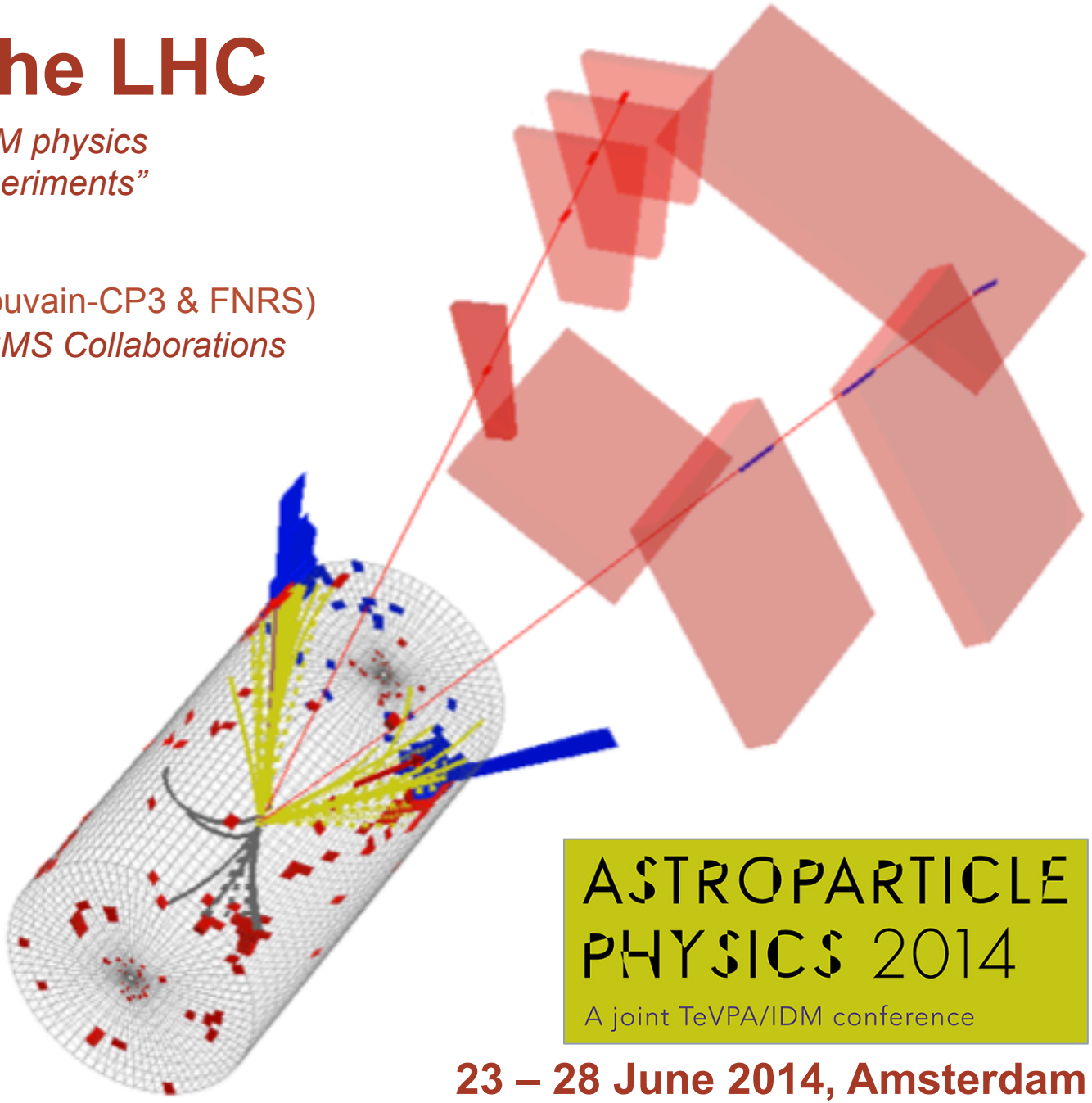
Exotica at the LHC

"Searches for non-susy BSM physics at the ATLAS and CMS experiments"

Tristan du Pree (UCLouvain-CP3 & FNRS)
on behalf of the ATLAS & CMS Collaborations



Outline

- *Heavy bosons*
- *Heavy fermions*
- *Other phenomena*

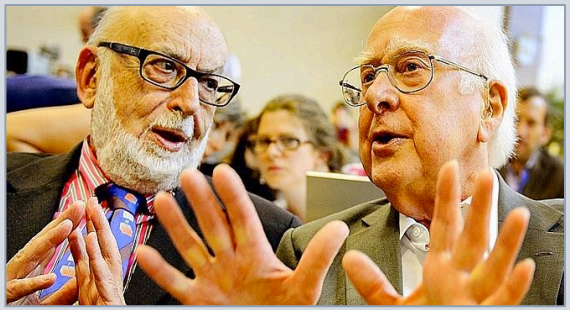
ASTROPARTICLE PHYSICS 2014

A joint TeVPA/IDM conference

23 – 28 June 2014, Amsterdam

Introduction

- **Higgs boson discovered…**
  - H-boson studies [see G.Mitselmakher, Thursday]
- **…but Standard Model not complete**
  - Dark Matter, hierarchy problem, baryogenesis, gravity, etc



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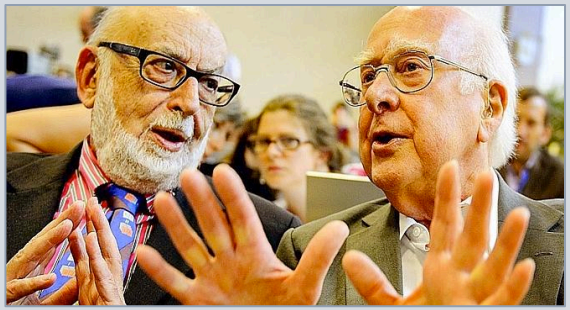
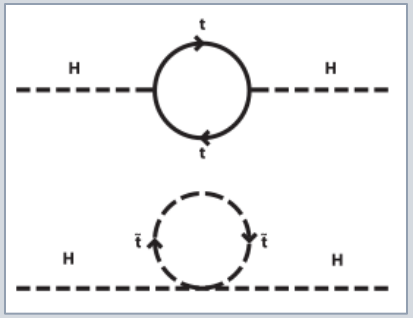


- **Supersymmetry…**
  - Solution to many open issues
  - E.g. Naturalness & Dark Matter
- **…but no proof of susy** (yet)
  - Supersymmetry searches [see T.Petersen, today]



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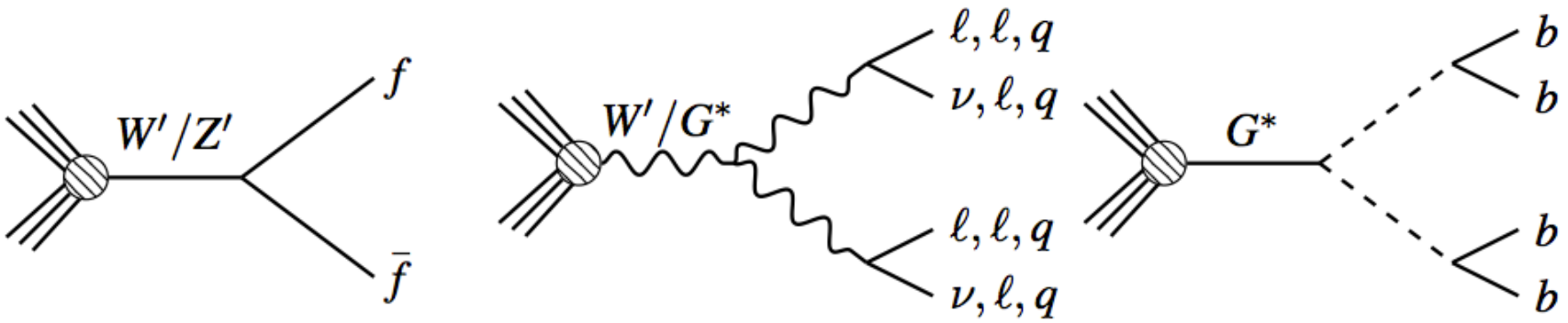
Non-susy BSM physics?

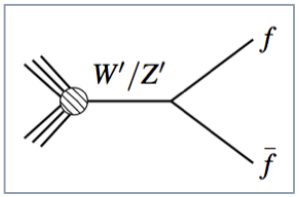
Subject of upcoming 15+5 minutes!

I. Heavy Bosons

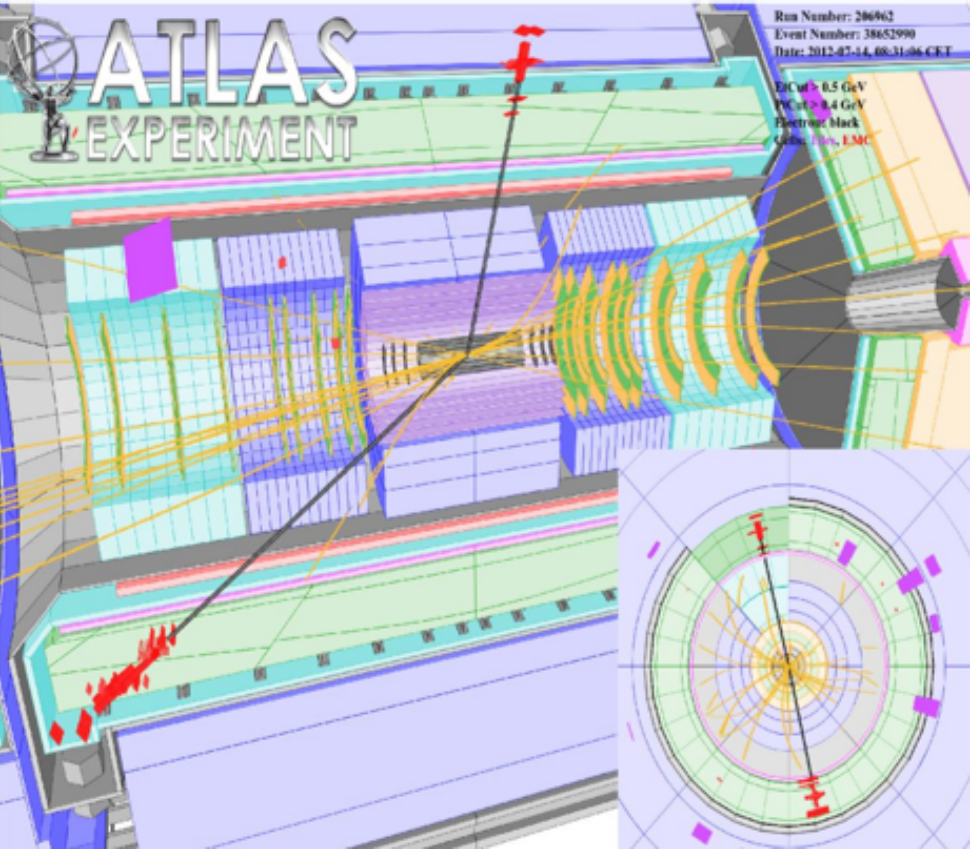
- **New strong sector**
  - Technicolor, Little Higgs?
- **Extra dimensions**
  - RS, Bulk G, Radion?



Z' candidates

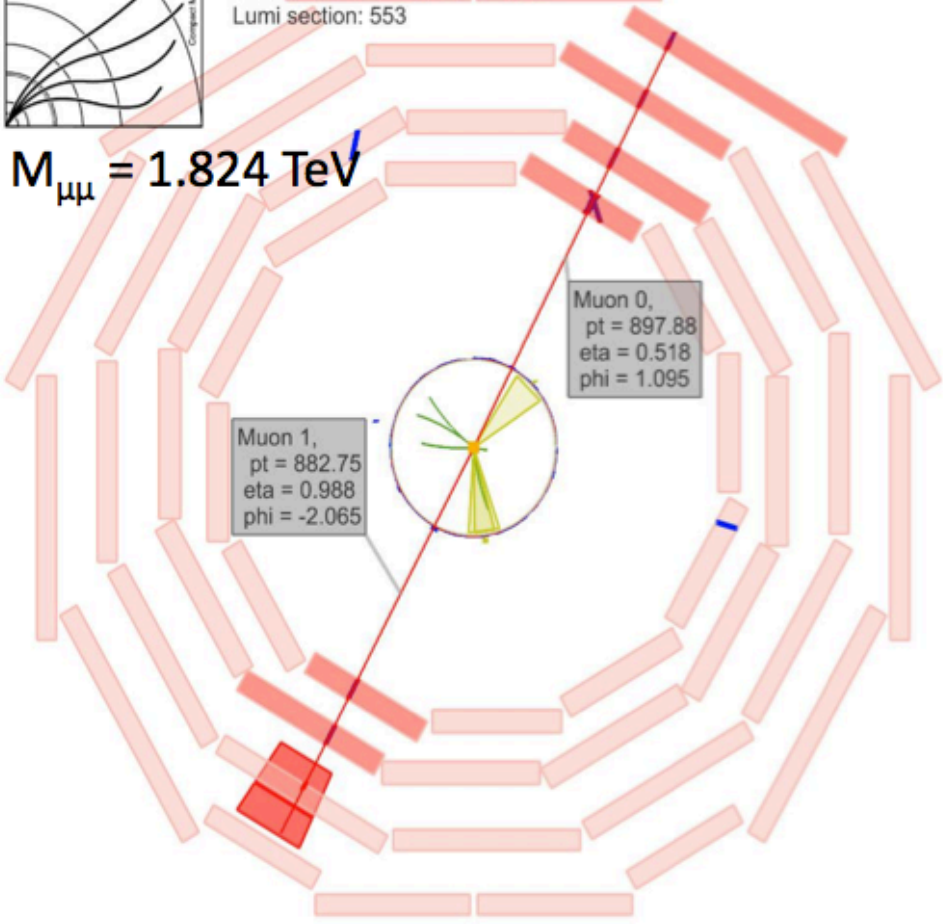


M_{ee} = 1.541 TeV



CMS Experiment at LHC, CERN
Data recorded: Sun Jul 22 06:02:46 2012 GMT-4
Run/Event: 199409 / 676990060
Lumi section: 553

