Probing the Goldstone Equivalence Theorem in Neutralino Decays via Z/Higgs

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Arnowitt Memorial Symposium /
Mitchell Collider & Dark Matter Workshop 2015

Work in progress with: Bhaskar Dutta, Yu Gao, David Sanford
Extending 1412.2774 (Dutta, Gao, Skakya)
See also: 1404.2691 (Jung)

Outline of Presentation

(I) Brief review of theory motivations & the NMSSM model
(See co-presentation by Yu Gao for an extended discussion)

(II) Extended consideration of collider final states that can probe the Goldstone Equivalence & their optimization in simulation

(III) (Time Permitting) introduction of original software tools used for collider analysis and plotting (Slides from talk at MC4BSM)

Goldstone Equivalence Theorem

- In a spontaneously broken symmetry, there are massless spin-0 (Goldstone) excitations along flat directions of the potential
- If the symmetry was gauged, these degrees of freedom are absorbed into longitudinal modes of the newly massive vectors
- At large collision energies, amplitudes for longitudinal vector bosons are equivalent to those of the associated Goldstone
- Since the Z mass arises from the Higgs VEV, they are linked, and a (near) unit ratio of Z/Higgs production is expected

Evading Goldstone Equivalence

- In the Standard Model, Goldstone Equivalence applies strongly, but there are no heavy electroweak states to decay
- In the MSSM, there is dependence of masses & the up/down Yukawas upon changes in tan β; Z/H ~ 1 to 2 is typical
- If the Higgs sector has an additional singlet component, coupling outside of SU(2), then the theorem is evaded in new ways
- This is a natural way to probe the NMSSM; Z/H < 1 is possible
- As an alternative (non-SUSY) example construction, see "Simplified Models of Mixed Dark Matter" with a pair of heavy weak doublets analogous to higgsinos 1311.5896 (Cheung, Sanford)

The NMSSM

- NMSSM is the Next-to-Minimal Supersymmetric Standard Model
- Attempts to explain why SUSY-preserving Higgsino mass mixing μ is of Electroweak order, canceling apparently independent soft terms
- The μ term arises as the VEV of a new singlet chiral supermultiplet containing a pair of CP +/- Higgs scalars as well as a 5^{th} neutralino
- The "singlino" neutralino is a Cold Dark Matter candidate, with relic density fixed by s-channel annihilation via the light pseudoscalar
- Next lightest neutralinos are typically higgsino dominated and may be generated directly by Drell-Yan or Vector Boson Fusion processes

The NMSSM

- Naturalness suggests higgsino mass $\mu \sim M_Z$, as given by $\mu = \lambda\langle S\rangle$
- Note that singlino mass is $\sim \kappa\langle S\rangle = \kappa\mu/\lambda$
- Higgs at 126 GeV is aided by contributions from larger λ (2^{nd} term) — avoids multi-TeV stops & eliminates hard tuning
- This simultaneously ($\sim 1/\lambda$) drives the singlino lighter

$$W_{\rm Higgs} \supset \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3}\hat{S}^3 .$$

$$M_h^2 \;\approx\; M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2 + \\ + \frac{3 m_t^4}{4\pi^2 v^2}\left(\ln\left(\frac{m_T^2}{m_t^2}\right) + \frac{(A_t - \mu\cot\beta)^2}{m_T^2}\left(1 - \frac{(A_t - \mu\cot\beta)^2}{12 m_T^2}\right)\right)$$

1412.2774

The NMSSM

- The large coupling λ suggests large higgsino-singlino mass mixing
- Dark matter direct detection constrains this model when the LSP is a higgsino-singlino mixture. So: the higgsino mass must be elevated
- This naturally leads to higgsino $\Rightarrow$ on-shell Z/H $\Rightarrow$ singlino chain
- But: this also suppresses collider production cross sections

$$\begin{matrix} \tilde{H}_d \\ \tilde{H}_u \\ \tilde{S} \end{matrix} \begin{pmatrix} 0 & -\mu & -v\lambda\sin\beta \\ -\mu & 0 & -v\lambda\cos\beta \\ -v\lambda\sin\beta & -v\lambda\cos\beta & \frac{2\kappa}{\lambda}\mu \end{pmatrix}$$

Higgsino-singlino block of the neutralino mass matrix

1412.2774

The NMSSM

- We study the parameter space where the singlet scalars are heavier than, or comparable to, the Higgs mass & then not distinguishable
- If the pseudo-scalar singlet is kinematically accessible & mixes into "Higgs", it couples to H but not Z & Z/H goes down (<1 typical)
- Analogous to parameter space of MSSM with higgsinos $\Rightarrow$ bino LSP
- Simulation will focus on benchmark "A" below

Benchmark	λ	κ	μ	$\tan\beta$	A_λ	A_κ	N_{15}^2	S_{h3}^2	m_{a_1}	σ_{SI} (pb)	$m_{\tilde\chi_1^0}$	$m_{\tilde\chi_2^0}$	$m_{\tilde\chi_3^0}$	$\tilde\xi^{Zh}$
A	0.8	0.25	220	2.9	710	45	62%	50%	161	9×10^{-11}	143	270	270	2.1
B	0.8	0.24	210	2.9	682	100	62%	42%	115	1.6×10^{-10}	133	259	261	0.7
C	0.8	0.25	230	2.9	710	100	64%	25%	119	3.4×10^{-10}	150	279	279	0.7
A' (MSSM), $M_1 = 140$GeV	-	-	260	20	-	-	93%($\tilde B$)	-	10^3	2.3×10^{-9}	134	270	275	1.6

TABLE I: Benchmark NMSSM points used in this study. Point A' is a MSSM counterpart to Point A with a similar light neutralino spectrum as described in the text. $\tilde\xi^{Zh}$ is the ratio of decay into Z to decay into h (see IV B).

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Z/Higgs Decay Modes

- Z decays to hadrons 70% (15% $b\bar{b}$), invisible 20%, leptons $l\bar{l}$ 10%
- 125 GeV SM Higgs: $b\bar{b}$ 58%, WW^* 22%, gg 8%, $\tau\bar{\tau}$ 6%, ZZ^* 3%, $c\bar{c}$ 3%
- From mixed Z/Higgs pairs, search for: $l\bar{l}\,l\bar{l}$, $l\bar{l}\,b\bar{b}$, and $b\bar{b}\,b\bar{b}$
- Isolating any 2 of these 3 channels gives a window on the Z/H ratio

Experimental Issues

- Production cross sections are very low (~ 50 fb) for M_{n2} ~ 270 GeV in the NMSSM; Below this there are direct detection limits
- If neutralino 1 is massless, LHC sets limits in the 4-b channel, but there are no limits for a massive neutralino system $M_{n1} > 0$
- Hard to boost MET close to the kinematic edge $M_{n2} - M_{n1}$ ~ 125 GeV
- It could be helpful to tag on initial state radiation jets in the absence of MET, but 2 ISR jets cost a half magnitude order in production
- The described model by Cheung/Sanford may allow ~ 10X larger production rates, allowing M_{n2} ~ 180 GeV

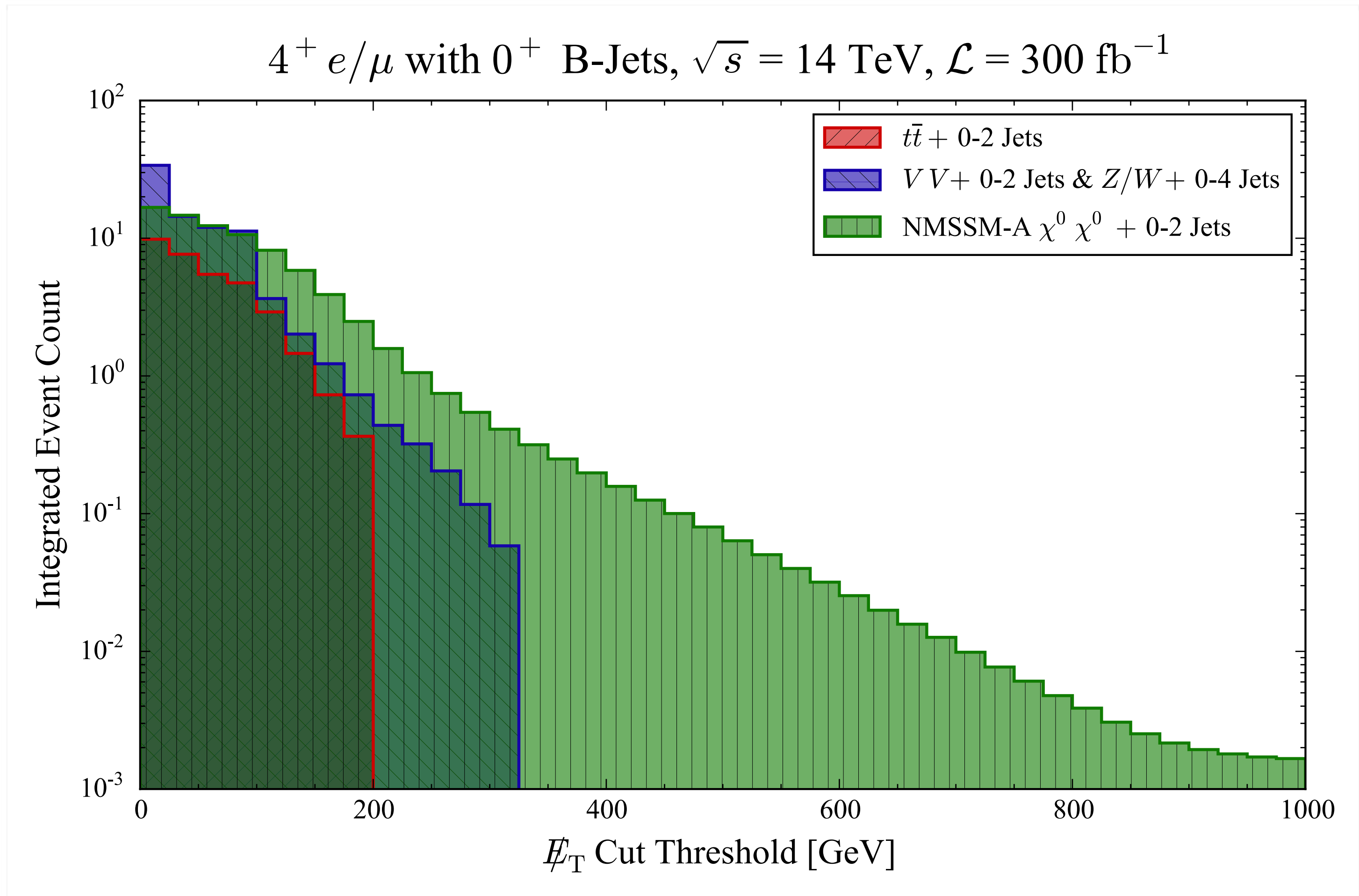
Production Rates

TABLE I: Matched production and residual effective cross-section (fb) at the LHC14 are tabulated for the three targeted final state event topologies, reported individually for the $t\bar{t}$+Jets and VV+Jets backgrounds, as well as the benchmark NMSSM signal.

Selection	$t\bar{t}$+Jets	VV+Jets	Signal
Matched Production	613,000	1,330	53
Cat I (4^+ e/μ, 0^+B's)	0.043	0.092	0.062
Cat II (2–3 e/μ, 2^+B's)	4080	0.176	0.137
Cat III (0–1 e/μ, 4^+B's)	949	0.097	0.058

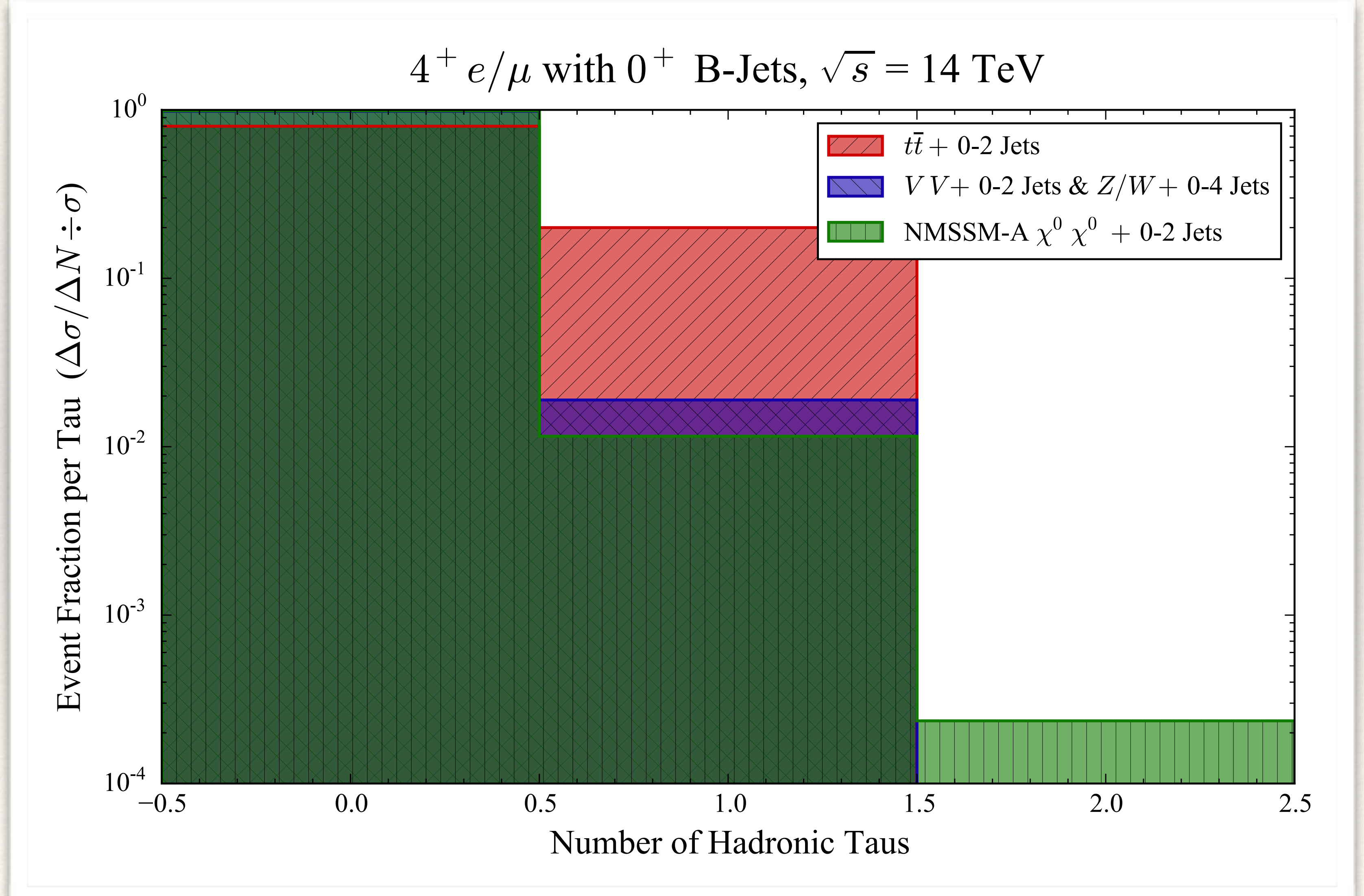
The 4-Lepton Channel

- The 4-lepton channel is intrinsically low-background, with 1/20 to 1/10 of a femtobarn residual for each $t\bar{t}$, VV and the NMSSM signal
- This channel was not studied explicitly in the prior work



