Search for Vector-like Top Quarks in di-Leptons

Anthony Barker

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What is a vector-like quark

- They are not actually vector particles; they're spin 1/2 fermions.
- They're "vector-like" in that left and right helicity components have the same quantum numbers and transform identically under gauge transforms.

$$m\psi\bar{\psi}$$

- No Yukawa coupling (y)
They don't get their mass from the Higgs
- They are typically an expansion of the third generation rather than a 4th generation (T mixes with top), so they're not excluded by 4th gen searches.

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{t}_L^0 & \bar{T}_L^0 \end{pmatrix} \begin{pmatrix} y_{33}^u \frac{v}{\sqrt{2}} & y_{34}^u \frac{v}{\sqrt{2}} \\ y_{43}^u \frac{v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} t_R^0 \\ T_R^0 \end{pmatrix}$$

v is the Higgs VEV

Motivation

Theory

- VLQ's are REQUIRED if the Higgs is a pseudo-Goldstone boson, and in the partially-composite theories of flavor, including little Higgs and composite Higgs models.

  ➡ In both mechanisms, VLQ have sizable mixings with 3rd generation SM quarks, hence top and bottom partners.

Observation

- VLQs can improve the fit of electroweak observables to data:

$$\chi^2_{SM} = 10.97, \chi^2_{VLQ} = 1.61$$

Analysis

- Largely model independent analysis
  - Few free parameters.
  - VLQ's are the simplest type of colored fermions still experimentally allowed.

Aguilar–Saavedraa, Benbrikc, Heinemeyer, Pérez-Victoria
arXiv 1306.0572

The cast of characters:

Particle$^{\text{Elec. Charge}}$	Decays
$T^{2/3}$	bW^+, tH, tZ
$B^{-1/3}$	tW^-, bH, bZ
$X^{5/3}$	tW^+
$Y^{-4/3}$	bW^-

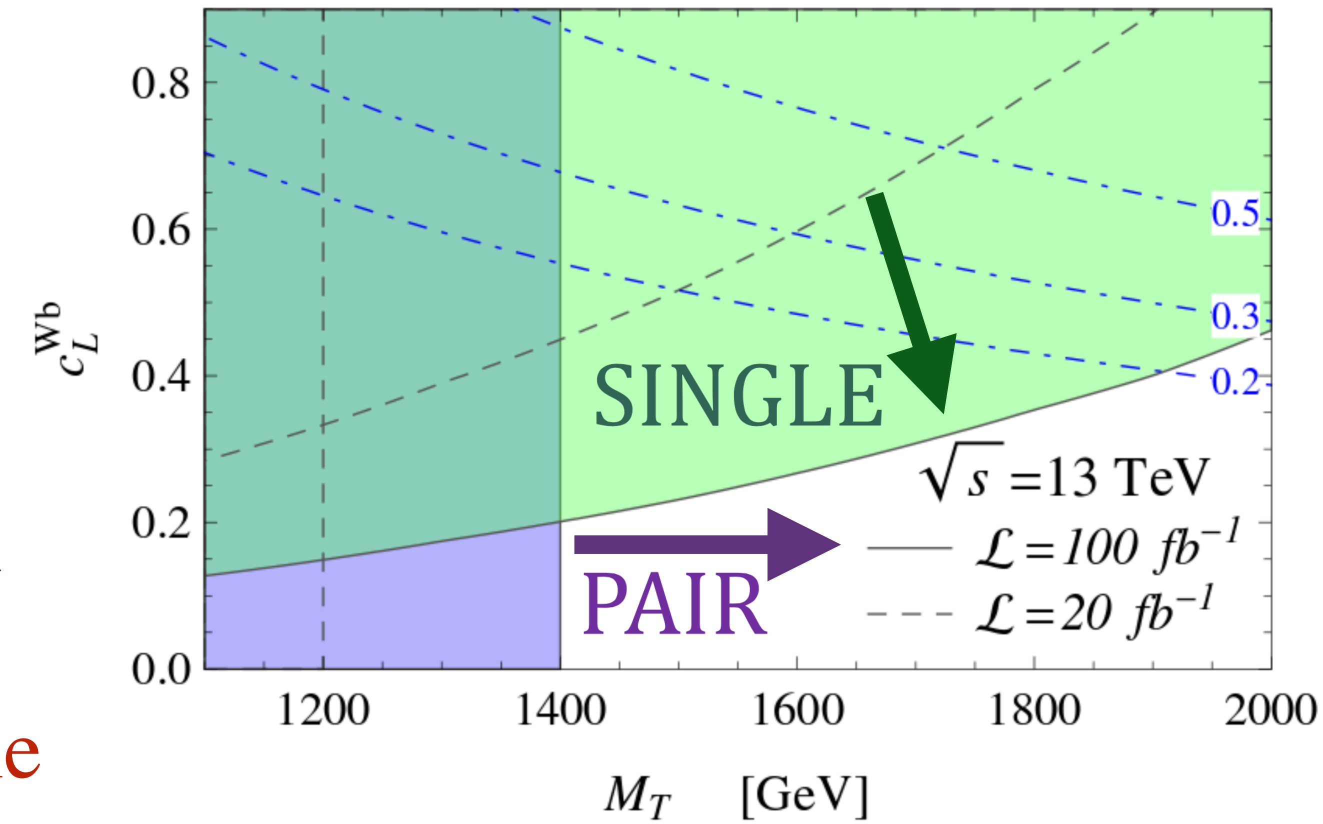
7 Allowed Combinations

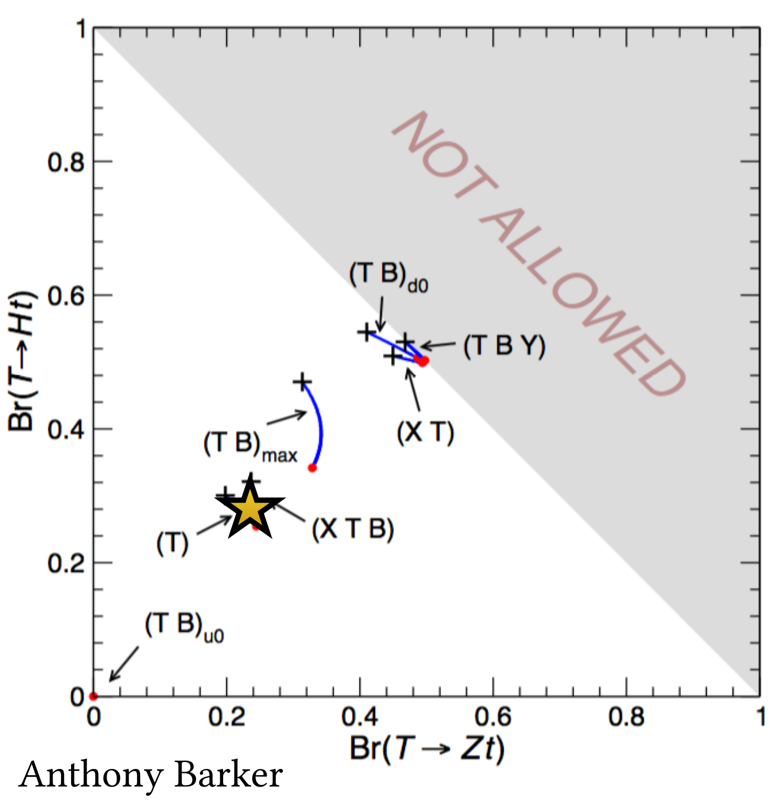
Singlets	T B
Doublets	T, B T, X B, Y
Triplets	T, B, X T, B, Y