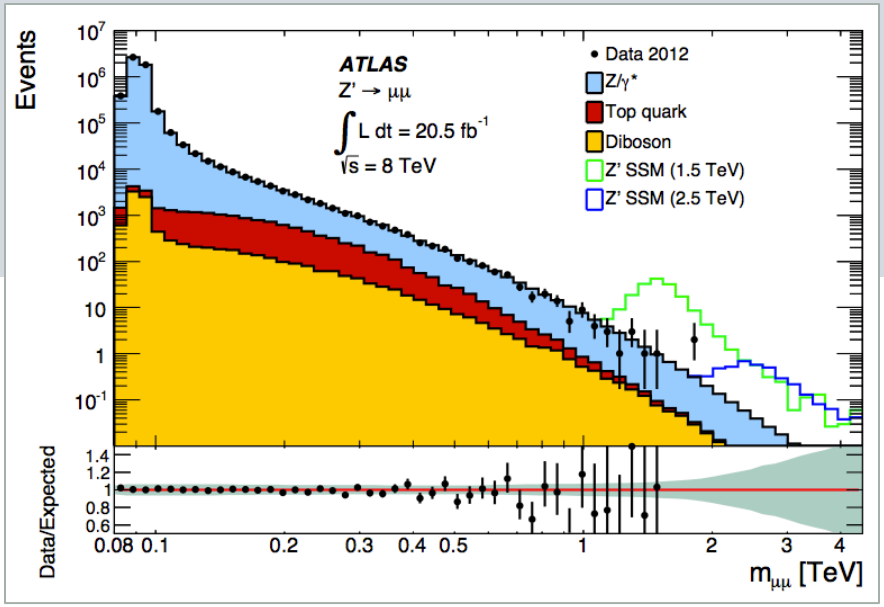
$M_{\mu\mu}$ = 1.824 TeV

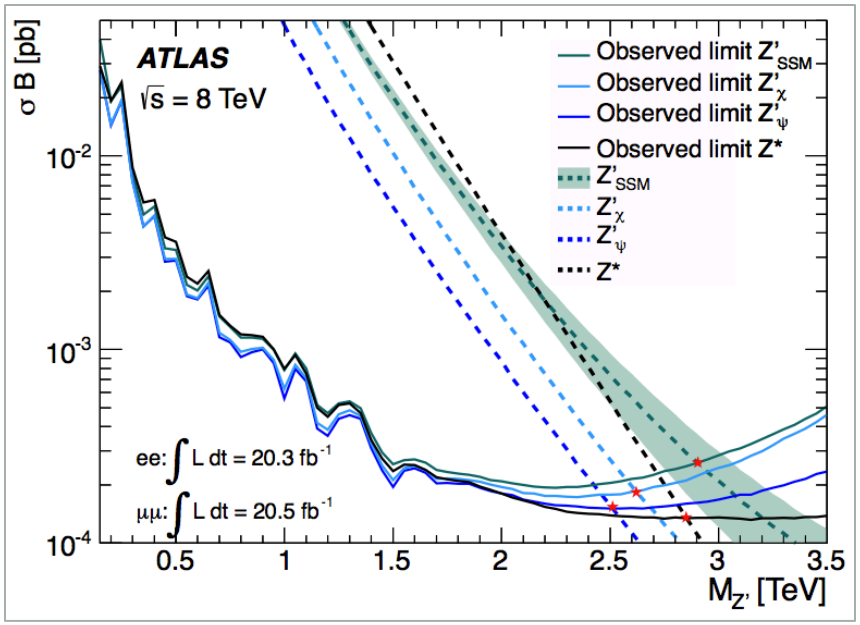


Z'→ll

arXiv:1405.4123

- Use M_{ll} mass for search
  - Sensitive at low masses
- No excess observed





- **Various interpretations**
  - SSM, E6, Z*, Technicolor
    RS-Graviton, Quantum Black Holes
    Minimal models
- Exclusion below **$M_{Z'}$ ~2.5 TeV**

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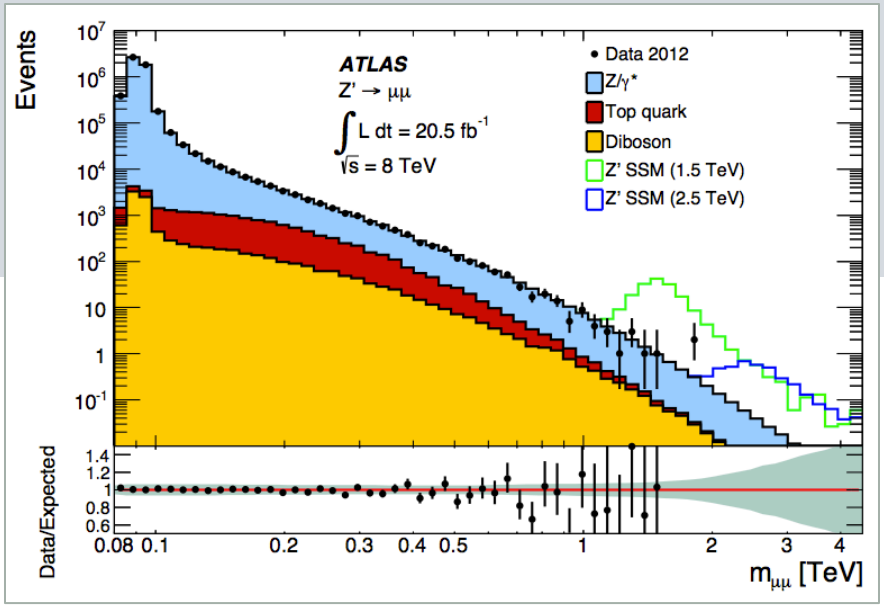
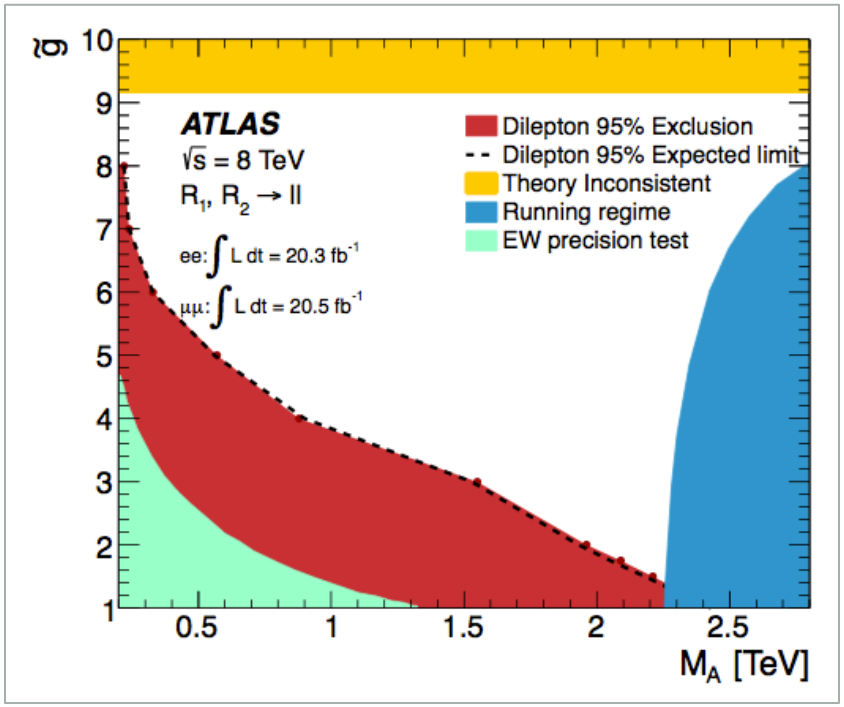




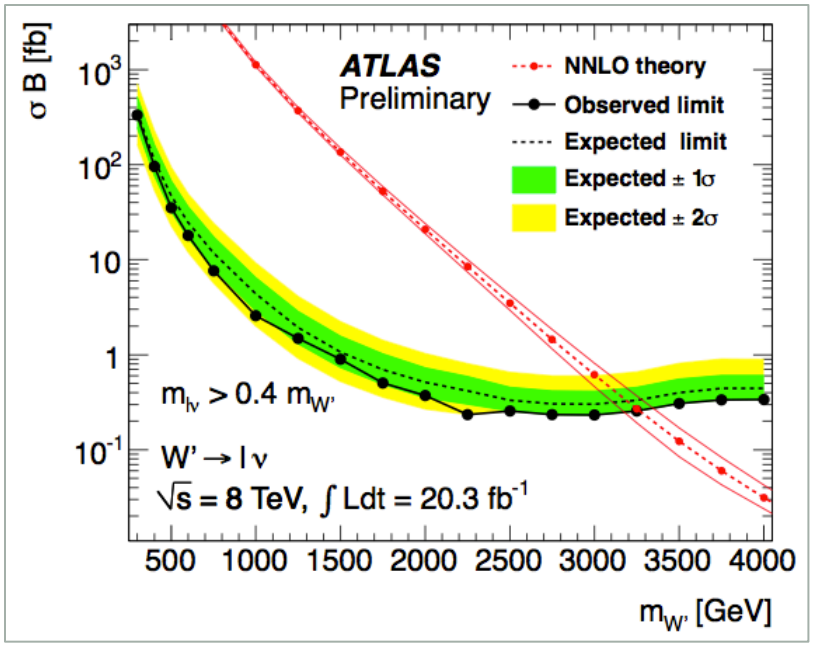
- **Various interpretations**
  - SSM, E6, Z*, Technicolor
    RS-Graviton, Quantum Black Holes
    Minimal models
- Exclusion below **$M_{Z'}$ ~2.5 TeV**

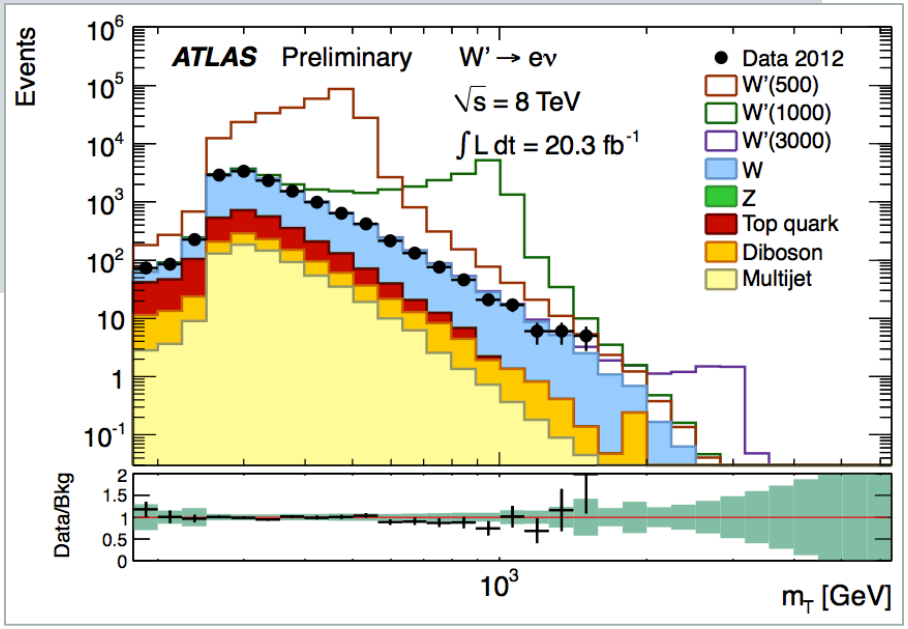
W'→lν

ATLAS-CONF-2014-017

- Main discriminant: transverse mass

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$





- Limits on various models
  - W', W*
- Exclude typically **$M_{W'}$ < 3TeV**
  - New: Dark Matter (EFT)

