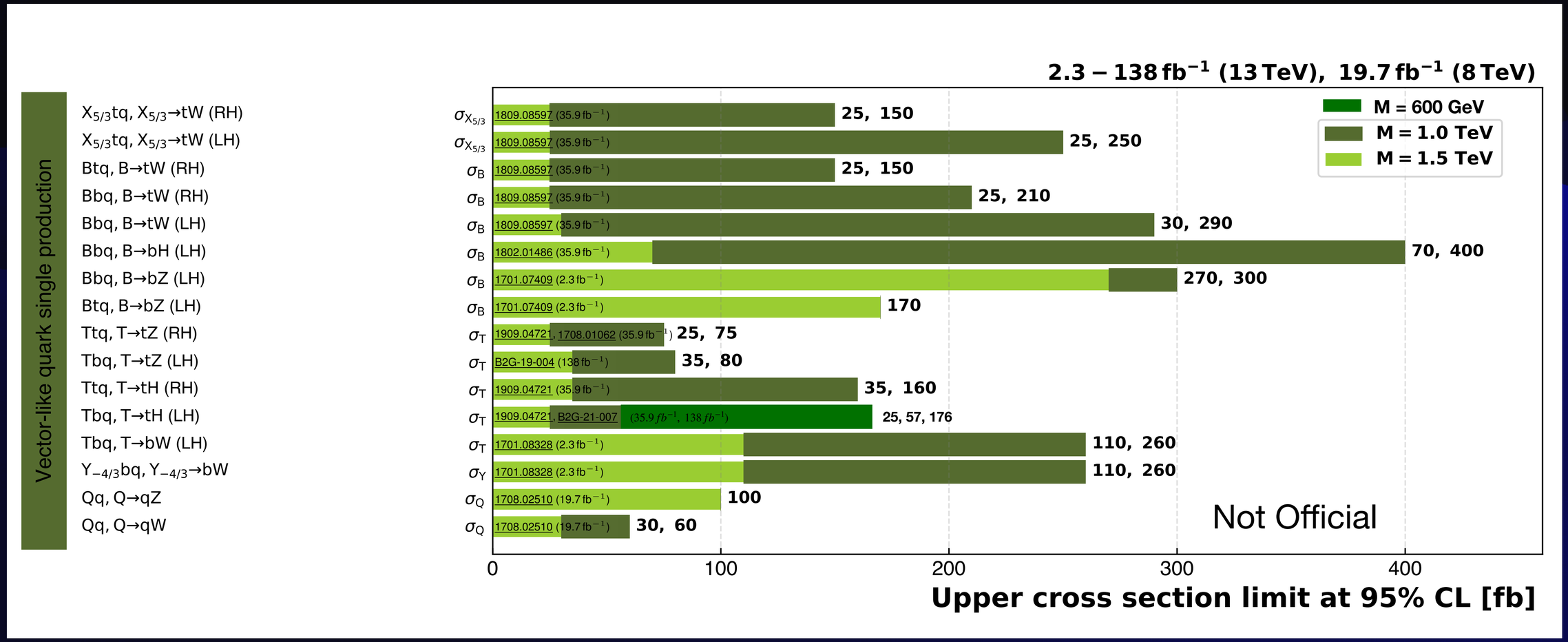
Vector Like Quarks and Leptons

Recent results of searches for non-chiral BSM partners of 3rd generation fermions at the CMS Experiment

Johan Sebastian Bonilla Castro
Pronouns: They/Them
On Behalf of the CMS Collaboration
ICHEP 2022 - Bologna, Italy
7th of July, 2022

NOTE: Summary Plots in Approval Process, Official Result at Public B2G twiki (link)

Coverage of VLQs/VLLs @CMS



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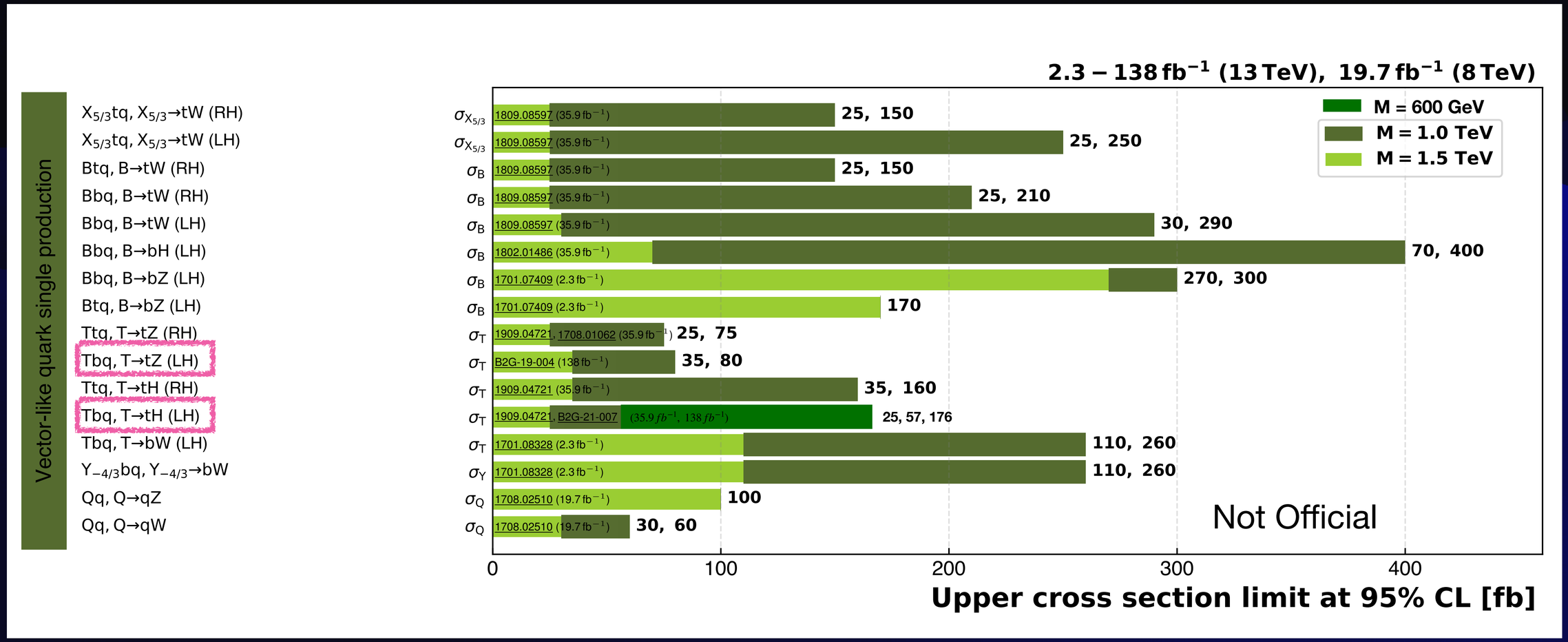

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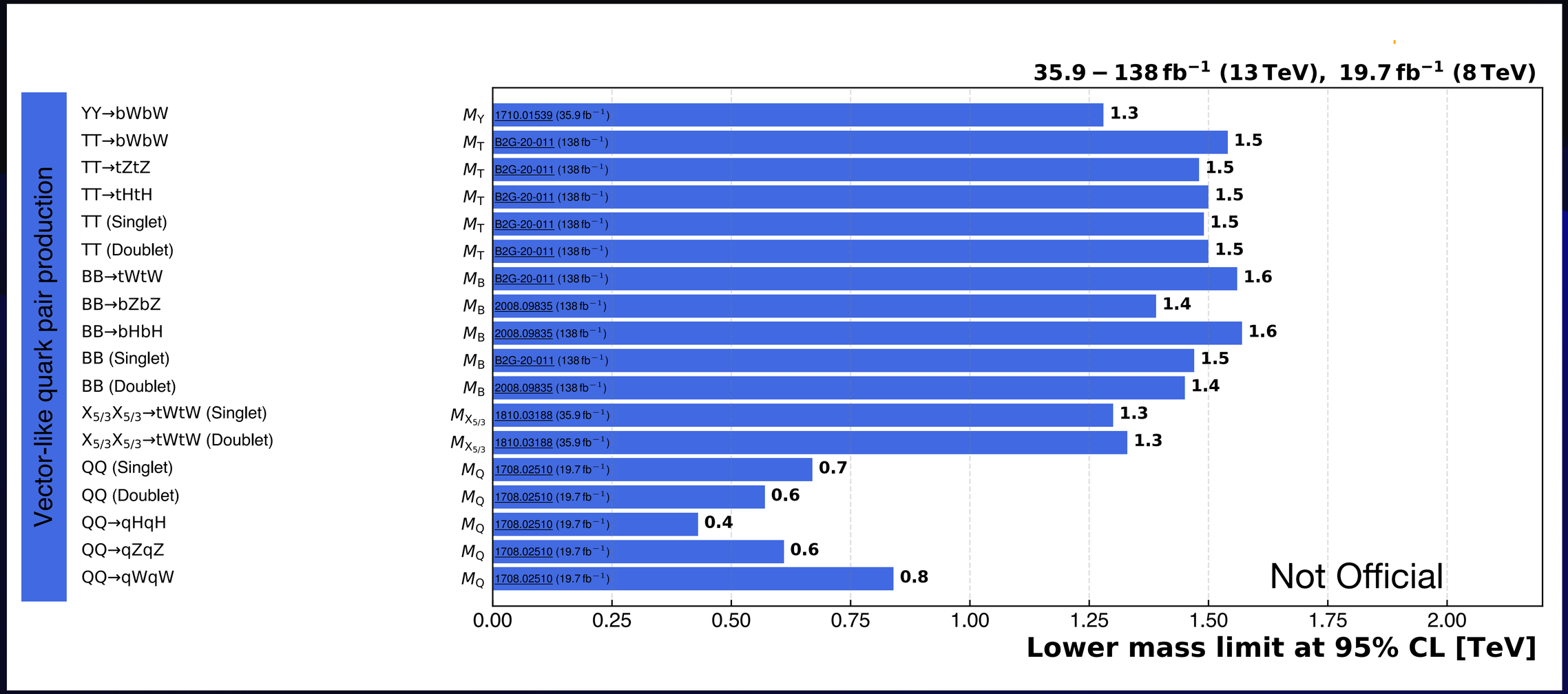

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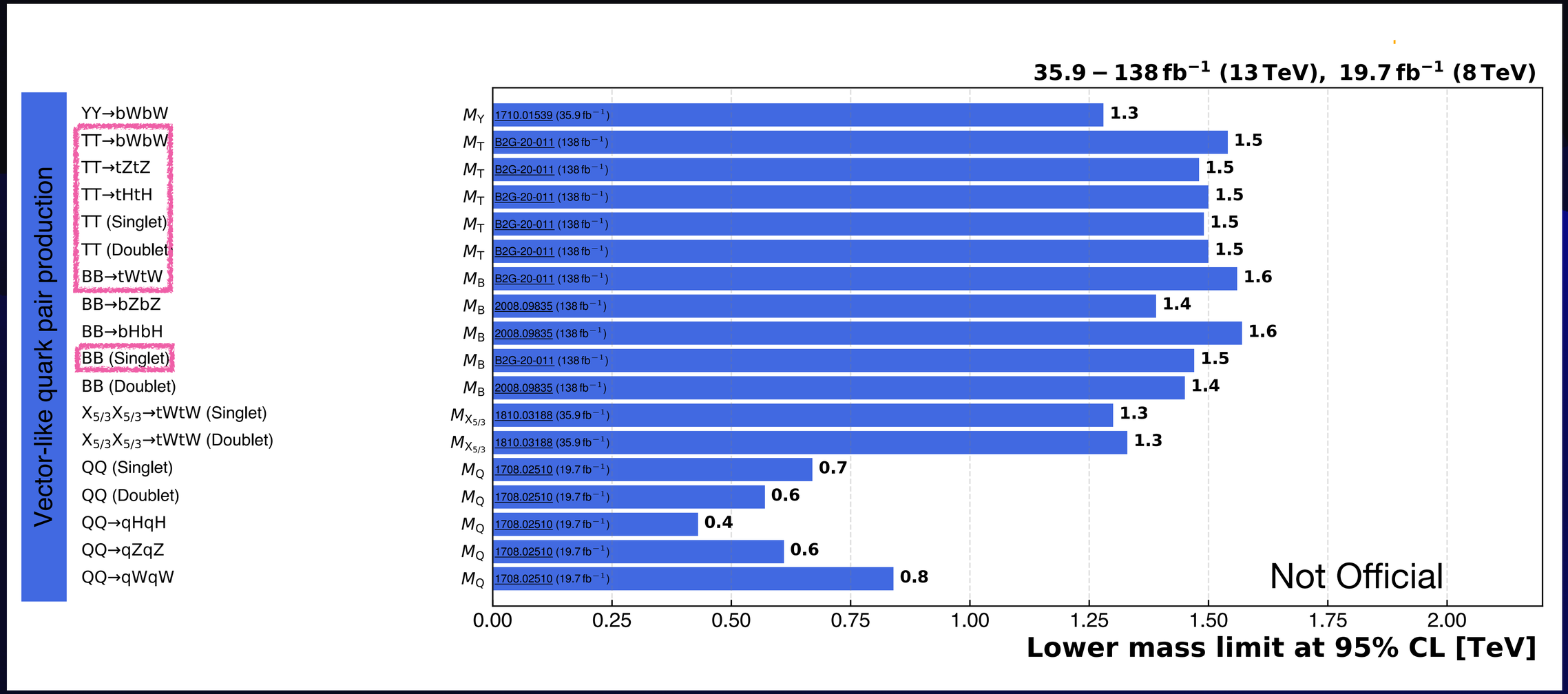

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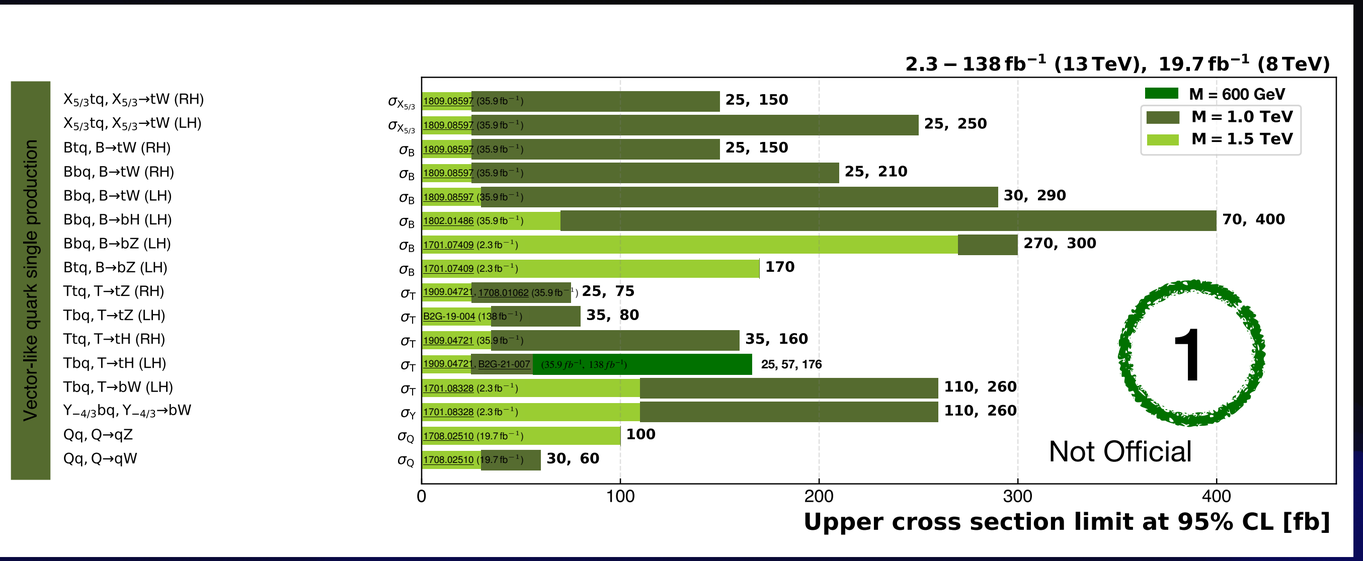
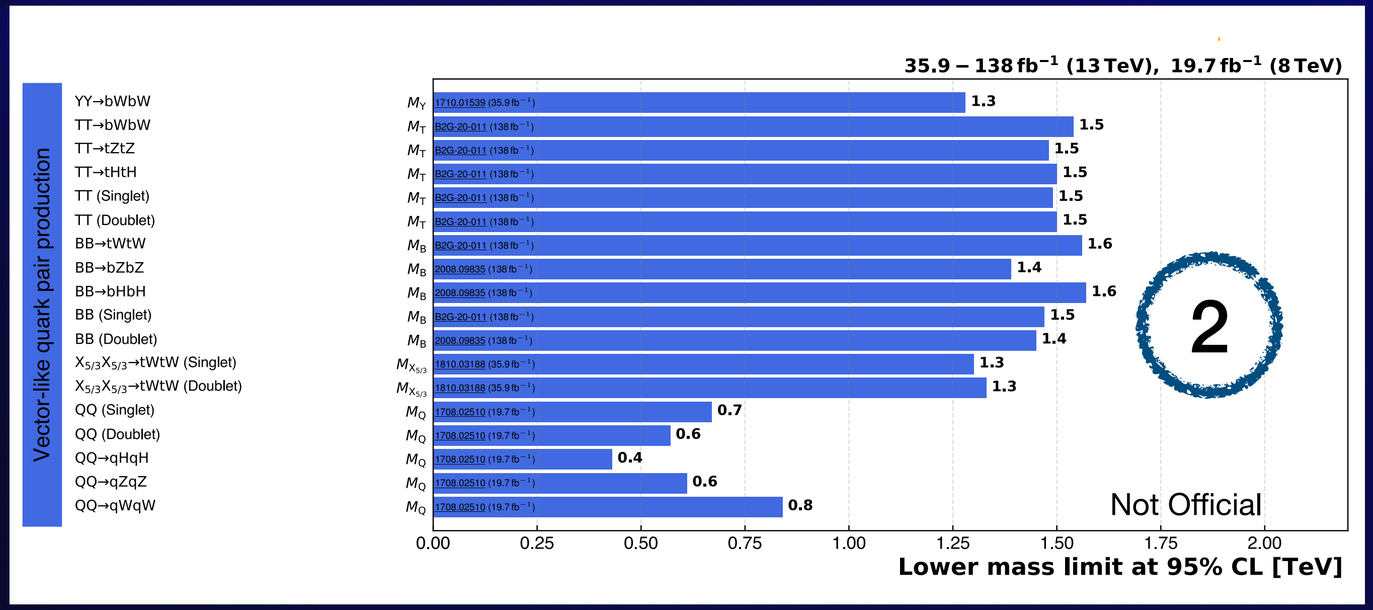


NEW! VLL Result 3



Vector-Like Quarks

Overview of Theoretical and Experimental Motivations

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Many extensions of SM have VLQs

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— Can be singlets, doublets, triplets, …

$$Q_L^0 = \begin{pmatrix} T_{L,R}^0 \\ B_{L,R}^0 \end{pmatrix} \qquad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

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- Higgs properties align with SM
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- Possible explanation for BSM phenomena,
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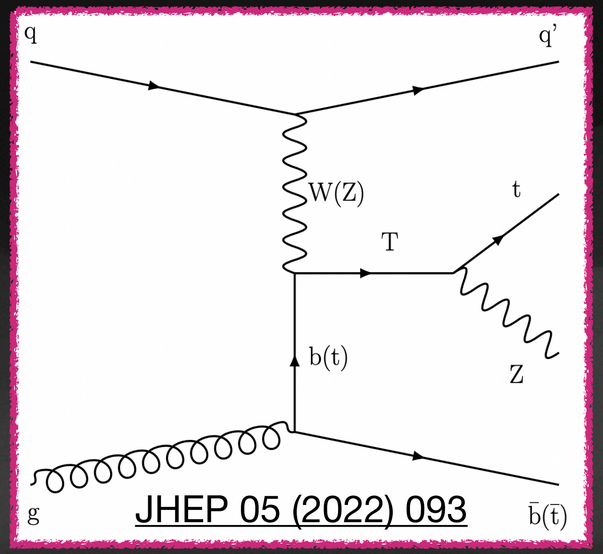

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Pair-Production: Strong

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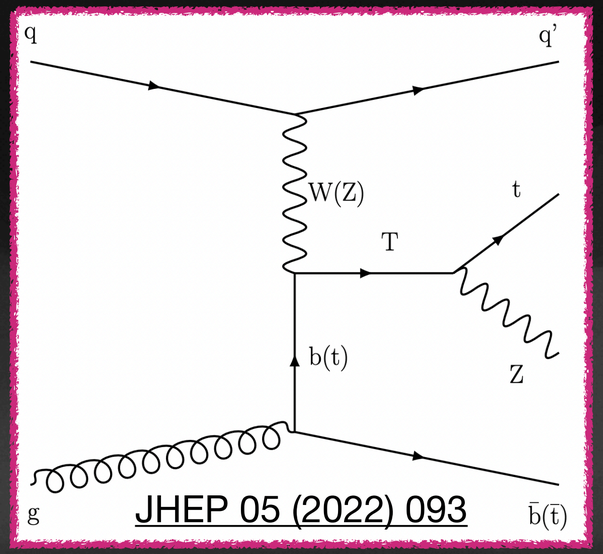

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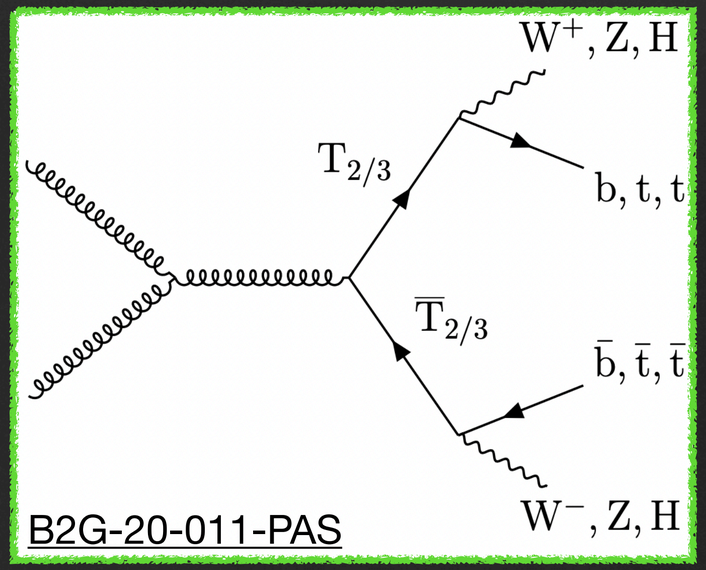

B2G-20-011-PAS

Production and Decay Modes of Vector Like Quarks

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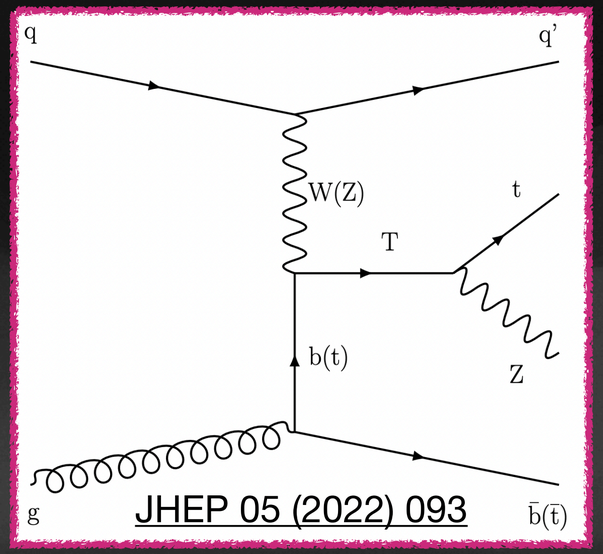
Recent non-minimal mechanisms
e.g. Chromo-magnetic moment
=> gluon-t/b-T/B vertex



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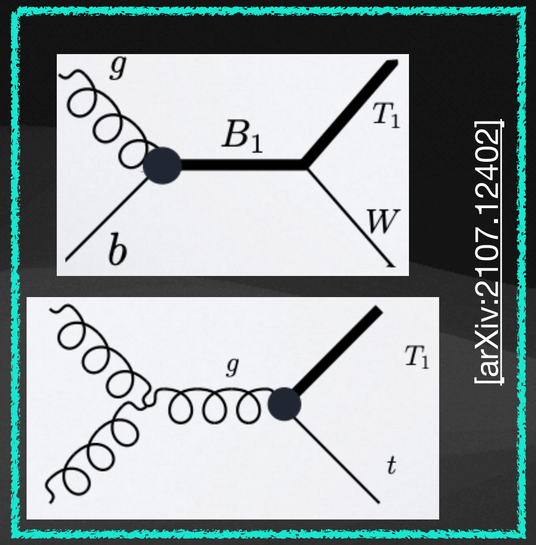

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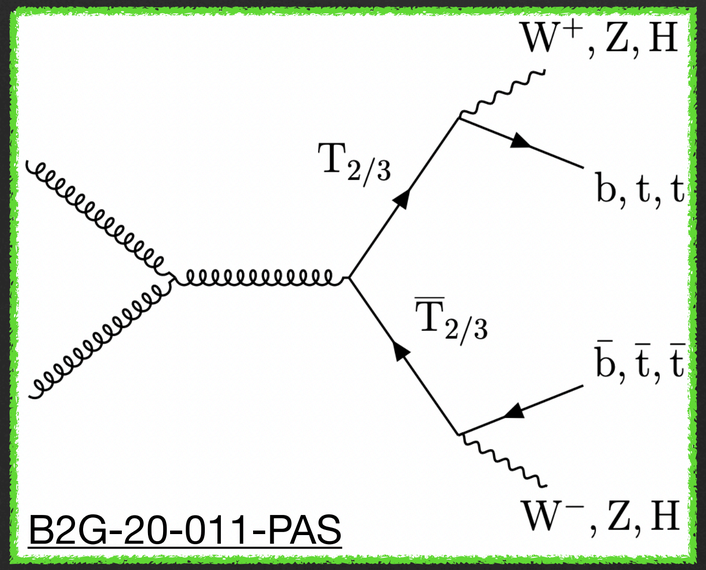

