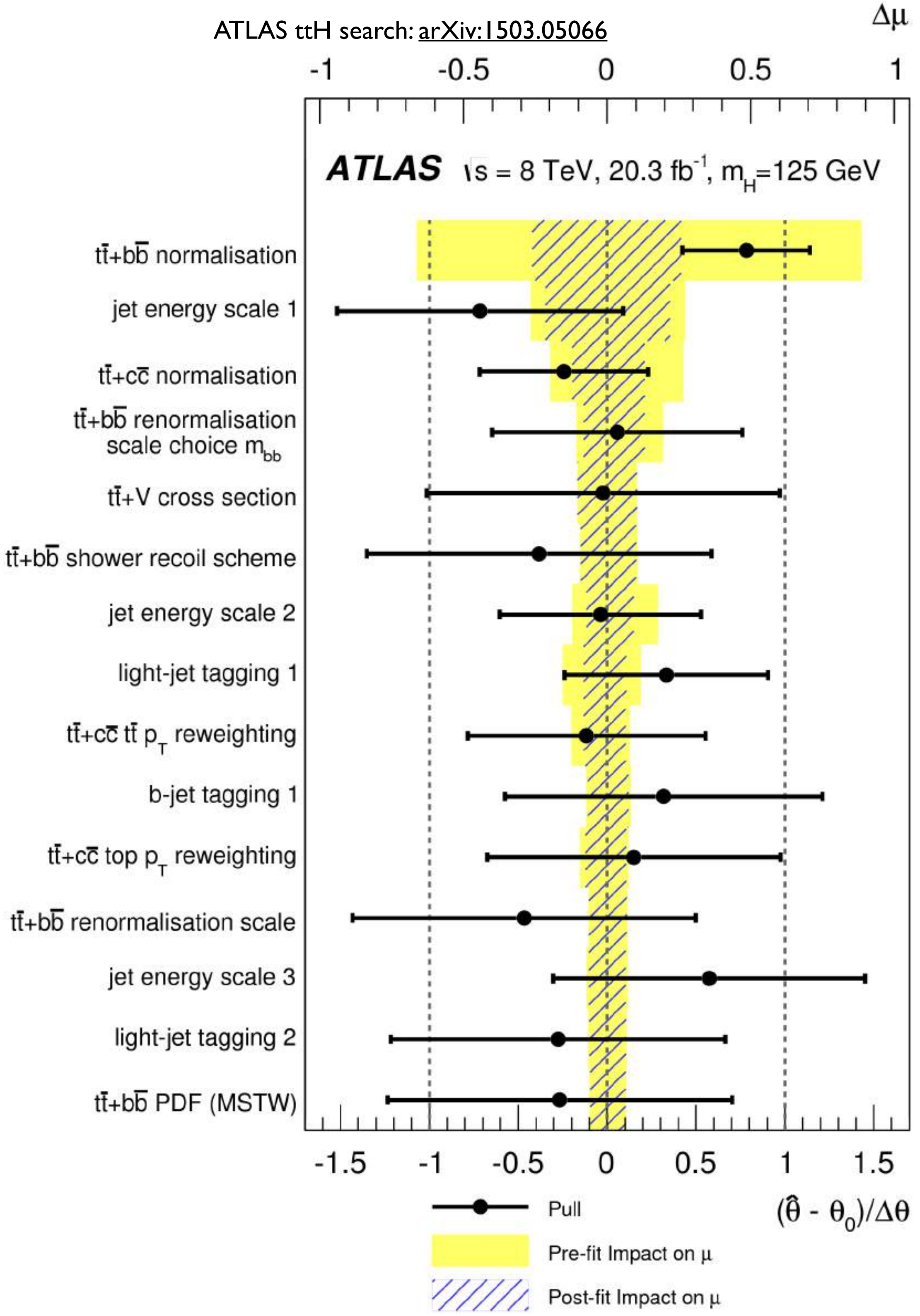
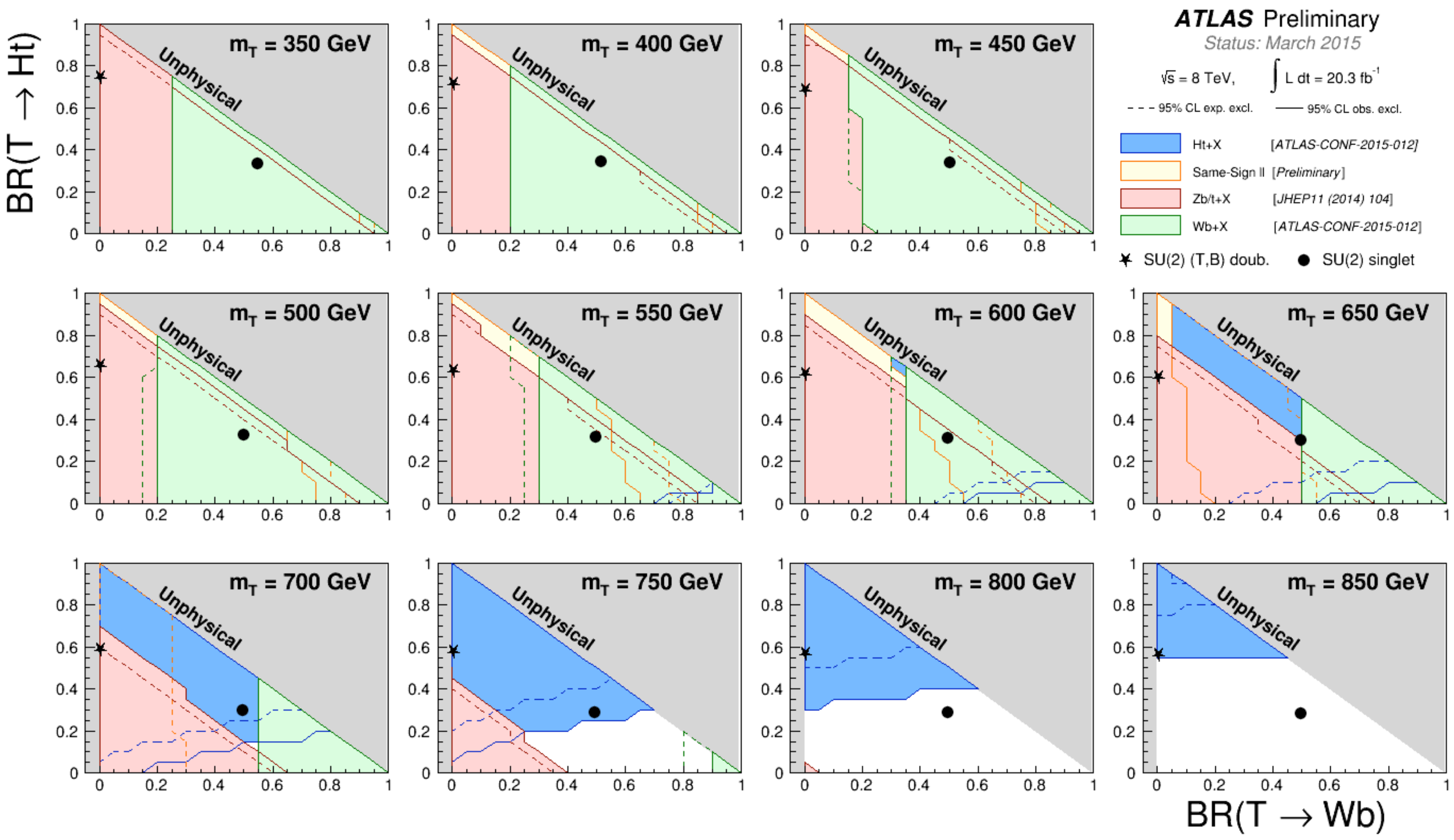
Fit Results

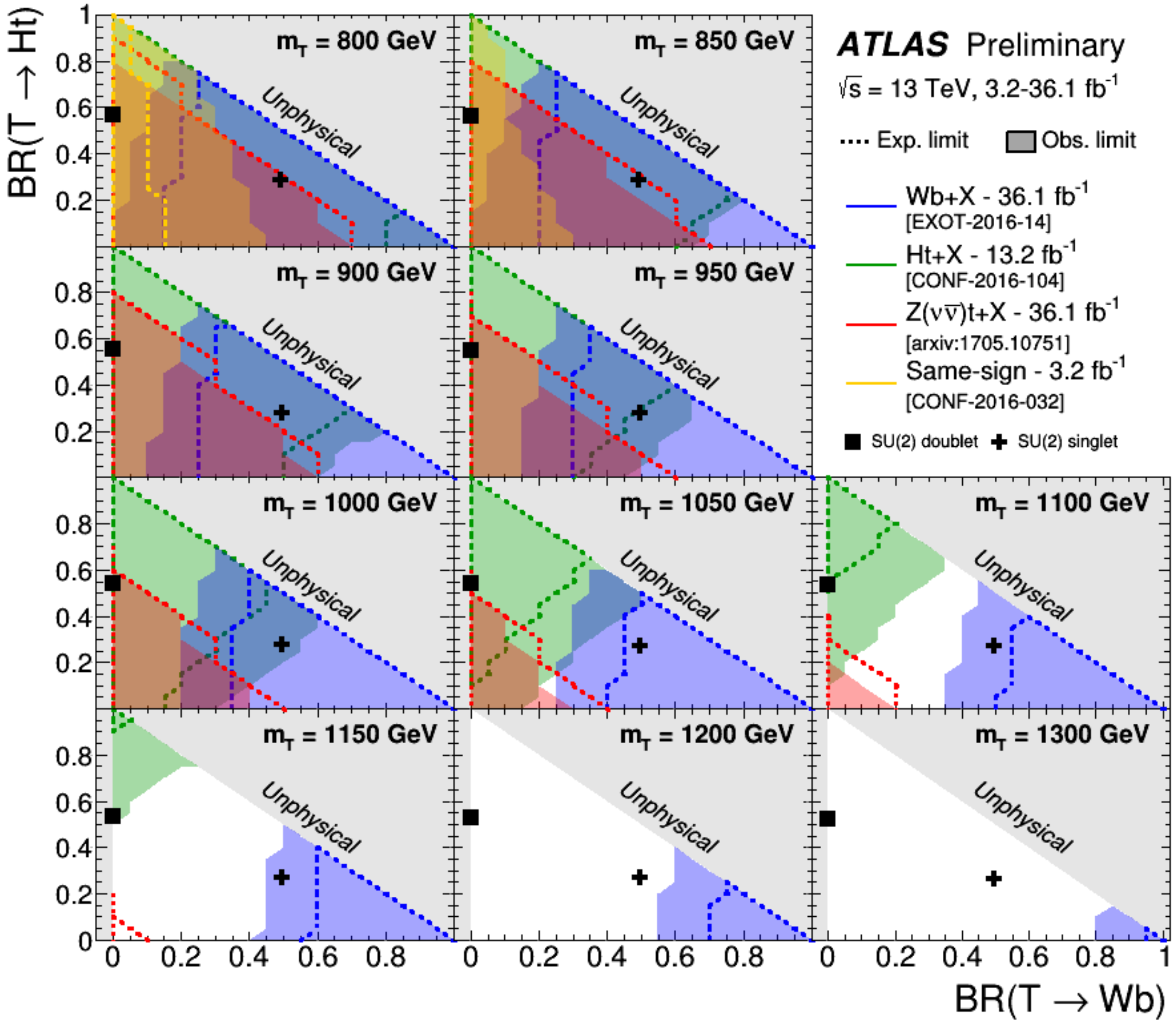
- Need to compare starting point and results
  - Pathologies due to lack of MC stats in some areas, strong correlations, …
- Crucial to design analysis with good control regions the fit can use to address least understood systematics

ATLAS ttH search: arXiv:1503.05066



All Together Now

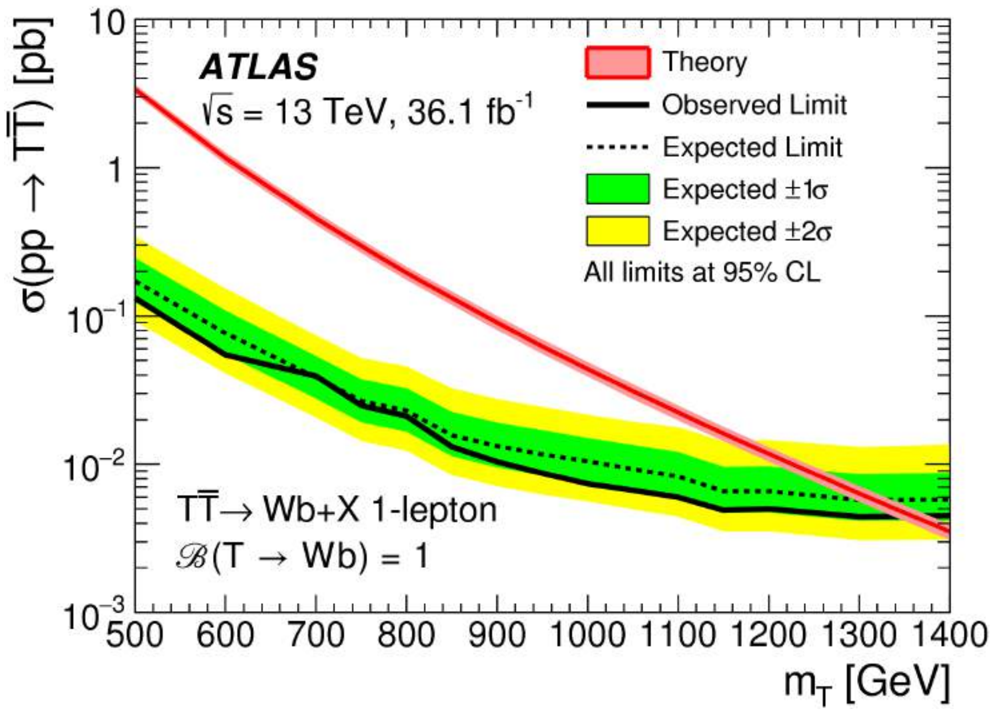




Numbers very similar as for stop….

Choosing a Topic

- Scalar and fermionic top partner searches have very similar high mass sensitivity
  - Not surprising: cross-section higher for fermions, but mass limit only moderately sensitive to that
    - Low background at high mass
- What about overlaps?
  - Turns out SUSY searches have good sensitivity to vector-like quarks!
    - SUSY large MET requirement maps to e.g. $Z \rightarrow \nu\nu$



arXiv:1608.01312

TTK-16

Complementarity of Resonant Scalar, Vector-Like Quark and Superpartner Searches in Elucidating New Phenomena

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(Dated: August 30, 2016)

The elucidation of the nature of new phenomena requires a multi-pronged approach to understand the essential physics that underlies it. As an example, we study the simplified model containing a new scalar singlet accompanied by vector-like quarks, as motivated by the recent diphoton excess at the LHC. To be specific, we investigate three models with $SU(2)_L$-doublet, vector-like quarks with Yukawa couplings to a new scalar singlet and which also couple off-diagonally to corresponding Standard Model fermions of the first or third generation through the usual Higgs boson. We demonstrate that three classes of searches can play important and complementary roles in constraining this model. In particular, we find that missing energy searches designed for superparticle production, supply superior sensitivity for vector-like quarks than the dedicated new quark searches themselves.

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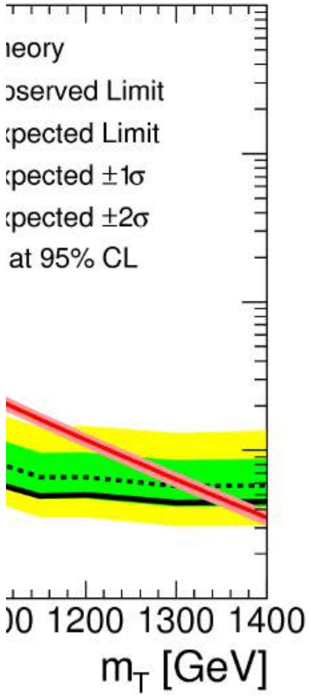
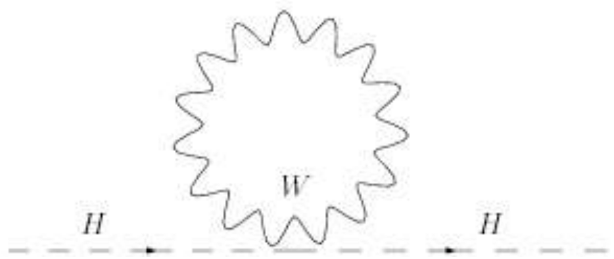


Parity

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! (The whole point of the Higgs mechanism is to decouple masses from interactions!)
    - But even the Higgs wants W/Z partners!



