

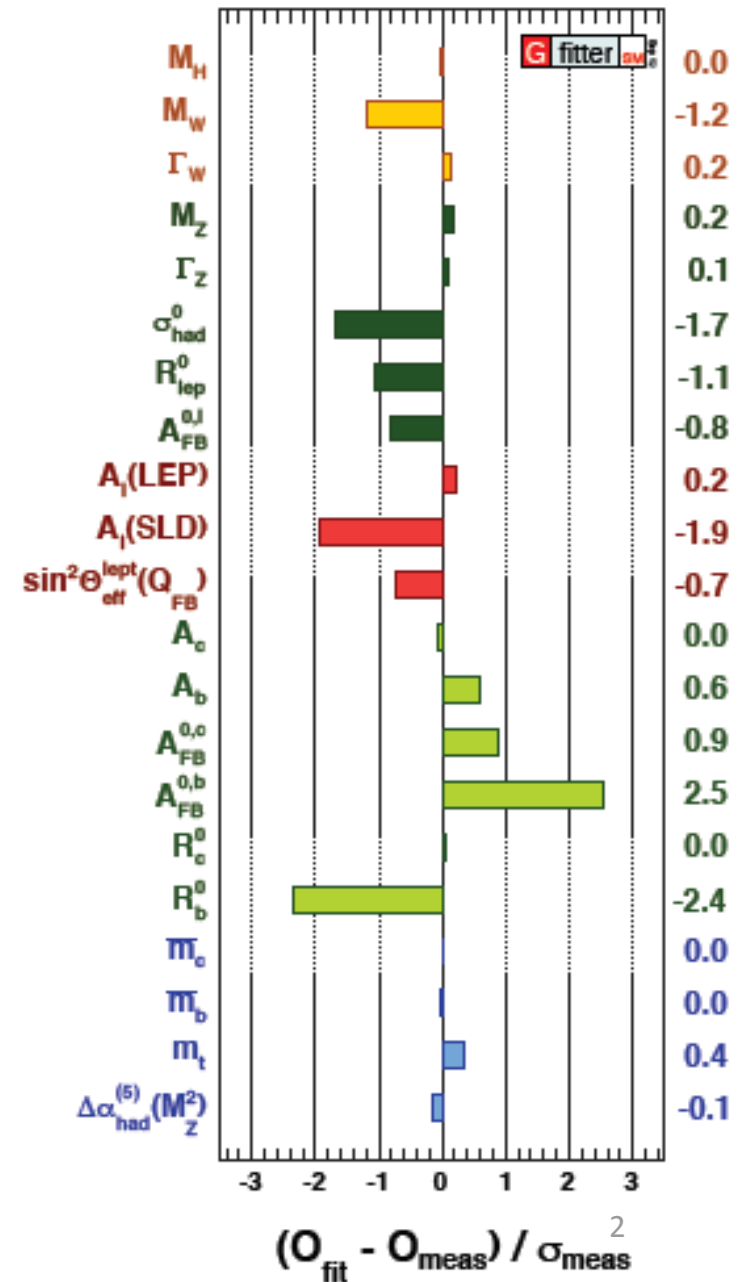
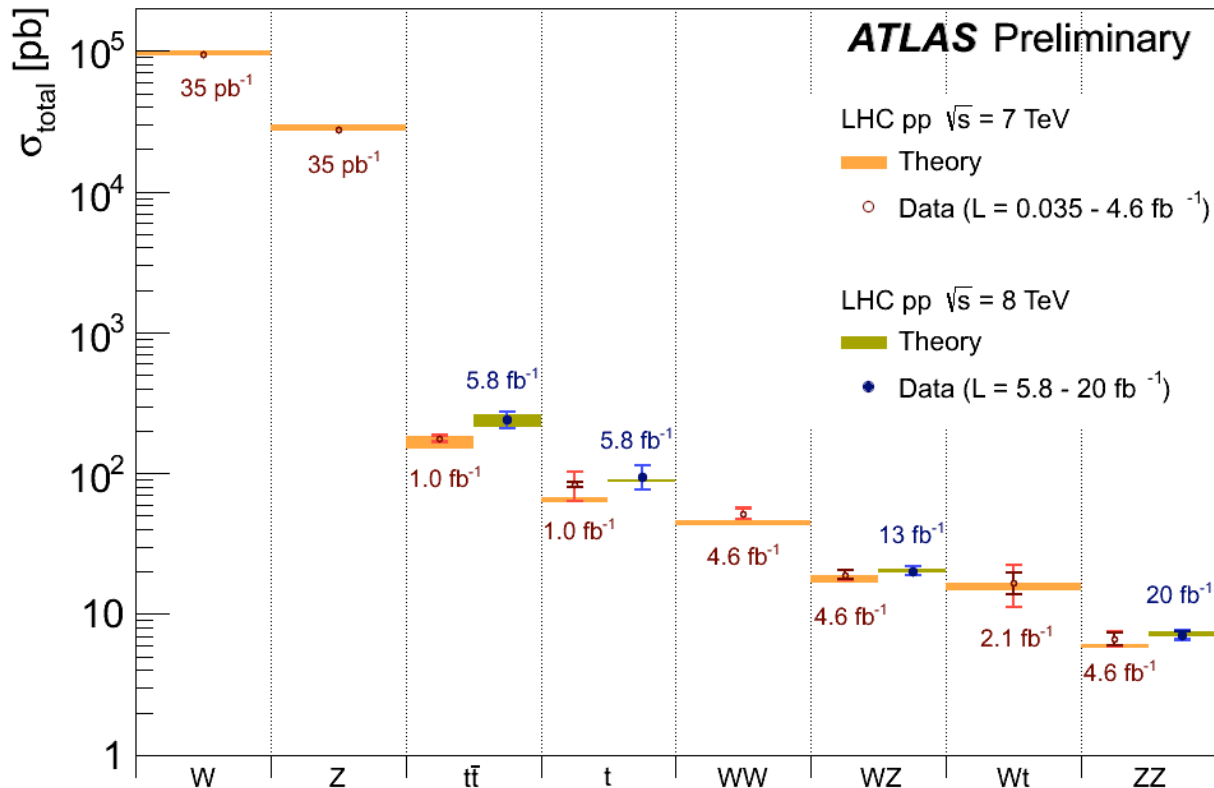
# Exotics Searches

aka Non-SUSY Searches

Tobias Golling (Yale)

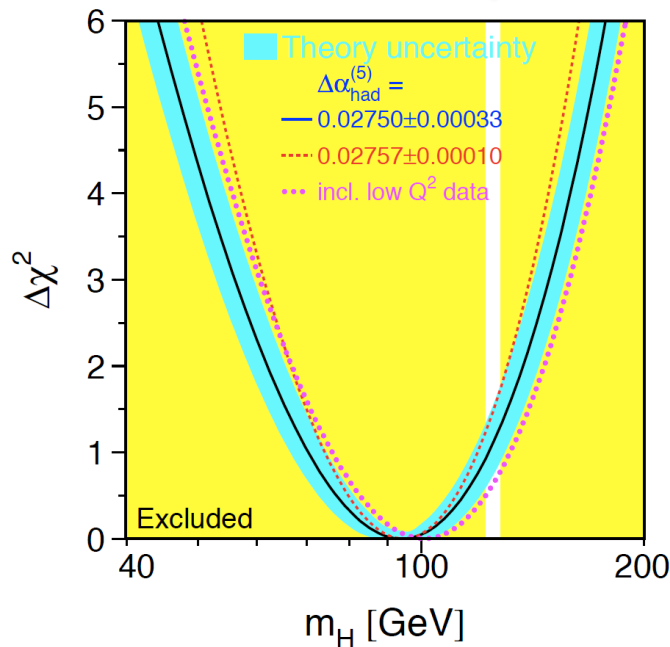
25<sup>th</sup> Rencontres de Blois, May 26-31 2013

# The SM Works!



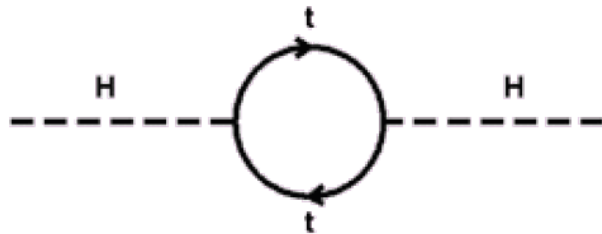
# The LHC is a Discovery Machine

- Proof:



# Higgs – Manifestation of Hierarchy Problem

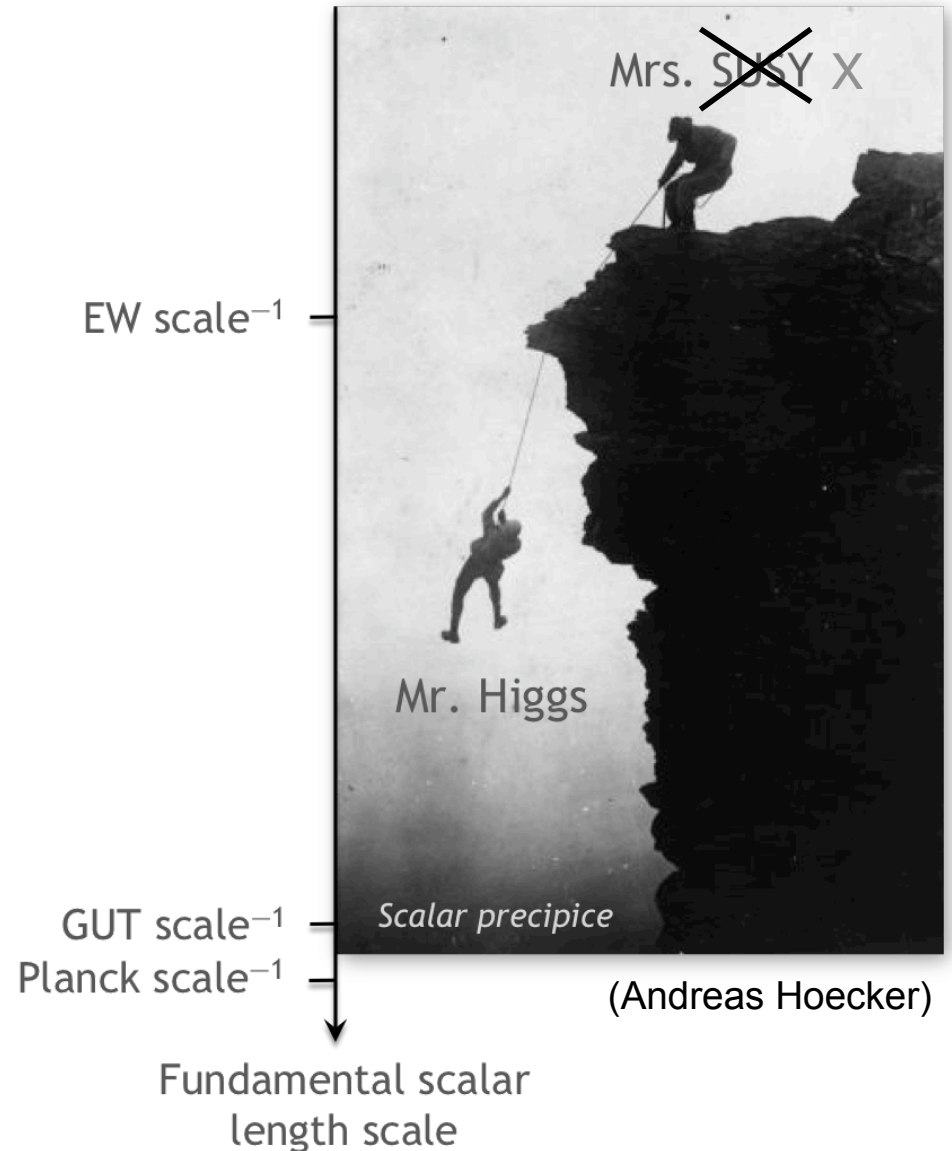
Not only SUSY to rescue!



$$\Delta m_H^2 / m_H^2 \sim 10^{32} !$$

Other problems of the SM:

- Dark matter
- Unification problem
- Flavor puzzle
- How does gravity fit in?
- ...

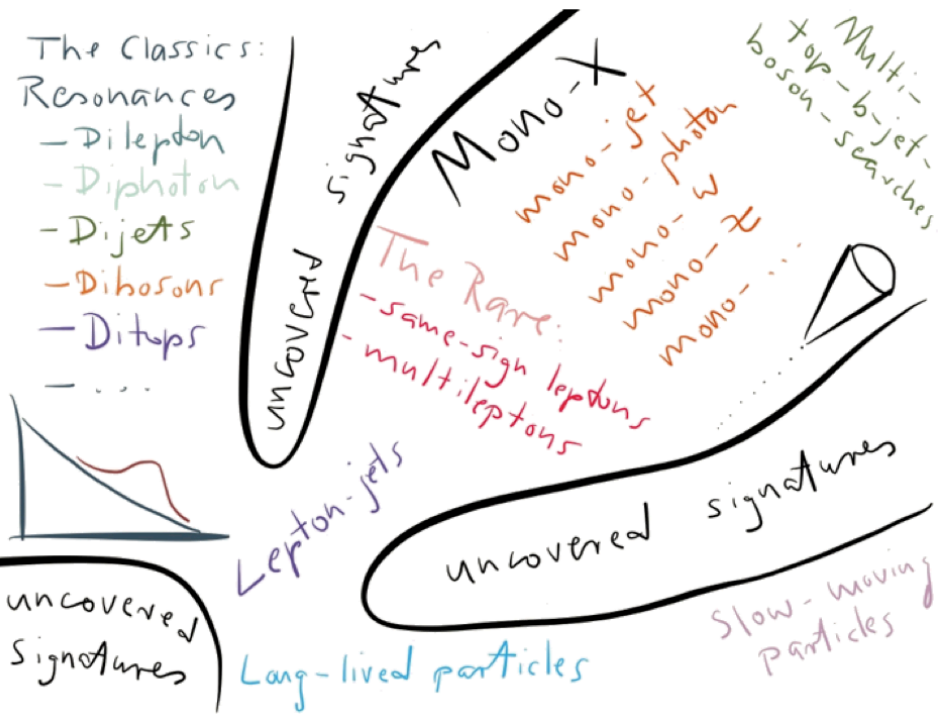


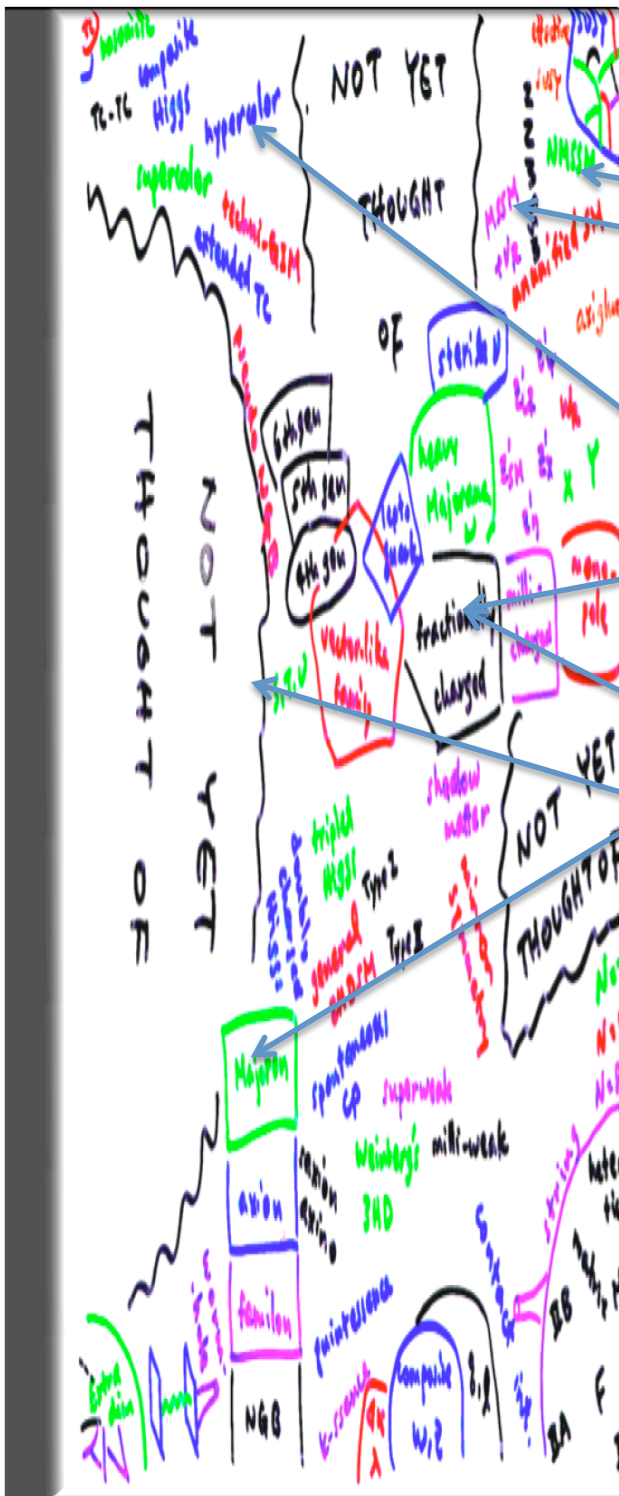


(Hitoshi Murayama)

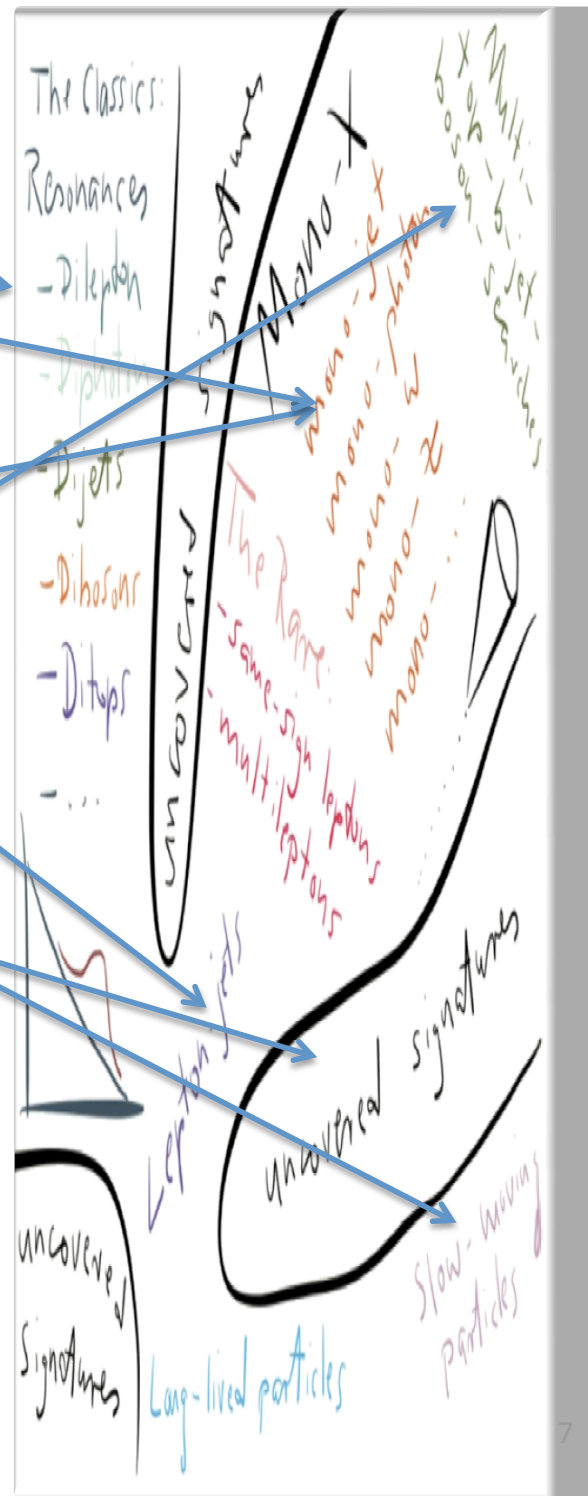


(Hitoshi Murayama)



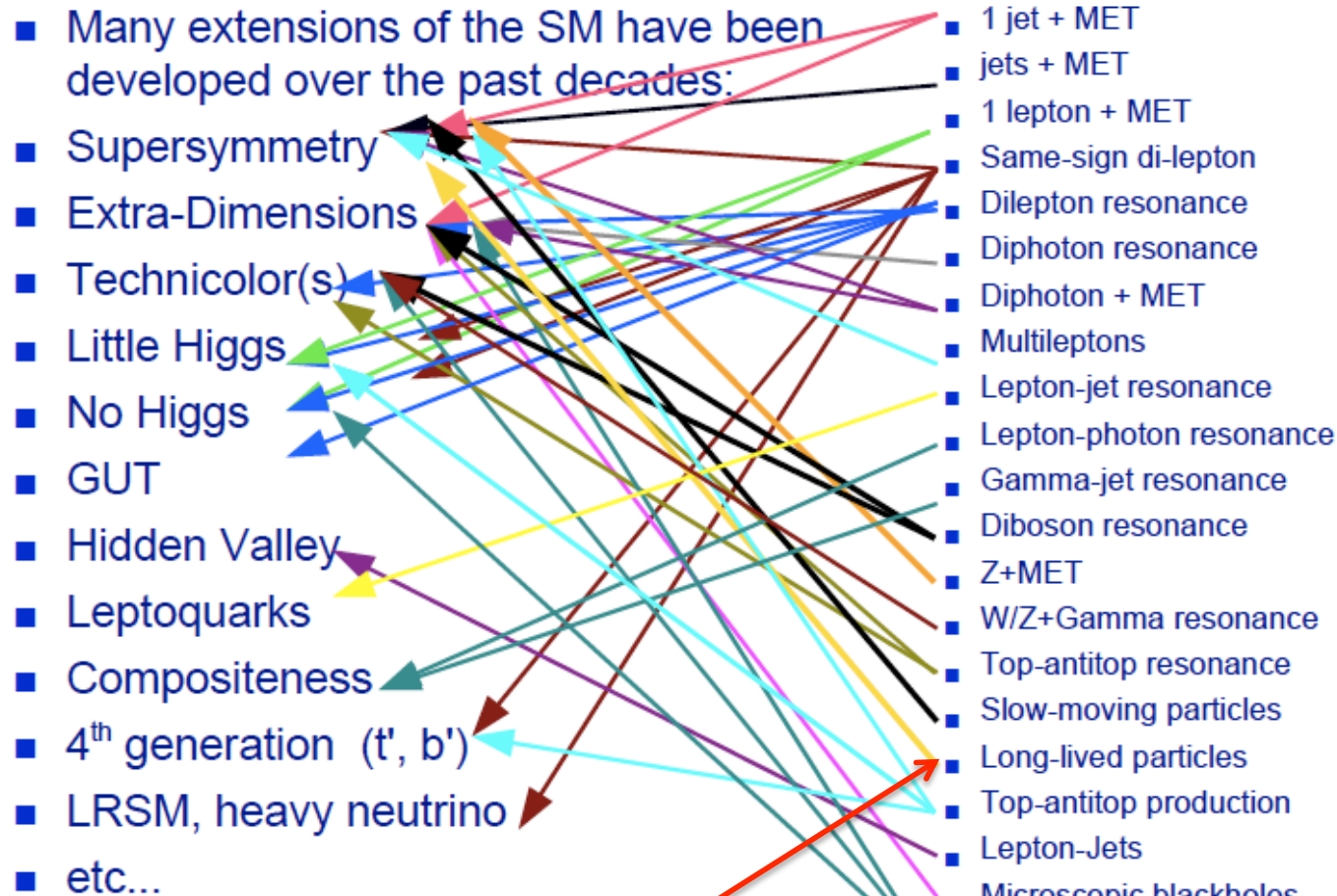


Tobias Golling, Yale



# Signature-Driven Searches

(Henry Bachacou)



- Not yet thought of
- New ideas
- ??

- Signature ?
- Signature ??
- ...

- We know that all models are probably “wrong”
- Use models as guidance where to look
- Try to cover all possible signatures
- Interpret results using benchmarks

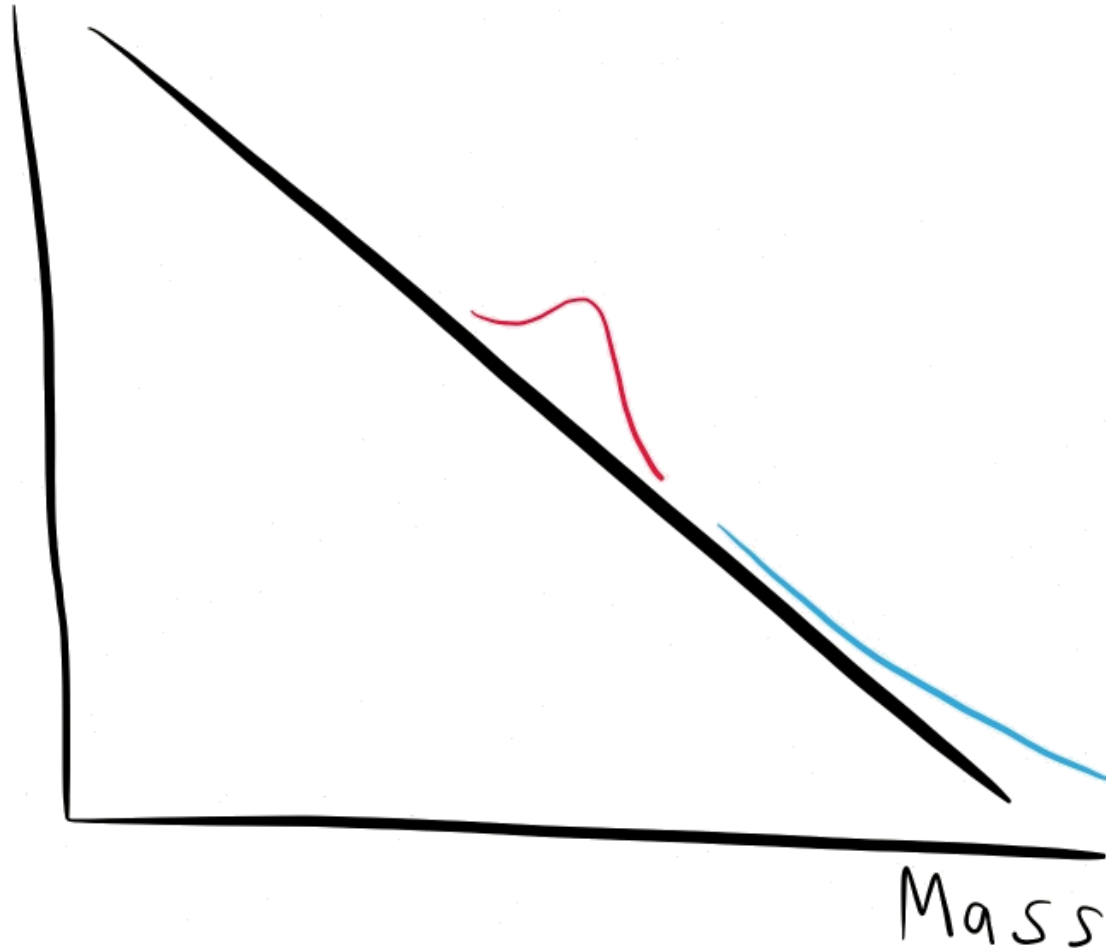
# More in the Parallel Talks this Afternoon

- Search for rare top quark decays and resonances for new physics models
  - Marco Cardaci (National Central Univ., Taiwan)
- Searches for heavy resonances at the LHC
  - Aram Avetisyan (Boston Univ.)
- Searches for Extra Dimensions, LeptoQuarks and Technicolor at the LHC
  - Sergio Grancagnolo (Humboldt Univ. of Berlin)

# Resonances

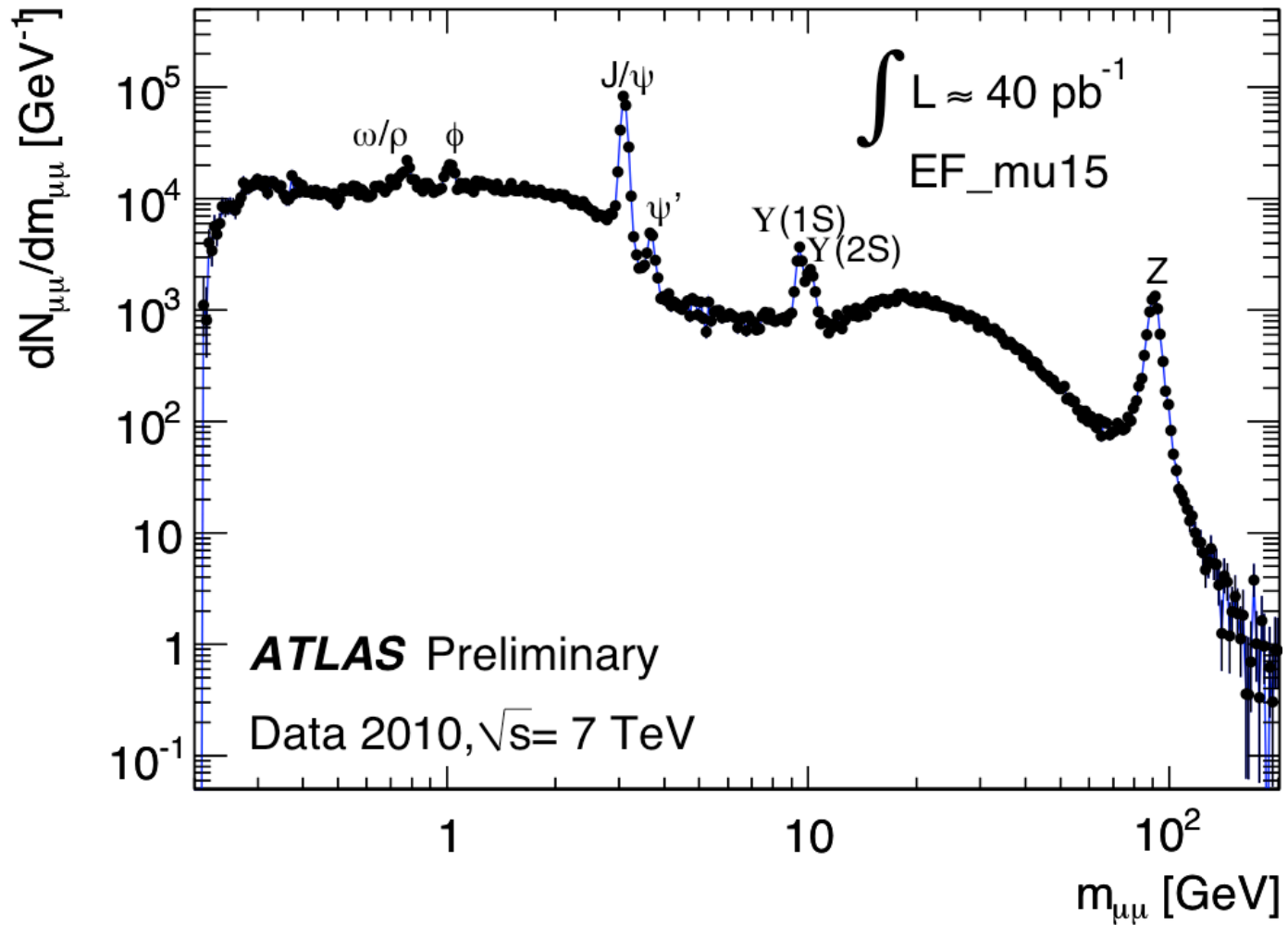


- Smooth BG
  - From MC or fit
- Search for bump (or excess in tail)

