Beyond the Standard Model Physics
African School of Physics 2016

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RUTGERS
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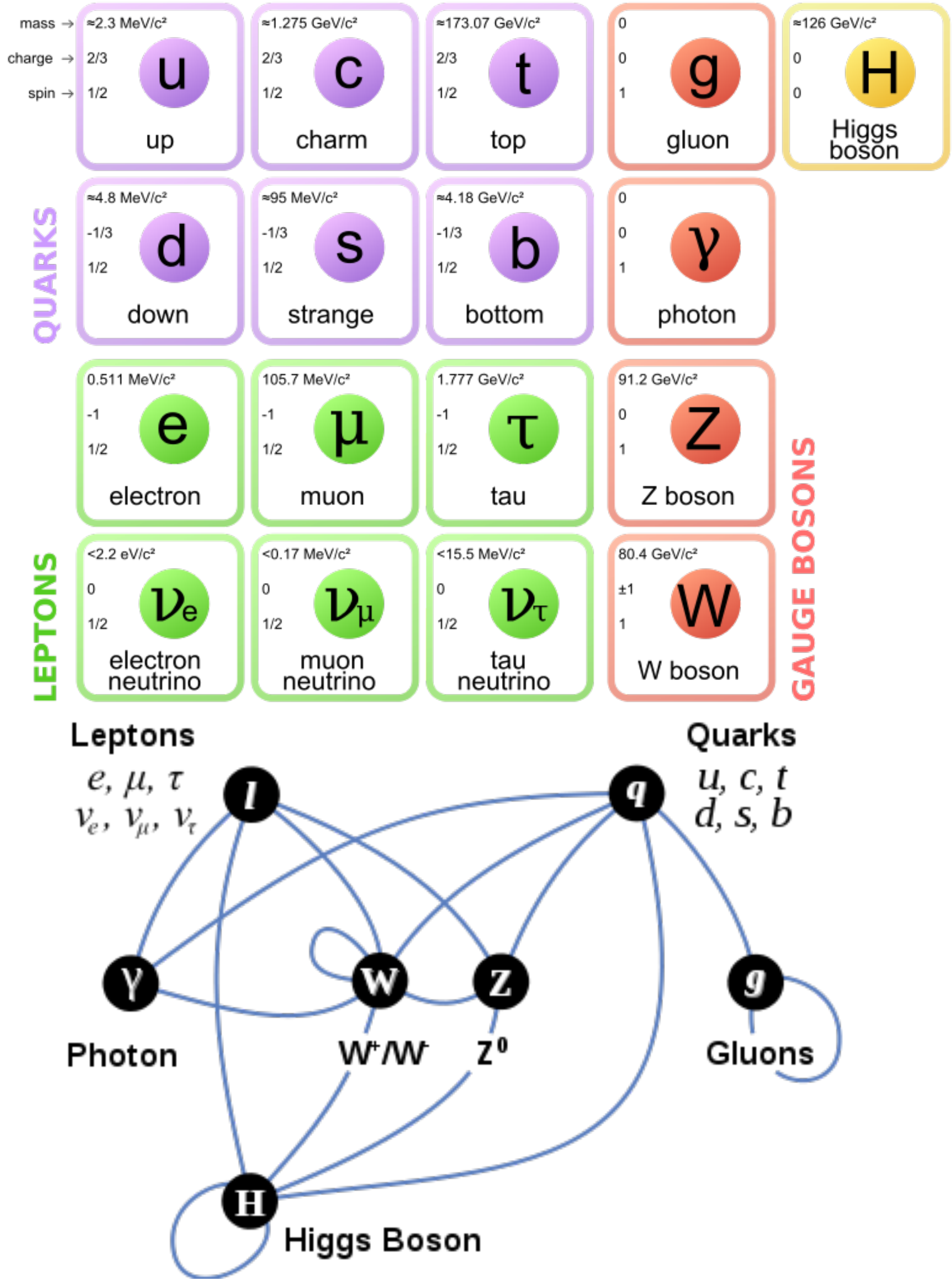
OF NEW JERSEY

OUTLINE

- The questions of particle physics
- The experimental apparatus
- Searches
  - Bump Hunts
  - Dark Matter
  - Long-lived particles
- Conclusions

PARTICLE PHYSICS

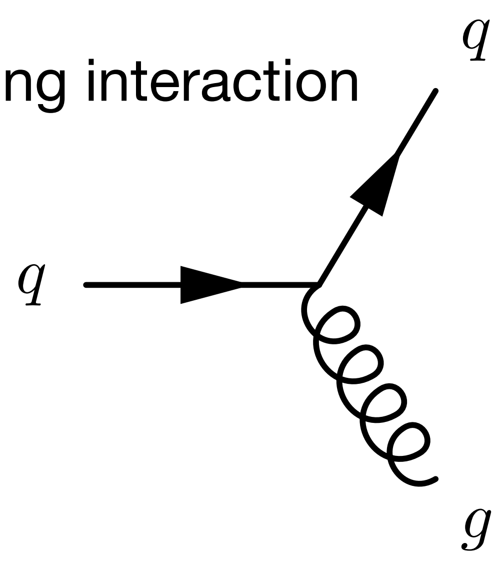
- The standard model of particle physics describes a remarkable range of phenomena
  - The interactions of particles are described by Quantum Field Theory (i.e. Quantum Mechanics + Special Relativity)
  - Matter and energy, at the lowest level of organization, is composed of some combination of quarks and leptons interacting via force carrying bosons



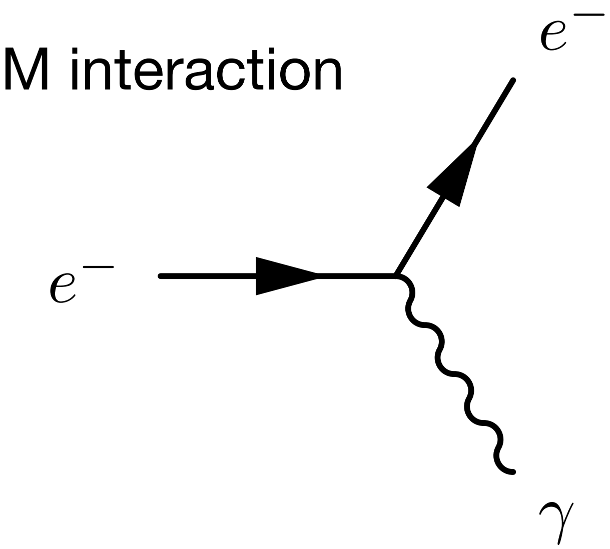
FOUR FORCES OF NATURE

- Strong Force (~10)
  - Keeps the nucleons in the atom together
  - All “colored” particles (e.g. quarks/gluons) interact via strong force
  - Force is mediated by the gluon
- Electromagnetic Force (~10^{-2})
  - All “charged” particles interact under this force
  - Field description discovered by Maxwell
  - Force is mediated by the photon
- Weak Force (~10^{-13})
  - Governs many radioactive decays ($n\rightarrow p^{+}e^{-}v$)
  - Both leptons and quarks interact under this force
  - Force is mediated by “heavy photons” ($W^{\pm}$ and Z^{0})
- Gravitational Force (~10^{-42})
  - Not a part of the standard model
  - non-renormalizable quantum theory
  - Force is mediated by the graviton

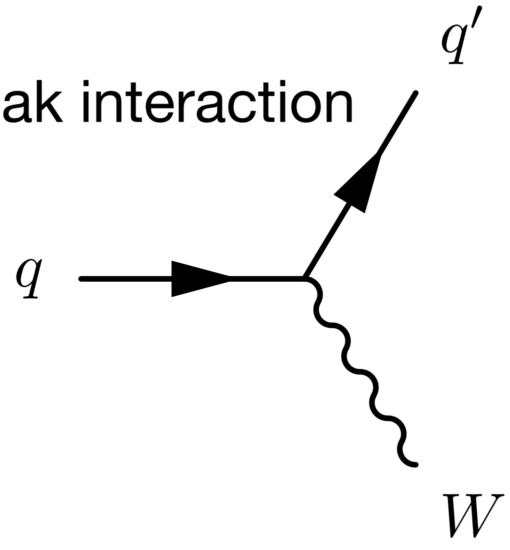
strong interaction



EM interaction



Weak interaction

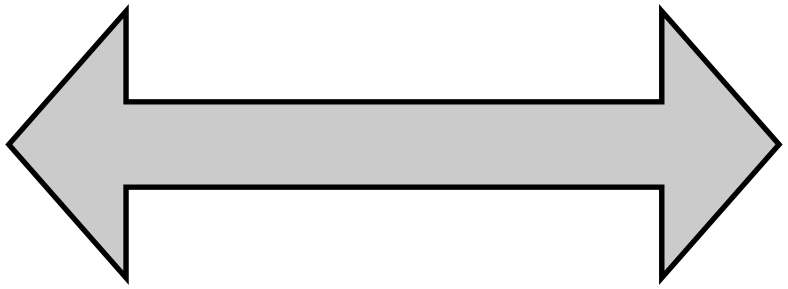


WHAT IS PARTICLE PHYSICS ABOUT?

- Particle physics is not *principally* about particles
  - There is more to particle physics than simply measuring and cataloging the properties of particles and related phenomena
    - Particle physics is primarily concerned with understanding the *structure* of energy and matter at the lowest (fundamental) level of reality
    - Classifying the different types of particles, their properties, and their interactions, helps us understand this structure

NEWTON AND UNIFICATION

Celestial Gravity



$$\mathbf{F} = -\frac{G_{\rm N} m_1 m_2}{\mathbf{r}^2}\hat{\mathbf{r}}$$

Terrestrial Gravity

CAVENDISH

- In 1797-98, 110 years after Newton published *Principia*, Cavendish performed his famous torsion experiment

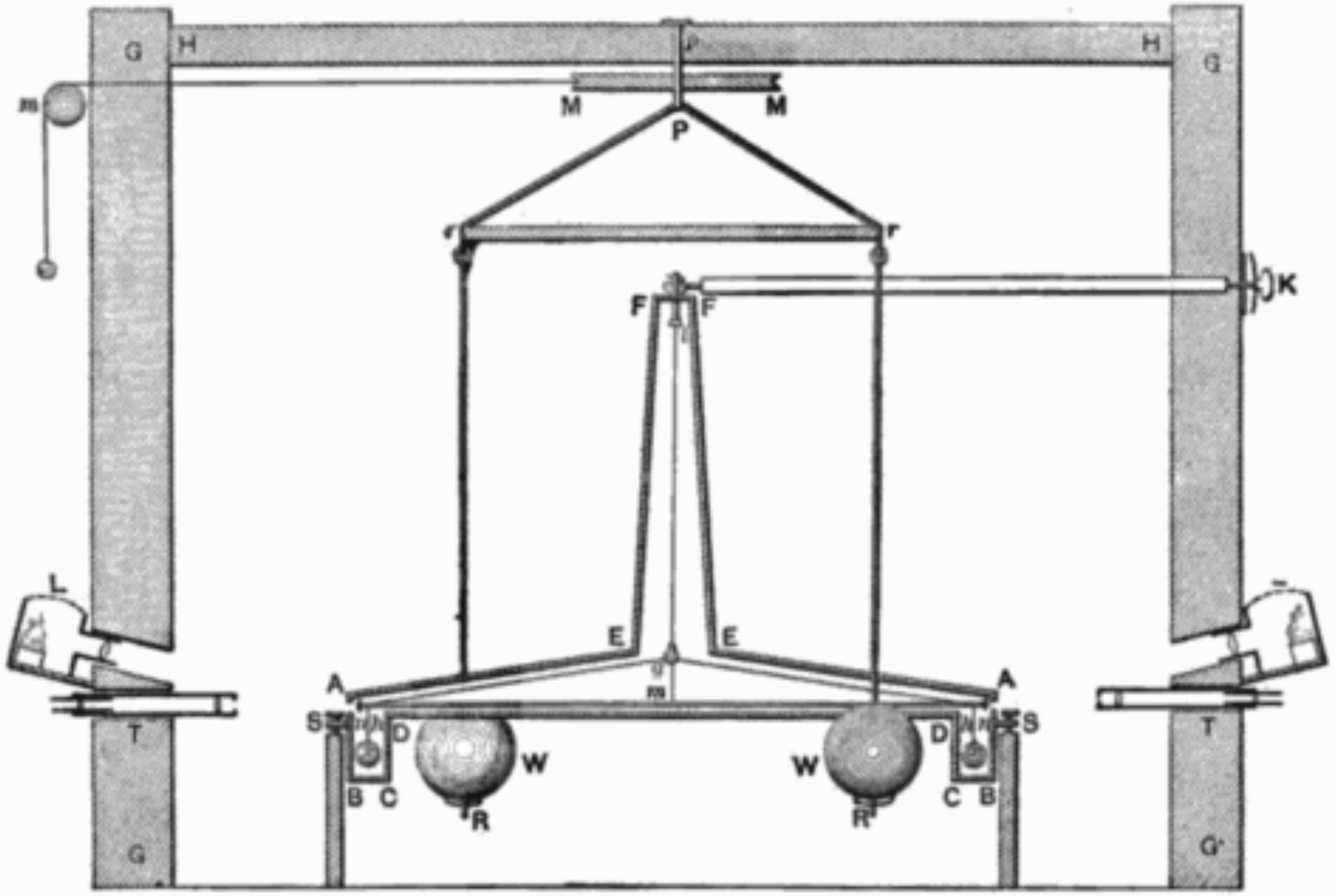
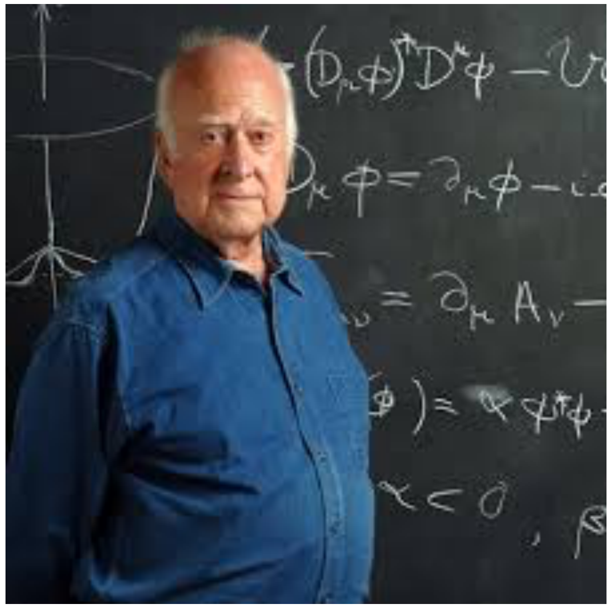


Fig. 1

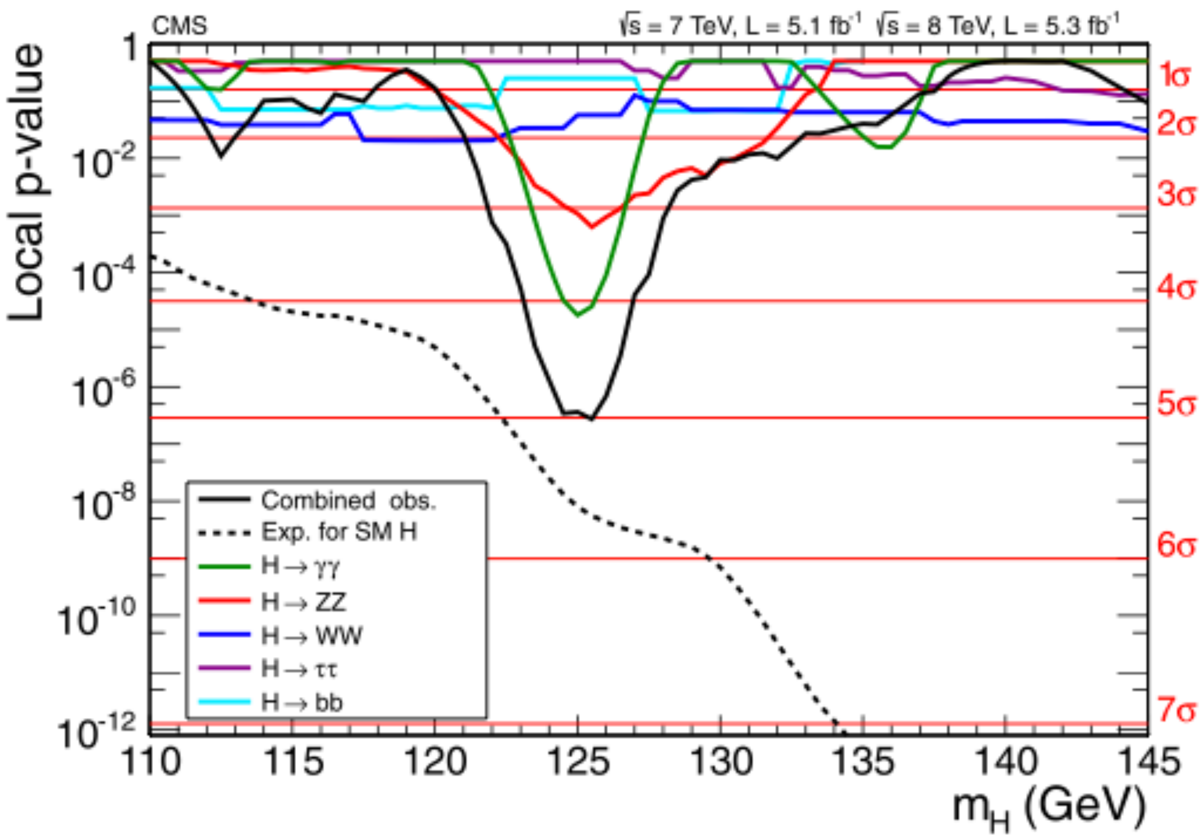
  - this confirmed the principle of Universal gravitation and determined Newton's constant

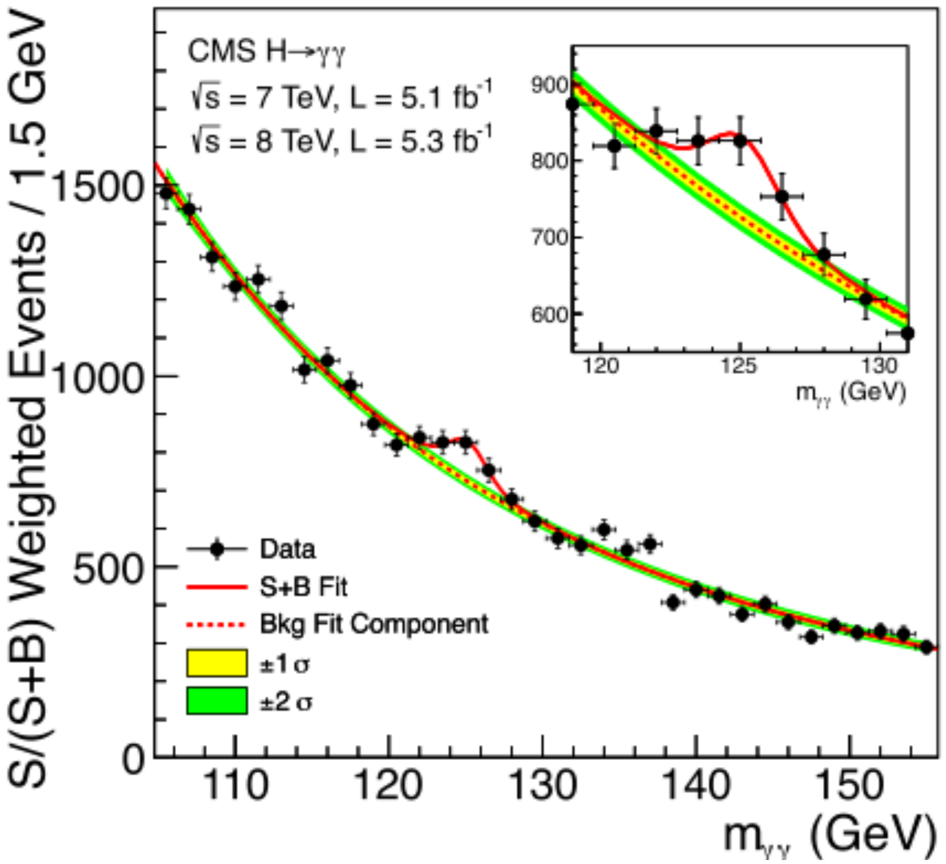
THE HIGGS MECHANISM

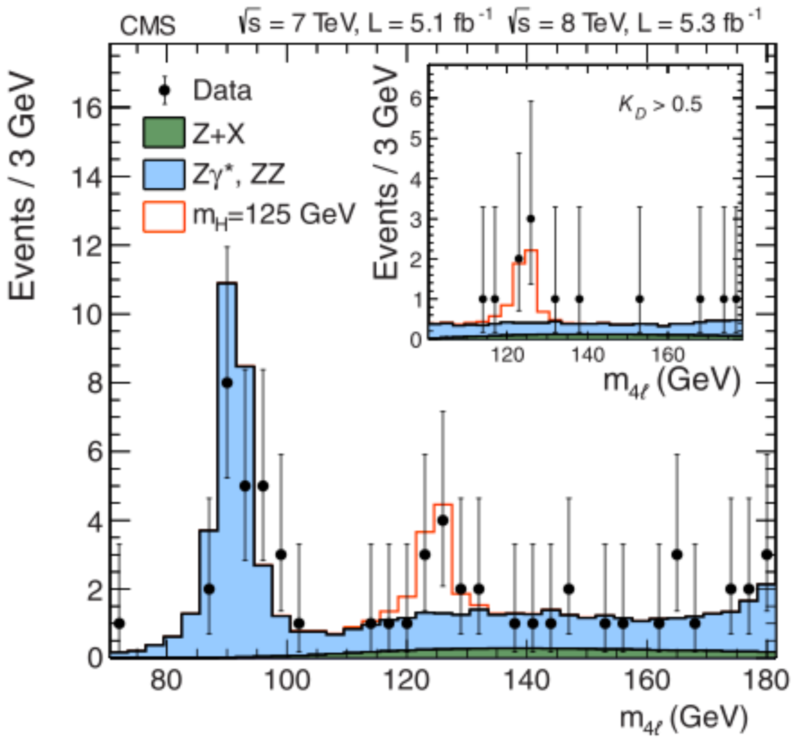
- In 1964, three papers proposed the Higgs Mechanism, by which a gauge boson could acquire mass
  - Subsequent papers showed how this could be used to *unify* the theory of the electromagnetic and weak forces

