APS DPF 2017 Conference, Fermilab.

13 TeV search for pair of top-like, vector-like quarks decaying to leptons and jets final states

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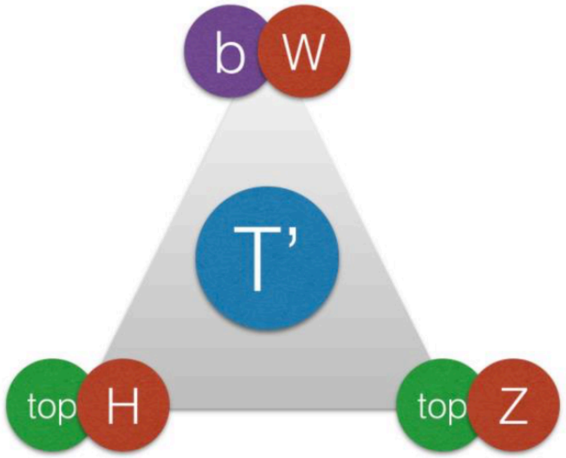
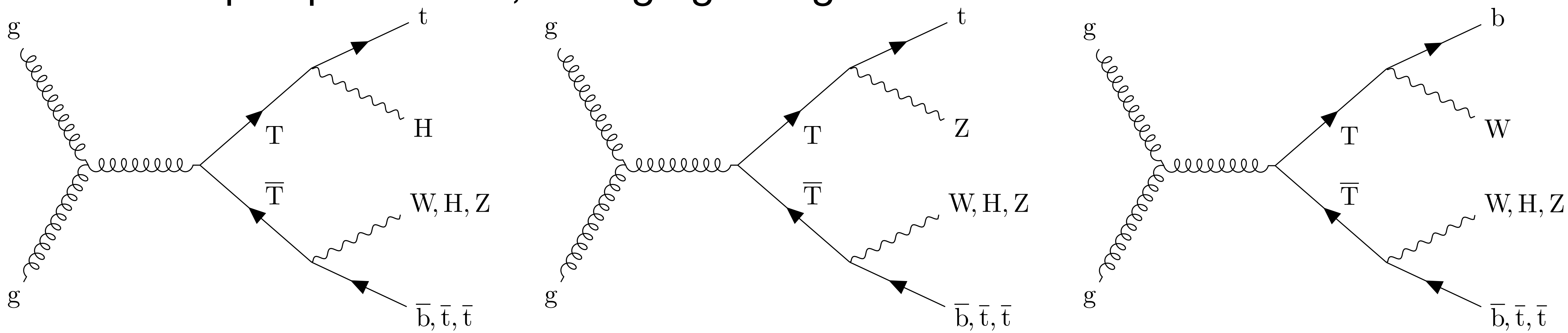
Introduction - VLQ

- Many BSM theories predict additional quarks: solves the naturalness/fine tuning problem
- Vector-like-quarks (VLQ):
  - left and right chiralities transform in the same way under SU(2)⊗U(1) symmetry group
- 13 TeV search for VLQ $T_{2/3}$
- VLQ $T_{2/3}$—> bW, tZ, tH —> 1 lep + jets, 3 leps + jets
- Benchmark: $\mathcal{BR}$(bW) = 2 x $\mathcal{BR}$(tZ, tH) = 0.5 (electroweak singlet)
- $\mathcal{BR}$(bW) = 0, $\mathcal{BR}$(tZ)=$\mathcal{BR}$(tH) = 0.5 (electroweak doublet)



- Search for pair production, through gluon-gluon fusion.



Channels and Grouping

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Single lepton channel

- Events with exactly one 1 lepton
- Most sensitive to T—> bW decays.
- lepton from direct decay of W
- SM MC backgrounds:
    - **TOP** group
        - tt dominant
        - single top
    - **EWK** group
        - W+jets dominant
        - DY
        - VV
    - **QCD**
- Utilizes **large radius jets** and **jet substructure variables** to perform W, H tagging

Trilepton channel

- Events with 3 or more leptons
- Most sensitive to T—> tZ, tH decays.
- leptons mostly from direct decay of W/Z
- prompt leptons (SM MC):
    - **VV/VVV**
    - **tt+V**
- nonprompt leptons **(derived from data)**:
    - tt
    - V+Jets
- Estimate nonprompt leptons background from events with 'loose' lepton quality requirement in data

Dilepton presented by a previous talk

Single Lepton

- **Event selections**:
  - Fires a single lepton trigger
  - exactly 1 lepton, passes ‘tight' quality requirements
  - pT > 60 GeV and centrally produced
  - E_T^{miss} > 75 GeV
  - At least 3 AK4 jets pT > 300 GeV, 150 GeV, 100 GeV and centrally produced
  - At least 2 AK8 jets

- **W-jet tagging**: AK8 jet that satisfies:
  - pT > 200 GeV and centrally produced
  - 65 GeV < M_{pruned} < 105 GeV
  - ratio of n-subjettiness $\tau_2/\tau_1 < 0.6$
- **H-tagging**: AK8 jet that satisfies:
  - pT > 300 GeV and centrally produced
  - 60 GeV < M_{pruned} < 160 GeV
  - at least 1 b-tagged subject

20 Categories

H tag:1+	
subjet b-tag:1	subjet b-tag: 2

(require extra AK4 b-tag)

H tag:0	
W-tag: 0 subjet b-tag: 0/1/2/3+	W-tag: 1+ subjet b-tag: 0/1/2/3+

(require extra AK4 pT>30GeV)

lepton flavor: e/μ

Single Lepton

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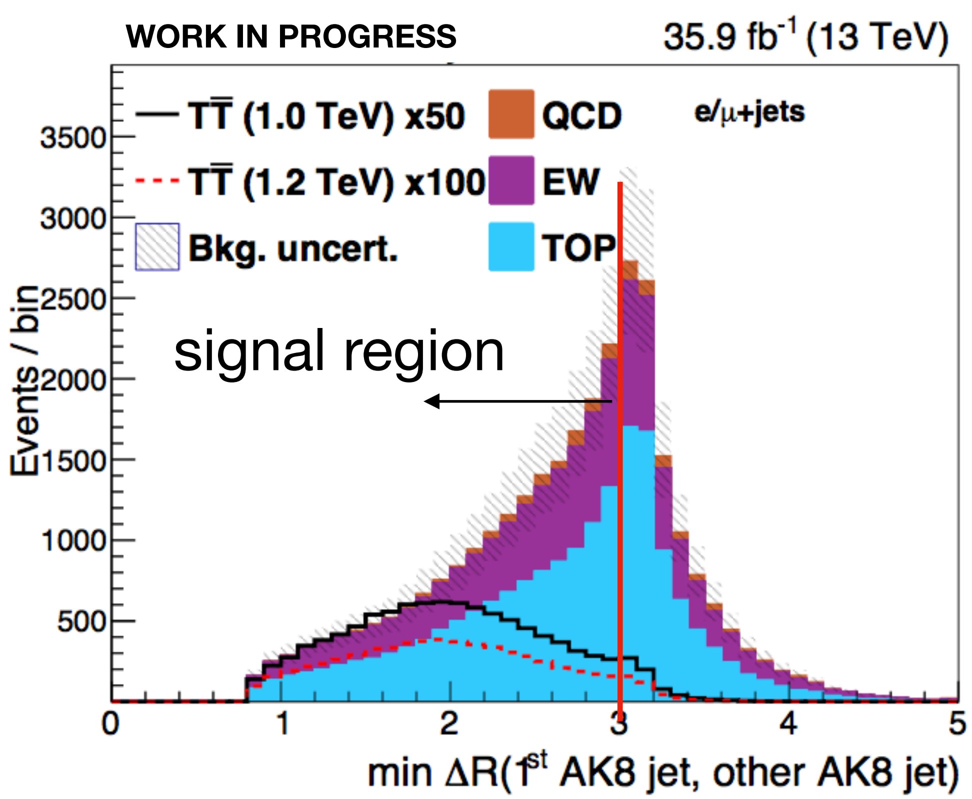
Signal Region

