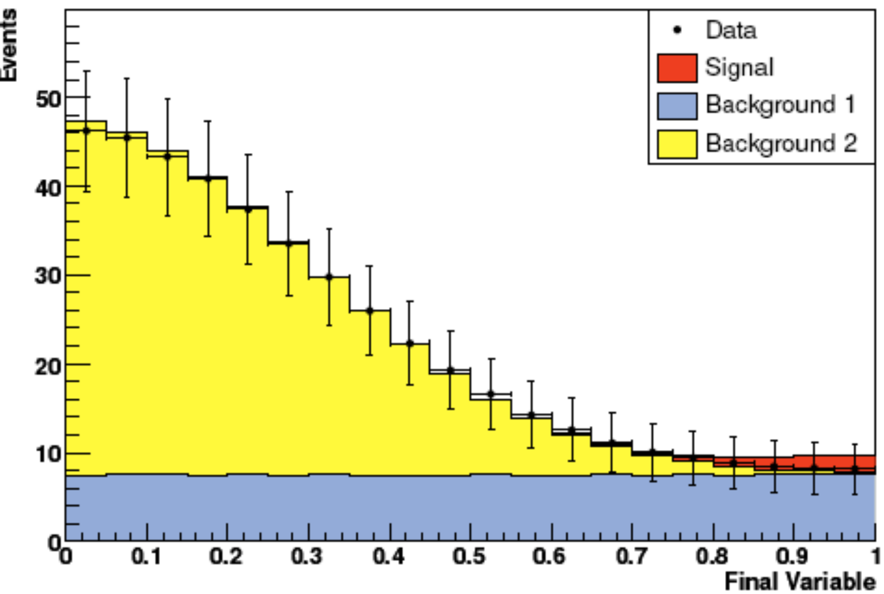
Systematics Profiling

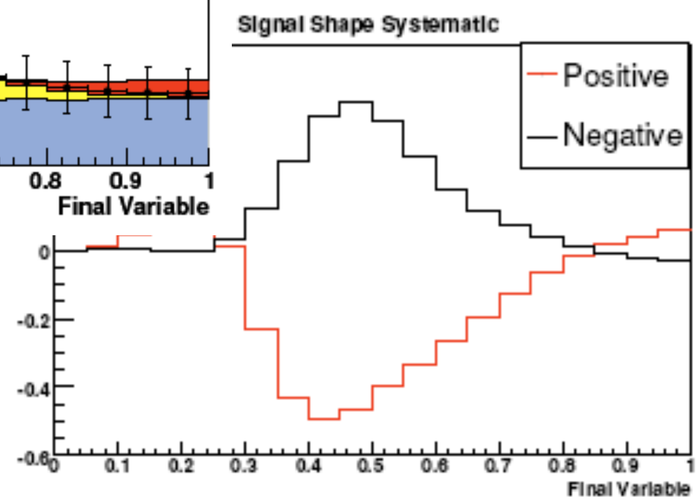
- Systematic uncertainties are propagated through the full analysis chain to the discriminating distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet/lepton/photon reconstruction efficiency, energy scale and resolution, p_T distributions, background models), others only normalization (lepton reconstruction efficiencies and momentum calibration, background normalizations, theoretical cross-sections and luminosity)
  - Systematic uncertainties are treated as nuisance parameters when fitting signal+background to the data
    - I.e. modify signal and background shape
    - Can be fixed, or allowed to change

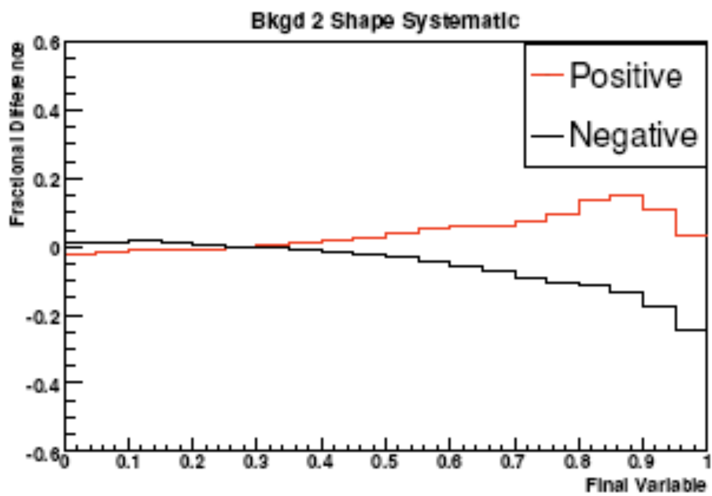
Systematics Profiling

- ❖ Nuisance parameters tend to be correlated, but not 100%, among backgrounds
  - Can affect rates, shapes, or both (in any distribution), and often asymmetric and non-gaussian

Toy Example (W. Fisher)



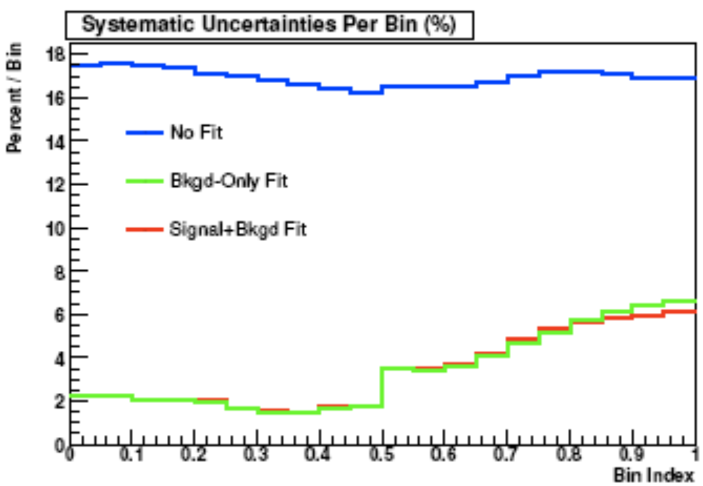




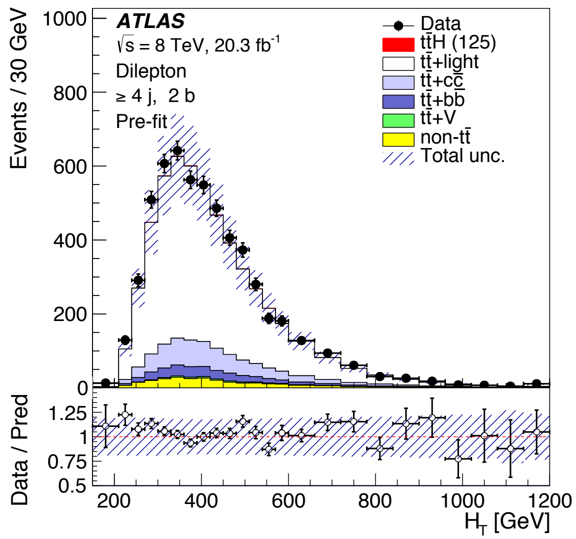
- Generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
  - Variations in background (& S+B) prediction
    - Compare results to data using log-likelihood ratio
- We can maximize likelihood ratio as a function of nuisance parameters → constrain them
  - I.e. use full shape of distribution(s) to see which background uncertainties are over/underestimated
    - Of course limited to size of statistical fluctuations
  - Can remove bins with large S/B if needed
    - Mostly important if uncertainties lead to similar shape distortions
  - Want enough background-rich phase space in fit!
    - Even include control regions

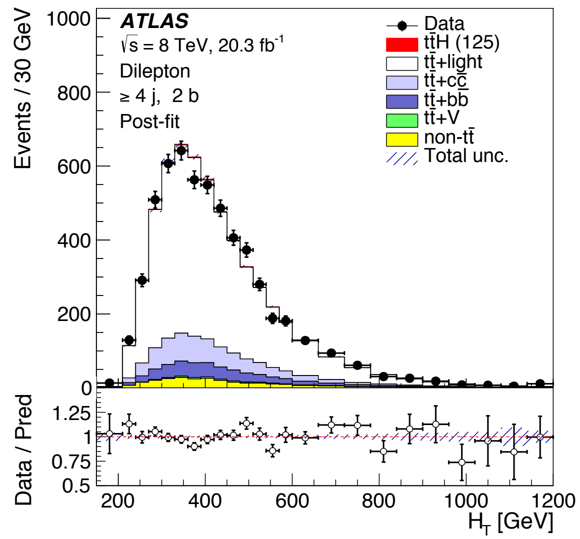
❖ Test example:

- Data constructed to disagree with background-only hypothesis (wrong estimates for background uncertainties)
- But to agree with background-only better than signal+ background
    - Improvement quite spectacular (by construction in example)



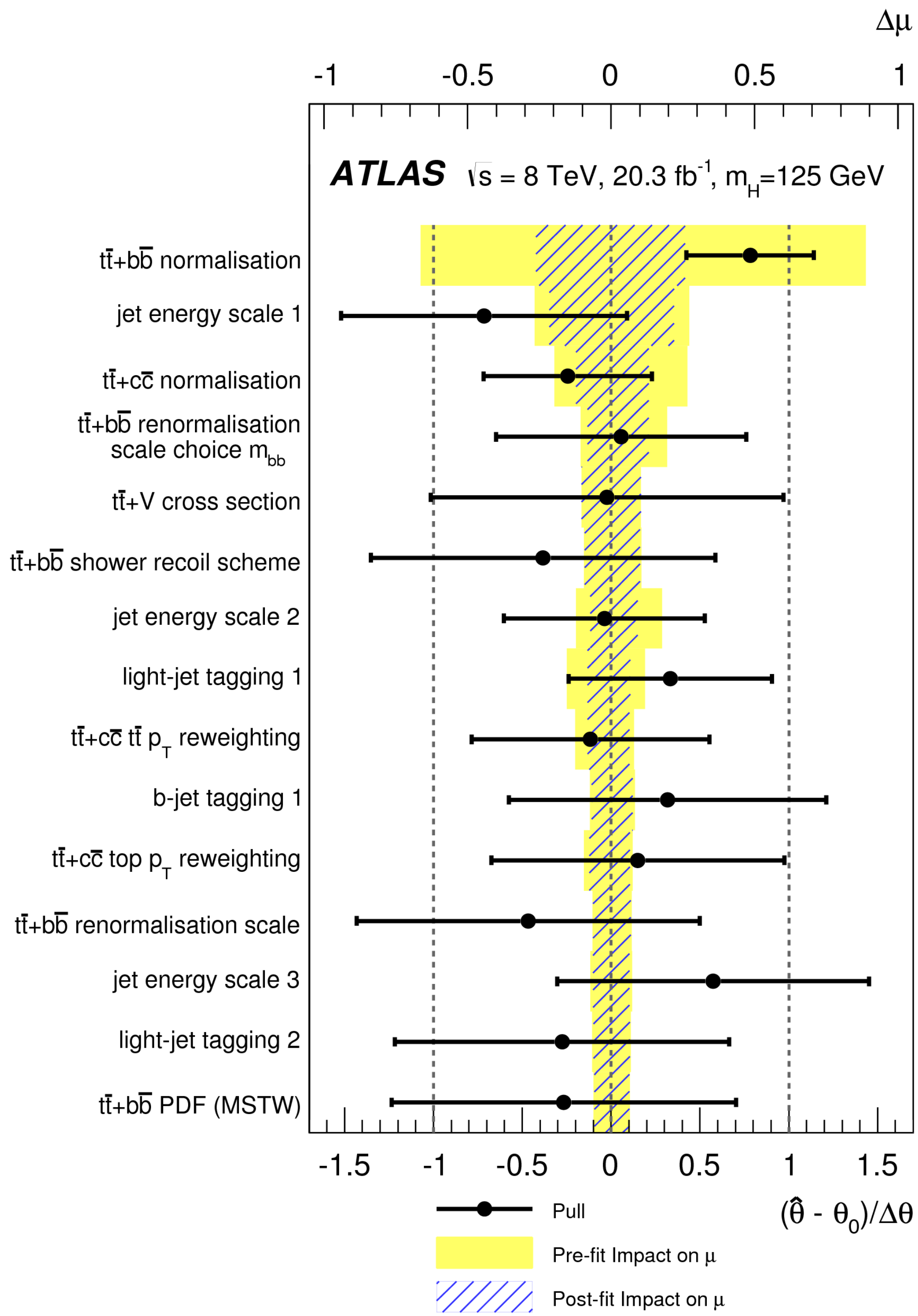
ATLAS ttH search: arXiv:1503.05066





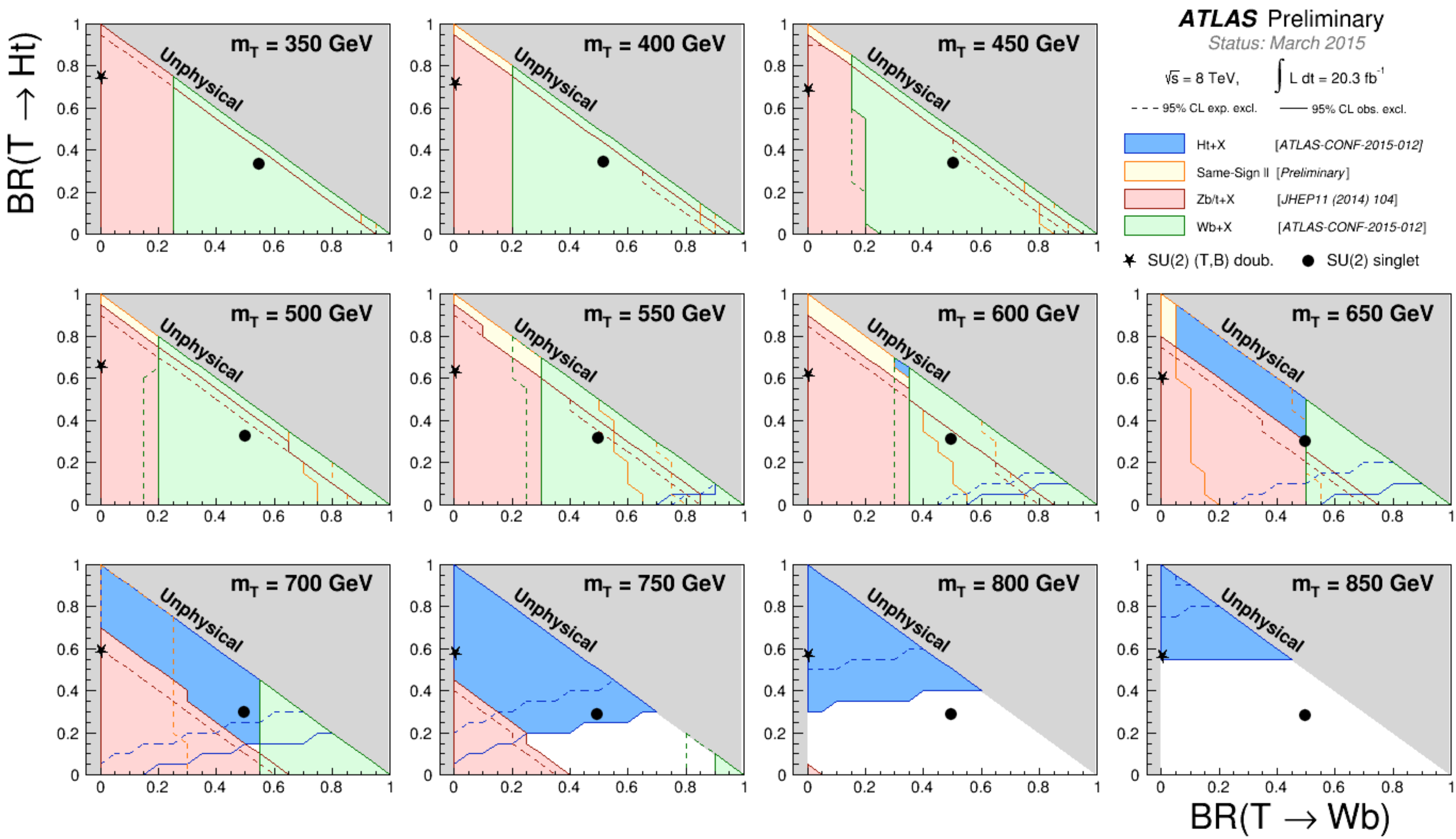
Fit Results

- ❖ Need to compare starting point and results
  - Pathologies due to lack of MC stats in some areas, strong correlations, …
- ❖ Crucial to design analysis with good control regions the fit can use to address least understood systematics

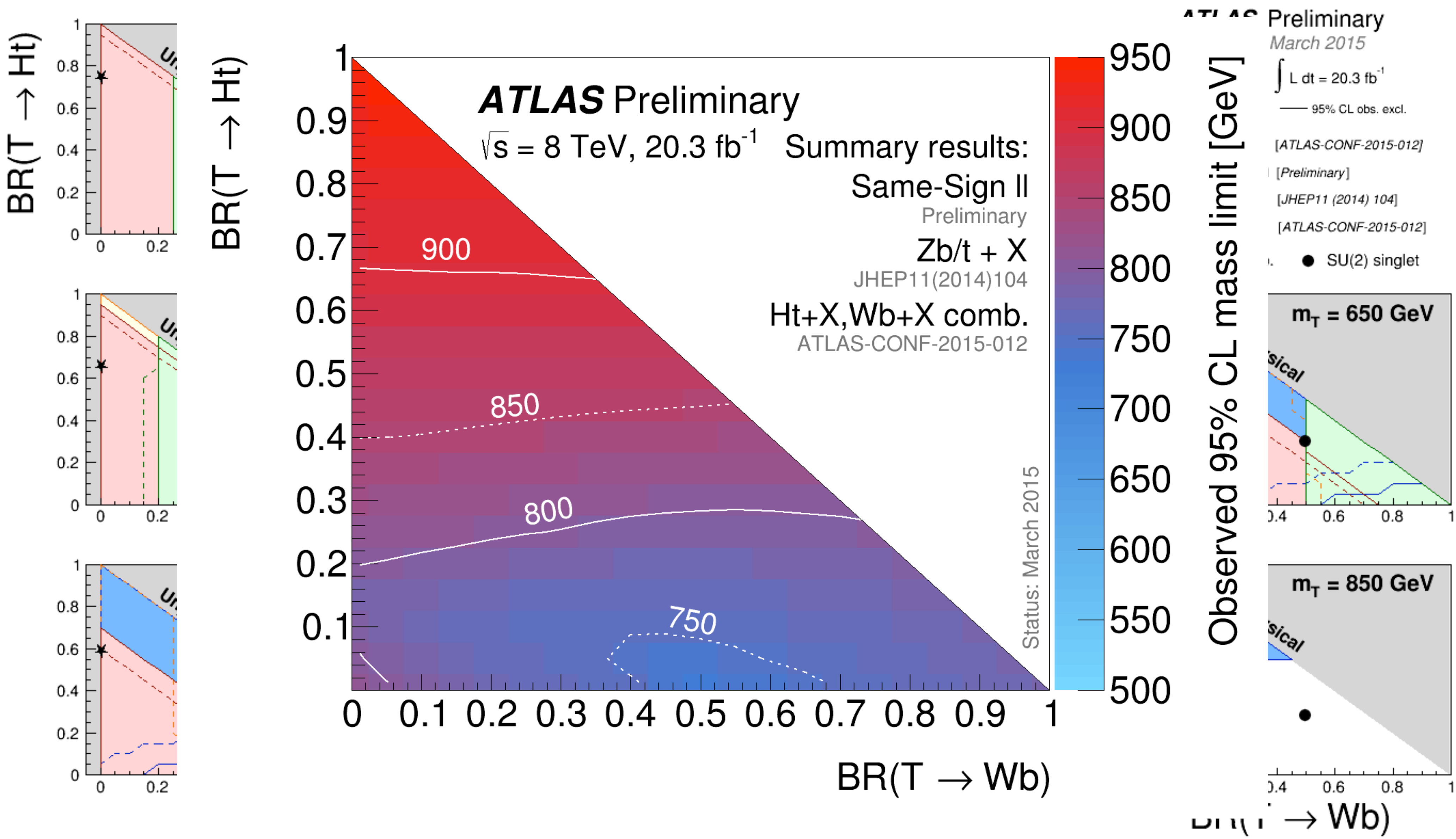


ATLAS ttH search: arXiv:1503.05066

All Together Now



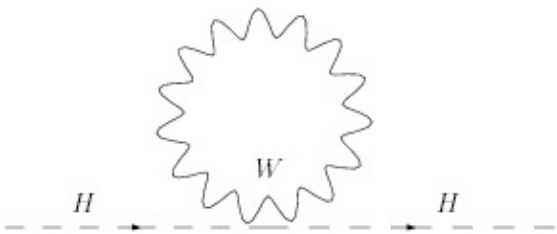
Presented Differently



Parity

V-A is The Problem!