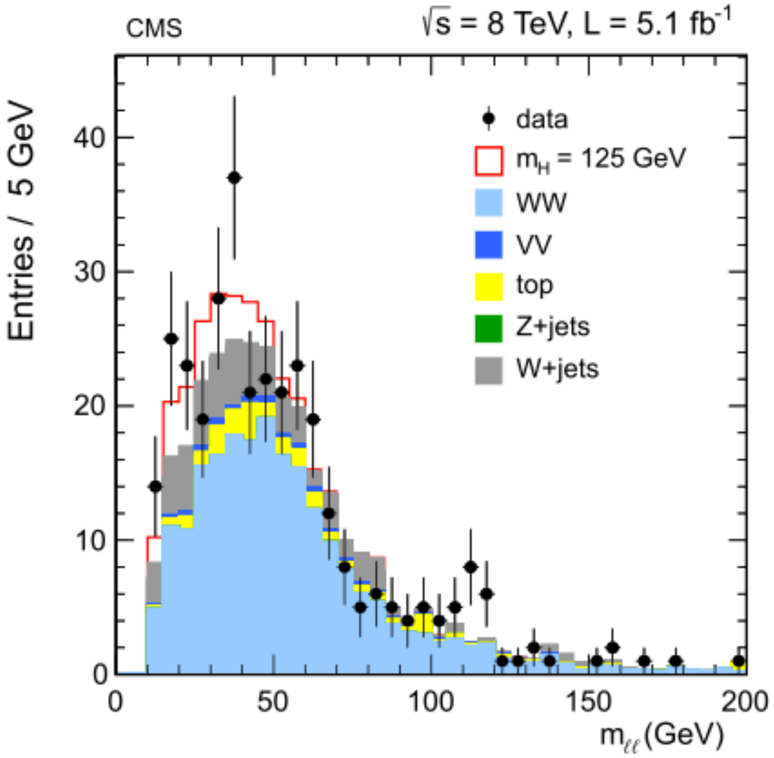


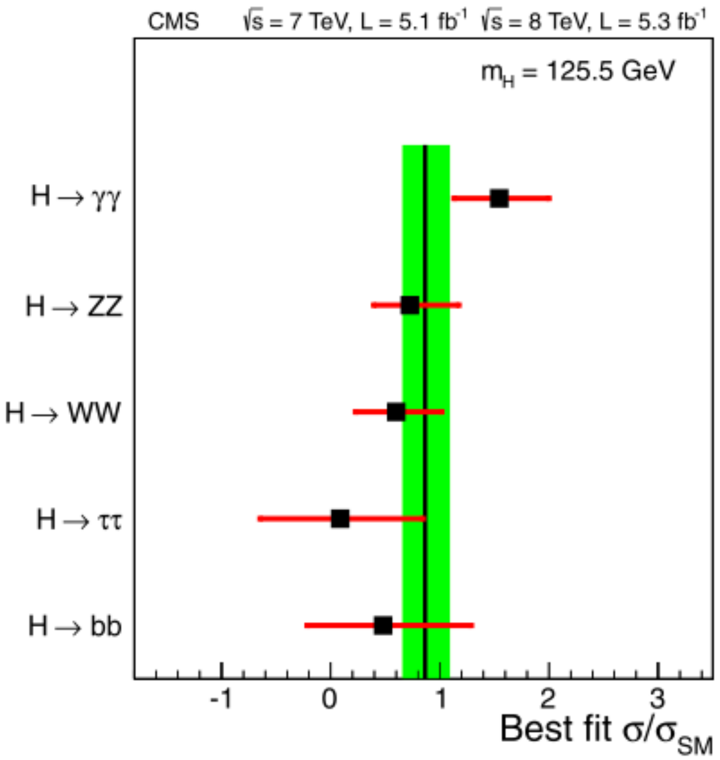
DISCOVERY ~50 YEARS LATER







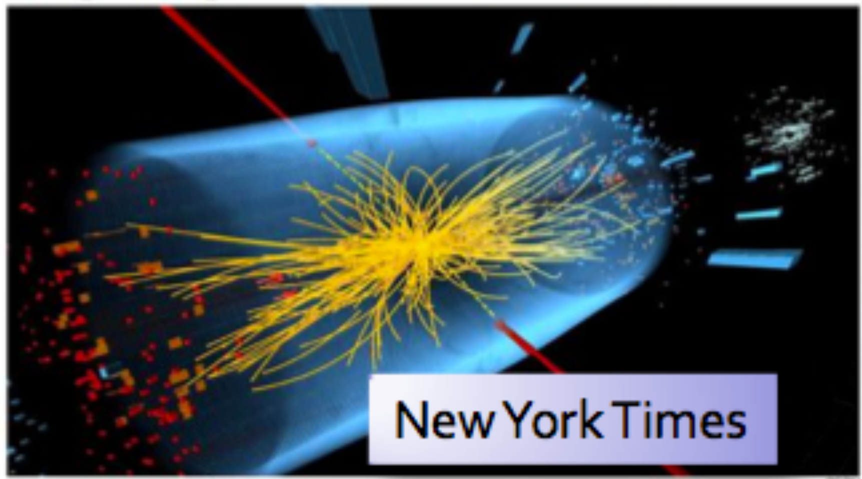




DISCOVERY ~50 YEARS LATER

CERN Press Conference

A Blip That Speaks of Our Place in the Universe

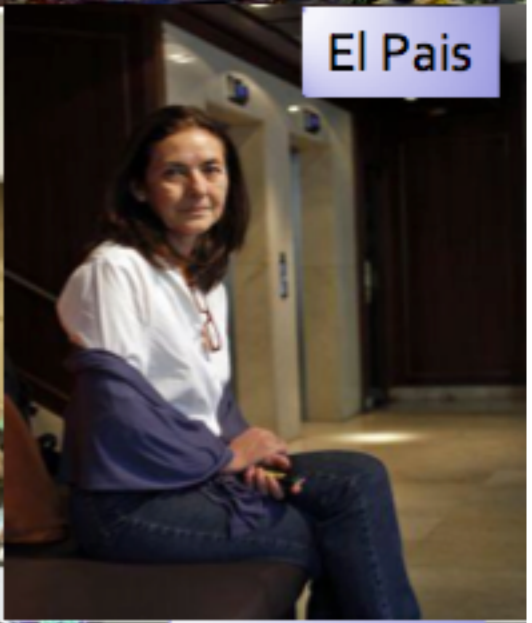


New York Times

La Republicca

ABC Breakfast News, Aus.

The Economist



El Pais

CERN Press Conference

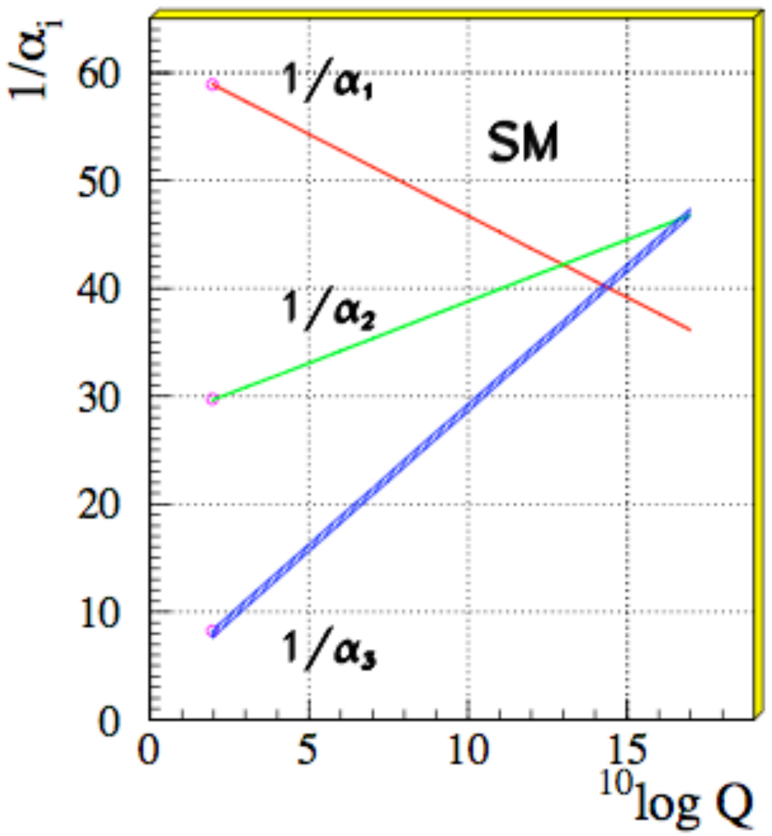
CERN Press Conference

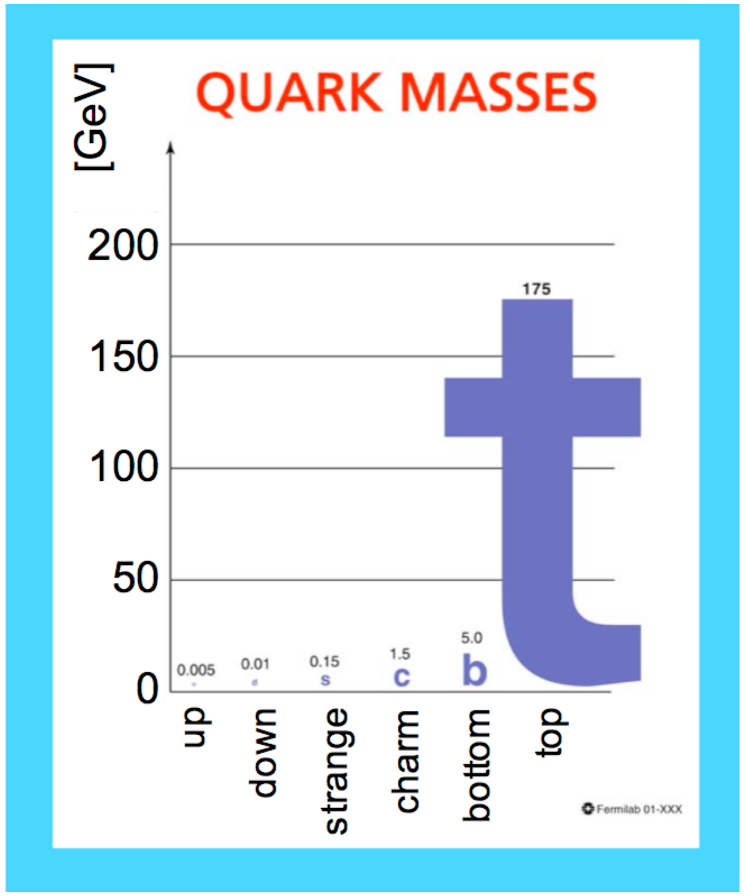
Paris Match

La salle de contrôle du Large Hadron Collider au Cern. | Photo REUTERS/Denis Balibouse

PROBLEMS WITHIN THE STANDARD MODEL

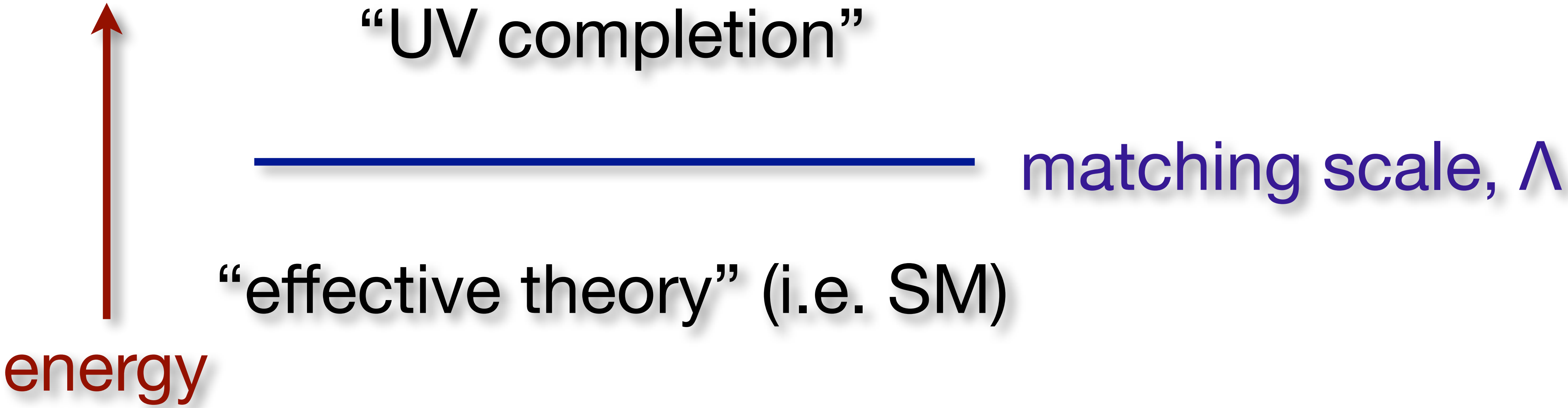
- The standard model doesn't explain a lot of things...
  - There are many free parameters (CKM phases, fermion masses)
  - Why is there a generational structure? Why three generations?
  - Why is the top quark so massive?
  - The gravitational force is neglected entirely from the SM
  - No coupling constant unification





THE HIERARCHY PROBLEM

- We must conclude that the SM is really *just an effective theory* which is completed in the UV by a new theory that takes over



"UV completion"

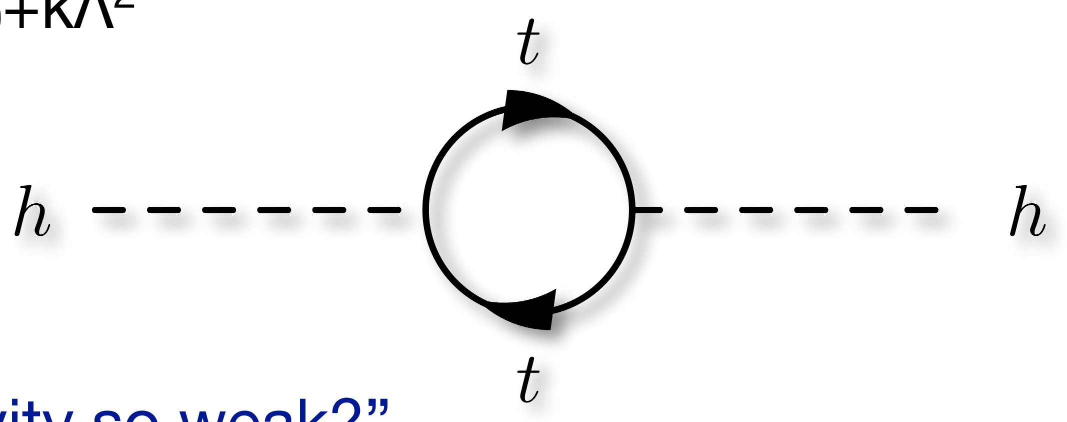
matching scale, Λ

"effective theory" (i.e. SM)

energy

- But even this is problematic
  - If Λ is at the gravitational scale (i.e. ~10^{19} GeV), the Higgs mass (presumably ~10^2 GeV, to be responsible for electroweak symmetry breaking) is not stable: quadratic dependence on the cutoff: $m^2_h \approx m^2_0 + k\Lambda^2$

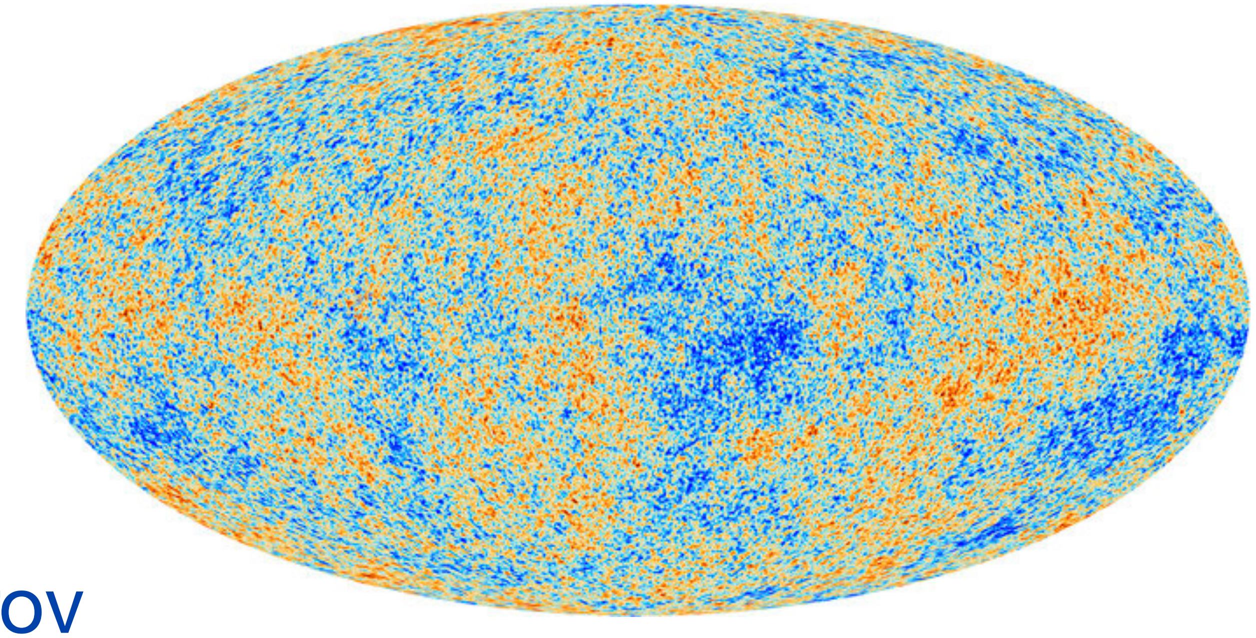
The value of the Higgs mass depends strongly on the specifics of the UV (short length scale) physics



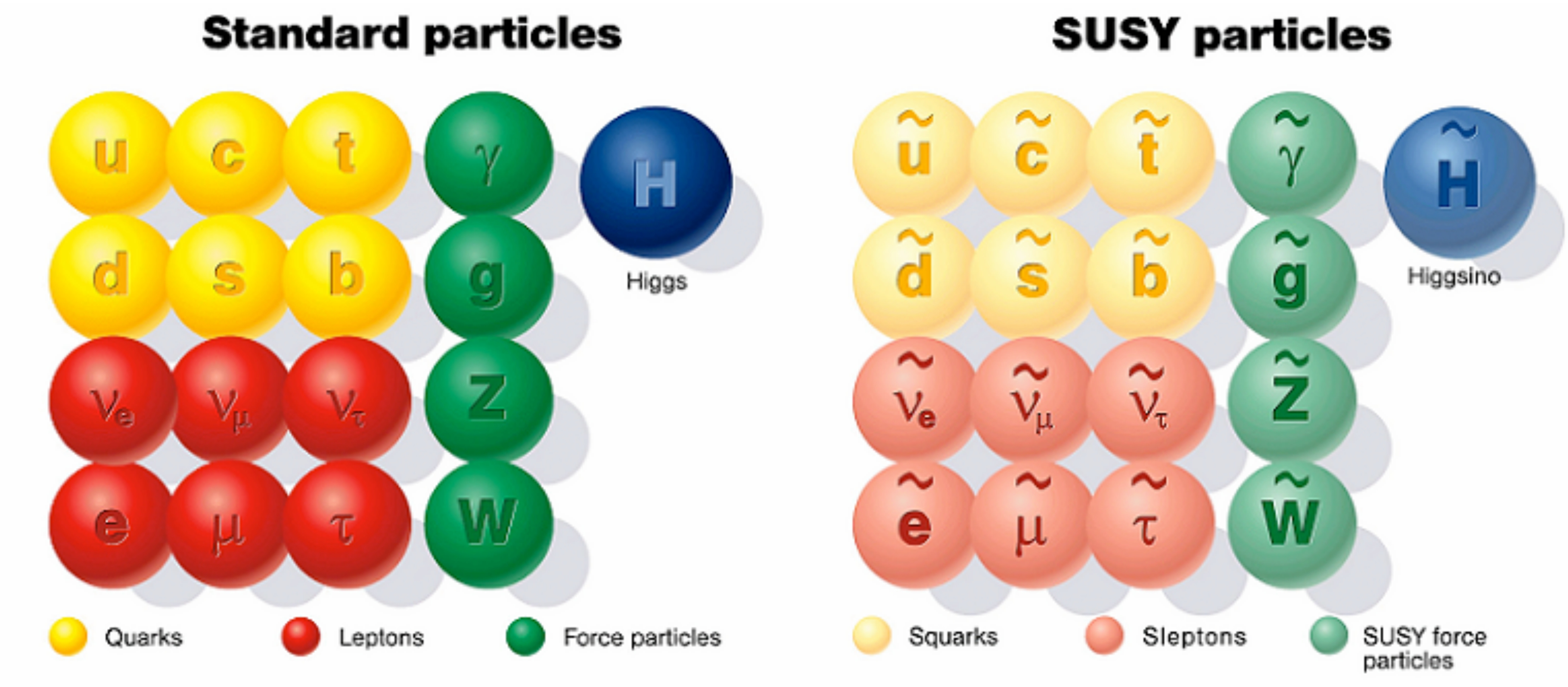
- The Hierarchy problem, colloquially: "Why is gravity so weak?"

