Exotic Searches at LHC and tevatron

Shahram Rahatlou

Seminario alla Russa

Roma, 29 September 2011

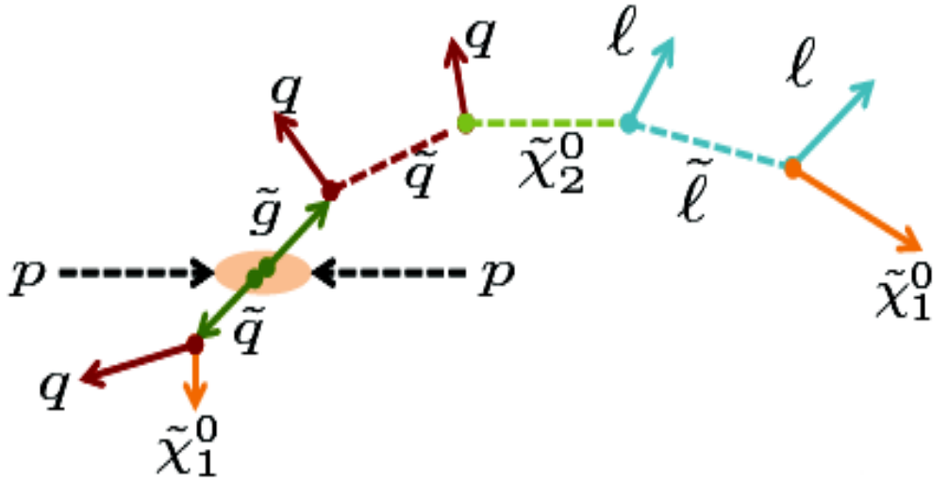
Dipartimento di Fisica

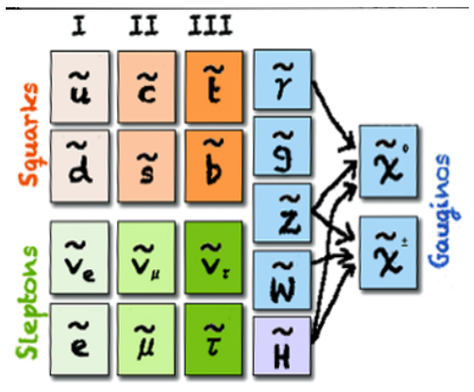
Sapienza
Università di Roma

DISCLAIMER

- More than 30 results produced by ATLAS and CMS alone for Summer in exotic searches
  - at least 20 more SUSY-only results!
  - 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  - Many of Tevatron results now superseded at LHC not reported due to time constraints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

SUSY OR EXOTIC?



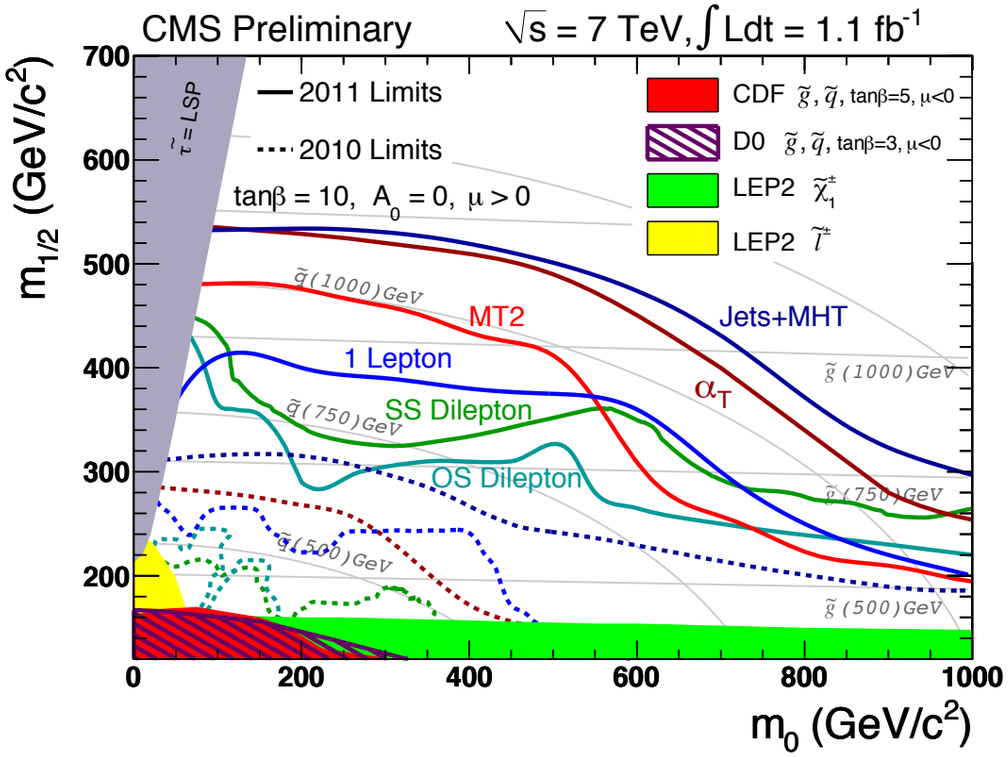


R-Parity conserving searches (RPC)

- 0-lepton
- 1-lepton
- 2-leptons
- Multi-leptons
- b-jet searches
- Photon searches

R-Parity violating searches (RPV)

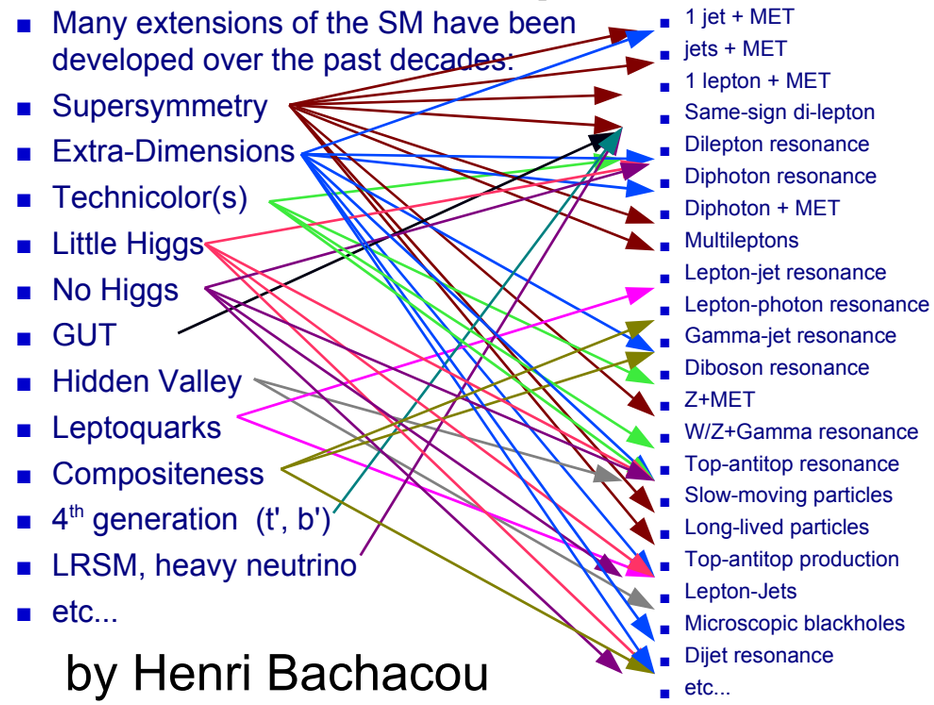
- SUSY signatures very rich and depend on particular choice of parameters
  - events divided in categories of lepton or b-jets
  - look at MET and look for excess on top of Standard Model
- Experimentally: divide searches based on MET
  - SUSY: searches where MET is main or only discriminator
  - EXOTIC: where there is no MET or at least not the **only** discriminator
    - resonances, heavy particles, decays in final state ALSO with MET
- SUSY results typically provided in (m_0,$m_{1/2}$) or (m_q,m_g) plane
  - primary parameters determining mass of SUSY particles



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

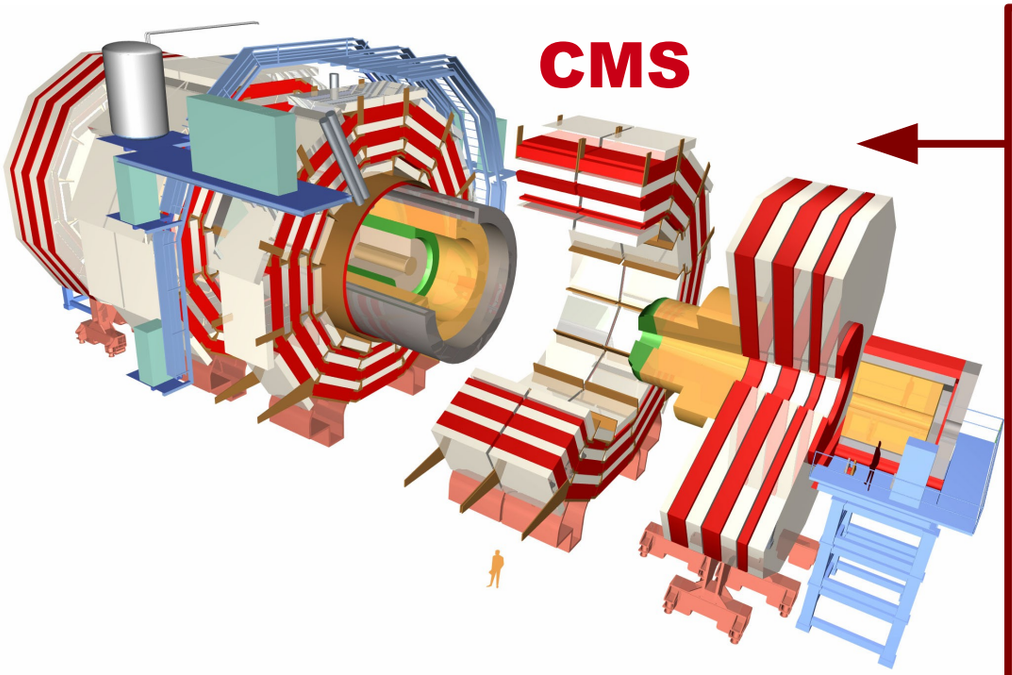


- This talk following a topic-based approach
  - easier to combine constraints on model from different topologies
  - Same final state is not simple re-interpretation
    - often optimization redone to deal with different acceptance for very different models
    - different analysis strategy and signal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

OUTLINE

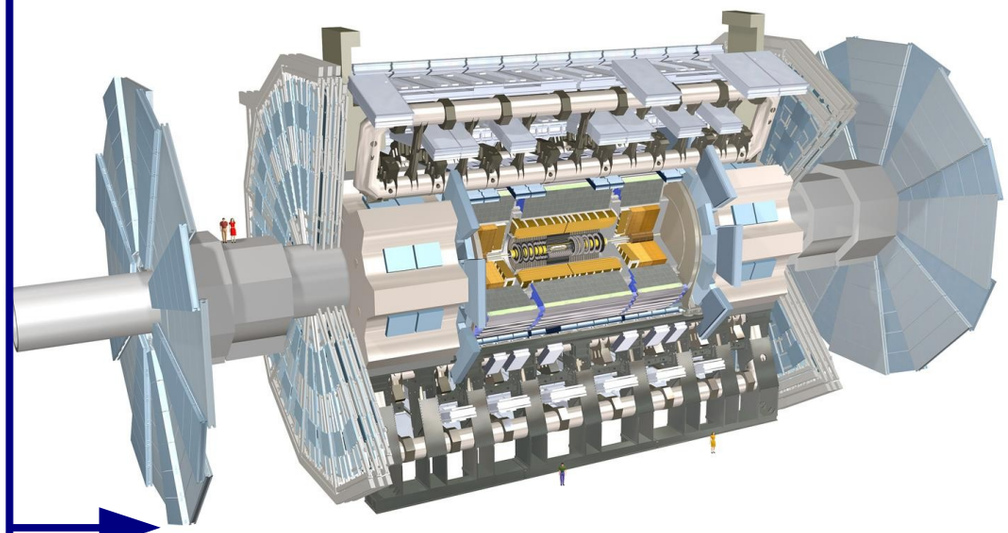
- Heavy Resonances
  - dileptons
  - lepton+MET
  - diphotons
  - dijets
  - heavy neutrinos
  - WZ
  - W+jj
- Extra dimensions
  - dileptons
  - diphotons
  - jet/photon + MET
  - Black Holes
- LeptoQuarks
  - 1st generation
  - 2nd generation
- 4th generation b'/t'
  - all hadronic
  - semileptonic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

ATLAS AND CMS

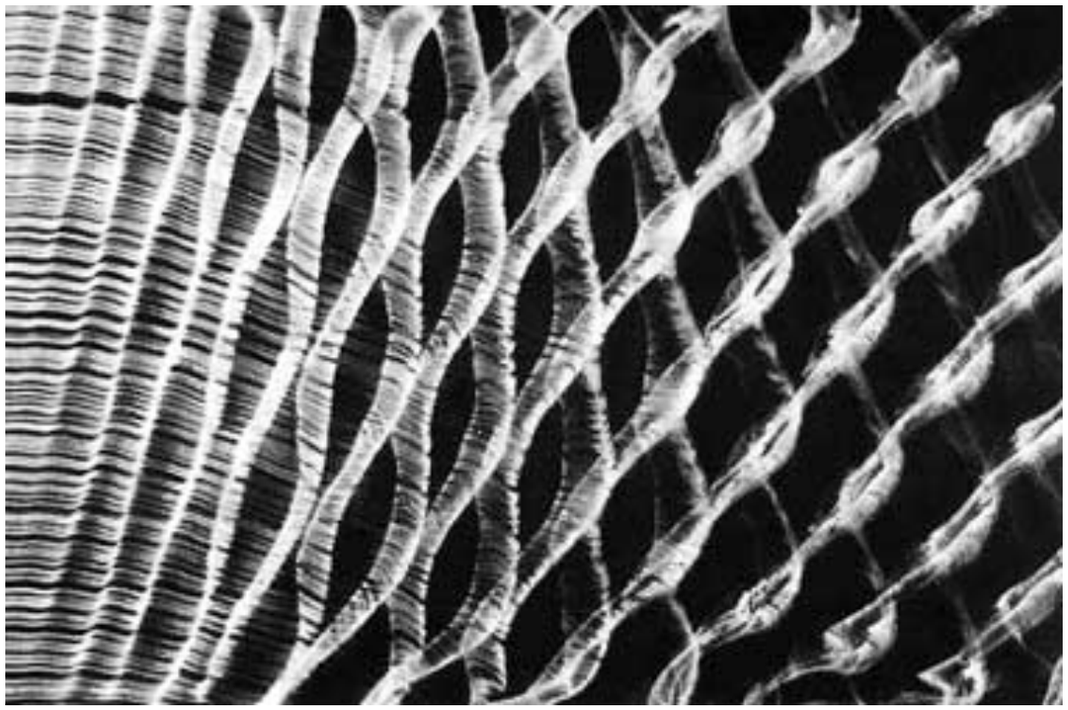


- 3.8T solenoid containing calorimeters
- Silicon tracker: $\sigma(p_T)/p_T \sim 15\%$ at 1TeV
- EM cal: homogeneous Lead-Tungstate crystal, $\sigma_E/E \sim 3\%/\sqrt{E[GeV]} \oplus 0.5\%$
- HAD cal: Brass-scint., $\geq 7\lambda_0$
  $\sigma_E/E \sim 100\%/\sqrt{E[GeV]} \oplus 5\%$
- Iron return yoke muon spectrometer

- 2T solenoid inside calorimeters
- Silicon+TRT tracker + electron ID
- EM cal: Longitudinally segmented Lead-Ar:
  $\sigma_E/E \sim 10\%/\sqrt{E[GeV]} \oplus 0.7\%$
- HAD cal: Fe-scint + Cu-Ar, $\geq 11\lambda_0$
  $\sigma_E/E \sim 50\%/\sqrt{E[GeV]} \oplus 3\%$
- Air-toroid muon sp.: $\int \sqrt{B}.dl = 1$ to 7 T.m



ATLAS

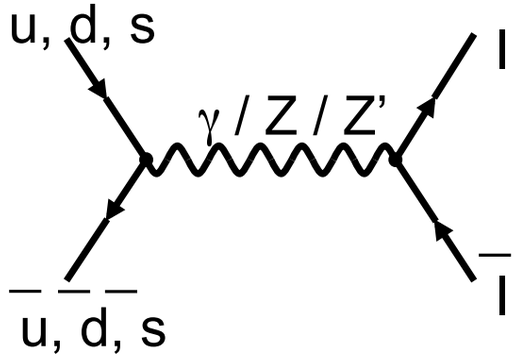


Heavy Resonances

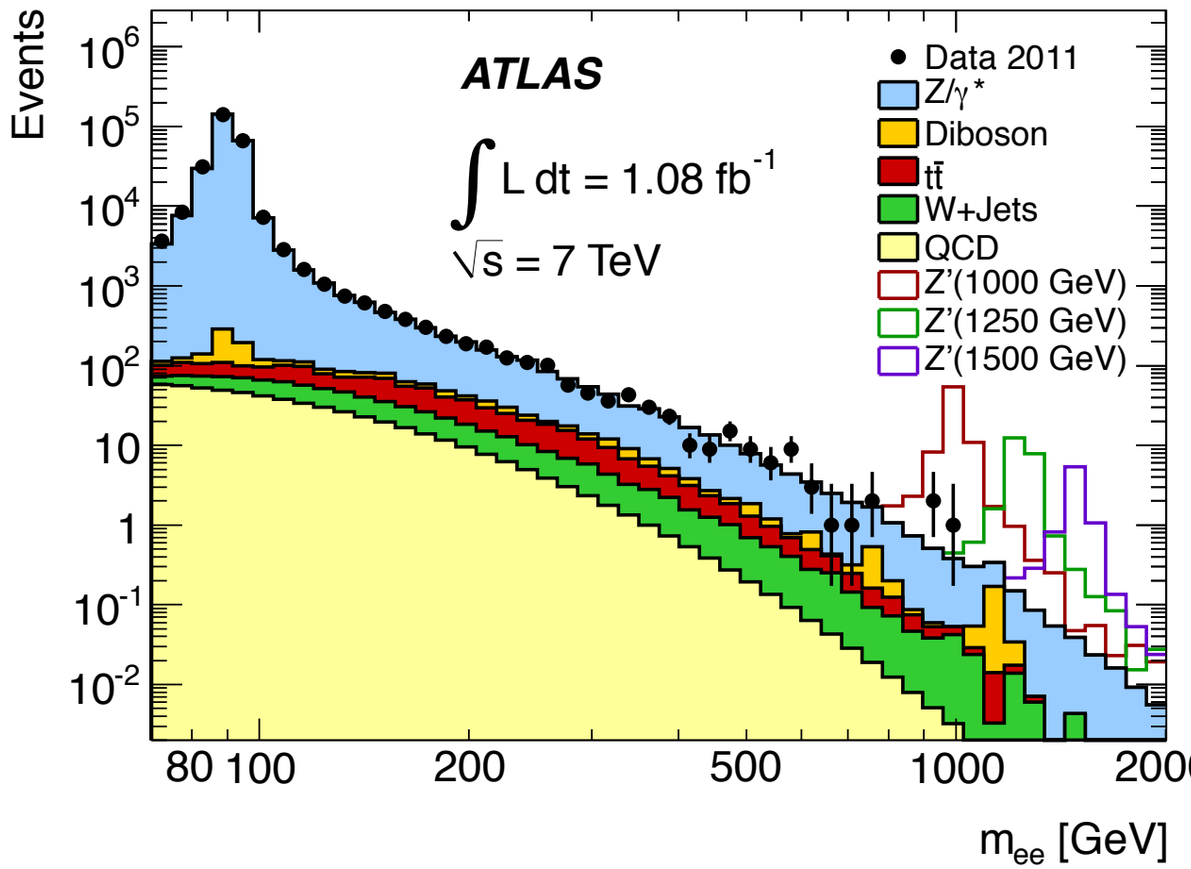
HEAVY RESONANCES

- 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

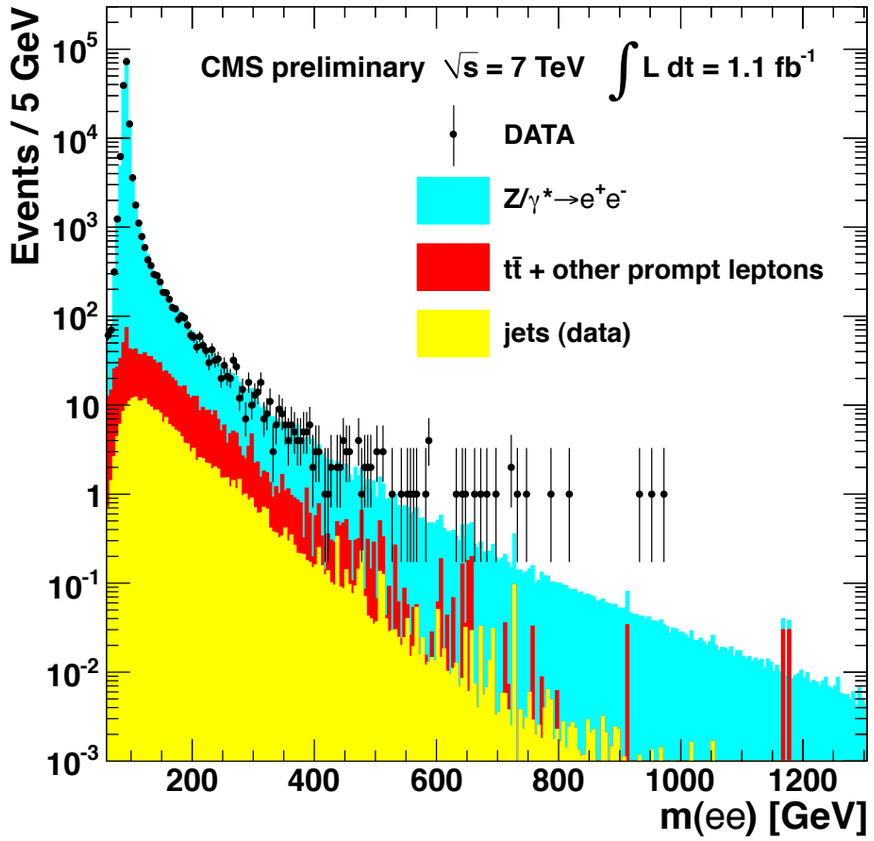
DI-ELECTRON

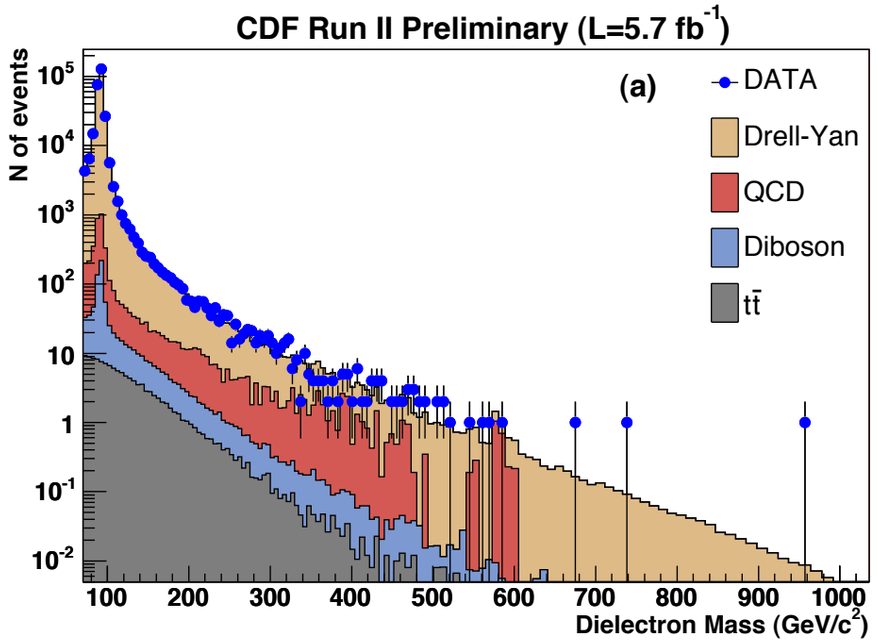


ATLAS: arXiv:1108.1582



CMS: PAS EXO-11-019

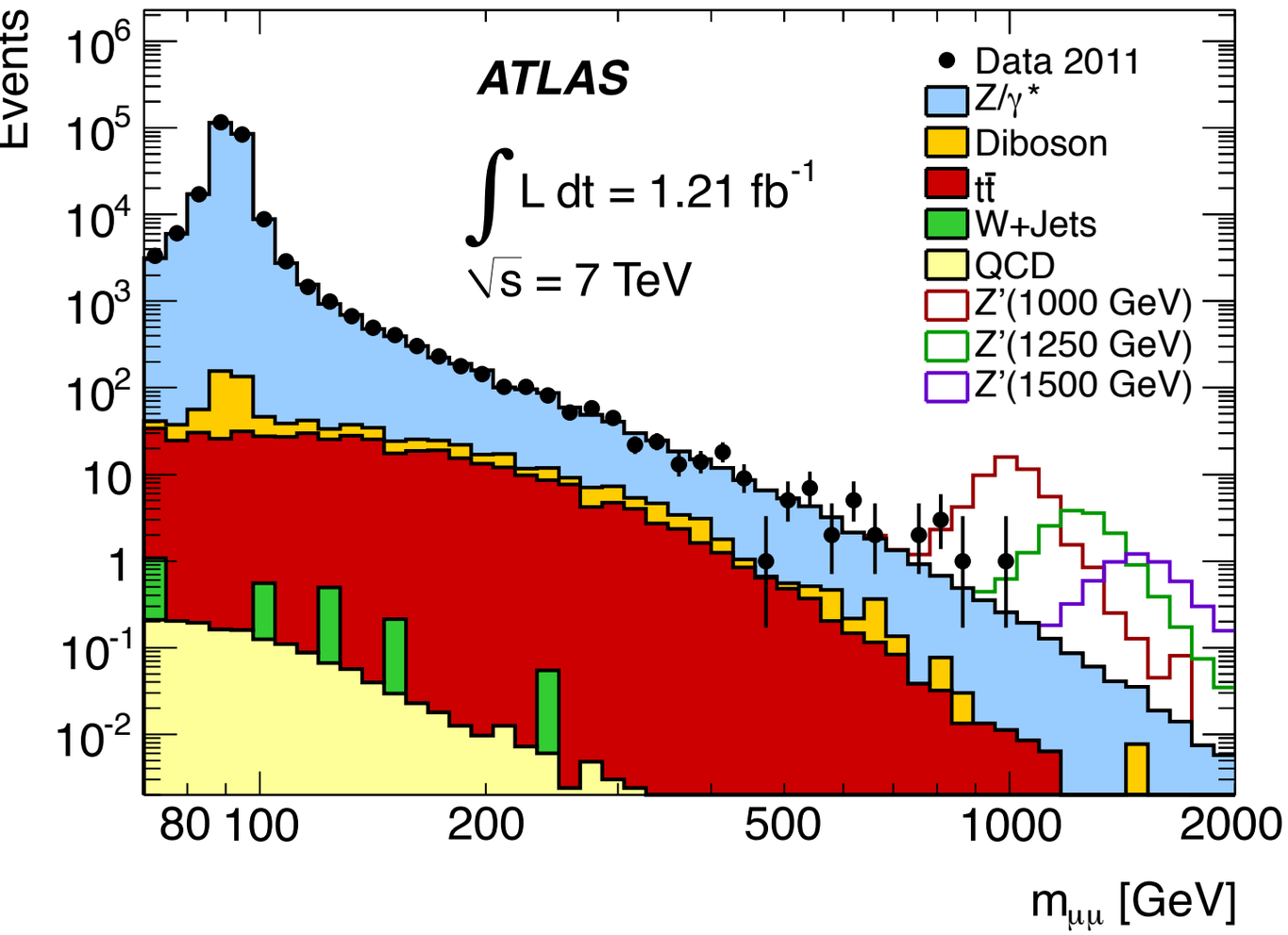




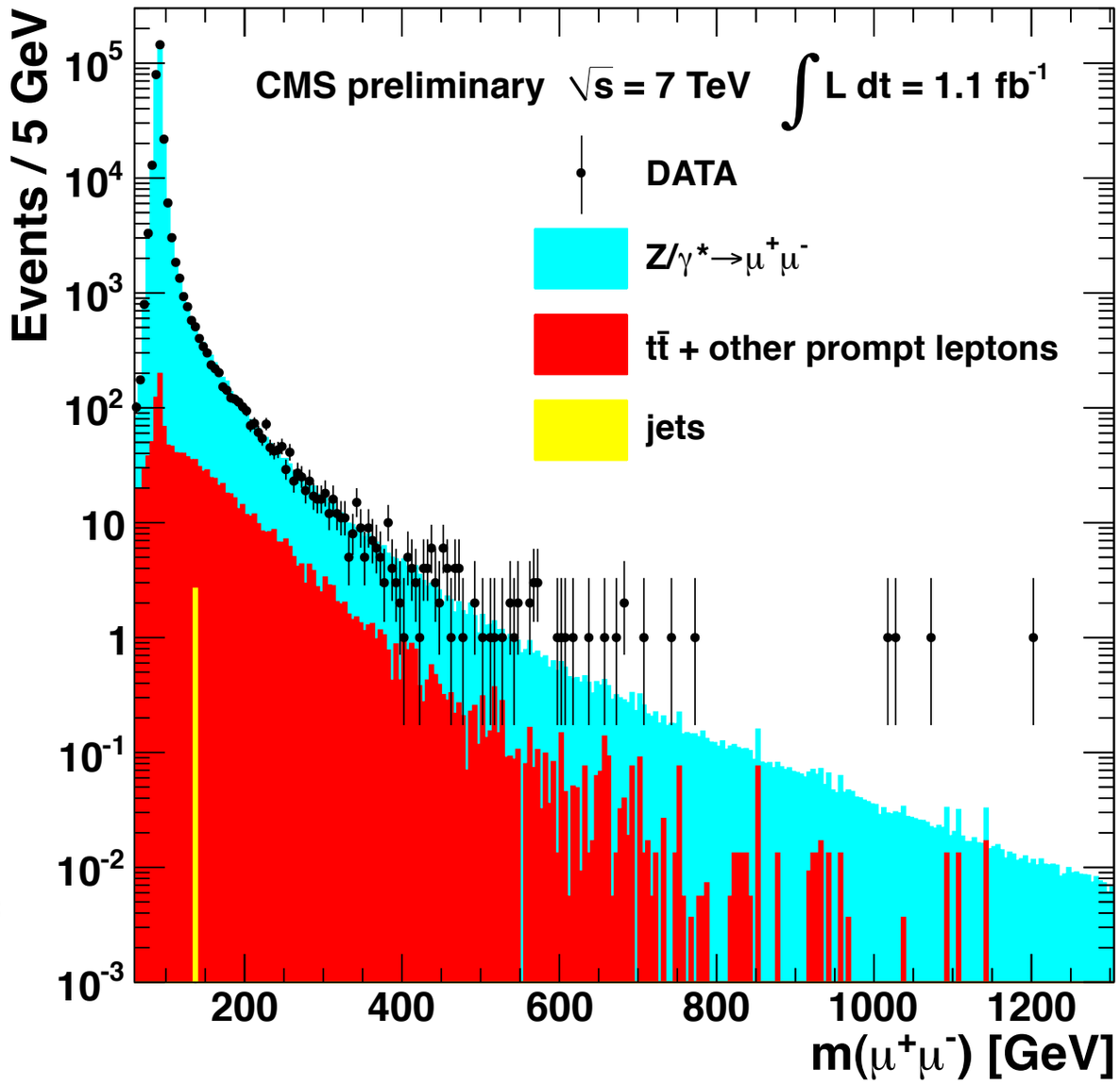
- Background estimation
  - ATLAS: QCD from data, ttbar and DY from MC
  - CMS: QCD and ttbar from data, DY from MC

