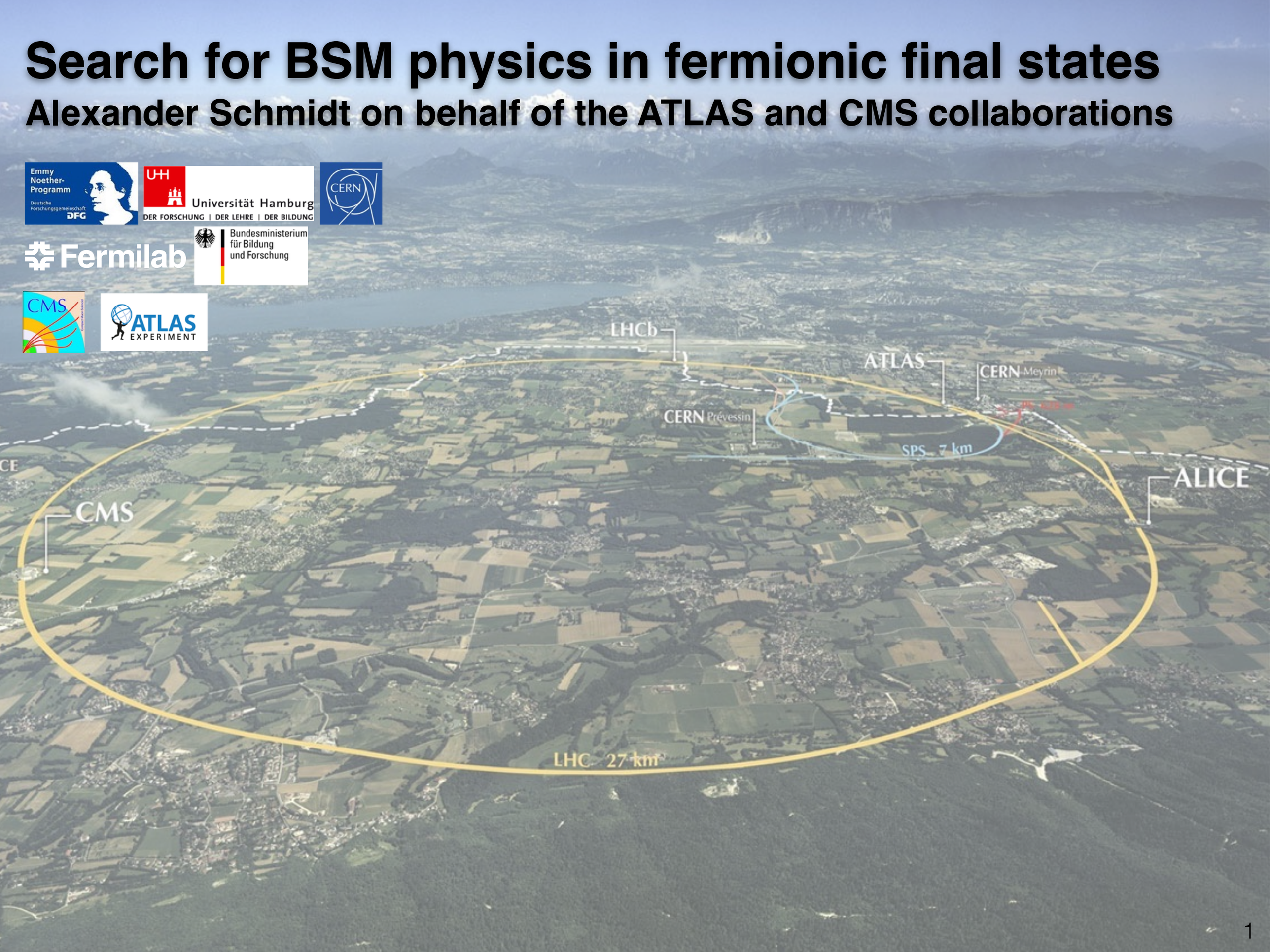
Search for BSM physics in fermionic final states

Alexander Schmidt on behalf of the ATLAS and CMS collaborations



Search for BSM physics in fermionic final states

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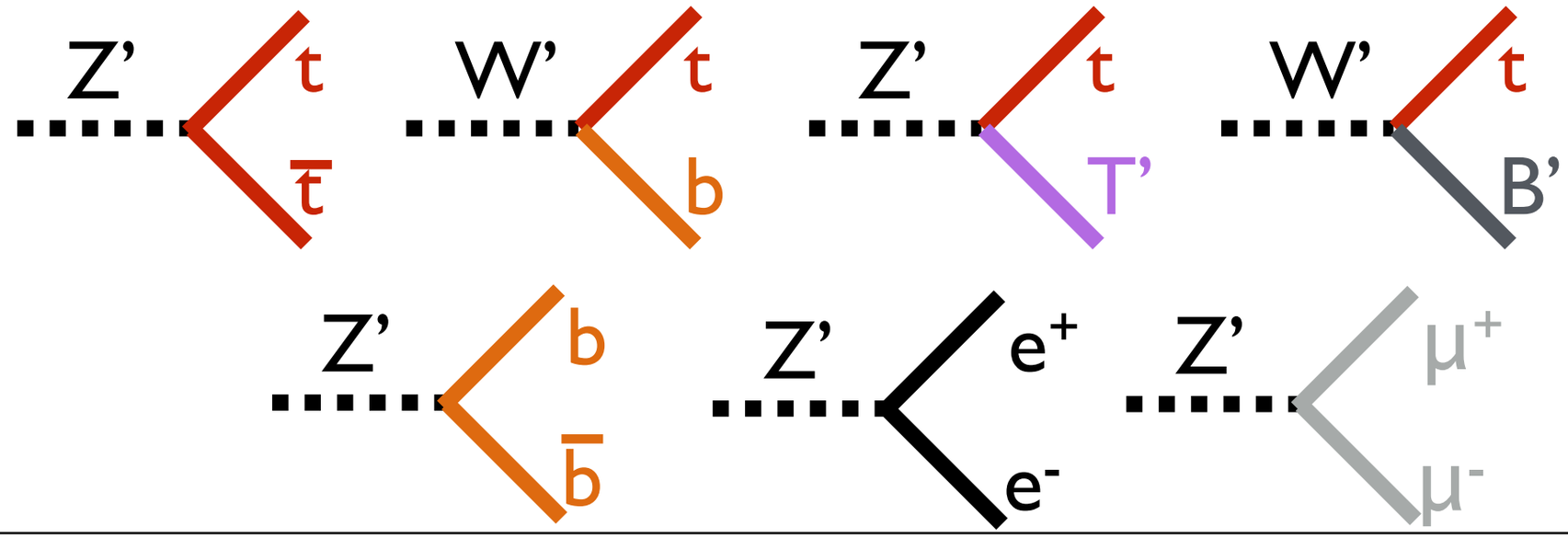
Vauxhall Astra BSM Diecast Model Car by Vanguards

(click image below for more detail)

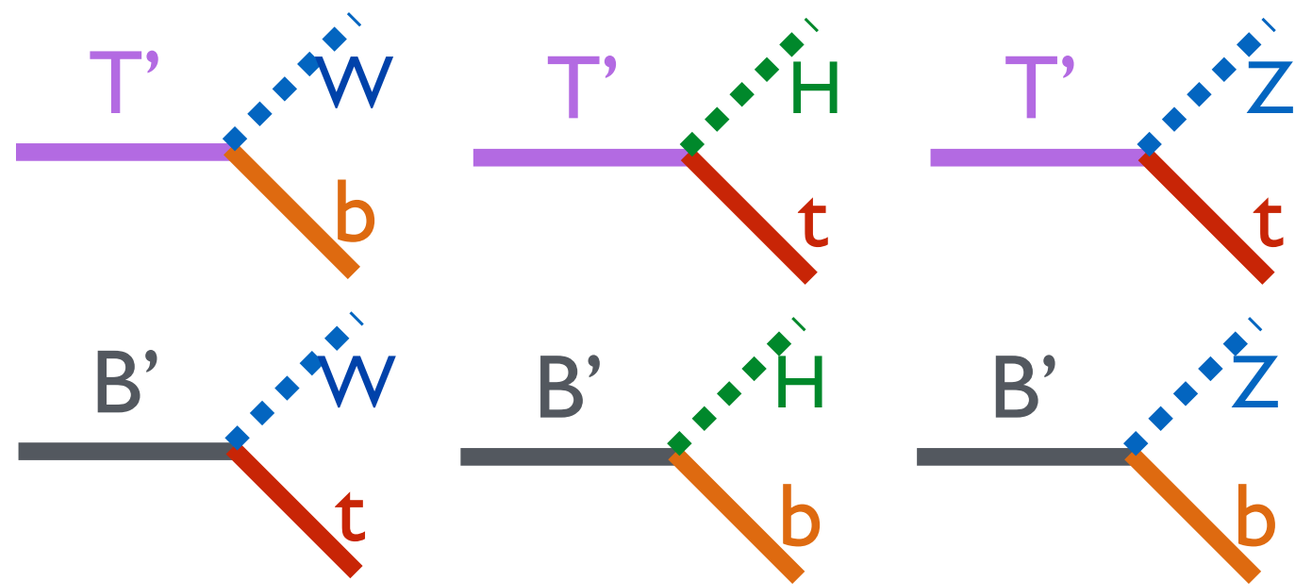
Price	**Currently Unavailable** (Standard UK delivery from £2.50)
Made By	Vanguards
Stock Code	VA09408
Stock Level	Sold Out (sorry, this item is no longer available)
Scale	1:43
Size	10cm long (3.9 inches)
Colour	Silver
Working Features	wheels
Free Number Plate	Sorry, free number plates not available on this item
Despatch	This item is sold out

typical signatures

fermion resonances

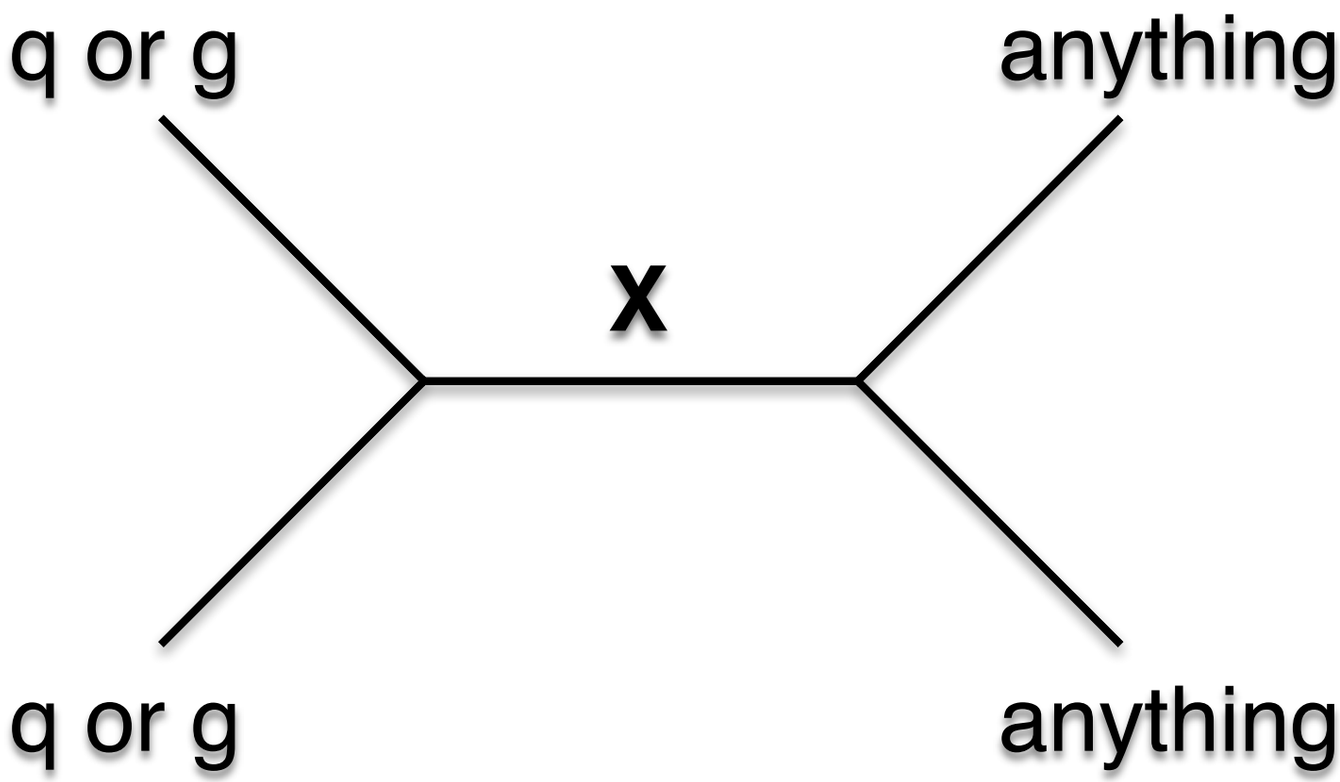


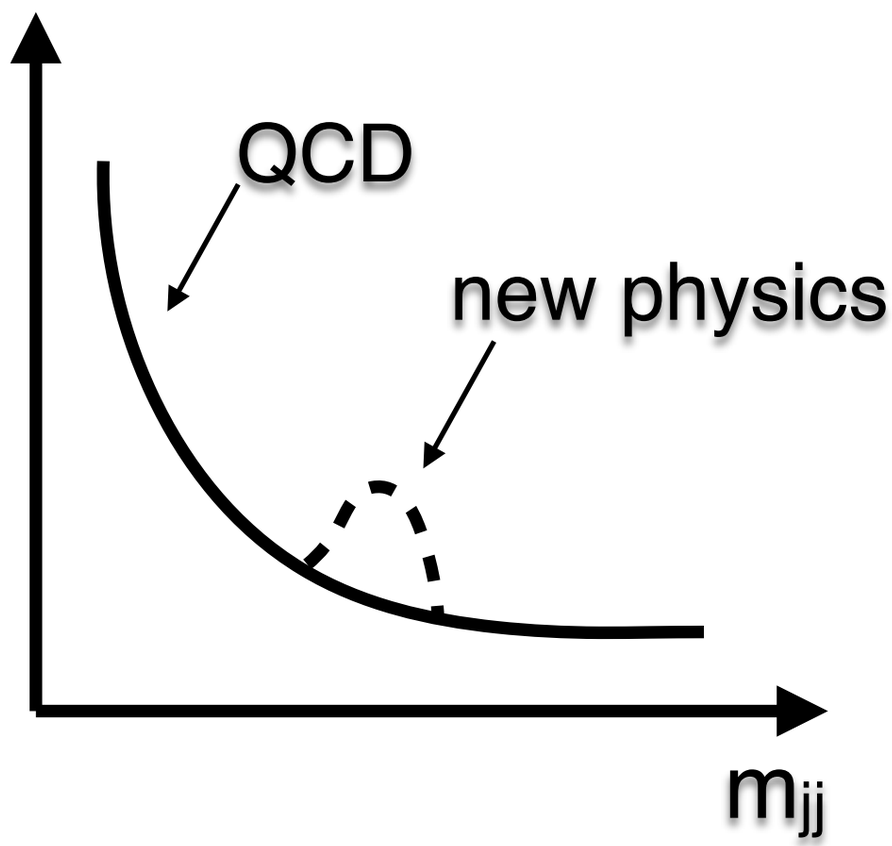
vector-like quarks



excited quarks, leptoquarks

search for exotic resonances



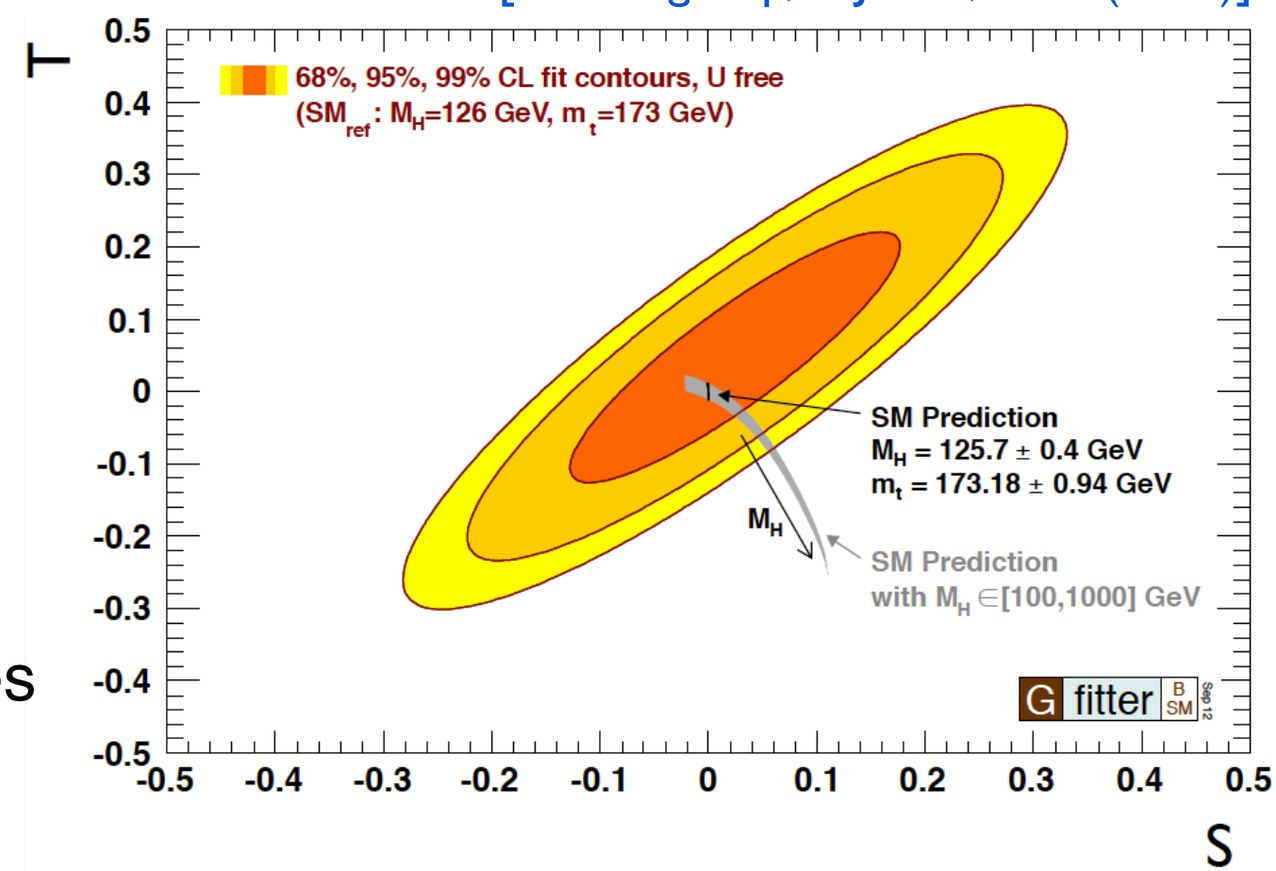


beyond the standard model

non-SUSY BSM

- similar motivations as SUSY
- examples:
  - extra dimensions: warped extra dimension models where fermions propagate in the bulk
  - composite Higgs: Heavy Vector Triplet model, with new W'±, Z' states
  - contributions to S and T parameters must be small

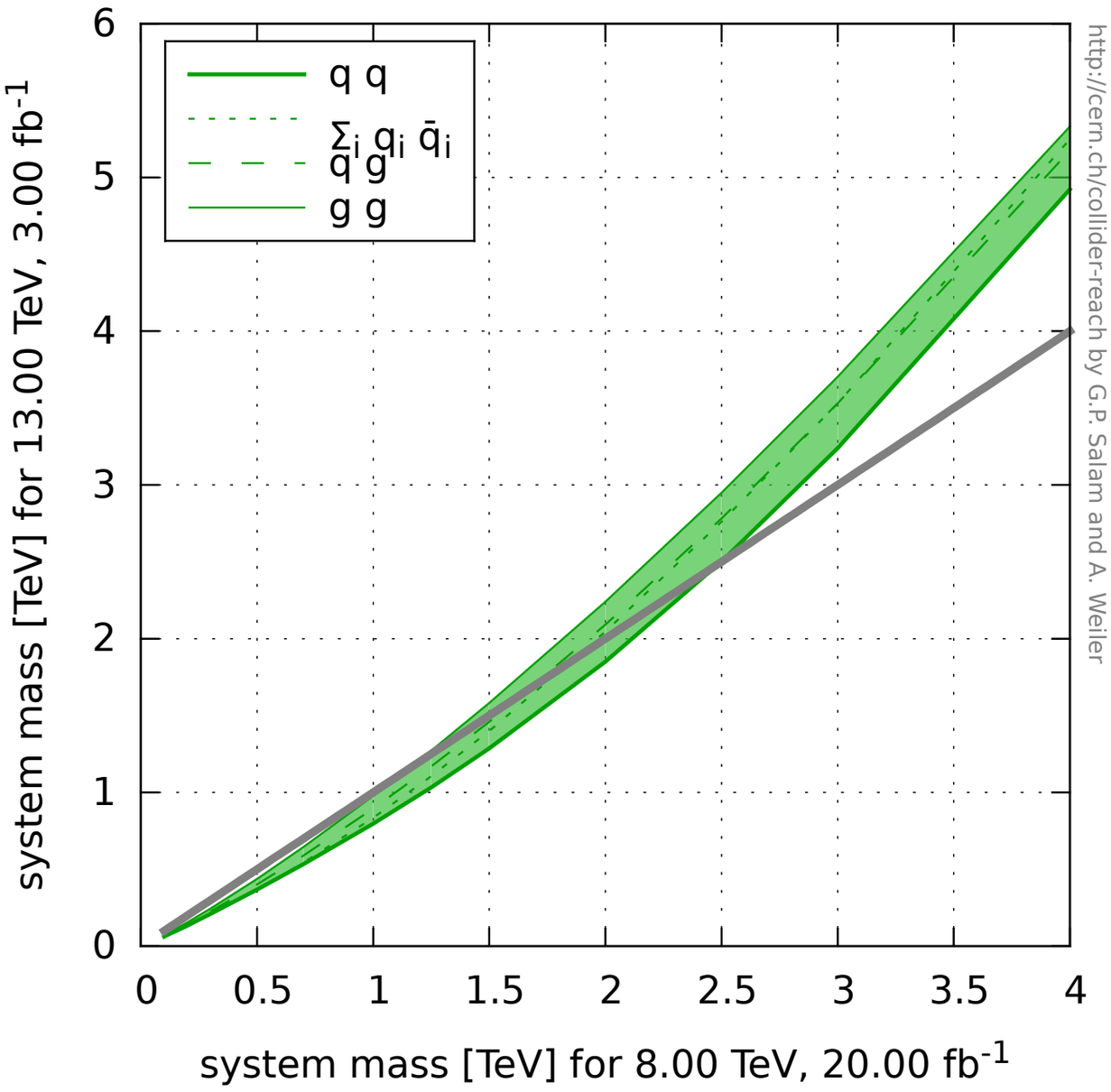
[Gfitter group, EPJC 72, 2205 (2012)]



→high resonance masses

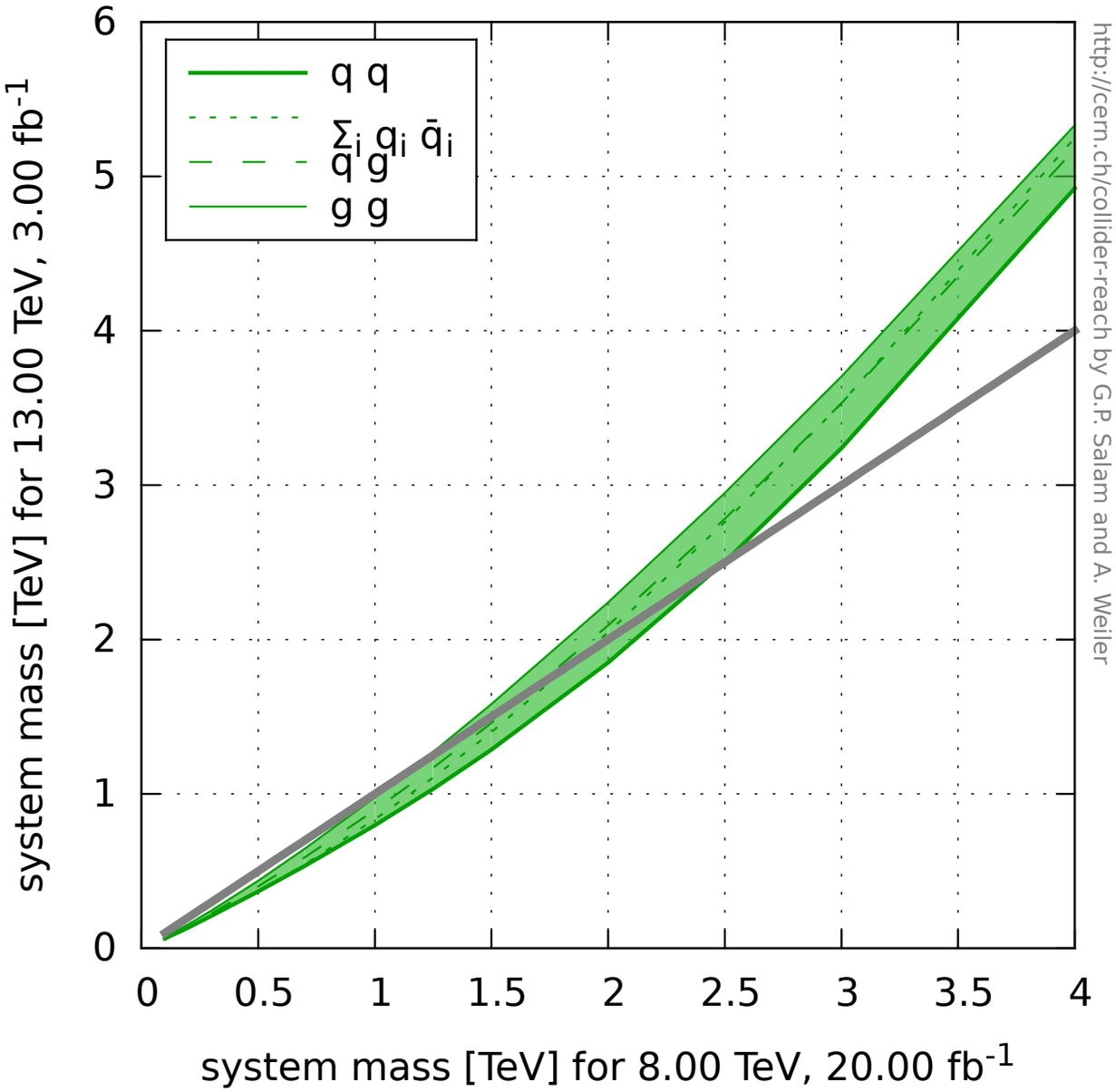
collider reach

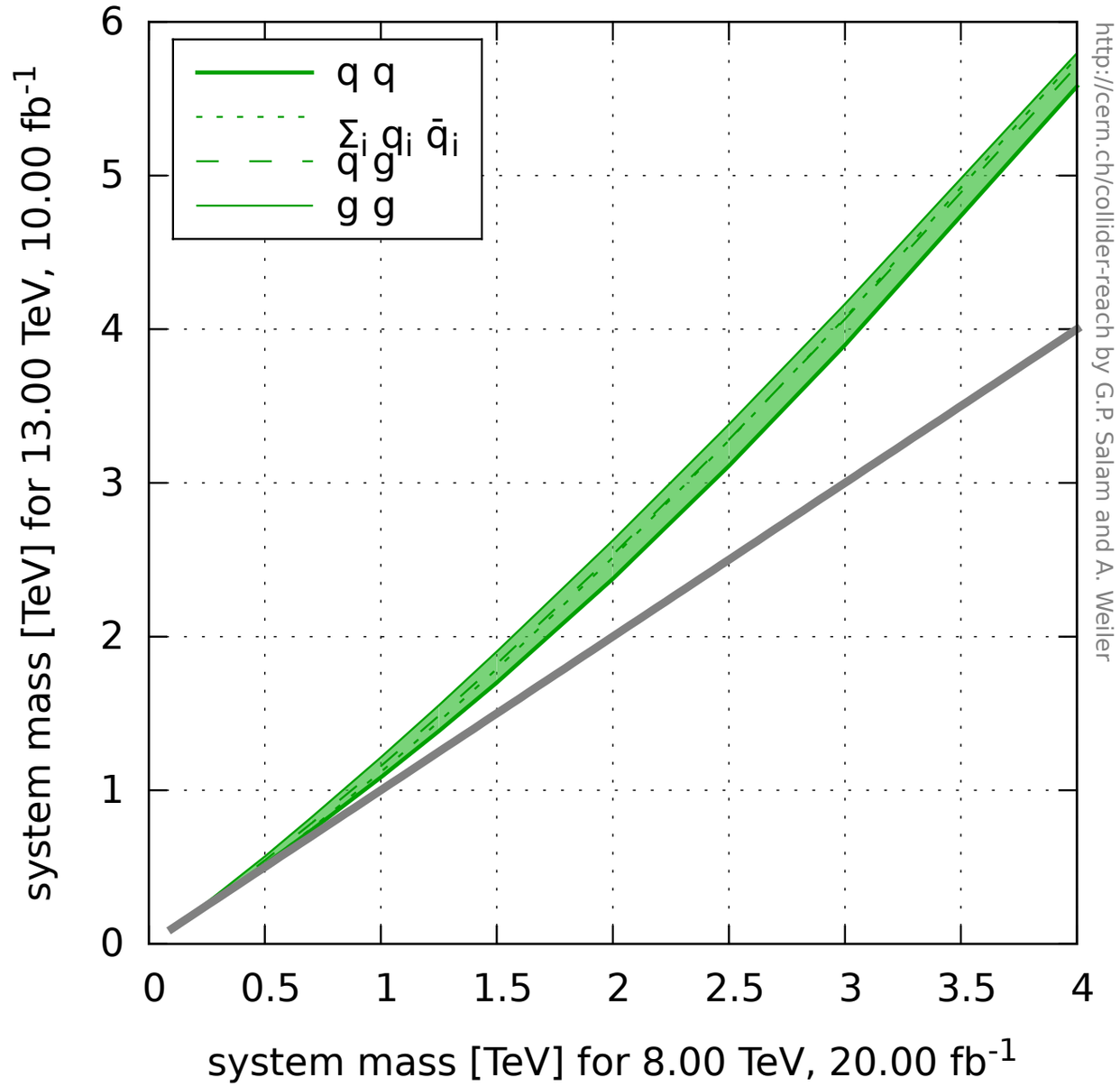
parton luminosity scaling:



collider reach

parton luminosity scaling:



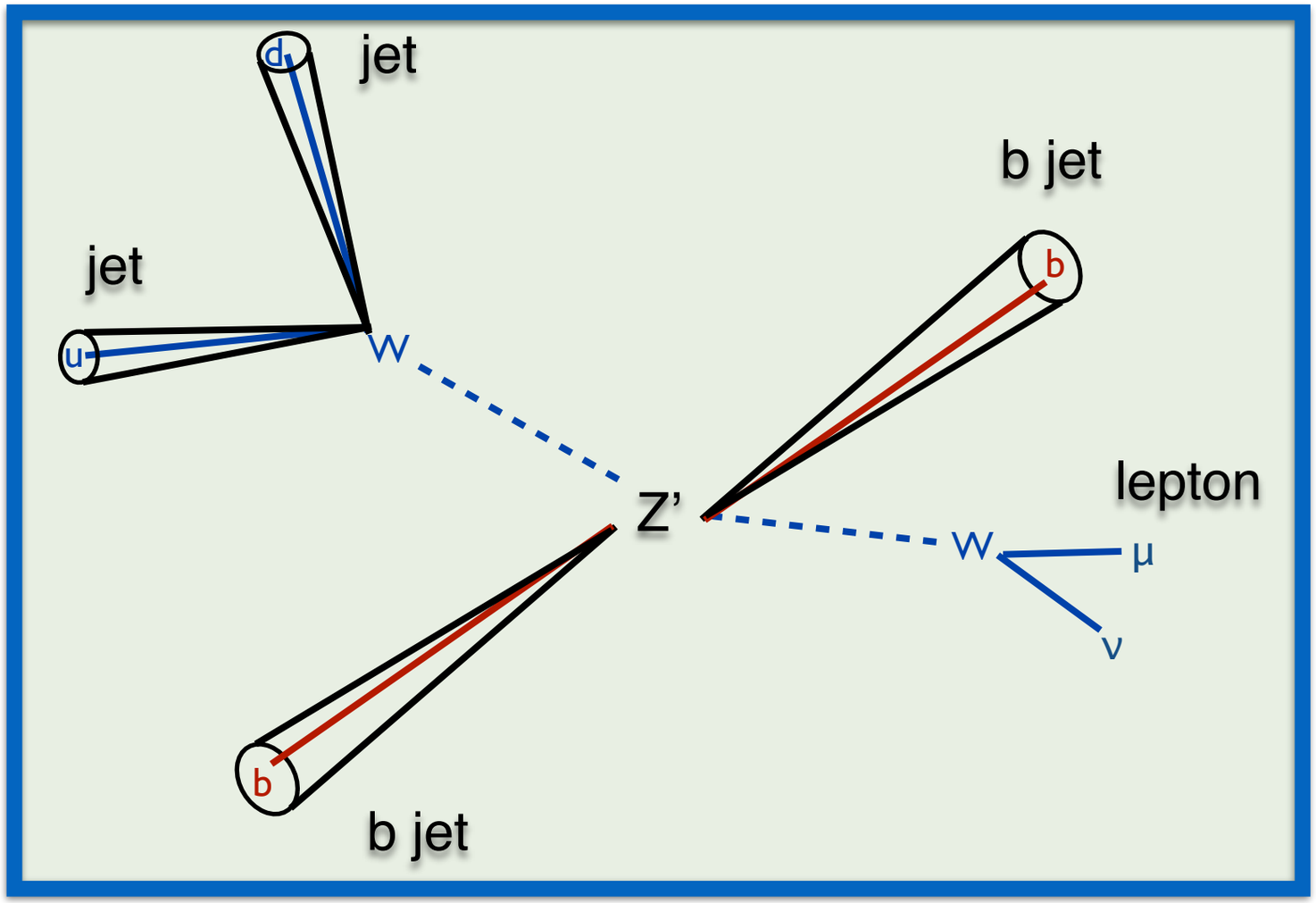


- we do better at high masses

topology of a tt resonance

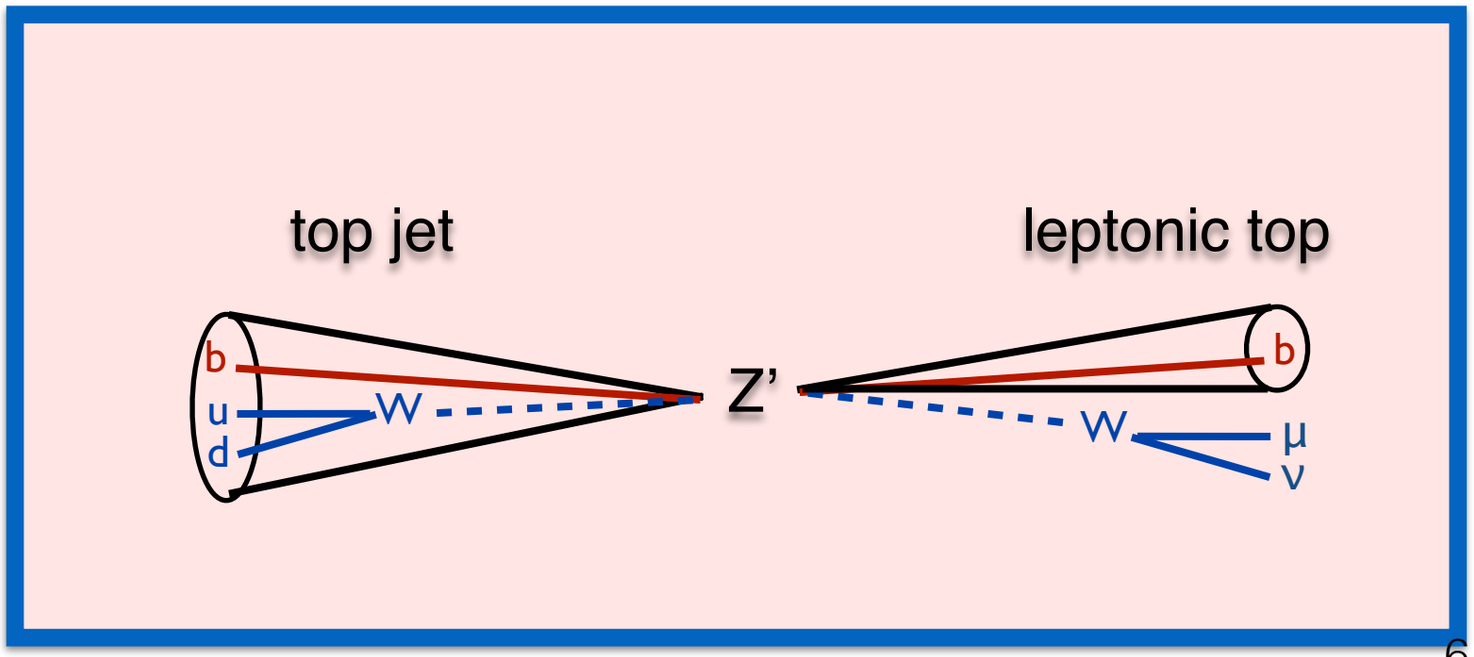
light resonances (M ~ 500 GeV):

- “classical” event topology



heavy resonances (M ~2 TeV):

- decay products p_T~1TeV
- large γ factor (>5 -10)
- jets overlap and merge
- special reconstruction techniques needed !

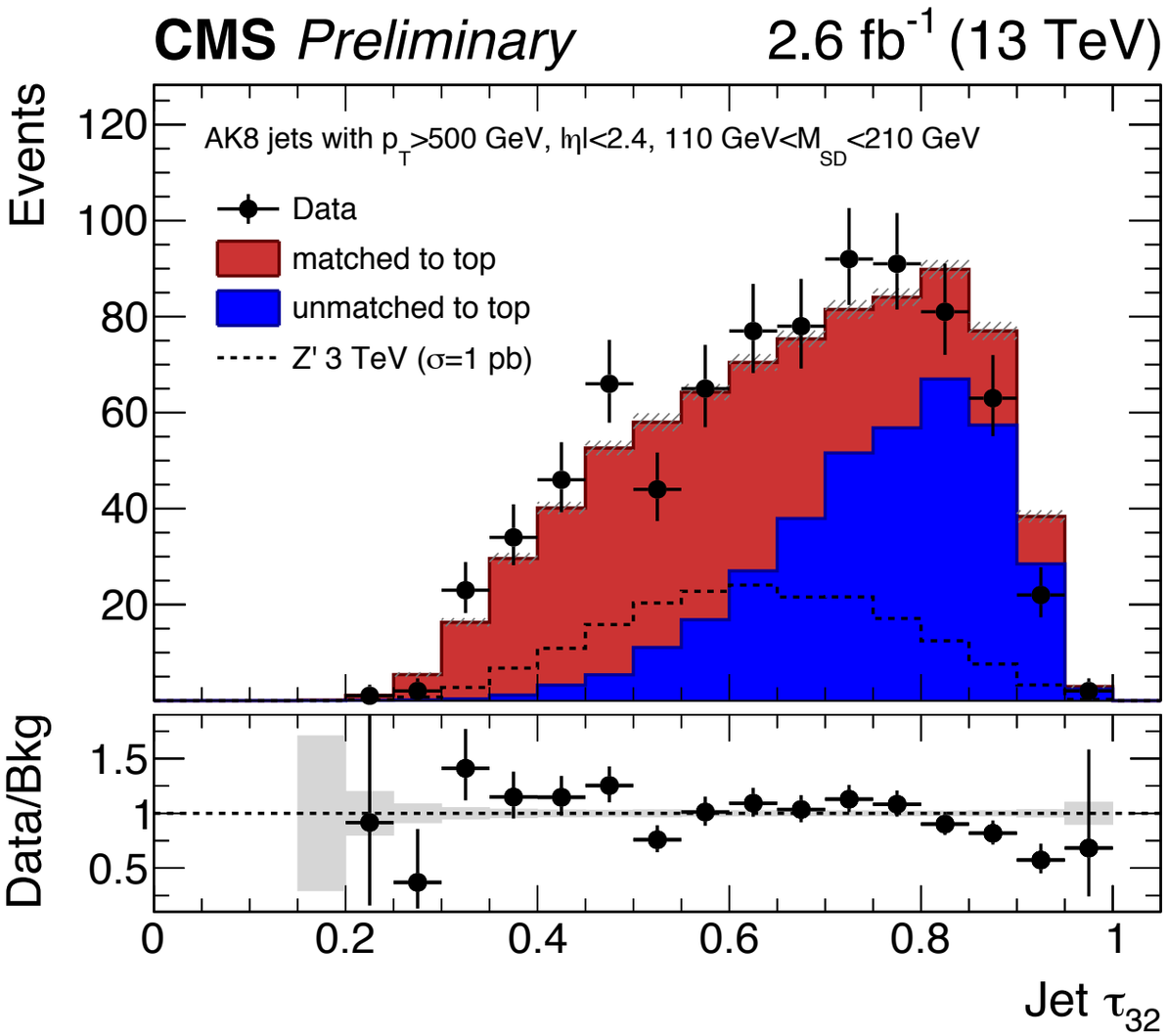


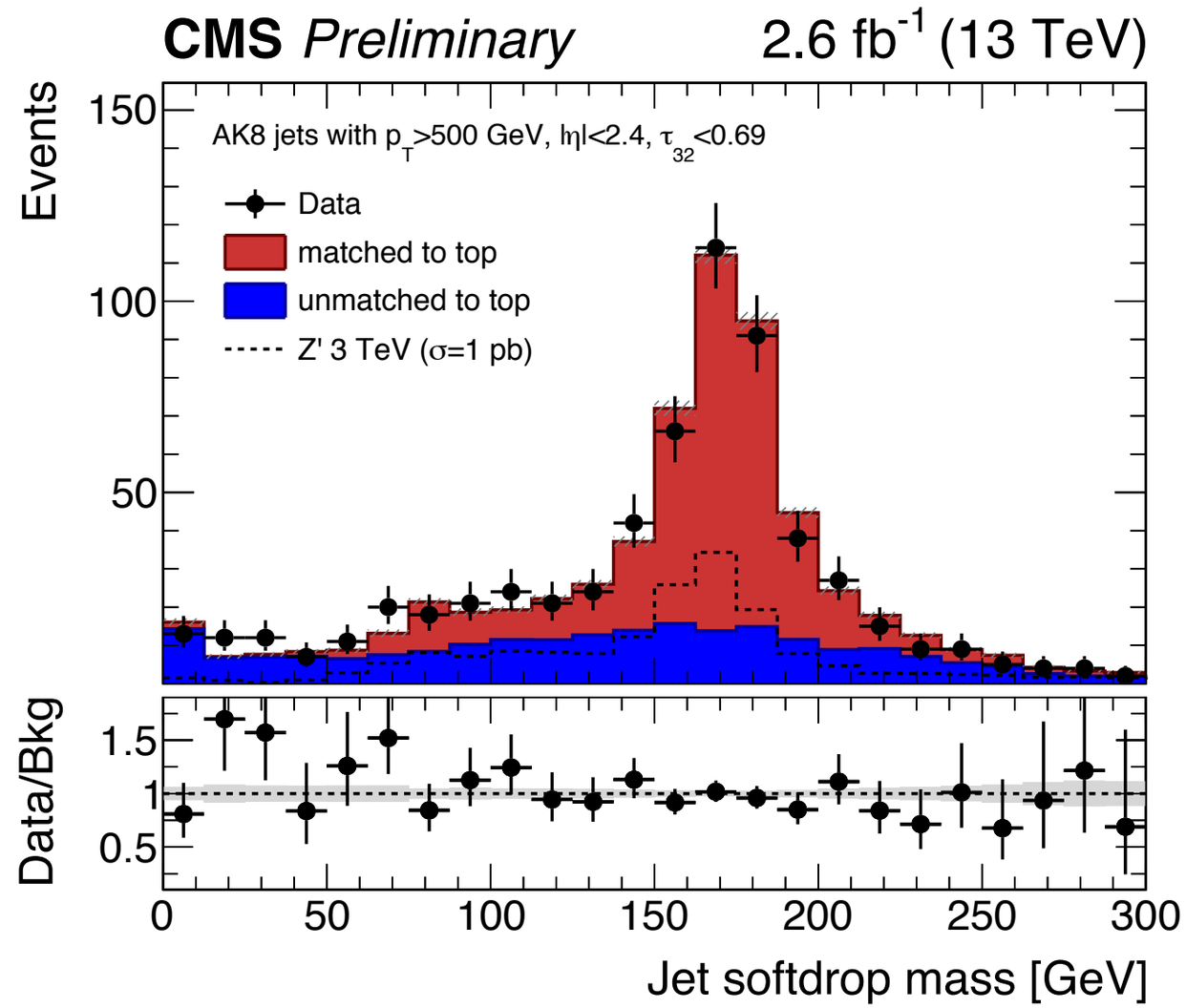
boosted t tagging

[CMS-PAS-B2G-15-002]

modeling of boosted variables at 13 TeV:

- semi-leptonic top selection





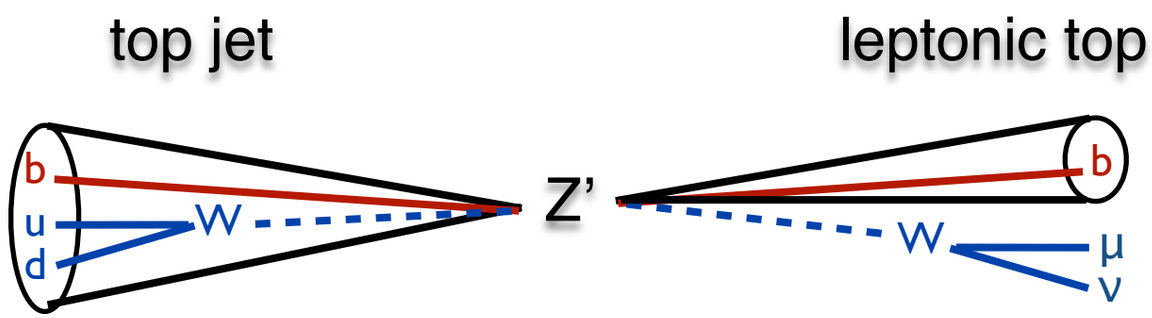
- after initial difficulties at the start of Run II, **things look very good now**