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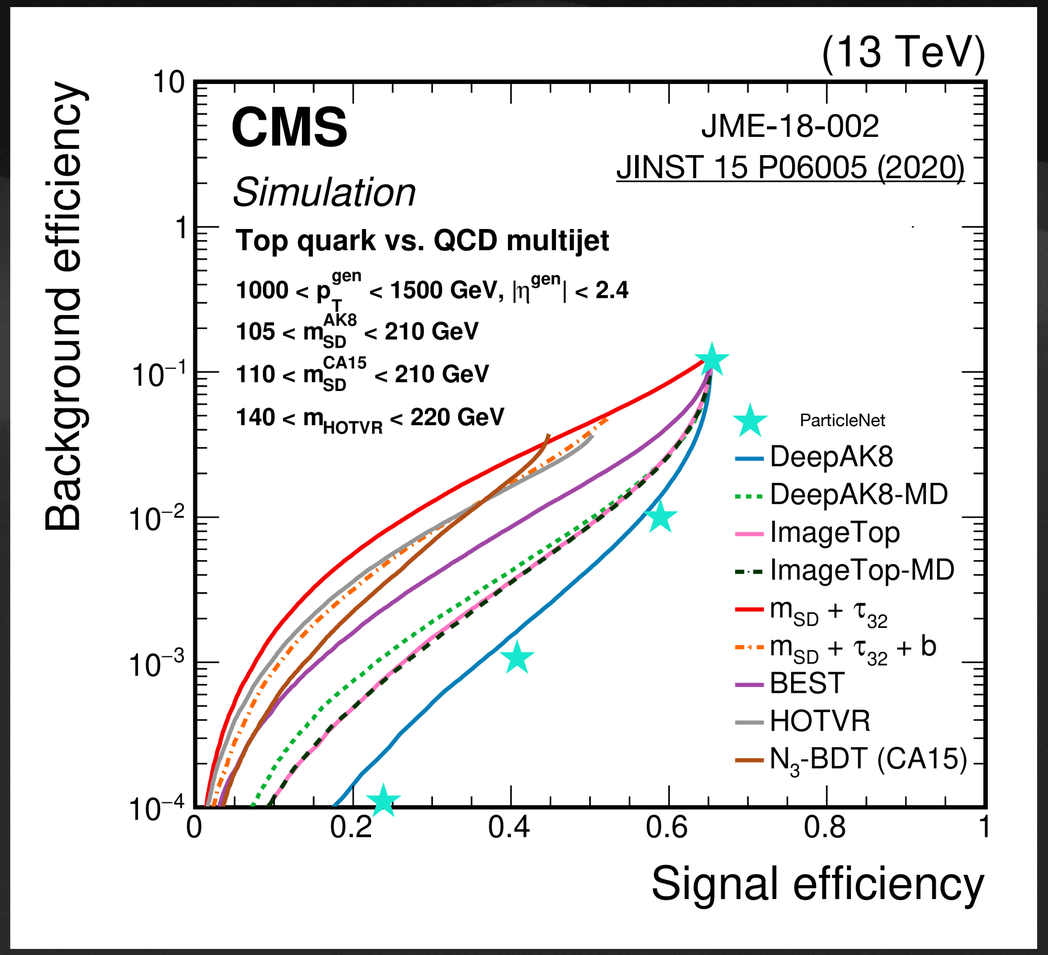
Jet Tagging in CMS

Evolving Architectures During Run 2



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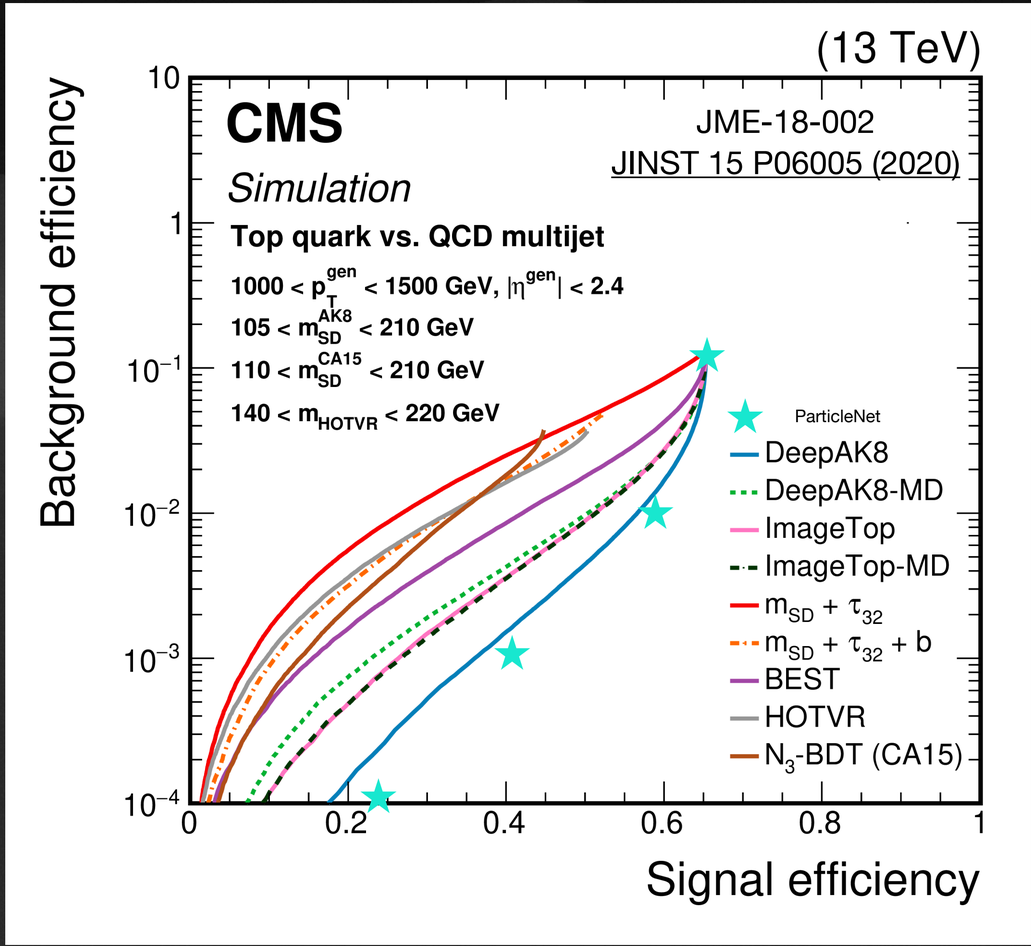
Evolving Architectures During Run 2

Increasing Sophistication

$m_{SD}, \tau_{32}, ECF, N_b$

Traditional JSS

HOTVR



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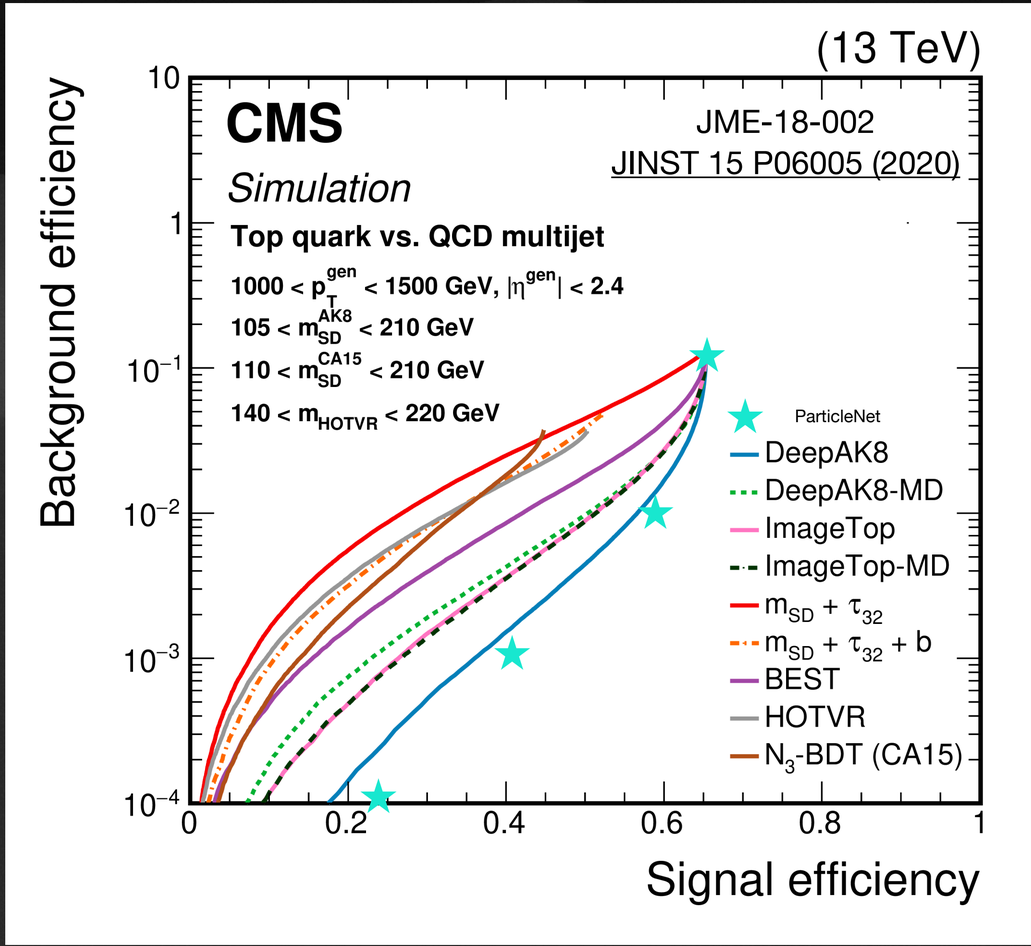
N_3 BDT

Boosted Decision Trees



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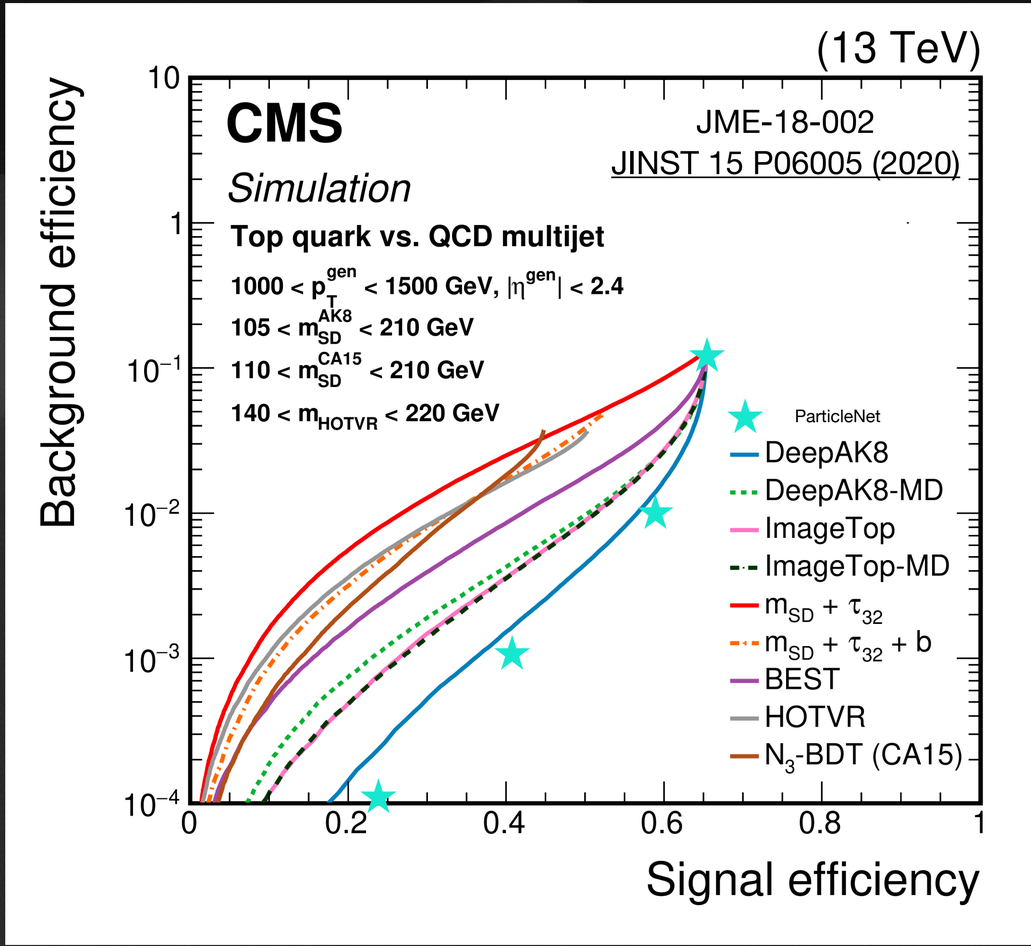
N_3 BDT — Boosted Decision Trees

Boosted Event Shape Tagger — Deep Neural Net



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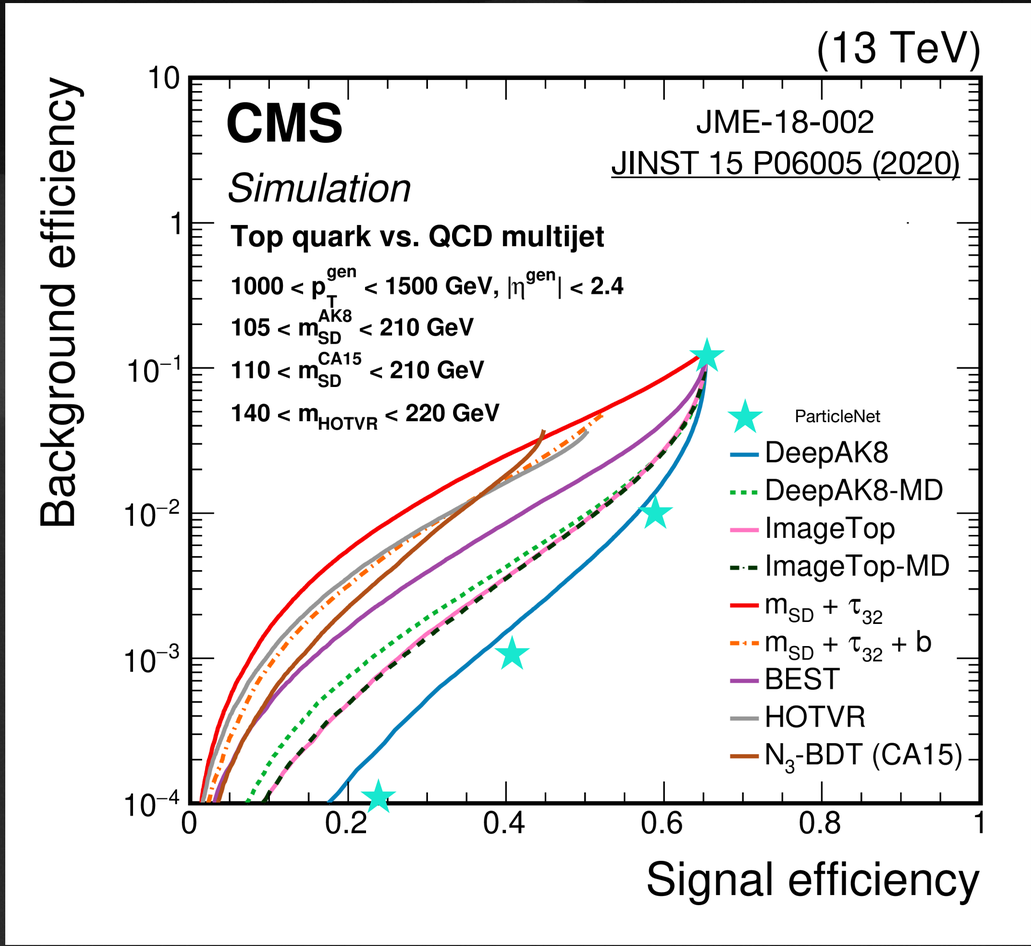

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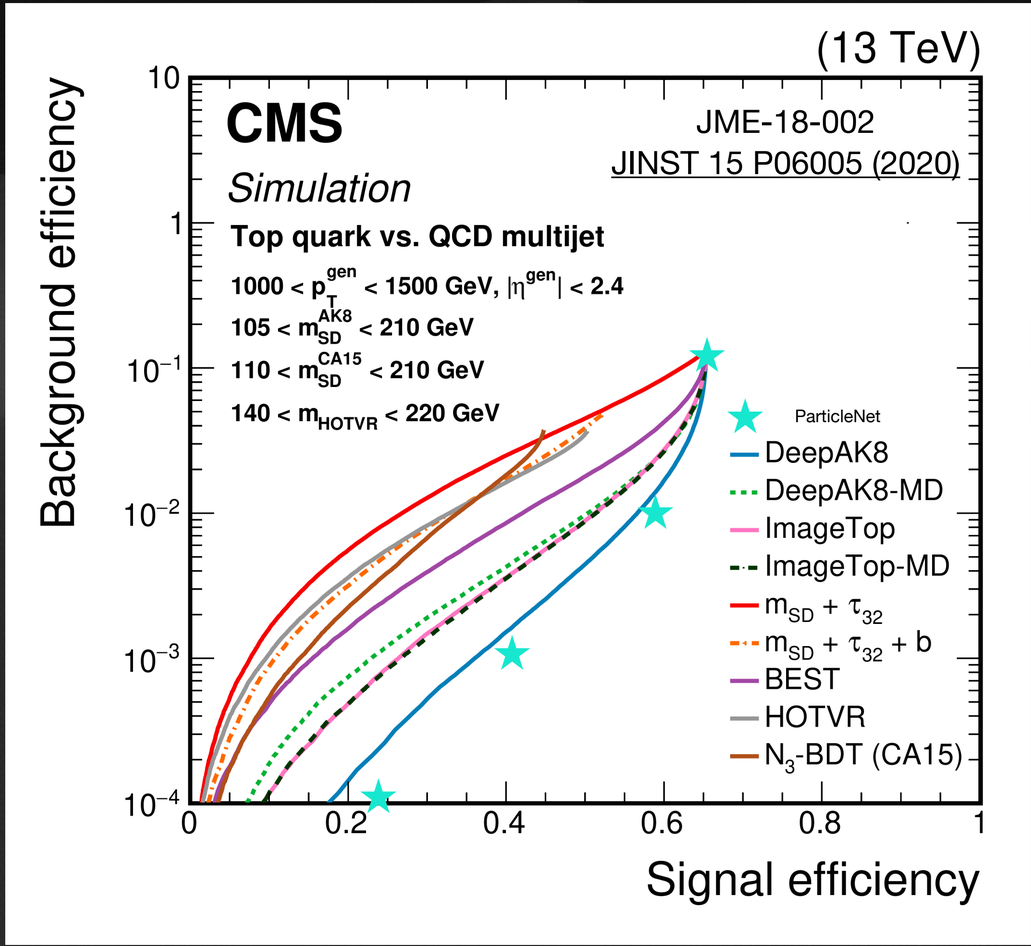

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Evolving Architectures During Run 2

$$\Delta R < \frac{2m}{p_T};\ p_T(t) < 400 \rightarrow \Delta R > 0.8$$

For details on mass-decorrelated use of ParticleNet
See Cristina Mantilla Suarez's talk (17h30, 8 Jul)

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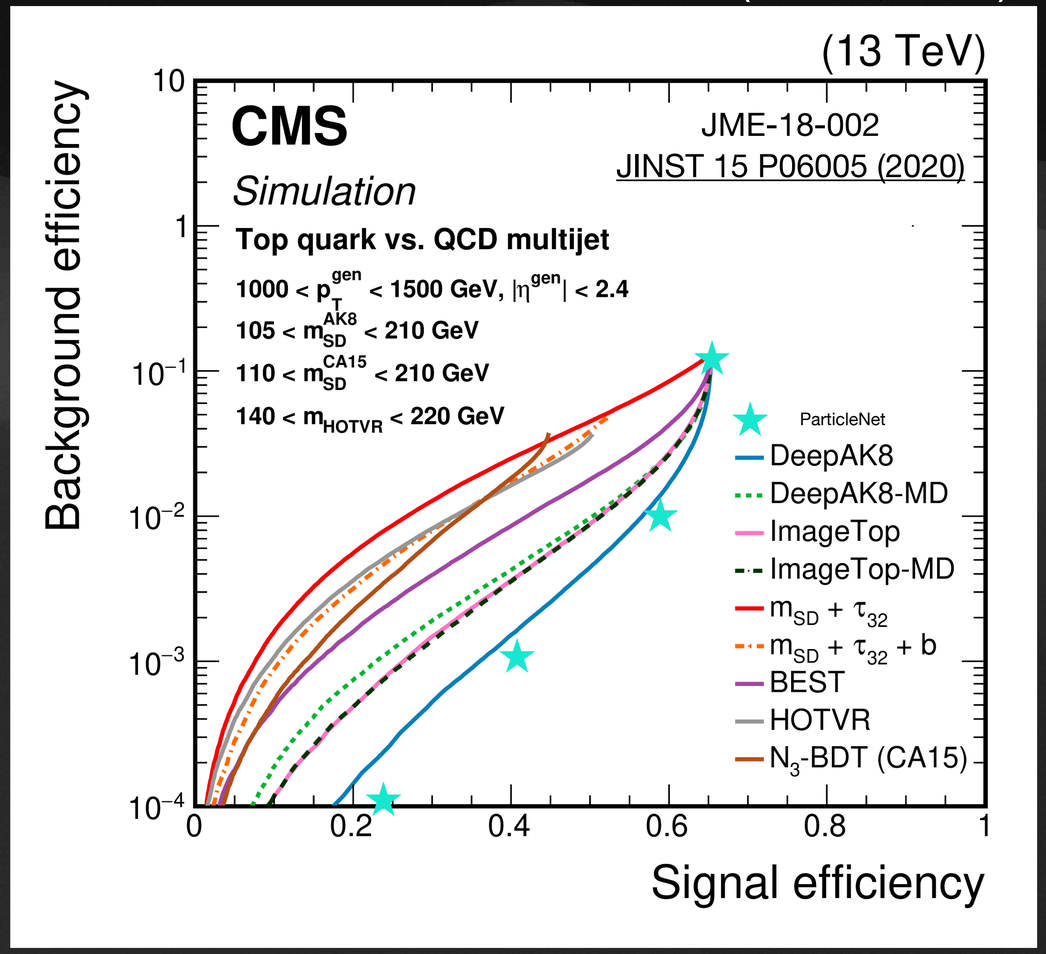

Single VLQ Production

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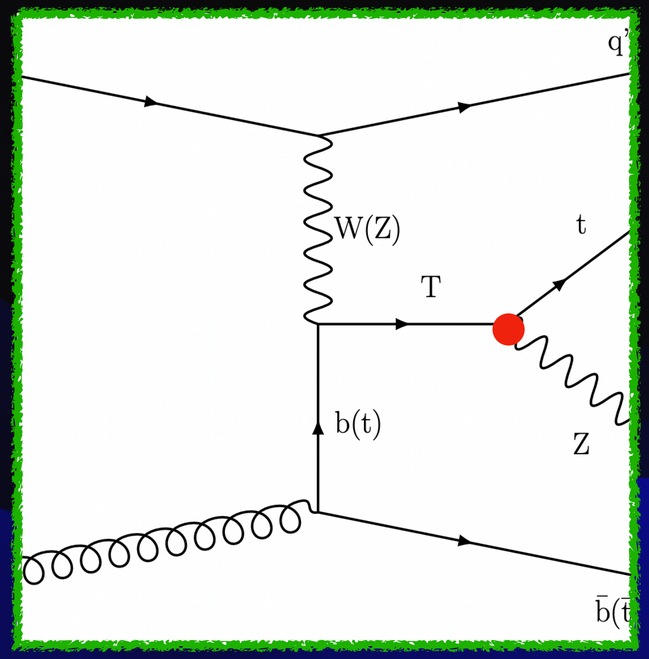
Search for $T \to tZ$

$Z \to \nu\nu$ (invisible)

B2G-19-004, JHEP05(2022)



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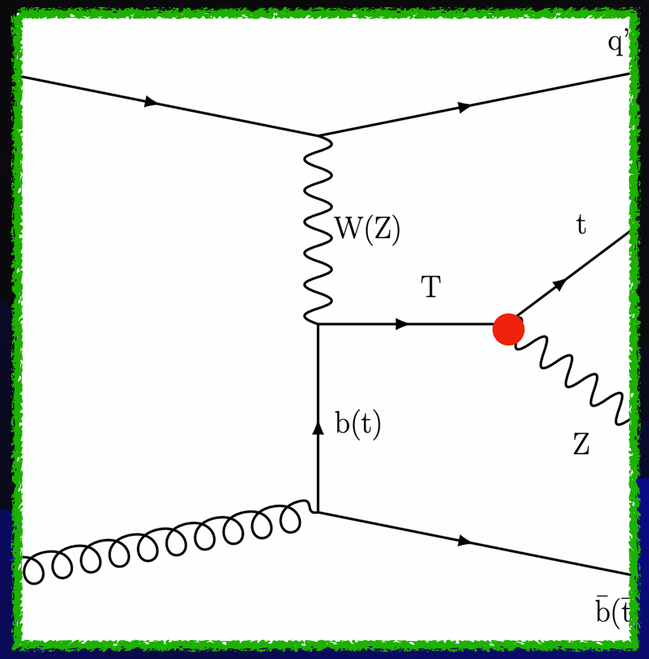
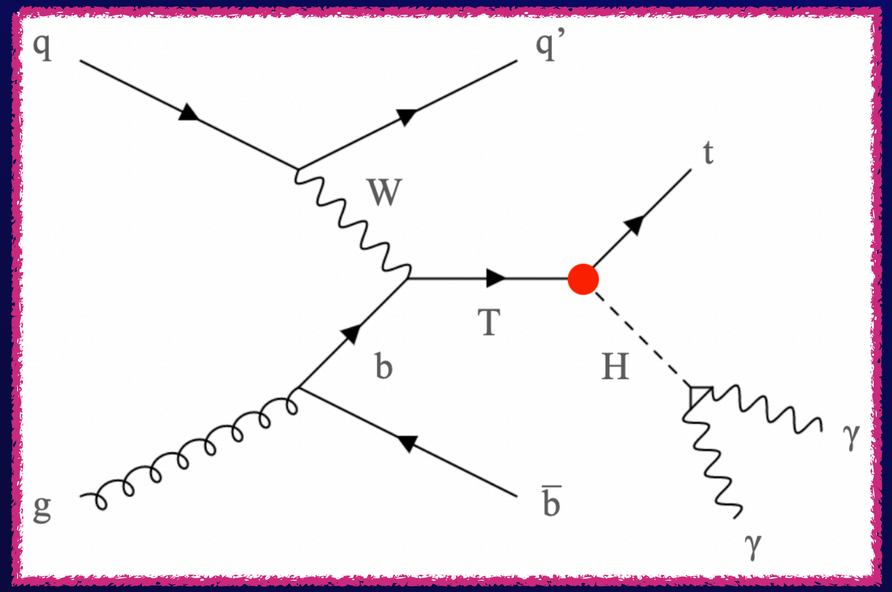


