

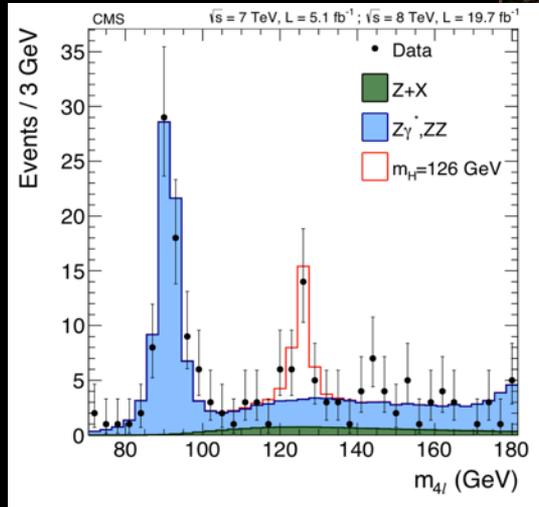
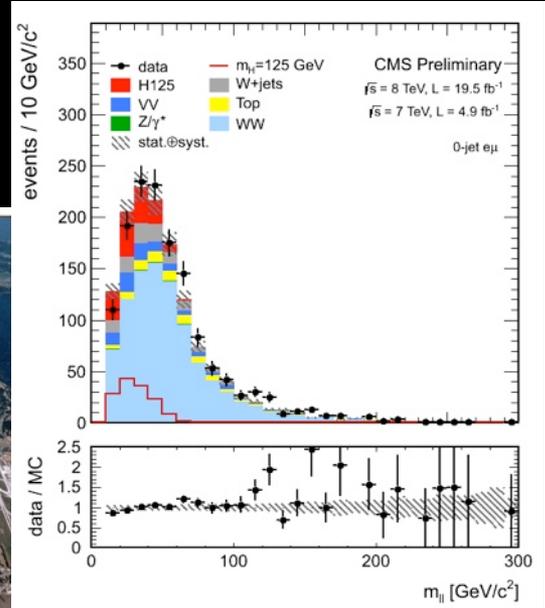
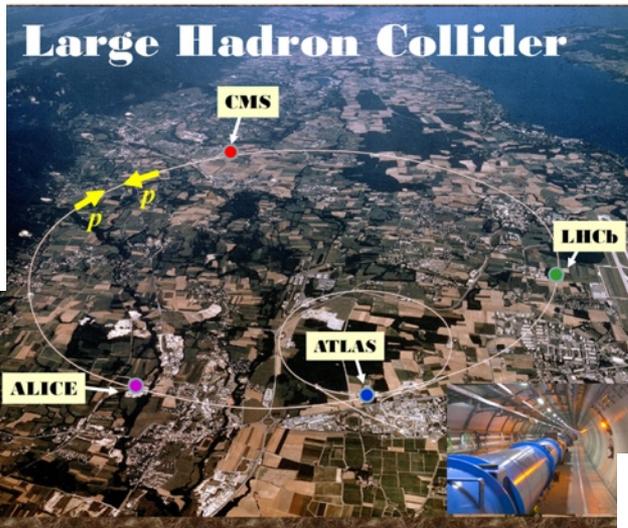
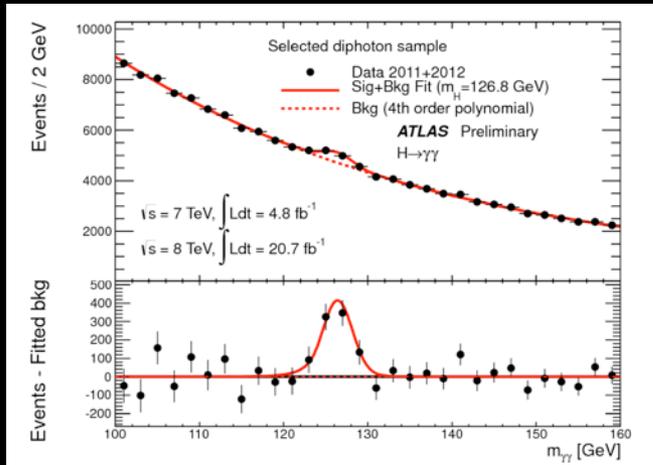
Jet Substructure and LHC New Physics Searches

Brock Tweedie

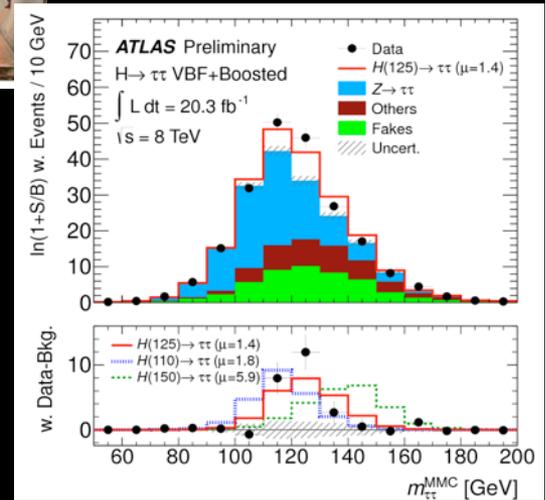
PITT PACC, University of Pittsburgh
@ Lawrence Berkeley National Laboratory

08 April 2014

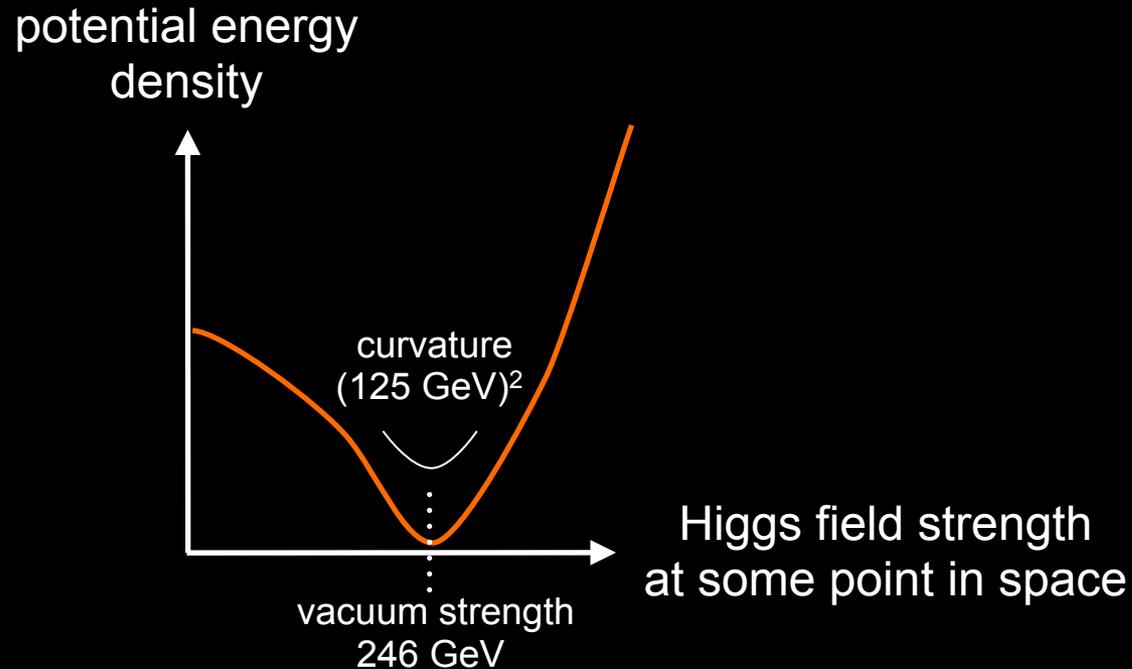
Meet The Higgs Boson



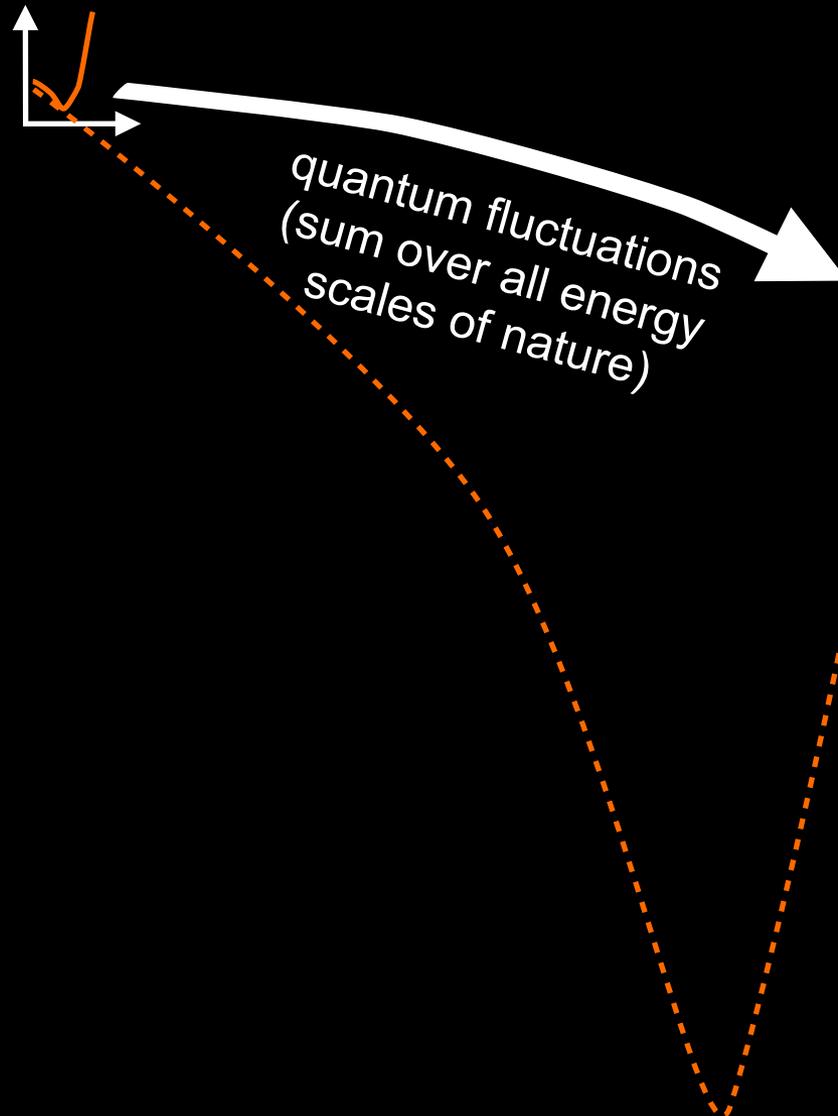
Englert & Higgs (2013)



The Higgs Potential

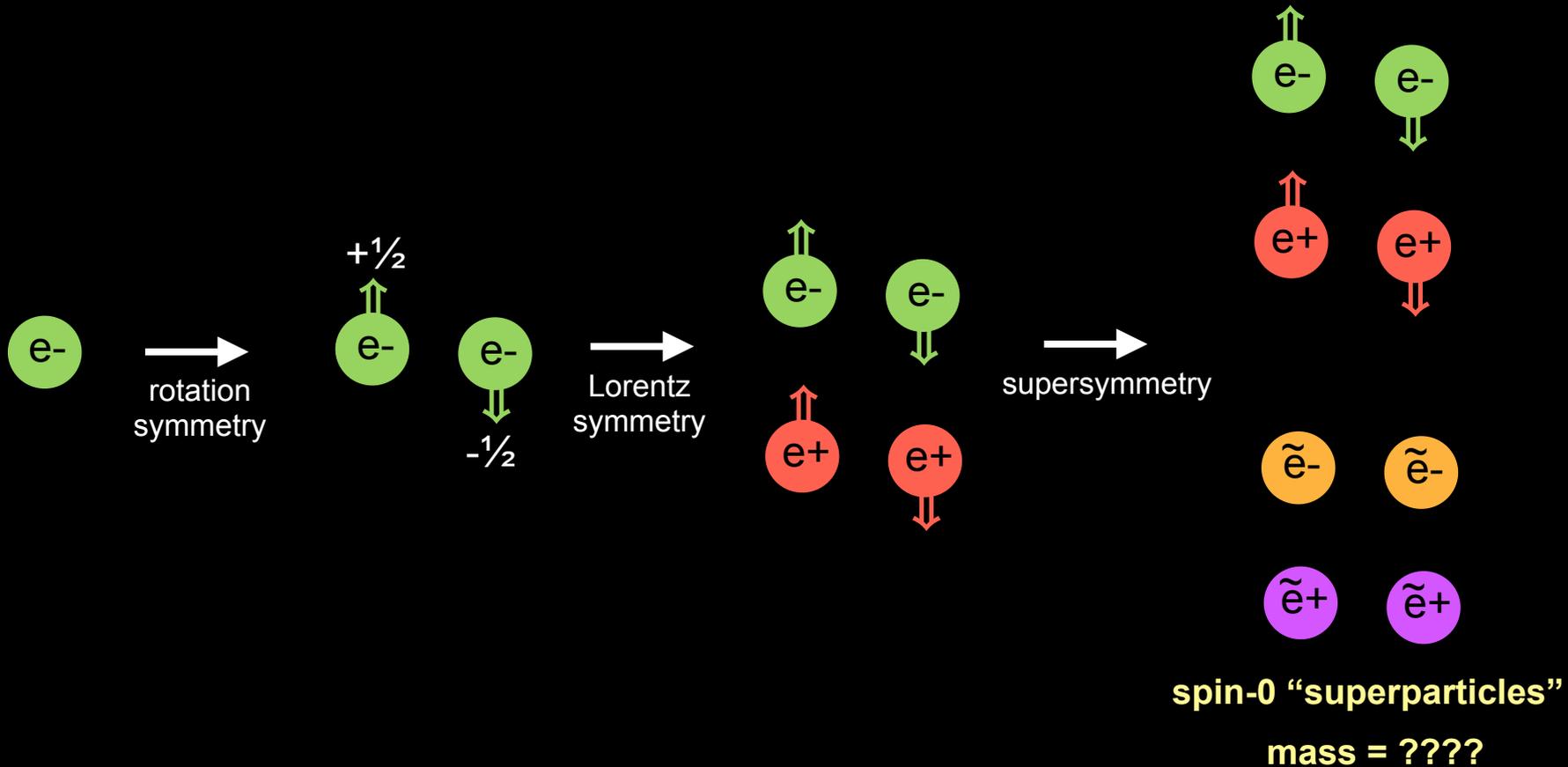


The Higgs UV Catastrophe



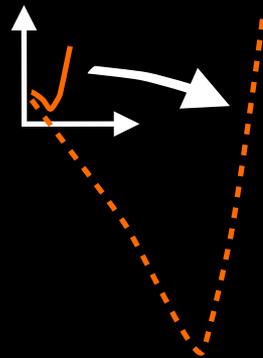
* Not drawn to scale!

Supersymmetry

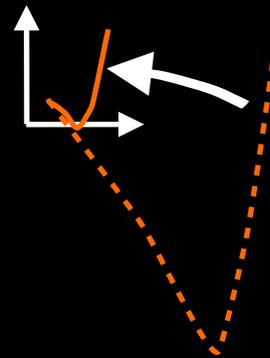


Supersymmetry

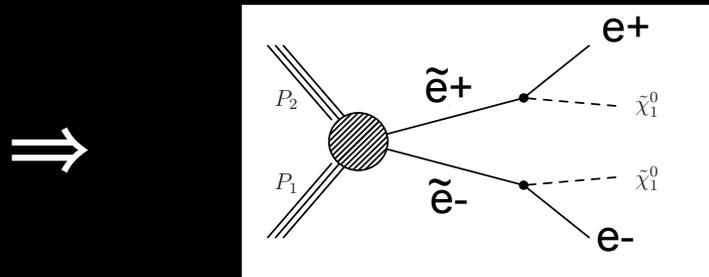
Contributions from
normal particles



Contributions from
superparticles

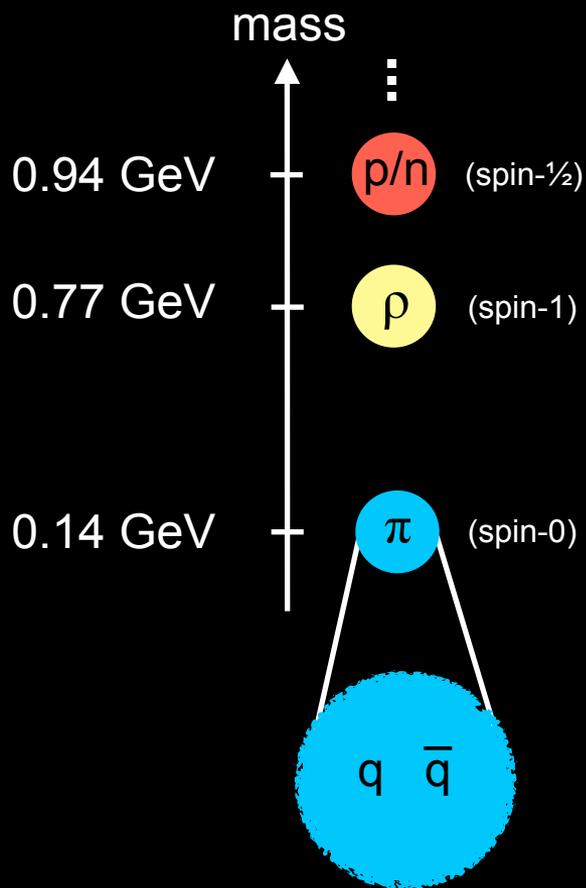


Superparticle production & decay
at the LHC

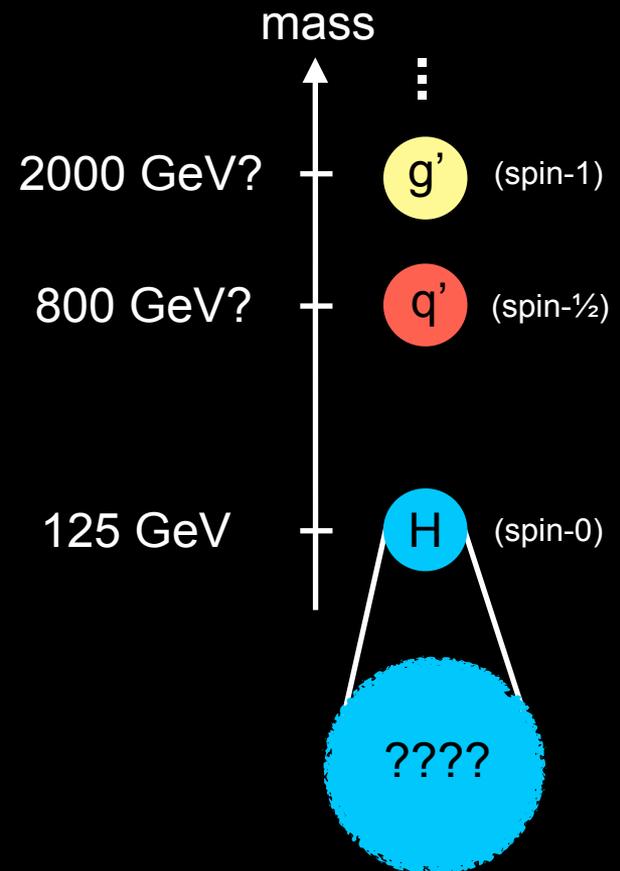


Composite Higgs Field

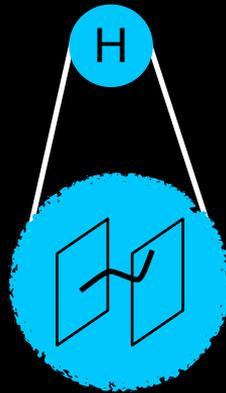
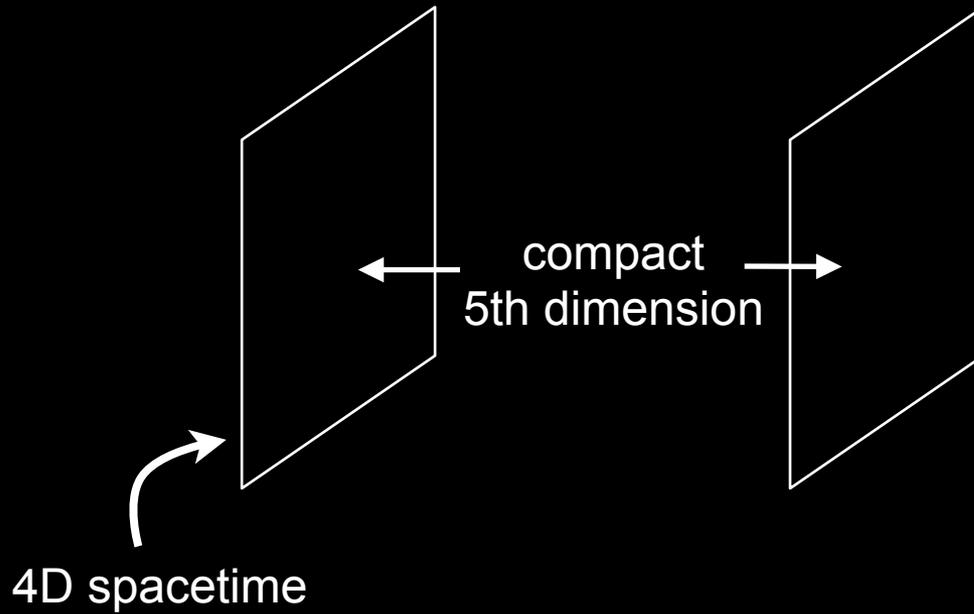
Strong force composite states (hadrons)



