Exotic Searches

Shahram Rahatlou

Physics in Collision 2011

Vancouver, 31 August 2011

Dipartimento di Fisica
Sapienza Università di Roma
INFN Roma

On behalf of
ATLAS, CDF, CMS, and D0
Collaborations

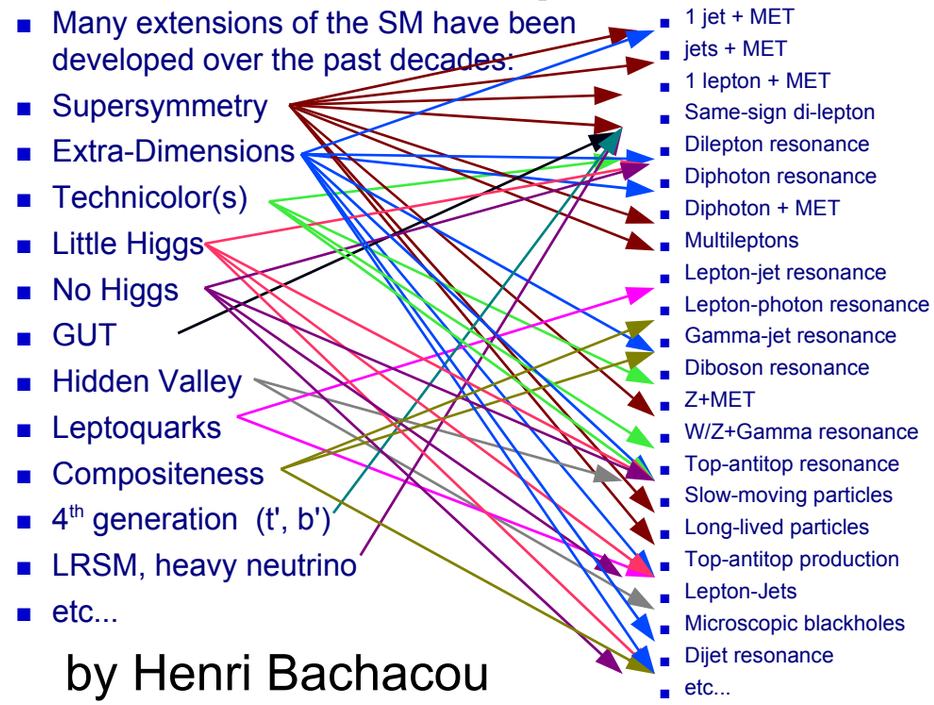
DISCLAIMER

- More than 30 results produced by ATLAS and CMS alone for Summer
  - A wonderful 2011 for LHC so far
- More than 60 results from Tevatron and LHC covering a large variety of theoretical models
- Snapshot of most recent results and not a comprehensive review
  - Many of Tevatron results now superseded at LHC not reported due to time constraints
- Complete list of results
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - CDF: http://www-cdf.fnal.gov/physics/physics.html
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  - D0:http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

SIGNATURE- OR TOPIC-BASED?

- Same final state often probing very different models or topics
  - 2 leptons, 2jets + MET, lepton+jet+MET

- Topological presentation requires jumping between different types of physics being addressed

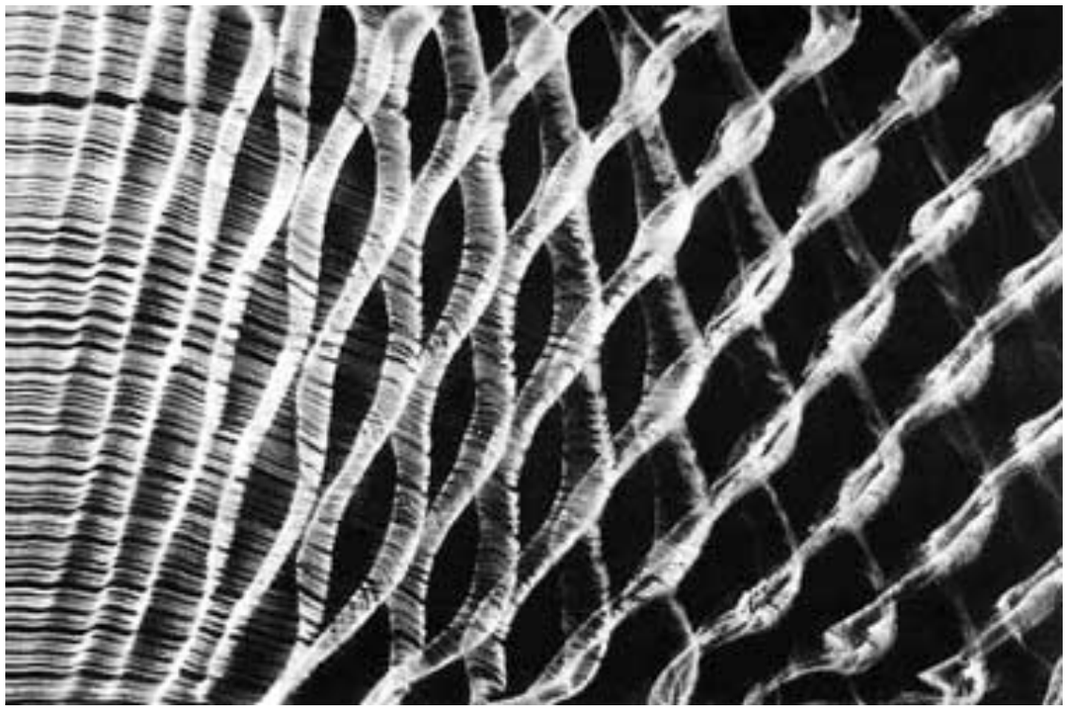


- This talk following a topic-based approach
  - easier to combine constraints on model from different topologies
  - Same final state is not simple re-interpretation
    - often optimization redone to deal with different acceptance for very different models
    - different analysis strategy and signal extraction methods

OUTLINE

- Heavy Resonances
  - dileptons
  - lepton+MET
  - diphotons
  - dijets
  - heavy neutrinos
  - WZ
  - W+jj
- Extra dimensions
  - dileptons
  - diphotons
  - jet/photon + MET
  - Black Holes
- LeptoQuarks
  - 1st generation
  - 2nd generation
- 4th generation b'/t'
  - all hadronic
  - semileptonic
- Long-lived particles
  - stopped particles
  - displaced vertices

For ttbar related searches see Francesco Spano's talk on Monday

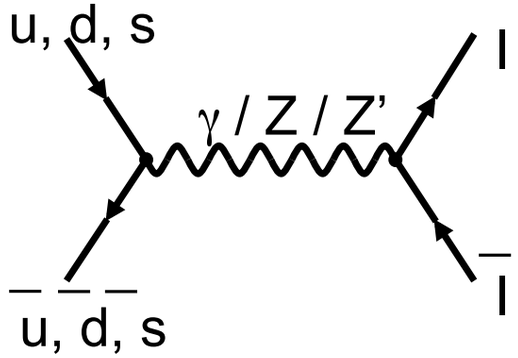


Heavy Resonances

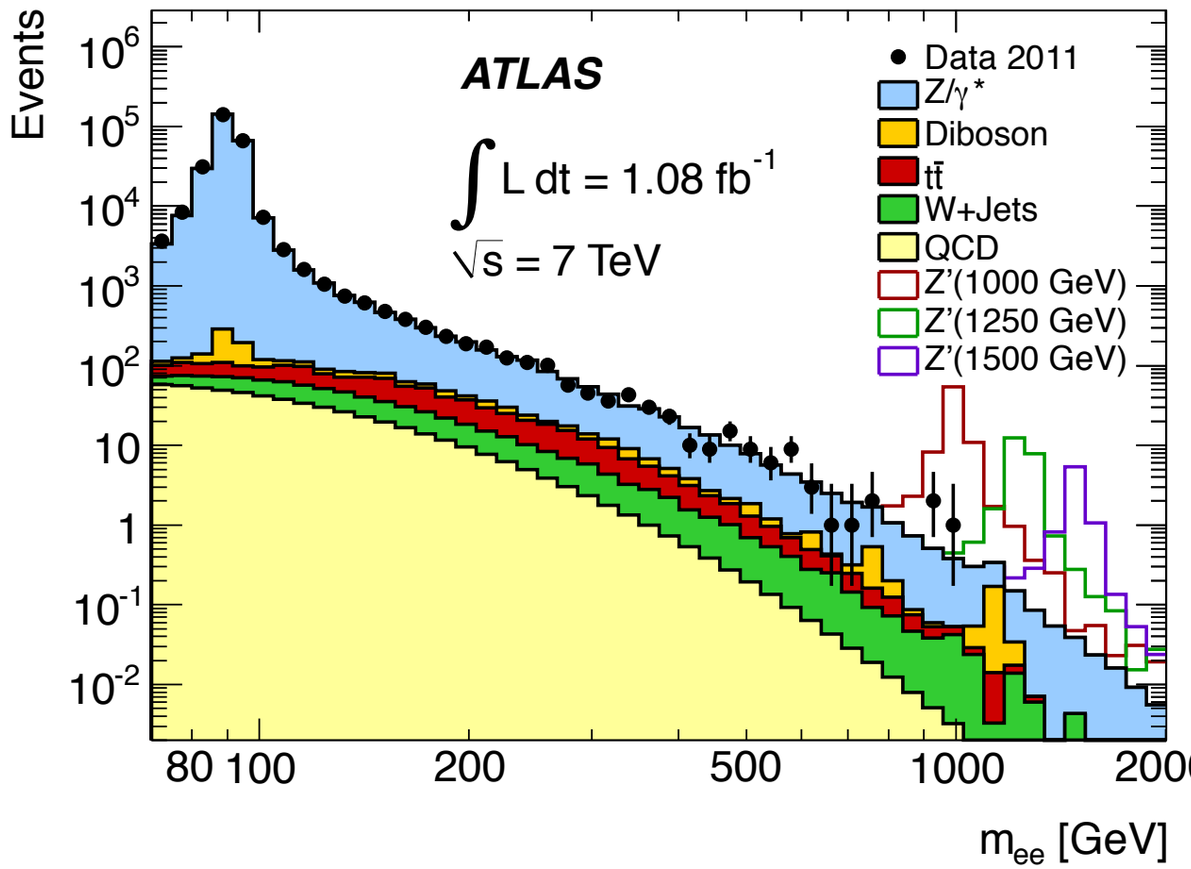
HEAVY RESONANCES

- New gauge bosons predicted by many extensions of the Standard Model with extended gauge symmetries
  - Z_{SSM} in Sequential Standard Model with same Z0 coupling as in Standard Model
  - Z' models from E6 and SO(10) GUT groups
  - The Kaluza-Klein model from Extra Dimension
  - Little, Littlest Higgs model
- No precise prediction for mass scale of gauge bosons
- Technicolor also predicts variety of narrow heavy particles
- Backgrounds
  - relatively clean with good S/B
  - mostly tails of SM processes
- Experimental challenges
  - detector resolution can be a key player
  - extra care for energy/momentum reconstruction above 1 TeV

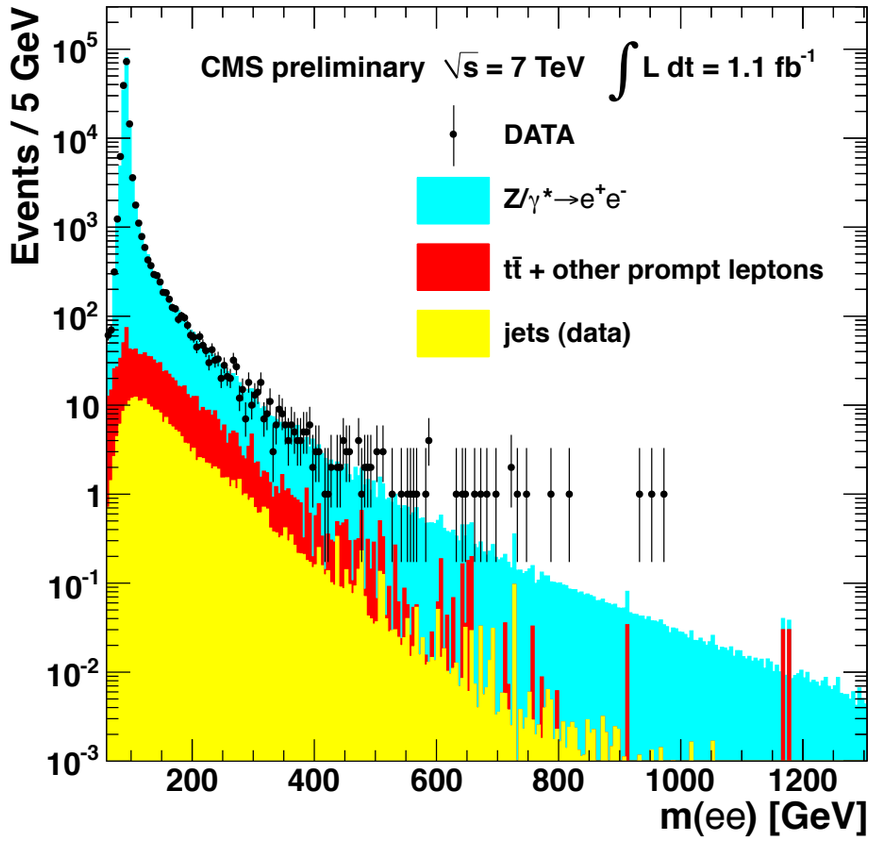
DI-ELECTRON

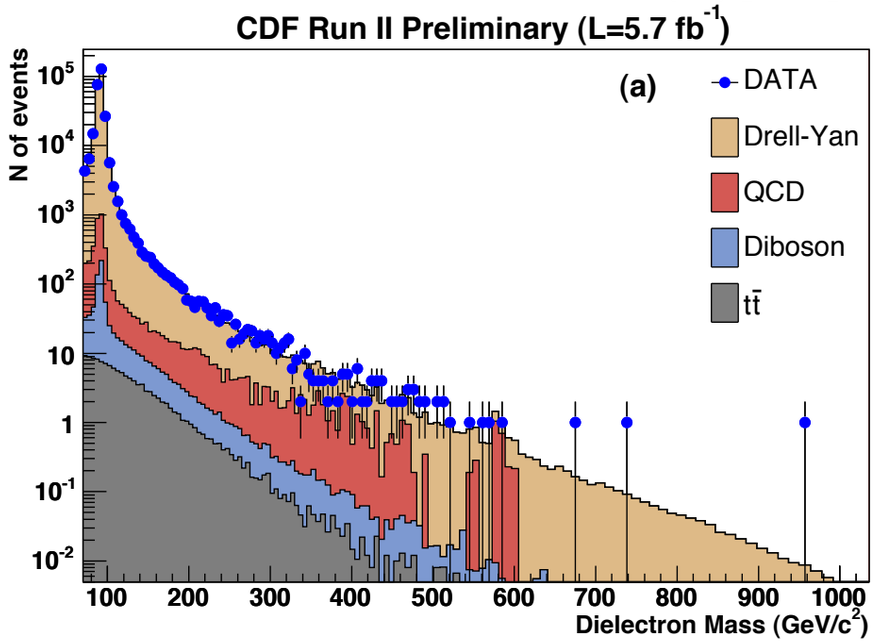


ATLAS: arXiv:1108.1582



CMS: PAS EXO-11-019

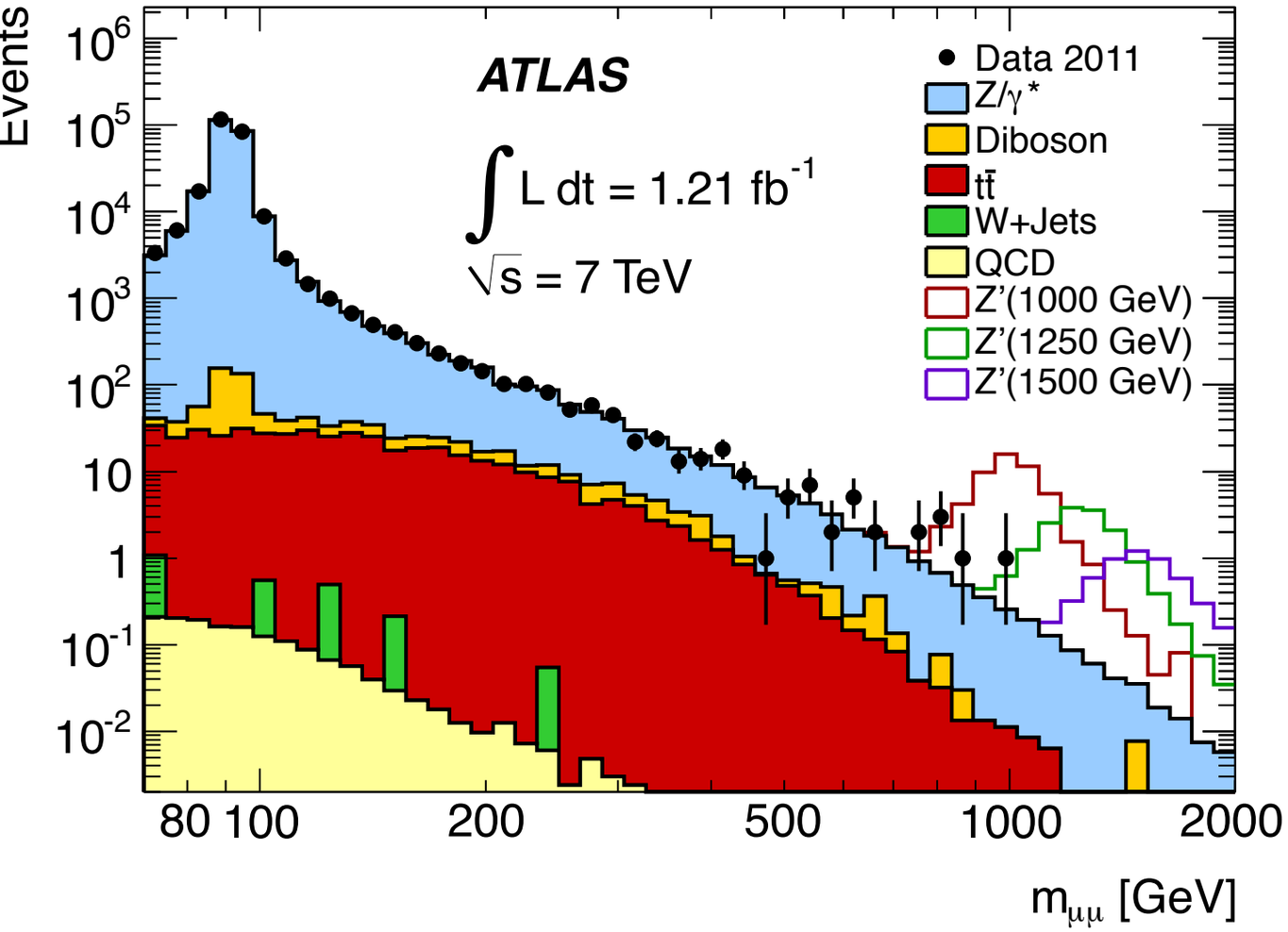




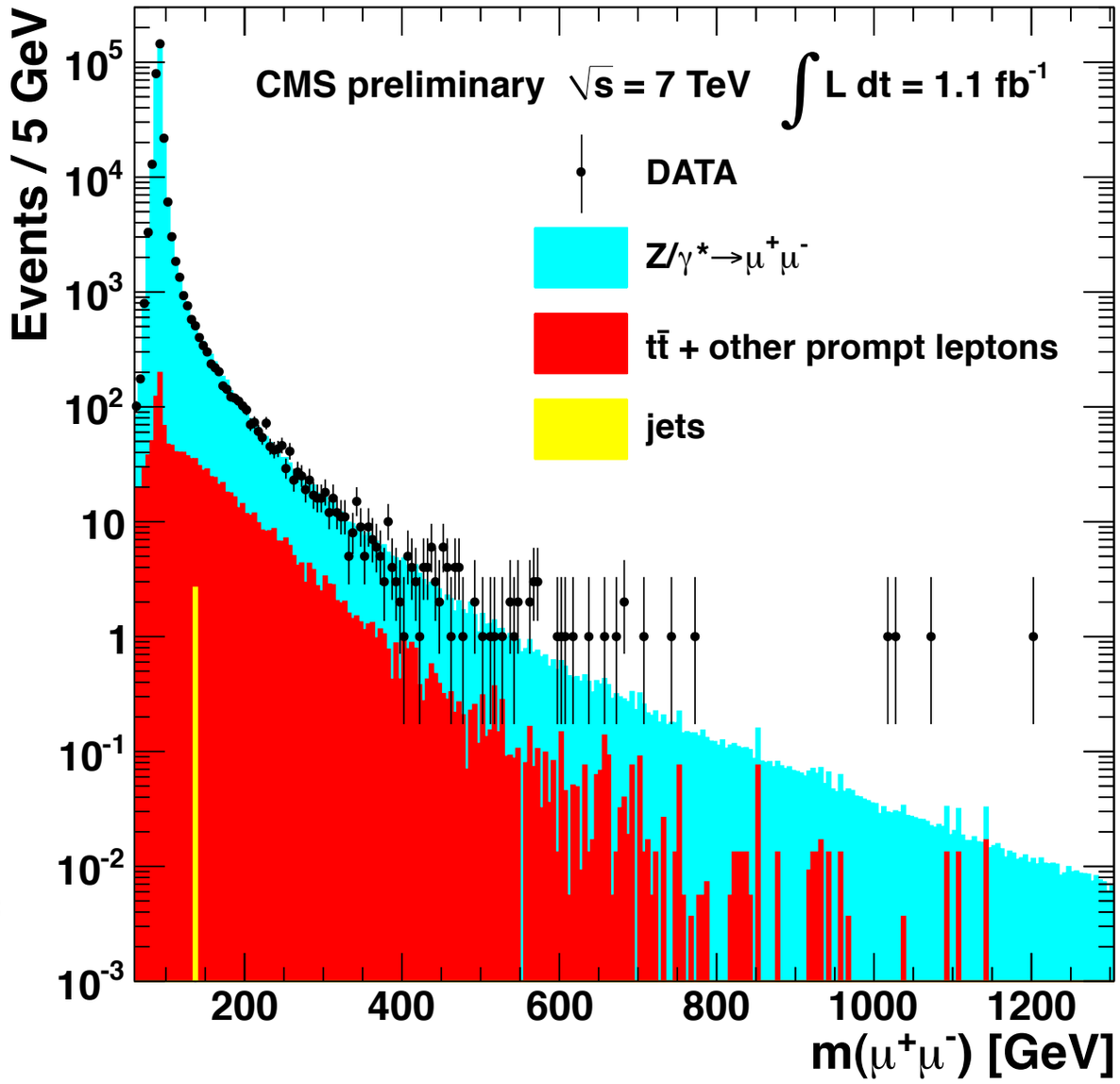
- Background estimation
  - ATLAS: QCD from data, ttbar and DY from MC
  - CMS: QCD and ttbar from data, DY from MC

DI-MUON

ATLAS: arXiv:1108.1582

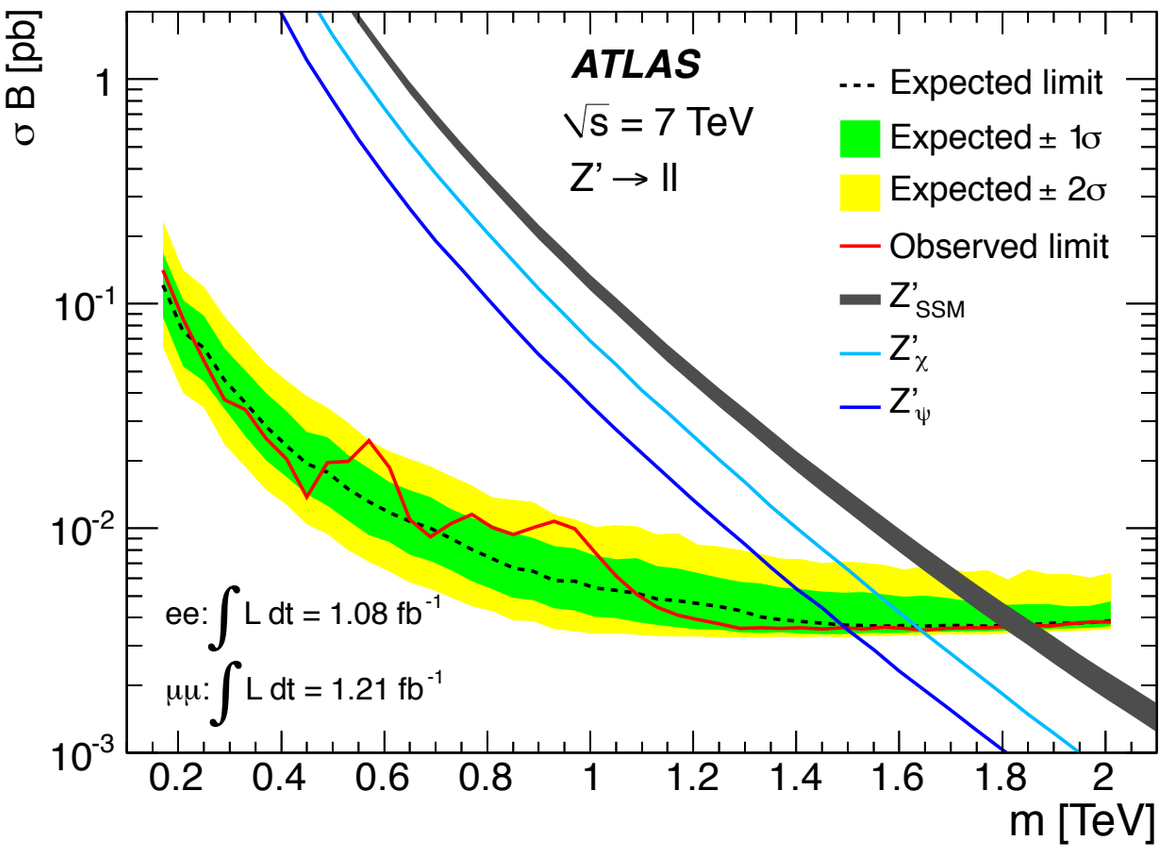


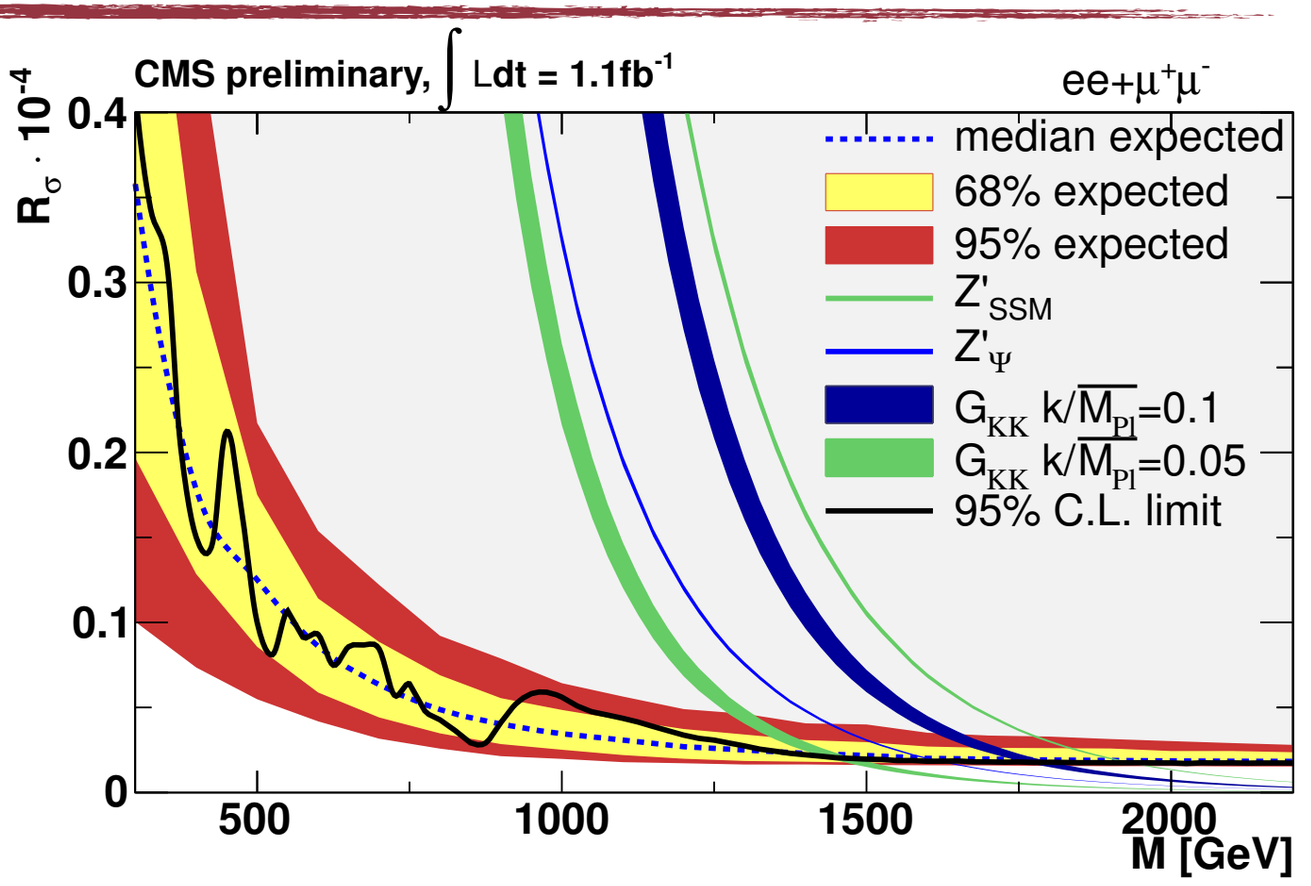
CMS: PAS EXO-11-019



- Several events with mass of 1 TeV

DI-LEPTON EXCLUSIONS

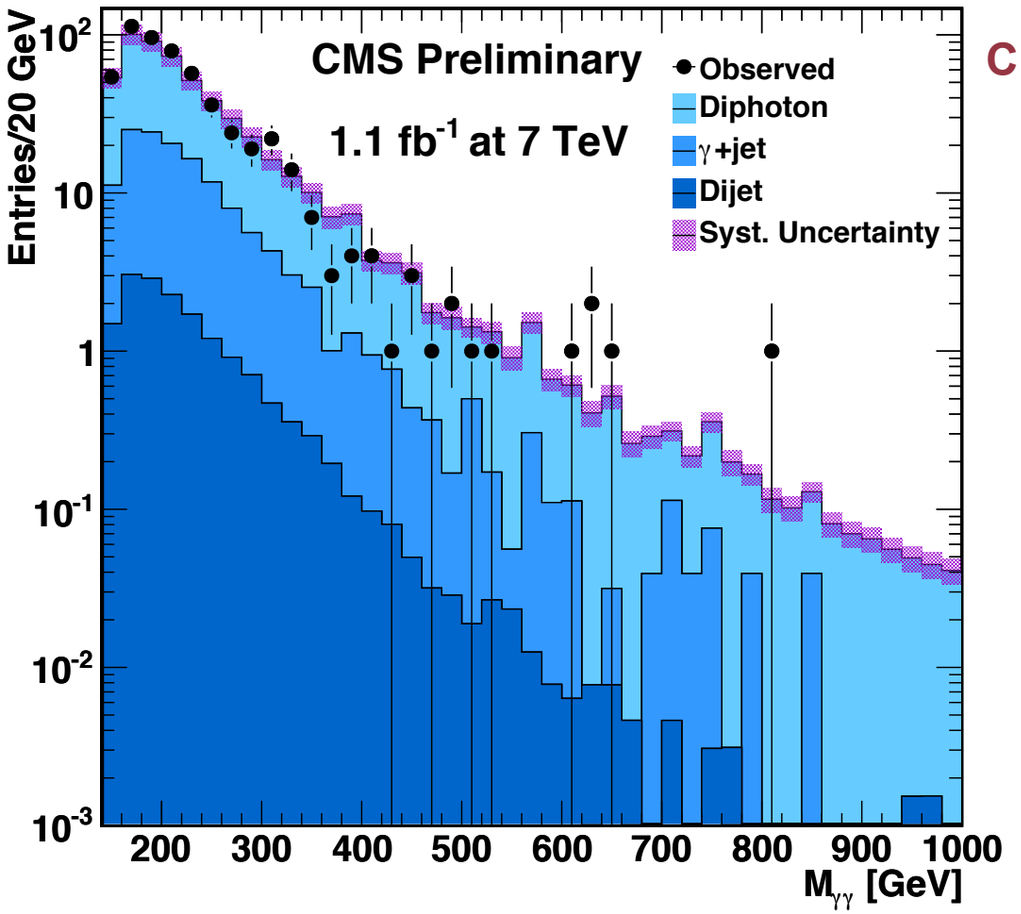




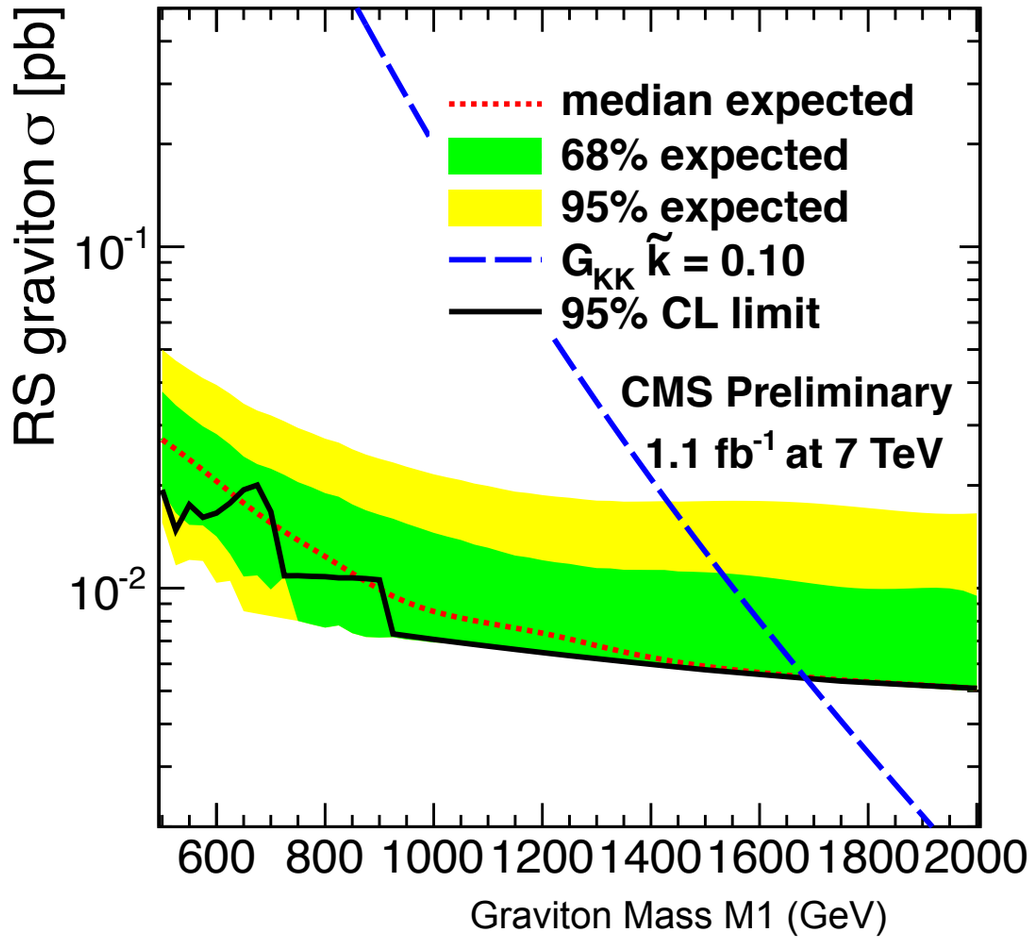
- Limits approaching 2 TeV for most models
- Similar expected and observed 95% CL limits for both experiments