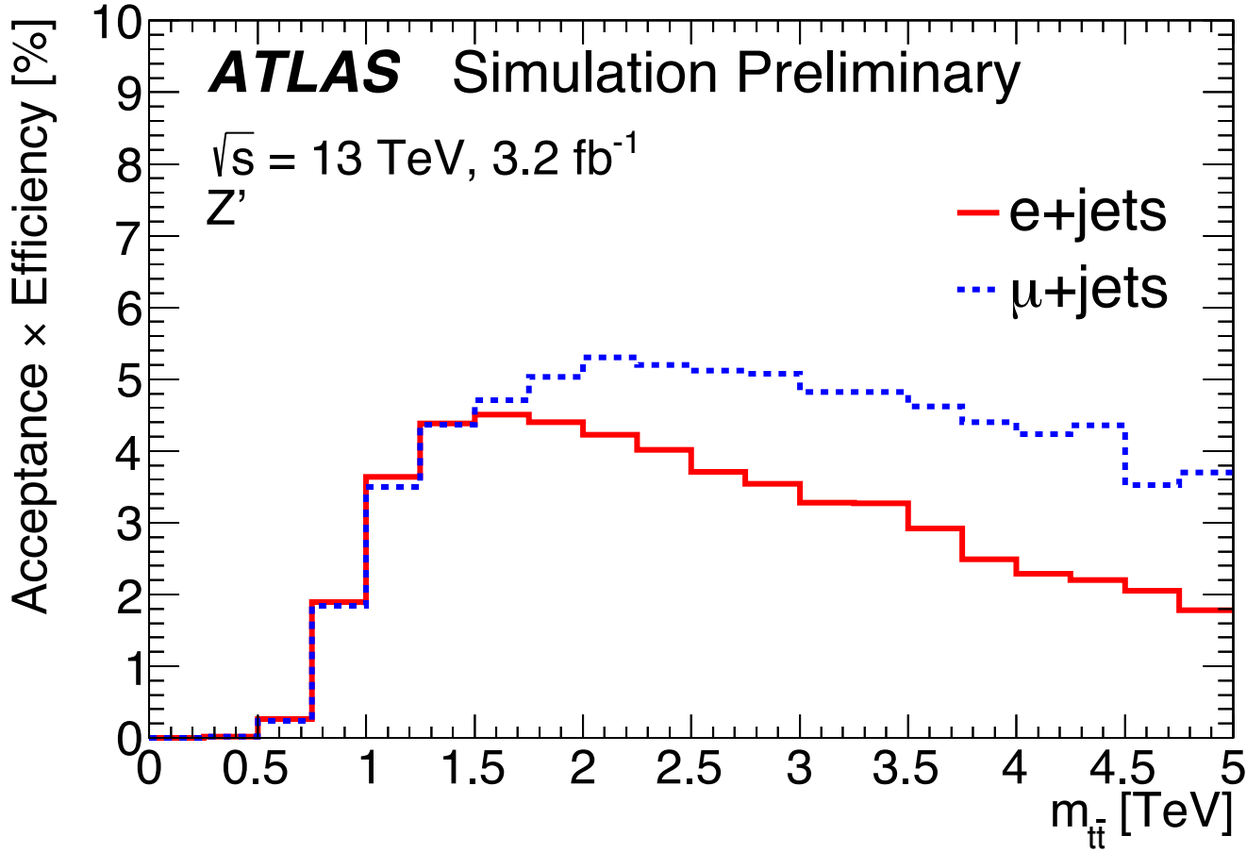
tt resonances: semi-leptonic

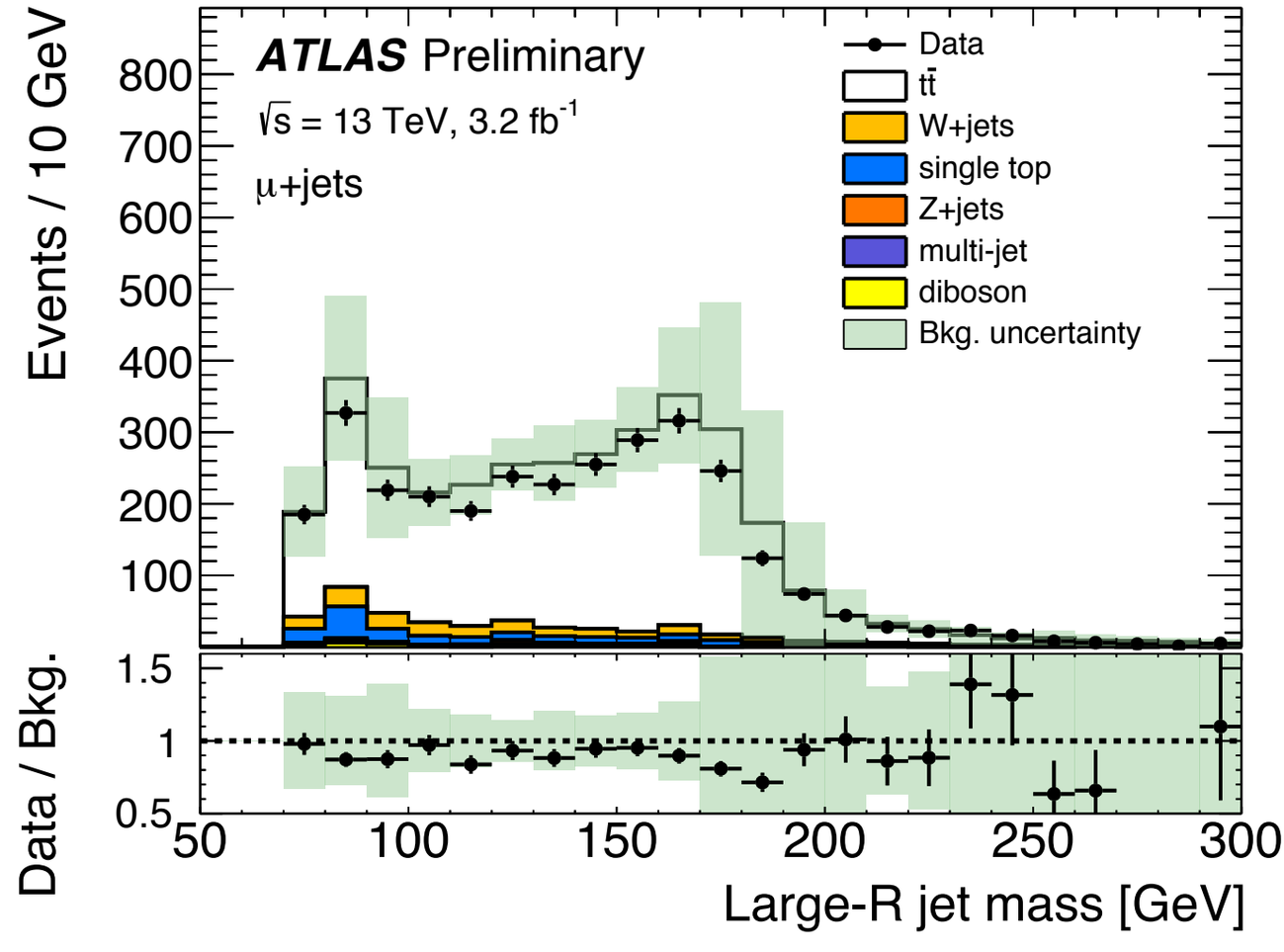
[ATLAS-CONF-2016-014]

event selection

- three types of jets:
  - small-R jets (R=0.4)
  - large-R jets (R=1) for top-tagging
  - track jets (R=0.2) for b-tagging
- p_T dependent lepton isolation





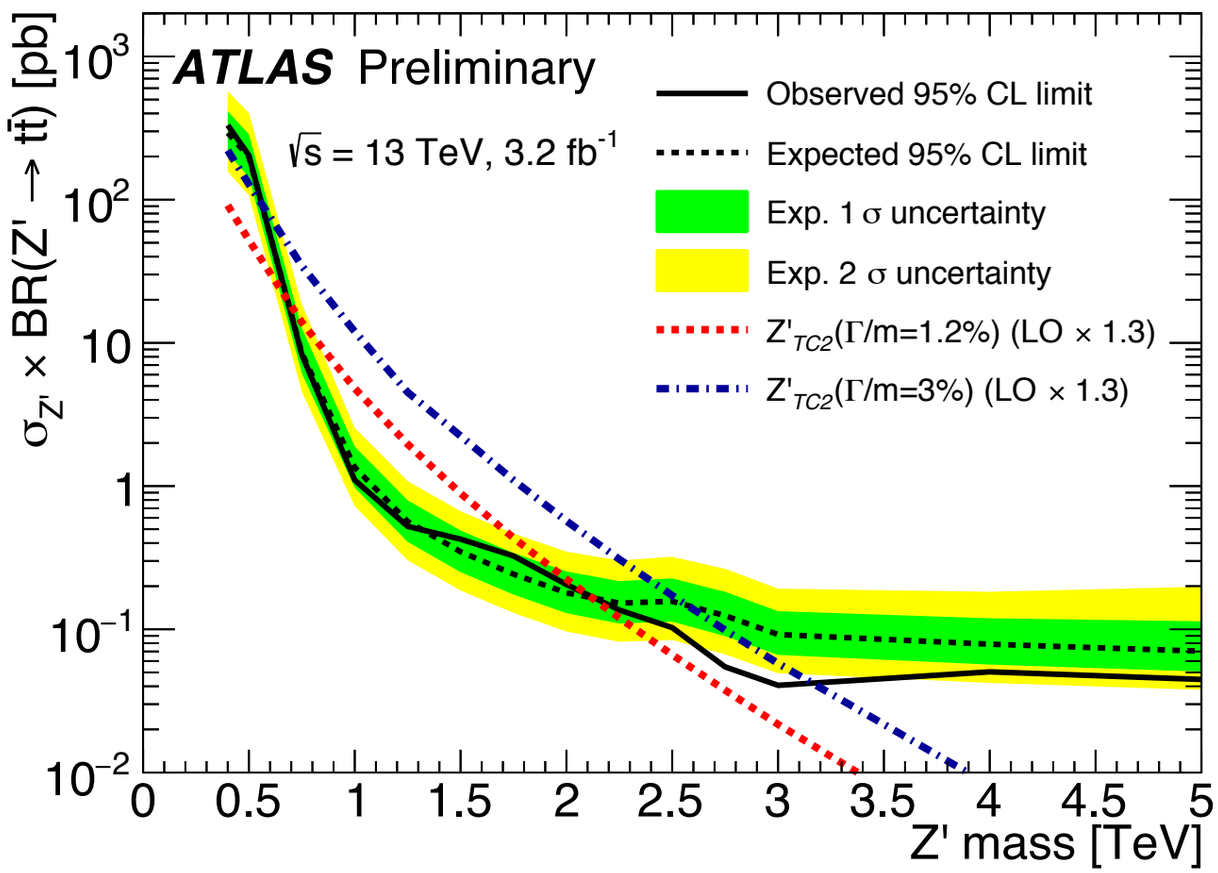


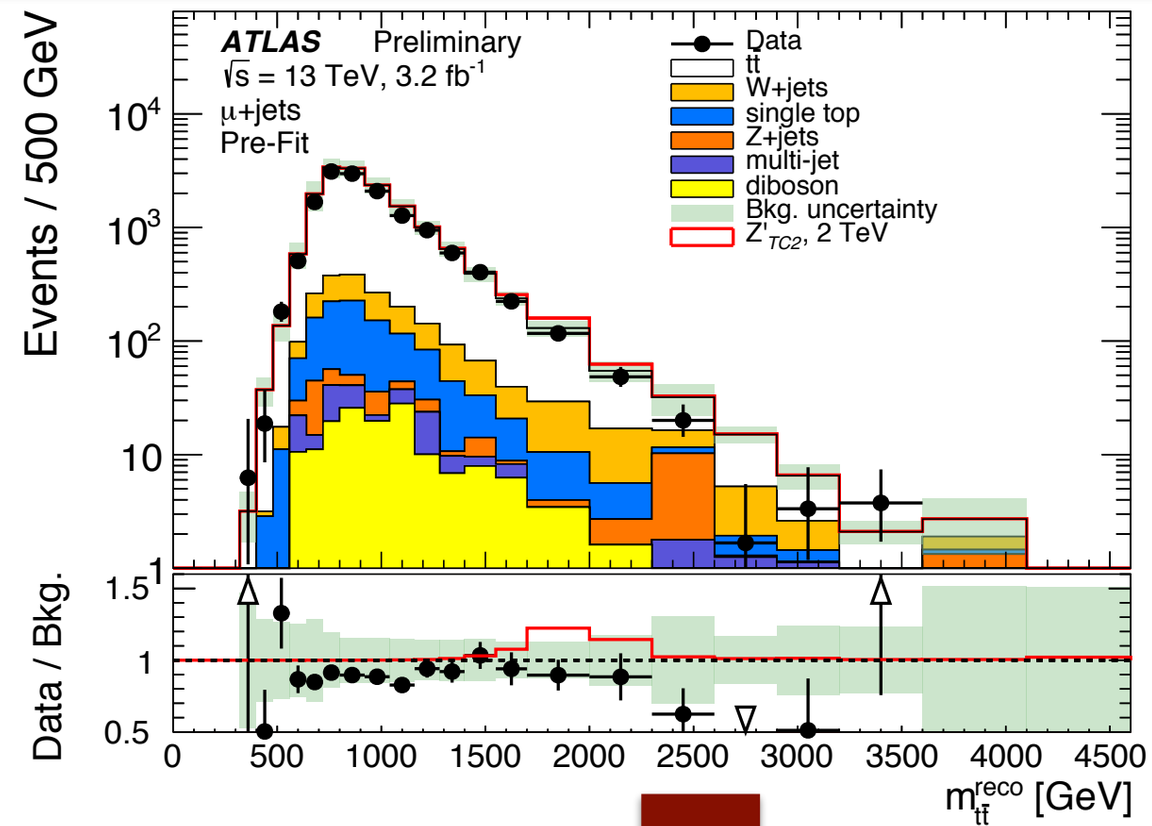
tt resonances: semi-leptonic

[ATLAS-CONF-2016-014]

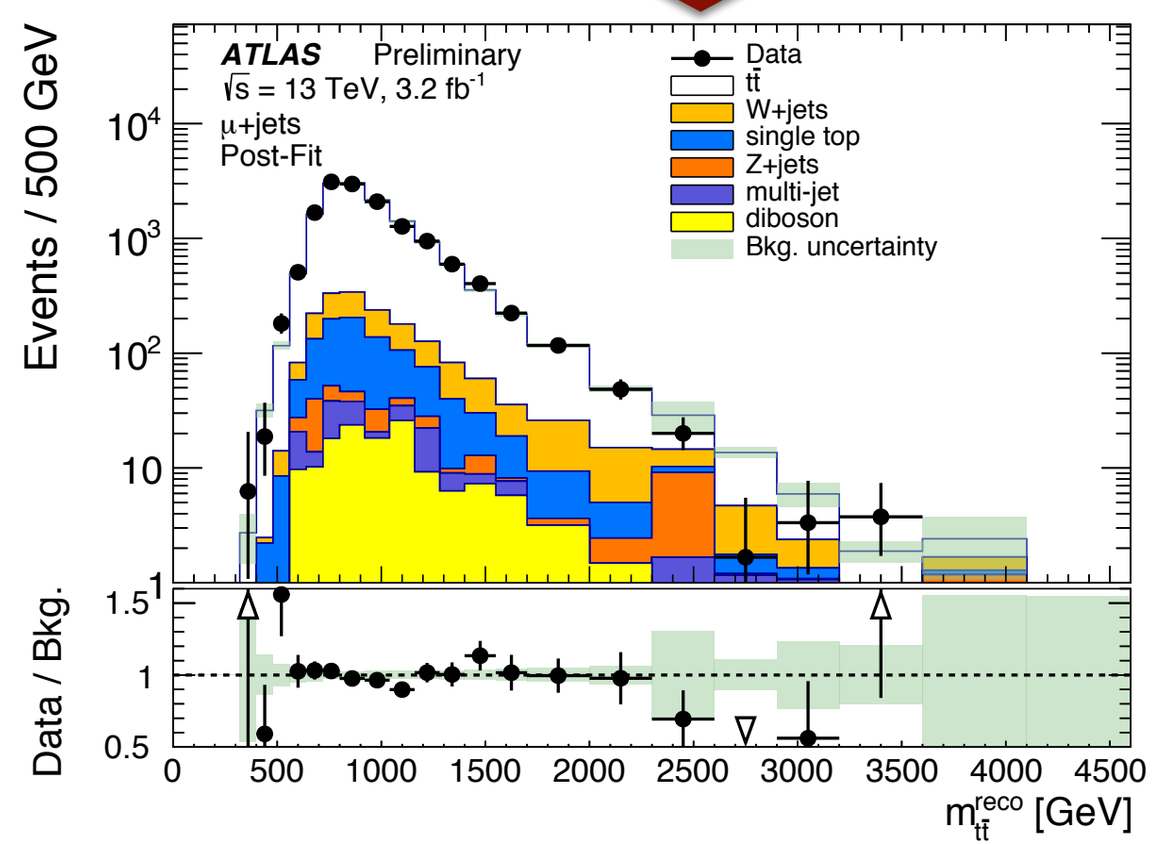
results:

- fit m_{tt} distribution to data





fit



benchmark Z' model:

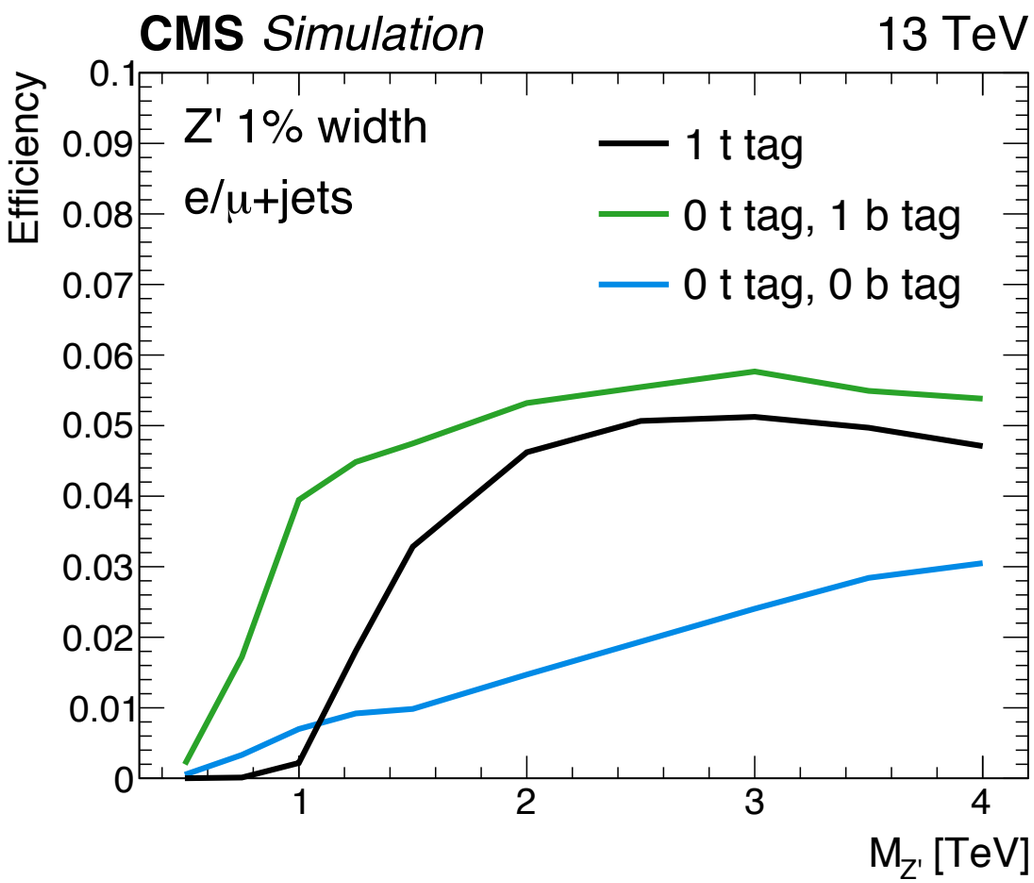
- narrow width 1.2%:
  excl 0.7 TeV < m < 2 TeV (Run 1: <1.8TeV)
- width 3%:
  excl 0.7 TeV < m < 3.2 TeV (Run 1: <2.3TeV)

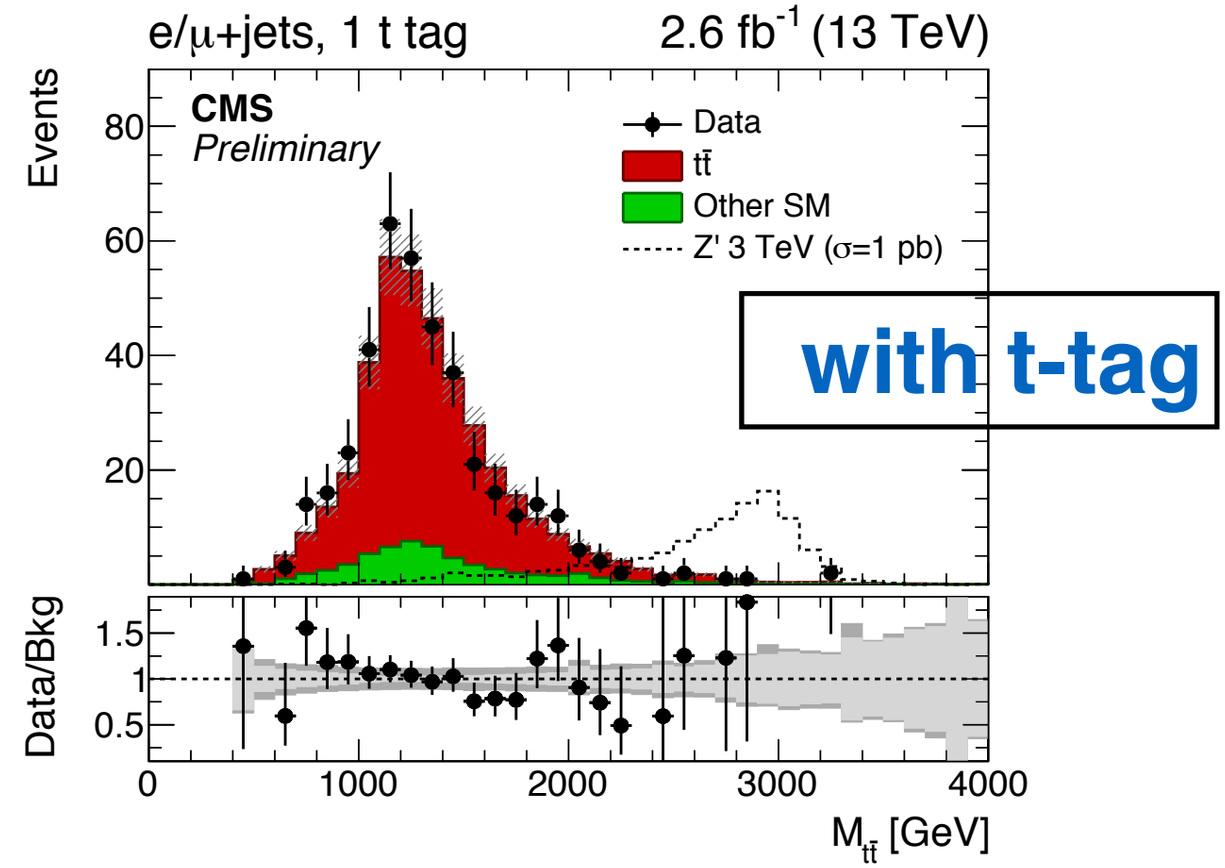
tt resonances: semi-leptonic

[CMS-PAS-B2G-15-002]

event categorisation:

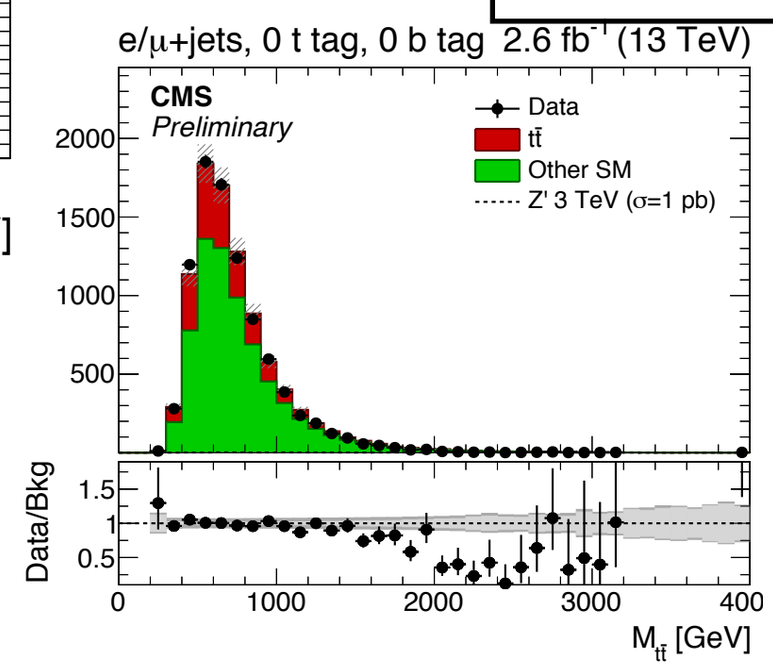
- t-tagging, b-tagging

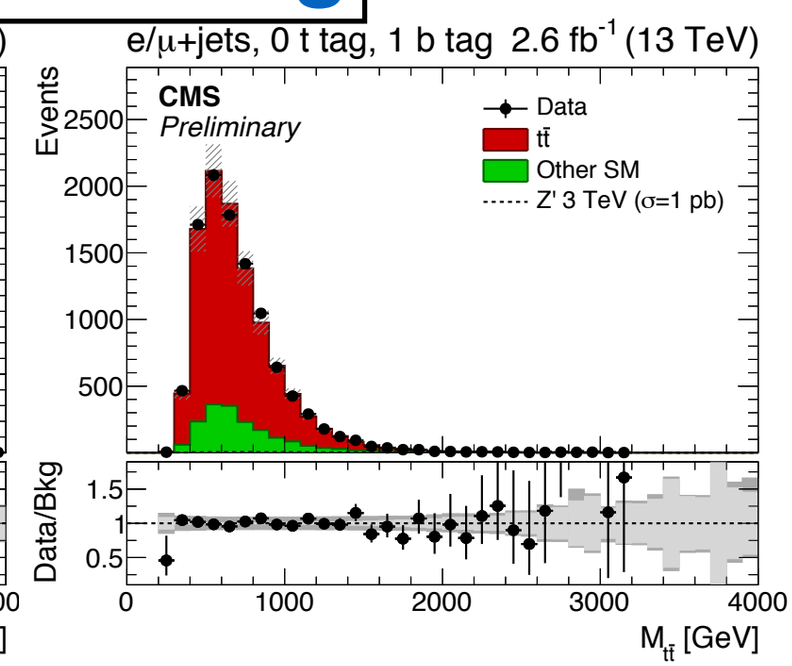




with t-tag

without t-tag



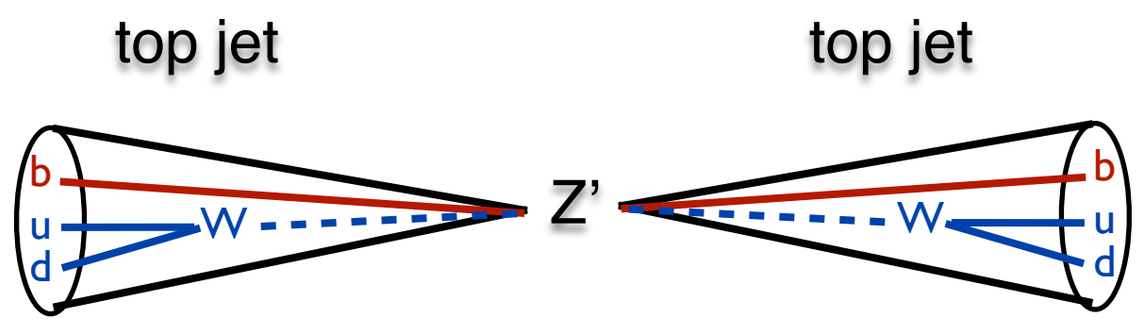


- similar limits as ATLAS

tt resonances: hadronic

[CMS-PAS-B2G-15-003]

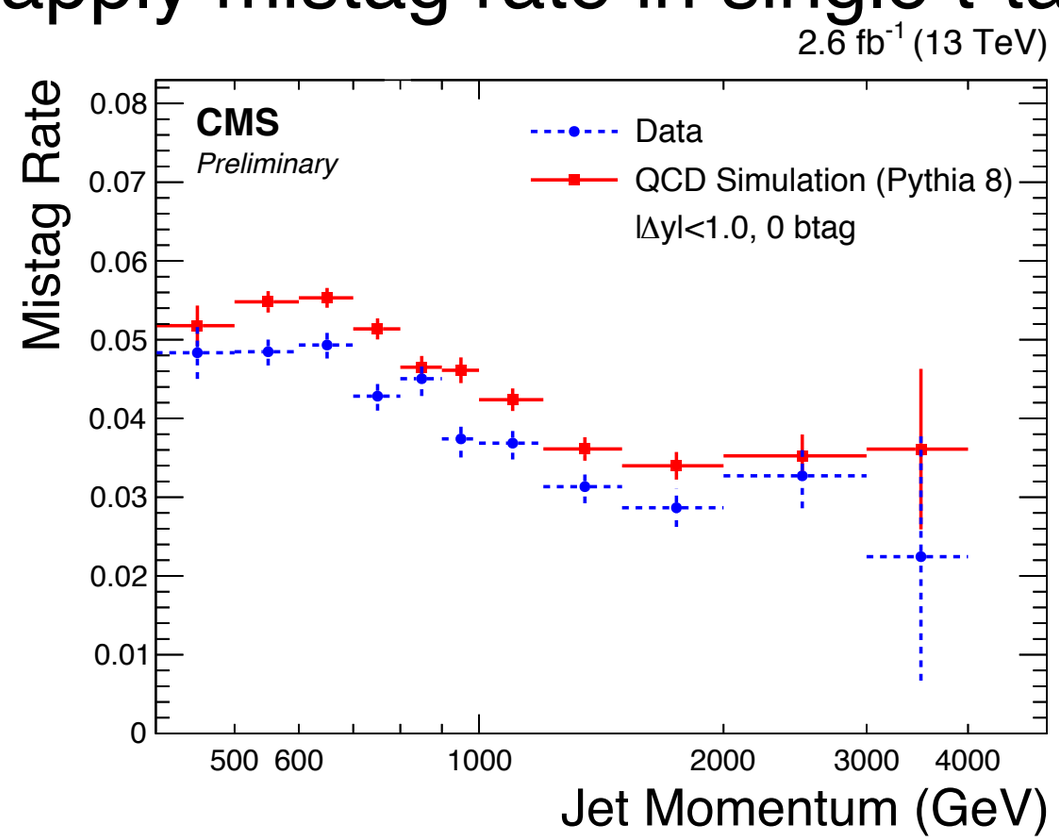
- top tagging
- subjet b-tagging

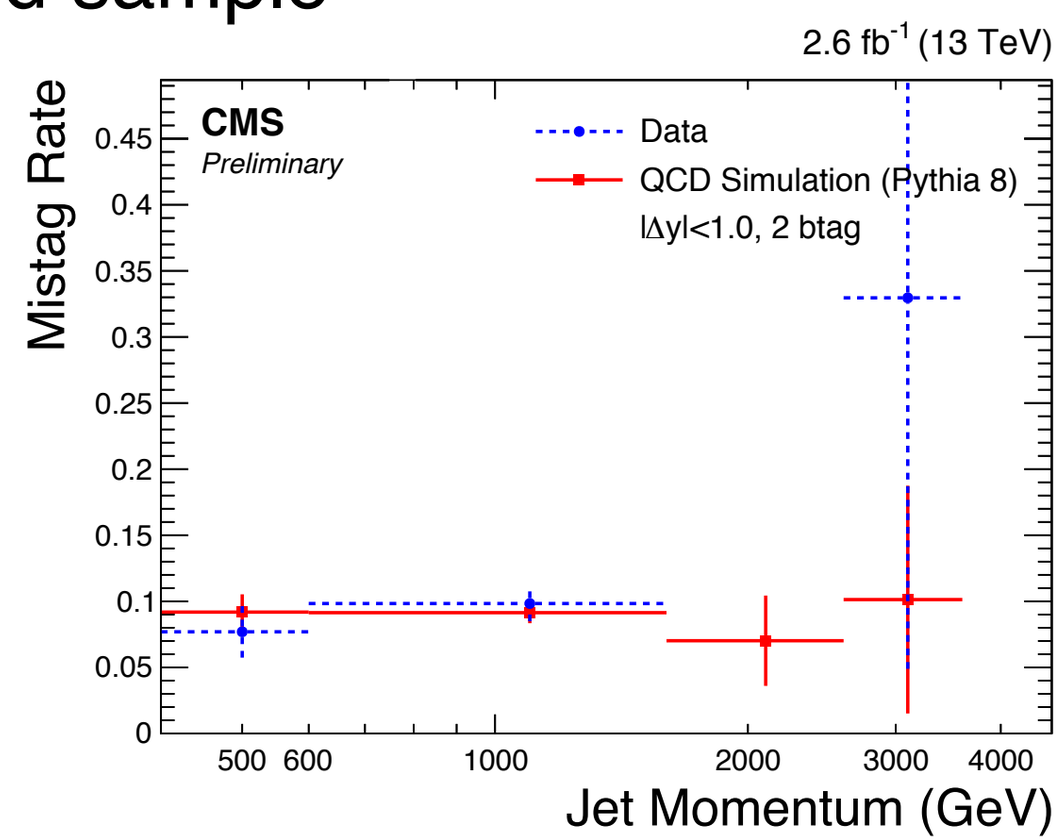


NEW

background from data:

- invert substructure selection criterion on **one** jet (QCD region)
- measure mistagging probability of **other** jet
- parameterised in bins of b-tag and p_T
- apply mistag rate in single t-tagged sample

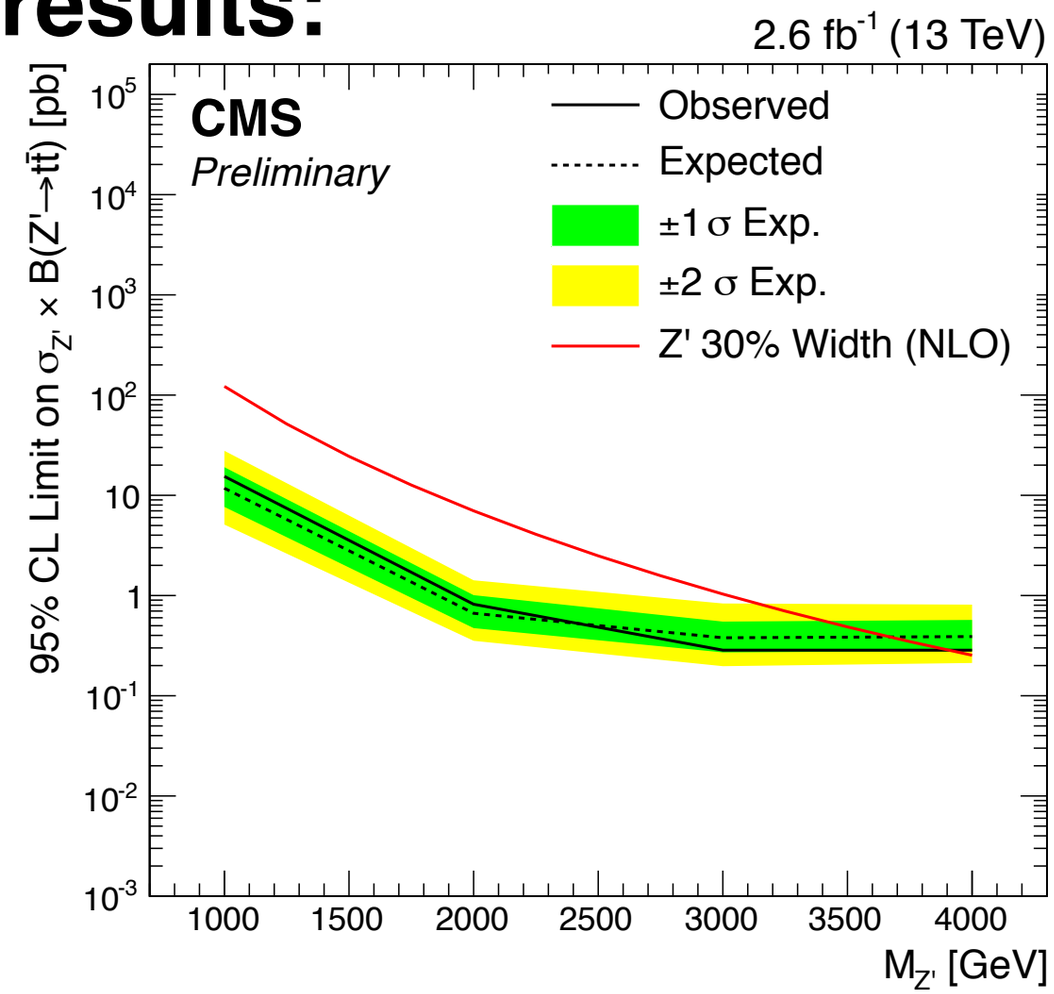


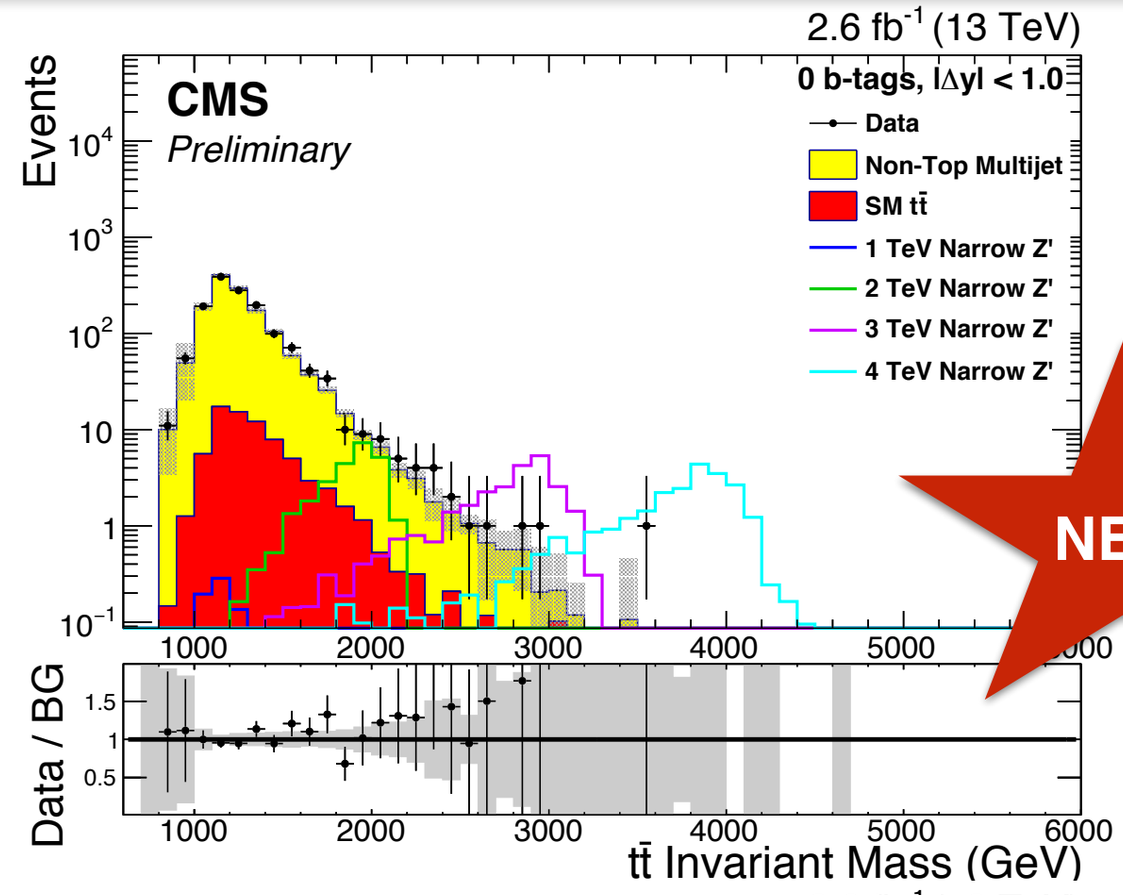


tt resonances: hadronic

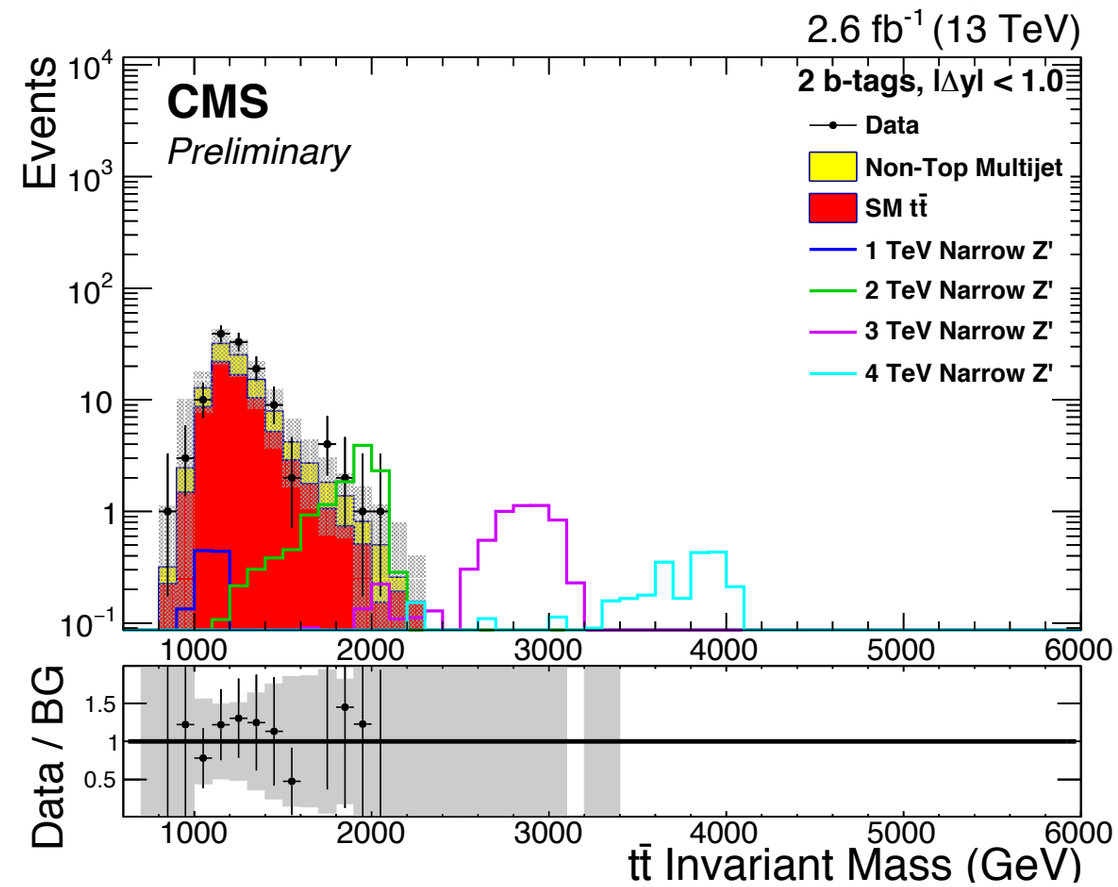
[CMS-PAS-B2G-15-003]

results:





NEW



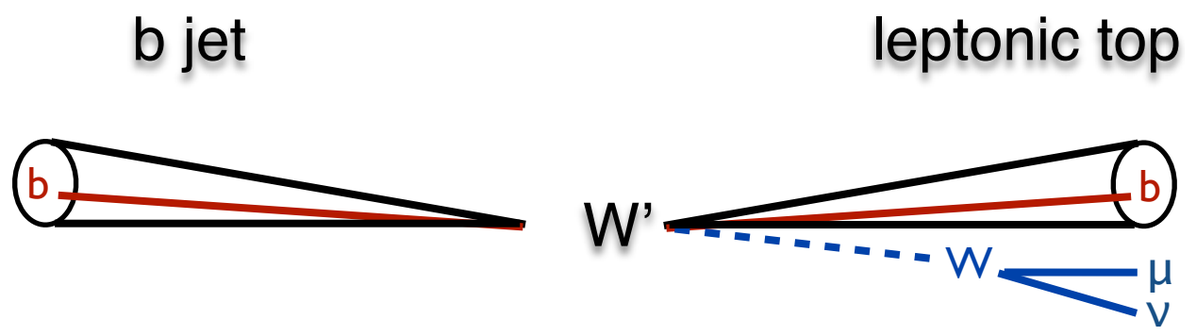
Mass Exclusion Limits

Signal Model	Exclusion Ranges (TeV)	
	Expected	Observed
Z′ (1% Width)	1.2 – 1.6	1.4 – 1.6
Z′ (10% Width)	1.0 – 3.1	1.0 – 3.3
Z′ (30% Width)	1.0 – 3.7	1.0 – 3.8
RS Gluon	1.0 – 2.5	1 – 2.4

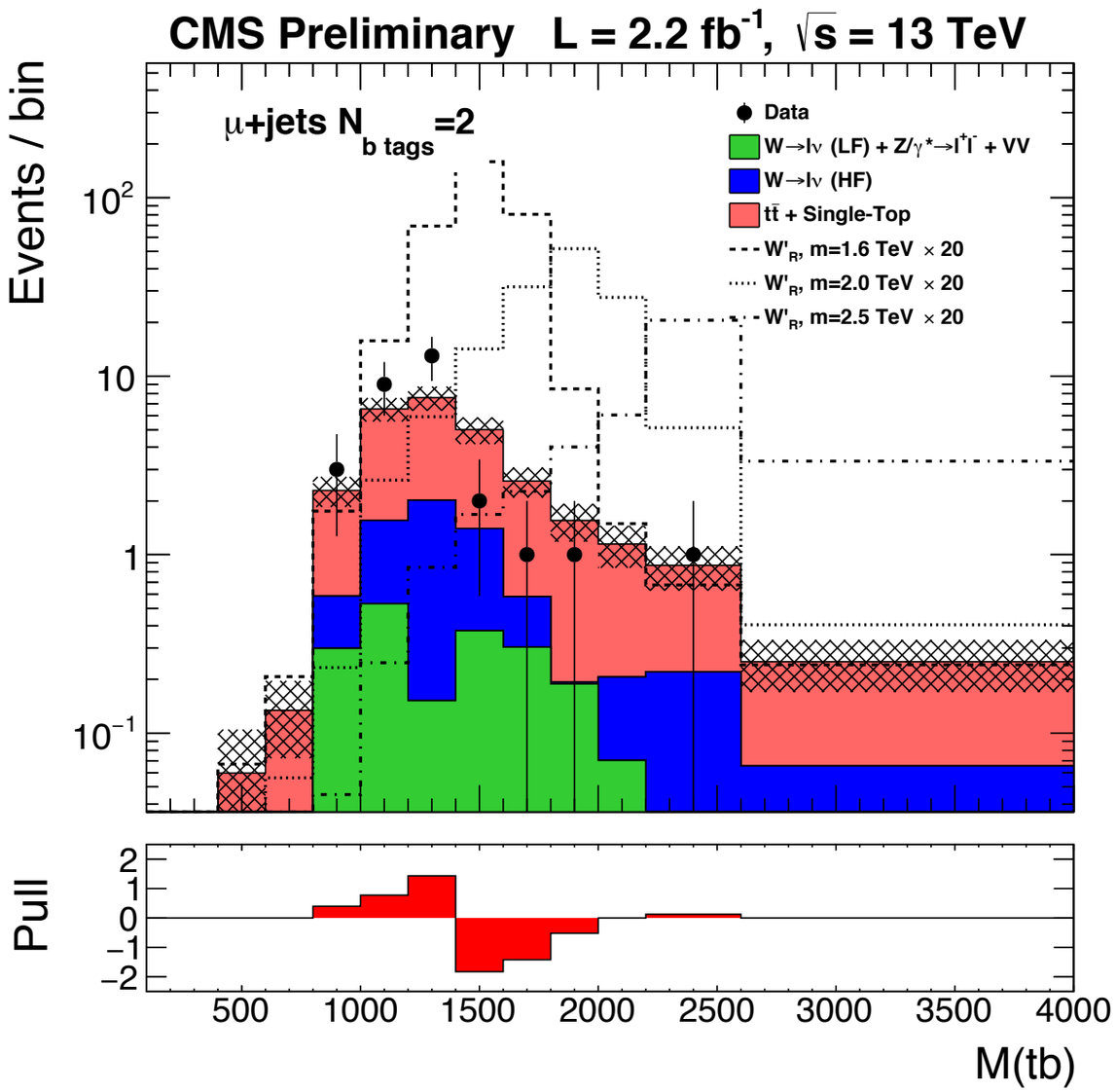
tb resonances: semi-leptonic

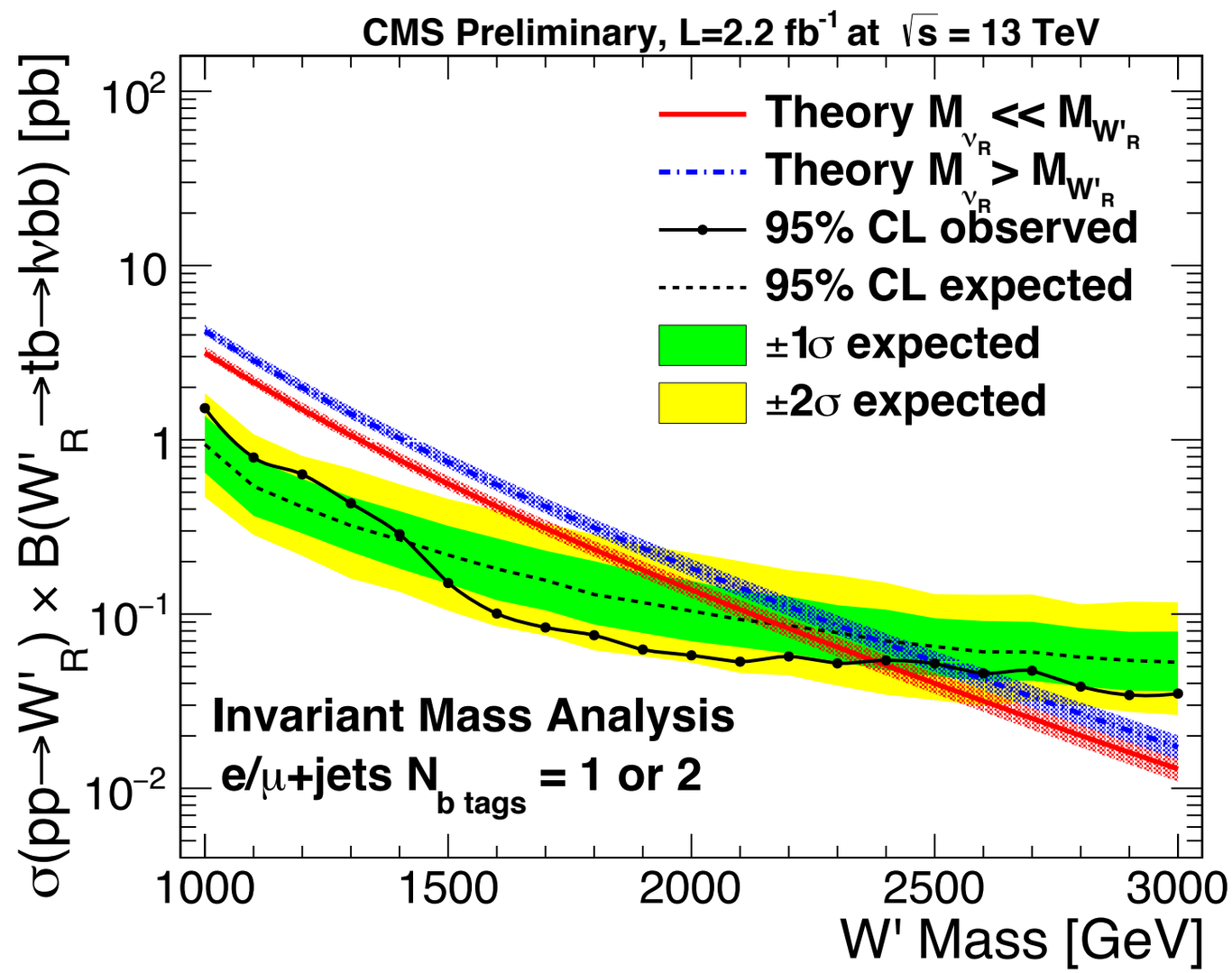
[CMS-PAS-B2G-15-004]