W'→lν

ATLAS-CONF-2014-017

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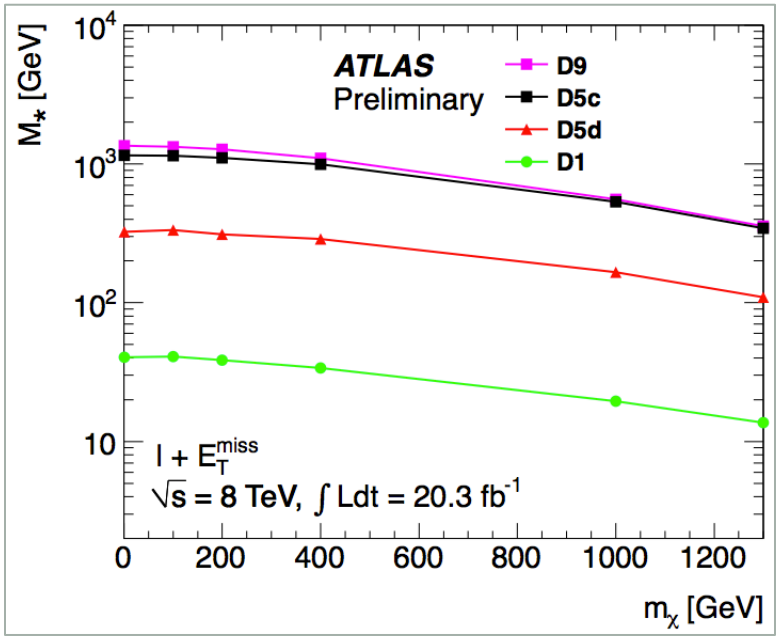
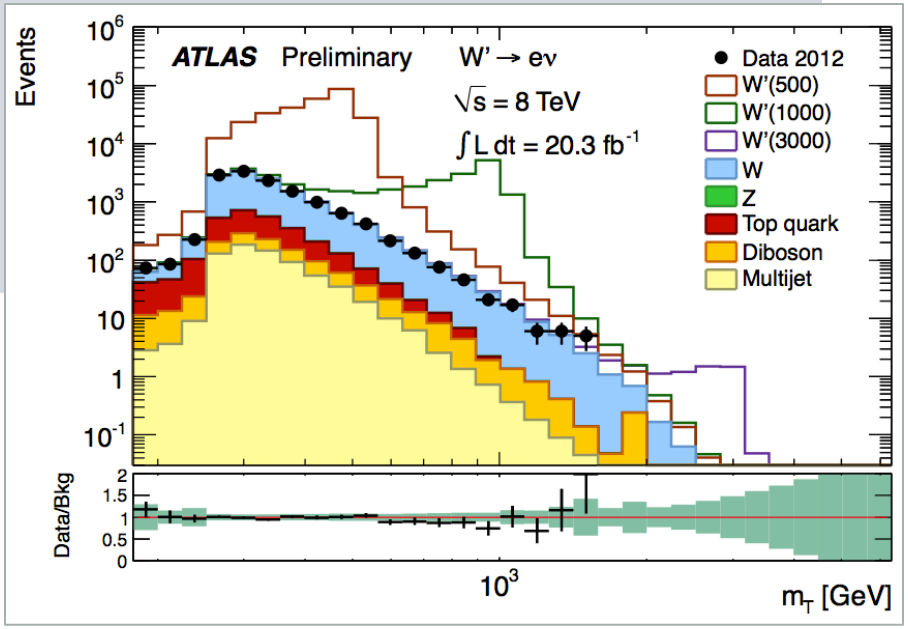




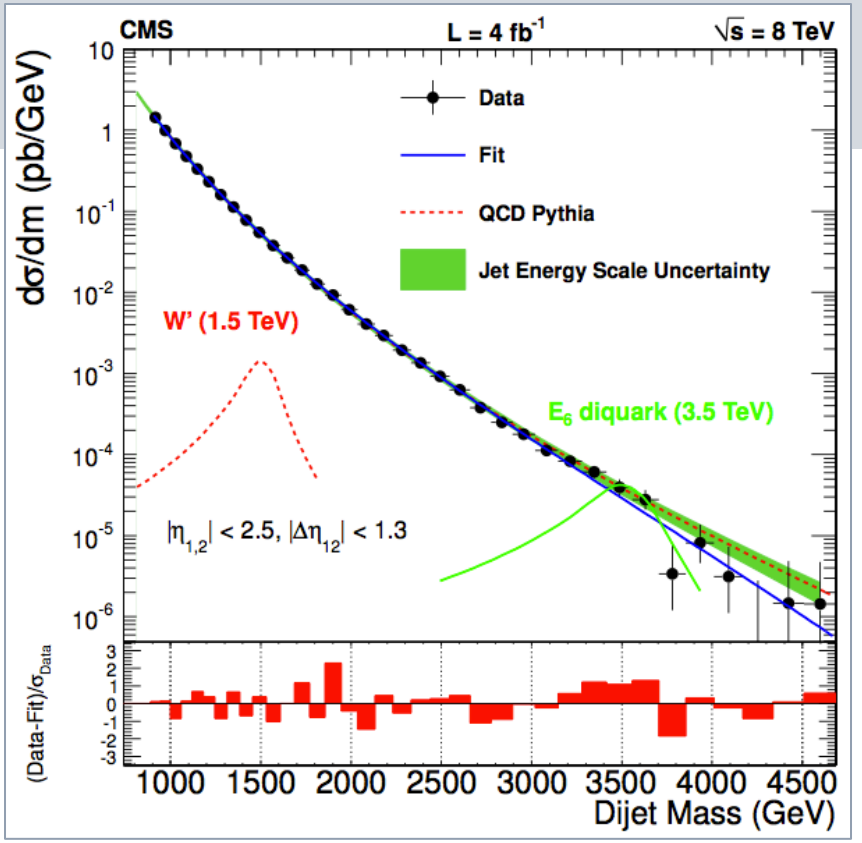
- Limits on various models
  - W', W*
- Exclude typically $M_{W'} < 3$TeV
  - New: Dark Matter (EFT)

Dijet resonances

- Search in **dijet spectrum** for narrow resonance

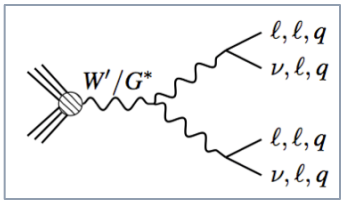
CMS-EXO-12-016

Model	Final state	Observed excluded mass range [TeV]	Expected excluded mass range [TeV]
String Resonance	qg	[1.0, 4.78]	[1.0, 4.75]
Excited Quark	qg	[1.0, 3.19]	[1.0, 3.47]
E_6 Diquark	qq	[1.0, 4.28]	[1.0, 4.16]
Axigluon/Coloron	$q\bar{q}$	[1.0, 3.27]	[1.0, 3.60]
S8 Resonance	gg	[1.0, 2.79]	[1.0, 2.54]
W′ Boson	$q\bar{q}$	[1.0, 1.73]	[1.0, 1.97]
Z′ Boson	$q\bar{q}$	[1.0, 1.62]	[1.0, 1.58]
RS Graviton	$q\bar{q} + gg$	[1.0, 1.45]	[1.0, 1.29]

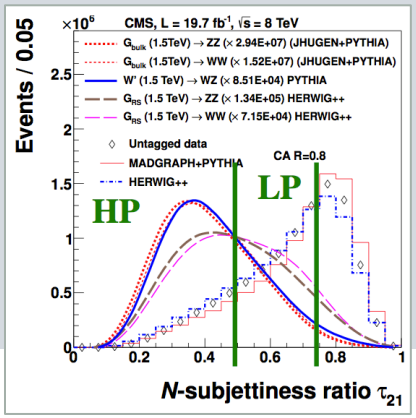


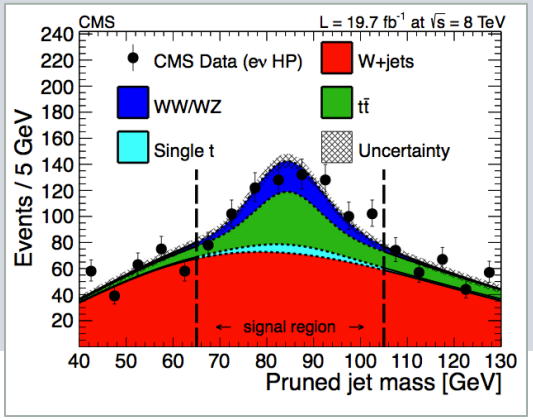
- Limits
  - Various final states: **qq, qg, gg**
  - Various models: **1 - few TeV**
- First limit on G_{RS} **in dijet**

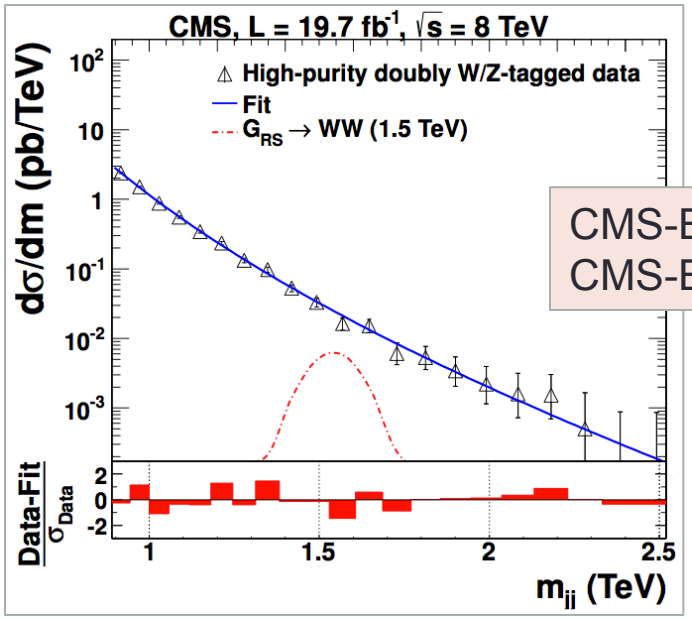
V'→VV



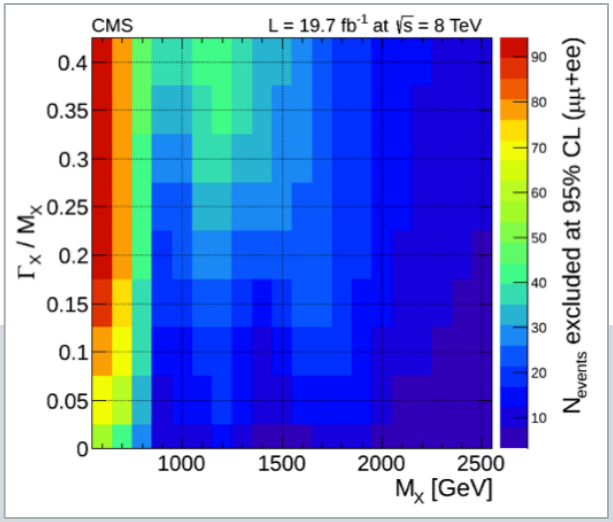
- Final states: semileptonic & fully hadronic
- **Boost**: jet substructure
  - Purity: N-subjettiness
- Limits on **W'** and G_{RS}





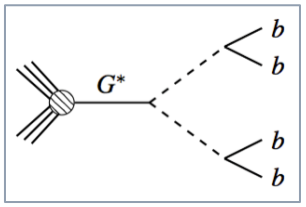


CMS-EXO-12-024-003
CMS-EXO-13-009-003



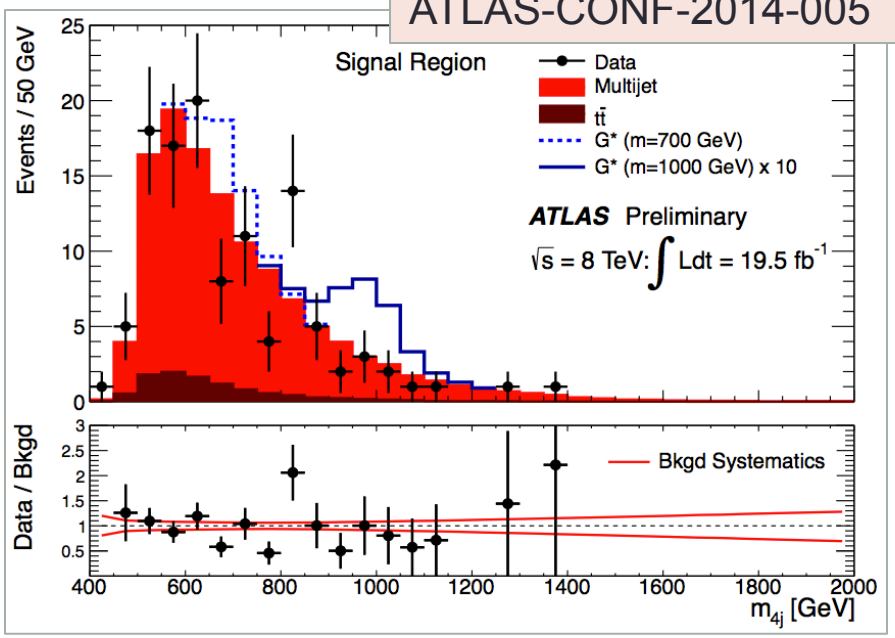
- And **model-independent** limits!

