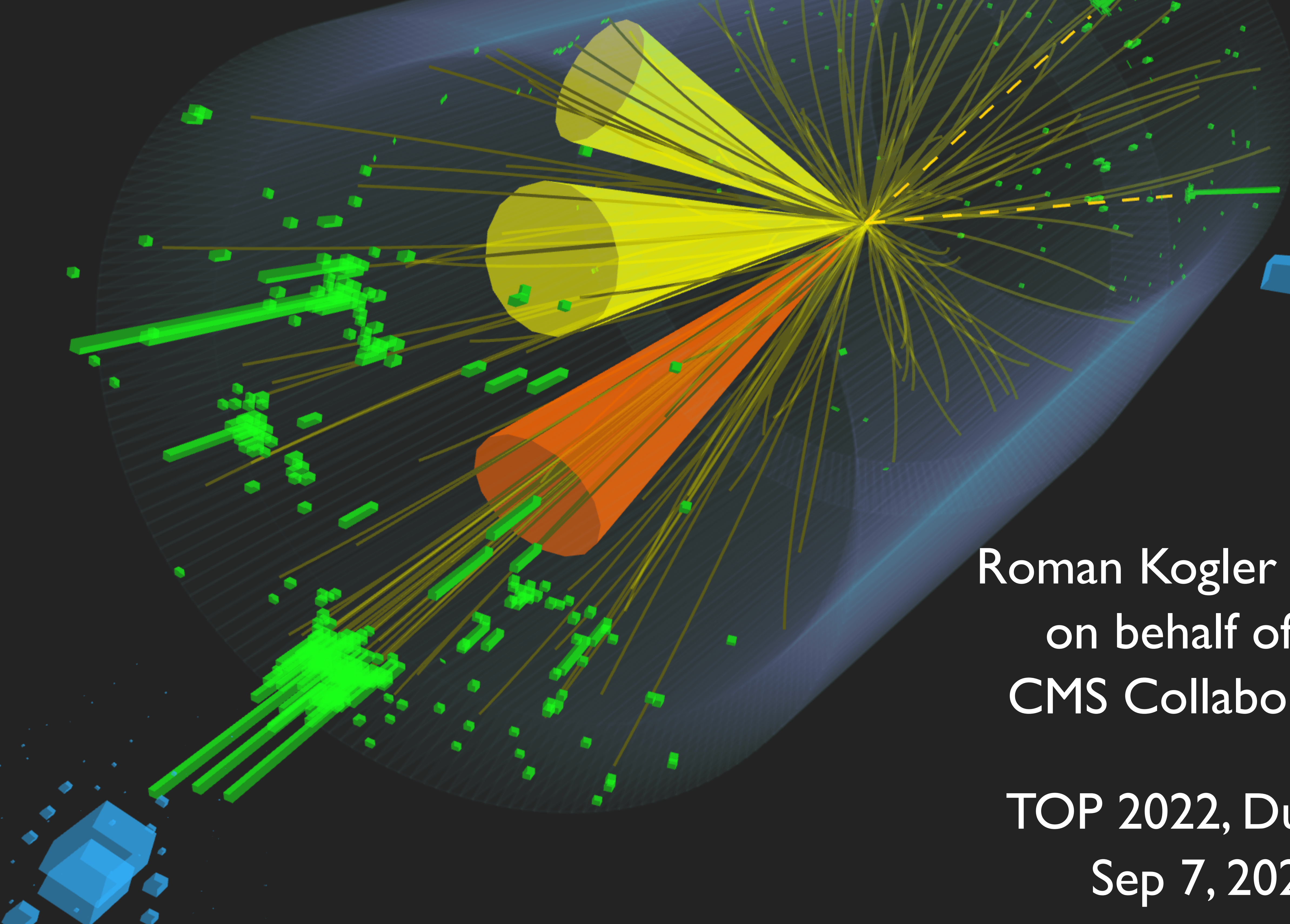
Searches for new physics with top quark final states



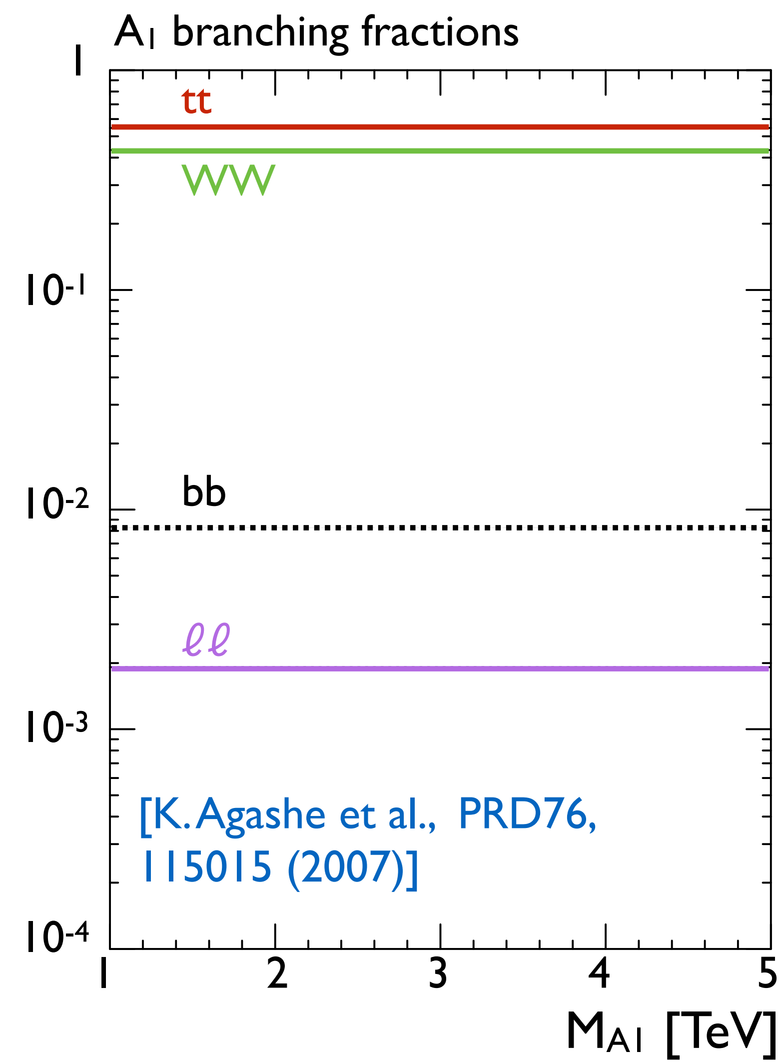
Roman Kogler (DESY)
on behalf of the
CMS Collaboration

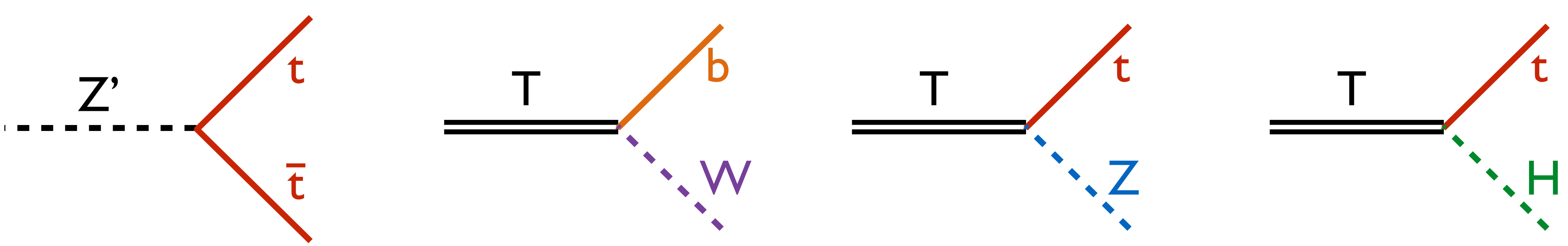
TOP 2022, Durham
Sep 7, 2022

New Physics with Top Quarks

The 3rd Generation

- Focus on t and b quarks in model building
  - Addresses a number of questions (Naturalness, mass hierarchies…)
  - Couplings to t and b dominant
- Weak constraints from EWPO and low energy measurements
- Many incarnations: new gauge groups, extended scalar sectors, axions, extra dimensions…

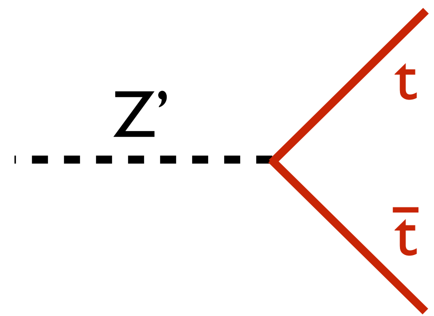




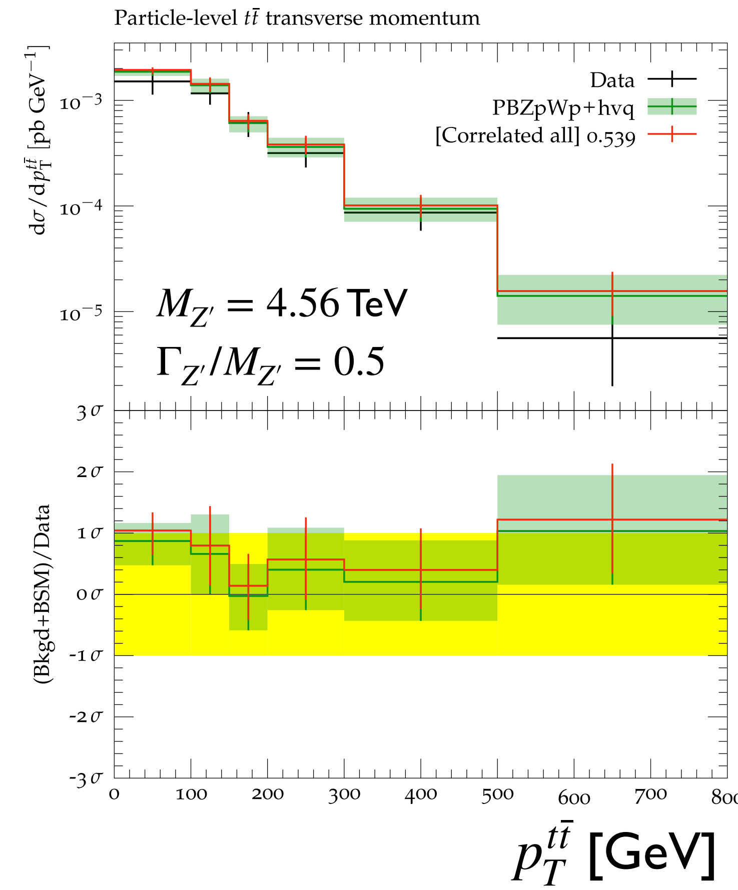
Resonances   *Vector-like quarks (VLQs)*

Why We Do Searches

Study Leptophobic Topcolor Z'



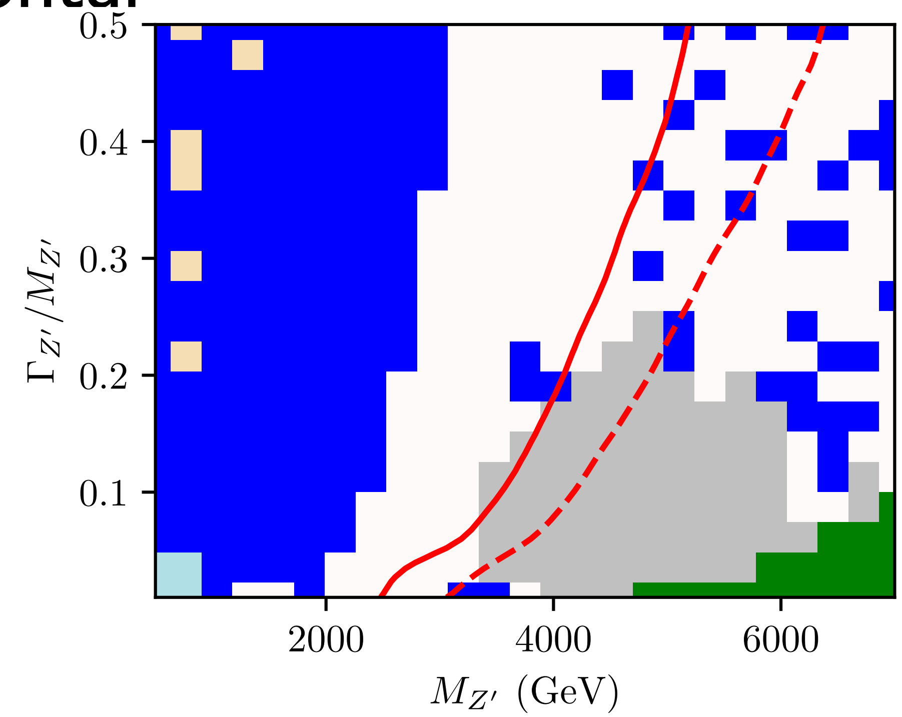
- Include many particle level measurements
  - $t\bar{t}$ in all-had, ℓ+jets and $\ell\ell$
  - inclusive and dijets
  - MET+jet

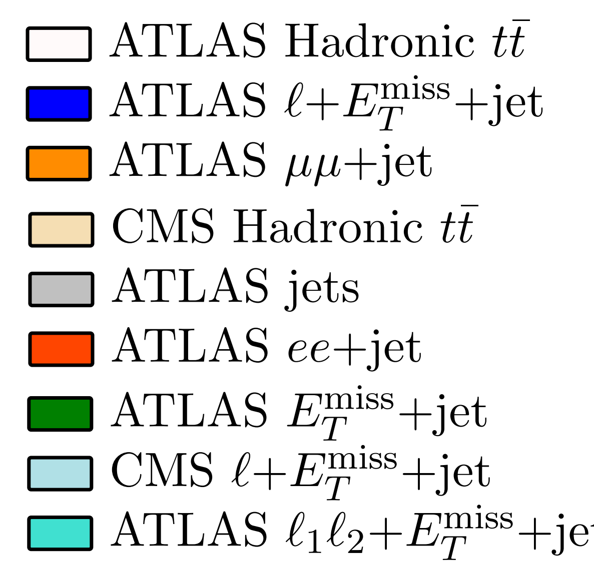


- Derive mass limits using Contur
  [Butterworth et al., JHEP 03, 78 (2017)],
  [Buckley et al., SciPost Phys. Core 4, 013 (2021)]

- Weaker constraints than from direct searches by 1.5-2.5 TeV
  [ATLAS, JHEP 10, 61 (2020)],
  [CMS, JHEP 04, 31 (2019)]

(but can access larger widths)

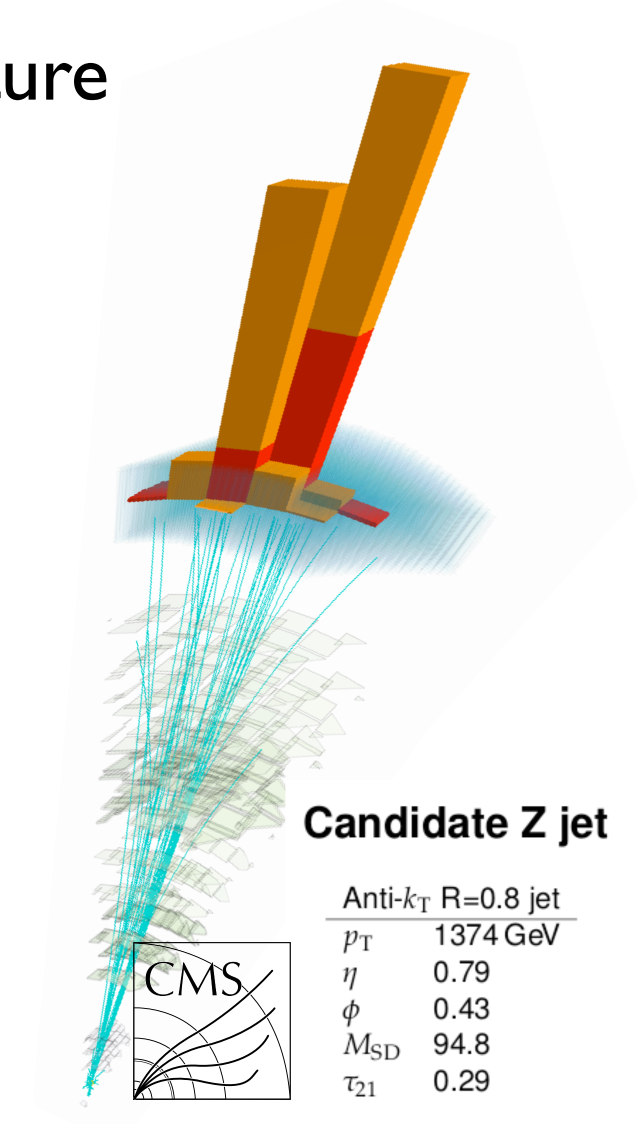




[Altakach et al., 2111.15406]

Jet Substructure at CMS

- Large-R jets: anti-k_T R=0.8 or 1.5 jets
  - Particle flow candidates for computation of substructure
  - Pileup mitigation: PUPPI [CMS, JINST 15 (2020) P09018]
  - Soft drop for groomed jet mass
  - N-Subjettiness ratios for 2- and 3-prong tagging
  - Subjet b tagging for t and H jets



Advanced techniques

- HOTVR: variable-R jet clustering
- DeepAK8: CNN for large-R jet identification
- ImageTop: image recognition with jet pixelization
- ParticleNet: graph NNs, new! [CMS DP2020-002]

[CMS, JINST 15 (2020) P06005]

HOTVR

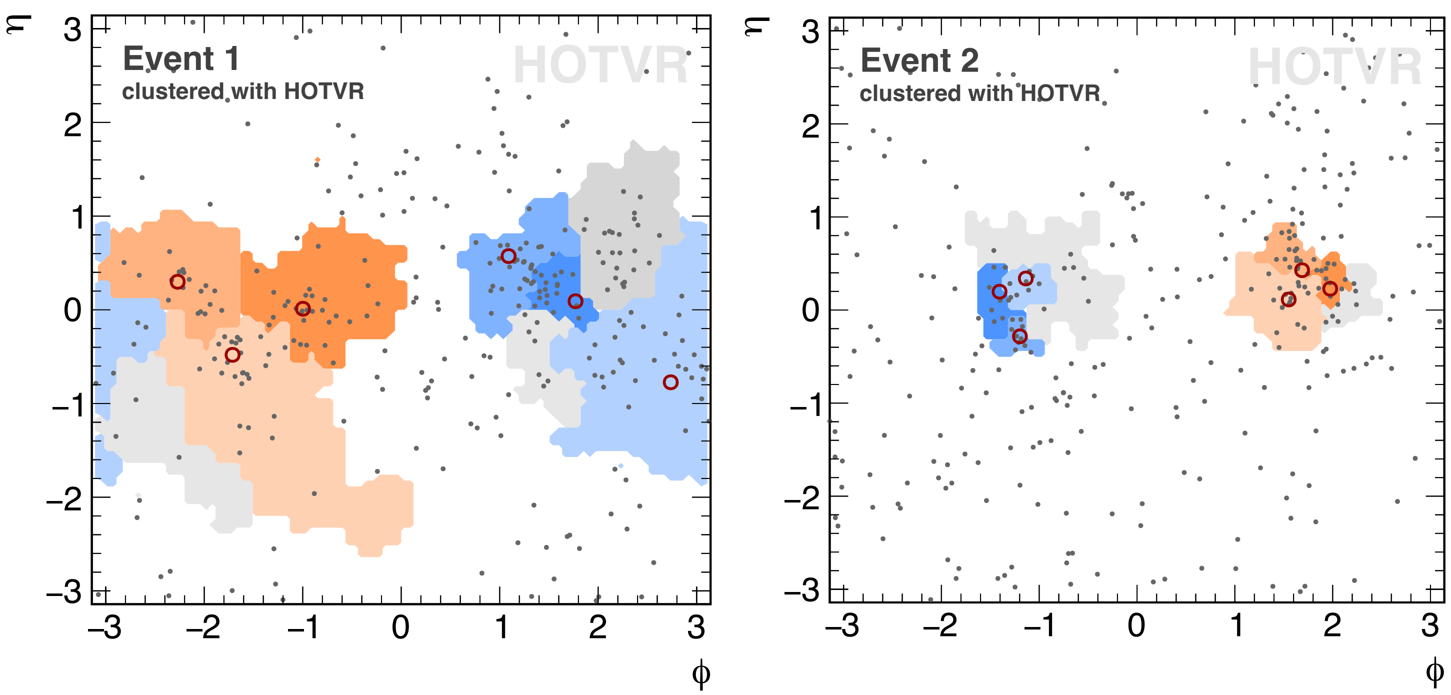
[Lapsien, RK, Haller, EPJ C 76, 600 (2016)]

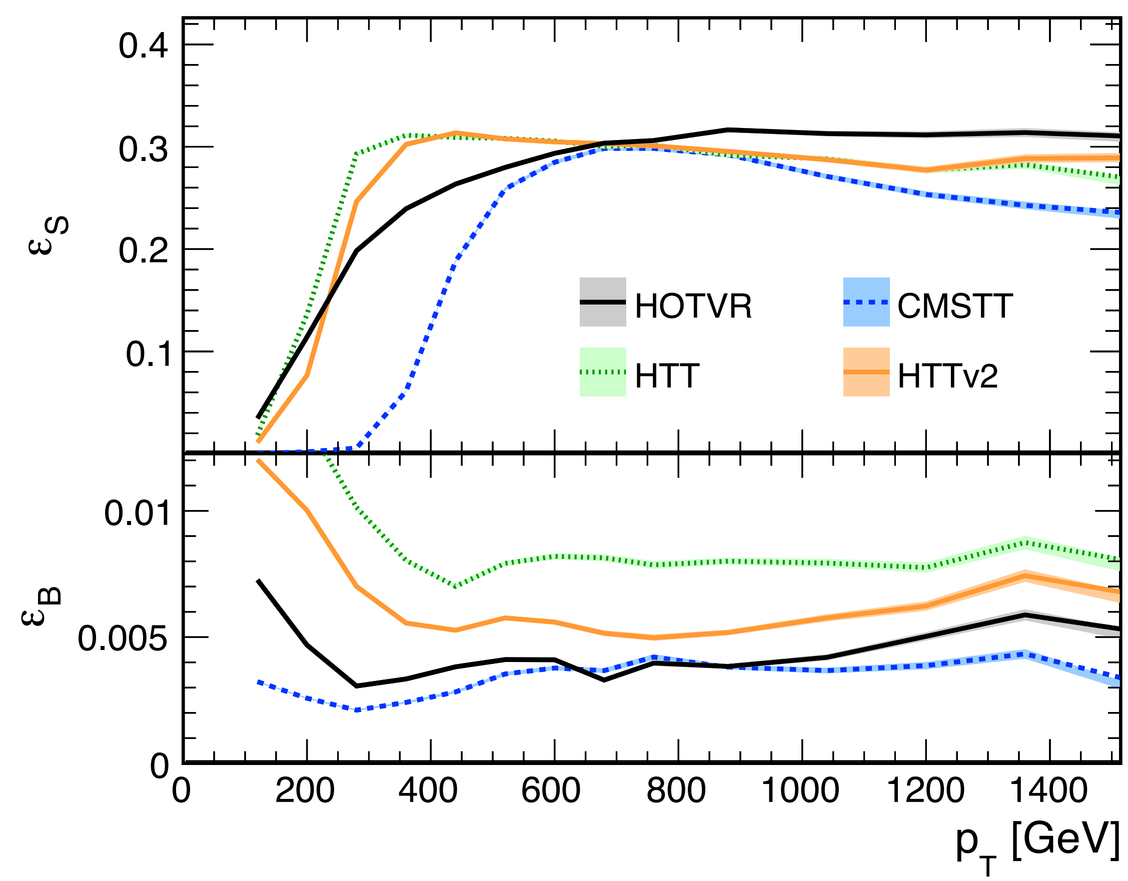
Heavy Object Tagger with Variable R

- Adaptive jet radius with VR
  - drawback: large catchment area at low p_T
- Solution: vetoed jet clustering
  - mass jump condition
  - remove soft/wide angle rad.