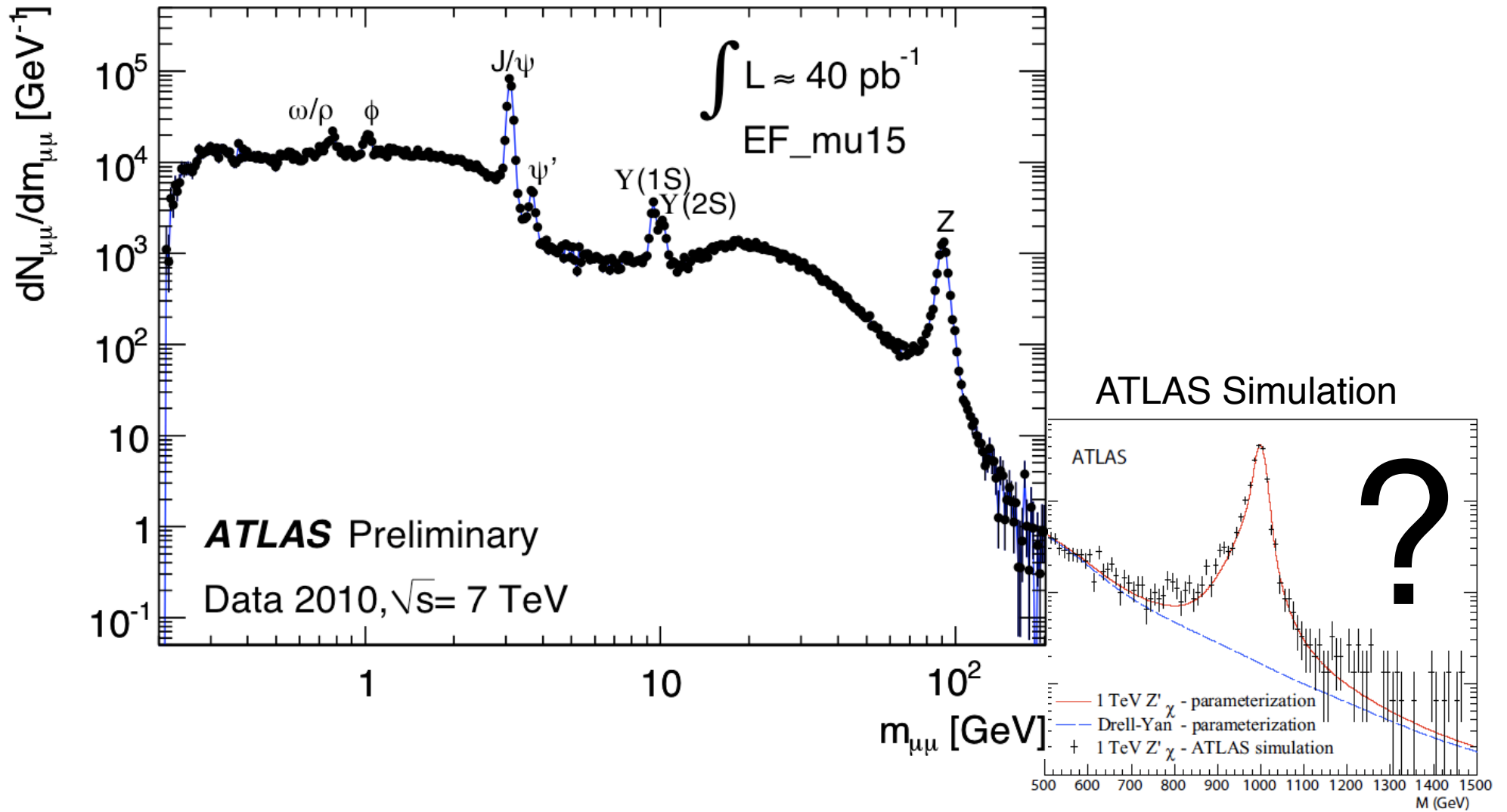




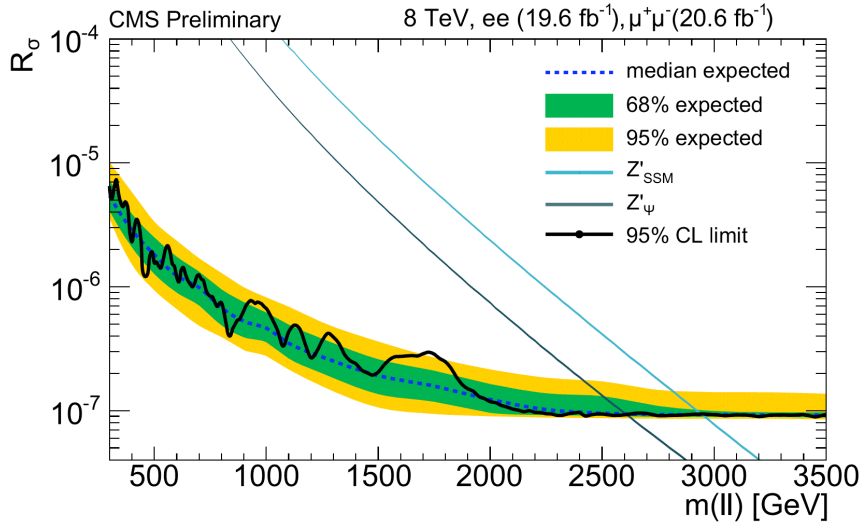
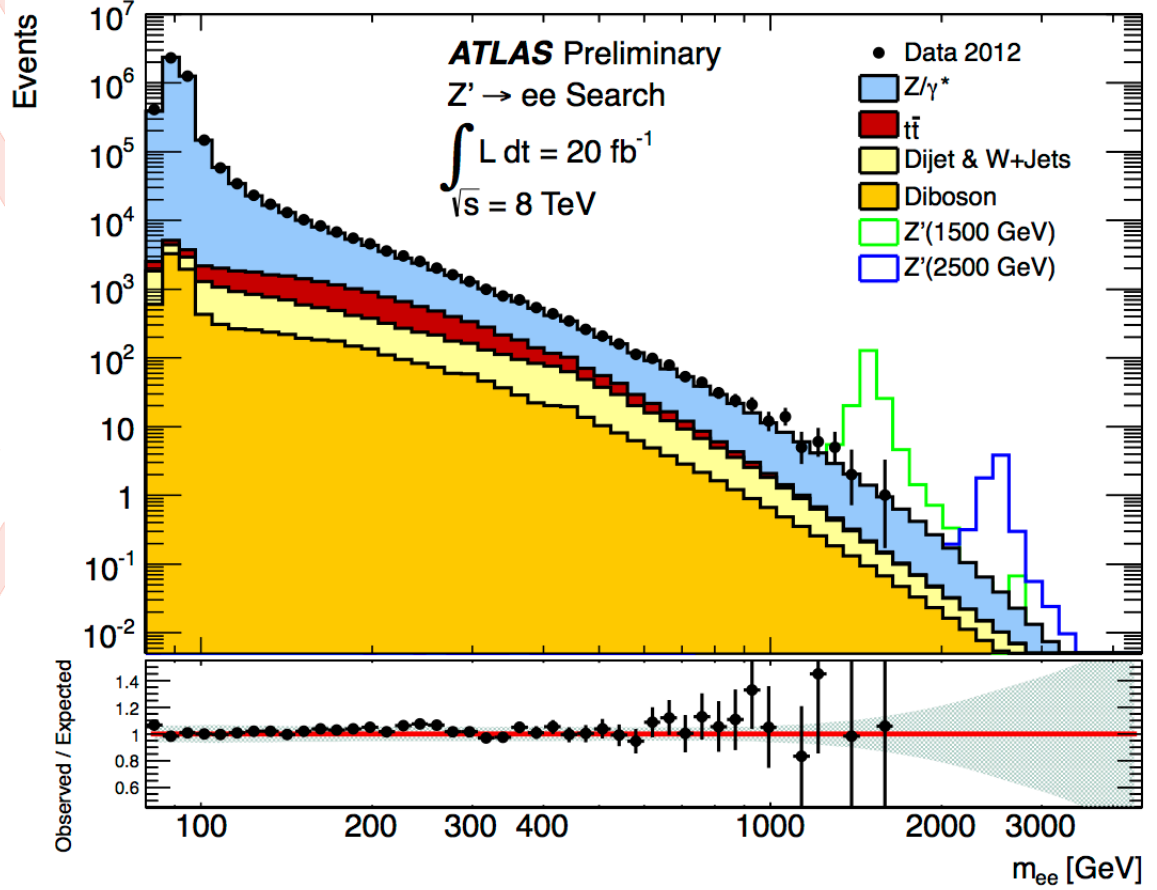
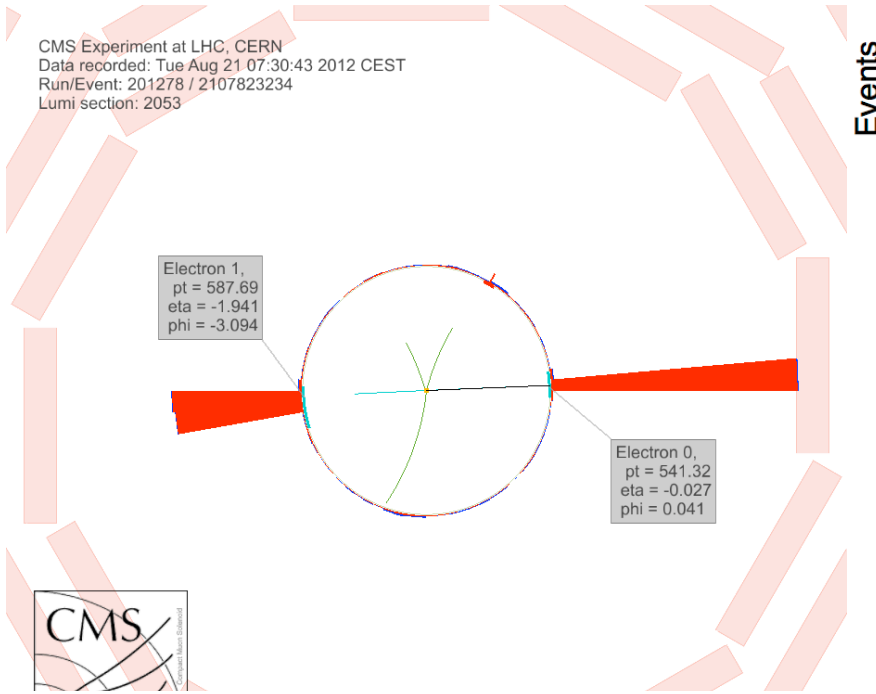
# More Resonances in this Spectrum?



# More Resonances in this Spectrum?

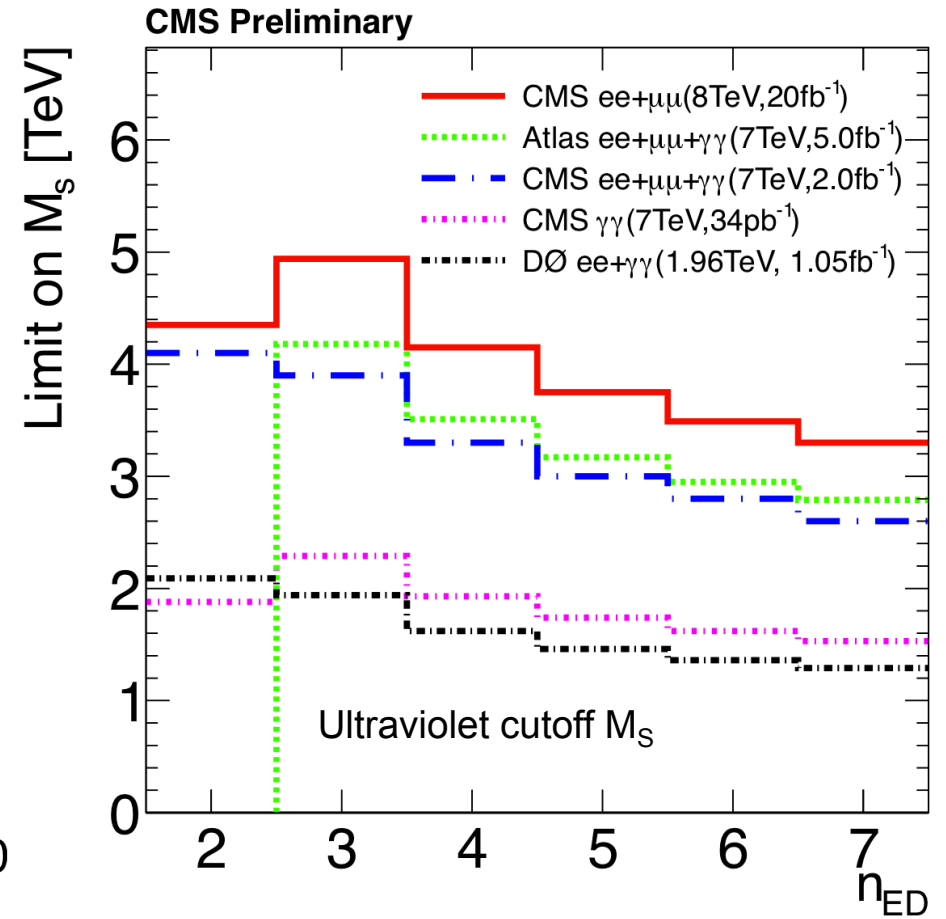
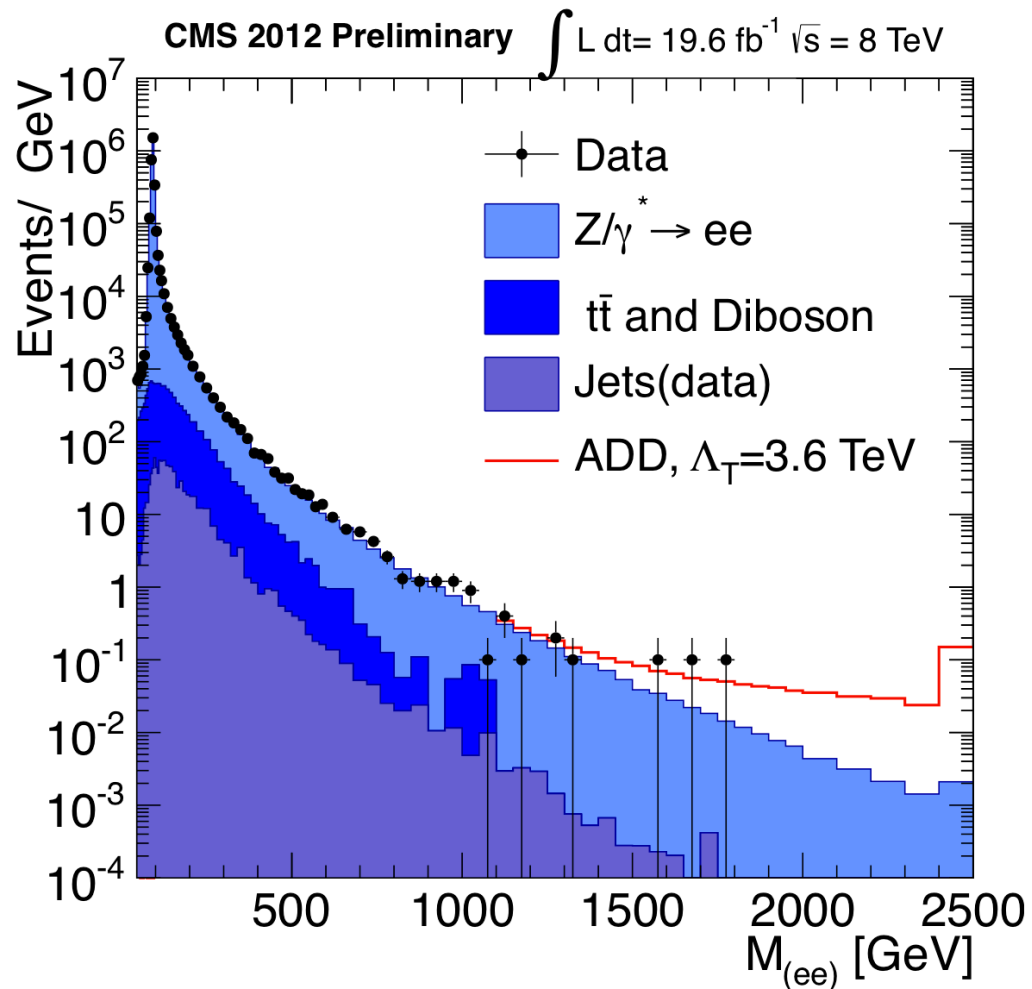


# Dilepton Resonances



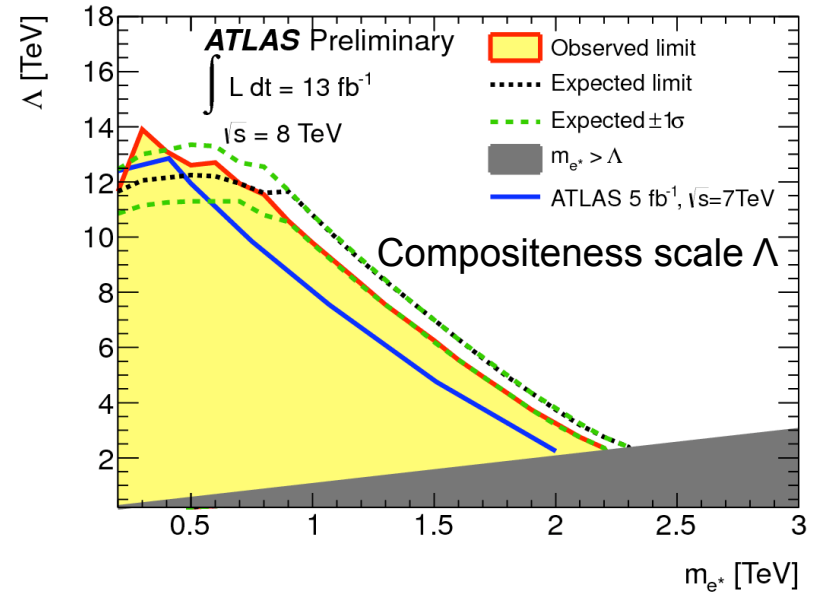
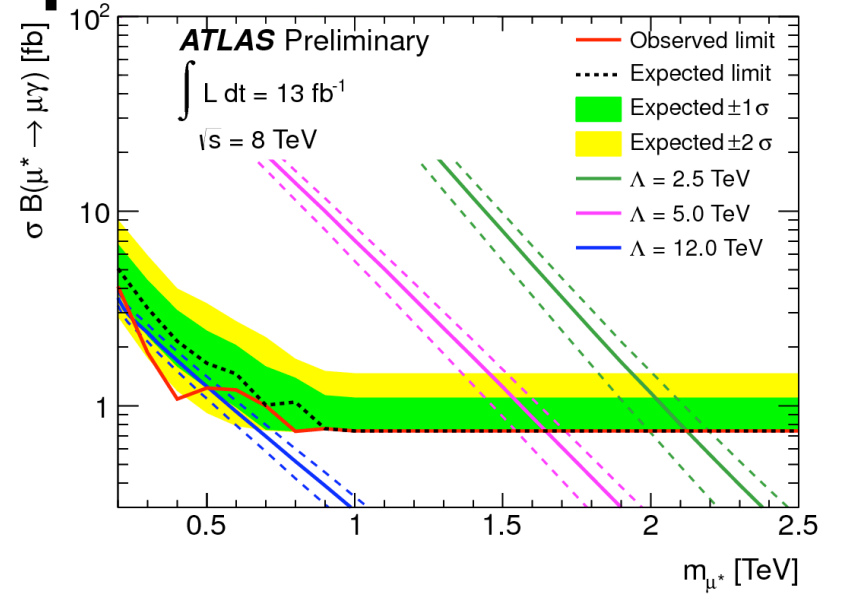
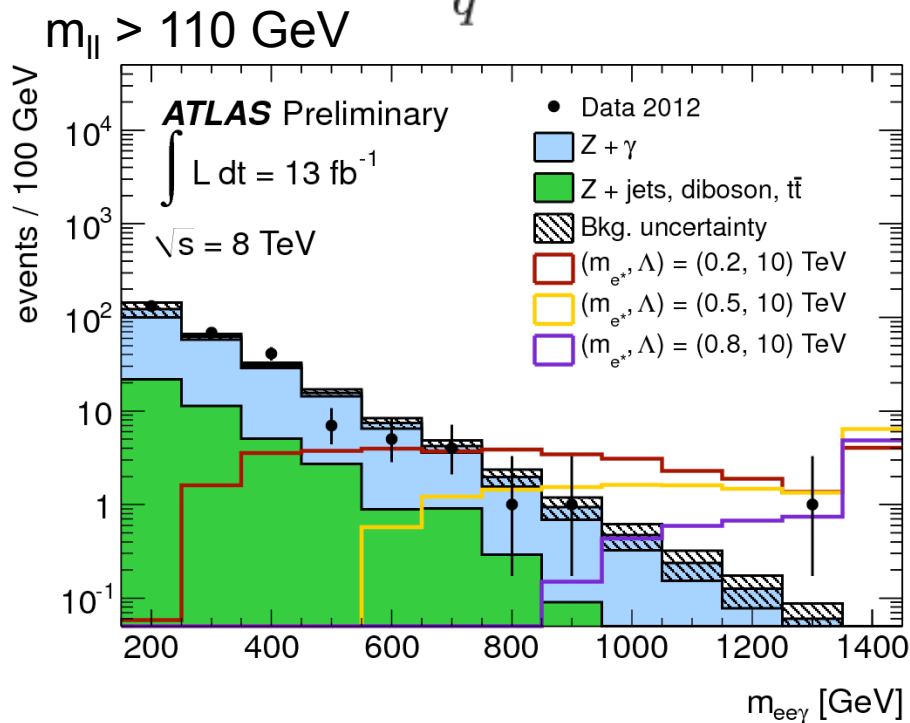
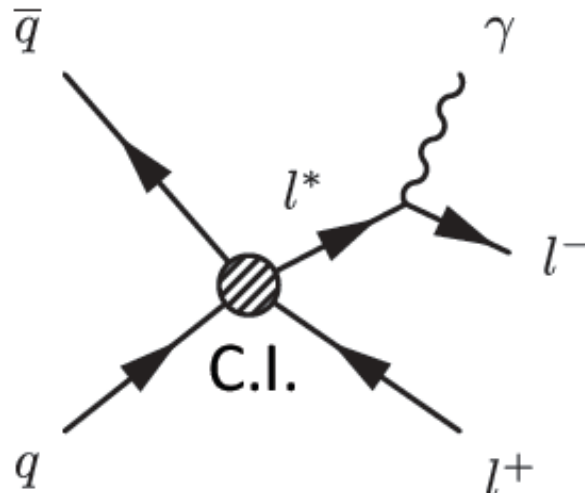
- Exclude @ 95% CL  $Z'_{SSM}$  with Mass < 2.96 TeV

# Non-resonant Dilepton Searches

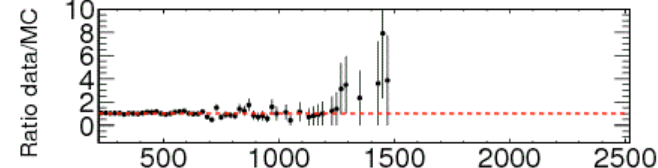
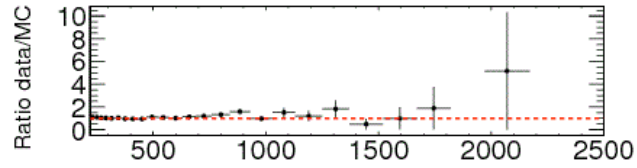
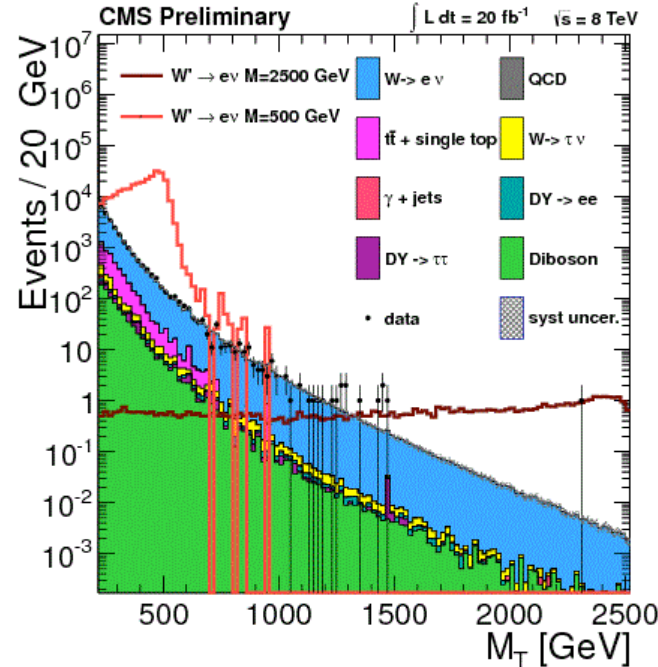
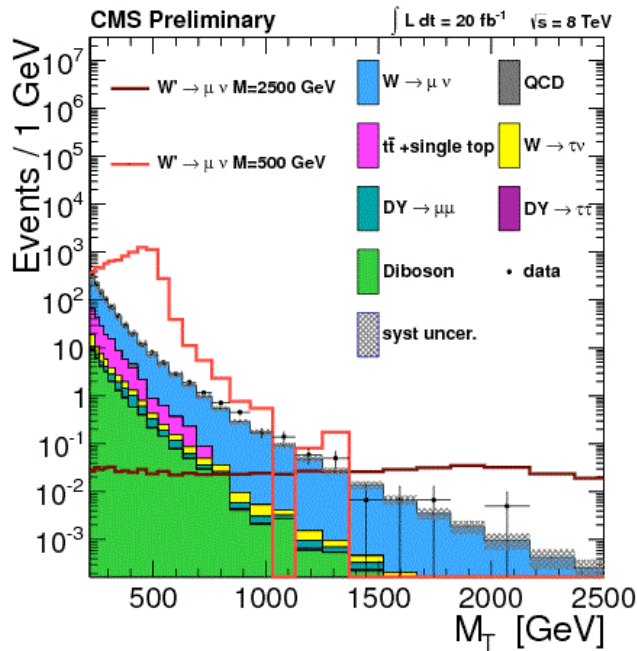


