Status of direct searches for top-quark partners at the LHC

today: vector-like quarks

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on behalf of the ATLAS and CMS Collaborations

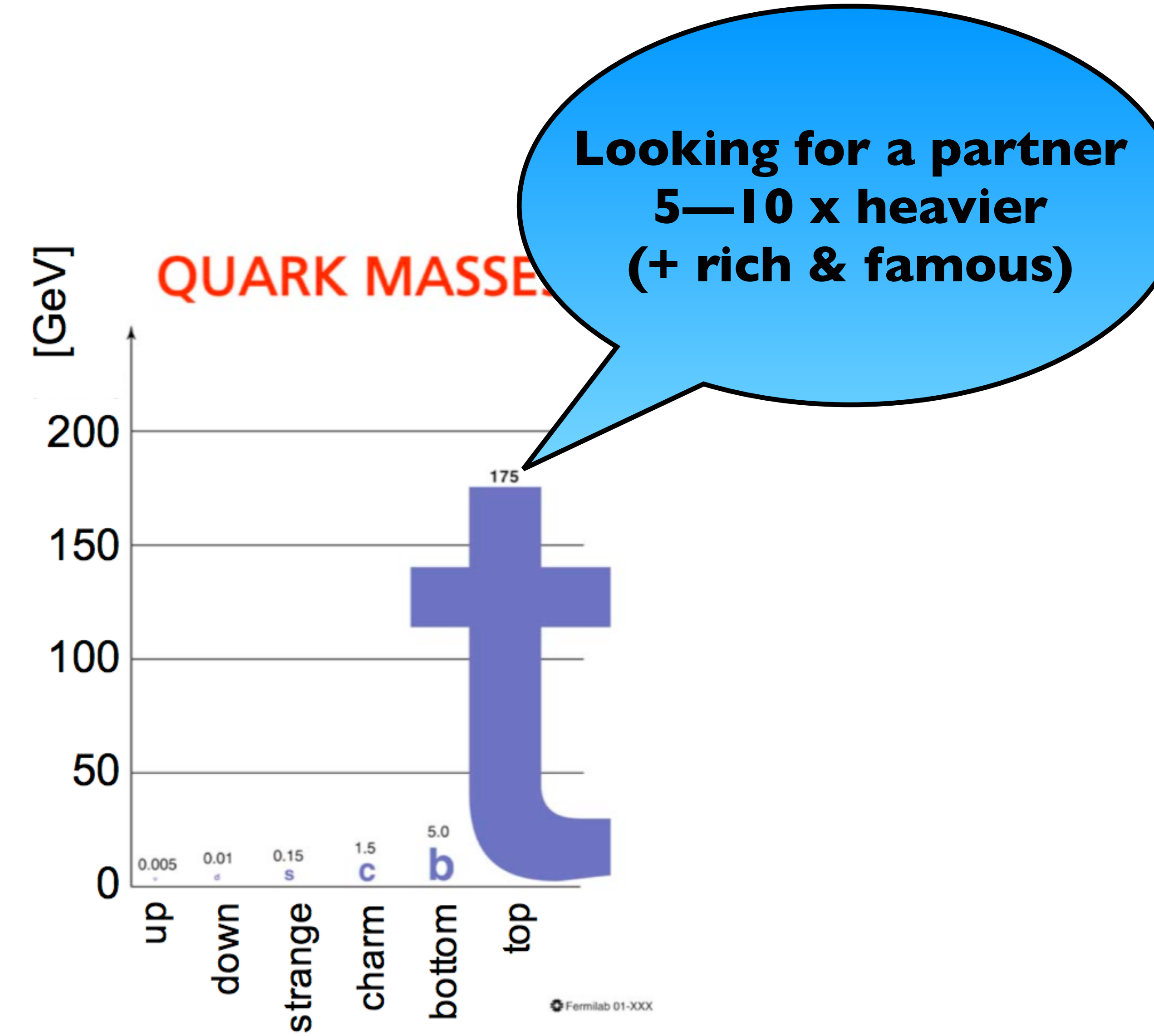
A First Glance Beyond the Energy Frontier
Trieste, 08.09.2016

Outline

- Brief introduction
- Status after Run-1
- Overview status Run-2
  - Pair production
  - Single production

  incl. remarks on **B O O S T** *techniques*
- Conclusions

ElitePartner

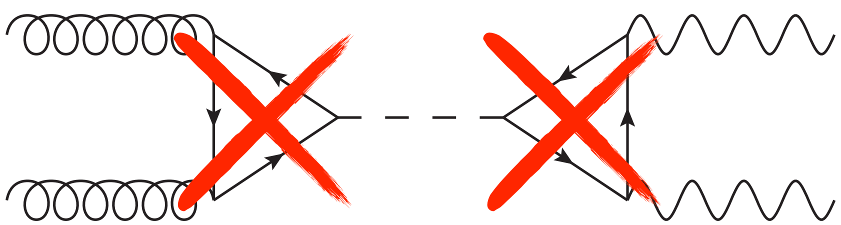


Spoiler alert !

→ *No new physics found, yet.*

VLQ

Chiral 4th Quark Generation

- excluded by Higgs discovery
- 

Vector-like quarks (VLQ)

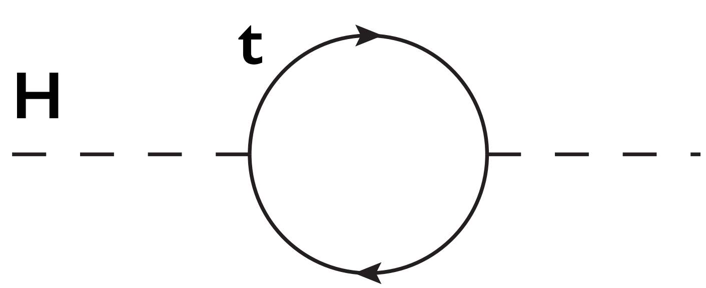
- LH and RH same SU(2) transformation
  - direct mass term allowed : $m\bar{\psi}\psi$
- mix with SM quarks
- multiplets w/ SU(3)xSU(2)xU(1) quantum no.

	VLQ	Q [e]	T3
singlets	(T) (B)	+2/3 -1/3	0
doublets	(X,T) (T,B) (B,Y)	+5/3, +2/3 +2/3, -1/3 -1/3, -4/3	± 1/2
triplets	(X,T,B) (T,B,Y)	+5/3, +2/3, -1/3 +2/3, -1/3, -4/3	+1, 0, -1

H

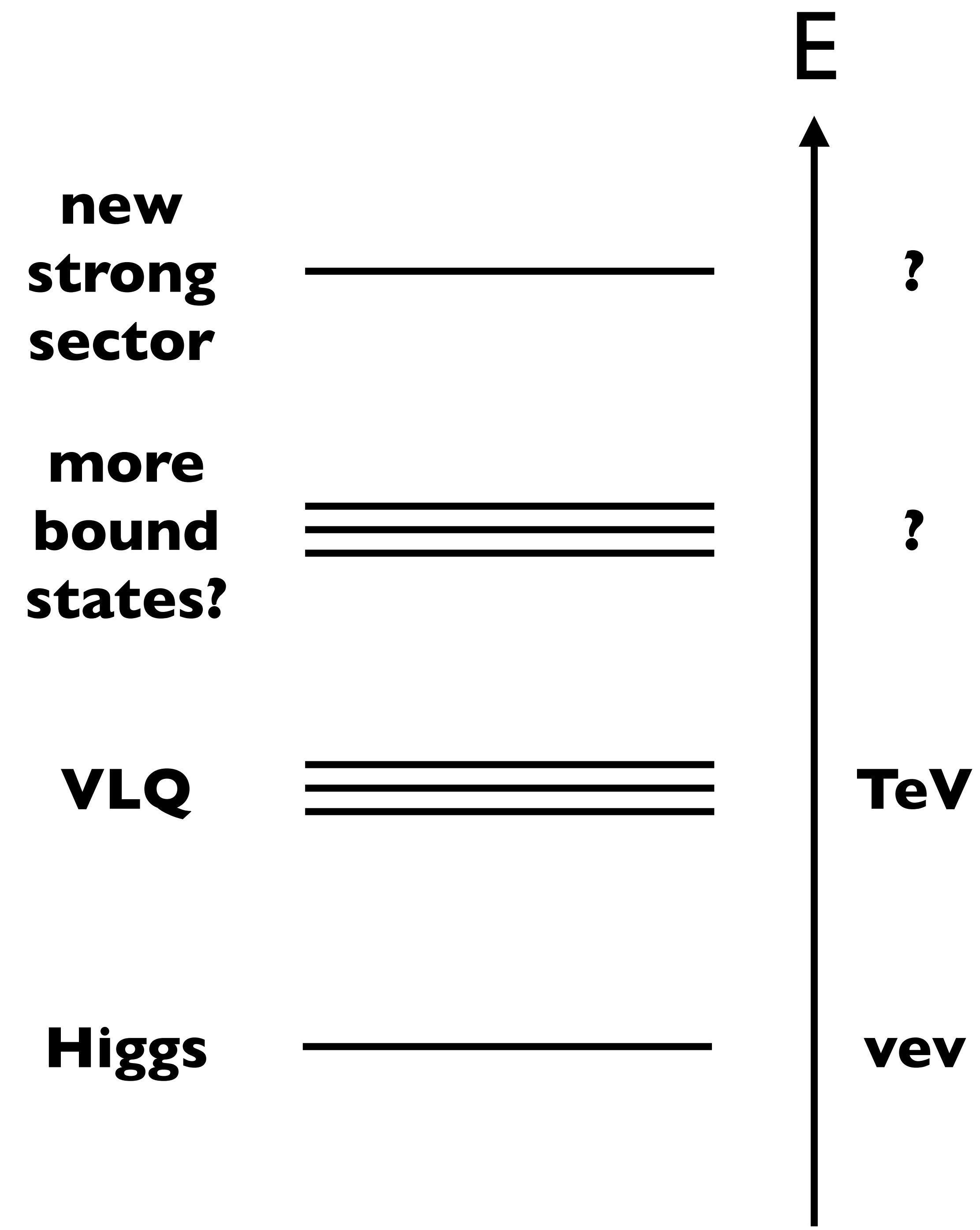
The Higgs is special

- only known elementary scalar
- Δm_H quadratically divergent



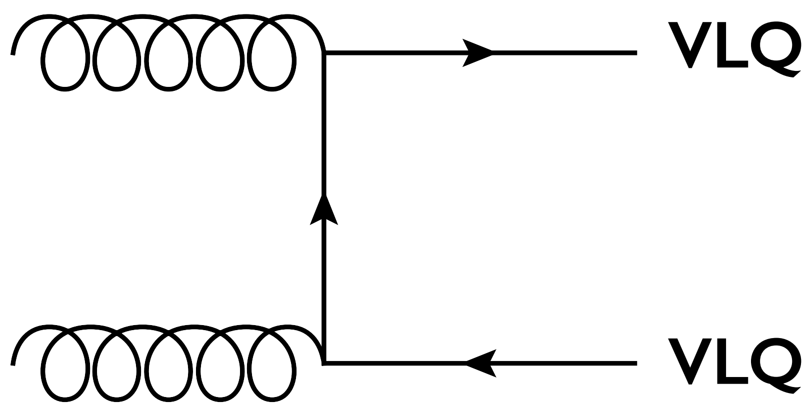
→ *Perhaps not elementary ?*

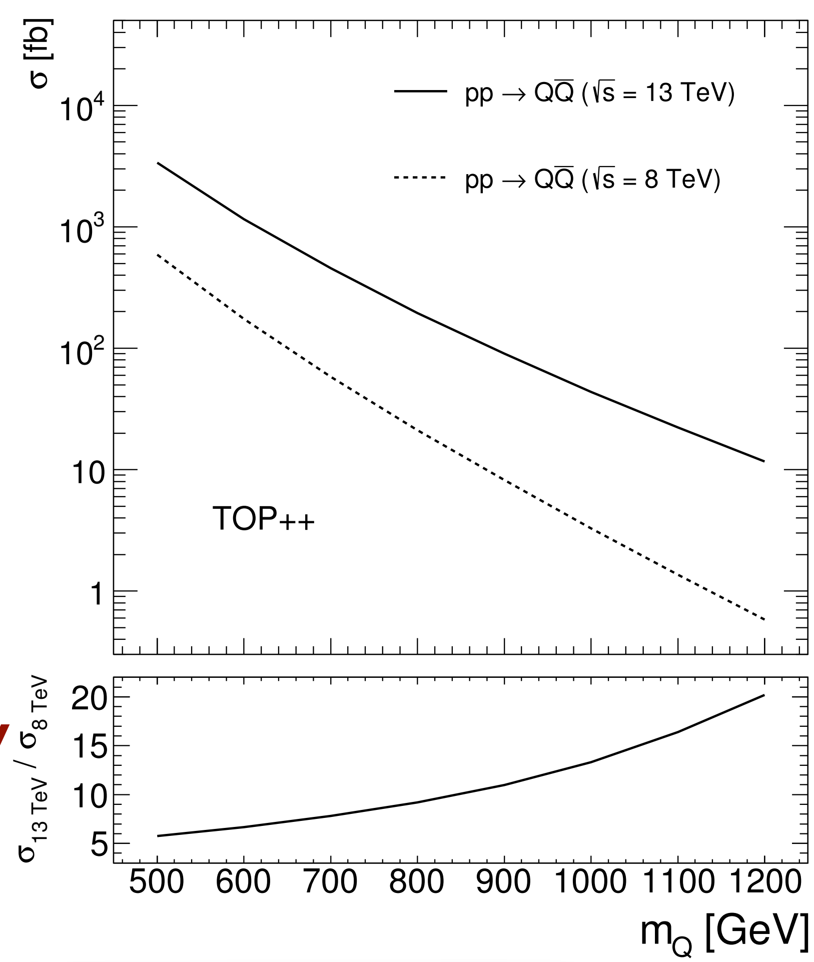
- (pseudo-)Nambu-Goldstone boson of new strongly interacting sector ?
- VLQ predicted with m ≲ O(2 TeV)
  - indirect constraints exist, but model dependent — need ***direct searches*** !



Pair Production & VLQ Decay

Strong pair production

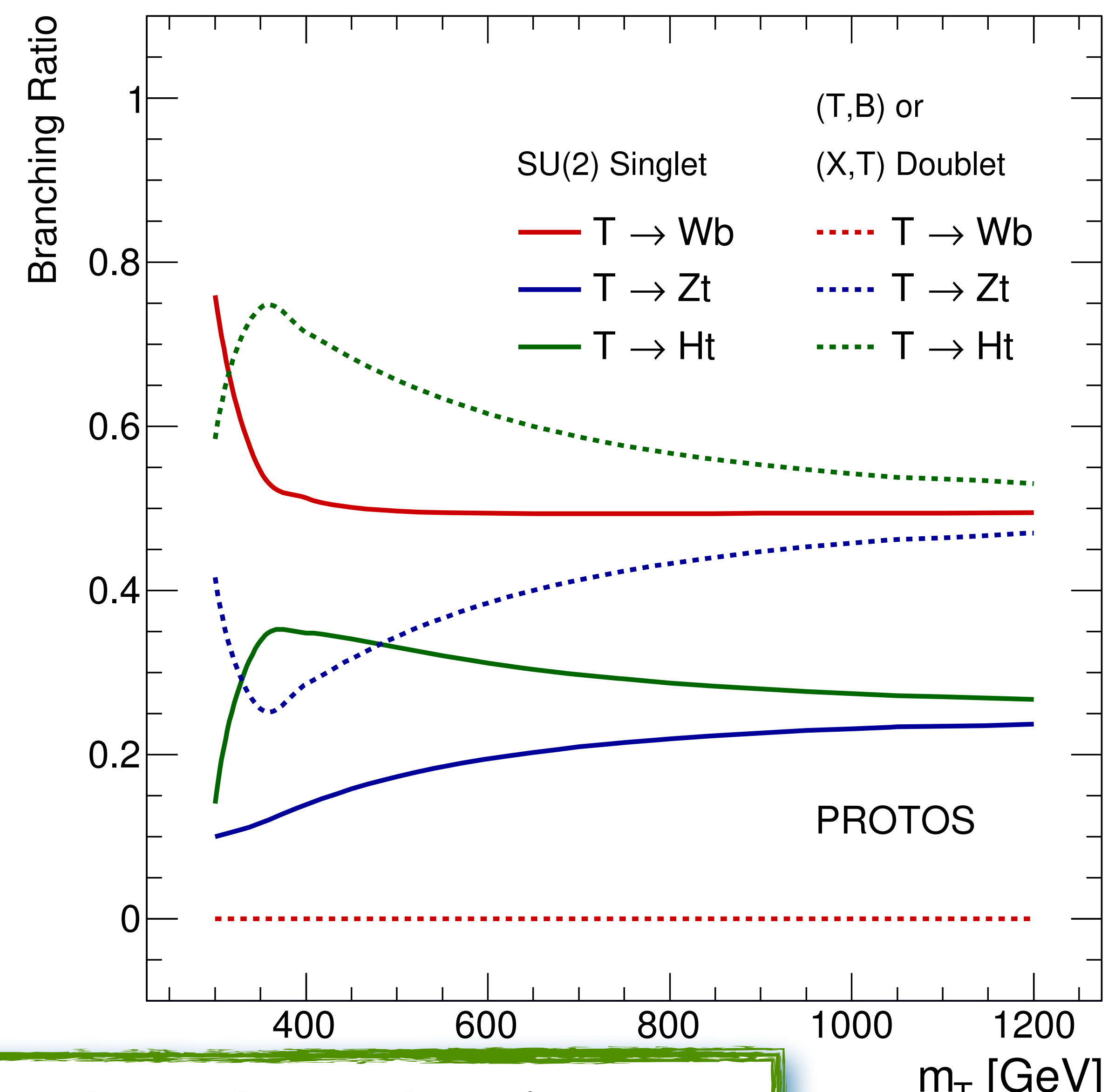




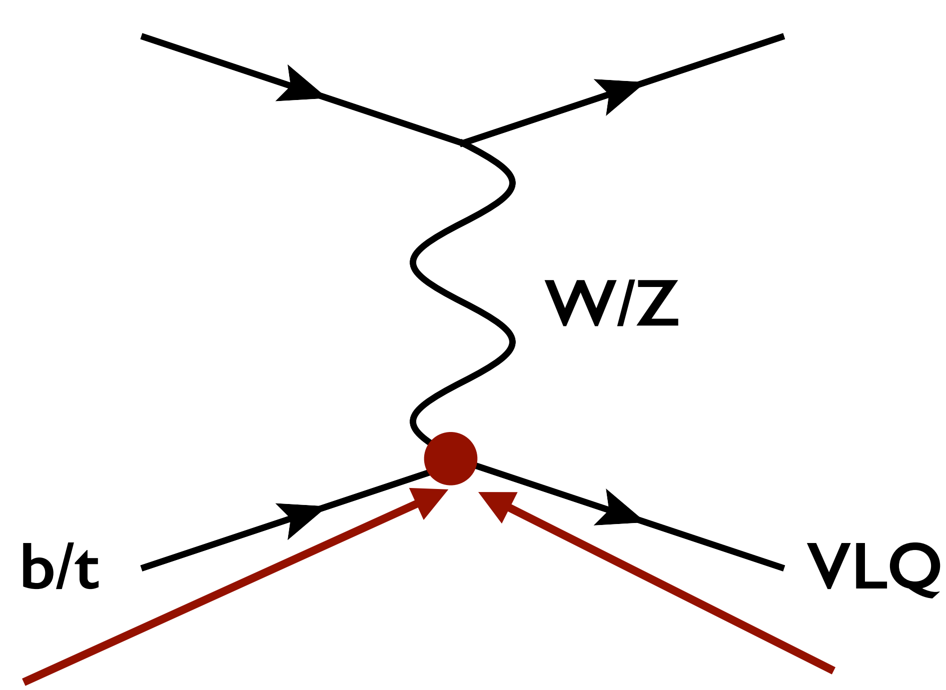
σ increases strongly for 13 TeV

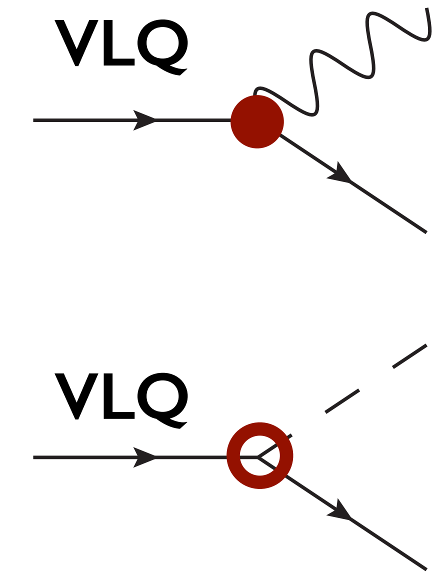
Decay

- assume : only coupling to 3[rd] gen.
- VLQ → t/b + W/Z/H
- BRs given by multiplet



Strong production — model-independent !
(decay kinematics may be different for different couplings)





$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = U^u_{L,R} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^u_{L,R} & -\sin\theta^u_{L,R} e^{i\phi_u} \\ \sin\theta^u_{L,R} e^{-i\phi_u} & \cos\theta^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}$$

(Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria, Phys. Rev. D 88 (2013) 094010)

$$\sigma_{\rm sing}(X\bar{t}) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{V\bar{t}}(M_X) + c_L^{XV}\, c_R^{XV} \left(\frac{m_t}{M_X + m_t}\right) \sigma'_{V\bar{t}}(M_X)\,,$$
$$\sigma_{\rm sing}(X\bar{b}) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{V\bar{b}}(M_X)\,,$$
$$\sigma_{\rm sing}(\overline{X}t) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{\overline{V}t}(M_X) + c_L^{XV}\, c_R^{XV} \left(\frac{m_t}{M_X + m_t}\right) \sigma'_{\overline{V}t}(M_X)\,,$$
$$\sigma_{\rm sing}(\overline{X}b) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{\overline{V}b}(M_X)\,.$$

(Matsedonskyi, Panico, Wulzer, JHEP 12 (2014) 097; also: Buchkremer, Cacciapaglia, Deandrea, Panizzi, Nucl. Phys. B 876 (2013) 376)

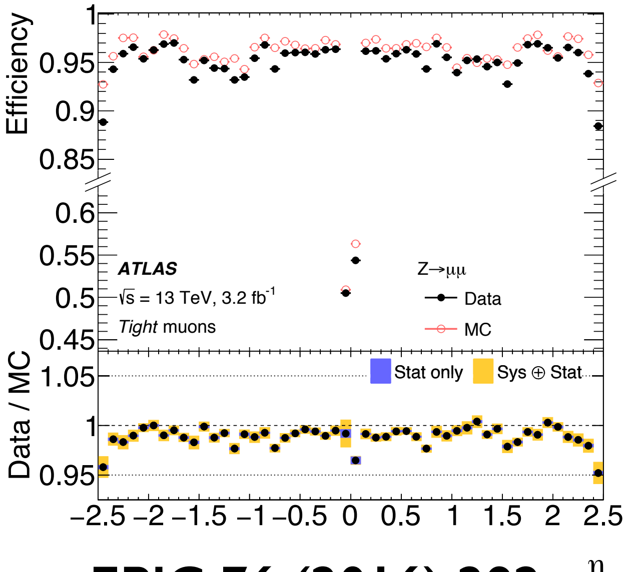
Mixing angles not independent

→ LH/RH dominates in each multiplet

$$\tan\theta^q_R = \frac{m_q}{m_Q}\tan\theta^q_L \quad (\text{singlets, triplets})\,,$$
$$\tan\theta^q_L = \frac{m_q}{m_Q}\tan\theta^q_R \quad (\text{doublets})\,,$$

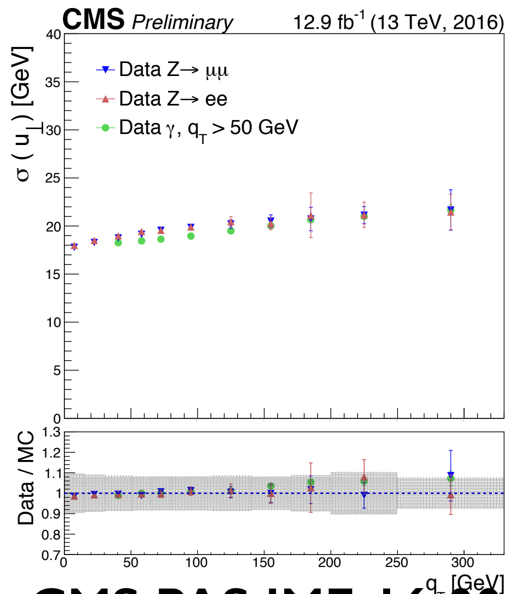
Experimental Challenges

Leptons



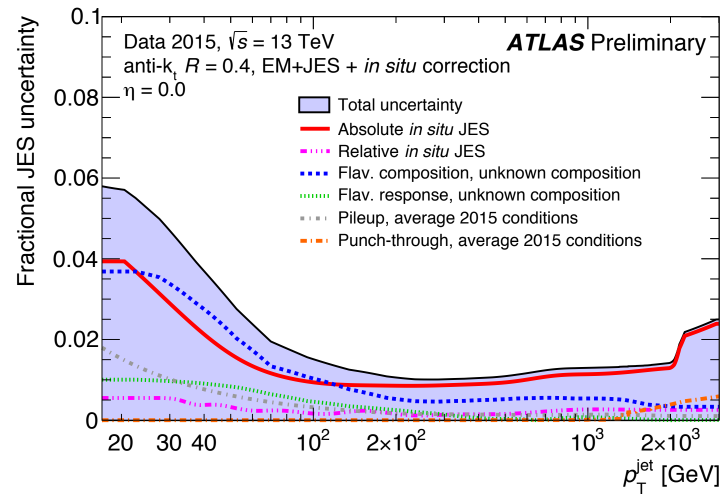
EPJC 76 (2016) 292

MET

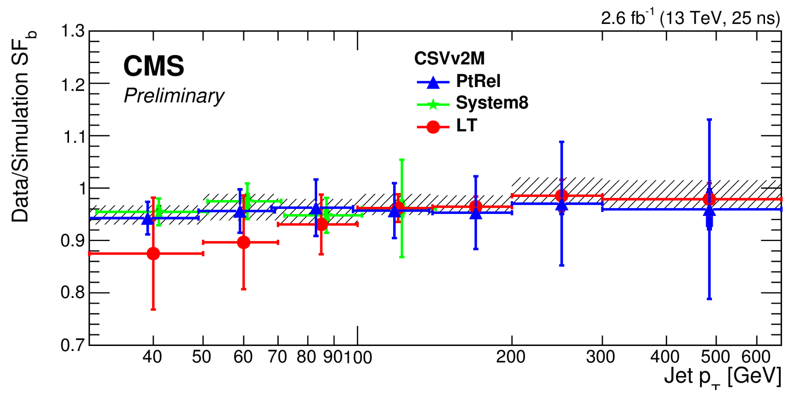


CMS PAS JME-16-004

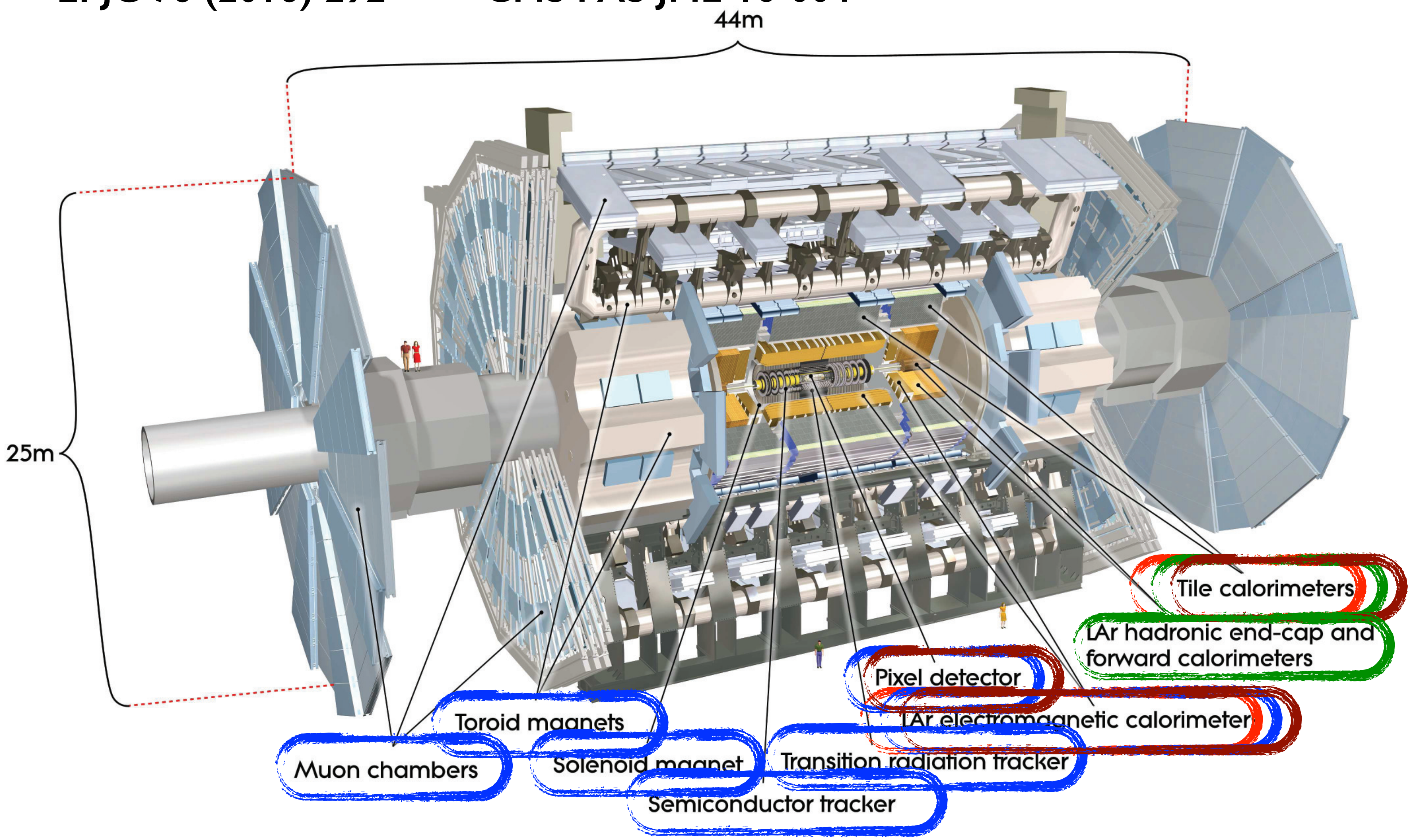
Jets



b-tags



CMS PAS BTV-15-001



Impressed tourist pic

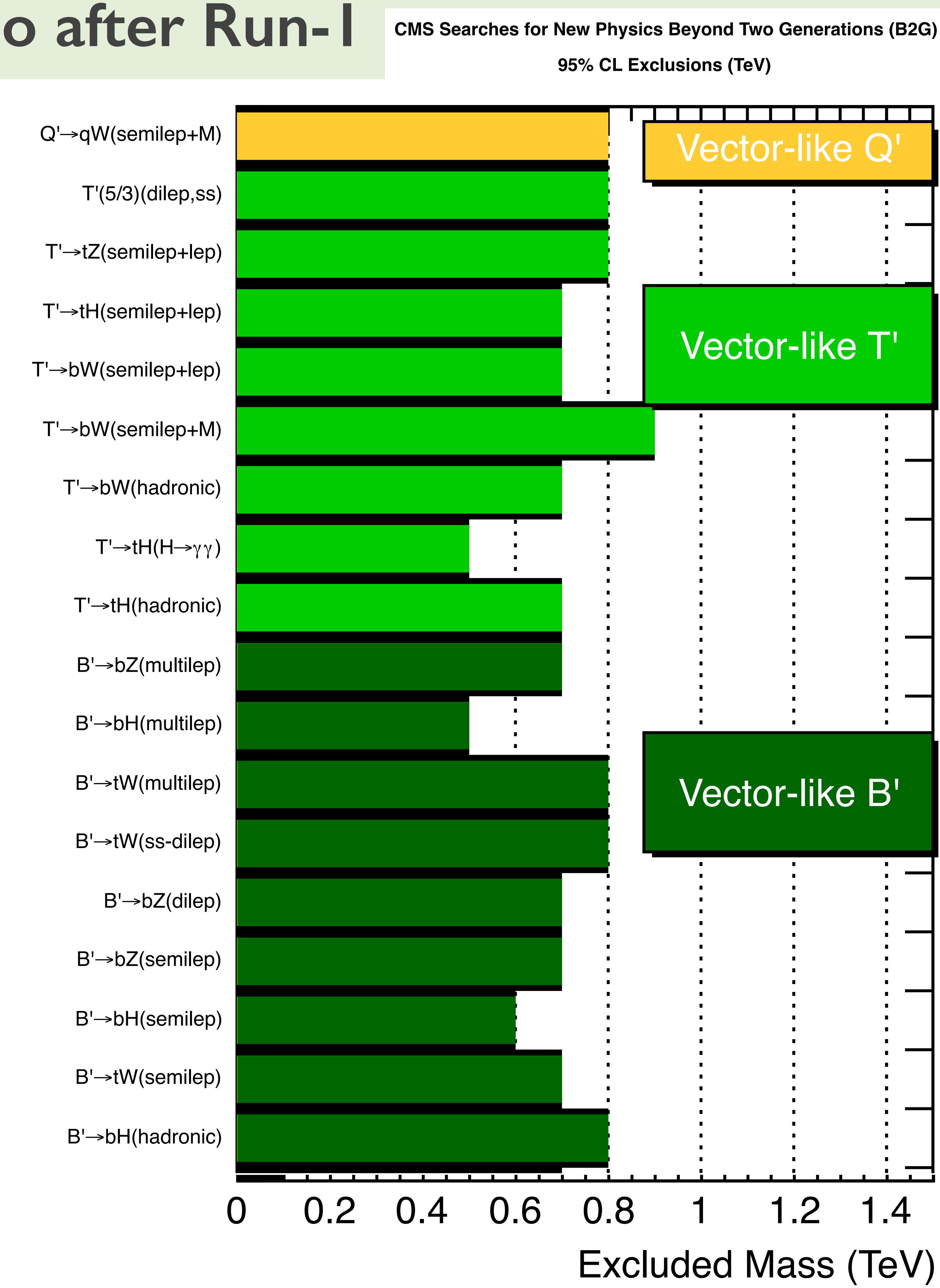
Status Quo after Run-1

- Extensive search program for pairs
- Mass limits from ~700 to ~900 GeV
  - Depend on assumed BRs

ATLAS example : (JHEP 08 (2015) 105)

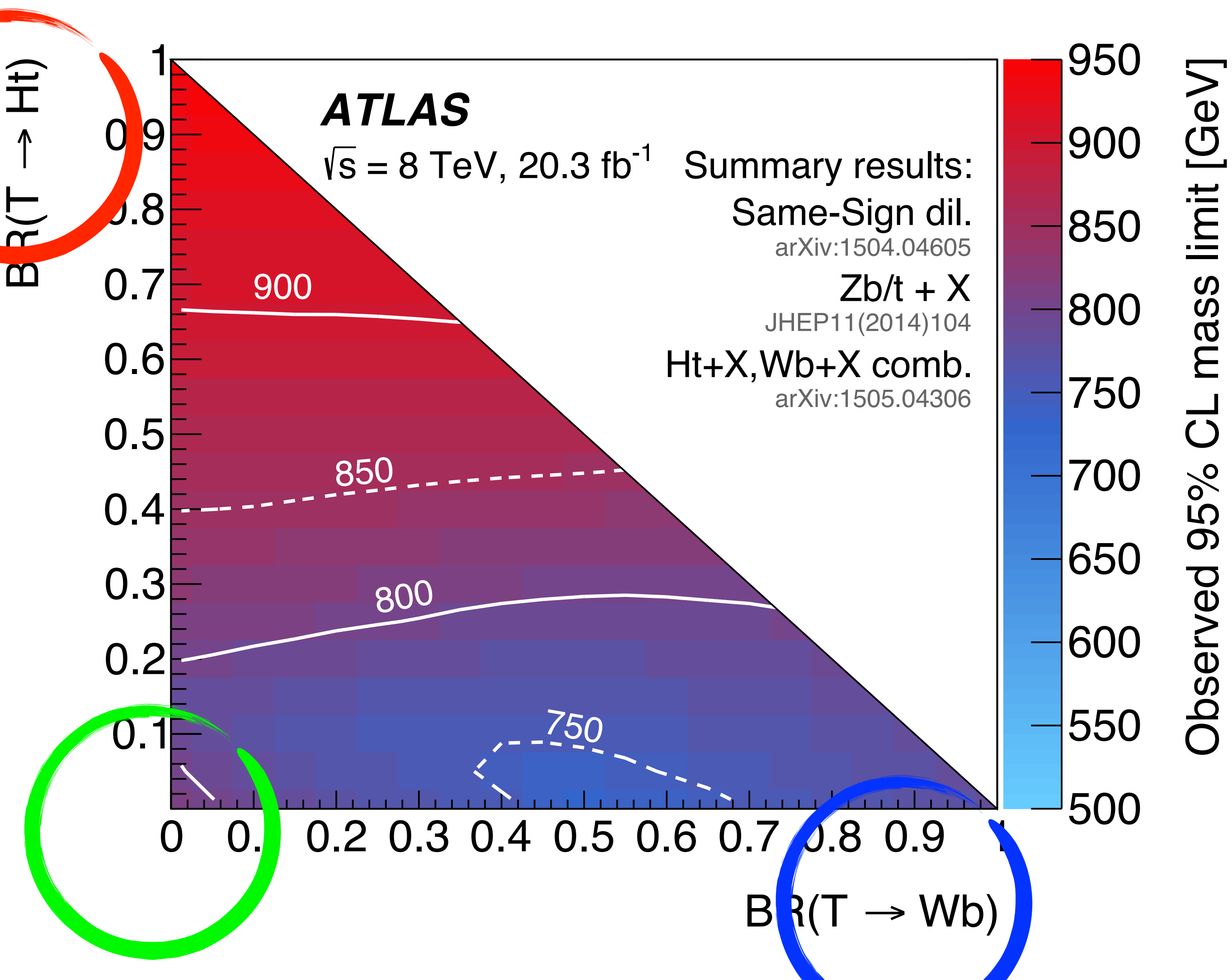
singlet T: m > 765 GeV

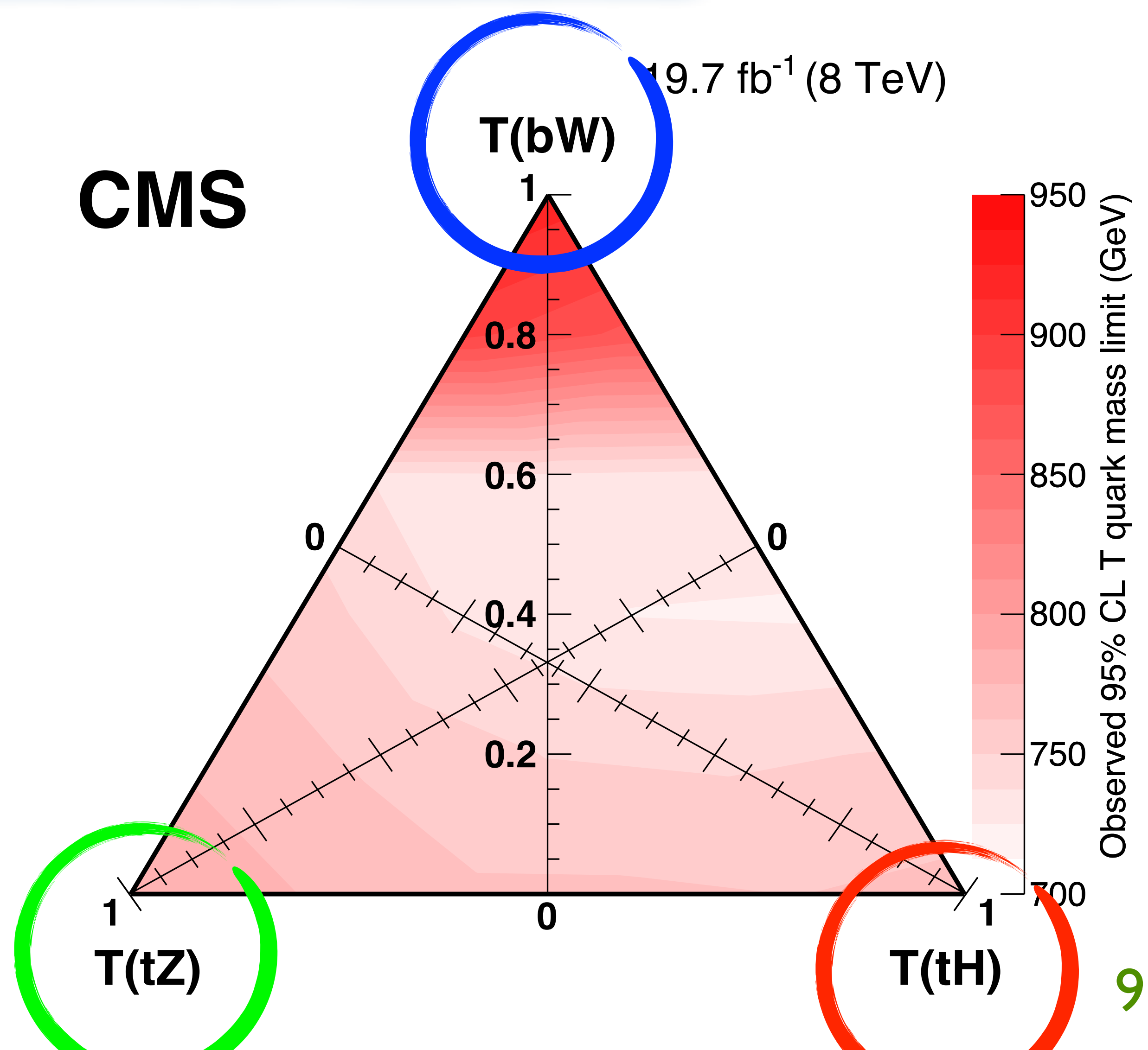
doublet T: m > 855 GeV



Run-1 Strategies

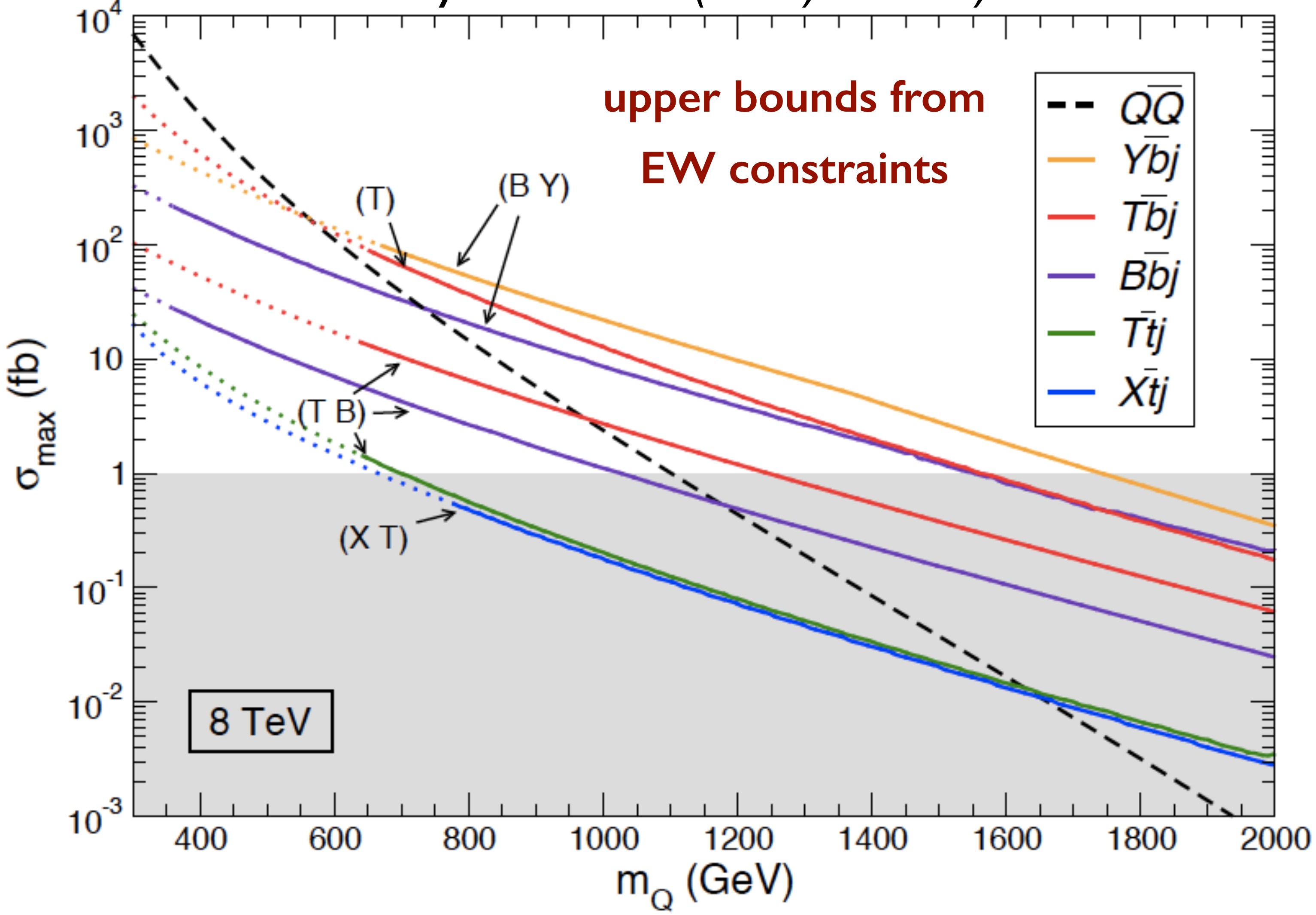
- σ dominated by pair production
- Focus on decay to 3rd gen.
- Exploiting the full ***BR triangle***
- ATLAS strategy inclusive (‘TT→Ht+X’)
- CMS strategy more exclusive (‘TT→bWbW’)
  - combination papers (*PRD 93 (2016) 012003* and *112009*)





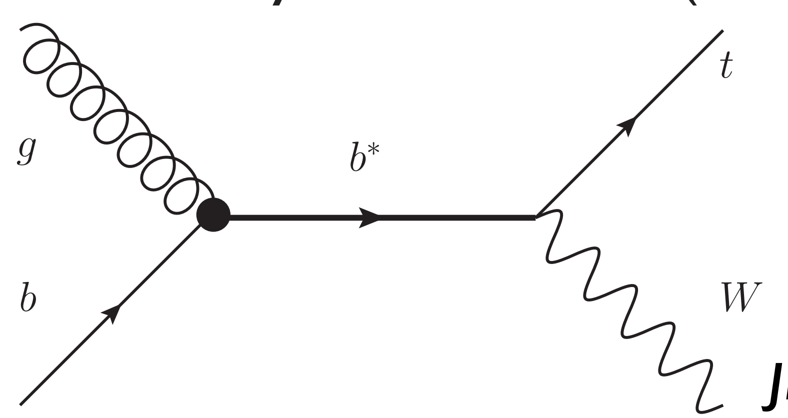
Single Production @ Run-1

(Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria, Phys. Rev. D 88 (2013) 094010)



- Pair production dominates for m < ~1 TeV
- EW single production may dominate at high m

Single production may be enhanced (here: excited b)



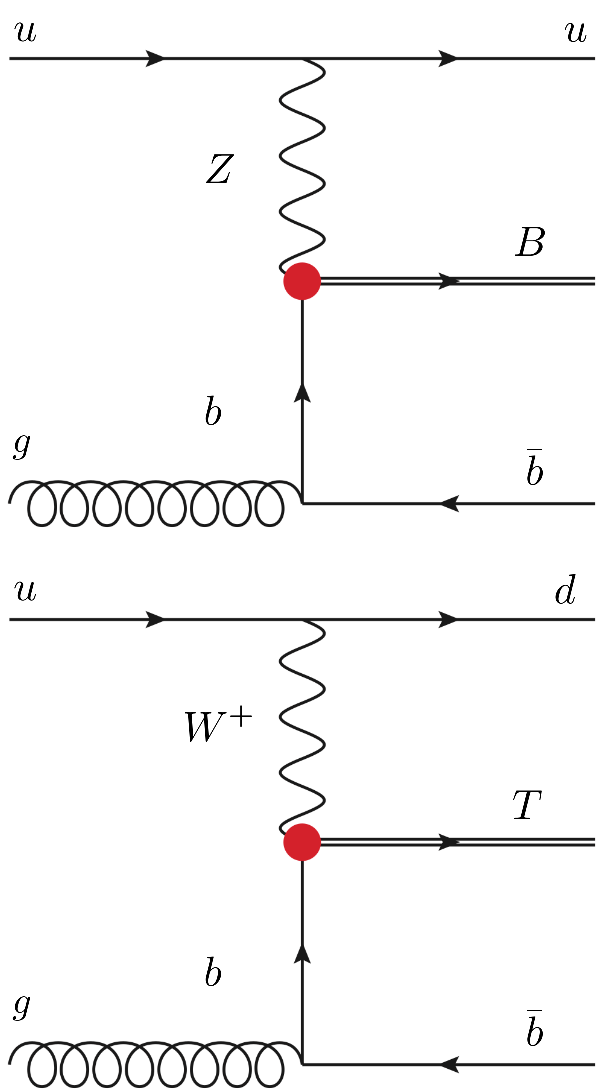
JHEP 01 (2016) 166

Single Production @ Run-1

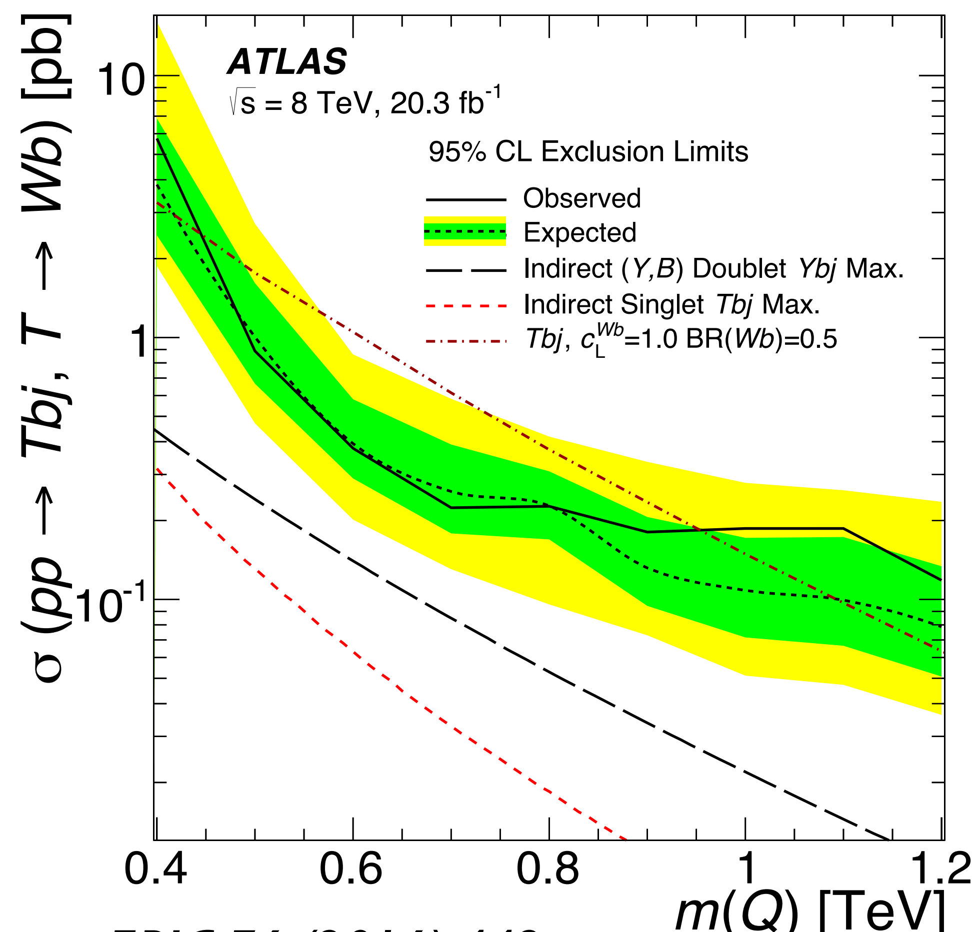
Sensitivity to single production challenging at 8 TeV

low σ for EW

JHEP 11 (2014) 104
also JHEP 02 (2016) 110



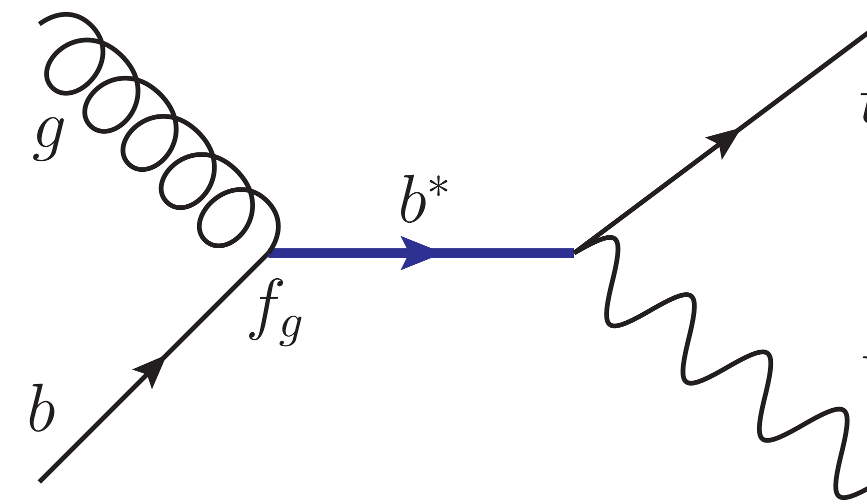
with large coupling



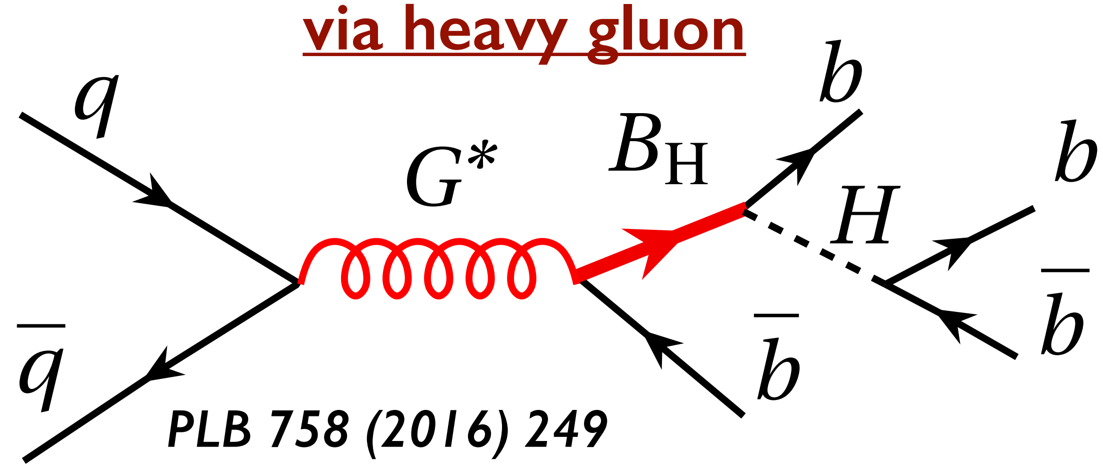
EPJC 76 (2016) 442

excited b-quark

JHEP 02 (2016) 110



via heavy gluon

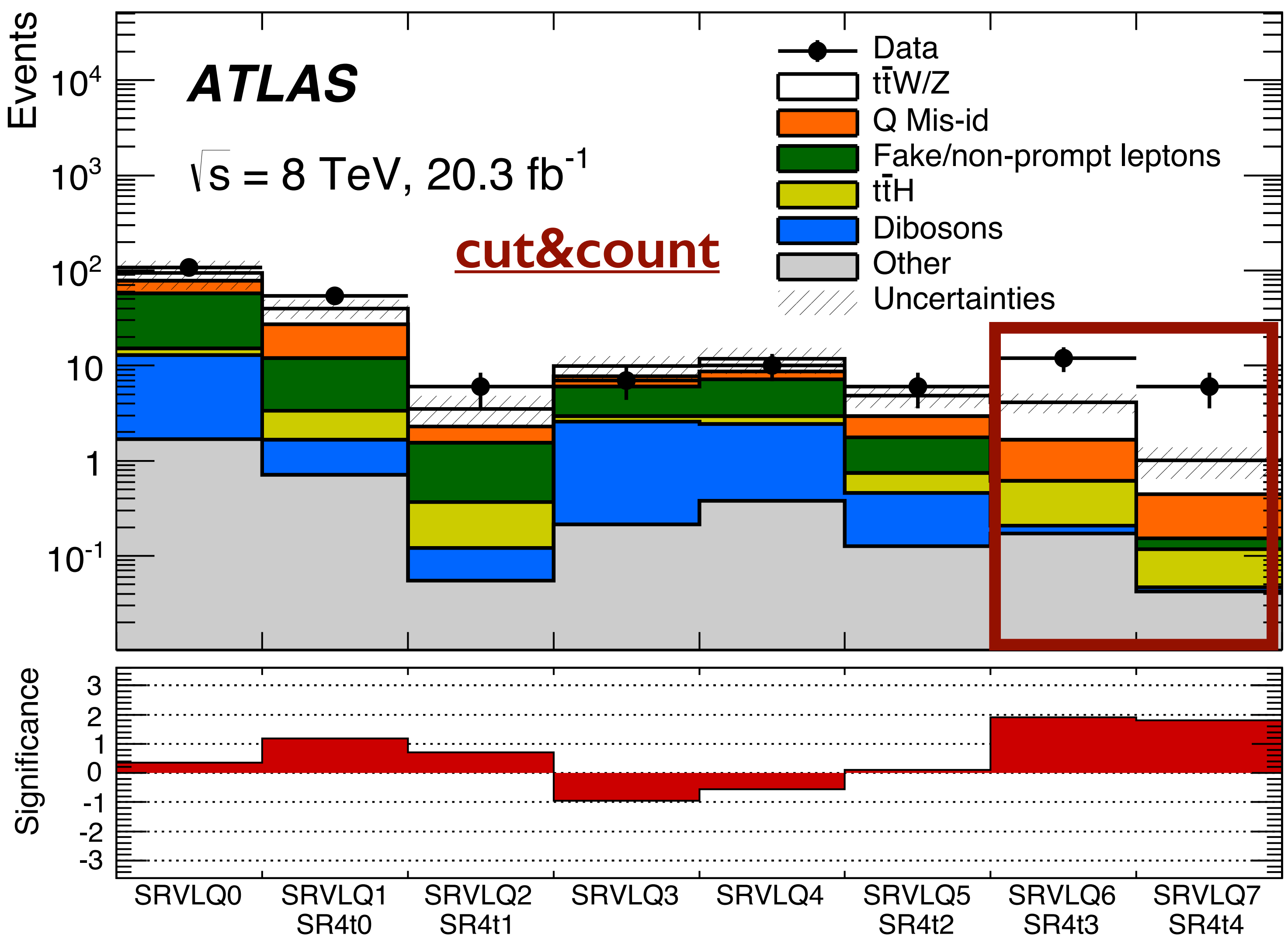


PLB 758 (2016) 249

Some Excitement @ Run-1

Same-sign leptons + b-quarks

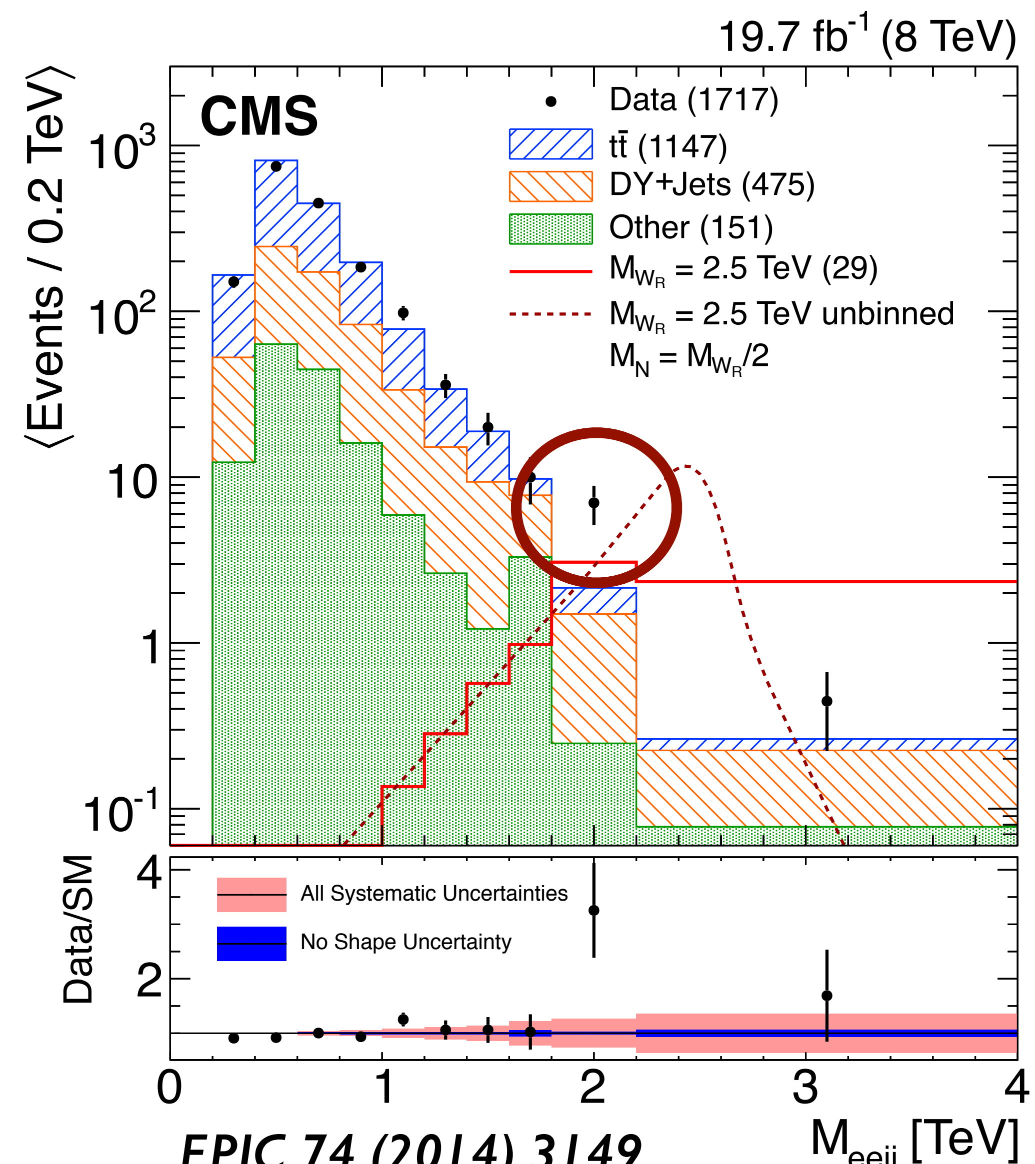
JHEP 10 (2015) 150



Link to other Run-1 excesses?