[Stoll, JHEP 04, 111 (2015)]

- Stable performance with little algorithmic complexity over large range in p_T



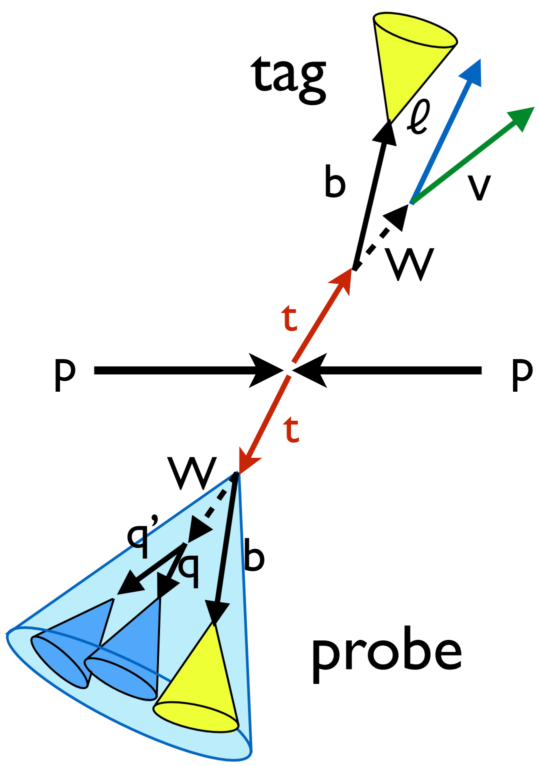


Tagging Efficiencies

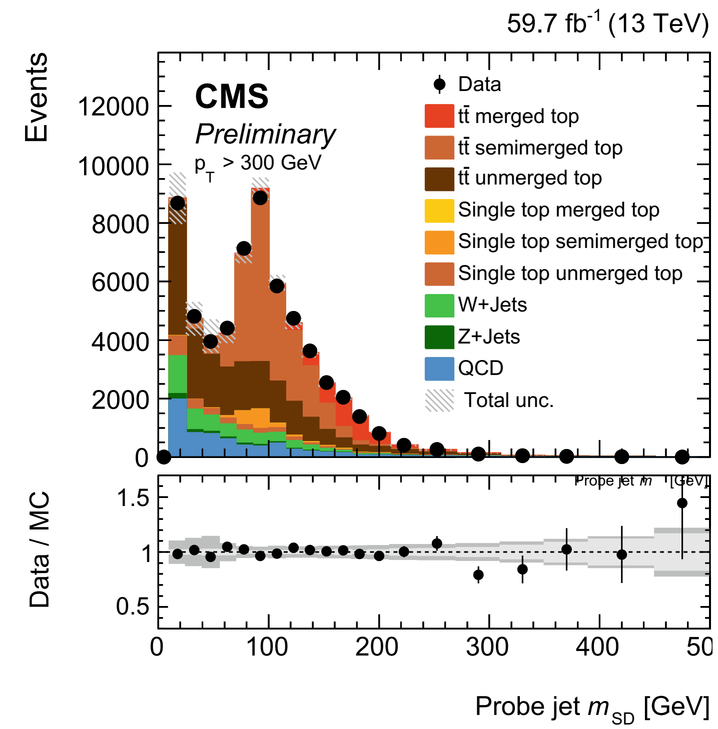
[CMS-DP-2020-025]

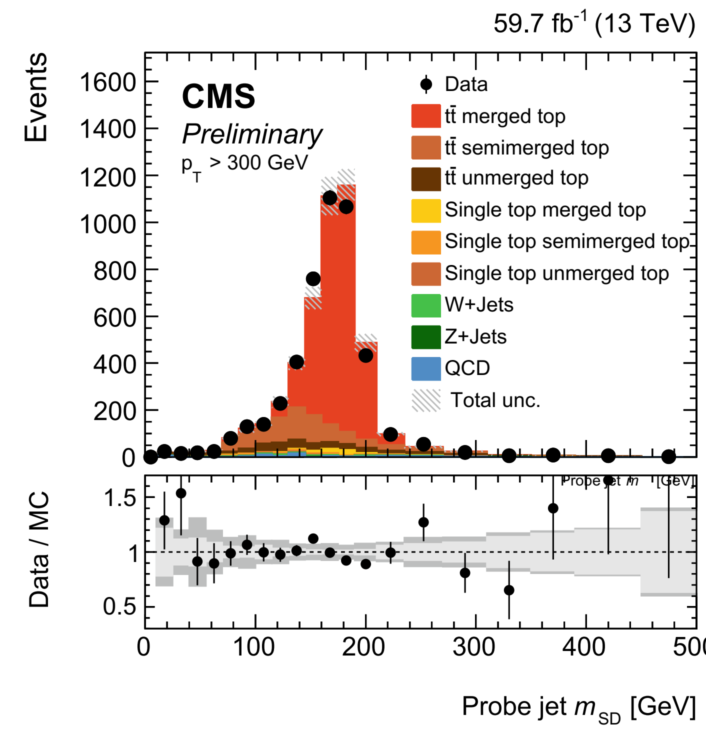
Tag-and-probe measurements

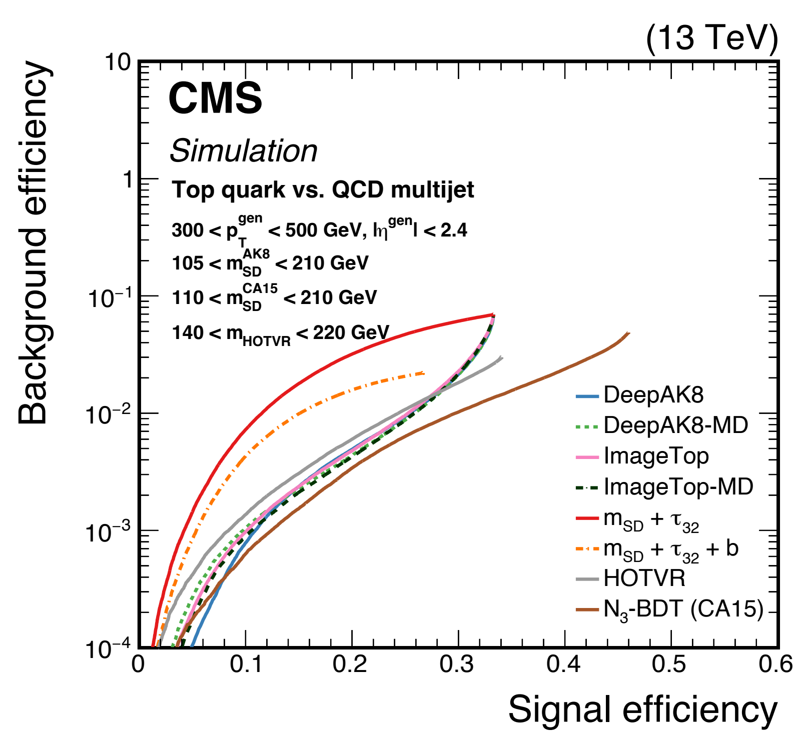
- $t\bar{t}$ production for W and t tagging

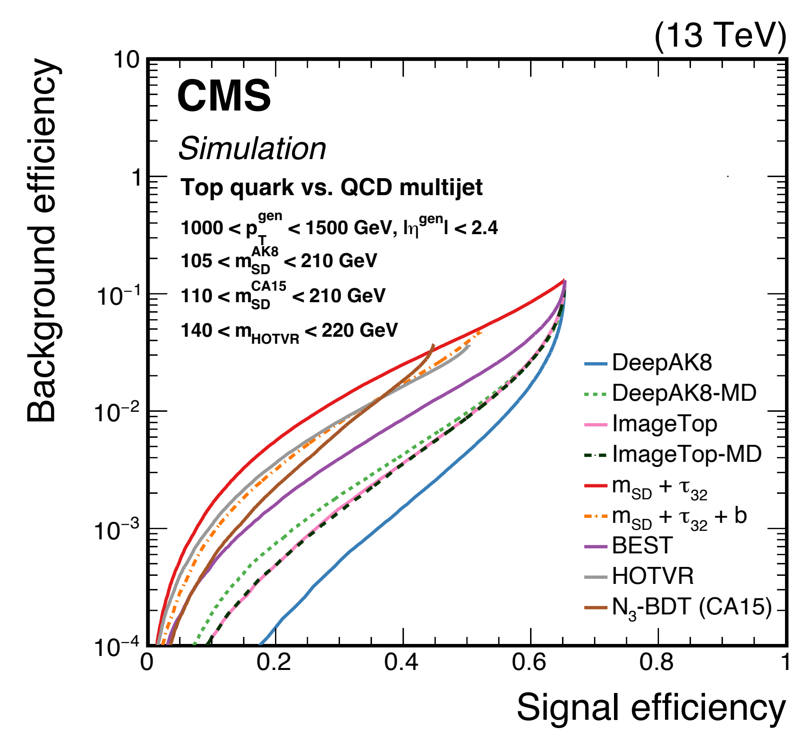


- Extrapolations to Z and H from simulation





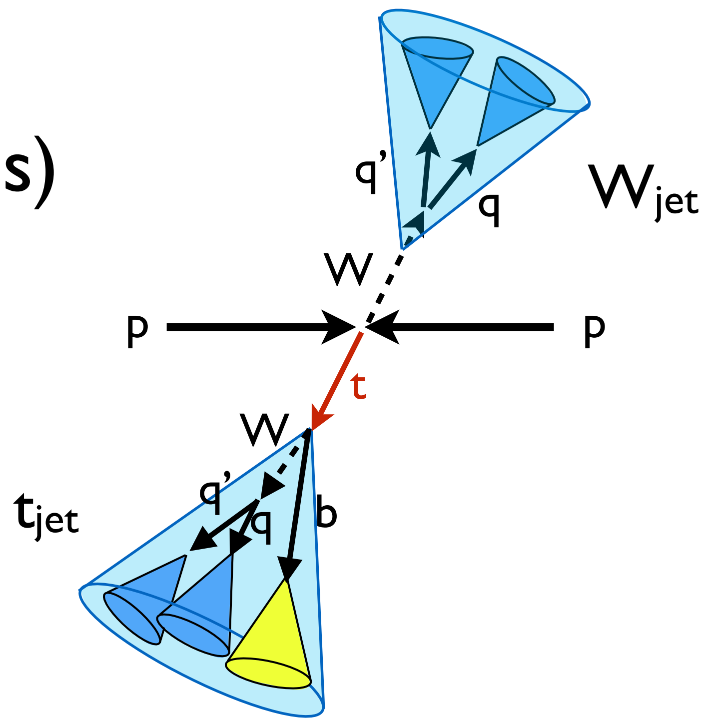


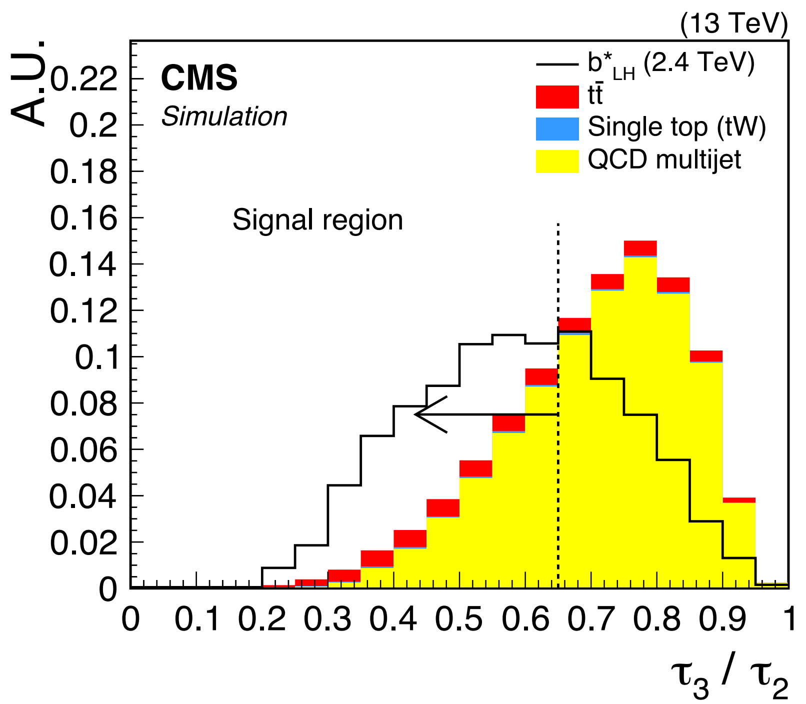


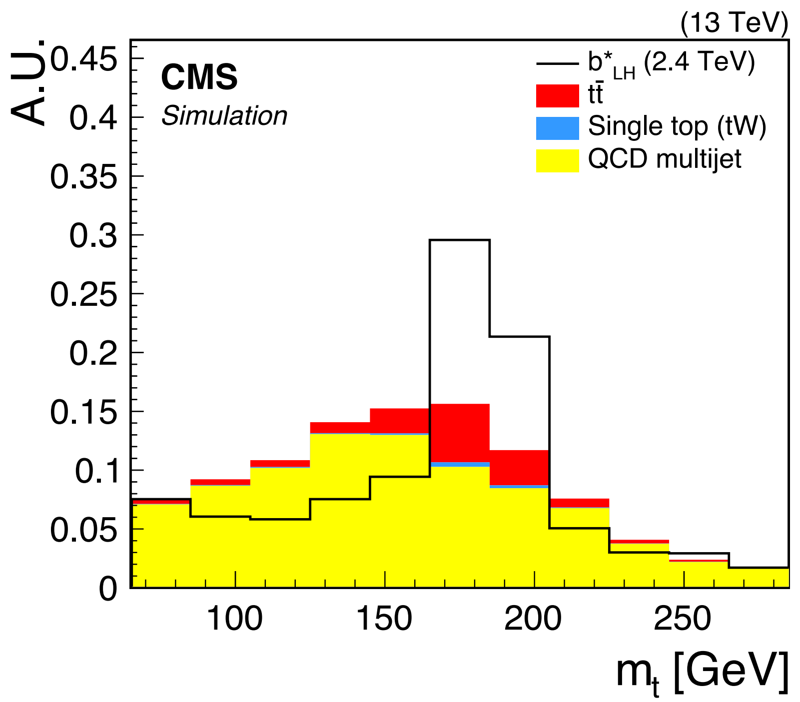
[CMS, JINST 15 (2020) P06005]

tW Resonances

- Target excited b* → tW (about 40% BR at high mass)
  - Single top production in tW channel
  - Resonance structure at high mass
- All-hadronic channel features dijet topology
  - Suppress QCD multijet background using t and W tagging with τ_{21} and τ_{32}

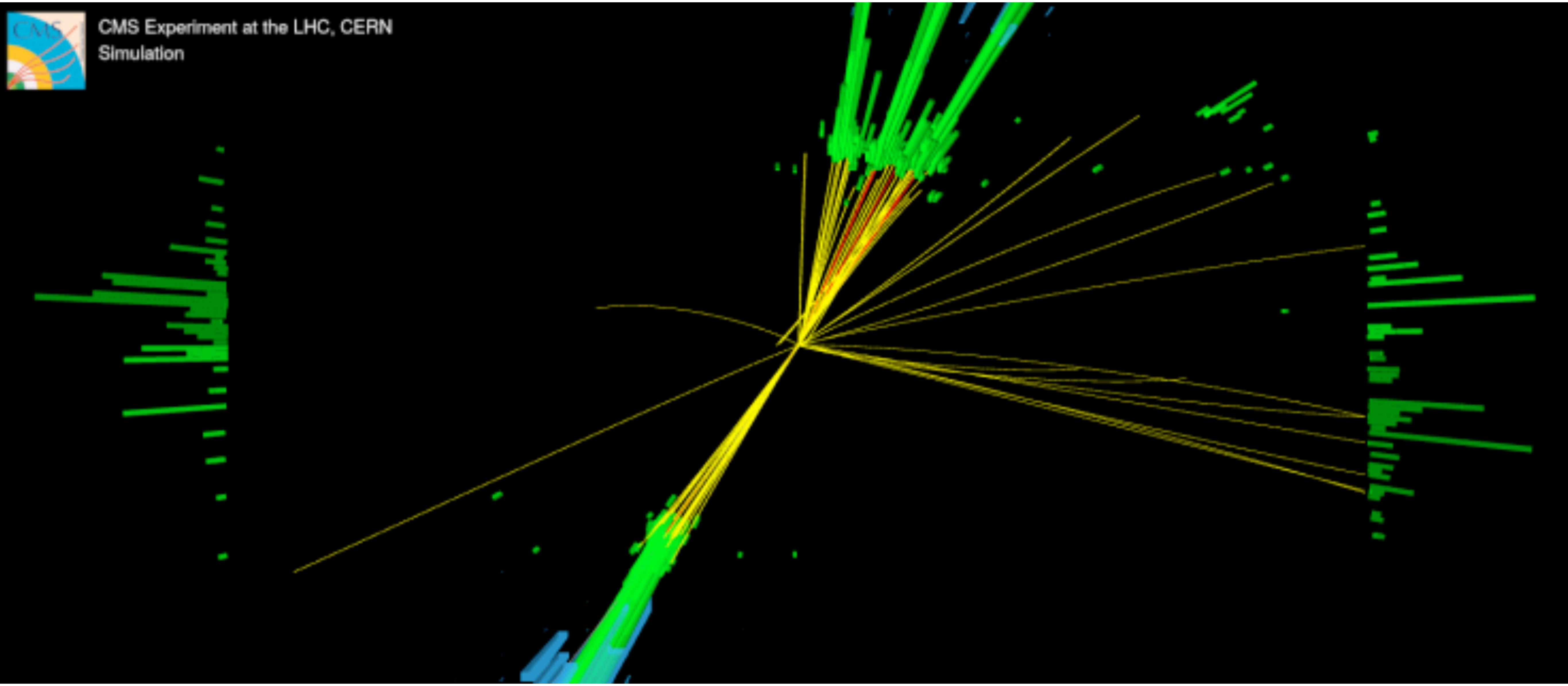






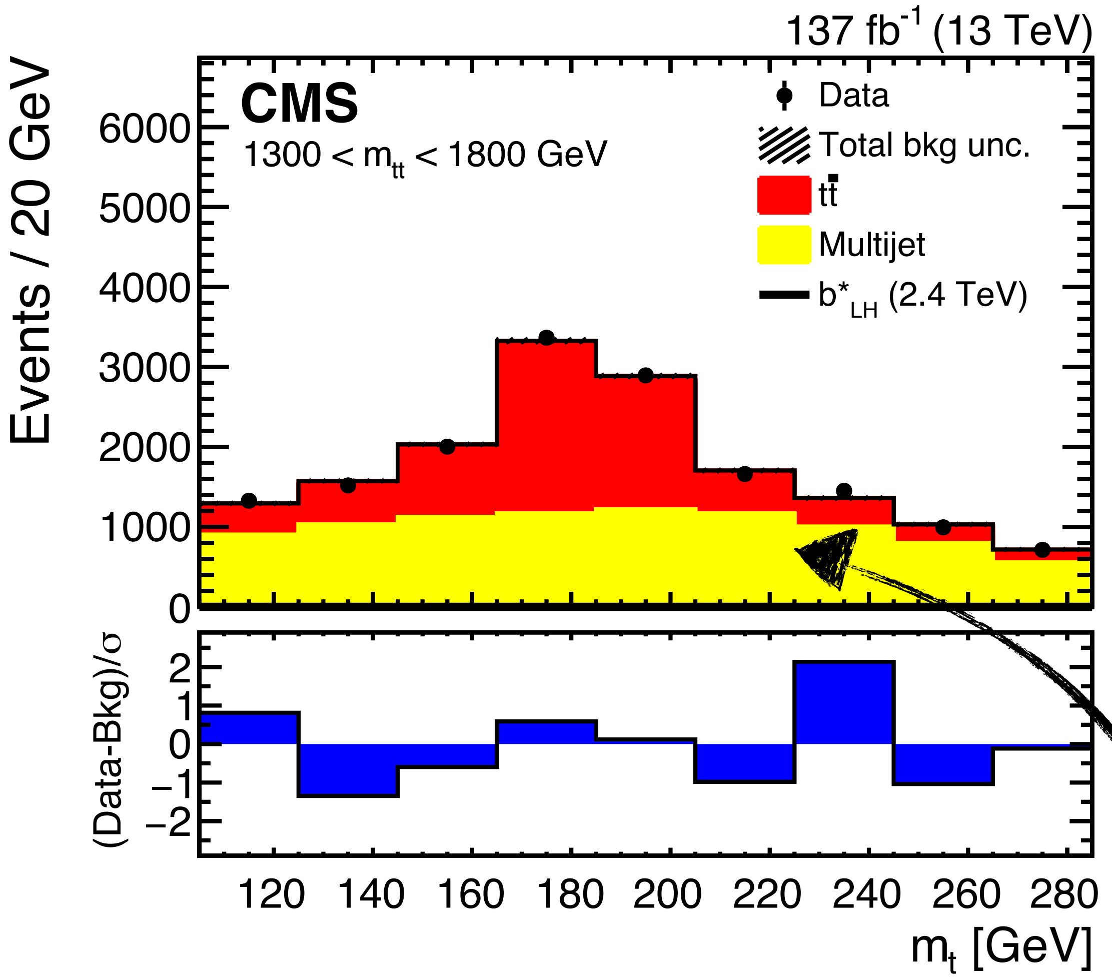
[CMS, JHEP 12, 106 (2021)]

tW Resonances

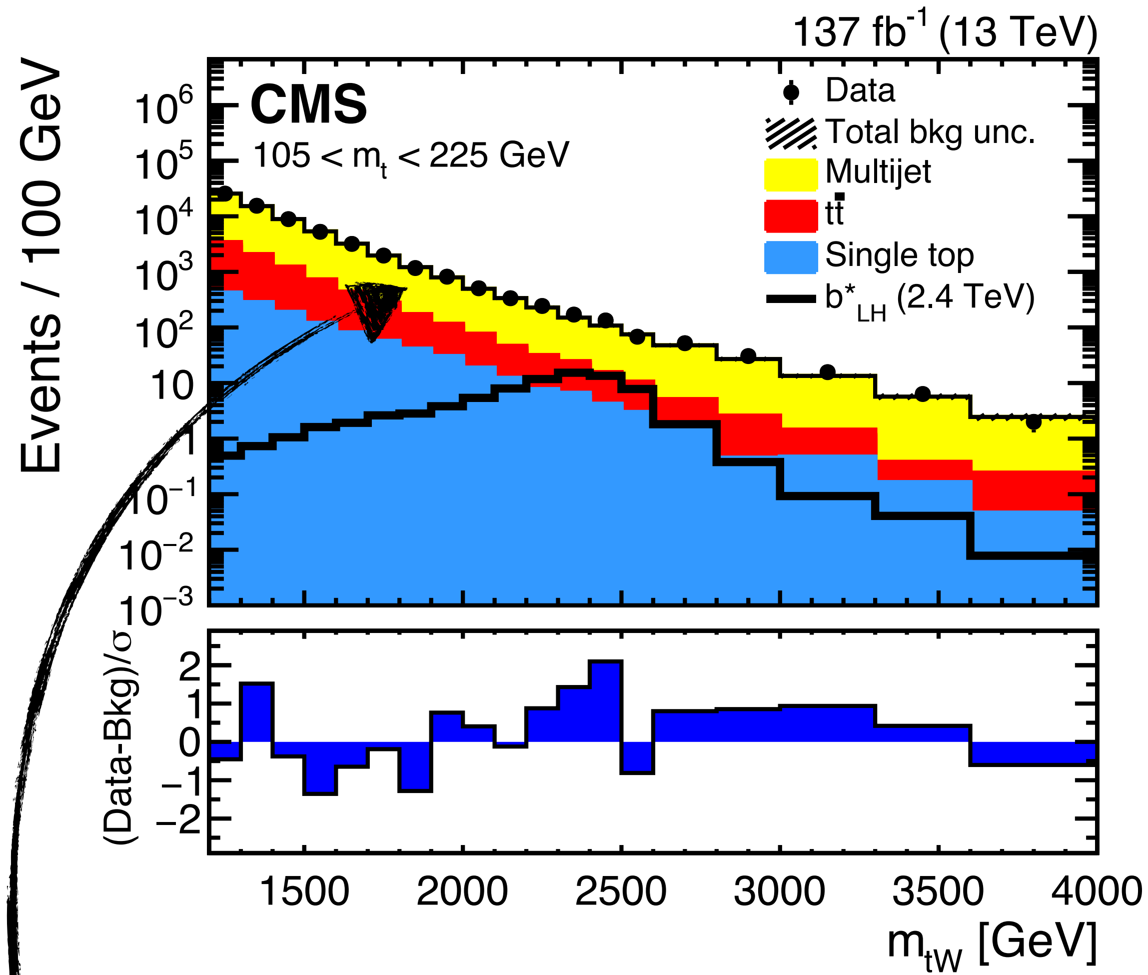


tW Resonances

$t\bar{t}$ measurement region
passing t tagger



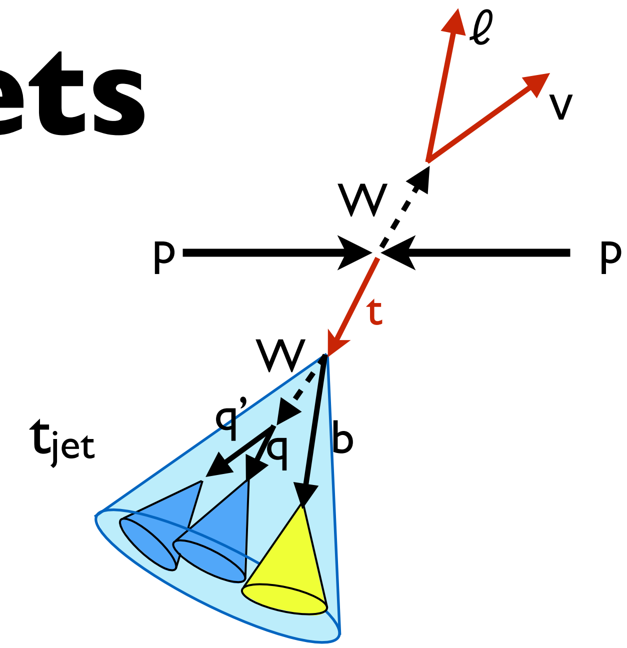
Signal region



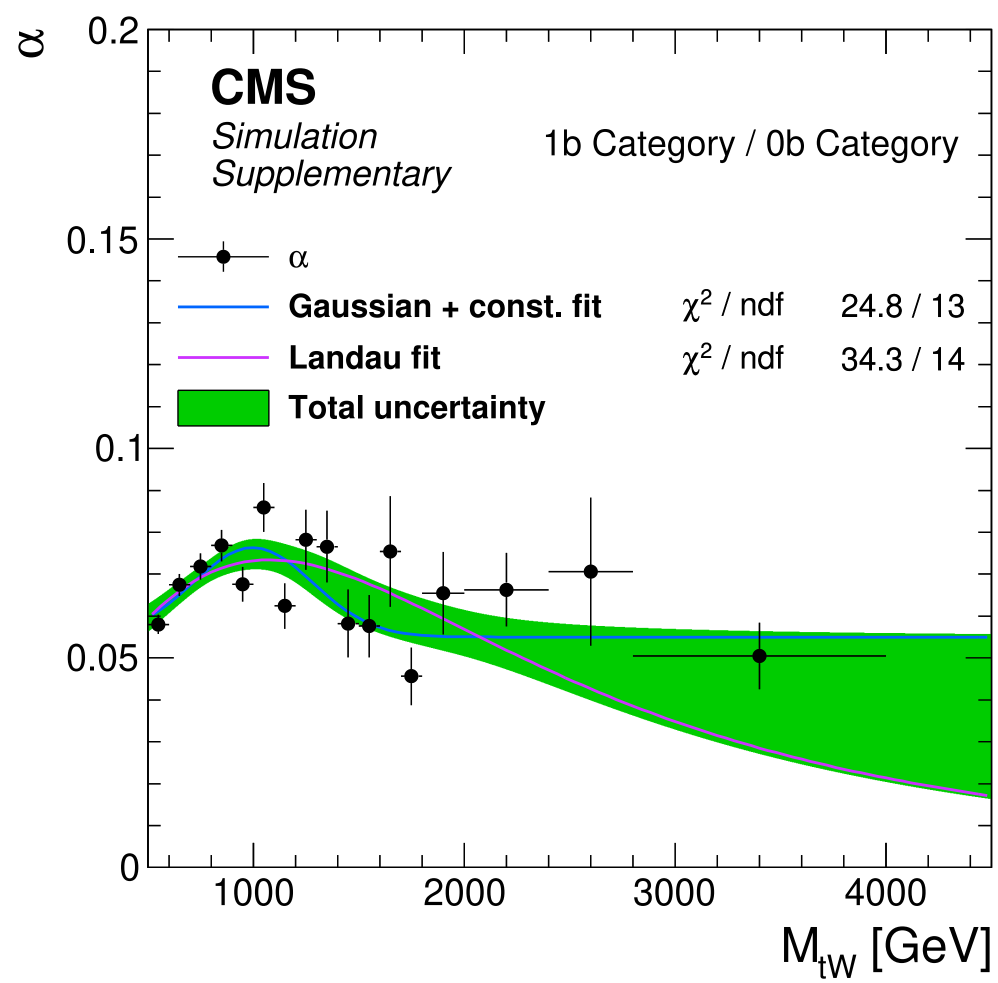
Multijet background estimated
from 2D pass-fail ratio