PROBLEMS FROM COSMOLOGY

- Dark Matter
  - From studying microwave background:
    - ~70% of the universe is energy
    - ~5% is baryonic matter
    - ~25% is some non-baryonic cold dark matter
  - Confirmation from galactic rotation curves, type IA supernovae and gravitational lensing
- Baryon (matter/antimatter) Asymmetry
  - More CP violation (and phase transition) need to satisfy Sakharov conditions



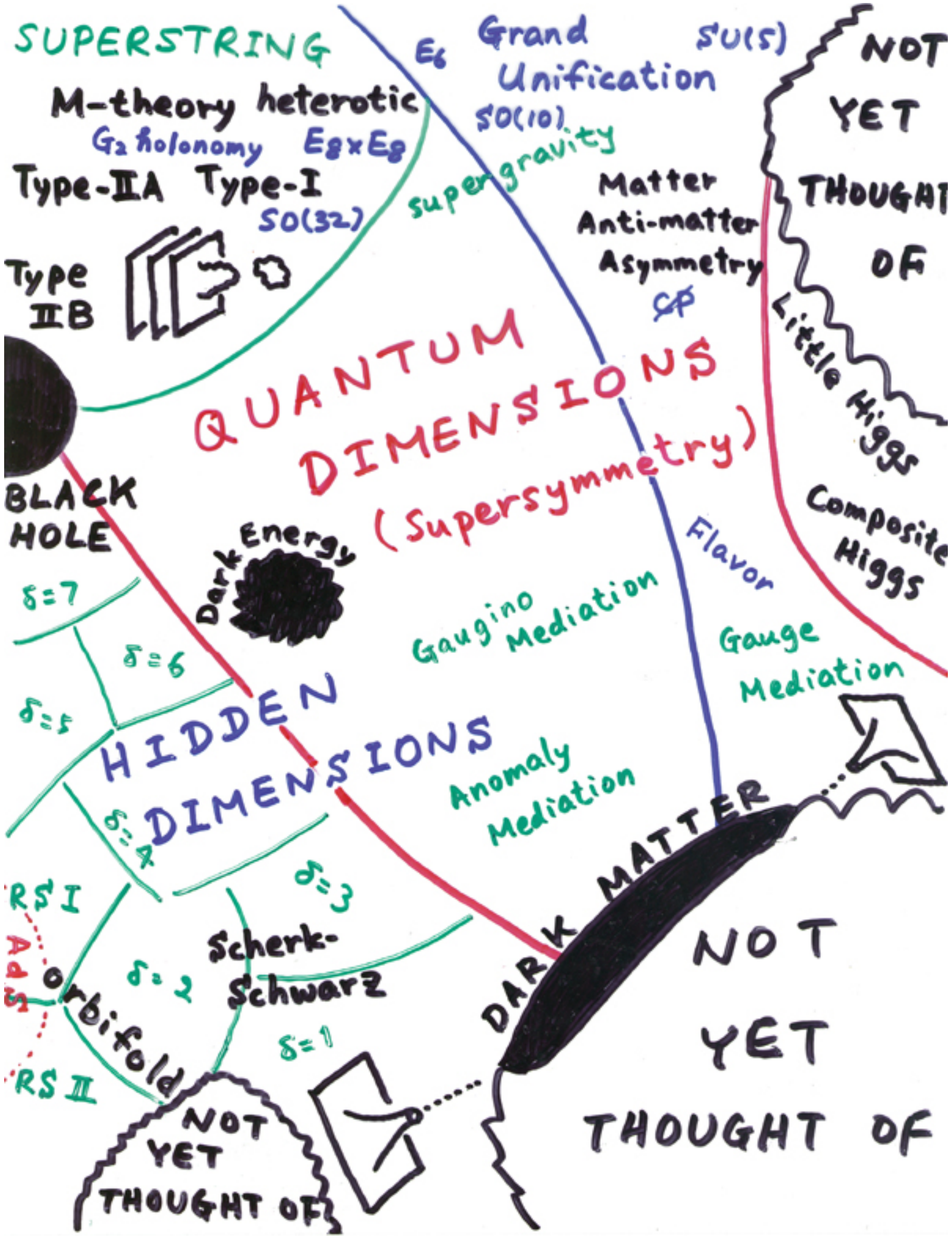
SUPERSYMMETRY



- Probably the leading Beyond the SM (BSM) theory
  - provides gauge-coupling unification
  - natural dark matter candidate (if lightest super-particle is neutral and stable)
  - solves the Hierarchy problem
    - Only problem is that we haven’t seen it yet..

MODELS, MODELS, EVERYWHERE…

- Of course, that's just one prominent example
  - These can solve some, all, or none of the problems I've already mentioned
  - Still, there seems to be a strong sense that new physics should be accessible at the LHC
    - maybe the most likely model is "not yet thought of"…



The Large Hadron Collider

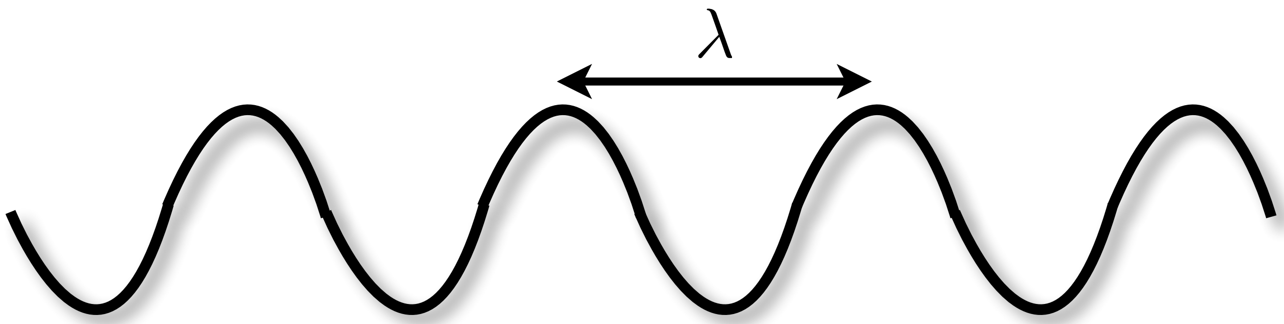
PARTICLE COLLIDERS AS MICROSCOPES

- Wave-particle duality: particles exhibit both particle- and wave-like behavior

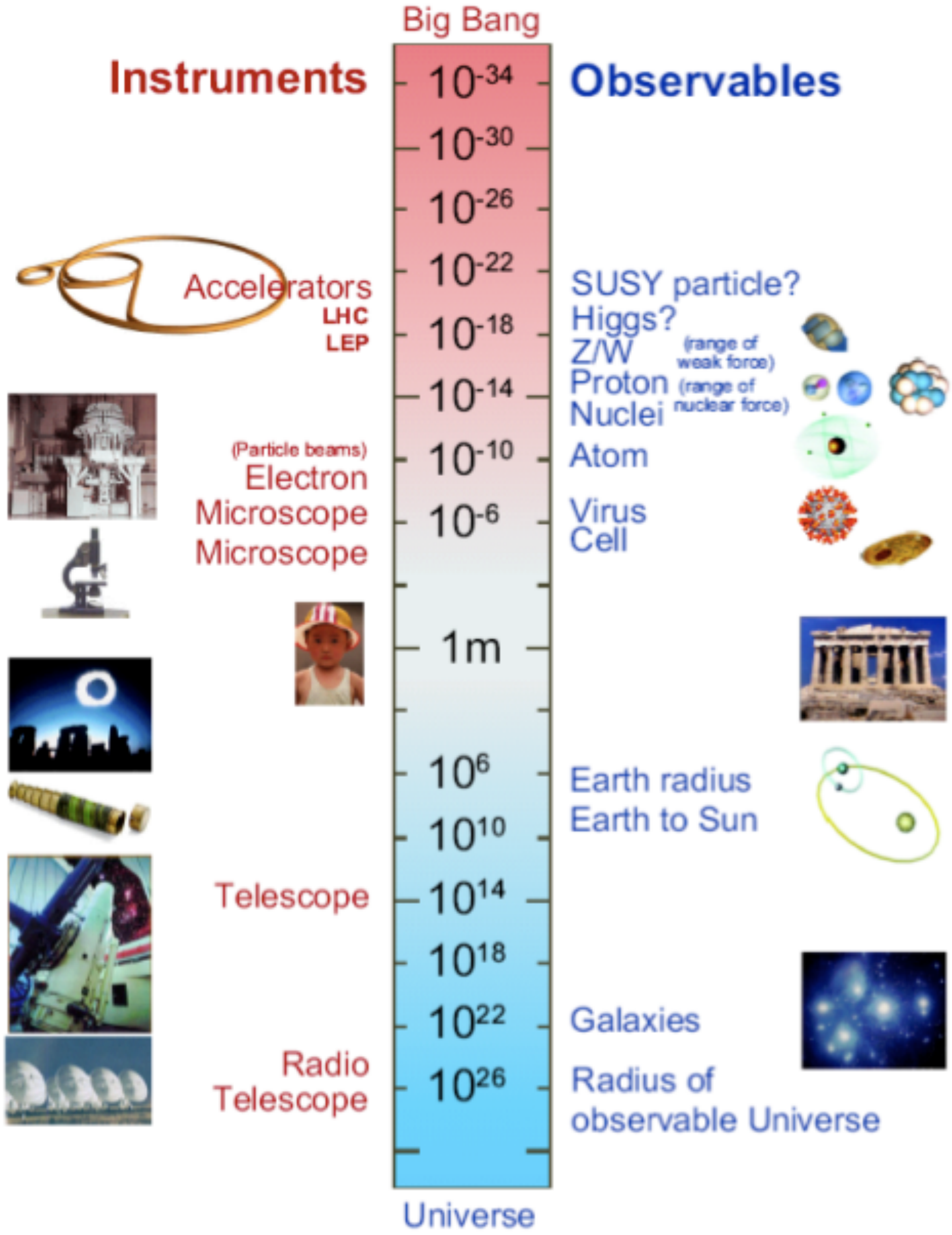
particle momentum → $p = \frac{h}{\lambda}$ ← Planck's constant

← wavelength

- If you want to probe short length scales, use high momenta particles!

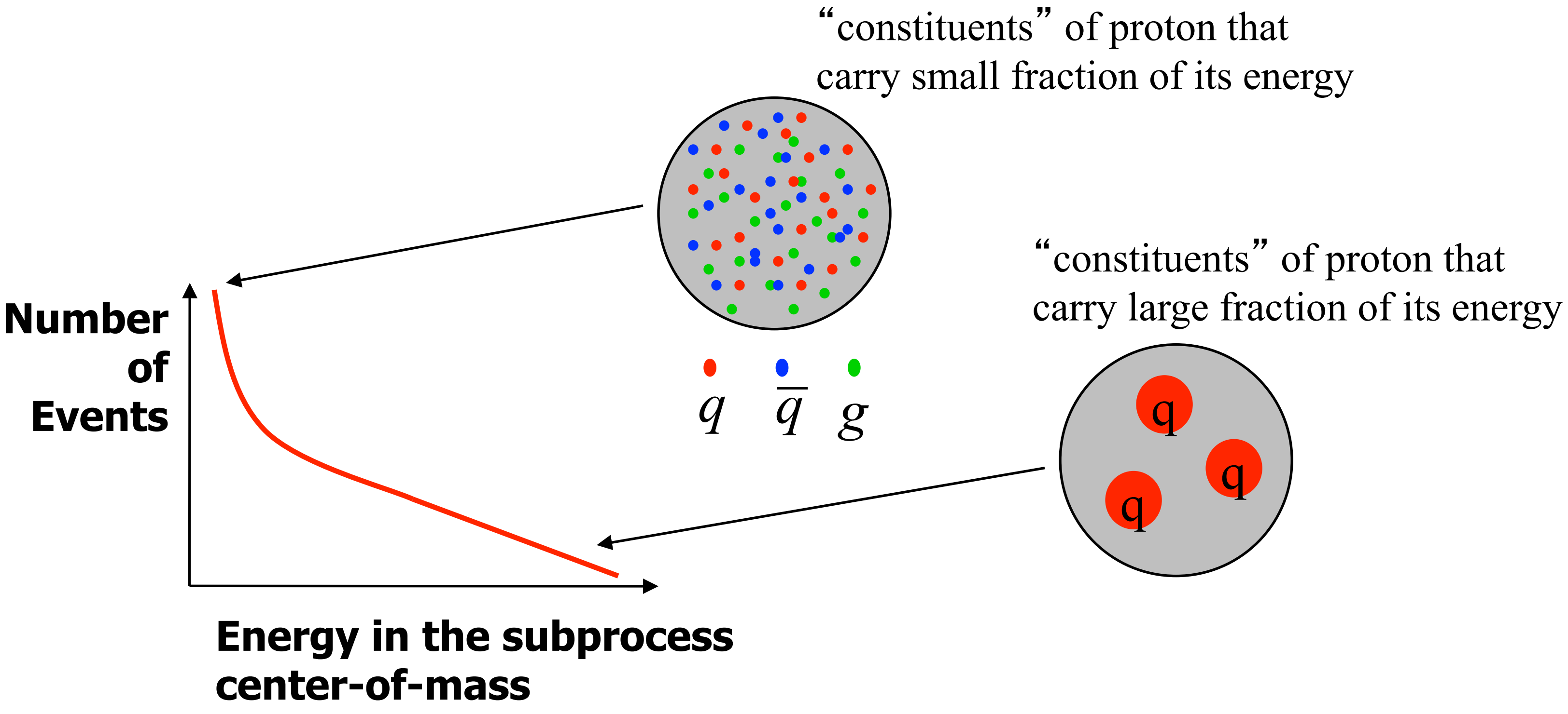


- We collide high energy protons to study the smallest length scales (particles)



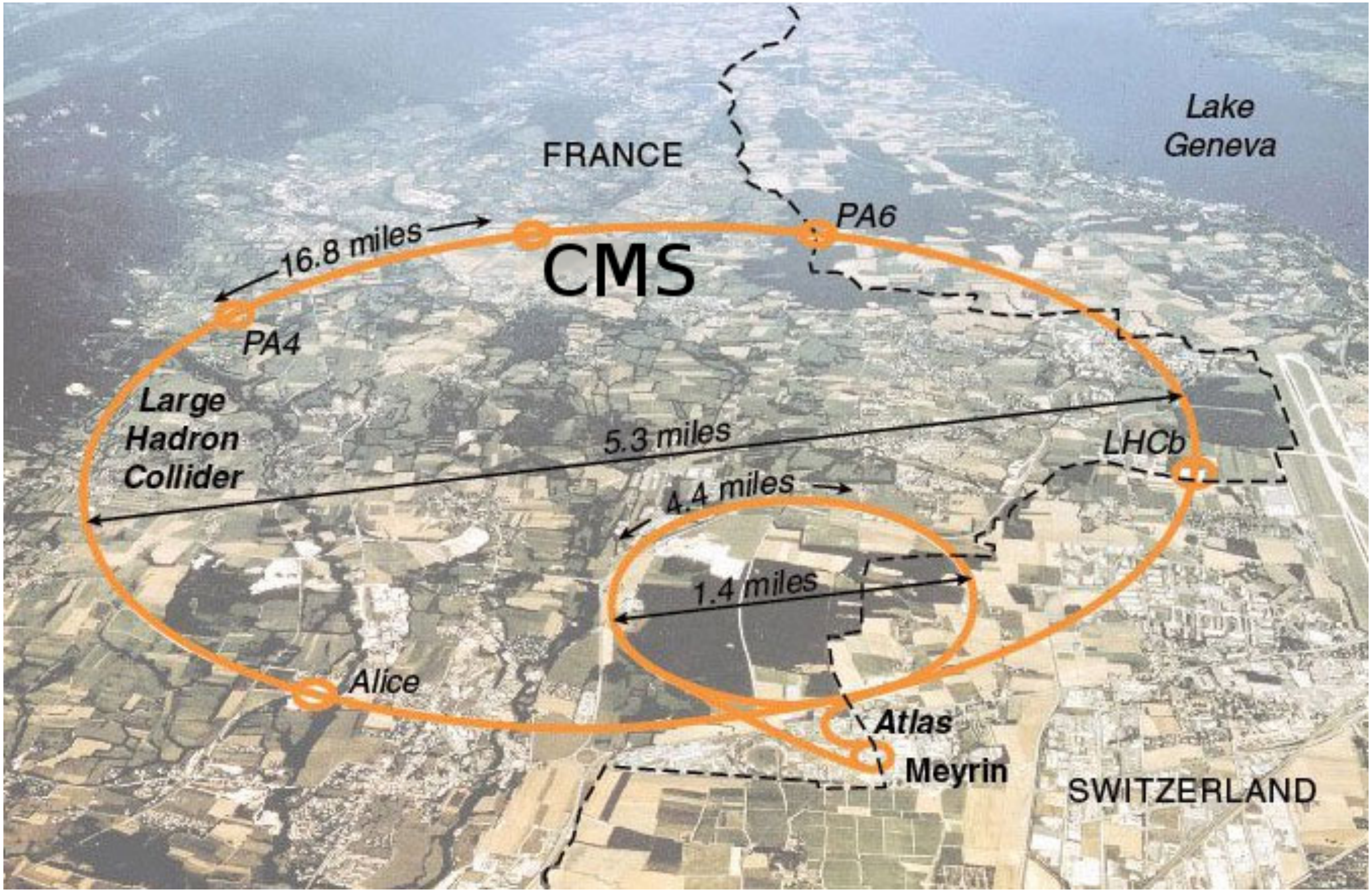
HADRON COLLIDERS

- Easiest way to achieve high center-of-mass energy is colliding beams of protons or anti-protons
  - heavy, so no synchrotron radiation
  - stable, so can take time accelerating
- But: messy!
  - hadron colliders are really quark/gluon colliders
  - The center of energy of a pp collision is not known: **rely on transverse momentum conservation**



THE LARGE HADRON COLLIDER

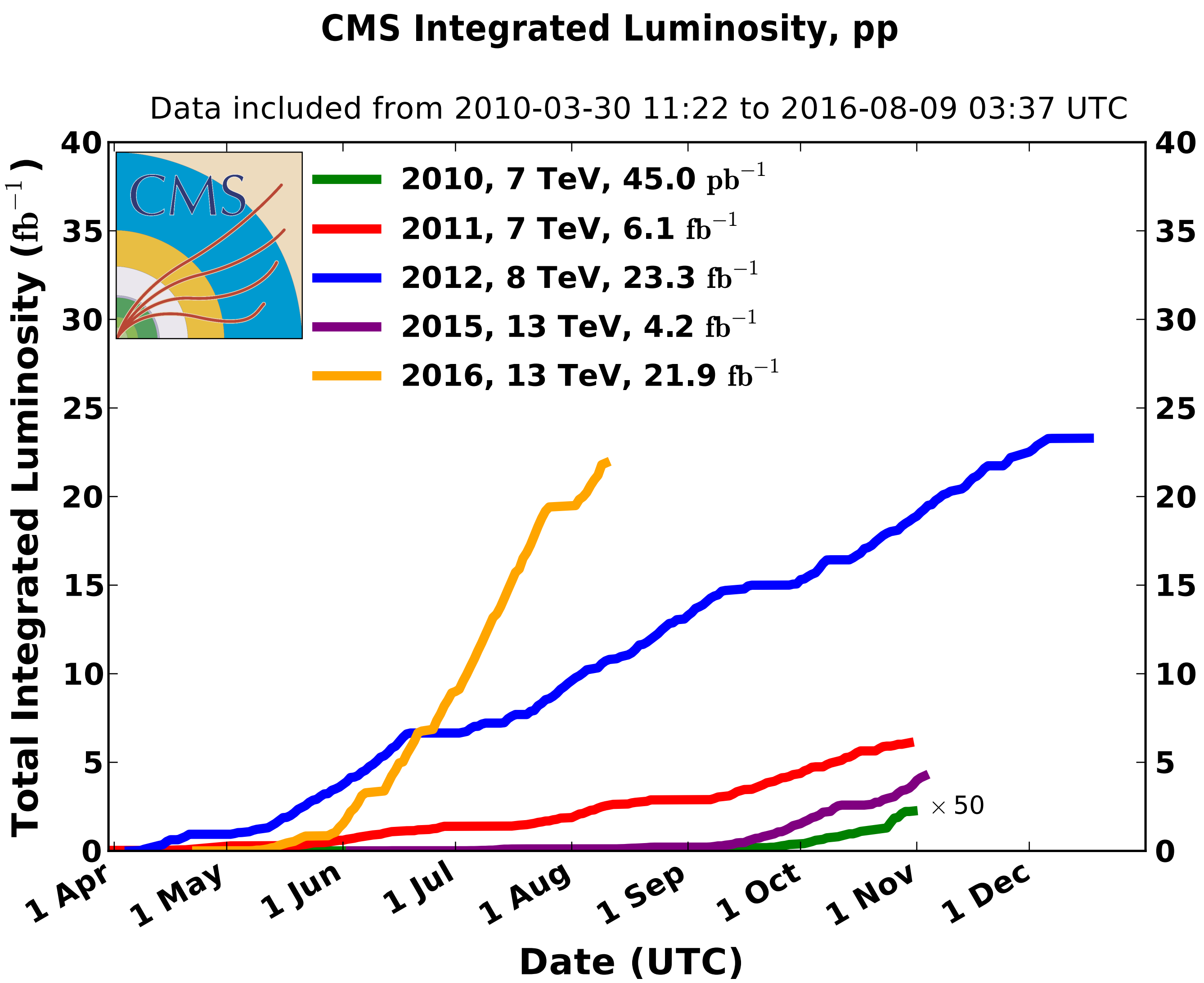
- The LHC is the world's highest energy particle collider

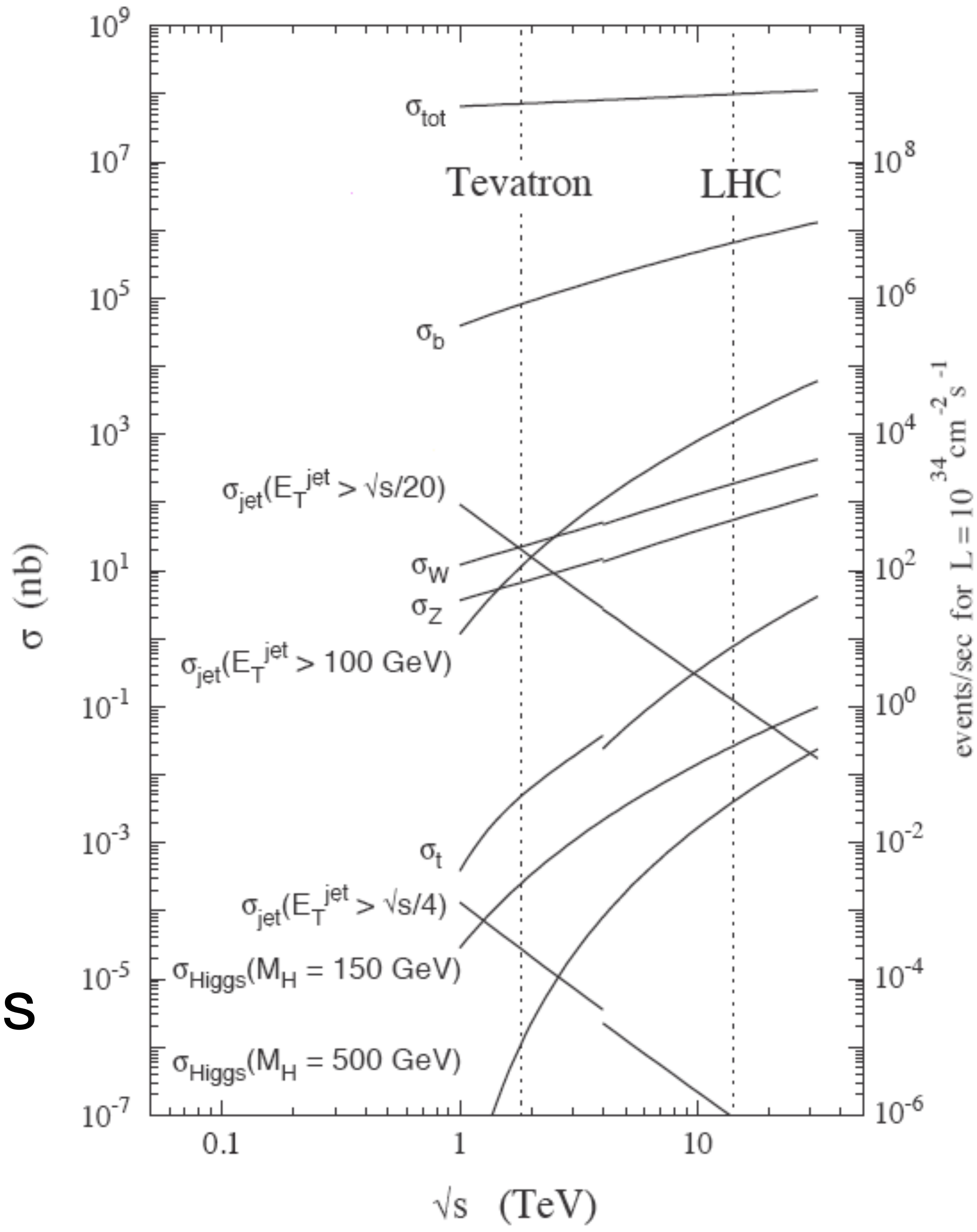


UNITS

- A few notes about units in this talk
  - We typically measure energy, momentum, and mass in units of GeV, GeV/c, and GeV/c^2 (often you will see c=1)
  - Measure cross sections (σ) in units of barns and luminosity (L) in inverse barns
  - Expected number of events from a process (i.e. pp→h) is: $\langle N \rangle = L \times \sigma$
- Some helpful numbers
  - The proton mass is approximately 0.938 GeV
  - The LHC collides protons at a center-of-mass energy $\sqrt{s}$=13 TeV
  - The integrated luminosity delivered *this year* at the LHC is ~20 fb^{-1}
  - Tracking detectors at the LHC have a spatial resolution as low as 10 μm

