New physics in top at the LHC in Run II and beyond

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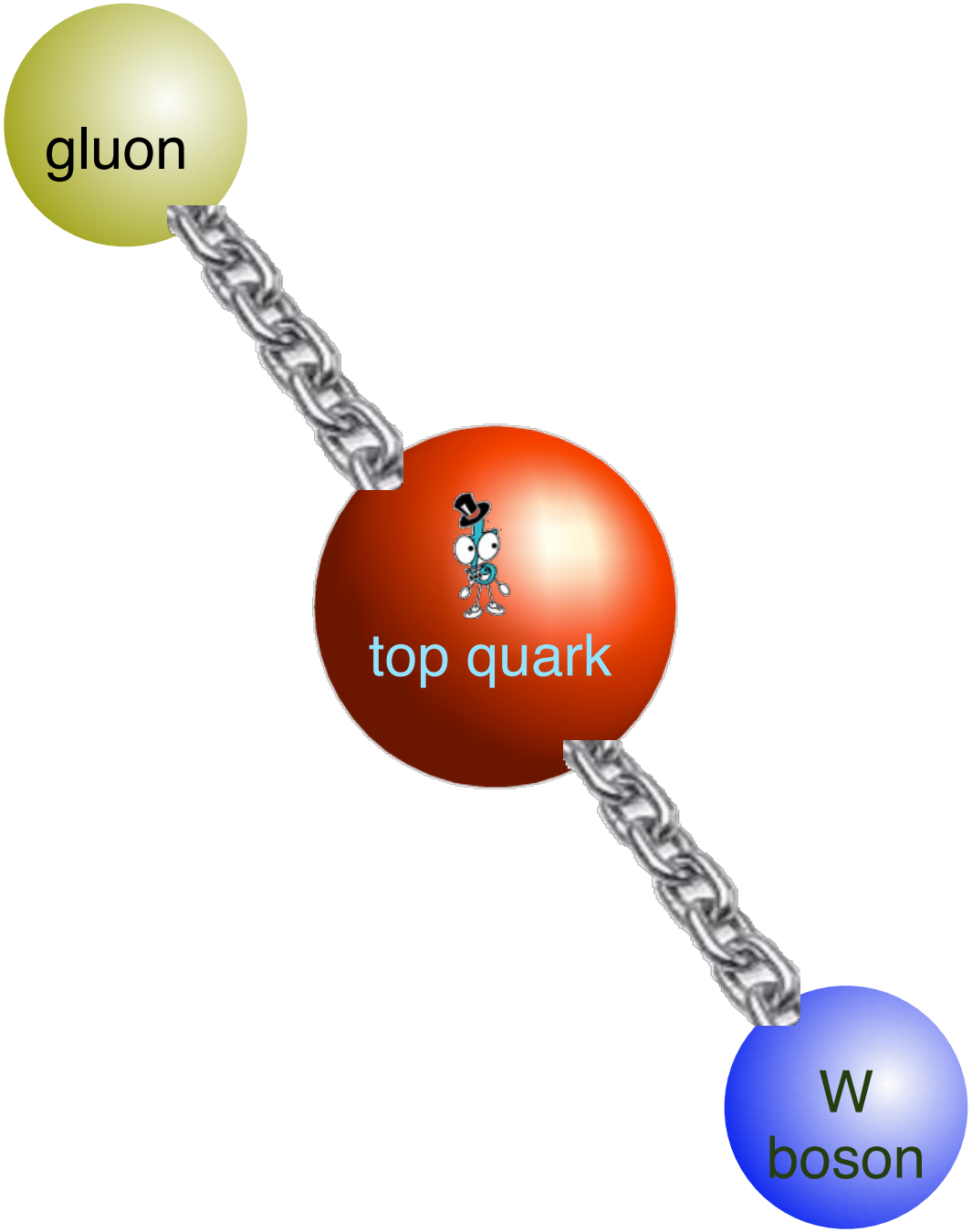
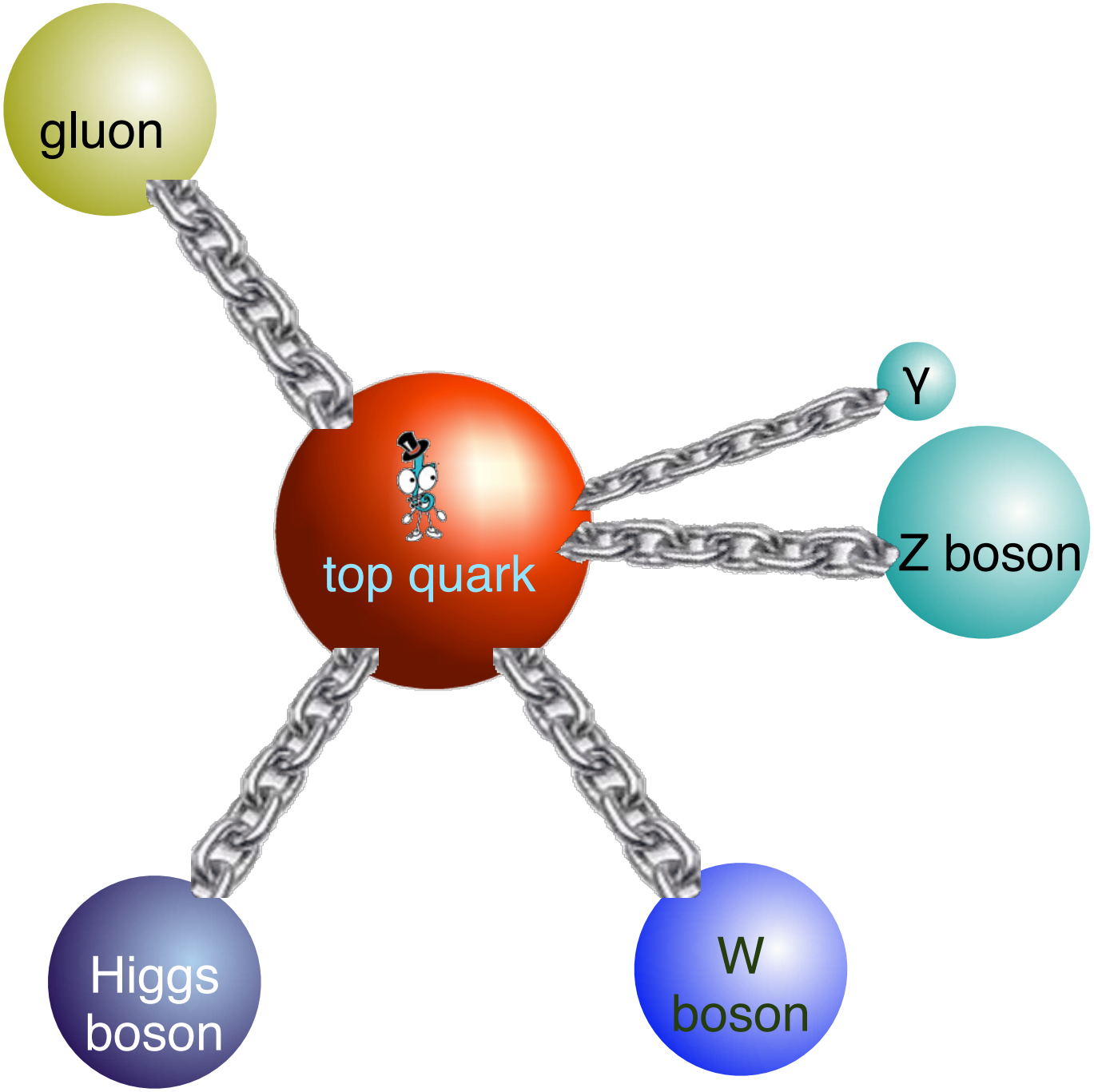
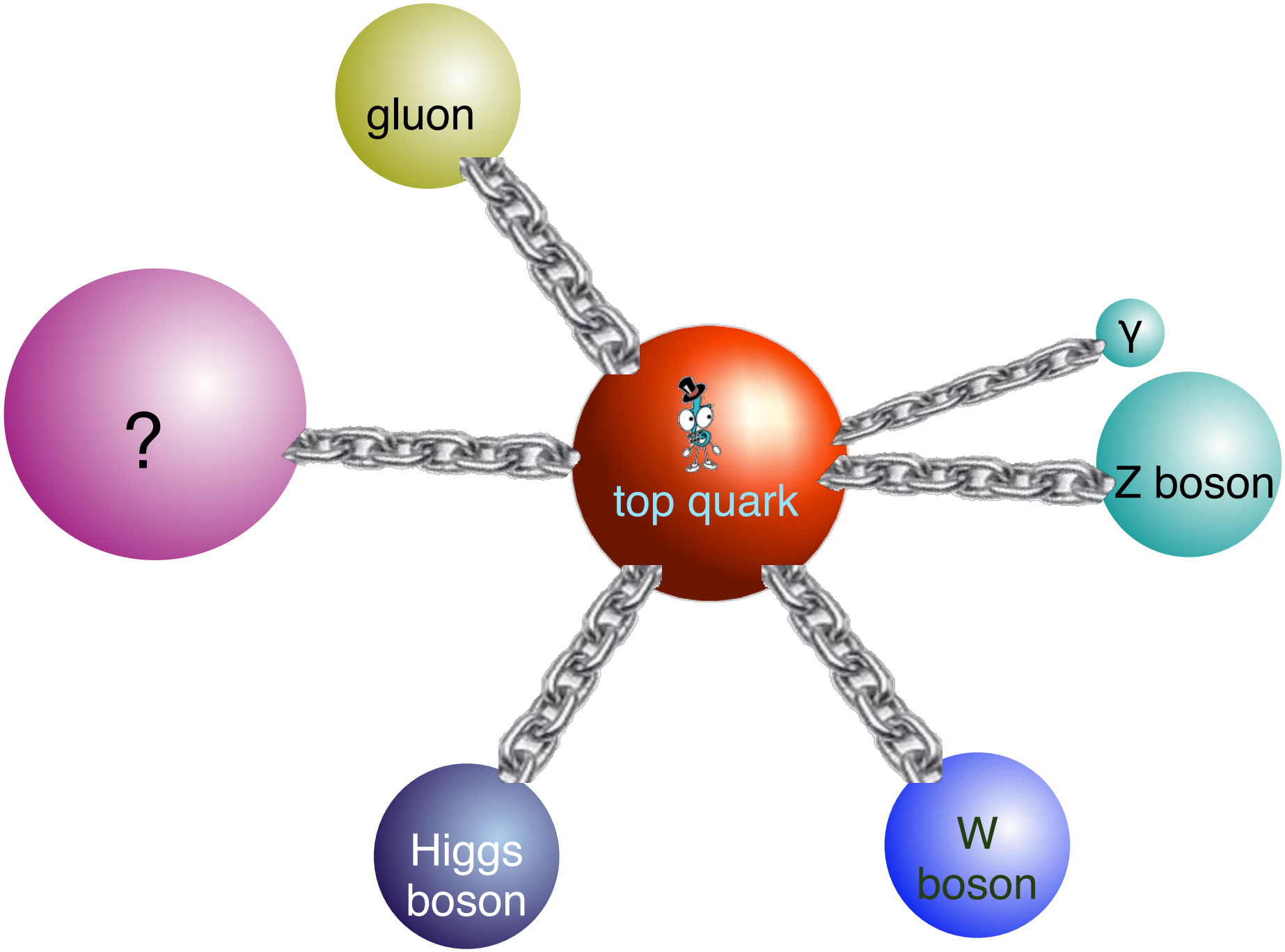
Enigmass
The enigma of mass

Introduction


gluon
top quark
W
boson


gluon
top quark
γ
Z boson
Higgs boson
W boson


gluon
?
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Z boson
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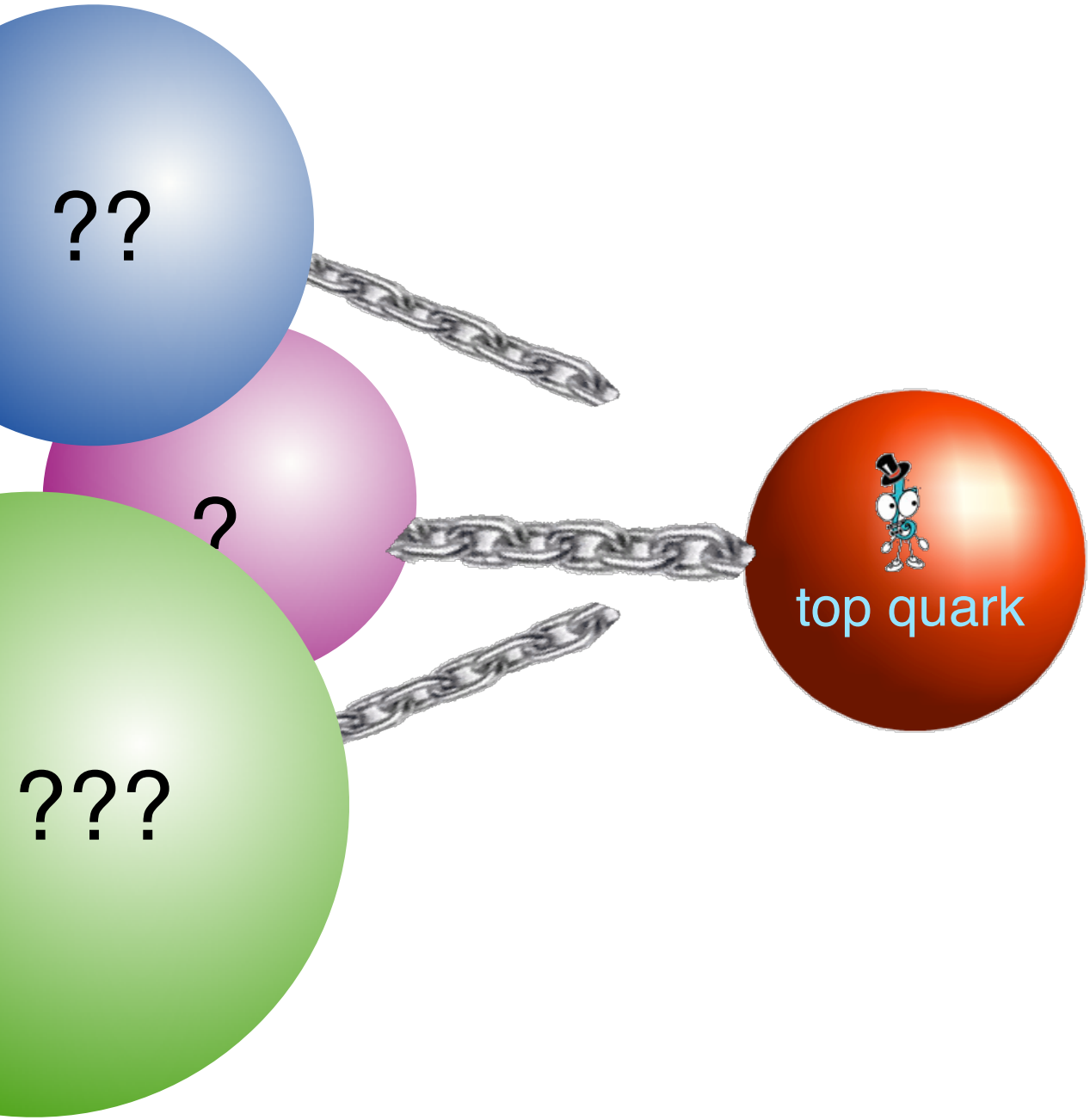
W boson


??
?
???
top quark

Window to new physics

modified couplings

4th gen quarks

b'

t'

anomalous KM matrix

anomalous Wtb couplings

vector-like quarks

CP violation

Z'

W'

