DPG-Frühjahrstagung 2013

Technische Universität Dresden, Germany
March 4 – 8, 2013

Needles in a Haystack
Searches for New Physics at the LHC

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Needles in a Haystack

Introduction

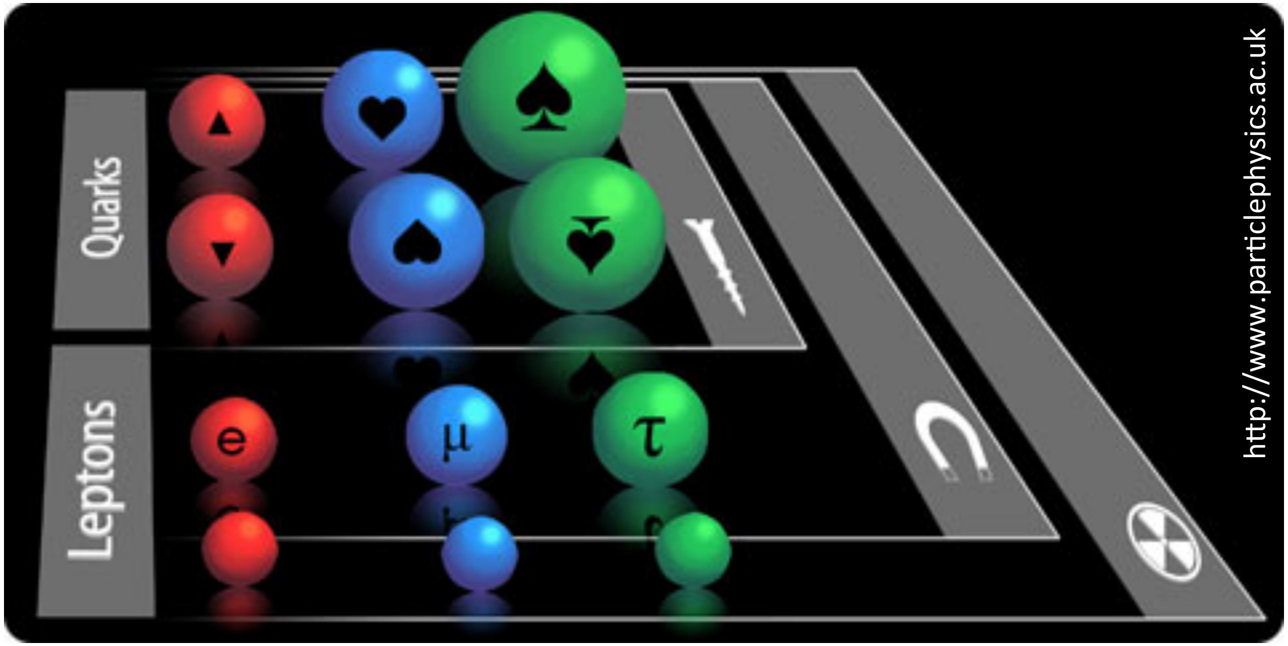
Experimental search techniques

- SUSY search with razor
- Boosted object search for bulk RS graviton
- Light Higgs decay to long-lived particle

More searches

Conclusions

Standard Model



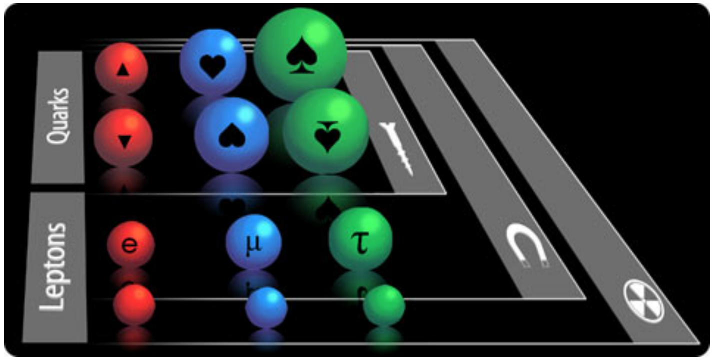
The Standard Model is in impressive agreement with experiments at all energy scales probed so far. Why look beyond?

E.g. John Ellis, 2002: Supersymmetry for Alp Hiker. Chapter 1 - Getting Motivated

> *The Standard agrees with all confirmed experimental data from accelerators, but is theoretically very unsatisfactory.*

Or less theoretically (next talk), let's ask some fundamental questions …

Fundamental Questions



Why are there twelve fundamental particles? Perhaps they are not fundamental after all?

We know what only 4% of the universe is made of. What else is out there? What is dark matter? Dark energy?

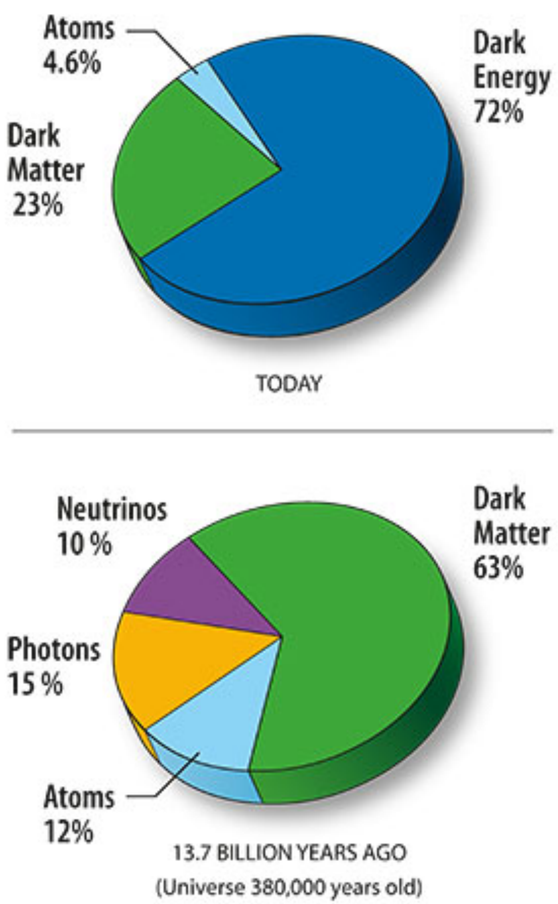
And where has all the anti-matter gone?

We know of three spatial dimensions in everyday life. Einstein added a forth, time. Are there more? Is this how gravity fits in?

What is mass? The Higgs? And why do the quark masses vary by five orders of magnitude?

Why is there at least five orders of magnitude of nothing between the neutrinos and the quarks?

Fundamental Questions



http://map.gsfc.nasa.gov/media/080998/index.html

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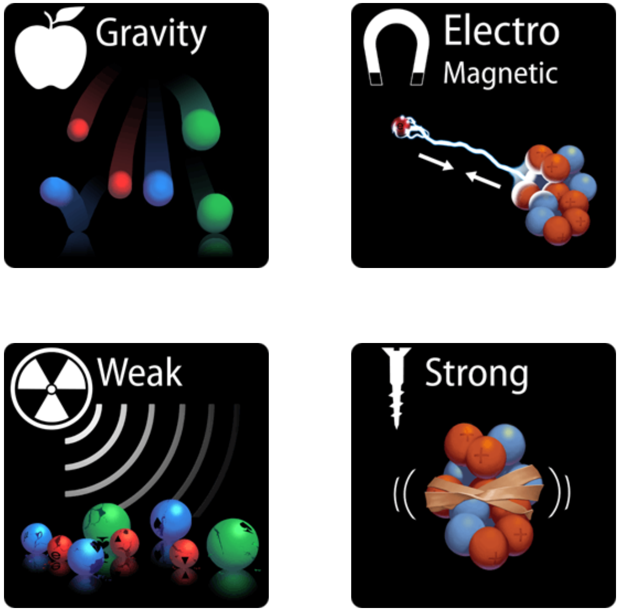

http://www.particlephysics.ac.uk

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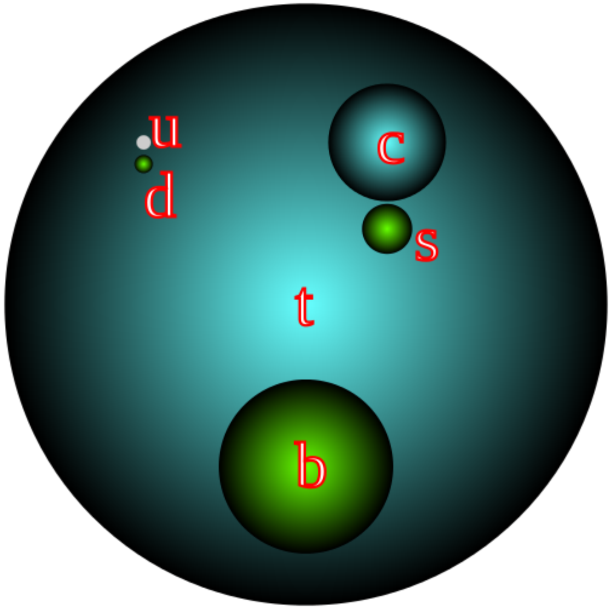
Fundamental Questions

http://en.wikipedia.org/wiki/Quark



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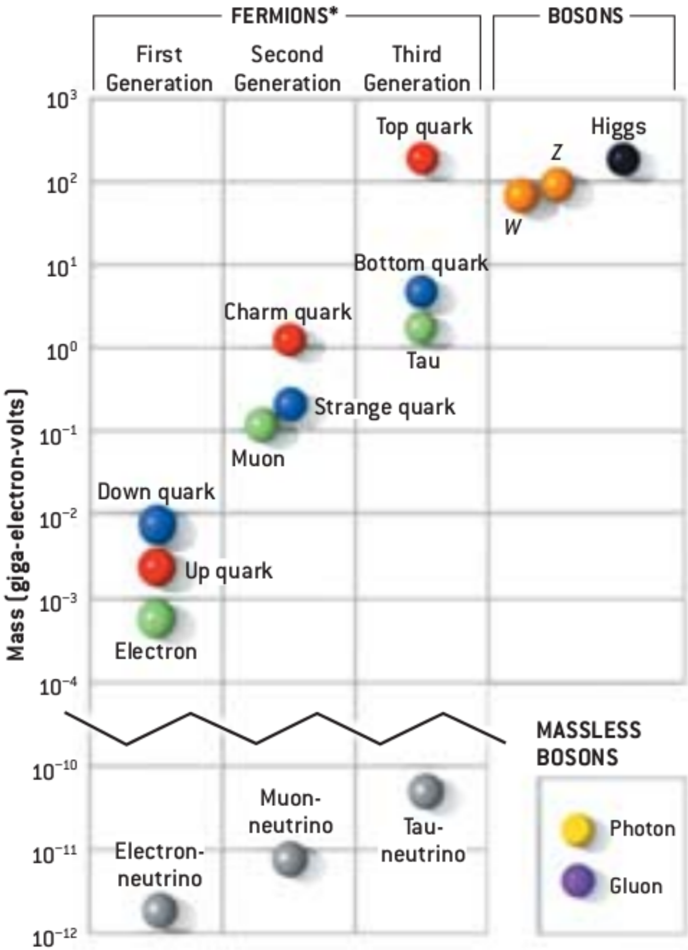

Gordon Kane, *The Dawn of Physics beyond the Standard Model*; Scientific American, May 2003

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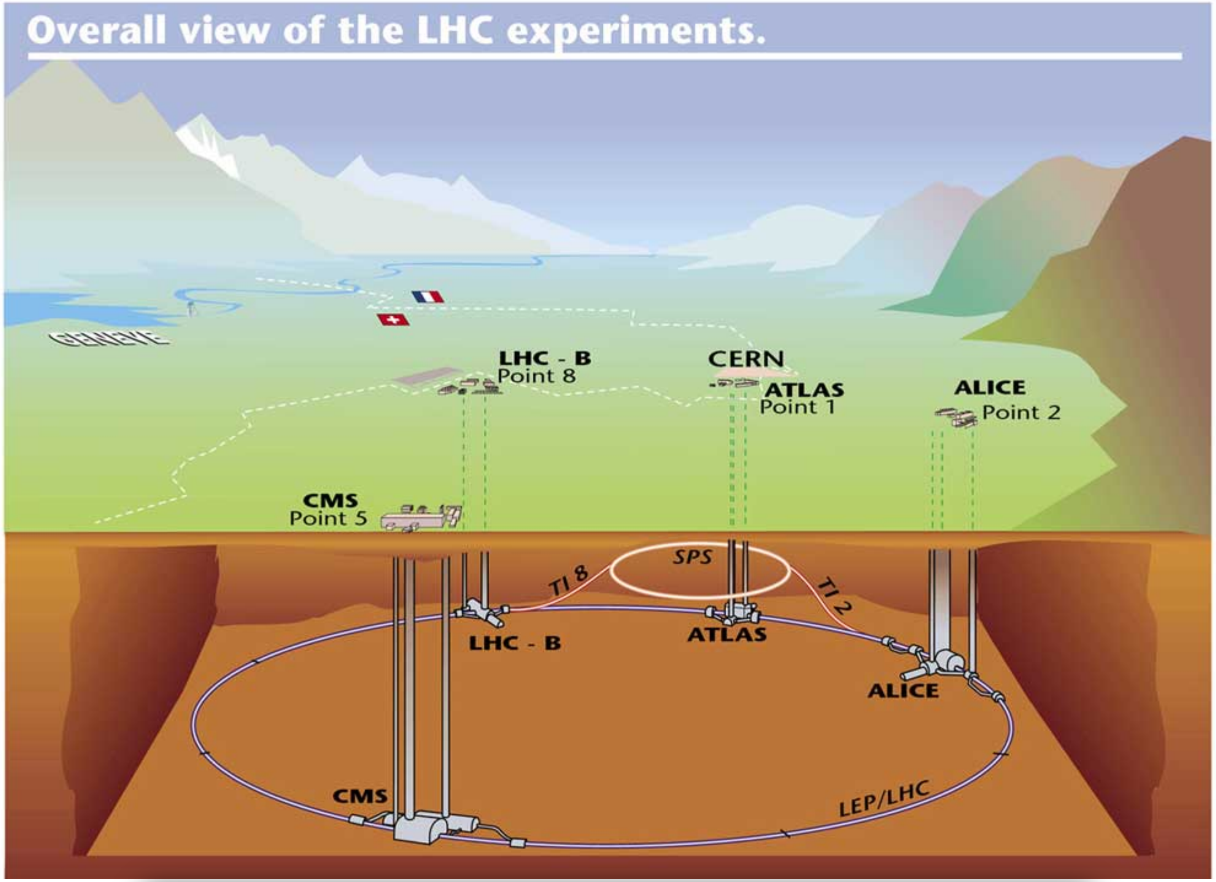
The LHC Ends Run 1



Comments (21-Feb-2013 09:05:25)

Phone:77600

*** END OF RUN 1 ***

No beam for a while. Access required

time estimate: ~2 years

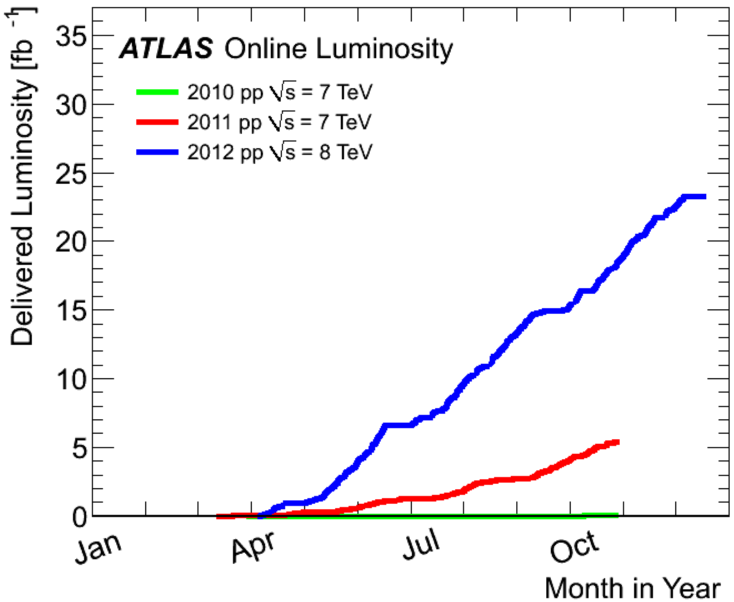
LHC Performance

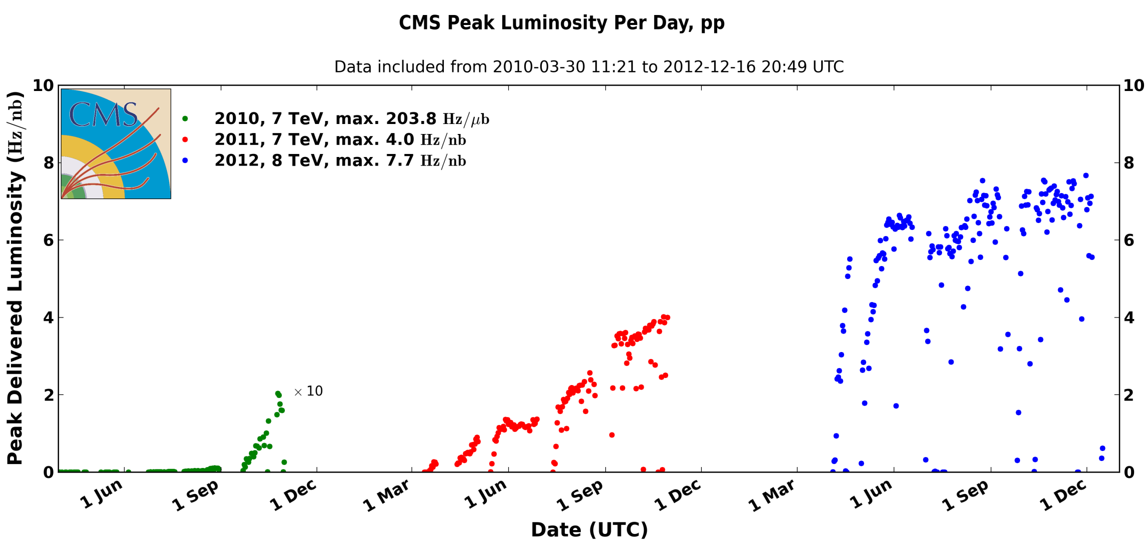
Proton-proton running at √s = 7 and 8 TeV