Search for $T \to tH$

$H \to \gamma\gamma$

B2G-21-007



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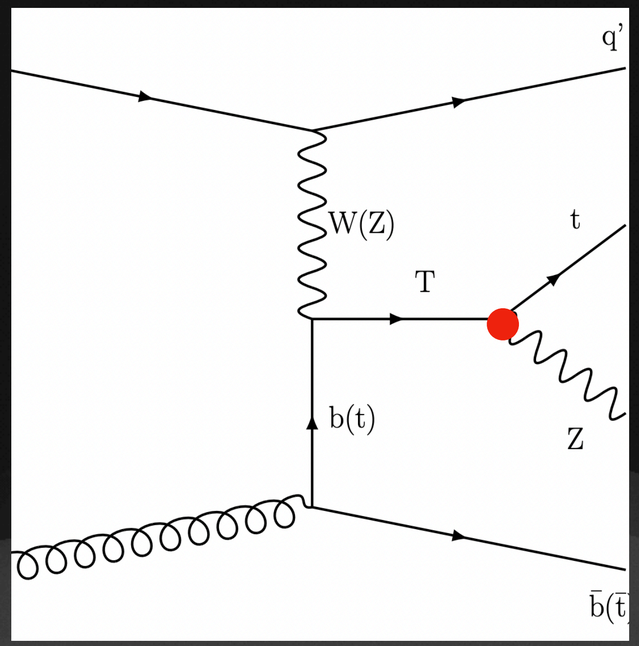

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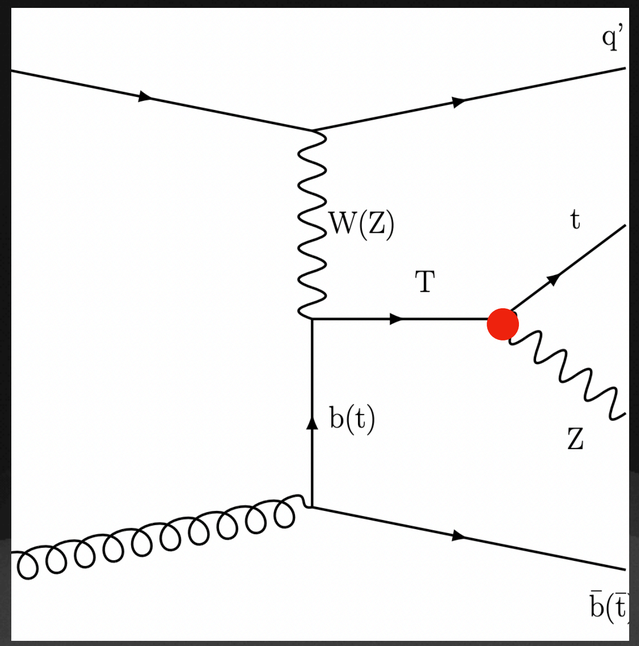

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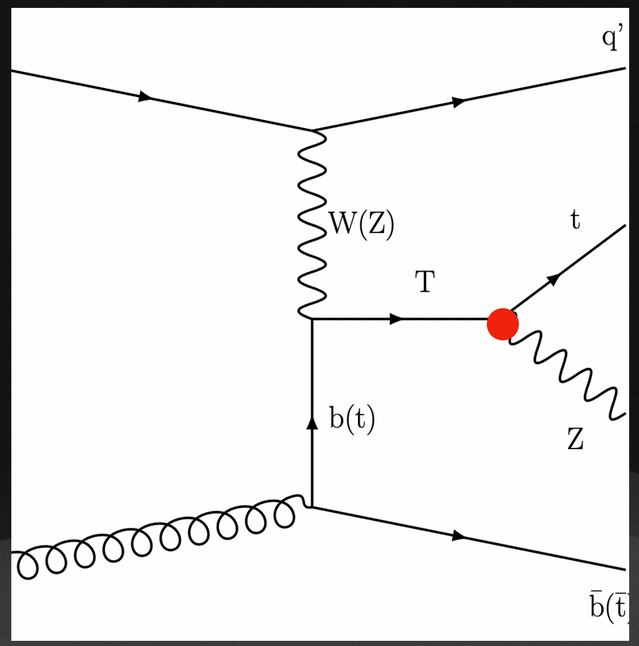

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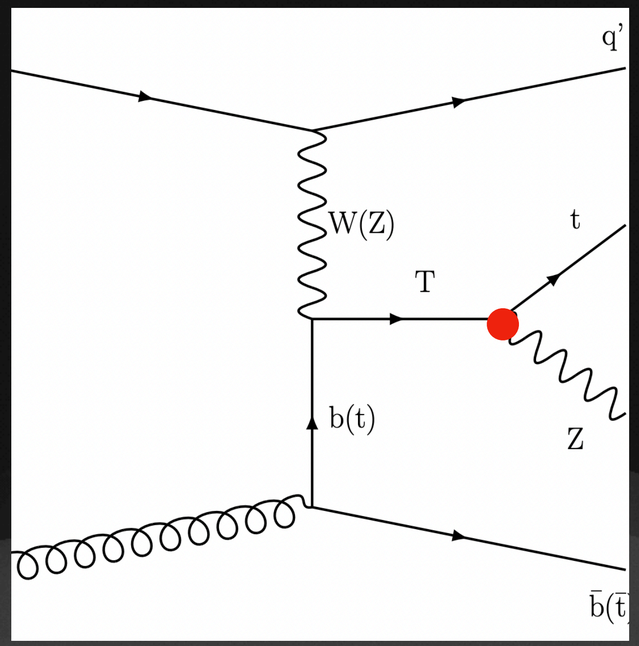

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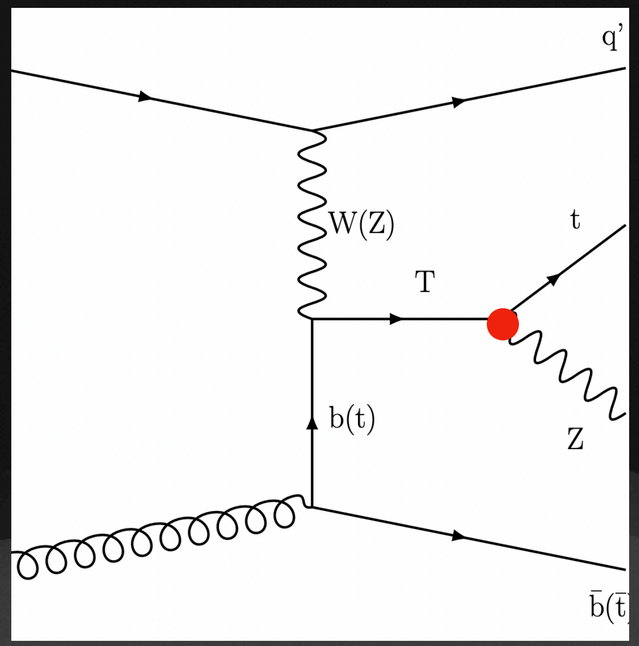

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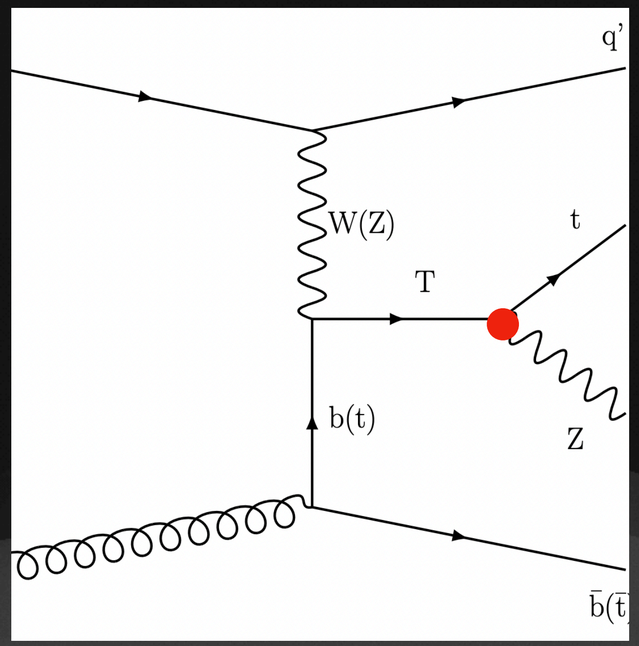

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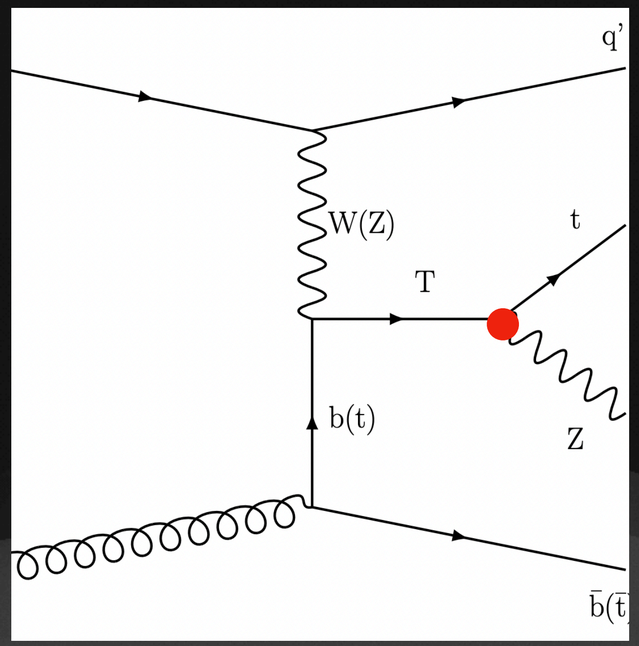

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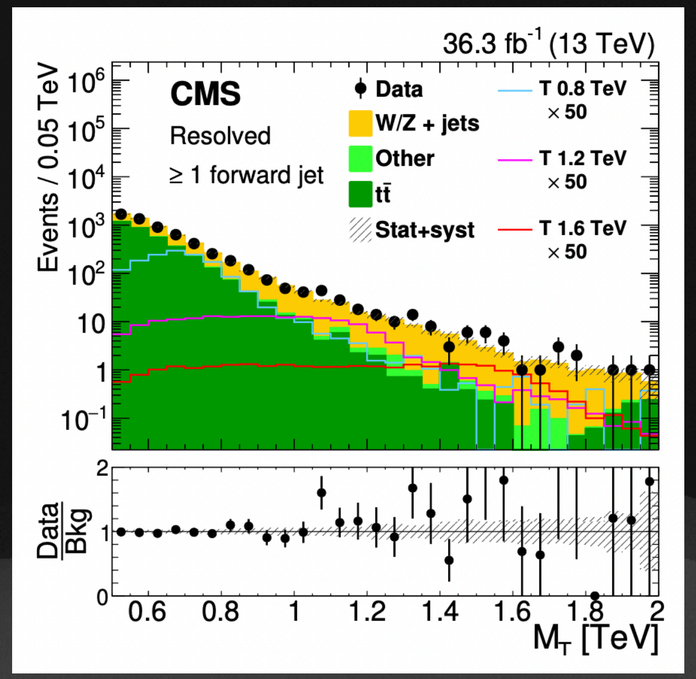

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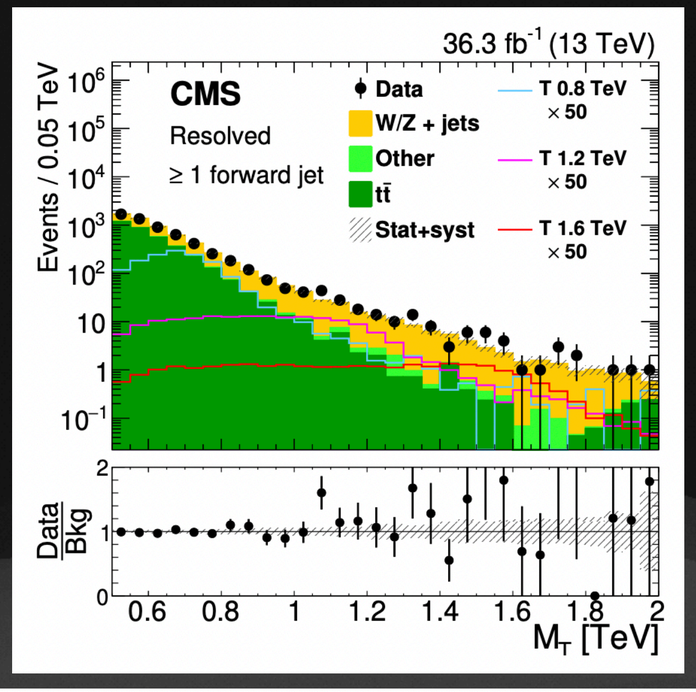

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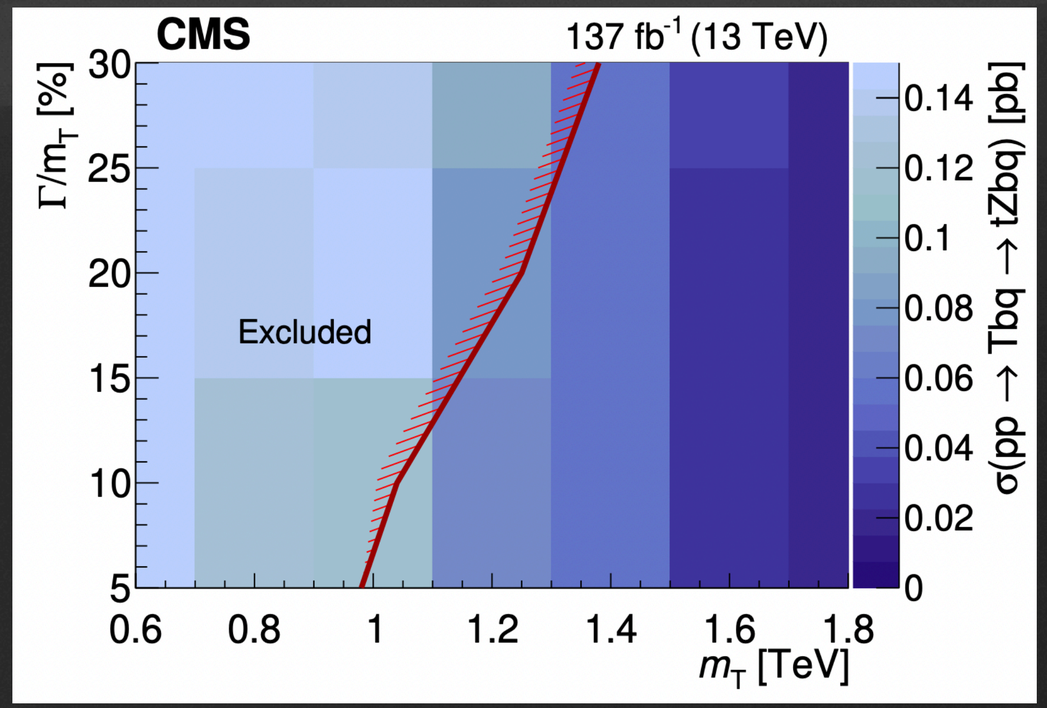

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All-Hadronic $T \to tZ,\ Z \to \nu\nu$

$Z \to \nu\nu$ (invisible): Missing p_T

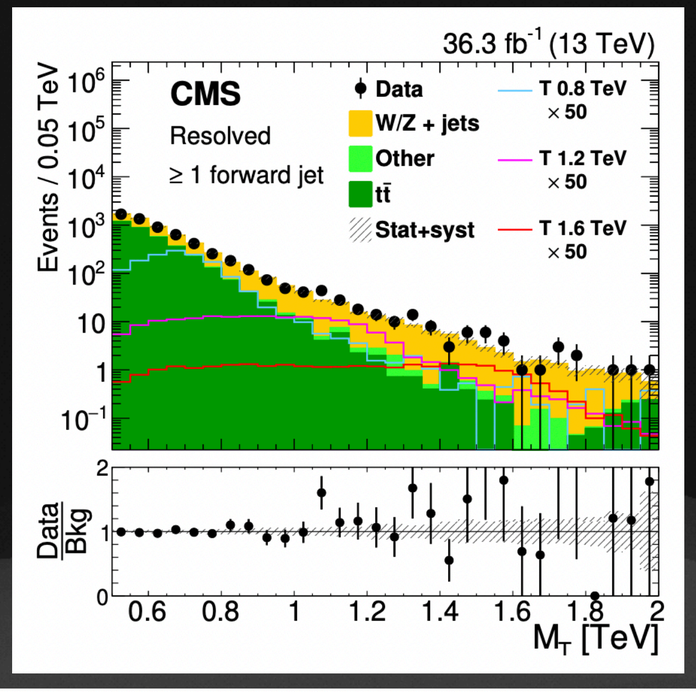
Top Reconstruction: b+W
(b-tagging: DNN-based discriminator for AK4 jets)

- Resolved: 1 AK4 (b) jet + 1 AK8 $m_{SD} \in [65,105]$ GeV
  $\tau_{21}^{DDT} < .43$
- Merged: 1 AK8 jet w/ $m_{SD} \in [105,220]$, $\tau_{32} < .65$

Major BG: W/Z+jets

SR Categorization:
Fit w/ M_T

Cen Merged	Fwd Merged
Cen Resolved	Fwd Resolved



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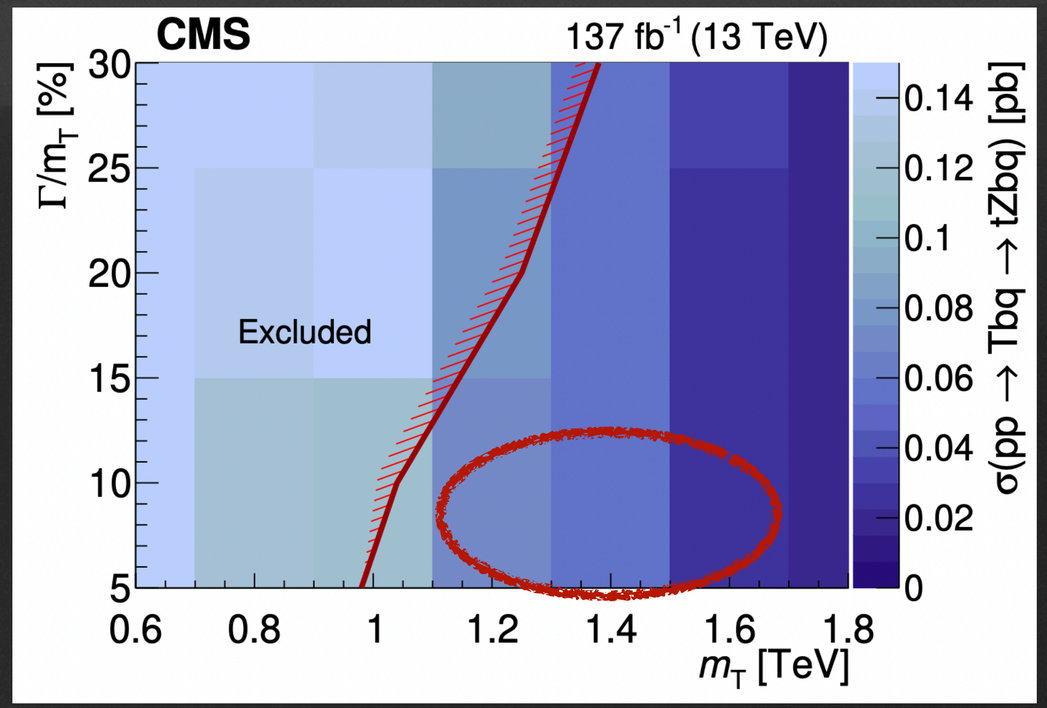

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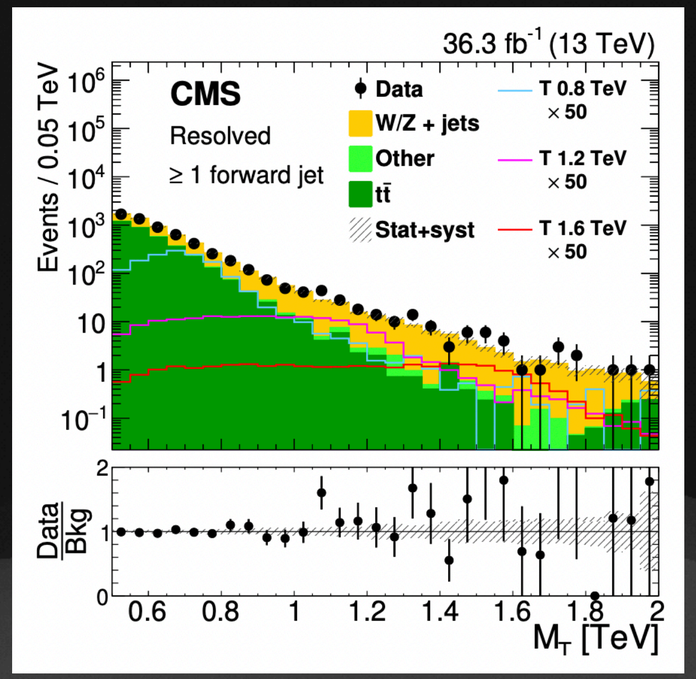

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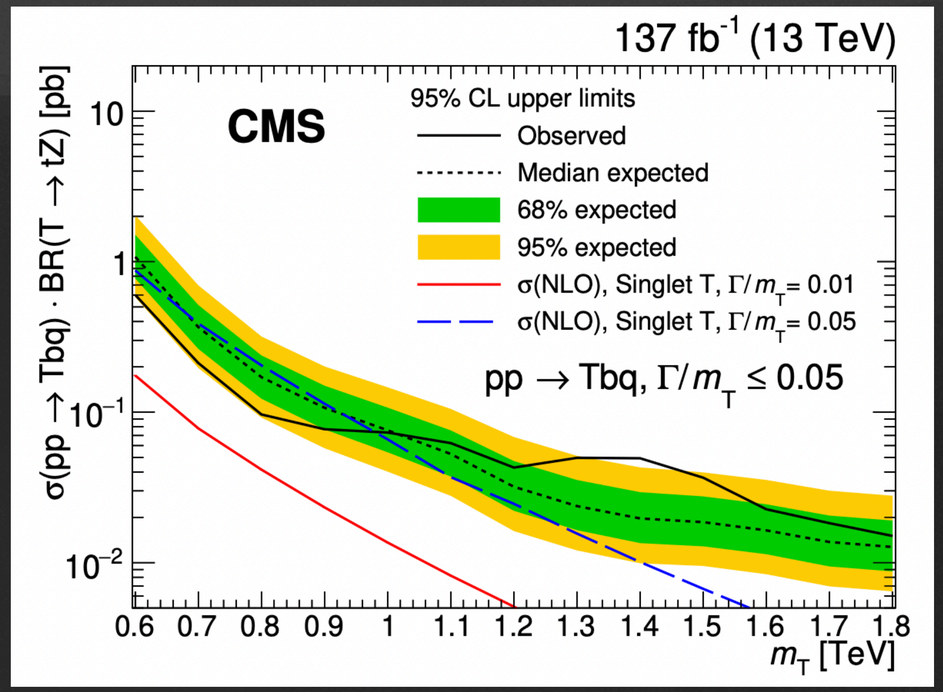

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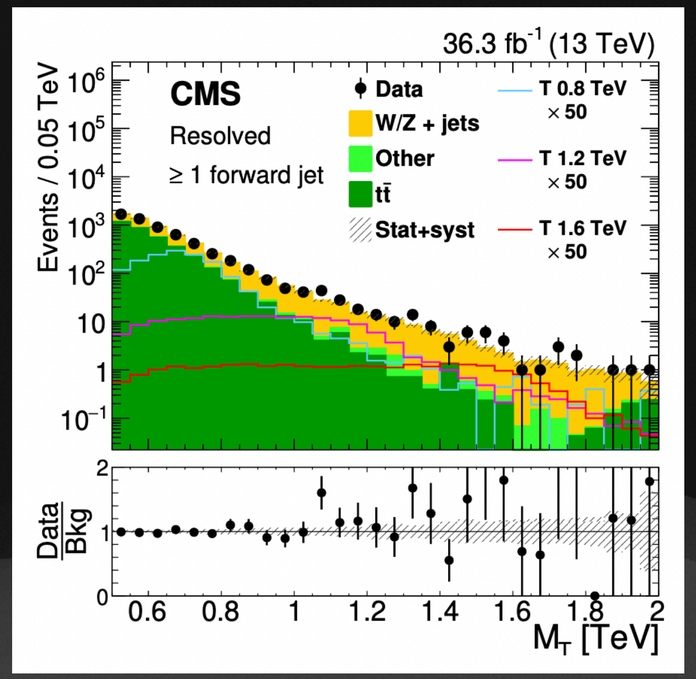