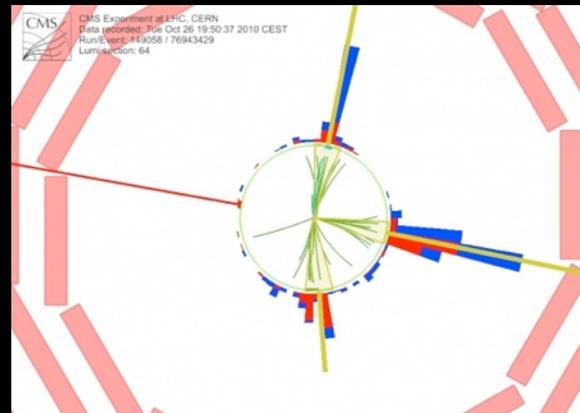
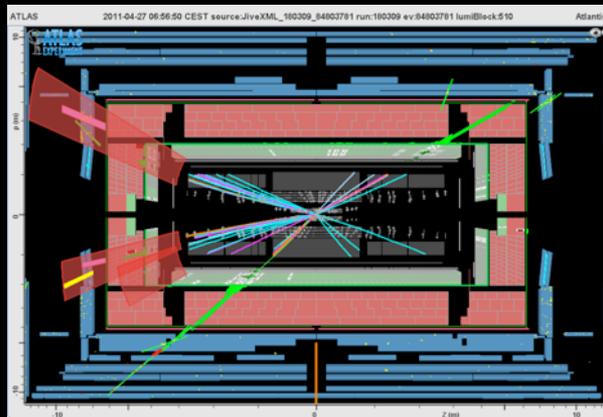
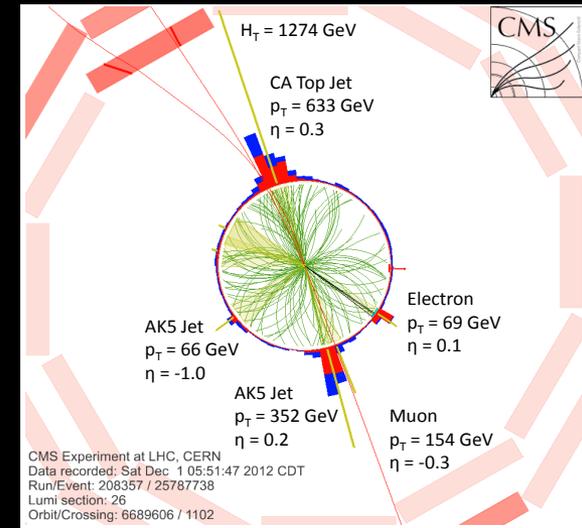
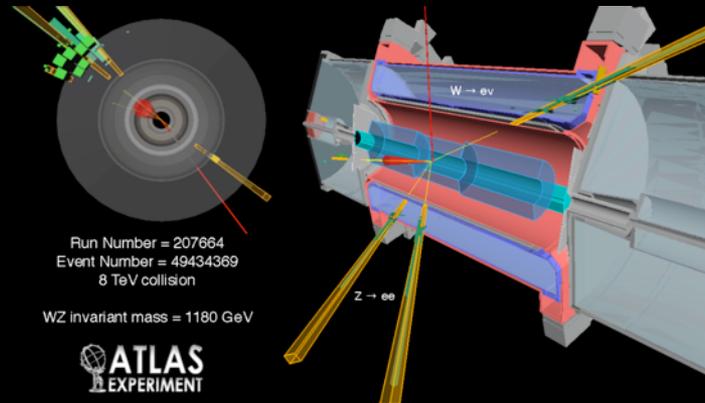
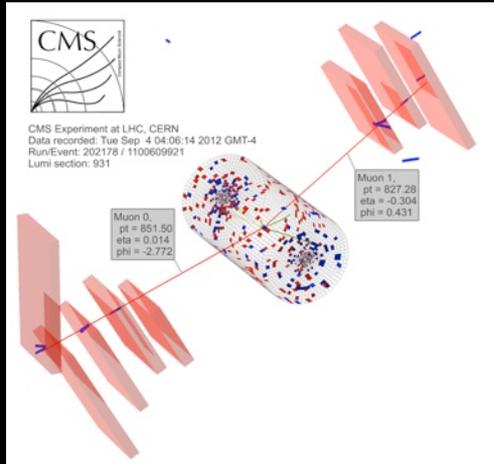
Composite Higgs sector



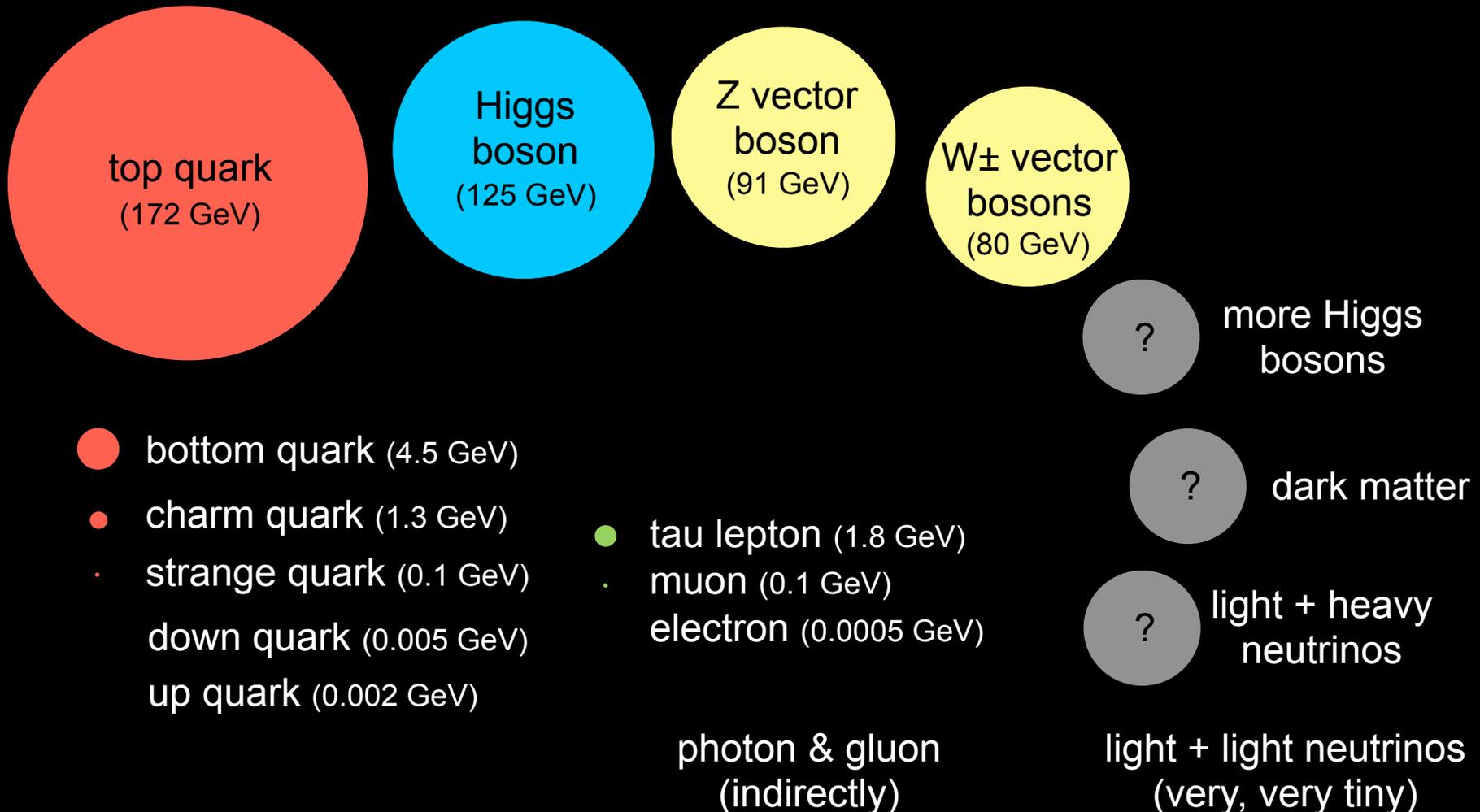
Extra Spatial Dimensions



The Many Faces of New Physics

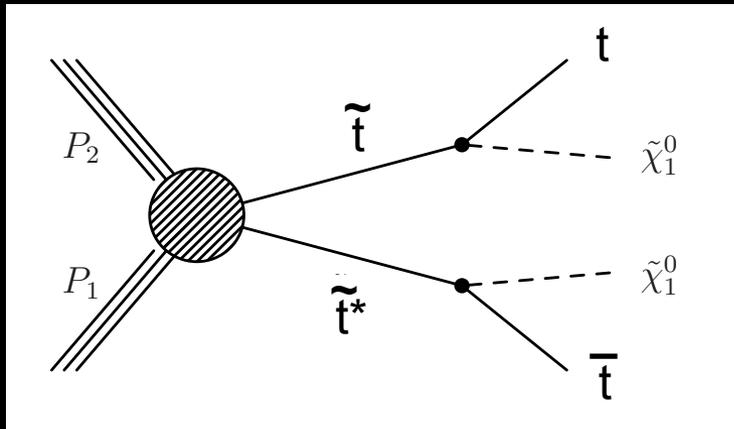


The Worldview of the Higgs Boson

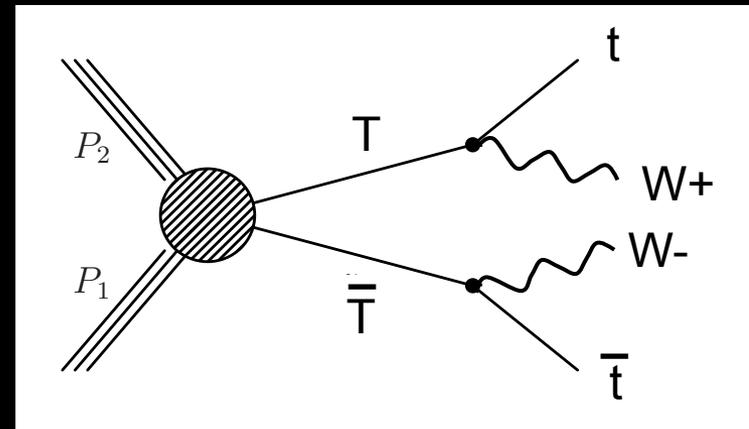


Is New Physics Top-Biased?

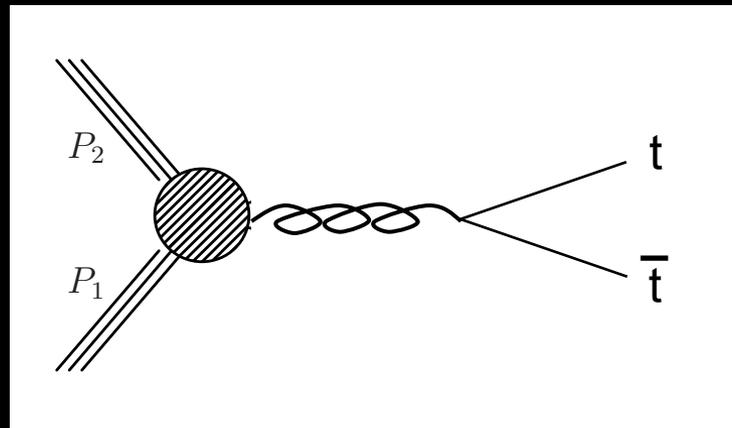
supersymmetric top quark pair



heavy top quark pair



heavy gluon



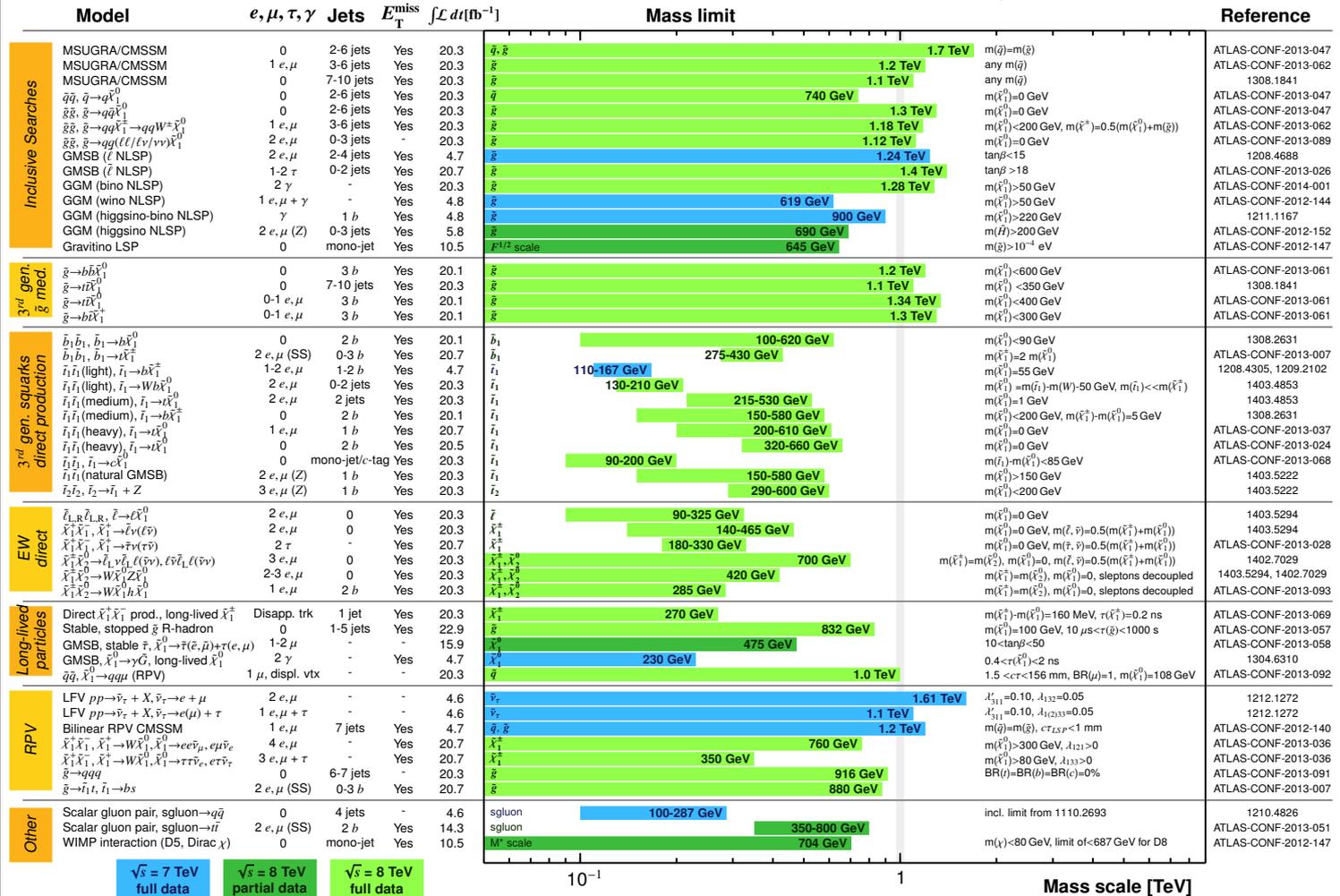
LHC Midterm Assessment

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$

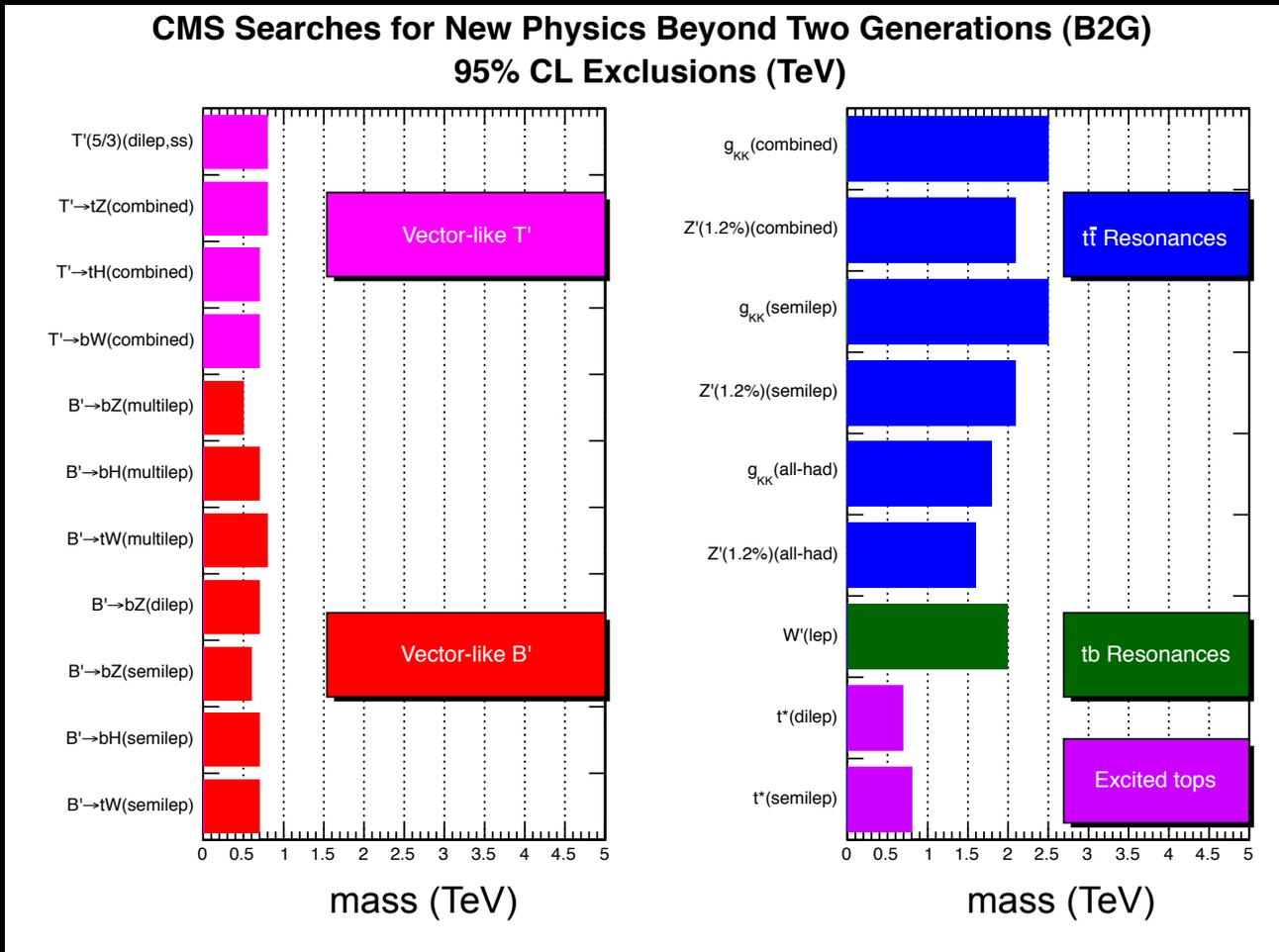


$\sqrt{s} = 7 \text{ TeV}$ full data
 $\sqrt{s} = 8 \text{ TeV}$ partial data
 $\sqrt{s} = 8 \text{ TeV}$ full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