- Steadily increasing peak luminosity
- Operation at 50ns bunch spacing, increasing bunch numbers and charge
- Integrated lumi delivered to ATLAS/CMS

  2012: ~23 fb^{-1} 2011: ~6 fb^{-1} 2010: ~0.5 fb^{-1}

- Recorded with high efficiency above 90% by experiments



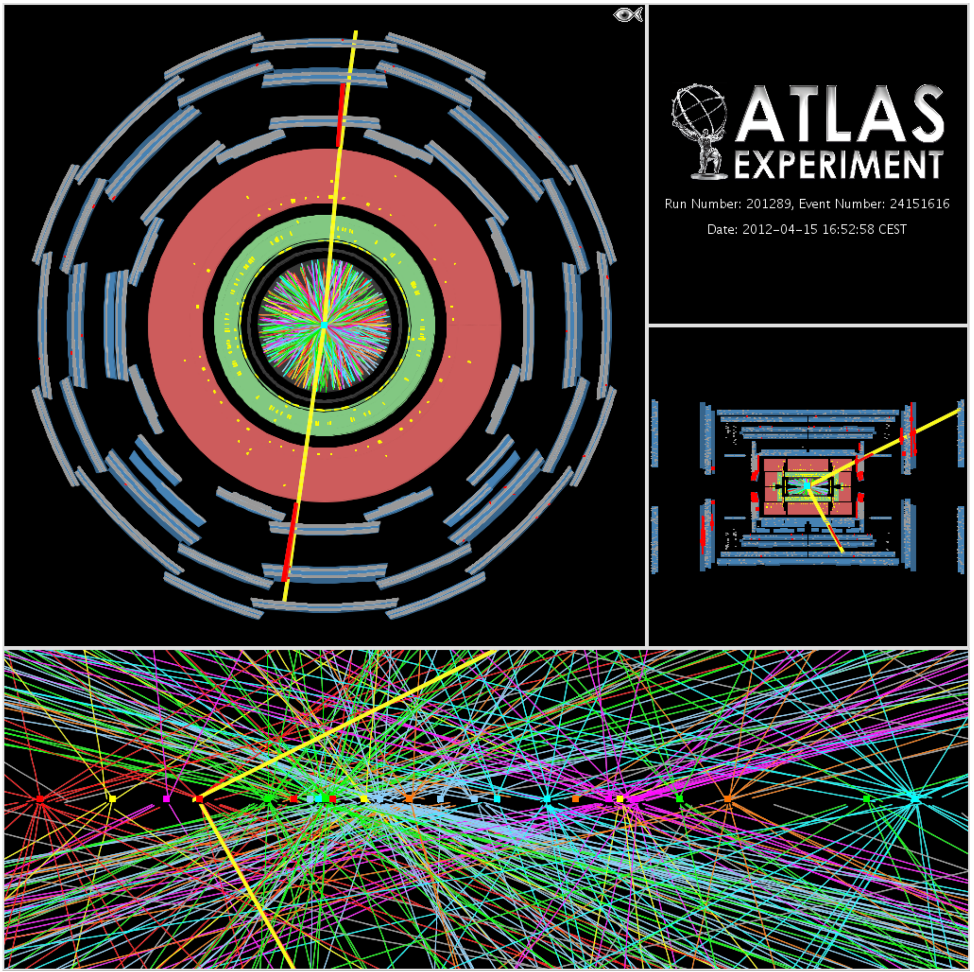


Successful heavy ion collisions

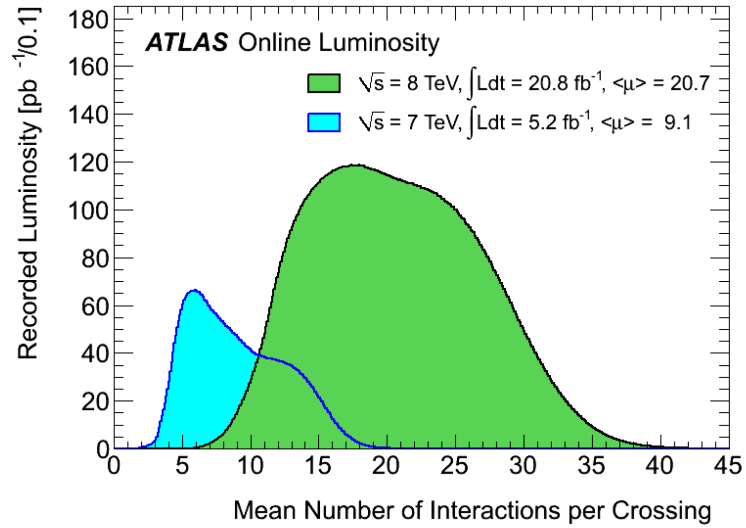
2011: PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

2013: pPb at $\sqrt{s_{NN}}$ = 5.02 TeV

Pile-up: A Price to Pay



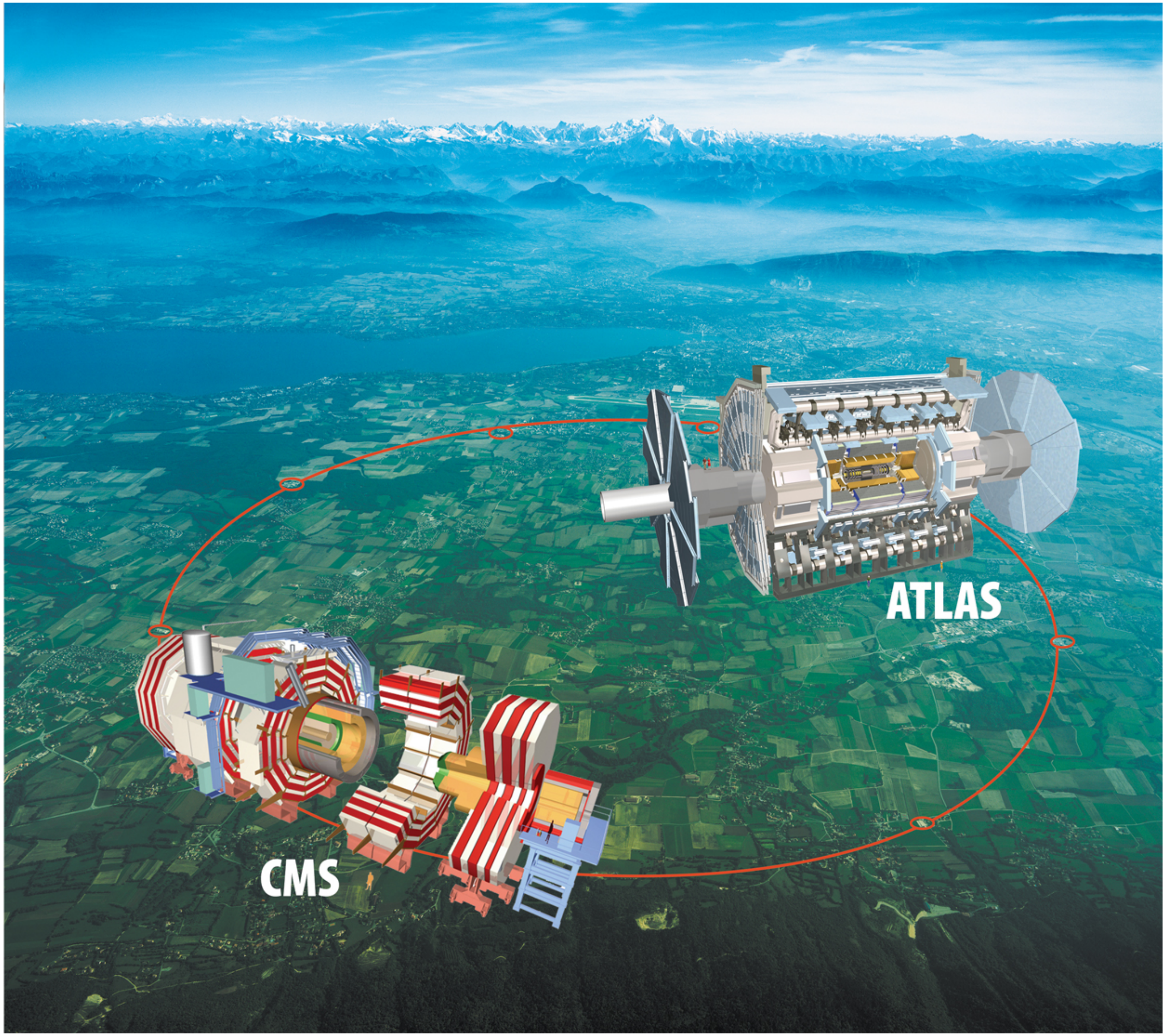
Z→ μμ candidate with 25 reconstructed vertices



- Up to 40 pile-up interactions, exceeding design conditions
- Challenging e.g. for trigger and DAQ, lepton/photon isolation, vertexing, E_T^{miss}, jet energy scale

→ Continuing performance studies to understand impact of pile-up

ATLAS and CMS



Two gigantic multi-purpose detectors

Different designs but similar design goals

ATLAS emphasis on excellent jet/MET resolution, particle ID and muon reconstruction

CMS emphasis on excellent resolution for electrons, muons and photons

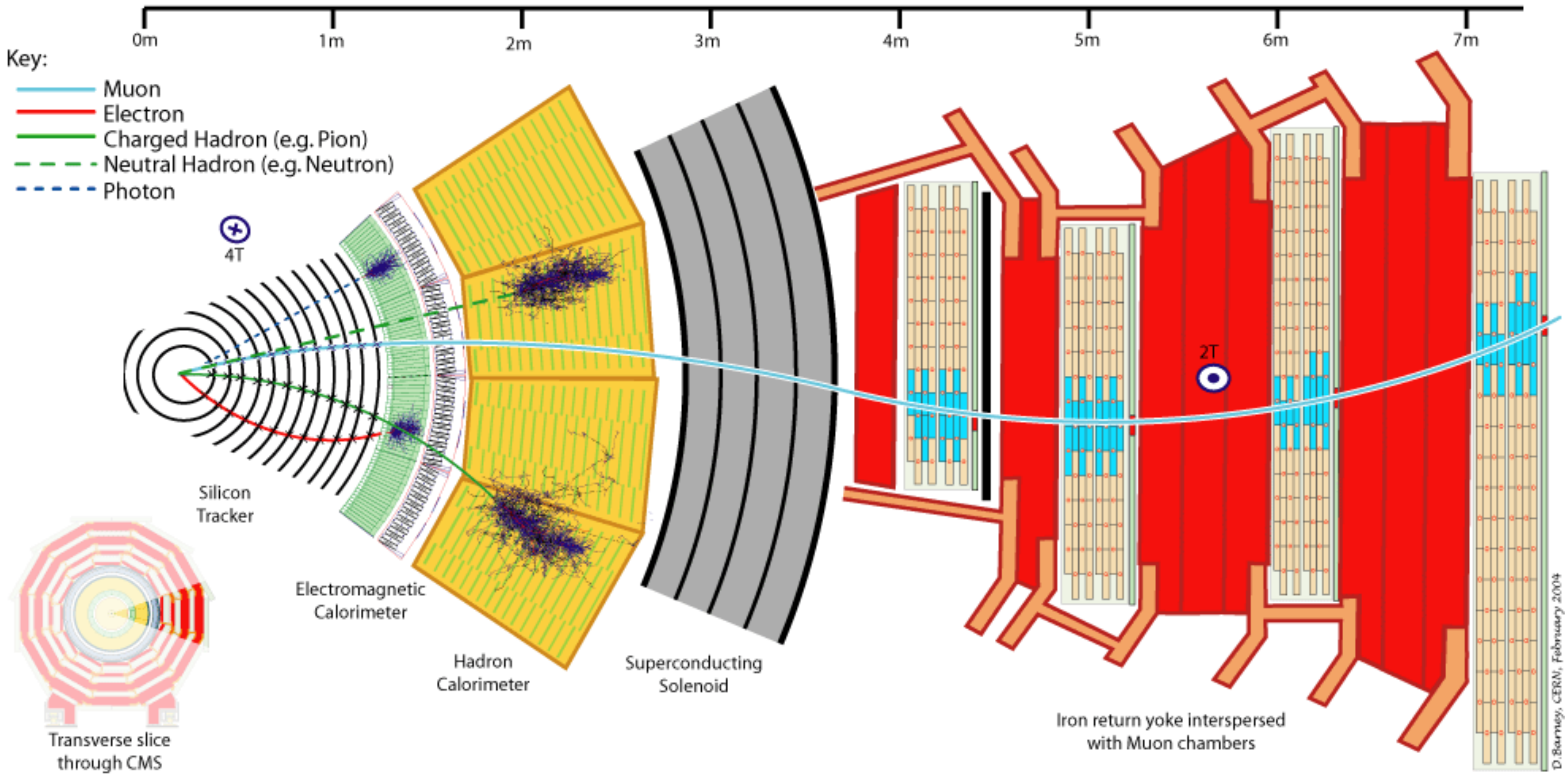
Particle Identification

Tracking
- Momentum measurement and particle ID

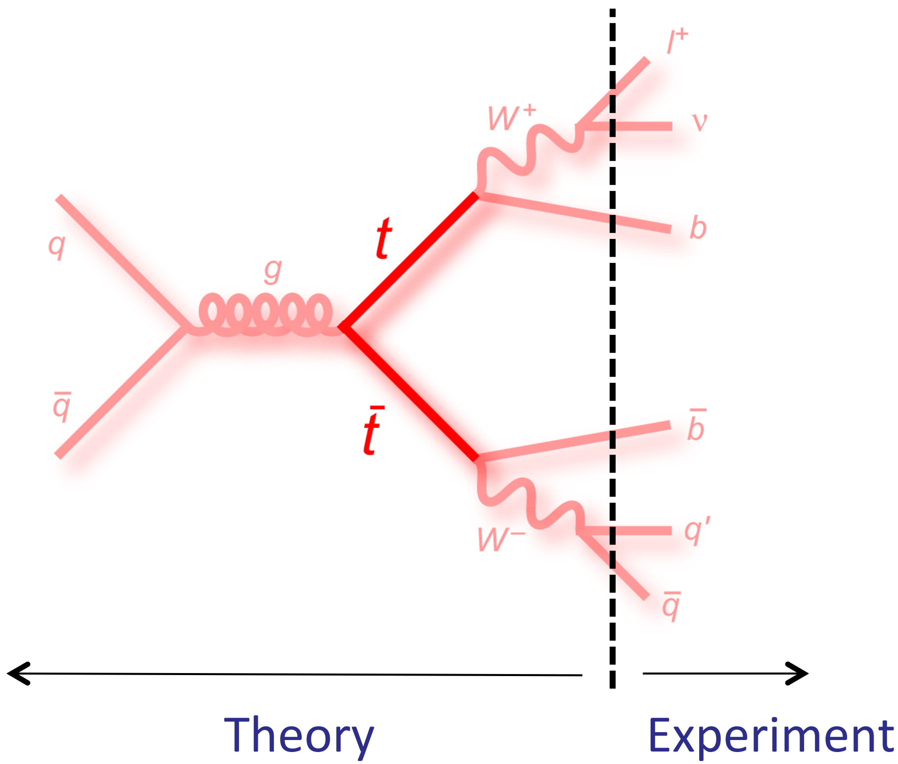
Calorimetry
- Energy measurement by absorption