DI-MUON

ATLAS: arXiv:1108.1582

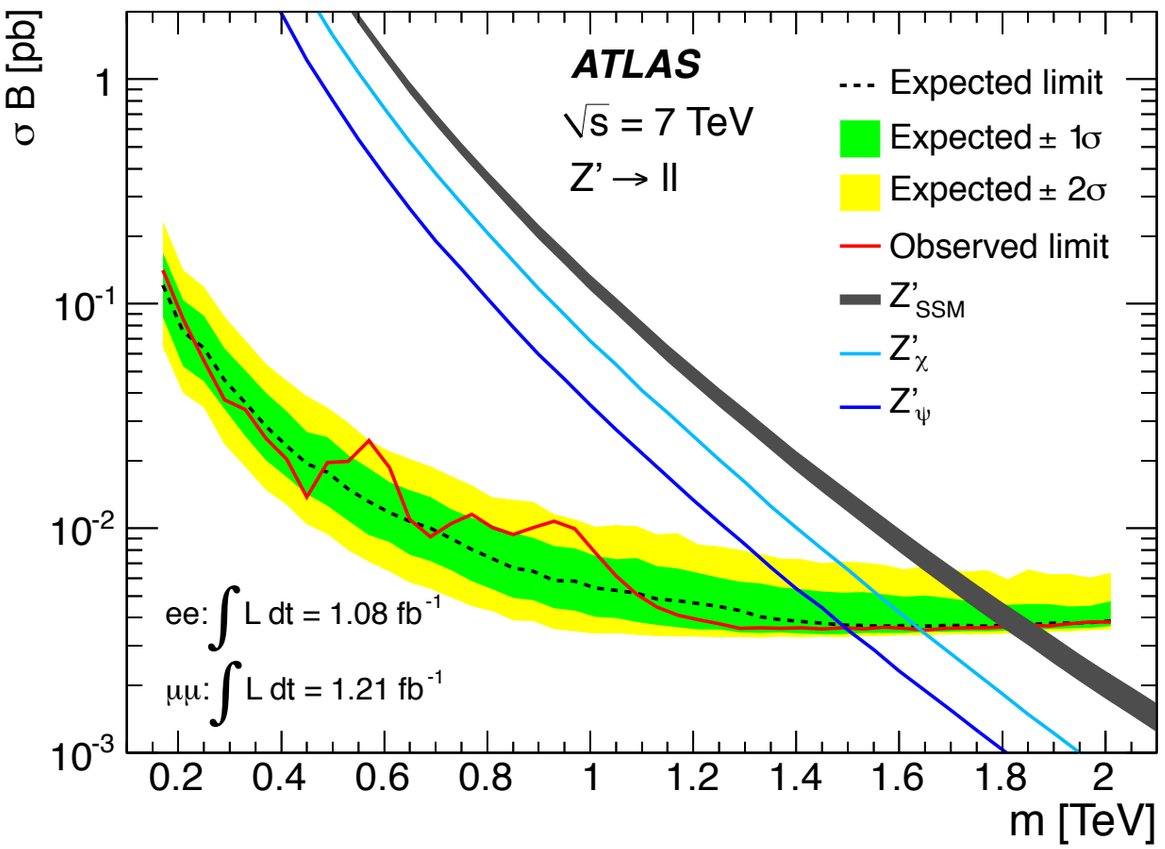


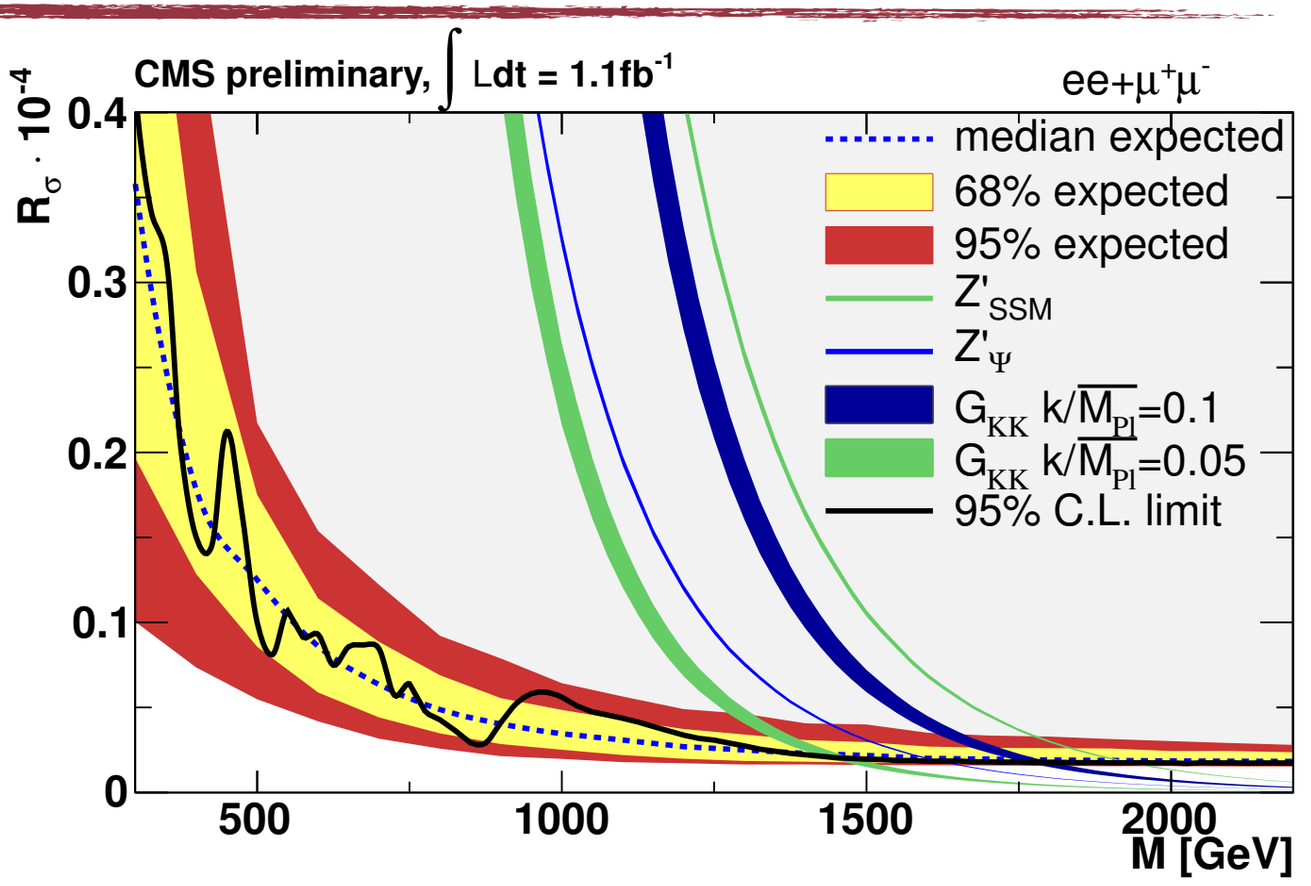
CMS: PAS EXO-11-019



- Several events with mass of 1 TeV

DI-LEPTON EXCLUSIONS

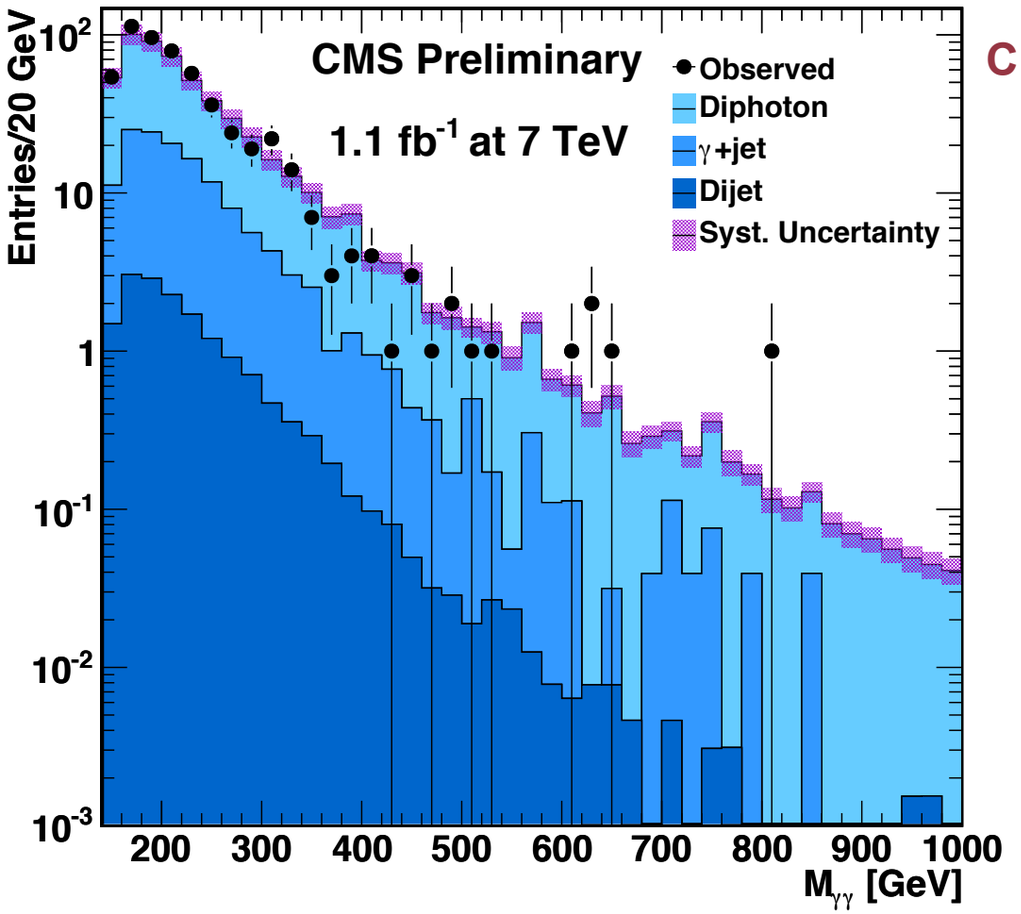




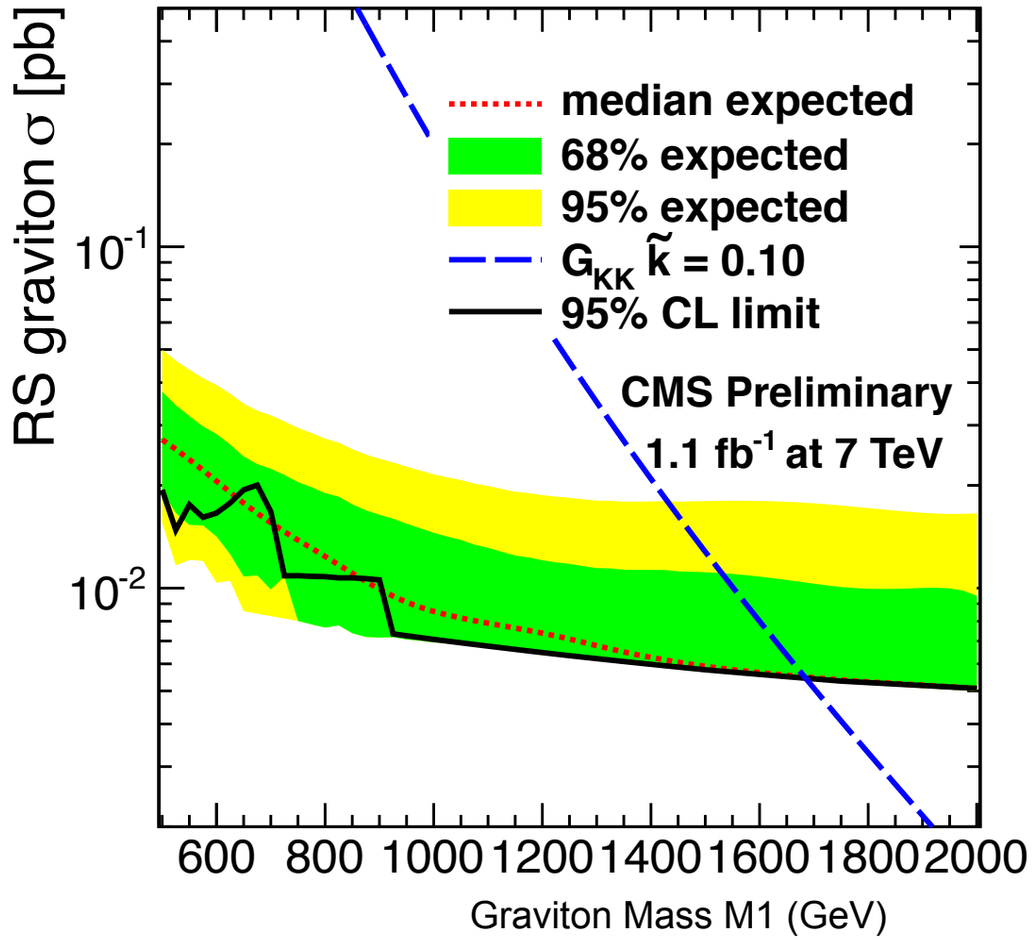
- Limits approaching 2 TeV for most models
- Similar expected and observed 95% CL limits for both experiments

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

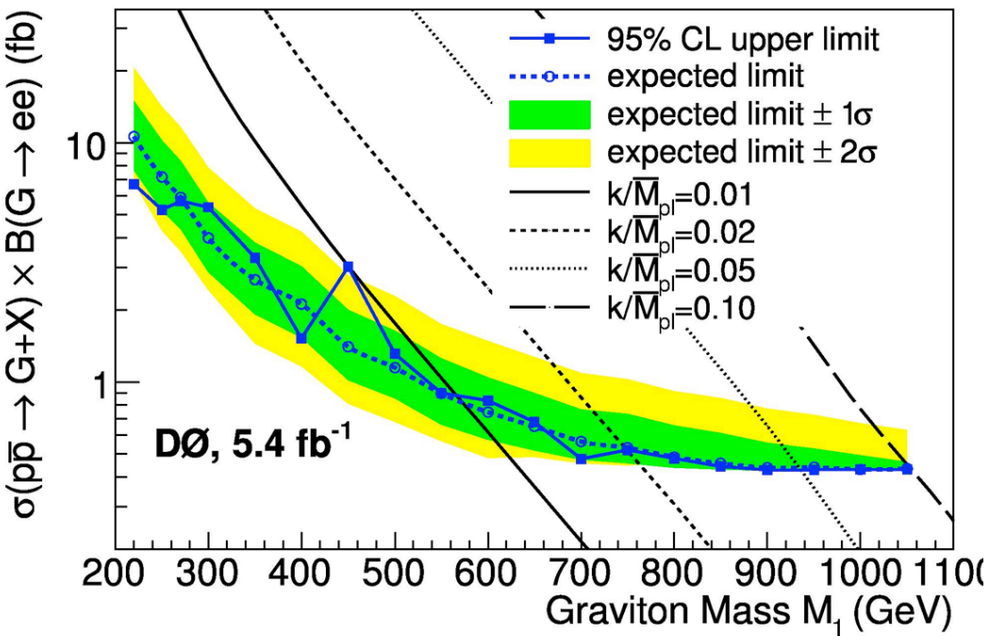
γγ



CMS: PAS EXO-11-038



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



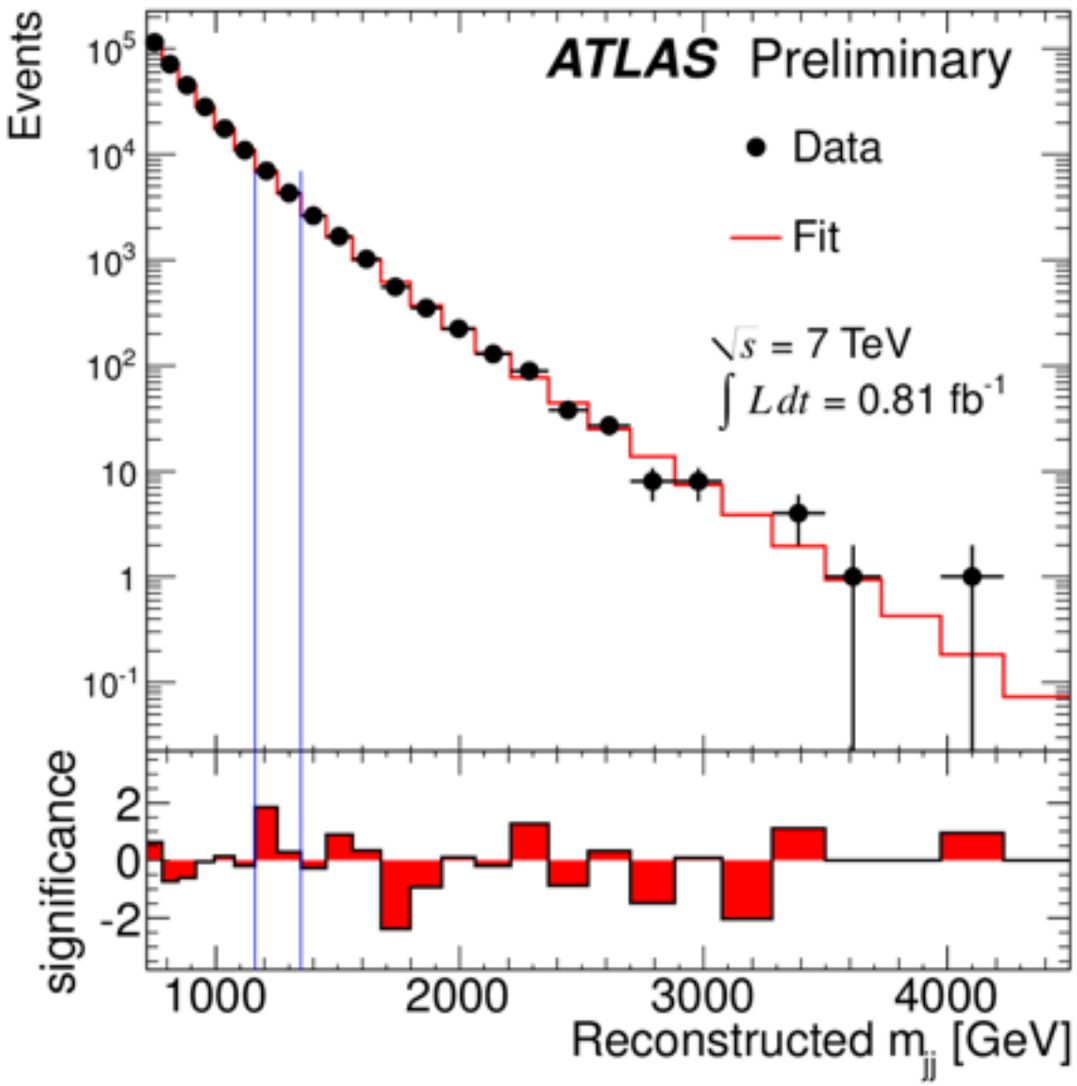
ATLAS-CONF-2011-044 D0: PRL 104(2010) 241802

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

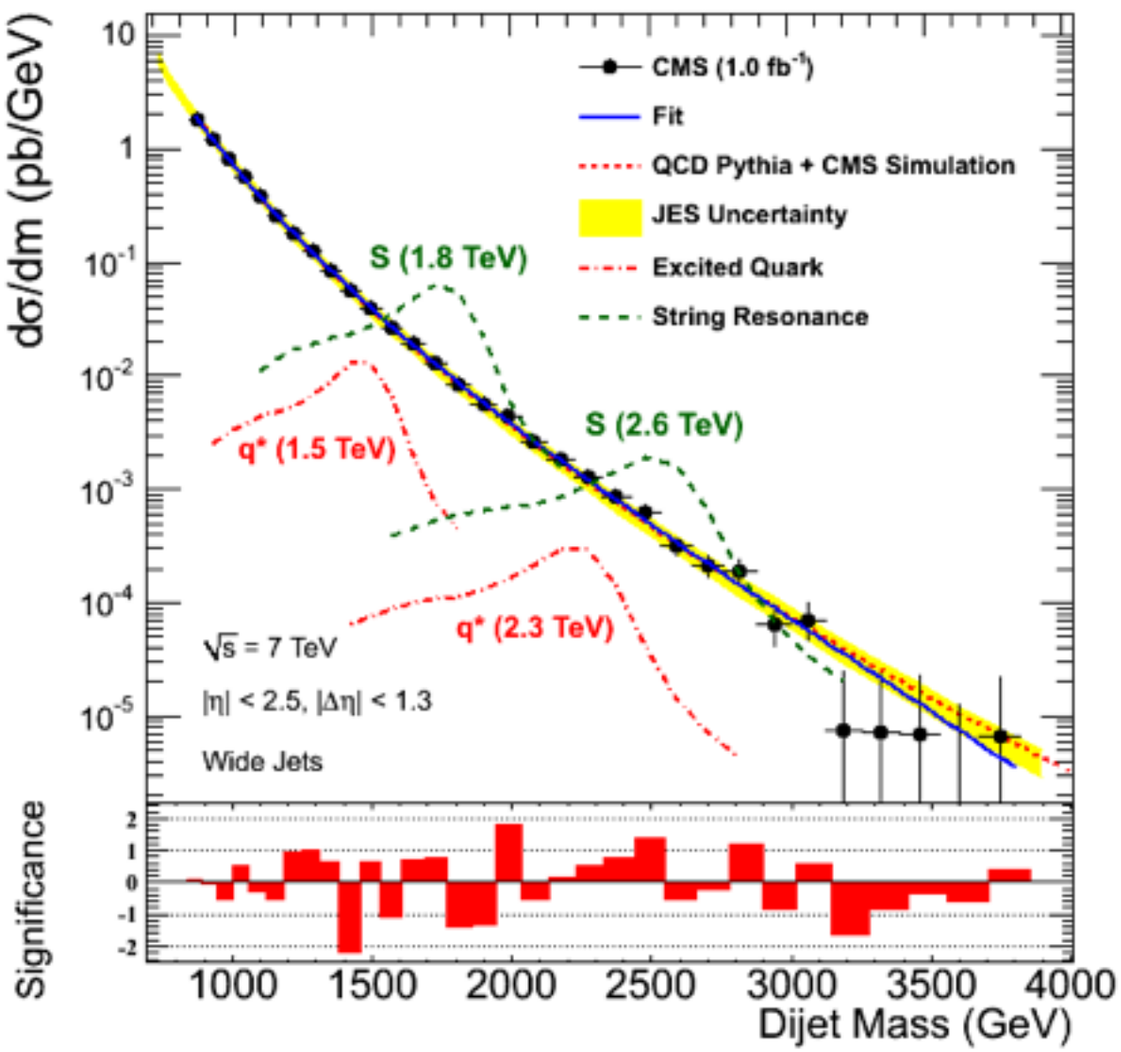
CDF: http://www-cdf.fnal.gov/ physics/exotic/r2a/20110214.gravitonee/index.html

DI-JET

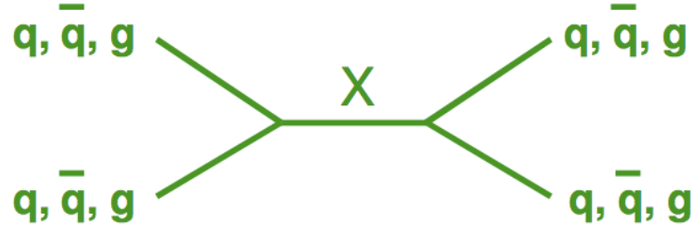
ATLAS-CONF-2011-095



CMS: arXiv:1107.4771

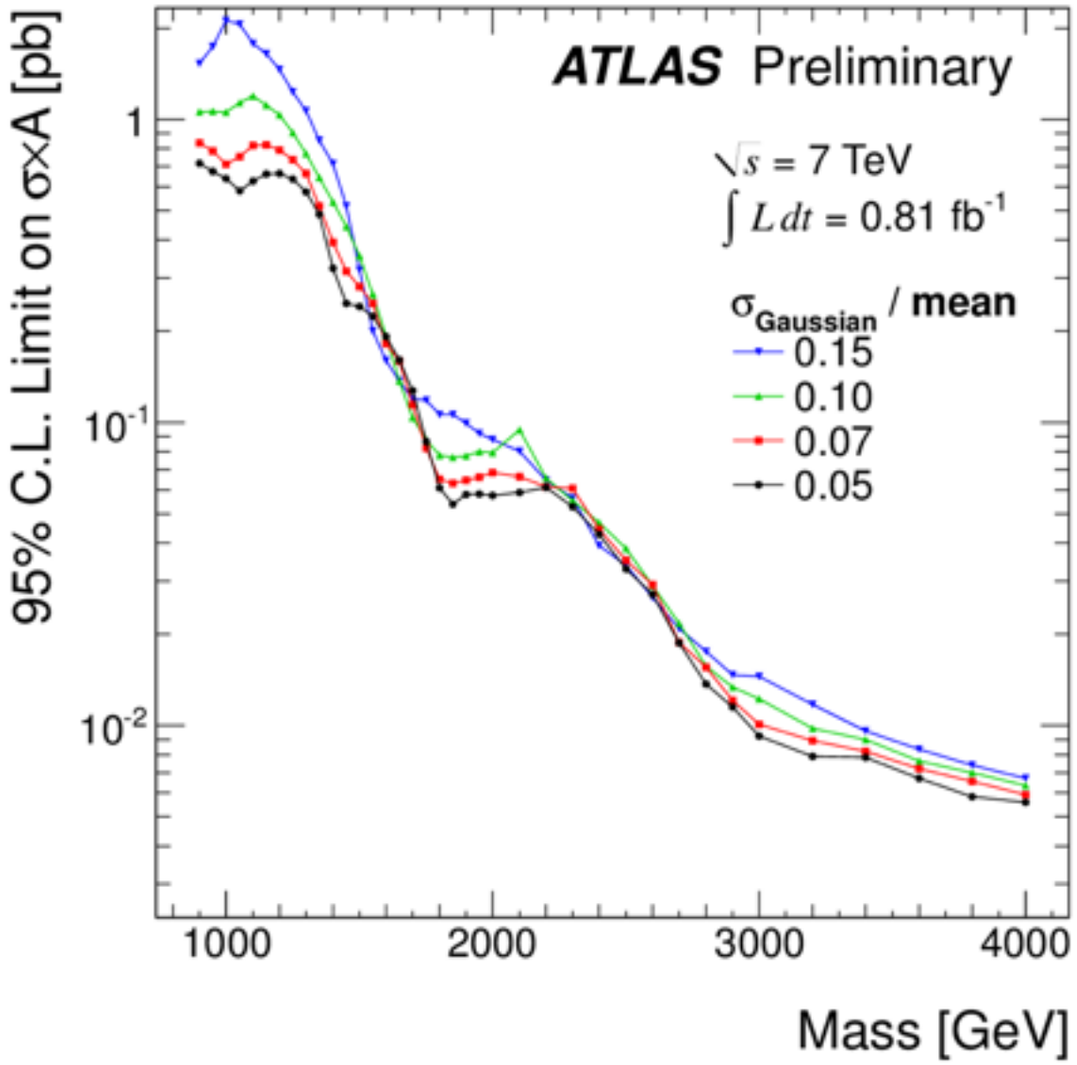


- Resonances predicted in numerous models
  - larger branching fraction compared to dileptons
  - much higher background from QCD

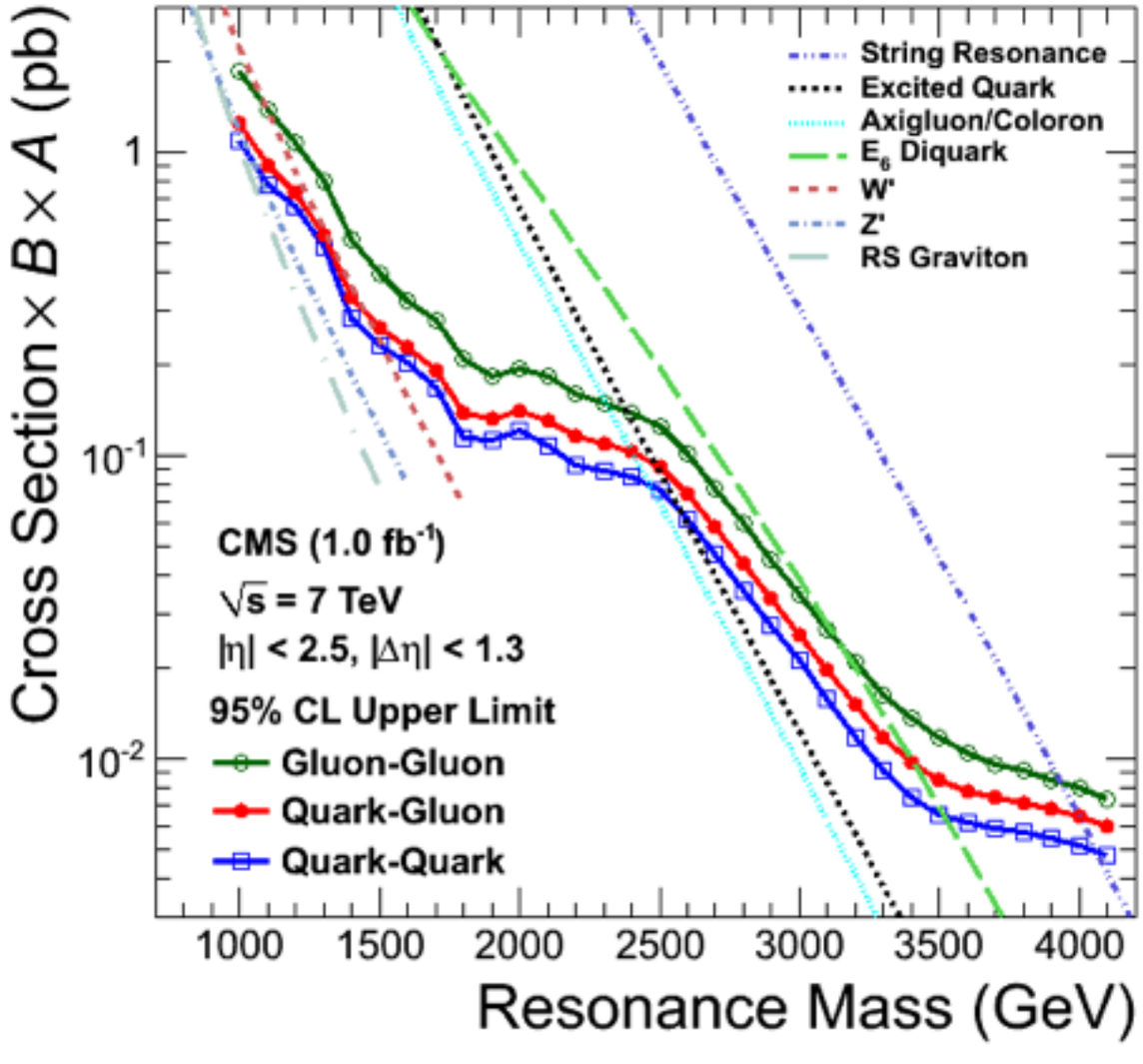


DI-JET EXCLUSION LIMITS

ATLAS-CONF-2011-095



CMS: arXiv:1107.4771

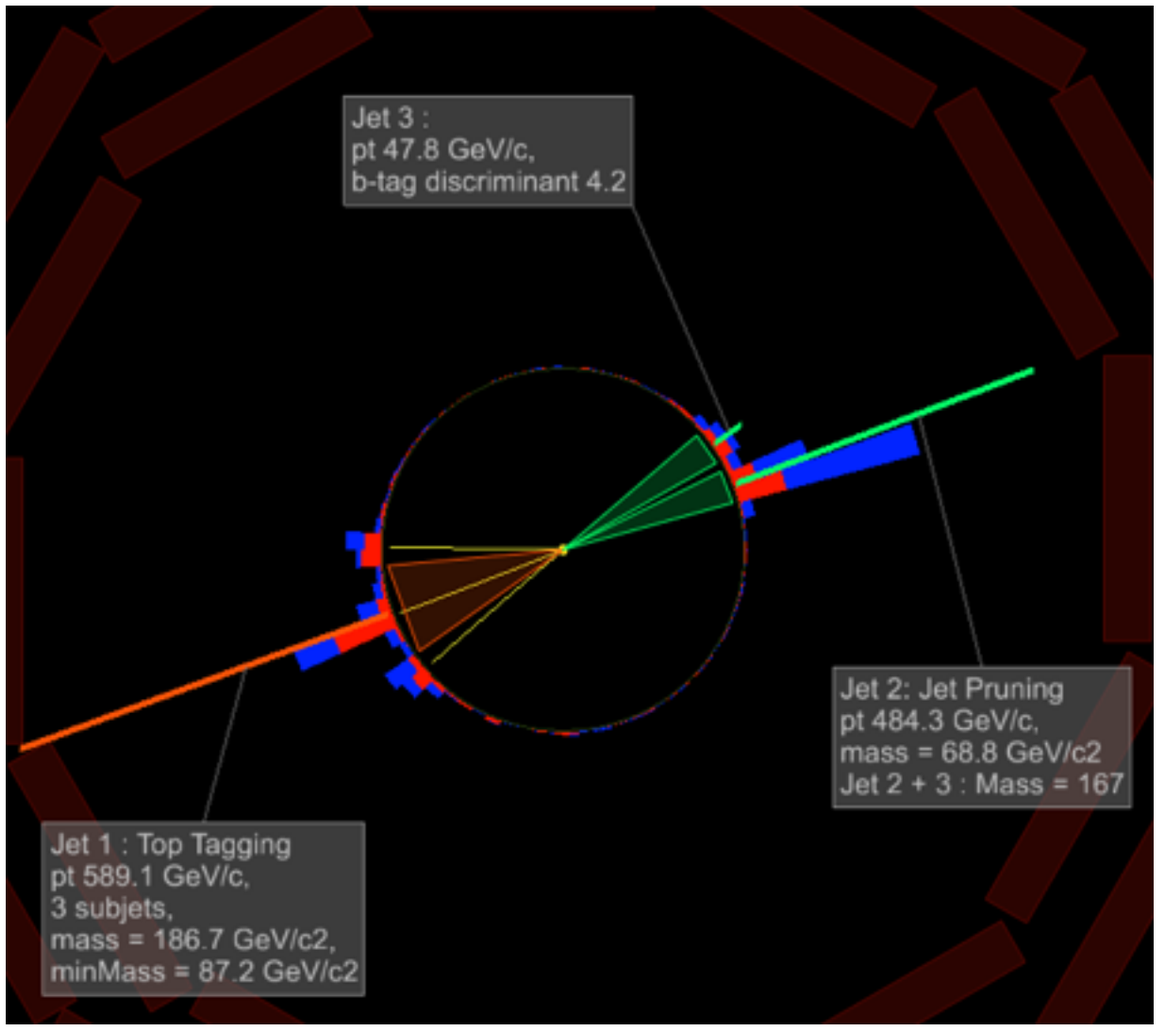


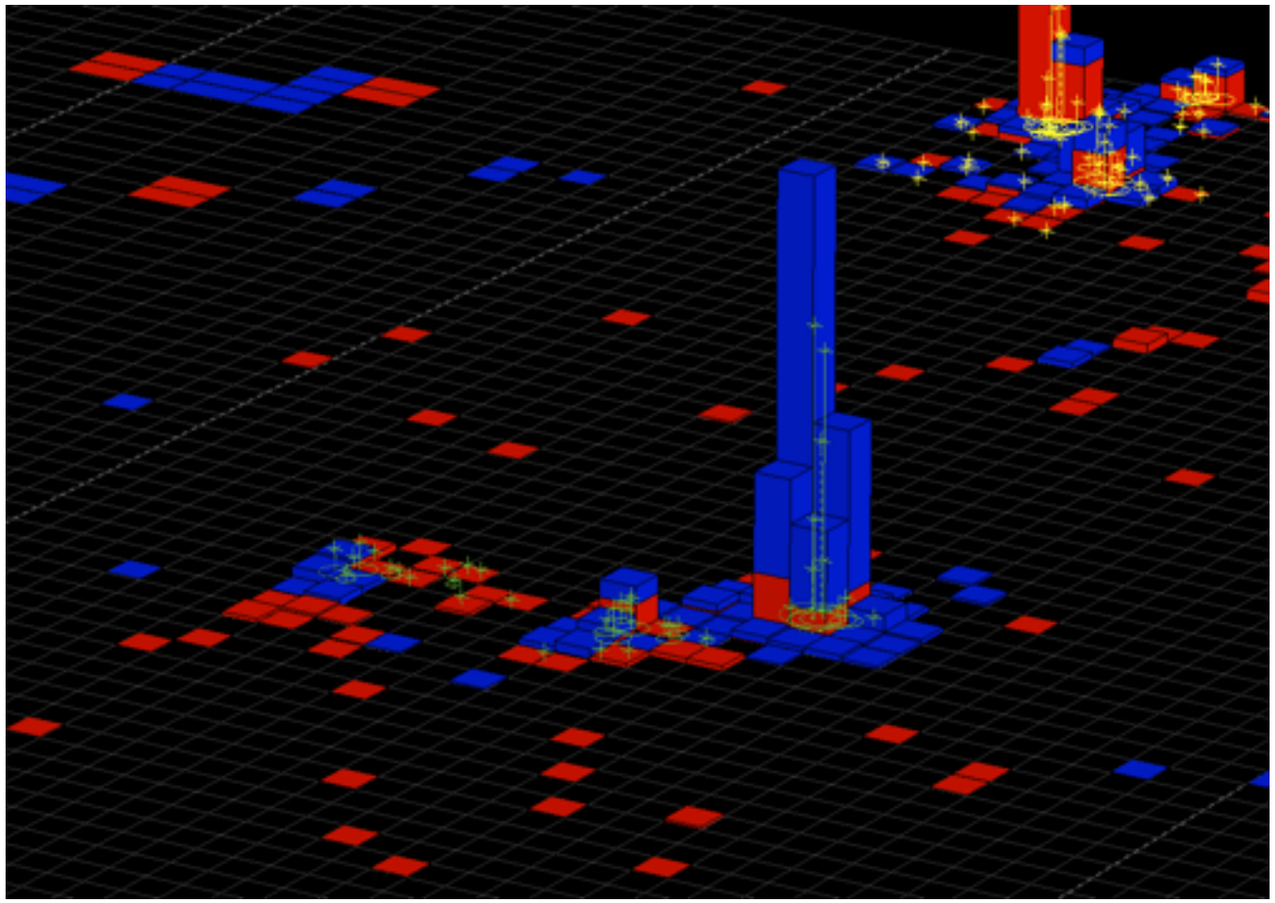
- Now excluding resonances below 2 TeV for variety of models