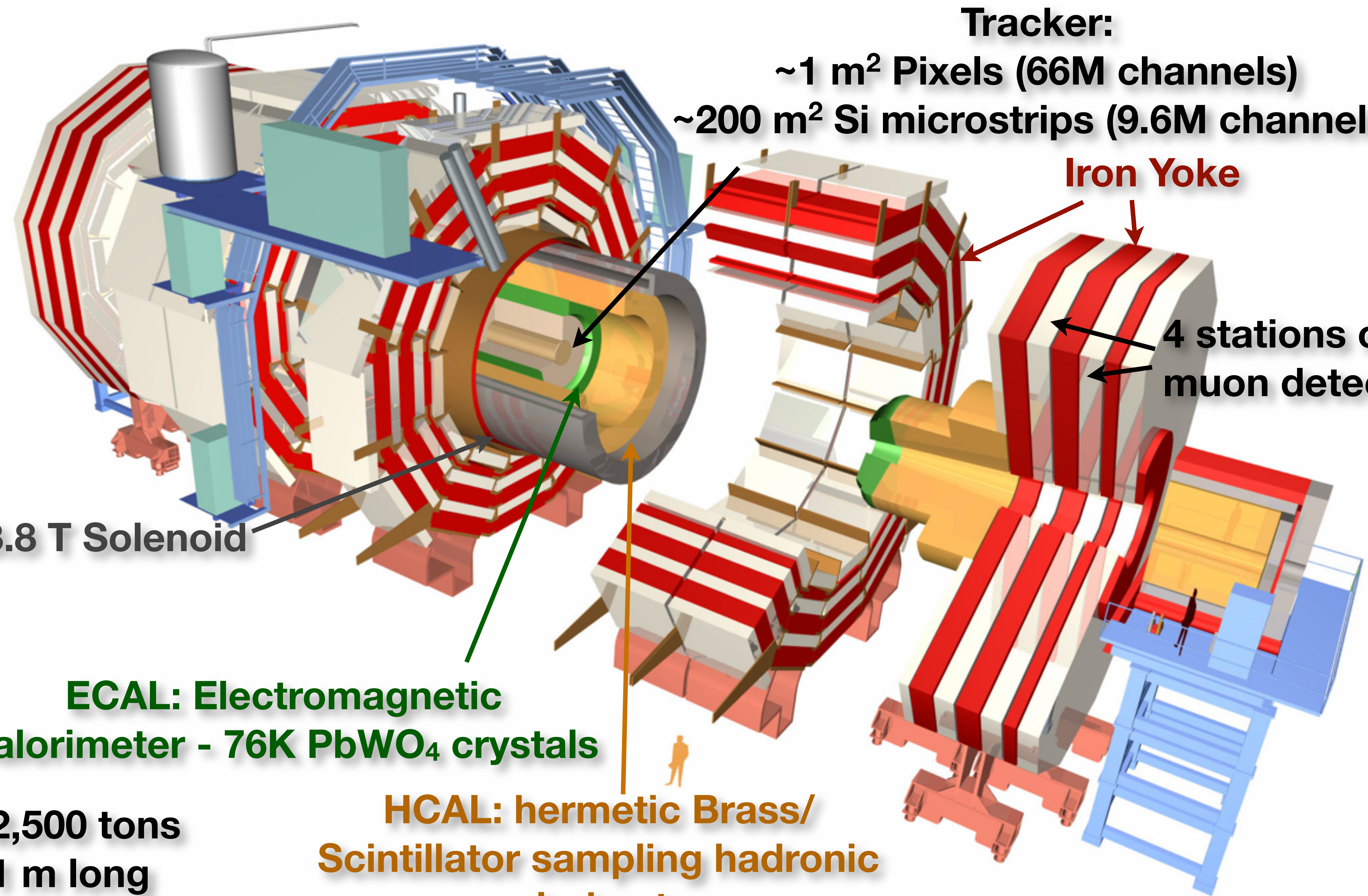
LUMINOSITY AND CROSS SECTION





- Peak instantaneous luminosity is about 12 nb^{-1} per second

THE CMS EXPERIMENT



Tracker:
~1 m^2 Pixels (66M channels)
~200 m^2 Si microstrips (9.6M channels)

Iron Yoke

4 stations of muon detectors

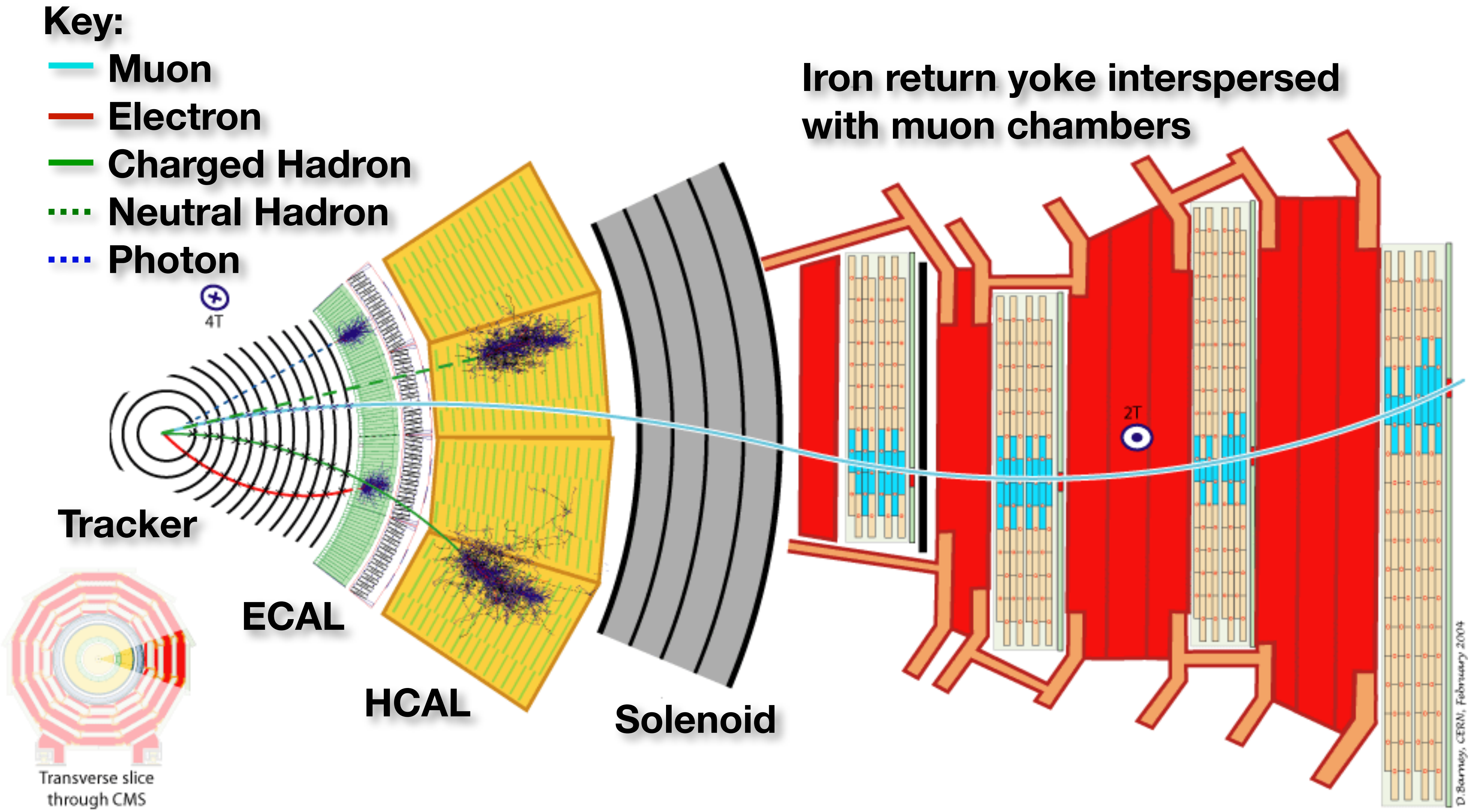
3.8 T Solenoid

ECAL: Electromagnetic calorimeter - 76K $PbWO_4$ crystals

HCAL: hermetic Brass/ Scintillator sampling hadronic calorimeter

12,500 tons
21 m long
15 m diameter

PARTICLE DETECTION (AT CMS)



Key:

- Muon
- Electron
- Charged Hadron
- Neutral Hadron
- Photon

Iron return yoke interspersed with muon chambers

Tracker

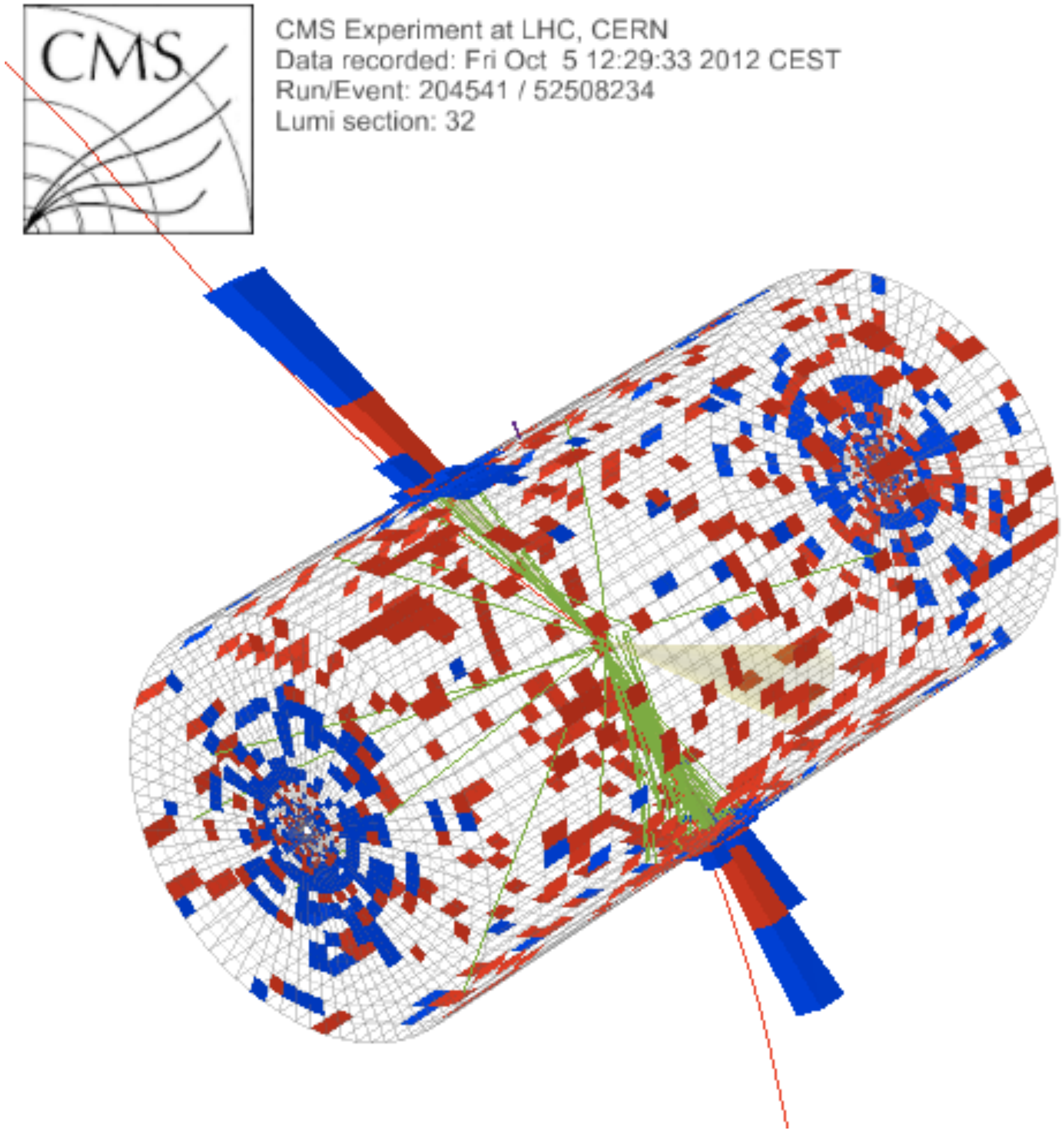
ECAL

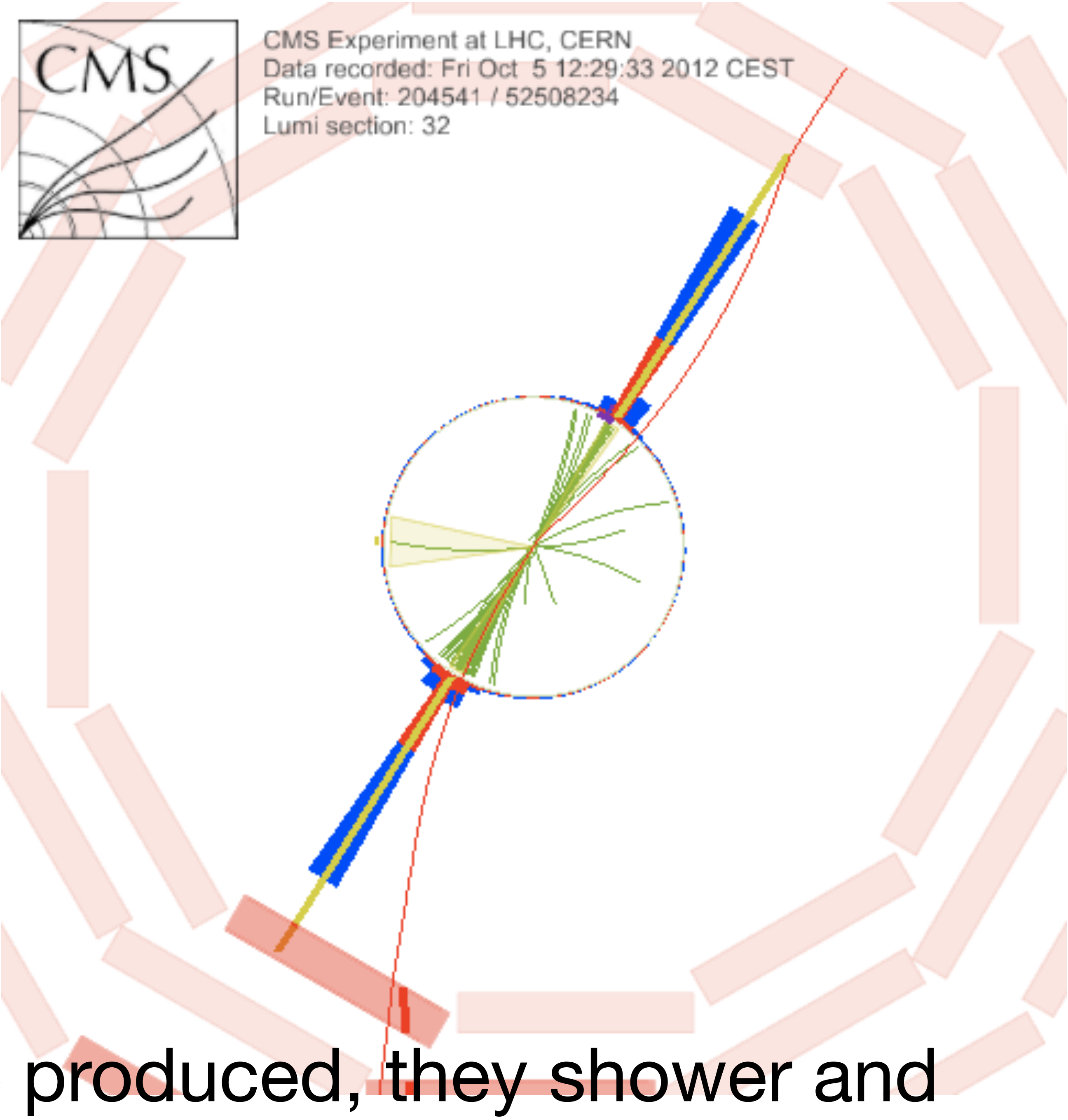
HCAL

Solenoid

Transverse slice through CMS

JETS



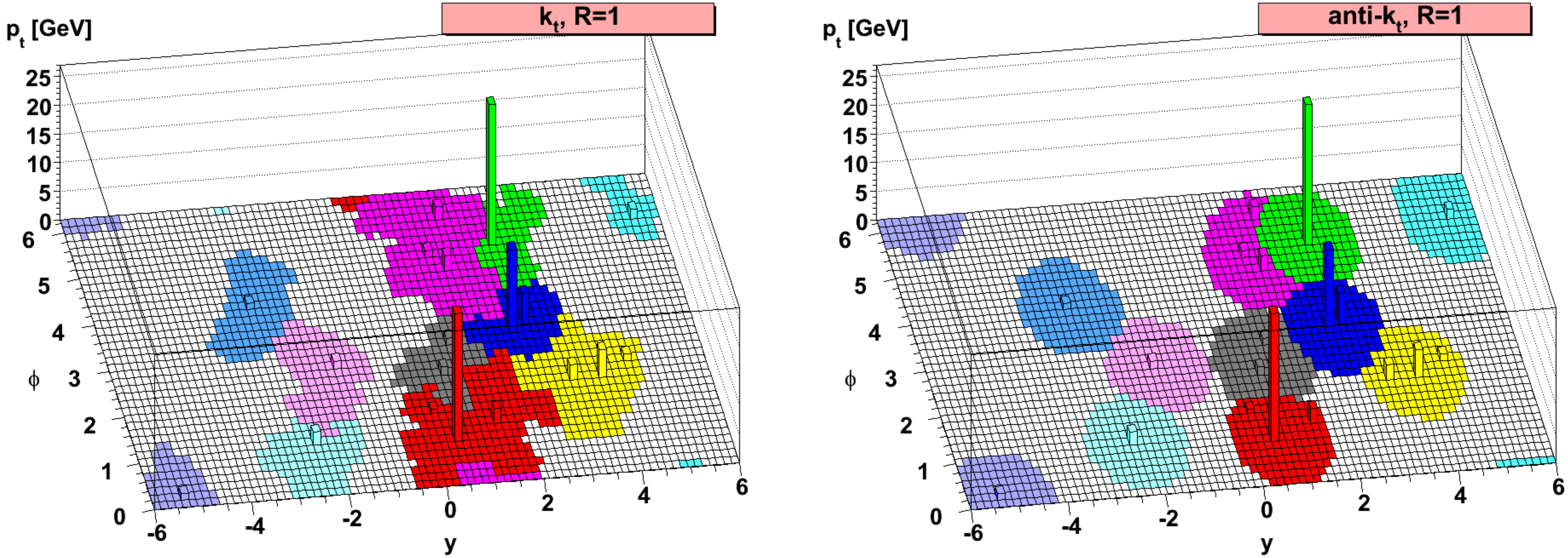


- When **quarks and gluons** are produced, they shower and hadronize to form “jets”, collimated streams of pions, kaons, protons, etc.