Excluded mass (TeV)	Z'_{SSM}	$Z'\psi$	RS G* k =0.05	RS G* k=0.10
ATLAS	1.83	1.49	1.33	1.63
CMS	2.00	1.62	1.49	1.79

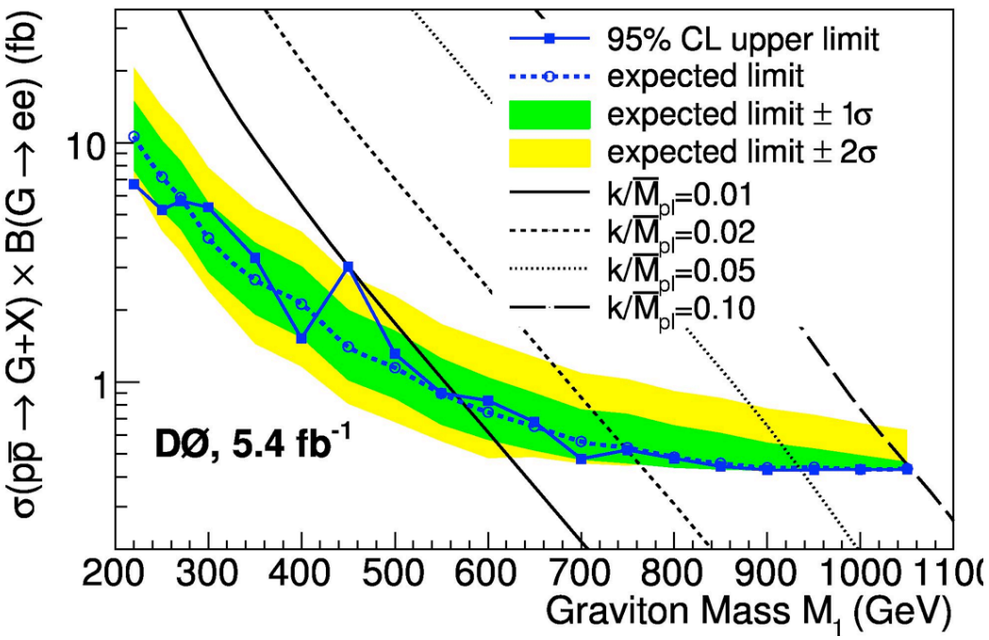
γγ



CMS: PAS EXO-11-038



- Randall-Sundrum gravitons propagation in extra dimensions
- Background: genuine diphoton production



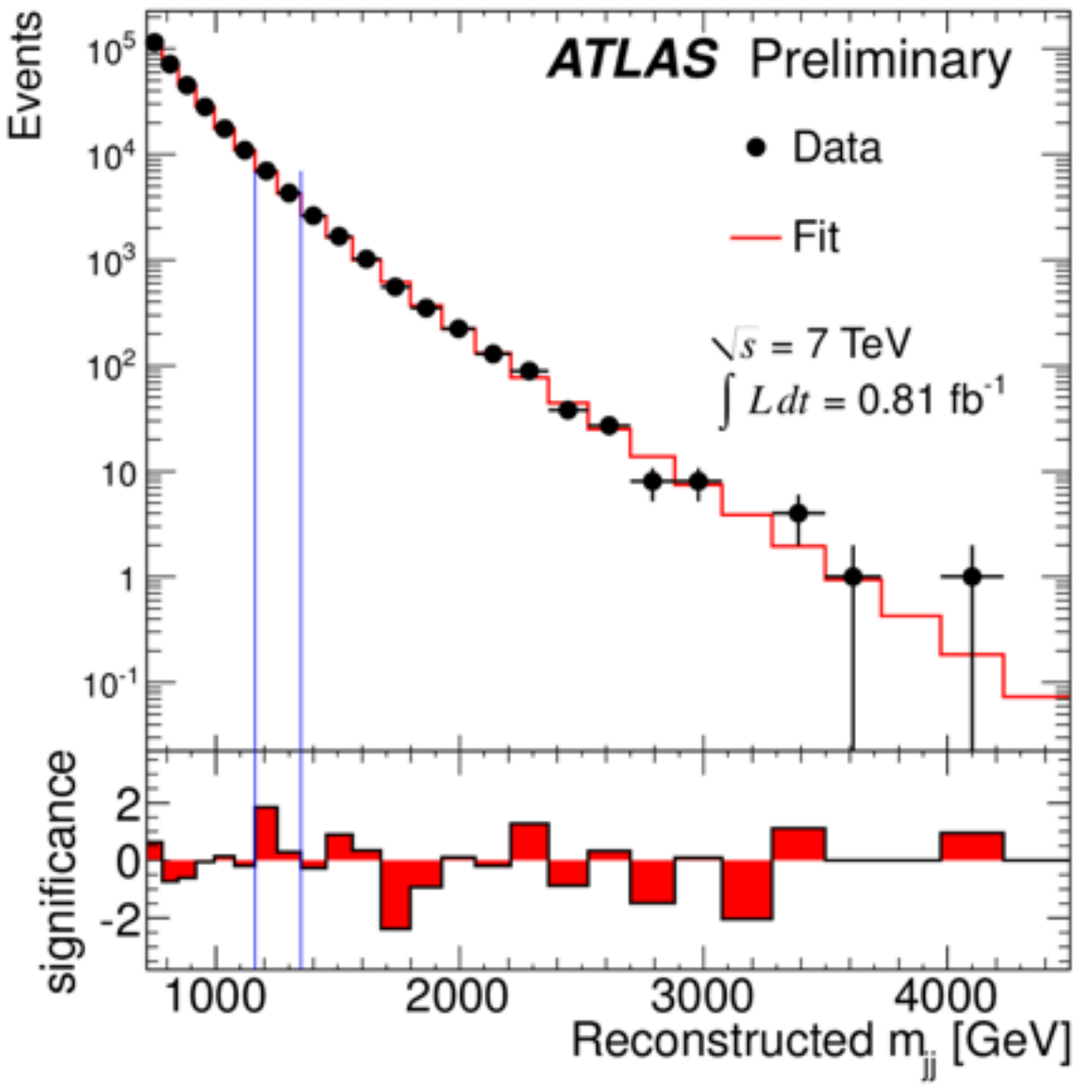
ATLAS-CONF-2011-044 D0: PRL 104(2010) 241802

Excluded mass (GeV)	CMS 1.1 fb^{-1}	ATLAS 36 pb^{-1}	CDF (ee+γγ) 5.7 fb^{-1}	D0 (ee+γγ) 5.4 fb^{-1}
k = 0.05	1360	700	937	940
k = 0.10	1685	--	1055	1050

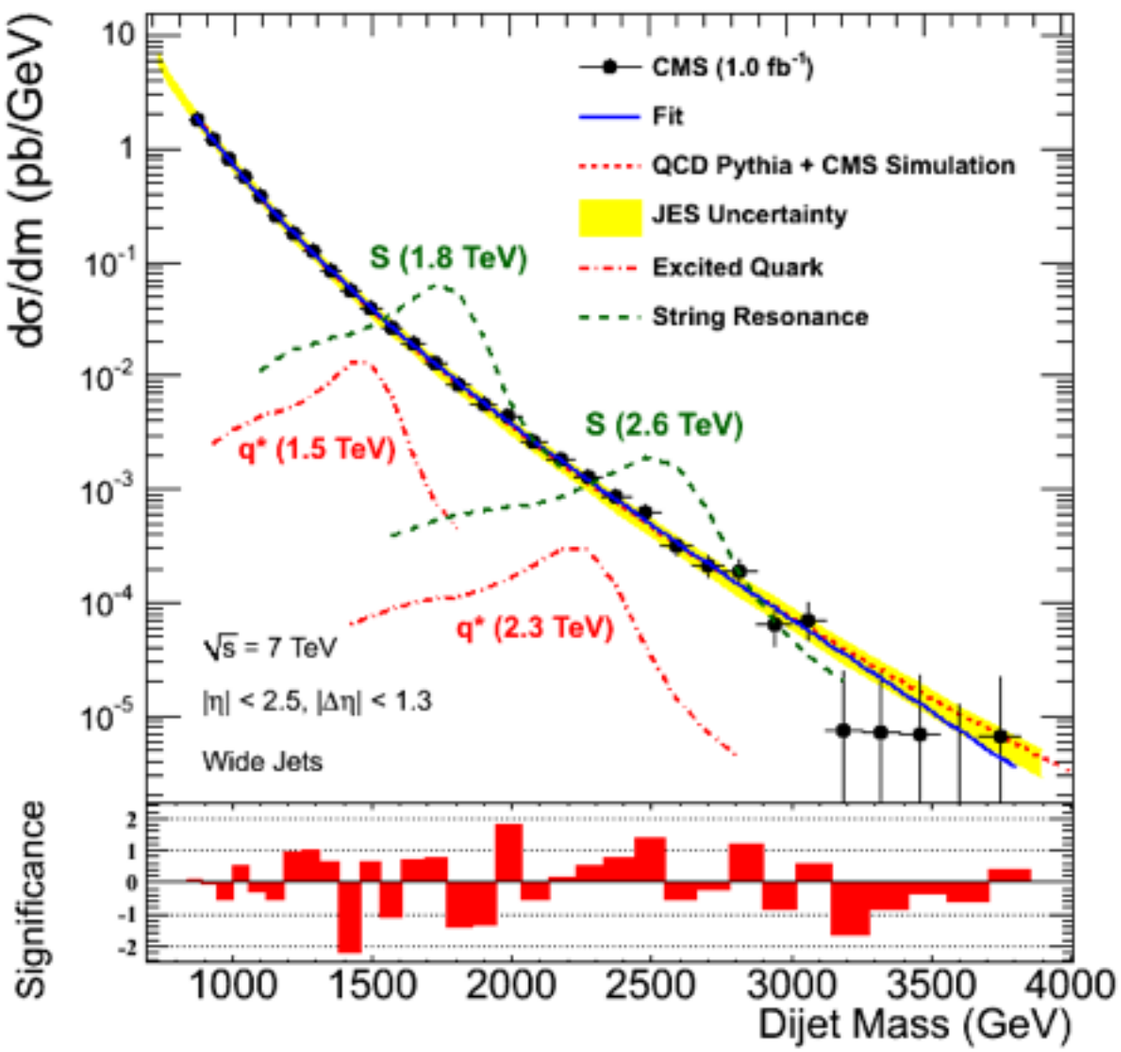
CDF: http://www-cdf.fnal.gov/ physics/exotic/r2a/20110214.gravitonee/index.html

DI-JET

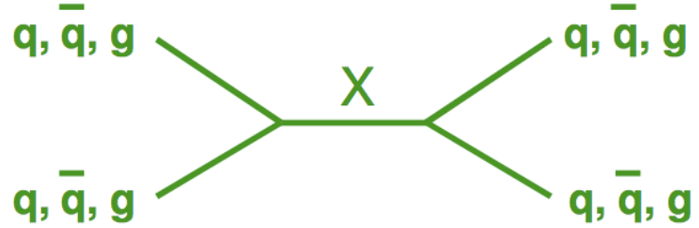
ATLAS-CONF-2011-095



CMS: arXiv:1107.4771

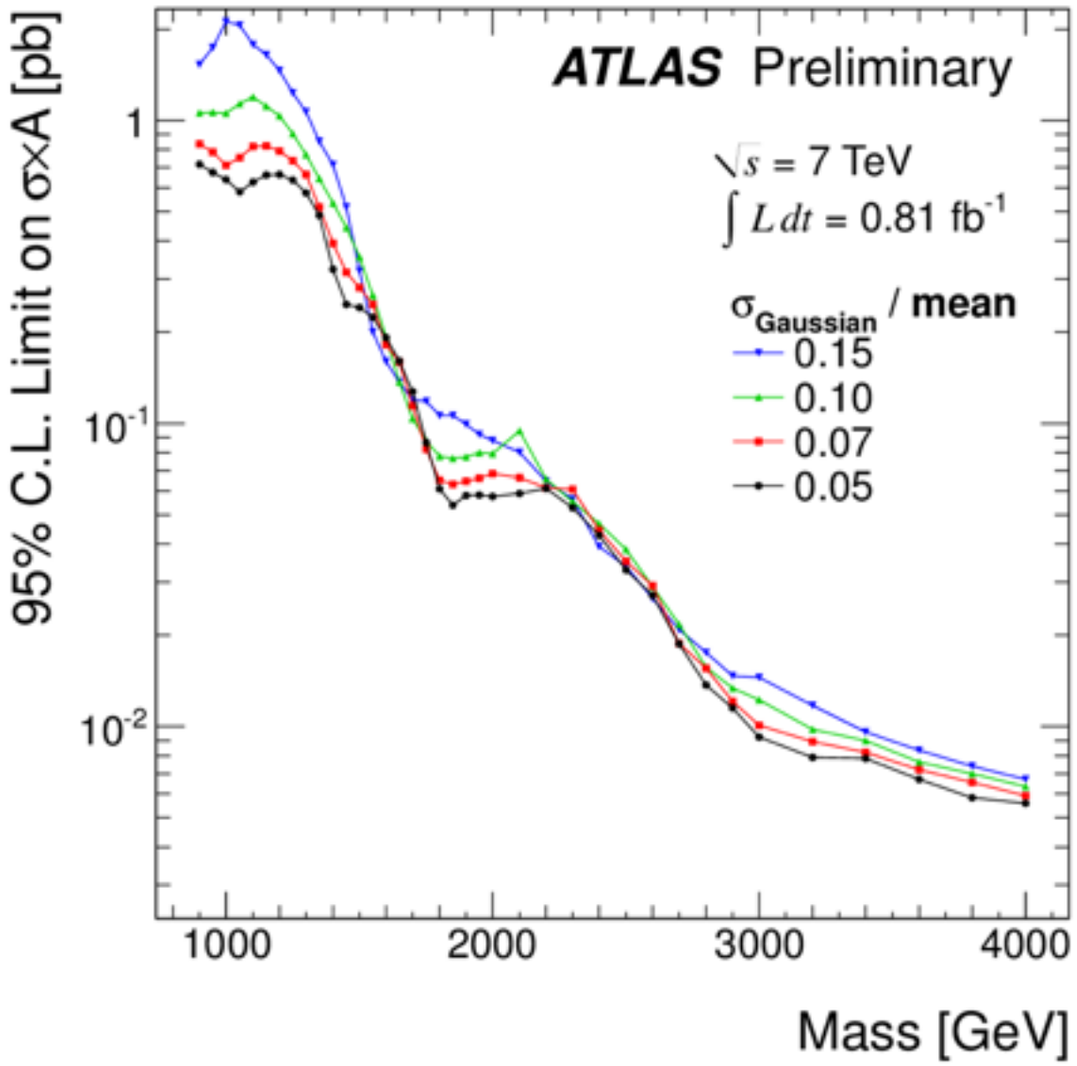


- Resonances predicted in numerous models
  - larger branching fraction compared to dileptons
  - much higher background from QCD

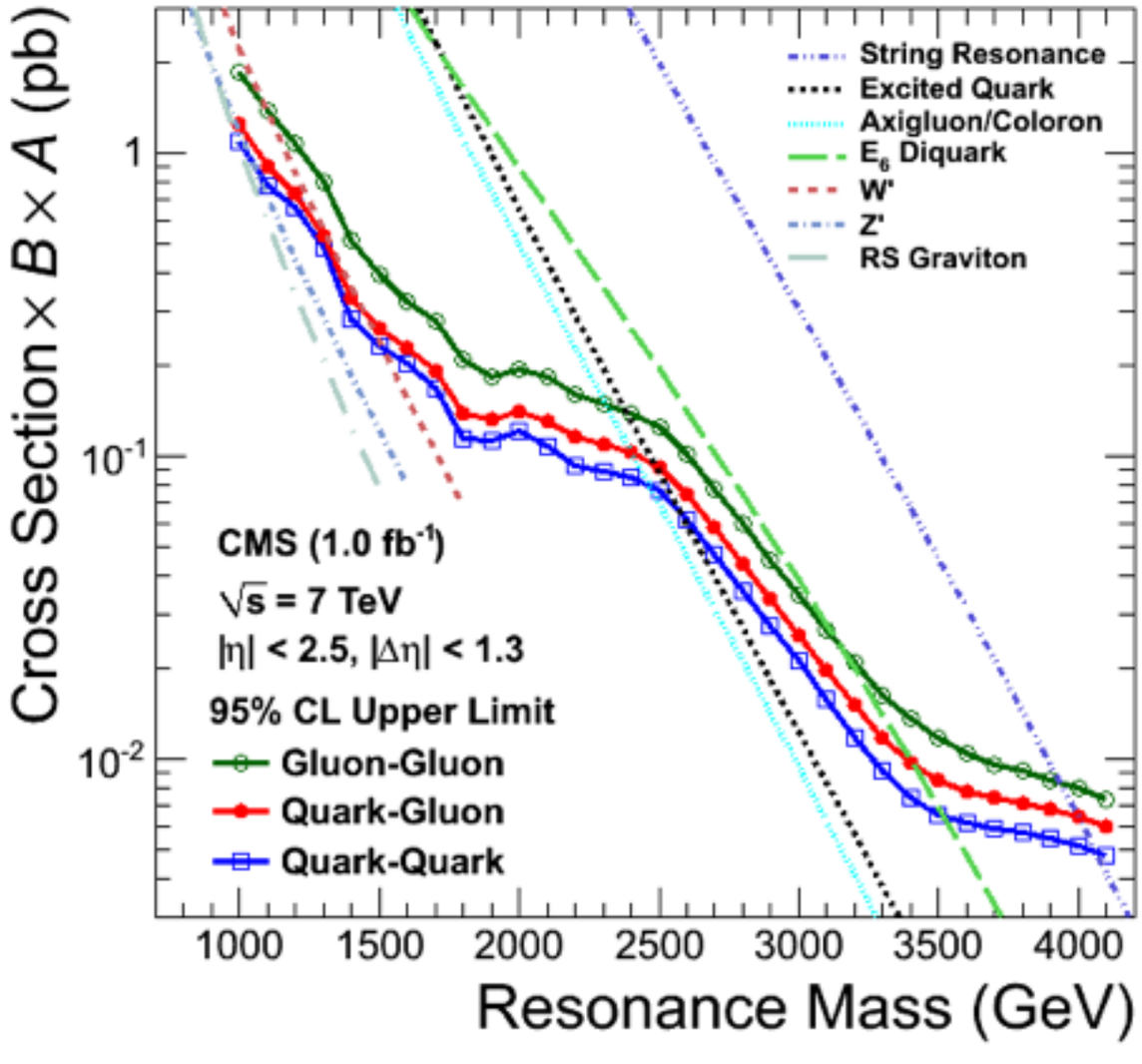


DI-JET EXCLUSION LIMITS

ATLAS-CONF-2011-095



CMS: arXiv:1107.4771

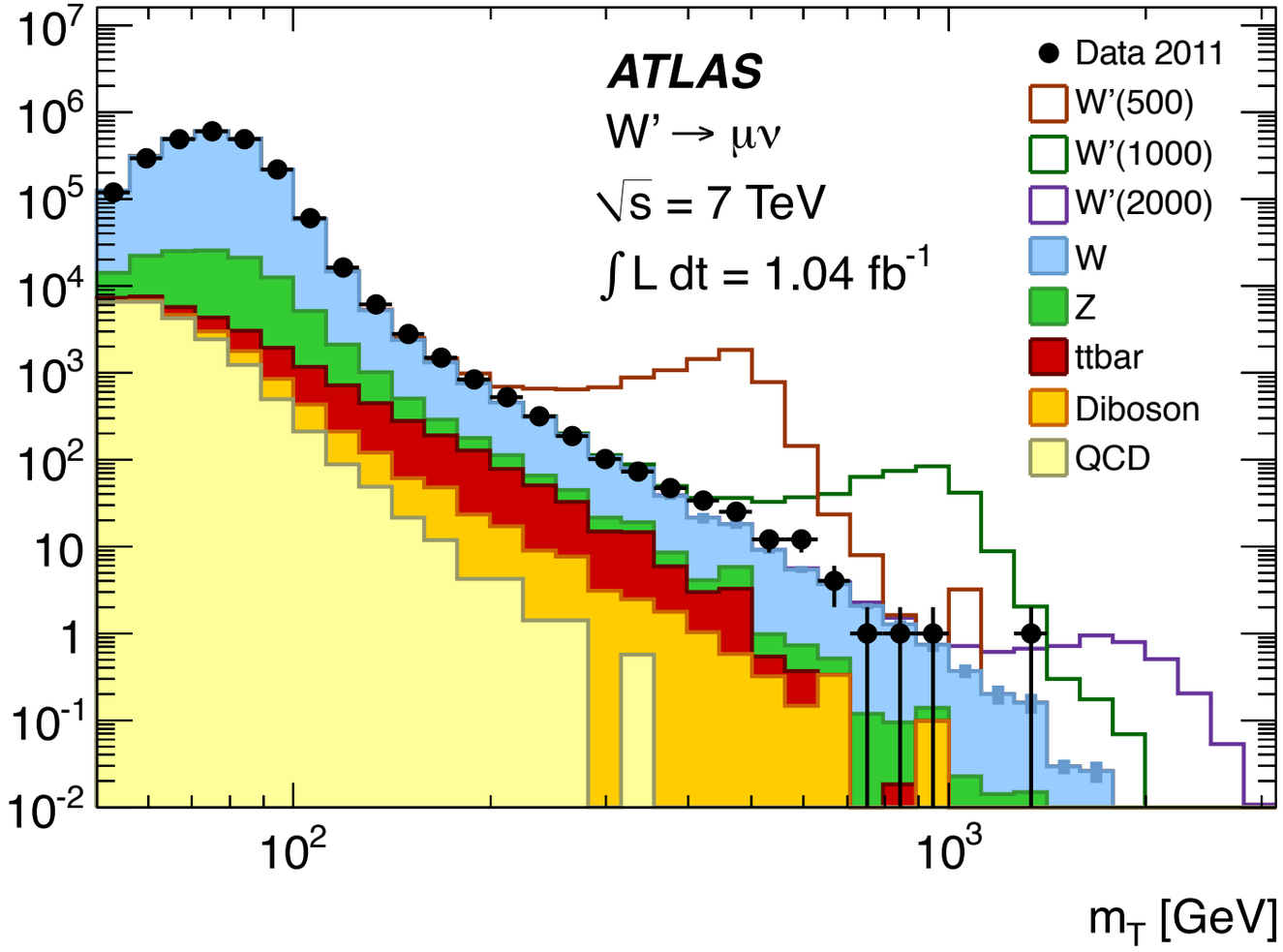


- Now excluding resonances below 2 TeV for variety of models

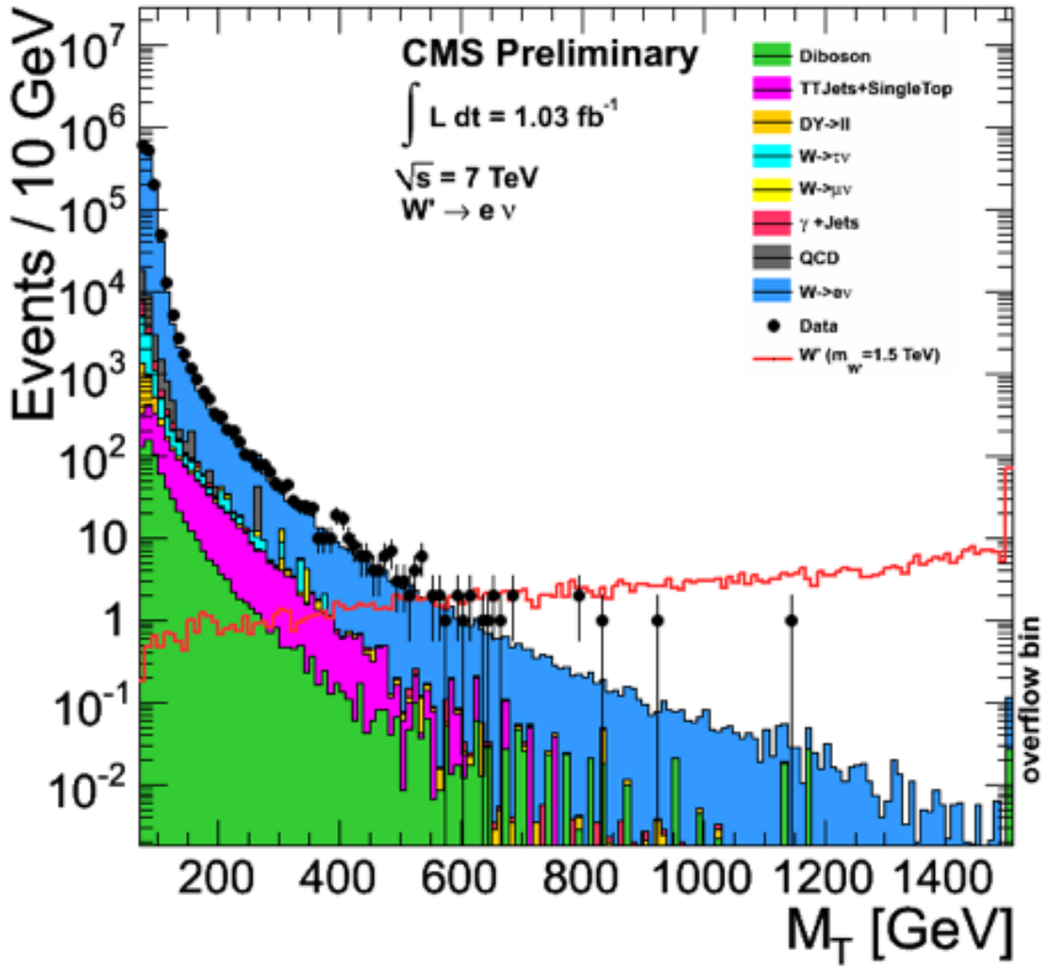
Excluded mass (TeV)	q*	Axigluon Coloron	Color octet scalar	String resonances	E6 diquark
ATLAS	2.91	3.21	1.91		
CMS	2.49	2.47		4.00	3.52

