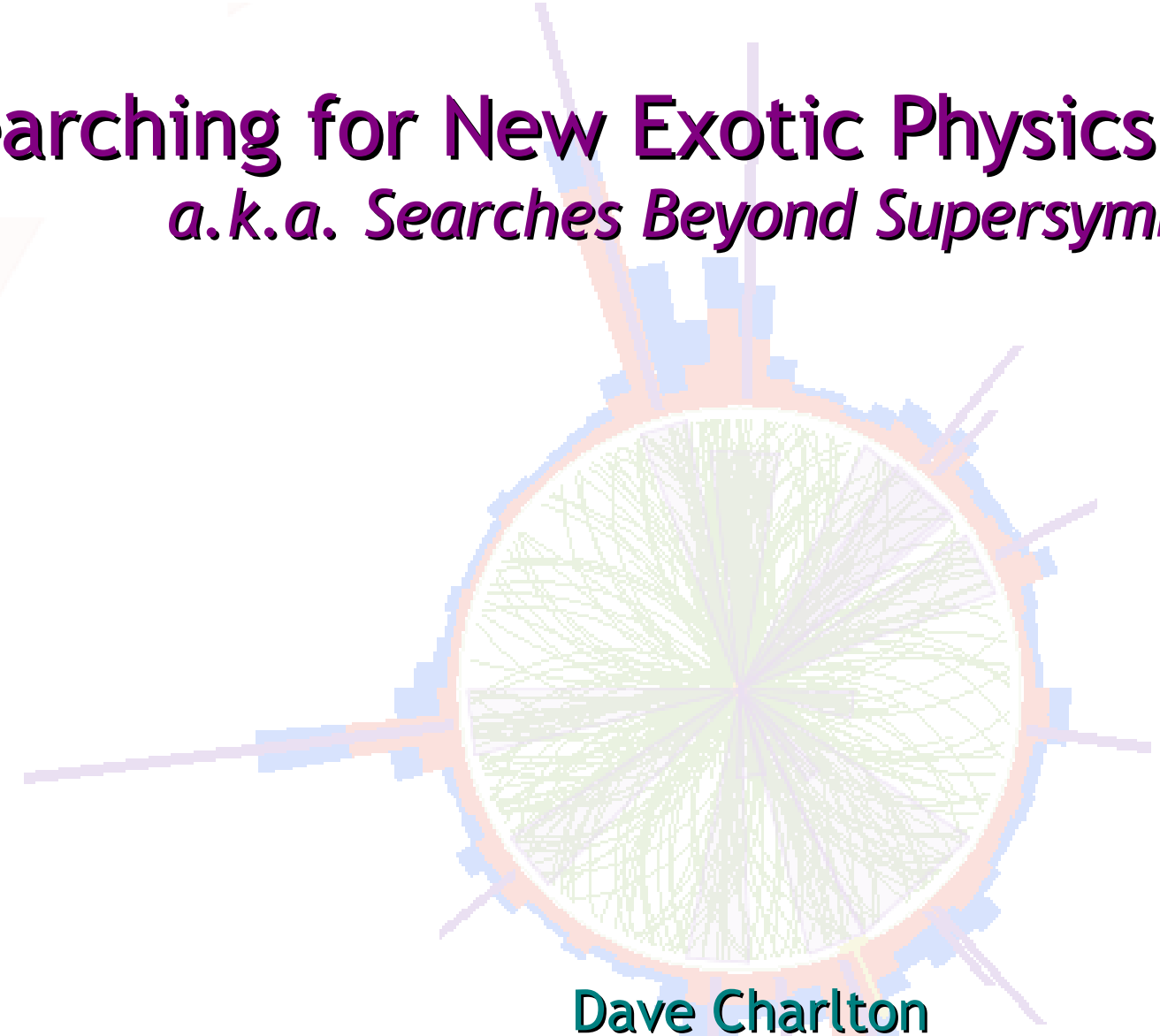
Searching for New Exotic Physics at the LHC

a.k.a. Searches Beyond Supersymmetry



Dave Charlton
University of Birmingham

Before, Behind and Beyond the Discovery of the Higgs Boson
Royal Society, 20-21 January 2014

Menu

Why search for exotic physics?

- Simple event types - “bump hunting”
- Top as a probe
- Long-lived particles
- Dark matter

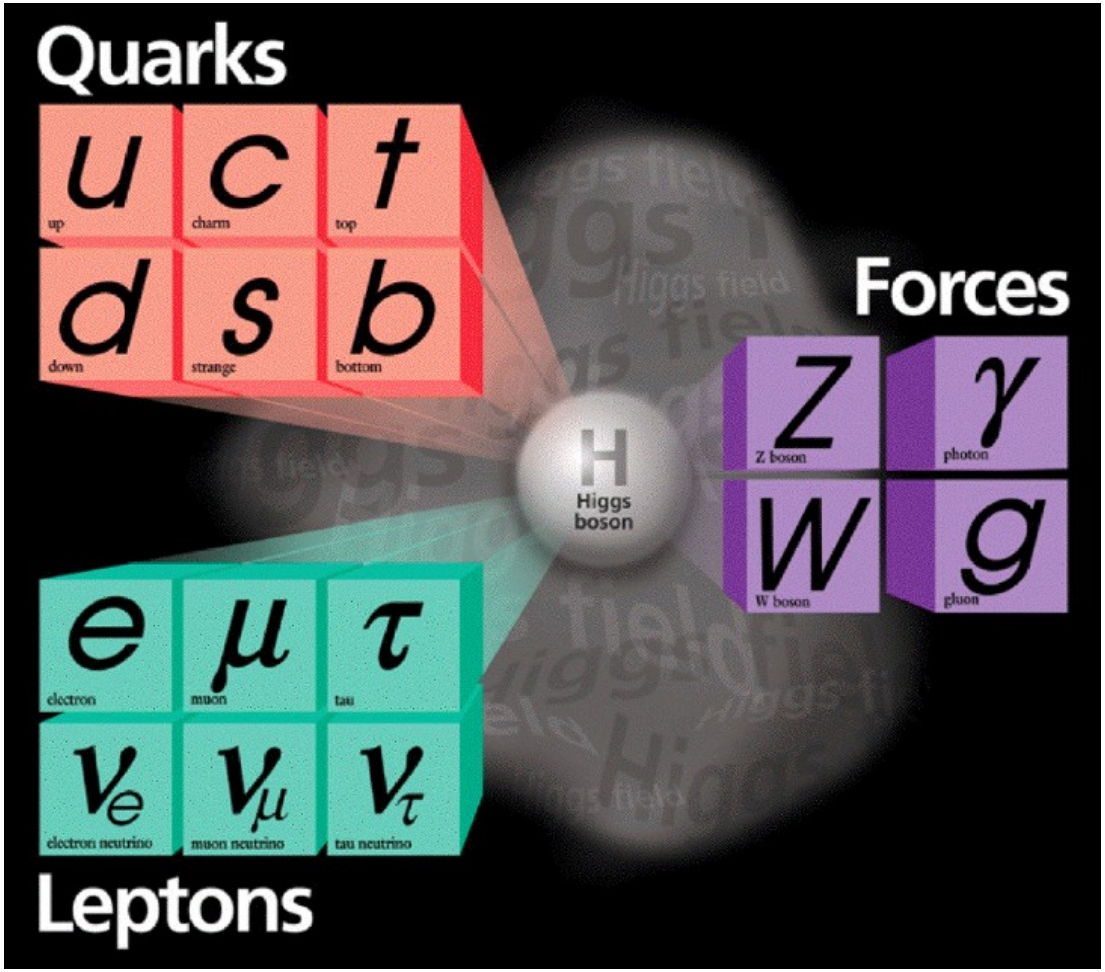
Conclusions

The end of physics?

The Standard Model works fantastically, and is now completed by the H discovery

But it leaves so many questions unanswered...

- Why three families – are there only three?
- Why the symmetry between quarks and leptons?
- Why the huge imbalances in particle masses?
- What is most of the matter in the universe?
- Where has the antimatter gone?
- What are the next steps in unification of forces?
- Unification with gravity?



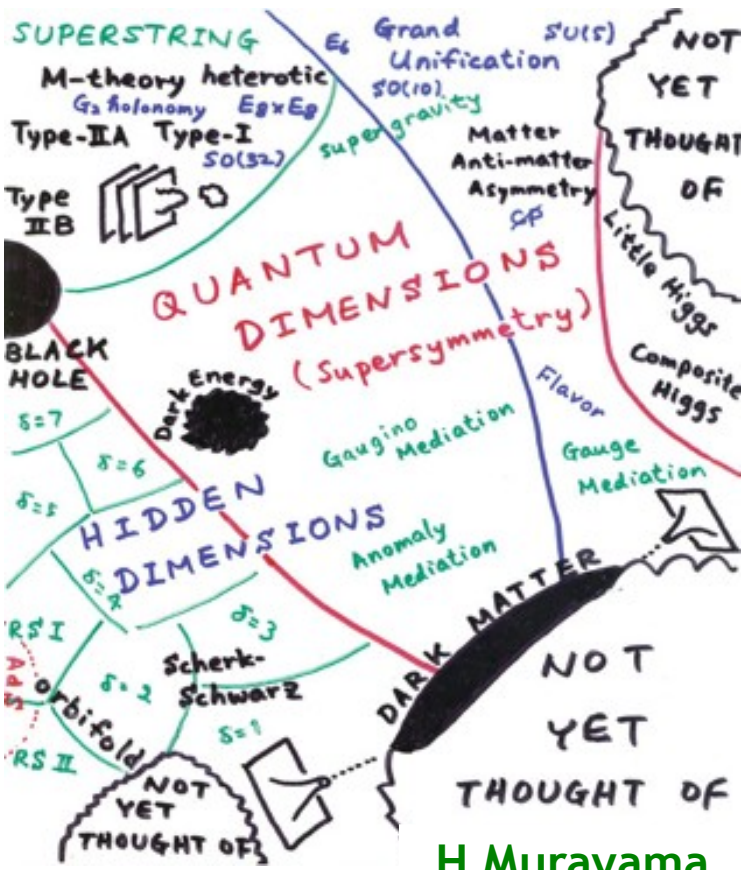
This is not the end of fundamental physics – but where and what comes next?

Previous talks laid the arguments for new physics at the TeV scale

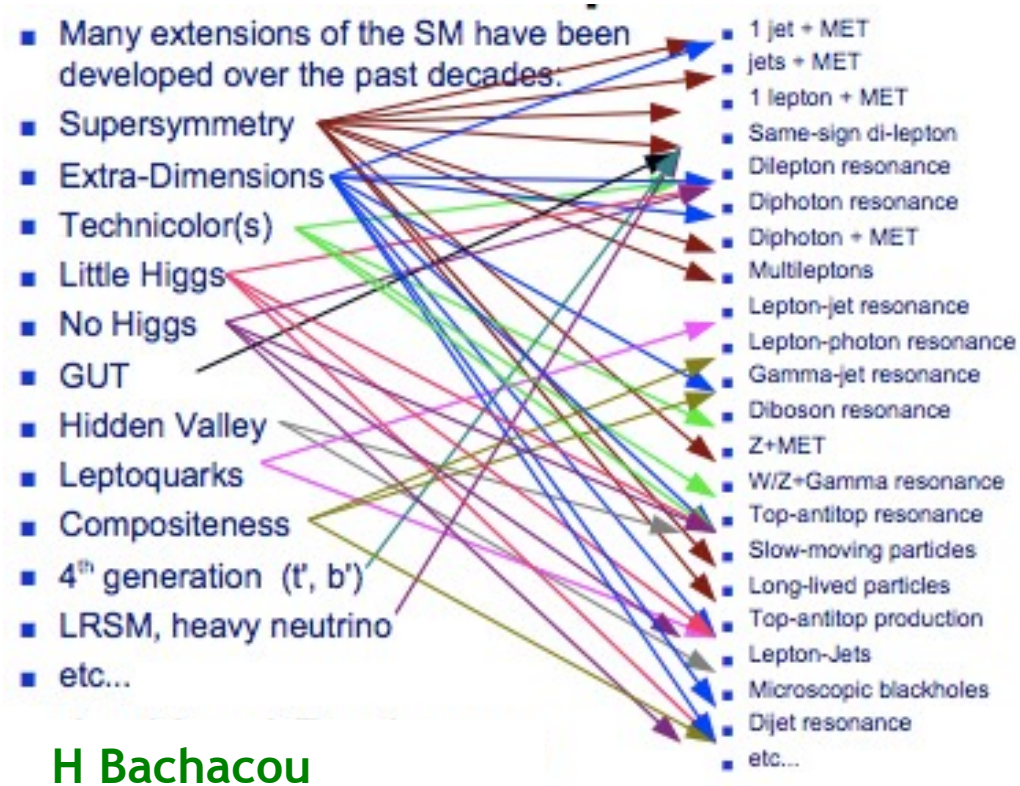
“Exotic” searches

ATLAS and CMS design comprehensive search strategies for new physics beyond the Standard Model (BSM)

- Open perspective – we do not know what we may find
- There are many many possible models – and event signatures
- Searches started with simple signatures, expand to more complex events
- Models act as benchmarks and guides – but we are open to as much as we can



H Murayama



H Bachacou

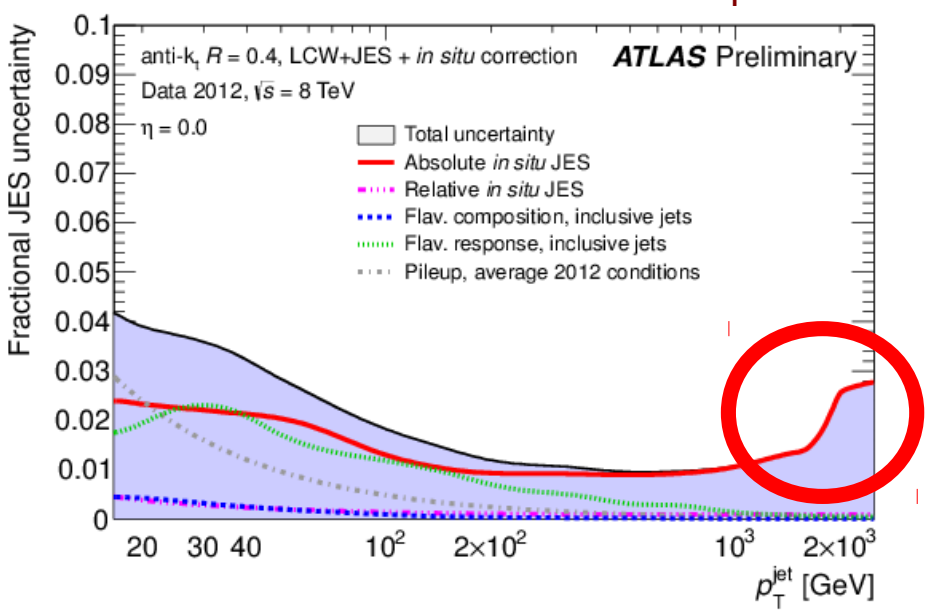
"Exotic" searches

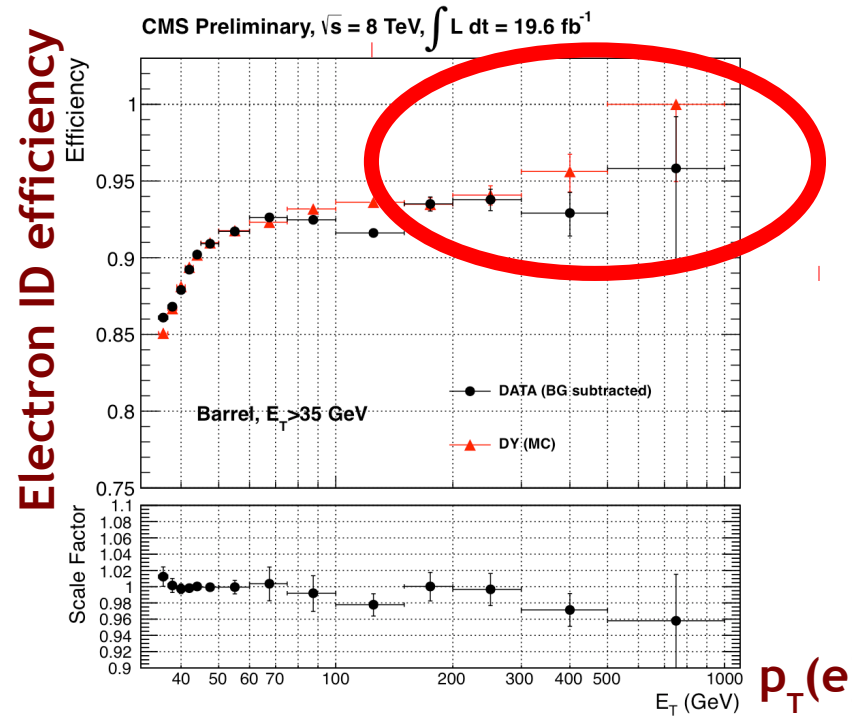
ATLAS and CMS design comprehensive search strategies for new physics beyond the Standard Model (BSM)

- Reconstruct high momentum (p_T) objects (leptons, photons, jets...)
- Reconstruct decays of heavy objects (W, Z, top ...)
- Look for **rare** events with typically several such objects
- SM backgrounds derived from data where possible, guided by simulations

Measurement of detector performance is trickier at high p_T, but generally only small effects on results from increased errors

Jet energy scale error vs p_T(jet)

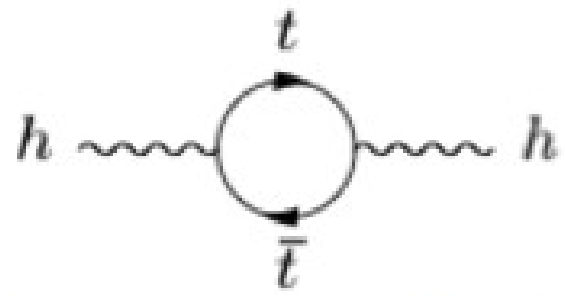




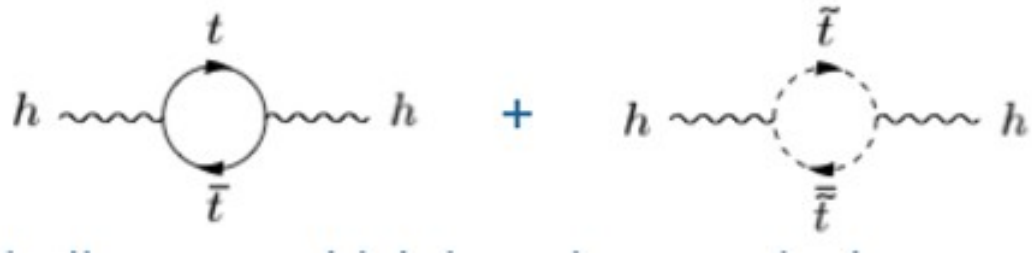
p_T(e)

Some motivations for models (I)

The low-mass Higgs boson with "only" the SM requires "fine-tuning" → suggests new physics at TeV scale ("naturalness" problem)



SUSY provides a simple and elegant solution – but introduces many new particles



Can we solve this in other ways?