- ΔR_{min}(AK8,AK8) < 3.0



Control Regions

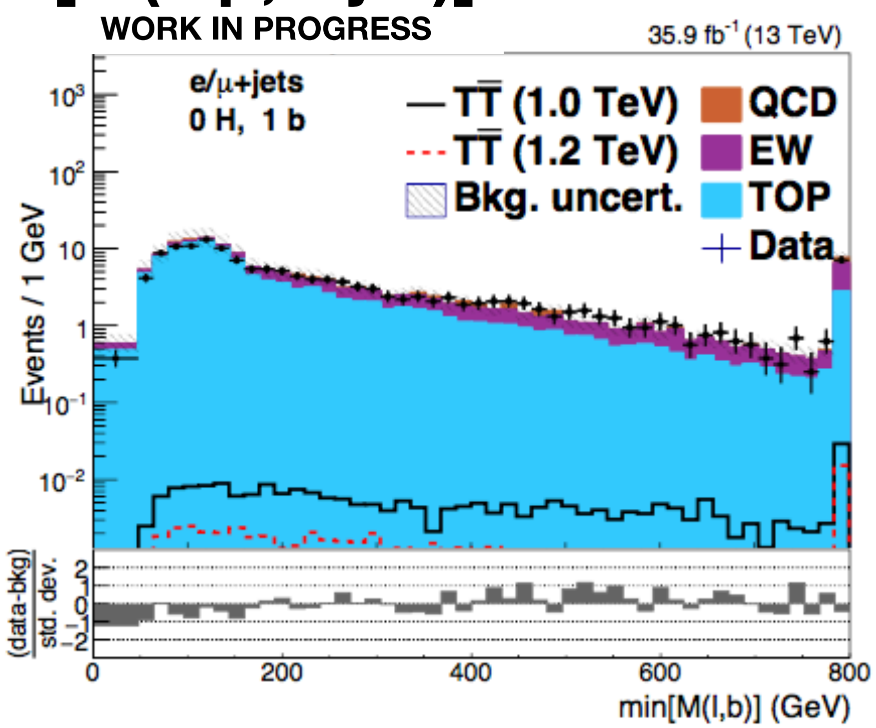
- no H-tags:
  - ttbar enriched: 1/2/3+ b-tagged AK4
  - W+jets enriched: 0 / 1+ W-tags , no b-tags
- 1+ H-tags:
  - 0 / 1+ b-tag (not overlapping with H-tag)

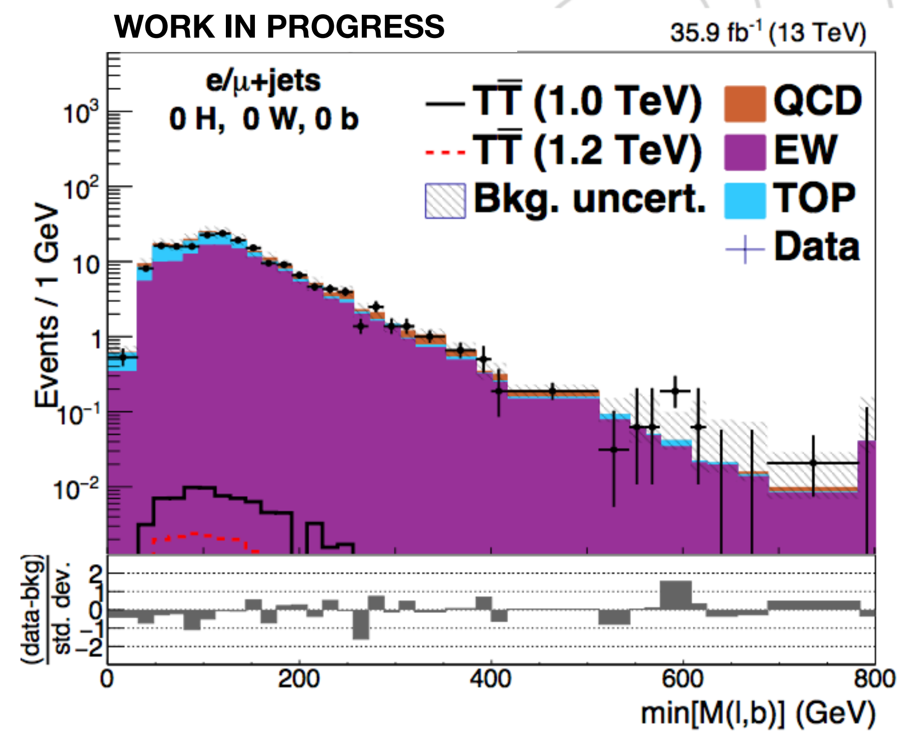
Discriminating variables:

- **min[M(lep,b-jet)]** - minimum mass constructed from leptons and a b-tagged AK4 jet.
  - construct mass with normal jets if there no b-tagged jets
- **ST** - sum of AK4 pT, leptons pT, and E_T^{miss}

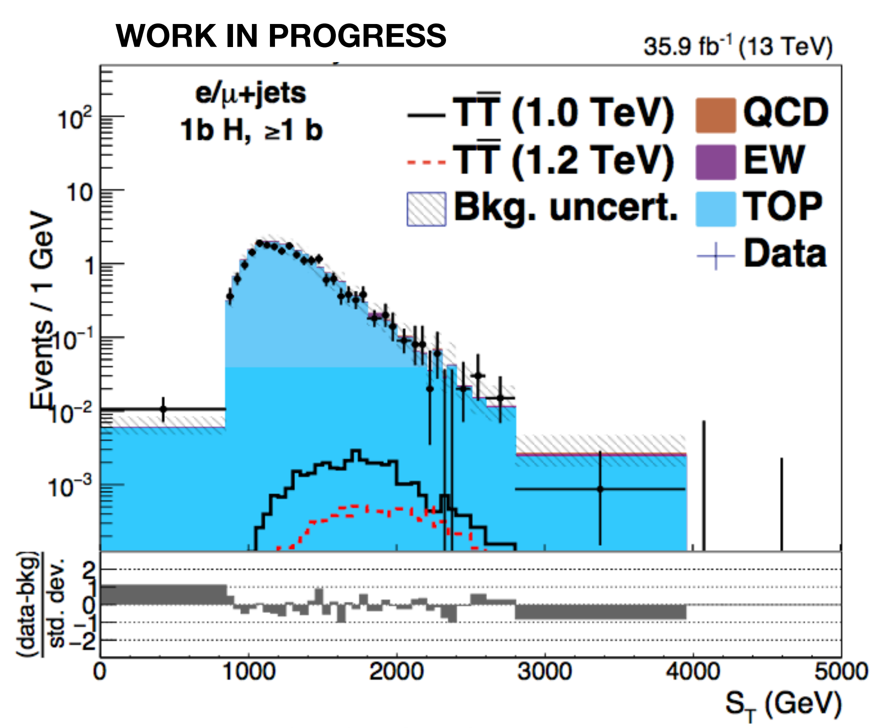
Single Lepton

- Checking control regions for events with **no H-tagged jets**.
- look at **min[M(lep,b-jet)]**