- b-tagging



- b-tagging
- missing energy
- lepton isolation





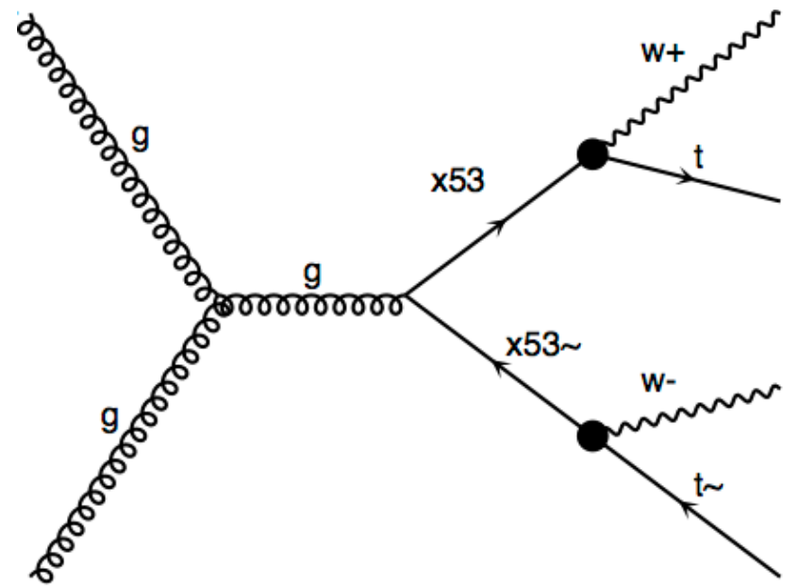
Z' and W' exceed 8 TeV results already now

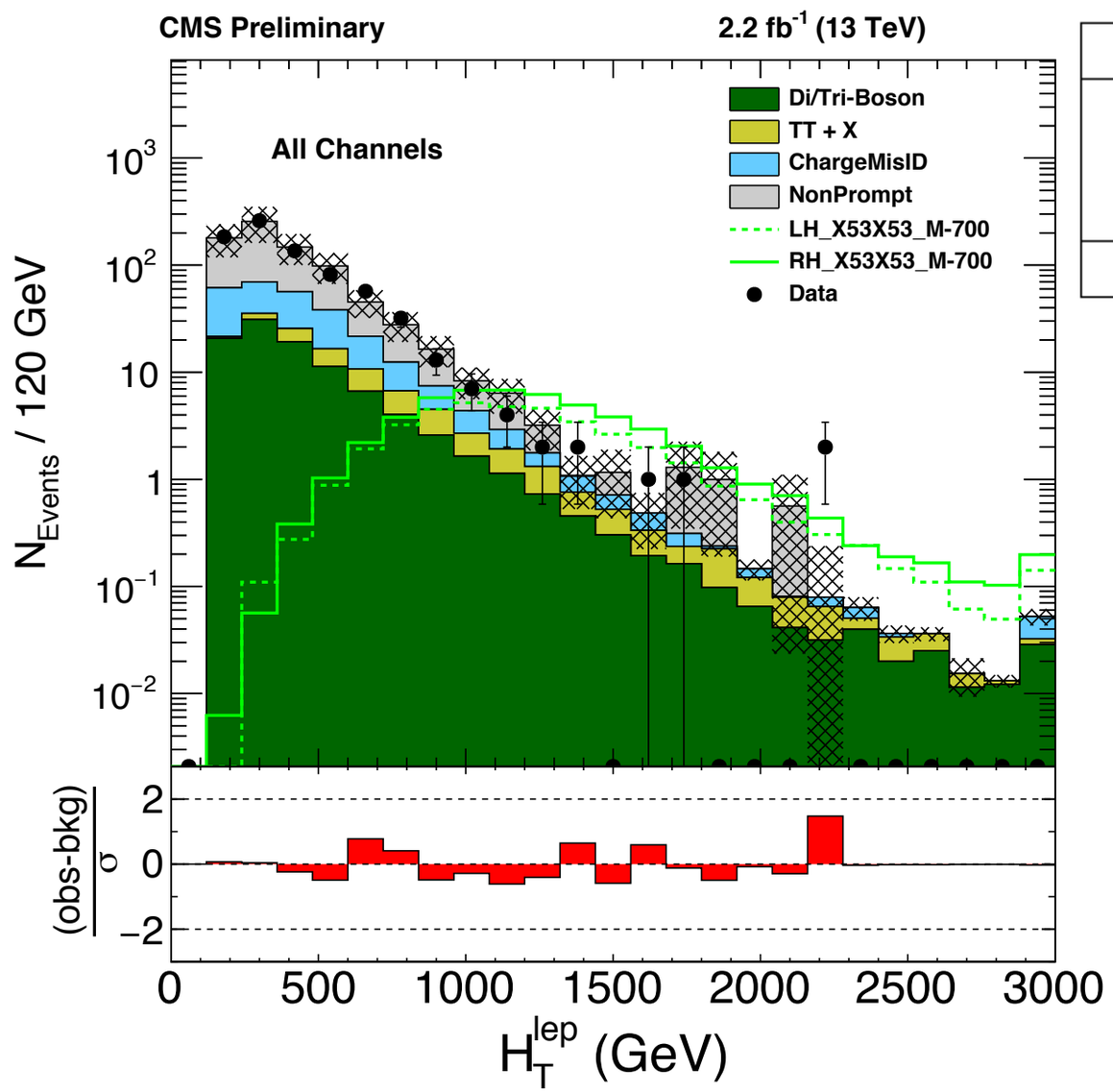
vector-like quarks: pair production

[CMS-PAS-B2G-15-006]

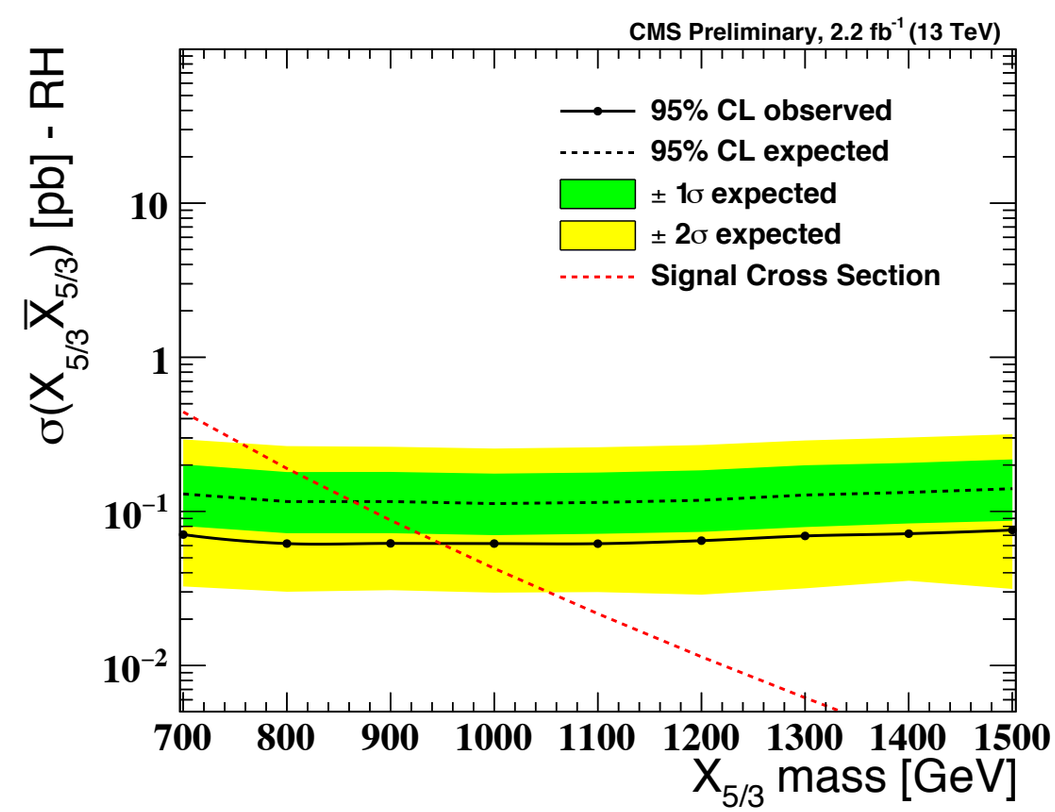
$X^{5/3}$ in same-sign di-lepton final state:

- first VLQ result at 13 TeV
- clean same-sign lepton selection
- backgrounds from opposite-sign events with charge mis-measurements





Channel	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	6.47 ± 2.02	4.38	7
Electron-Muon	8.72 ± 3.24	9.14	3
Di-muon	2.80 ± 1.70	3.55	1
All	17.98 ± 5.58	17.06	11



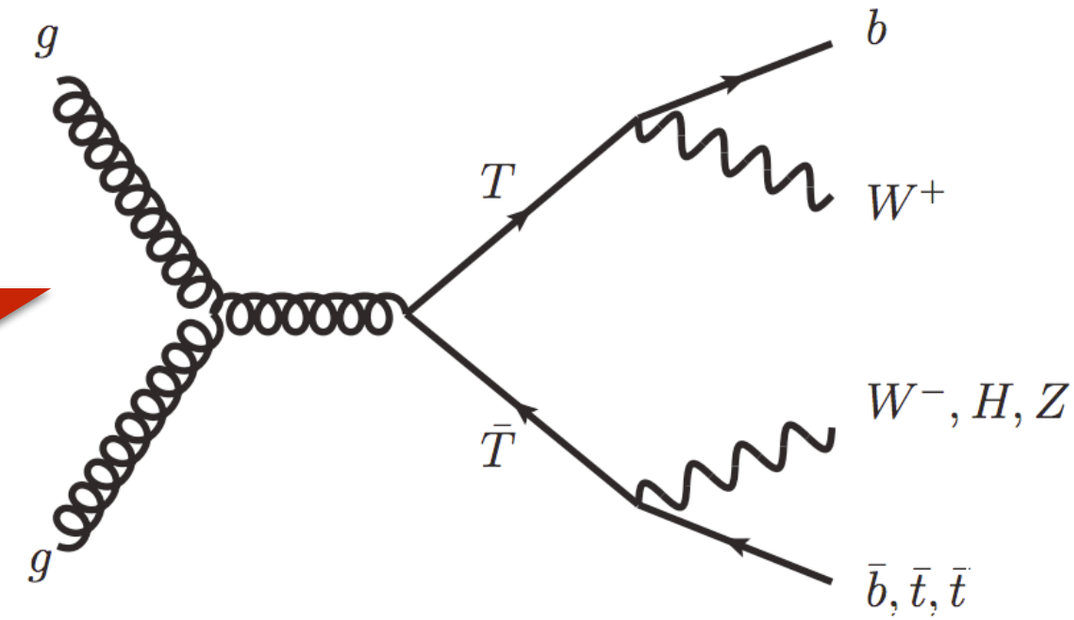
vector-like quarks: pair production

[ATLAS-CONF-2016-032]

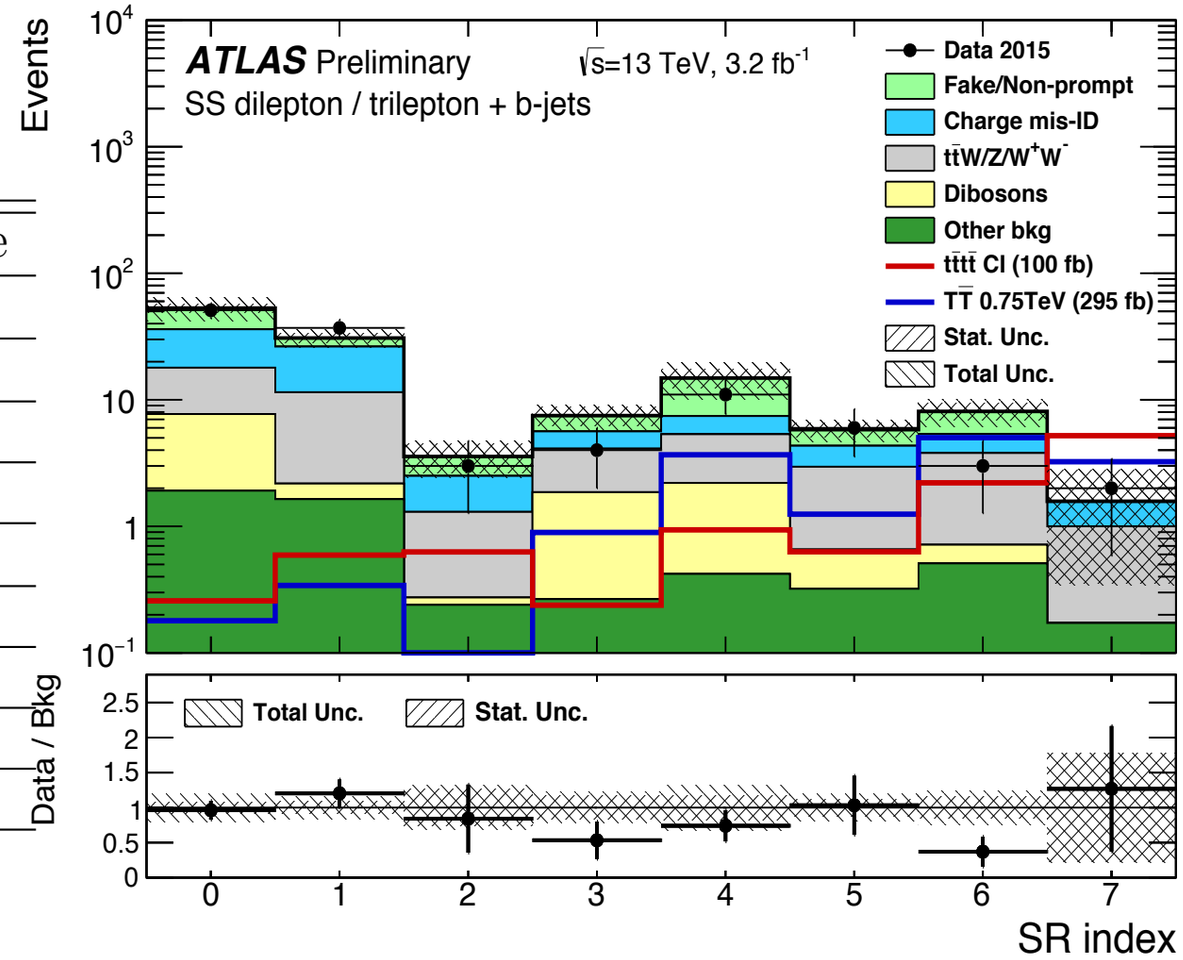
$X^{5/3}$, $T^{2/3}$, $B^{-1/3}$ in SS di-lepton +b-jet final state:

NEW

- 8 signal regions, sensitive to different final states
- also sensitive to four-top production



Definition			Name
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_{\text{T}} < 700 GeV$	$N_b = 1$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_{\text{T}} \geq 700\ GeV$	$N_b = 1$	$40 < E_{\text{T}}^{\text{miss}} < 100 GeV$	SR3
		$E_{\text{T}}^{\text{miss}} \geq 100\ GeV$	SR4
	$N_b = 2$	$40 < E_{\text{T}}^{\text{miss}} < 100 GeV$	SR5
		$E_{\text{T}}^{\text{miss}} \geq 100\ GeV$	SR6
	$N_b \geq 3$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR7

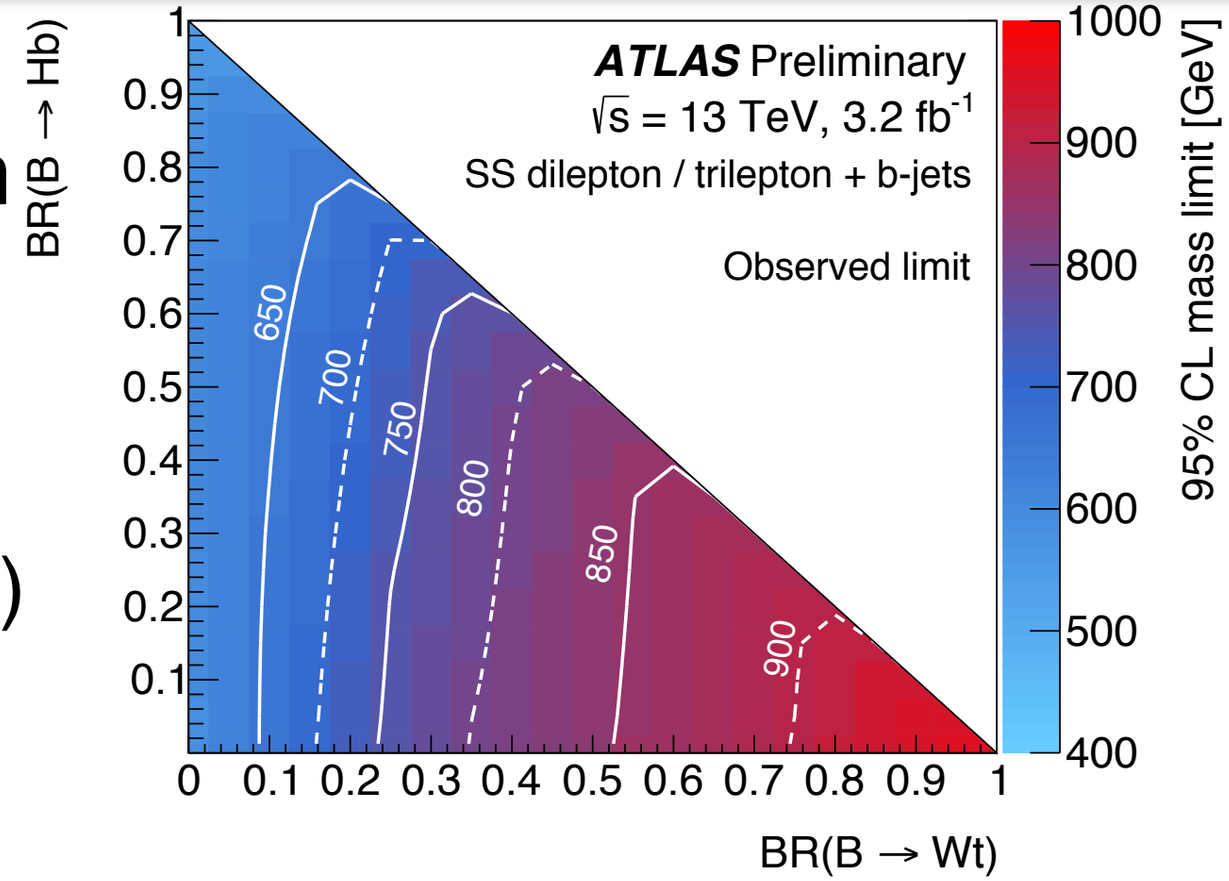


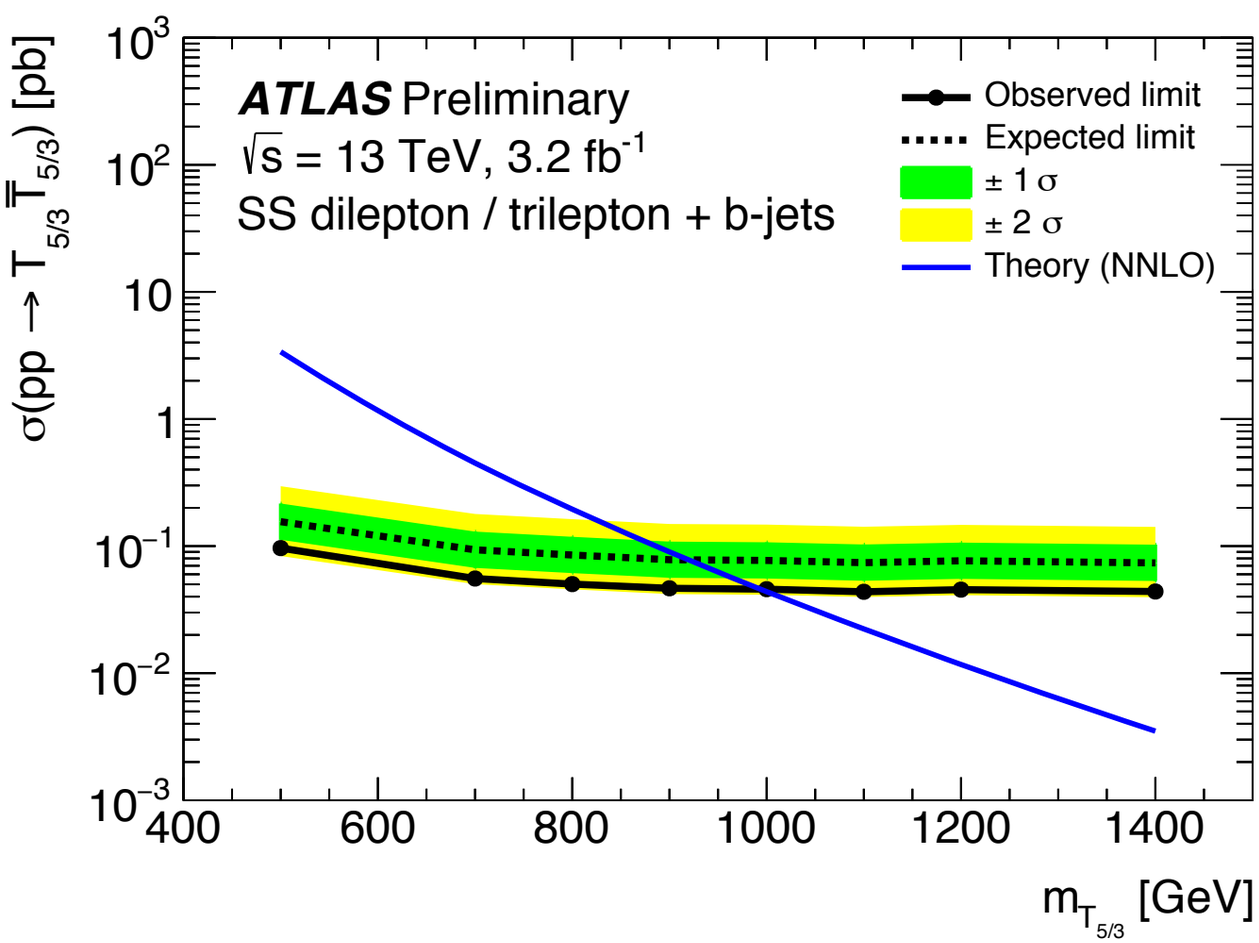
vector-like quarks: pair production

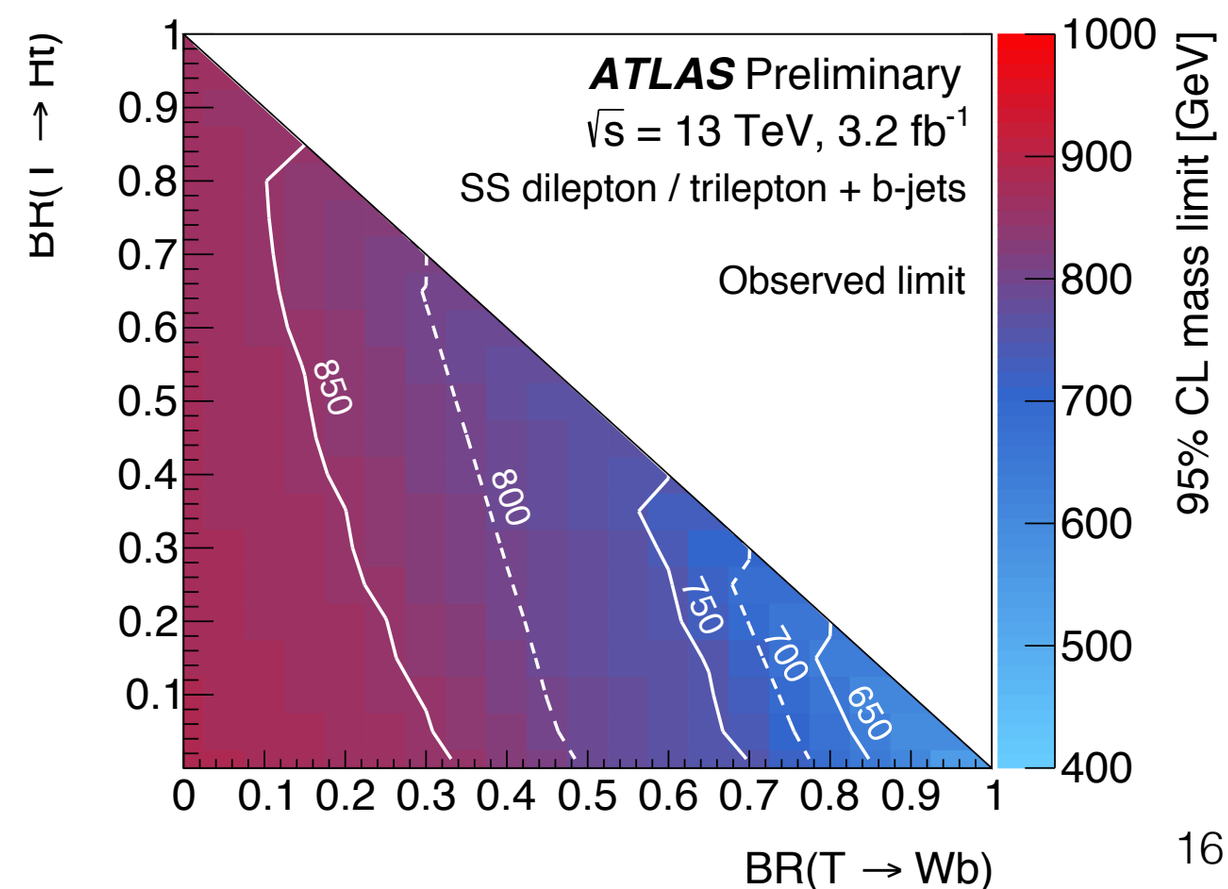
[ATLAS-CONF-2016-032]

$X^{5/3}$, $T^{2/3}$, $B^{-1/3}$ in SS di-lepton +b-jet final state:

- results interpreted for all VLQ species (and four-top production)





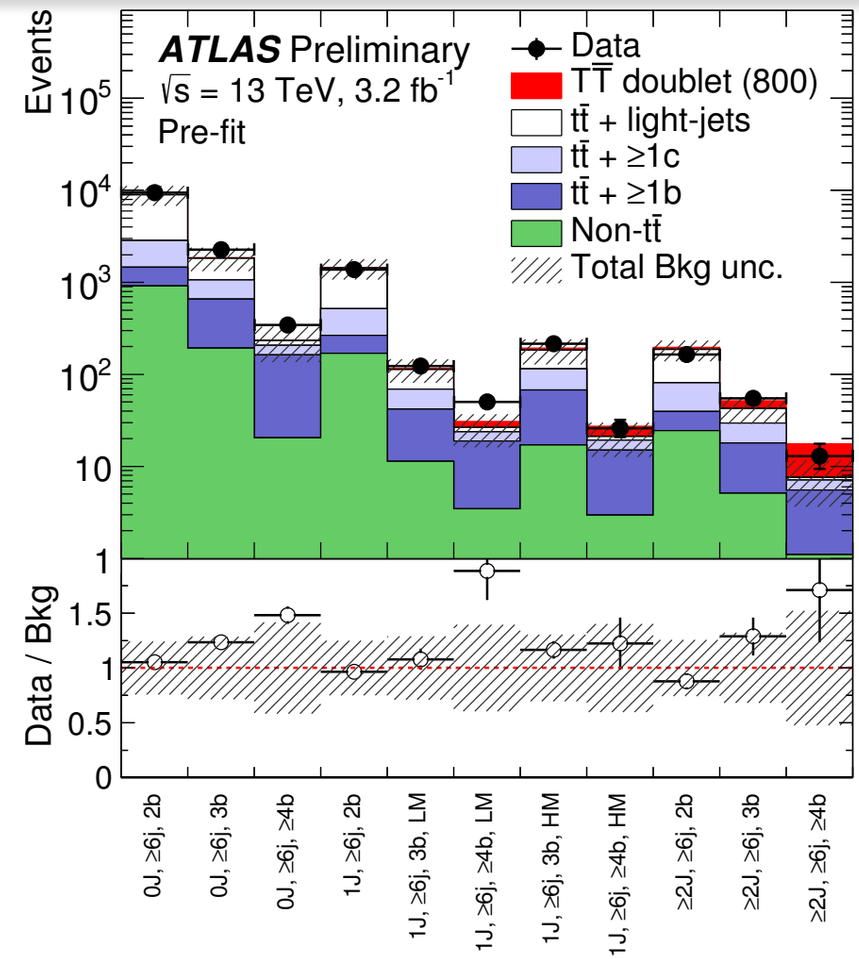


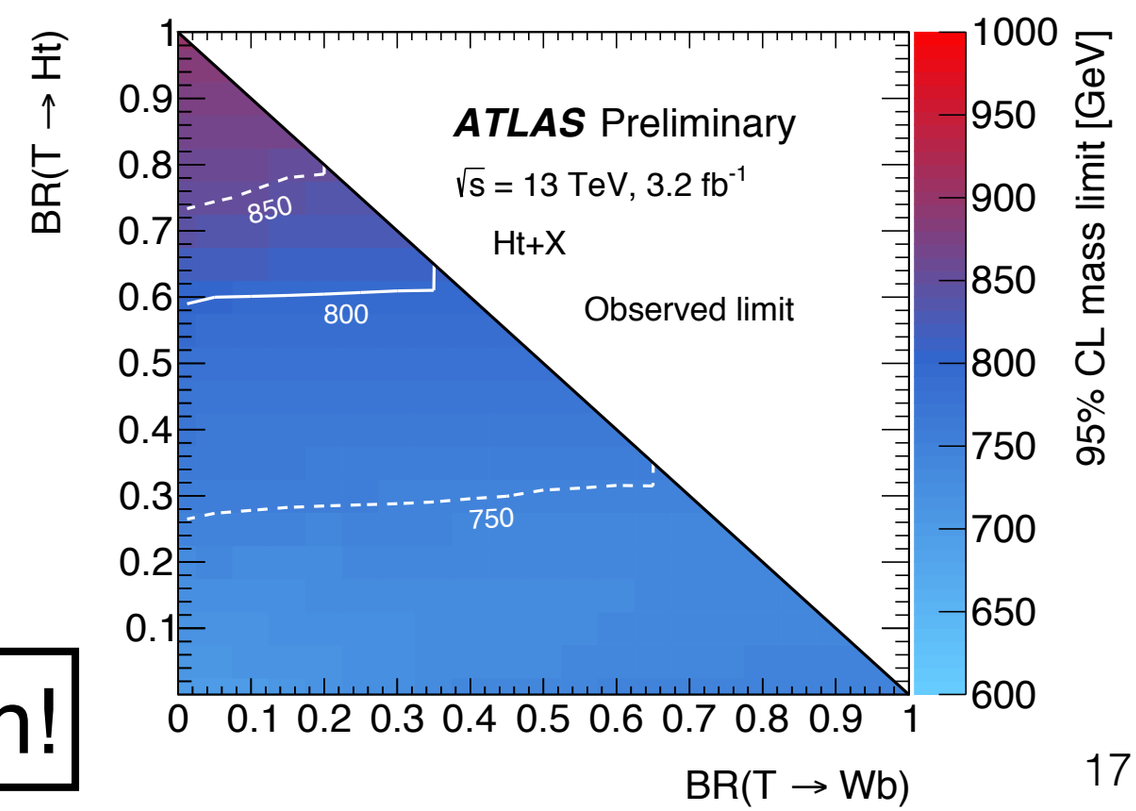
vector-like quarks: pair production

[ATLAS-CONF-2016-013]

$T^{2/3}$ in lepton+jets final state:

- optimised for T→tH + X (with H→bb)
- signal characterised by high (b)-jet multiplicity
- 11 categories based on
  - jet multiplicity (>6 for signal)
  - multiplicity of mass-tagged large-R jets(m_J>100GeV)
  - b-tag multiplicity
  - mass of two close b-jets
    - high mass m_{bb}>100 GeV
    - low mass m_{bb}<100 GeV



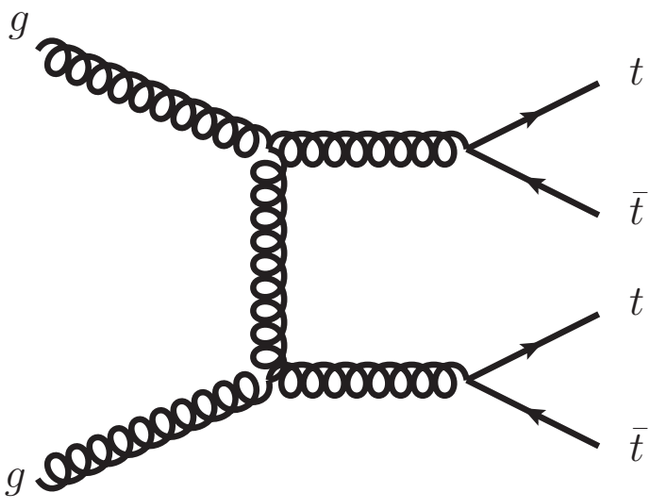


also sensitive to 4-top production!

four-top production

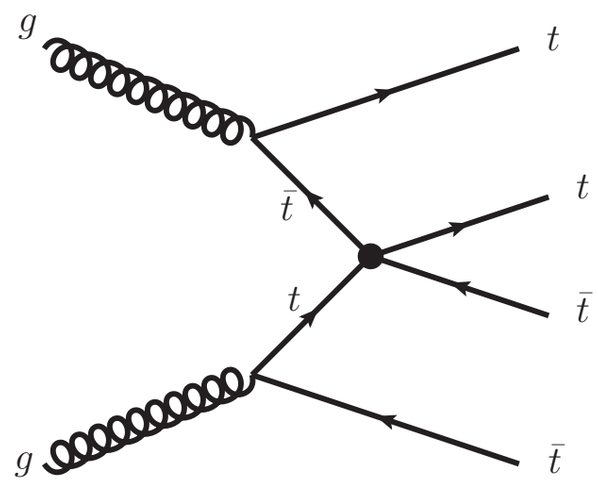
[ATLAS-CONF-2016-020]
[ATLAS-CONF-2016-013]
[ATLAS-CONF-2016-032]

SM



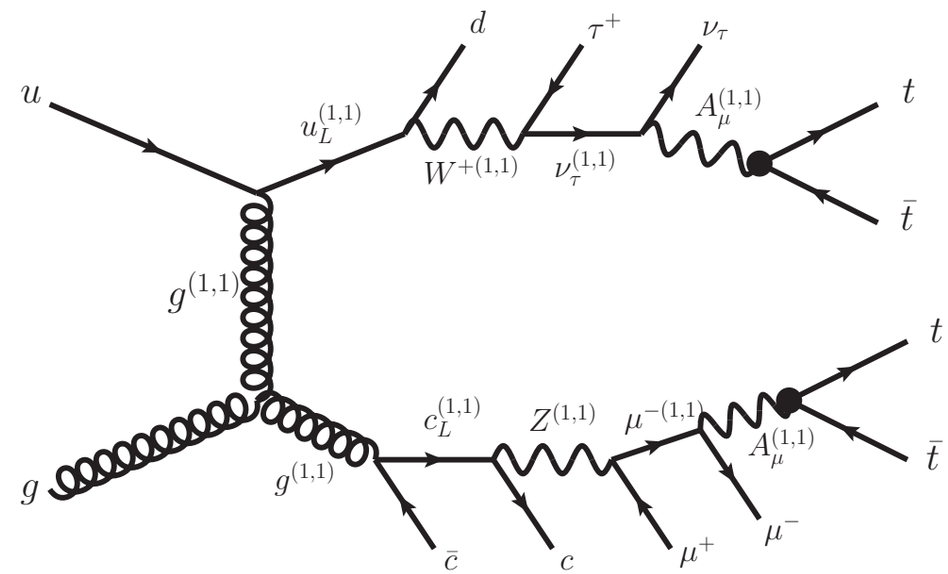
- exp. exclusion: σ > 107 fb (12 times SM)
- obs. exclusion: σ > 95 fb (11 times SM)

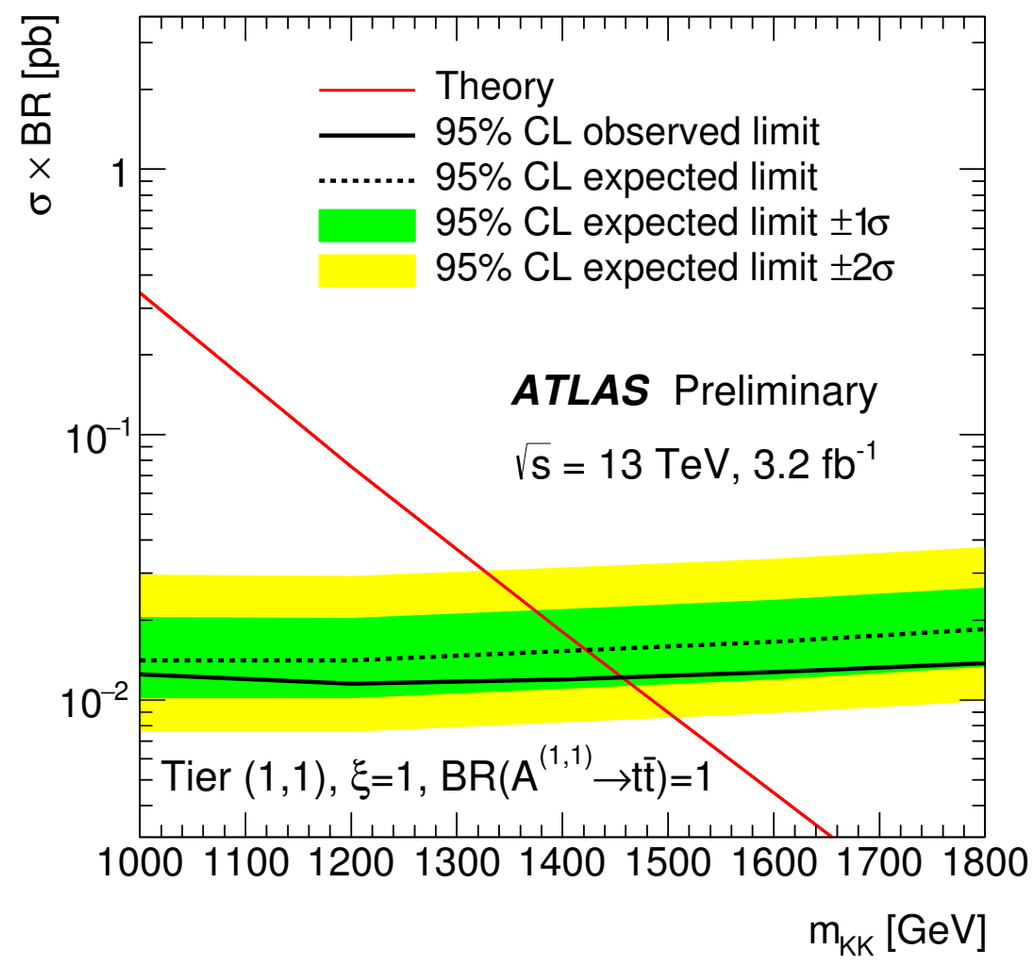
EFT



- exp. exclusion: σ > 67 fb
- obs. exclusion: σ > 79 fb

2UED/RPP



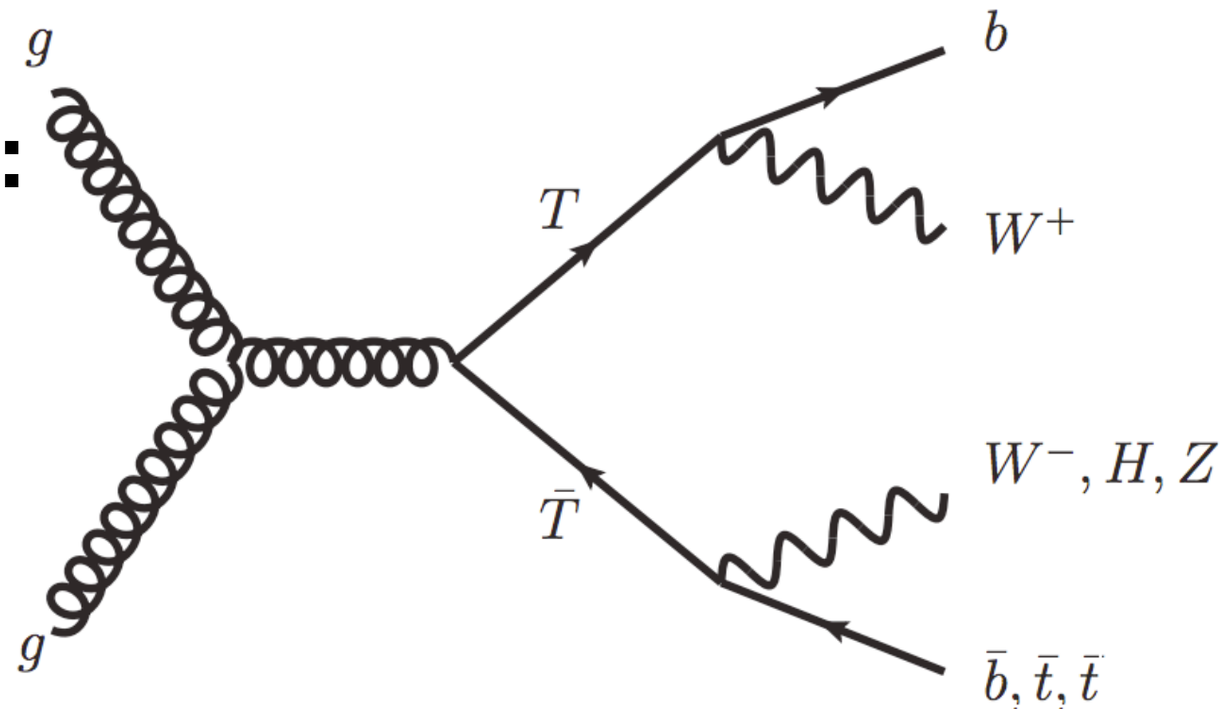


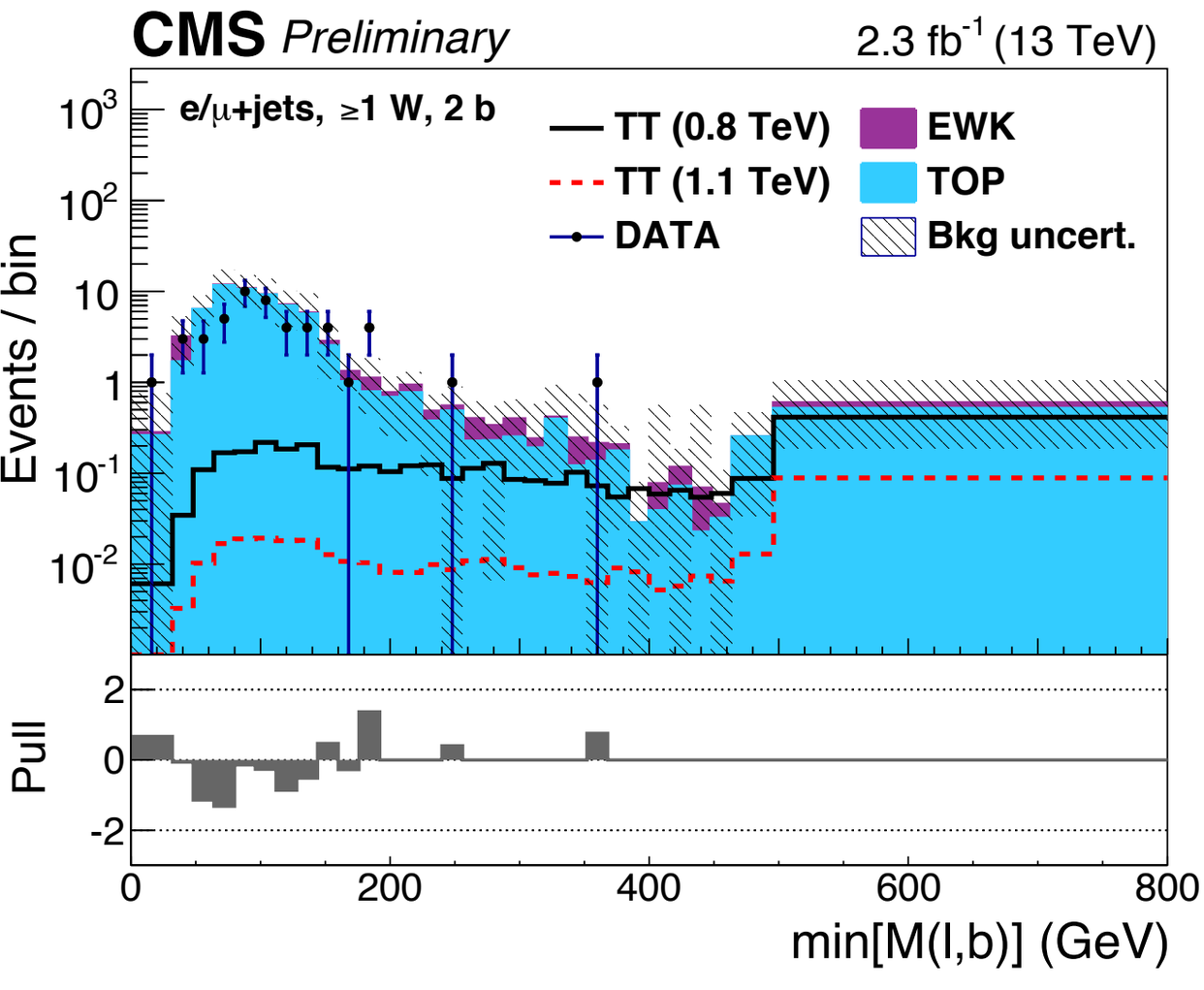
vector-like quarks: pair production

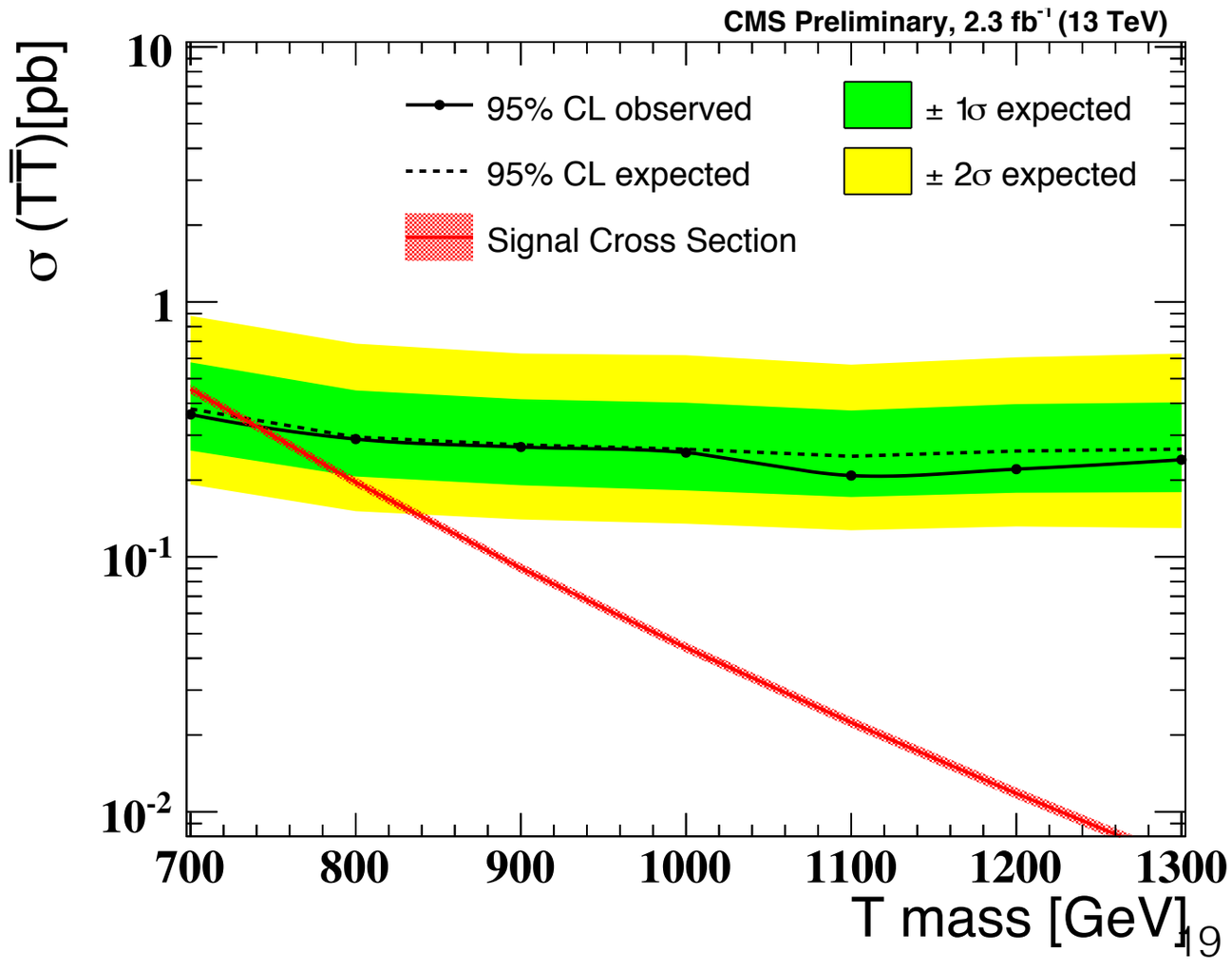
[CMS-PAS-B2G-16-002]