- Violation of parity in weak interactions is The Problem
  - What, really, *is* (weak iso)spin?
- What if the fermion mass scale ~ parity restoration scale? (and the Higgs mass flows from that)
  - Can we then, as a next step, hope to understand relative fermion masses?
  - BTW, did you notice that inside a generation, the more a fermion interacts the heavier it is?
    - "Eek!" said the Higgs!
- And even the Higgs wants W/Z partners!



$$\rightarrow \frac{1}{16\pi^2} g^2 E^2$$

Parity Restoration: Signals

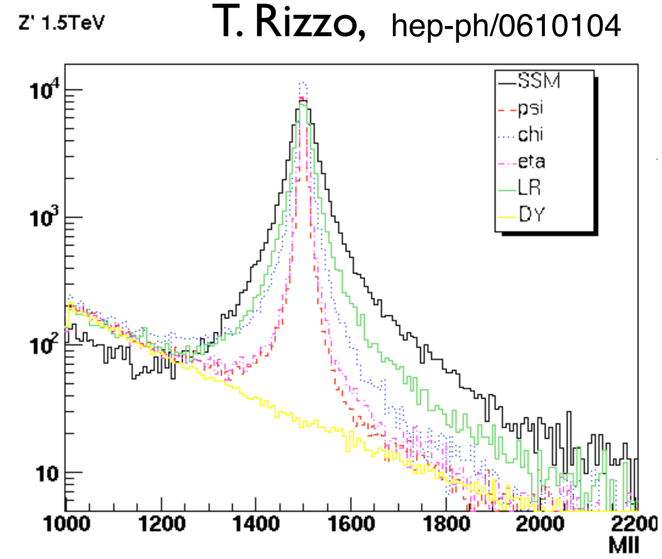
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances (Z') offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p_T
  - $t\bar{t}$ decays visible
  - ν_R is presumably heavy, W' may not decay to leptons
    - Only dijet or diboson
    - If ν_R lighter than W'/Z', ν_R decays become important
- Note: many kinds of Z' - review by Langacker
  - W'/Z' would also require new fermions…

arXiv:0801.1345

Z' Production and Decay

- Production from u, d quarks is dominant at LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\kappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes ν_R heavier

T. Rizzo, hep-ph/0610104



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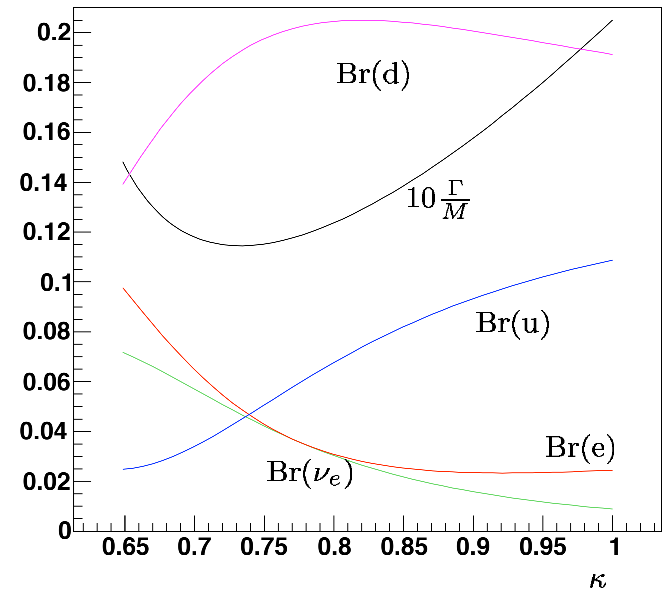
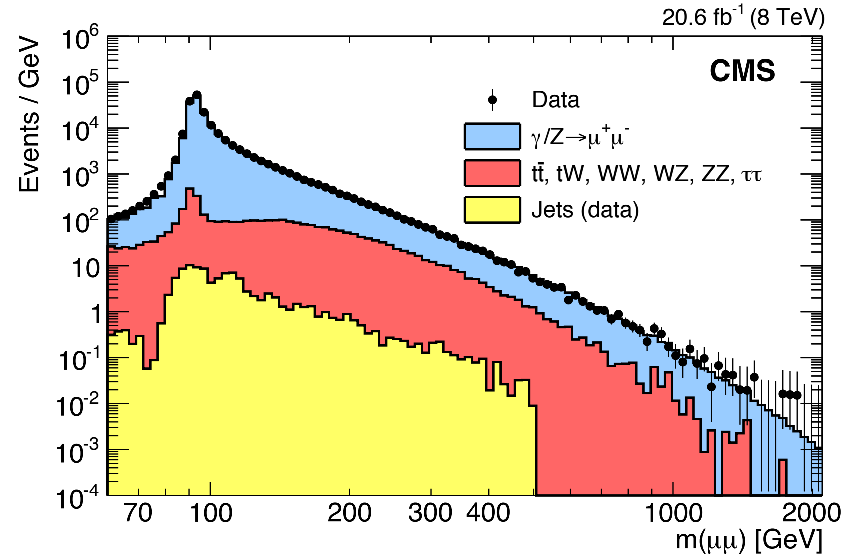


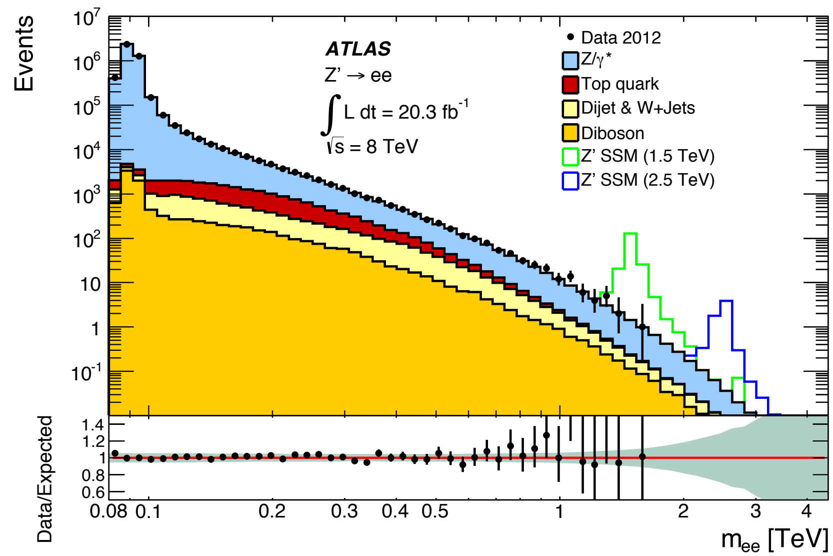
Z' → ee/μμ

- Most promising channels:
  - Backgrounds very low!
  - "Self-calibrating"
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- LHC extended Tevatron reach immediately!

CMS, J. High Energy Phys. 04 (2015) 025



ATLAS, Phys. Rev. D. 90, 052005 (2014)



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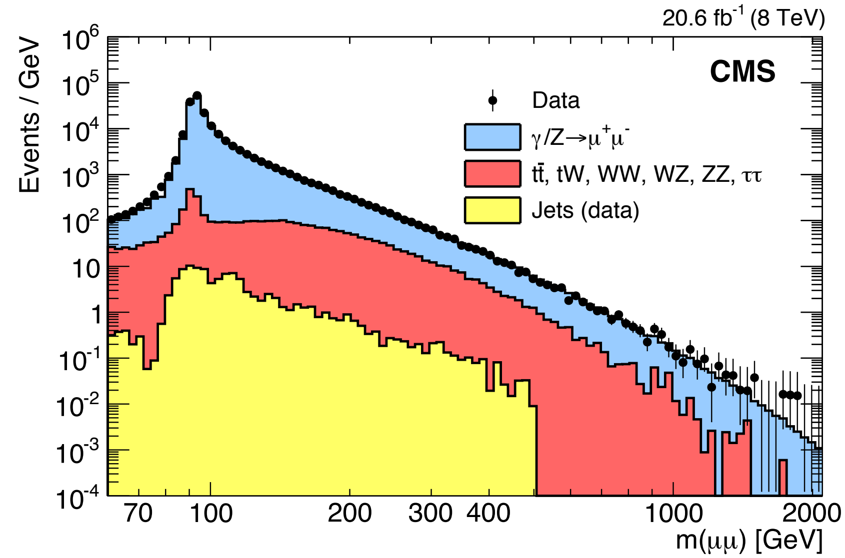

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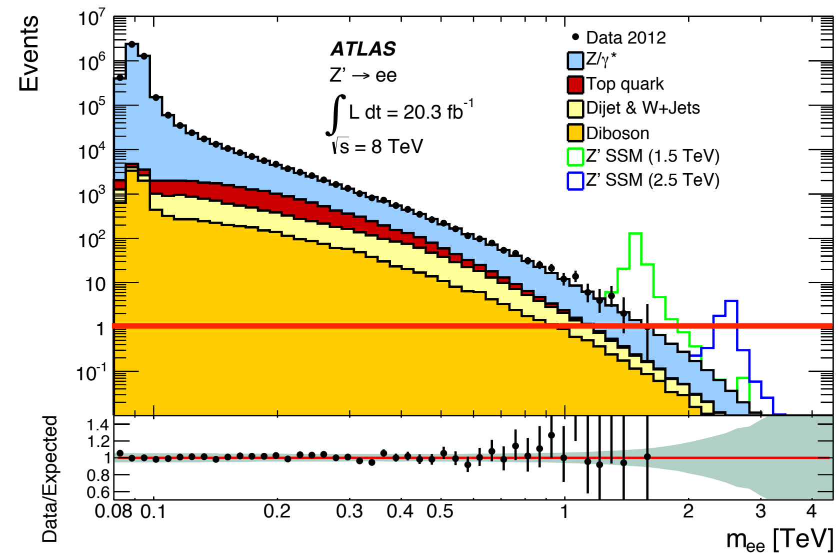

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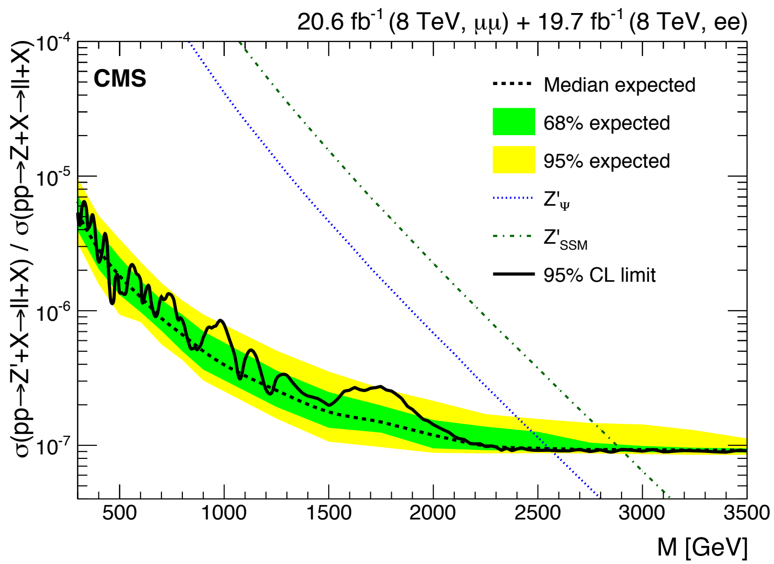
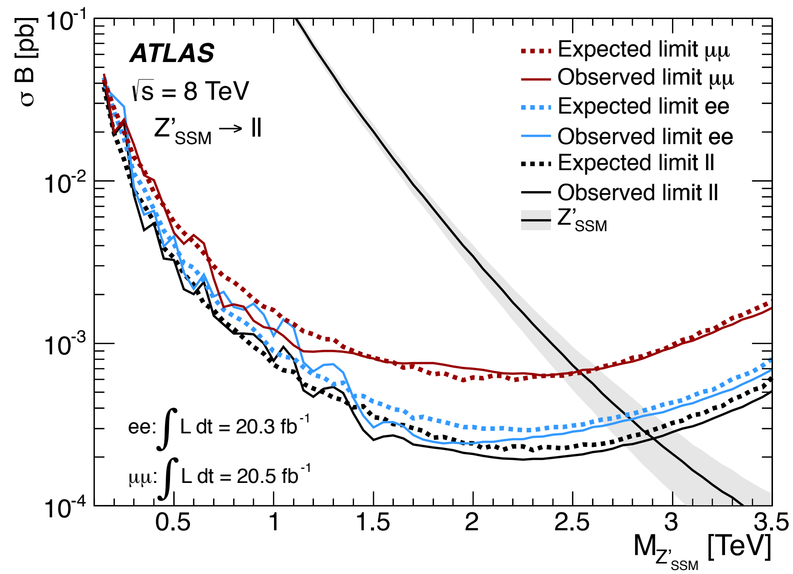


ATLAS, Phys. Rev. D. 90, 052005 (2014)



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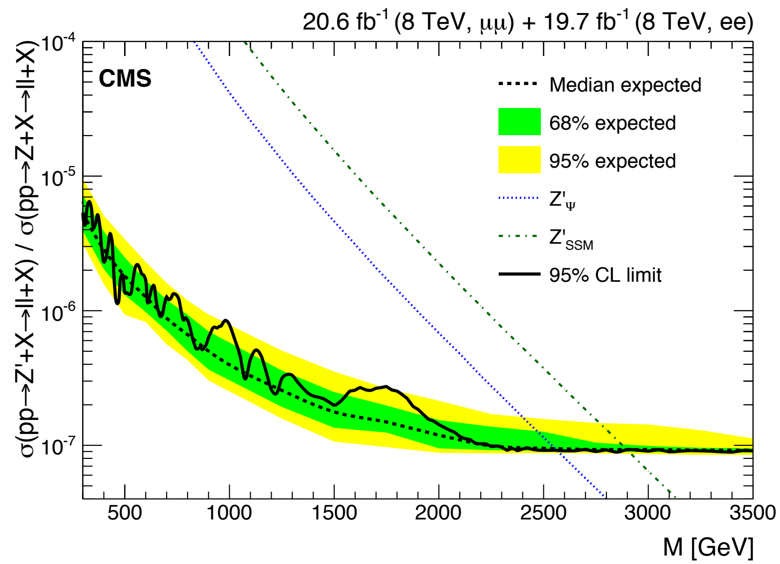
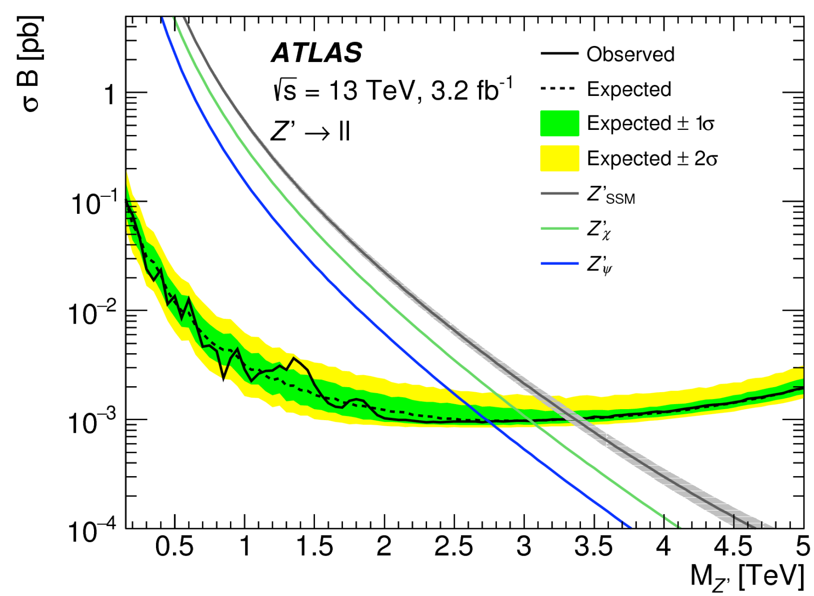