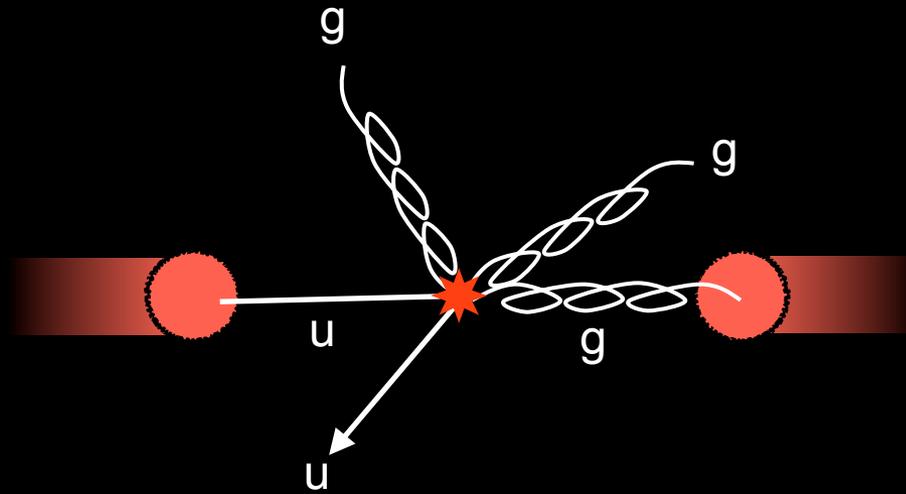
Supersymmetry "simplified models"

LHC Midterm Assessment

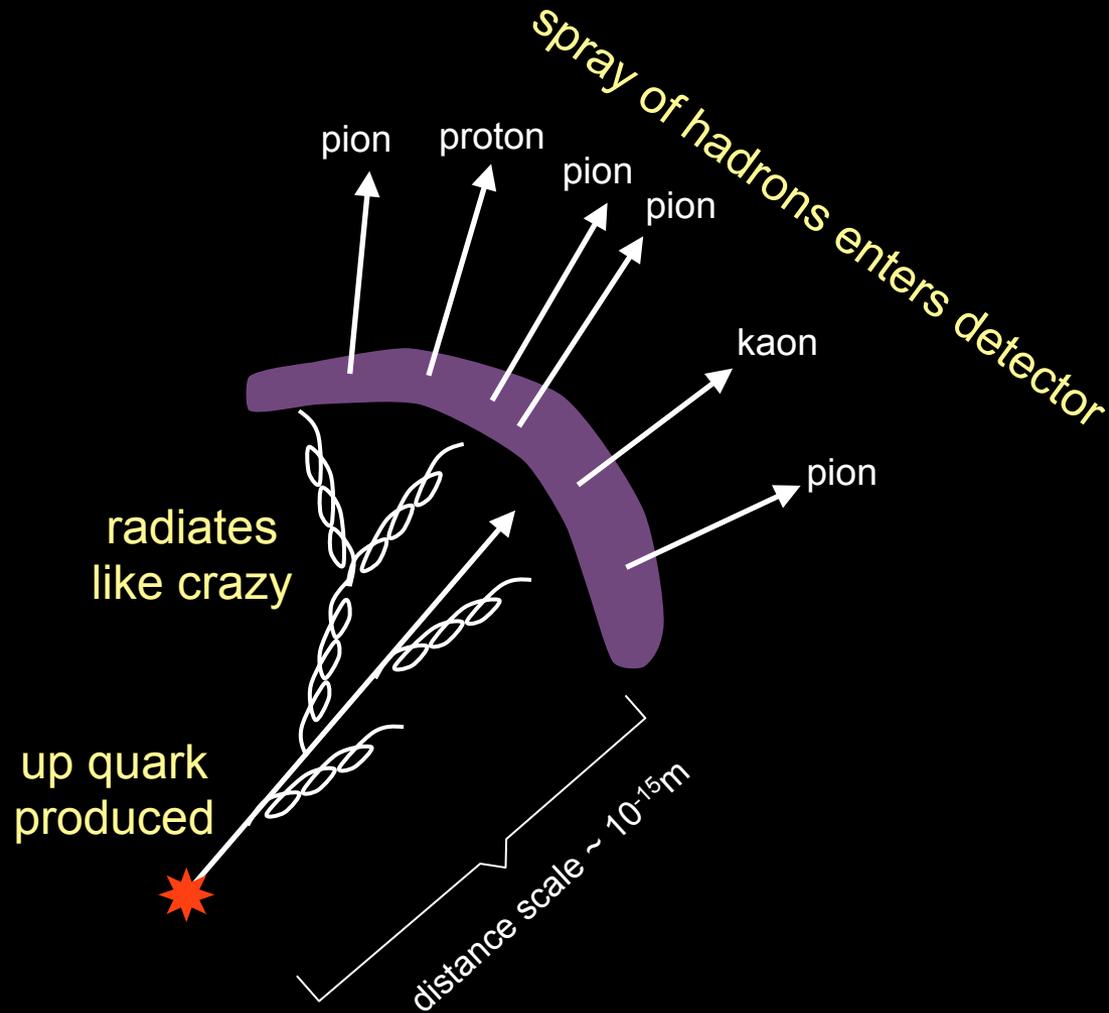


Composite Higgs / Extra-dimensions simplified models

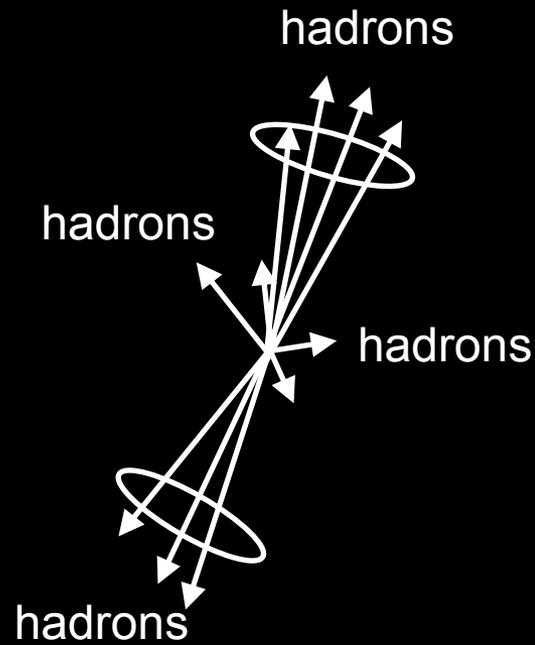
The LHC: Mostly Boring



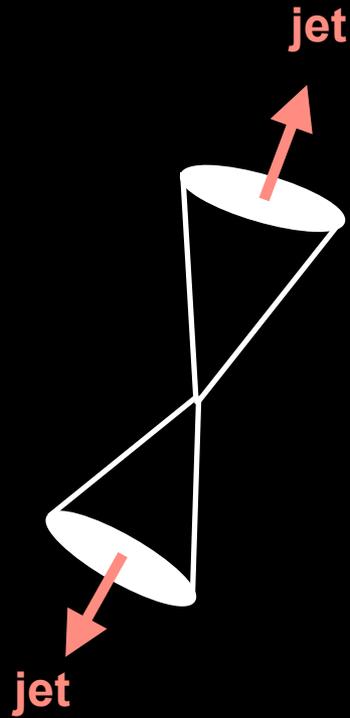
Color Radiation & Hadron Formation



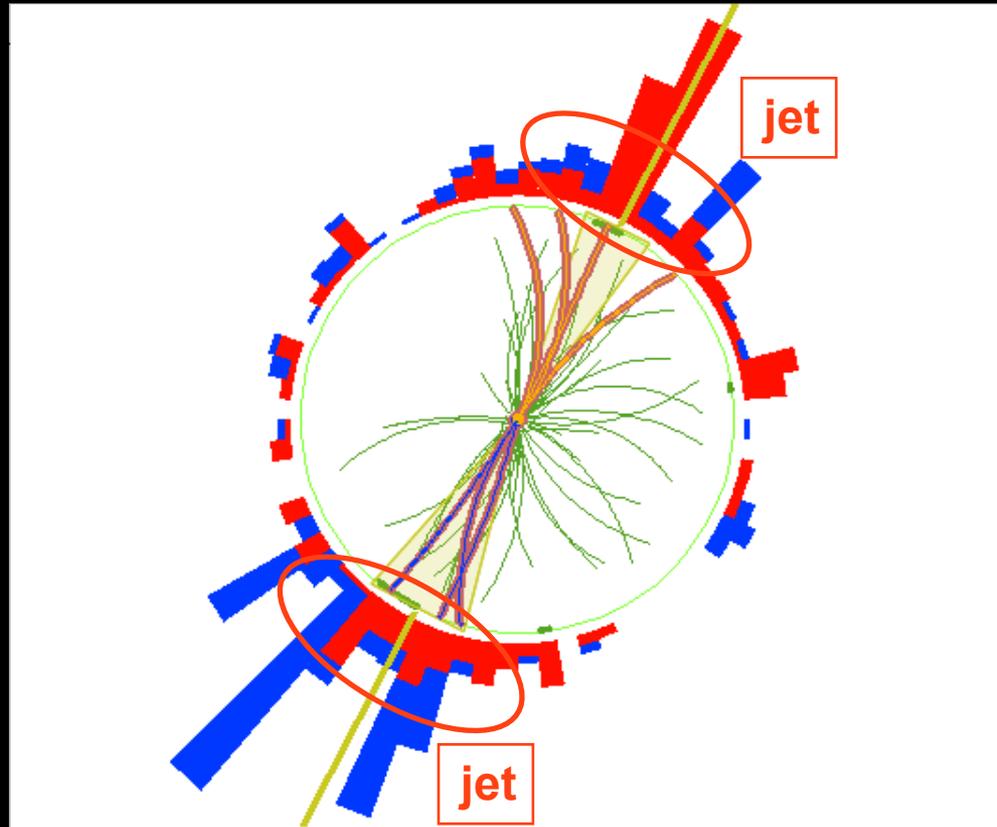
Jets



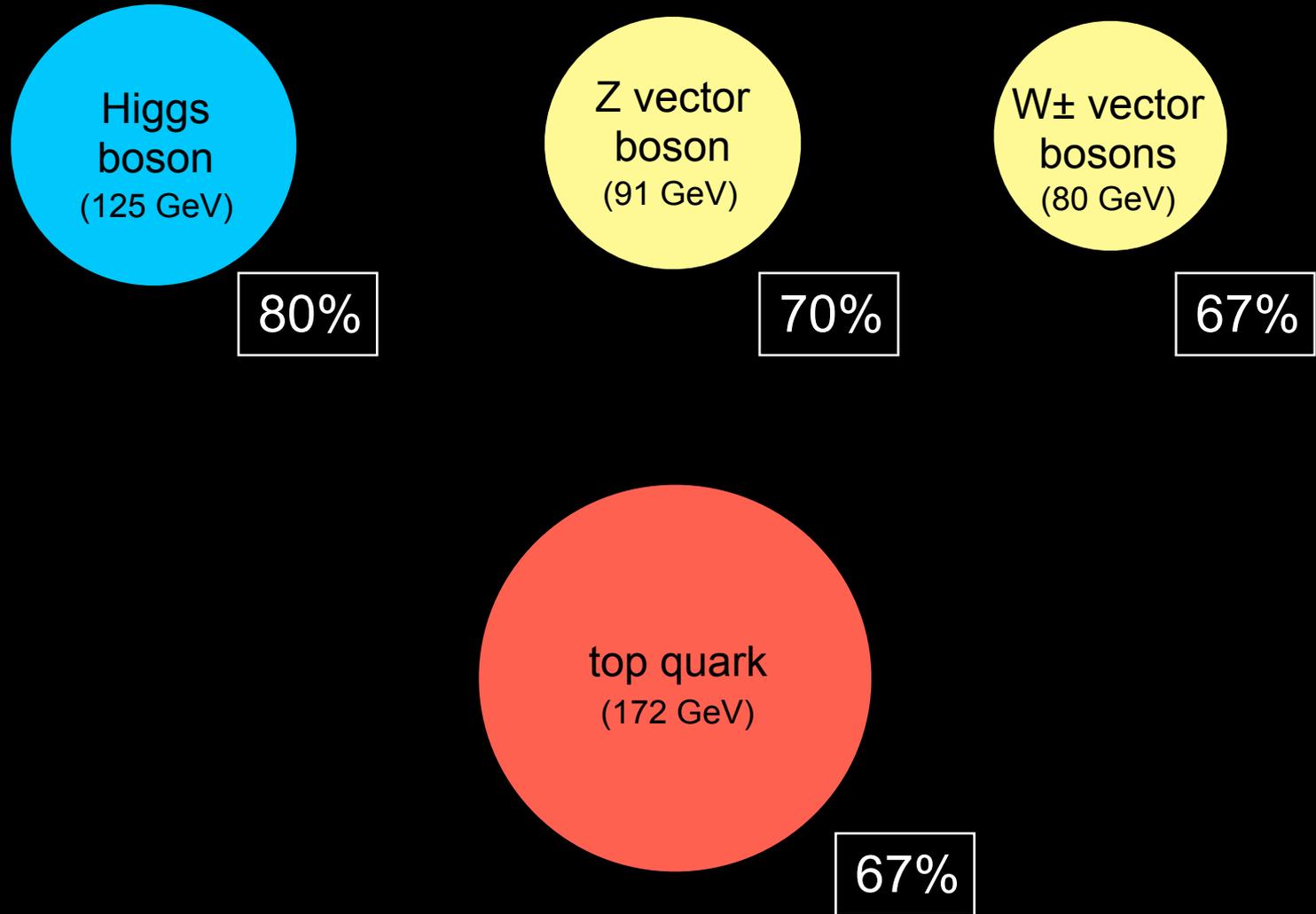
Jets



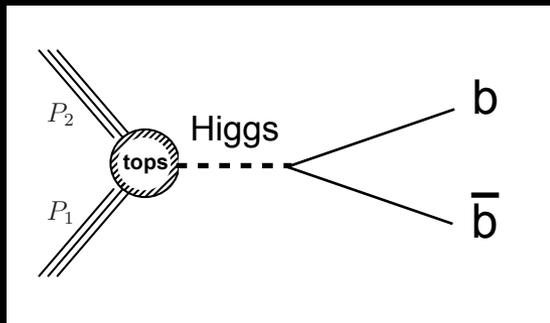
Jets



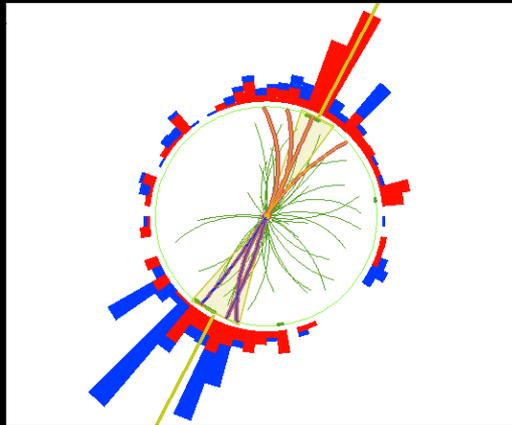
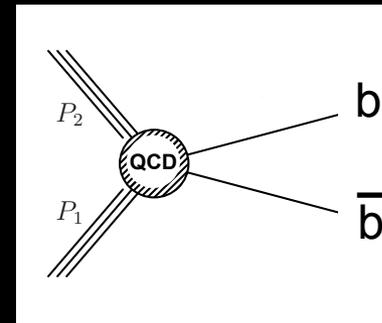
Decay Rates Into Only Jets



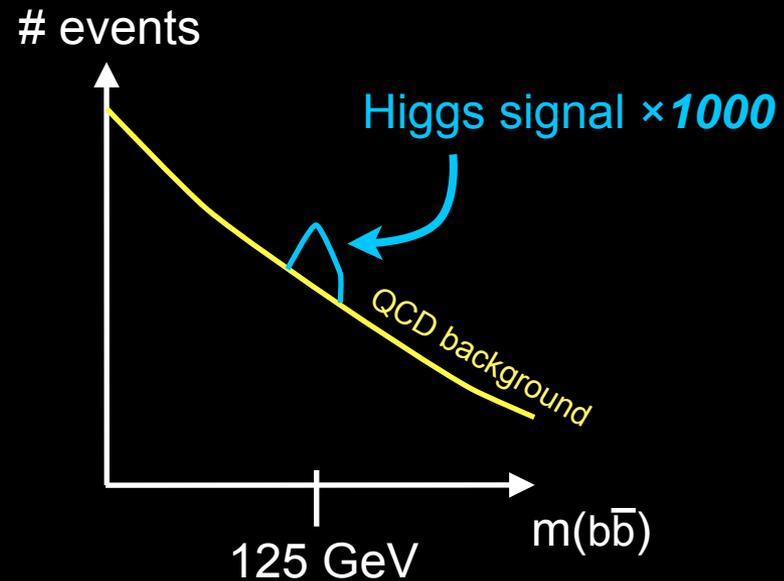
How NOT to Discover the Higgs Boson



VS

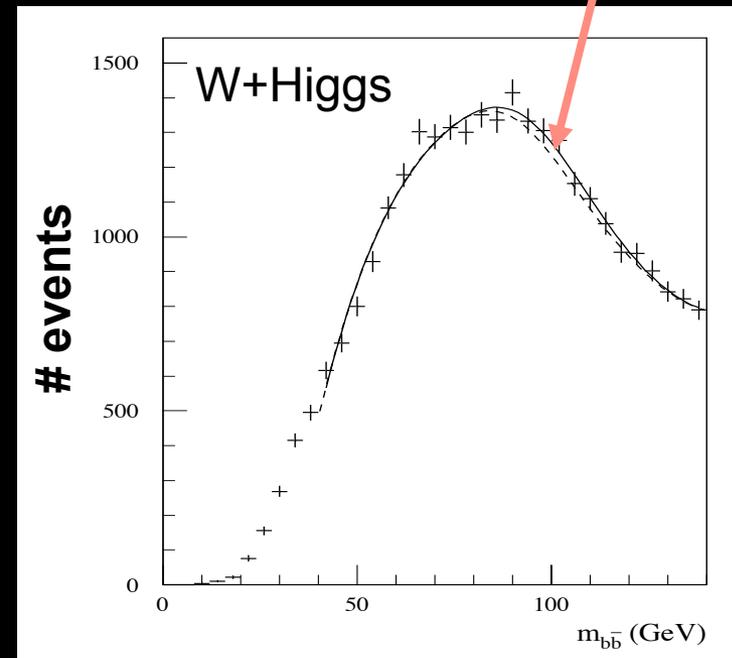
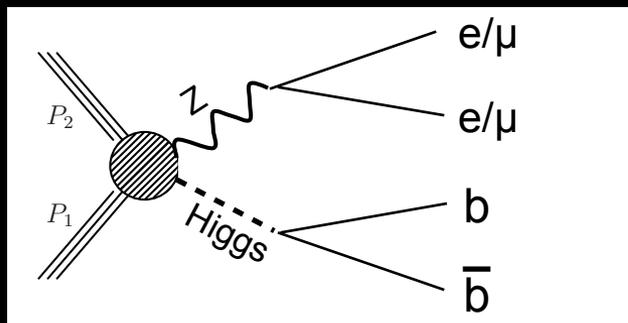
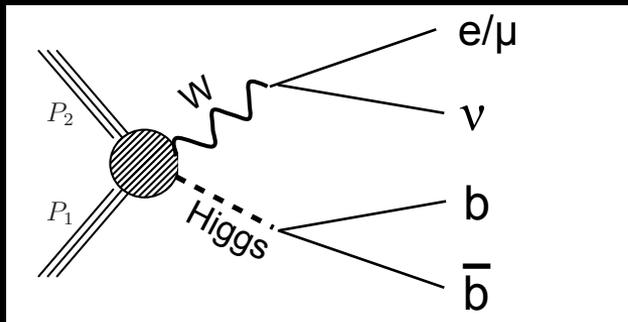


~300,000 Higgs events look like this



... Part 2 ?