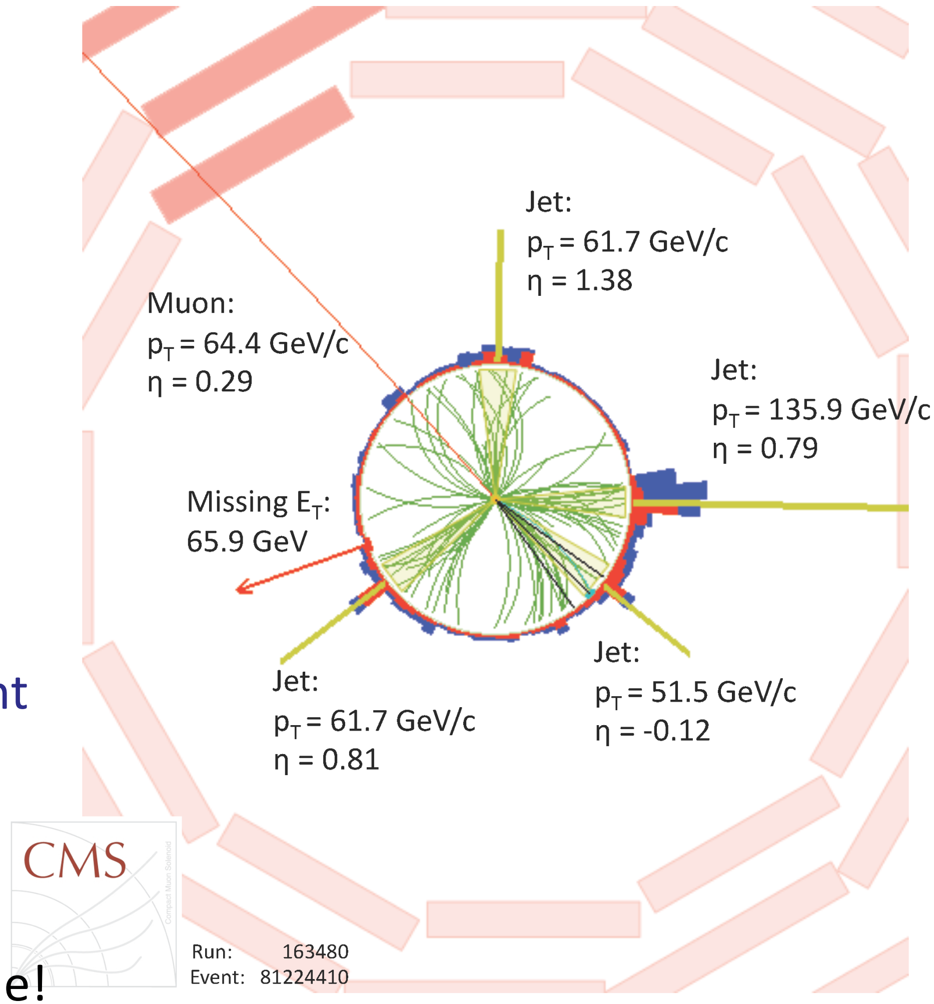
Magnet

Muon Spectroscopy
- A gigantic tracker for penetrating (charged) particles



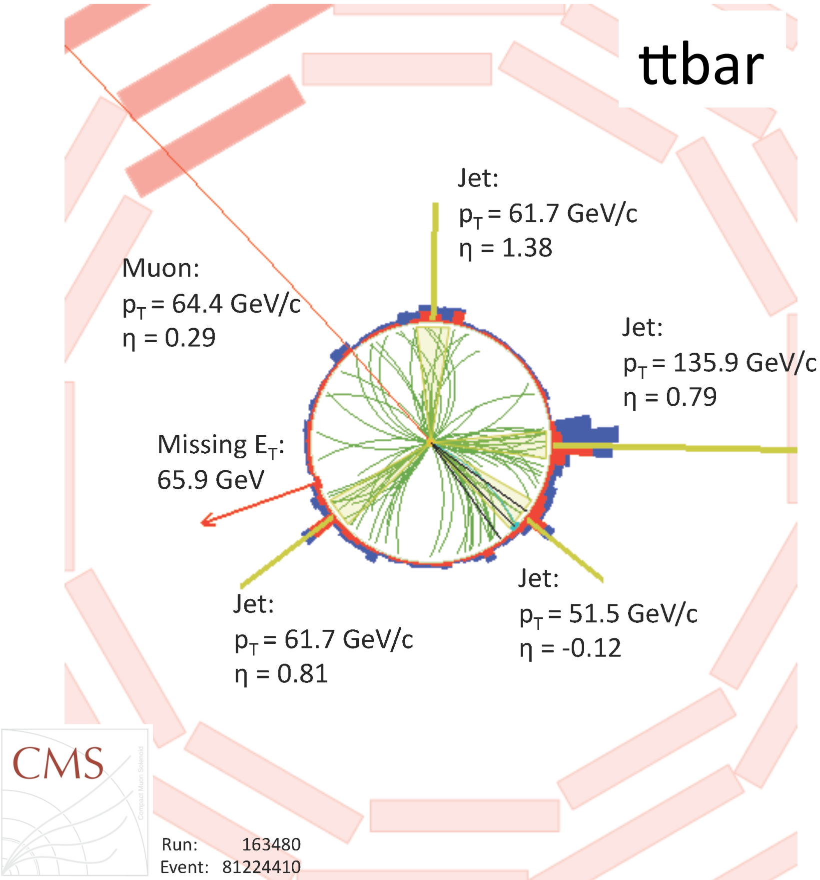
Event Signatures

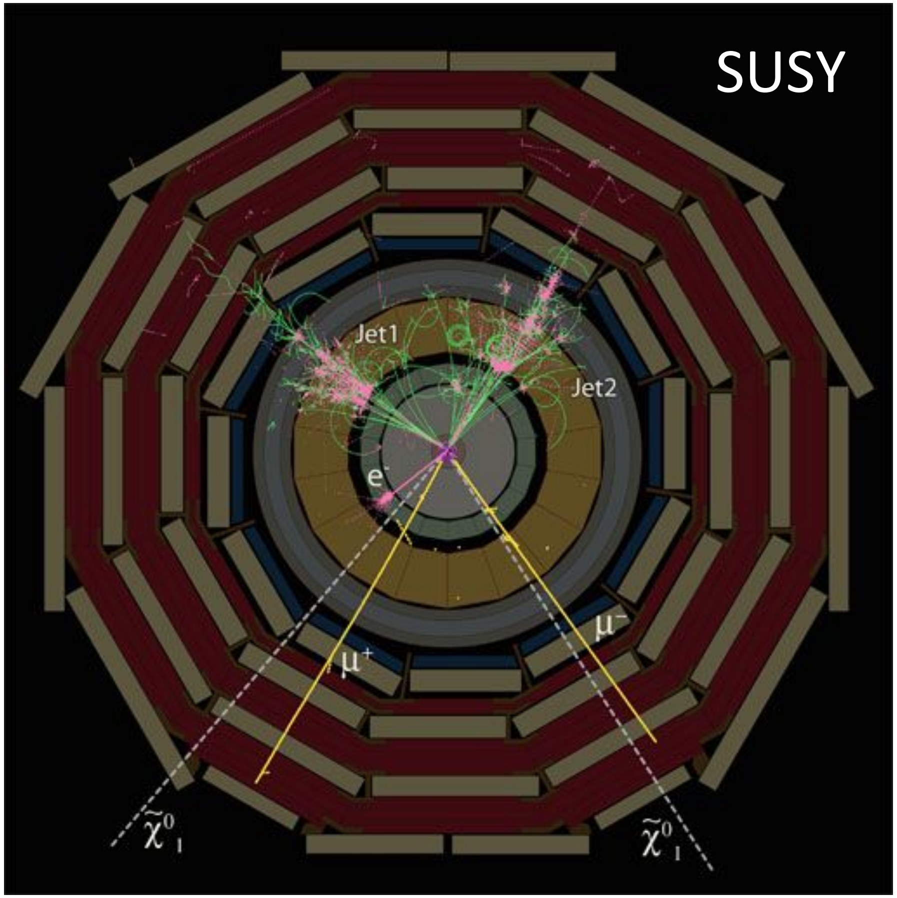




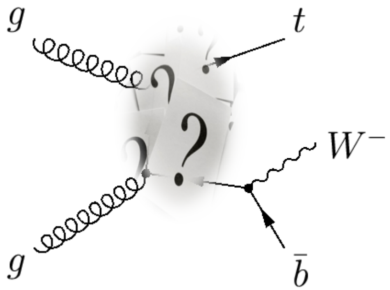
- Experimentalists measure final states composed of multiple objects
  - Those are "theoretically" not unique!
- Multiple models can yield the same final states

Exploiting Event Properties



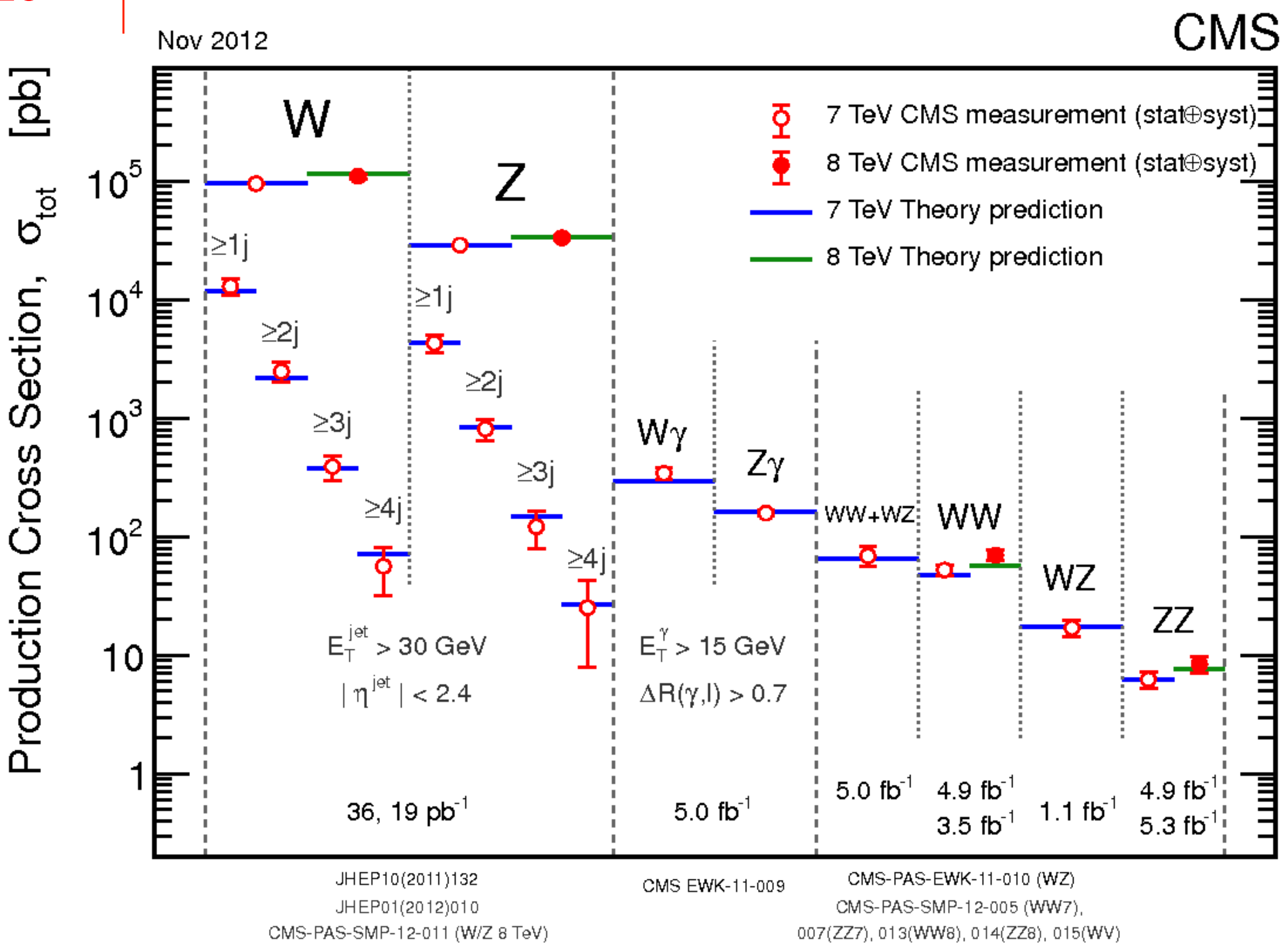


- New physics? Search for deviations from expectation, taking into account detector effects and backgrounds
- Interpretation in specific theoretical framework



Not Just One Haystack

σ(dijet) ~ 10^{18}



~σ(H→WW)
M_H~125GeV

New Physics?

It's a problem that's been likened to finding a needle in many, many haystacks!

Needles in a Haystack

Introduction

Experimental search techniques

- *SUSY search with razor*
- Boosted object search for bulk RS graviton
- Light Higgs decay to long-lived particle

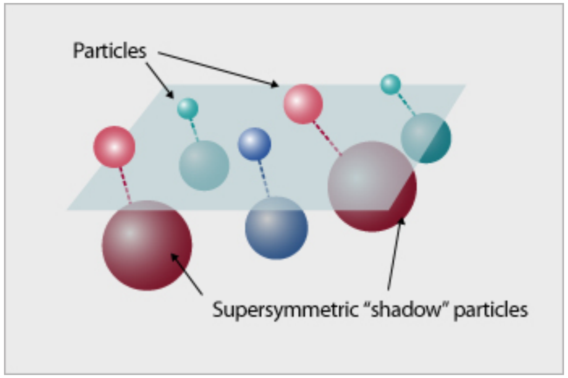
More searches

Conclusions

Supersymmetry

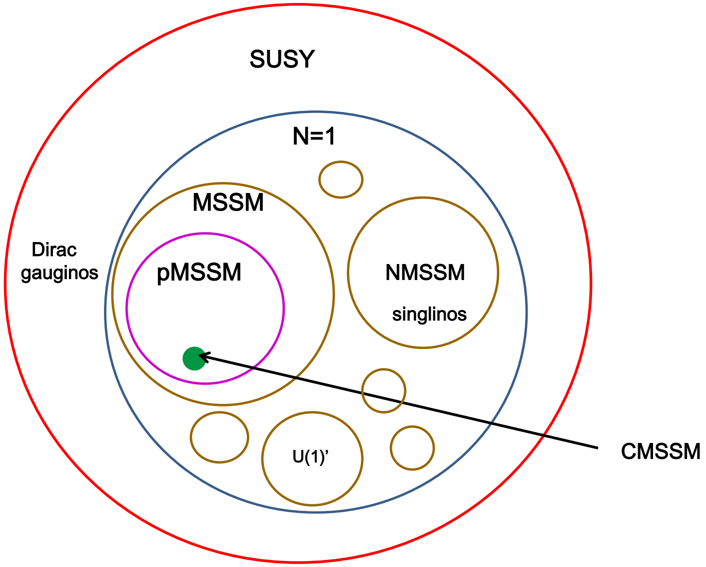
SM with prominent problems, SUSY most studied BSM theory

- Extends SM by new symmetry predicting heavier superpartners with spin-½ compared to the SM (s-fermions, gauginos)
- Bonus features: No/little fine tuning due to Higgs radiative corrections, unification of forces, dark matter candidate exists



But: No SUSY particle has ever been seen yet!

- SUSY not a perfect symmetry, must be broken by some mechanism
- Many possible variations, more than 100 free parameters even in minimal models (MSSM)
- R-parity = $(-1)^{2S+3B+L}$ conservation?
  If not, (finite) lifetime of lightest sparticle



T.G. Rizzo, 40th SLAC Summer Institute

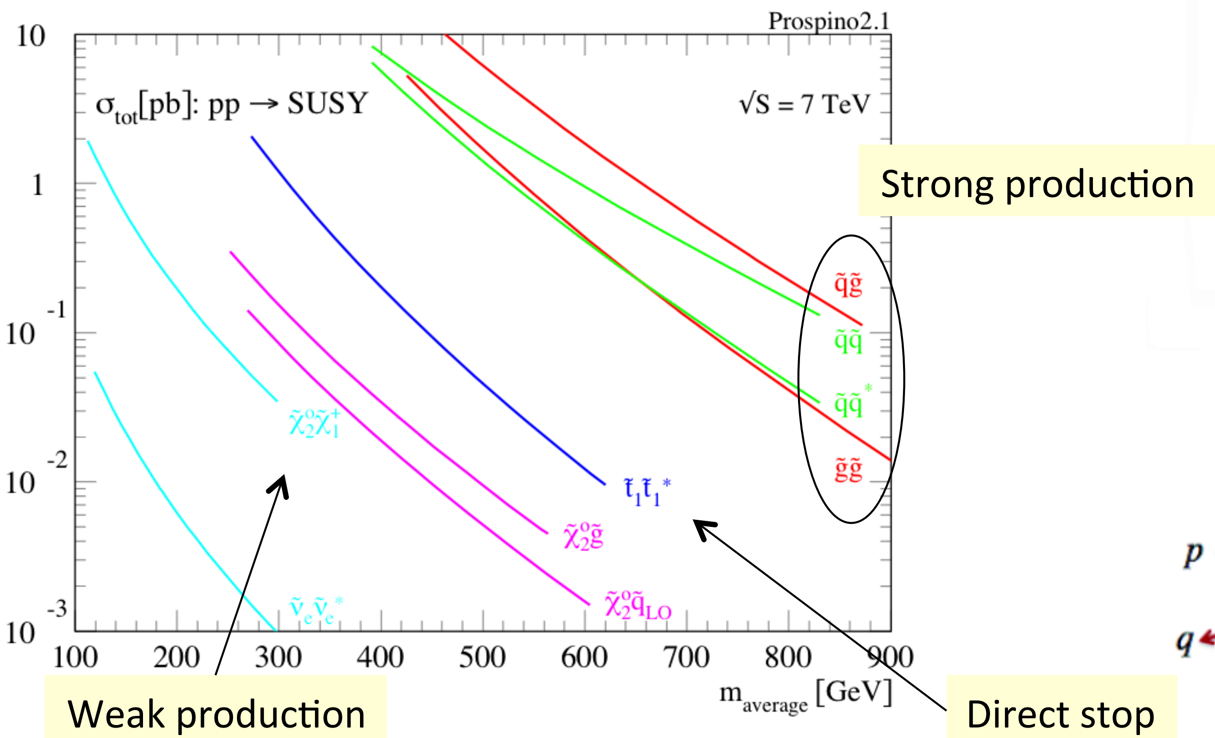
What Does SUSY Look Like?

