

Nuisance Parameters