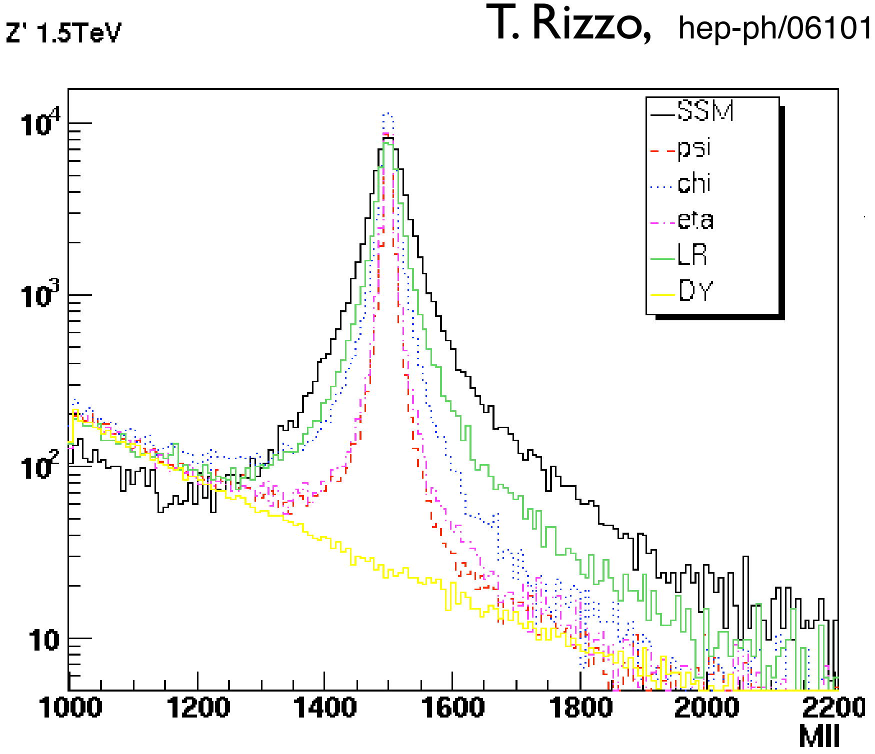
$$\longrightarrow \frac{1}{16\pi^2} g^2 E^2$$

Parity Restoration: Signals

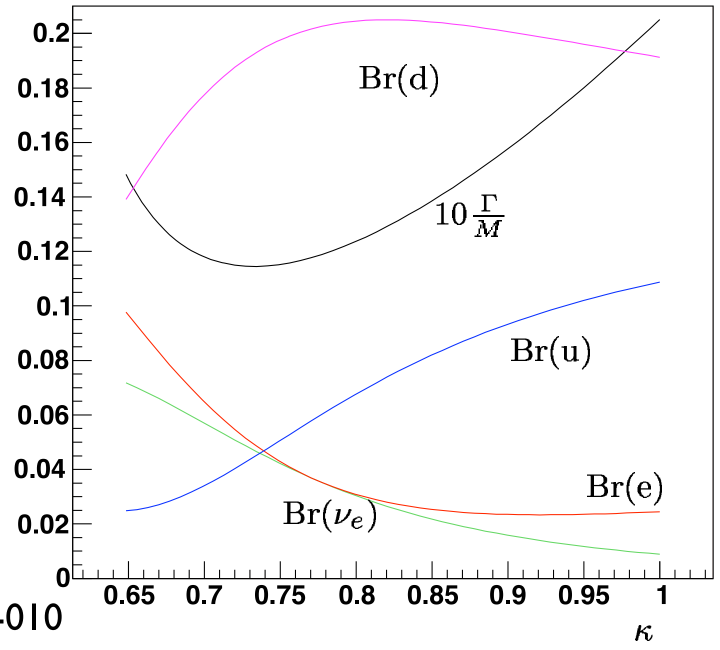
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances (Z') offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p_T
  - $t\bar{t}$ decays visible
  - 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 arXiv:0801.1345
  - W'/Z' would also require new fermions…

Z' Production and Decay

T. Rizzo, hep-ph/0610104



- ❖ 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

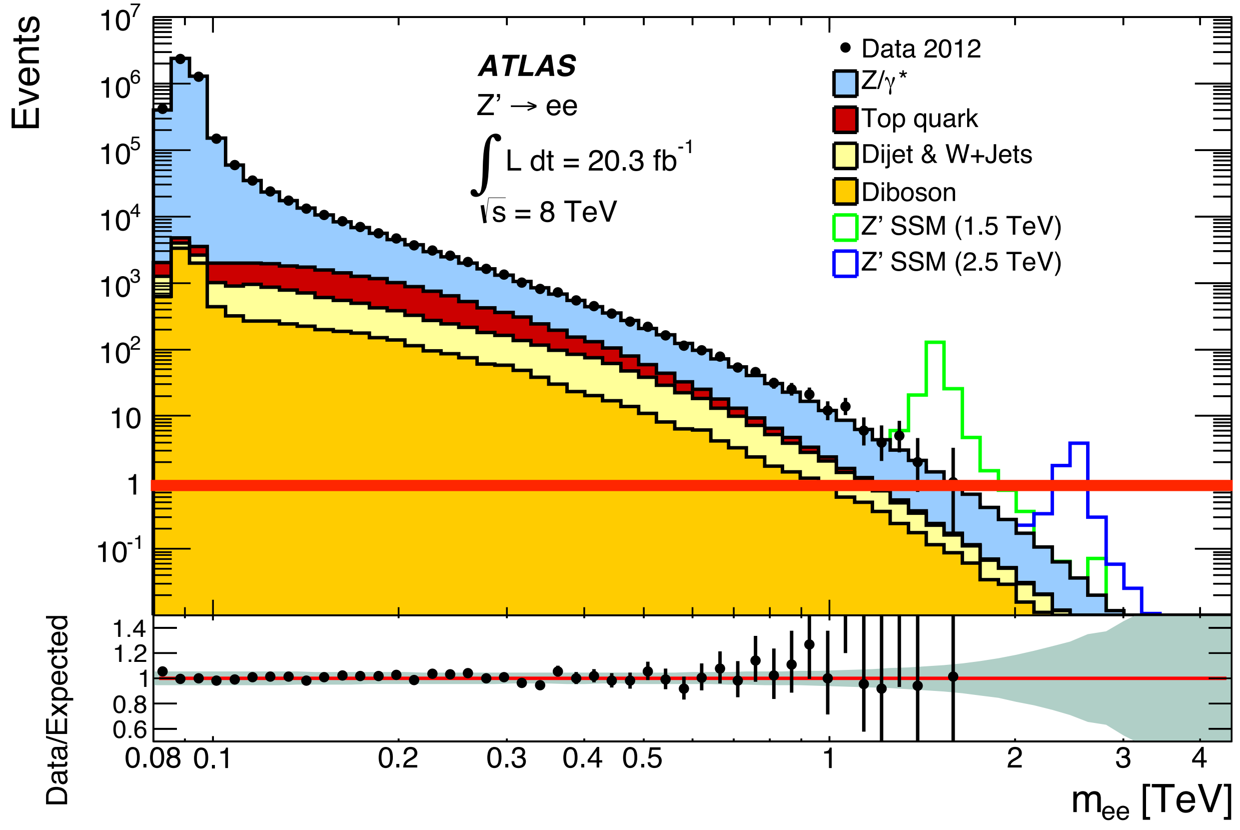


ATL-PHYS-PUB-2005-010

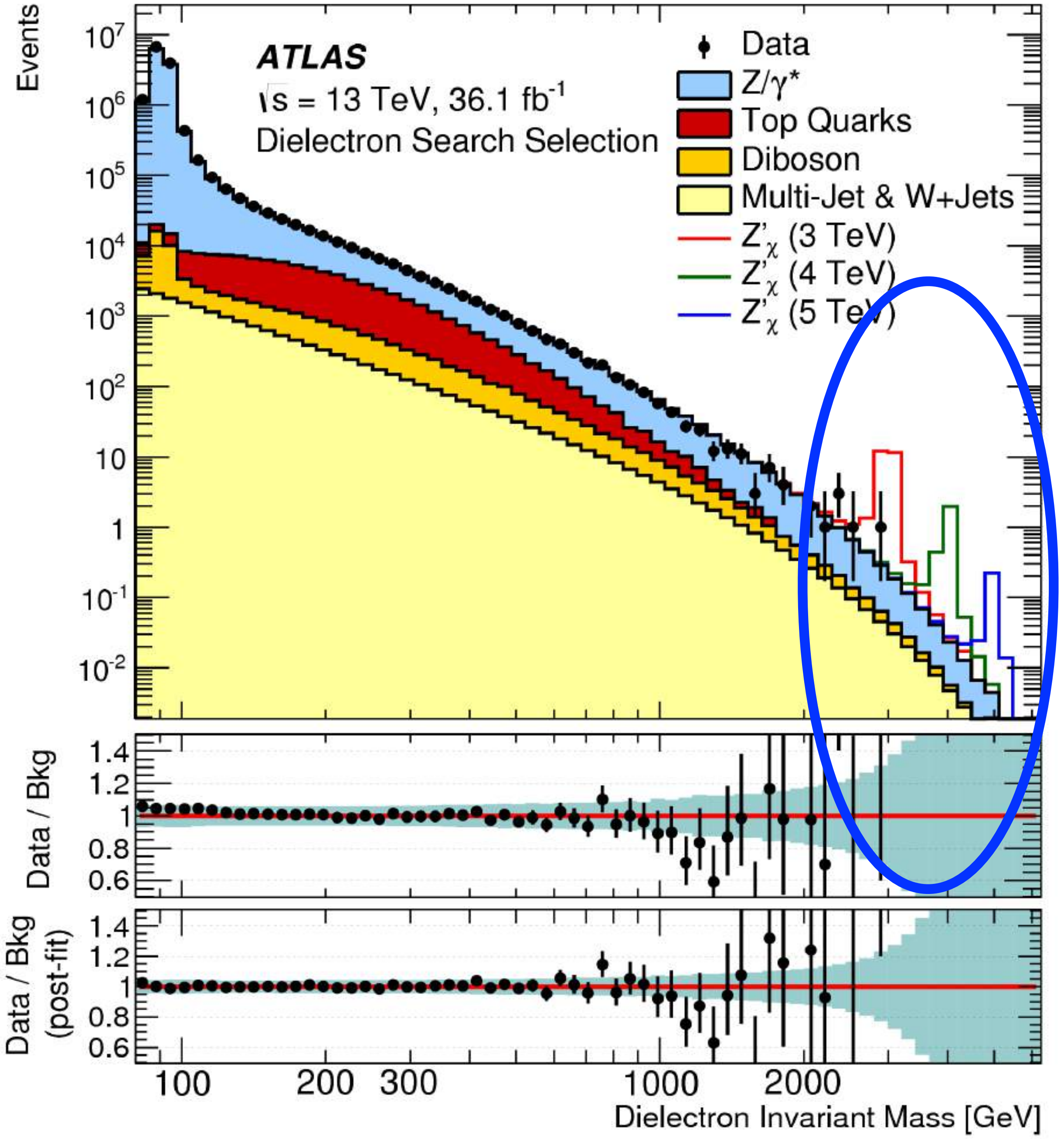
$Z' \to ee/\mu\mu$

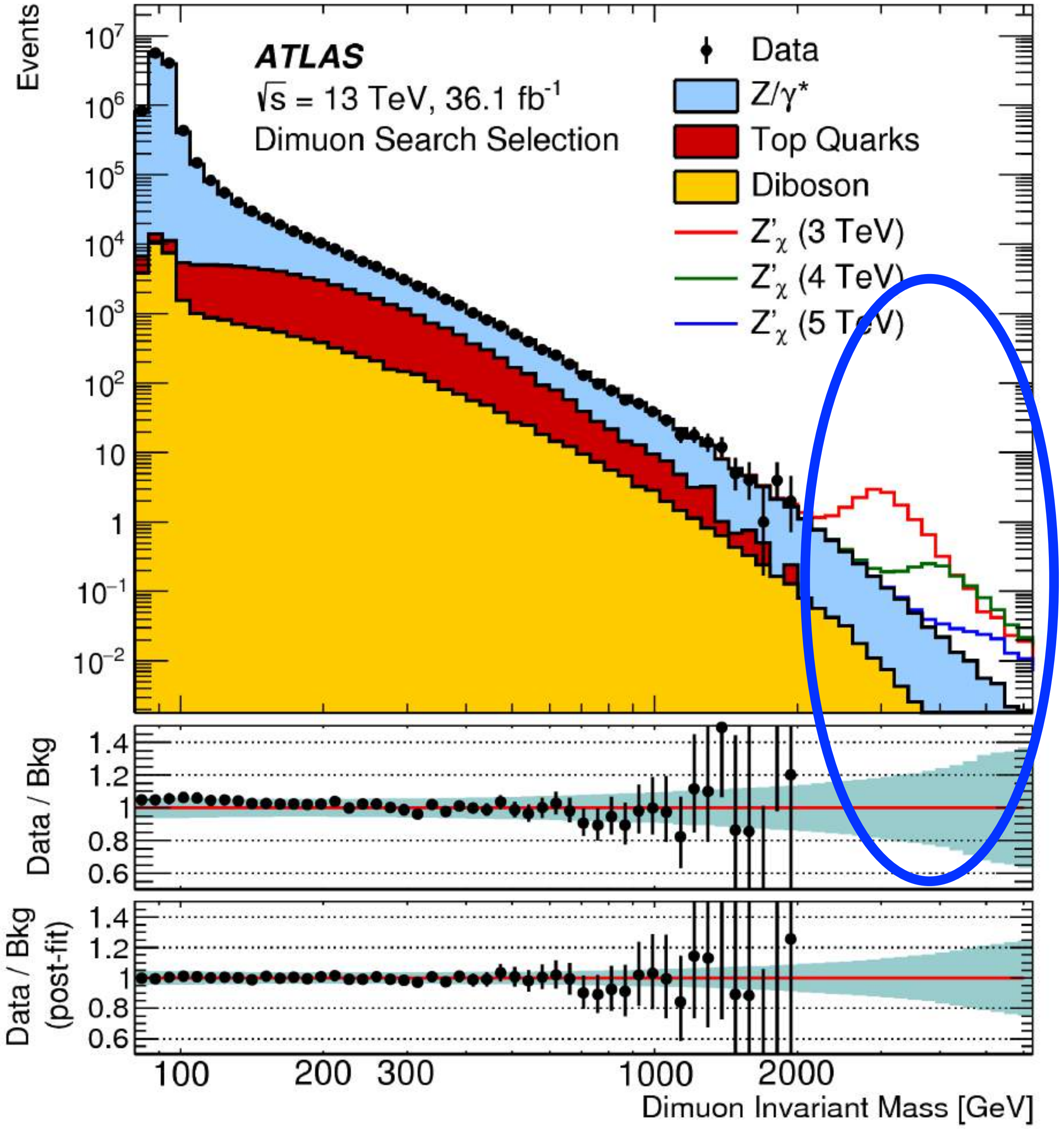
- Most promising channels:
  - Backgrounds very low!
  - "Self-calibrating"
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- LHC extended Tevatron reach immediately!
  - Limits now hitting 4+ TeV

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



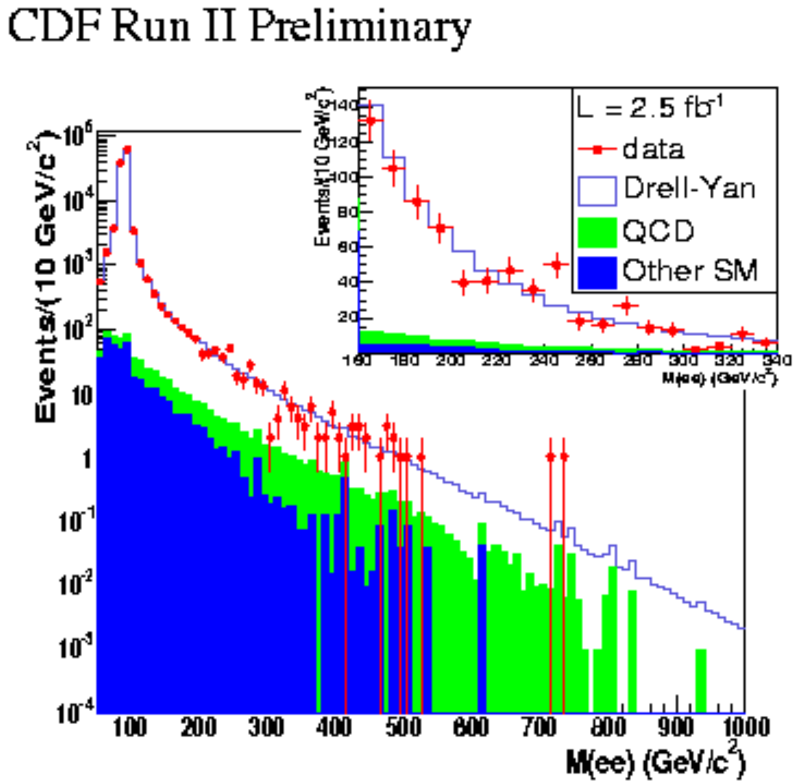
e vs μ

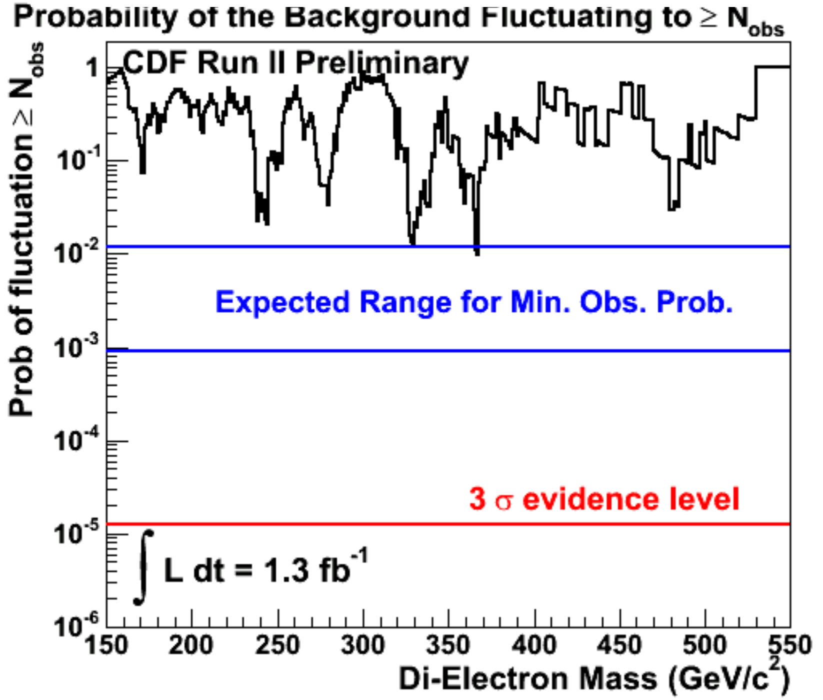

ATLAS
√s = 13 TeV, 36.1 fb-1
Dielectron Search Selection
Data
Z/γ*
Top Quarks
Diboson
Multi-Jet & W+Jets
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
Data / Bkg
Data / Bkg (post-fit)
Dielectron Invariant Mass [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
Dimuon Search Selection
Data
Z/γ*
Top Quarks
Diboson
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
Data / Bkg
Data / Bkg (post-fit)
Dimuon Invariant Mass [GeV]

"Look Elsewhere" Effect

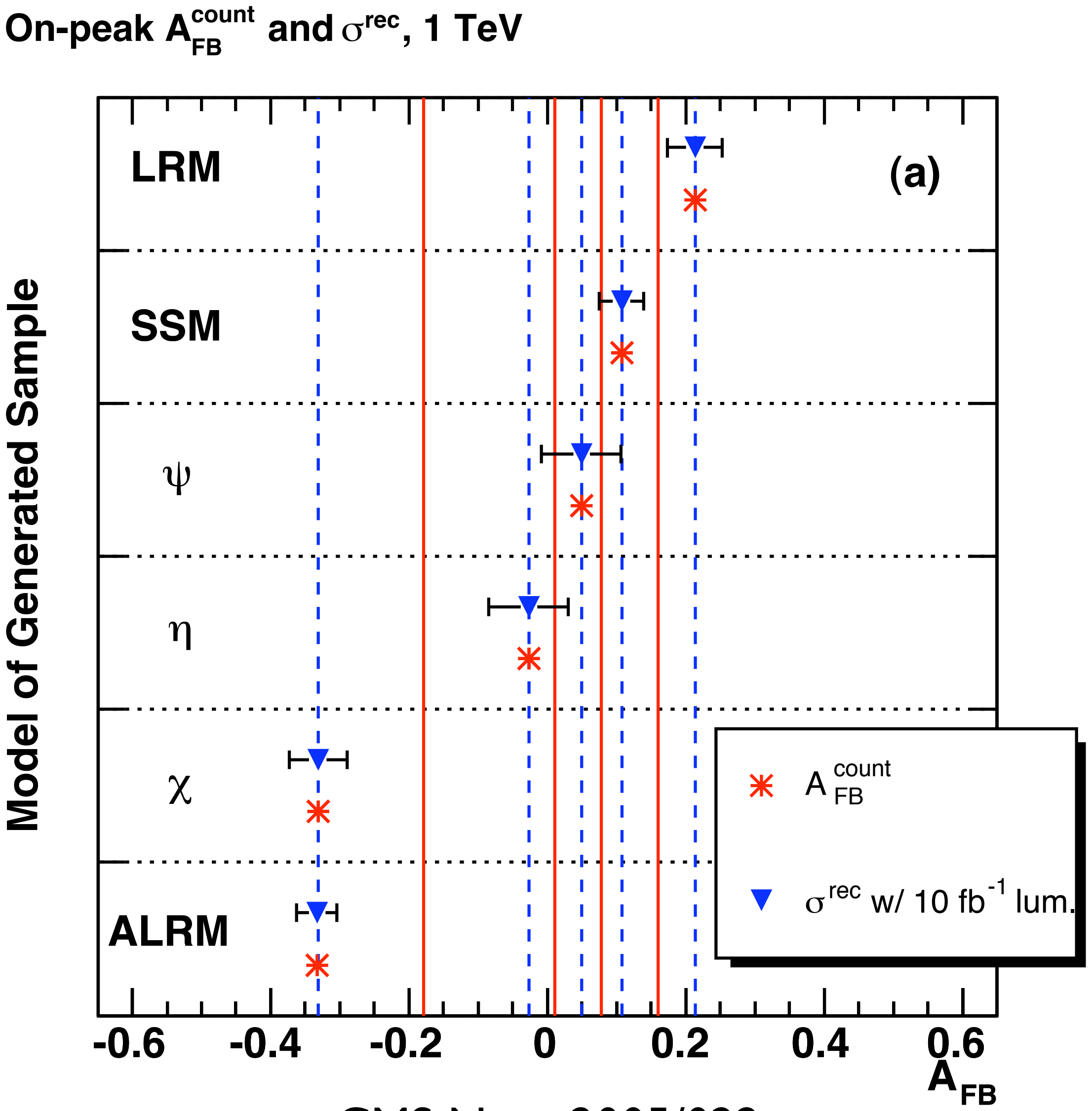
- ❖ If search is done by counting experiment in a shifting mass window, need to factor in "look elsewhere" effect ($\propto$ # of windows)
  - Always an excess if look at enough distributions...
- ❖ Global fit to the (DY) spectrum is another approach
  - Let fit find the mass
  - Shape analysis more sensitive
- ❖ Run pseudo-experiments!