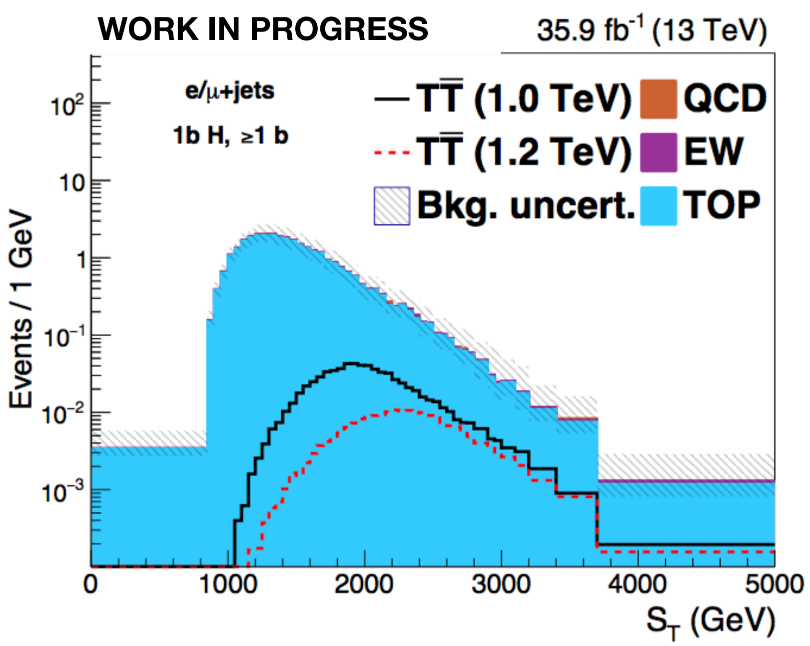


- Checking control regions for events with **at least 1 H-tagged jets**
- Look at **ST**

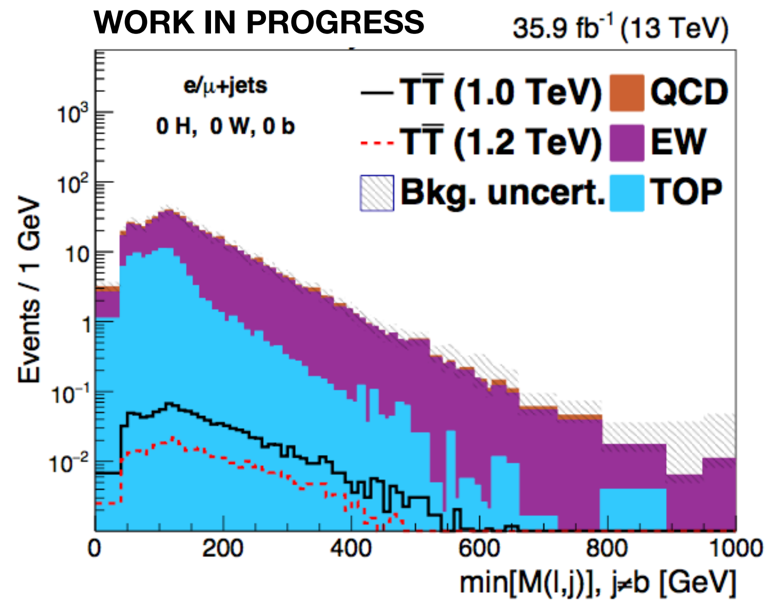


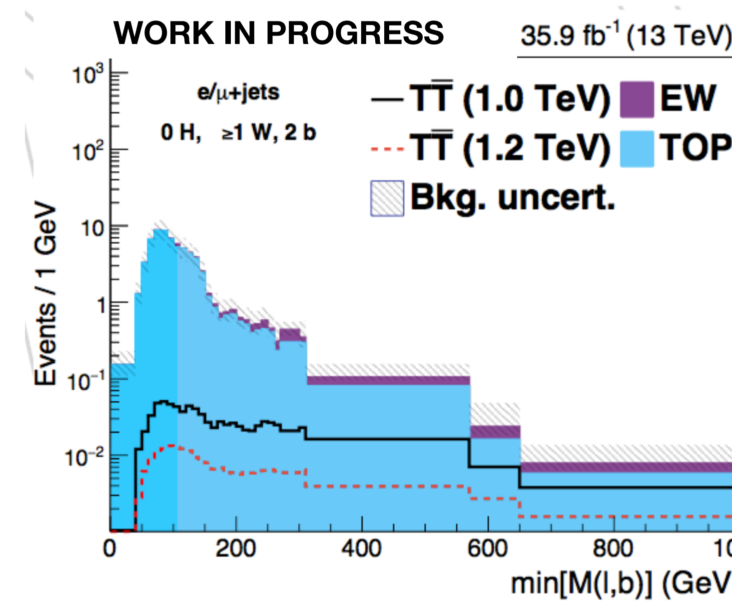
Single Lepton

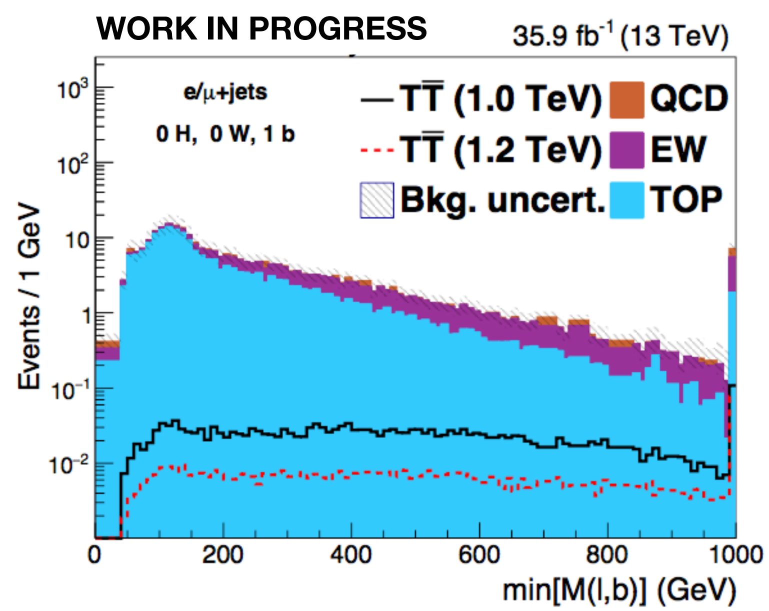
- Final templates for upper limits measurements. (blinded)