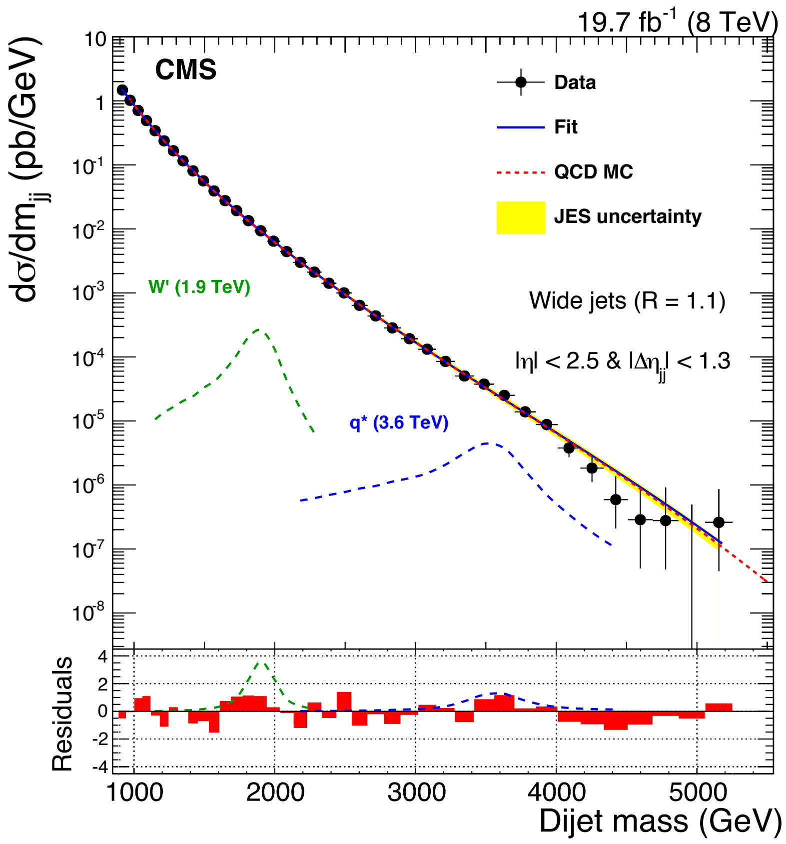
ATLAS, arXiv:1607.03669



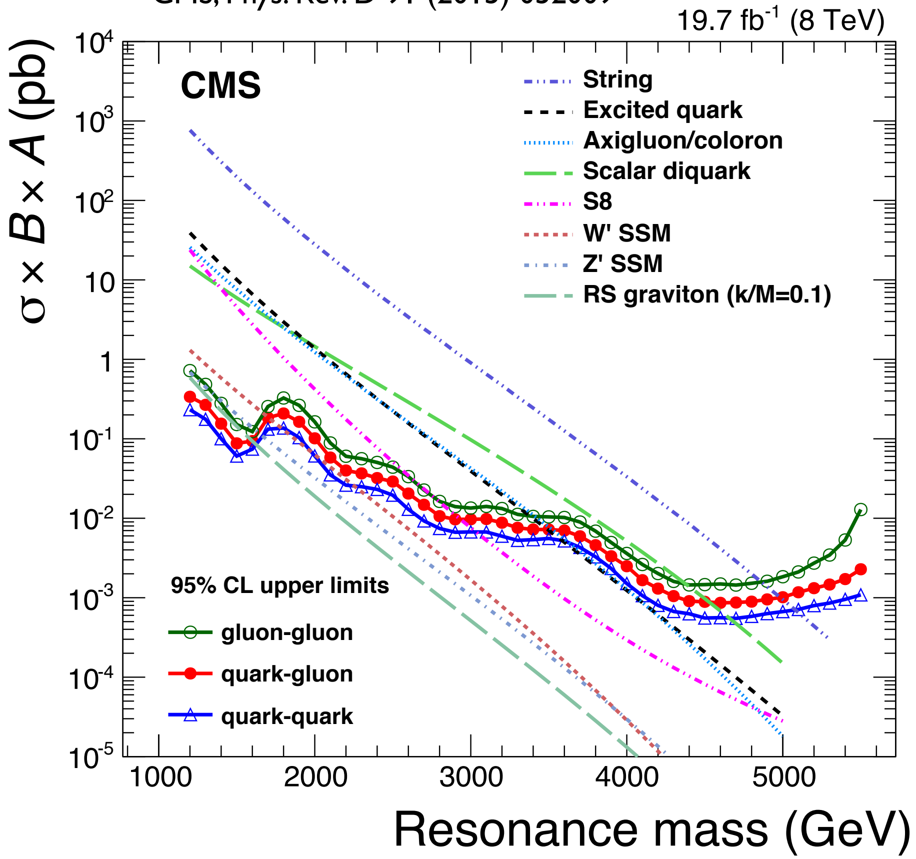
Dijets

❖ SM Background obviously much larger

- But single source
- And opens the door to strongly interacting objects



CMS, Phys. Rev. D 91 (2015) 052009



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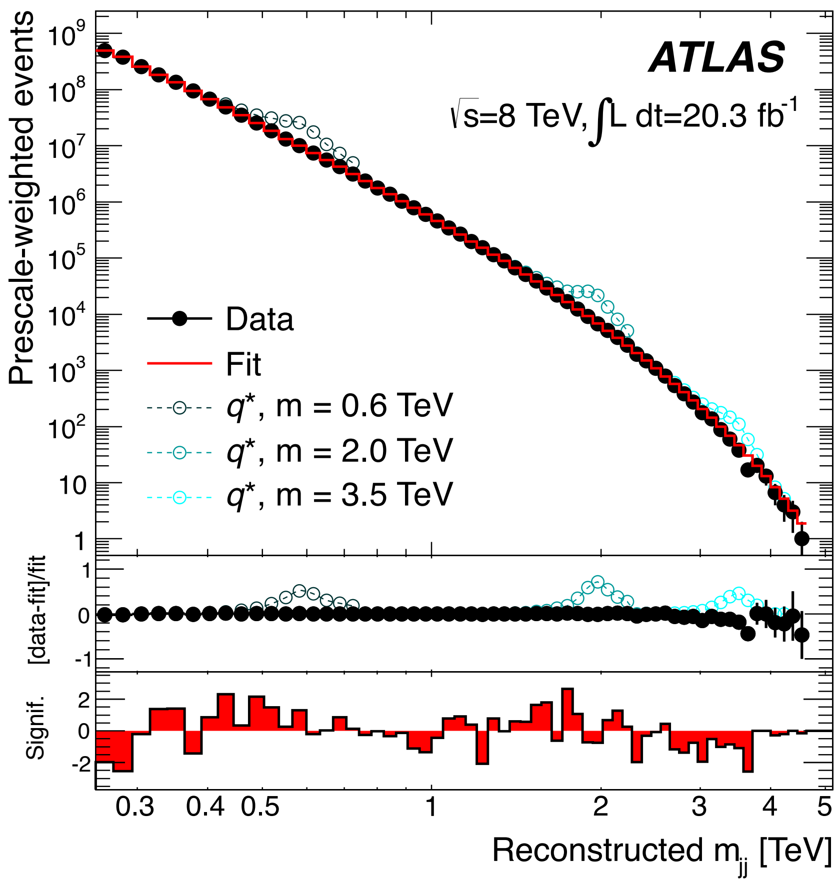
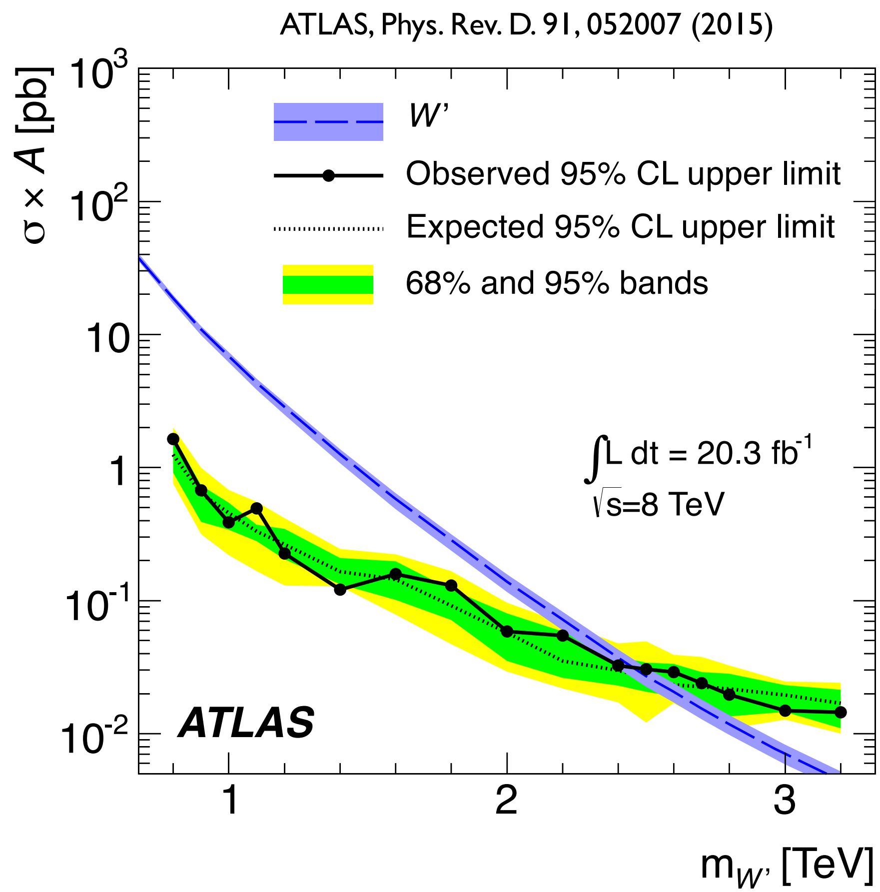
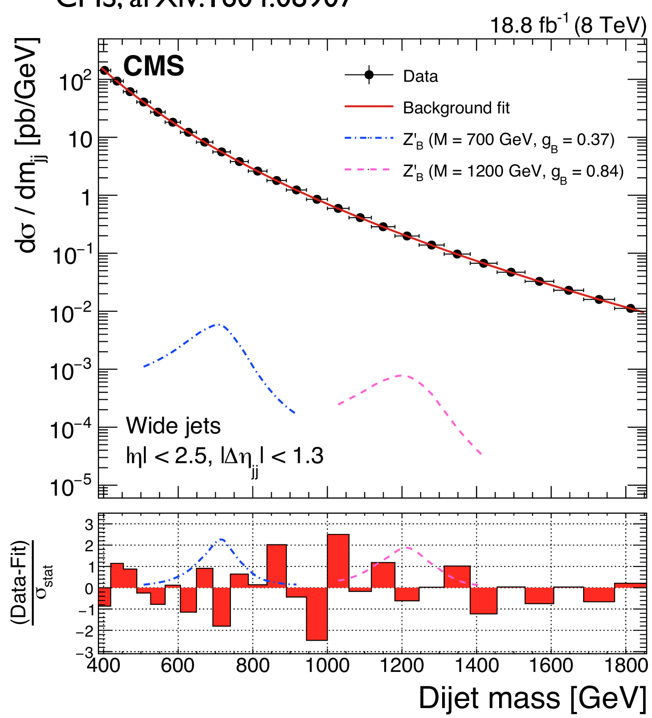




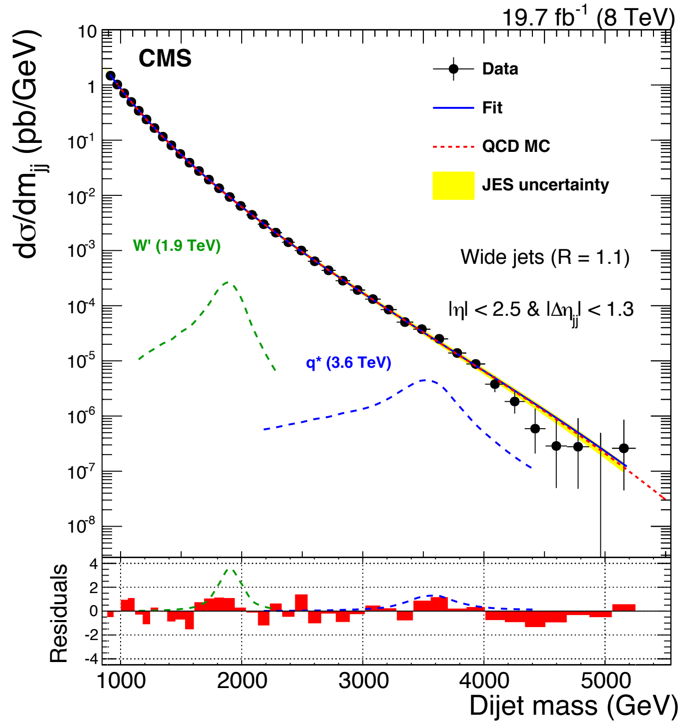
Scouting

- ❖ Dijet resonances at moderate masses are tough
  - Unprescaled single jet trigger thresholds now > 400 GeV
    - Below m = 1 TeV no sensitivity!
- ❖ Both experiments now implement "data scouting"
  - Only keep jet information in high level trigger to make events small

CMS, arXiv:1604.08907



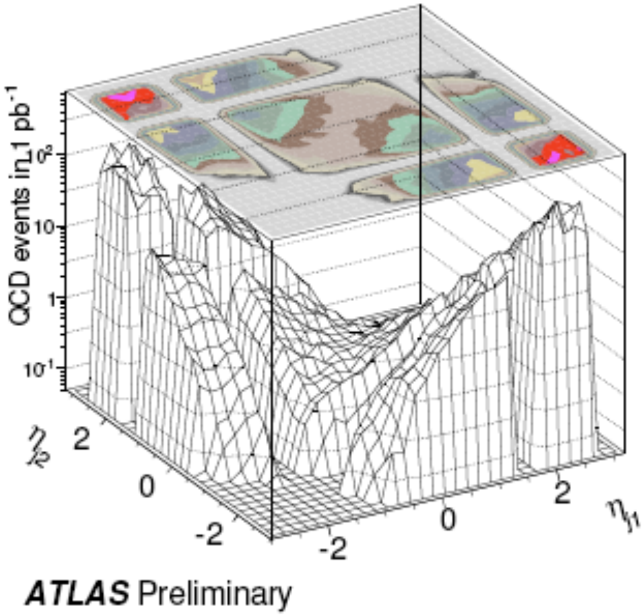
Compare to

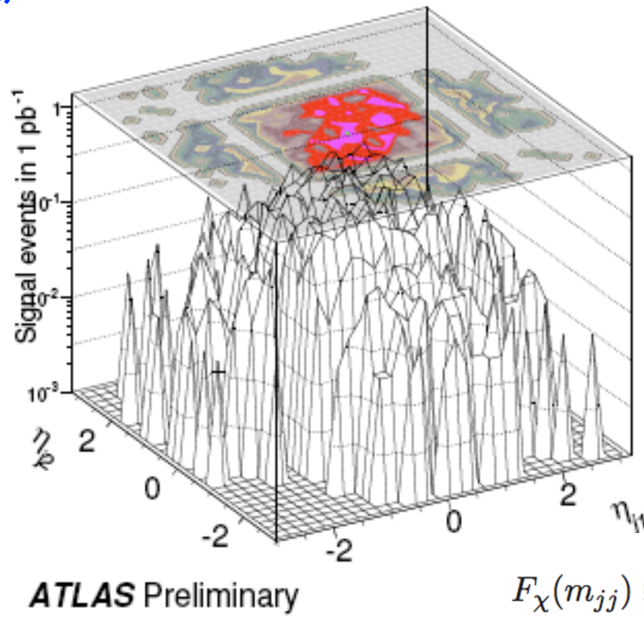


Angles

875 GeV < m_{jj} < 1020 GeV

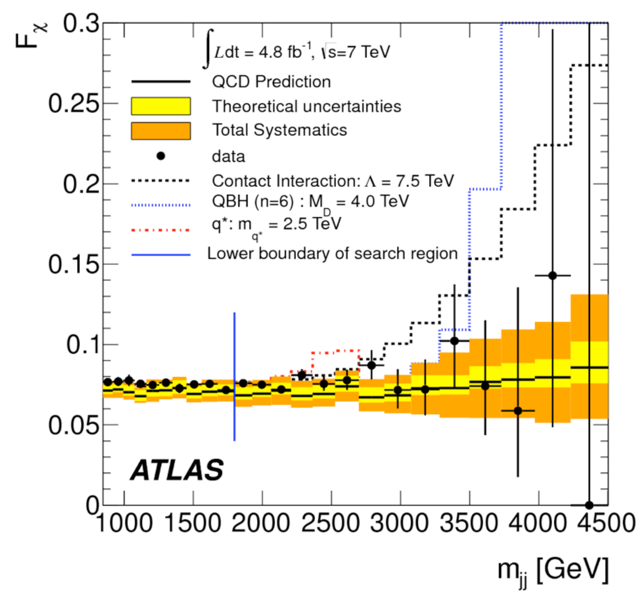
QCD





q*

$$F_\chi(m_{jj}) \equiv \frac{dN_{\text{central}}/dm_{jj}}{dN_{\text{total}}/dm_{jj}}$$



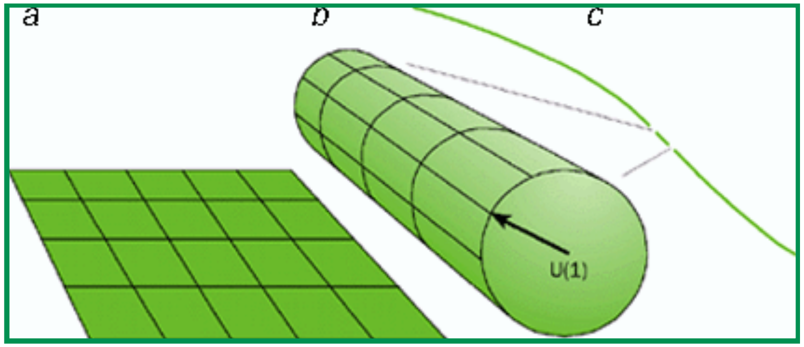
- High mass object → large boost → central
  - But background dominated by QCD "elastic" scatters and larger angle = higher mass
  - "Δη" cuts used in many analyses

Gravity and Hierarchy

(or: Out of This World?)

Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified



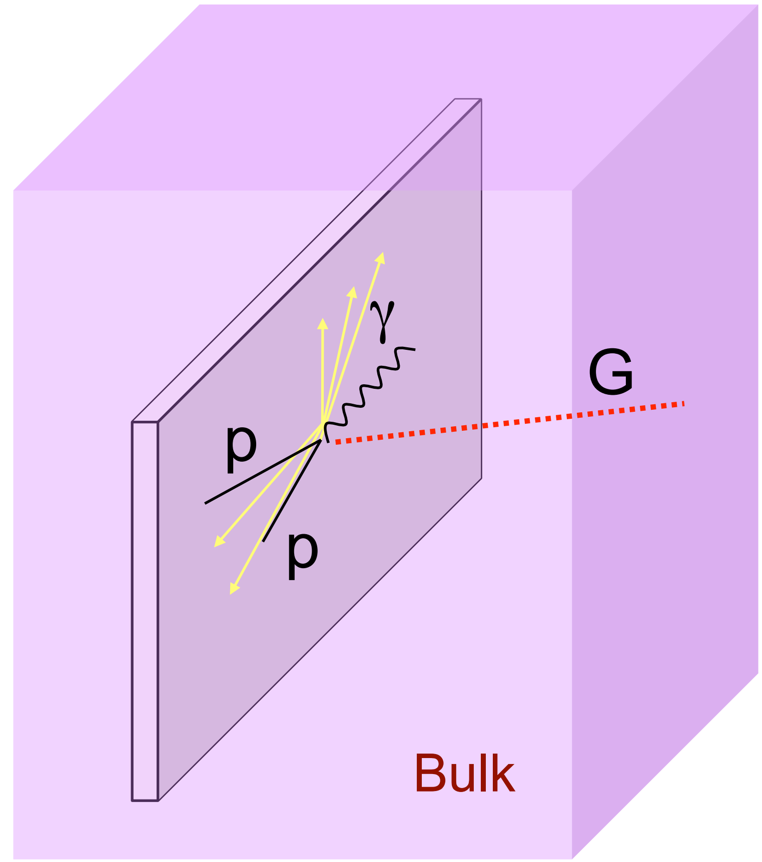
Source: PhysicsWorld

- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

Phys.Lett.B246:377-384,1990

"ADD"

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali): Phys.Lett. B429 (1998) 263-272
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

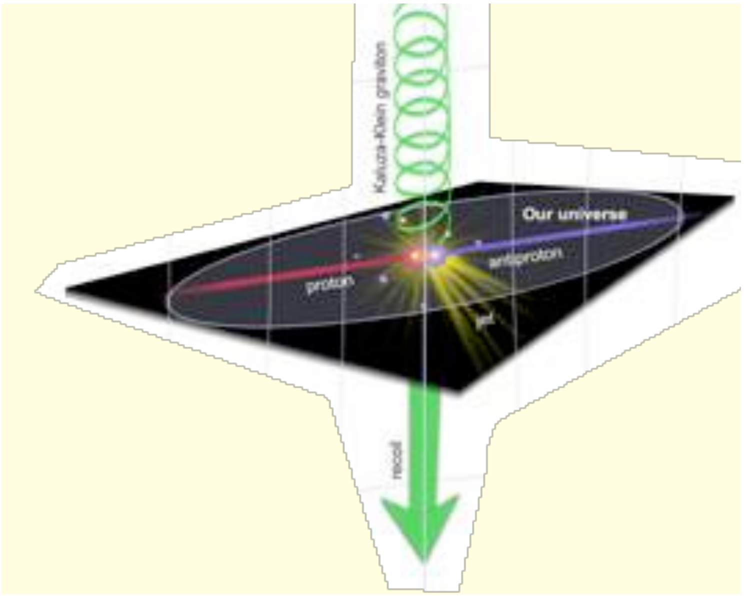


Drawing by K. Loureiro

ADD Signatures

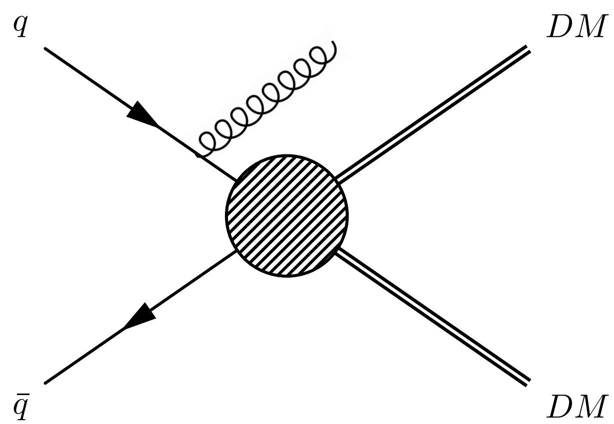
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantized
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

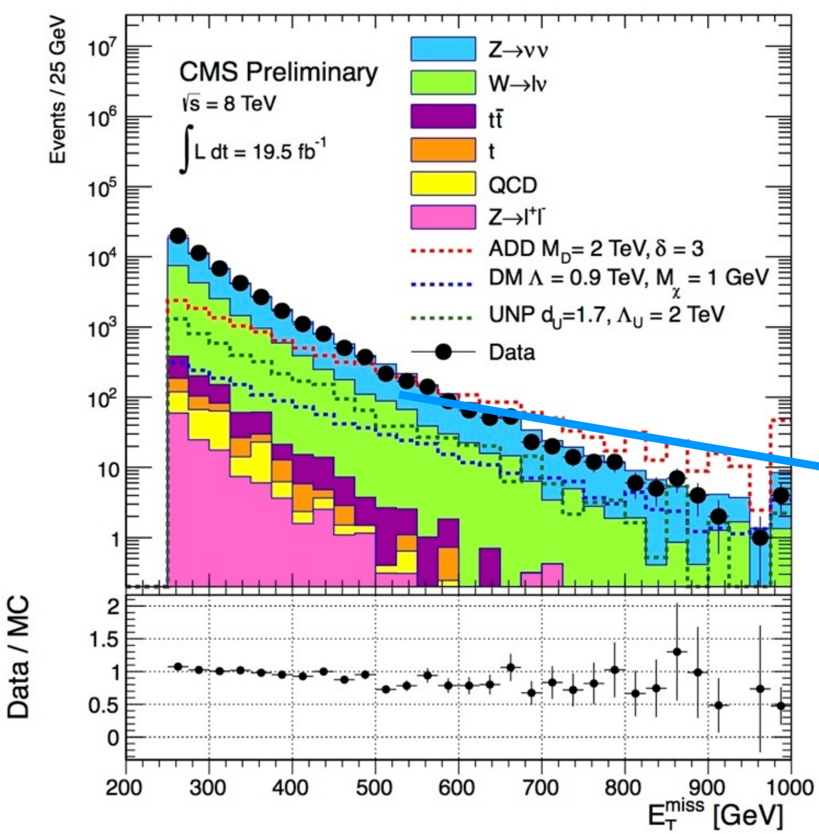
- ❖ Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- ❖ Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!

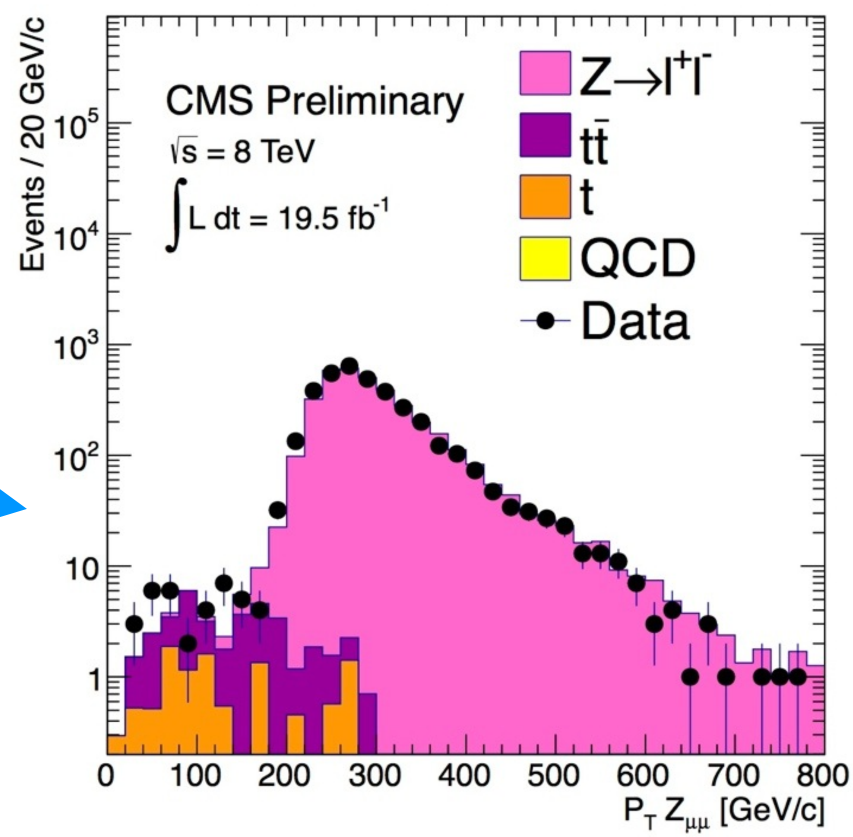


Monojet

- Not just graviton signature!
  - "Hard ISR" to probe dark matter, compressed SUSY, etc.
  - Can get at Z → νν through Z → μμ, but…