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

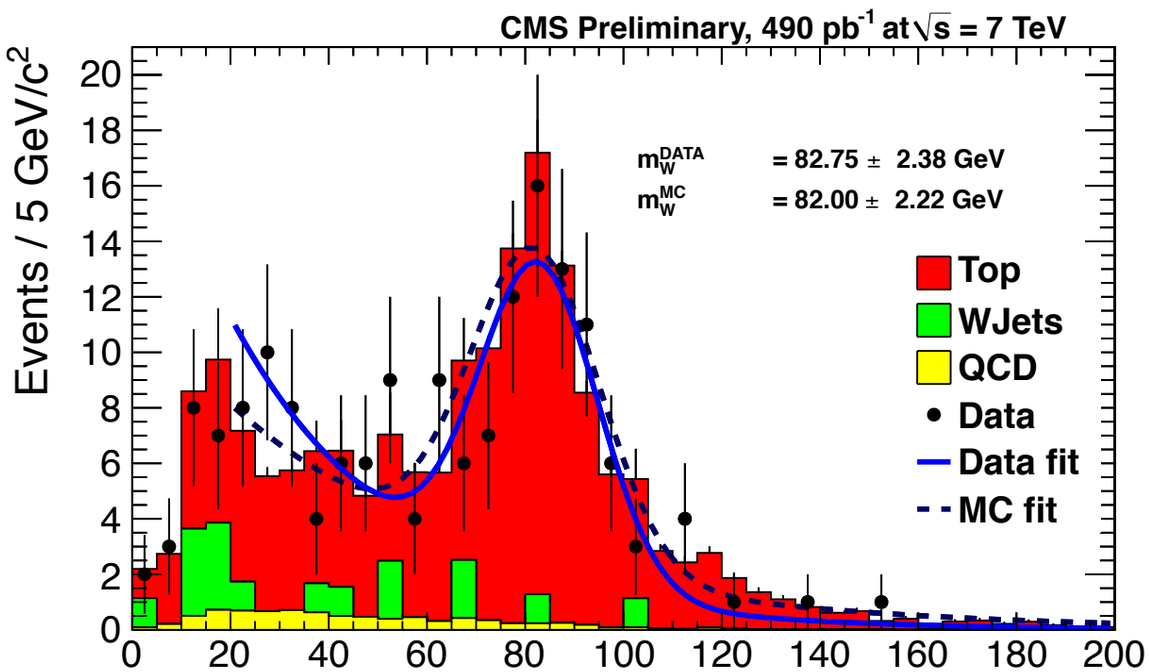
$t\text{-}t_{bar}$

- Boosted top jets for heavy resonances
- Take advantage of sub-structure in t →bW

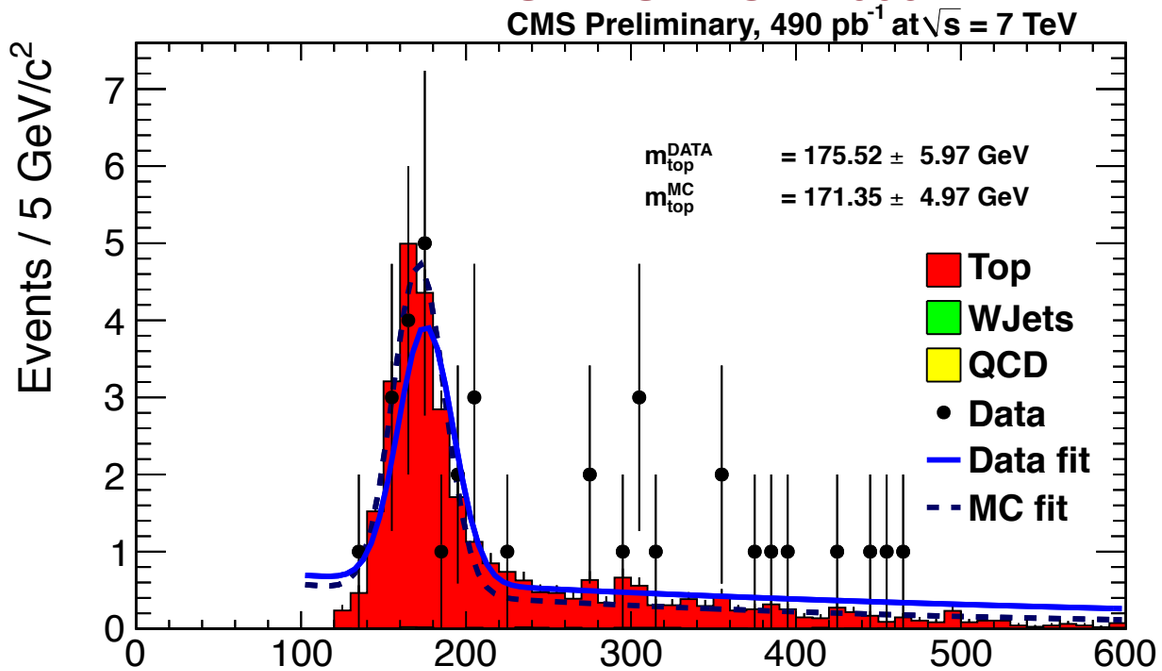


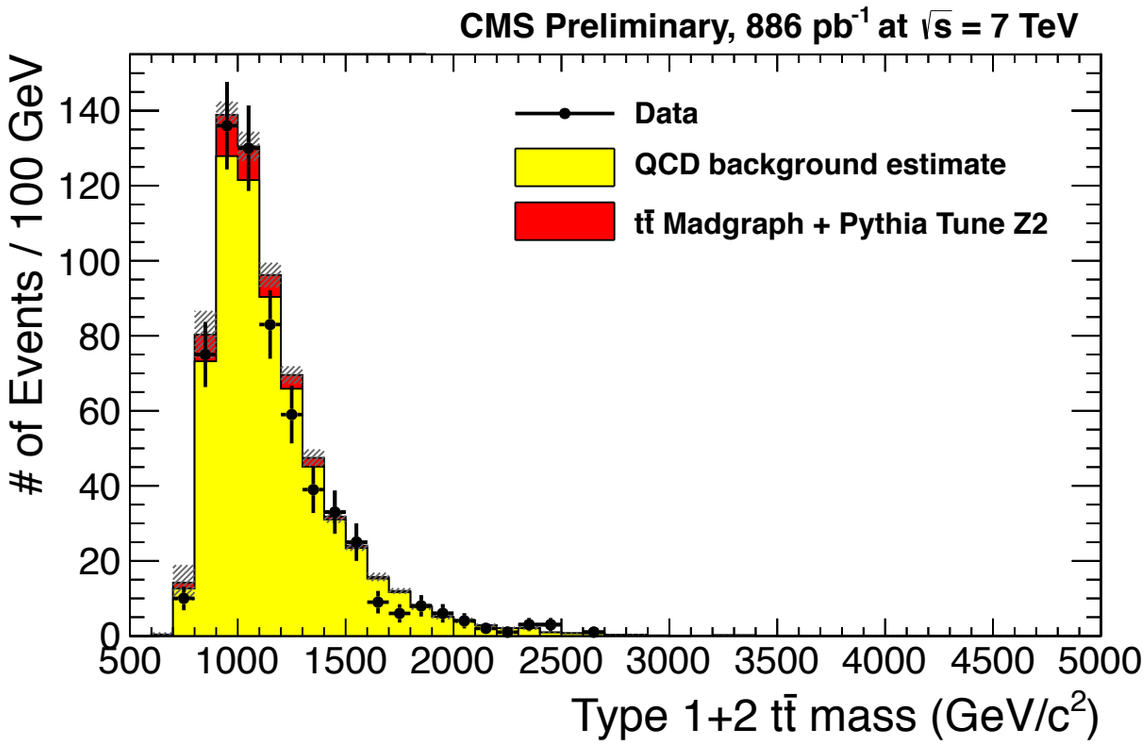


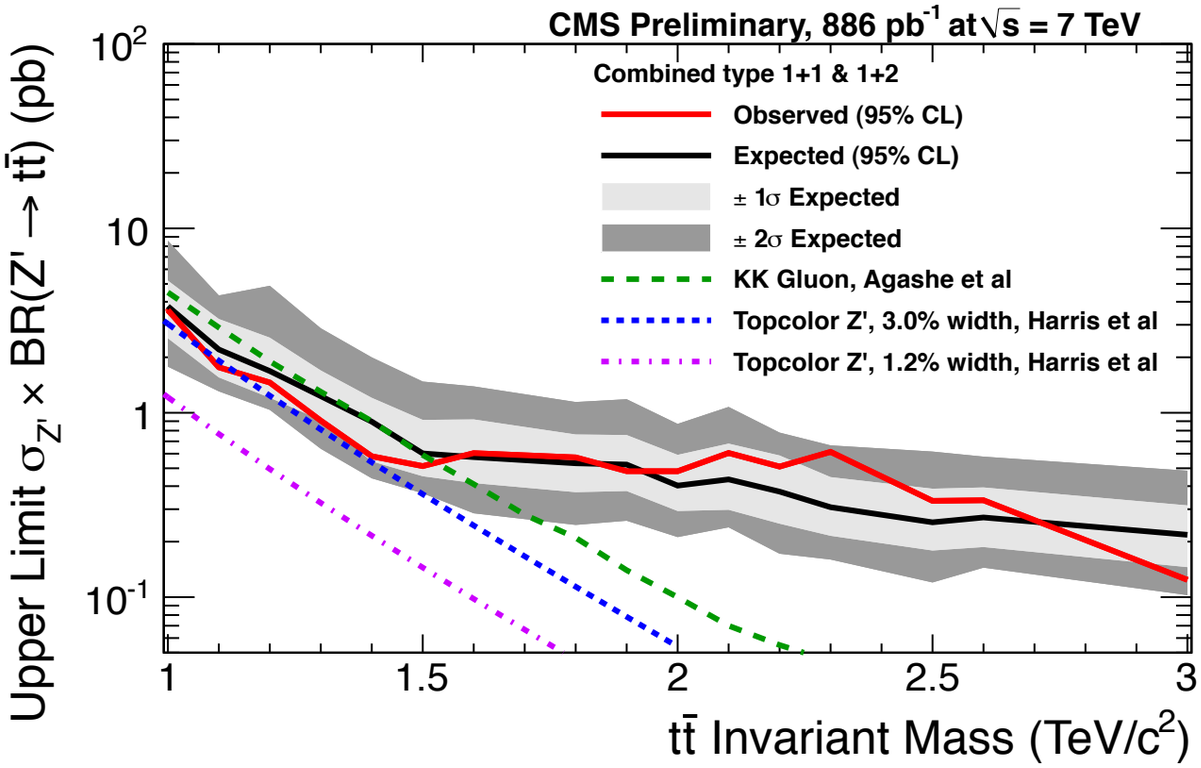
t-t_{bar}



CMS: PAS EXO-11-006

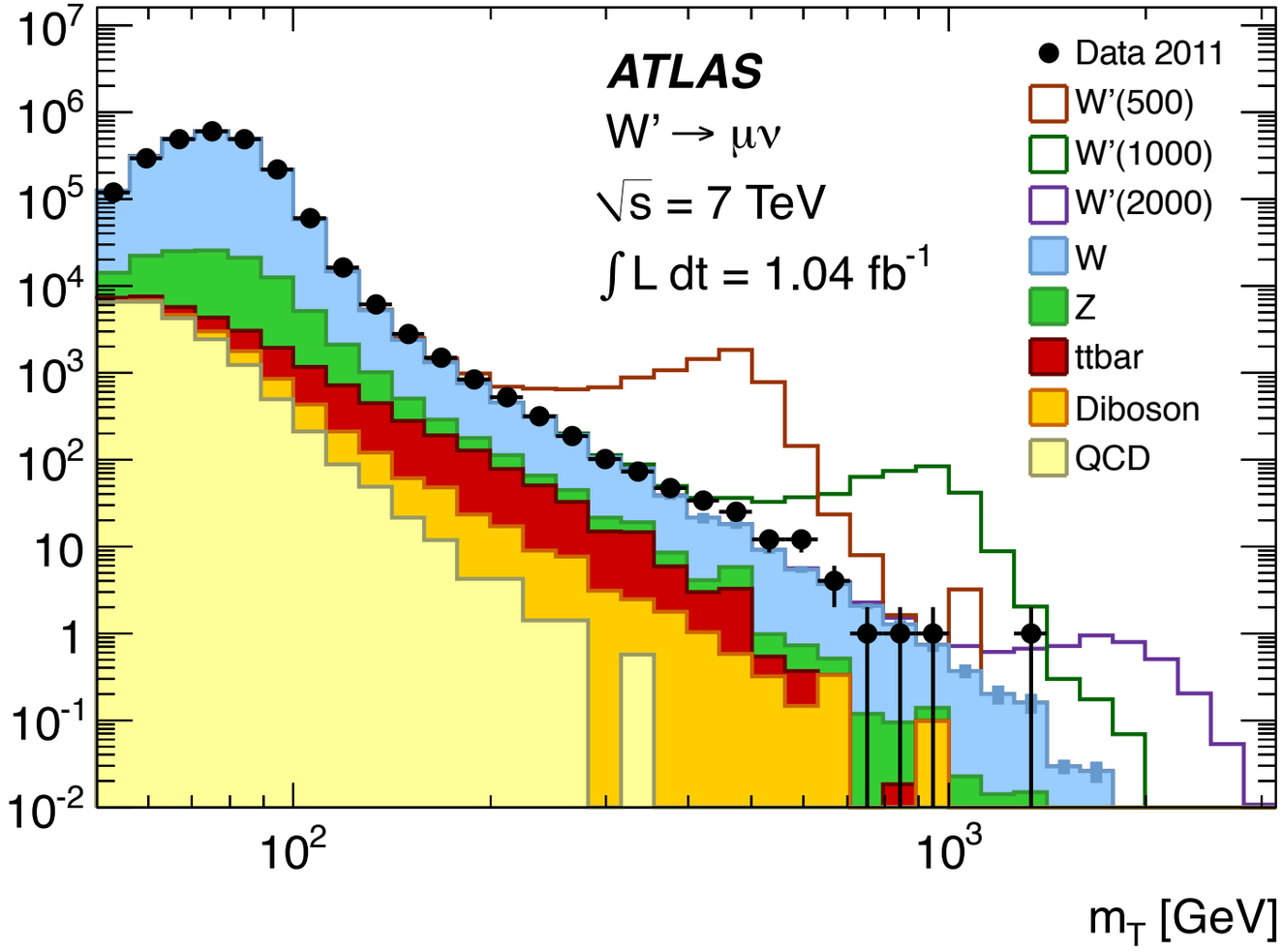




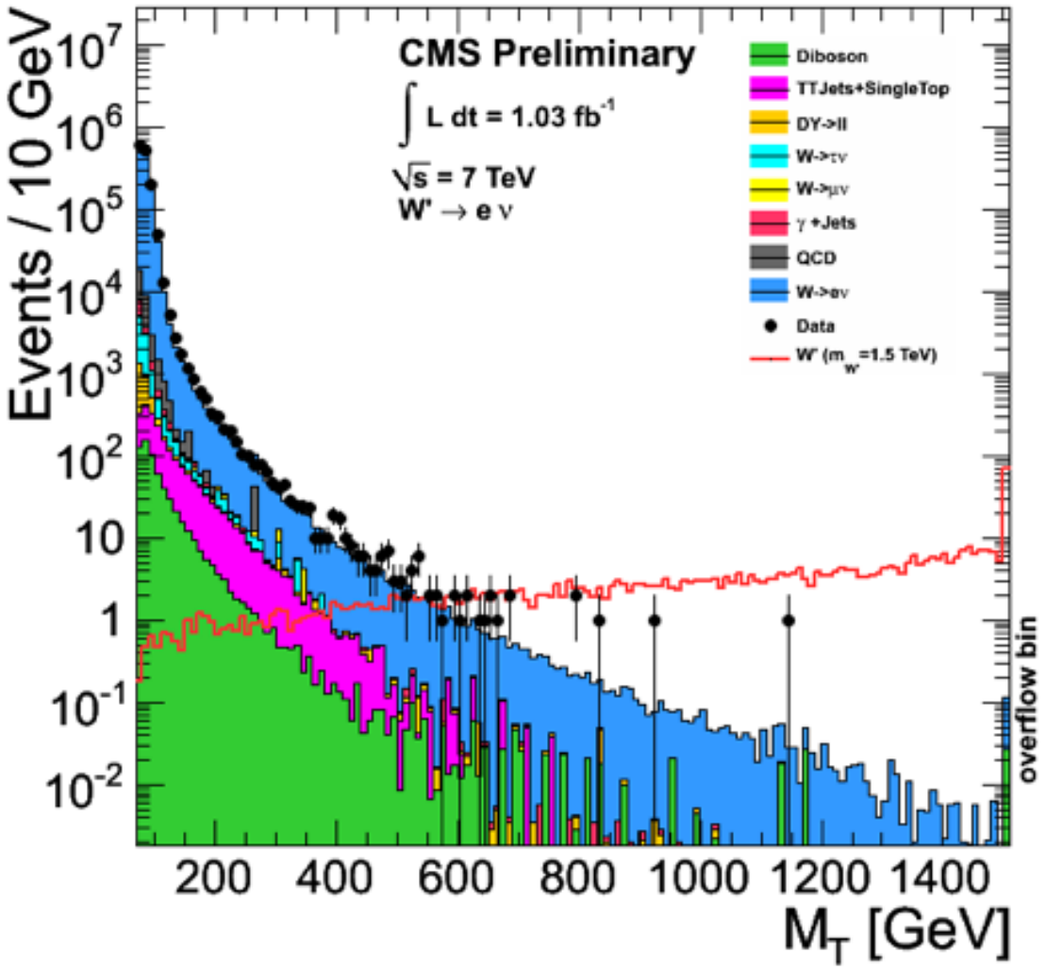


LEPTON+MET

ATLAS: arXiv:1108.1316



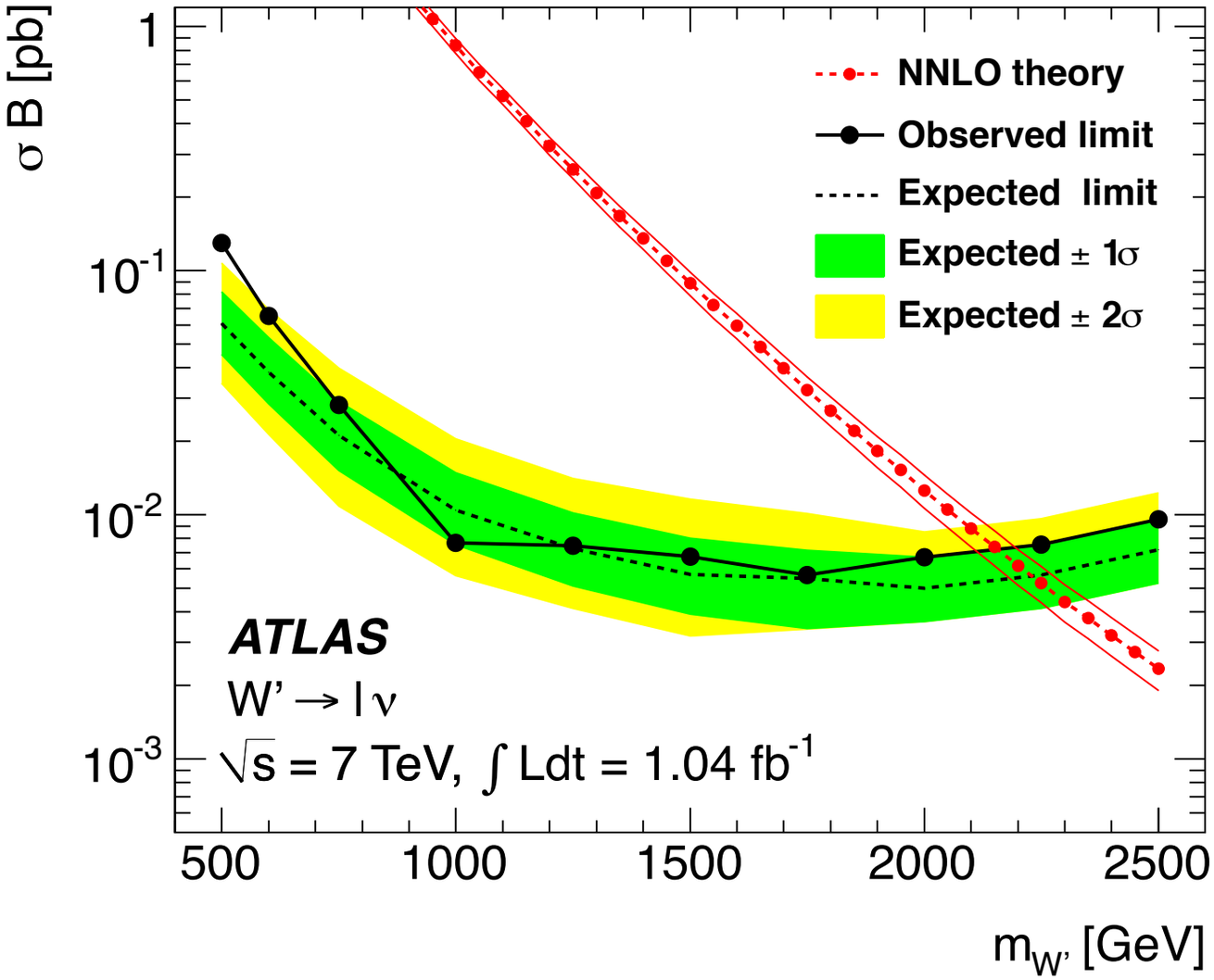
CMS: PAS EXO-11-024



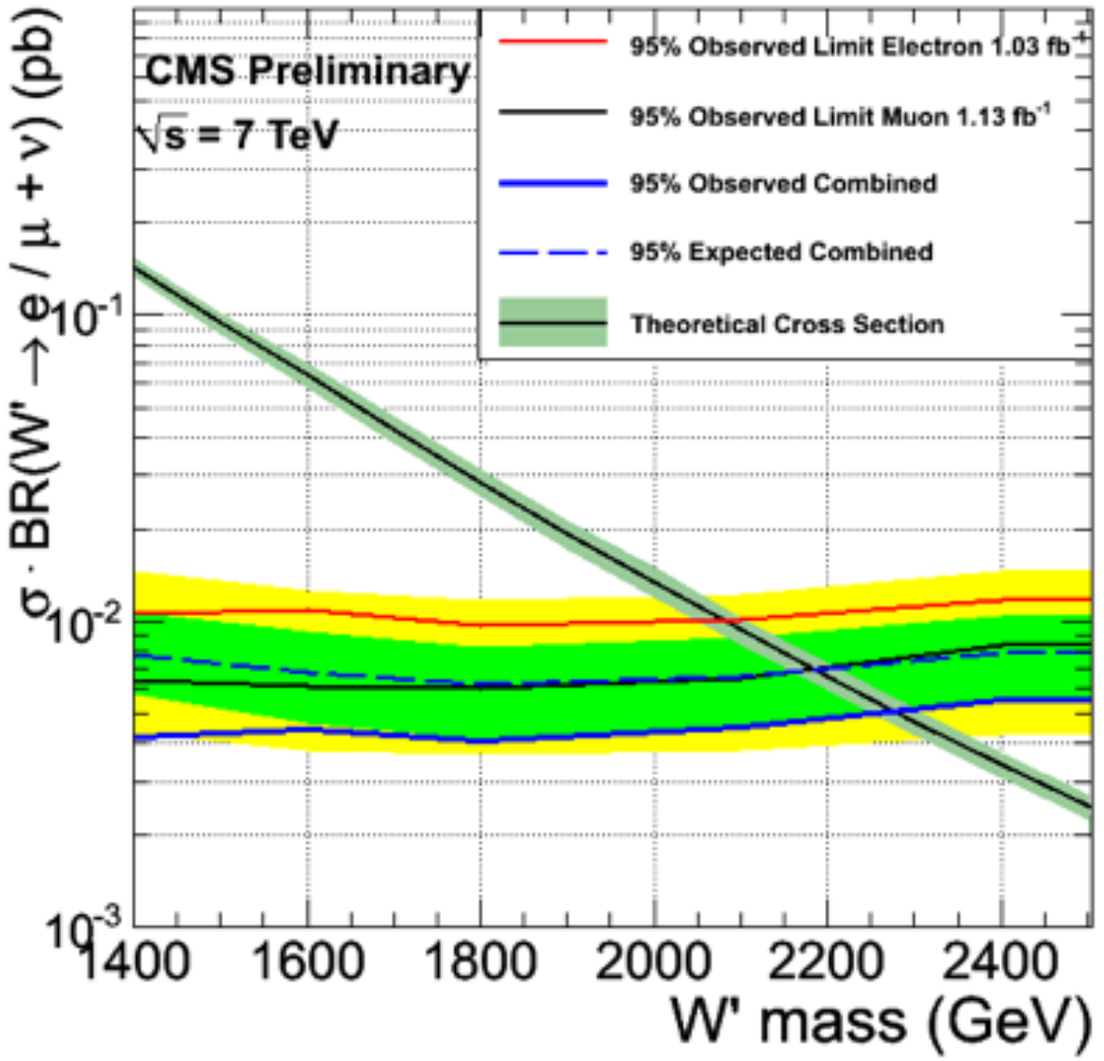
- Look for heavy W-like Jacobian peak in transverse mass $m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$
  - e.g. Sequential SM and Technicolor
- Dominant background: W production in Standard Model

W' → lν Exclusion Limits

ATLAS: arXiv:1108.1316

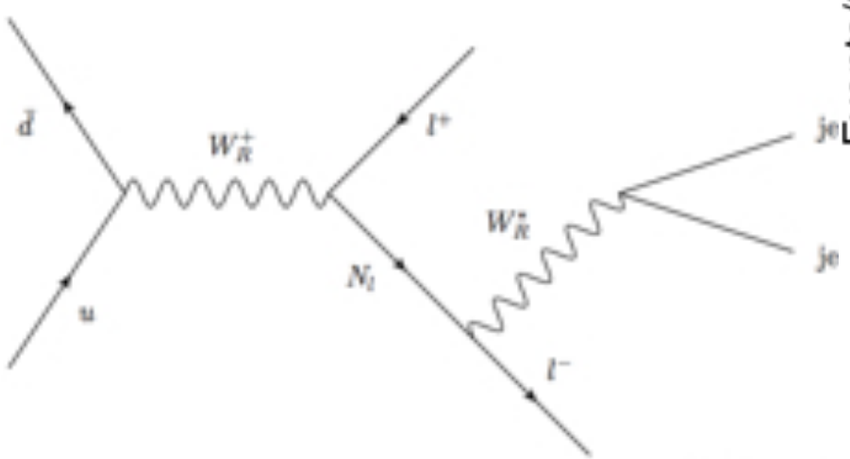


CMS: PAS EXO-11-024

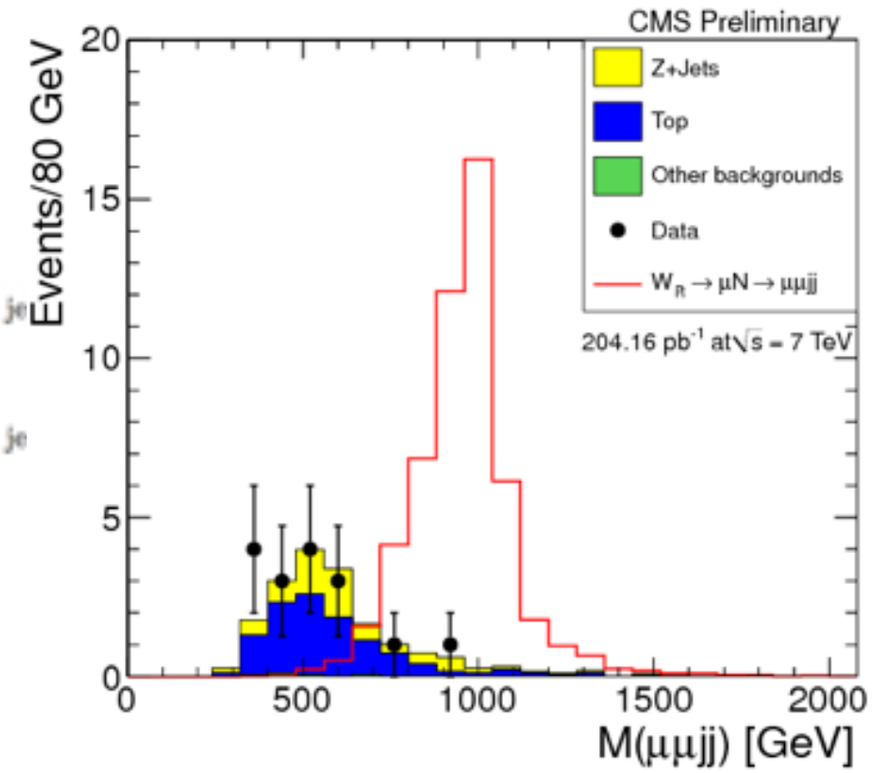


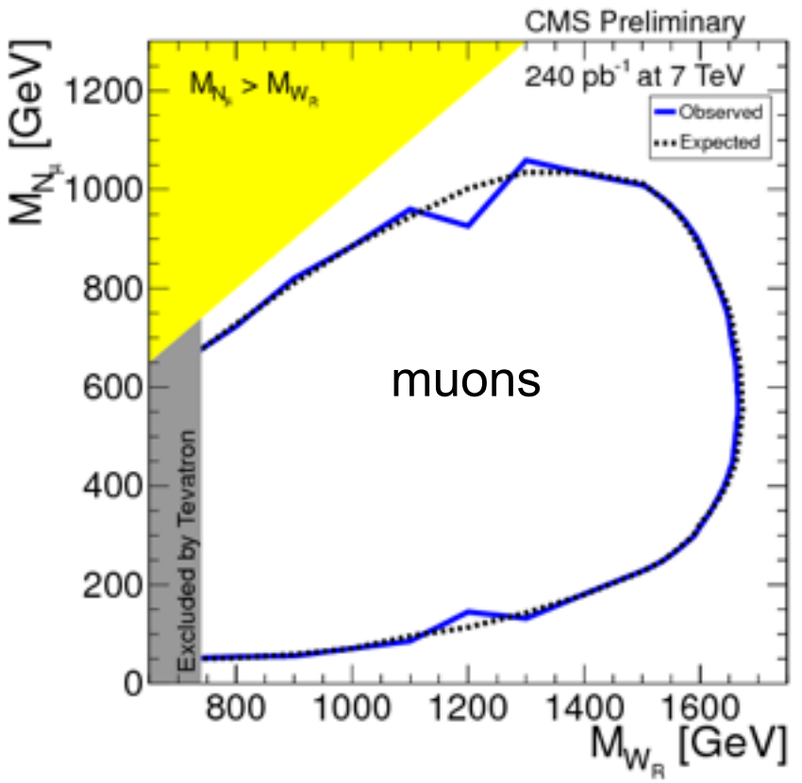
- Exclusion Limits now past 2 TeV

HEAVY NEUTRINO AND W_R



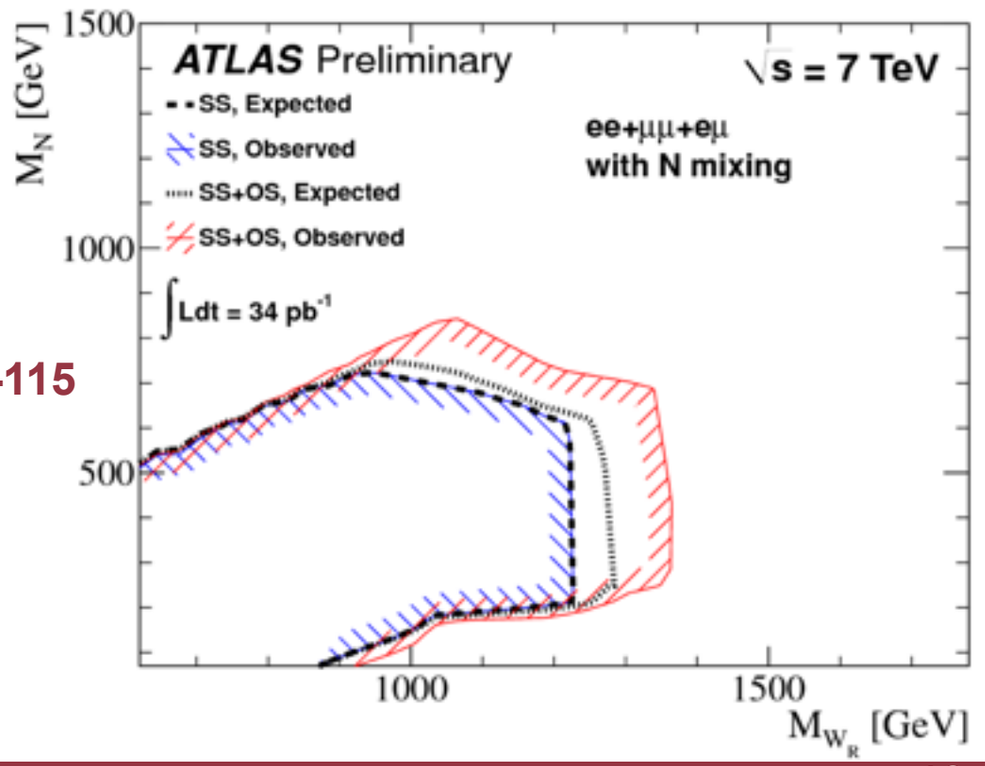
- Explain parity violation through L-R symmetry
- Heavy neutrino mass from see-saw mechanism
- Search for lljj resonance
- Most stringent limits today!
- Gets very interesting for theory once limits at 2.5 TeV