# Non-resonant $l\gamma$ Search

Excited leptons with radiative decay

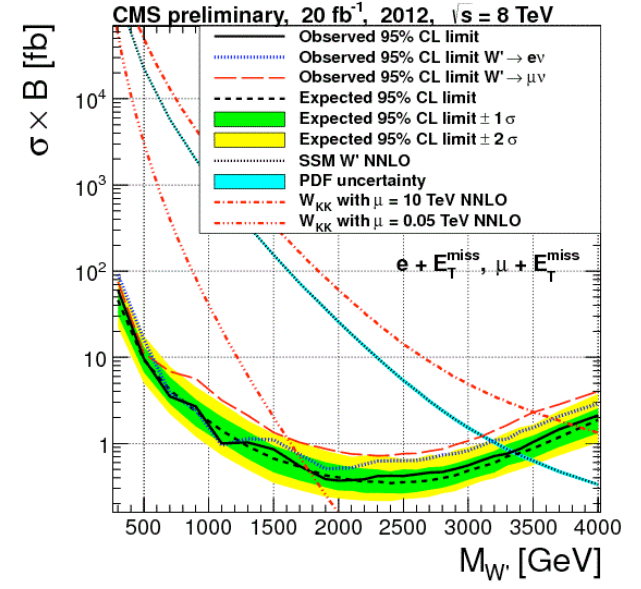


# IV Resonances

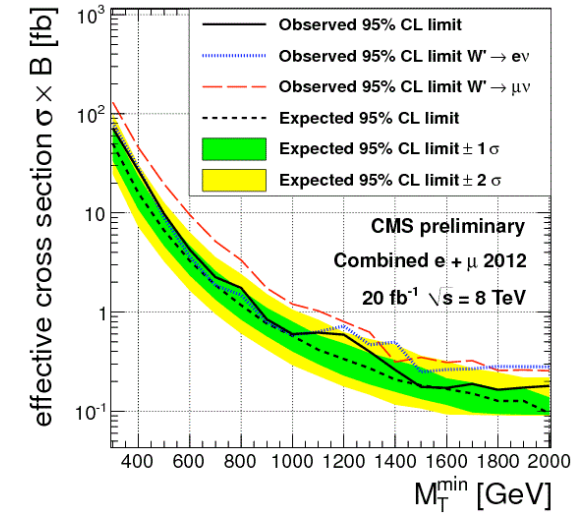


- Exclude @ 95% CL  $W'_{SSM}$  with mass  $< 3.35$  TeV

UED bulk mass parameter  $\mu$

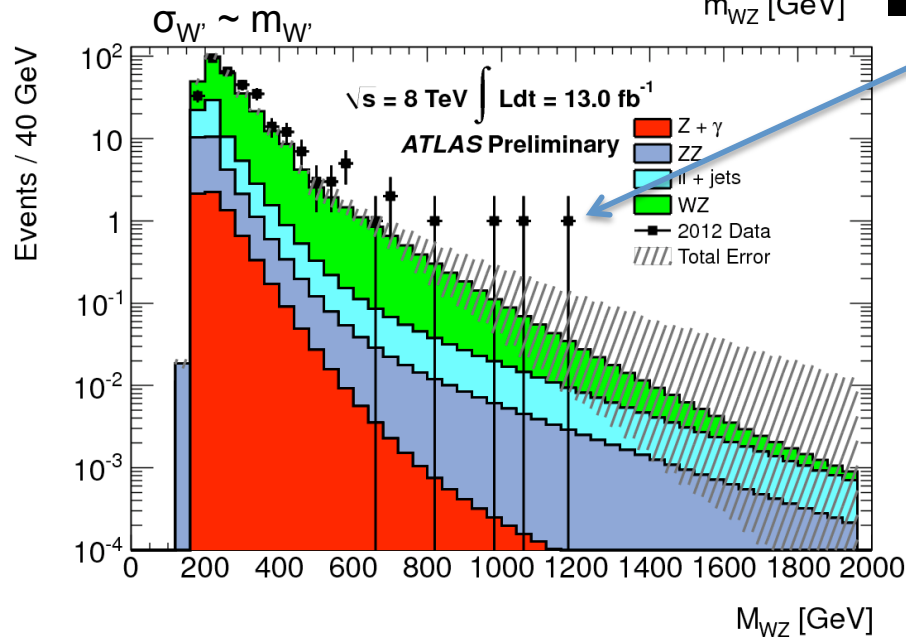
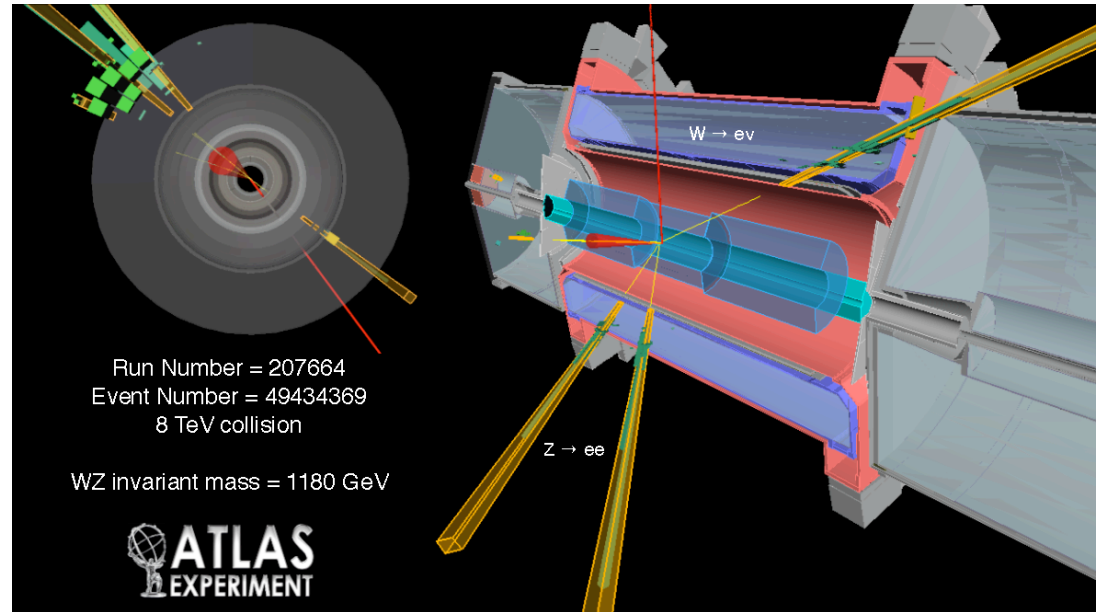
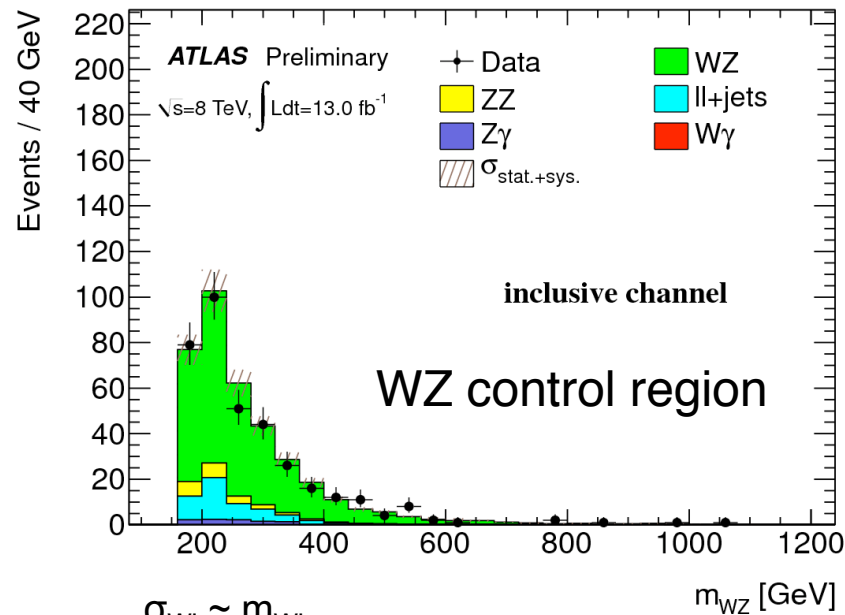


Limit for unspecified signal using bin from  $M_T^{min}$  to  $\infty$



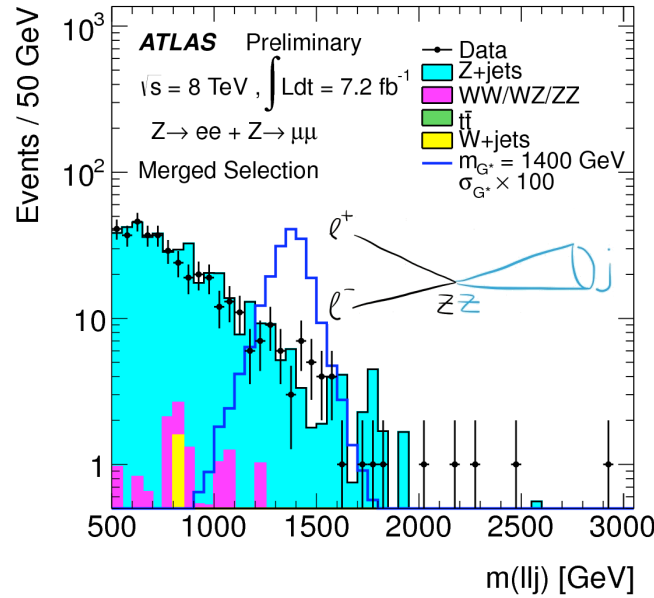
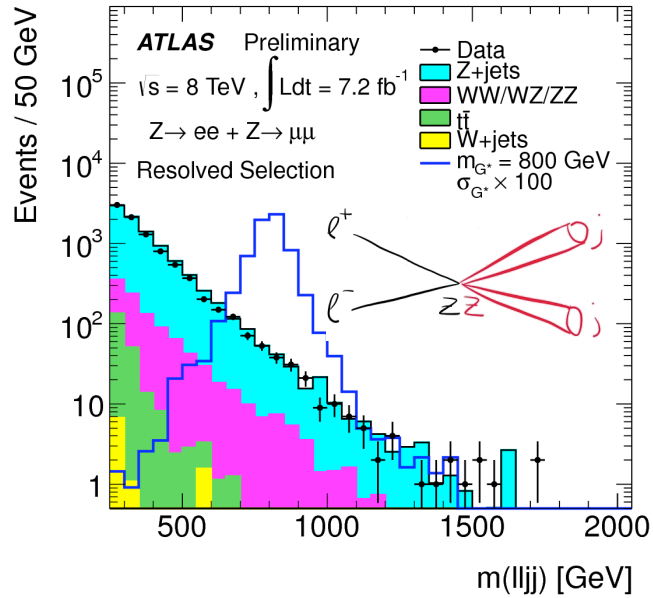


# WZ → lνl Resonances

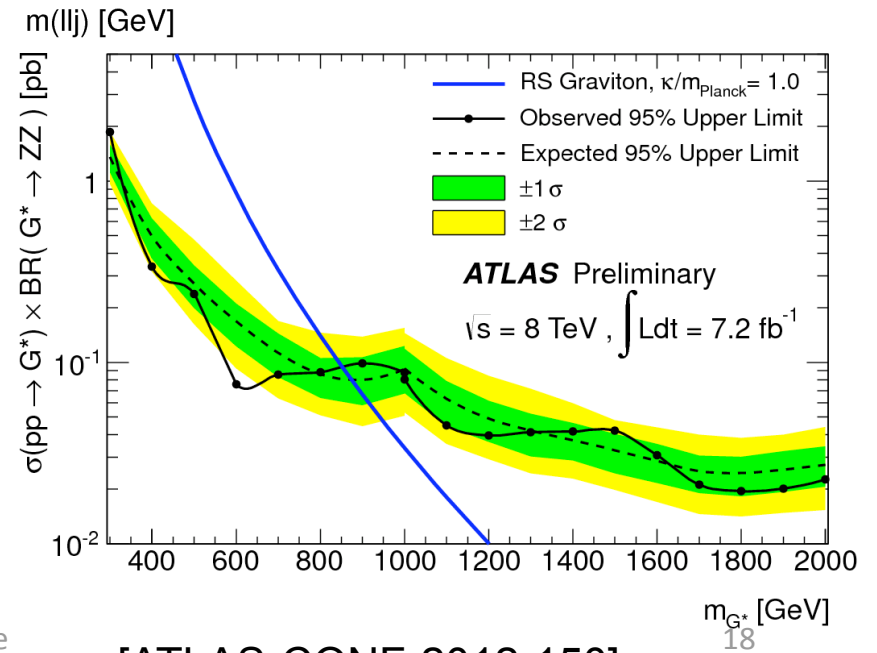
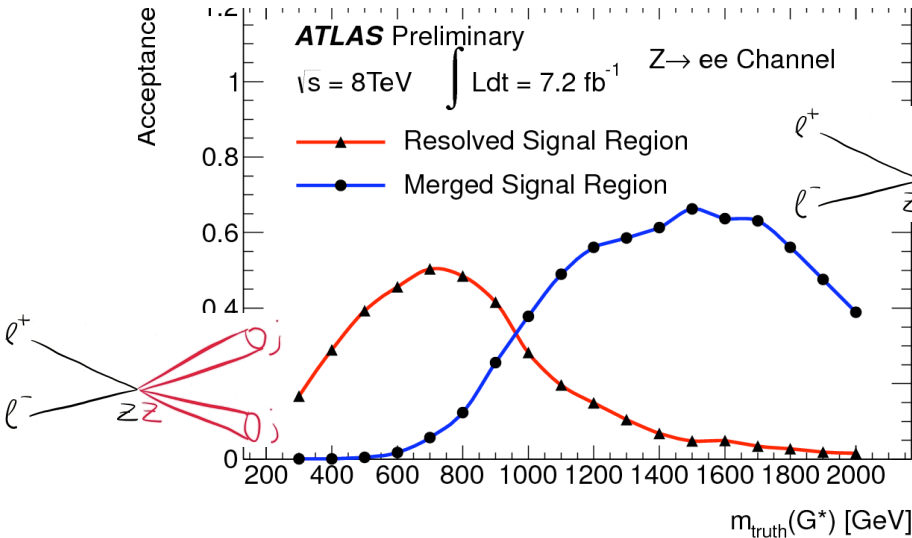


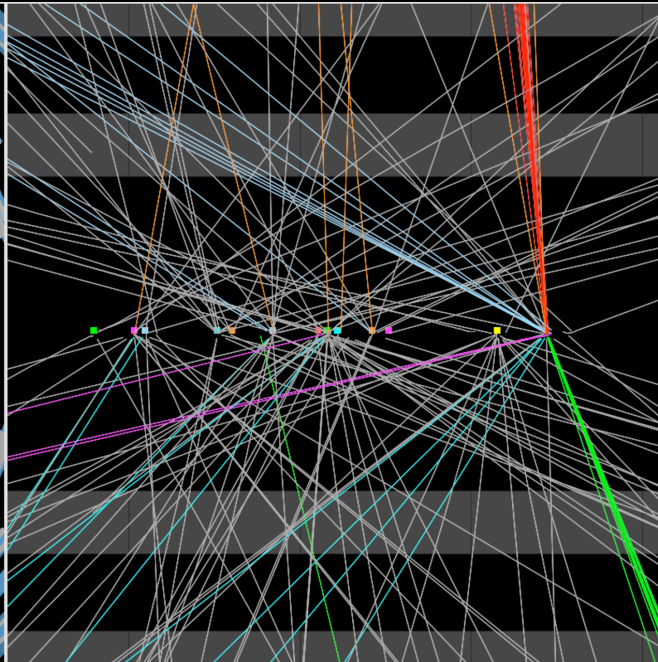
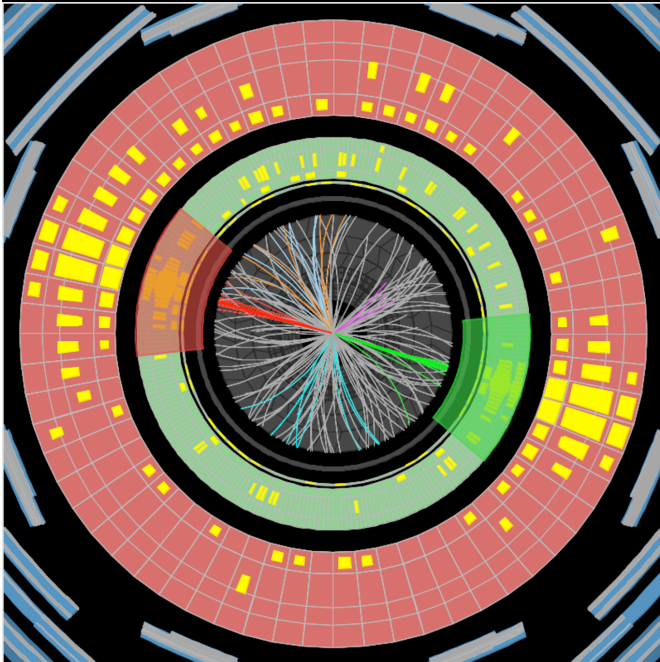
- Exclude @ 95% CL
  - $W'_{\text{EGM}}$  with mass < 1.18 TeV
  - Technirho with mass < 920 GeV

# $ZZ \rightarrow lljj$ / $llj$ Resonances



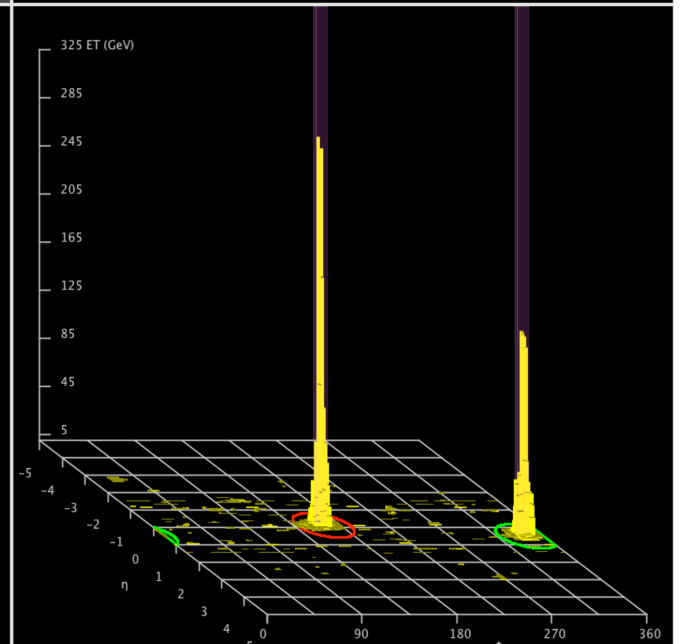
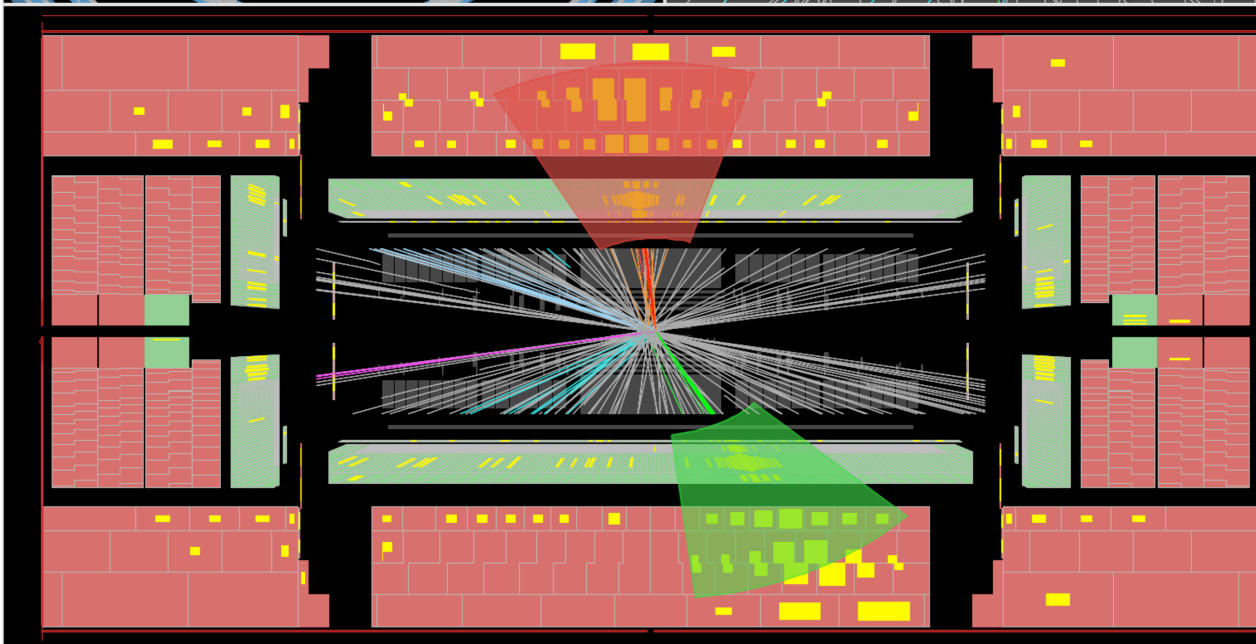
Exclude @ 95% CL bulk RS (RS1) model (coupling parameter  $k/\bar{M}_{\text{Pl}}=1.0$ ) with  $m_{G^*} < 850 \text{ GeV}$





Run Number: 209580, Event Number: 179229707

Date: 2012-08-31 20:24:29 CEST



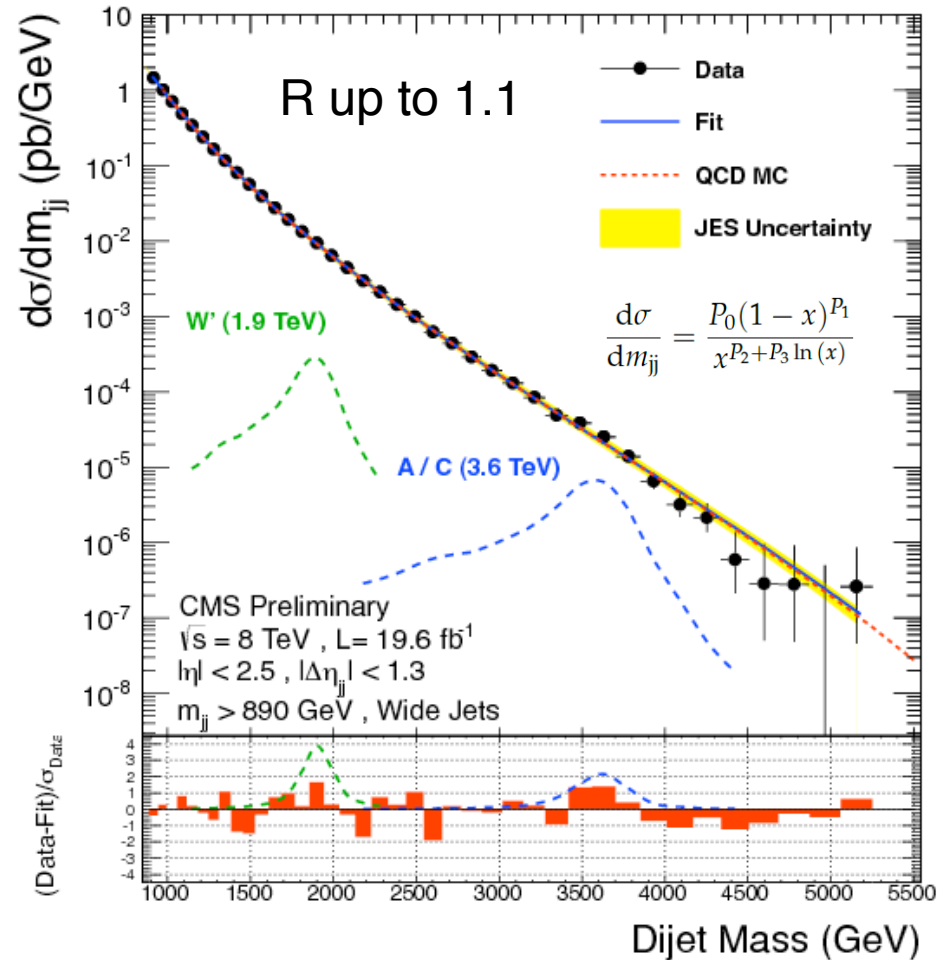
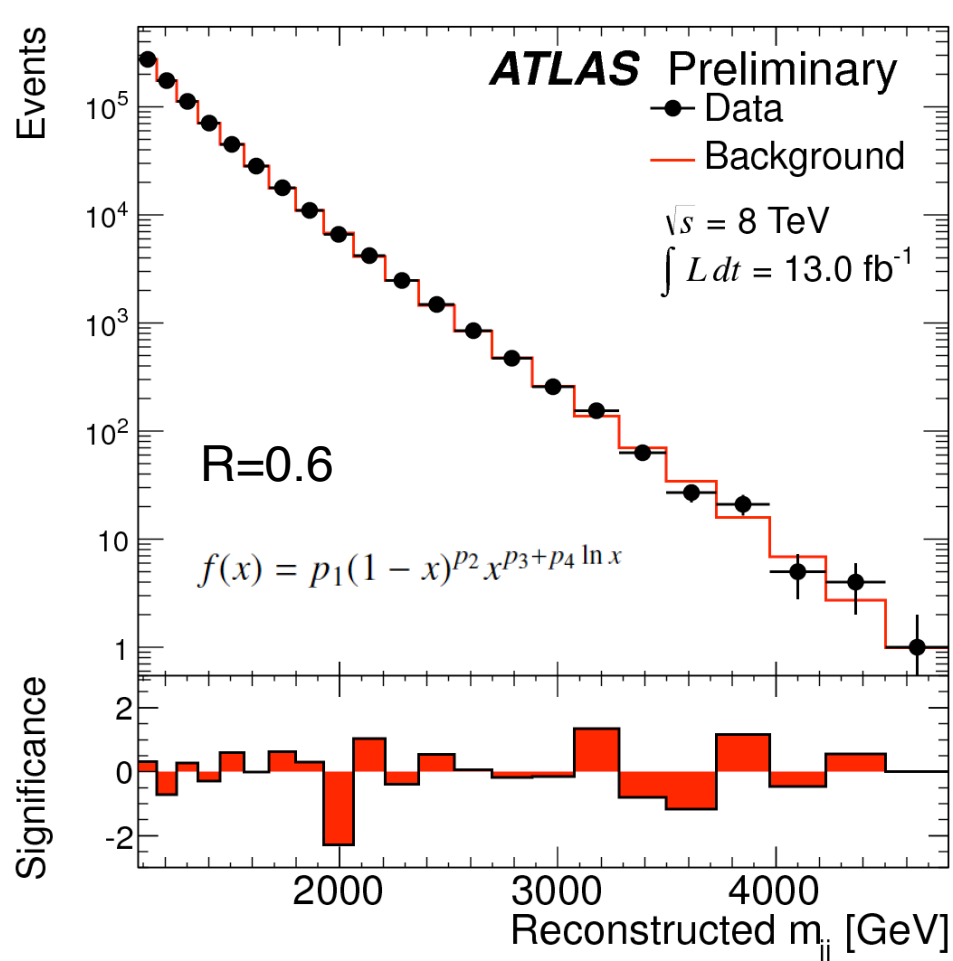
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$m_{jj} = 4.7 \text{ TeV}, E_T^{\text{miss}} = 47 \text{ GeV}$  19

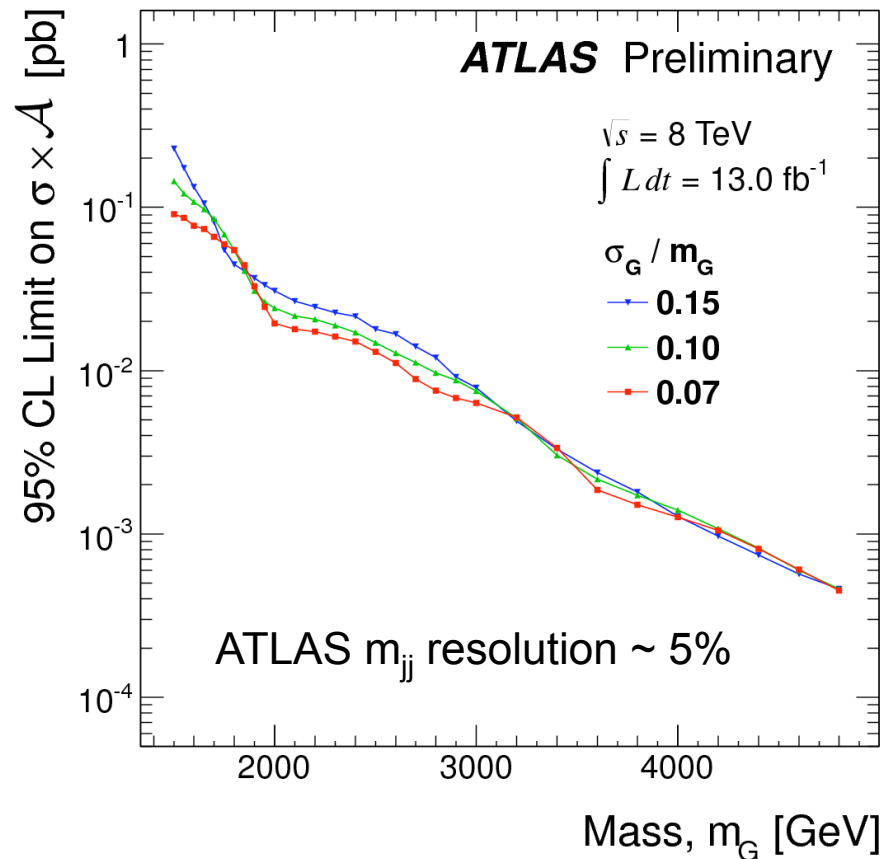
# Dijet Resonances

- Observables: dijet mass and angular distributions
  - Binning according to mass resolution

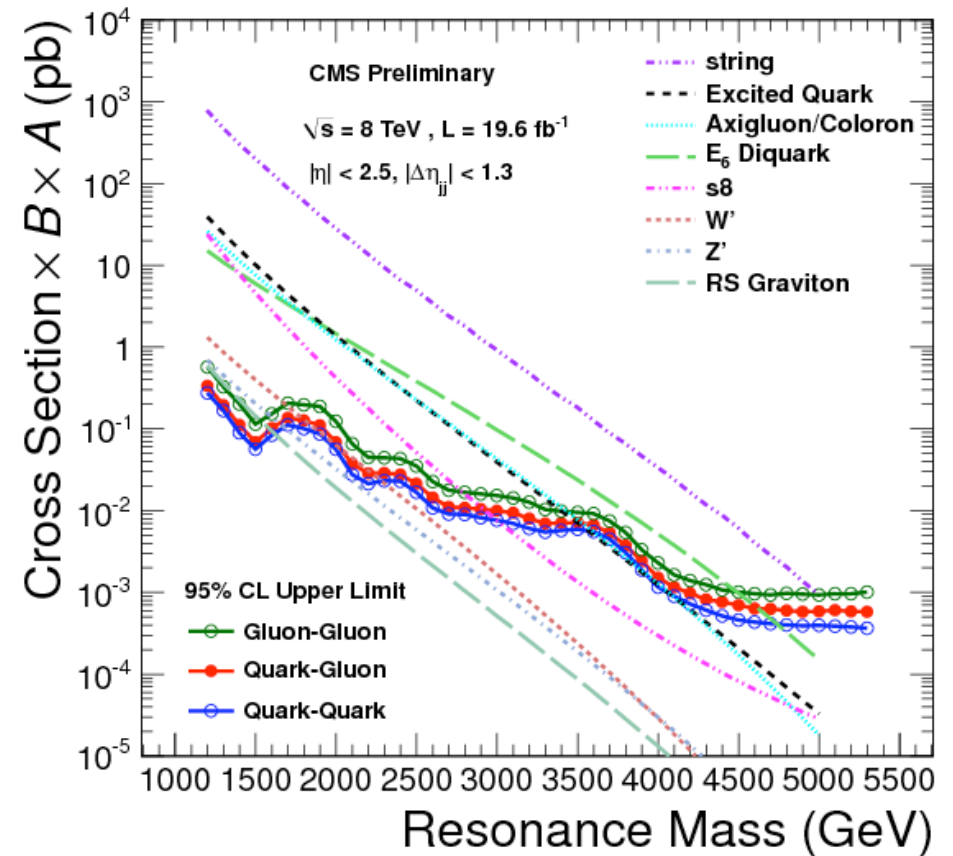


# Generic Limits for Narrow Dijet Resonances

Dependence on width of resonance



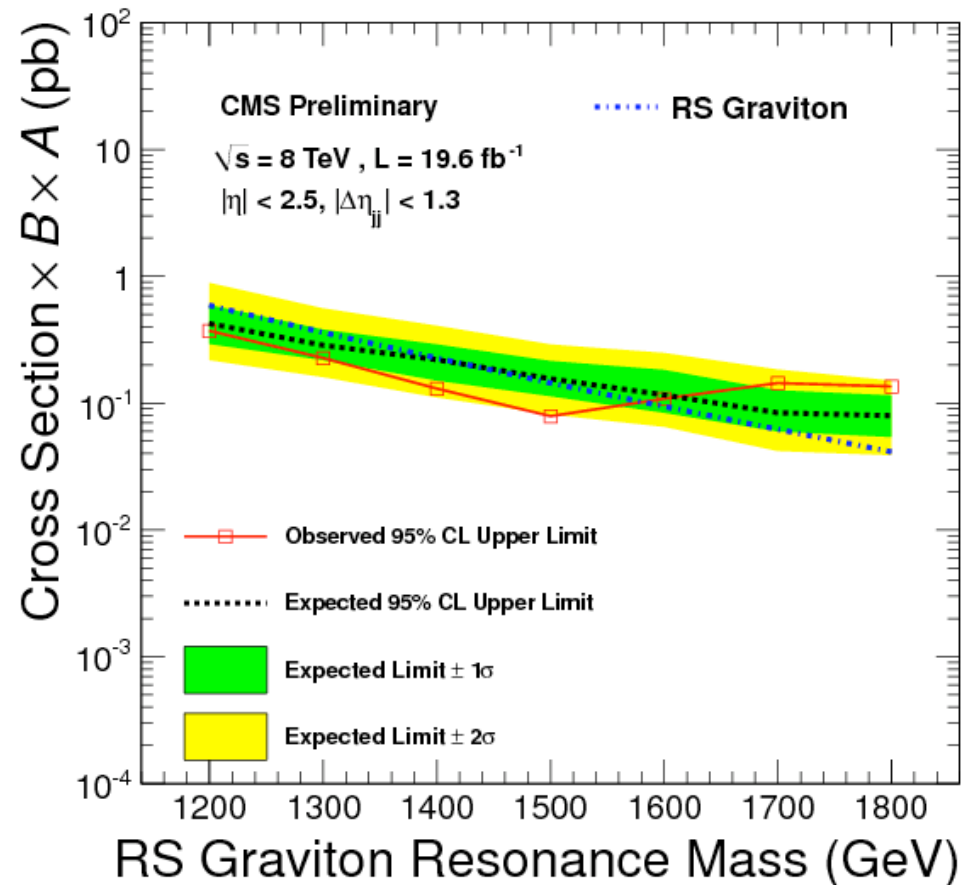
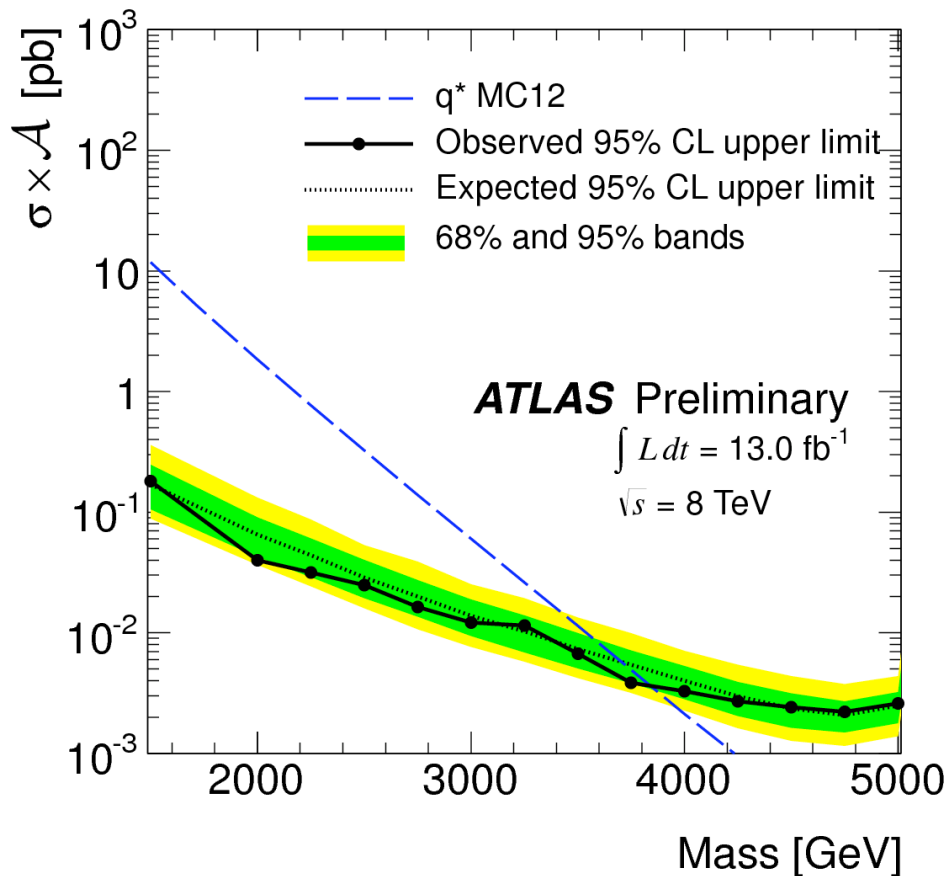
Resonance decays to quarks and gluons