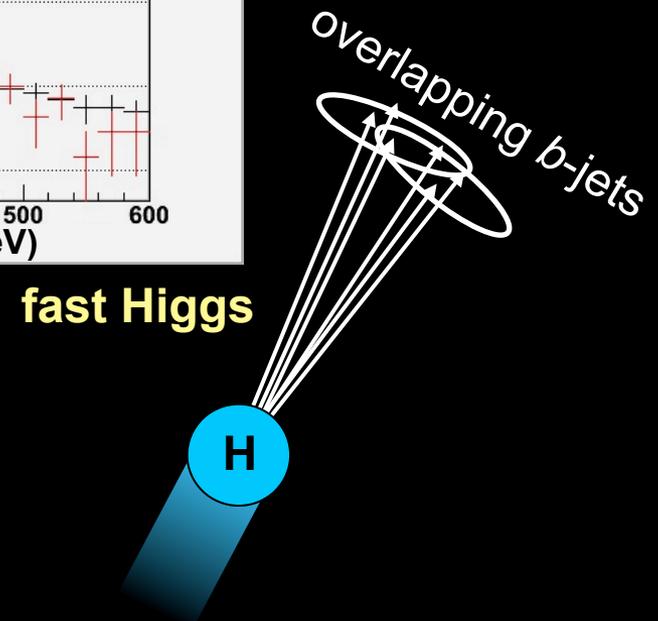
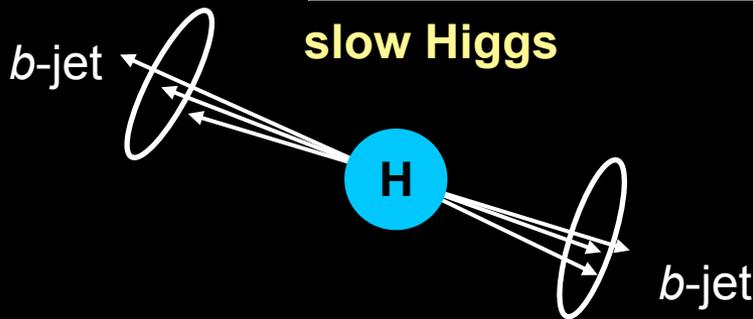
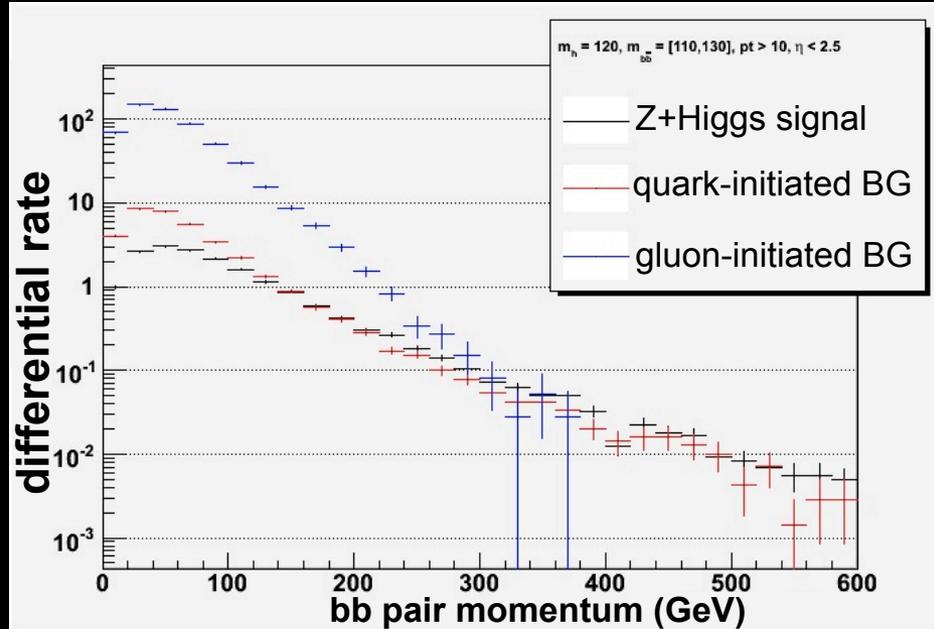
“extraction of a signal... will be very difficult”



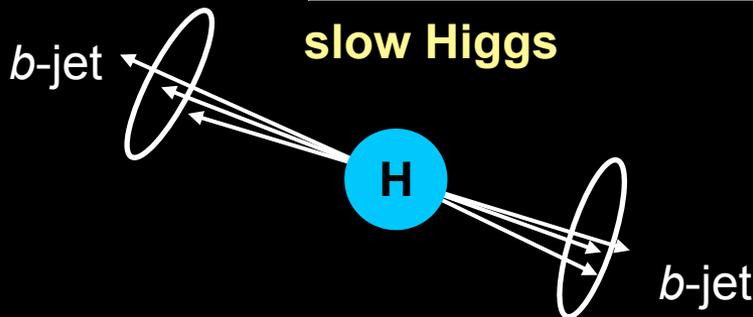
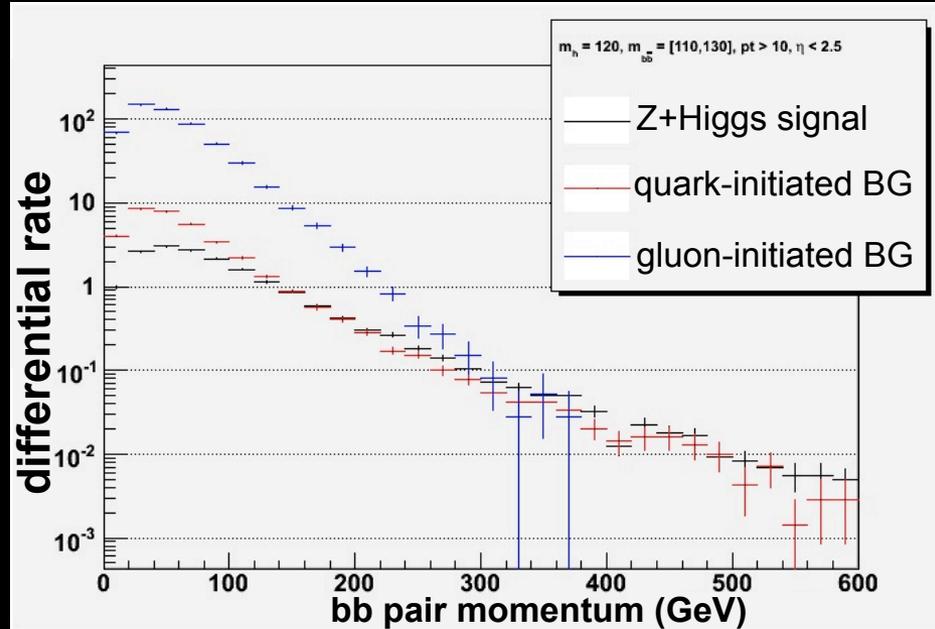
ATLAS TDR (1999)

$m(\text{Higgs}) = 100 \text{ GeV}$

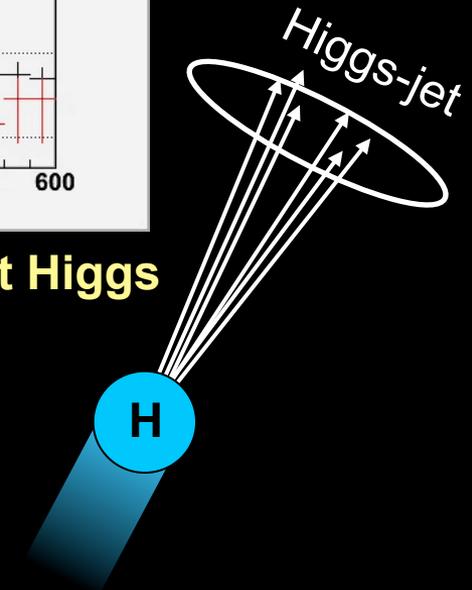
Going to High Momentum



Going to High Momentum

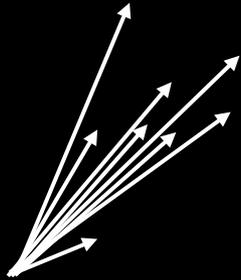


fast Higgs



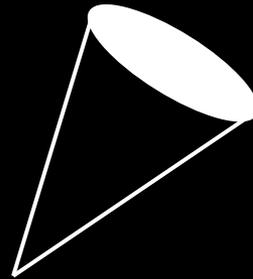
Dissecting Higgs–Jets with Jet Substructure

energetic spray of particles



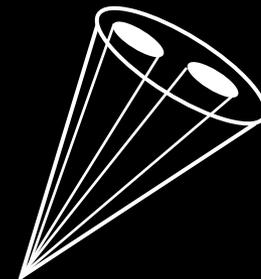
Did this come from
a Higgs decay?

jet



Standard view integrates out
all internal structure

substructure

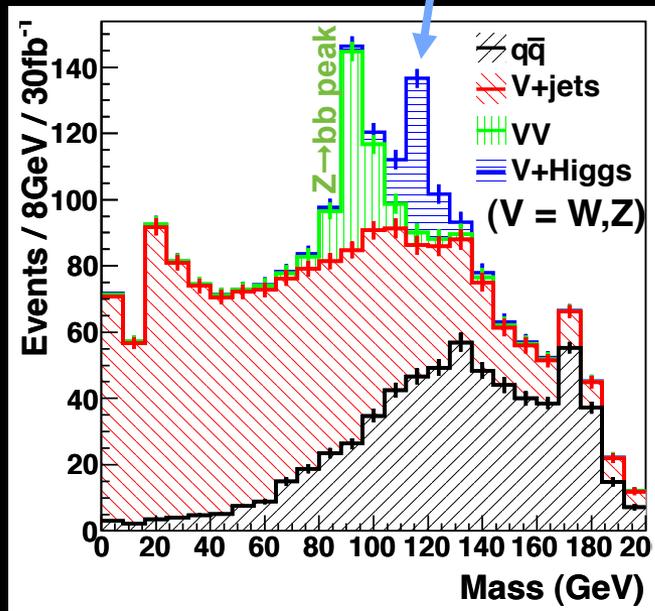


Modern methods let us “peek”
inside in a controlled way

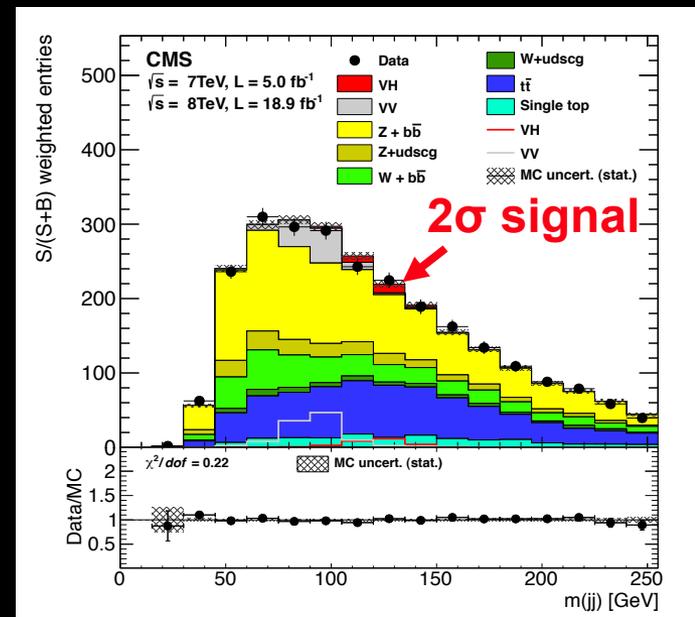
Butterworth, Davison, Rubin, Salam (2008)
building on work by
Seymour (1994)
Butterworth, Cox, Forshaw (2002)

Resurrecting W/Z + Higgs

4.5 σ Higgs signal

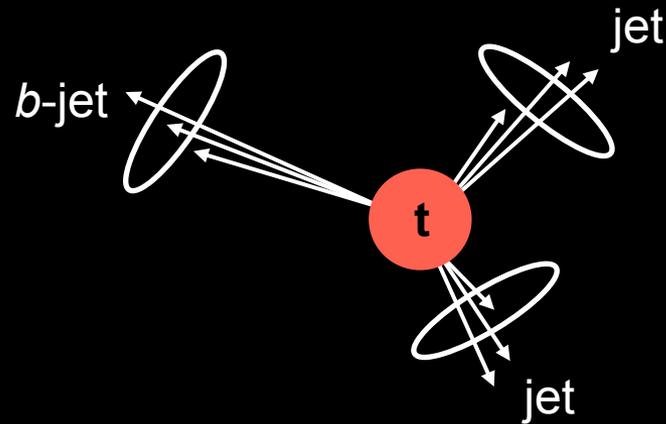
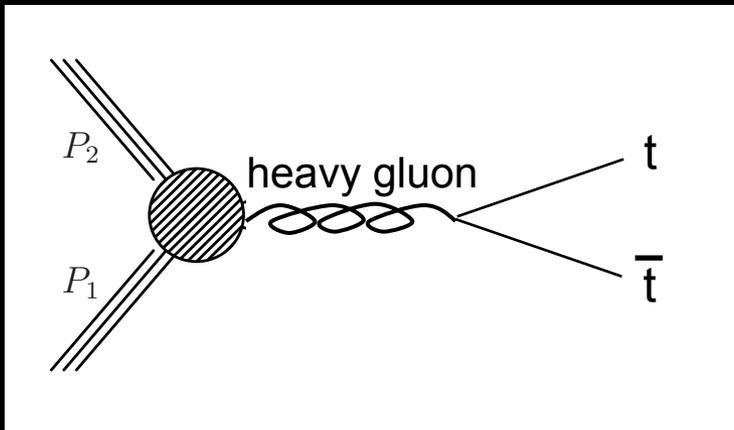


Their projection
7 TeV per beam

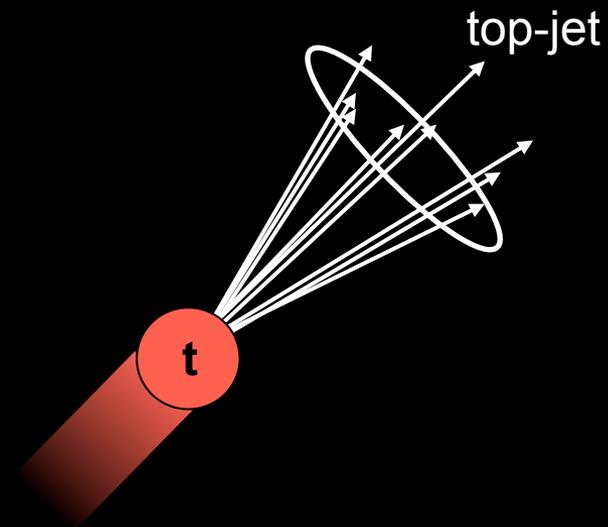
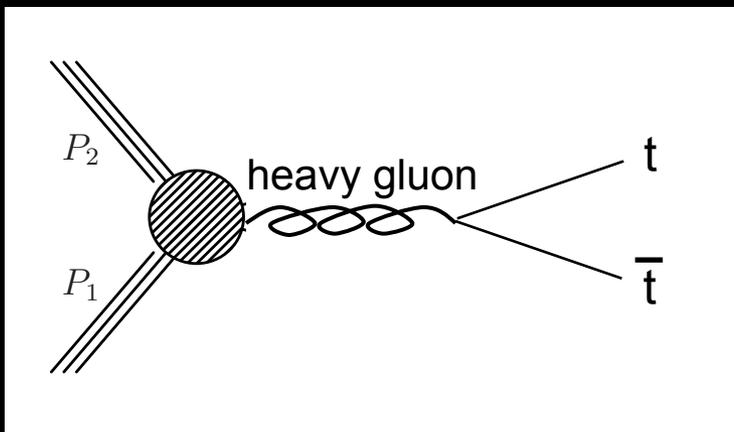


Current situation
3.5–4.0 TeV per beam (CMS)
Weighted sum over momentum regions
No jet substructure (yet)

How NOT to Discover the Heavy Gluon?

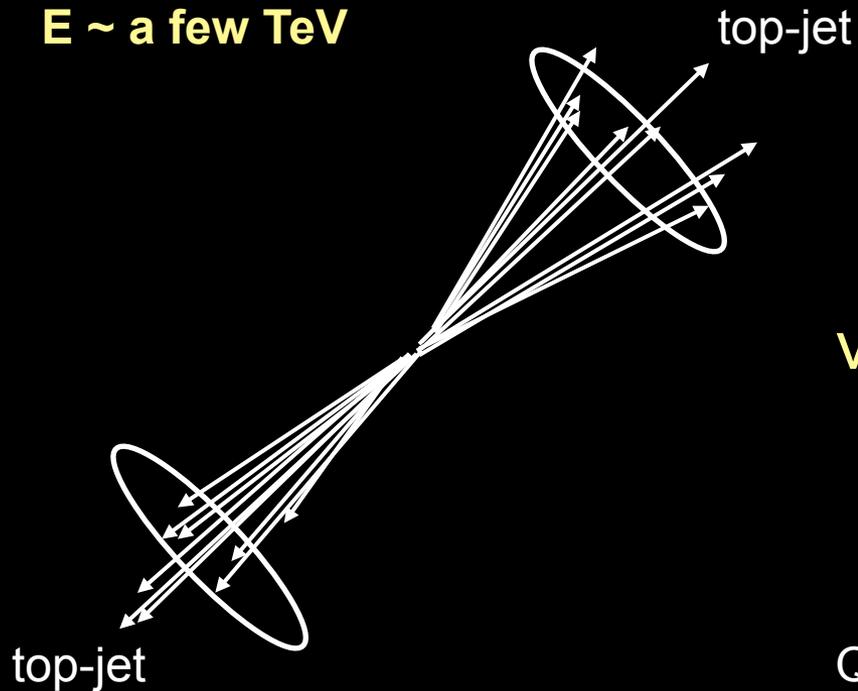


How NOT to Discover the Heavy Gluon?