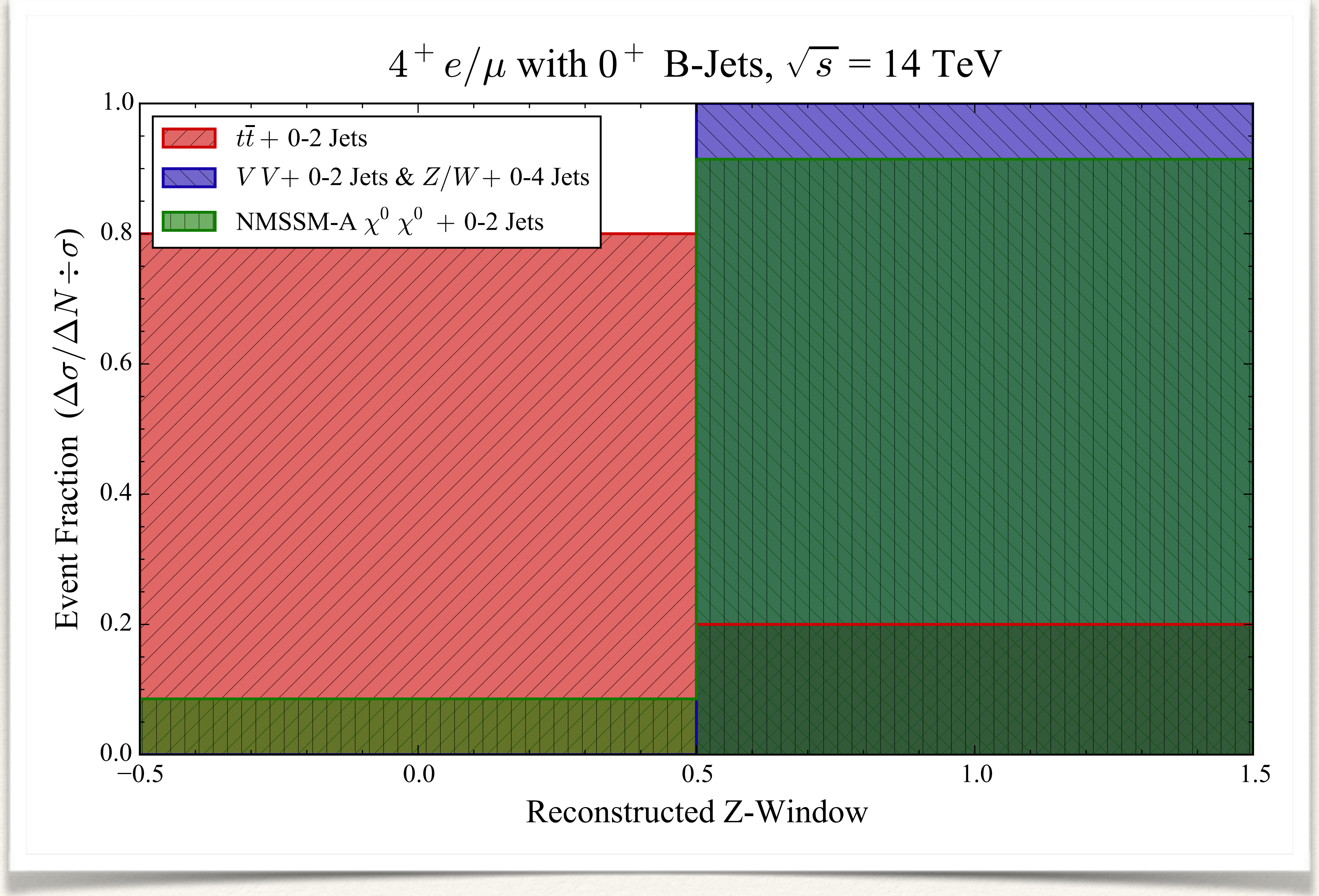
4-Lepton Refinements

- Hadronic taus are easily faked, and moreso for the jetty BG: VETO



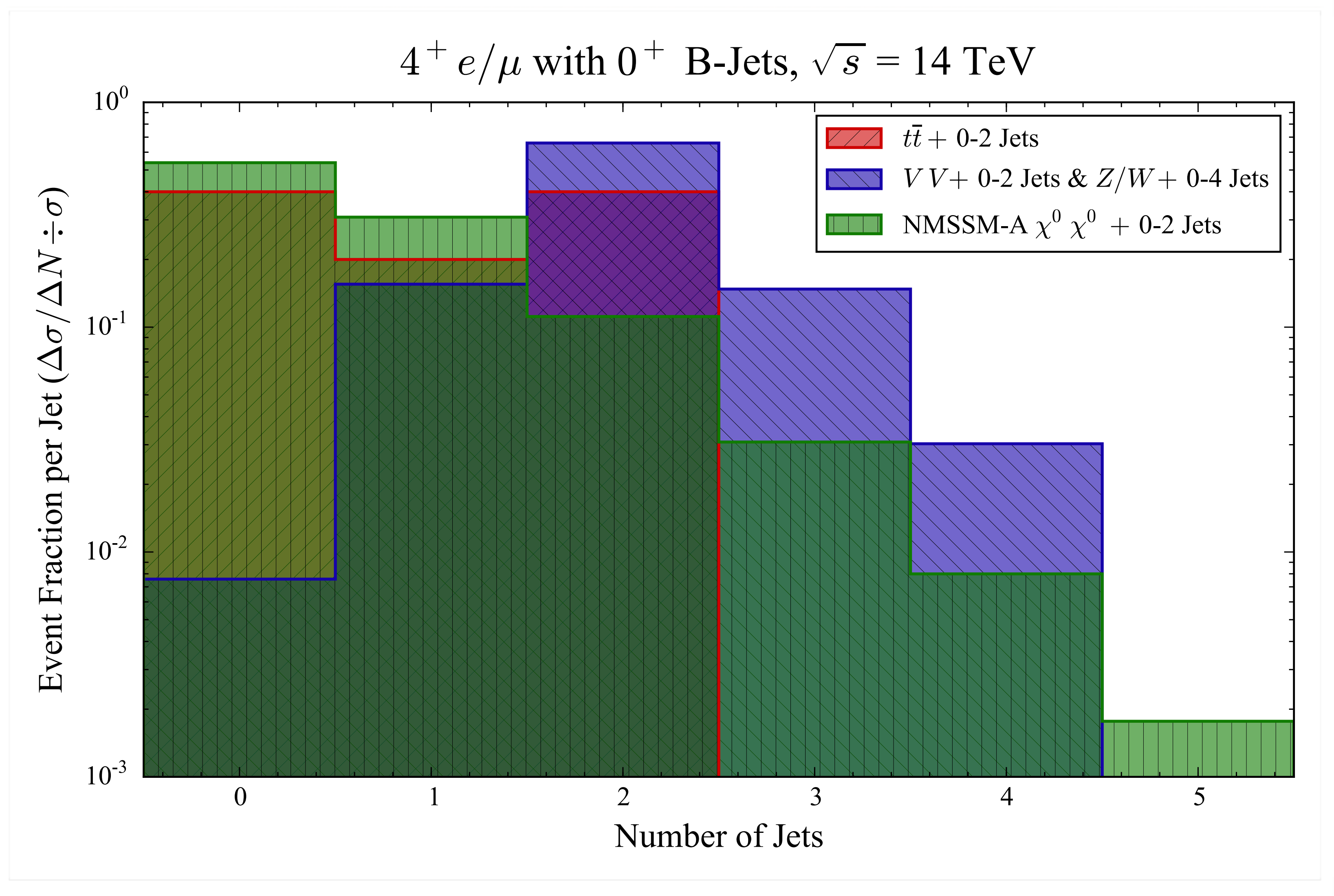
4-Lepton Refinements

- True 4-Lepton from ZZ events are much more likely to reconstruct at least one pair with invariant mass at 91 ± 5 GeV: ENFORCE IT