Some motivations for models (II)

Many other models have been suggested, predicting other new particles/effects in the TeV energy regime

Examples:

- New families of quarks - e.g. "vector-like" quarks (VLQs)

- Large extra dimensions – the Planck scale (quantum gravity) is close to the electroweak scale
  - Solves the "hierarchy" problem
  - Predicts new particles and new physics effects

n extra "compact" dimensions

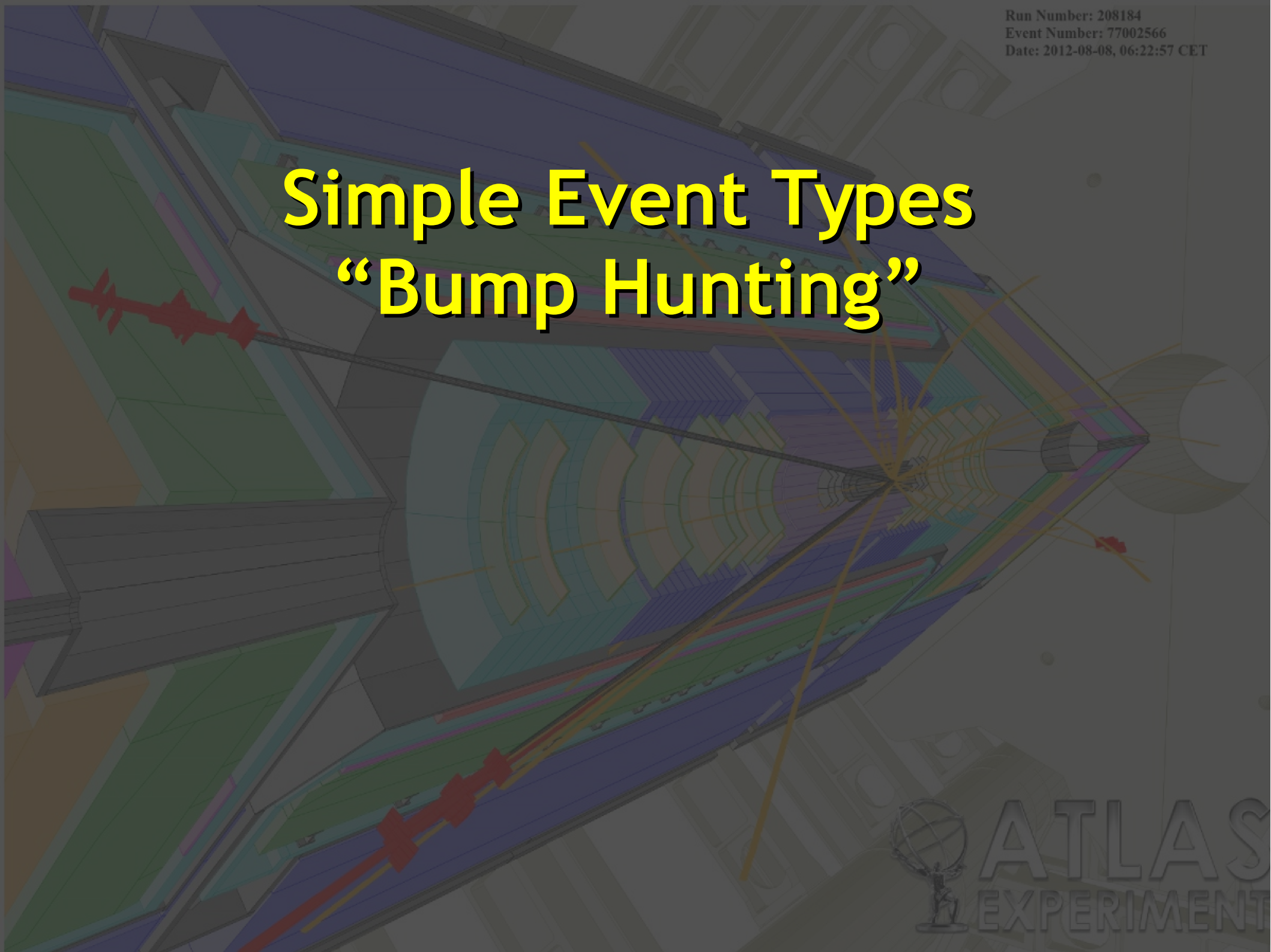
$$M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n$$

Planck scale in 4 dimensions

Planck scale in 4+n dimensions

Radius of extra "compact" dimensions

Simple Event Types
“Bump Hunting”

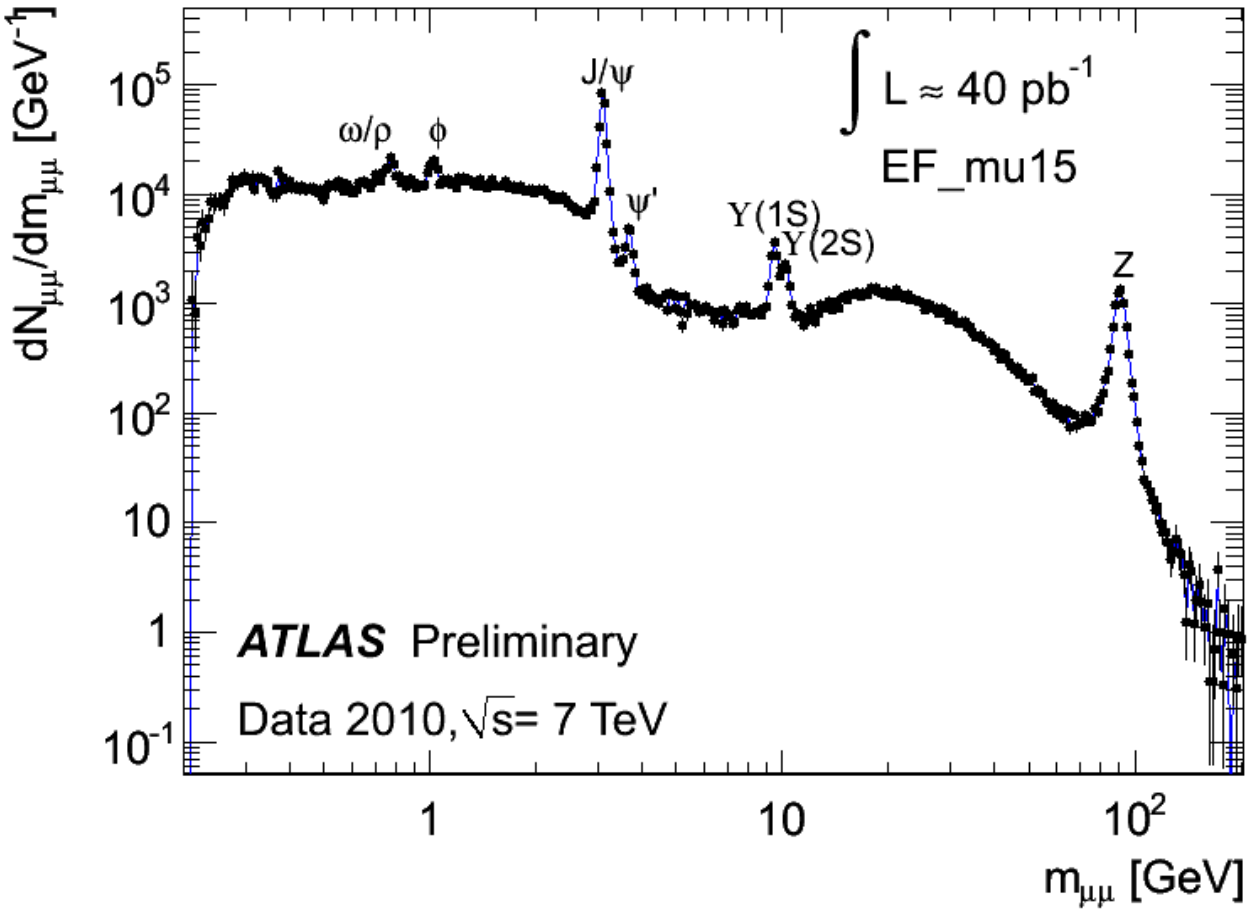


Dilepton resonances

Historical guidance:
Look for mass peaks in dilepton invariant mass distribution (ee, μμ, ττ)

Variety of models

- New SM Z-like sequential bosons Z'_{SSM}
- Grand Unified Theory inspired models ("E_6-motivated")
- Randall-Sundrum spin-2 gravitons G* in extra dimension models

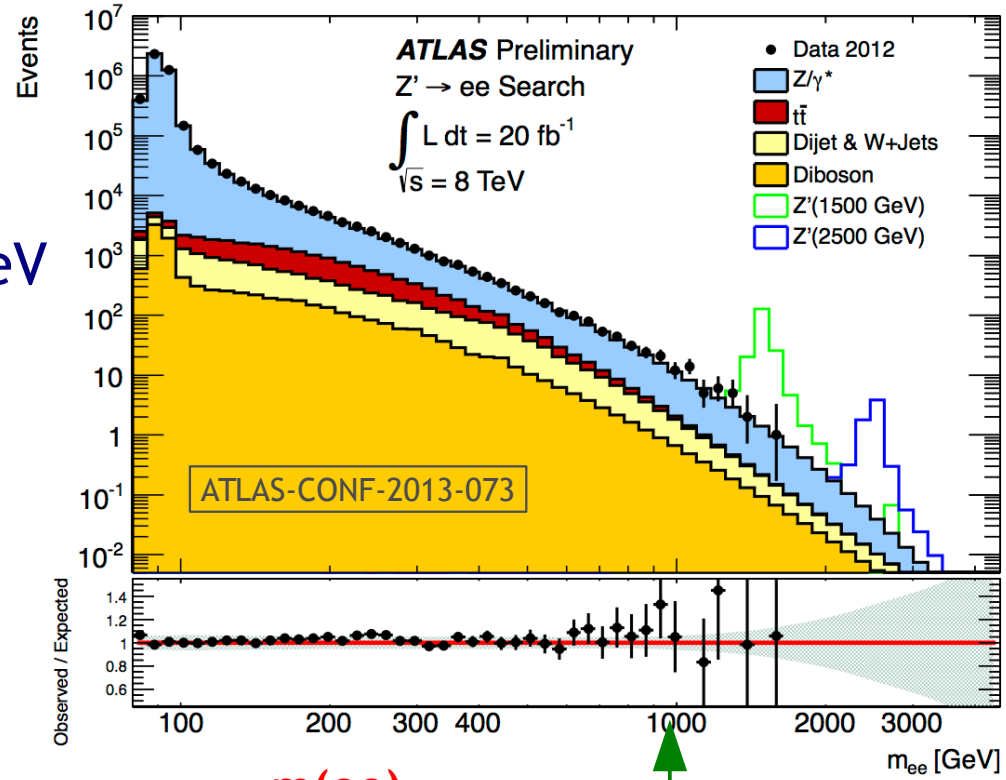


Dilepton resonances

Select two high-p_T e or μ, p_T>~30 GeV

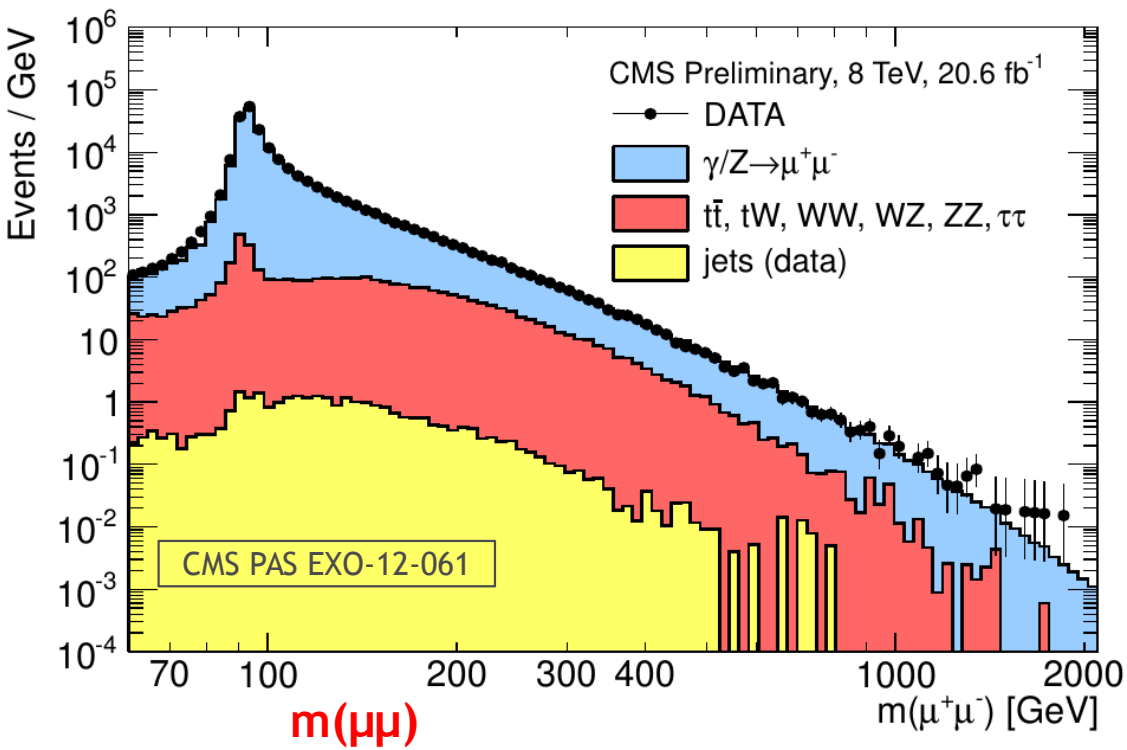
Require isolated electrons – suppresses (jet → e) background

Acceptance x efficiency ~75% for 2 TeV invariant mass object decaying



m(ee)

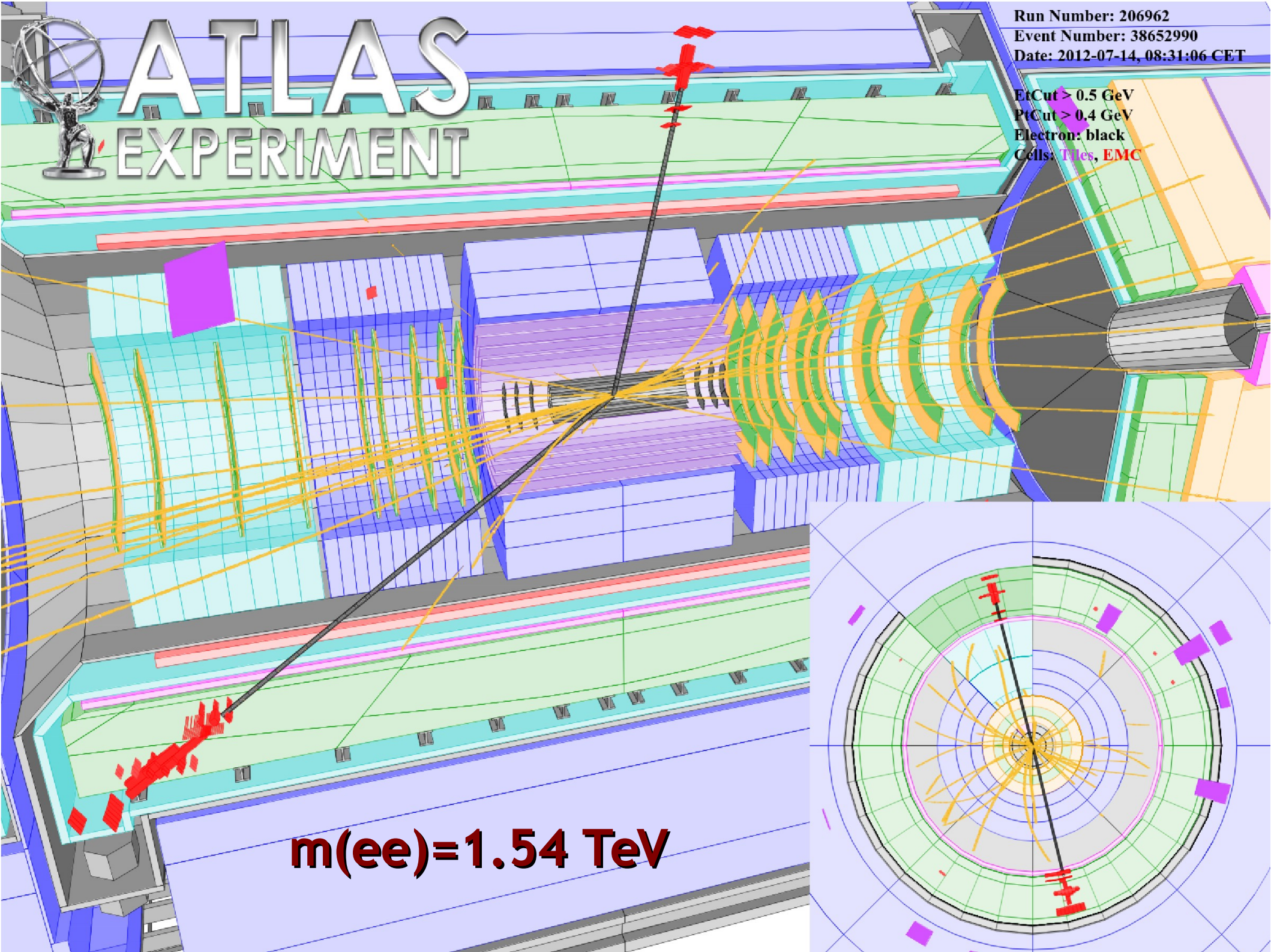
1 TeV

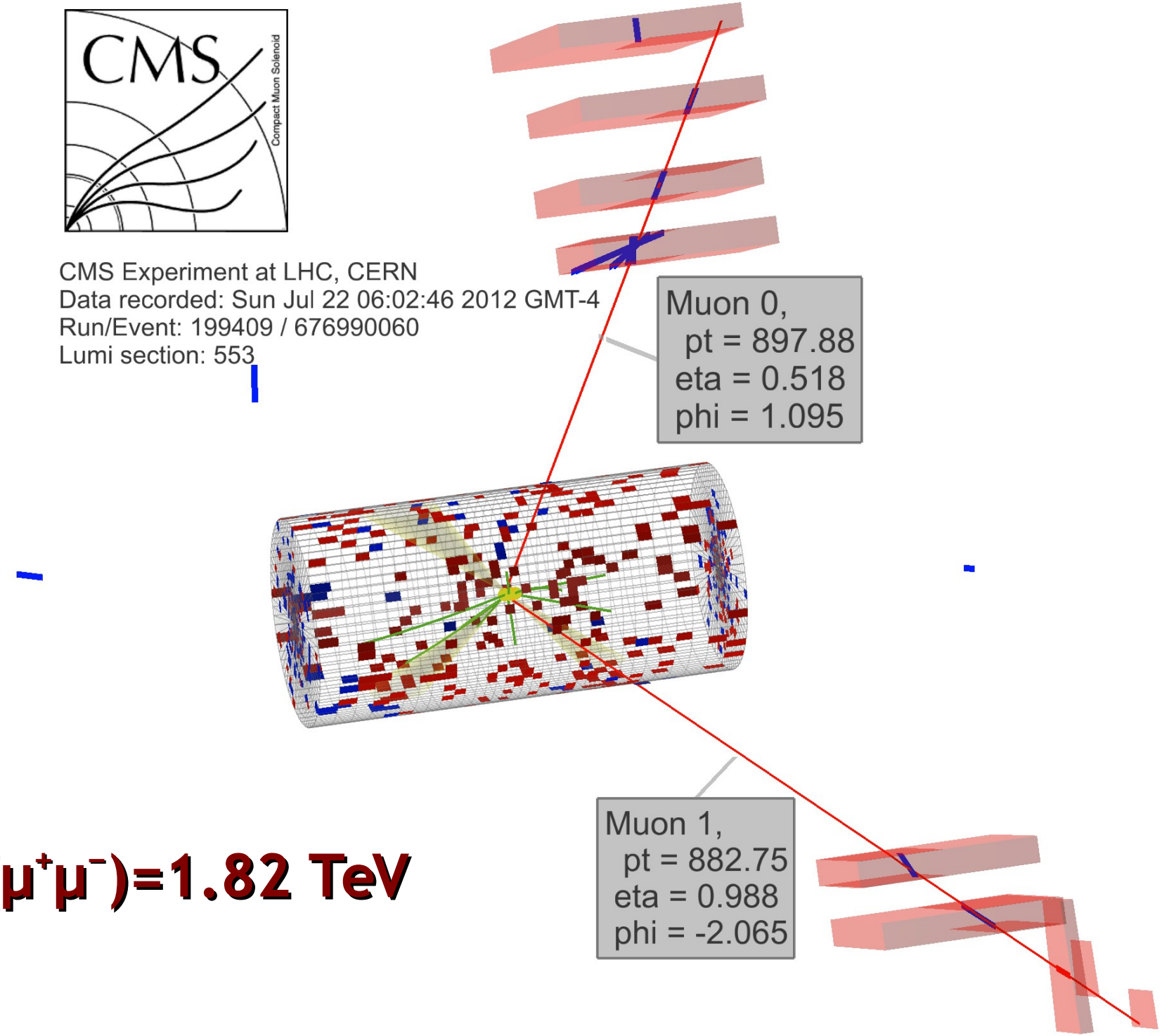


m(μμ)