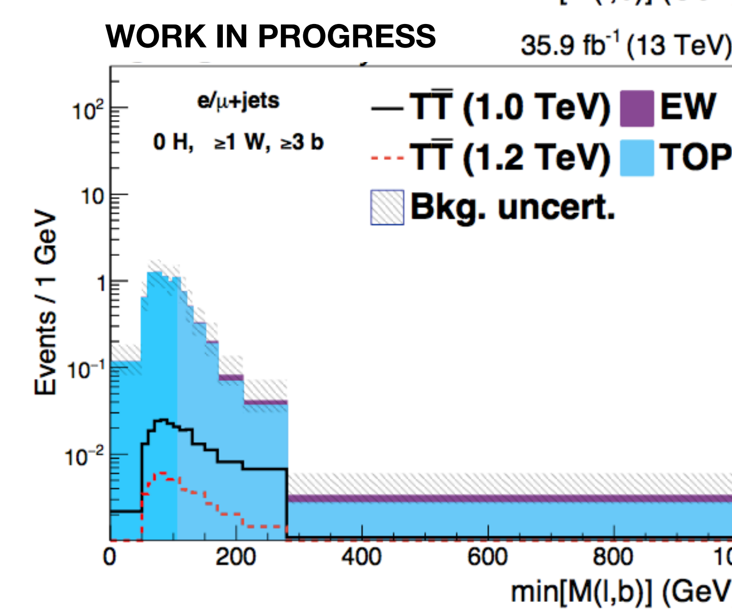


H tag:1+
subjet b-tag:1









H tag:0	
W-tag: 0	W-tag: 1+
subjet b-tag: 0/1	subjet b-tag: 2/3+

Triple Lepton

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Event selections

- Fires a dilepton trigger (depending on category)
- At least 3 leptons, pass 'tight' quality requirements
- pT > 30 GeV and centrally produced
- veto events with M_{OSll} < 20 GeV
- At least 3 AK4 jets pT > 30 GeV and centrally produced
- At least 1 b-tagged AK4 jet
- E_T^{miss} > 20 GeV

4 Categories

- eee
- eeμ
- eμμ
- μμμ

Nonprompt lepton background estimation

- Use leptons that fail the 'tight' (***t***) lepton quality requirement, or 'loose' (***l***), to estimate the number of events containing fake leptons that pass the 'tight' lepton quality requirements
- Construct matrix M consisting of prompt (fake) rates: rate at which prompt (nonprompt=fake) leptons pass the 'tight' quality requirement.

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Single lepton case

Triple Lepton

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Single lepton case

N_p

Triple Lepton

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Single lepton case

pN_p

Triple Lepton

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Single lepton case

$$pN_p +$$

Triple Lepton

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Single lepton case

$$pN_p + \quad N_f$$

Triple Lepton

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Single lepton case

$$pN_p + fN_f$$

Triple Lepton

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Single lepton case

$$N_t = pN_p + fN_f$$

Triple Lepton

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Single lepton case

$$N_t = pN_p + fN_f$$

$$N_l = (1-p)N_p + (1-f)N_f$$

Triple Lepton

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CMS

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Single lepton case

$$N_t = pN_p + fN_f$$

$$N_l = (1-p)N_p + (1-f)N_f$$

$$\begin{pmatrix} N_t \\ N_l \end{pmatrix} = M \begin{pmatrix} N_p \\ N_f \end{pmatrix}$$

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$$\begin{pmatrix} N_t \\ N_l \end{pmatrix} = M \begin{pmatrix} N_p \\ N_f \end{pmatrix}$$

$$M = \begin{pmatrix} p & f \\ 1-p & 1-f \end{pmatrix}$$

Triple Lepton

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Single lepton case

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$$\begin{pmatrix} N_t \\ N_l \end{pmatrix} = M \begin{pmatrix} N_p \\ N_f \end{pmatrix} \qquad M = \begin{pmatrix} p & f \\ 1-p & 1-f \end{pmatrix}$$

$$\begin{pmatrix} N_p \\ N_f \end{pmatrix} = M^{-1} \begin{pmatrix} N_t \\ N_l \end{pmatrix}$$

Triple Lepton

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Single lepton case

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$$fN_f = N_t - pN_p$$

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$$fN_f = N_t - pN_p$$
$$fakes = N_t - real$$

$$\begin{pmatrix} N_p \\ N_f \end{pmatrix} = M^{-1} \begin{pmatrix} N_t \\ N_l \end{pmatrix}$$

Triple Lepton

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Triple lepton case

Triple Lepton

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Triple lepton case

$$M = \begin{pmatrix} p^3 & p^2 f & p f^2 & f^3 \\ 3p^2(1-p) & p^2(1-f) + 2p(1-p)f & 2pf(1-f) + (1-p)f^2 & 3f^2(1-f) \\ 3p(1-p)^2 & 2p(1-p)(1-f) + (1-p)^2 f & p(1-f)^2 + 2(1-p)f(1-f) & 3f(1-f)^2 \\ (1-p)^3 & (1-p)^2(1-f) & (1-p)(1-f)^2 & (1-f)^3 \end{pmatrix}$$

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Triple lepton case

$$\begin{pmatrix} N_{ttt} \\ N_{ttl} \\ N_{tll} \\ N_{lll} \end{pmatrix} = \mathbf{M} \begin{pmatrix} N_{ppp} \\ N_{ppf} \\ N_{pff} \\ N_{fff} \end{pmatrix}$$

$$M = \begin{pmatrix} p^3 & p^2 f & p f^2 & f^3 \\ 3p^2(1-p) & p^2(1-f) + 2p(1-p)f & 2pf(1-f) + (1-p)f^2 & 3f^2(1-f) \\ 3p(1-p)^2 & 2p(1-p)(1-f) + (1-p)^2 f & p(1-f)^2 + 2(1-p)f(1-f) & 3f(1-f)^2 \\ (1-p)^3 & (1-p)^2(1-f) & (1-p)(1-f)^2 & (1-f)^3 \end{pmatrix}$$

Triple Lepton

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Triple Lepton

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CMS

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4 Categories

- eee
- eeμ
- eμμ
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- Lepton *prompt rates* measured using tag and probe in Drell-Yan events
- Lepton *fake rates* measured in **control region.**