LEPTON+MET

ATLAS: arXiv:1108.1316



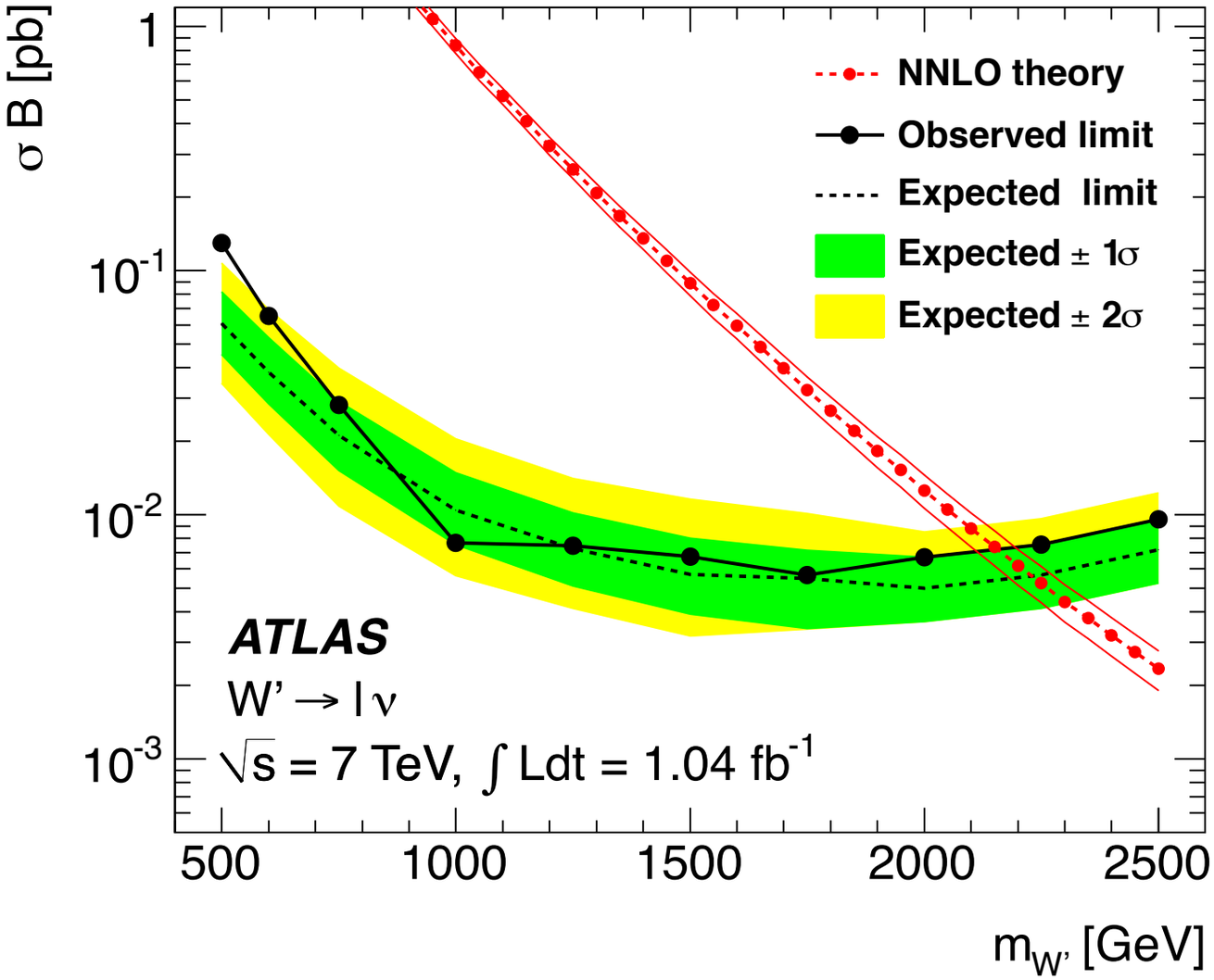
CMS: PAS EXO-11-024



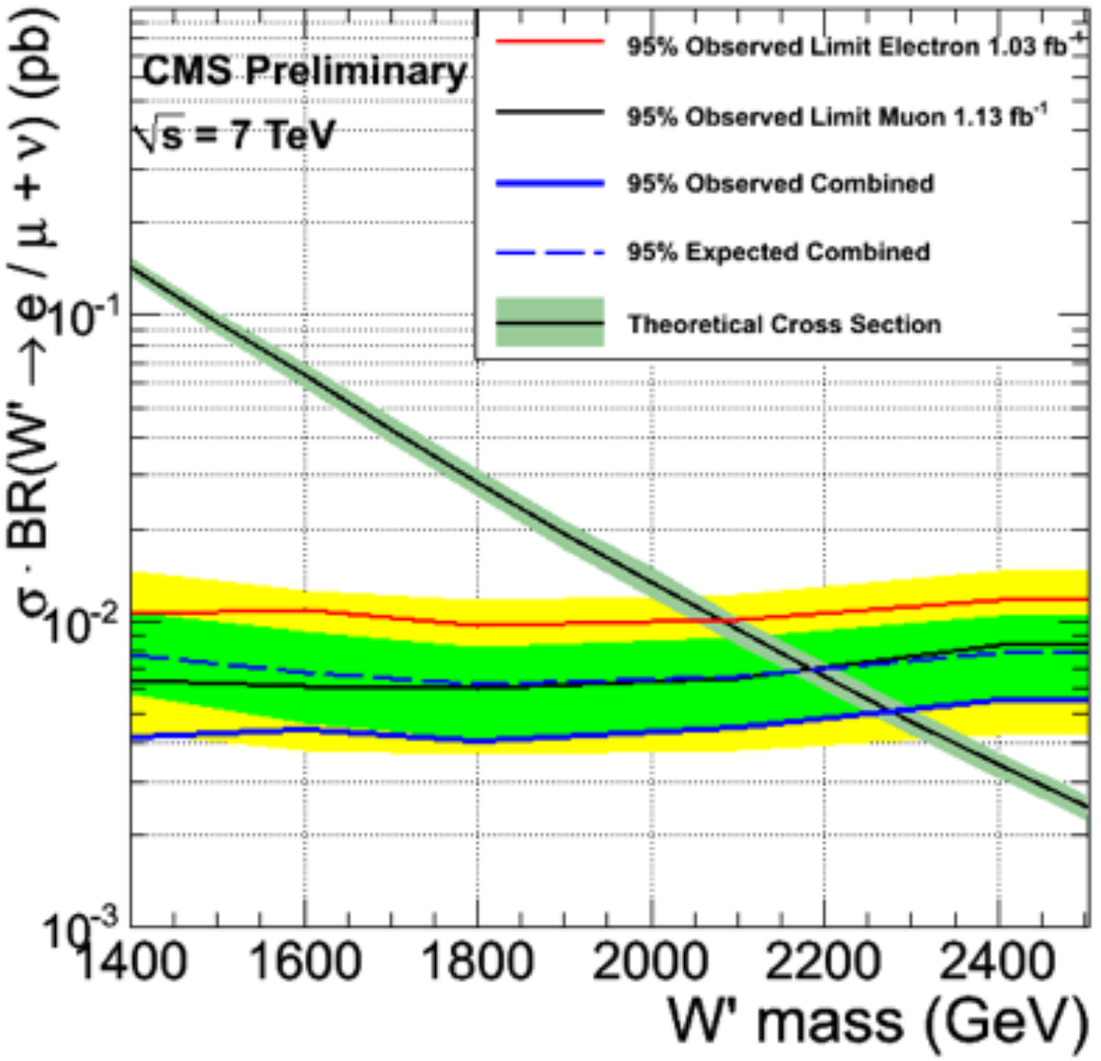
- Look for heavy W-like Jacobian peak in transverse mass $m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$
  - e.g. Sequential SM and Technicolor
- Dominant background: W production in Standard Model

W' → lν Exclusion Limits

ATLAS: arXiv:1108.1316

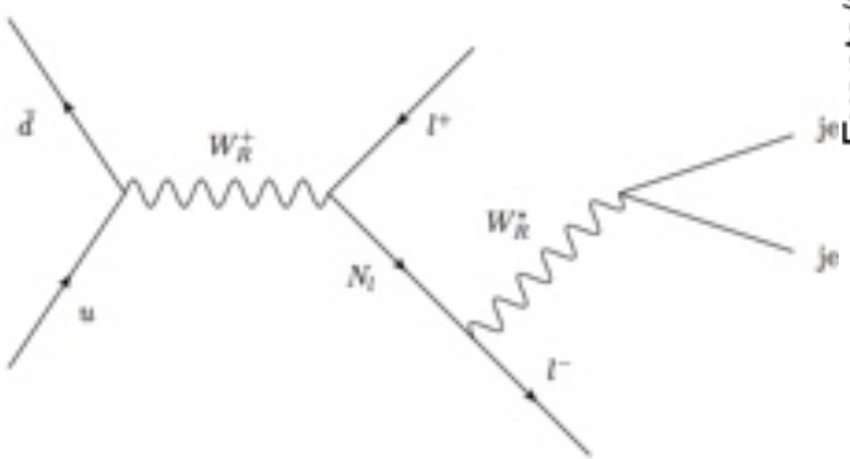


CMS: PAS EXO-11-024

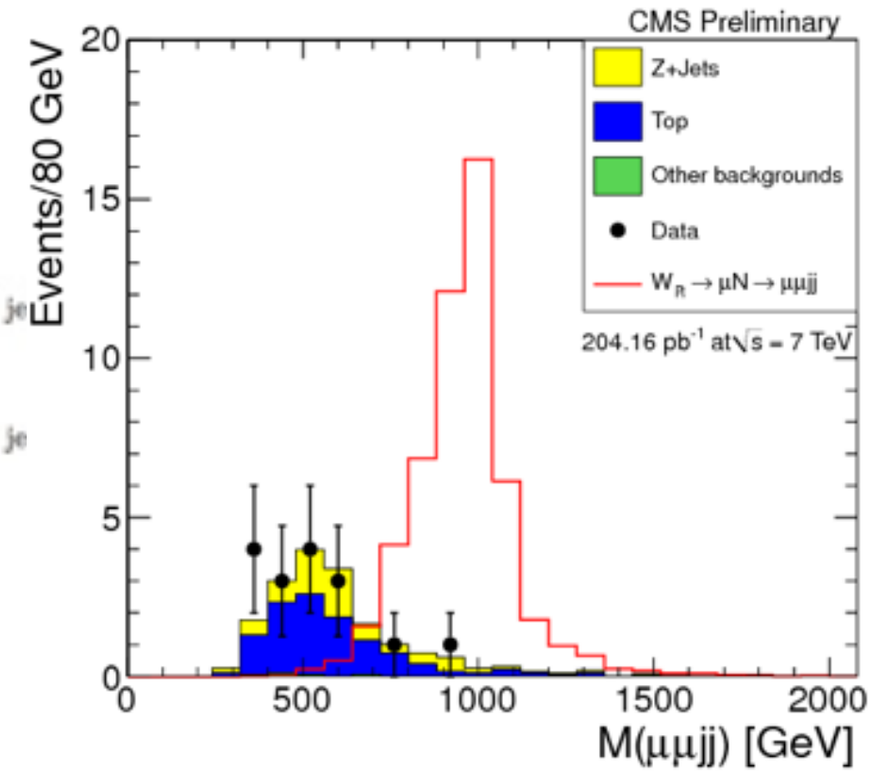


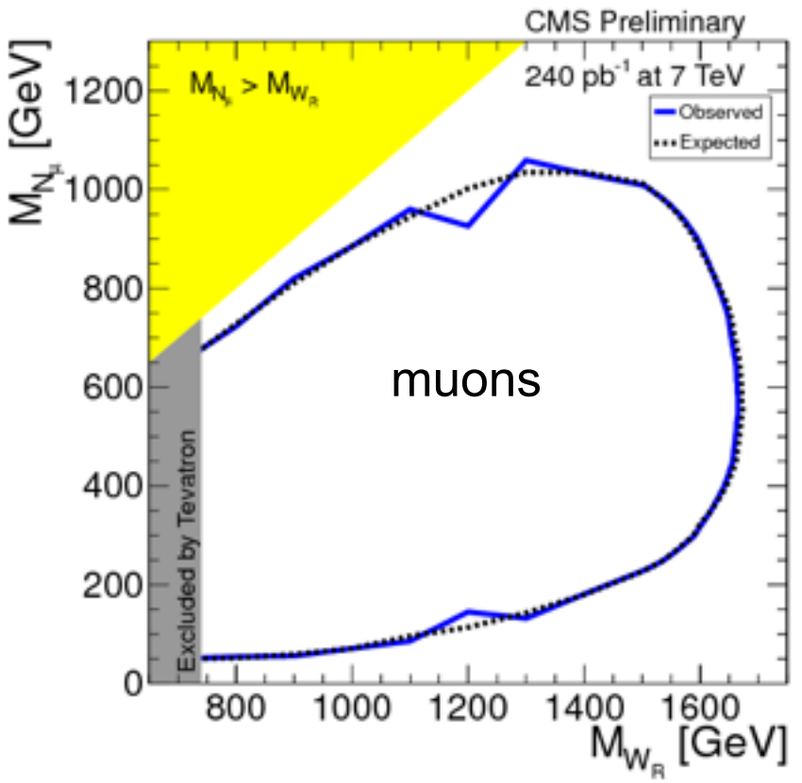
- Exclusion Limits now past 2 TeV

HEAVY NEUTRINO AND W_R



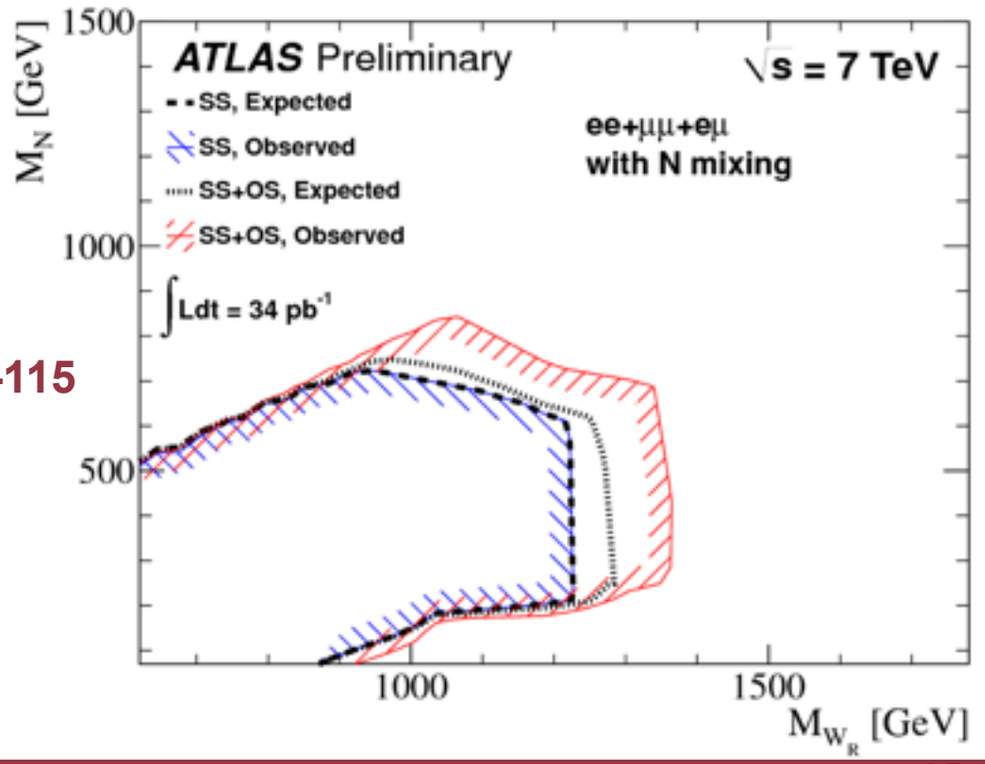
- Explain parity violation through L-R symmetry
- Heavy neutrino mass from see-saw mechanism
- Search for lljj resonance
- Most stringent limits today!
- Gets very interesting for theory once limits at 2.5 TeV





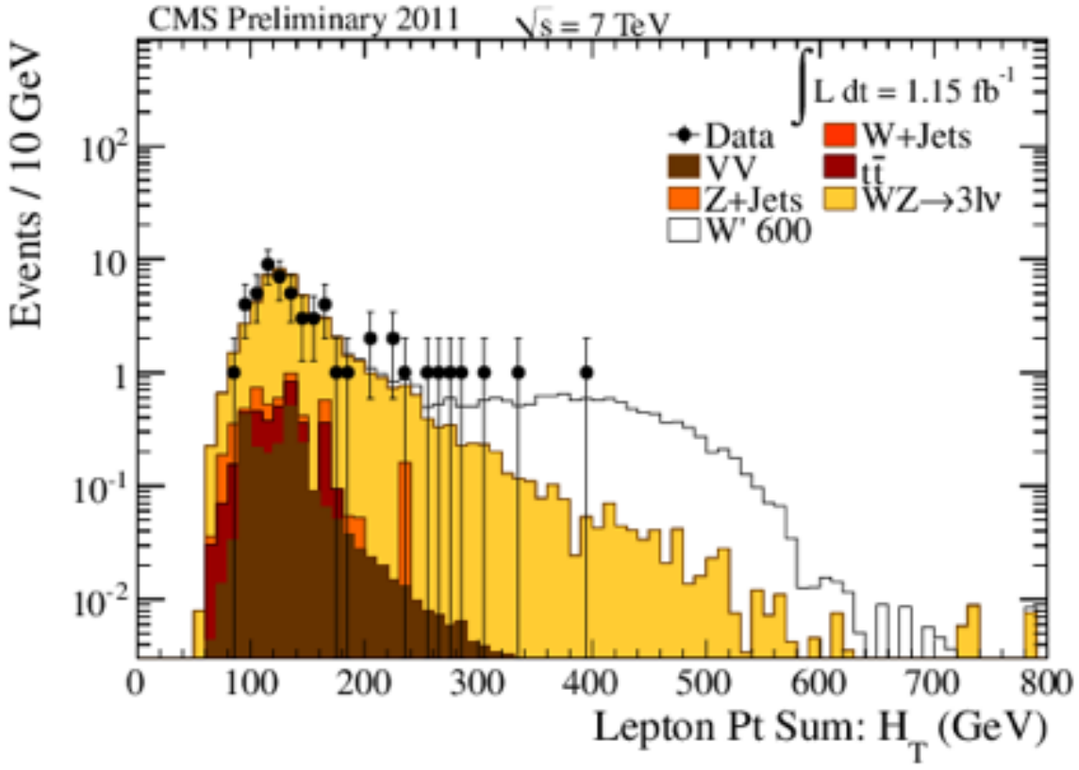
CMS: PAS EXO-11-002

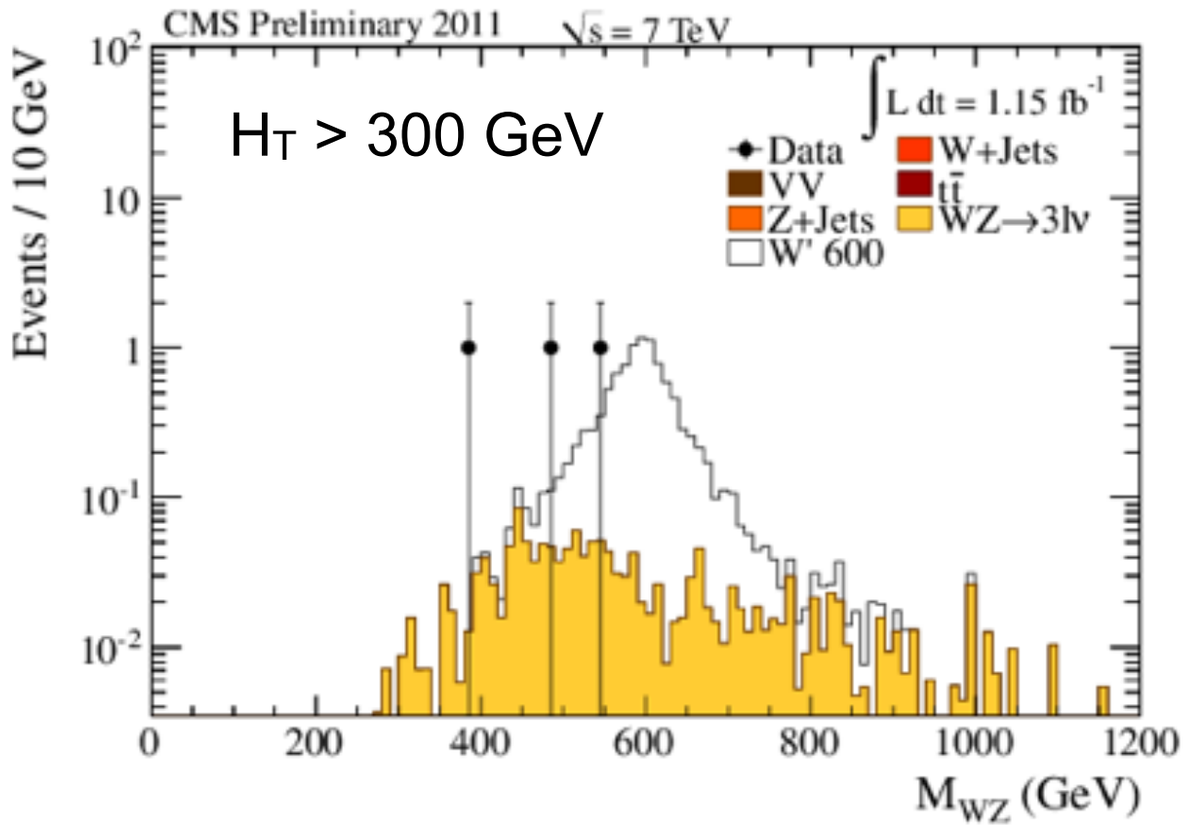
ATLAS: ATLAS-CONF-2011-115



WZ Resonances

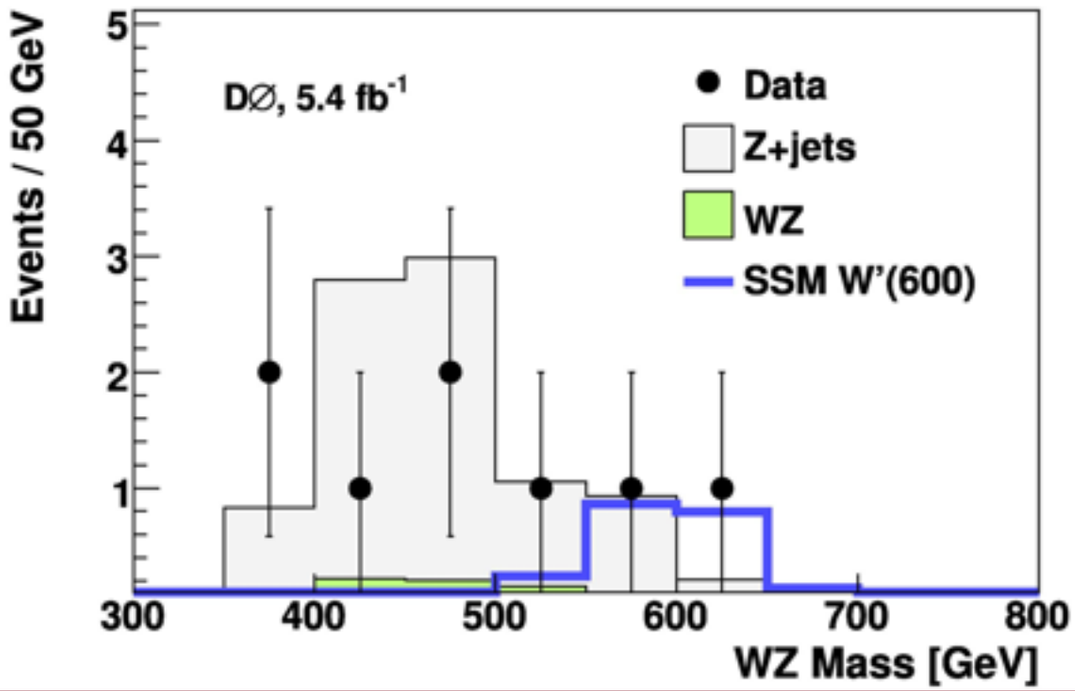
CMS: PAS-EXO-11-041



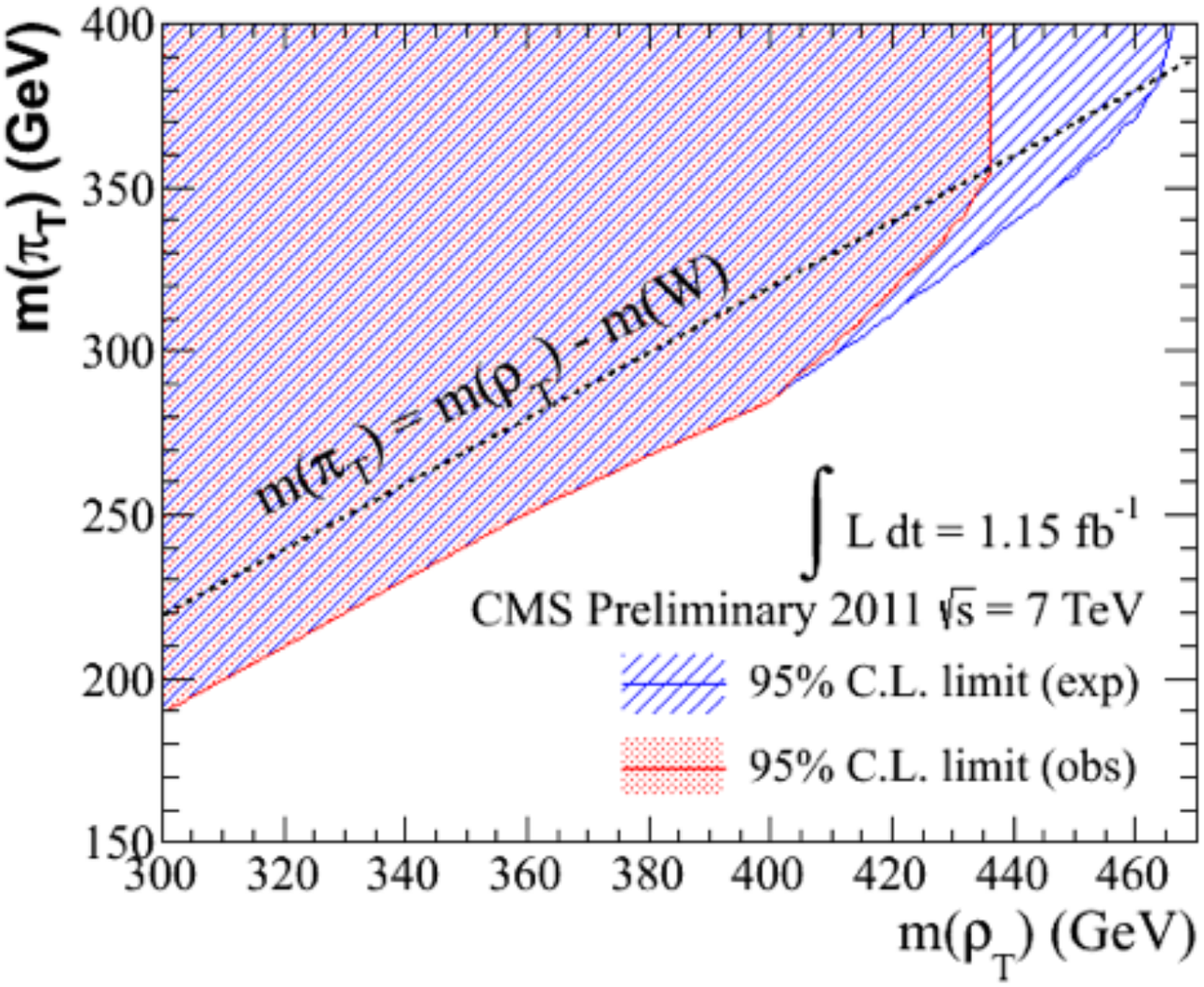


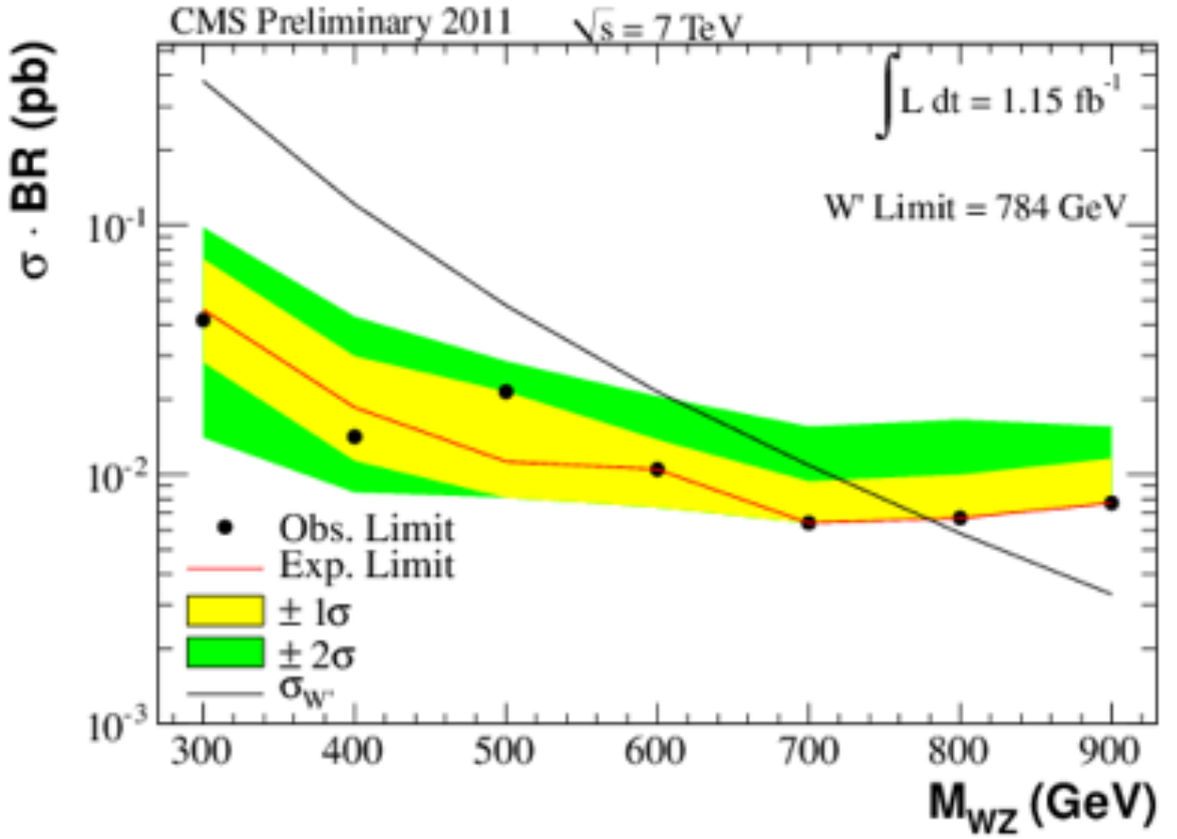
- Sensitive to sequential SM and techni-hadrons (rho and pi)
- CMS: 3 leptons + missing energy
  - Sum of lepton Pt
  - WZ invariant mass with W mass constraint
- D0: also hadronic W/Z decays
  - 1 or 2 jets, 1-3 leptons
  - 3 exclusive categories

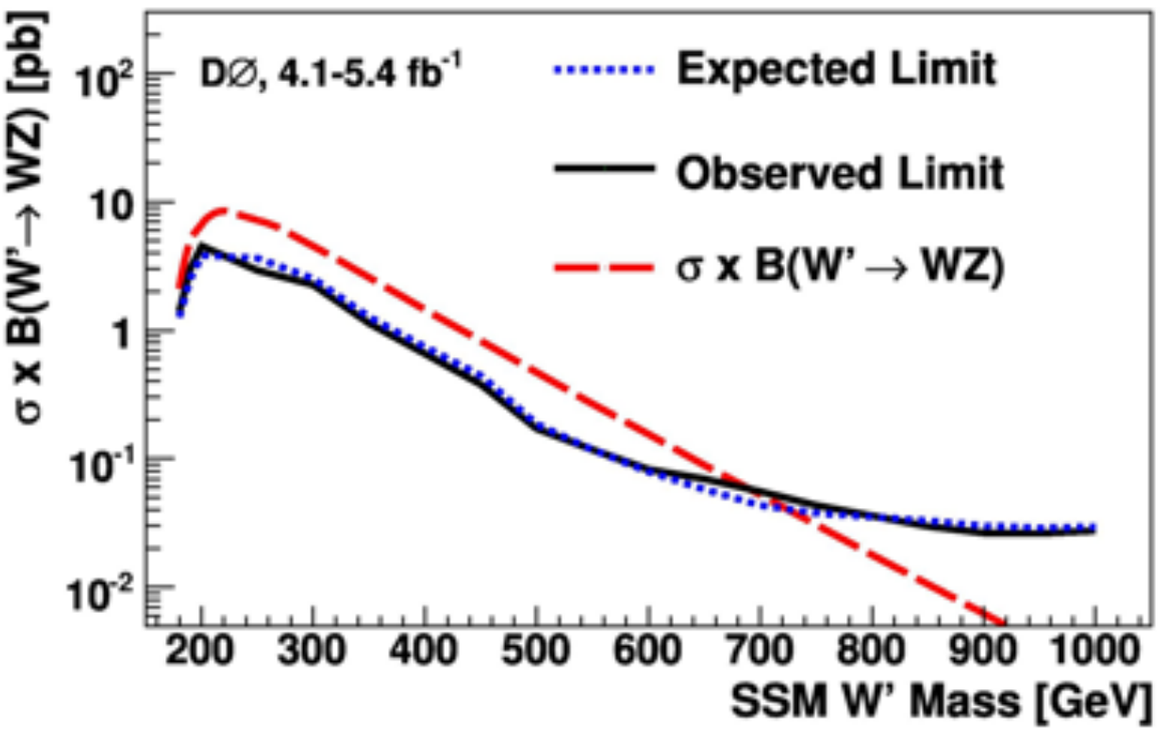
D0: PRL 107, 011801 (2011)