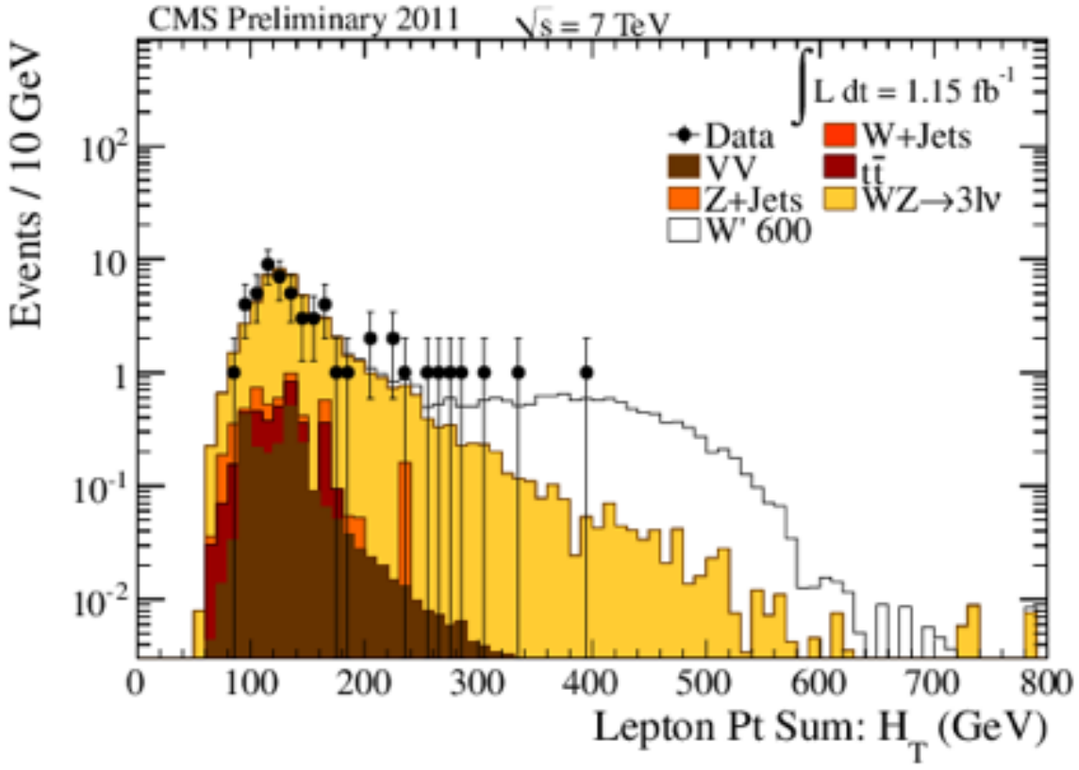
CMS: PAS EXO-11-002

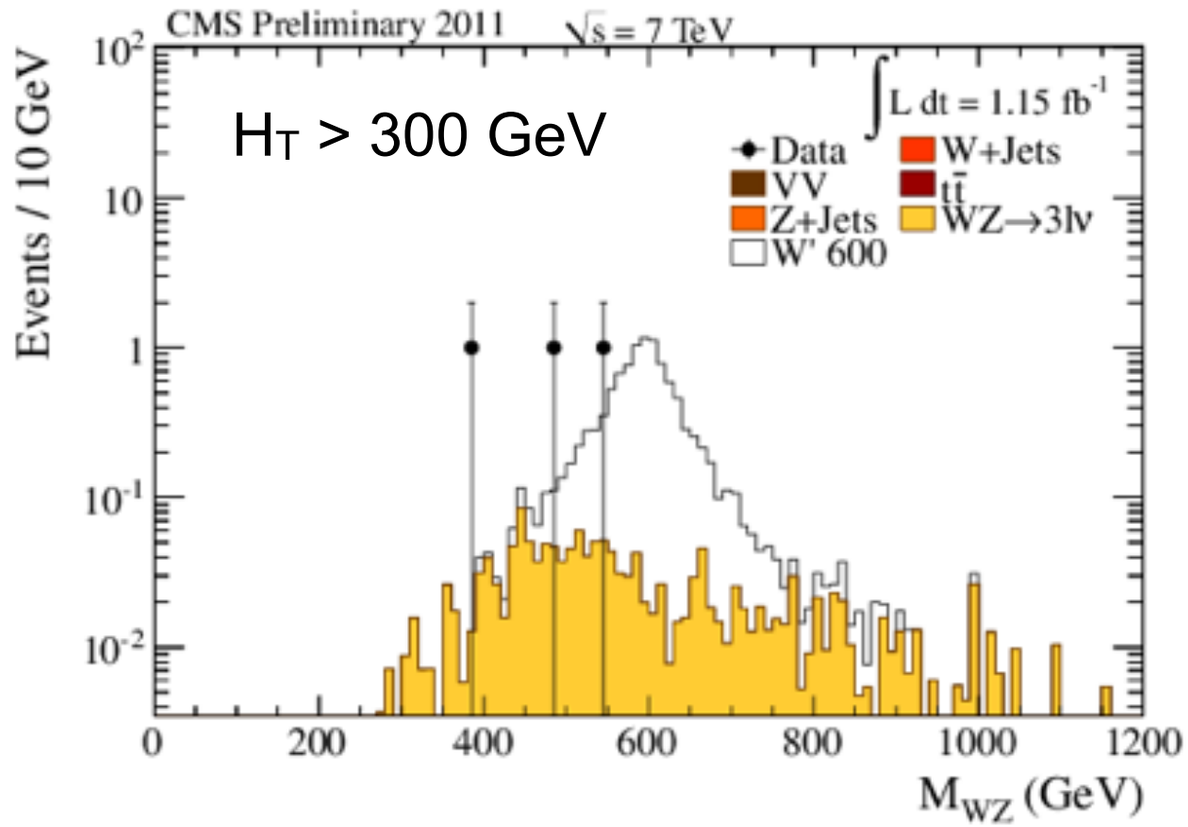
ATLAS: ATLAS-CONF-2011-115



WZ Resonances

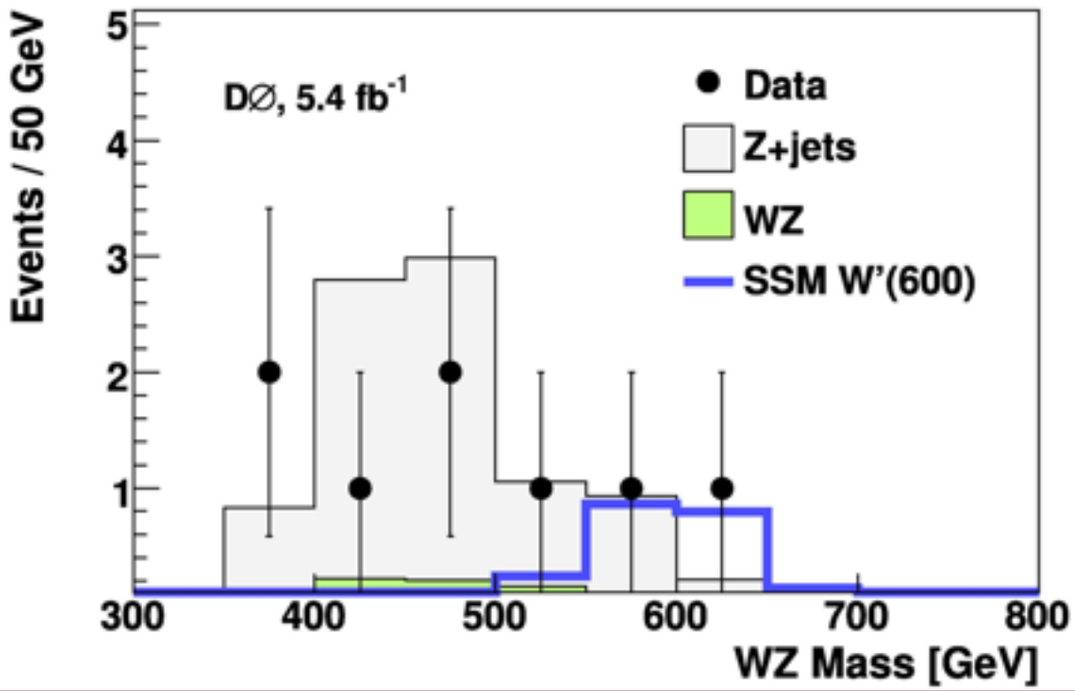
CMS: PAS-EXO-11-041



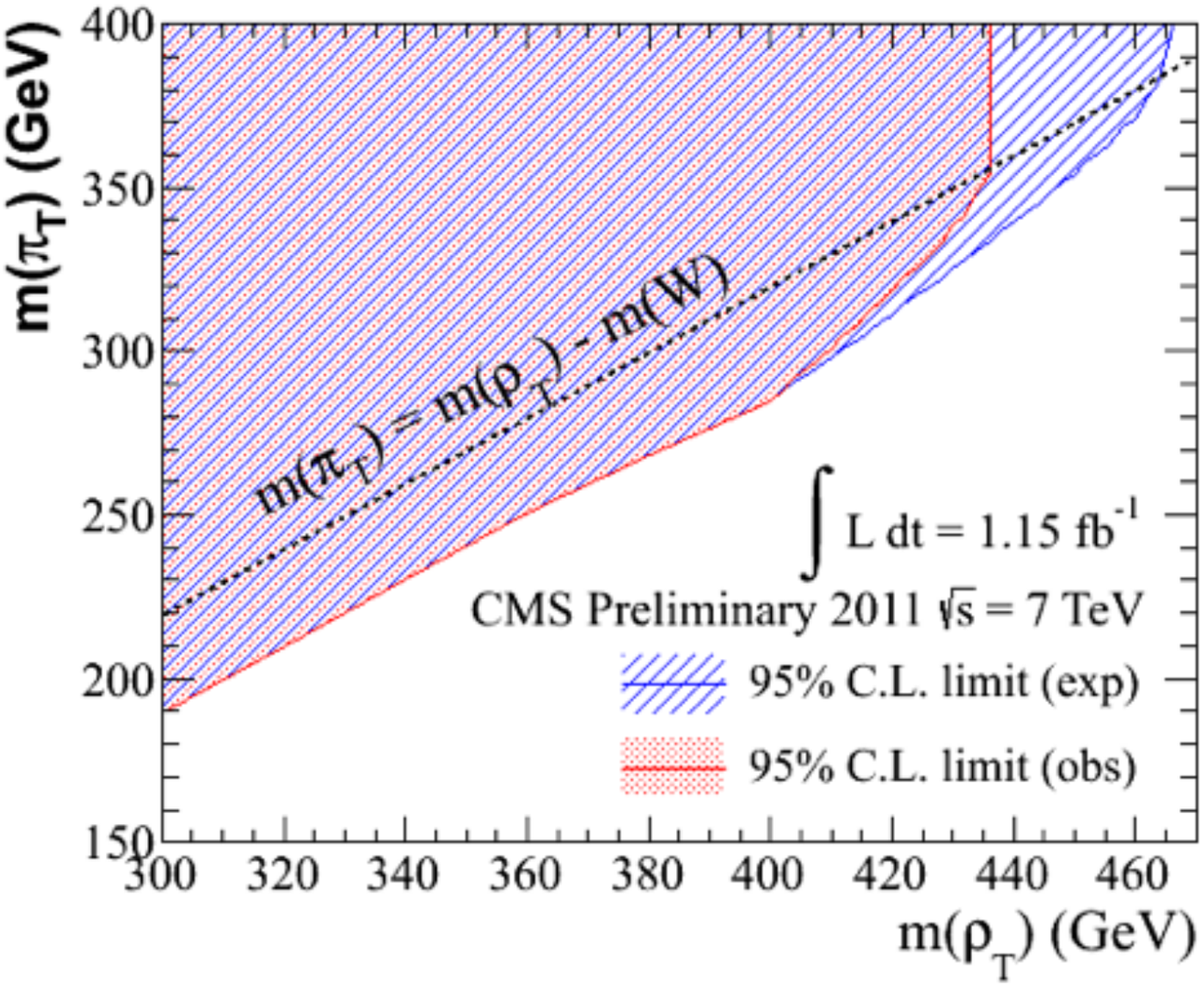


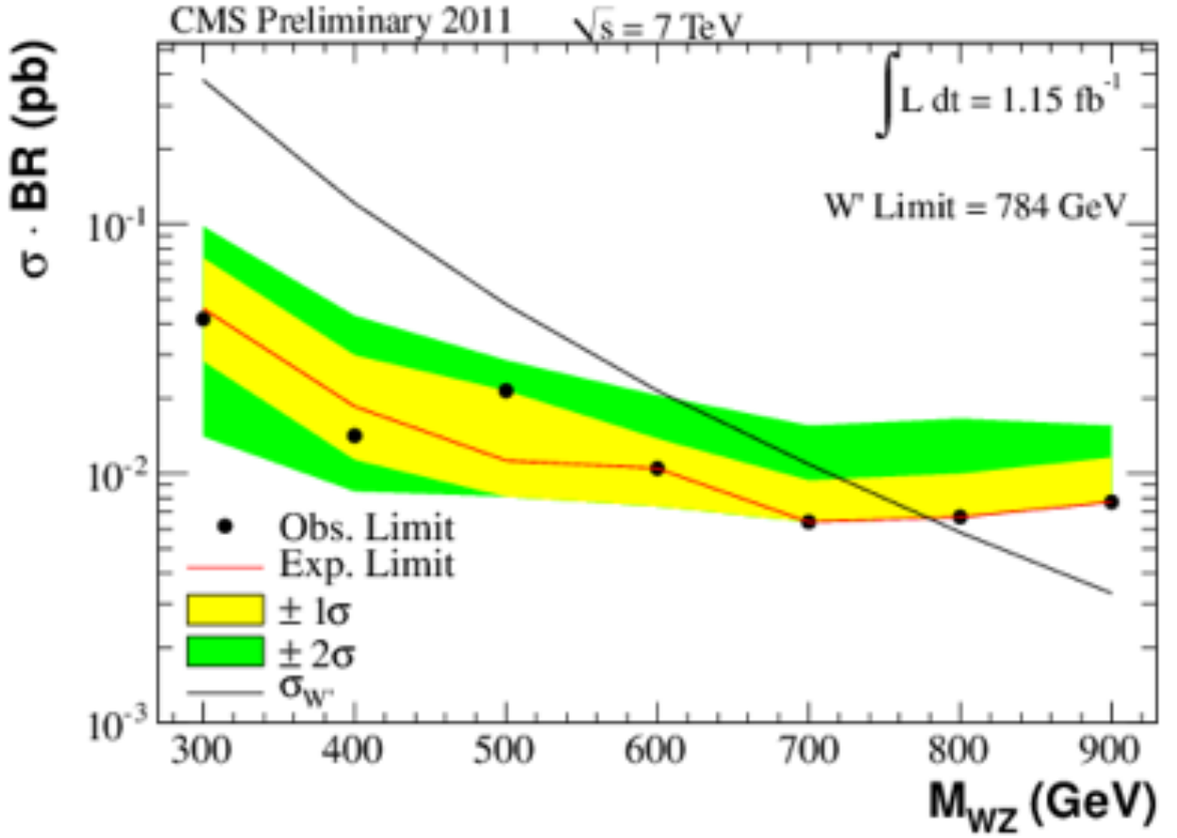
- Sensitive to sequential SM and techni-hadrons (rho and pi)
- CMS: 3 leptons + missing energy
  - Sum of lepton Pt
  - WZ invariant mass with W mass constraint
- D0: also hadronic W/Z decays
  - 1 or 2 jets, 1-3 leptons
  - 3 exclusive categories

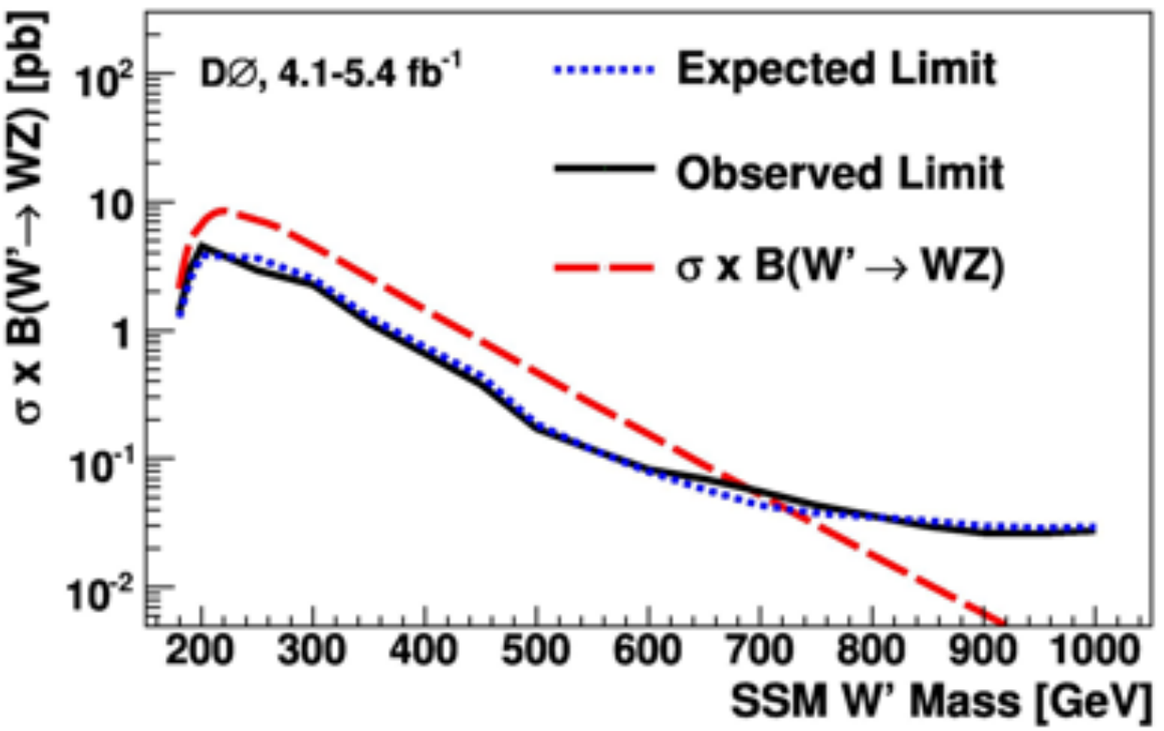
D0: PRL 107, 011801 (2011)



WZ Exclusion Limits





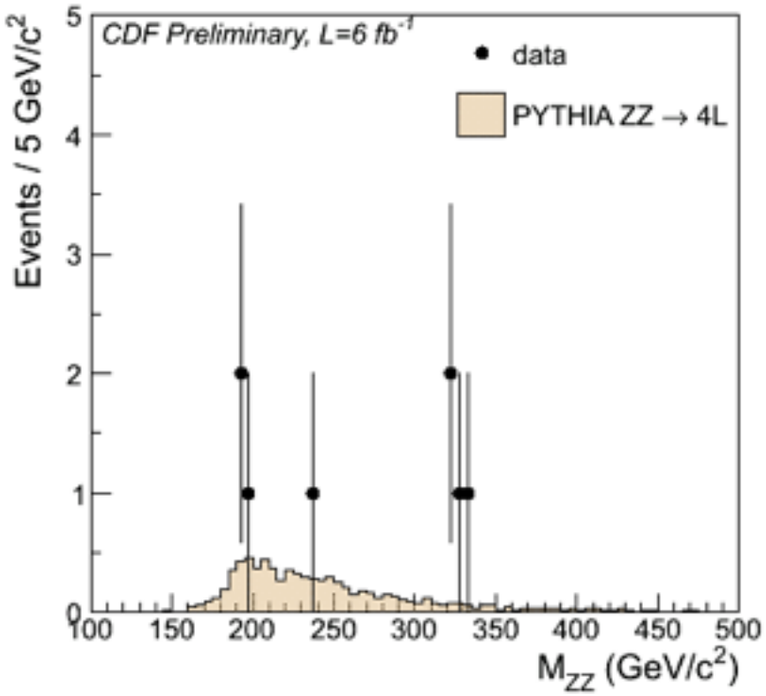


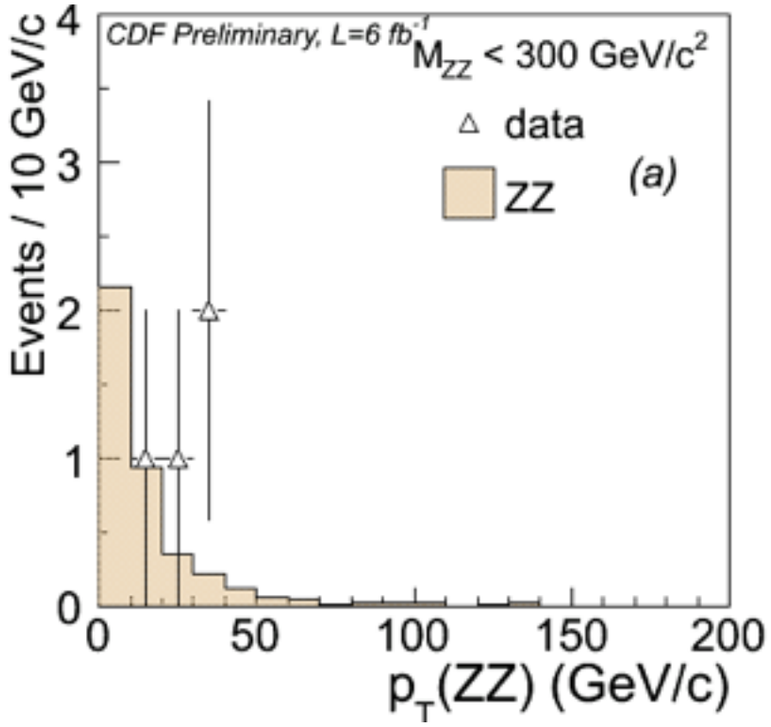
W'_{SSM}: 784 GeV

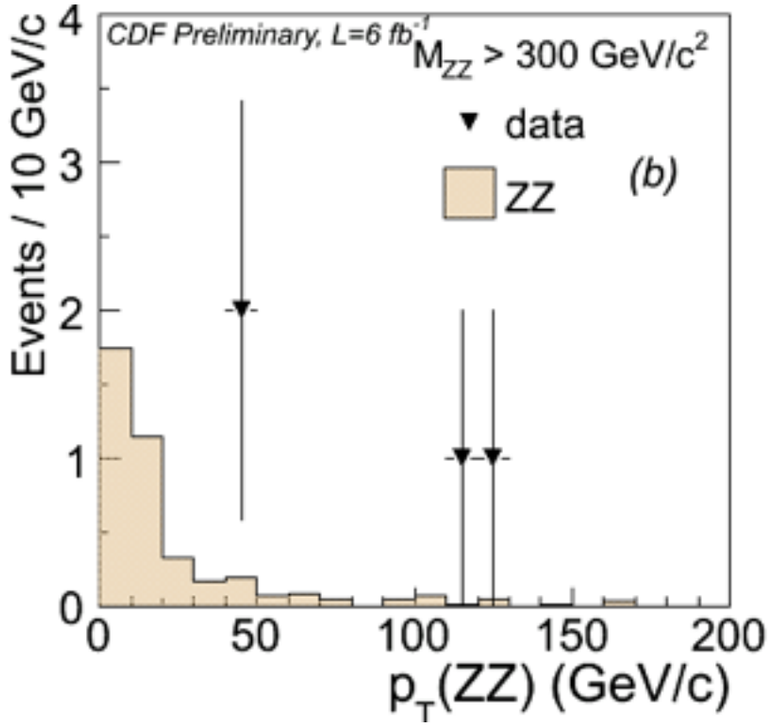
ρ_{TC}: 382 GeV ($M_{\pi_{TC}} = \frac{3}{4} M_{\rho_{TC}}$-25 GeV)

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

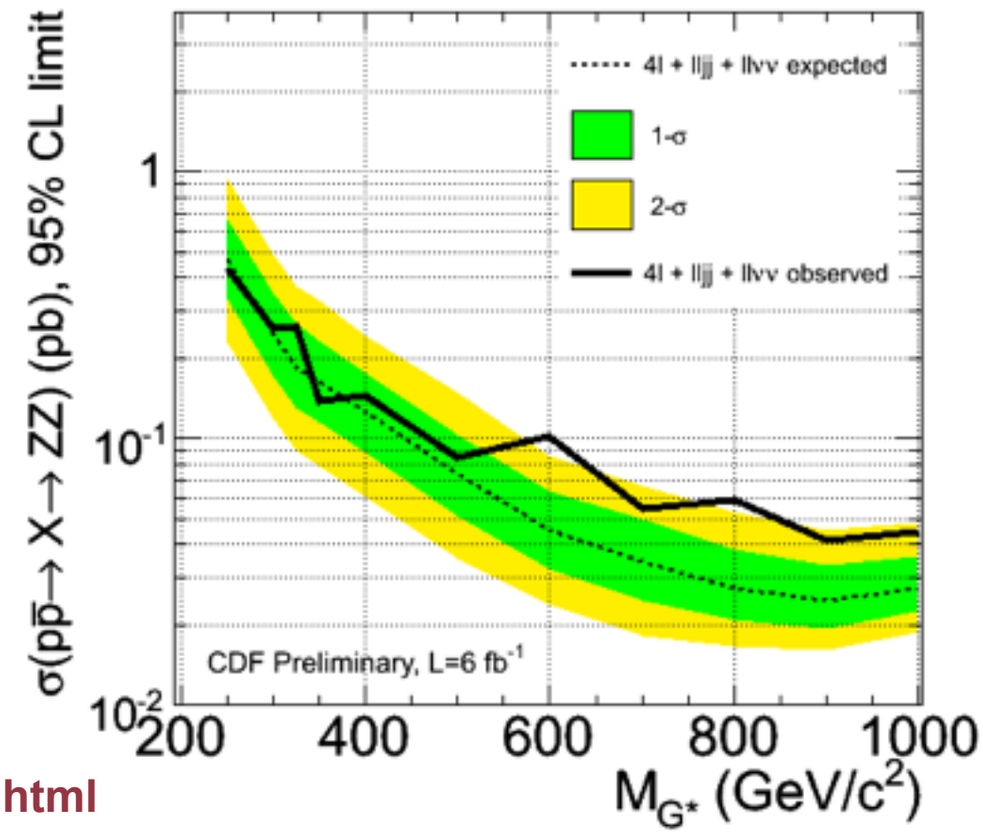
ZZ Resonance







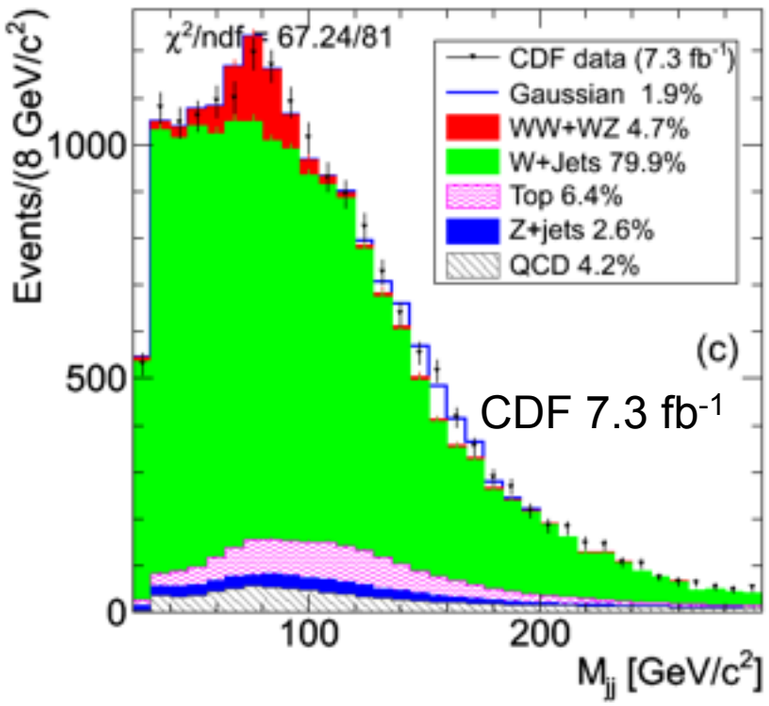
- 3 topologies considered: $Z \rightarrow ll + Z \rightarrow ll, jj, \nu\nu$
- 4 interesting events in 4l final state
  - Also high P_T for same for events
  - Probability of background fluctuation ~10^{-4}
- No excess in lljj nor ll+MET final states

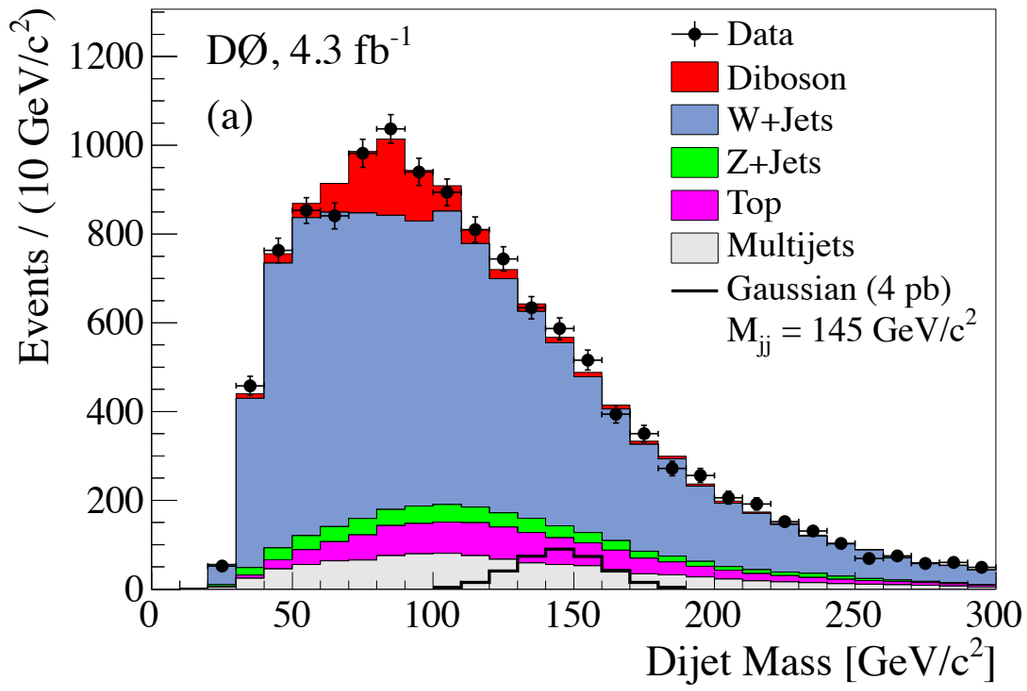


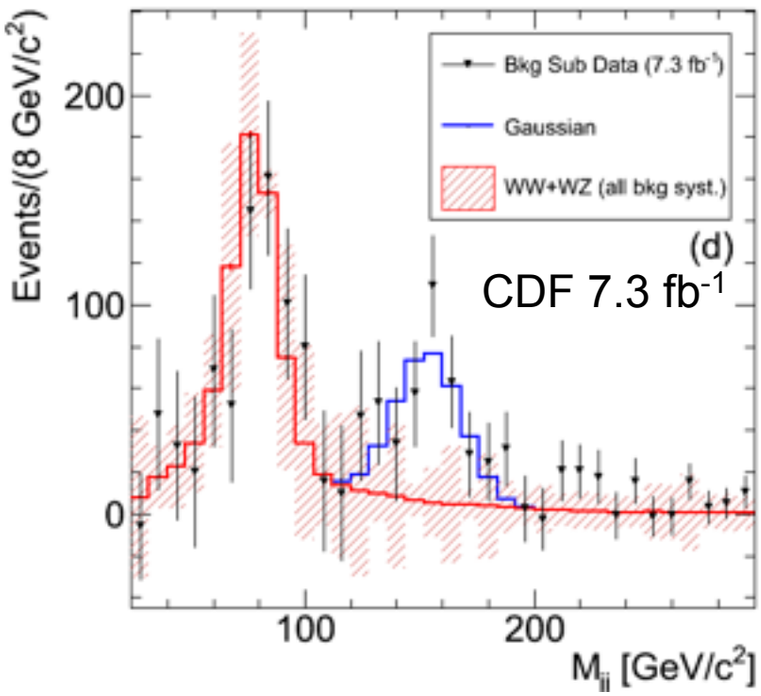
http://www-cdf.fnal.gov/physics/exotic/r2a/20110718.highmasszz/index.html