Exclude @ 95% CL mass up to 5.1 TeV (string resonance)



# Limits for Dedicated Dijet Models

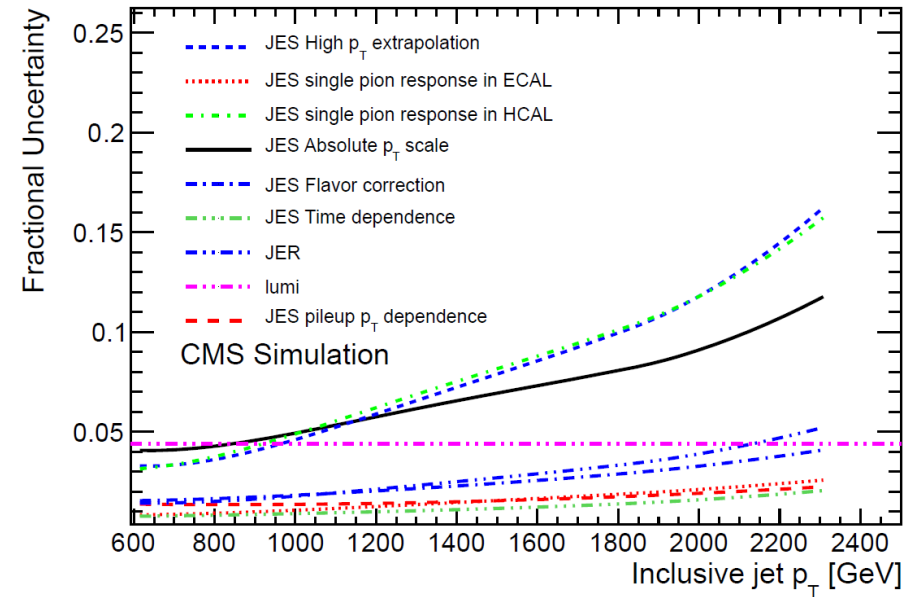
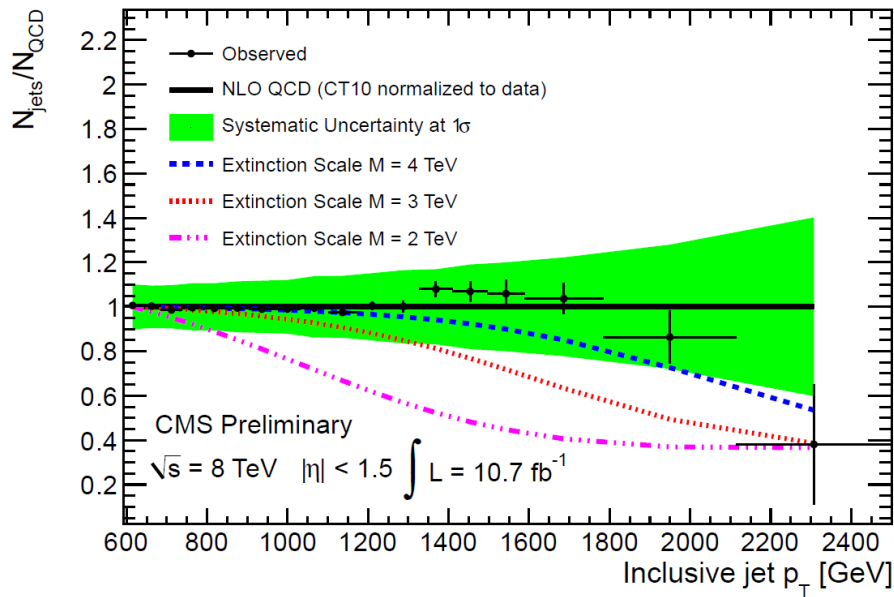


- Tevatron sensitivity below  $\sim 1$  TeV and LHC sensitivity above  $\sim 1$  TeV due to jet trigger thresholds
- Mass region around 1 TeV not probed  $\Rightarrow$  ATLAS delayed triggers, CMS parked data & data scouting

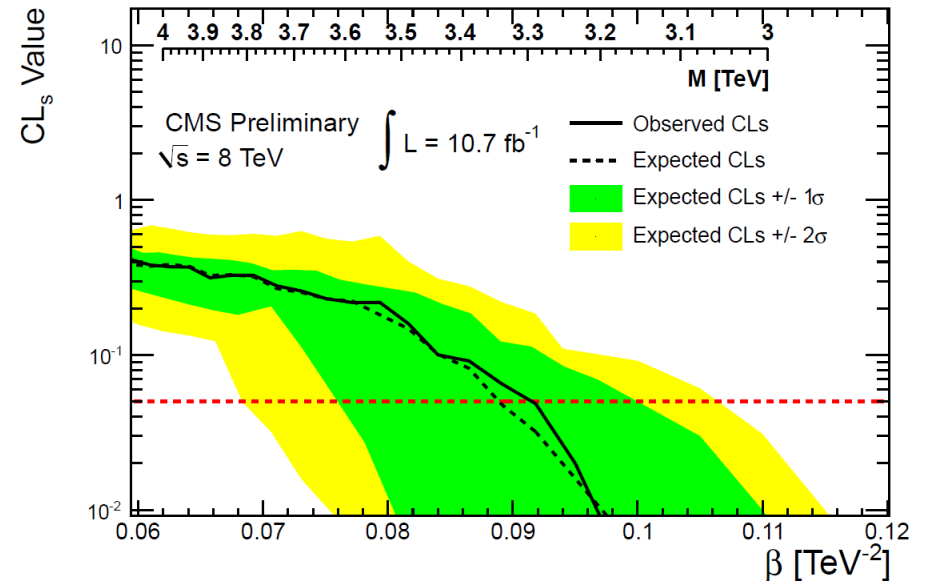


# Excursion: jets / non-resonant

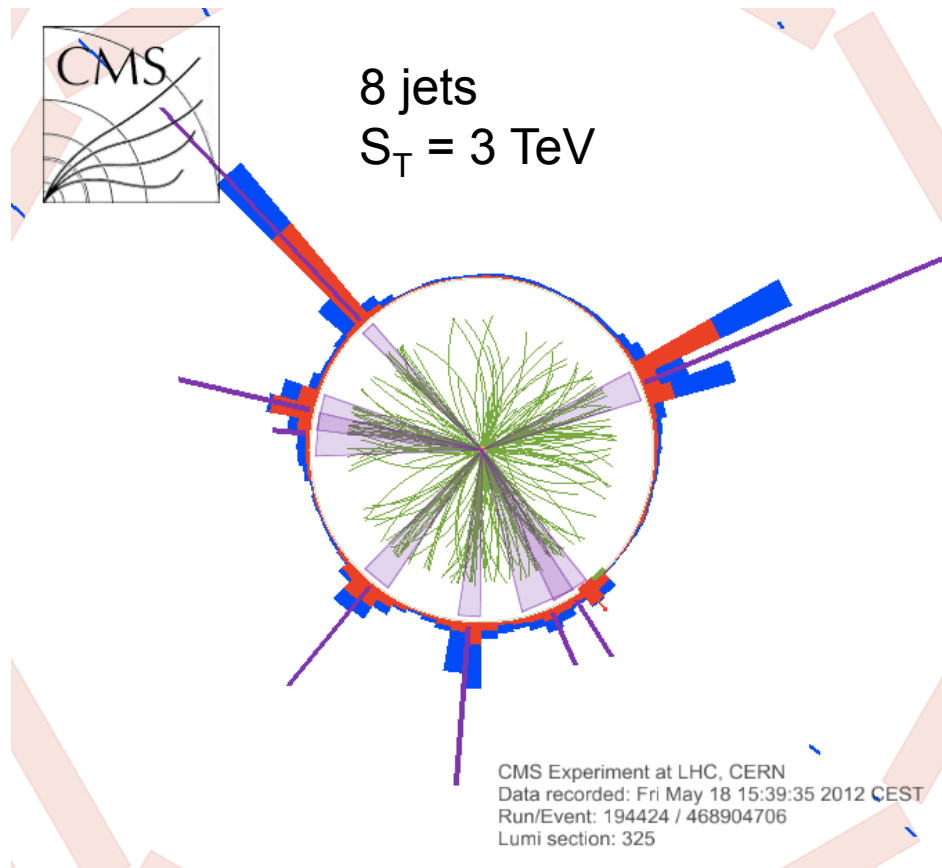
# Search for Jet Extinction



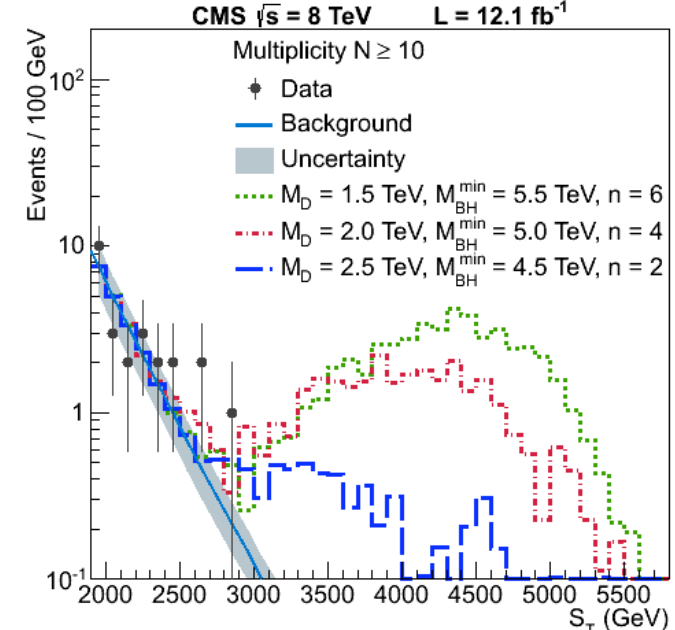
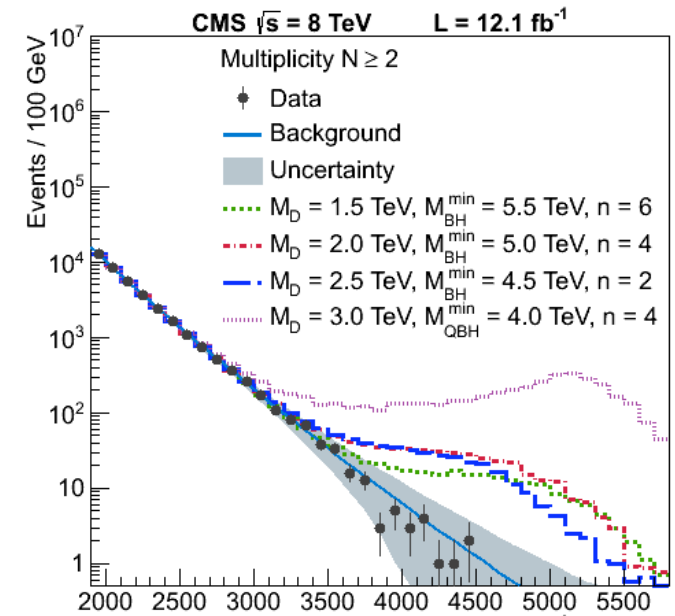
- Terascale gravity can modify jet  $p_T$  spectrum
- Sensitive to systematics across jet  $p_T$  bins
- Exclude @ 95% CL extinction energy scale  $M < 3.3$  TeV



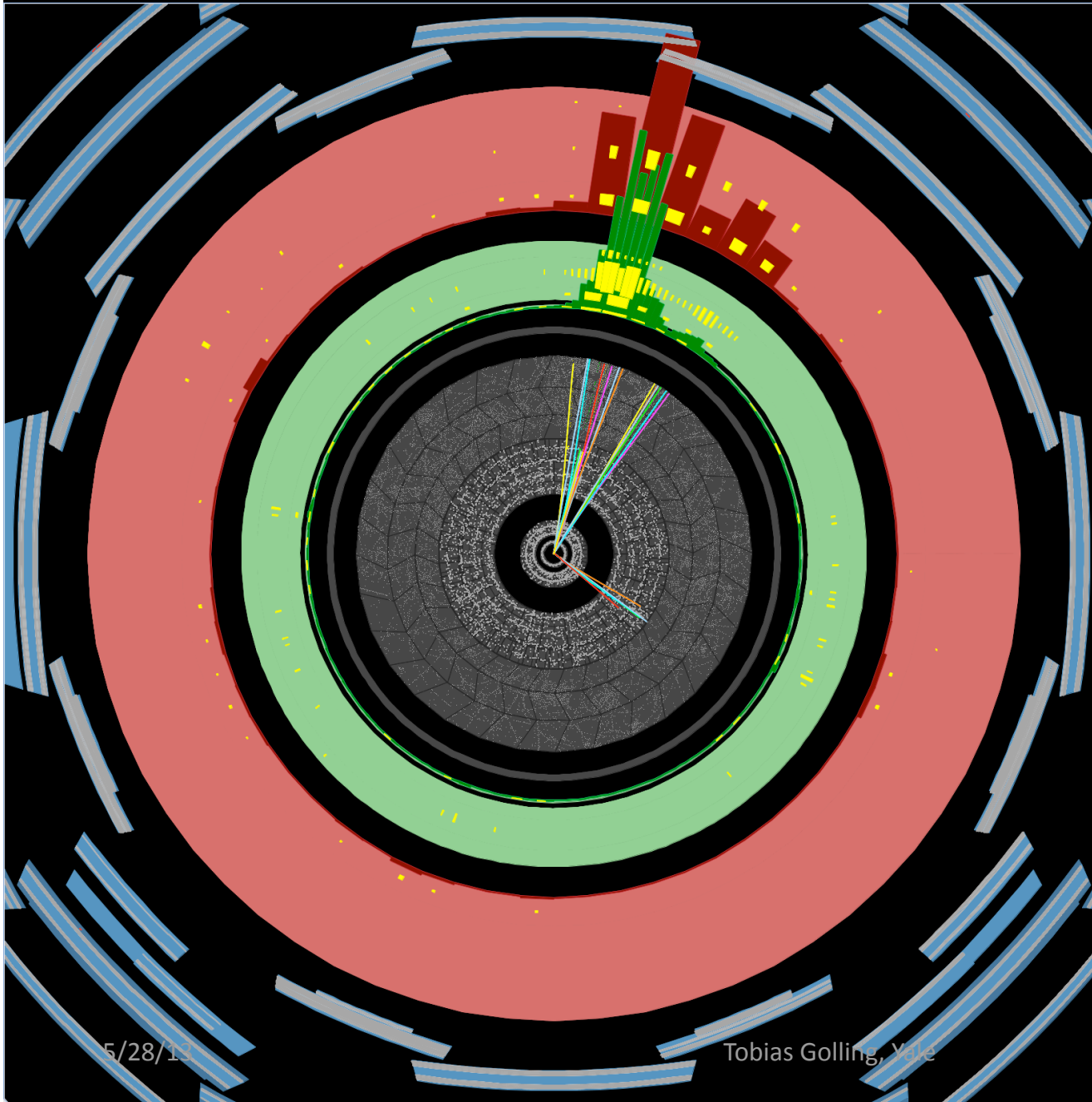
# Search for Microscopic Black Holes



- Quantum gravity through large extra dimensions
- High multiplicity (jets, leptons,  $\gamma$ ) and large  $S_T = \sum p_T$
- Exclude @ 95% CL semiclassical and quantum black holes with masses below 4.3–6.2 TeV



# Mono-Jet (or Mono-Photon\*) Searches

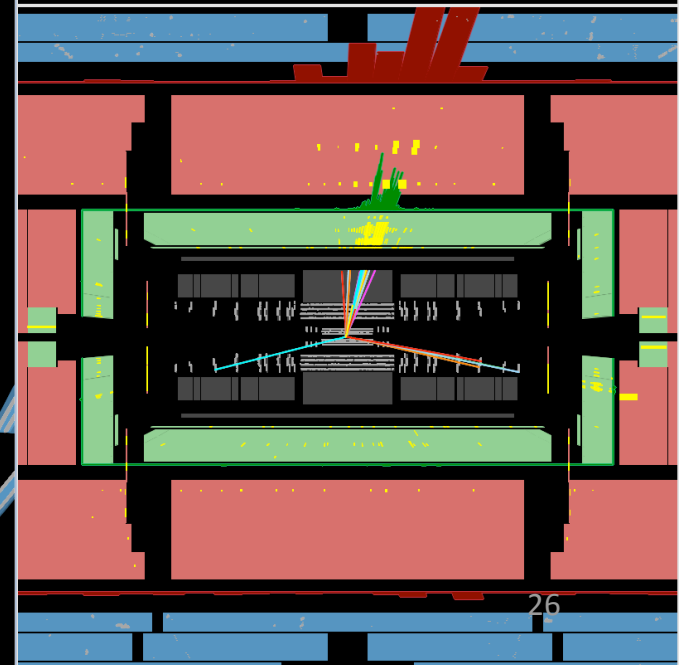


\* ATLAS-CONF-2012-085

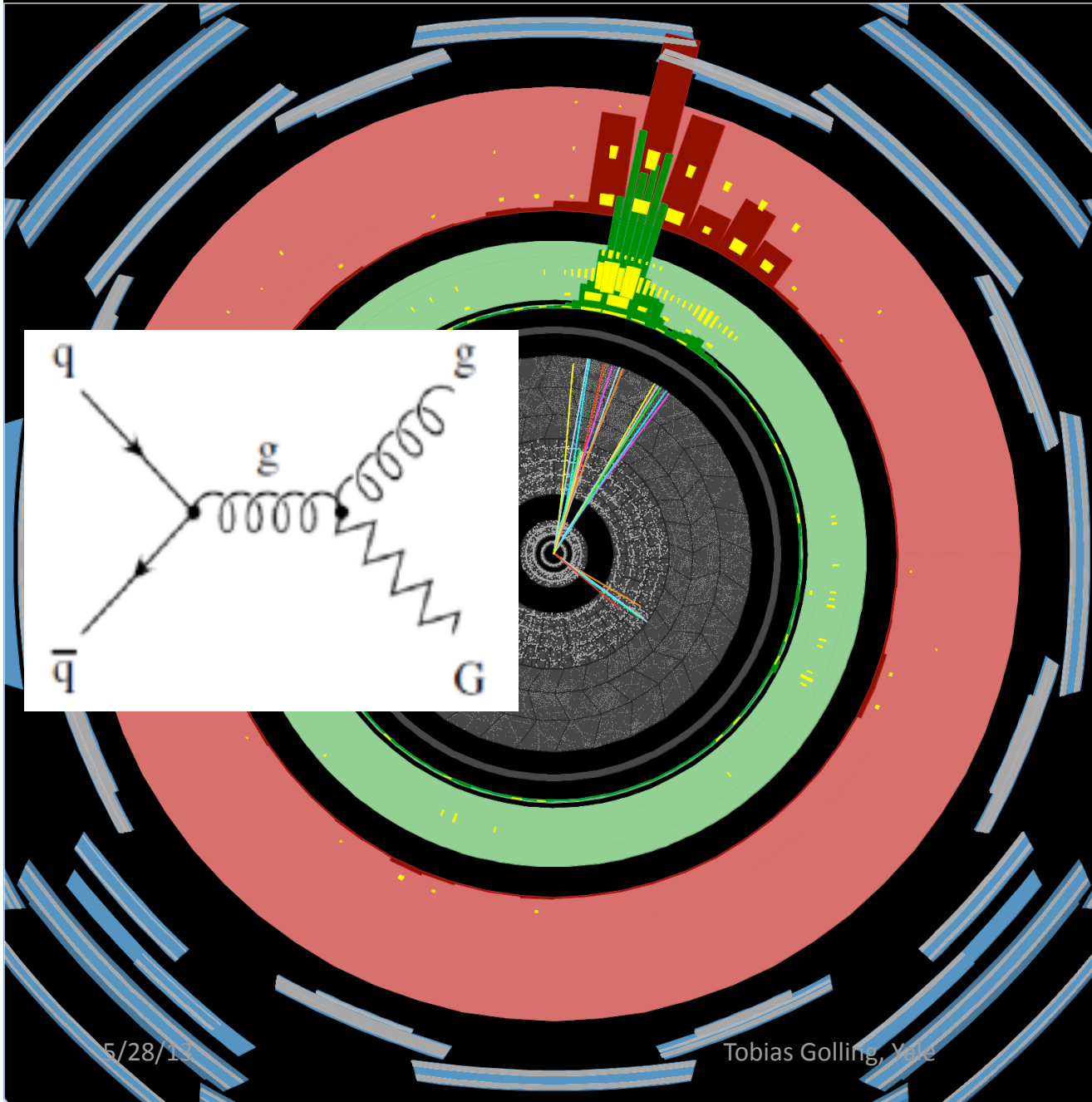


Run Number: 206962, Event Number: 55091306

Date: 2012-07-14 10:42:26 CEST

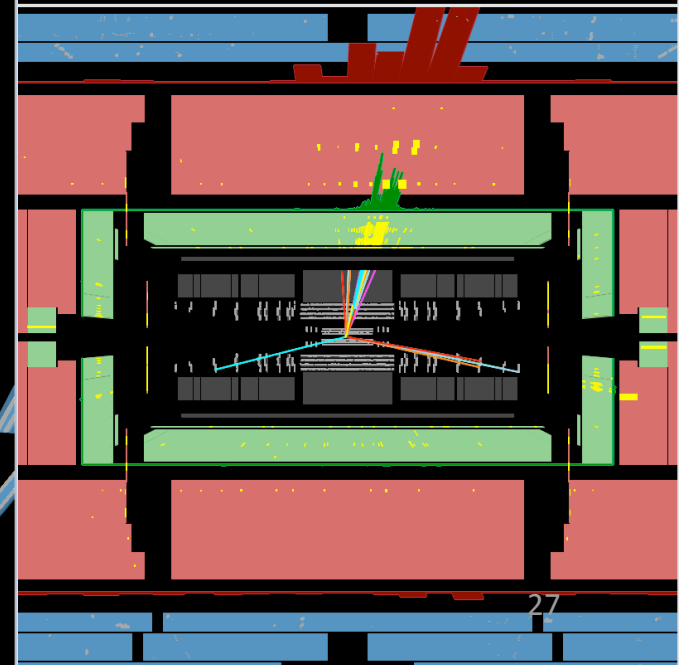


# Mono-Jet: Graviton Searches



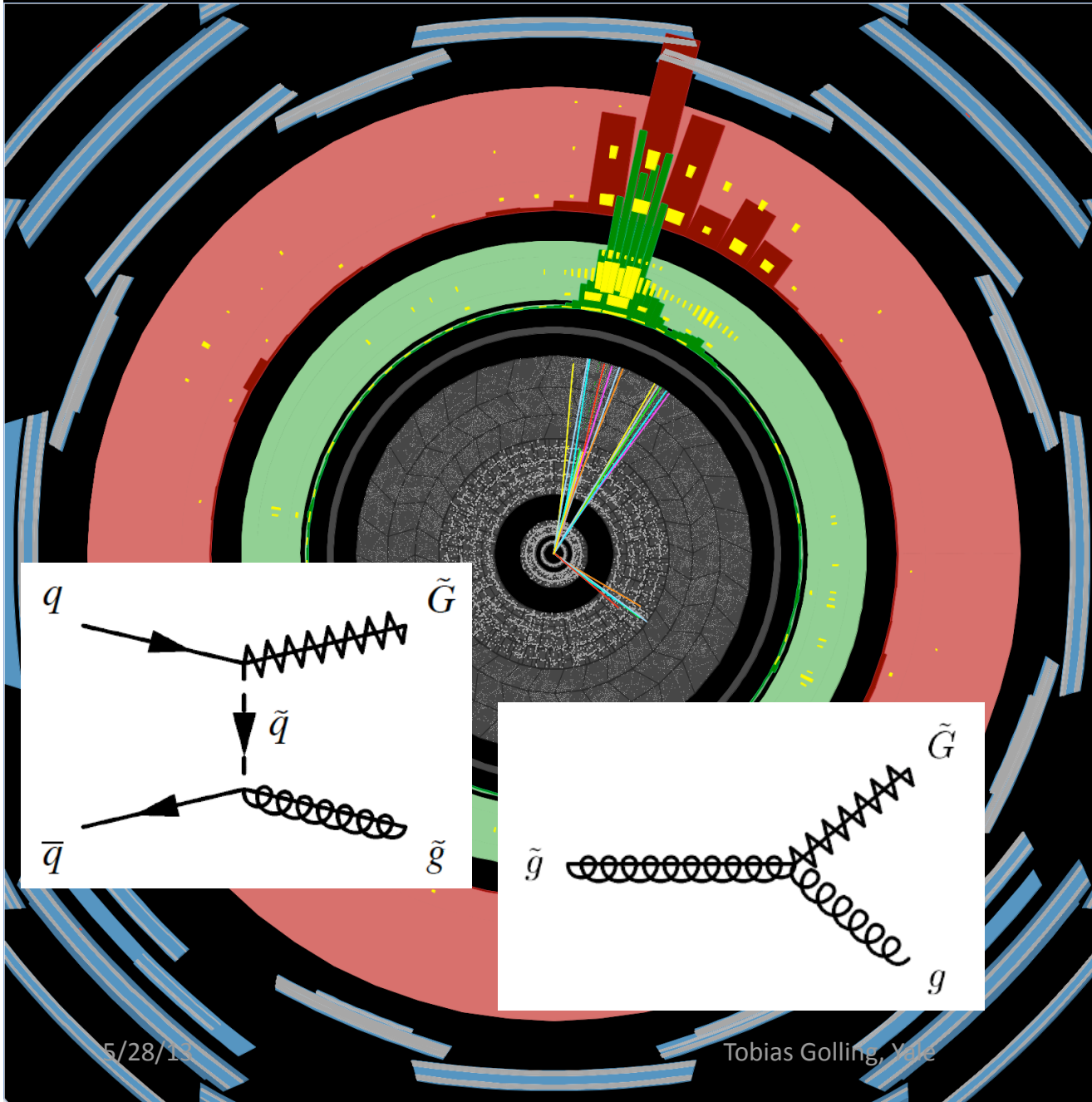
Run Number: 206962, Event Number: 55091306