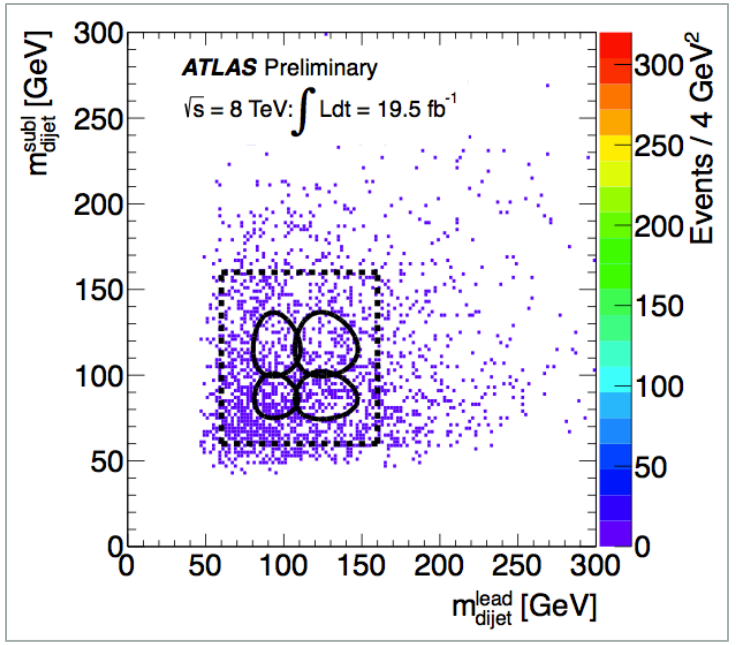
X→H(bb)H(bb)



- TeV resonance → HH
  - **Background**: suppress QCD with b-tags
  - **Signal**: define with M_{jj}

ATLAS-CONF-2014-005





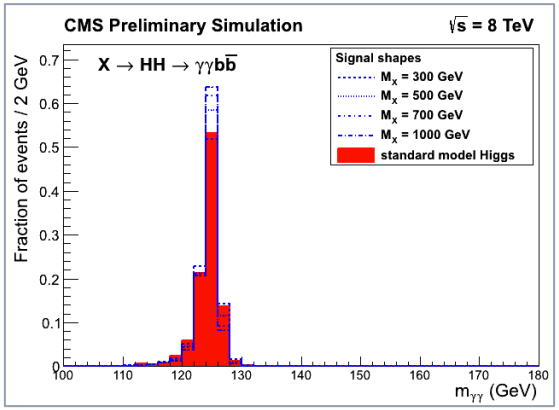
- No excess
  - Limits on KK G*
    - RS extra dimensions
  - **0.59-0.71 TeV**

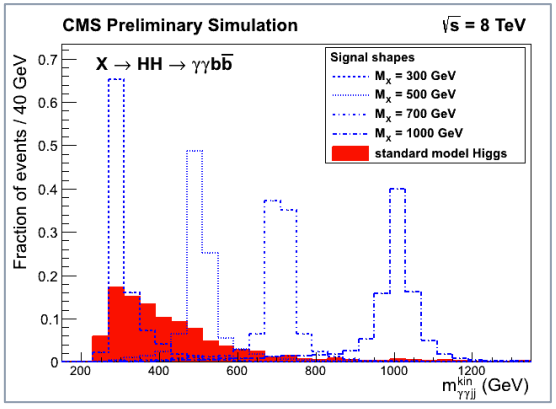
X→H(γγ)H(bb)

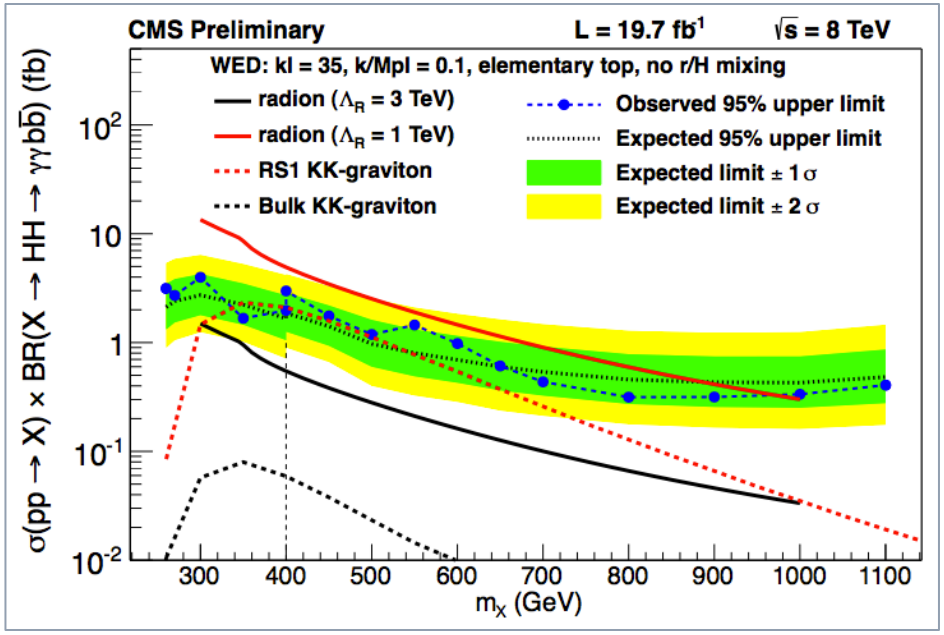
CMS-HIG-13-032

Search HH resonance

- m_X = [260,1100] GeV
  - **2 γ & 1/2 b**-tagged jets
  - >400 GeV: **kinematic fit**
  - <400 GeV: $M_{\gamma\gamma}$







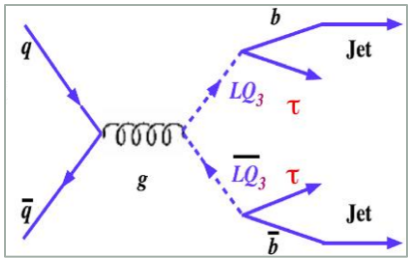
Spin hypothesis

- Test spin-0 and spin-2 models
- Selection minimally sensitive

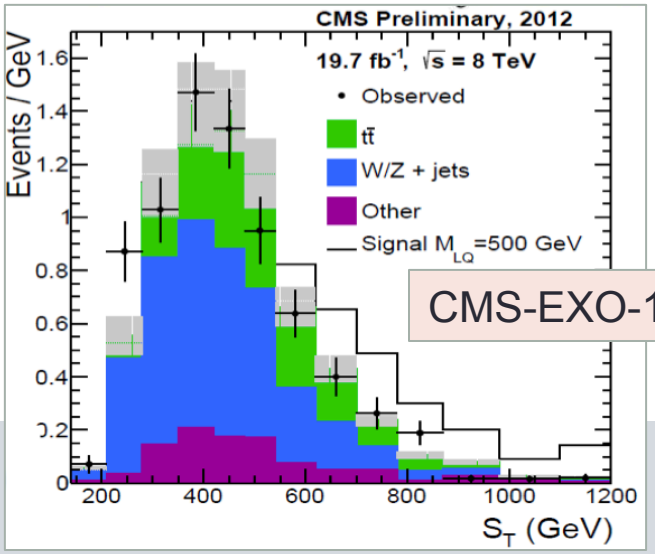
Limits

- Warped extra dimensions
  - Radion scale Λ_R = 1 TeV
  - **Radion mass exclusion: M_X < 970 GeV**

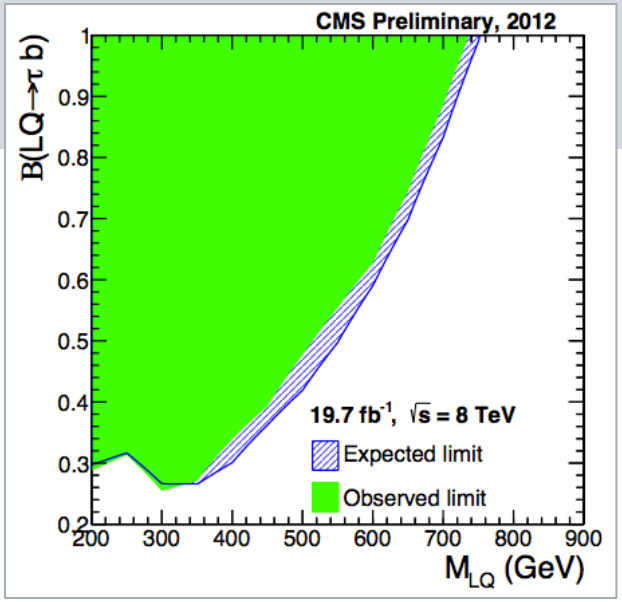
Leptoquarks



- Pair production of **heavy scalars**
  - Also interpreted as RPV stop

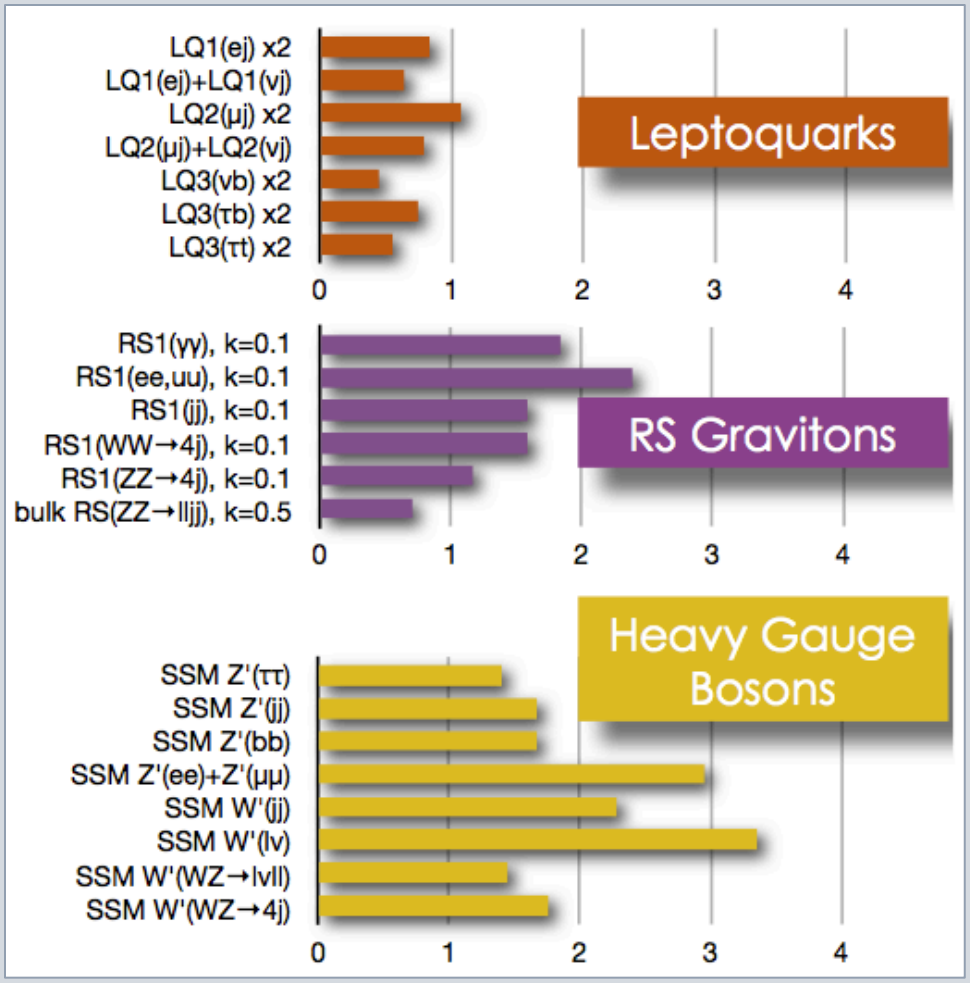


CMS-EXO-12-032



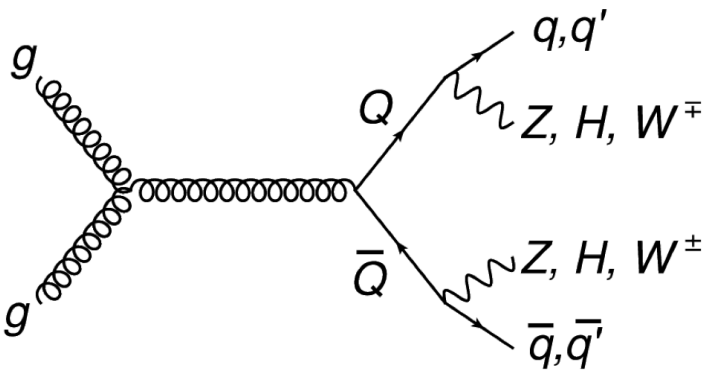
- Exclude **M_{LQ} < 740 GeV**
  - For BR(LQ)→**b+τ** = 100%

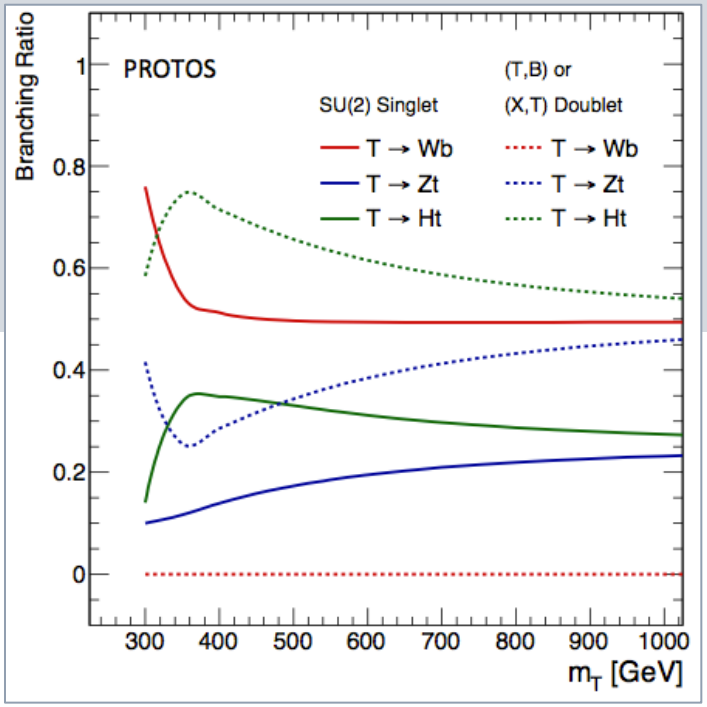
Bosons summary



I. Heavy Fermions

- **Chiral 4th generation excluded**
  - By H boson with SM-like couplings
- **Additional fermions possible**
  - With vector-like couplings!