charged Higgs

new heavy bosons

new couplings

Flavor-changing neutral currents

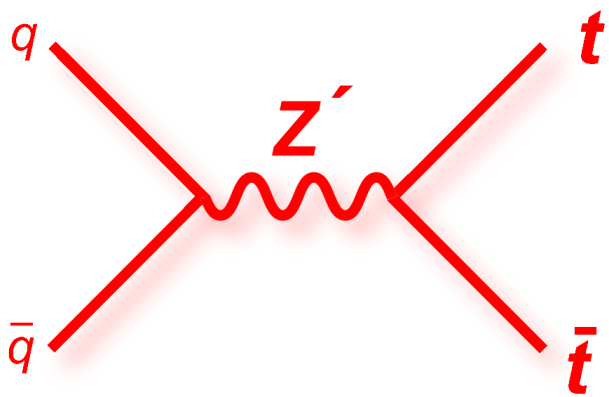
Supersymmetry

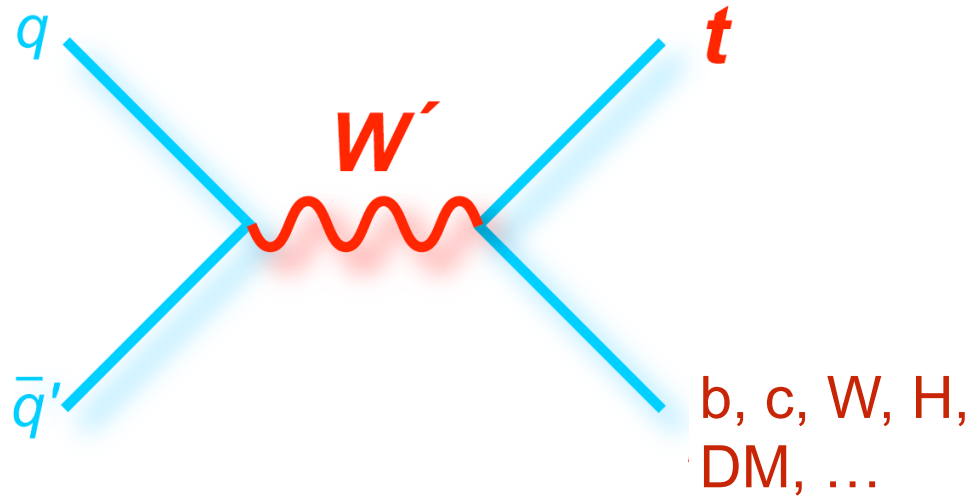
Extra dimensions

Higgs-less models

Other new physics models

Top coupling to new bosons



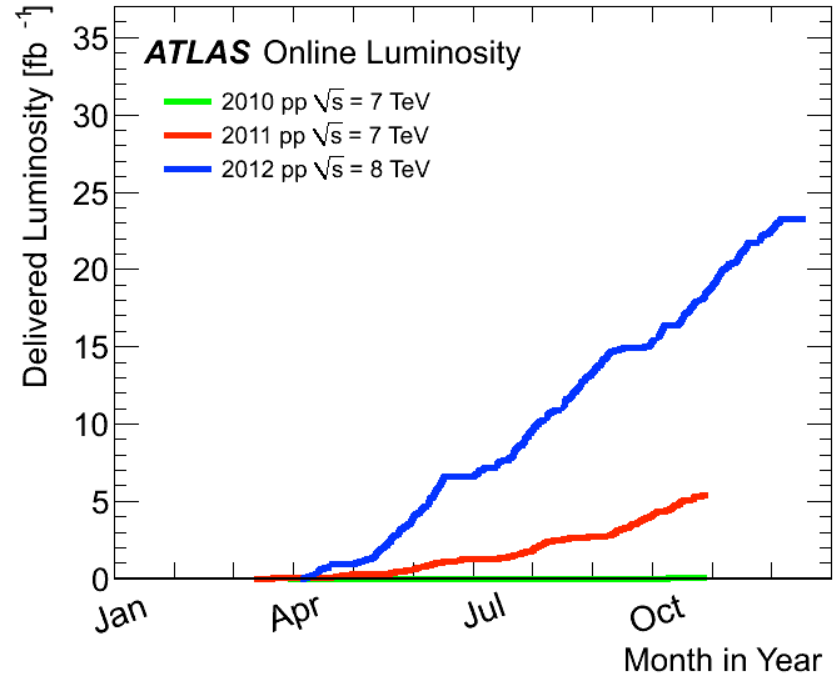


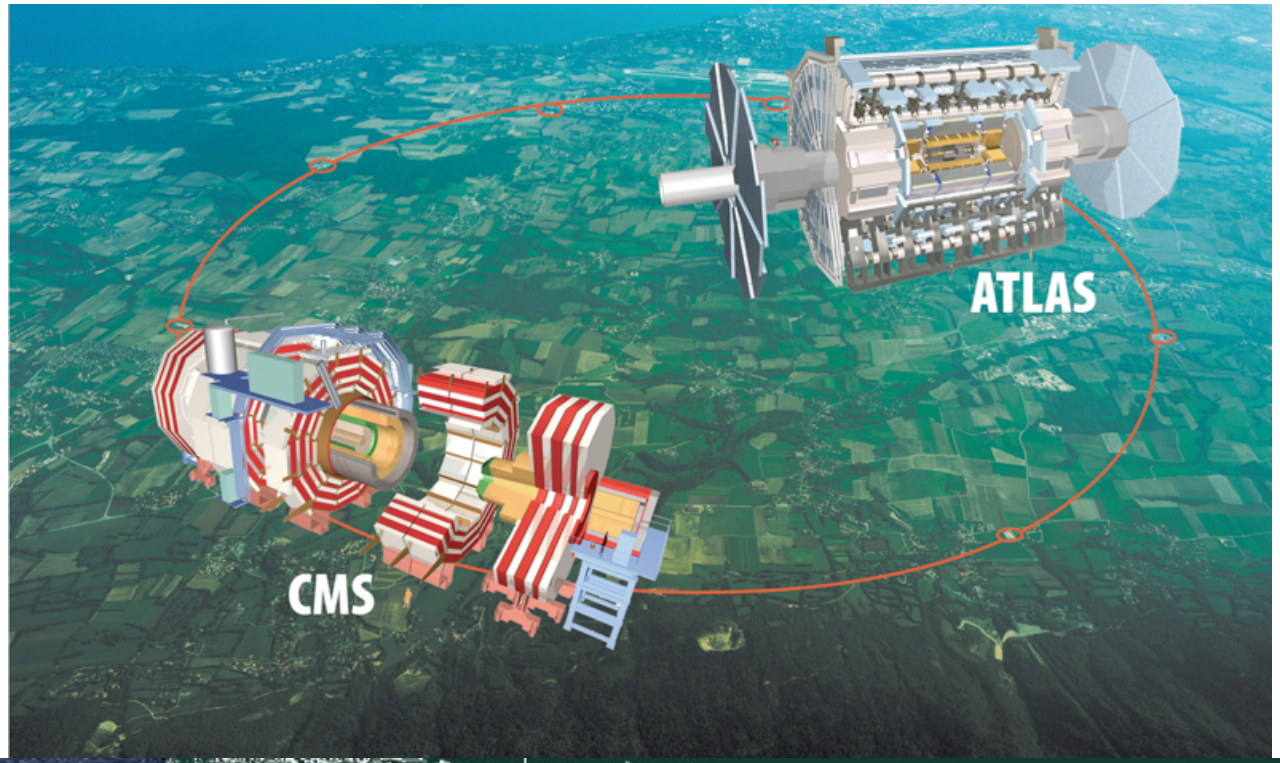
KKg
gravitino
colored resonance
…

KKg
H^+
colored resonance
vector-like quark
…

LHC in Run 1

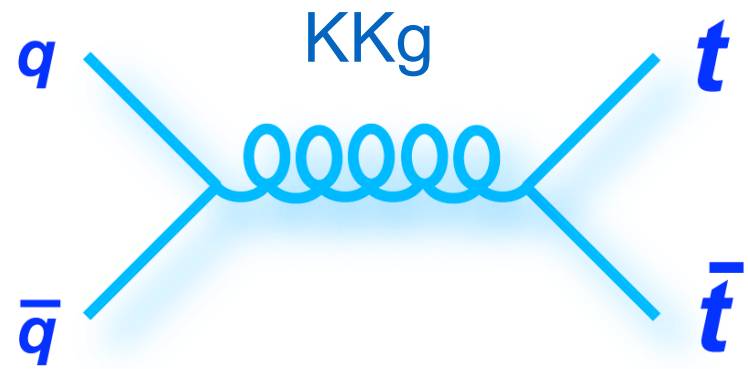
- proton-proton collider
- 7 TeV in 2011 → 5 fb^{-1}
- 8 TeV in 2012 → 20 fb^{-1}
- gluon-dominated initial states
  - top quark factory
    - > 5 M SM top pairs produced so far

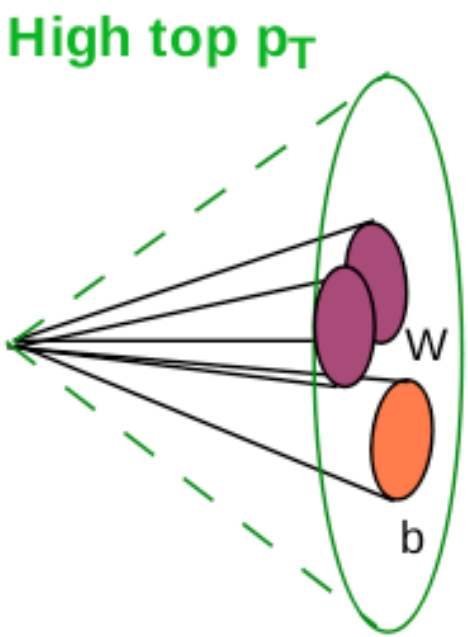


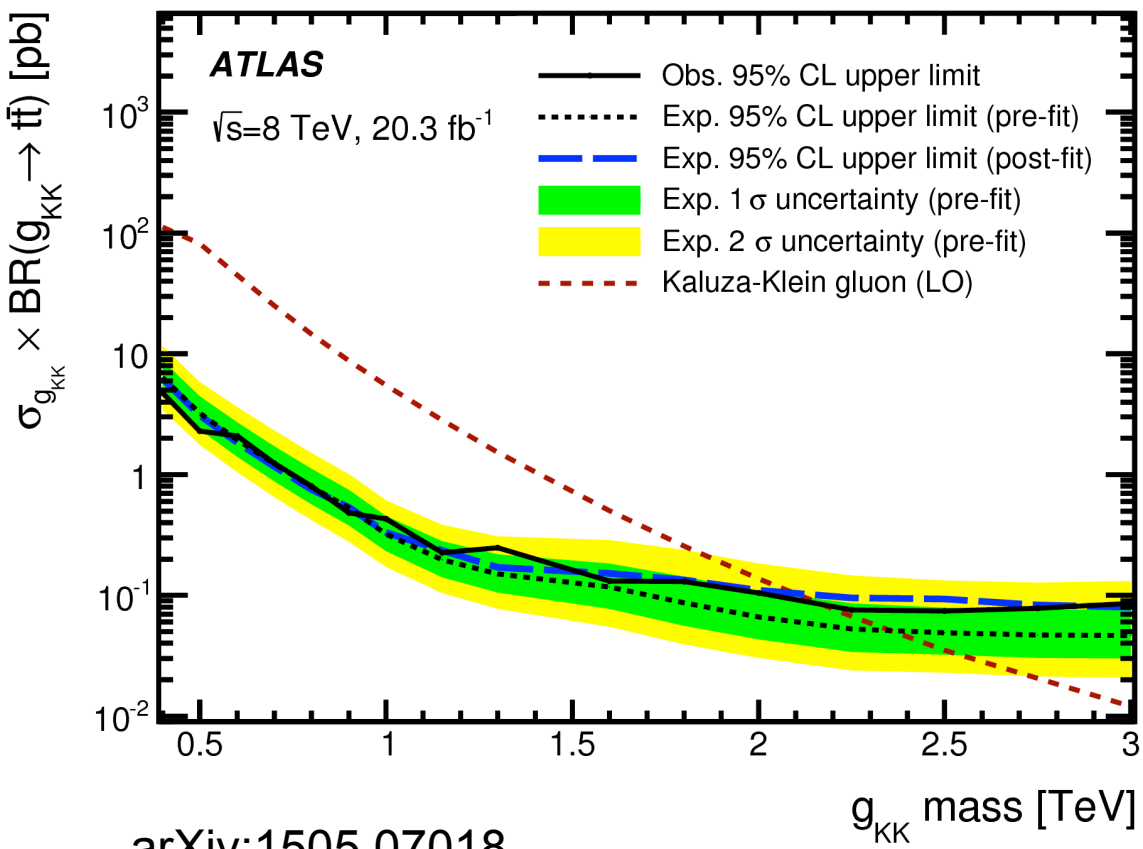


Resonances in top pair production

- Strong coupling
  - Kaluza-Klein gluon
  - Large cross-section
  - Boosted top techniques

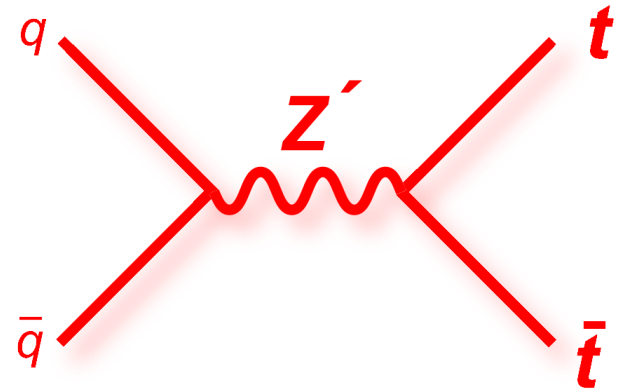




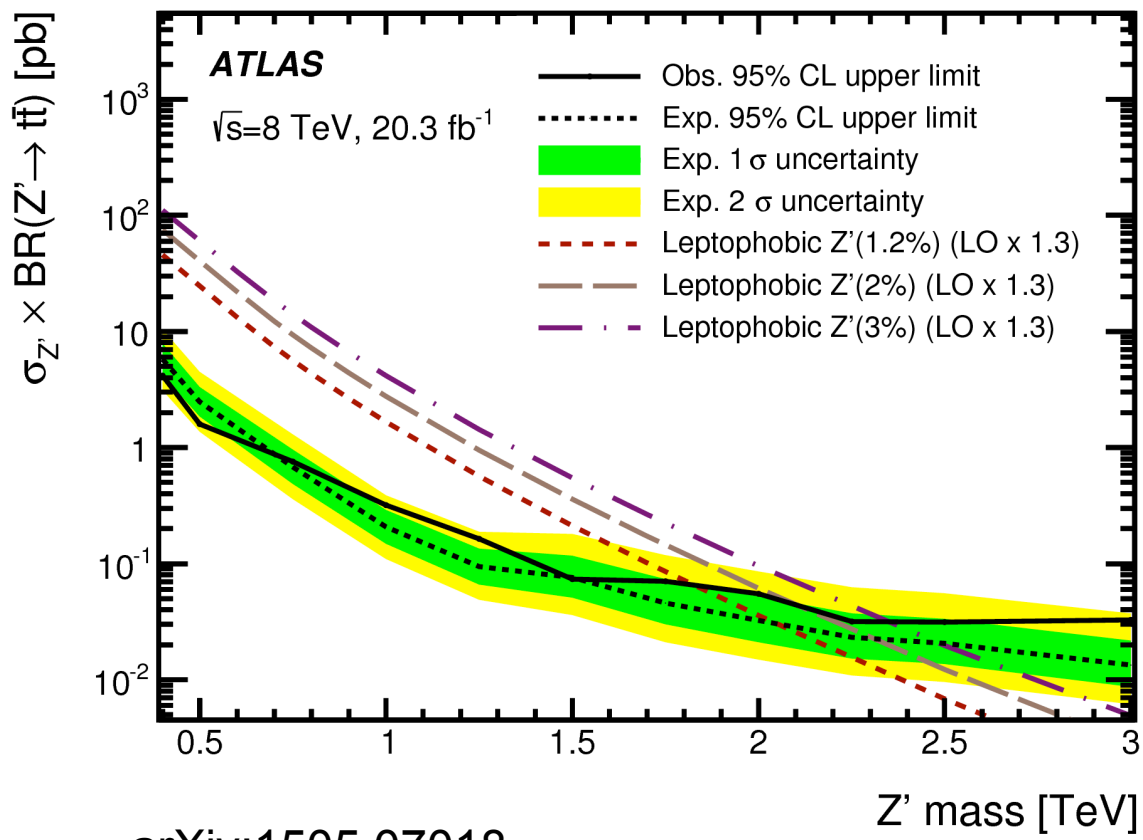


arXiv:1505.07018

Resonances in top pair production



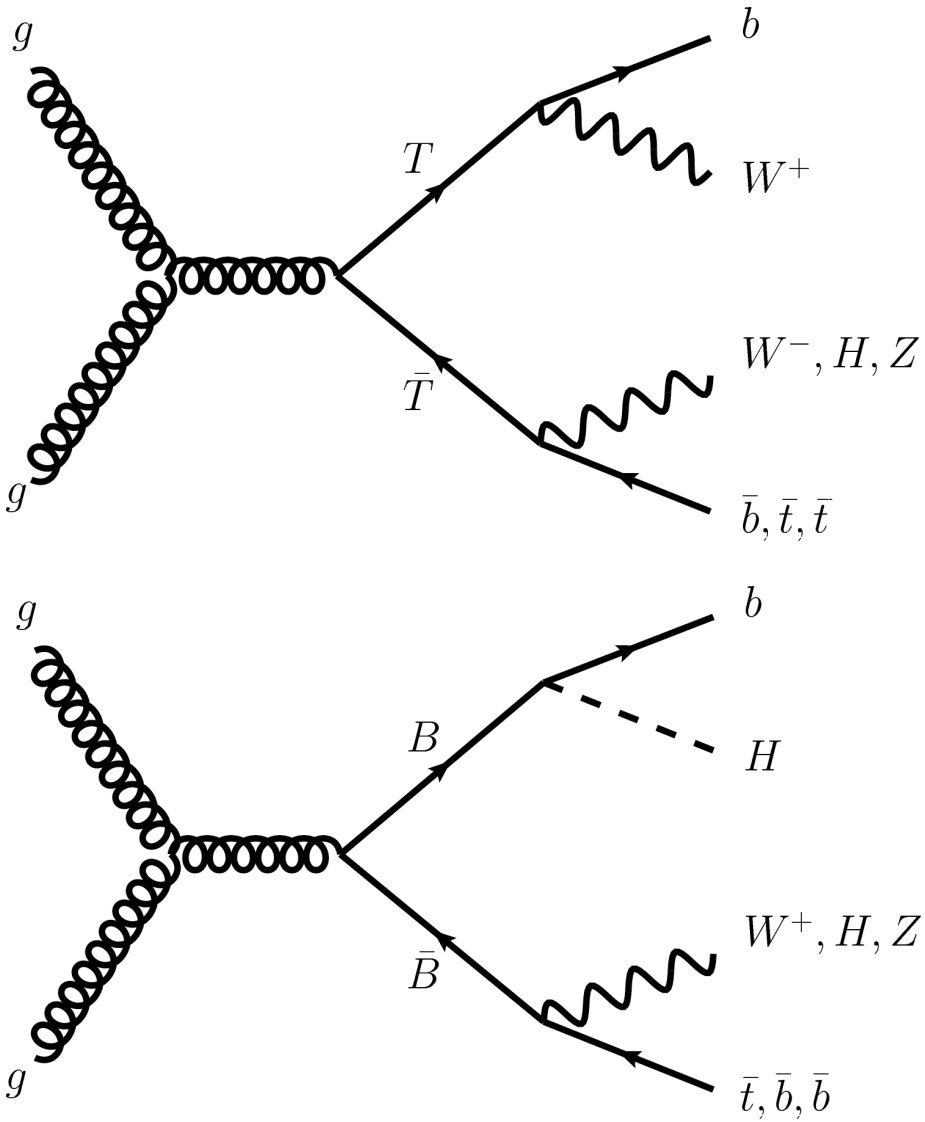
- Weak coupling
  - Z′, gravitino
  - Smaller cross-section
  - Model-dependent limits
    - Coupling
    - Width
    - Decay modes

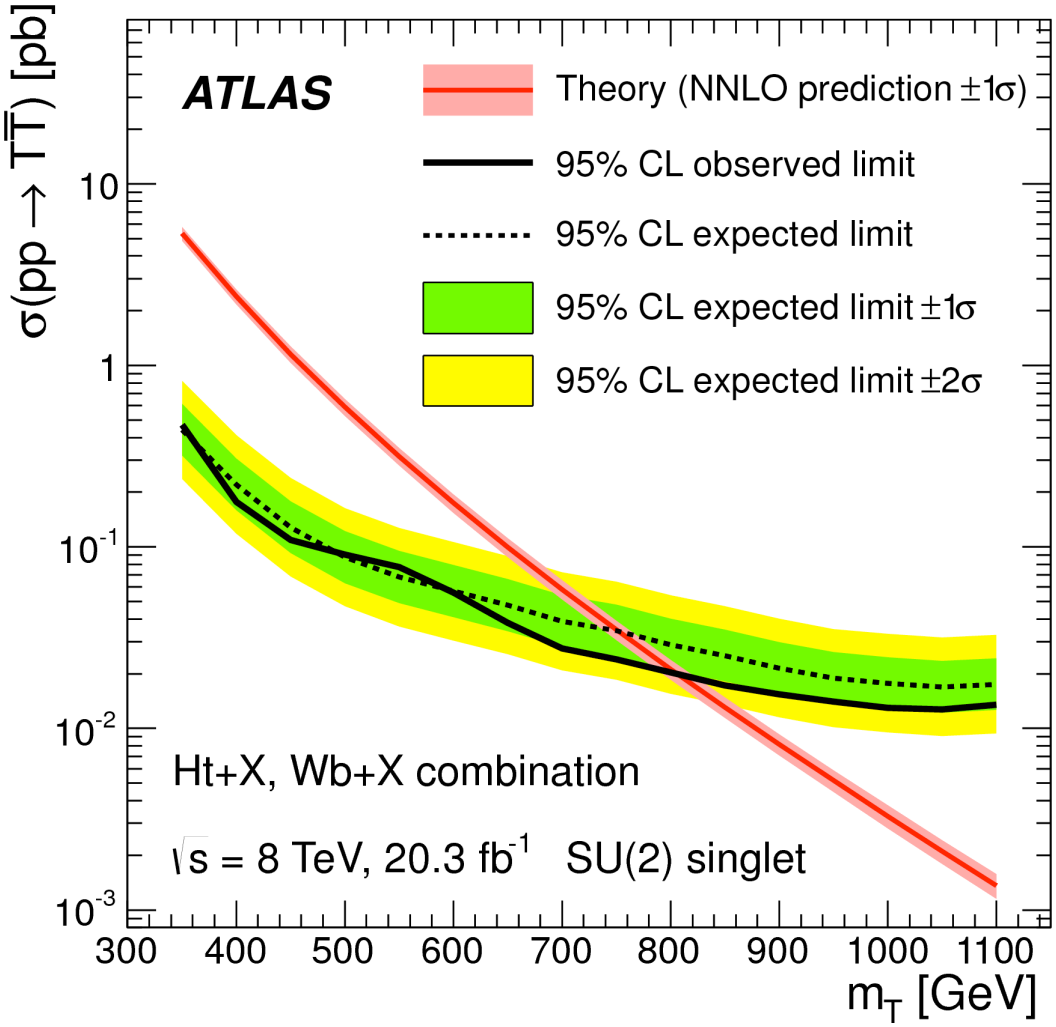


arXiv:1505.07018

Resonances in VLQ pair production

- Vector-like quarks decay to top quarks
  - Strong production
  - Many possible final states
  - Sensitivity depends on decay BRs (T→Wb, T→Zt, T→Ht)