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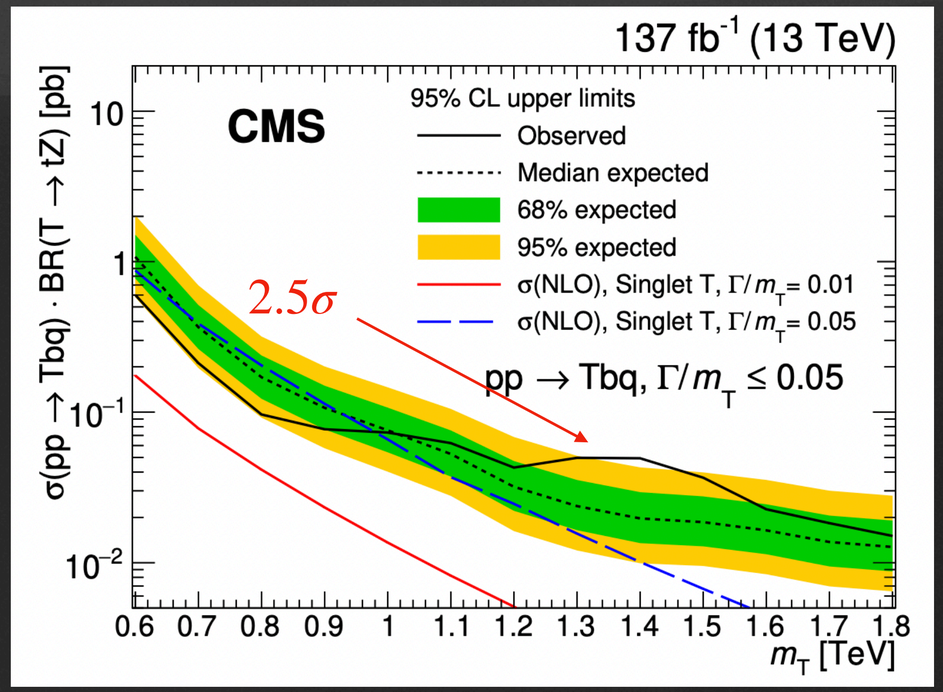

Full Run 2 $T \to tH, H \to \gamma\gamma$

Using $H \to \gamma\gamma$ as a probe for T

B2G-21-007-PAS

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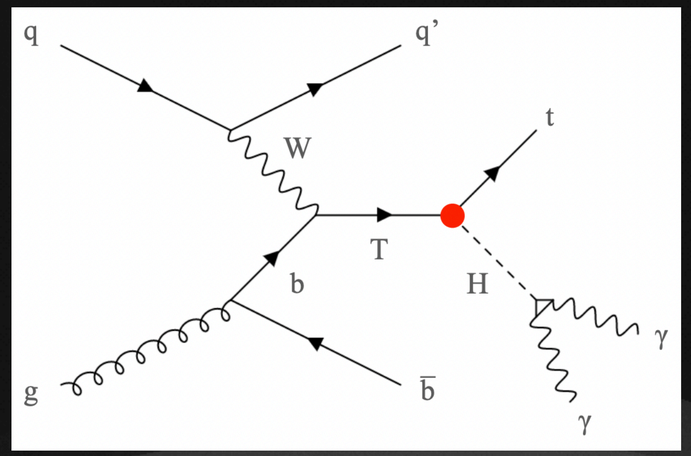


B2G-21-007-PAS

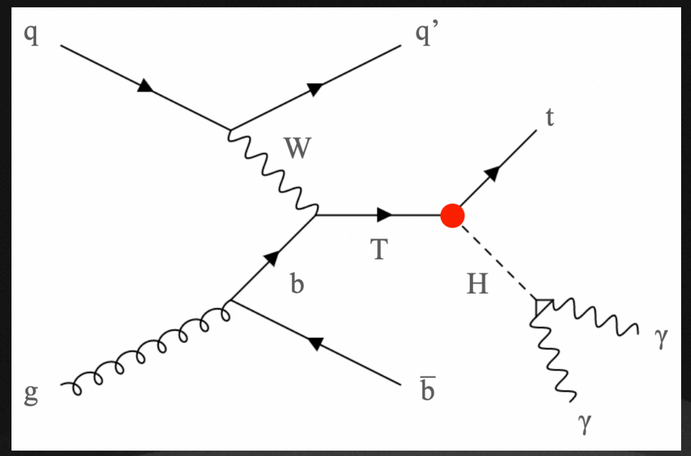
Full Run 2 $T \rightarrow tH, H \rightarrow \gamma\gamma$

Using $H \rightarrow \gamma\gamma$ as a probe for T

Reconstructing top quark

— Leptonic: $b_{ID} + \ell + E_T^{miss}$

— Hadronic: min χ^2 method



B2G-21-007-PAS

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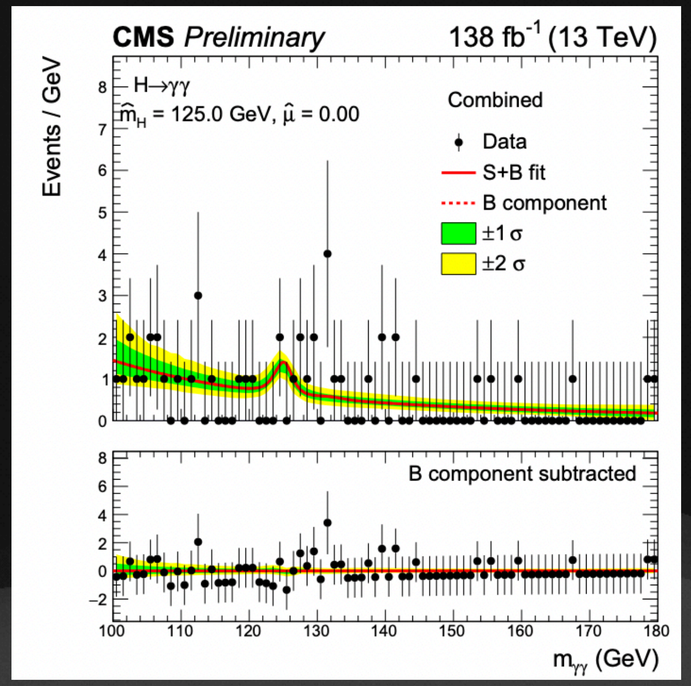
Reconstructing $H \rightarrow \gamma\gamma$
- Need high resolution
- γ-Reco -> Vertex Selection -> $\gamma/\gamma\gamma$ ID



B2G-21-007-PAS

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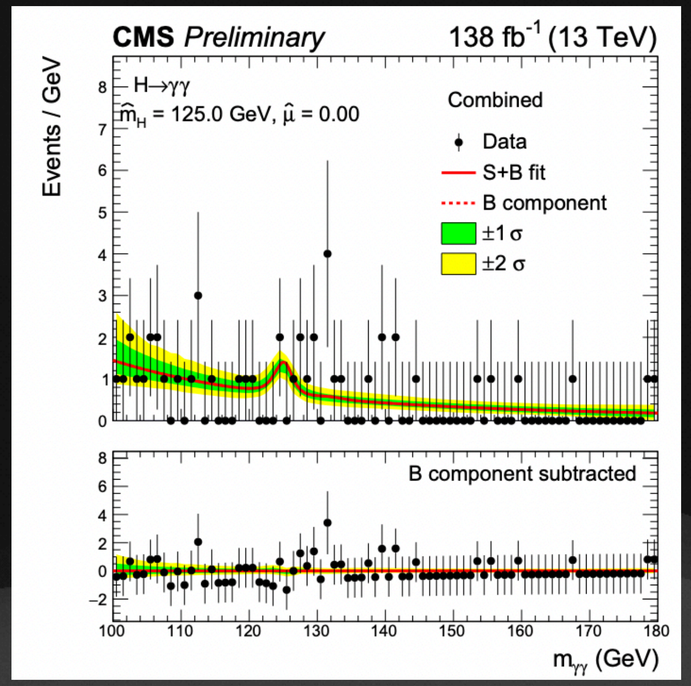
Use of BDTs
- Suppress Non-Resonant Background
- Event categorization (based on m_T)



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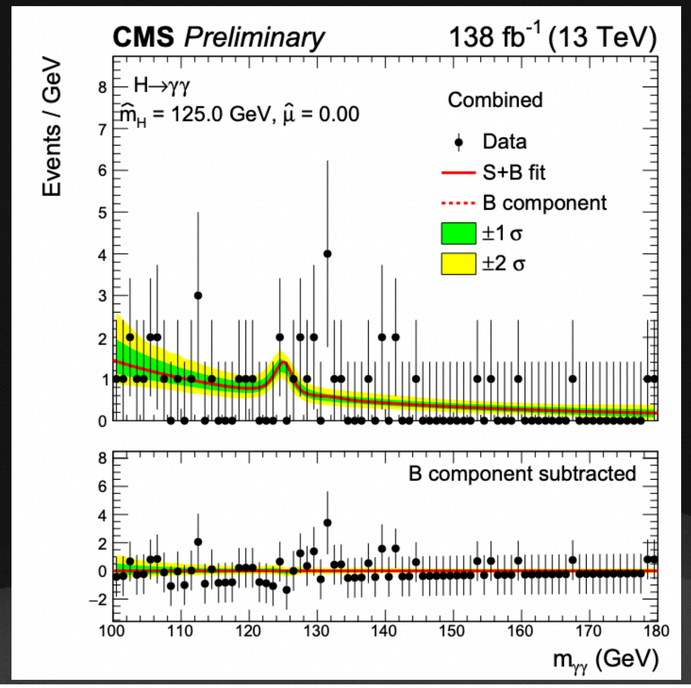

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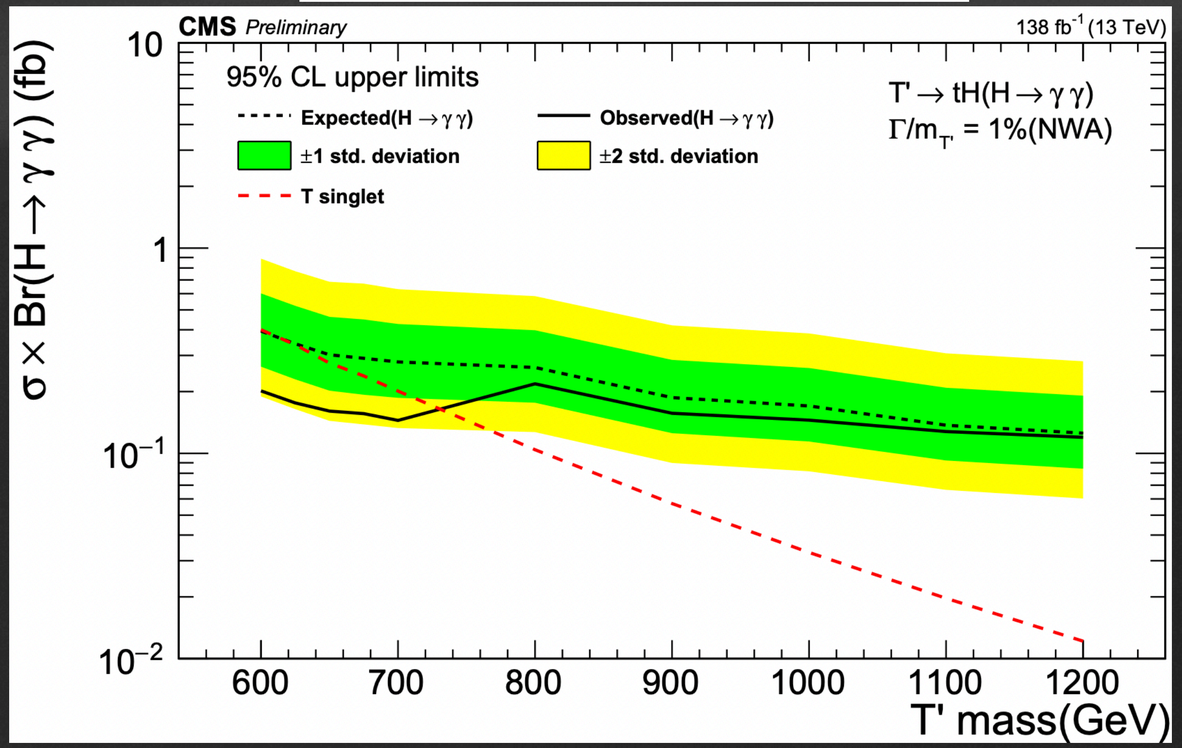

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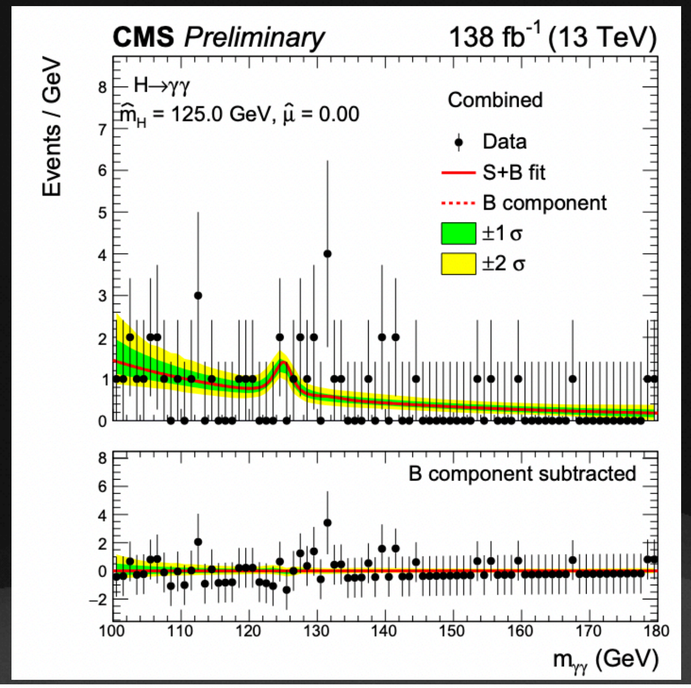

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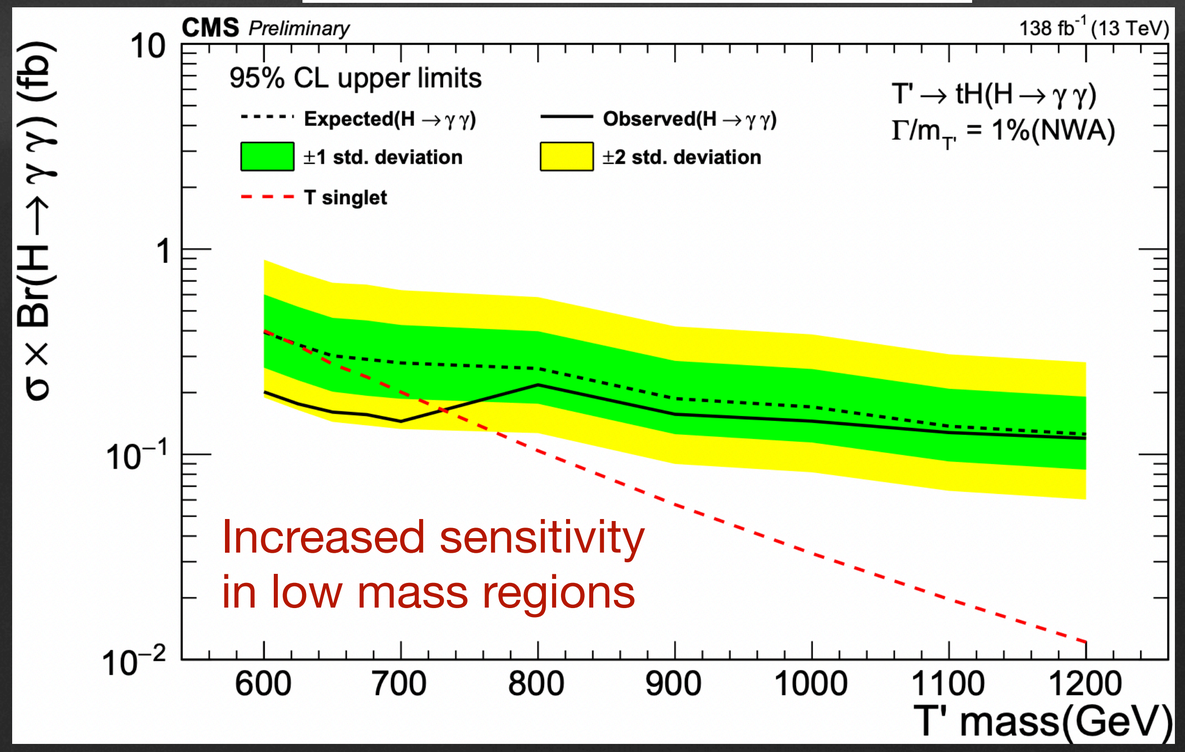

Pair-Produced VLQs

Full Run 2
Search for TT/BB
in Leptonic Channels

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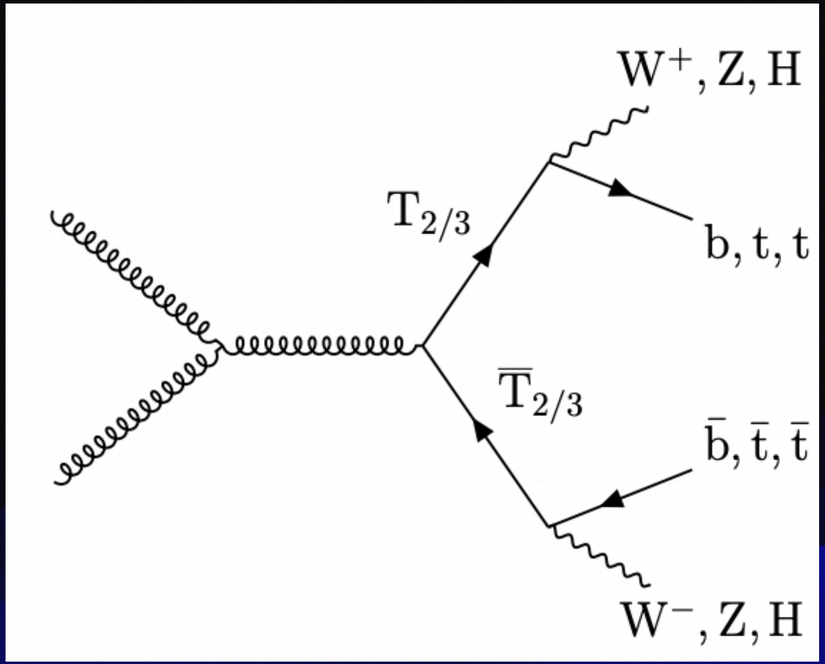
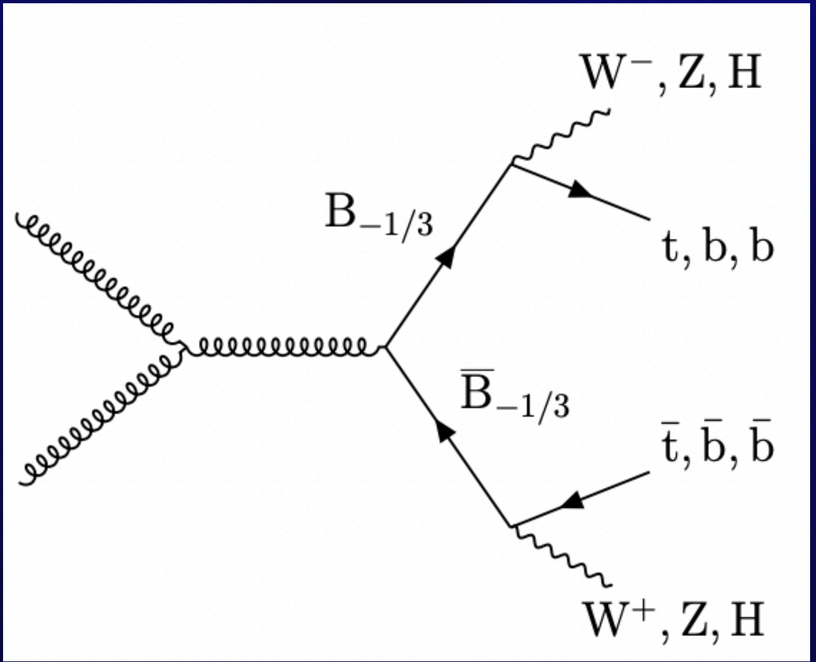
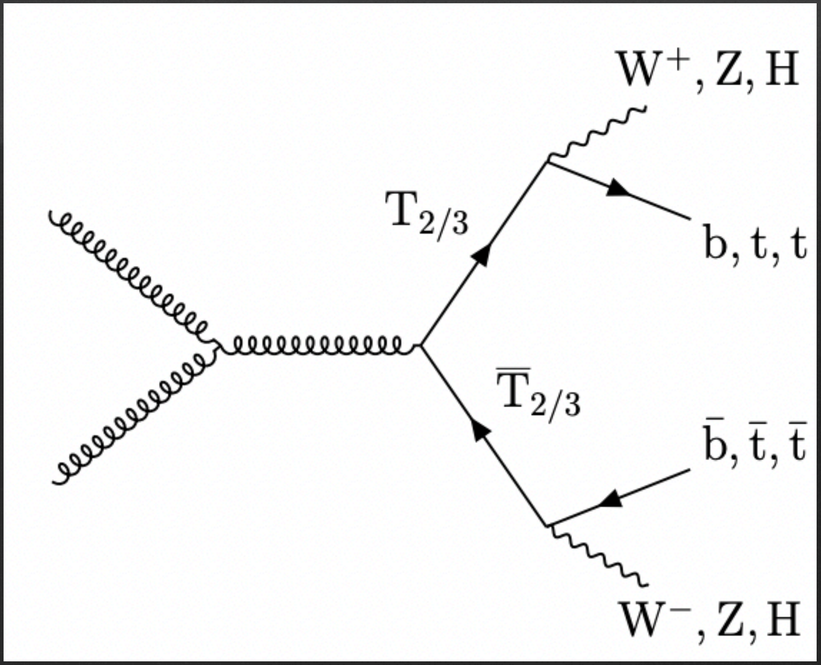




Leptonic Decays of TT/BB



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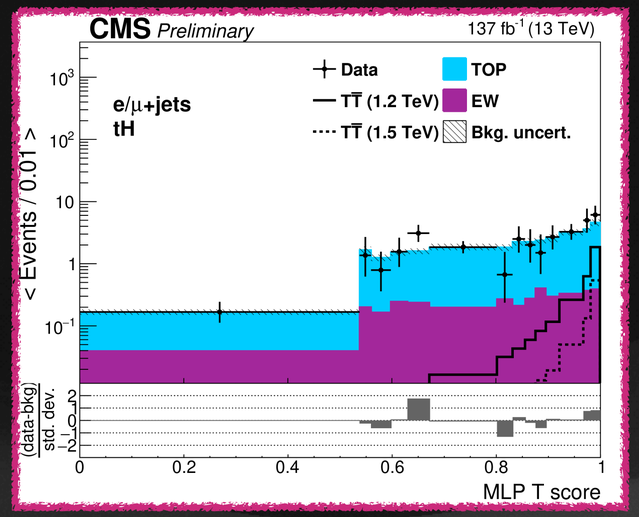