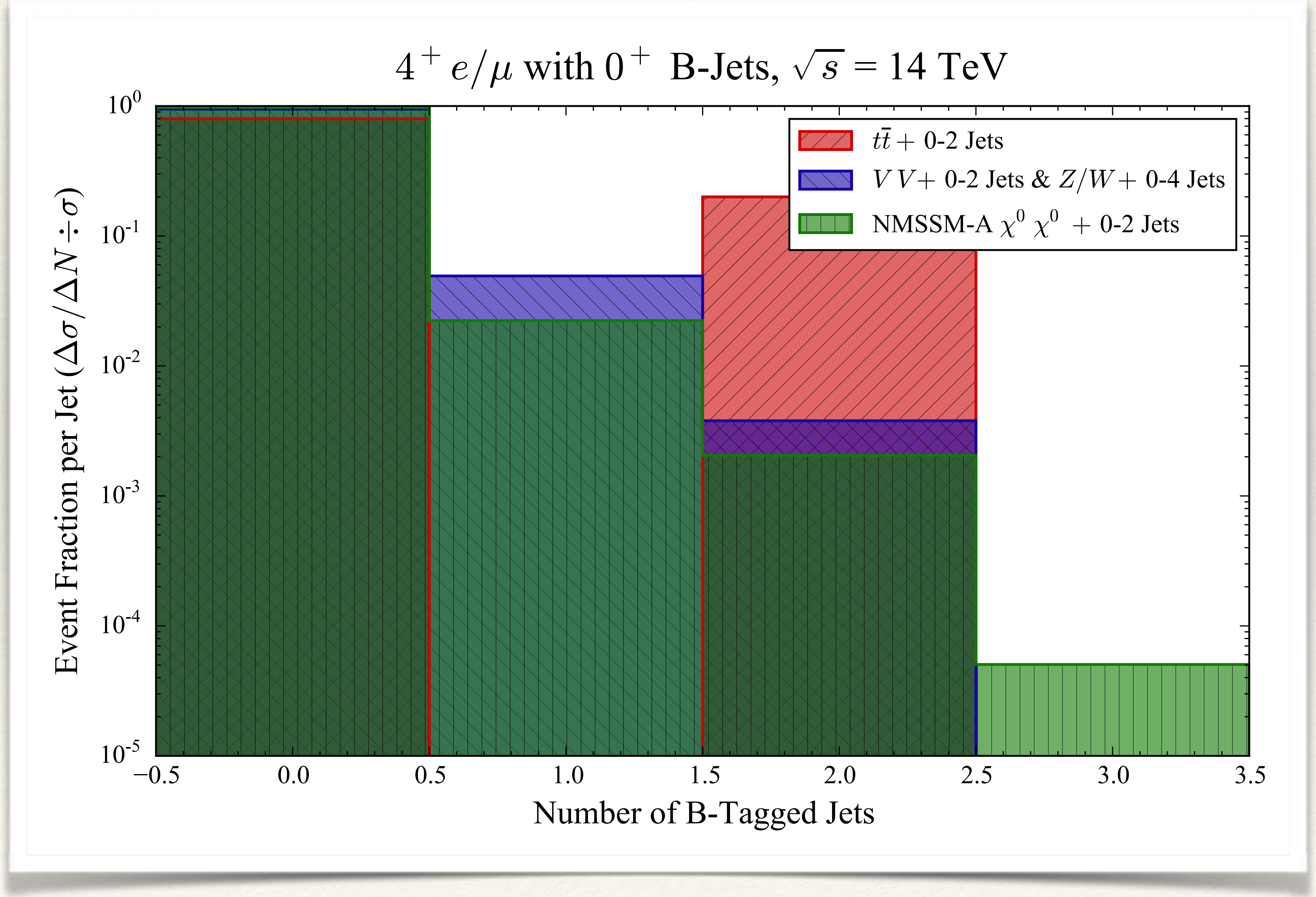
4-Lepton Refinements

- Backgrounds are much more likely to have 2 or more jets: LIMIT to 1



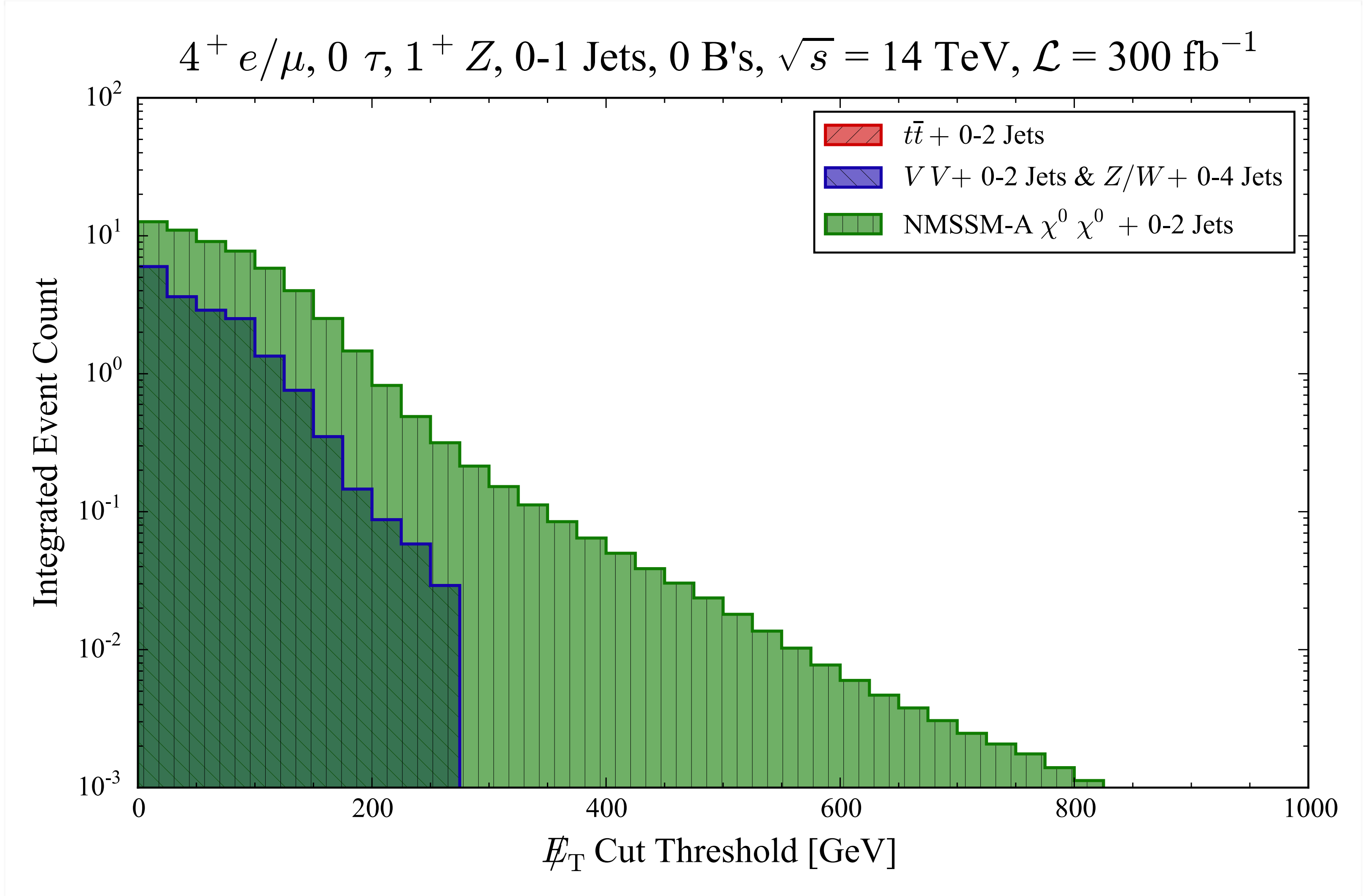
4-Lepton Refinements

- Backgrounds are much more likely to have a B-Jet: VETO



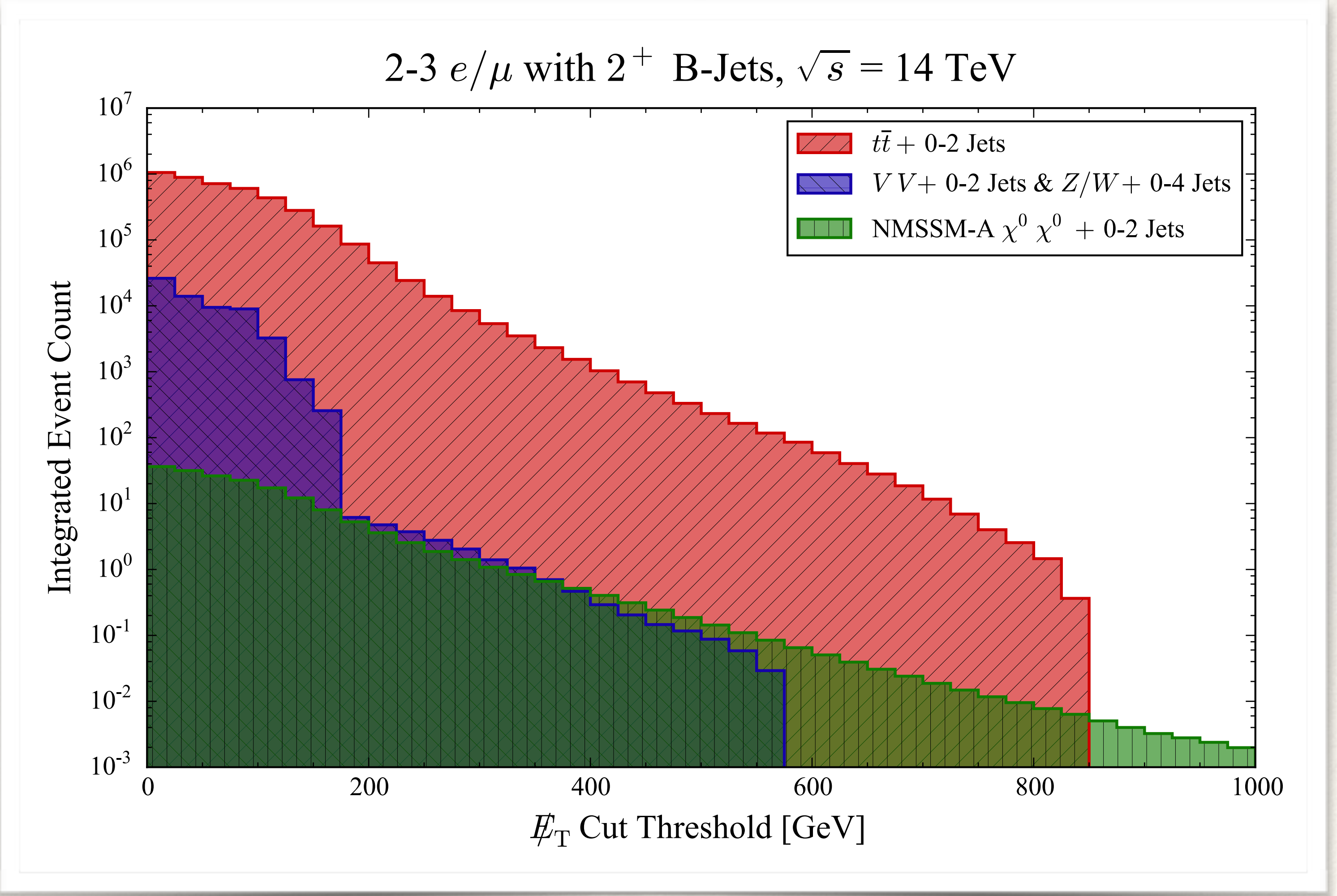
The 4-Lepton Optimization

- With these optimizations, the benchmark NMSSM 4-lepton signal is clearly visible at LHC 14, with about 8 events over 3 (MET > 100 GeV)



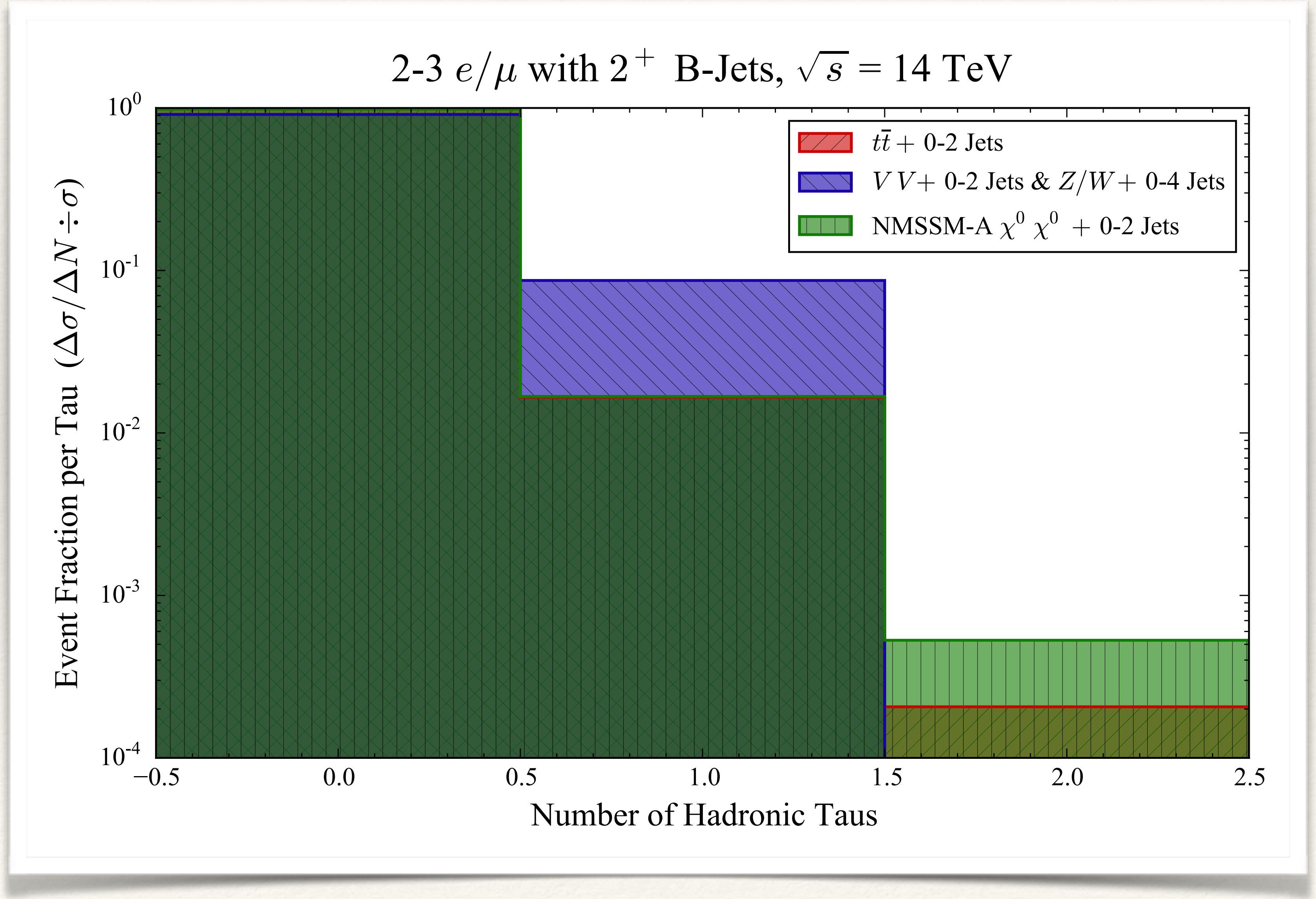
The 2 Lepton / 2 B-Tag Channel

- The 2l+2b channel is high background. ZZ (see peak at left with low MET - no neutrinos) and $t\bar{t}$ ($t \Rightarrow Wb \Rightarrow \bar{l}\nu b$) can produce it naturally.
- This channel was not considered explicitly in the prior work



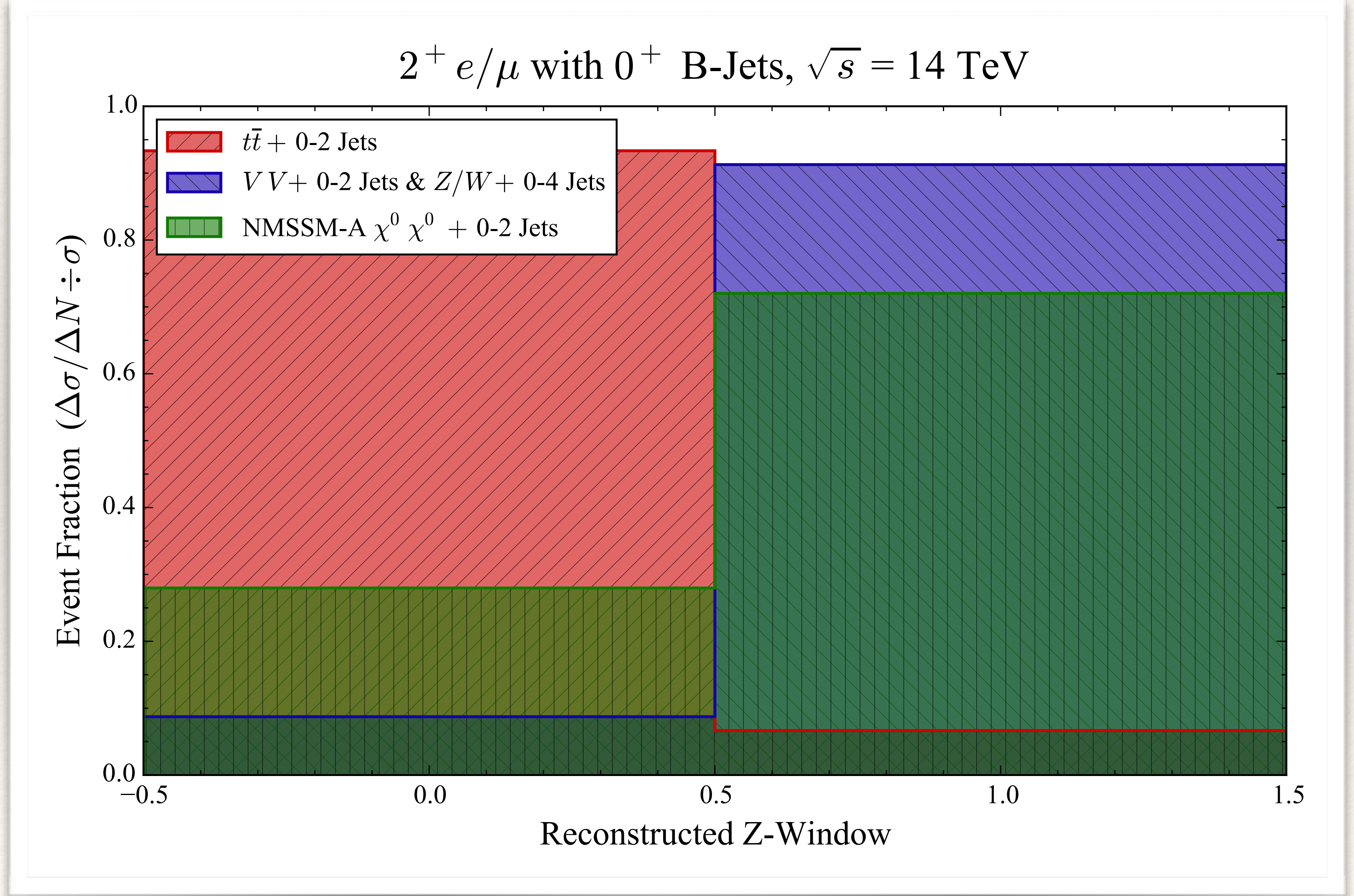
2L/2B Refinements

- Hadronic taus are easily faked, and moreso for the jetty BG: VETO



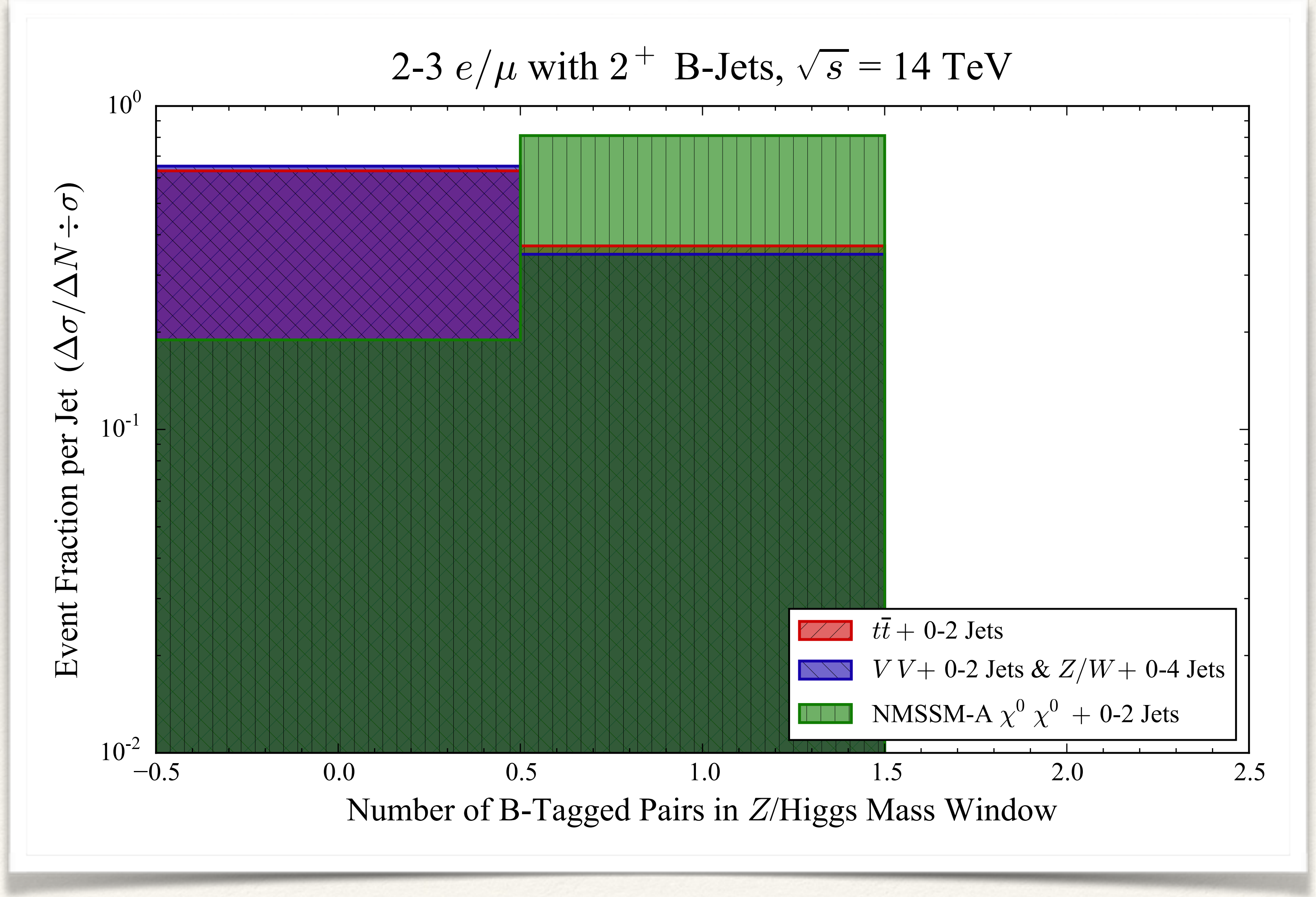
2L/2B Refinements

- About 70% of signal features a reconstructed deletion in the Z-boson mass window (92±5 GeV), vs. only about 5% of $t\bar{t}$: ENFORCE IT