WZ Exclusion Limits





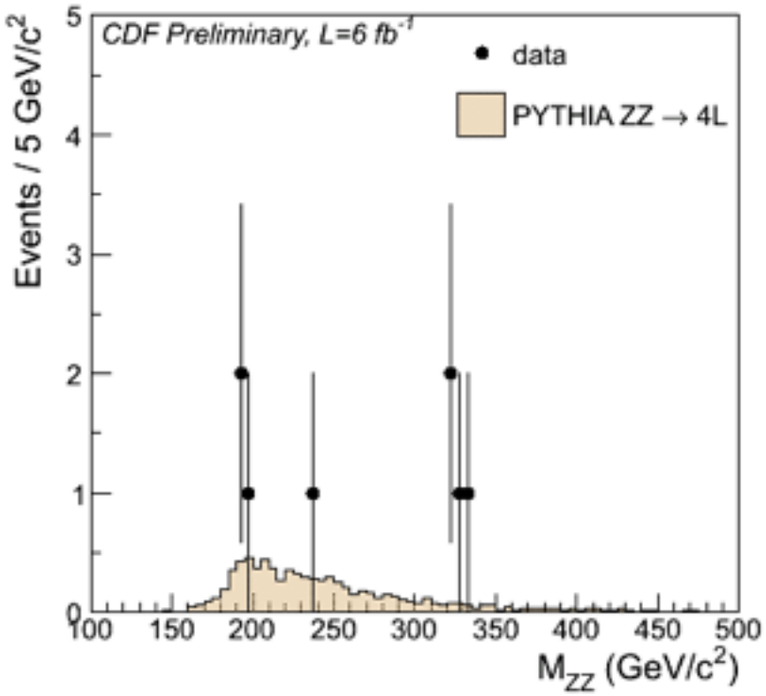


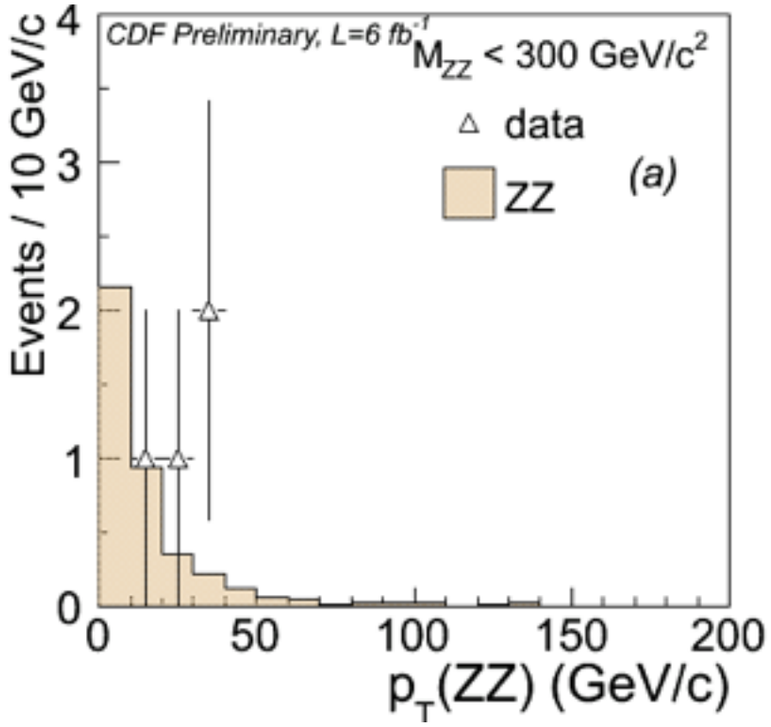
W'_{SSM}: 784 GeV

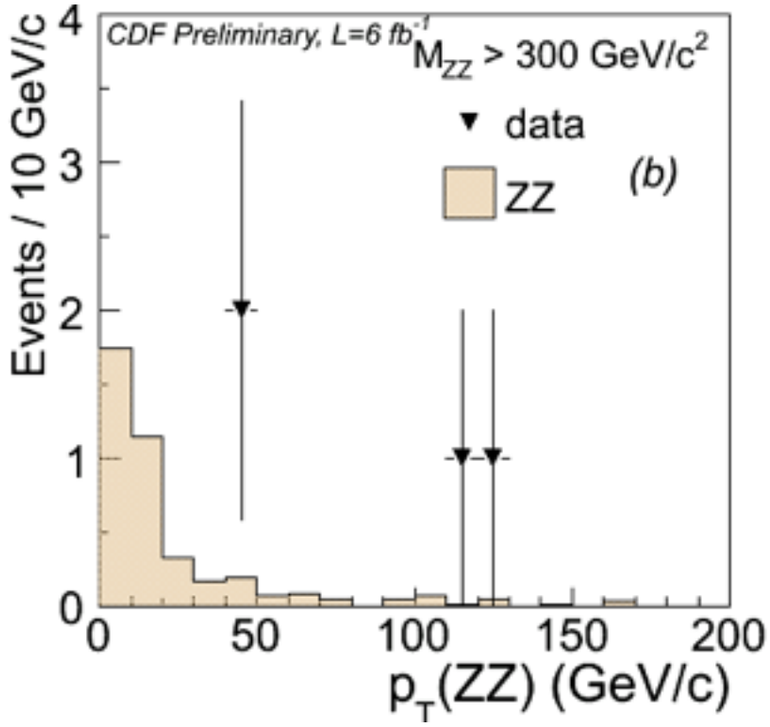
ρ_{TC}: 382 GeV ($M_{\pi_{TC}} = \frac{3}{4} M_{\rho_{TC}}$-25 GeV)

ρ_{TC}: 436 GeV ($M_{\rho_{TC}} < M_{\pi_{TC}} + M_W$)

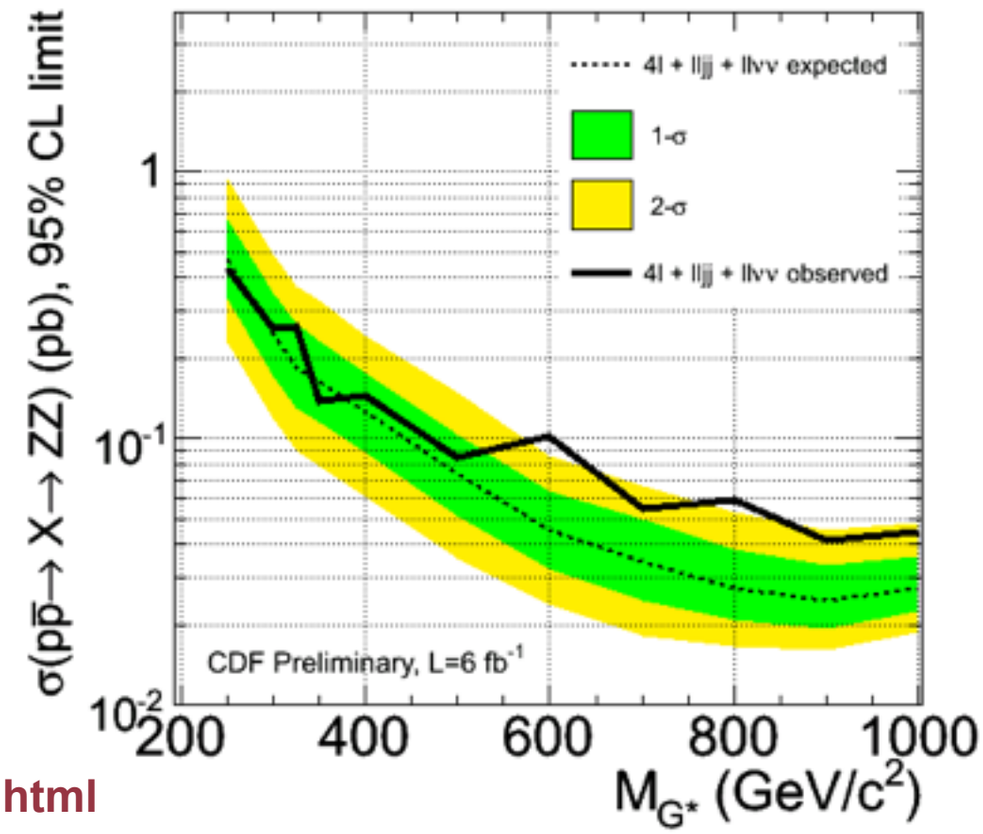
ZZ Resonance







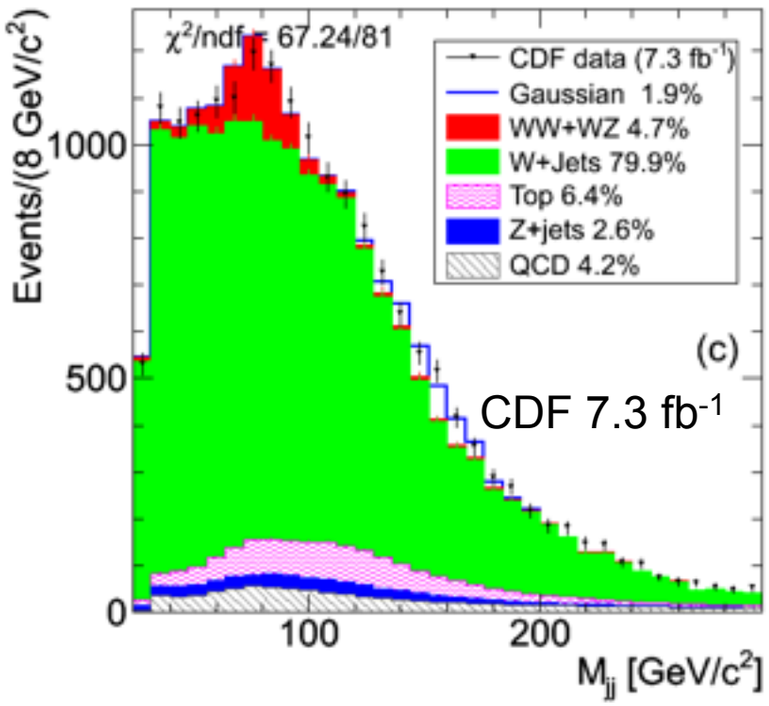
- 3 topologies considered: $Z \rightarrow ll + Z \rightarrow ll, jj, \nu\nu$
- 4 interesting events in 4l final state
  - Also high P_T for same for events
  - Probability of background fluctuation ~10^{-4}
- No excess in lljj nor ll+MET final states

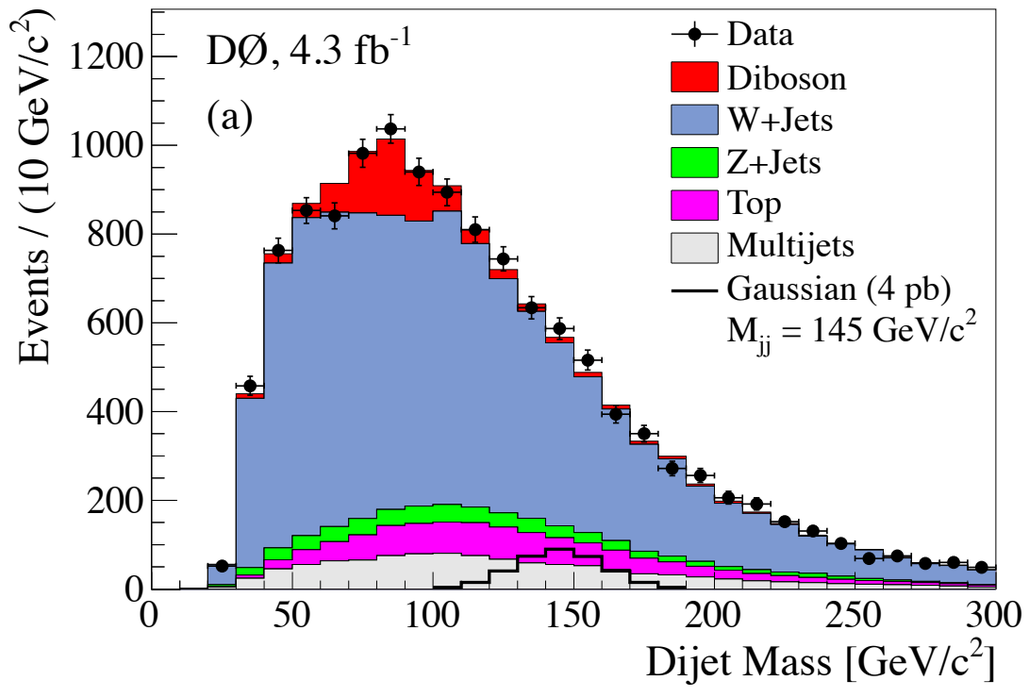


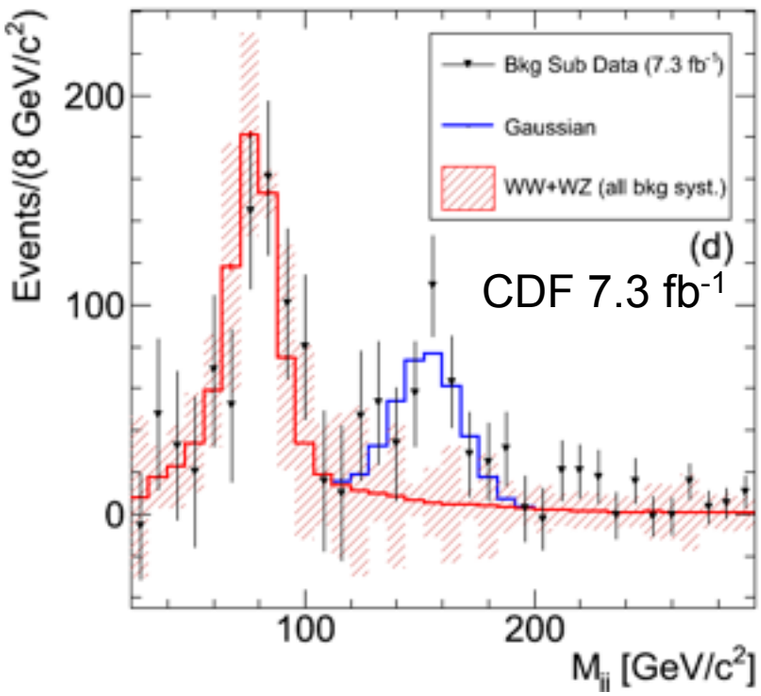
http://www-cdf.fnal.gov/physics/exotic/r2a/20110718.highmasszz/index.html

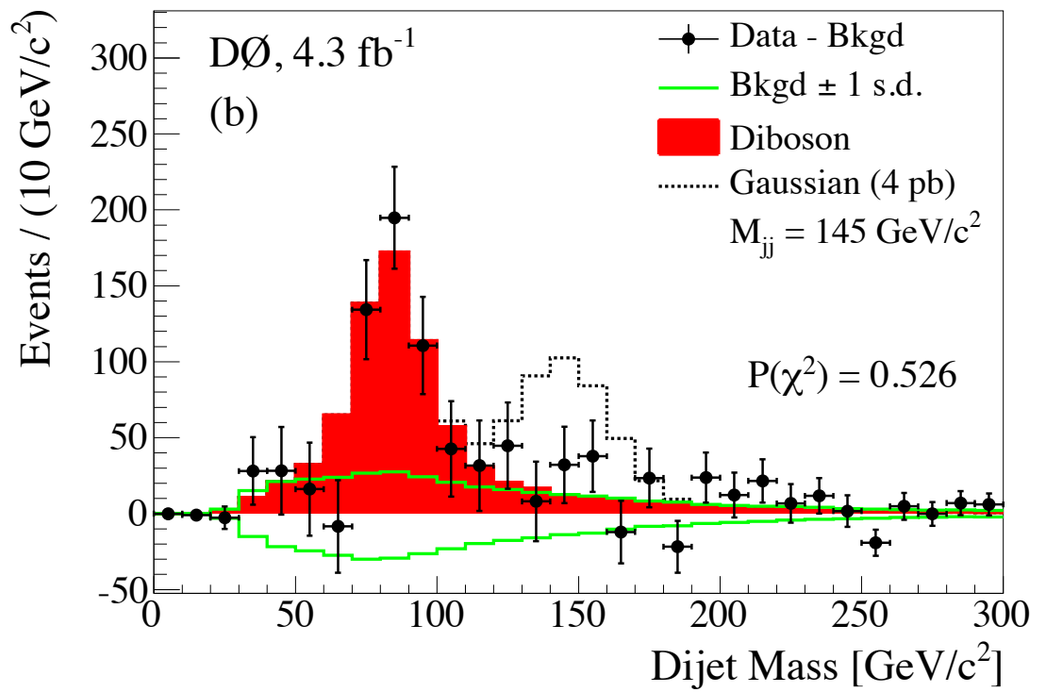
W+JJ

- Structure in M_{jj} in W+W/Z cross section measurement reported by CDF
  - Background of interest for Higgs and several exotic searches



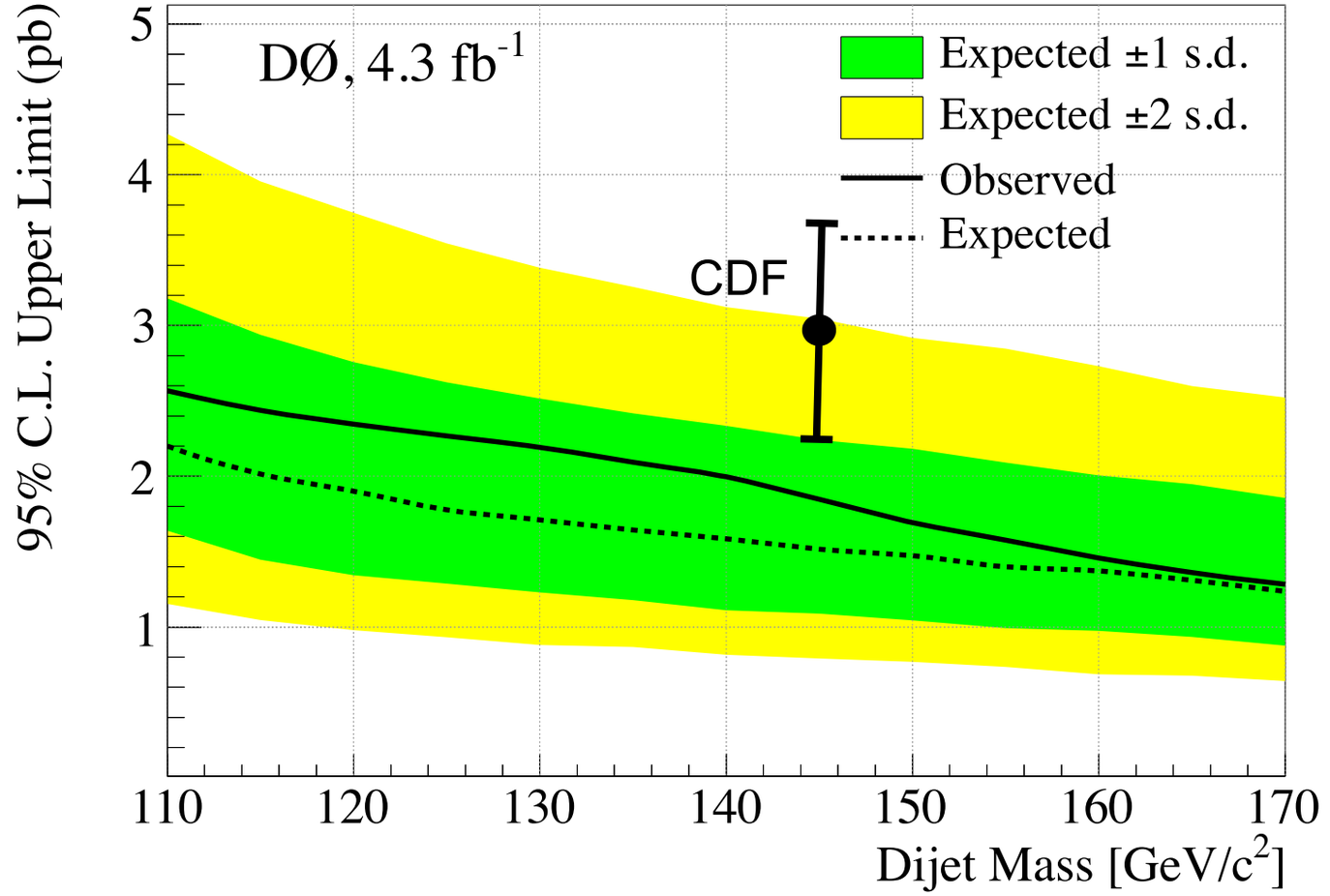






SUMMARY OF W+JJ AT TEVATRON

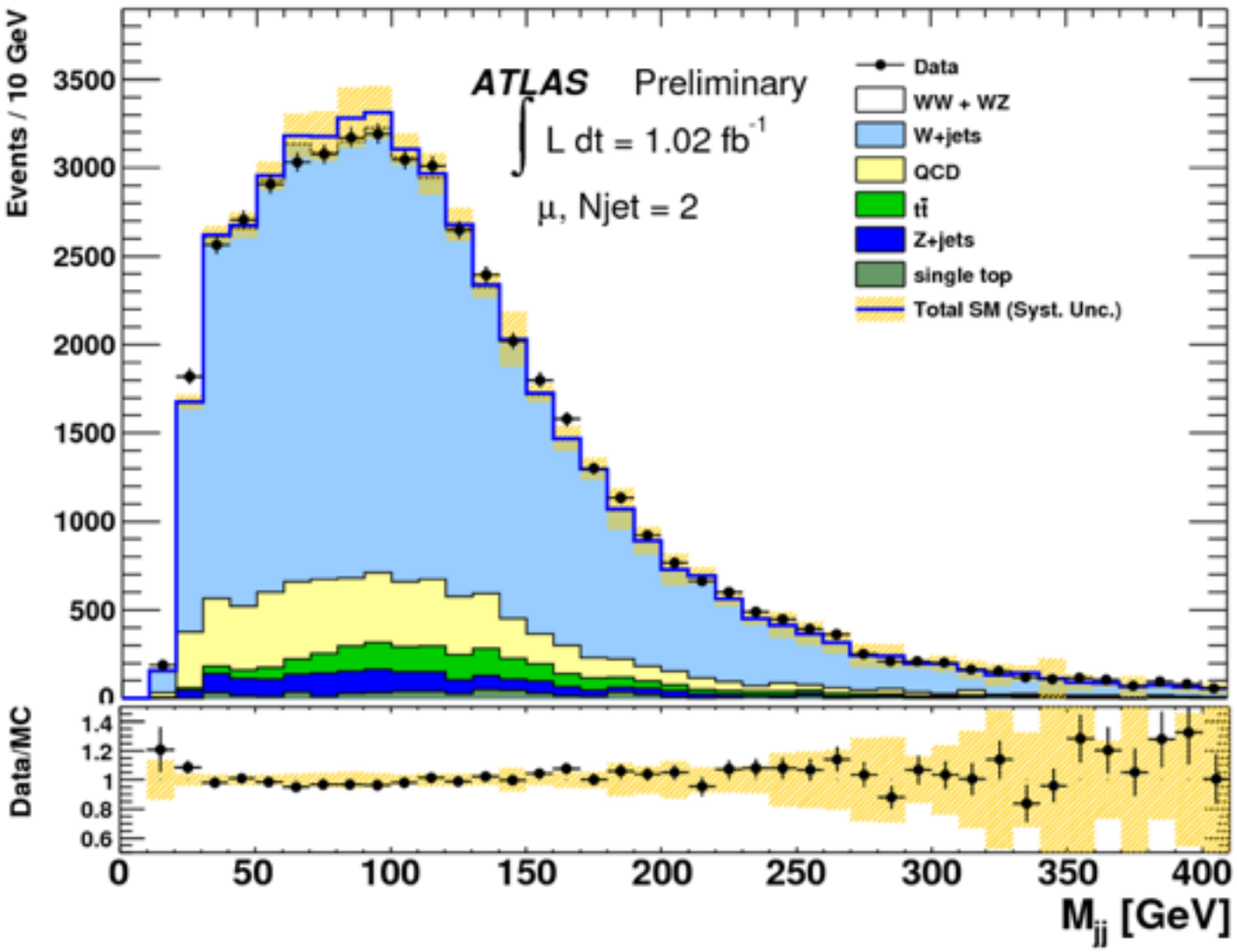
- M_{jj} structure not confirmed by D0
  - small differences exist but unlikely to wash out a peak
- D0 measured cross section: 0.82 ± 0.83 pb **D0: PRL 107, 011804 (2011)**
- Original CDF cross section: ~4 pb
- Latest CDF: 3.0 ± 0.7 pb **CDF: http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html**
- interesting cross check at LHC

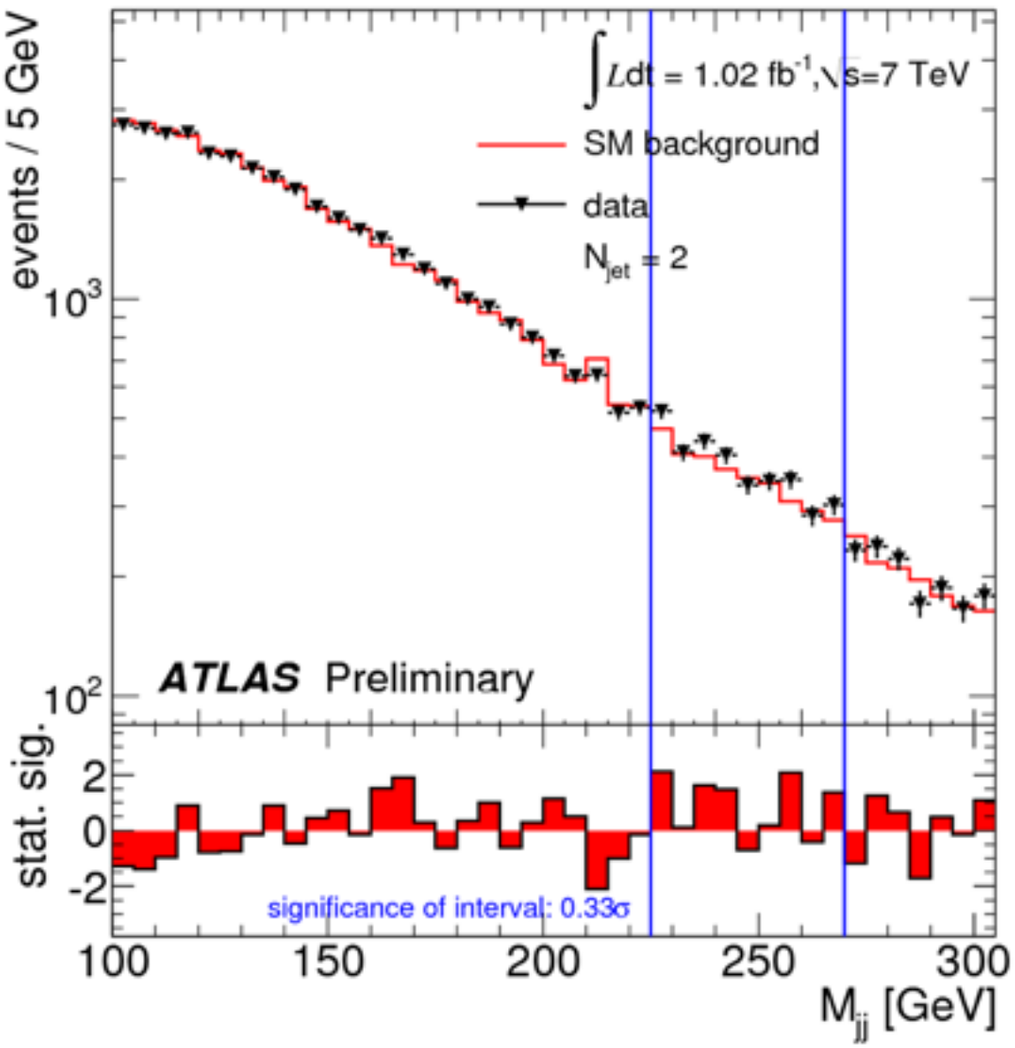


W+JJ AT LHC

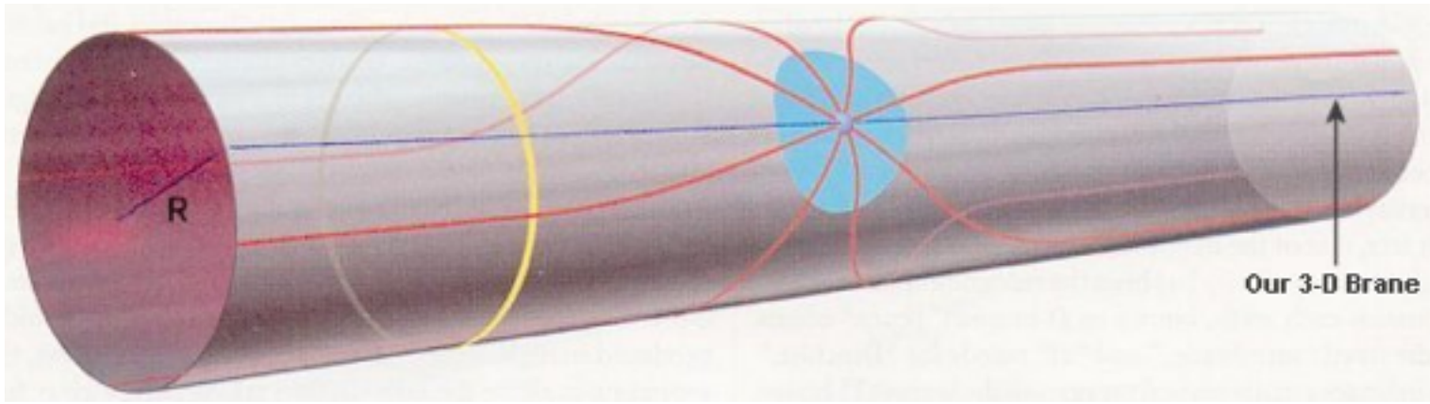
- Similar strategy and selection as CDF
  - #jet = 2 at CDF probably should be relaxed at LHC
  - Significance of 0.95 sigma in N>=2 sample