Model Determination

- Angular distribution gives excellent handle on g_V, g_A for various fermions
  - Charm may be possible
- This will come after an initial determination of branching ratios (obviously)
  - Complementary information in determining nature of resonance

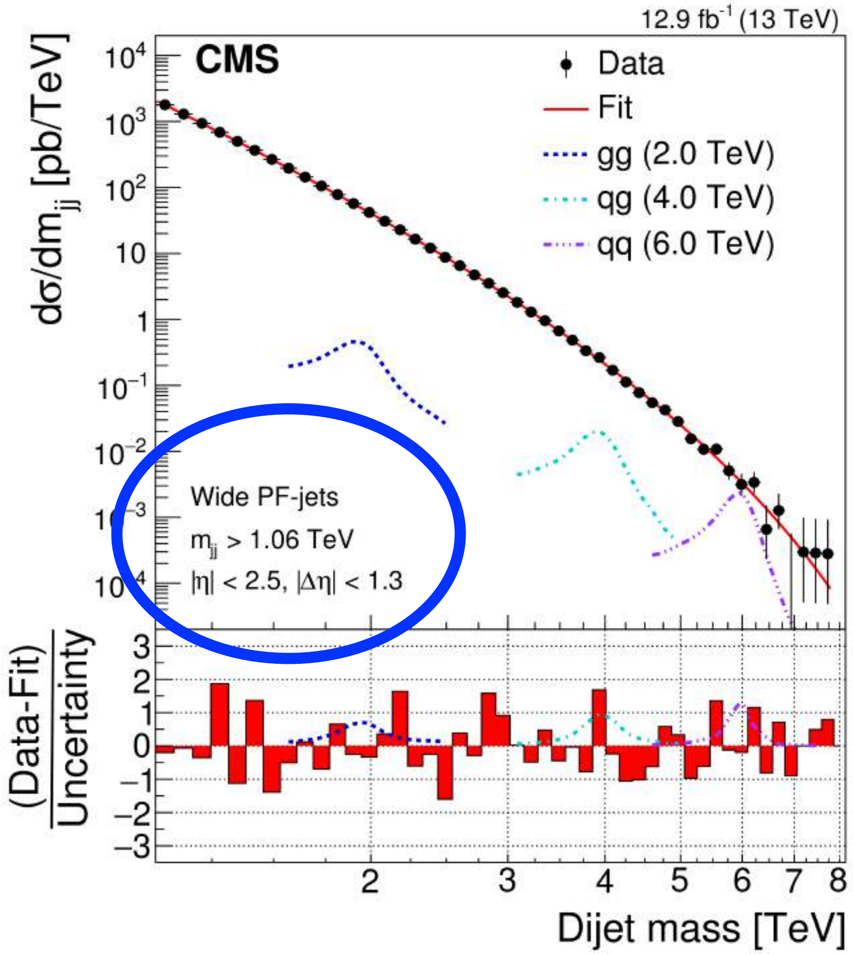


CMS Note 2005/022

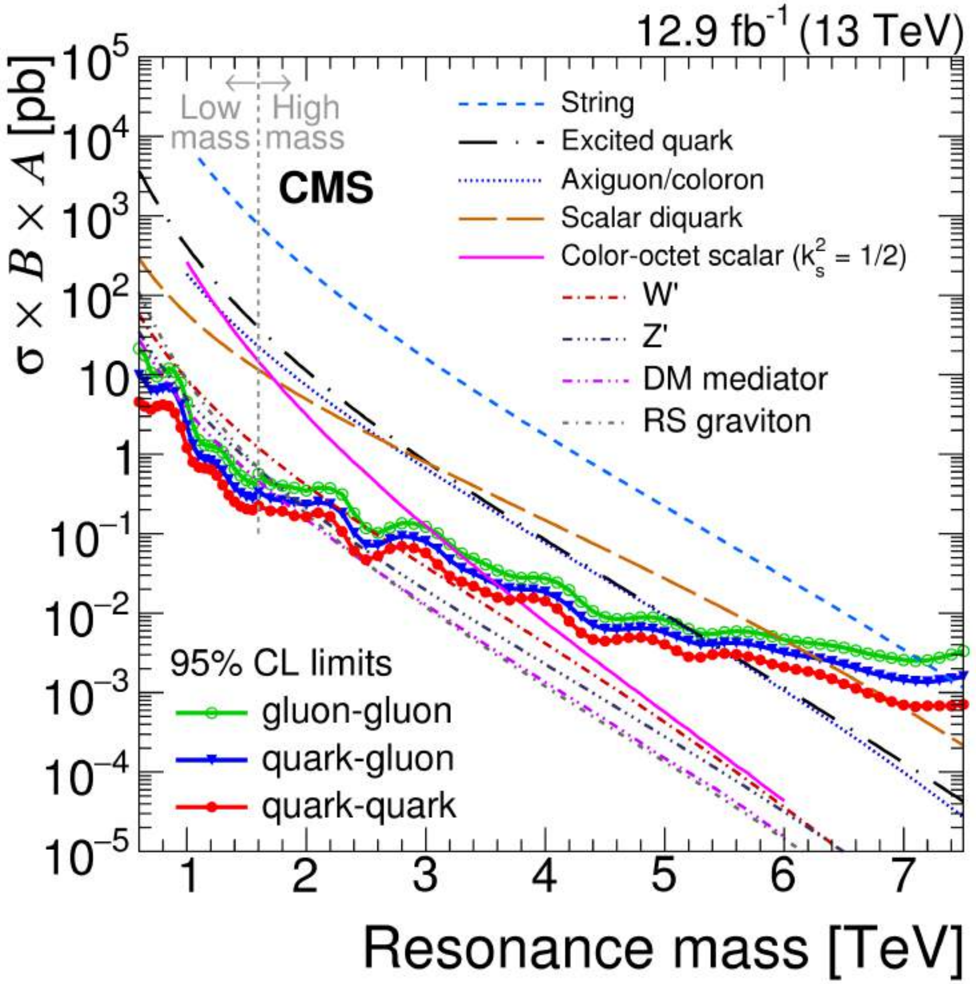
Dijets

❖ SM Background obviously much larger

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

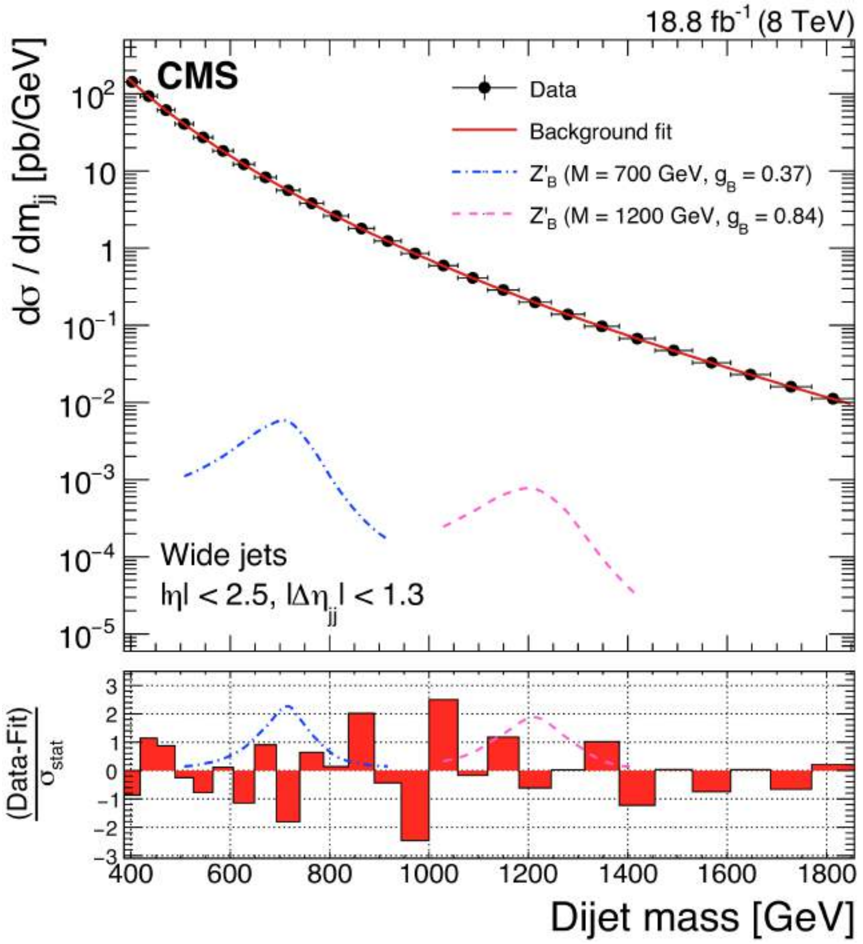


CMS
[Phys. Lett. B 769 (2017) 520]



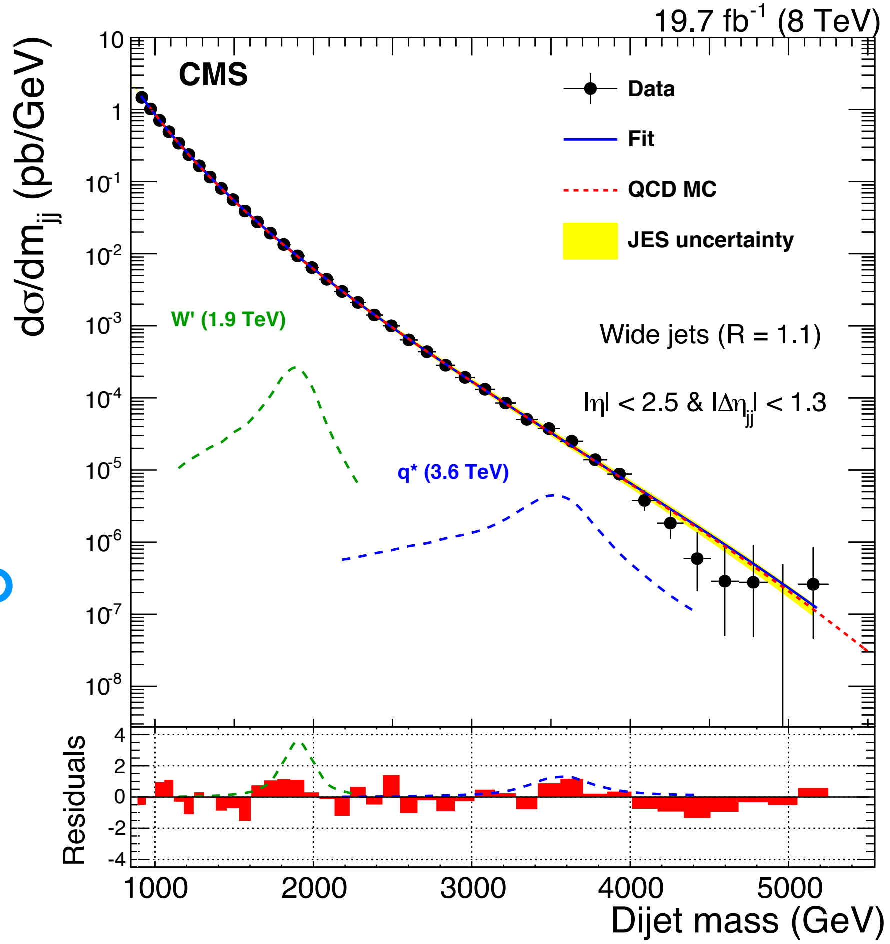
Scouting

- ❖ 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

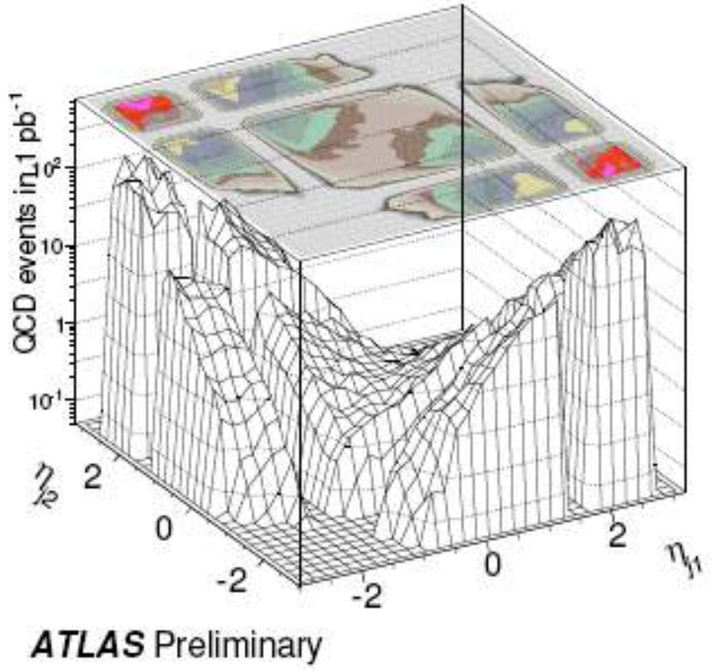
Compare to

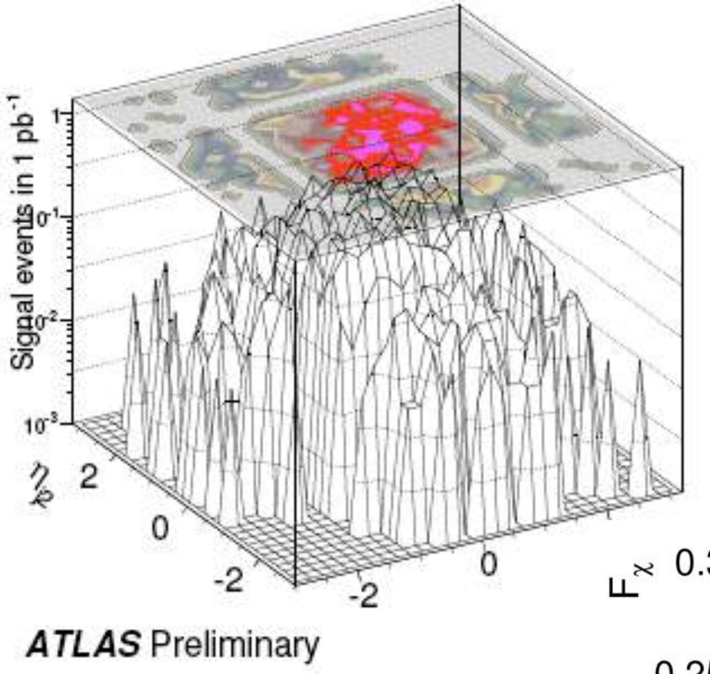


Angles

875 GeV < m_{jj} < 1020 GeV

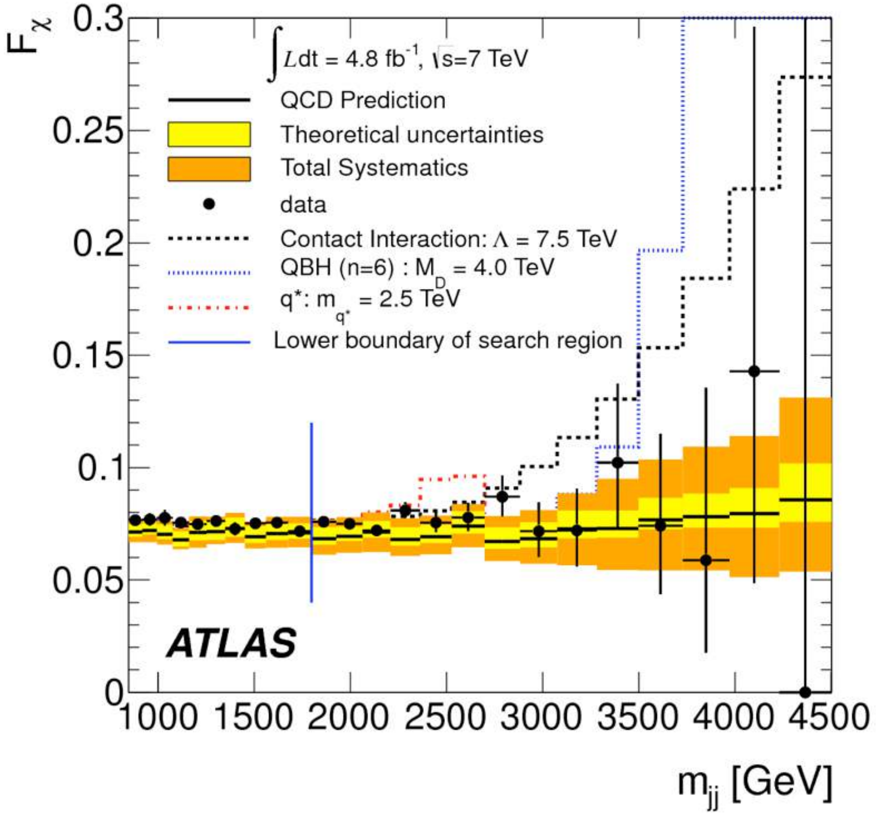
QCD





q*

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



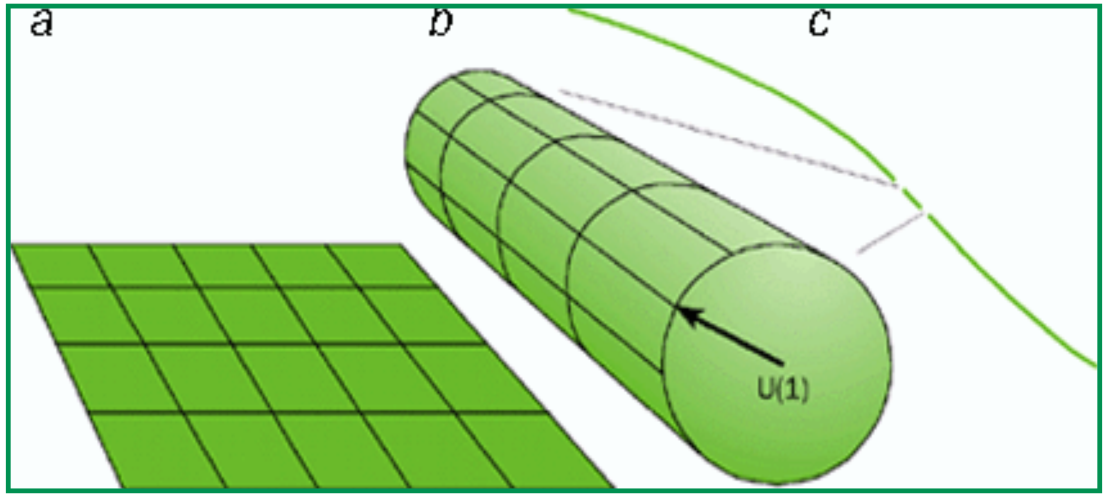
- ❖ High mass object → large boost → central
  - But background dominated by QCD "elastic" scatters and larger angle = higher mass
  - "Δη" cuts used in many analyses