Date: 2012-07-14 10:42:26 CEST



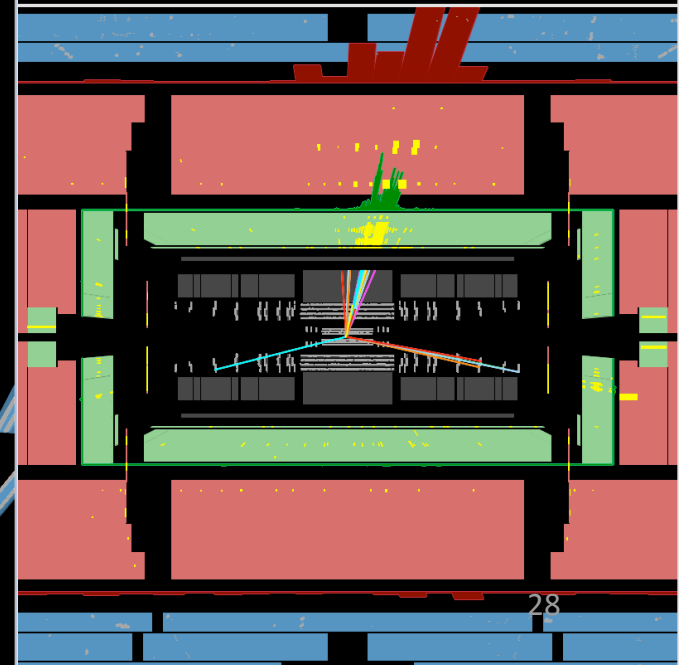


# Mono-Jet: Gravitino Searches



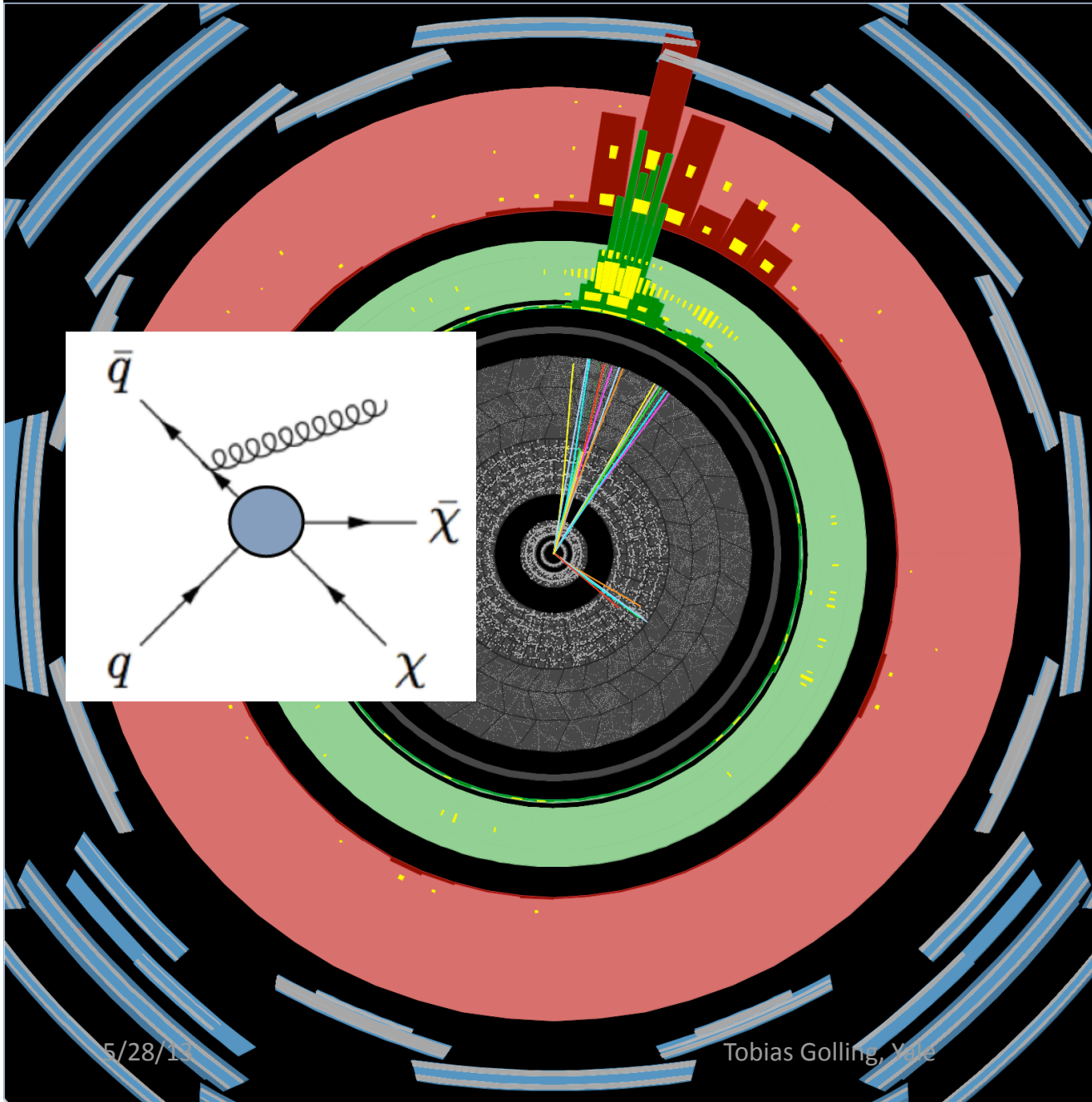
Run Number: 206962, Event Number: 55091306

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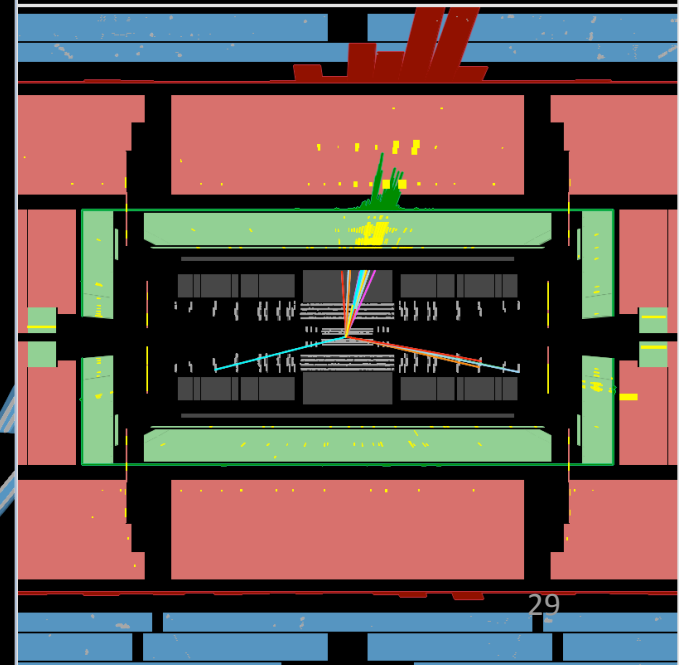


# Mono-Jet: Pair-produced Dark Matter

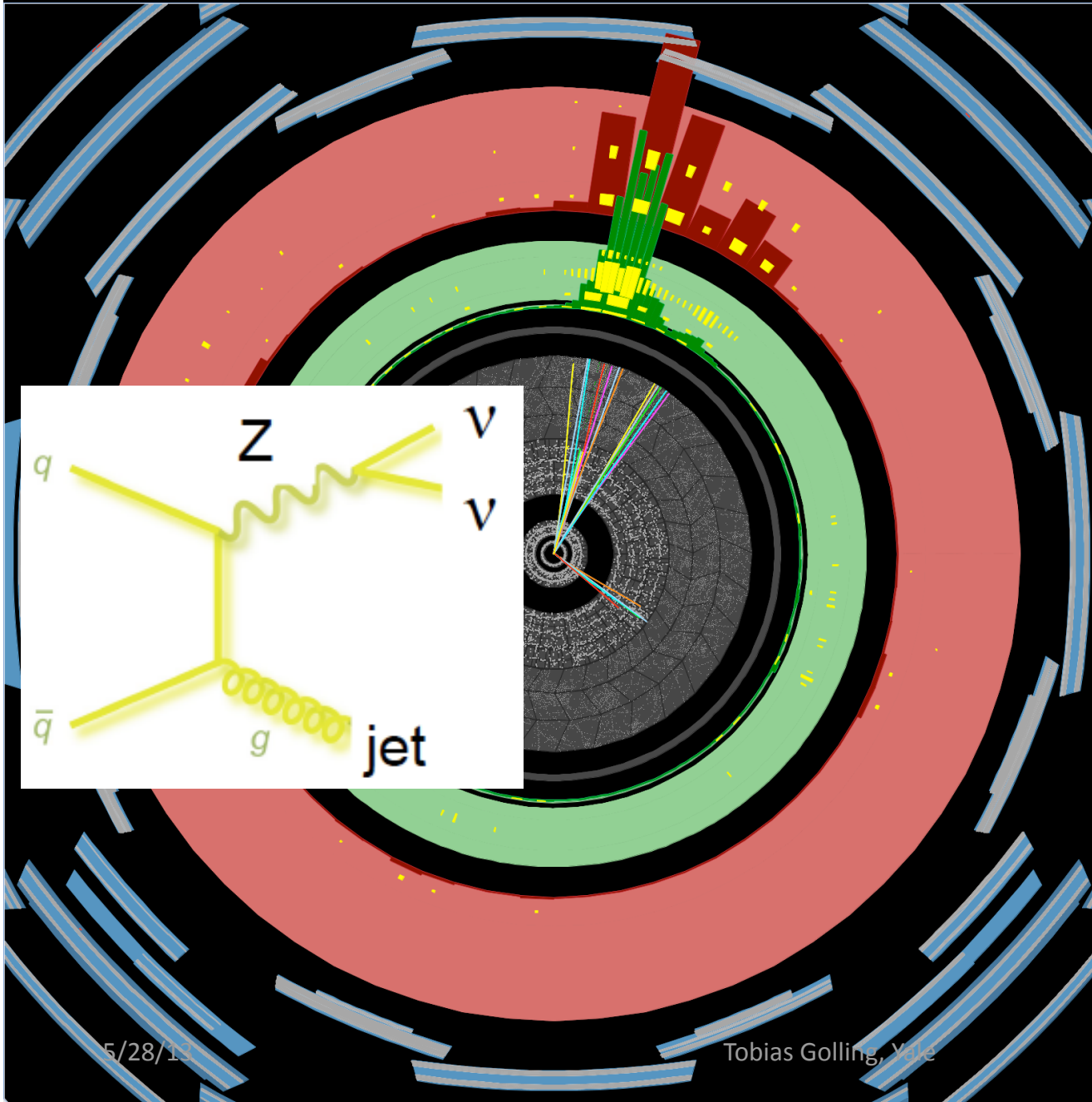


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Date: 2012-07-14 10:42:26 CEST

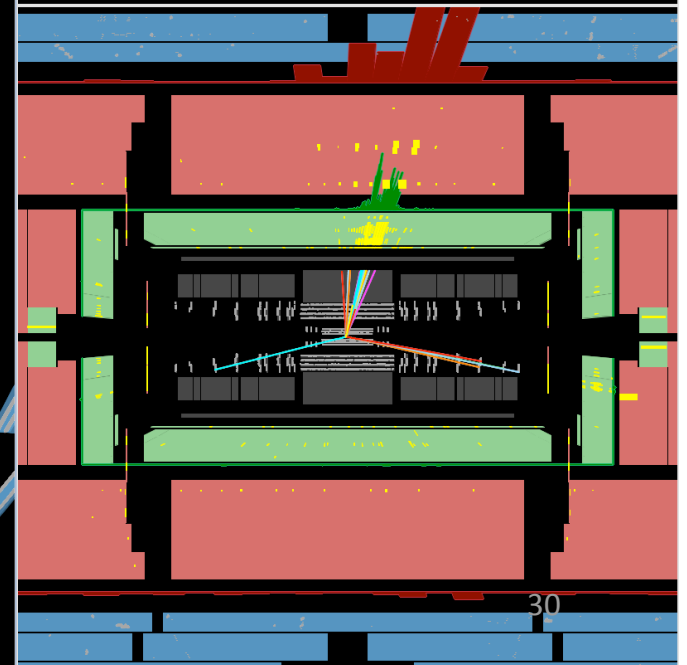


# Mono-Jet: Dominant BG: Z+jets

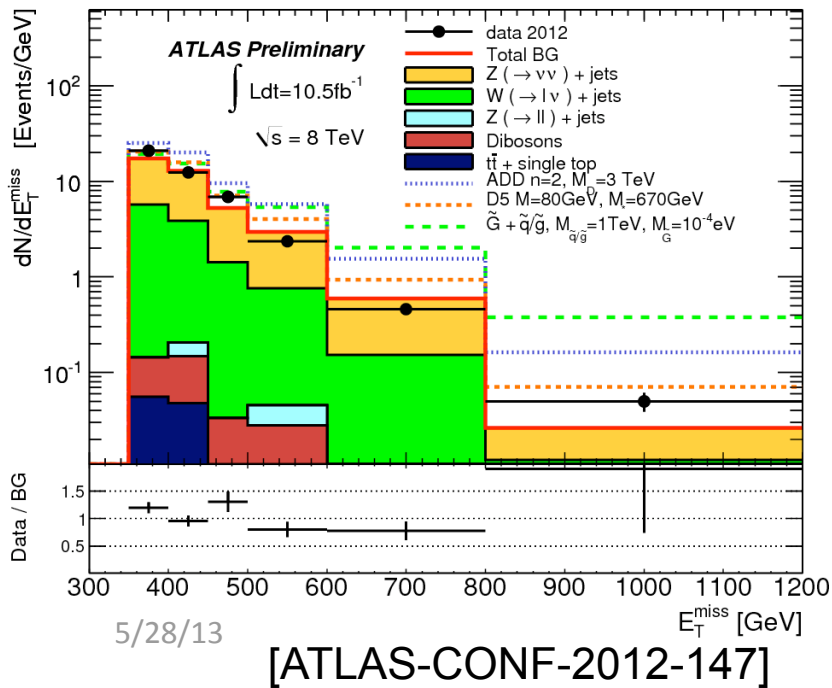
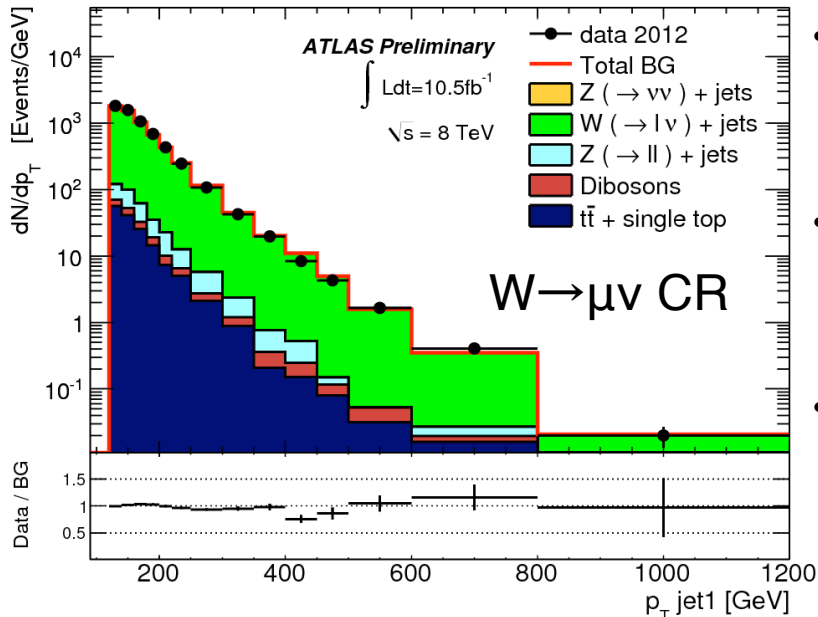


Run Number: 206962, Event Number: 55091306

Date: 2012-07-14 10:42:26 CEST



# Mono-Jet Results

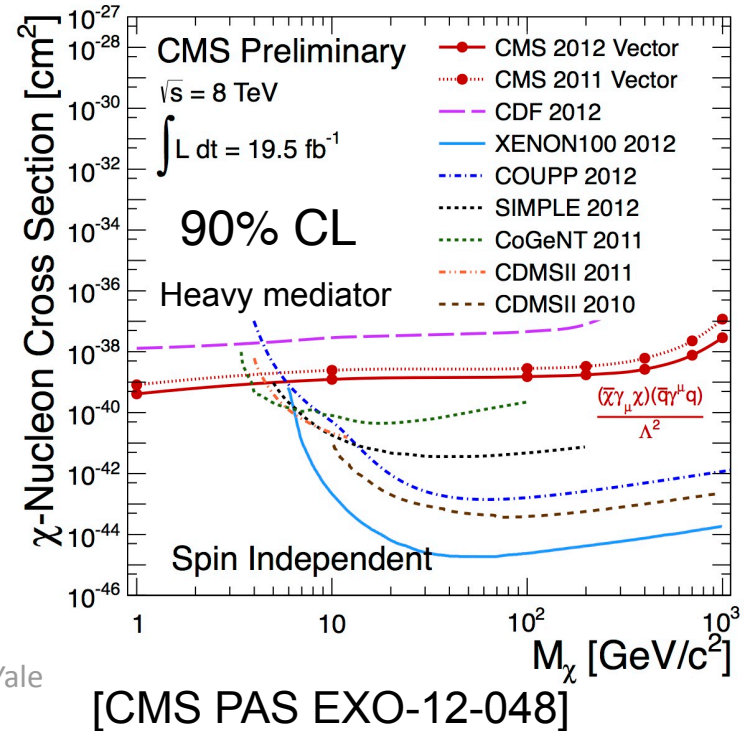
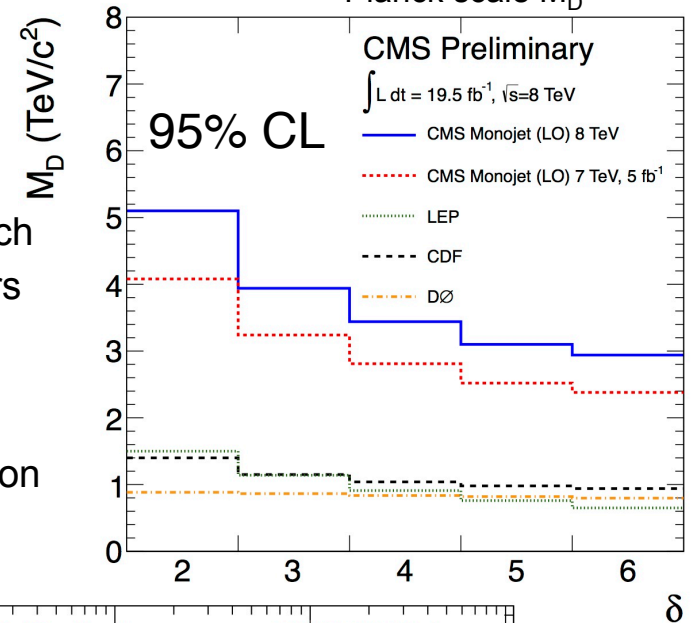


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[ATLAS-CONF-2012-147]

- LHC sensitivity nearing CoGeNT/DAMA excess
- Effective theory approach for dark matter operators
- Limits on CI scale  $\Lambda \Rightarrow$  DM-nucleon cross section limits

Limits on fundamental Planck scale  $M_D$

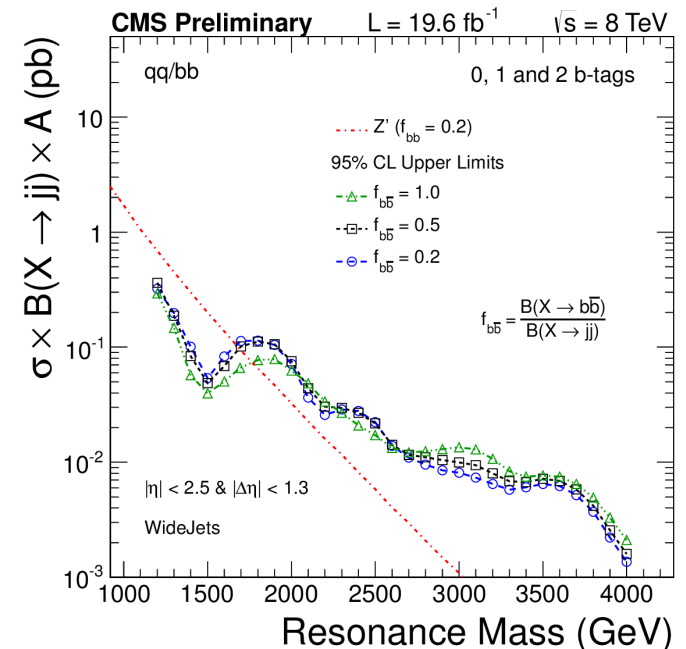
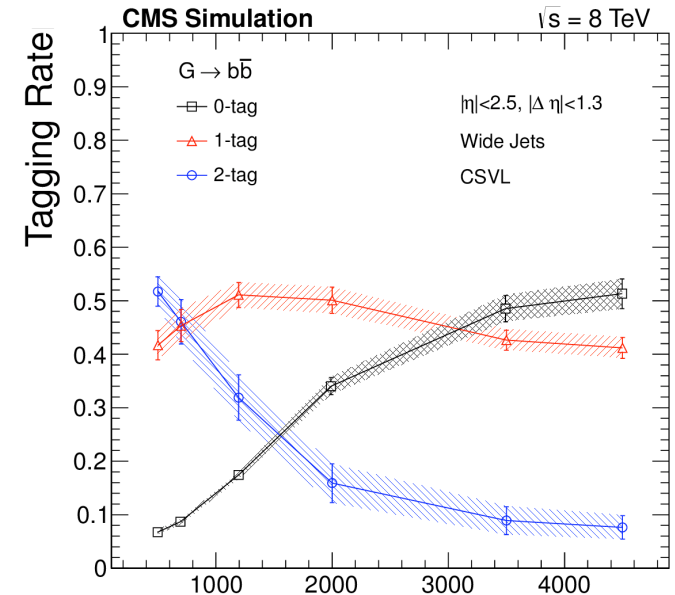


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[CMS PAS EXO-12-048]

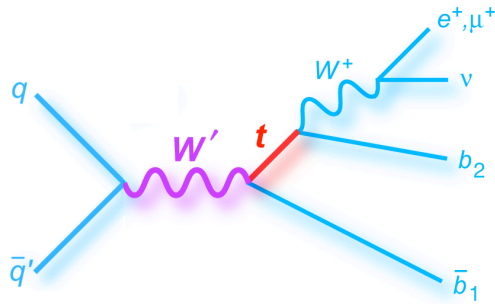
# $b\bar{b}$ and $bg$ Resonances

- Same fit as for untagged analysis
- B-tagging deteriorates for higher jet  $p_T$
- Improvements mainly for moderate resonance mass
- Exclude @ 95% CL  $b^* \rightarrow bg$  with  $m$  in [1.34 TeV, 1.54 TeV]

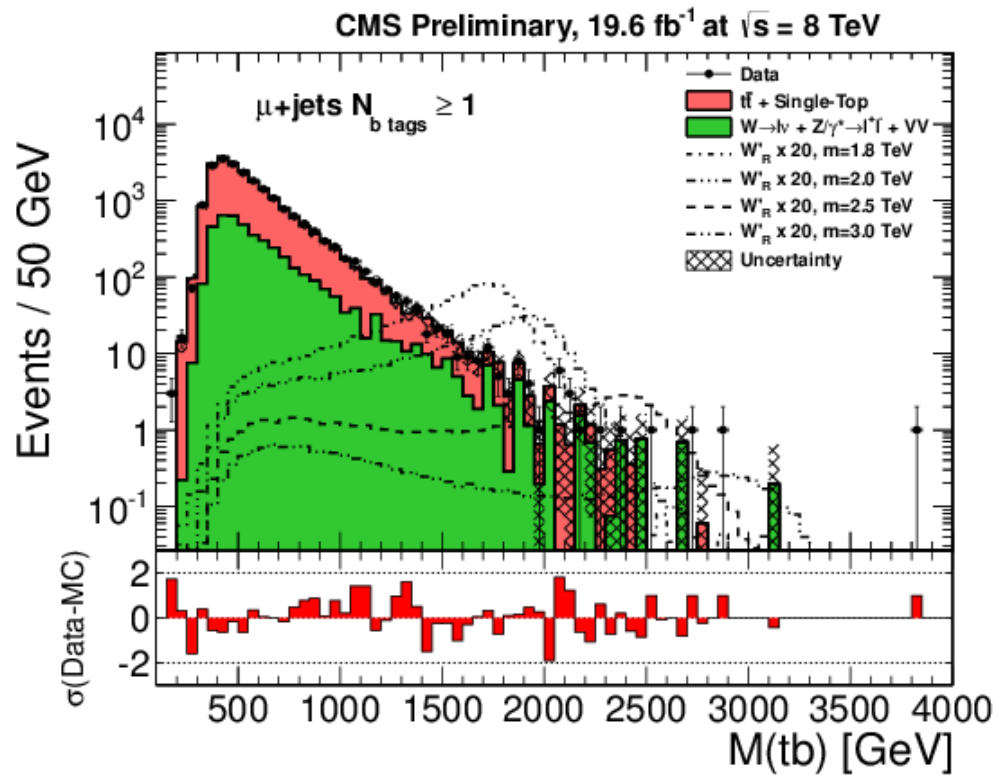


$W'_L, W'_R$

# tb Resonances



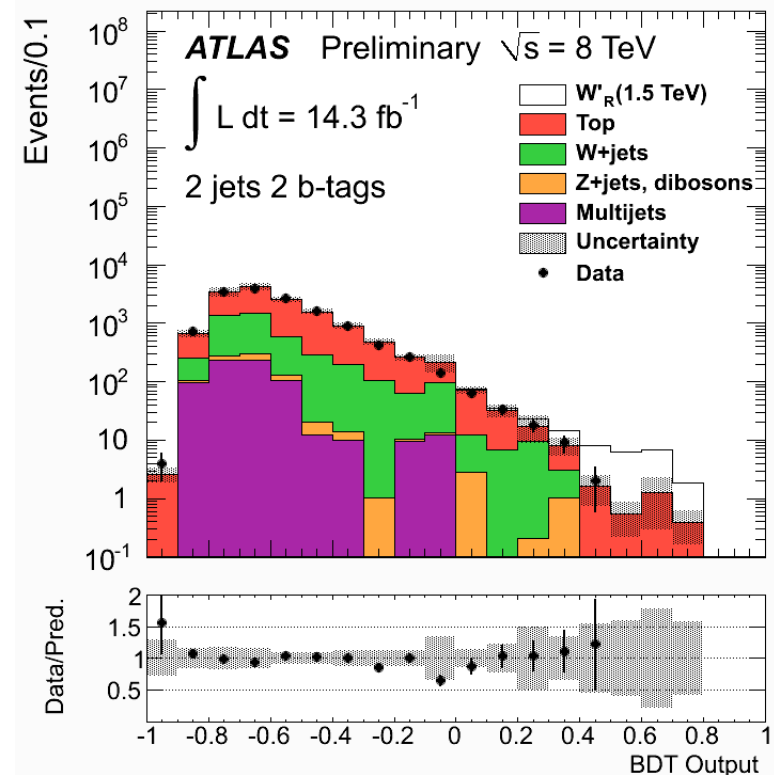
- Discriminant:  $m_{tb}$  or BDT
- Exclude @ 95% CL  $W'_R$  and  $W'_L$  with  $m < 2.03$  TeV
- Also present limits vs coupling



5/28/13

[CMS PAS B2G-12-010]

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[ATLAS-CONF-2013-050]

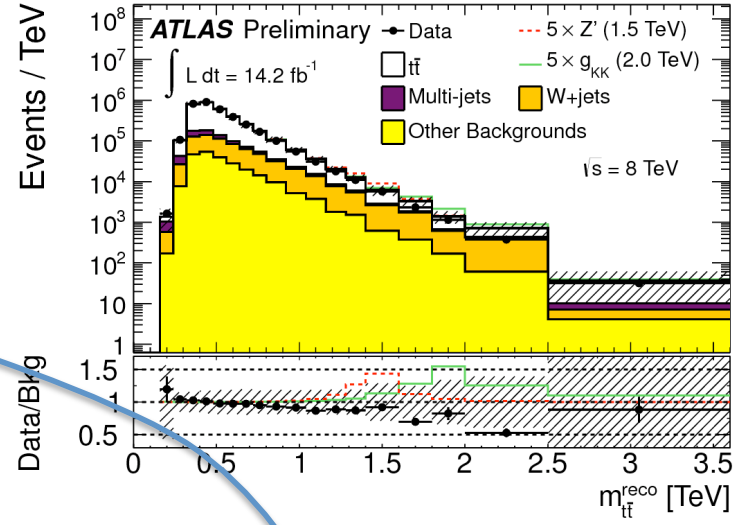
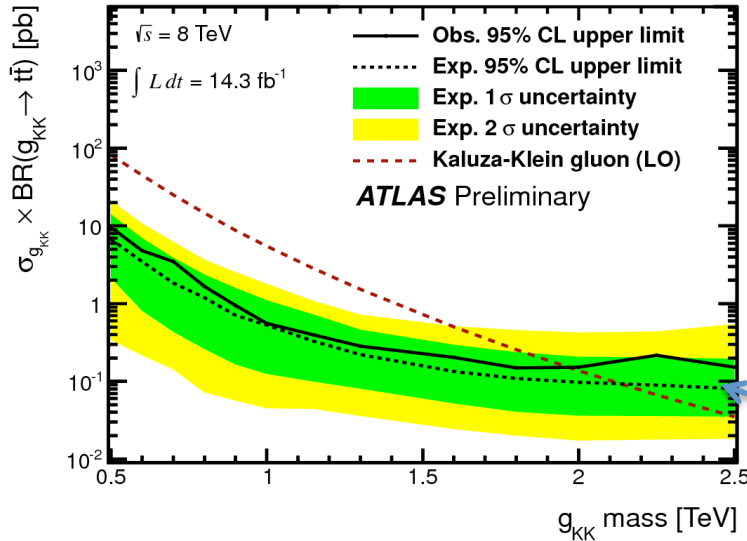
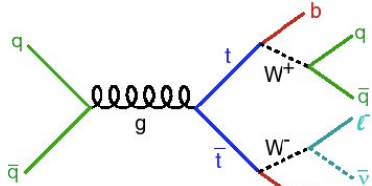
33



# $t\bar{t}$ Resonances – “L+jets Channel”

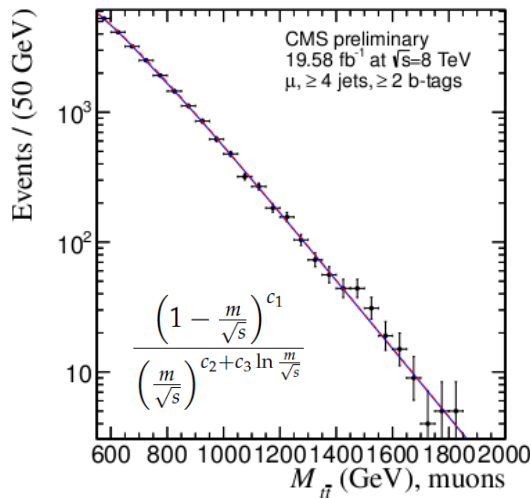
Exclude @ 95% CL:

- Leptophobic top color  $Z'$  with  $m < 2.1$  TeV ( $\Gamma/m = 1.2\%$ )
- RS KK gluon with  $m < 2.5$  TeV ( $\Gamma/m = 15\%$ )