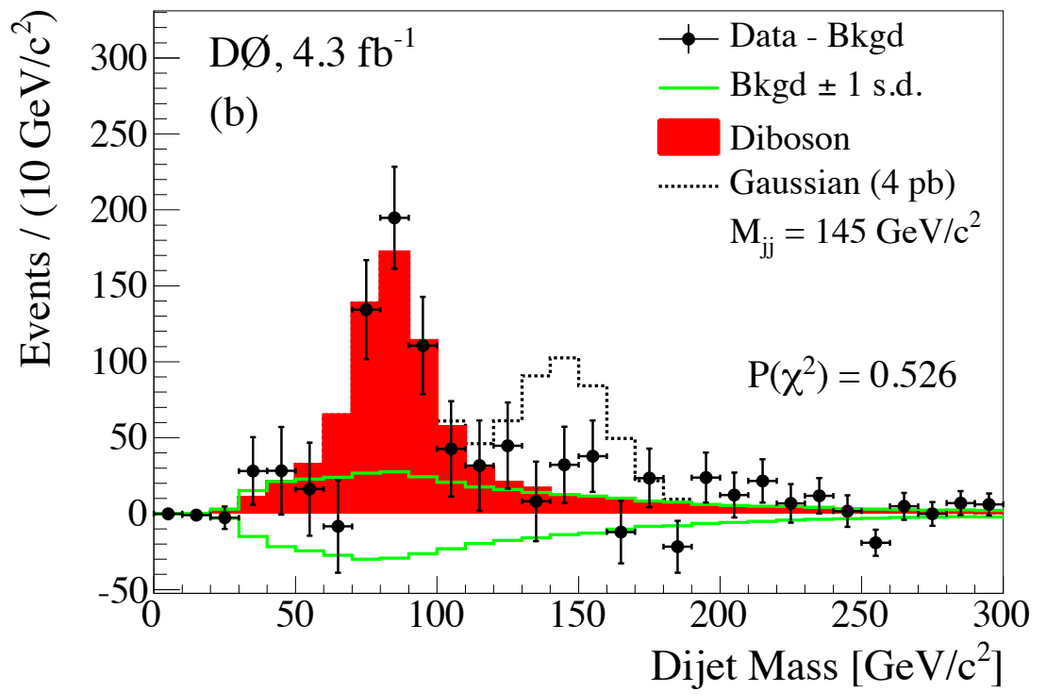
W+JJ

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



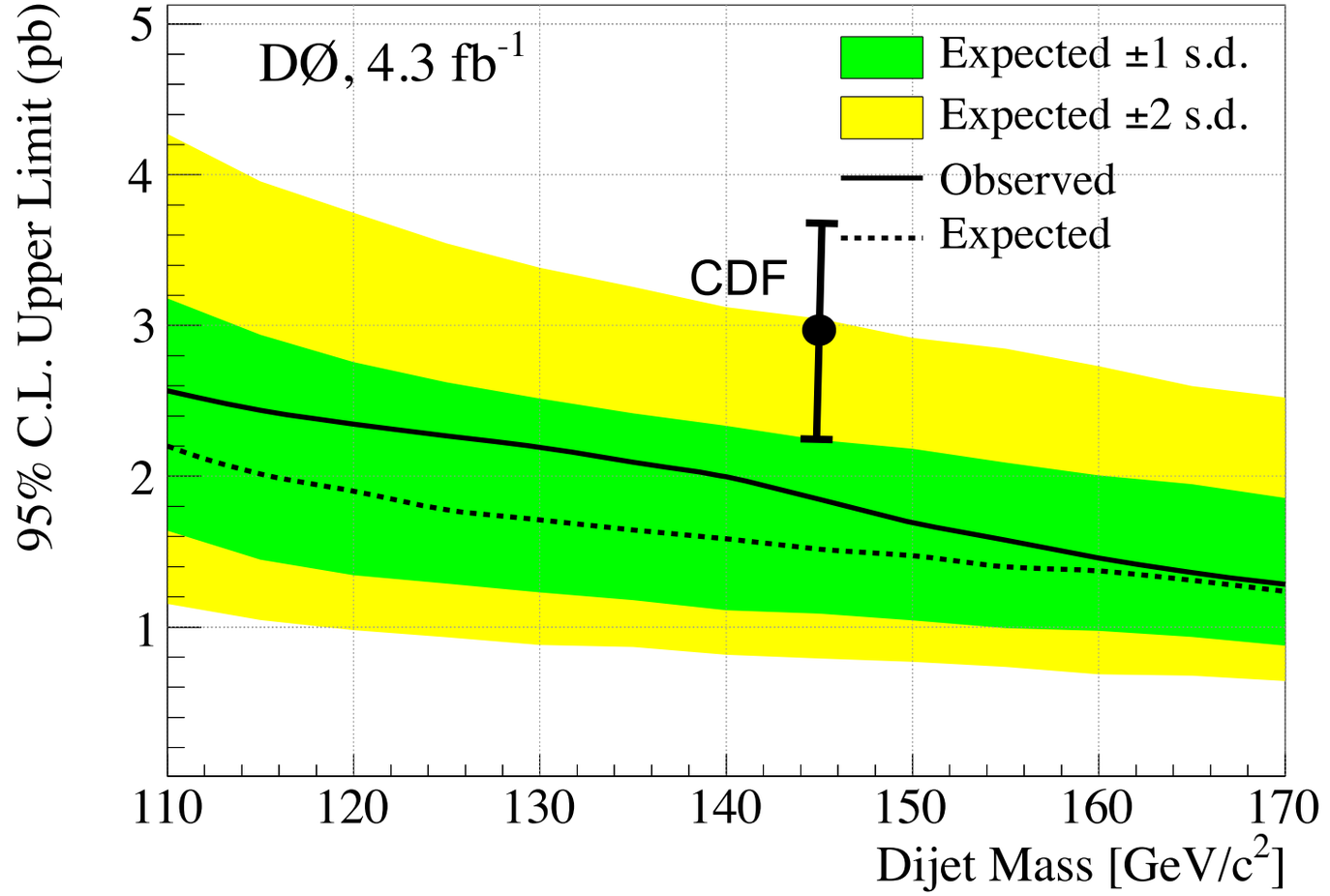






SUMMARY OF W+JJ AT TEVATRON

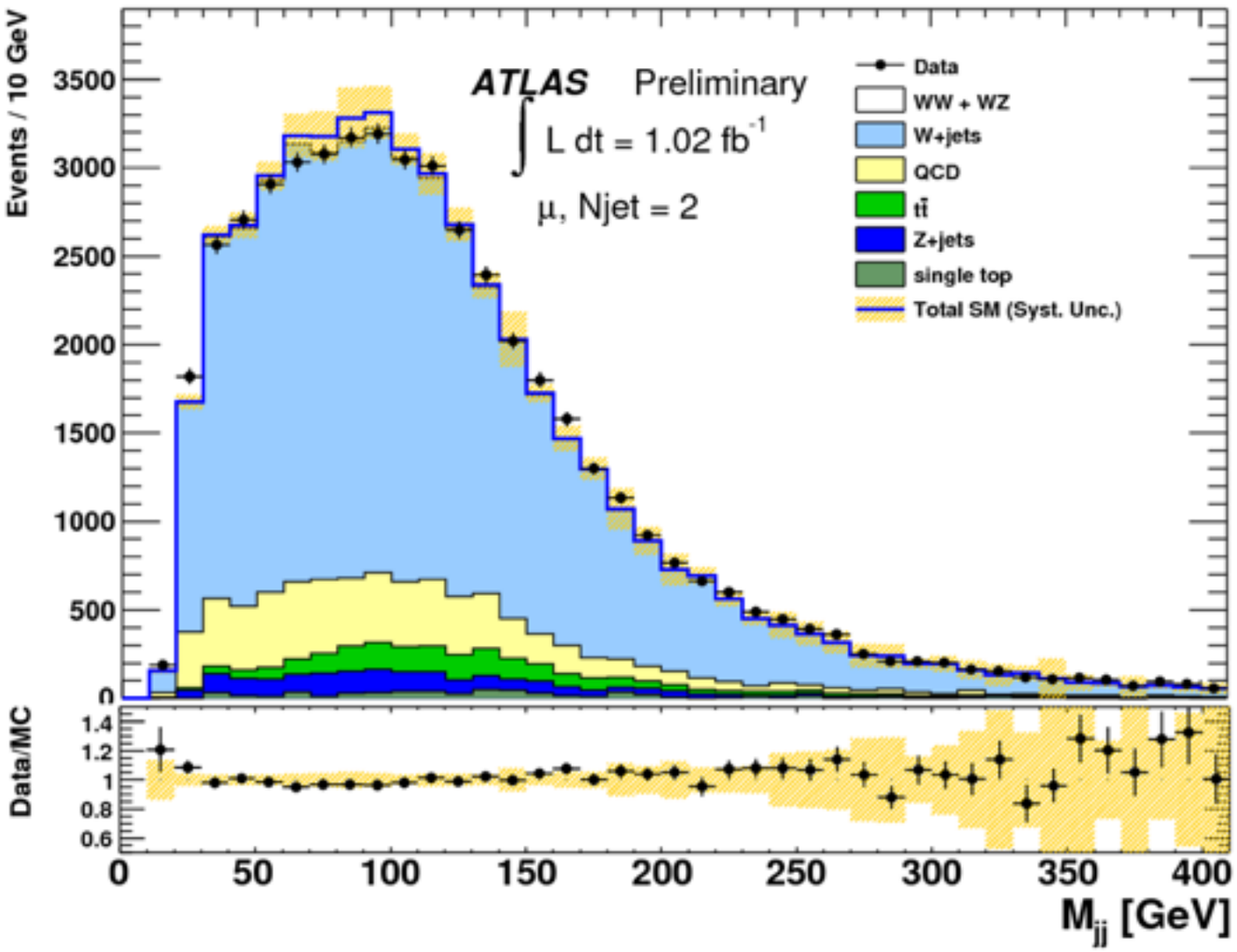
- M_{jj} structure not confirmed by D0
  - small differences exist but unlikely to wash out a peak
- D0 measured cross section: 0.82 ± 0.83 pb **D0: PRL 107, 011804 (2011)**
- Original CDF cross section: ~4 pb
- Latest CDF: 3.0 ± 0.7 pb **CDF: http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html**
-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

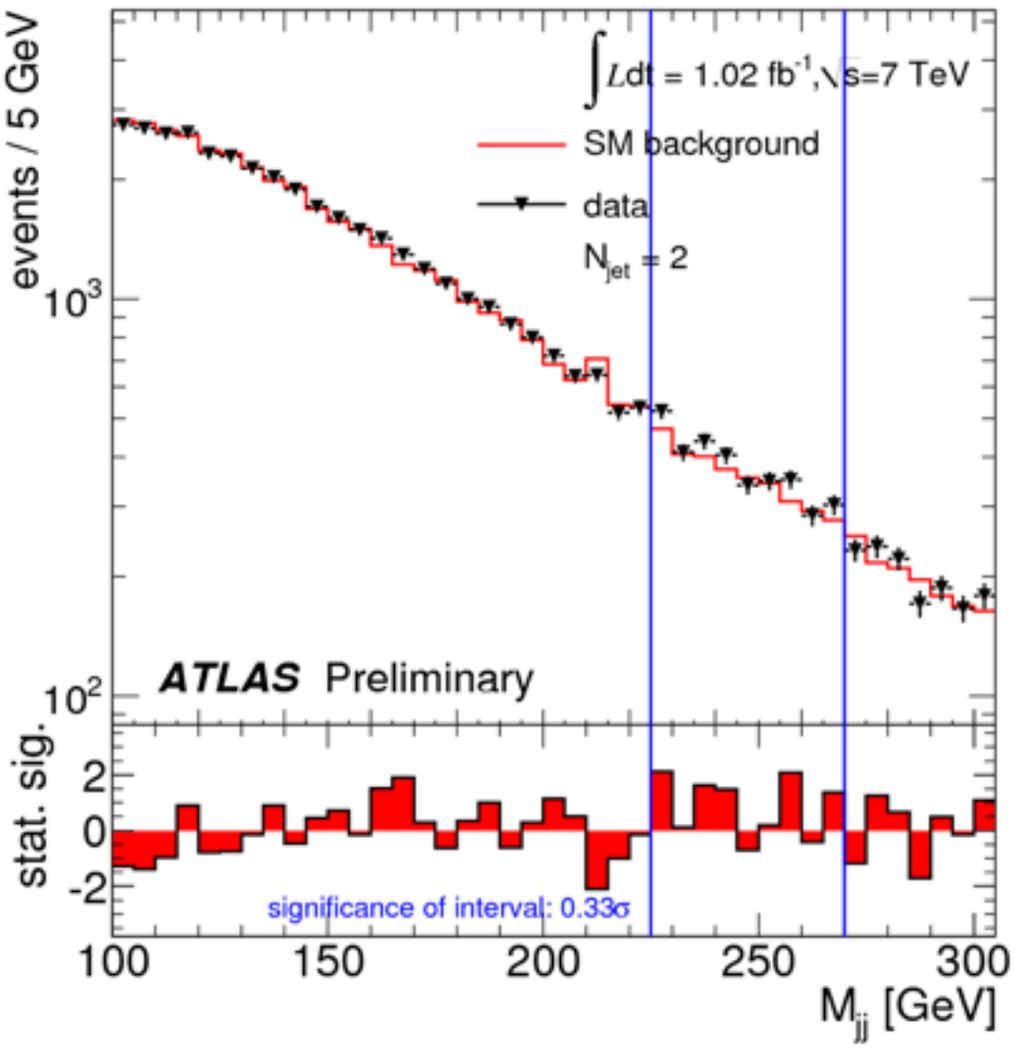


W+JJ AT LHC

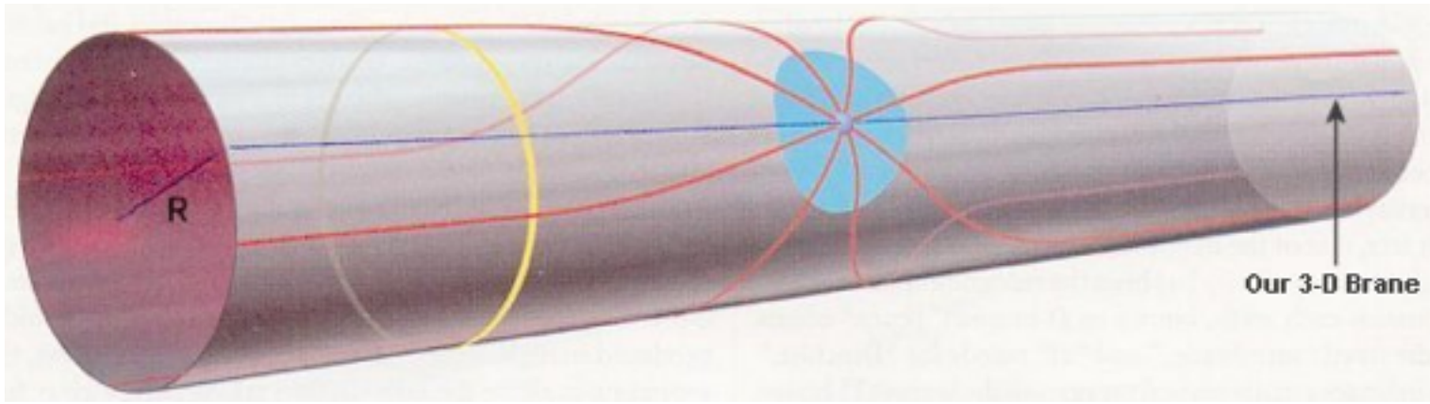
- Similar strategy and selection as CDF
  - #jet = 2 at CDF probably should be relaxed at LHC
  - Significance of 0.95 sigma in N>=2 sample

ATLAS-CONF-2011-096





- No deviation from SM observed



Fundamental Planck Scale

Apparent Planck Scale

# of EDs

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

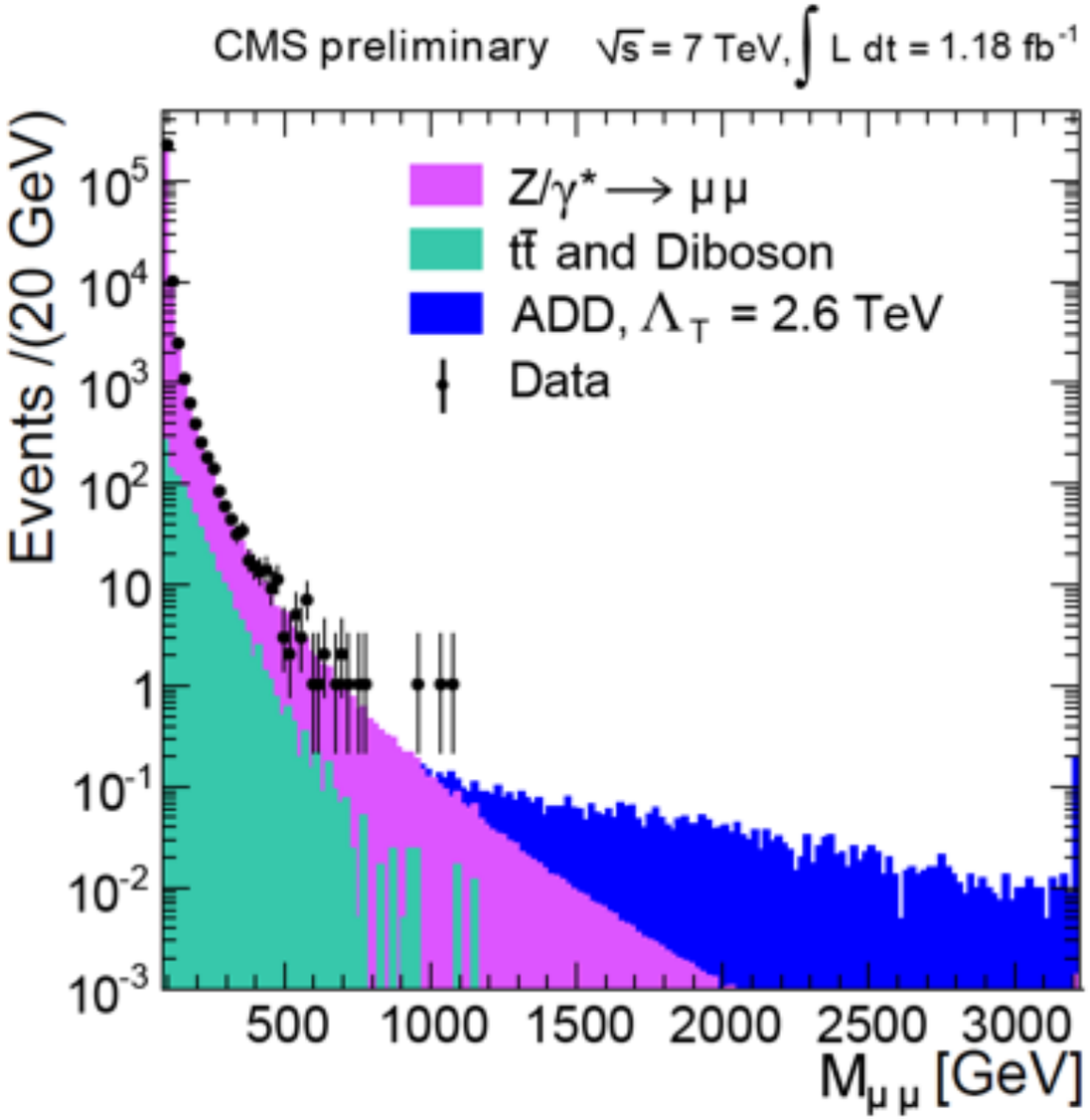
Size of ED

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



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

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

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

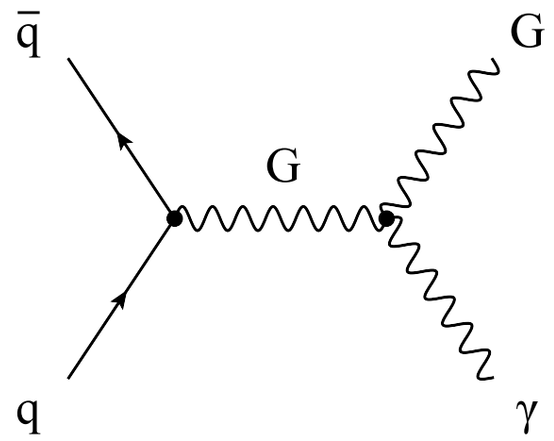
Upper Limit on M_s (no K-factor)

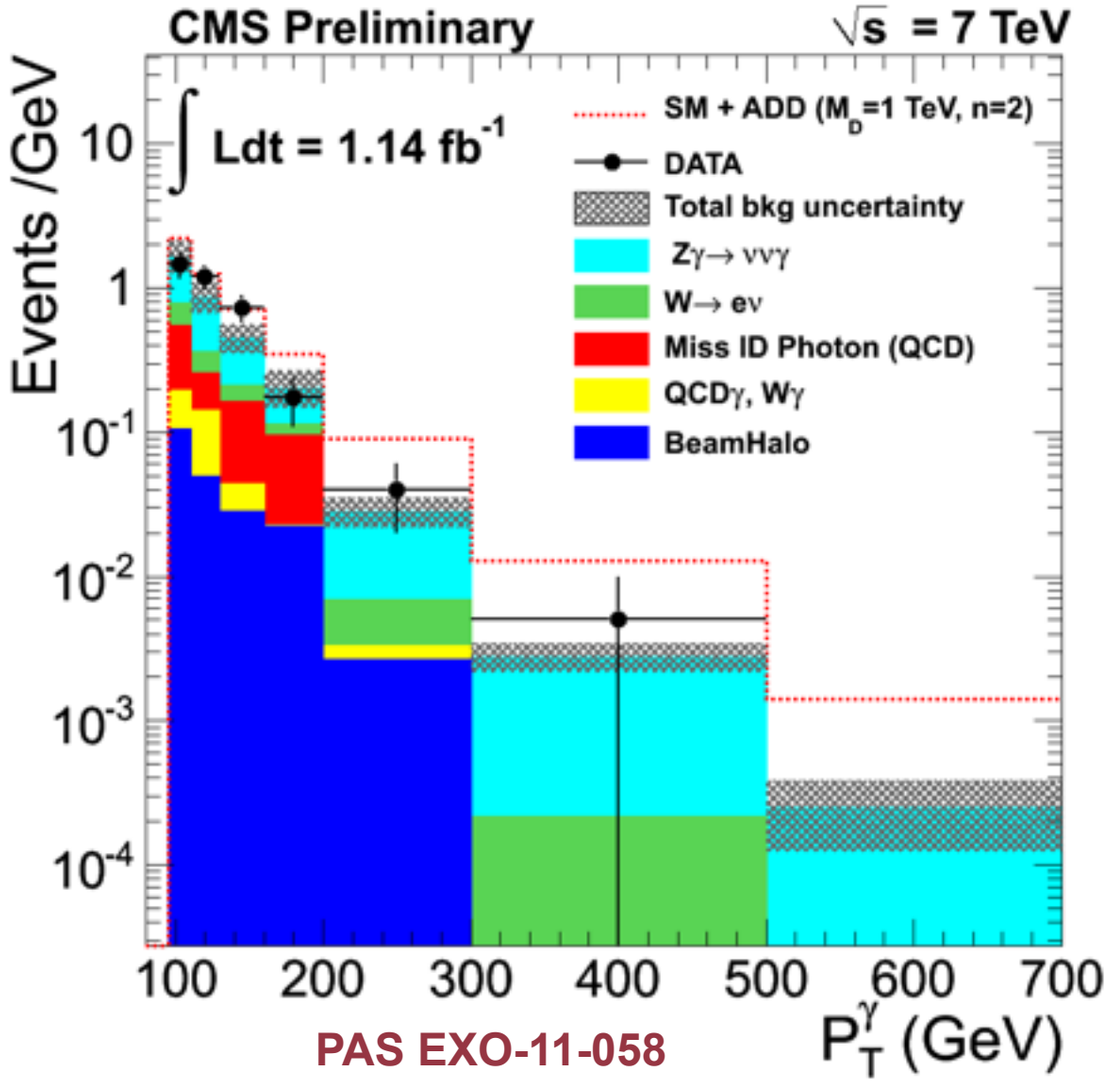
	n = 2	n = 3	n = 4	n = 5	n = 6	n = 7
μμ	2.6	3.1	2.6	2.3	2.1	2.0
γγ	3.2	3.4	2.8	2.6	2.4	2.2