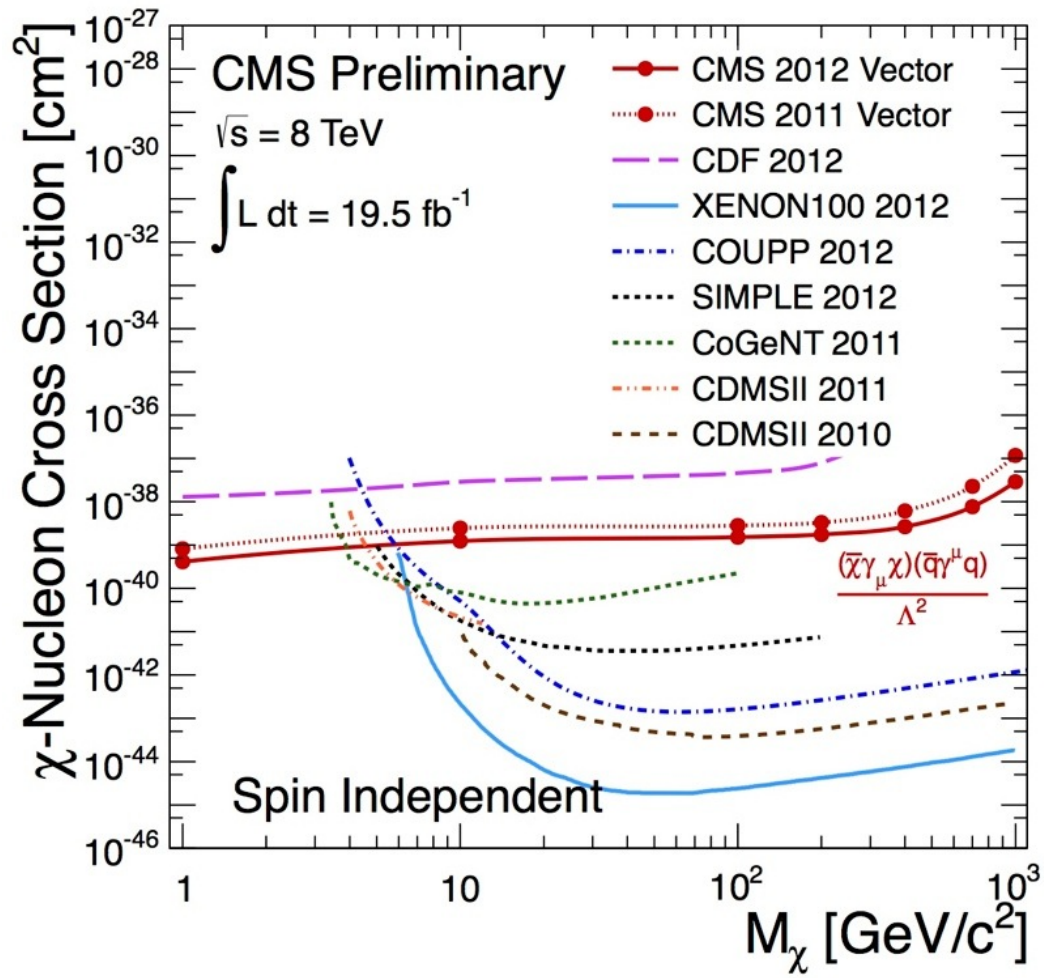






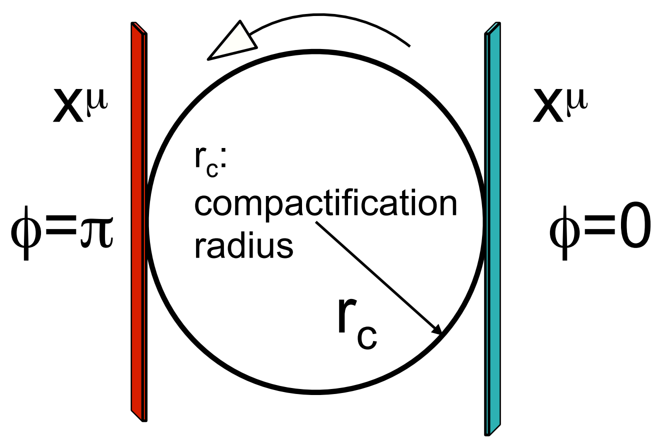
Dark Matter Interpretation

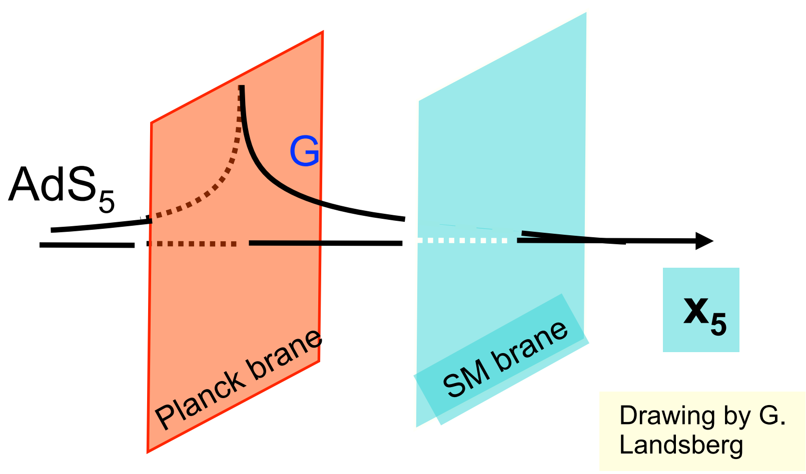
- Effective theory!
  - Not valid everywhere
  - Impact of mediator mass, perturbativity
  - Bound on Λ vs. bound on σ
- Careful when interpreting
  - Plots will improve...



Warped Extra Dimensions

- “Simple” Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is “warped” by a factor $\exp(-2kr_C\phi)$
  - (Requires 2 branes)





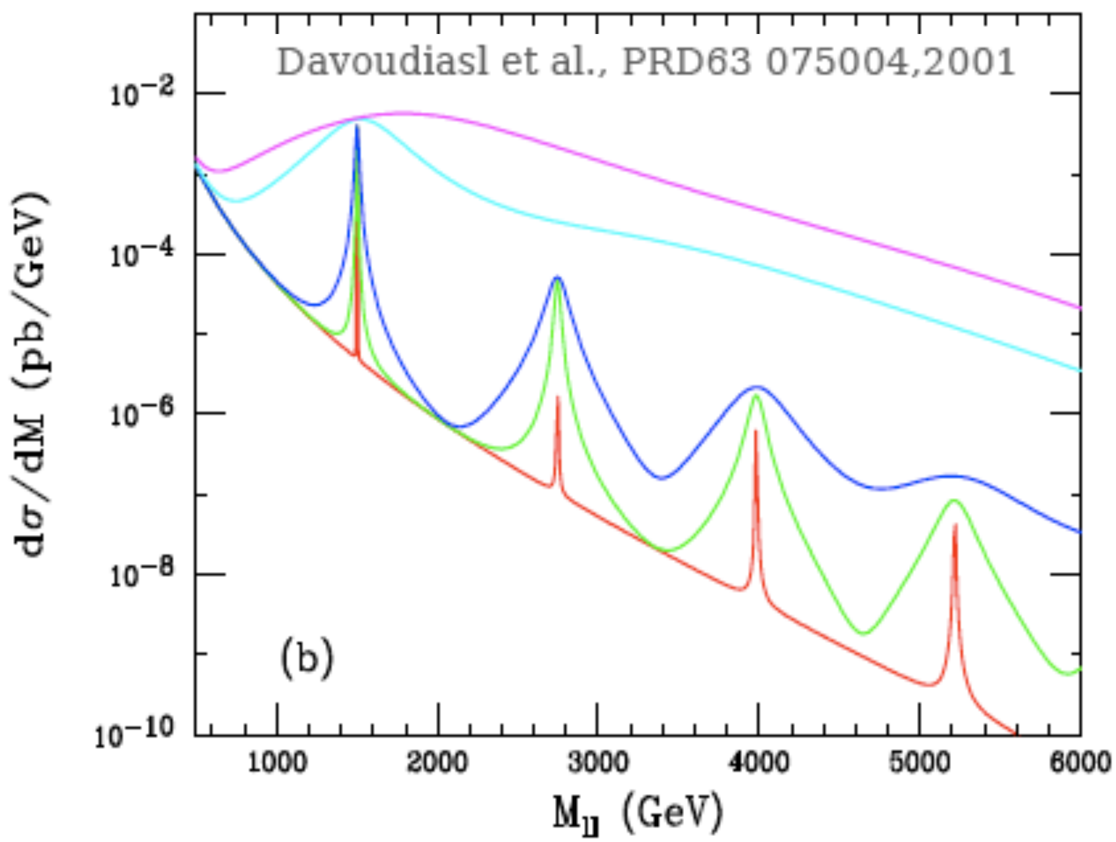
Graviton Excitations

❖ In RS, get a few massive graviton excitations

- Widths depend on warp factor k
- Mass separation = zeros of Bessel function

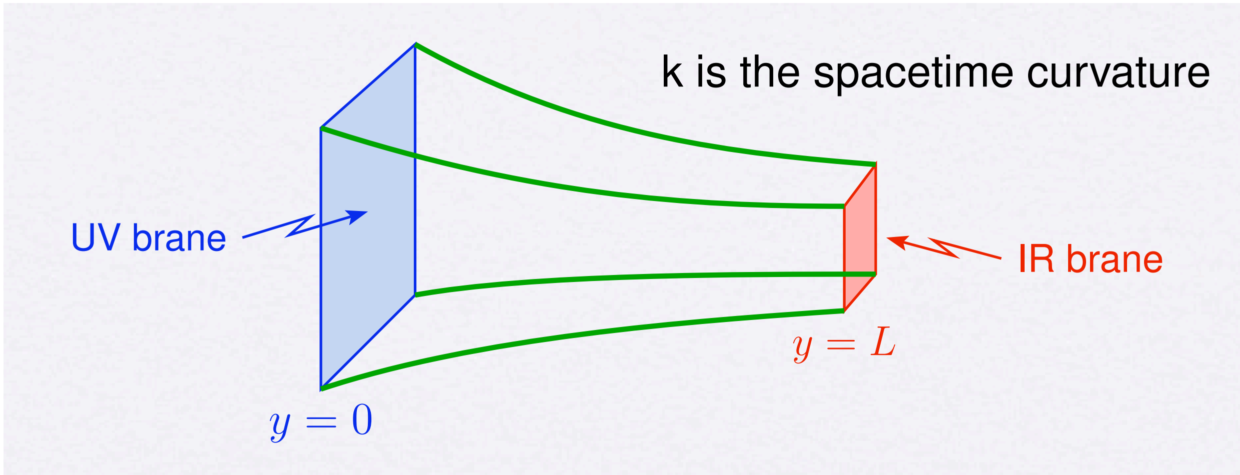
➡ Smoking gun!

(BRs also different than Z':
e.g. γγ allowed)



Hierarchies

❖ Physics on a curved gravitational background:



❖ Scales depend on position along extra dimensions

- UV brane scale is $M_{Pl} = 2 \times 10^{18}$ GeV
- IR brane scale is $M_{Pl}\, e^{-kL} \sim 1$ TeV if $kL \sim 30$

❖ If were to localize Higgs on IR brane, naturally get EW scale ~ 1TeV (from geometry!)

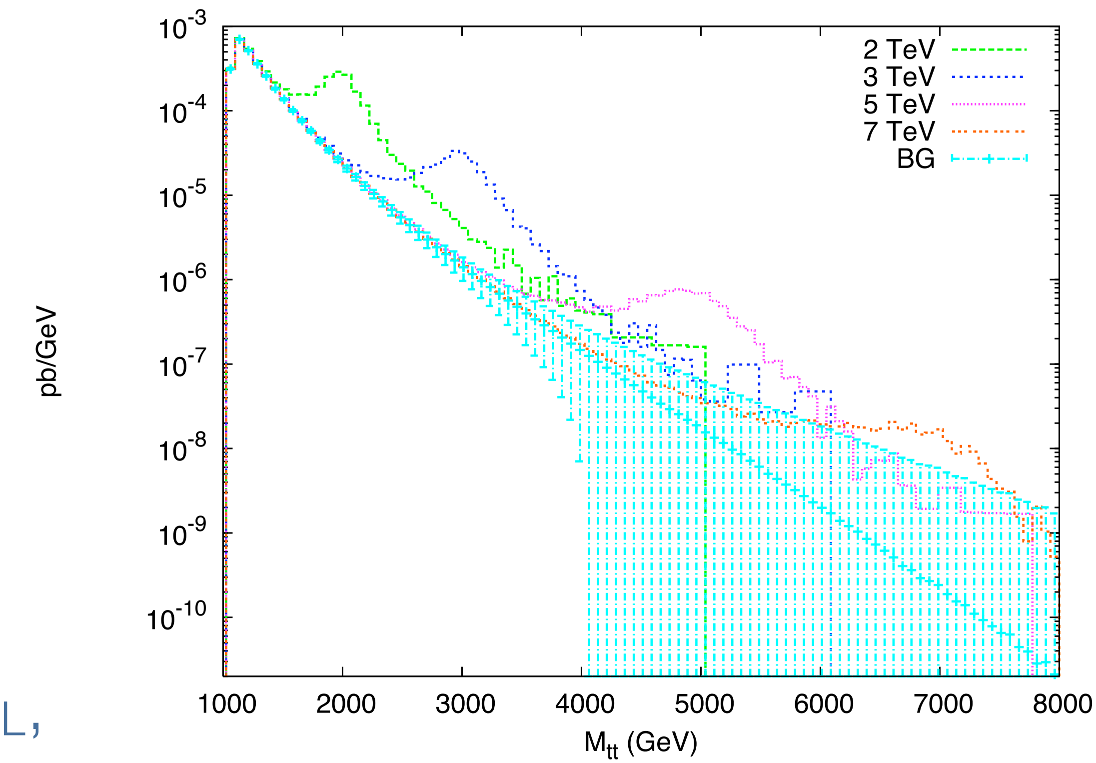
Flavor

- Interesting variation has fermions located along the extra dimension
  - Fermion masses generated by geometry
  - Heavier fermions are closer to IR brane, and gauge boson excitations as well
    - Gauge boson excitations expected to have masses in the 3-4 TeV range (bounds from precision measurements)
    - Couple mainly to top/W/Z (!)
  - Flavor changing determined by overlap of fermion “wave function” in the ED
    - Nice suppression of FCNC etc.

Gauge Boson Excitations

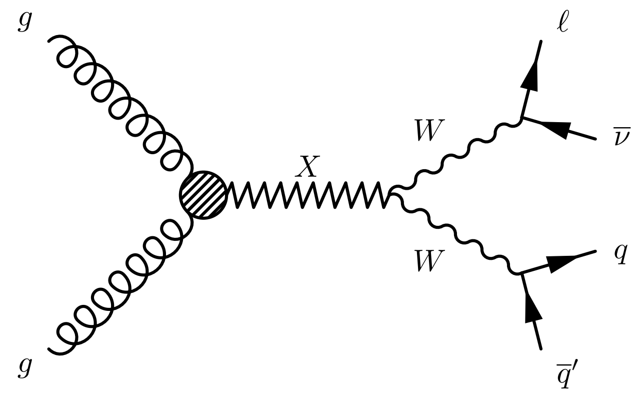
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

B. Lillie et al., JHEP 0709:074,2007

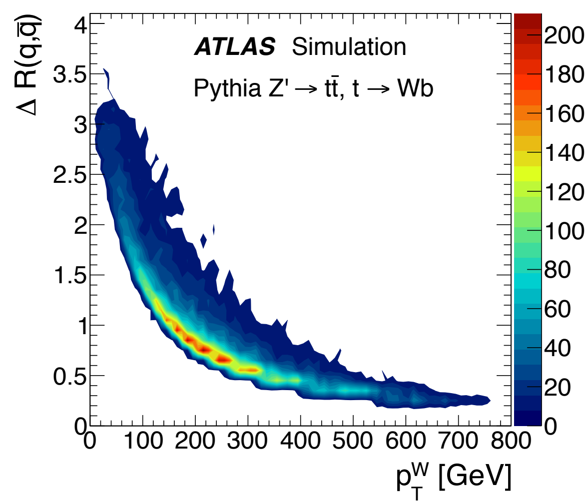


Dibosons

- Signature of Randall-Sundrum excitations as well as W', Z'
  - Can look for e.g. W' → WZ, WH
    - Many final state options: lνll, lνqq, qqll, qqqq, …
    - Three leptons → low background but low branching ratio: good at low mass where backgrounds are large
    - Fully hadronic → high branching ratio but substantial multi-jet background: good at high mass where cross-section is lower



- For high mass W', Z' decay products are boosted…ok for leptonic decays,
  - … but hadronic decay products merge:
    - $\Delta R \sim 2m/p_T \Rightarrow$ for $p_T \sim 500$ GeV, $\Delta R \sim 0.4$, typical jet size



Fully Hadronic Decays

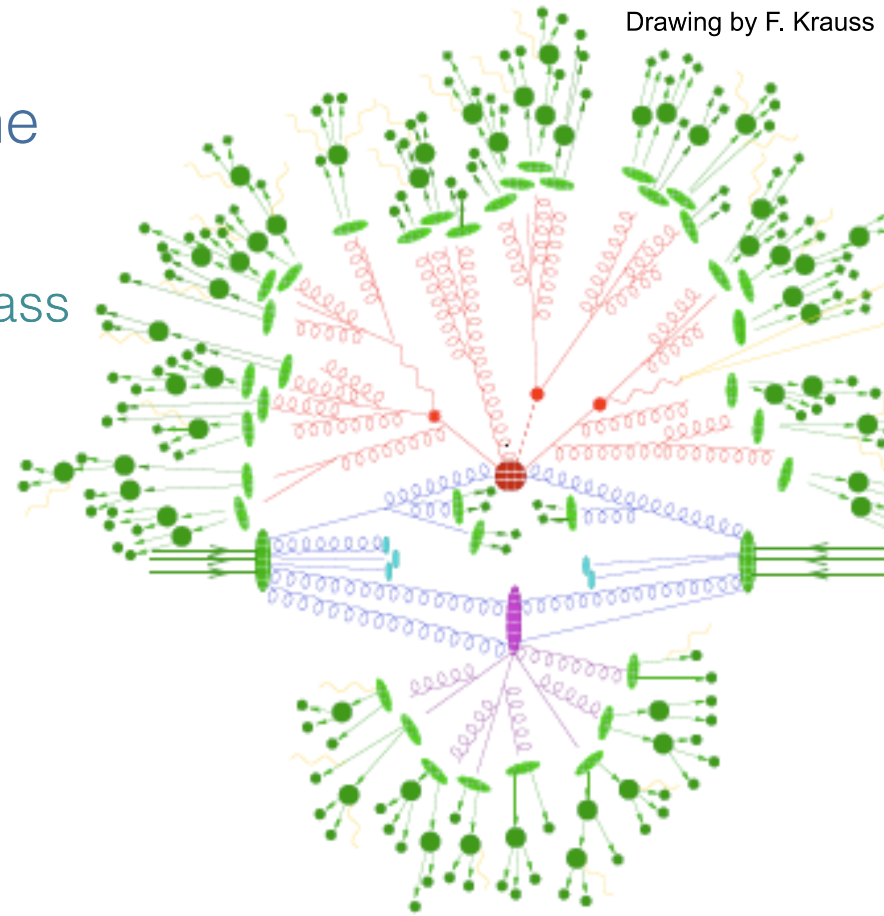
❖ Decay hadrons reconstructed as a single jet

- But even if it looks like a single jet, it originates from a massive particle decaying to two (W, Z, H) or three (top) hard partons, not one

- If I measured each of the partons in the jet perfectly, I would be able to:
  - Reconstruct the "originator's" invariant mass
  - Reconstruct the direct daughter partons

But

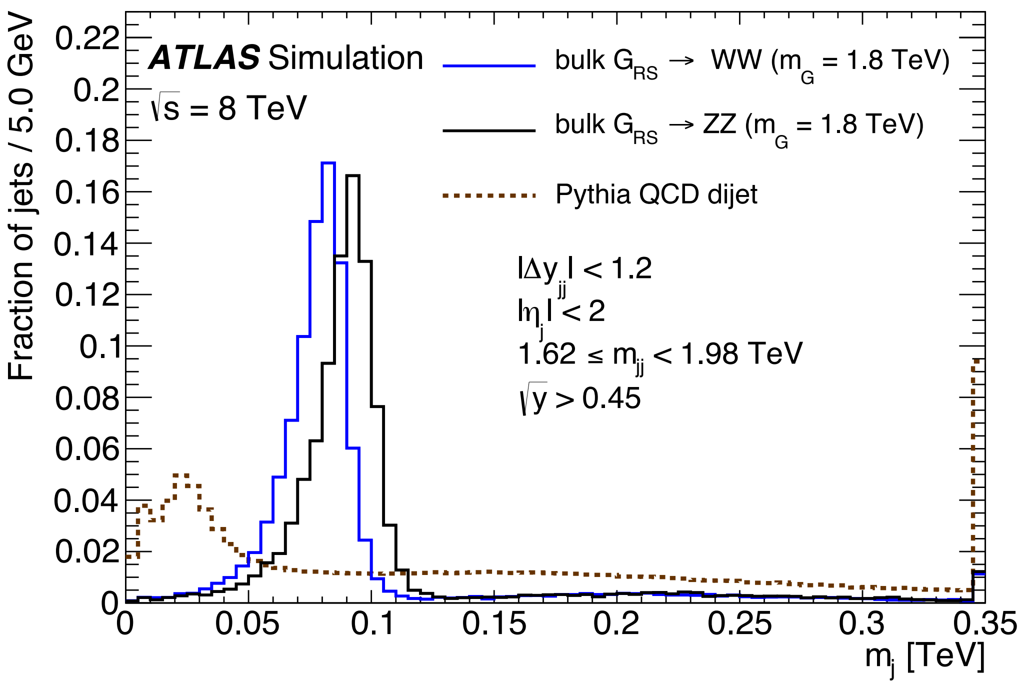
- Quarks hadronize → cross-talk
- My detector can't resolve all individual hadrons



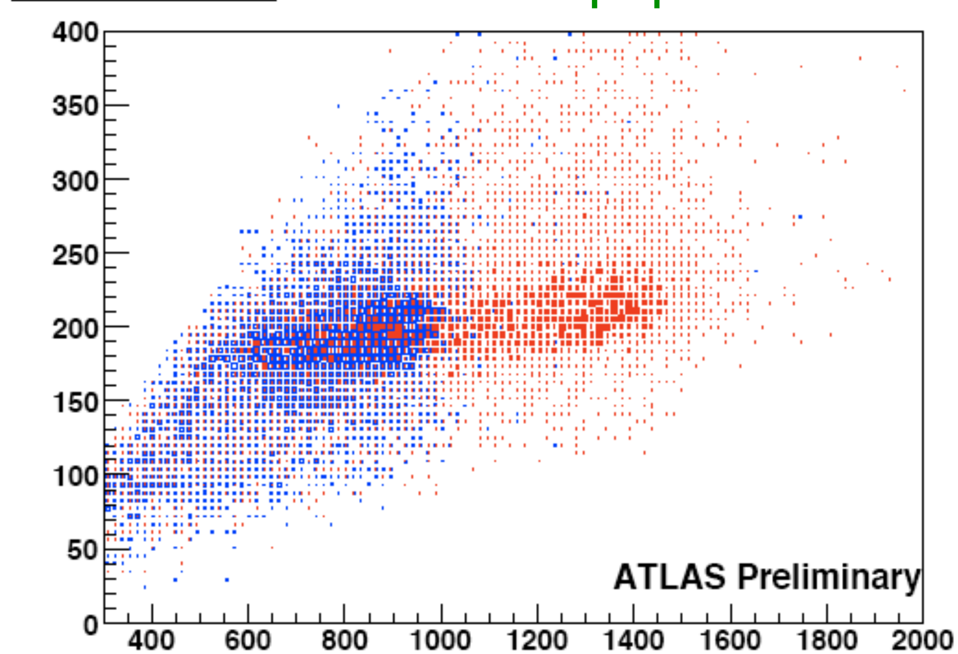
Jet Mass

- Jet mass: invariant mass of all jet constituents
  - In principle, close to object mass
  - and invariant!