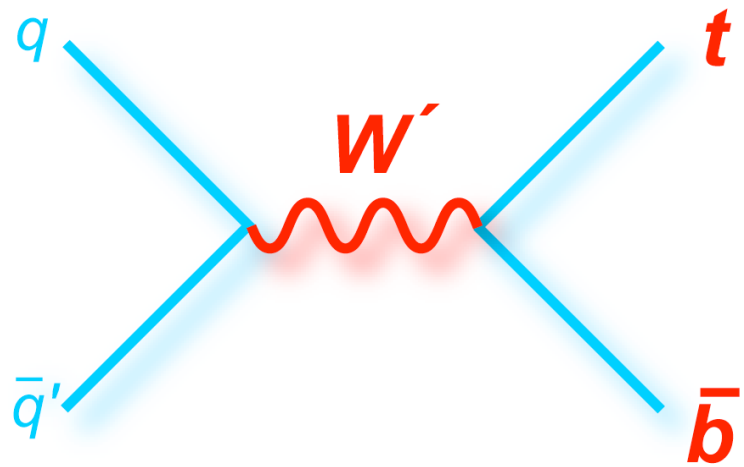


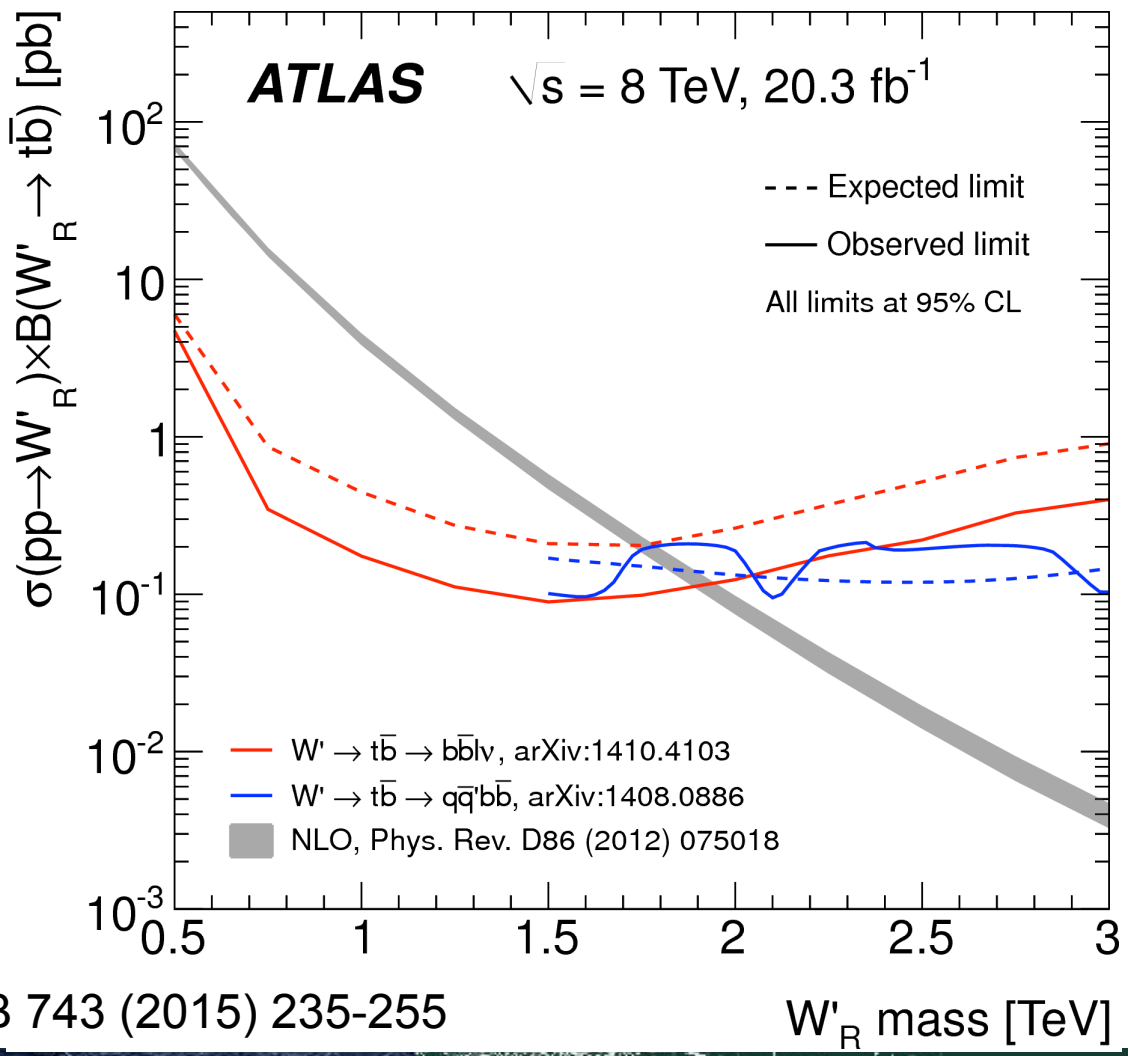


arXiv:1505.04306

Resonances in single top production

- Weak production
  - W′
    - Left-handed or right-handed couplings
  - Charged Higgs boson





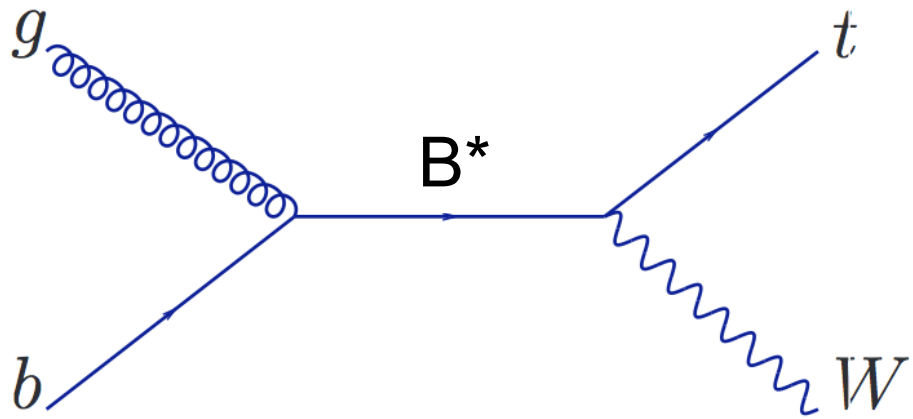
Leptonic top decay

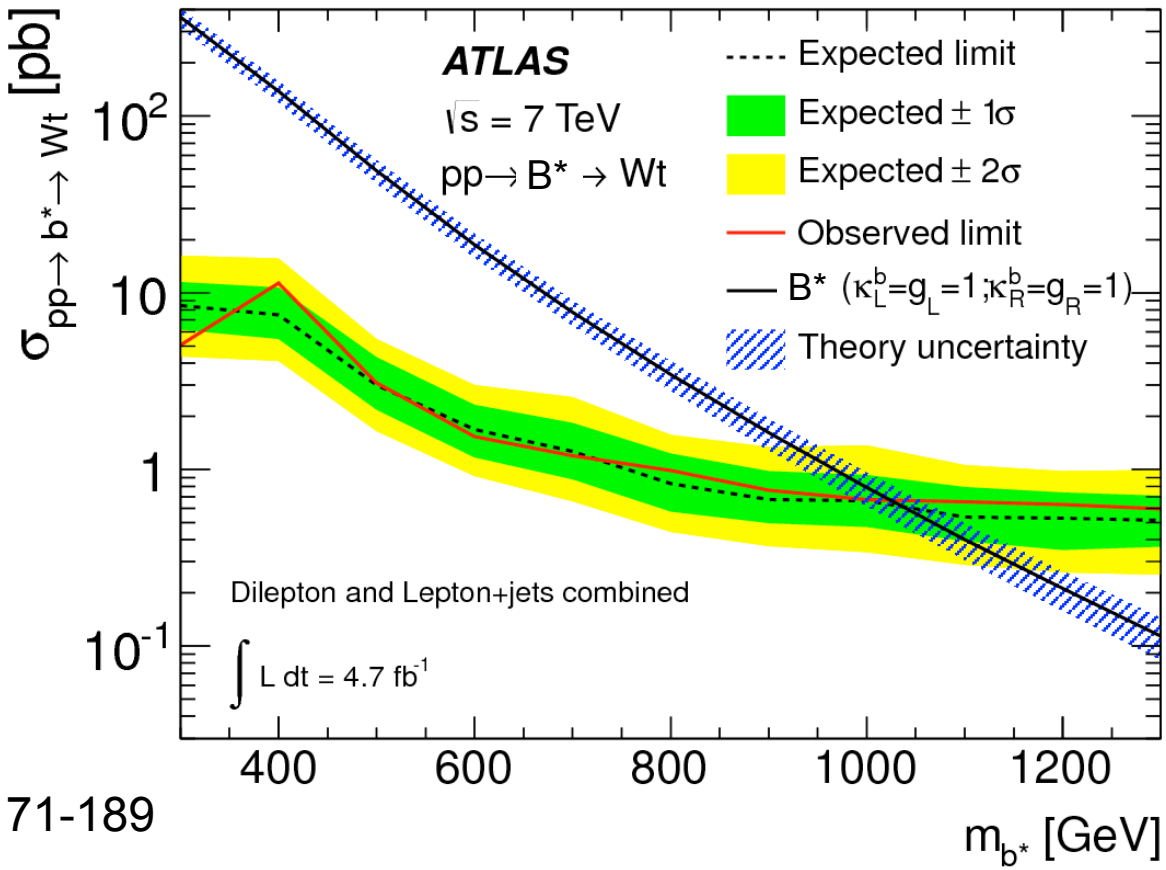
Boosted top

PLB 743 (2015) 235-255

Other resonances in single top production

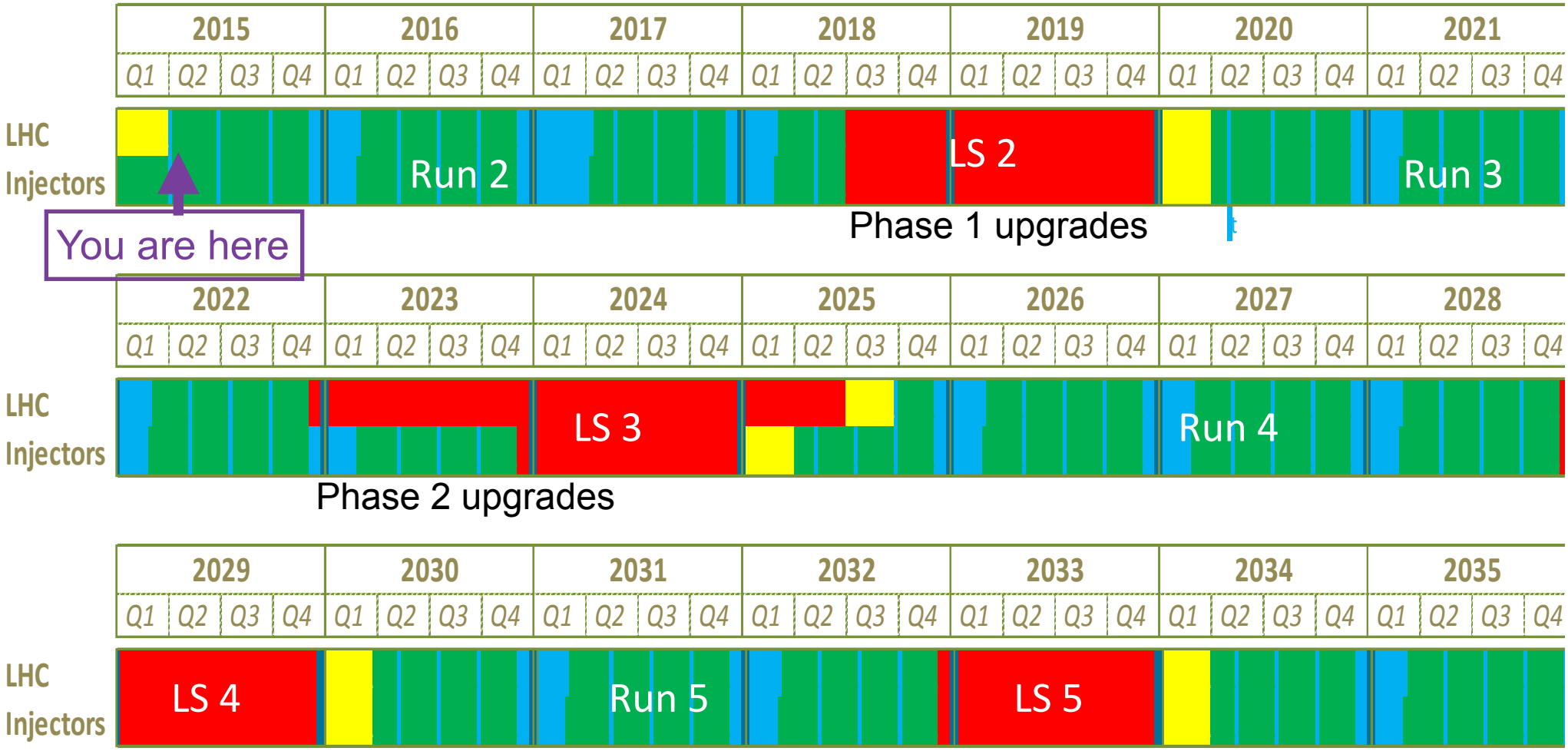
- Wt, Zt, Ht final states
  - VLQ T and B
  - Excited quark B*→tW, T*→tg



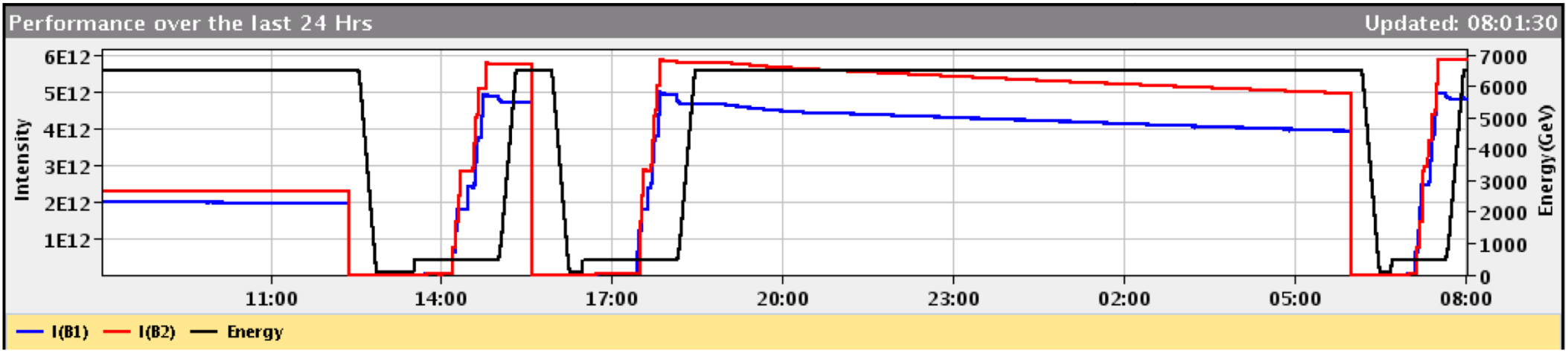


PLB 721 (2013) 171-189

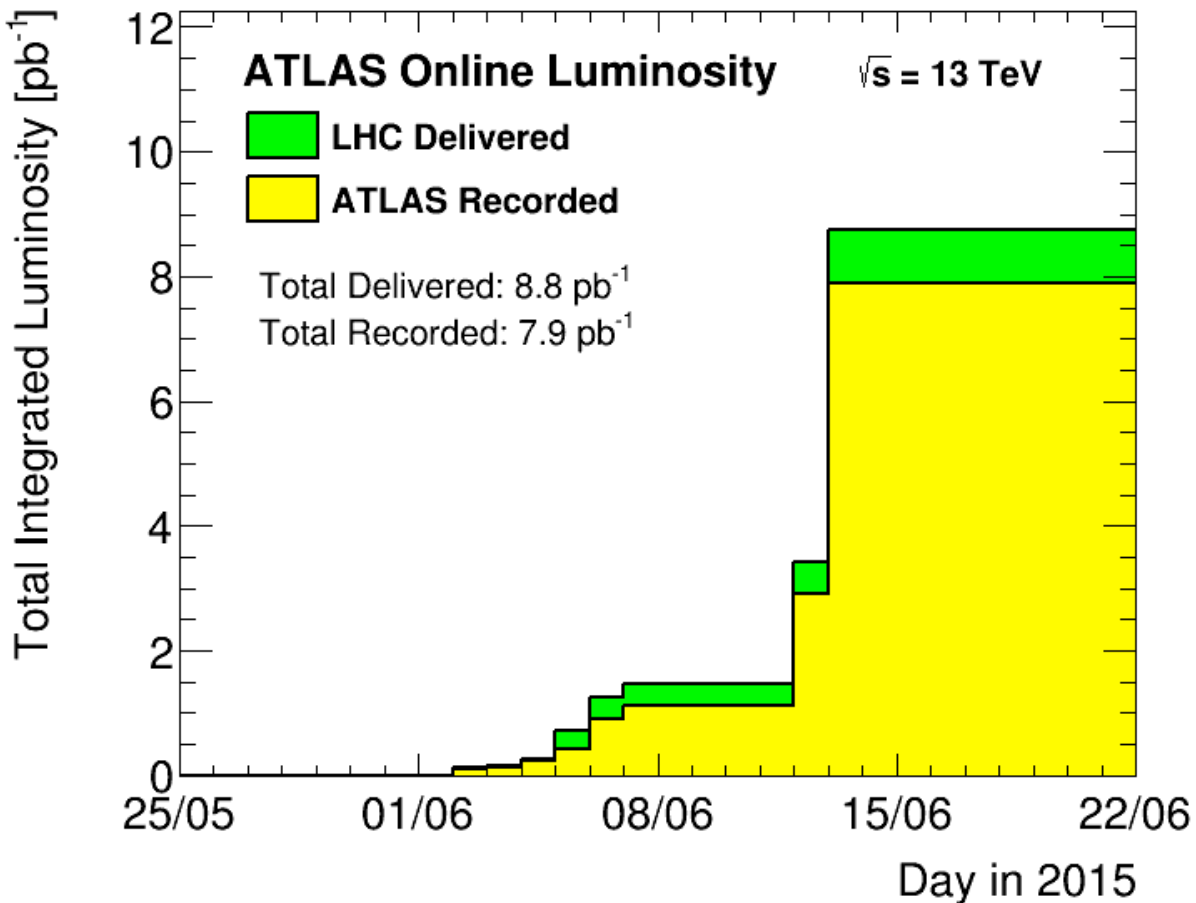
LHC schedule



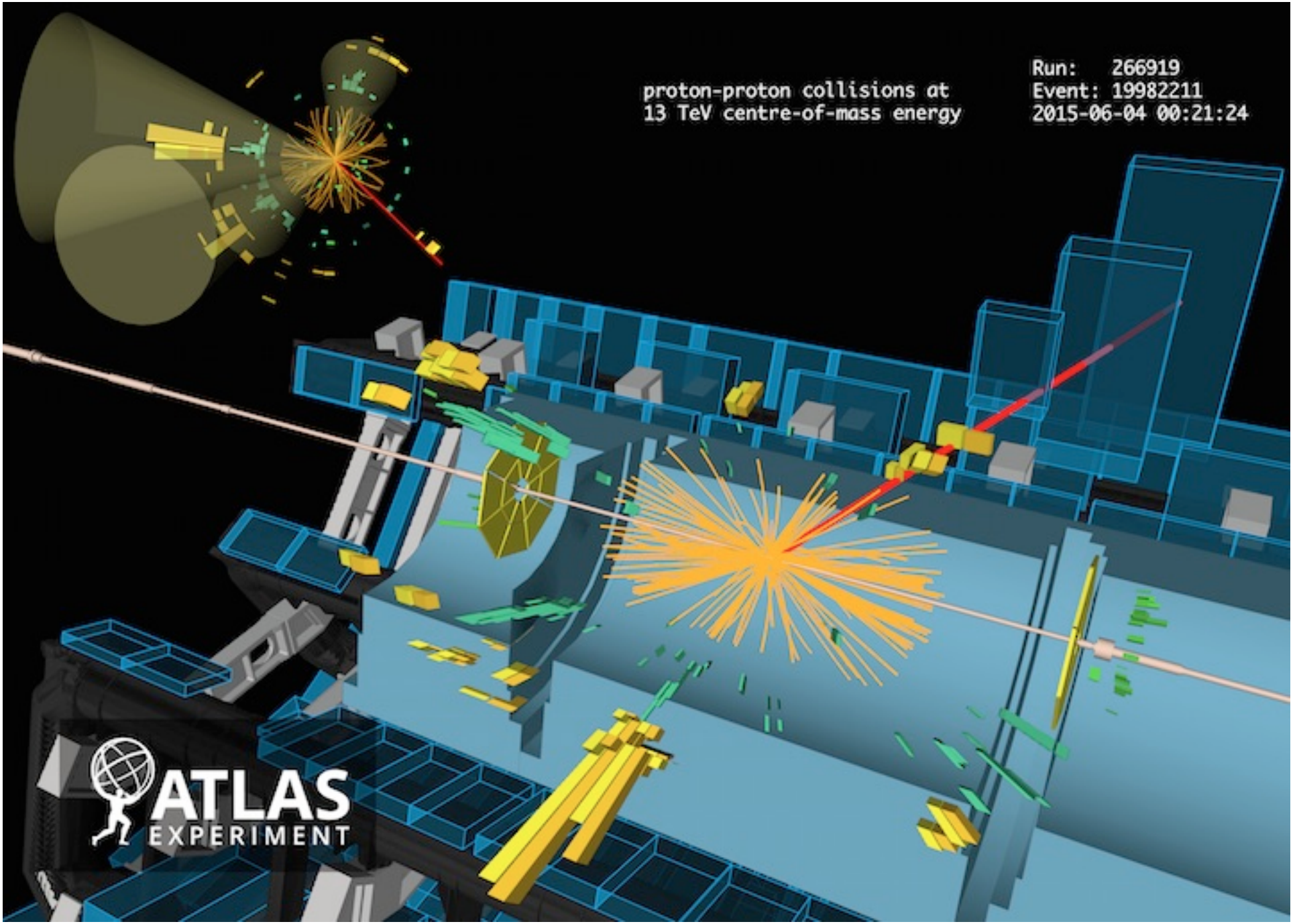
Run 2 has started



- 13 TeV operation
- bunch spacing
  50 ns → 25 ns
- Number of bunches
  slowly increasing