JET CLUSTERING

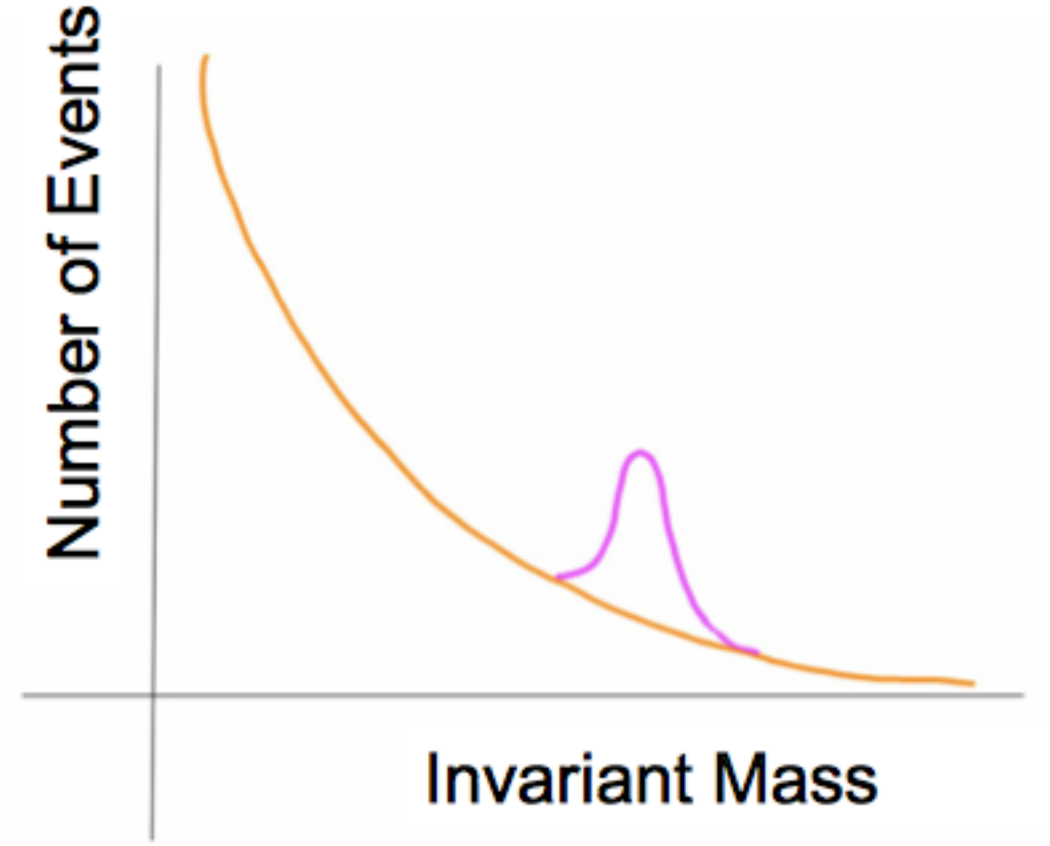
- Since jets are composite objects, we need an "clustering algorithm" to associate differ parts of the jets together
  - It turns out that there are many different ways to do this
  - Recently, collider experiments have favored the "anti-k_T algorithm"

[JHEP 0804:063]



MOTIVATING BUMP HUNTS

- One of the most direct ways to find new physics at the TeV scale is to **search for new resonances**



INVARIANT MASS

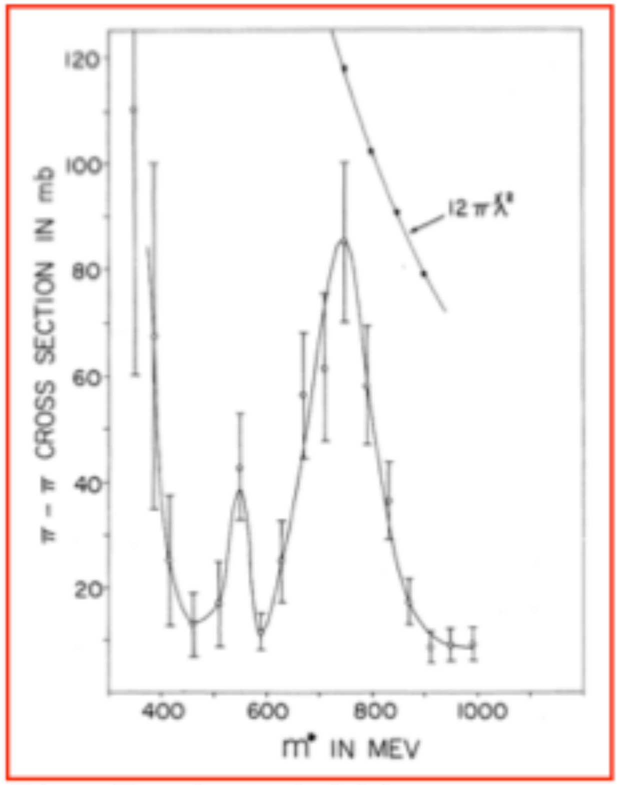
- When a particles decays into N particles, the invariant mass of the initial particle can be determined by the relation

$$m^2 = \left(\sum_i^N E_i\right)^2 - \left(\sum_i^N \vec{p}_i\right)^2$$

  - This value is a relativistic invariant, meaning that it's value does not depend on the reference frame that it is measured in
    - This is convenient because you have no guarantee that a particle would be produced at rest in the lab/detector frame

A CLASSIC EXAMPLE

1961: $\rho(770) \rightarrow \pi\pi$



PhysRevLett.6.628

1961: $K^*(892) \rightarrow K\pi$

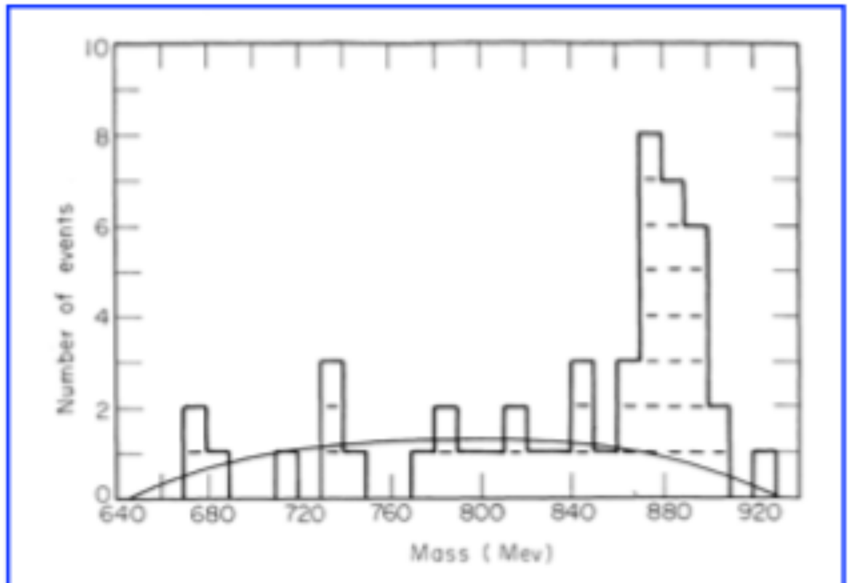
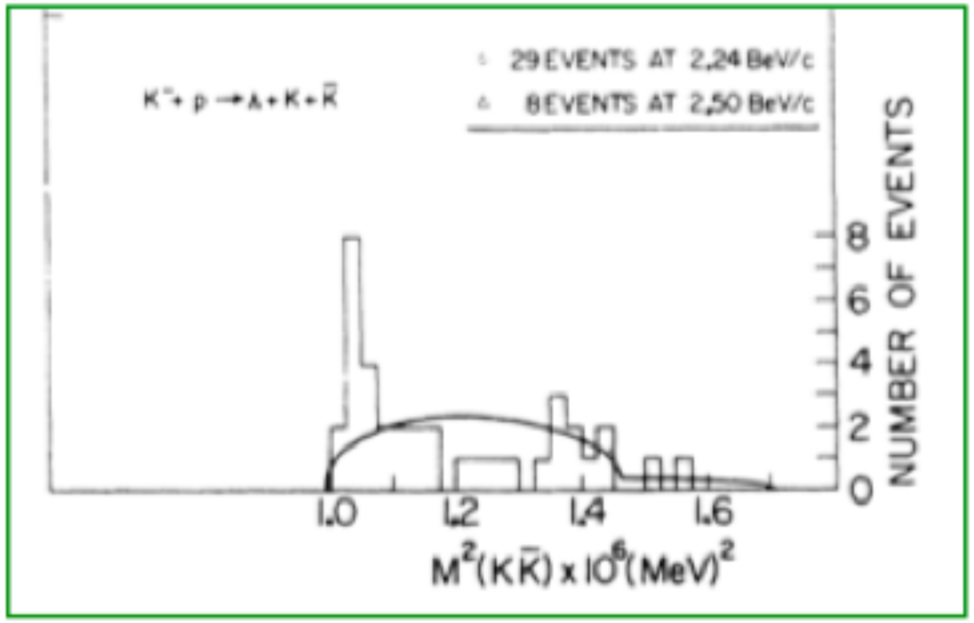


FIG. 2. Mass spectrum of the $\bar{K}^0 - \pi^-$ system. The solid line represents the phase-space curve normalized to background events.

PhysRevLett.6.300

1961: $\phi(1020) \rightarrow KK$



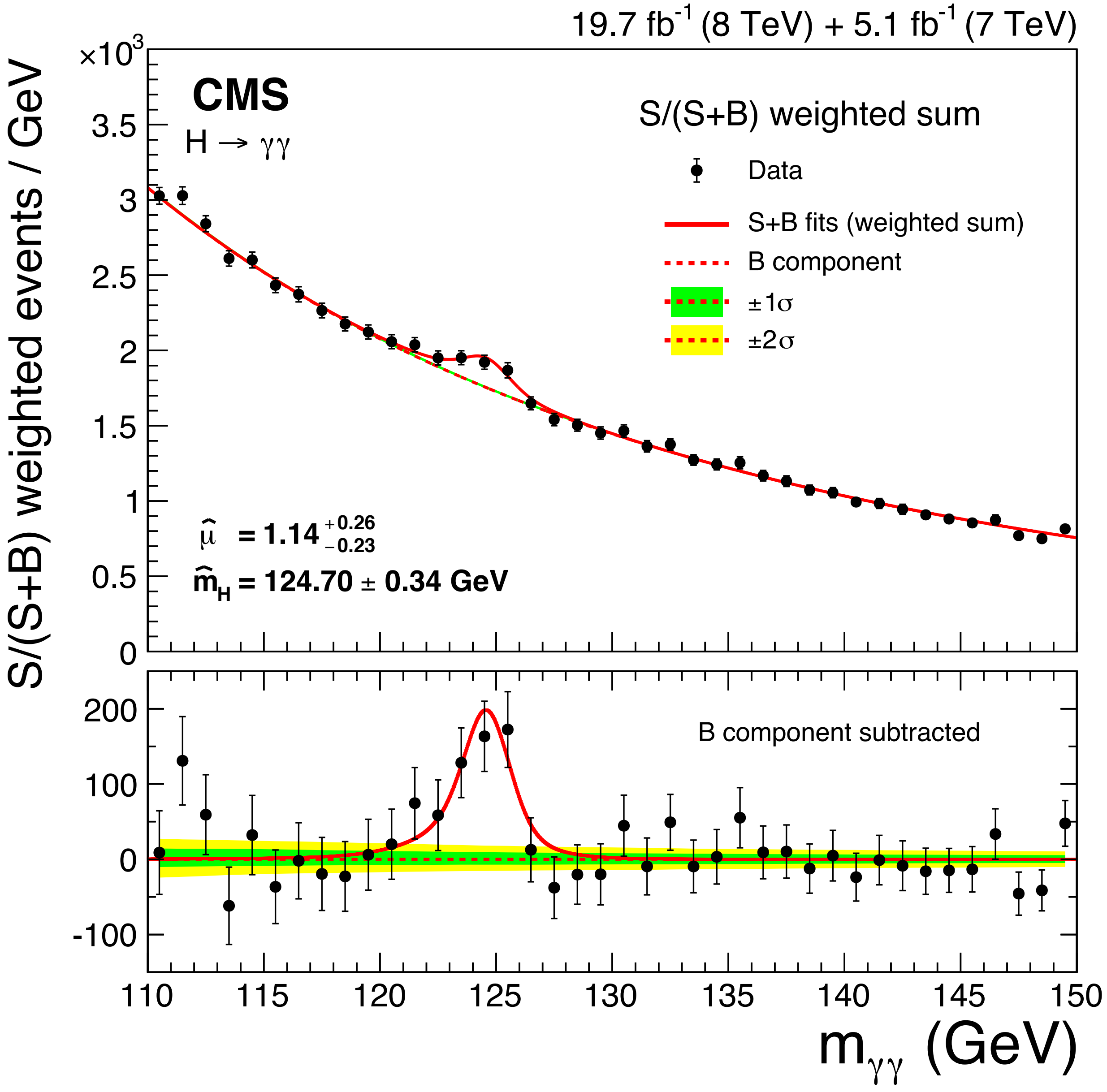
PhysRevLett.9.180

and many more after…

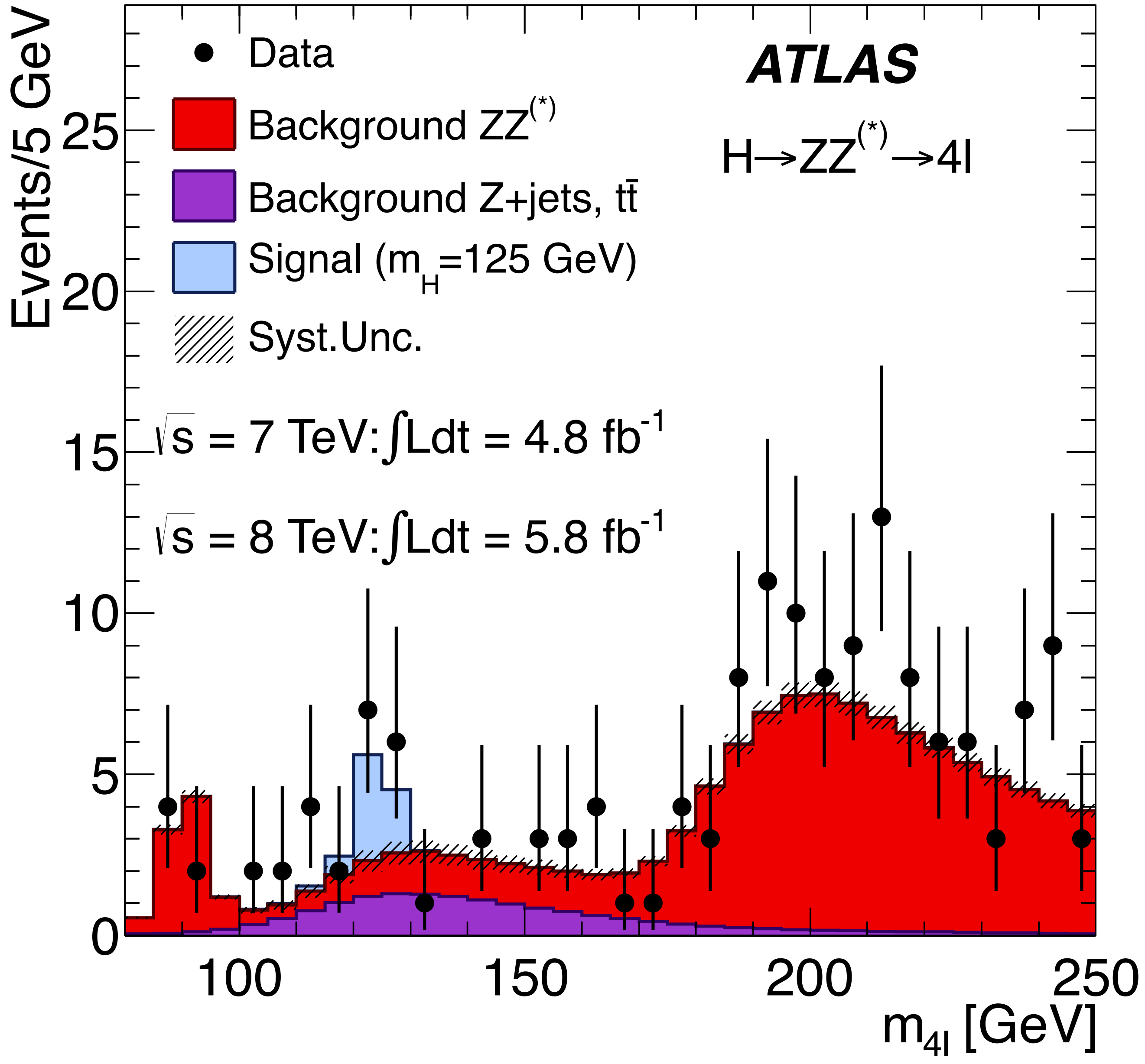
- In the early 60s, the energy of hadron collisions increased to a few GeV
  - new resonances appeared!

A RECENT EXAMPLE

Invariant Mass of two photons



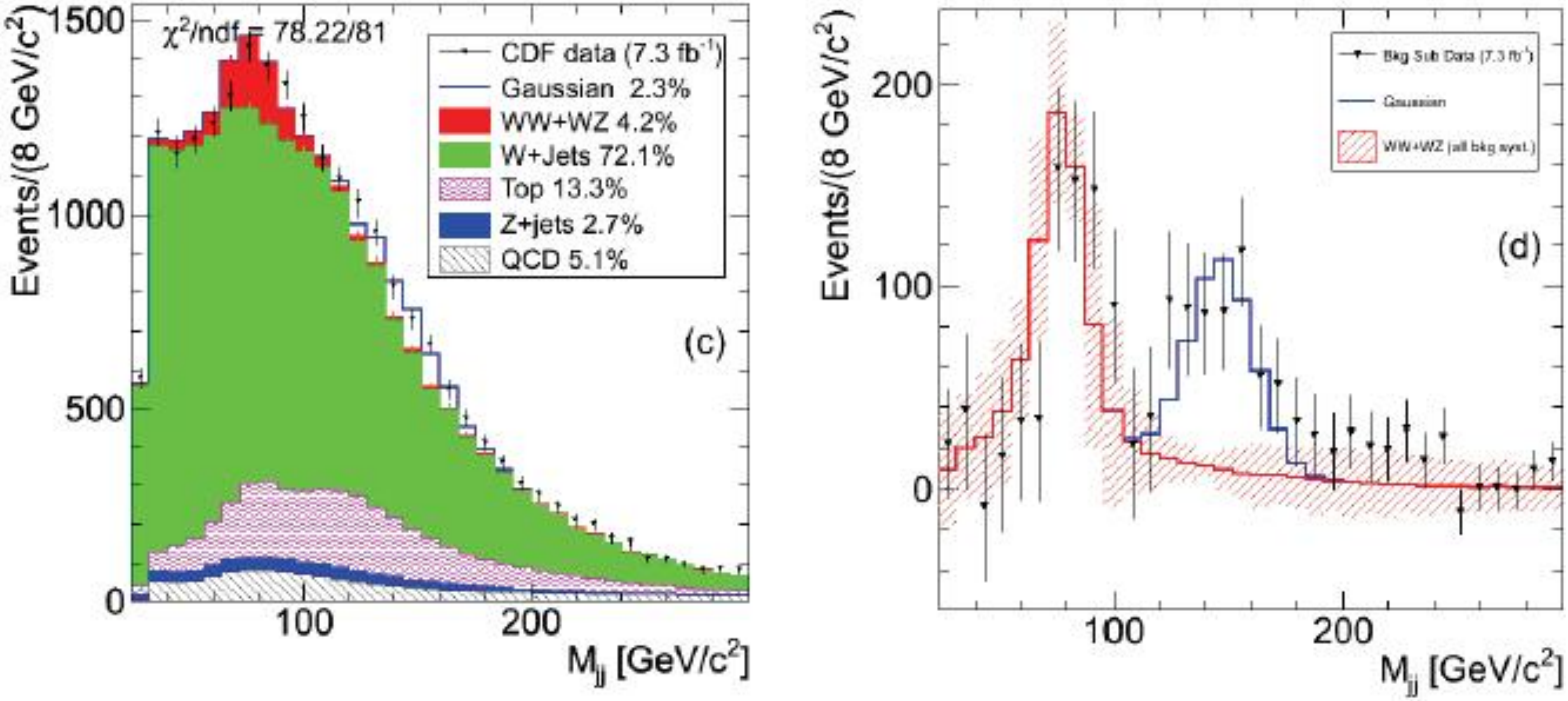
Invariant Mass of two Z bosons (each decaying to two photons)



- The discovery of the Higgs boson was performed through a “bump hunt”

A RECENT COUNTER-EXAMPLE

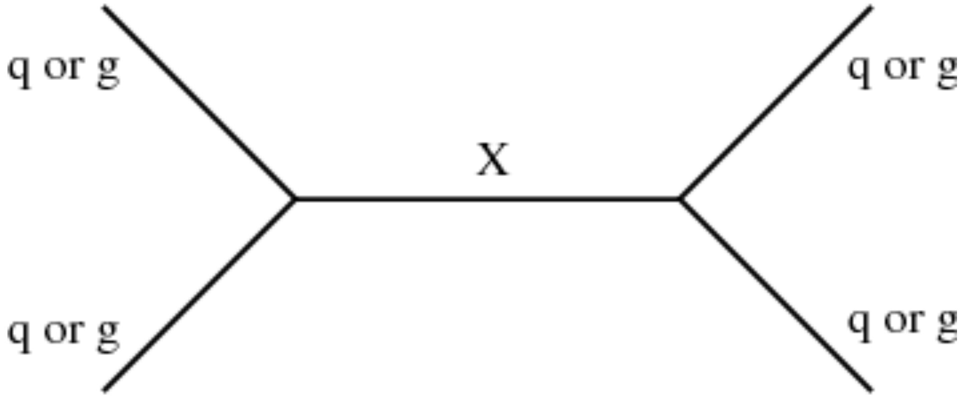
- Of course, not all bumps may be what they seem…
  - There is a long history of statistically significant bumps later going away with more statistics/scrutiny (more on this topic later)



Invariant mass of two jets (produced in association with a W→ℓν)

LOOKING FOR DIJET RESONANCES

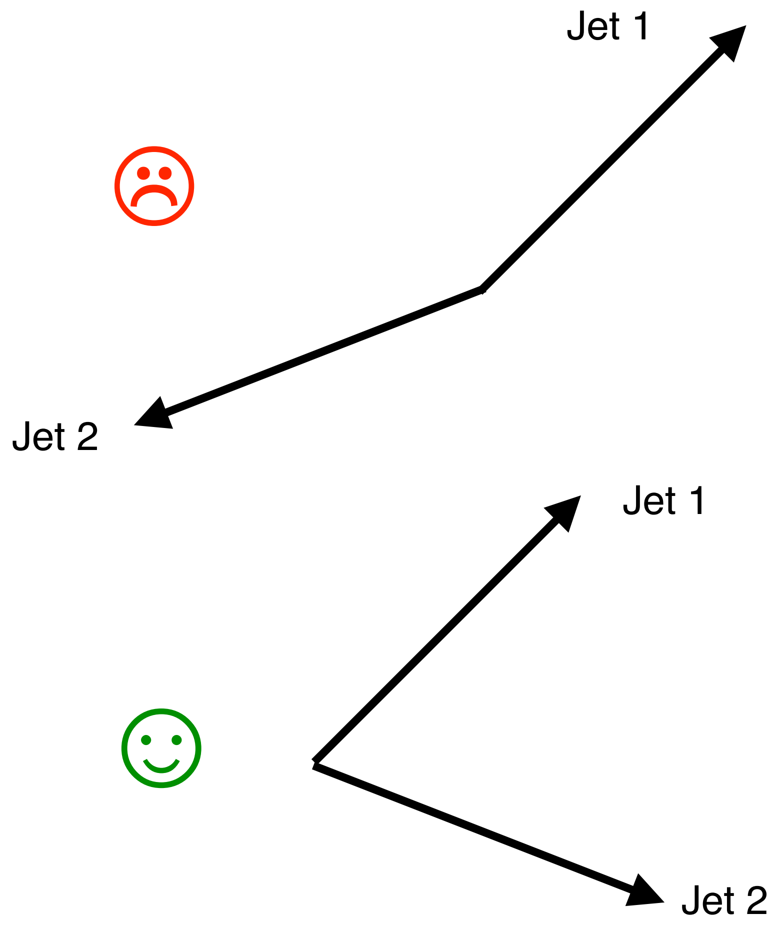
- Lots of models (grand unified theories, extra dimensions, etc.) predict resonances decaying into two quarks or gluons