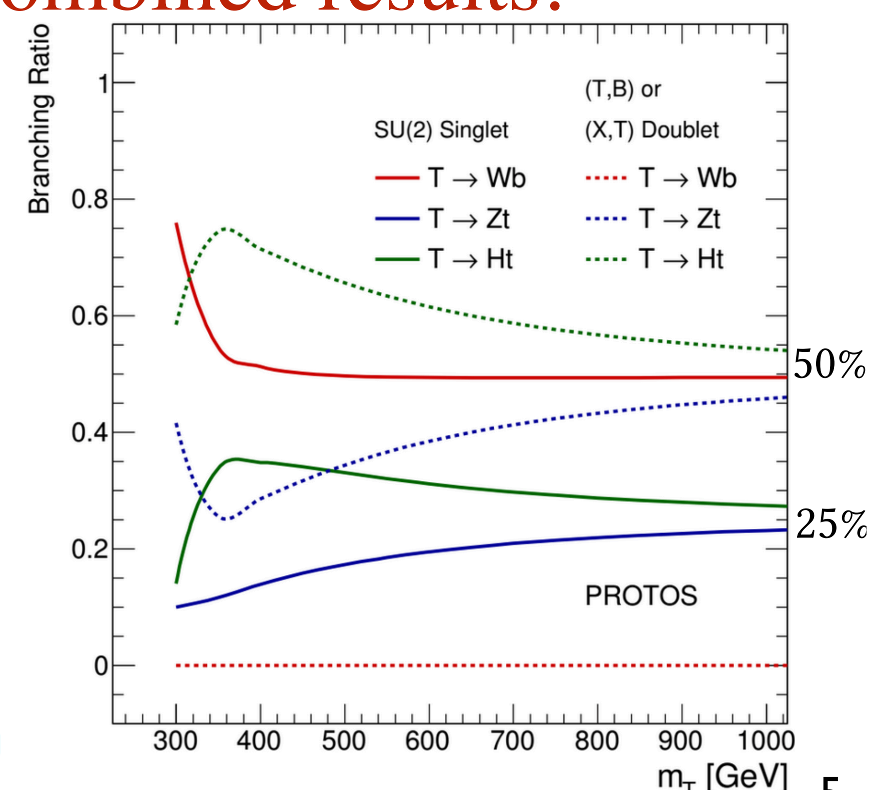
What they look like

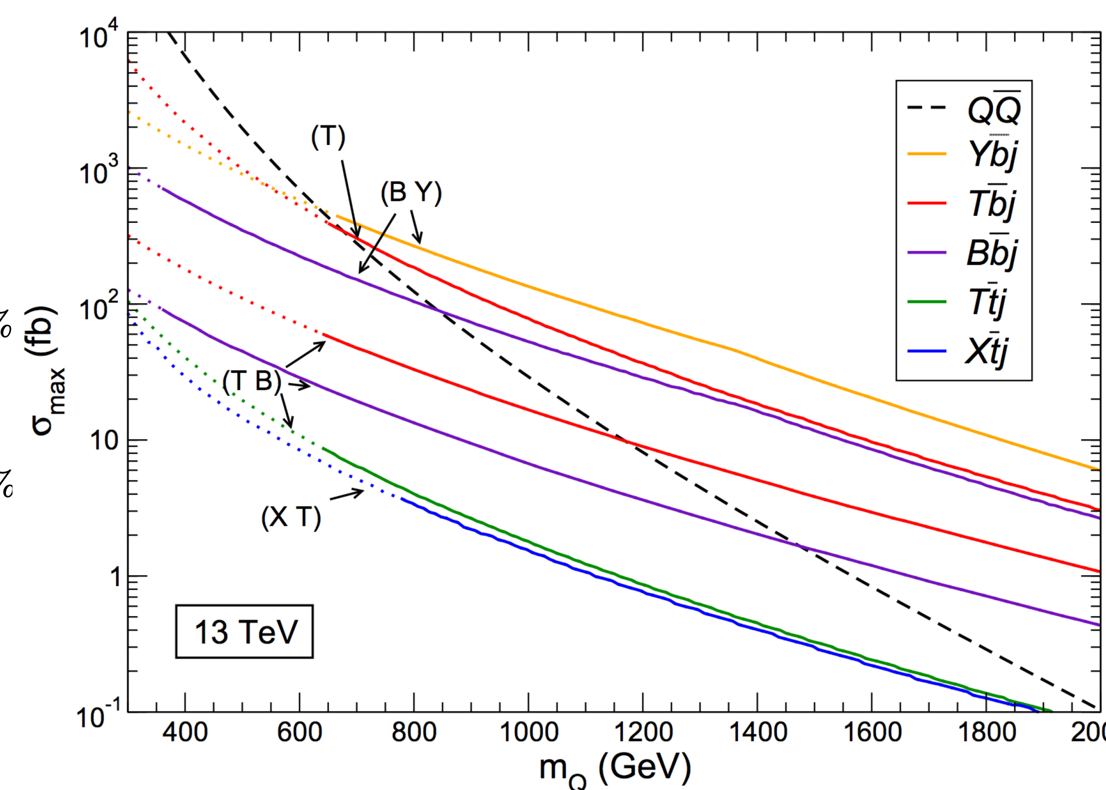
1311.7667 and 1311.7667

- VLQ can be produced singly or in pairs.
- Pair production is insensitive to couplings.
- Limits depend on the branching ratios—a function of multiplet and mass.
- Complicated decays! Need multiple approaches and combined results.