ATLAS-CONF-2011-096





- No deviation from SM observed



Fundamental Planck Scale

Apparent Planck Scale

# of EDs

$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

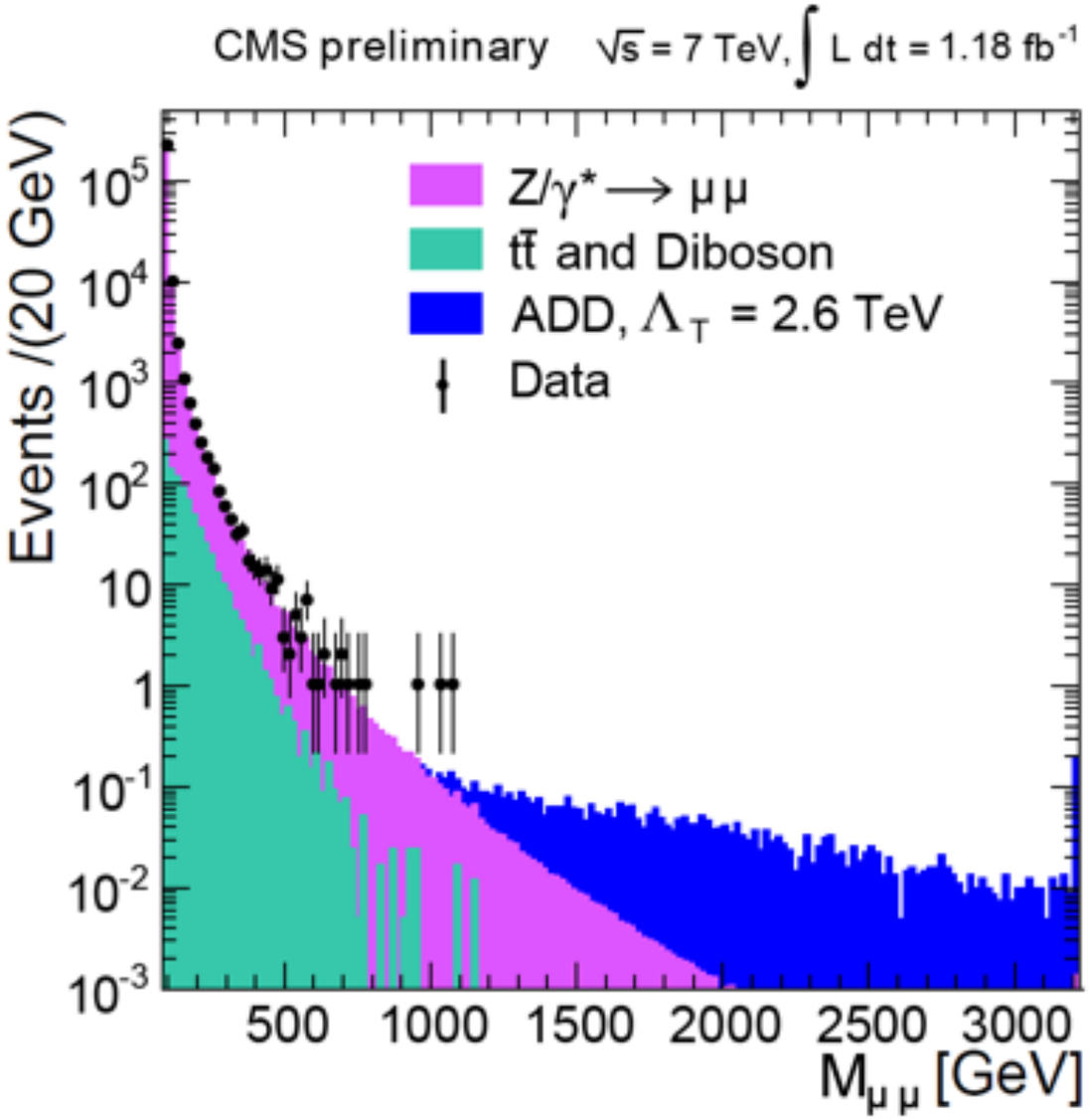
Size of ED

EXTRA DIMENSIONS

- Large Extra Dimension (ADD)
  - only graviton propagates in the bulk
- Warped Extra Dimension (a la Randall-Sundrum)
  - as ADD with warped geometry for extra dimension $M_{\mathrm{D}} = M_{\mathrm{Pl}} e^{-k r_c \pi}$
- Universal Extra Dimension (UED)
  - all particles propagate in the bulk

μμ AND γγ

- Enhanced cross section at high mass
  - Large number of KK states
  - not a single resonance to resolve but rather a continuum enhancement
- Counting experiment for M > M_{min}
  - M_{min} μμ: 1.1 TeV M_{in} γγ: 0.8 TeV



$$\sigma_{\mathrm{ADD}} = \sigma_{\mathrm{SM}} + A\eta_G\,\sigma_{\mathrm{int}} + B\eta_G^2\,\sigma_{\mathrm{ED}}$$

$$\eta_G = \mathcal{F}/M_S^4$$

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & \text{if } n_{\mathrm{ED}} = 2 \\ \frac{2}{(n_{\mathrm{ED}}-2)} & \text{if } n_{\mathrm{ED}} > 2 \end{cases}$$

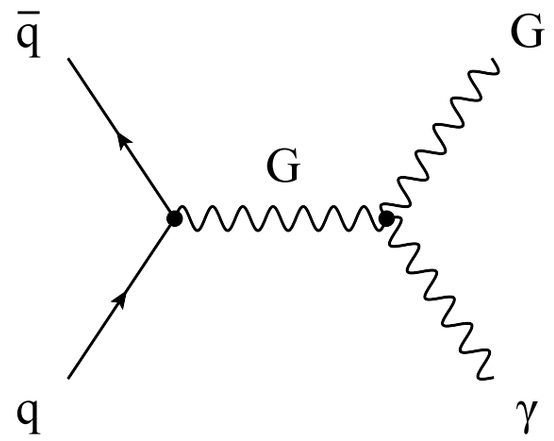
Upper Limit on M_s (no K-factor)

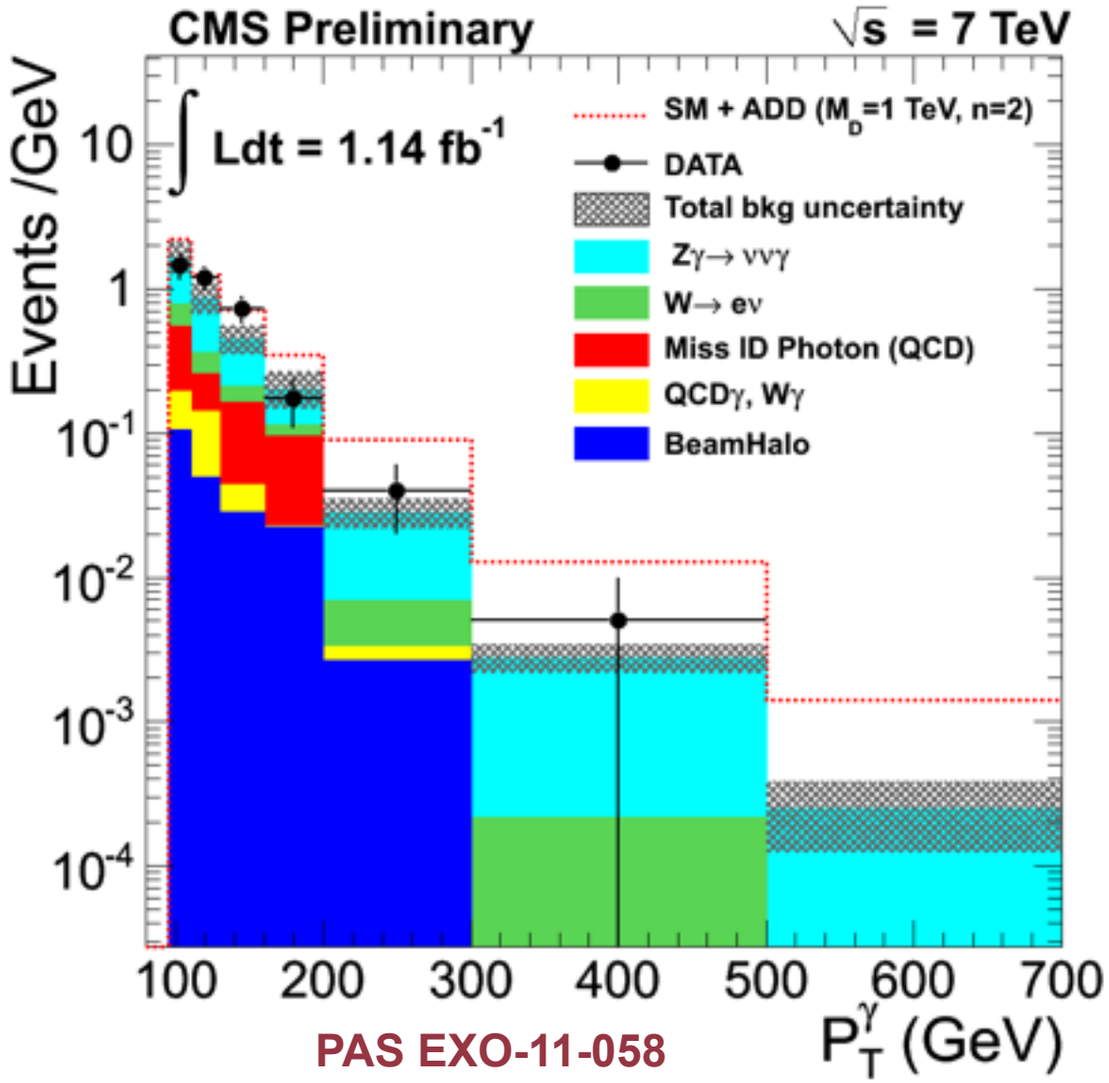
	n = 2	n = 3	n = 4	n = 5	n = 6	n = 7
μμ	2.6	3.1	2.6	2.3	2.1	2.0
γγ	3.2	3.4	2.8	2.6	2.4	2.2

μμ: PAS-EXO-11-039 **γγ: PAS EXO-11-038**

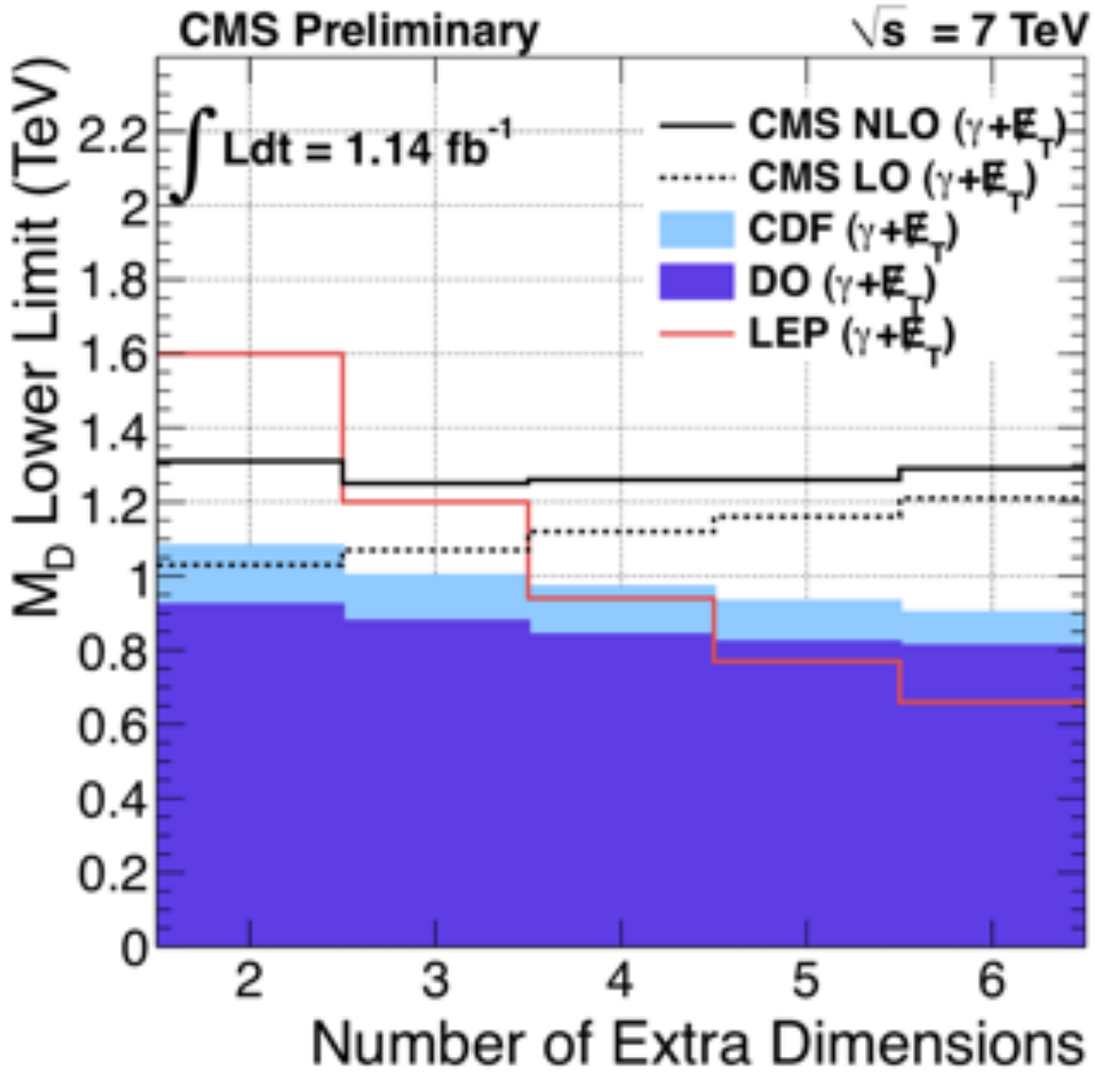
MONO-PHOTON + MET

- Experimentally challenging
  - 1 photon, MET and no other activity
  - excellent estimate of non-beam background with ECAL time measurement
- Look for excess in photon p_T spectrum



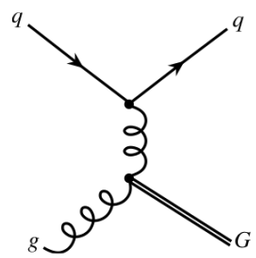


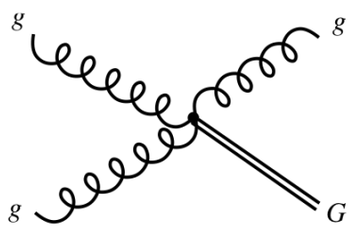
PAS EXO-11-058

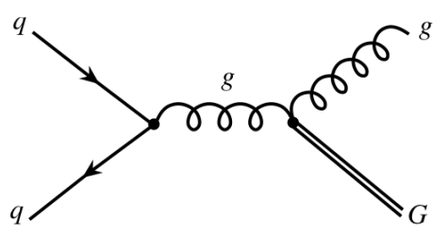


MONO-JET + MET

- Similar challenge to monophoton
  - 1 jet and MET
  - main background from invisible Z measured with data driven method
- Comparable limits in M_D from both experiments

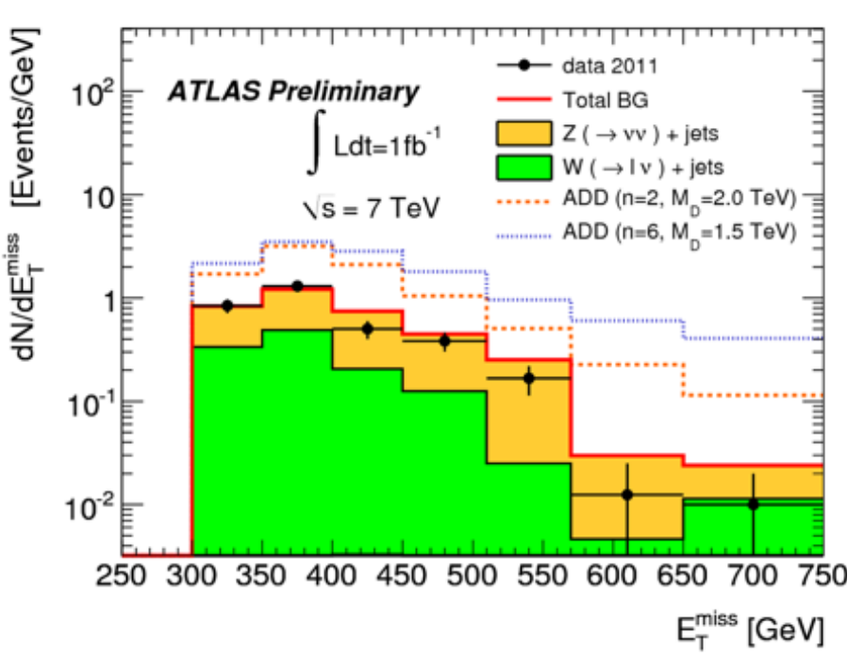


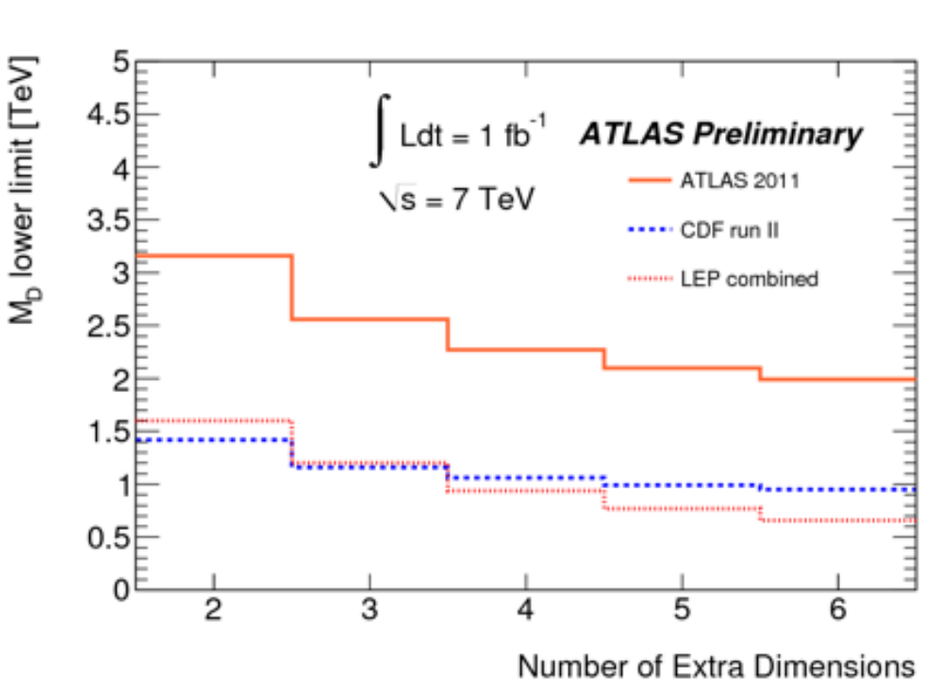


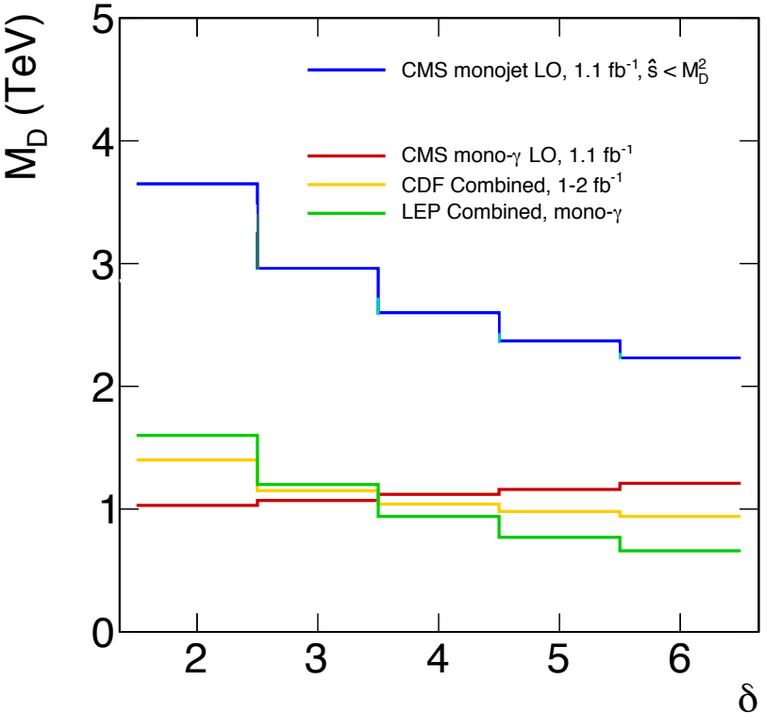


ATLAS-CONF-2011-096

CMS: PAS EXO-11-059

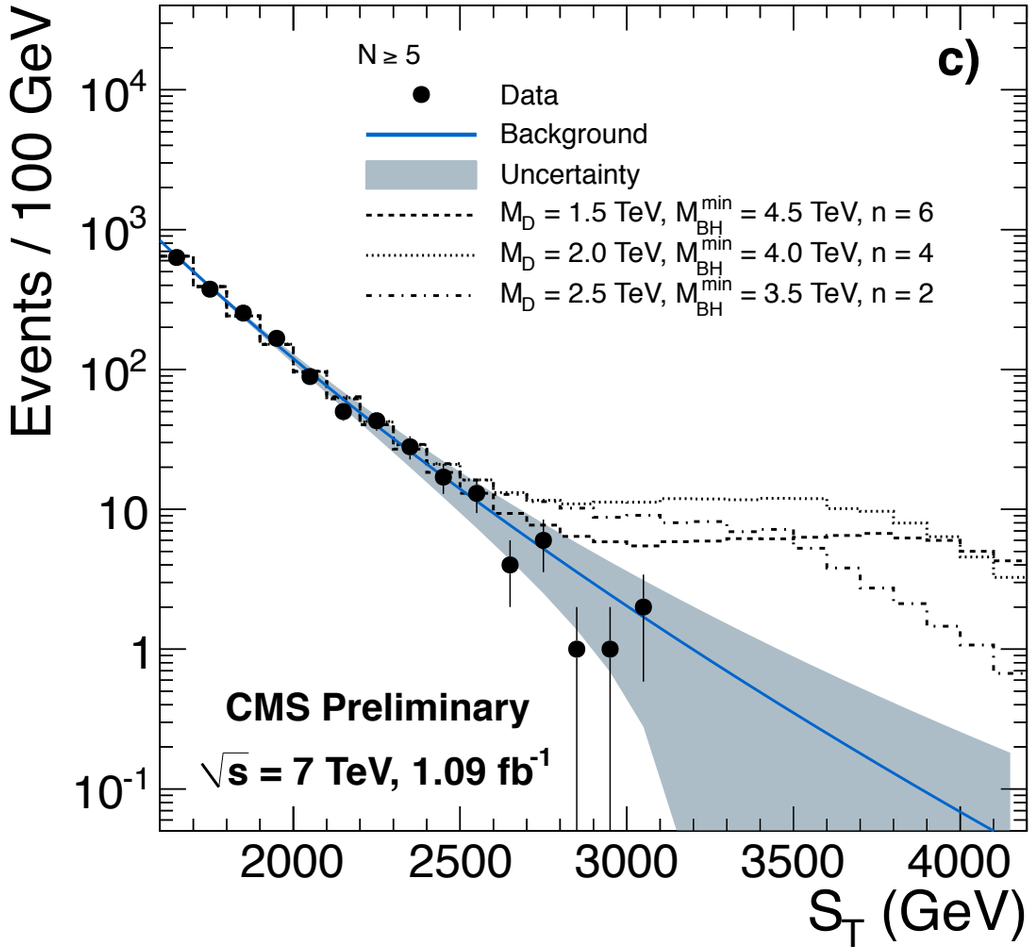


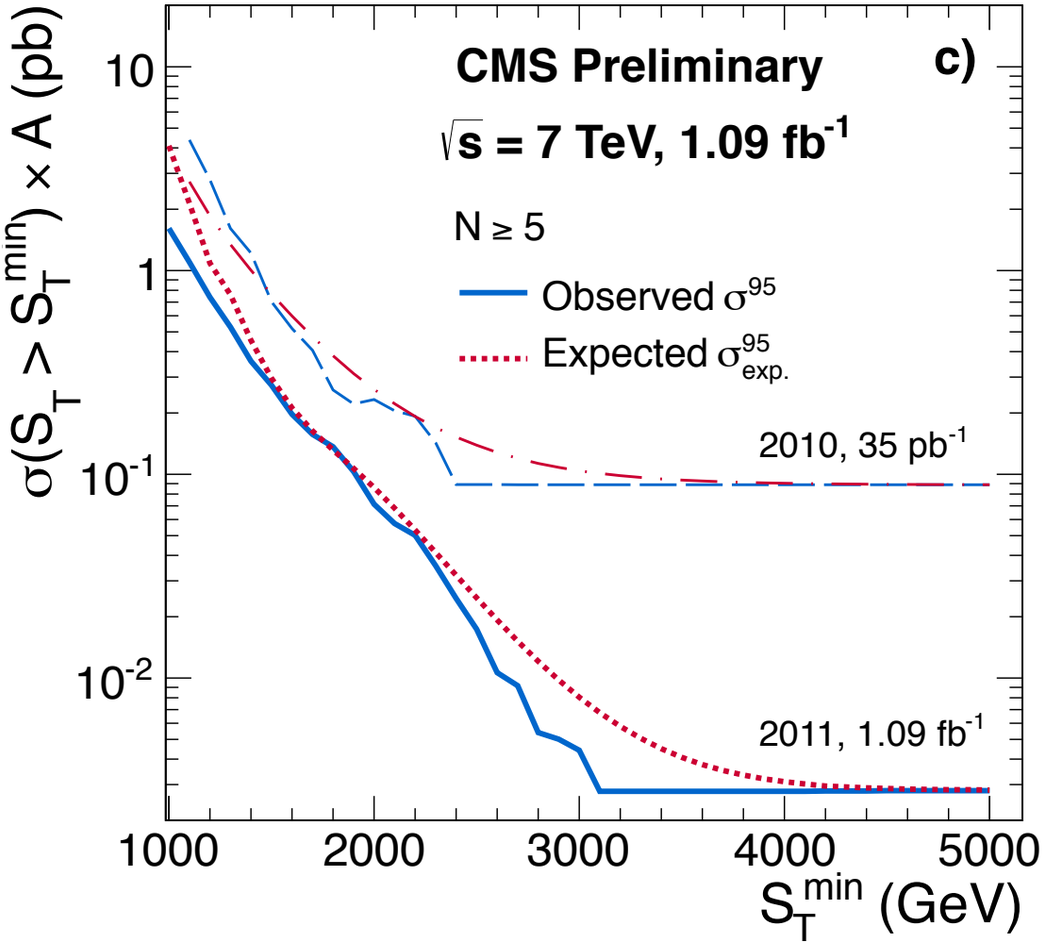


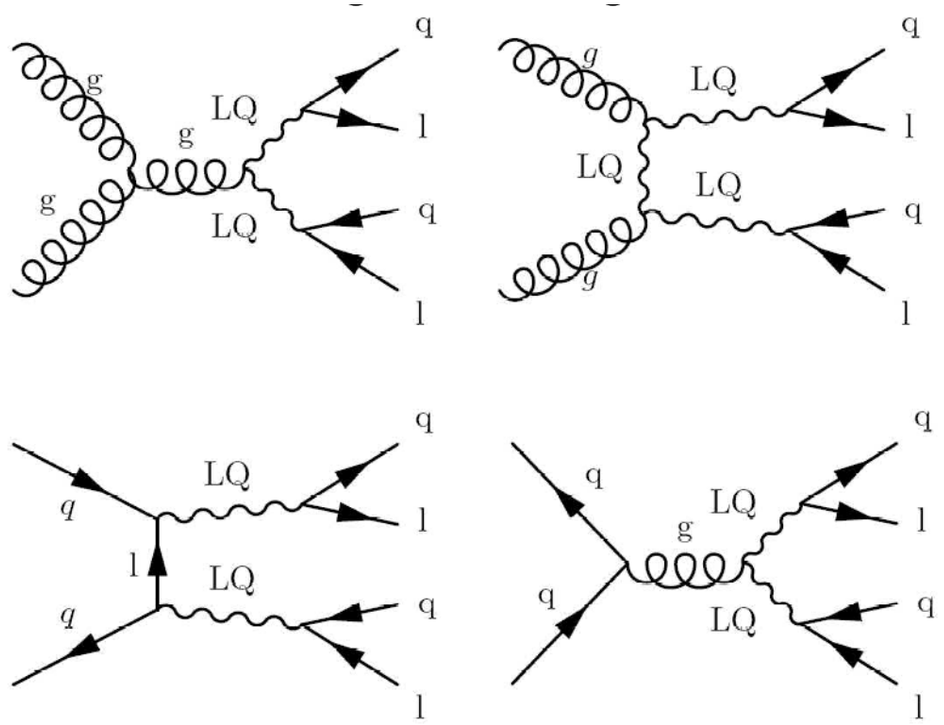


MICROSCOPIC BLACK HOLES

- Microscopic black holes decaying due to Hawking radiation
- General assumption: isotropic and democratic decay in all species
  - high multiplicity final state — **CMS: PAS EXO-11-071**
  - CMS: multi-jet+lepton events with large total transverse energy — **ATLAS-CONF-2011-065**
  - ATLAS: multijet. Also same-sign dilepton in high track-multiplicity events — **ATLAS-CONF-2011-068**
    - Also search for Quantum Black Holes in di-jet final state — **ATLASNew Journal of Physics 13 (2011) 053044**





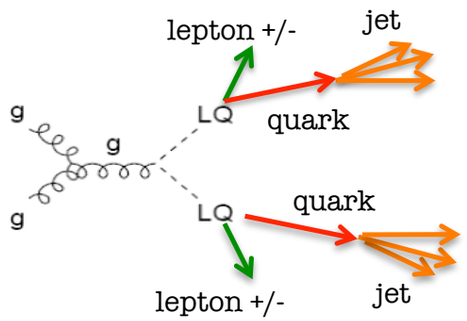


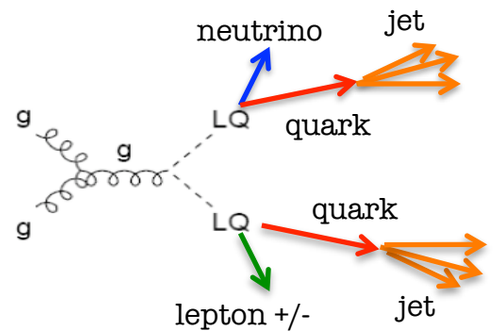
LEPTOQUARKS

1ST GENERATION

- Many theories predict the existence of Leptoquarks
  - Grand Unified Theories
  - Superstring-inspired E6 models
  - Technicolor Schemes
  - Composite Models
- Assume coupling only to 1 SM generation
- Main observables: LQ mass and

M_{LQ}	LQ mass
β	BR(LQ→$l^{+/-}$ + q)