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

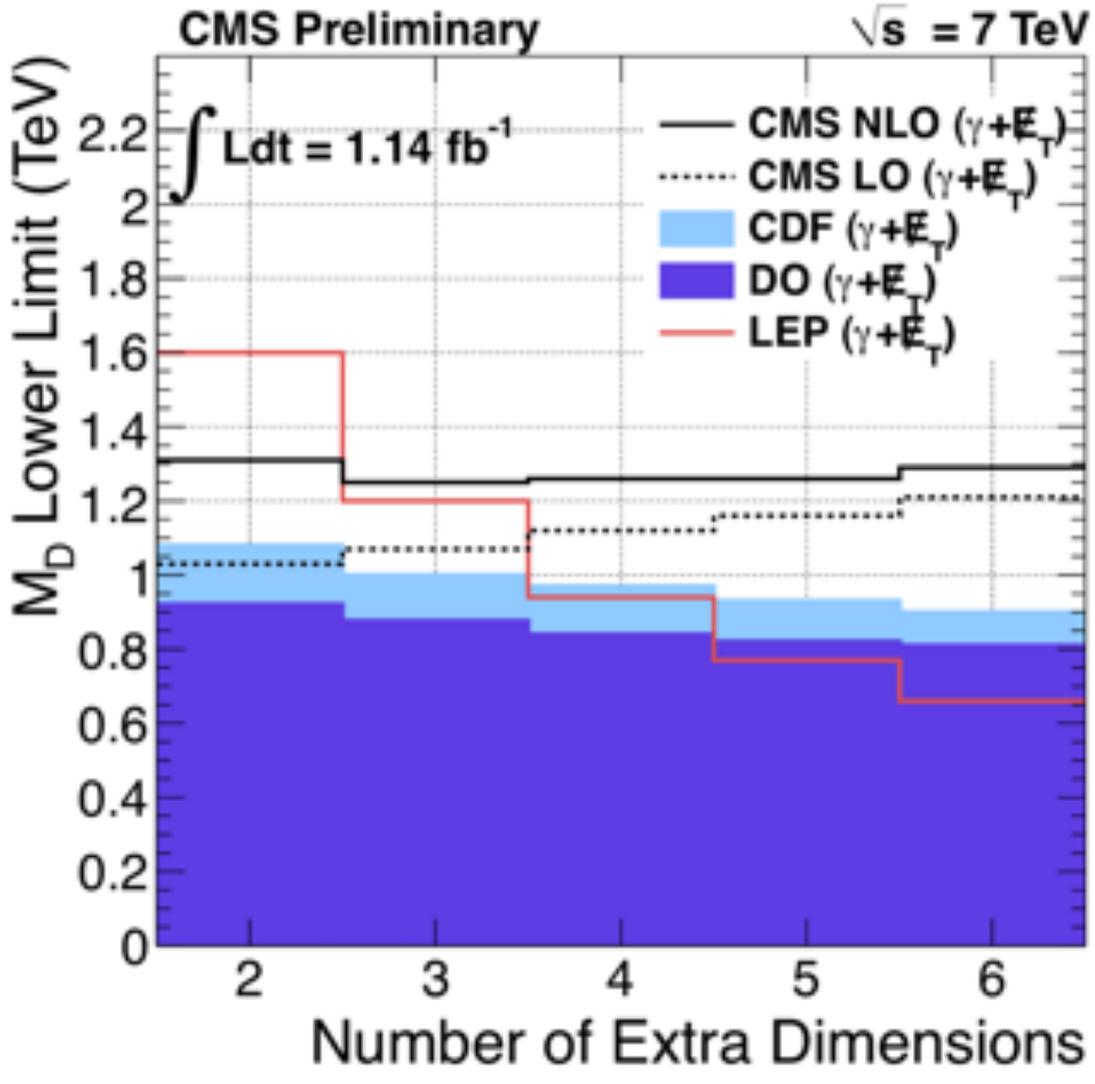
MONO-PHOTON + MET

- 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



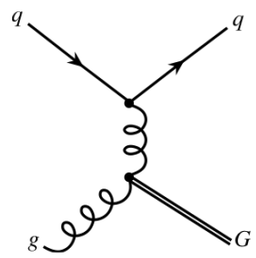


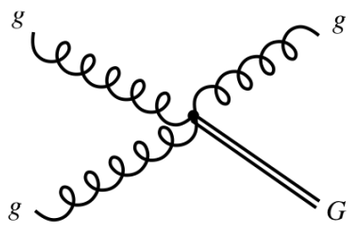
PAS EXO-11-058

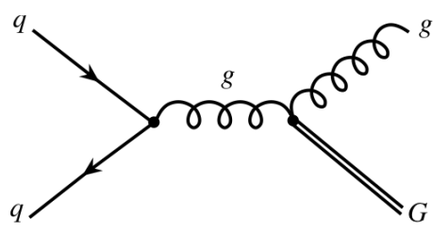


MONO-JET + MET

- 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

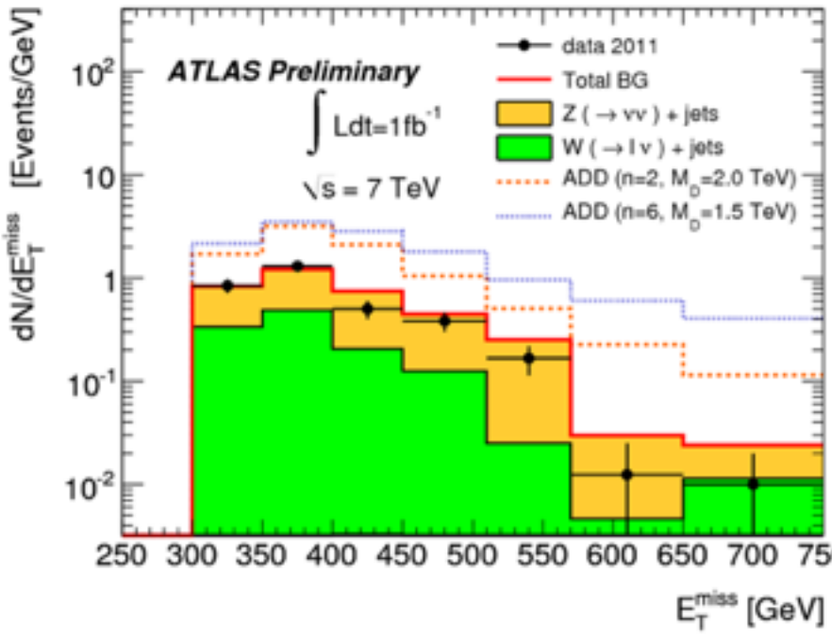


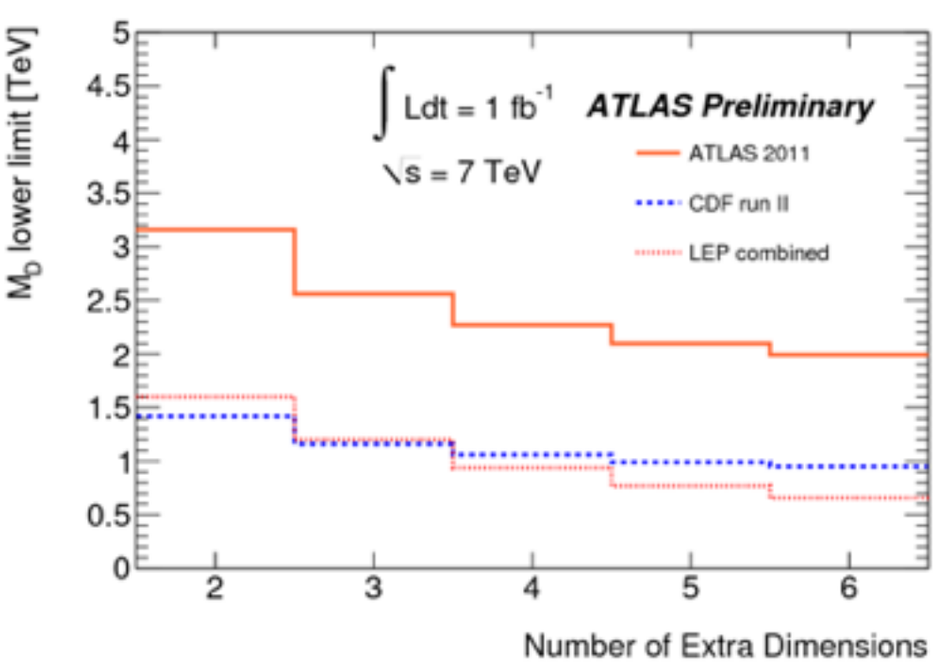


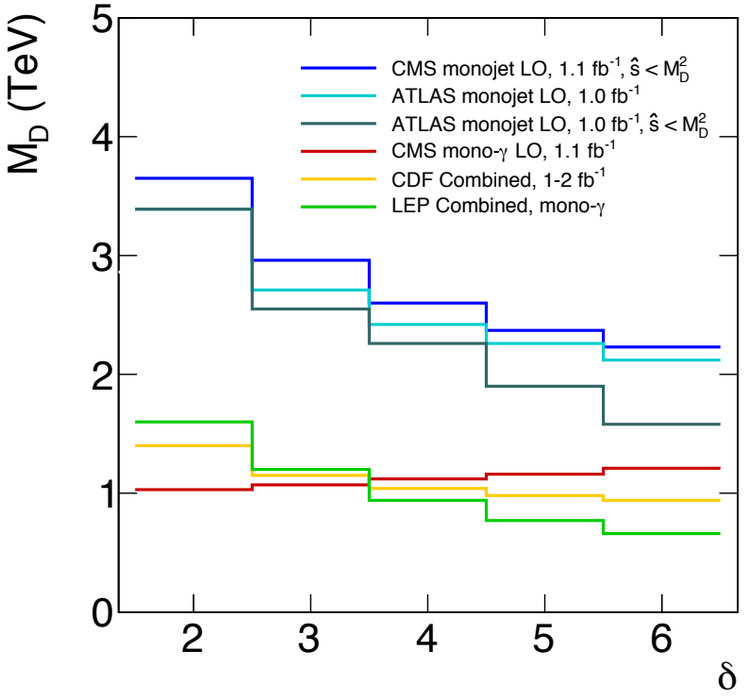


ATLAS-CONF-2011-096

CMS: PAS EXO-11-059

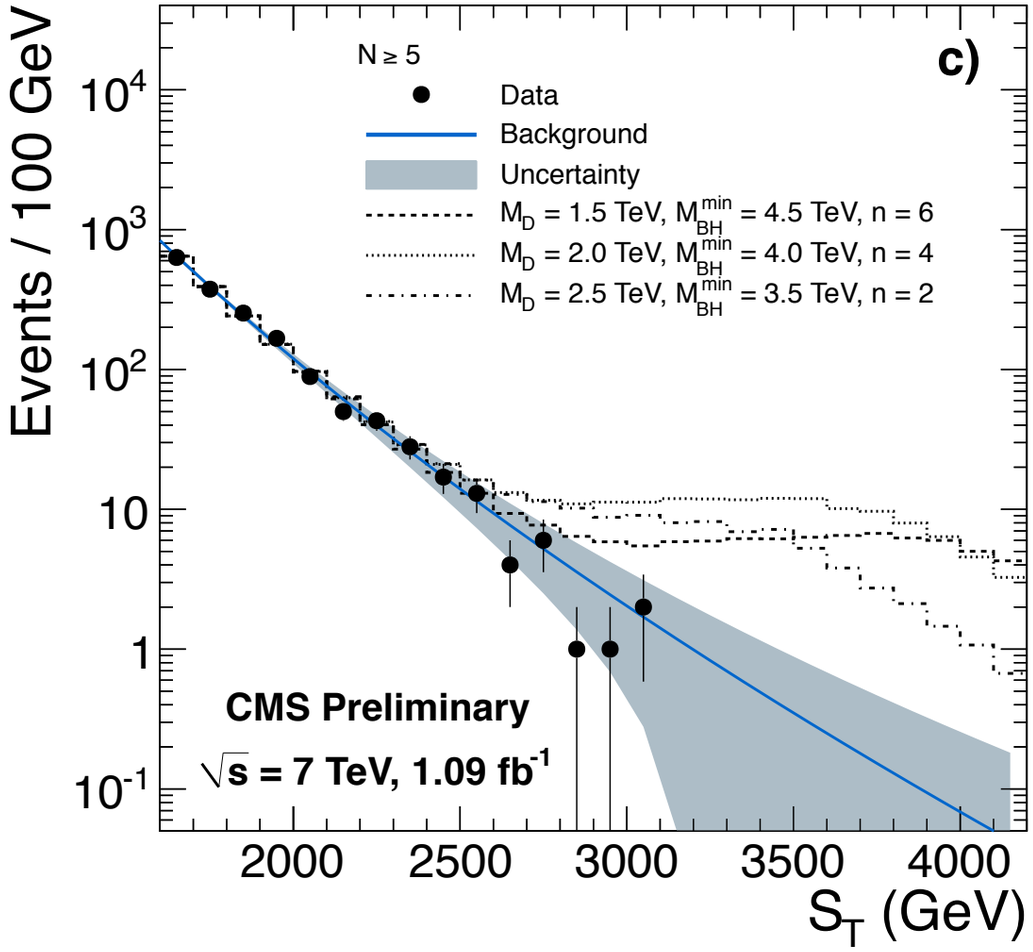


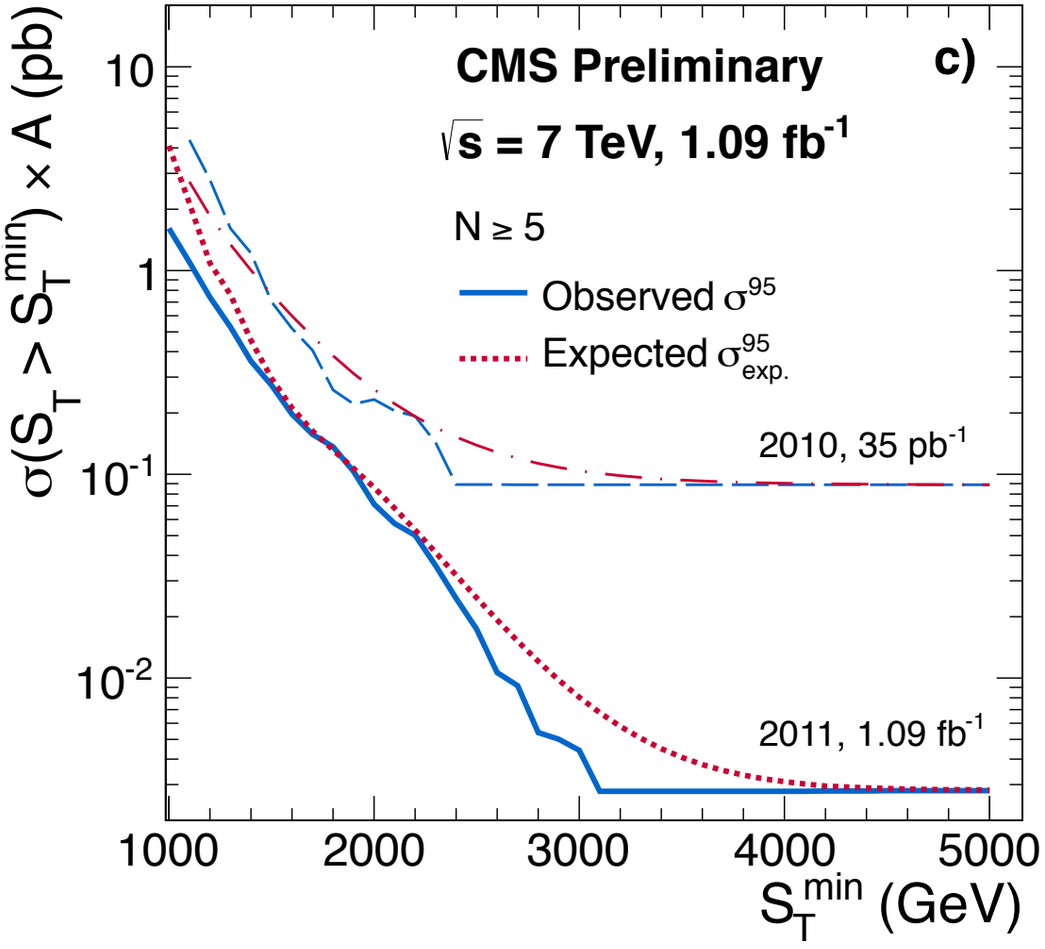


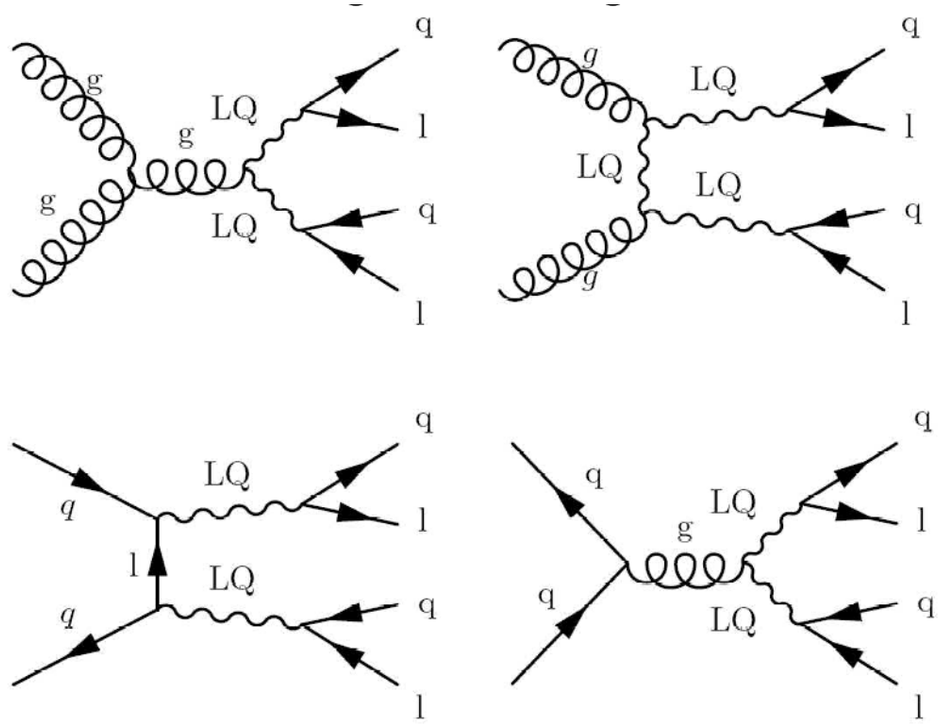


MICROSCOPIC BLACK HOLES

- 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**





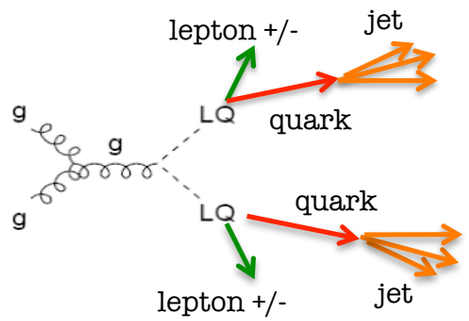


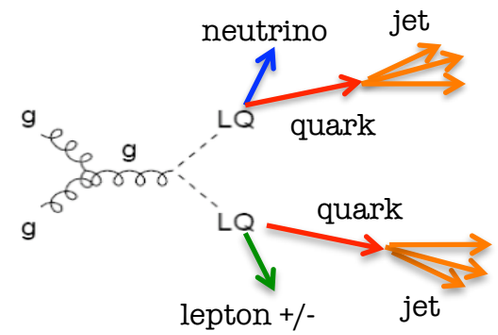
LEPTOQUARKS

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)

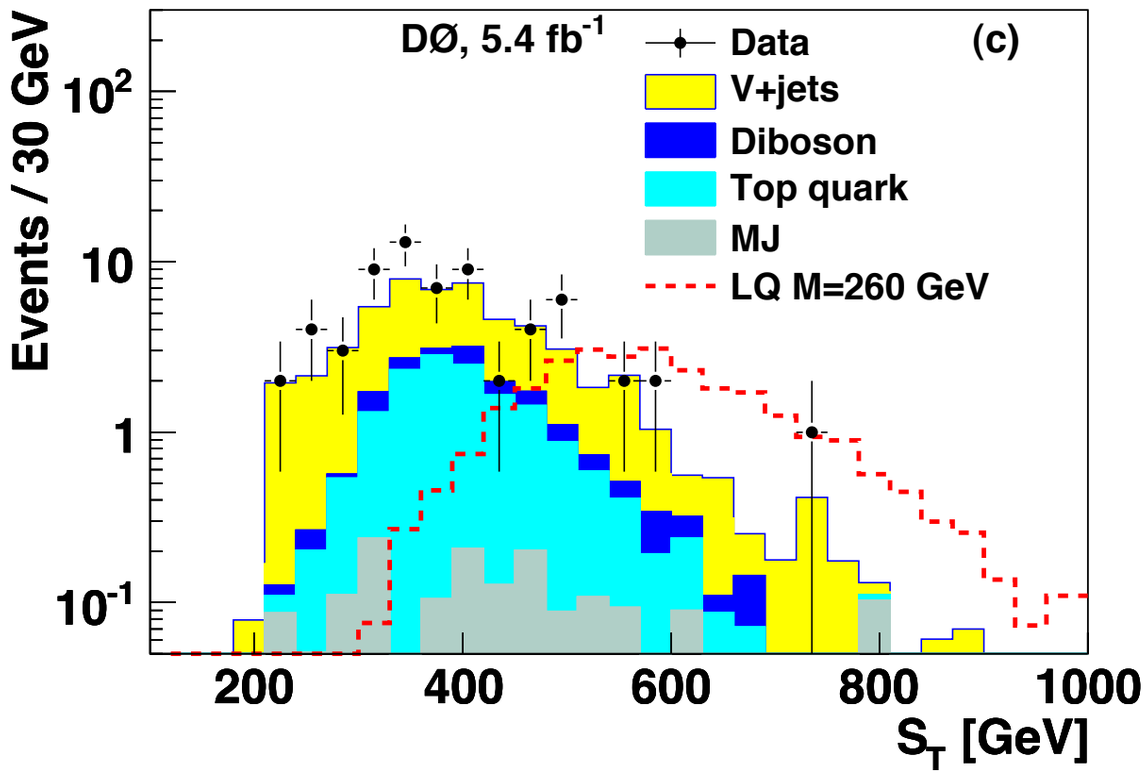


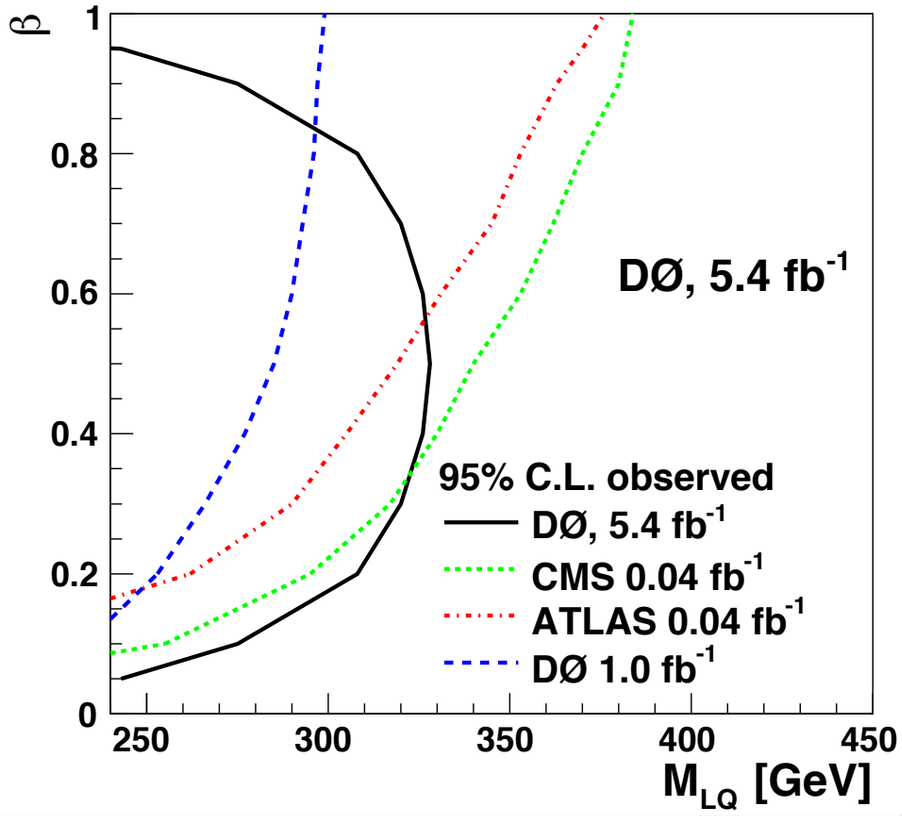


$$S_T = p_T^{\ell 1} + p_T^{\ell 2} + p_T^{j1} + p_T^{j2}$$

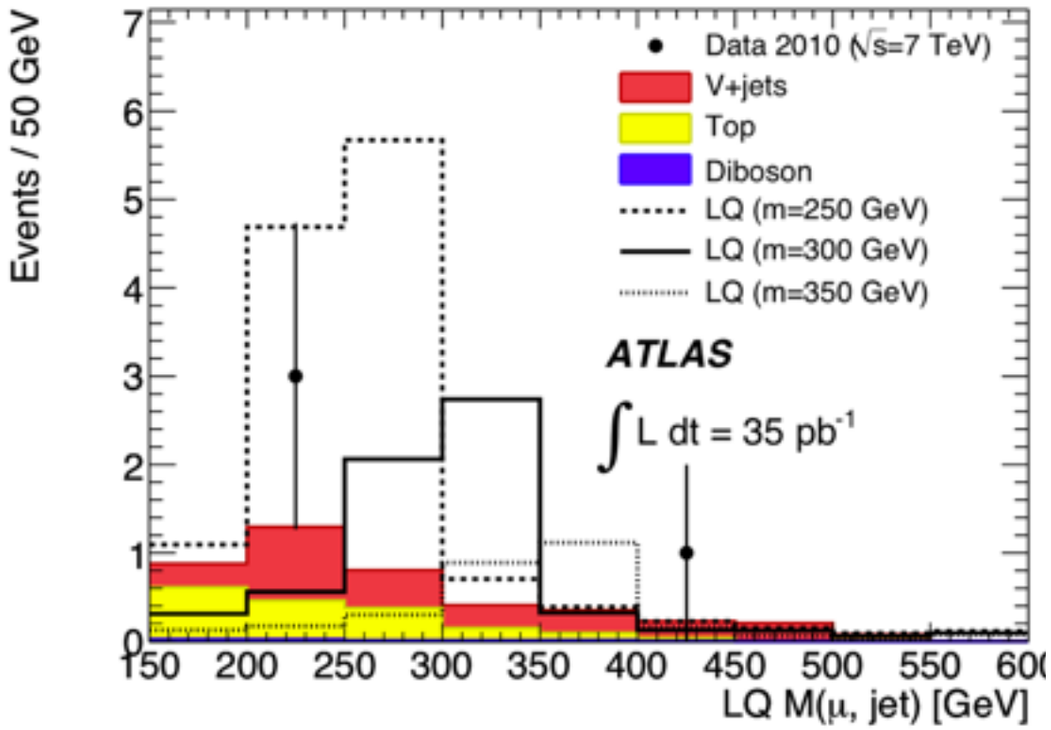
$$S_T = p_T^{\ell 1} + MET + p_T^{j1} + p_T^{j2}$$

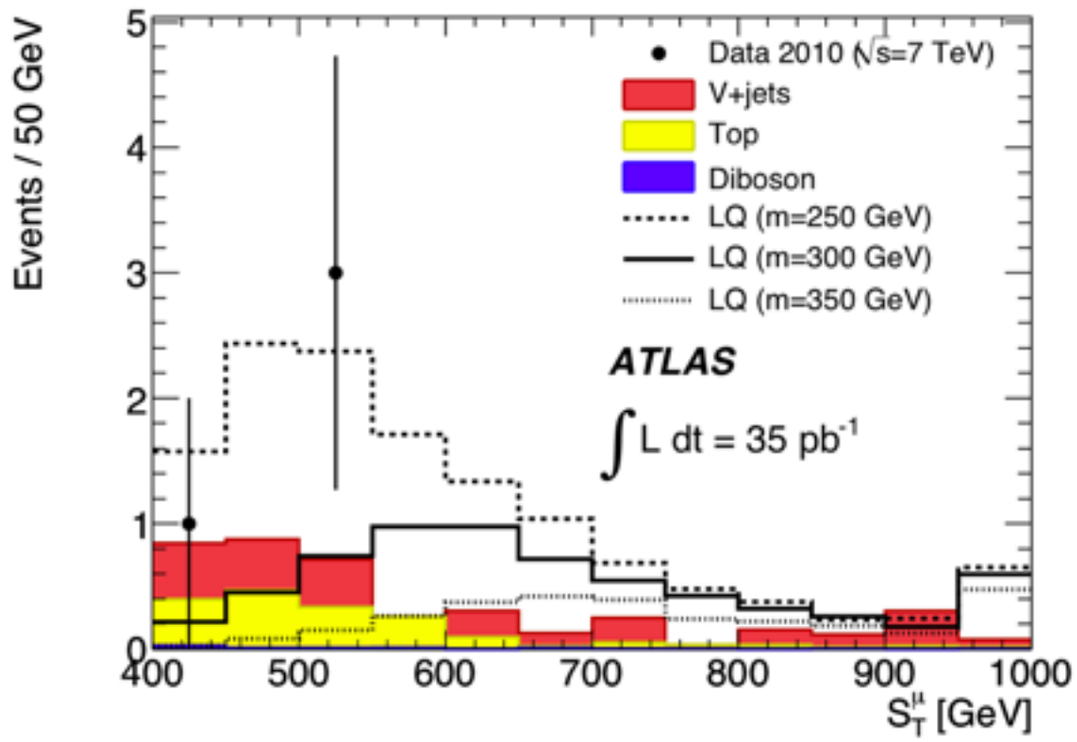
ATLAS: arxiv:1104.4481 CMS: 10.1016/j.PhysLetB.2011.07.089 D0: arXiv:1107.1849v1





2ND GENERATION

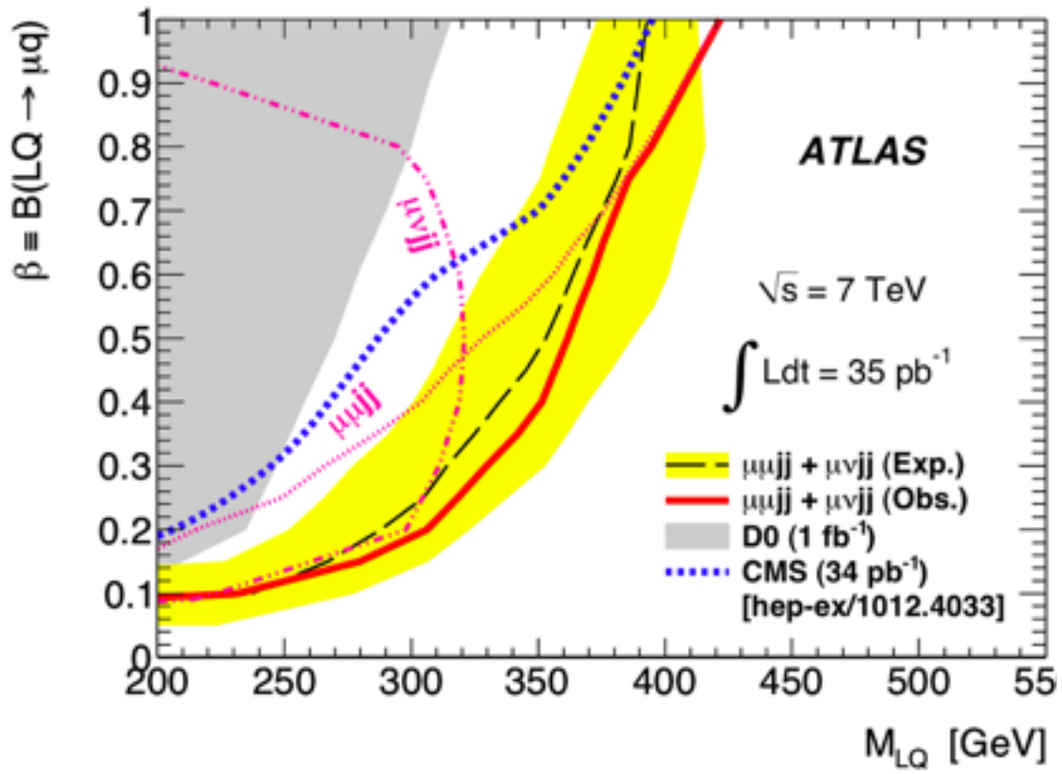




CMS: 10.1103/PhysRevLett.106.201803

ATLAS: arxiv:1104.4481

D0: arXiv:1107.1849v1



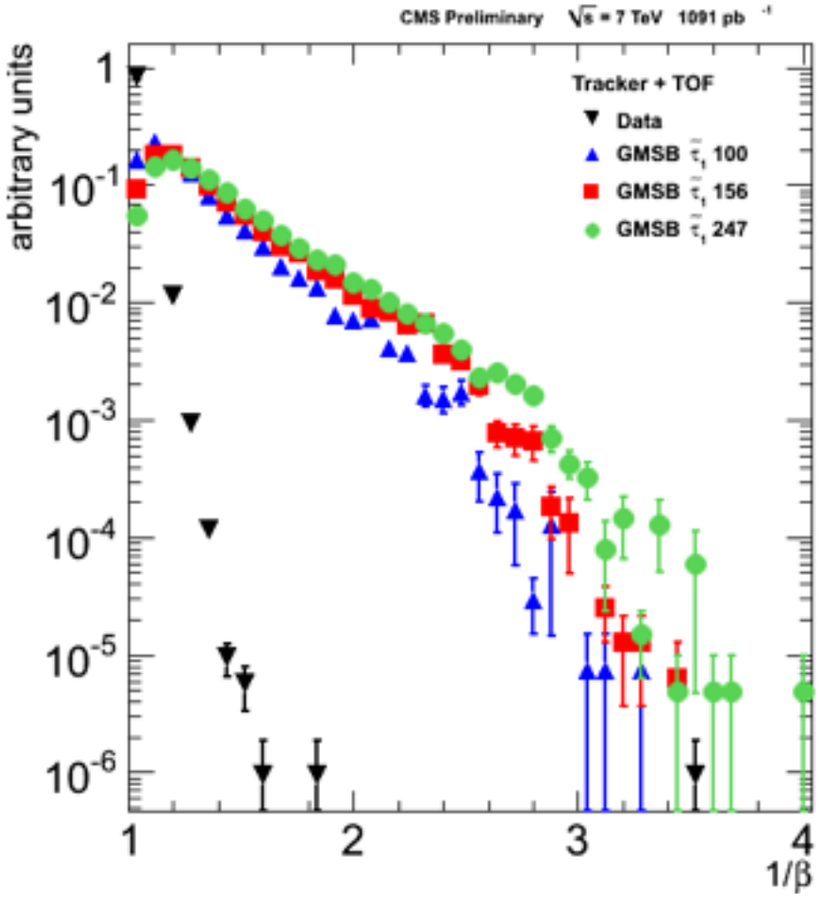
Long-Lived Particles

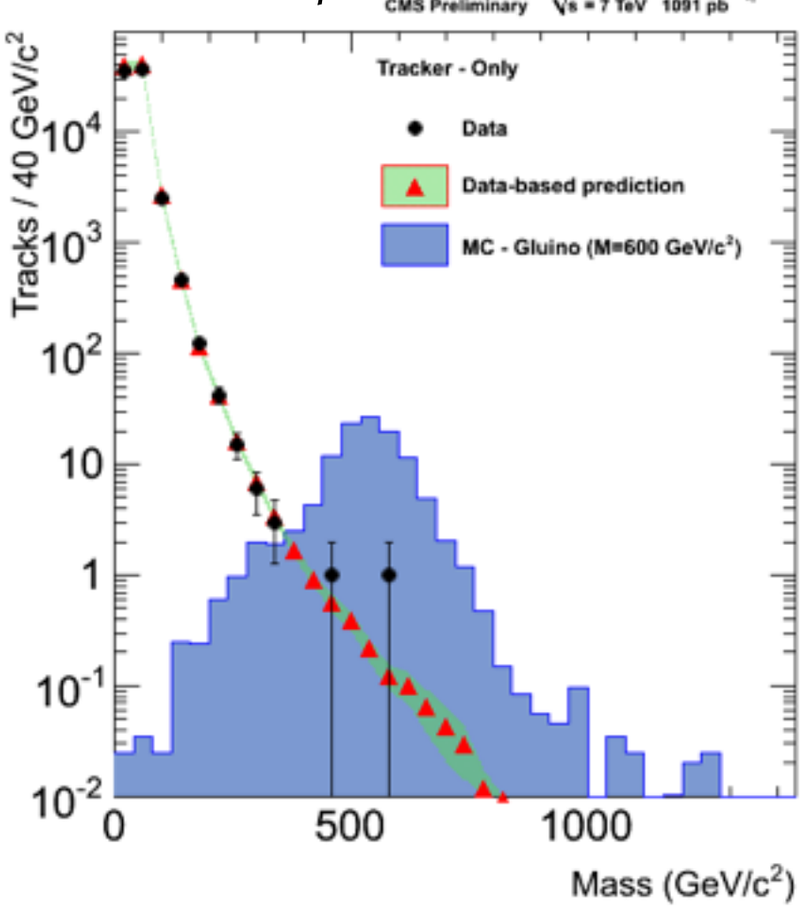
HEAVY STABLE CHARGED PARTICLES

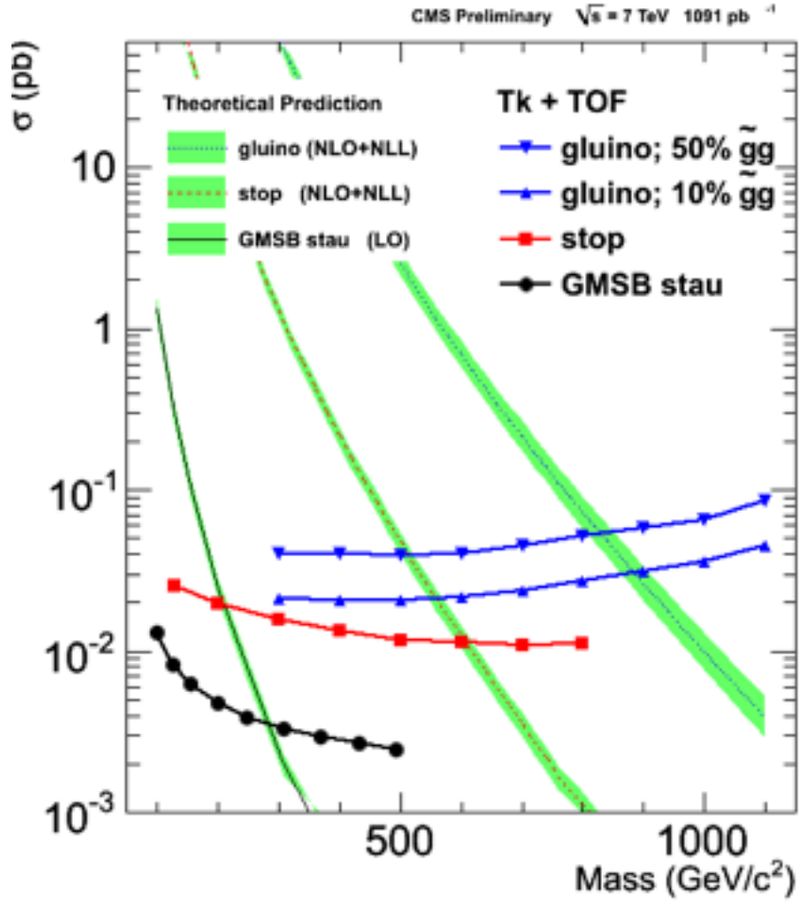
- Gluinos and stops hadronizing in heavy R-hadrons (mixture of SM and SUSY particles)
  - Large ionization in silicon tracker
  - Very slow hence long time of flight (TOF)
- Dedicated muon-like reconstruction and mass estimate from TOF and dE/dX

CMS: PAS EXO-11-022

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



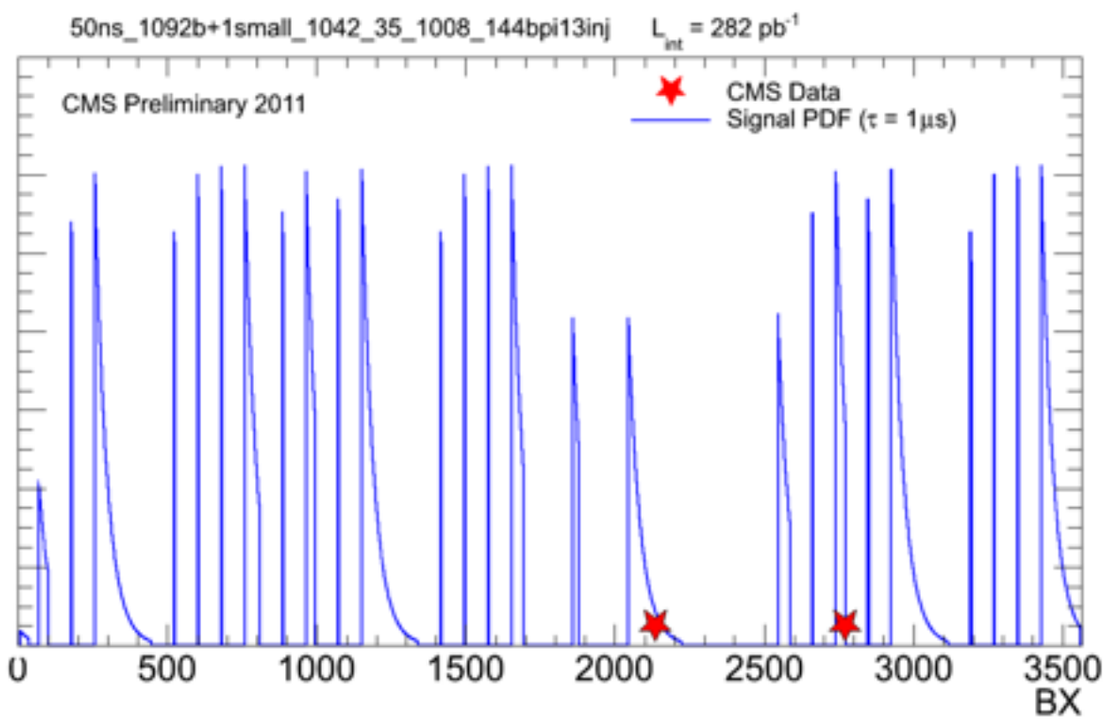


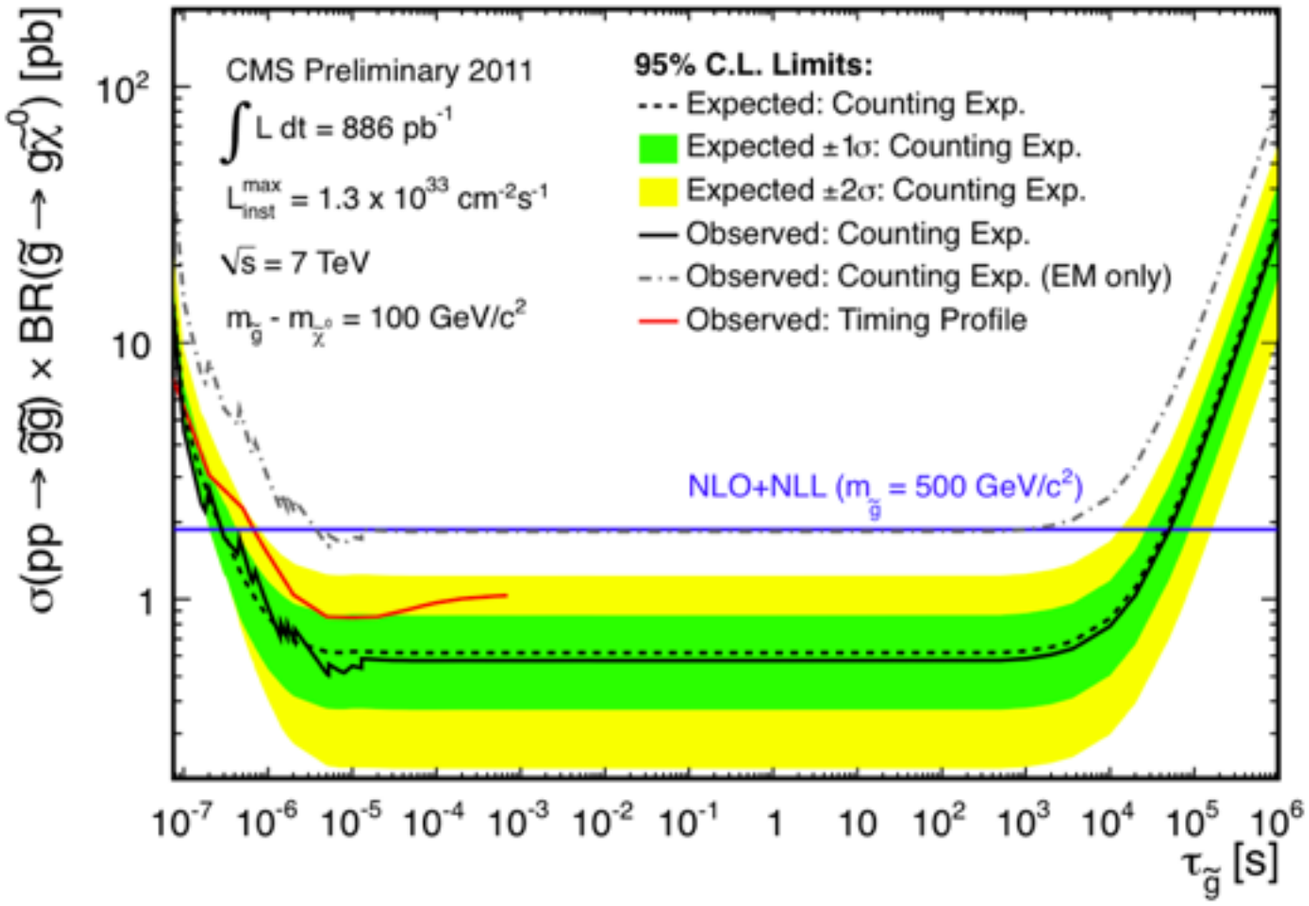


STOPPED HEAVY PARTICLES

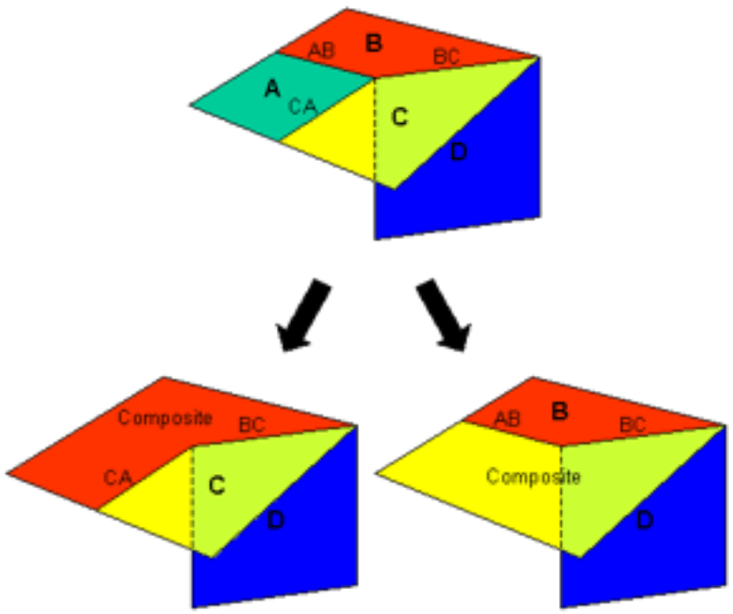
- Some heavy R-hadrons could stop due to large ionization
- Detect interactions out-of-time wrt bunch collisions
  - Special trigger for data acquisition while no collisions
  - main background instrumental and non-beam related
- Crucial to have long data-taking periods not just luminosity
- Signal probability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