Top quark candidate



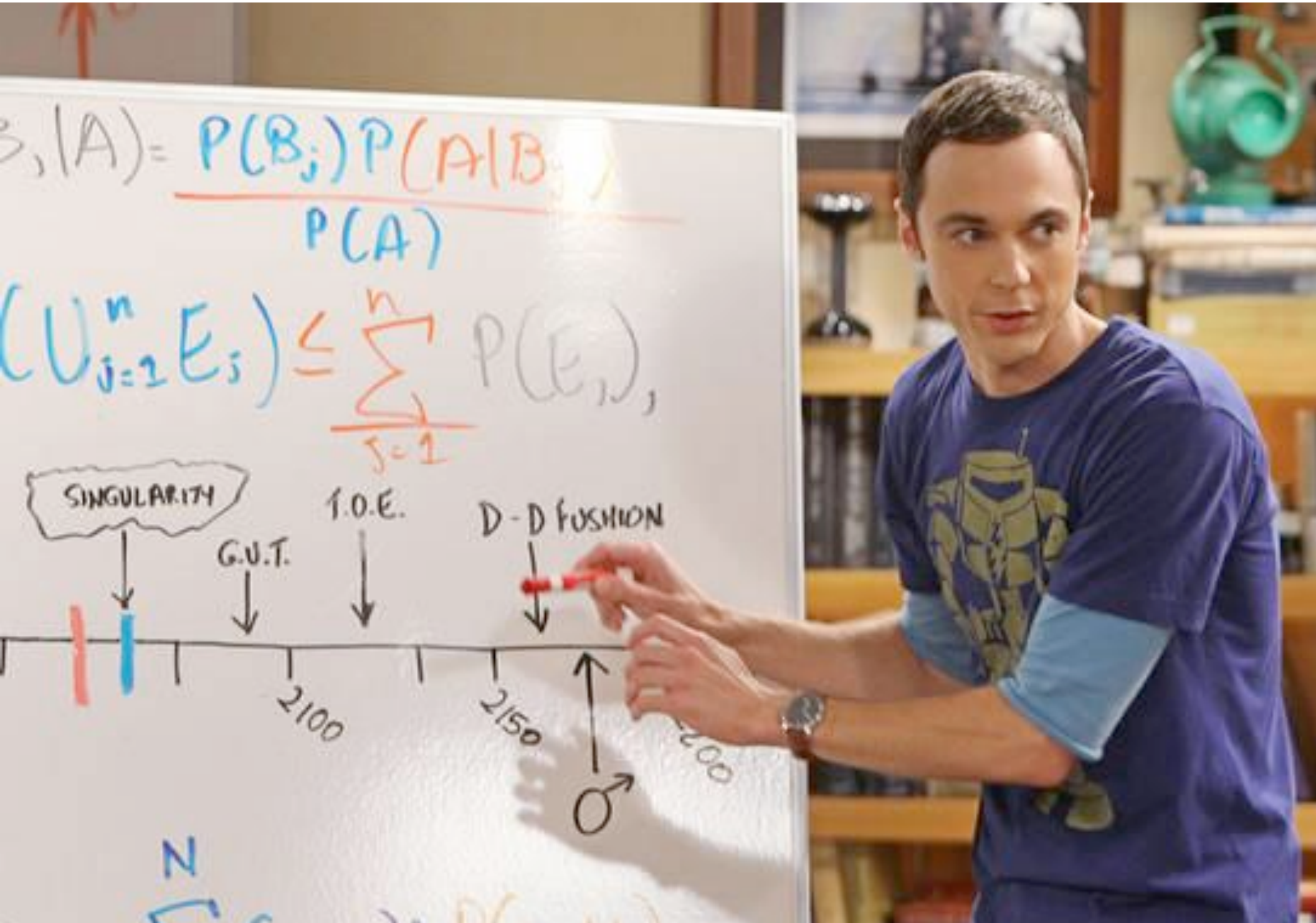
LHC Run 2 and beyond

- Run 2 at 13 TeV, Runs 3-5 at 14 TeV
- Expect 3000 fb^{-1} total

Let’s travel to the future

Let’s travel to the future

The world during LHC running



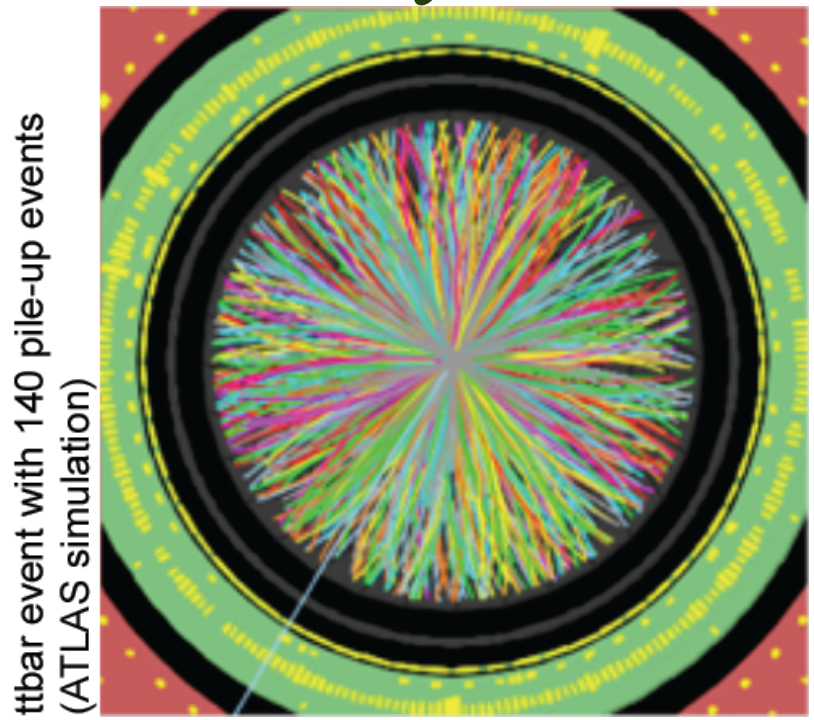
Collider theory calculations in a few years

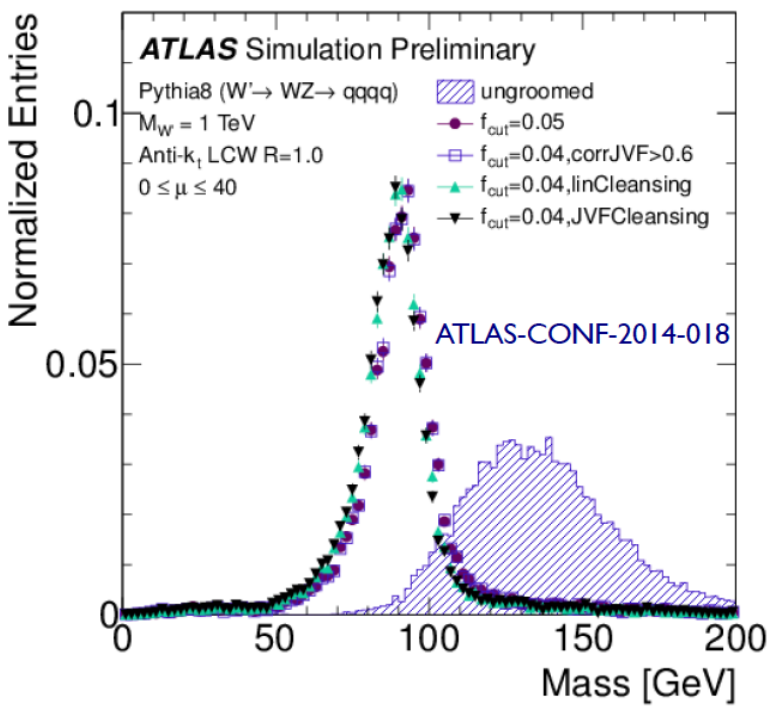
Process	Calculation
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+V$	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
VV'	$d\sigma$ @ NLO QCD + NLO EW
Z', W', VLQ	$d\sigma$(top decays) @ NLO QCD + NLO EW

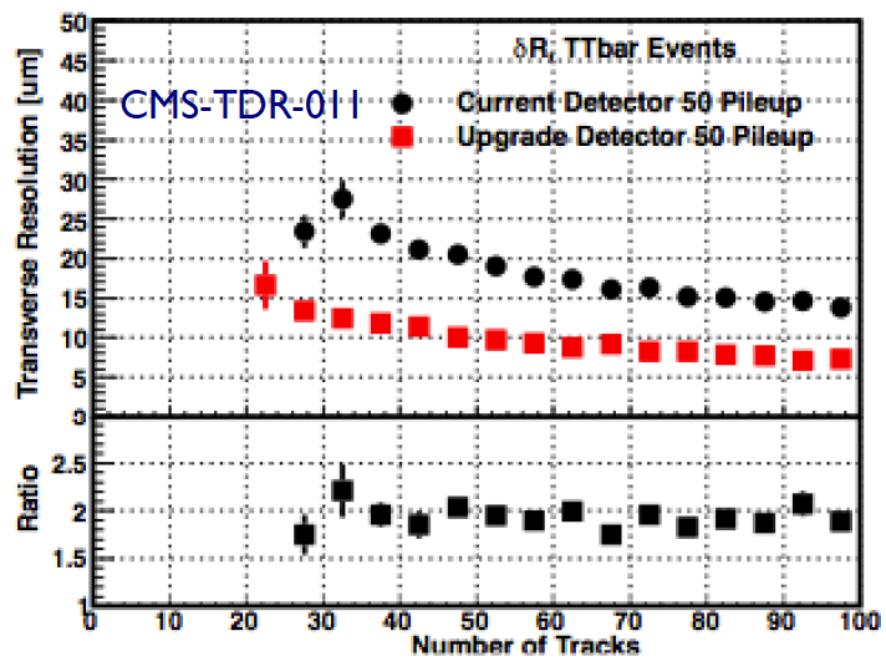
- Adapted from 2013 Les Houches wish list
  - Similar tables for other production modes for H, W, Z, top
- Expect to have predictions at ~1% level or better
- In ~10 years, expect to have automatic tools for NNLO QCD and NLO EW calculations
  - Including decays and off-shell particles

Detector challenges at high-luminosity LHC

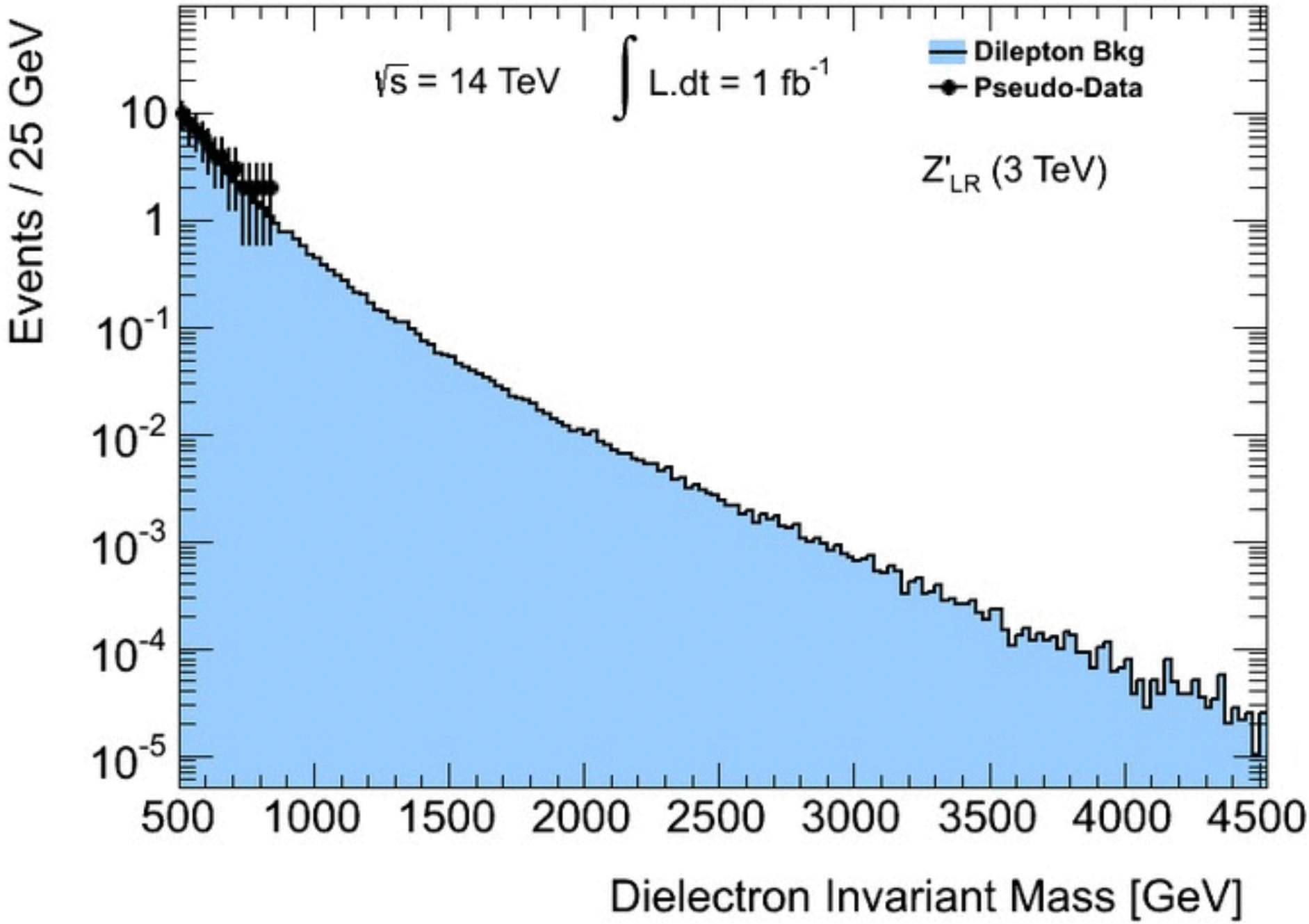
- 14 TeV p-p collisions
- Collect 3000 fb^{-1} total lumi
- $5*10^{34}$ $cm^{-2}sec^{-1}$ instantaneous lumi
- Pile-up of 140-200
- ATLAS and CMS upgrades:
  - New inner tracker
  - Replace electronics, upgrade DAQ
  - new/replace forward calorimeters