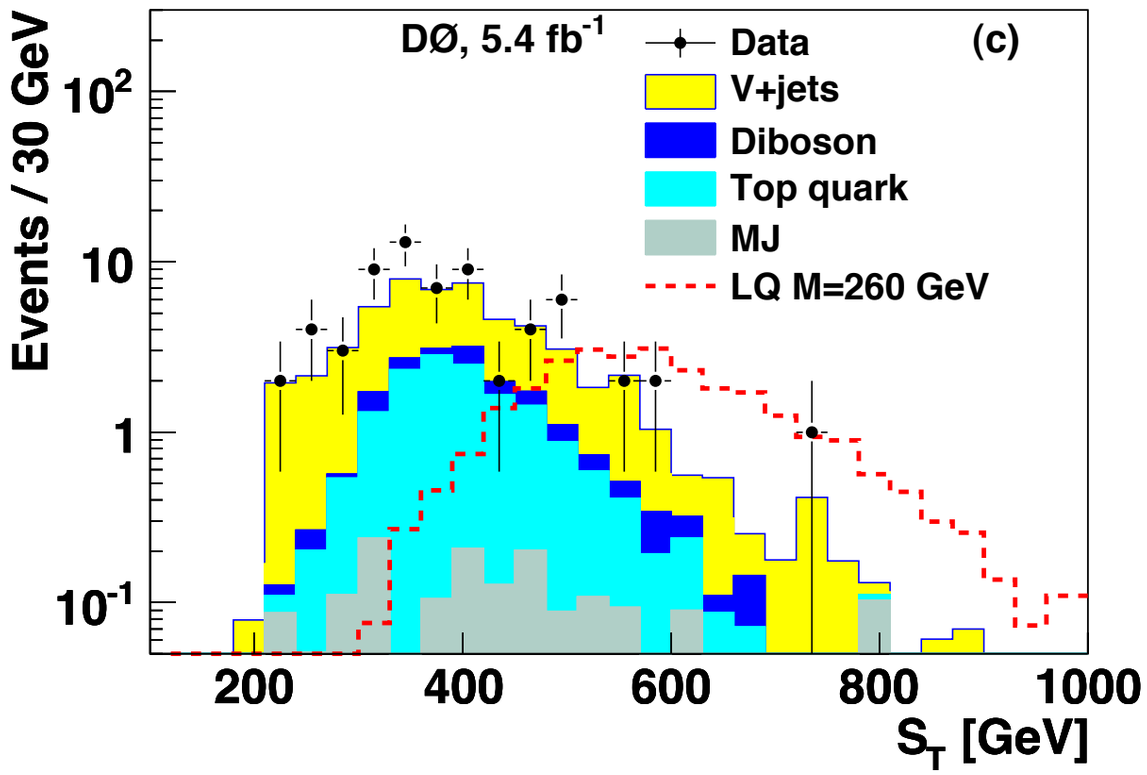


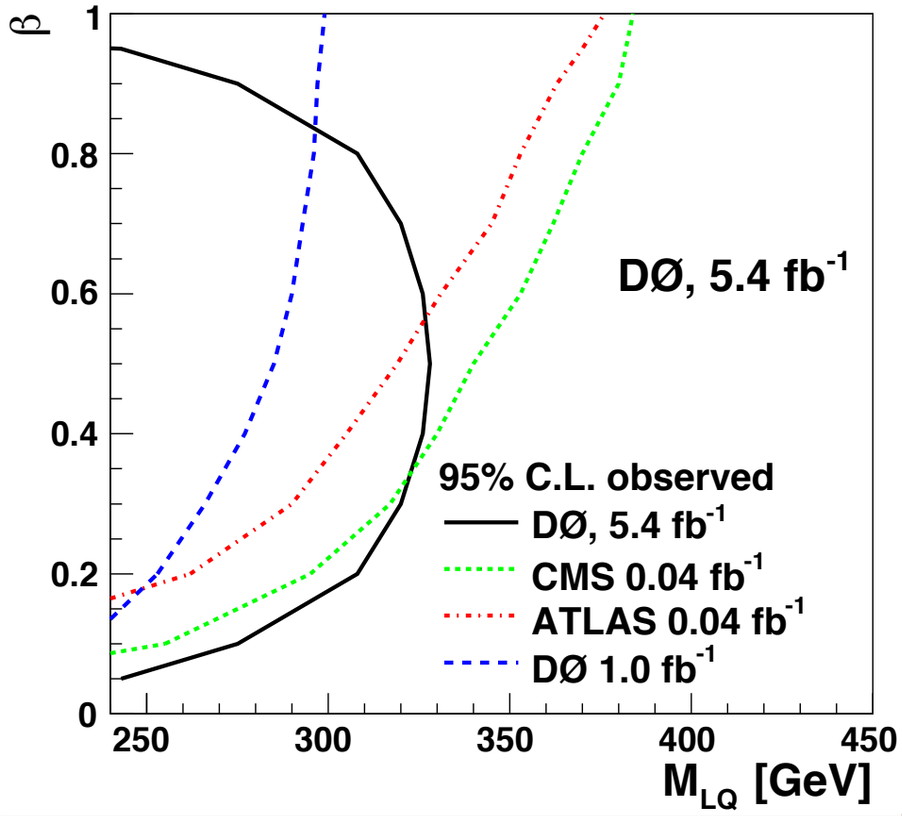


$$S_T = p_T^{\ell 1} + p_T^{\ell 2} + p_T^{j1} + p_T^{j2}$$

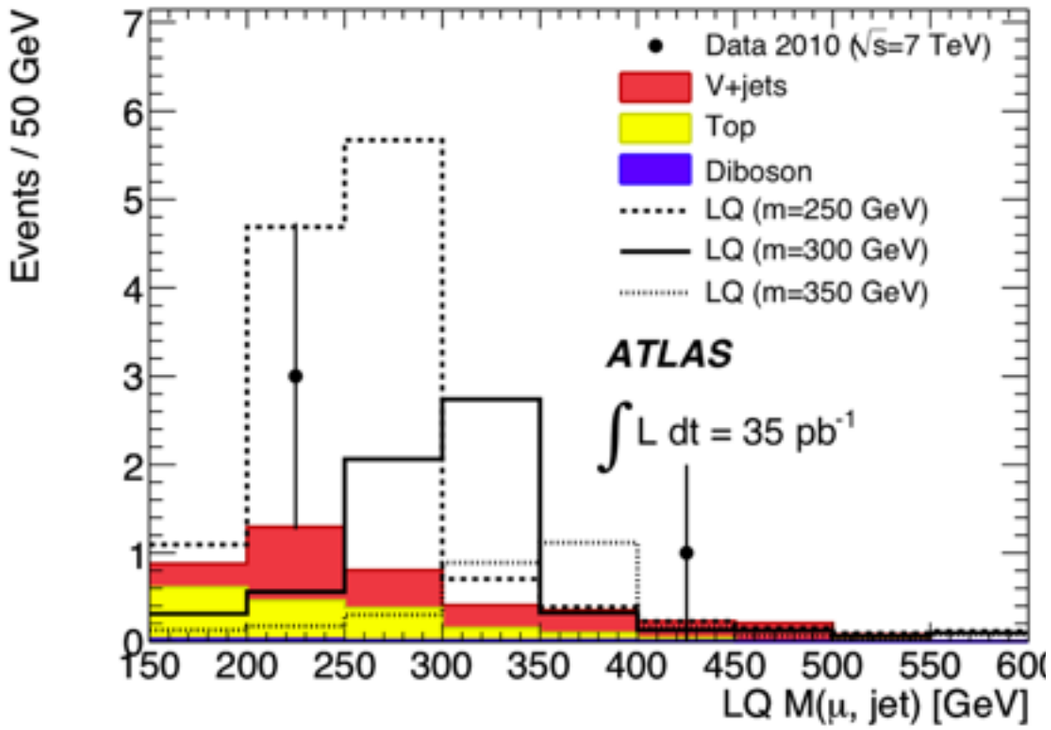
$$S_T = p_T^{\ell 1} + MET + p_T^{j1} + p_T^{j2}$$

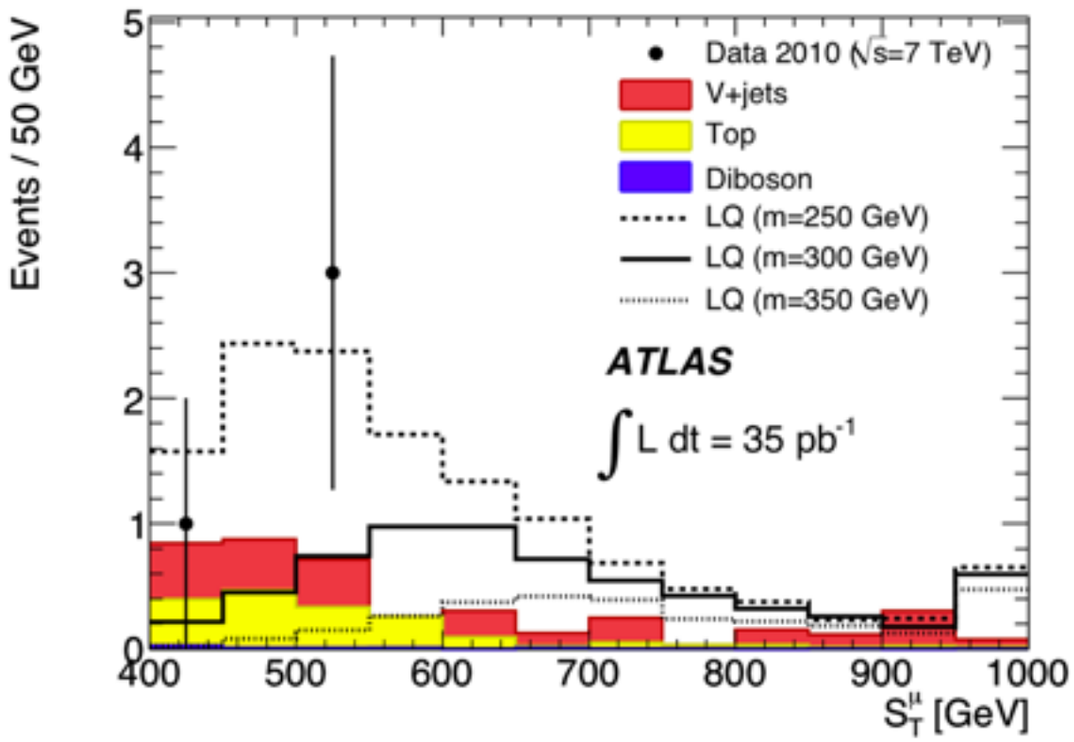
ATLAS: arxiv:1104.4481 CMS: 10.1016/j.PhysLetB.2011.07.089 D0: arXiv:1107.1849v1





2ND GENERATION

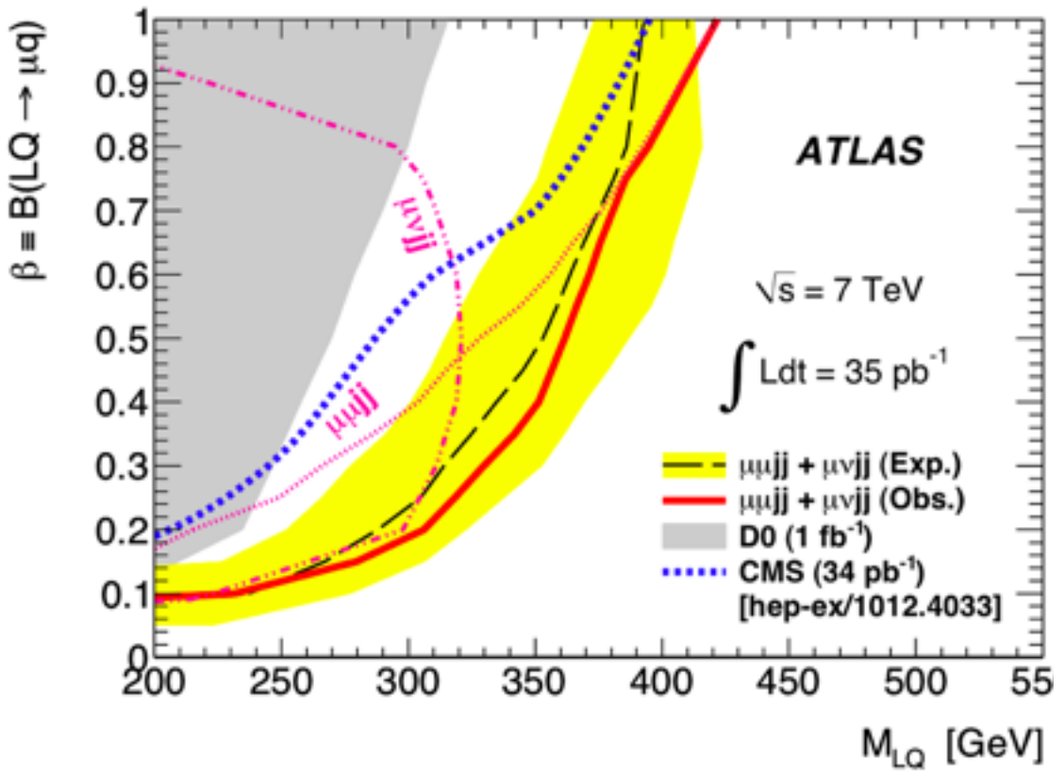




CMS: 10.1103/PhysRevLett.106.201803

ATLAS: arxiv:1104.4481

D0: arXiv:1107.1849v1



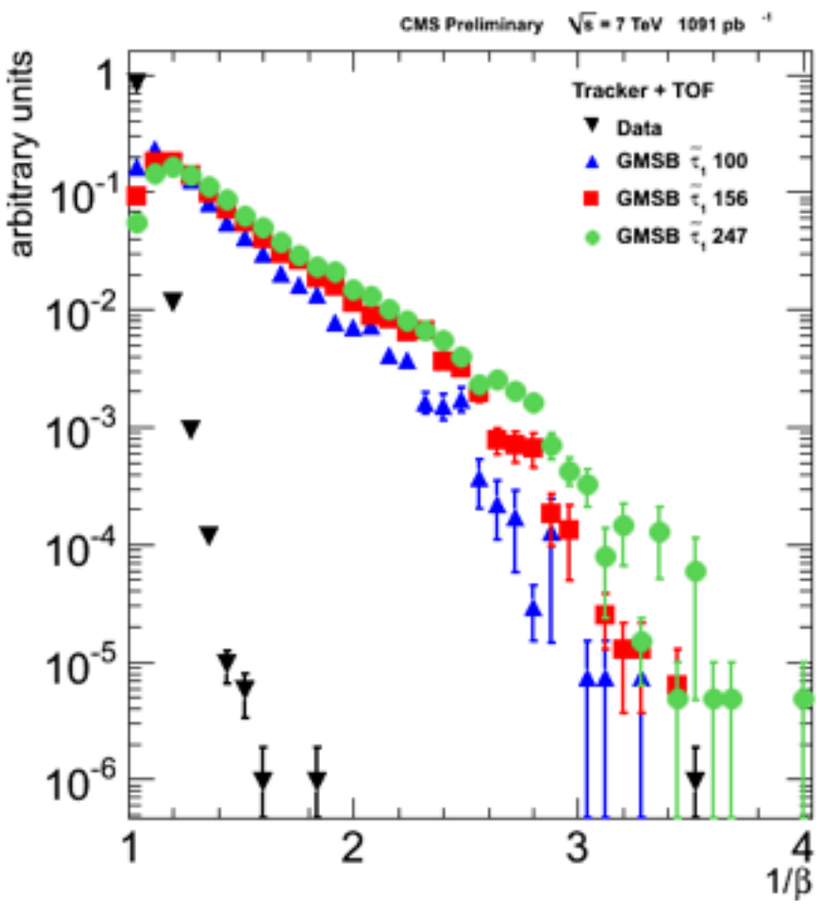
Long-Lived Particles

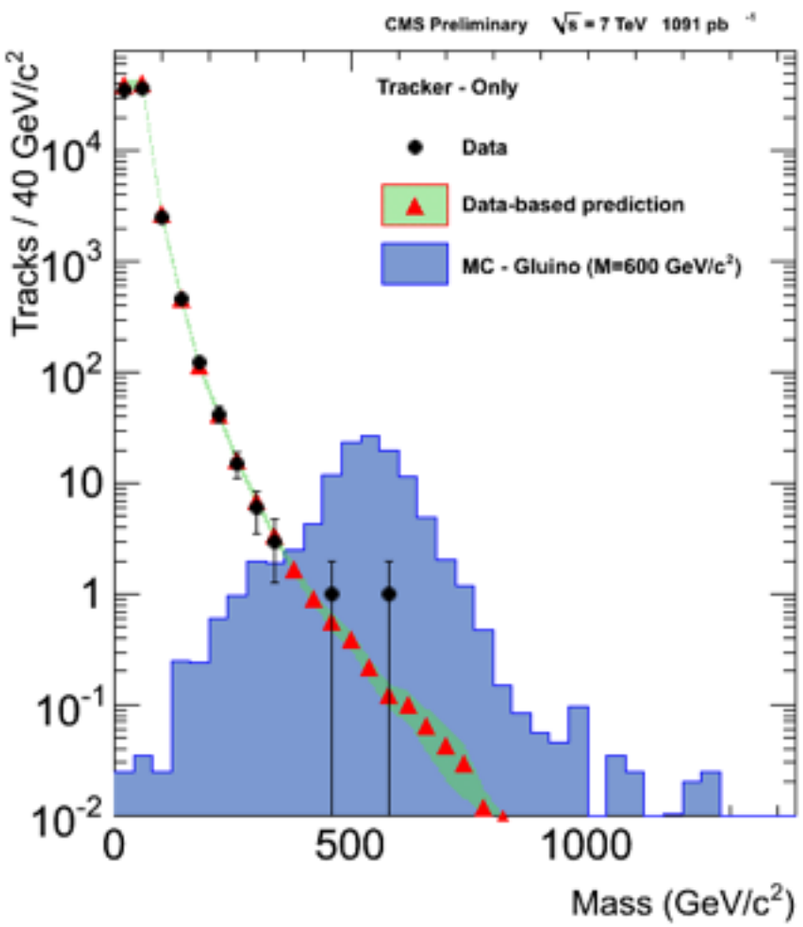
HEAVY STABLE CHARGED PARTICLES

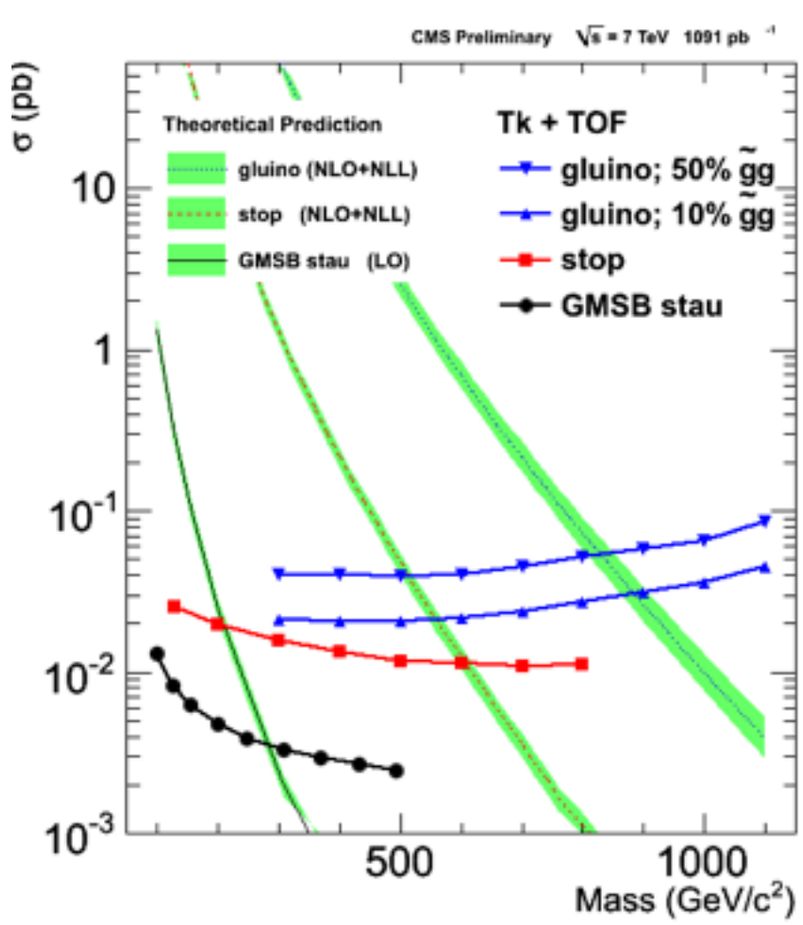
- Gluinos and stops hadronizing in heavy R-hadrons
  - Large ionization in silicon tracker
  - Very slow hence long time of flight (TOF)
- Dedicated muon-like reconstruction and mass estimate from TOF and dE/dX

CMS: PAS EXO-11-022

$$I_h = K\frac{m^2}{p^2} + C$$



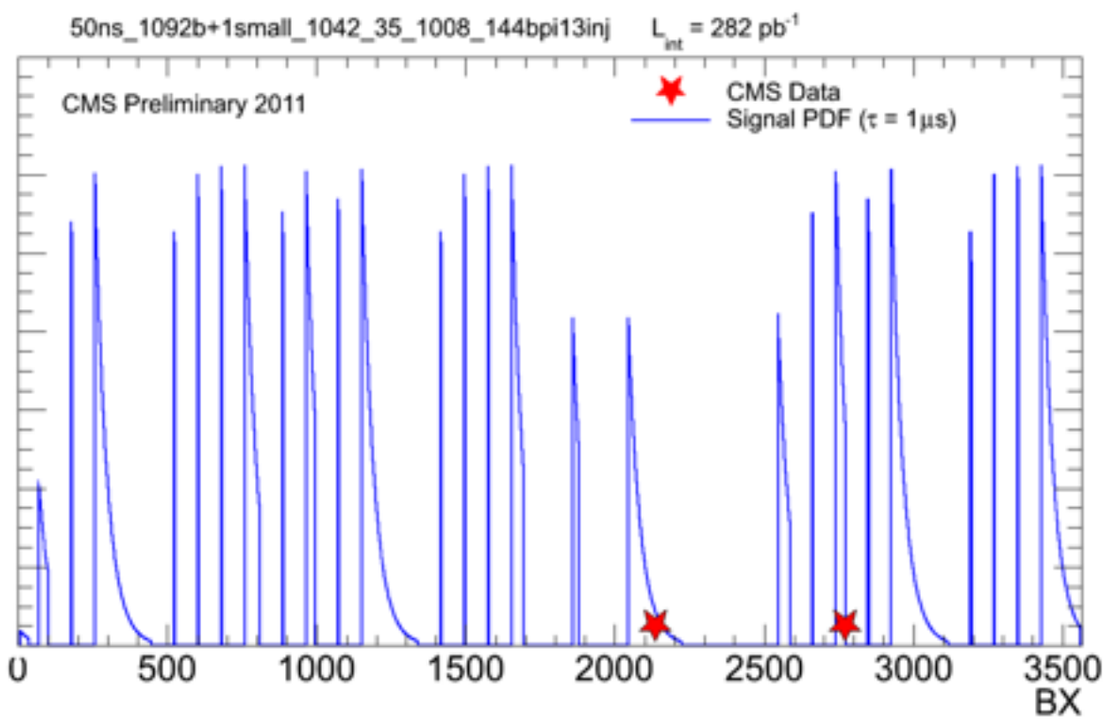


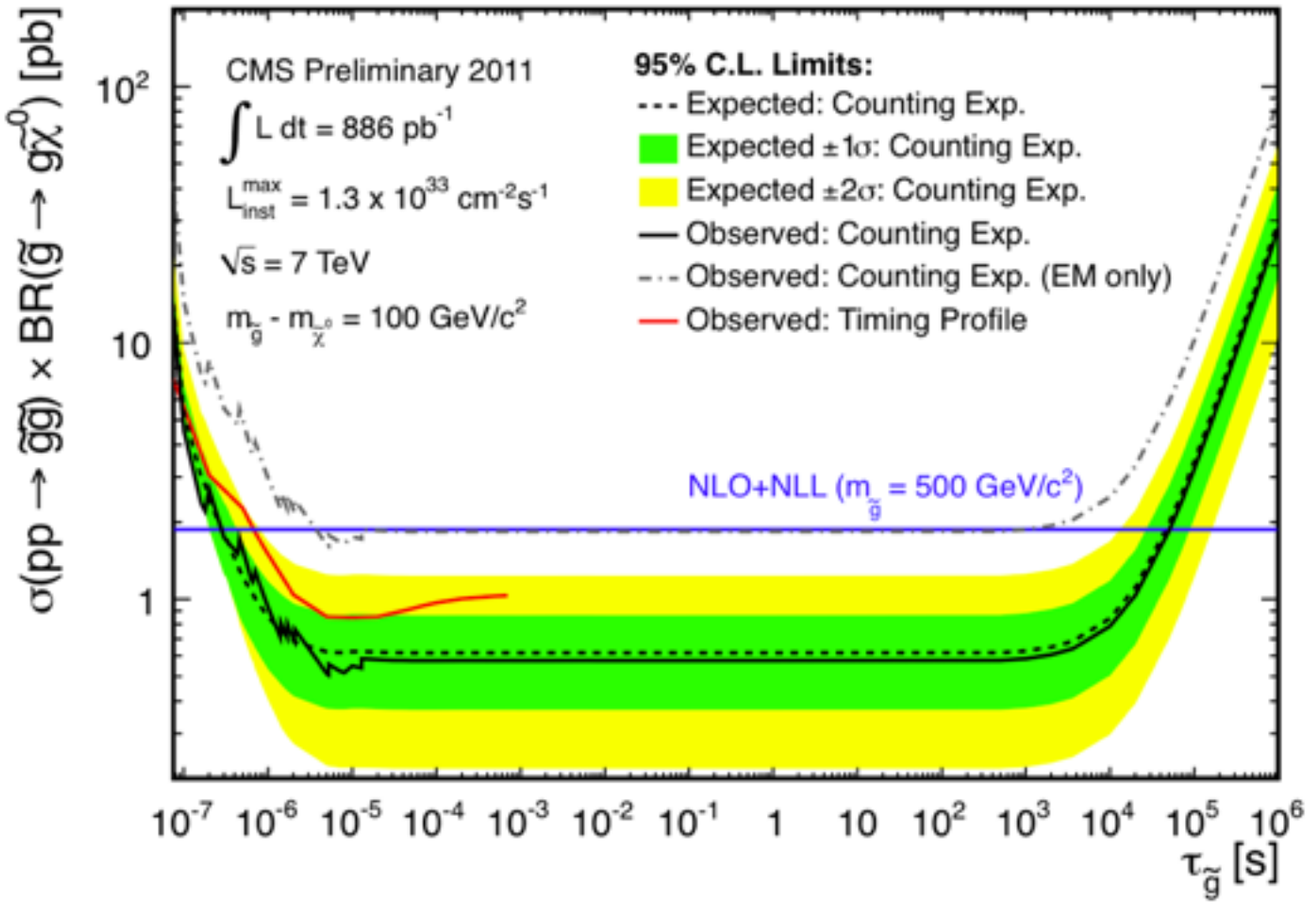


STOPPED HEAVY PARTICLES

- Some heavy R-hadrons could stop due to large ionization
- Detect interactions out-of-time wrt bunch collisions
  - Special trigger for data acquisition while no collisions
  - main background instrumental and non-beam related
- Crucial to have long data-taking periods not just luminosity
- Signal probability determined for each LHC filling scheme

CMS: PAS EXO-11-020



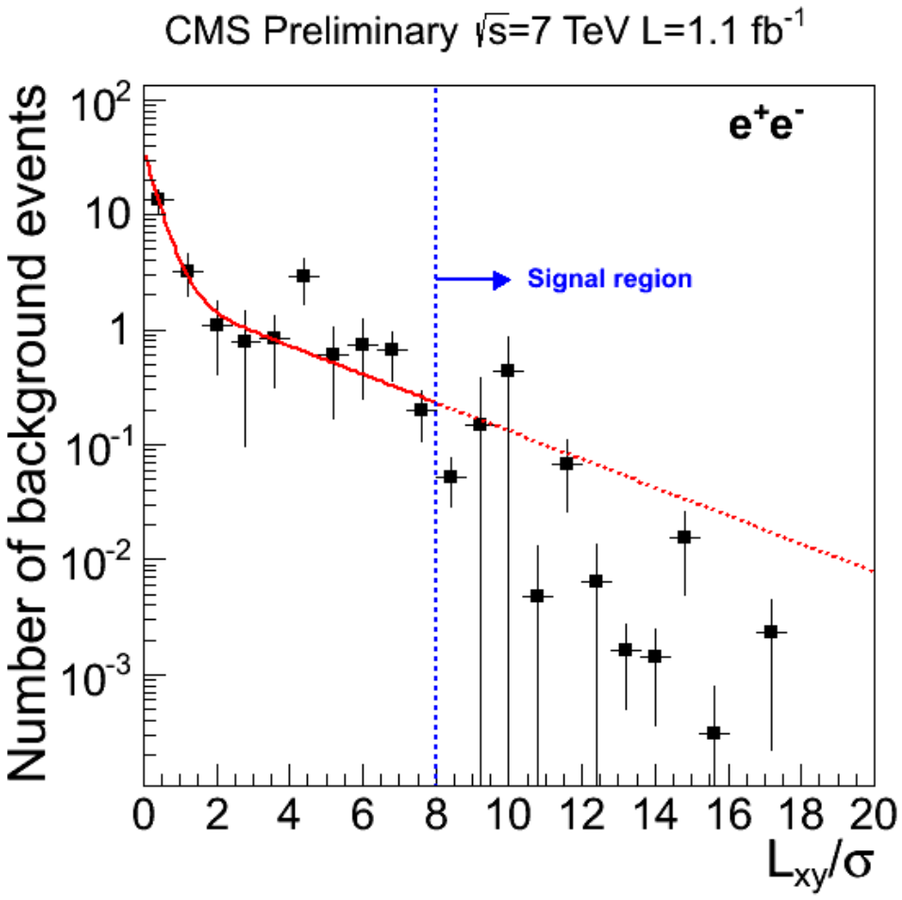


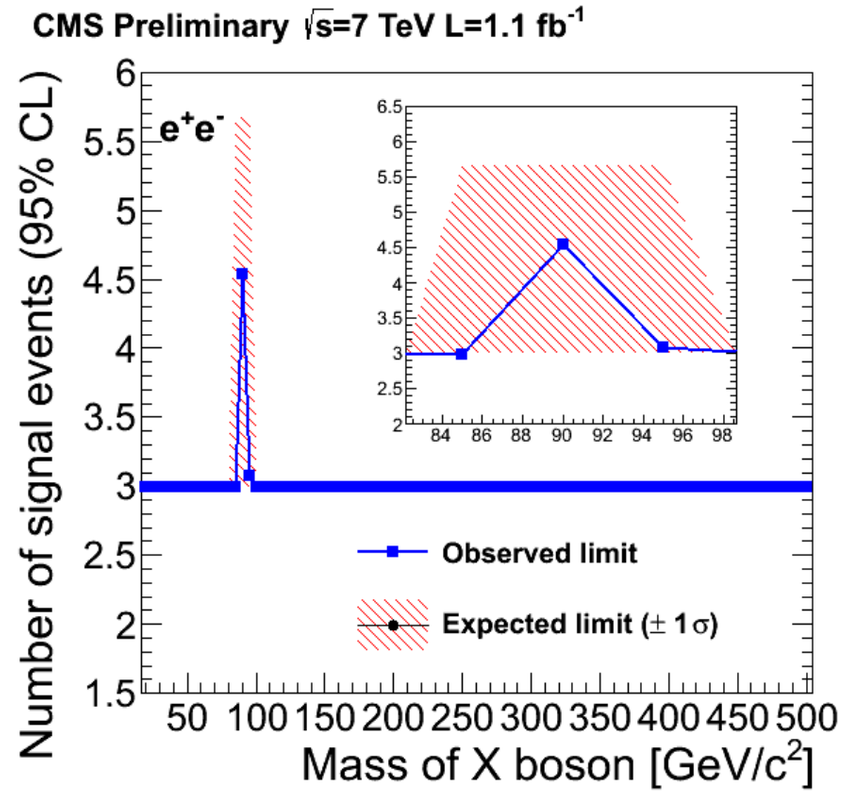
DISPLACED LEPTONS

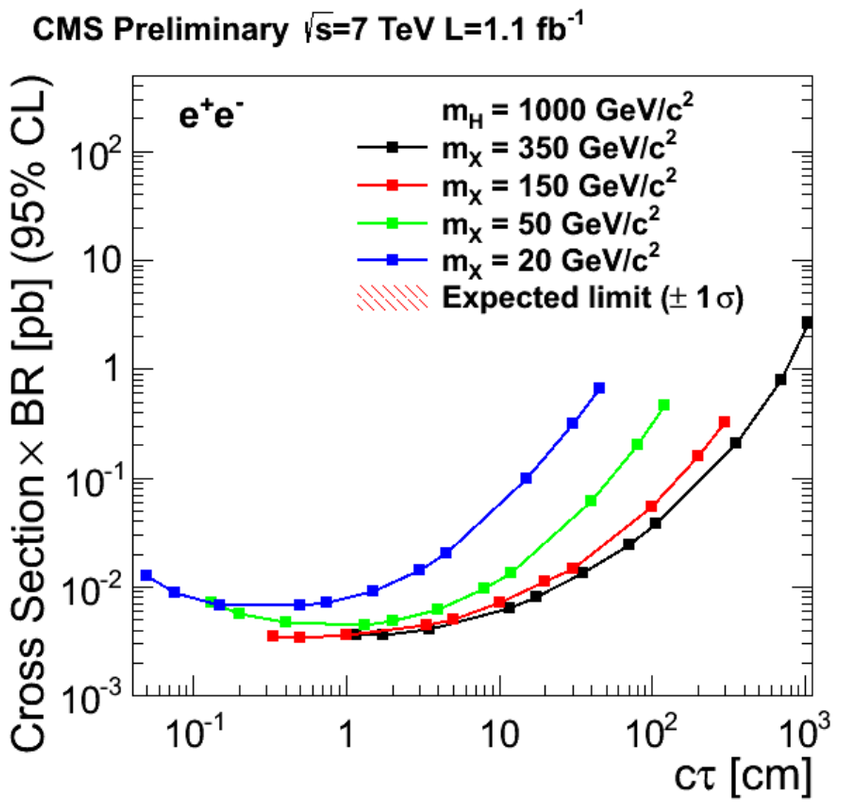
- non-pointing leptons from decay of heavy long-lived