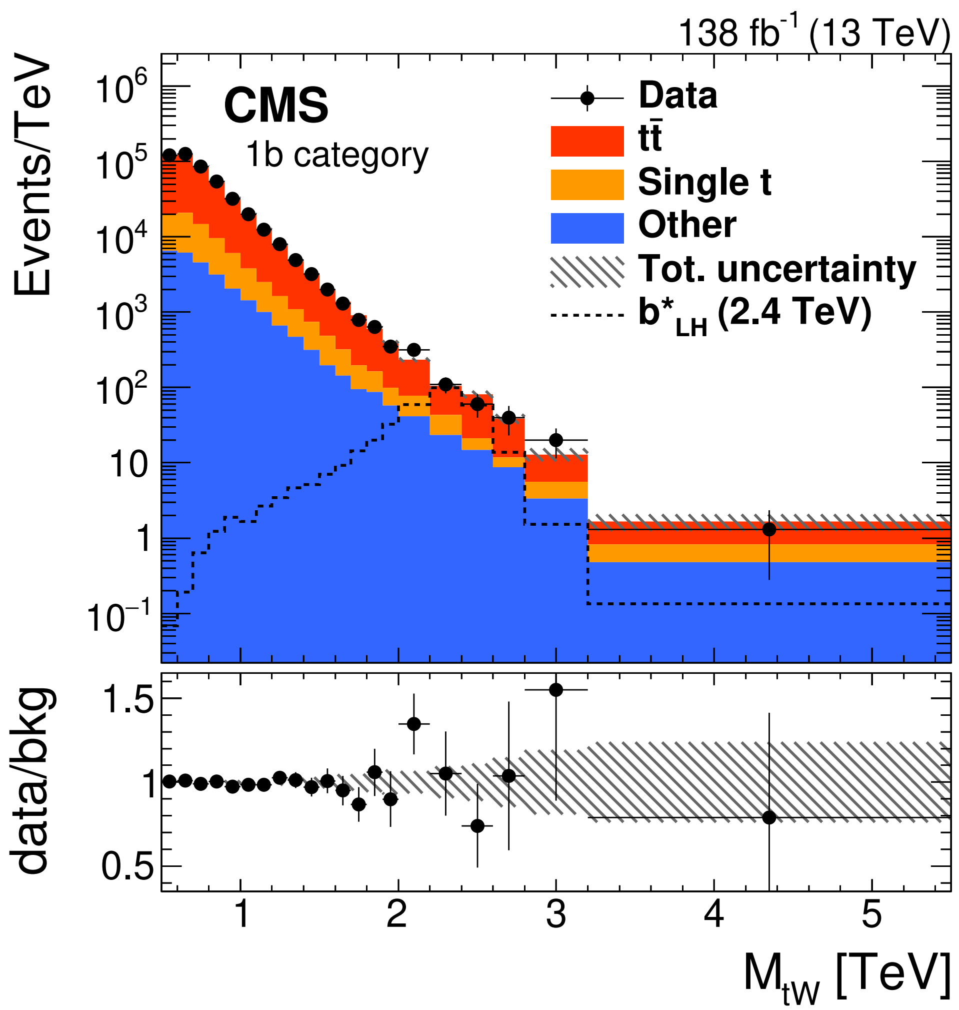
[CMS, JHEP 12, 106 (2021)]

tW Resonances in ℓ+Jets



- Extend sensitivity down to 700 GeV using lepton triggers and HOTVR
- Background from misidentified t jets extrapolated from sideband

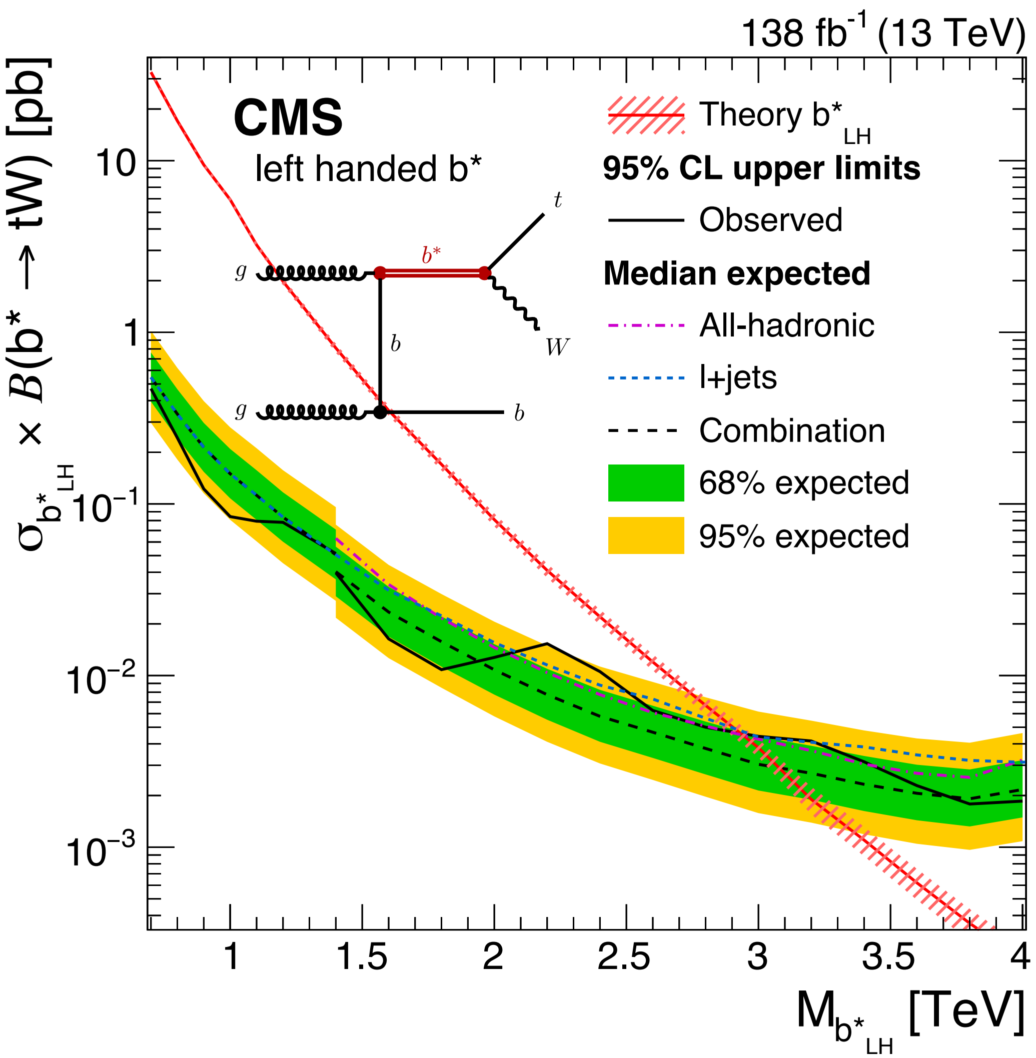




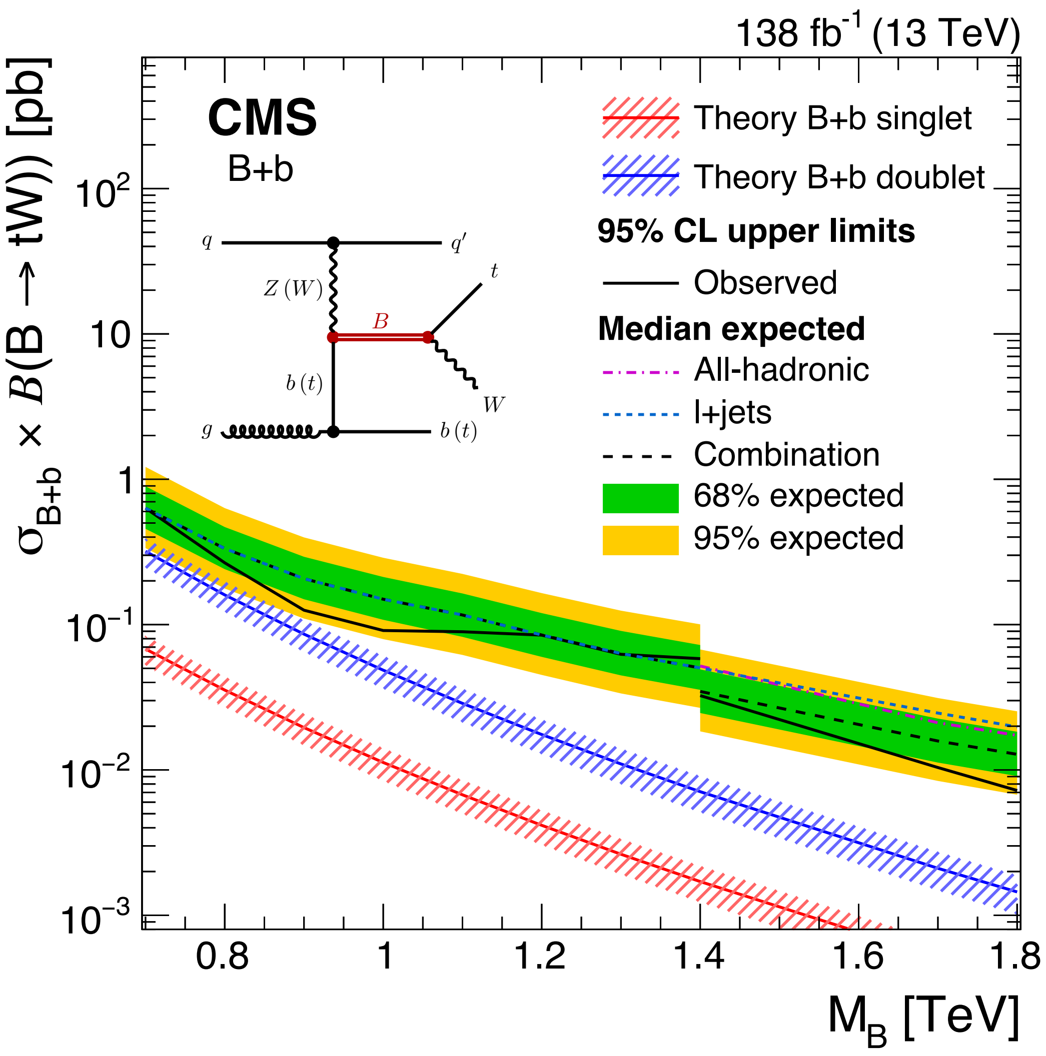
[CMS, JHEP 04, 48 (2022)]

tW Resonances: Results

Excited b* (Strong production)



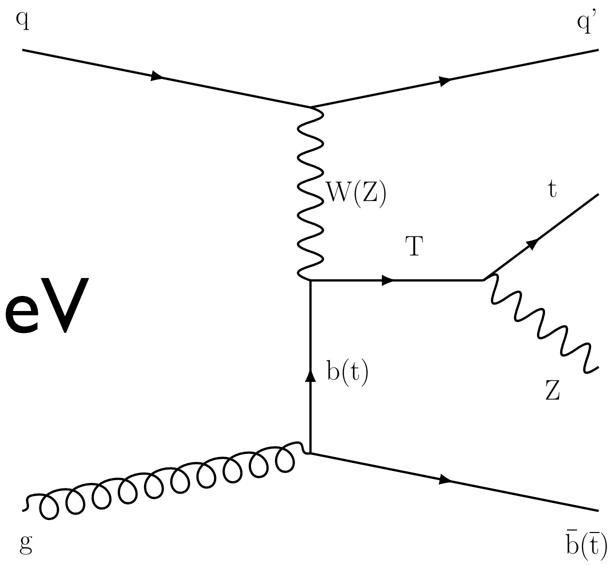
Vector-like quark B (EW production)



[CMS, JHEP 04, 48 (2022)]

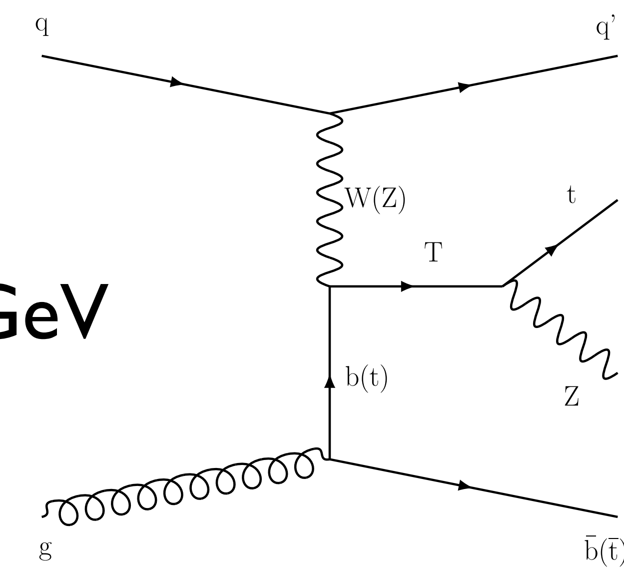
Single Vector-Like Quark

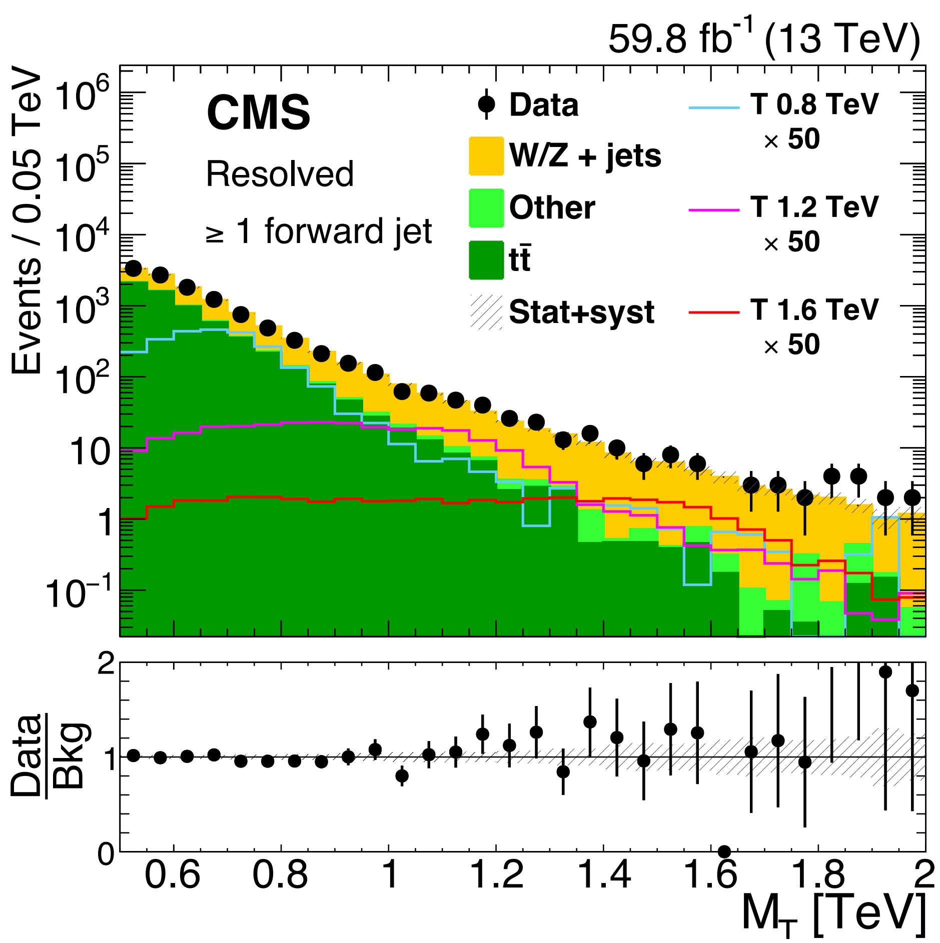
- Single production of VLQ T
  - Decays to tZ, tH and bW
- All-hadronic search (36 fb^{-1}): 3σ excess at $M_T \approx 650$ GeV

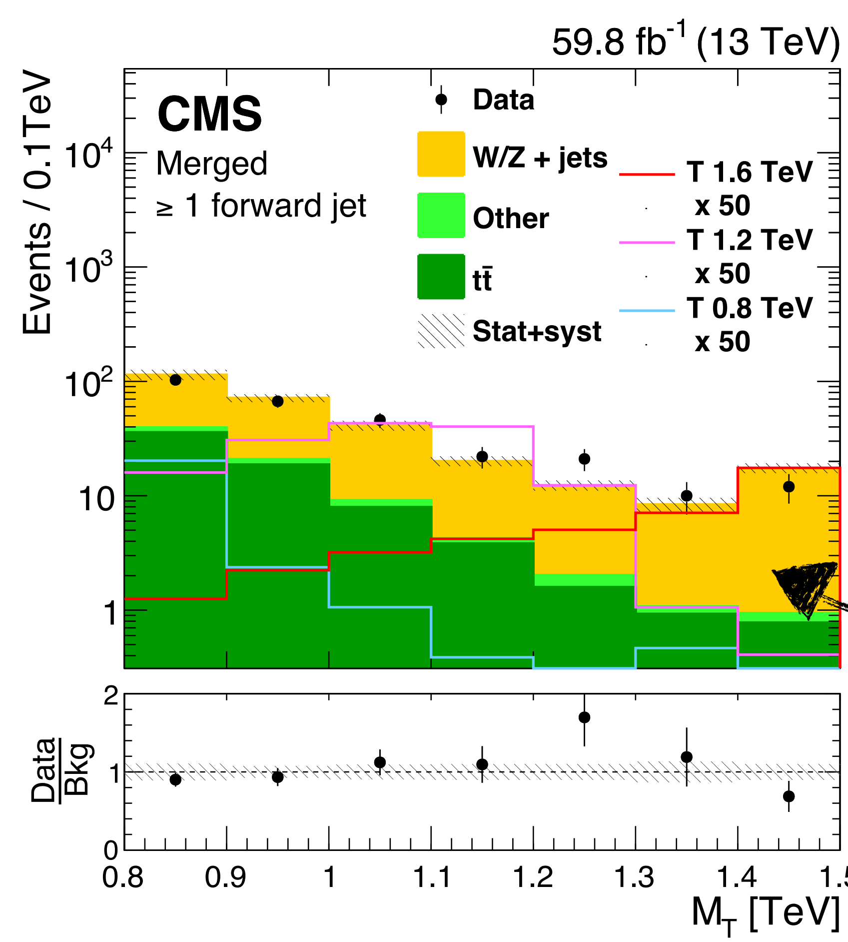


Single VLQ T→tZ

- Single production of VLQ T
  - Decays to tZ, tH and bW
- All-hadronic search (36 fb^{-1}): 3σ excess at $M_T \approx 650$ GeV
- Orthogonal channel: T→tZ(→νν)
  - Resolved, partially, and fully merged top decays





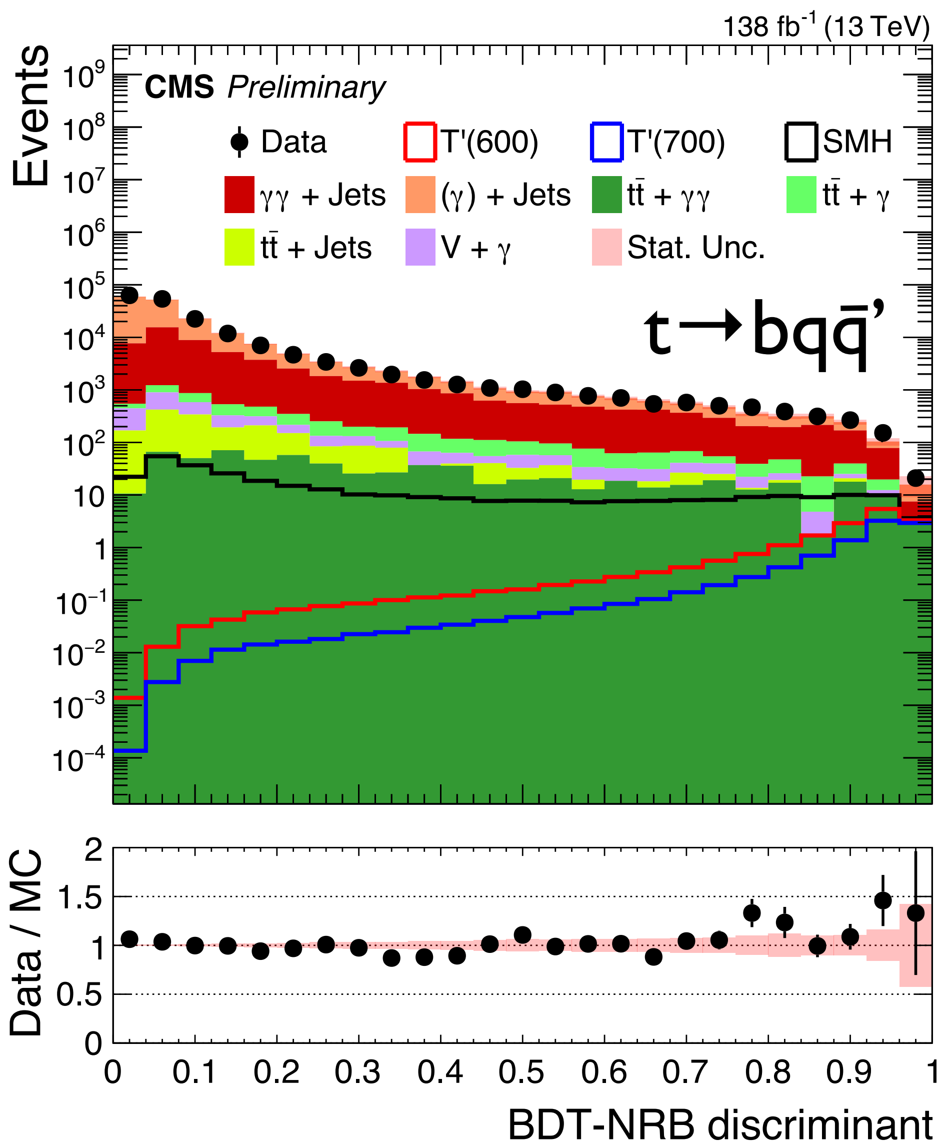


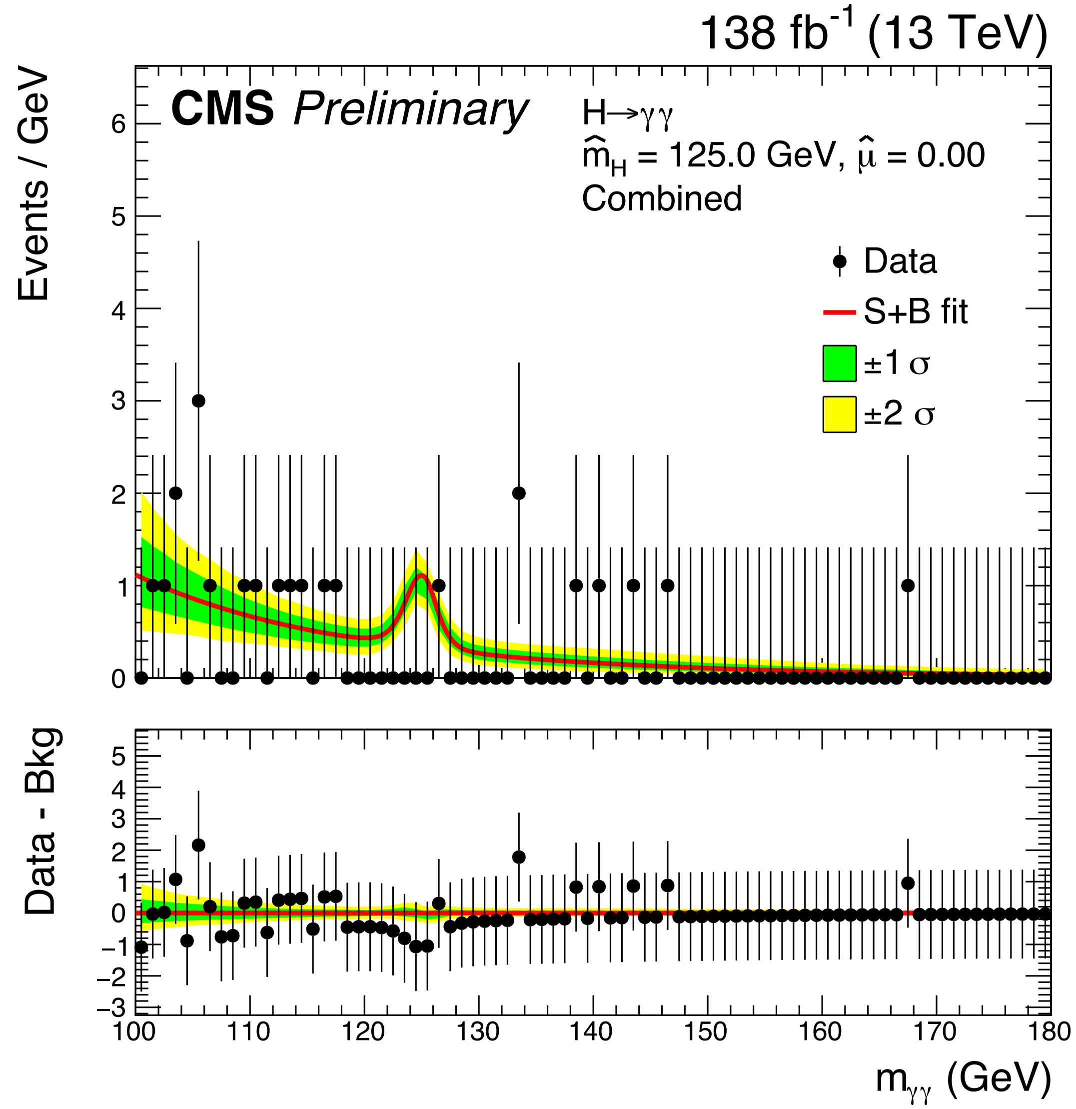
SM backgrounds adjusted using control regions