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

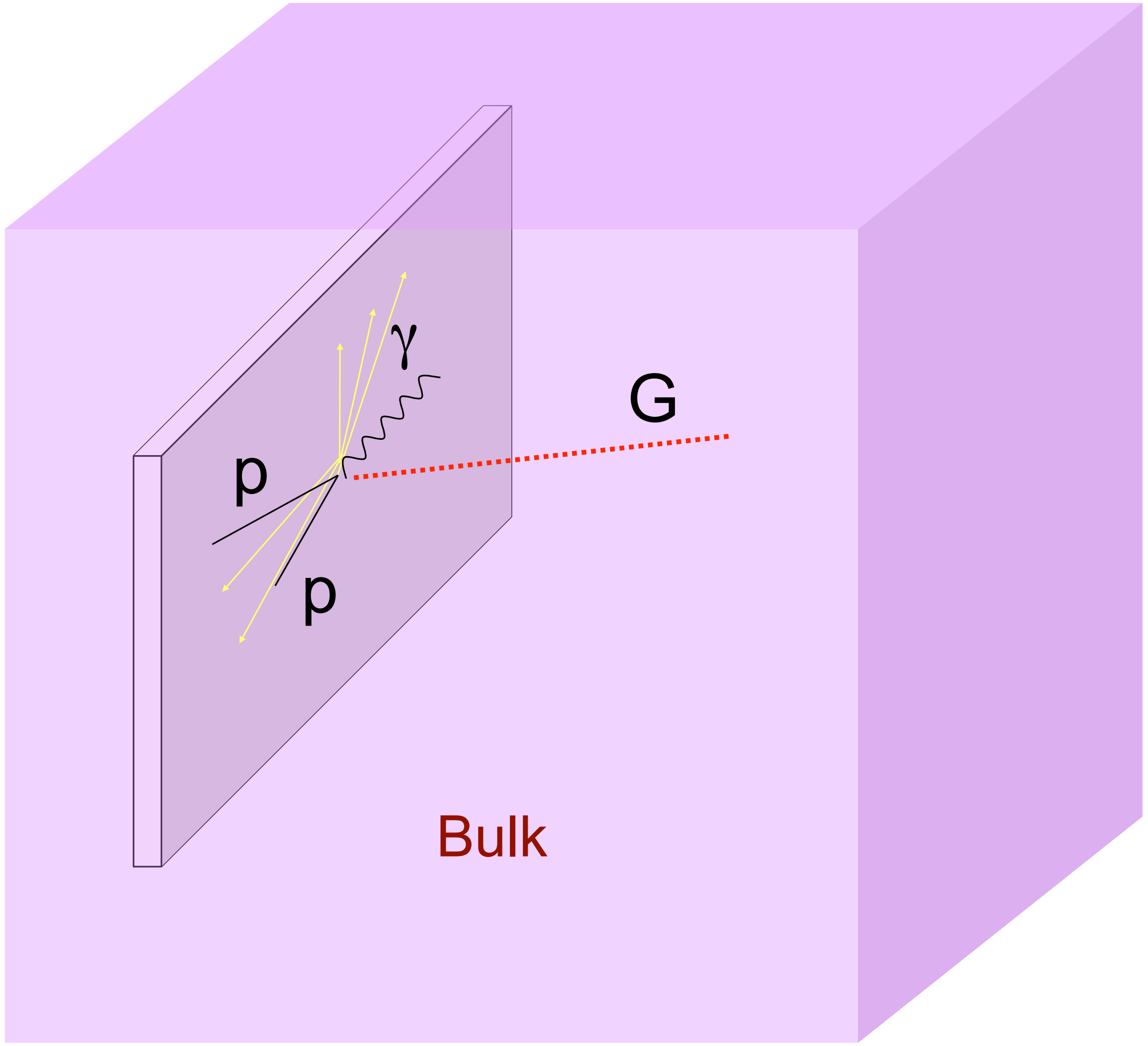
- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

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"

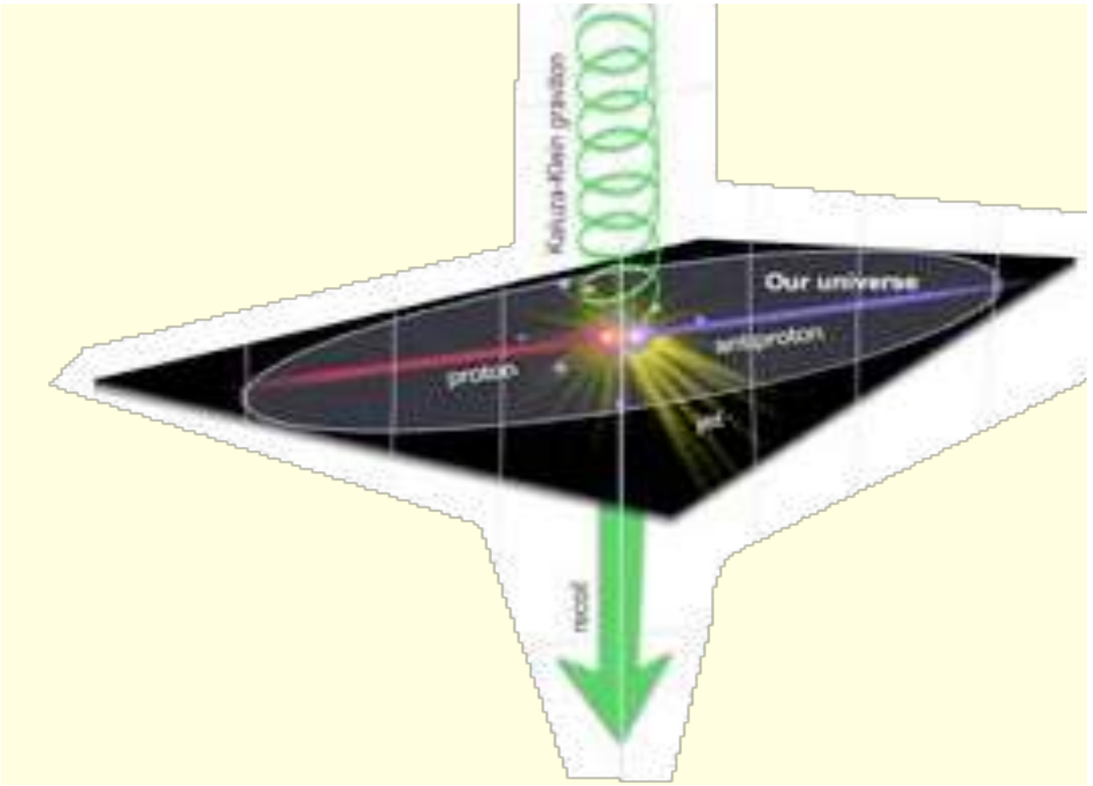


Drawing by K. Loureiro

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)

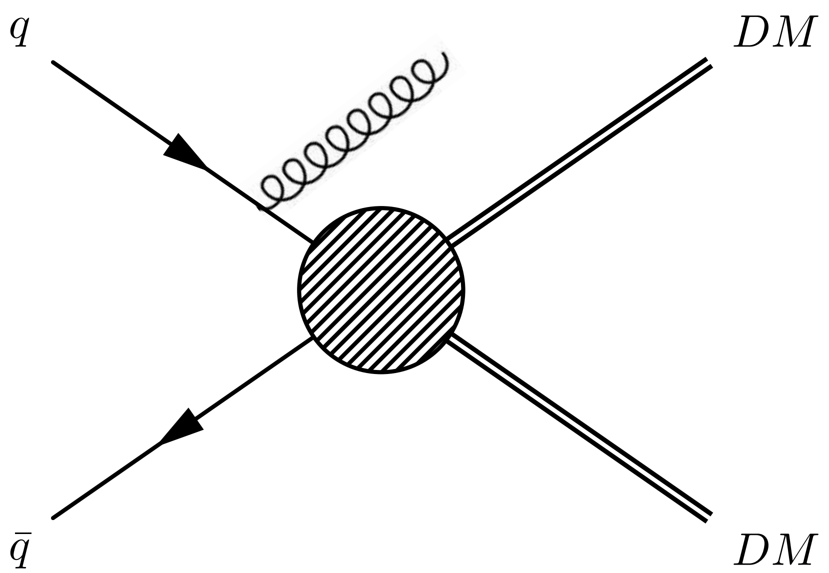
- ❖ Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
  - ... because graviton disappears in bulk right away
- ❖ Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in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

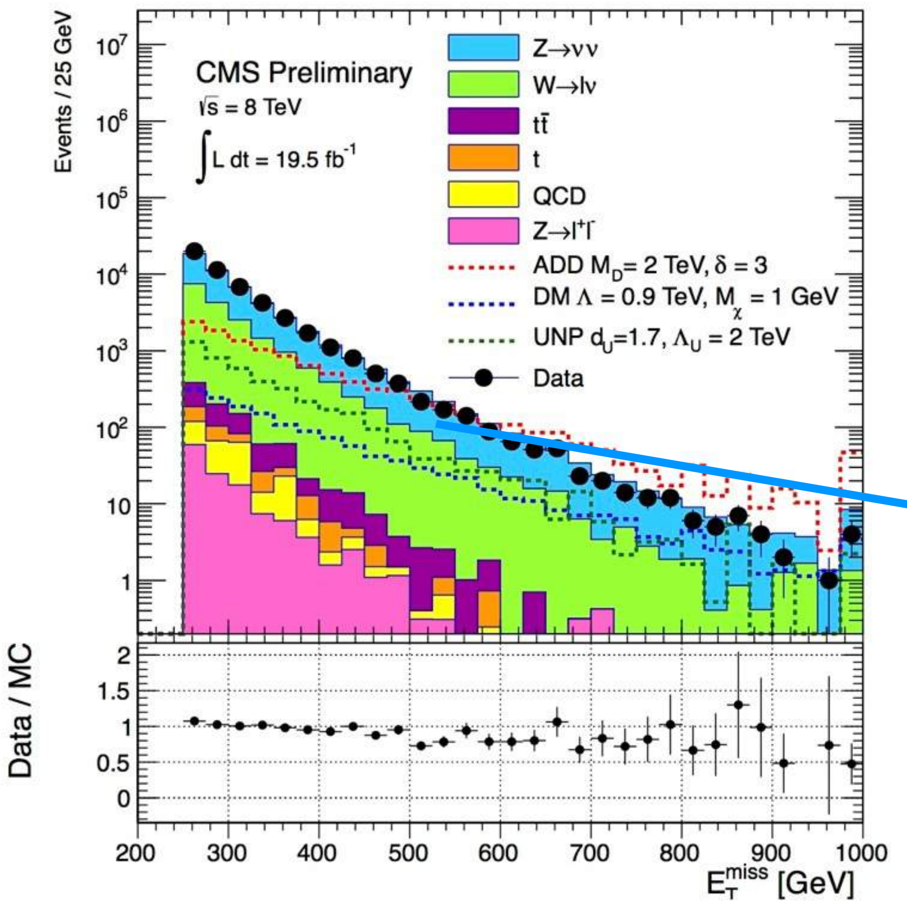


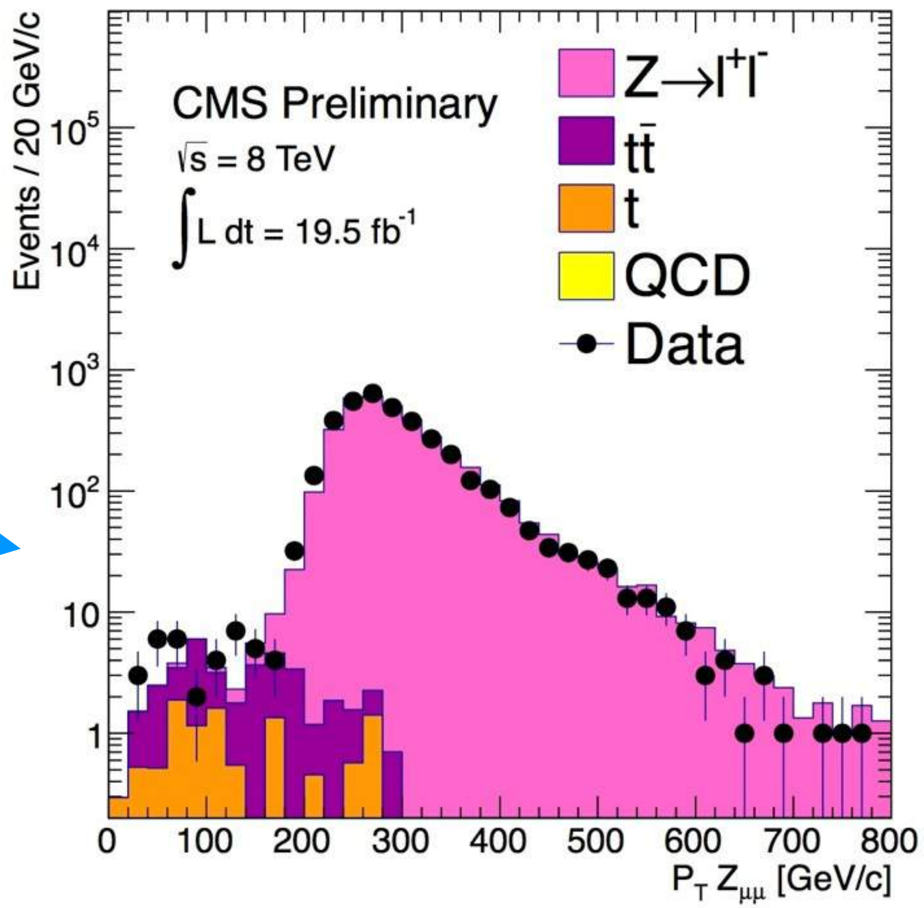
Monojet

❖ Not just graviton signature!

- "Hard ISR" to probe dark matter, compressed SUSY, etc.
- Can get at Z → νν through Z → μμ, but...



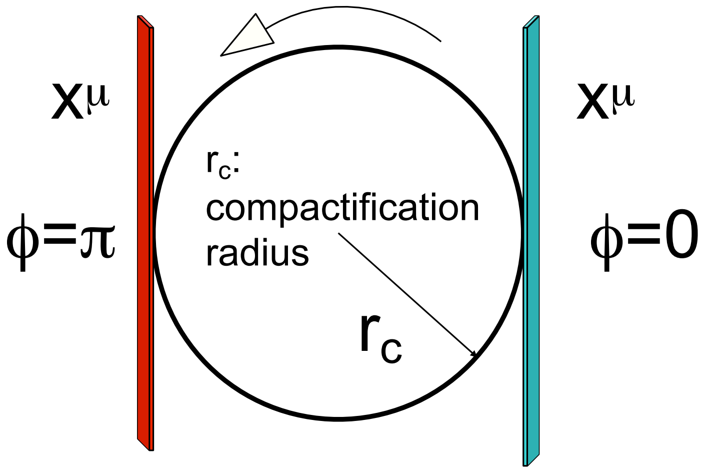


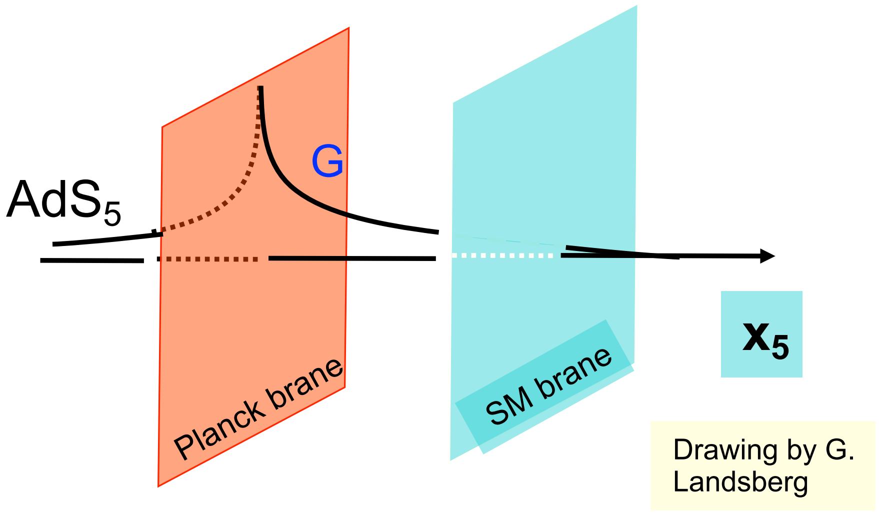


Warped Extra Dimensions

❖ "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)