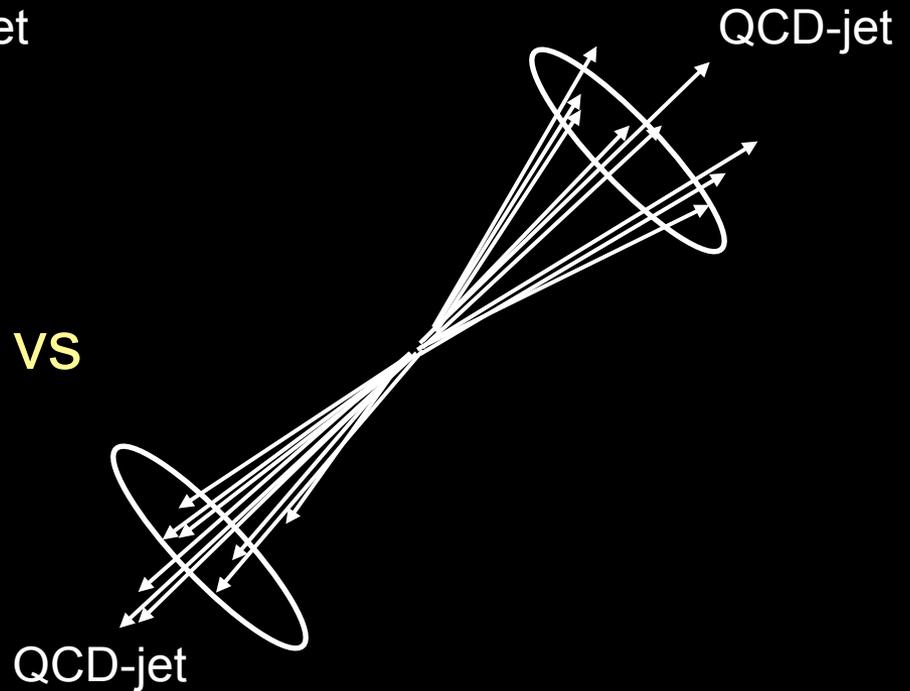


How NOT to Discover the Heavy Gluon?

$E \sim$ a few TeV

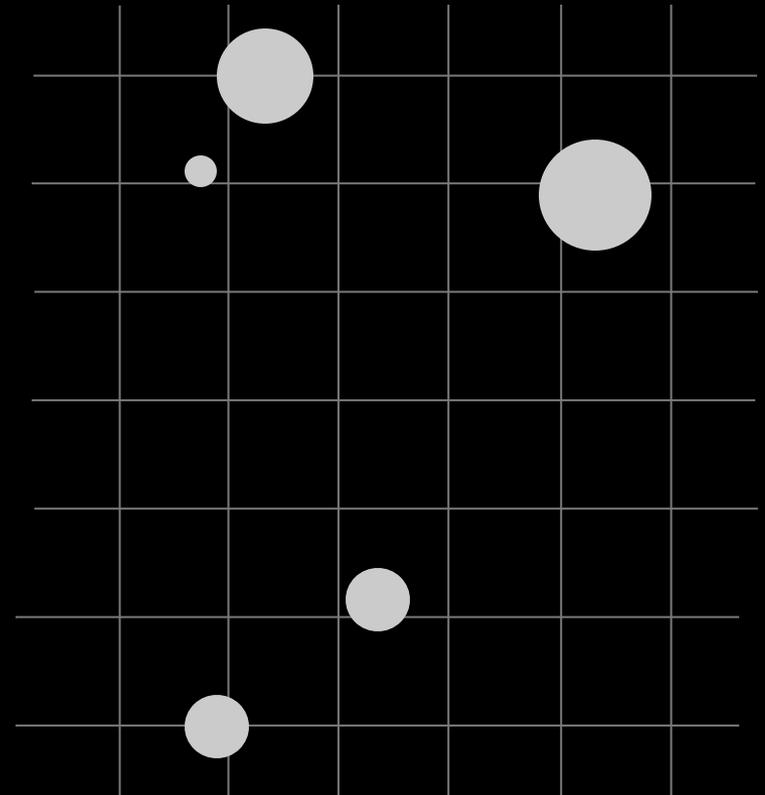
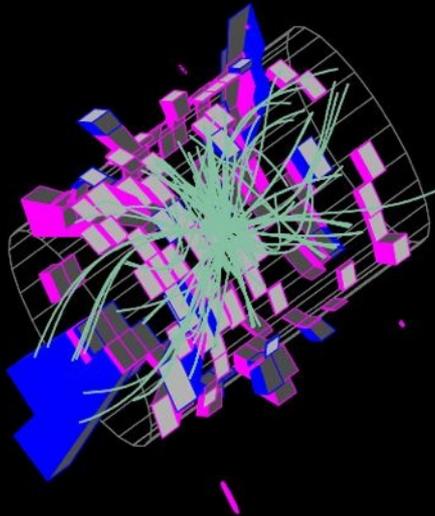


VS

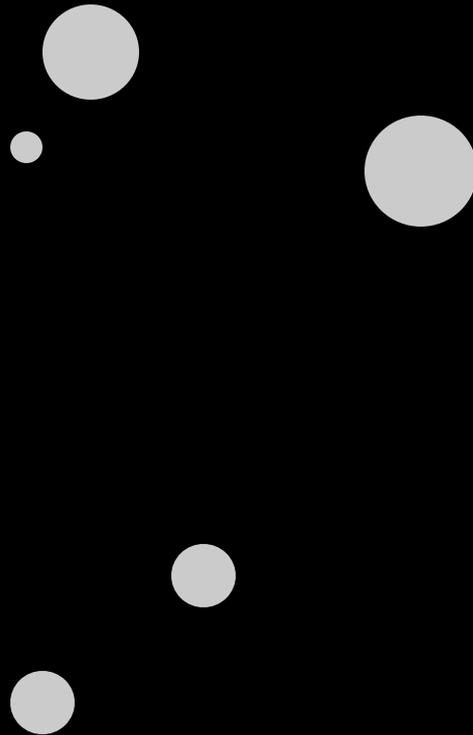


Nearest-Neighbor Jet Clustering Example

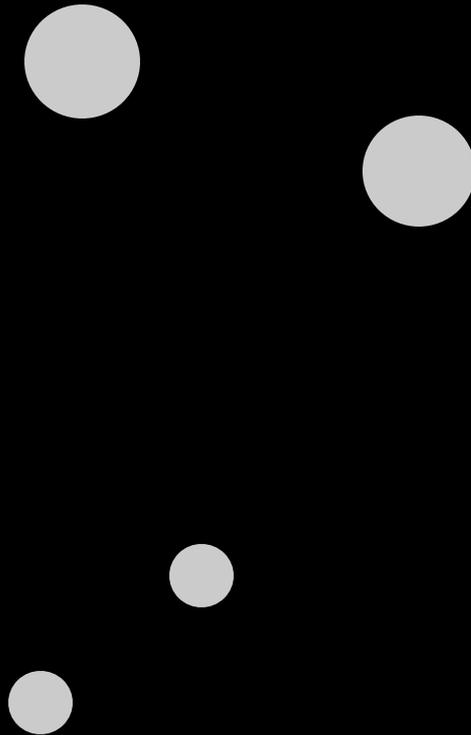
* a.k.a. the Cambridge/Aachen algorithm



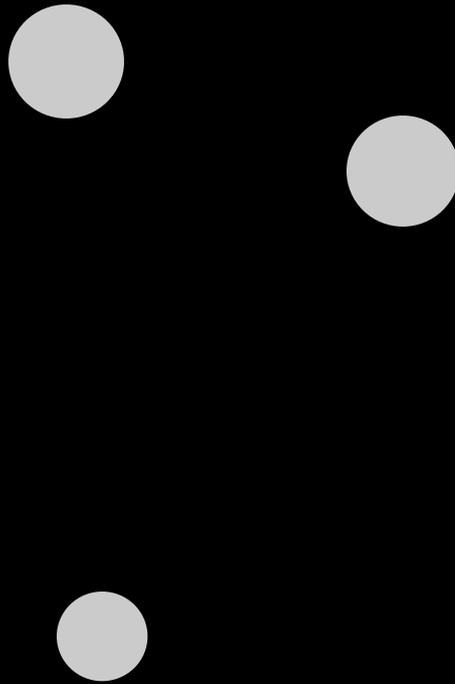
Nearest-Neighbor Jet Clustering Example



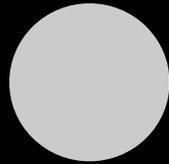
Nearest-Neighbor Jet Clustering Example



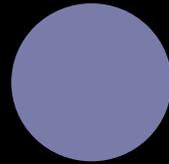
Nearest-Neighbor Jet Clustering Example



Nearest-Neighbor Jet Clustering Example



Nearest-Neighbor Jet Clustering Example

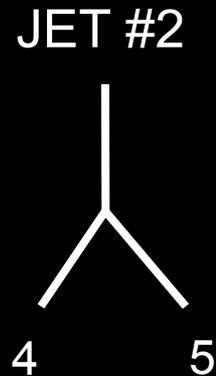
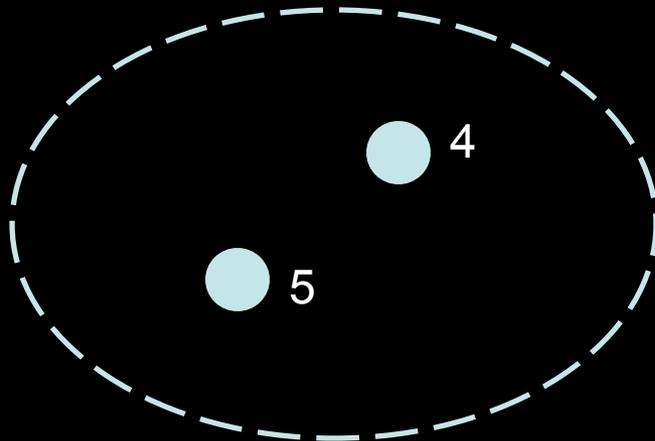
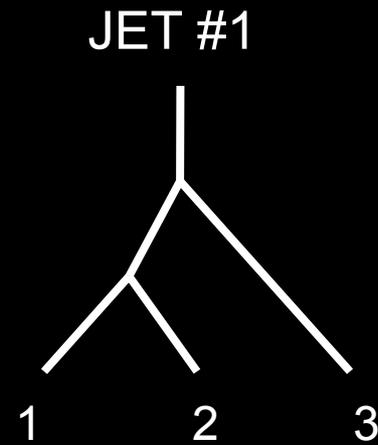
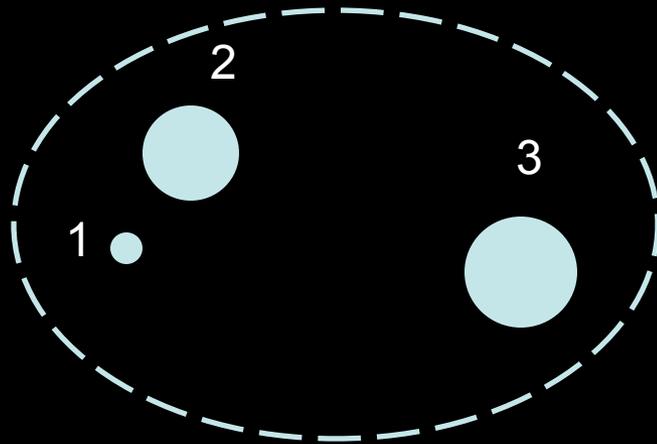