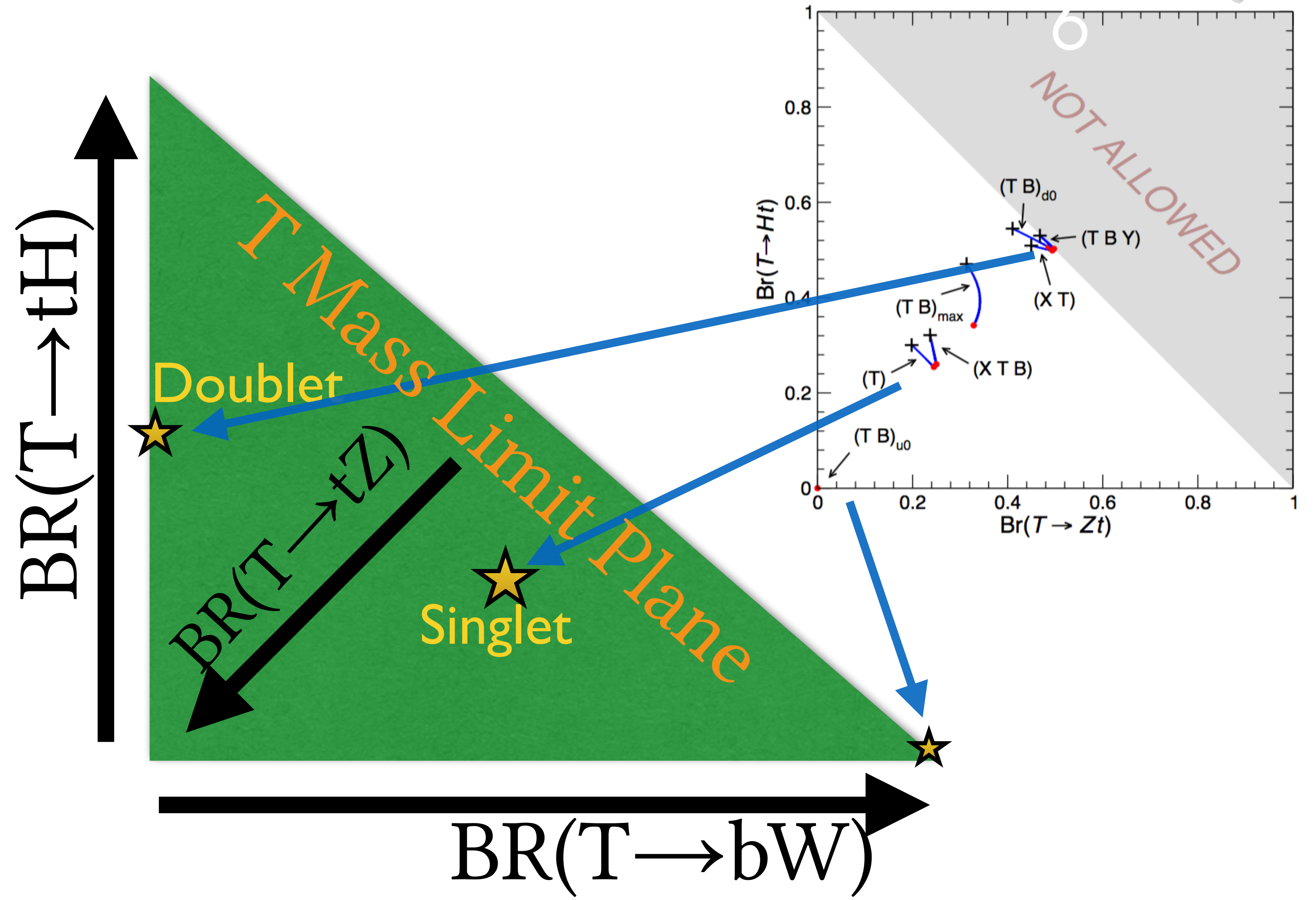


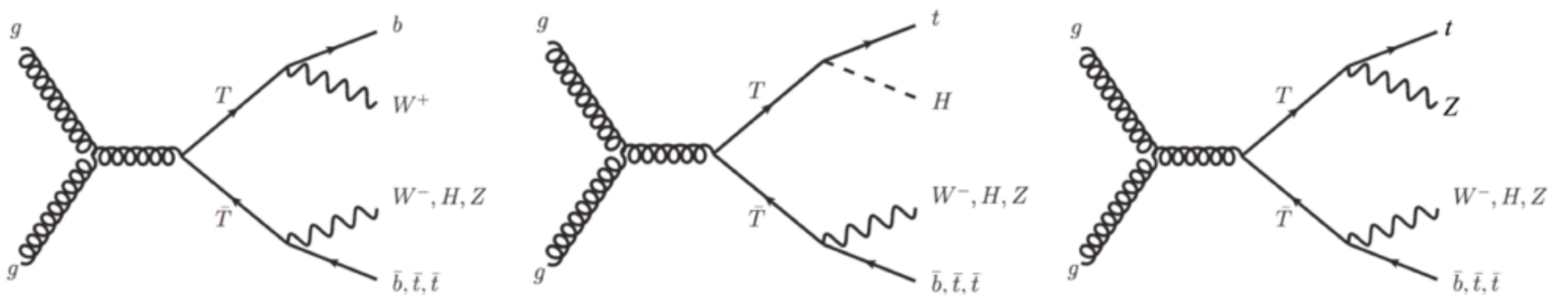
T’ decay and Feynman diagrams

Complex decays, thousands of final states

Need multiple analyses combine

3 corners, many possible approaches





Last Year's Limits

M(T) ≤ 850 GeV
Fully Excluded

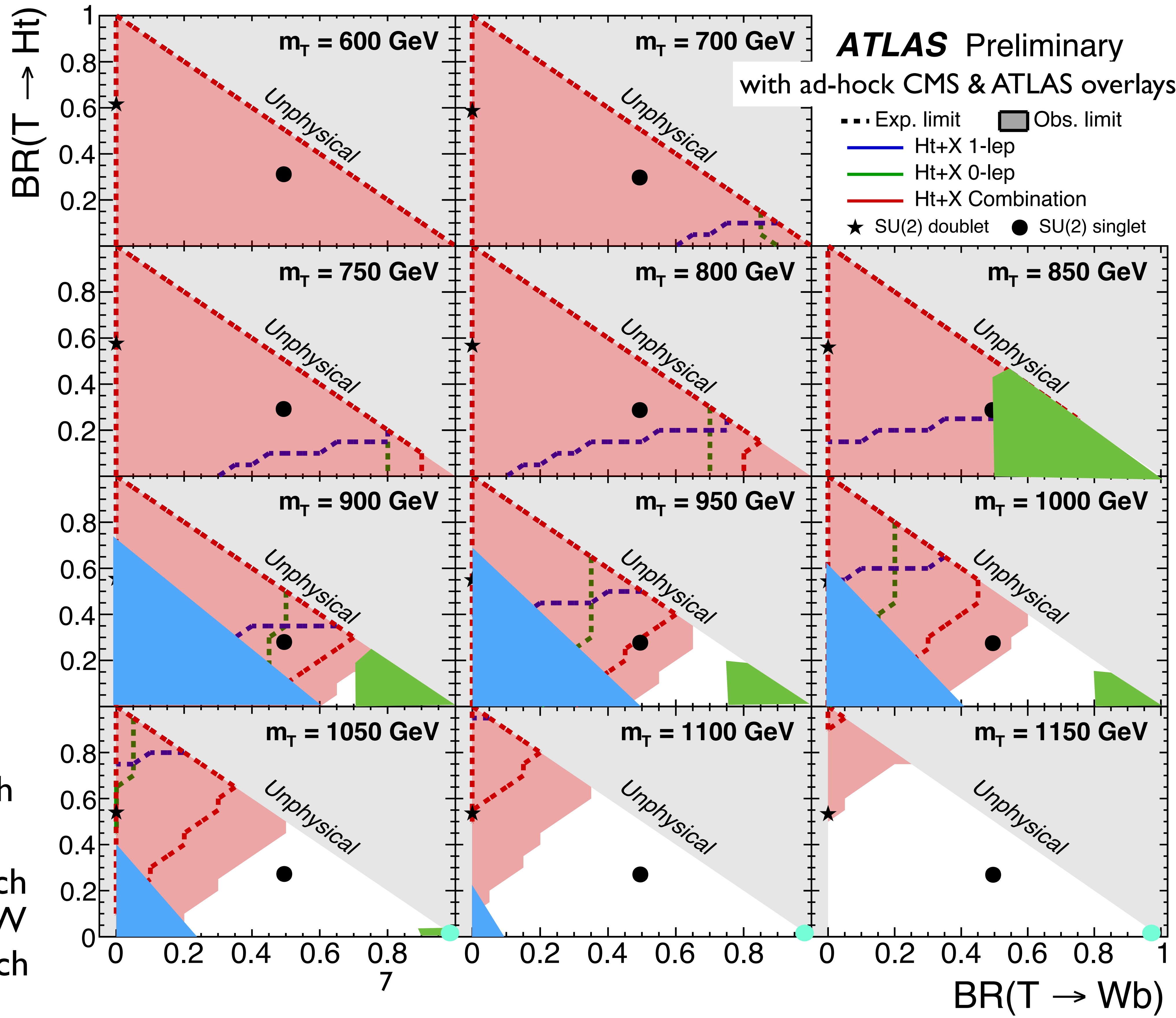
Singlet Excluded
below 1000 GeV

Doublet Excluded
below ~1150 GeV

Pure bW Excluded
below 1300 GeV

Incomplete list

- Extant
- Excluded by tH search
- Excluded by 1 lep + MET search
- Excluded by bW+hadrons search
- Excluded by bWbW semi-leptonic search