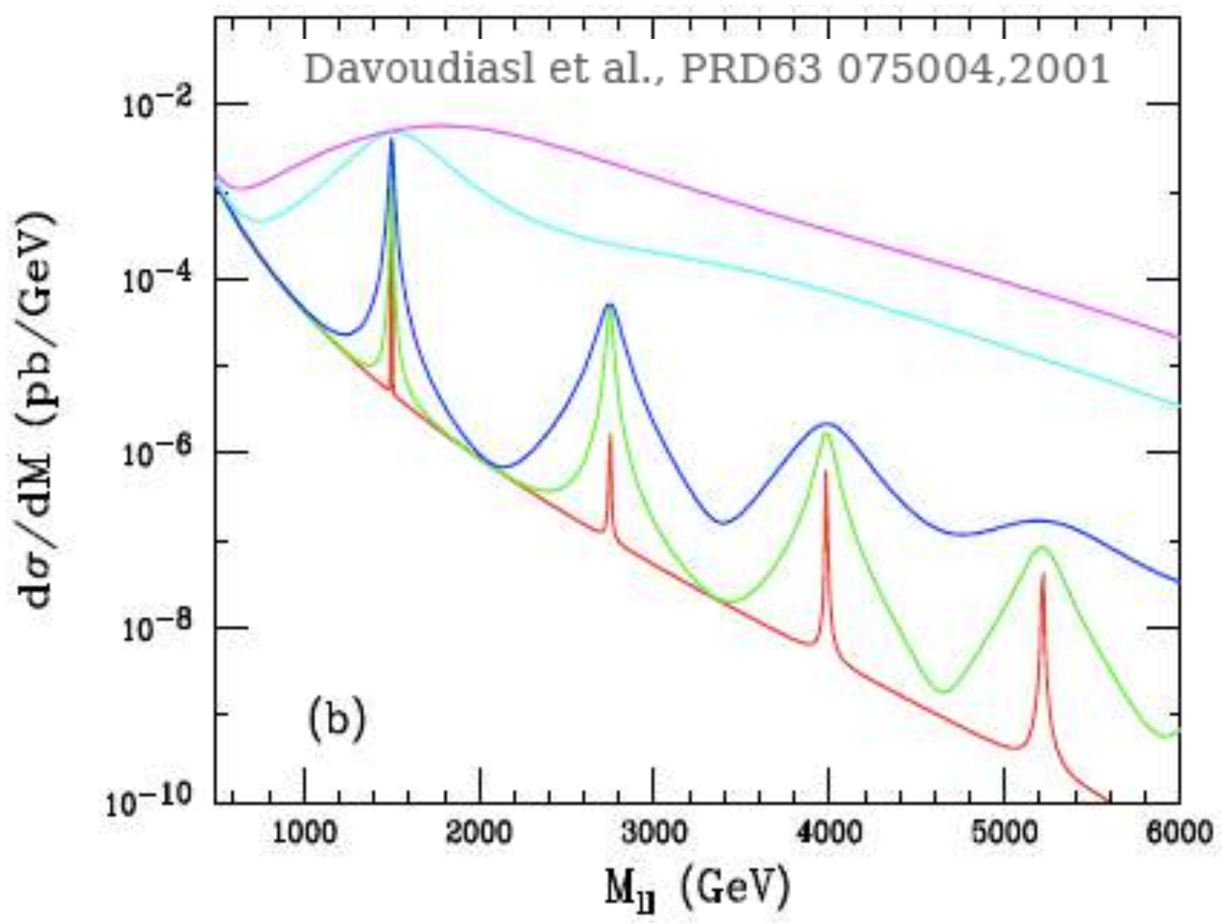




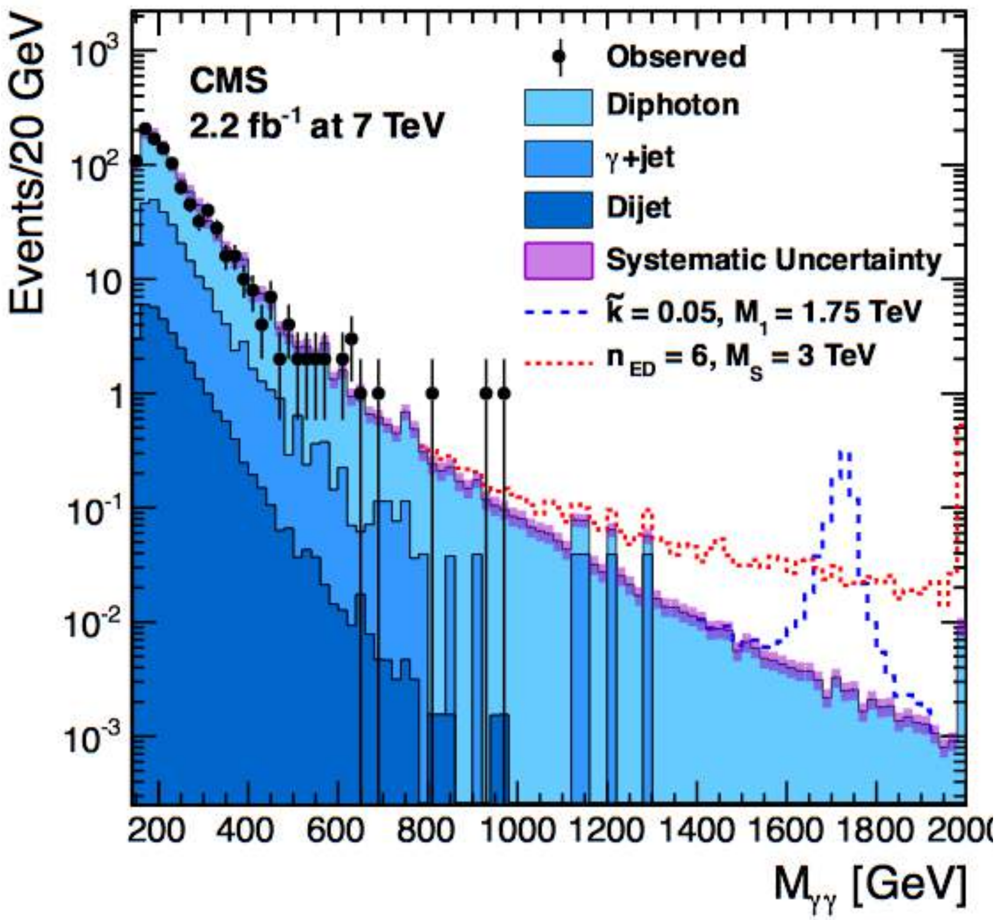
Graviton Excitations

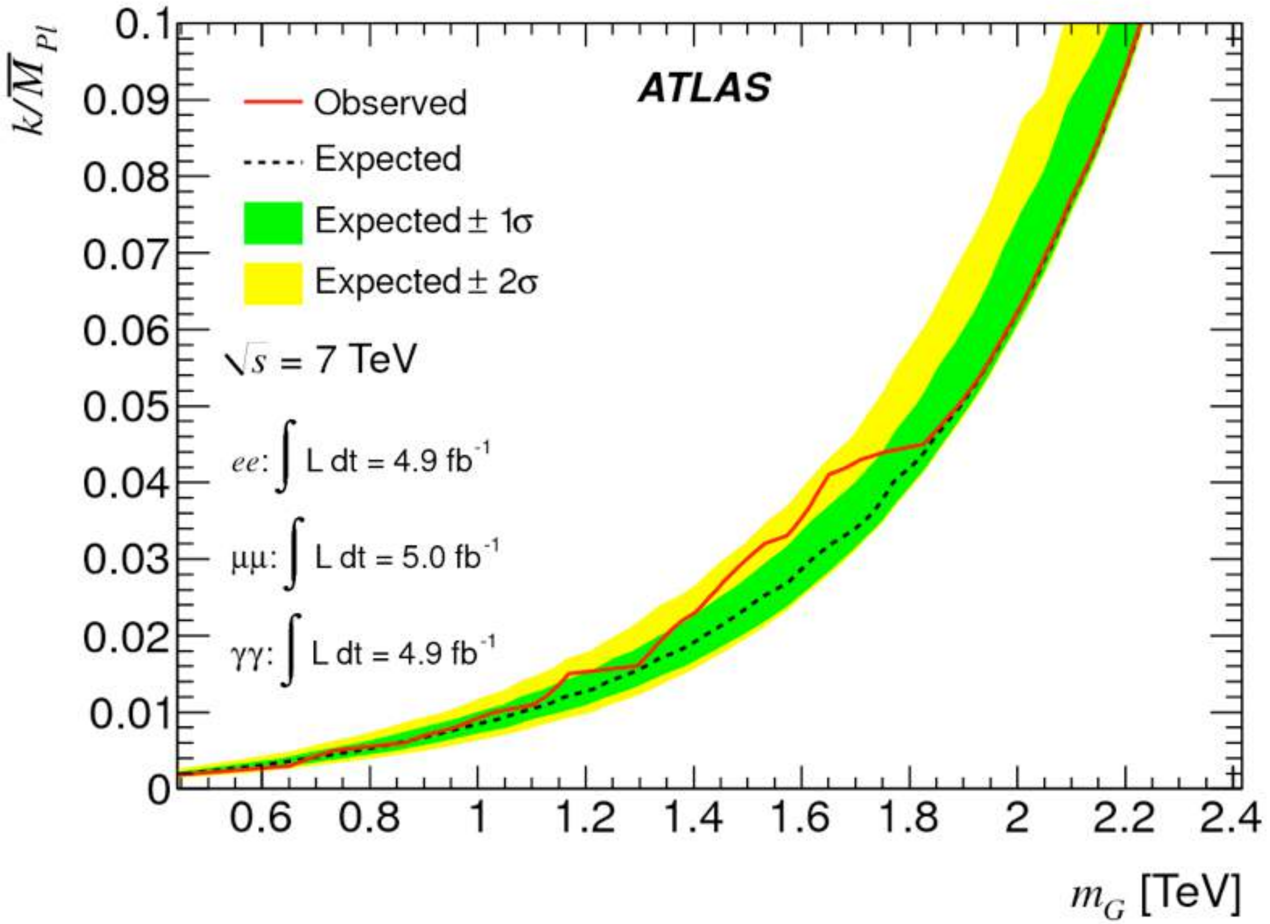
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function
    - ➡ Smoking gun!

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



Dielectrons/Diphotons



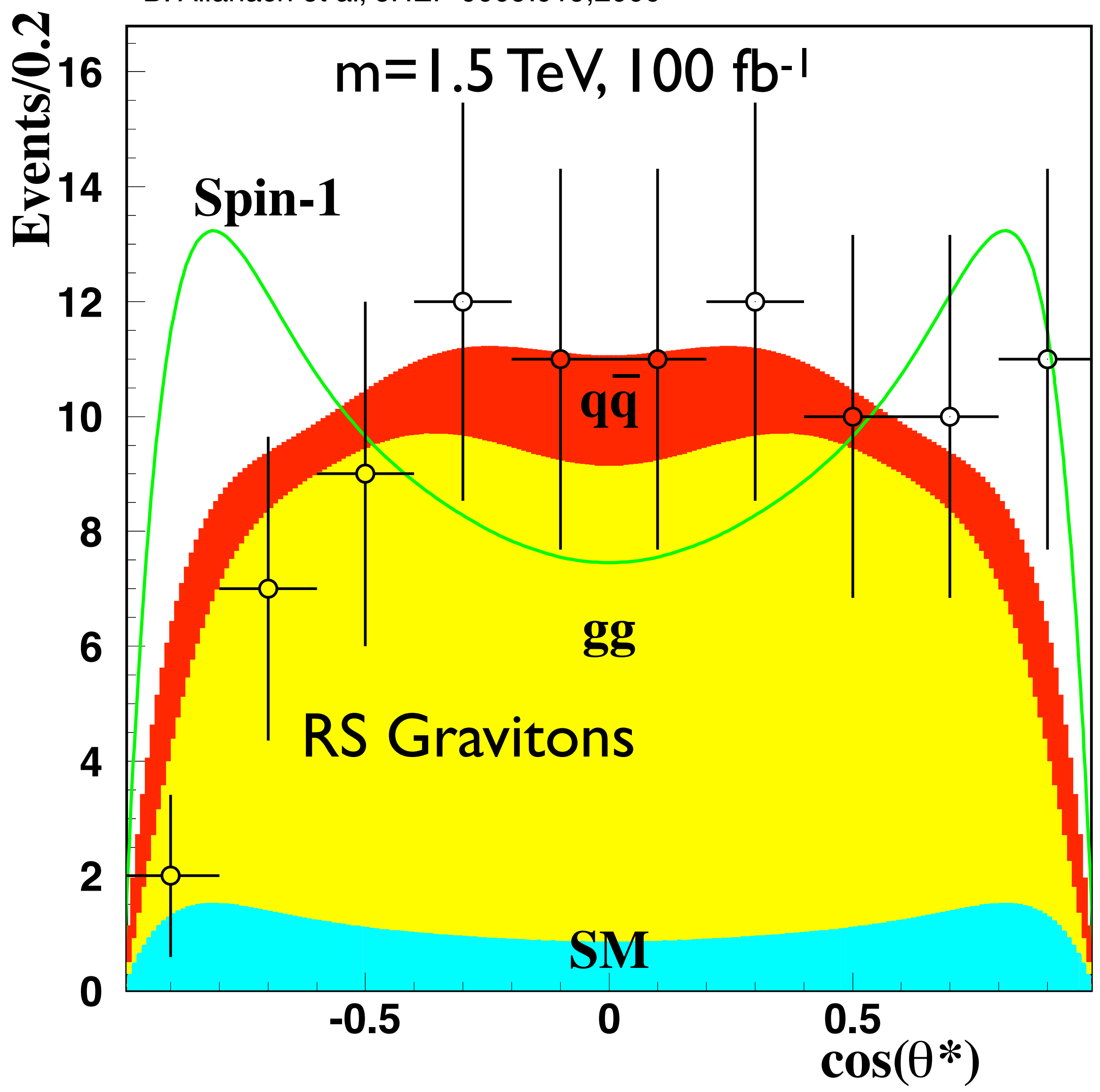


- ❖ Separate dielectrons from diphotons:
  - Targeted background rejection yields better limits
  - Diphotons more sensitive

Spin Determination

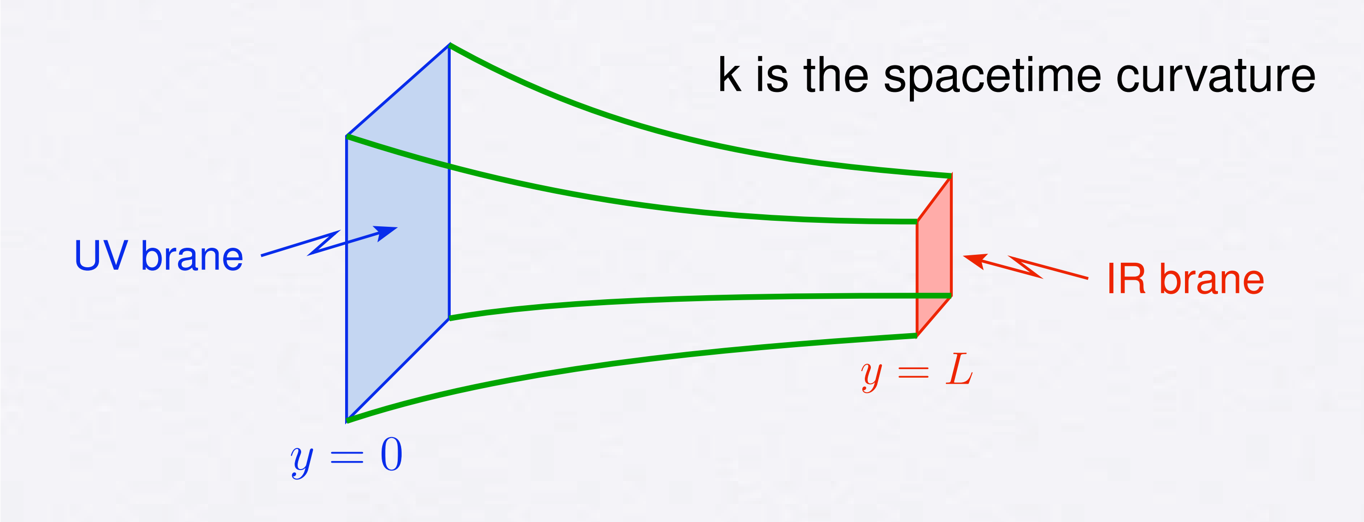
- Look at angle between lepton and beam direction
  - Spin 1 particles tend to emit leptons closer to beam
- Plot is potentially optimistic: sensitivity is in the forward region where lepton identification not nearly as efficient or pure
  - And for heavy resonances decay products are central...

B. Allanach et al, JHEP 0009:019,2000



Hierarchies

❖ Physics on a curved gravitational background:



❖ Scales depend on position along extra dimensions

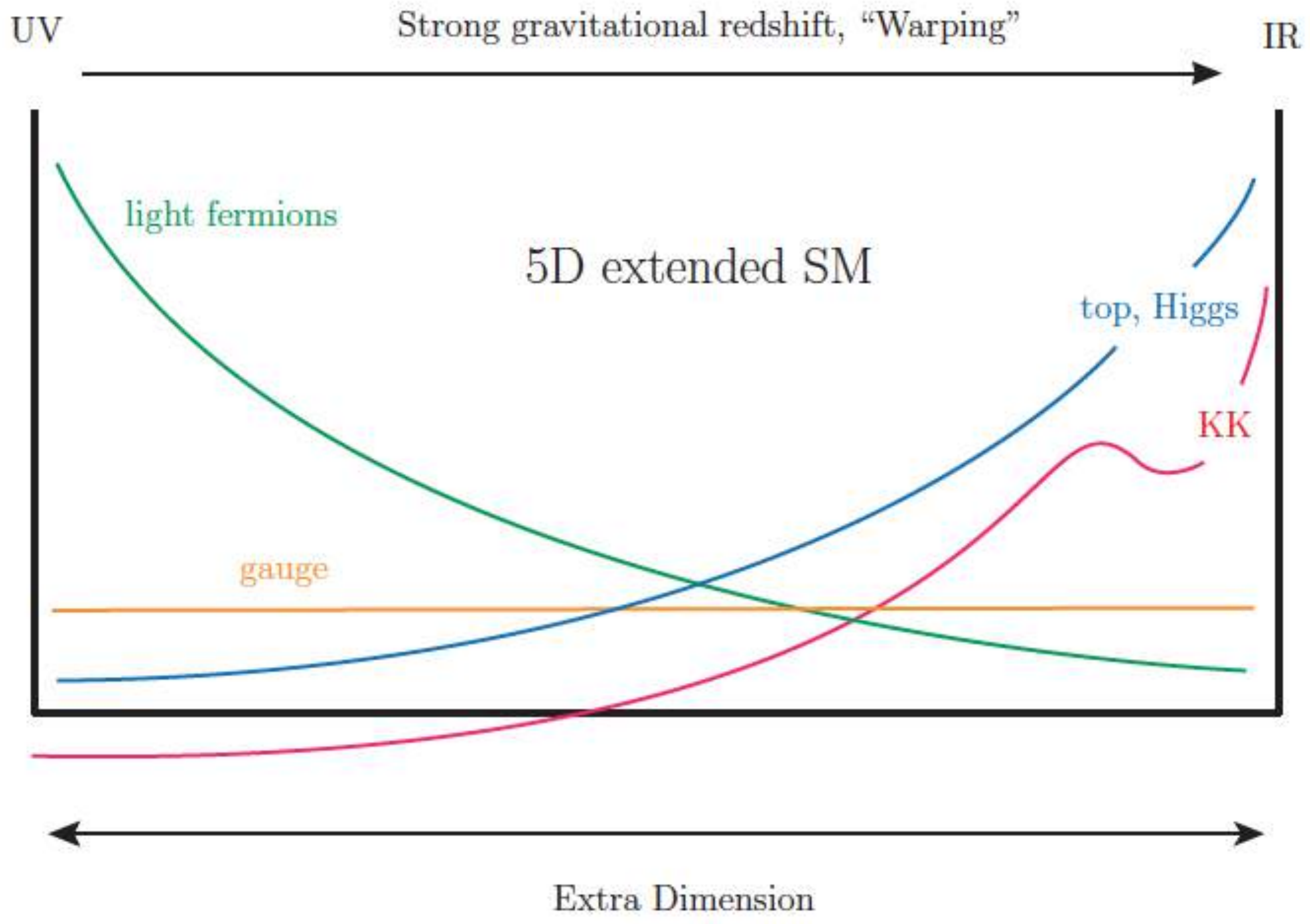
- UV brane scale is $M_{Pl} = 2 \times 10^{18}$ GeV
- IR brane scale is $M_{Pl}\, e^{-kL} \sim 1$ TeV if $kL \sim 30$

❖ 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.