JET #1

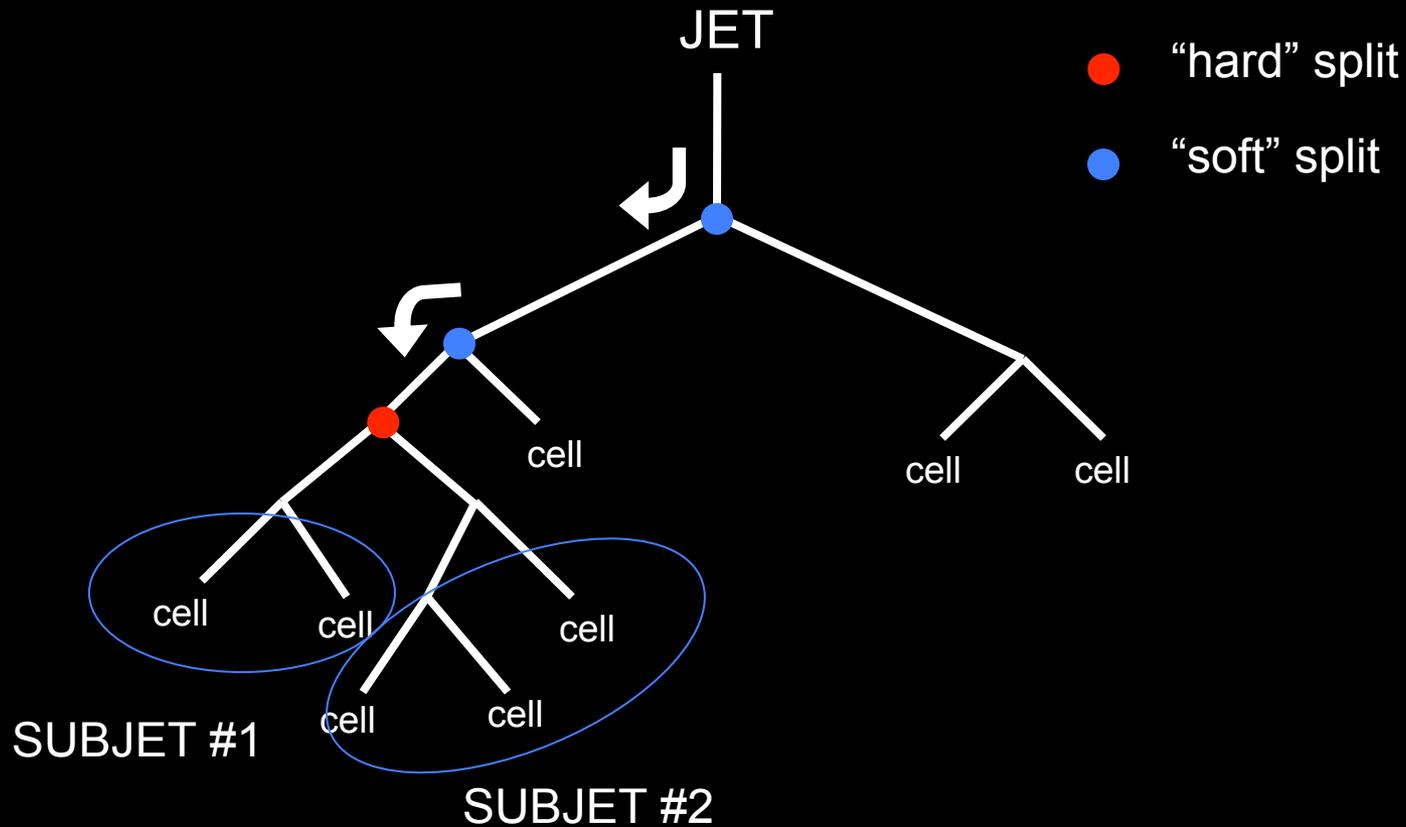


JET #2

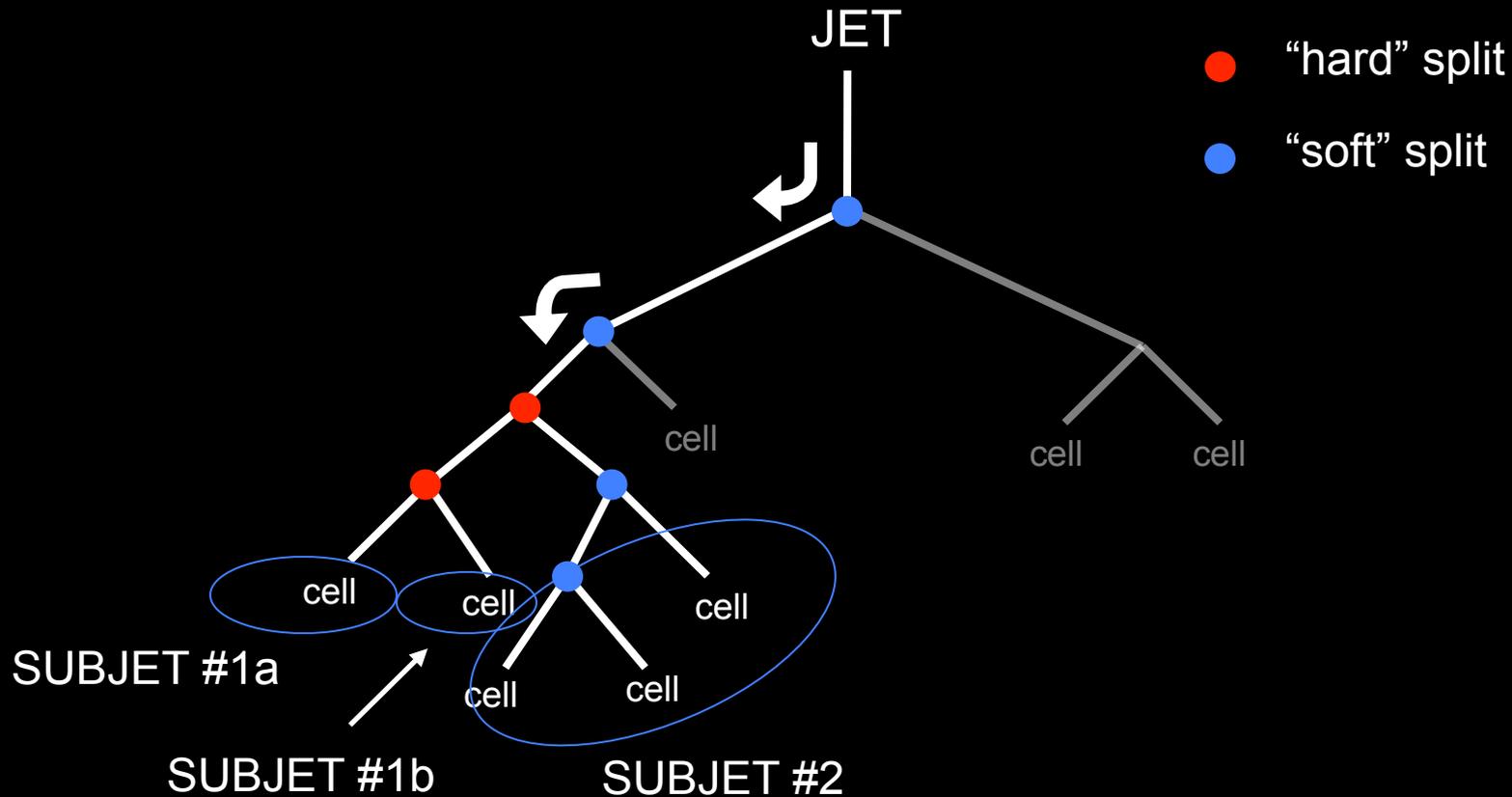
Jet Clustering History



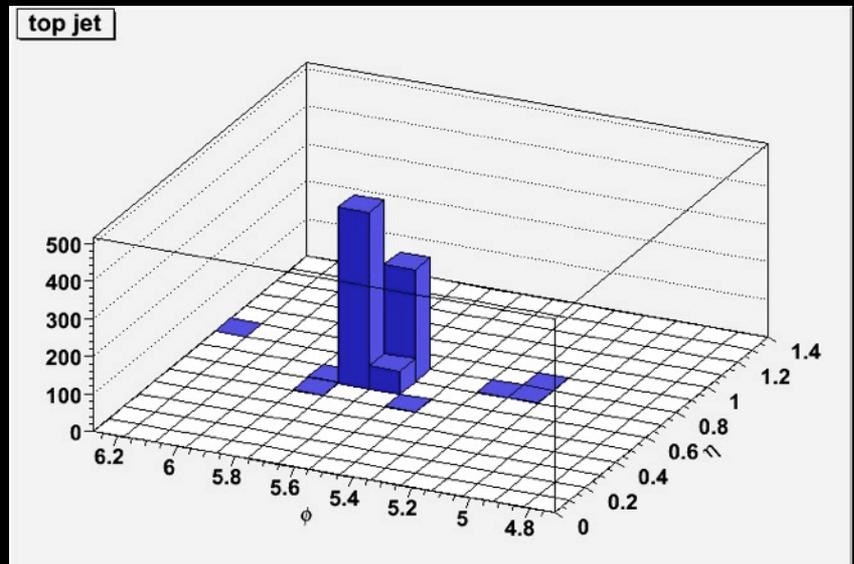
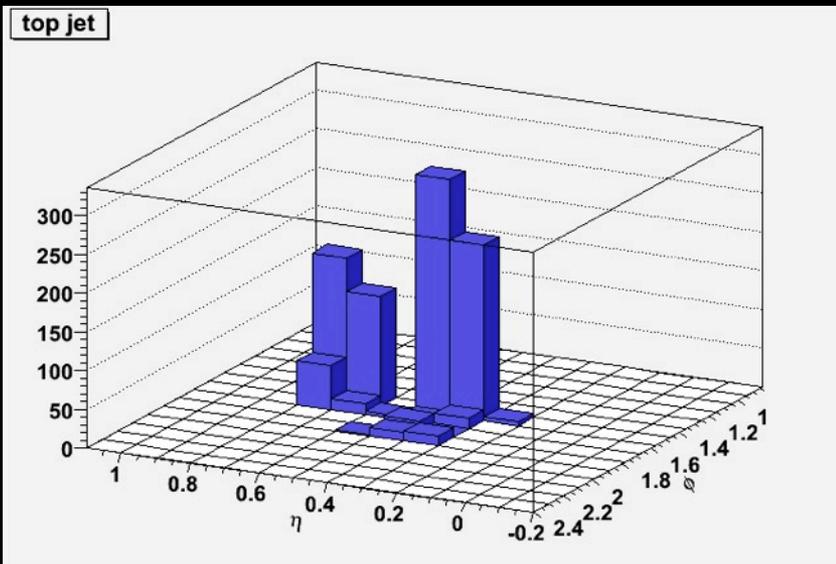
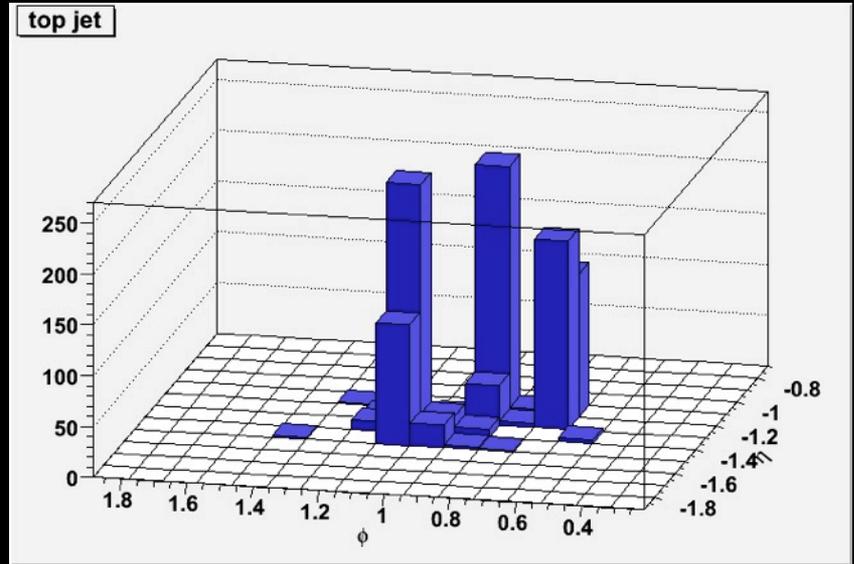
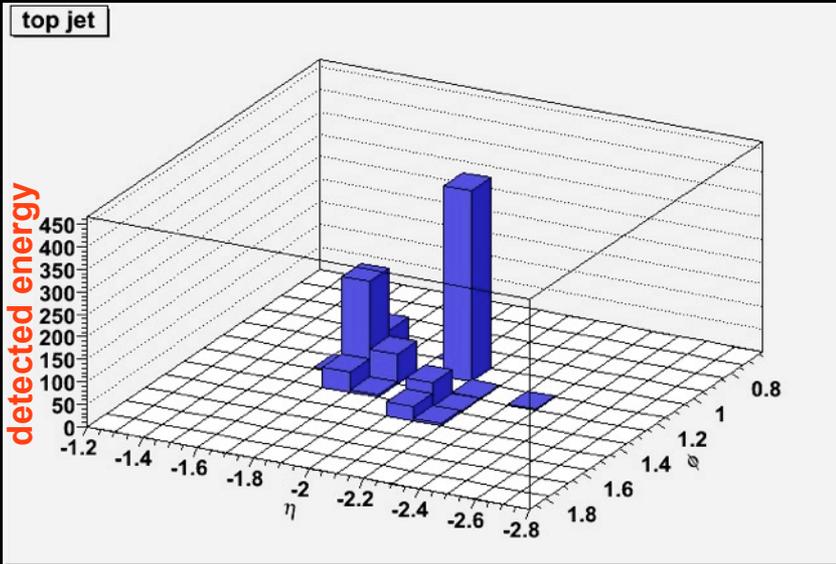
Top-Jet Substructure via Declustering



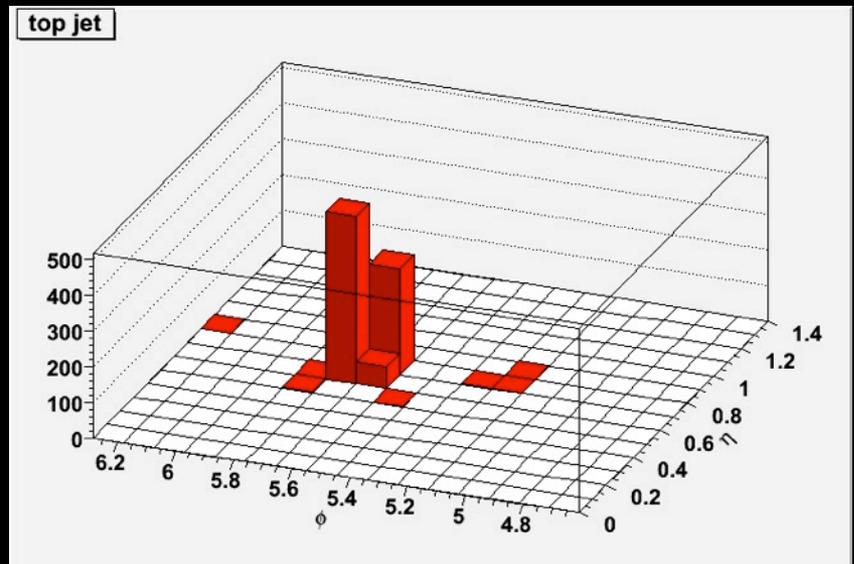
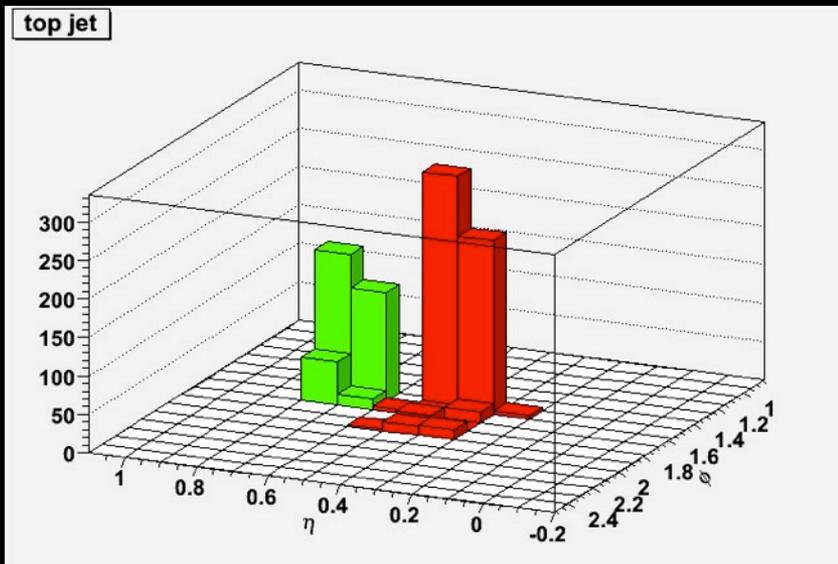
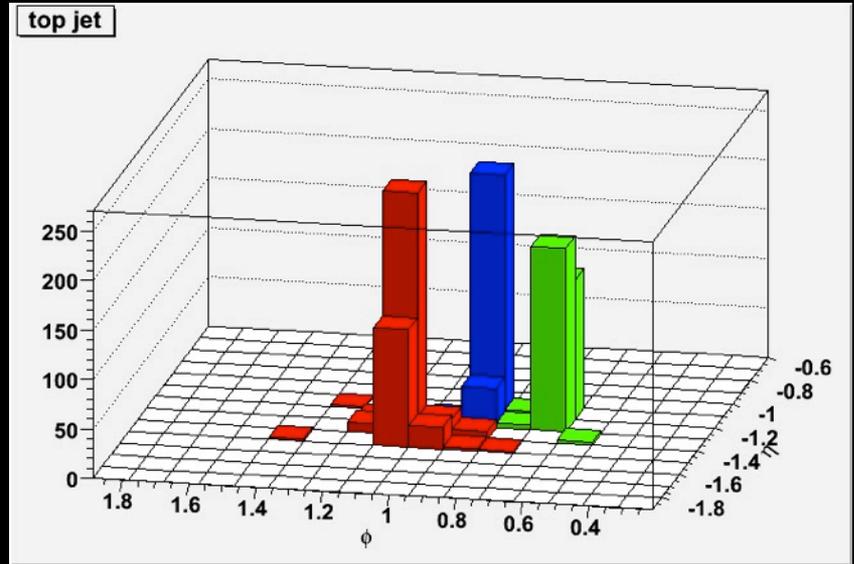
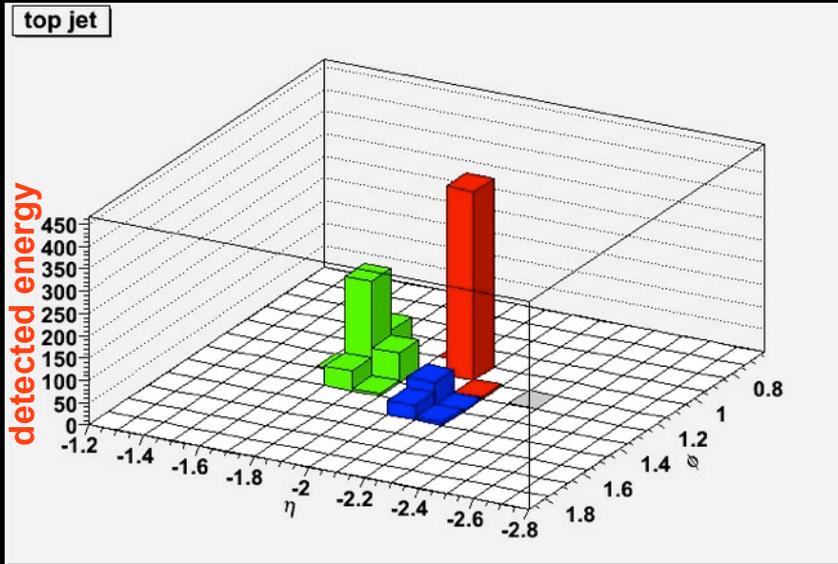
Top-Jet Substructure via Declustering



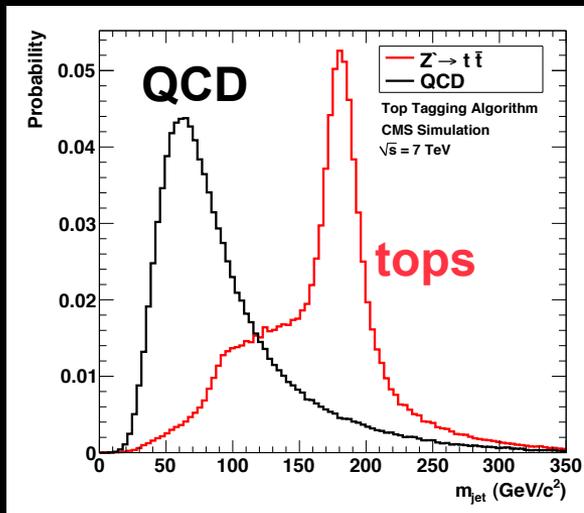
$E = 1$ TeV Top-Jet Gallery



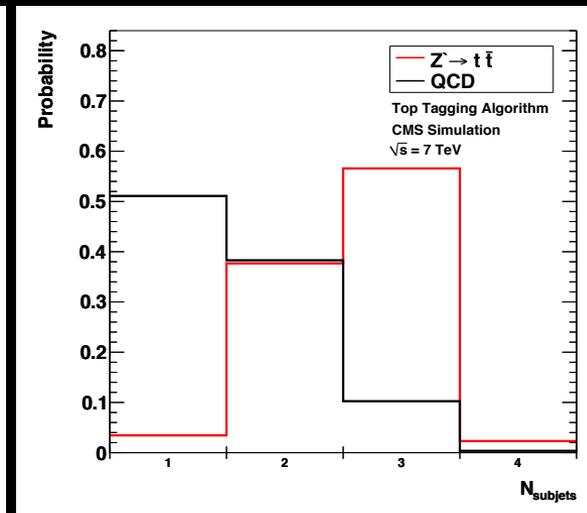
$E = 1$ TeV Top-Jet Gallery



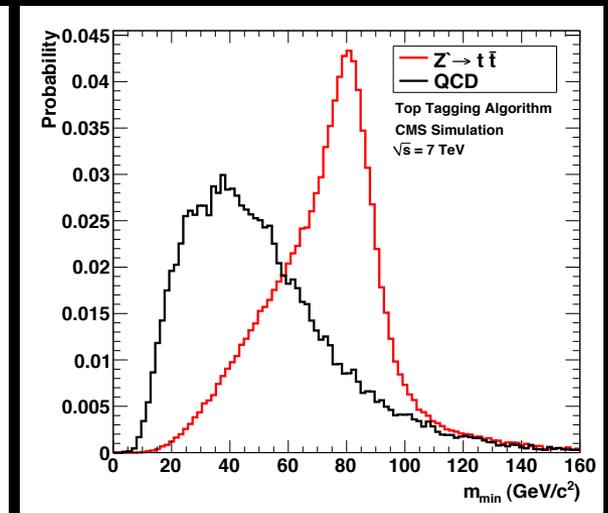
Internal Jet Kinematics



jet mass

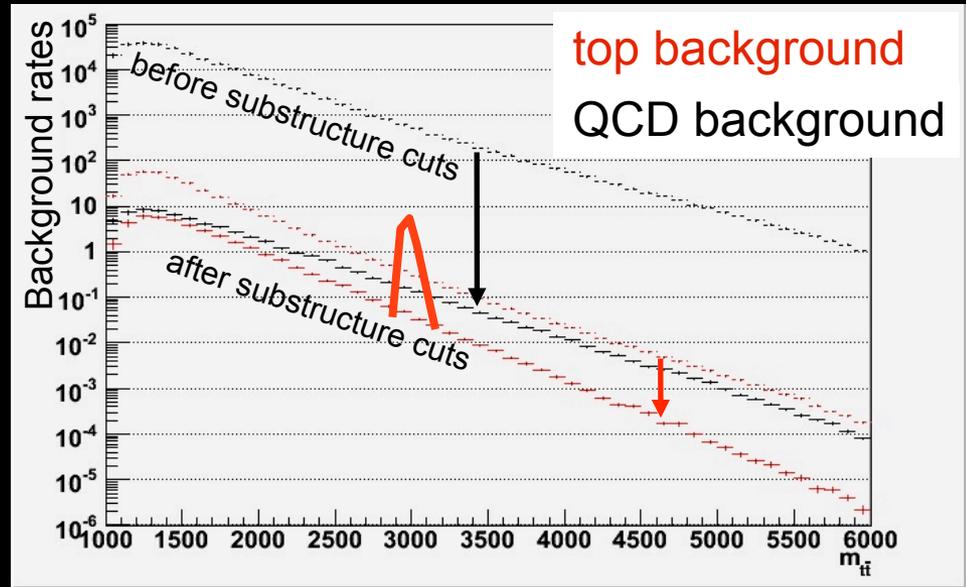
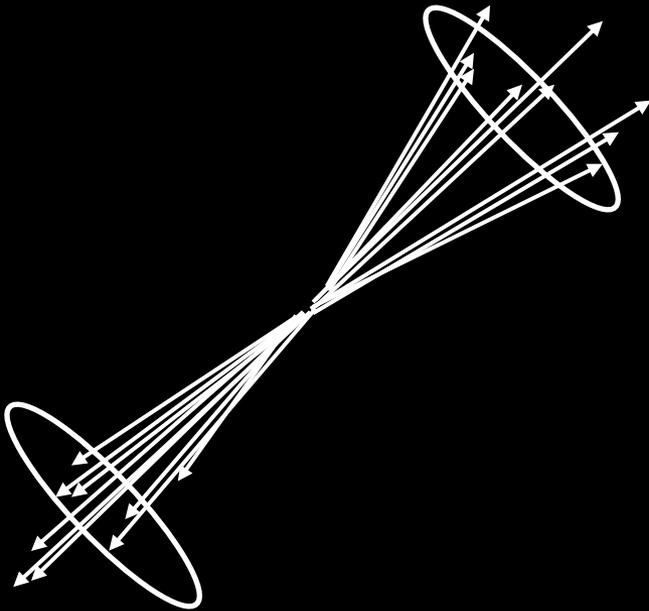