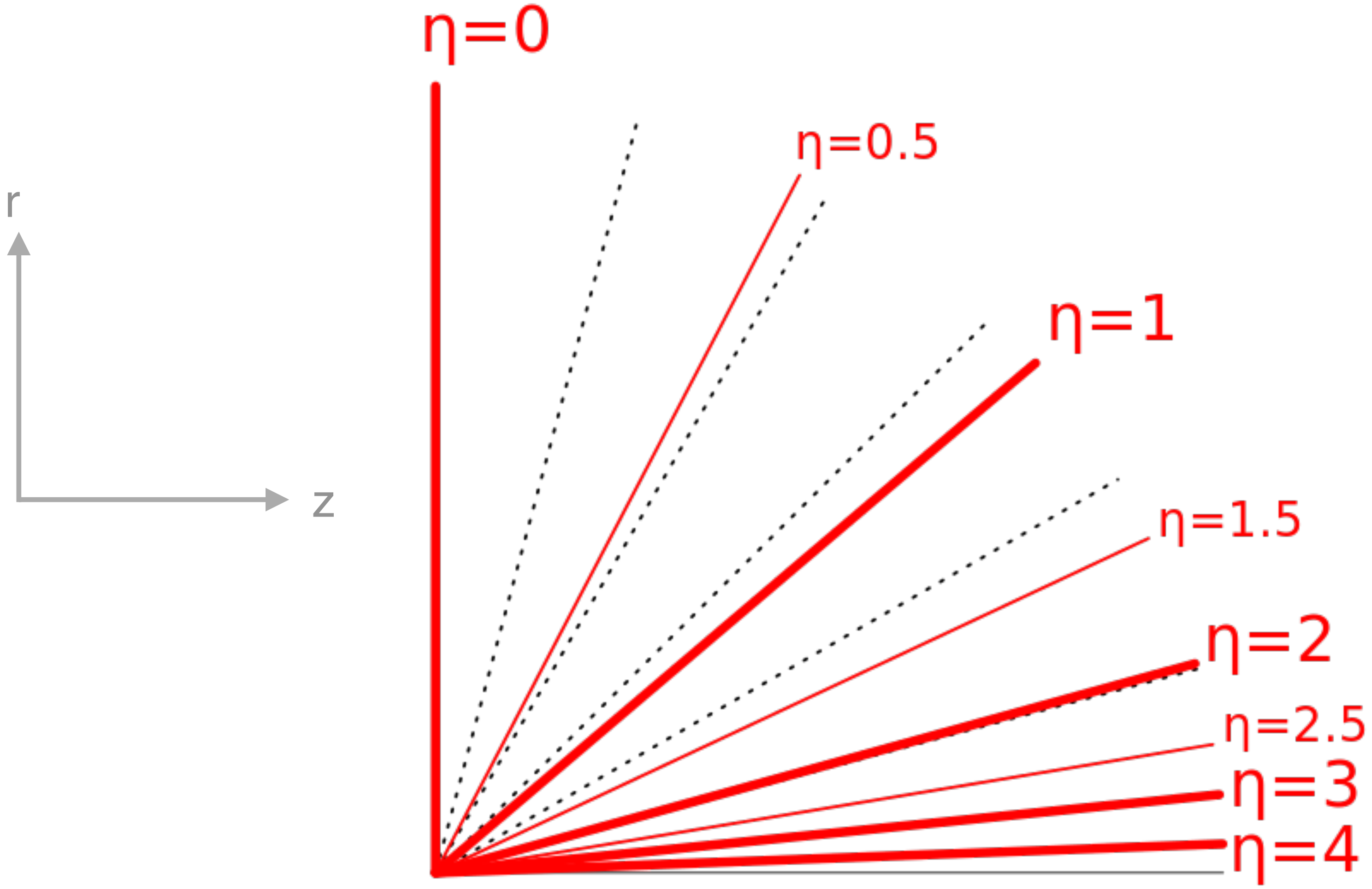


  - Imagine an s-channel resonance produced from two colliding partons (quarks or gluons)
    - Regardless of how else it might decay, if it gets produced with two quarks/gluons, **it must also decay into two quarks/gluons**
- Experimentally, qq/gg resonances are characterized by two key parameters: the mass and width
  - **If the width is smaller than the detector resolution, we call the resonance “narrow”**

SELECTION

- Find events with two jets, and compute the invariant mass with the two jets **with the highest p_T**
  - require that each jet is in the "central" region of the detector, that is: $|\eta|<2.5$
  - Also require that the **resonance decays centrally**: $|\Delta\eta_{ij}|<1.3$, where $\Delta\eta_{ij}$ is the difference in pseudorapidity between the two jets



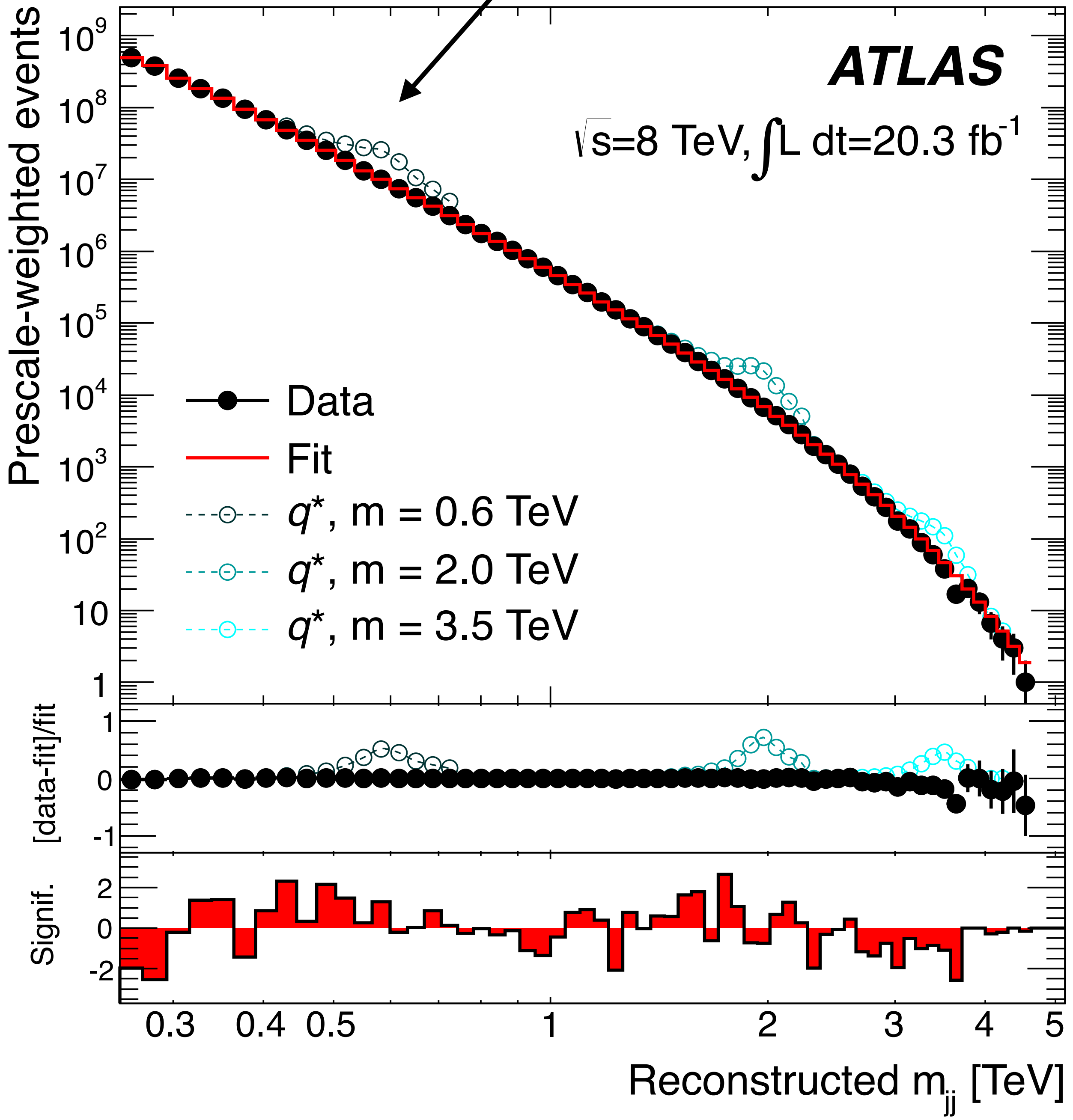


INVARIANT MASS DISTRIBUTION

- The dijet invariant mass distribution is not especially well modeled by simulation
  - Fit for the background **directly with the data**
    - important that the background function is smooth and falling

$$f(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log x}}; \qquad x \equiv M_{\mathrm{jj}}/\sqrt{s}$$

- Important to test the rate of false positives and false negatives
  - also known as type-I and type-II error rates, respectively



[EXOT-2013-11]

hypothetical signal shape

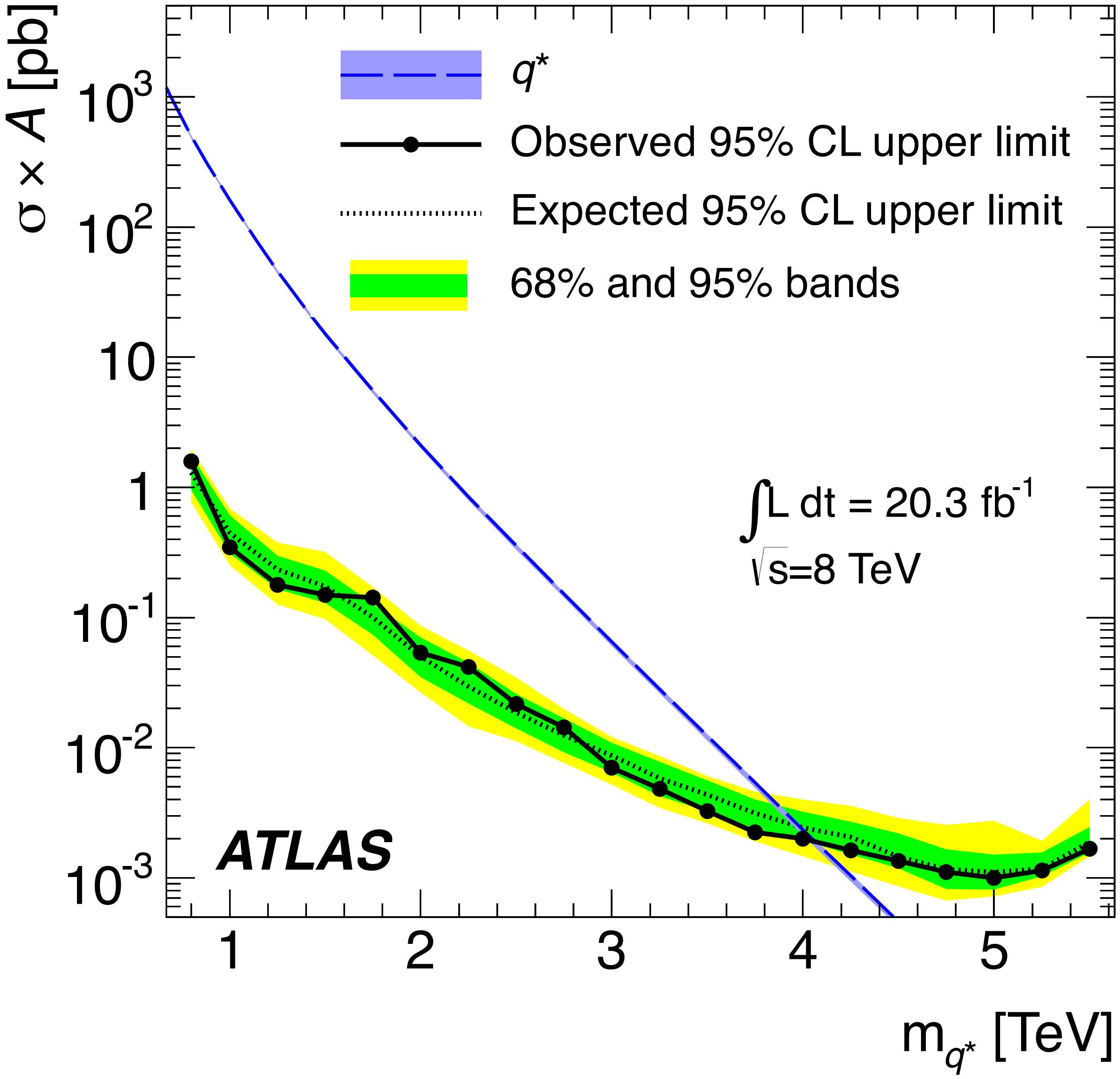
SYSTEMATIC UNCERTAINTIES

- Captures uncertainties related to analysis assumptions
  - How well do you know the **shape** of the signal?
    - jet energy scale
    - jet energy resolution
    - test simulation of the gluon emission modeling
  - How well do you know the **rate** of the signal production?
    - luminosity uncertainty
    - theoretical uncertainties in the model
  - How well do you know the background shape?
    - try different functional forms for the background fit
    - consider statistical uncertainties on the background fit parameters
  - Did you account for all of the backgrounds? Did you get rid of all of the instrumental noise? Anything we forgot?
- In general, the careful experimentalist will spend a lot of time considering sources of systematic uncertainties

LIMIT SETTING

- Uses a Bayesian formalism
  - “integrate out nuisance parameters”
    - i.e. “average the likelihood over the systematic uncertainties”
  - assumes a uniform prior on the xs
    - this gives good Frequentist properties, namely coverage!

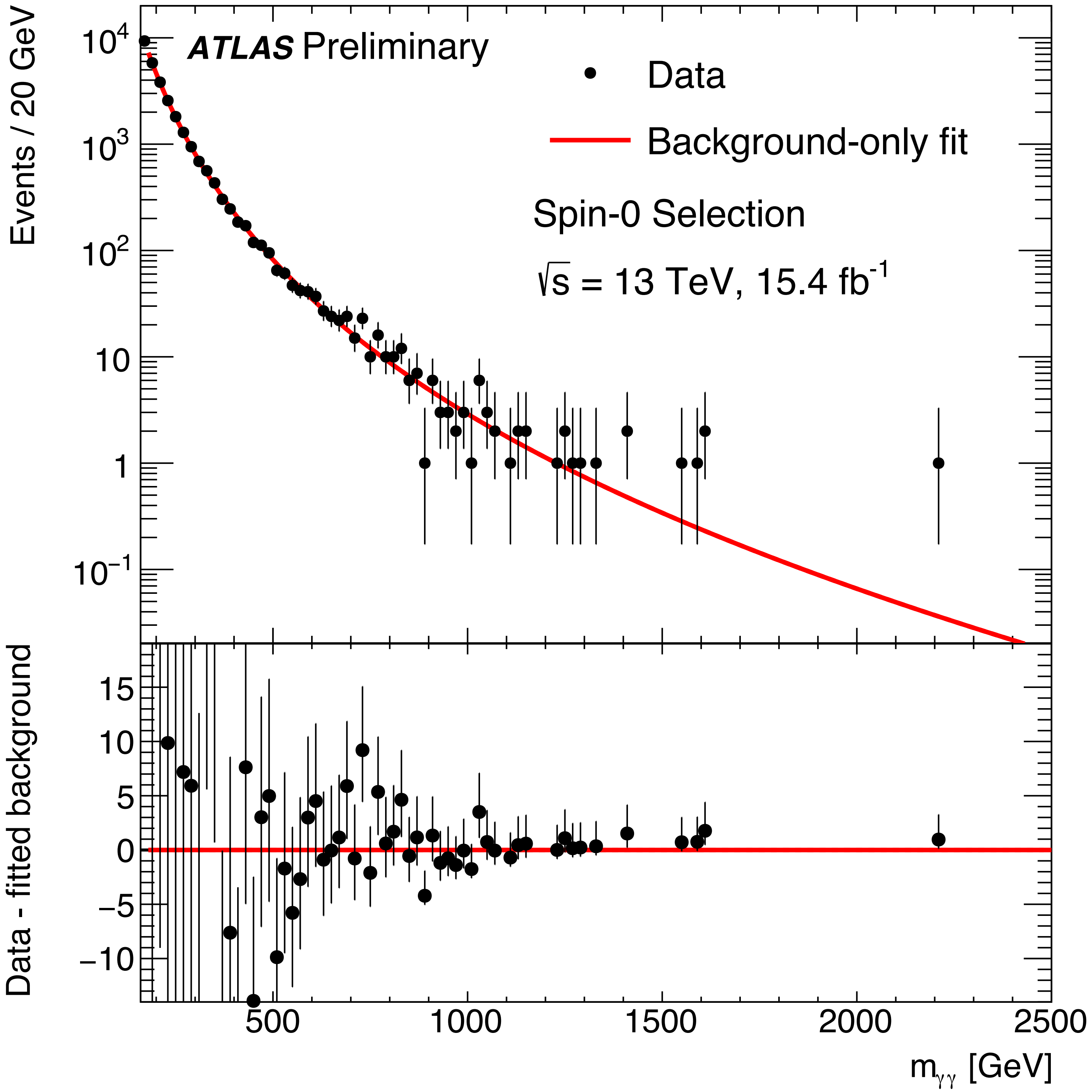
[EXOT-2013-11]



OTHER BUMP HUNTS

- Dijets are not the only kind of bump hunt you can perform
  - Just about any combination of objects can be combined to form an invariant mass
    - This the ATLAS's most recent diphoton bump hunt

[ATLAS-CONF-2016-059]

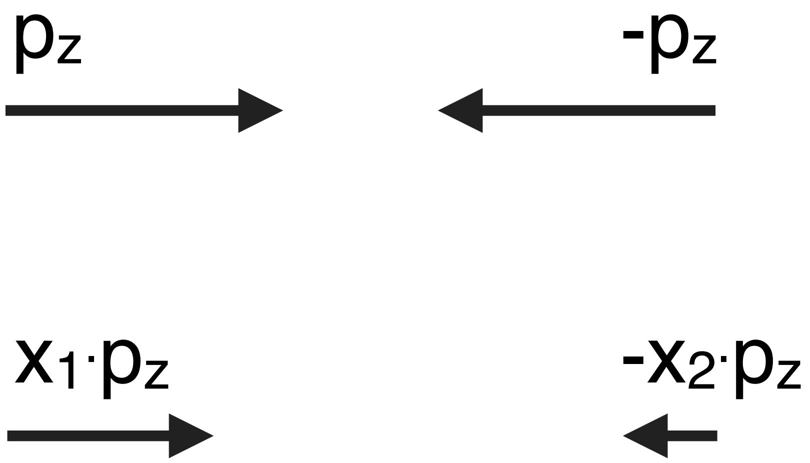


MISSING TRANSVERSE MOMENTUM

- When you collide two protons, it is really the gluons or quarks **inside the proton** that collide
  - the gluons and quarks (a.k.a. partons) carry an **unknown fraction** of the total momentum of the proton
    - Hence you **do not know a priori** what the p_z of the final state is

Incoming protons
with 0 total momentum

Incoming partons
with *non-0* total momentum

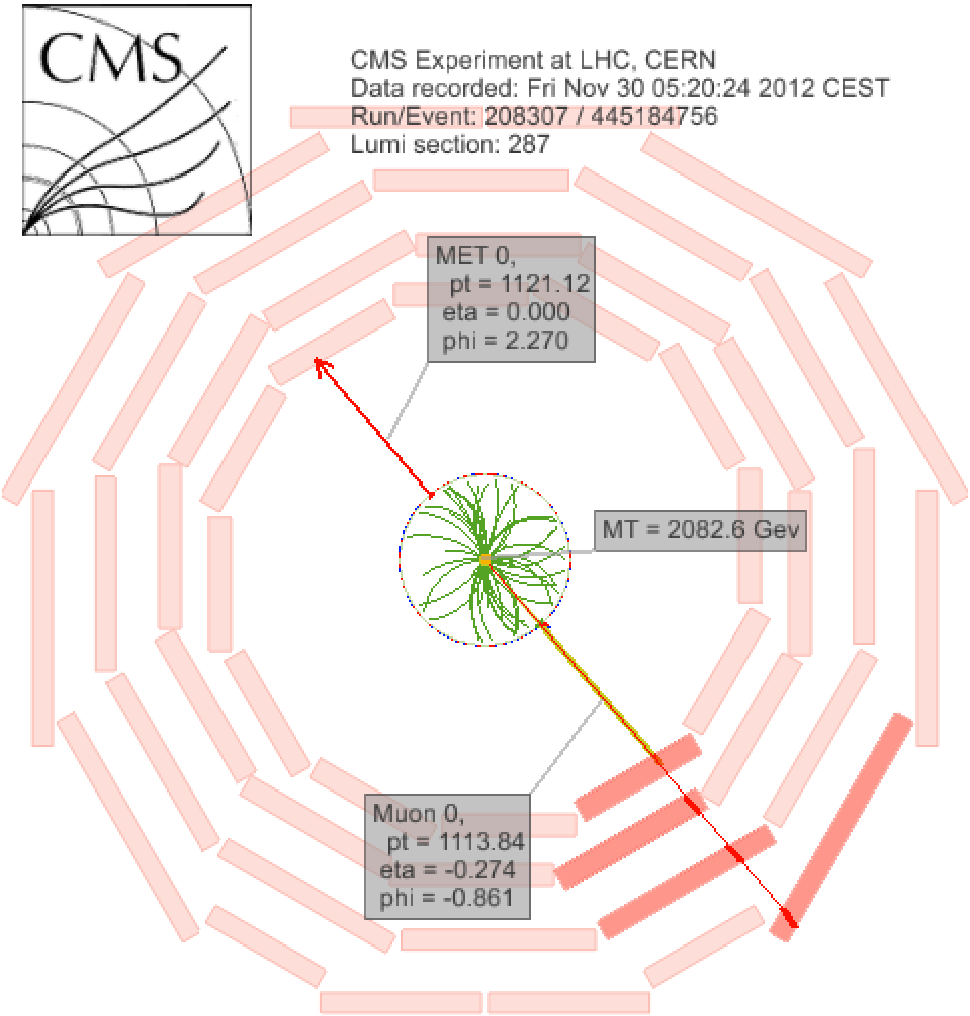


(x_1 and x_2 are the unknown momentum fractions)