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Dilepton Channel

Part of a program of several lepton analyses

5% branching fraction of TT goes to dileptons

Di-Lepton Selection

- OSDL1 Channel
  Targets bWbW
  - 2 Tight OSDL
  - Z veto (76-106 GeV)
  - 2-3 Jets
  - ≥ 1 B-jet
  - ST > 1000 GeV
  - Min M_{lb} > 170 GeV
    Top Rejection
  - HT > 325 GeV
  - MET > 30 GeV,
  - M_{ll} > 20 GeV

- SSDL Channel
  Target tH+X
  - 2 Tight SSDL
  - ≥ 3 Jets
  - ≥ 1 B-jet
  - ST > 1100 GeV
  - HT > 500 GeV
  - MET > 30 GeV
  - M_{ll} > 20 GeV

Ele Pt threshold: 30 GeV
Muon Pt threshold: 30 GeV

Data Driven Background Method for Dilepton

- Non-prompt and charge fake backgrounds are obtained using a matrix method that relates counts between selection regions using loose leptons, tight leptons, and charge match requirement inversion.
- Background is the expected number of events in tight-tight selection that do not originate from prompt leptons of the desired charge-match.
- The matrix method extends previous work by including charge-fake backgrounds in addition to the non-prompt background.
- Background contributions are handled event-by-event to account for the Pt and Eta dependence of the electron charge misID rate.

Observed counts

Counts of produced events destined to pass loose

Background contributions to tight-tight

$$\begin{pmatrix} n\_ttss \\ n\_tlss \\ n\_llss \\ n\_ttos \\ n\_tlos \\ n\_llos \end{pmatrix} = \begin{pmatrix} a\,p^2 & a\,f\,p & a\,f^2 & b\,p^2 & b\,f\,p & b\,f^2 \\ 2a(1-p)p & a(f(1-p)+(1-f)p) & 2a(1-f)f & 2b(1-p)p & b(f(1-p)+(1-f)p) & 2b(1-f)f \\ a(1-p)^2 & a(1-f)(1-p) & a(1-f)^2 & b(1-p)^2 & b(1-f)(1-p) & b(1-f)^2 \\ b\,p^2 & b\,f\,p & b\,f^2 & a\,p^2 & a\,f\,p & a\,f^2 \\ 2b(1-p)p & b(f(1-p)+(1-f)p) & 2b(1-f)f & 2a(1-p)p & a(f(1-p)+(1-f)p) & 2a(1-f)f \\ b(1-p)^2 & b(1-f)(1-p) & b(1-f)^2 & a(1-p)^2 & a(1-f)(1-p) & a(1-f)^2 \end{pmatrix} \begin{pmatrix} N\_ppss \\ N\_pfss \\ N\_ffss \\ N\_ppos \\ N\_pfos \\ N\_ffos \end{pmatrix}$$

$a = (1 - q1)(1 - q2) + q1*q2$

$b = q1*(1-q2) + q2*(1-q1)$

q1 is the charge mistag probability for electron 1; q1 is the charge mistag probability for electron 2

Probability matrix to be inverted

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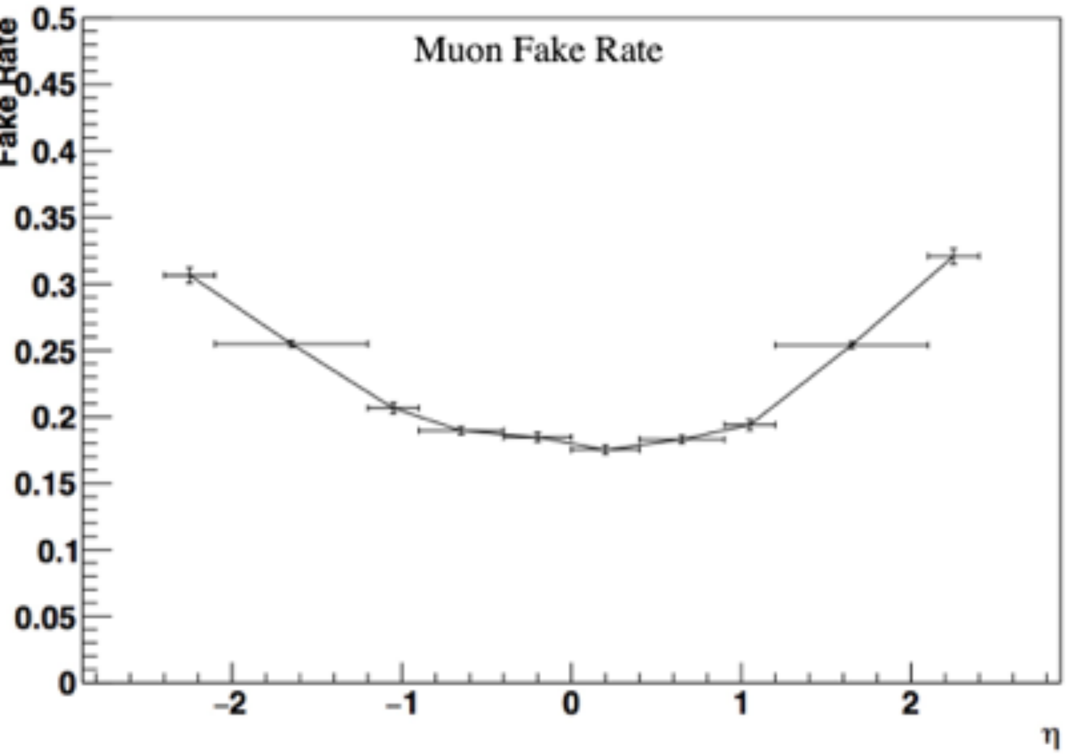
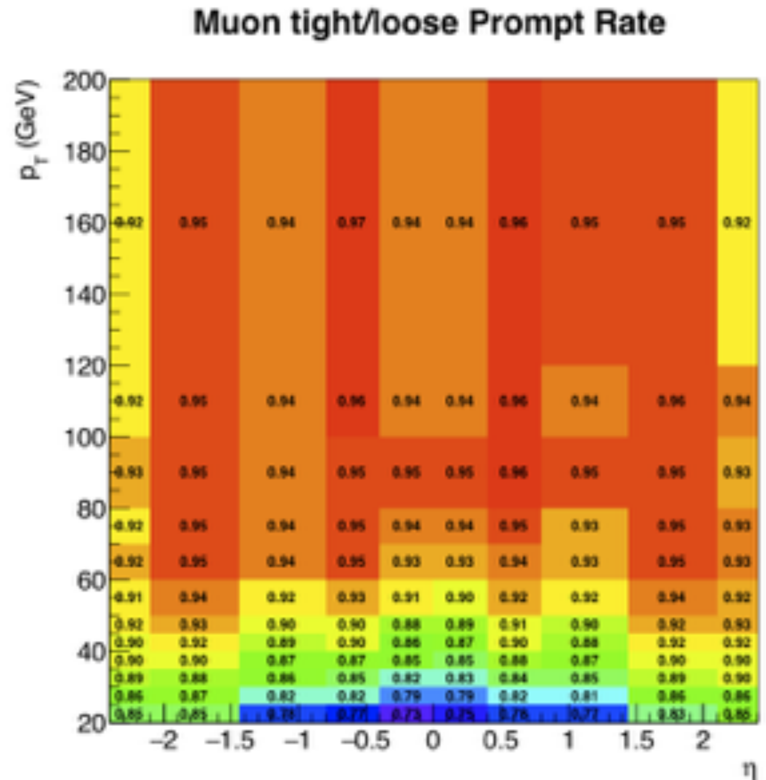
Fake Rate Prompt Rate Charge-flip Rate