Graphically

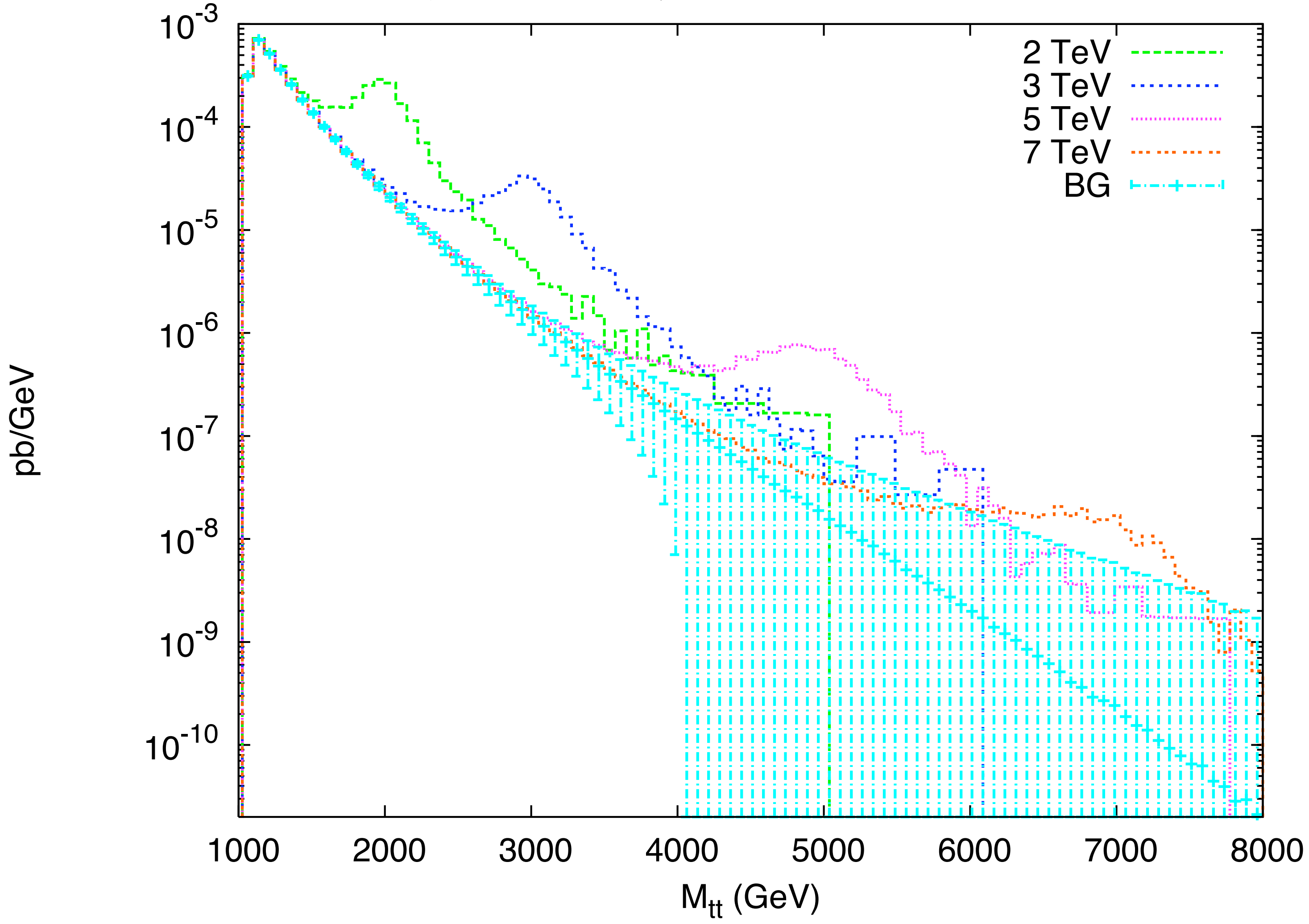


(From K Agashe et al, arXiv:1608.00526)

Gauge Boson Excitations

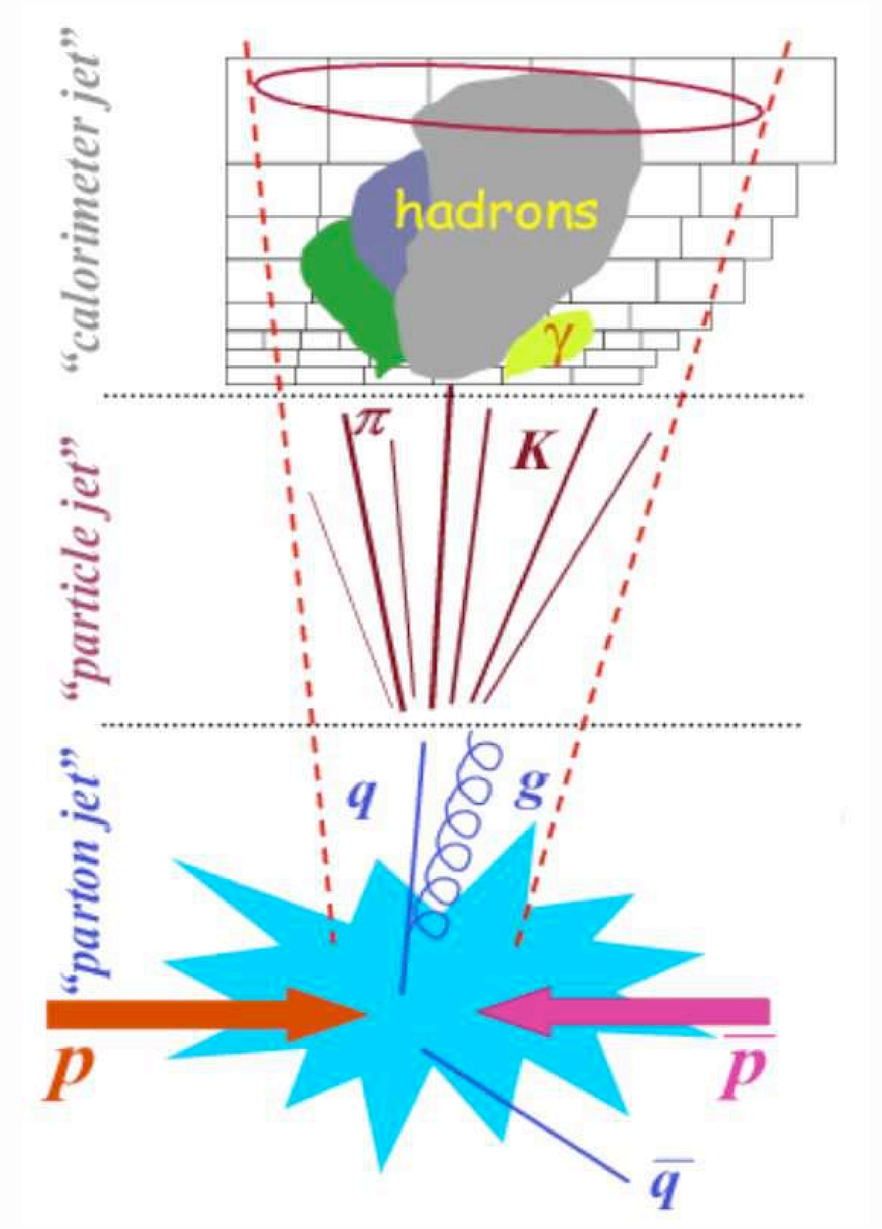
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

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



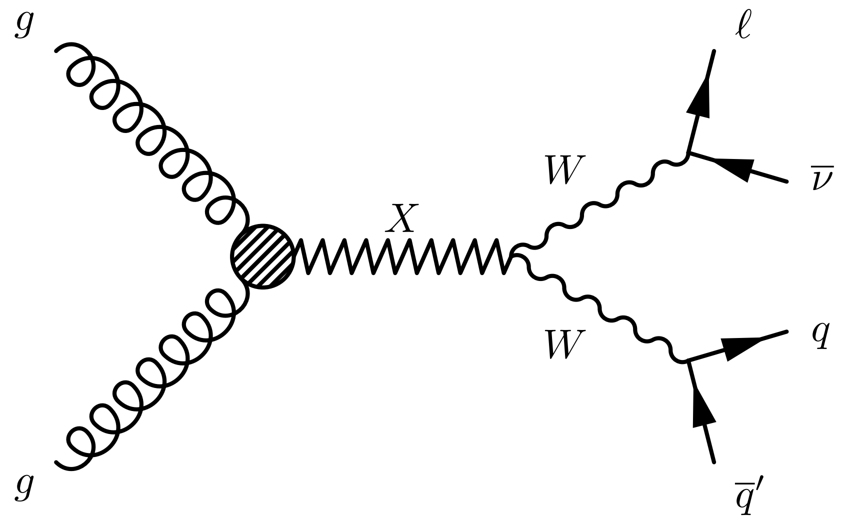
New Experimental Phenomenology

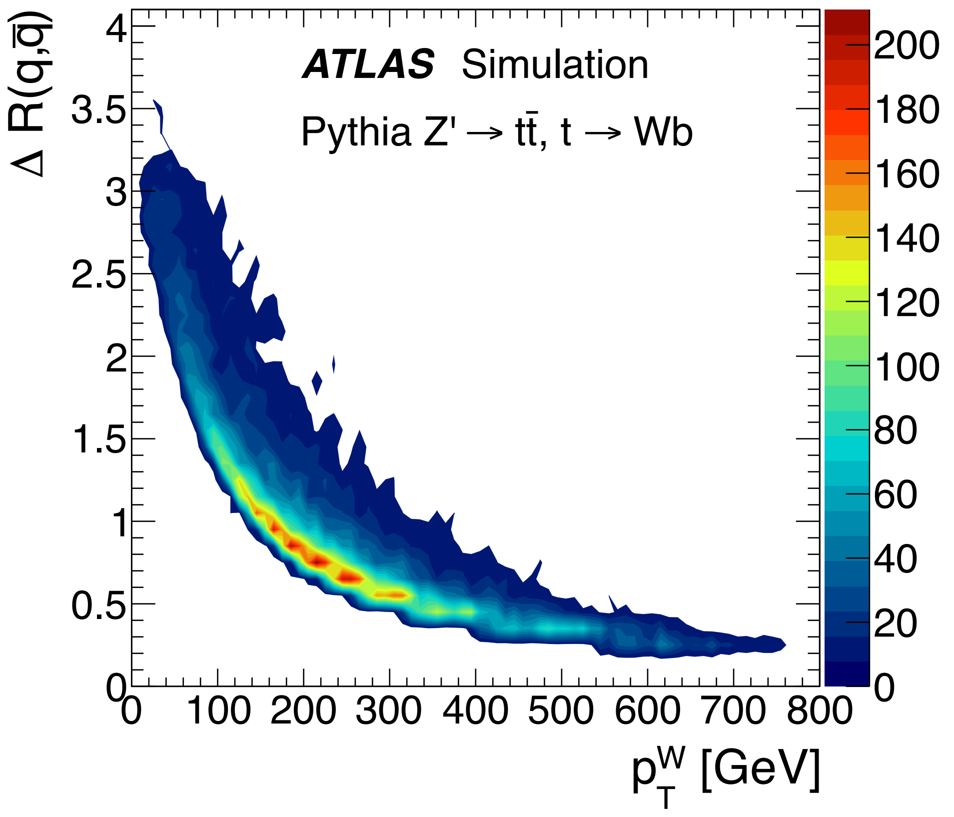
- ❖ Possibility to produce heavy resonances decaying to top quarks, W and Z bosons
  - Heavy objects with momentum >> mass
    - Decay products collimated
  - For leptonic W/Z decays, not a big issue since we measure isolated tracks very well
  - But hadronic decays lead to jets, which are intrinsically wide



Dibosons

- Signature of Randall-Sundrum excitations as well as W', Z'
  - Can look for e.g. W' → WZ, WH
    - Many final state options: lvll, lvqq, 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