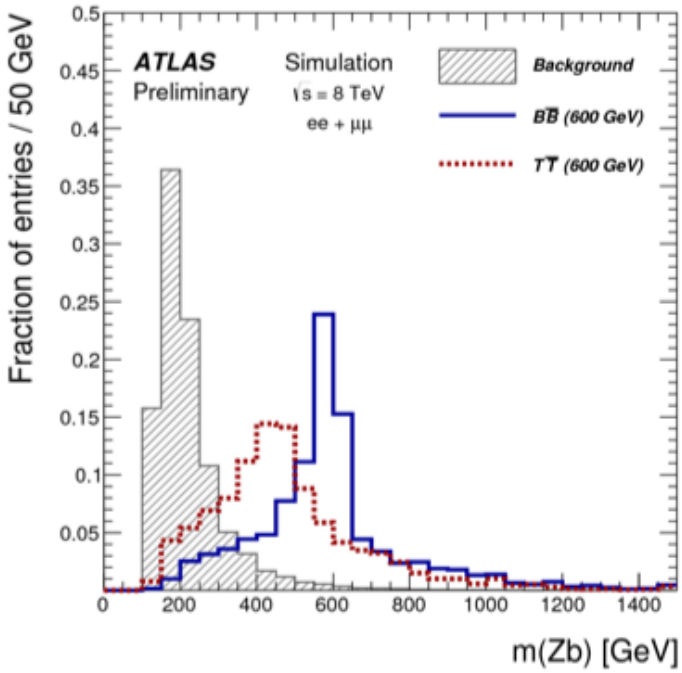


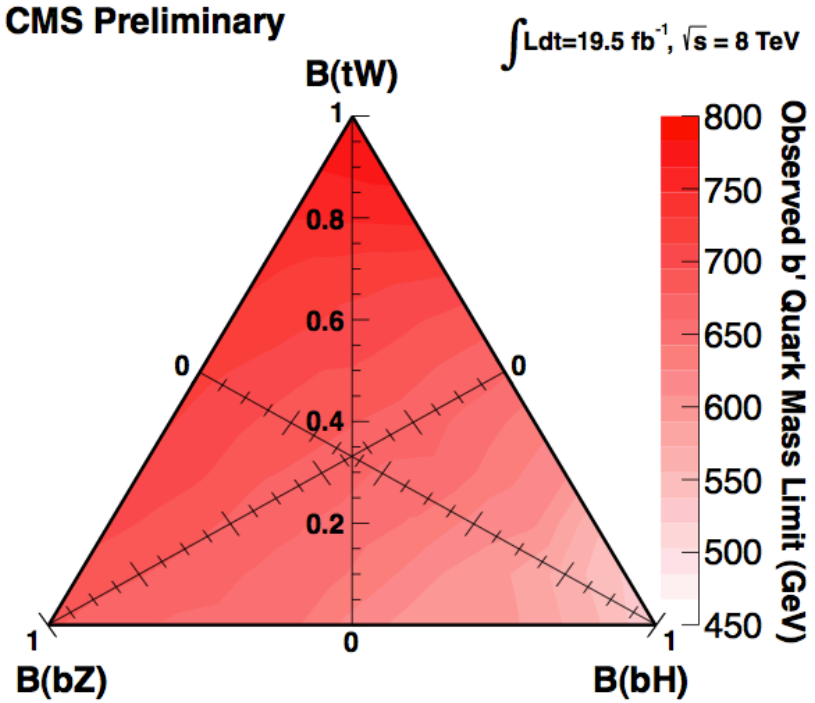
VLB

Vector-like Bottom

CMS-B2G-13-003

ATLAS-CONF-2013-056





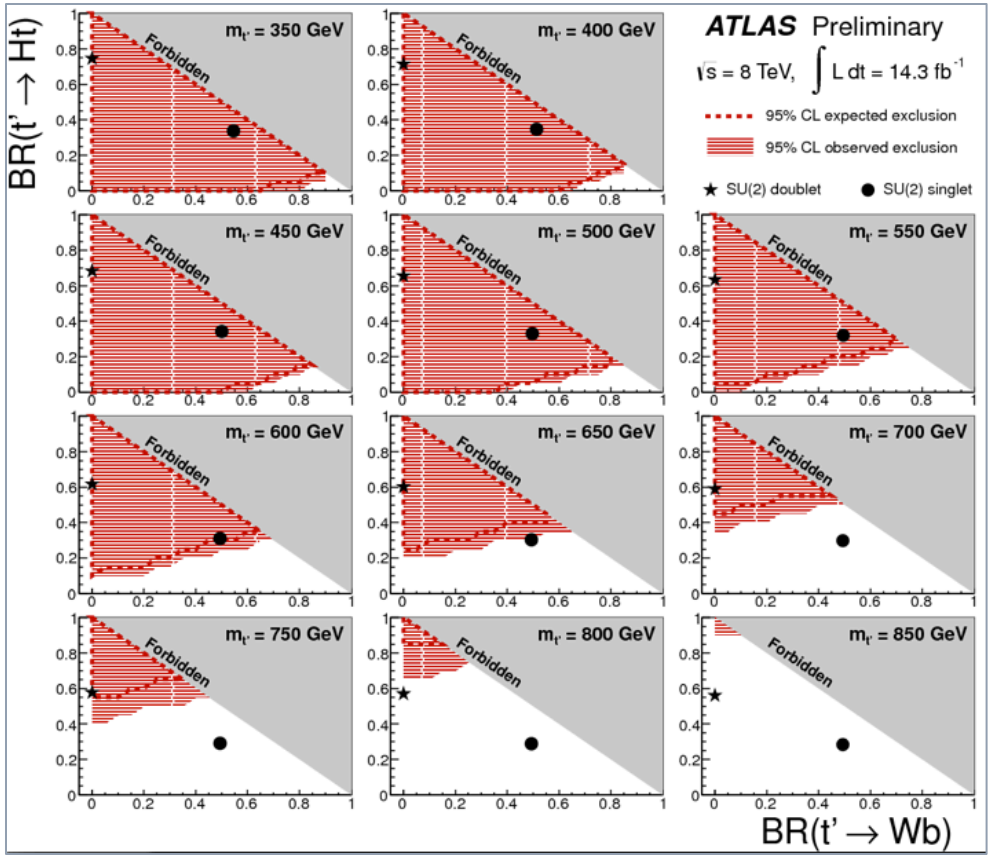
- Exclusion limits M_B < 500-800 GeV

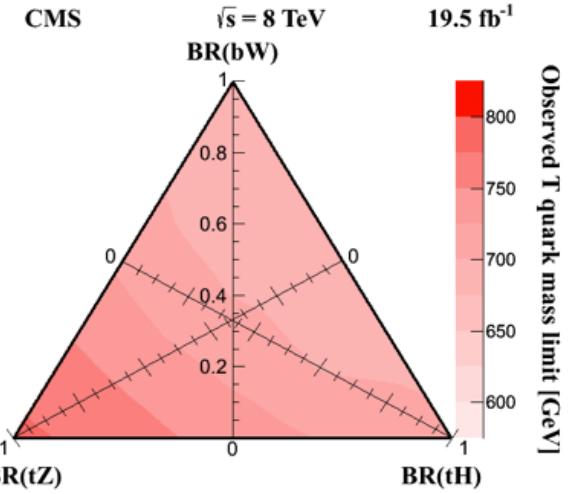
VLT

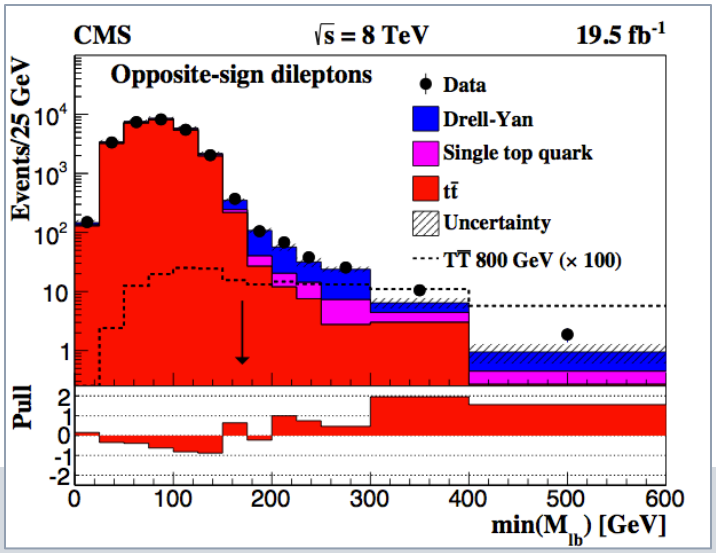
Vector-like Top

ATLAS-CONF-2013-018

CMS-B2G-12-015



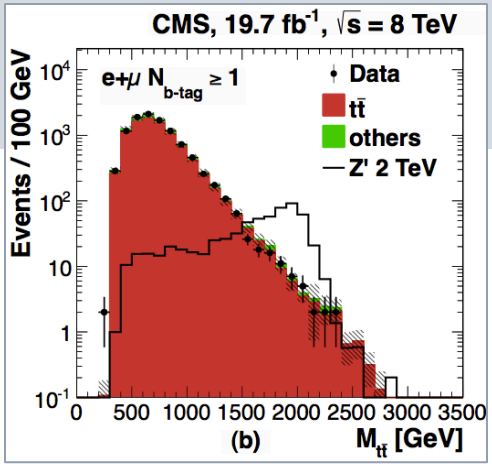


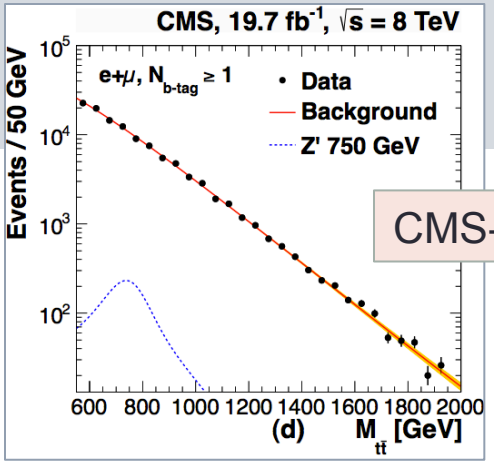


- Similar limits for M_T

More at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Other searches with tops





ttbar (also boosted)

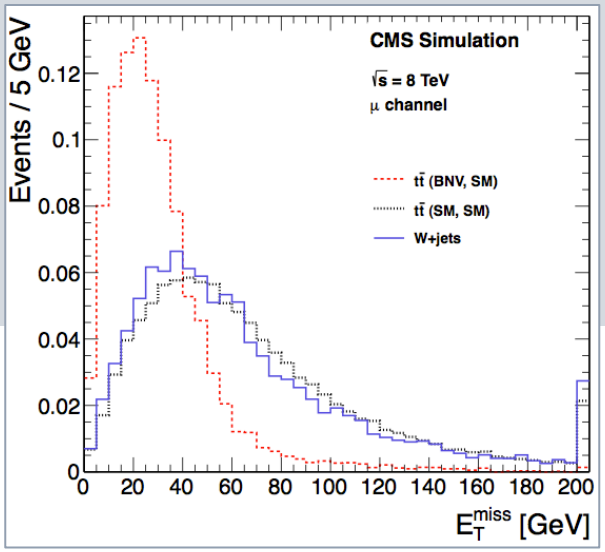
- Z', **KK gluon**

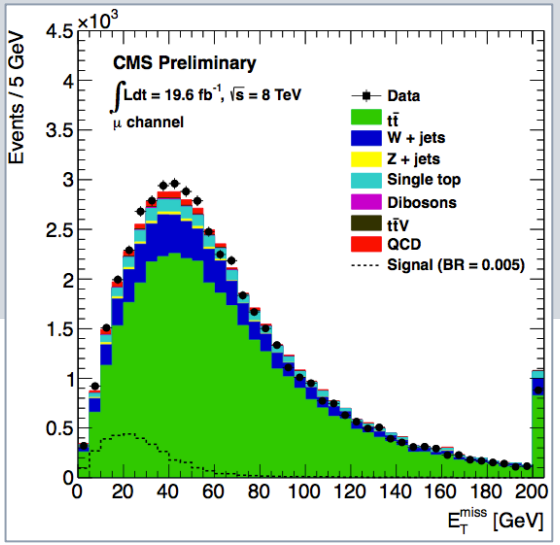
CMS-B2G-13-001

Model	Observed Limit	Expected Limit
Z', $\Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
Z', $\Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV