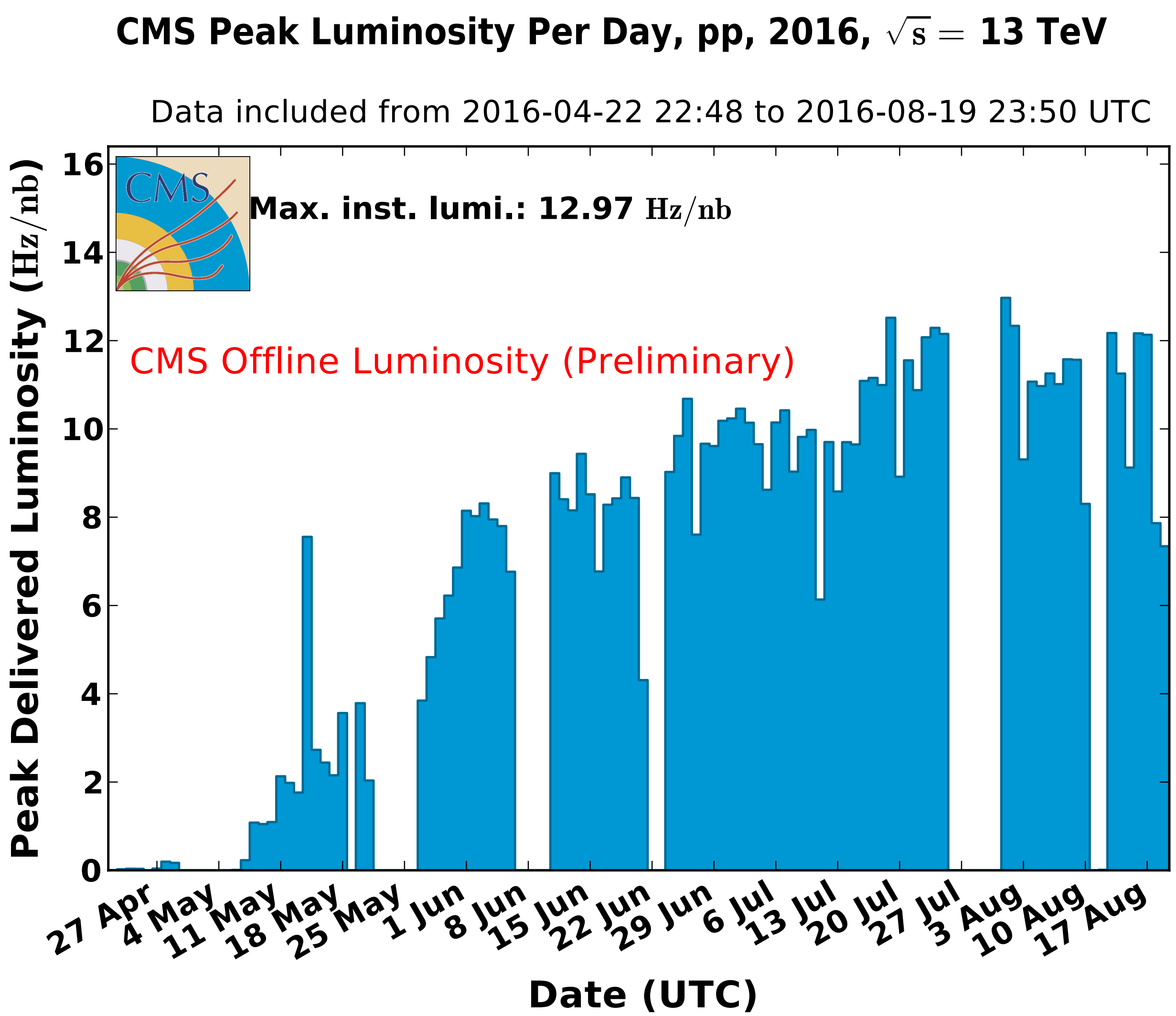
(just one ex. ***Dobrescu, Liu, JHEP 10 (2015) 118***

propose $W' \to H^+ A^0/H^0 \to t\bar{b}t\bar{t}$)

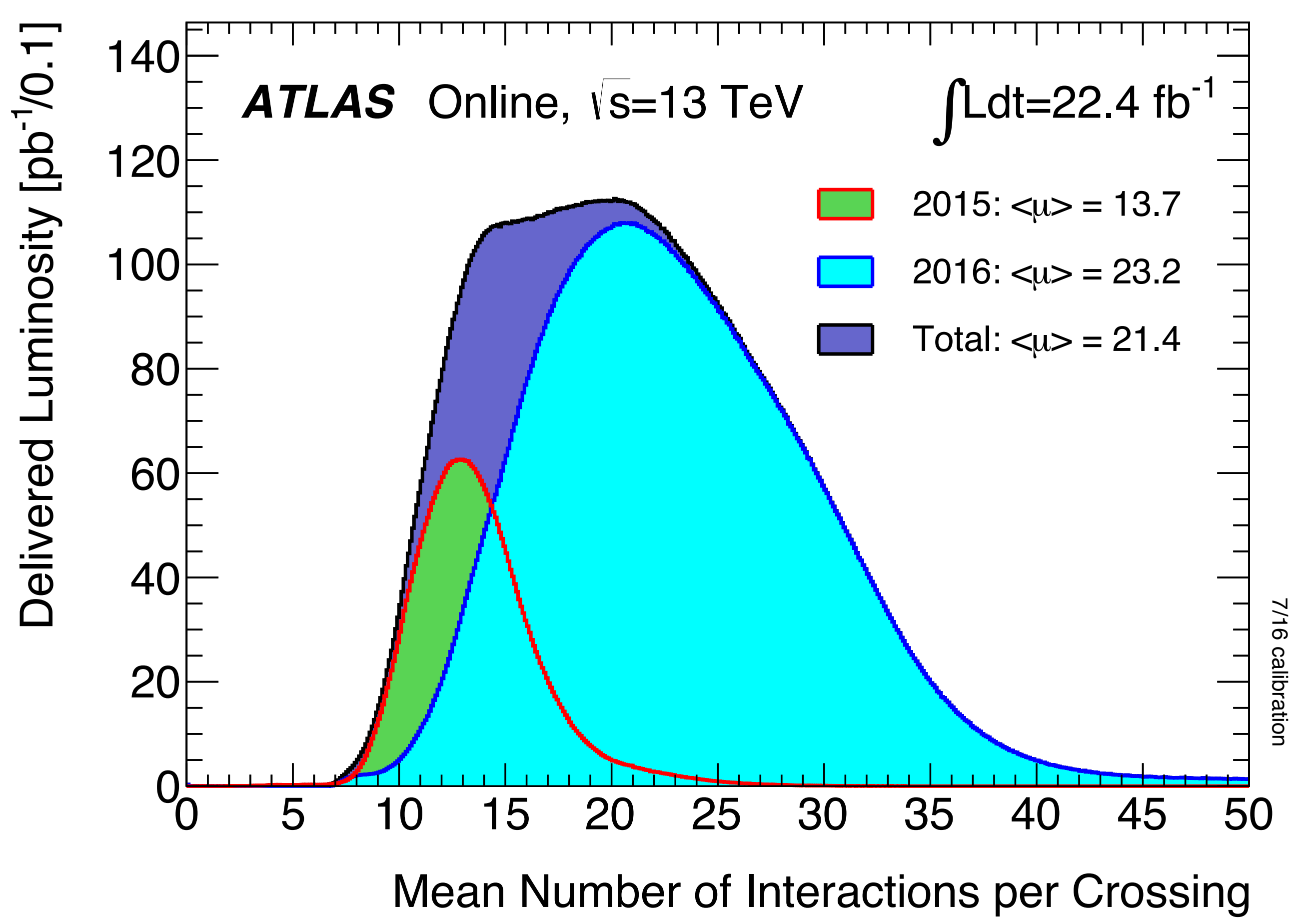


EPJC 74 (2014) 3149

From 8 TeV to 13 TeV

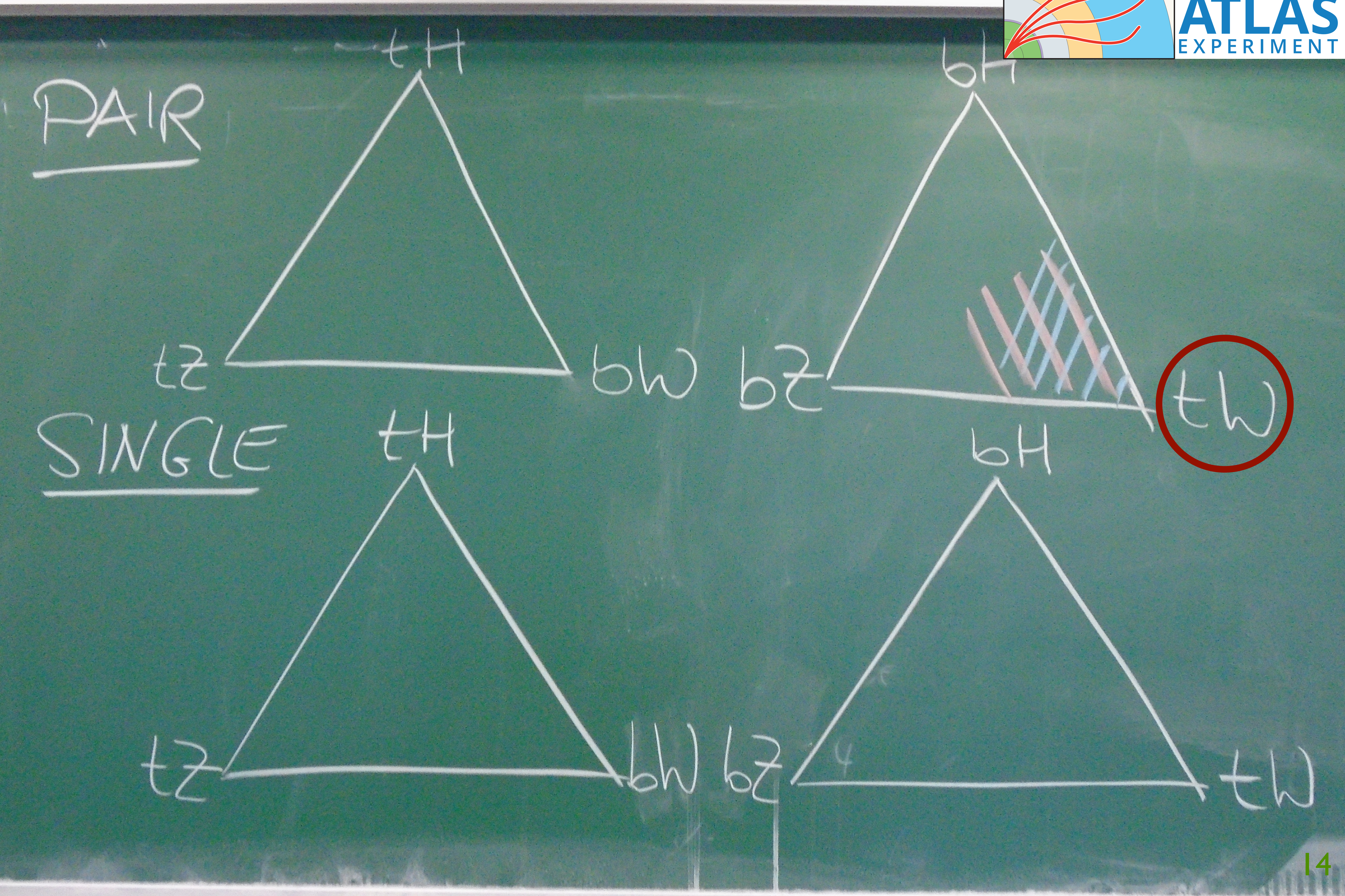


$$= 10^{34}\,\mathrm{cm}^{-2}\,s^{-1}$$

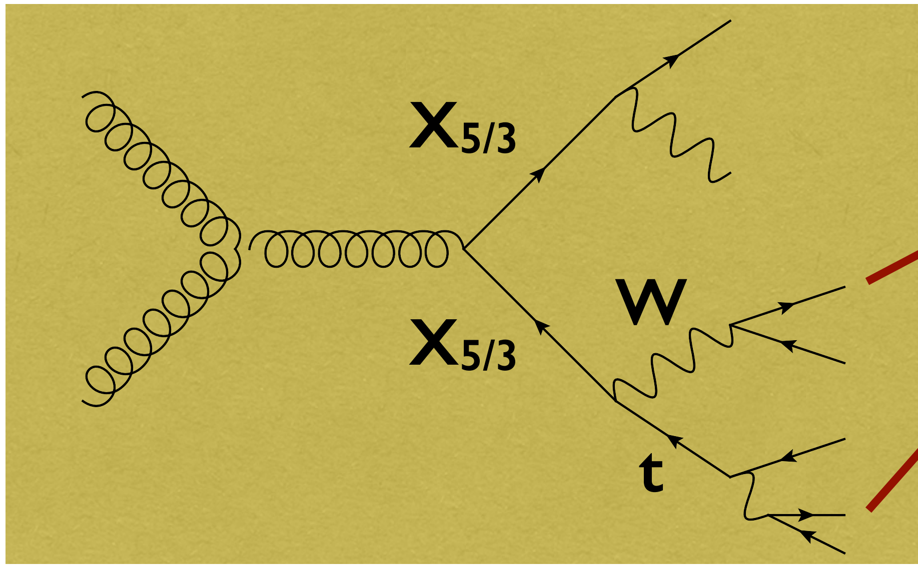


- Record in instantaneous luminosity !
- Comes with higher pile-up
- Results in this talk based on 2015 data

Same-Sign Leptons

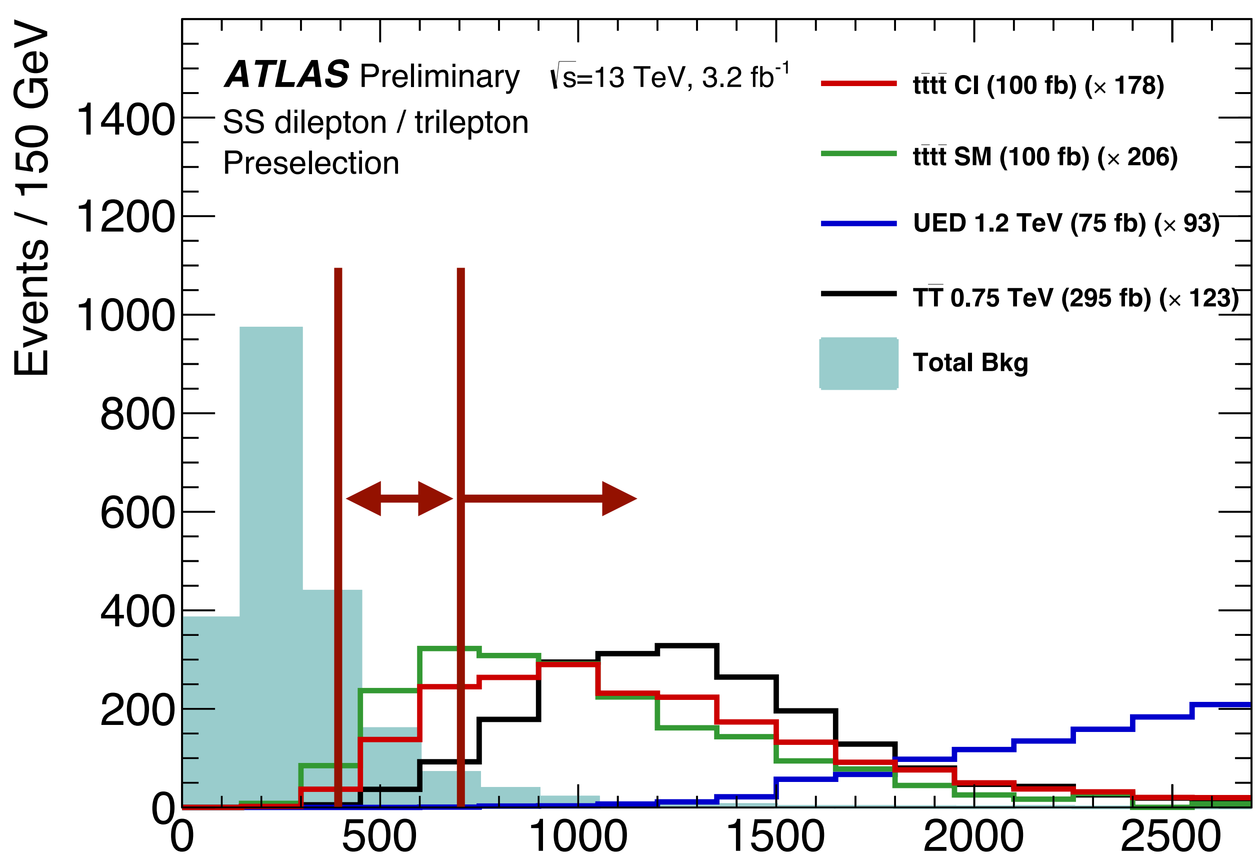


Same-Sign Leptons

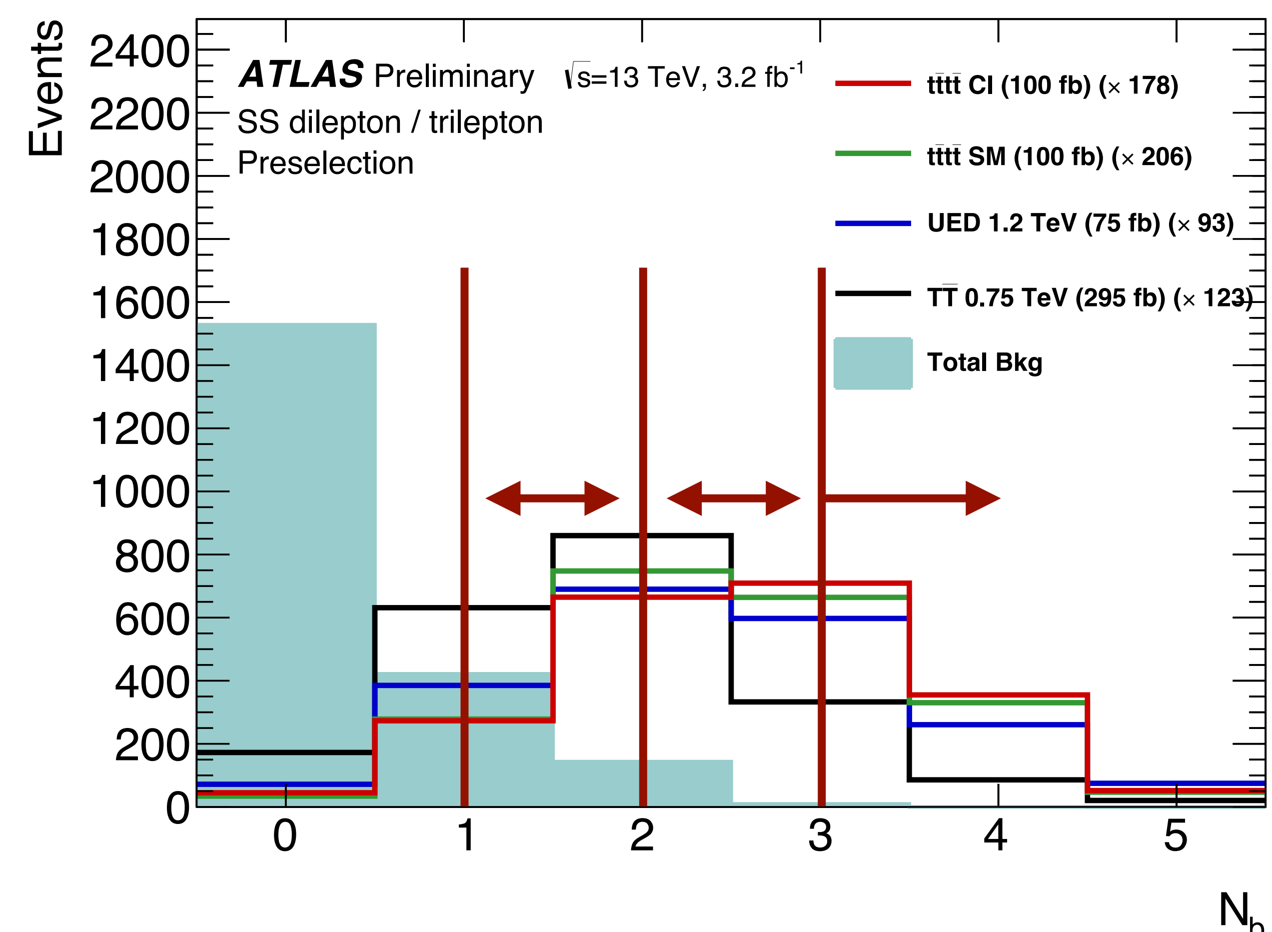


- $e^\pm e^\pm$ + $\mu^\pm \mu^\pm$ + $e^\pm \mu^\pm$ + trilepton
- J/ψ and Z vetos
- high : H_T & b-tag multiplicity & MET
- categorize and count !

(same 8 categories as Run-1)



$H_T = \Sigma p_T(\text{jets}) + \Sigma p_T(\text{leptons})$ H_T [GeV]



Same-Sign Leptons

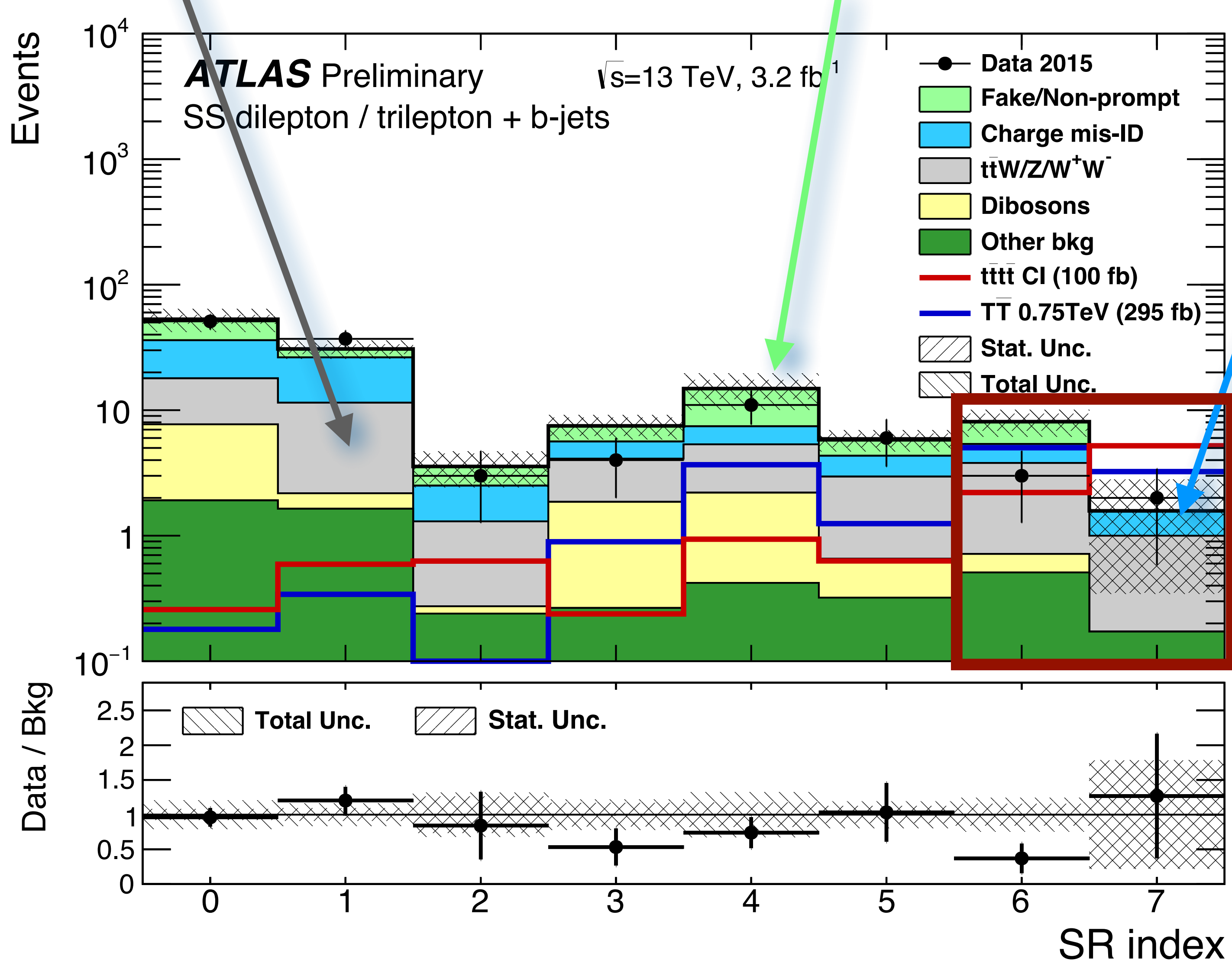
Main Backgrounds

$t\bar{t} + W/Z/\ldots$
- from MC

$t\bar{t} \rightarrow \ell + b\bar{b} + X$
- fake leptons
- from matrix method
- 54% systematics

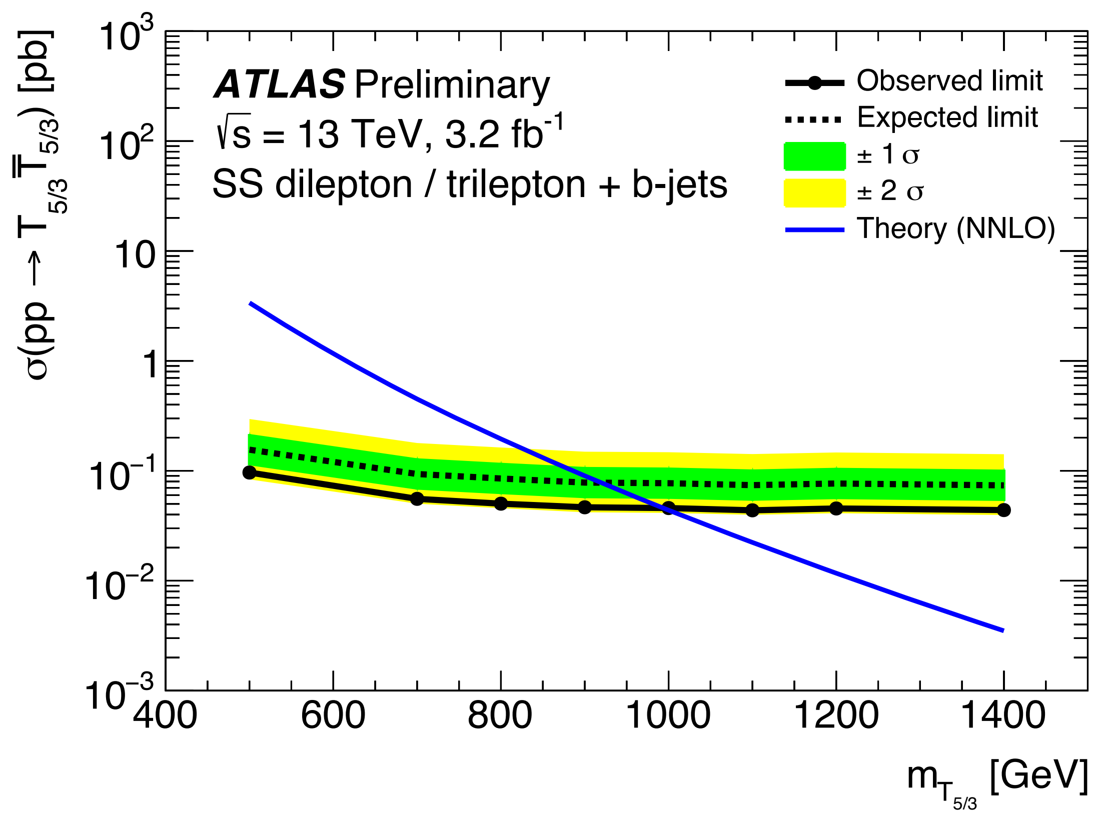
$t\bar{t} \rightarrow \ell^+\ell^- + b\bar{b} + X$
- charge mis-ID (only $e^\pm$)
- from $Z \rightarrow e^+e^-$
- 25% systematics
- *trident electrons :*
  - *charge mis-ID*
  - *fake leptons from γ conversions*

→ *fake lepton subtraction to avoid double-counting*

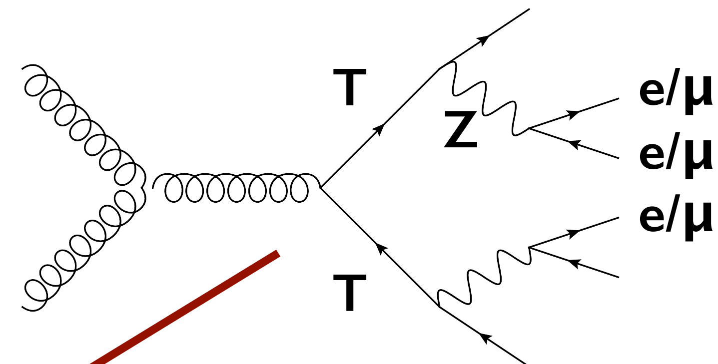


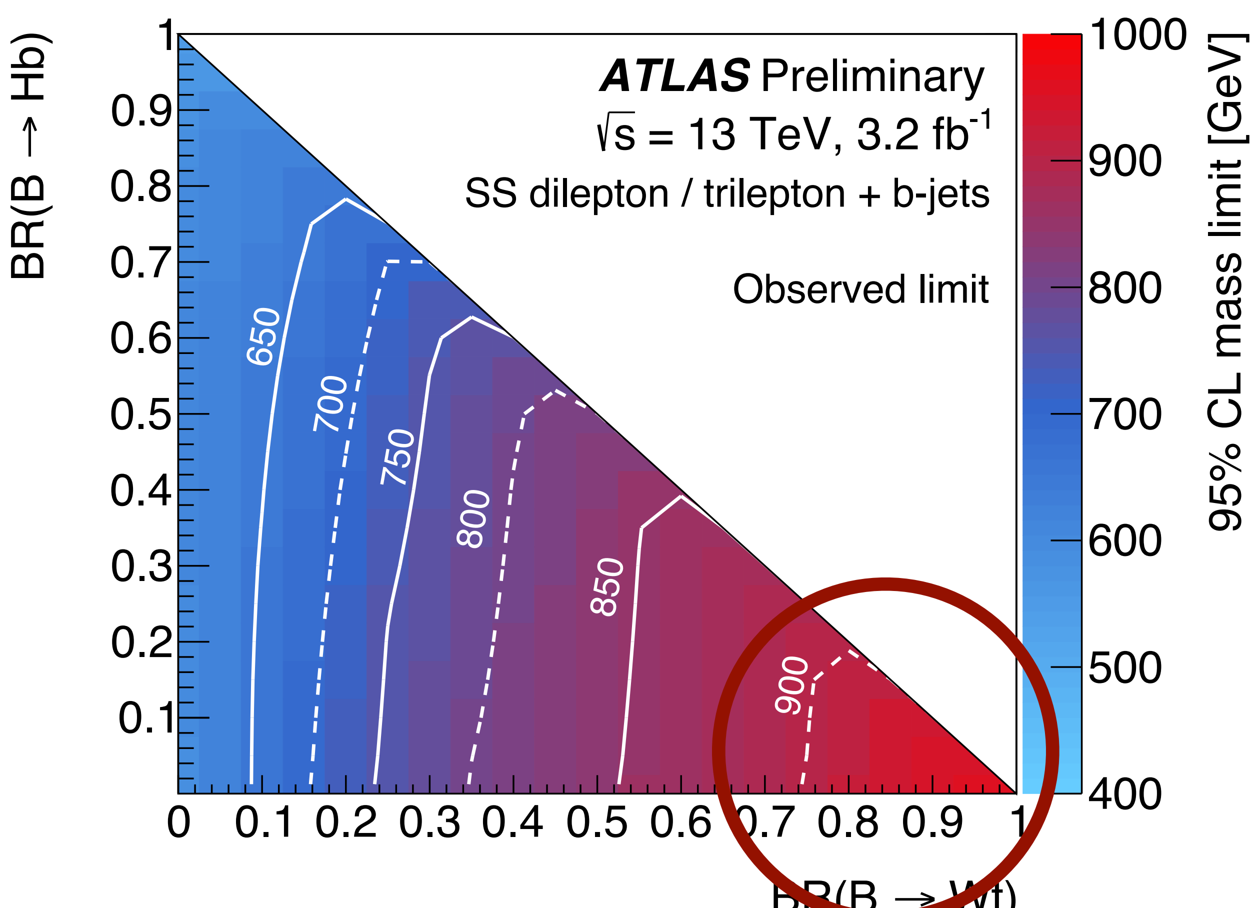
Run-1 excess not reproduced

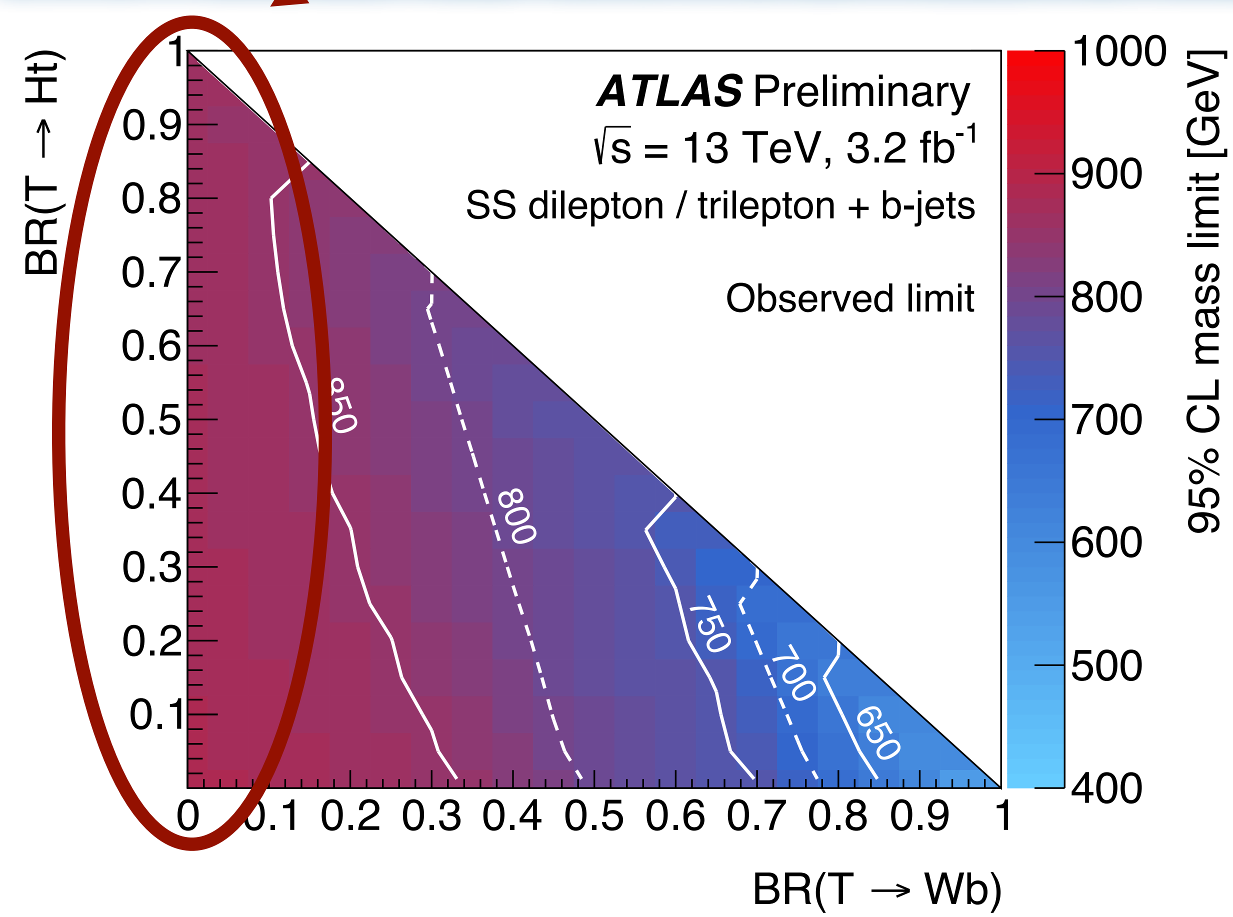
Same-Sign Leptons



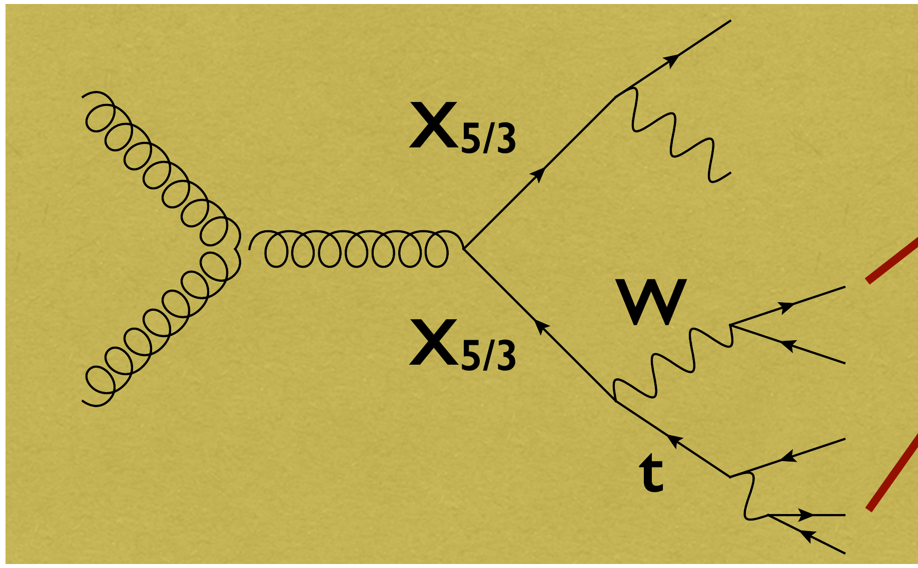
- m($X_{5/3}$) > 0.99 TeV *(was 0.74 TeV @ Run-1)*
- m(B|singlet) > 0.83 TeV *(was 0.69 TeV)*
- m(T|singlet) > 0.78 TeV *(was 0.66 TeV)*
- sensitivity to T via H → WW* or Z → l^+l^-





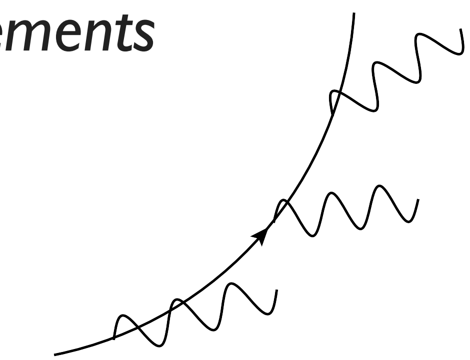


Same-Sign Leptons & l+jets



- $e^{\pm}e^{\pm}$ + $\mu^{\pm}\mu^{\pm}$ + $e^{\pm}\mu^{\pm}$
- J/ψ and Z vetos
- high : H_T & p_T(lep) & #(jets+leptons)
- no b-tag requirement
- count in lepton flavor categories !

- *$e^{\pm}$ charge mis-ID suppressed by comparing up to 3 charge measurements*
  - *standard track reconstruction (Kalman filter)*
  - *Gaußian sum filter → improve bremsstrahlung modeling*
  - *rel. position of cluster and track (for p_T < 100 GeV)*



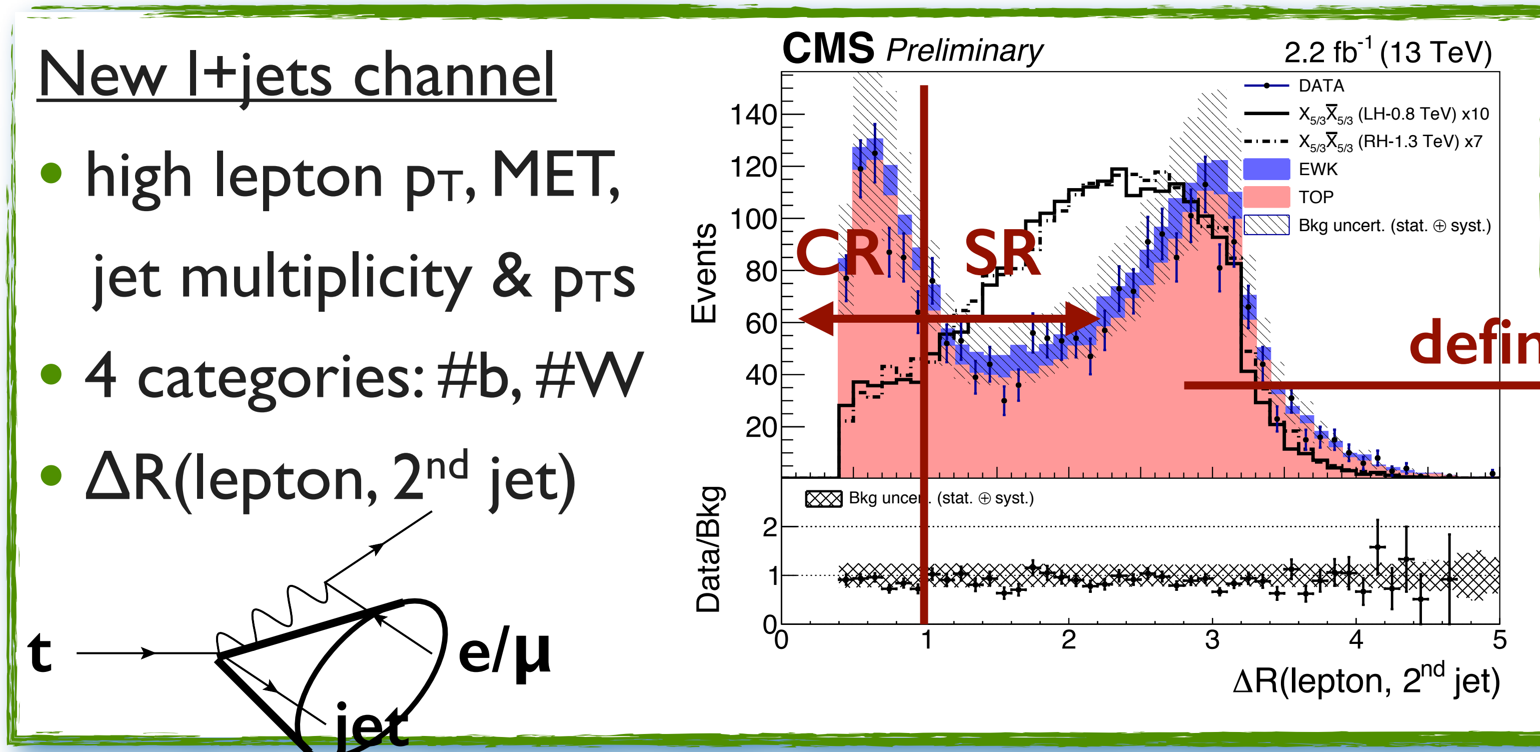
prompt same-sign

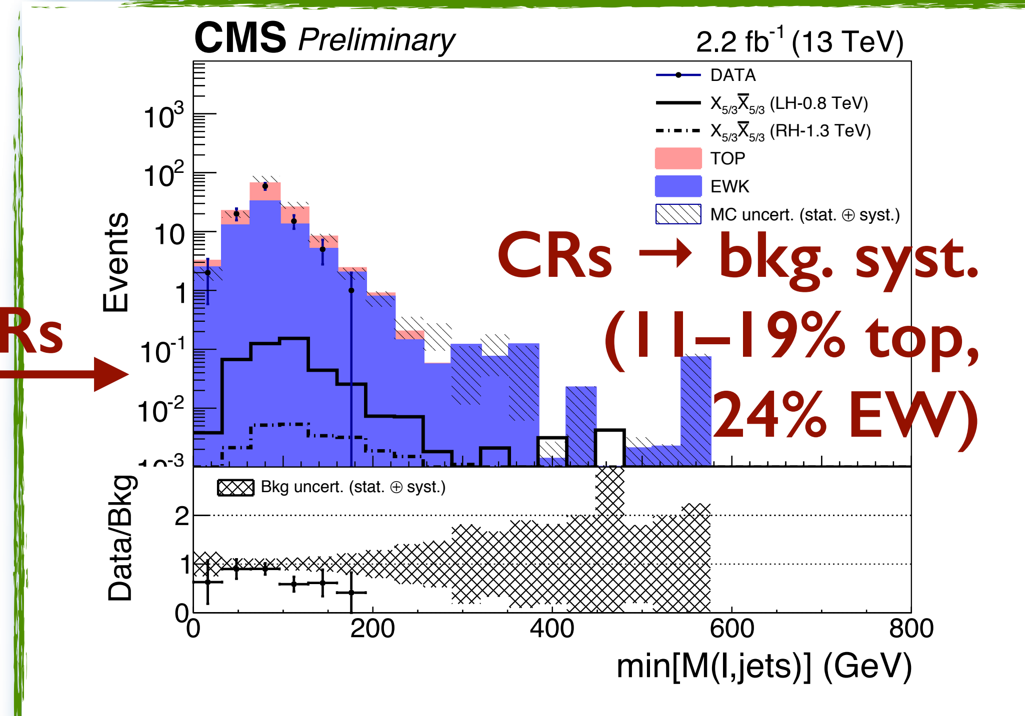
Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
Electron-Muon	2.98 ± 0.36	5.20 ± 3.21	0.54 ± 0.18	8.72 ± 3.24	9.14	3
Di-muon	0.70 ± 0.12	2.09 ± 1.69	0.00 ± 0.00	2.80 ± 1.70	3.55	1
All	6.09 ± 0.67	9.45 ± 5.49	2.44 ± 0.76	17.98 ± 5.58	17.06	11

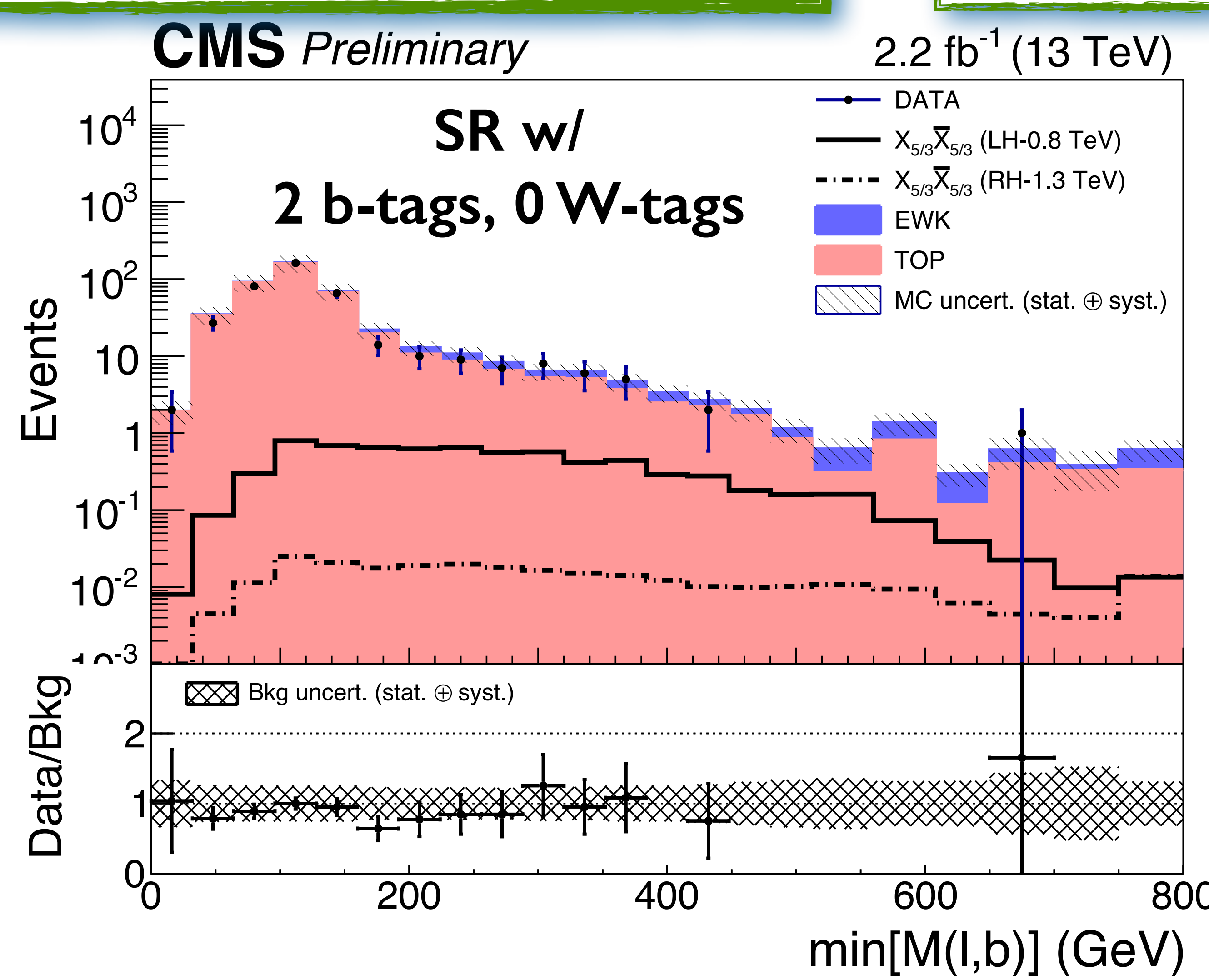
Same-Sign Leptons & l+jets

<u>New l+jets channel</u>

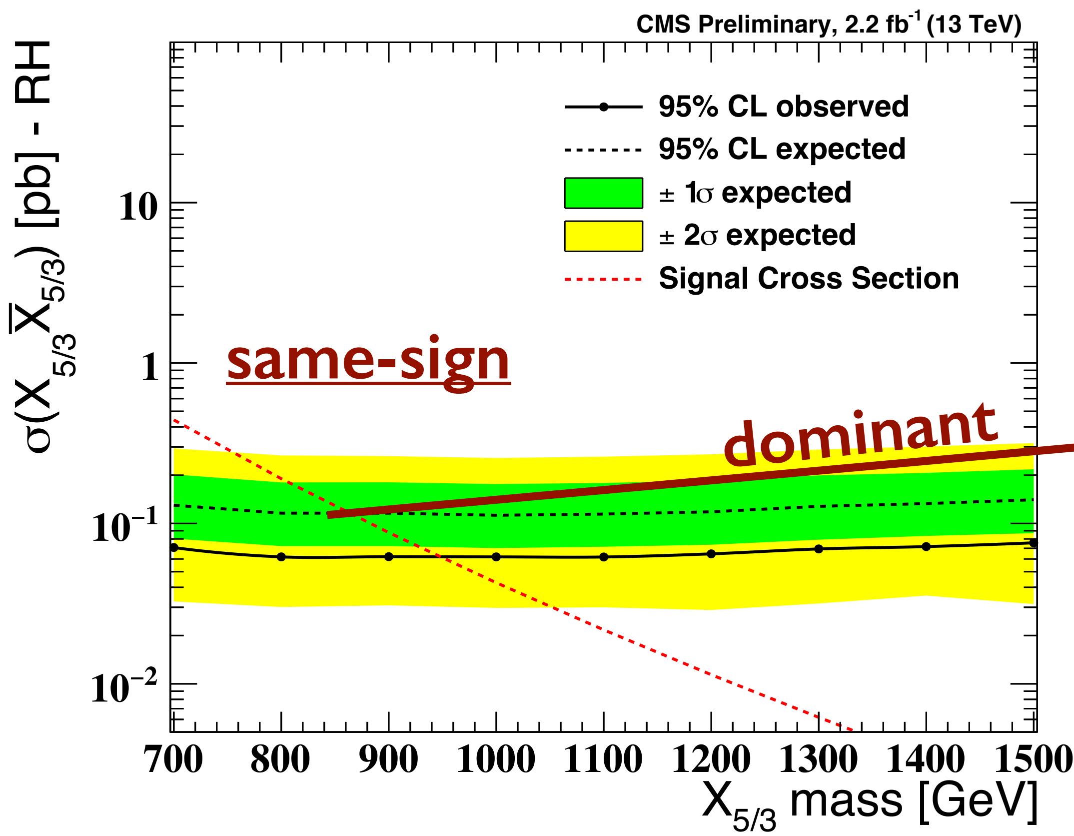
- high lepton p_T, MET, jet multiplicity & p_Ts
- 4 categories: #b, #W
- ΔR(lepton, 2[nd] jet)

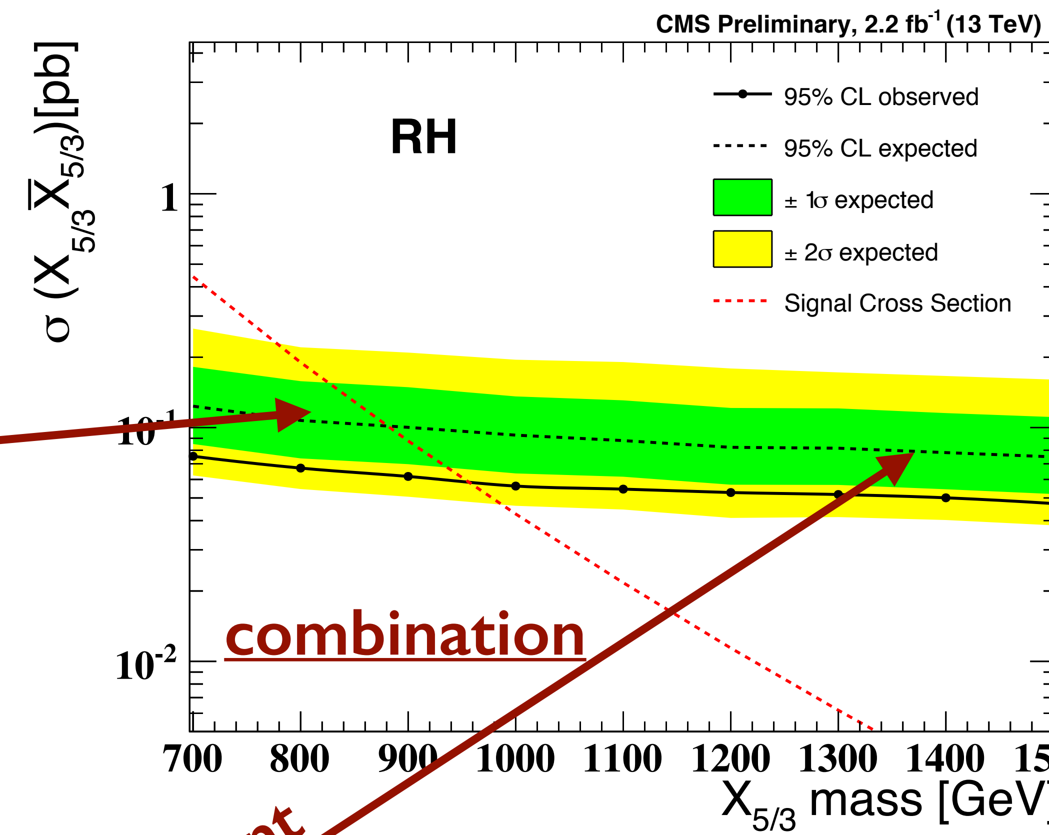


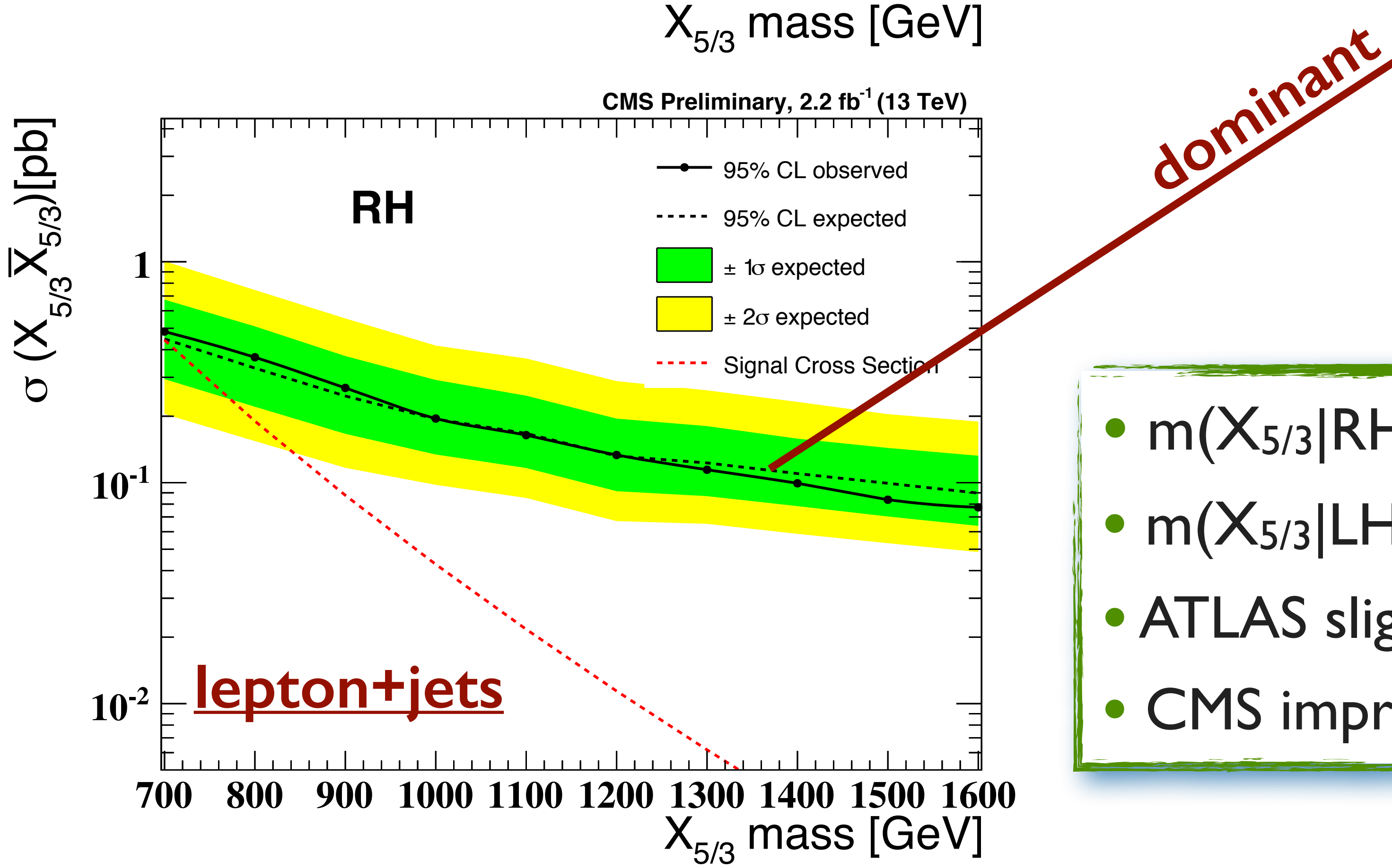




Same-Sign Leptons & l+jets

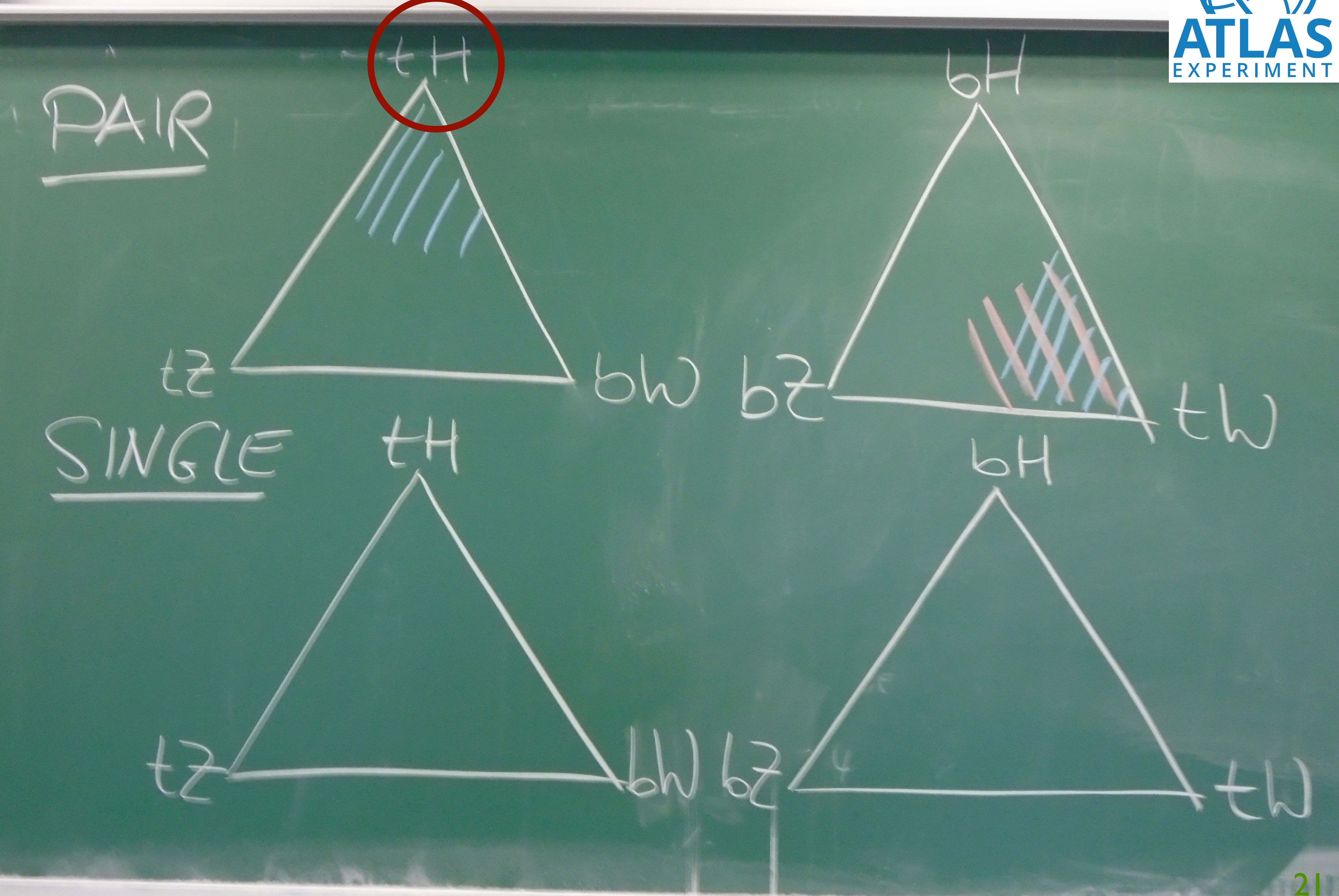




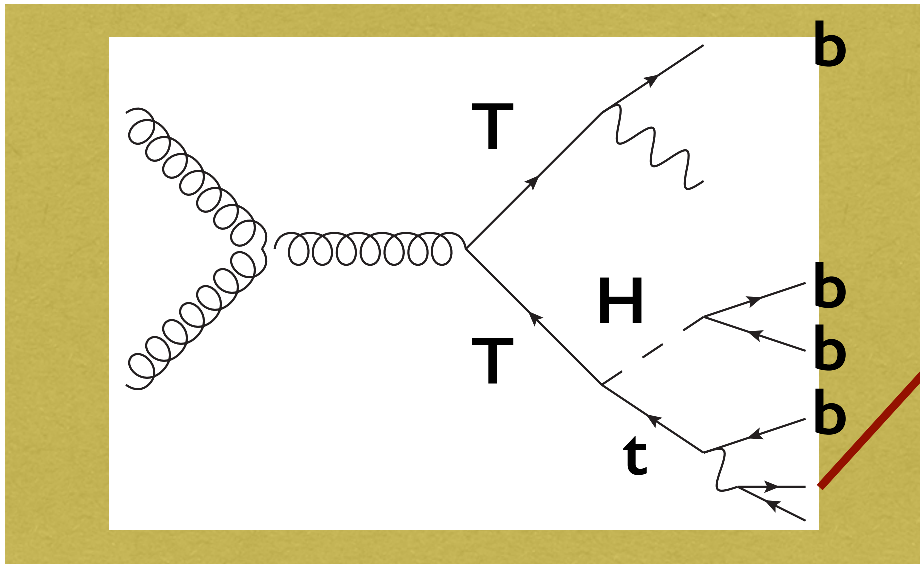


- $m(X_{5/3}|RH)$ > 950 GeV *(was 800 GeV)*
- $m(X_{5/3}|LH)$ > 910 GeV *(was 800 GeV)*
- ATLAS slightly more sensitive (920 vs. 900/860 GeV)
- CMS improves at high mass due to l+jets