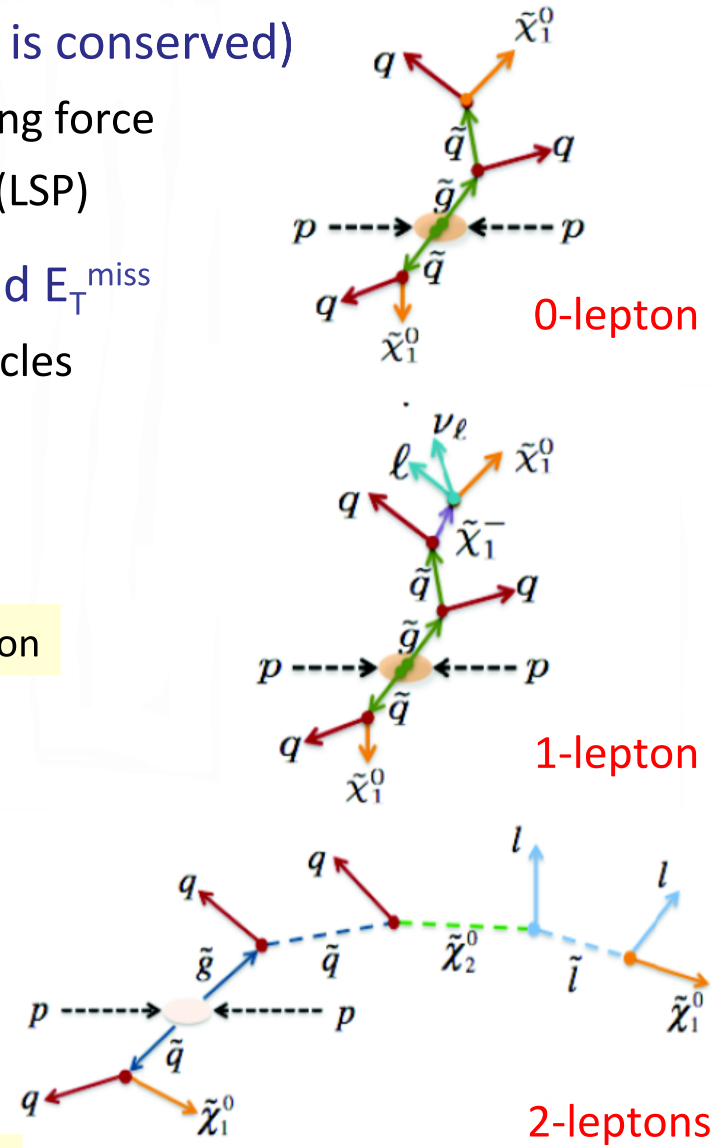
At LHC SUSY particles are pair-produced (if R-parity is conserved)

- Dominant: Production of squarks and gluinos via strong force
- Cascade decay to lighter and finally lightest sparticle (LSP)

Common signature: Multiple, high energetic jets and E_T^{miss}

- Can reduce backgrounds by requiring additional particles (zero, one, two leptons … two photons …. b-jets …)

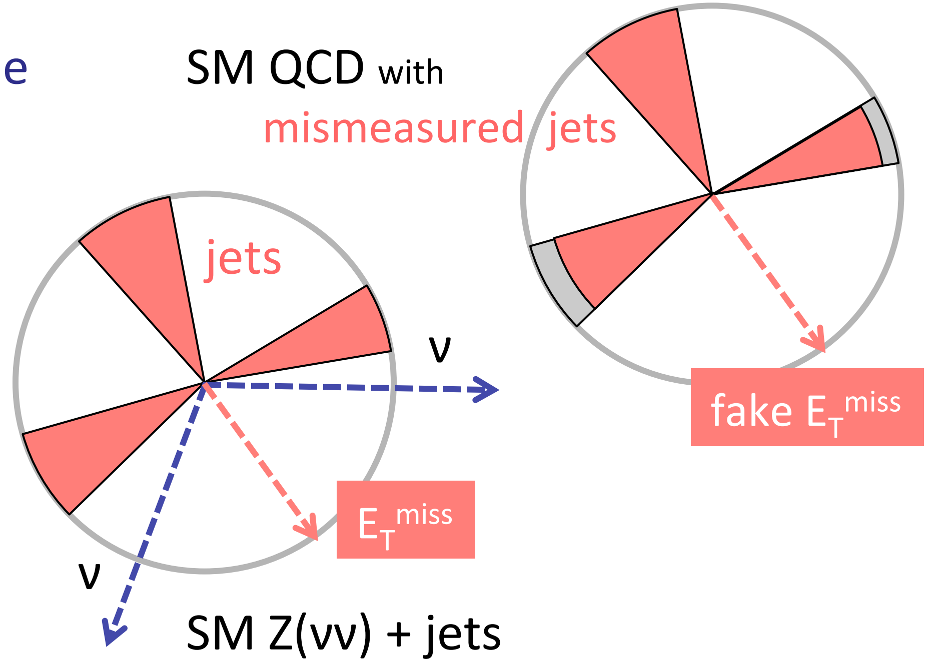


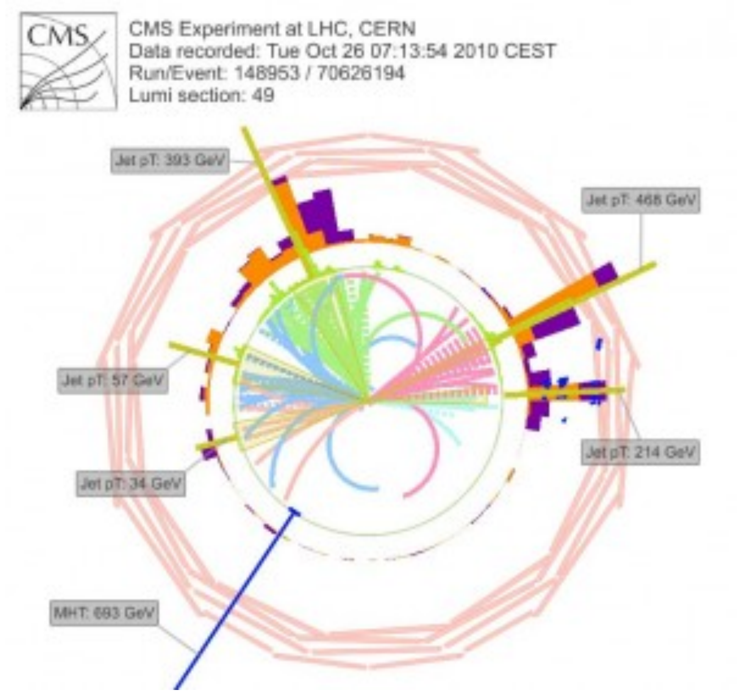


Classic SUSY Searches

The typical signature: A lot of energy in the detector recoiling against a lot of E_T^{miss}

- Hadronic signatures: large SUSY cross section, overwhelming QCD background
- Leptonic signatures: reduced QCD background, reduced production rate





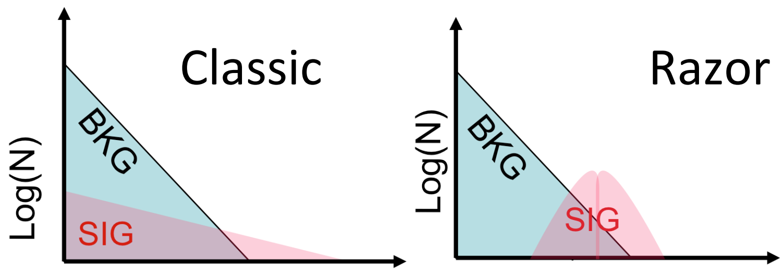
Modeling and controlling high-energy tails for QCD processes challenging

- Large uncertainties on QCD cross sections and kinematic properties (number and p_T of jets)
- Background estimates include data-driven methods, dedicated control samples, multiple methods for cross checks

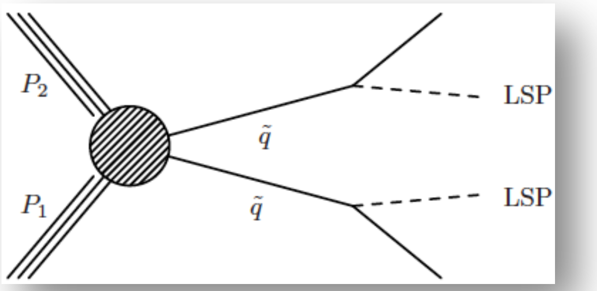
The Razor Approach

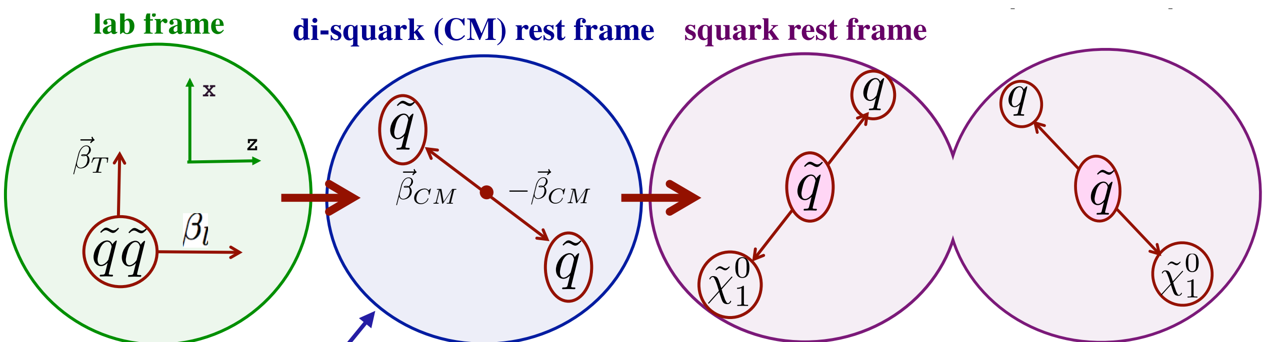
- Classic SUSY analyses involve searching for deviations in exponentially falling spectra

→ *Is there an observable which allows for better separation?*



- Consider a general SUSY topology: squark-squark → (q LSP)(q LSP)





$$|\vec{\beta}_T| \ll 1$$

$$2\gamma_{CM} M_\Delta = \sqrt{\hat{s}}$$

- This frame is approximated as the *R-frame* where the energies of the two jets are equal
- Define M_R which estimates the scale event by event
- M^R_T acts as transverse mass and has a cut-off at M_Δ

Here the mass scale is M_Δ: Large for signal events!

$$M_\Delta = \frac{M_{\tilde{q}}^2 - M_\chi^2}{M_{\tilde{q}}}$$

SUSY Bump Hunting

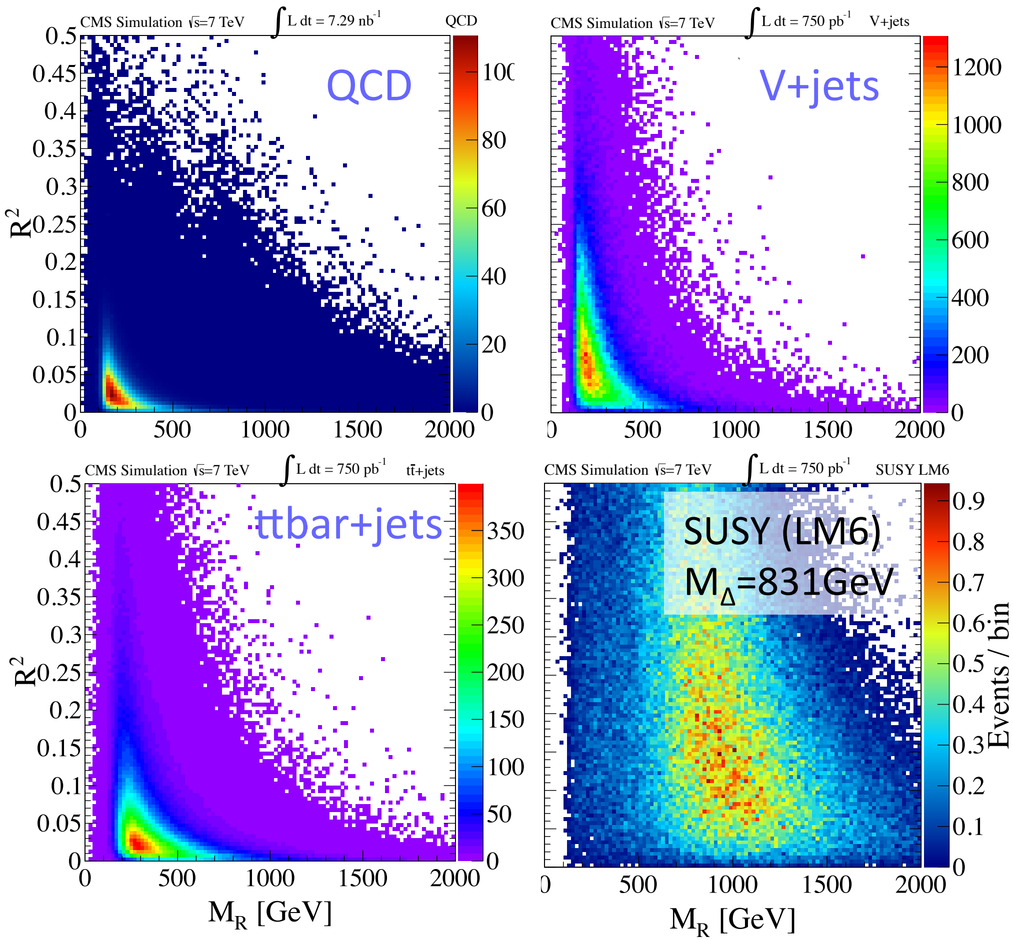
Dimensionless *razor variable R*

- Small for QCD, large for signal

$$R = \frac{M_T^R}{M_R}$$

$$M_R \equiv \sqrt{(|\vec{p}^{\,j1}|+|\vec{p}^{\,j2}|)^2 - (p_z^{j1} + p_z^{j2})^2}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$



M_R peaks at M_Δ for signal, exponentially falling for background

Each background has own shape in R^2-M_R plane

M_R peak moves to the right as scale increases

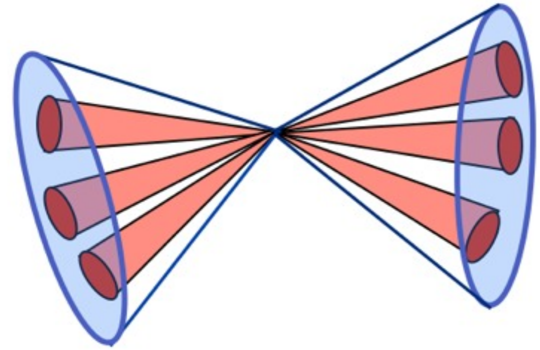
SUSY search becomes a bump hunt on exponentially falling tail