$$Y \rightarrow XX \rightarrow ll\ ll$$

- Background discrimination
  - decay length significance
  - dilepton mass





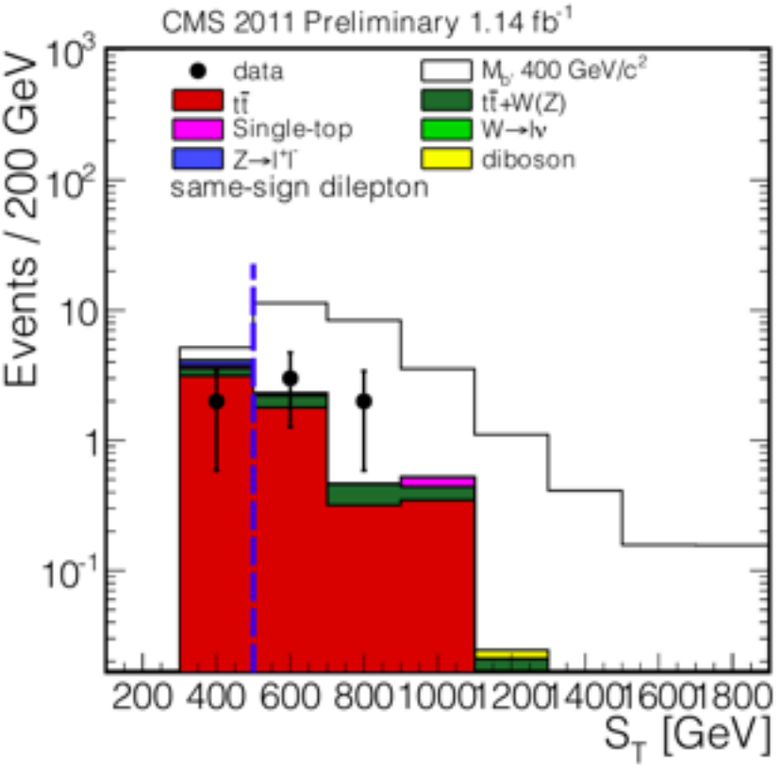


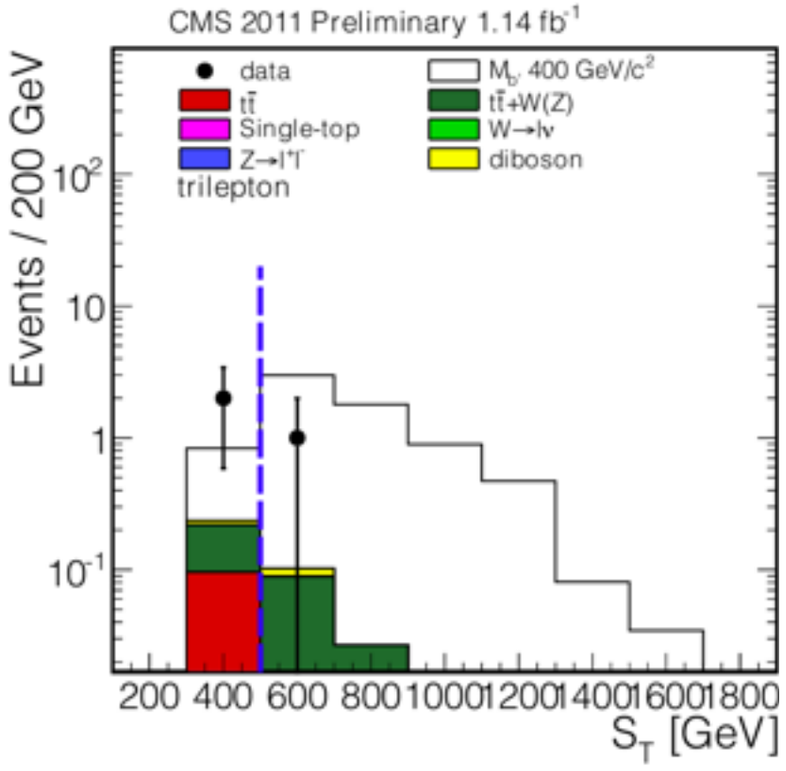
4TH GENERATION

b'→ t + W

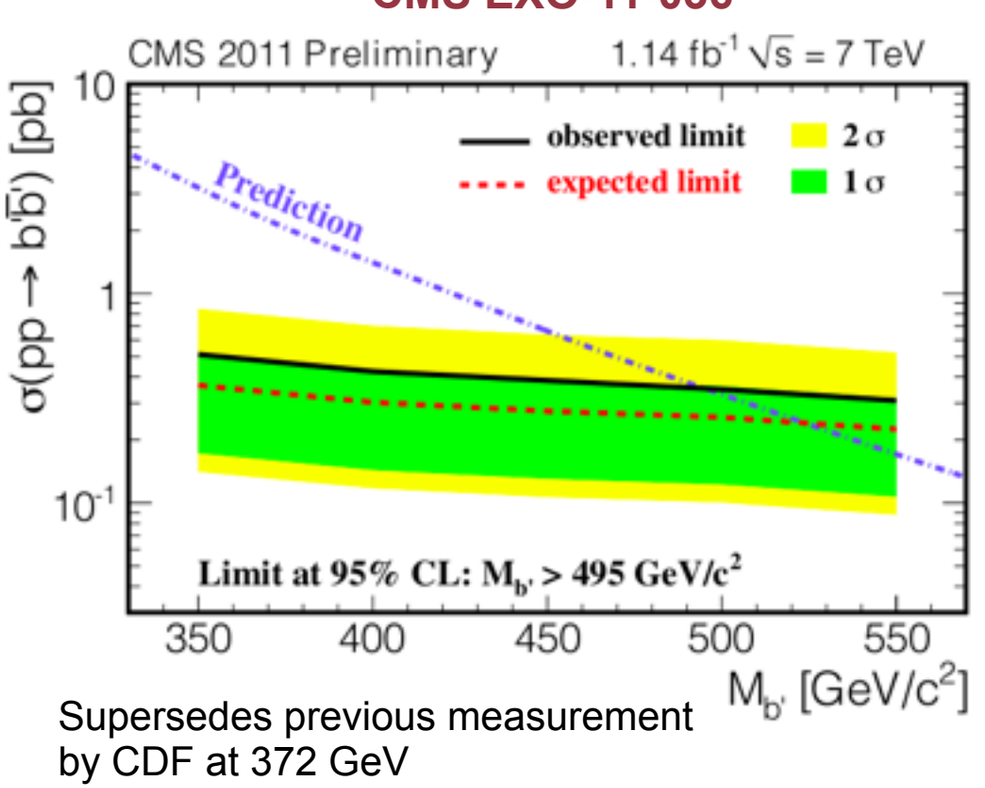
$$b'\bar{b}' \rightarrow tW^-\bar{t}W^+ \rightarrow bW^+W^-\bar{b}W^-W^+$$

- At least 1 b-jet, 2 or 3 leptons
- Main backgrounds determined from lepton fake rate in data
- Dominant systematic uncertainty: b-tagging and lepton efficiency
- Main background discrimination from total transverse energy $\sum p_{\mathrm{T}}(\mathrm{jets}) + \sum p_{\mathrm{T}}(\mathrm{leptons}) + \not{E}_{\mathrm{T}}$





CMS EXO-11-036

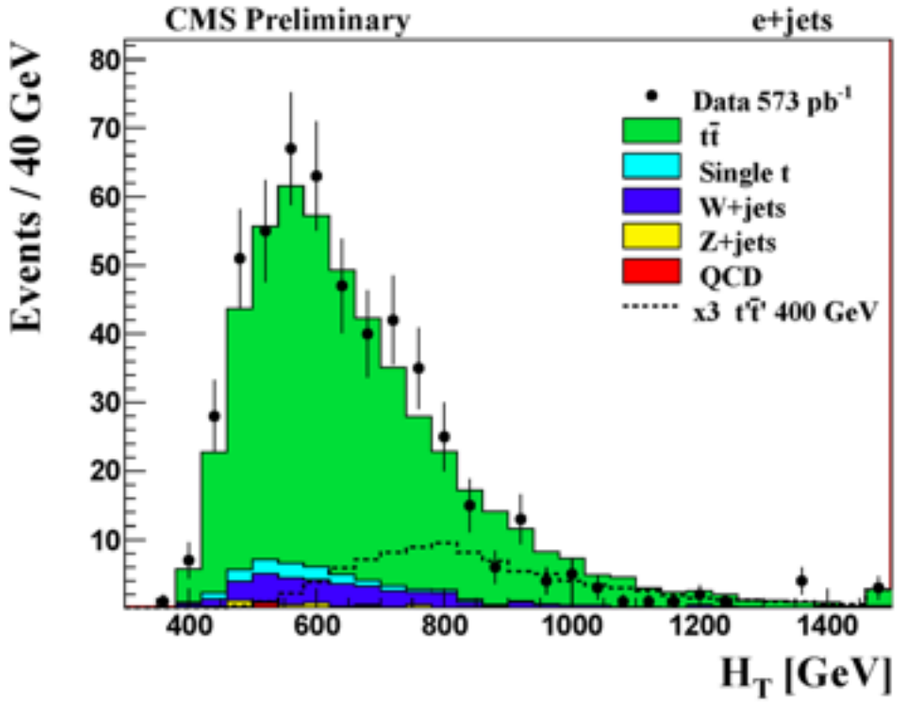


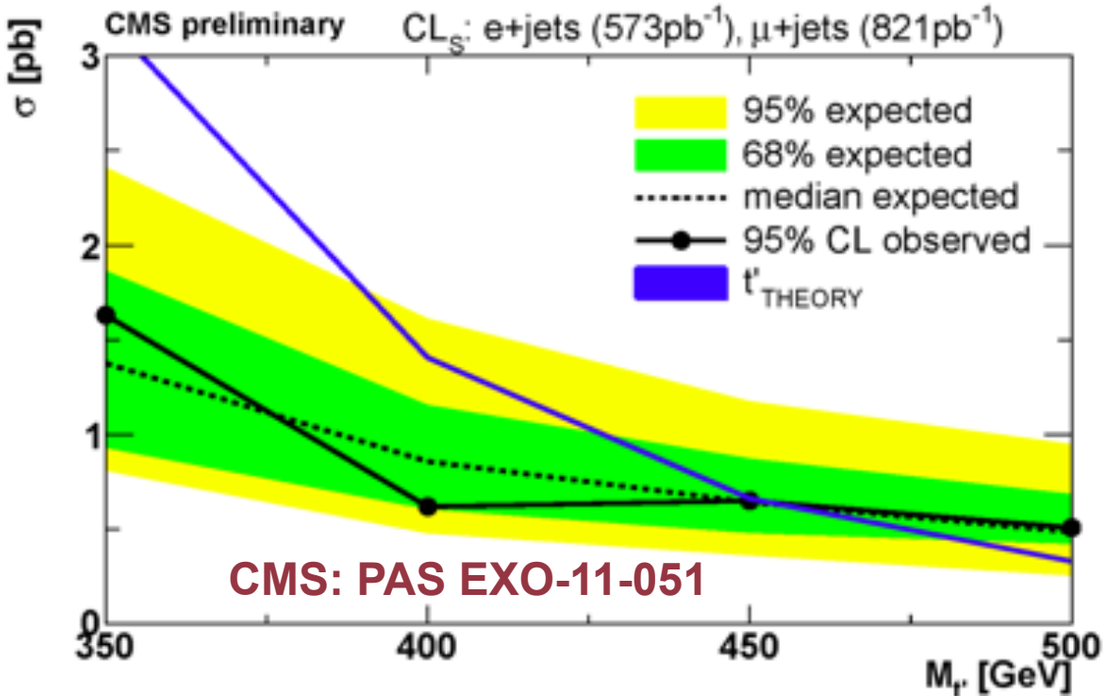
Supersedes previous measurement by CDF at 372 GeV

CDF: PRL106.141803 (2011)

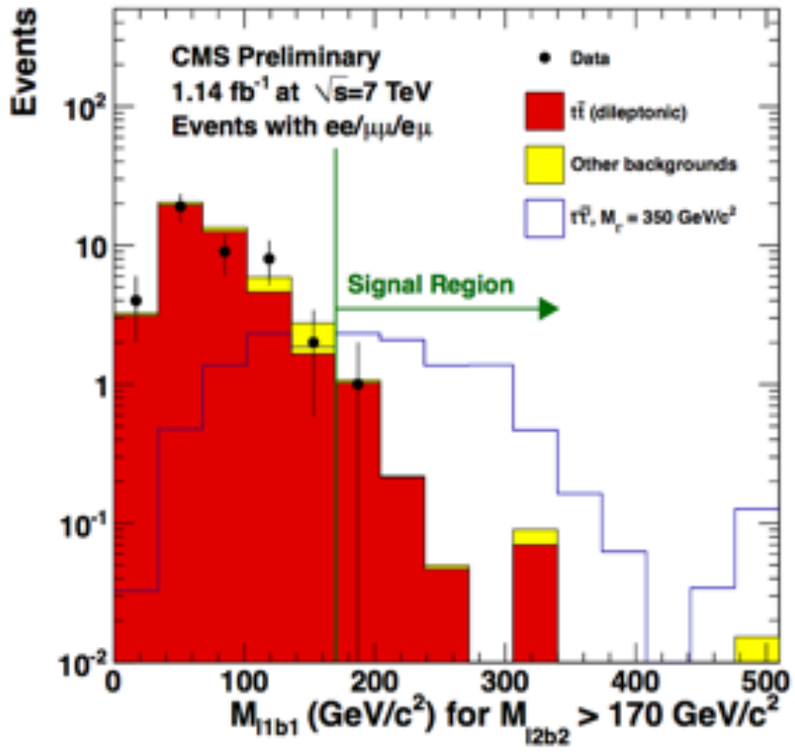
T'→ b + W @ LHC

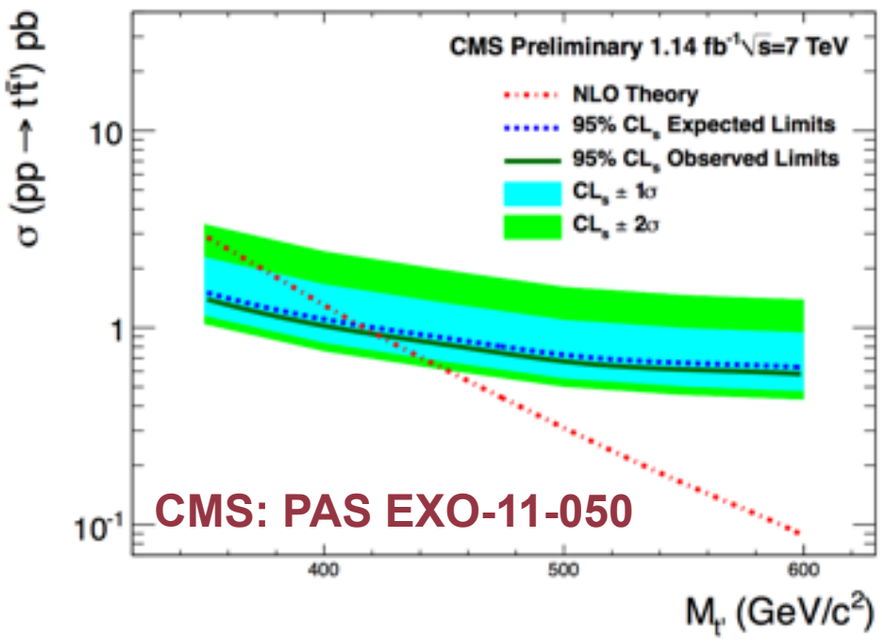
$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$





$t'\bar{t}' \rightarrow bW\bar{b}W \rightarrow bl\nu\bar{b}l\nu$



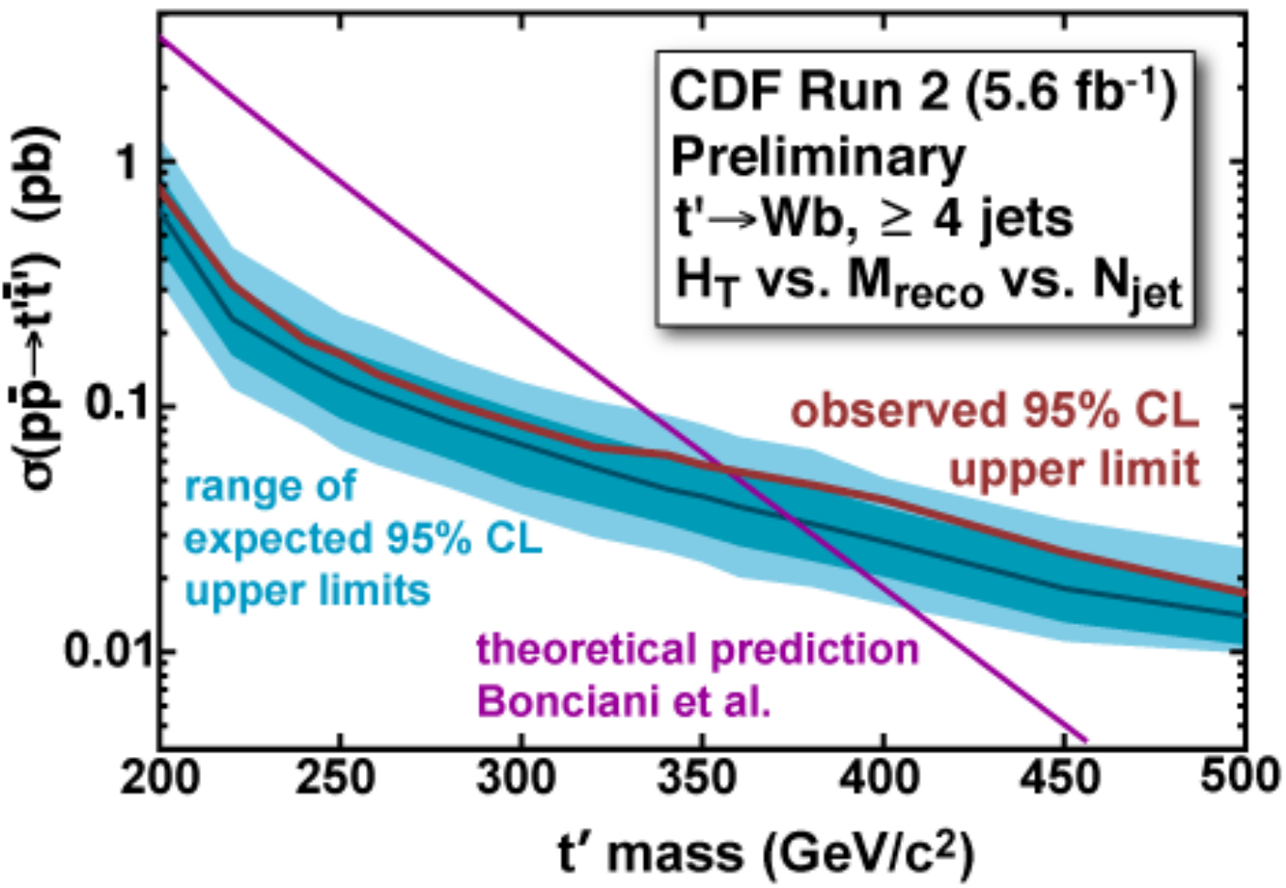


$m_{Q4} > 270$ GeV with 35 pb^{-1} **ATLAS-CONF-2011-022**

T'→ b + W @ TEVATRON

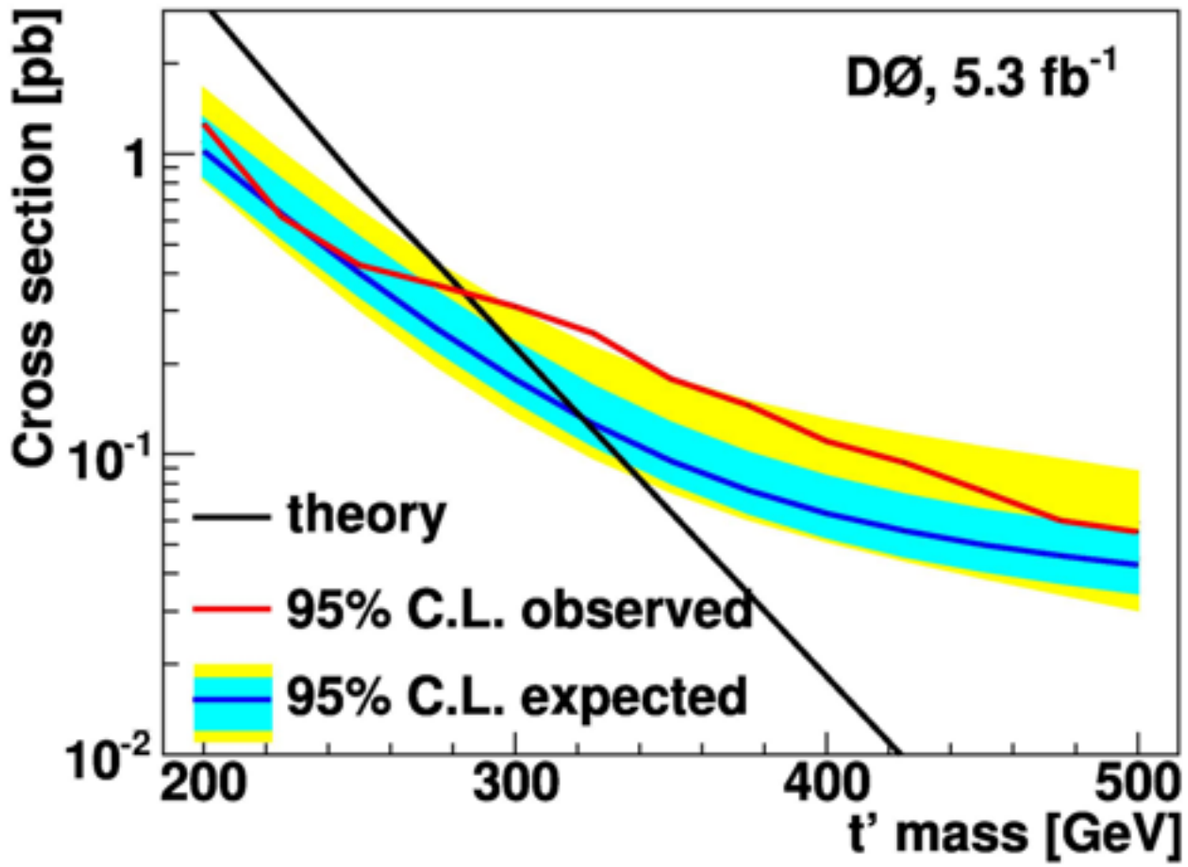
$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$$

CDF Conf. Note 10395



$m_{t'} > 358\ GeV$

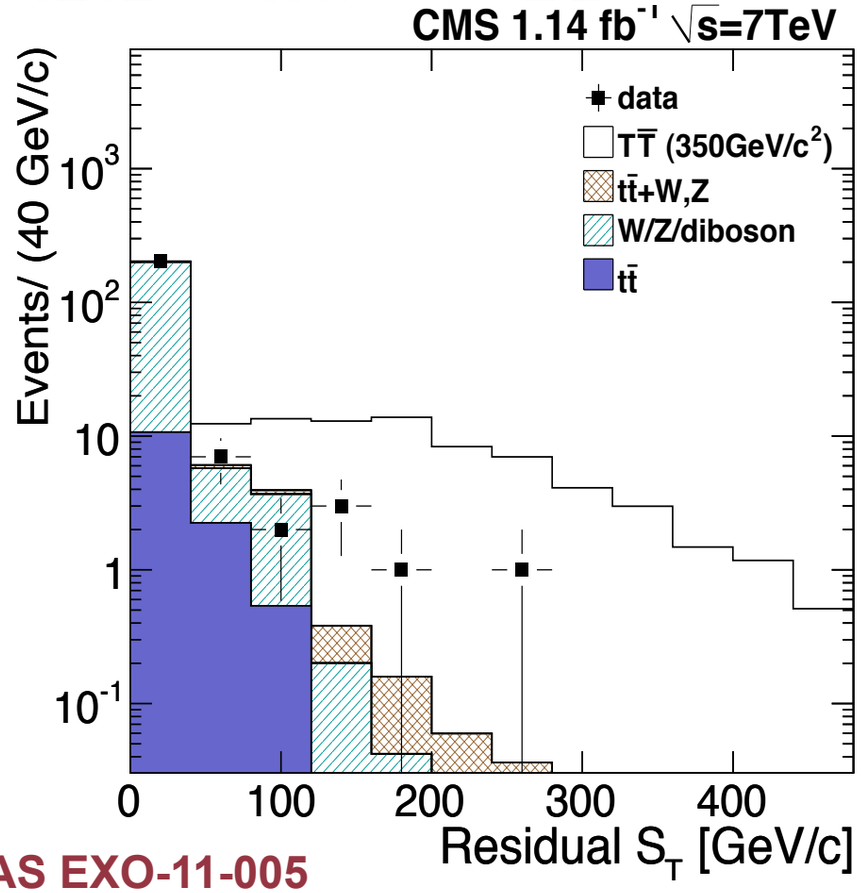
D0: PRL 107, 082001 (2011)