$T^{2/3}$ in lepton+jets final state:

- inclusive search for all possible decay modes (many!)
- divide events in 16 categories (lepton, b-tag, W-tag)

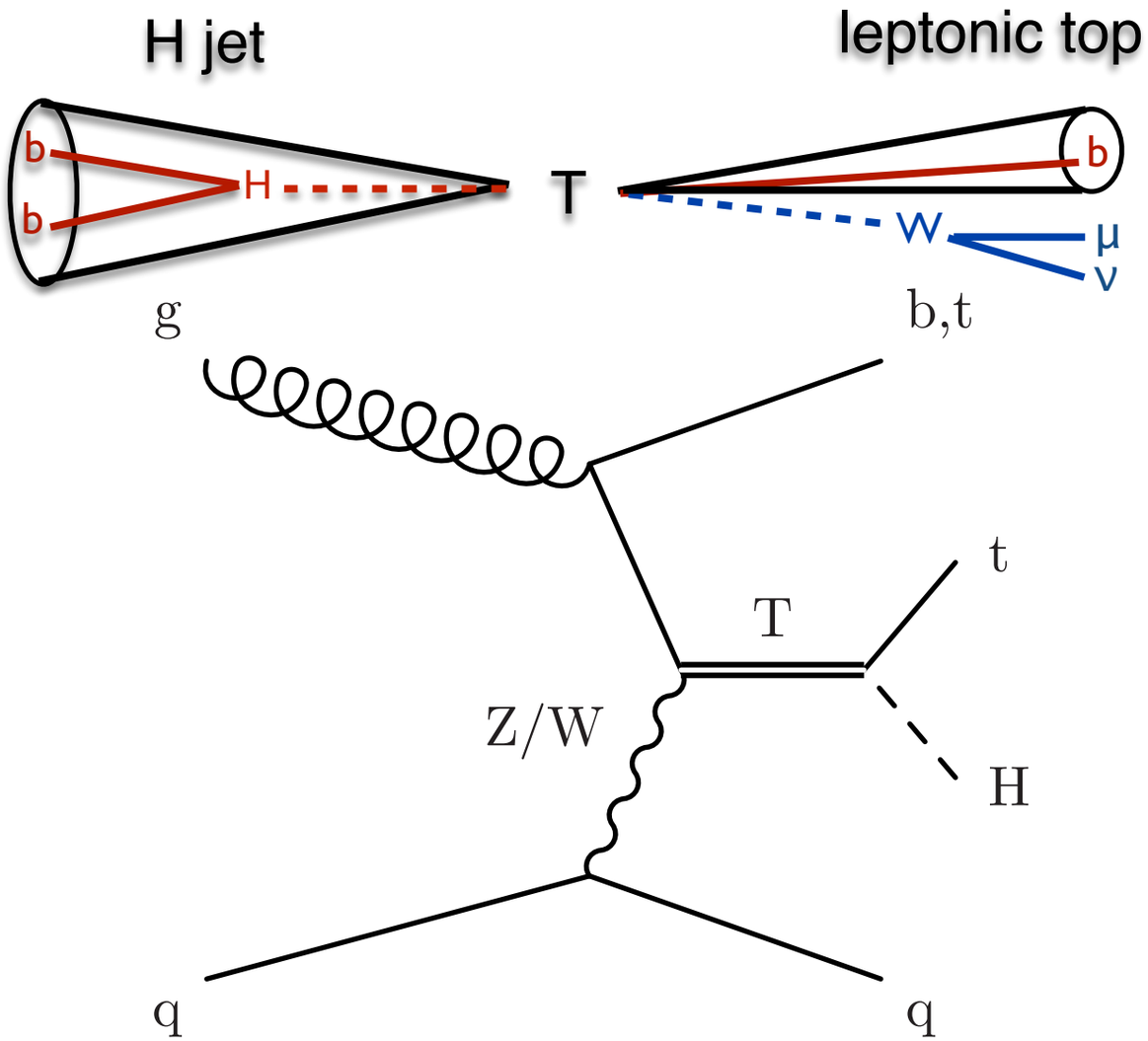


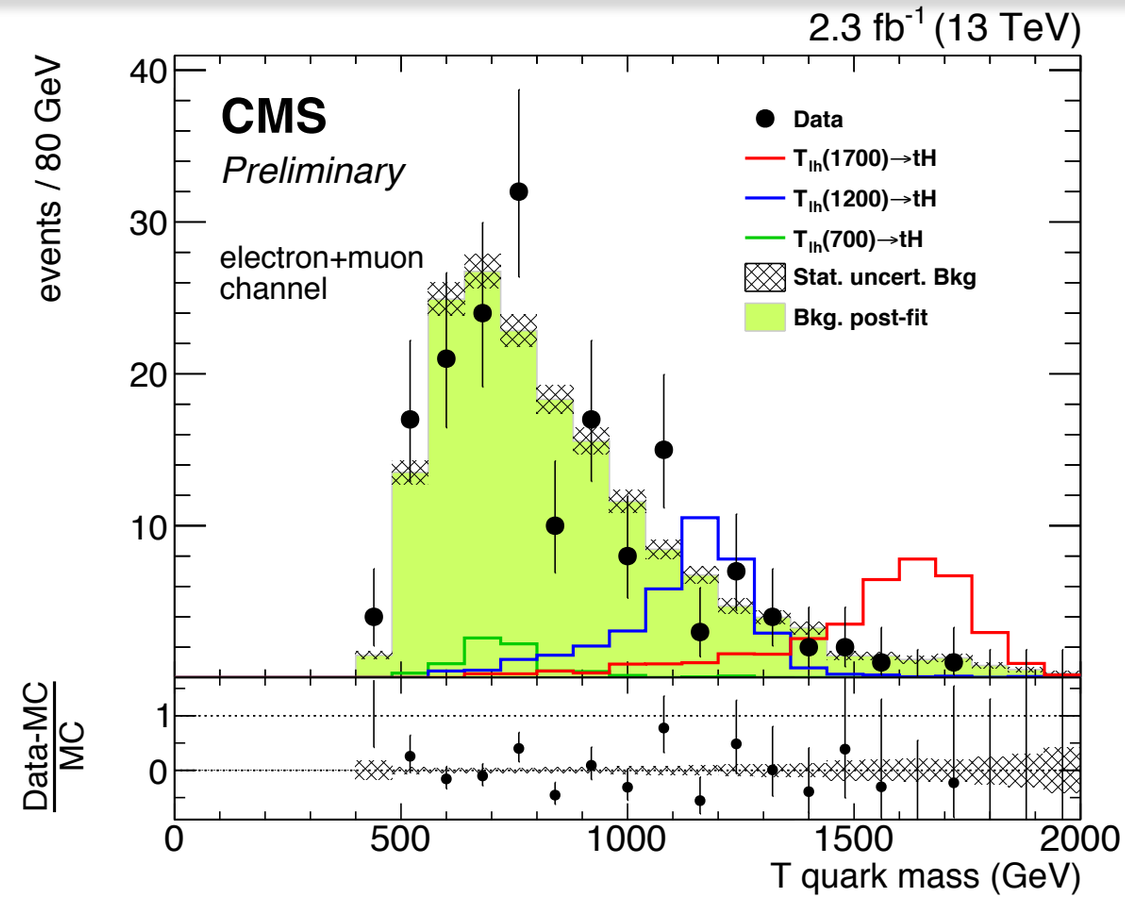


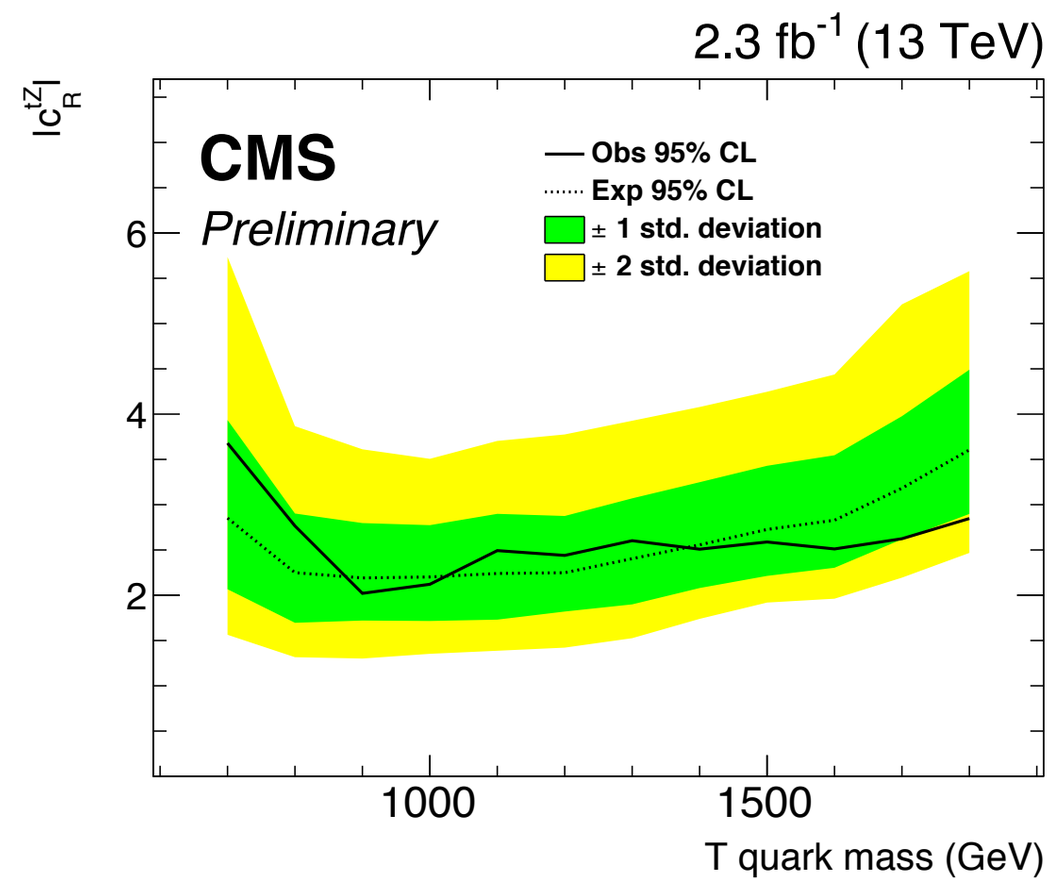


vector-like quarks: single production

[CMS-PAS-B2G-15-008]





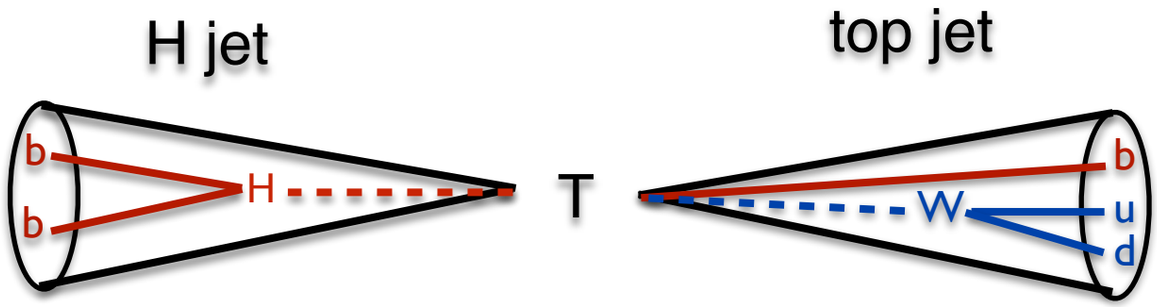


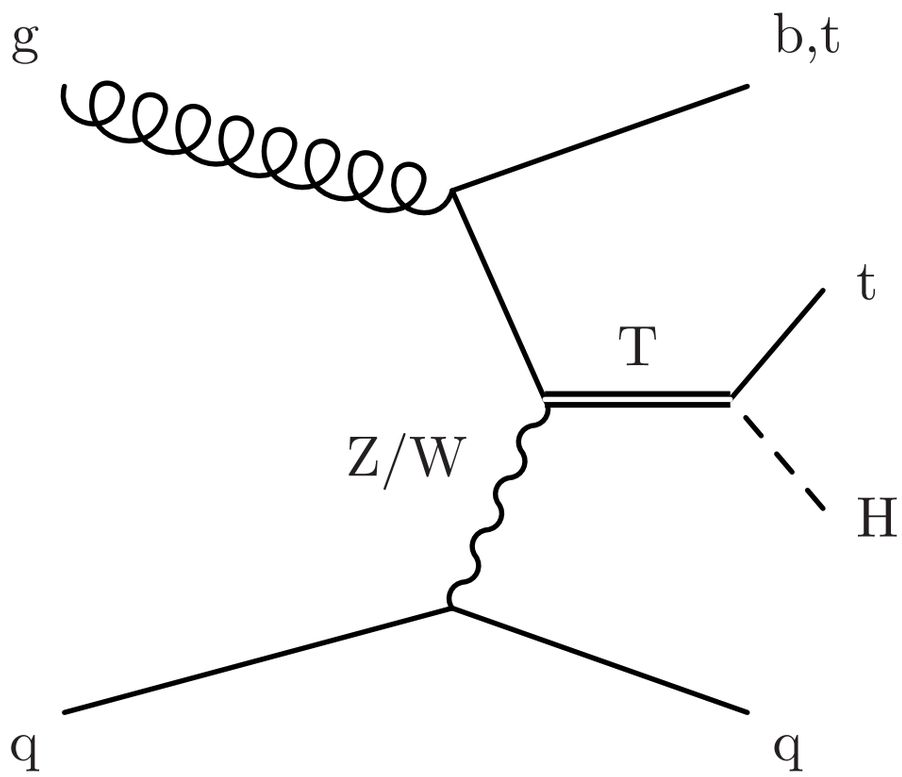
search for single $T^{2/3} \rightarrow tH$:

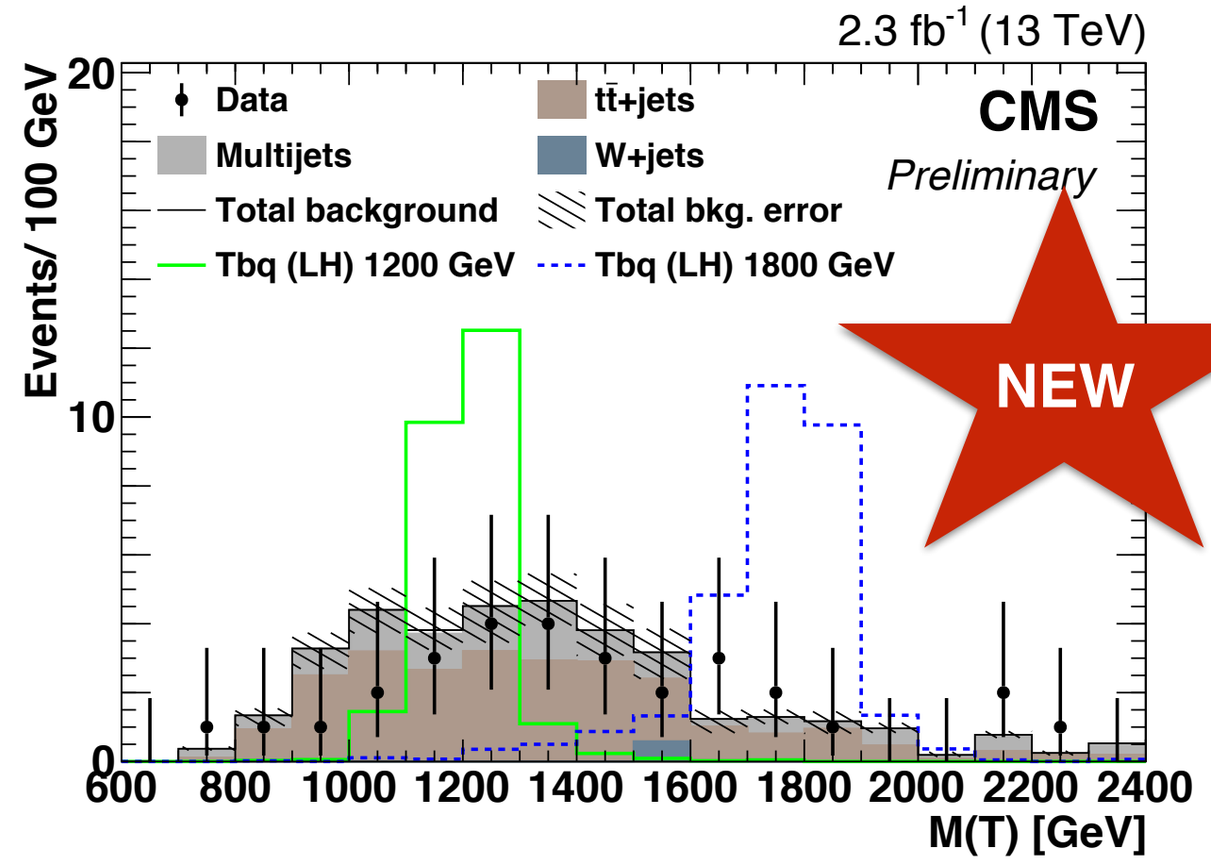
- first single VLQ result from CMS (and first at 13 TeV)
- forward jet tag
- boosted Higgs tag:
  - softdrop mass 90< m < 160 GeV
  - subjet b-tags

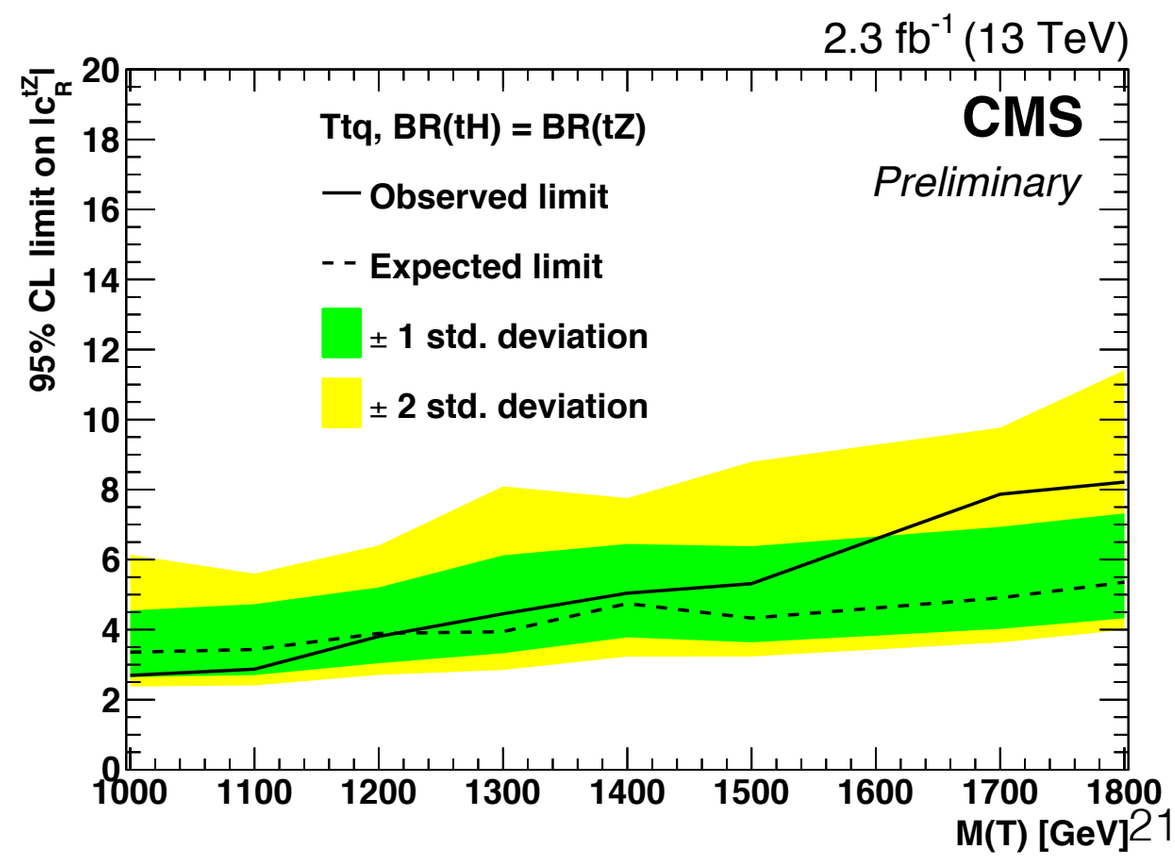
vector-like quarks: single production

[CMS-PAS-B2G-16-005]









search for single $T^{2/3} \rightarrow tH$:

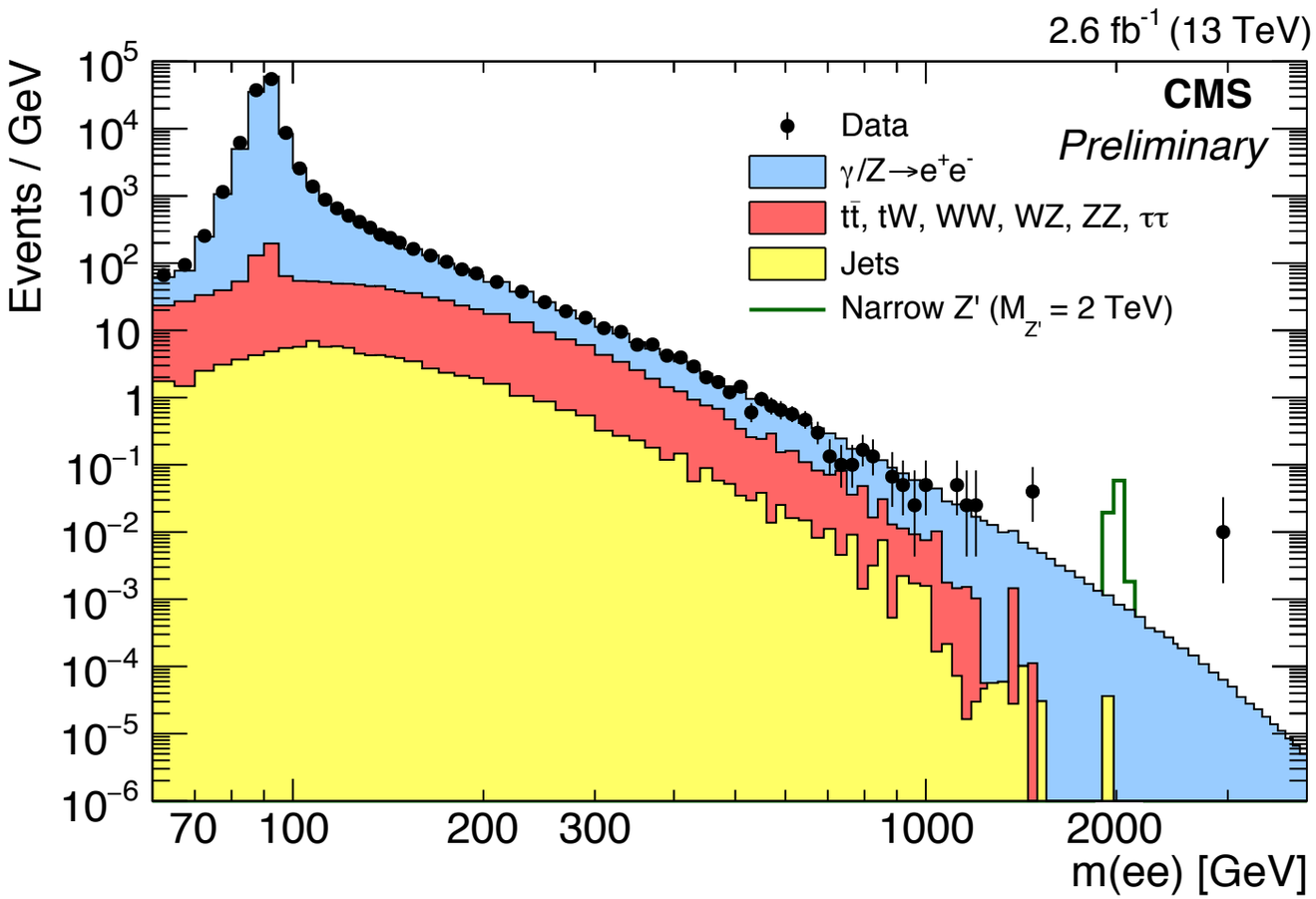
- all-hadronic final state
- boosted Higgs- and top-tags

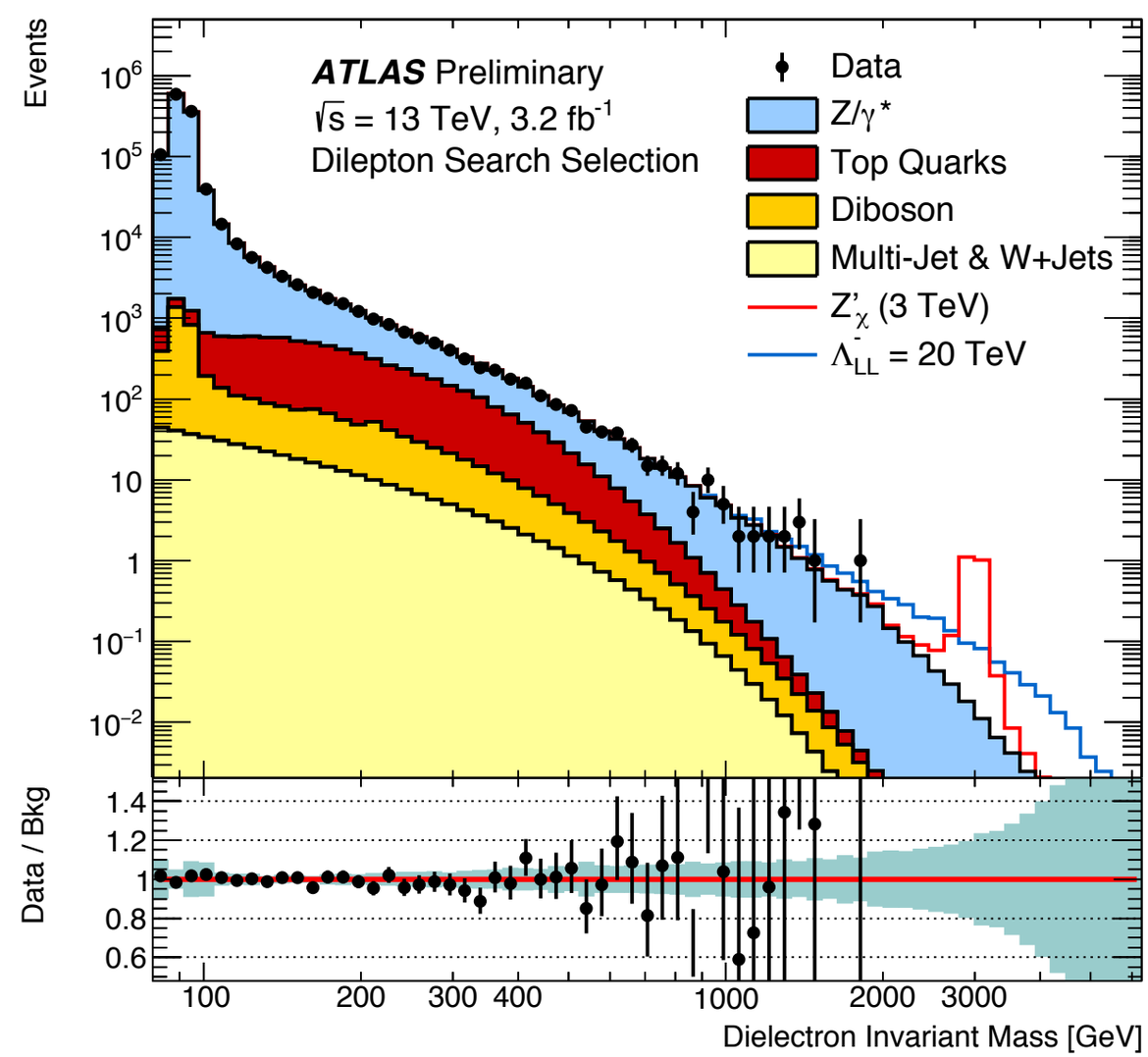
dilepton resonances

[ATLAS-CONF-2015-070]
[CMS-PAS-EXO-15-005]

experimental challenges:

- lepton reconstruction at high momenta
- efficiency and fake rate calibration (extrapolation from low to high momenta)
- background estimation (extrapolation)





- highest mass event: m_{ee}=2.9 TeV
  (0.3 events expected above 2 TeV)
  (0.08 events expected above 2.5 TeV)

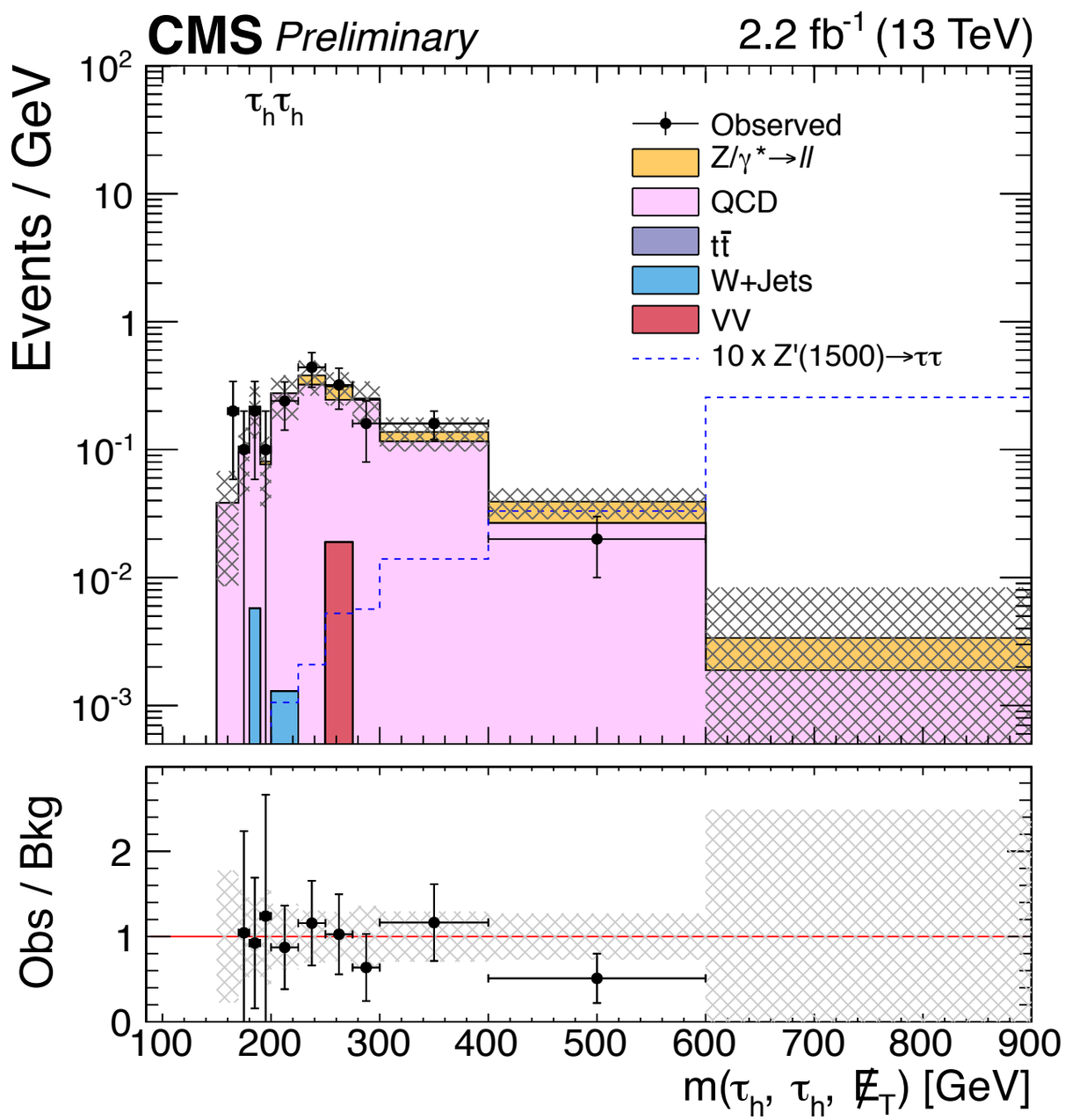
dilepton resonances

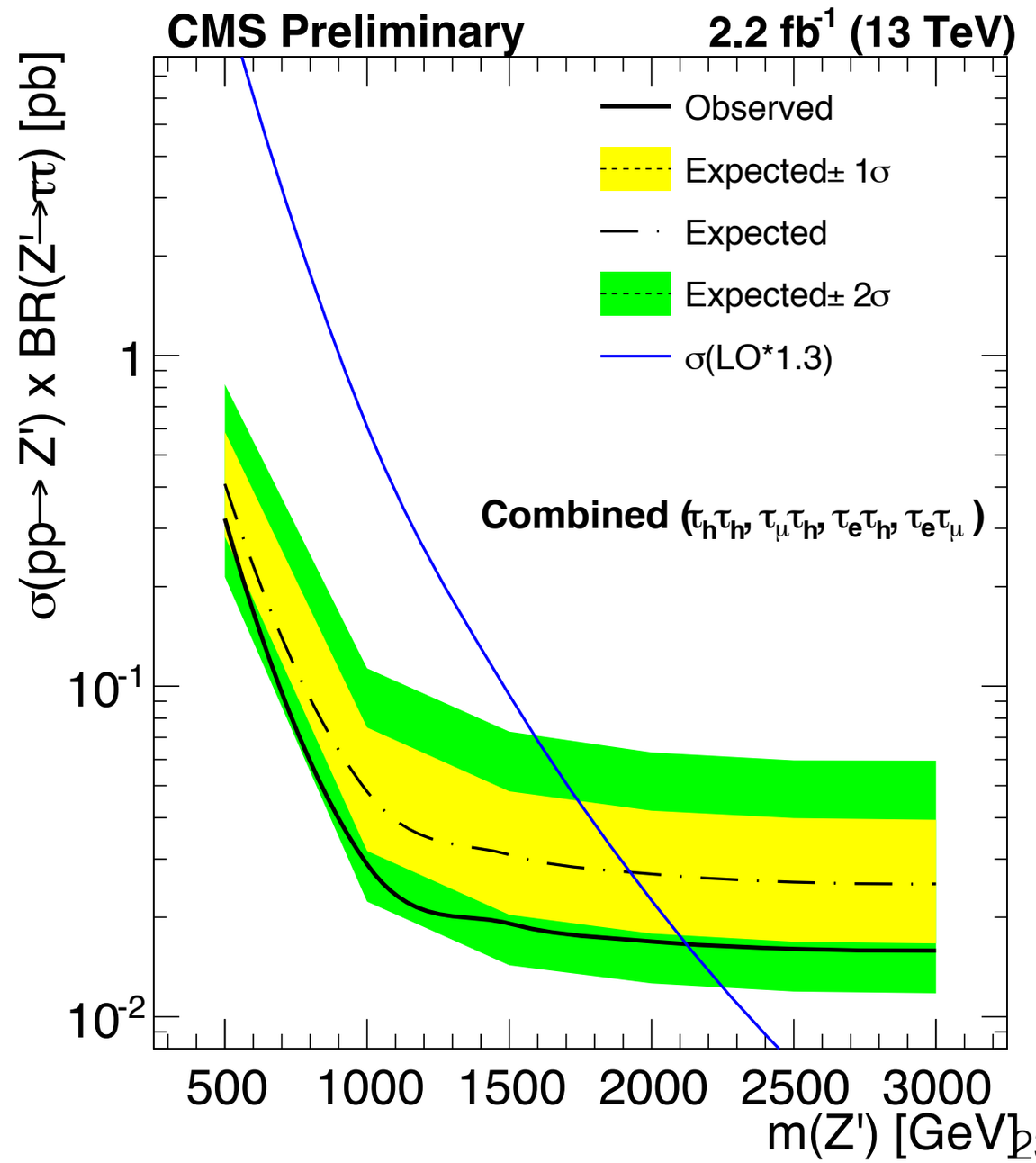
[CMS-PAS-EXO-16-008]

NEW

search for di-tau resonances:

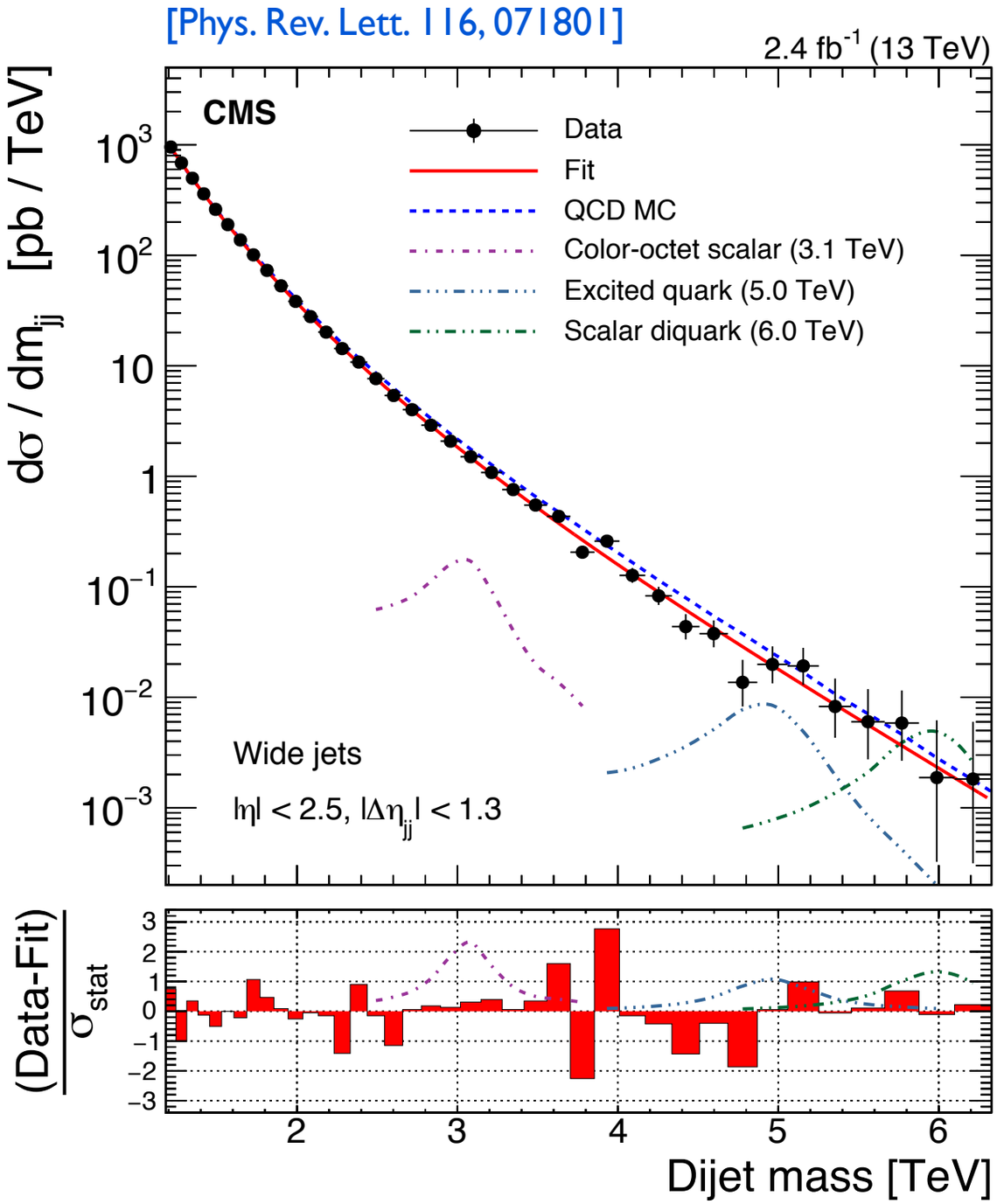
- first di-tau result at 13 TeV
- four final states considered: $\tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_e$



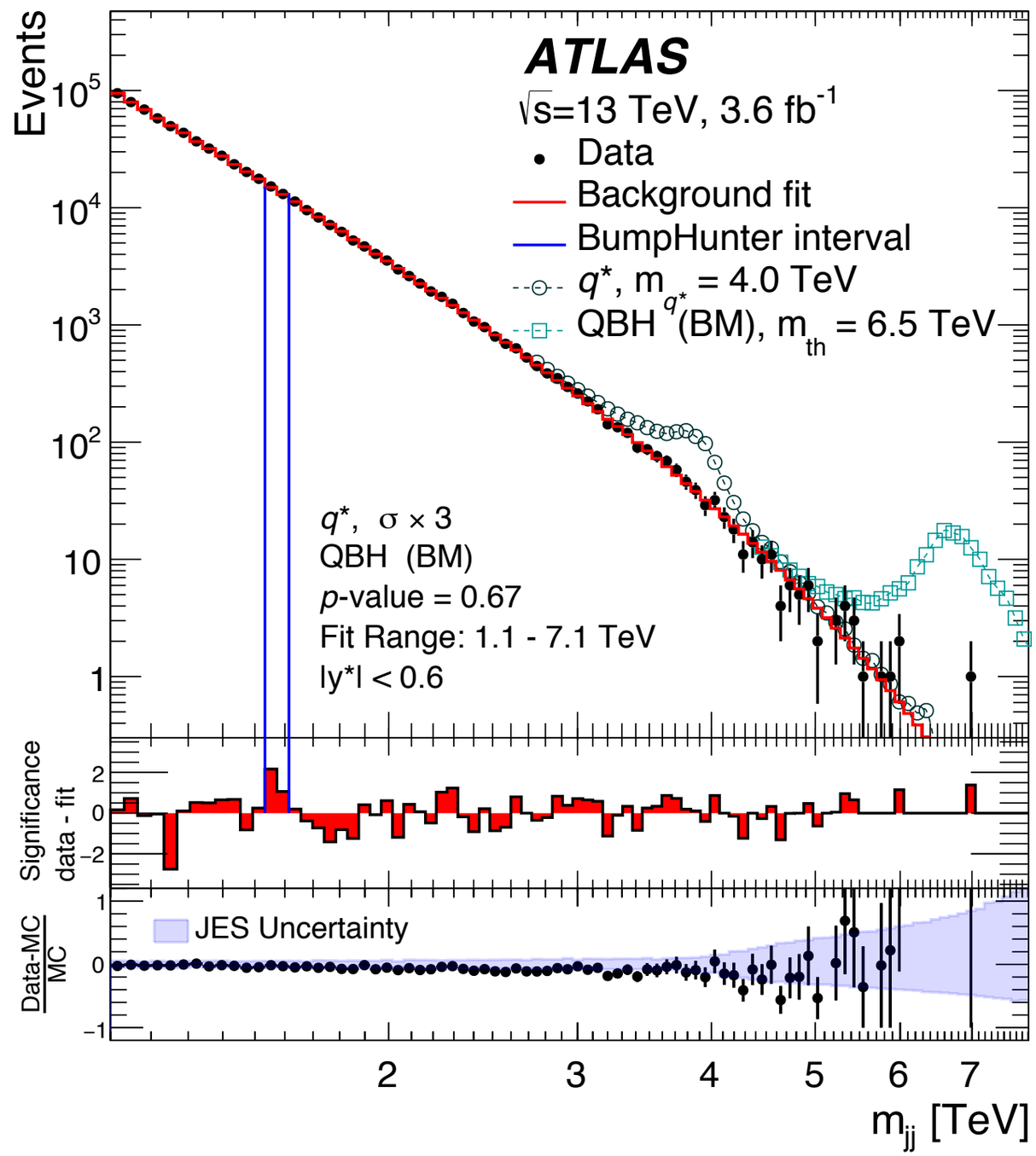


high-mass dijet resonances

[Phys. Rev. Lett. 116, 071801]

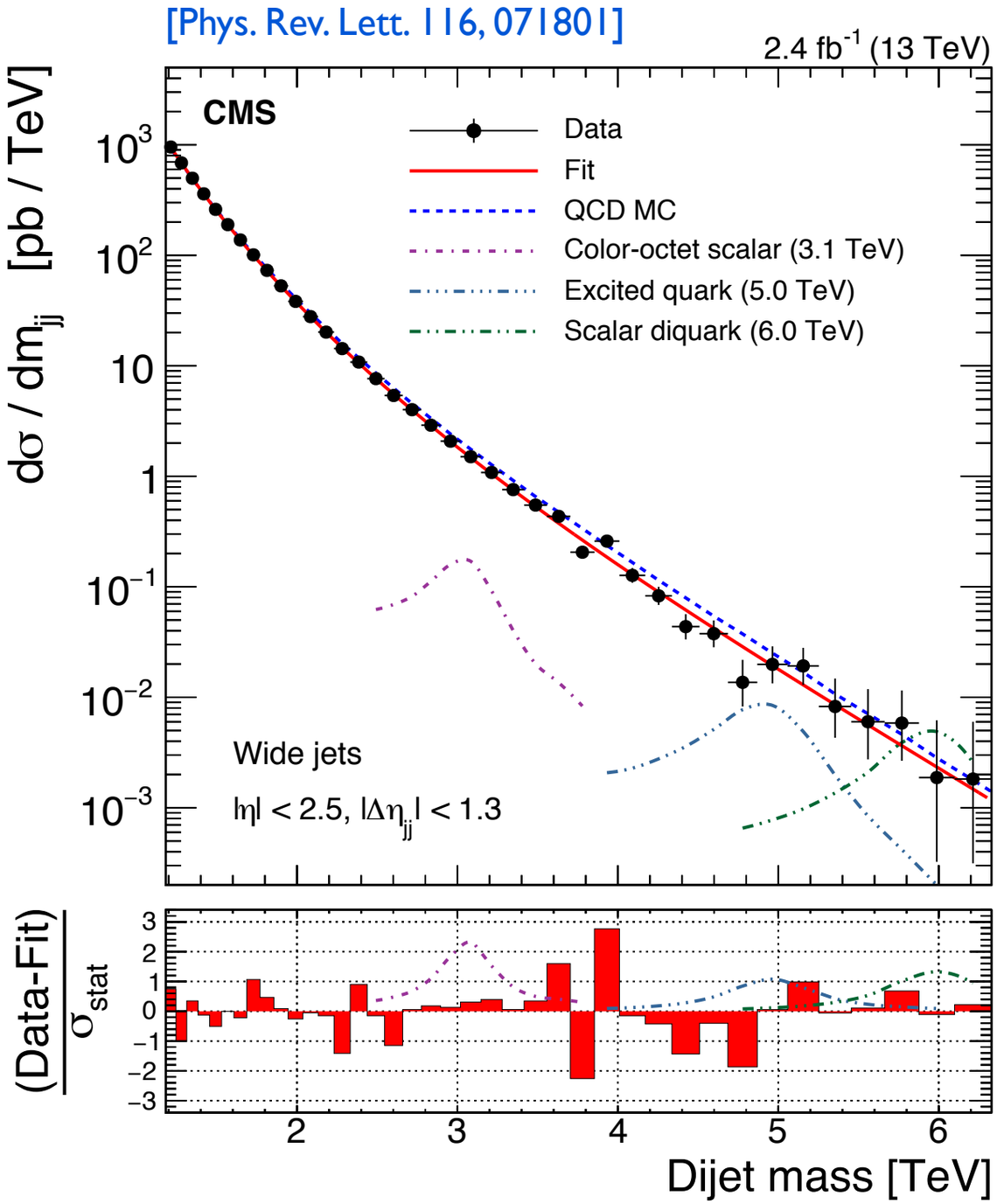


[Phys. Lett. B 754, 302]