ATLAS, arXiv:1506.00962

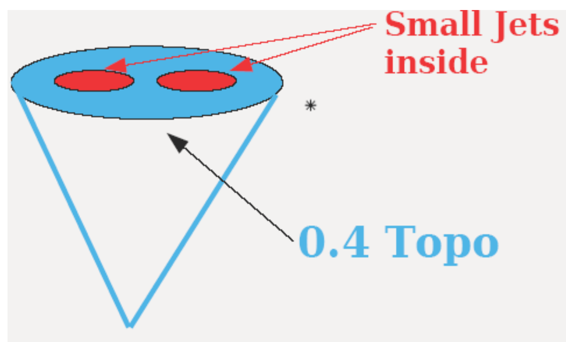


For top quarks…



Subjets

- Jet mass is not sensitive to structure
  - Can't tell whether a jet is isotropic or not
- Expect "blobs" with higher concentration of energy for jets from top/W/Z decays



- Multiple ways of exploiting this....
  - k_T splitting scales, "mass drop"

J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *Phys. Rev.* **D65** (2002) 096014

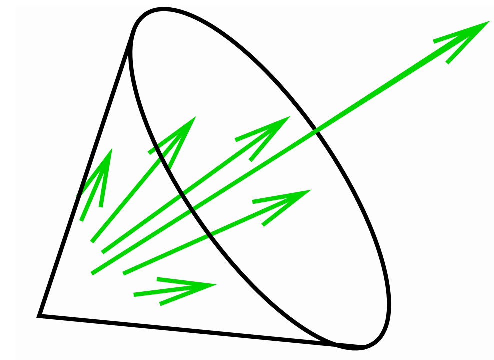
k_T Splitting Scales

- k_T jet algorithm is much better suited to understand jet substructure than cone:
  - Cone maximizes energy in an η x ϕ cone
  - k_T is a "nearest neighbor" clusterer

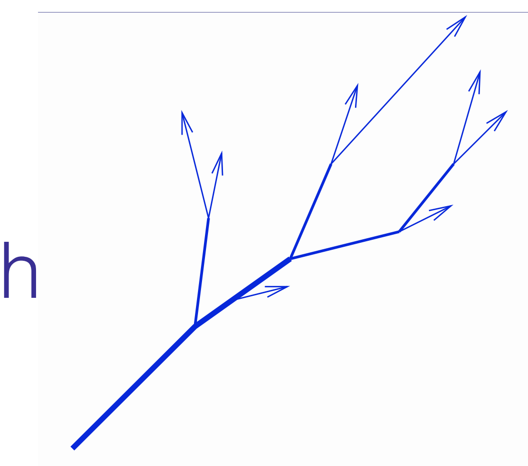
$$y_2 = \min\left(E_a^2, E_b^2\right) \bullet \theta_{ab}^2 / p_{T(jet)}^2$$

$$Y \text{ scale } = \sqrt{p_{T(jet)}^2 \bullet y_2}$$

- Can use the k_T algorithm on jet constituents and get the (y-)scale at which one switches from 1 → 2 (→ 3 etc.) jets
  - Scale is related to mass of the decaying particle

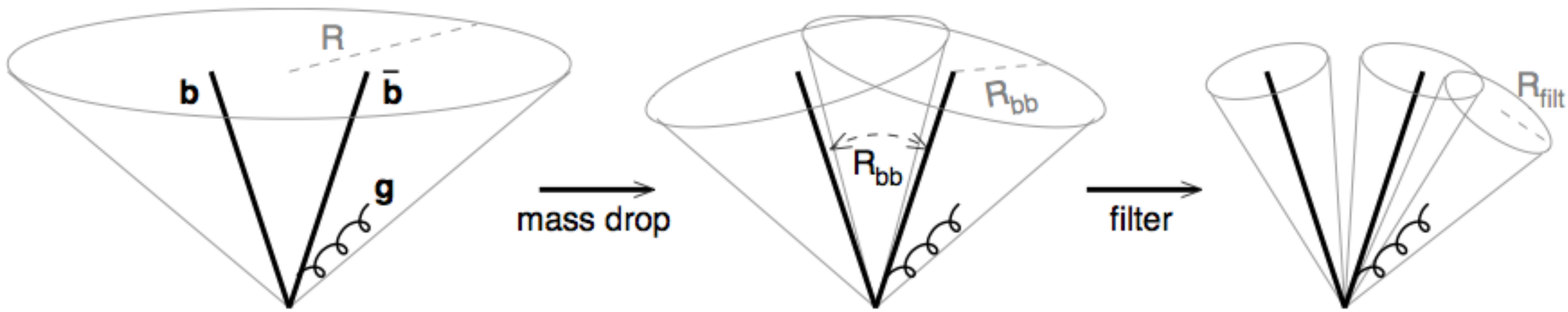


Cone



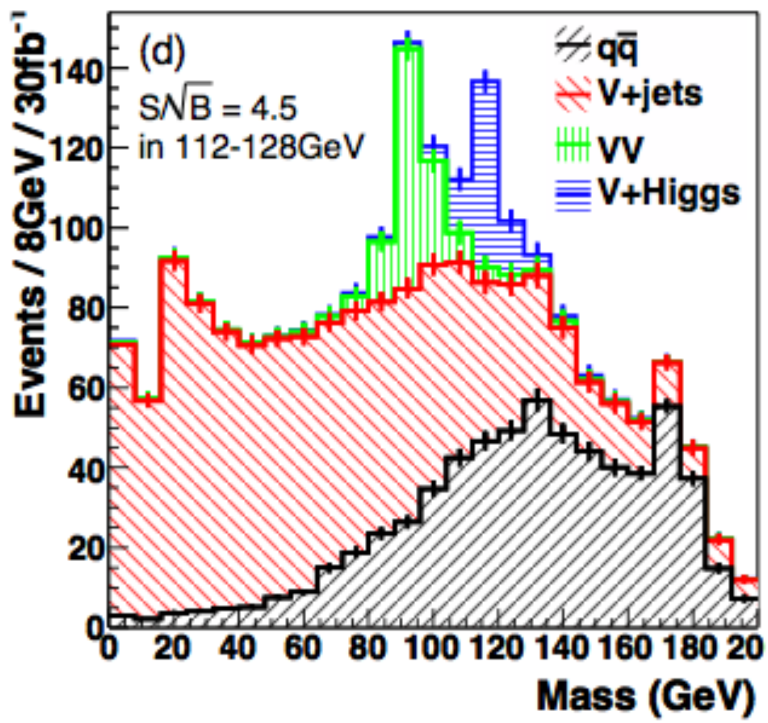
k_T

Mass Drop



BDRS, Phys.Rev.Lett. 100 (2008) 242001

- Introduced to recover (W/Z)H→ (W/Z)bb at the LHC
  - In boosted regime, Wbb and Zbb backgrounds easier to manage
  - But strategy can be used more generically

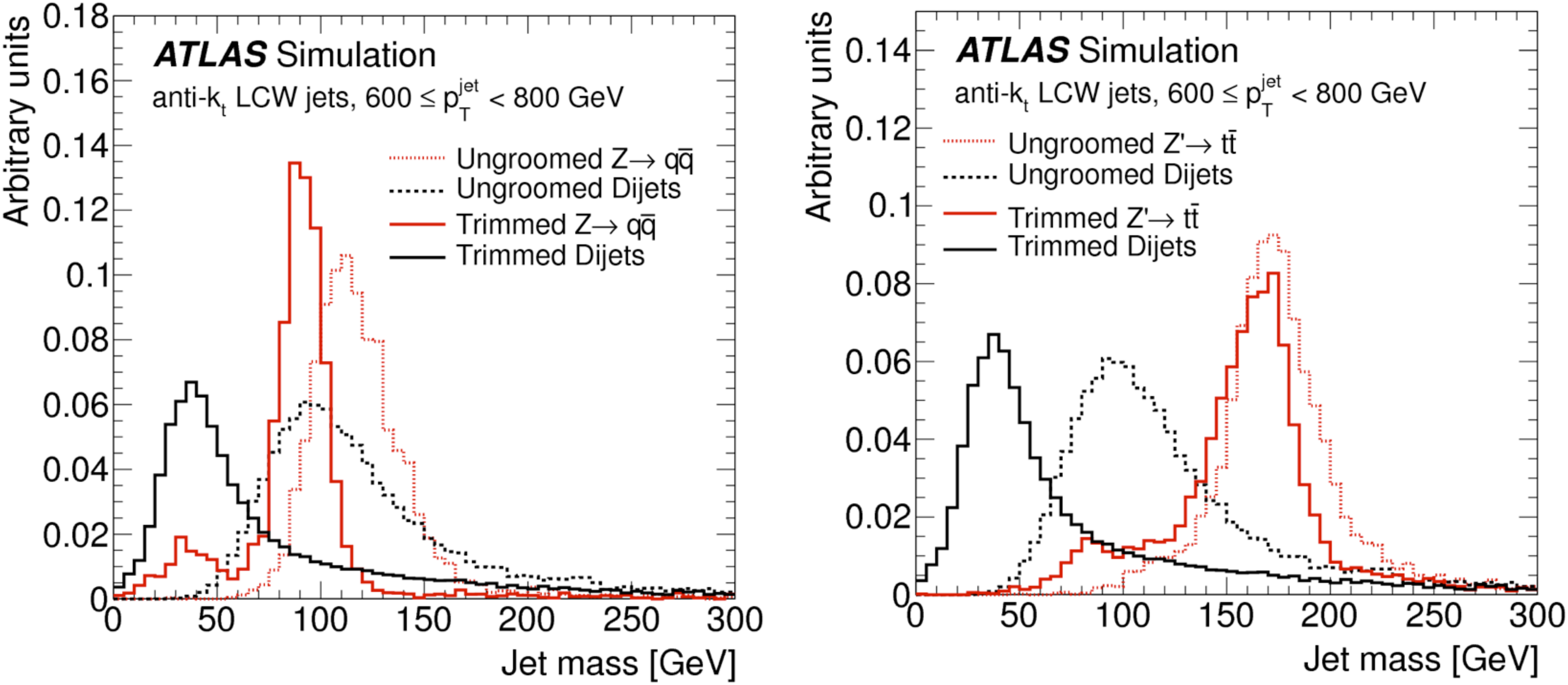


Grooming

❖ Decluster (or recluster with small R), and remove soft stuff

- Clean up soft QCD radiation/connection to underlying event

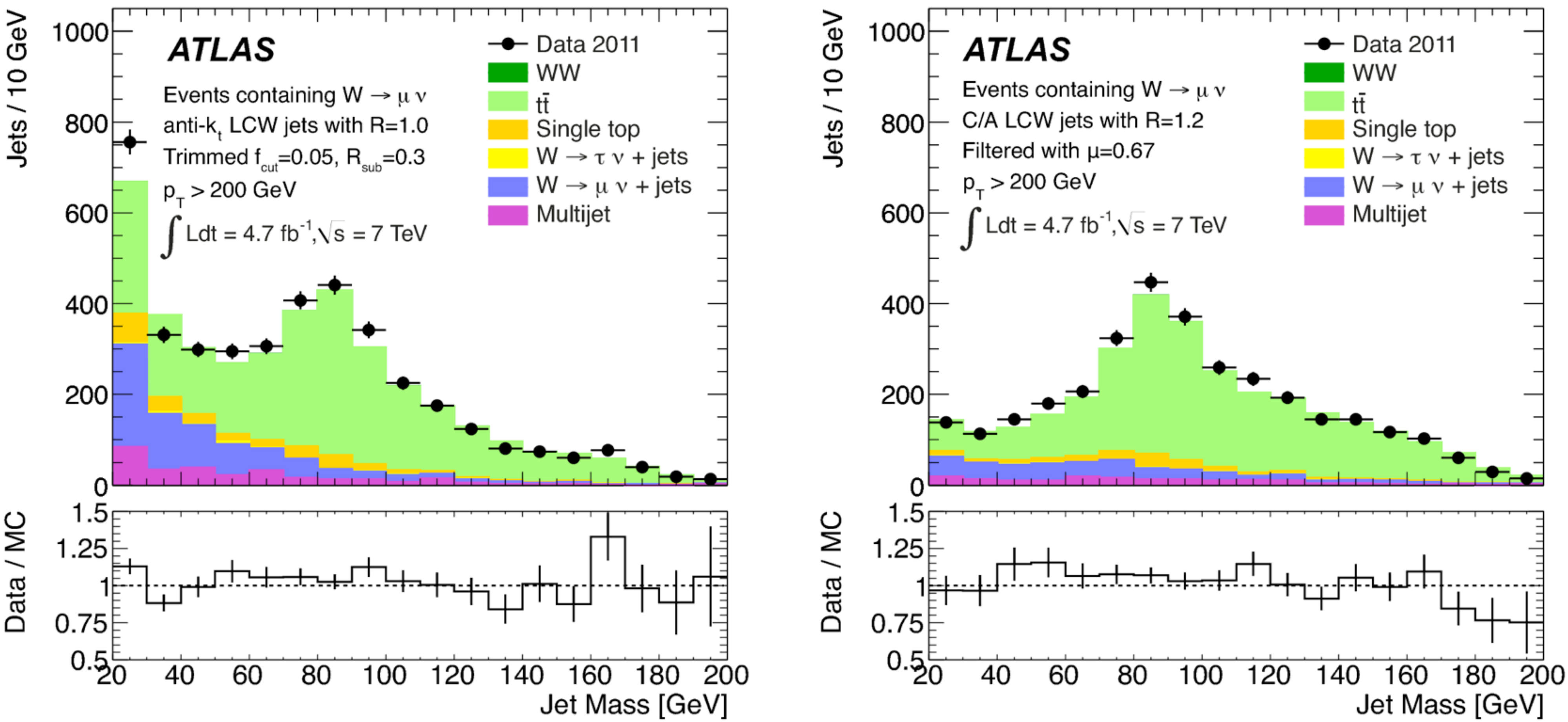
ATLAS, JHEP09 (2013) 076



Proof of Principle

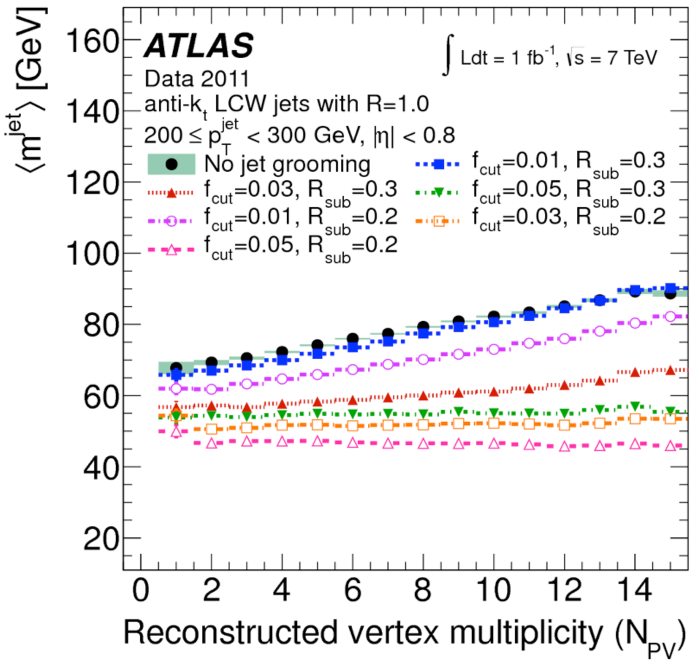
❖ W-jets from top quarks

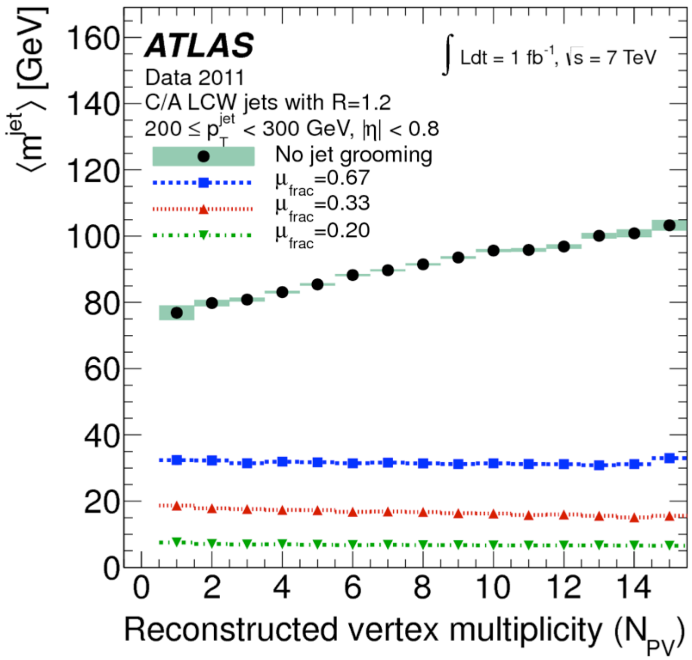
ATLAS, JHEP09 (2013) 076



Added Benefits

- Pile-up is a big deal at hadron colliders
  - Low-p_T, “uninteresting” QCD will always have a much larger cross-section than rare processes we’re hunting





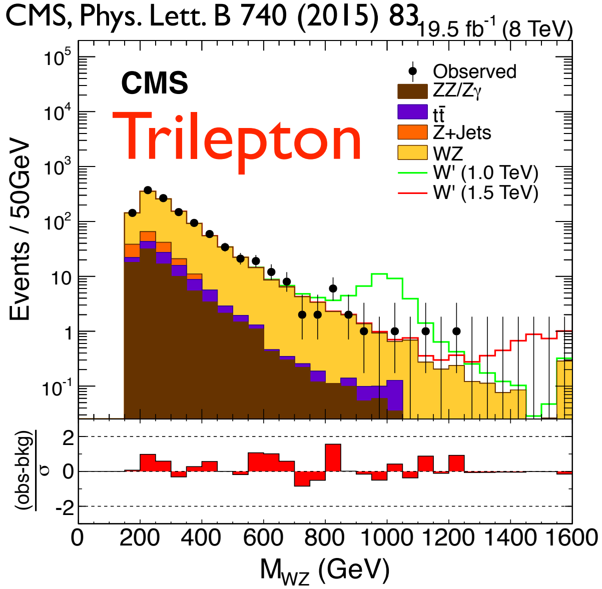
!Optimal parameter set/strategy is detector-dependent!

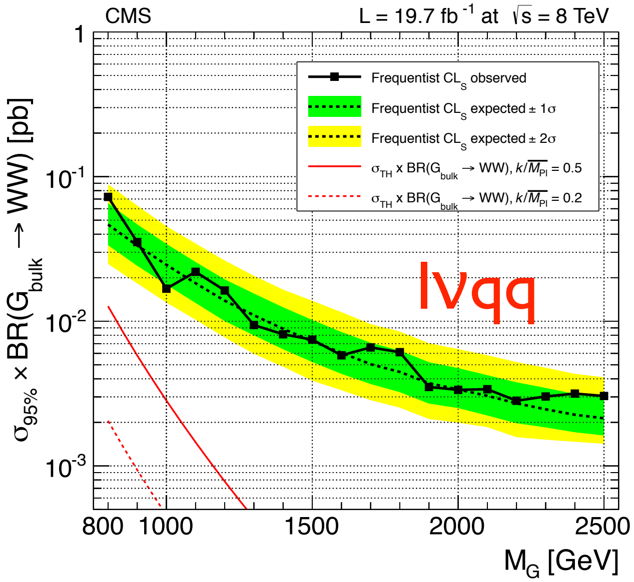
Many More Techniques

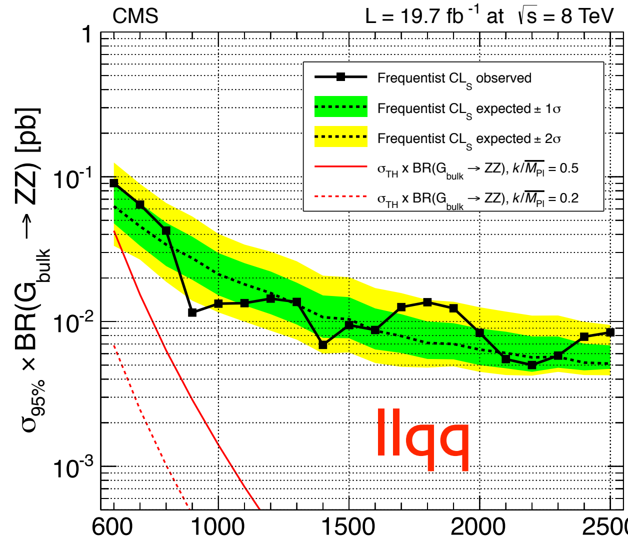
- Whole “jet structure” community exists
  - Reports of BOOST workshops a very useful resource:
    - **Boosted objects: A Probe of beyond the Standard Model physics, A. Abdesselam et al, Eur.Phys.J. C71 (2011) 1661; Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks, A. Abdesselam et al, J.Phys. G39 (2012) 063001**
  - Direct comparison of multiple taggers, and “groomers”
  - More tools have been developed, and also more extensive non-perturbative calculations of the jet structure
  - Many of the tools available in the fastjet library (Cacciari, Salam, Soyez)
    - http://www.lpthe.jussieu.fr/~salam/fastjet/