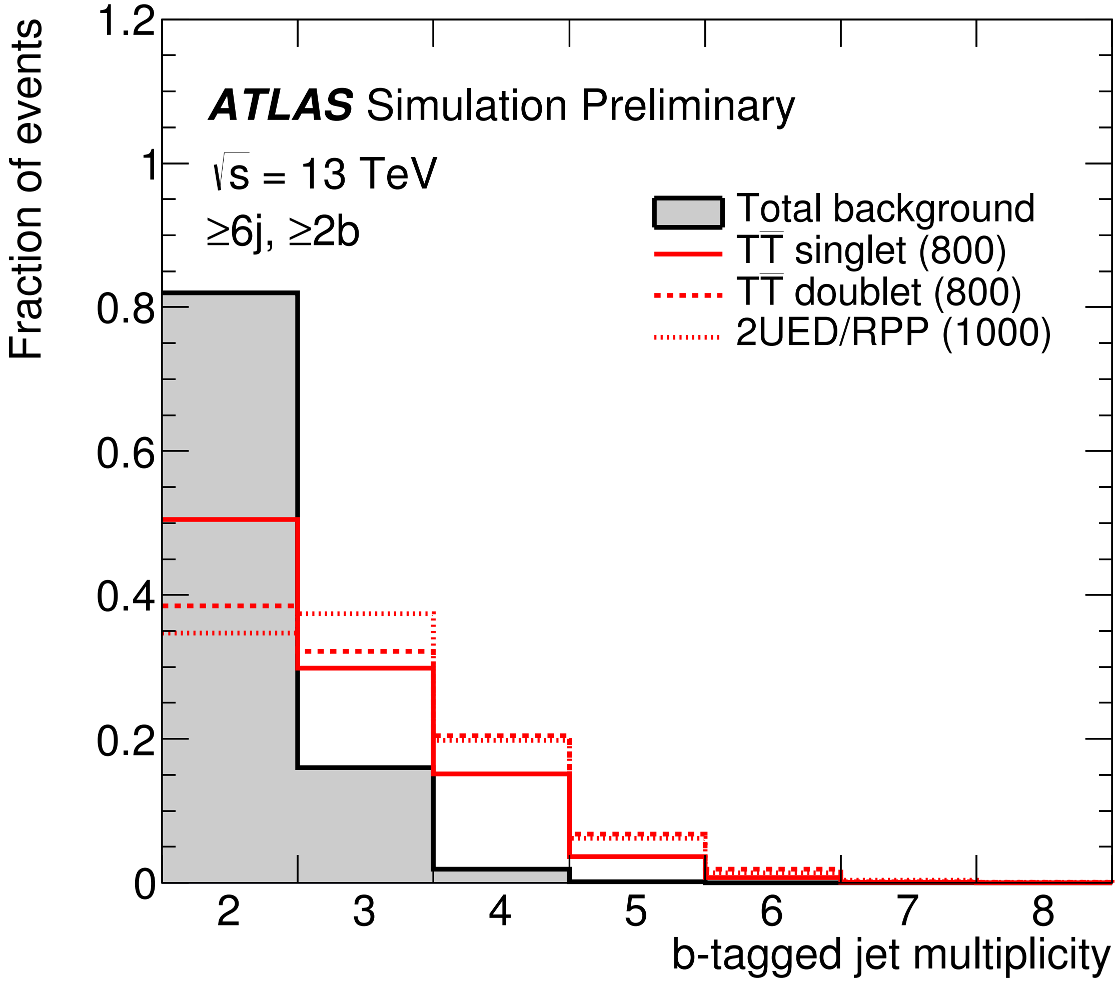
Ht+X

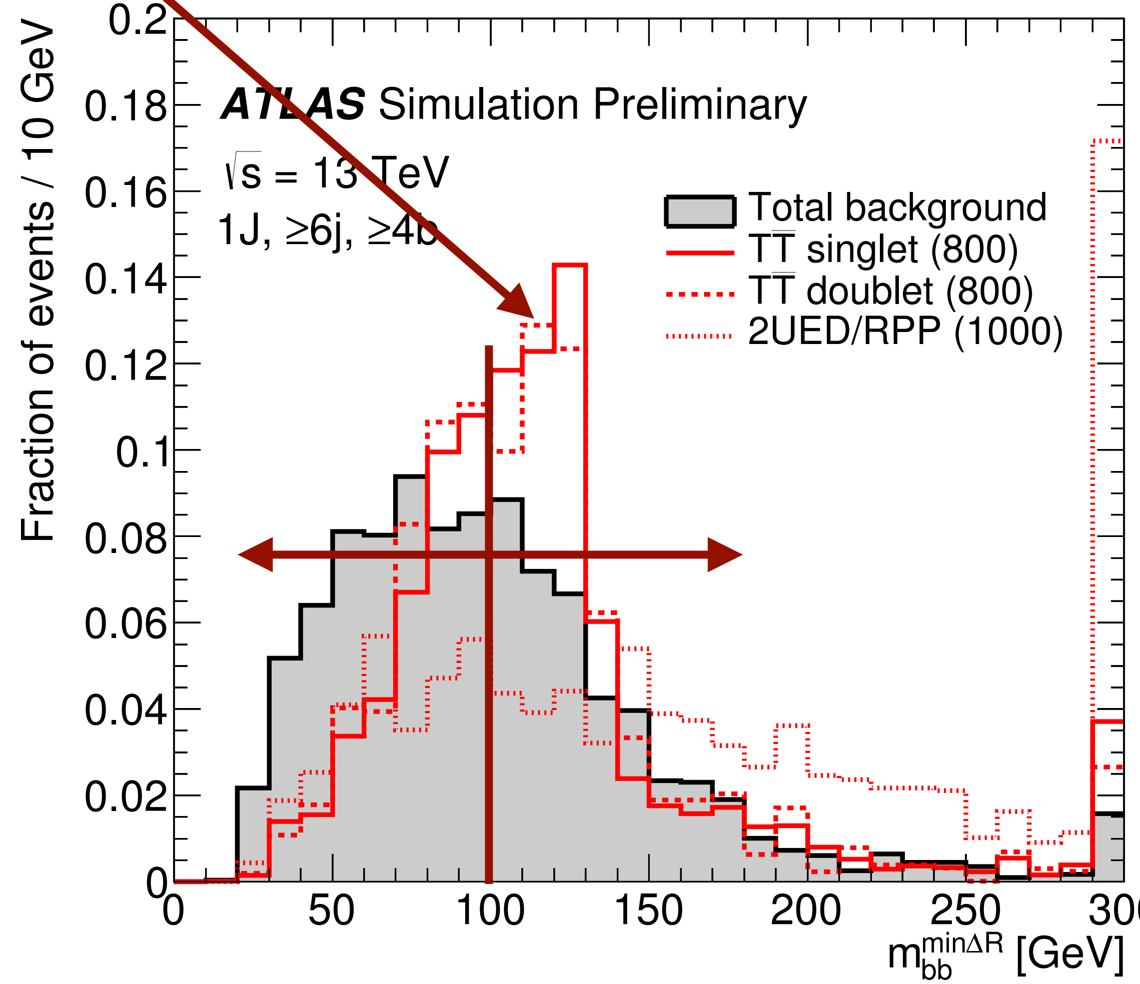


Ht+X

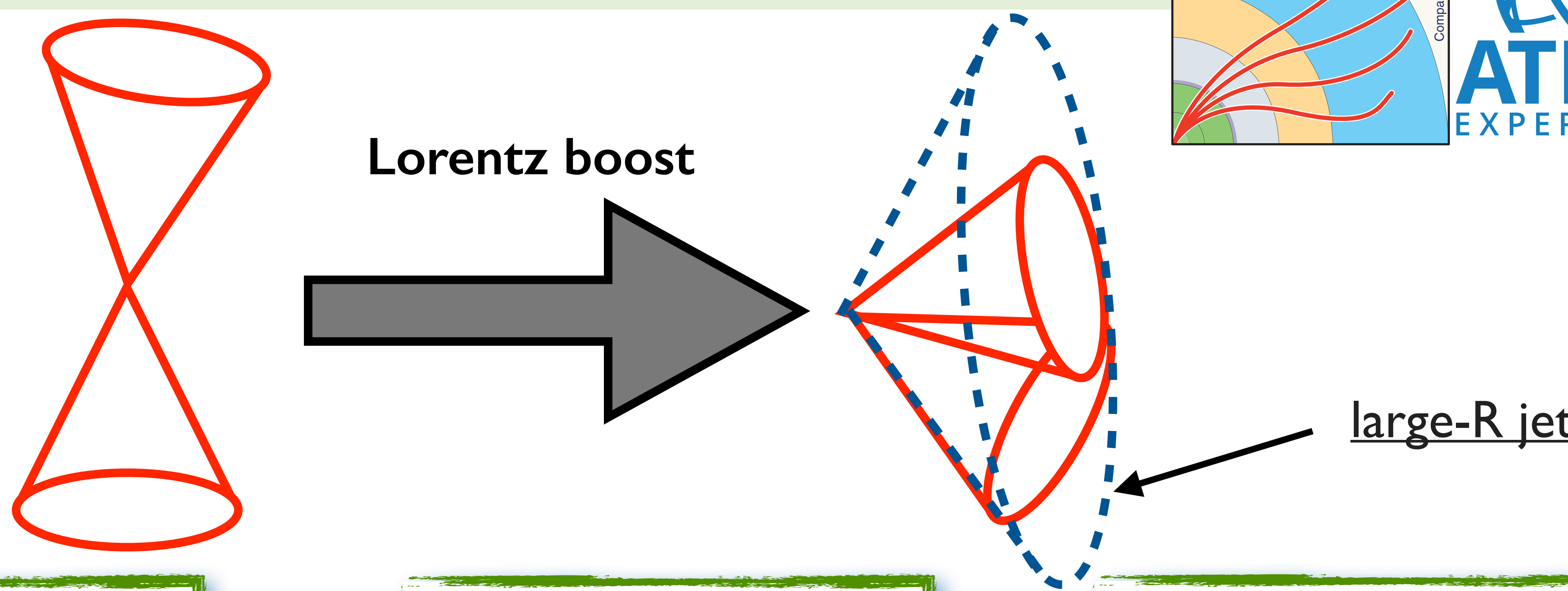


- Exactly one lepton
- Many b-jets, many jets, some MET
- Dominant background : top+b/c+X
- Categorize in #b, #fat-jets (next slide), m_{bb} of closest b-jets (from Higgs)





Fat ('Large-R + Massive') Jets

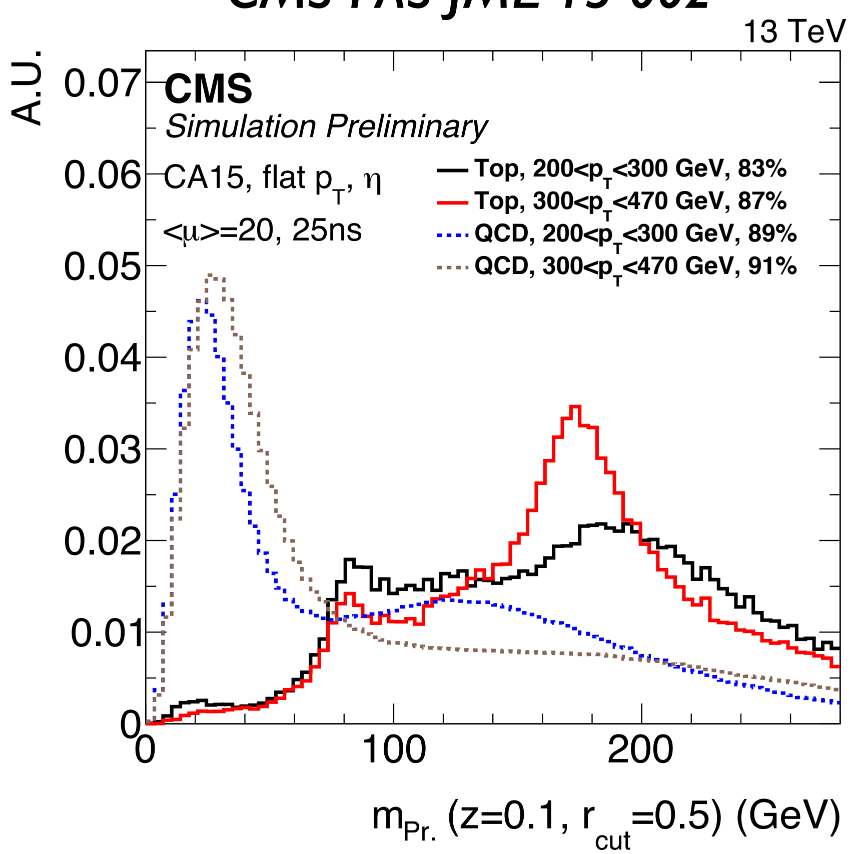


Excellent discriminant

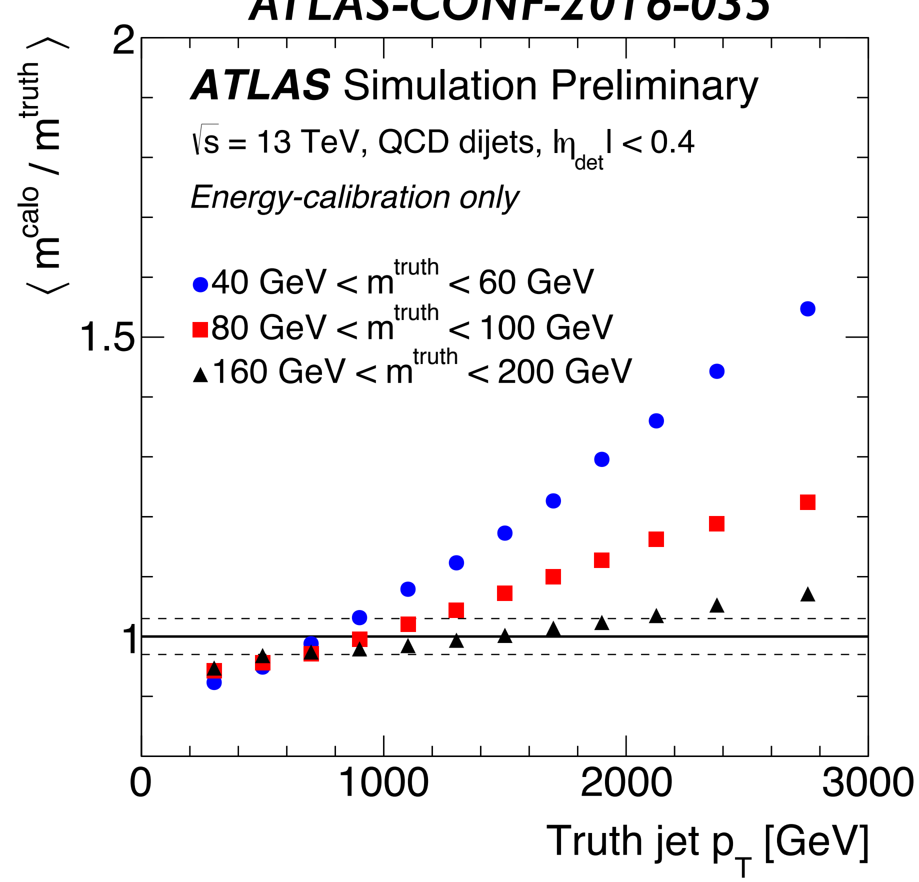
Needs calibration

Or : recluster small-R jets

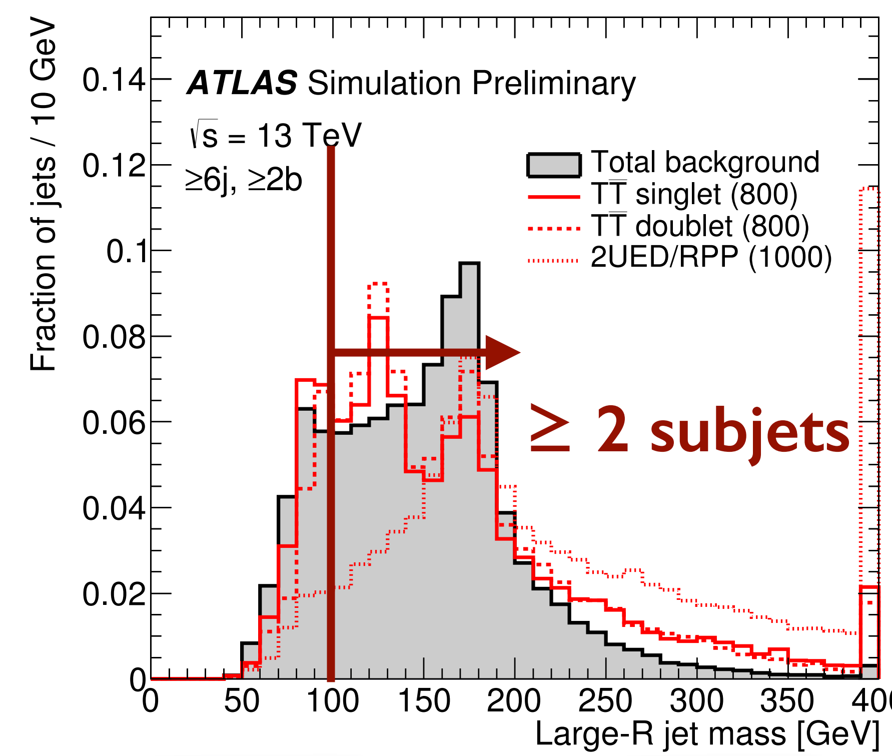
CMS PAS JME-15-002



ATLAS-CONF-2016-035



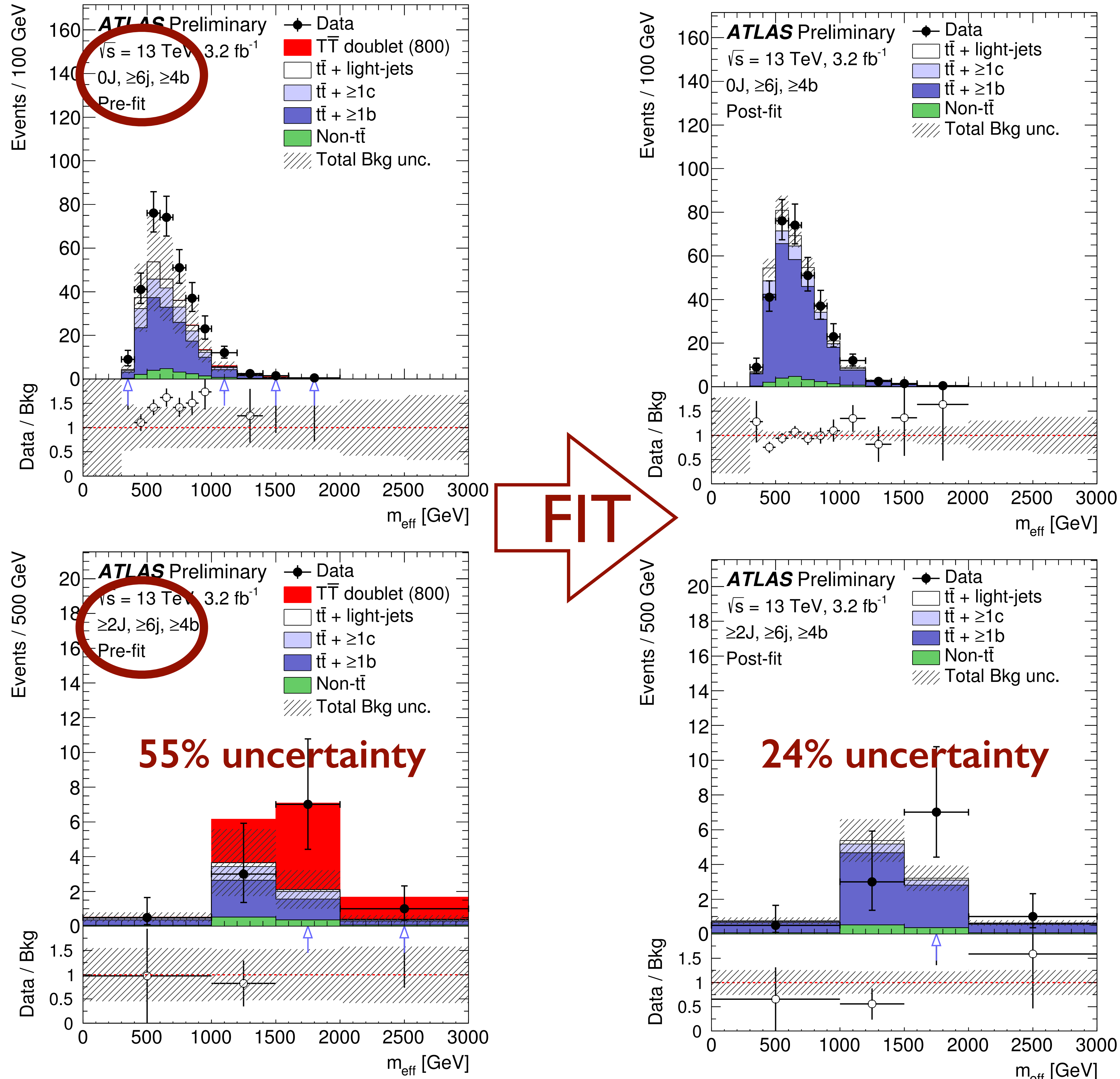
ATLAS-CONF-2016-013



→ simple "mass tagging"

ATLAS-CONF-2016-013 (03/16)

Ht+X



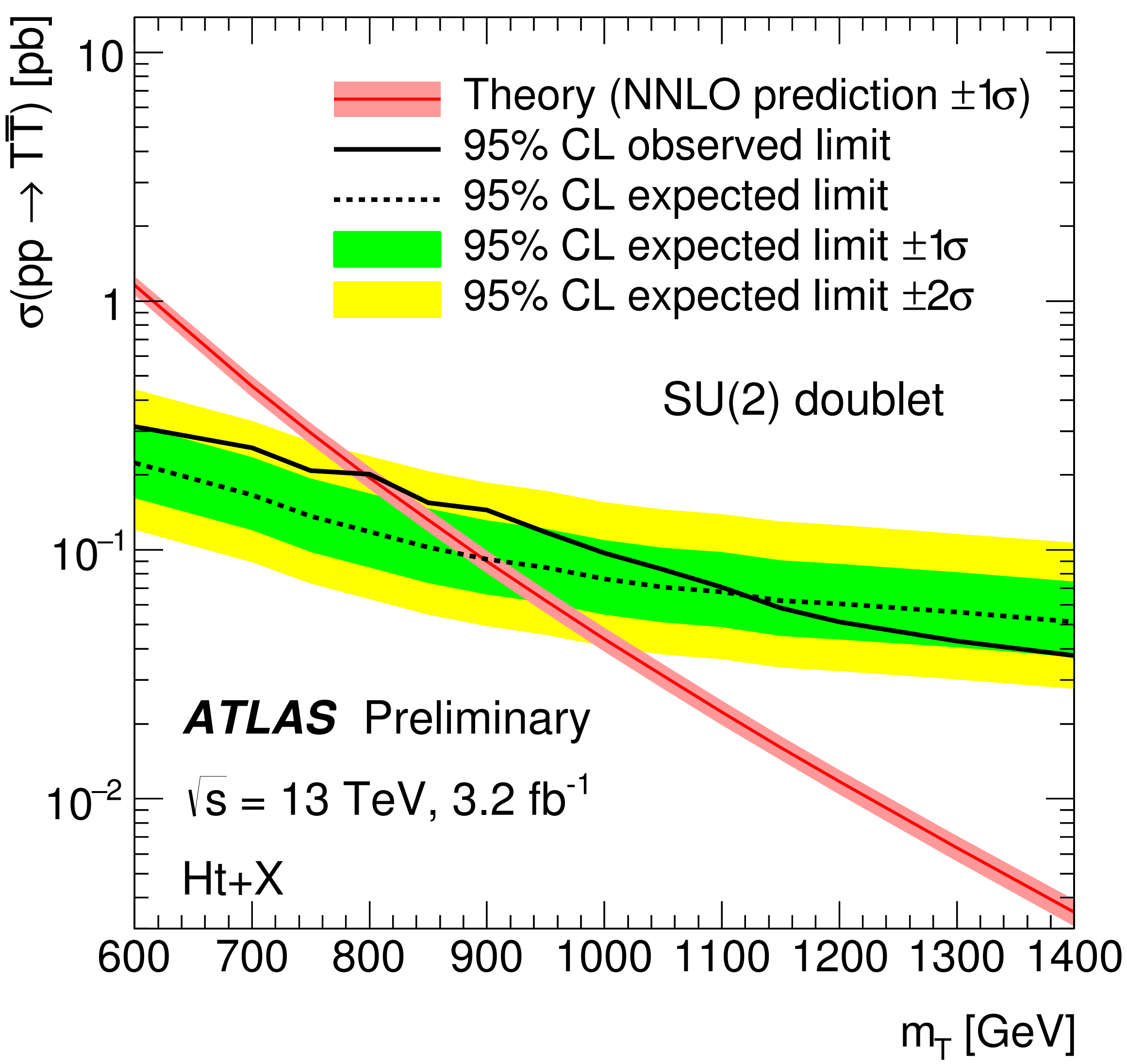
Heavy Profiling

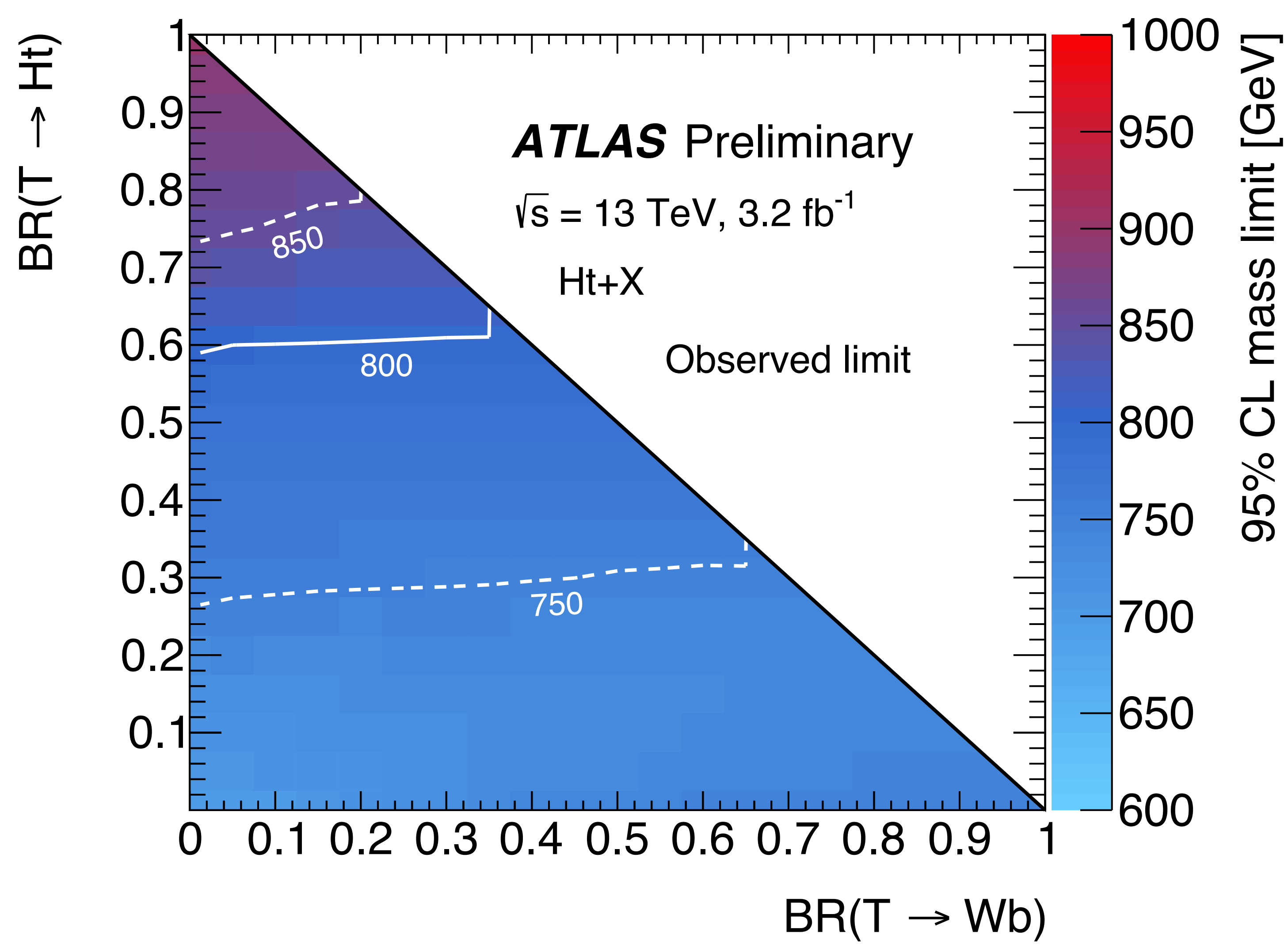
top+HF poorly known

- 11 categories fit with complex top model
  - low to high sig. purity
- profile top+LF/c/b
- *systematics: decorrelate certain top modeling uncertainties for top+LF/c/b*
- key to controlling bkg.

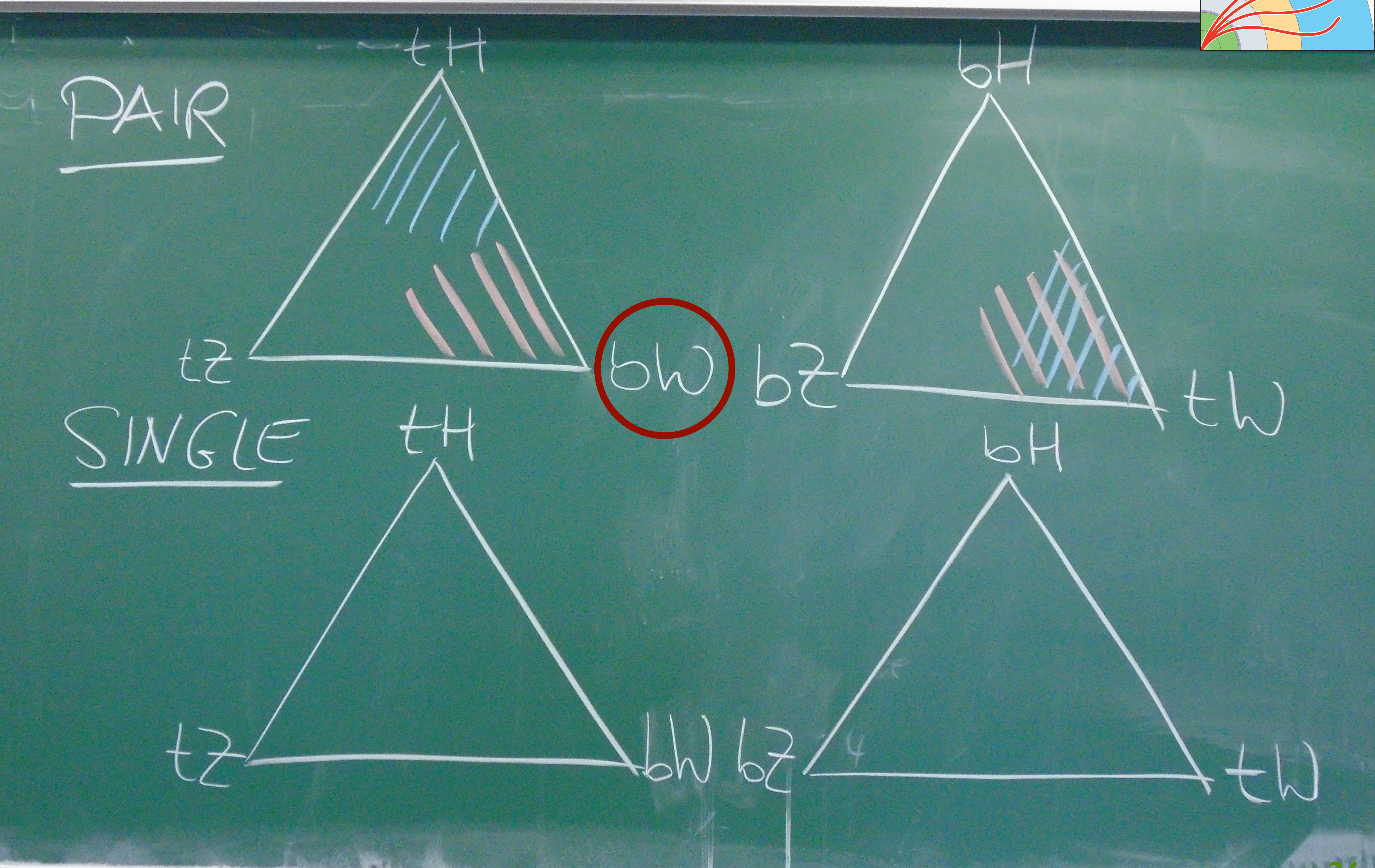
Ht+X

- m(T|singlet) > 750 GeV *(was 765 GeV)*
- m(T|doublet) > 800 GeV *(was 855 GeV)*
- expected limits improved by 60 GeV (singlet), 80 GeV (doublet)

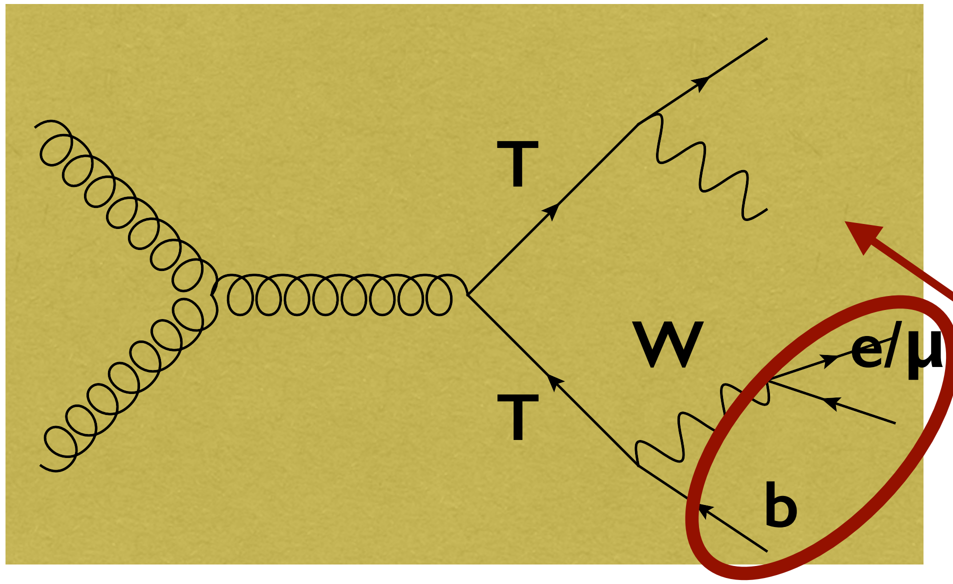




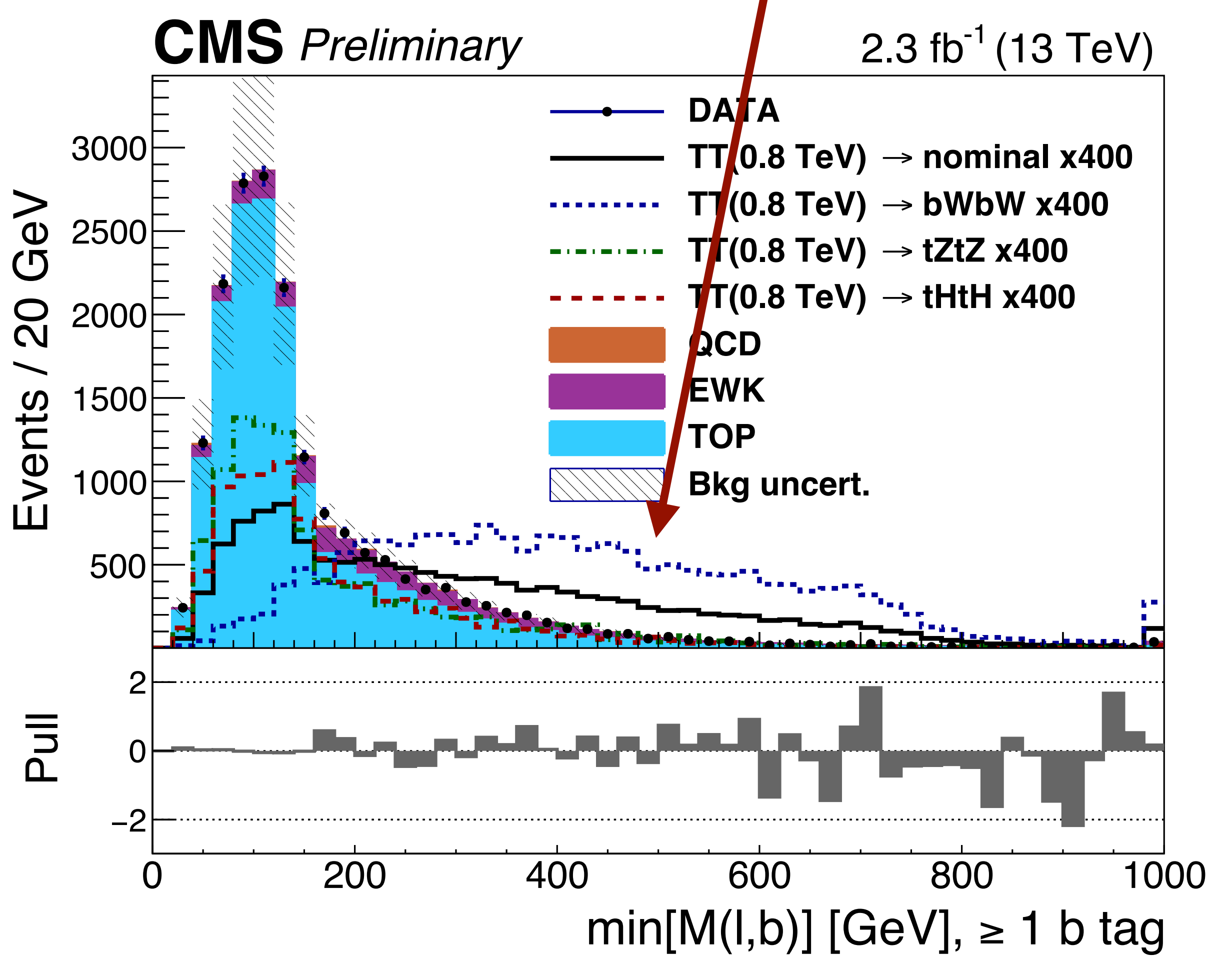
Wb+X

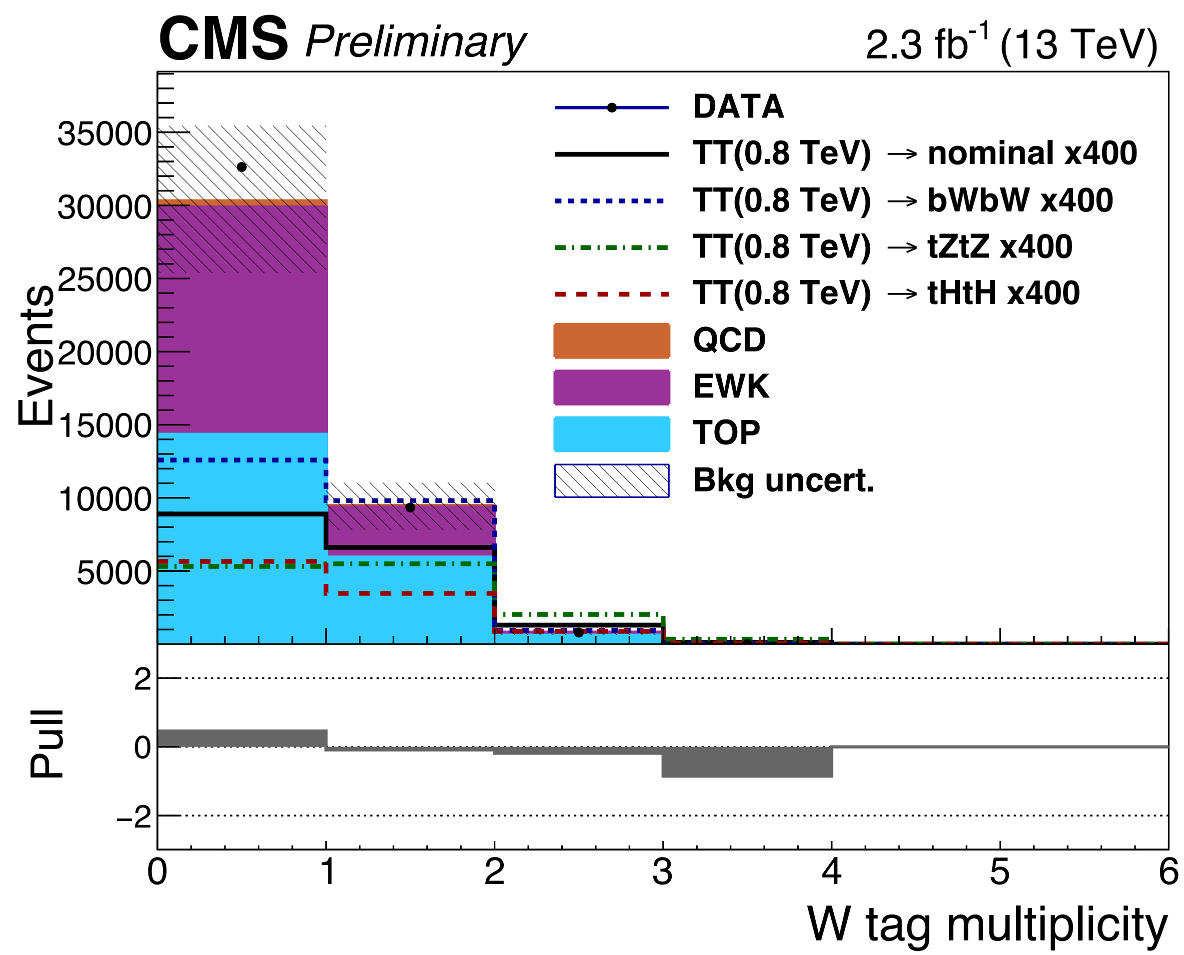


Wb+X

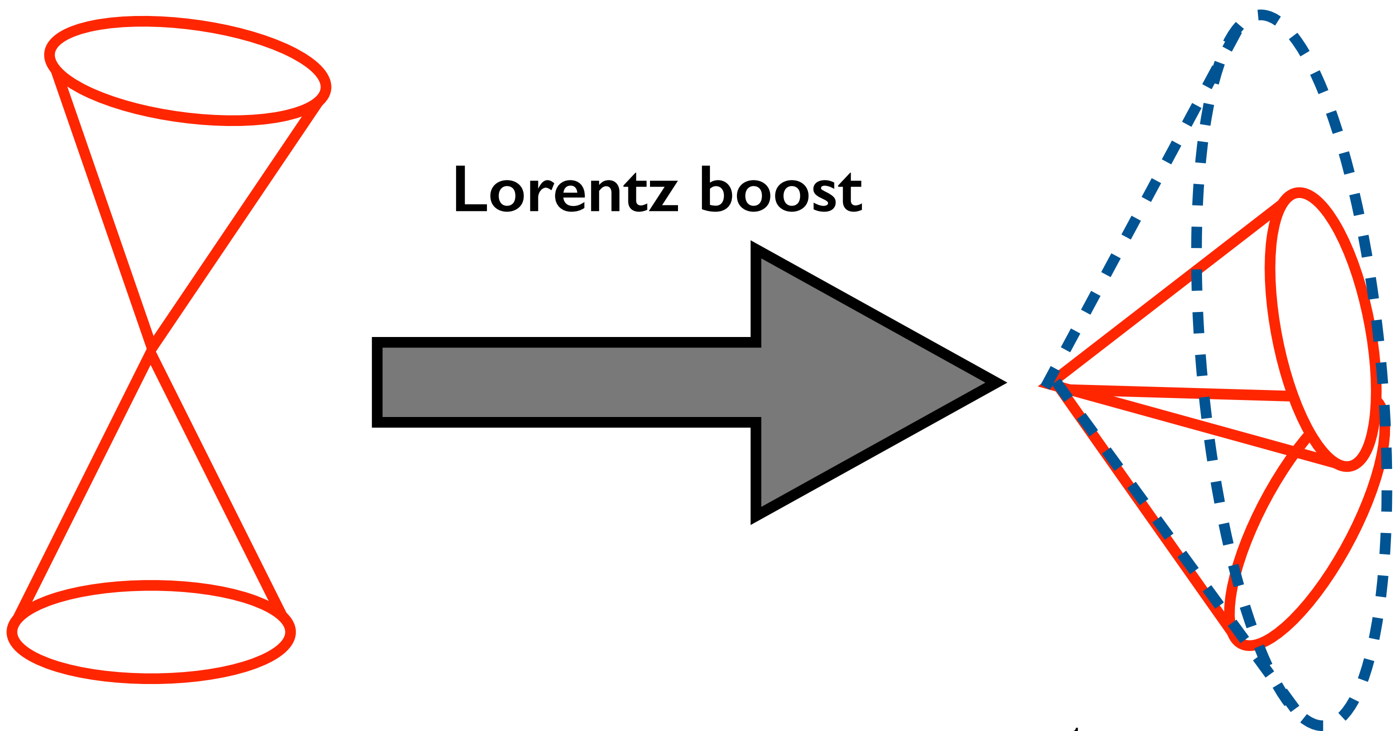


- 1 e/μ, MET, ≥ 3 high-p_T jets
- final discriminant :
  - min(m(lb))
- categorization in #b-tags + #W-tags from other T-branch

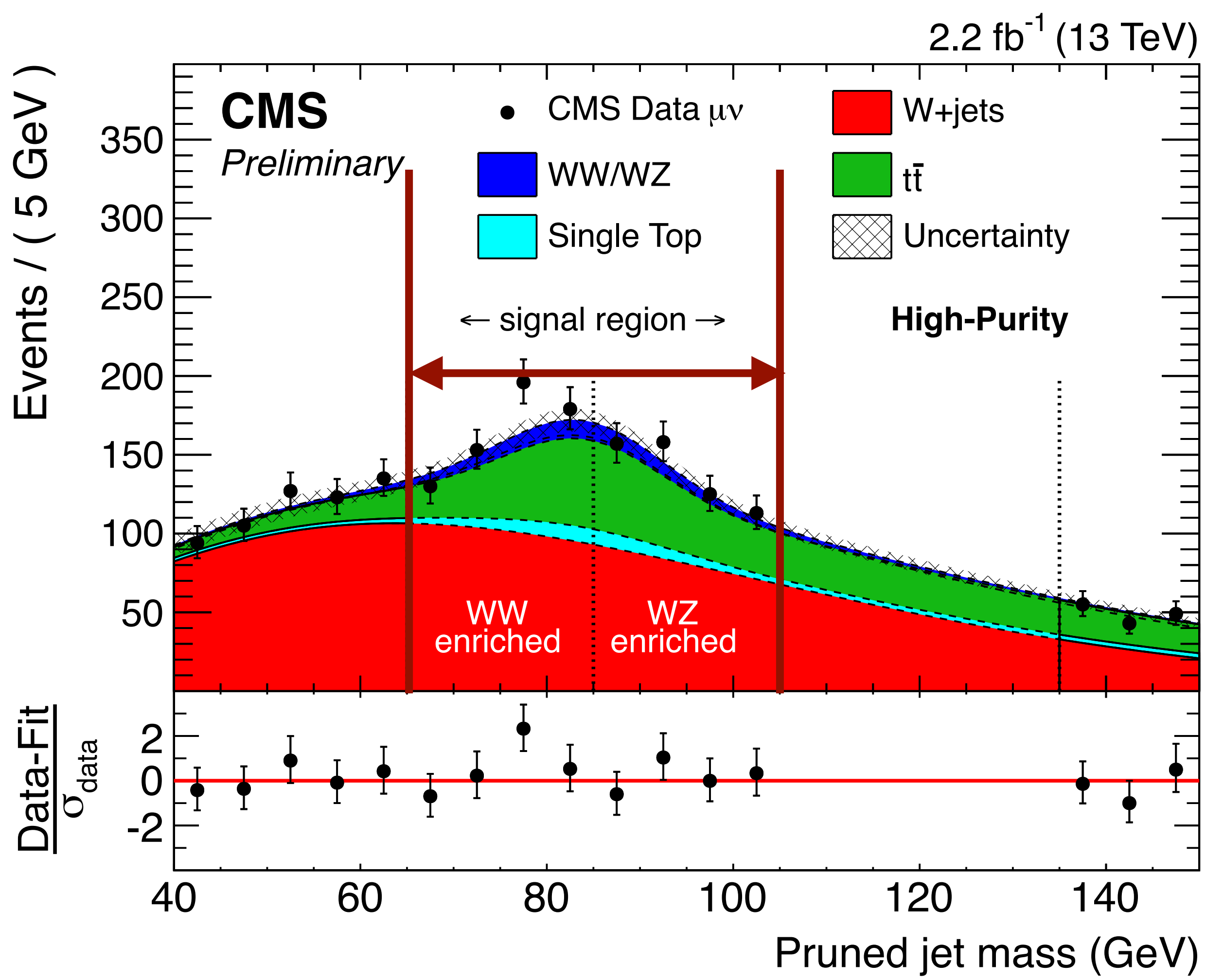




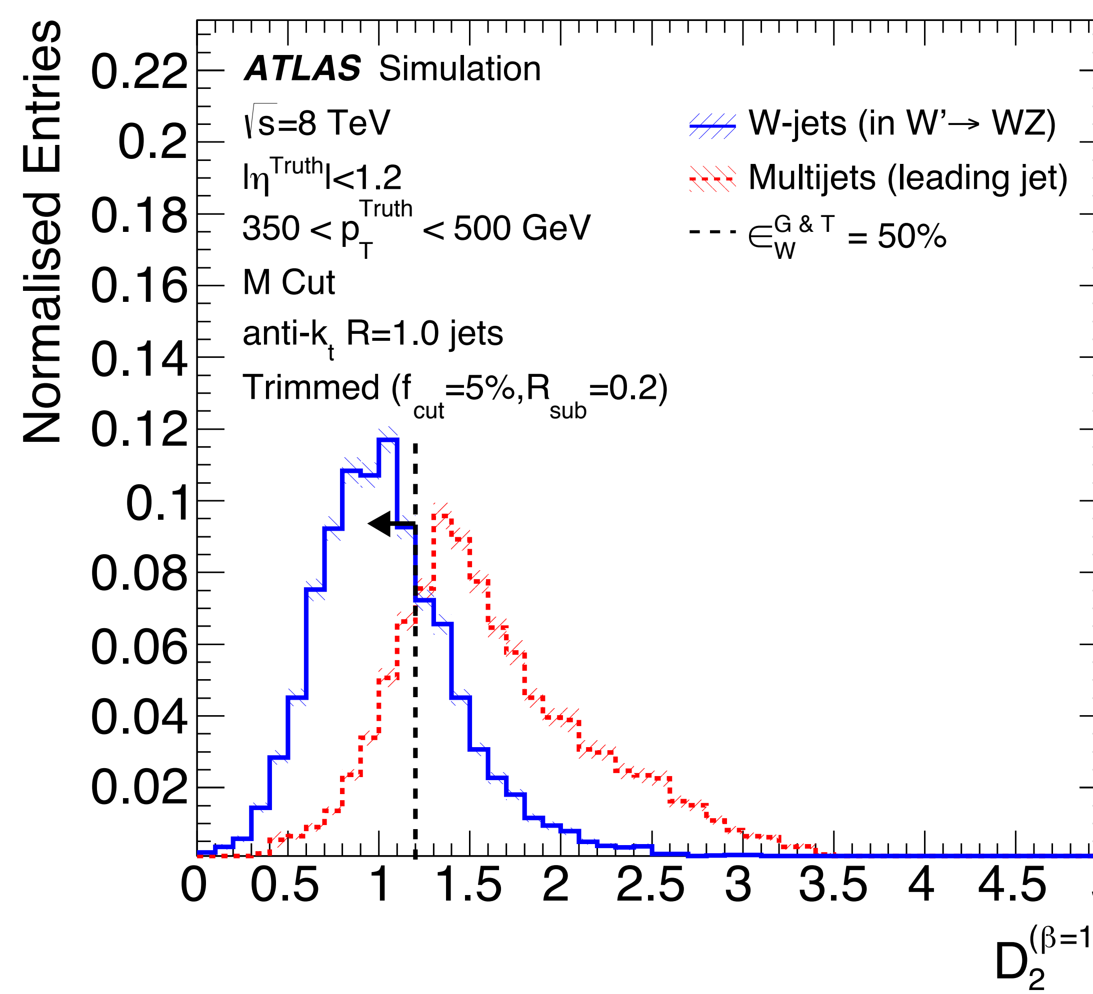
Tagging W Bosons



- mass window around m_W
- two-prong-sensitive variable
  - N-subjettiness (CMS)
  - energy correlation D_2 (ATLAS)