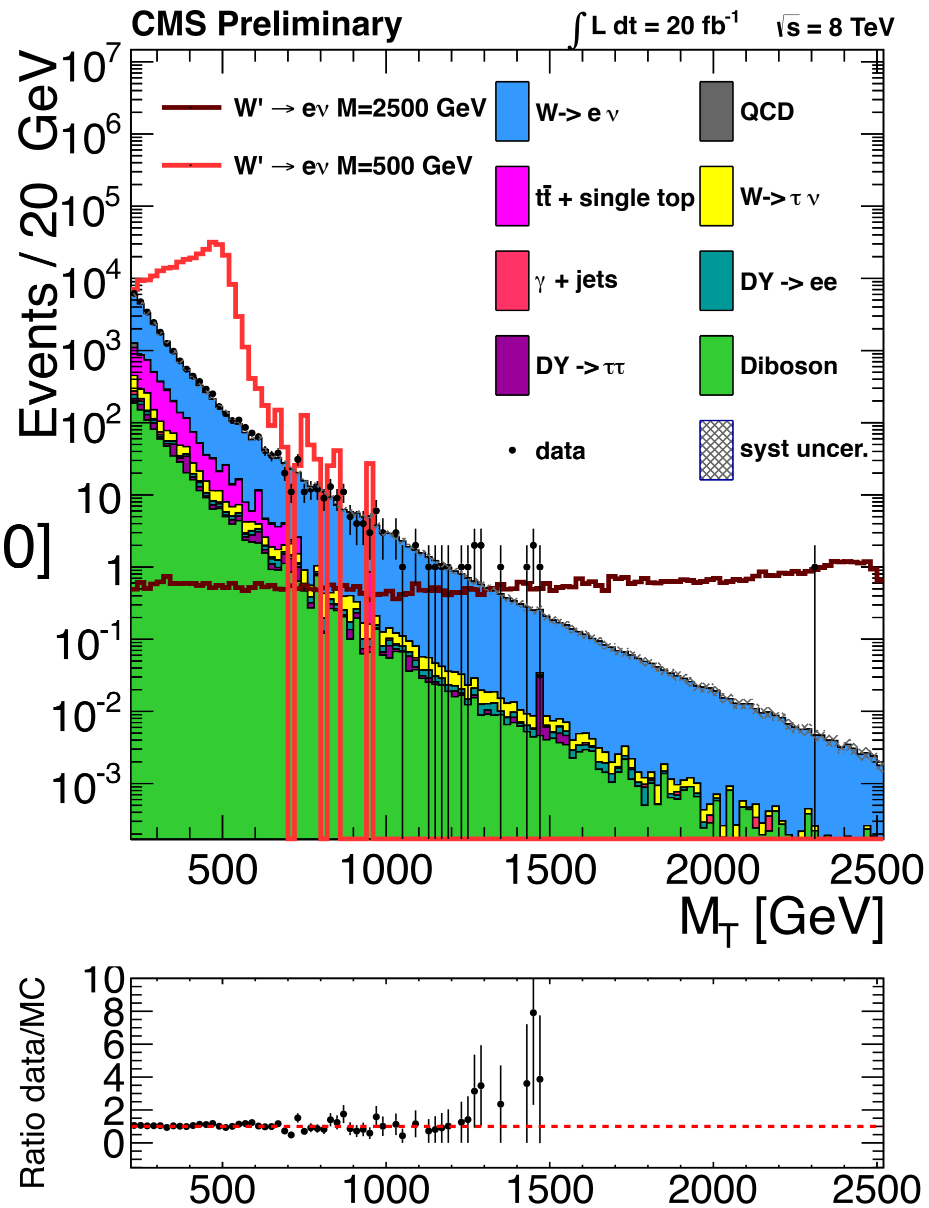
  - You only know that the total momentum **transverse to the beam axis** (px and py) should be 0
    - An imbalance in momentum in the transverse plane indicates the presence of at least one undetected particle

NOT EVERY SEARCH CAN BE A BUMP HUNT

- Consider the search for a W’→eν or μν
  - The p_z of the neutrino is unknown, so there is no longer an invariant mass bump
    - This analysis is crucially reliant on MC to give an accurate prediction of the spectrum

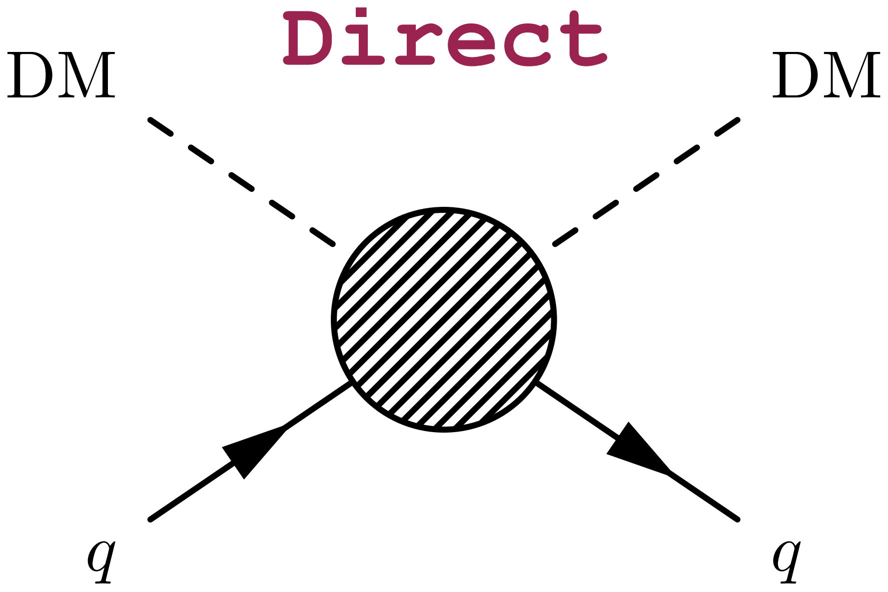


[EXO-12-060]

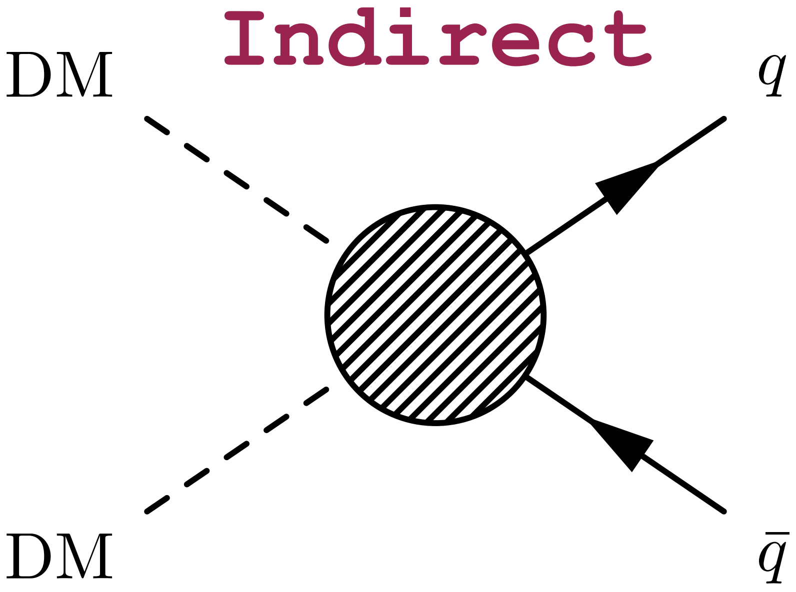


HOW TO FIND DARK MATTER

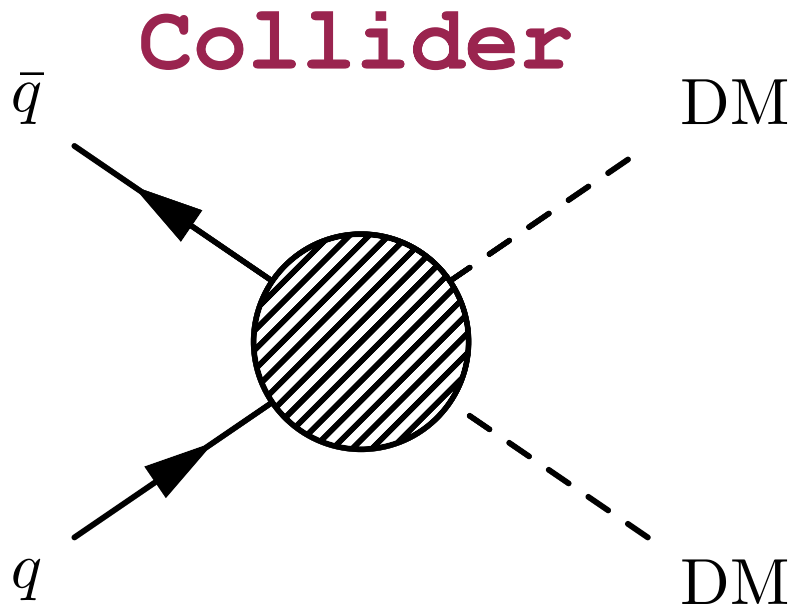
- Direct detection: look for galactic dark matter that bumps into your detector
- Indirect detection: look for the products of dark matter annihilating with itself
- Collider detection: produce dark matter in the detector through pp collisions



Direct



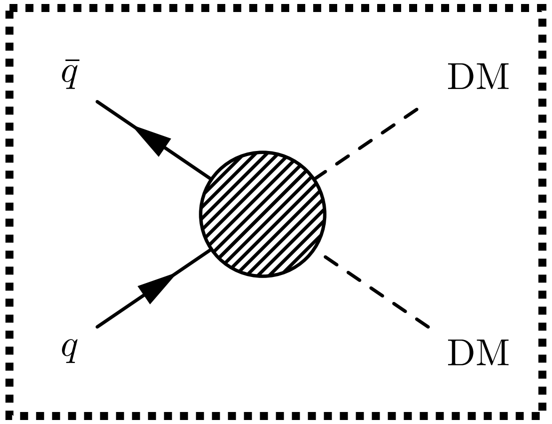
Indirect



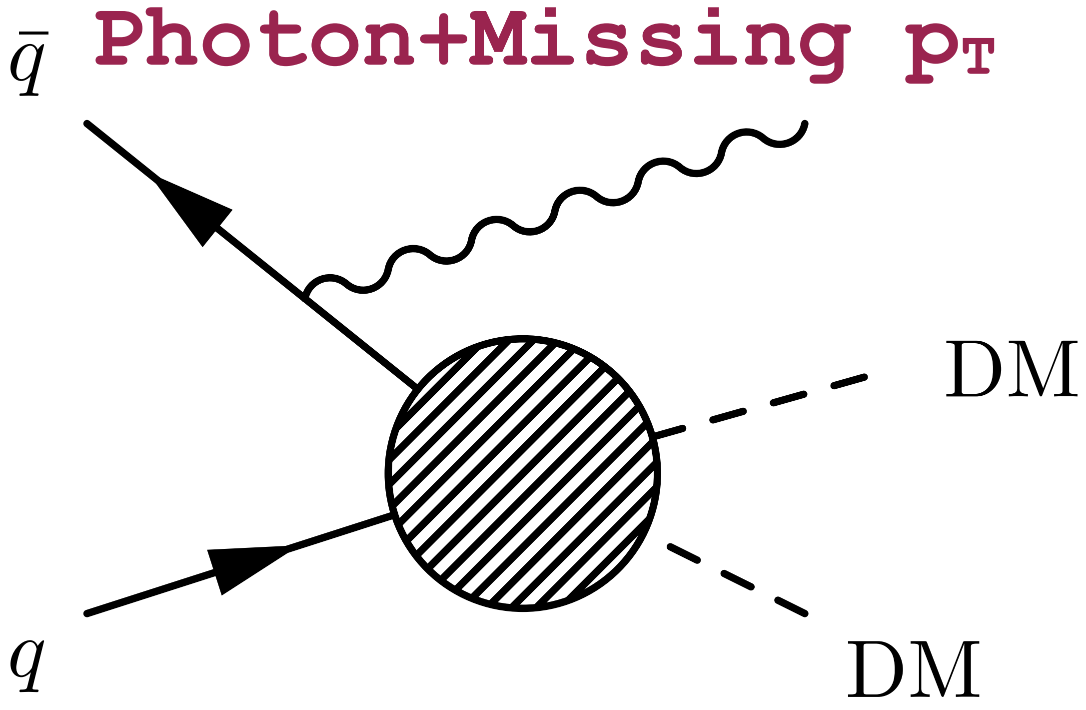
Collider

Time $\Longrightarrow$

DARK MATTER SIGNATURES

- Of course  is not observable at a collider

  - Use QED/QCD initial state radiation (ISR) to “tag” DM events
    - results in a “monophoton” or “monojet” signature with missing momentum balancing the photon or jet

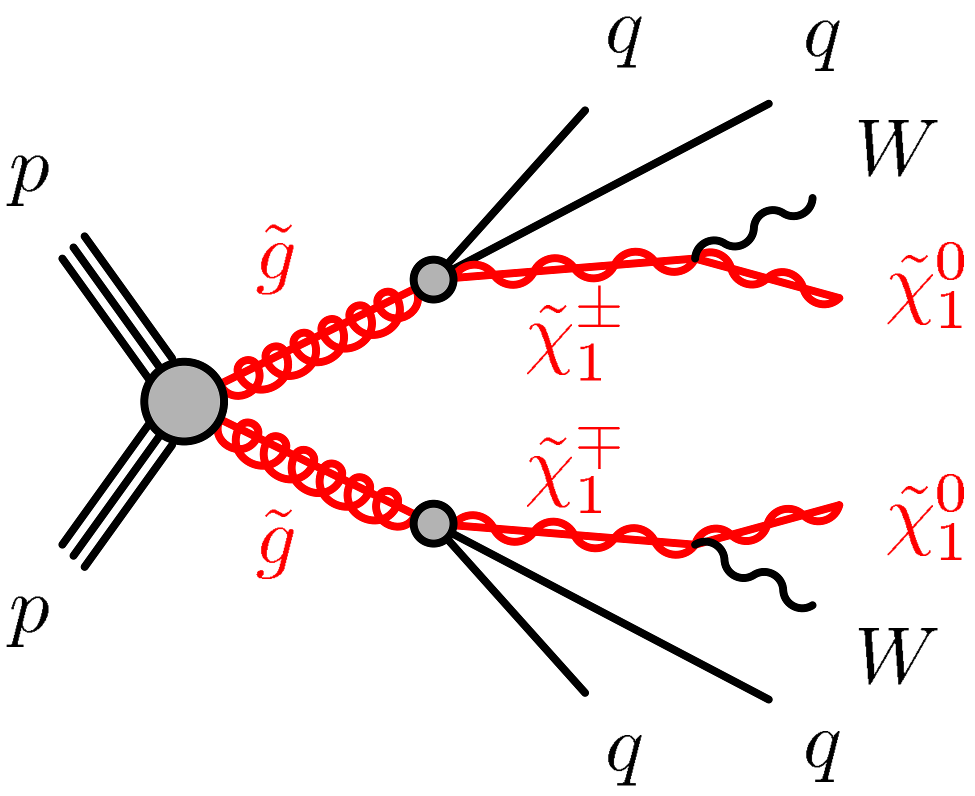


Photon+Missing p_T

Jet+Missing p_T

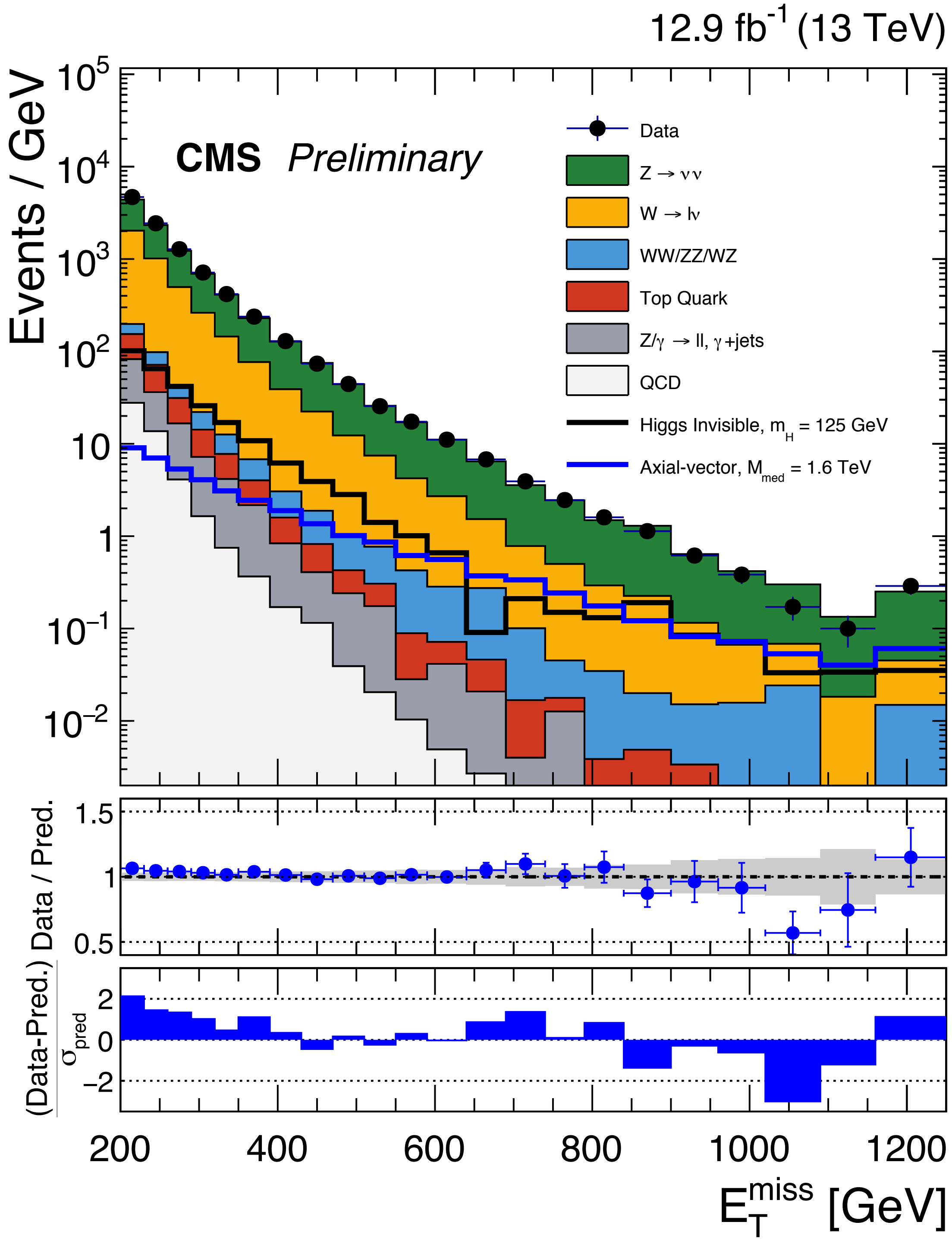
MORE DARK MATTER SIGNATURES

- In fact, just about anything can act as the recoiling object:
  - W bosons, Z bosons, Higgs bosons, one or more top quarks, one or more b quarks, etc.
    - A common dark matter search is to look for X+missing p_T where X is a particle
- Supersymmetry can provide signatures with many more particles in addition to the two dark matter particles



MONOJETS

- The signal is a jet recoiling against missing p_T and no detected leptons.
  - What other processes look like that?
    - Z(→νν)+jet
    - W(→lν)+jet
    - W(→lν)+W(→jj)
    - W(→jj)+Z(→νν)
    - Z(→jj)+Z(→νν)
    - t(→lνb)+t(→lνb)
  - How do you know what the rates are?
    - Measure similar processes in the data, and use simulation to transfer

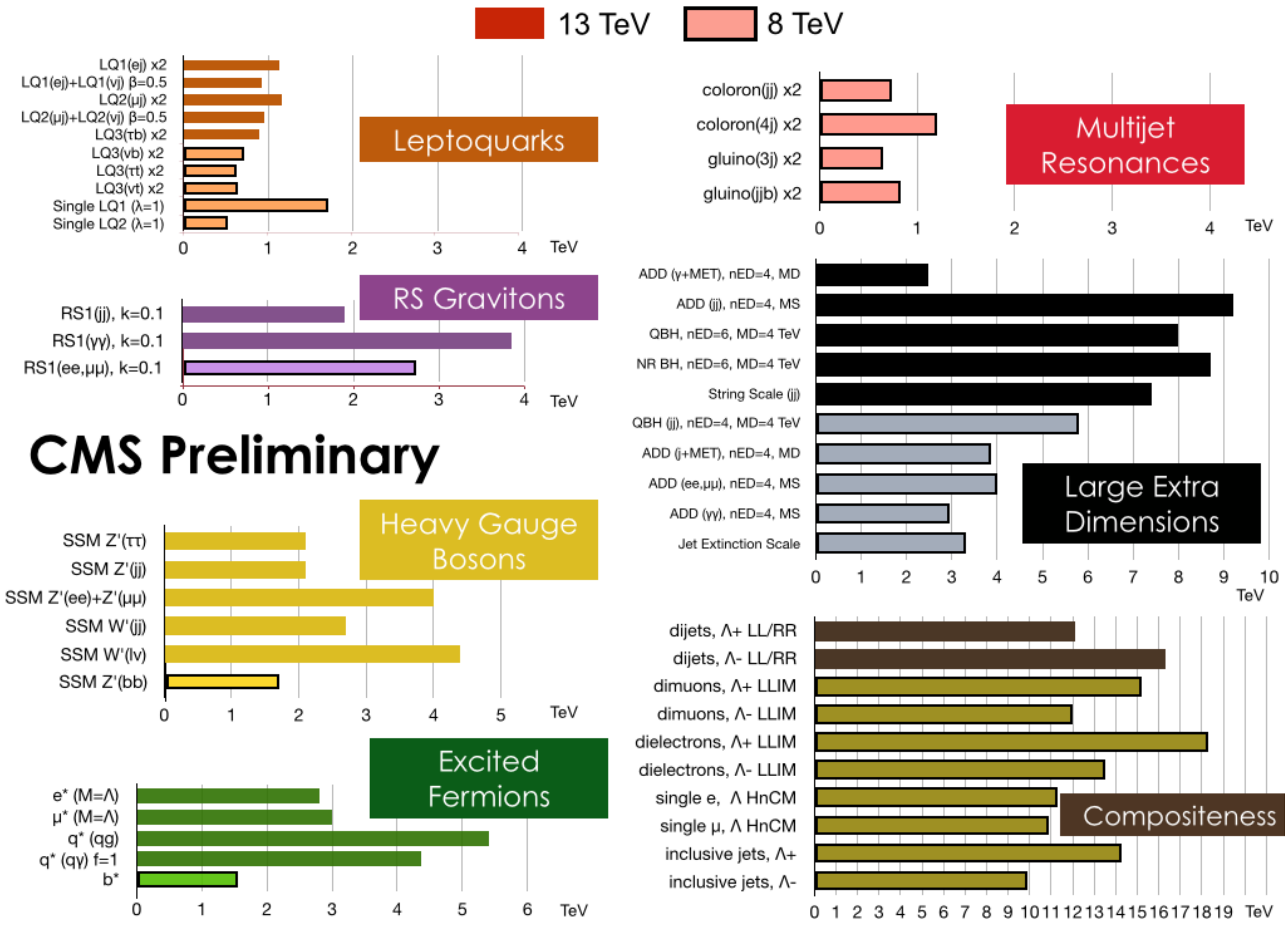


SO HAVE WE FOUND ANYTHING?