Diboson Resonance Results: CMS

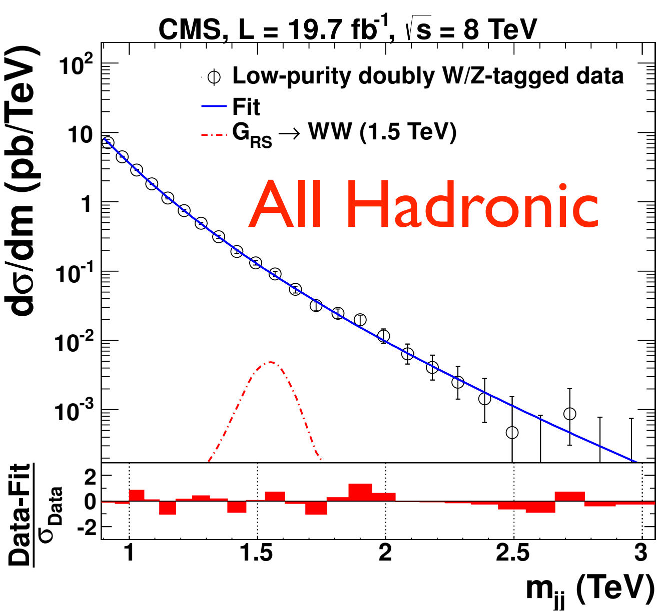
CMS, Phys. Lett. B 740 (2015) 83

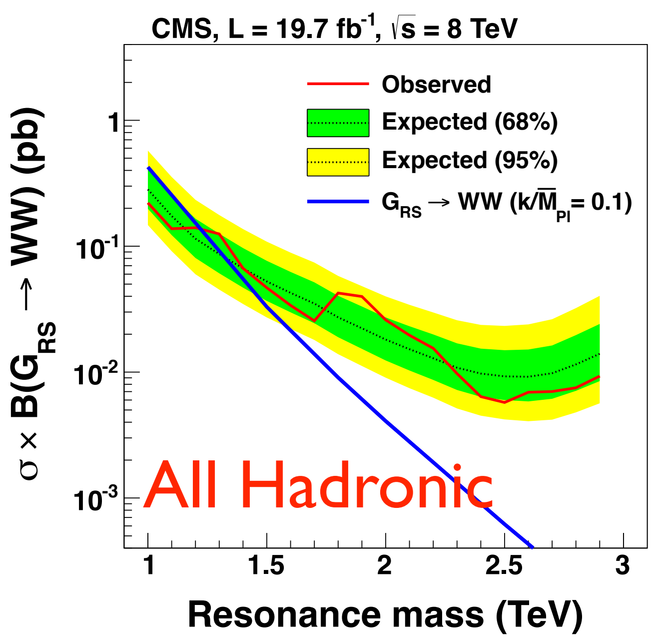






CMS, J. High Energy Phys. 08 (2014) 174 M_G [GeV]



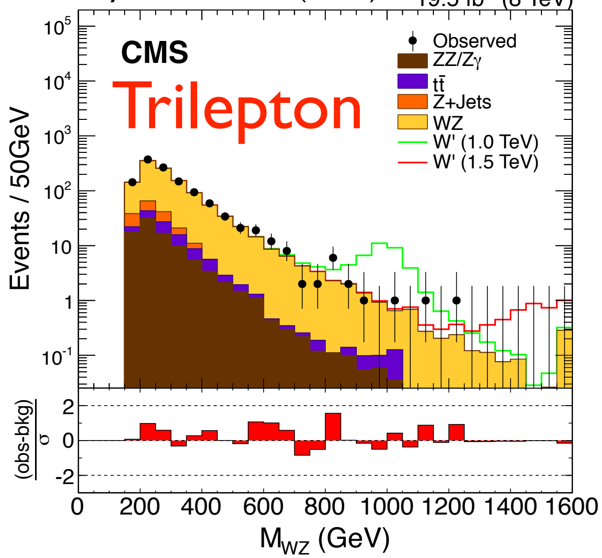


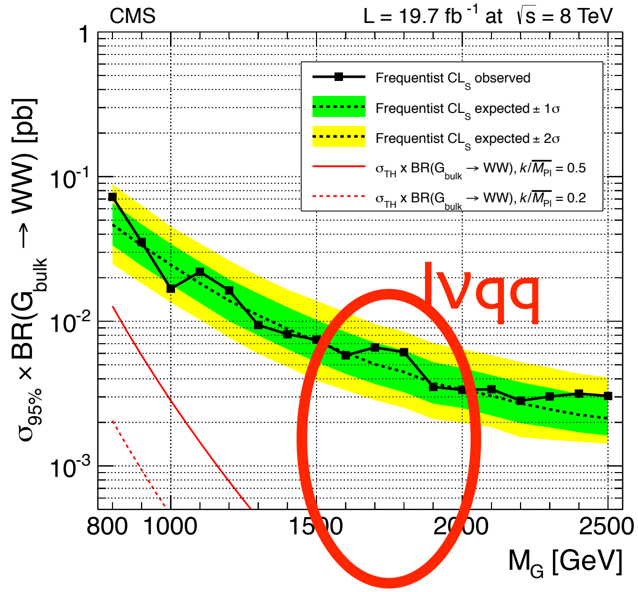
No evidence…

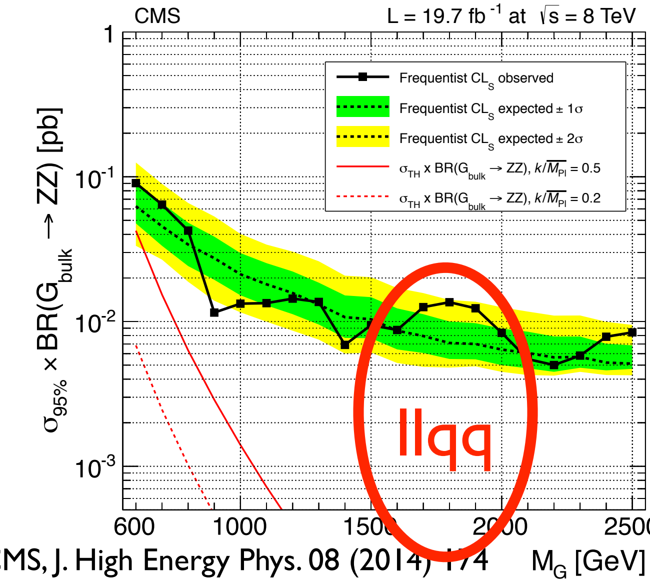
CMS, J. High Energy Phys. 08 (2014) 173

Diboson Resonance Results: CMS

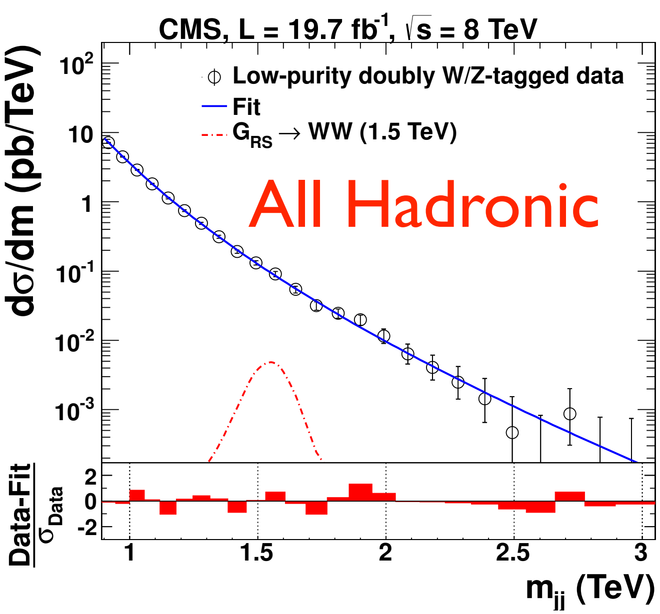
CMS, Phys. Lett. B 740 (2015) 83

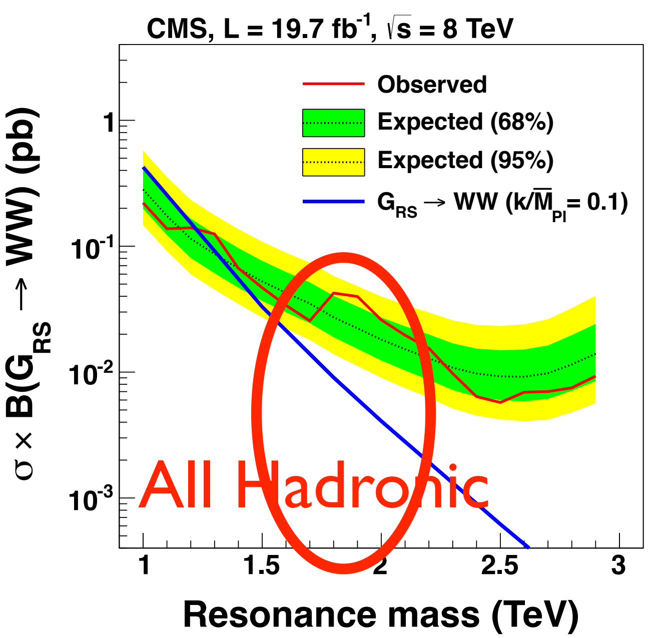






CMS, J. High Energy Phys. 08 (2014) 174





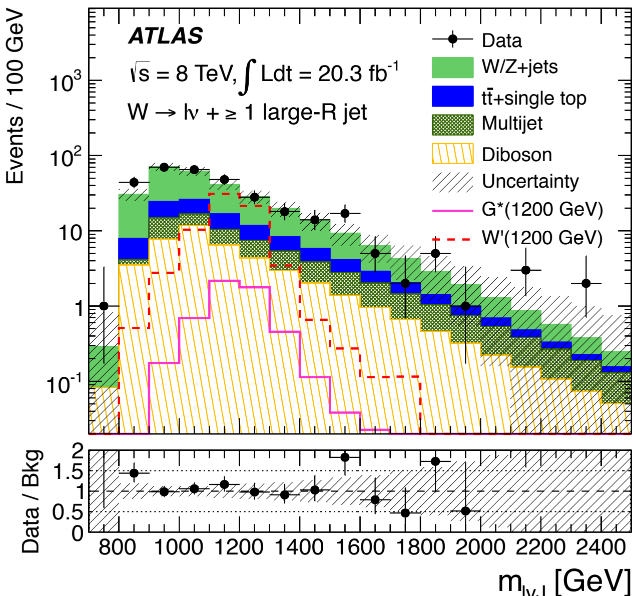
No evidence…

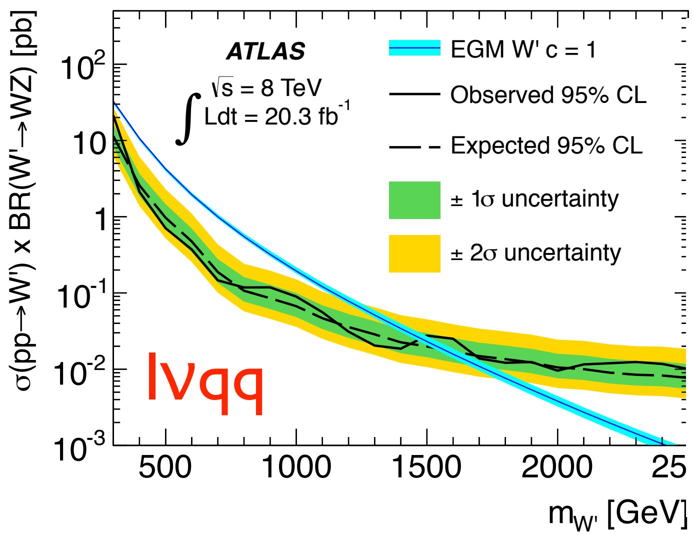
but a coincidence?

CMS, J. High Energy Phys. 08 (2014) 173

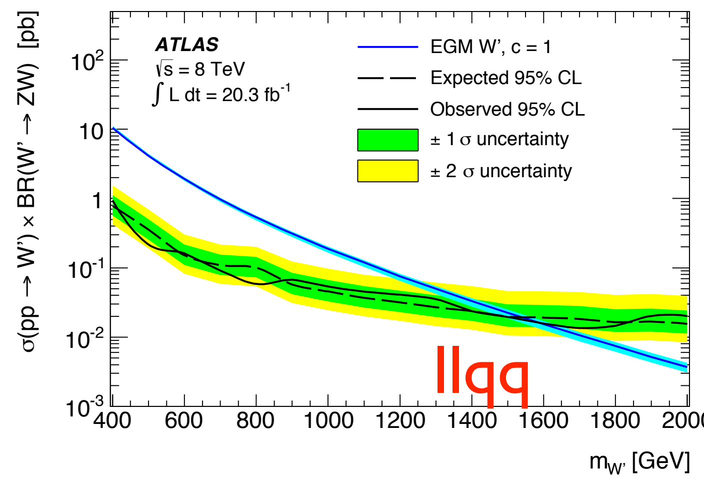
Diboson Resonance Results: ATLAS

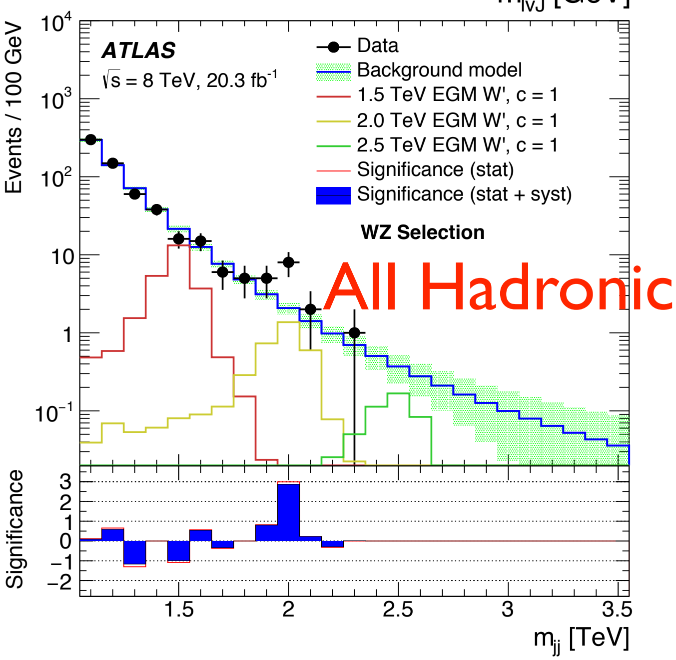
ATLAS, Eur. Phys. J. C (2015) 75:209



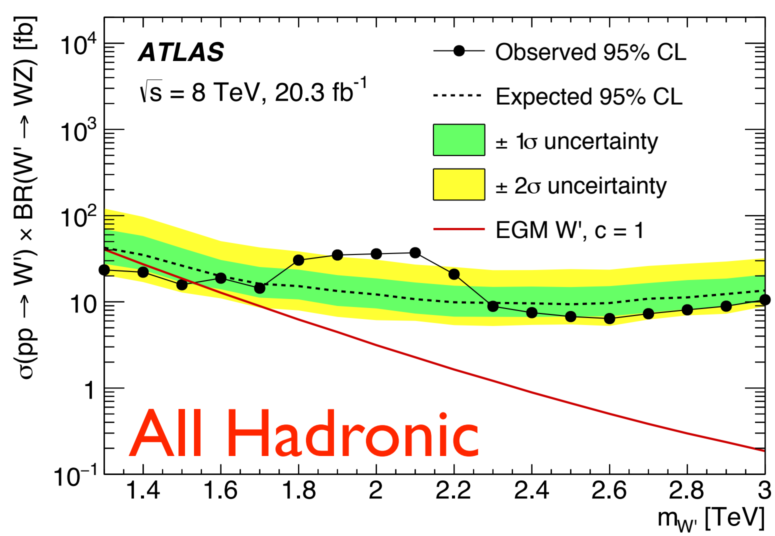


ATLAS, Eur. Phys. J. C (2015) 75:69





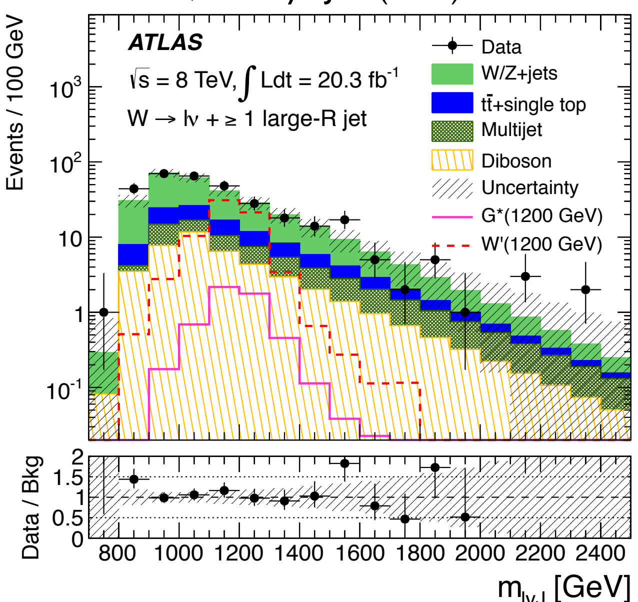
ATLAS, arXiv:1506.00962

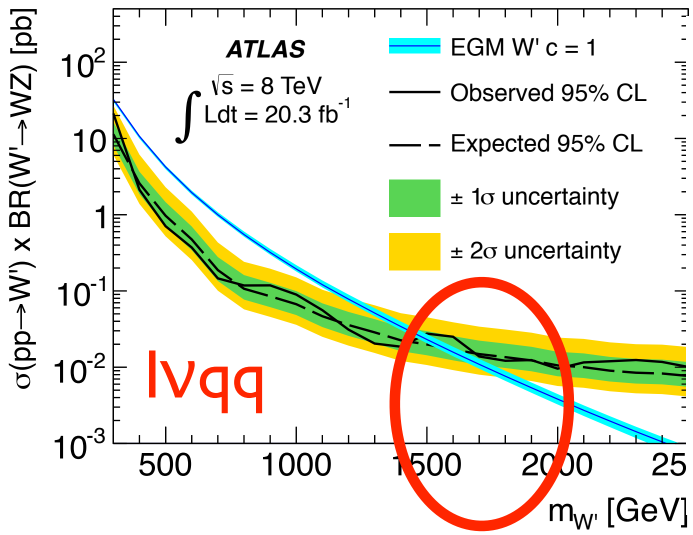


No evidence…

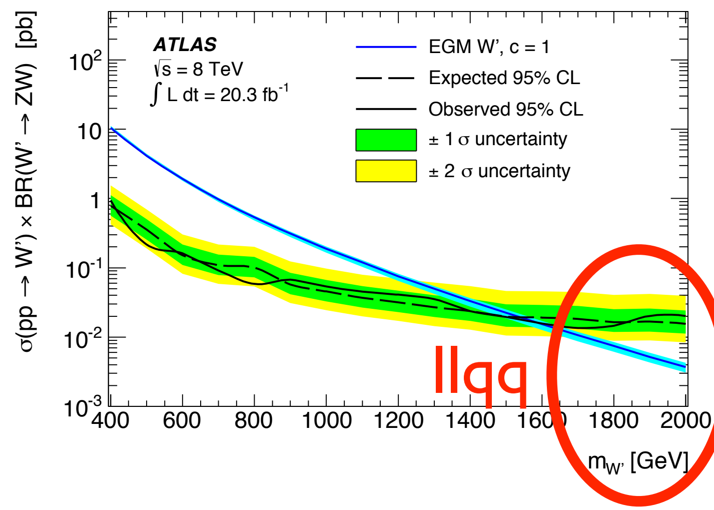
Diboson Resonance Results: ATLAS

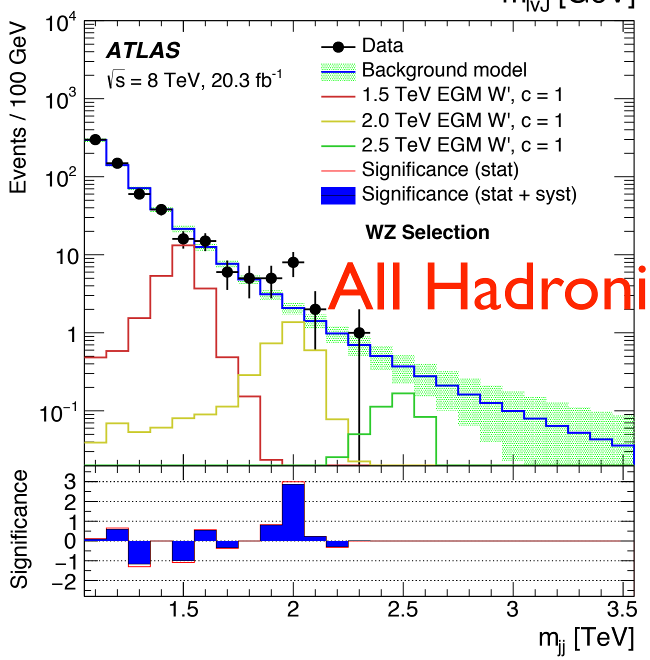
ATLAS, Eur. Phys. J. C (2015) 75:209



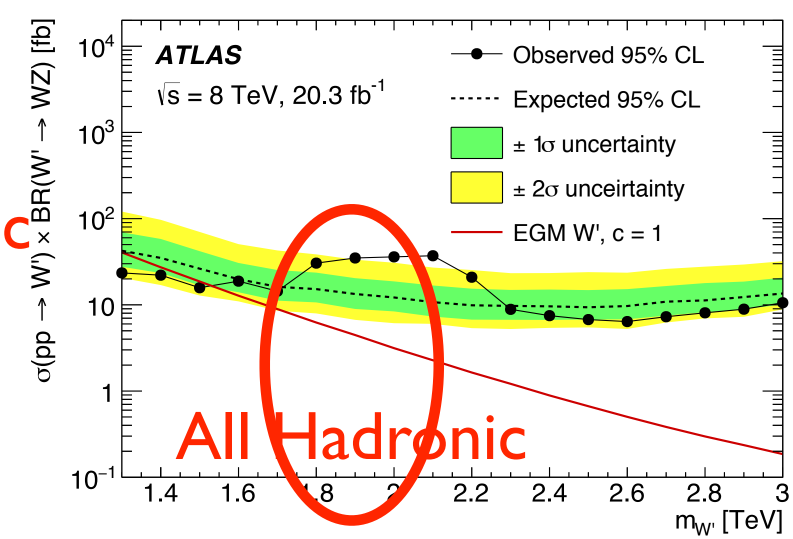


ATLAS, Eur. Phys. J. C (2015) 75:69





ATLAS, arXiv:1506.00962



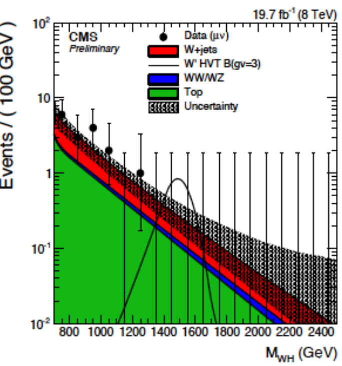
No evidence…

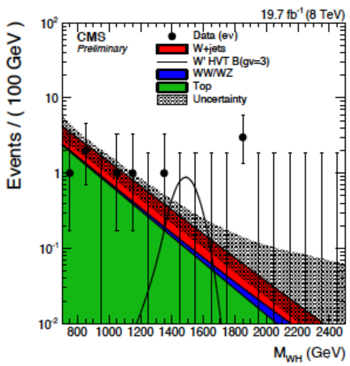
lesser coincidence?