subjects

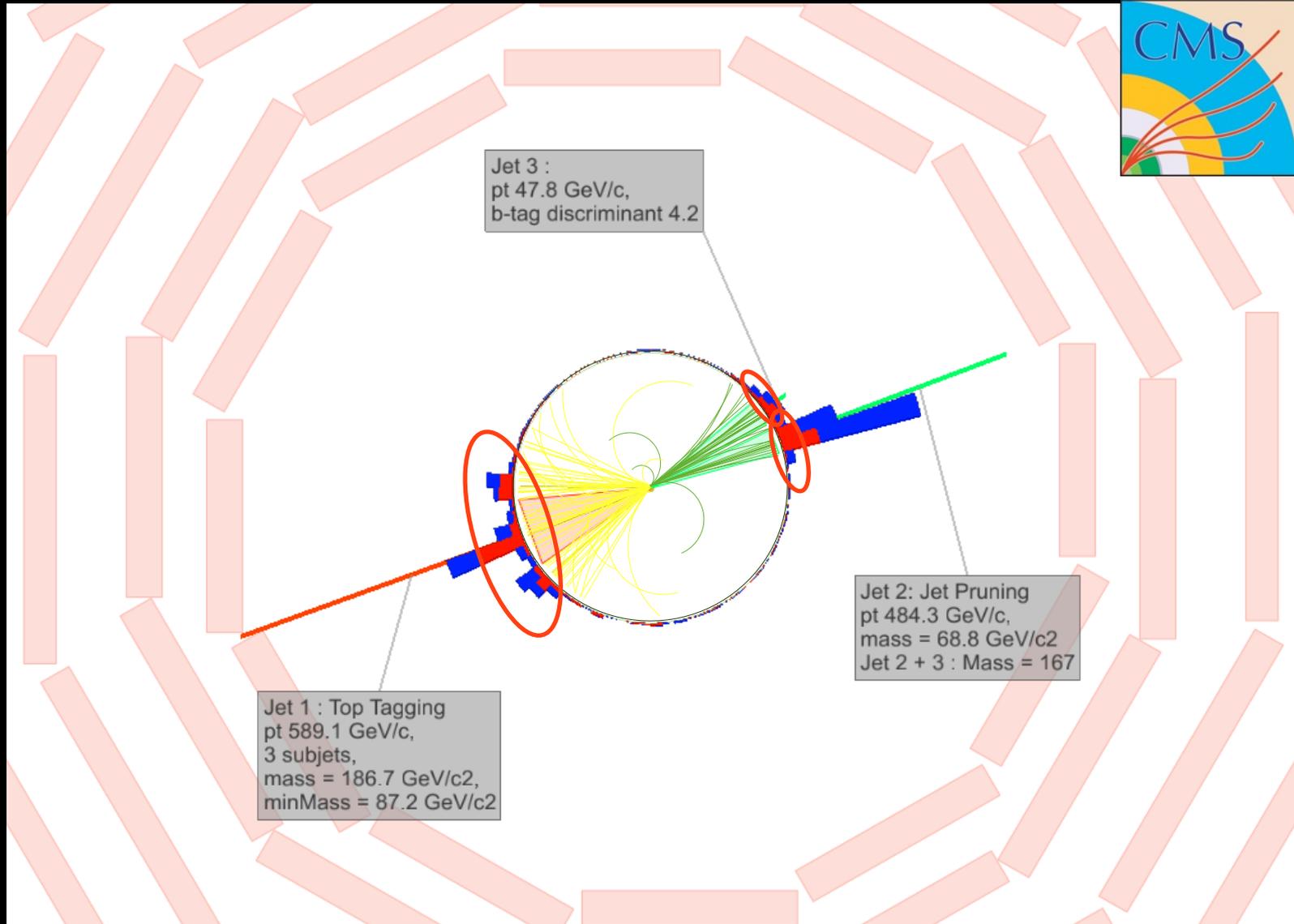


min subject pairwise mass

All-Jets Background Mass Spectra



CMS Heavy Gluon Search

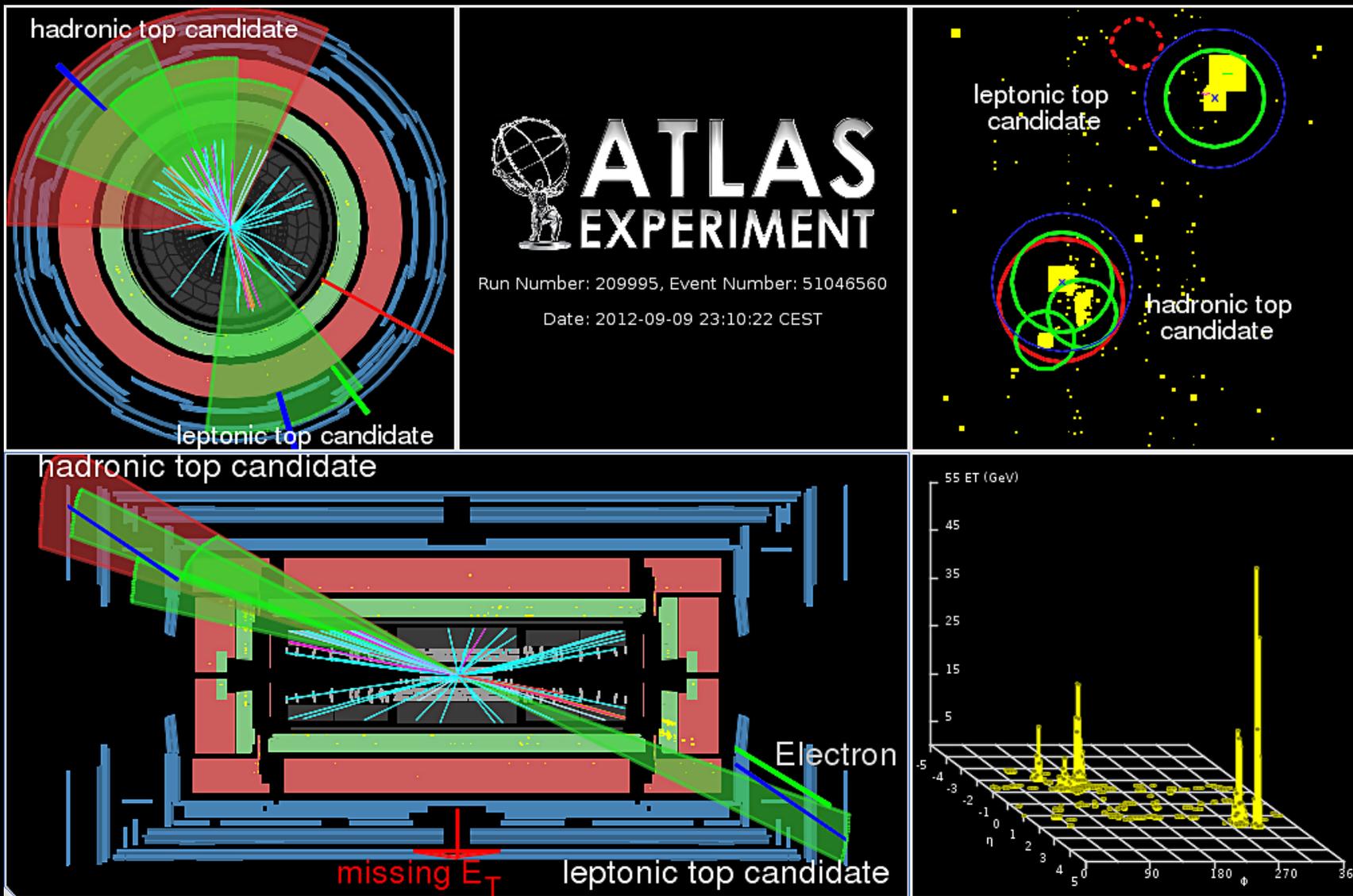


$M > 1.8$ TeV fully jetty

$M > 2.5$ TeV combining channels

arXiv:1309.2030 & Phys Rev Lett

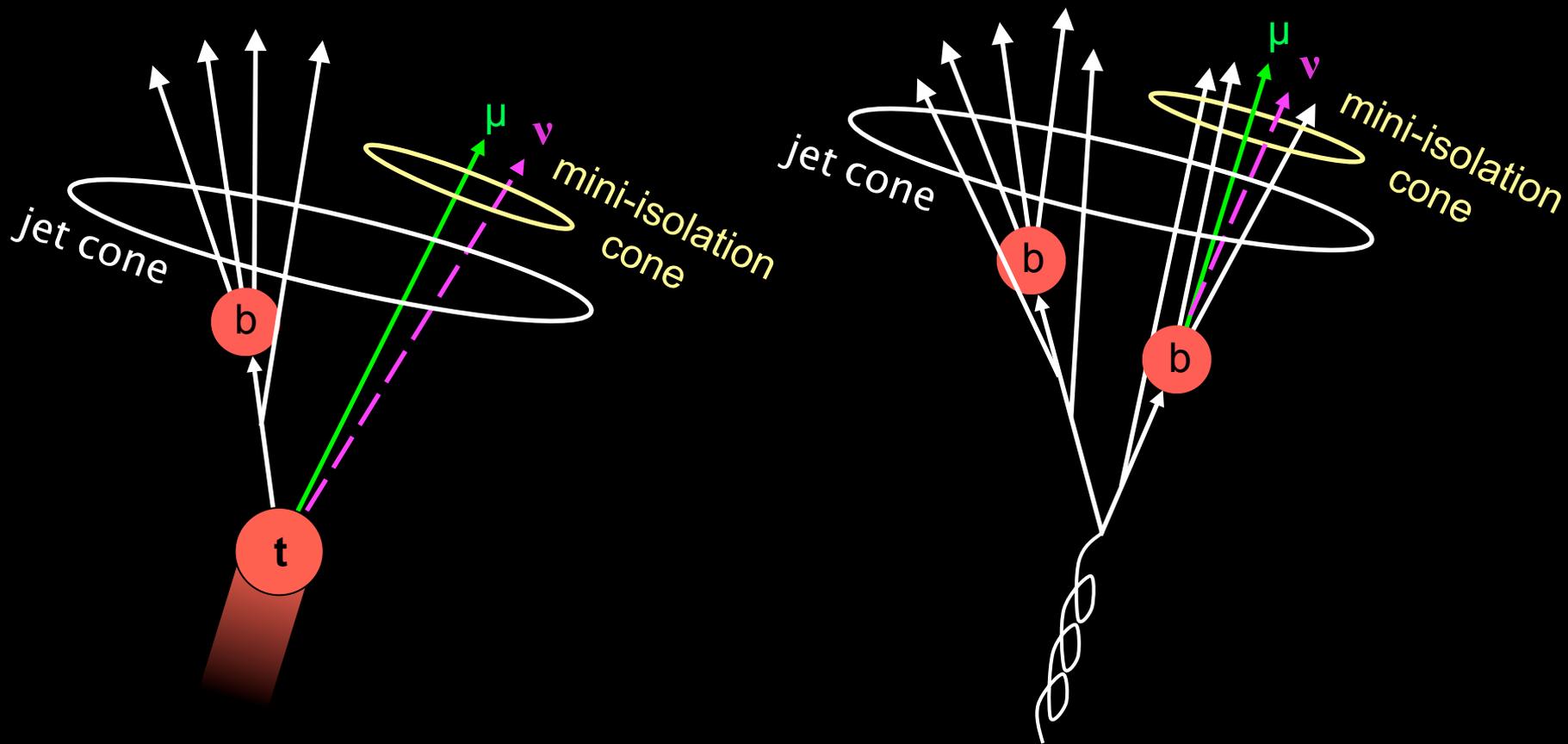
ATLAS Heavy Gluon Search



$M > 1.6$ TeV fully jetty

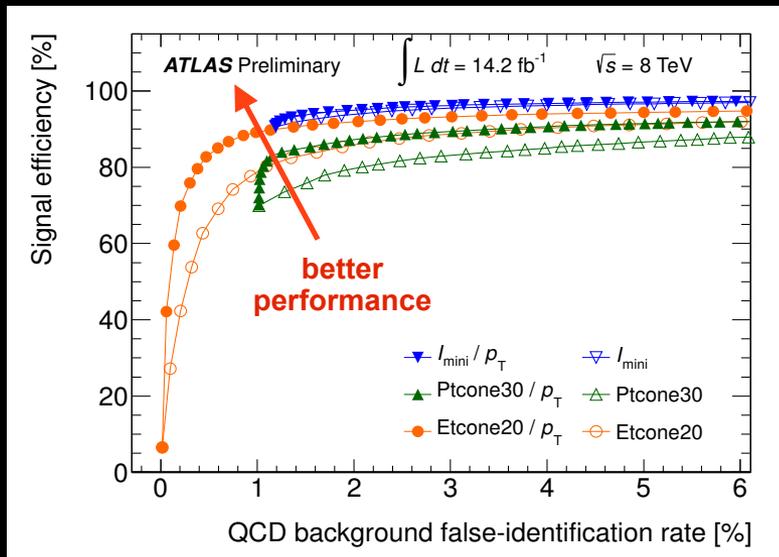
$M > 2.0$ TeV semi-leptonic

Semileptonic “Top-Jets”

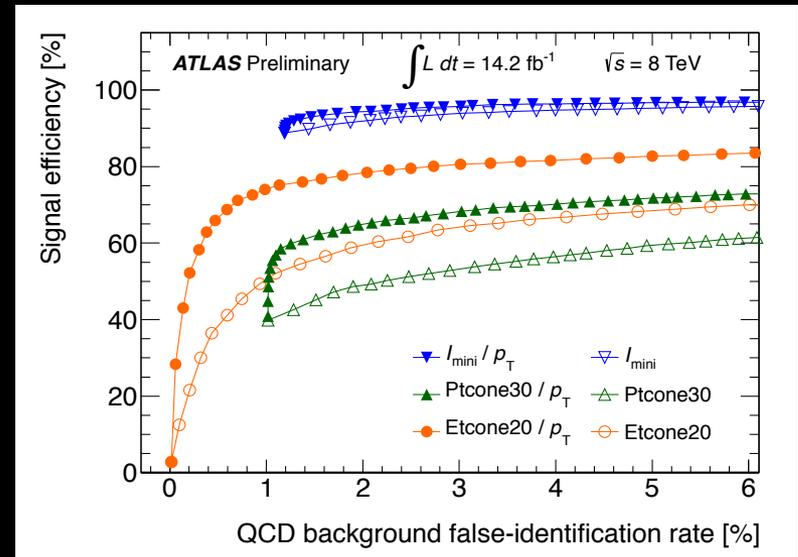


mini cone angular radius $\propto 1/E(\mu)$

Mini-Isolation Performance



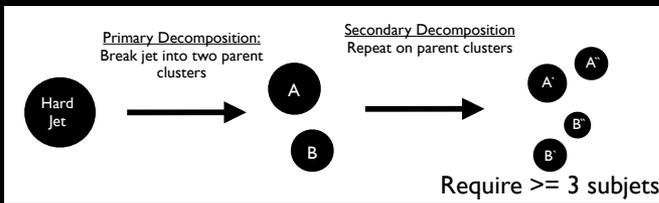
Low-energy top quarks



Energetic top quarks from
2 TeV resonance decay

Substructure Tactics Multiply

Declustering



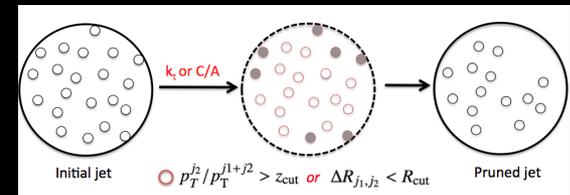
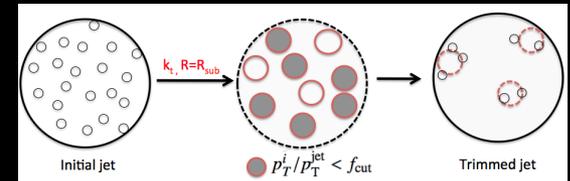
Analytic Methods

$$OV_3 = \max_{\{\tau_n\}} \exp \left[- \sum_{i=1}^3 \frac{1}{2\sigma_i^2} \left(E_i - \sum_{\Delta R(\text{topo},i) < 0.2} E_{\text{topo},i} \right)^2 \right]$$

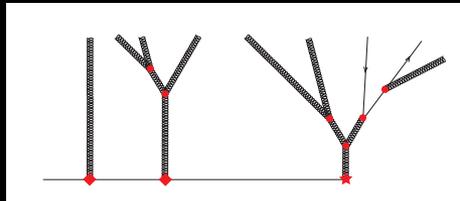
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, R_{2,k}, \dots, R_{N,k} \}$$

$$\Delta \mathcal{G}(R) \equiv R \frac{\sum_{i \neq j} p_{T,i} p_{T,j} \Delta R_{ij}^2 K(R - \Delta R_{ij})}{\sum_{i \neq j} p_{T,i} p_{T,j} \Delta R_{ij}^2 \Theta(R - \Delta R_{ij})}$$