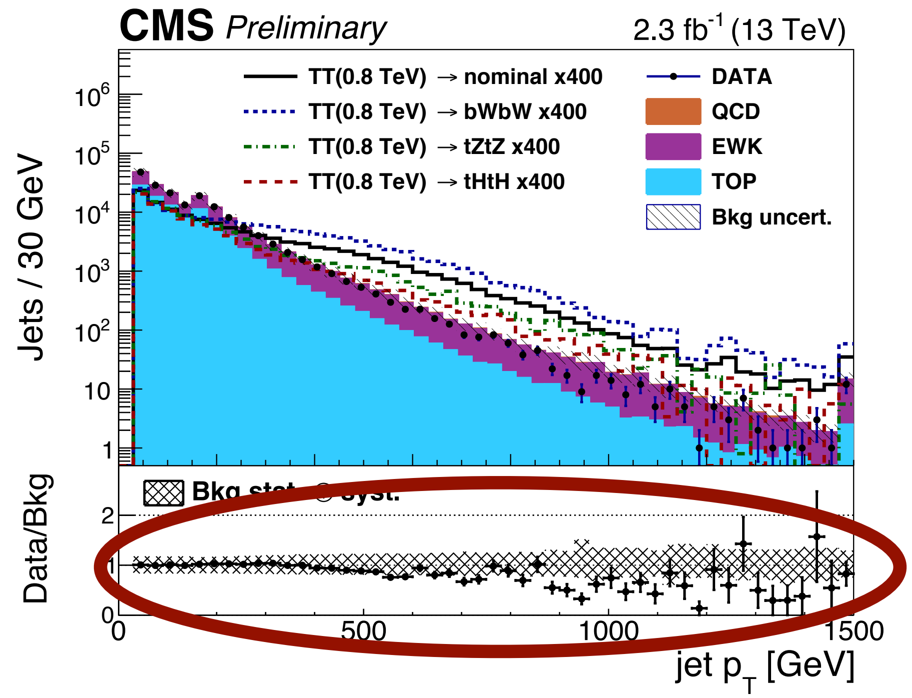
CMS PAS EXO-15-002

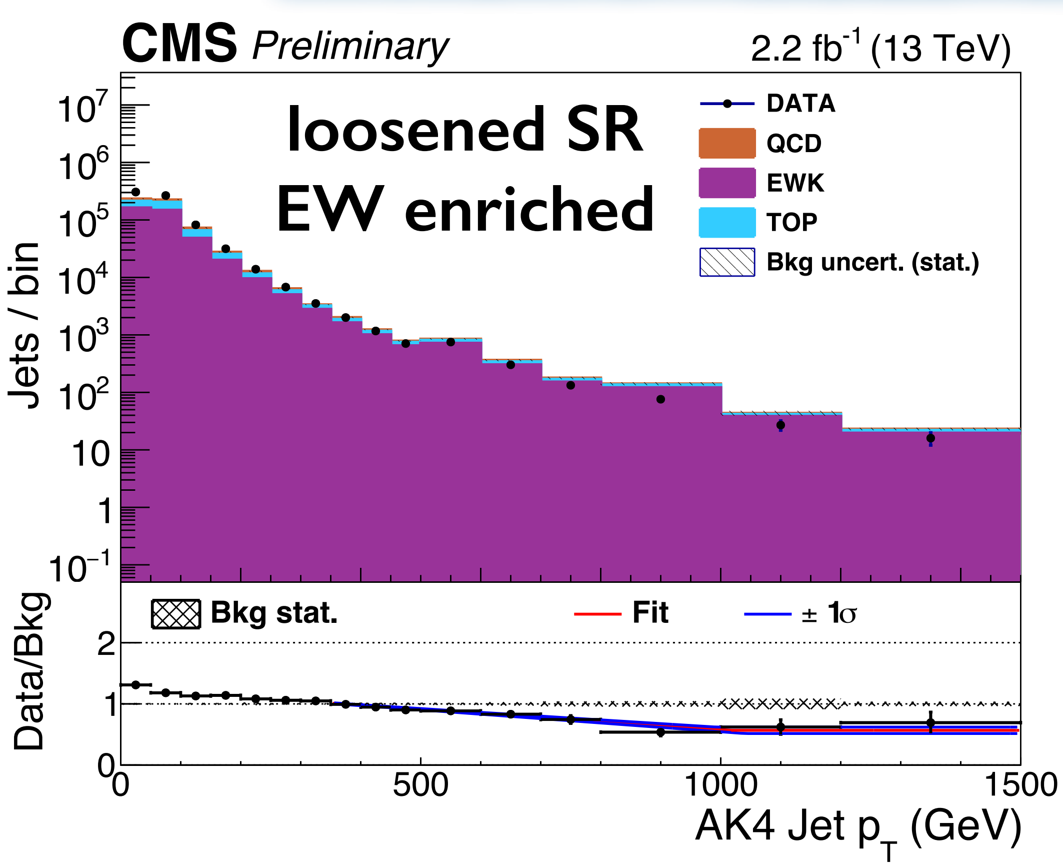


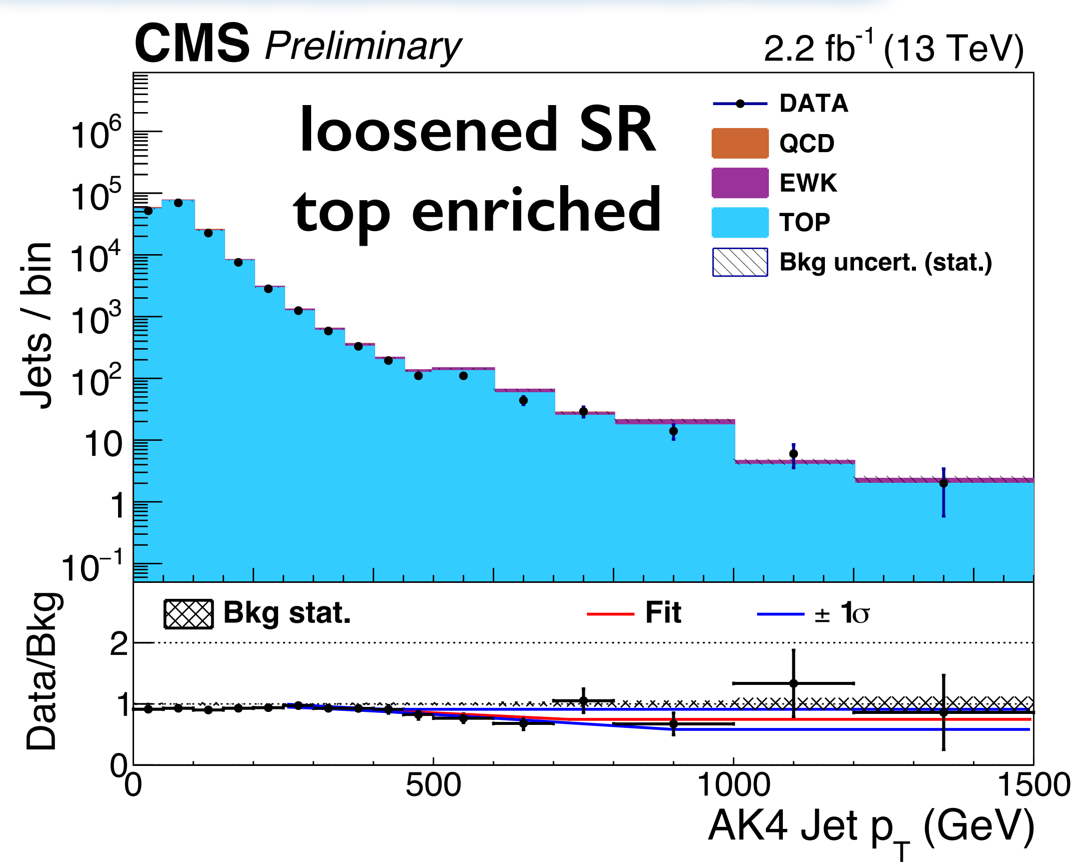
Wb+X

Mismodeling of jet p_T

- observed in inclusive SR
- linear correction derived
- separately for top & EW
- conservative syst. from lower statistics top CR

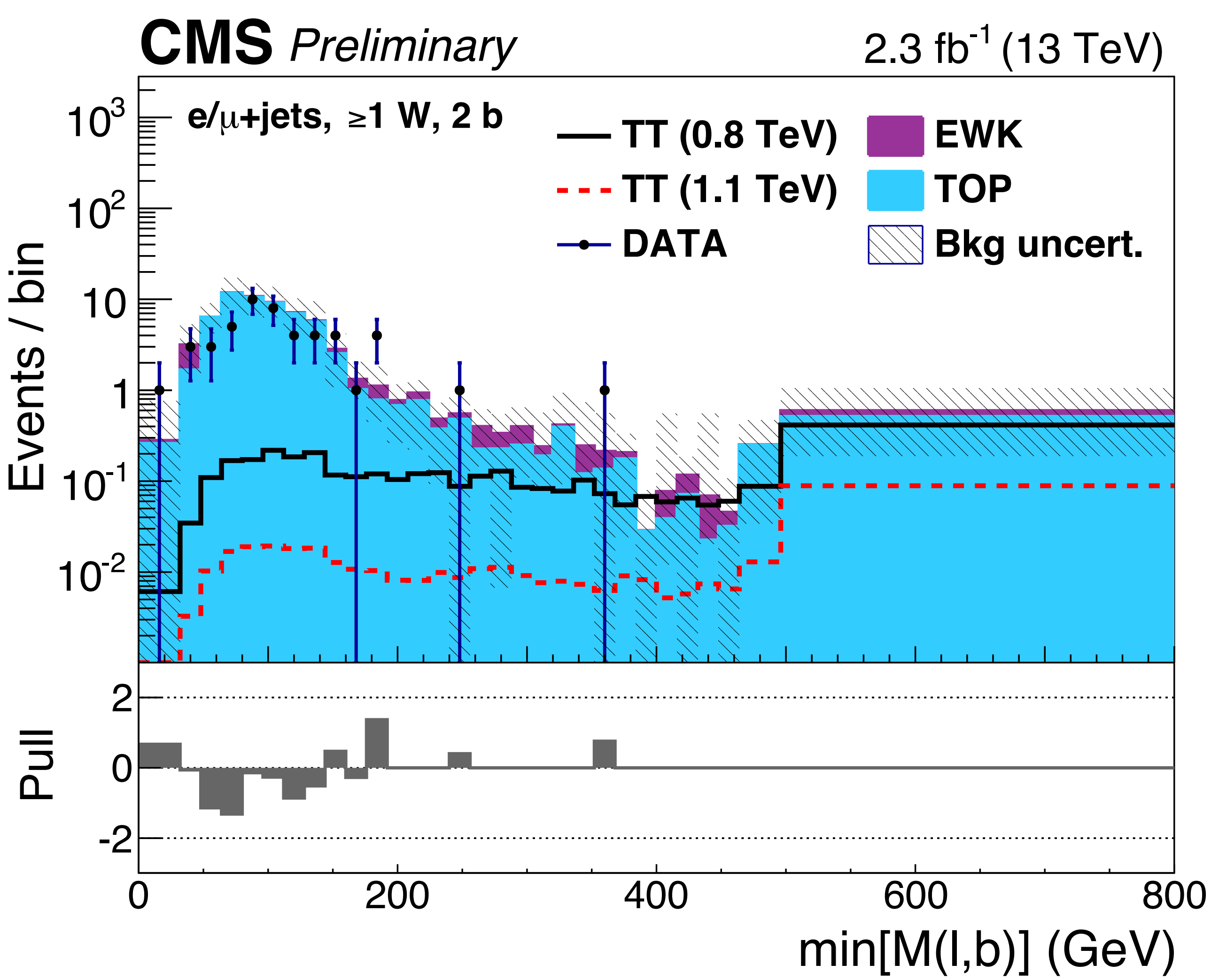


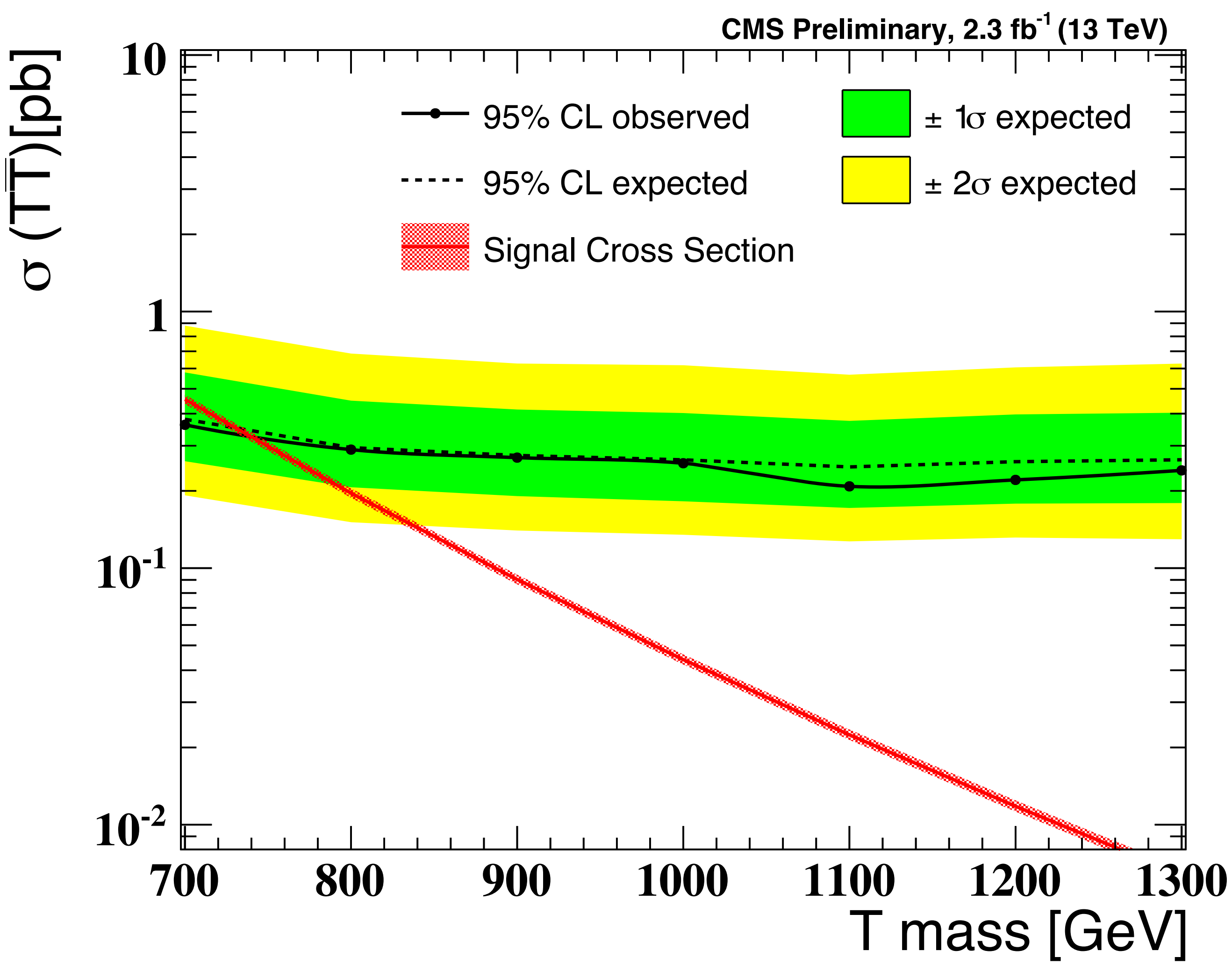




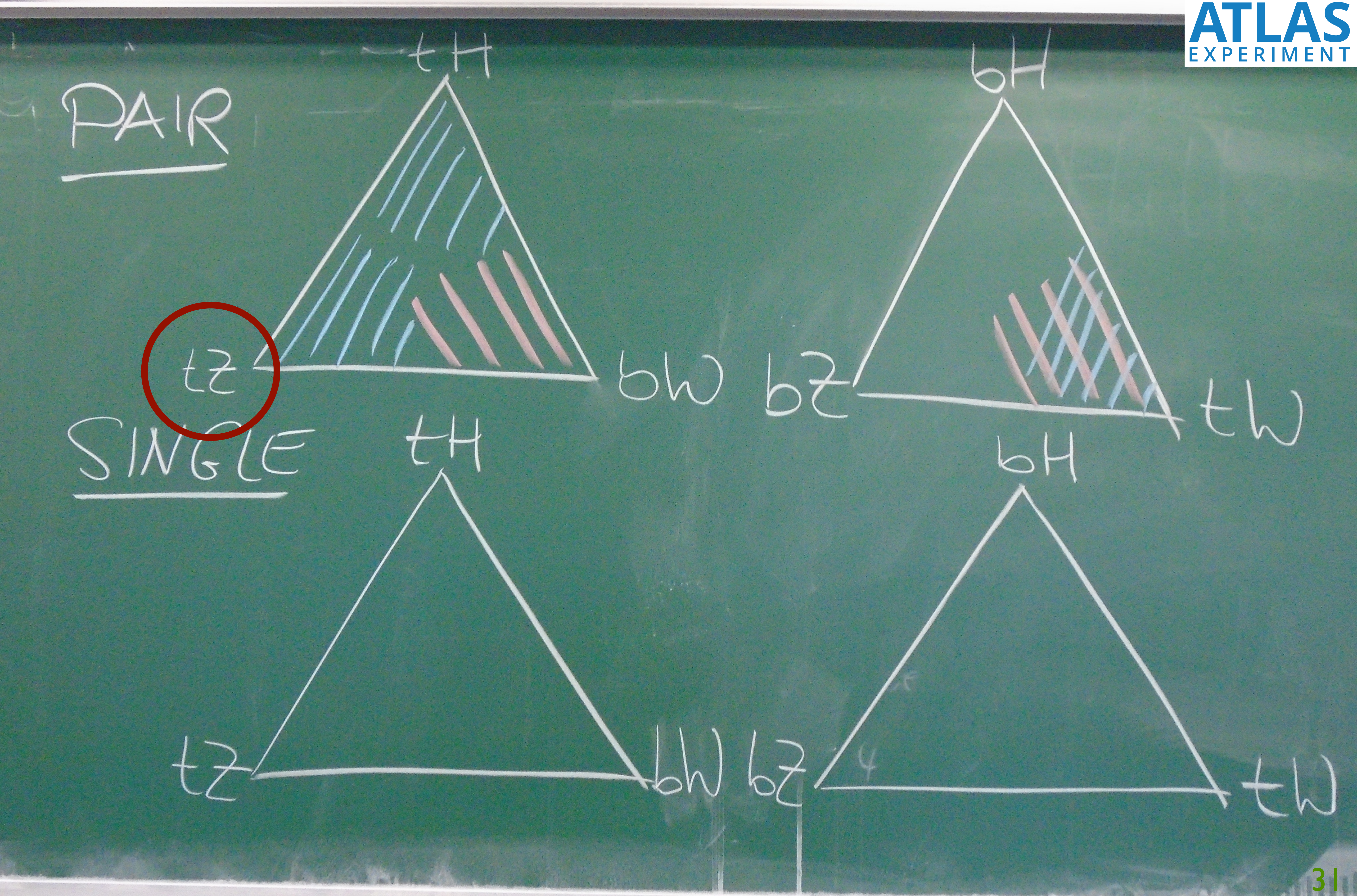
Wb+X

- m(T|singlet) > 750 GeV *(was 696 GeV)*
- T → Wb not allowed for doublet
- benchmark interpretation :
  - Wb:Zt:Ht = 50%:25%:25%

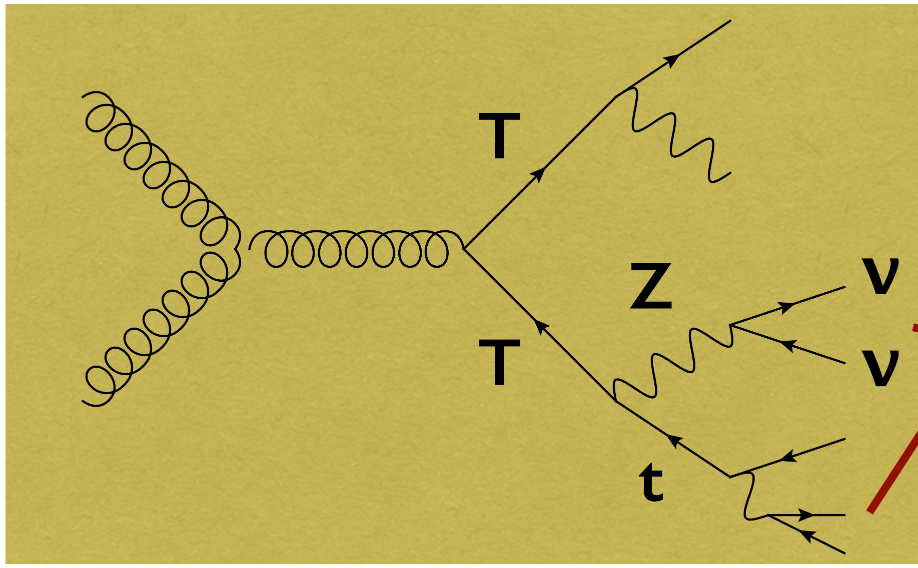




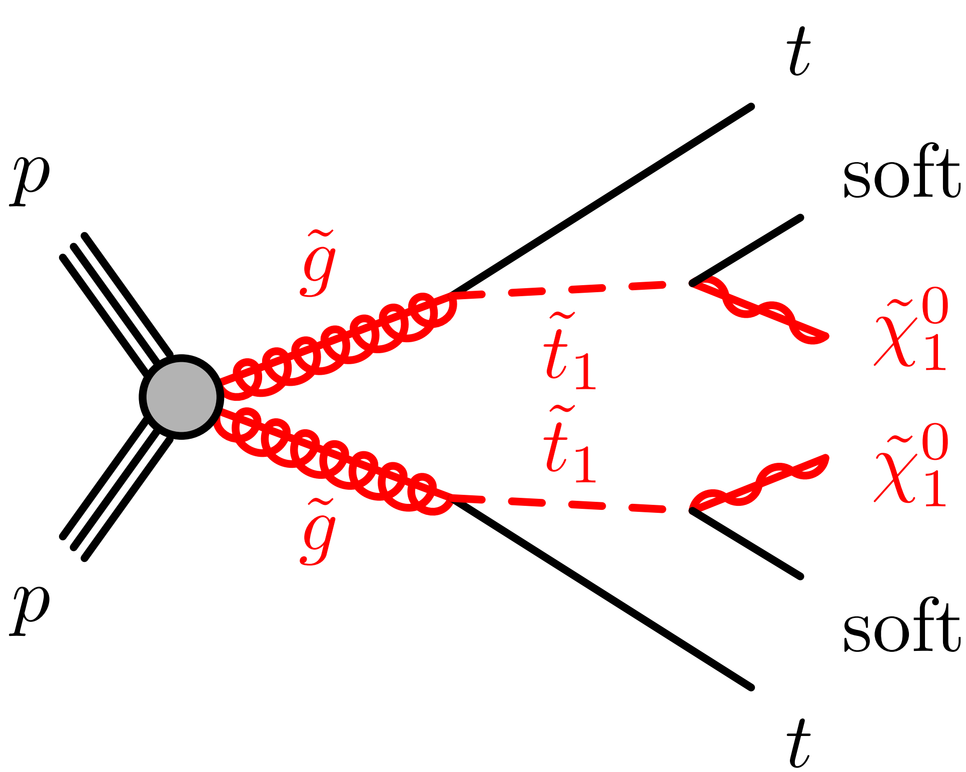
Stops and Zt+X

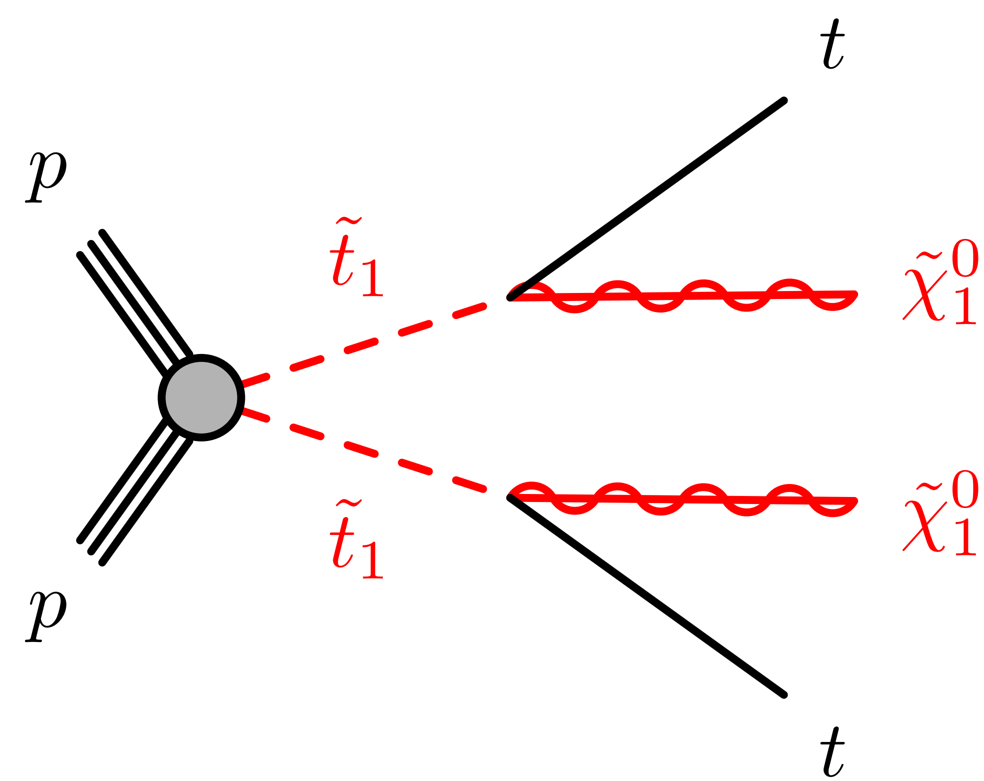


Stops and Zt+X



- 1 e/μ + ≥ 4 jets
- QCD and τ vetos
- optimized SRs targeting $t\bar{t} + E_T^{miss}$ with
  - MET > 260/350/480 GeV
  - b-tags, large-R jet, kinematic requirements



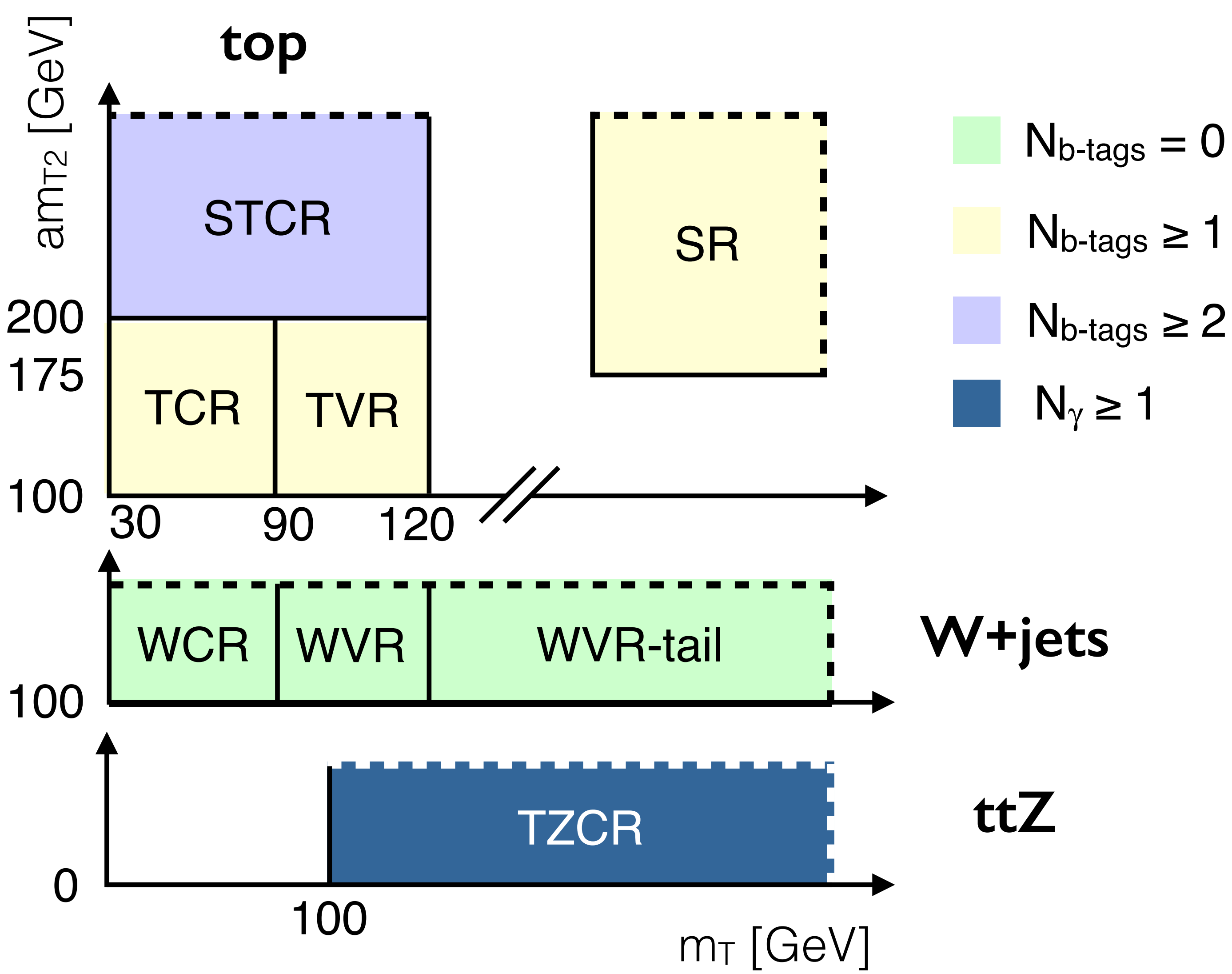


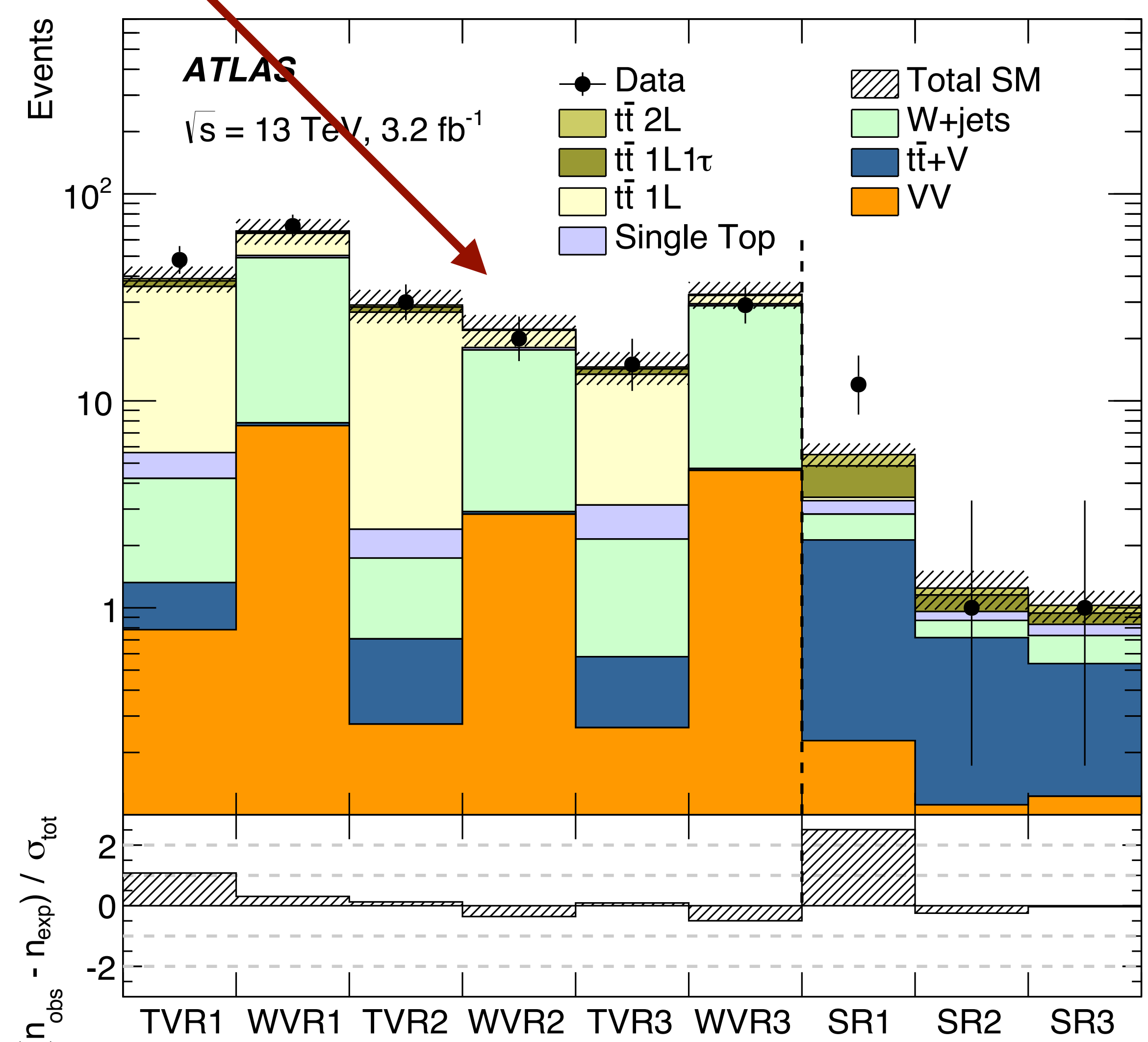
updated with 2016 data in ATLAS-CONF-2016-050
(but w/o VLQ interpretation)

Stops and Zt+X

'SUSY-style analysis strategy'

- 3 SRs defined
- each SR fitted with several CRs for main backgrounds
- fit validated in VRs — overall yields consistent



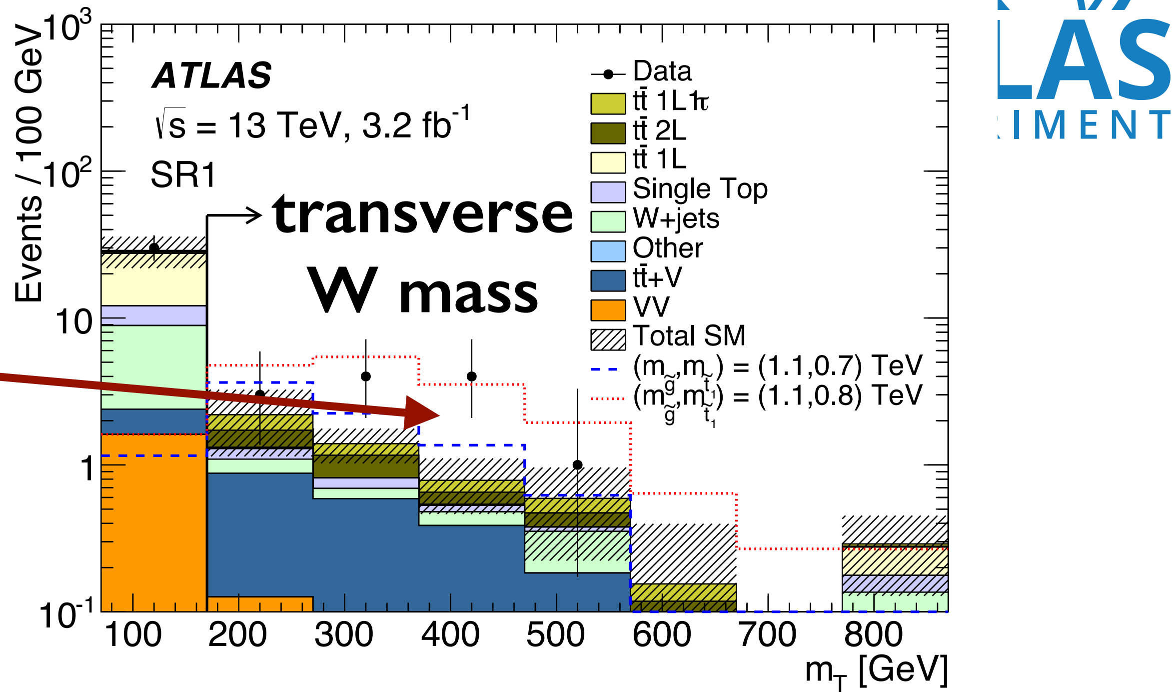


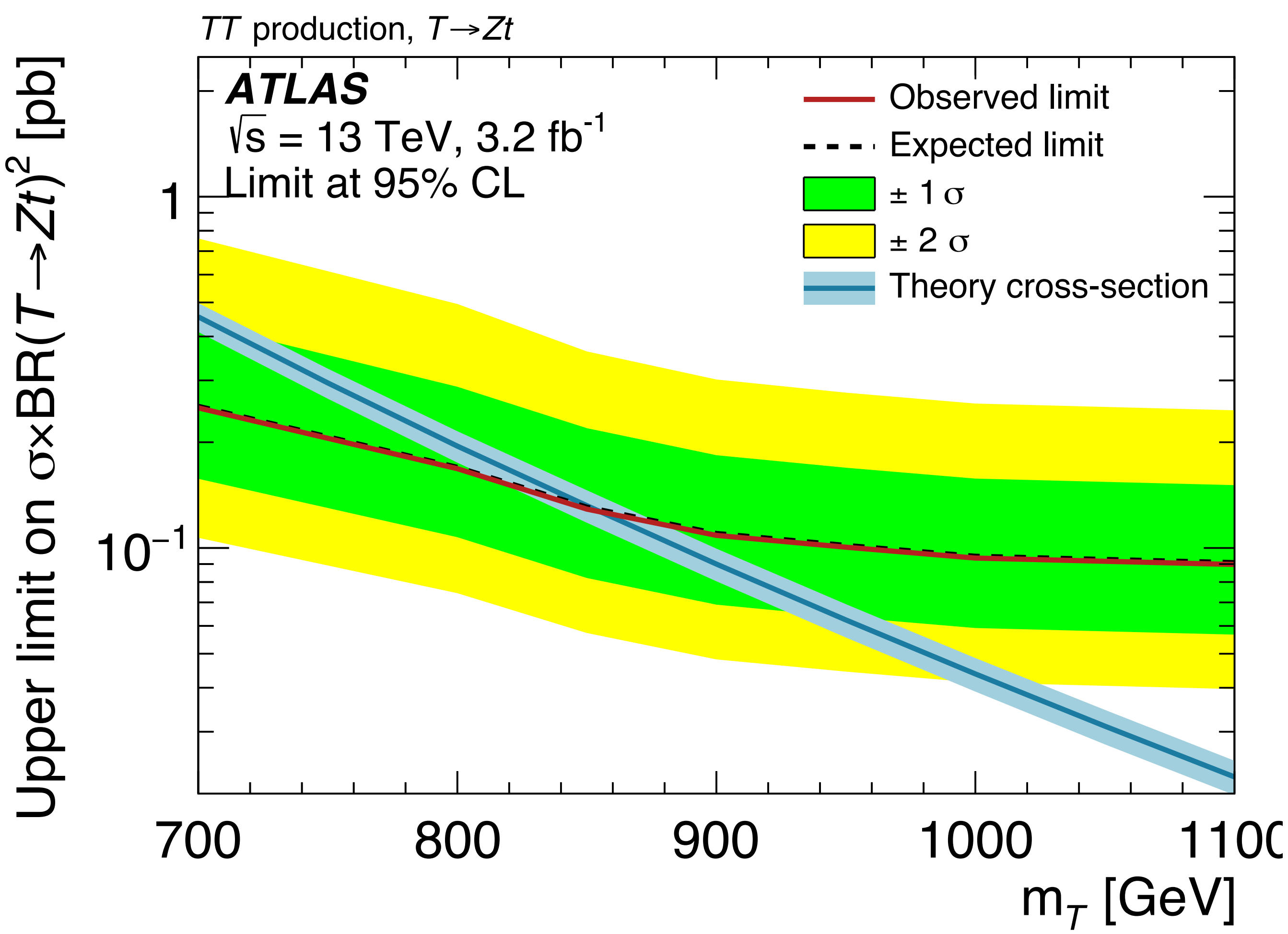
arXiv:1606.03903, submitted to PRD (06/16)

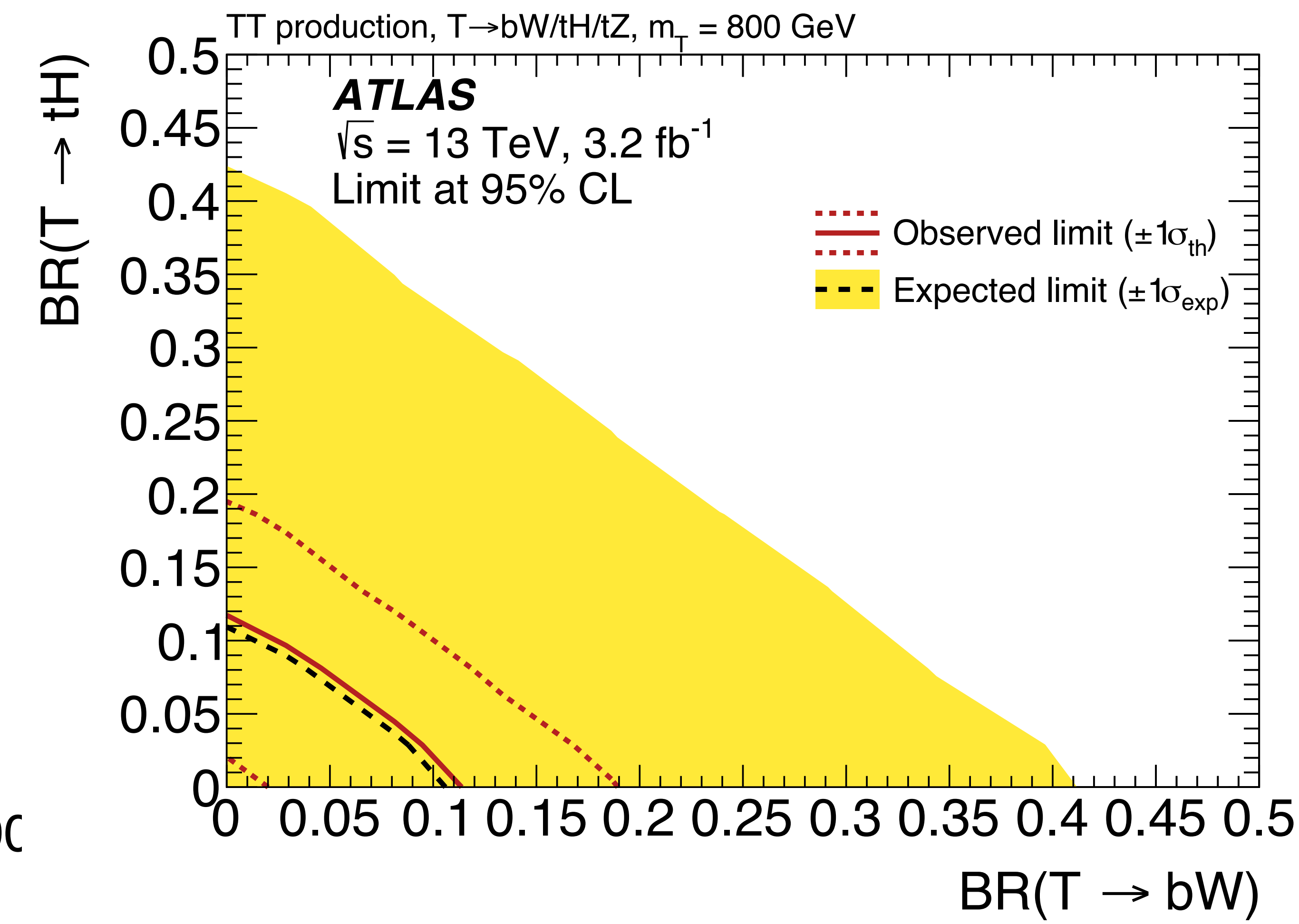
Stops and Zt+X

- m(T|BR=100%) > 850 GeV

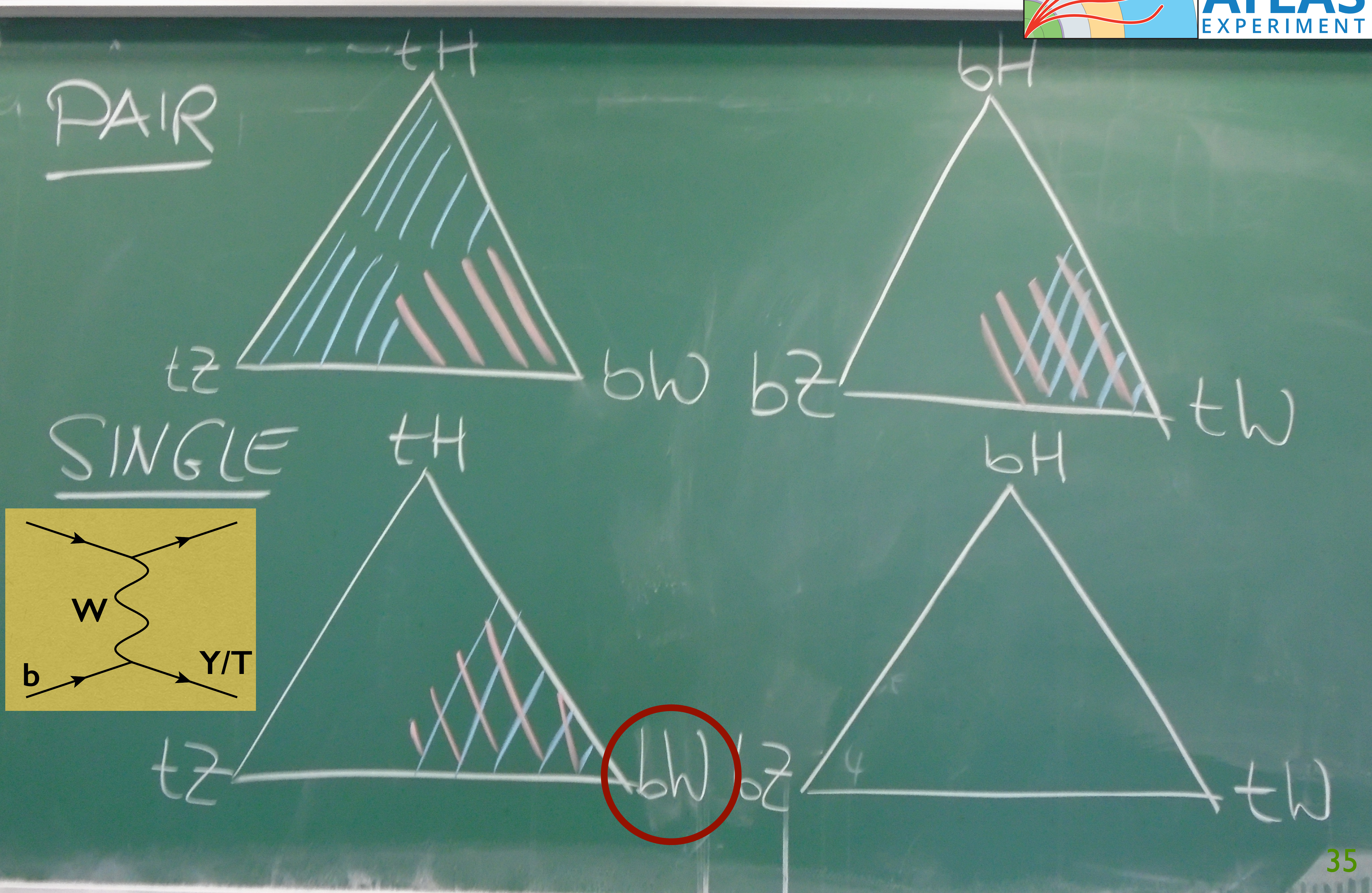
  (was 810 GeV in dilepton analysis)
- stat. fluctuation in SR1 *not* VLQ-like
- valuable reinterpretation
- new search channel



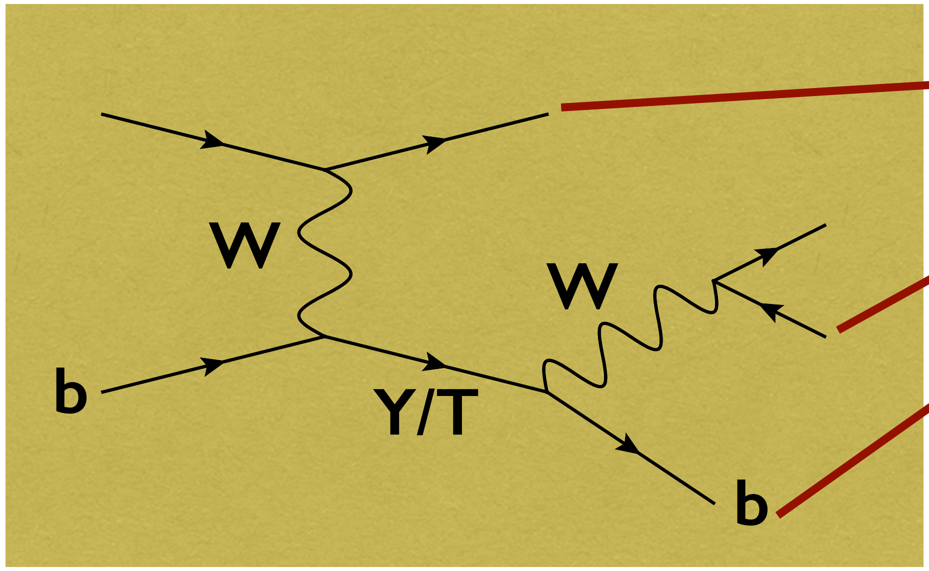




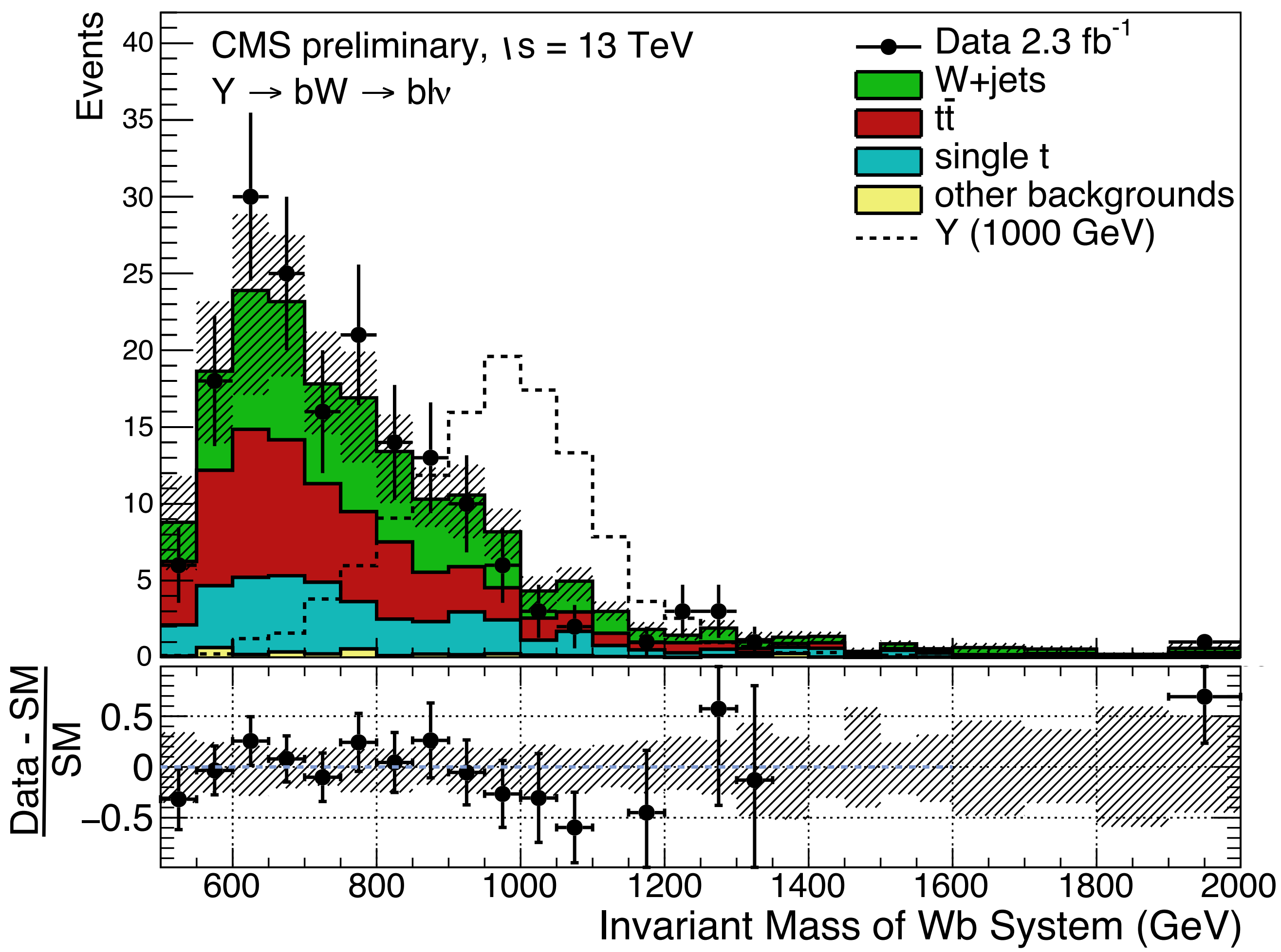
Single VLQ → Wb

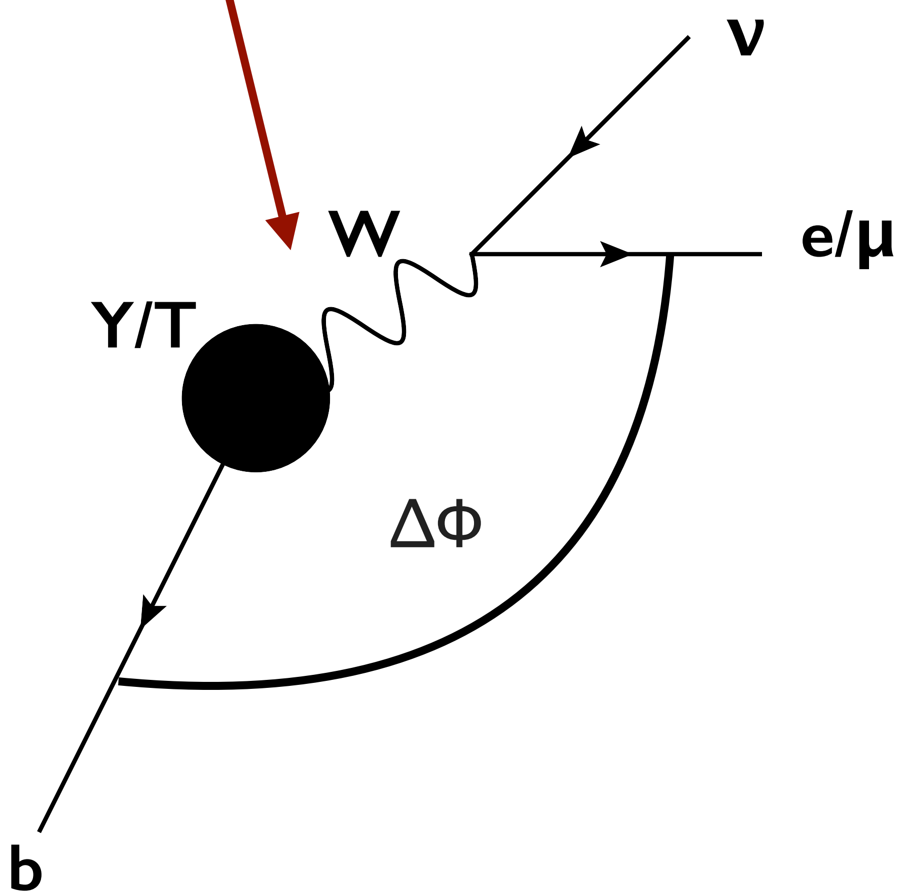


Single VLQ → Wb



- ≥ 1 forward jet
- = 1 e/μ + tight veto on 2nd lepton
- ≥ 1 high-p_T central jet with b-tag
- high MET & $S_T = p_T^\ell + E_T^{miss} + p_T^{b-jet}$
- W-like $m_T(W)$ & ΔΦ(lep., b) > 2.0





Single VLQ → Wb

CMS PAS TOP-16-005

Measurement of the top quark pair production cross section using $e\mu$ events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector

$$\sigma_{t\bar{t}} = 793 \pm 8\,(\text{stat}) \pm 38\,(\text{syst}) \pm 21\,(\text{lumi})\ \text{pb}$$

CMS PAS TOP-16-003

Measurement of the inclusive cross section of single top quark production in the t channel at $\sqrt{s} = 13$ TeV

$$\sigma_{t\text{-ch.}} = 227.8 \pm 9.1\,(\text{stat.}) \pm 14.0\,(\text{exp.})\,^{+28.7}_{-27.7}\,(\text{theo.}) \pm 6.2\,(\text{lumi.})\ \text{pb}$$

source		W+Jets	$t\bar{t}$	Single Top	Signal
Luminosity	rate	2.7%	2.7 %	2.7 %	2.7 %
Jet energy scale	shape	5%	6%	5%	3%
Jet energy resolution	shape	2%	1%	1%	2%
B-tagging efficiency	shape	3%	5%	5%	5%
Multiple interactions	shape	1%	1%	1%	1%
Lepton ID/ISO scale factor	rate	2%	2%	2%	2%
Trigger efficiency	rate	2%	2%	2%	2%
Cross Section	rate	9.2%	5.6%	14.7%	—
Top P_T reweighting	shape	—	38%	—	—
W+jets H_T reweighting	shape	5.3%	—	—	—
Q^2 Scale	shape	14%	16%	16%	25%
PDF	shape	5.5%	2.3%	8.5%	6.7%
Forward jet reweighting	rate	15%	15%	15%	15%

8 TeV differential linear correction → Top P_T reweighting, W+jets H_T reweighting

data/MC difference → Forward jet reweighting

CMS PAS SMP-15-004

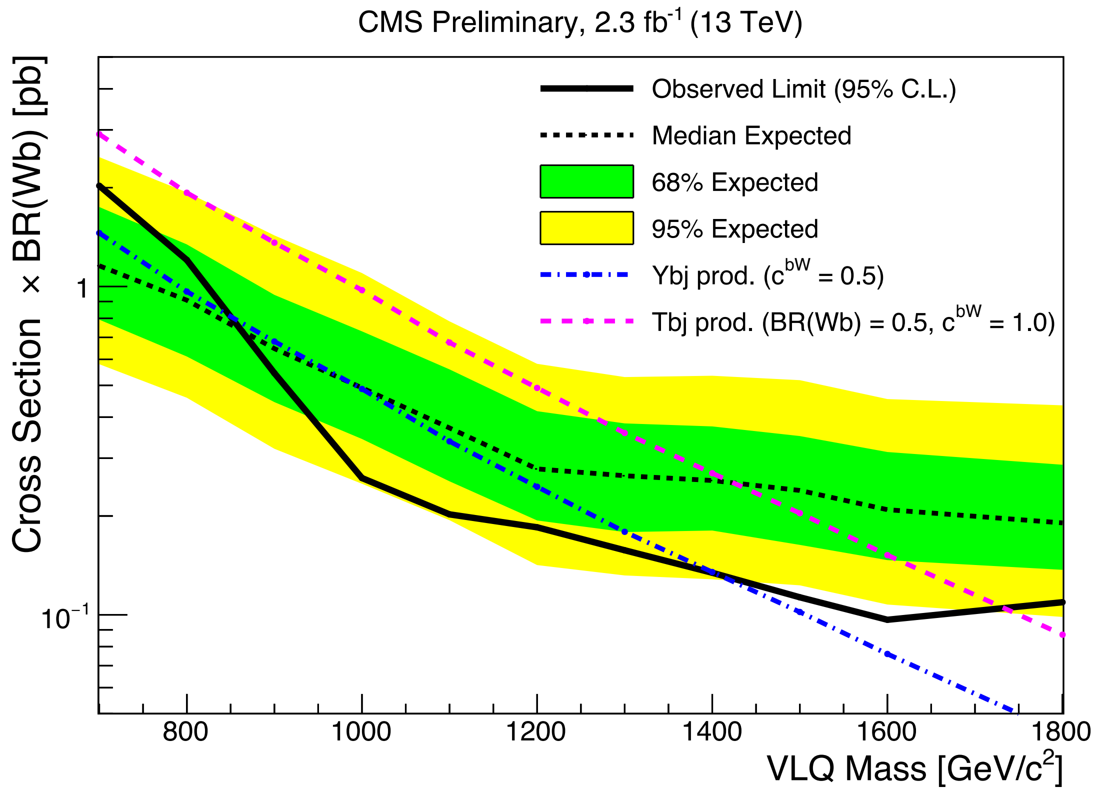
Measurement of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV

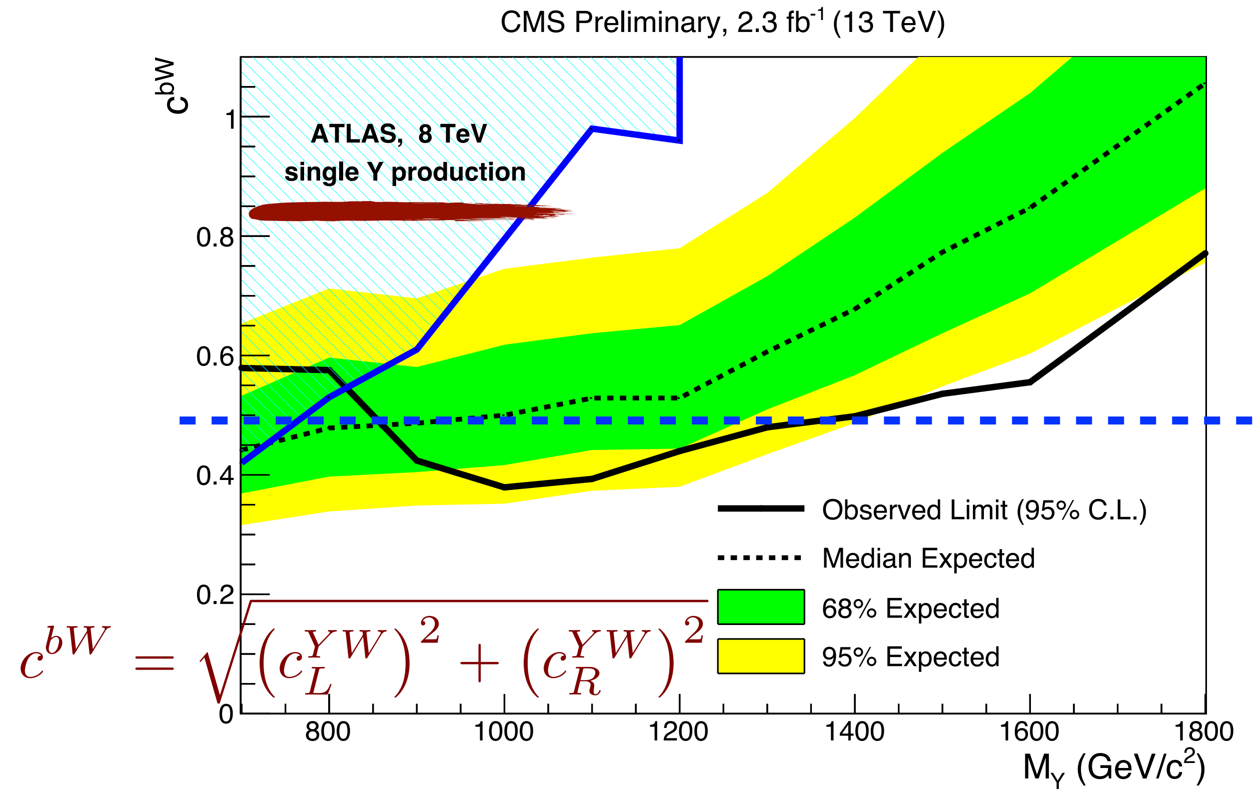
Measurement of the differential cross section for the production of a W ($\rightarrow \mu\nu$) boson in association with jets at $\sqrt{s} = 13$ TeV