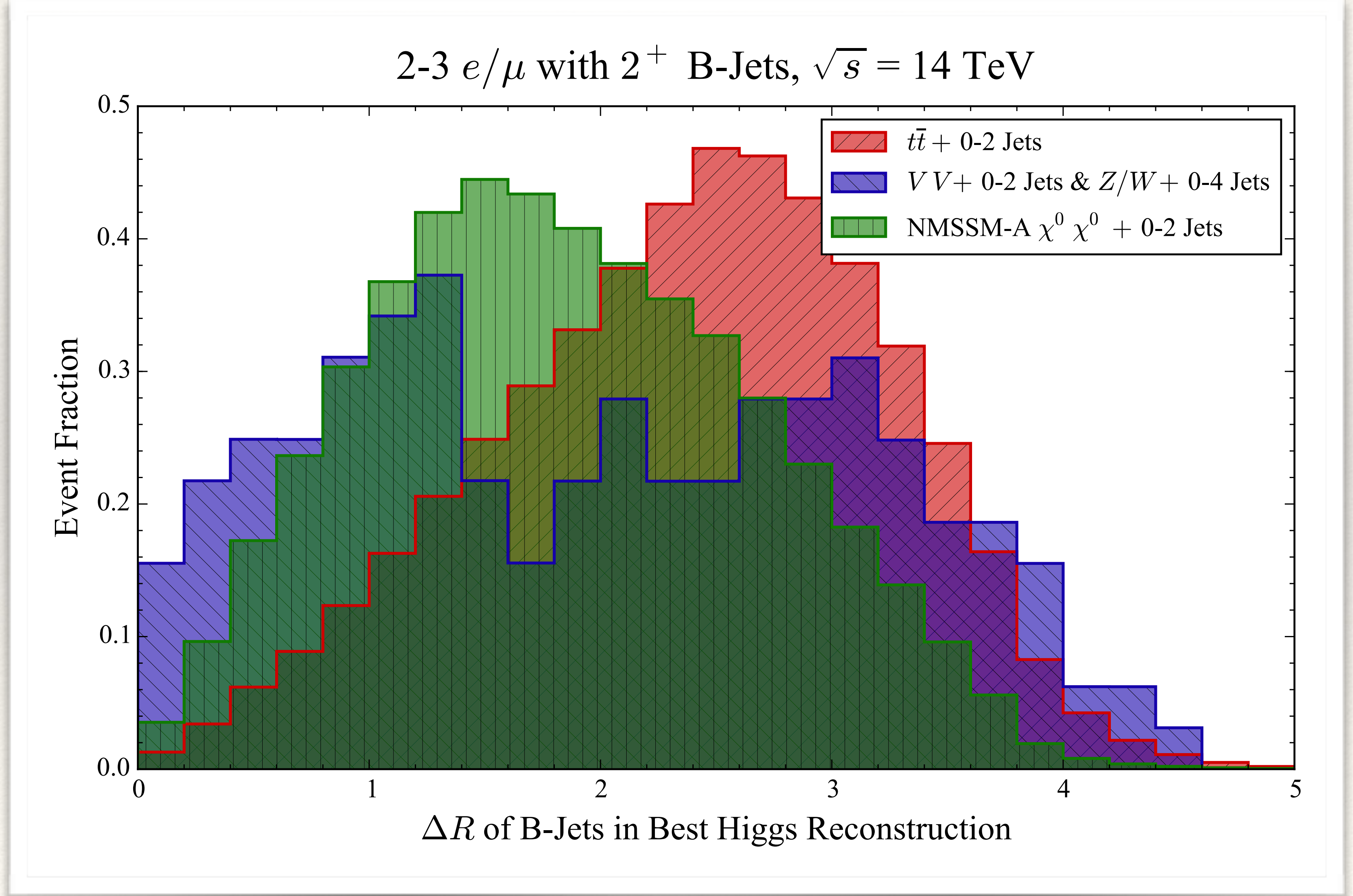
2L/2B Refinements

- Over 80% of signal features a reconstructed b-jet pair in the Z/Higgs mass window (92-20 to 126+20 GeV), vs. 35% for BG: ENFORCE IT



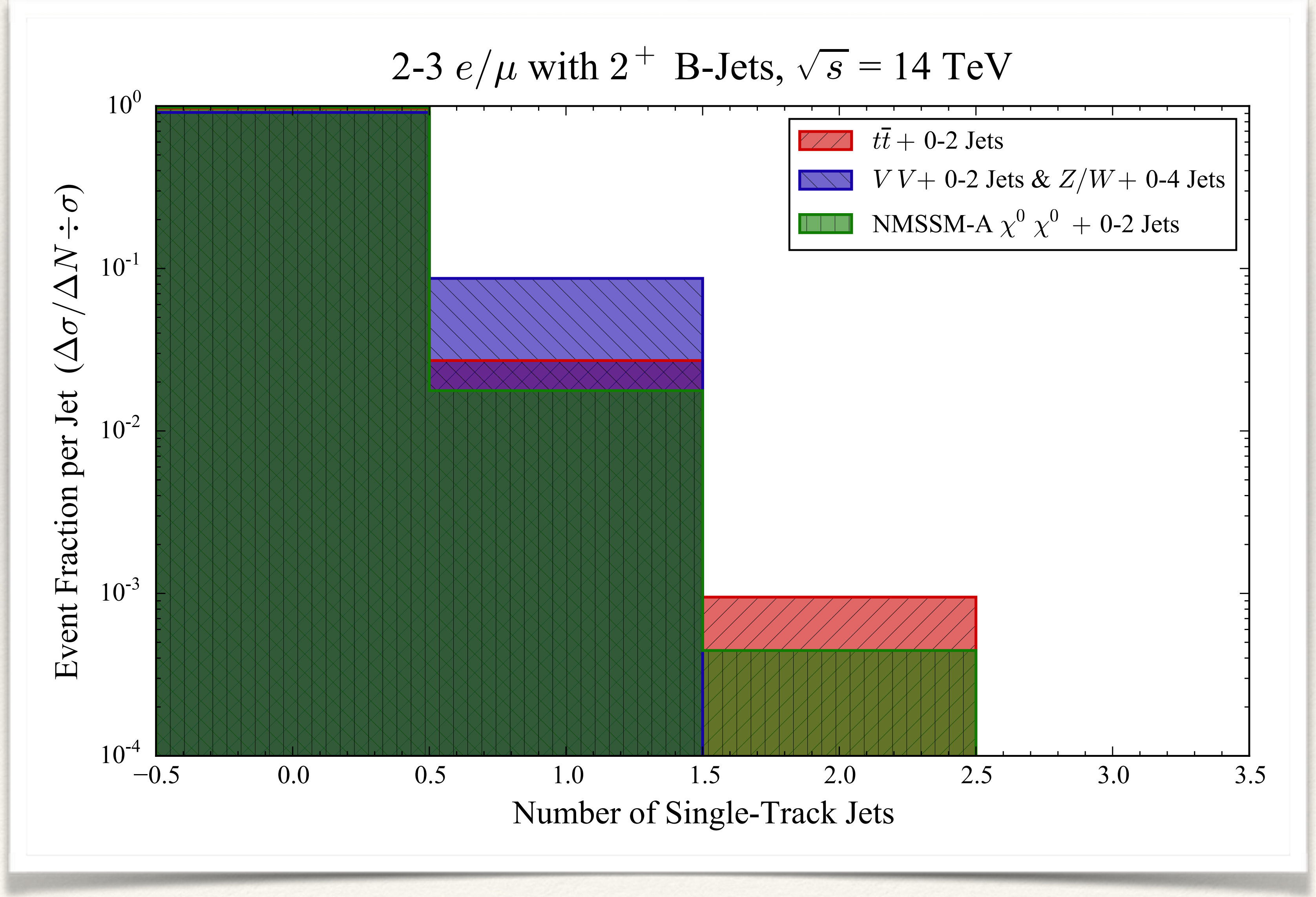
2L/2B Refinements

- The angular separation of the jet pair closest to the Higgs is systematically smaller for signal than BG: ENFORCE $\Delta R < 2.5$



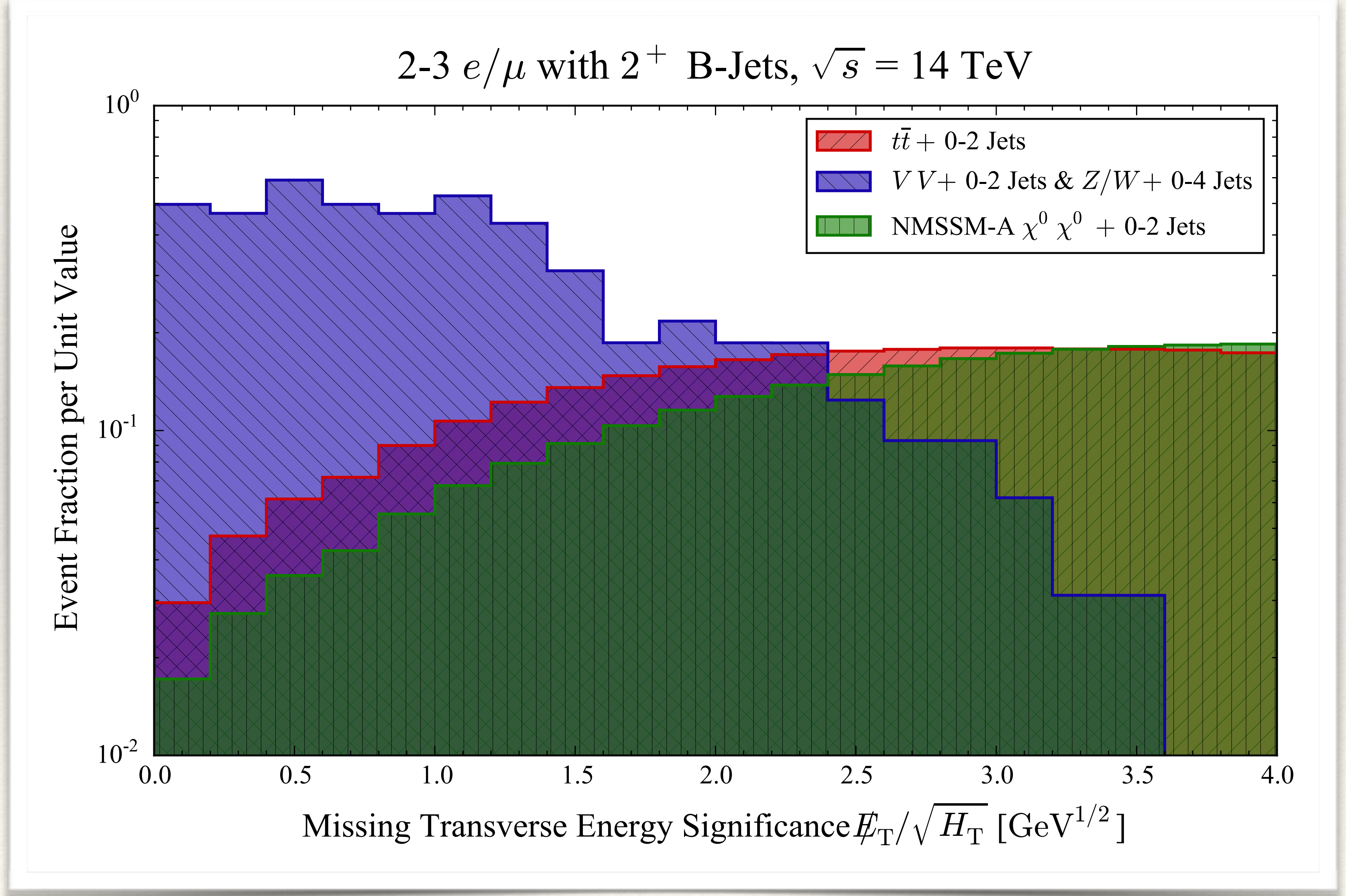
2L/2B Refinements

- Signal has no single-track jets, whereas ~10% of VV does: VETO



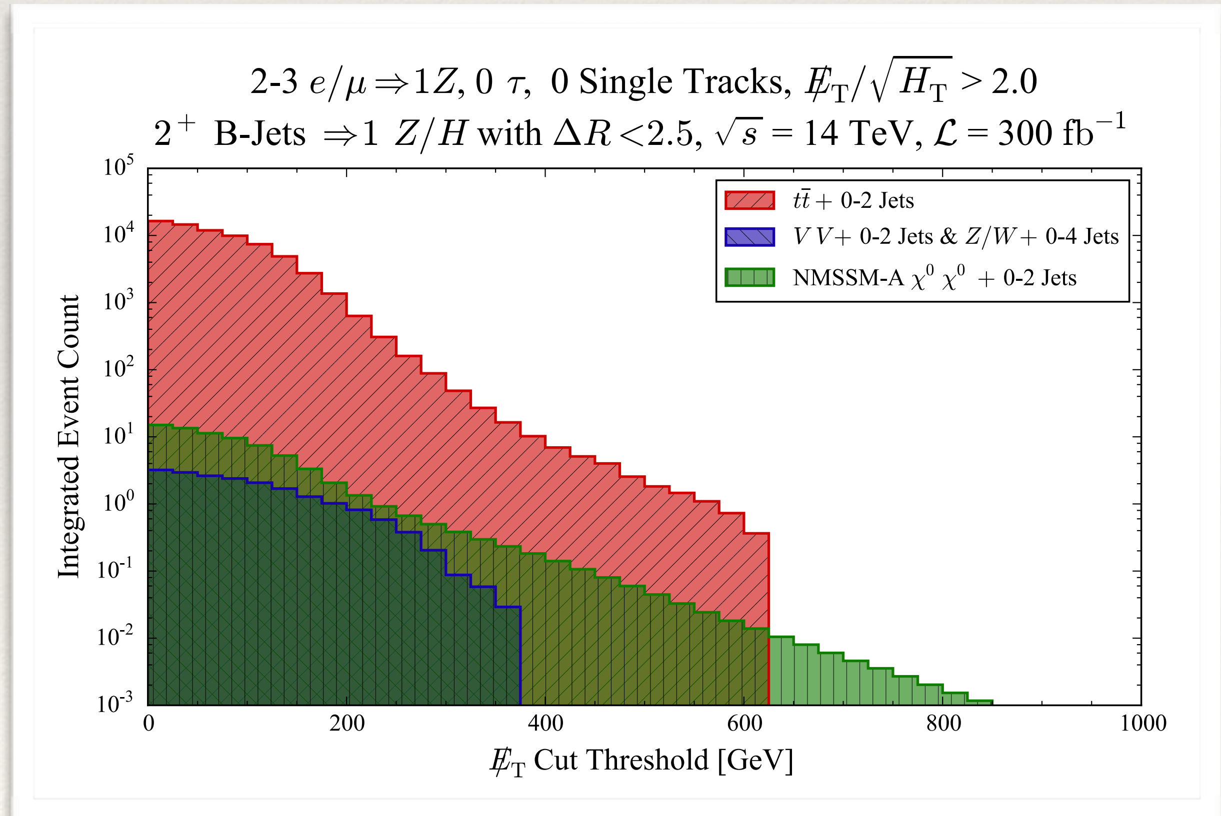
2L/2B Refinements

- The most critical VV background has no real MET source, and very low MET signficance: ENFORCE MET / √HT > 2.0 GeV$^{1/2}$