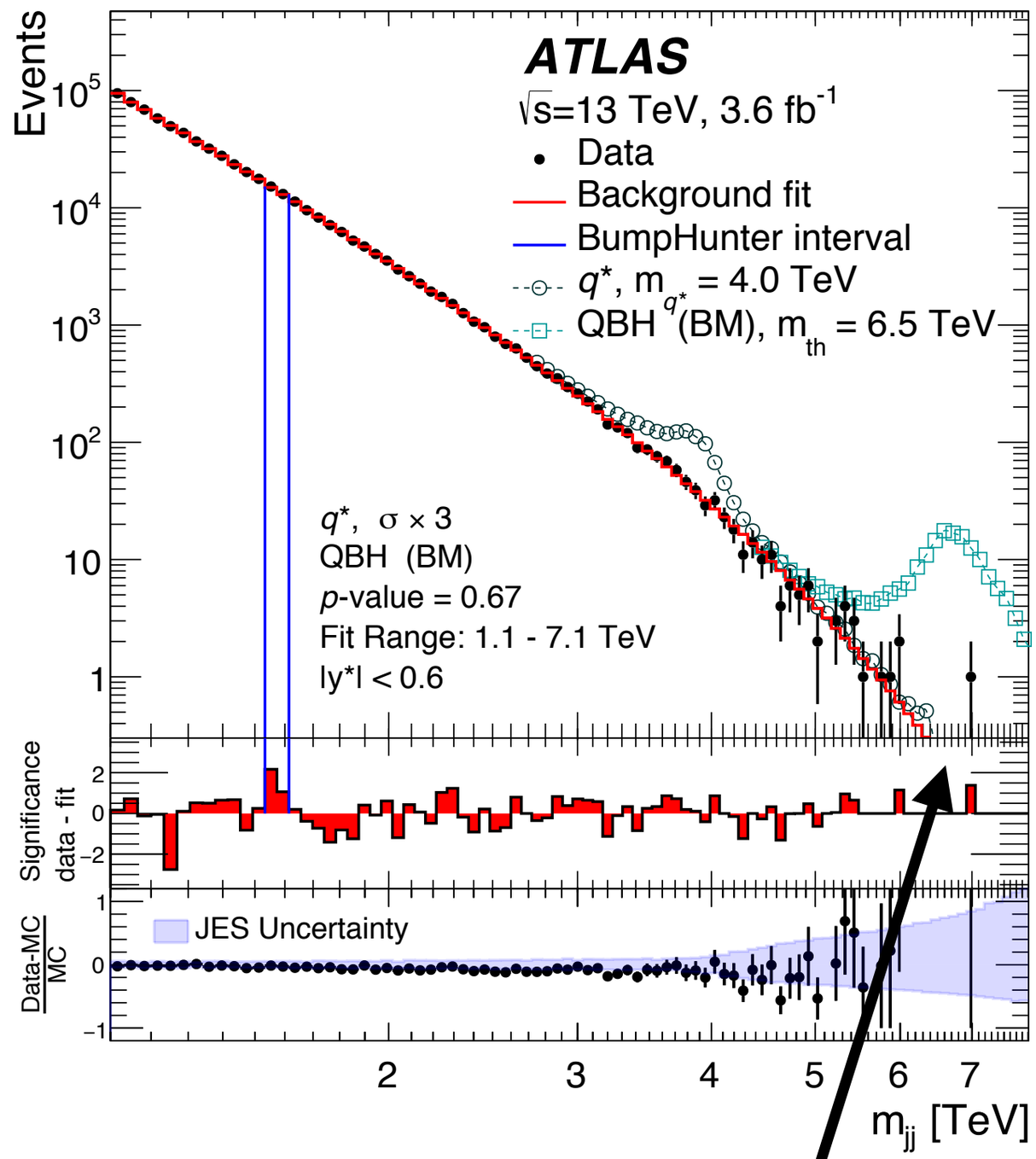


high-mass dijet resonances

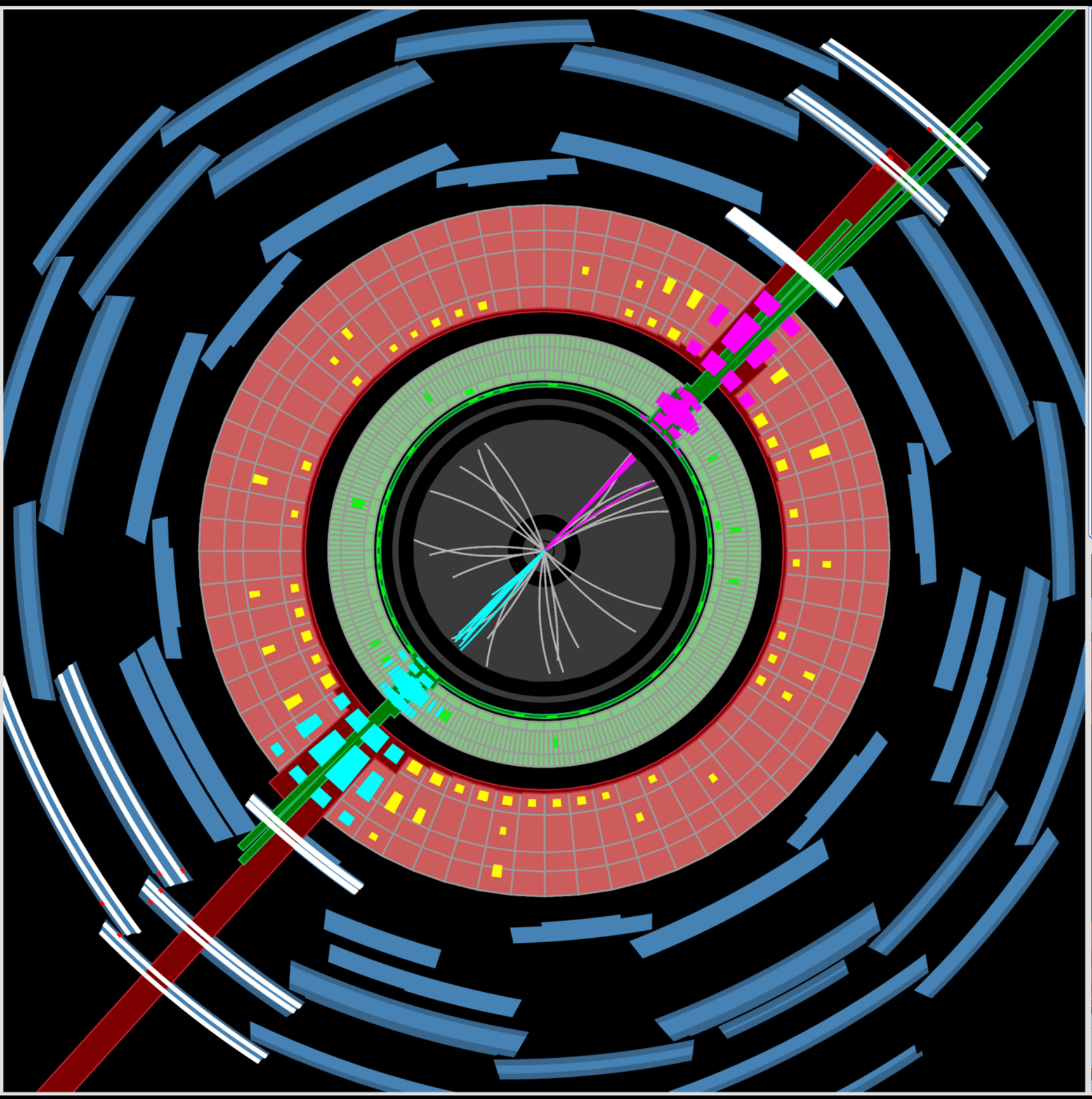
[Phys. Rev. Lett. 116, 071801]

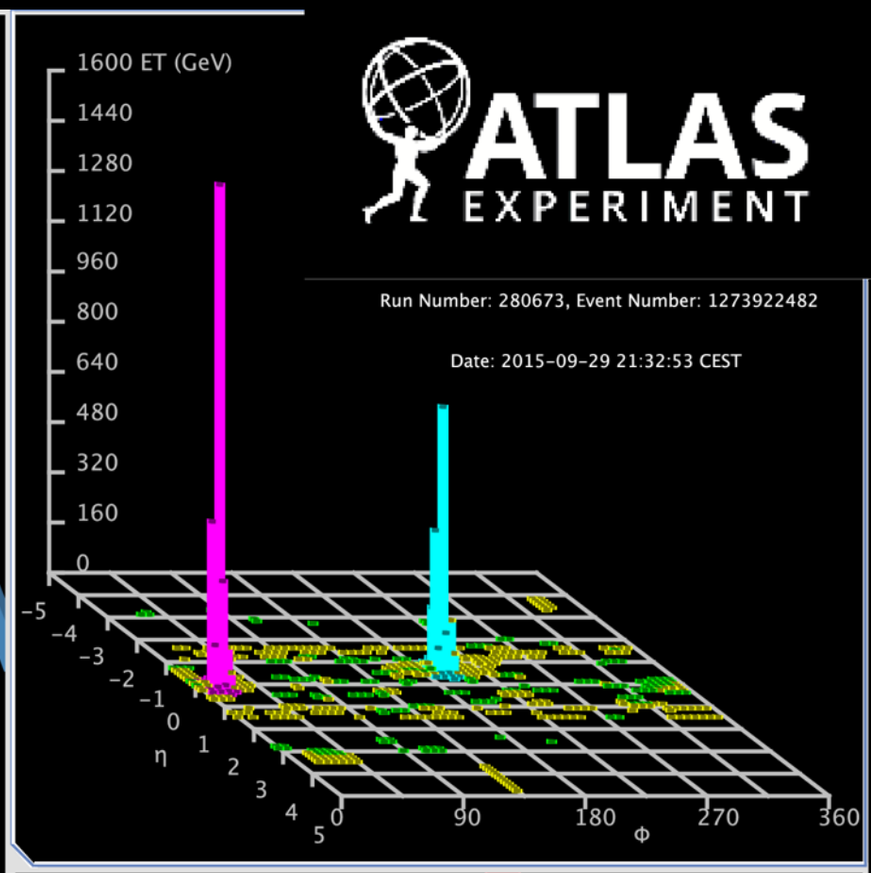


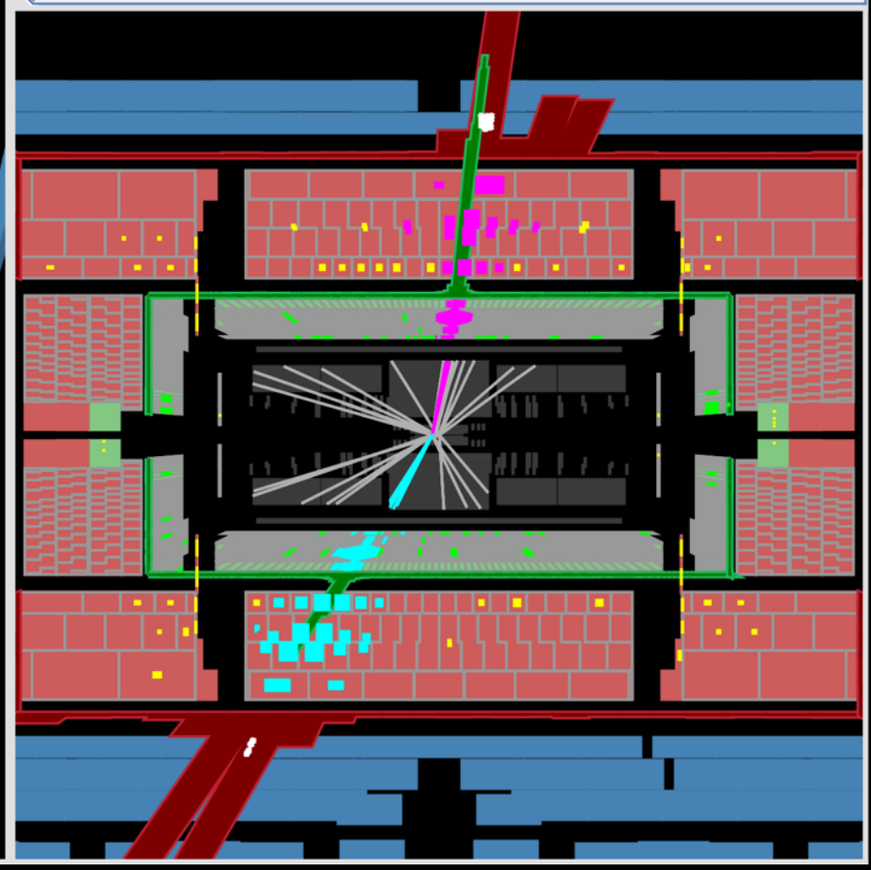
[Phys. Lett. B 754, 302]



highest di-object mass ever observed

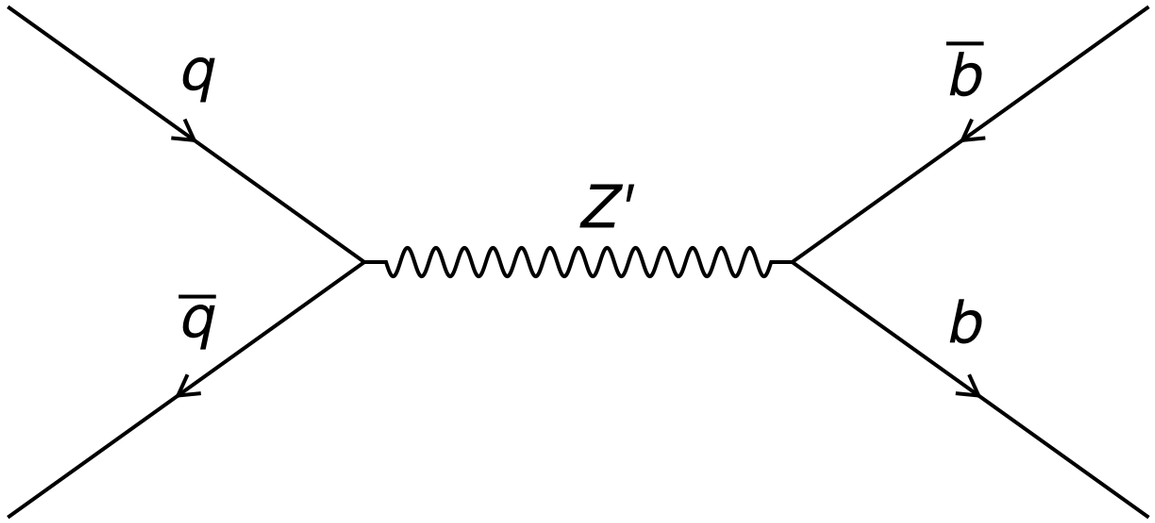



ATLAS
EXPERIMENT
Run Number: 280673, Event Number: 1273922482
Date: 2015-09-29 21:32:53 CEST
1600 ET (GeV)
1440
1280
1120
960
800
640
480
320
160
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ



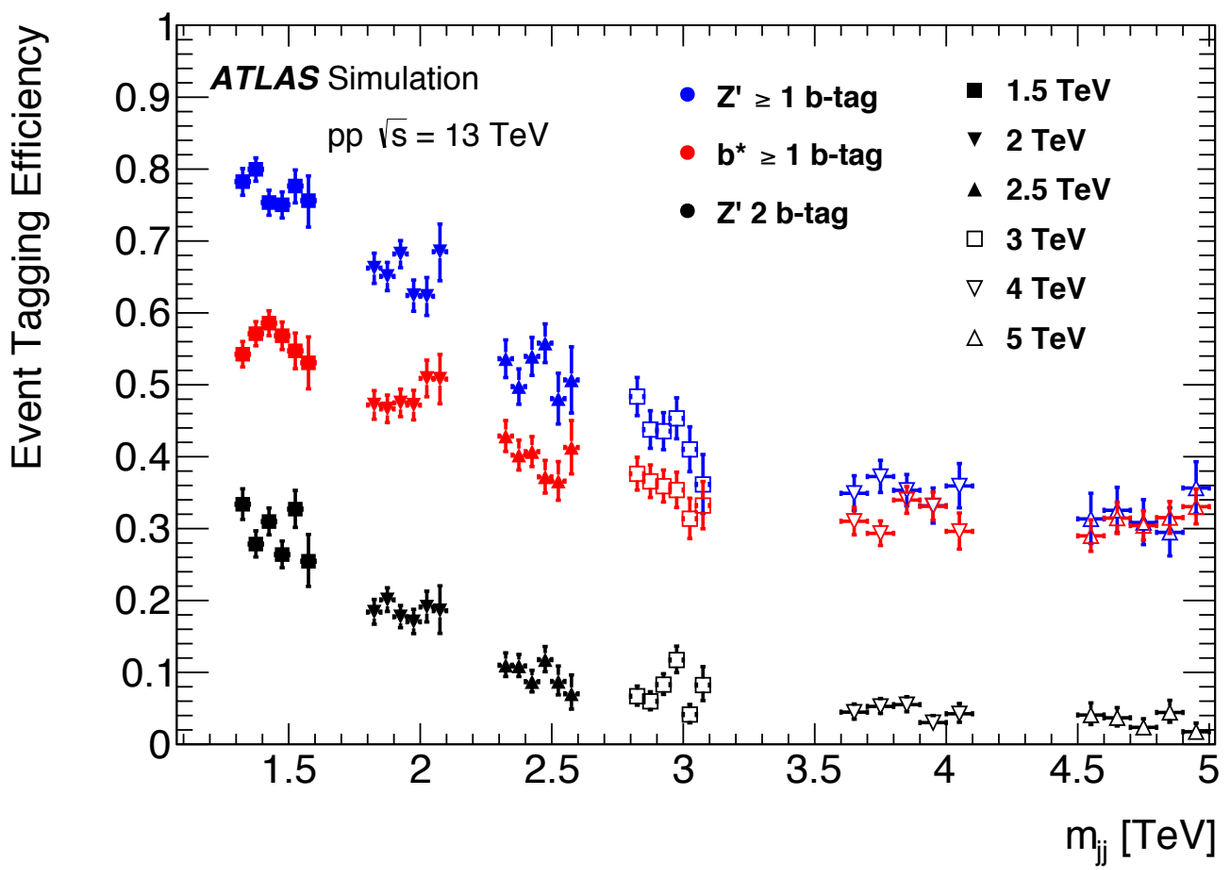
high-mass di-b-jet resonances

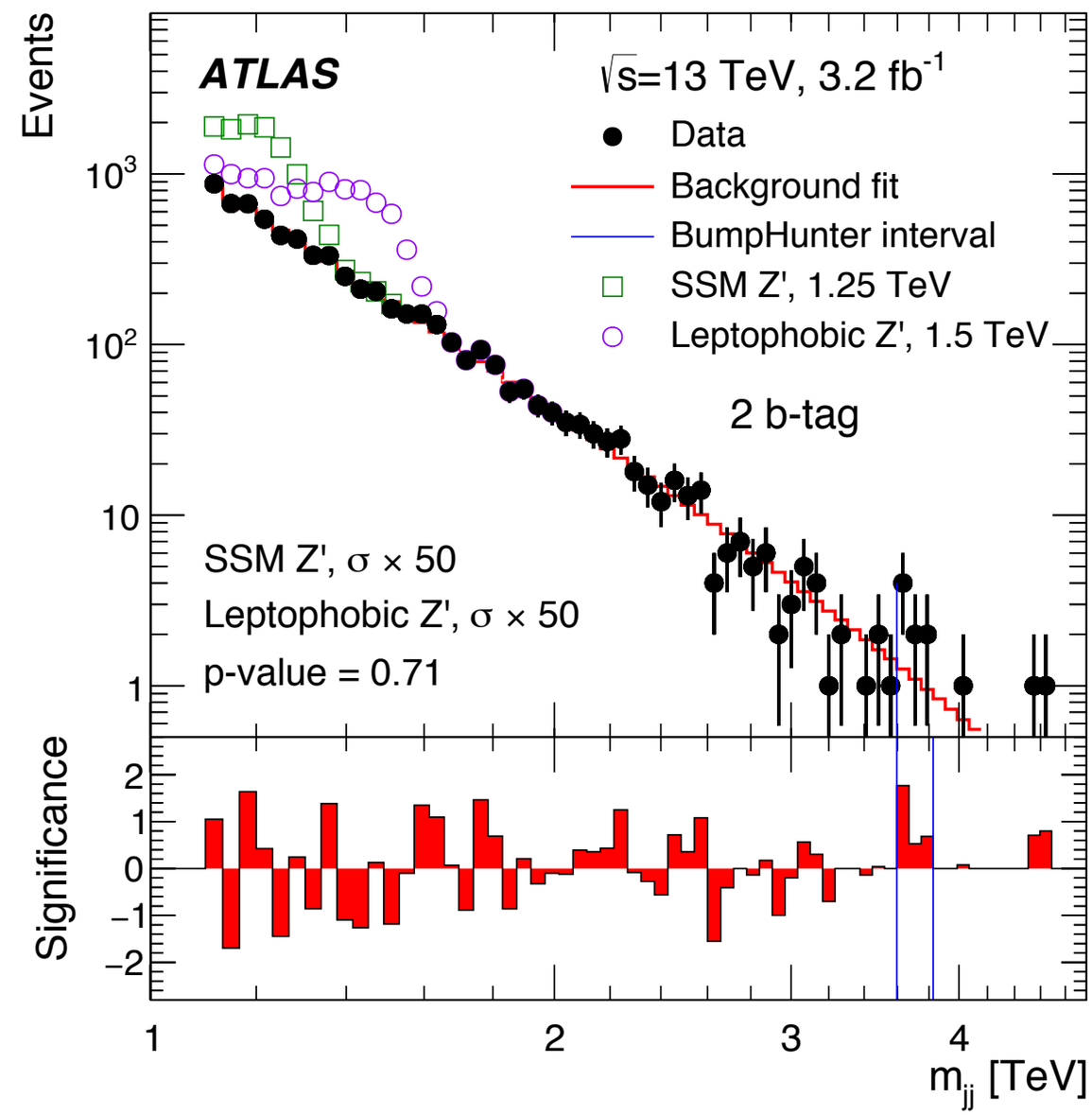
[Phys. Lett. B 759, 229]



challenge:

- b-tagging efficiency at high p_T (instrumental limitations)





low-mass dijet resonances

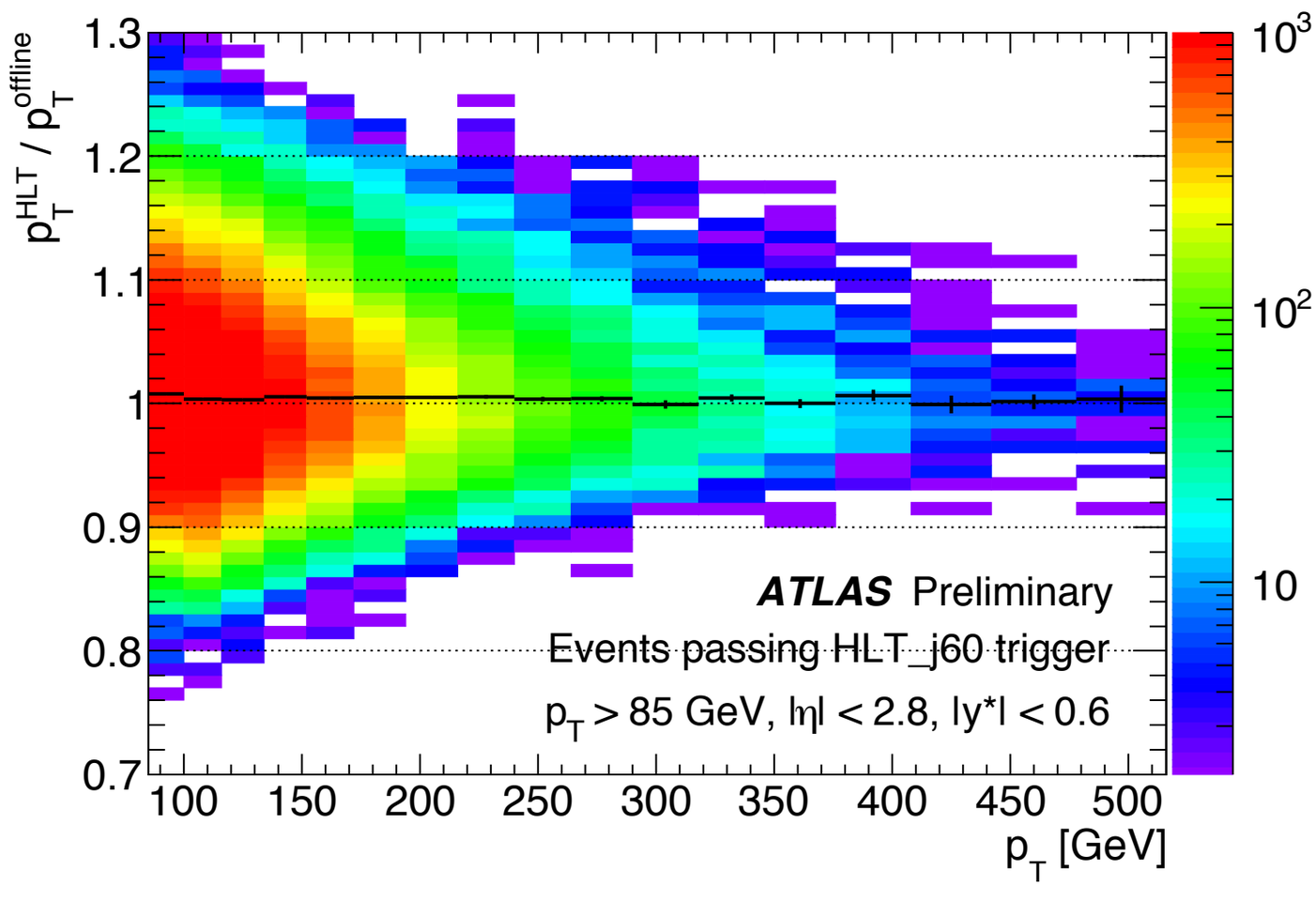
[ATLAS-CONF-2016-030]

NEW

hot from the press:

- data scouting (trigger-object-level) search in mass region 450 - 900 GeV
- avoids high trigger pre-scales for full analysis

- dedicated trigger-level jet calibration



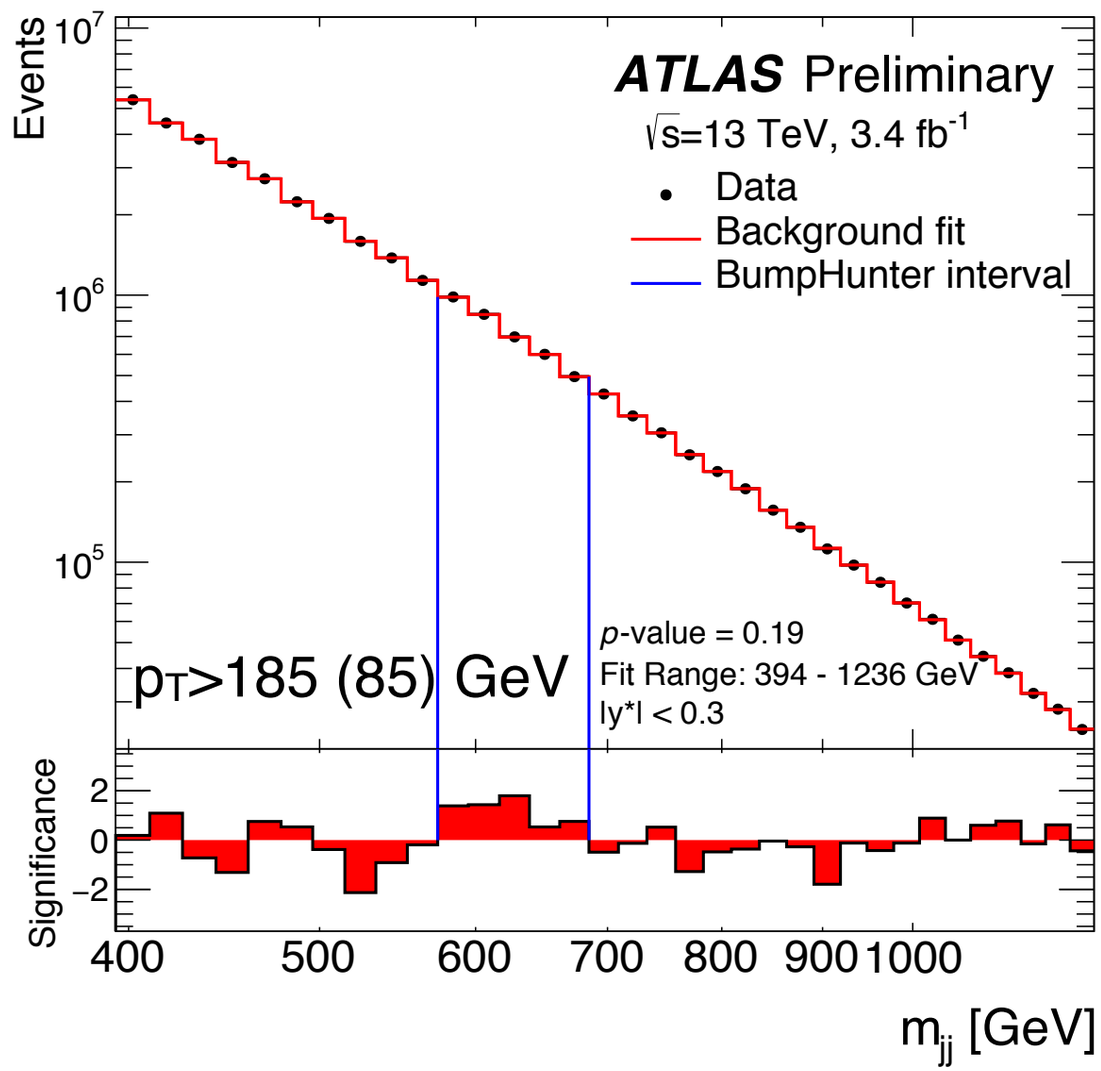
low-mass dijet resonances

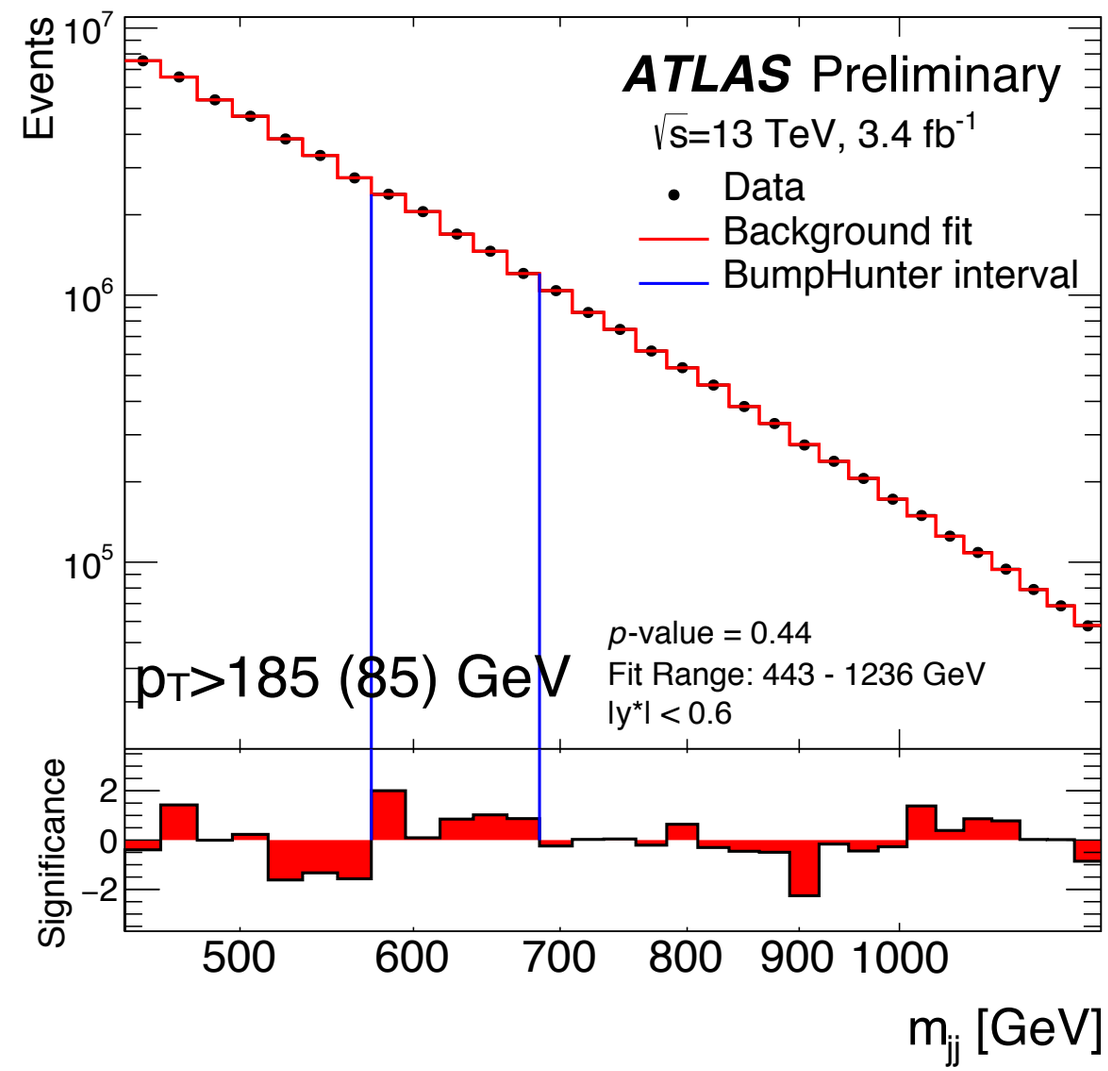
[ATLAS-CONF-2016-030]

NEW

results:

- empirical function to fit the background spectrum
- analyse all possible mass intervals for excess
- most discrepant interval 574-685 GeV (0.8 σ)
- excludes gaussian excess with cross sections 3 pb (450 GeV) to 0.7 pb (900 GeV)





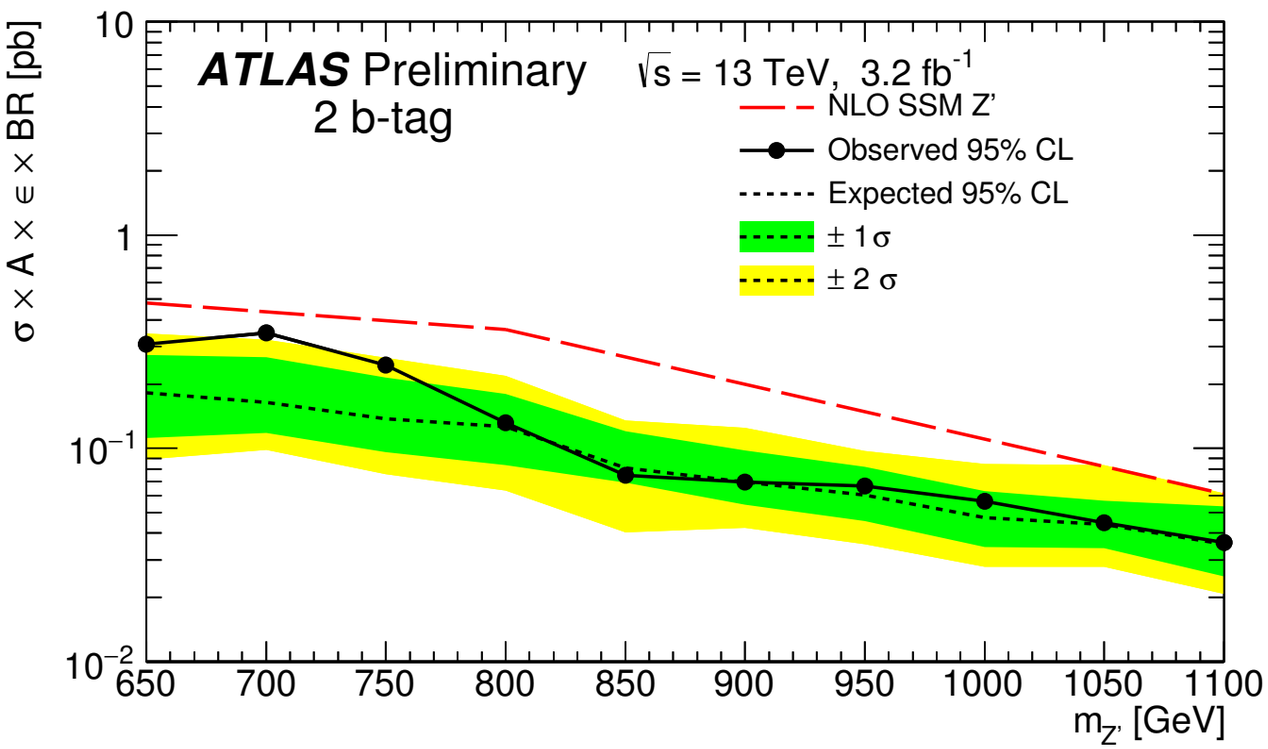
low-mass di-b-jet resonances

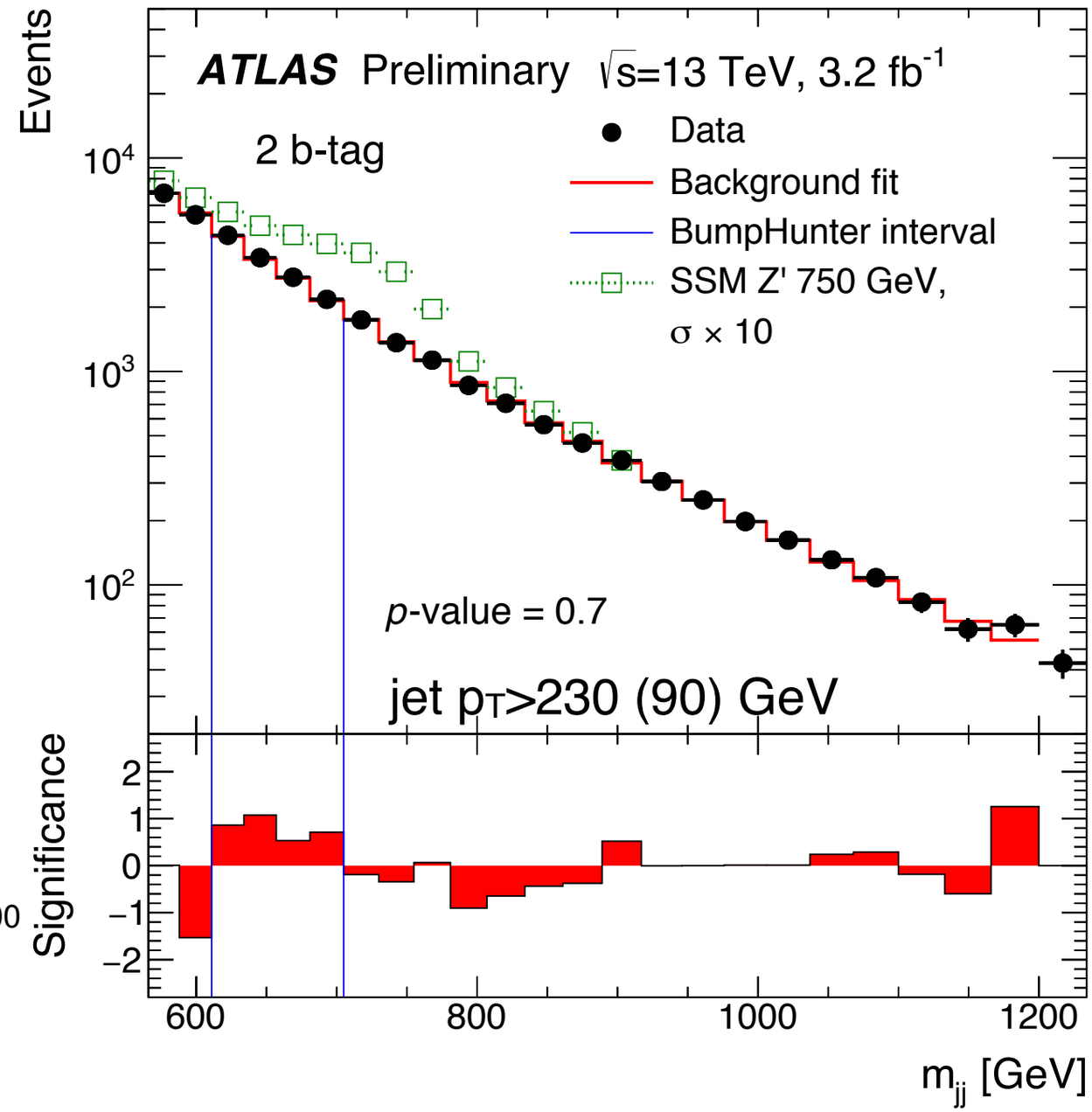
[ATLAS-CONF-2016-031]

NEW

hot from the press:

- search in mass region 570 - 1200 GeV
- b-tagged triggers → full offline analysis





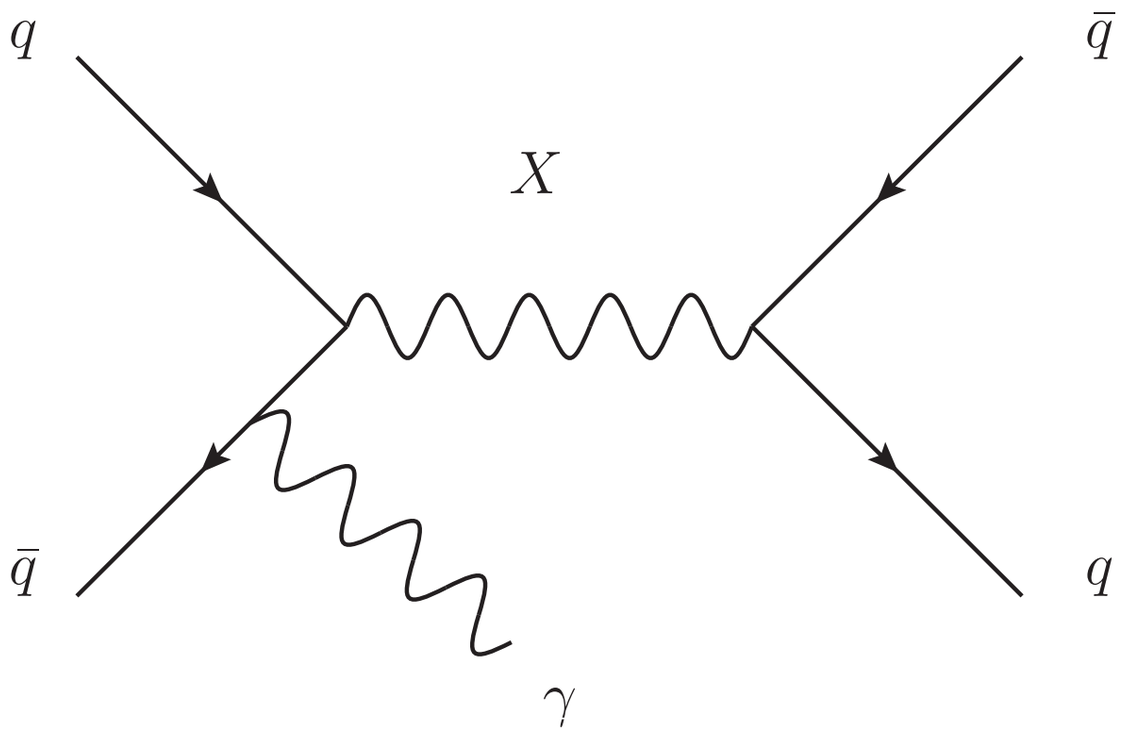
low-mass dijet resonances

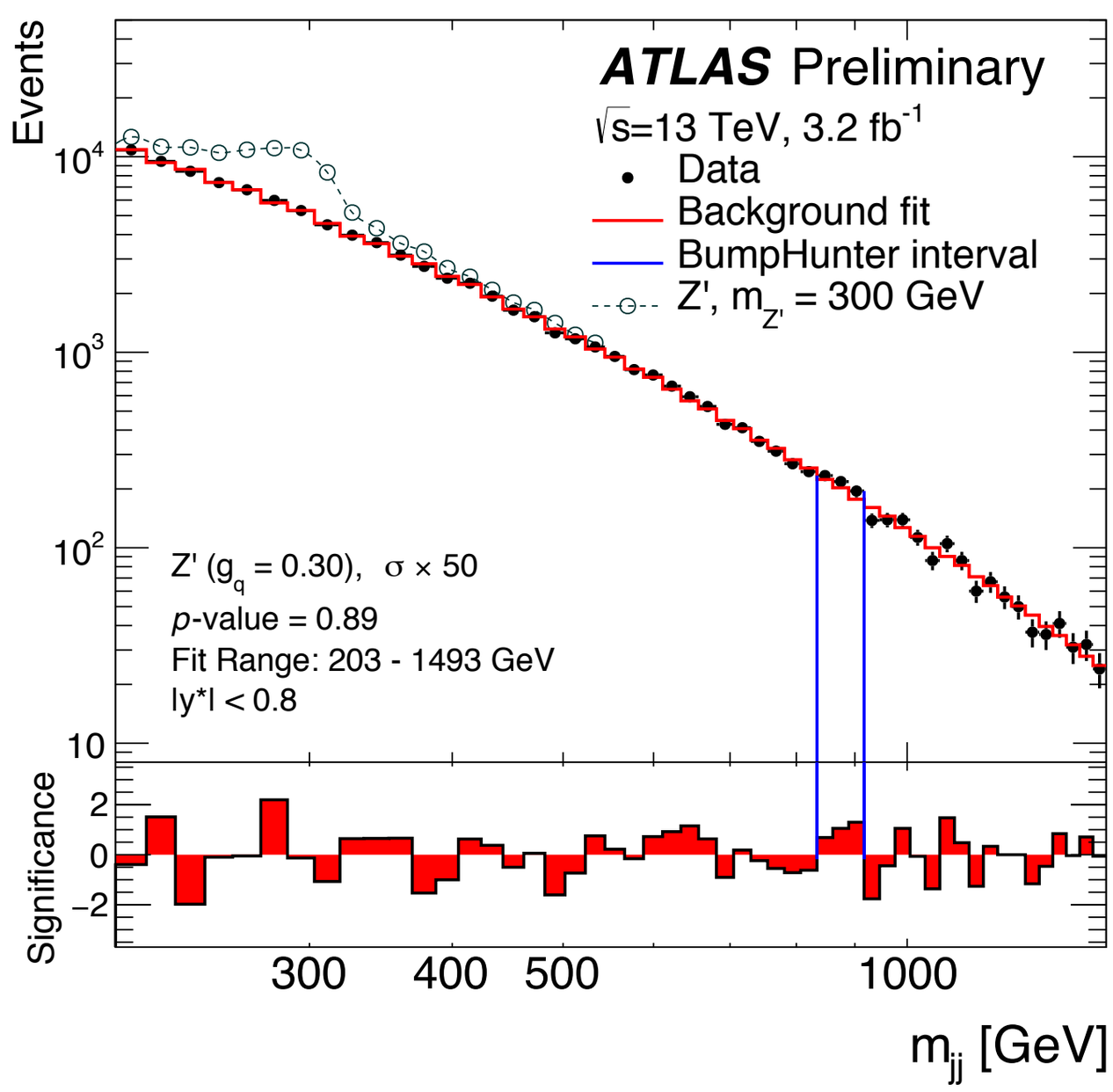
[ATLAS-CONF-2016-029]

NEW

alternative approach:

- exploit initial state photon for triggering dijets (isolated photon p_T>120 GeV)





- excludes gaussian excess with cross sections 100 fb (250 GeV) to 10-20 fb (1200 GeV)

summary

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (3.2 - 20.3) fb^{-1} $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.86 TeV	$n = 2$	Preliminary
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	M_{th} 8.3 TeV	$n = 6$	1512.01530
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	ATLAS-CONF-2016-006
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	3.2	G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	3.2	G_{KK} mass 475-785 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-017
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	3.2	Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		Preliminary
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	3.2	W' mass 4.07 TeV		ATLAS-CONF-2015-063
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	3.2	W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \to WZ \to qqqq$ model A	–	2 J	–	3.2	W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	3.2	W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \to ZH \to \nu\nu bb$ model B	0 e, μ	1-2 b, 1-0 j	Yes	3.2	Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	Λ 17.5 TeV	$\eta_{LL} = -1$	1512.01530
	CI $qq\ell\ell$	2 e, μ	–	–	3.2	Λ 23.1 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2015-070
	CI $uutt$	2 e, μ (SS)	≥ 1 b, 1-4 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 140$ GeV	Preliminary
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A 650 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 10$ GeV	Preliminary
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.07 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.03 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	3.6	q^* mass 5.2 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.01530
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	3.2	b^* mass 2.1 TeV		Preliminary
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

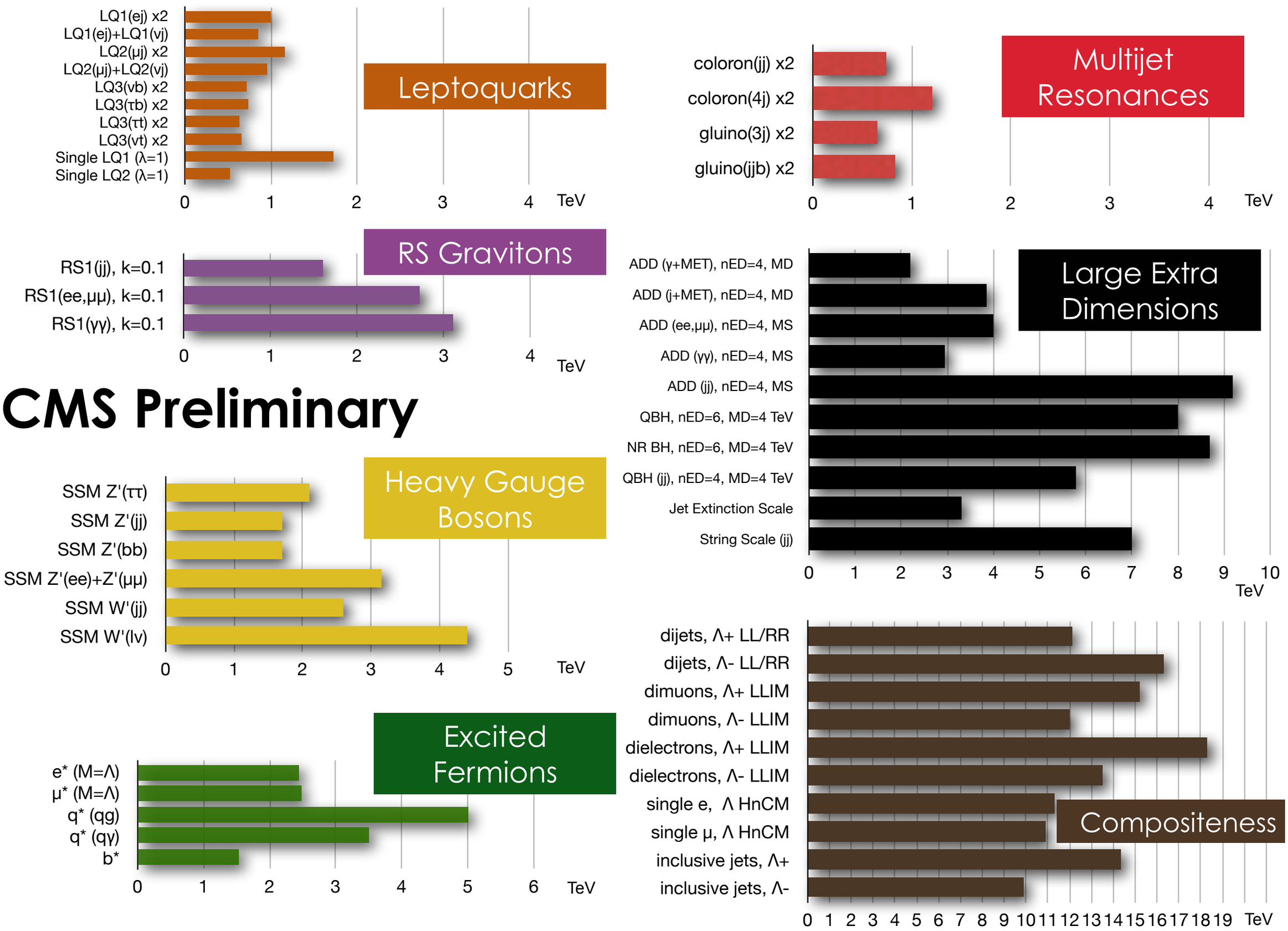
$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