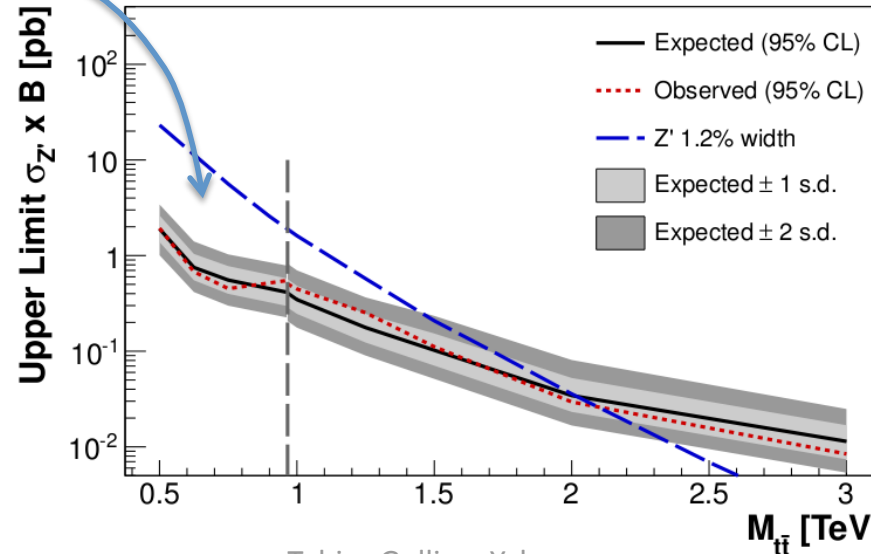


Exp. mass resolution  $\sim 10\%$

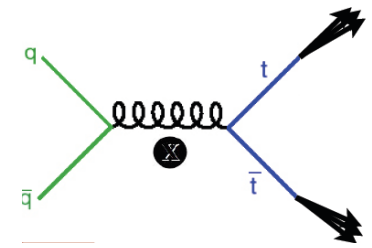
“Resolved”



CMS, L = 19.6 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV  $Z'$  with 1.2% Decay Width

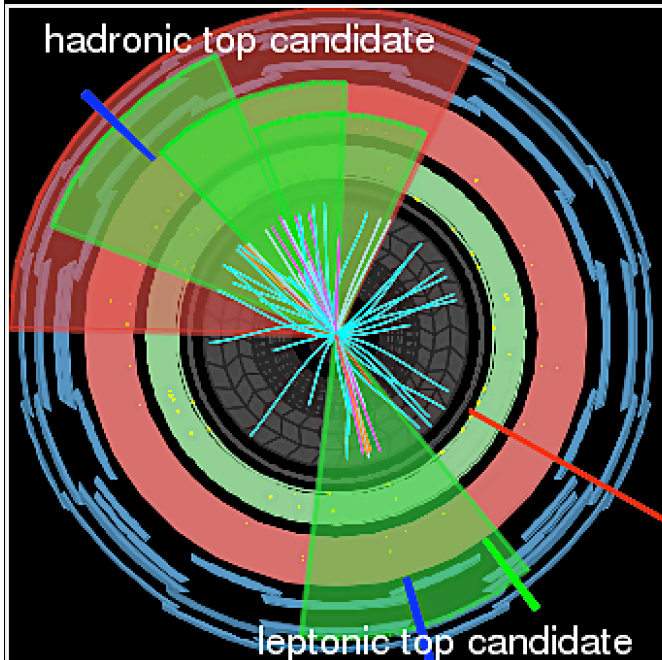


“Boosted”



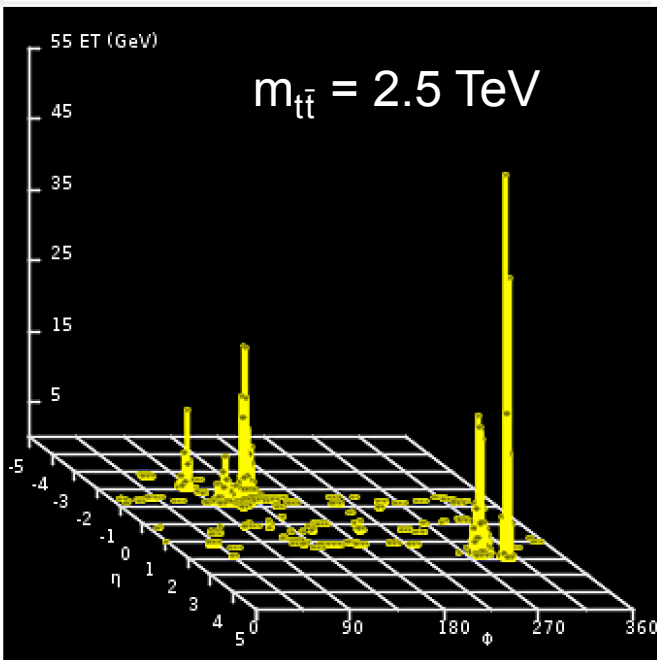
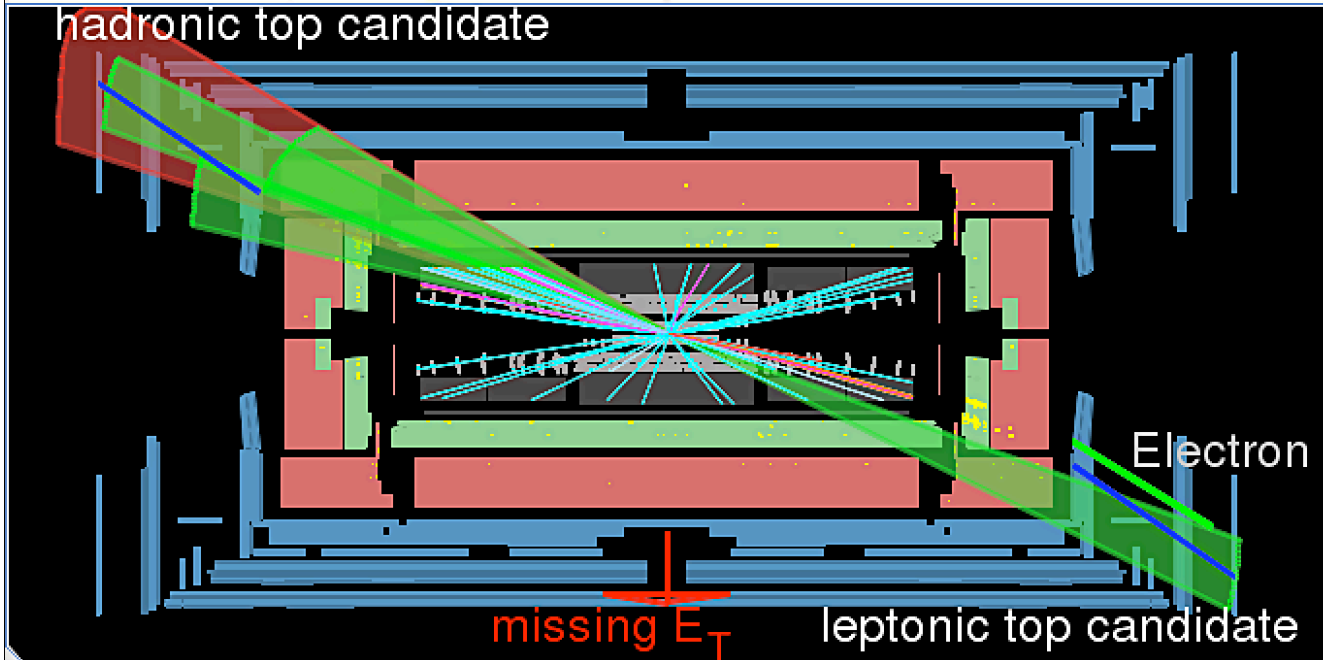
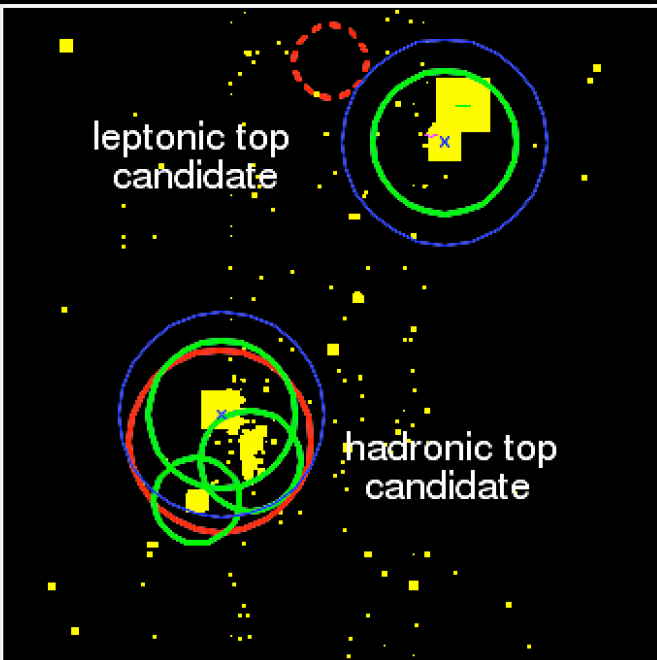
See also arXiv:  
1305.2756 [hep-ex]





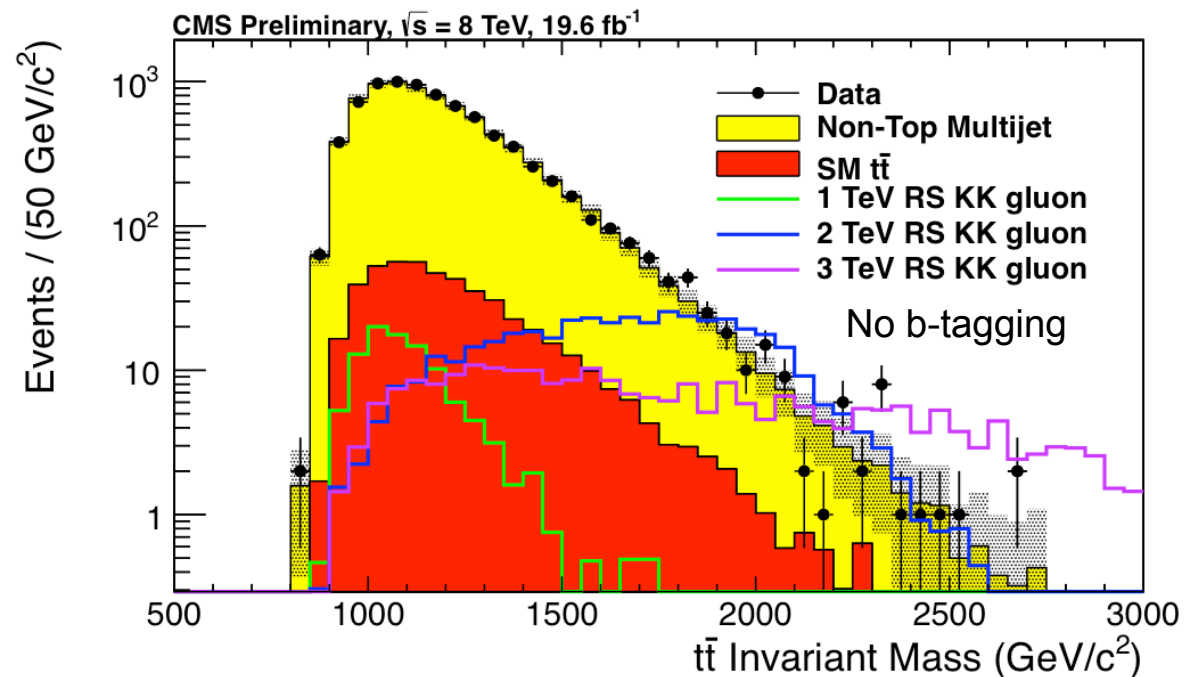
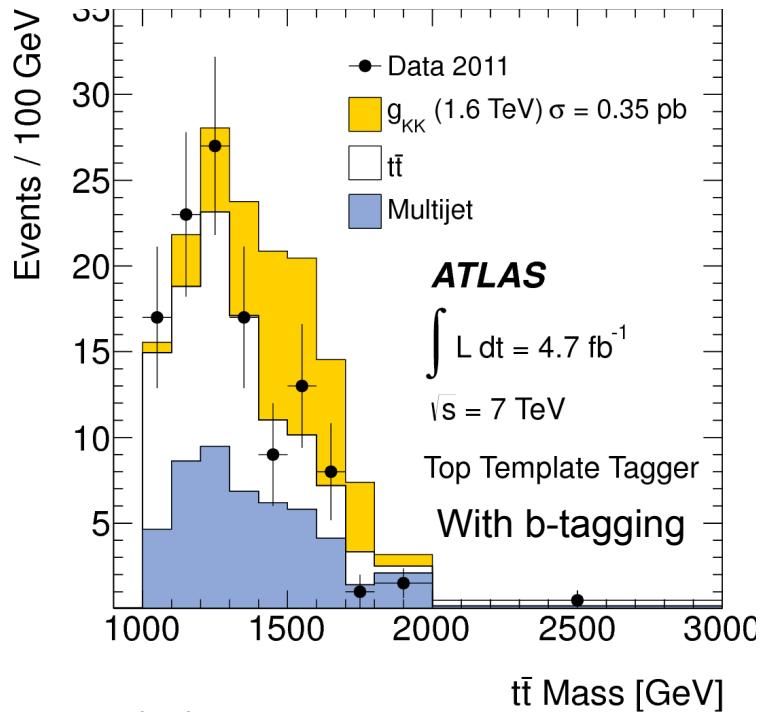
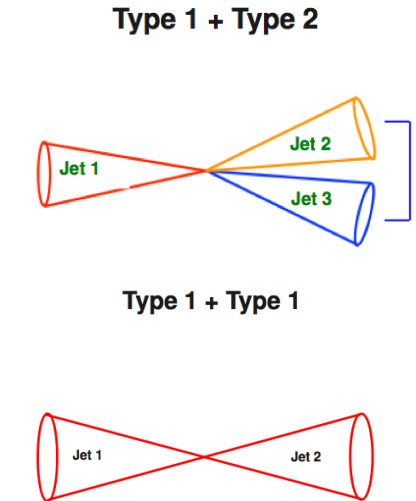
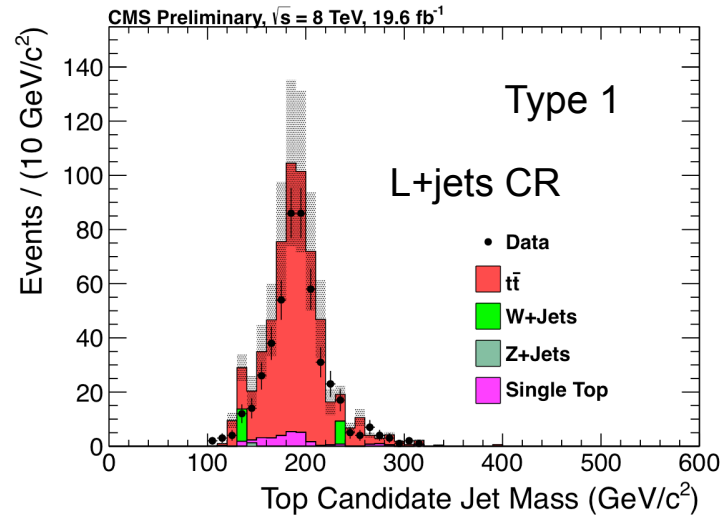
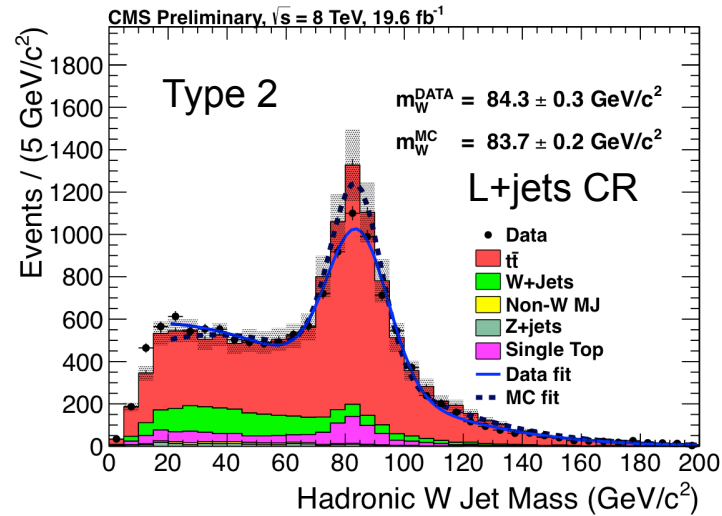
# ATLAS EXPERIMENT

Run Number: 209995, Event Number: 51046560  
Date: 2012-09-09 23:10:22 CEST



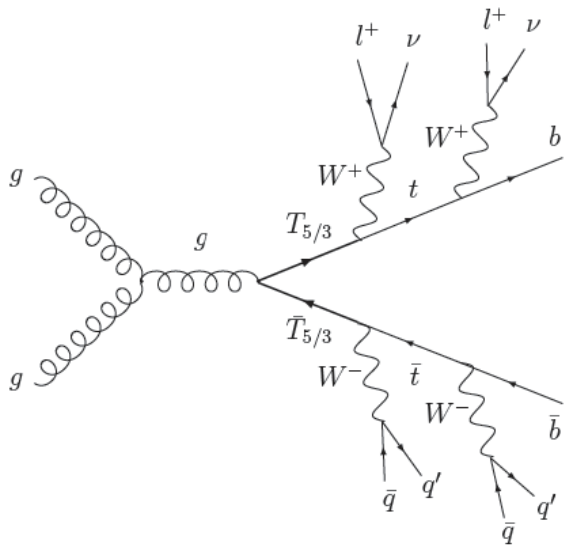
# $t\bar{t}$ Resonances – “All-jets Channel”

Topcolor, RS models

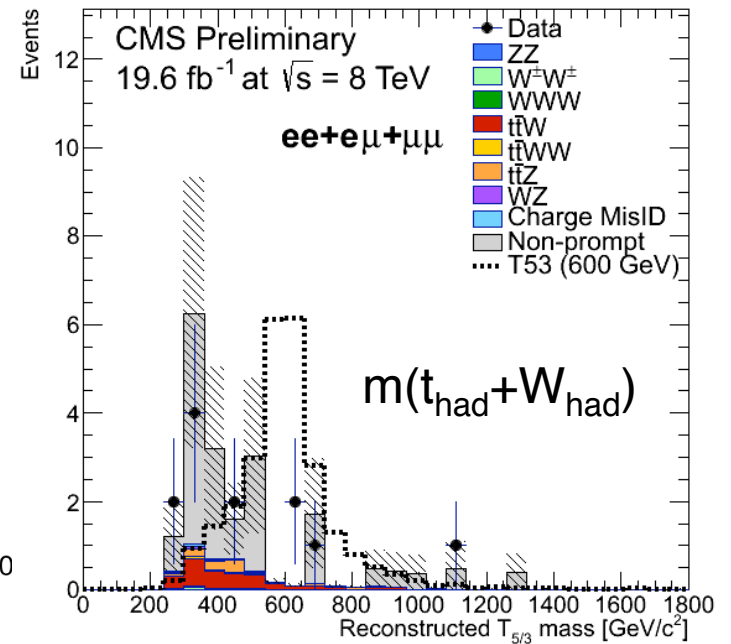
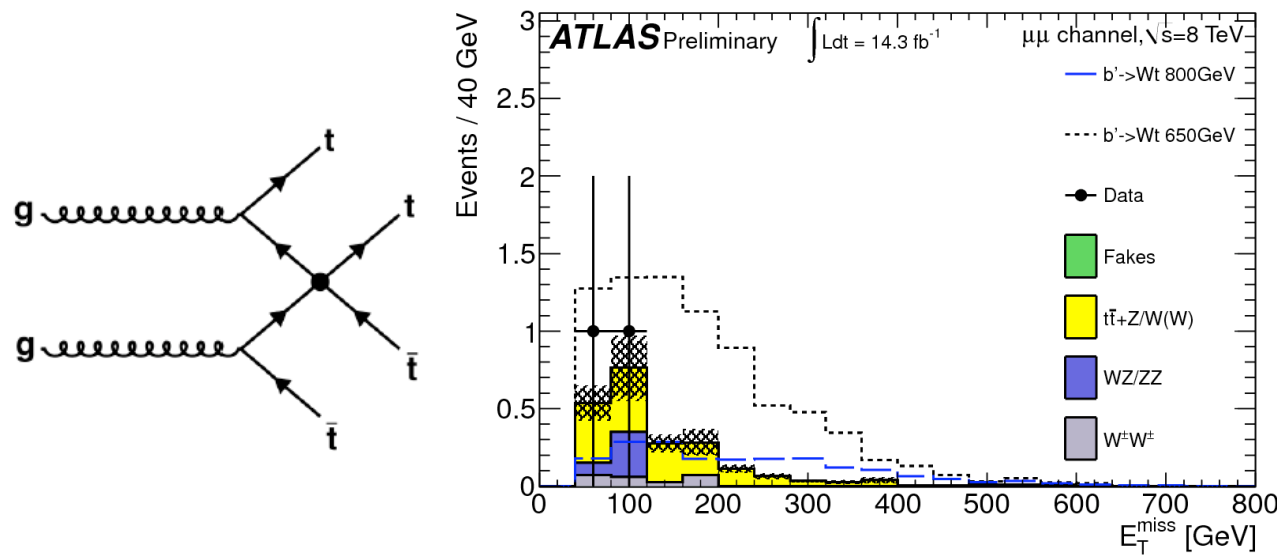


# The Rare – Same-Sign Leptons

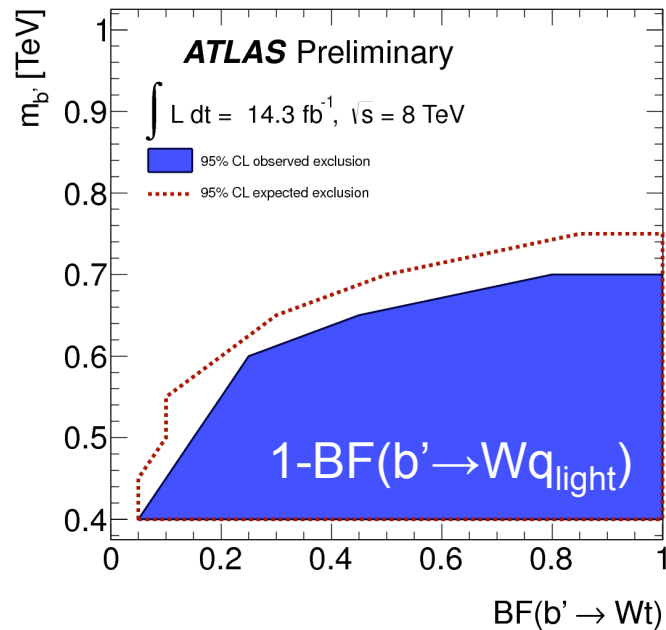
# Same-Sign Leptons



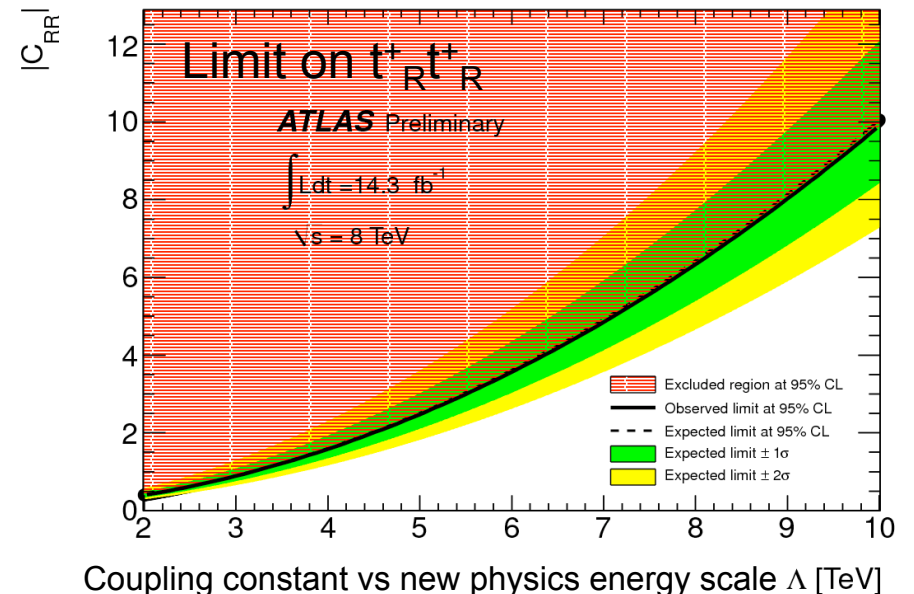
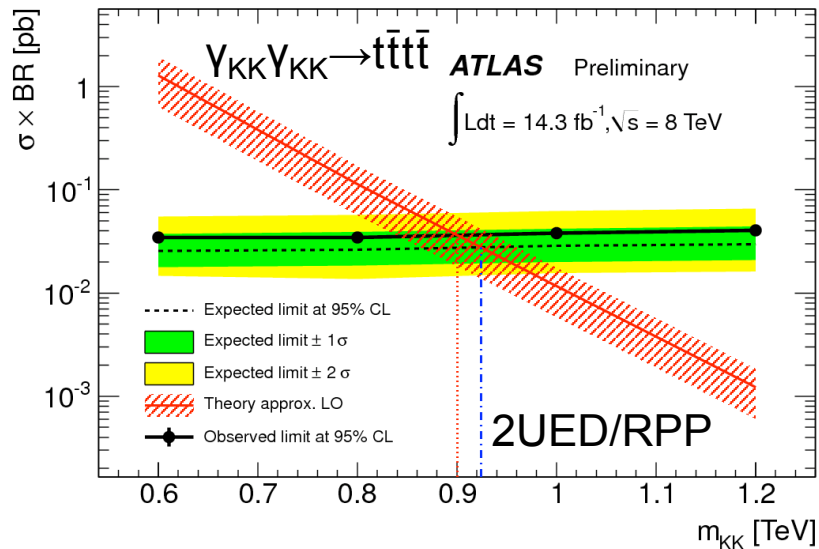
- Very Low SM backgrounds
- Many NP scenarios (including SUSY)
  - $b'$ ,  $T_{5/3}$ ,  $tt$ , 4-tops, gluino-mediated stop,  $H^{++/--}$ , heavy neutrino (seesaw), TeV-scale gravity (mini-black holes),...
- Background estimate
  - Data-driven fakes-lepton estimate
  - Charge flip (e only), determined using Z events
  - Irreducible  $VV$  and  $t\bar{t}+V$  background



# Beautiful Set of Same-Sign Interpretations



- Exclude @ 95% CL
  - $m(T_{5/3}) < 0.77 \text{ TeV}$
  - $m(b') < 0.72 \text{ TeV}$
  - $m(\text{VLB singlet}) < 0.59 \text{ TeV}$
  - $m(\text{VLT singlet}) < 0.54 \text{ TeV}$
  - ...
  - More VLQ limits later

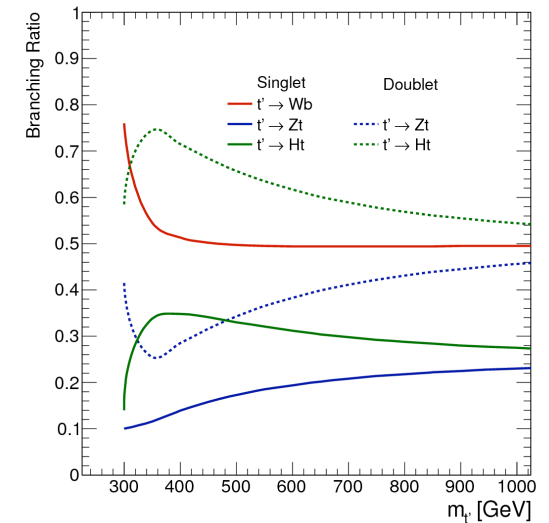
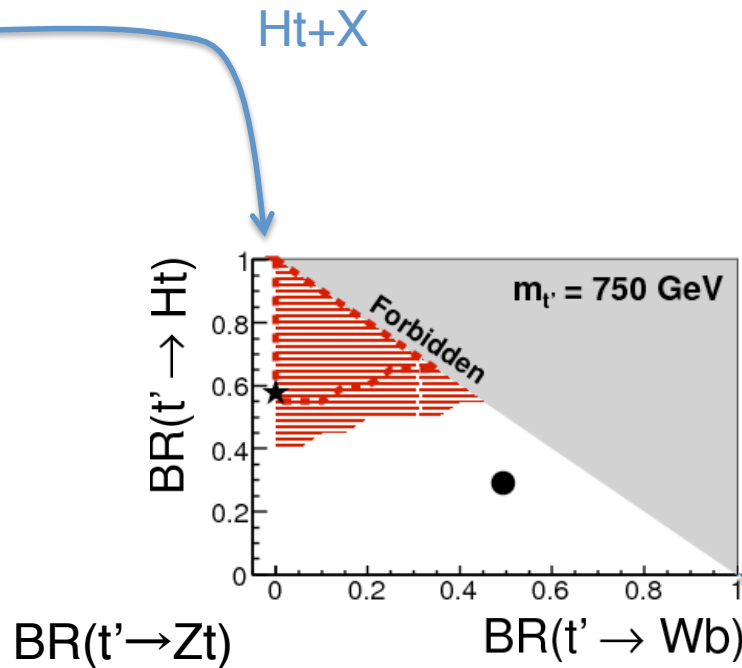
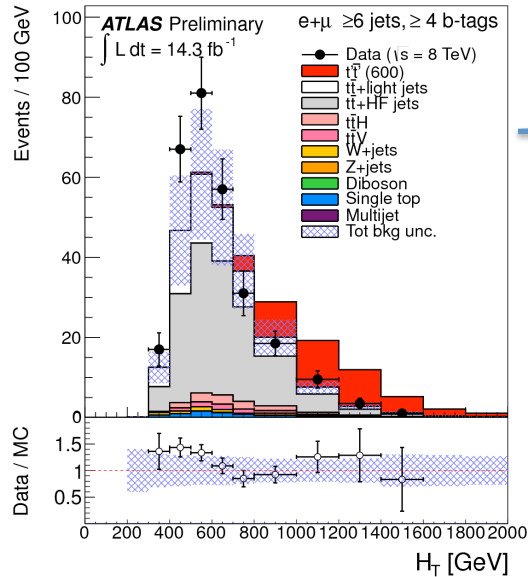


# Heavy Quarks (pair-produced)

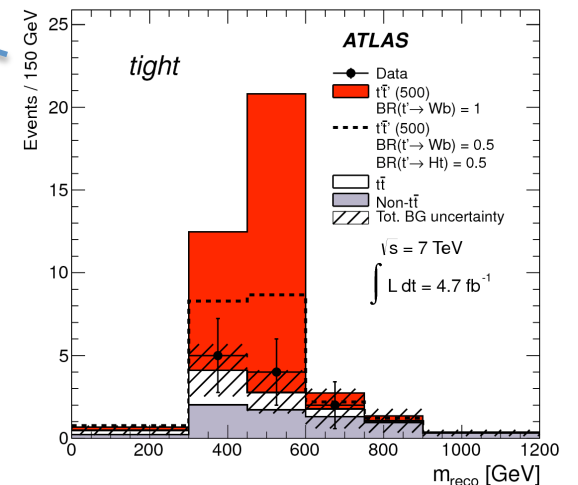


# Vector-Like Quark (VLQ) Searches

VLQ: Same electroweak charges for LH and RH components



Also same-sign leptons



- Exclude @ 95% weak isospin  $t'$  doublet with mass  $< 790$  GeV

[ATLAS-CONF-2013-018]