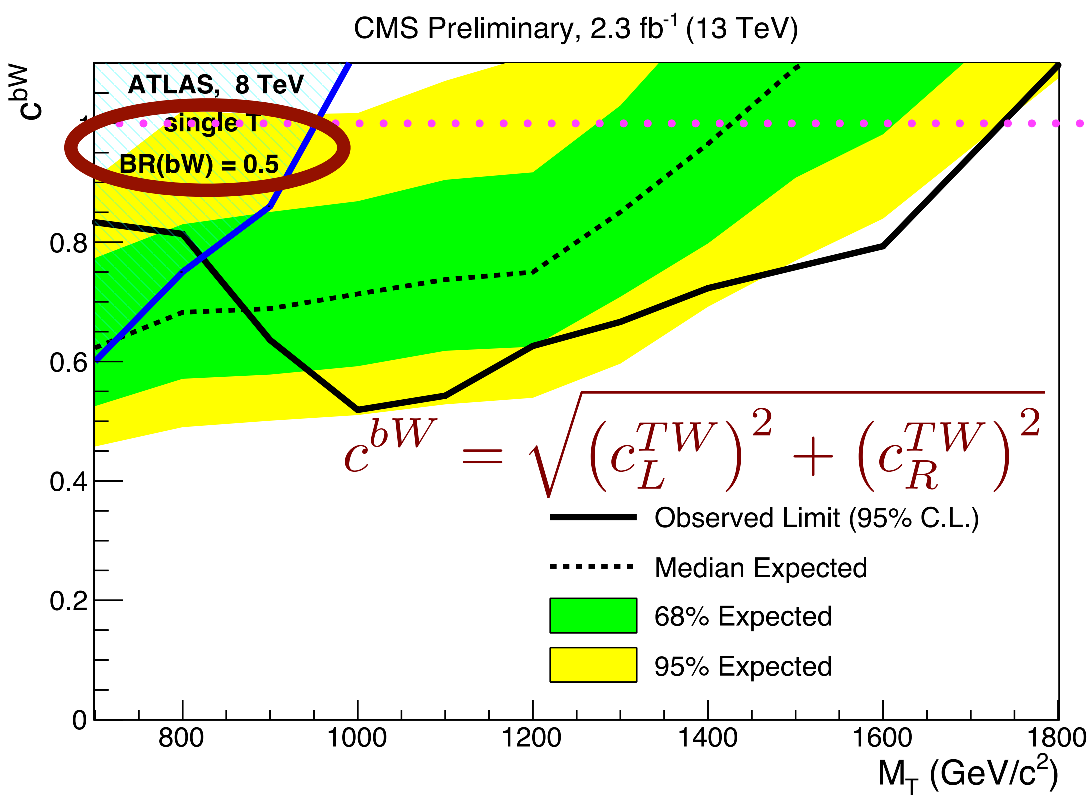
CMS PAS SMP-15-006

- <u>Main background Xsec uncertainties</u> from 13 TeV measurements !
- No need to correlate w/ other systematics, as scale, fwd. jet & top p_T reweighting dominate

Single VLQ → Wb







Interpretation

- mass limits for (large) benchmark couplings
- coupling limits for given BRs

$$\sigma_{\rm sing}(X\bar{t}) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{V\bar{t}}(M_X) + c_L^{XV}\, c_R^{XV} \left(\frac{m_t}{M_X + m_t}\right) \sigma'_{V\bar{t}}(M_X)\,,$$

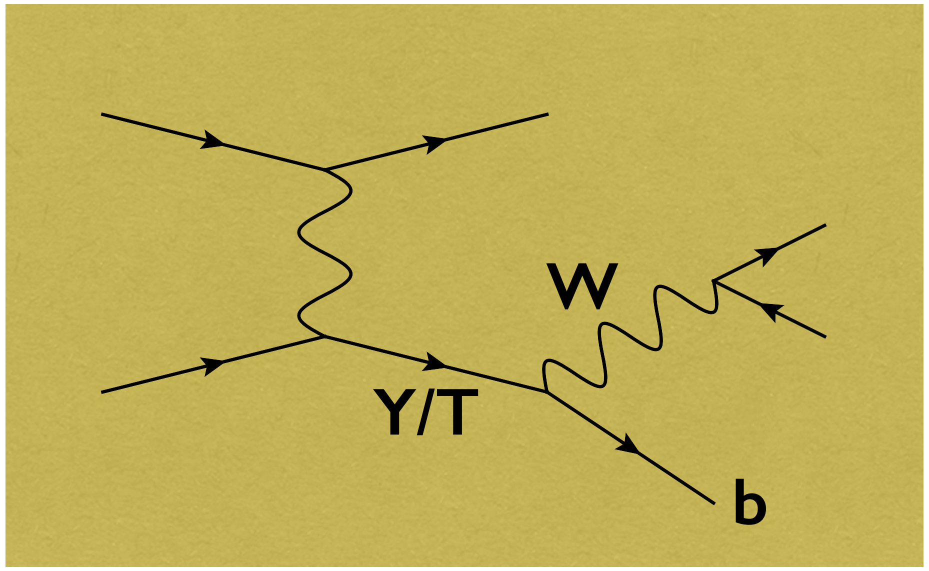
$$\sigma_{\rm sing}(X\bar{b}) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{V\bar{b}}(M_X)\,,$$

$$\sigma_{\rm sing}(\overline{X}t) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{\overline{V}t}(M_X) + c_L^{XV}\, c_R^{XV} \left(\frac{m_t}{M_X + m_t}\right) \sigma'_{\overline{V}t}(M_X)\,,$$

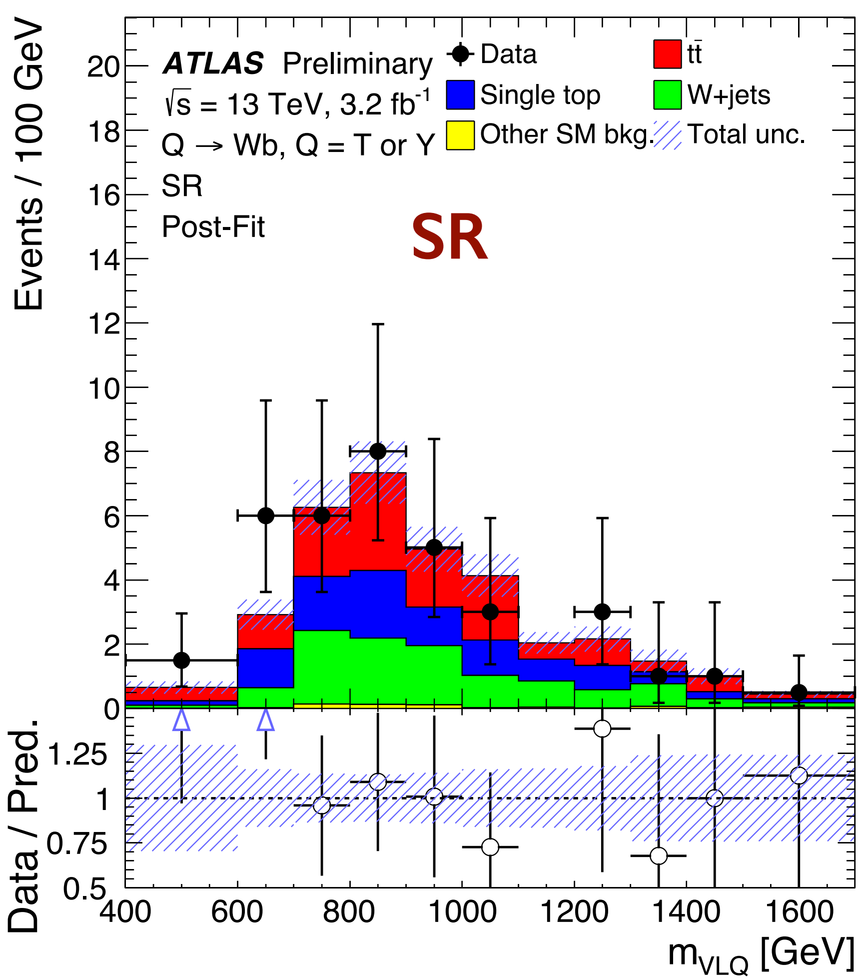
$$\sigma_{\rm sing}(\overline{X}b) = \left[\left(c_L^{XV}\right)^2 + \left(c_R^{XV}\right)^2\right] \sigma_{\overline{V}b}(M_X)\,.$$

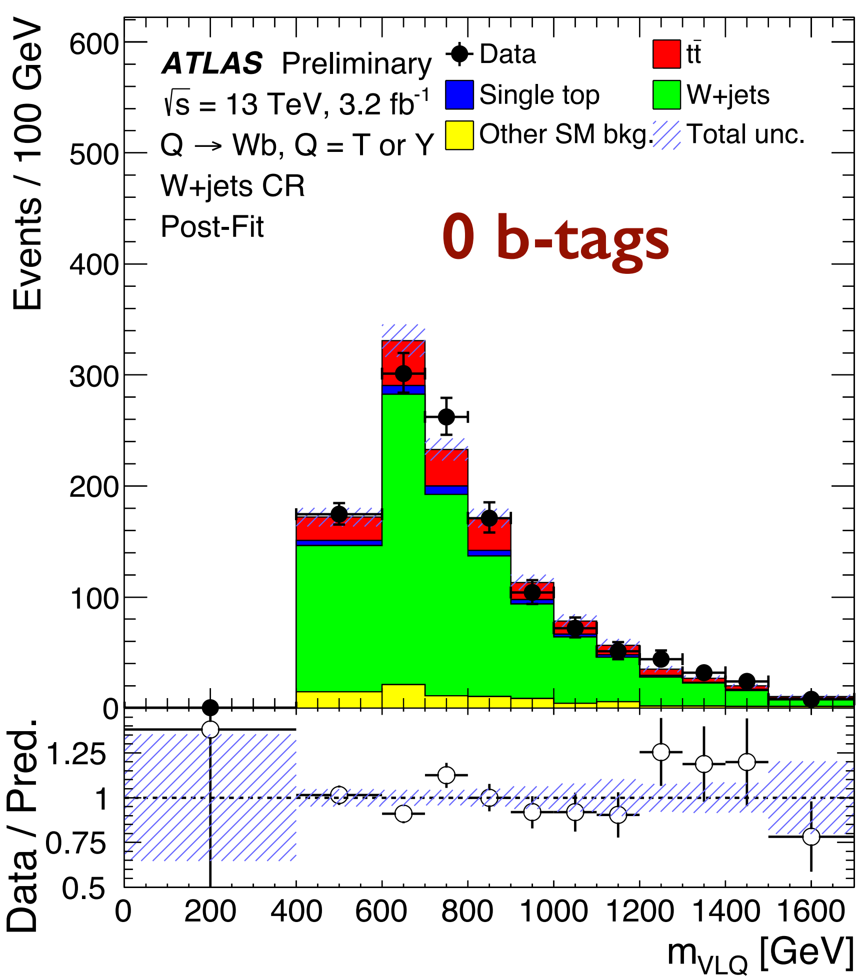
(Matsedonskyi, Panico, Wulzer, JHEP 12 (2014) 097)

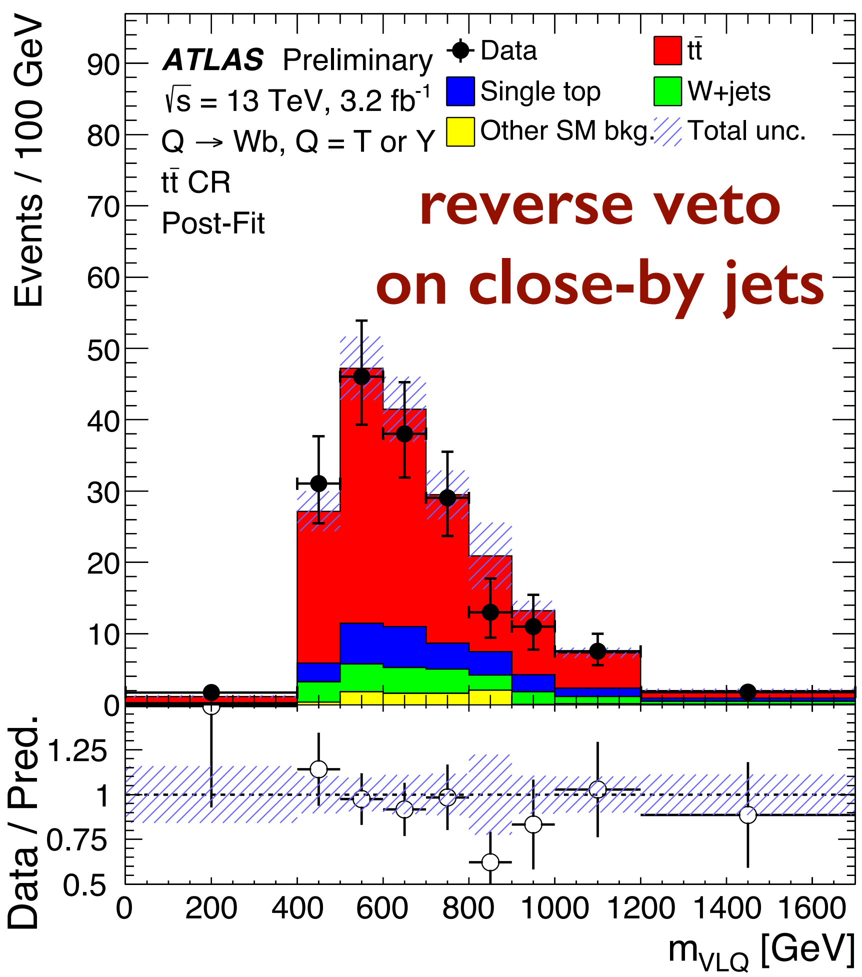
Single VLQ → Wb



- very similar strategy as CMS
- + veto jets close/opposite leading jet (suppresses top background)
- simultaneous SR+CRs (top, W+jets) fit
- also here : W+jets needs correction (CR fit)



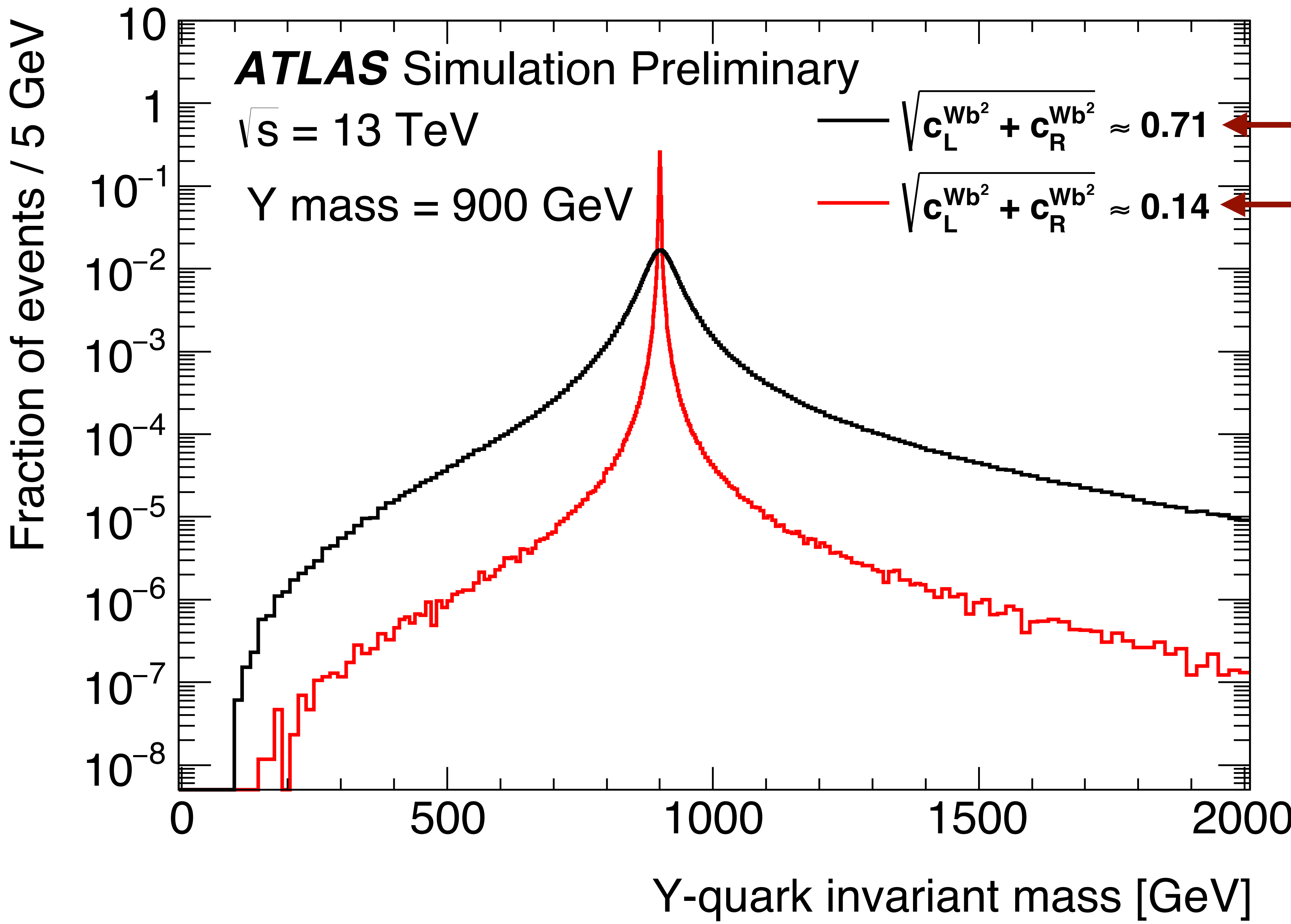




Single VLQ → Wb

Width effects for different coupling values

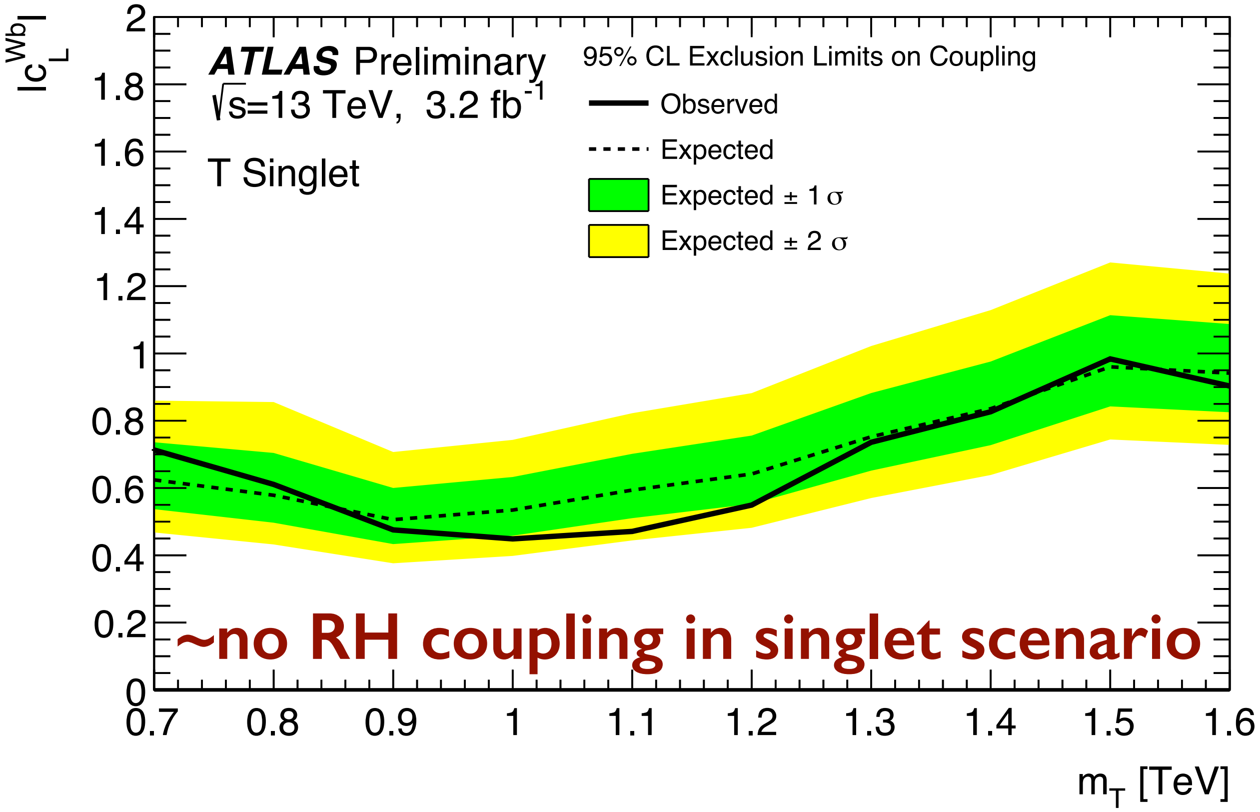
- non-negligible at truth level
- found to be small after reconstruction

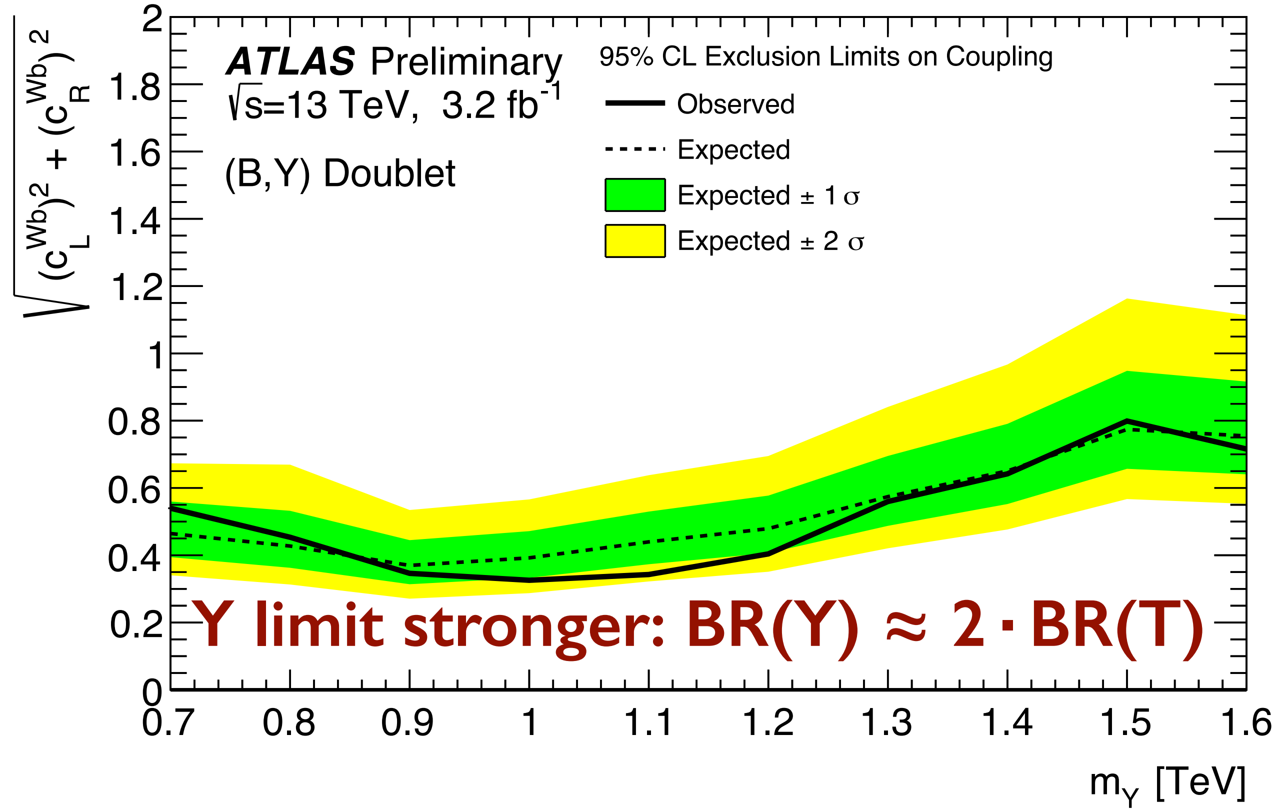


$c_L^{bW} = c_R^{bW} = 0.5$

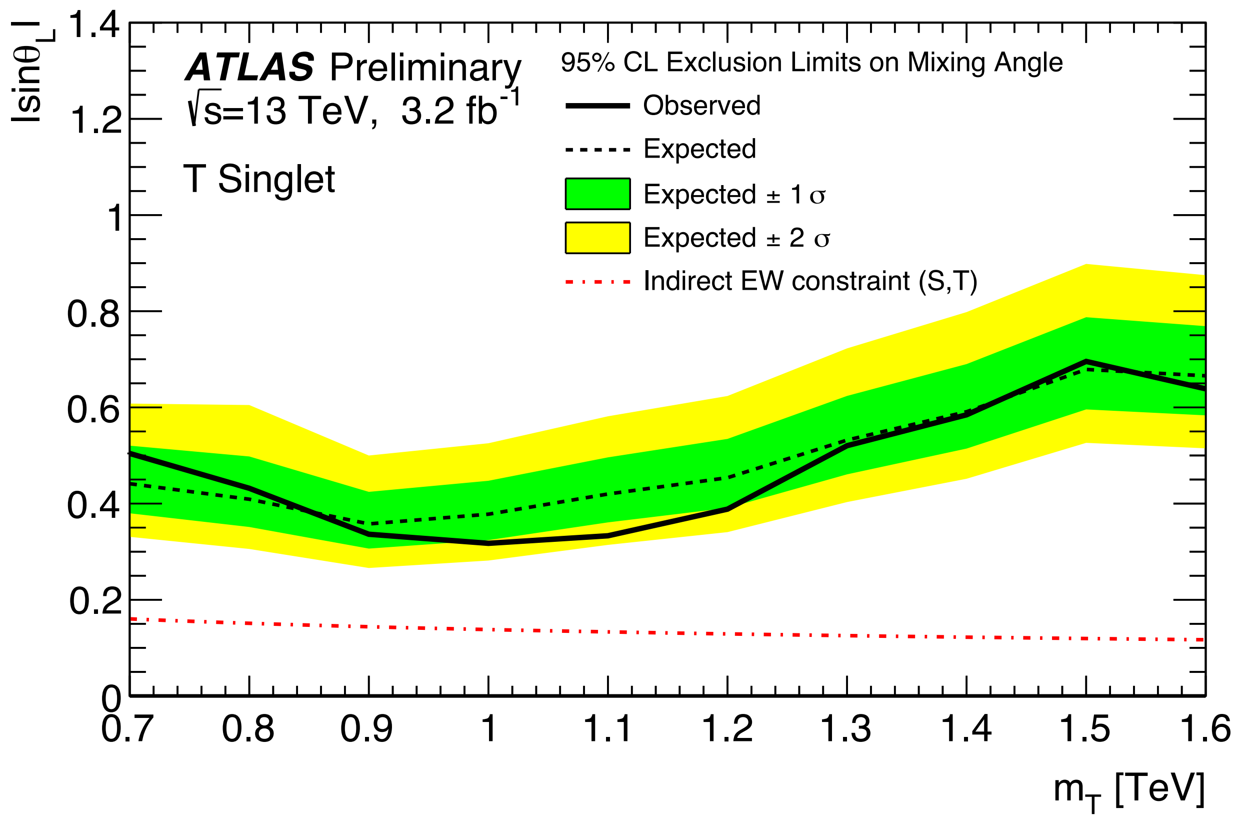
$c_L^{bW} = c_R^{bW} = 0.1$

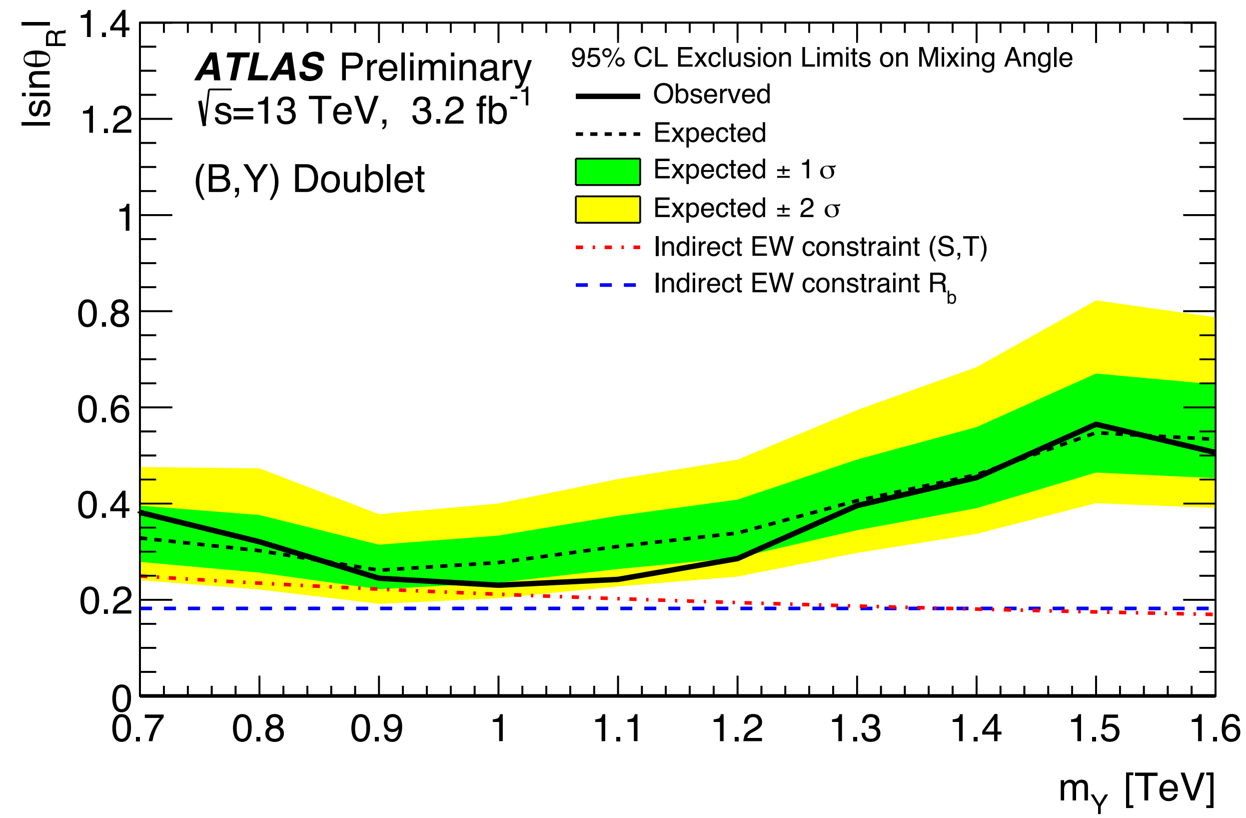
Single VLQ → Wb



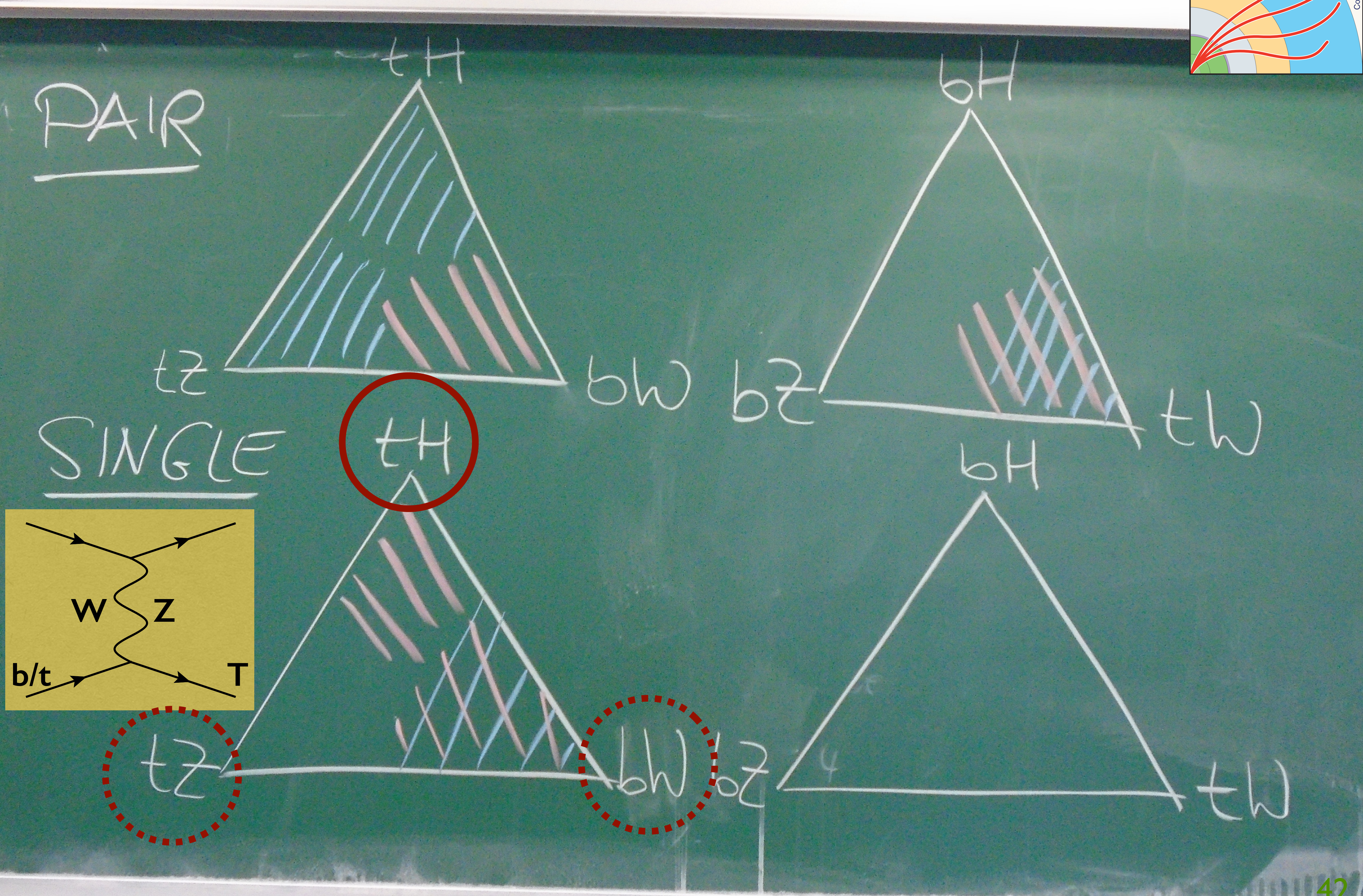


Also: limits on mixing angles $\theta_{L/R}$ — need to take into account also BR($\theta_{L/R}$)

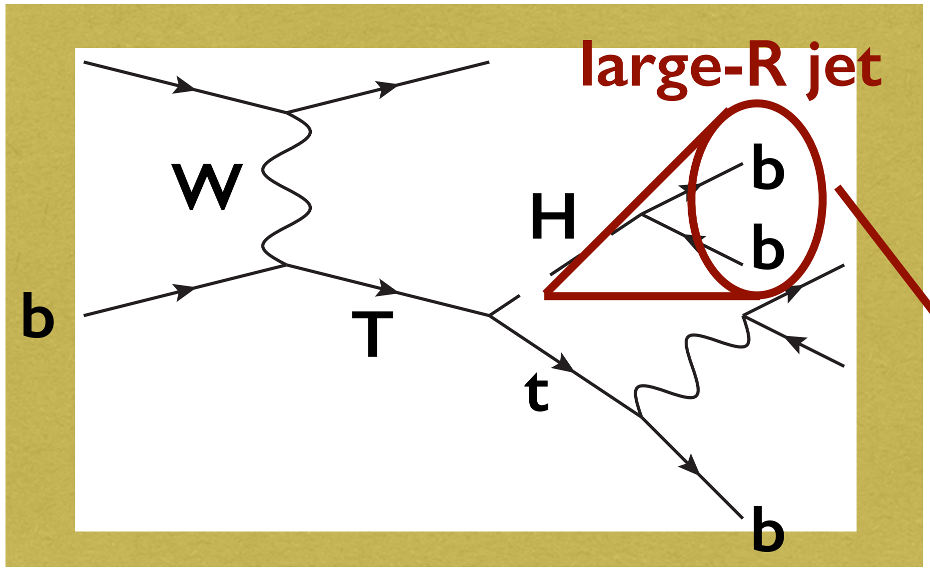




Single VLQ → tH



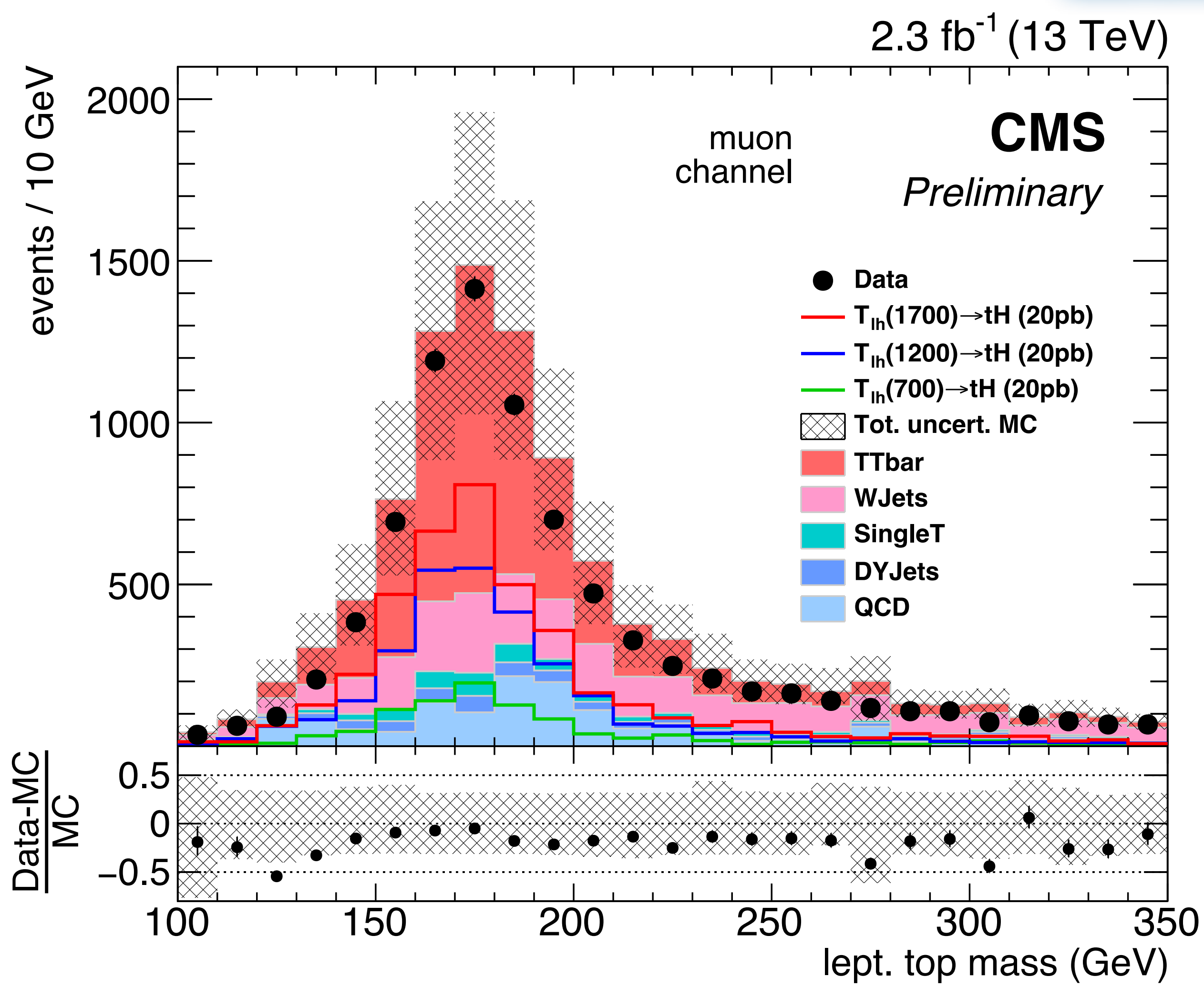
Single VLQ → tH (*leptonic top*)

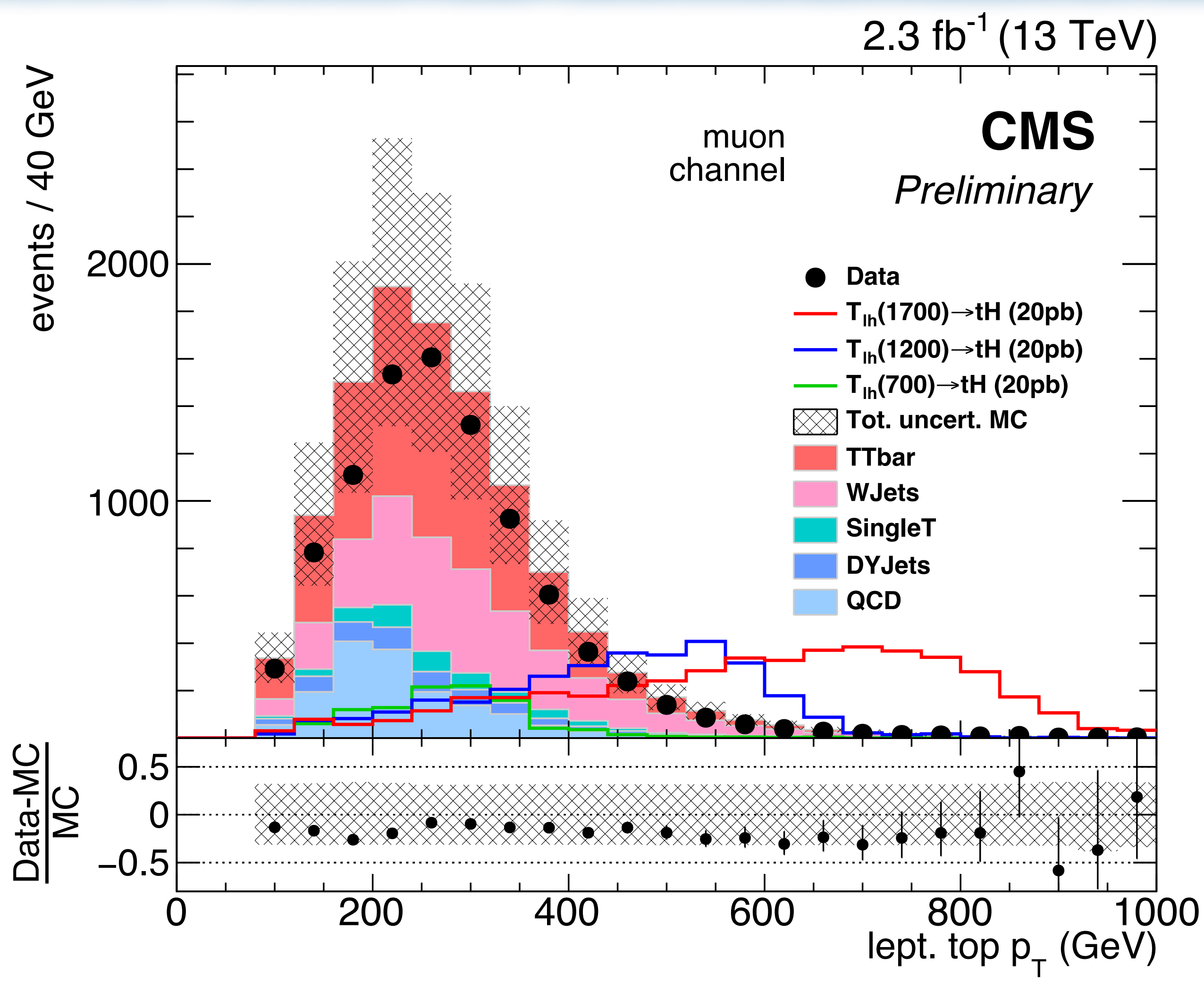


- e/μ with isolation modified for high-p_T tops
- high-p_T central jets, high S_T, ≥ 1 forward jet
- kinematic top quark reconstruction :

$$\chi^2 = \left(\frac{M_{H,MC} - M_{H,rec}}{\sigma_{M_H,MC}}\right)^2 + \left(\frac{M_{t,MC} - M_{t,rec}}{\sigma_{M_t,MC}}\right)^2 + \left(\frac{\Delta R(t,H)_{MC} - \Delta R(t,H)_{rec}}{\sigma_{\Delta R,MC}}\right)^2$$

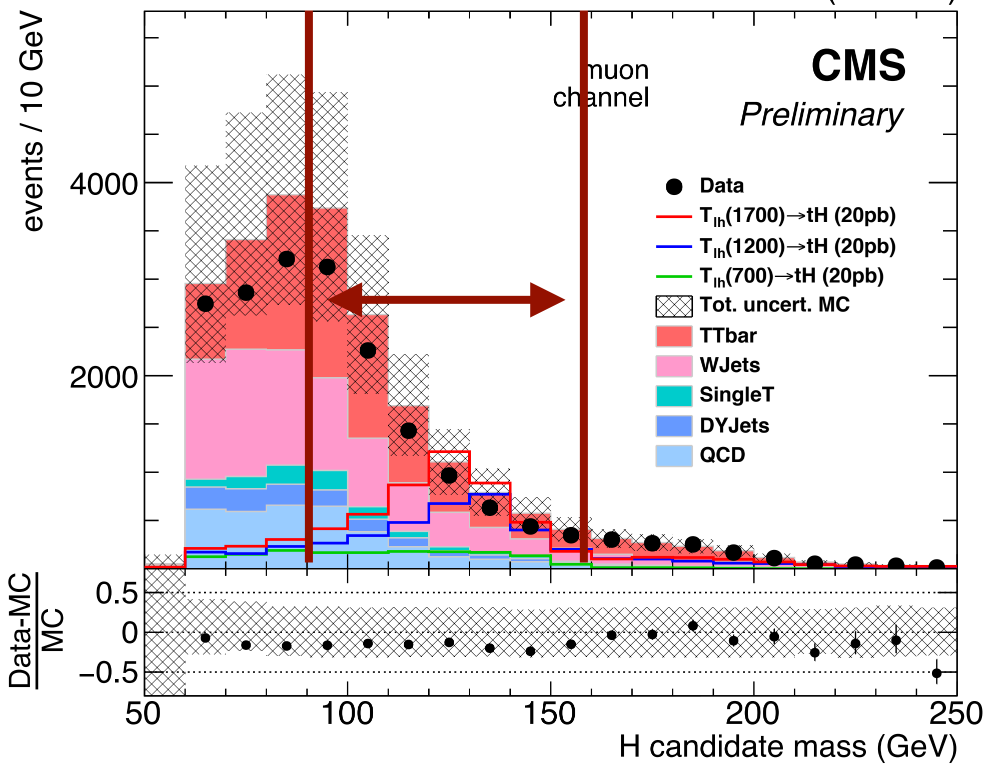
- ≥ 1 Higgs-tagged large-R jet (next slide)





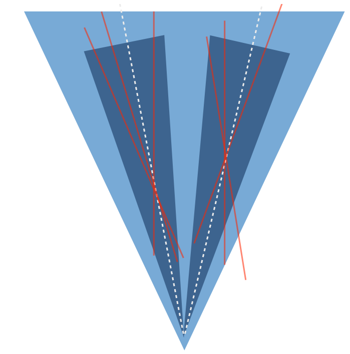
Tagging Higgs Bosons

CMS PAS B2G-15-008

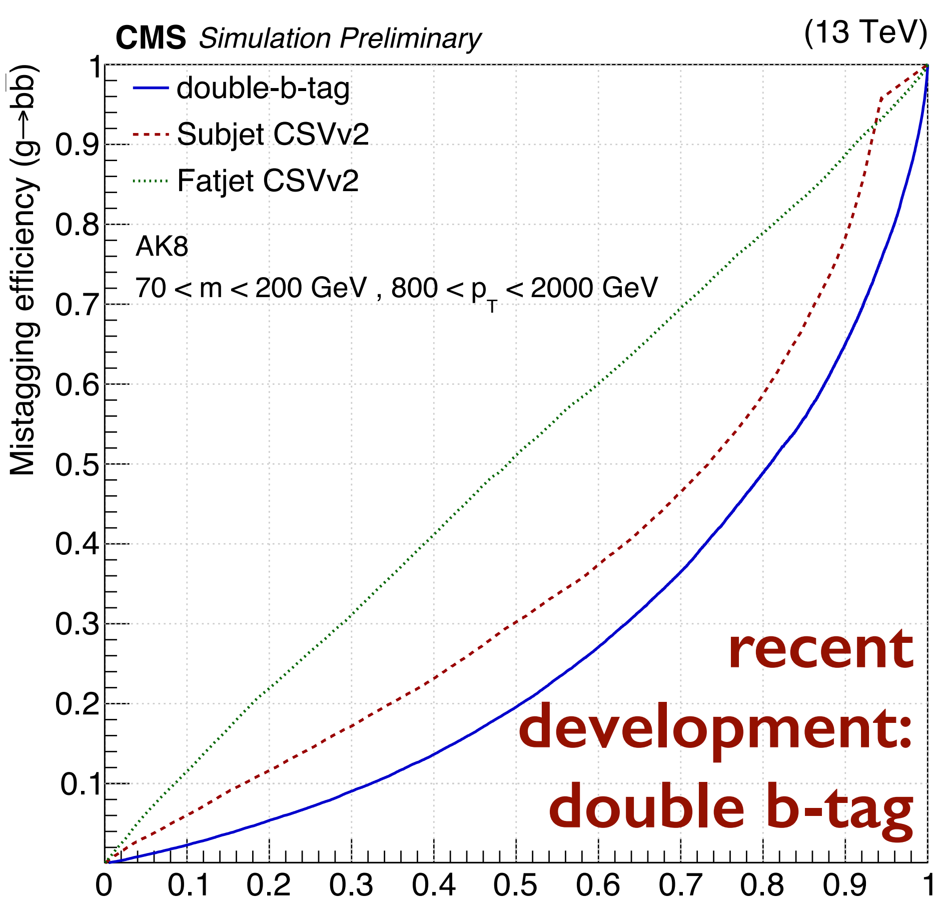


- jet mass: here — 90 GeV < m_{SD} < 160 GeV
- b-tagging is key:

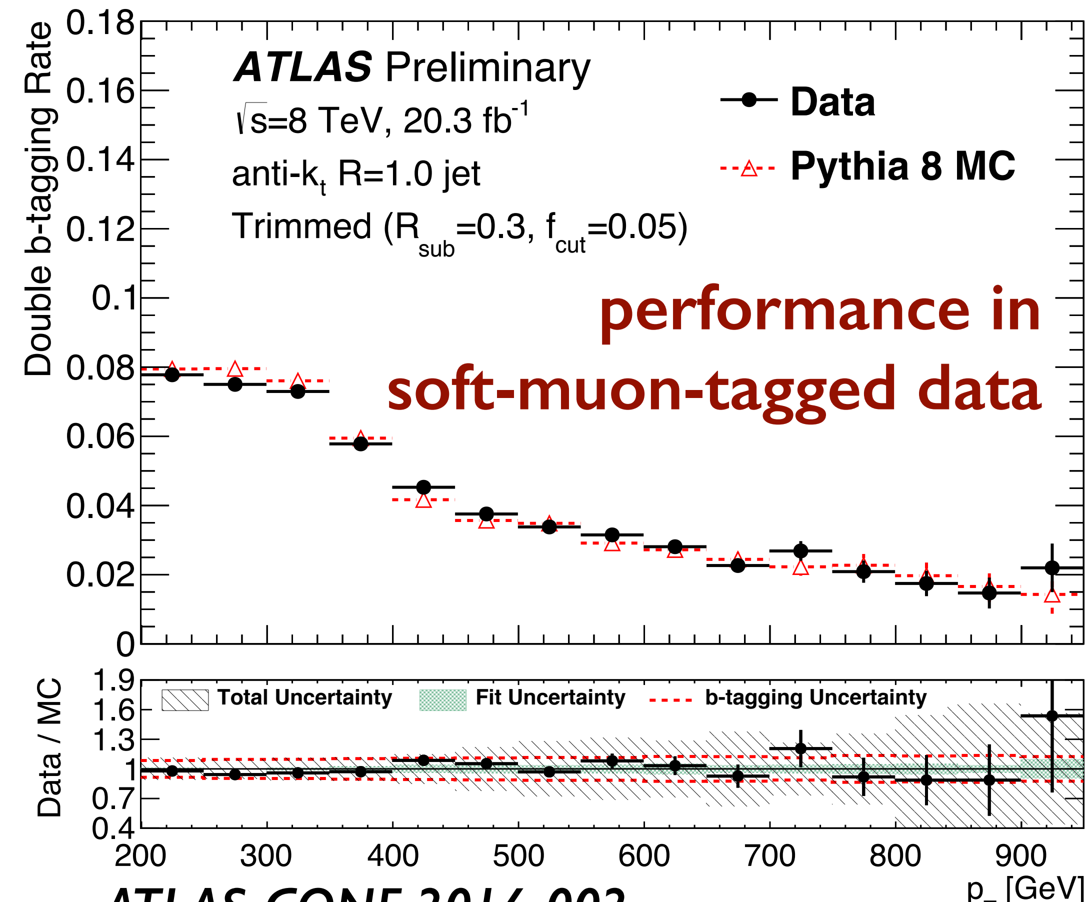
here — subjet b-tagging



CMS PAS BTV-15-002

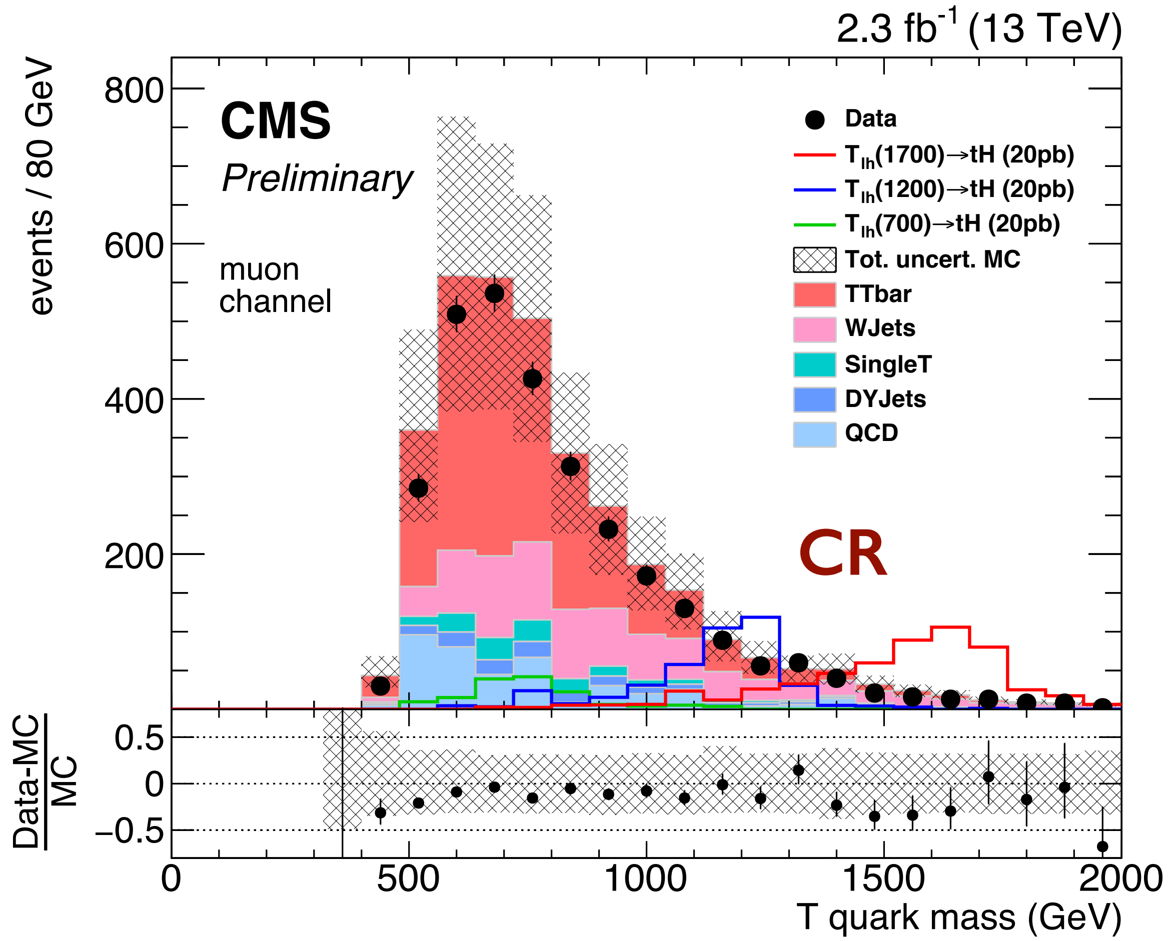


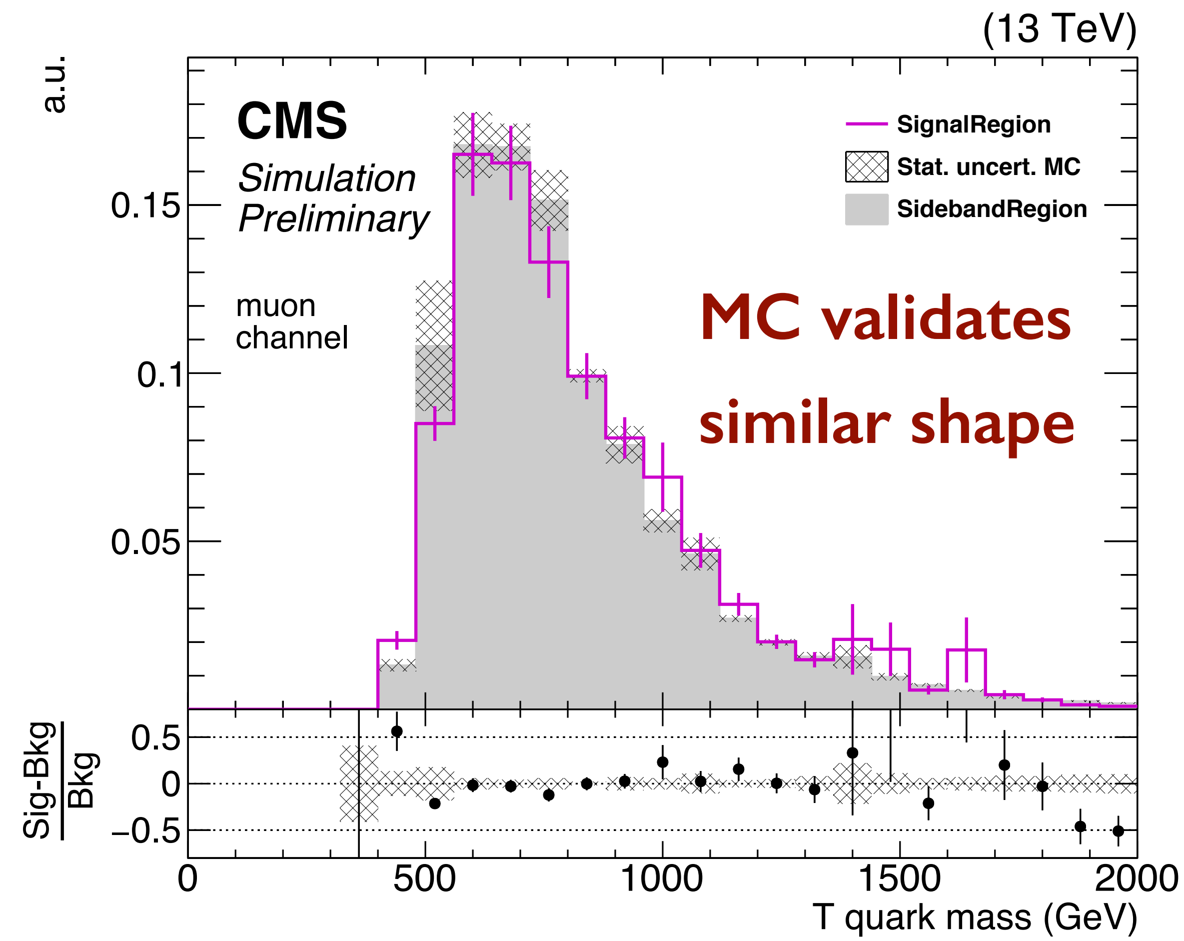
CMS PAS BTV-15-002



ATLAS-CONF-2016-002

Single VLQ → tH (*leptonic top*)

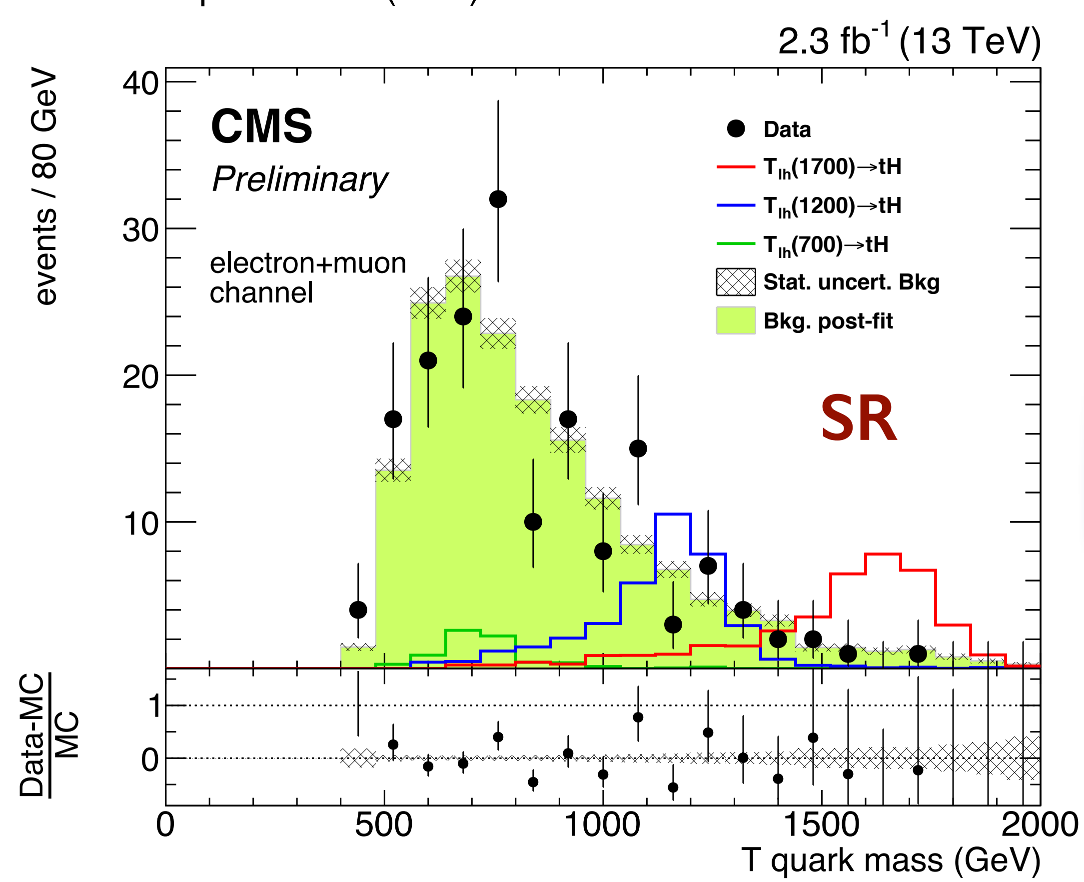




<u>Full background shape taken from CR</u>

CR defined by
- no fwd. jet
- 1 b-tag in H cand.