Measured inputs to data driven background method

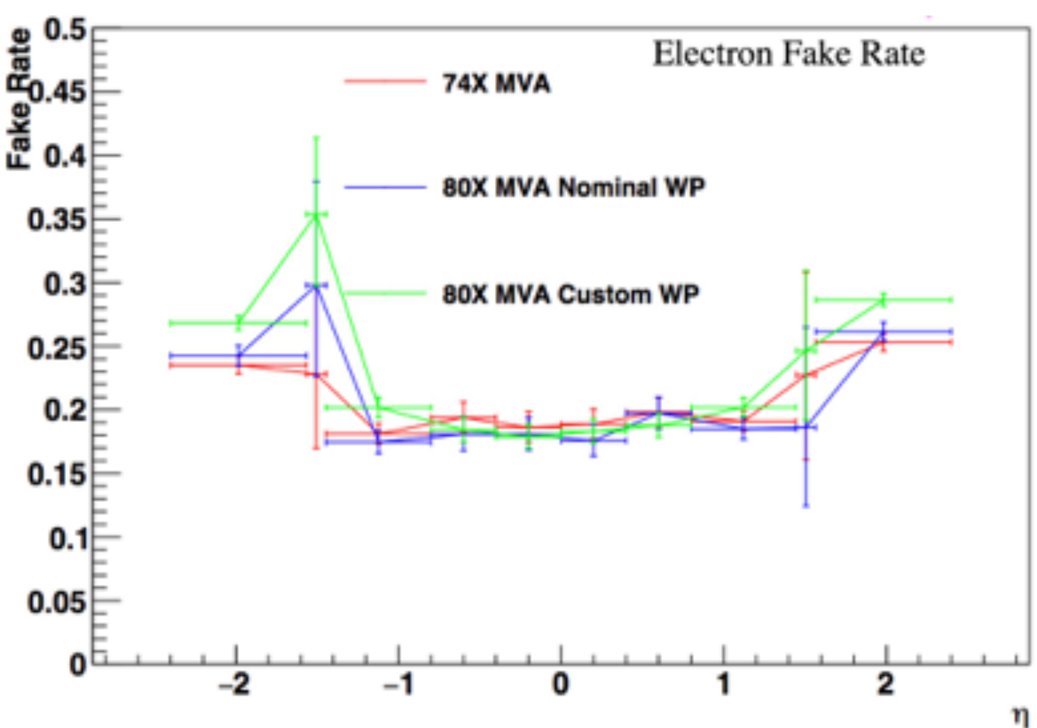


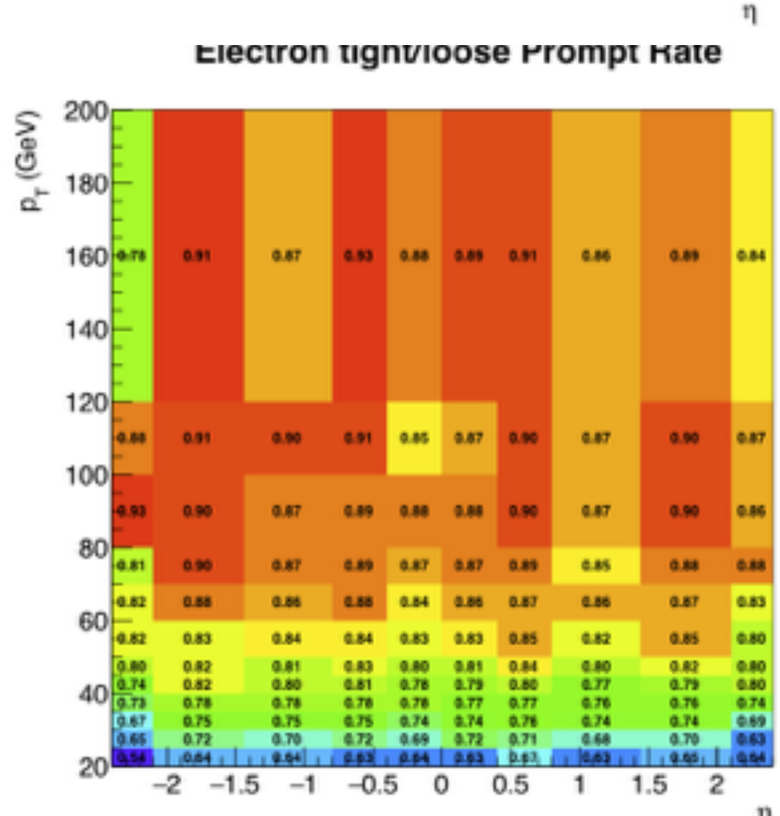


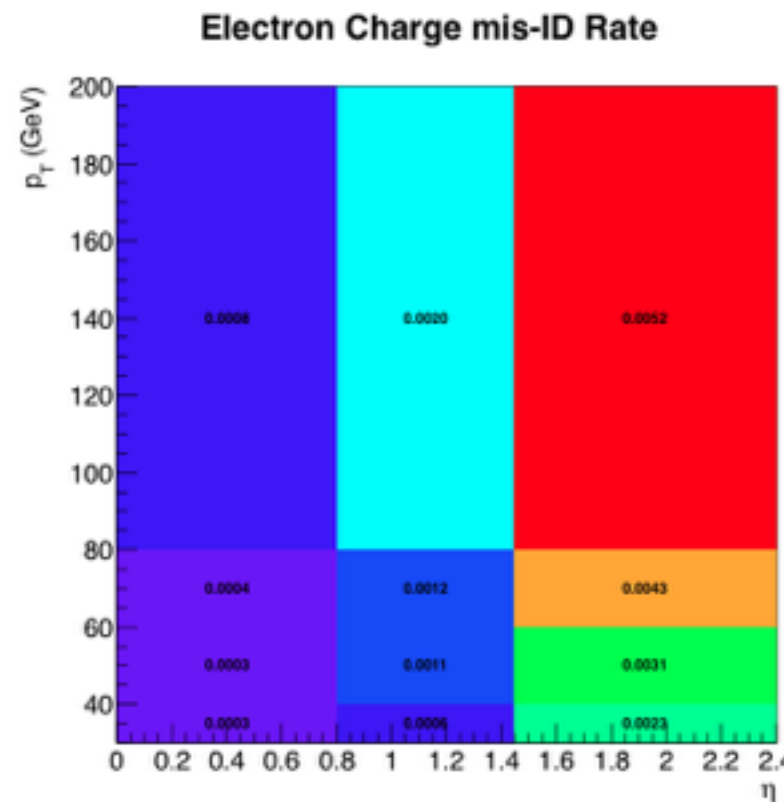
Work in Progress

Fake rate measured in Lep+Jet data

Prompt and charge flip measured in DY data