Observed spectra extend well beyond 1 TeV

No statistically significant excesses


ATLAS
EXPERIMENT
Run Number: 206962
Event Number: 38652990
Date: 2012-07-14, 08:31:06 CET
EtCut > 0.5 GeV
PtCut > 0.4 GeV
Electron: black
Cells: Tiles, EMC
m(ee)=1.54 TeV



$m(\mu^+\mu^-)$=1.82 TeV

Dilepton resonances

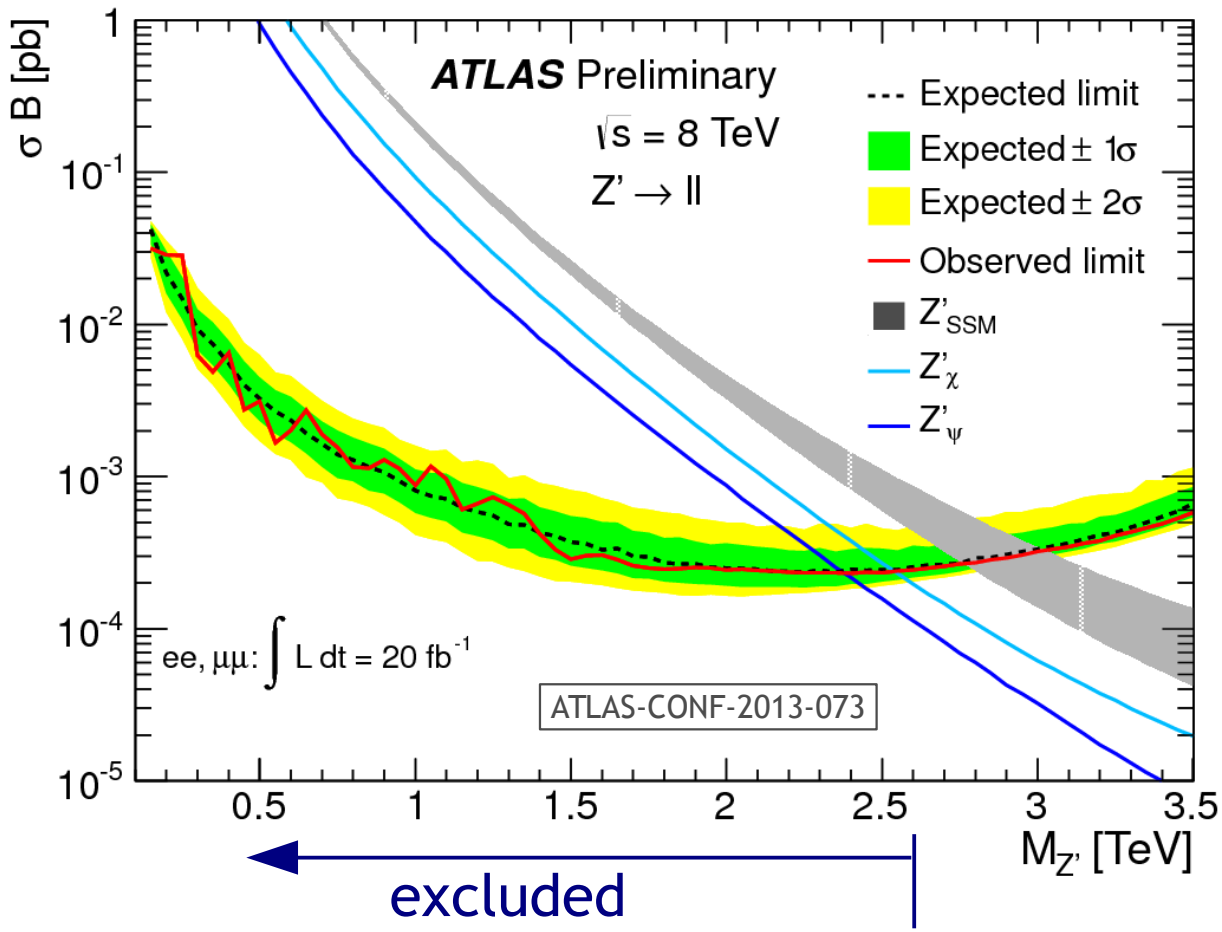
Model	Mass limit (95% CL)	
Z'_{SSM}	2.96 TeV	CMS
$Z'(\psi)$	2.60 TeV	CMS
Z'_{SSM}	2.86 TeV	ATLAS
Z'(E6 models)	2.38-2.54 TeV	ATLAS
$G^*(k/M_{Pl}=0.1)$	2.47 TeV	ATLAS

Upper limits placed on rate of events (cross-section times branching ratio $\sigma \cdot B(X \to \ell\ell)$ at 95%CL)

Convert to lower mass limits for specific models

In these models, mass of a new resonance must be more than 2-3 TeV

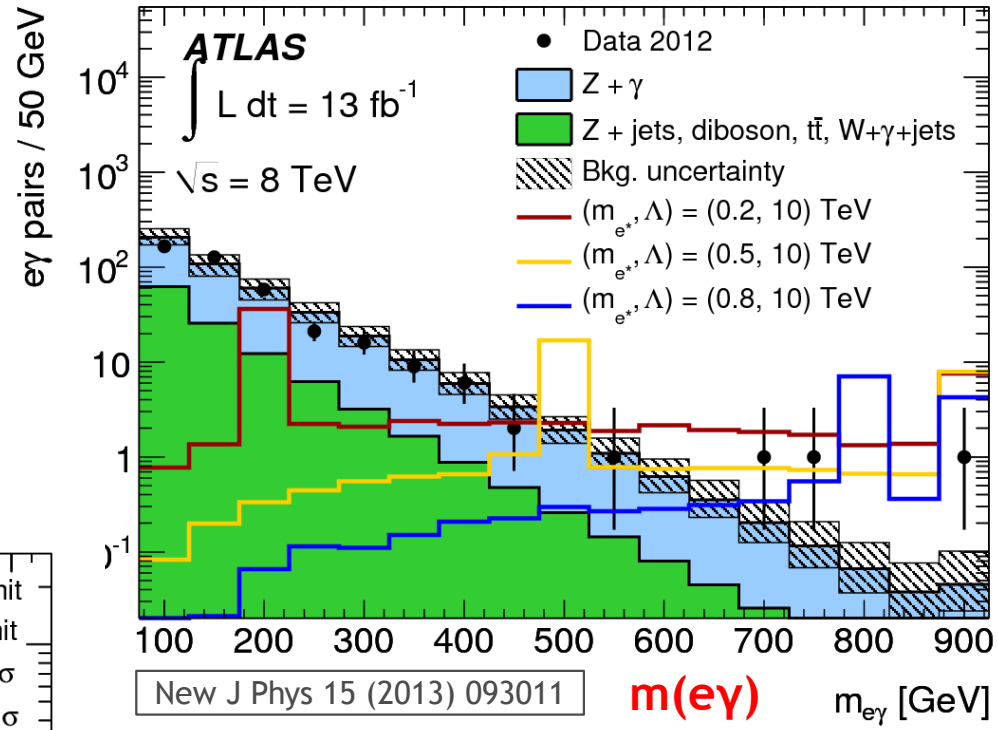
Next step:
13 TeV LHC operation – mass reach will ~double



Lepton-photon resonances

Search for excited leptons ℓ^* decaying $\ell^* \to \ell\gamma$, event: $\ell\ell\gamma$

No excess seen → set limits in the same way as previously



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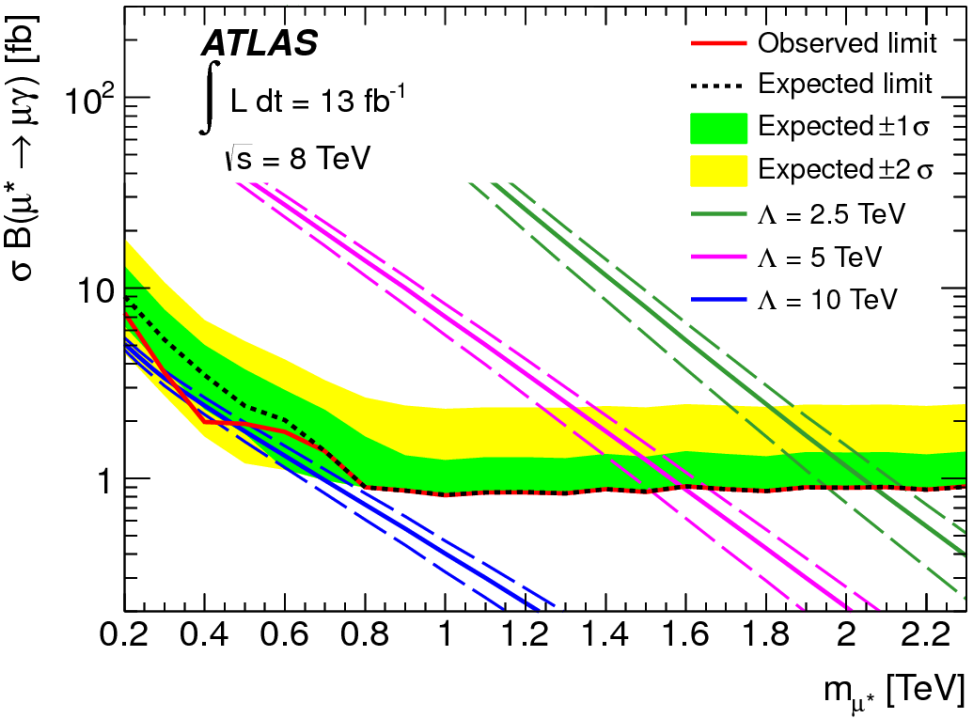
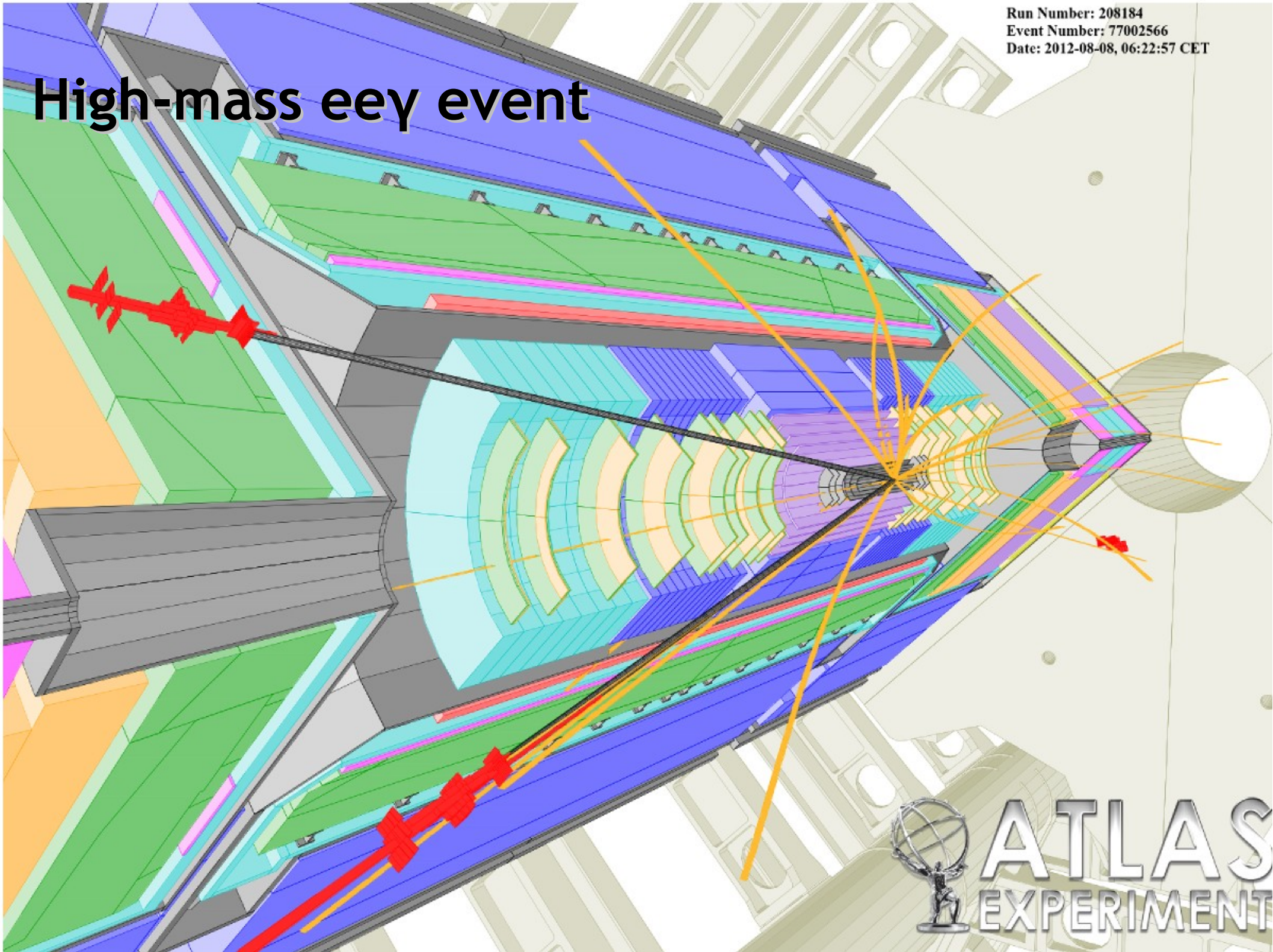
m(eγ)



Production and decay model introduces a scale Λ, for Λ = $m(\ell^*)$ excited leptons excluded with mass below 2.2 TeV at 95% CL