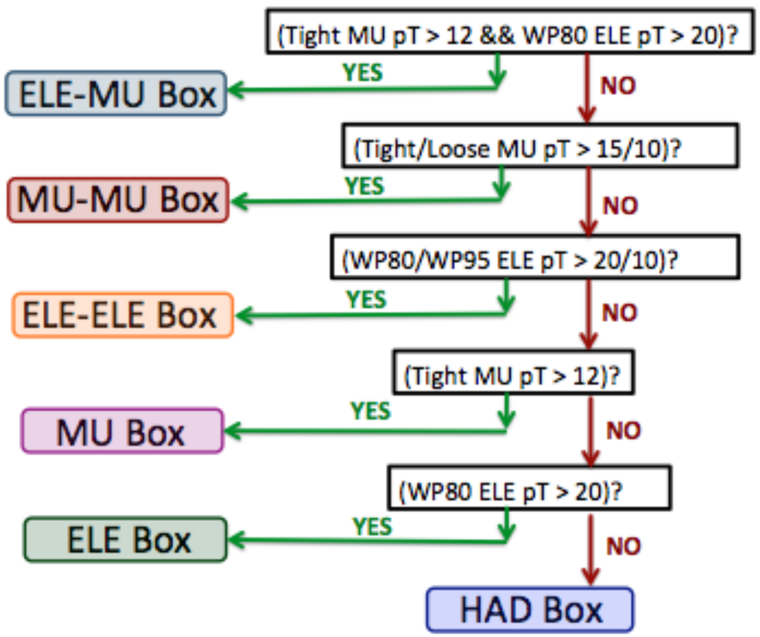
Inclusive Razor Analysis

arXiv:1212.6961
L = 4.7 fb^{-1}
$\sqrt{s}$ = 7 TeV

CMS inclusive razor analysis in 4.7 fb^{-1} at 7TeV

- Each event is treated dijet-like by grouping the reconstructed jets into two mega-jets





Very inclusive selection requiring at least two jets (60GeV)

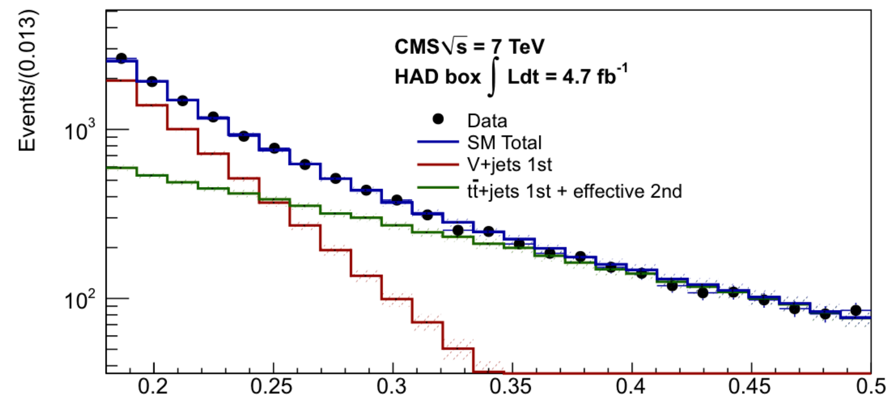
- Events are assigned to one of six "boxes" according to lepton flavor (e, mu) and their number (0-2)
- Six additional boxes for events with at least one b-jet

Inclusive Razor Analysis

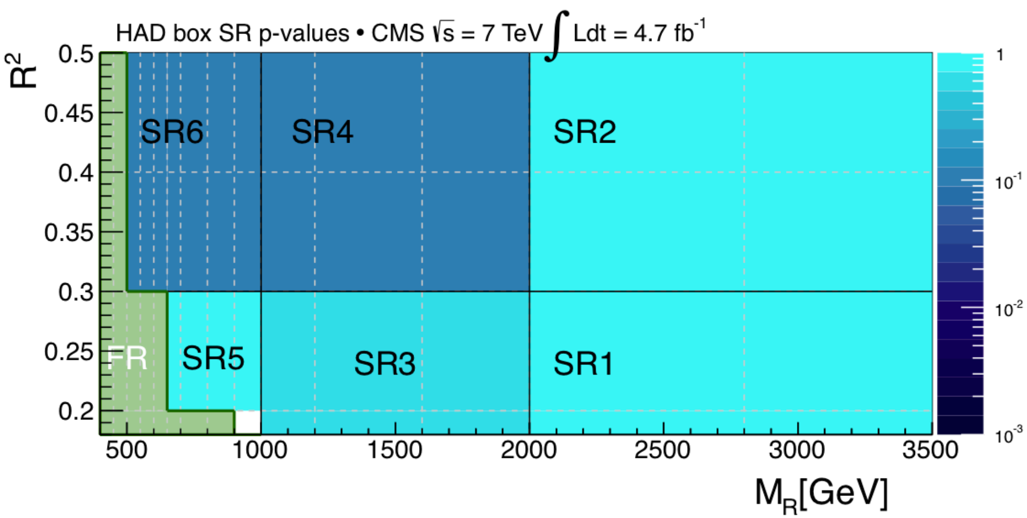
arXiv:1212.6961
L = 4.7 fb^{-1}
$\sqrt{s}$ = 7 TeV

- After M_R/R^2 cuts QCD background negligible
- Use 2D fit function in R^2-M_R plane to model the backgrounds
  - Fit in low M_R/R^2 fit region
  - Extrapolate to signal region
  - For each box multiple signal regions to validate background model

E.g. for HAD box: M_R>400GeV, 0.18<R^2<0.5



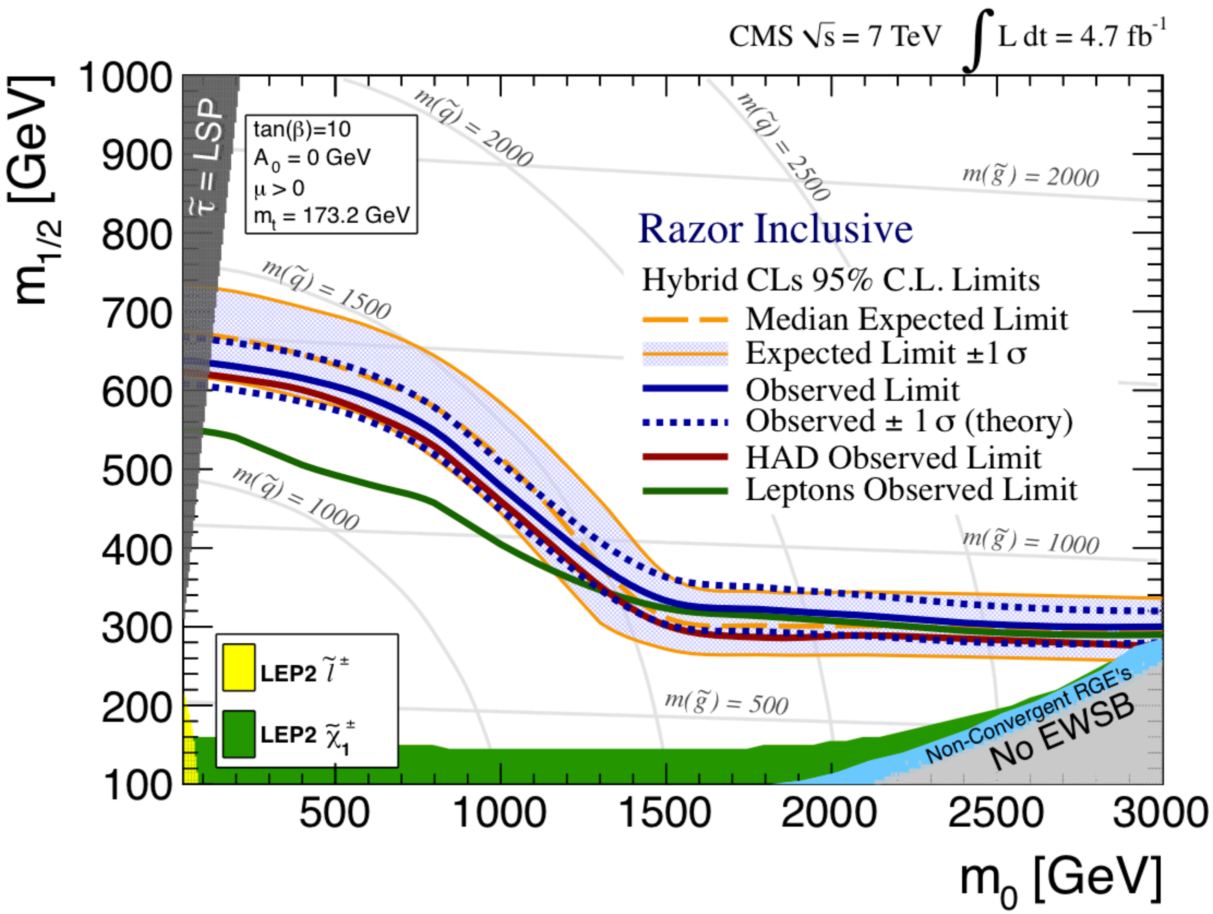
1D projection R^2



HAD	68% range	mode	median	observed	p-value
SR1	(0, 0.7)	0.5	0.5	0	0.99
SR2	(0, 0.7)	0.5	0.5	0	0.99
SR3	(45, 86)	73	69	74	0.68
SR4	(4, 15)	9.5	10.5	20	0.12
SR5	(530, 649)	566	593	581	0.82
SR6	(886, 1142)	987	1020	897	0.10

Inclusive Razor Results

arXiv:1212.6961
L = 4.7 fb^{-1}
√s = 7 TeV



No significant deviation between data and SM prediction observed

→ Gluinos up to 800 GeV and squarks up to 1.35 TeV excluded (CMSSM)

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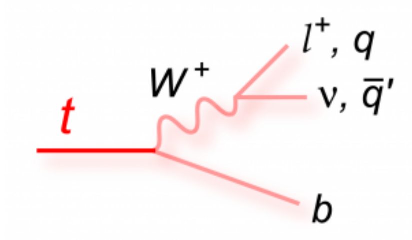
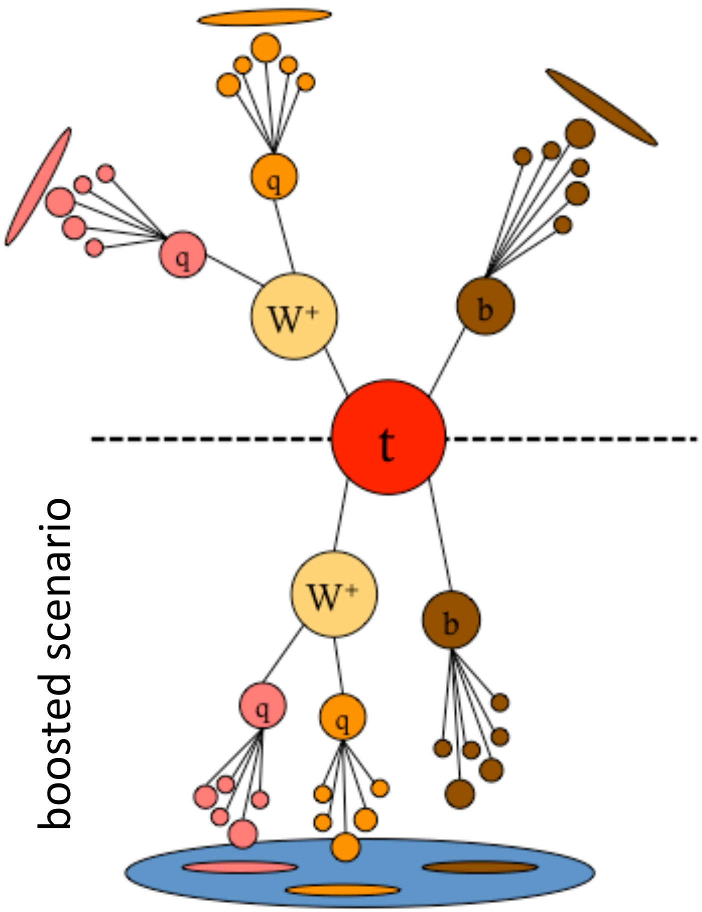
Boosted Objects





A heavy particle will give a boost to its decay products

- Hunting massive particles = search boosted final state objects

As e.g. seen in SUSY search before, exclusion limits approaching TeV scale

- Many searches now looking for heavy particles, SUSY and elsewhere

Define "boosted object"

- Include all decay products in single object
- Deploy substructure to improve S/B

Large Radius Jets

In general, jets from hadronically decaying t/W/Z/H begin to merge under boost

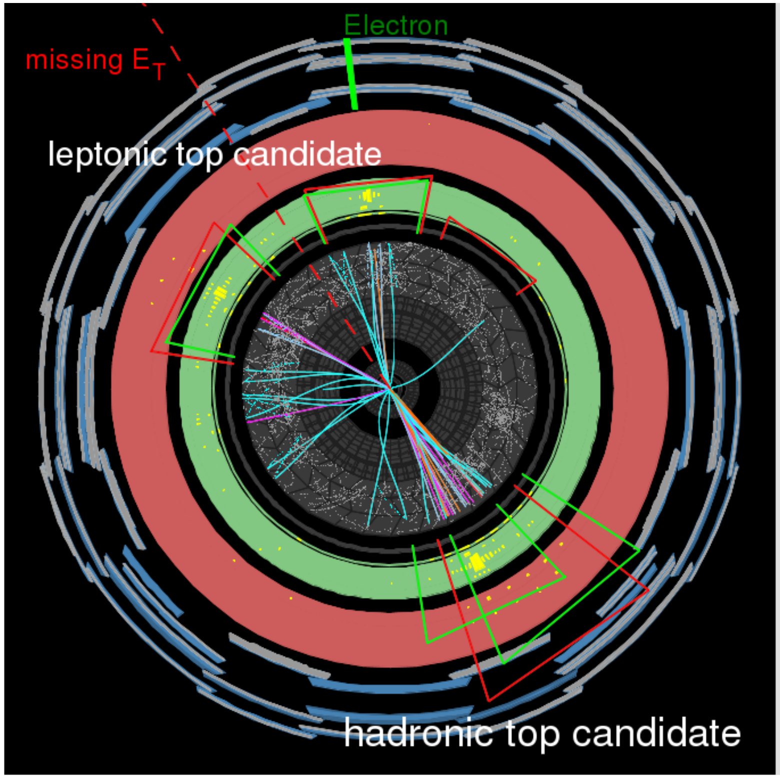
Solution: Large-radius jets, but

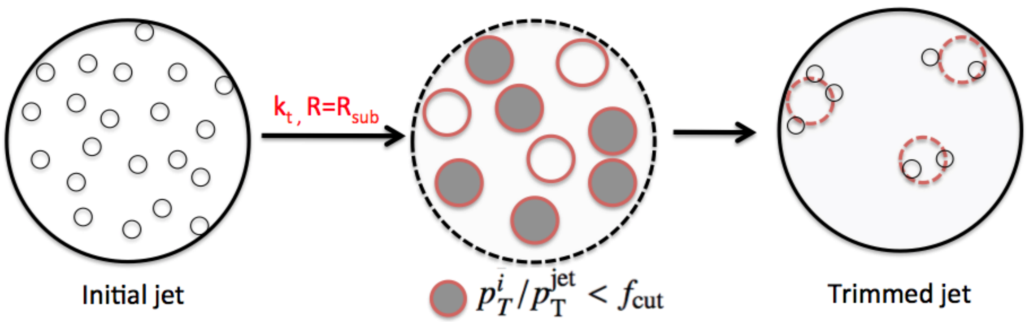
- Large area = more pile-up noise

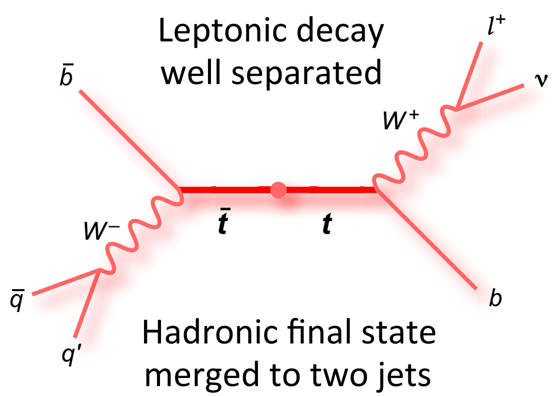
→ Need jet cleaning (grooming = trimming, pruning, mass drop/filtering)

- Single jet = more QCD background

→ Deploy substructure







E.g. jet trimming: Removal of soft subjets greatly reduces pile-up dependence

Background Discriminants

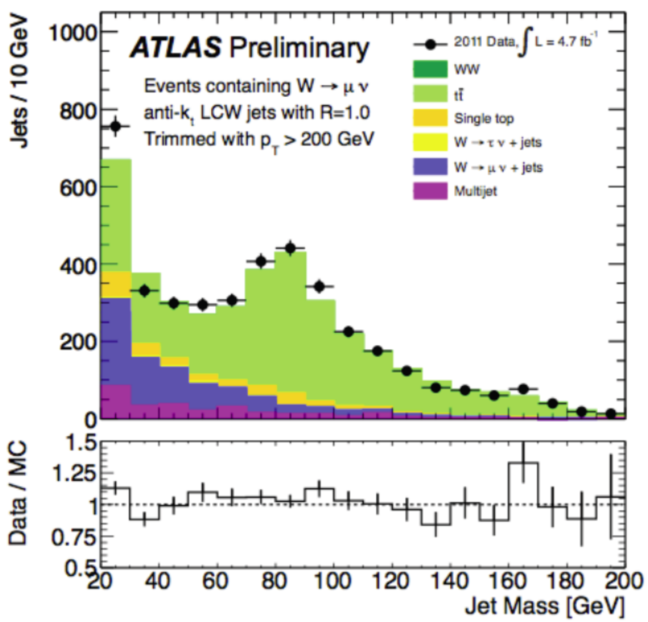
Jet mass can be a powerful discriminator