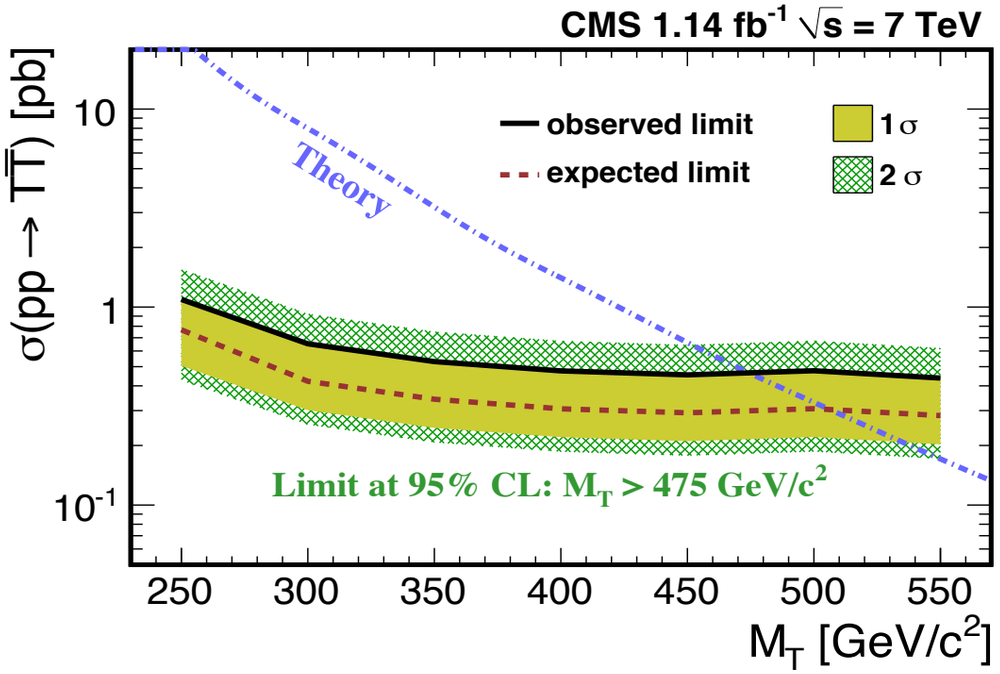
$m_{t'} > 285\ GeV$

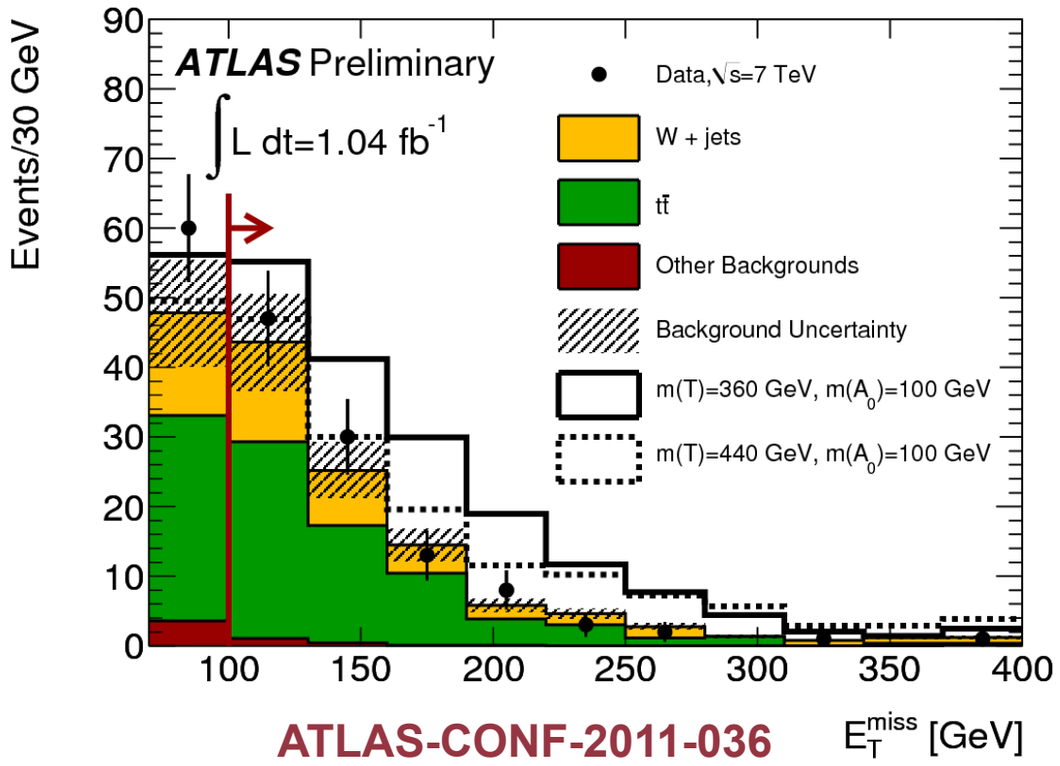
T’→ t + Z/A_0

$T'\bar{T}' \to tZ\bar{t}Z \to b\bar{b}W^+W^-ZZ$

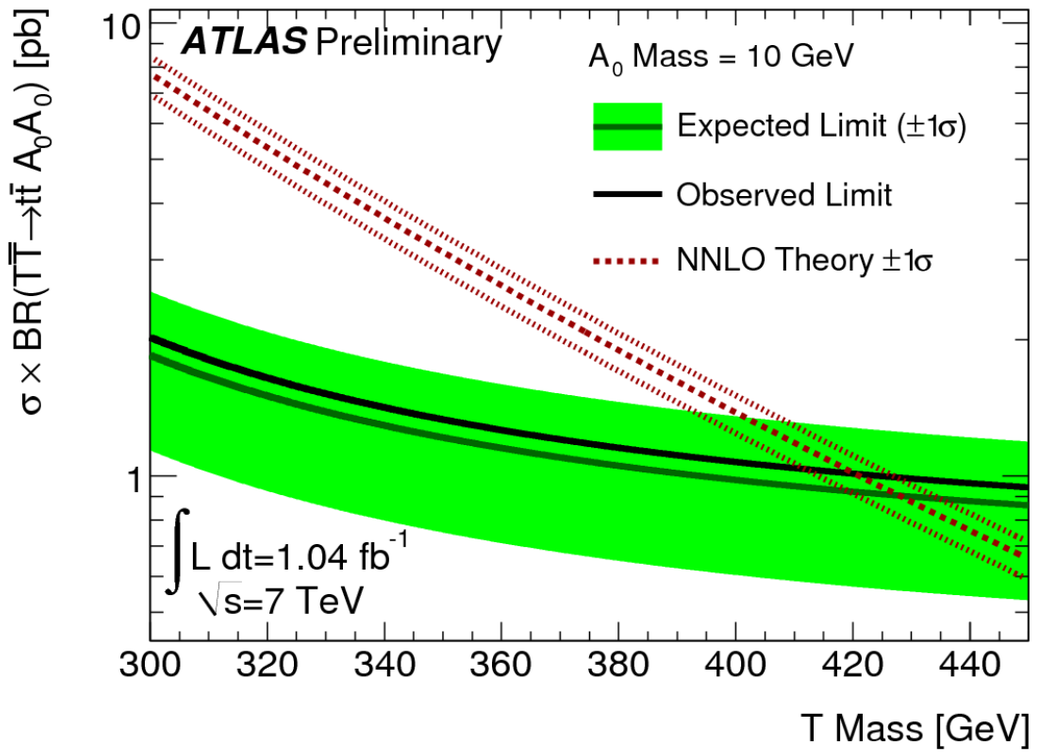


CMS: PAS EXO-11-005



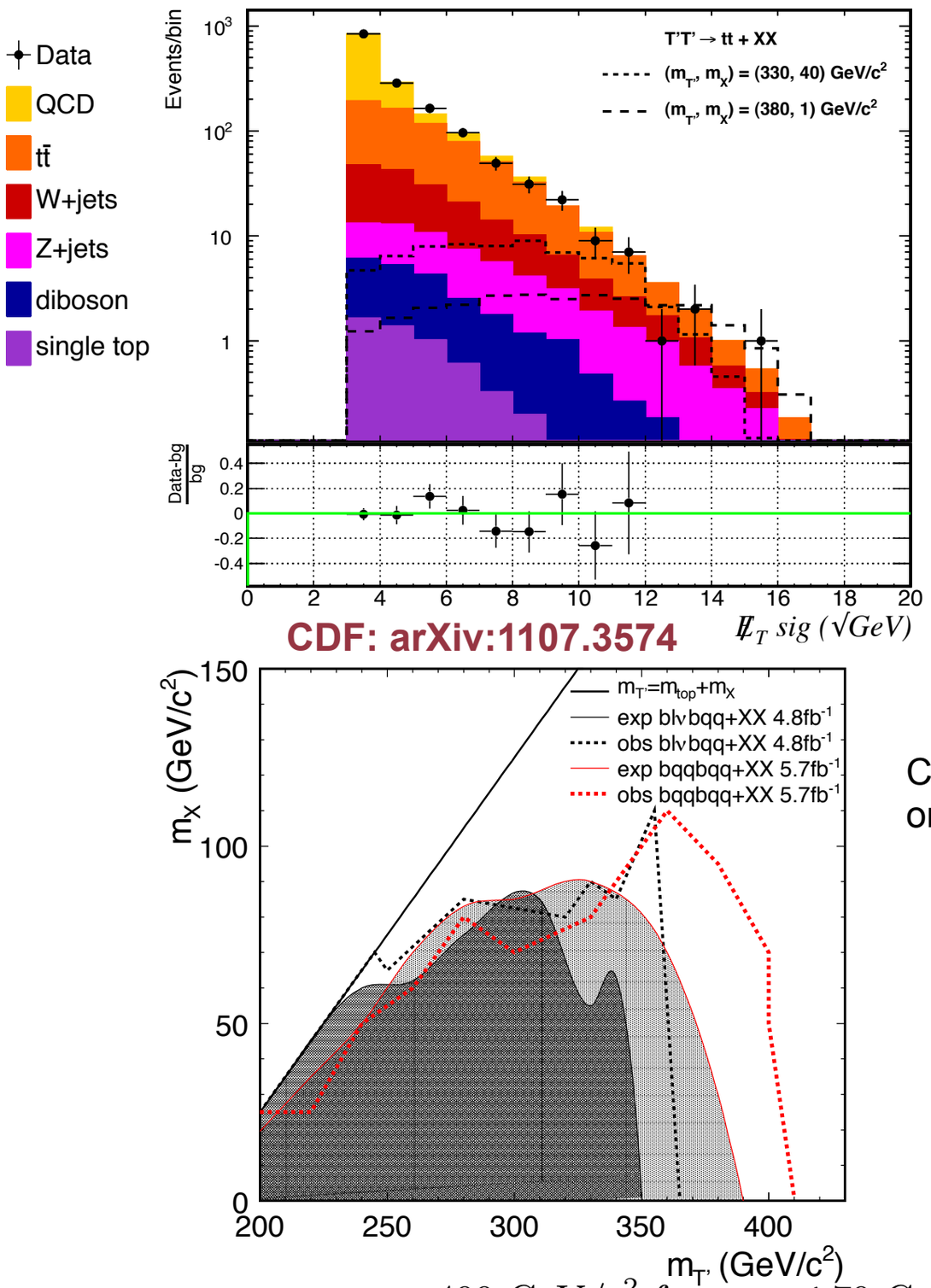


ATLAS-CONF-2011-036



T'→ t + X

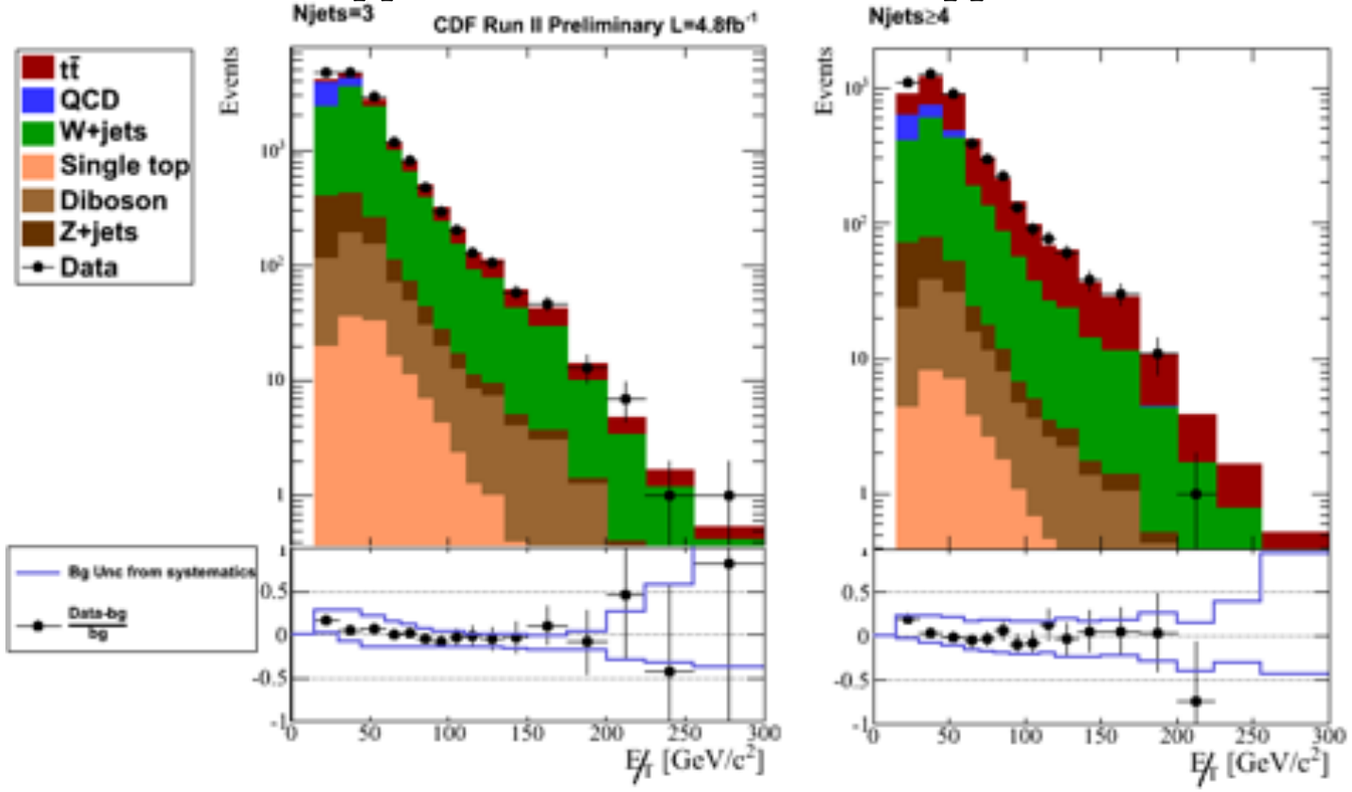
$$p\bar{p} \to T'\bar{T}' \to t\bar{t} + X\bar{X} \to bq\bar{q}\,\bar{b}q\bar{q} + X\bar{X}$$



CDF: arXiv:1107.3574

Exclusion up to: $m_{T'} = 400\ \mathrm{GeV}/c^2$ for $m_X \leq 70\ \mathrm{GeV}/c^2$

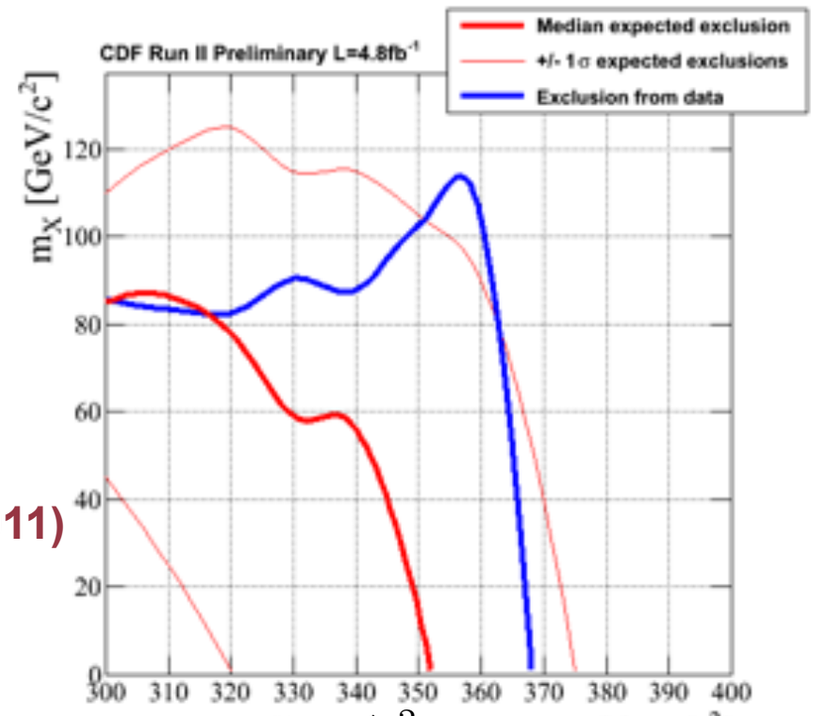
$$p\bar{p} \to tt + X + X \to \ell\nu bqq'b + X + X$$



Candidate dark matter or stop decay at LHC

$$\tilde{t} \to t\chi^0$$

CDF: PRL 106 191801 (2011)



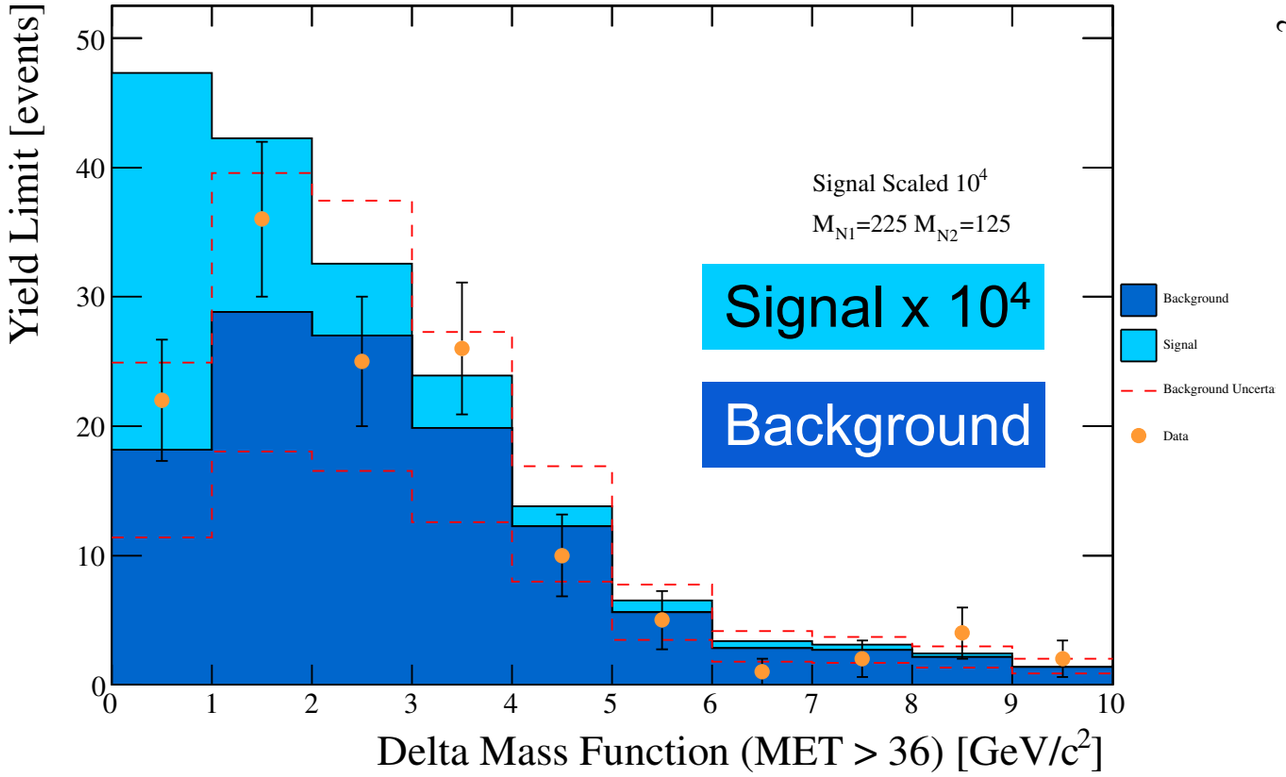
$m_{T'} = 360\ \mathrm{GeV}/c^2$ for $m_X \leq 100\ \mathrm{GeV}/c^2$

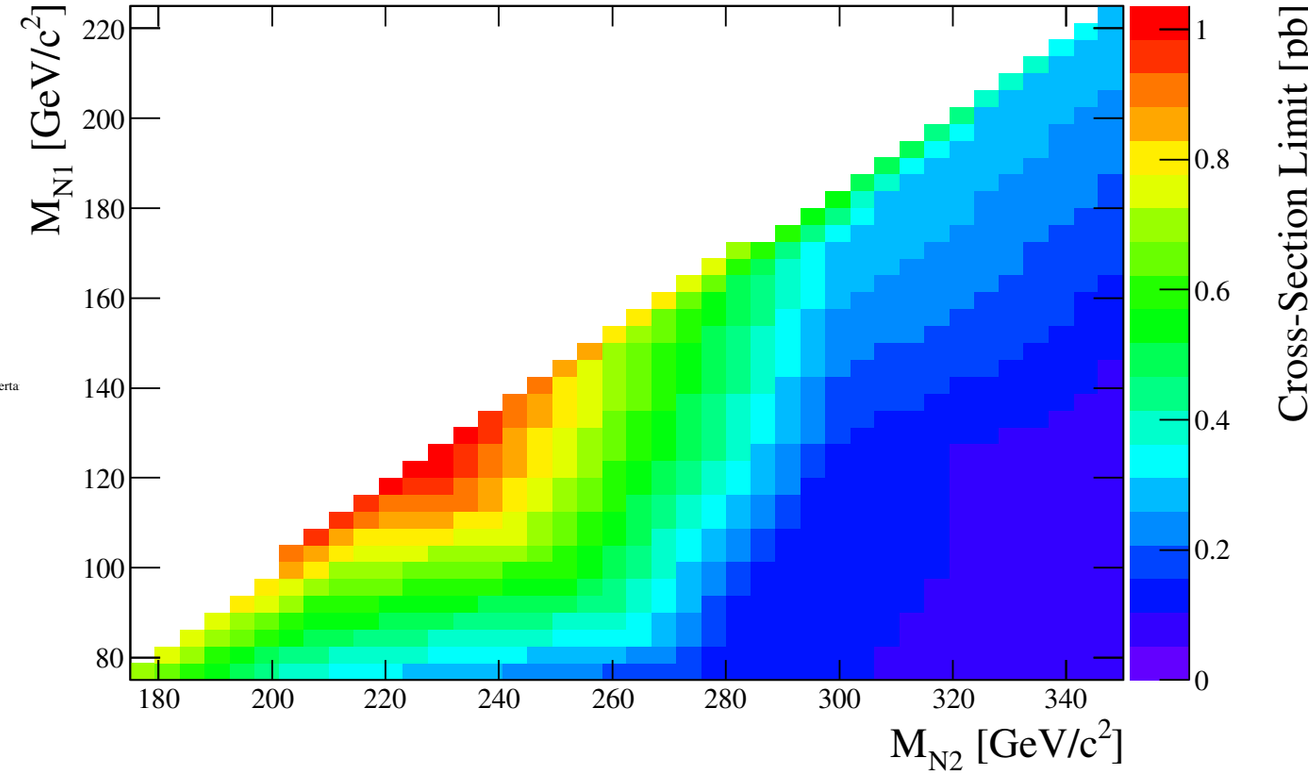
HEAVY NEUTRINO

$$p\bar{p} \to Z/\gamma^* \to N_2 N_2 \to N_1 Z N_1 Z \to lljj N_1 N_1$$

- Assume heavy neutrinos being lightest 4th generation particles
  - mixture of Dirac and Majorana states
- leptonic and hadronic Z decays and missing energy from lightest heavy neutrino

http://www-cdf.fnal.gov/physics/exotic/r2a/20110603.zzmet/index.html





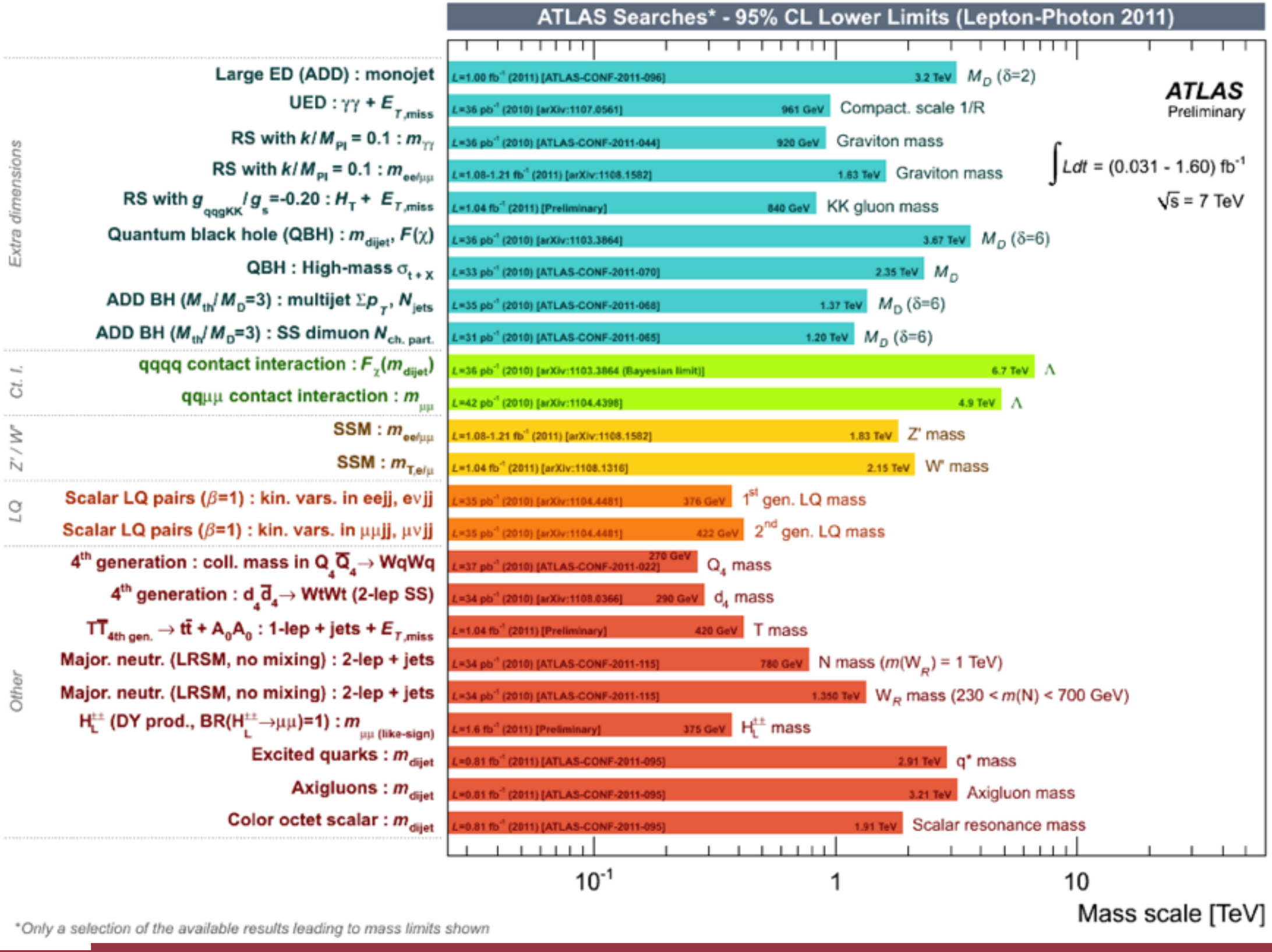
$$\sqrt{\left(\frac{M_{ll} - 91.6}{10}\right)^2 + \left(\frac{M_{jj} - 85.3}{15}\right)^2}$$

SUMMARY OF 4TH GENERATION SEARCHES

Decay	Experiment	Method	Excluded mass (GeV)	Luminosity (fb^{-1})	Notes
b'→ t + W	CMS	lepton + jet	495	1.1	
	CDF		372	4.8	
Q_4→ q + W	ATLAS	dilepton	270	0.035	
T'→ b + W	CMS	dilepton	422	1.1	
	CDF	lepton + jet	358	5.6	
	D0		285	5.3	
T'→ t + Z	CMS	lepton + jet	417	0.2	
T'→ t + A_0	ATLAS	lepton + jet	410	1.0	m_{A0} < 30 GeV
T'→ t + X	CDF	hadronic	400	5.7	m_X ≤ 70 GeV
T'→ t + X		lepton + jet	360	4.8	m_X ≤ 100 GeV

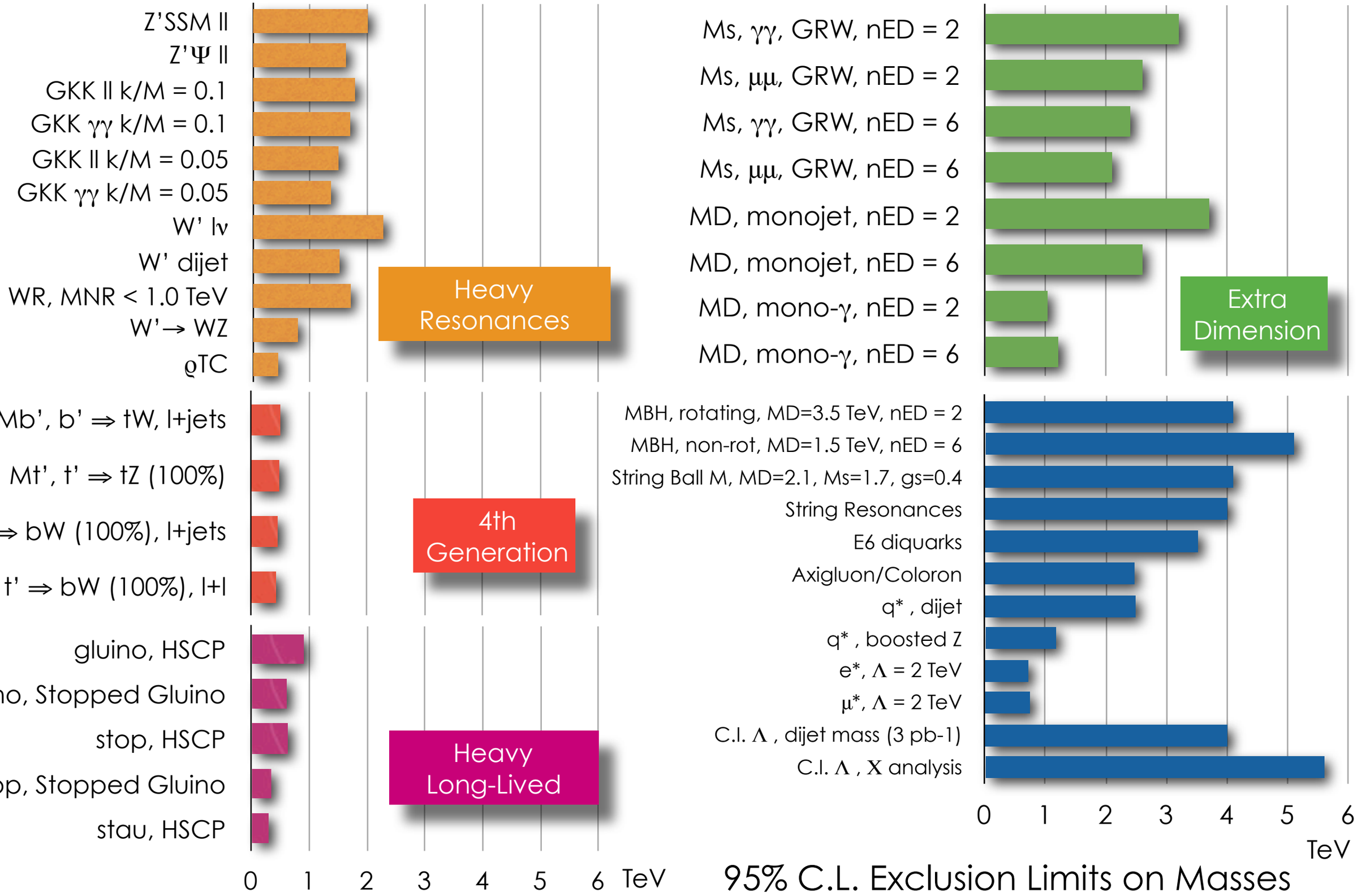
Conclusions

ATLAS Grand Summary



*Only a selection of the available results leading to mass limits shown

CMS Grand Summary



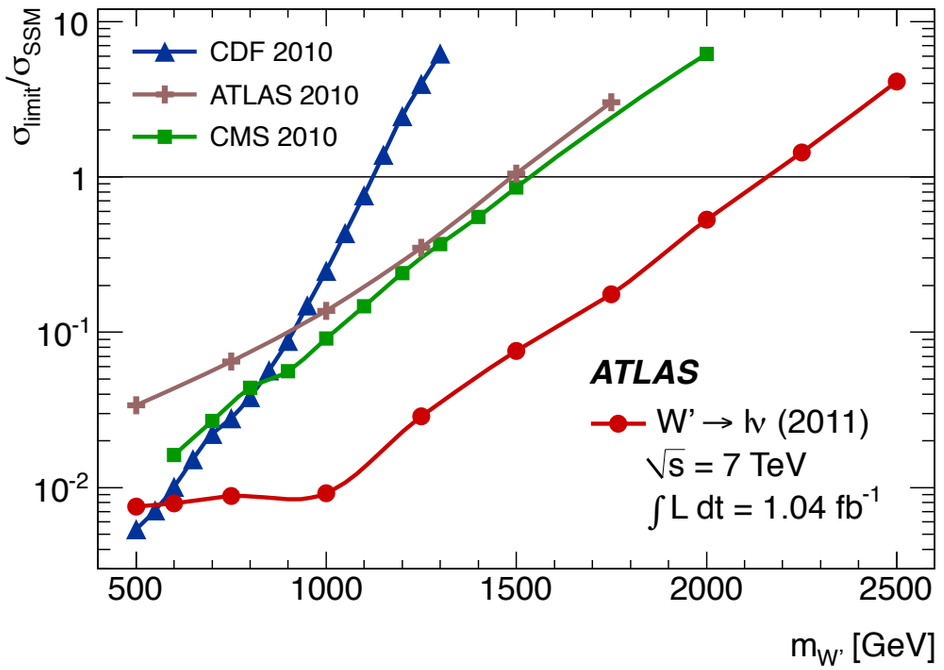
95% C.L. Exclusion Limits on Masses

FANTASTIC 1ST YEAR AT LHC

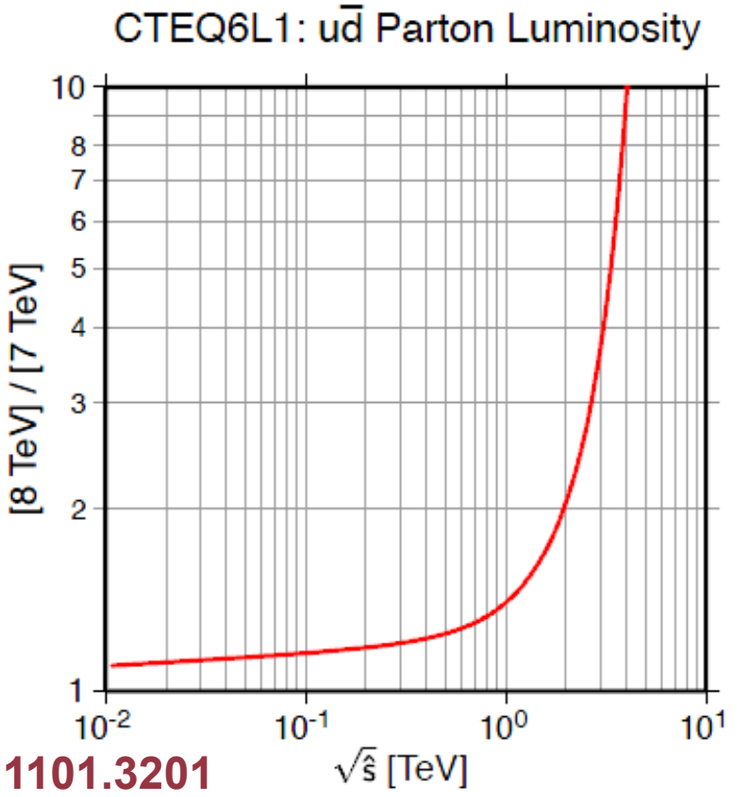
- Outstanding performance of detector, trigger, computing, and offline in ATLAS and CMS
  - last chunk of 1 fb^{-1} dataset delivered last week of June
  - Most of results using full dataset by 3rd week of July!
- Good news
  - excellent detector performance
    - b-tagging and MET reliable and under control since day 1
  - surprisingly good data/MC agreement
- Bad news
  - So far only exclusion limits and no discovery
  - No hint of New Physics yet
- LHC measurement competing with Tevatron after 1 year of data

OUTLOOK

- Heavy resonances excluded past 2 TeV
- 4th generation excluded up to ~0.5 TeV
- Increase of x35 in data from 2010 to Summer 2011 improved exclusion limits sometime less than 20%
  - and has not brought any breakthrough discovery yet



- Higher center-of-mass energy perhaps a better option than x10 data at 7 TeV
  - big gains in cross section for several processes
  - modest gain in parton luminosity from 7 TeV to 9 TeV
- Searches in 2012
  - many data-driven methods rely on extrapolation from low to high mass/pt
    - works until nothing seen. What if we actually see events out there?
  - Trigger thresholds rising with luminosity
    - many exotic searches so far relying on generic triggers
    - dedicated triggers will be necessary in 2012



arxiv:1101.3201