5/28/13

[ATLAS-CONF-2013-051]

Tobias Golling, Yale

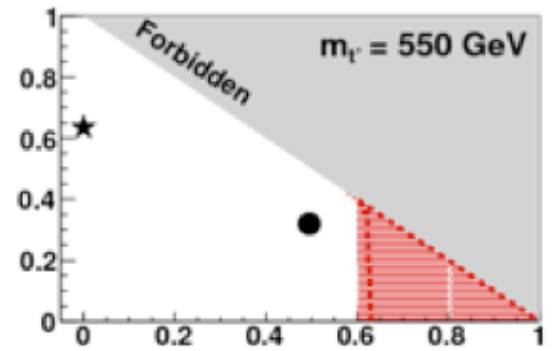
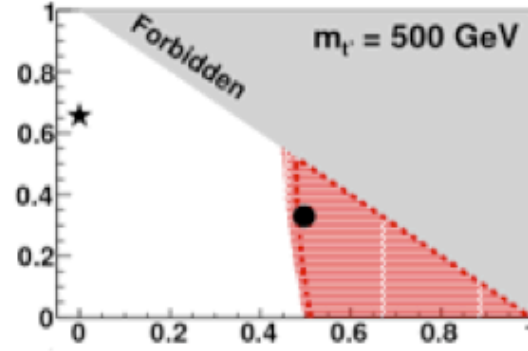
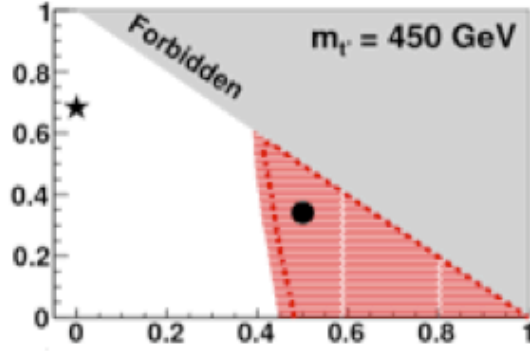
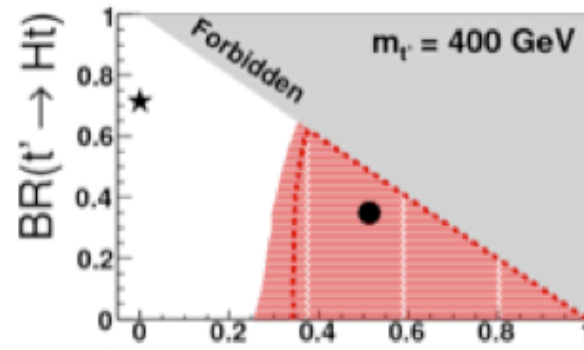
[PLB 718, 1284 (2013)]

41

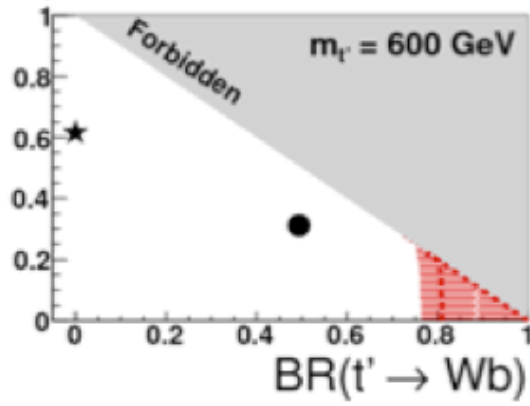
# ATLAS

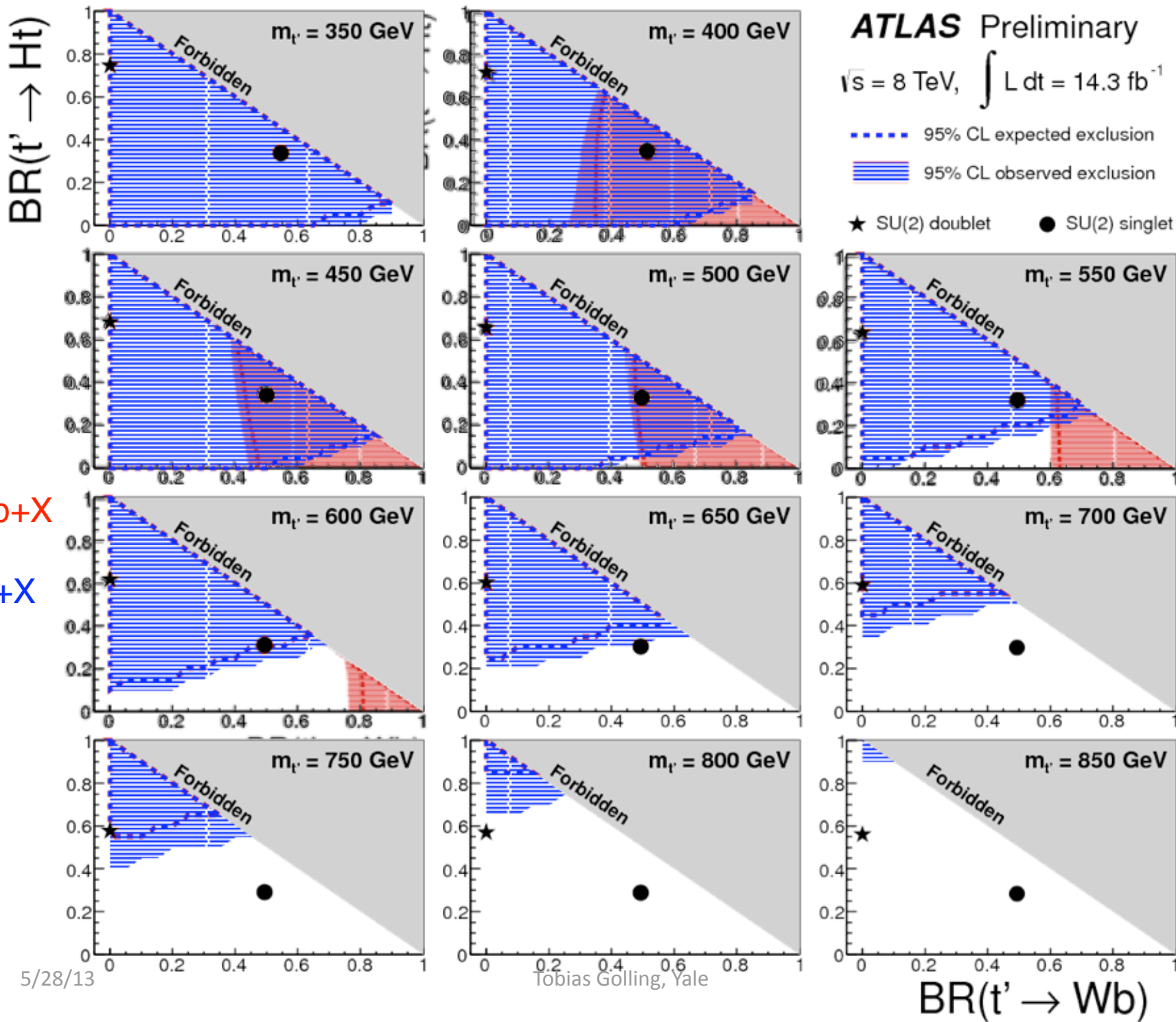
$$\sqrt{s} = 7 \text{ TeV}, \quad \int L dt = 4.7 \text{ fb}^{-1}$$

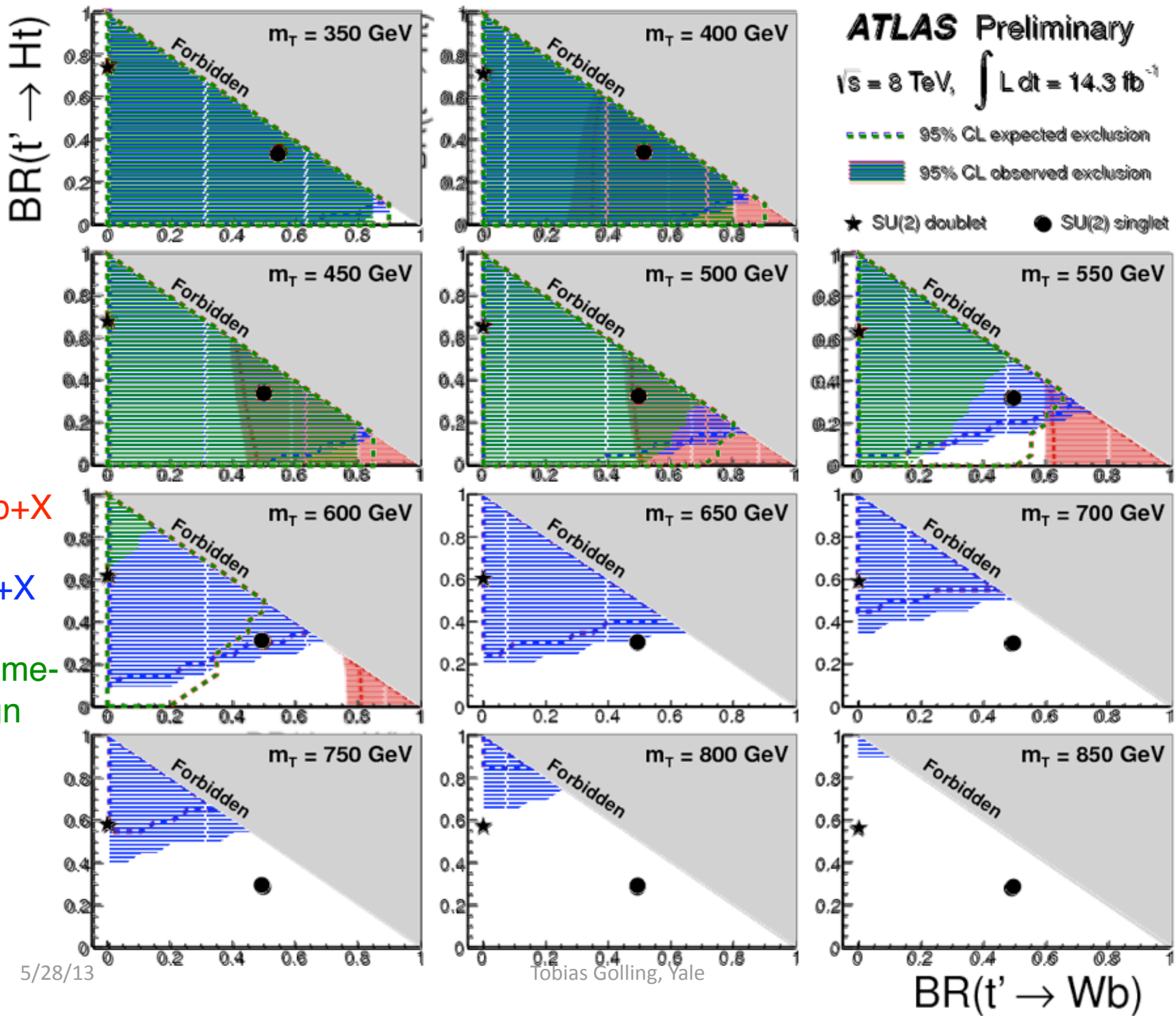
- - - 95% CL expected exclusion      ● SU(2) singlet
- ▨ 95% CL observed exclusion      ★ SU(2) doublet



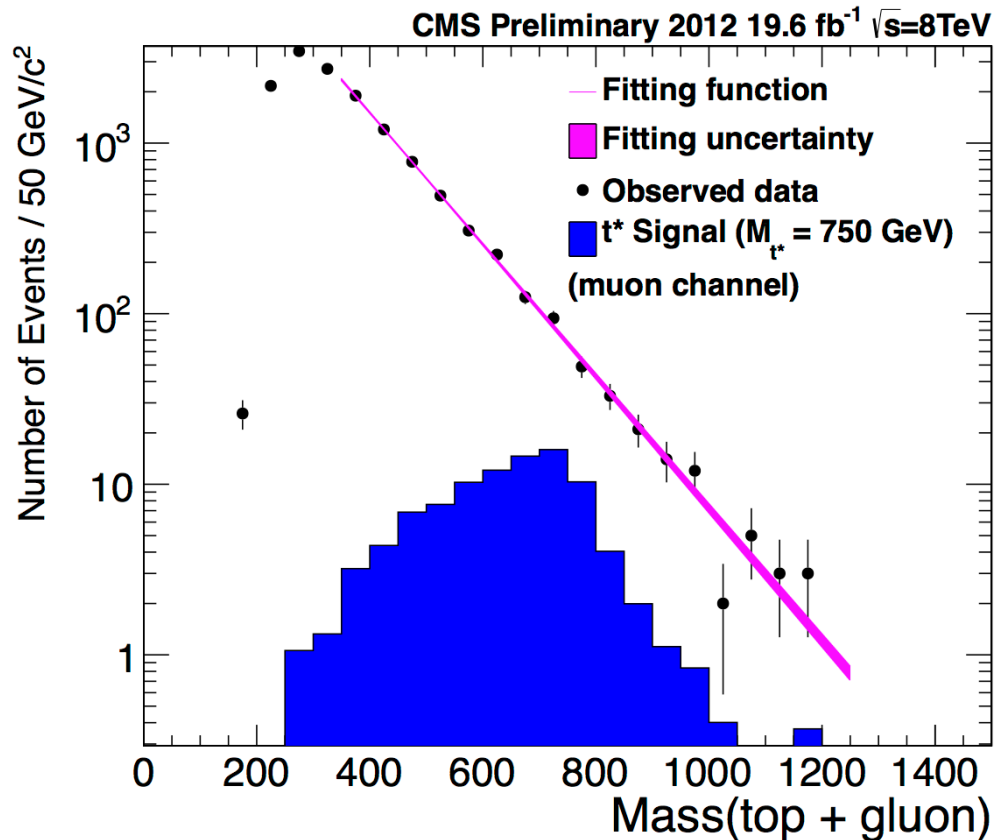
Wb+X



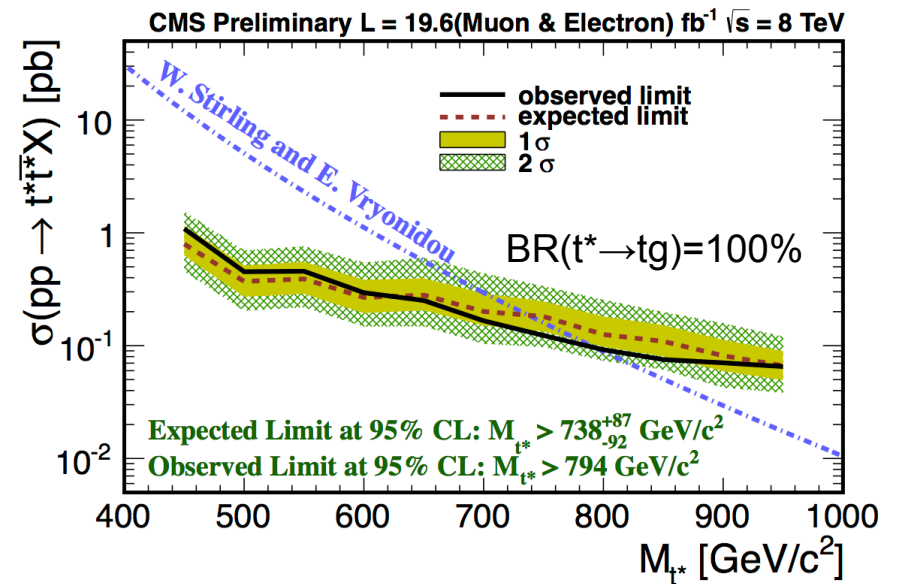




# Search for non-SM Production of $t\bar{t}+gg$



- $t^*t^* \rightarrow t\bar{t}+gg$
- $t^*$  spin 3/2
- Exclude @ 95% CL  $t^*$  masses below 790 GeV



$$m(l\nu) = m(q\bar{q}) = M_W$$

$$m(l\nu b) = m(q\bar{q}b) = M_t$$

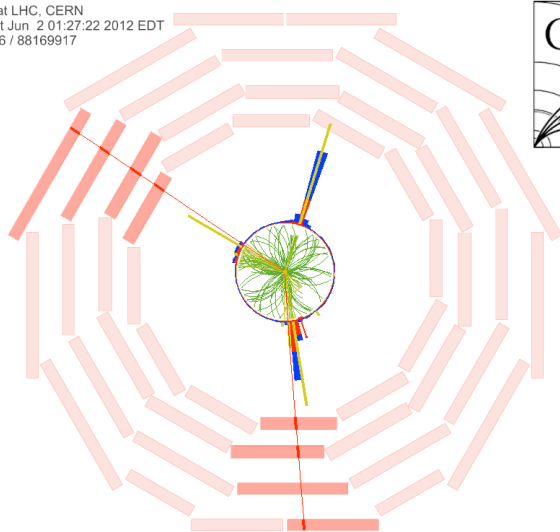
$$m(l\nu bg) = m(q\bar{q}bg) = M_{t+g}$$

See also PRD 86, 091103 (2012) (ATLAS) for a search with a similar final state

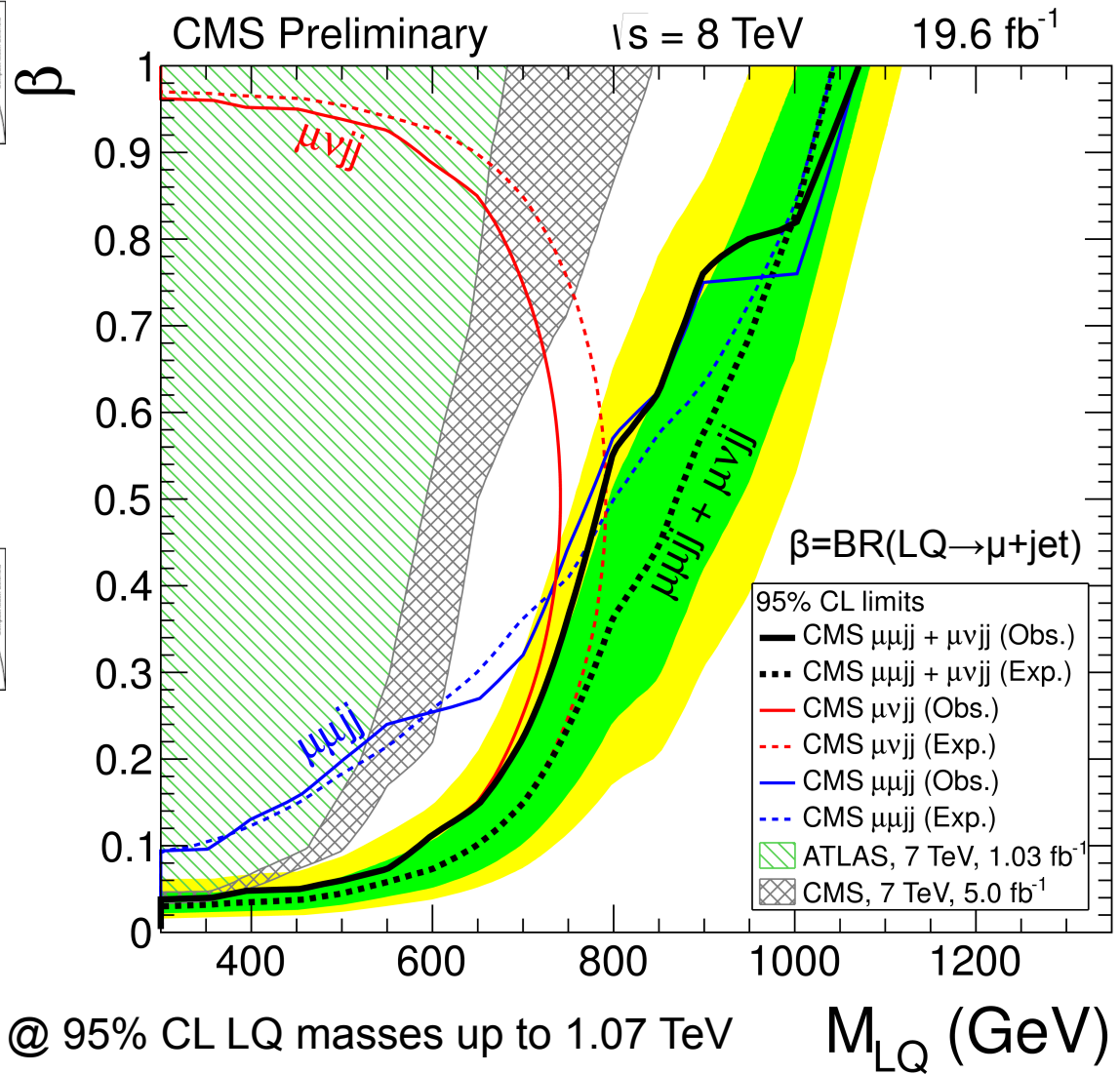
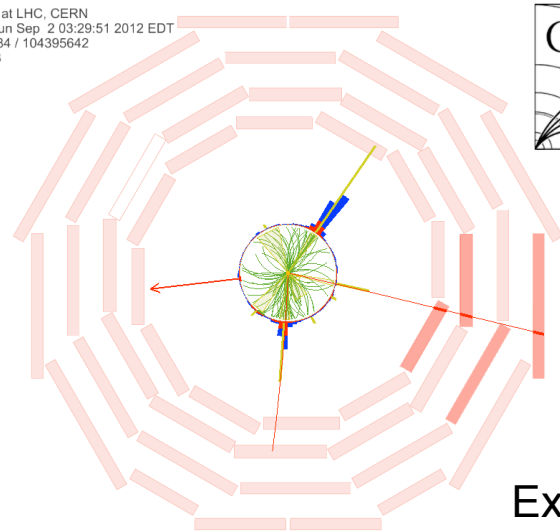


# Search for Second Generation Leptoquarks

CMS Experiment at LHC, CERN  
 Data recorded: Sat Jun 2 01:27:22 2012 EDT  
 Run/Event: 195396 / 88169917  
 Lumi section: 89



CMS Experiment at LHC, CERN  
 Data recorded: Sun Sep 2 03:29:51 2012 EDT  
 Run/Event: 202084 / 104395642  
 Lumi section: 133



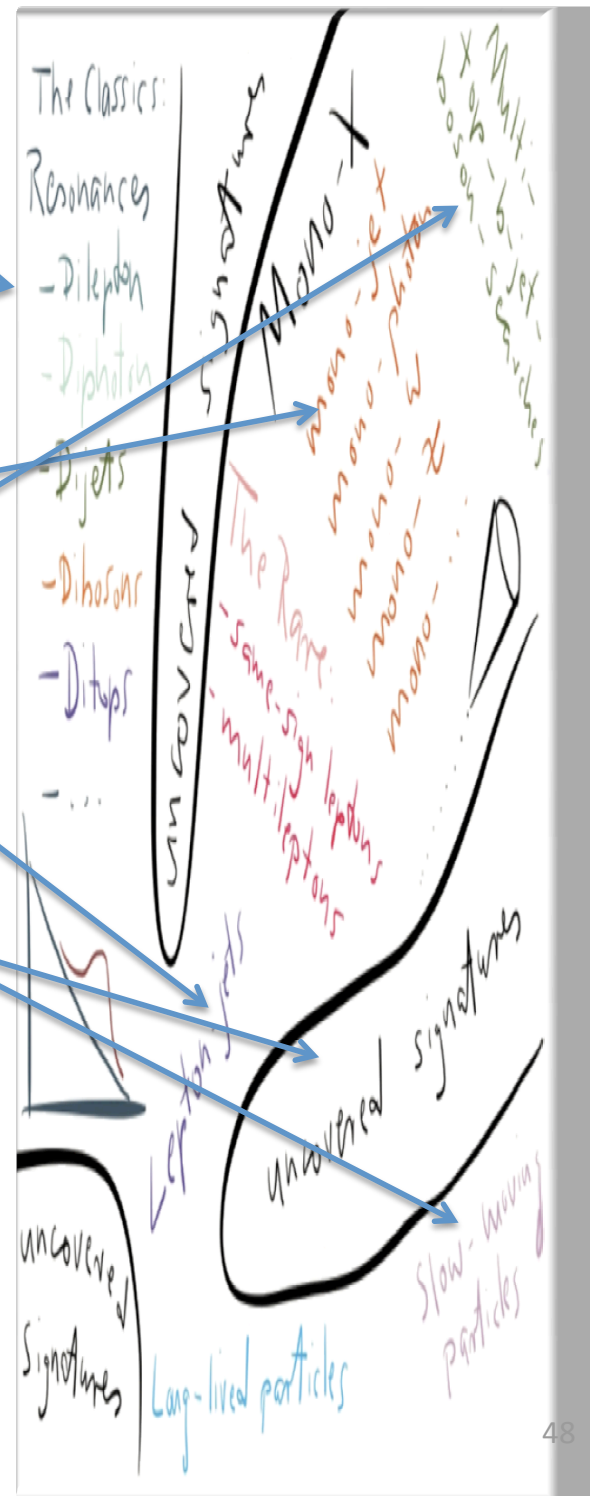
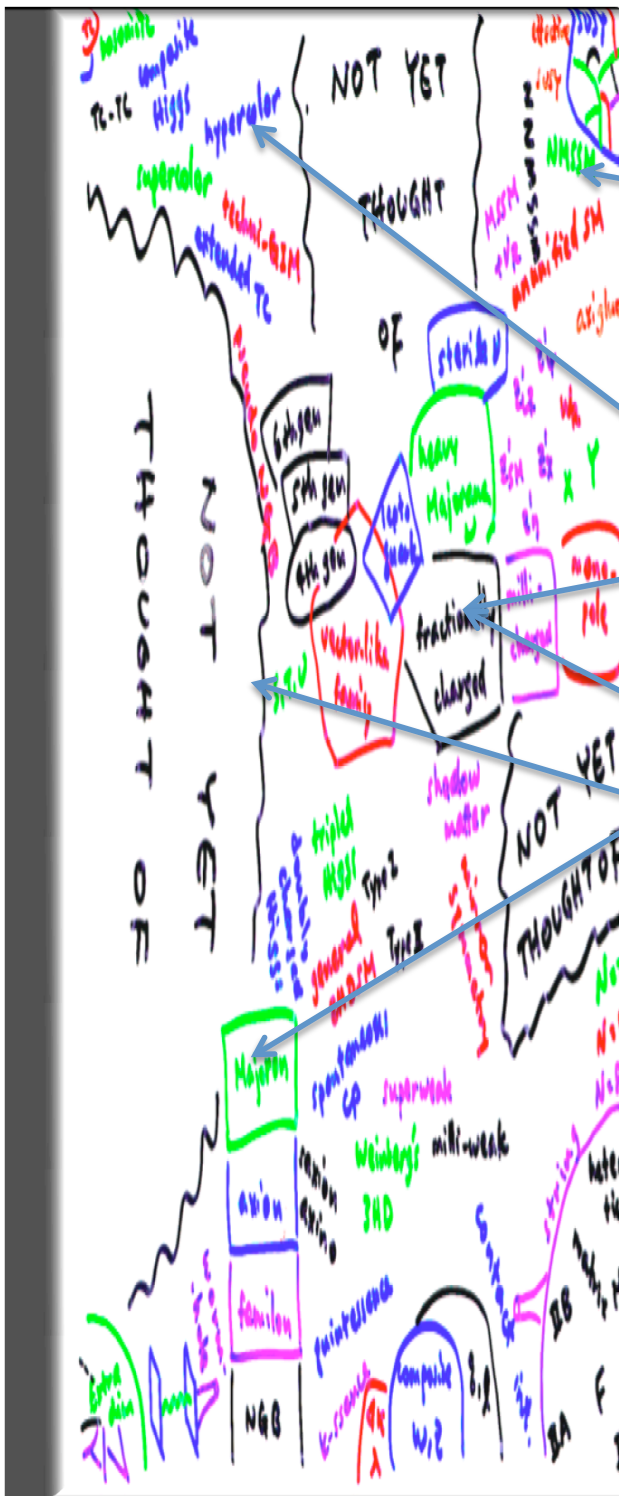
Also 1<sup>st</sup> & 3<sup>rd</sup> generation LQ searches, see e.g.

ATLAS: arXiv:1303.0526, submitted to JHEP; CMS: JHEP 12 (2012) 055 & PRL 110, 081801 (2013)



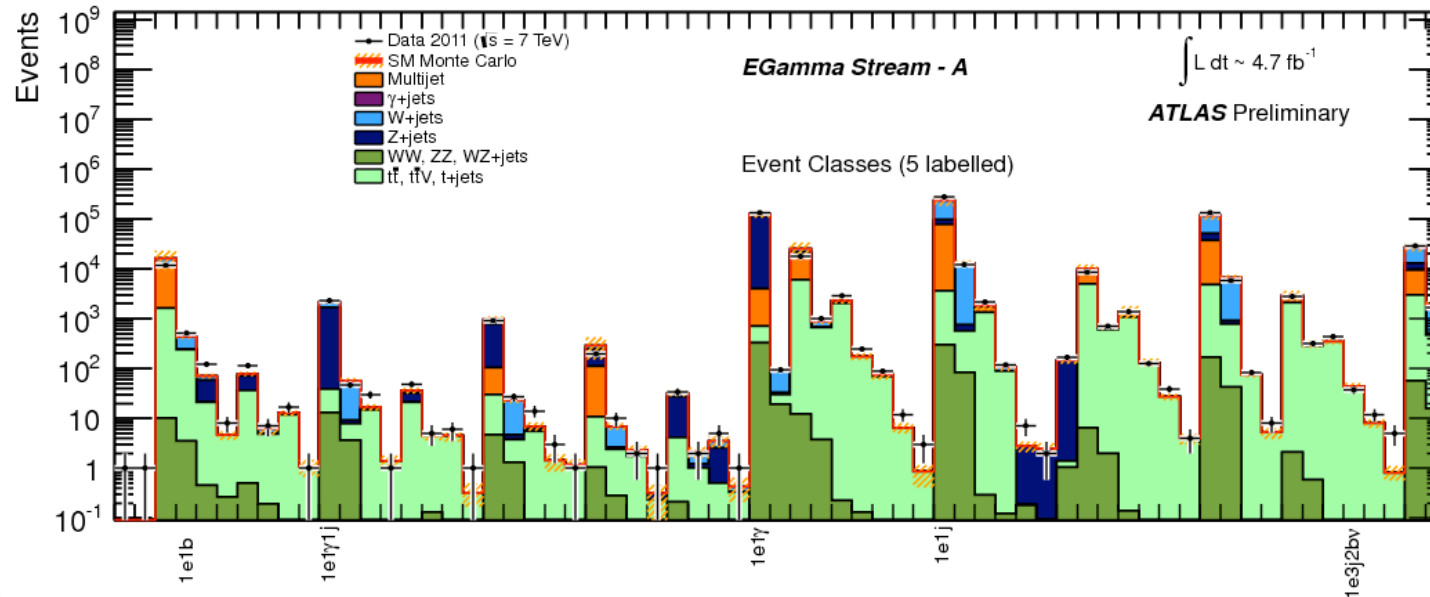
# Are we REALLY Covering All Signatures?