- **BNV** with tops
  - Limit:
    BR < 0.2%

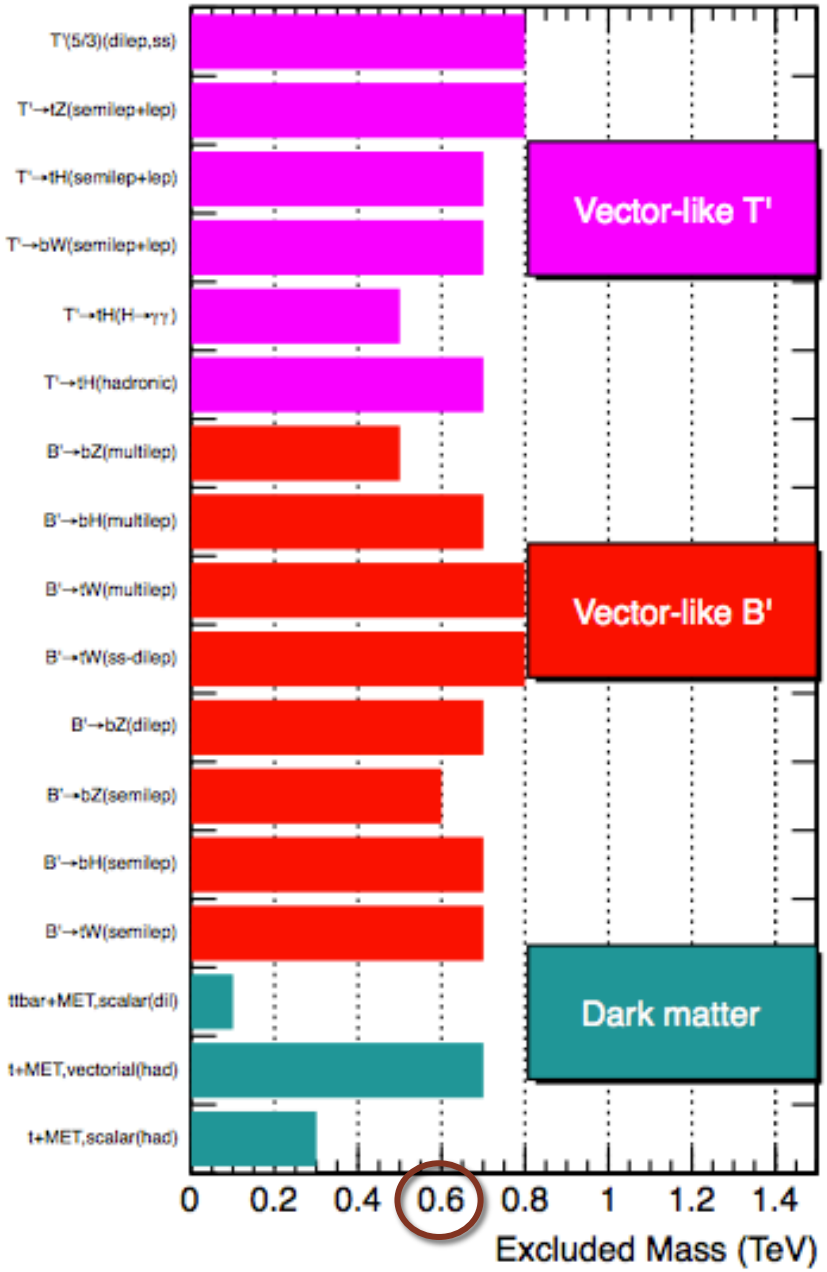
CMS-B2G-12-023

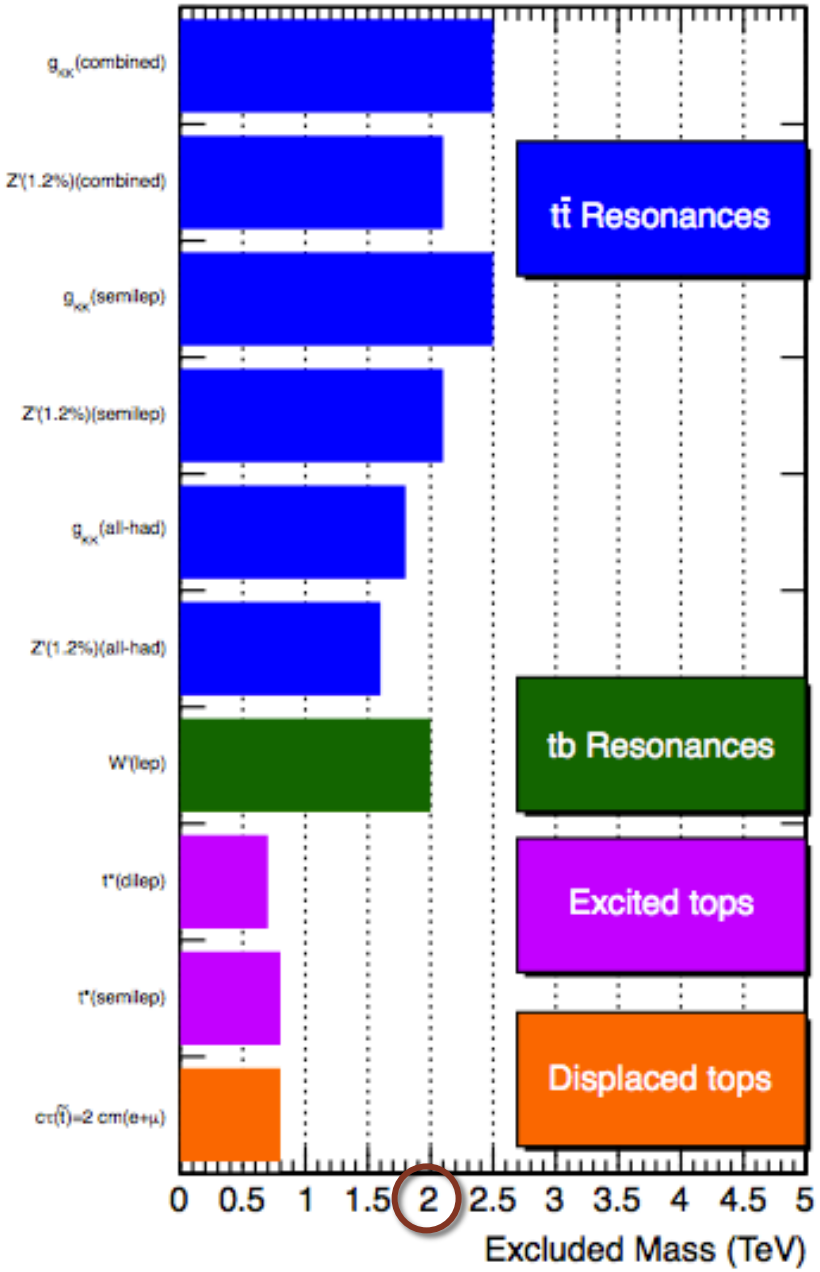




CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)



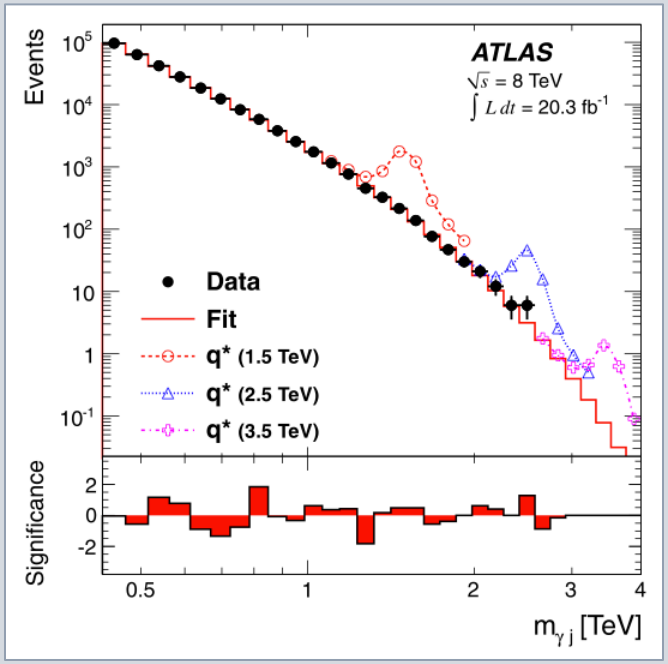


Excited fermions

PLB 728 (2013) 562

Generic searches

- **Excited quarks**
  - q*→γj, jj
- **Excited leptons**
  - l*→llγ
- **Vector-like leptons**
  - v'→lljj, l'→Zl
    - LR-symm models
    - Seesaw



Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt$[fb^{-1}]	Mass limit
Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q* mass 3.5 TeV
Excited quark $q^* \to qg$	–	2 j	–	13.0	q* mass 3.84 TeV
Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass 870 GeV
Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ* mass 2.2 TeV
LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV
Type III Seesaw	2 e, μ	–	–	5.8	$N^\pm$ mass 245 GeV

$\sqrt{s}$ = 7 TeV

$\sqrt{s}$ = 8 TeV

10^{-1} 1

Other phenomena

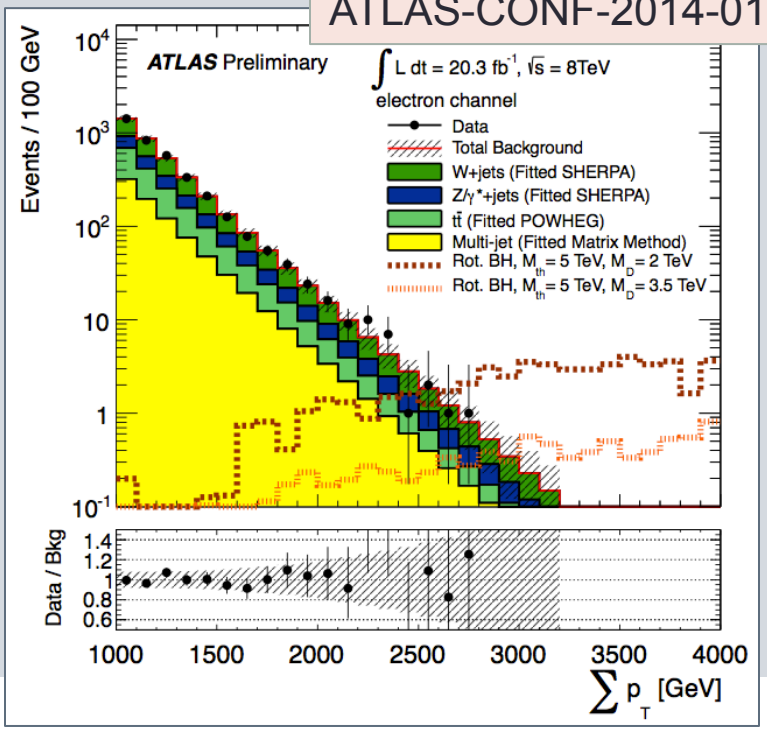
Black holes

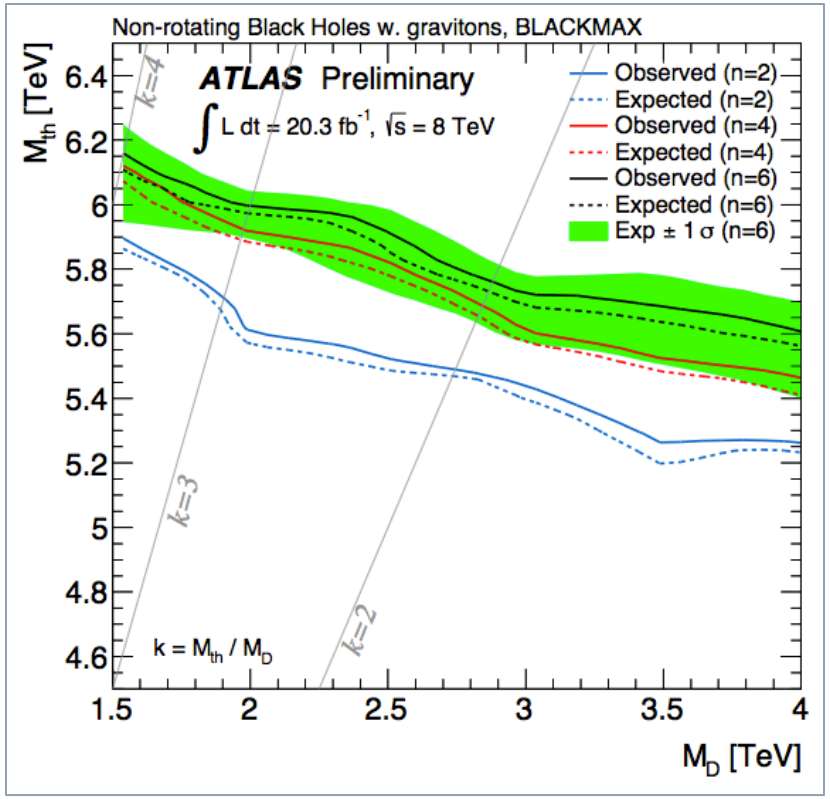
- High-p_T leptons+jets

$$\sum p_T = \sum_{\ell,\text{jets}} p_T \quad \text{for } p_T^{\ell,\text{jet}} > 100 \text{ GeV}$$