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

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

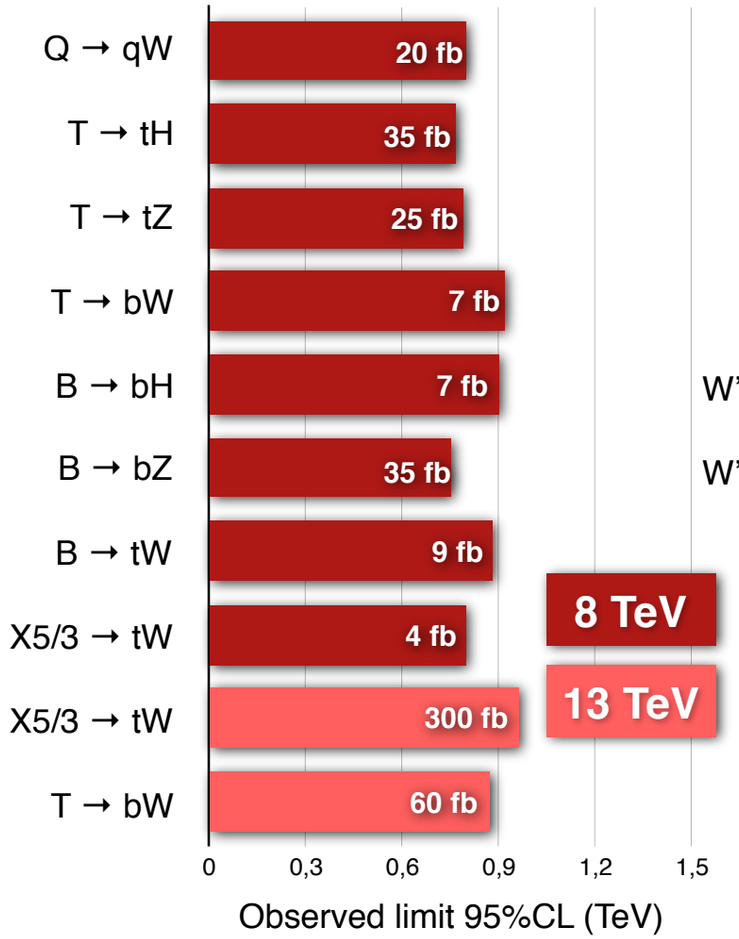
†Small-radius (large-radius) jets are denoted by the letter j (J).

summary

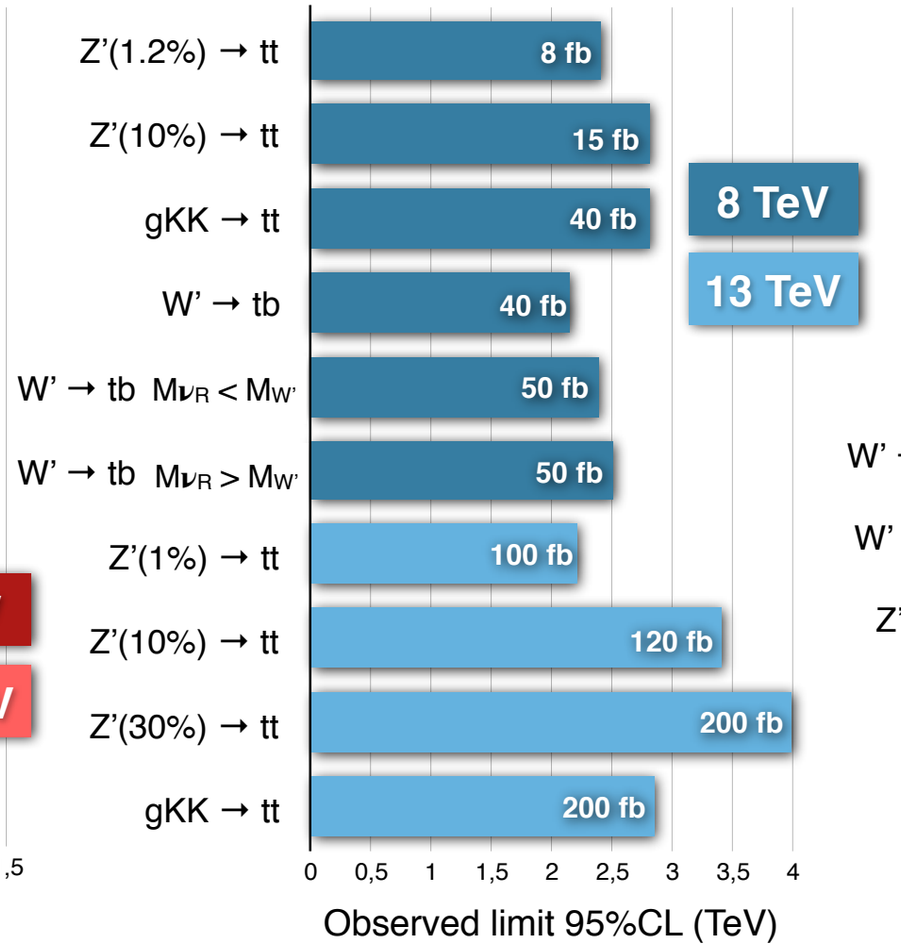

Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(ee,μμ), k=0.1
RS1(γγ), k=0.1
0 1 2 3 4 TeV
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 1 2 3 4 5 6 7 8 9 10 TeV
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
0 1 2 3 4 5 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4 5 6 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV

summary

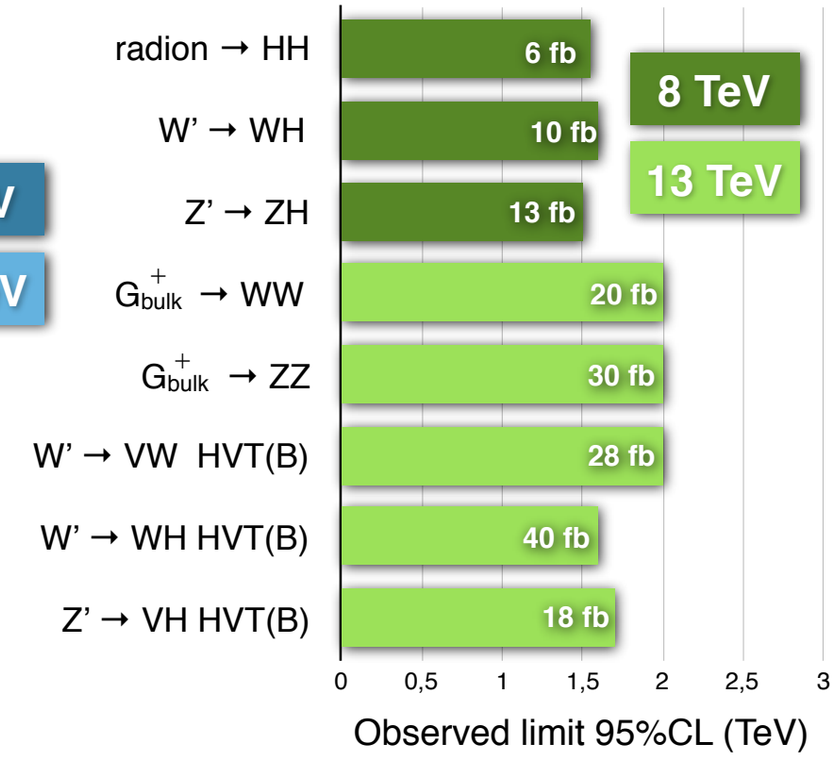
Vector-like quark pair production



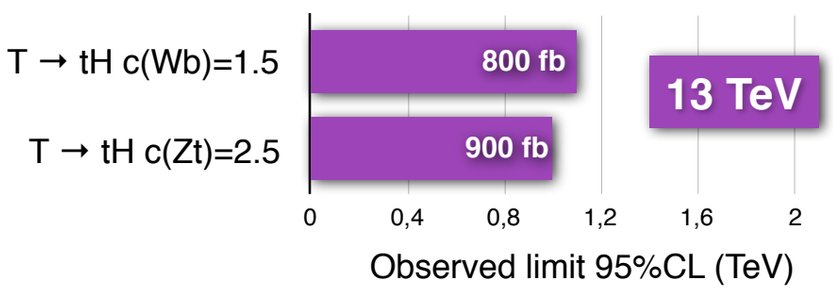
Resonances to heavy quarks



Resonances to dibosons

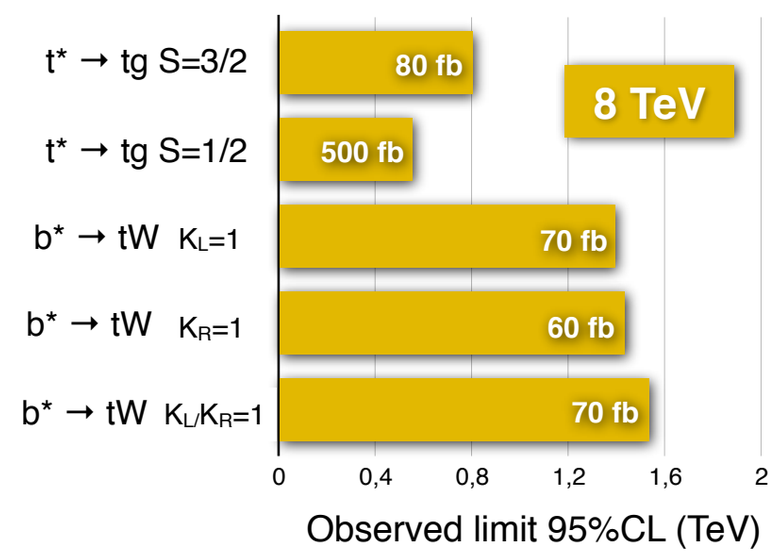


Vector-like quark single production



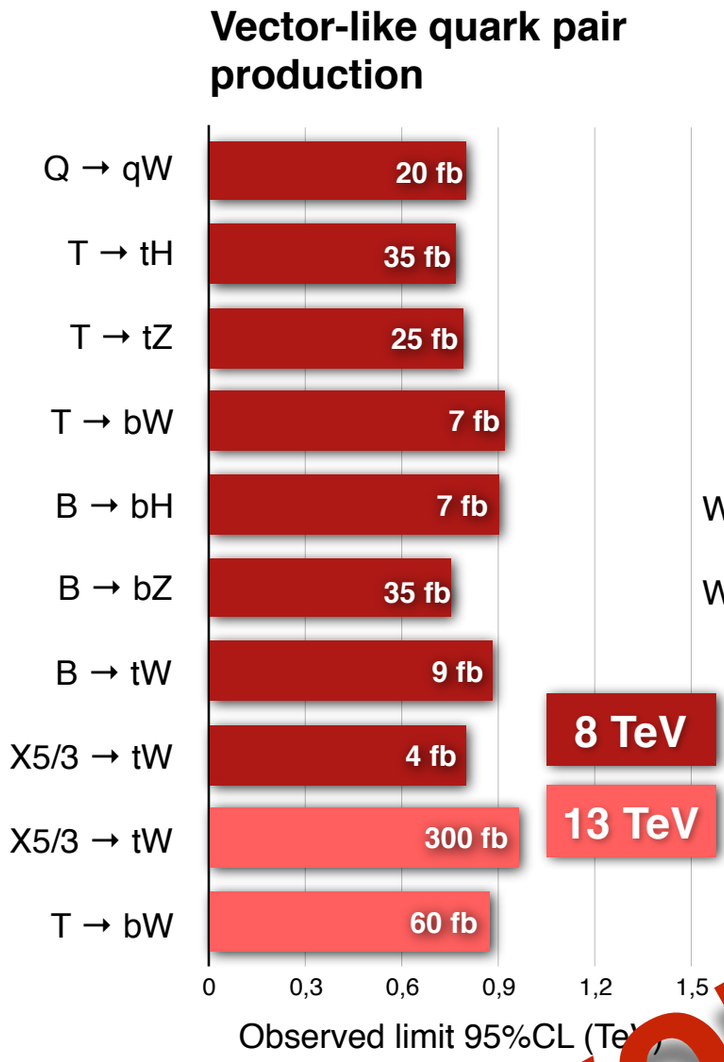
B2G: new physics searches with heavy SM particles

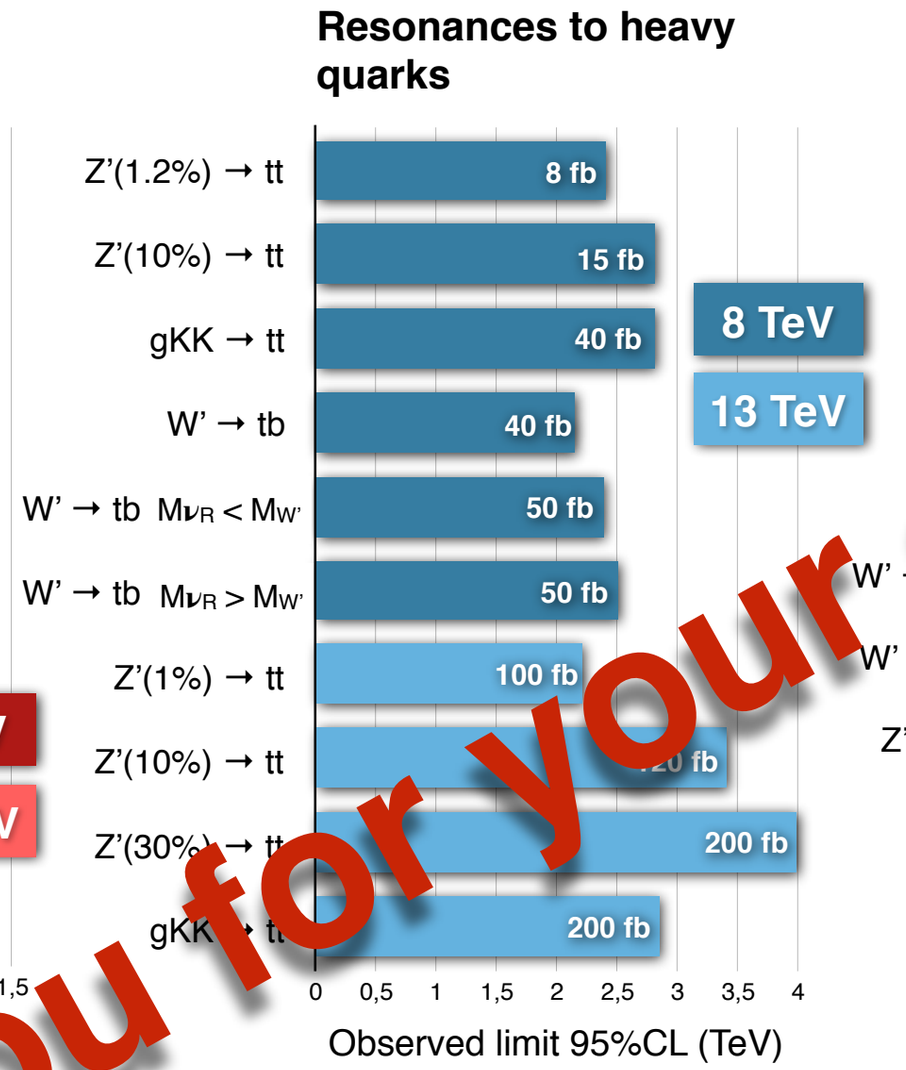
Excited quarks

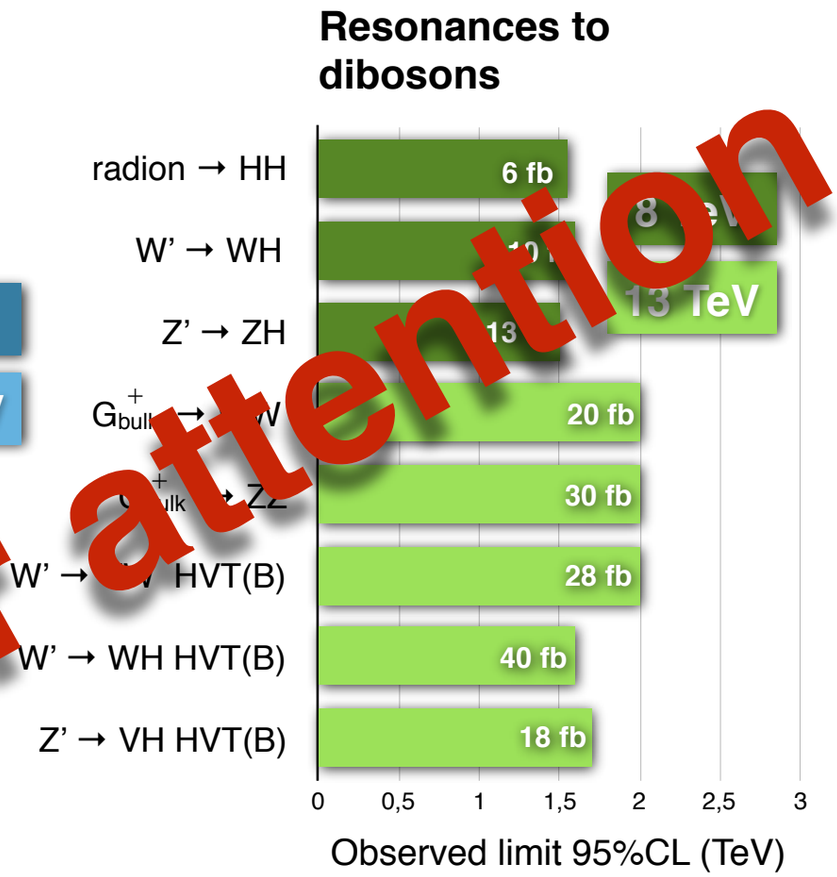


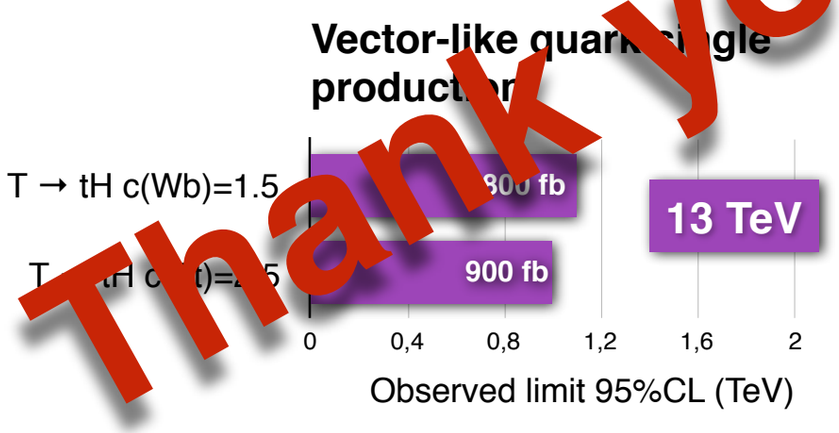
+model-independent

summary

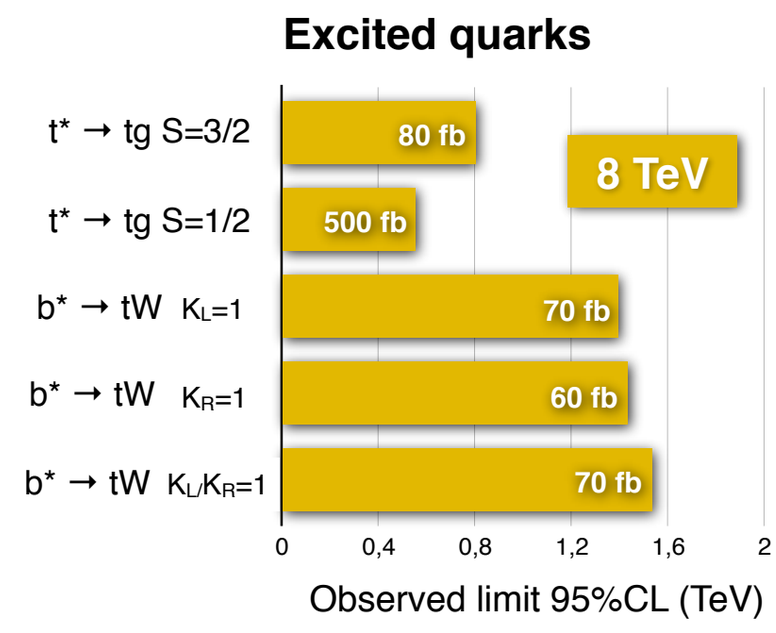








B2G: new physics searches with heavy SM particles



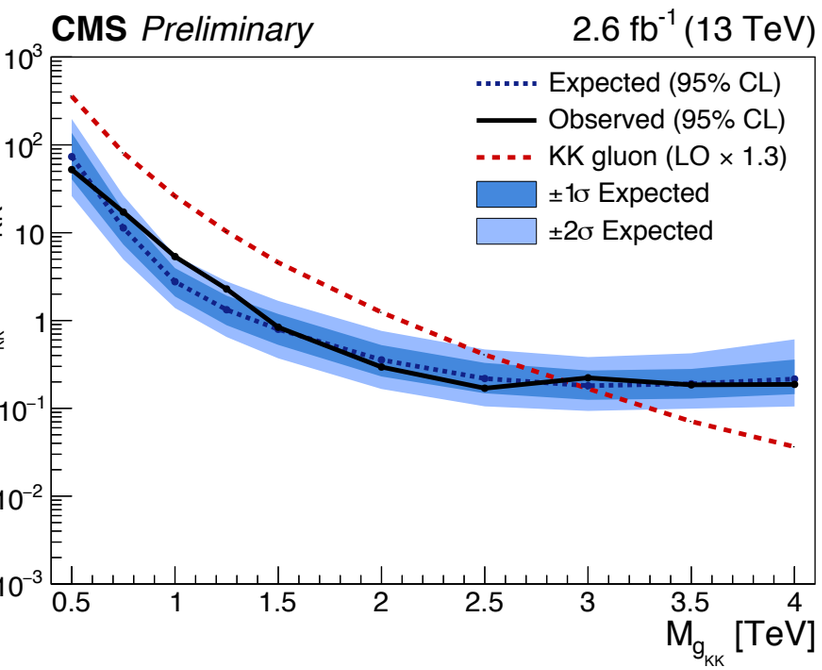
Thank you for your attention

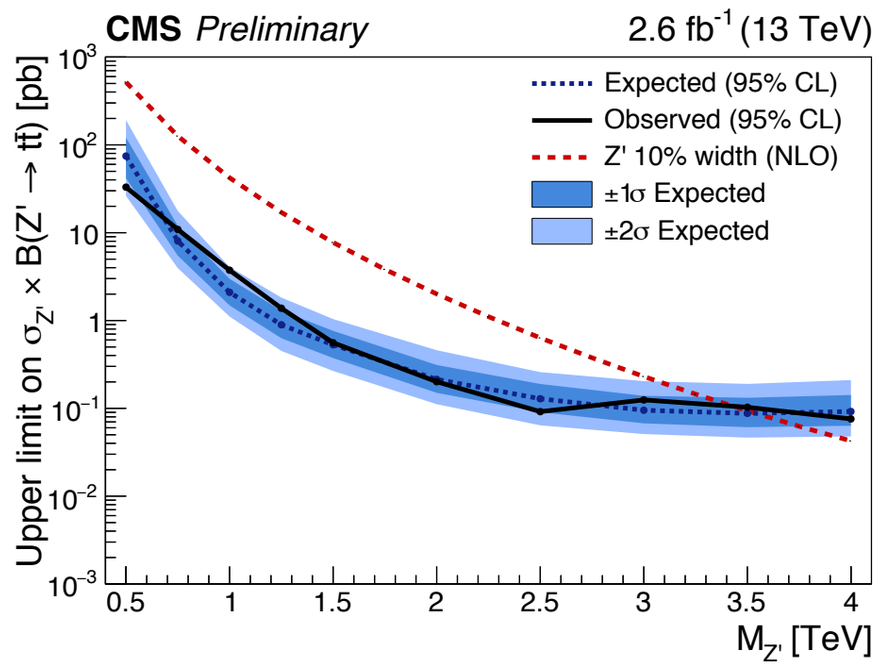
+model-independent

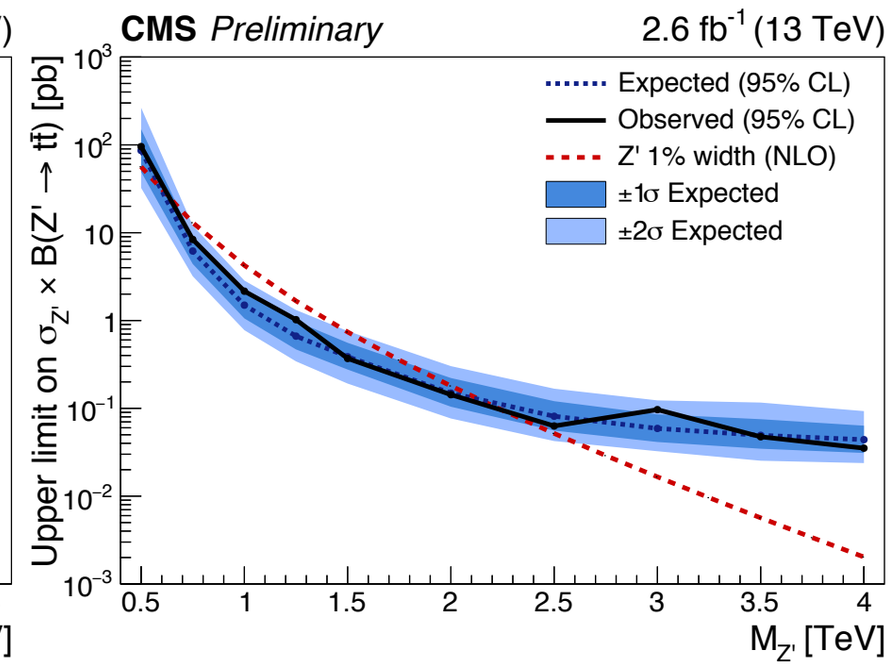
backup

tt resonances: semi-leptonic

[CMS-PAS-B2G-15-002]



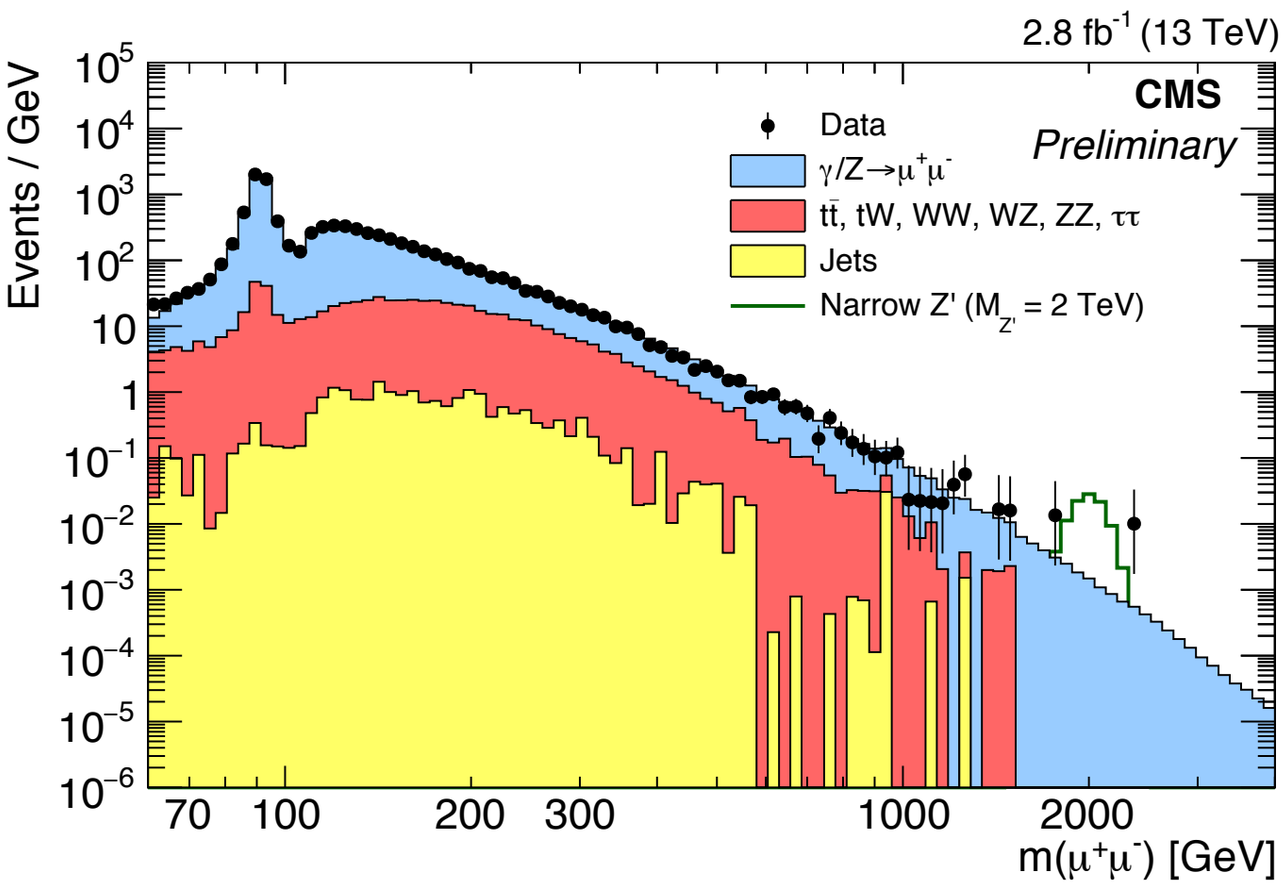


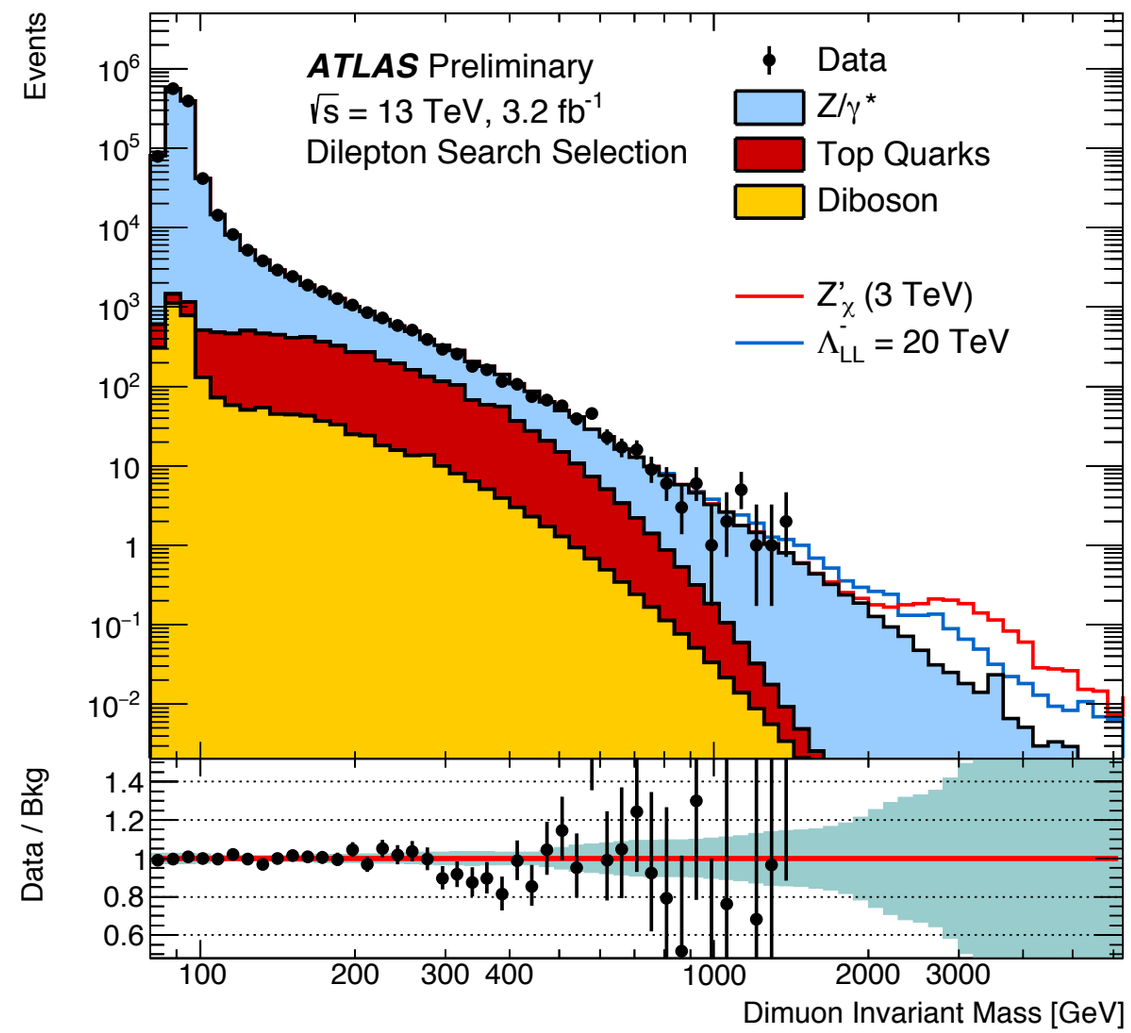


signal	excluded mass regions [TeV]			8 TeV combination
	μ + jets observed (expected)	e + jets observed (expected)	combination observed (expected)	
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)	2.4 (2.4)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)	2.9 (2.8)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)	
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)	2.8 (2.7)

dilepton resonances

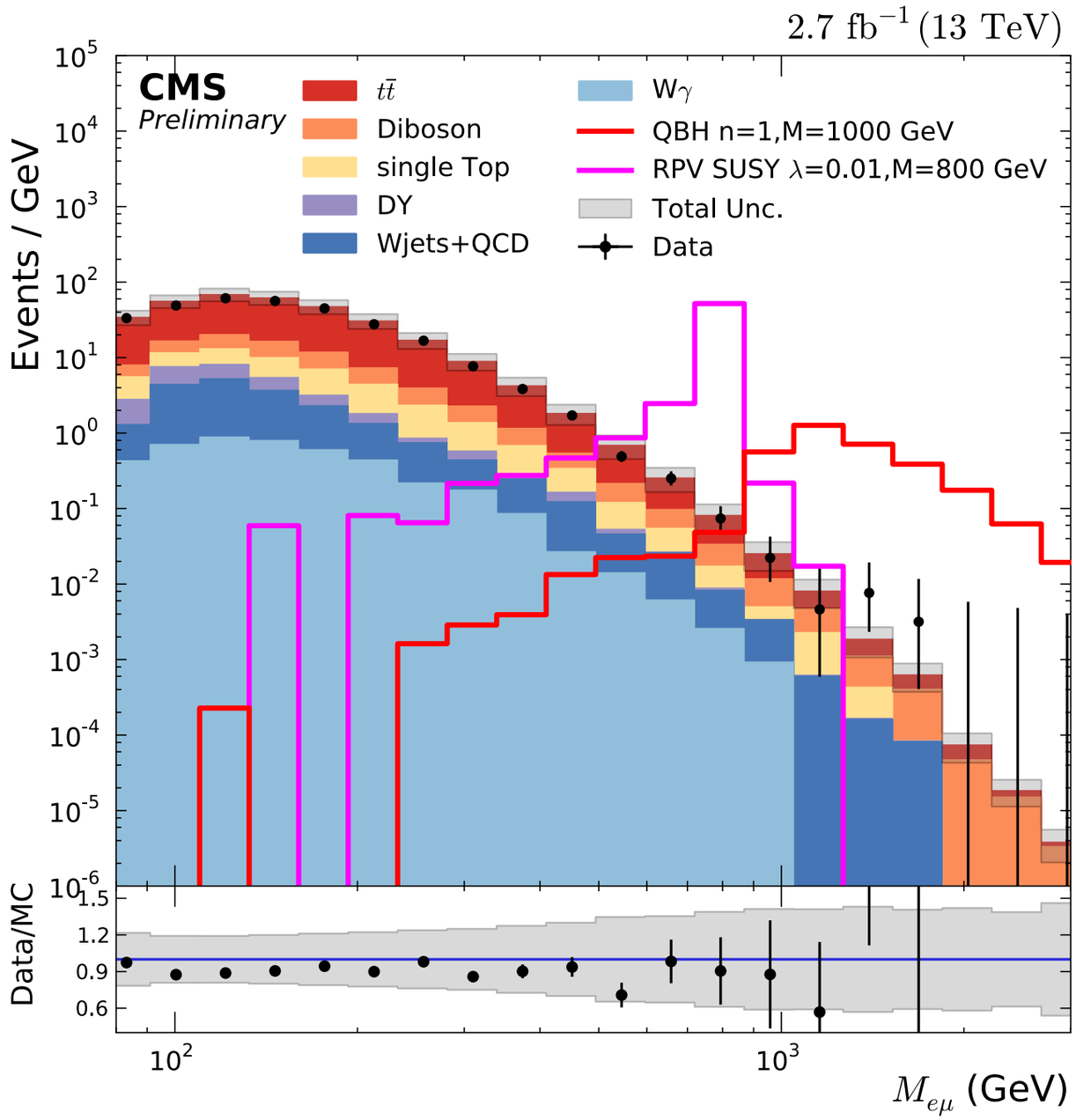
- muons

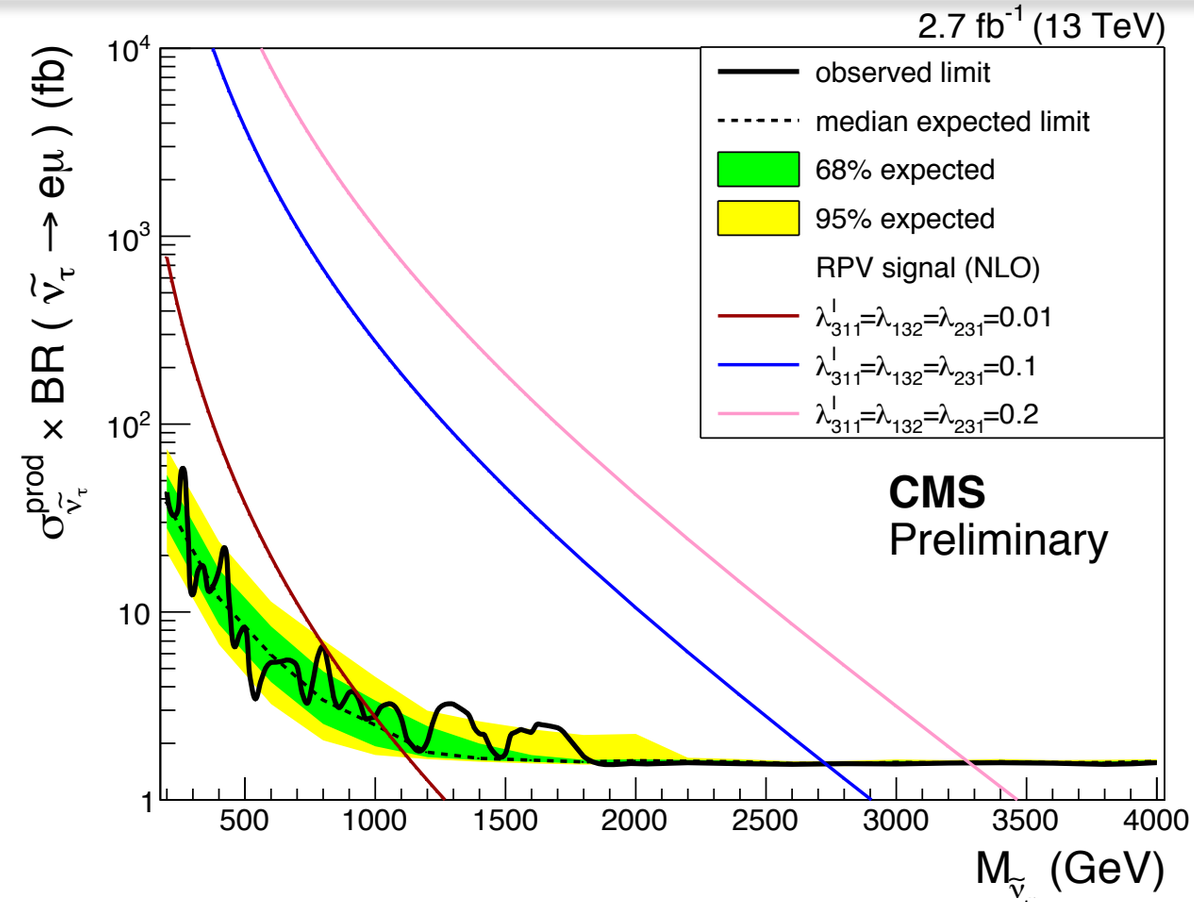


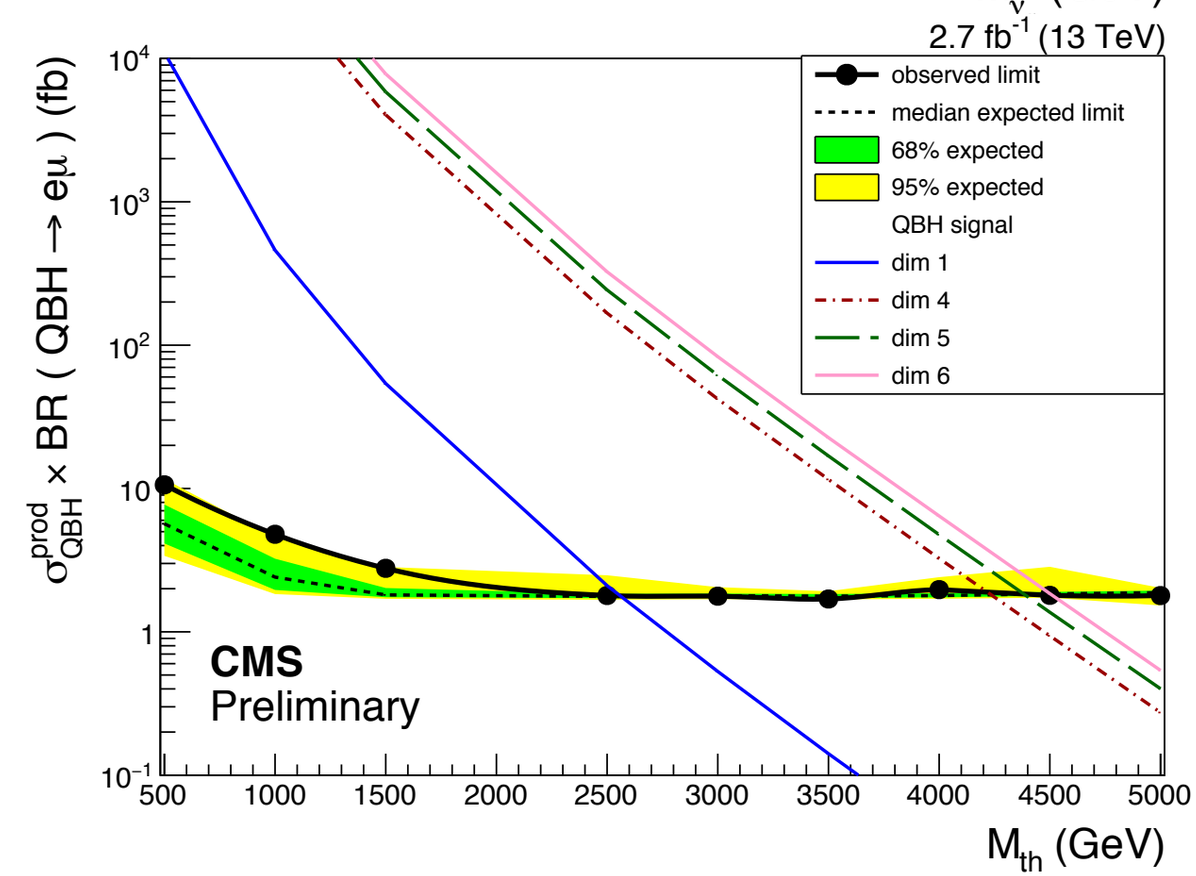


e-mu resonances

[CMS-PAS-EXO-16-001]



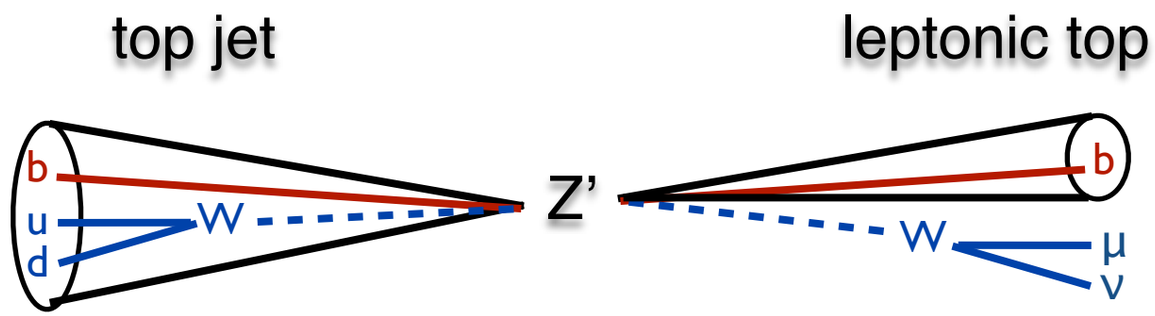




tt resonances: semi-leptonic

[CMS-PAS-B2G-15-002]

- top tagging
- b-tagging



- b-tagging
- **lepton isolation**

lepton isolation:

- mini-isolation:

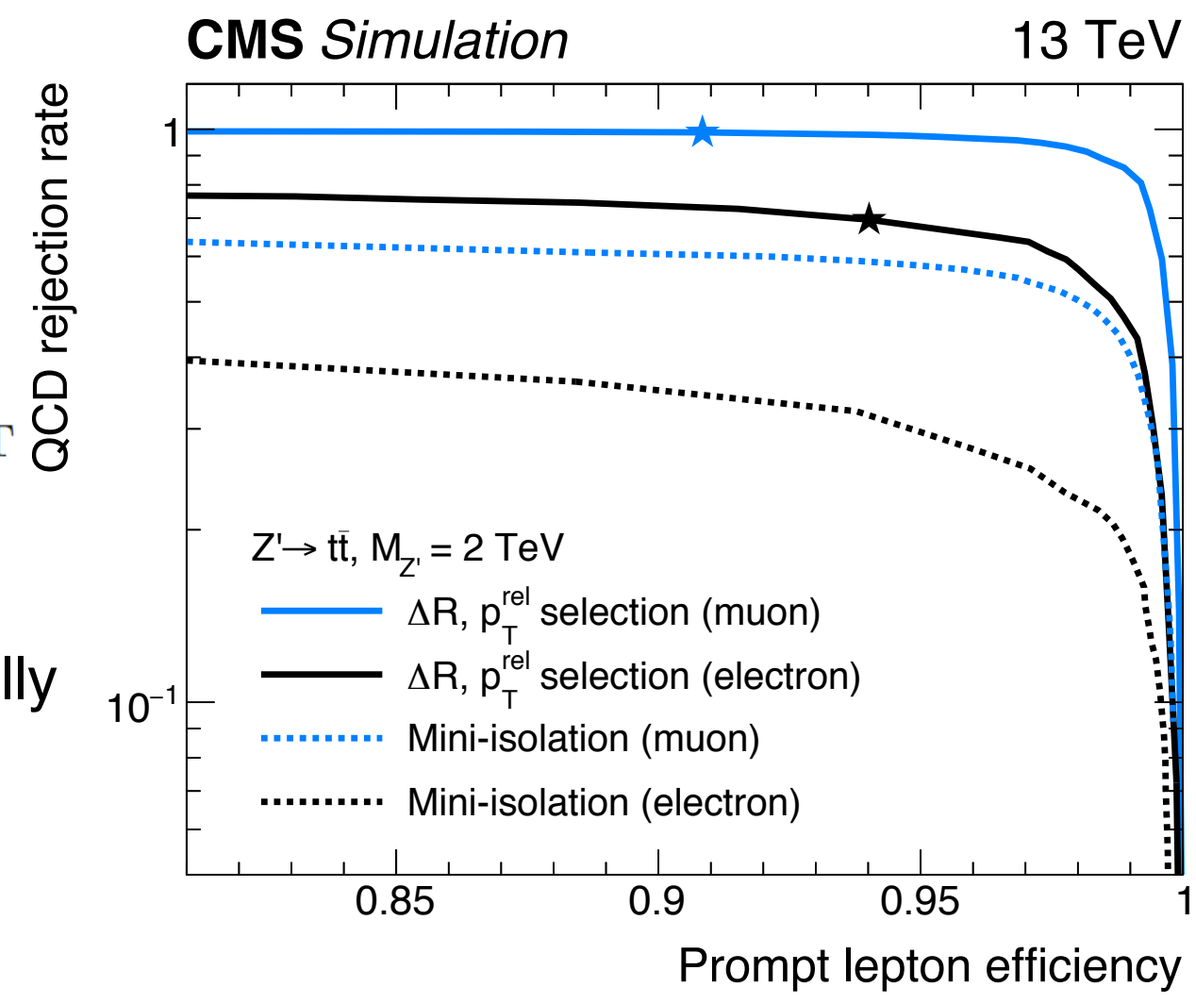
$$I^{\ell}_{\mathrm{mini}} = \sum_{\mathrm{tracks}} p_{\mathrm{T}}^{\mathrm{track}} \,, \quad \Delta R(\ell, \mathrm{track}) < K_{\mathrm{T}}/p^{\ell}_{\mathrm{T}}$$

$I^{\ell}_{\mathrm{mini}}/p^{\ell}_{\mathrm{T}} <$ desired value

chosen empirically

- 2D isolation:

$$\Delta R(\ell, j) > 0.4 \text{ or } p_T^{\mathrm{rel}}(\ell, j) > 20\,\mathrm{GeV}$$



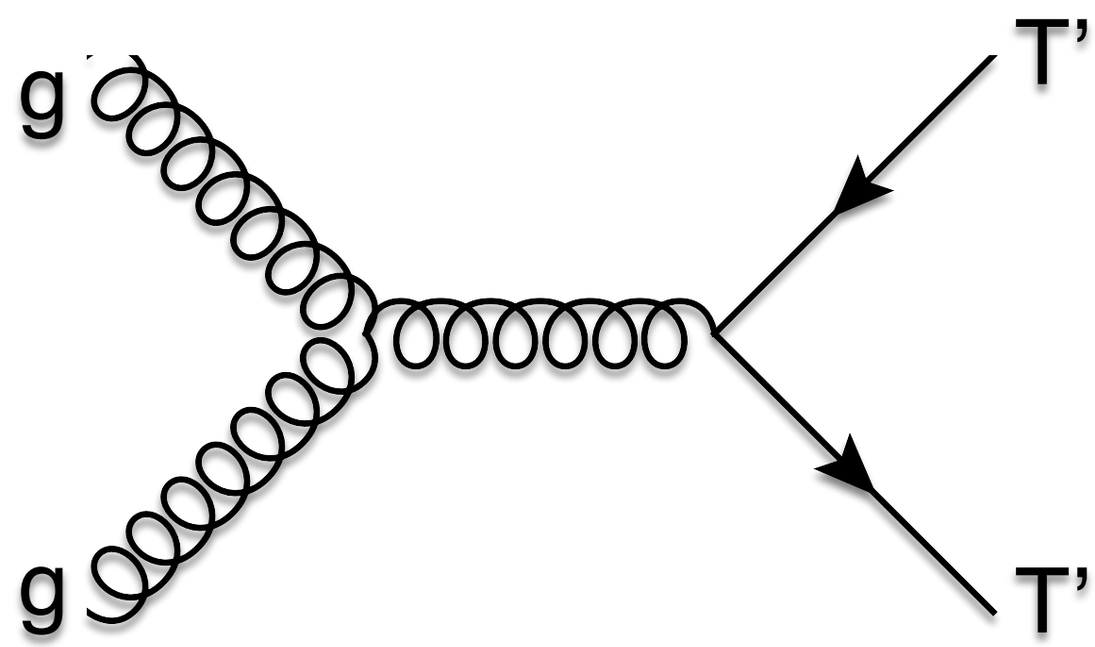
vector-like quarks

what are VLQ:

- they are quarks: coloured, charged, spin 1/2 particles
- no difference between chiralities: they couple to left- and right-handed charged currents (in the same way)

➡ VL quarks can have mass terms without violating gauge invariance!