High-mass eeγ event



W' decaying to leptons

Simplest case: W' → ℓν

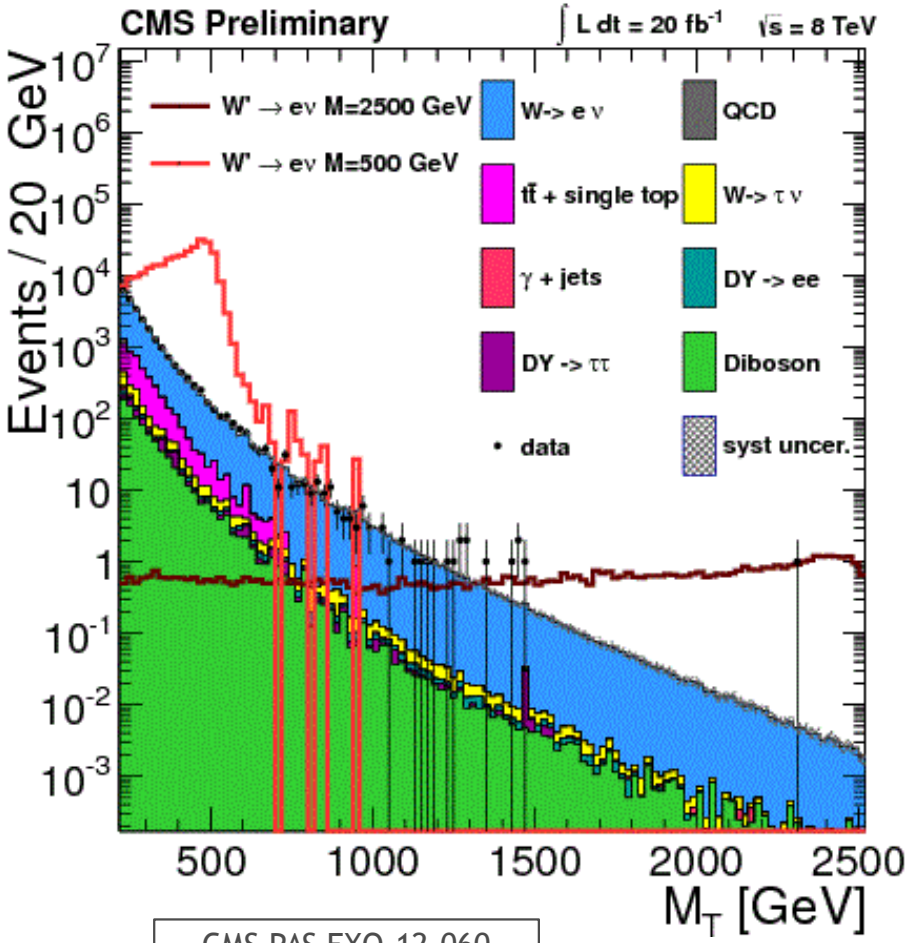
- Single high-p_T lepton and E_t^{miss}

$$m_T^W = \sqrt{2p_T^\ell E_T^{miss}(1-\cos(\Delta\phi))}$$

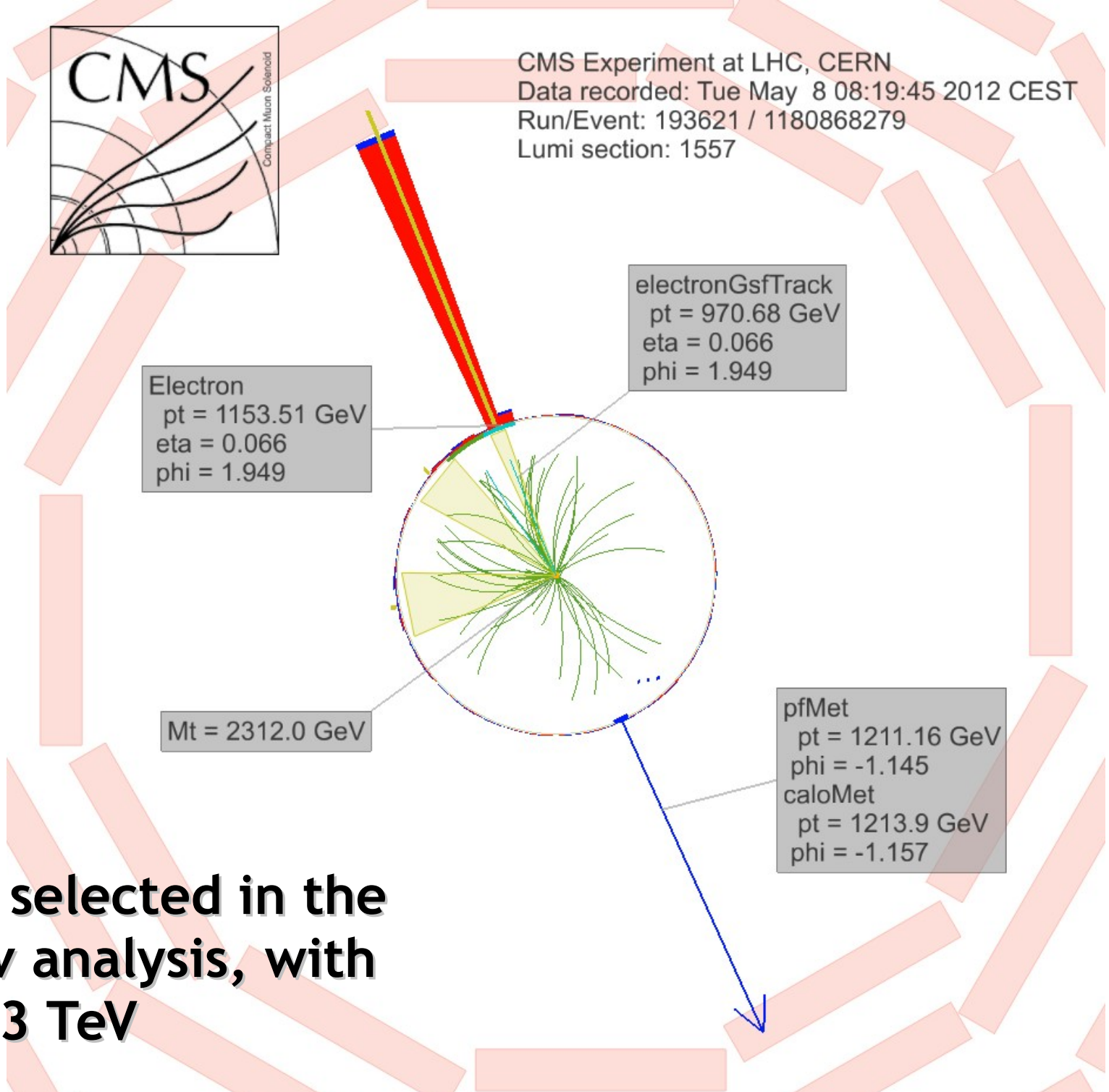
Again, no excess above backgrounds observed

Combining e,μ channels, SM-like W' excluded by CMS for

m(W') > 3.35 TeV (95% CL)



CMS PAS EXO-12-060

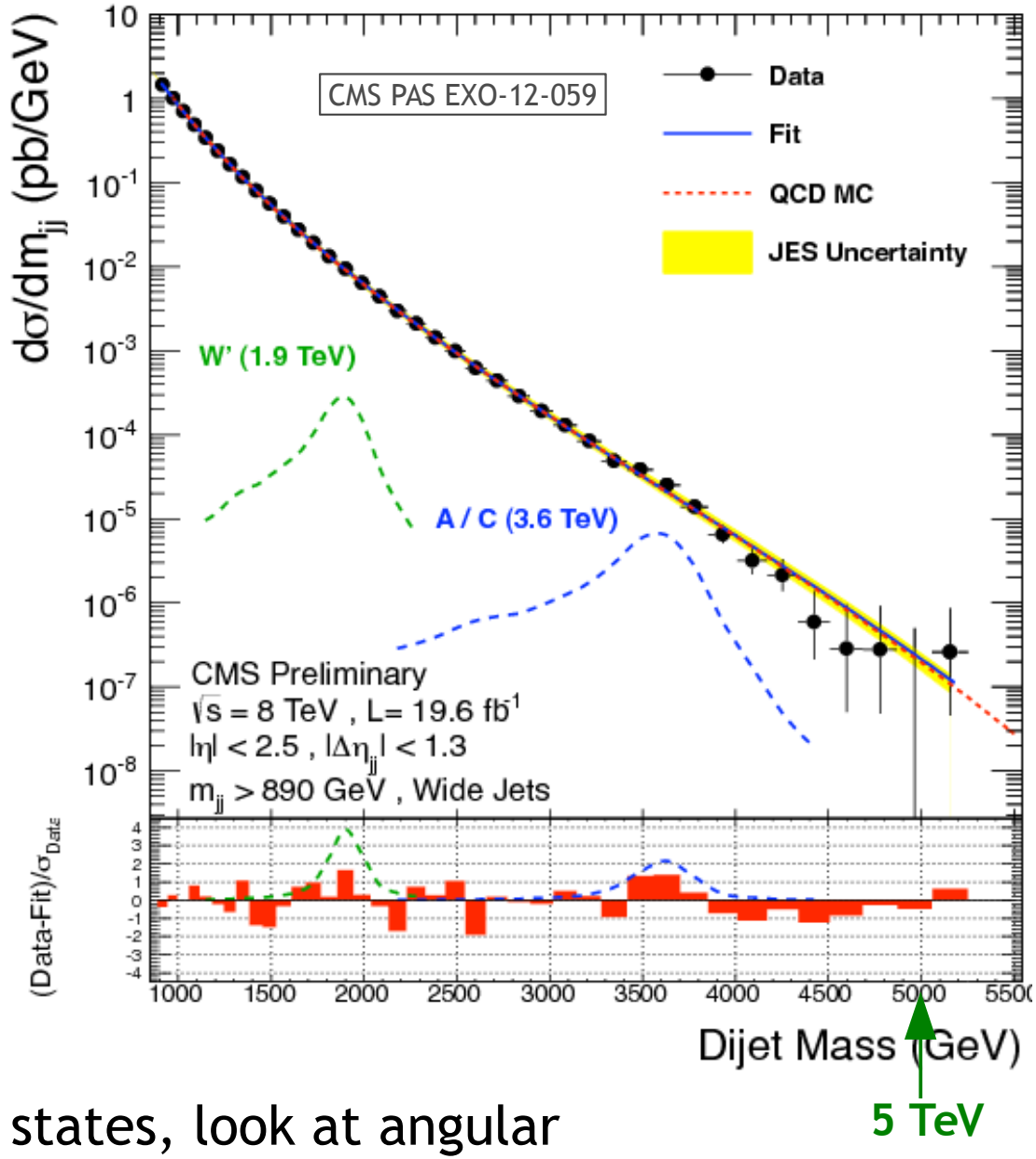


Event selected in the $W' \rightarrow \ell\nu$ analysis, with m_T=2.3 TeV

Searches in dijets

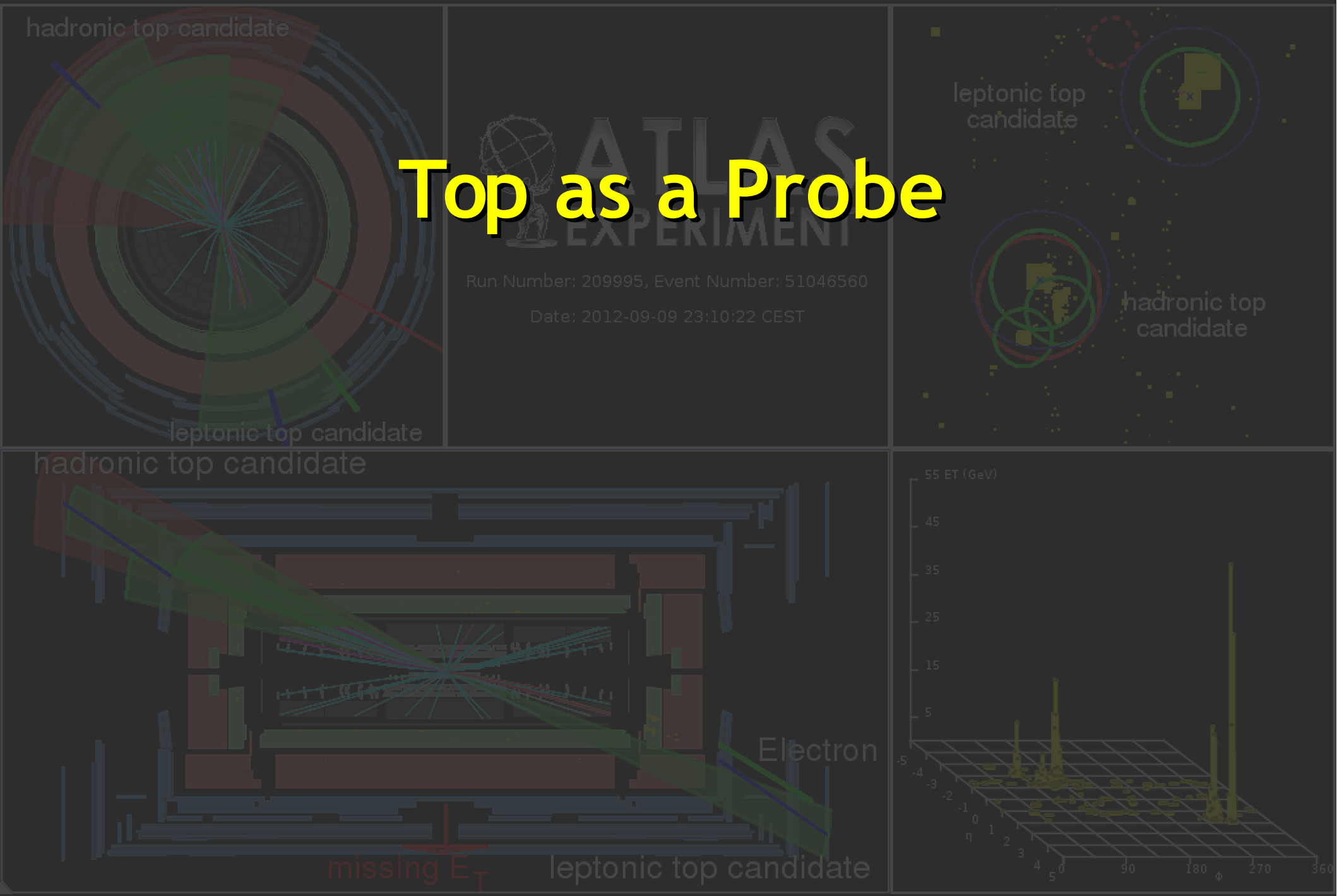
Inclusive dijet mass spectrum – extends up to 5 TeV!
Fit with smooth function, look for resonances

Limits on many models: string resonances, excited quarks, axigluons, colorons, s8 resonances, E6 diquarks, W' and Z' bosons, and Randall-Sundrum gravitons, up to 5 TeV



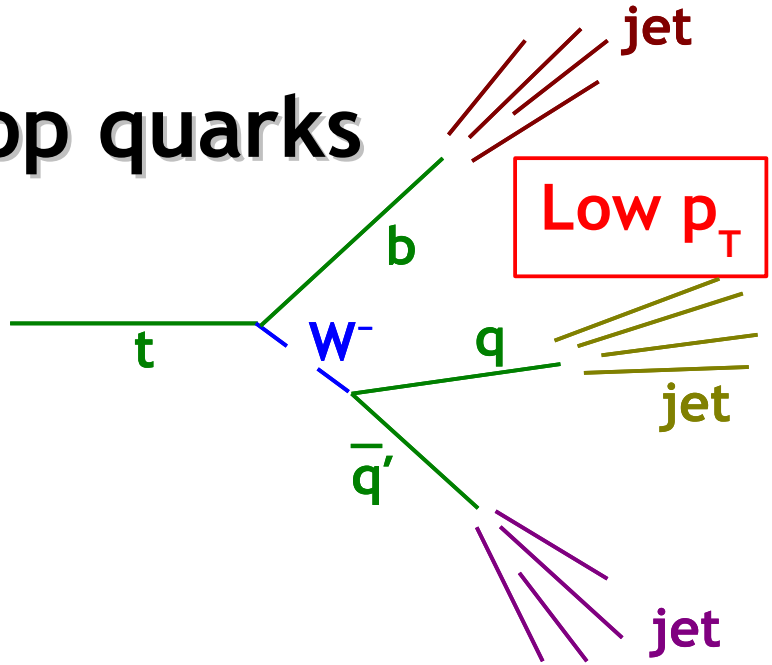
Further searches in: dijet final states, look at angular distributions in the detector, look at b-tagged jets; multijet topologies searching for 3-jet resonances … …

Top as a Probe

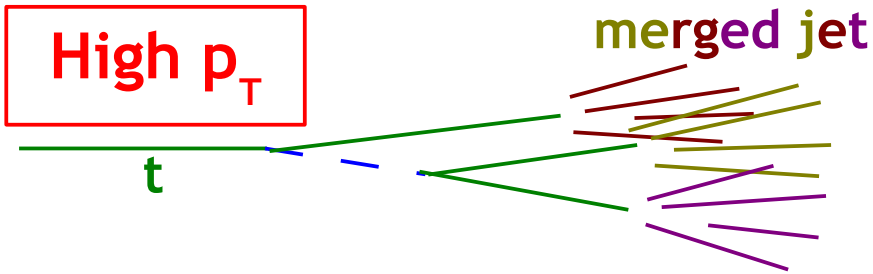


High transverse momentum top quarks

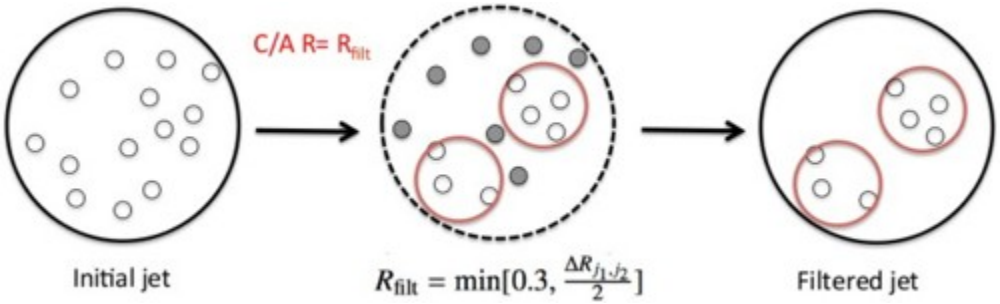
Common experimental challenge for searches for heavy particles decaying to top quarks – identification of high-p_T tops



At high-p_T, the top decay products can merge into a single "fat" jet



Sophisticated "jet substructure" techniques to identify these

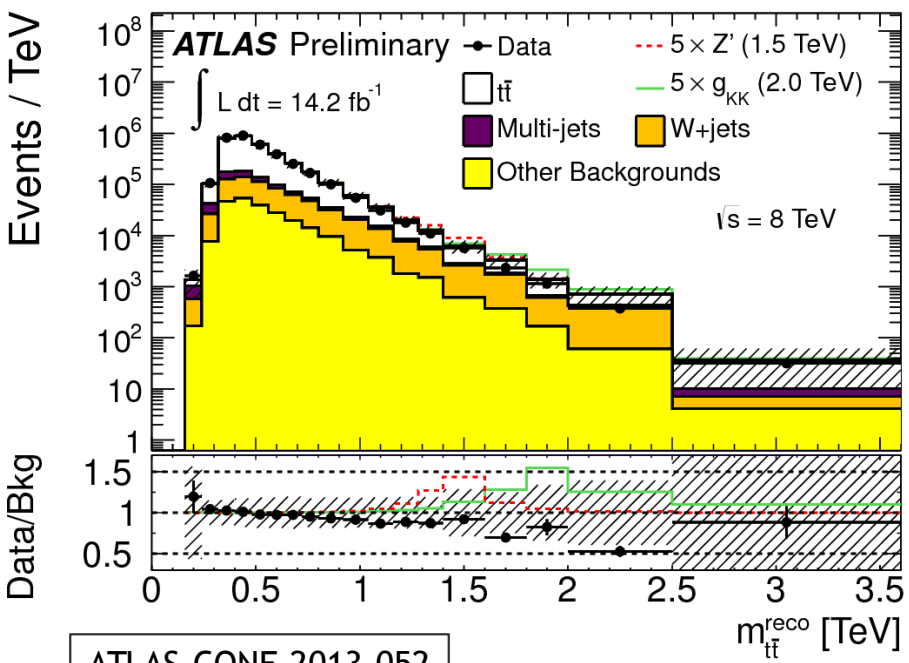


Search for X → $t\bar{t}$

Search for a heavy particle decaying to $t\bar{t}$

- Both semileptonic ($t\bar{t} \rightarrow b\ell\nu\bar{b}q\bar{q}'$) and hadronic ($t\bar{t} \rightarrow b\bar{q}q'\bar{b}q''\bar{q}'''$) decays

Search both for resolved and merged jets → extend to very high momentum top quarks