# Or Have We Missed Anything?



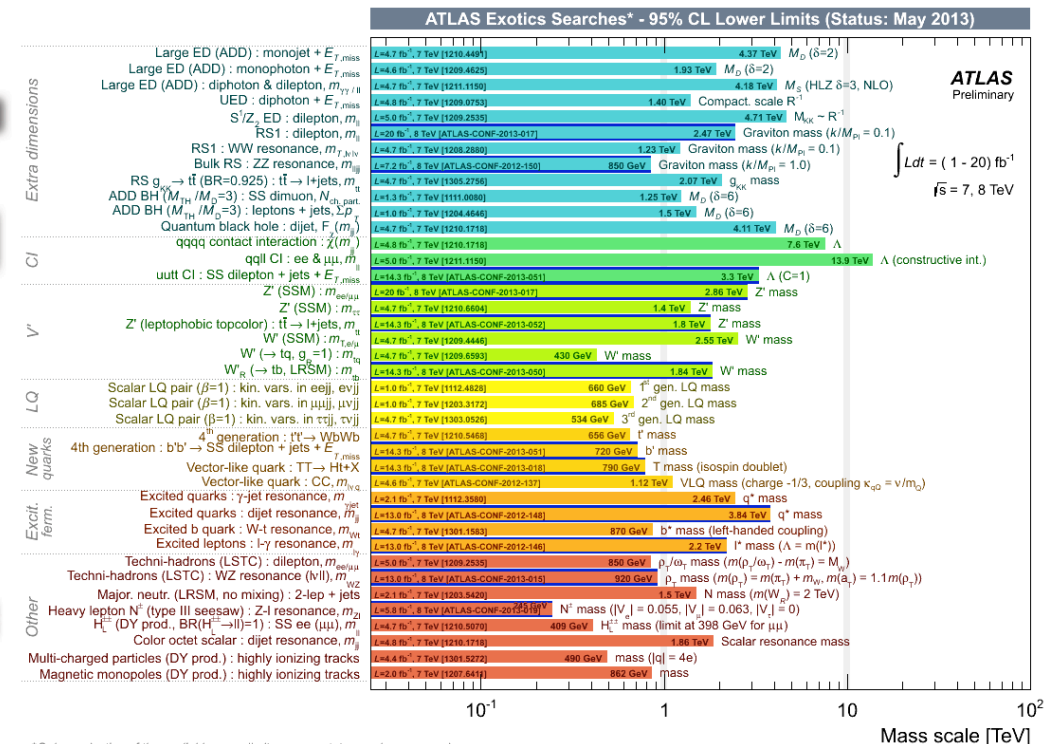
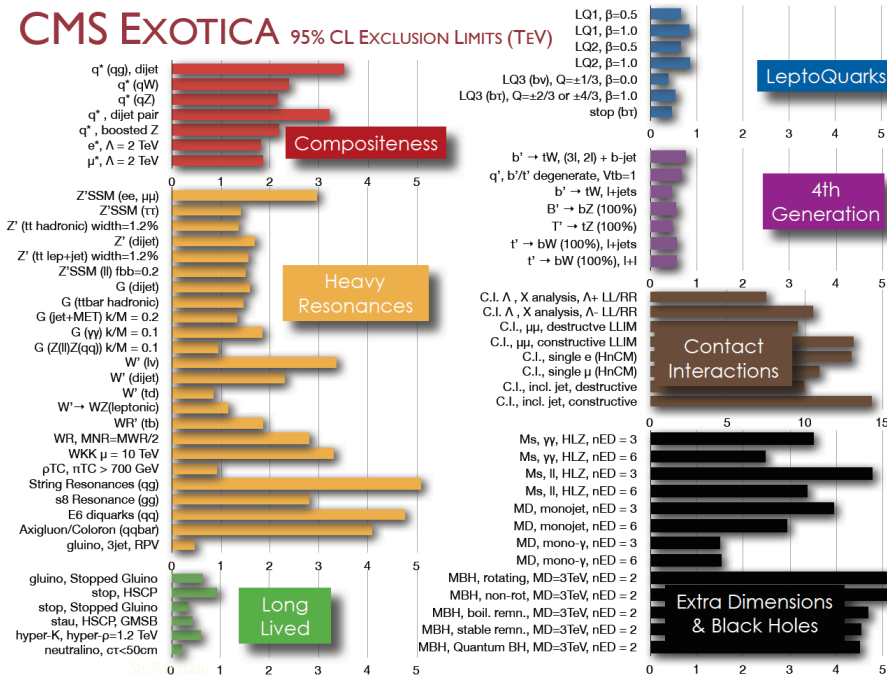
# Fill In the Blanks

- General search for NP, assumption: “NP at high  $p_T$ ”
- Hundreds of exclusive analysis channels
  - High  $p_T$  e’s, mu’s, photons, neutrinos, jets, b-jets
  - SM BG from MC-only
  - Algorithm searches for largest data-MC deviations
    - Sensitive to MC mismodelling
  - Dedicated analysis needed in case of discrepancy observed



# Conclusions

- We are prepared for new physics and we try to cover all the bases
  - Priority: don't want to miss anything (trigger!)
  - Focus so far on signatures, combinations for dedicated models to come
- Focused on latest 8 TeV results here - apologies if I missed your favorite signature
  - Many more 8 TeV results to come – NP could still hide in the data recorded
- Run II with 13-14 TeV will significantly increase reach of these searches



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

# Don't Give Up Looking!



Thank You!

# Backup

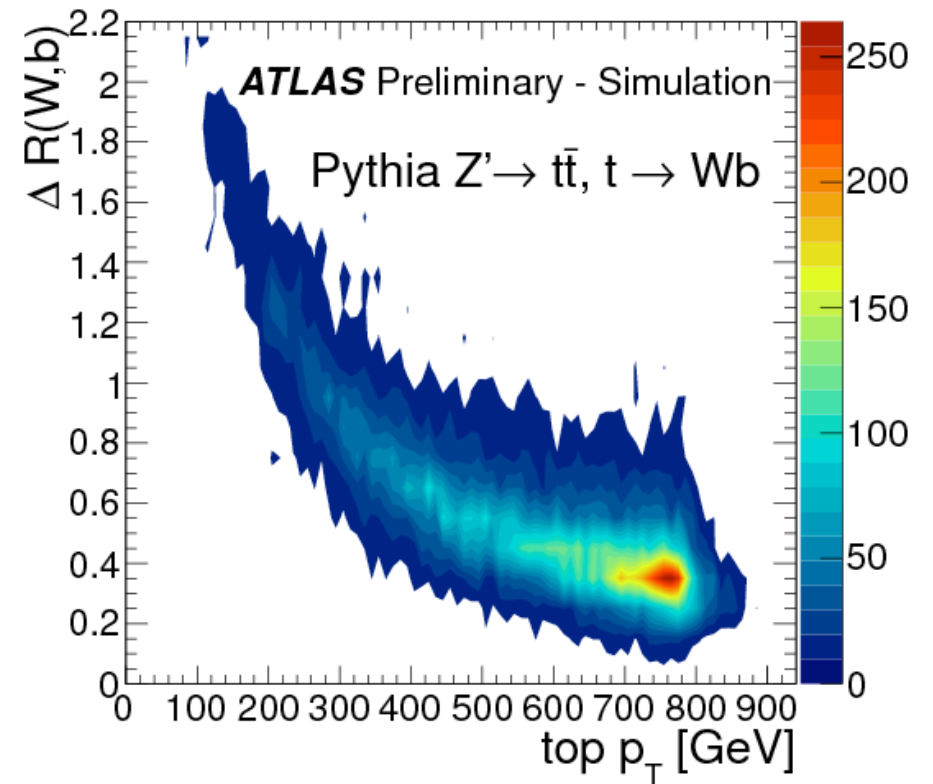
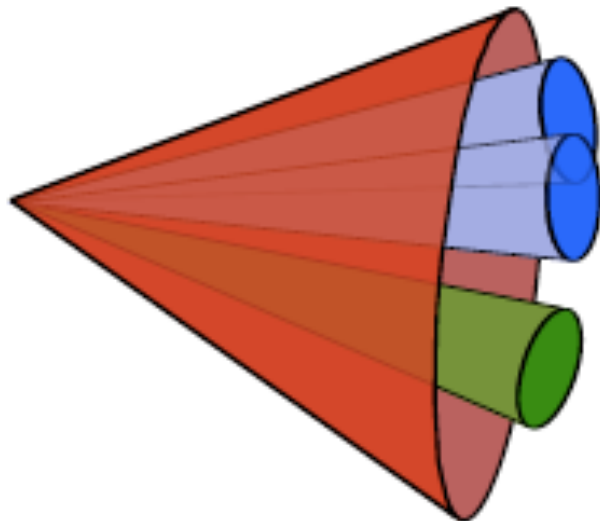


# Index of Benchmarks Used

- 2UED/RPP = Two universal extra dimensions under the real projective plane geometry
- ADD = Large Extra Dimension model proposed by Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali
- CH = Composite Higgs
- CI = Contact Interactions
- E6 = possible gauge group in GUTs
- ED = Extra Dimensions
- EGM = Extended Gauge Model
- GMSB = Gauge Mediated Supersymmetry Breaking
- GUT = Grand Unification Theory
- LH = Little Higgs
- LSTC = Low Scale Technicolor
- RS = Randall-Sundrum warped extra-dimensional model
- SSM = Sequential Standard Model
- TC = Technicolor
- UED = Universal Extra Dimensions
- Unparticles in conformal sector  $\Rightarrow$  long-lived weakly-interacting particles

# Jet Substructure

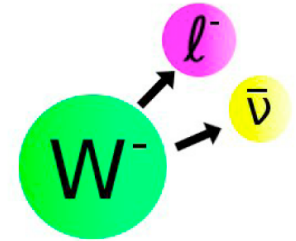
- Use jets with large radii (e.g. anti- $k_T$ ,  $R = 1.0$ ) to collect all products of hadronic top decays
- Rule of thumb:  $\Delta R \sim 2M/p_T$



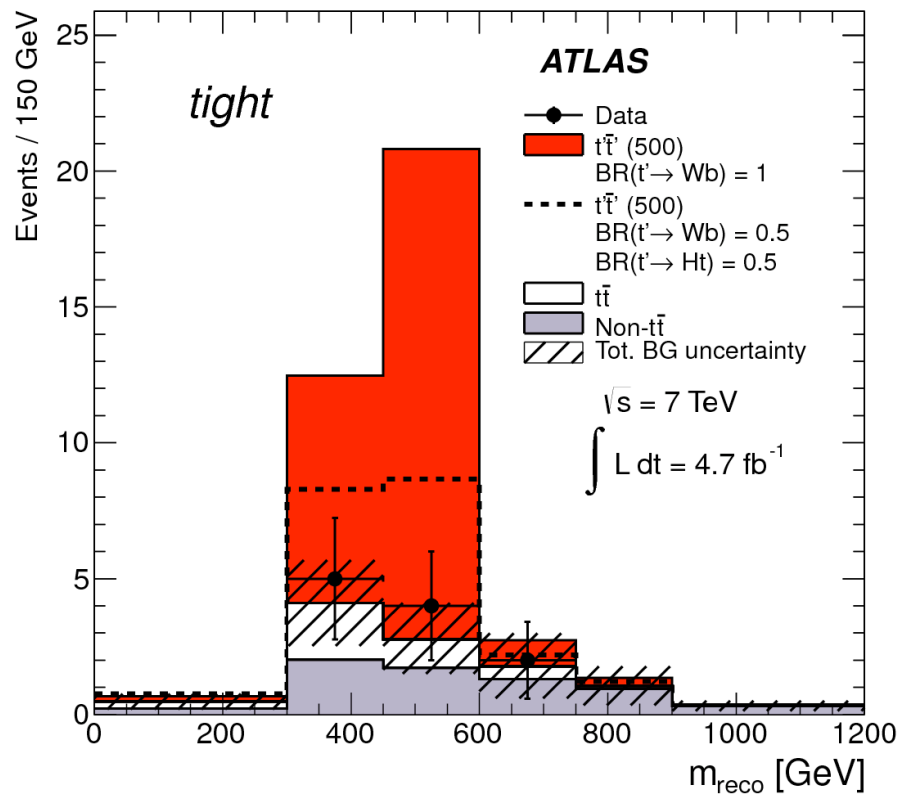
- Investigate substructure
- Jets with larger radii suffer more from contamination by underlying event and pile-up
  - ✓ “Grooming” allows to remove soft radiation

# L+jets Channel: Search for $t'\bar{t}' \rightarrow WbW\bar{b}$

- Reconstruct boosted  $W \rightarrow jj$ 
  - either as single jet,  $p_T > 250$  GeV,  $60 < m < 110$  GeV
  - or  $\Delta R(j,j) < 0.8$ ,  $p_T > 150$  GeV,  $60 < m < 110$  GeV



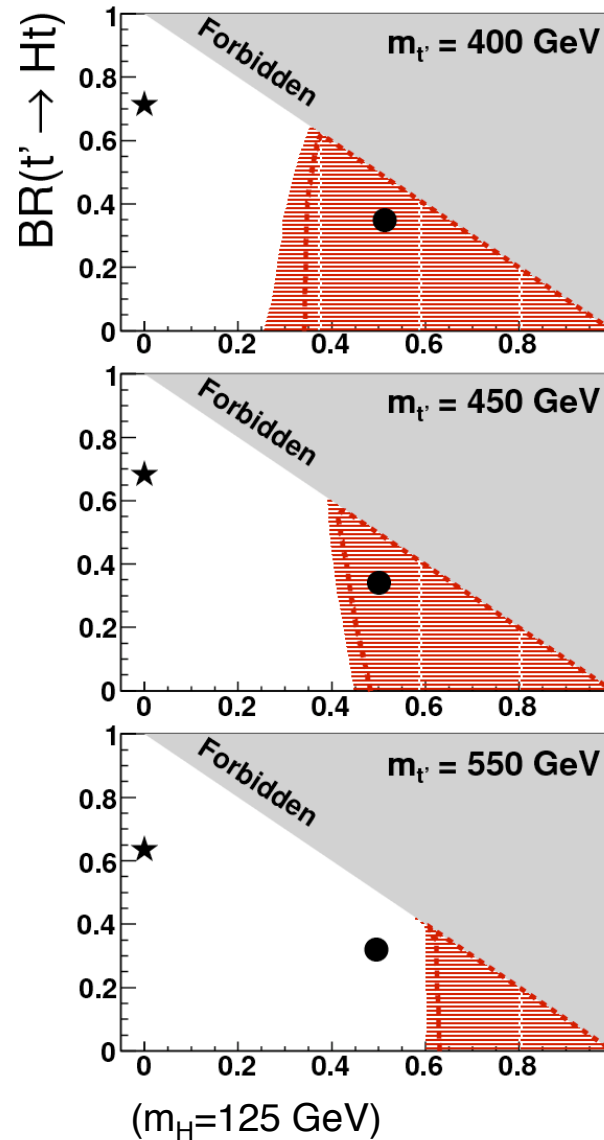
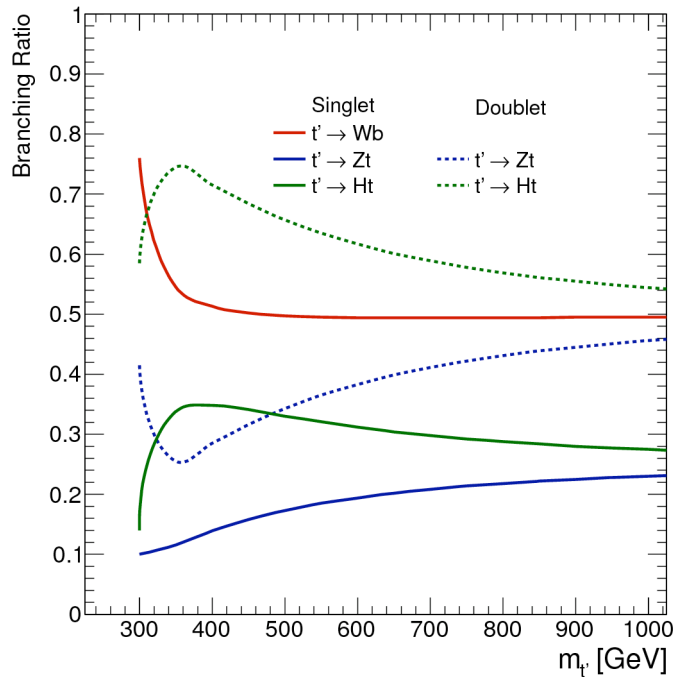
Boosted  $W$  decay products are collinear in the lab frame



- Discriminant: candidate  $t'$  mass using kinematic fit
- b-jet candidates: 2 jets with highest b-tag discriminant
- $H_T(l, \nu, \text{jets}) > 750$  GeV
- $\Delta R(l, \nu) < 1.4$
- $\Delta R(W_{\text{had}}, b_{1,2}) > 1.4$
- $\Delta R(l, b_{1,2}) > 1.4$

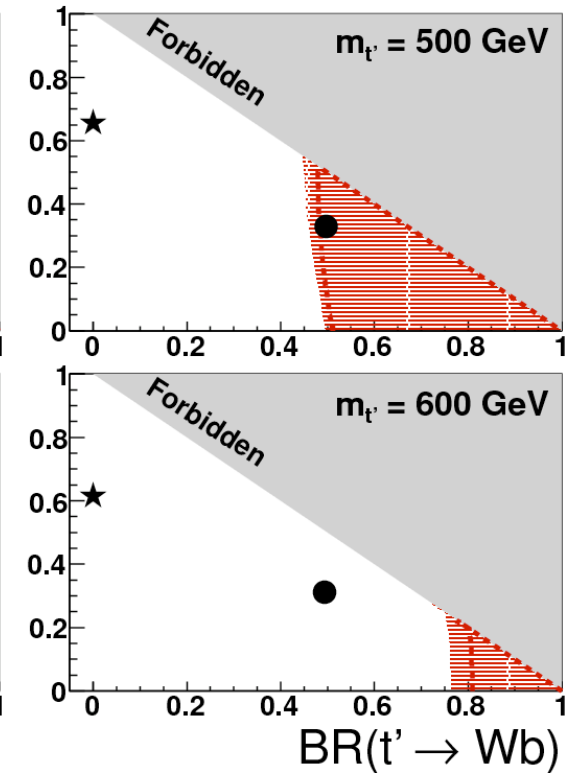
# VLQ Interpretation: $t'\bar{t}' \rightarrow WbW\bar{b}$

- Interpret limit in vector-like quark model where
  - $t' \rightarrow Wb$
  - $t' \rightarrow Ht$
  - $t' \rightarrow Zt$
- Sum of 3 BR's is unity

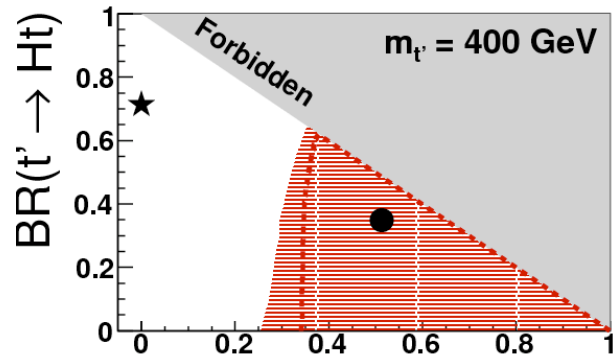


**ATLAS**  
 $\sqrt{s} = 7 \text{ TeV}, \quad \int L dt = 4.7 \text{ fb}^{-1}$

⋯ 95% CL expected exclusion    ● SU(2) singlet  
▨ 95% CL observed exclusion    ★ SU(2) doublet



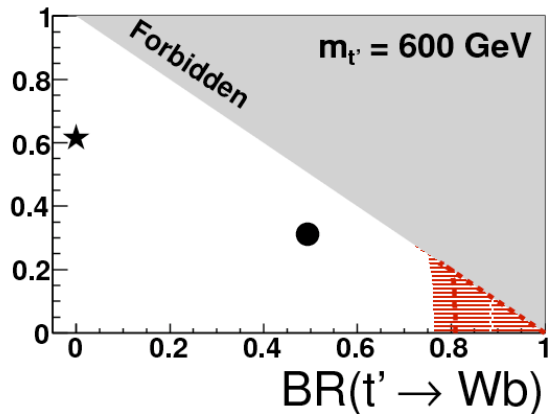
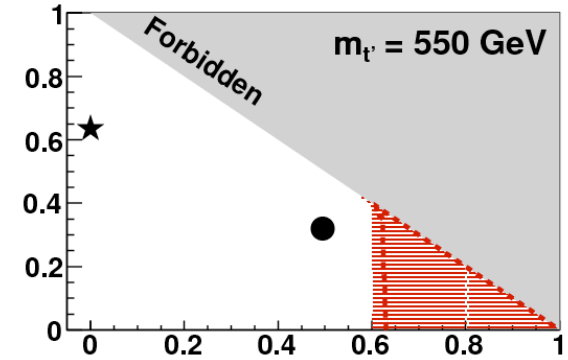
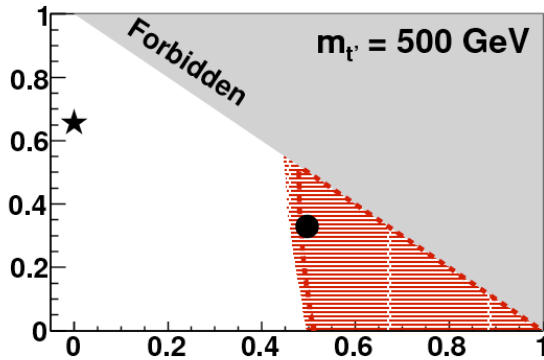
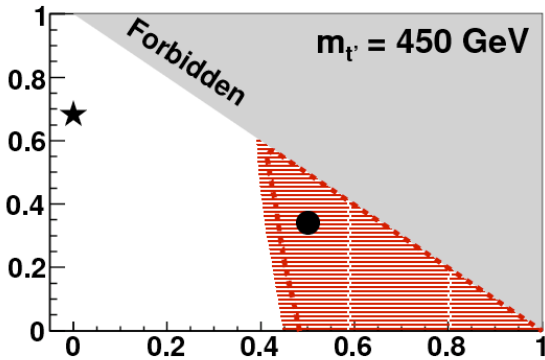
# VLQ limits



**ATLAS**

$$\sqrt{s} = 7 \text{ TeV}, \quad \int L dt = 4.7 \text{ fb}^{-1}$$

- 95% CL expected exclusion
- 95% CL observed exclusion
- SU(2) singlet
- ★ SU(2) doublet

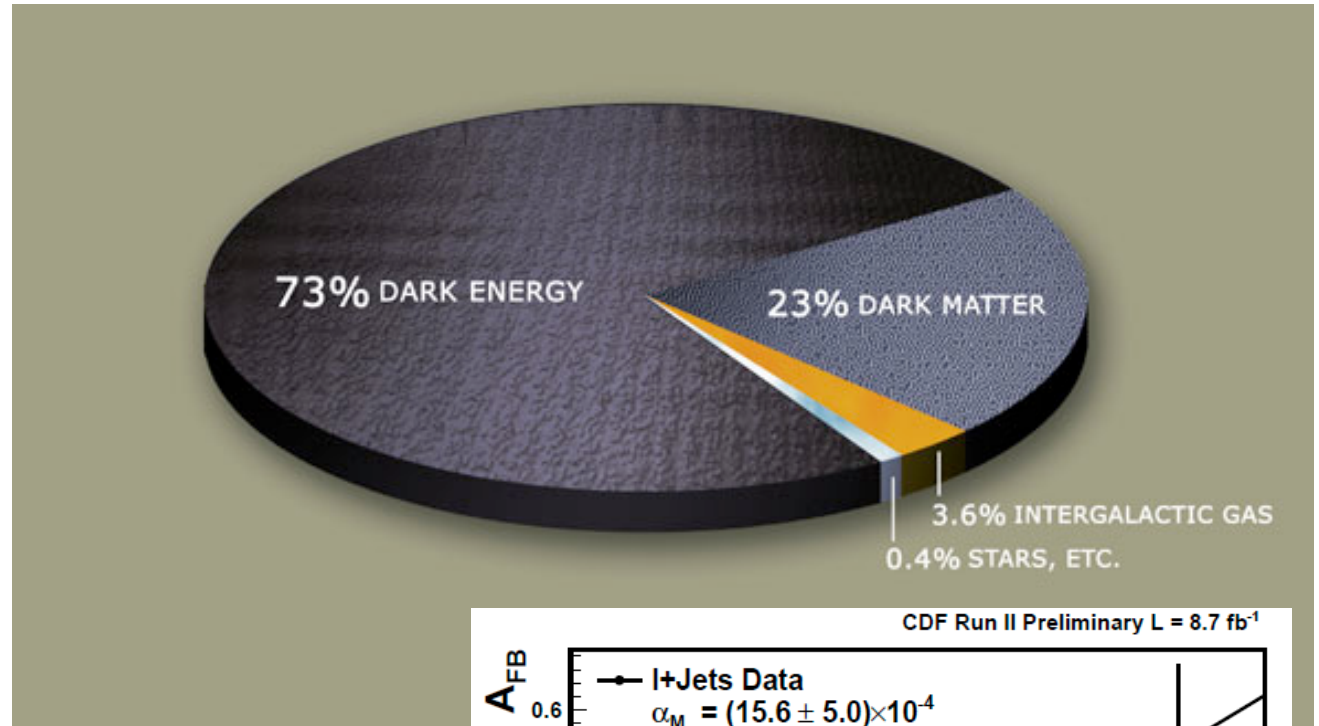


# Same-Sign Leptons

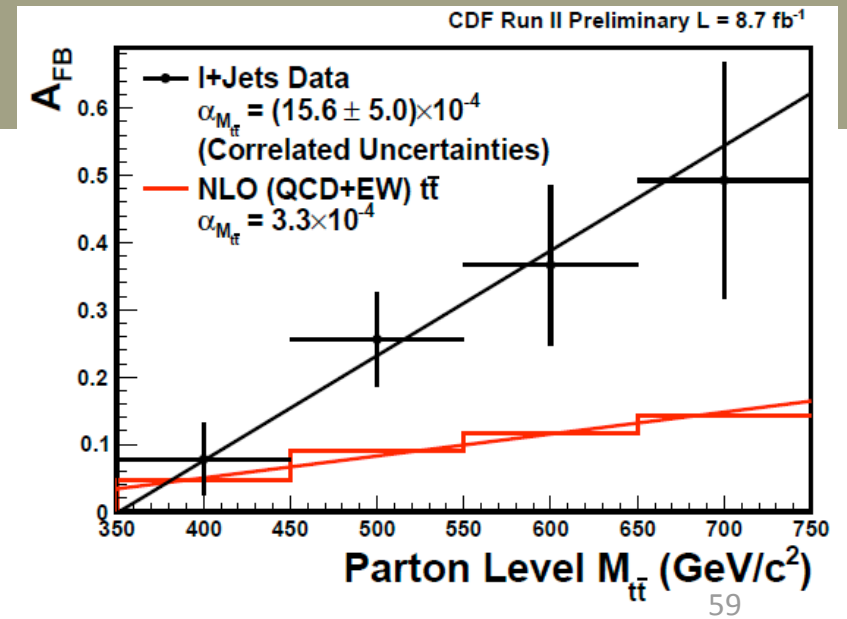
- Very Low SM backgrounds
- Many NP scenarios (including SUSY)
  - $b'$ ,  $T5/3$ ,  $tt$ , 4-tops, gluino-mediated stop,  $H^{++}/--$ , heavy neutrino (seesaw), TeV-scale gravity (mini-black holes)
- Beautiful set of SS analyses
  - SS inclusive: generic search, model-independent fiducial XS limits
  - Cut harder and smarter
    - SS+MET: look for SUSY (e.g. gluino-mediated stop production)
    - SS+HT/jets/b-jets:  $b'$ ,  $T5/3$ ,  $tt$ , 4-tops
    - SS+mass reconstruction: heavy neutrino (seesaw)
    - SS+boosted (does not exist yet)
- Background estimate
  - Fakes, determined using matrix method and fake factor method
  - Charge flip (e only), determined using Z events
  - Irreducible  $VV$  and  $t\bar{t}+V$  background



# Signs of Physics Beyond the SM

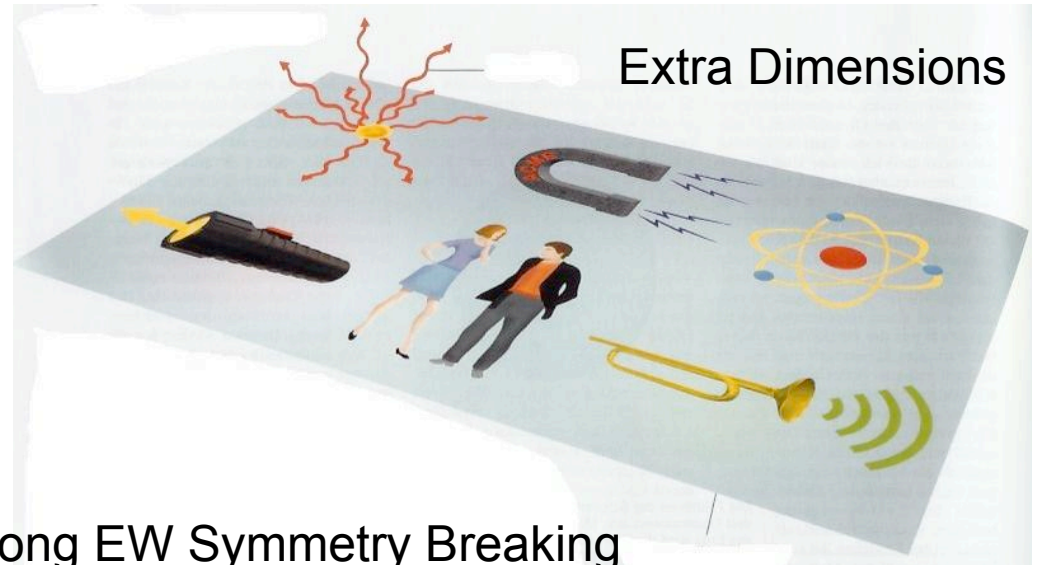


- Dark energy
- Dark matter
- Neutrino masses
- Matter-antimatter asymmetry
- $t\bar{t}$  forward-backward asymmetry
- ...



# How to Fix the SM?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i Y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



## Strong EW Symmetry Breaking

- Technicolor
- Composite Higgs
- New heavy vector bosons
- Vector-like quarks
- ...

- ✓ Dark matter
- ✓ Hierarchy Problem
- ✓ Gauge Unification
- ✓ ...

## Supersymmetry