  - Complementary to searches for
    - High-track multiplicity
    - Multijet

ATLAS-CONF-2014-016



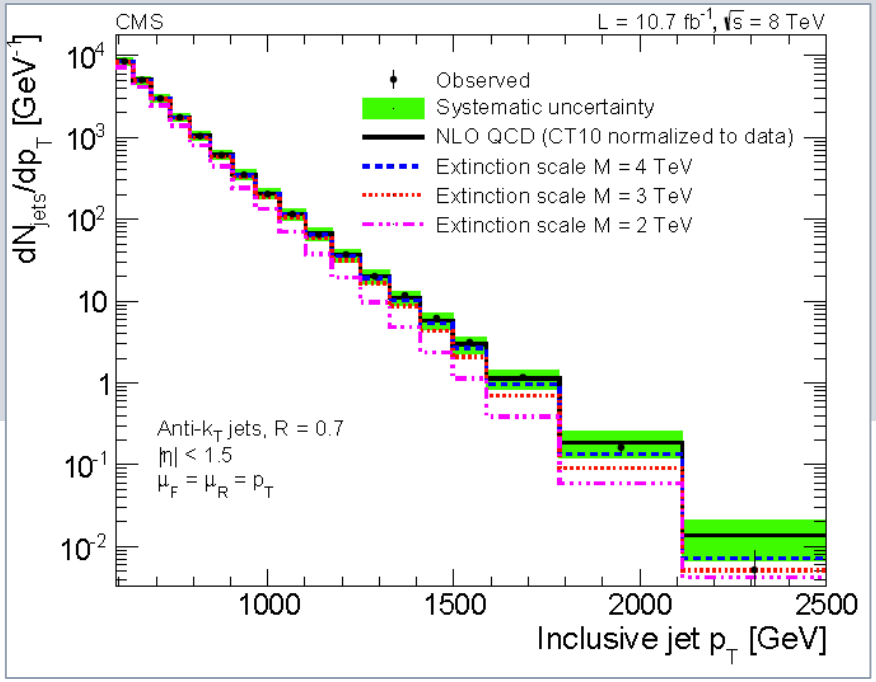


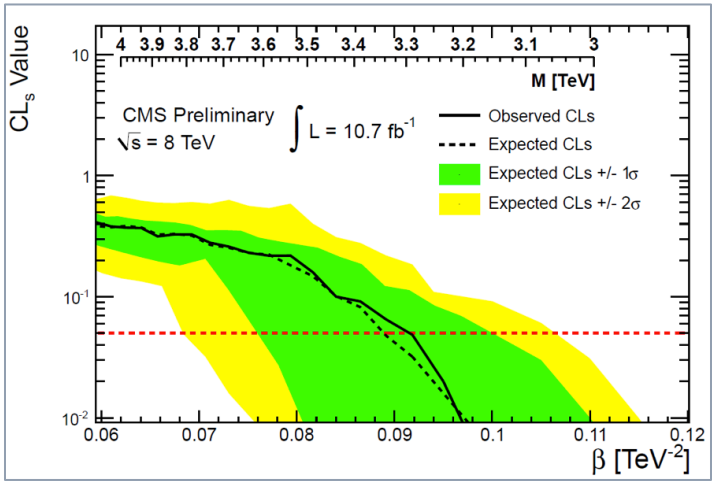
- Interpret in **ADD models**
  - 2 / 4 / 6 extra dimensions
    - Scale of extra dim.: **M_D**
    - Production threshold: **M_{th}**
- **Limit: M_{th} > 5.0 – 6.2 TeV**

Jet extinction

CMS-EXO-12-051

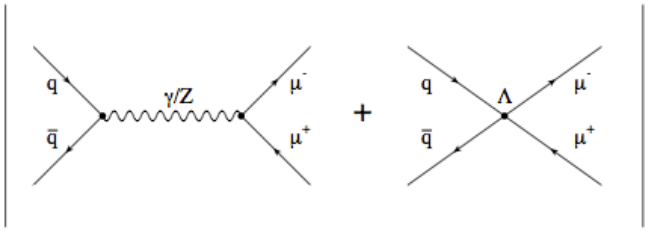
- **Strong gravity at TeV scale**
  - String couplings in the strong-coupling limit
- **Suppression of high-p_T** SM processes
  - Beyond certain energy scale





- Compare p_T spectrum
  - Limit on extinction
- Exclude below **3.3 TeV**

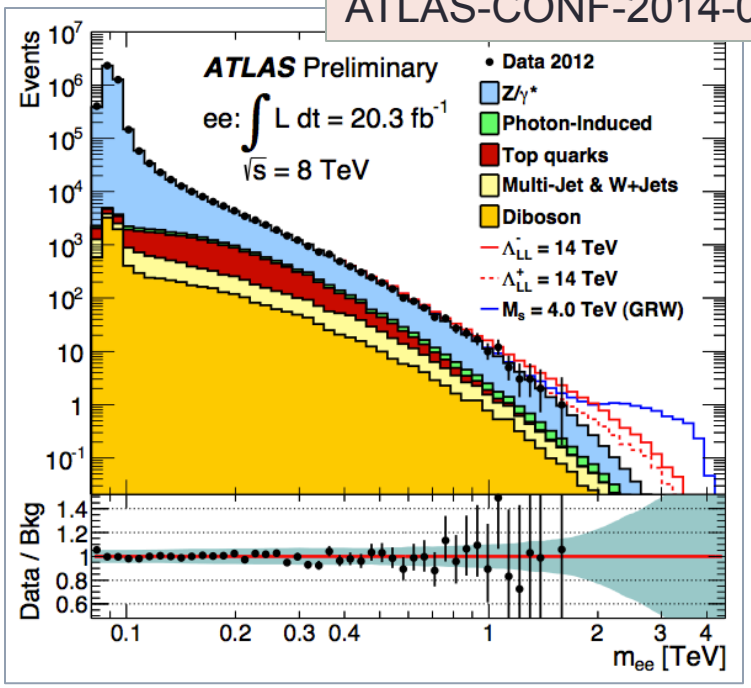
Contact interactions

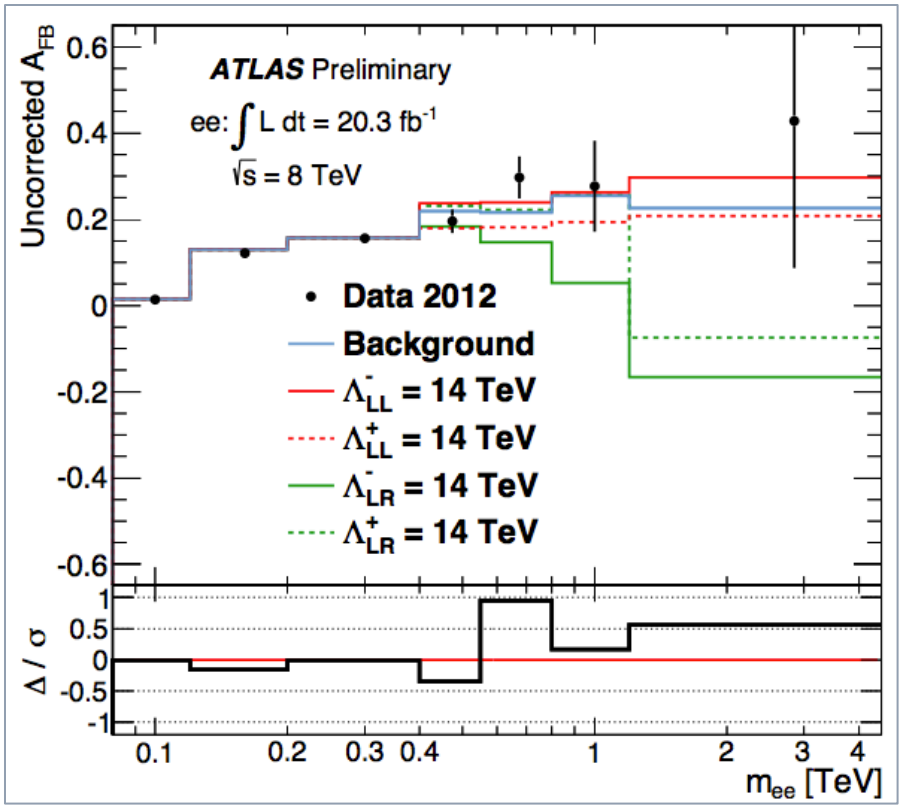


- Discriminating variables:

$$m(\ell\ell),\ \cos\theta^* = \frac{p_Z(\ell\ell)}{|p_z(\ell\ell)|}\,\frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell\ell)\sqrt{m(\ell\ell)^2 + p_T(\ell\ell)^2}}$$

ATLAS-CONF-2014-030



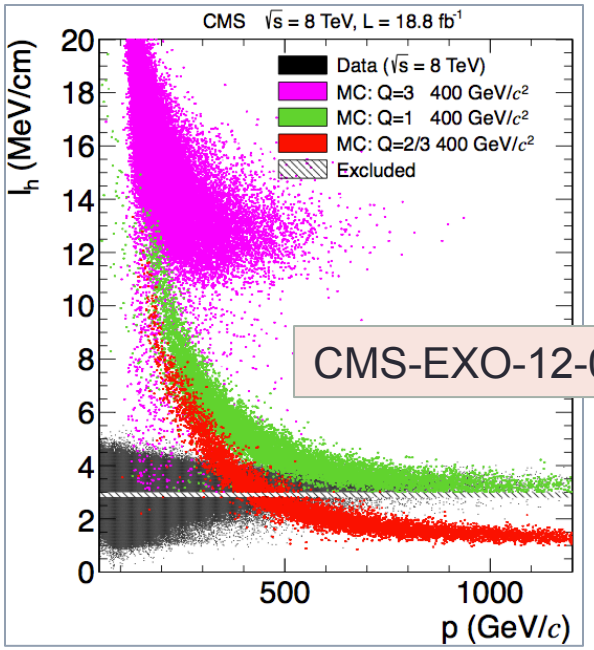


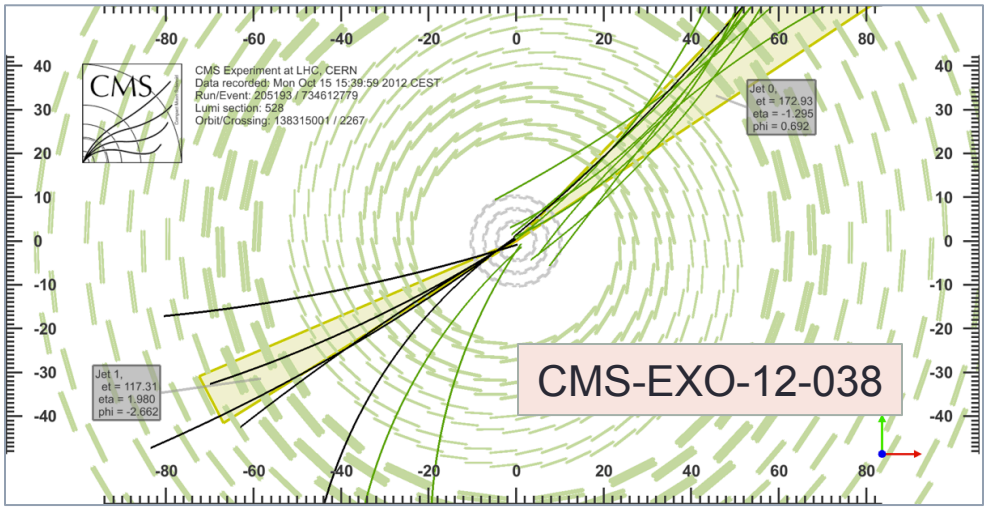
➢ Exclude comp.scale **Λ < 15.6-26.3 TeV**

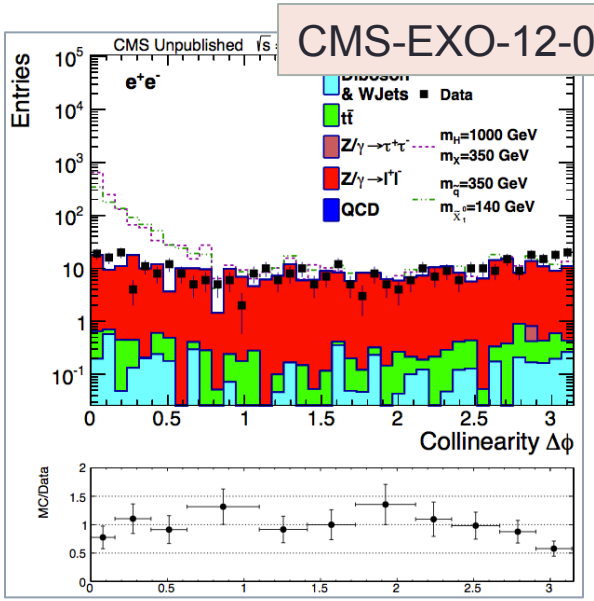
Long-lived particles

- Various searches for long-lived particles
  1. **Heavy stable charged particles**
  2. Long-lived → **pair of leptons**
  3. Long-lived → **quark-antiquark pair**