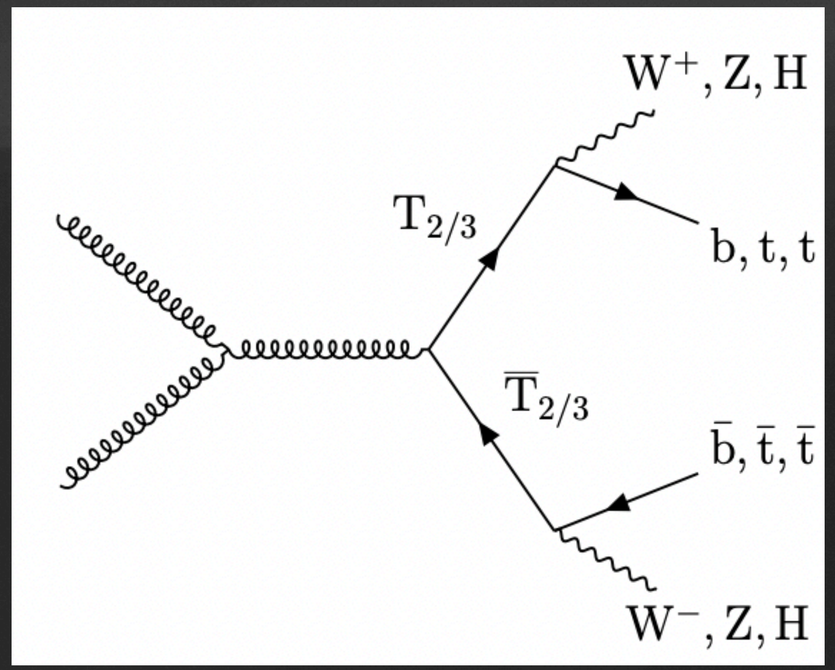

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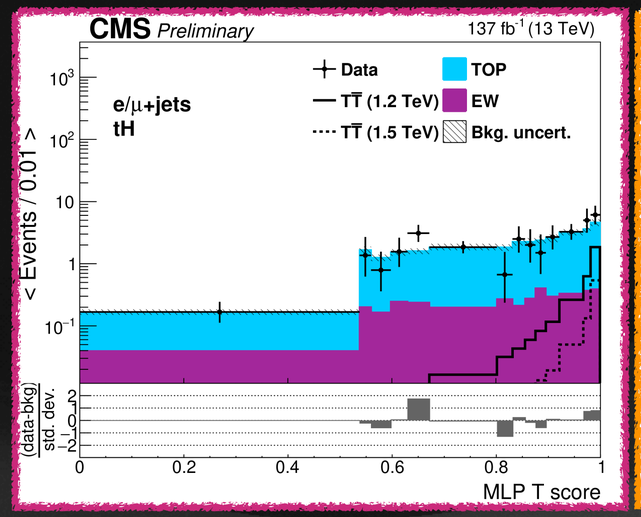
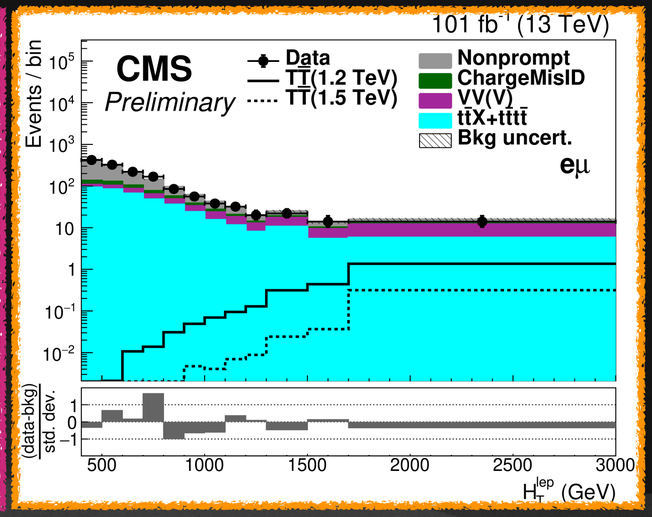
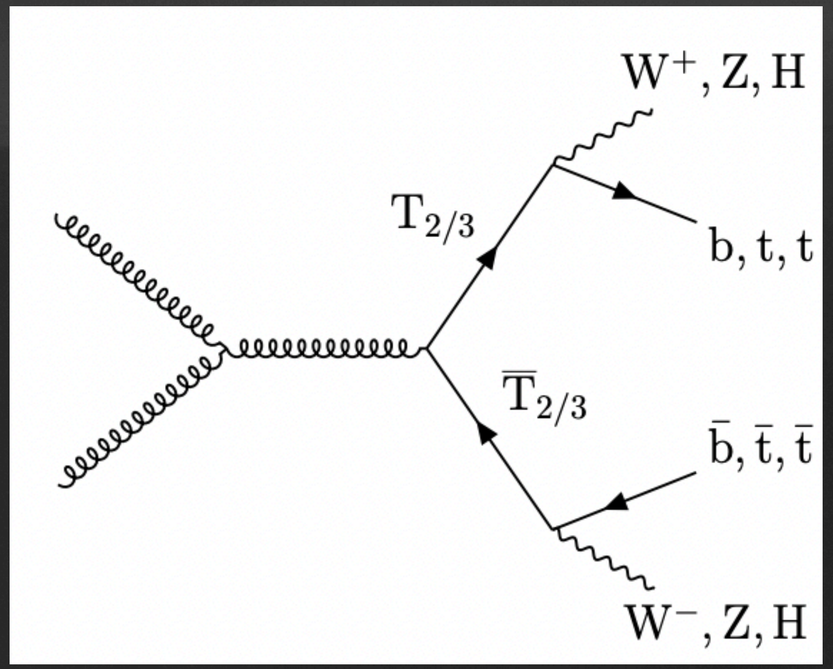
Same-Sign leptons, quarkonia/Z veto
3 SRs: ee, emu, mumu







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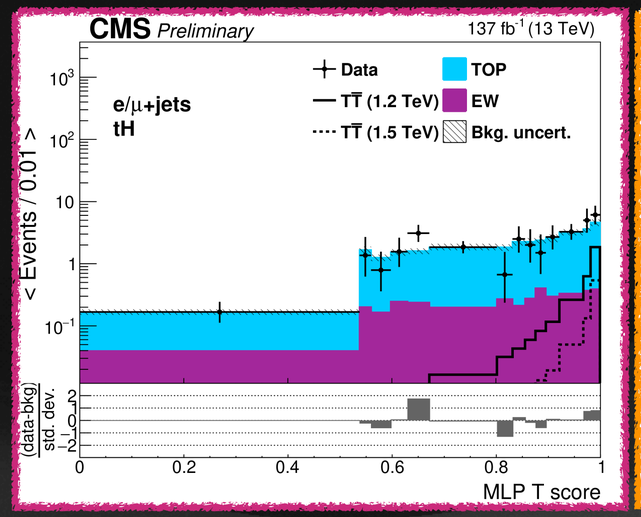
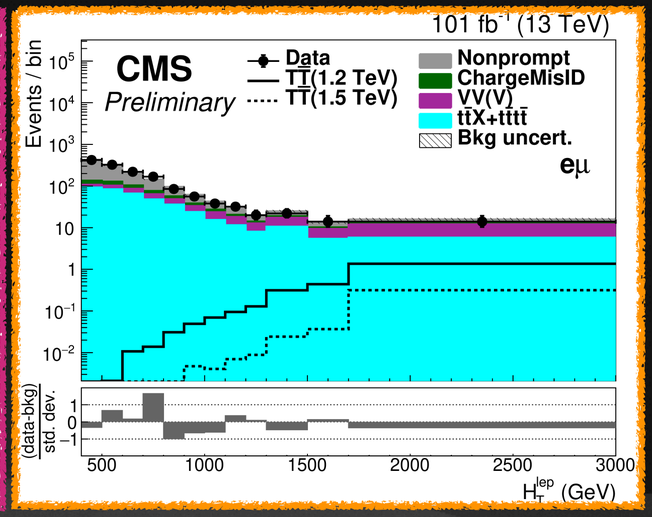
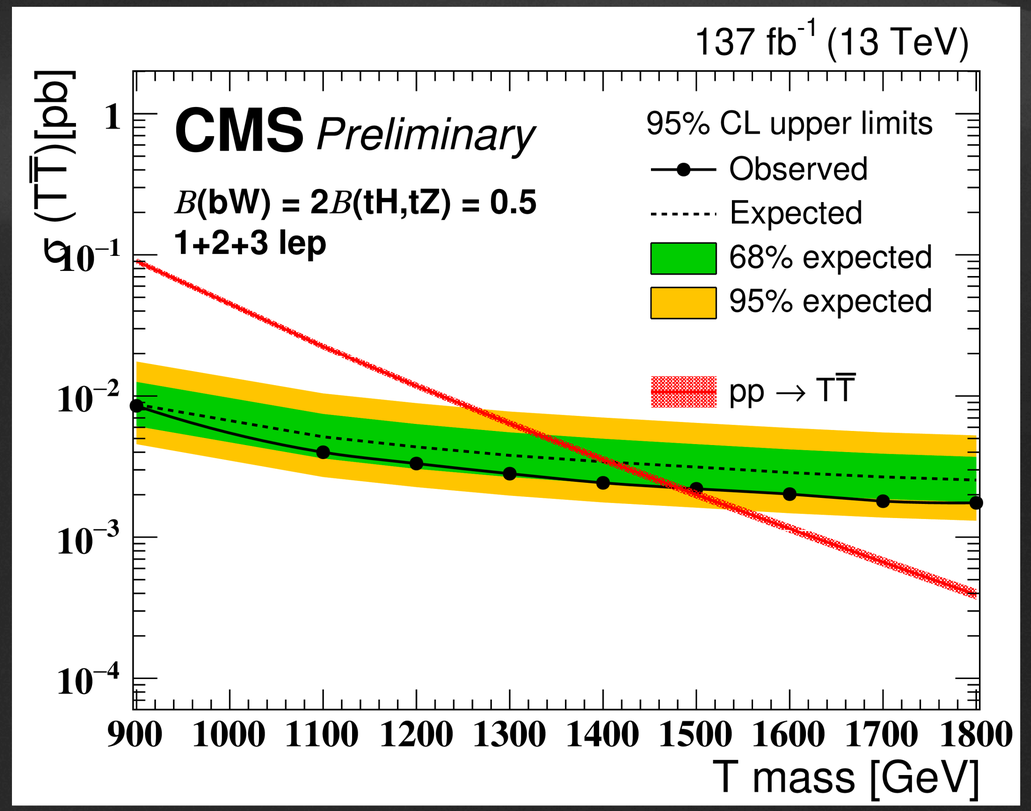
Single SR w/ S_T as discriminator







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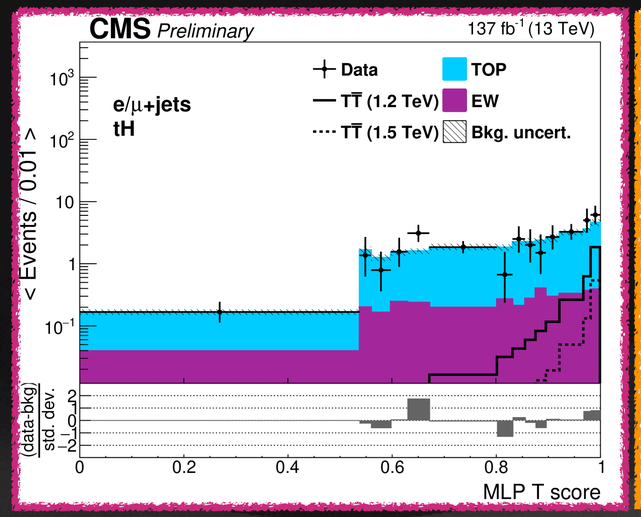

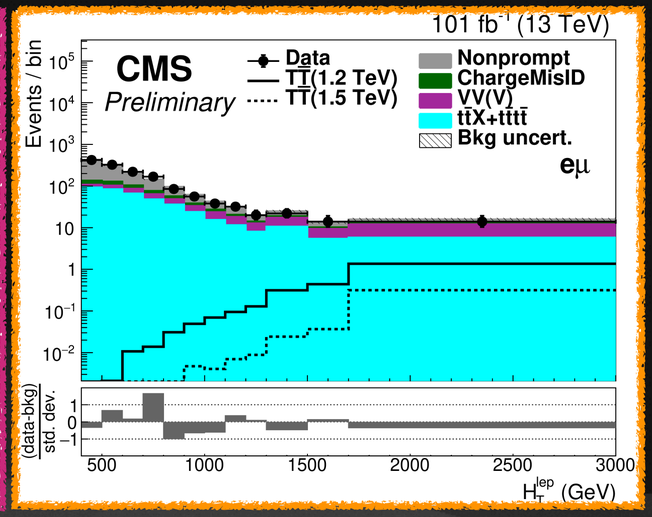

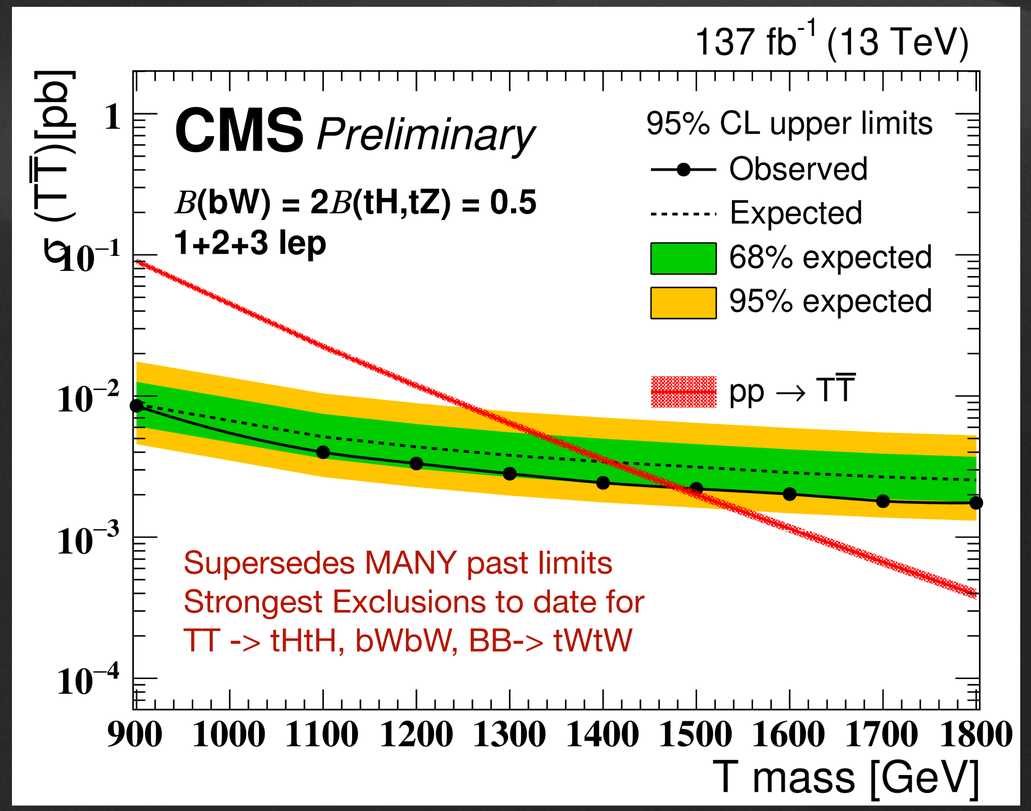

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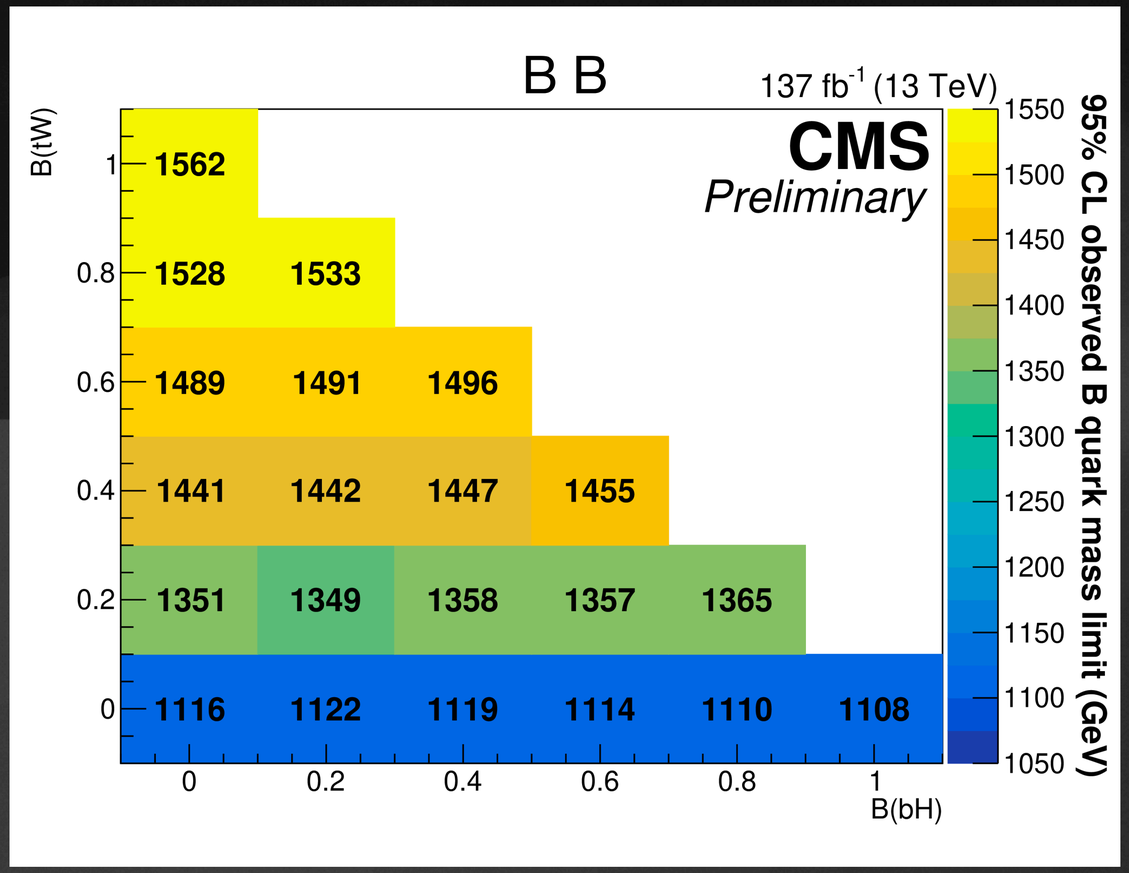
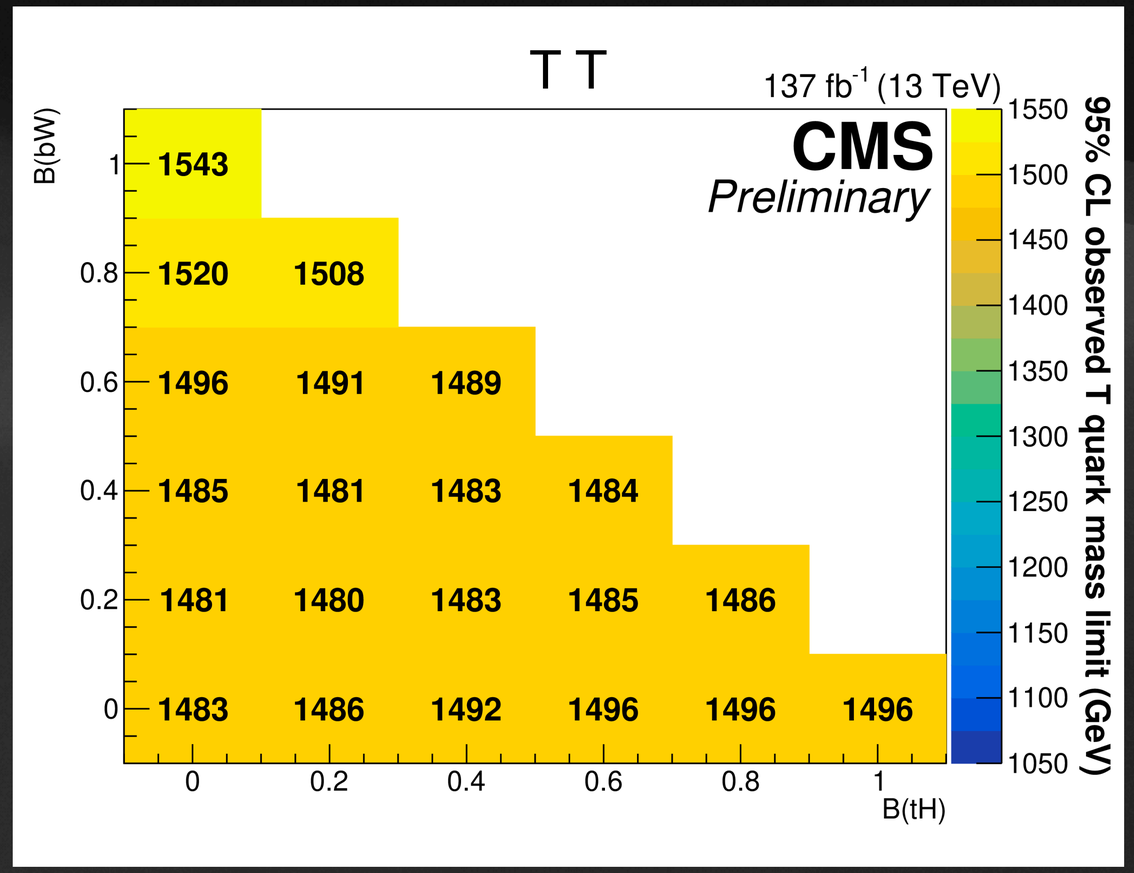
Exclusion Limits TT/BB

Scanning over VLQ Decay Branching Fractions





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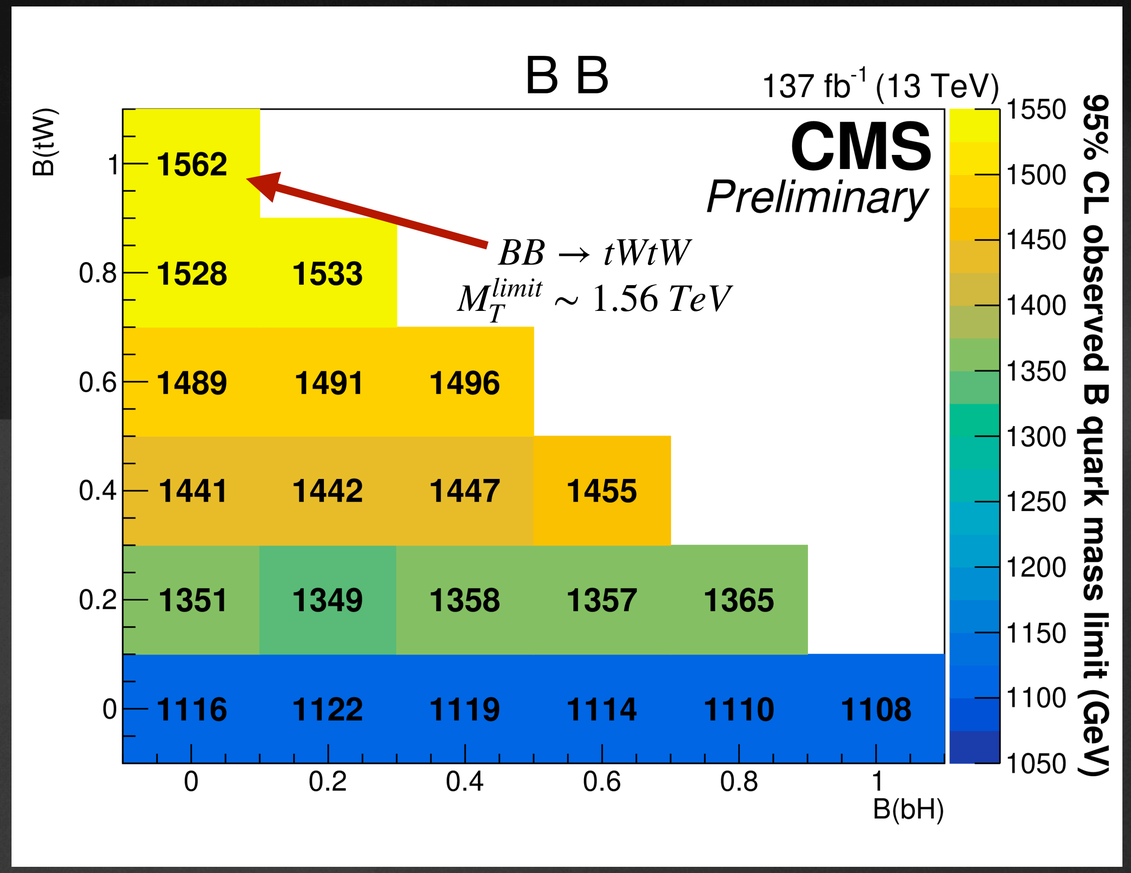

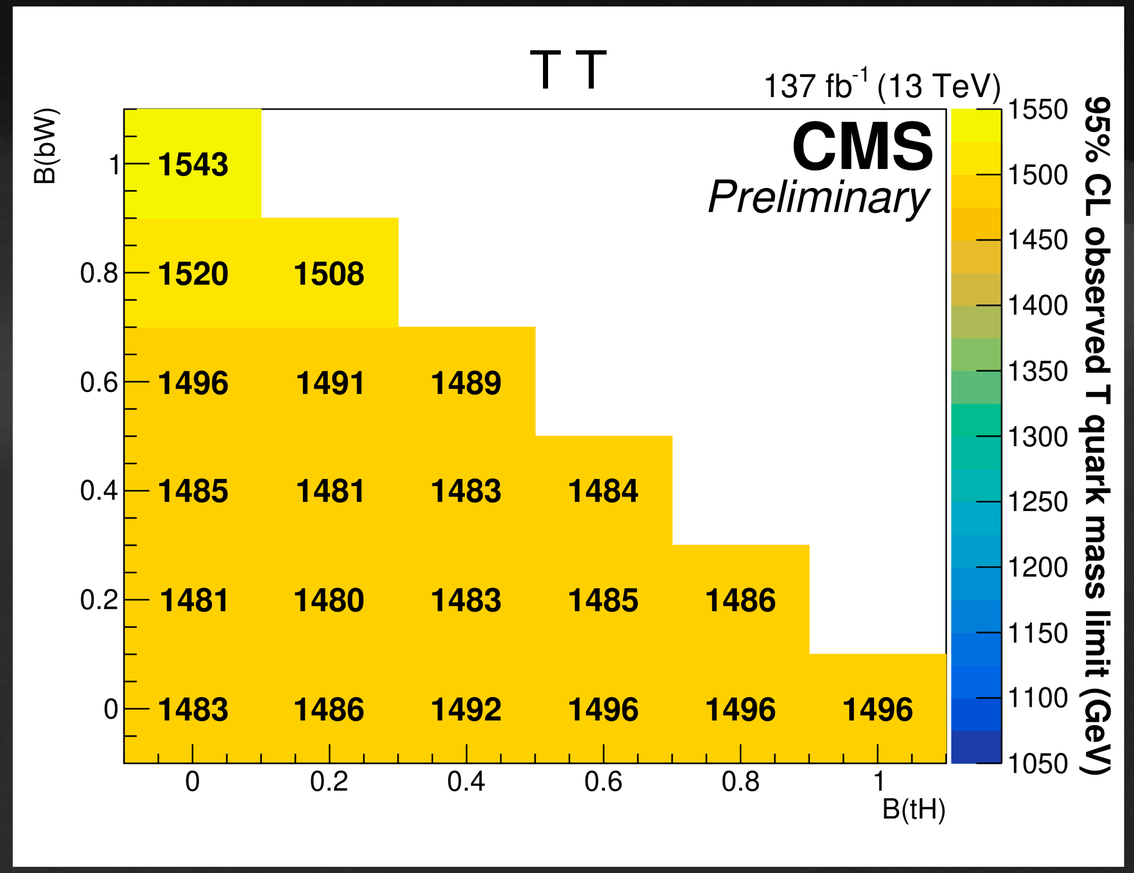

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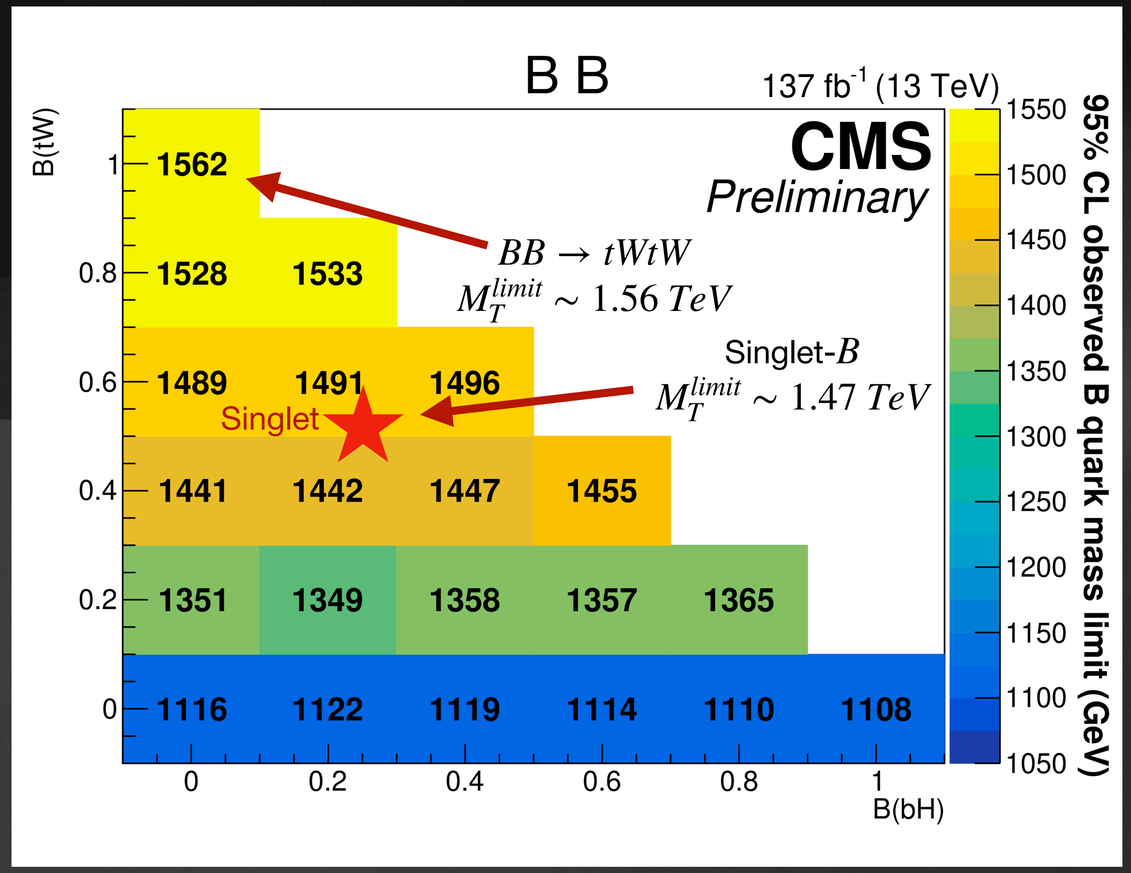