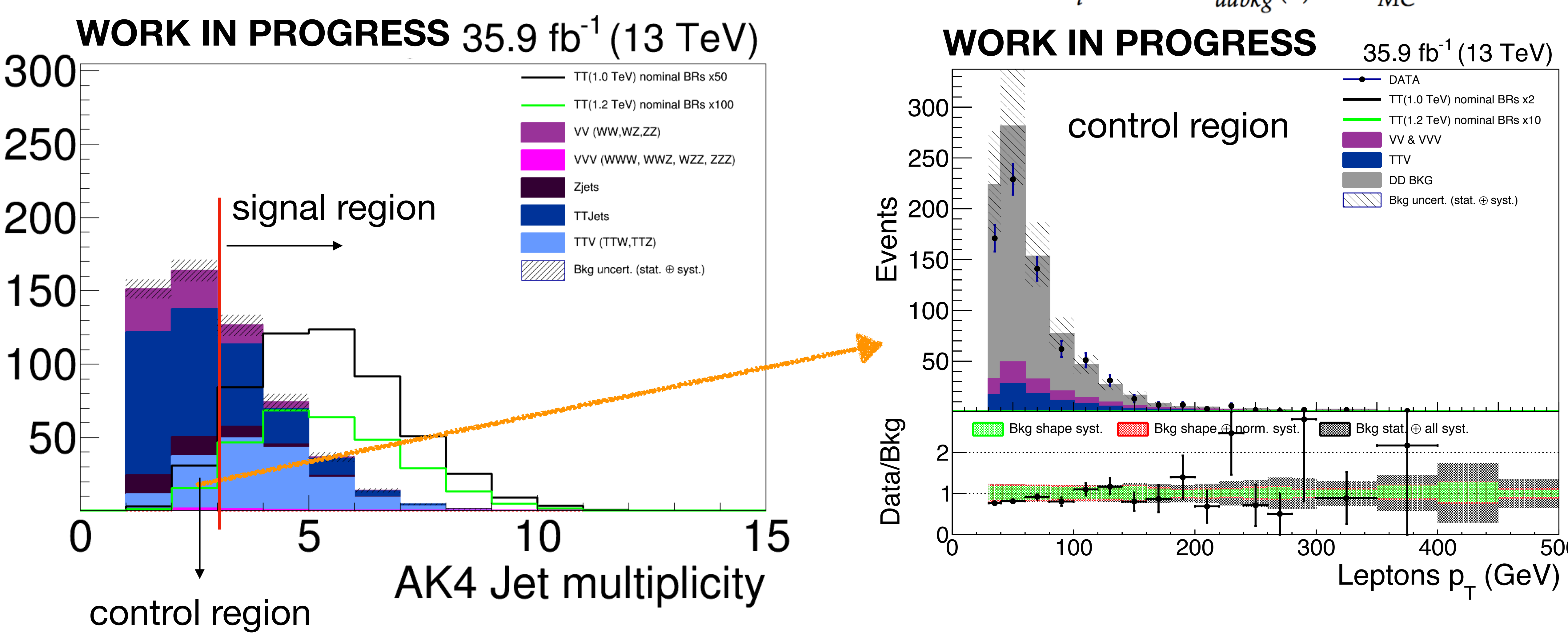
Control Region

- Same selections as previously defined, except:
  - exactly 2 jets
  - exactly 3 leptons

Method

- Calculate χ^2 statistics in lepton pT distribution in all categories from fits of the predicted to data.
- Scan and select a set of electron, muon fake rates that gives minimum of χ^2

$$\chi^2(r) = \sum_i \frac{(N^i_{data} - (N^i_{ddbkg}(r) + N^i_{MC}))^2}{N^i_{ddbkg}(r) + N^i_{MC}}$$



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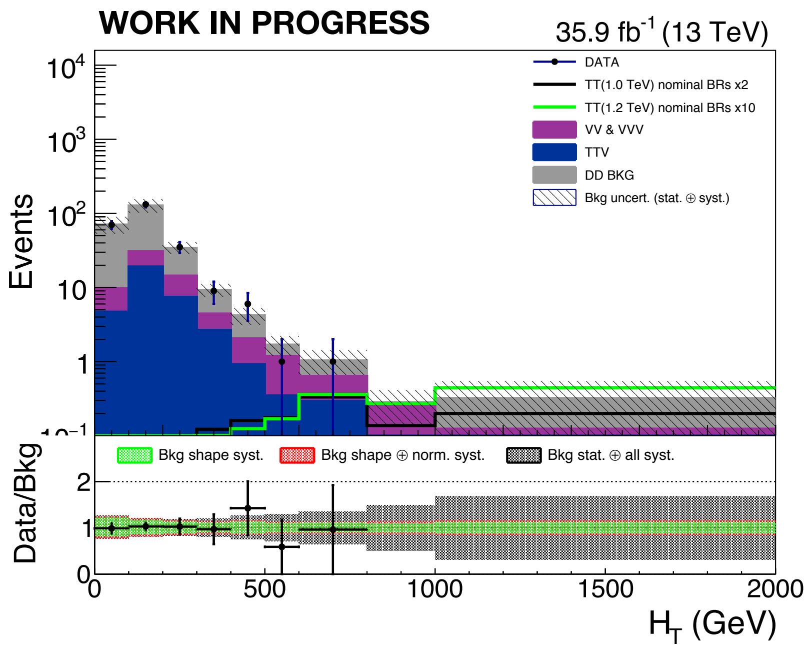
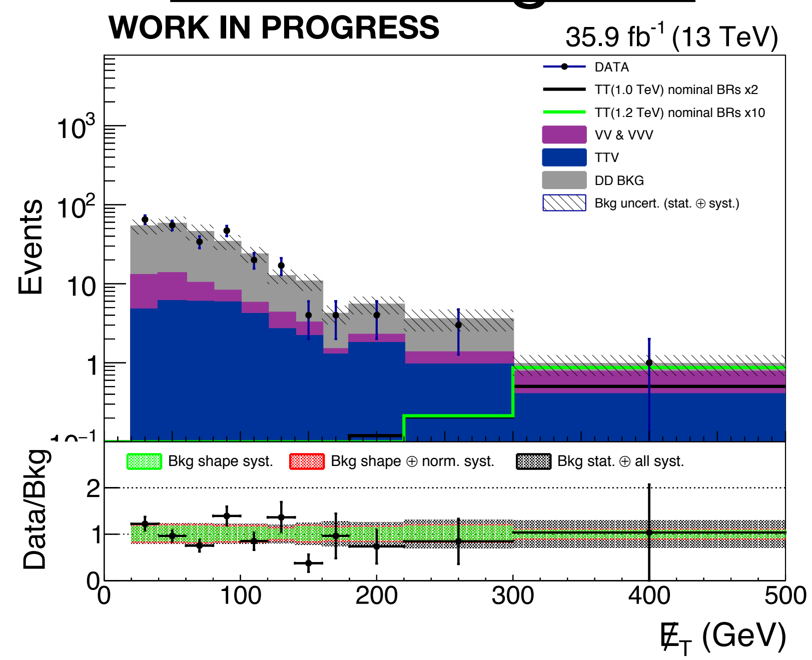
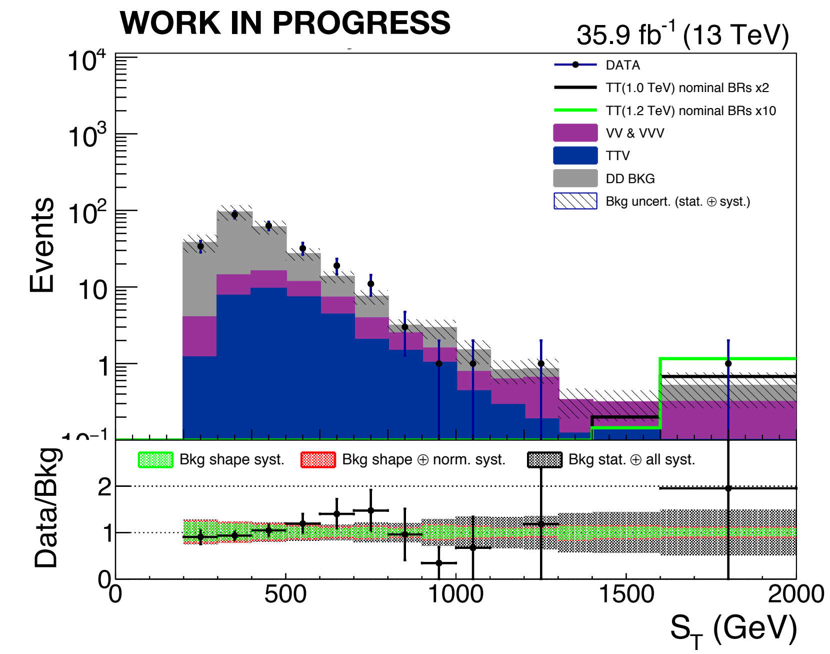
Control regions