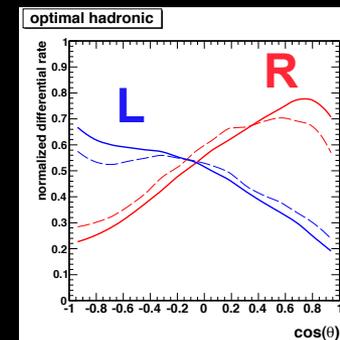
Grooming



Color-flow / Radiation pattern

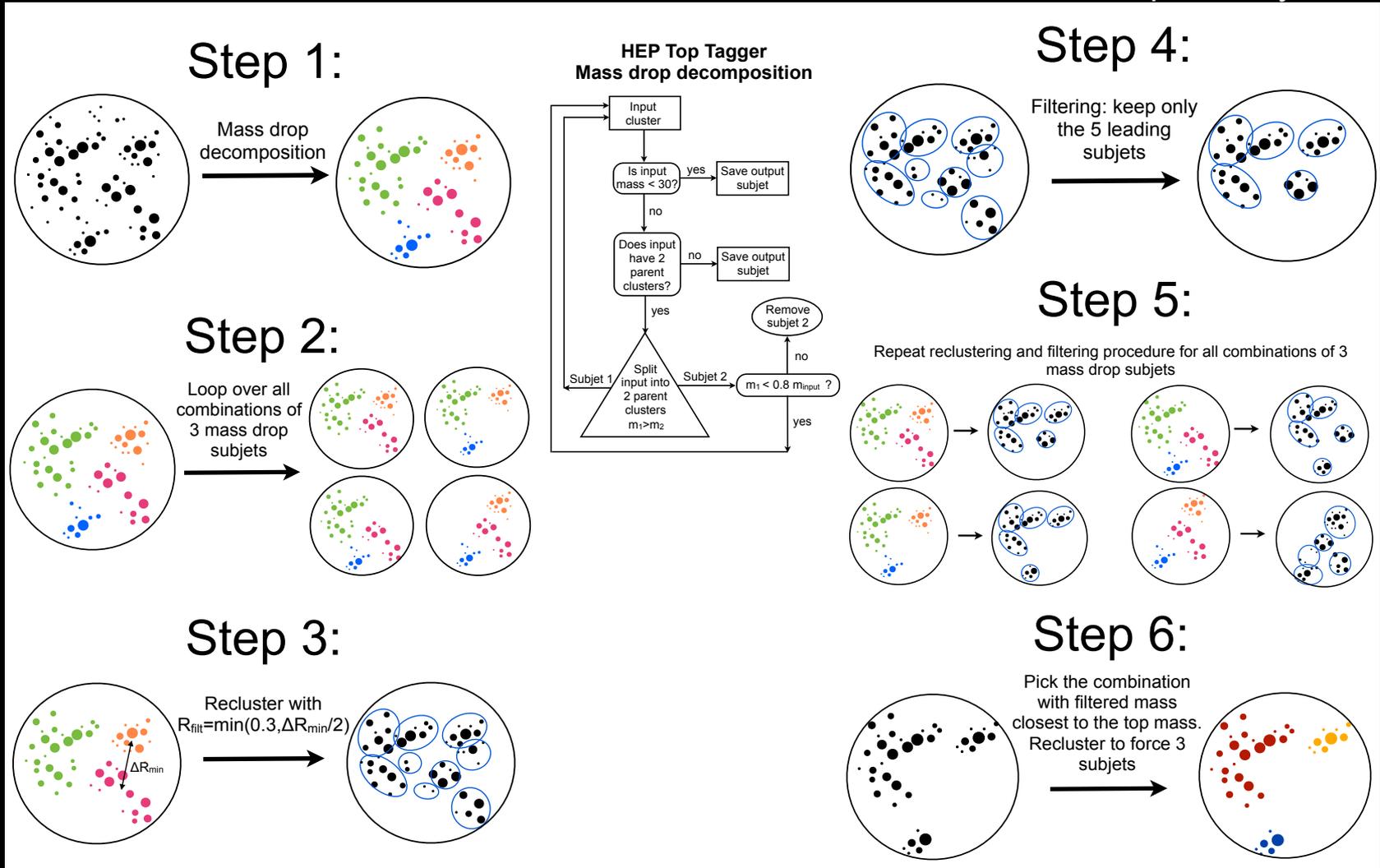


Polarization

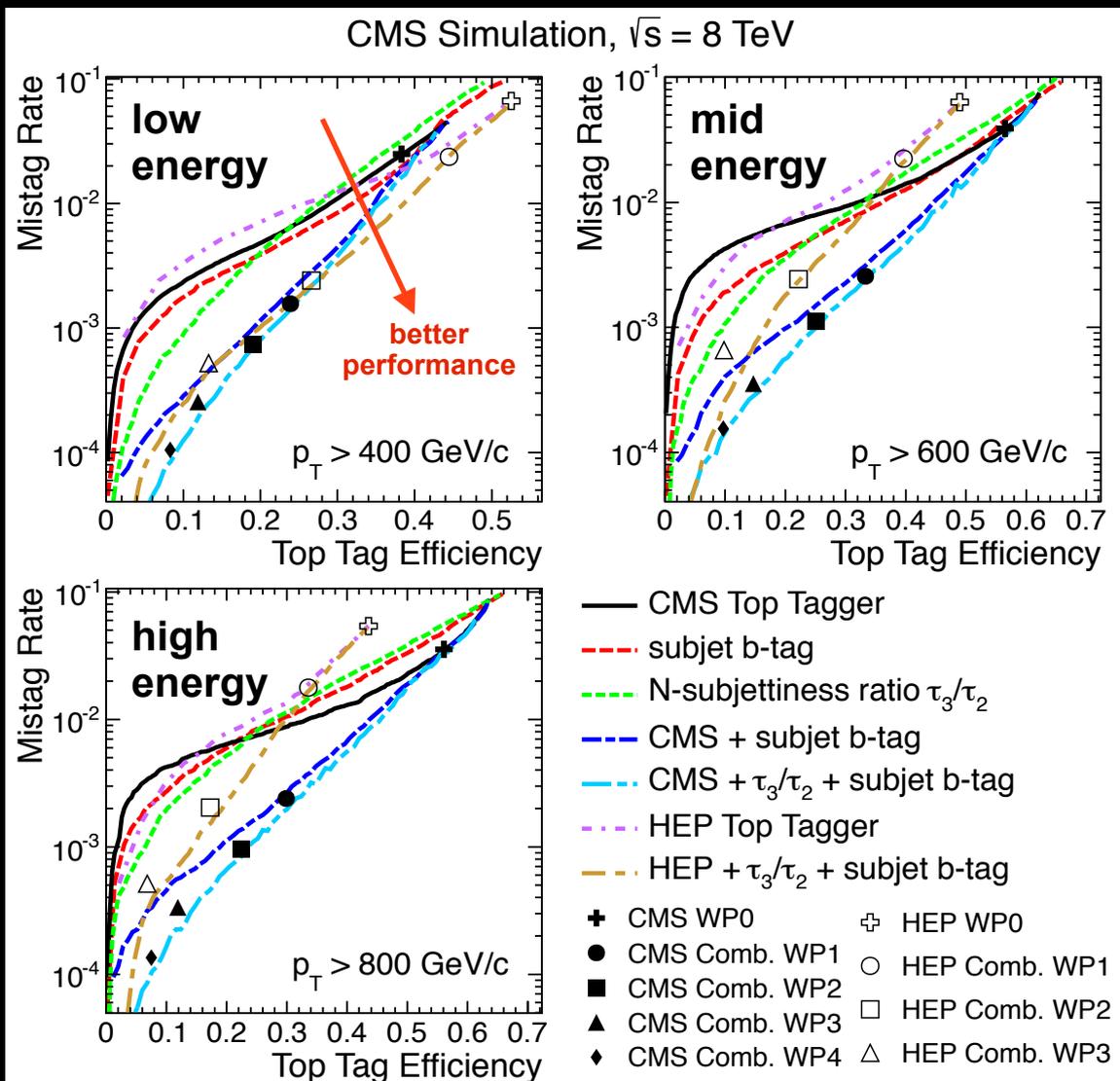


An ATLAS “Top-Tagger”

* also now explored by CMS



New CMS “Top-Taggers”

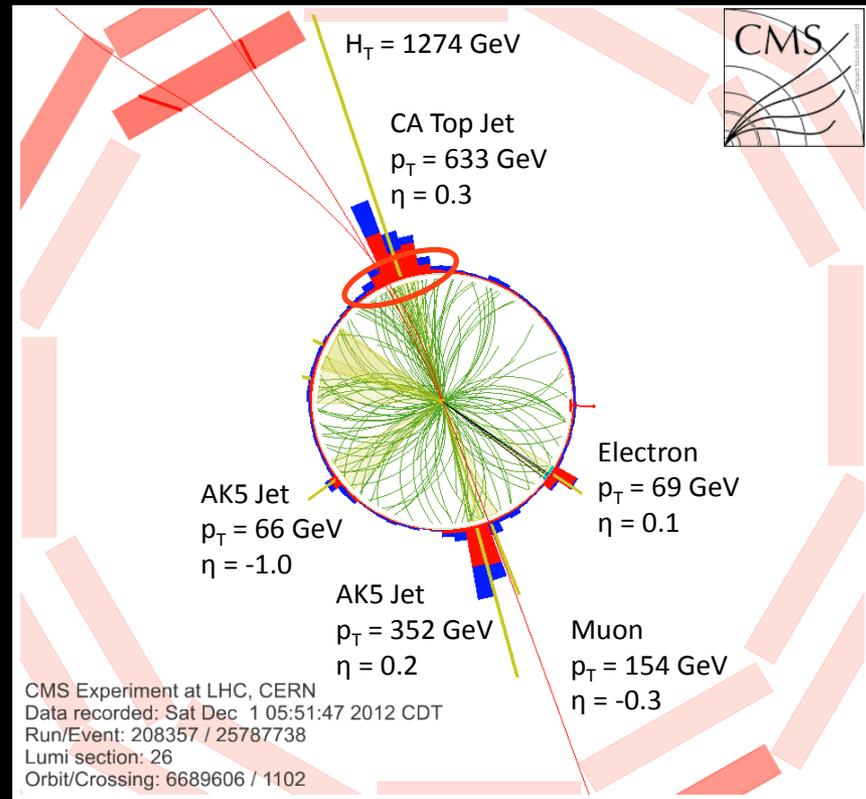


Substructure Applications Multiply

- resonant WW / WZ / WH / ZH
- supersymmetric particle decays
- composite fermion decays
- top + Higgs associated production
- TeV-scale weak boson scattering
- energetic Higgs decays to W 's, tau leptons
- spin measurements
- dark matter + Higgs associated production
- very high-multiplicity exotic particle decays
-

Heavy Exotic “Top Partner”

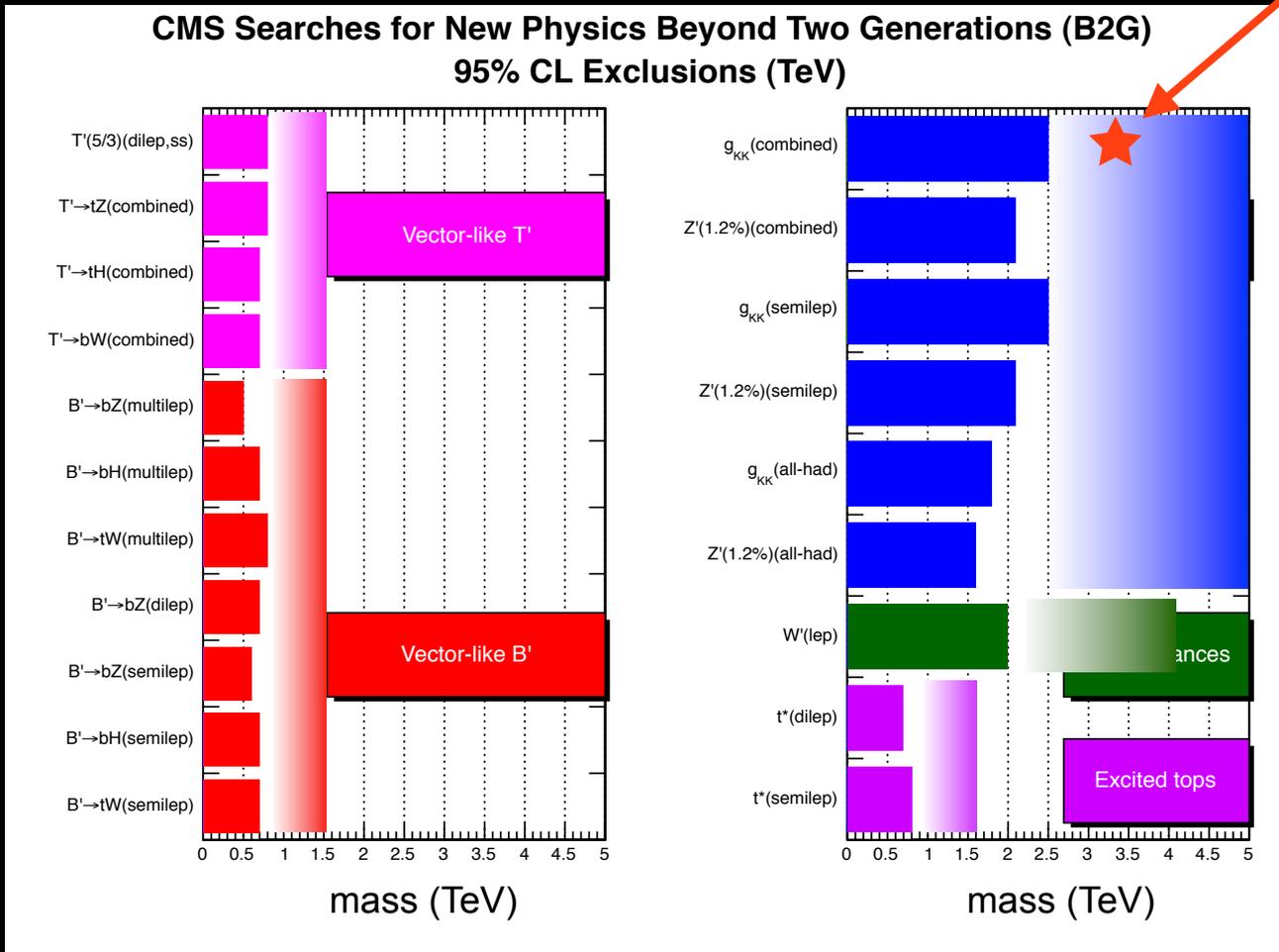
$$Q = +5/3$$



Mass limit $M > 770 \text{ GeV}$

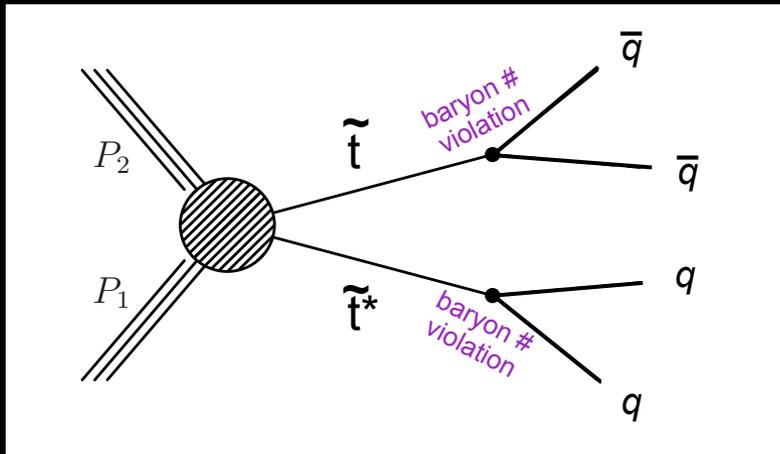
LHC 2020 Assessment?

The next discovery?

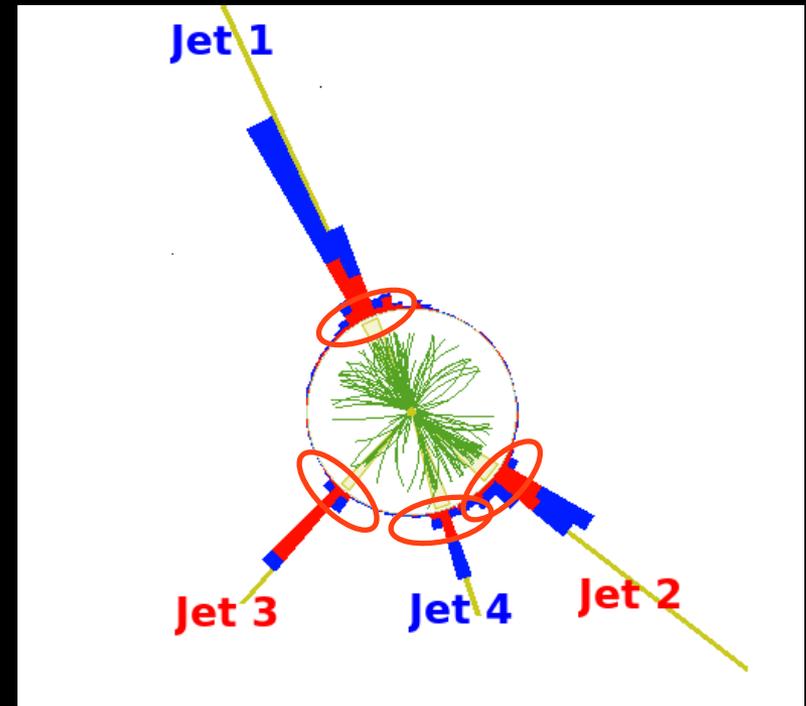


Composite Higgs / Extra-dimensions simplified models

Hiding the Supersymmetric Top-Quark



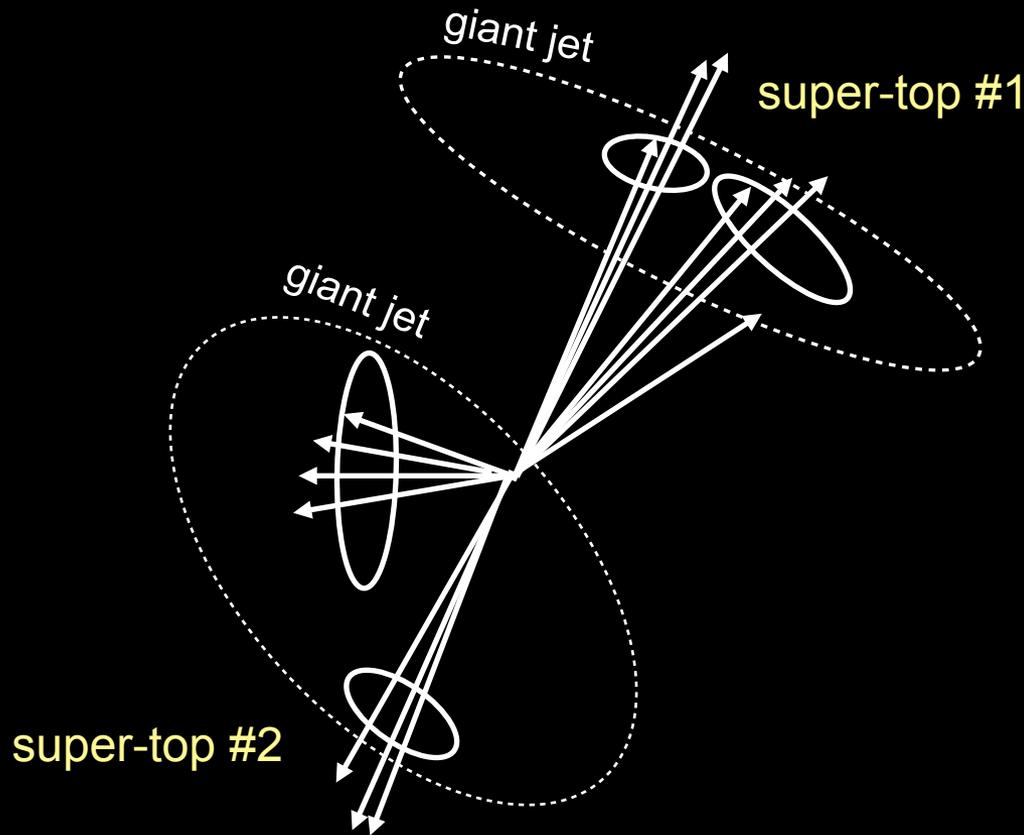
100% jetty decay



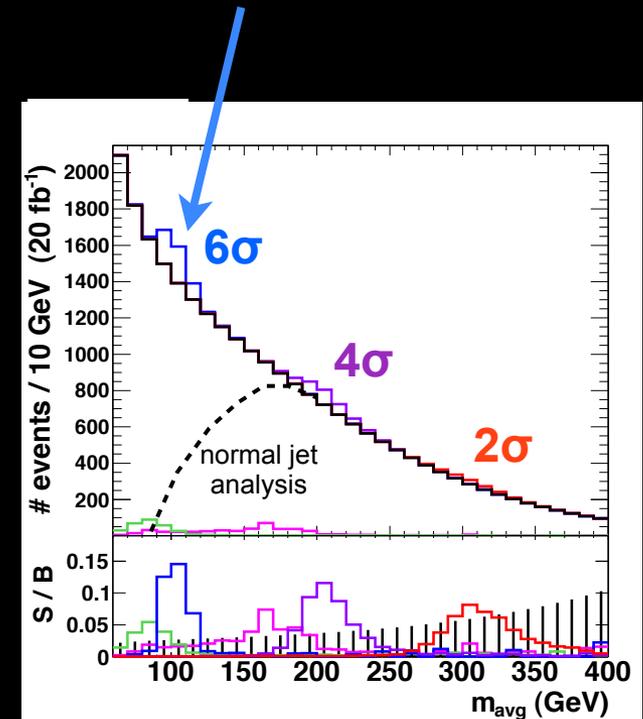
No sensitivity at LHC

(Pre-existing limit: $M > 100$ GeV)

Recapturing the Signal with Substructure



The next discovery? (2014)



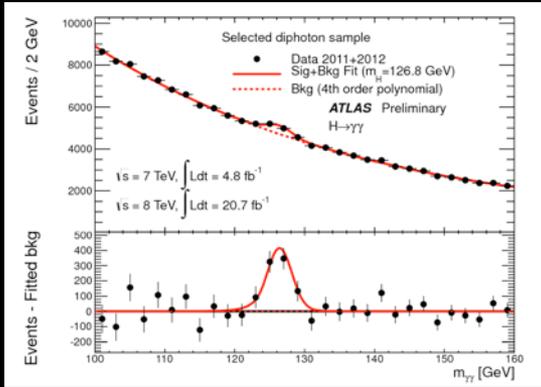
Our simulation of current data set

(background curve derivable from data)

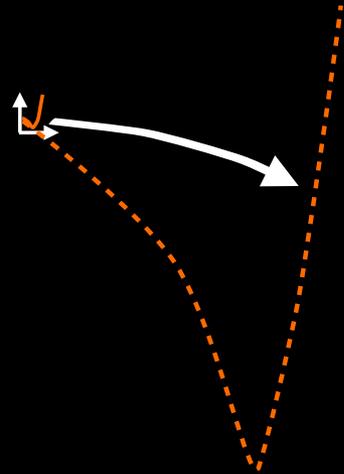
Some Next Steps

- Continue expanding applications
- “Event substructure”
- Color charge measurement
- Limitations (e.g. weak radiation)
- Future colliders

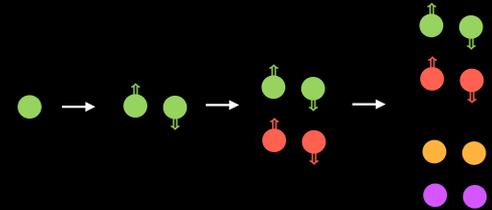
Summary



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Summary