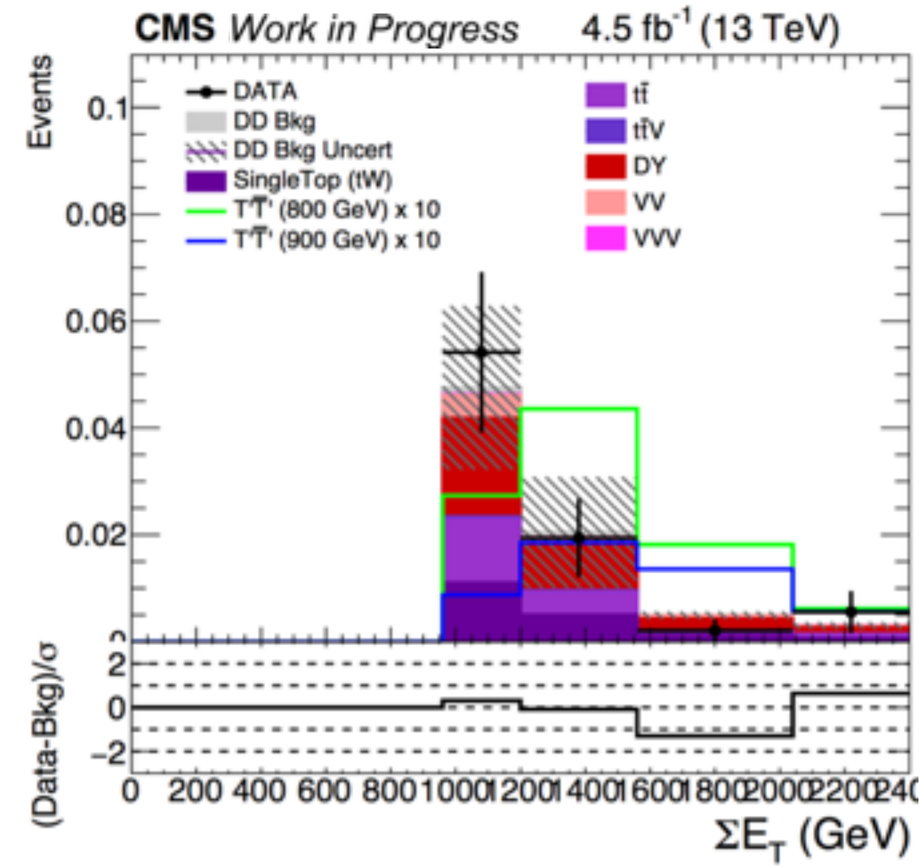


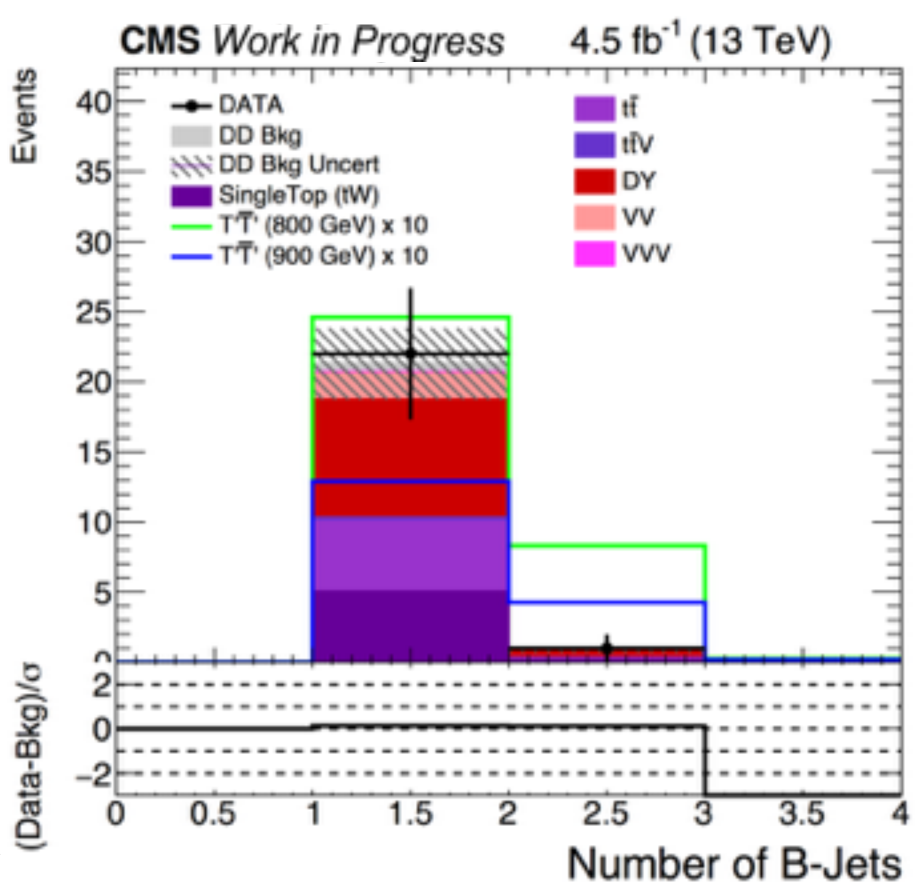


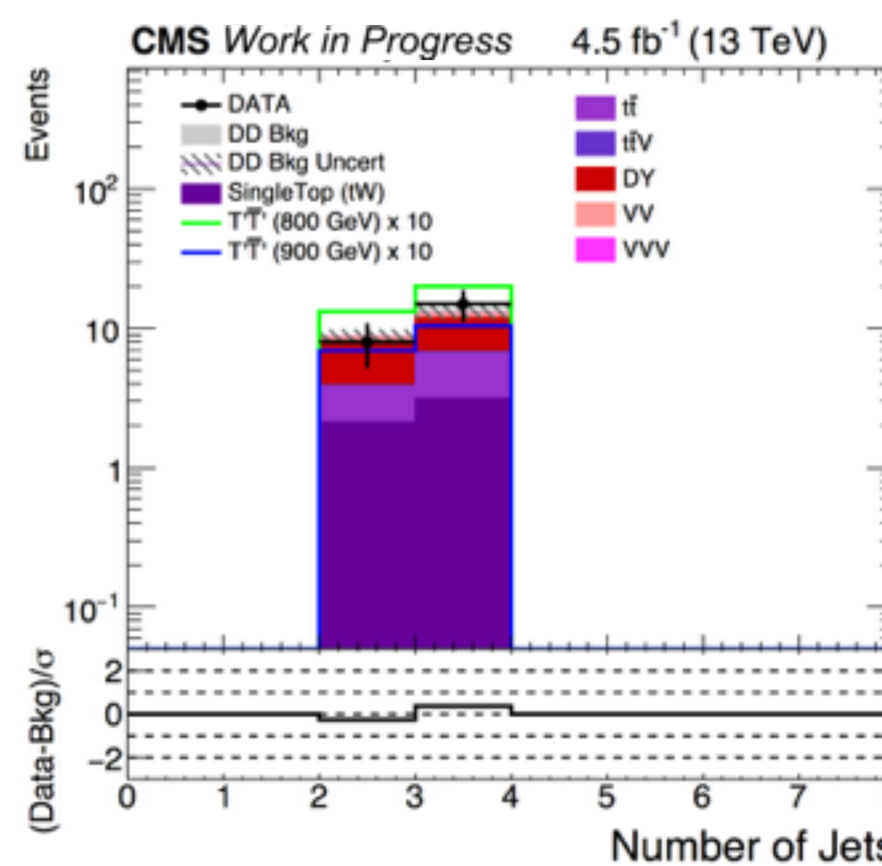


Result Plots

- Significant reliance on MC
  - 12 systematic uncertainties just from MC
  - 17 systematic uncertainties total
- Prescaled 8x for partial blinding