→ ~ uncorrelated with m_T shape



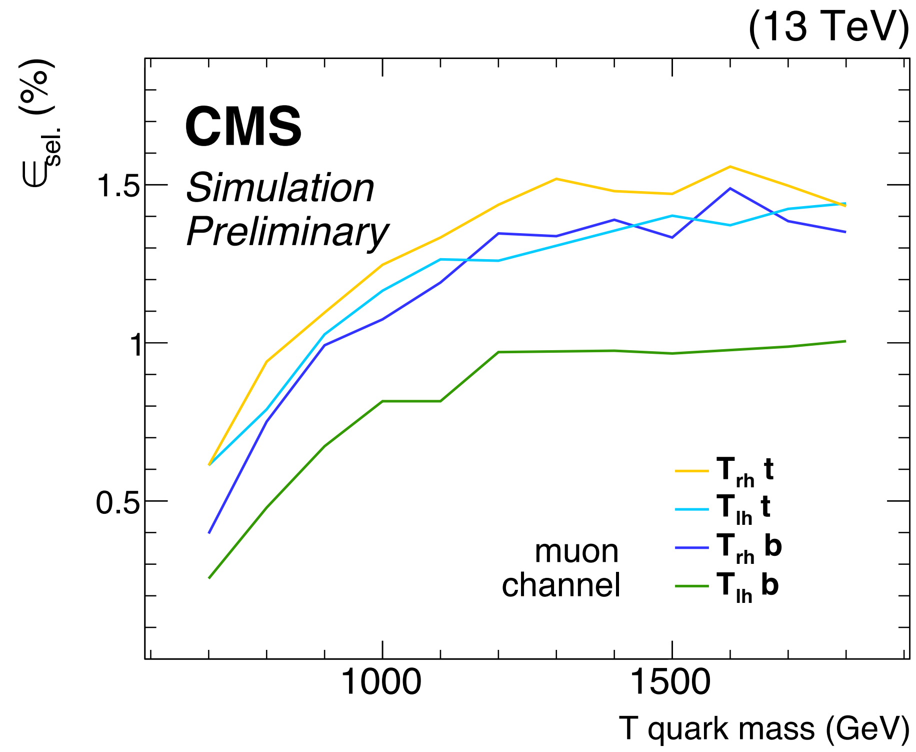
Norm(bkg.) free in SR fit
- 12% post-fit uncertainty

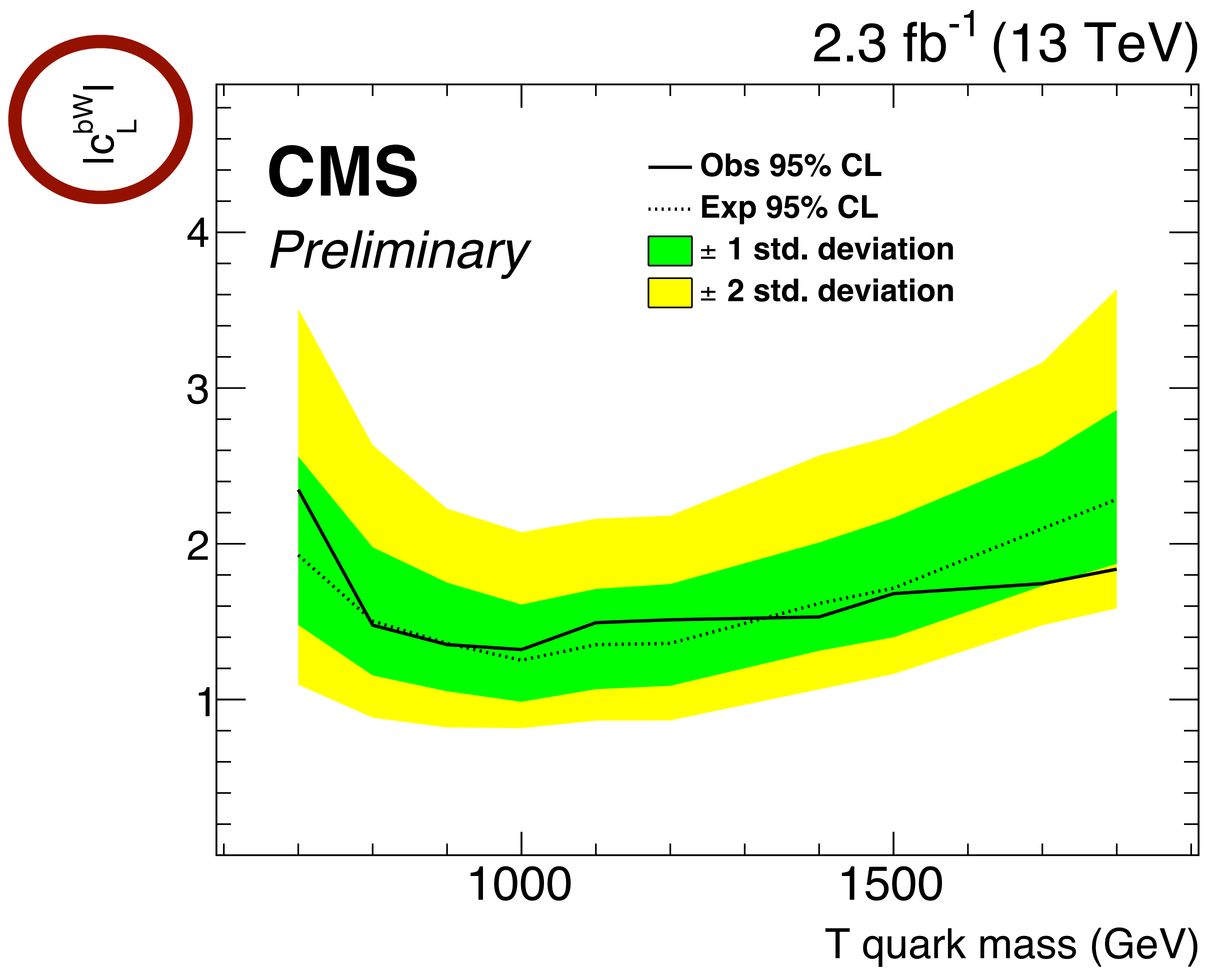
Single VLQ → tH (*leptonic top*)

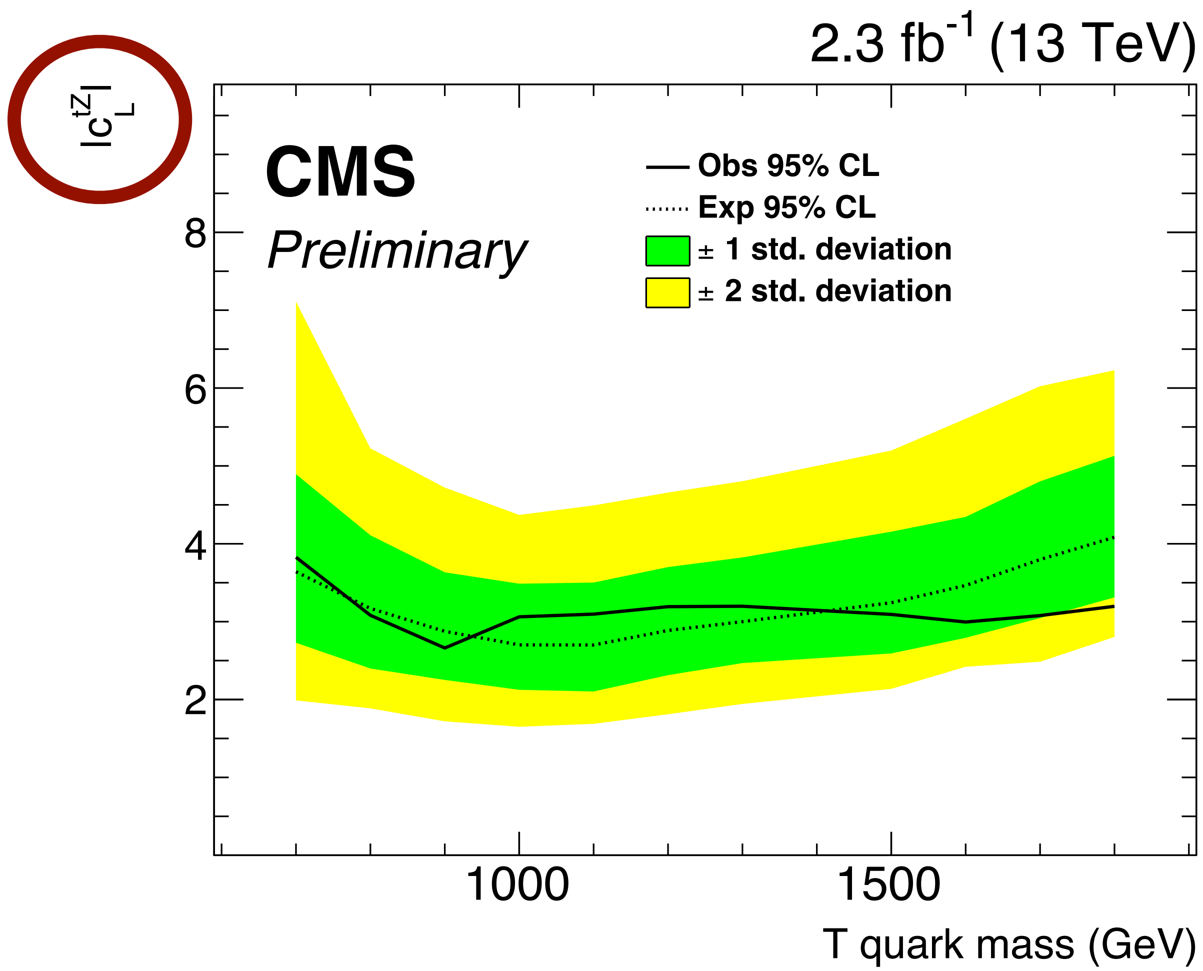
Benchmark interpretations

BR	Wb	Zt	Ht
Tbq	50%	25%	25%
Ttq	0%	50%	50%

ε depends on LH/RH and Tbq/Ttq

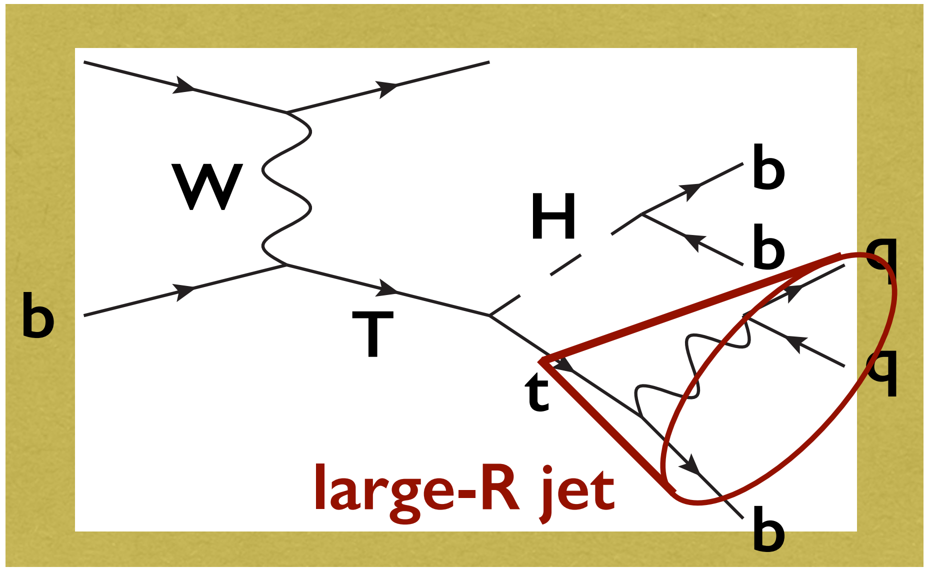




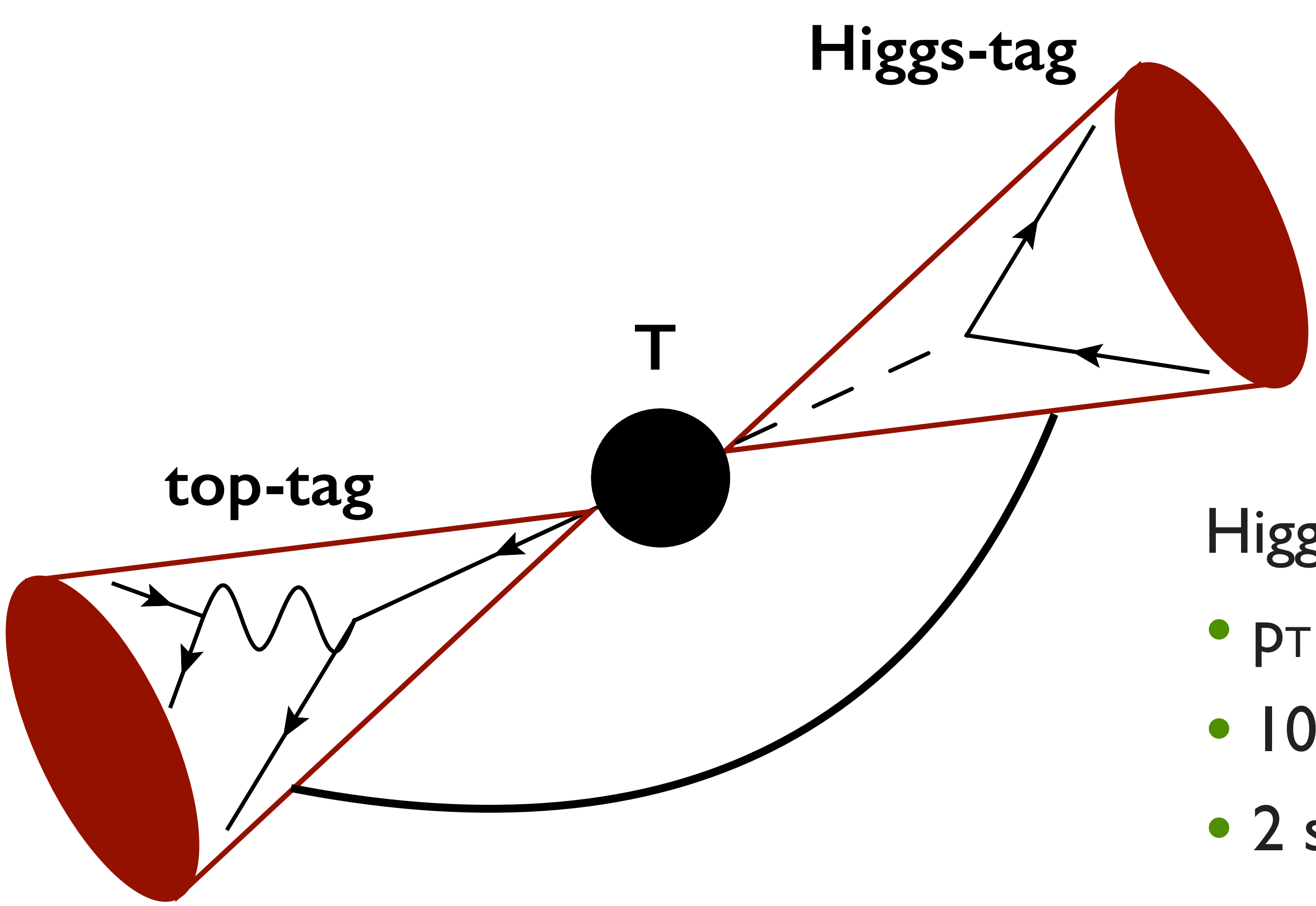


Not shown: limits on RH coupling

Single VLQ → tH (*hadronic top*)



- fully hadronic analysis
- sum(jet activity) ≥ 800 GeV @ trigger
- ≥ 1 Higgs-tag & ≥ 1 top-tag with $\Delta R > 2.0$
  → construct T candidate



Higgs-tag here:

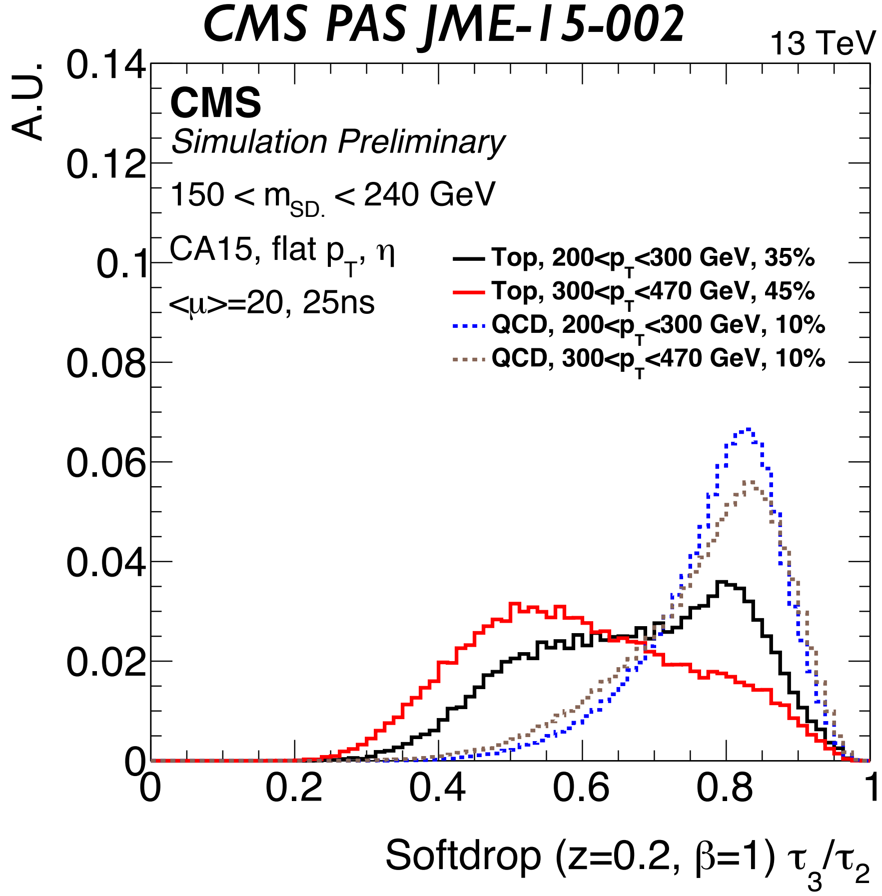
- $p_T > 300$ GeV
- $105 < m_{prun} < 135$ GeV
- 2 subjet b-tags
- $\tau_{21} < 0.6$

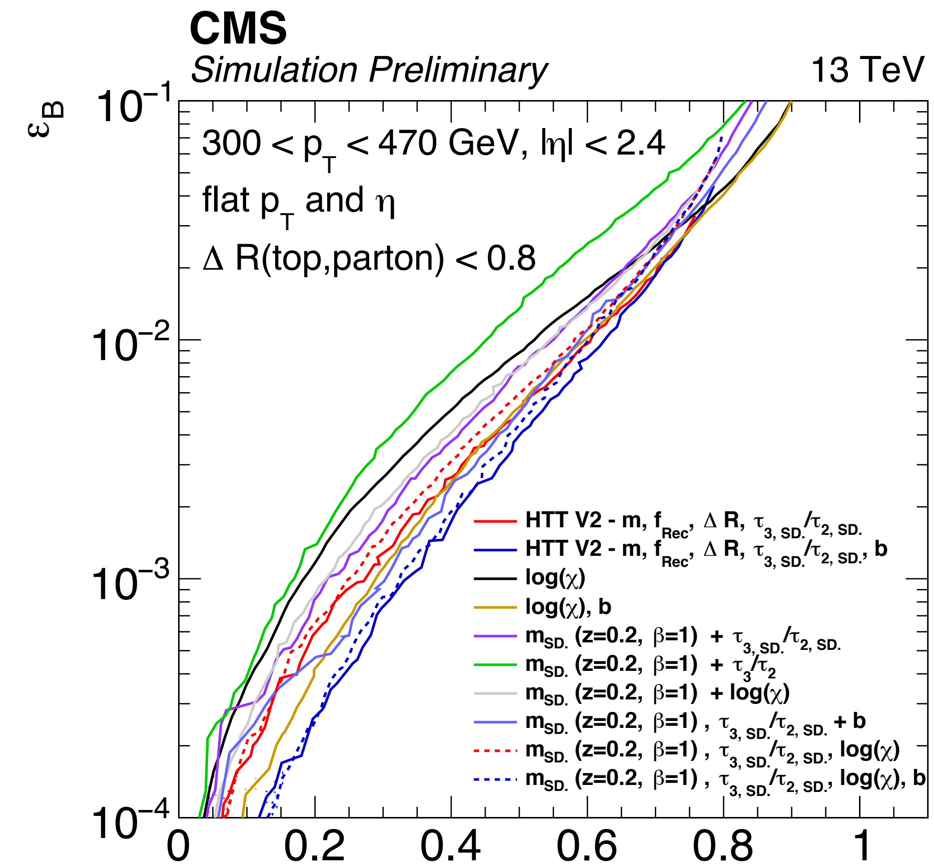
Tagging Top Quarks

top-tag here:

- p_T > 400 GeV
- τ_{32} < 0.54
    - 3- vs. 2-prong
- 1 subjet b-tags

CMS PAS JME-15-002

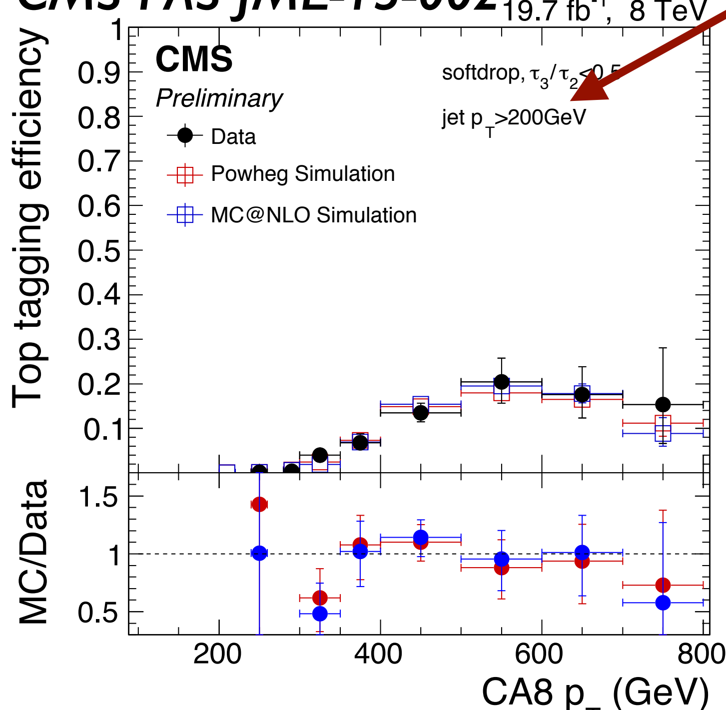


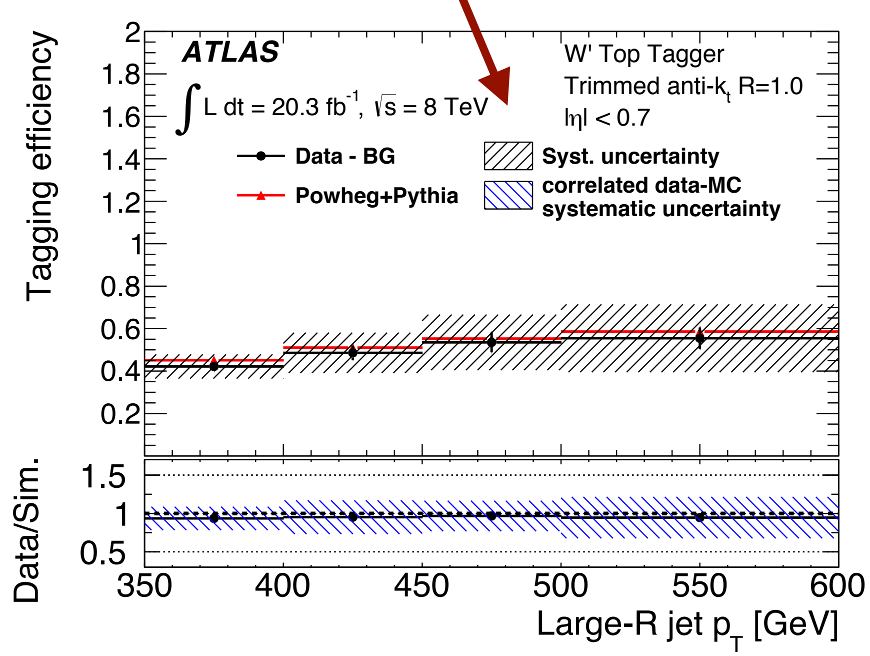


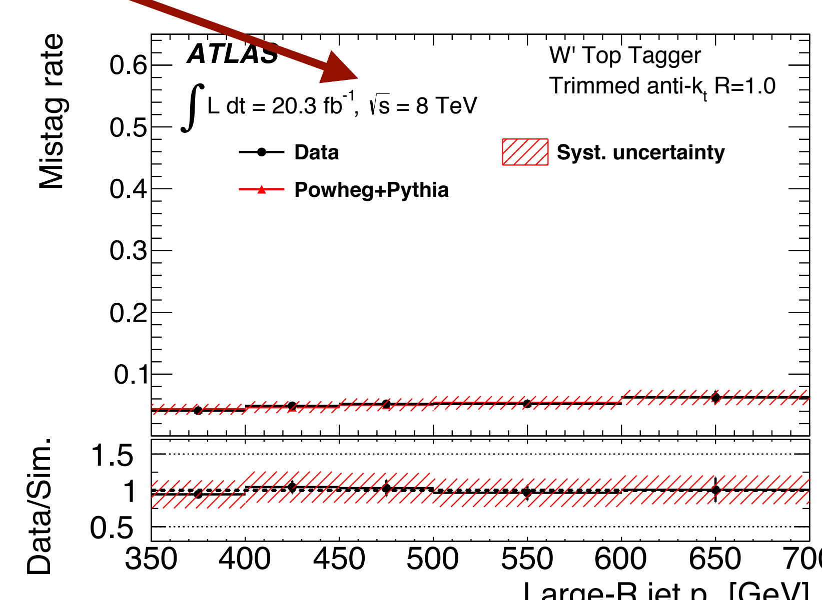
CMS PAS JME-15-002

Top-tagging thoroughly validated with 8 TeV data

CMS PAS JME-15-002







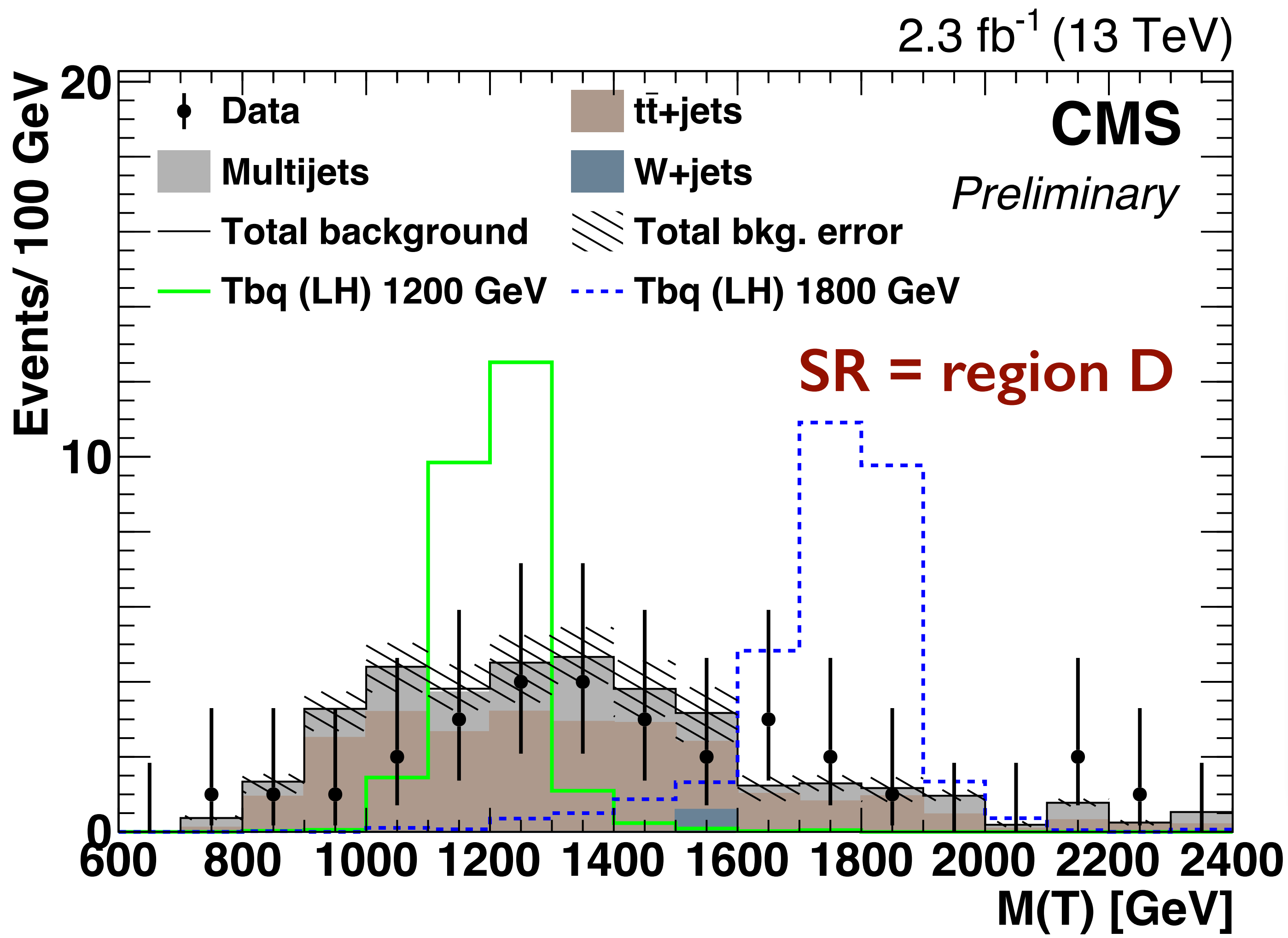
JHEP 06 (2016) 093 *JHEP 06 (2016) 093*

Single VLQ → tH (*hadronic top*)

QCD multijet background

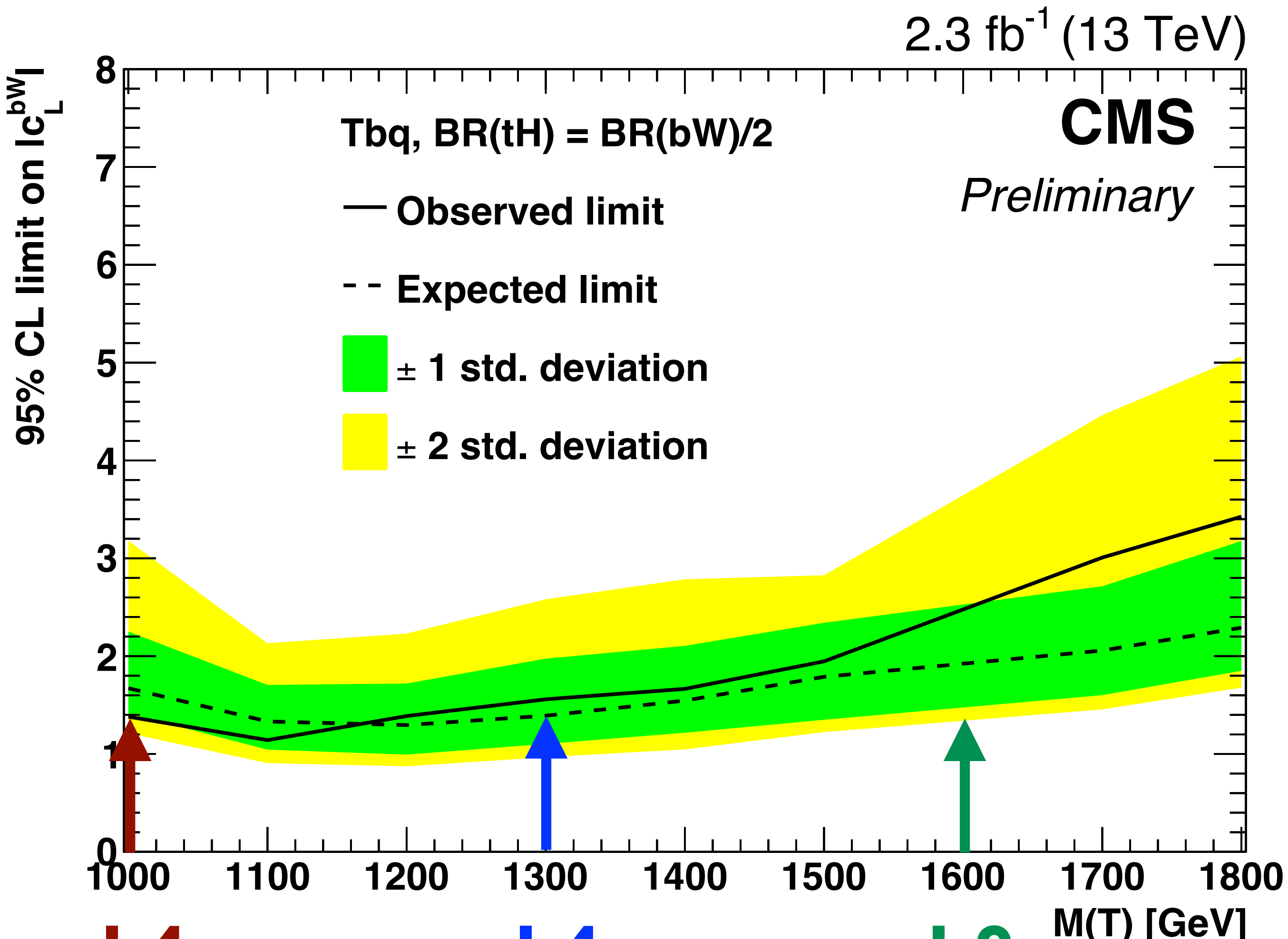
ABCD method : $N_D = N_B \cdot \frac{N_C}{N_A}$

QCD percentage	no top-tag	top-tag
no H-tag	A ~100%	B ~80%
H-tag	C ~70%	D = SR ~30%

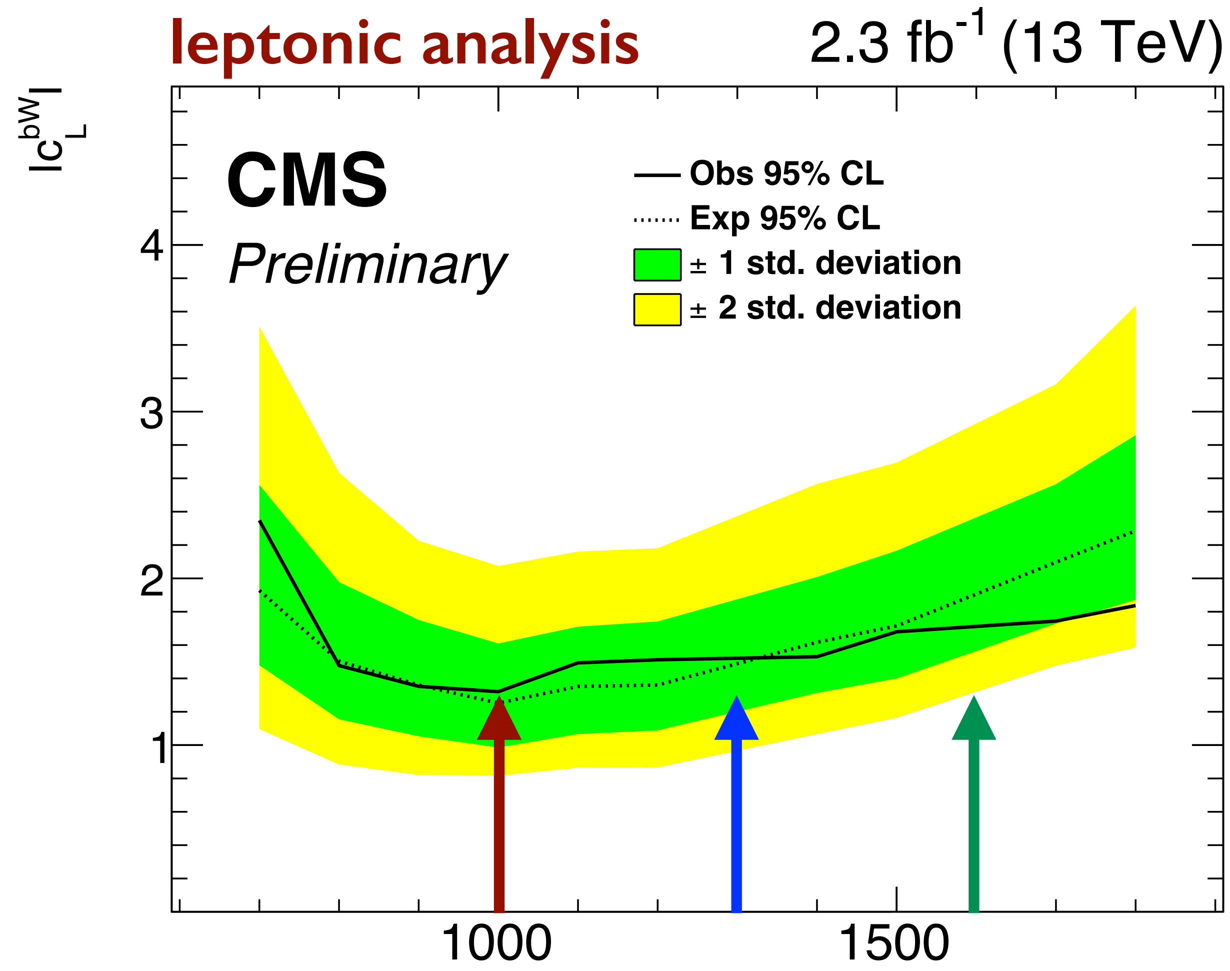


- *QCD syst. from bkg. subtraction*
  - *(anti-)correlated in stat. analysis*
- significant systematics
  - Higgs-tag N-subjettiness 12.5%
  - jet mass 10%
  - top-tagging 15-30%

Single VLQ → tH (*hadronic top*)



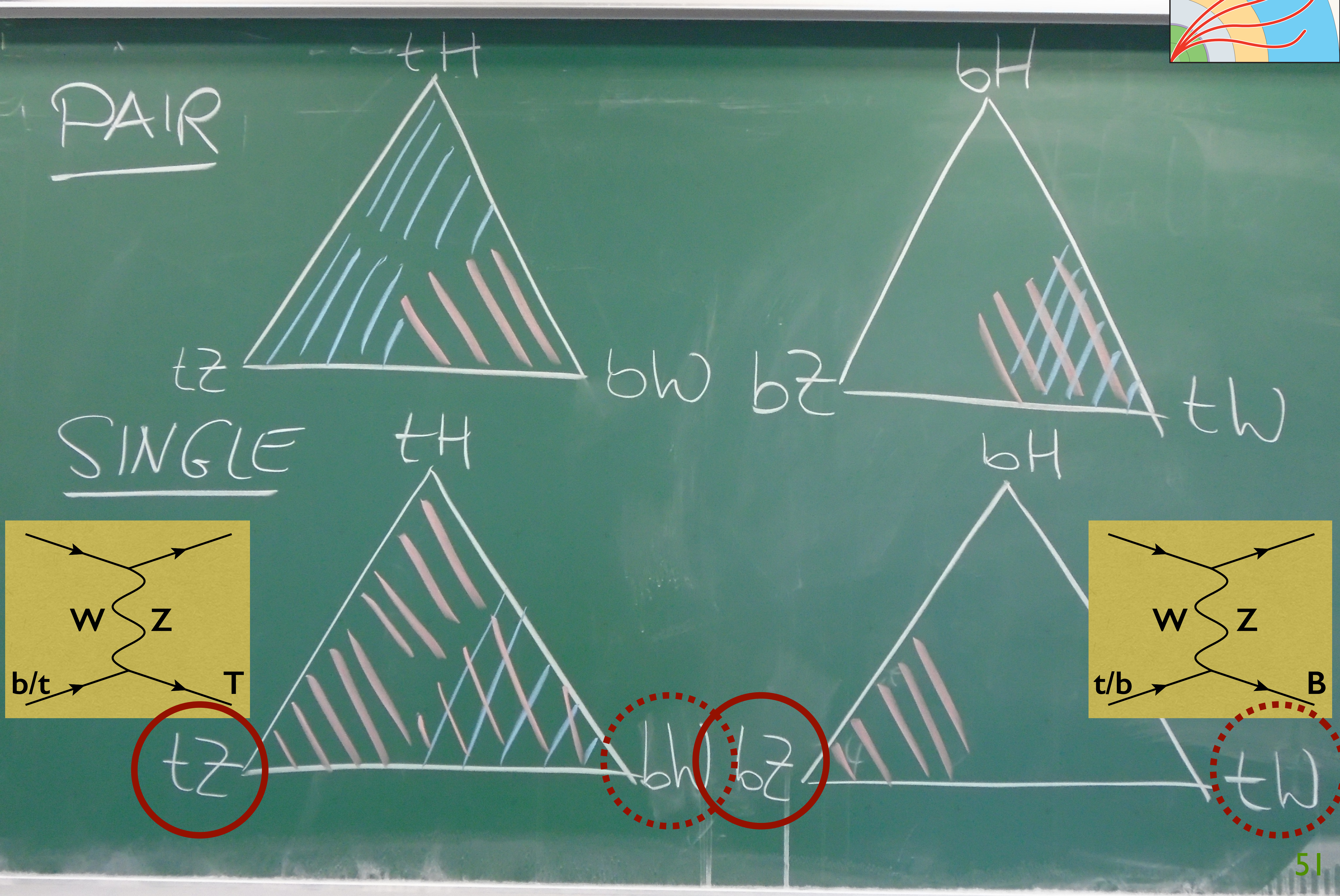
~1.4 (expected limit) **~1.4** **~1.9**



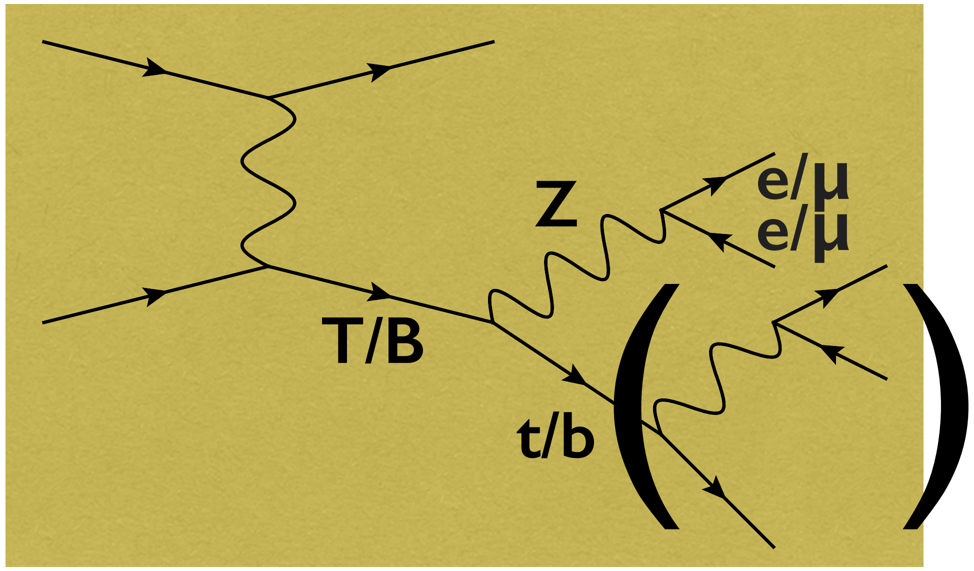
~1.2 **~1.2** **~1.9**

- Sensitivity for m > 1 TeV
- Similarly sensitive as leptonic analysis
- Interpretation:
  - singlet-BR: c_L^{bW} (much better limits)
  - doublet-BR: c_R^{tZ}

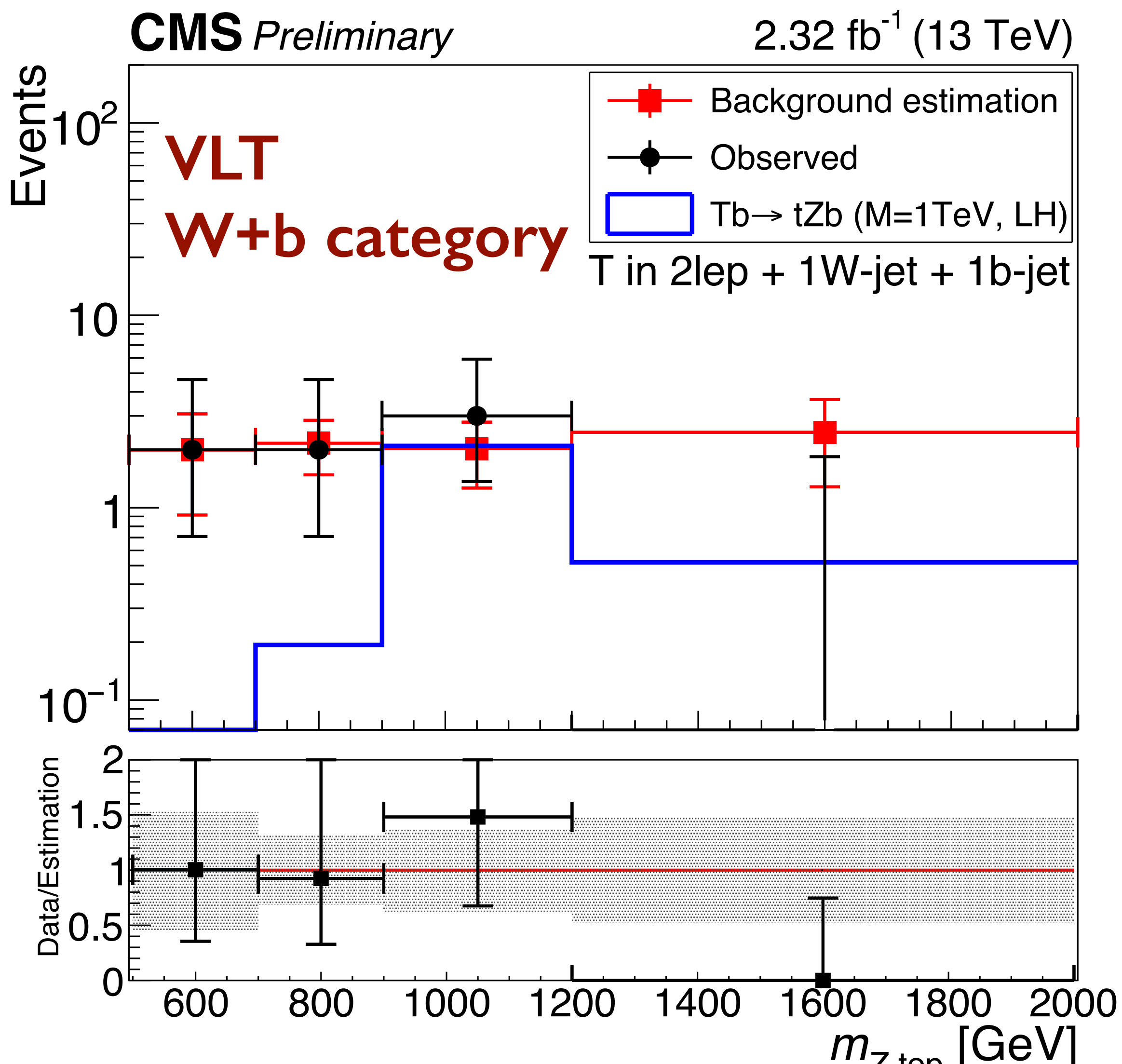
Single VLQ → Zt / Zb

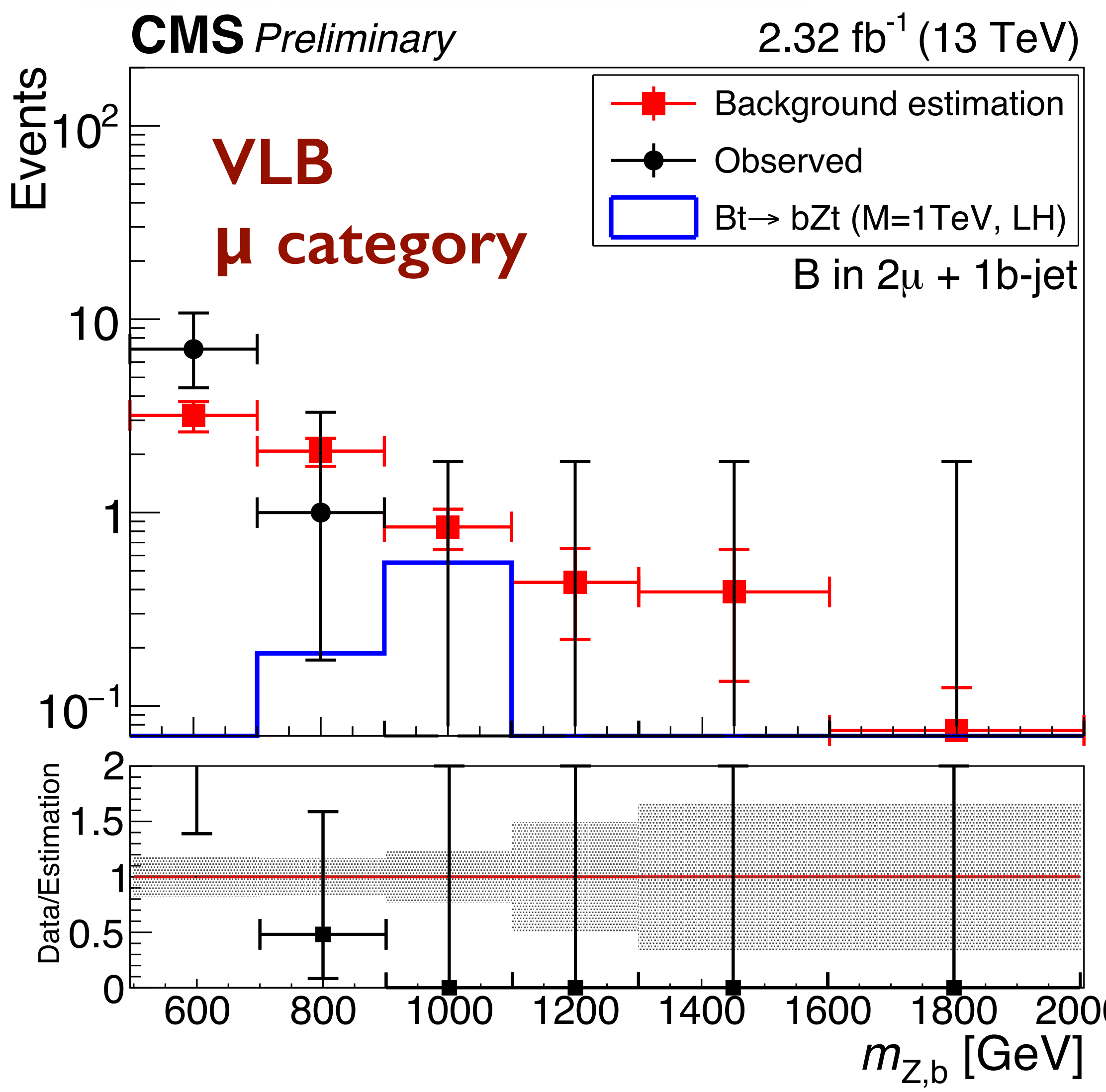


Single VLQ → Zt / Zb



- Z from ee or μμ with small ΔR
- top: top-tag || W-tag+b || b+2j
- high leading lepton p_T
- VLT = Z + t
- VLB = Z + leading b

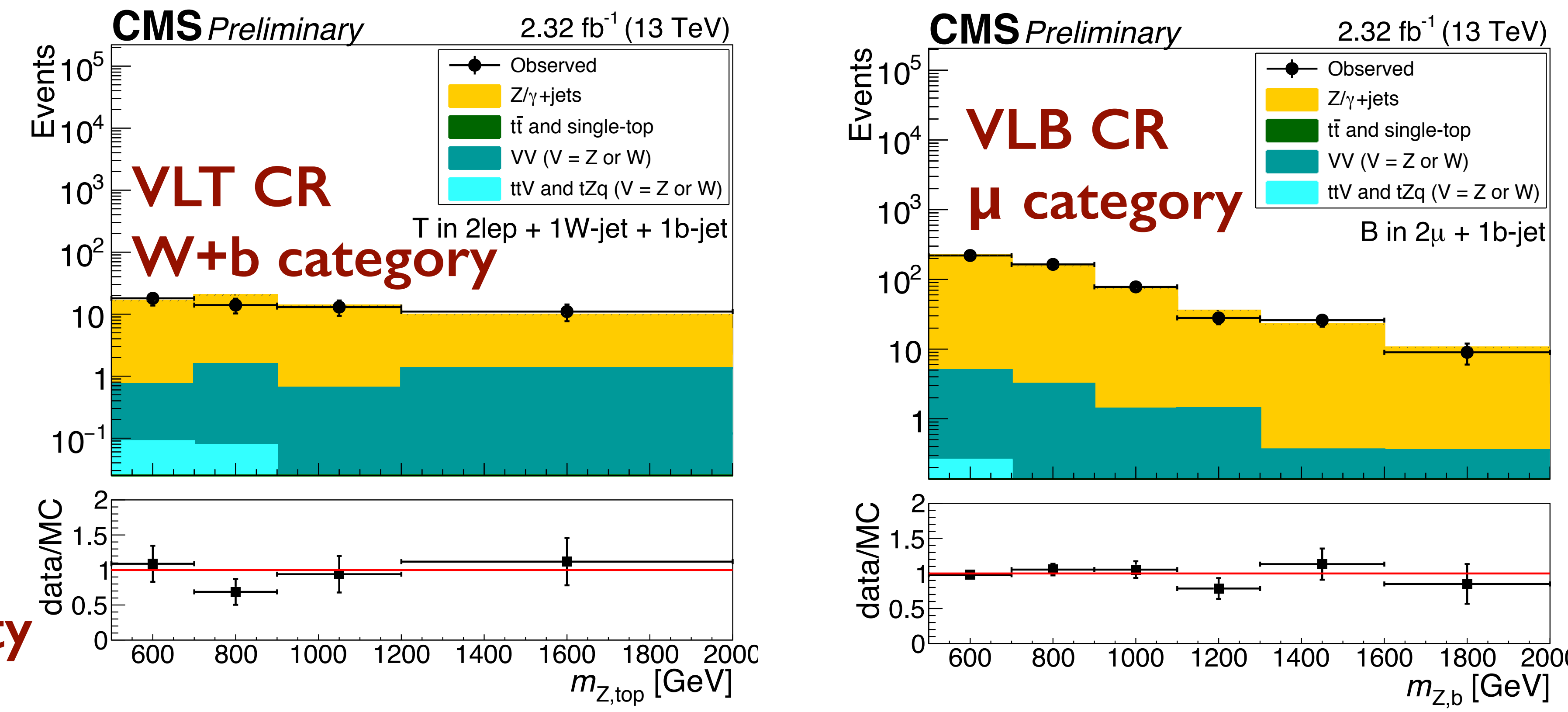




Single VLQ → Zt / Zb

Background with 'α-method'

- scale all backgrounds to data in CR (0 b-tags)
- scale factors all close to 1 → good !