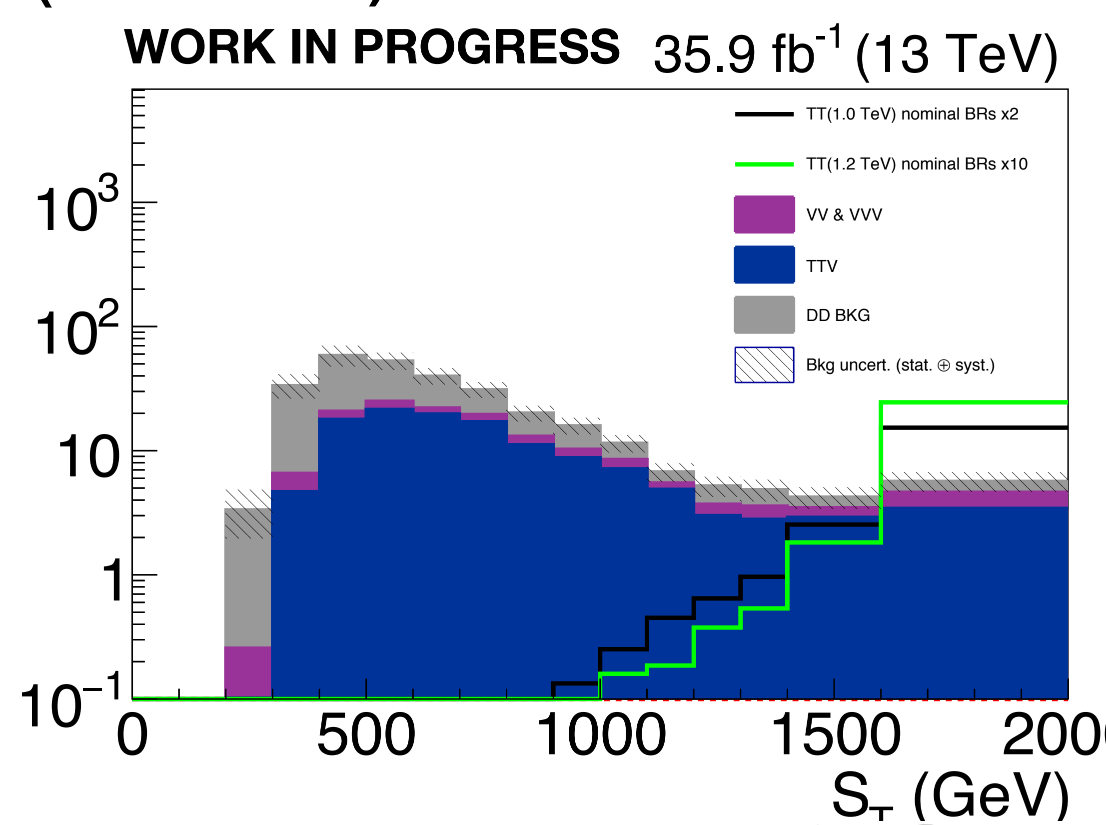






Signal region (blinded)

- S_T = lepton pT + jet pT + E_T^{miss}
- Use S_T as discriminating variable
- Use as templates for limit calculation



Triple Lepton Sys Unc.

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Systematic Uncertainties

(nonprompt lepton background)

Source	Uncertainty
Lepton mis-ID rate	6 – 42%
Muon mis-ID in η	12 – 29%
NP method closure	20 – 24%
Prompt rate (e)	2 – 21%
Prompt rate (μ)	2 – 7%

- lepton mis-ID : measured by observing the difference in fake rate in tt MC sample when applying signal region selection and control region selection.
- Muon mis-ID in η : taking into account η dependence of the muon fake rate
- Nonprompt (NP) method closure: measured using tt MC sample
- Prompt rate: uncertainties due to measurement of the prompt rate.

Combined Sys Unc.

Systematic Uncertainties

Source	Uncertainty	Single lepton Sig	Single lepton Bkgd	Trilepton Sig	Trilepton Bkgd
Luminosity	2.5%	Yes	All	Yes	MC
Reconstruction	1%	Yes	All	Yes	MC
Identification	2%(e), 3%(μ)	Yes	All	Yes	MC
Isolation (e, μ)	1%	Yes	All	–	–
Trigger (e or μ)	$\pm\sigma(p_{\mathrm{T}}, \eta)$	Yes	All	–	–
Trigger ($\ell\ell\ell$)	3%	–	–	Yes	MC
Pileup	$\sigma_{\mathrm{inel.}} \pm 4.6\%$	Yes	All	Yes	MC
Jet energy scale	$\pm\sigma(p_{\mathrm{T}}, \eta)$	Yes	All	Yes	MC
Jet energy res.	$\pm\sigma(\eta)$	Yes	All	Yes	MC
Top p_{T} weight	env(no weight, weight)	Yes	$t\bar{t}$	–	–
H_{T} scaling	env(uppper, lower fits)	No	W+jets	–	–
b tag: b	$\pm\sigma(p_{\mathrm{T}})$	Yes	All	Yes	MC
b tag: light	$\pm\sigma$	Yes	All	Yes	MC
W tag: τ_2/τ_1	$\pm\sigma$	Yes	All	–	–
W tag: τ_2/τ_1 p_{T}	$\pm\sigma(p_{\mathrm{T}})$	Yes	All	–	–
W/H tag: mass scale	$\pm\sigma(p_{\mathrm{T}}, \eta)$	Yes	All	–	–
W/H tag: mass res.	$\pm\sigma(\eta)$	Yes	All	–	–
H tag: propagation	5%	Yes	All	–	–
Renorm./Fact. scale	env($\times 2$, $\times 0.5$)	Shape	All	Shape	MC
PDF	$\pm\sigma$	Shape	All	Shape	MC
VV rate	15%	No	VV	–	–
Single tW rate	16%	No	tW	–	–

Combined Results

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Expected Limits

- Apply Bayesian inference to calculate 95% CL expected upper limits on the production cross section of pair of VLQ $T_{2/3}$ at each simulated mass point. —> Work is still in progress.

- Expected upper limits from the single lepton + jets search using the 13 TeV 2015 data (arXiv:1706.03408v1):
  - VLQ $T_{2/3}$ at mass of 1 TeV (for the singlet & doublet $\mathcal{BR}$) is ~ 0.1 pb.

- Cross section for VLQ $T_{2/3}$ at mass of 1 TeV is ~ 0.045 pb.

- From the factor of 10 more luminosity, improved techniques and addition of other final state signatures, **we project that the expected upper limits for VLQ $T_{2/3}$ at mass of 1 TeV for the singlet (doublet) $\mathcal{BR}$ will be ~ 0.02 (0.01) pb.**

Summary

- We perform a search for pair of VLQ $T_{2/3}$ particle decaying into bW, tZ, tH
- We look at two channels
  - single lepton + jets
  - triple lepton (or more) + jets
- Results are still blinded and work is still in progress for the 95% CL expected upper limits for the production cross section of pair of VLQ $T_{2/3}$
- We project to exclude VLQ $T_{2/3}$ with mass up to 1 TeV for both the singlet and doublet $\mathcal{BR}$.