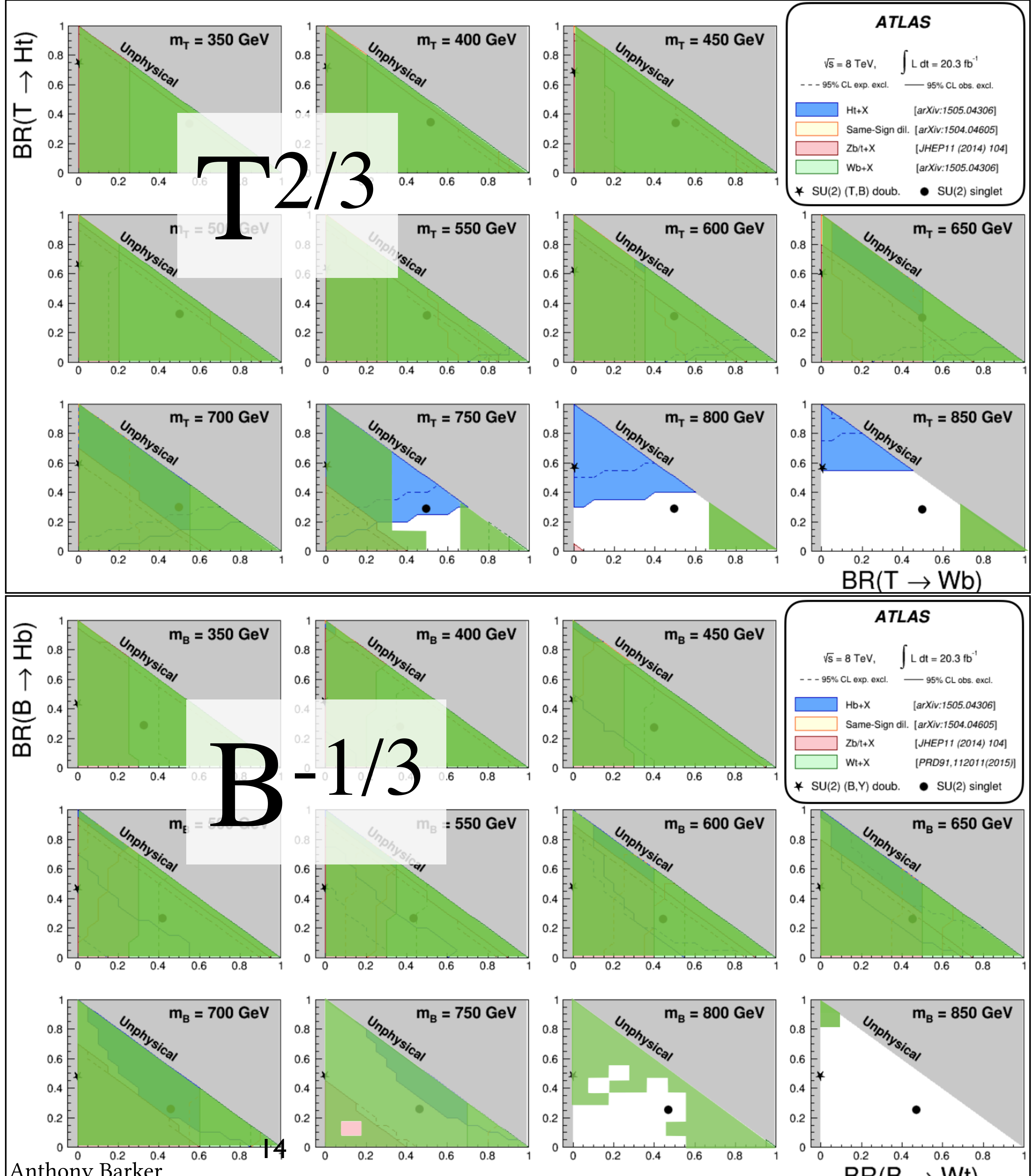






Back-up

CMS & ATLAS 8 TeV Limits



CMS Exclusion Overlay

White = Extant

ATLAS Results page

CMS $T^{2/3}$: B2G-13-005

CMS $B^{1/3}$: B2G-13-006

Branching fractions of TT

- Analyzed with Particle Branch Ratio Counter
  - Full decay tree explored, including all permutations of final states.
- tH(WW) is necessary on at least one branch for SSDL
  - second lepton usually from a top, or W on the other branch.

Branching fractions in TT

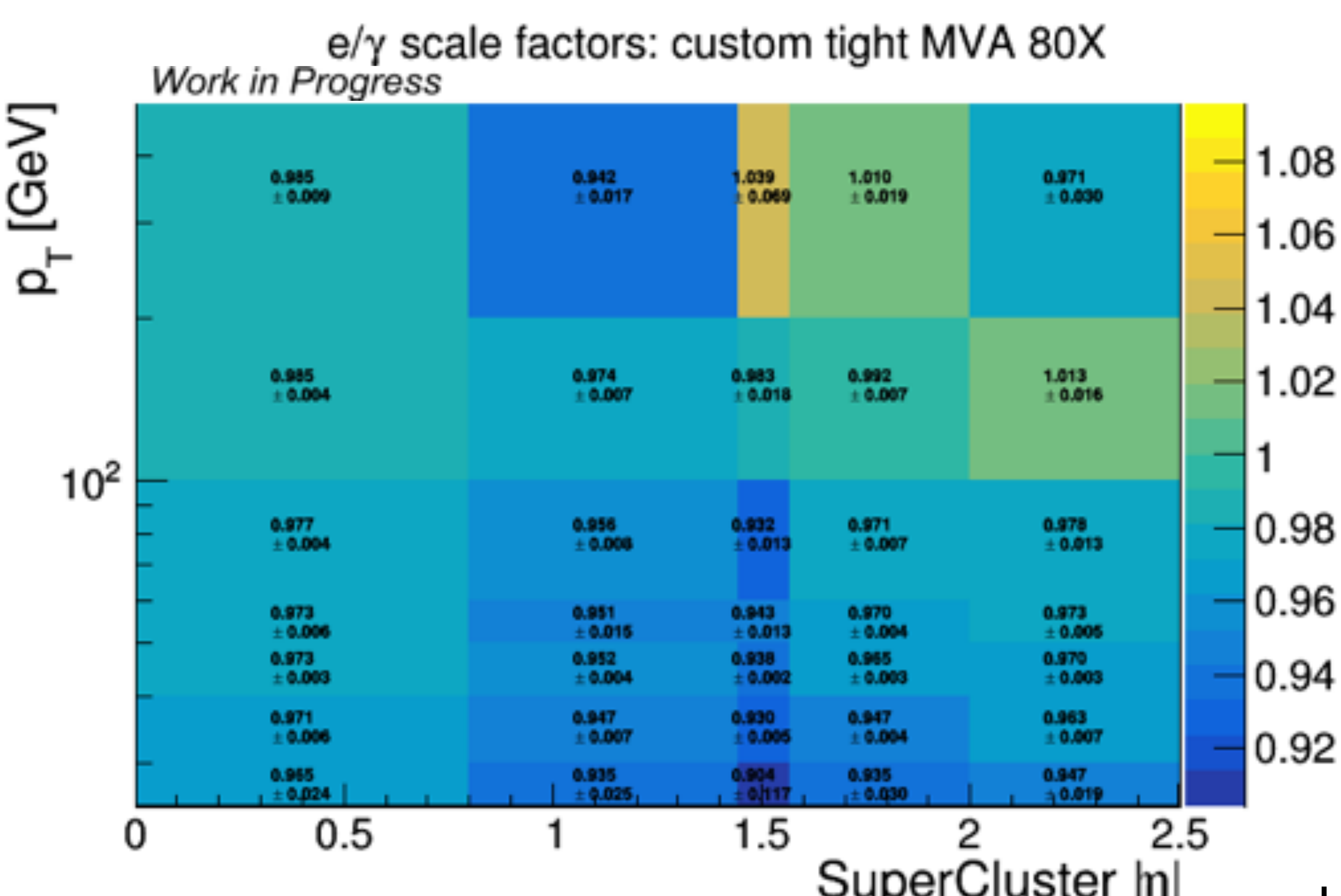
Process	DL	OSDL	OSSF	OSOF	SSDL	SSSF	SSOF
TT	0.076	0.070	0.046	0.025	0.006	0.003	0.003
bWbW	0.011	0.011	0.006	0.006	0	0	0
bWtZ	0.021	0.021	0.016	0.005	0	0	0
bWtH	0.018	0.015	0.008	0.007	0.003	0.002	0.002
tHtH	0.006	0.005	0.003	0.002	0.002	0.001	0.001
tHtZ	0.013	0.012	0.008	0.003	0.001	0.001	0.001
tZtZ	0.007	0.007	0.006	0.001	0	0	0
bW+X	0.050	0.047	0.029	0.018	0.003	0.002	0.002
bW+tV	0.039	0.036	0.023	0.012	0.003	0.002	0.002
tH+X	0.038	0.032	0.019	0.013	0.006	0.003	0.003
tH+not tH	0.031	0.027	0.016	0.011	0.004	0.002	0.002
tZ+X	0.041	0.039	0.030	0.010	0.001	0.001	0.001
tZ+not tZ	0.034	0.032	0.024	0.008	0.001	0.001	0.001
All not bWbW	0.065	0.059	0.040	0.019	0.006	0.003	0.003