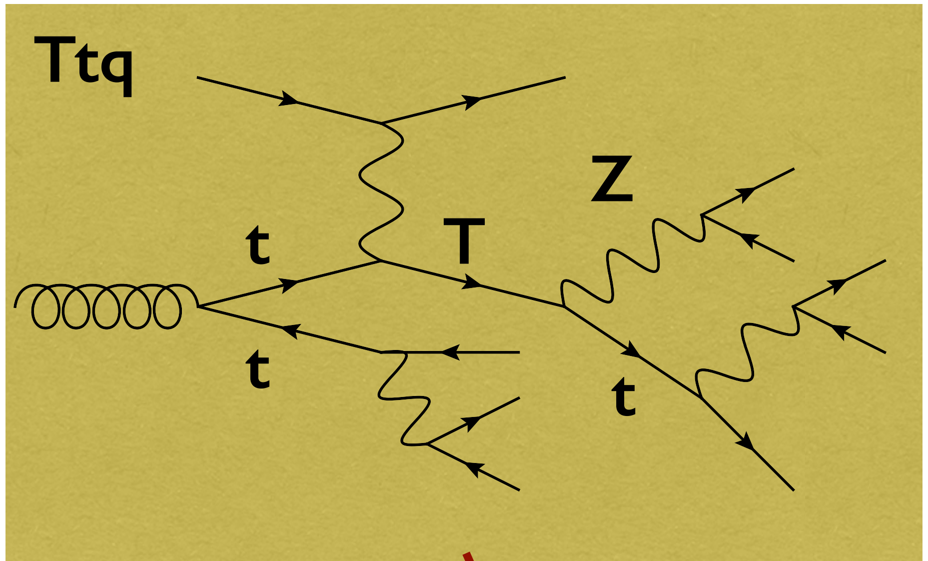


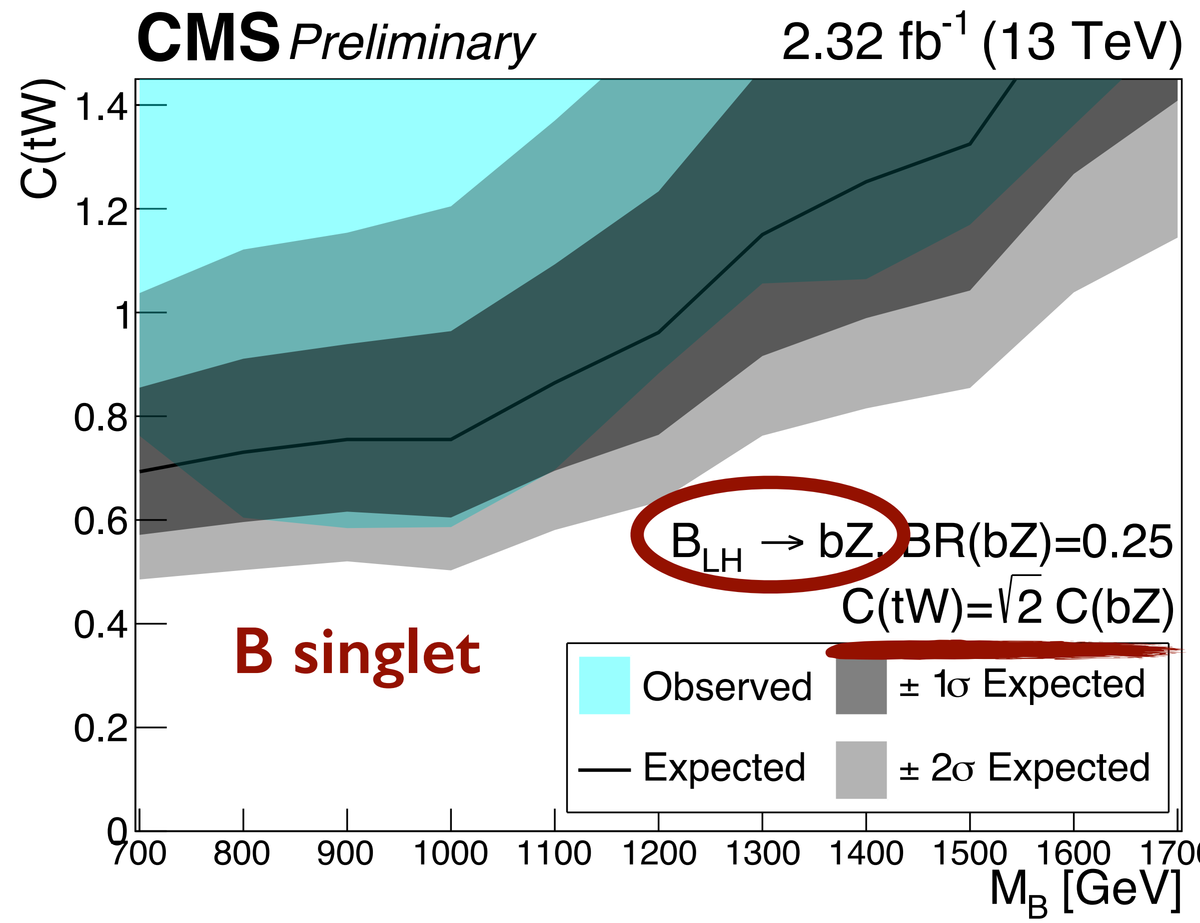
stat. uncertainty

Channel	2ℓ+1*top-jet*	2ℓ+1*W-jet*+1*b-jet*	2μ+1*b-jet*+2*jets*	$2e$+1*b-jet*+2*jets*	2μ+1*b-jet*	$2e$+1*b-jet*
Background systematics on shape (range between bins)						
Background α-method	58%	29-32%	10-23%	13-32%	13-42%	17-40%
Closure test	8%	3-32%	3-60%	3-60%	3-60%	3-60%
b-tag	5%	2-6%	4-5%	4-6%	9-12%	6-16%
Z+jets composition	-	9-44%	3-22%	4-21%	2-13%	4-11%

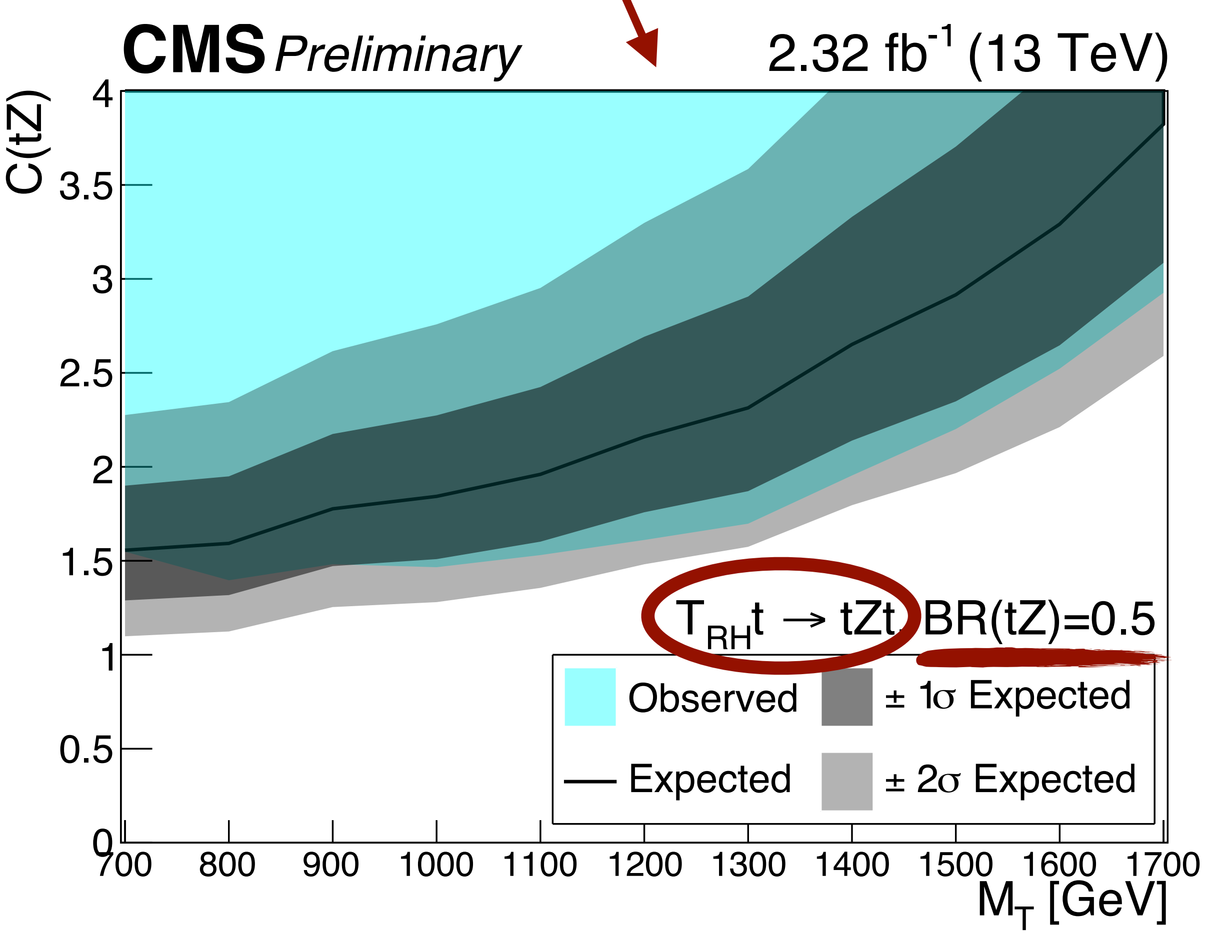
closure test in data CR (!) w/ 2 jets

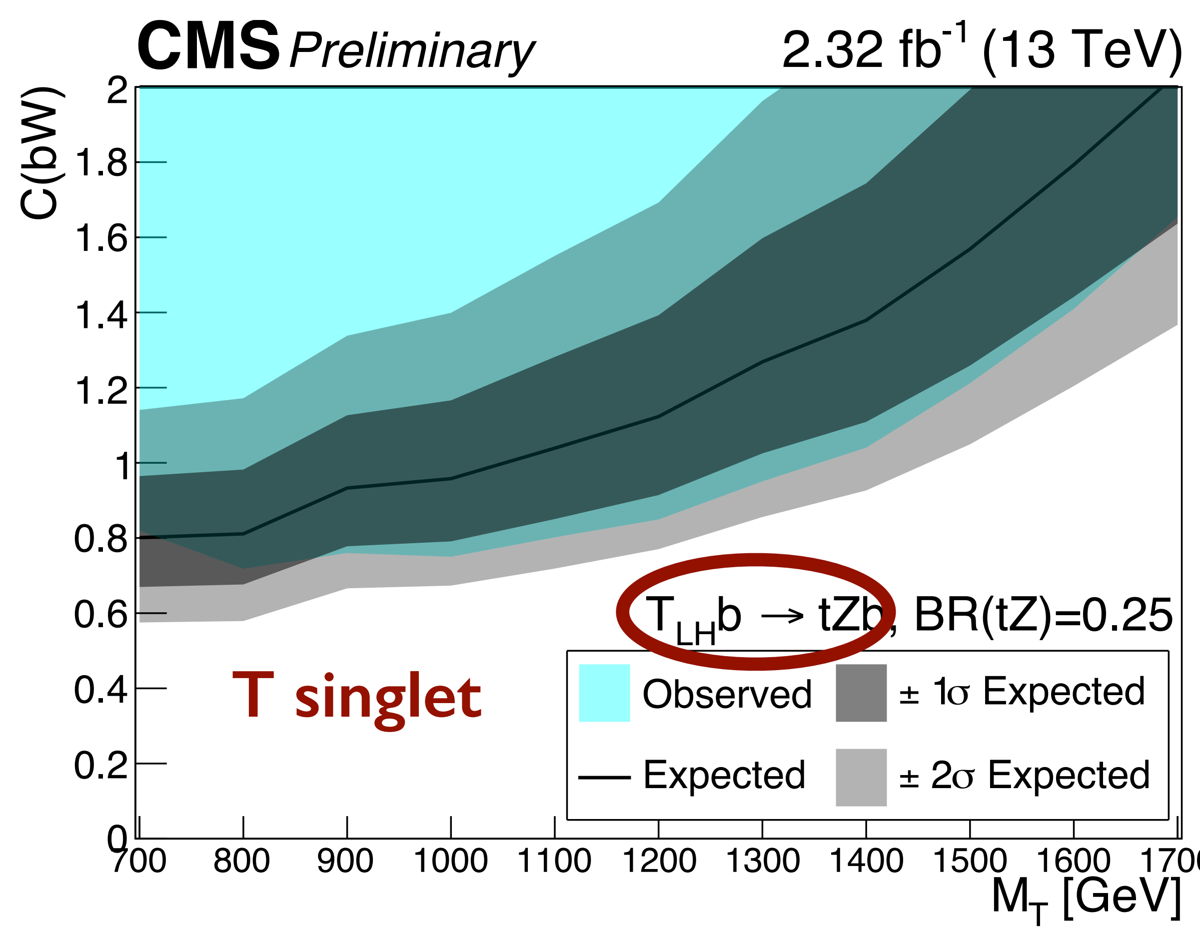
Single VLQ → Zt / Zb



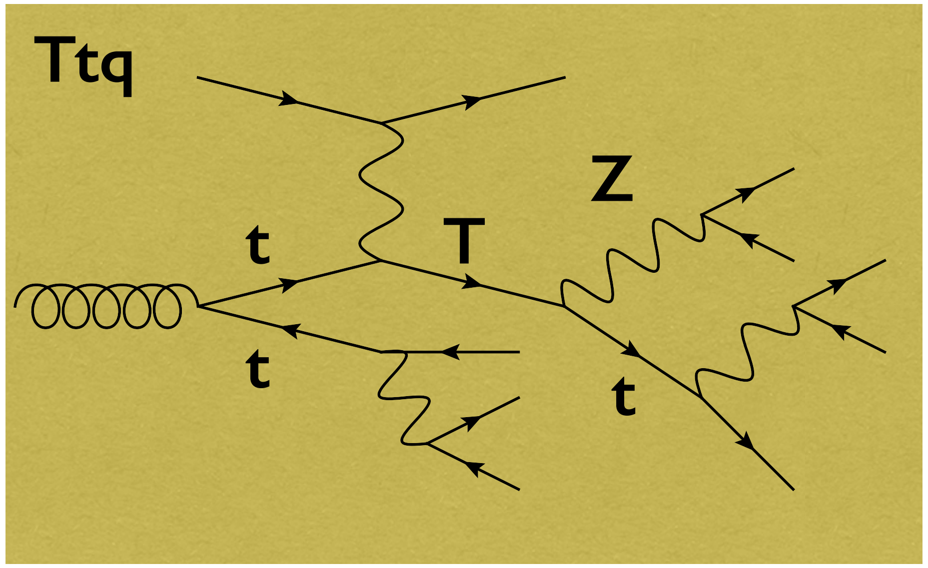


for (T,B) doublet
$C^{bW} = 0$

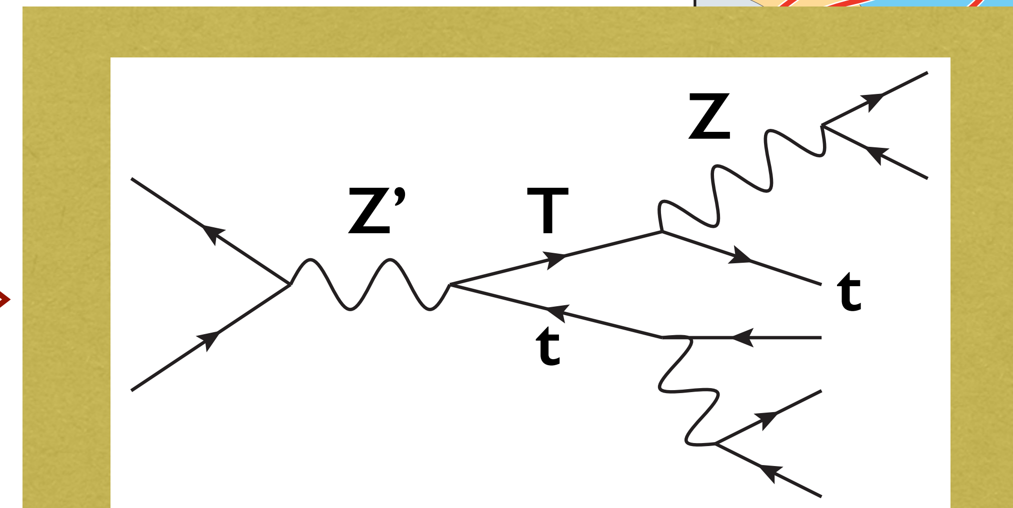




Reinterpretation : Z’ → Tt → Ztt

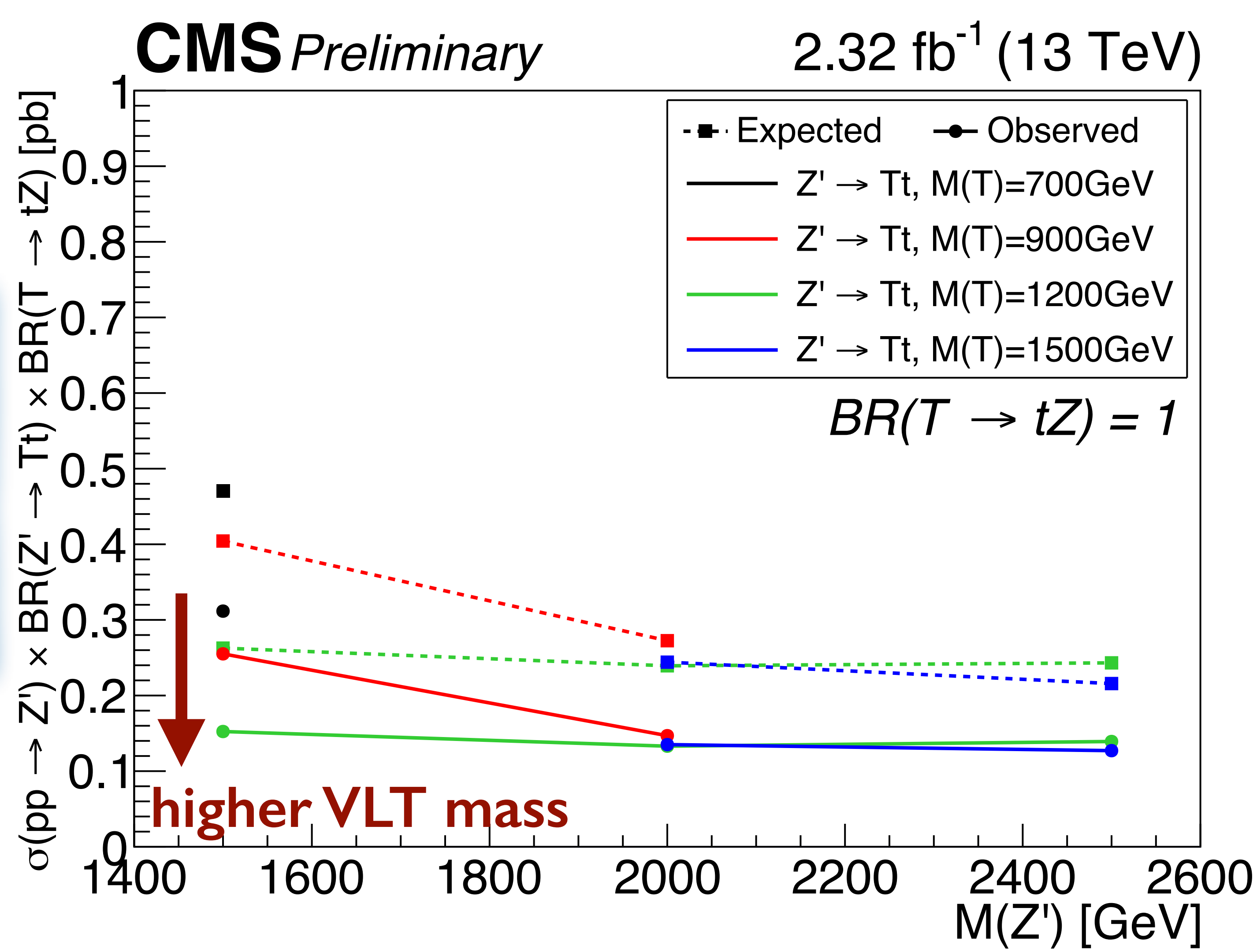


reinterpret



(Bini, Contino, Vignaroli, JHEP 01 (2012) 157)

- assume BR(T→tZ) = 100%
- limits improve when more boosted
  - with higher m(T)
  - with higher m(Z’)



Challenges for Interpretation

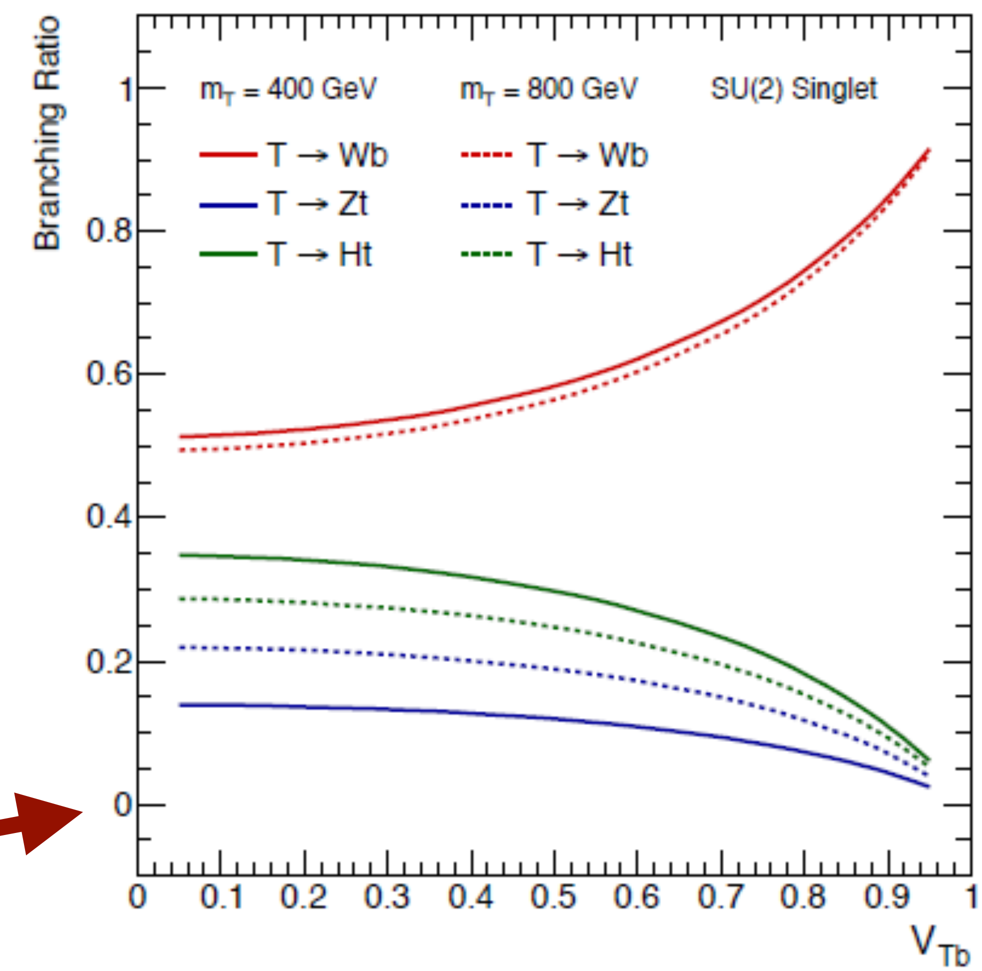
- Experimental assumptions
  - VLQ width effects on exp. observables ?
  - LH/RH differences in exp. observables ?
    - basis for 'BR reweighting'
  - pair *and* single production ?
  - additional production mechanisms ?

    (for ex. via heavy G → VLQ + q

    or heavy G → 2 VLQ)
- Interpretation
  - BRs : small coupling approximation ?
  - additional production mechanisms ?
  - Coupling to 1st/2nd generation ?
  - More than one VLQ multiplet ?
  - Extended scalar sector ?

  → allow recasting via HEPData info ?

  → publish σ limits for full BR triangle ?



BR vs. V_{Tb}
SU(2) singlet T @ m_T = 400, 800 GeV

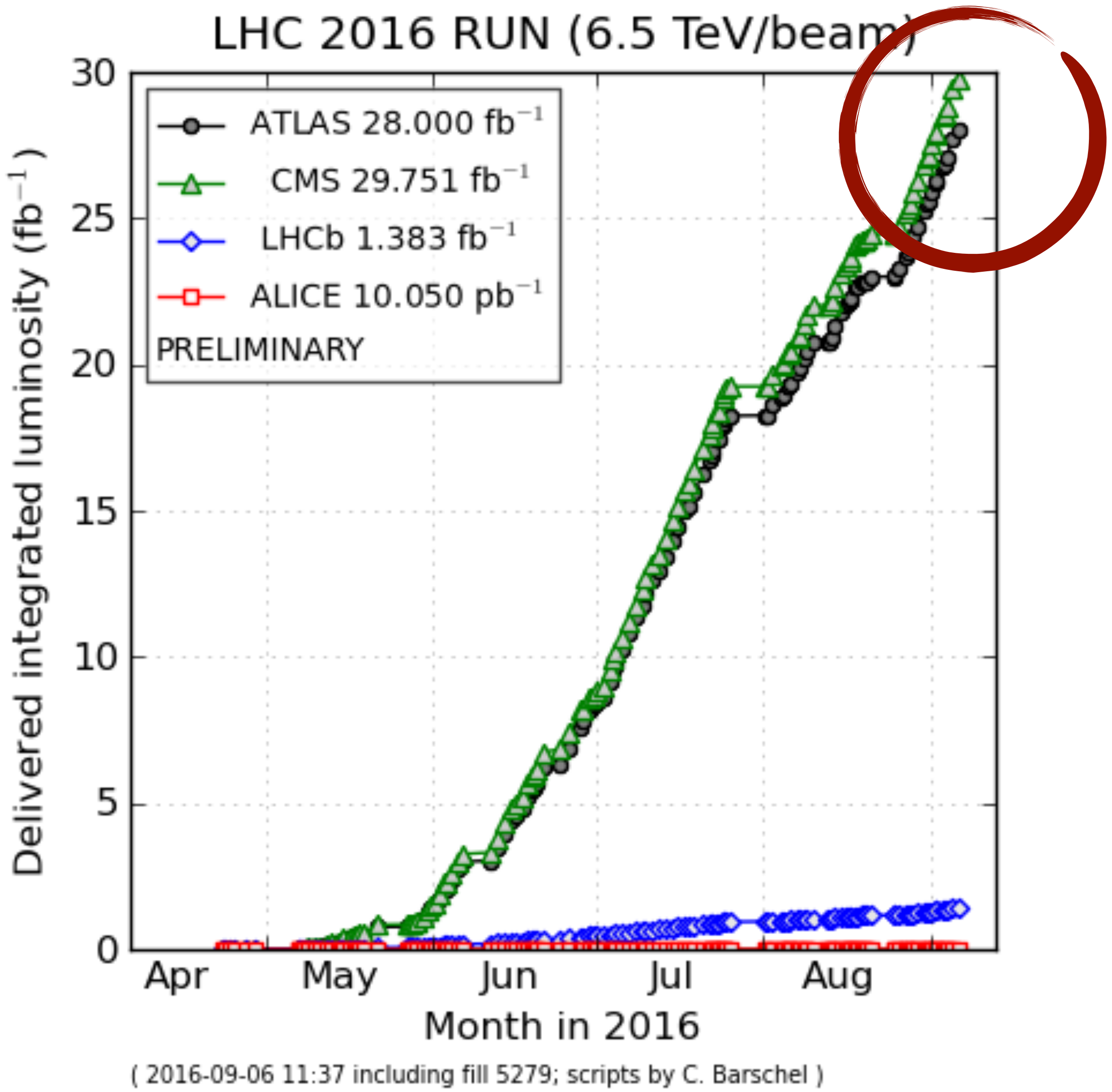
Conclusions

- Broad search program for VLQ
- Focus shifted towards single production
  - But pair production not forgotten !
    - Limits approaching 1 TeV

- Experimental methods
  - Variety of background methods reassuring
  - Time for boosted strategies has come

- Interpretation
  - More tricky with growing interest in single production

VLQ @ 1.X TeV ?



Backup

Impact of couplings on kinematics

Aguilar-Saavedra, JHEP 11 (2009) 030

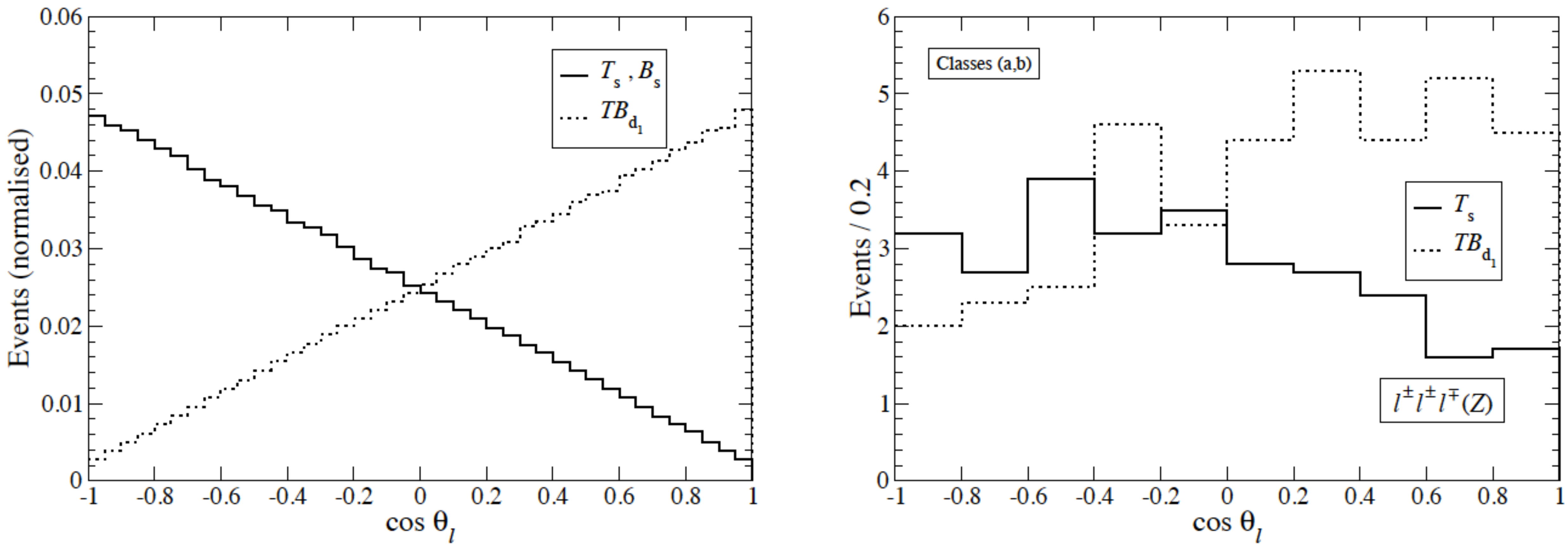
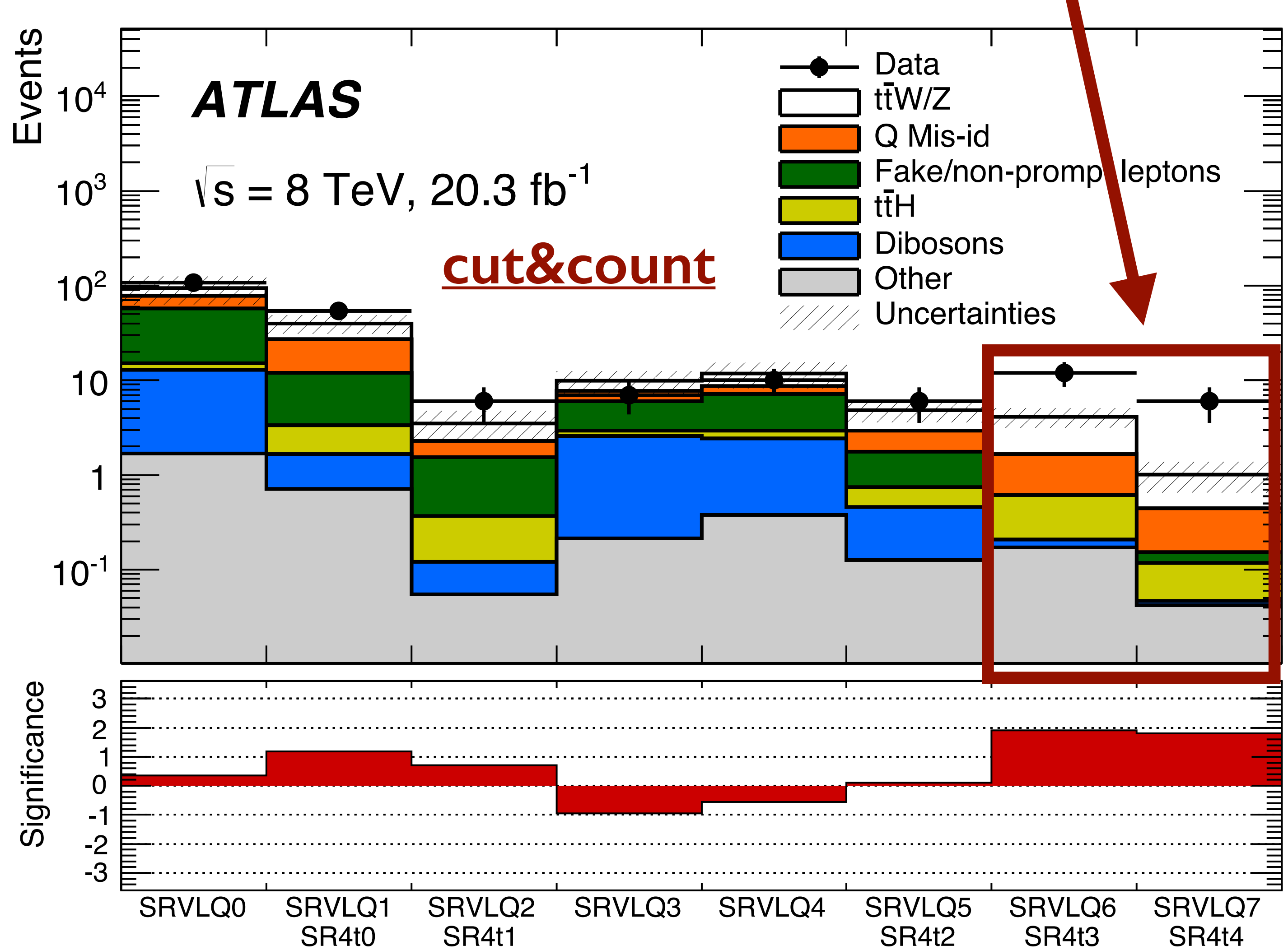


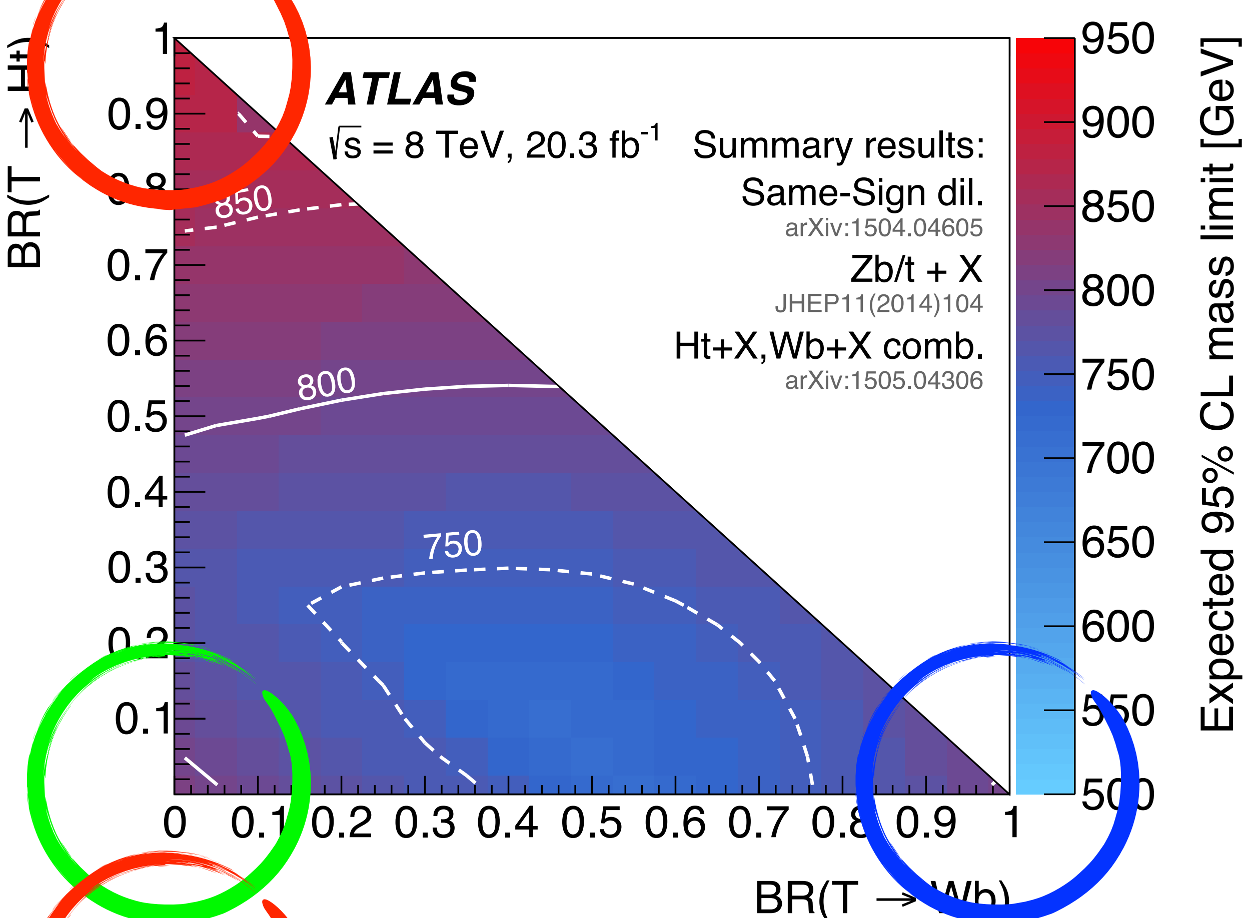
Figure 9: Left: Charged lepton distribution in the top quark rest frame for $T \to Zt$ and $B \to W^- t$ decays. Right: distribution for the T singlet and $(T\,B)$ doublet after simulation.

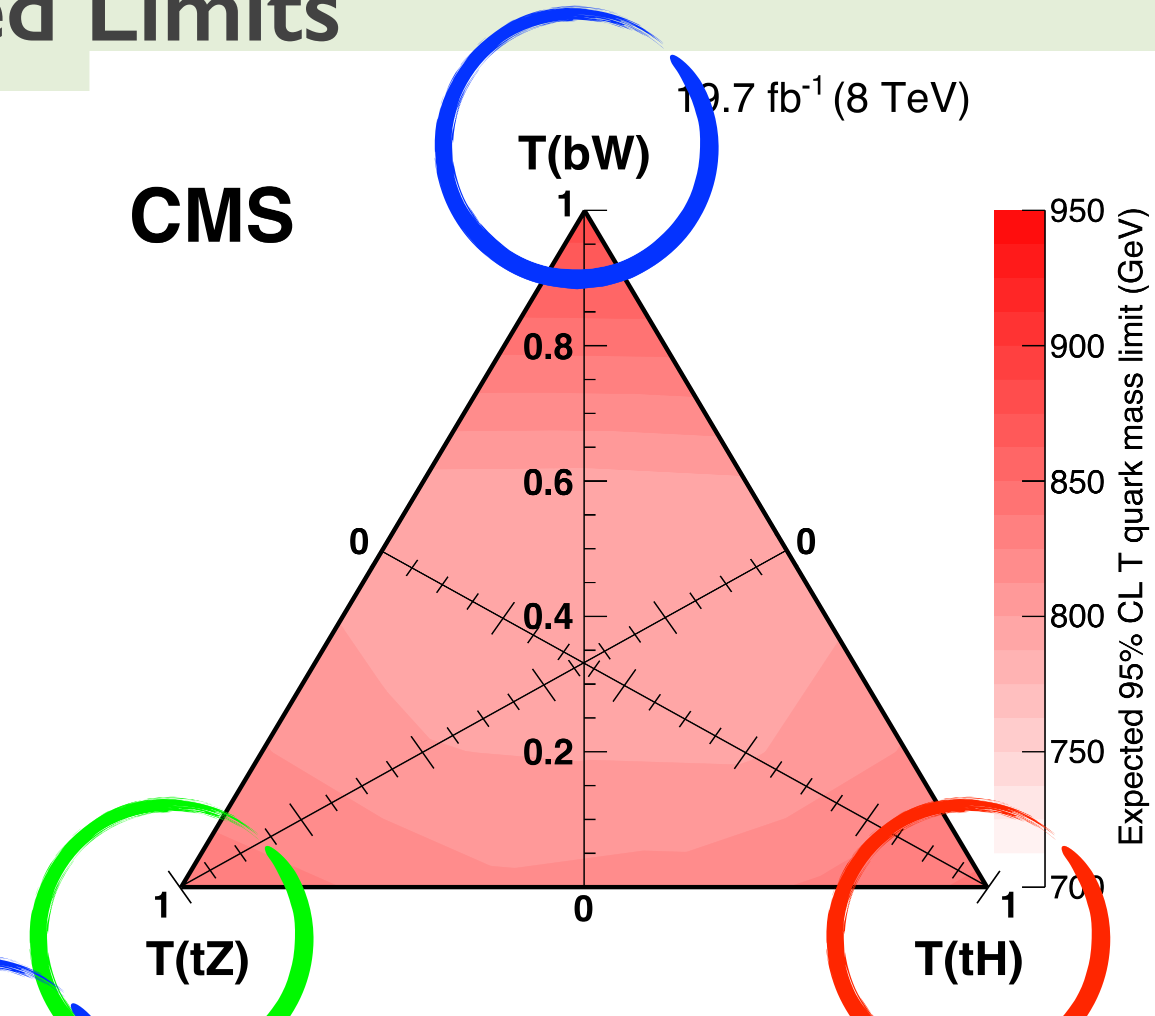
Same-sign leptons + b-quarks

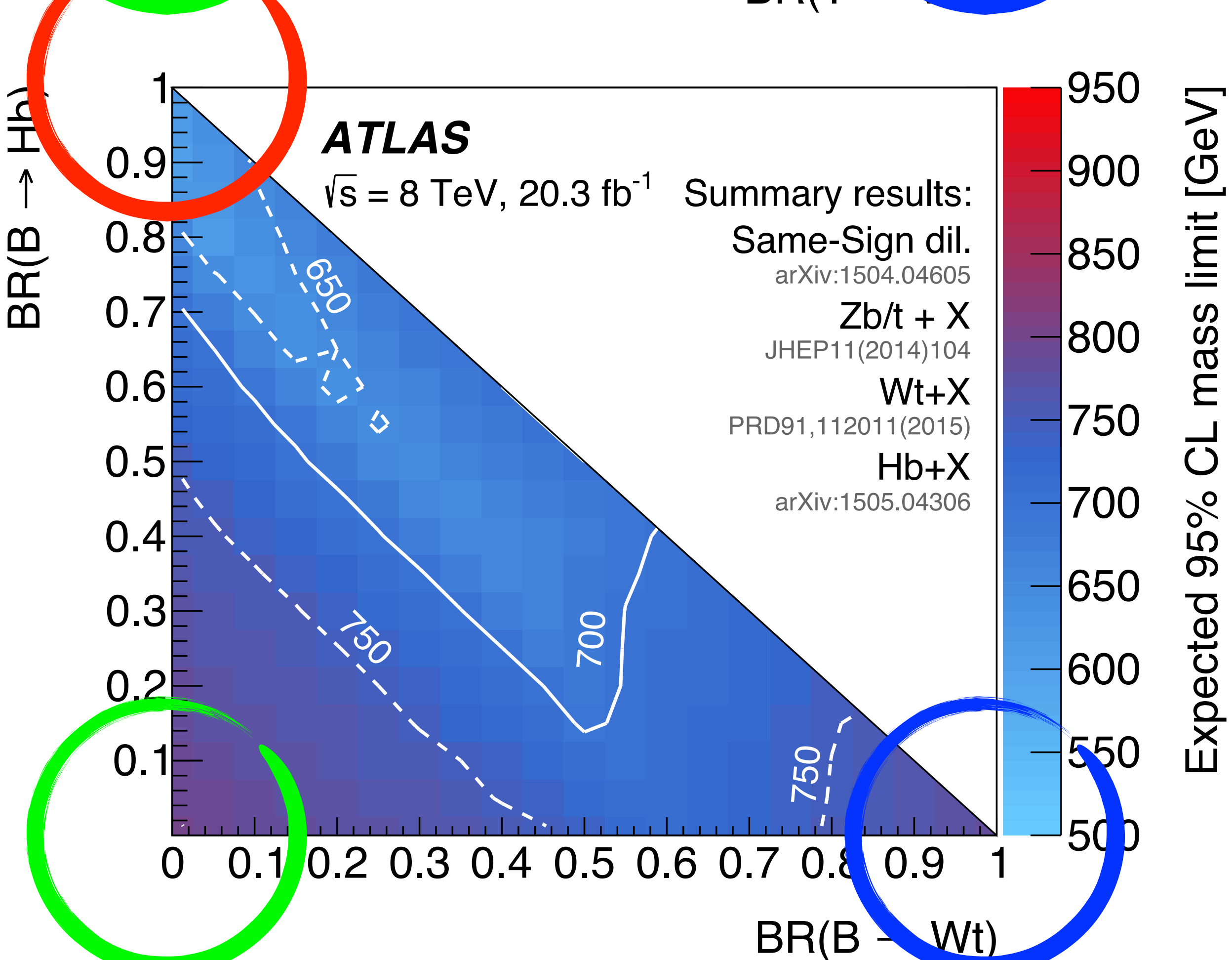
Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu,\ N_j \geq 2$				
$400 < H_{\mathrm{T}} < 700GeV$	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_{\mathrm{T}} \geq 700\ GeV$	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ3	
		$E_{\mathrm{T}}^{\mathrm{miss}} > 100\ GeV$	SRVLQ4	
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ5	SR4t2
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ7	SR4t4
$e^{+}e^{+},\ e^{+}\mu^{+},\ \mu^{+}\mu^{+},\ N_j \in [2,4],\ \Delta\phi_{\ell\ell} > 2.5$				
$H_{\mathrm{T}} > 450\ GeV$	$N_b \geq 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRttee, SRtteμ, SRtt$\mu\mu$	

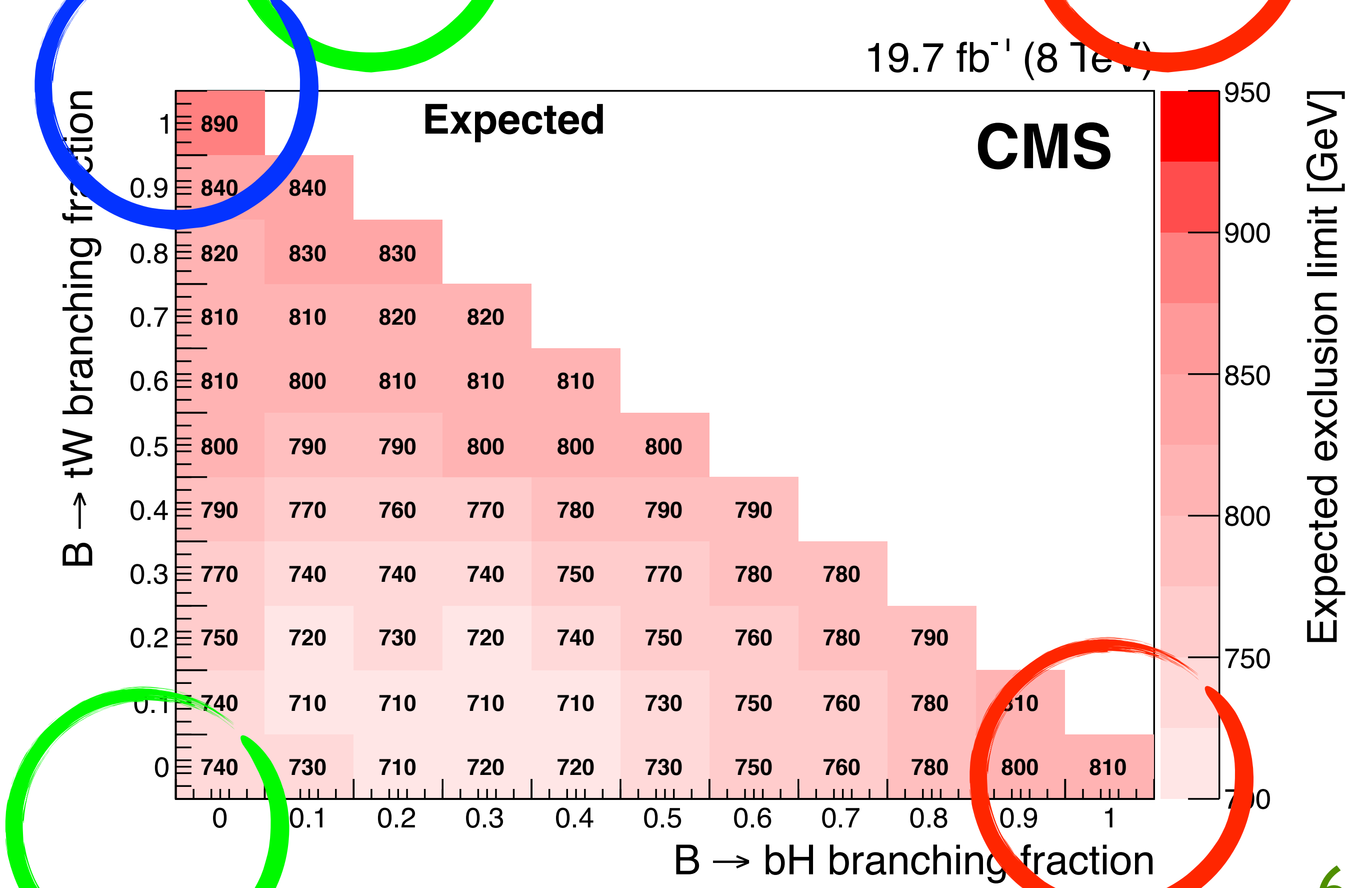


Run-I : Expected Limits









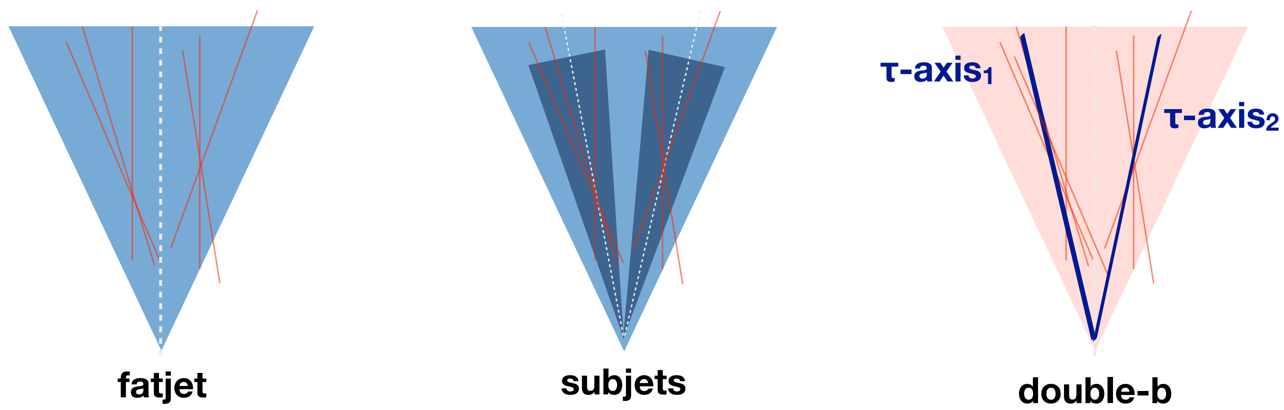
ATLAS-CONF-2016-032

	SR0	SR1	SR2	SR3	SR4
Fake/Non-prompt	16.3 ± 9.5	4.2 ±3.3	1.0 ± 0.9	1.8 ± 1.4	7.1±4.5
Charge mis-ID	18.1± 4.1	14.9±3.5	1.2 ± 0.3	1.5 ± 0.4	2.1±0.5
$t\bar{t}W/Z/W^+W^-$	10.1± 1.4	9.2 ±1.3	1.0 ± 0.3	2.2 ± 0.3	3.1±0.5
Dibosons	5.8 ± 1.0	0.5 ±0.2	0.03±0.07	1.6 ± 0.4	1.8±0.4
Other bkg.	2.0 ± 1.0	1.7 ±0.9	0.3 ± 0.2	0.3 ± 0.2	0.5±0.3
Total bkg.	52 ± 11	31 ± 5	3.6 ± 1.0	7.4 ± 1.5	15 ± 5
$t\bar{t}t\bar{t}$ (SM)	0.5 ± 0.1	0.8 ±0.1	0.9 ± 0.1	0.2 ± 0.1	0.5±0.1
$t\bar{t}t\bar{t}$ (CI)	0.26±0.04	0.6 ±0.1	0.6 ± 0.1	0.24±0.05	0.9±0.1
UED 1.2 TeV	<0.01	<0.01	<0.01	0.3 ± 0.1	3.8±0.8
$T\bar{T}$ 0.75 TeV	0.2 ± 0.1	0.31±0.1	0.04±0.04	0.9 ± 0.2	3.7±0.4
Data	51	37	3	4	11
mis-ID fraction	**35%**	**48%**	**33%**	**20%**	**14%**

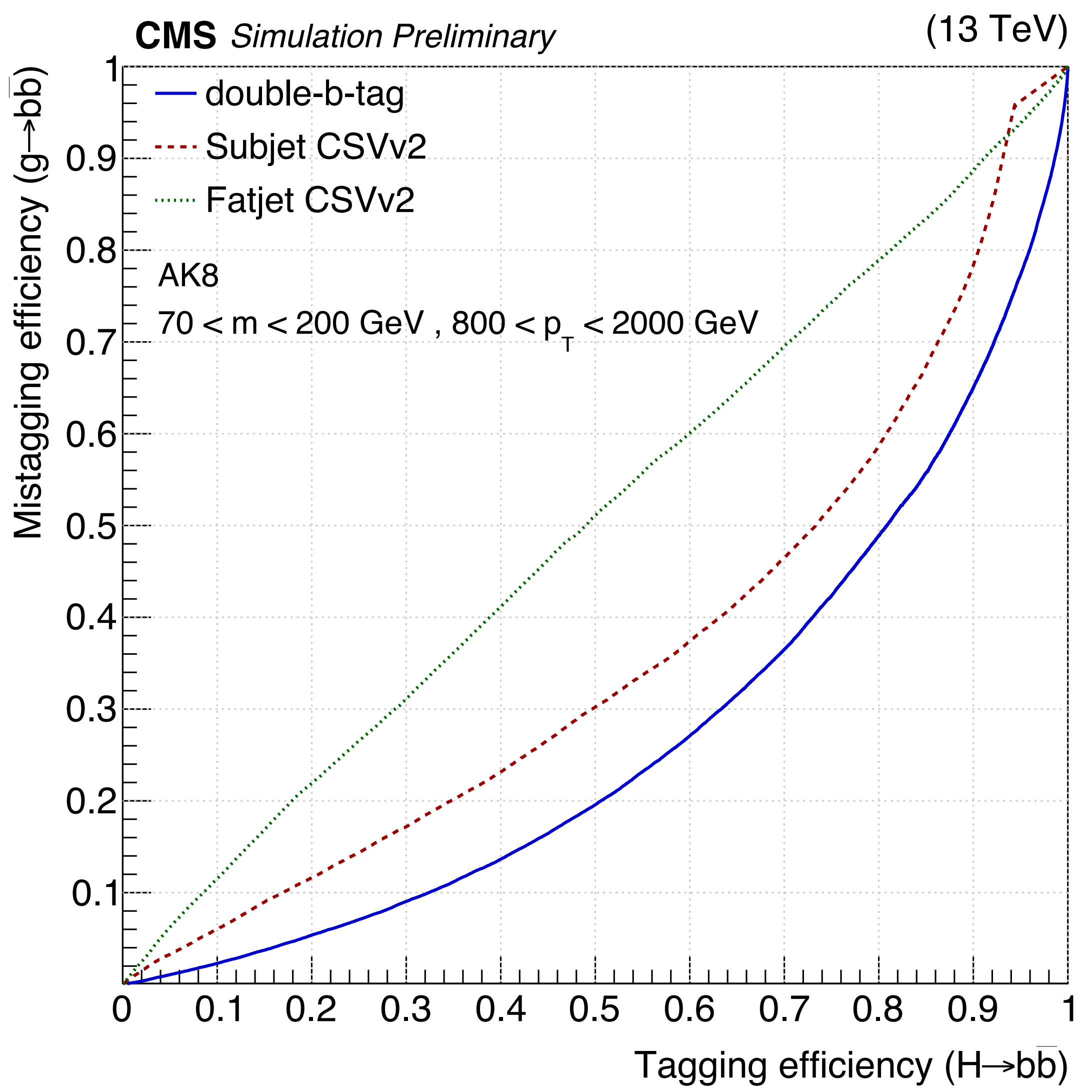
	SR5	SR6	SR7
Fake/Non-prompt	1.4±0.9	2.6±1.8	0.0 ±0.6
Charge mis-ID	1.4±0.4	1.6±0.5	0.6 ±0.2
$t\bar{t}W/Z/W^+W^-$	2.3±0.6	3.0±0.7	0.8 ±0.4
Dibosons	0.3±0.1	0.2±0.1	0.0 ±0.1
Other bkg.	0.4±0.2	0.7±0.4	0.5 ±0.3
Total bkg.	5.8±1.2	8.1±2.0	1.9 ±0.8
$t\bar{t}t\bar{t}$ (SM)	0.7±0.1	1.8±0.2	3.6 ±0.4
$t\bar{t}t\bar{t}$ (CI)	0.6±0.1	2.2±0.2	5.2 ±0.4
UED 1.2 TeV	0.6±0.1	6.6±0.7	10.1±0.8
$T\bar{T}$ 0.75 TeV	1.3±0.2	5.0±0.5	3.2 ±0.4
Data	6	3	2
	24%	**20%**	**32%**

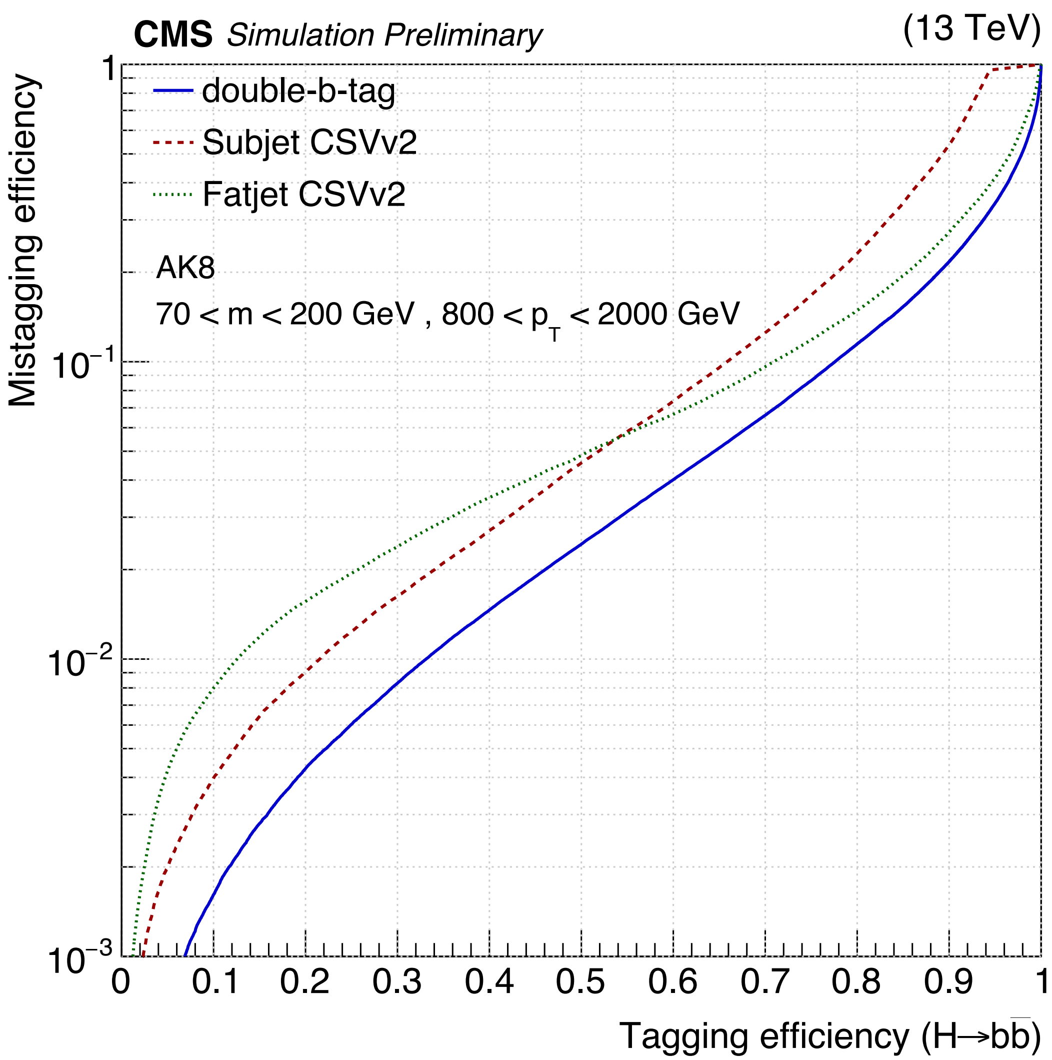
CMS 13.6% total mis-ID fraction

CMS PAS BTV-15-002



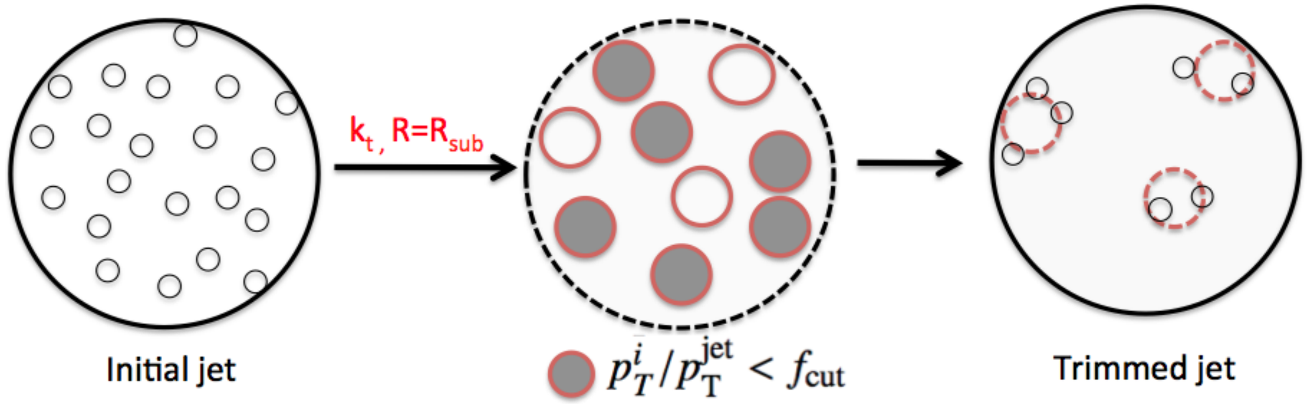
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$$