[CMS, JHEP 05, 93 (2022)]

Single VLQ T→tH

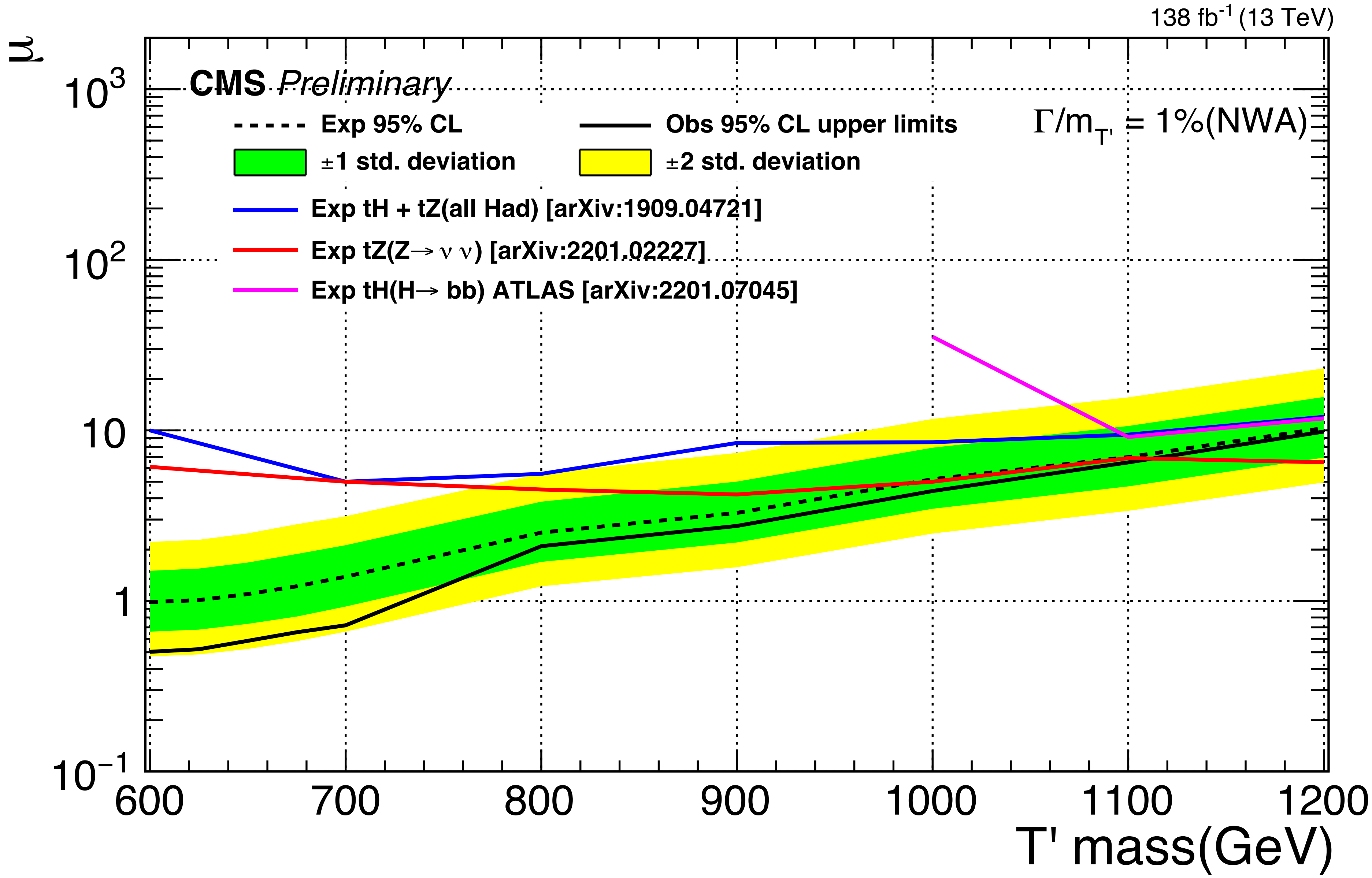
- Use clean $H\to\gamma\gamma$ decay, search for peak in $m_{\gamma\gamma}$ spectrum
- Search in $t\to bq\bar{q}'$ and $t\to b\ell\nu$ channels
- BDT for suppression of non-resonant and resonant SM backgrounds





[CMS PAS-B2G-21-007]

Single VLQ T→tH



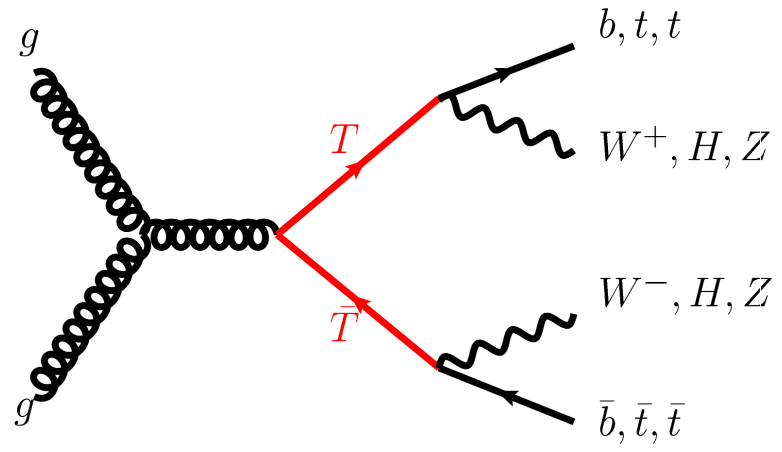
- Best sensitivity for $M_{T'}$ < 1100 GeV
- Excess from all-hadronic channel not confirmed

[CMS PAS-B2G-21-007]

VLQ Pair Production

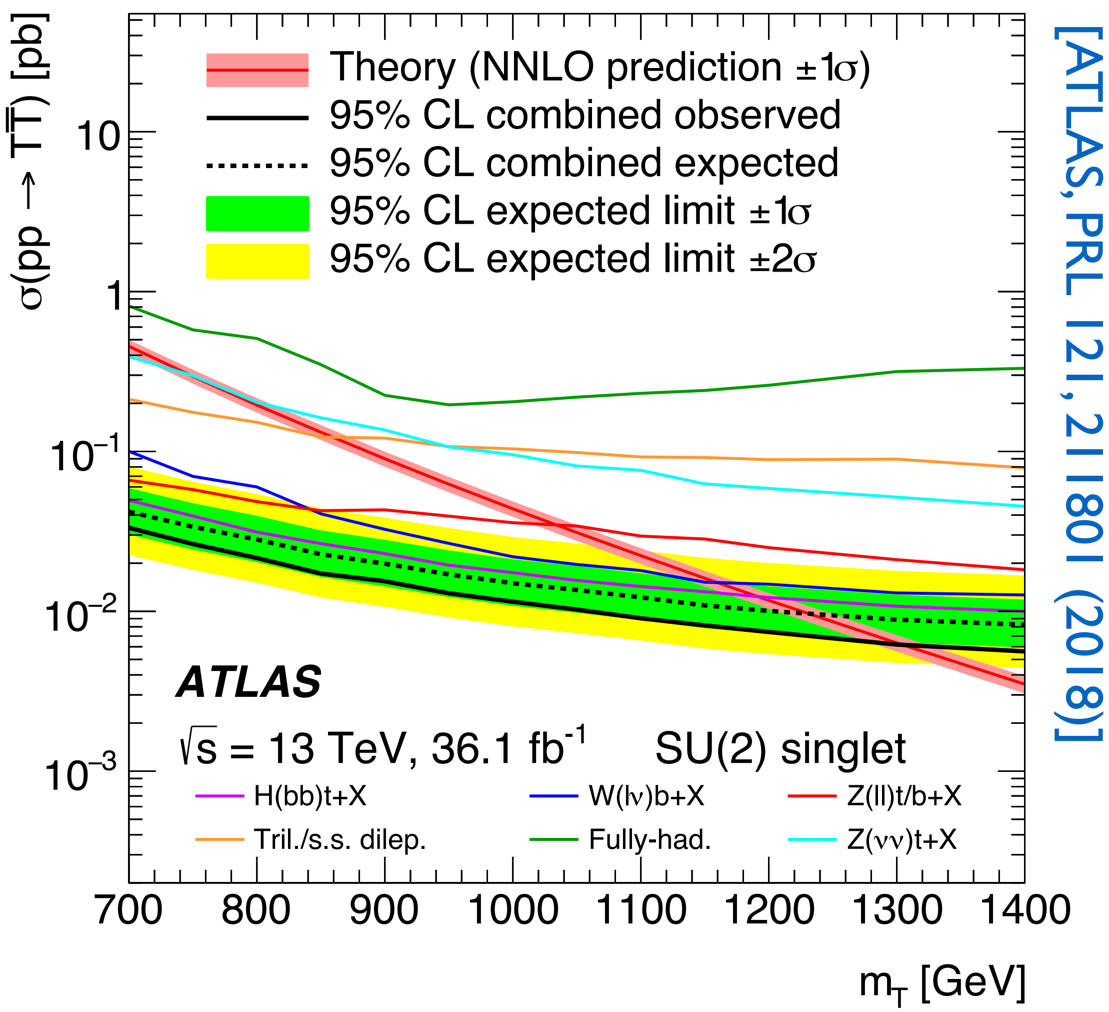
$T\overline{T}$ and $B\overline{B}$ pair production

- Rich phenomenology
  - $T \to bW, tZ, tH$
  - $B \to tW, bZ, bH$



- Numerous searches profit from jet substructure tagging
  - orthogonality: leptonic and hadronic channels (tags)

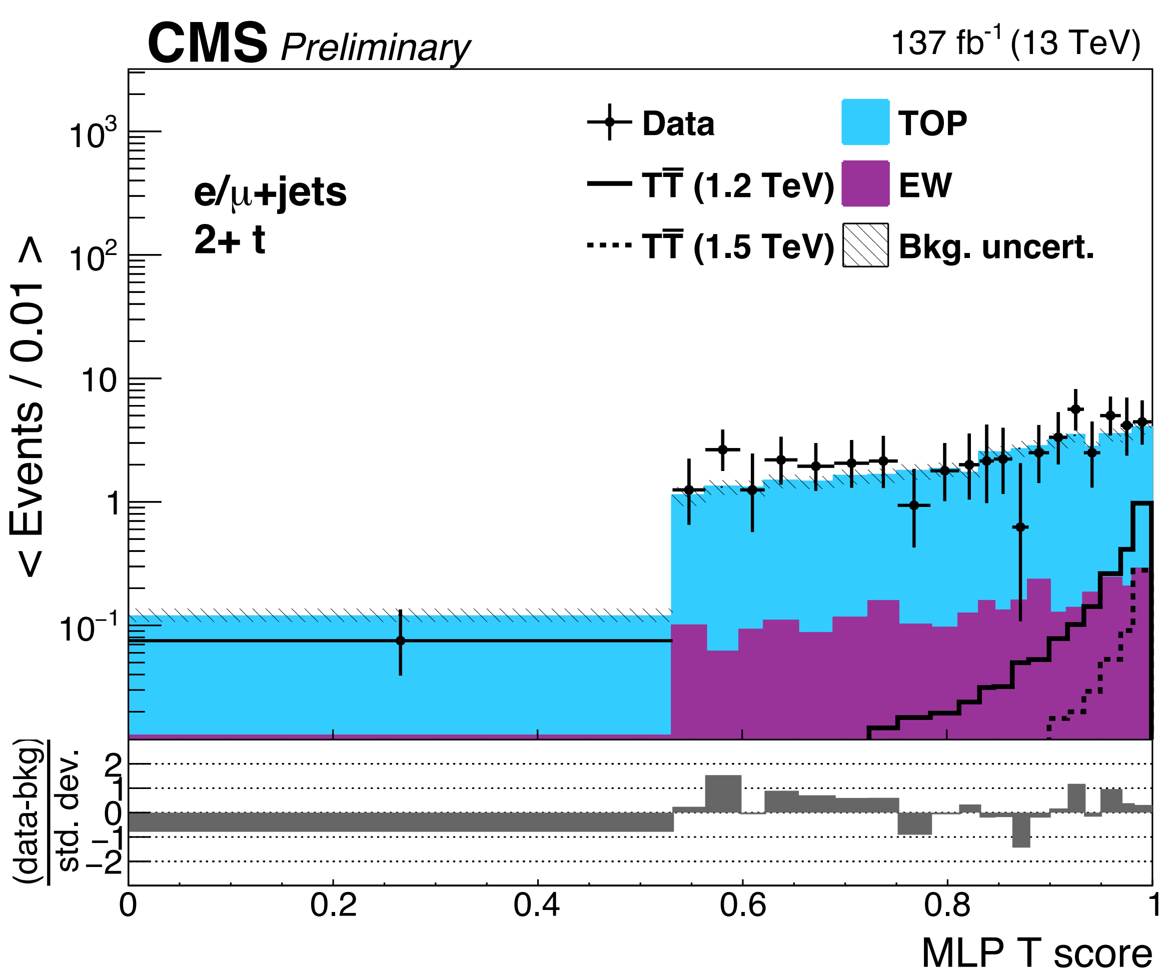
- Grand combination: Exclusion of T / B below 1.3 / 1.2 TeV at 95% CL

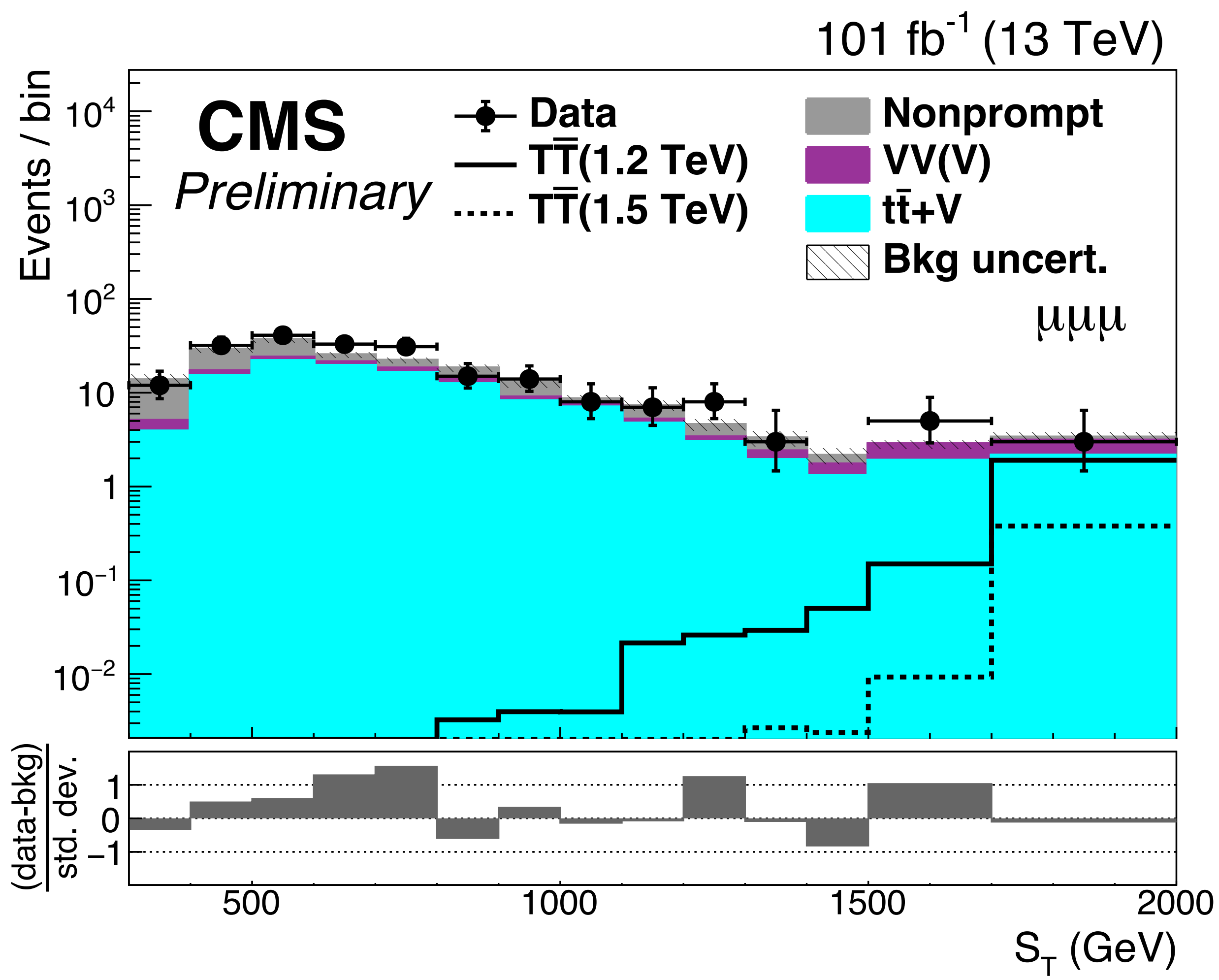


[ATLAS, PRL 121, 211801 (2018)]

$T\bar{T}$ and $B\bar{B}$ in 1, 2 and 3ℓ+Jets

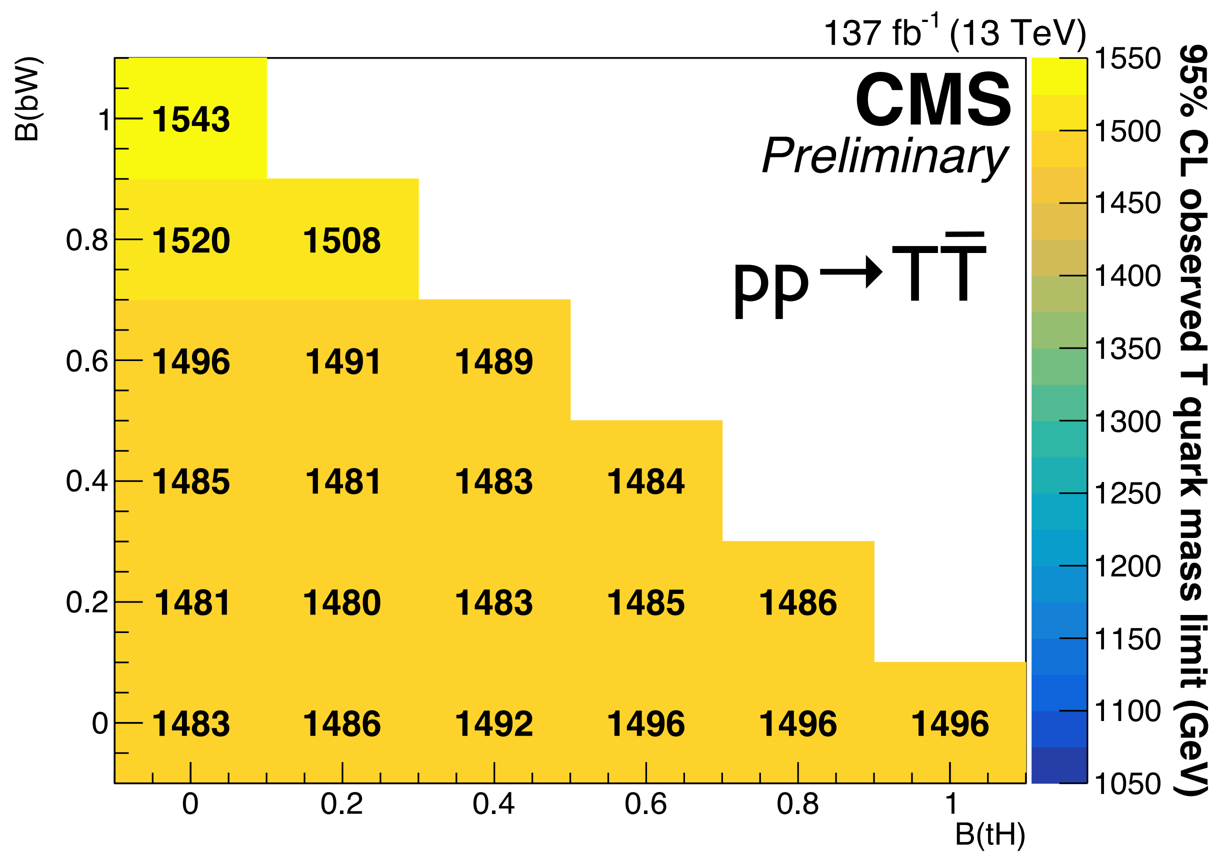
- Inclusive search, targeting a number of decays (tW, tZ, tH, bZ, bW)
- 1ℓ+3 large-R jets with DeepAK8, MLP trained for signal enhancement
- 2 (3)ℓ + 4 (3) small-R jets, use S_T distribution

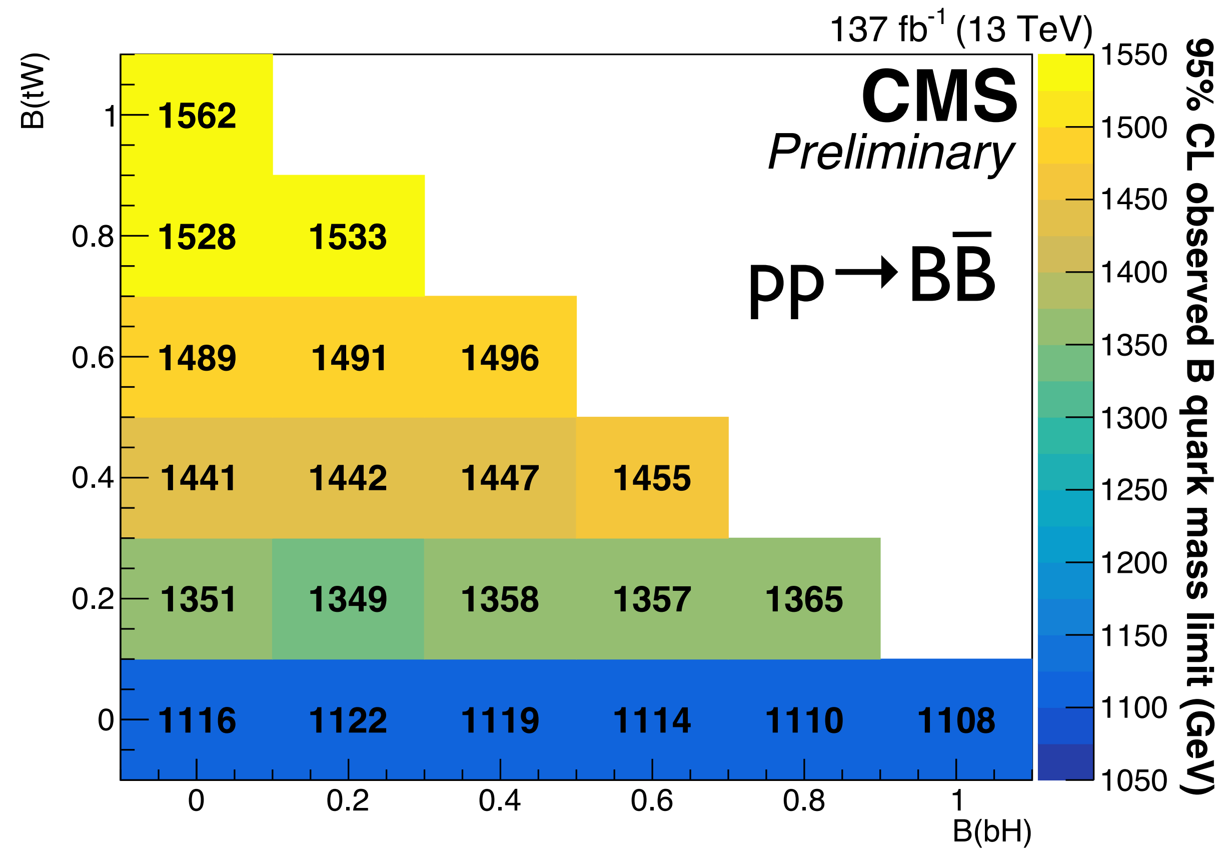




[CMS PAS-B2G-21-011]