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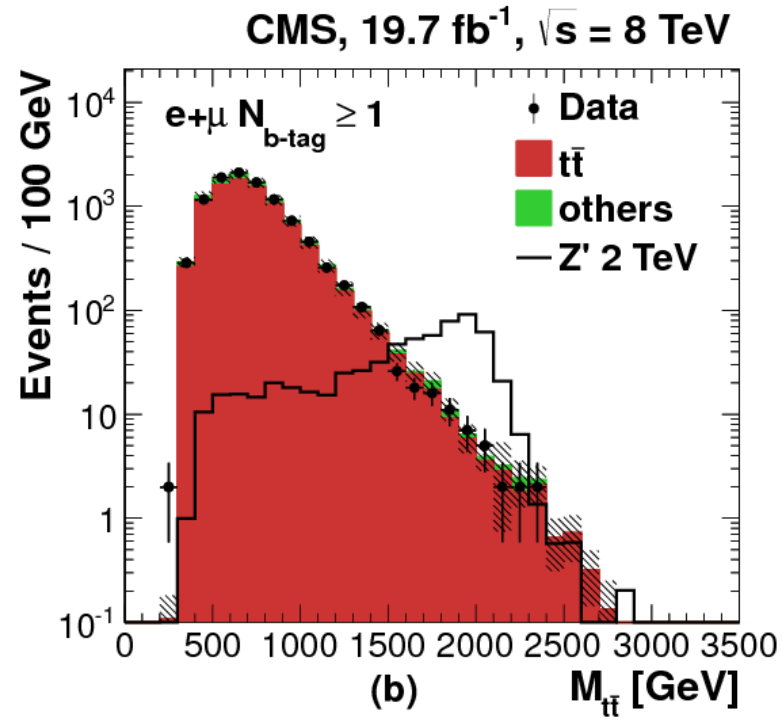
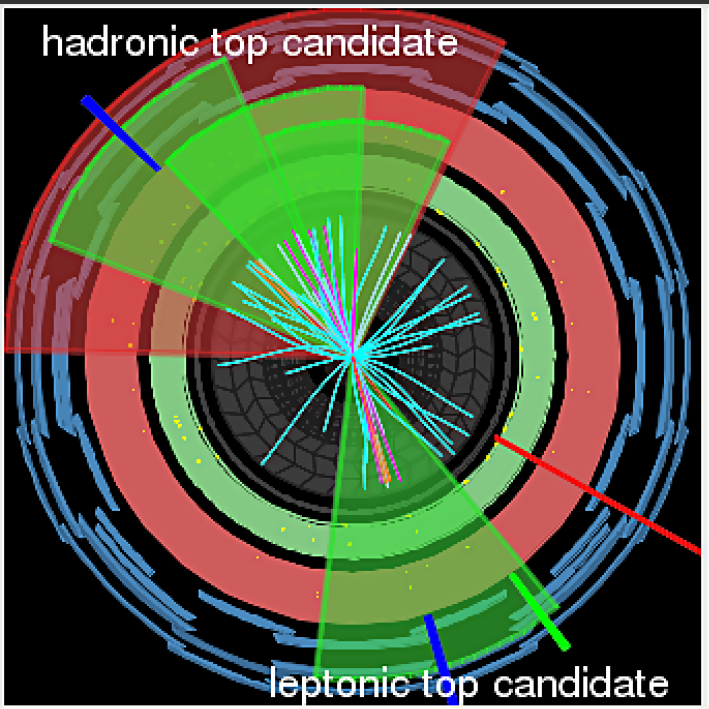
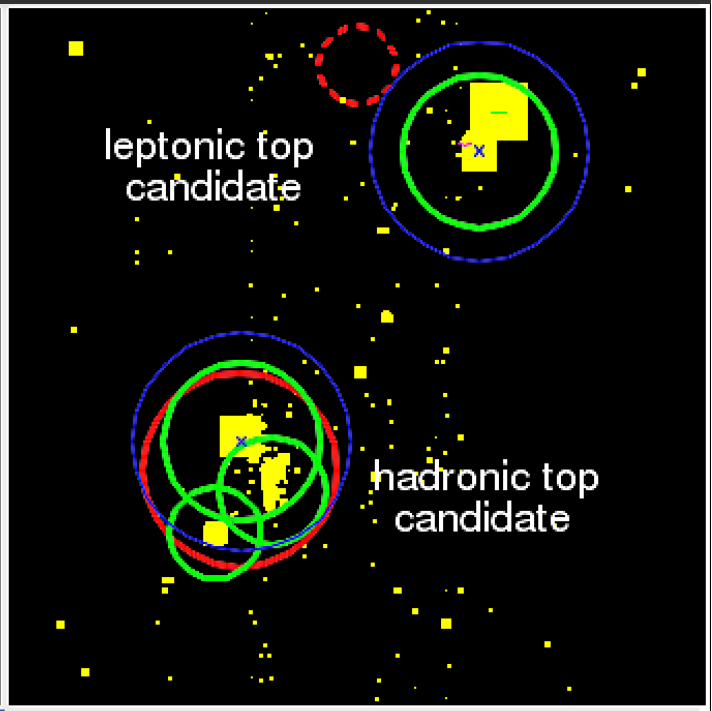
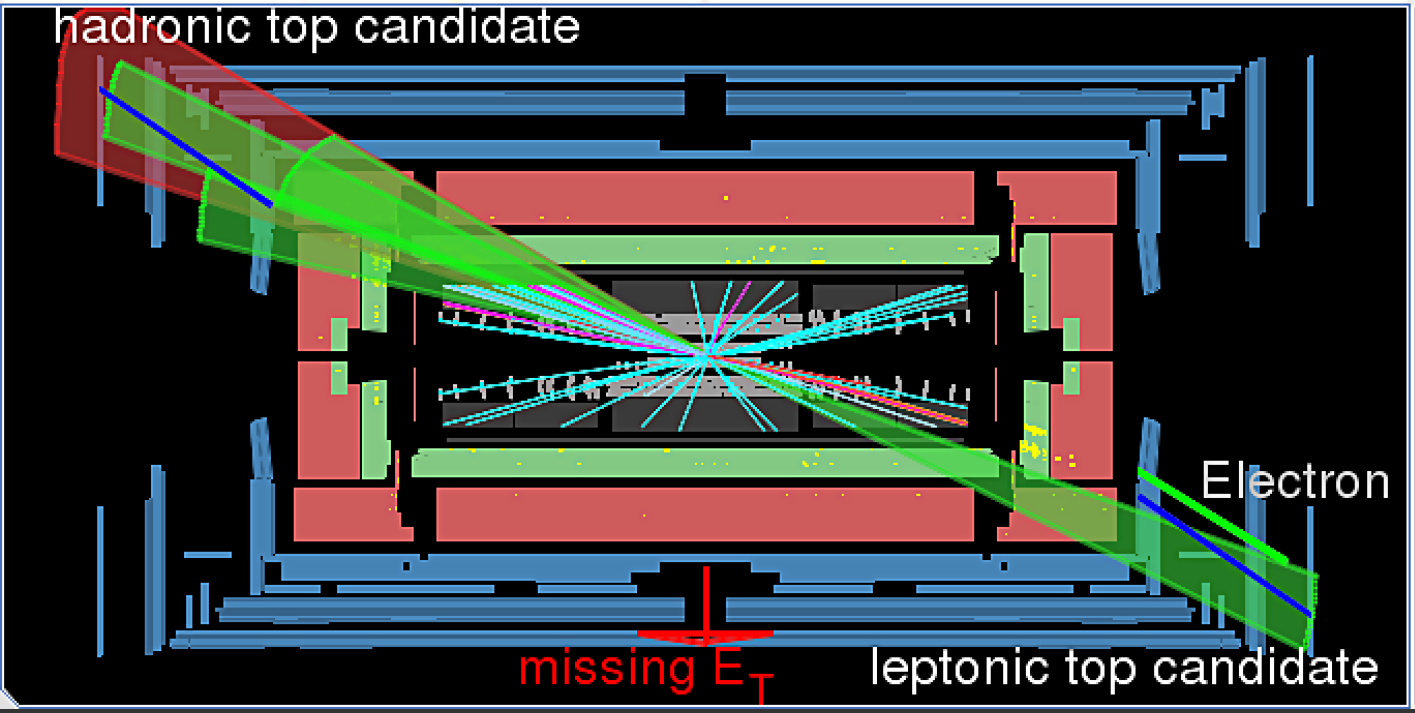


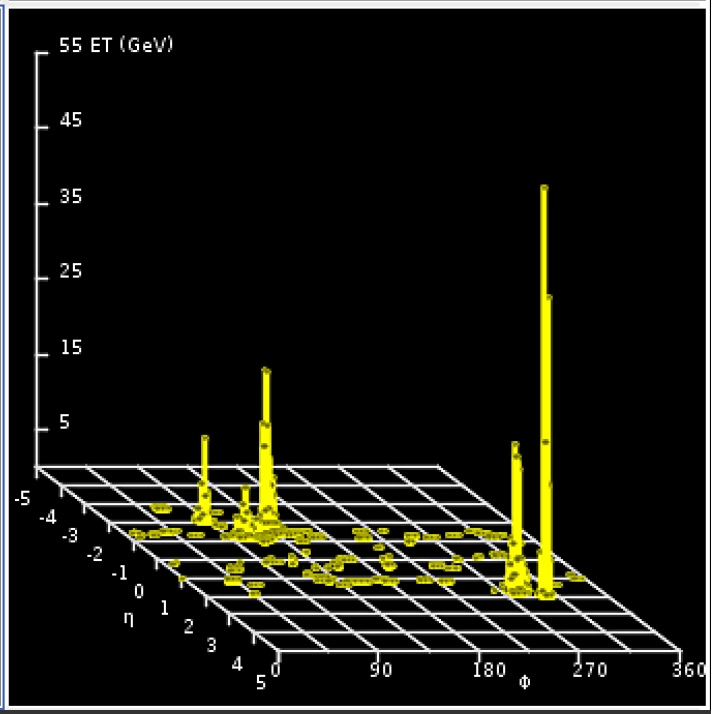
Phys Rev Lett 111 (2013) 211804

Candidate $t\bar{t}$ event with $m(t\bar{t})$=2.6 TeV





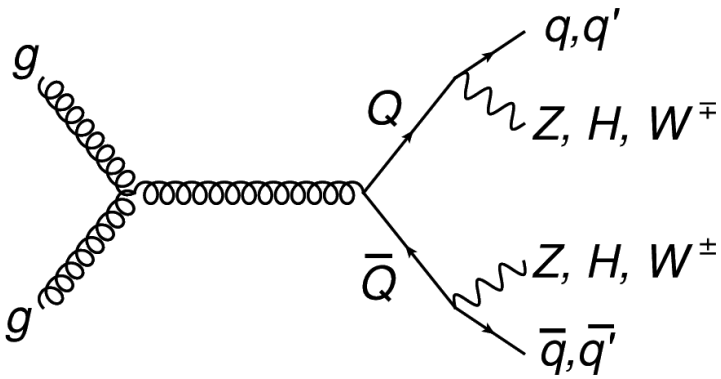




New heavy quarks ("vector-like")

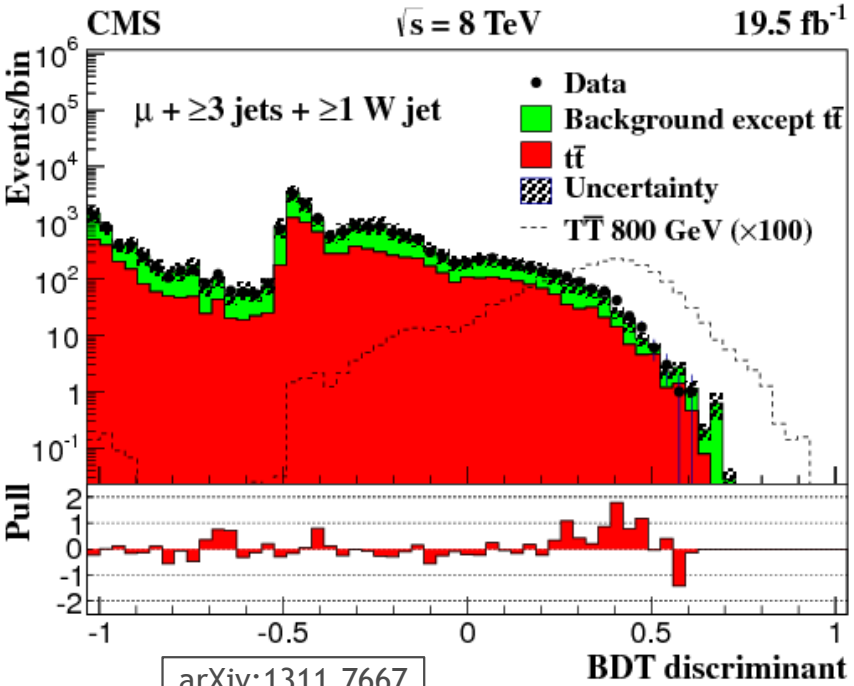
New heavy quarks (T, B): decay modes

- T → bW, T → tZ, T → tH
- B → bZ, B → tW, (B → bH)



Several event signatures:

- Single lepton plus jets/E_T^{miss}
- Same- and opposite-sign dileptons plus jets/E_T^{miss}
- Trileptons plus jets/E_T^{miss}
- Use b-tagging to improve signal/background