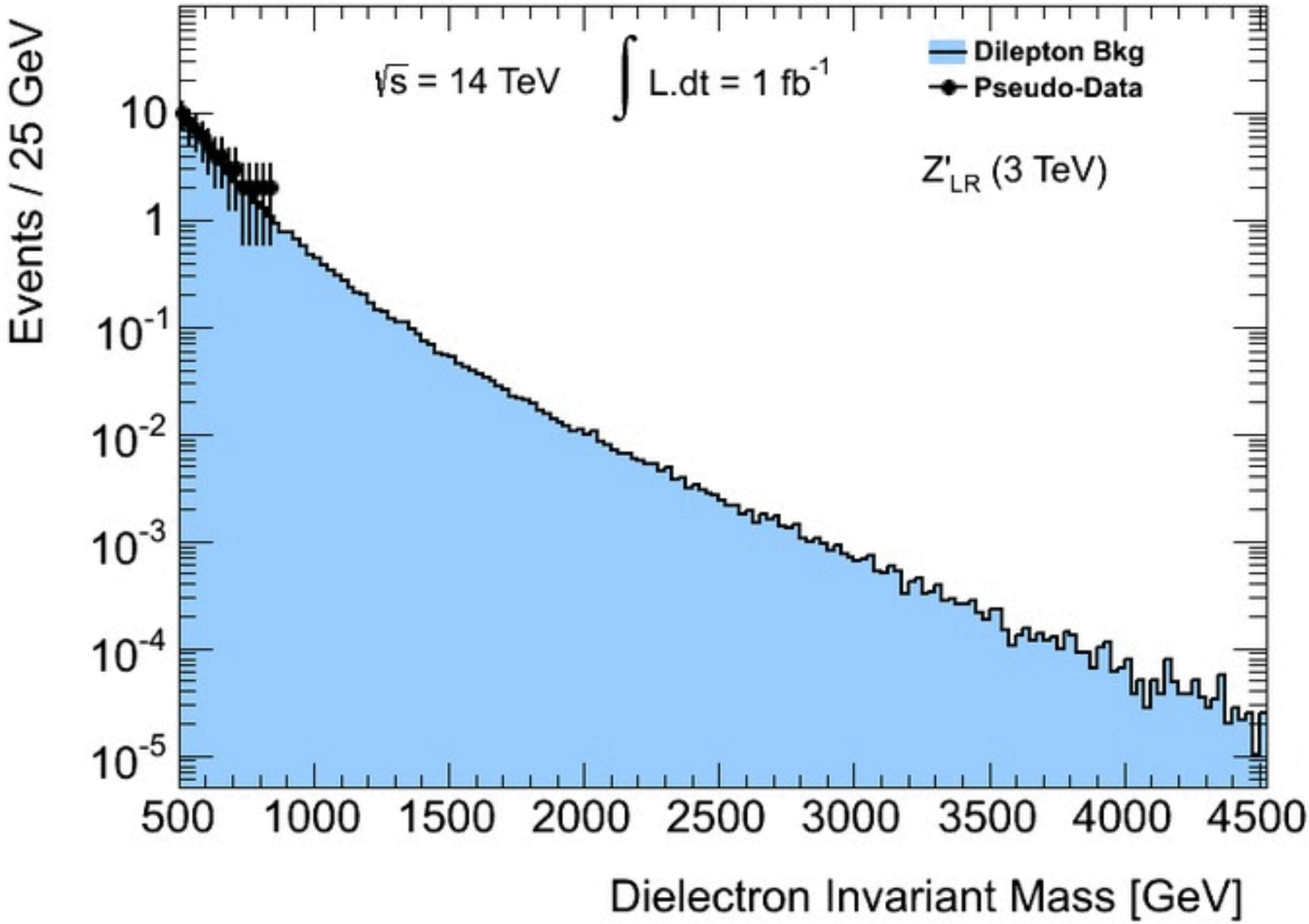




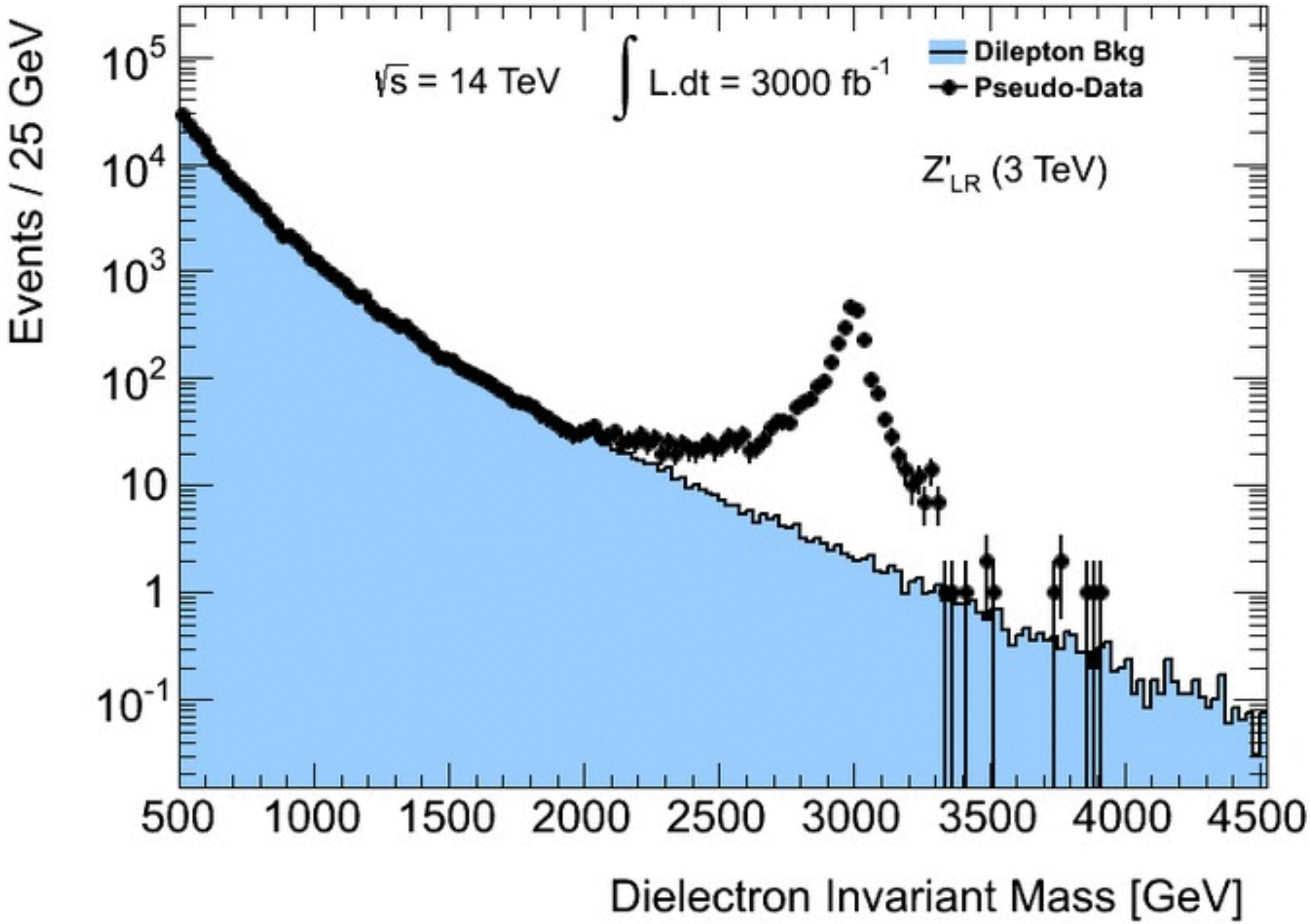
High-mass resonances



High-mass resonances



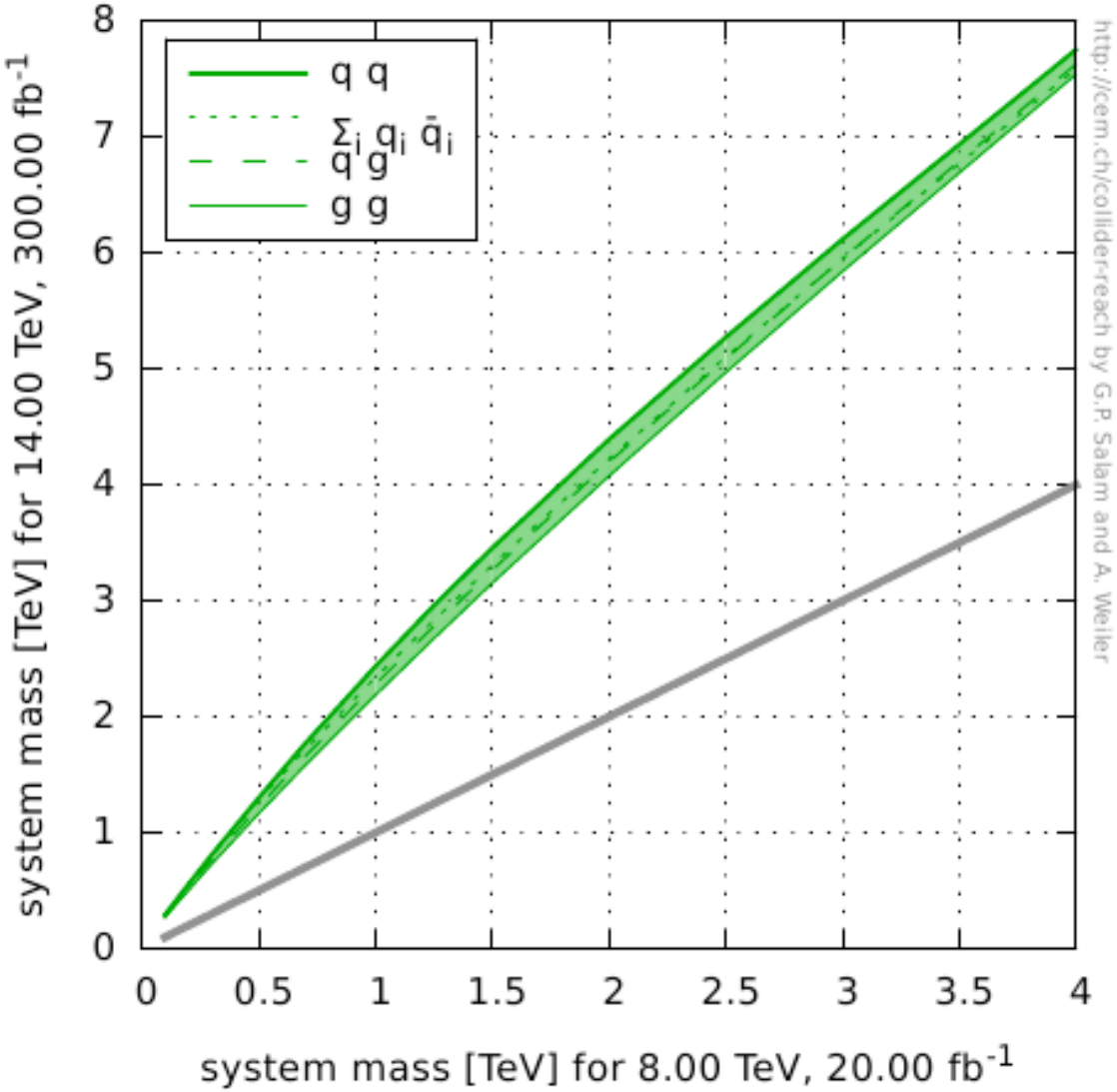
High-mass resonances



Resonance sensitivity Run 1 → HL-LHC

- For a given signal process and background, scale cross section and number of events -> sensitivity

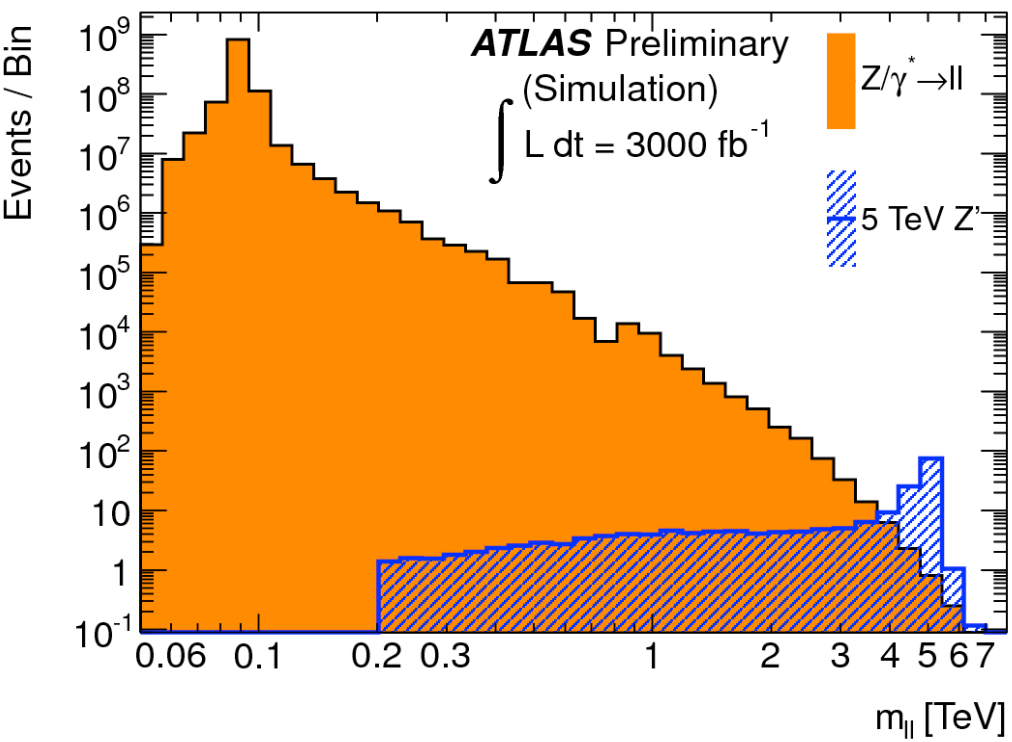
HL-LHC



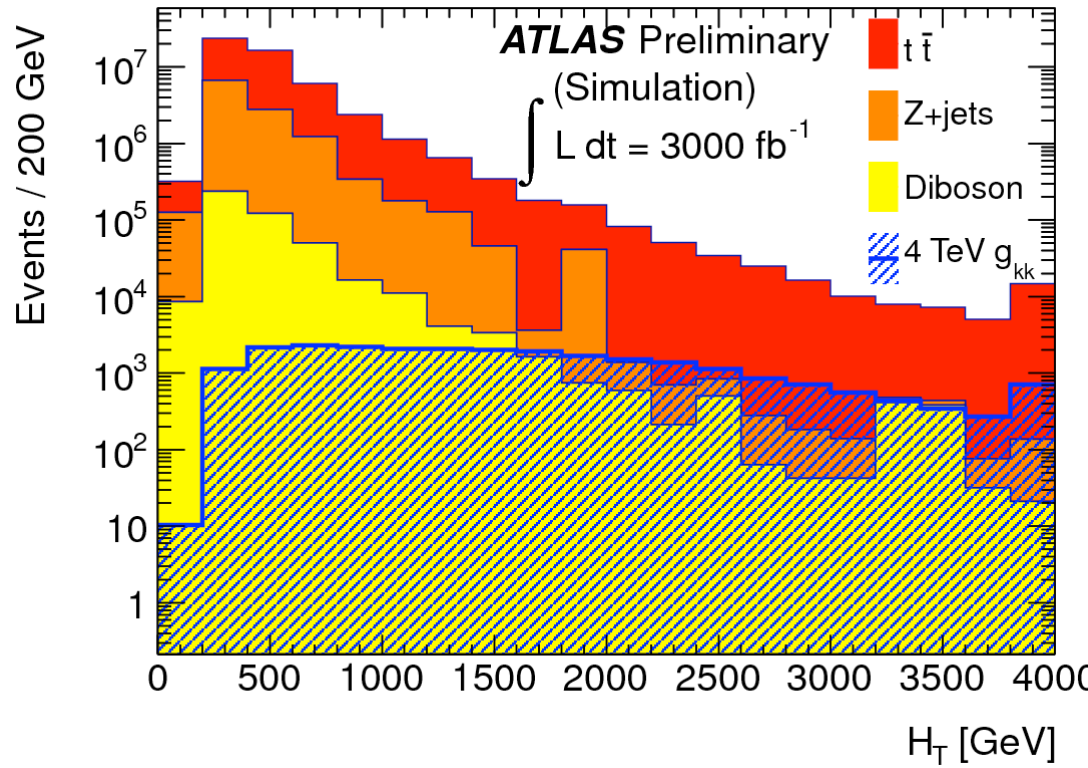
Run 1

High-mass resonances at HL-LHC

Dilepton
and ttbar in lepton+jets



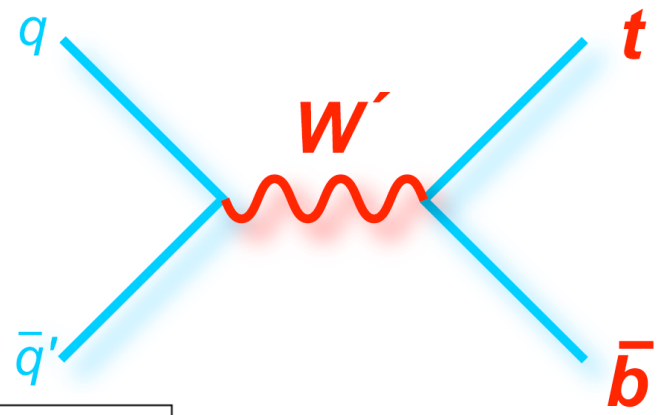
Top pair
in *ll*

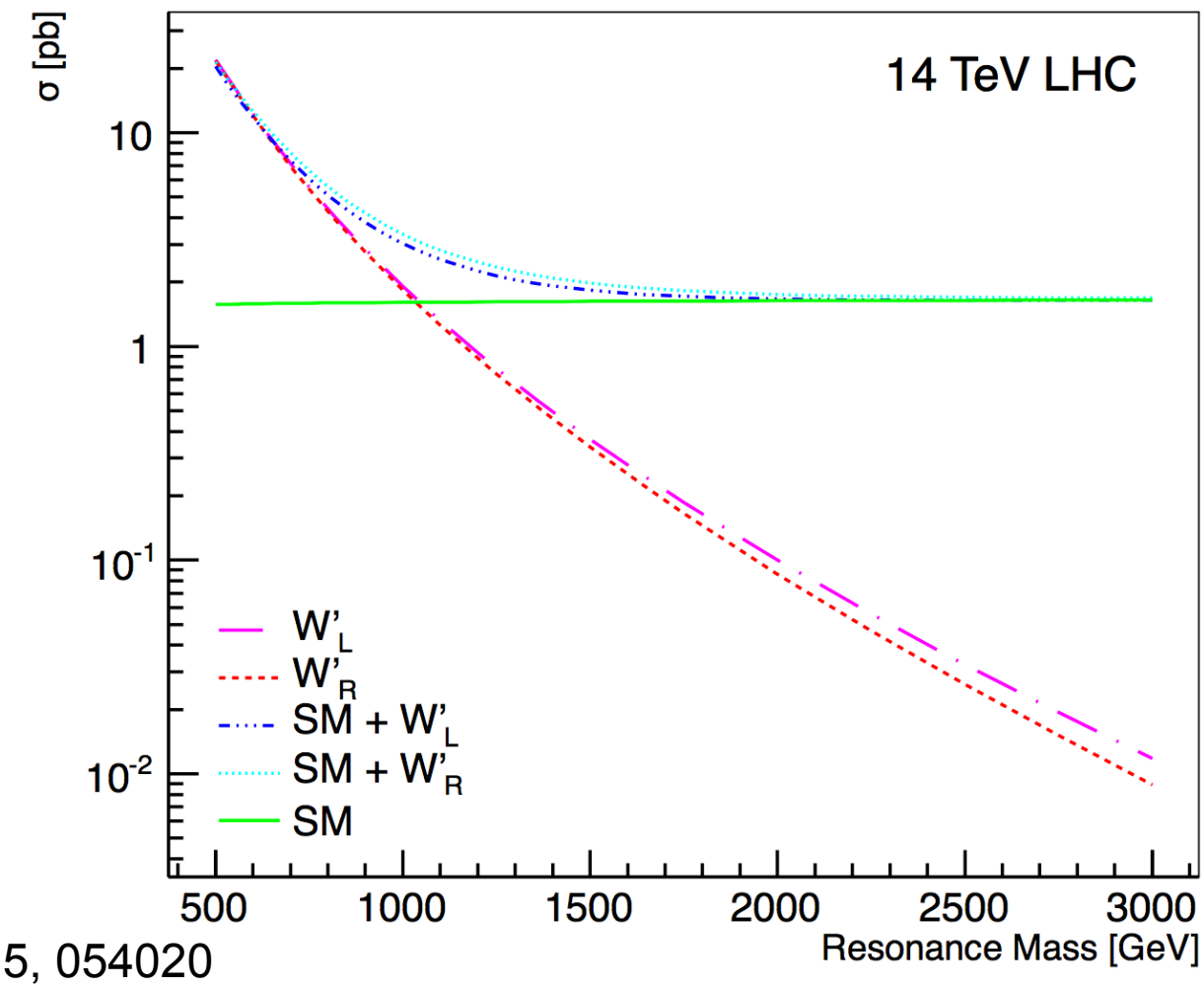


- Challenging to isolate NP signal even after observation
- Many off-shell NP particles

Resonances in single top production

- Weak production
  - W′
    - Left-handed or right-handed couplings
    - Different cross-sections at high masses





PRD91 (2015) 5, 054020

Resonances in single top production

- Weak production
  - W′
    - Left-handed or right-handed couplings
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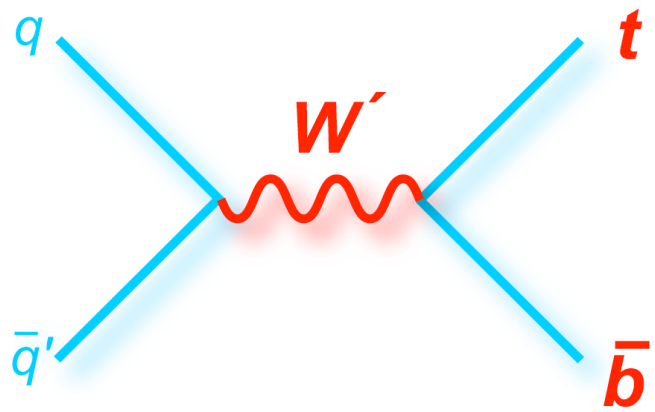