END

Quick Glossary

- MC: Monte Carlo
- E_T^{miss} : Magnitude of missing transverse momentum vector.
- pT : transverse momentum
- η : pseudo-rapidity
- M_{OSll} : invariant mass of opposite-sign dilepton
- prompt (nonprompt) rates : rate of prompt (nonprompt) leptons passing the ‘tight’ lepton quality requirements
- AK4 : Anti-k_T jets with R=0.4
- AK8 : Anti-k_T jets with R=0.8
- n-subjettiness (τ_n) : measure of number of prongs in a jet **arXiv:1011.2268**
- b-tagged jet : jet identified as a result of B-hadron decay (from b quark)
- pruned mass: Mass of AK8 jet after applying ‘Pruning’ jet grooming technique **arXiv:0912.0033**

Lepton Quality Requirements

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Electron

- A multivariate discriminant is to identify electrons. Looks at variables that measure:
  - track quality,
  - association between the track and electromagnetic shower, shower shape, and
  - likelihood of the electron being produced in a photon conversion in the detector.
- **Two quality levels:**
  - **a tight level with ≈88% efficiency and**
  - **a loose level with ≈95% efficiency.**

Muon

- Muon Identification algorithms consider
  - the quality of this fit,
  - the number or fraction of valid hits in the trackers and muon detectors,
  - track kinks, and
  - the distance between the track from the silicon tracker and
  - the primary interaction vertex.
- **Two quality levels:**
  - **a tight level with ≈97% efficiency and**
  - **a loose level with 100% efficiency in the barrel region of the detector.**

Isolation

- We apply an isolation criteria for the leptons. Evaluated using a variable called 'mini Isolation' (I_{mini}):
  - sum of particle flow candidate p_T within a p_T-dependent cone around the lepton (R), corrected for the effects of pileup and divided by the lepton p_T.

$$R = \frac{10\,\text{GeV}}{\min(\max(p_T, 50\,\text{GeV}), 200\,\text{GeV})}.$$

- **The reconstructed electrons and muons must have:**
  - **I_{mini} < 0.1 to be labeled tight, and**
  - **I_{mini} < 0.4 to be labeled loose.**

Samples

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- T pair and and all SM processes **simulated using MC**
- NLO tt, single top, WZ, ZZ events uses **POWHEGv2**[1-4] matrix element generator
- NLO tt+W, tt+Z, triboson, s- and t- channel of single top events uses **MADGRAPH5_aMC@NLO 2.2.2**[5] with **FxFx**[6] merging.
- LO W+jets, Drell-Yan, multijet events uses **MADGRAPH 5.2.2.2**[5] with **MLM**[7] merging.
- Parton showering, underlying events, diboson events simulated using **PYTHIA 8.212**[8,9].
- Detector simulation for all MC samples performed using **GEANT4**[10].

1. P. Nason, "A New method for combining NLO QCD with shower Monte Carlo algorithms", JHEP 11 (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
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3. S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX", JHEP 06 (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
4. S. Frixione, P. Nason, and G. Ridolfi, "A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction", JHEP 09 (2007) 126, doi: 10.1088/1126-6708/2007/09/126, arXiv:0707.3088.
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Jet Grooming Algorithms

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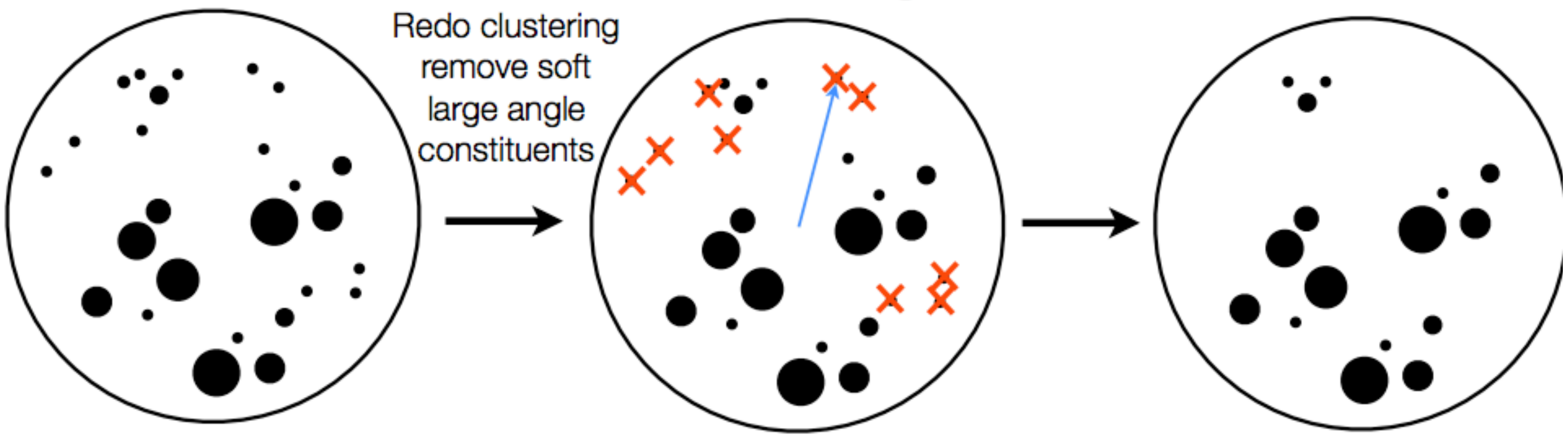
Pruning



$$z = \frac{\min(p_{Ti}, p_{Tj})}{p_{Tp}} < z_{\rm cut} \quad \text{and} \quad \Delta R_{ij} > D_{\rm cut}.$$