➢ Limits on e.g. decay of **heavy scalar** to long-lived particles







SUMMARY

…including many other results
that could not be shown

ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

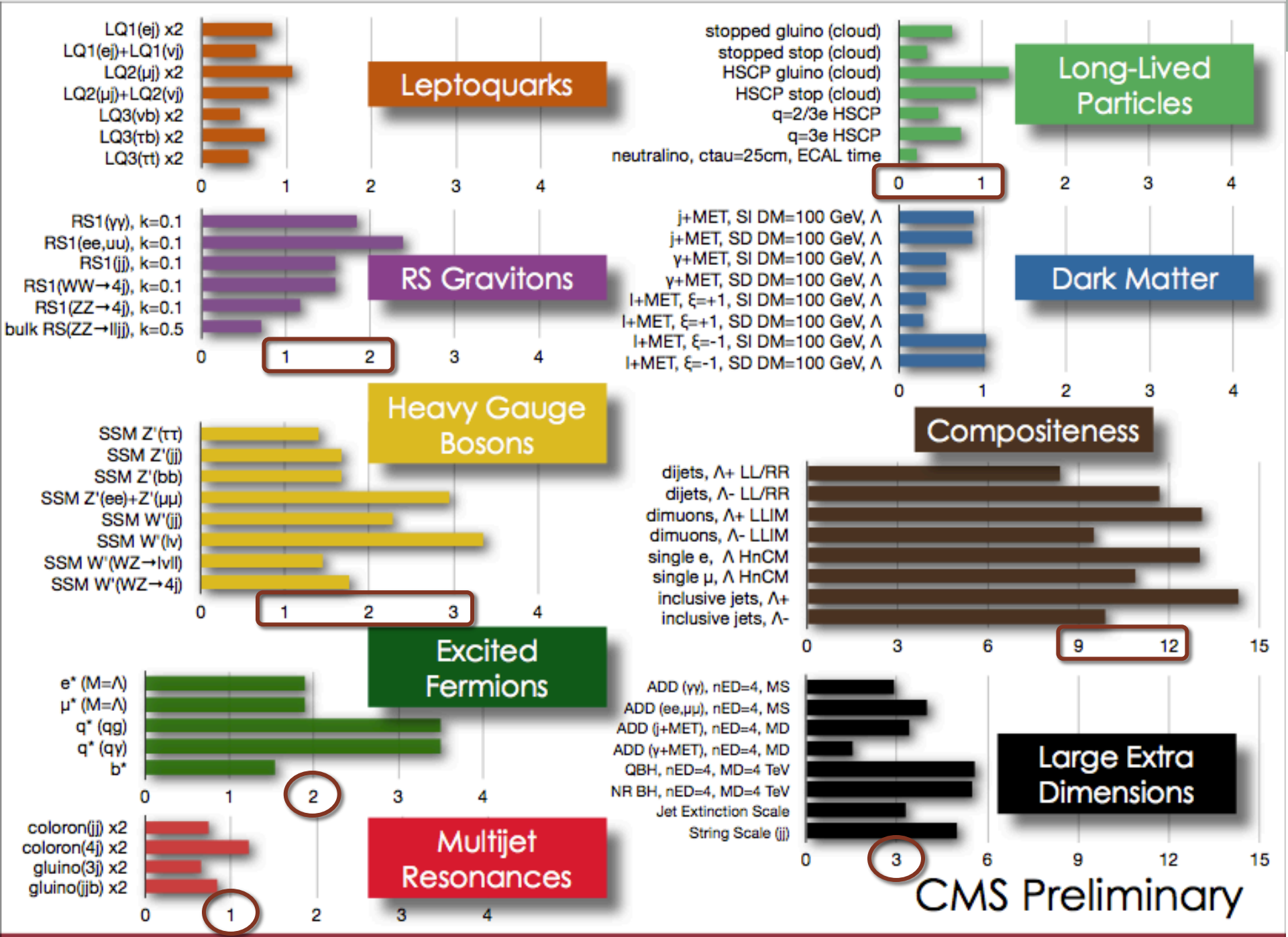
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8\ \text{TeV}$

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	M_S 4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\rightarrow \ell q$	$1\, e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	$2\, \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\, e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \rightarrow \ell\ell$	$2\, e, \mu$	–	–	20.3	G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \rightarrow ZZ \rightarrow \ell\ell qq/\ell\ell\ell\ell$	2 or 4 e, μ	2 j or –	–	1.0	G_{KK} mass 845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$	$2\, e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	$1\, e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\, e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\, \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2\, e, \mu$	–	–	20.3	Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z' \rightarrow \tau\tau$	$2\, \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \rightarrow \ell\nu$	$1\, e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3\, e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R \rightarrow t\bar{b}$	$1\, e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\, e, \mu$	–	–	5.0	Λ 13.9 TeV	$\eta_{LL} = -1$	1211.1150
	CI νutt	$2\, e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\, e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\, \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\, e, \mu, 1\, \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$	$1\, e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \rightarrow Wb + X$	$1\, e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB \rightarrow Zb + X$	$2\, e, \mu$	≥ 2 b	–	14.3	B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB \rightarrow Wt + X$	$2\, e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1\, \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	13.0	q^* mass 3.84 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2012-148
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2\, e, \mu, 1\, \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LRSM Majorana ν	$2\, e, \mu$	2 j	–	2.1	N^R mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\, e, \mu$	–	–	5.8	N^1 mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2\, e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \rightarrow \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

10^{-1} 1 10 **Mass scale [TeV]**

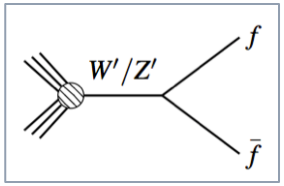
**Only a selection of the available mass limits on new states or phenomena is shown.*

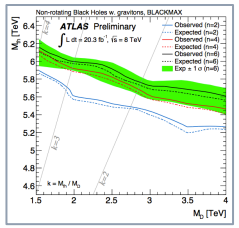

Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(vj)
LQ2(μj) x2
LQ2(μj)+LQ2(vj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
0 1 2 3 4
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
0 1 2 3 4
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→lljj), k=0.5
0 1 2 3 4
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
0 1 2 3 4
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 3 6 9 12 15
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 3 6 9 12 15
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4
CMS Preliminary

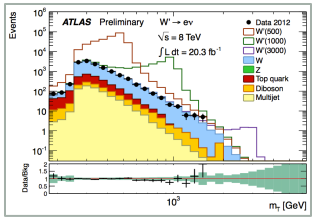
Conclusions

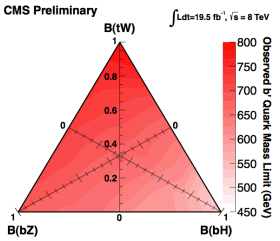
Non-susy BSM Physics

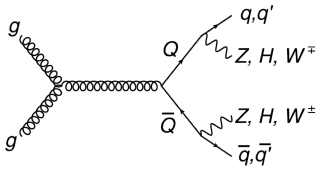
- Many searches at the LHC
  - **Heavy bosons**
    - Excluded below **few TeV**
  - **Heavy fermions**
    - Excluded below **~700 GeV**
  - **Other phenomena** at high energy scales
    - Excluded up to **tens of TeV**











Atlas References

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

CMS References

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Conclusions

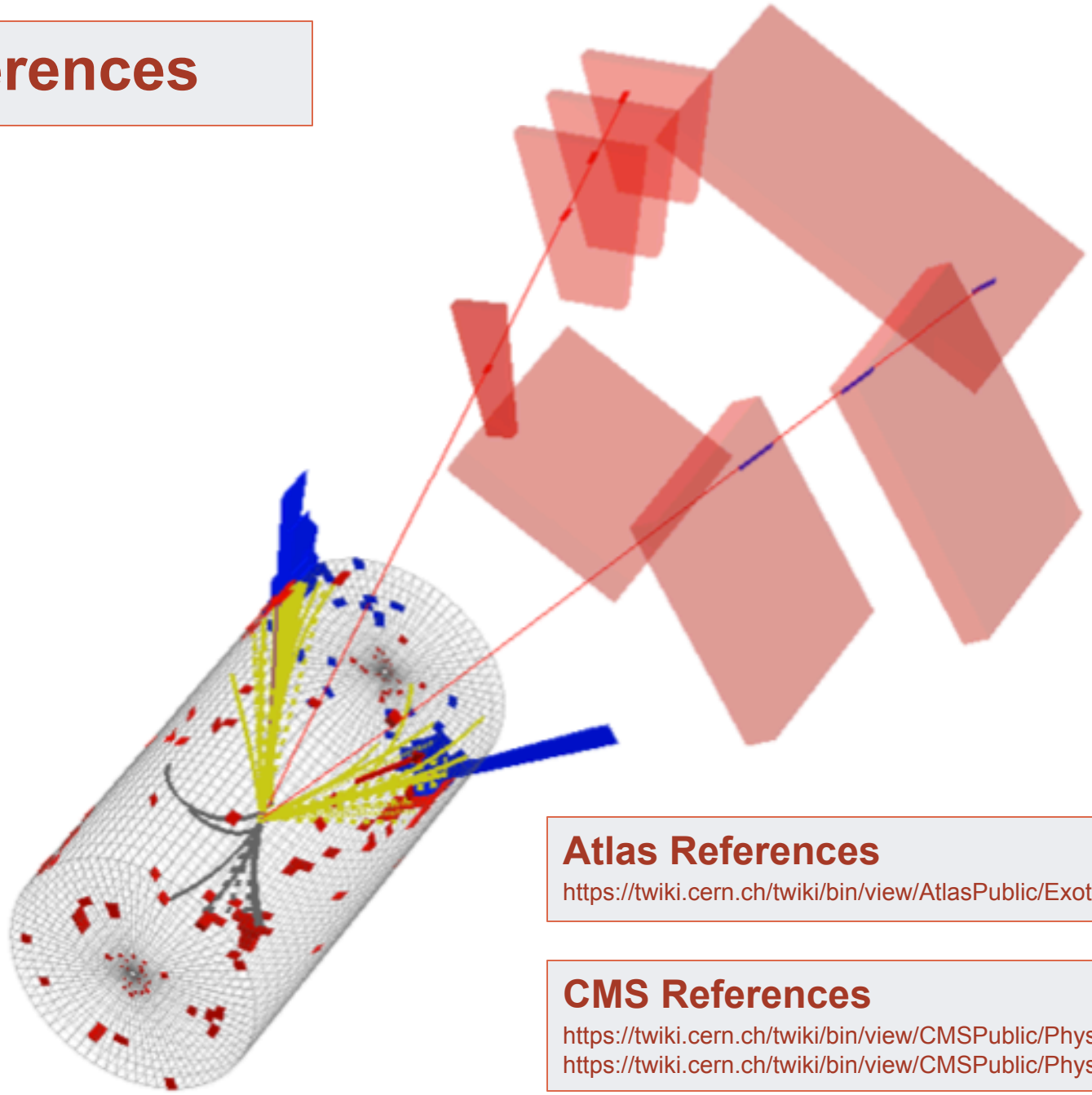
Non-susy BSM Physics

- Many searches at the LHC
  - **Heavy bosons**
    - Excluded below **few TeV**
  - **Heavy fermions**
    - Excluded below **~700 GeV**
  - **Other phenomena** at high energy scales
    - Excluded up to **tens of TeV**

- **Outlook**
  - Increased interest in **boosted topologies**
  - **Broader range** of models, incl. e.g. low mass
  - Make results accessible for **reinterpretation**


Thank you for your attention
and enjoy Amsterdam!

References



Atlas References

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

CMS References

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

BACKUP

Reach in Run 2 and Beyond

While we complete the Run 1 program, eagerly awaiting data at higher $\sqrt{s}$!

- Searches for high-mass objects will be more sensitive with only a few fb^{-1}
- New challenges to meet with higher energy, luminosity:
  - Increased emphasis on boosted topologies
  - Sensitivity to rare SM processes as backgrounds

Expected Mass Limits [TeV] from the Collider Reach Tool [Salam, Weiler]

- Extrapolations using parton luminosities
- Assume sensitivity scales directly with signal yield

	8 TeV	14 TeV			
	20 fb^{-1}	3 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Vector-like quarks	0.7	0.8	1.2	1.7	2.2
$W' \to VV$	1.5	1.3	2.3	3.3	4.4
$W' \to ff$	2.0	2.1	3.2	4.2	5.4
$W' \to \ell\nu$	3.2	4.1	5.2	6.3	7.3
Excited quarks	3.2	4.1	5.2	6.3	7.3
Black Holes	5.0	8.2	8.5	9.0	10