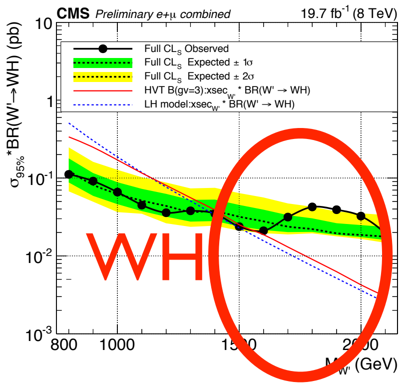
Decays to VH?

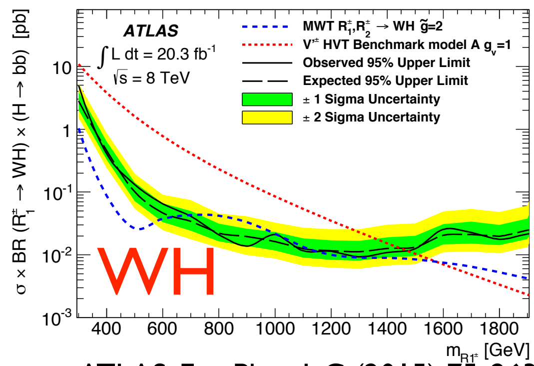
- Both ATLAS & CMS have analyses with b-tags
  ⇒ reduced acceptance

CMS-PAS-EXO-14-010

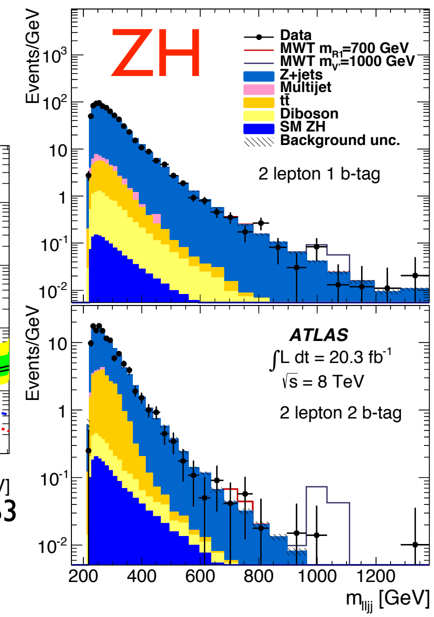






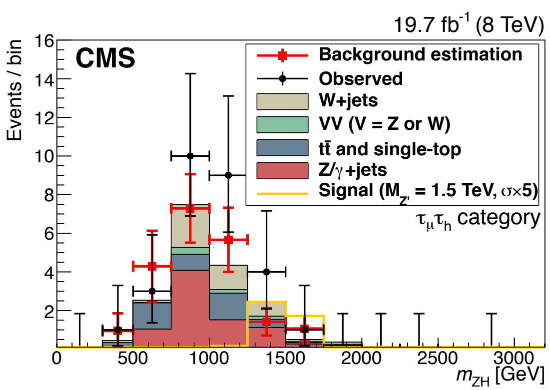


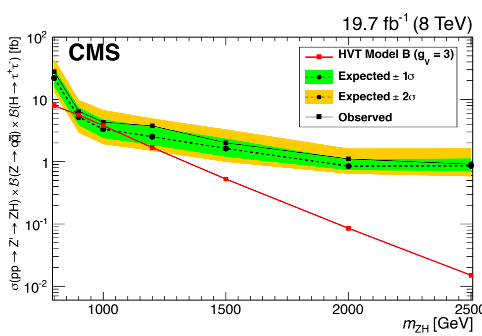
ATLAS, Eur. Phys. J. C (2015) 75: 263



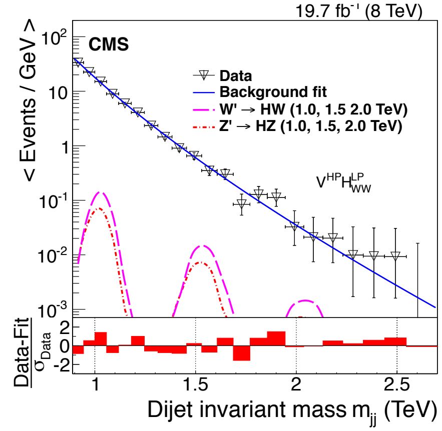
- CMS ZH ⇒ ττJ and all-hadronic VH

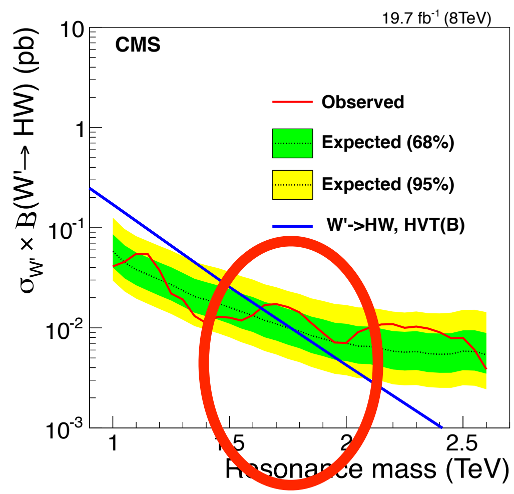
CMS, arXiv:1506.01443





CMS, arXiv:1502.04994

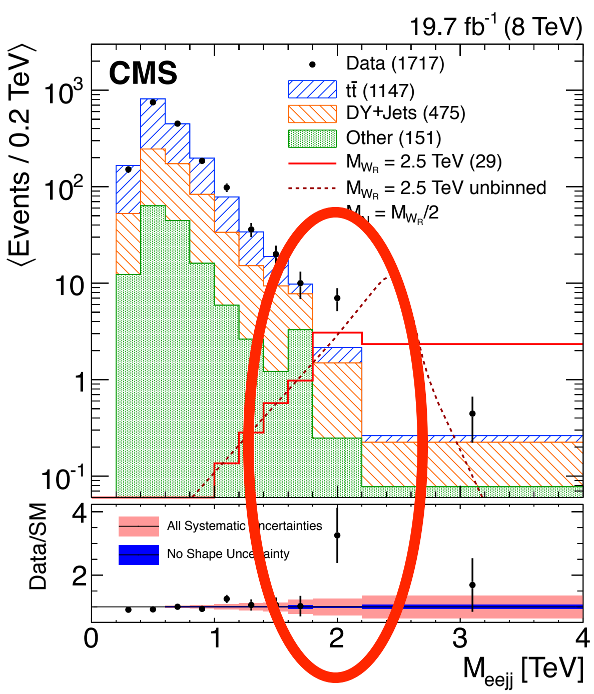


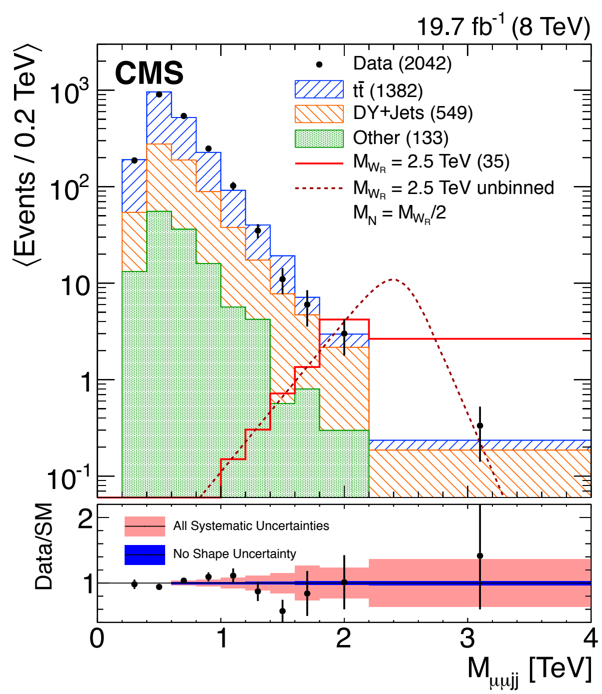


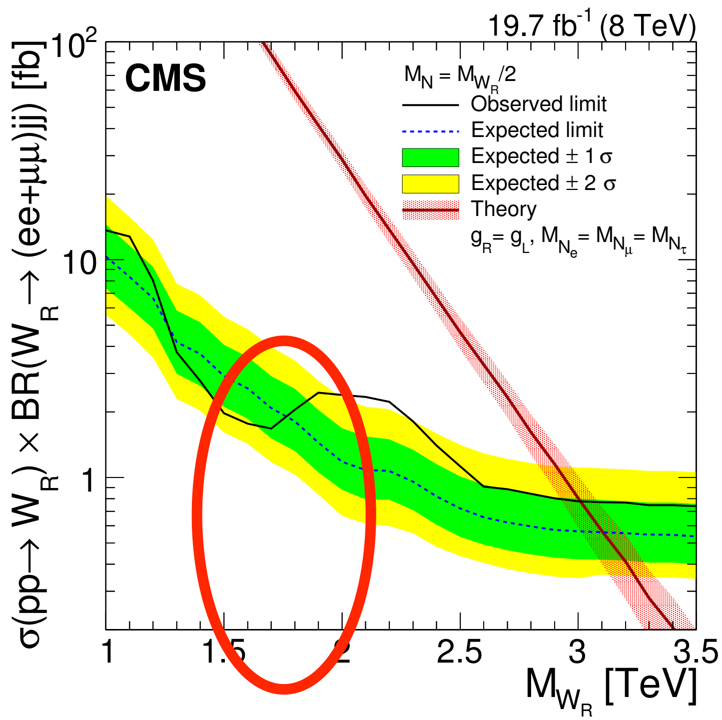
Speculating…

- Hints for a W'?
  - If it's W_R it might decay via ν_R: $W_R \to \ell\nu_R^{(*)} \to \ell(\ell W_R^*) \to \ell(\ell(q\bar{q}'))$
    - Dilepton + two jets final state

CMS, Eur. Phys. J. C 74 (2014) 3149

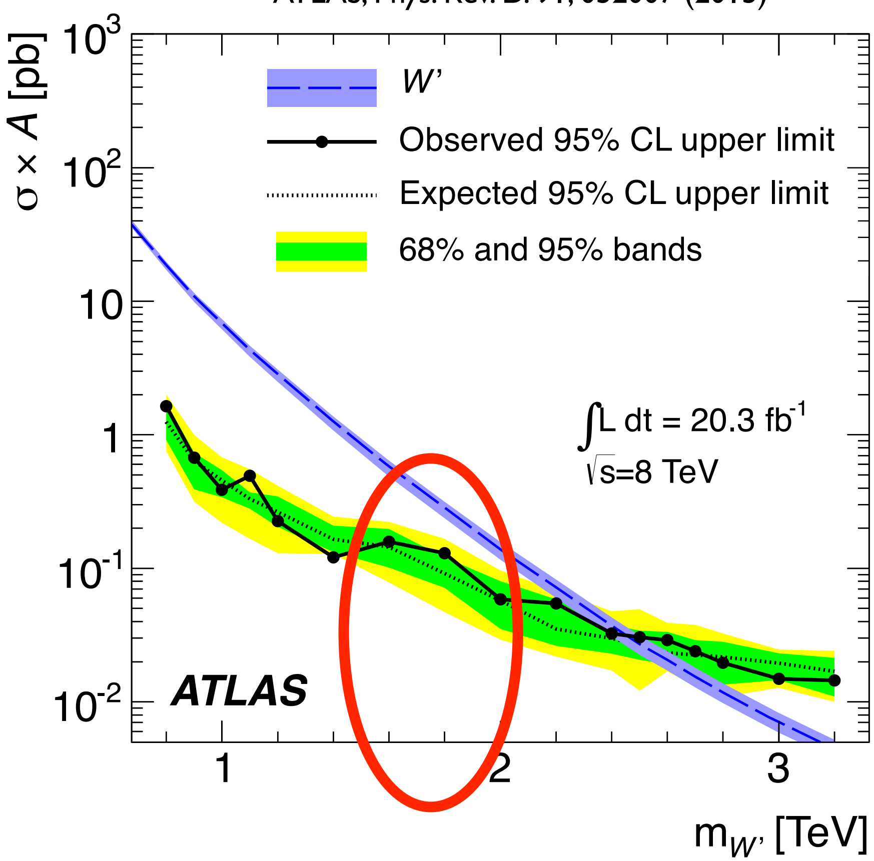




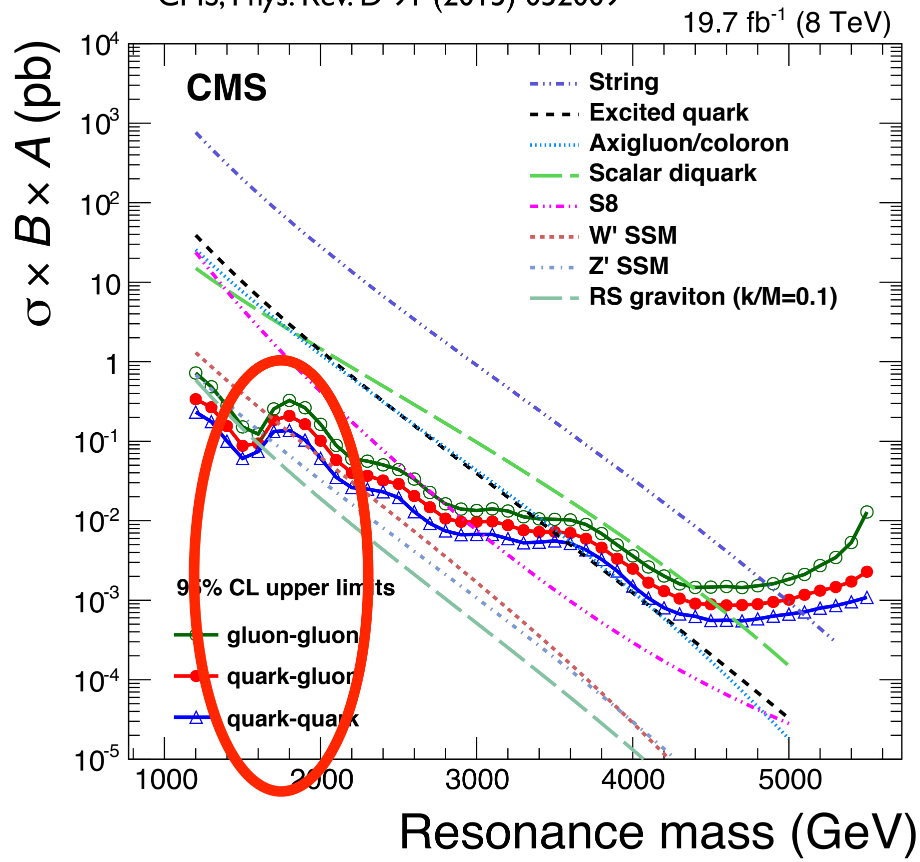


And Remember Dijets

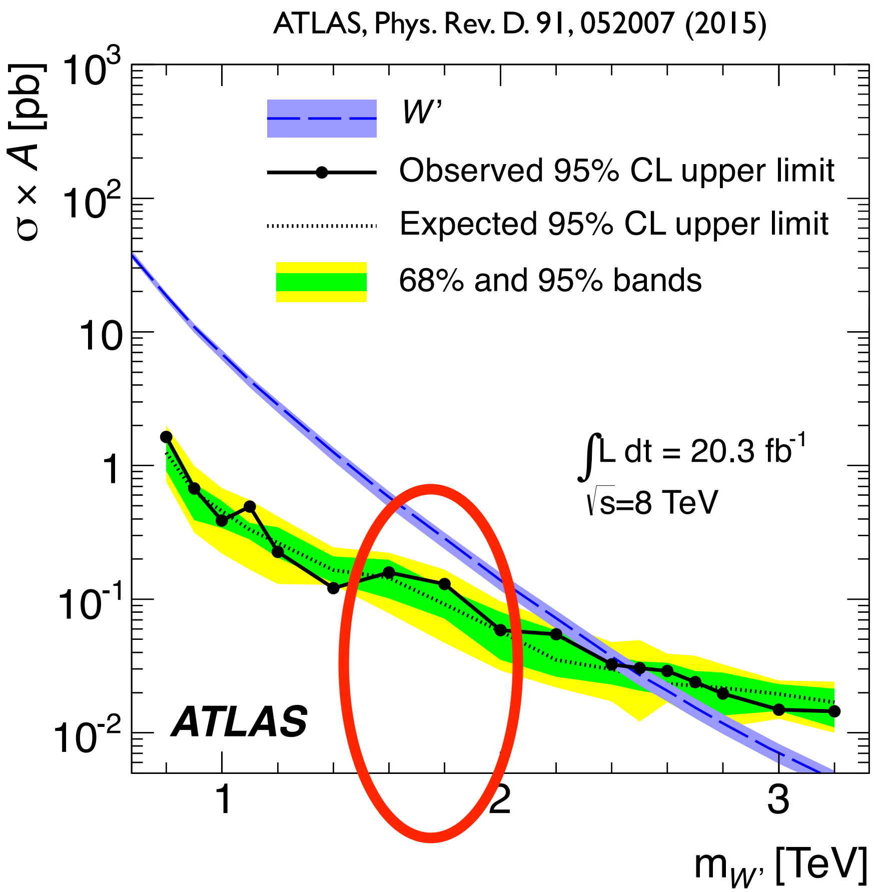
ATLAS, Phys. Rev. D. 91, 052007 (2015)

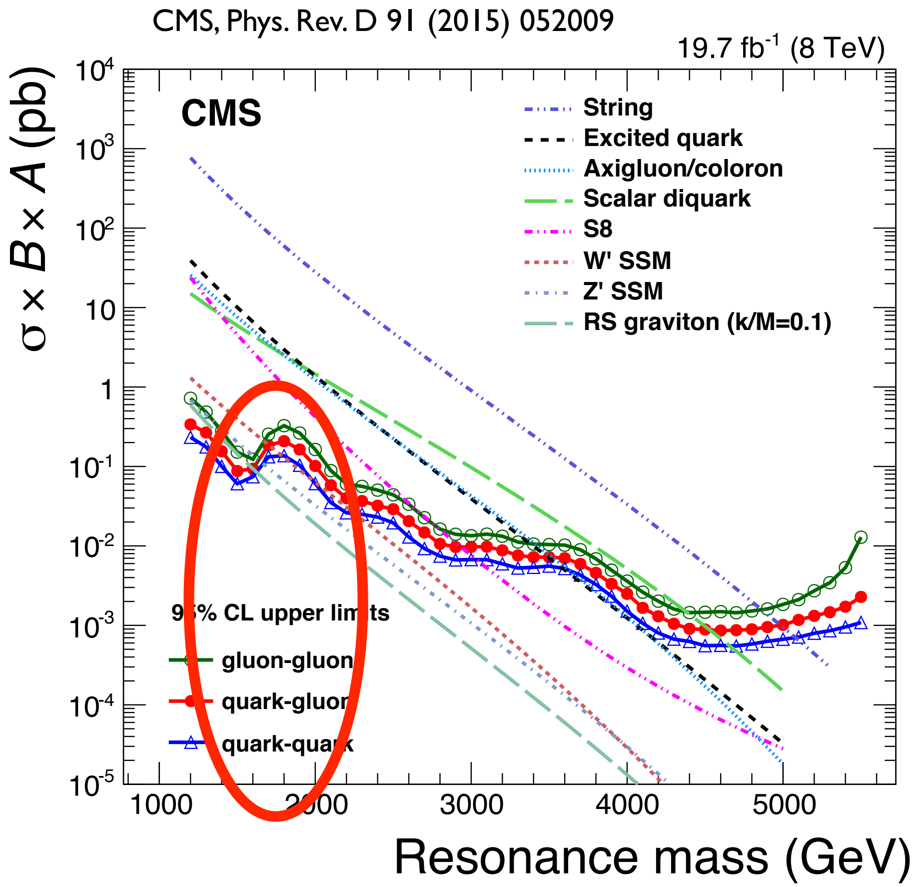


CMS, Phys. Rev. D 91 (2015) 052009



And Remember Dijets

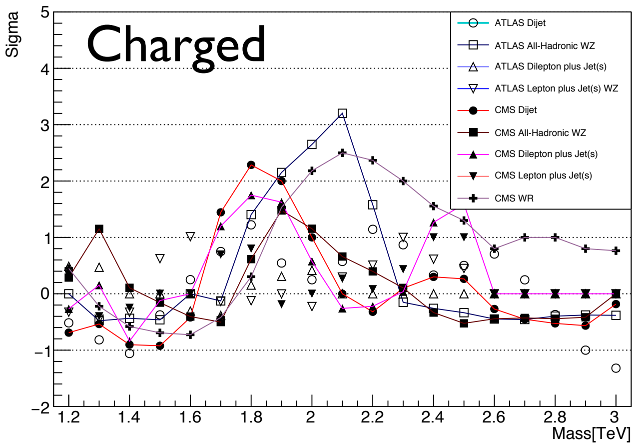


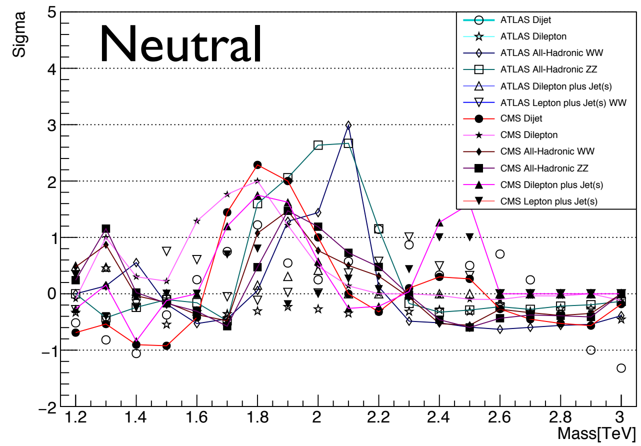


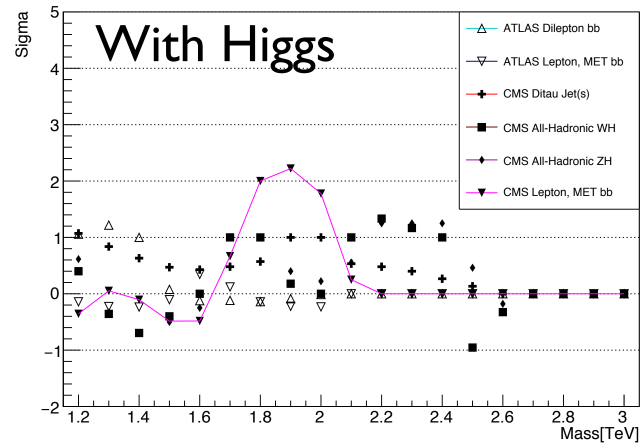
- ➡ Intriguing number of 1-2 sigma excesses at ~1.9 TeV (mostly at edge of kinematic range):
  - 2 in ATLAS: all-hadronic diboson, dijet
  - 5 in CMS: all-hadronic, llJ, WH diboson, W_R, dijet, dilepton

Comparing Excesses

- ❖ Are they all at the same mass?