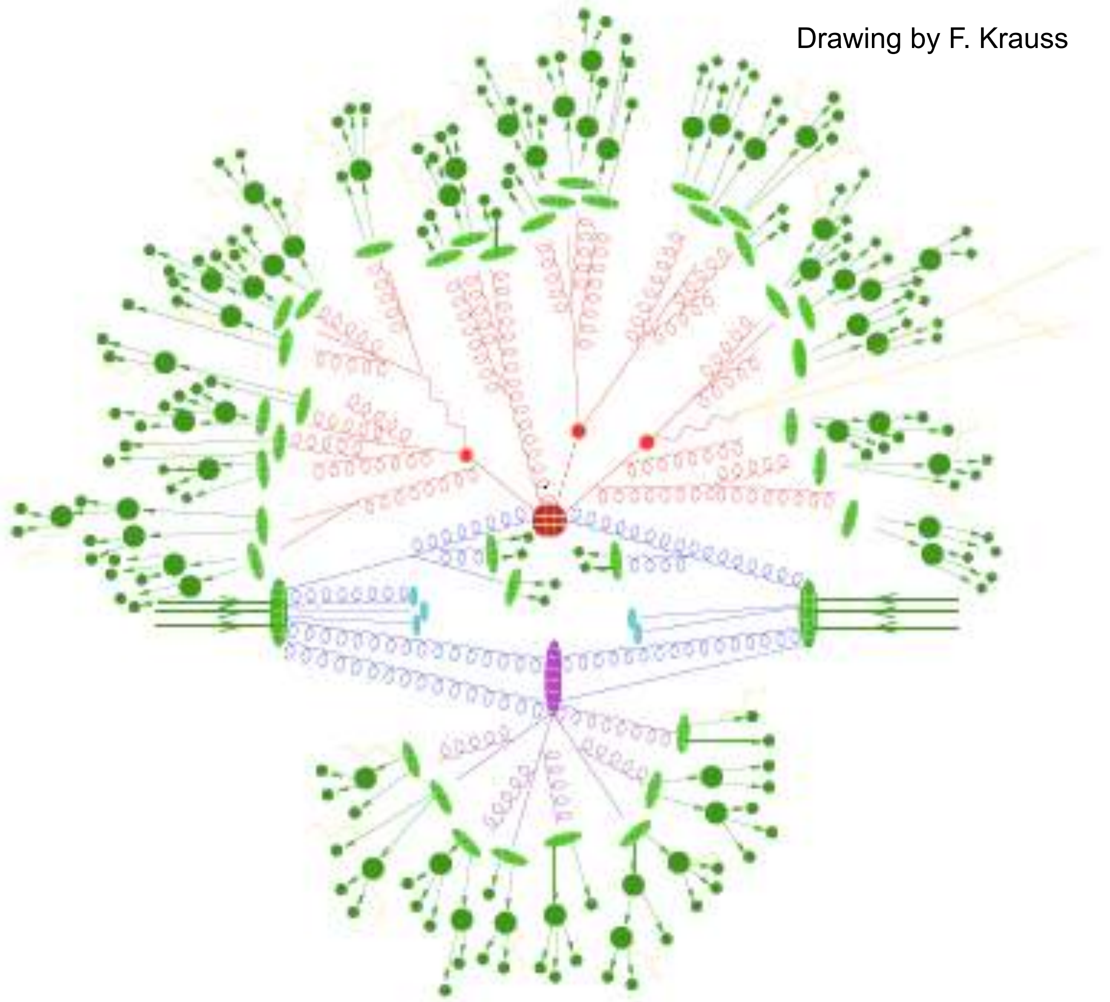
Fully Hadronic Decays

❖ 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

Drawing by F. Krauss



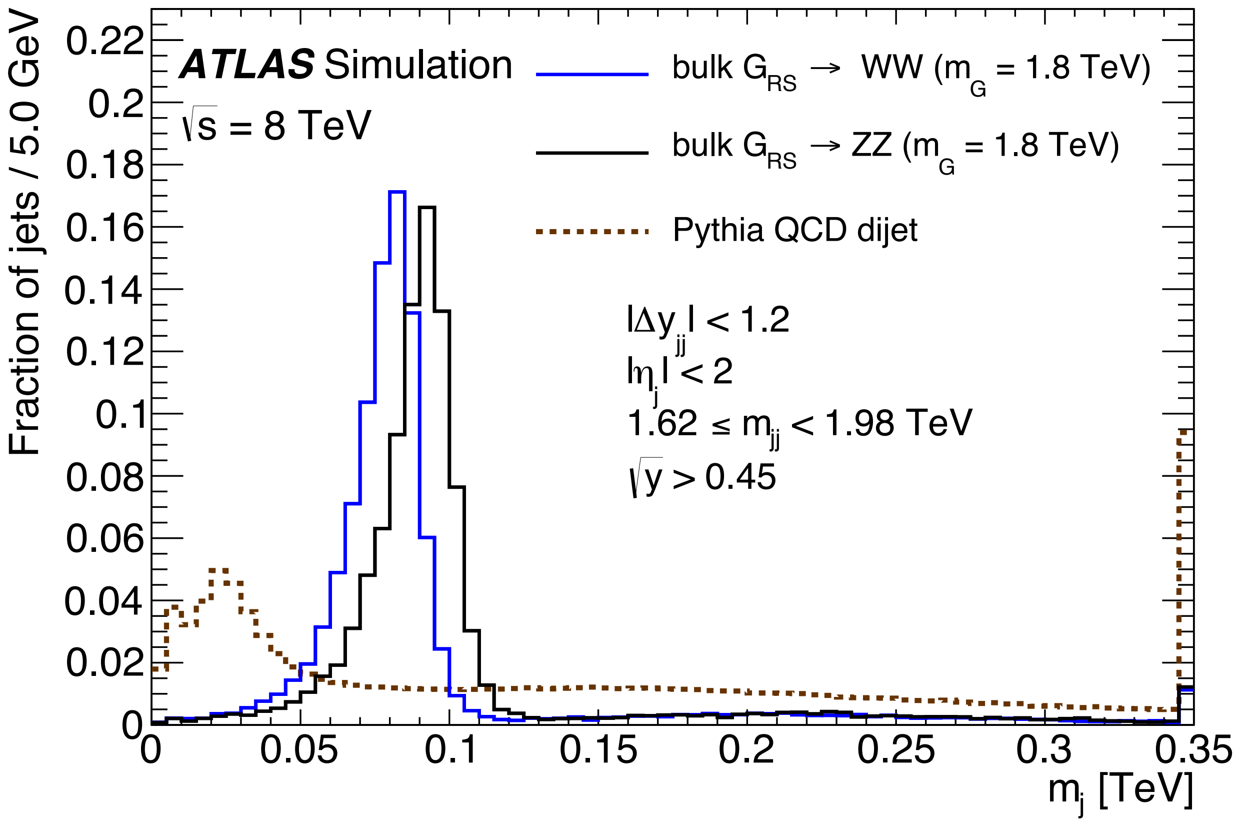
But

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

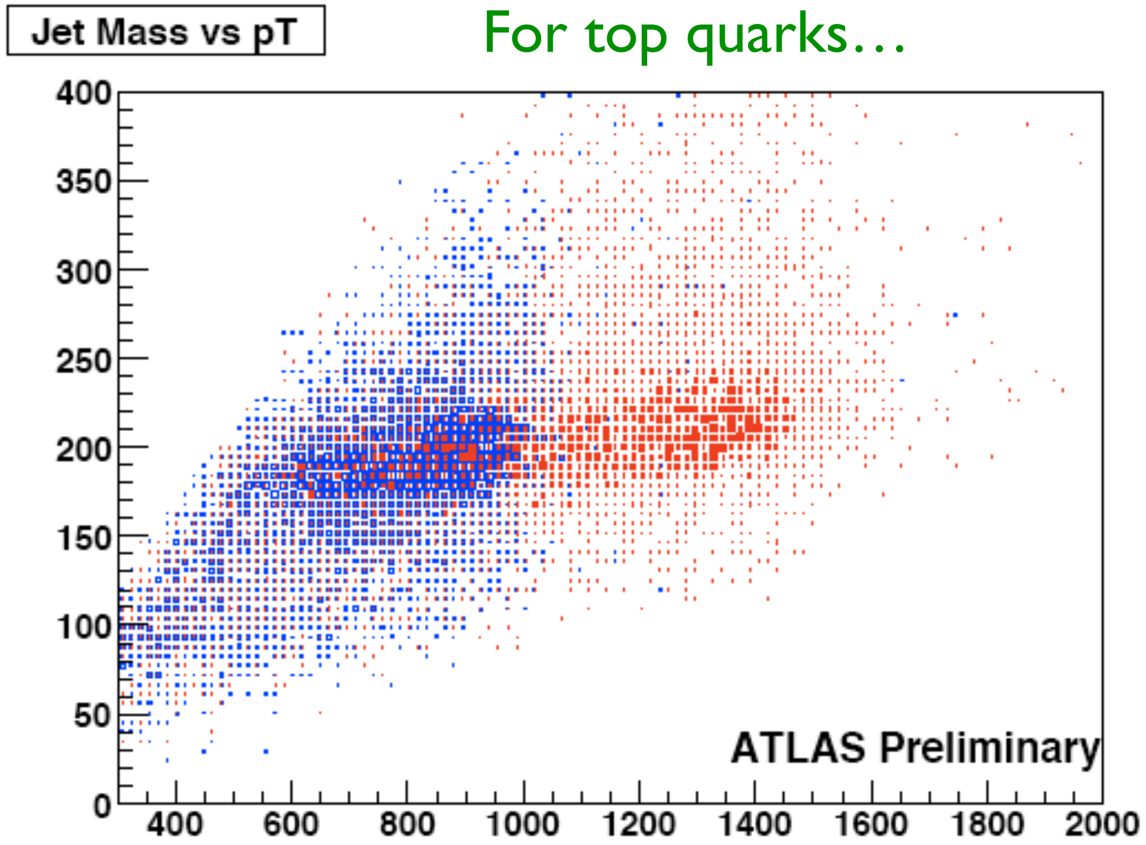
Jet Mass

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

ATLAS, arXiv:1506.00962

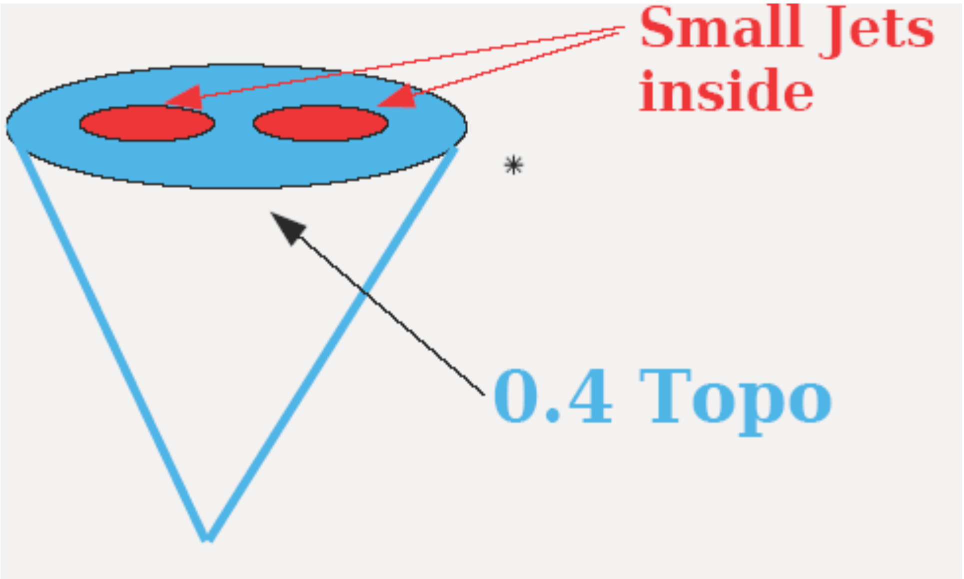


For top quarks…



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"

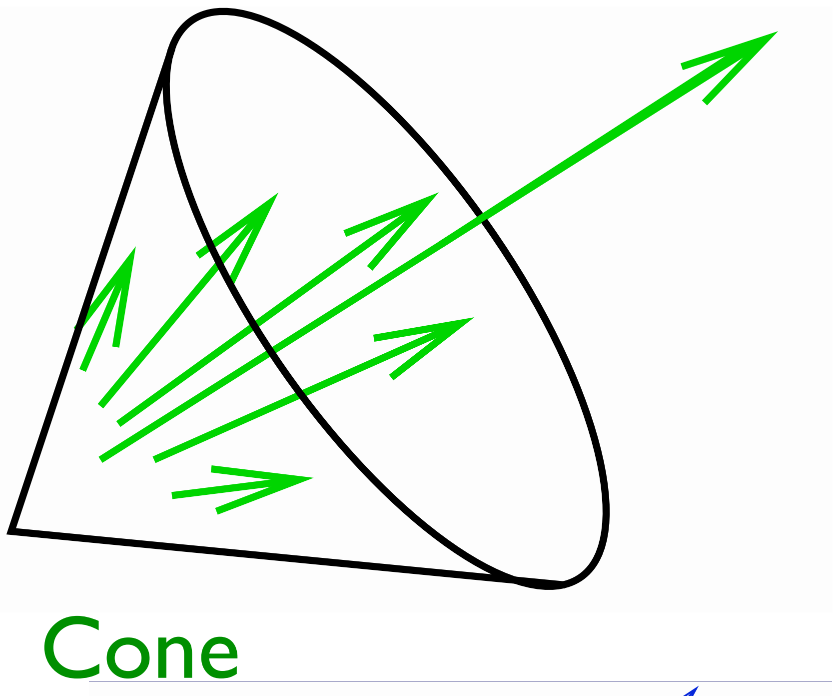
J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *Phys. Rev.* **D65** (2002) 096014

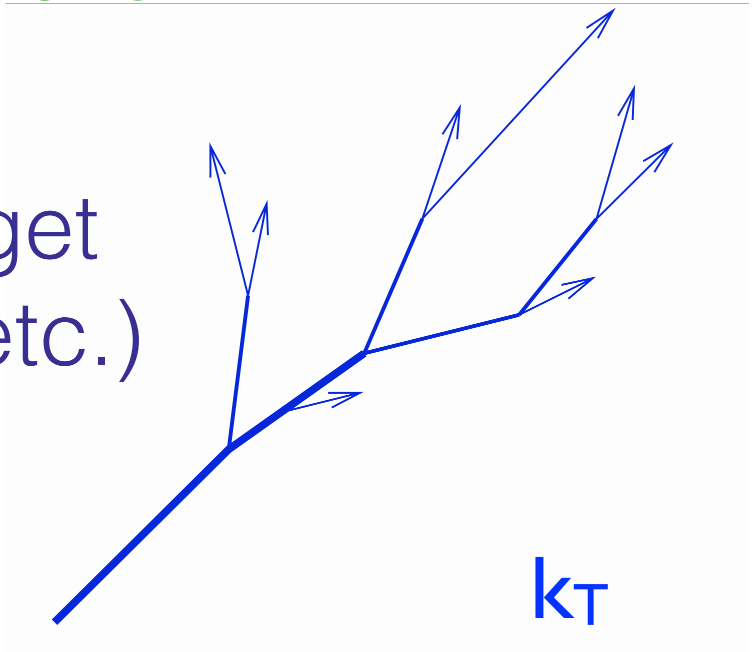
Nearest Neighbor vs Cone

- Nearest neighbor (eg. k_T) algorithms 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

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

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

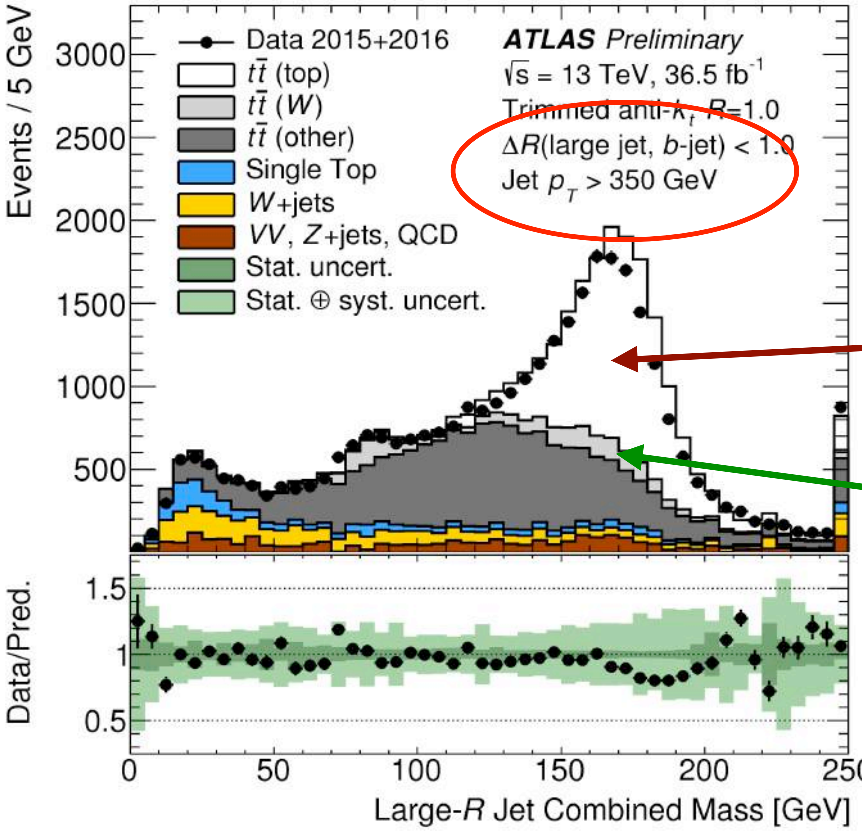




- Can e.g. use the k_T algorithm on jet constituents and get the (y-)scale at which one switches from 1 → 2 (→ 3 etc.) jets
  - Scale is related to mass of the decaying particle

Boosted Taggers

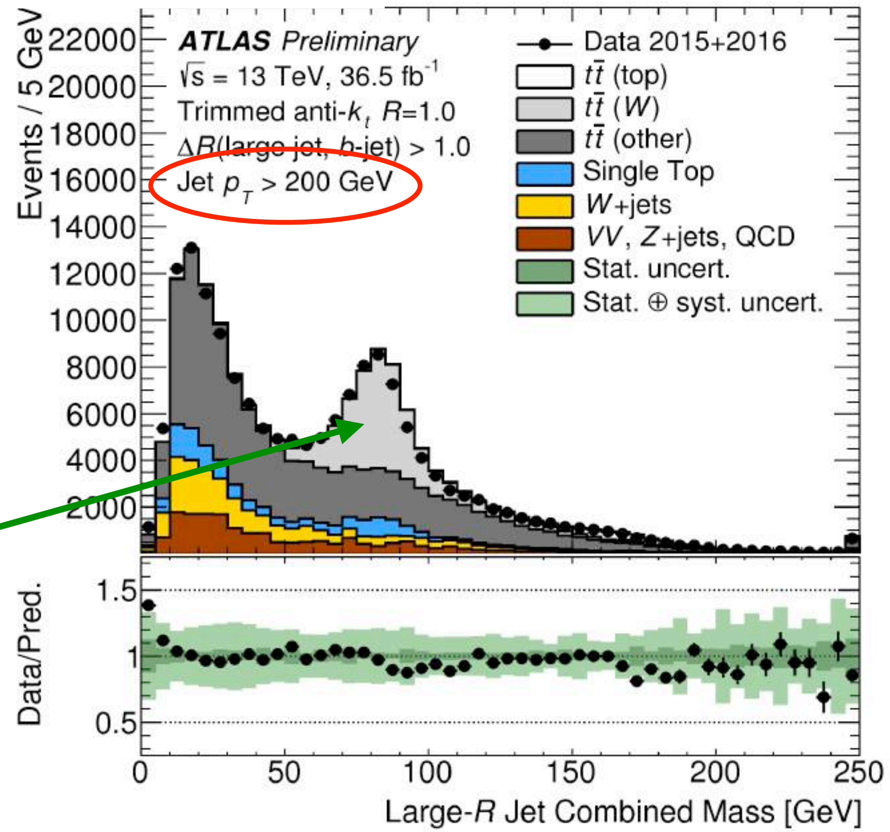
- Many substructure variables “on the market”
  - Optimal choice partially depends on detector
- Data-based validation exploits large (and rather pure) tt̄ “lepton+jets” sample for signal, dijets for background
  - ATLAS: Lepton, MET, R=0.4 b-tagged jet, high-p_T trimmed R=1.0 jet
- ATLAS jet mass now “track-assisted”: $m_J \equiv w_{\text{calo}} \times m_J^{\text{calo}} + w_{\text{track}} \times \left(m_J^{\text{track}} \frac{p_T^{\text{calo}}}{p_T^{\text{track}}} \right)$



ATLAS-CONF-2016-035

Large-R jet matched to truth top quark

Large-R jet matched to truth W boson



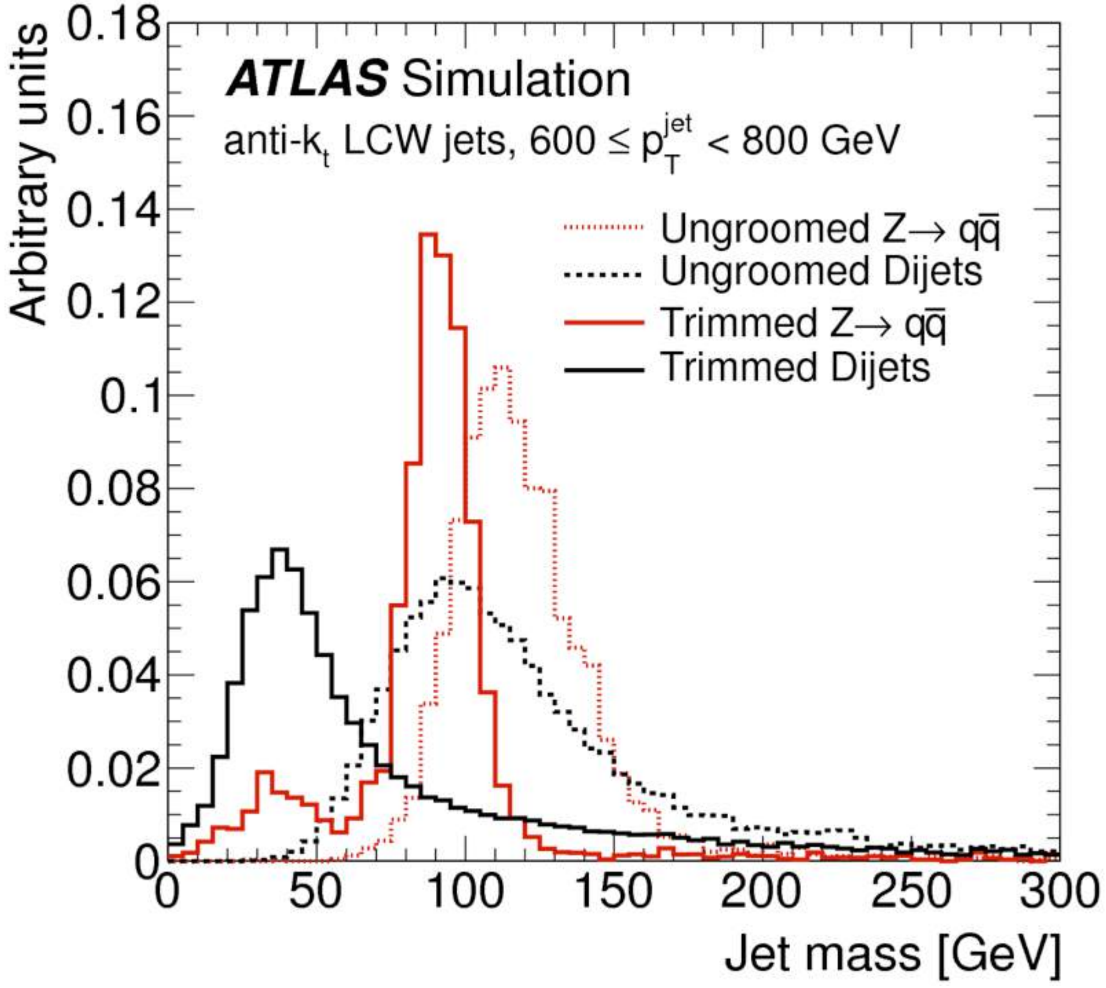
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2017-004/