arXiv:0912.0033

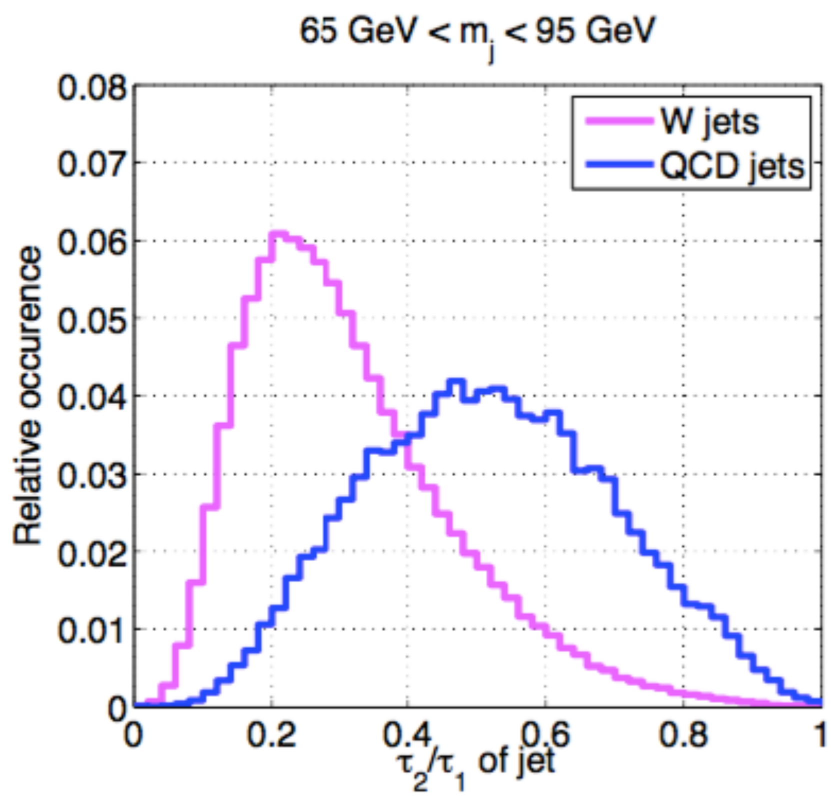
N-subjettiness

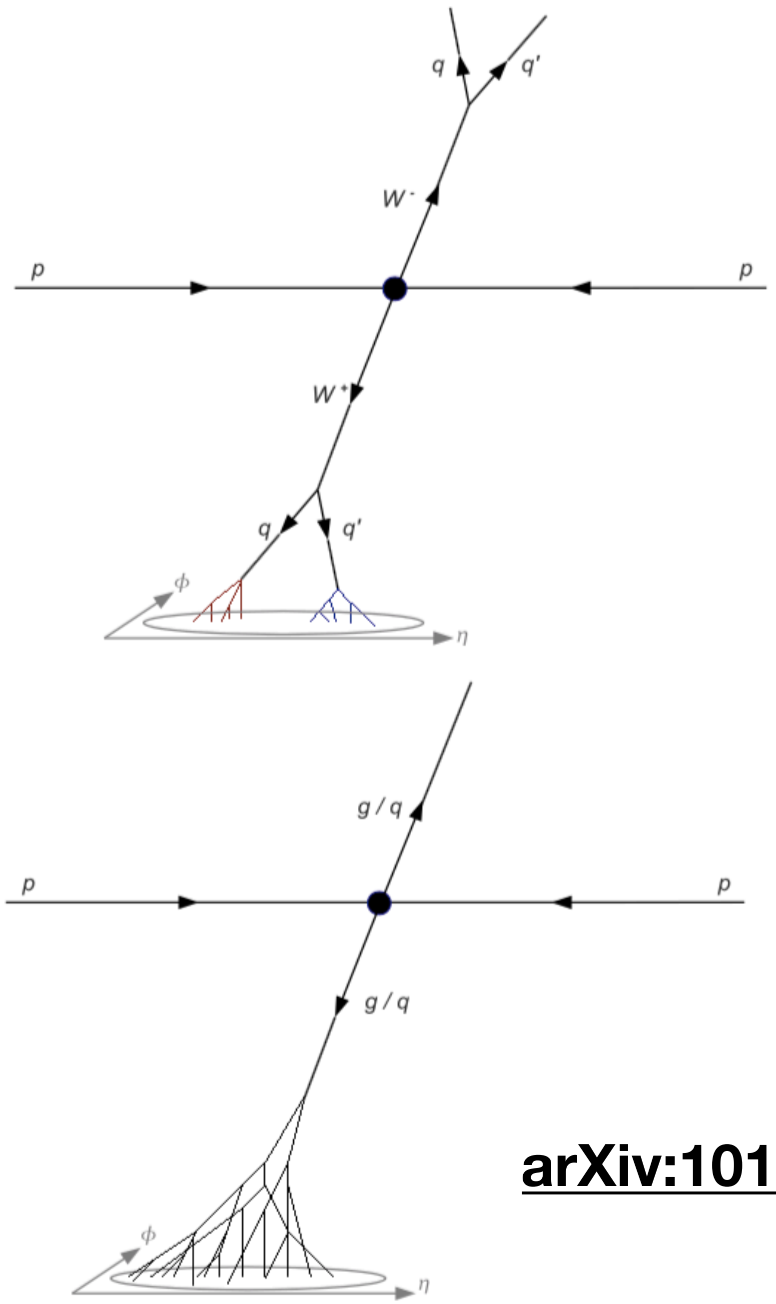
- Use k_T jet clustering algorithm to find potential subject —> defines τ axes
- τ_N —> measure of how likely the jet has N-prongs

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

$$d_0 = \sum_k p_{T,k} R_0,$$

$$\Delta R_{J,k} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$





arXiv:1011.2268

LHC, CMS experiment

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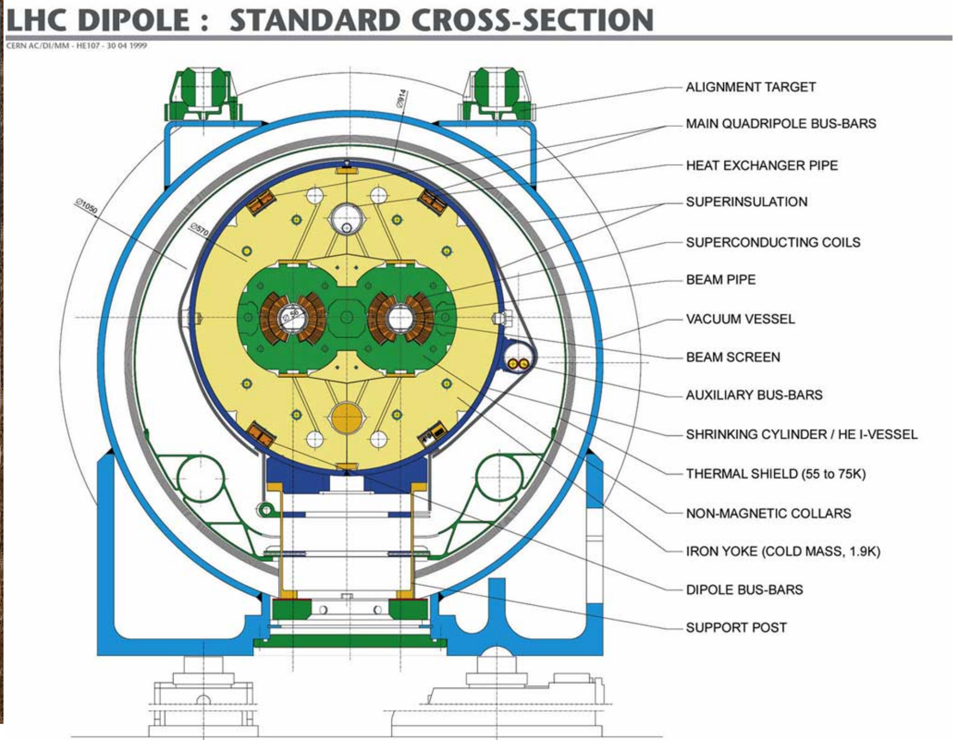

Large Hadron Collider (LHC)

- ~27 km circumference ring tunnel
- ~100 m underground
- Up to 14TeV c.o.m energy (Now at 13 TeV)
- 25 ns bunch spacings (40 MHz peak bunch crossing rate

Compact Muon Solenoid (CMS)

- Silicon Tracker
- Electromagnetic Calorimeter (ECAL)
- Hadronic Calorimeter (HCAL)
- Muon Chambers
- 3.8 T magnetic field