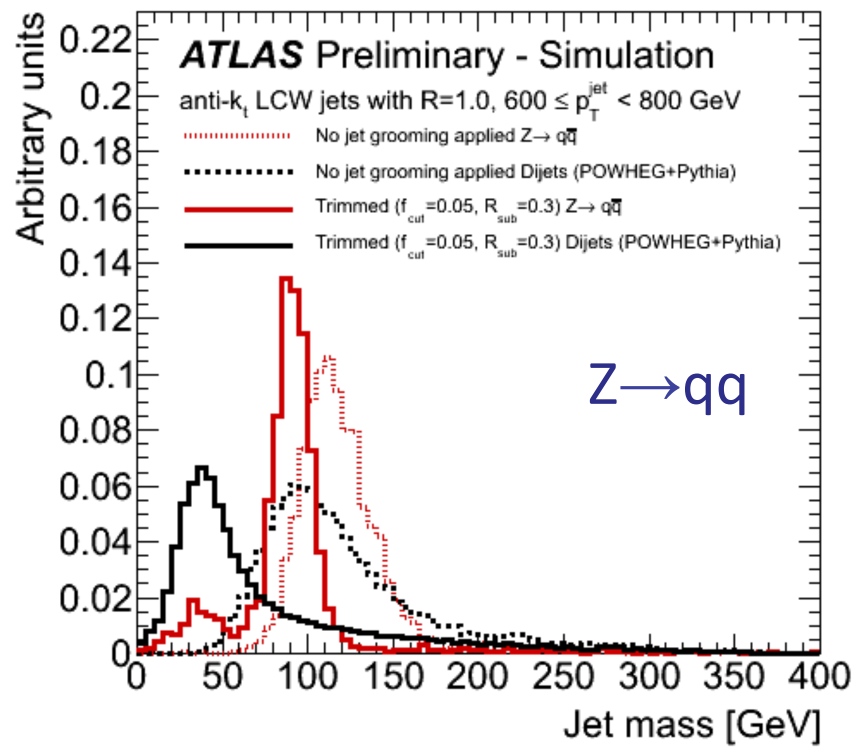
- Needs substructure methods to reduce QCD background

$$(\text{Jet Mass})^2 = (\Sigma E_i)^2 - (\Sigma p_i)^2$$

Jet mass subject to soft, wide angle constituents

- Jet mass is calibrated to MC truth
- Validated in data, e.g. ttbar



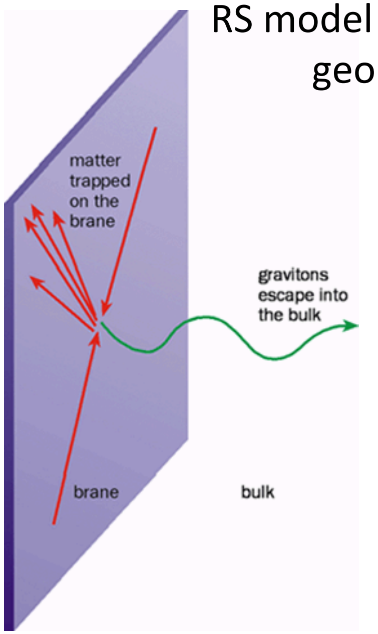


- Many other substructure and combined methods (e.g. see talk E. Kuutmann)

Search for Resonant ZZ Production

L = 7.2 fb^{-1}
√s = 8 TeV

RS model = "5D warped geometry theory"



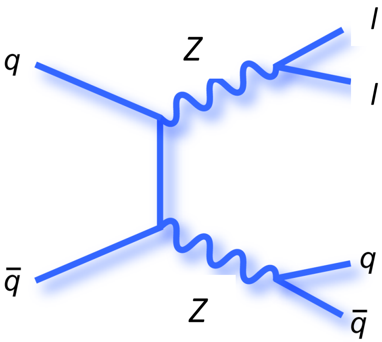
Many extensions to the SM predict heavy resonances decaying to pairs of EW gauge bosons

In the "Bulk" Randall-Sundrum (RS) Model

- All SM particles except for the Higgs are free to propagate into the bulk
- Decay Graviton G^* to t/W/Z/H pairs enhanced

ATLAS search for resonant ZZ production in 7.2 fb^{-1} data at 8TeV

- Use semi-leptonic final state ZZ → ll qq
  - Reduces multi-jet background
- Analysis optimized for both low and high resonance masses
  - Signal mass range from 300 to 2000 GeV



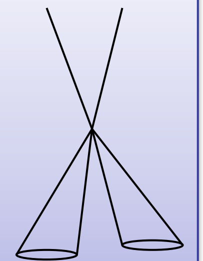
$G^* \to ZZ \to ll\,qq$

ATLAS-CONF-2012-150
$L = 7.2\ fb^{-1}$
$\sqrt{s} = 8$ TeV

Z pre-selection: Exactly two same flavored leptons (e, μ) with $66<m_{ll}<116$GeV

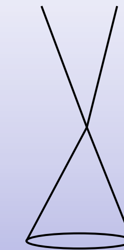
Resolved region

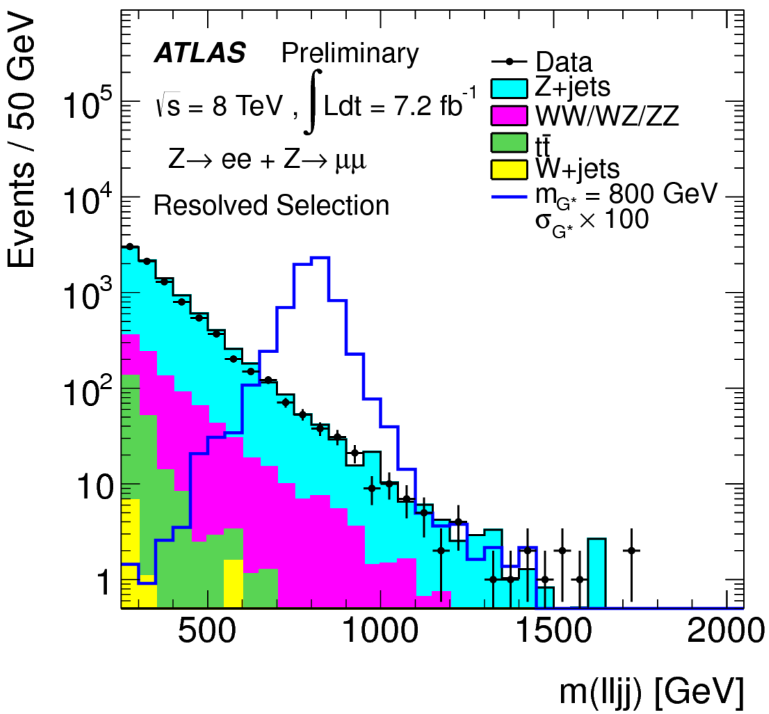
- $p_T^{ll} > 50$ GeV
- Two anti-k_T R=0.4 jets with $\Delta\Phi^{jj}<1.6$ and $65<m_{jj}<115$ GeV

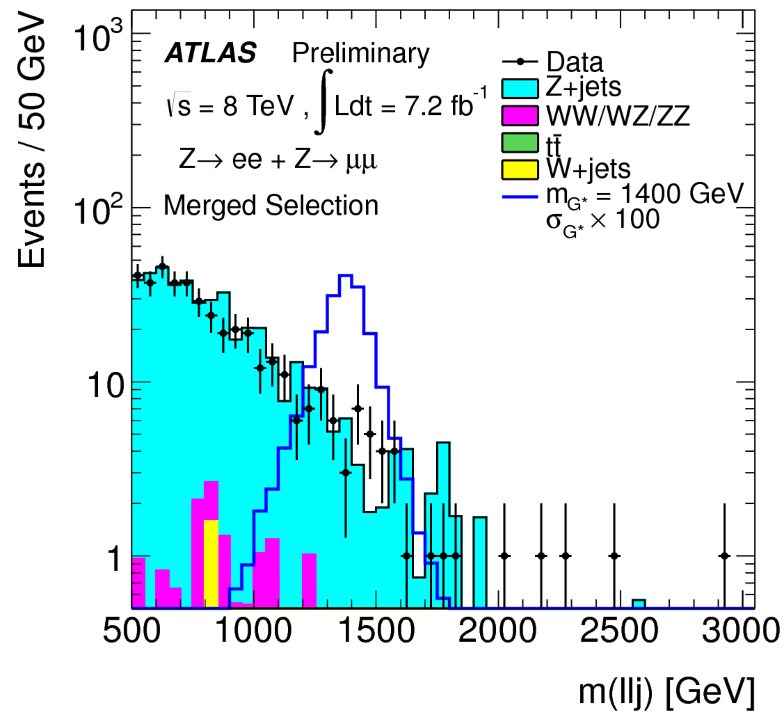


Merged region

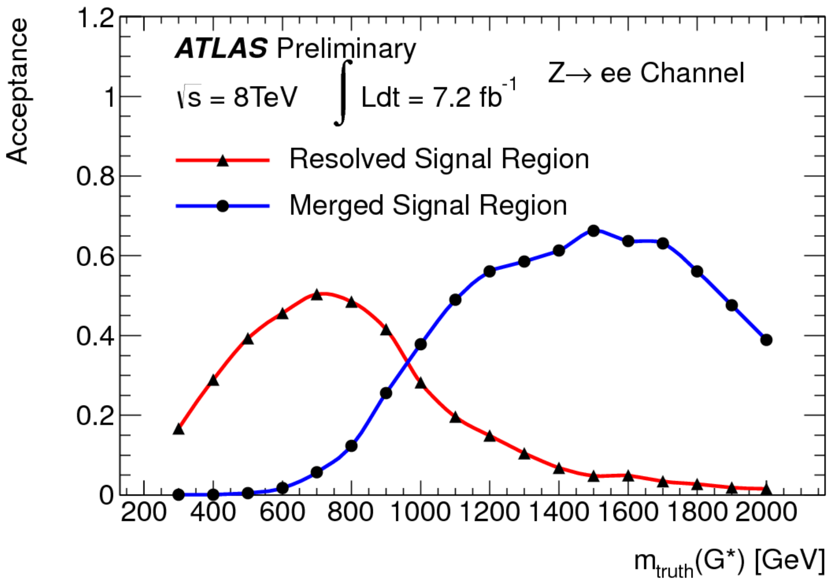
- $p_T^{ll} > 200$ GeV
- One anti-k_T R=0.4 jet with $p_T^{j}>200$GeV and $m_j>40$GeV







Bulk RS Graviton Results

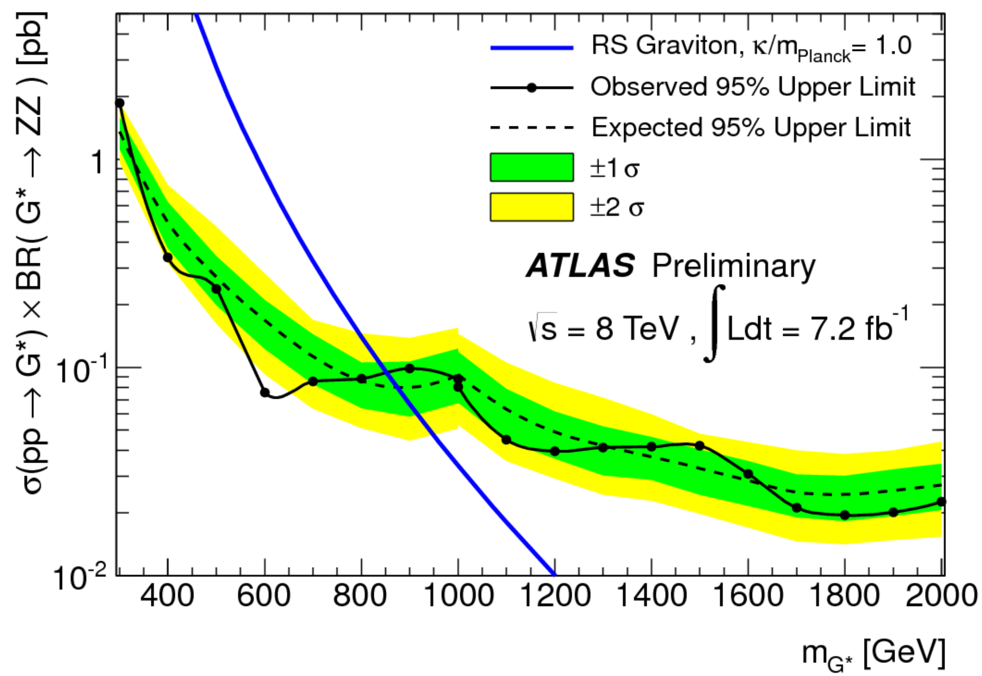


Acceptance computed using signal MC

- Combined approach of resolved and merged selection yields good acceptance over whole mass range

No resonance structure is observed in data (bump hunter algorithm)

- Lower limit on RS graviton mass is 850 GeV for this model



Needles in a Haystack

Introduction

Experimental search techniques

- SUSY search with razor
- Boosted object search for bulk RS graviton
- *Light Higgs decay to long-lived particle*

More searches

Conclusions

Long Lived Particles (LLPs)

Hidden Valley

RPV SUSY LSP

SUSY/DM

R-hadrons

Stable sleptons

(RPV) SUSY

Magnetic Monopoles

Several New Physics models could give rise to new, massive particles, with long lifetimes

Lifetime of LLPs can have large range, resulting in macroscopic decay lengths up to or exceeding detector volume

LLP Signatures

Many experimental signatures for long-lived particles!

Neutral massive LLPs signatures

- Decay inside detector: displaced vertices/jets
- Decay outside detector: MET

Charged massive LLPs signatures

- Decay: kinked, forked, disappearing tracks
- Slow: highly ionizing, dE/dx
- Really slow: stop, decay out of time window

Hidden Valley

RPV SUSY LSP

SUSY/DM

R-hadrons

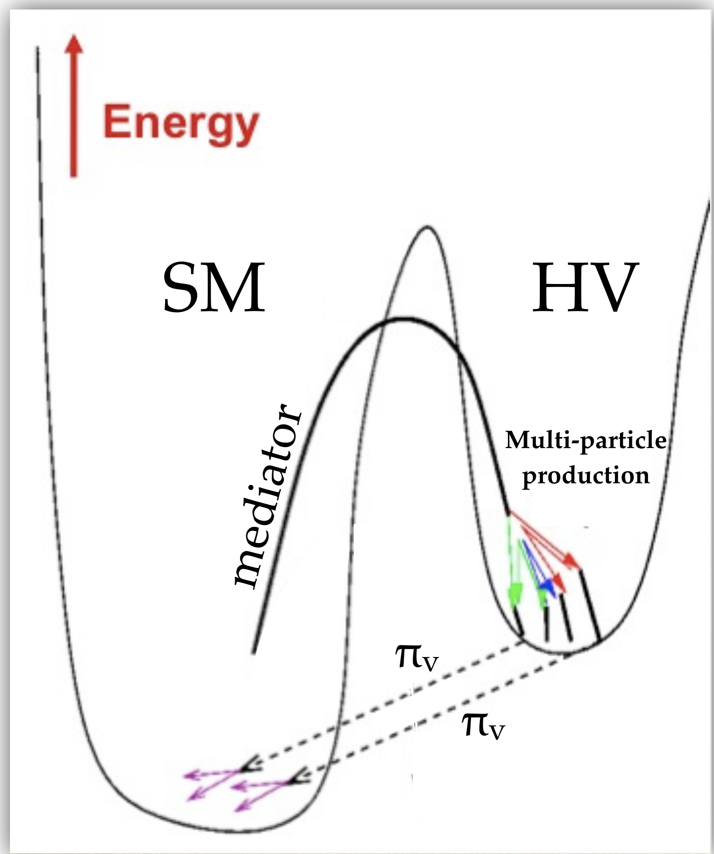
Stable sleptons

(RPV) SUSY

Magnetic Monopoles

→ Wide range of analyses, looking for many different signatures and often using the detector in “non-standard” ways!