CMS: PAS EXO-11-020





COMPOSITENESS

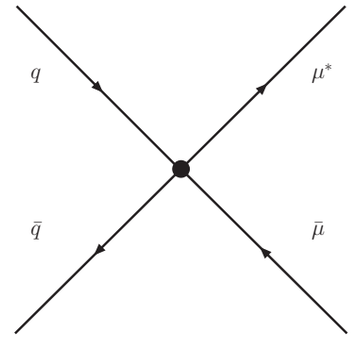


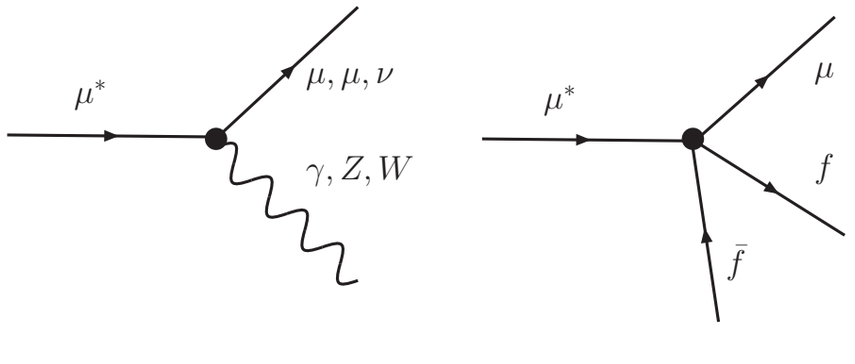
EXCITED LEPTONS

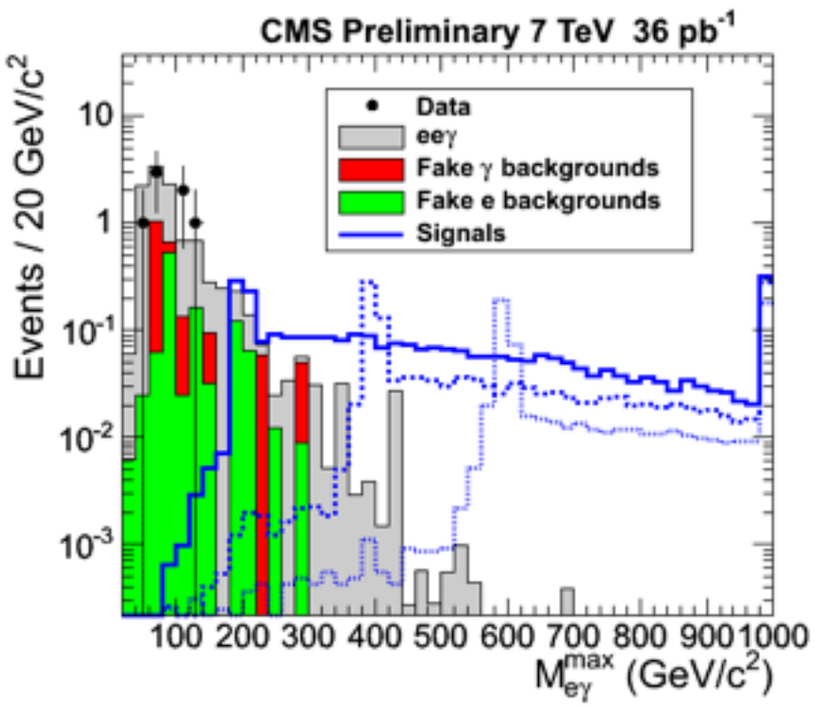
- Analysis with 2010 data
  - 36 pb-1
- Production via Contact Interaction
- Search for resonance in lγ final state with one additional isolated lepton

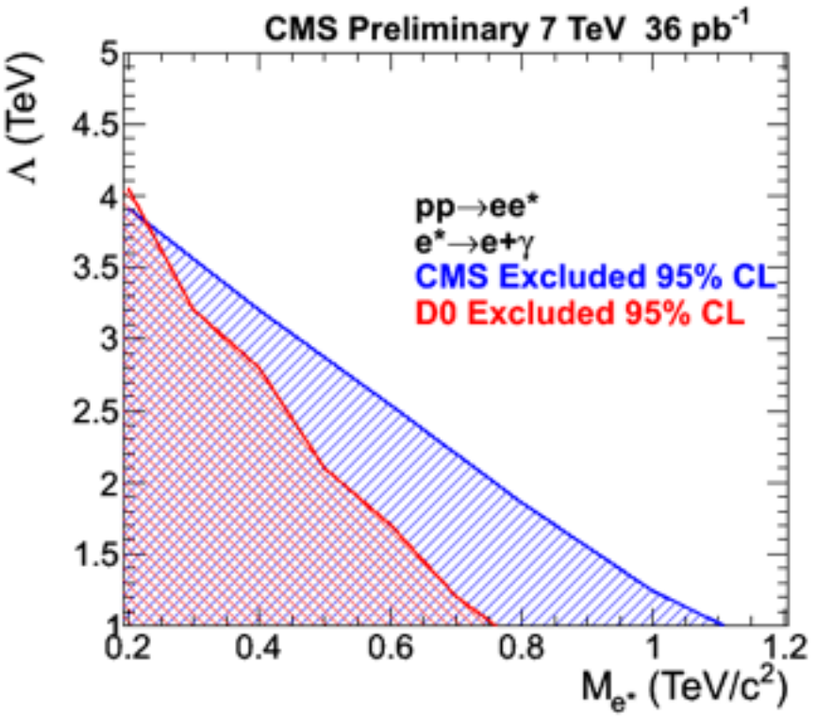
$$\mathcal{L}_{\mathrm{CI}} = \frac{g^2}{2\Lambda^2} j^\mu j_\mu \qquad j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}^*_L \gamma_\mu f^*_L + \eta''_L \bar{f}^*_L \gamma_\mu f_L + h.c. + (L \to R).$$

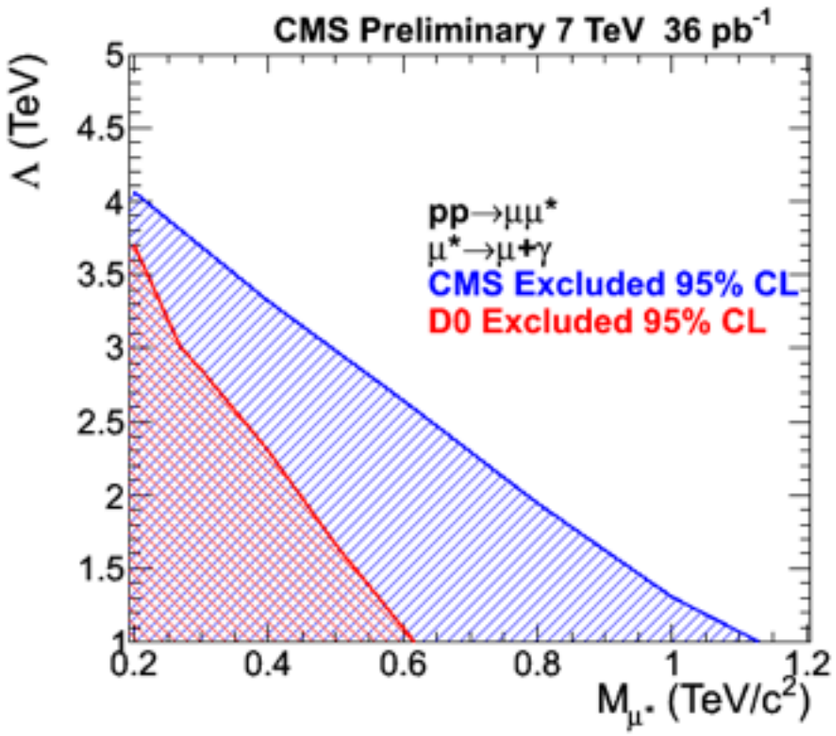
$$\hat{\sigma}(q\bar{q} \to ll^*, l^*\bar{l}) = \frac{\pi}{6\hat{s}}\left(\frac{\hat{s}}{\Lambda^2}\right)^2\left(1 + \frac{1}{3}\left(\frac{\hat{s} - m^{*2}}{\hat{s} + m^{*2}}\right)\right)\left(1 - \frac{m^{*2}}{\hat{s}}\right)^2\left(1 + \frac{m^{*2}}{\hat{s}}\right)$$









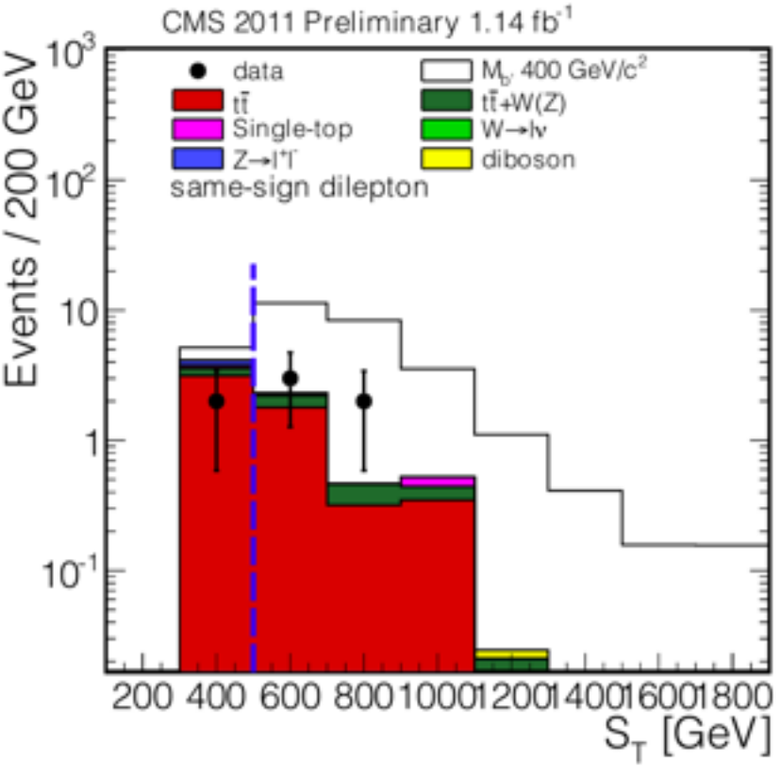


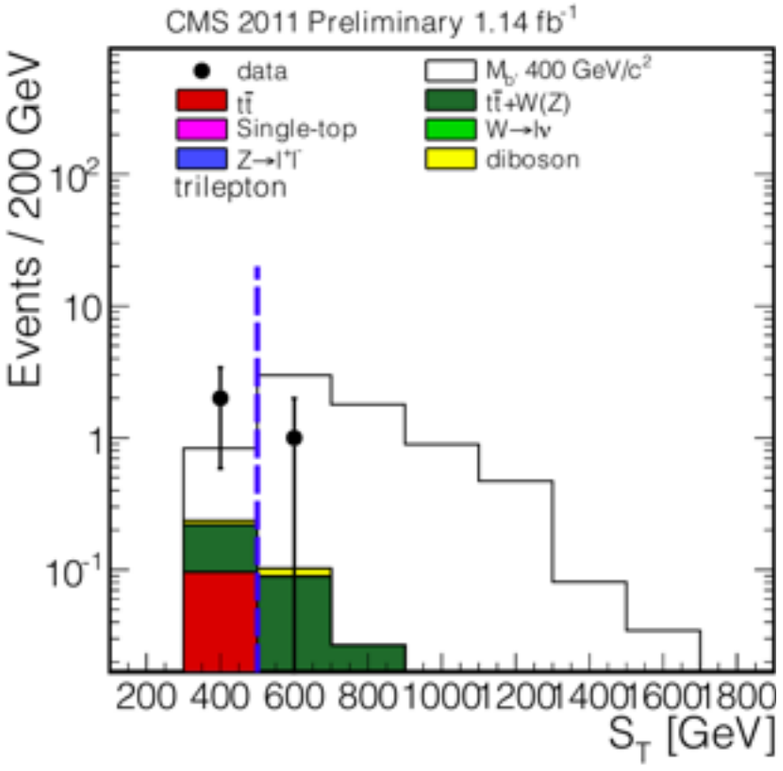
4TH GENERATION

b'→ t + W

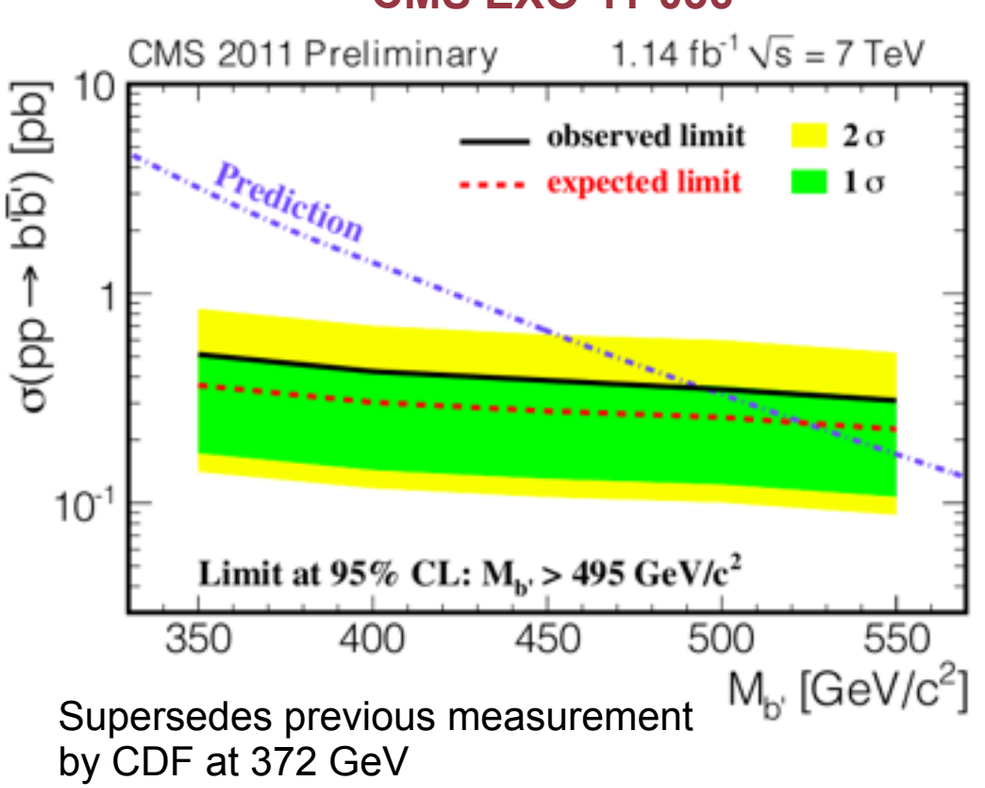
$$b'\bar{b}' \rightarrow tW^-\bar{t}W^+ \rightarrow bW^+W^-\bar{b}W^-W^+$$

- 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

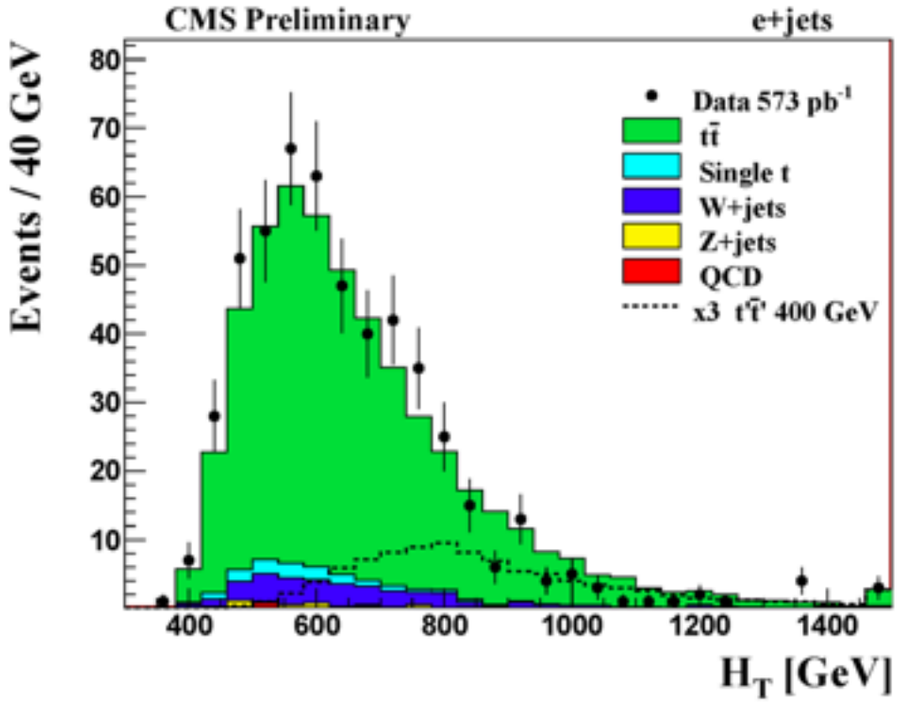


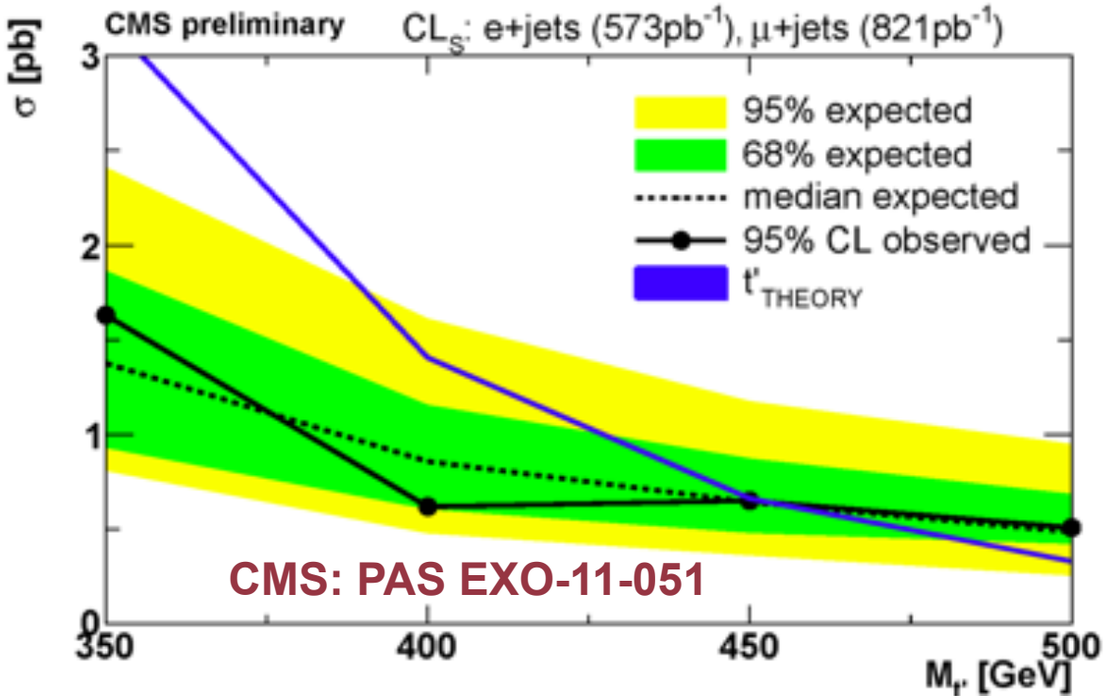
Supersedes previous measurement by CDF at 372 GeV

CDF: PRL106.141803 (2011)

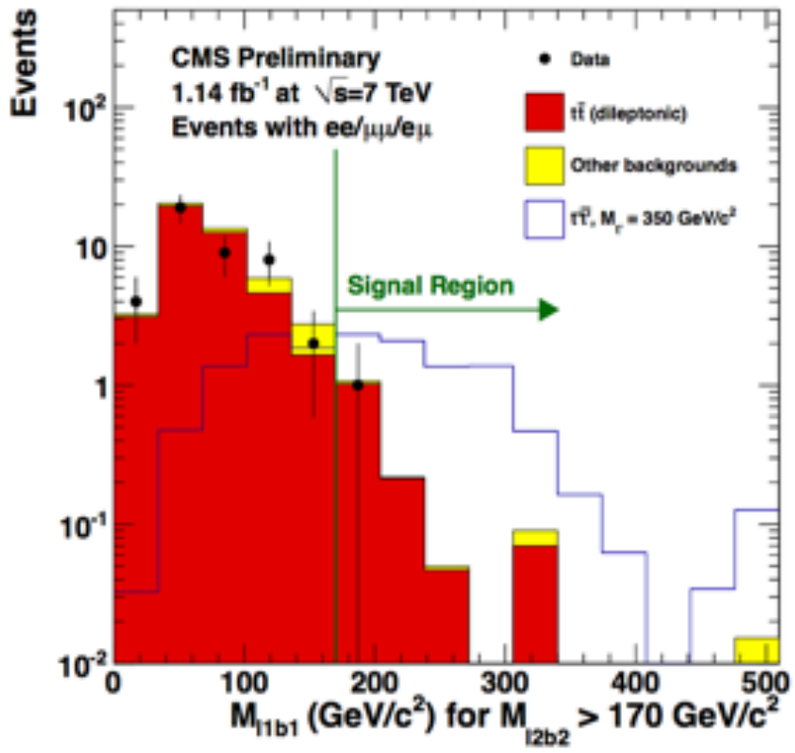
T'→ b + W @ LHC

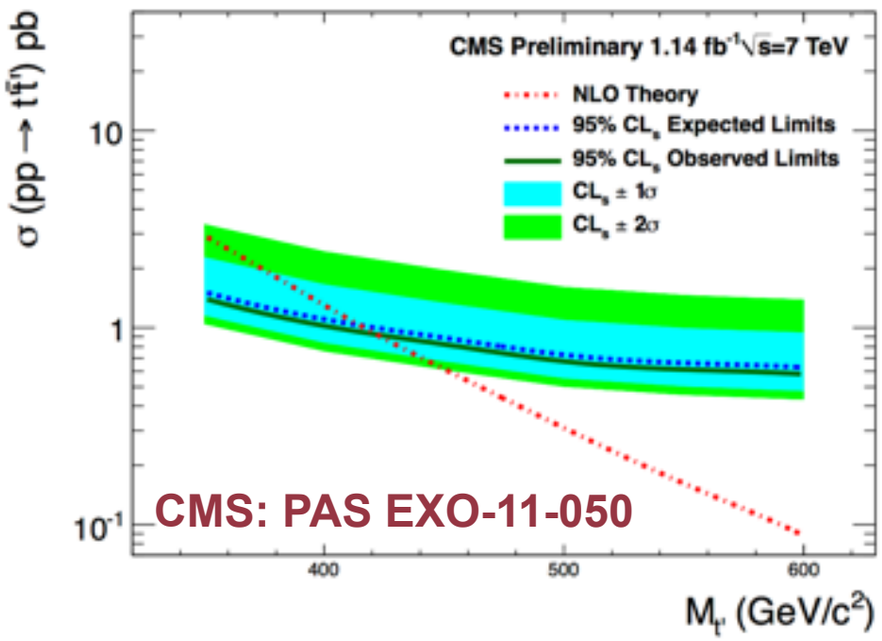
$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$





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



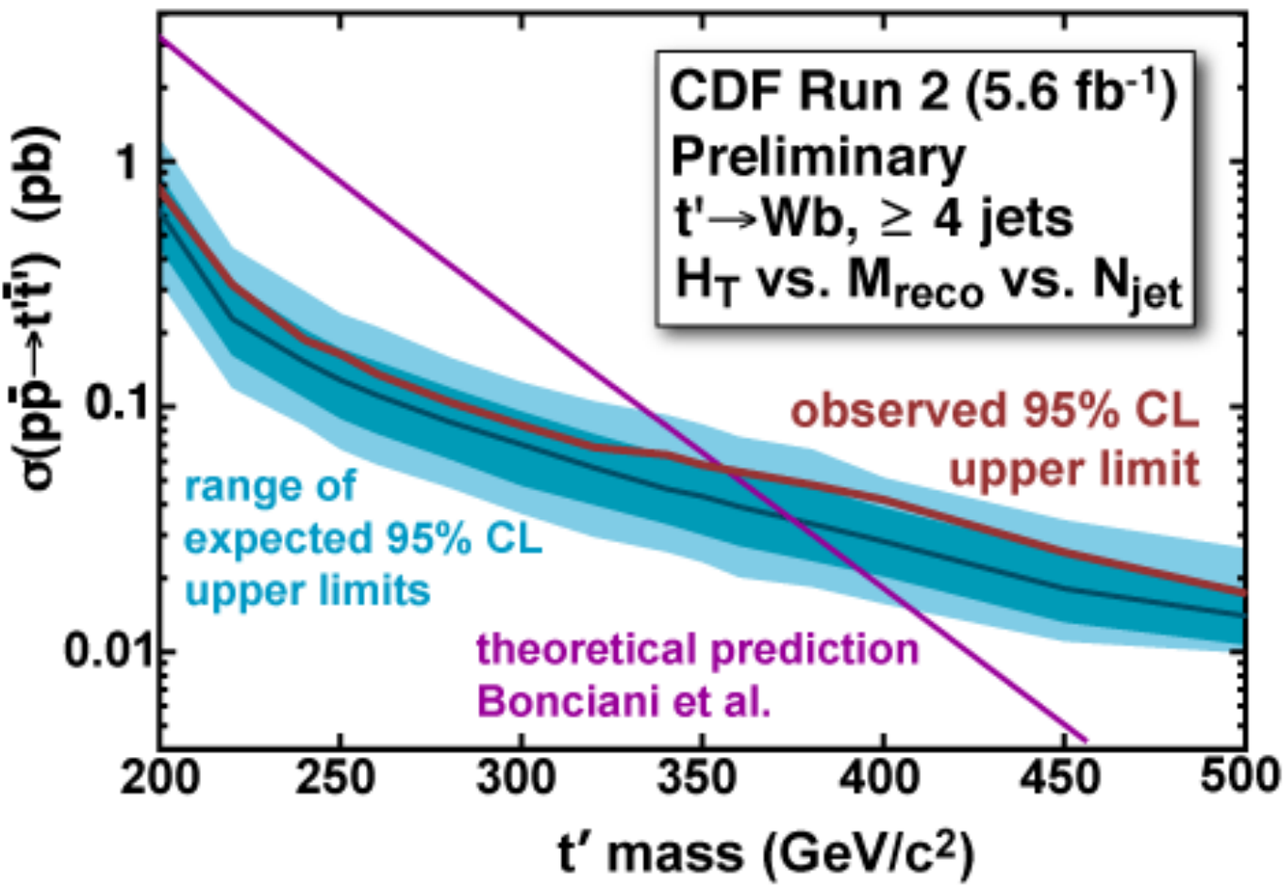


$m_{Q4} > 270$ GeV with 35 pb^{-1} **ATLAS-CONF-2011-022**

T'→ b + W @ TEVATRON

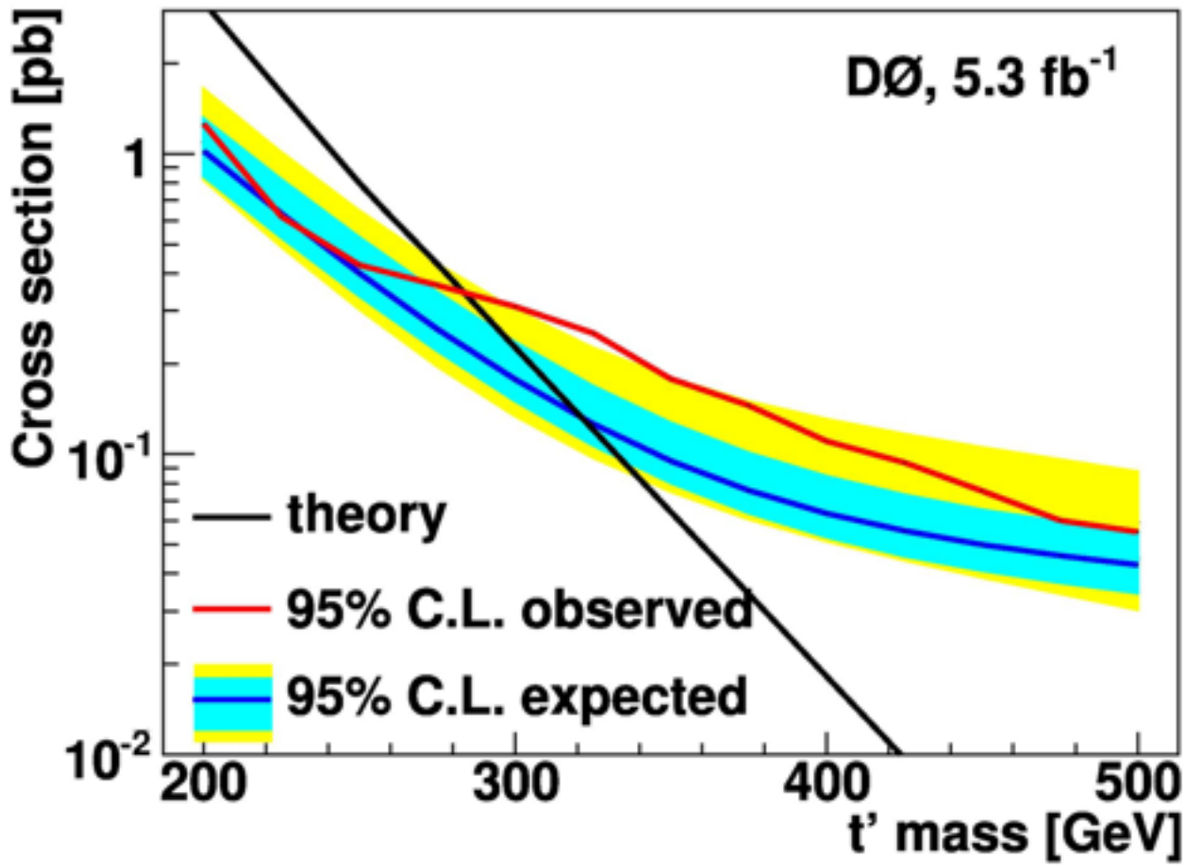
$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$$

CDF Conf. Note 10395



$m_{t'} > 358\ GeV$

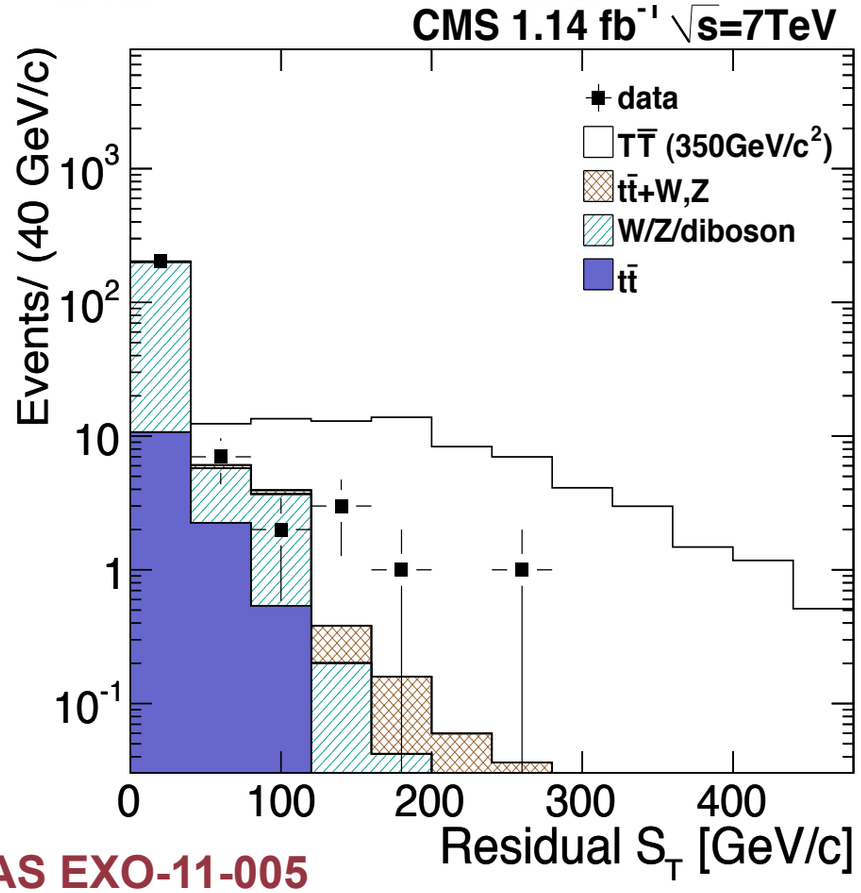
D0: PRL 107, 082001 (2011)