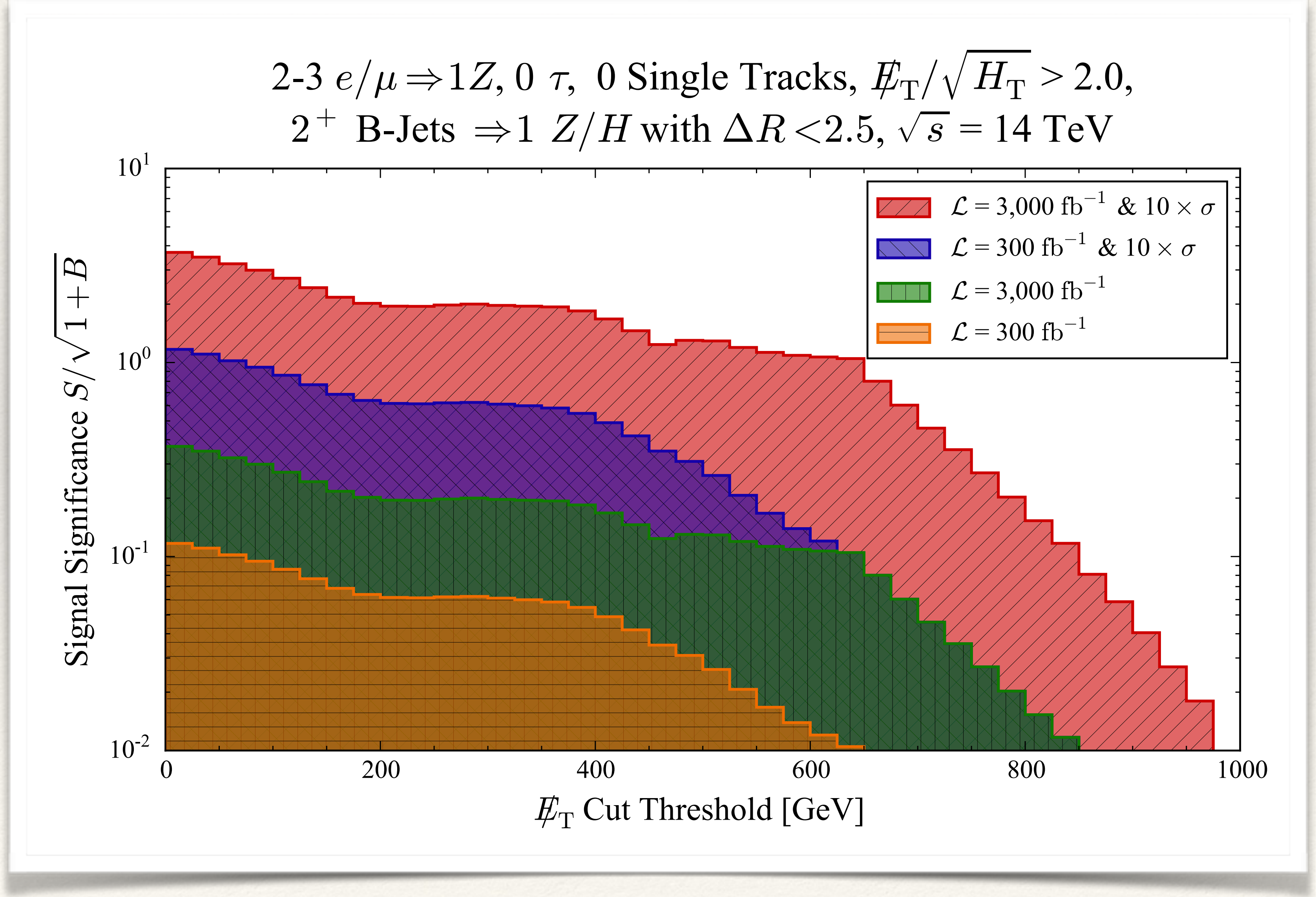
2L/2B Optimization

- The optimized selections cut the BG by ~ 2 magnitude orders, but the signal by only about 50%. However, $t\bar{t}$ still dominates by 2-3 orders.
- A cut on MET provides no real handle. Neither do a "kitchen sink" of specialized statistics (e.g. M_{T2}, $M_{T2}W$, jet-Dilepton Z-balance, Razor, α_T, MET-Jet $\Delta\varphi$, biased $\Delta\varphi$, lepton W-projection, thrust & shape vars).



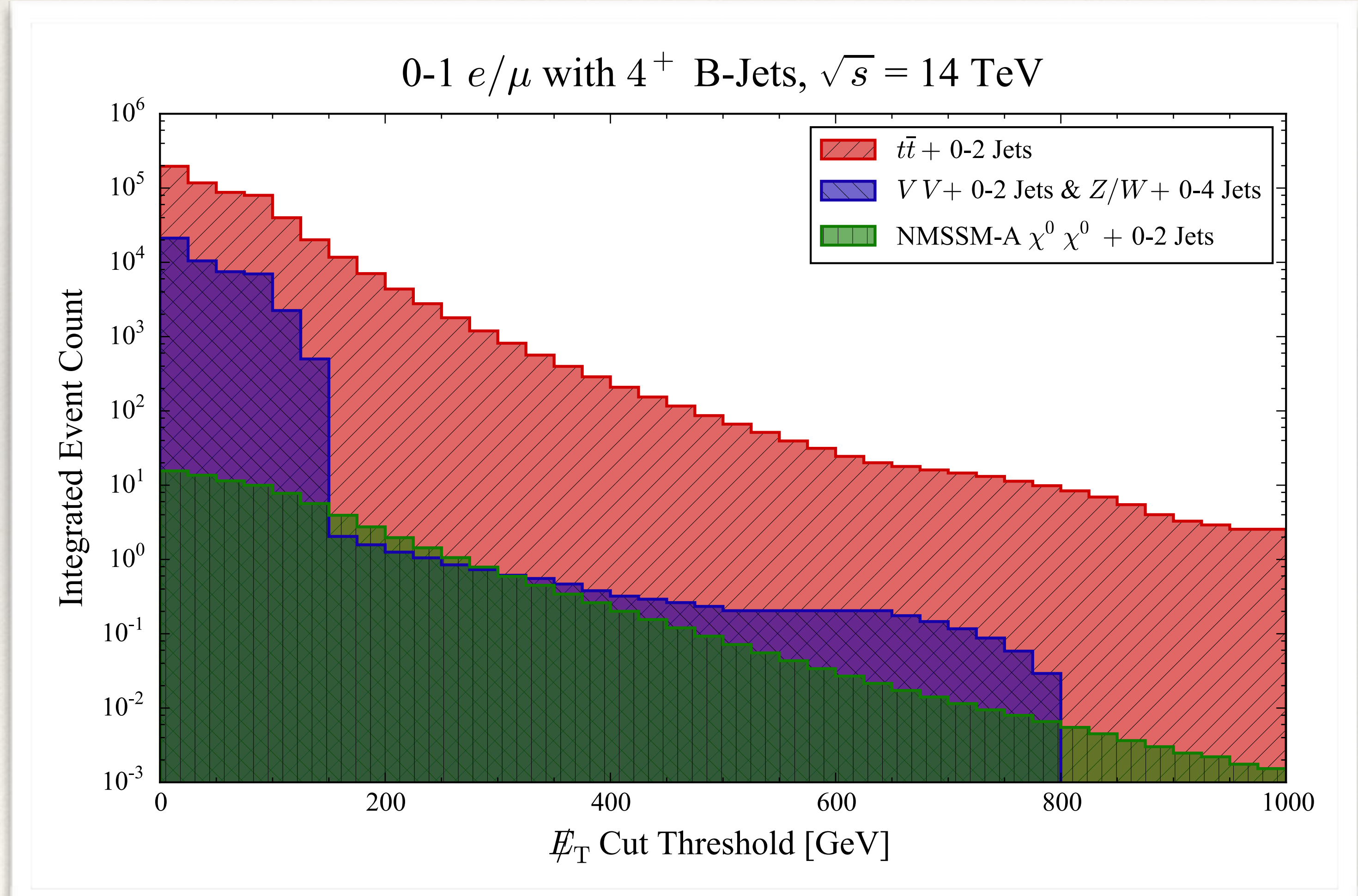
2L/2B Visibility

- The 2l+2b channel is not visible at 300/fb for the NMSSM benchmark, but with a 10X boost in both cross section and luminosity, it is visible.



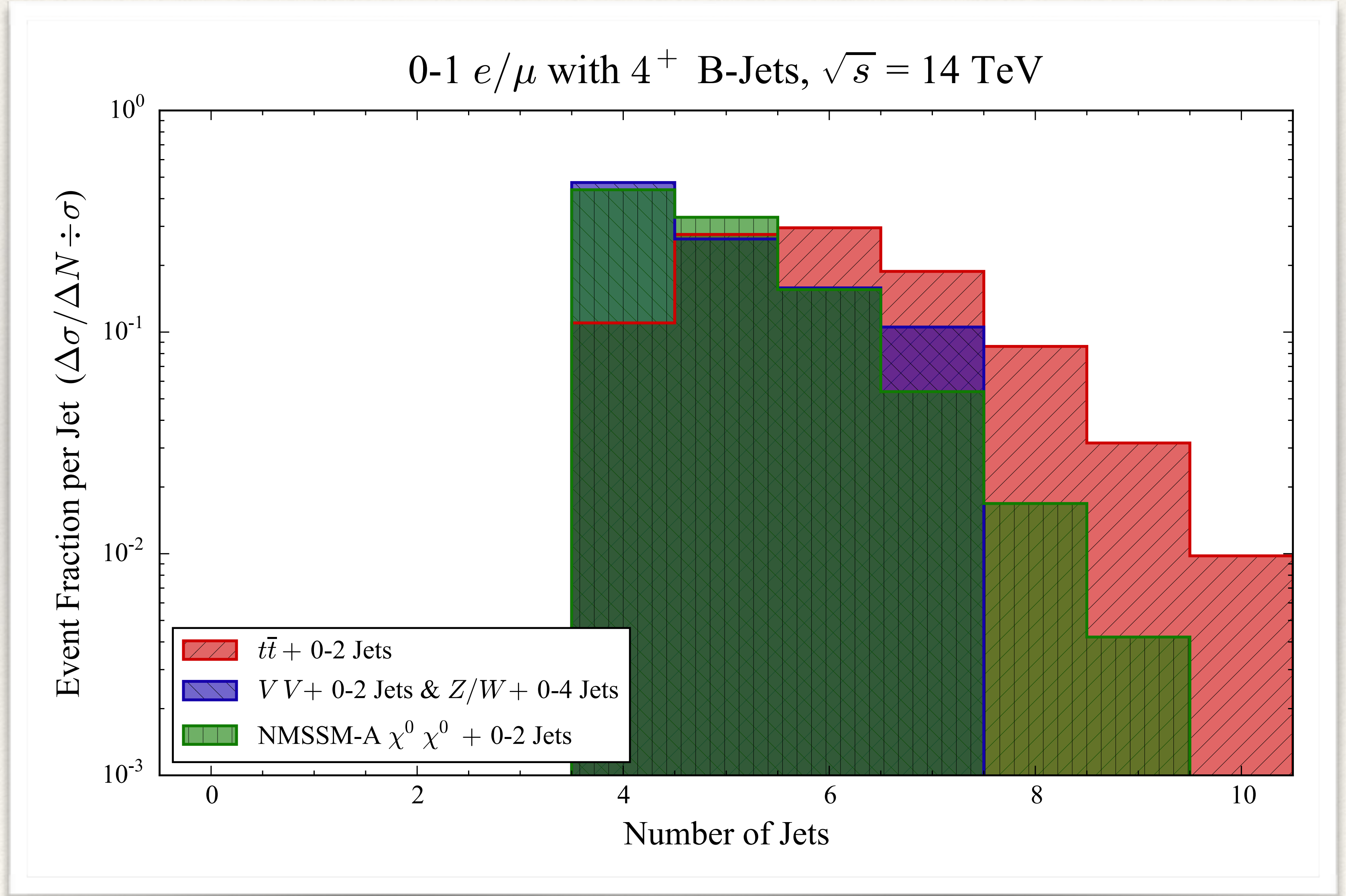
The 4 B-Tag Channel

- The 4b channel is high background. There is a real contribution from ZZ. Extra fake b's in hadronic $t\bar{t}$ modes are the larger problem.
- Similar preference for tau veto, single track veto, & MET significance.



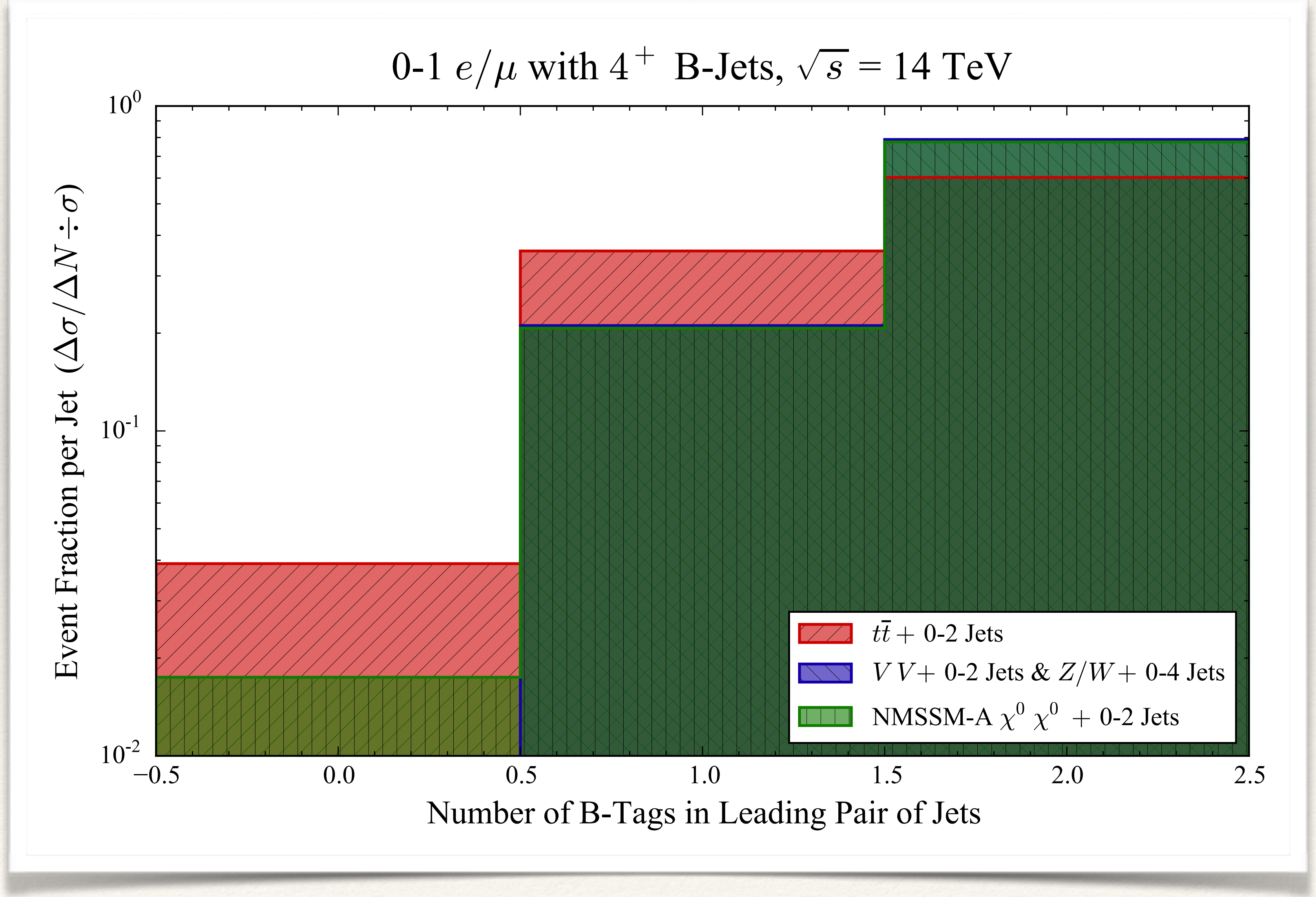
4 B-Tag Refinement

- The $t\bar{t}$ BG is quite a bit jettier than the signal, with a larger fraction of events at six or more jets: CUT ABOVE FIVE