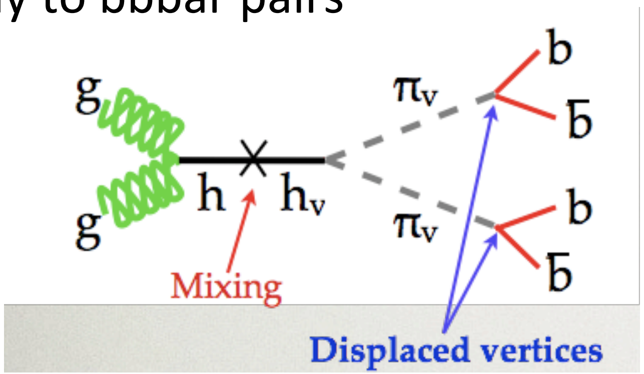
Hidden Valley Scenario



- Hidden valley (HV) sector and SM communicate via heavy communicator particle (Z, Z', Higgs, neutralinos, other)
- Weak coupling between HV and SM can lead to particles with long lifetimes

Consider light Higgs boson decay $h^0 \rightarrow \pi_v \pi_v$

- π_v = neutral, long-lived, displaced decay mainly to bbbar pairs



→ Use specially developed trigger algorithms, specialized tracking and vertexing algorithms to reconstruct displaced vertices

Triggering LLPs

First challenge to accept events: new physics → need every event

But e.g. lowest unprescaled jet threshold at ~200 GeV

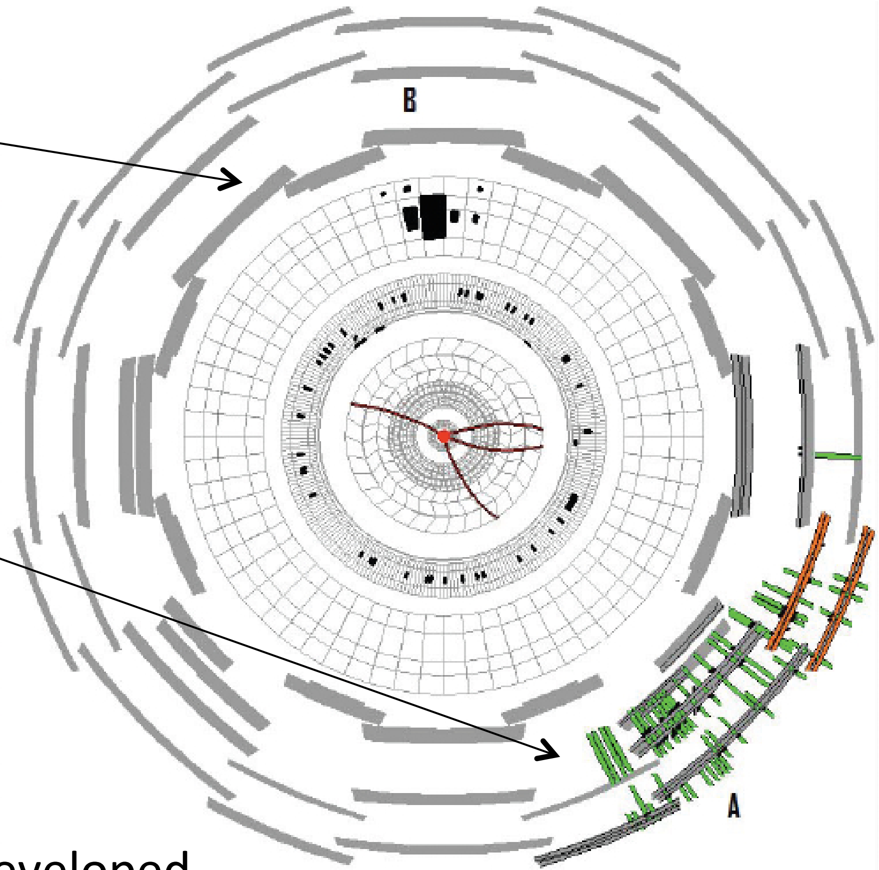
→ Different triggering techniques required for each section of the detector

Decay in calorimeters (B)

- Narrow jet like object
- Little energy in ECal, but large energy deposit in HCal, $\log(E_{HAD}/E_{EM})$
- No visible track from jet to IP

Decay in muon spectrometer (A)

- Large number of muon clusters in narrow region
- Usually no associated tracks in ID
- No calorimeter activity



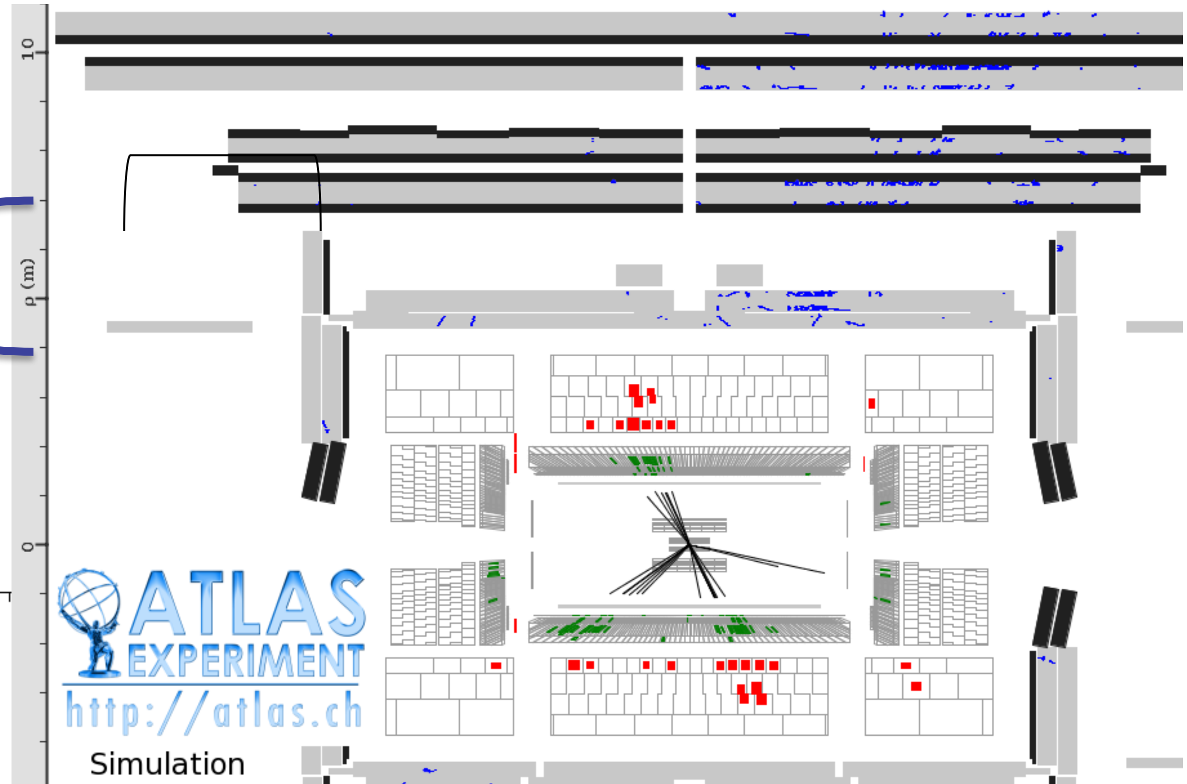
→ Special triggers for these signatures developed

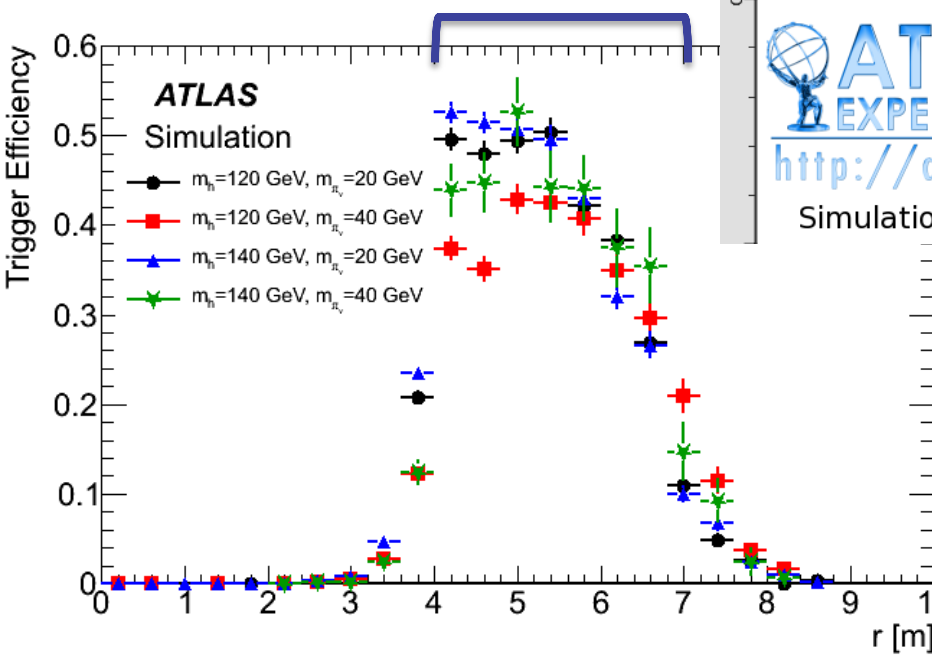
Trigger and Vertex Efficiencies

arXiv:1203.1303
L = 1.94 fb^{-1}
$\sqrt{s}$ = 7 TeV

Using specialized muon trigger results in high selection efficiency

Sensitive to decays in range 4 < r < 7m



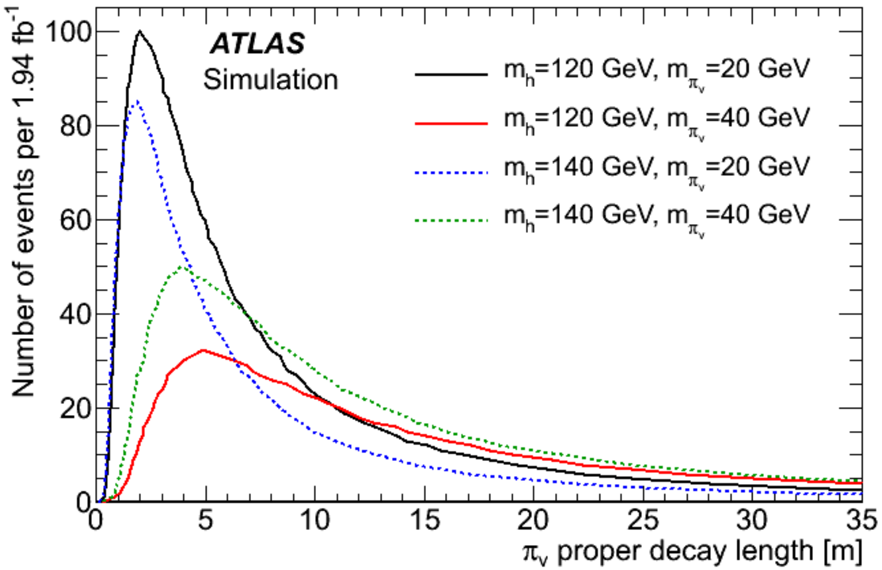


Event selection

- 2 back-to-back vertices in the MS with no nearby jet or track activity
- Vertex reconstruction efficiency of the MS approximately 40%

arXiv:1203.1303
L = 1.94 fb^{-1}
√s = 7 TeV

Light Higgs to LLP Results



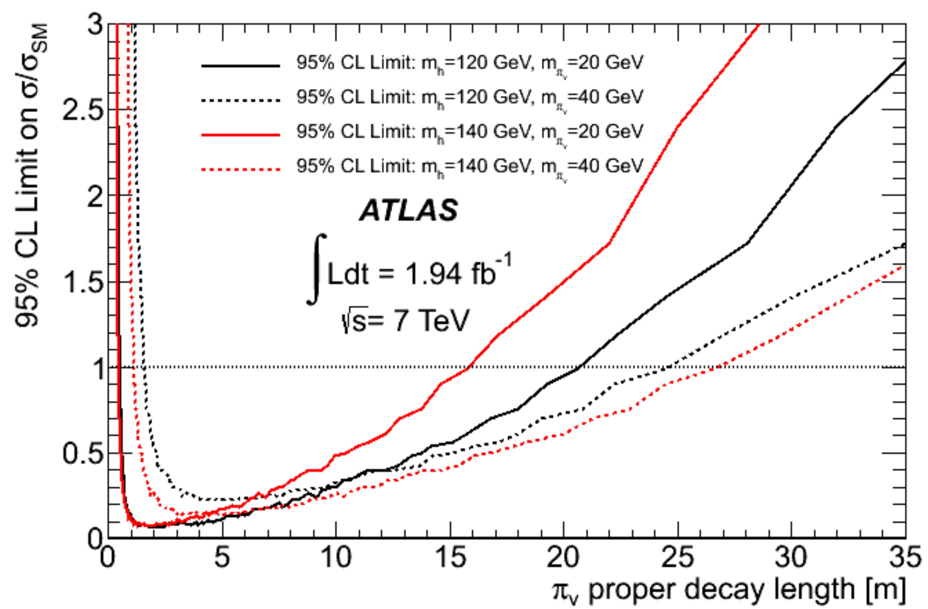
- Expected background from punch-through jets 0.03±0.02 events

→ No events observed in 1.9 fb^{-1} data

A broad range of π_v decay length excluded at 95% CL

- Assuming 100% BR for $h^0 \rightarrow \pi_v \pi_v$

New results expected late this summer



More Searches

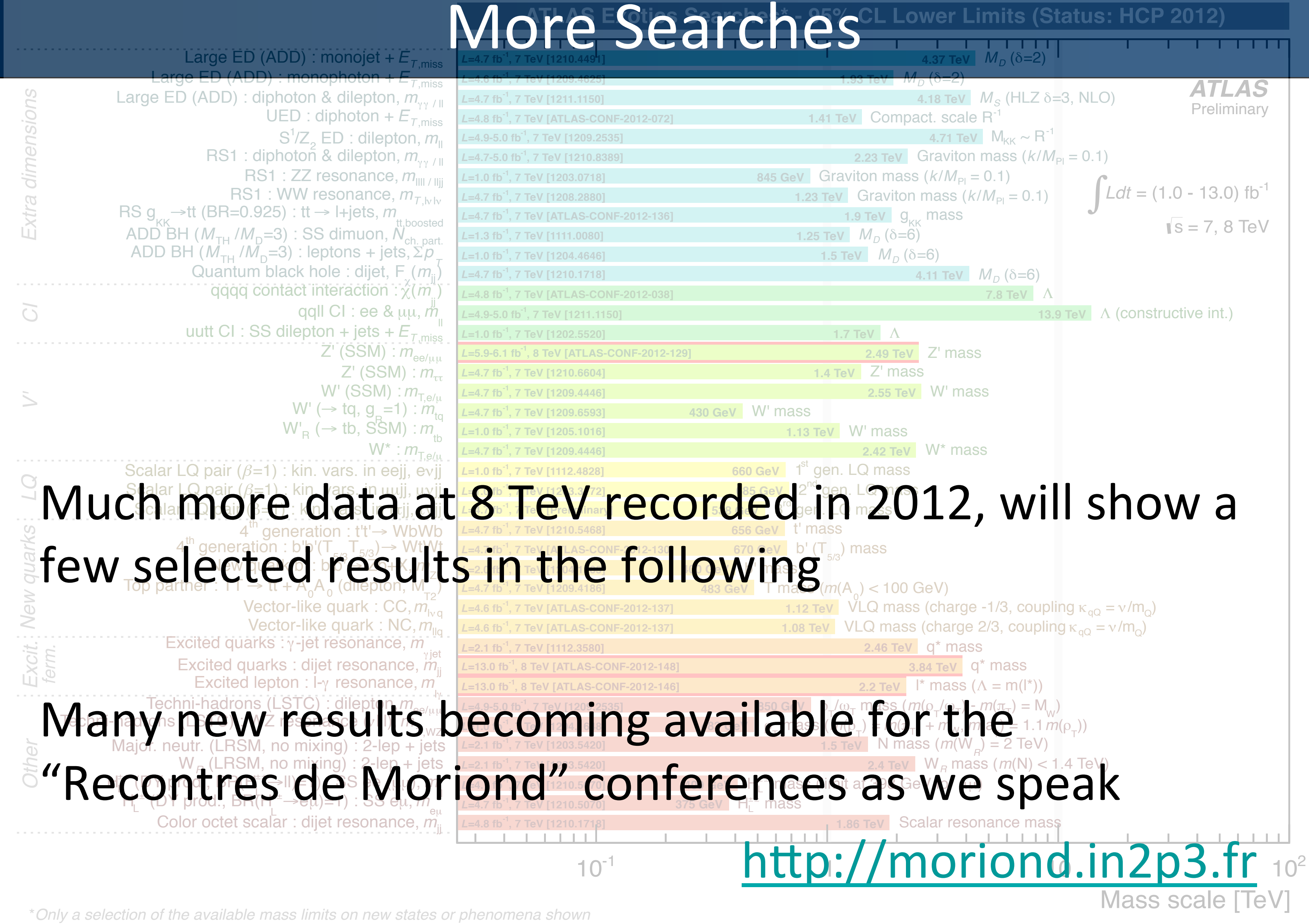
Focused here on experimental techniques for searches

- SUSY search with razor
- Boosted object search for bulk RS graviton
- Light Higgs decay to long-lived particle

Both ATLAS and CMS have probed many, many different models for new physics!