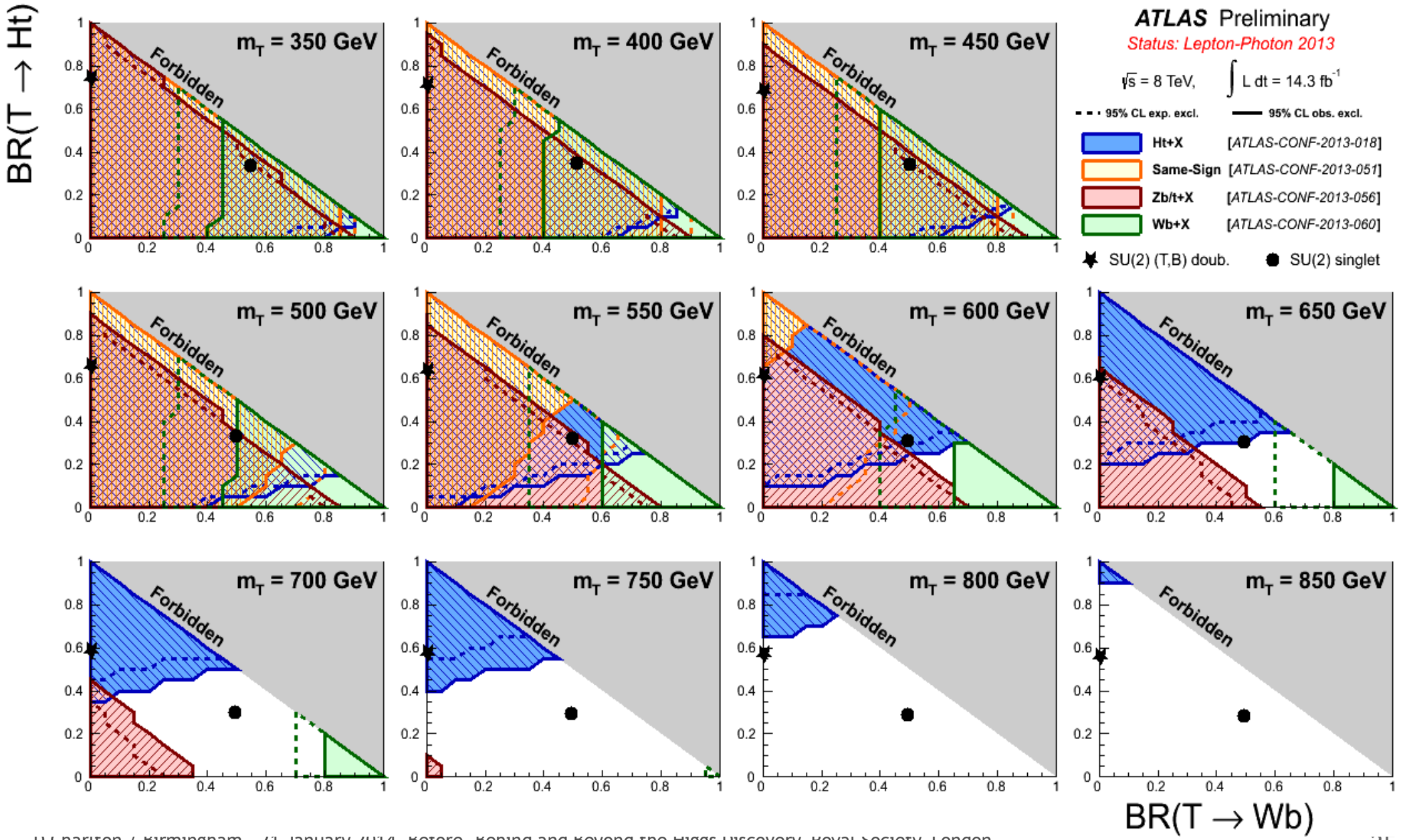


arXiv:1311.7667

Specially constructed discriminant

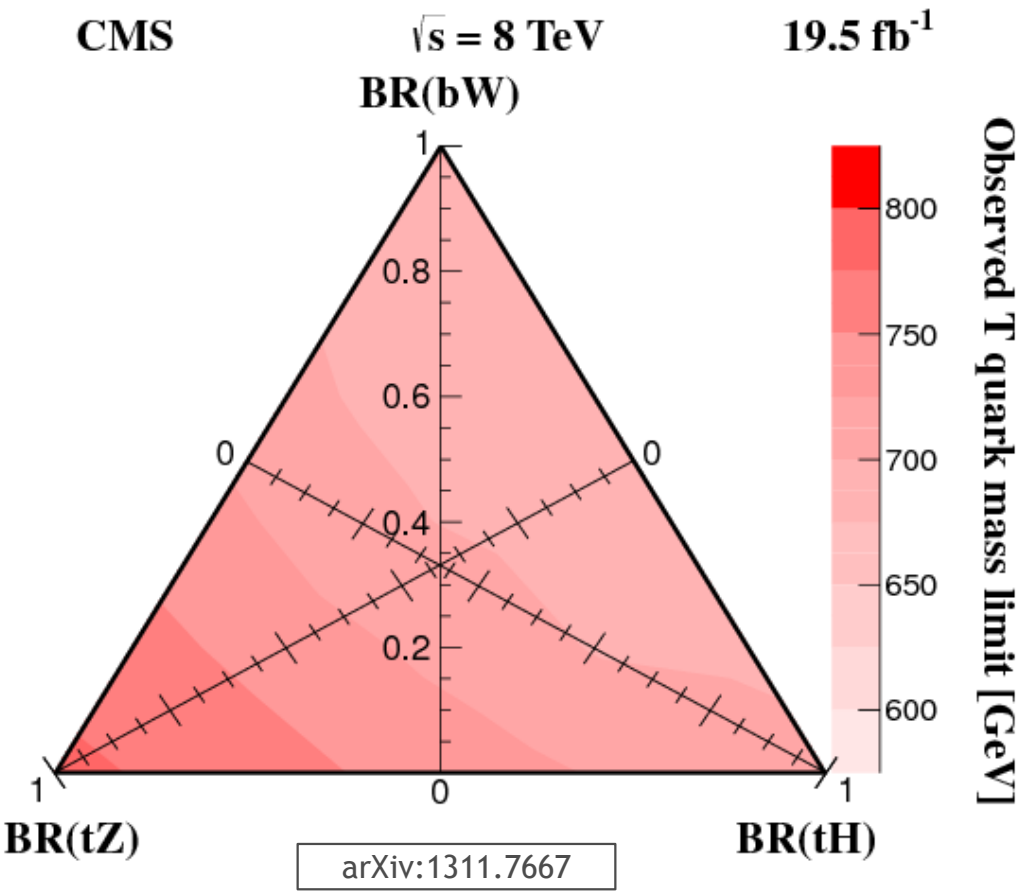
Vector-like quarks

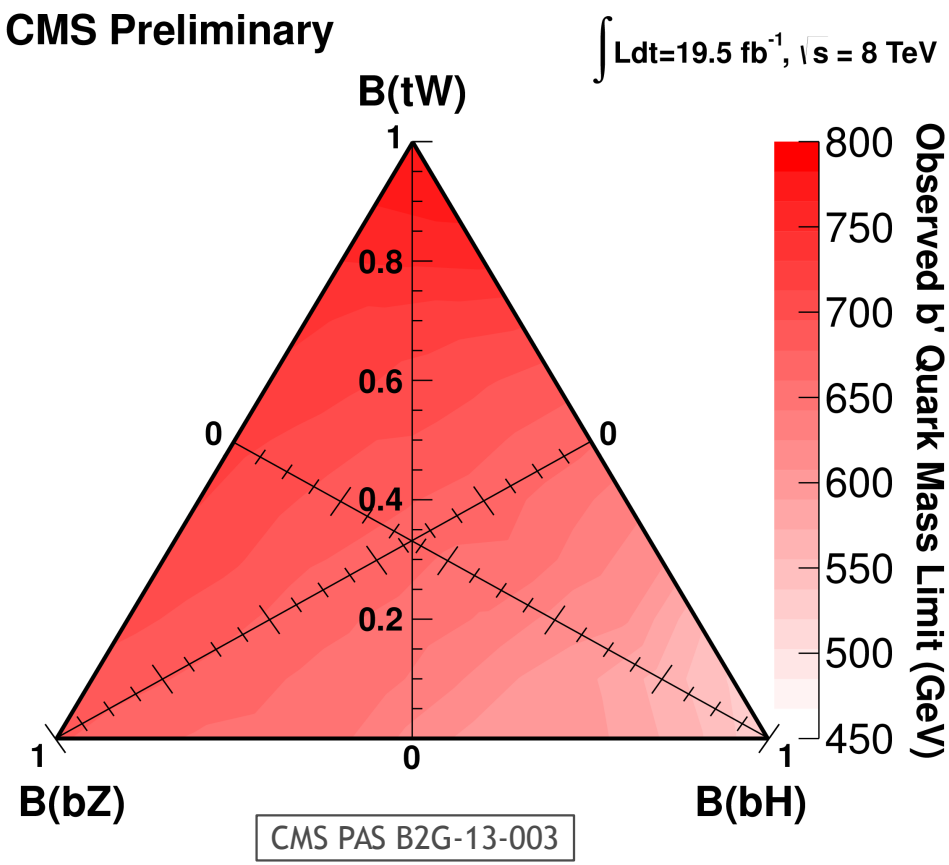
Put all the information together – complex multidimensional exclusion



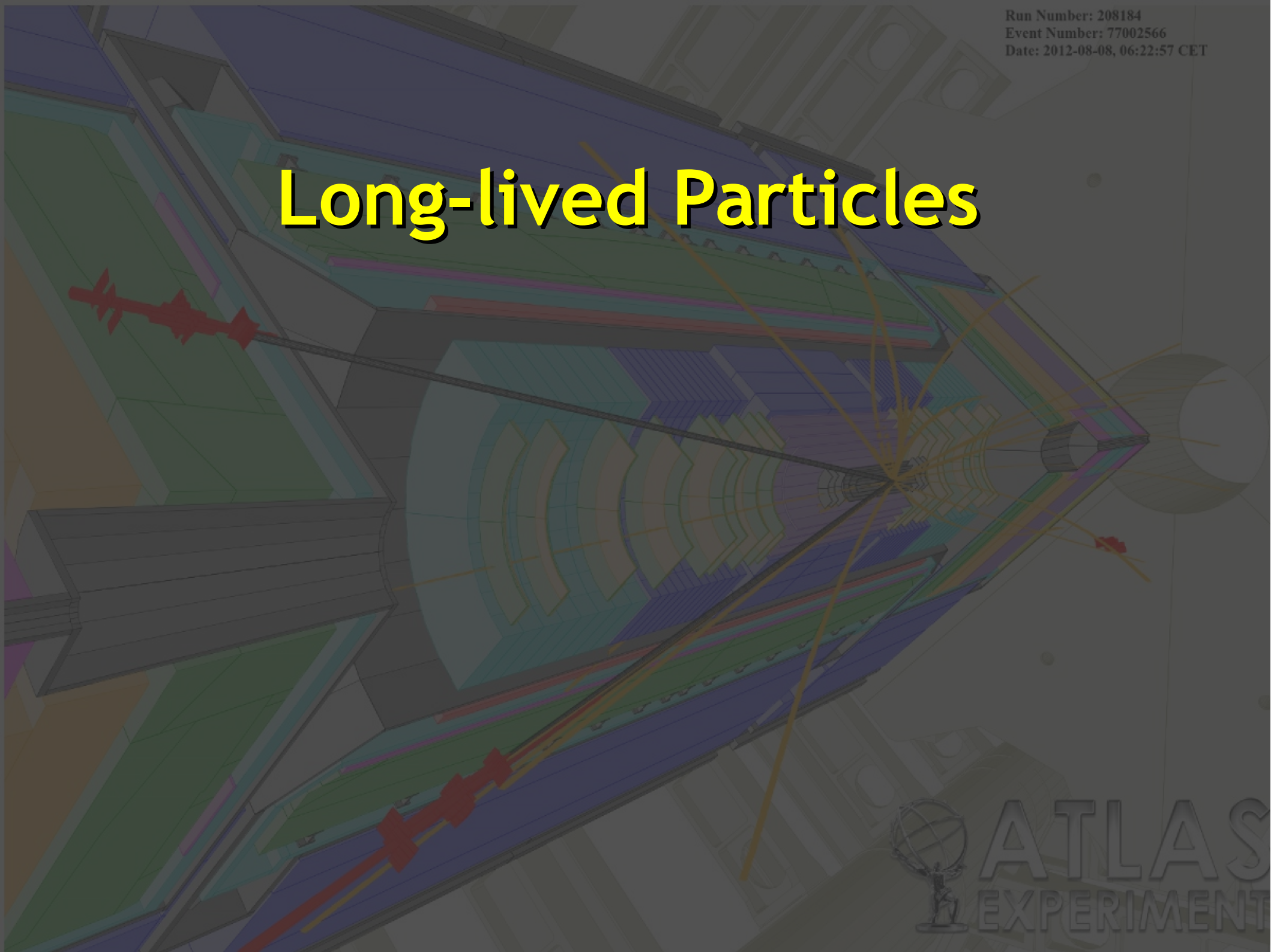
Vector-like quarks

Combining all channels analysed, CMS obtain lower mass limits of
m(T) > 690-782 GeV (95% CL)
m(B) > 520-785 GeV (95% CL)





Long-lived Particles



Long-lived particles

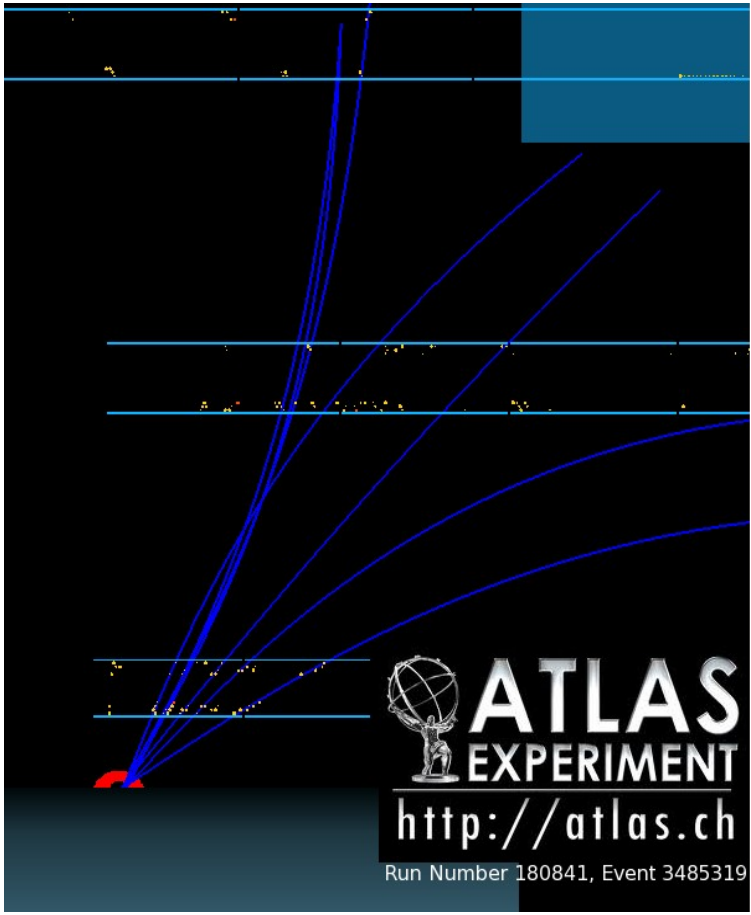
Several models predict massive long-lived particles

- Split, Gauge Mediated and R-parity violating SUSY
- "Hidden valley" models
  - e.g. H(125) may decay to a pair of particles with long lifetime

Signatures in detector can be very different

- Heavy highly-ionising charged particles which stop, or which travel right out
- Displaced vertices in the tracking detectors
- Displaced vertices further out (calorimeter, muons...)
- Out-of-time decays in the detector, unassociated with interactions

Challenging both to trigger on such events, and to reconstruct them

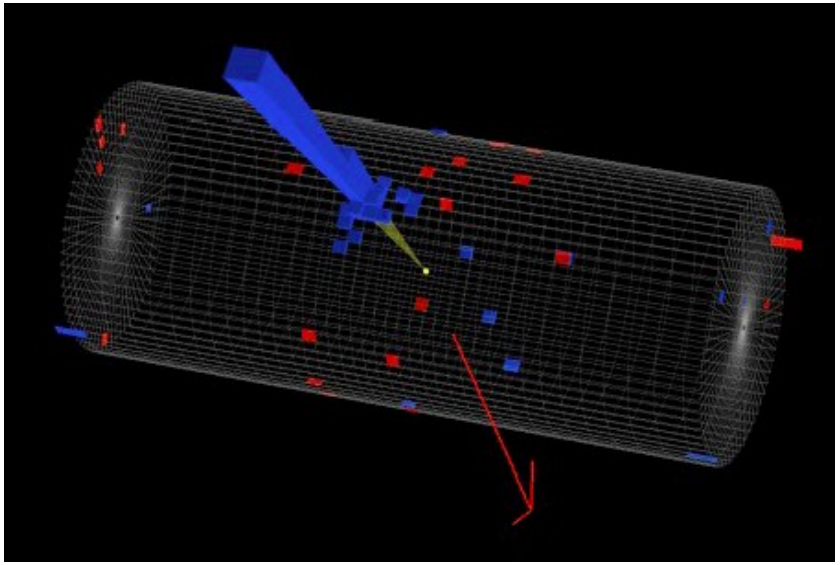


Reconstructed displaced vertex in data – apparent hadronic interaction at back of hadron calorimeter

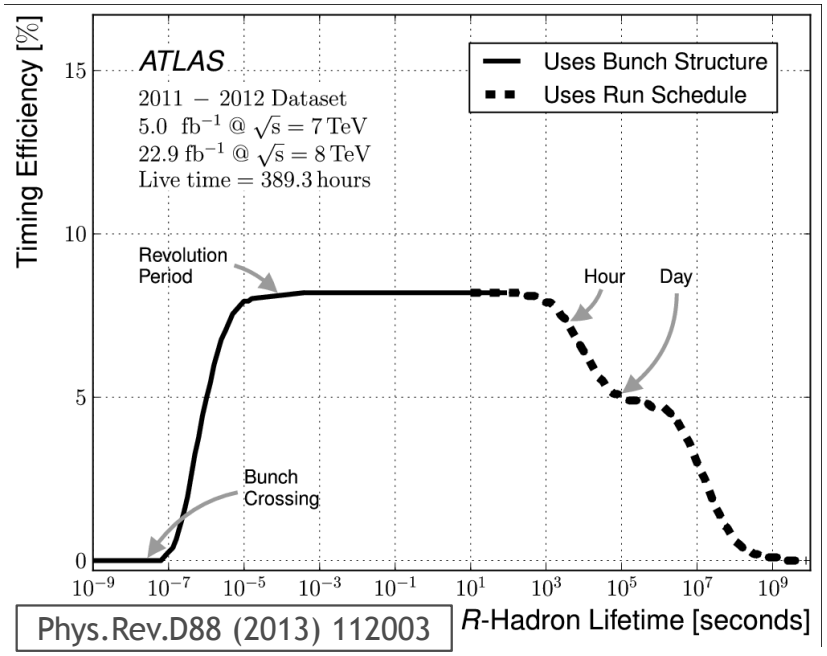
Stopped R-hadrons

Semi-stable massive particles (gluinos, squarks...) can hadronise, pass into detector and stop in calorimeter

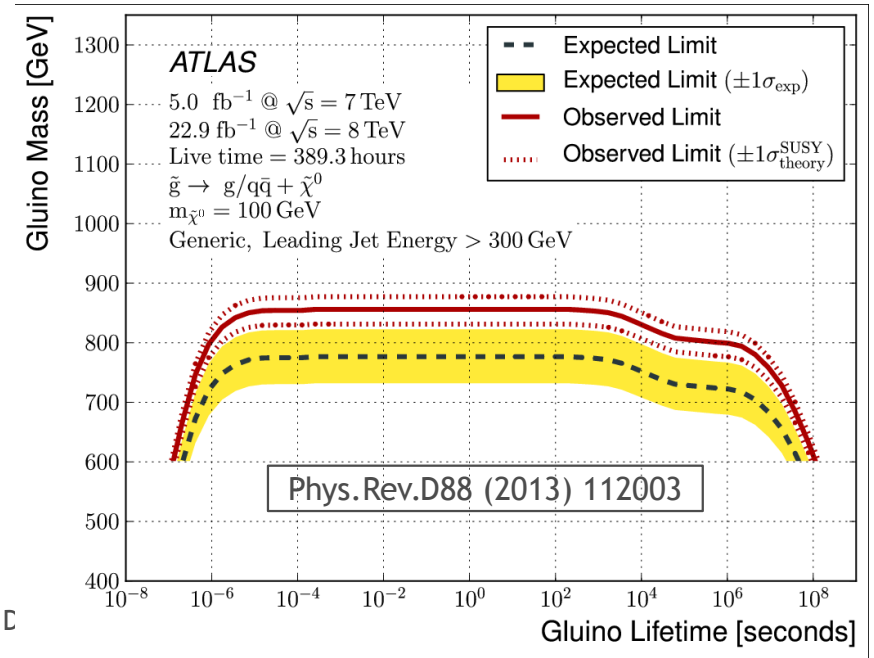
If lifetime > tens of ns, decay products seen in a different event!
Trigger on high energy deposit in empty bunch-crossings (no pp collisions)



Spectacular events!



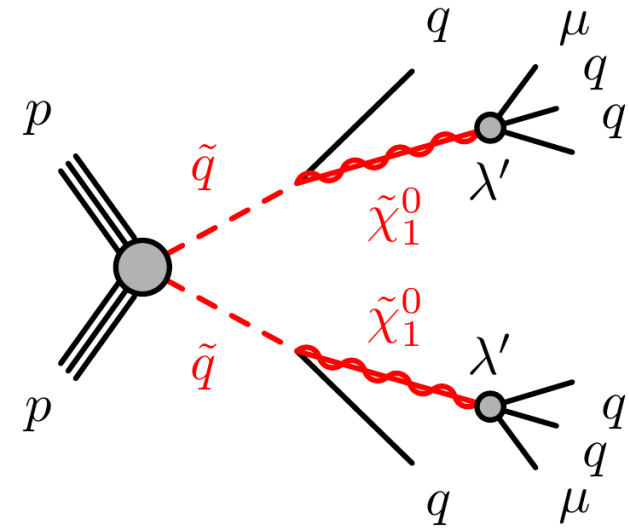
Backgrounds from cosmic rays and muons travelling along with the beam – can measure from early data (low luminosity)

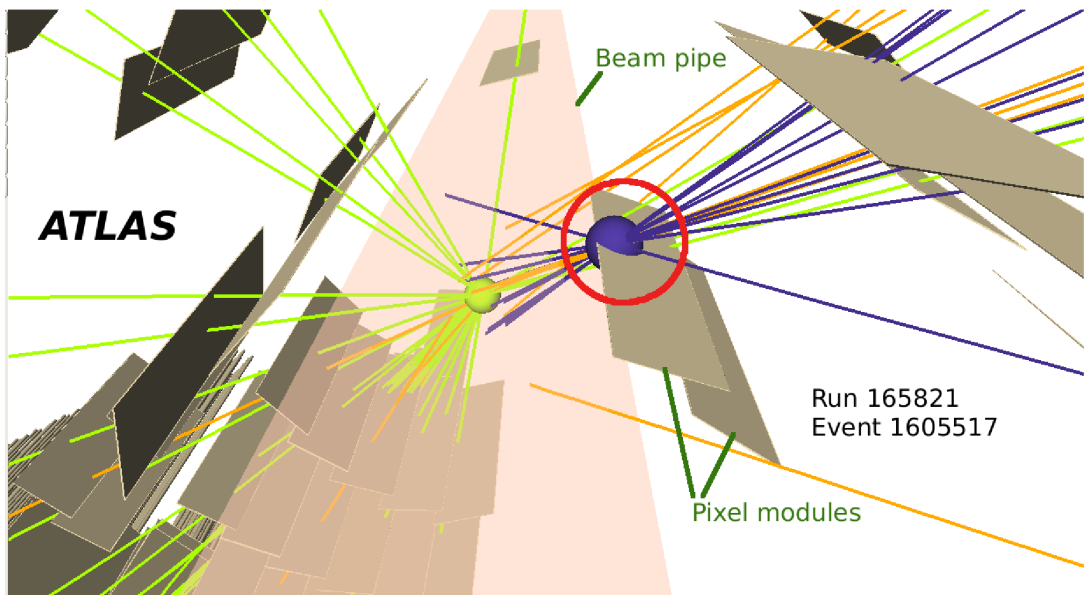


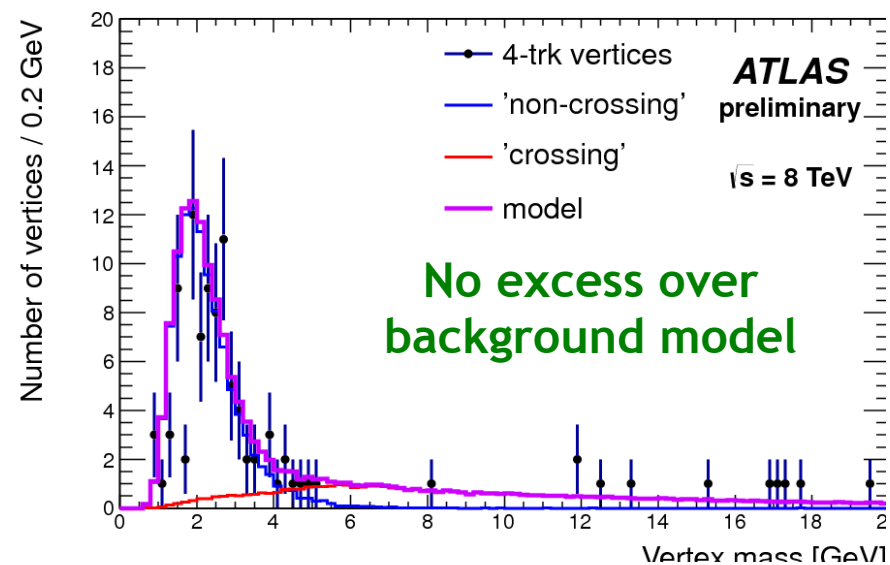
Displaced vertices in tracker

New massive particles with decay lengths of ~10-20 cm could be seen as displaced vertices in the tracking system