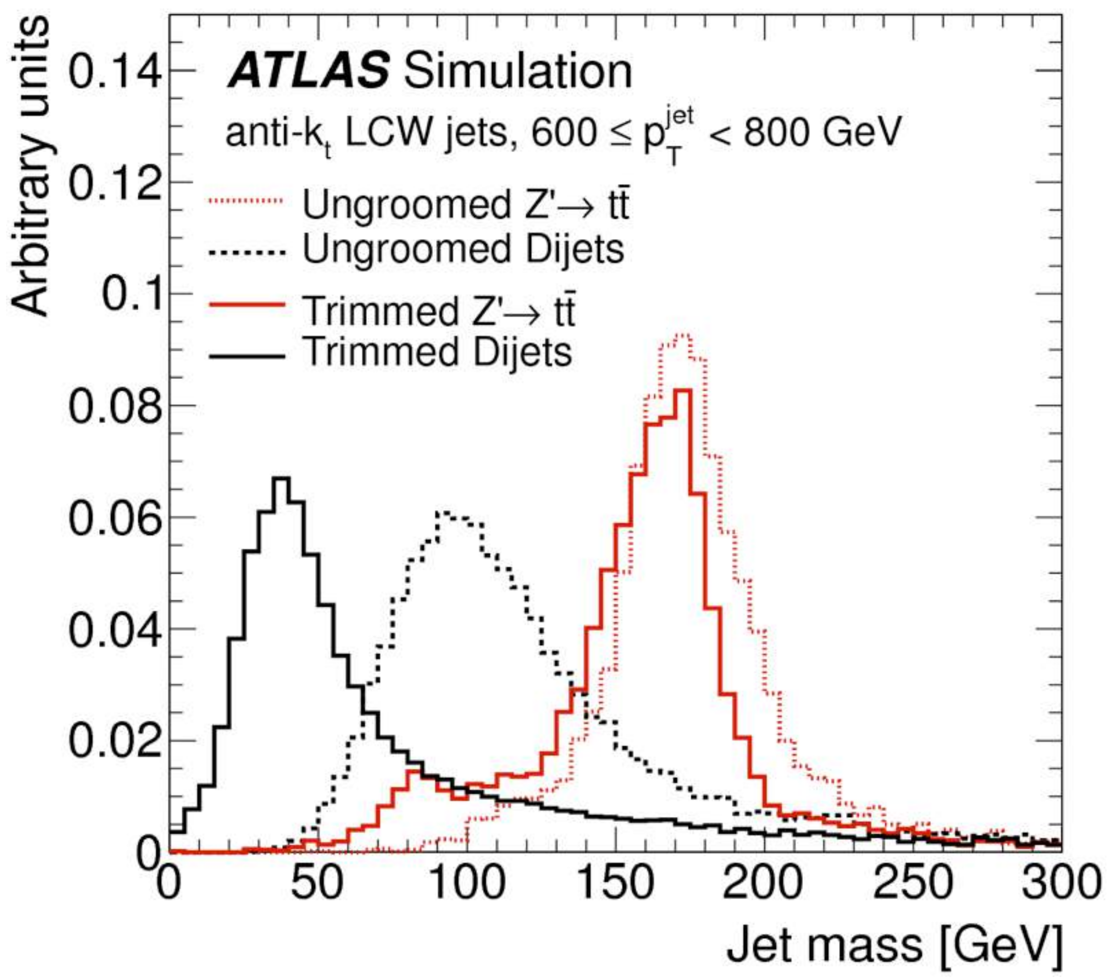
Grooming

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

- Clean up soft QCD radiation/connection to underlying event

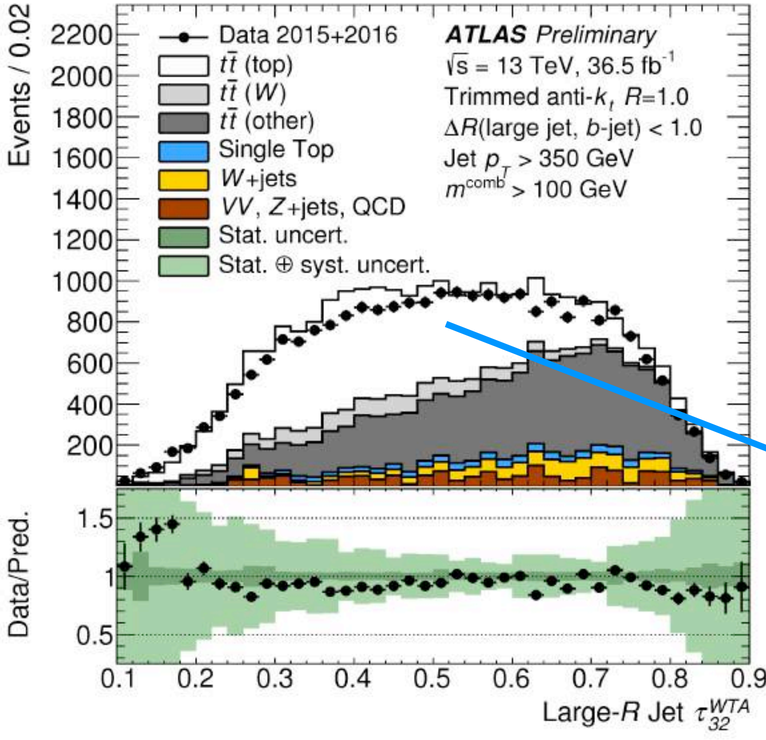
ATLAS, JHEP09 (2013) 076

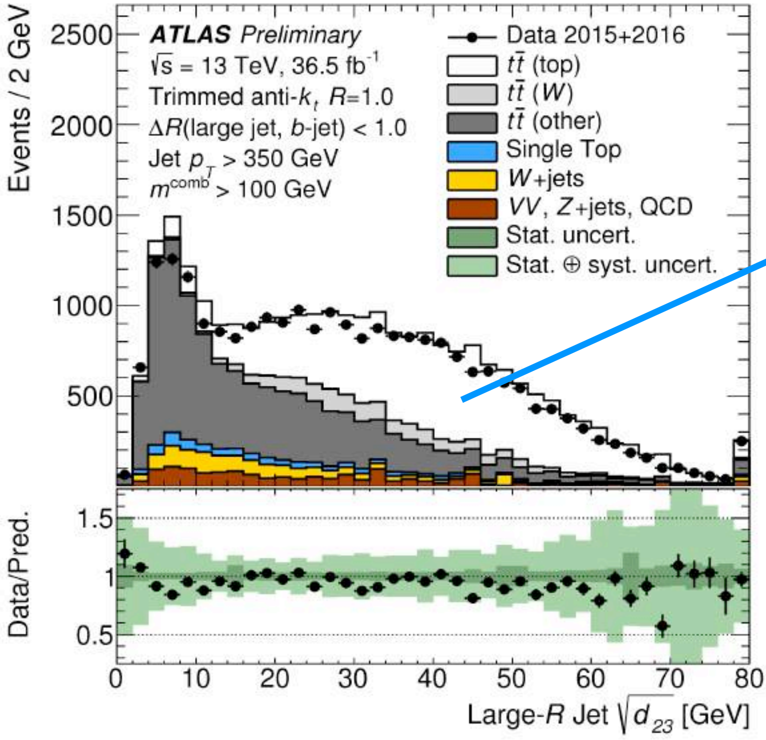


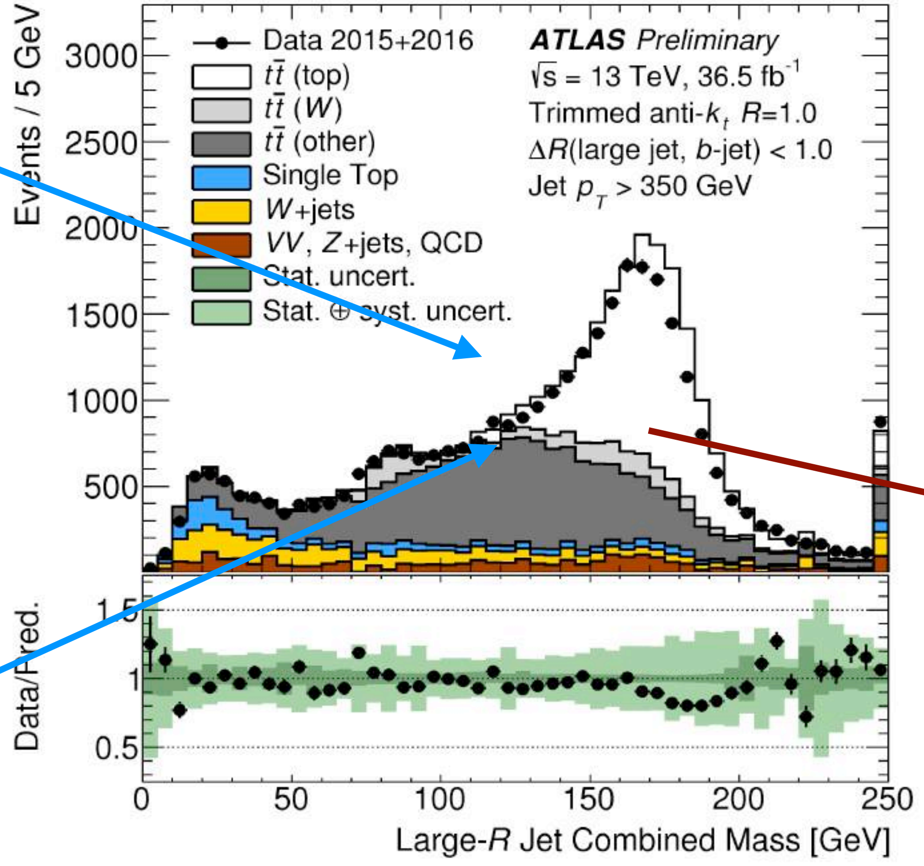


Top

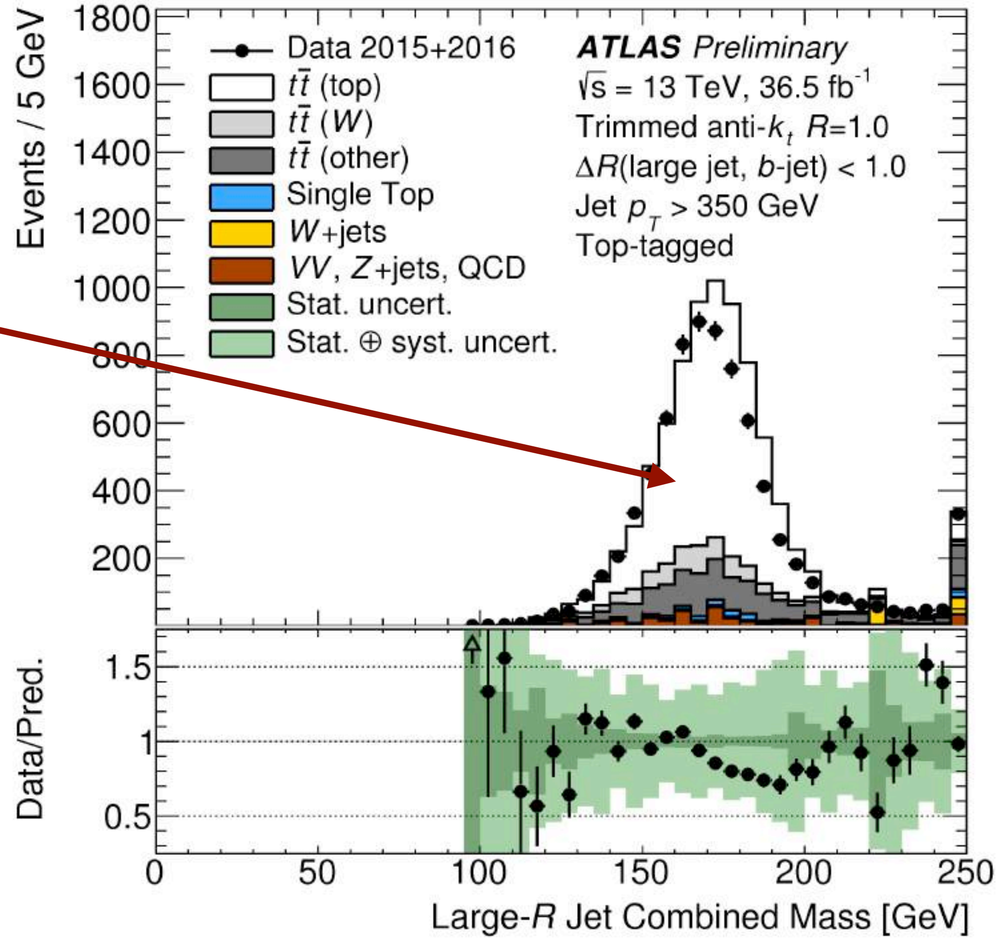
❖Select on τ_{32}-N-subjettiness and $\sqrt{d_{32}}$ splitting scale







ATL-PHYS-PUB-2015-053



$$\tau_{32} = \tau_3/\tau_2$$

$$\tau_N = \sum_{i \in J} p_{\mathrm{T},i} \min_j \Delta R(\text{axis } j, \text{constituent } i)$$

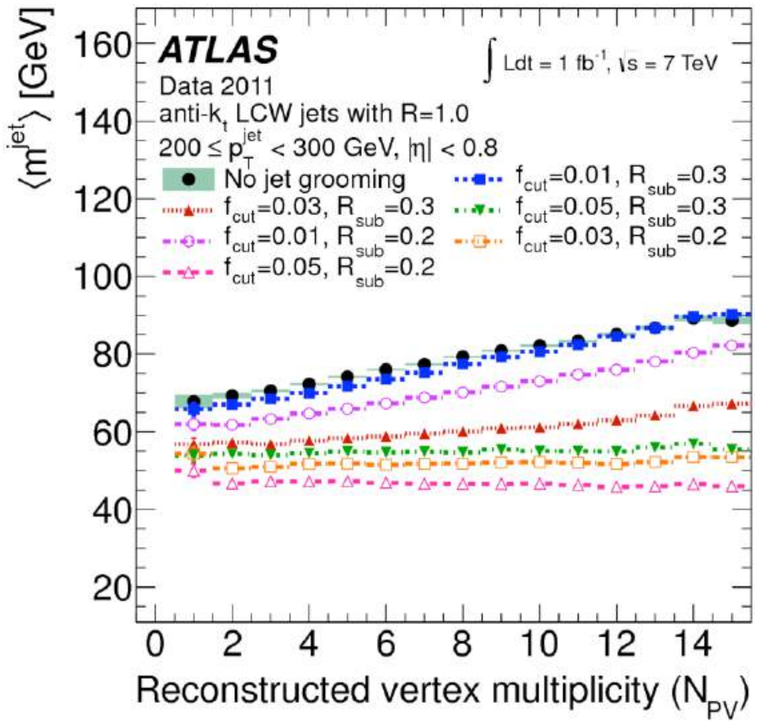
$$\sqrt{d_{12}} = \min(p_{\mathrm{T},1}, p_{\mathrm{T},2}) \times \Delta R_{12}$$

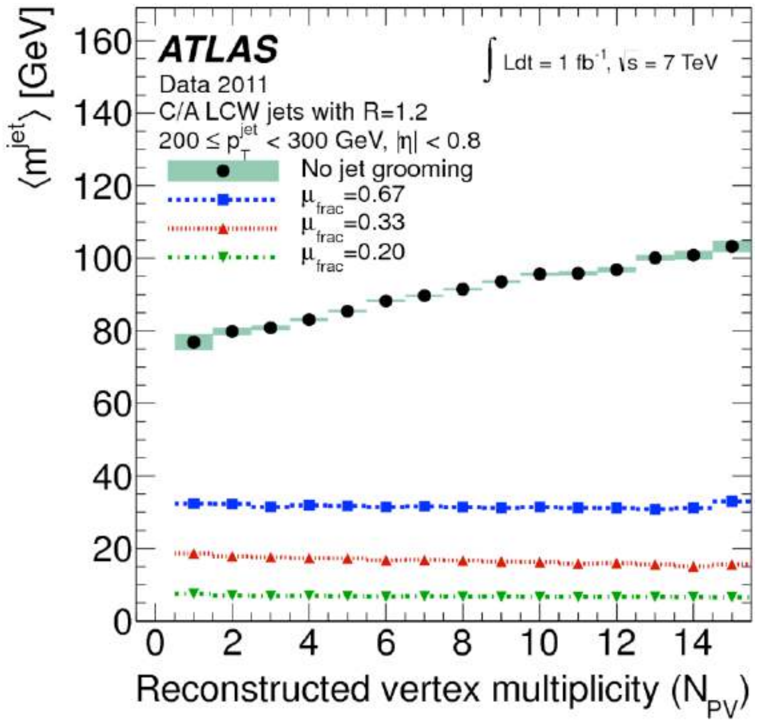
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2017-004/

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



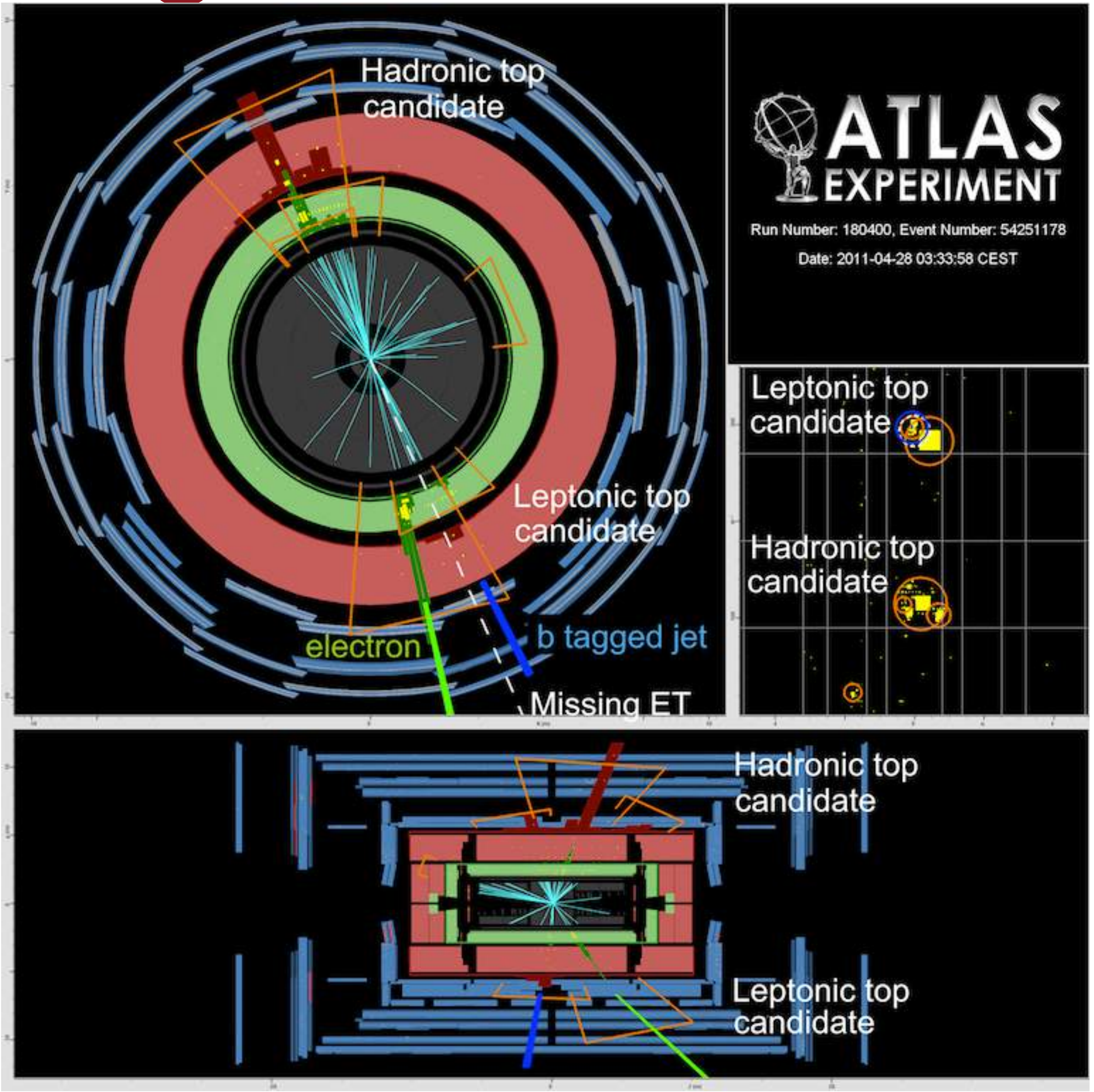


!Optimal parameter set/strategy is detector-dependent!

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/

High Mass tt Event



Looking Forward

Projects Tend To Be Long

- LHC (the longest yet)
  - Inception in 1980s
  - Experiments confirmed mid-1990s
  - Operation start 2007
  - Major upgrade 2025
  - End of operations planned ~2037
- A full career!
- Worldwide planning is a must

Future Projects

- ❖ Energy Frontier
  - HE-LHC, FCC
  - ILC, CEPC
- ❖ Baryon number violation
  - DUNE, Hyper-K
  - NNbar

Hadron Colliders

- 2025: High Luminosity LHC upgrade
  - Go to 5-7.5 x 10^{34}, pile-up of 200
  - New interaction region focusing magnets and crab cavities
  - Significant detector "upgrades"
    - Replace inner trackers, detector readout and trigger and data acquisition systems
      - Basically, only keep magnets, calorimeters and muon chambers
  - Overall, 1 GCHF construction project
  - Then run until ~2037 to collect 3000-4000 fb^{-1}
    - Still not enough to measure di-Higgs production (if it's SM strength!)
      - Who knows, we may get smarter