$T\bar{T}$ and $B\bar{B}$ in 1, 2 and 3ℓ+Jets





[CMS PAS-B2G-21-011]

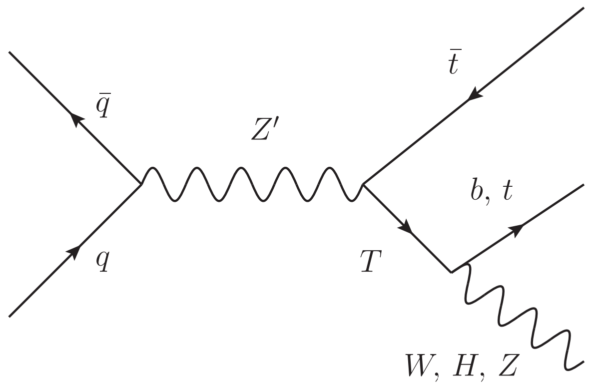
- TT production: m_T > 1480 GeV, independent of BR
- BB production: m_B > 1350 GeV for *B*(tW) ≥ 0.2
  - Dedicated search for B→bH: m_B > 1570 GeV [CMS PRD 102, 112004 (2020)]

(all limits at 95% CL)

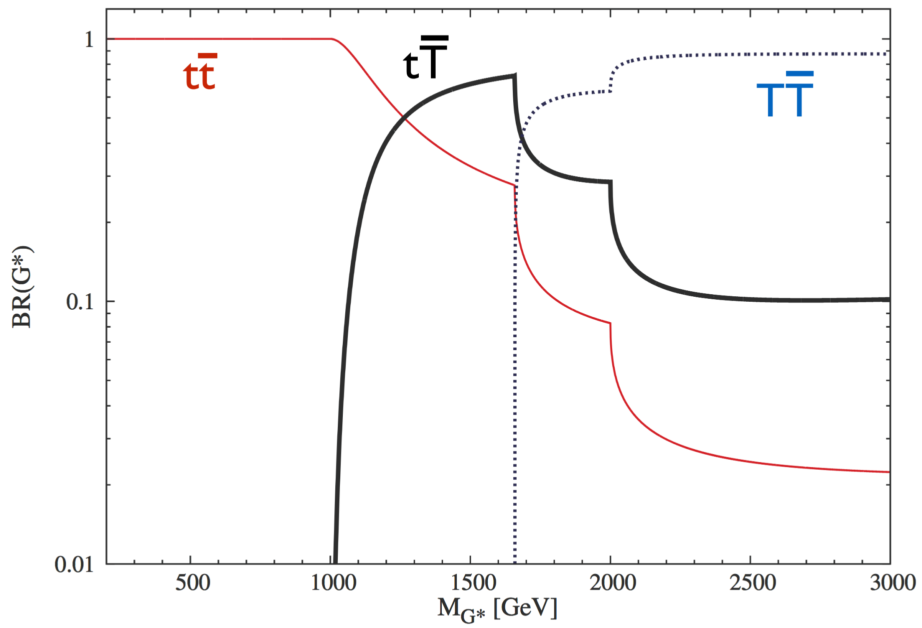
VLQs from Resonance Decays

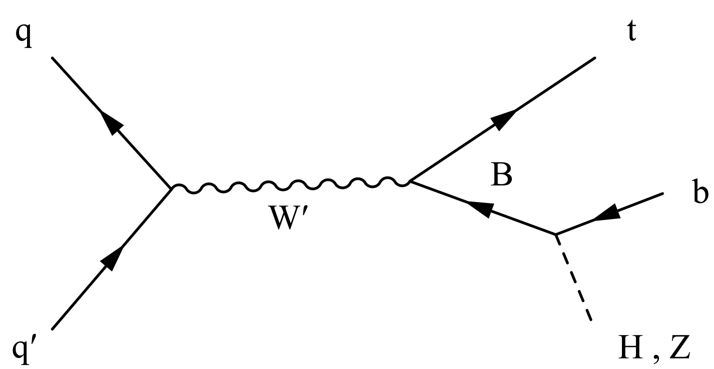
No signals in $t\bar{t}$ or $T\bar{T}$ production ($t\bar{b}$ or $T\bar{B}$)

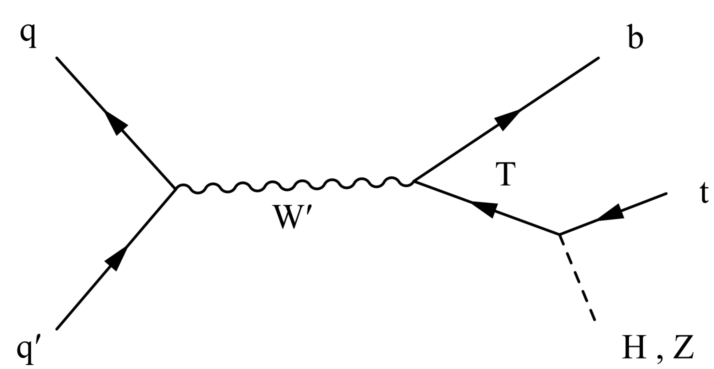
- Traditional searches: No sensitivity in $t\bar{T}$, $b\bar{T}$ or $t\bar{B}$



[C. Bini et al., JHEP 1201, 157 (2012)]







- Z' production: resonant $t\bar{t}Z$ and $t\bar{t}H$ final state [CMS EPJC 79, 208 (2019)]
- W' production: resonant $t\bar{b}H$ and $t\bar{b}Z$ final state
  - Collimation depends on ratio of Z' (W') and VLQ masses

W' → tbH or tbZ

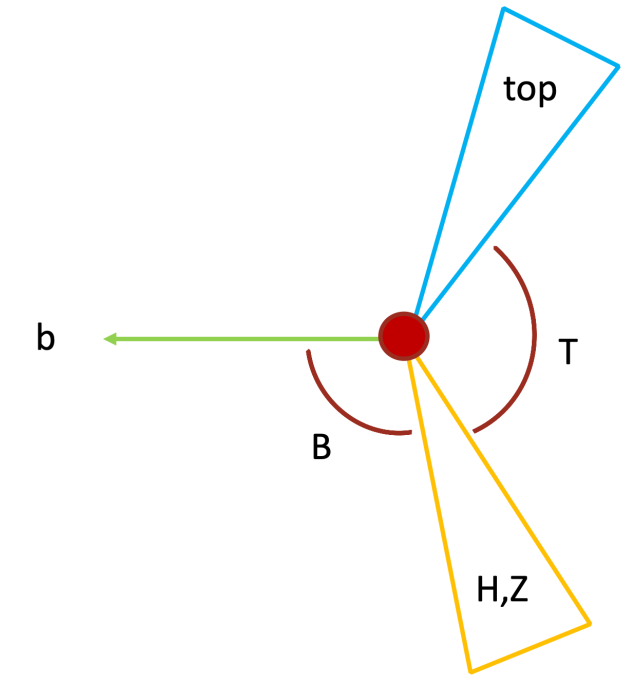
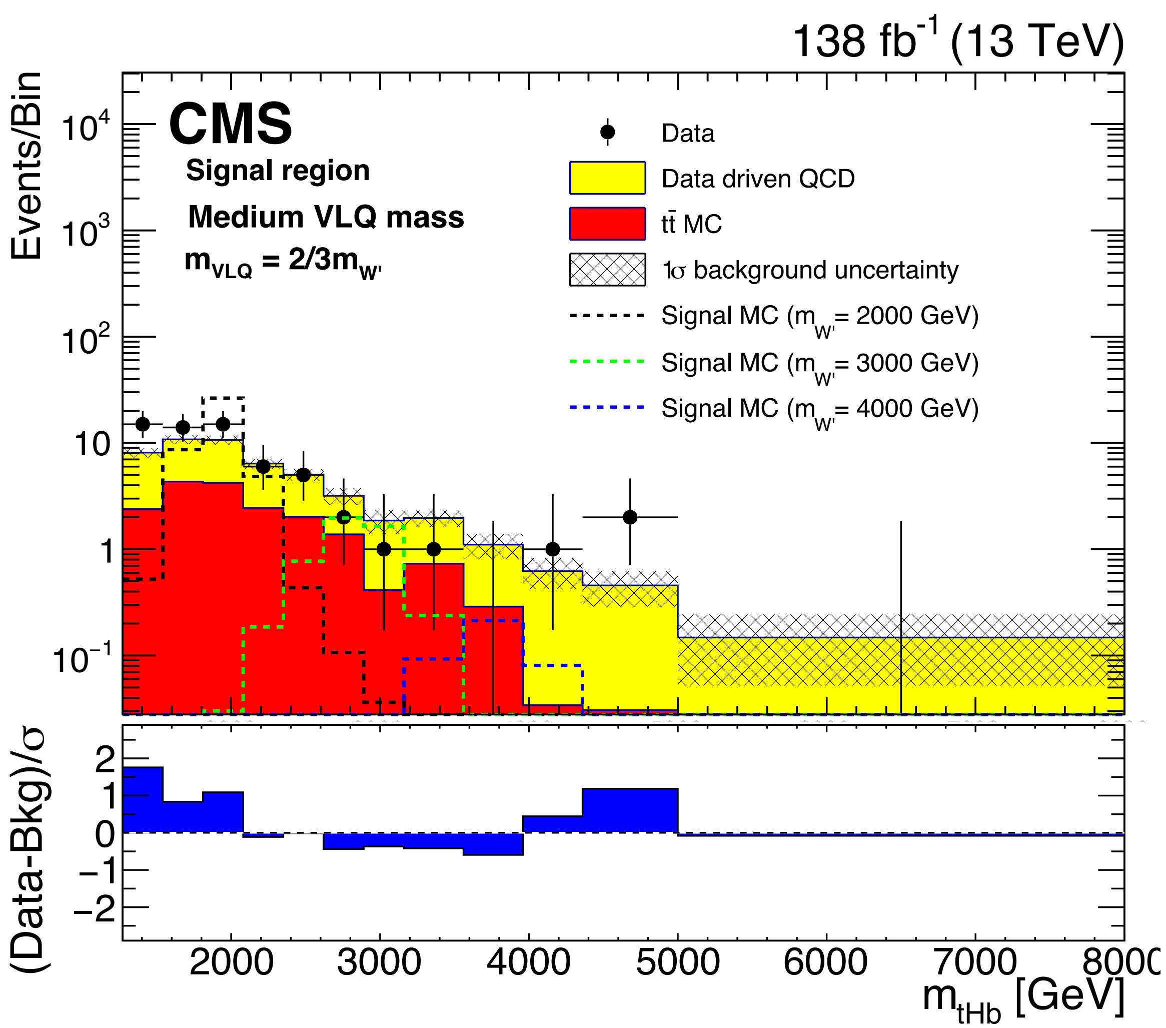
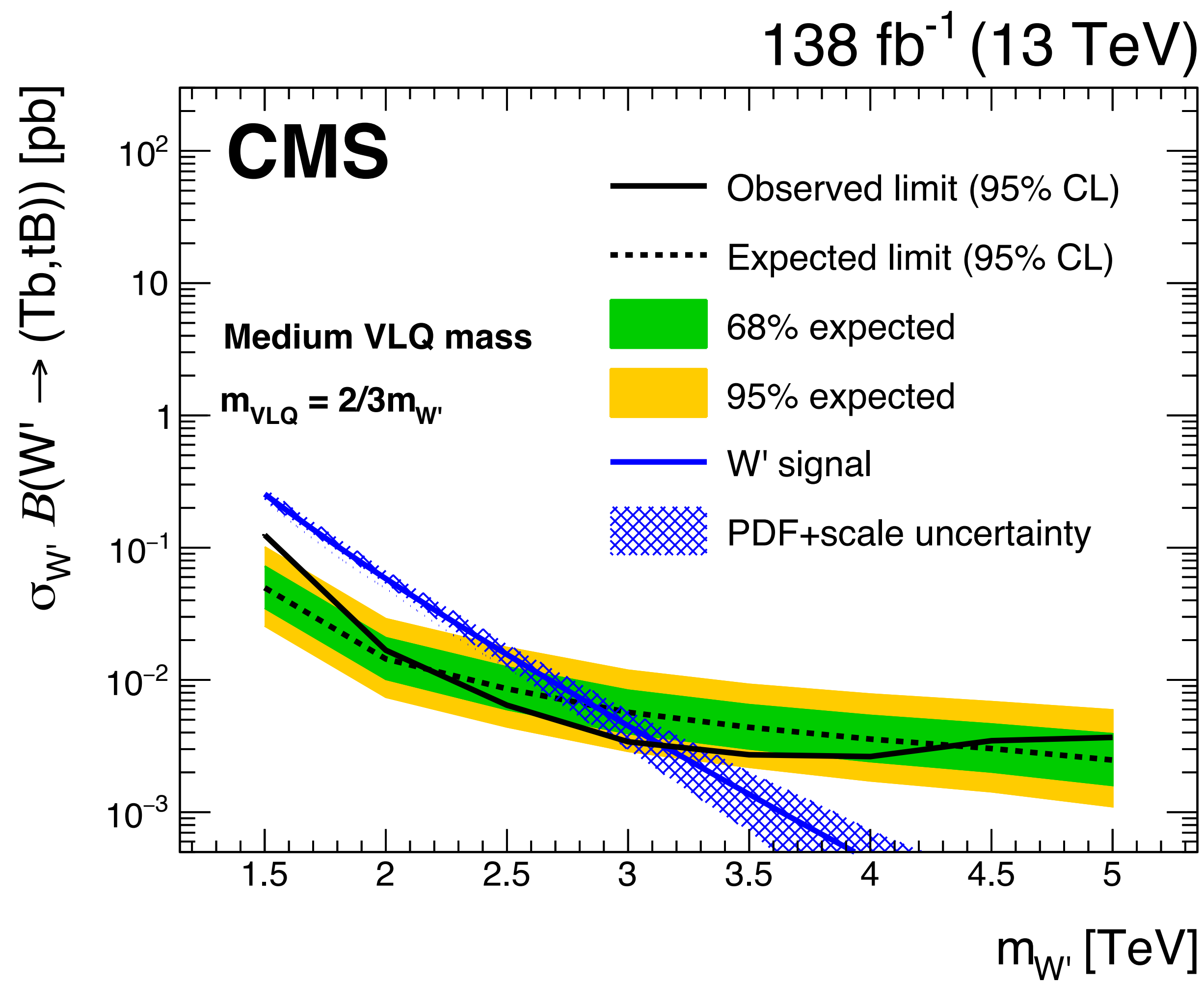


Image: K. Nash

- All-hadronic search for tbH or tbZ resonances
  - Sensitive variable: 3-jet mass
- ImageTop with mass decorrelation for top tagging
- Double-b for H and τ_{21} for Z jets





[CMS 2202.12988]

Leptoquarks

- Nature of possible LQs
  - Model dependent
  - Additional constraints from $B(B \to K\nu\nu)$, Δm_{Bs}, $D_{(s)} \to \mu\nu$…
  - Global fits to flavour data: suggest at least one LQ state with mass O(1-3) TeV

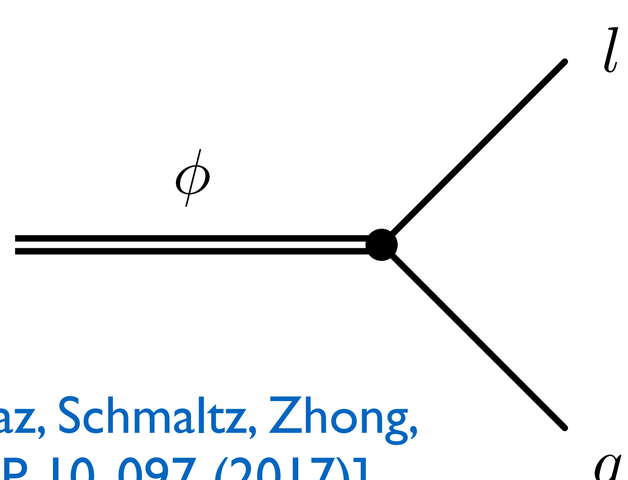
	Y	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
scalar	1/3	S_1	✗*	✓	✗*
	7/6	R_2	✗*	✓	✗
	1/6	$\widetilde{R}_2$	✗	✗	✗
	1/3	S_3	✓	✗	✗
vector	2/3	U_1	✓	✓	✓
	2/3	U_3	✓	✗	✗

Combinations of scalar LQs can explain $R_{K(*)}$ and $R_{D(*)}$, e.g. S_1 and S_3

[Angelescu et al., JHEP 10, 183 (2018)]

Loop-induced LQ-top couplings

- Probe the full flavour matrix!



[Diaz, Schmaltz, Zhong, JHEP 10, 097 (2017)]

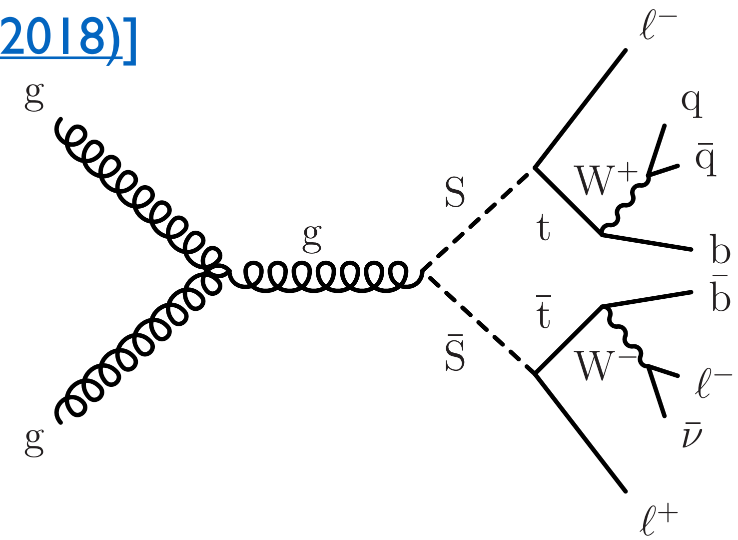
$$Y_{L,R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y^{c\mu}_{L,R} & Y^{c\tau}_{L,R} \\ 0 & Y^{t\mu}_{L,R} & Y^{t\tau}_{L,R} \end{pmatrix}$$

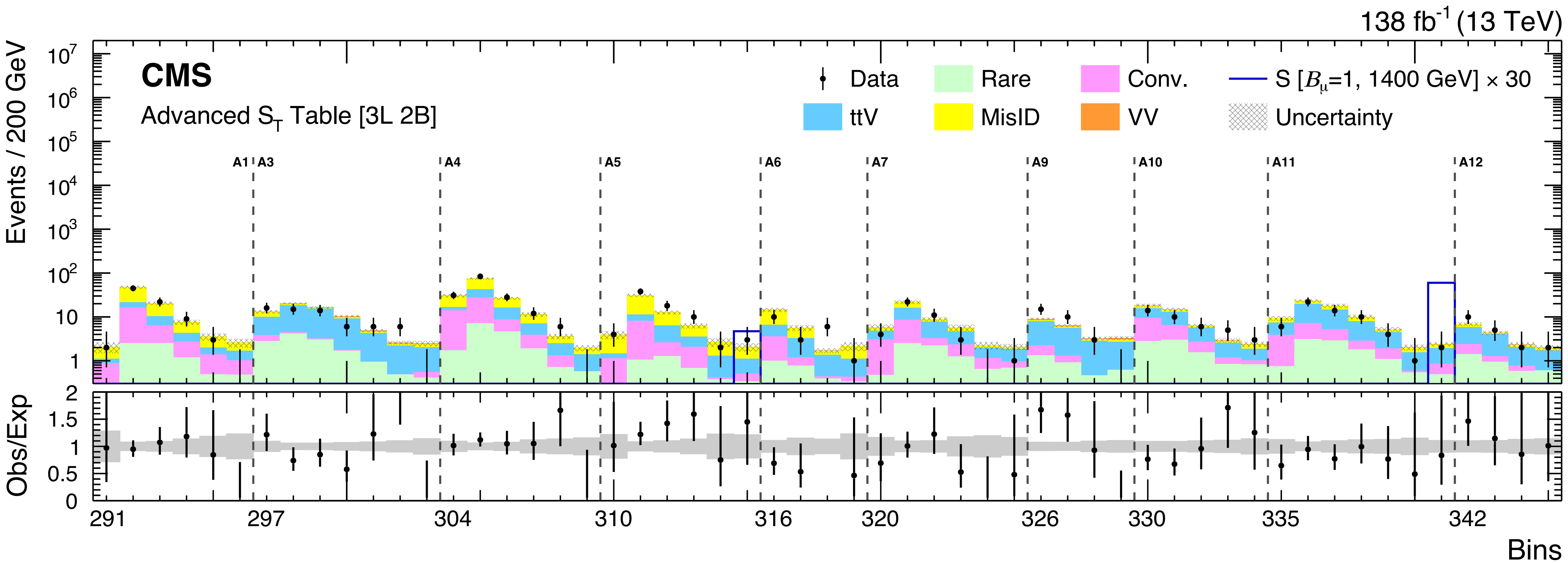
and $\ell_i \to \nu_i$

	j	b	t
ν			
ℓ			
τ			

LQ Pair Production

- Dedicated searches for tτ and tμ [CMS PRL 121, 241802 (2018)] as well as tνbτ [CMS PLB 819, 136446 (2021)]
- Inclusive search for multilepton final states
- Non-resonant: no mass reconstruction
  - BDTs for signal enhancement after selection



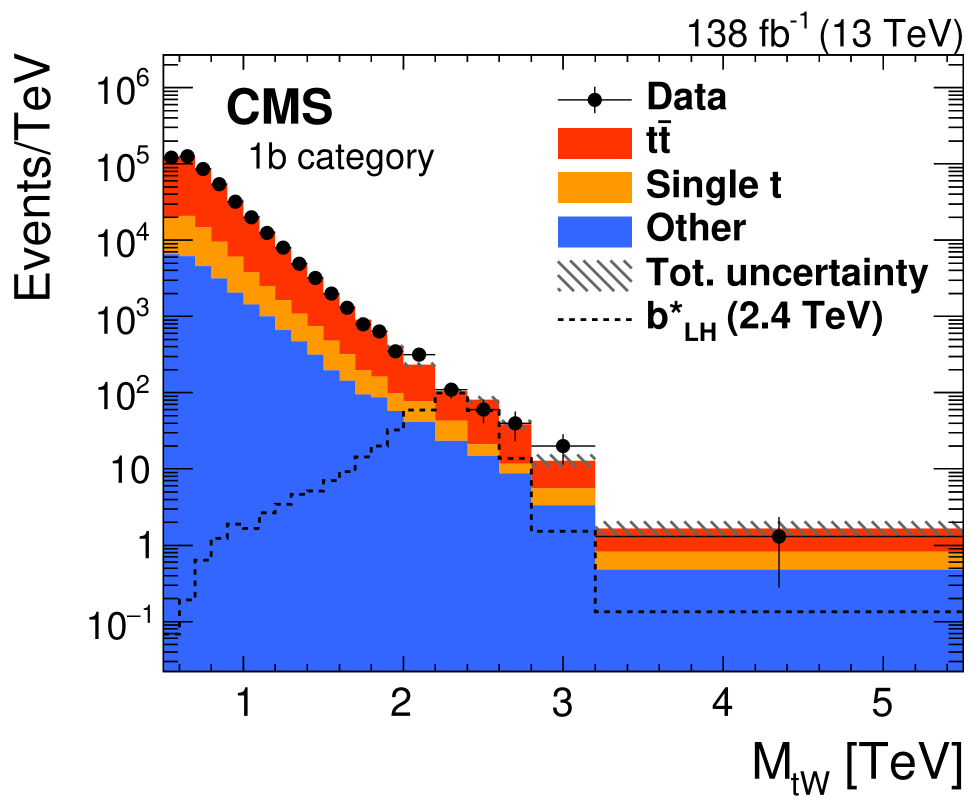


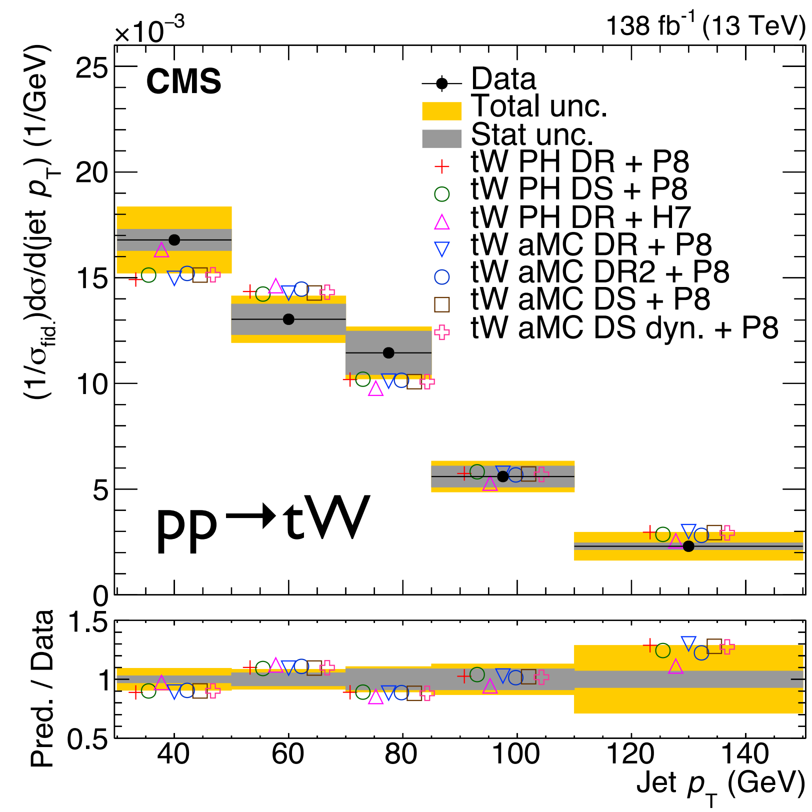
- m_S > 1340 (te), 1420 (tμ), and 1120 (tτ) GeV at 95% CL

[CMS PRD 105, 112007 (2022)]

Summary

- We continue to push the boundary of sensitivity with direct searches
- Many more Run 2 searches in progress
- Consolidate local excesses with orthogonal searches and new data
- Run 3 data taking in progress!