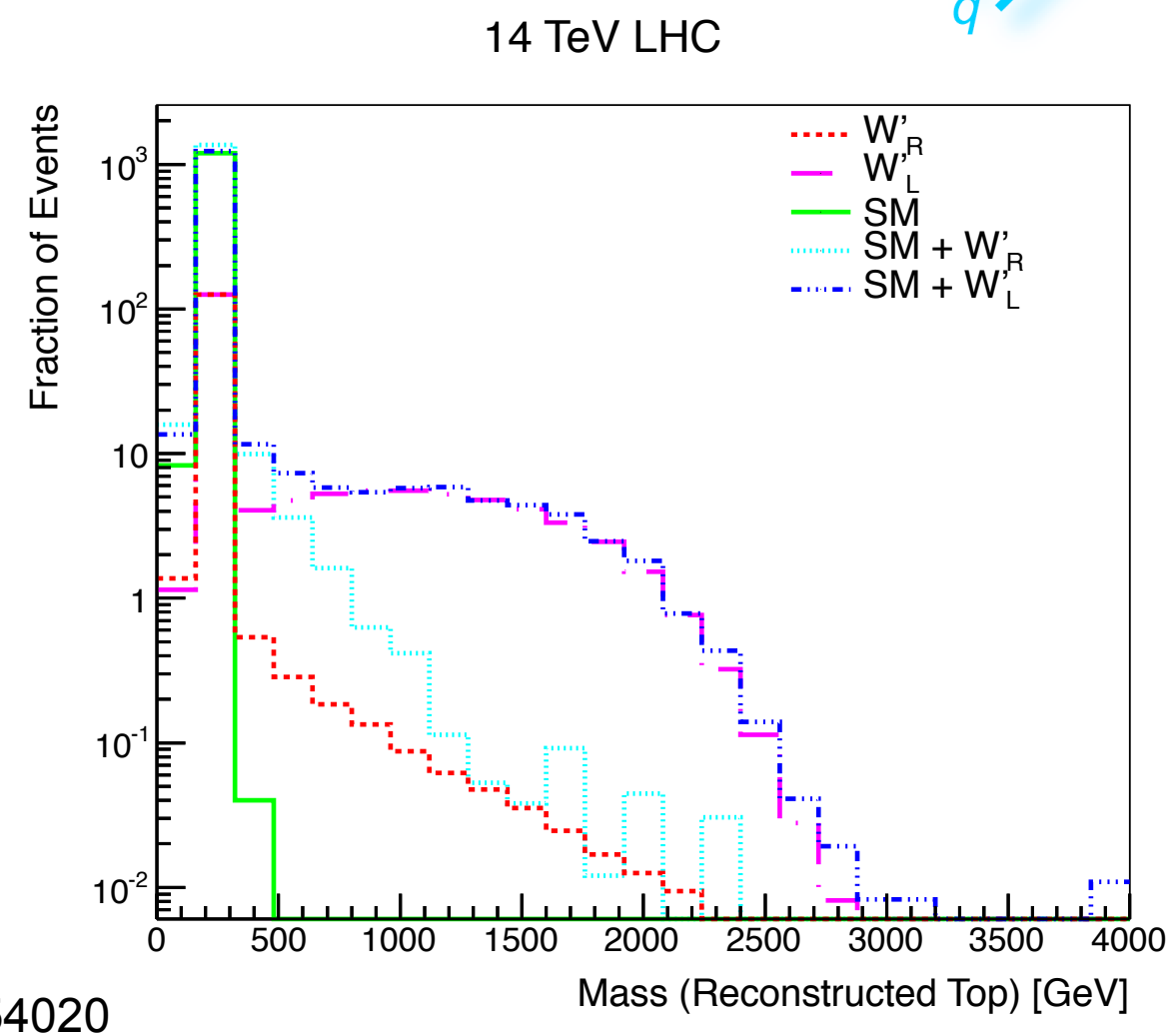

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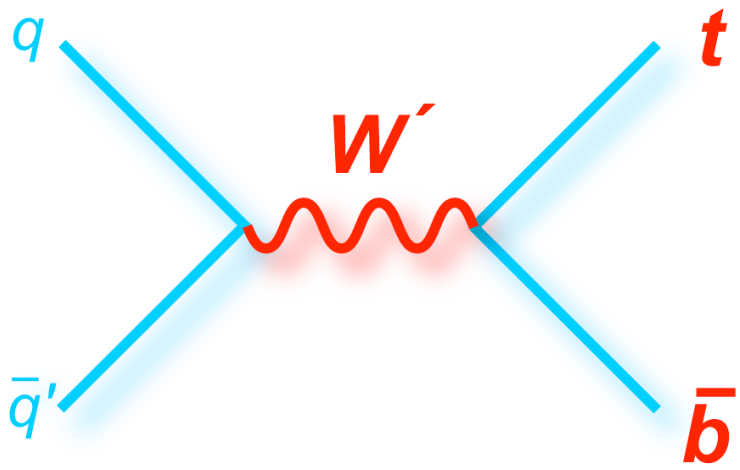
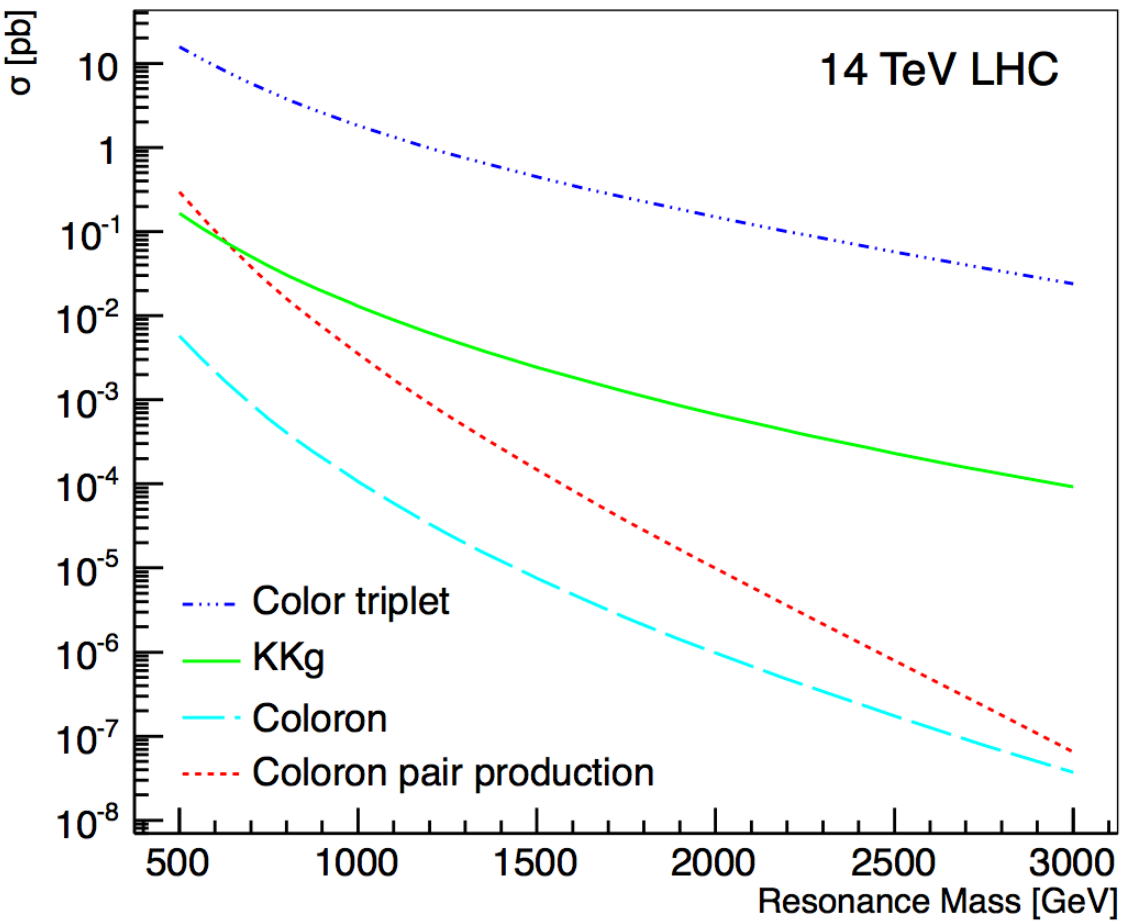
Resonances in single top production

- Weak production
  - W′
    - Left-handed or right-handed couplings
    - Different cross-sections at high masses
  - Charged Higgs boson to tb
  - Z′ with FCNC decay to tc



Resonances in single top production

- Strong production
  - Color triplet to tb
  - KKg to tc
  - Coloron to tc



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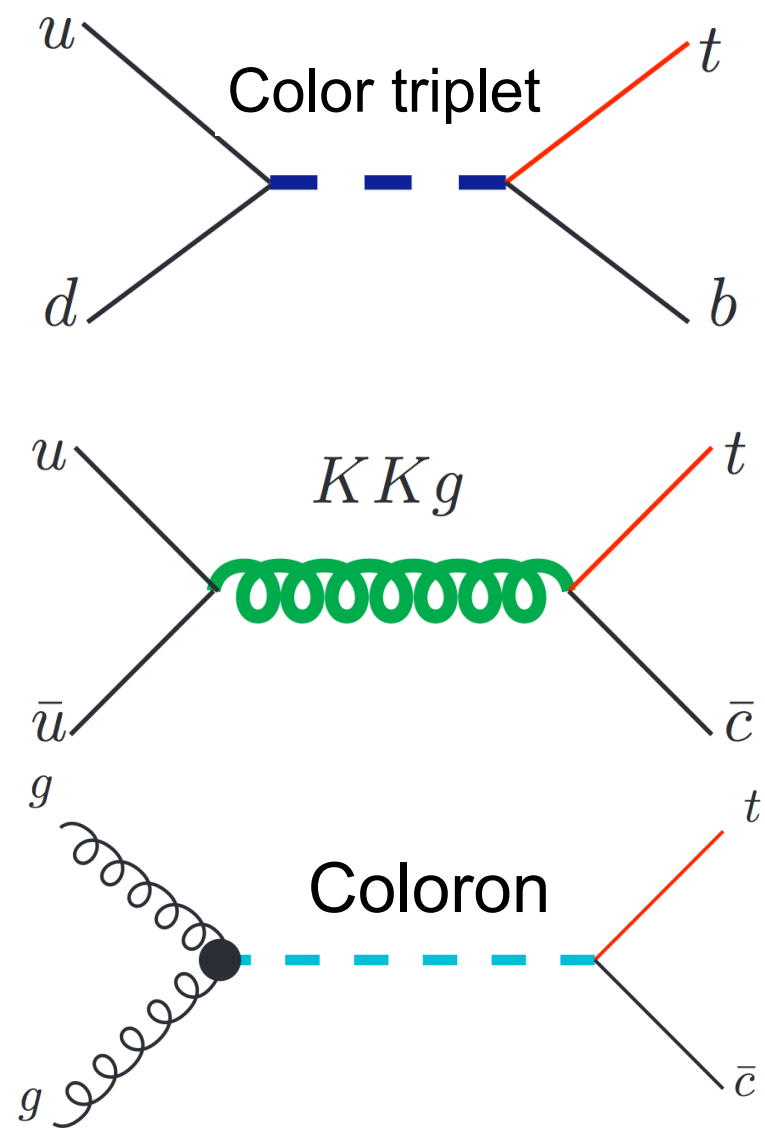
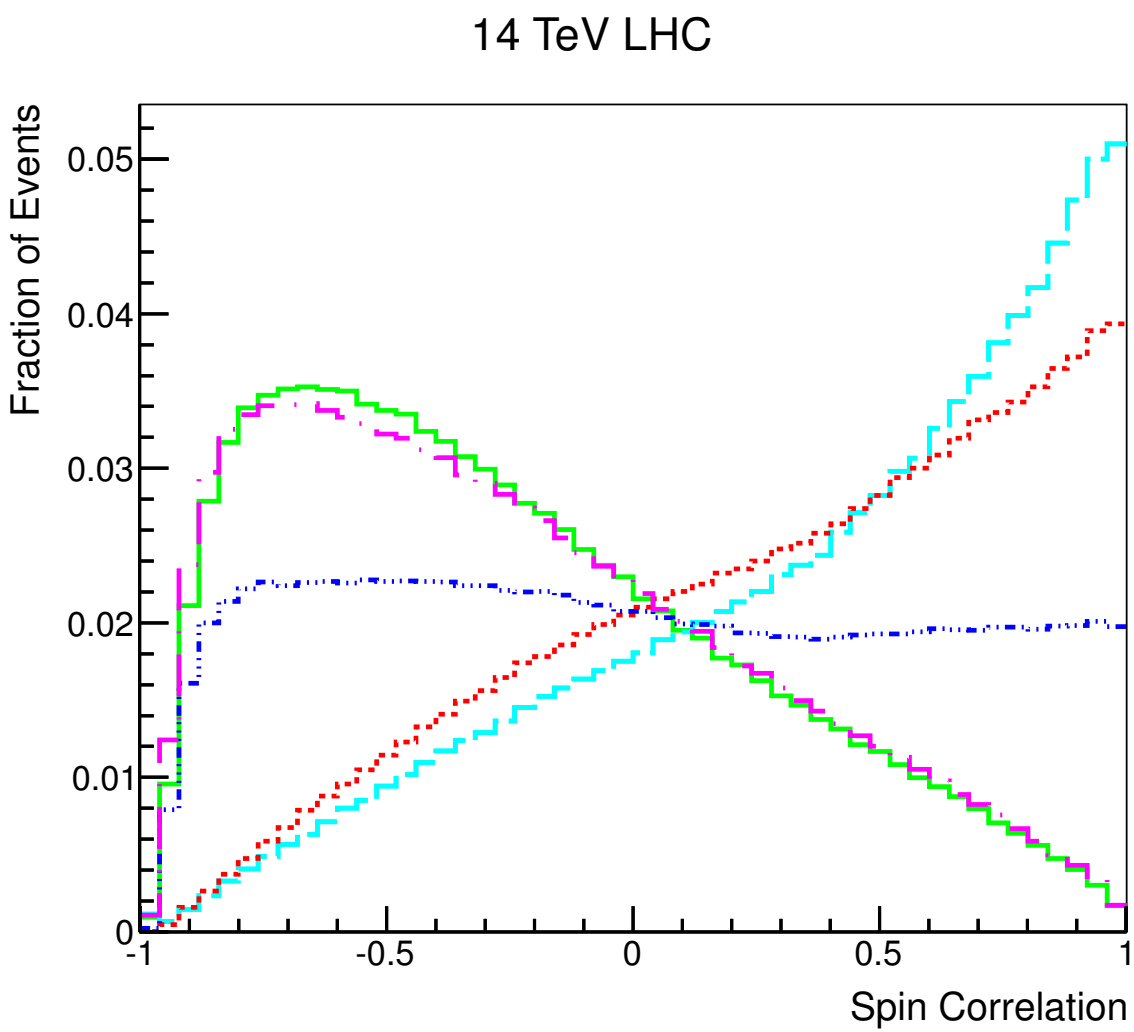
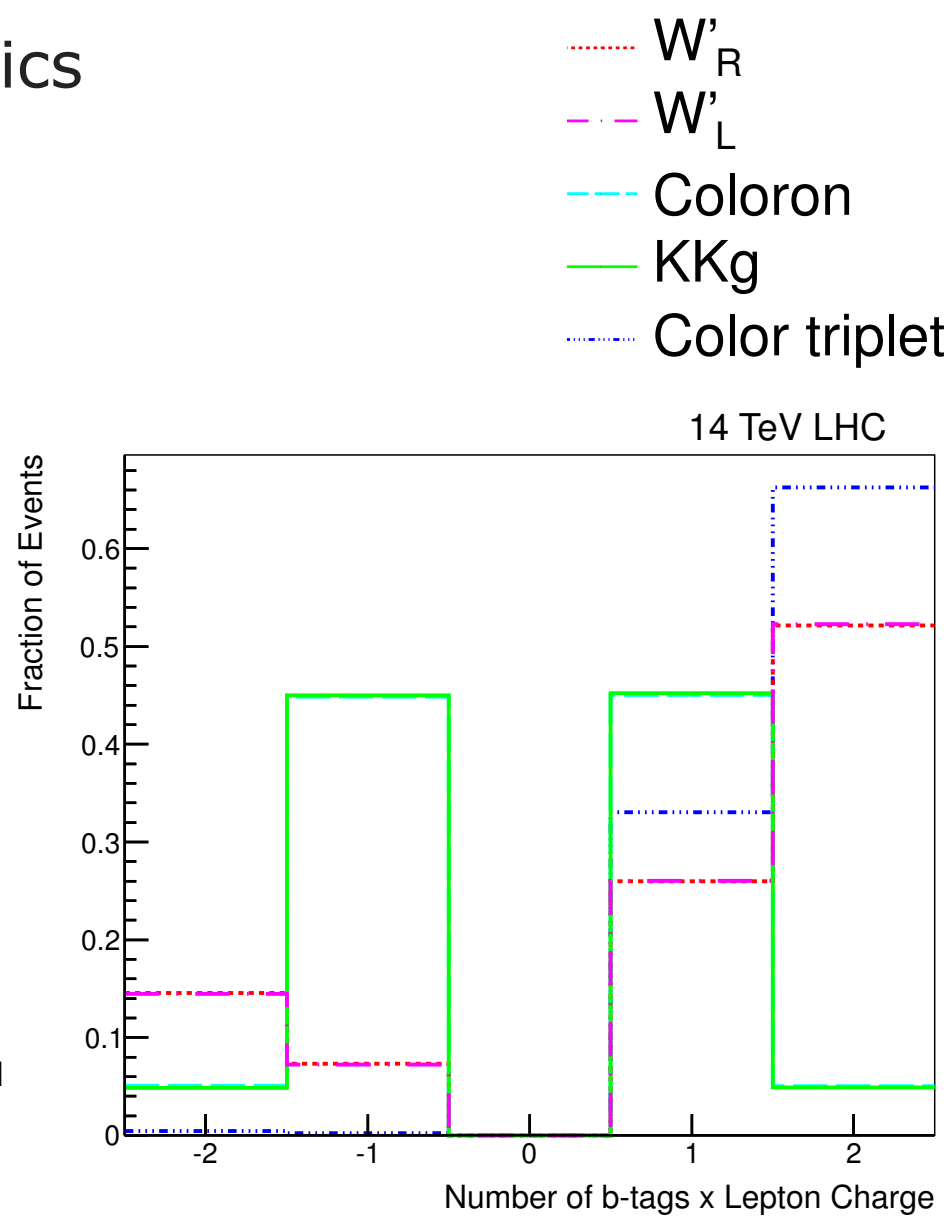


Post-observation measurements: Distinguishing new physics models

- Measurements of event kinematics





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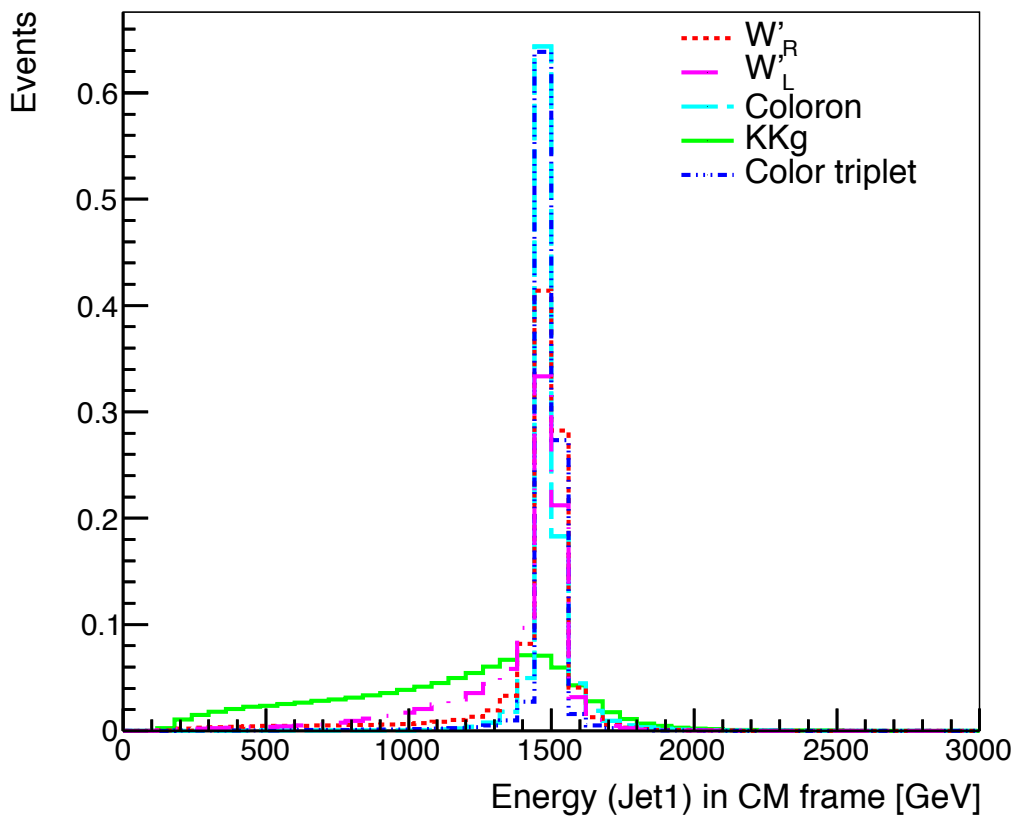
3 TeV resonance