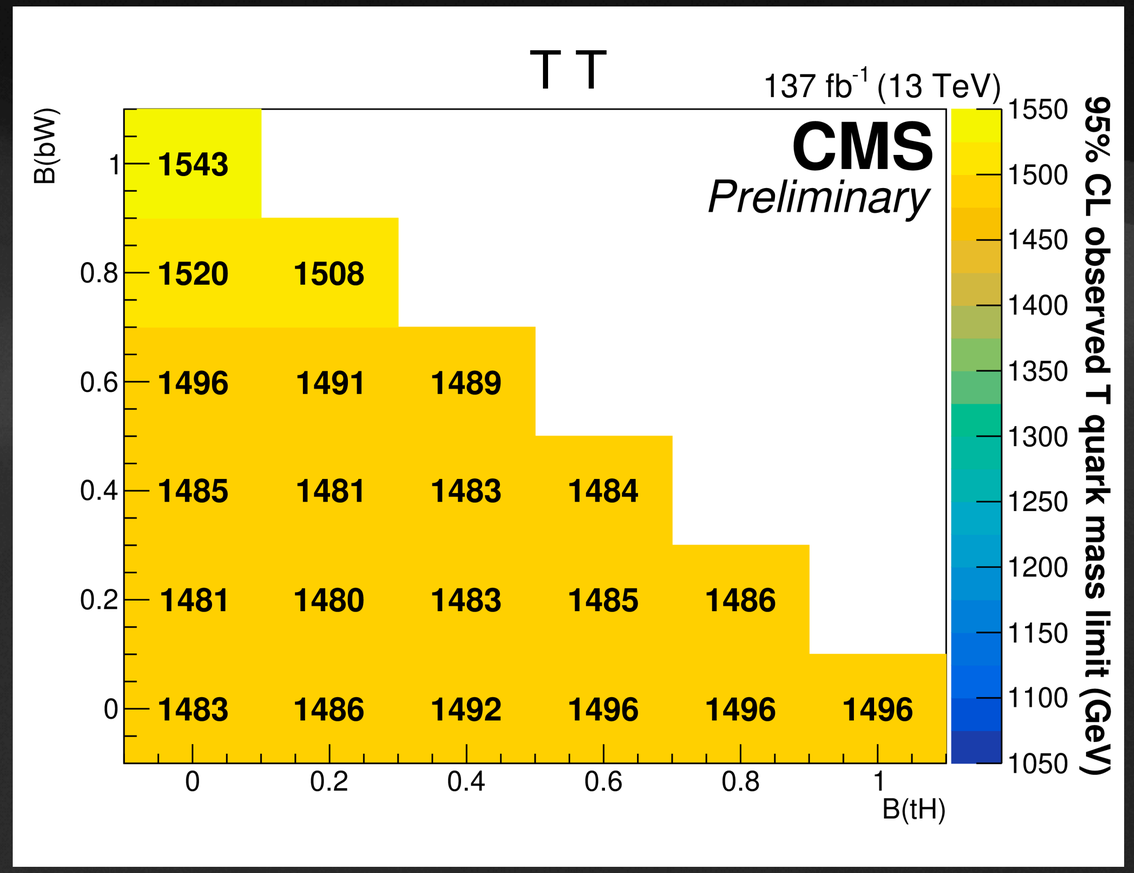

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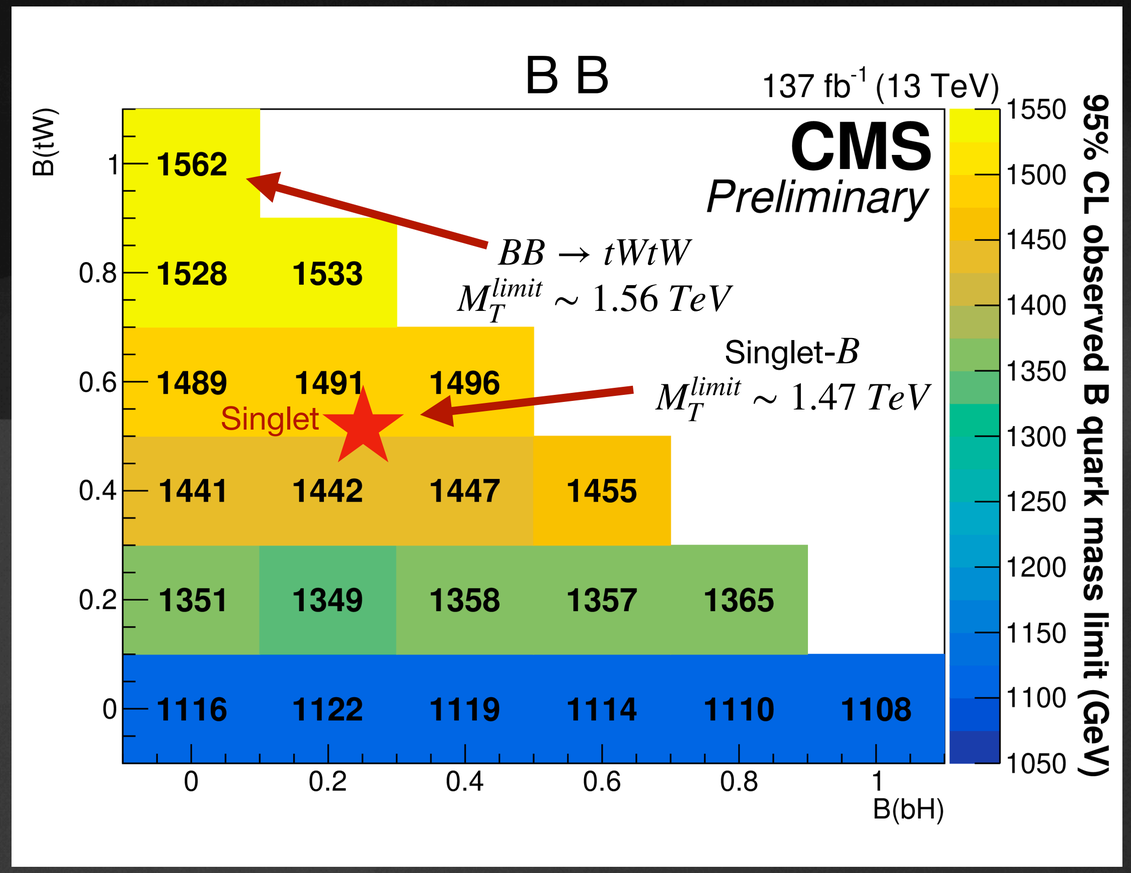

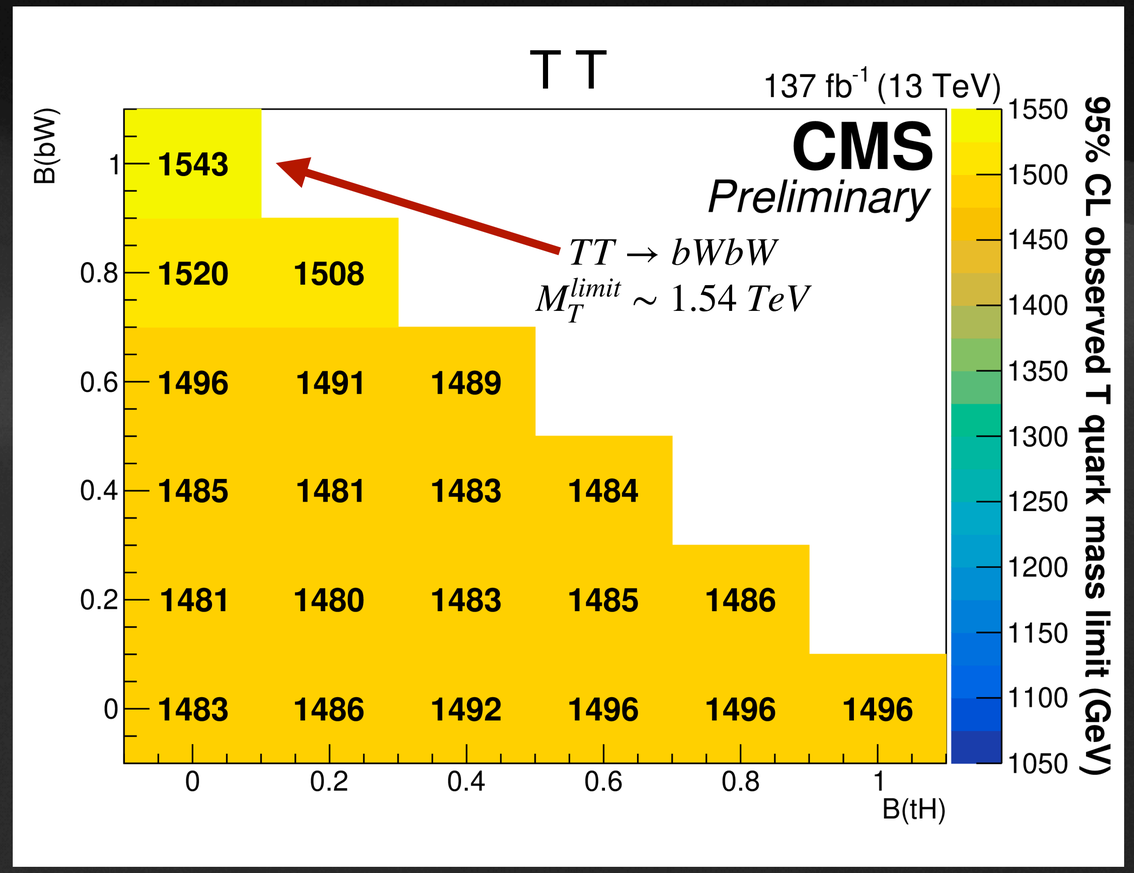

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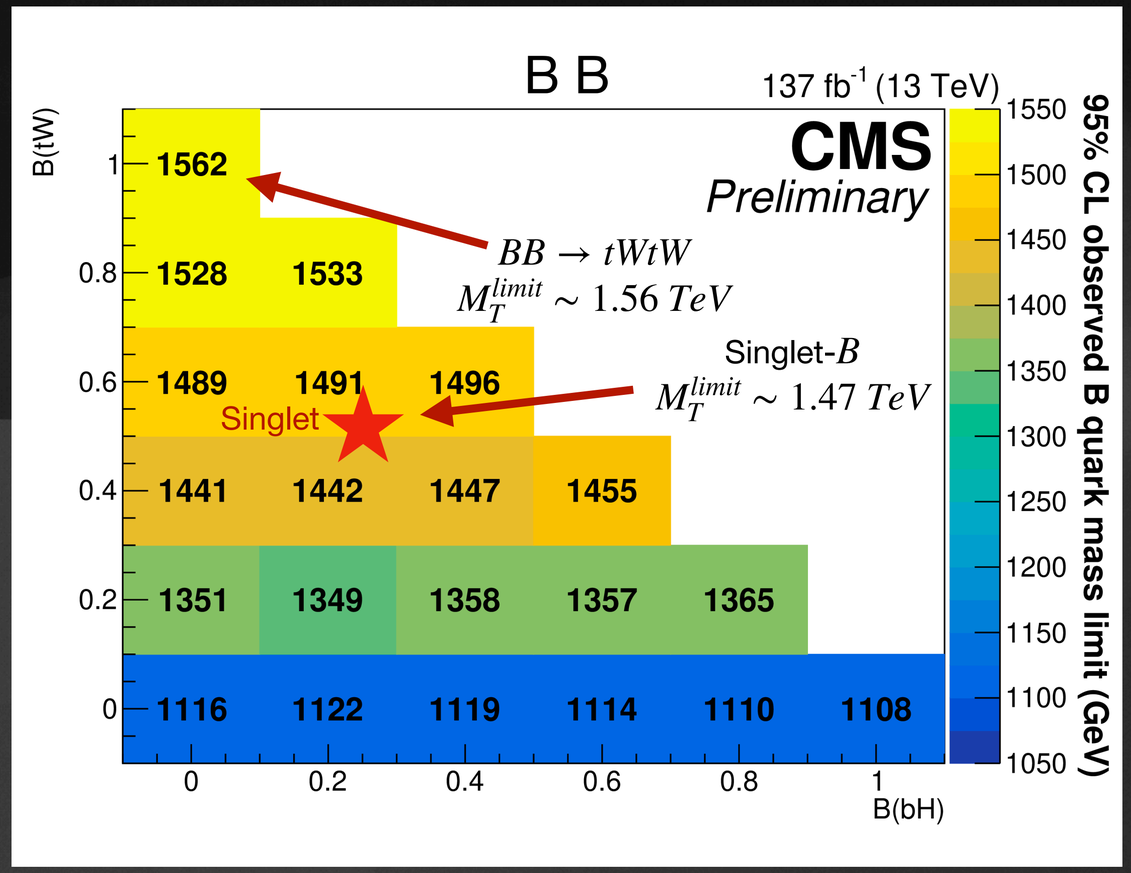

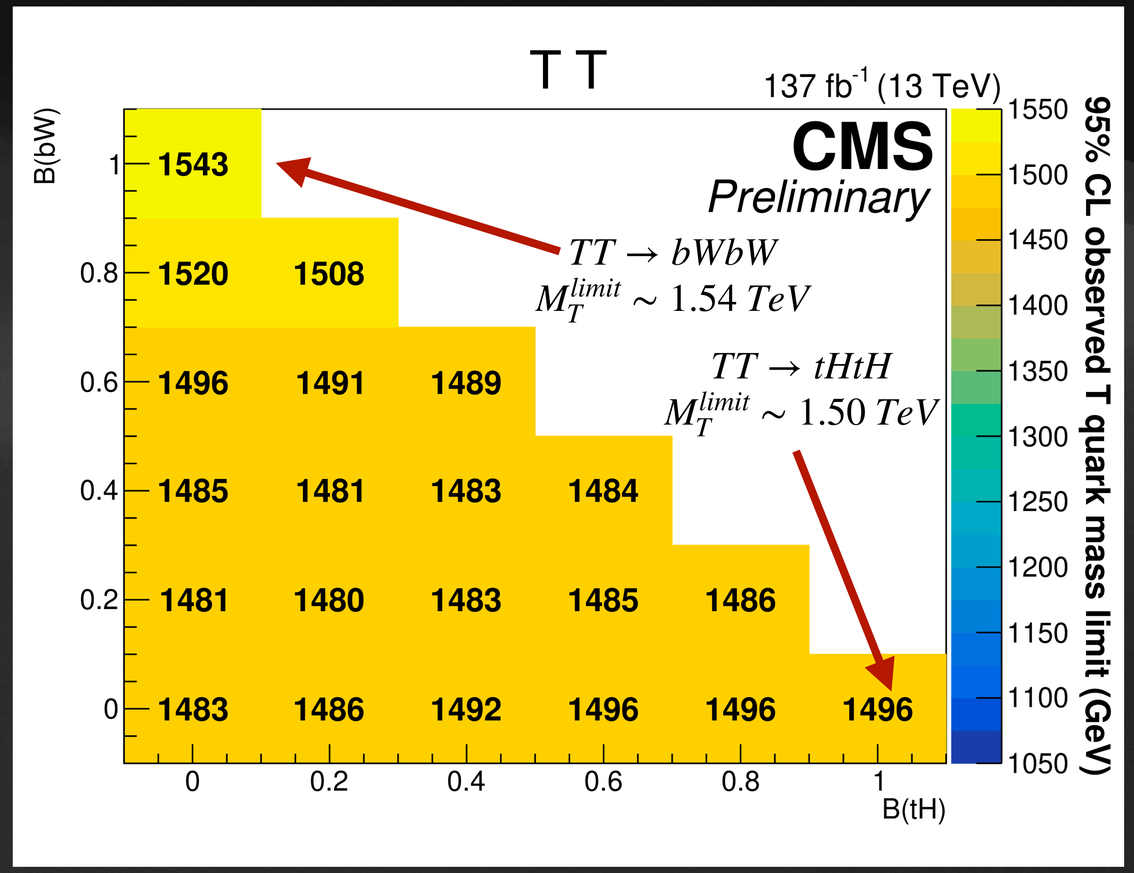

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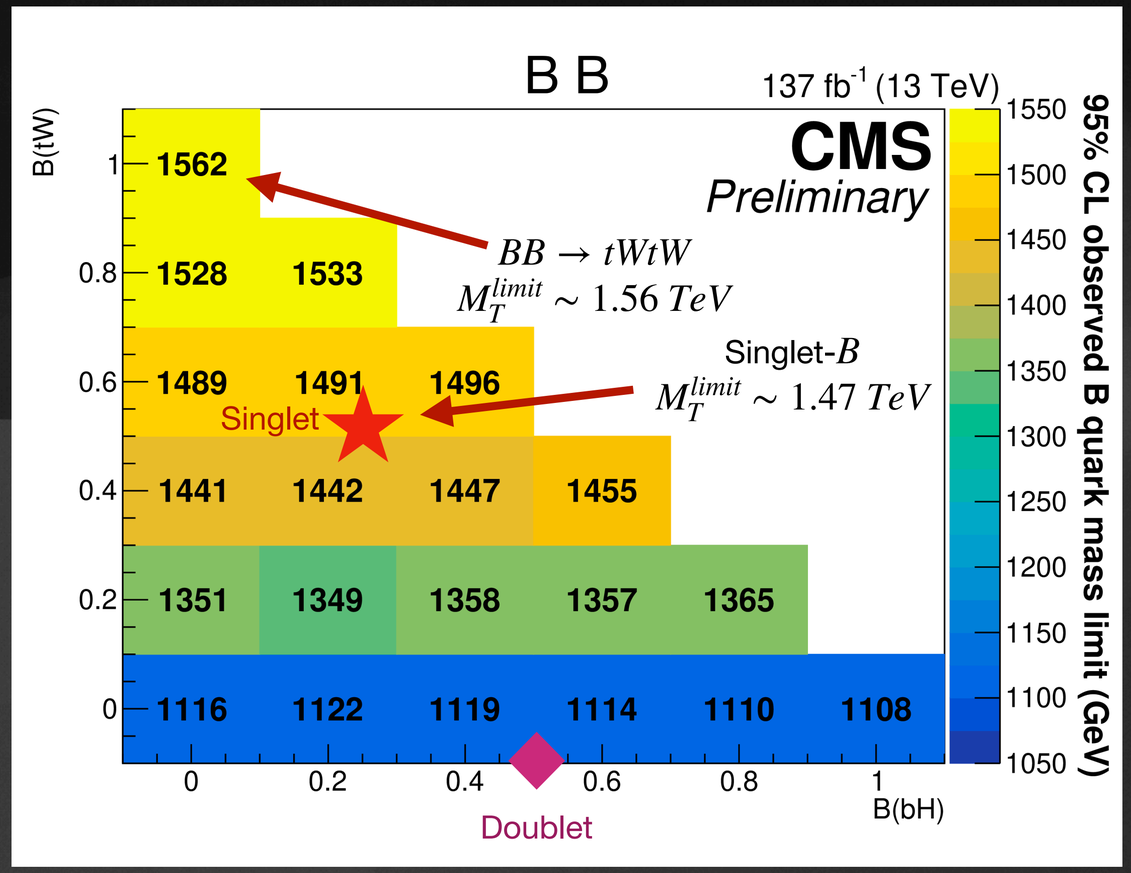

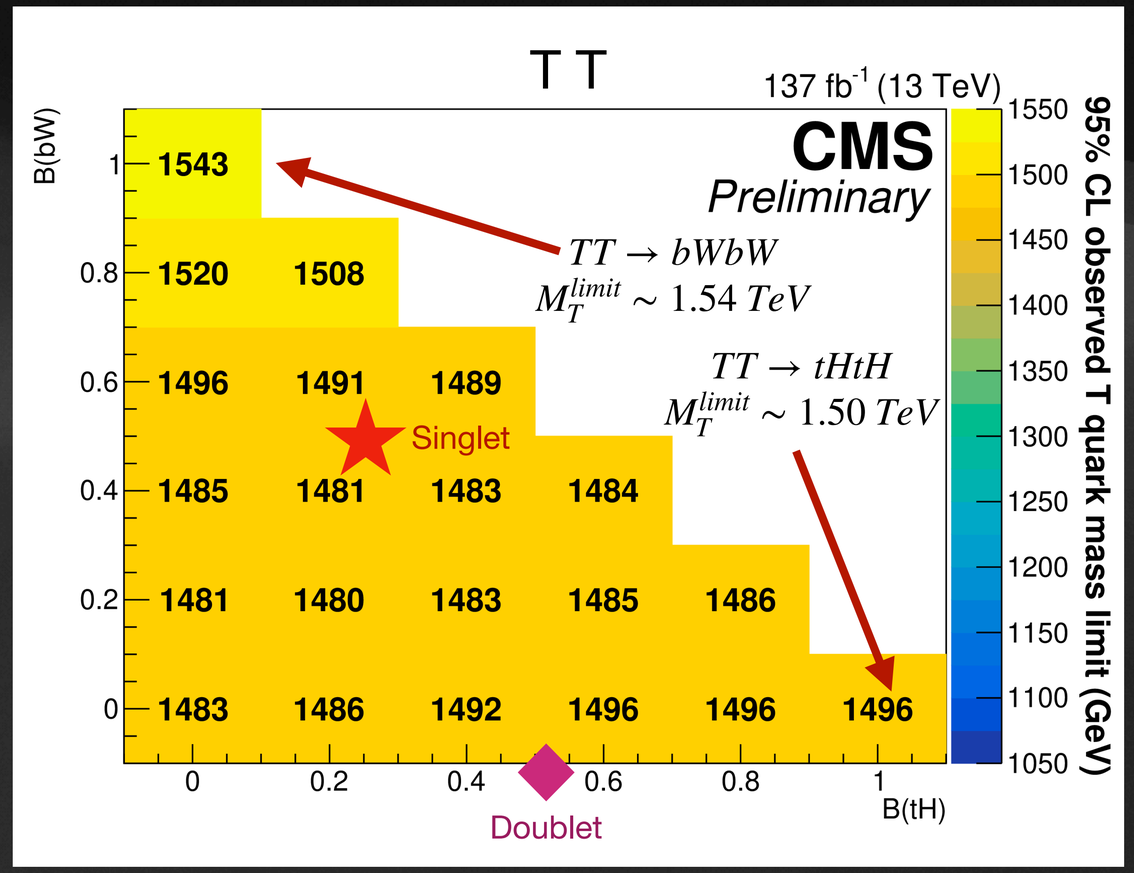

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Vector-Like Leptons

Motivations from B-Physics Anomalies For Signatures at CMS

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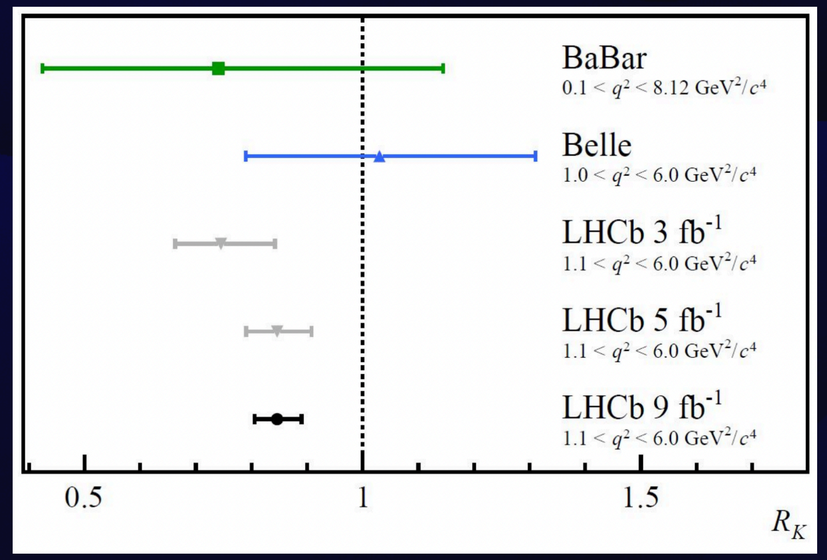
Phys.Rev.Lett. 115, 159901 (2015)