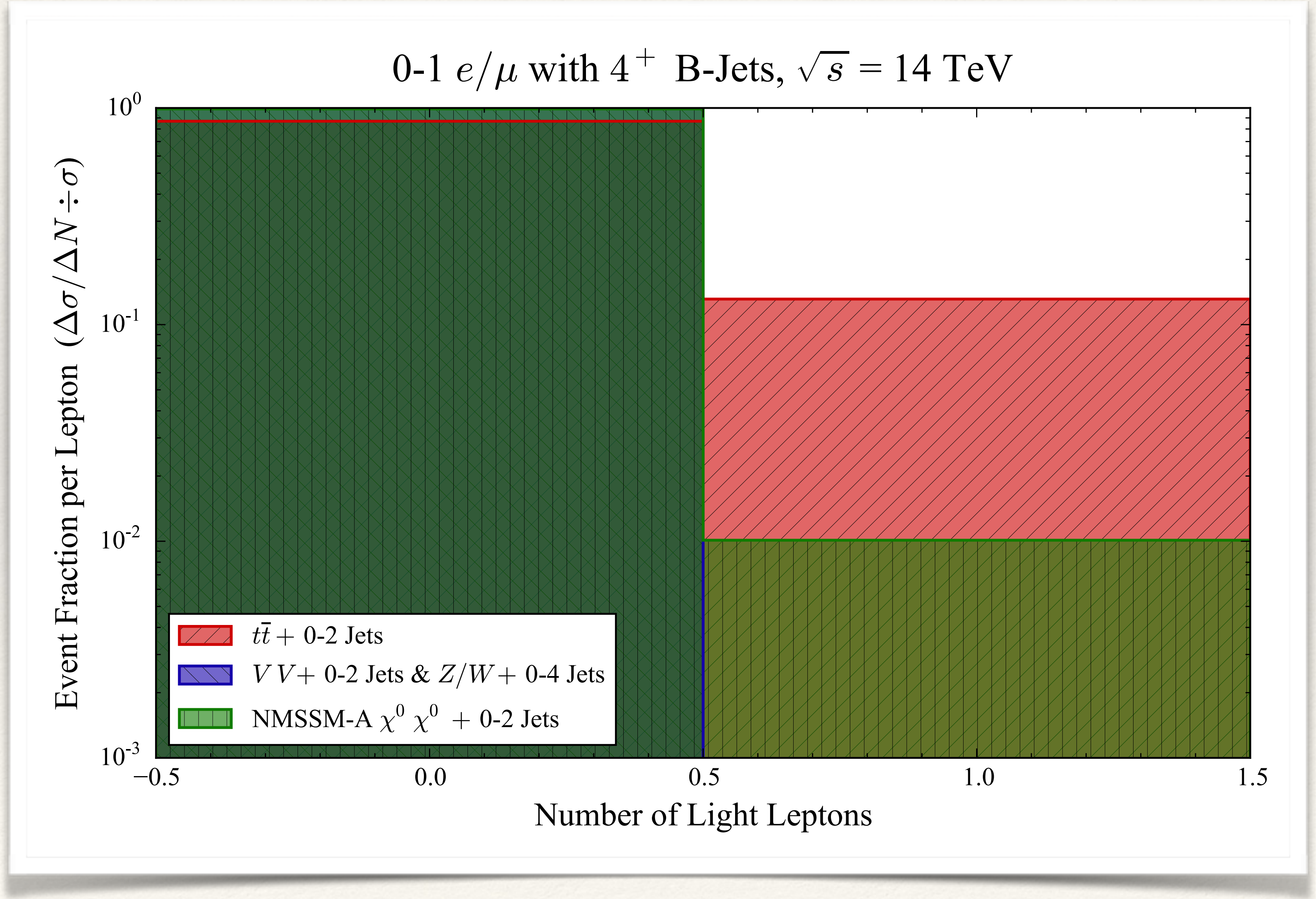
4 B-Tag Refinement

- The leading pair of jets is more likely b-tagged for the signal than the $t\bar{t}$ BG, where they are often initial state radiation: ENFORCE TAGS



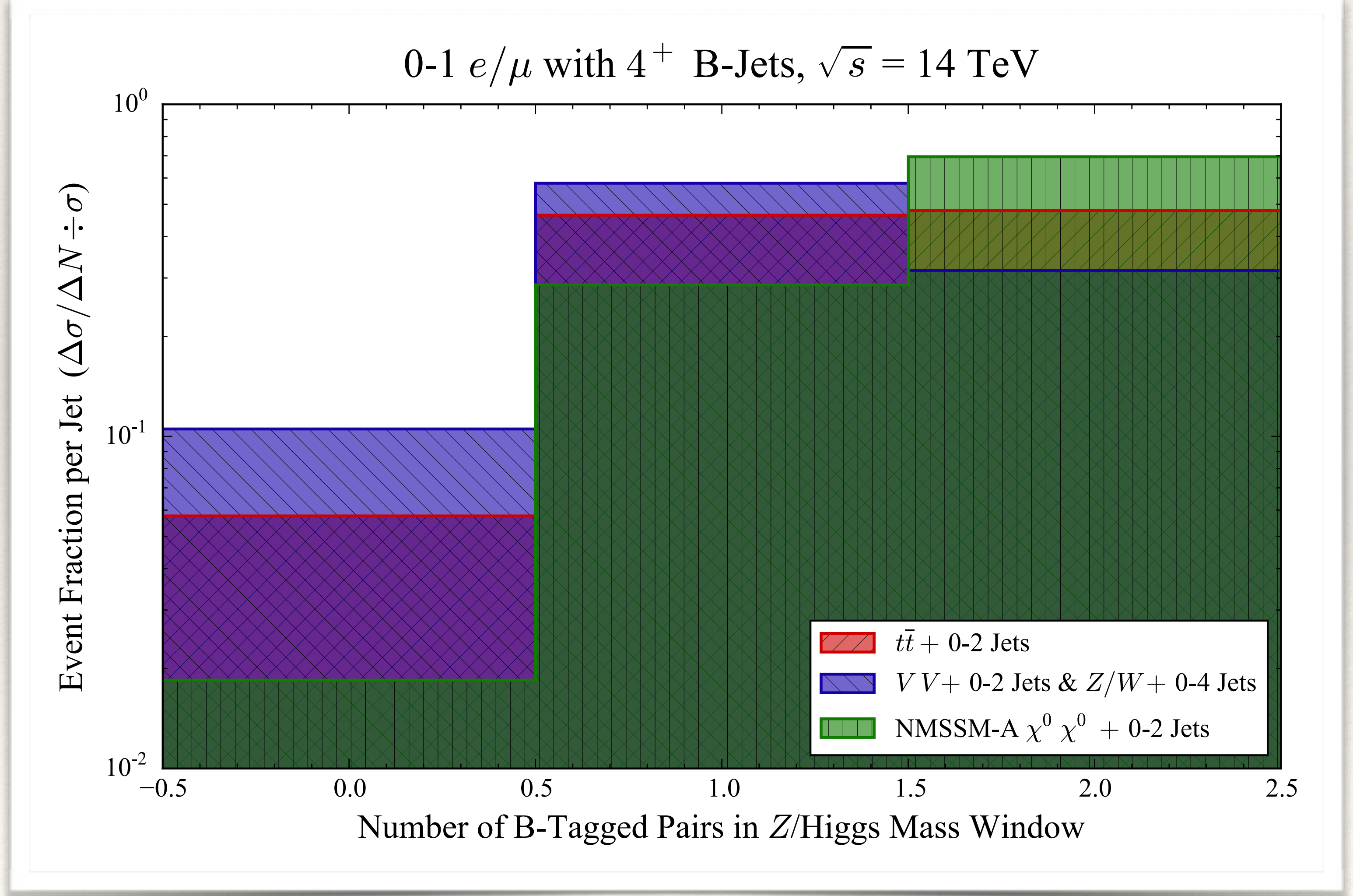
4 B-Tag Refinement

- The $t\bar{t}$ channel is substantially more likely to retain a single lepton (achieving b-tags via more fakes) than signal: VETO



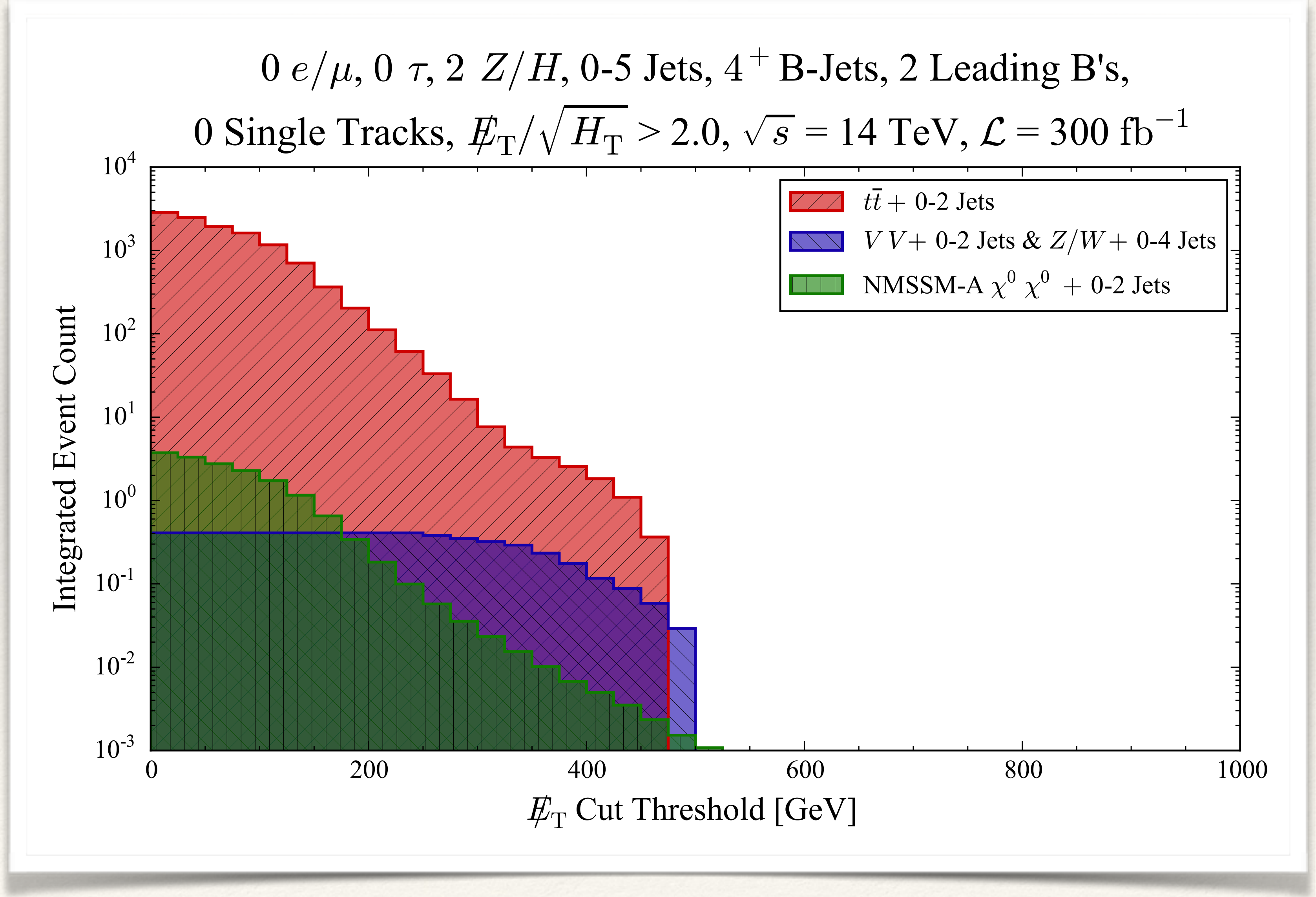
4 B-Tag Refinement

- Around 70% of signal features 2 pairs of b-jets reconstructing the Z/Higgs mass window, vs. around 50% or 30% for $t\bar{t}$ / VV: ENFORCE IT
- Combinatoric BG's limit efficacy & preclude angular separation cuts



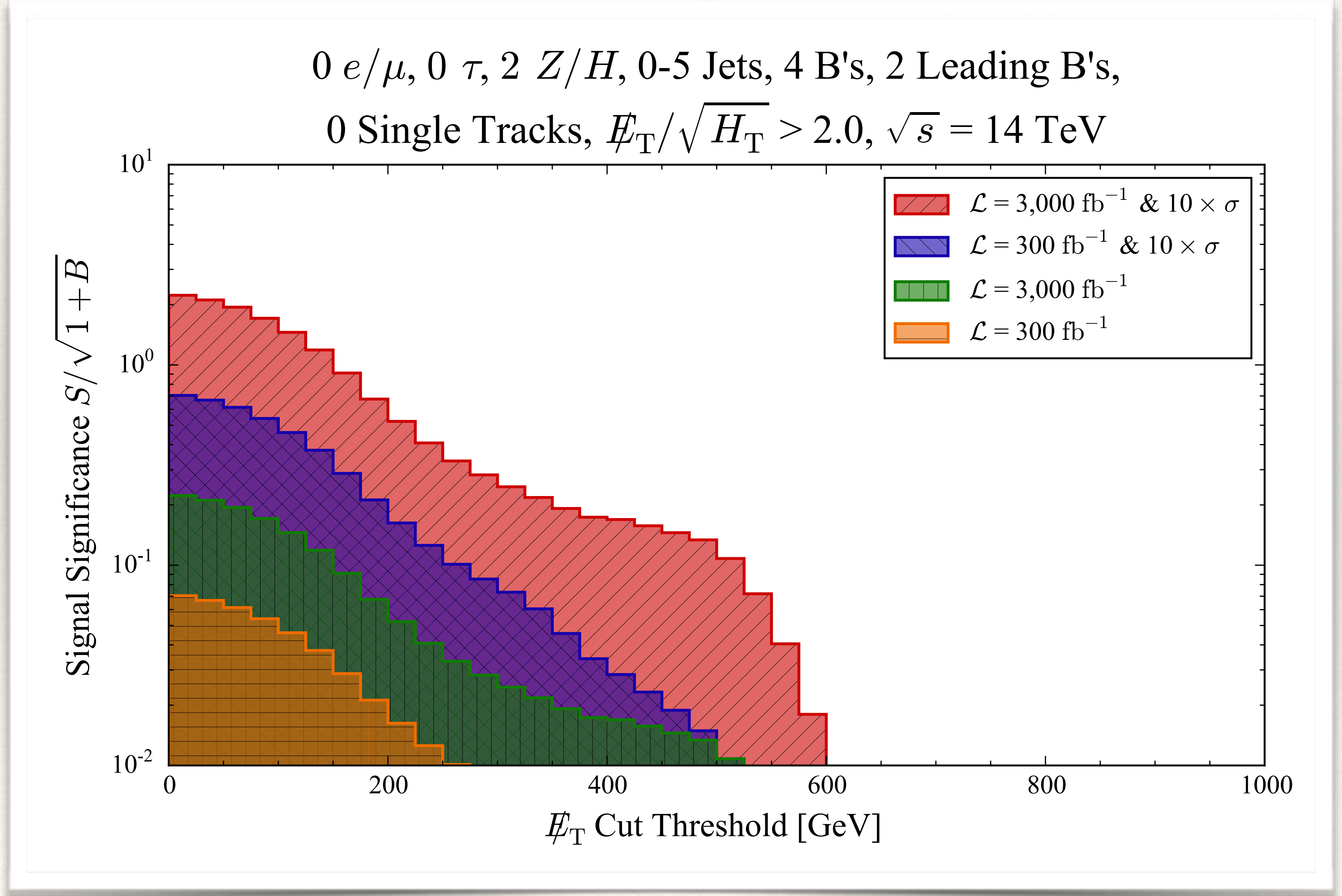
4 B-Tag Optimization

- The optimized selections reduce BG by ~ 2 magnitude orders, and signal by a factor close to 3, but BG still dominates.



4 B-Tag Visibility

- The 4b channel is not visible at 300/fb for the NMSSM benchmark or even with a 10X boost in both cross section and luminosity.