- not constrained through Higgs discovery
- new motivation through di-photon excess
- decay modes:
  T→ tH, tZ, bW
  B→bH, bZ, tW



$X^{5/3} \rightarrow tW$

vector-like quarks

[JHEP 08 (2015) 105]

Singlets

$$\mathbf{1}_{2/3} = T$$

$$\mathbf{1}_{-1/3} = B$$

Doublets

$$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$$

$$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$$

$$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$$

Triplets

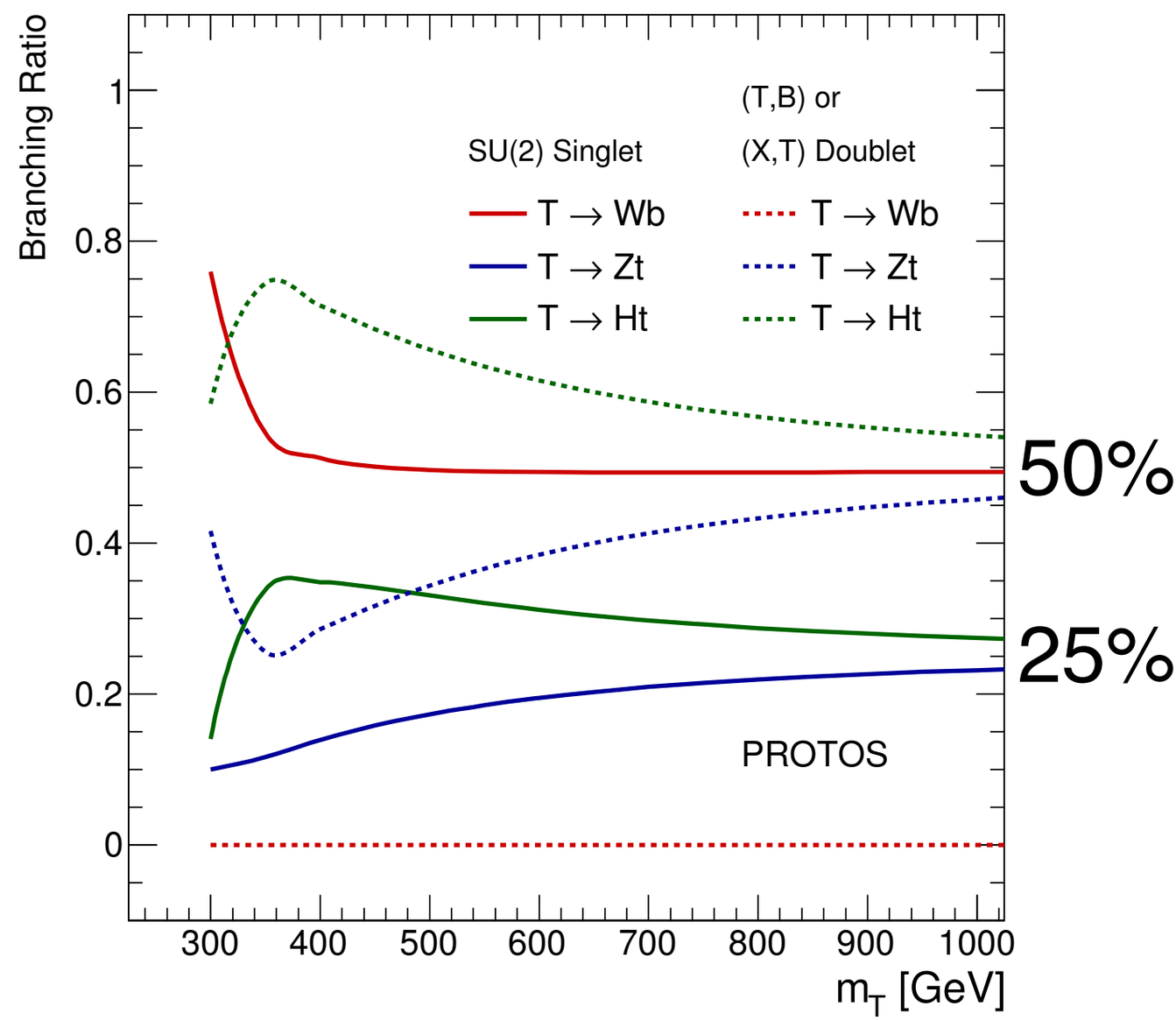
$$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$$

$$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$$

Notation:

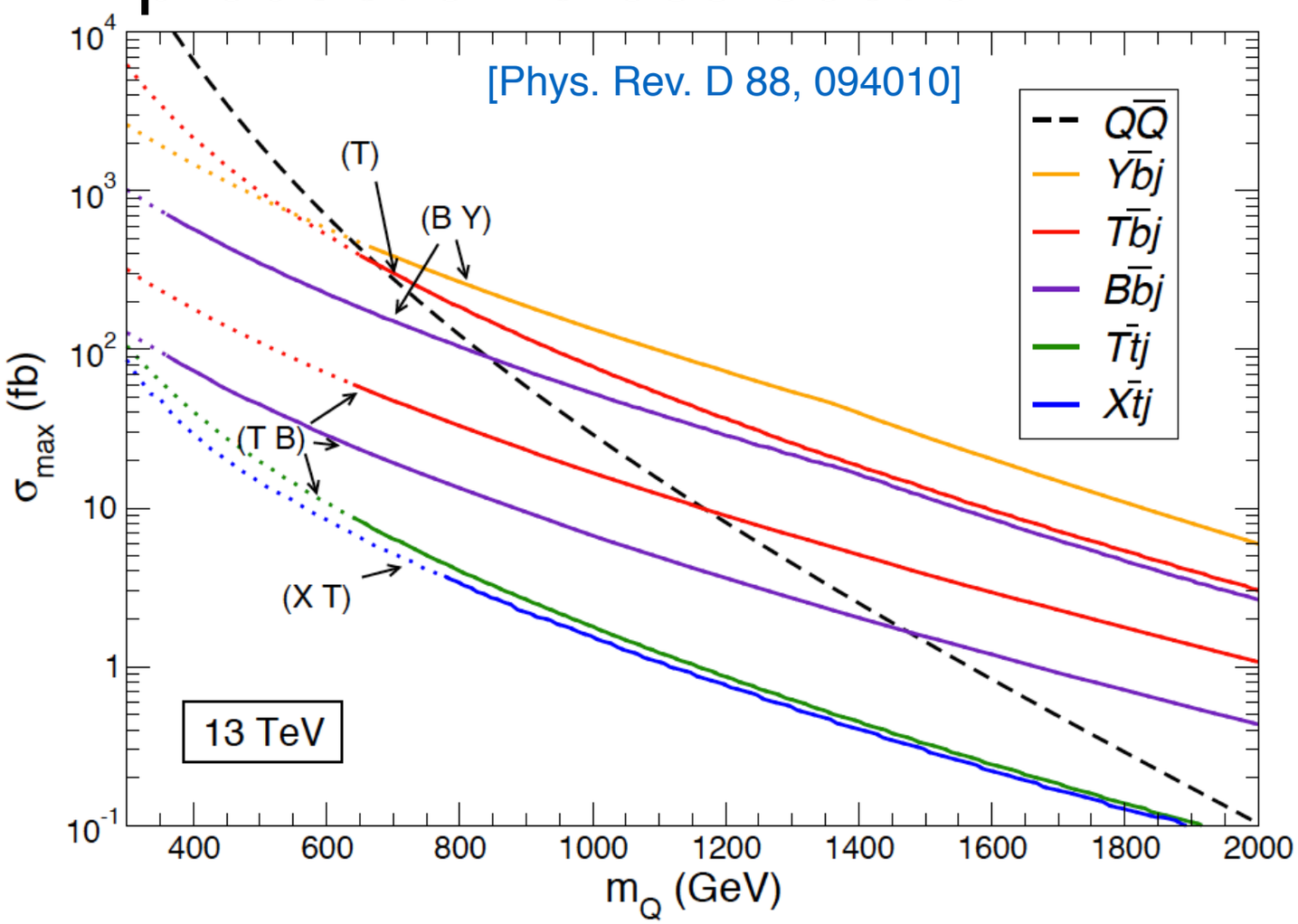
$\text{Isospin}_{\text{Hypercharge}}$

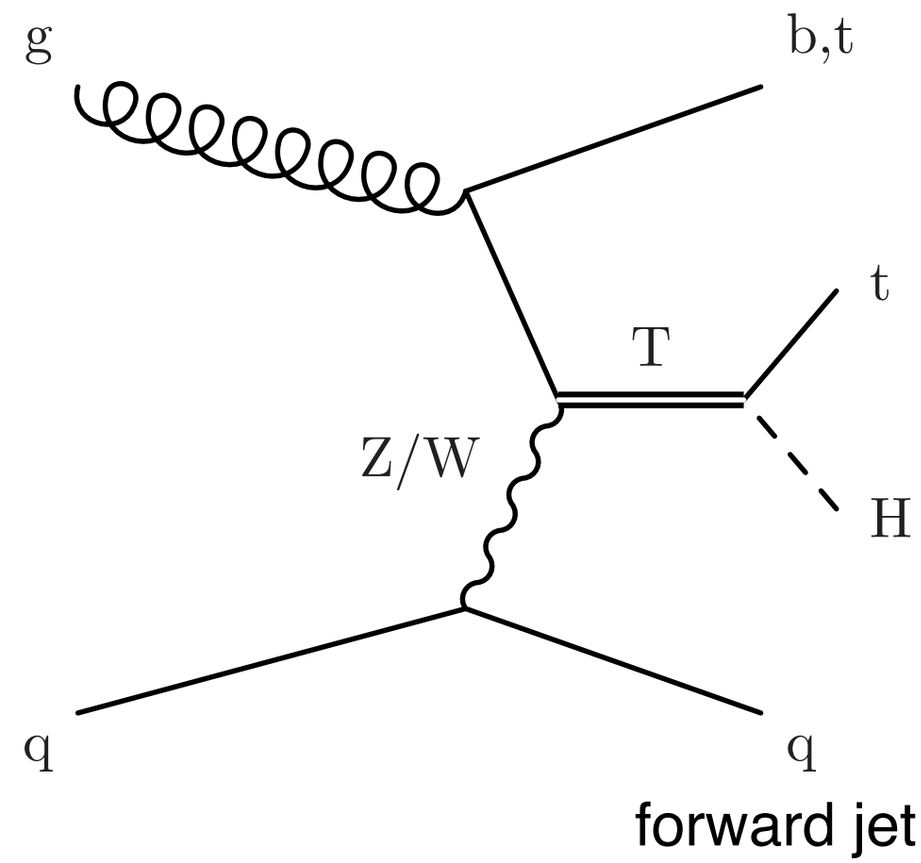
$$\left.\begin{array}{l} T \to +2/3 \\ B \to -1/3 \\ X \to +5/3 \\ Y \to -4/3 \end{array}\right\} \text{Electric charge}$$



vector-like quarks: single production

production cross-section:





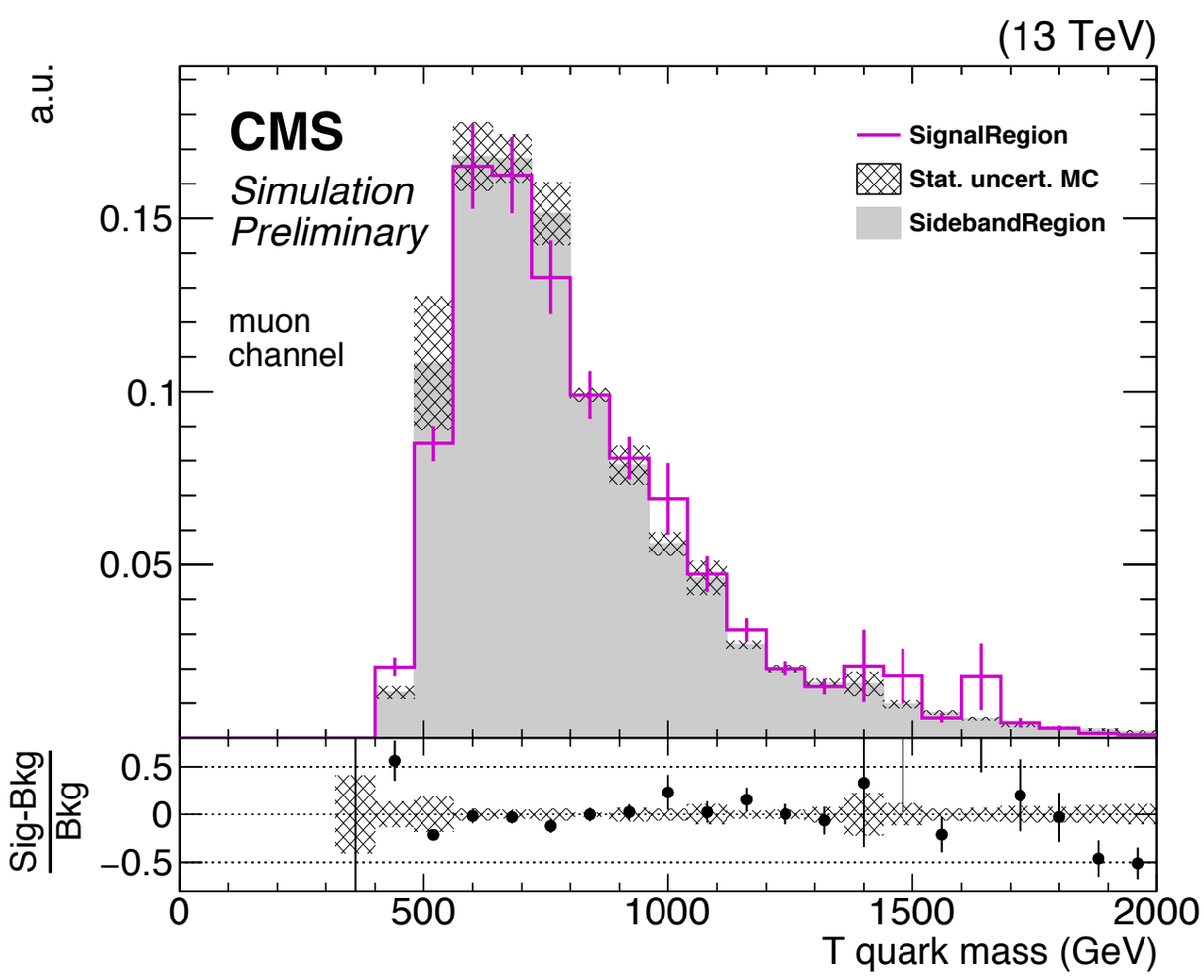
- higher cross sections at high masses
- allows to set limits on model parameters

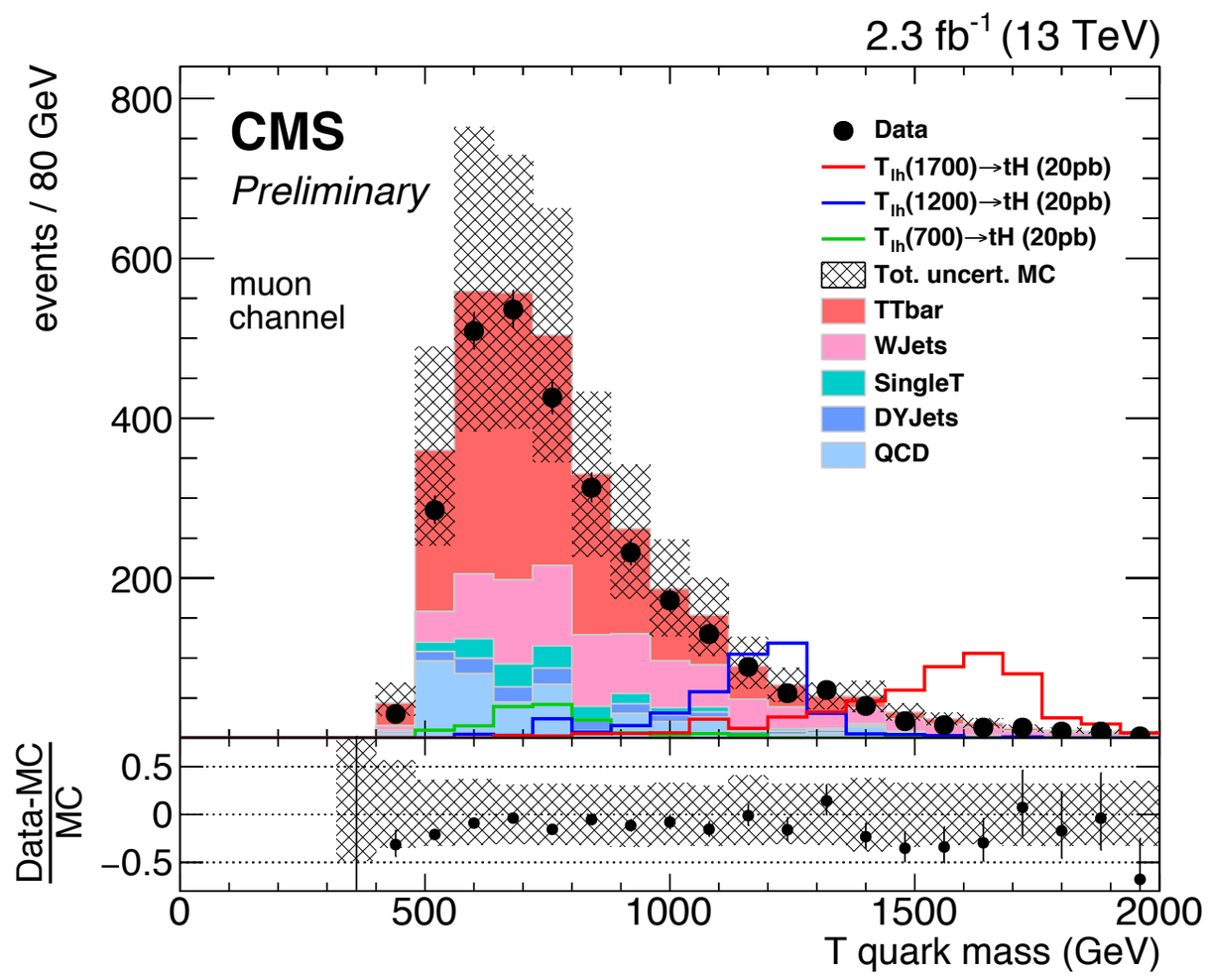
vector-like quarks: single production T→tH [CMS-PAS-B2G-15-008]

background estimation

- entirely data-driven (shapes and normalisation)
- background region: no forward jet, subjet b-tag veto

region	signal	sideband
number of subjet b-tags (H cand.)	exactly 2	exactly 1
number of forward jets	at least 1	exactly 0



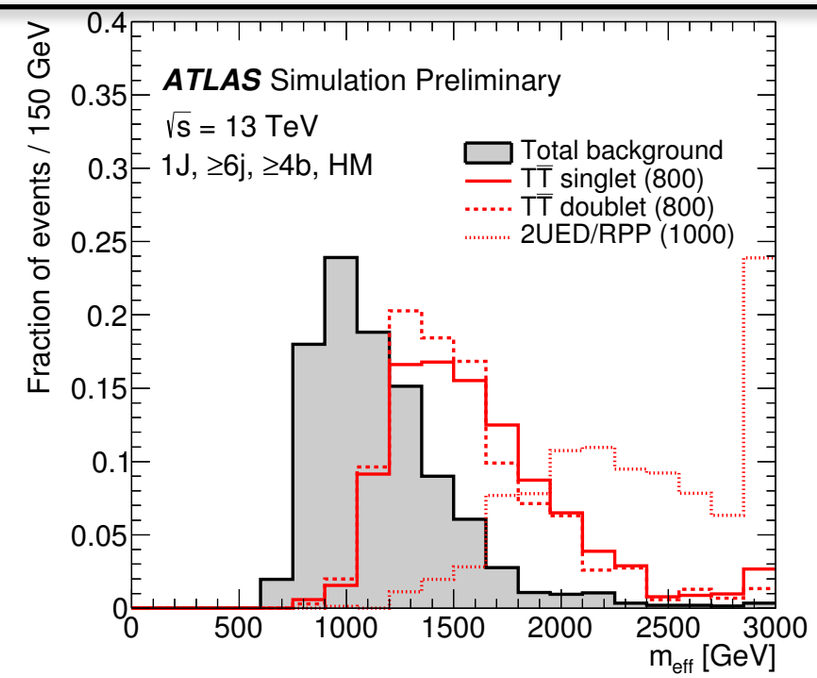


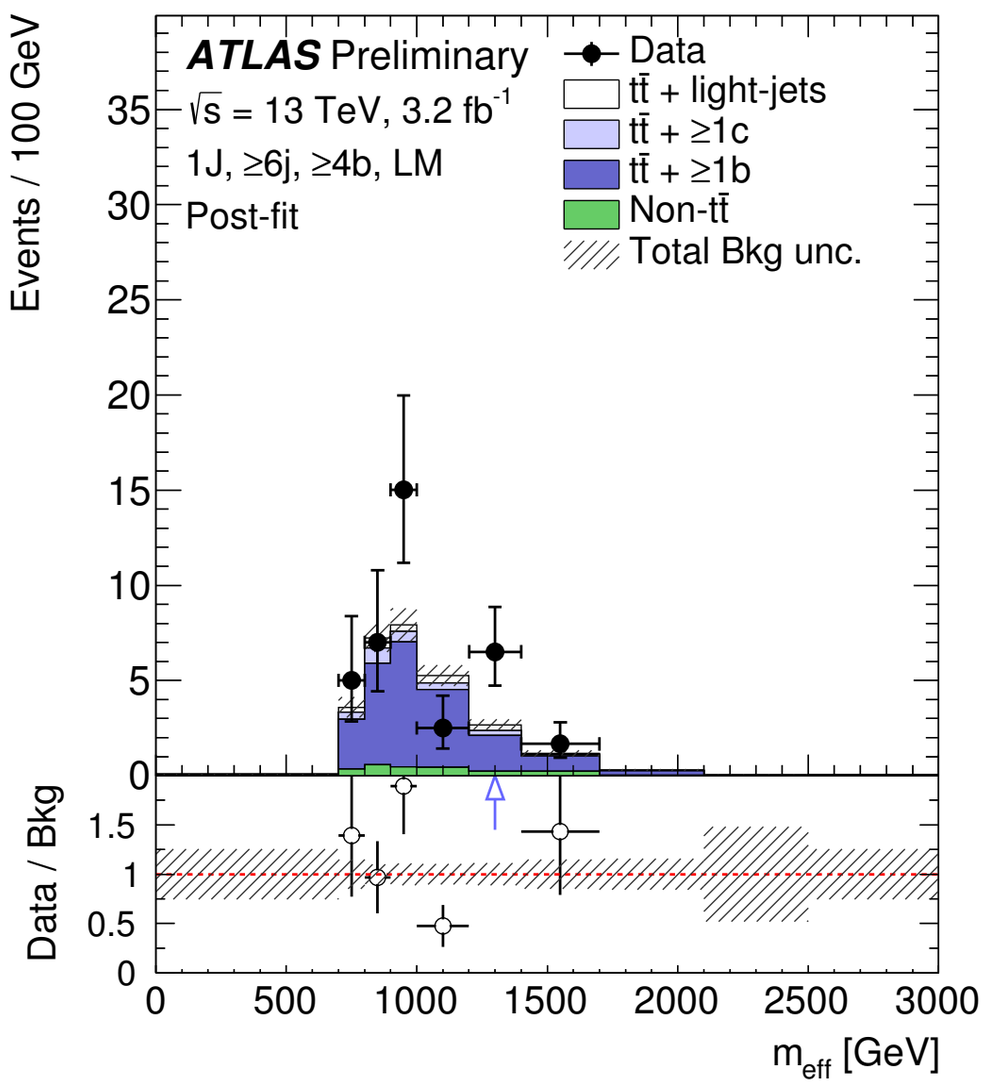
vector-like quarks: pair production

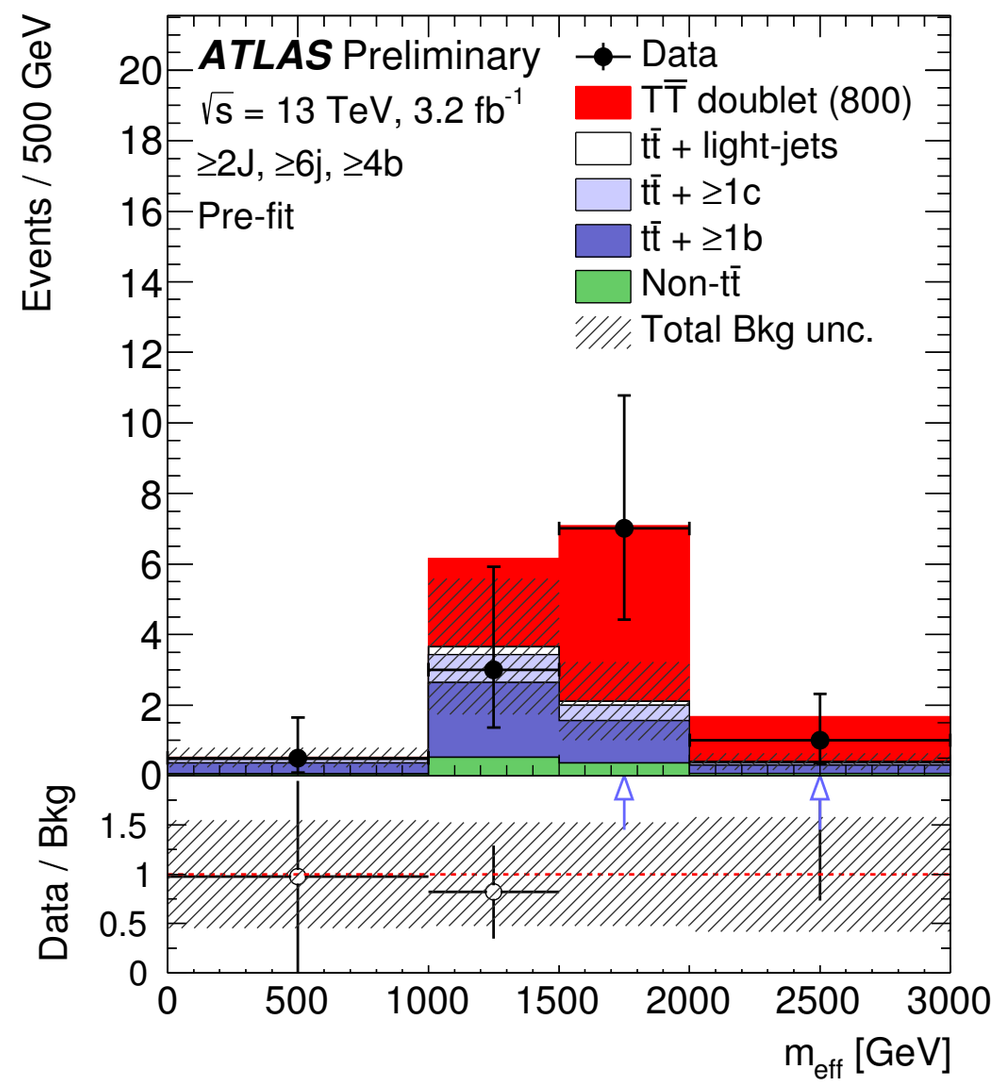
[ATLAS-CONF-2016-13]

effective mass

- scalar sum of lepton, jets, missing energy
- used to discriminate signal and background





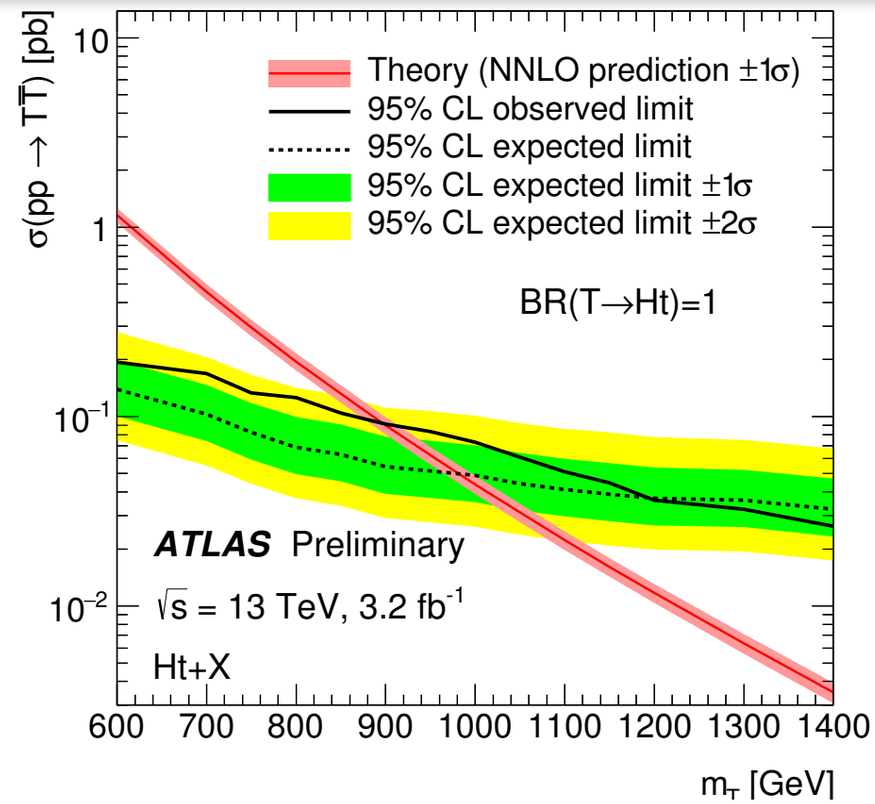


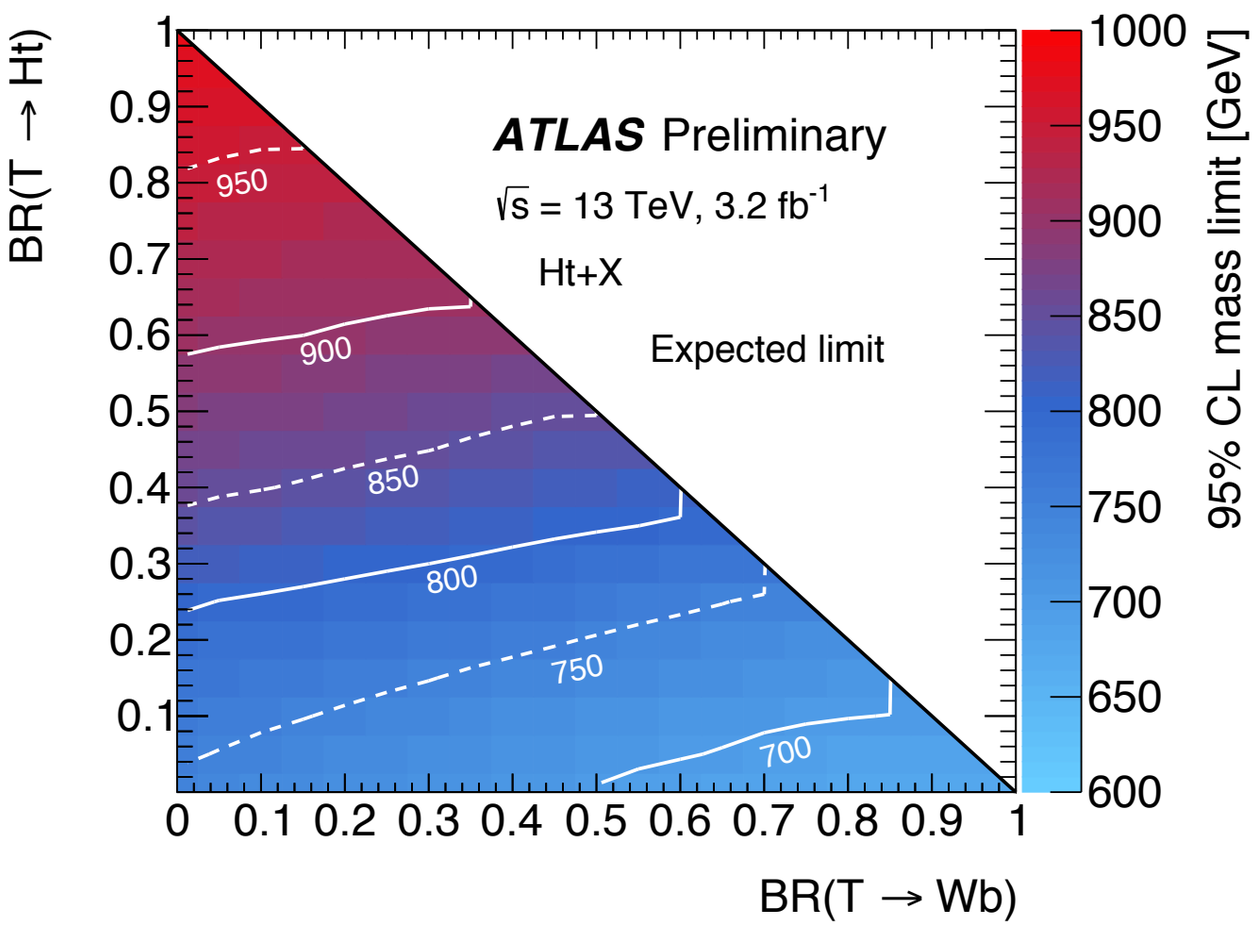
vector-like quarks: pair production

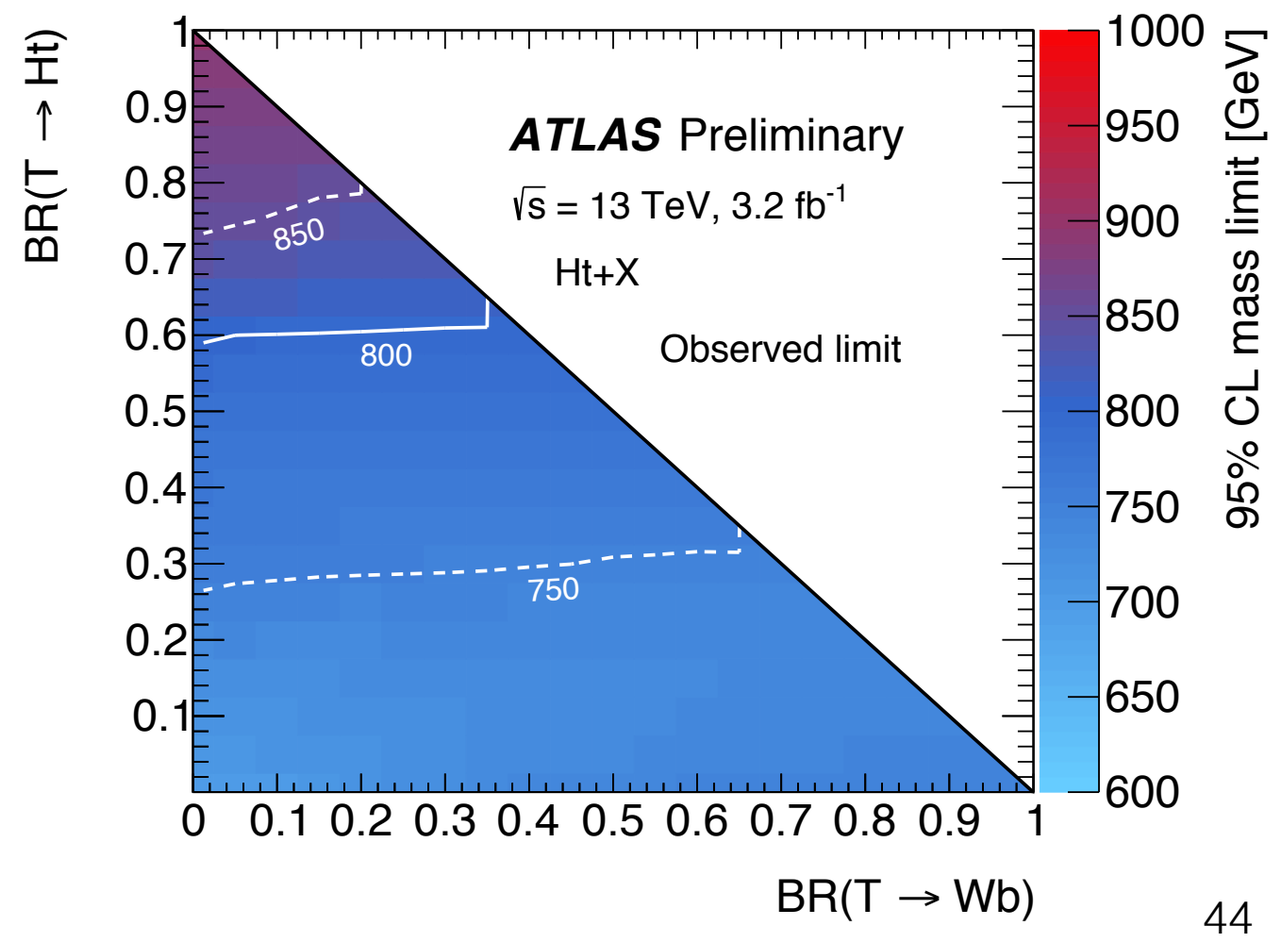
[ATLAS-CONF-2016-13]

results

- all decay branching modes scanned in steps of 5%
- sensitive to all decays
- 1.9 sigma excess for BR(T→tH)=1







$X^{5/3}$ in same-sign di-lepton final state:

After requiring two tight, same-sign leptons with p_T greater than 30 GeV we impose the following requirements:

- Quarkonia Veto: $M_{ll} > 20\,\text{GeV}$
- Associated Z-boson Veto: veto any event where either of the leptons in the same-sign pair reconstructs to within 15 GeV of the mass of the Z-boson with any other lepton in the event not in the same-sign pair.
- Primary Z-boson Veto: invariant dilepton mass (M_{ll}) $>$ 106.1 or $<$ 76.1 GeV for dielectron channel only. If the muon charge is mismeasured, its momentum will also be mismeasured so a selected muon pair from a Zboson will not fall within this invariant mass range.
- Leading lepton $p_T > 40\,\text{GeV}$
- Number of Constituents $>= 5$
- $H_T^{lep} > 900\,\text{GeV}$

$X^{5/3}$ in lepton+jet final state:

We begin by defining event preselection criteria consistent with the signal topology. The following selection is applied: lepton $p_T > 50$ GeV, $E_T^{miss} > 100$ GeV, $N_{jets} \geq 3$ with jet $p_T > 30$ GeV and $|\eta| < 2.4$, p_T (leading jet) > 200 GeV, and p_T (sub leading jet) > 90 GeV. In addition at least one of the jets is required to be tagged as originating from a b quark [28]. In Fig. 4, we show the differences in signal and background as characterized by a few kinematic variables, the number of jets (N_{jets}), missing E_T (E_T^{miss}). Decay products of heavy particles such as $X_{5/3}$ can have large Lorentz boost, and their subsequent decay products can merge into a single jet. The "n-subjettiness" [29] algorithm measures the likelihood of a jet having n subjets (1, 2, 3, etc). Mass grooming techniques are used to remove soft jet constituents so that the mass of the hard constituents can be measured more clearly. The "pruning" [30] algorithm is currently used to identify boosted hadronic W boson decays. We require a W tagged jet to have $p_T > 200$ GeV, $|\eta| < 2.4$, pruned mass between 65 and 105 GeV, and the ratio of n-subjettiness variables $\tau_2/\tau_1 < 0.55$. Figure 4 shows the number of b tagged and W tagged jets (bottom row).

$T^{2/3}$ in lepton+jets final state:

We select events with one electron or muon, usually from the decay of a W boson in the bW channel or from the $t \to Wb$ decay in the tZ or tH channels. Electrons and muons must have $p_T > 40$ GeV and pass the tight identification and isolation requirements described previously. We discard events having extra loose electrons or muons with $p_T > 10$ GeV.

We select events with three or more jets, where the highest corrected jet p_T is greater than 150 GeV, and the second highest p_T is greater than 75 GeV. E_T^{miss} must be greater than 60 GeV to reduce multijet background events. The final selection criterion is a veto on boosted Higgs tagged jets, which creates a signal region orthogonal to that of an ongoing dedicated $T \to tH$ analysis. Figure 2 shows distributions of lepton p_T, jet p_T, E_T^{miss} along with the total number of jets, number of b tagged jets, and number of W tagged large-radius jets. These distributions include the jet p_T reweighting procedure described below.

In addition, a Universal Extra Dimensions (UED) model is considered involving new heavy particles. The UED model considered has two extra dimensions that are compactified using the geometry of the real projective plane (2UED/RPP) [41], leading to a discretisation of the momenta along their directions. A tier of Kaluza–Klein towers is labelled by two integers, k and ℓ, referred to as "tier (k,ℓ)". Within a given tier, the squared masses of the particles are given at leading order by $m^2 = k^2/R_4^2 + \ell^2/R_5^2$, where πR_4 and πR_5 are the sizes of the two extra dimensions. The model is parameterised by R_4 and R_5 or, alternatively, by $m_{\mathrm{KK}} = 1/R_4$ and $\xi = R_4/R_5$. Four-top-quark production can arise from tier (1,1), where particles from this tier have to be pair produced because of symmetries of the model. Then they chain-decay to the lightest particle of this tier, the heavy photon $A^{(1,1)}$, by emitting SM particles (Fig. 3(c)). The branching ratios of $A^{(1,1)}$ into SM particles are not predicted by the model, although the decay into $t\bar{t}$ is expected to be dominant [42]. Four-top-quark events can also arise from tiers (2,0) and (0,2) via a similar mechanism. In this case the expected cross section for four-top-quark production is reduced compared to that from tier (1,1) since each state in tiers (2,0) and (0,2) can decay directly into a pair of SM particles or into a pair of states in tiers (1,0) or (0,1) via bulk interactions, resulting in smaller branching ratios for the decay into $t\bar{t}$ [42]. In the following, when considering four-top-quark production from a given tier, it is assumed that the A photon in that tier decays exclusively into $t\bar{t}$ while A photons from other tiers cannot decay into $t\bar{t}$. Within this model, observations of dark-matter relic abundance prefer values of m_{KK} between 600 GeV and 1200 GeV [43].

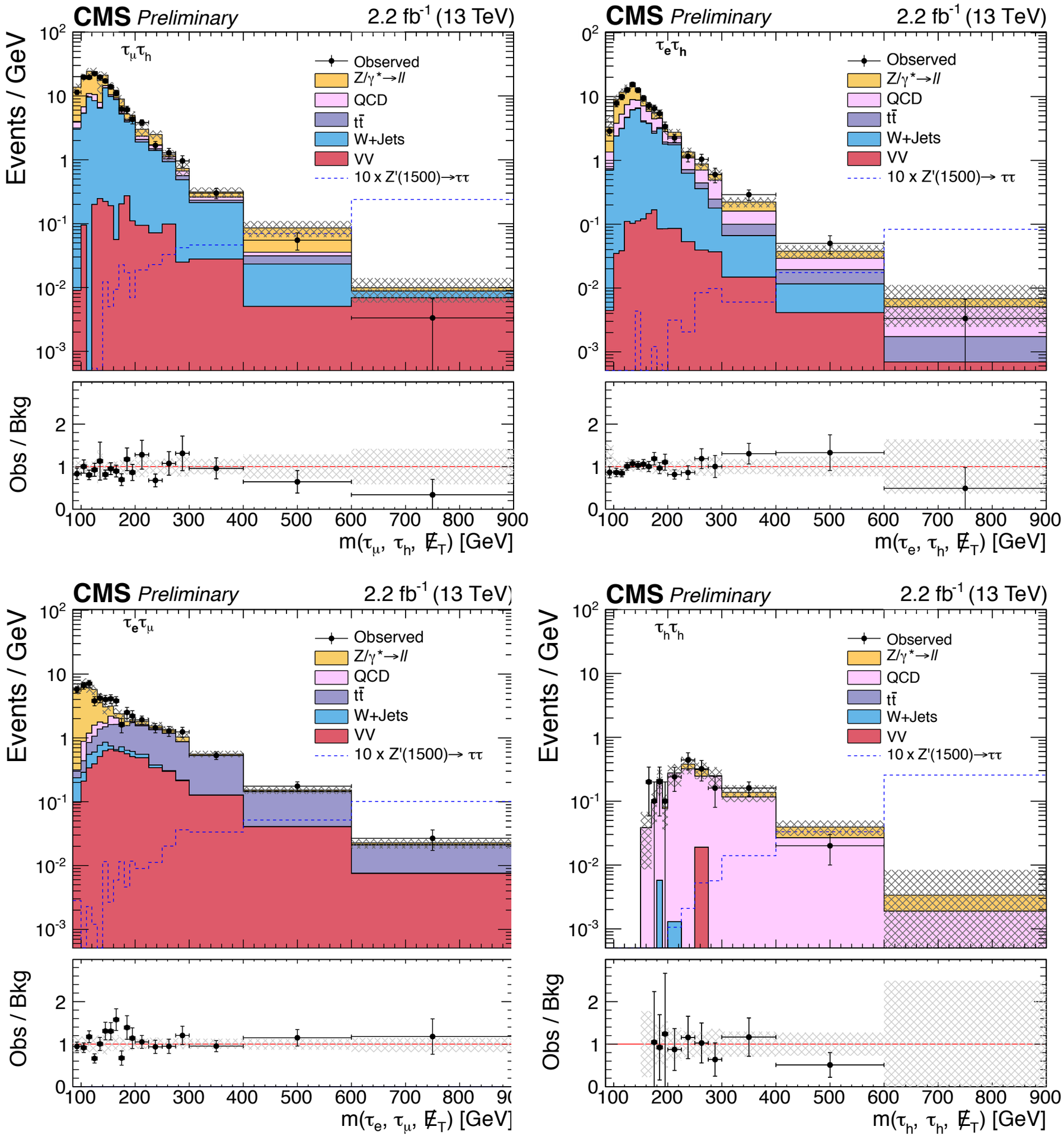
2.3 Trigger-Level Analysis in ATLAS

Partially-built events are collected by means of an additional TLA data stream. In this stream, all events containing at least one L1 jet ROI with $E_T > 75$ GeV at the electromagnetic scale [2] are recorded. For each trigger jet recorded at the HLT with $p_T > 4$ GeV, the stream records the jet four-momentum and a set of variables characterizing the detector information within the jet (such as variables needed for jet identification [25], and limited information about the structure of the jet). The data format does not include any readout of individual calorimeter elements, nor does it record information from the tracking or muon detectors. The size of partially-built TLA events in 2015 data is less than 5% of the size of full events, allowing for higher event rates to be recorded. TLA events are recorded with a rate of 2 kHz, in addition to the fully-recorded higher p_T events.