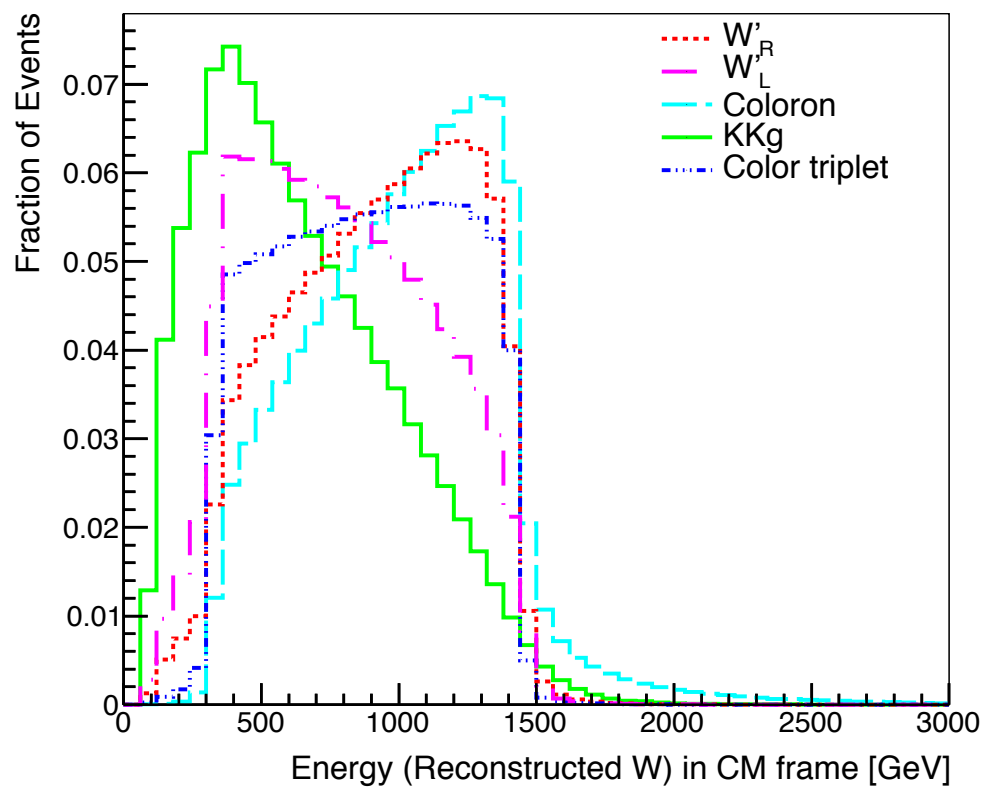
Distinguishing tq resonances

- Reconstruct W boson and top quark (hadronic or leptonic)
- Boost into CM frame

3 TeV resonance

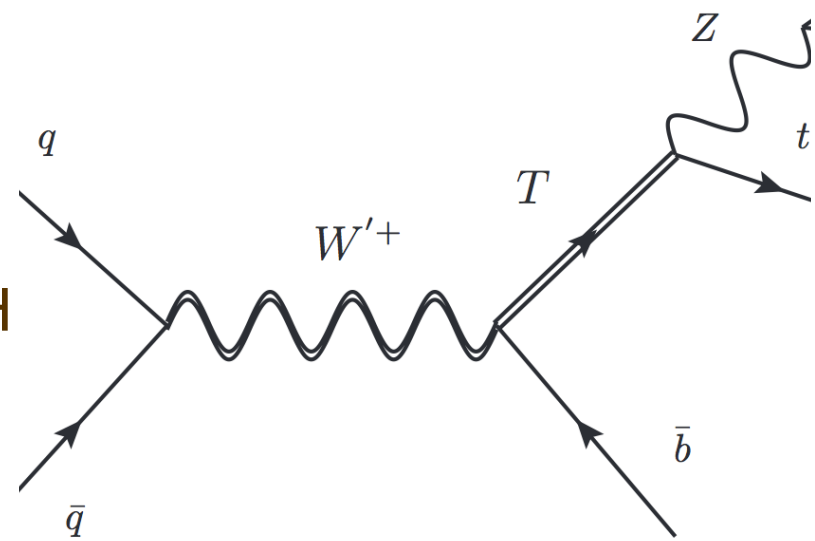


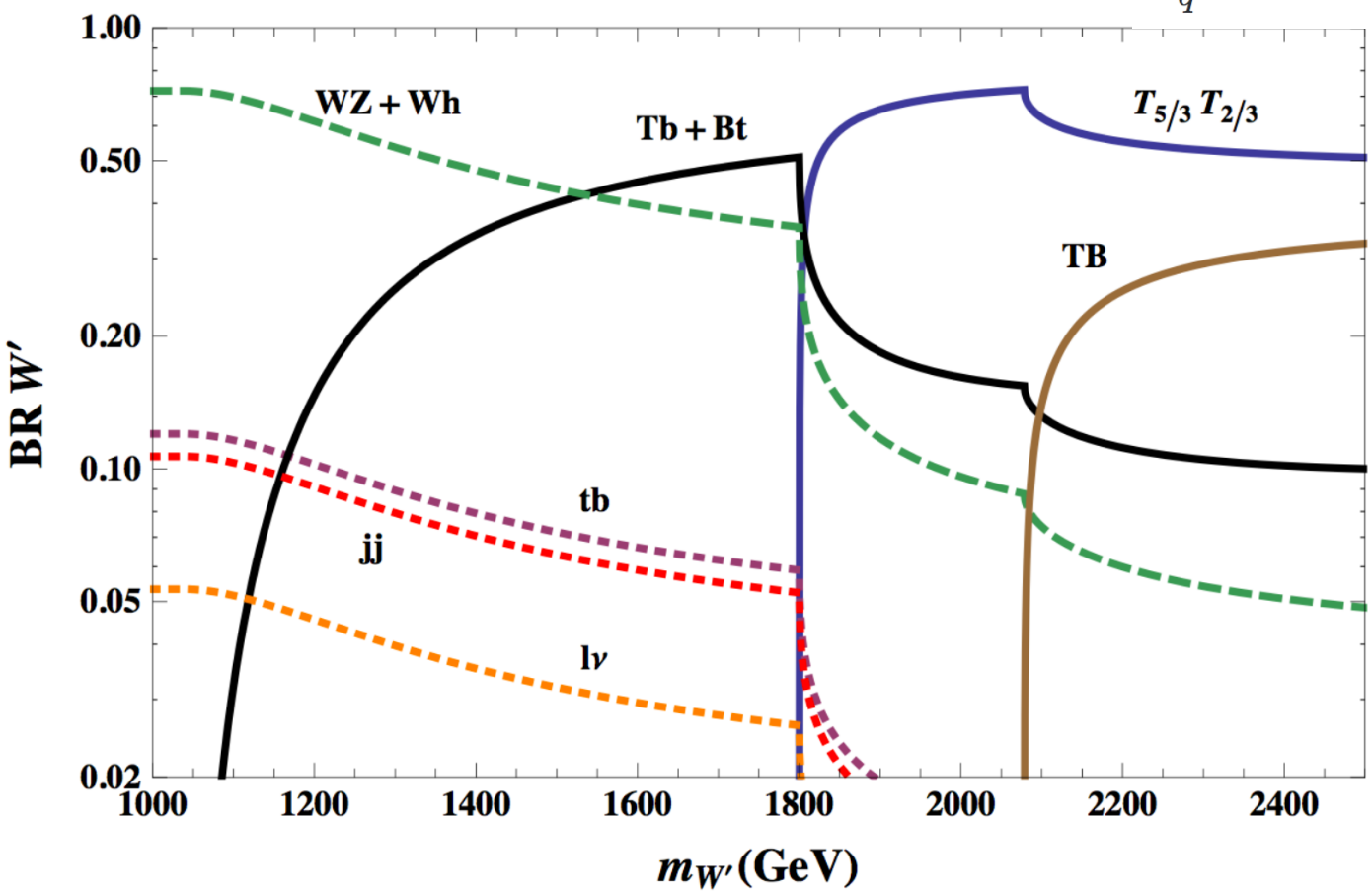
14 TeV LHC



Other W' decay modes

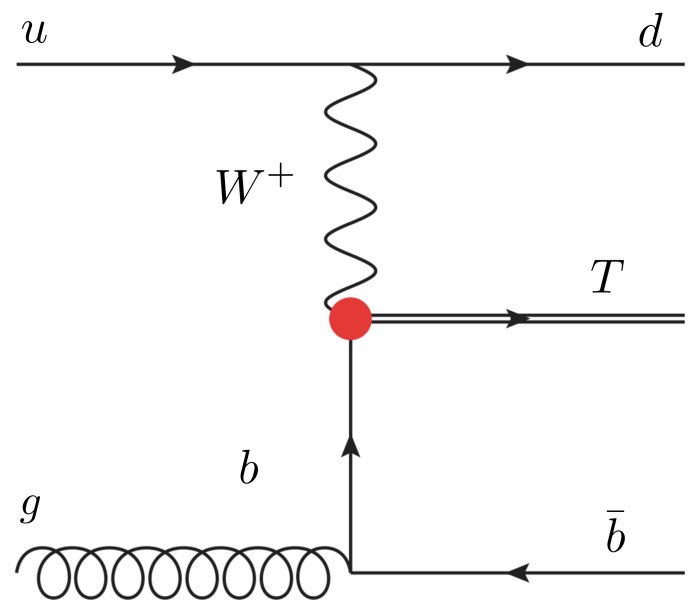
- Decay modes in a composite Higgs model
- Include decays to top partners
  - Final states tbZ, tbH, ttW, ttWZ, ttWH

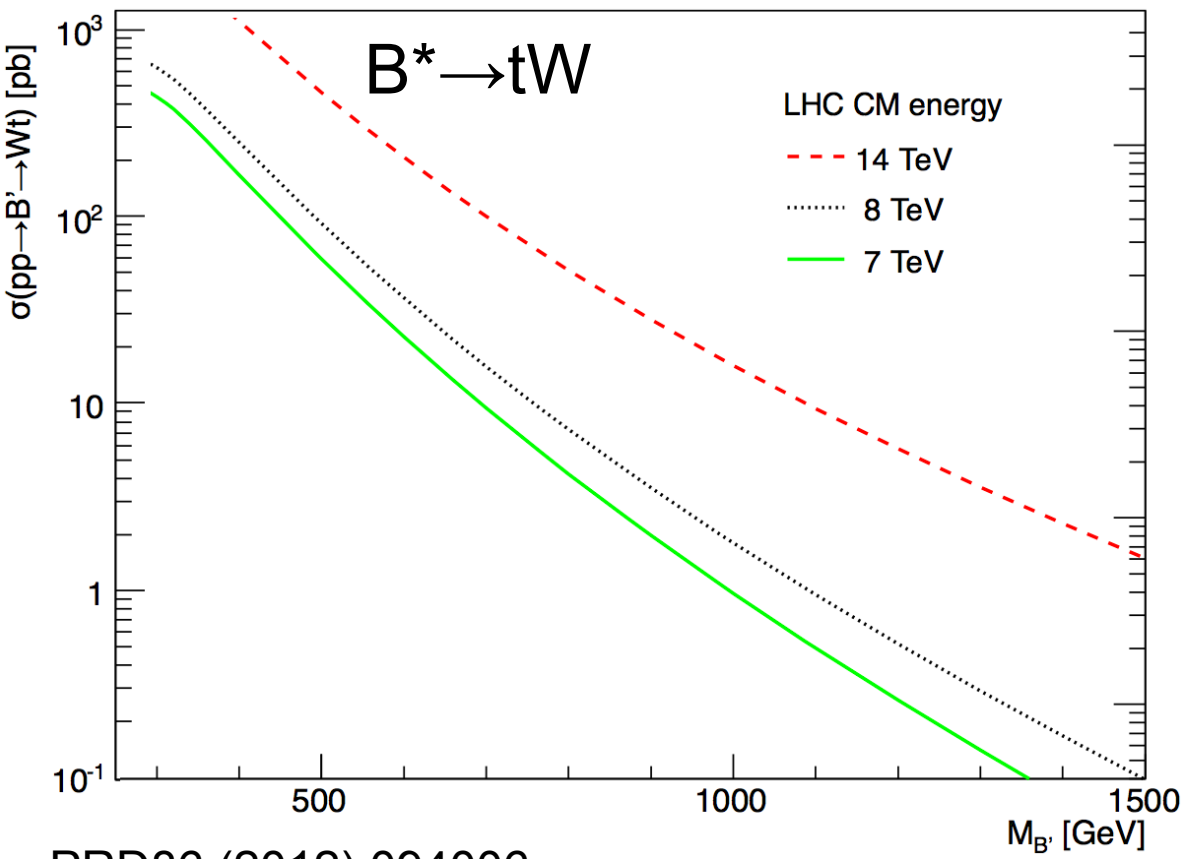




Other resonances in single top production

- Wt, Zt, Ht final states
  - VLQ T→tZ, tH and B→tW
  - Excited quark B*→tW, T*T*→tgtg





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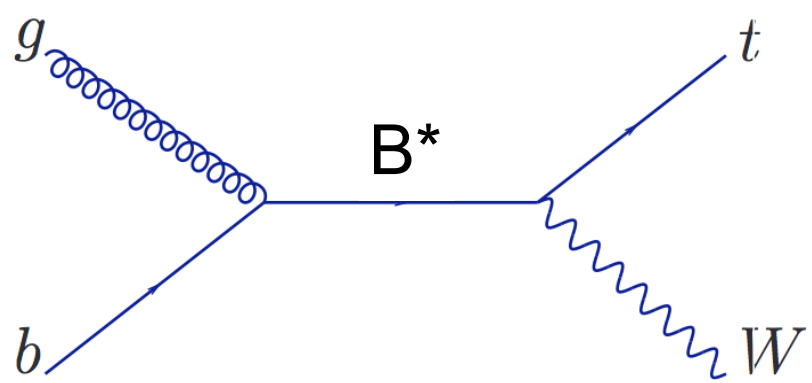
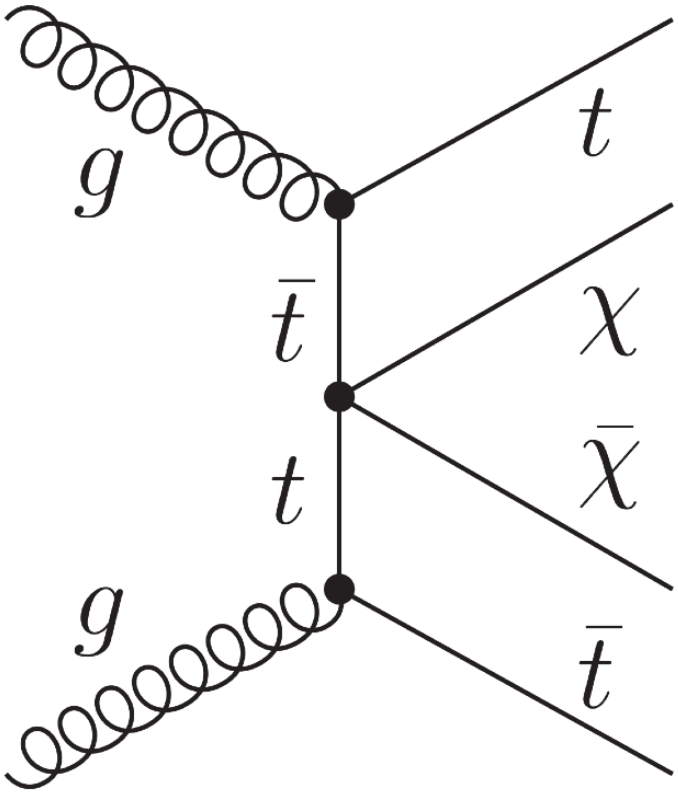
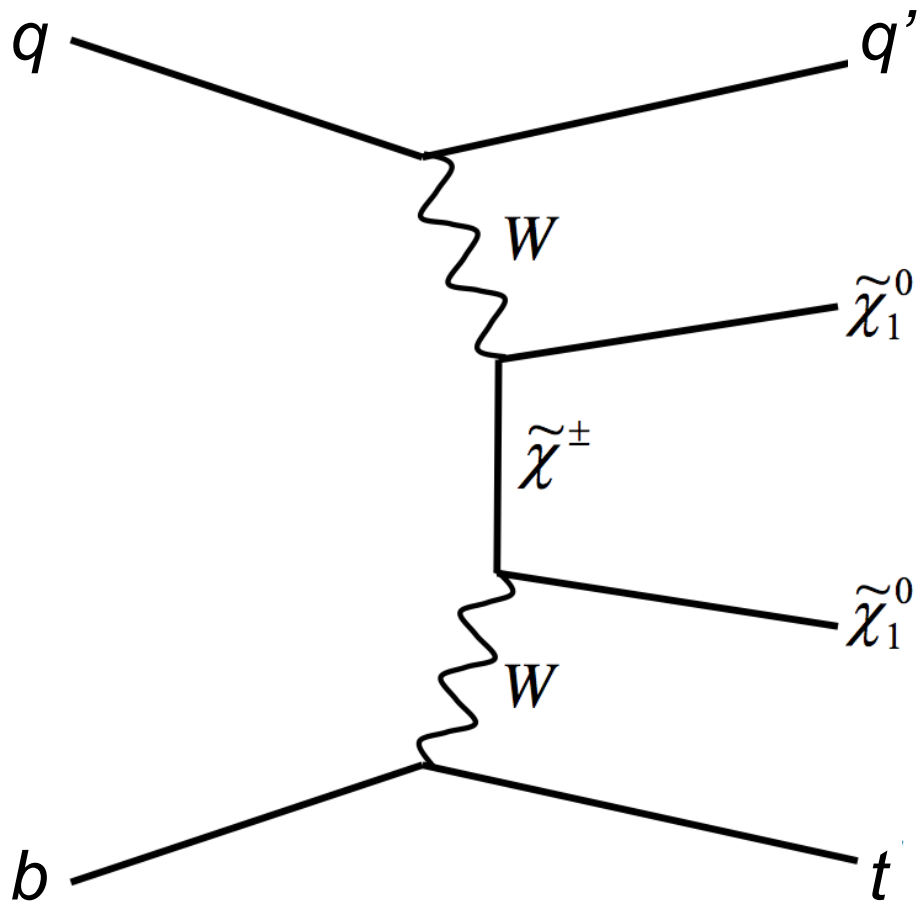


Top and dark matter

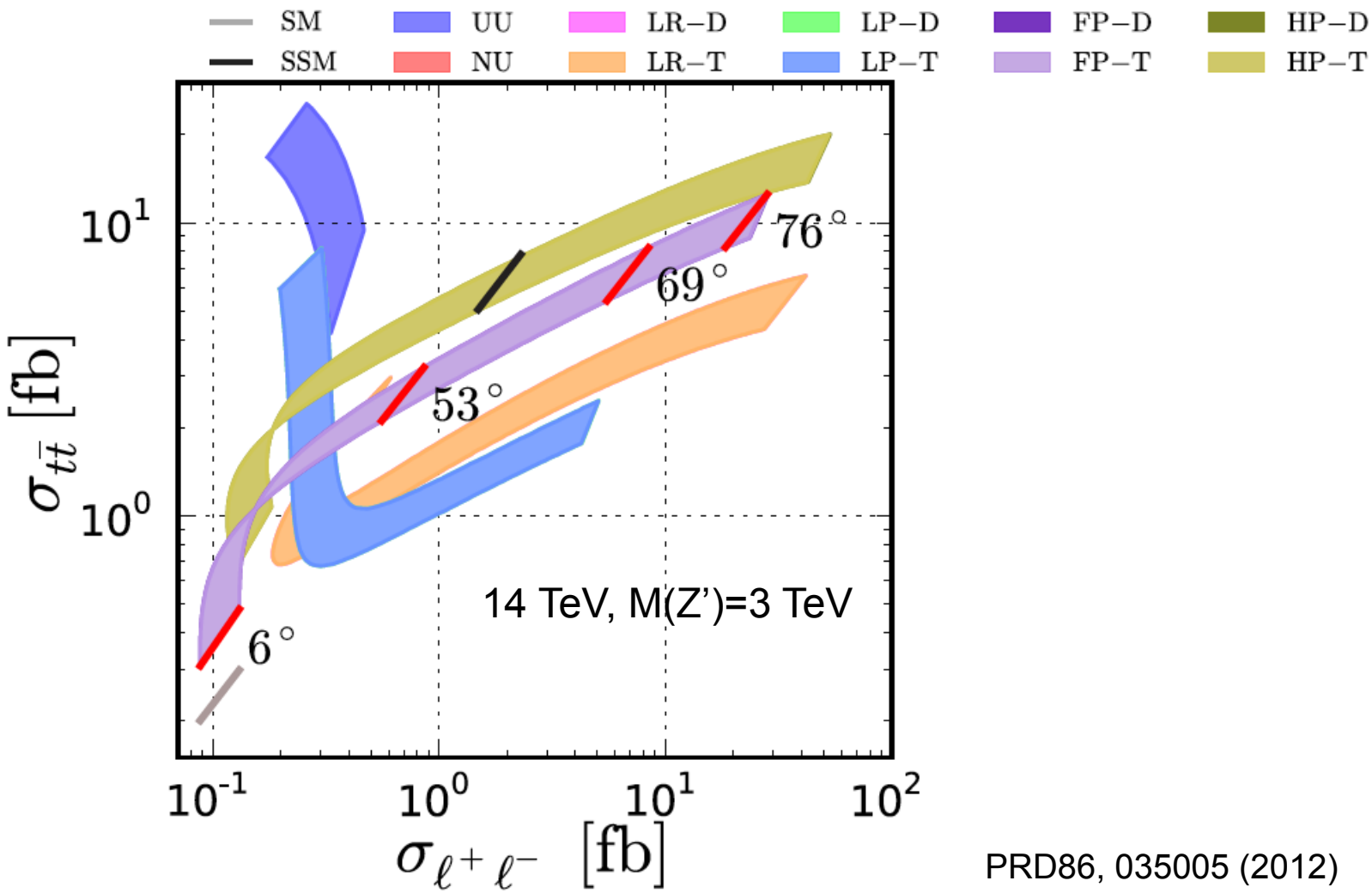
- Run 2 will be sensitive to dark matter coupling to top
- And to W and Z and H