Proportion of each column by source

Process	DL	OSDL	OSSF	OSOF	SSDL	SSSF	SSOF
TT	1	1	1	1	1	1	1
bWbW	0.144	0.156	0.120	0.224	0	0	0
bWtZ	0.269	0.292	0.339	0.205	0	0	0
bWtH	0.24	0.22	0.17	0.30	0.51	0.51	0.51
tHtH	0.08	0.07	0.05	0.09	0.25	0.25	0.25
tHtZ	0.17	0.17	0.18	0.14	0.23	0.23	0.23
tZtZ	0.093	0.101	0.130	0.047	0	0	0
bW+X	0.65	0.66	0.63	0.73	0.51	0.51	0.51
bW+tV	0.51	0.51	0.51	0.50	0.51	0.51	0.51
tH+X	0.494	0.451	0.411	0.525	1	1	1
tH+not tH	0.41	0.38	0.36	0.43	0.75	0.75	0.75
tZ+X	0.53	0.56	0.65	0.39	0.23	0.23	0.23
tZ+not tZ	0.44	0.46	0.52	0.34	0.23	0.23	0.23
All not bWbW	0.856	0.844	0.880	0.776	1	1	1

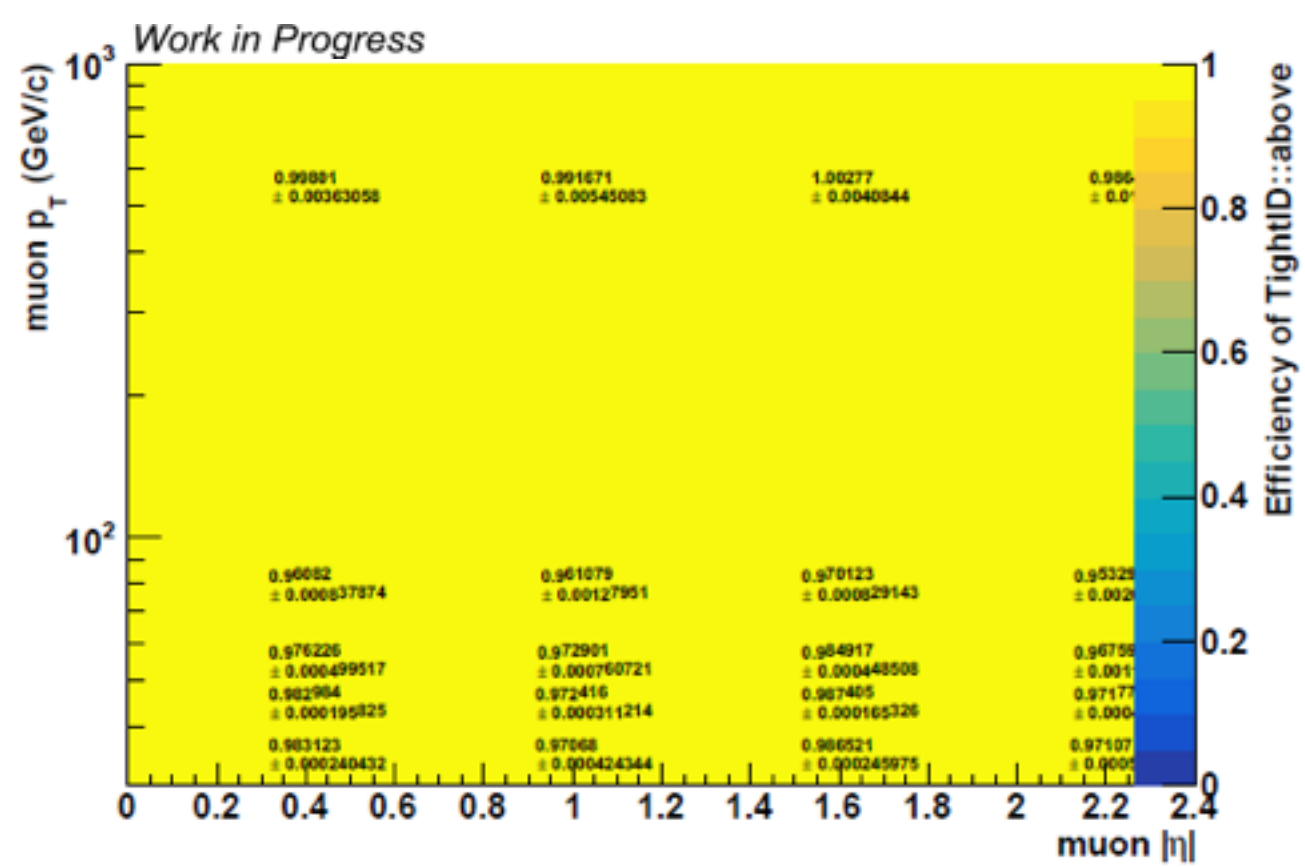
Electrons

- Pt > 30, |Eta| < 2.4
- mini-iso < 0.1 for tight
- mini-iso < 0.4, used for background studies
- Custom MVA working point
- Electron scale factors



Muons

- Pt > 30, |Eta| < 2.4
- mini-iso < 0.1 for Tight
- mini-iso < 0.4 for background studies
- Muon scale factors



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Systematic Uncertainties

- All of the following systematic uncertainties are included and fully implemented as shape uncertainties:
  - Renormalization scale uncertainty
  - Parton Shower E Scale uncertainty
  - PDF uncertainty
  - Jet scale factor uncertainty
  - Jet Energy Scale uncertainty
  - Jet energy resolution uncertainty
  - B-tagging scale factor uncertainty
  - light-jet ID scale factor uncertainty
  - HLT
  - Lepton ID SF uncertainty
  - Lepton Iso SF uncertainty
  - Top Pt reweighting
- Simple constant uncertainties:
  - Lumi uncertainty
- Bin-by-bin
  - Statistical (on plots)
  - Prompt rate uncertainty
  - Fake rate uncertainty
  - Charge flip uncertainty