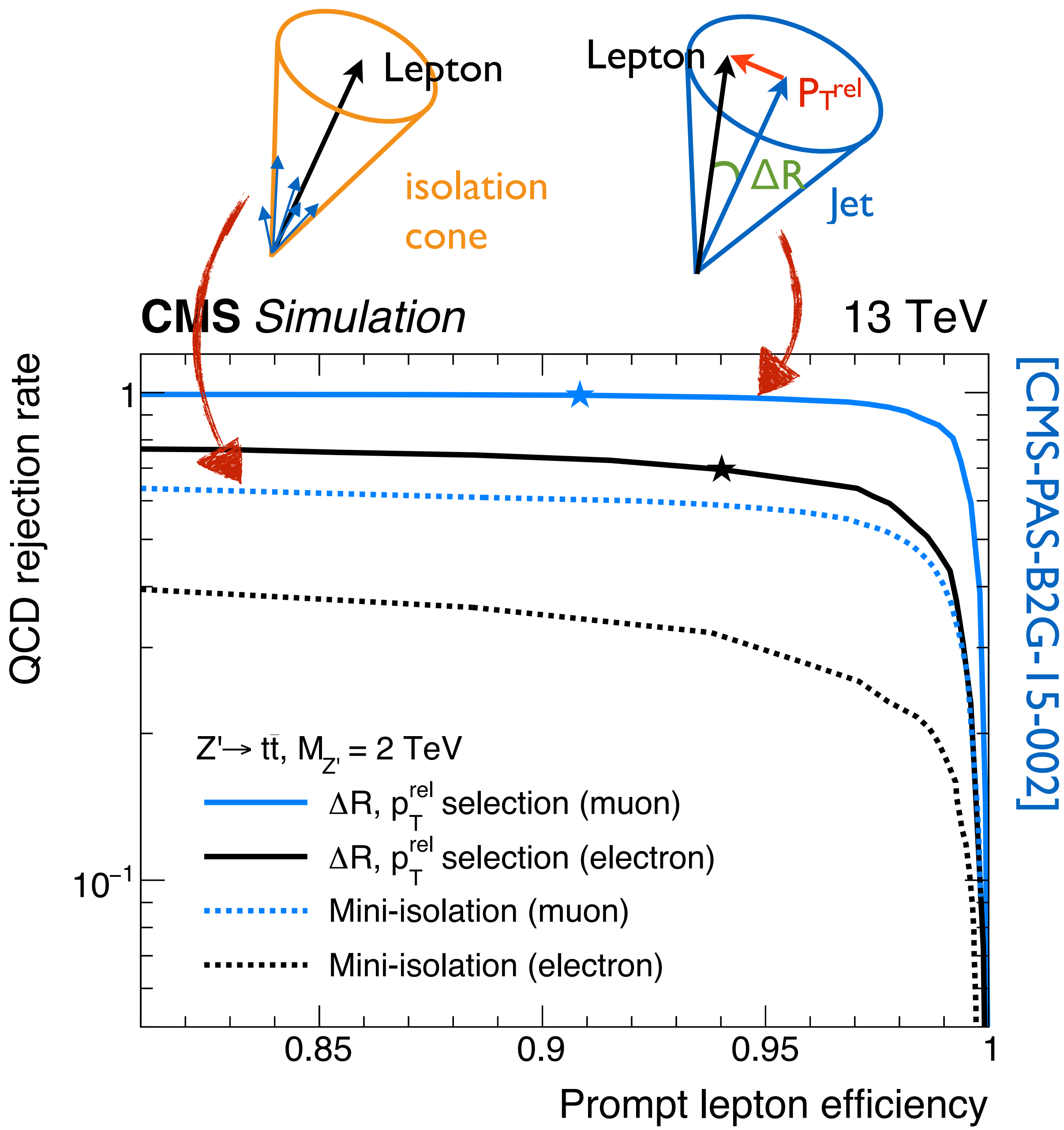


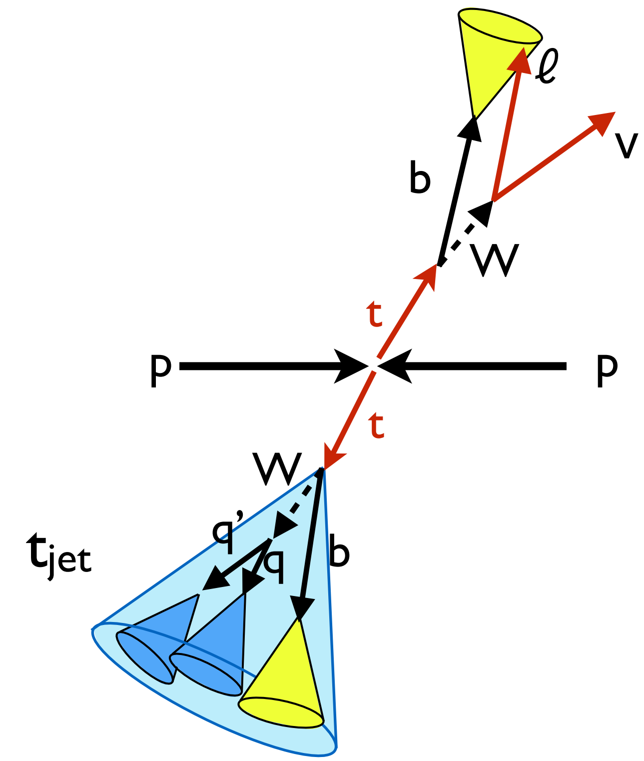
[CMS 2208.00924]

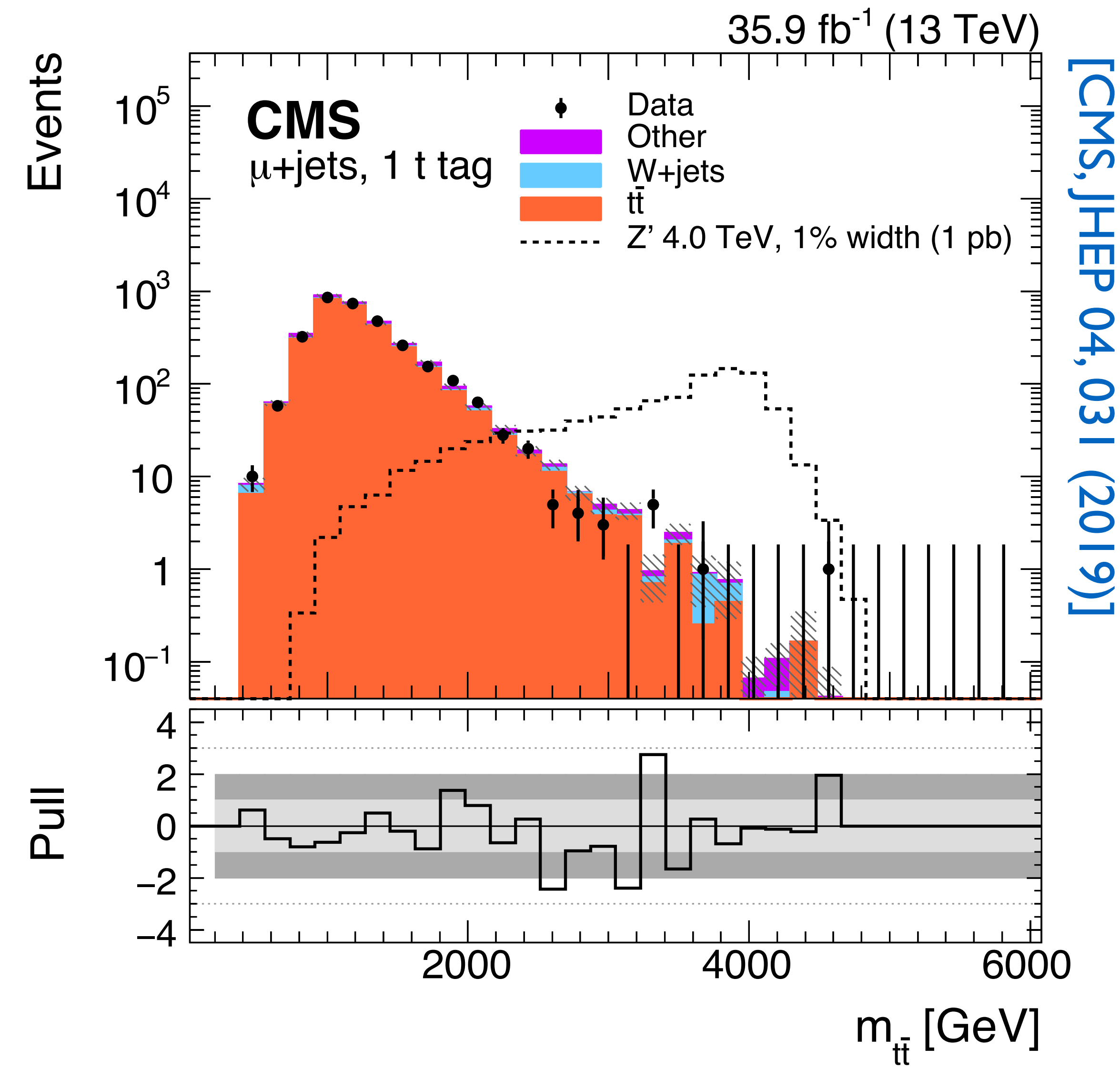
Exploit the complementarity between
direct searches and measurements (not only with EFTs)

Additional Material

$t\bar{t}$ Resonances

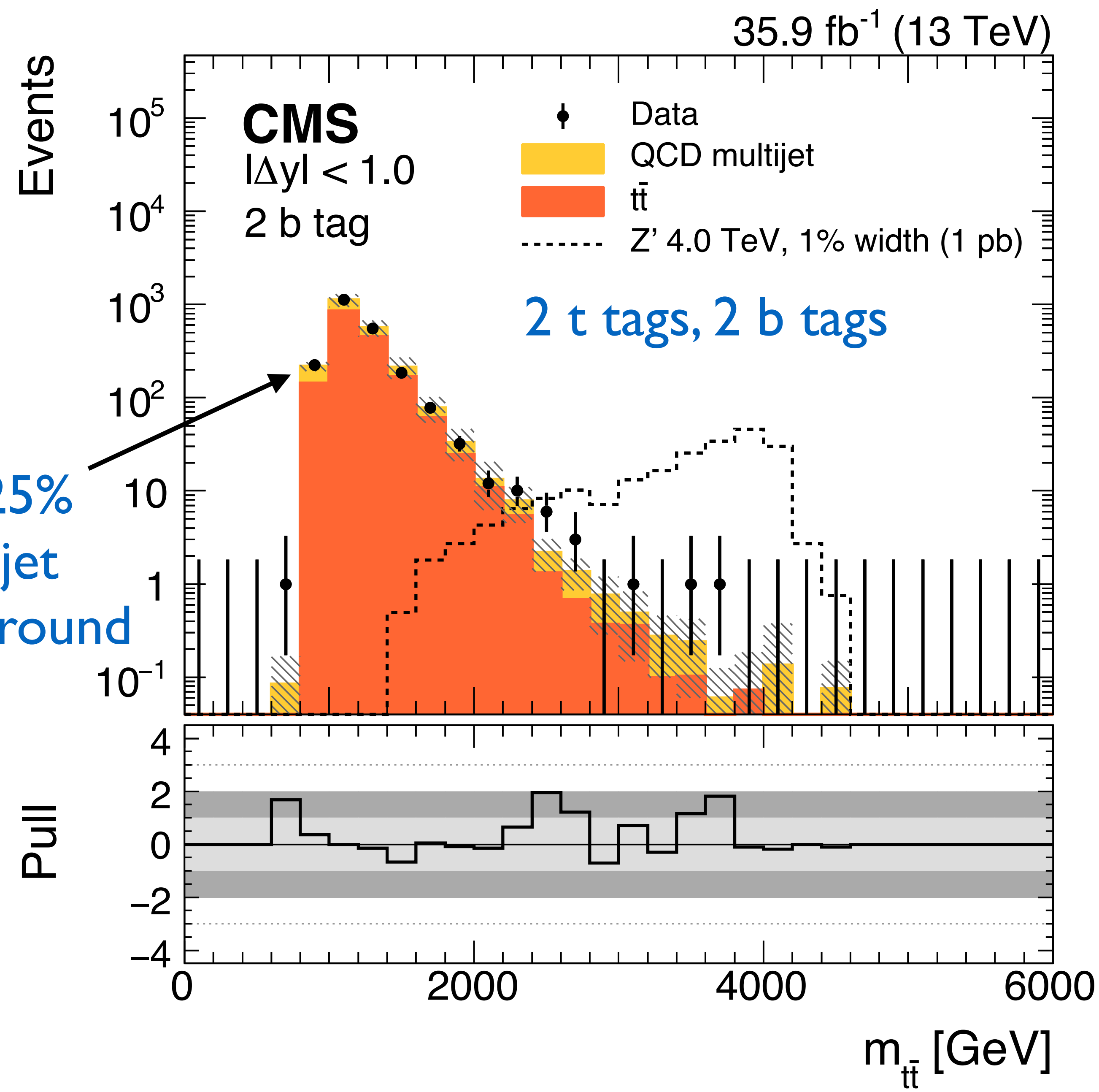




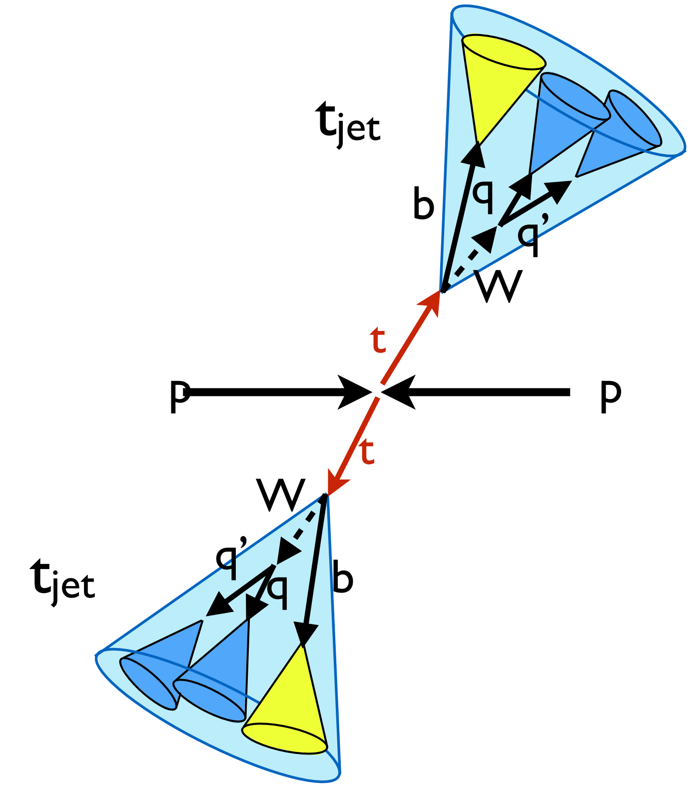


- improved PU mitigation, b-tagging
- BDT for W+jet suppression
- CRs to constrain backgrounds

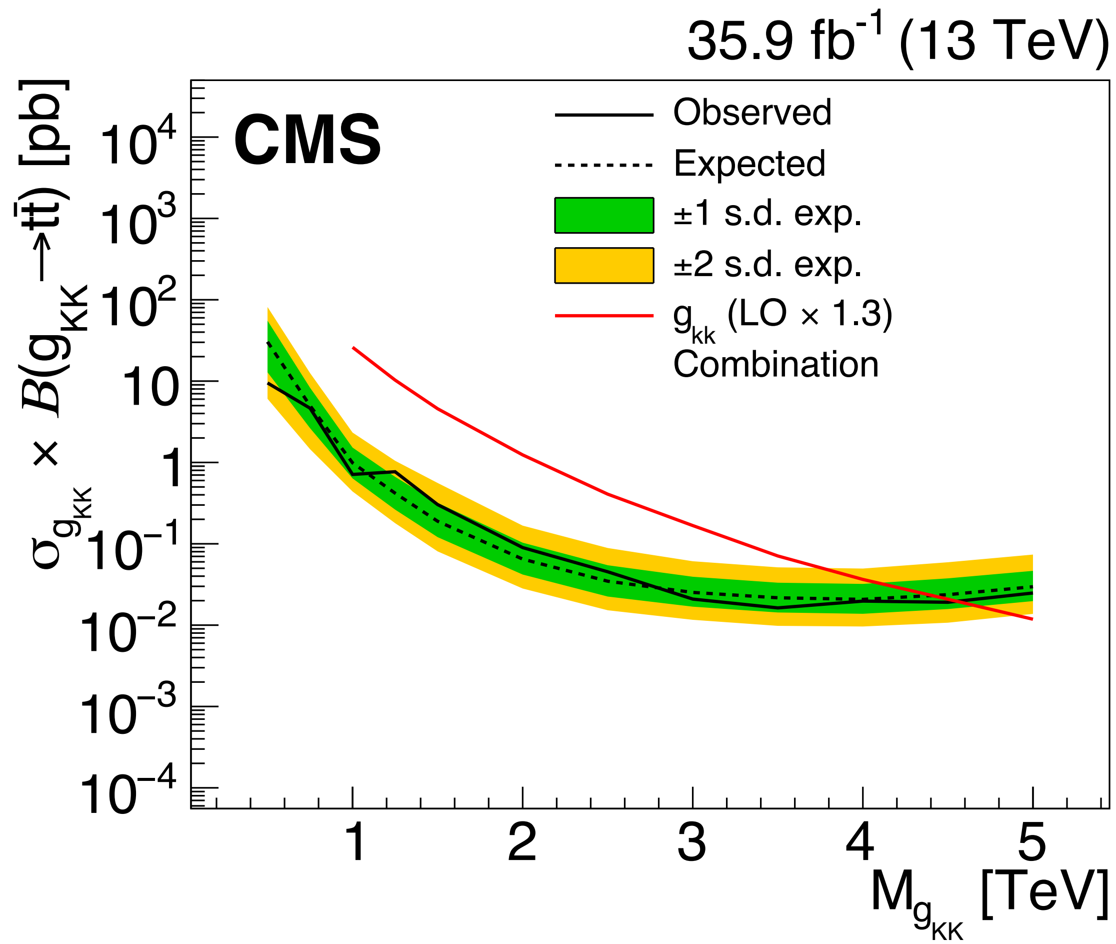
$t\bar{t}$ Resonances



only 25% multi-jet background



[CMS, JHEP 04, 031 (2019)]

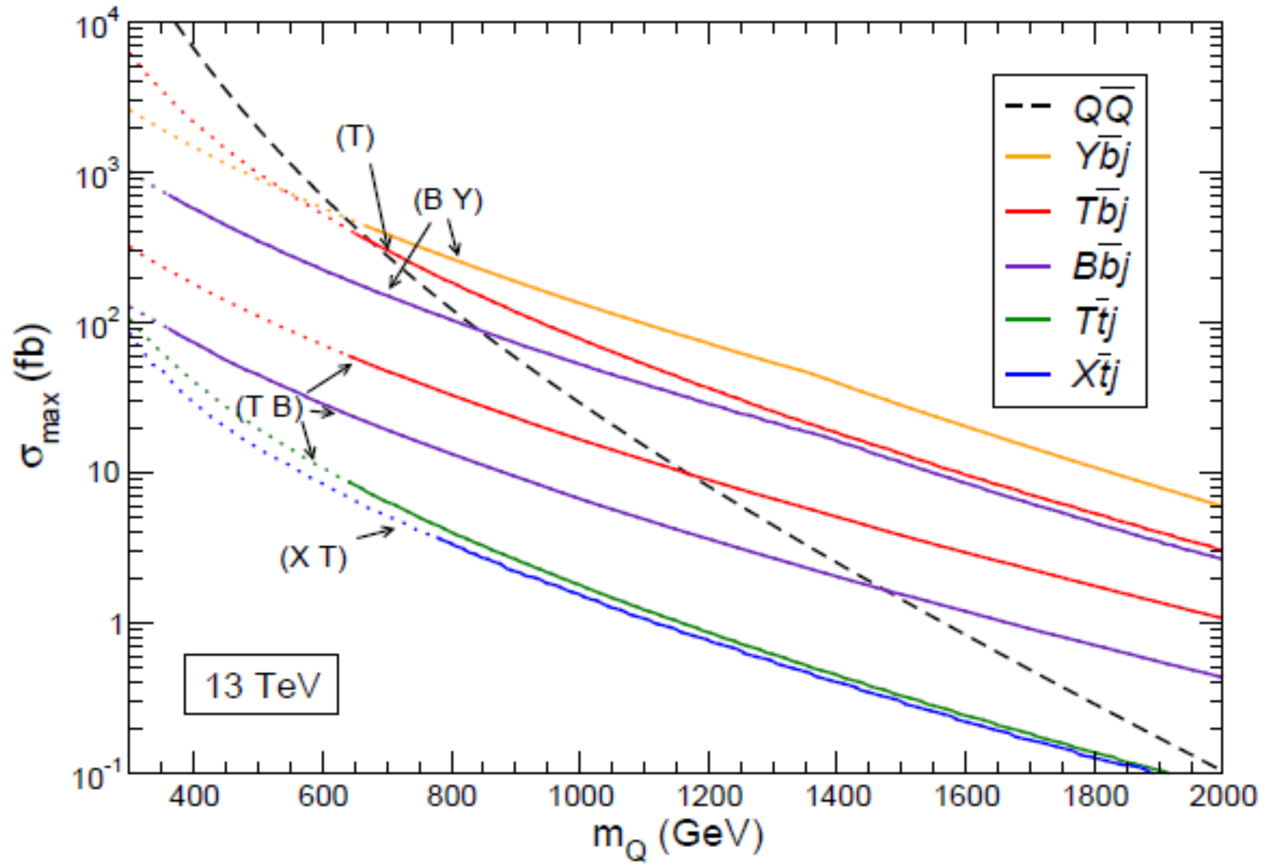


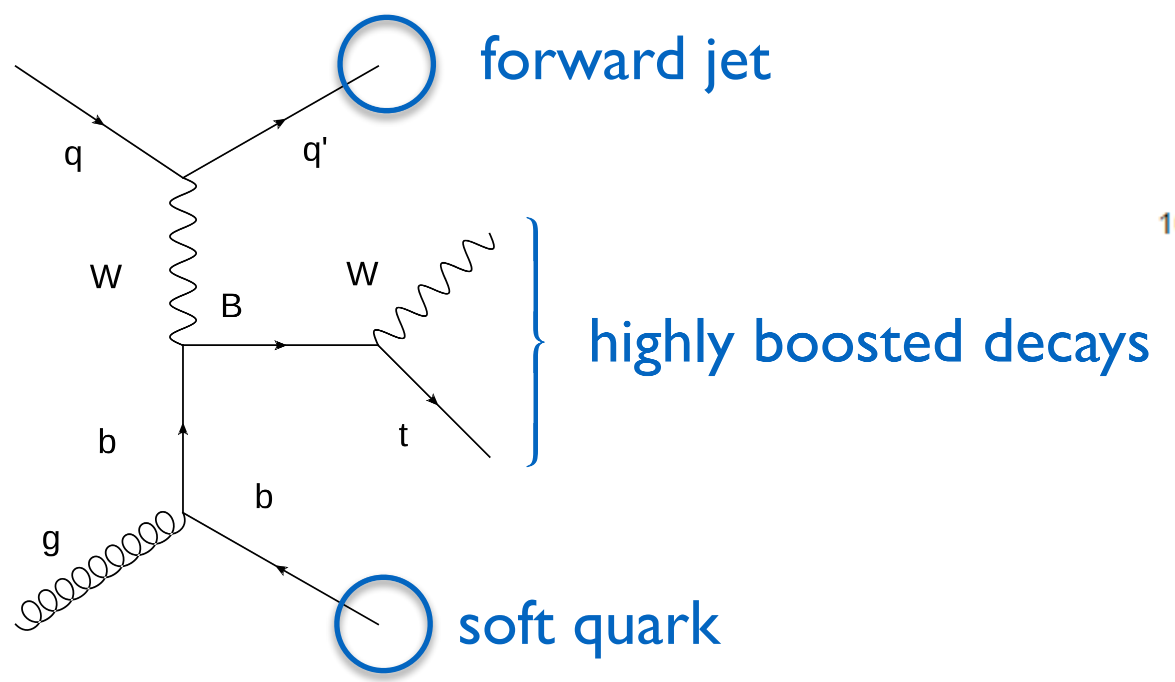
Combination of $\ell\ell$, ℓ+jets and all-hadronic channels:
Kaluza-Klein gluons excluded below **4.6 TeV**