- We've looked for many, many new phenomena:
  - squarks, sleptons, gluinos, leptoquarks, gravitons, vector-like quarks, compositeness, extra dimensions, heavy gauge bosons, long-lived particles…

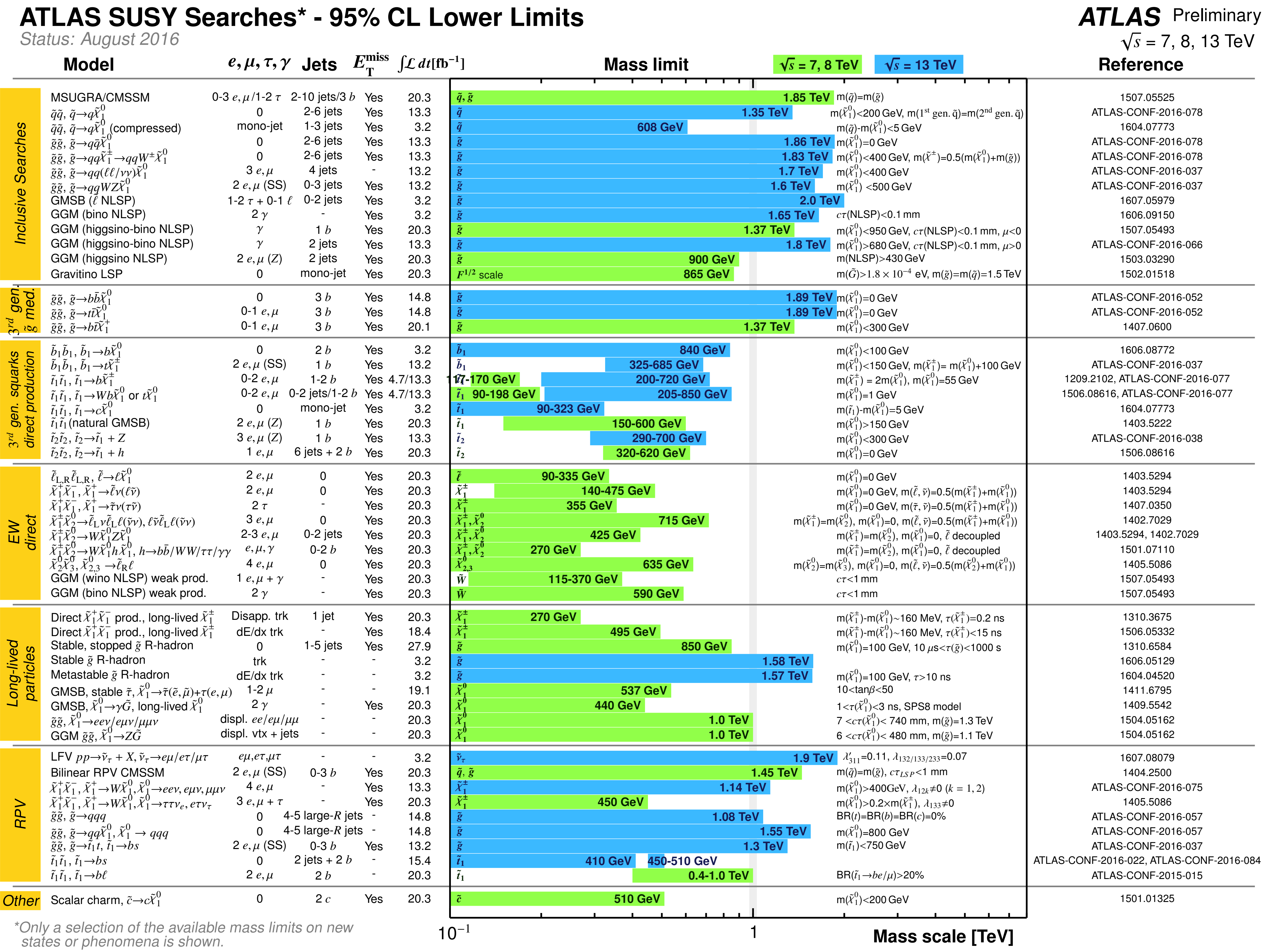
- So far, no hints of new physics have been found
  - That doesn't mean that new physics isn't around the corner
  - Perhaps we need to be more creative
  - Or perhaps we simply need more data

SEARCHES FOR NEW PHYSICS



CMS Exotica Physics Group Summary – ICHEP, 2016

SEARCHES FOR NEW PHYSICS



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

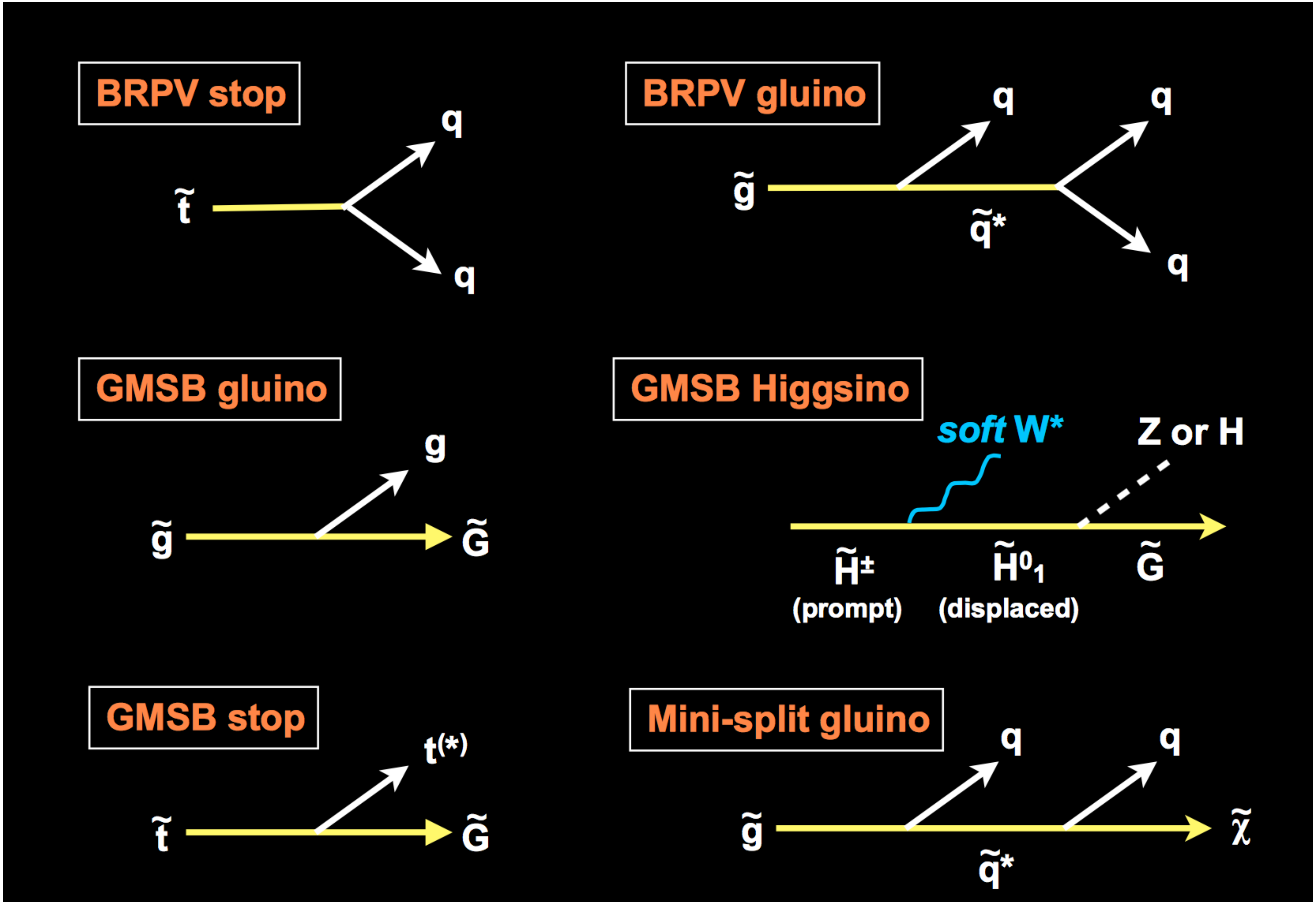
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	🟦 $\tilde{q}$ 1.35 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.86 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.83 TeV	$m(\tilde{\chi}_1^0)$<400 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	🟦 $\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	🟦 $\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$ 840 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	1 b	Yes	13.2	🟦 $\tilde{b}_1$ 325-685 GeV	$m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^\pm)$= $m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e,μ	1-2 b	Yes	4.7/13.3	🟩 $\tilde{t}_1$ 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}_1^\pm)$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	🟩 $\tilde{t}_1$ 90-198 GeV 🟦 205-850 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	13.3	🟦 $\tilde{t}_2$ 290-700 GeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$ 320-620 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-335 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 140-475 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 355 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 715 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 425 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_{2,3}^0$ 635 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}_1^\pm$ 495 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}_1^\pm$ 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ $(k=1,2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	13.2	🟦 $\tilde{g}$ 1.3 TeV	$m(\tilde{t}_1)$<750 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$ 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown.

DISPLACED DIJETS

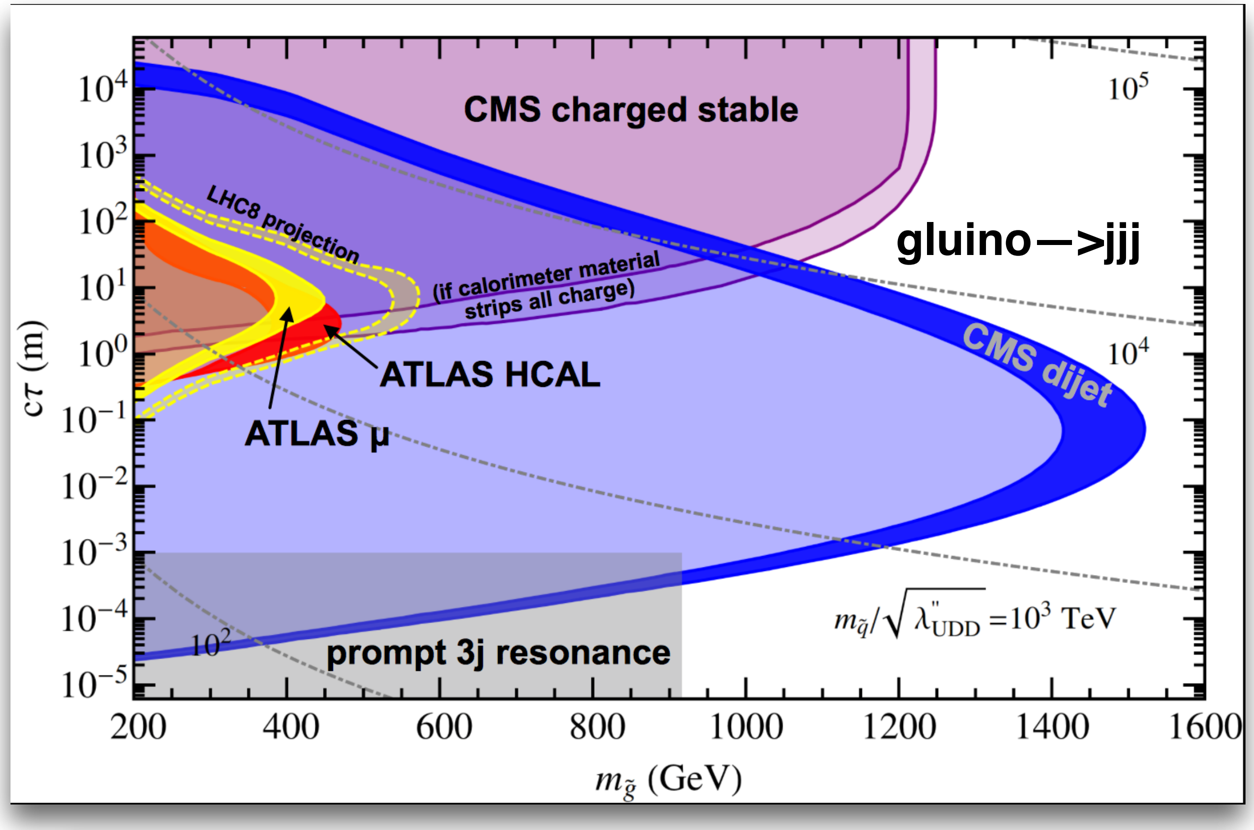
- New physics could manifest in particles with macroscopic lifetimes (> ps)
  - Being on the lookout for such unique signatures is critical if we want to explore the new physics landscape comprehensively
- Selection
  - **≥2** jets (p_T>60 GeV, $|\eta| < 2$) with small number of prompt tracks and prompt energy fraction
  - Scalar sum of the jets transverse momenta $H_T > 300$ GeV
  - both jets reconstruct to a **single, displaced vertex**
    - likelihood discriminant determines quality of the vertex and promptness of the jets
- Final result: ~fb xs·BR limits for ~mm cτ

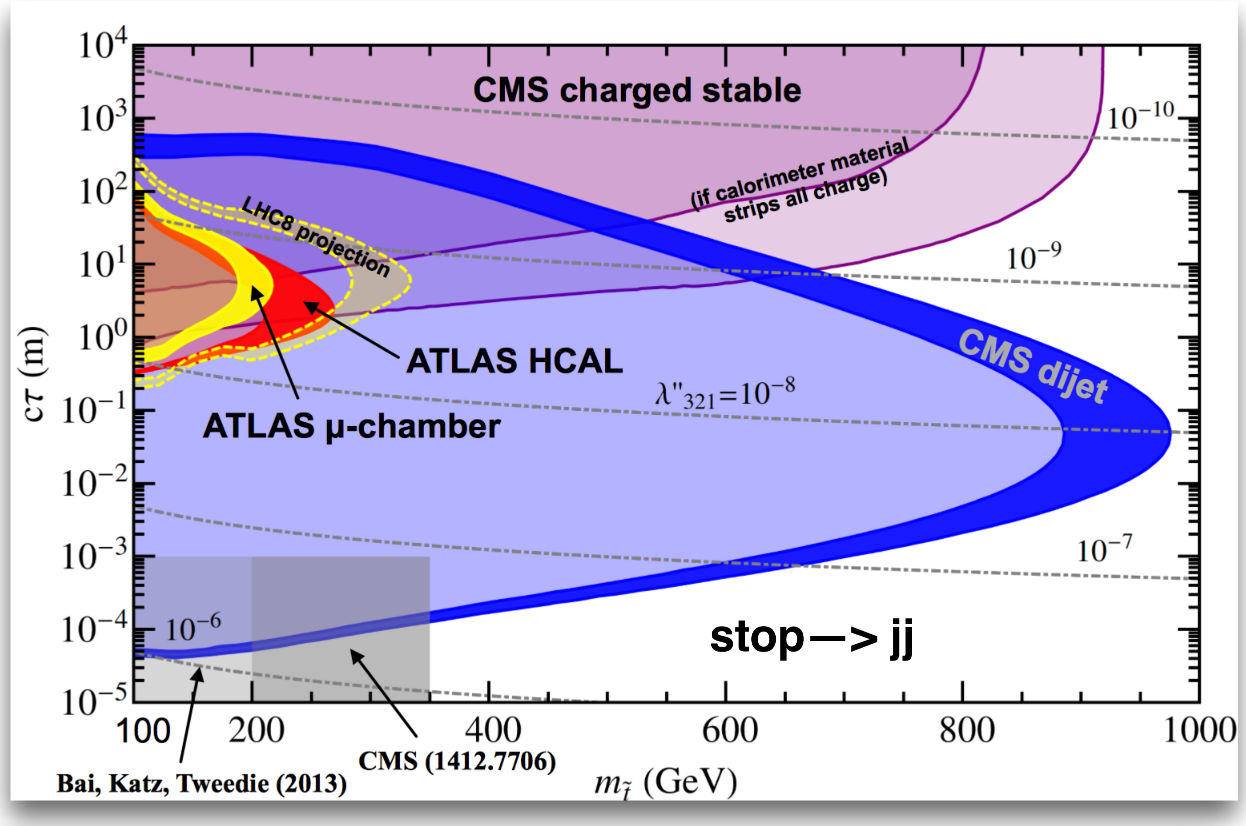
DISPLACED DIJET MODELS

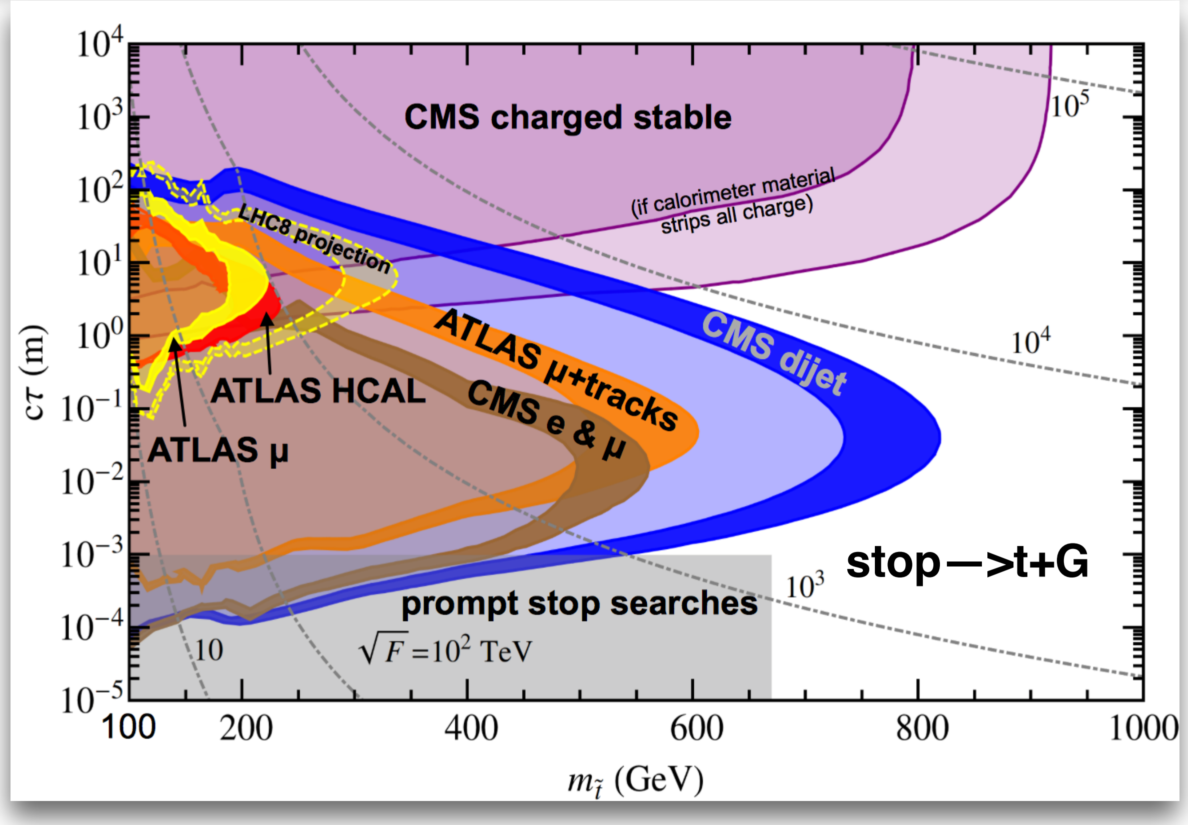


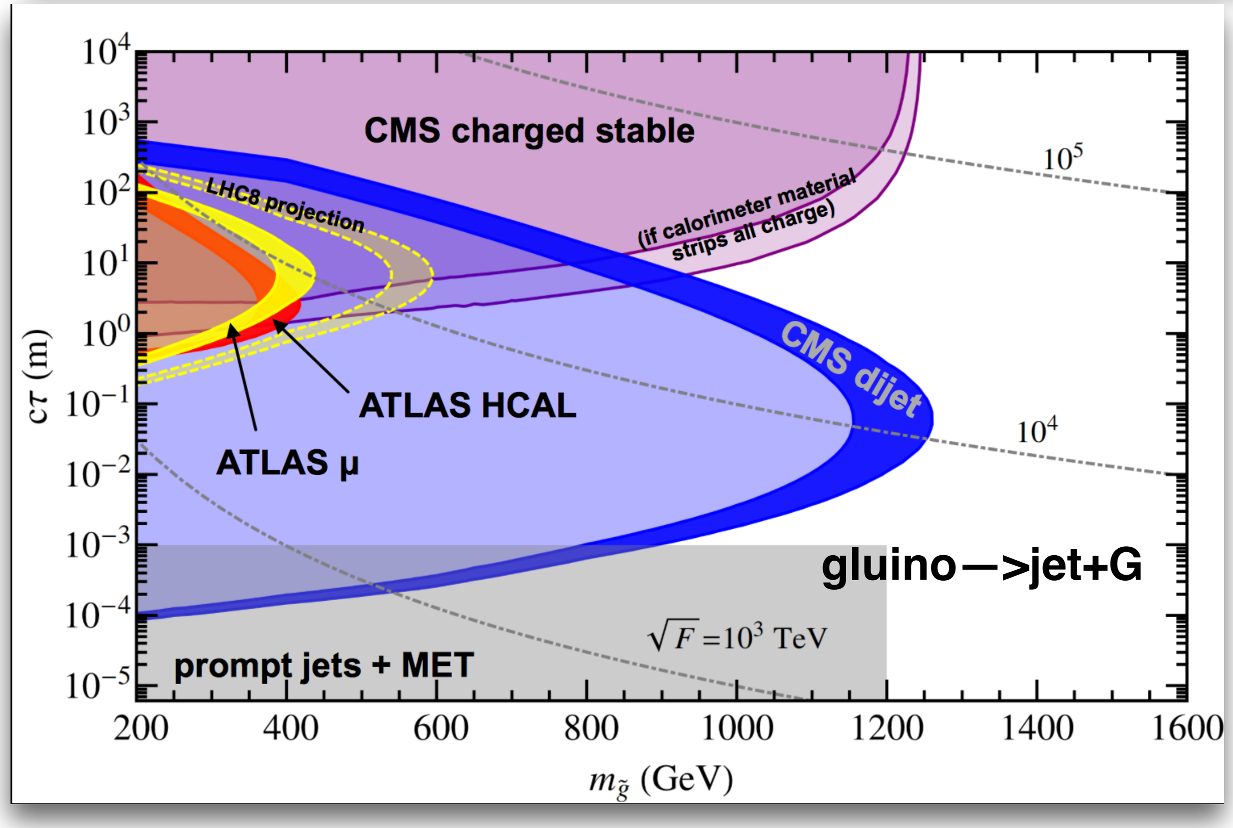
DISPLACED DIJET SENSITIVITY

Liu, Tweedie, arXiv:1503.05923









CONCLUSIONS

- The LHC is performing marvelously
  - It seems likely we will get at least 150/fb of integrated data at $\sqrt{s}=13$ TeV over the next two years
  - This is an enormous dataset with incredible potential to make a game-changing discovery
    - Any discovery of new physics, whether it addresses the problems I mentioned at the beginning or not, will bring with it a whole host of questions:
      - How does it relate to the other particles of the Standard Model?
      - What is the structure of this new sector of physics? Does it have friends?
      - Can it address the dark matter problem? The Hierarchy problem? Flavor? Gauge coupling unification?
- The next few years could well be the most exciting time in the history of particle physics