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

More Searches



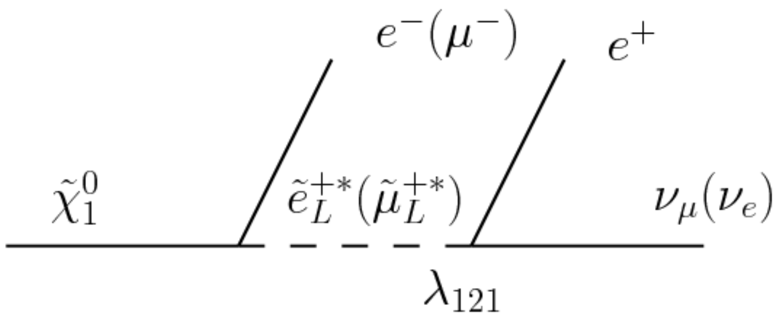
Much more data at 8 TeV recorded in 2012, will show a few selected results in the following

Many new results becoming available for the “Recontres de Moriond” conferences as we speak

http://moriond.in2p3.fr

Search for RPV SUSY

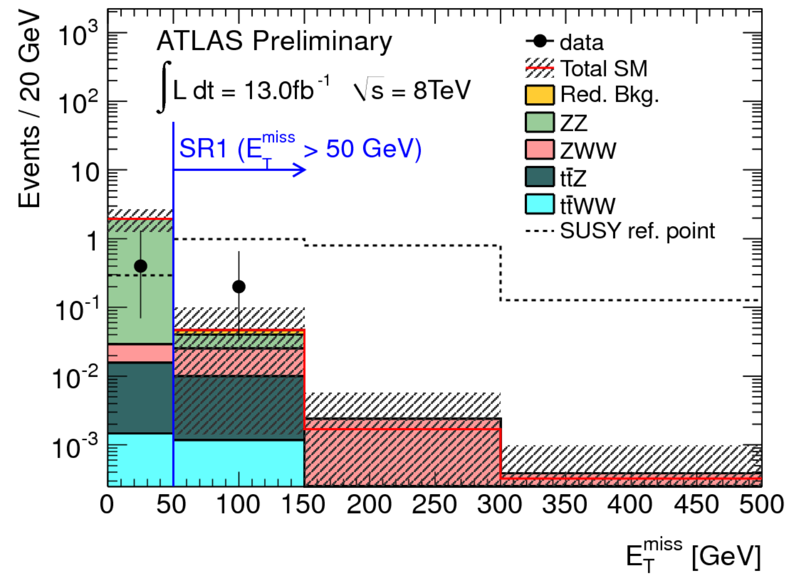
- Consider RPV models where LSP decays to 1^{st} and 2^{nd} generation leptons

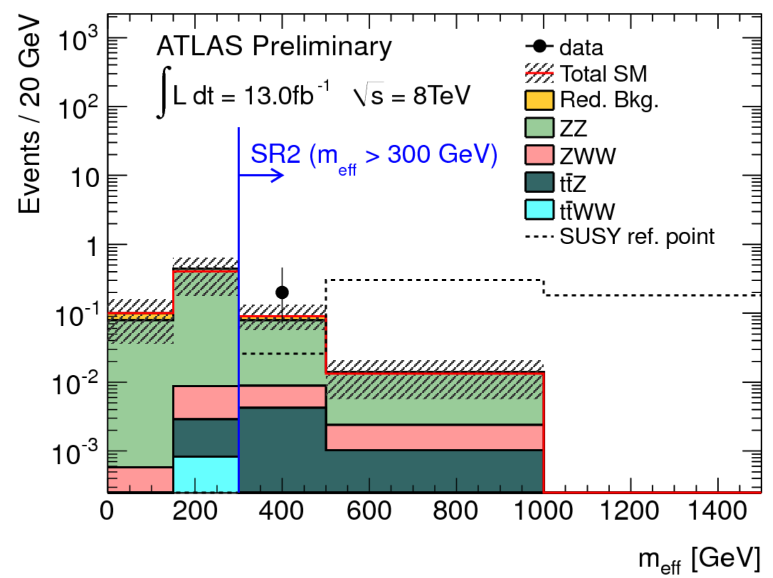


- Search in events with four or more leptons, electron or muon

- Two signal regions, vetoing Z production
  - E_T^{miss} > 50 GeV: obs. 1, exp. $0.25^{+0.29}_{-0.25}$
  - m_{eff} > 300 GeV: obs. 2, exp. 1.2±0.5

→ Exclusion limits set for various RPV simplified model

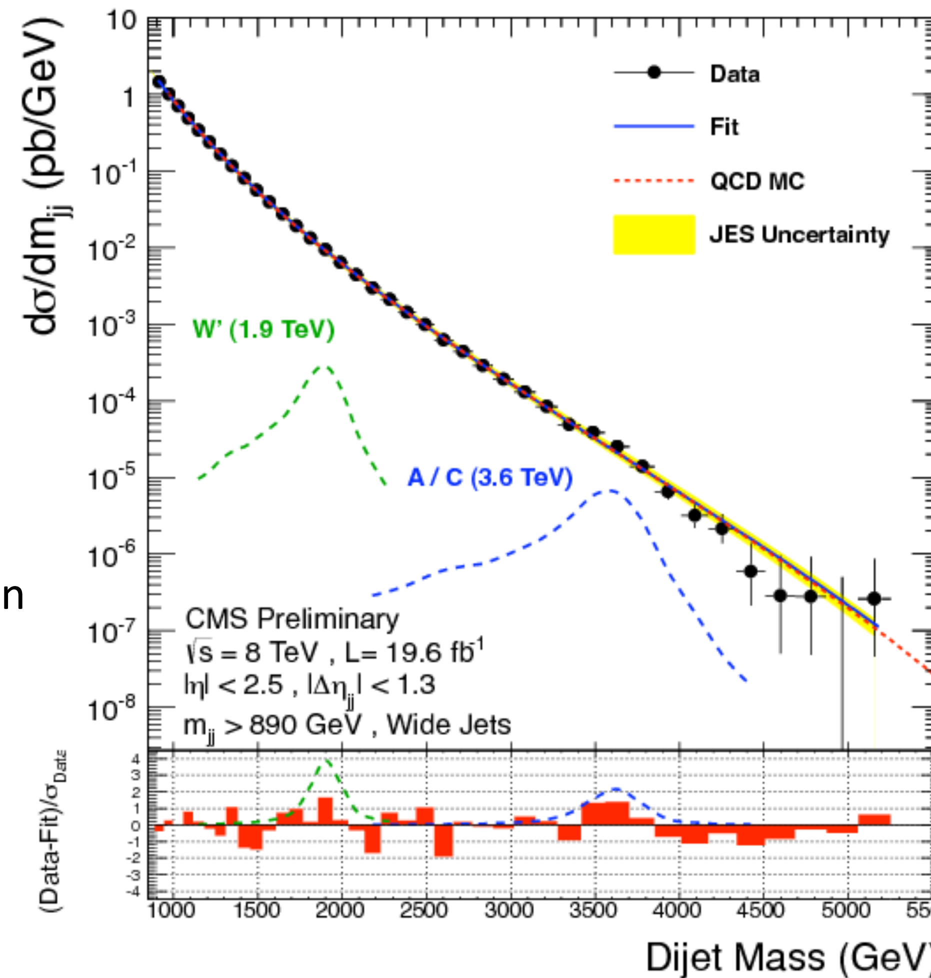




Search for Narrow Dijet Resonances

$L = 19.6\ fb^{-1}$
$\sqrt{s} = 8$ TeV

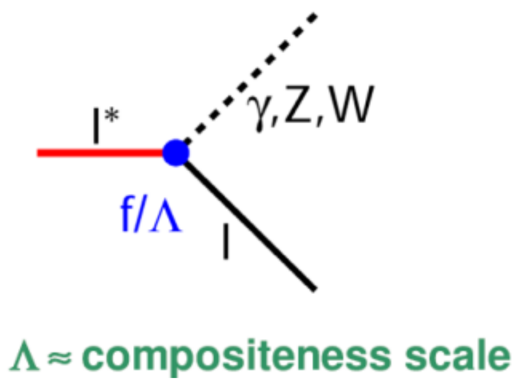
- Investigate dijet mass distribution of events with p_T^{jet}>30GeV
- Require $|\Delta\eta_{jj}|<1.3$ with each jet inside the region $|\eta|<2.5$
  - Enhances signal selection wrt. QCD background
- Use large-R jets with R=1.1
  - Minimizes sensitivity to gluon radiation
- QCD dijet background modeled with a smooth empirical parameterization

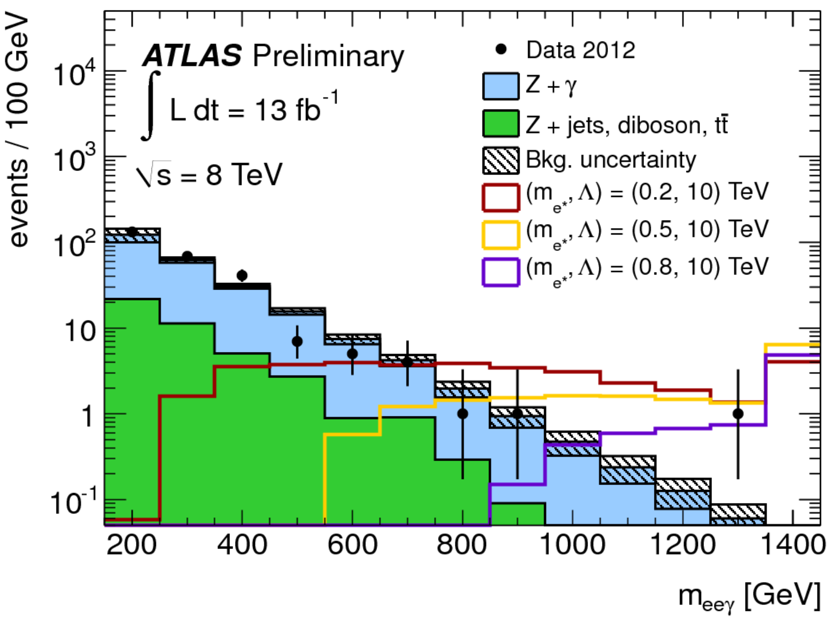


→ No statistically significant deviations between the data and SM prediction found

→ Masses up to 1.5TeV excluded depending on model

Search for Excited Leptons





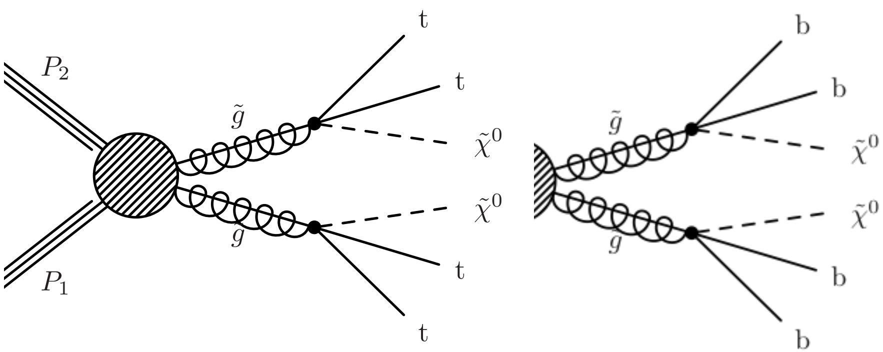
- Unambiguous signature for new matter substructure:
  - Observation of exited states
- Predicted by compositeness models, dominantly singly produced $qq \rightarrow l^{*}l$
- Search performed in clean EM radiative decay channel: $l^{*} \rightarrow l\,\gamma$ with $l = e, \mu$

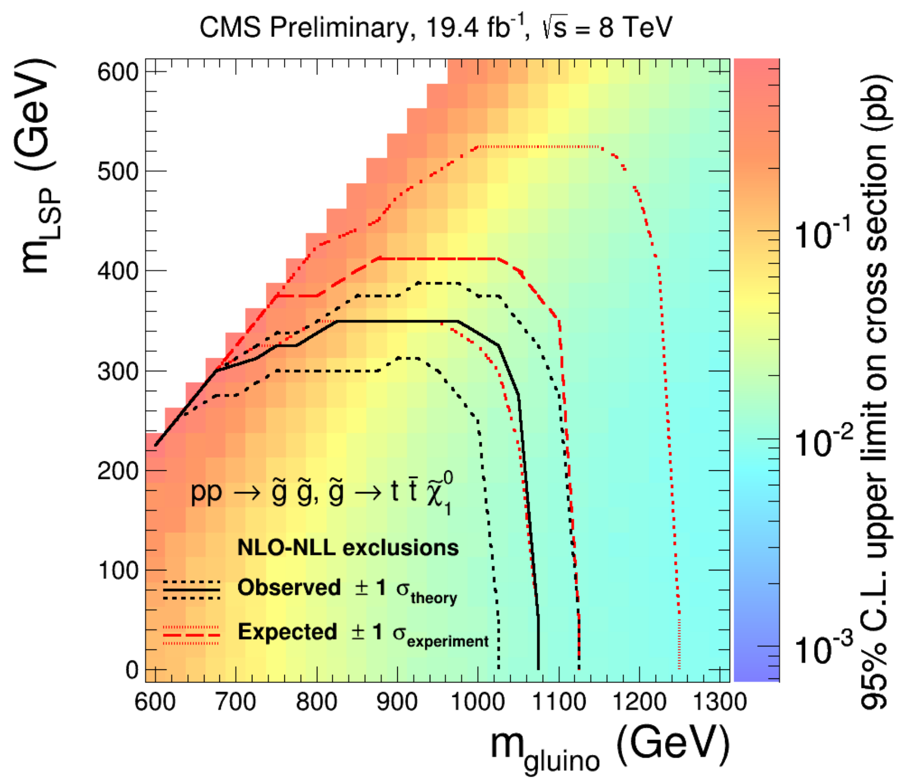
→ No evidence for excited leptons found, limits set on Λ as function of m_{l*}

→ For $\Lambda = m_{l*}$ masses below 2.2 TeV excluded for excited both electrons and muons

SUSY Search Using 3rd Generation

- Inclusive searches have heavily constrained 1st and 2nd generation squarks and gluinos
- Dedicated search for 3rd generation production

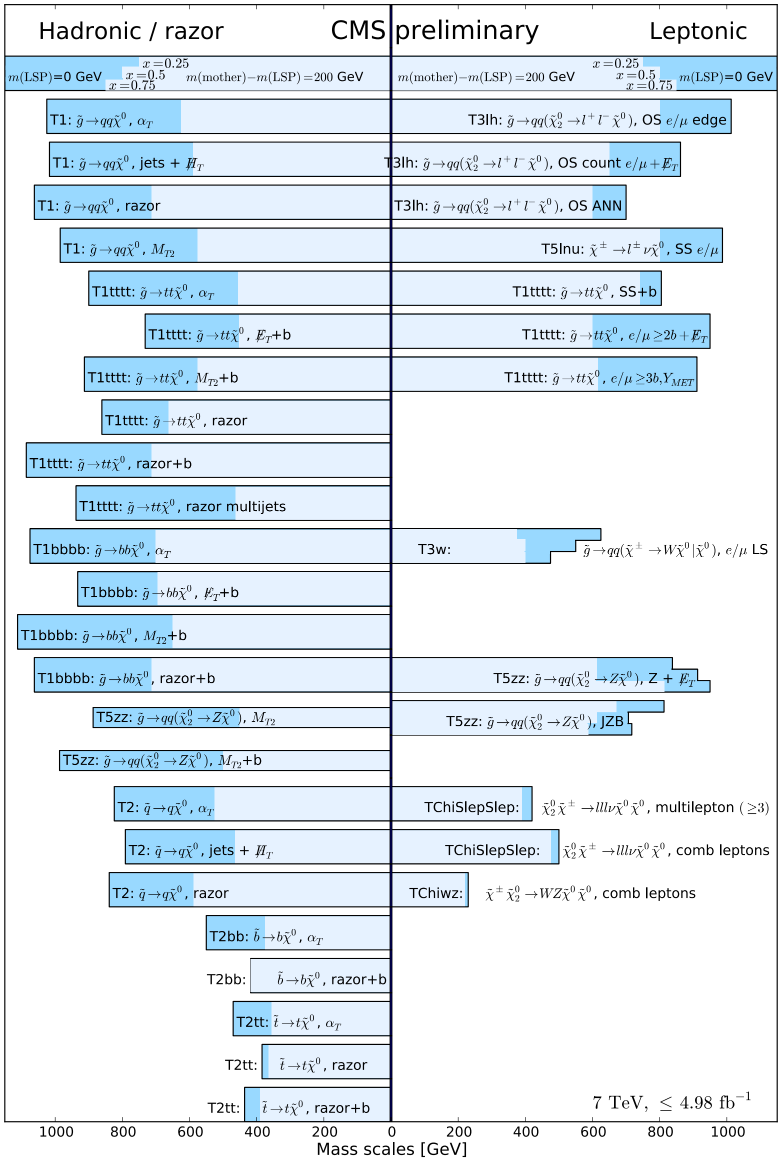




- Require at least 3 jets, at least one b tagged, no leptons and large MET

→ Observed number of events consistent with SM expectation

Conclusions



No signs of new physics yet at the LHC

Many analysis ongoing, also adjusting in light of a 125 GeV Higgs like particle

Looking forward to new 14 TeV data after the end of the shutdown in 2015