VLQ Single Production

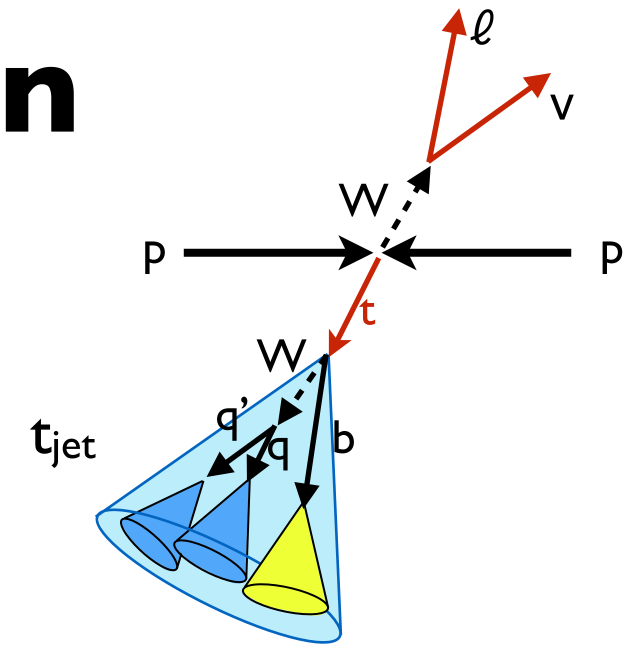
- Electroweak production can dominate for heavy VLQs
- Model dependent cross section:
  - Couplings (mixing parameters)
  - Weak quantum numbers
- Signature: one forward jet and associated production with a heavy quark

[J.A. Aguilar-Saavedra et al., PRD 88, 094010 (2013)]



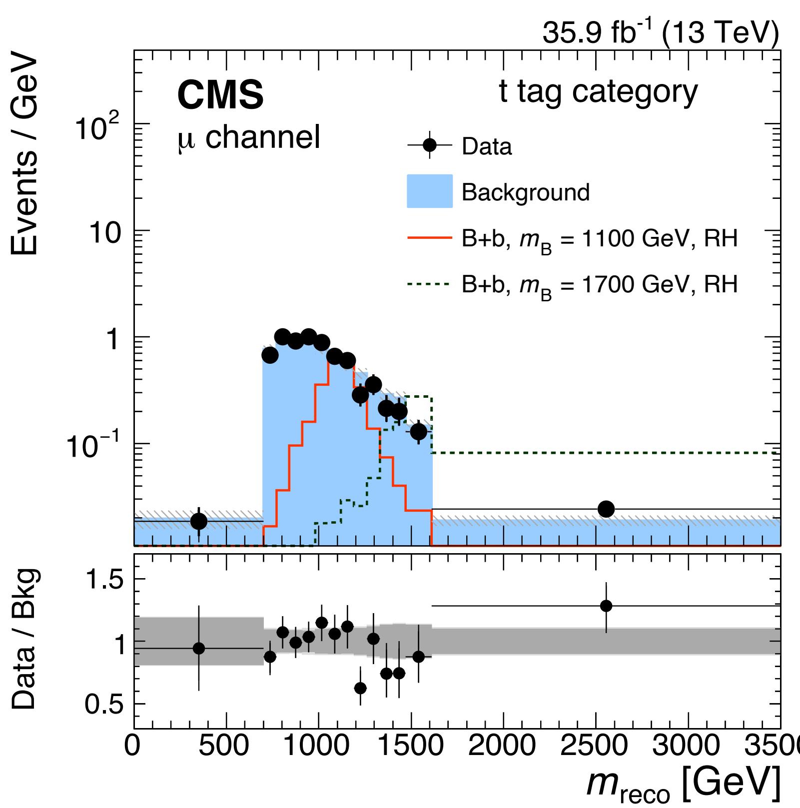


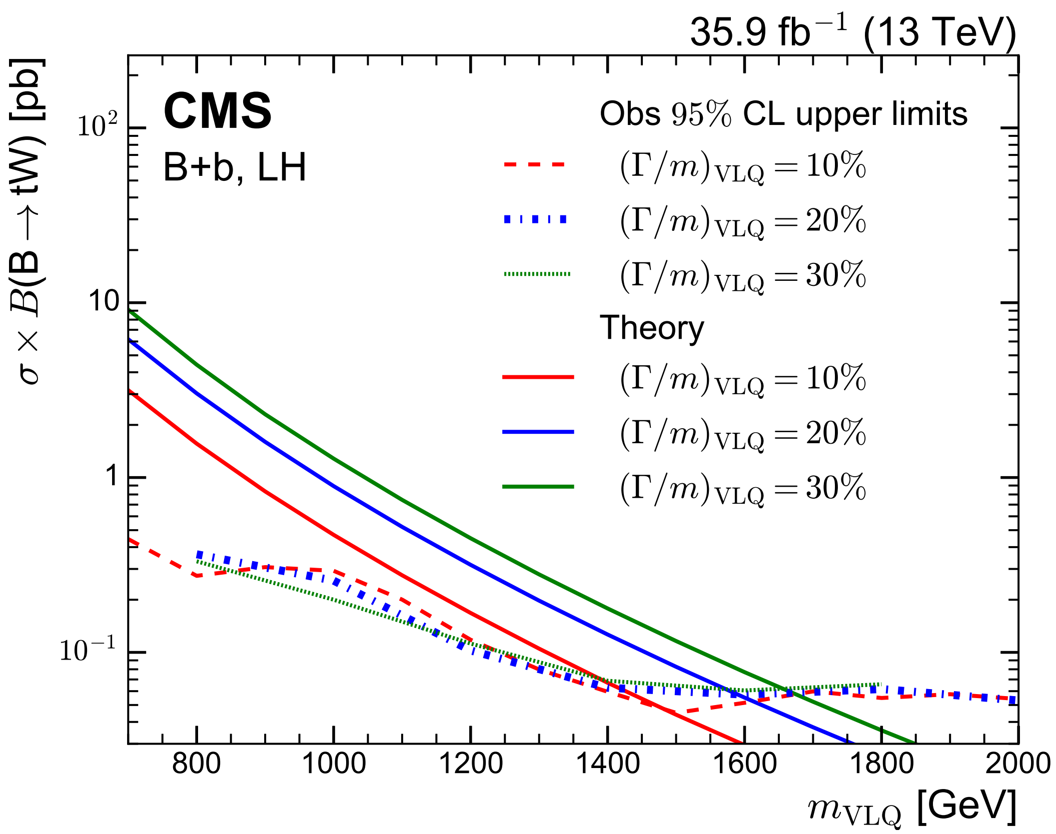
VLQ Single Production



Single B→tW (ℓ+jets)

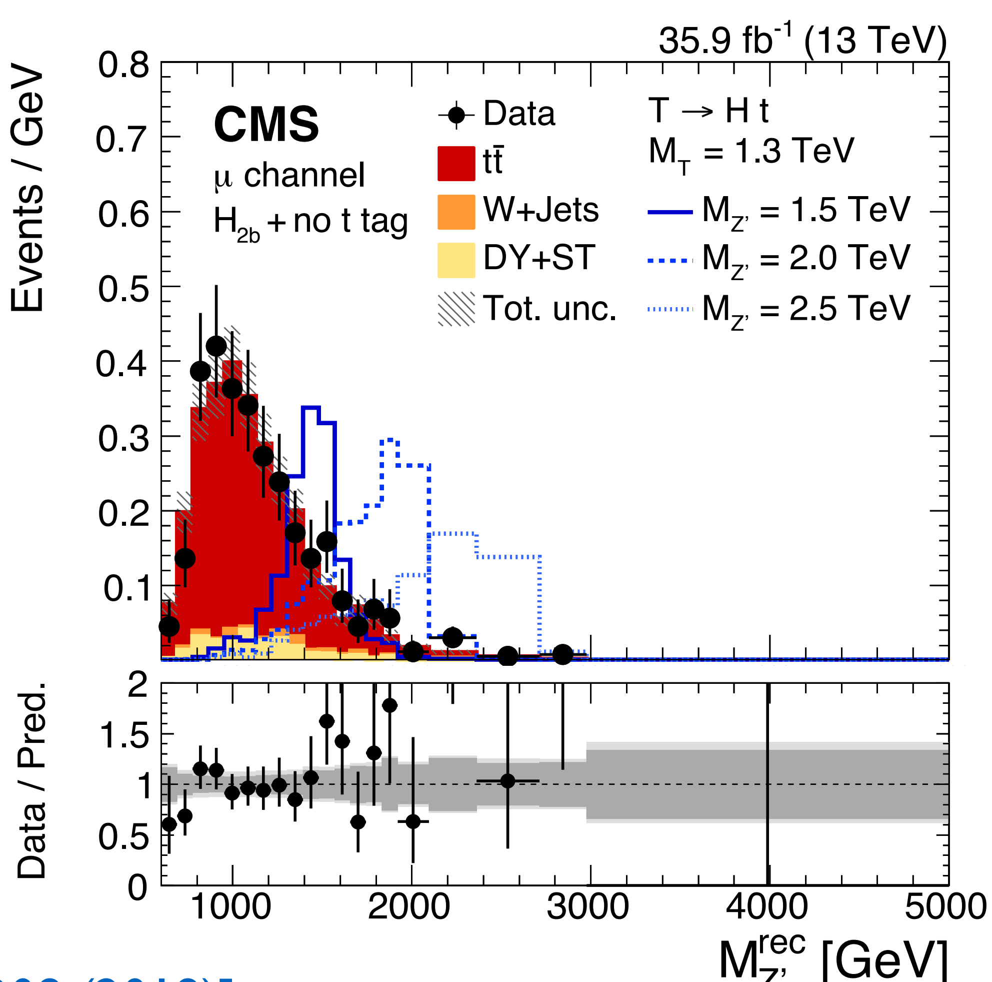
- Various decay possibilities
  - Jet assignment through t tag or χ^2 probabilities
  - VLQ mass reconstruction with ~10% resolution
- SM backgrounds from control region without forward jet
  - Validation region: small χ^2 values

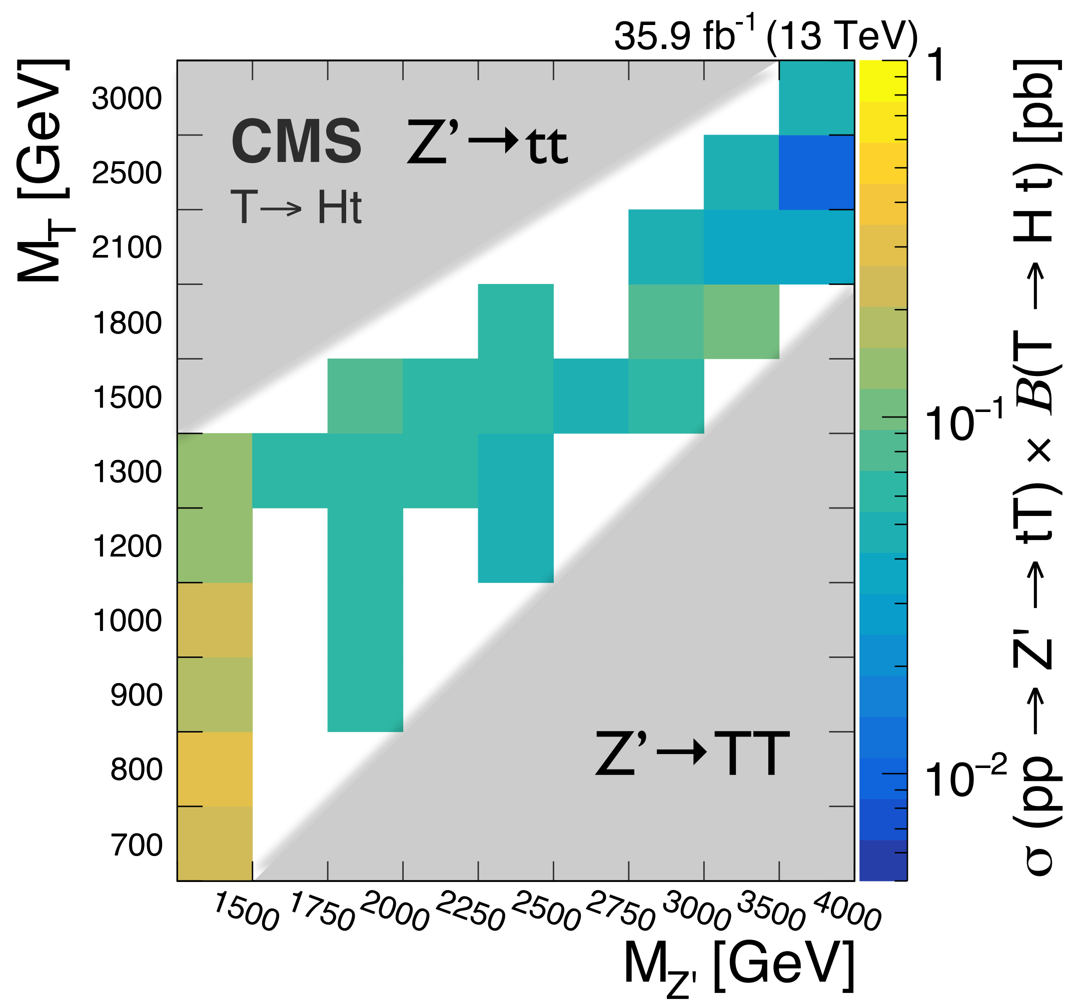




Resonant VLQ Production

- Search with Z/W/H/t tags
  - Validation of efficiency and mis-identification rates
- Z' reconstruction through minimum of χ^2 term
- Constrain dominant backgrounds from control regions (W+jets, $t\bar{t}$)





[CMS EPJC 79, 208 (2019)]

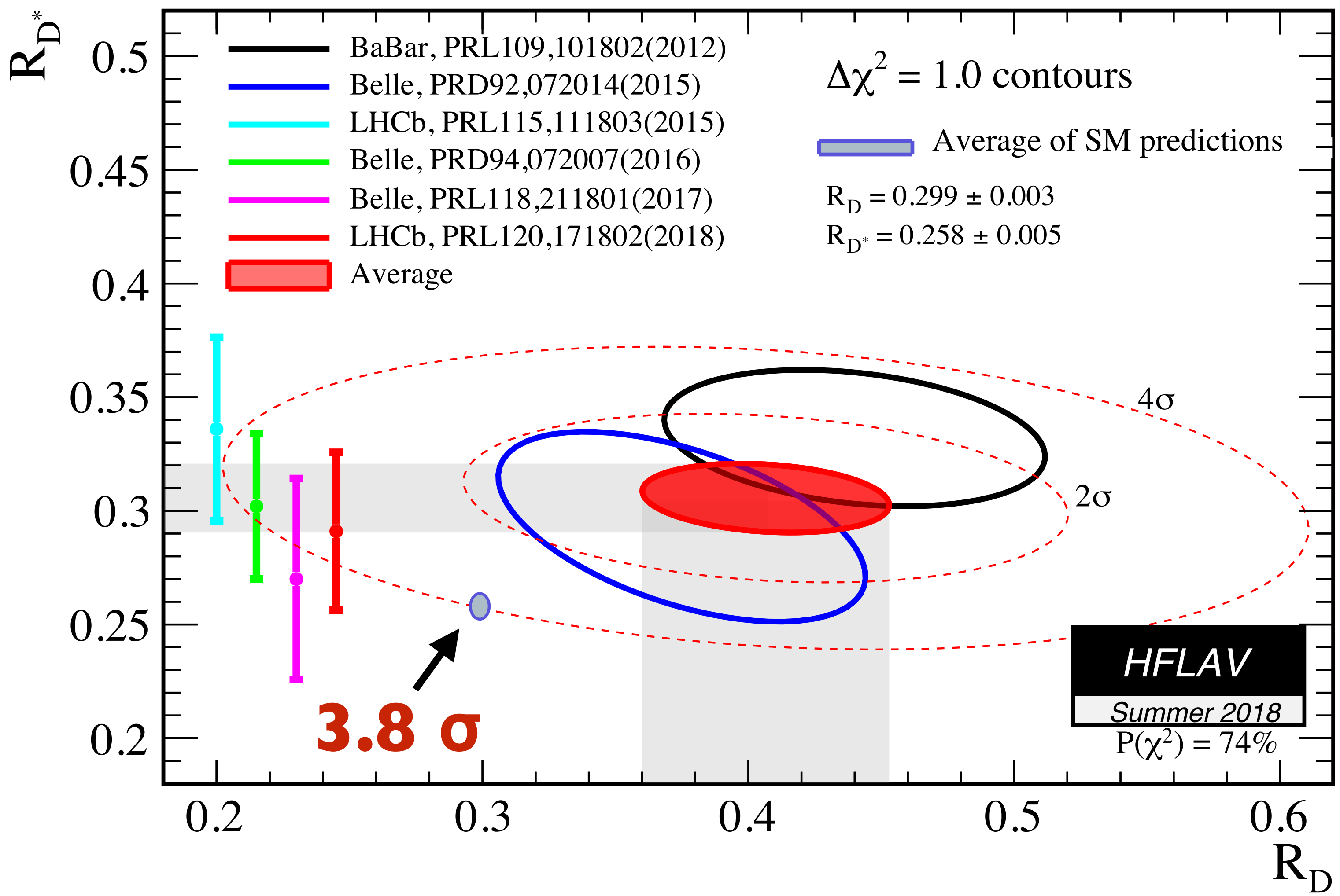
The Intriguing Flavour Story

- No hints for BSM effects from direct searches so far
  - Never stop looking for all (im)possible signatures
- We can get inspired by existing riddles
  - Anomalies in flavour data:

$R_{D^{(*)}} = \left.\dfrac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})}\right\vert_{l\in\{e,\mu\}}$	BaBar, Belle, LHCb	**3.8 σ**
$R_{J/\psi} = \dfrac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu})}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})}$	LHCb	**2.0 σ**
$R_{K^{(*)}}^{[q_1^2,q_2^2]} = \dfrac{\mathcal{B}'(B \to K^{(*)}\mu\mu)}{\mathcal{B}'(B \to K^{(*)}ee)}$	LHCb	**−2.5 σ**
$(g-2)_\mu$	E821, BNL	**3.5 σ**

Consequences at high p_T?

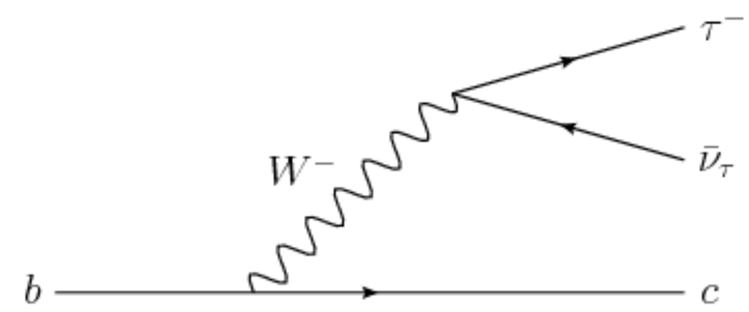
$R_{D^{(*)}}$ and $R_{J/\psi}$



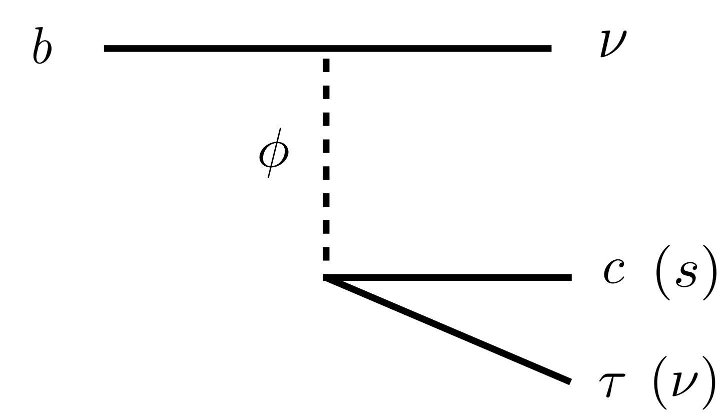
[HFLAV, EPJC77, 895 (2017)]

- Uncertainties in SM prediction
  - form factors for τ vs ℓ decay ~ m_τ
  - strong decay of D*
  - soft photon corrections
  - **total: ~4-5%**

SM weak decay



Possible BSM contribution from LQs



[Bauer, Neubert, PRL 116, 141802 (2016)]

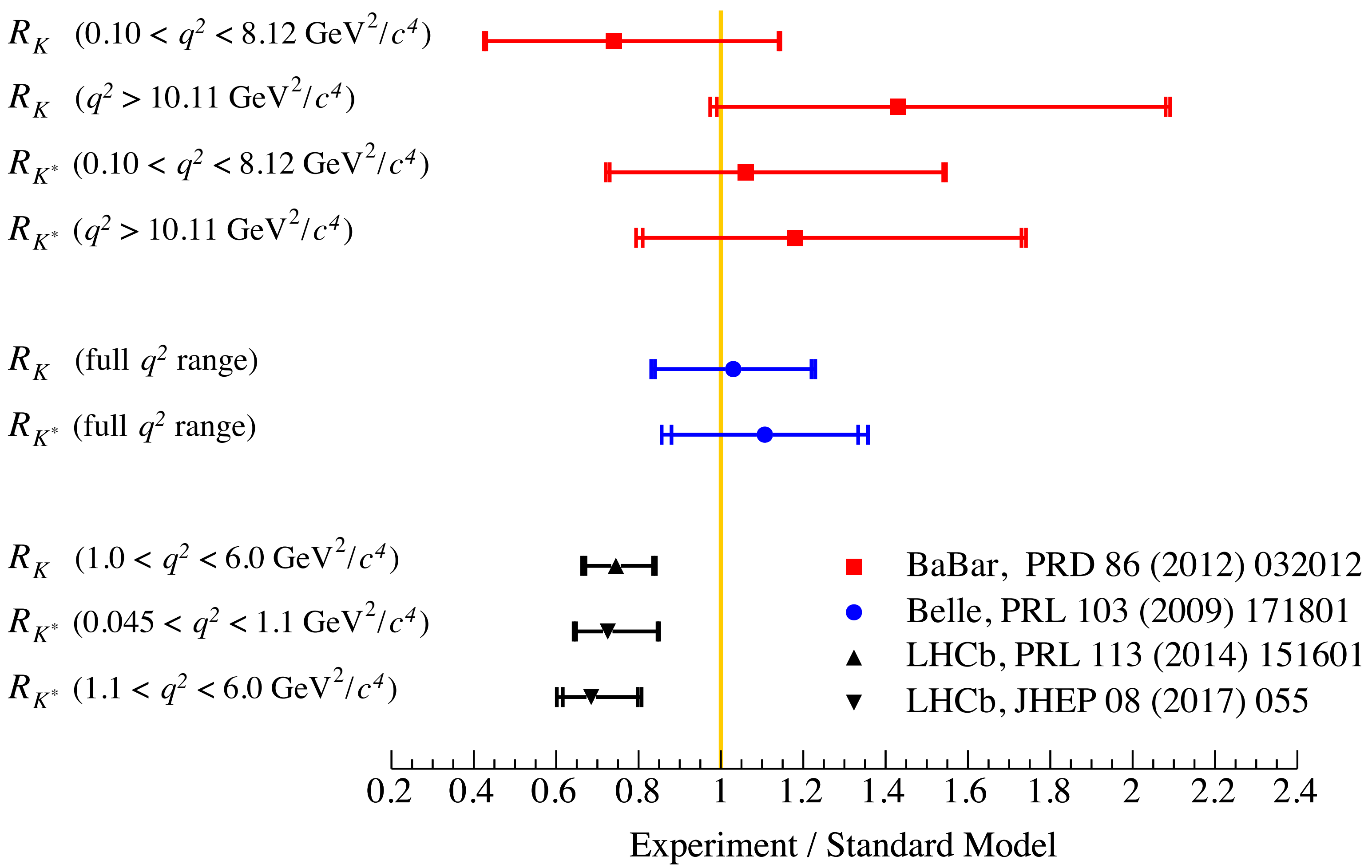
LQ couplings

tree-level: **bτ, cν, cτ, bν**

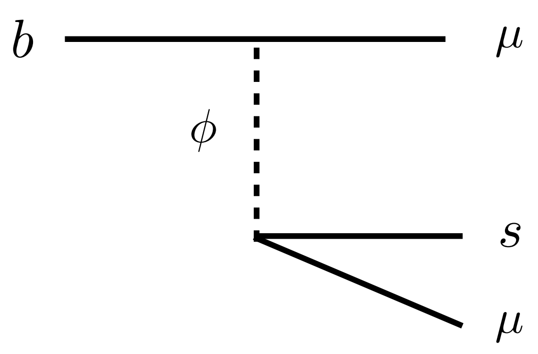
loop: **tτ, sν, sτ, tν**

$R_{K(*)}^{[q_1^2,q_2^2]}$

[Bifani et al.,arXiv:1809.06229]

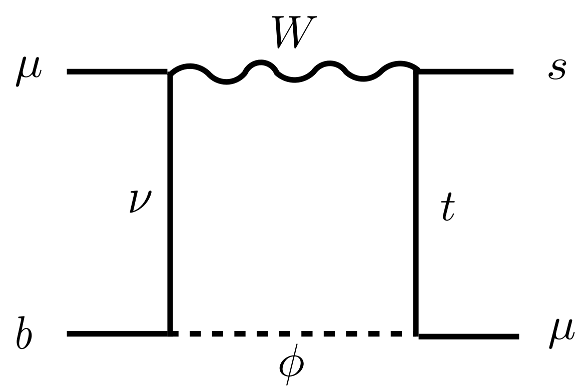


- Hadronic effects negligible
  - except with LFUV, then could have an effect
- LHCb measurements below SM by 2.1 - 2.6σ