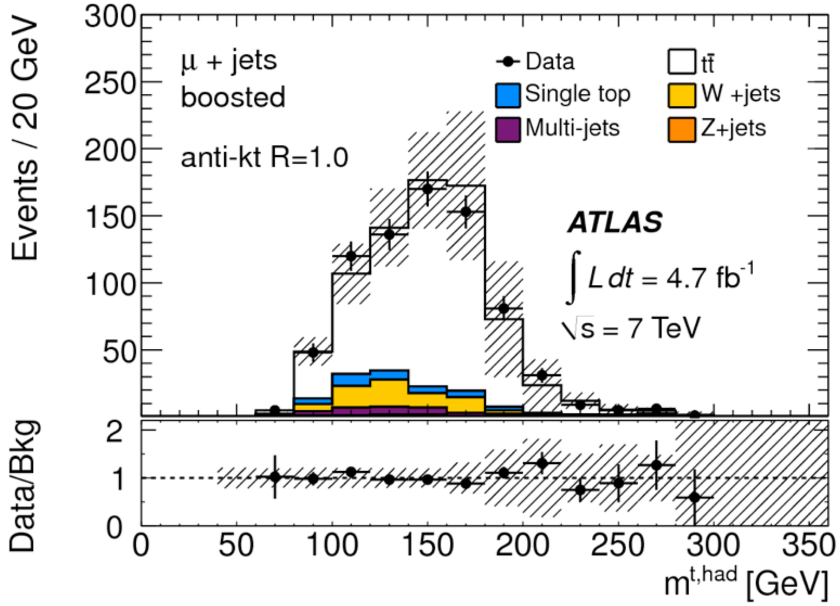




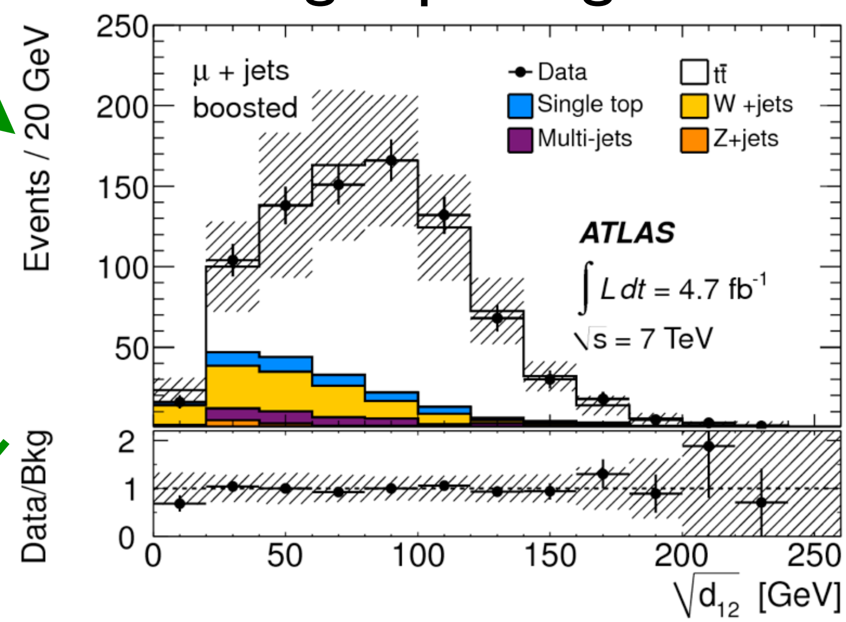
- ❖ Somewhat… need to see what 2016 data brings
  - 3.2 fb^{-1} not competitive as presumably q-$\bar{q}$ production
  - Need to wait for ICHEP results

Di-Top

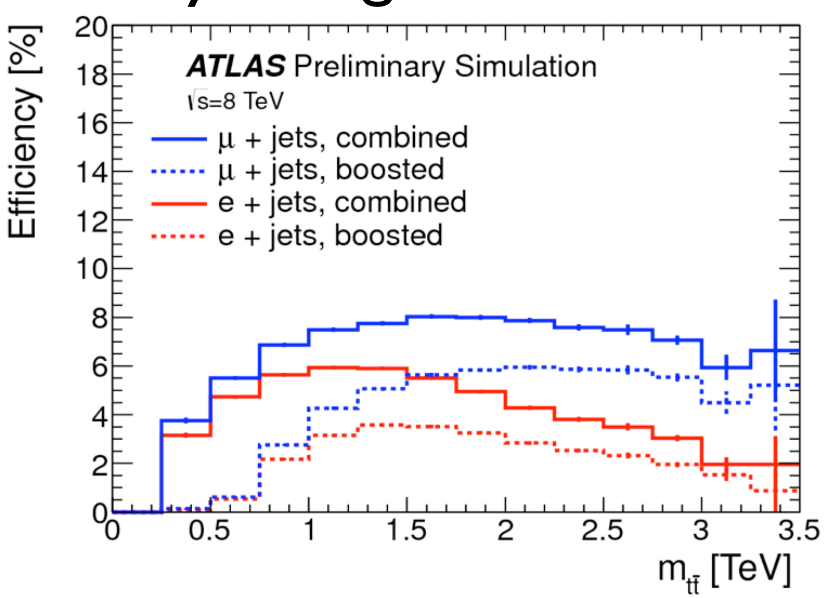
Massive, large-R jet



Large splitting scale

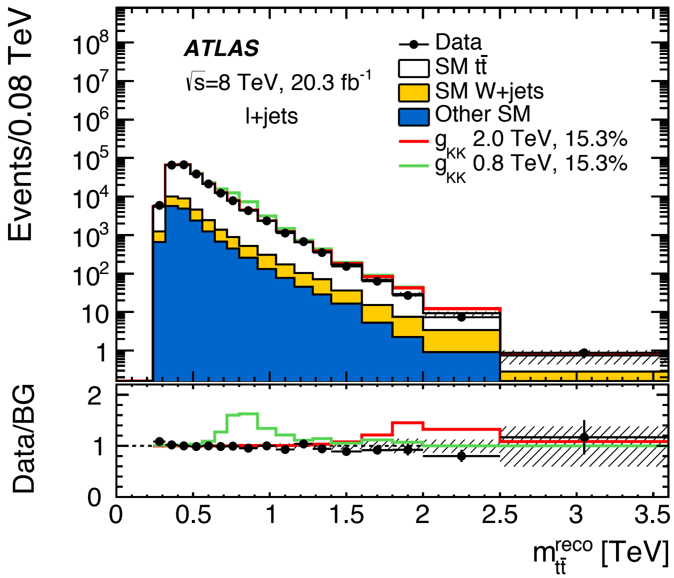


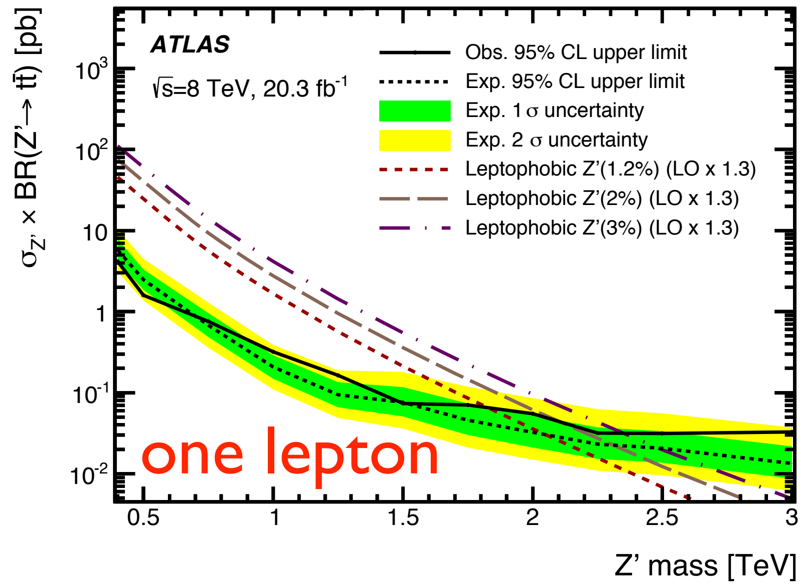
Efficiency at high mass

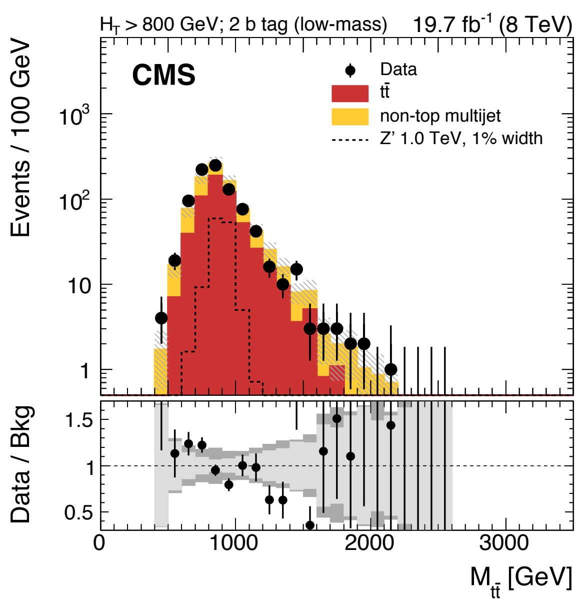


Results

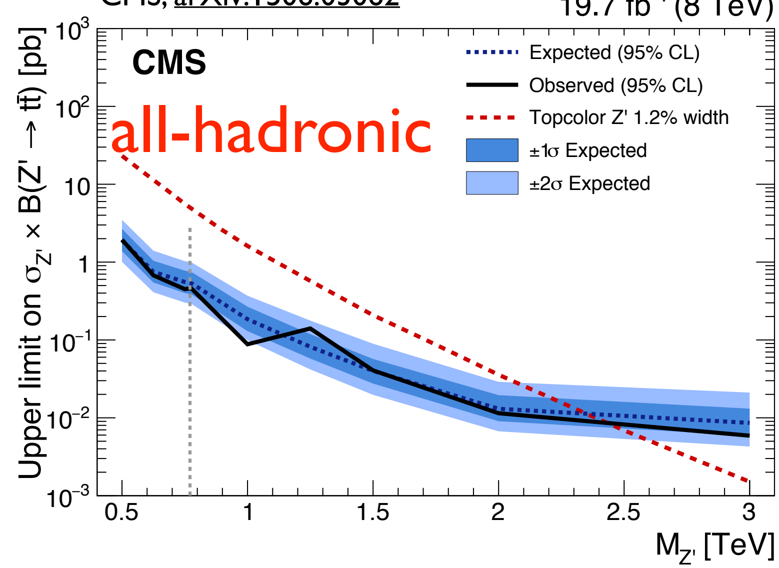
ATLAS, arXiv:1505.07018



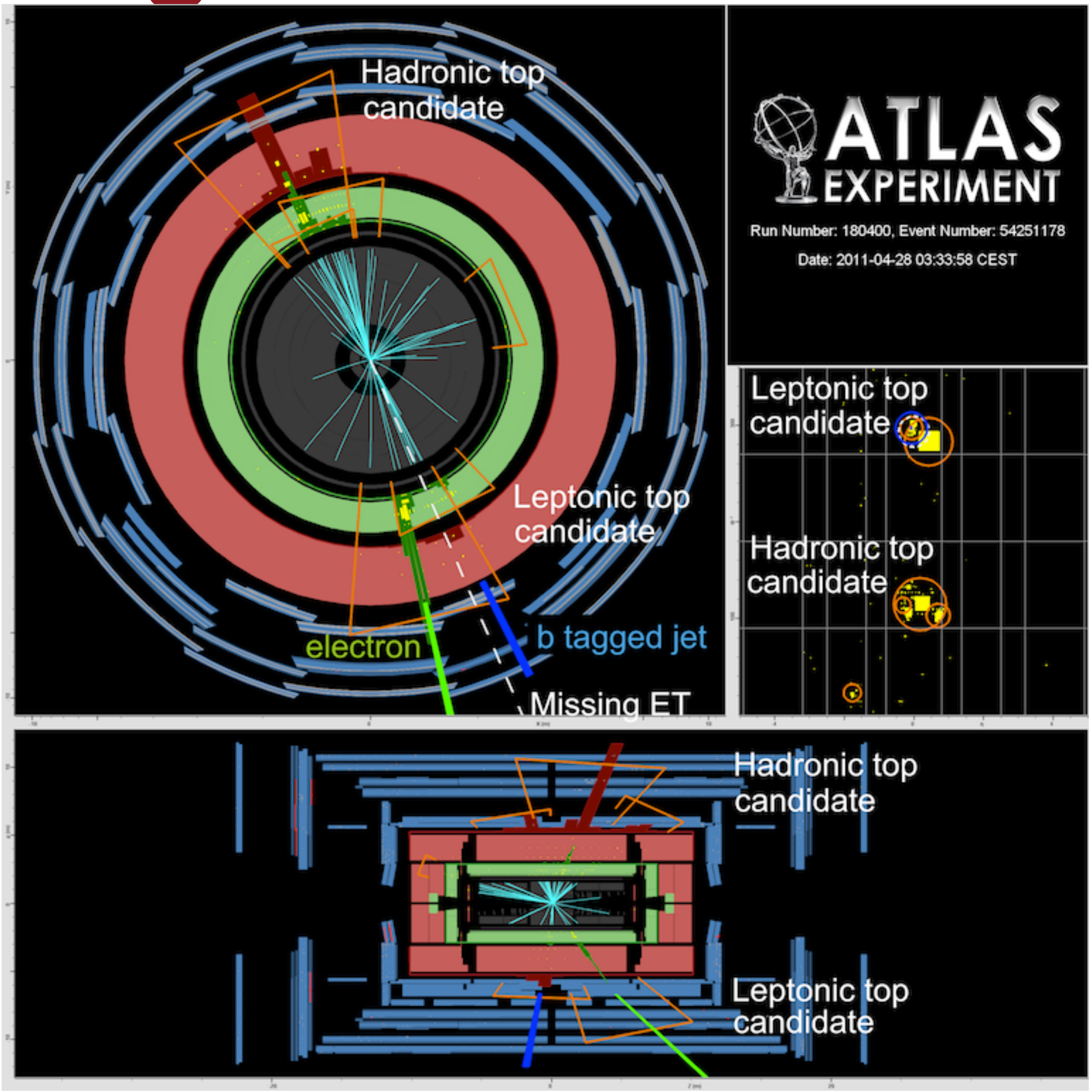




CMS, arXiv:1506.03062



High Mass tt Event

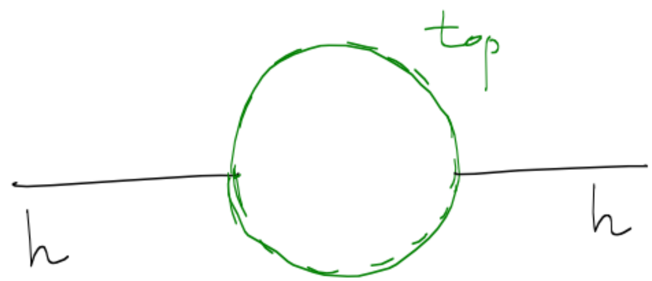


Too Short

- Many topics not or barely addressed
  - Long-lived particles, can decay halfway or outside detector, or get stuck and decay later...
  - “Quirks”
  - “Lepton jets”
  - RPV SUSY
  - Model-independent searches
  - ...
- Many new models have signatures that exist in other models!

The Future

- Convergence on “thoughts for the next machine”
  - Substantial investment ⇒ careful weighing of goals and potential for return on investment
  - Quoting Nima: https://indico.bnl.gov/getFile.py/access?sessionId=9&resId=6&materialId=0&confId=571



$$\left(\frac{\delta m_h^2}{m_h^2}\right) = \left(\frac{\Lambda}{350\,GeV}\right)^2$$

What is Λ?

How will we know?

- Higher Energy, Most Obviously!!
  - * Find Something! → End of discussion!
  - * Find Nothing → Tuning $\propto E^2_{machine}$
- Rare processes
- Precision measurements

} Indirect, Linear gain in tuning

LHC @ 13 TeV : Few % tuning

LHC @ 33 TeV : Sub-% tuning!

* Best for finding heavy particles
* Best + most direct quantifier of tuning

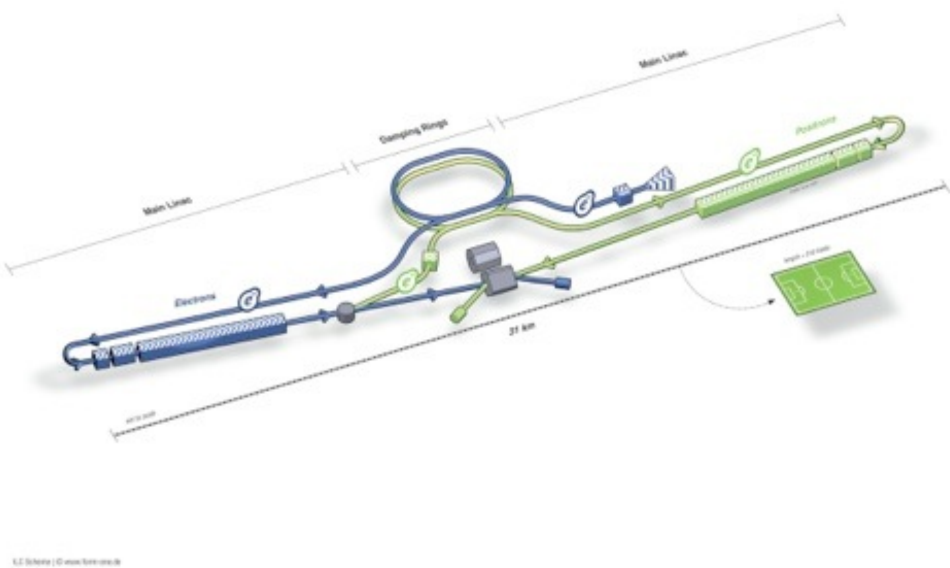
Precision Higgs Couplings

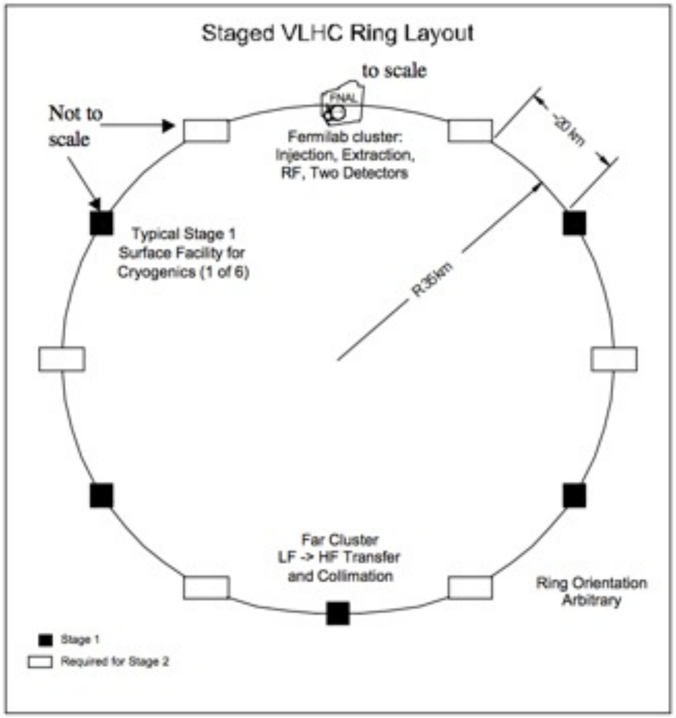
"LHC will get to 10%, Higgs factory to 1%"

* Can a deviation of 1% be solidly established?
* Doesn't LHC see underlying NP anyway?

To Close

- Proton stability, couplings suggest ~10^{16} GeV is an important scale
  - Can probe through EDMs, n-n̄, μ → e, ... *important!*
  - Implies fine-tuning, so, new physics nearby?
- New physics at 2 TeV?





Thanks

(and mainly: stay critical of what you're told!)