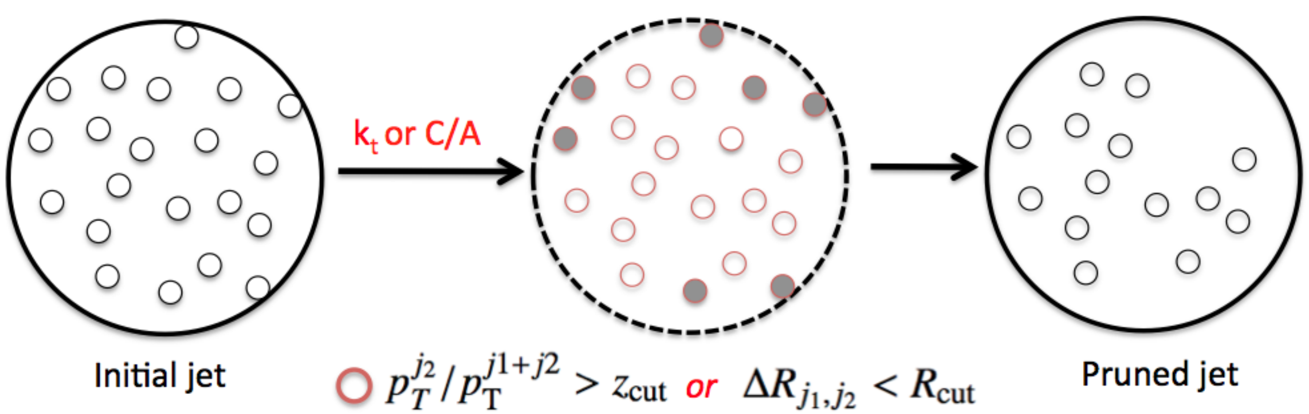


Grooming Techniques

Trimming



Pruning

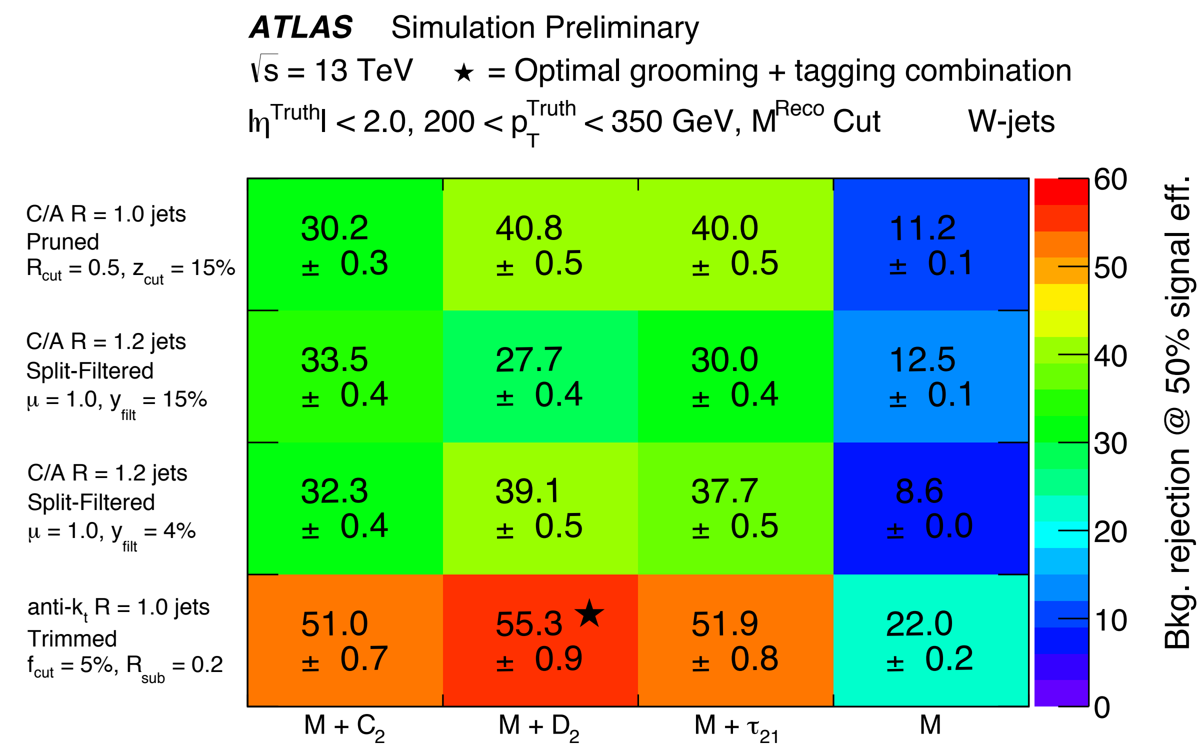


illustrations from JHEP 09 (2013) 076

$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^\beta$$

Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014) 146

ATL-PHYS-PUB-2015-033



CMS PAS JME-14-002

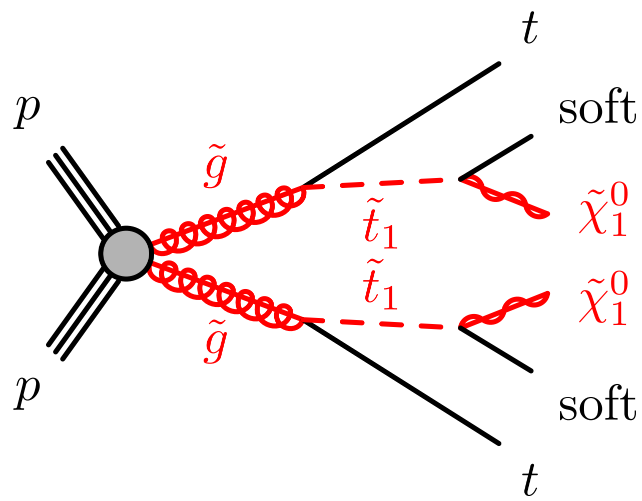
Rank	Z	Pairs of variables	
1.	38.5 ± 1.6	M_{Prune}	τ_2/τ_1
2.	37.9 ± 1.6	M_{Filt}	τ_2/τ_1
3.	37.8 ± 1.6	M_{Trim}	τ_2/τ_1
4.	37.7 ± 1.6	M_{Trim}	QGL Combo
5.	37.2 ± 1.6	M_{Prune}	QGL Combo
6.	36.7 ± 1.5	M_{SD} $\beta = -1$	τ_2/τ_1
7.	36.3 ± 1.5	M_{SD} $\beta = 0$	τ_2/τ_1
8.	35.8 ± 1.5	M_{SD} $\beta = 2$	τ_2/τ_1
9.	35.3 ± 1.4	M_{SD} $\beta = 1$	τ_2/τ_1
10.	35.0 ± 1.4	M_{SD} $\beta = -1$	QGL Combo

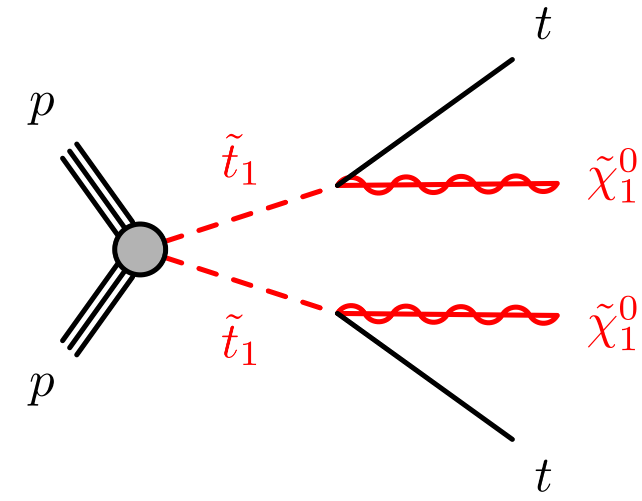
1606.03903

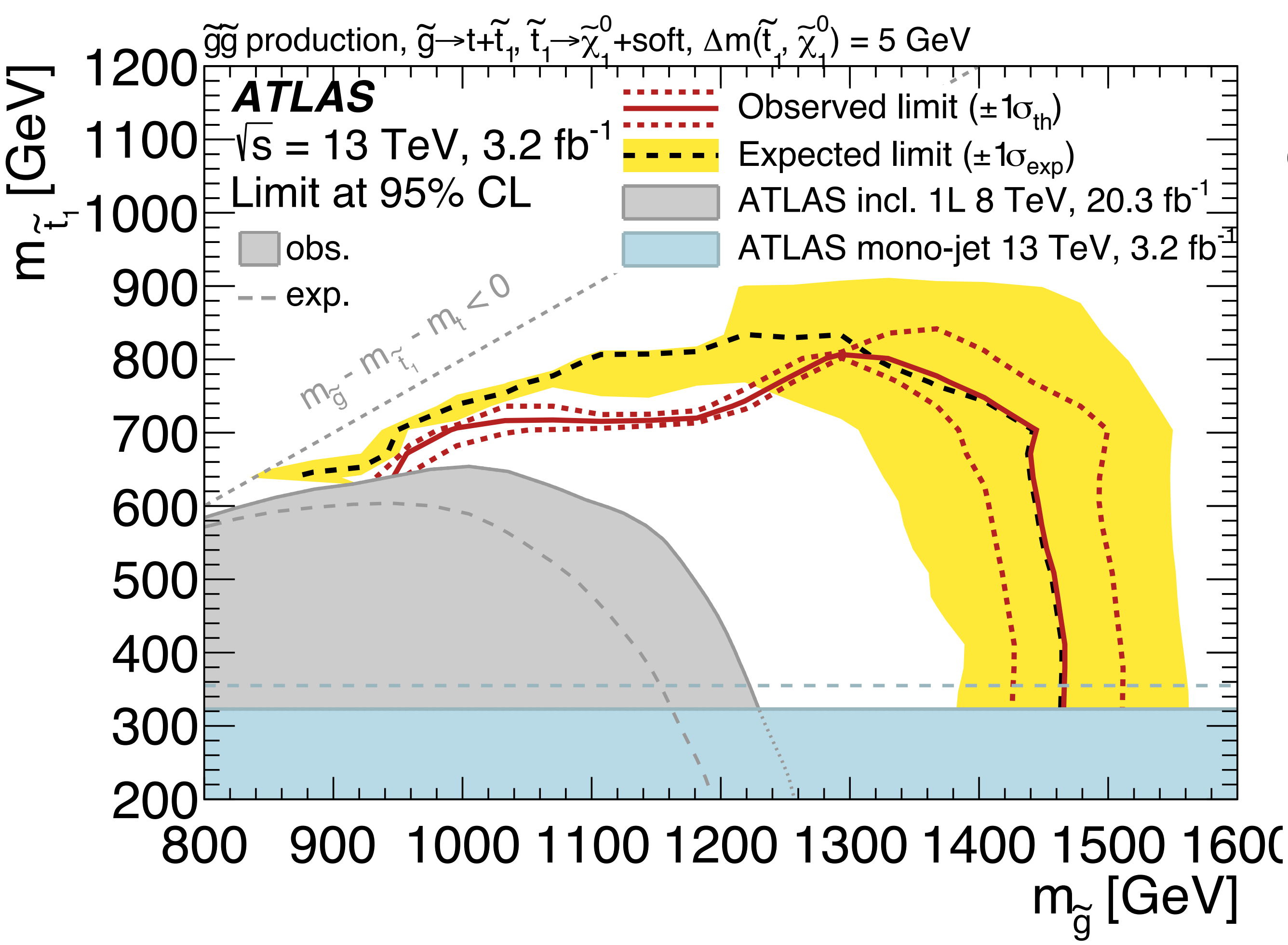
Variable	SR1
$\geq$4 jets with $p_T >$ [GeV]	(80 50 40 40)
E_T^{miss} [GeV]	> 260
$H_{T,sig}^{miss}$	> 14
m_T [GeV]	> 170
am_{T2} [GeV]	> 175
topness	> 6.5
m_{top}^{χ} [GeV]	< 270
$\Delta R(b, \ell)$	< 3.0
$\Delta R(b_1, b_2)$	–
Number of b-tags	≥ 1

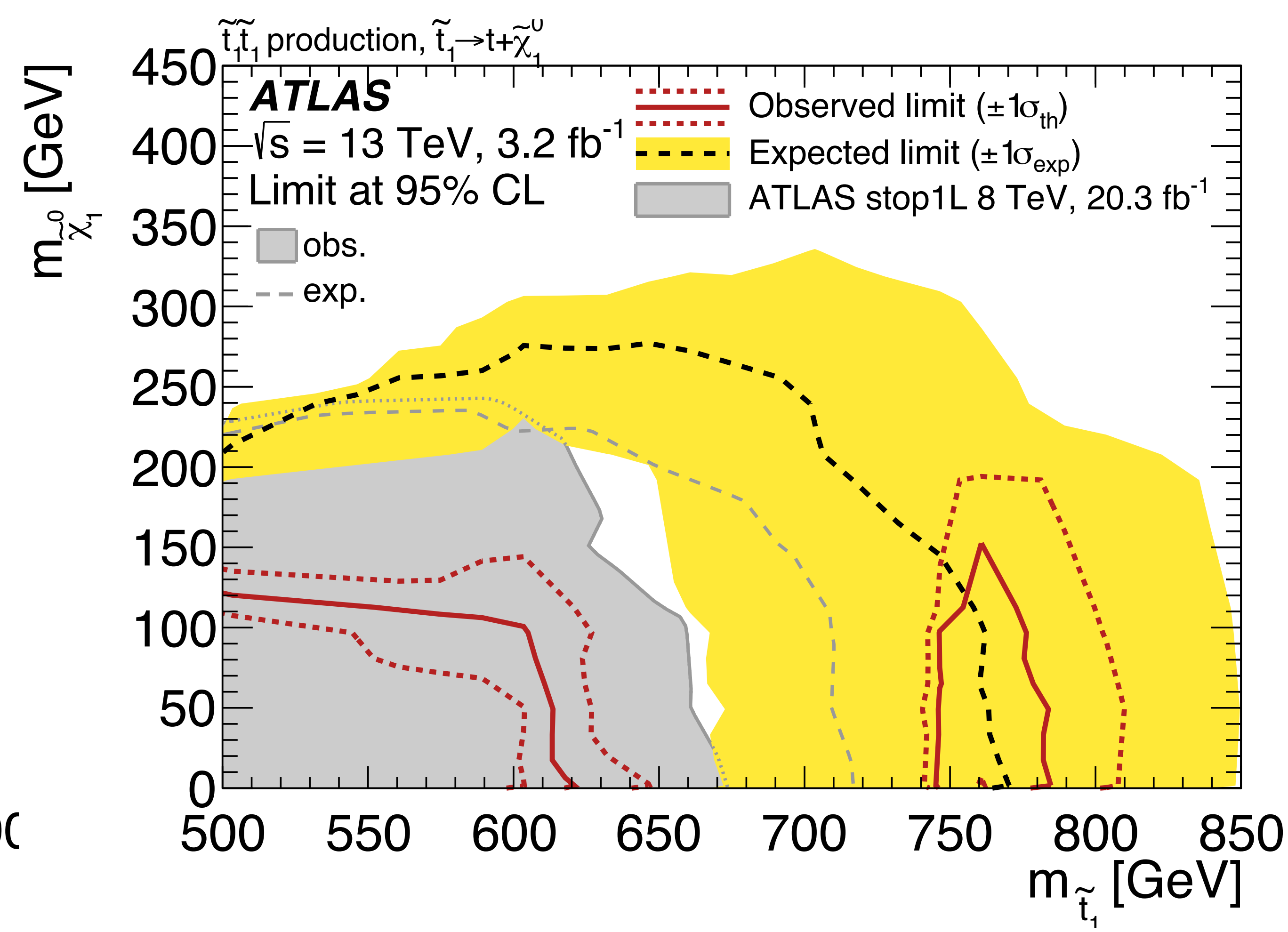
	SR2
$\geq$4 jets with $p_T >$ [GeV]	(120 80 50 25)
E_T^{miss} [GeV]	> 350
$H_{T,sig}^{miss}$	> 20
m_T [GeV]	> 200
am_{T2} [GeV]	> 175
$\Delta R(b, \ell)$	< 2.5
$\Delta R(b_1, b_2)$	–
Number of b-tags	≥ 1
Leading large-R jet p_T [GeV]	> 200
Leading large-R jet mass [GeV]	> 140
$\Delta\phi(\vec{p}_T^{miss}, 2^{nd}$large-R jet)	> 1.0

	SR3
$\geq$4 jets with $p_T >$ [GeV]	(120 80 50 25)
E_T^{miss} [GeV]	> 480
$H_{T,sig}^{miss}$	> 14
m_T [GeV]	> 190
am_{T2} [GeV]	> 175
topness	> 9.5
$\Delta R(b, \ell)$	< 2.8
$\Delta R(b_1, b_2)$	–
Number of b-tags	≥ 1
Leading large-R jet p_T [GeV]	> 280
Leading large-R jet mass [GeV]	> 70









SR1 dominates **SR2 dominates**

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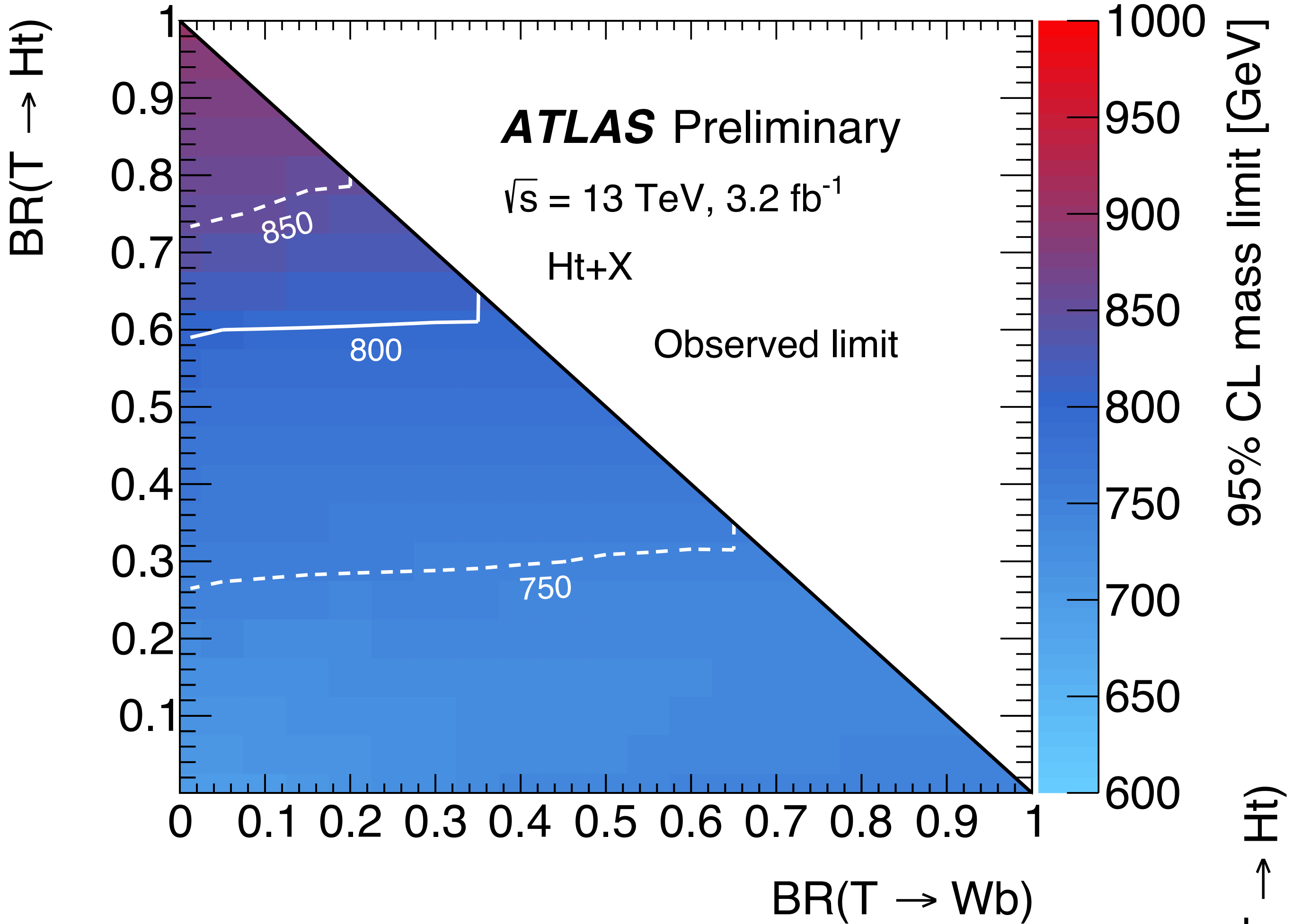
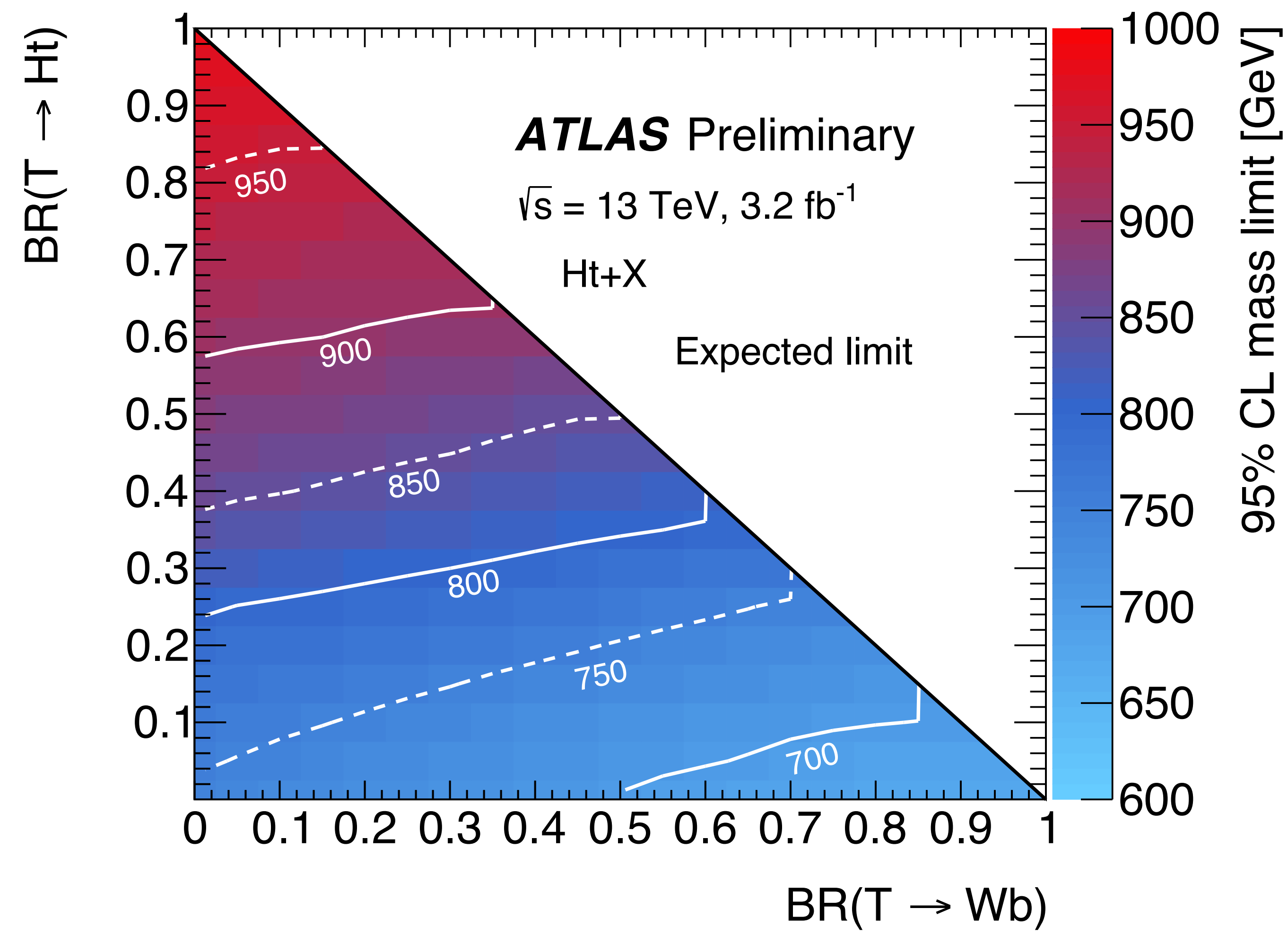
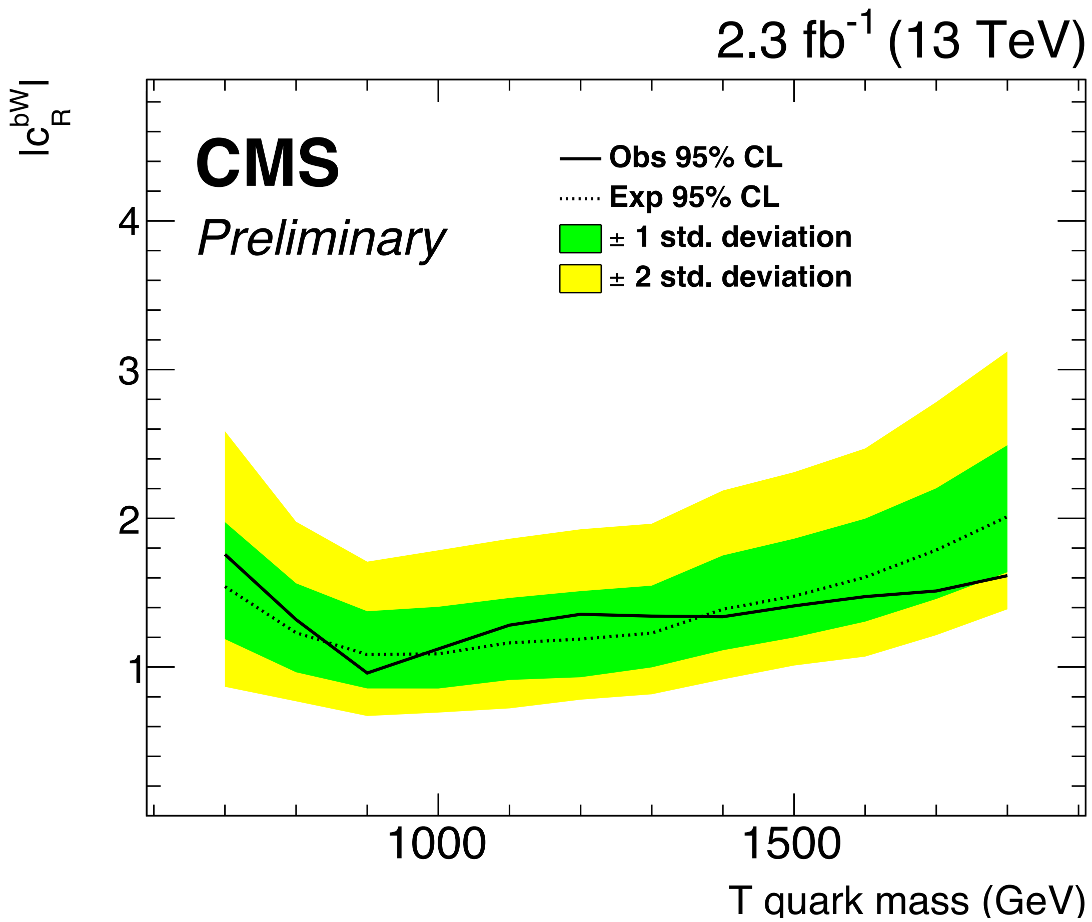
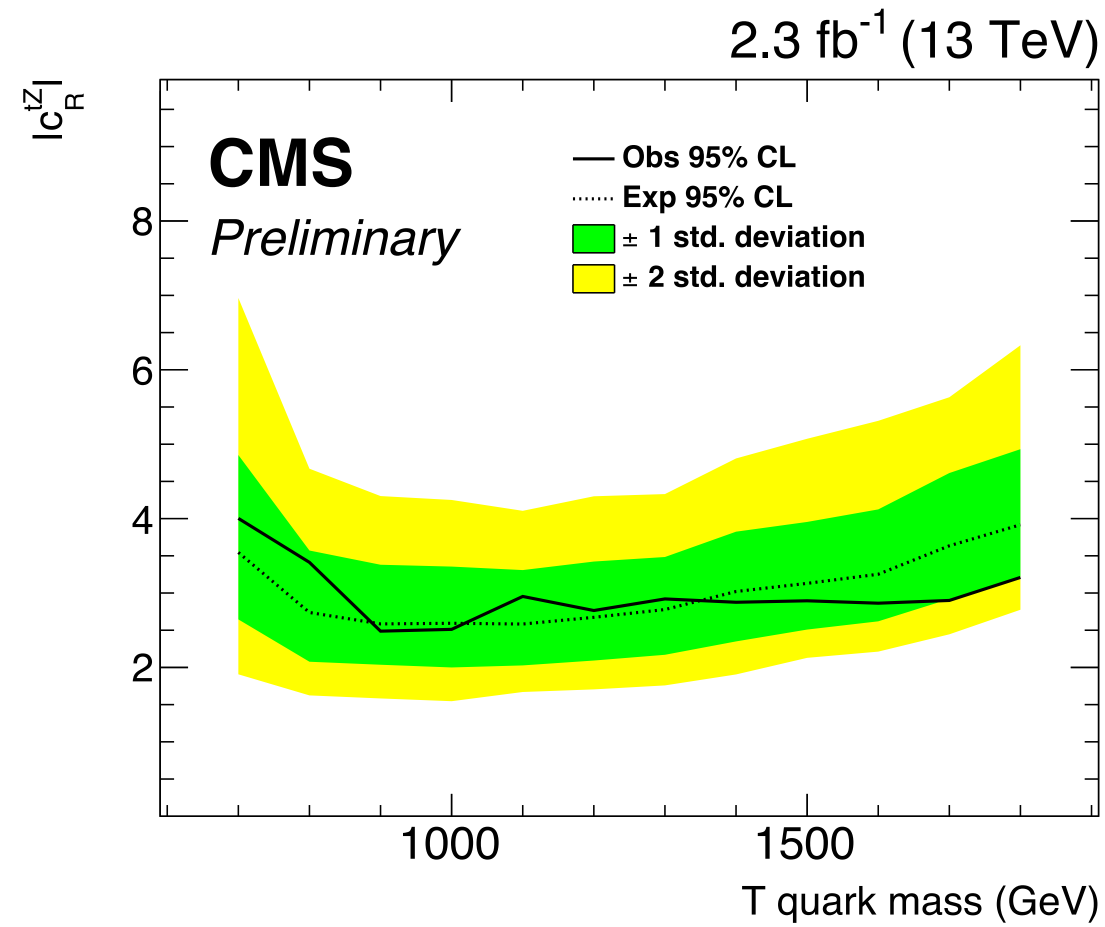




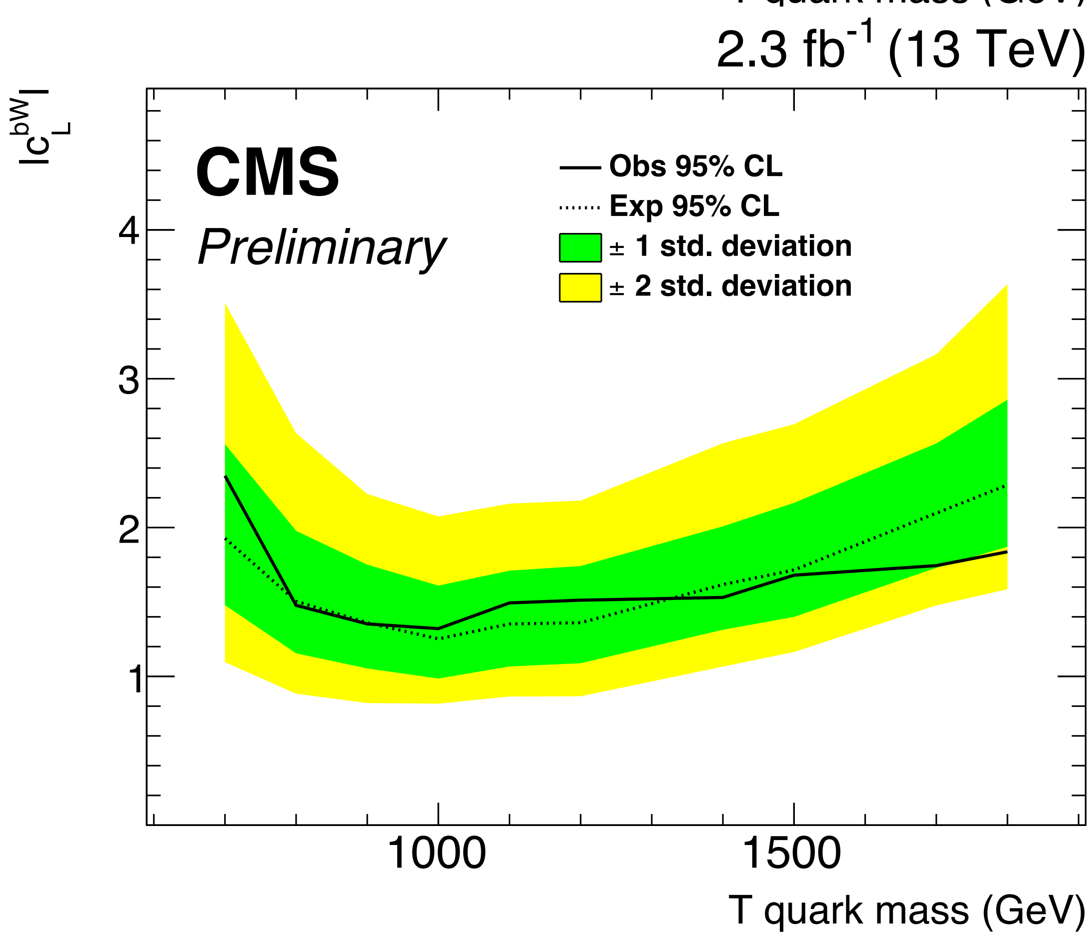
Johannes Erdmann

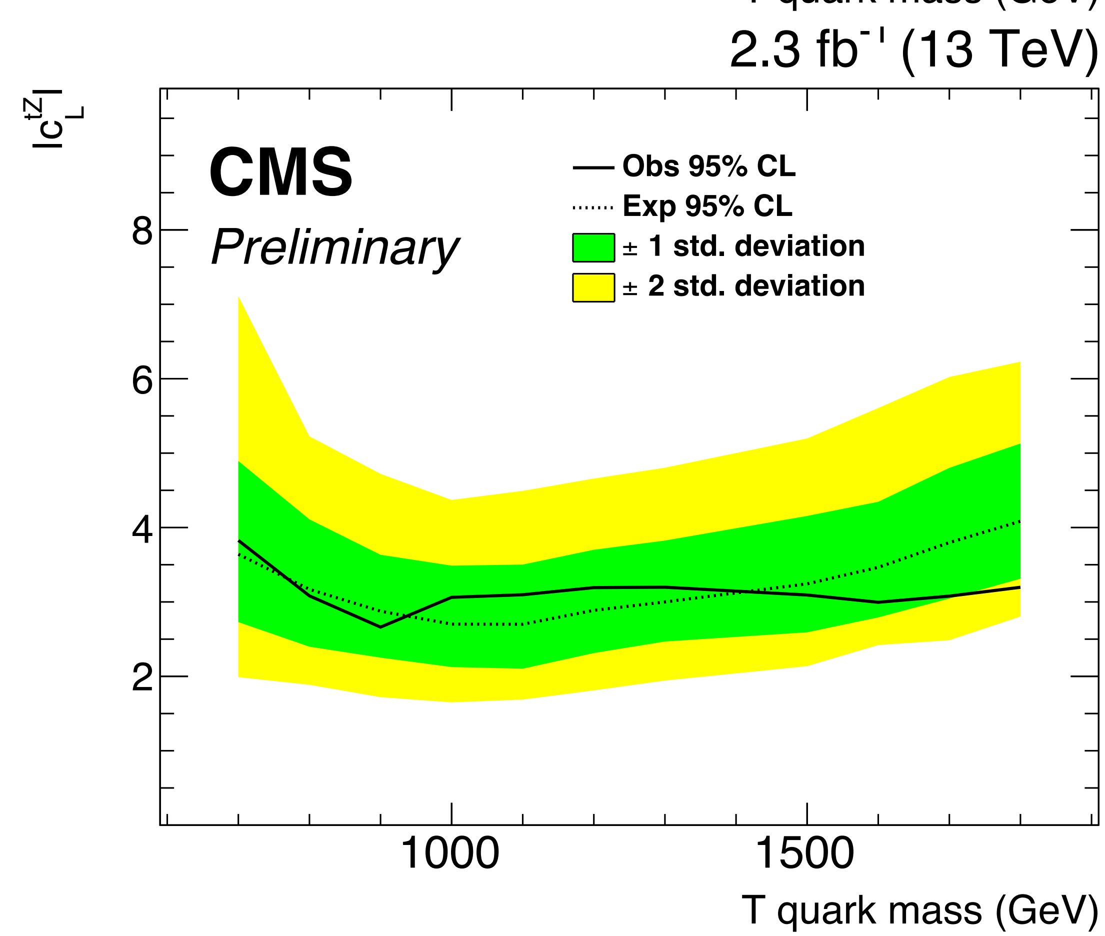
CMS PAS B2G-15-008



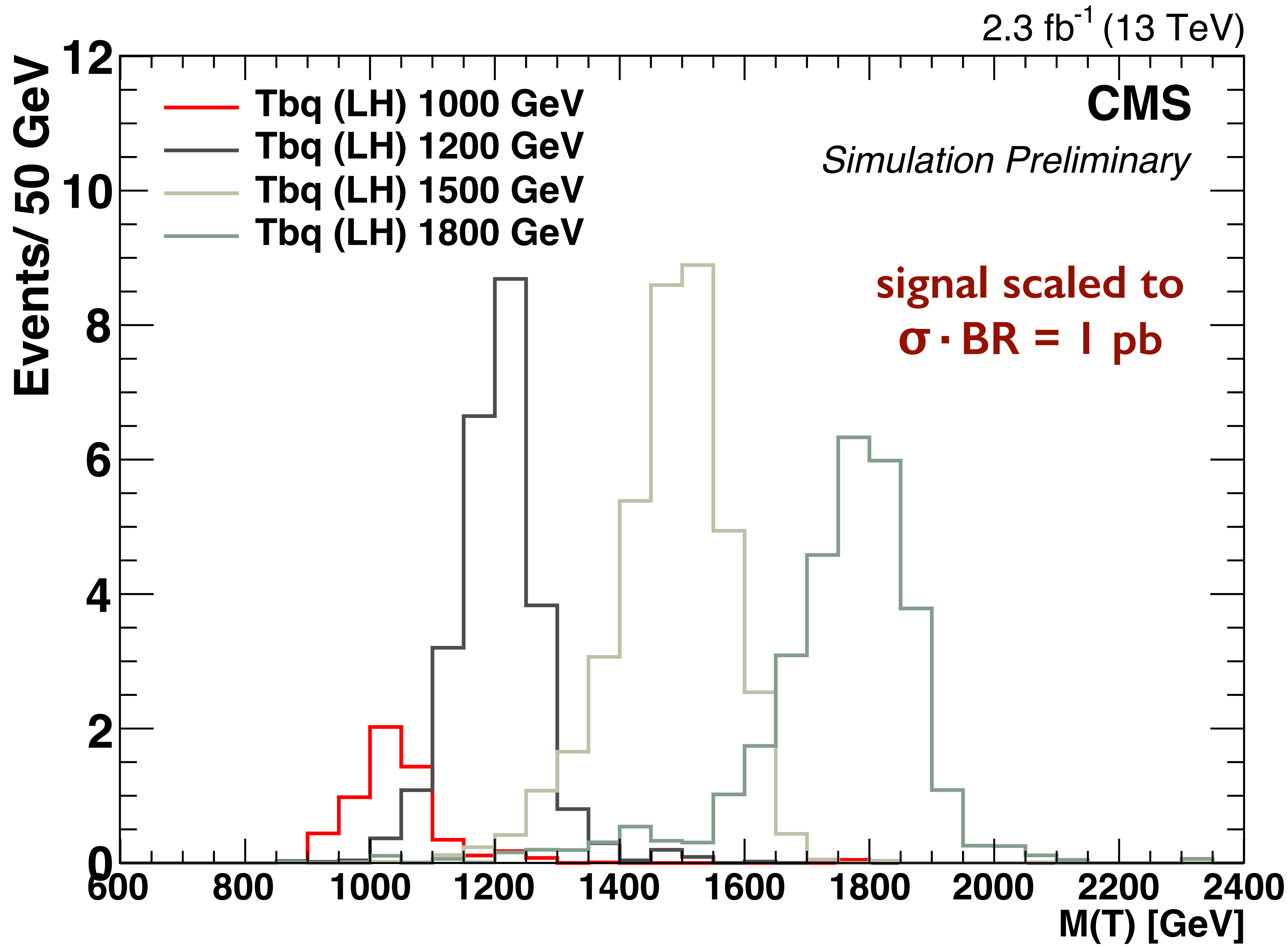


RH

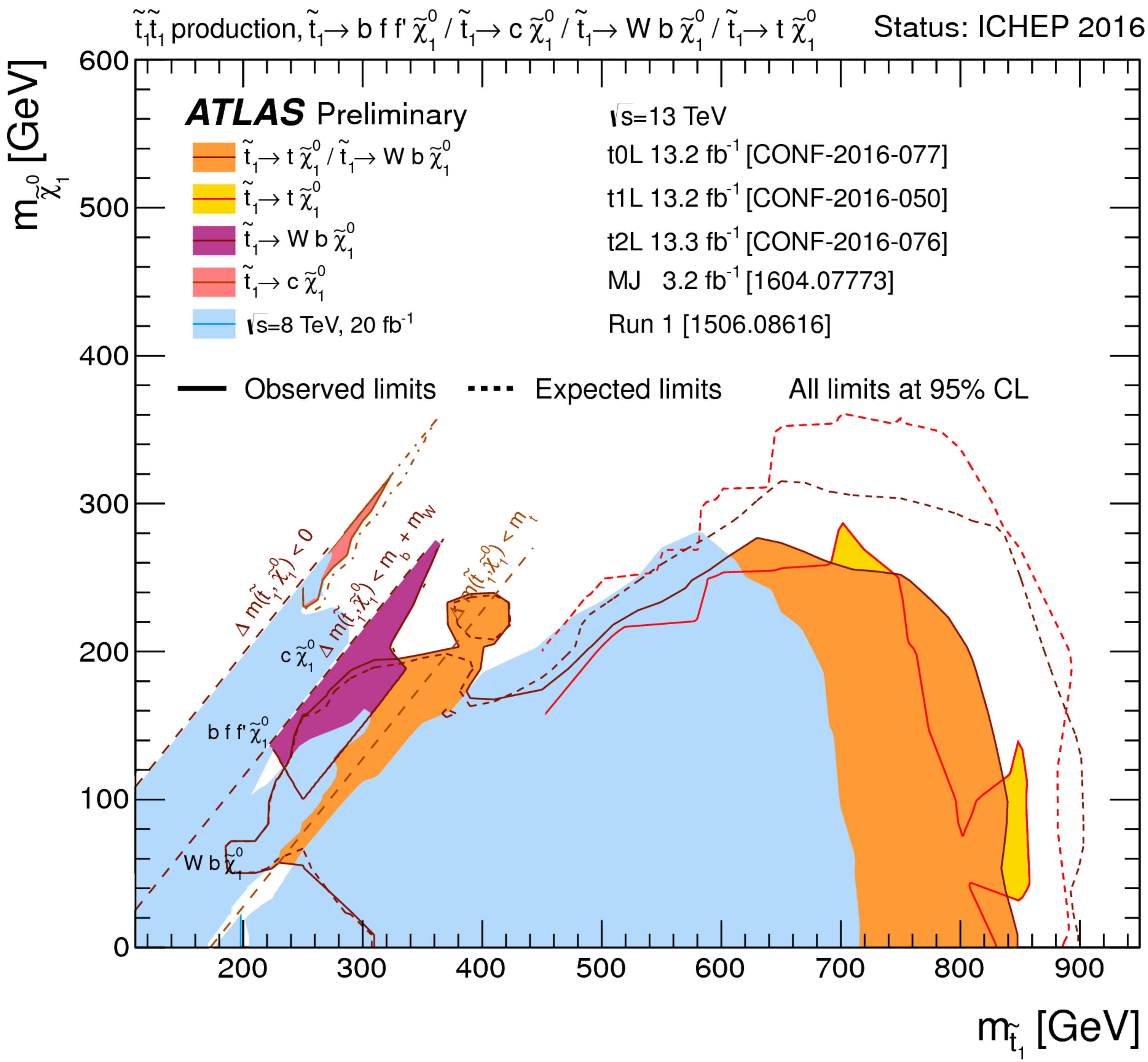




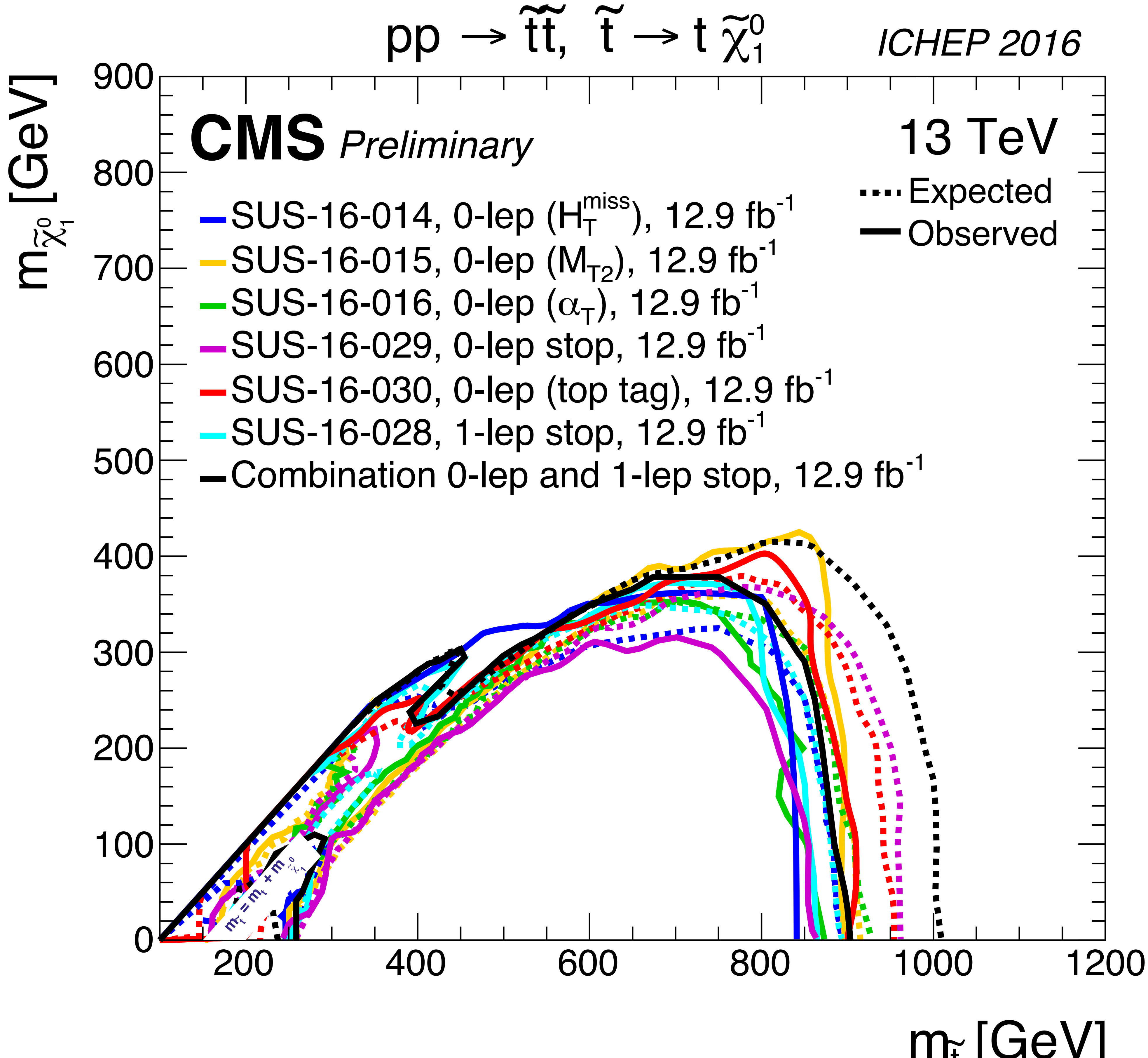
LH


2.3 fb^{-1} (13 TeV)
CMS
Simulation Preliminary
Tbq (LH) 1000 GeV
Tbq (LH) 1200 GeV
Tbq (LH) 1500 GeV
Tbq (LH) 1800 GeV
signal scaled to
σ · BR = 1 pb
Events/ 50 GeV
M(T) [GeV]
0
2
4
6
8
10
12
600
800
1000
1200
1400
1600
1800
2000
2200
2400

Stop Summary ATLAS



Stop Summary CMS



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Common event selection	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons
Jets	at least two signal jets, and $\lvert\Delta\phi(\mathrm{jet}_i, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert > 0.4$ for $i \in \{1, 2\}$
Hadronic τ veto*	veto events with a hadronic τ decay and $m_{\mathrm{T2}}^{\tau} < 80\,\mathrm{GeV}$

$\tilde{t}_1 \to t + \tilde{\chi}_1^0$

Variable	SR1	tN_high
Number of (jets, b-tags)	(≥ 4, ≥ 1)	(≥ 4, ≥ 1)
Jet $p_{\mathrm{T}} >$ [GeV]	(80 50 40 40)	(120 80 50 25)
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 260	> 450
$E_{T,\perp}^{\mathrm{miss}}$ [GeV]	–	> 180
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 14	> 22
m_{T} [GeV]	> 170	> 210
am_{T2} [GeV]	> 175	> 175
topness	> 6.5	–
m_{top}^{χ} [GeV]	< 270	–
$\Delta R(b, \ell)$	< 3.0	< 2.4
Leading large-R jet p_{T} [GeV]	–	> 290
Leading large-R jet mass [GeV]	–	> 70
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, 2^{\mathrm{nd}}$ large-R jet)	–	> 0.6

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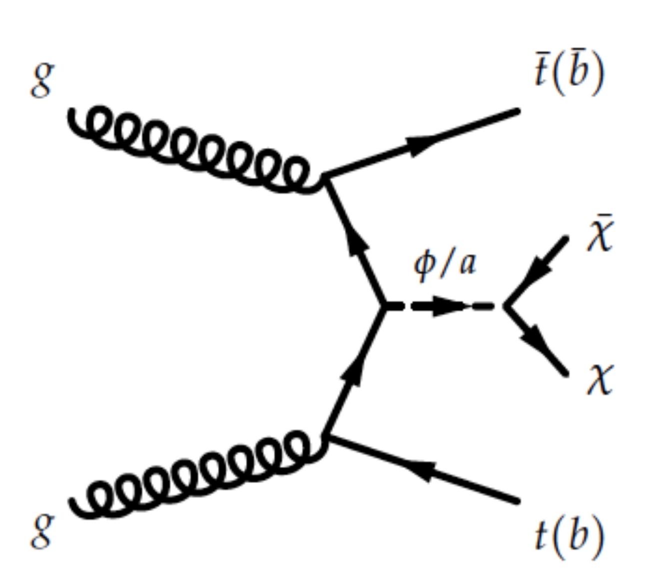
$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$ $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$

Variable	bC2x_diag	bC2x_med	bCbv
Number of (jets, b-tags)	$(\geq 4, \geq 2)$	$(\geq 4, \geq 2)$	$(\geq 2, = 0)$
Jet $p_T >$ [GeV]	(70 60 55 25)	(170 110 25 25)	(120 80)
b-tagged jet $p_T >$ [GeV]	(25 25)	(105 100)	–
E_T^{miss} [GeV]	> 230	> 210	> 360
$H_{T,sig}^{miss}$	> 14	> 7	> 16
m_T [GeV]	> 170	> 140	> 200
am_{T2} [GeV]	> 170	> 210	–
$\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert (i = 1)$	> 1.2	> 1.0	> 2.0
$\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert (i = 2)$	> 0.8	> 0.8	> 0.8
Leading large-R jet mass [GeV]	–	–	[70, 100]
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	–	–	> 1.2

Variable	DM_low	DM_high
Number of (jets, b-tags)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, \text{jet}_i))(i \in \{1-4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	–



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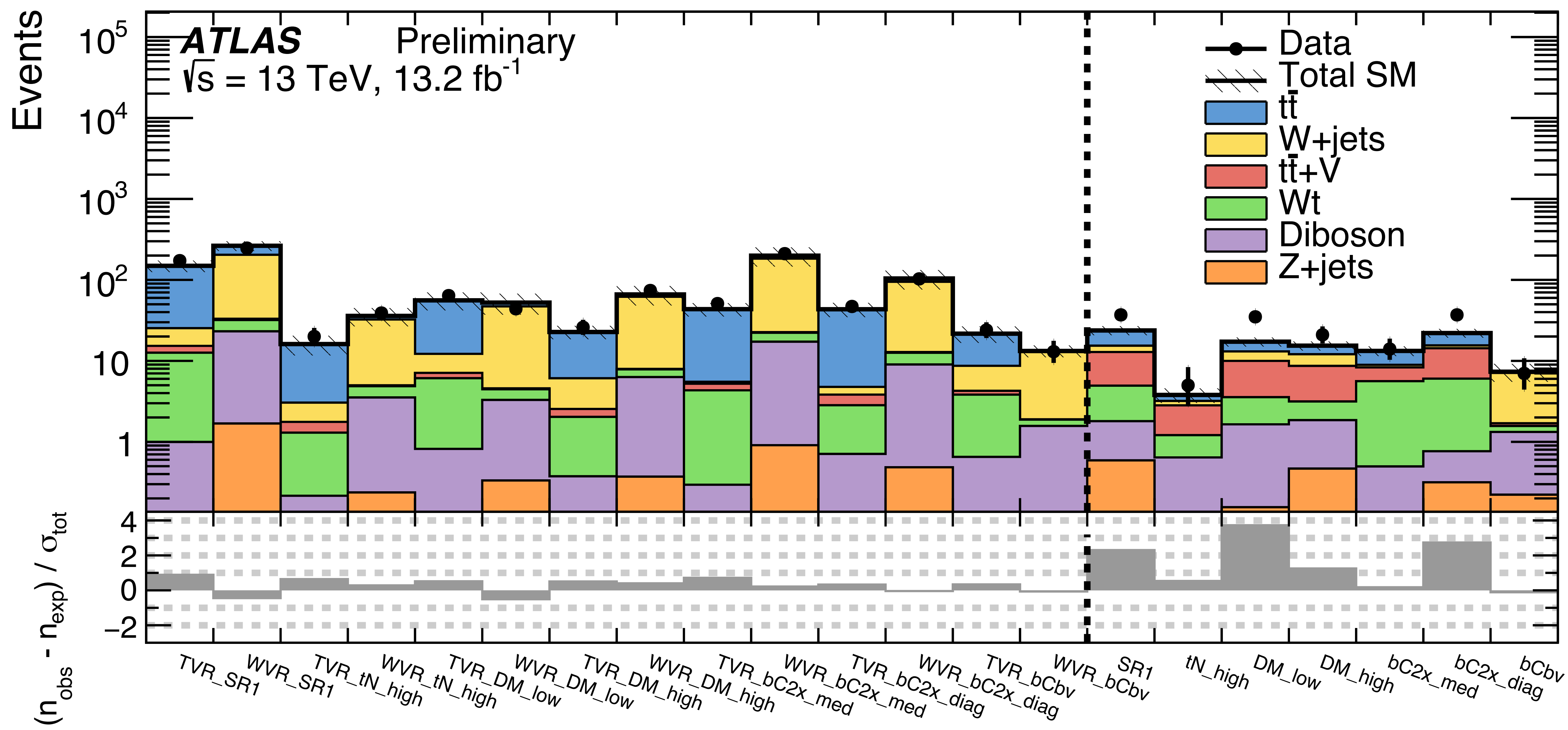

Signal region	SR1	tN_high	bC2x_diag	bC2x_med	bCbv	DM_low	DM_high
Observed	37	5	37	14	7	35	21
Total background	24 ± 3	3.8 ± 0.8	22 ± 3	13 ± 2	7.4 ± 1.8	17 ± 2	15 ± 2
$t\bar{t}$	8.4 ± 1.9	0.60 ± 0.27	6.5 ± 1.5	4.3 ± 1.0	0.26 ± 0.18	4.2 ± 1.3	3.3 ± 0.8
W+jets	2.5 ± 1.1	0.15 ± 0.38	1.2 ± 0.5	0.63 ± 0.29	5.4 ± 1.8	3.1 ± 1.5	3.4 ± 1.4
Single top	3.1 ± 1.5	0.57 ± 0.44	5.3 ± 1.8	5.1 ± 1.6	0.24 ± 0.23	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t} + V$	7.9 ± 1.6	1.6 ± 0.4	8.3 ± 1.7	2.7 ± 0.7	0.12 ± 0.03	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.2 ± 0.4	0.61 ± 0.26	0.45 ± 0.17	0.42 ± 0.20	1.1 ± 0.4	1.5 ± 0.6	1.4 ± 0.5
Z+jets	0.59 ± 0.54	0.03 ± 0.03	0.32 ± 0.29	0.08 ± 0.08	0.22 ± 0.20	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	1.03 ± 0.07	1.06 ± 0.15	0.89 ± 0.10	0.95 ± 0.12	0.73 ± 0.22	0.90 ± 0.17	1.01 ± 0.13
W+jets NF	0.76 ± 0.08	0.78 ± 0.08	0.87 ± 0.07	0.85 ± 0.06	0.97 ± 0.12	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.07 ± 0.30	1.30 ± 0.45	1.26 ± 0.31	0.97 ± 0.28	–	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t} + W/Z$ NF	1.43 ± 0.21	1.39 ± 0.22	1.40 ± 0.21	1.30 ± 0.23	–	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.012 (2.2)	0.26 (0.6)	0.004 (2.6)	0.40 (0.3)	0.50 (0)	0.0004 (3.3)	0.09 (1.3)
$N^{\text{limit}}_{\text{non-SM}}$ exp. (95% CL)	$12.9^{+5.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+5.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	26.0	7.2	27.5	9.9	7.2	28.3	15.6

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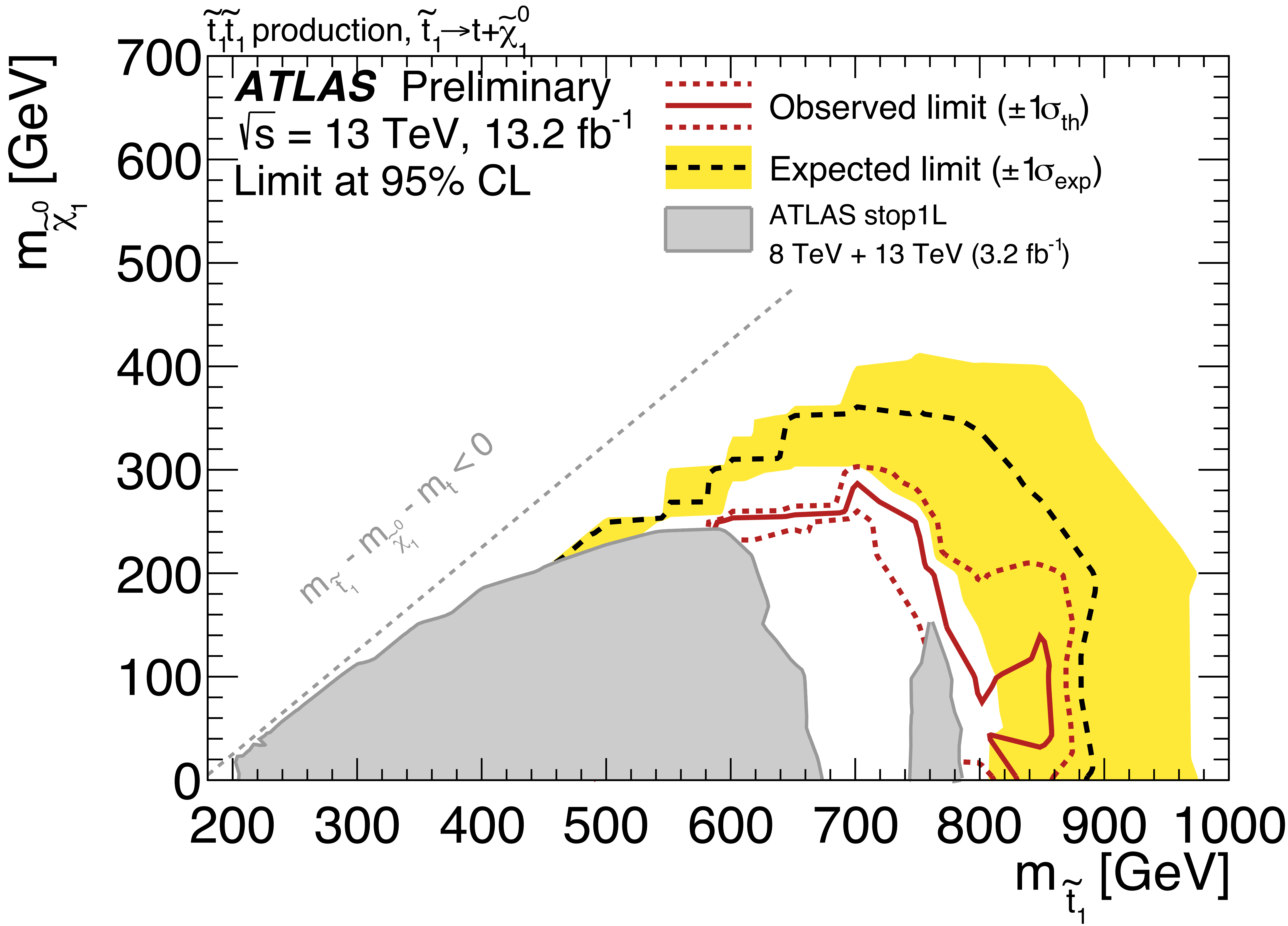

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