Artwork adapted from 4th century BC vase
Museum of Antiquities, Munich, Germany

“ Then spake Zeus: … ‘The cases are now indeed judged ill and it is because … many … who have wicked souls are clad in fair bodies and ancestry and wealth, and … the judges are confounded …, having their own soul muffled in the veil of eyes and ears and the whole body. … They must be stripped bare of all those things …, beholding with very soul the very soul of each immediately. … [I] have appointed sons of my own to be judges; two from Asia, **Minos** and **Rhadamanthus**, and one from Europe, **Aeacus**. These … shall give judgement in the meadow at the dividing of the road, whence are the two ways leading, one to the Isles of the Blest …, and the other to Tartaros.’ ”

– Plato, *Gorgias* (trans. Lamb)

Cutting with

AEACuS

(Algorithmic Event Arbiter and CUt Selector)

and Plotting with

RHADAMANTHUS

(Recursively Heuristic Analysis, Display, And MANipulation: The Histogram Utility Suite)

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MC4BSM, Fermi National Laboratory
May 18-20, 2015

With: Trenton Voth, Jesse Cantu, & William Ellsworth

Typical Process Flow

- **MadGraph (+ Others):** Matrix Element Generation
- **MadEvent (+ Others):** Hard Scattering Simulation
- **Pythia (+ Others):** Showering and Hadronization
- **DELPHES/PGS:** Detector Simulation
  (DEtector Level PHysics Emulation Software)
- **AEACUS:** Statistics Computation & Cut Selection
- **RHADAMANTHUS:** Graphical Event Analysis

Package Notes

- AEACuS and RHADAMANTHUS are written in Perl
- All Perl scripts are self contained - no libraries or installation
- RHADAMANTHUS calls the public Python MatPlotLib library
- Control is provided by simple reusable card files
- Directory structure is: "./Events" for input .lhco event files, "./Cards" for input cards, "./Cuts" & "./Plots" for output
- Cut with AEACuS: "`./aeacus.pl card_name event_name cross_section`"
- Plot with RHADAMANTHUS: "`./rhadamanthus.pl card_name`"

AEACuS (Goals)

- Automate model comparison against LHC data
- Replicate most current search strategies for new physics
- Embody lightweight, consumer-level, standalone design
- Decouple specific usage from general functionality
- Render event cut strategies compactly & unambiguously
- Merge power & flexibility with uniformity & simplicity
- Decouple phenomenology from software maintenance

AEACuS (Function)

- Reads from standardized LHCO format input
- Filters kinematics, geometry, isolation, charge & flavor
- Dilepton pair assembly (by like/unlike charge & flavor)
- Jet clustering (KT, C/A, Anti-KT) & Hemispheres (Lund, etc.)
- Missing E_T, scalar H_T, effective & invariant mass, ratios & products
- Transverse mass, 1- & 2-step asymmetric M_{T2} (with combinatorics), Tri-jet mass, α_T, Razor & α_R, Dilepton Z-balance, Lepton W-projection, $\Delta\phi$ (& biased $\Delta\phi^*$), Shape Variables (thrust & minor, spheri[o]city, F)

Cut Card Example

```
*** Object Reconstruction ****
        # ALL Jets
OBJ_JET_000 = PTM:30, PRM:[0.0,5.0], CUT:0
        # LEAD Jet
OBJ_JET_001 = SRC:+000, PRM:[0.0,2.5],
        CUT:[1,UNDEF,-1], OUT:PTM_001, ANY:0
        # SECOND Jet
OBJ_JET_002 = SRC:[+000,-001], PRM:[0.0,2.5],
        CUT:[1,UNDEF,-1], OUT:PTM_002, ANY:0
        # B-Tagged Jets
OBJ_JET_003 = SRC:+000, PRM:[0.0,2.5], HFT:0.5, CUT:0
        # Non-B Jets
OBJ_JET_004 = SRC:[+000,-003], PRM:[0.0,2.5], CUT:0
        # B-TAGS in Jets 1,2
OBJ_JET_005 = SRC:[+001,+002], HFT:0.5, CUT:0
        # Non-B Sub-Leading Jets
OBJ_JET_006 = SRC:[+000,-001,-002,-003],
        PRM:[0.0,2.5], CUT:0
        # 1 B-Tags in Z/Higgs Window
OBJ_JET_007 = SRC:+003, EFF:[WIN,92,20,126,20,1], CUT:0
        # 2 B-Tags in Z/Higgs Window
OBJ_JET_008 = SRC:+003, EFF:[WIN,92,20,126,20,2], CUT:0
        # 2 B-Tags in Higgs Window
OBJ_JET_009 = SRC:+003, EFF:[WIN,126,20,2], CUT:0
        # Single Track Jets
OBJ_JET_010 = SRC:+000, TRK:[1,1], CUT:0
        # Leading or B-Tagged Jets (No Output)
OBJ_JET_011 = SRC:[+001,+002,+003]
        # Nearest B-Tag Object Pair to Higgs Window
OBJ_JET_012 = SRC:+003, EFF:[OIM,126,UNDEF,-1]
        # Further B-Tag Object Pair from Higgs Window
OBJ_JET_013 = SRC:[+003,-012], EFF:[OIM,126,UNDEF,-1]
        # ALL Leptons
OBJ_LEP_000 = PTM:10, PRM:[0.0,2.5]
        # Light Soft Leptons
OBJ_LEP_001 = SRC:+000, EMT:-3, SDR:[0.3,UNDEF,1], CUT:0
        # Soft Taus
OBJ_LEP_002 = SRC:+000, EMT:+3, CUT:0
        # Light Hard Leptons
OBJ_LEP_003 = SRC:+001, PTM:20, CUT:0
        # Hard Taus
OBJ_LEP_004 = SRC:+002, PTM:20, CUT:0
        # 1 Lepton in Z Window
OBJ_LEP_005 = SRC:+001, EFF:[WIN,92,5], CUT:0
```

- Define hierarchical groupings of Jets & Leptons sorted on kinematics

```
        # Invariant Mass of Further Higgs Window Pair
EVT_OIM_002 = JET:013, OUT:1
        # Delta-R Separation of Nearest Higgs Window Pair
EVT_ODR_001 = JET:012, OUT:1
        # Delta-R Separation of Further Higgs Window Pair
EVT_ODR_002 = JET:013, OUT:1
****** Event Filtering *******
        # Category I: 4 Leptons, 0+ B-Jets
CUT_ESC_001 = KEY:LEP_001, CUT:4
CUT_ESC_002 = KEY:JET_003, CUT:0
CUT_CHN_001 = ESC:[+001,+002], OUT:"./Cuts/0b_4l"
        # Category II: 2-3 Leptons, 2+ B-Jets
CUT_ESC_003 = KEY:LEP_001, CUT:[2,3]
CUT_ESC_004 = KEY:JET_003, CUT:2
CUT_CHN_002 = ESC:[+003,+004], OUT:"./Cuts/2b_2l"
        # Category III: 0-1 Leptons, 4+ B-Jets
CUT_ESC_005 = KEY:LEP_001, CUT:[0,1]
CUT_ESC_006 = KEY:JET_003, CUT:4
CUT_CHN_003 = ESC:[+005,+006], OUT:"./Cuts/4b_0l"
```

Cut Card Example

- Compute statistics associated with referenced groups of kinematic objects, or with the event as a whole

```
              # B-TAGS in Jets 1,2
OBJ_JET_005 = SRC:[+001,+002], HFT:0.5, CUT:0
              # Non-B Sub-Leading Jets
OBJ_JET_006 = SRC:[+000,-001,-002,-003],
              PRM:[0.0,2.5], CUT:0
              # 1 B-Tags in Z/Higgs Window
OBJ_JET_007 = SRC:+003, EFF:[WIN,92,20,126,20,1], CUT:0
              # 2 B-Tags in Z/Higgs Window
OBJ_JET_008 = SRC:+003, EFF:[WIN,92,20,126,20,2], CUT:0
              # 2 B-Tags in Higgs Window
OBJ_JET_009 = SRC:+003, EFF:[WIN,126,20,2], CUT:0
              # Single Track Jets
OBJ_JET_010 = SRC:+000, TRK:[1,1], CUT:0
              # Leading or B-Tagged Jets (No Output)
OBJ_JET_011 = SRC:[+001,+002,+003]
              # Nearest B-Tag Object Pair to Higgs Window
OBJ_JET_012 = SRC:+003, EFF:[OIM,126,UNDEF,-1]
              # Further B-Tag Object Pair from Higgs Window
OBJ_JET_013 = SRC:[+003,-012], EFF:[OIM,126,UNDEF,-1]
              # ALL Leptons
OBJ_LEP_000 = PTM:10, PRM:[0.0,2.5]
              # Light Soft Leptons
OBJ_LEP_001 = SRC:+000, EMT:-3, SDR:[0.3,UNDEF,1], CUT:0
              # Soft Taus
OBJ_LEP_002 = SRC:+000, EMT:+3, CUT:0
              # Light Hard Leptons
OBJ_LEP_003 = SRC:+001, PTM:20, CUT:0
              # Hard Taus
OBJ_LEP_004 = SRC:+002, PTM:20, CUT:0
              # 1 Lepton in Z Window
OBJ_LEP_005 = SRC:+001, EFF:[WIN,92,5], CUT:0
```

```
****** Event Selection *******
              # MET-Jet Delta Phi (Leading+B-Tags)
EVT_MDP_001 = MET:000, JET:011, OUT:1
              # MET Significance MET / sqrt( HT )
EVT_RHR_001 = NUM:000, DEN:000, OUT:1
              # Invariant Mass of Nearest Higgs Window Pair
EVT_OIM_001 = JET:012, OUT:1
              # Invariant Mass of Further Higgs Window Pair
EVT_OIM_002 = JET:013, OUT:1
              # Delta-R Separation of Nearest Higgs Window Pair
EVT_ODR_001 = JET:012, OUT:1
              # Delta-R Separation of Further Higgs Window Pair
EVT_ODR_002 = JET:013, OUT:1
****** Event Filtering *******
              # Category I: 4 Leptons, 0+ B-Jets
CUT_ESC_001 = KEY:LEP_001, CUT:4
CUT_ESC_002 = KEY:JET_003, CUT:0
CUT_CHN_001 = ESC:[+001,+002], OUT:"./Cuts/0b_4l"
              # Category II: 2-3 Leptons, 2+ B-Jets
CUT_ESC_003 = KEY:LEP_001, CUT:[2,3]
CUT_ESC_004 = KEY:JET_003, CUT:2
CUT_CHN_002 = ESC:[+003,+004], OUT:"./Cuts/2b_2l"
              # Category III: 0-1 Leptons, 4+ B-Jets
CUT_ESC_005 = KEY:LEP_001, CUT:[0,1]
CUT_ESC_006 = KEY:JET_003, CUT:4
CUT_CHN_003 = ESC:[+005,+006], OUT:"./Cuts/4b_0l"
```

Cut Card Example

```
*** Object Reconstruction ****
              # ALL Jets
OBJ_JET_000 = PTM:30, PRM:[0.0,5.0], CUT:0
              # LEAD Jet
OBJ_JET_001 = SRC:+000, PRM:[0.0,2.5],
              CUT:[1,UNDEF,-1], OUT:PTM_001, ANY:0
              # SECOND Jet
OBJ_JET_002 = SRC:[+000,-001], PRM:[0.0,2.5],
              CUT:[1,UNDEF,-1], OUT:PTM_002, ANY:0
              # B-Tagged Jets
OBJ_JET_003 = SRC:+000, PRM:[0.0,2.5], HFT:0.5, CUT:0
              # Non-B Jets
OBJ_JET_004 = SRC:[+000,-003], PRM:[0.0,2.5], CUT:0
              # B-TAGS in Jets 1,2
OBJ_JET_005 = SRC:[+001,+002], HFT:0.5, CUT:0
```

- Create subclassifications of events matching certain selection criteria

```
OBJ_JET_010 = SRC:+000, TRK:[1,1], CUT:0
              # Leading or B-Tagged Jets (No Output)
OBJ_JET_011 = SRC:[+001,+002,+003]
              # Nearest B-Tag Object Pair to Higgs Window
OBJ_JET_012 = SRC:+003, EFF:[OIM,126,UNDEF,-1]
              # Further B-Tag Object Pair from Higgs Window
OBJ_JET_013 = SRC:[+003,-012], EFF:[OIM,126,UNDEF,-1]
              # ALL Leptons
OBJ_LEP_000 = PTM:10, PRM:[0.0,2.5]
              # Light Soft Leptons
OBJ_LEP_001 = SRC:+000, EMT:-3, SDR:[0.3,UNDEF,1], CUT:0
              # Soft Taus
OBJ_LEP_002 = SRC:+000, EMT:+3, CUT:0
              # Light Hard Leptons
OBJ_LEP_003 = SRC:+001, PTM:20, CUT:0
              # Hard Taus
OBJ_LEP_004 = SRC:+002, PTM:20, CUT:0
              # 1 Lepton in Z Window
OBJ_LEP_005 = SRC:+001, EFF:[WIN,92,5], CUT:0
```

```
****** Event Selection *******
              # MET-Jet Delta Phi (Leading+B-Tags)
EVT_MDP_001 = MET:000, JET:011, OUT:1
              # MET Significance MET / sqrt( HT )
EVT_RHR_001 = NUM:000, DEN:000, OUT:1
              # Invariant Mass of Nearest Higgs Window Pair
EVT_OIM_001 = JET:012, OUT:1
              # Invariant Mass of Further Higgs Window Pair
EVT_OIM_002 = JET:013, OUT:1
              # Delta-R Separation of Nearest Higgs Window Pair
EVT_ODR_001 = JET:012, OUT:1
              # Delta-R Separation of Further Higgs Window Pair
EVT_ODR_002 = JET:013, OUT:1
****** Event Filtering *******
              # Category I: 4 Leptons, 0+ B-Jets
CUT_ESC_001 = KEY:LEP_001, CUT:4
CUT_ESC_002 = KEY:JET_003, CUT:0
CUT_CHN_001 = ESC:[+001,+002], OUT:"./Cuts/0b_4l"
              # Category II: 2-3 Leptons, 2+ B-Jets
CUT_ESC_003 = KEY:LEP_001, CUT:[2,3]
CUT_ESC_004 = KEY:JET_003, CUT:2
CUT_CHN_002 = ESC:[+003,+004], OUT:"./Cuts/2b_2l"
              # Category III: 0-1 Leptons, 4+ B-Jets
CUT_ESC_005 = KEY:LEP_001, CUT:[0,1]
CUT_ESC_006 = KEY:JET_003, CUT:4
CUT_CHN_003 = ESC:[+005,+006], OUT:"./Cuts/4b_0l"
```

AEACuS Output

1000000 EVENTS PROCESSED IN TOTAL

5.316e-02 PB EVENT CROSS SECTION YIELDS 1.881e+07 PER PB LUMINOSITY

RESCALING BY 5.316e-04 TO TARGET LUMINOSITY OF 1.000e+04 PER PB

5.316e+02 SCALED EVENTS SURVIVE ALL CUTS WITH AN EFFECTIVE CROSS SECTION OF 5.316e-02 PB

000.000 % OF EVENTS CUT

CUT ID	% CUT	% SOLO
LEP_001	000.000	000.000
LEP_002	000.000	000.000
LEP_003	000.000	000.000
LEP_004	000.000	000.000
LEP_005	000.000	000.000
JET_000	000.000	000.000
JET_001	000.000	000.000
JET_002	000.000	000.000
JET_003	000.000	000.000
JET_004	000.000	000.000
JET_005	000.000	000.000
JET_006	000.000	000.000
JET_007	000.000	000.000
JET_008	000.000	000.000
JET_009	000.000	000.000
JET_010	000.000	000.000