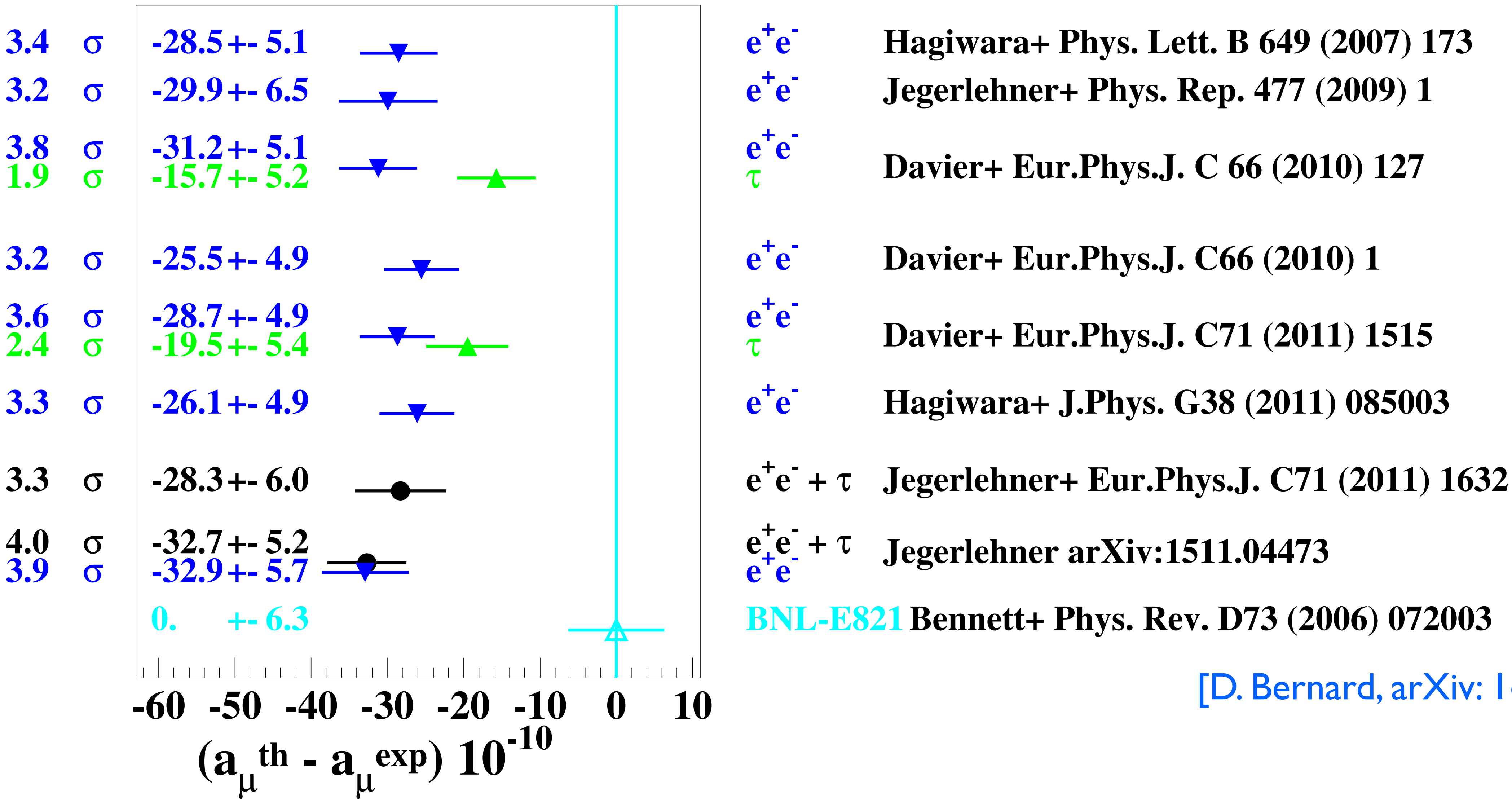
LQ couplings at tree-level: **sμ, bμ**

Can lead to enhancement of SM prediction



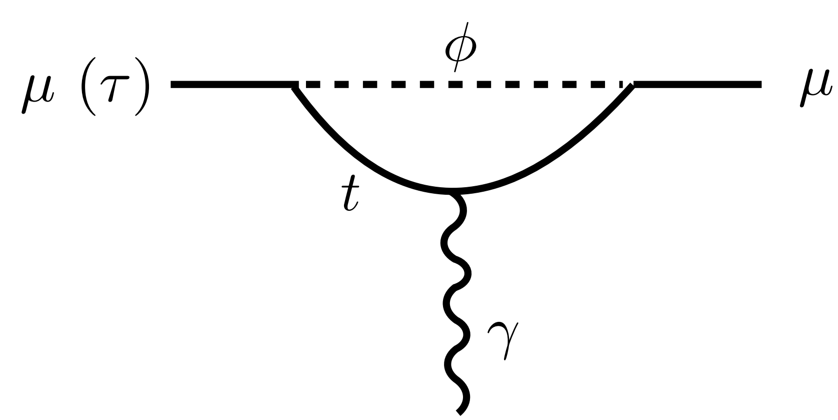
LQ couplings loop-induced: **tμ, cμ**

$(g-2)_\mu$



[D. Bernard, arXiv: 1607.07181]

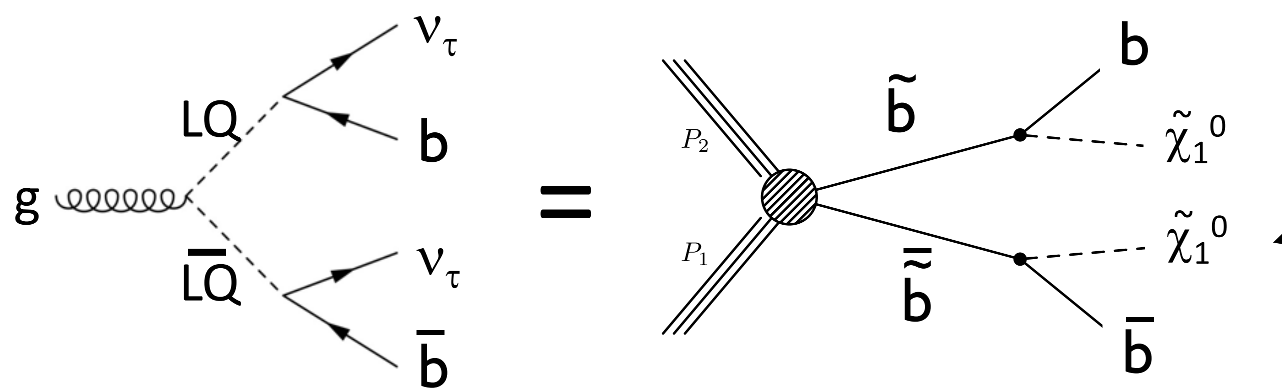
- About 3σ deviation, depending on $\Delta\alpha_{had}$ (e^+e^- or τ decays)
- LQ couplings loop-induced: **tμ**



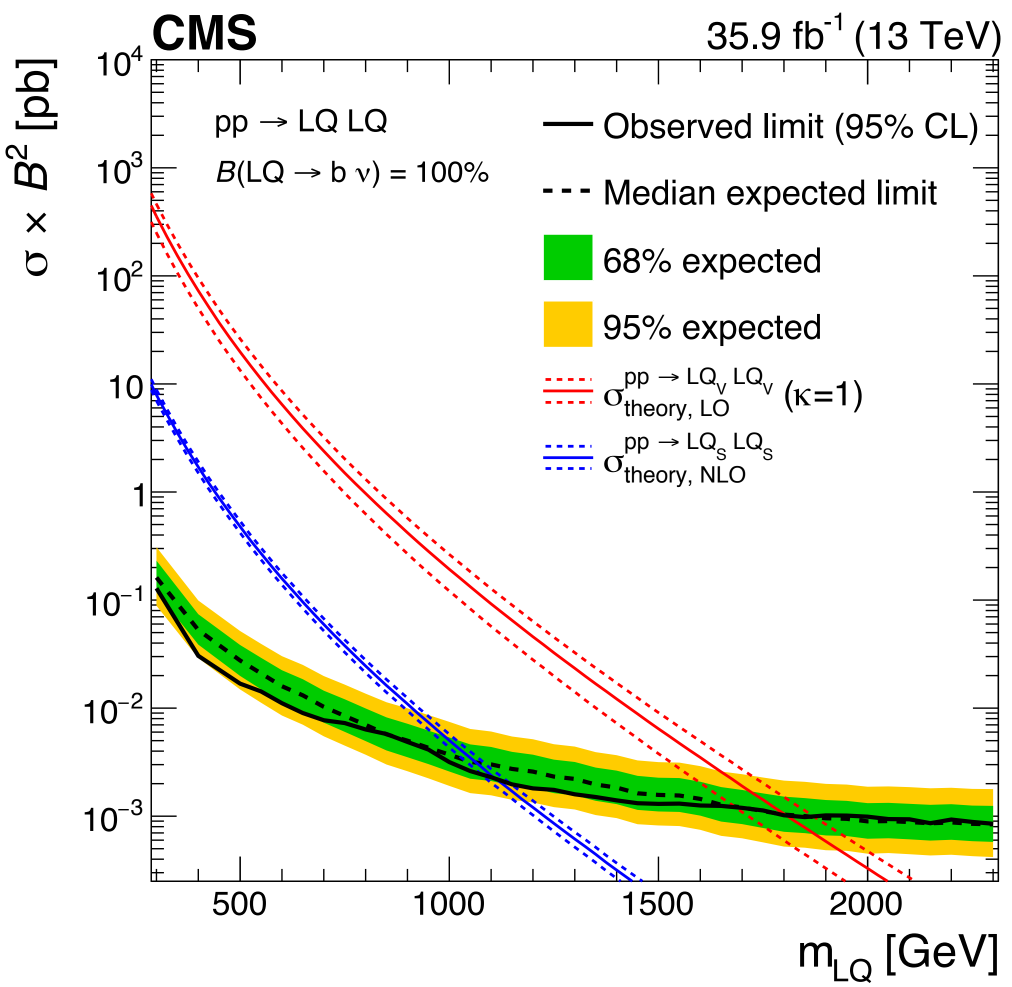
LQ Pair → νν+b$\bar{b}$(q$\bar{q}$)

[CMS, PRD 98, 032005 (2018)]

- Reinterpretation of SUSY M_{T2} sbottom search



Both $\tilde{b}$ and LQ are scalar
→ Equivalent under
m(χ_1^0) = m(LSP) = 0



Mass exclusions

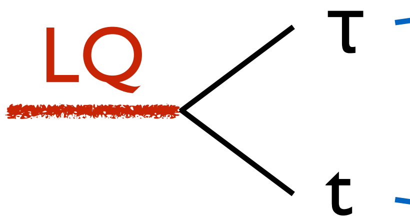
scalar LQs → bν: 1.1 TeV
vector LQs → bν: 1.8 TeV

scalar LQs → tν: 1.0 TeV
vector LQs → tν: 1.8 TeV

Relevant for $R_{D(*)}$ and $R_{K(*)}$

LQ Pair → $\tau\bar{\tau}$+$t\bar{t}$

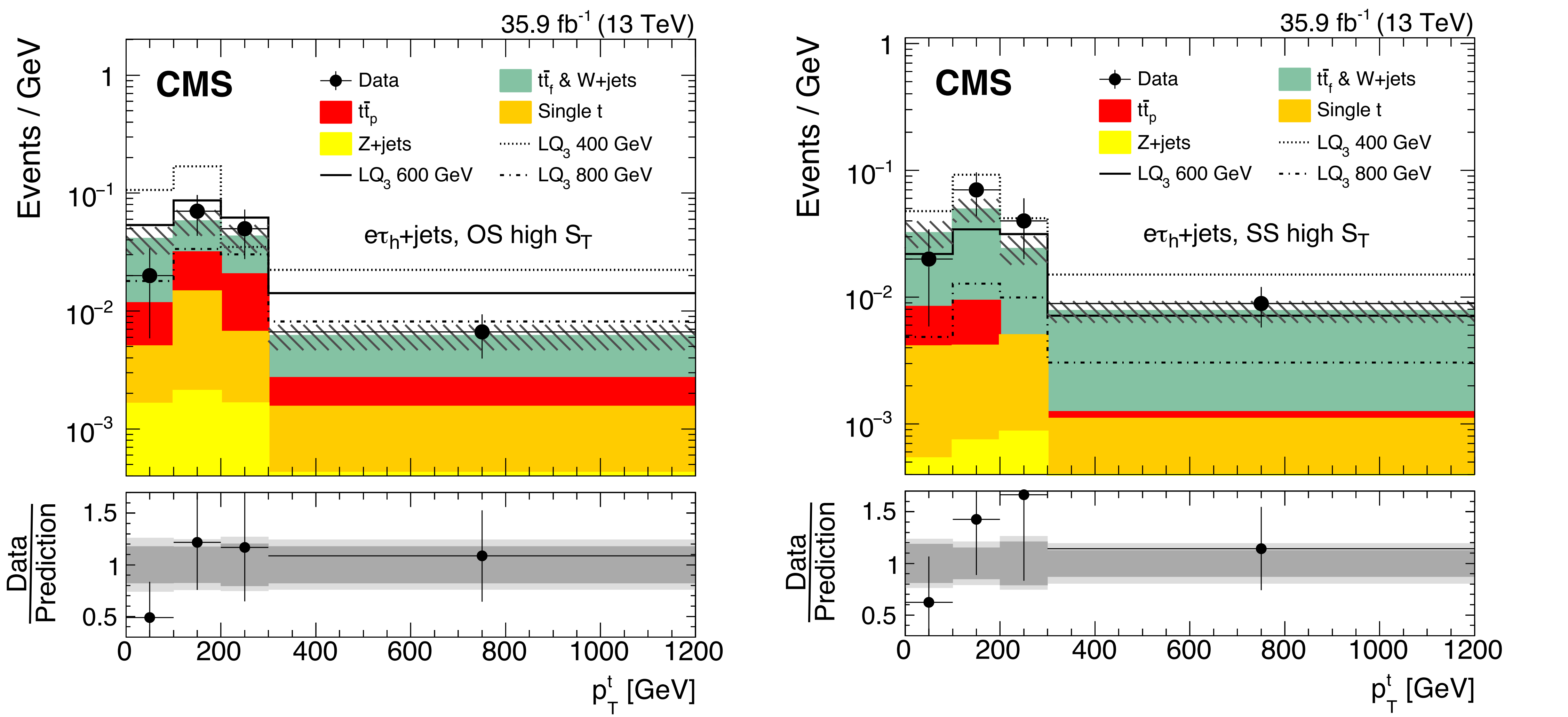
[CMS, EPJC 78, 707 (2018)]



Background estimation through ID inversion

Reconstruct top decay: p^t_T sensitive to m_{LQ}

- Cat A: ℓ + $2\tau_h$ + jets
  Sensitivity for low m_{LQ}
- Cat B: ℓ + τ_h + jets
  Sensitivity for high m_{LQ}



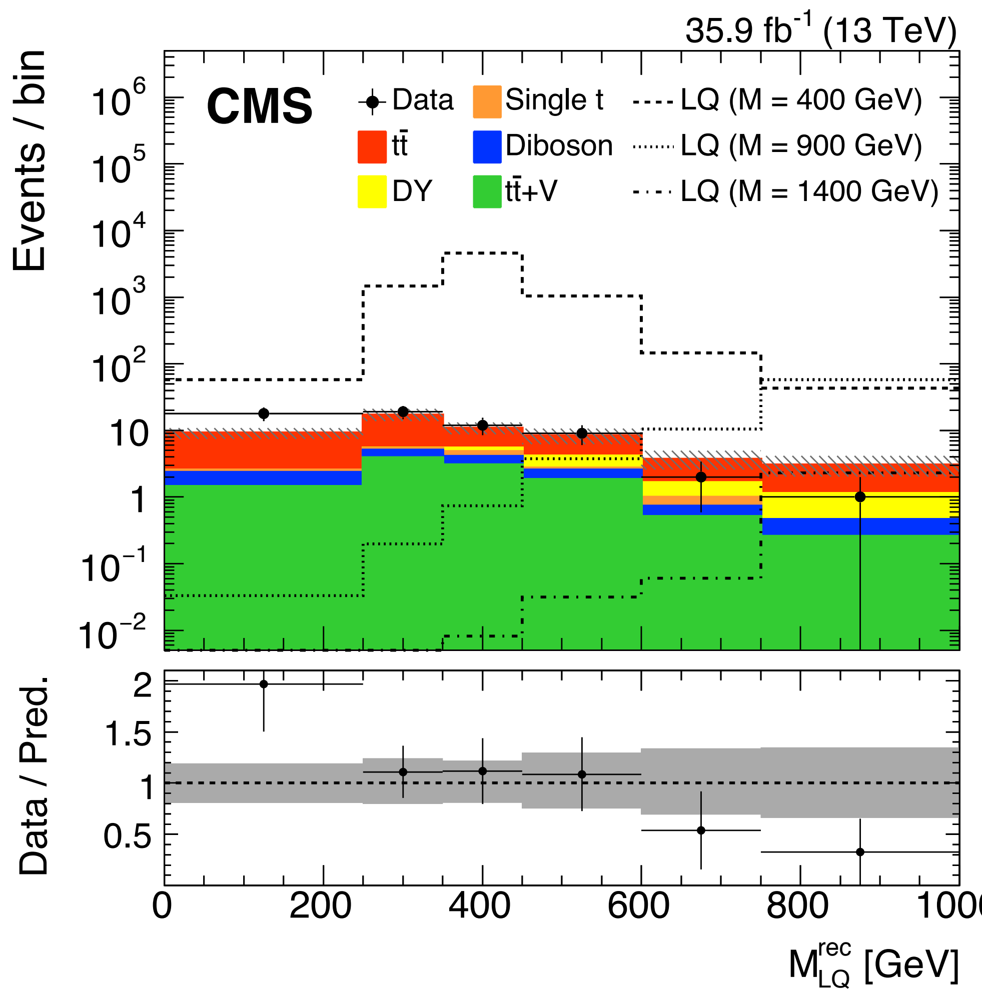
LQ Pair → $\mu\bar{\mu}+t\bar{t}$

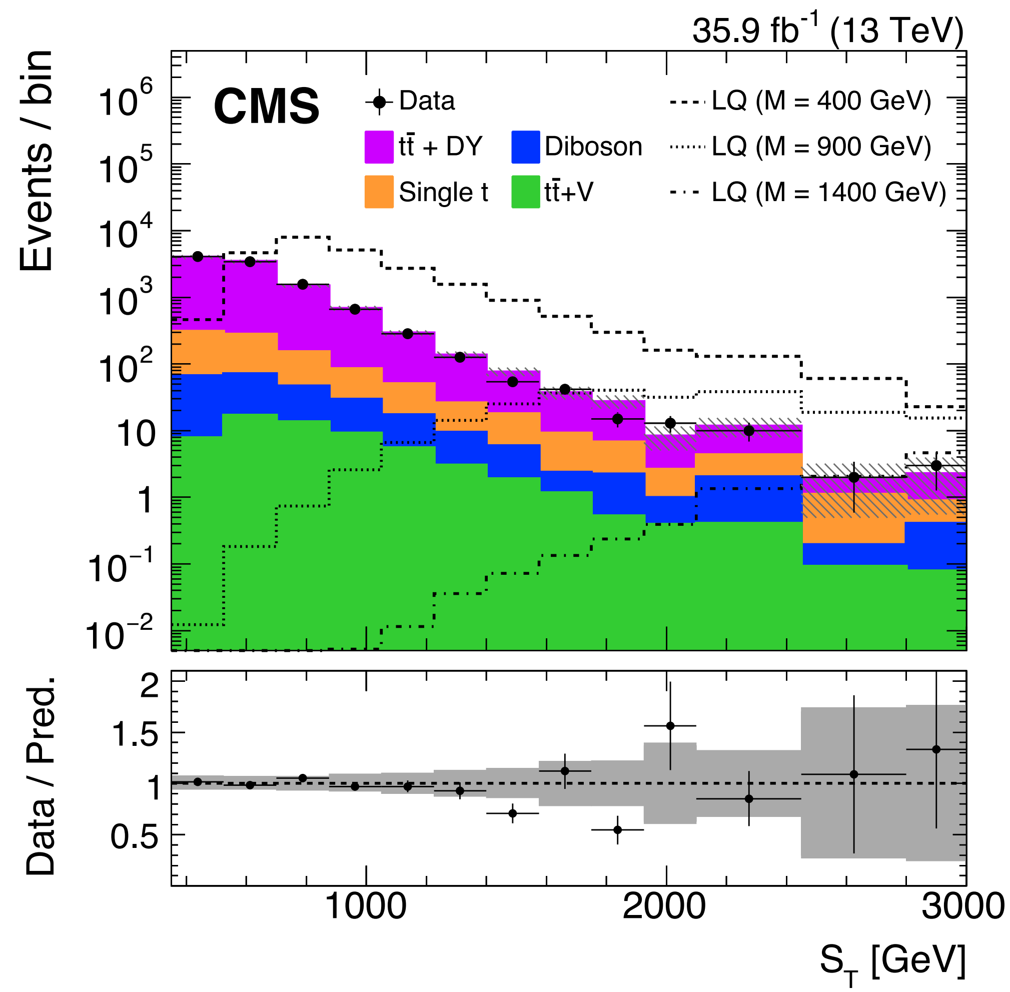
[CMS, PRL 121, 241802 (2018)]

- Up to 4 leptons in final state
  - two signal regions: $\underbrace{2\mu+\ell+\text{jets}}_{}$ and $\underbrace{2\mu+\text{jets}}_{}$

reconstruct M_{LQ} ↓ measured e and μ misID

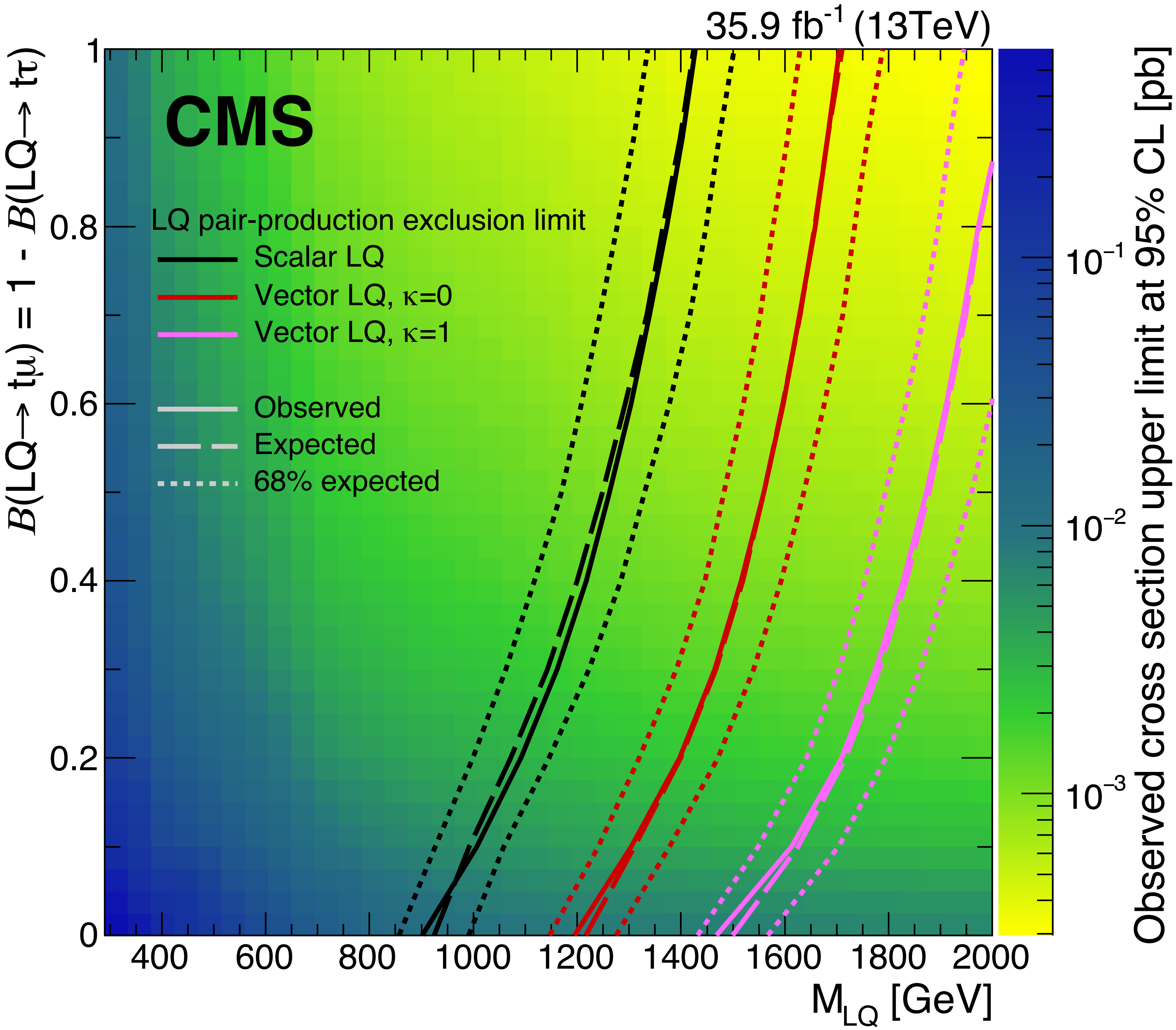
measure S_T ↓ $t\bar{t}$+DY obtained from 2e+jets CR





Combination

[CMS, PRL 121, 241802 (2018)]



Exclusion between **0.9** and **1.4 TeV** for tτ and tμ (scalar LQs)

Relevant for $R_{D(*)}$, $R_{K(*)}$ and $(g-2)_\mu$

Numerous other interesting channels to explore…