Special charged particle track reconstruction to recovers inefficiencies of standard tracking for particles produced far from the beam-line

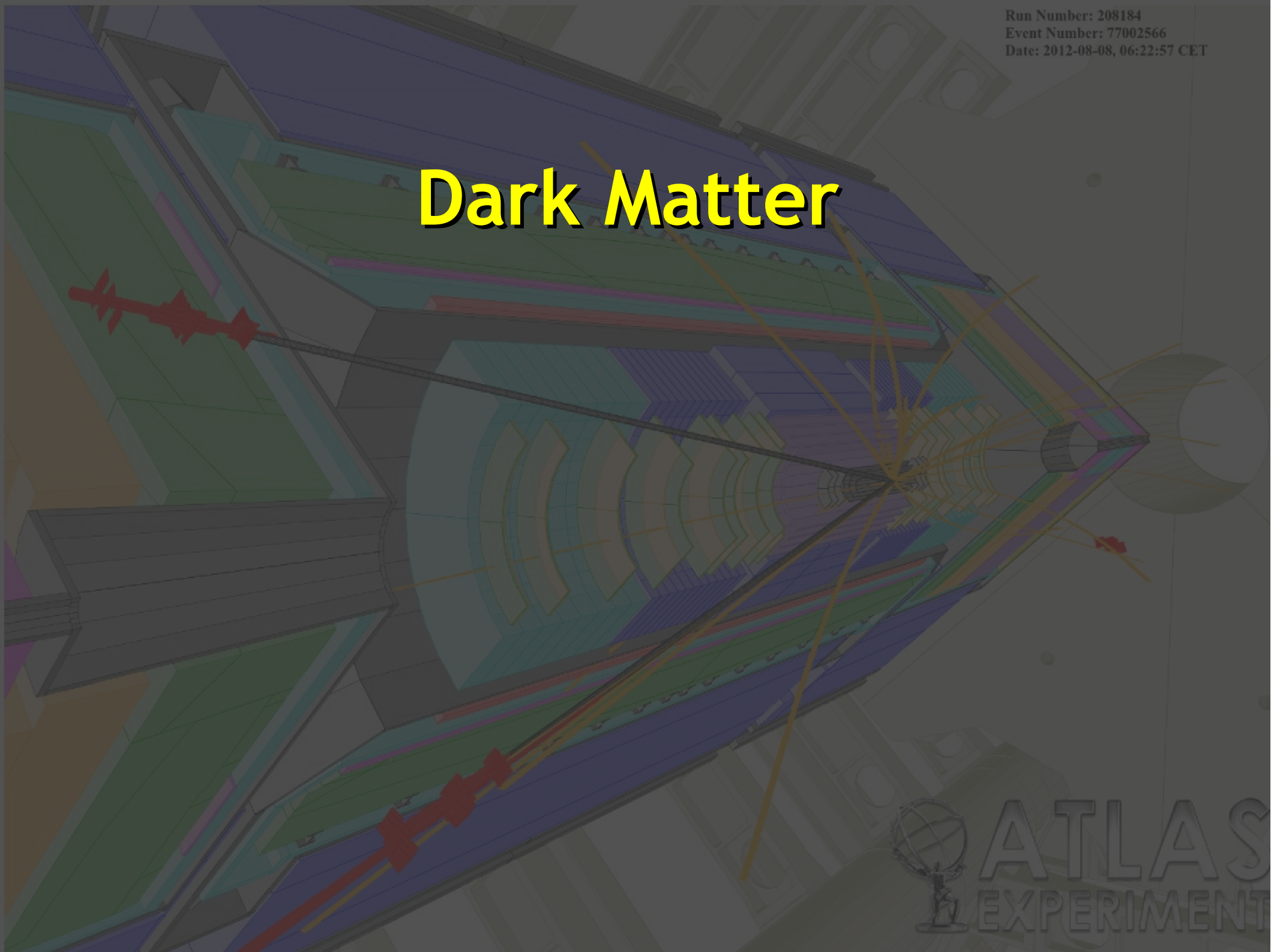






Invariant mass of particles coming from displaced vertex

Dark Matter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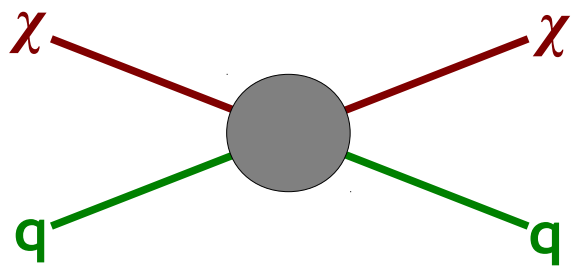
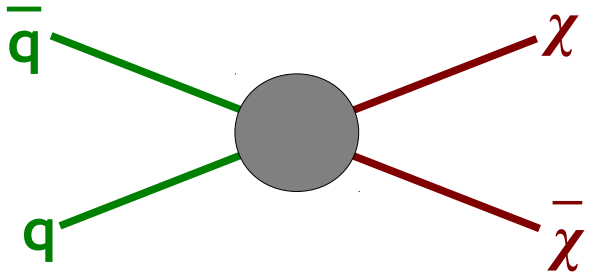
Date: 2012-08-08, 06:22:57 CET
ATLAS
EXPERIMENT

Dark Matter pair-production

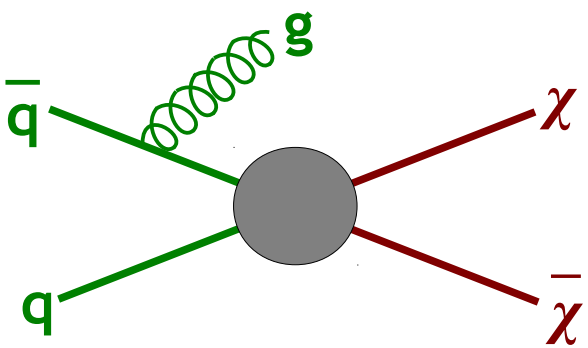
Traditional searches for dark matter interactions in matter - scattering of DM particles (χ) off nuclei

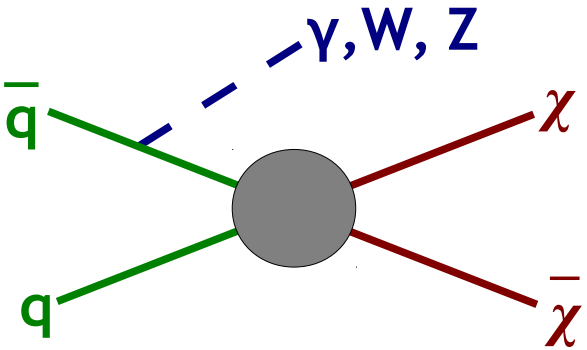


Crossed diagram at the LHC → pair-production of DM particles, gives *missing* transverse momentum (E_T^{miss})



To observe (trigger on) such events, we need additional activity, e.g. from initial-state radiation of a gluon, photon, W or Z particle



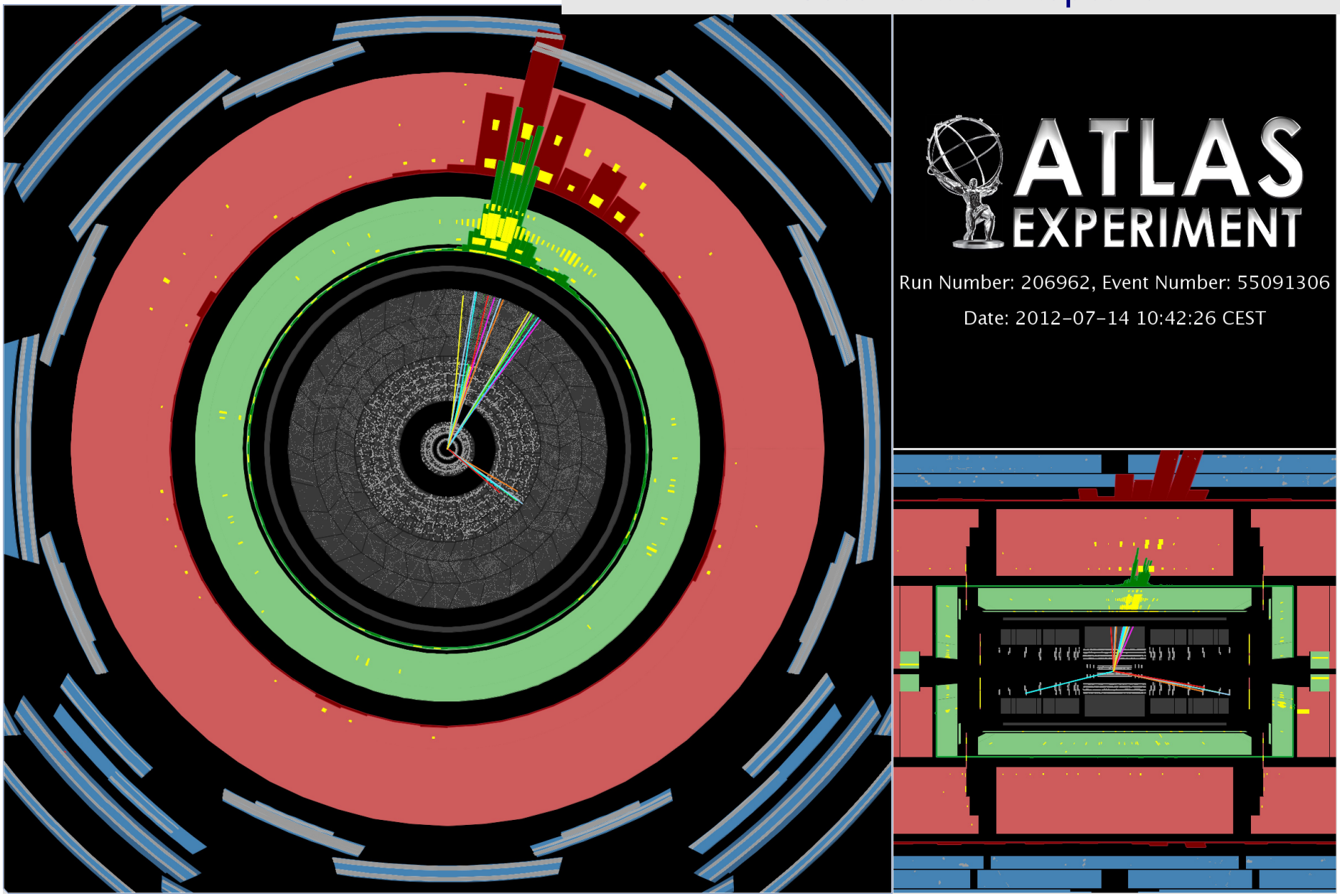


Mono-jet search

Leading jet p_T > ~120 GeV, high E_T^{miss}

Cuts on further jets - reduces QCD background

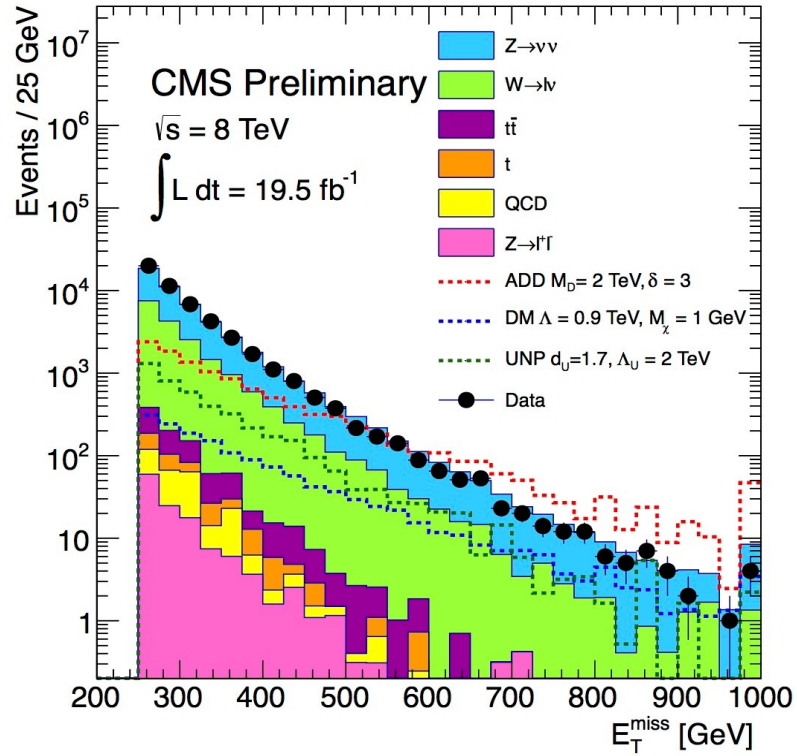
Veto isolated leptons

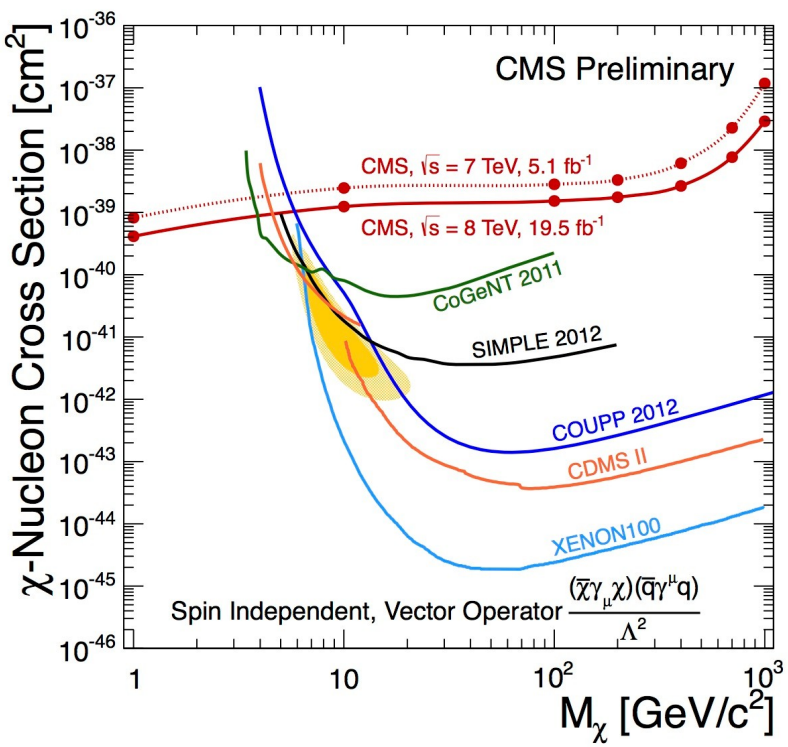


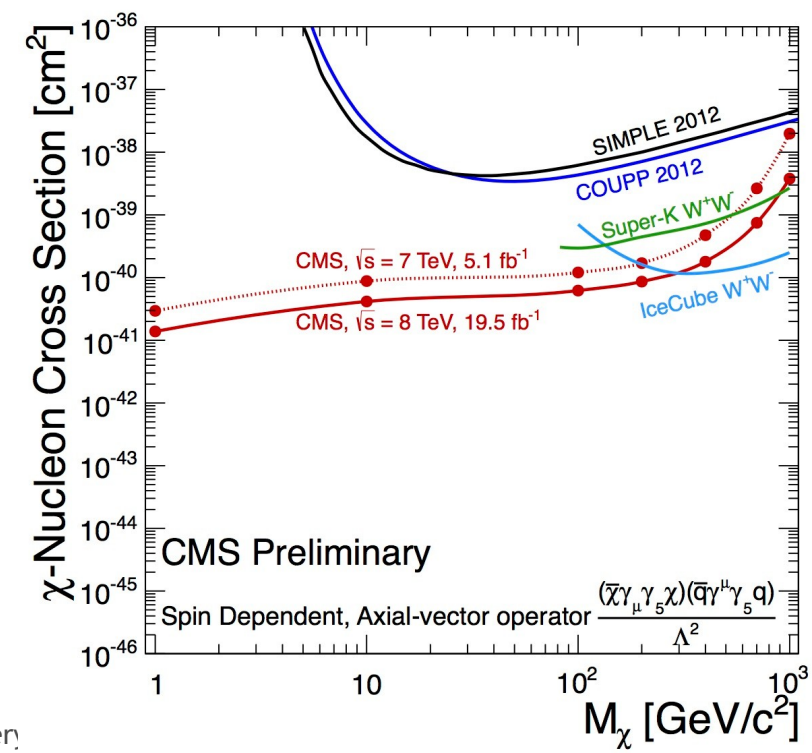
Mono-jet search

Dominant SM background from Z→νν+jet normalised using control regions in data (Z→ℓℓ+jet)

No excess above SM expectation → place limits on $\chi\chi$ production, and reinterpret in terms of χN cross-sections