The search uses a sample of events which contain at least one photon with $p_T > 130$ GeV as well as at least two jets. Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.8$. In addition, half the difference in rapidity y of the leading two jets,

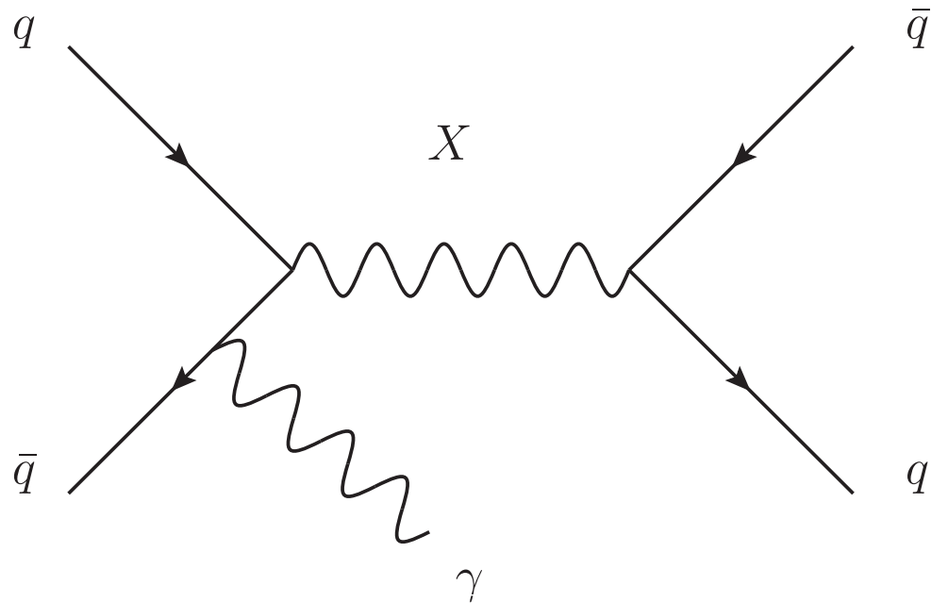
$$y^* = \frac{y_{j_1} - y_{j_2}}{2}$$

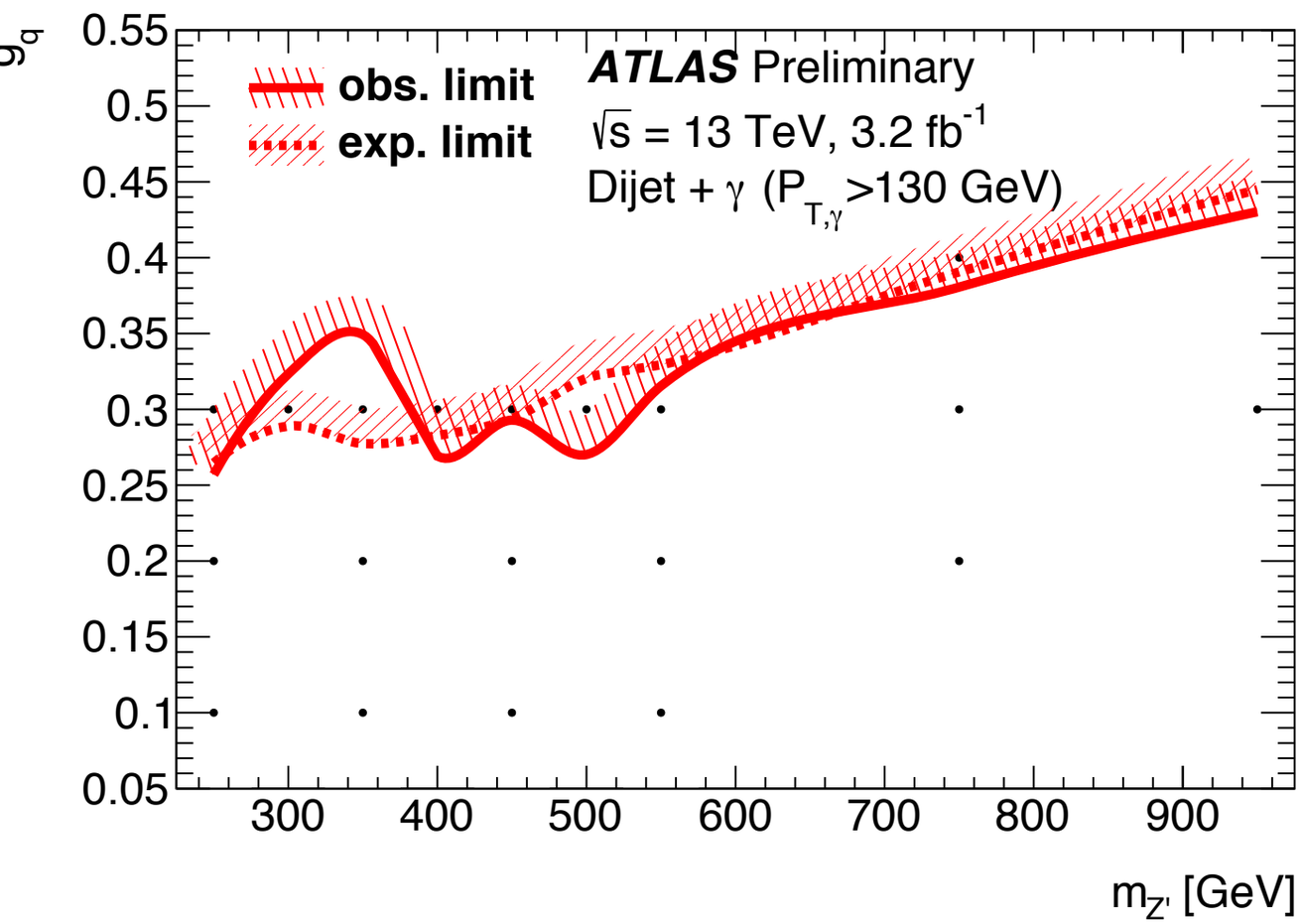
is required to satisfy $|y^*| < 0.8$ to reduce the backgrounds from processes that yield an ISR photon and a non-resonant jet pair from QCD processes, which tend to have higher-rapidity separation. To suppress such jets surviving the photon isolation criterion, and to further suppress background from fragmentation photons where the photon is inside or near a jet, the selected photon is required to be separated from the closest jet by $\Delta R > 0.85$. Figure 2 shows the m_{jj} distribution of events satisfying these criteria.

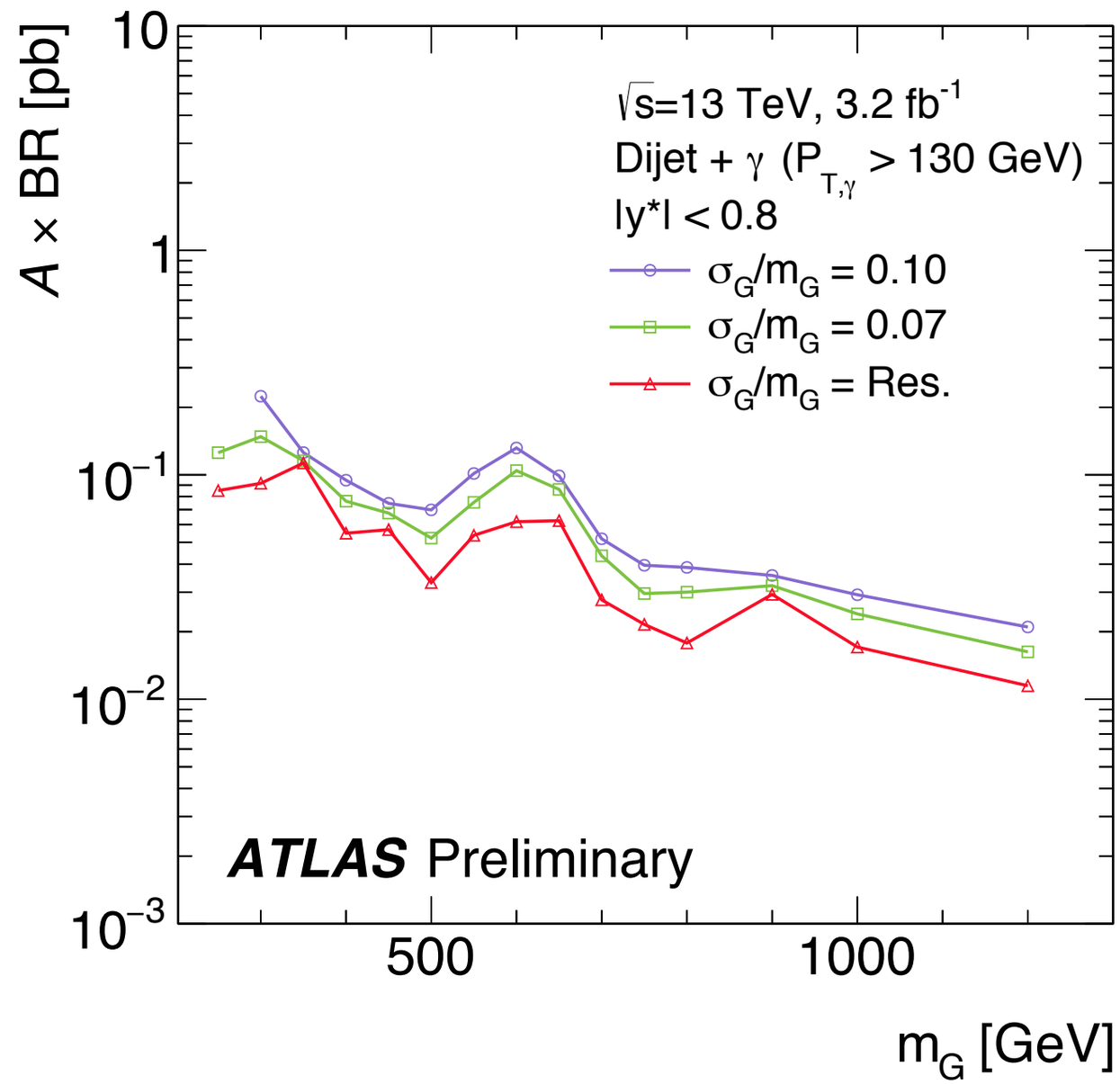


[CMS-PAS-EXO-16-008]

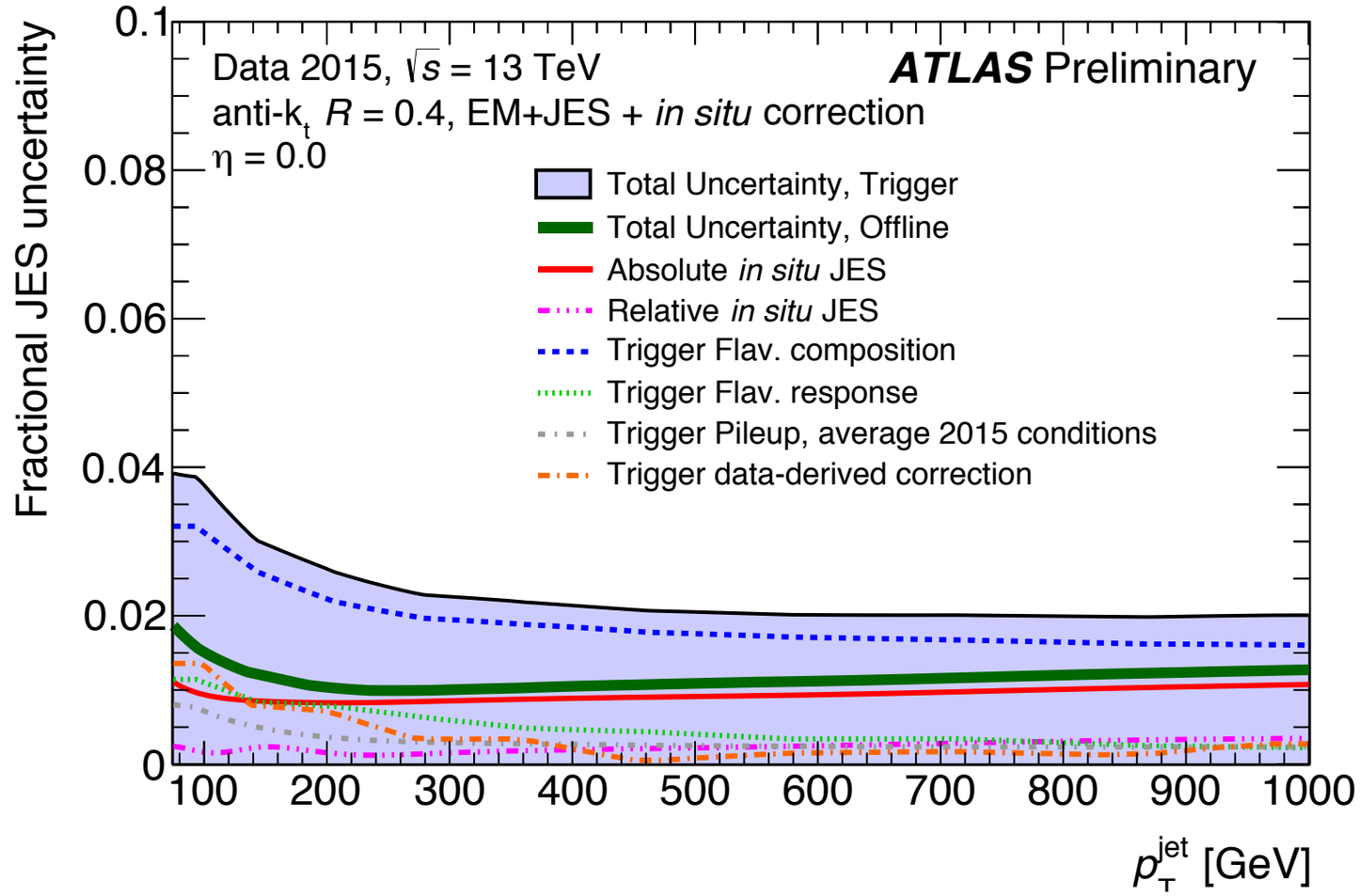
[ATLAS-CONF-2016-029]

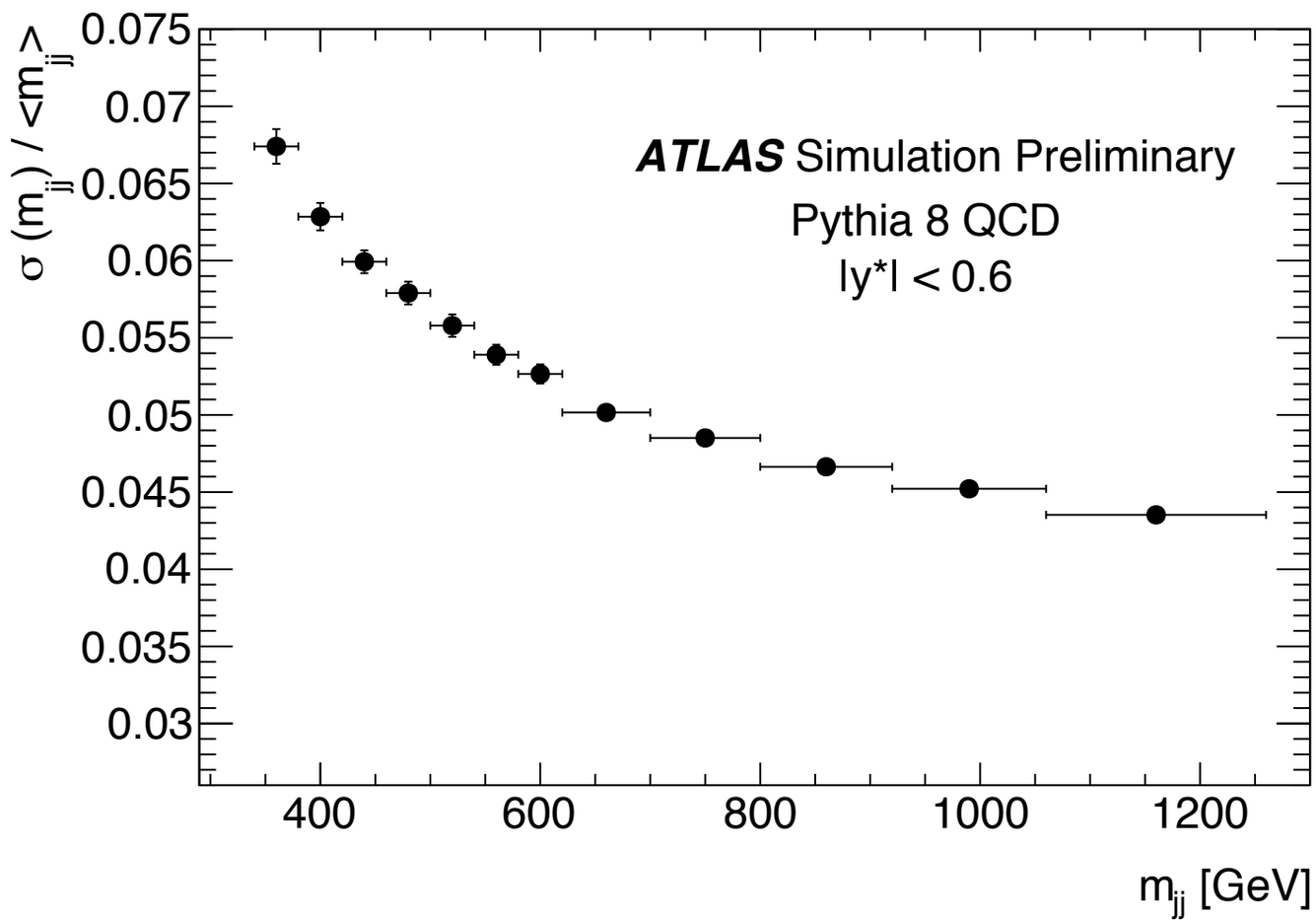




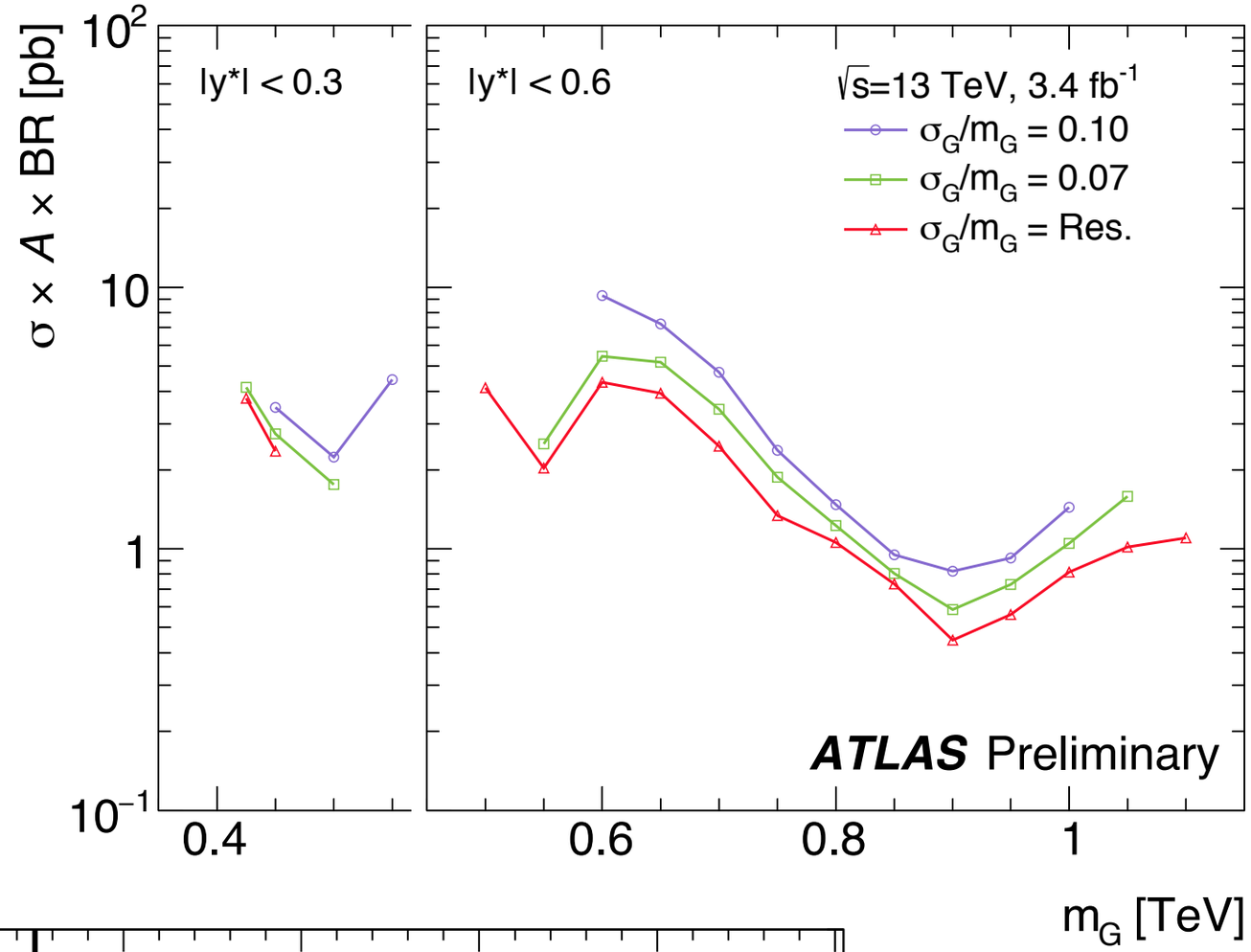


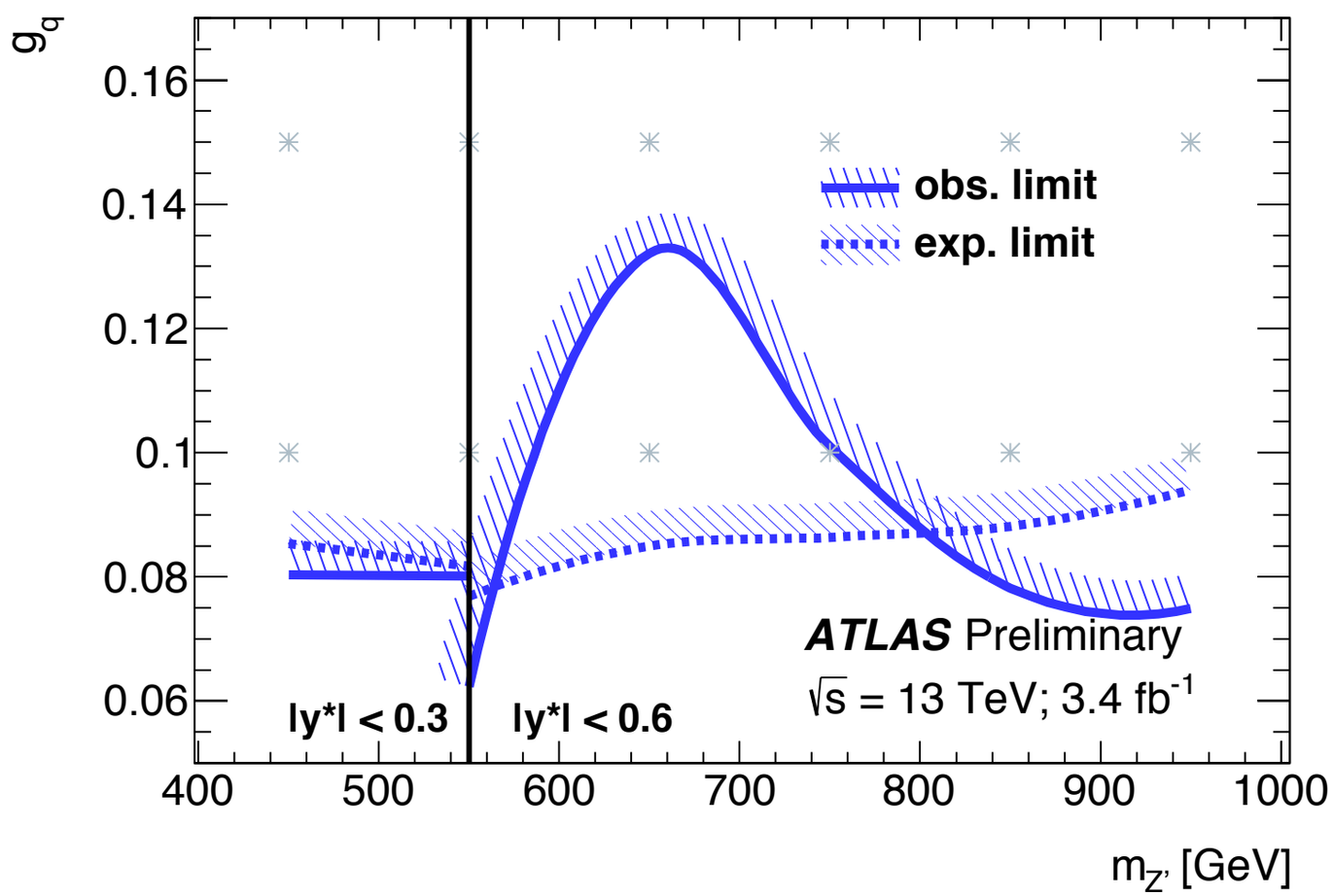
[ATLAS-CONF-2016-030]





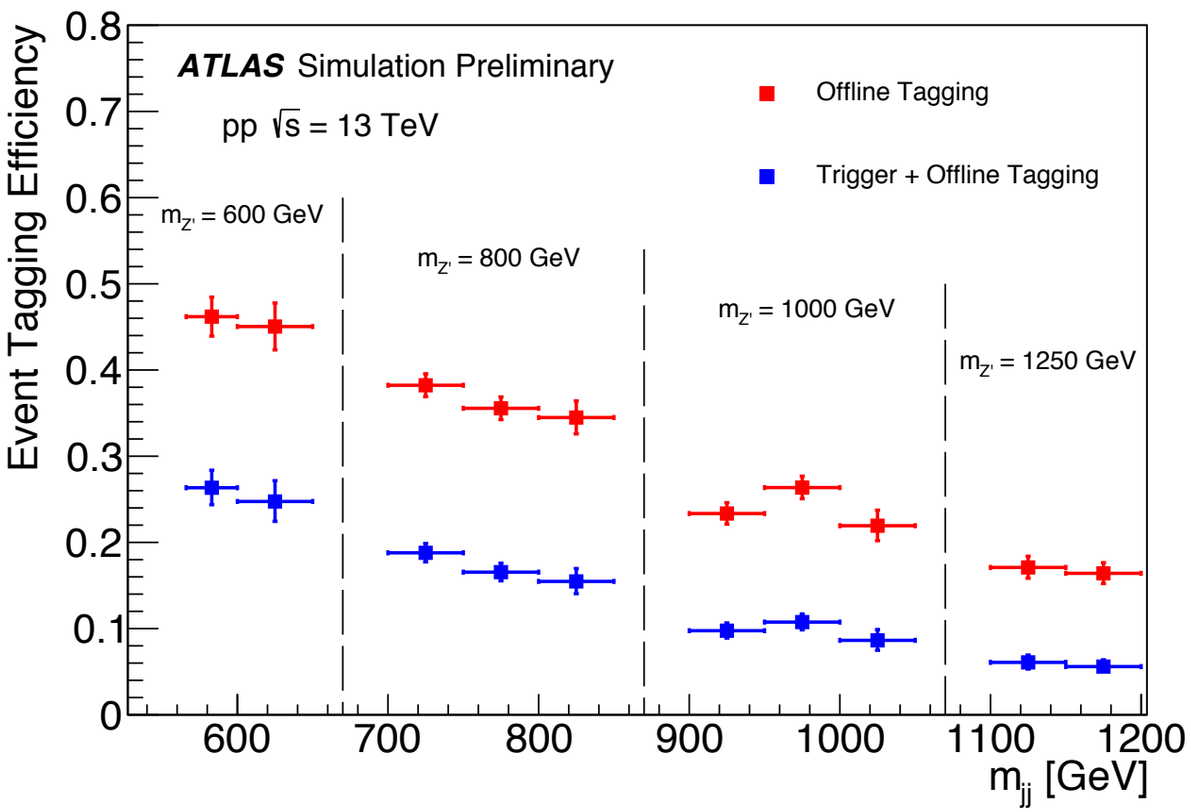
[ATLAS-CONF-2016-030]

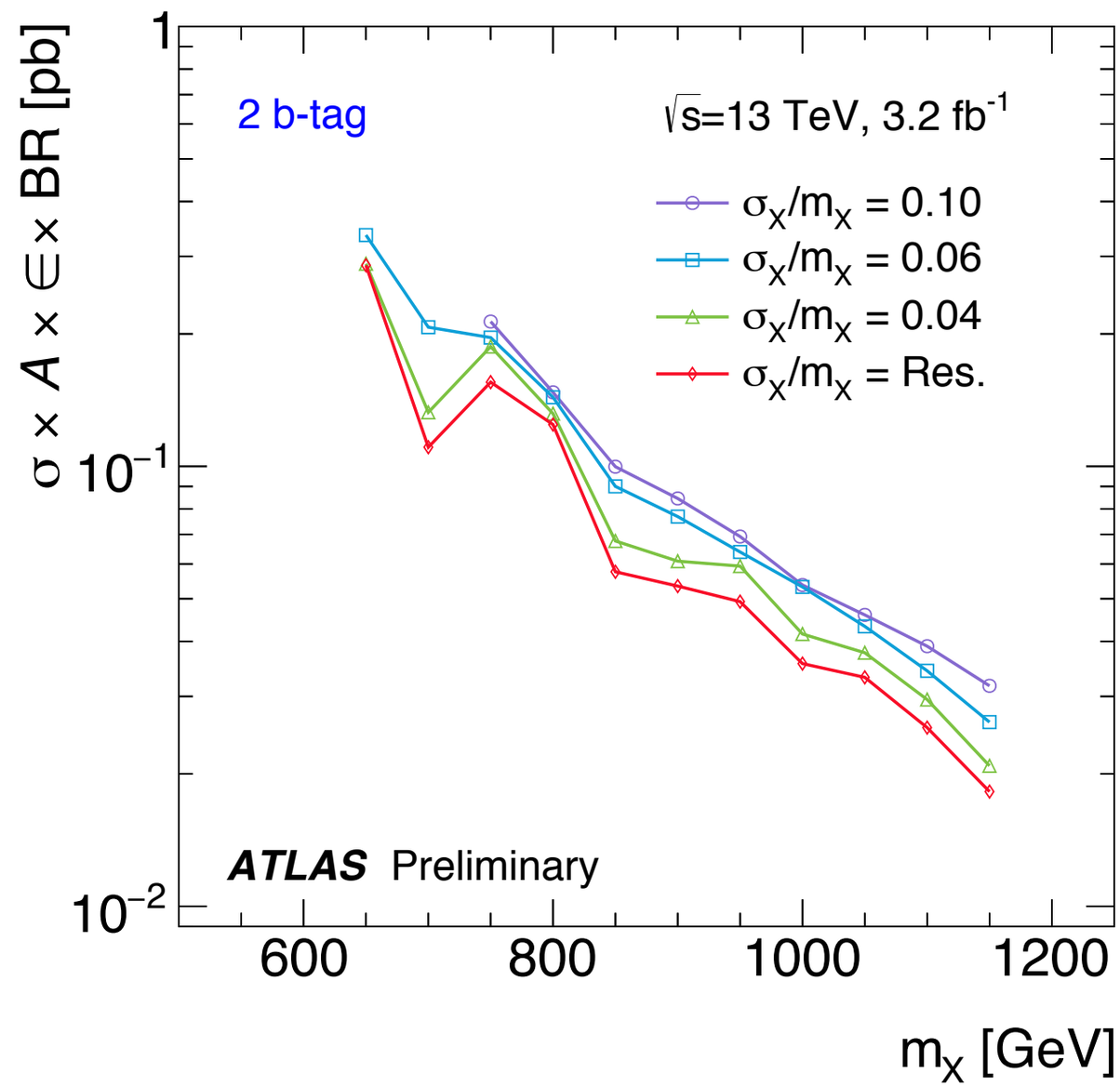




low-mass di-b-jet resonances

[ATLAS-CONF-2016-031]

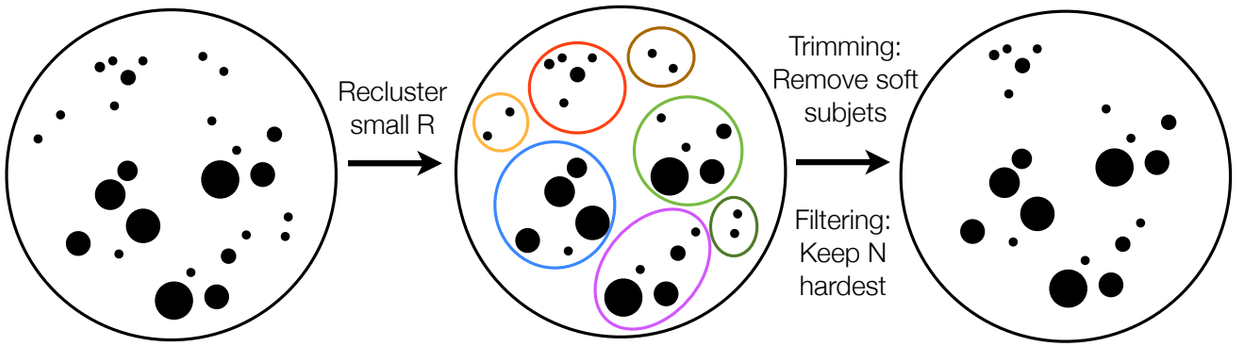




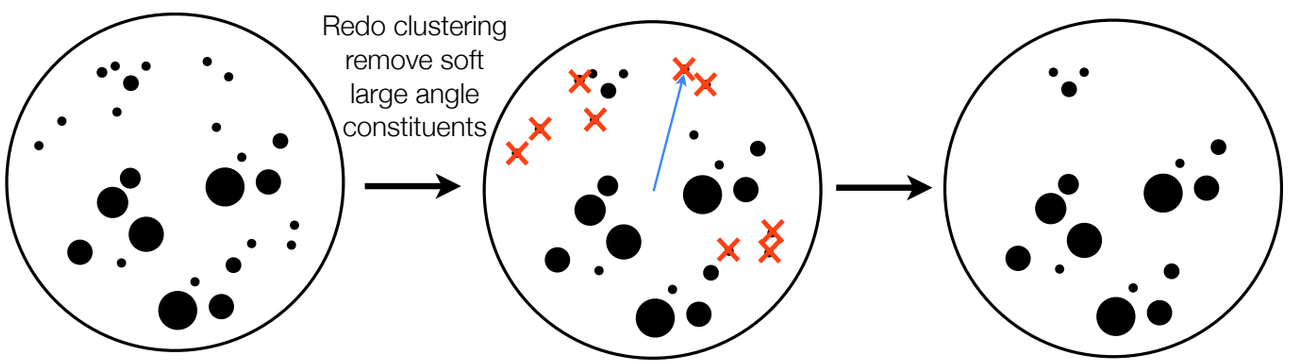
jet grooming

J. Dolen

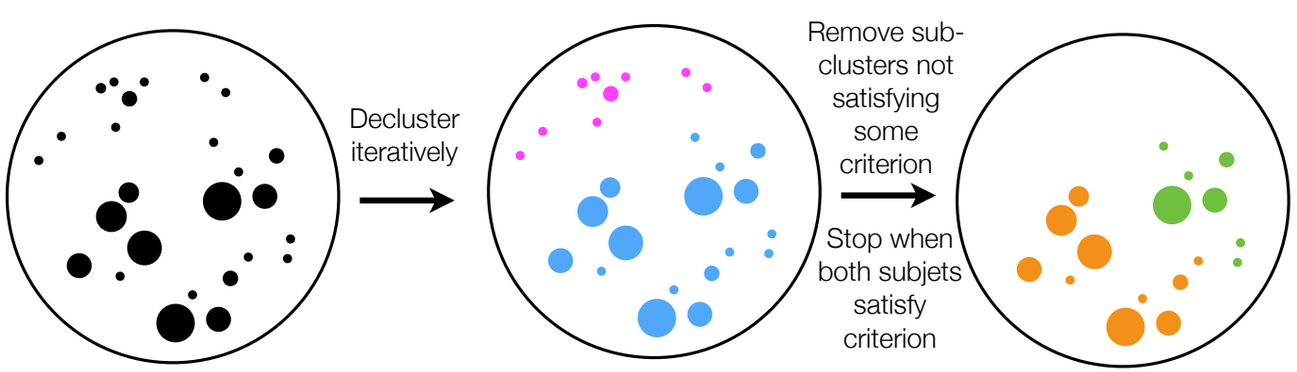
Trimming, Filtering - Recluster jet with smaller distance parameter. Condition based subjet removal.

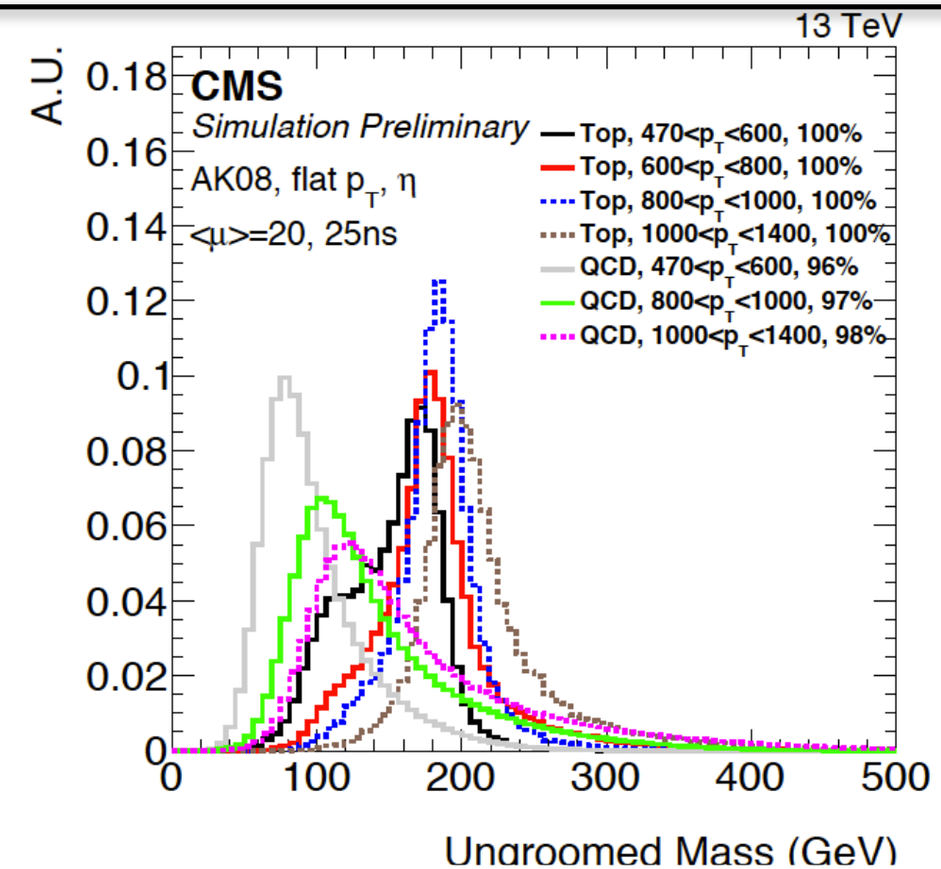


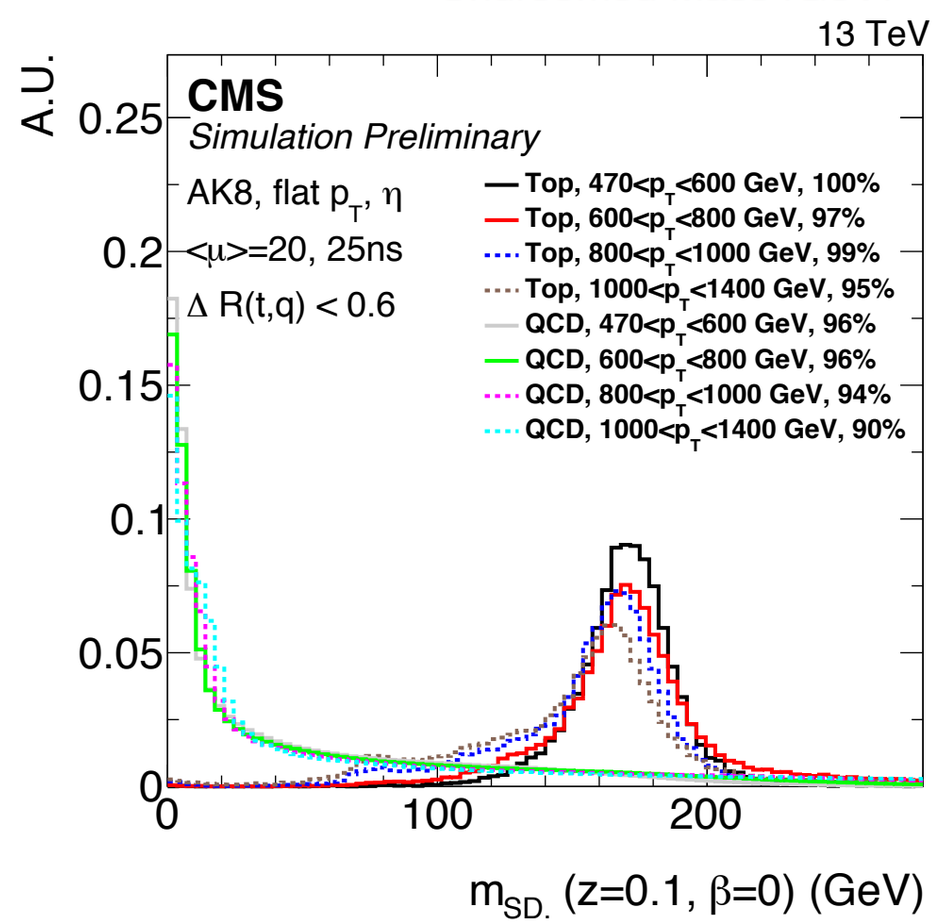
Pruning - Recluster jet. Remove soft large angle particles.



BDRS, MMDT, Soft Drop, JHU top tagger, CMSTT - Recursively decluster jet. Remove sub-clusters not satisfying algorithm condition. Stop declustering when both subjets satisfy condition.







jet shapes

[CMS-PAS-JME-13-006]

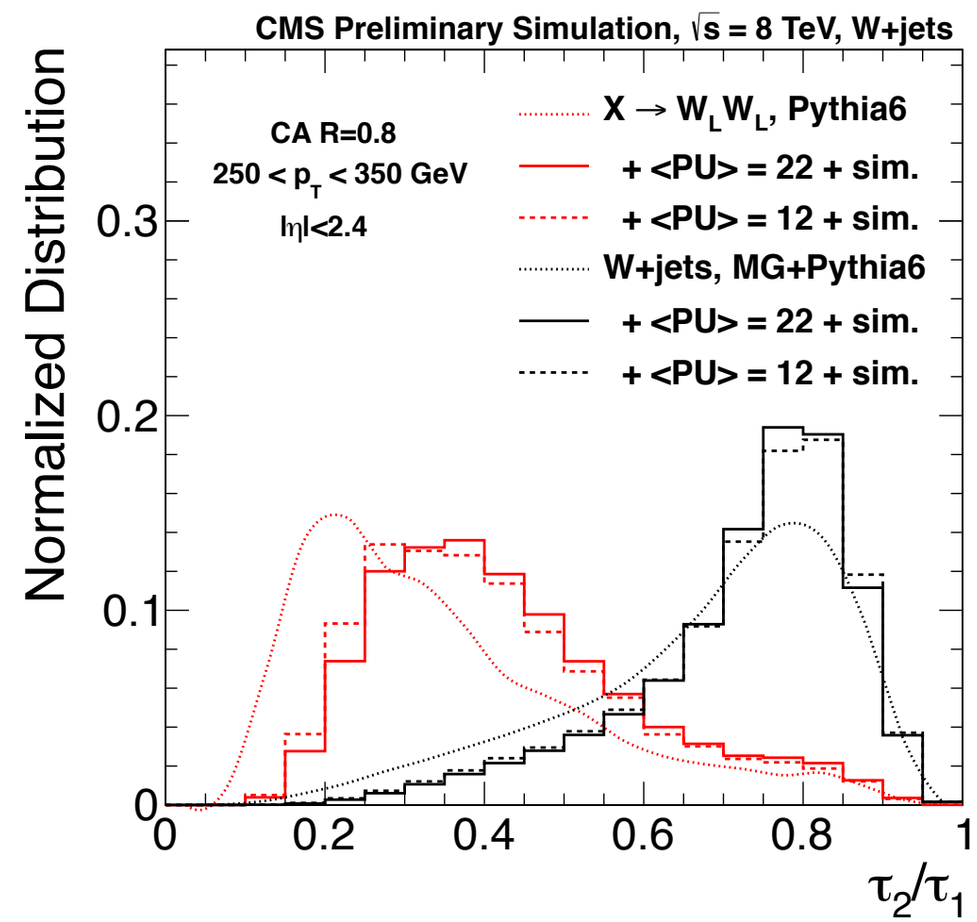
energy patterns within a jet:

- characterise multi-prong properties
- many definitions and varieties

n-subjettiness:

$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} R}$$

- how consistent is jet with having N subjets
- ratios discriminate hypotheses: τ_2/τ_1



many other on the market:

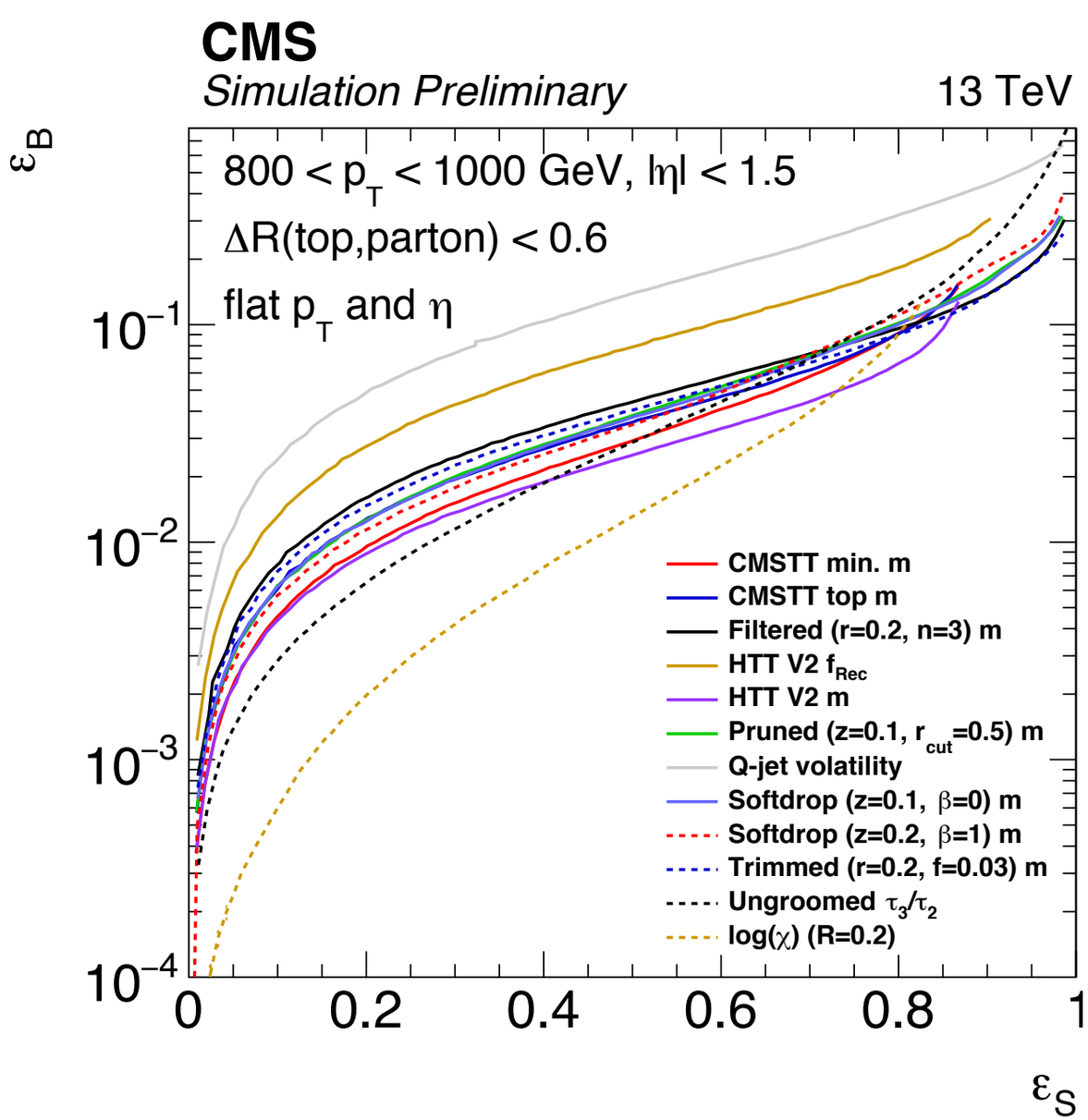
- energy correlation functions
- Q-jet volatility
- …

boosted t tagging

[CMS-PAS-JME-15-002]

performances:

- several variables scanned individually



- background rejection at 30% efficiency