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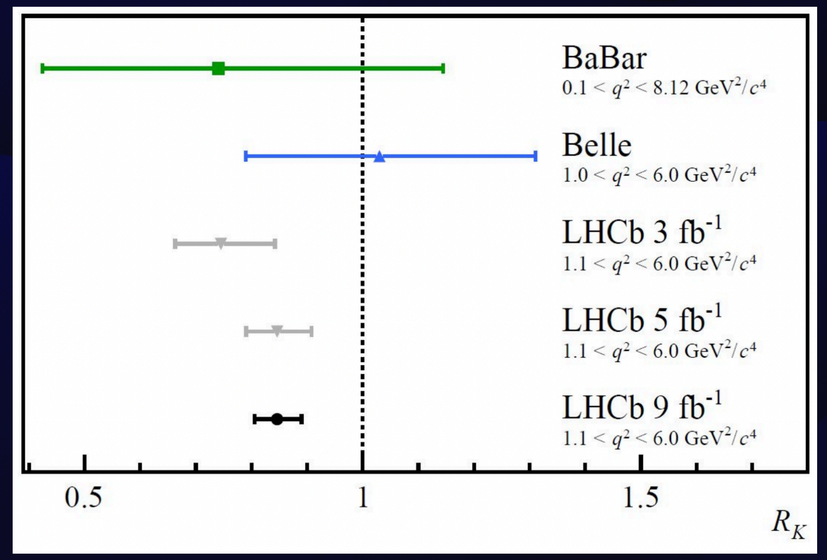
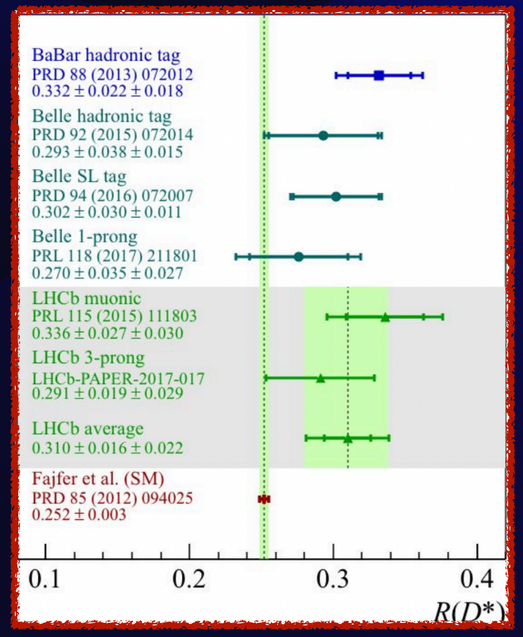


$$B^0 \to D^{(*)-}\tau^+\nu_\tau \,/\, D^{(*)-}\mu^+\nu_\mu$$

$$B^- \to D^{(*)0}\tau^-\bar{\nu}_\tau \,/\, D^{(*)0}\mu^-\bar{\nu}_\mu$$

Phys. Rev. Lett. 120 (2018) 171802



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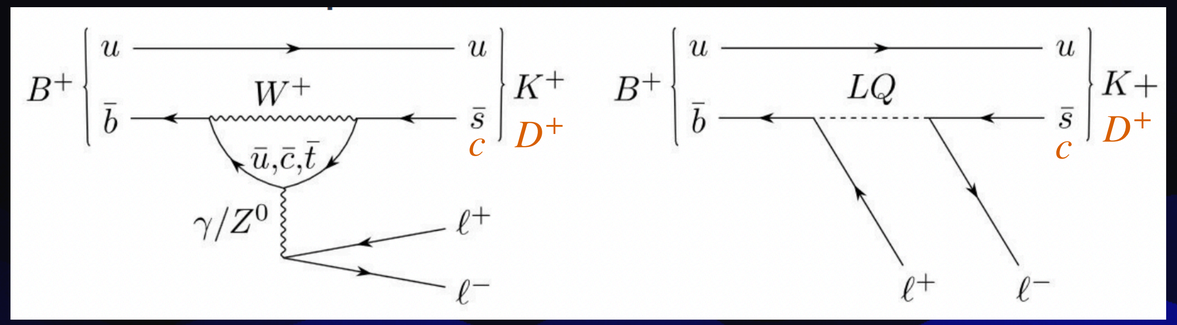

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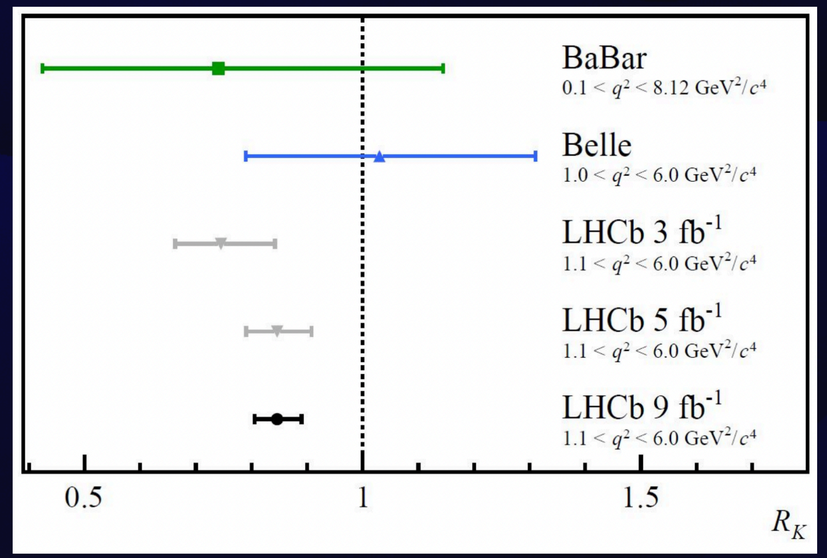

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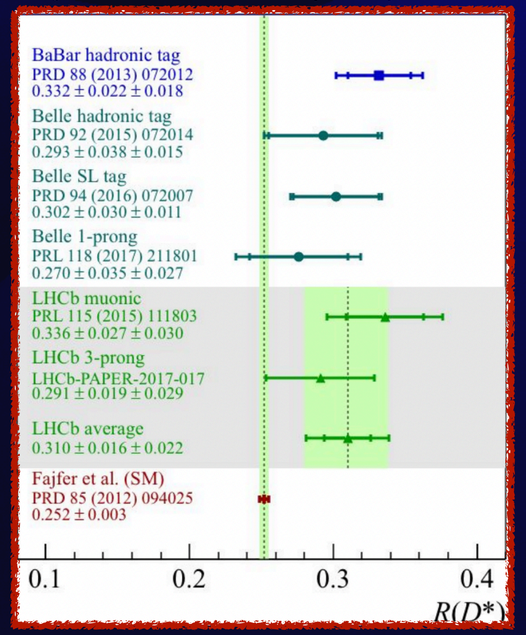

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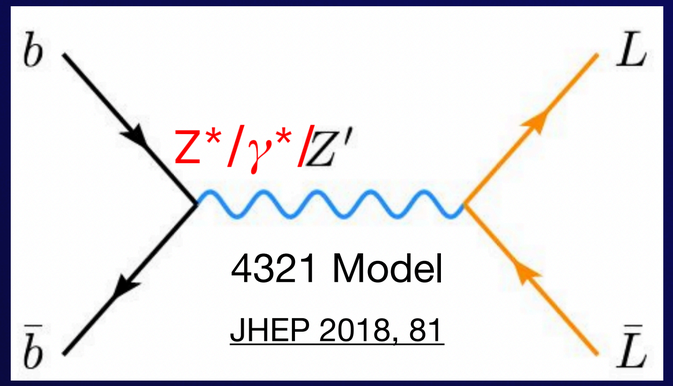
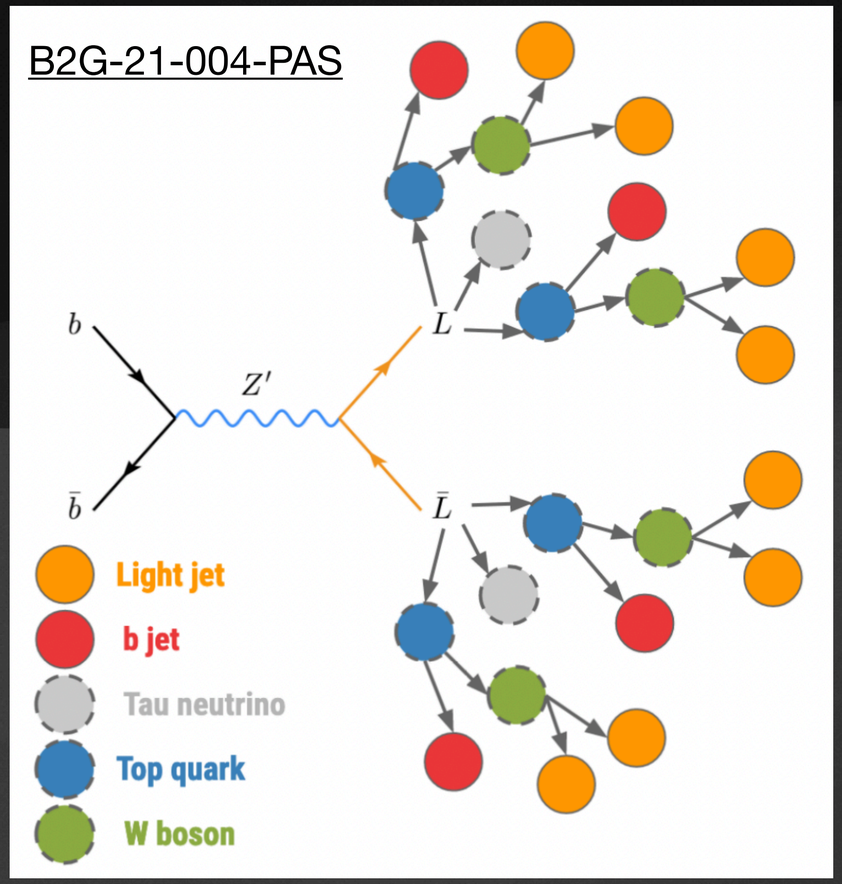
Leptoquarks can be a source of Lepton Favor Violation



Event-Wide Graph-Network

CMS-PAS-B2G-21-004



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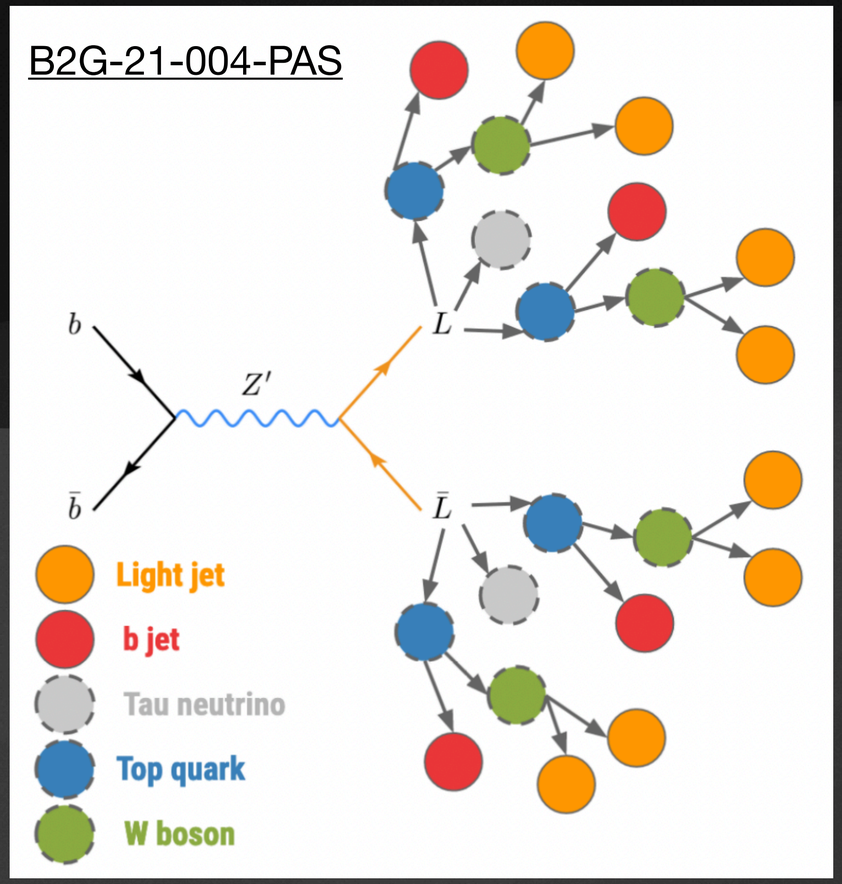


Pair-Produced VLL

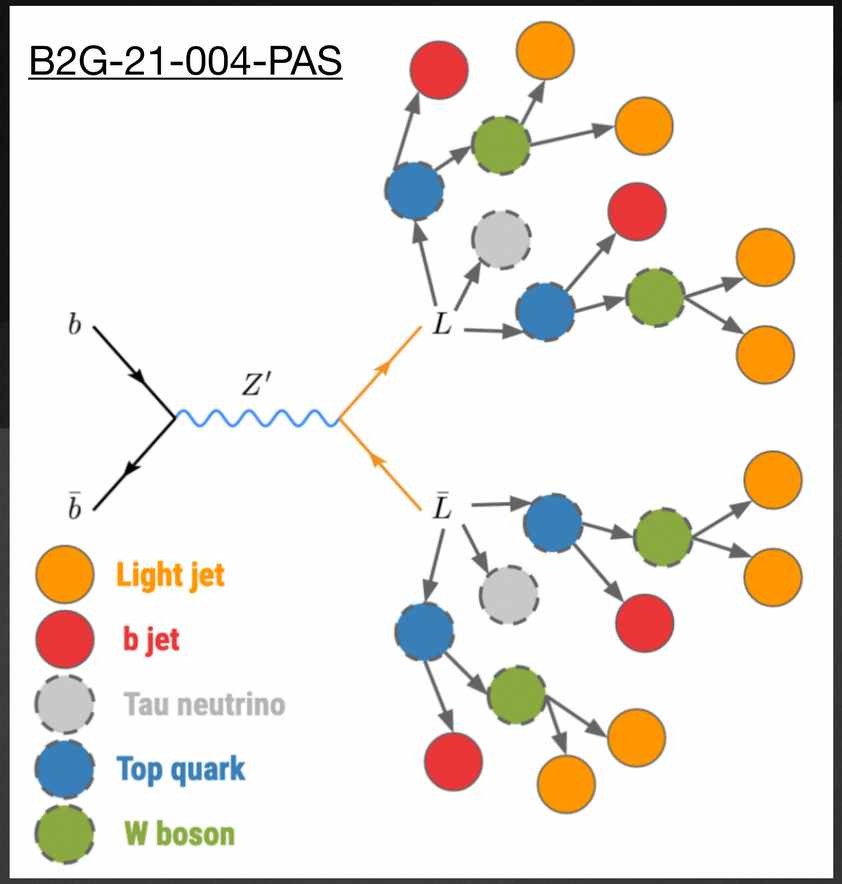
$$L \to t\bar{t}(\tau/\nu_\tau)$$

$$t \to bW, W \to qq'$$

Event-Wide Graph-Network

CMS-PAS-B2G-21-004

Inputs (N=10, F=6, k=8)
$(\eta, \phi, \log p_T, \log m, Q,$ DeepJet$)$



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Represent Hadronic Event as Point Cloud

Eur. Phys. J. Plus 135, 463 (2020)

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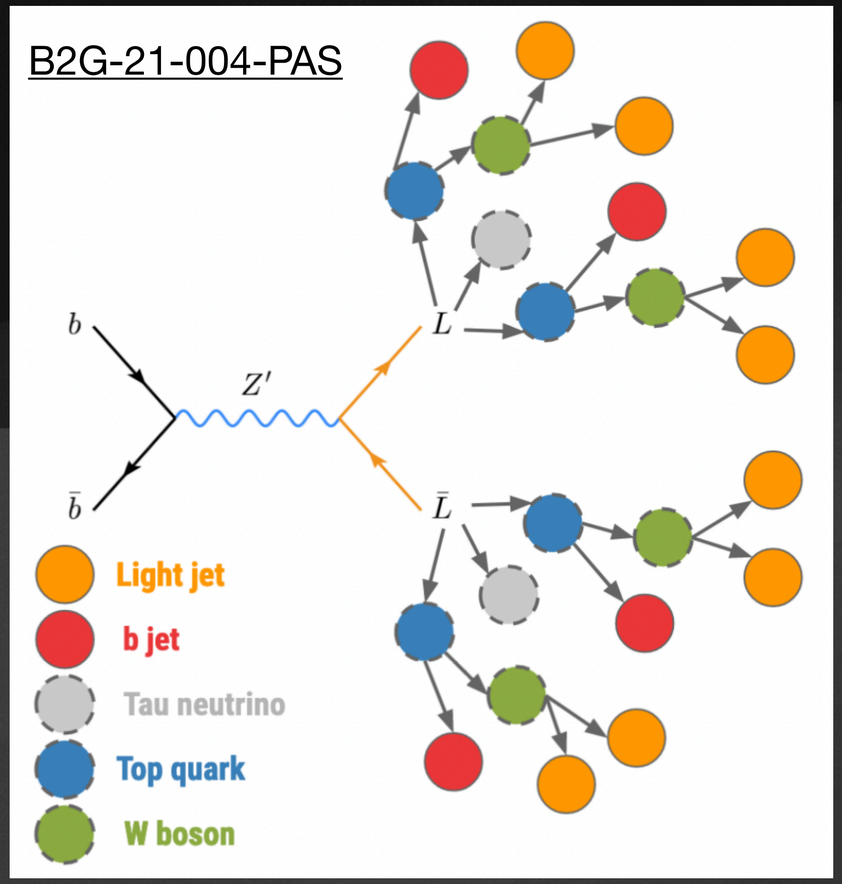
CMS-PAS-B2G-21-004



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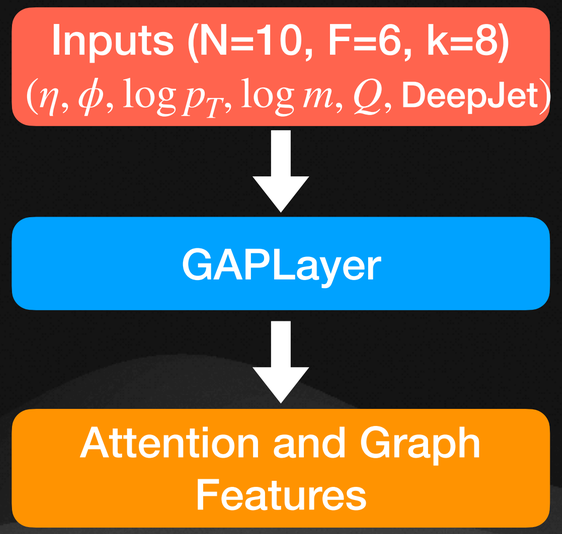
Attention Mechanism Provides Additional Non-Linearity/ Flexibility



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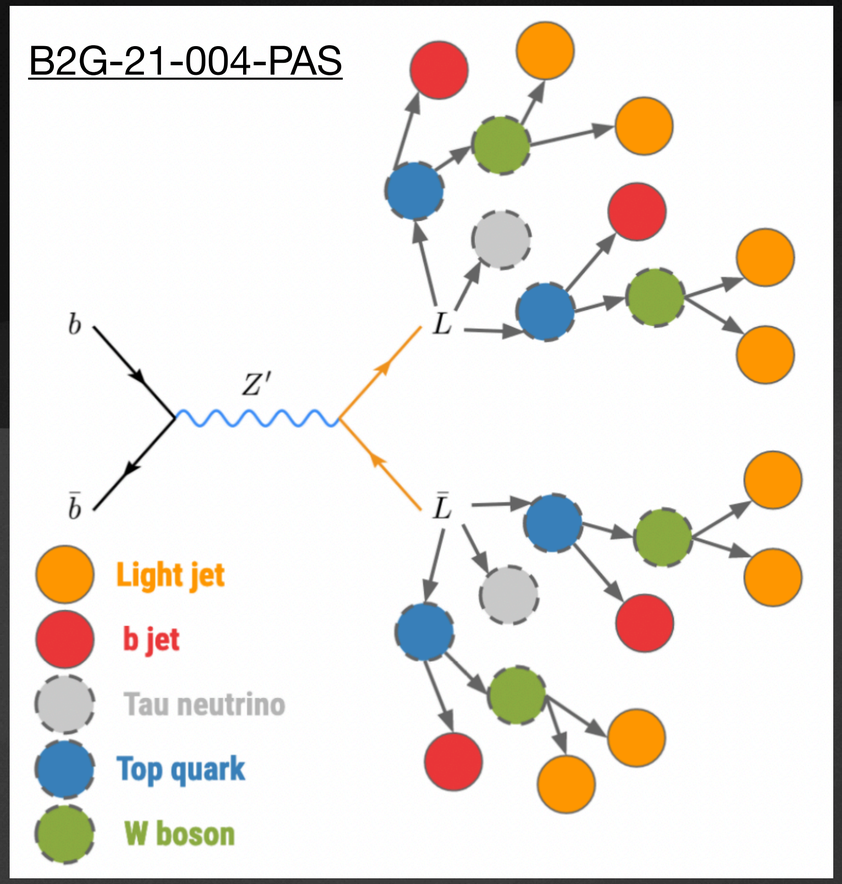

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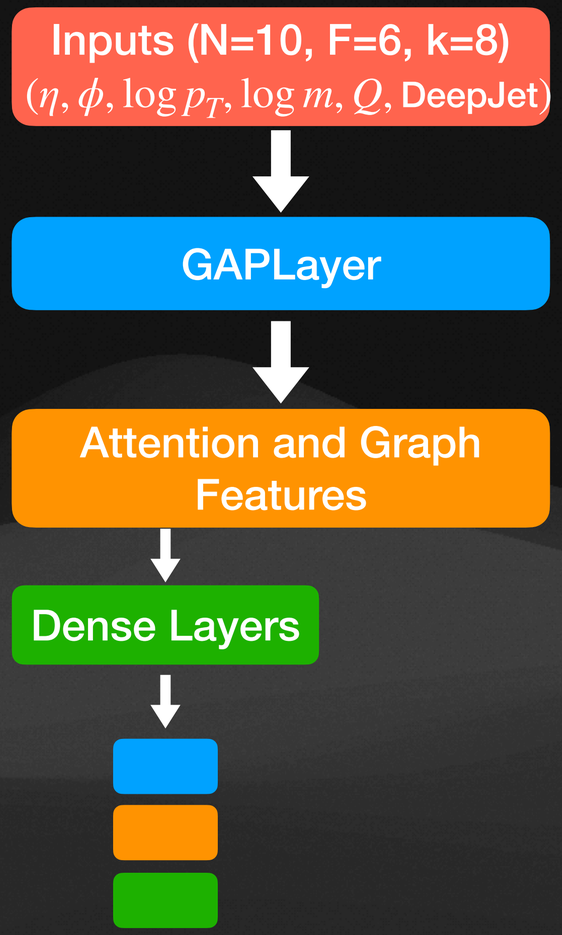

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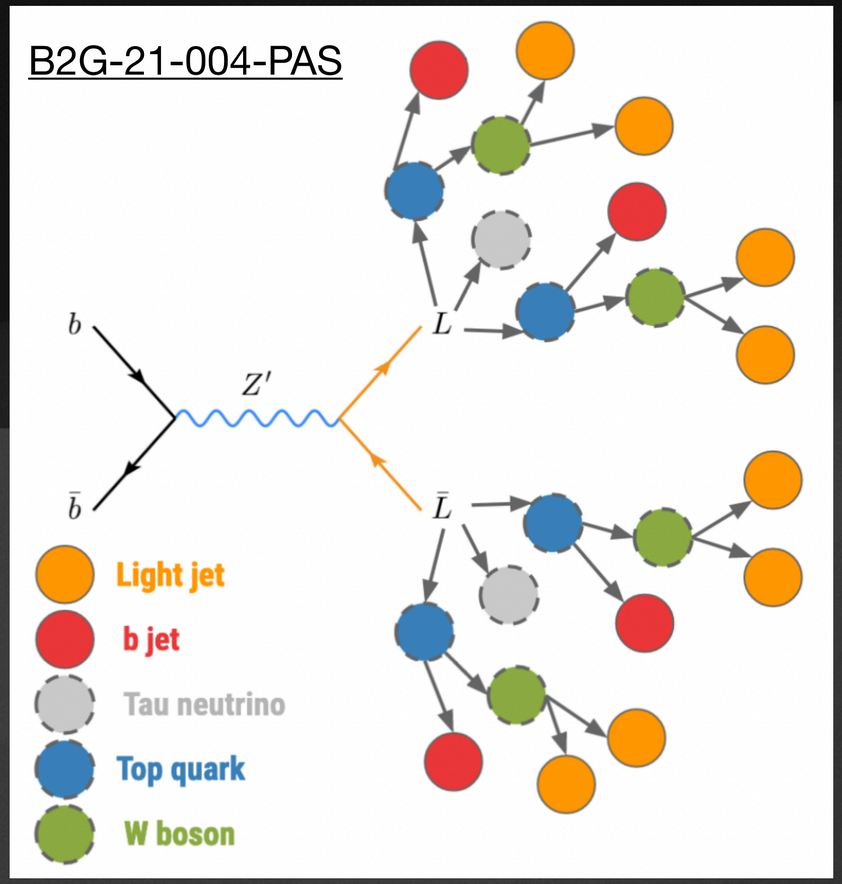