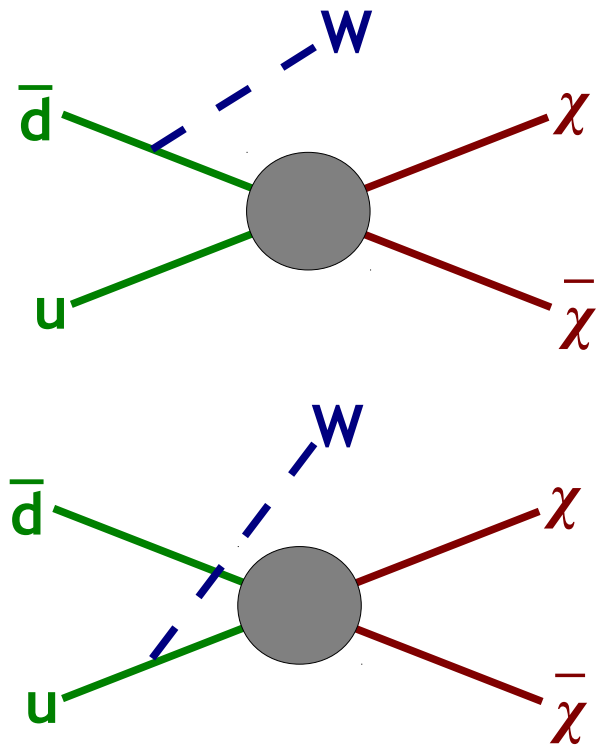
W + $\chi\chi$ production

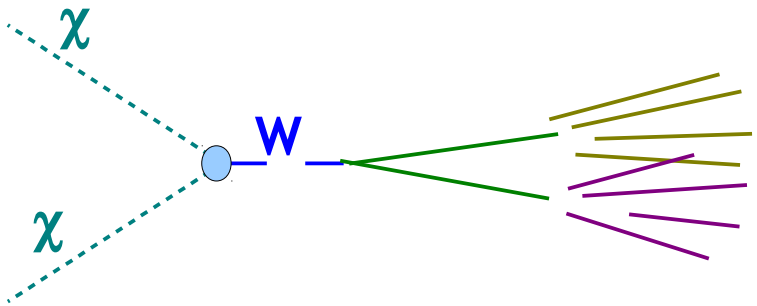
In the case of DM pair-production in association with a W, interference effects are important

Two diagrams interfere – relative sign of uu$\chi\chi$ and dd$\chi\chi$ coupling enters

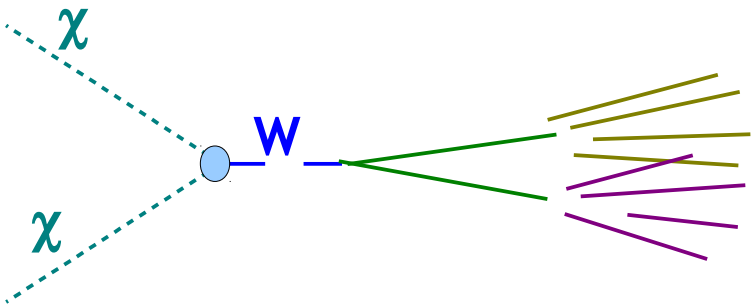
Two channels analysed

- "Monolepton" channel where W → ℓν (CMS)
- "Fat jet" channel where W → q$\bar{q}'$ (ATLAS)

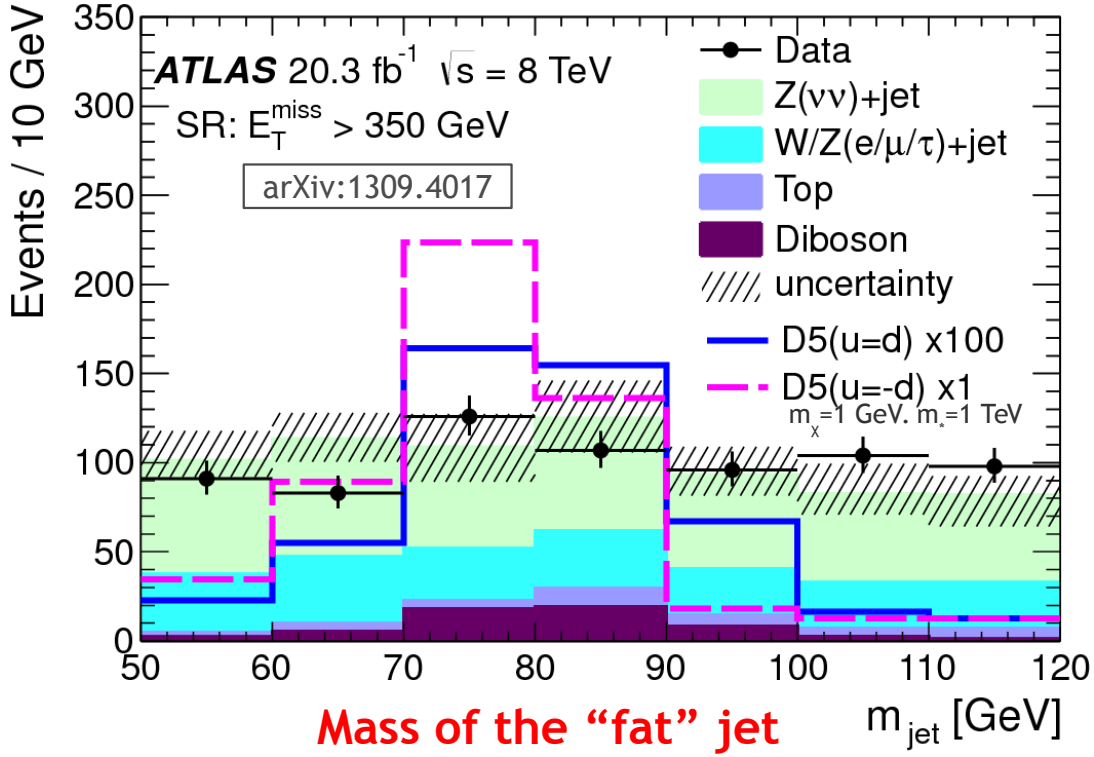


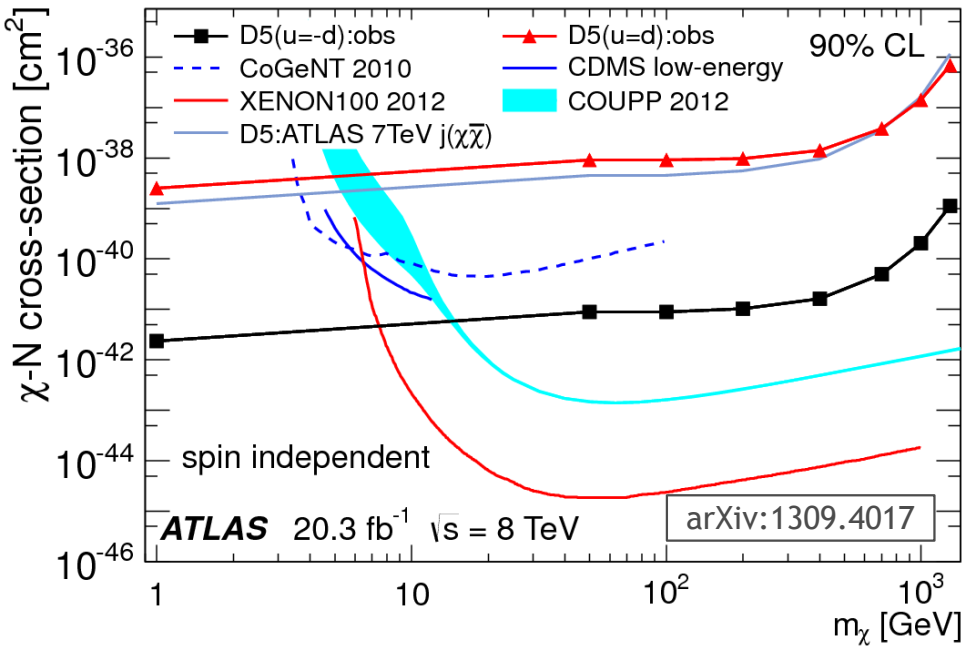


$W(\rightarrow q\bar{q})$ + $\chi\chi$ production

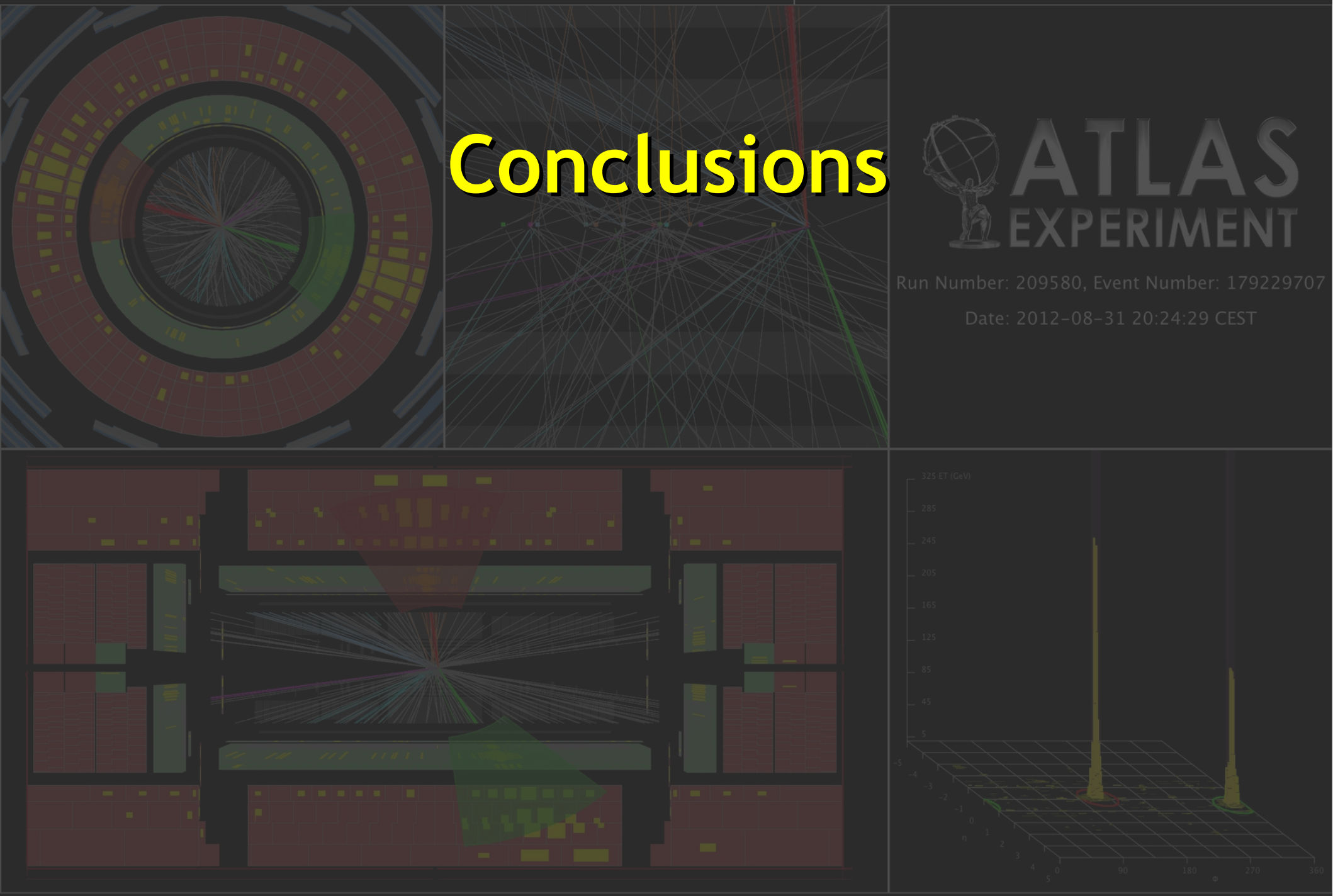


Monojet signature with a "fat jet" which could be from a W or Z decay



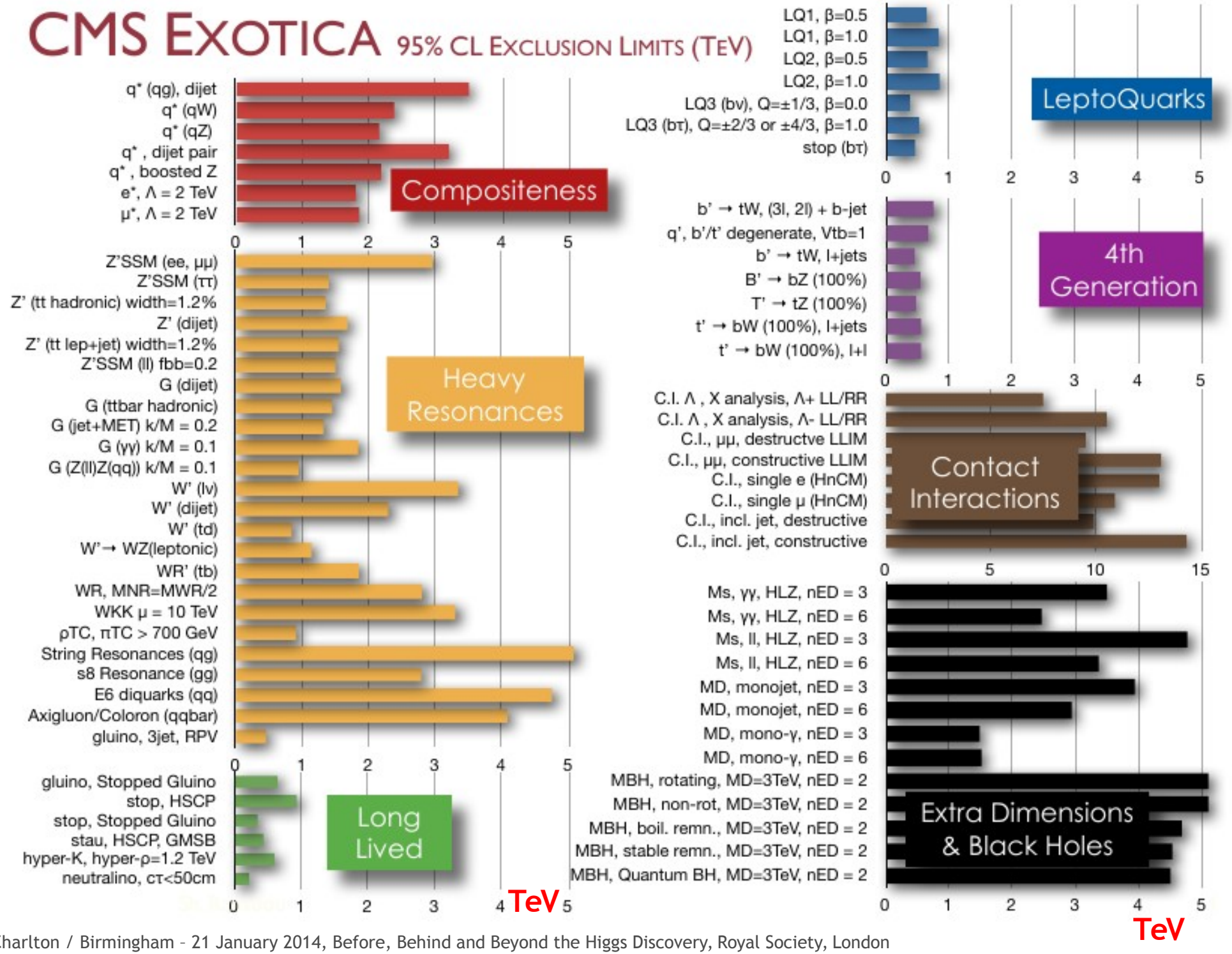


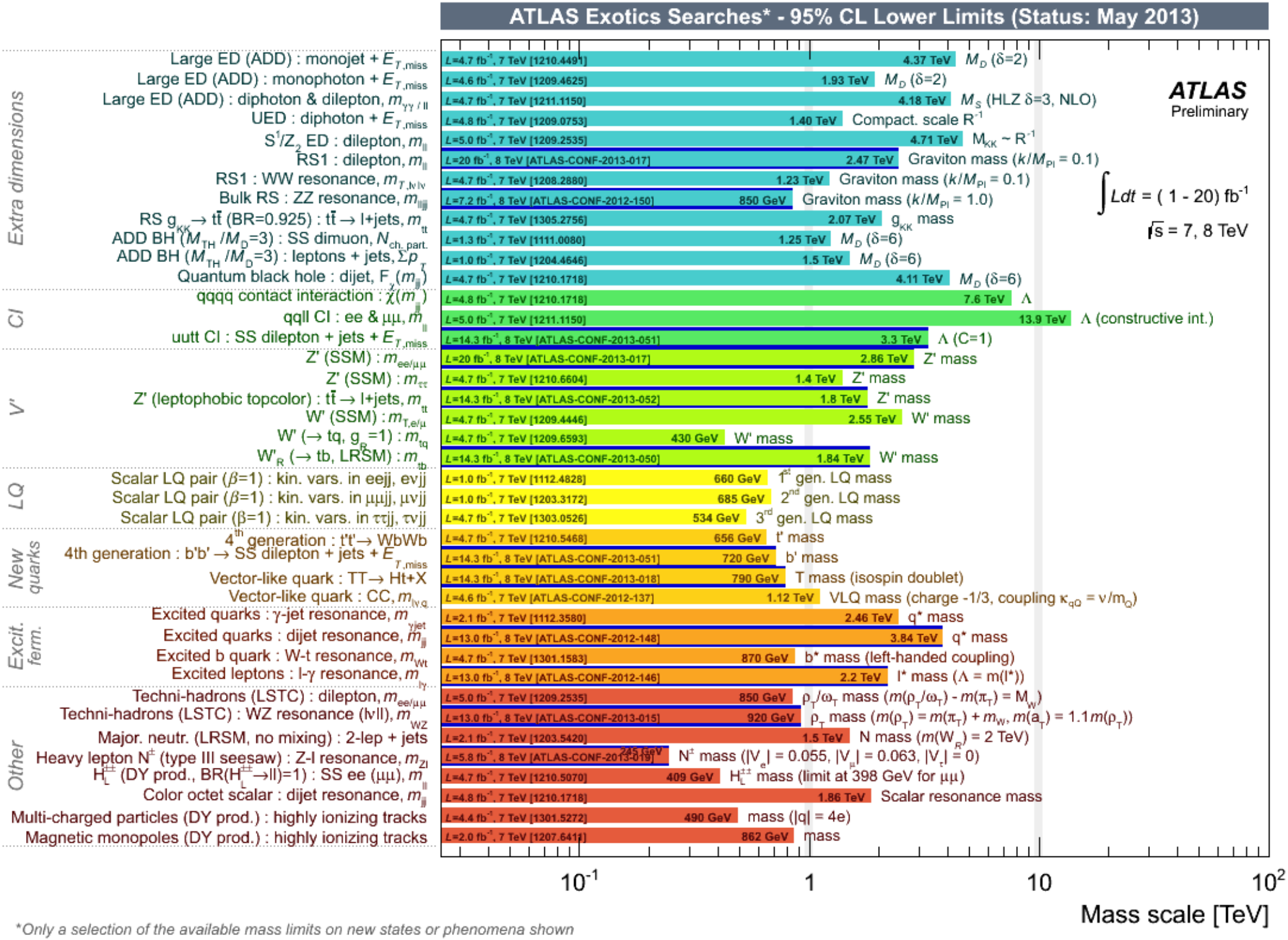
The highest-mass central dijet event. The two central high-p_T jets have an invariant mass of 4.69 TeV



Conclusions

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)





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

Conclusions

The discovery of the Higgs boson at 125 GeV, with close-to-SM properties, has energised, and helped re-focus, searches beyond the Standard Model

A huge wealth of event signatures has been explored – but, as yet, no sustained hints of new physics beyond the Standard Model

The increase of centre-of-mass energy to 13-14 TeV in 2015 and beyond will double the mass reach, well into the TeV region

Thanks to Steven Worm and Paris Sphicas