Post-observation measurements: Distinguishing new physics models

- Measurements in multiple final states



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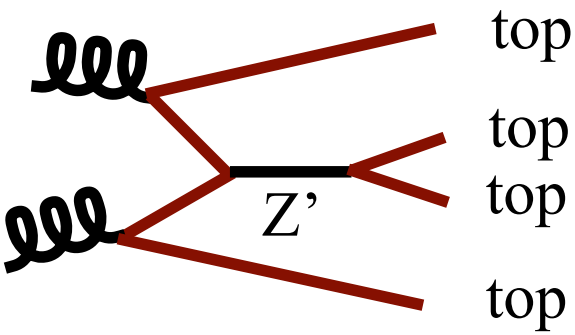
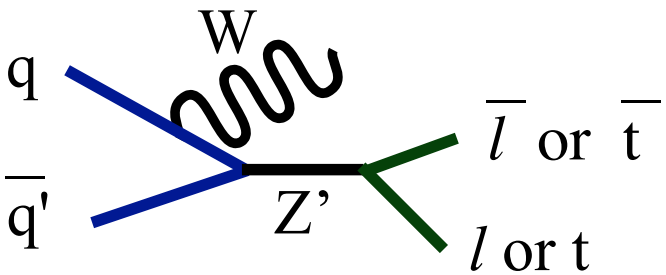
Distinguishing models in associated production

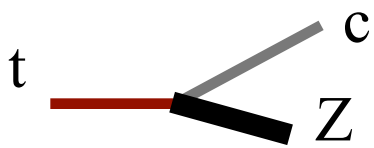


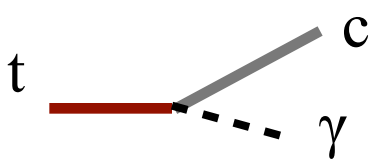


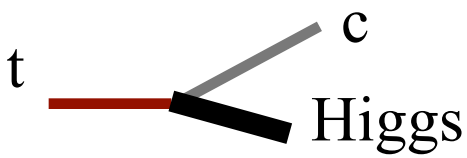
- Determine Z' coupling
  - Flavor-dependence
  - helicity dependence
- Discriminate different new physics models
  - Z' vs W' vs Dark matter coupling
  - Other NP intermediate particles

Rare top decays

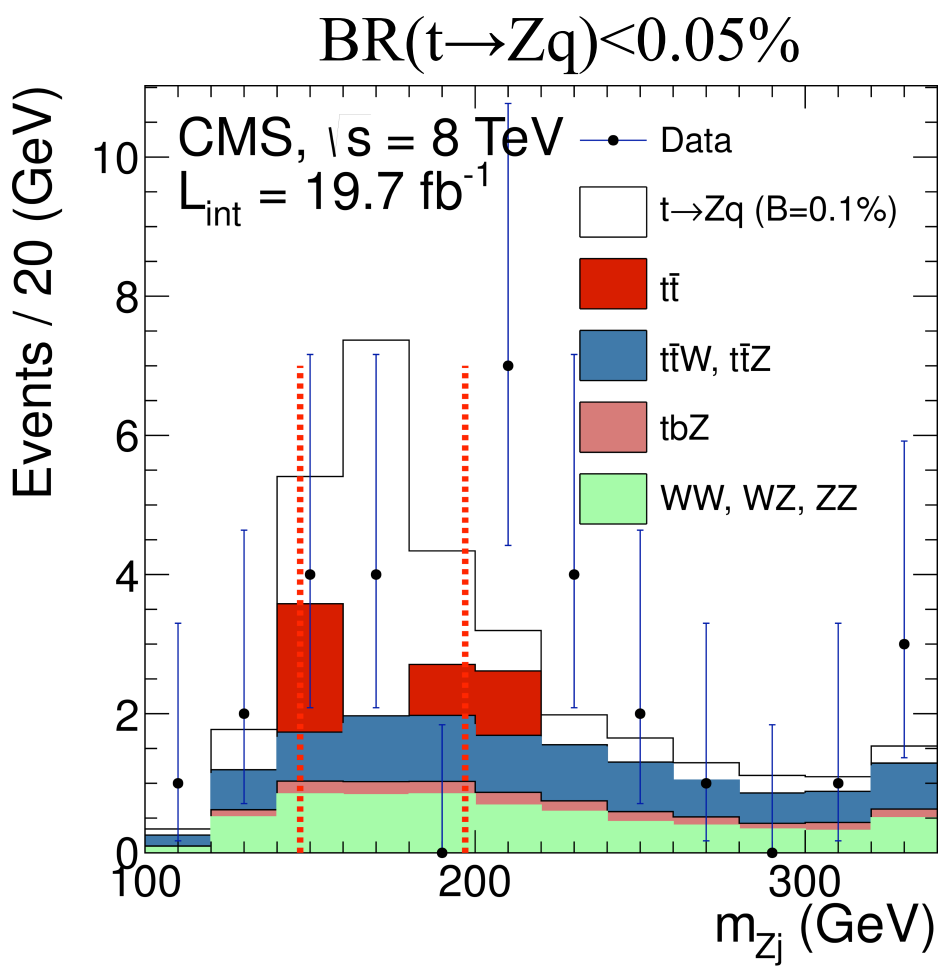
- Exotic decays?





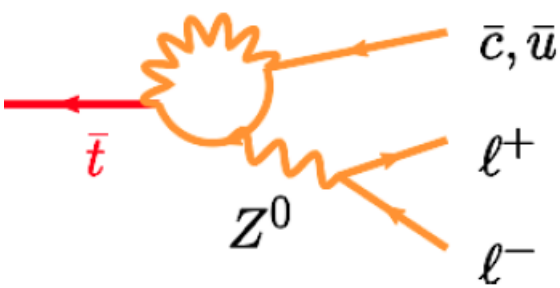


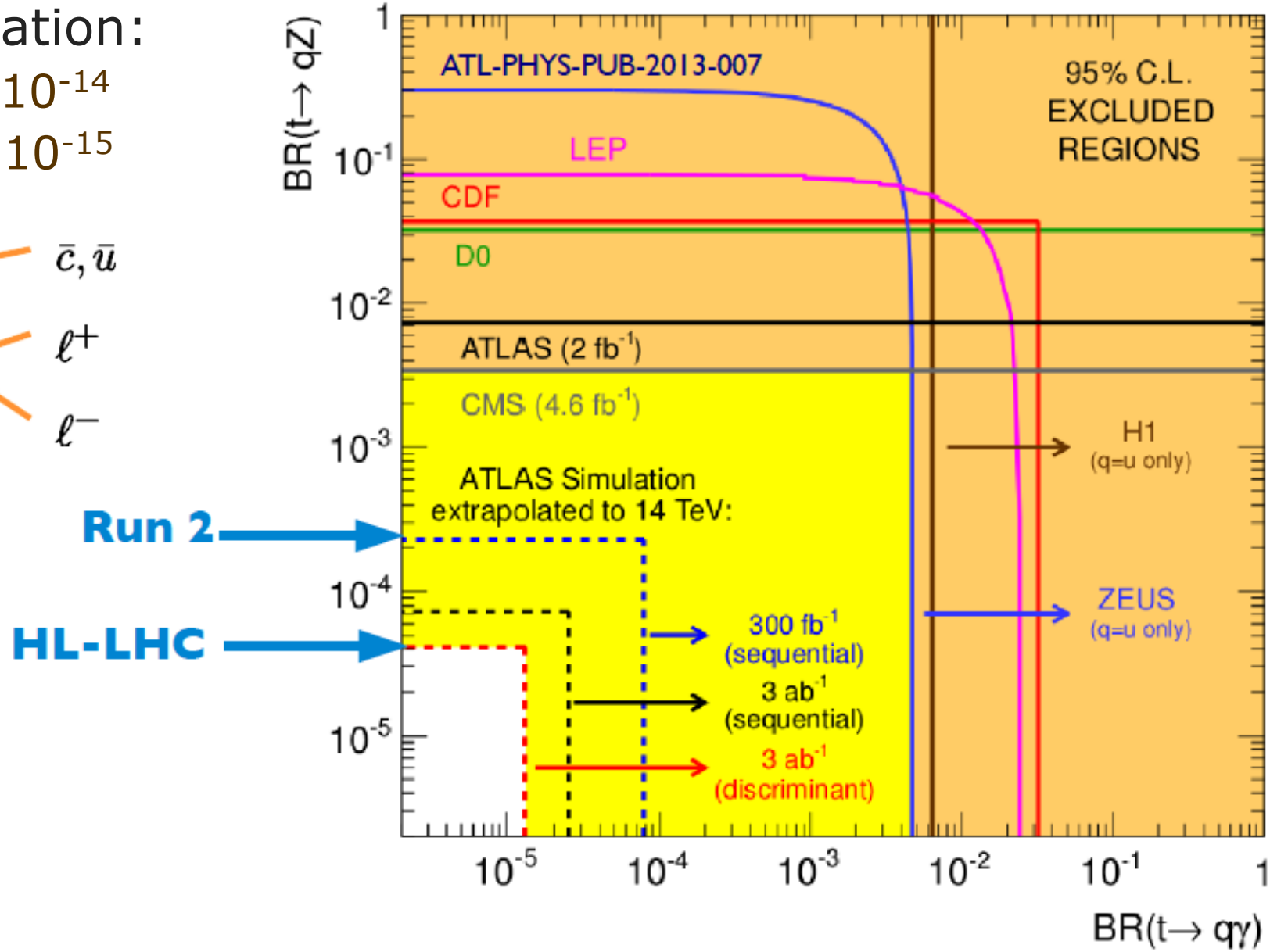
- What sensitivity can be reached at hadron and lepton colliders?
- Study rare processes in top production and decay
- CP violation in top sector?



Rare top quark decays

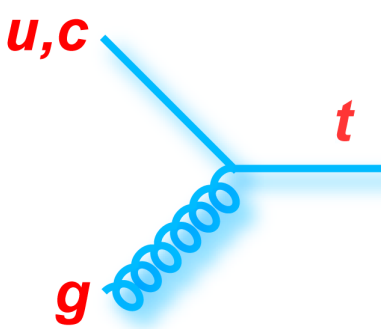
- FCNC in top, Higgs, Z
  - NP loops give ~ 10^{-5} BRs
- SM expectation:
  - $t \to Zc \sim 10^{-14}$
  - $t \to Hc \sim 10^{-15}$

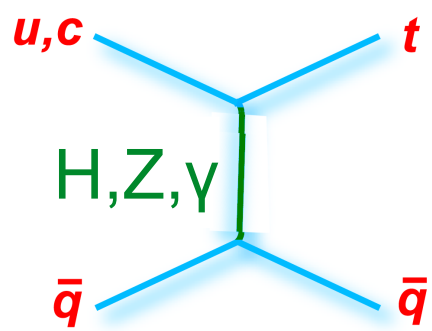


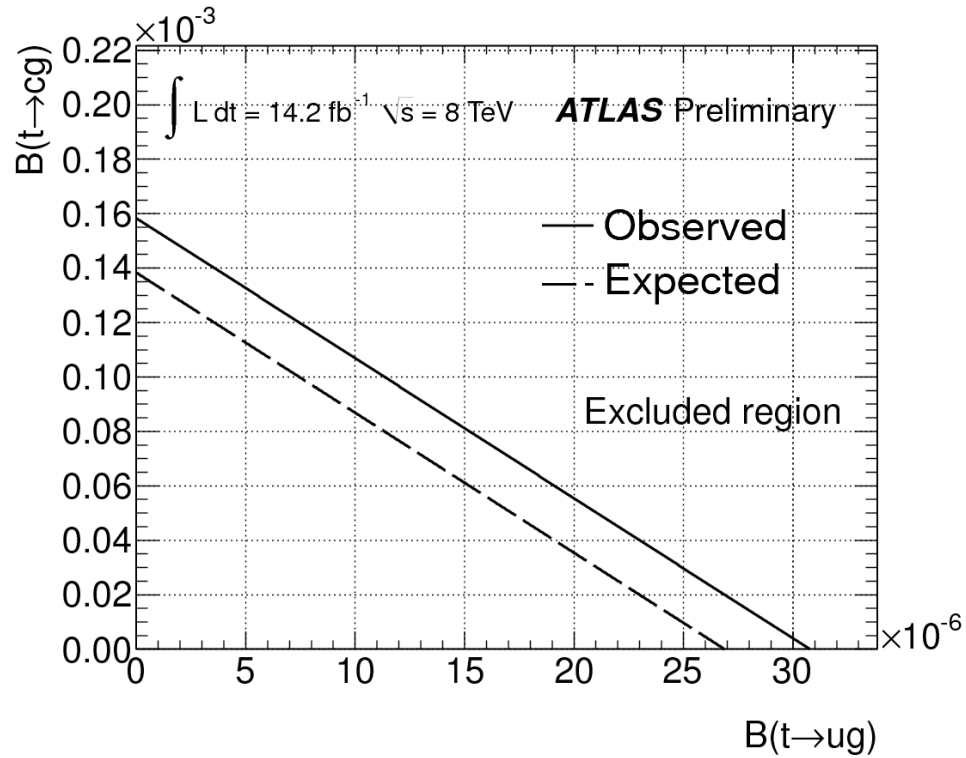


Flavor-changing neutral currents

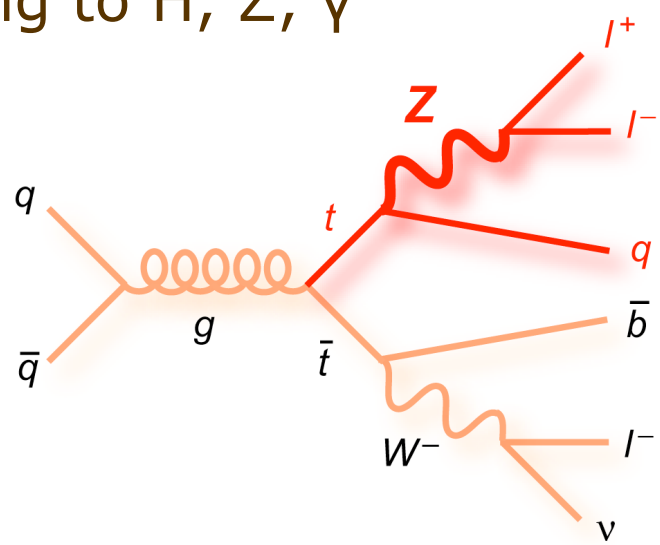
- In top production
  - Single top
  - FCNC coupling to gluon, H, Z





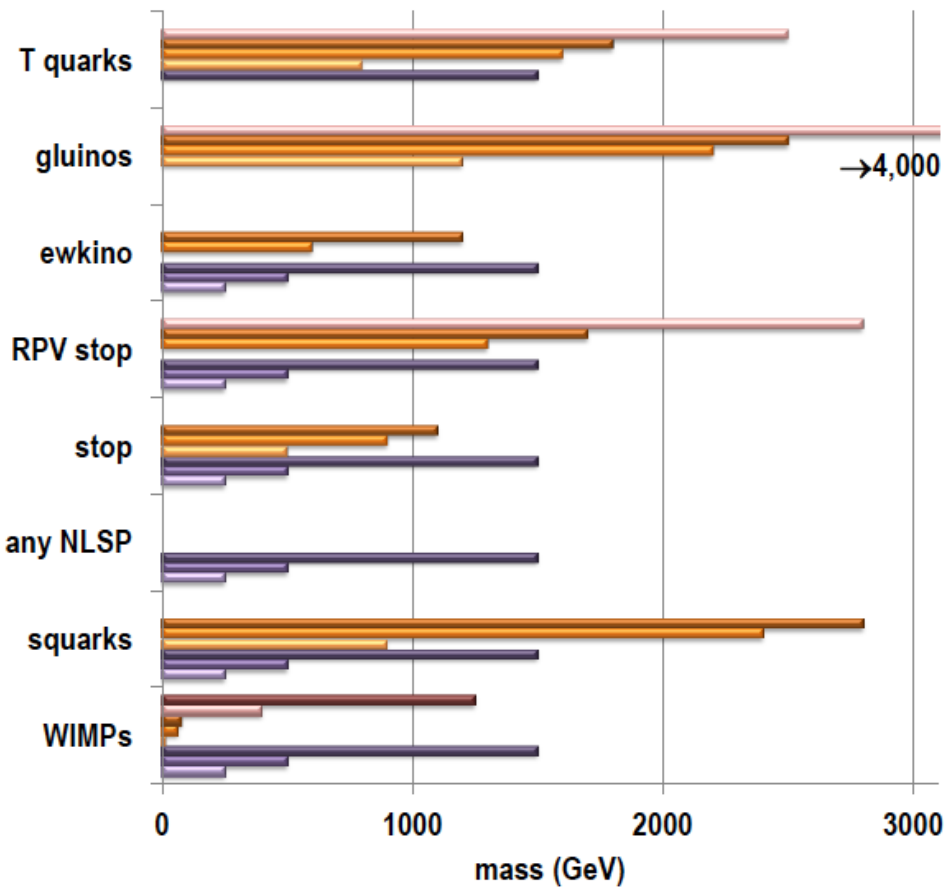


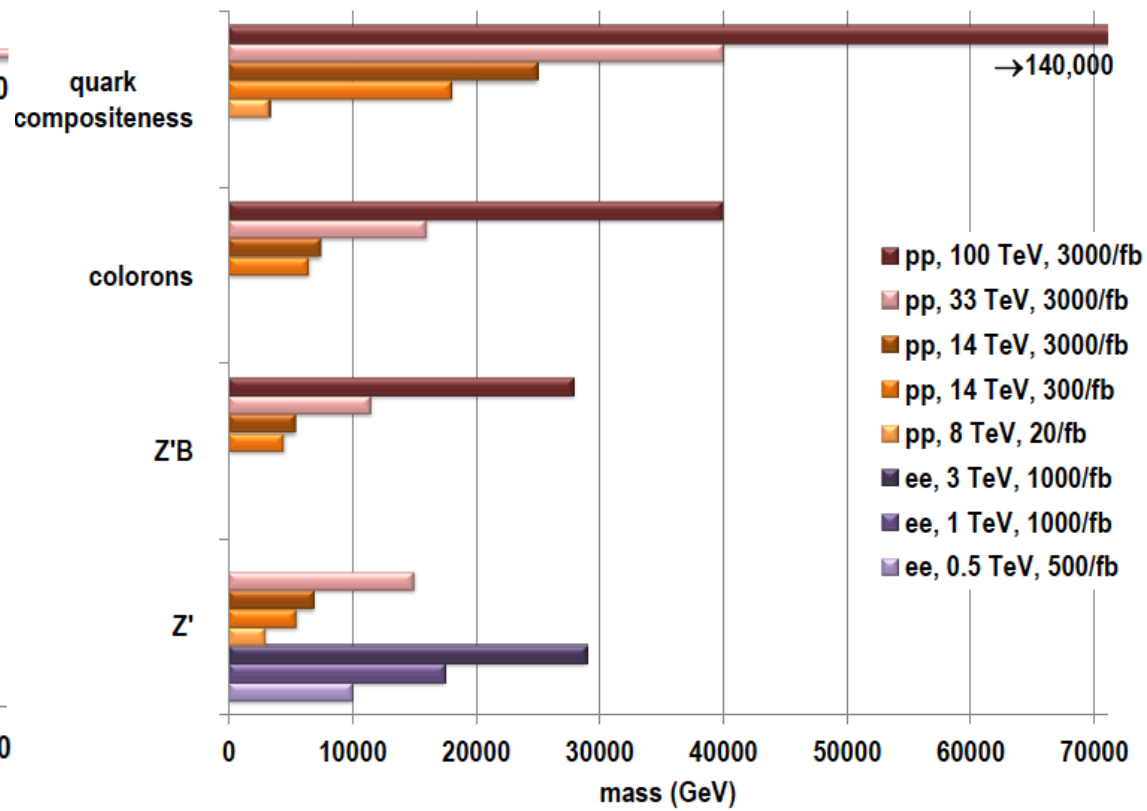
- In top quark decay
  - FCNC coupling to H, Z, γ



Future colliders

- 33 TeV in LHC tunnel
- VLHC - 100 TeV in 100 km tunnel
  - Complete coverage of TeV scale
- ILC - 0.5 TeV upgradable to 1 TeV
  - Highest precision mass and coupling measurements for Higgs, top, W, Z





Conclusions

- Top quark final states are critical in many new physics searches

- Run II will probe multi-TeV masses
  - Searches for Z' and W' are high priority with early 13 TeV data
  - Pair production and single production of top quarks
  - Start to probe weak production of TeV-scale resonances
  - In association with Z, W, H, MET, quarks, …
  - Indirectly through rare top quark couplings

- HL-LHC will make measurements of new physics
  - In all possible channels
  - Dark matter interactions with quarks, top, Higgs, W, Z

- The full (non-Higgs) LHC program is just starting

Thanks!

- ATLAS top physics results:
  http://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- CMS top physics results:
  http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

- Tevatron physics for the informed public
  http://www.fnal.gov/pub/today/frontier_science_result
- CDF top physics results:
  http://www-cdf.fnal.gov/physics/new/top/top.html
- DØ top physics results:
  http://www-d0.fnal.gov/Run2Physics/top/