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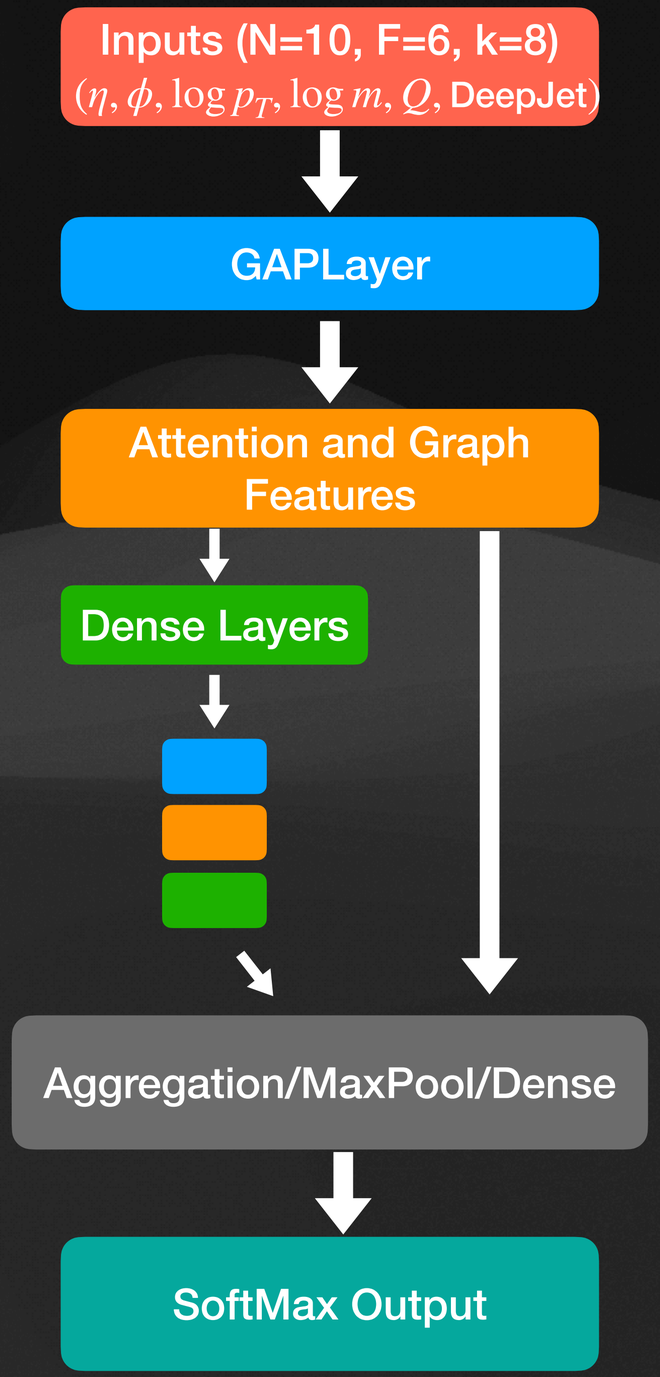

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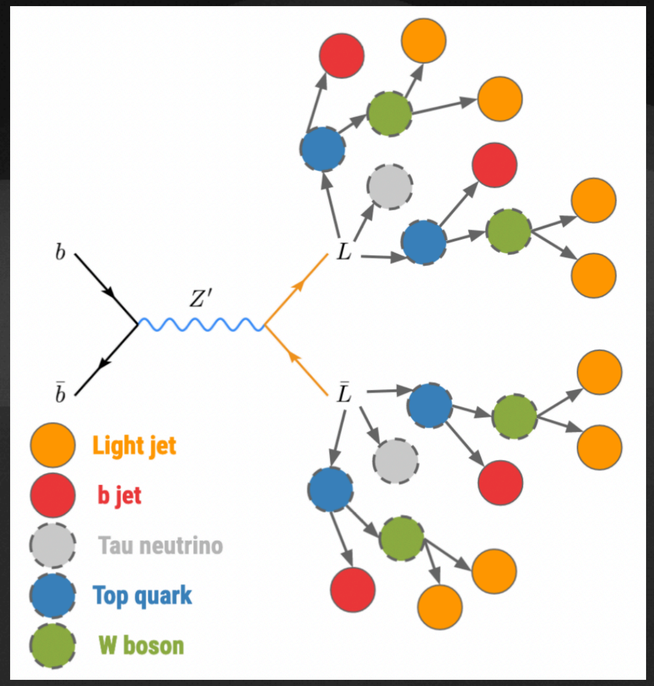
Results of VLL $N_\tau = 0 - 2$



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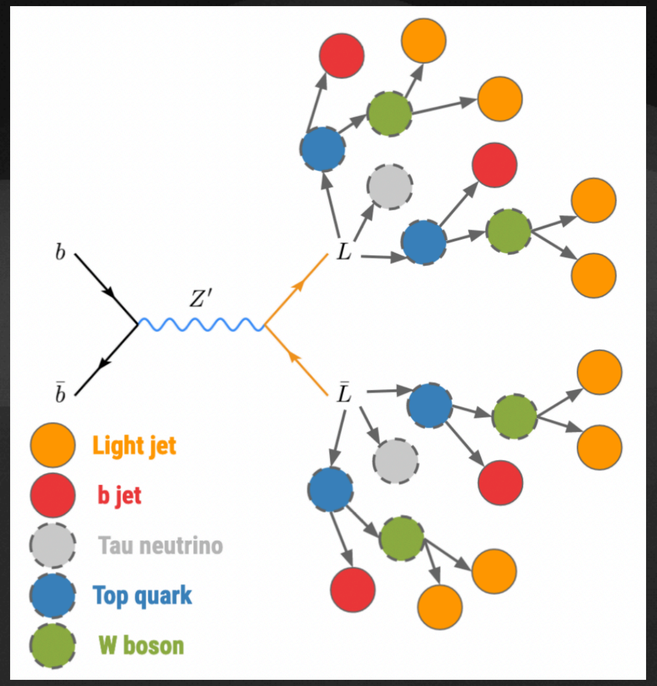

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Two Event-Wide Graph Networks:
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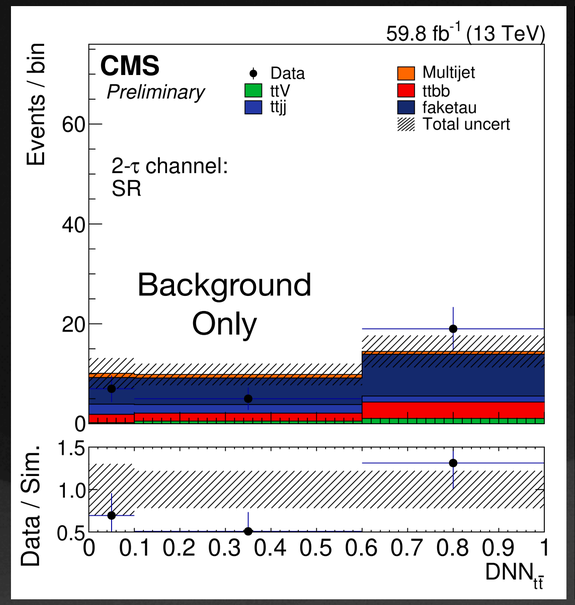

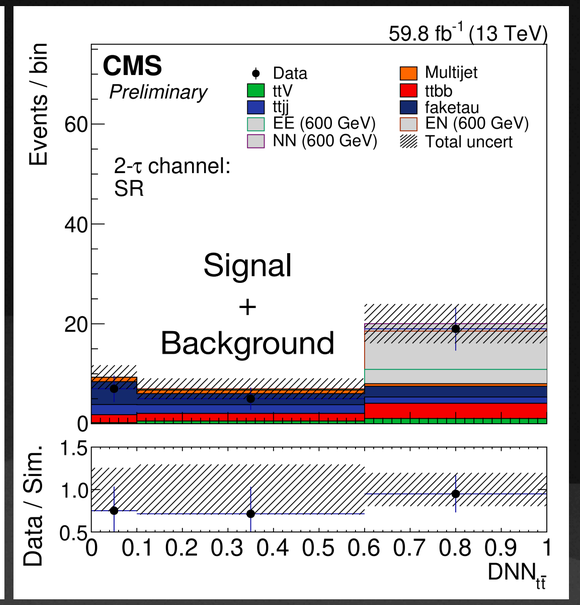

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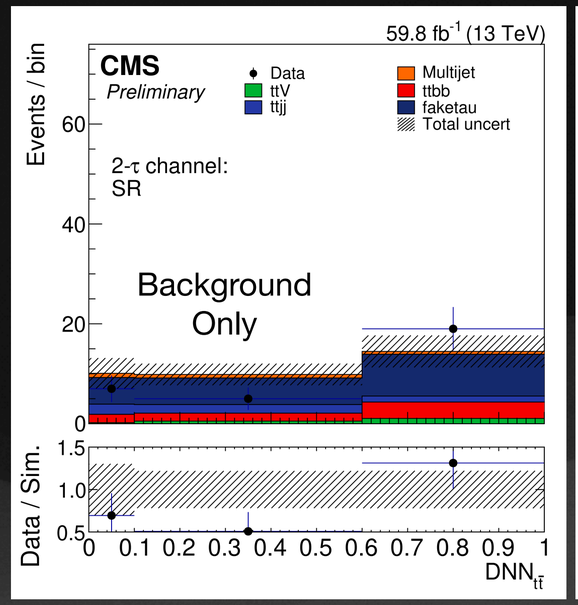
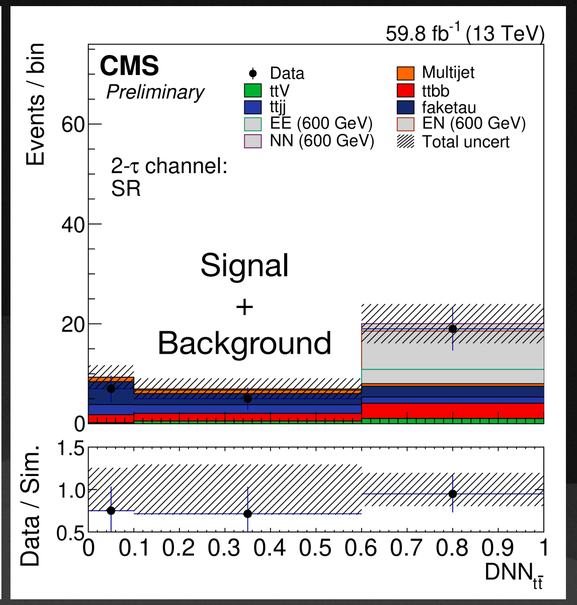
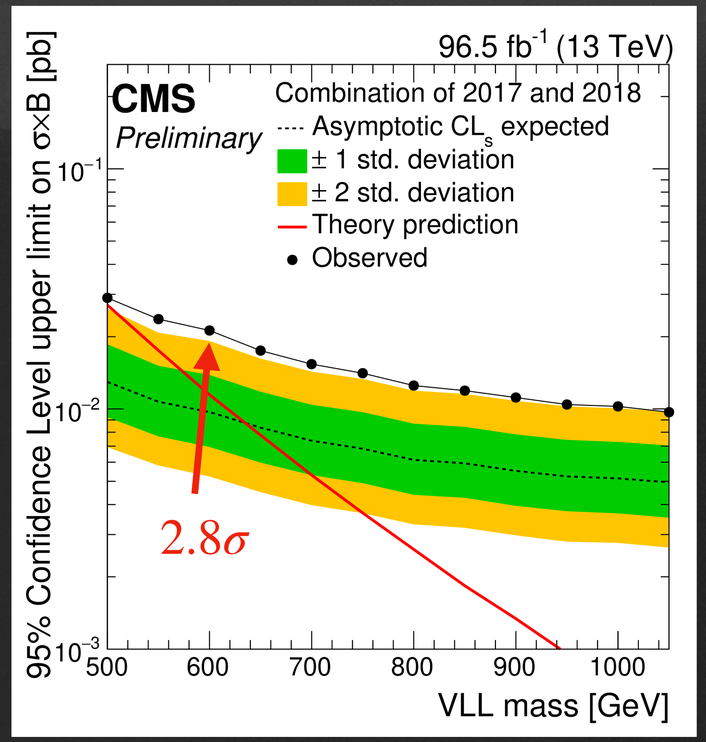
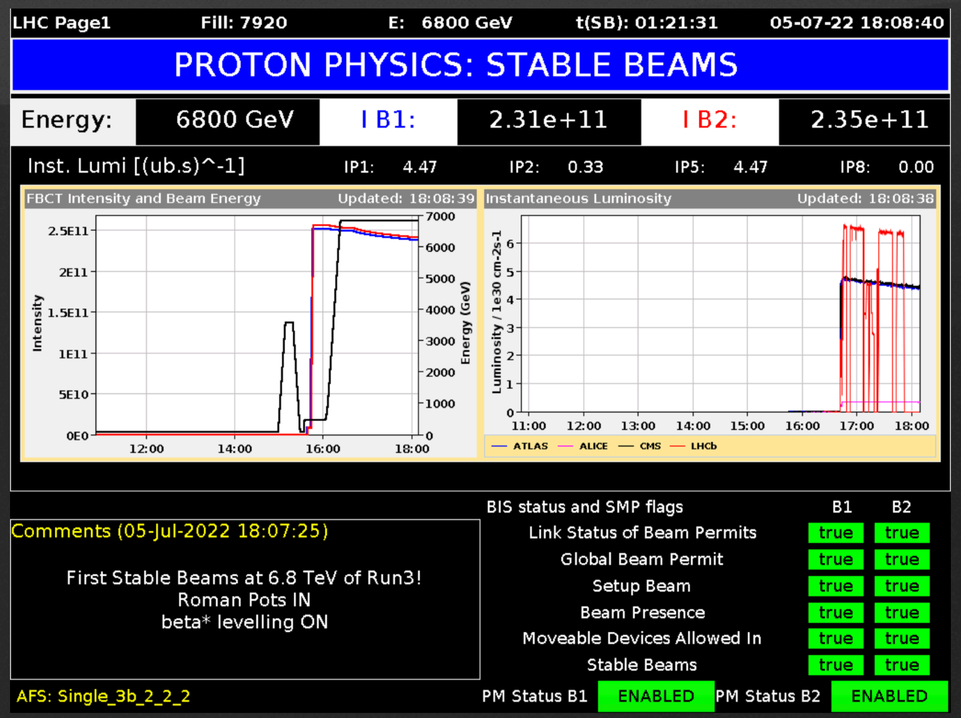
Mild Excess seen in 1τ and 2τ SRs
- Corresponding to large $DNN_{t\bar{t}}$ scores
- 2.8σ @ 600 GeV







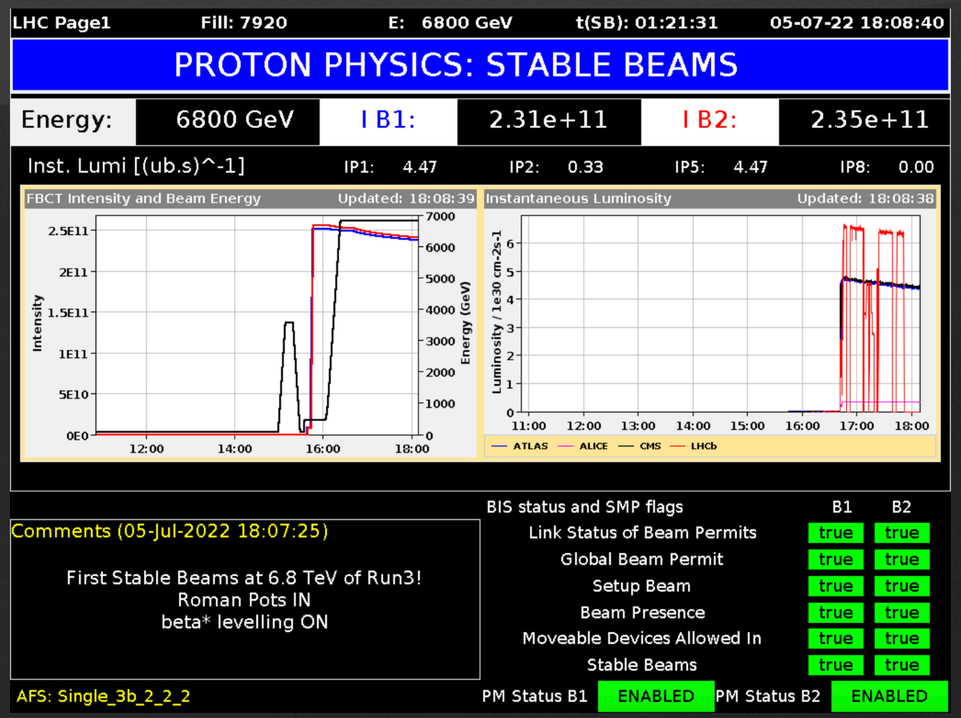
Conclusion and Outlook



Conclusion and Outlook

Today's Results

- $T \to tZ(\nu\nu)$, 2.5σ excess near 1.4 TeV
- $T \to tH(\gamma\gamma)$, strongest limits at low mass range
- TT/BB (lep), sets limits up to $M_{T/B} < 1.54/1.56$
- VLL (hadronic), excess throughout range up to 2.8σ



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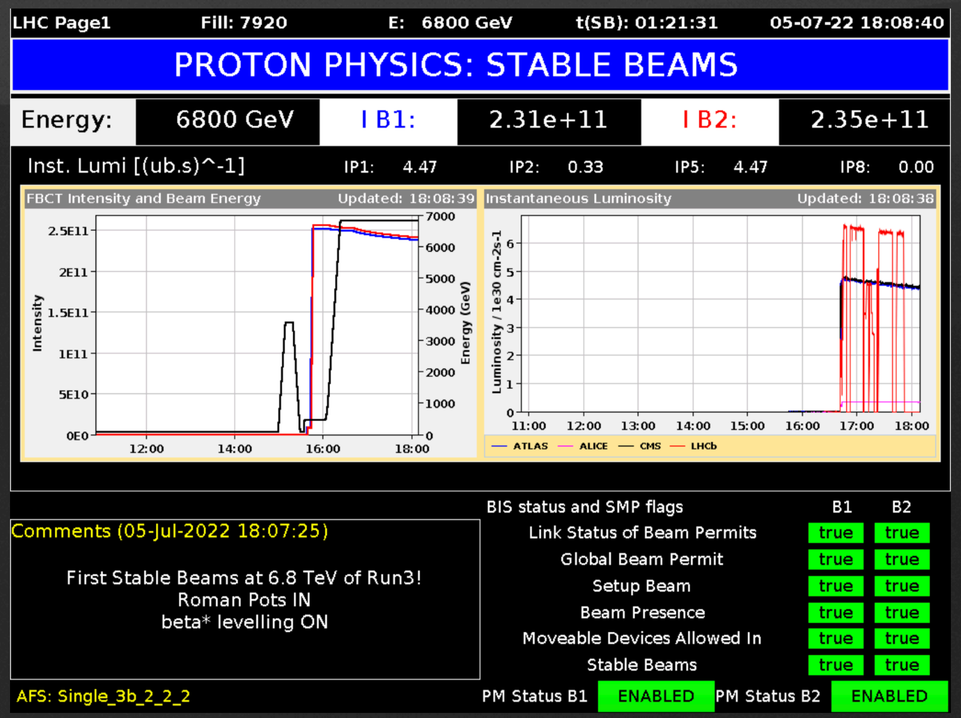
- Much of full data set to explore



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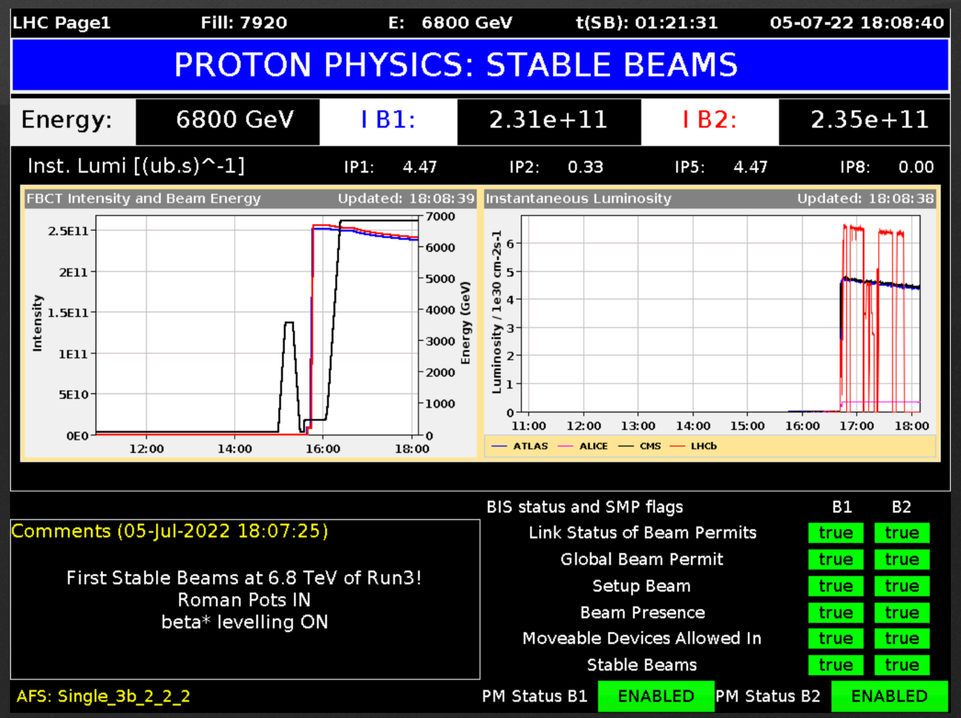
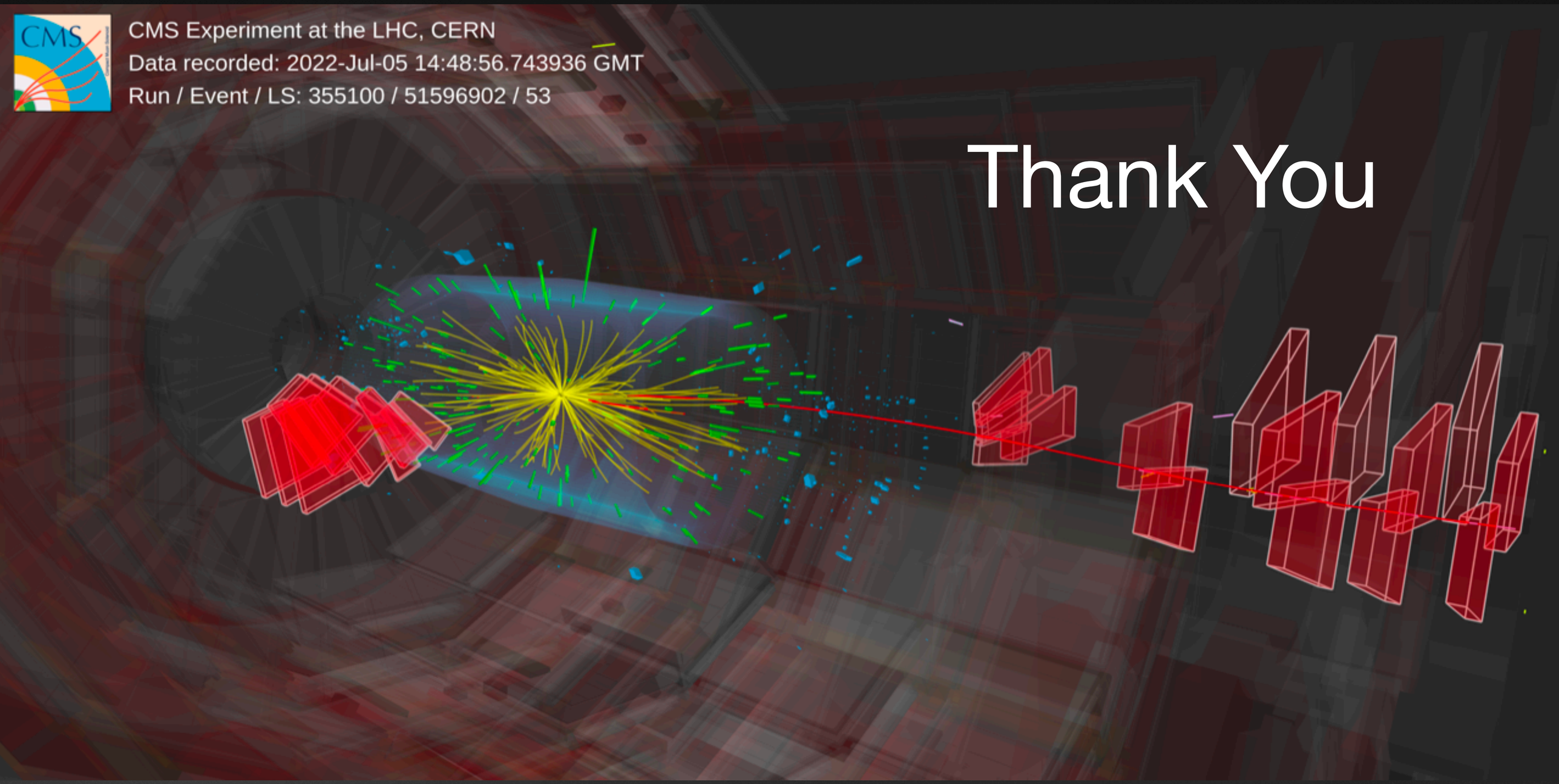
Run 3 has officially begun!
- July 5: First stable beams at 13.6 TeV
- 2022 data-taking ~30-50 fb^{-1}expected




CMS Experiment at the LHC, CERN
Data recorded: 2022-Jul-05 14:48:56.743936 GMT
Run / Event / LS: 355100 / 51596902 / 53

Thank You