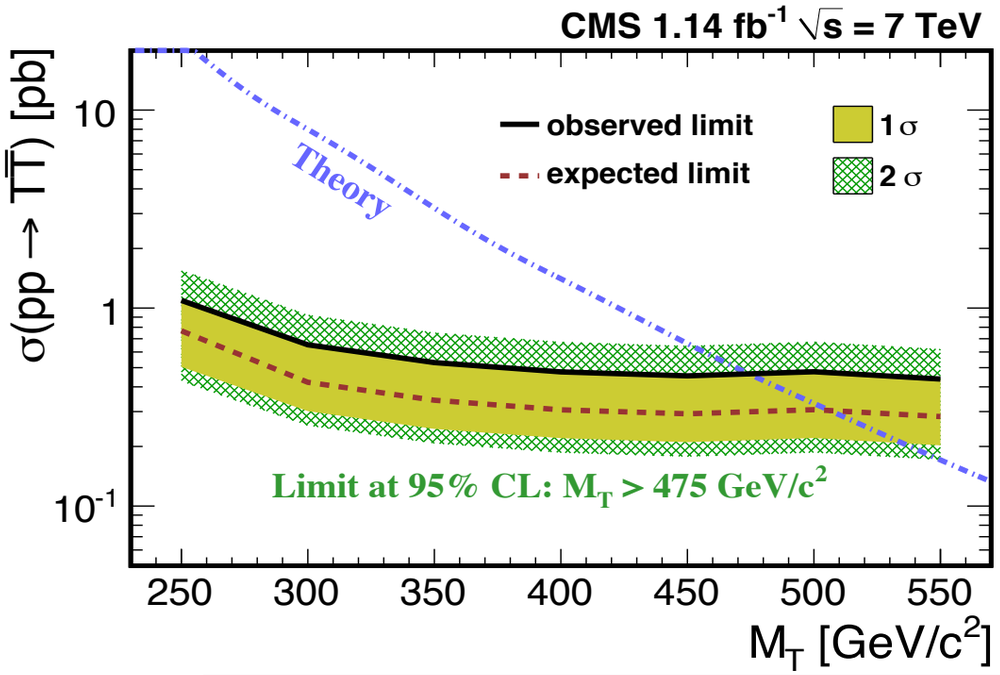
$m_{t'} > 285\ GeV$

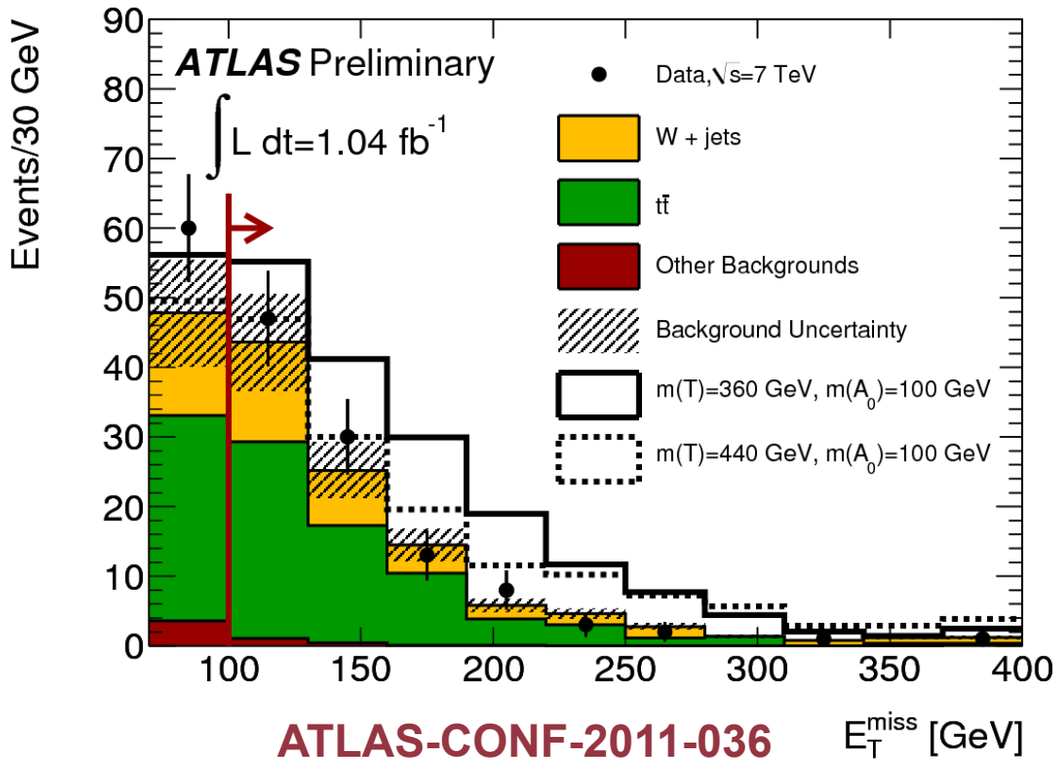
T’→ t + Z/A_0

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

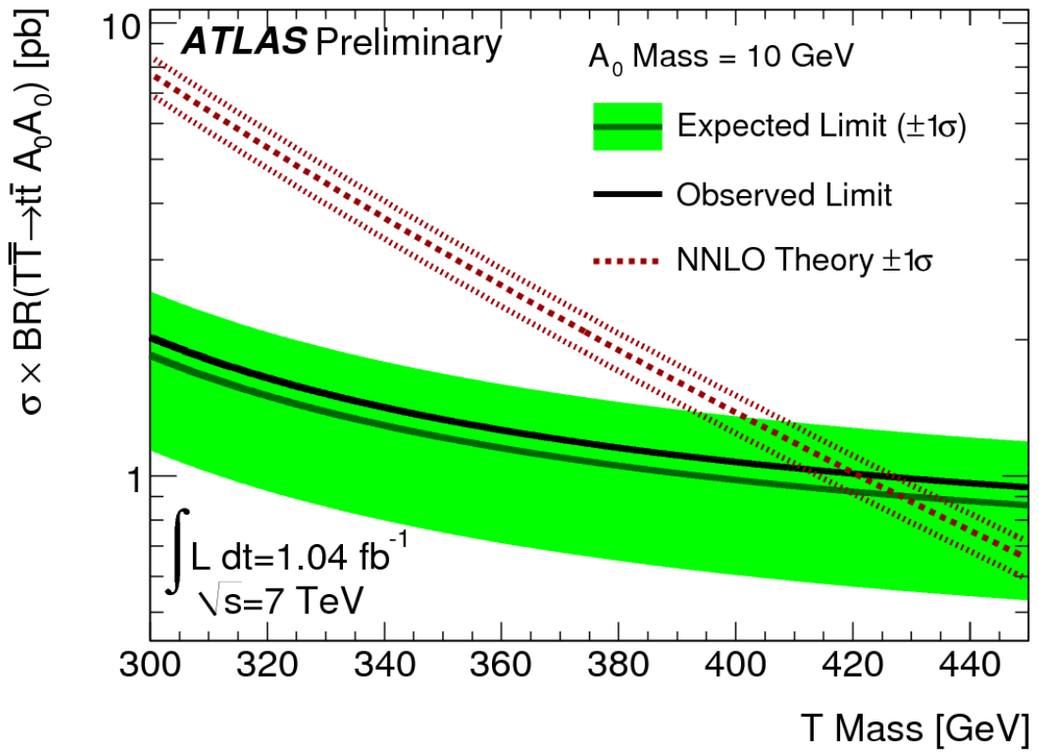


CMS: PAS EXO-11-005



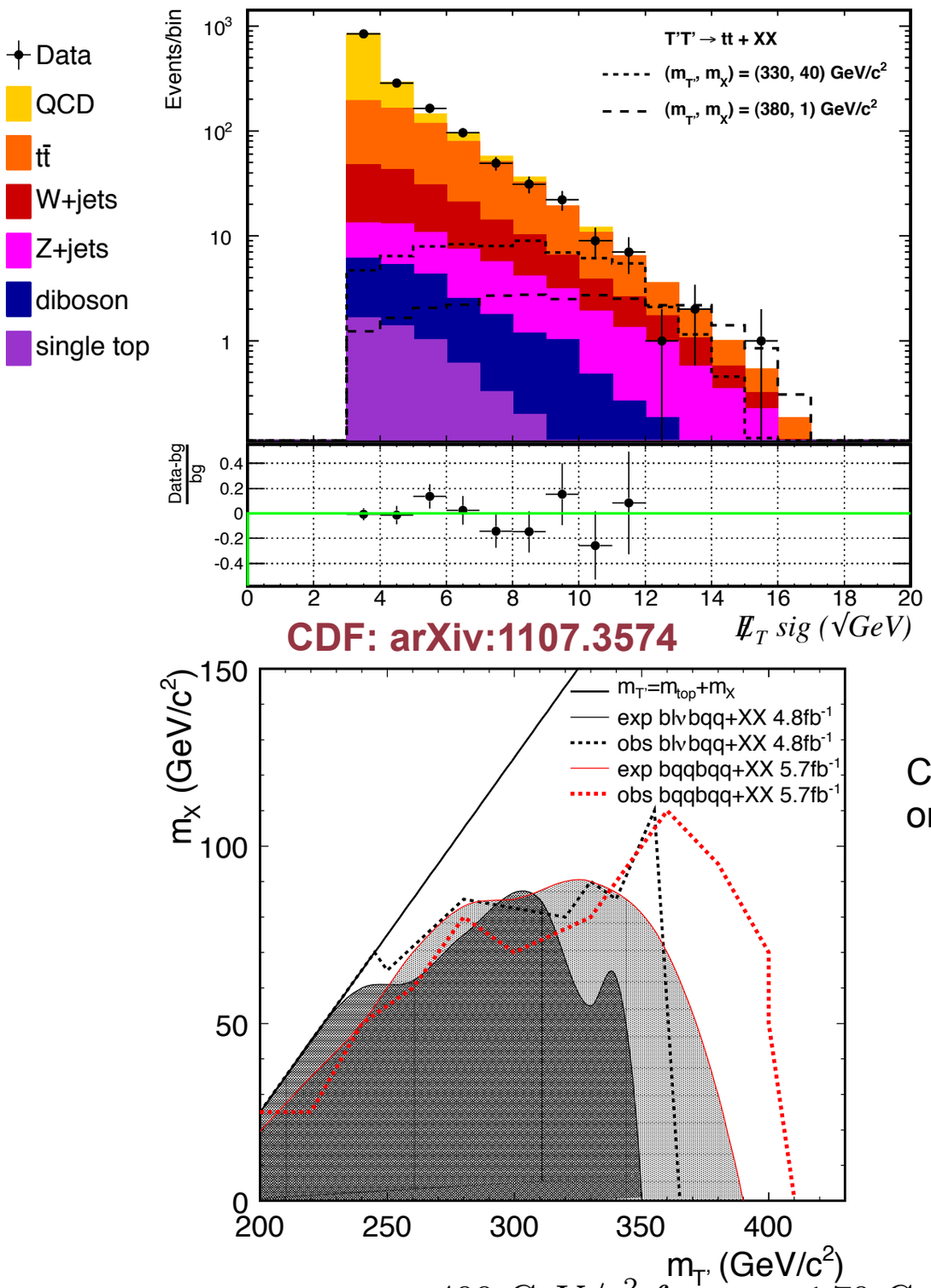


ATLAS-CONF-2011-036



T'→ t + X

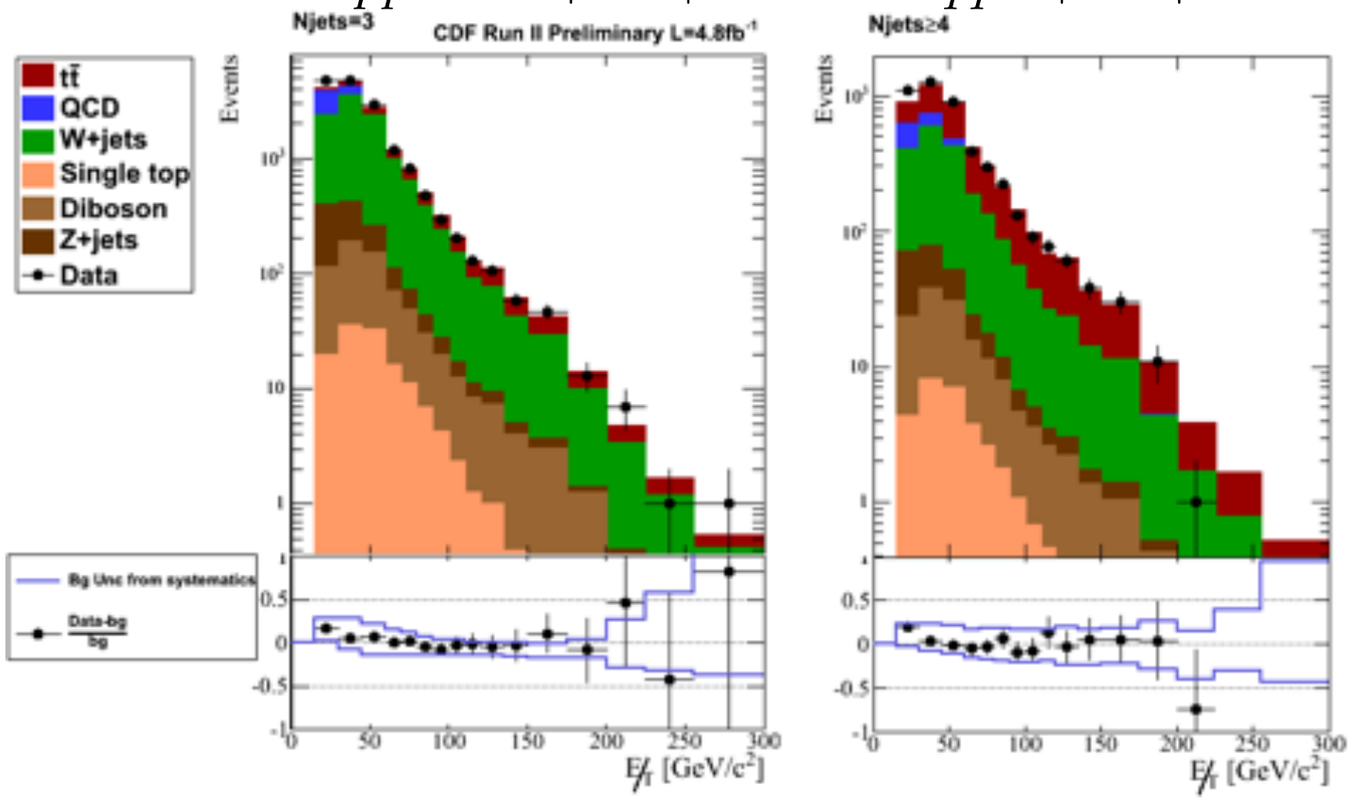
$p\bar{p} \to T'\bar{T}' \to t\bar{t} + X\bar{X} \to bq\bar{q}\,\bar{b}q\bar{q} + X\bar{X}$



CDF: arXiv:1107.3574

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

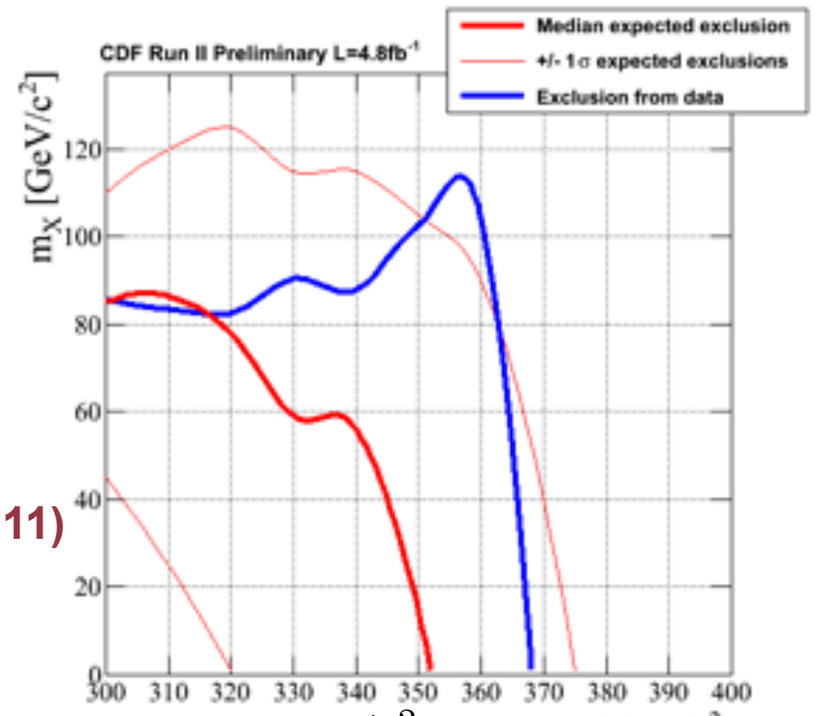
$p\bar{p} \to tt + X + X \to \ell\nu bqq'b + X + X$



Candidate dark matter or stop decay at LHC

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

CDF: PRL 106 191801 (2011)



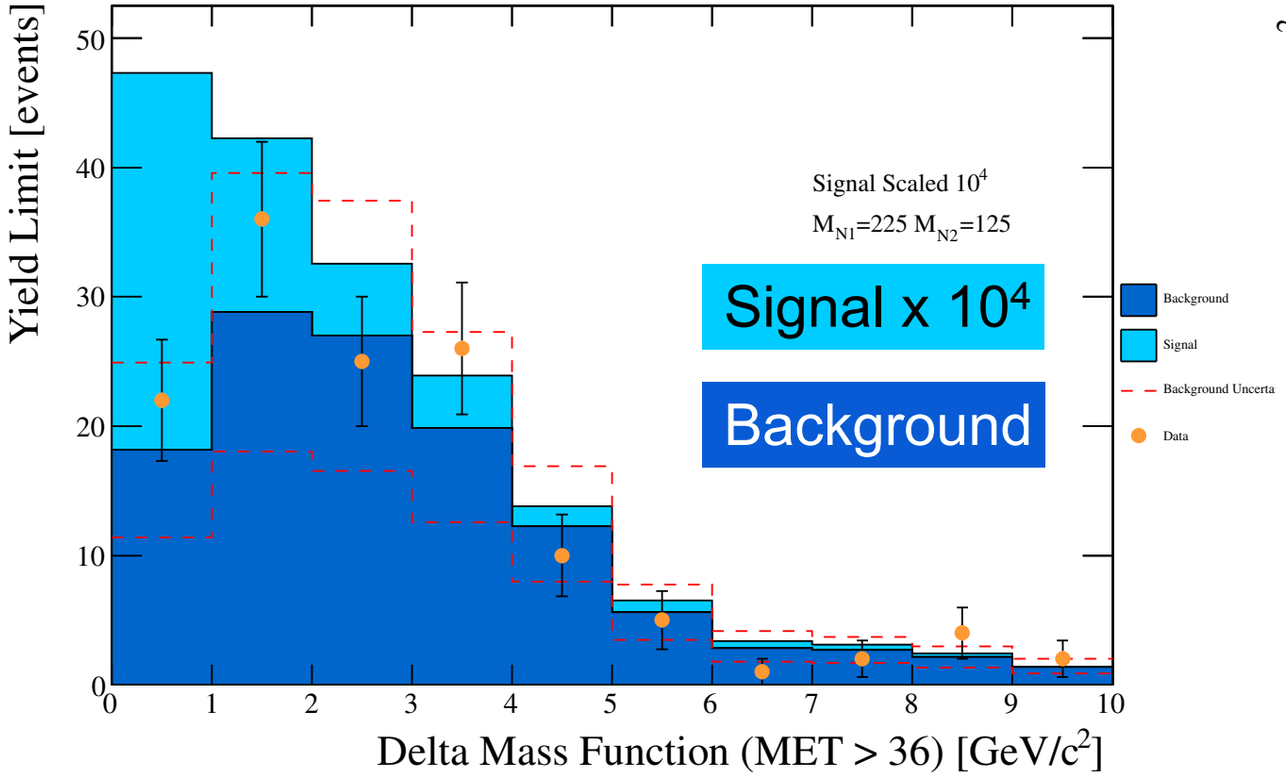
$m_{T'} = 360\ \mathrm{GeV}/c^2$ for $m_X \leq 100\ \mathrm{GeV}/c^2$

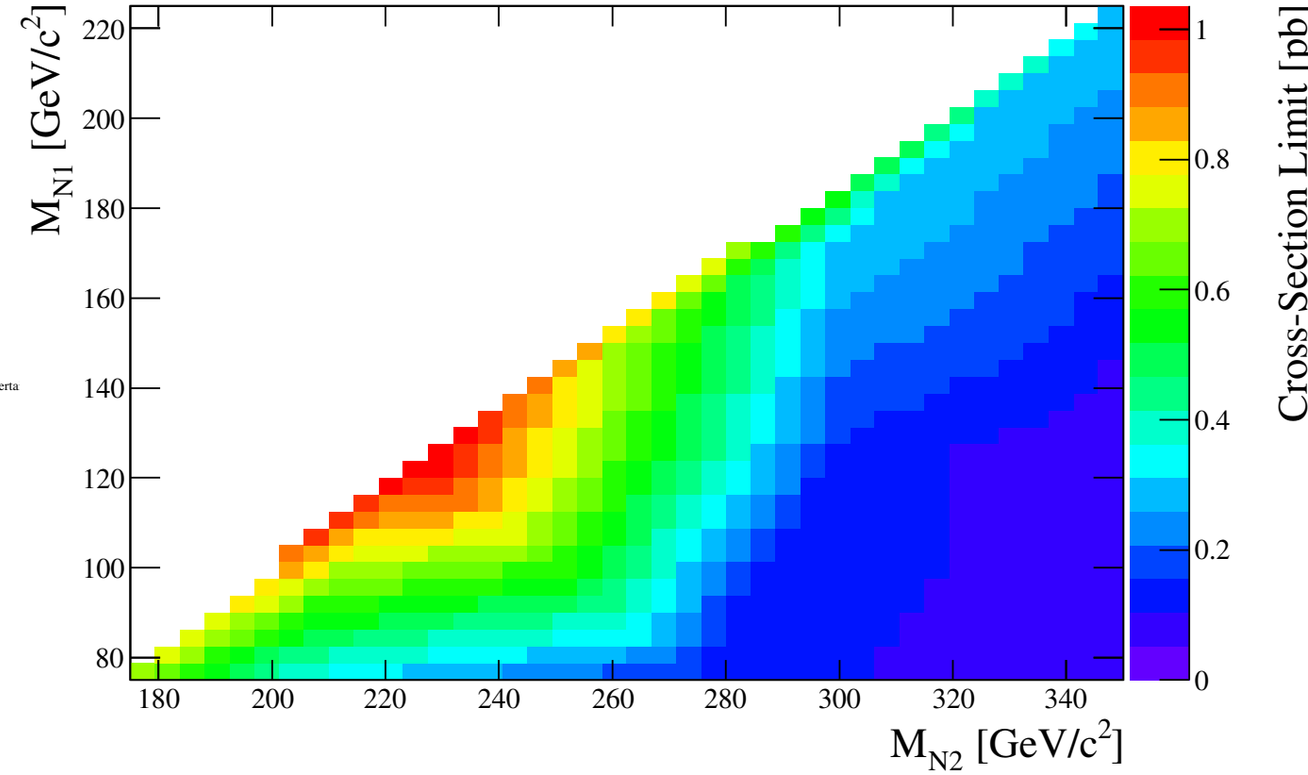
HEAVY NEUTRINO

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

- 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





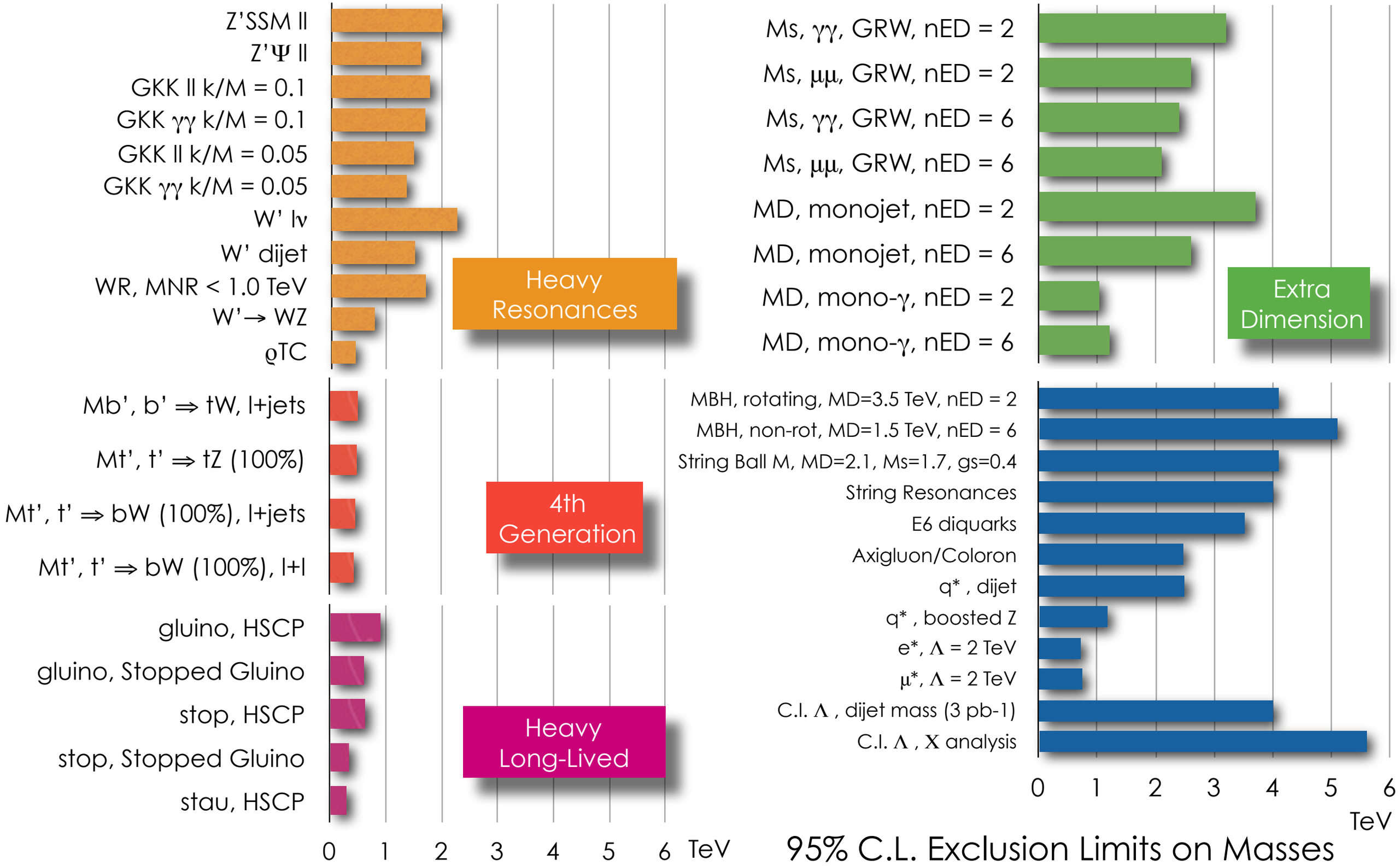
$$\sqrt{\left(\frac{M_{ll} - 91.6}{10}\right)^2 + \left(\frac{M_{jj} - 85.3}{15}\right)^2}$$

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	
		lepton + jet	450	1.1	
	CDF		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	$m_X \leq 70$ GeV
T'→ t + X		lepton + jet	360	4.8	$m_X \leq 100$ GeV

Conclusions

CMS Grand Summary



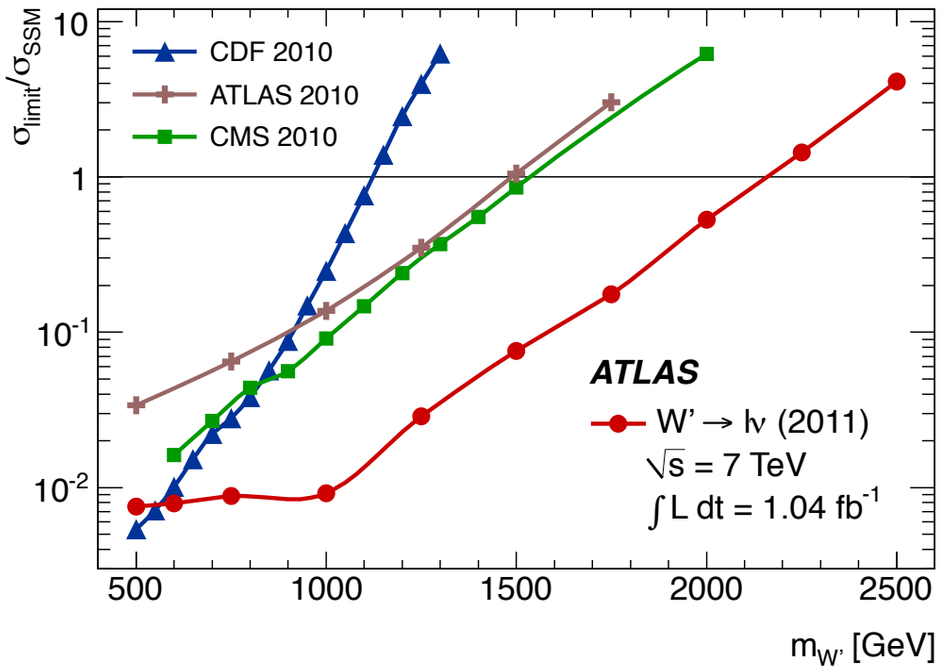
95% C.L. Exclusion Limits on Masses

FANTASTIC 1ST YEAR AT LHC

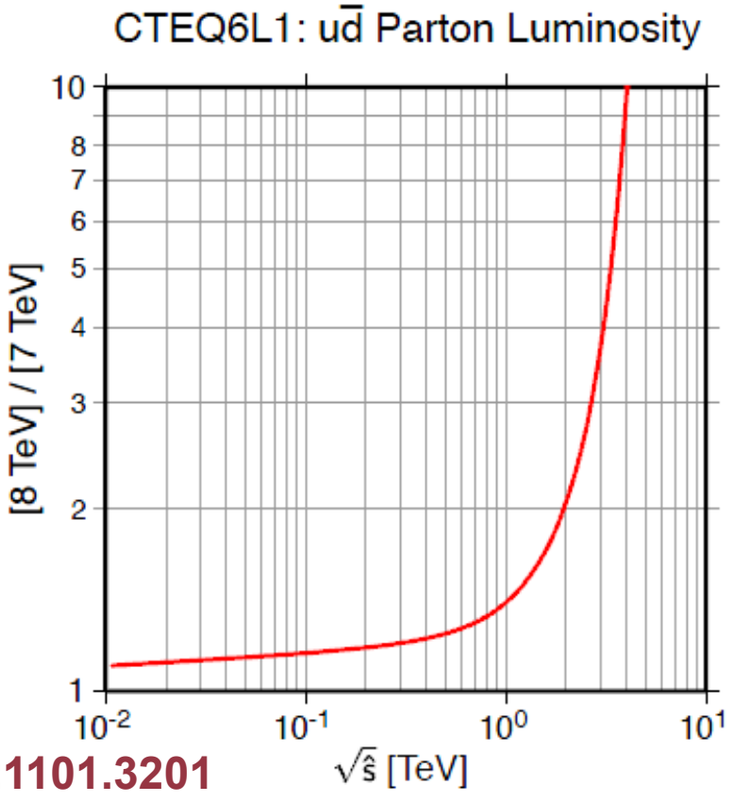
- Outstanding performance of detector, trigger, computing, and offline in ATLAS and CMS
  - last chunk of 1 fb^{-1} dataset delivered last week of June
  - Most of results using full dataset by 3rd week of July!
- Good news
  - excellent detector performance
    - b-tagging and MET reliable and under 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 superseding Tevatron searches already 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

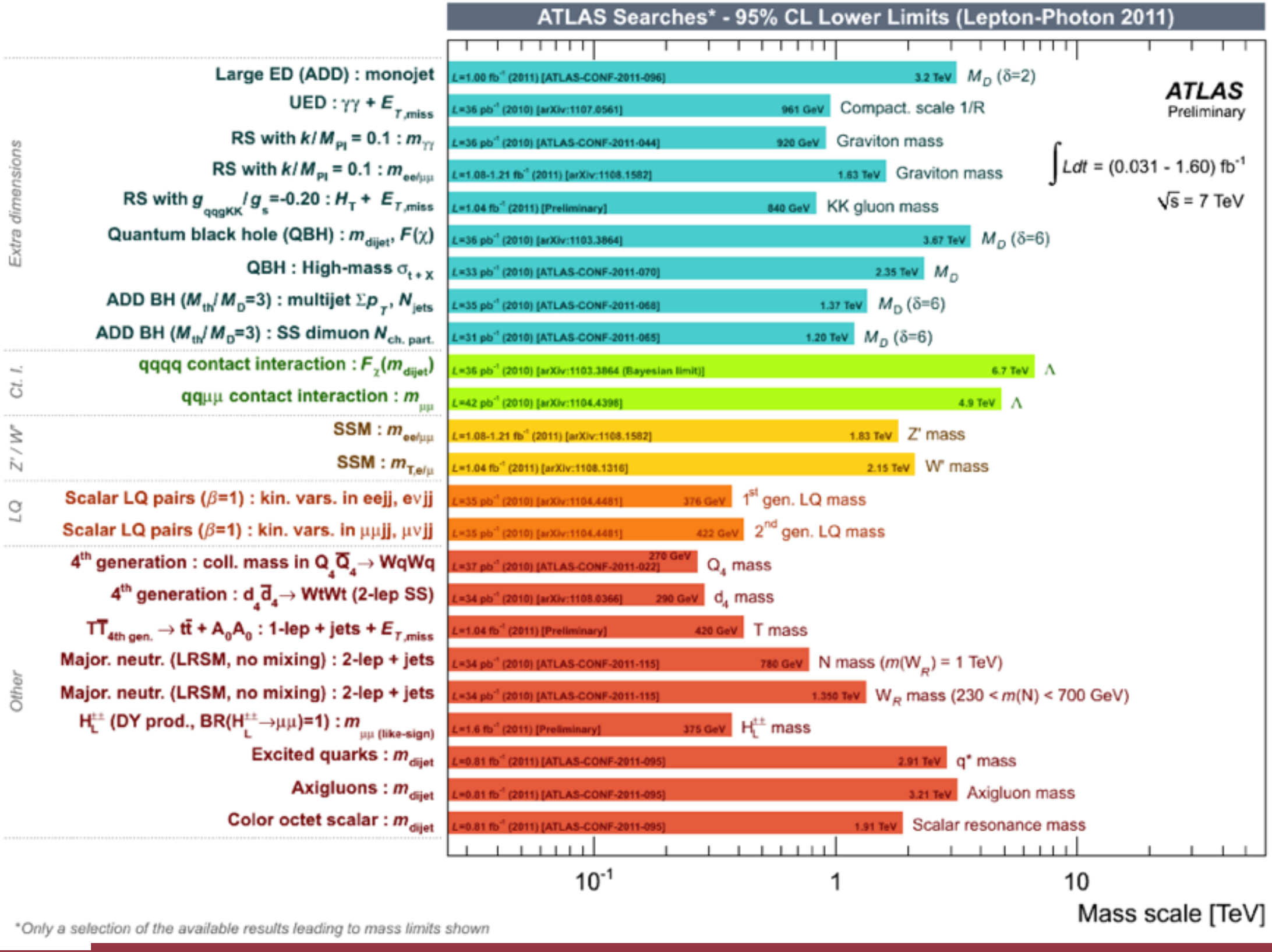


- Higher center-of-mass energy perhaps a better option than x10 data at 7 TeV
  - big gains in cross section for several processes
  - modest gain in parton luminosity from 7 TeV to 9 TeV
- Searches in 2012
  - many data-driven methods rely on extrapolation from low to high mass/pt
    - works until 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

ATLAS Grand Summary



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