INDIVIDUAL PASSING EVENT STATISTICS

EVENT_#	LEP_001	LEP_002	LEP_003	LEP_004	LEP_005	JET_000	JET_001	JET_002	JET_003	JET_004	JET_005	JET_006	JET_007	JET_008	JET_009	JET_010	PTM_001	PTM_002	MET_000	OIM_001	OIM_002	ODR_001	ODR_002	MDP_001
0003160	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	36.6	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0005003	4	0	3	0	1	2	1	1	0	2	0	0	0	0	0	0	76.1	72.2	173.0	UNDEF	UNDEF	UNDEF	UNDEF	1.834
0005115	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	37.6	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0005211	4	0	3	0	0	2	1	1	0	2	0	0	0	0	0	0	94.6	82.0	77.9	UNDEF	UNDEF	UNDEF	UNDEF	1.425
0007055	4	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	31.1	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0007418	4	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	104.3	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0008111	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	125.0	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0008333	4	0	4	0	1	1	1	0	0	1	0	0	0	0	0	0	36.4	UNDEF	27.7	UNDEF	UNDEF	UNDEF	UNDEF	0.175
0009493	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	111.8	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0009898	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	83.2	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0010023	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	108.3	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0010092	4	0	4	0	1	2	1	1	0	2	0	0	0	0	0	0	88.6	36.9	105.7	UNDEF	UNDEF	UNDEF	UNDEF	1.028
0010131	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	127.7	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0010219	4	0	4	0	1	2	1	0	0	1	0	0	0	0	0	1	79.0	UNDEF	46.5	UNDEF	UNDEF	UNDEF	UNDEF	2.291
0011575	4	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	93.9	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0013805	4	0	4	0	1	2	1	1	0	2	0	0	0	0	0	0	123.5	36.5	92.3	UNDEF	UNDEF	UNDEF	UNDEF	1.640
0015150	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	60.7	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF

- Basically, output is a spreadsheet reporting requested statistics & cut fractions
- It is often convenient to make no cuts at the lowest level, but only to compute
- Names such as "JET_001" have no invariant meaning - they are defined in a card_file

Plot Card Example

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"

PLT_CHN_001 = DAT:[001,002,003], KEY:MET_000

PLT_HST_001 =
        IFB:300,
        CHN:001,
        LFT:0, RGT:1000, SPN:25,
        MIN:0.001, MAX:UNDEF,
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$ with $0^+$ B-Jets, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[
               "$t\overline{t}+$ 0-2 Jets",
               "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
               "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

Plot Card Example

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"
```

- Data Sets are built out of groups of ".cut" files from AEACuS
- Wildcards "*" are allowed to match multiple files
- Cross-sections are imported automatically
- Files with common trailing digits (name_NNN.cut) are averaged
- Files with unique names are summed

```
                "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

Plot Card Example

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"

PLT_CHN_001 = DAT:[001,002,003], KEY:MET_000
```

- Channels are built out of groups of datasets
- The plotting key refers to a statistic computed by AEACuS

```
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$ with $0^+$ B-Jets, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[
                "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

Plot Card Example

- Histograms are built out of groups of channels
- Line continuation is indicated simply by indentation
- The luminosity may be specified in "IPB", "IFB", "IAB", etc.

```
PLT_HST_001 =
        IFB:300,
        CHN:001,
        LFT:0, RGT:1000, SPN:25,
        MIN:0.001, MAX:UNDEF,
        SUM:-1, NRM:0, AVG:3,
```

- By default, events are oversampled and scaled down to the target luminosity
- There is a warning on scale factors < 1
- Optionally specify trim at exact luminosity "IFB:[300,-1]"
- Bins are specified by "LFT" = left, "RGT" = right, "SPN" = bin span
- Optionally "BNS" = number of bins may be used instead of one prior
- "MIN" and "MAX" provide optional manual limits on range

Plot Card Example

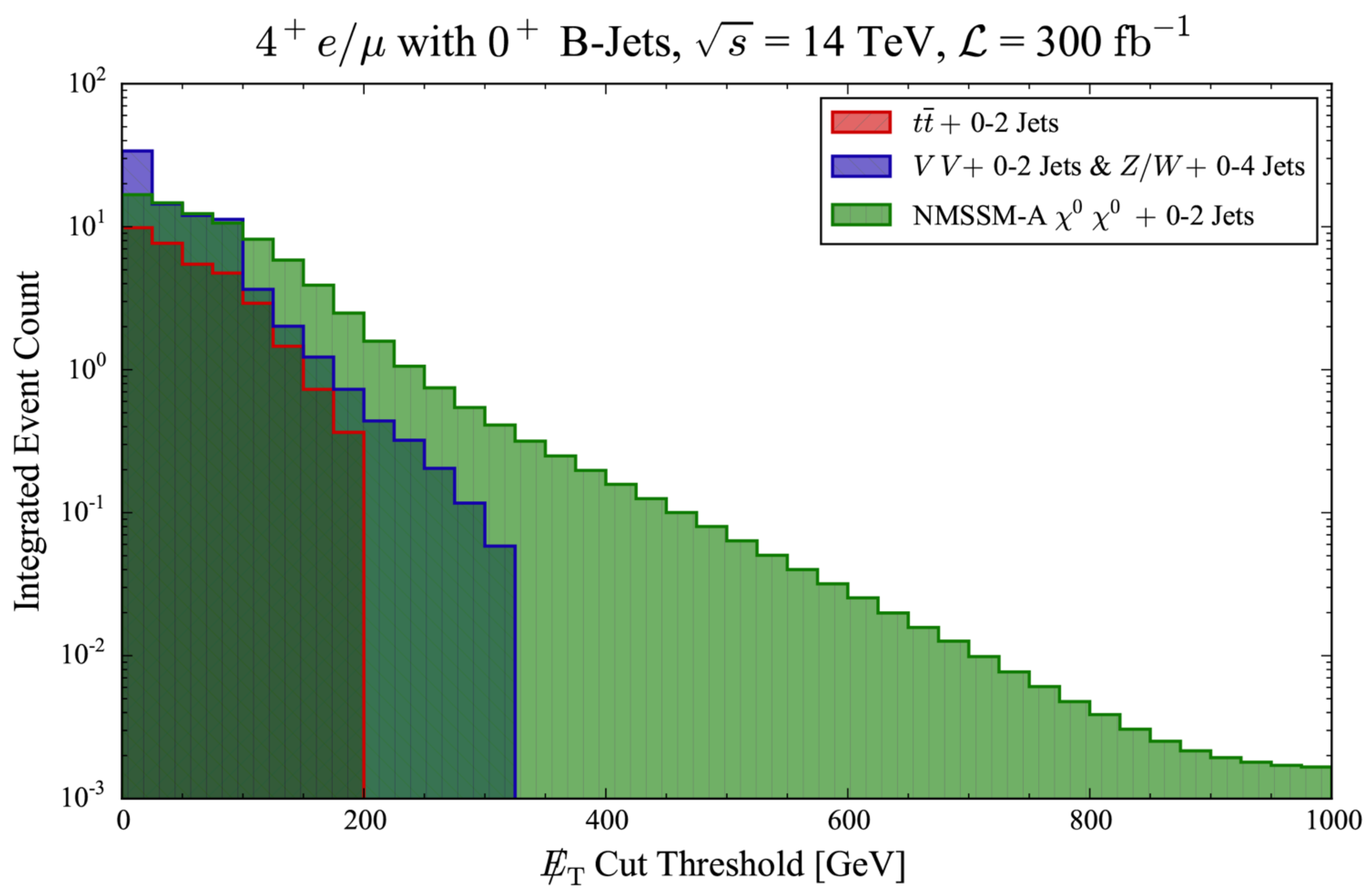
```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
```

- SUM +/- 1 compound bin counts to the right/left for threshold plots
- NRM facilitates normalization as for shape plots
- AVG engages bin smoothing with preservation of integrated counts
- LOG = 1/0 enables/disables logarithmic dependent axis

```
        MIN:0.001, MAX:UNDEF,
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$ with $0^+$ B-Jets, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[
                "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

- Inline LaTeX is used to input formulas for title, axis labels, and legends
- Several preconfigured notations are accessible via shorthand
- Available vector output formats include publication quality “EPS” & “PDF”
- Optionally specify intermediate Python source output “FMT:[PDF,1]”

Plot Output



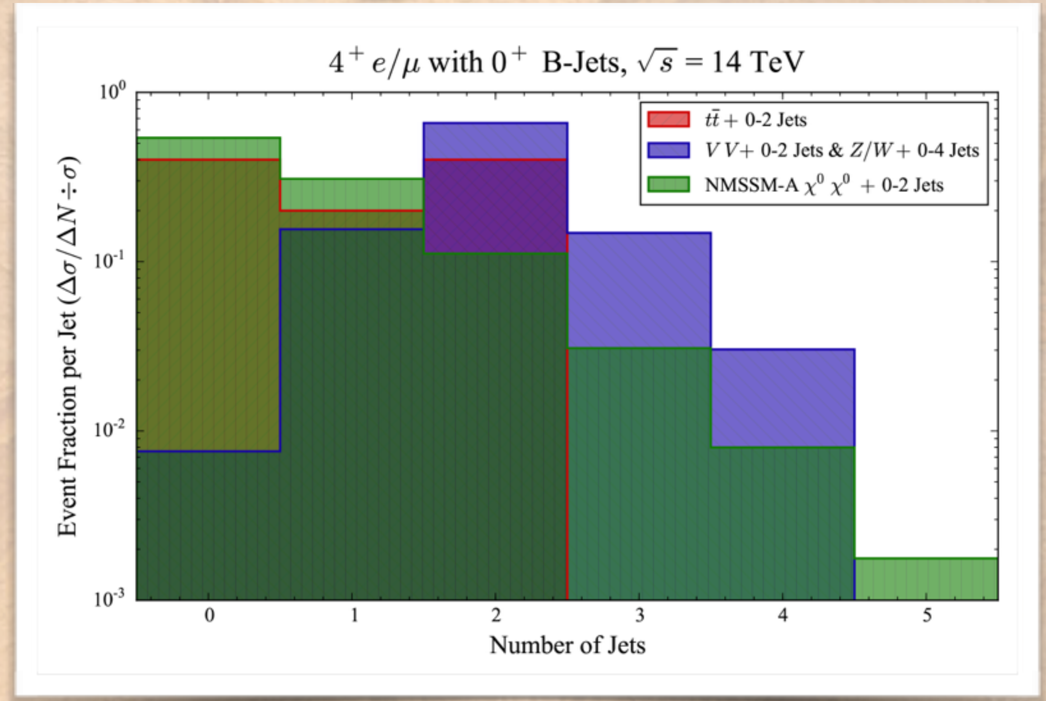
$4^+ \ e/\mu$ with 0^+ B-Jets, $\sqrt{s} = 14$ TeV, $\mathcal{L} = 300$ fb^{-1}
$t\bar{t}+$ 0-2 Jets
$VV+$ 0-2 Jets & $Z/W+$ 0-4 Jets
NMSSM-A $\chi^0\ \chi^0$ + 0-2 Jets
Integrated Event Count
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
1000
$\not\!\!E_T$ Cut Threshold [GeV]

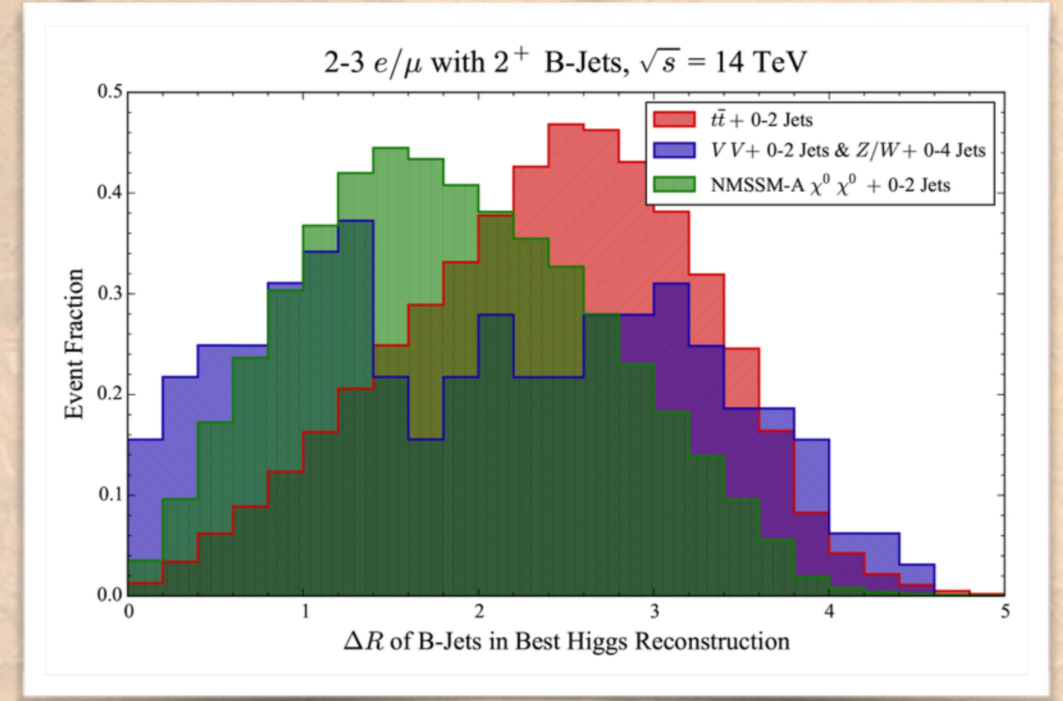
Optimize By Shape

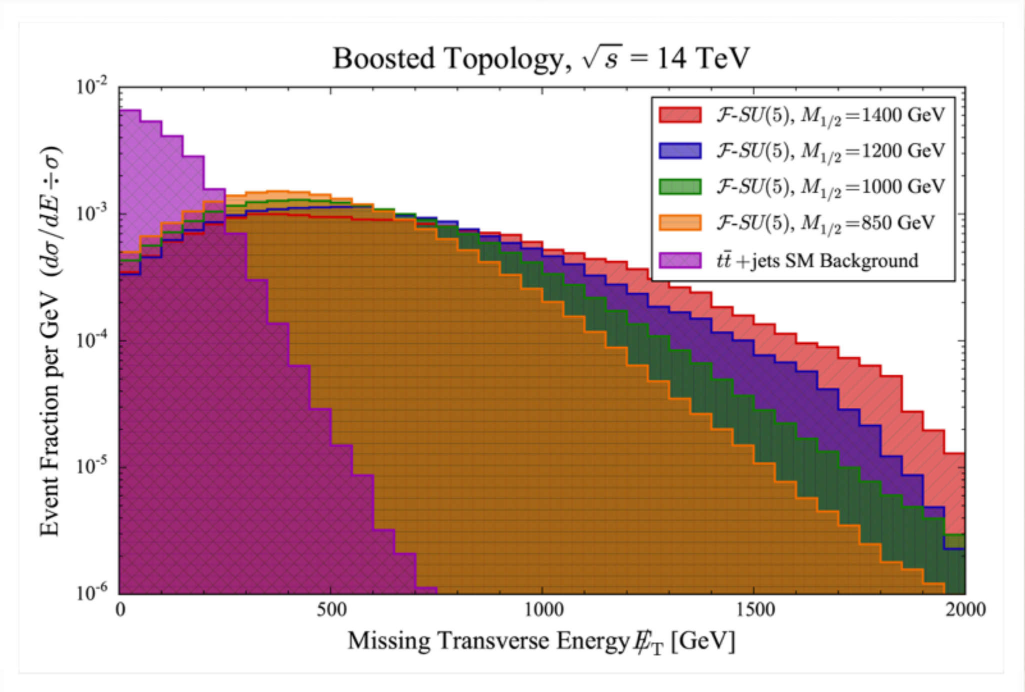
```
PLT_DAT_001 = DIR:"./Cuts", FIL:"Forward:BG:MEG:TTBAR_*"
PLT_DAT_002 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:850_*"
PLT_DAT_003 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:1000_*"
PLT_DAT_004 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:1200_*"
PLT_DAT_005 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:1400_*"

PLT_CHN_001 = DAT:[005,004,003,002,001], KEY:MET_000

PLT_HST_
        MIN:0.000001, MAX:UNDEF,
        SUM:0, NRM:1, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"Boosted Topology, <RTS> = 14 TeV",
        LBL:[   "Missing Transverse Energy <MET> [GeV]",
                "Event Fraction per GeV  (<DEF>)" ],
        LGD:[   "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1400$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1200$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 850$ GeV",
                "$t\overline{t}+$jets SM Background" ],
        OUT:"./Plots", NAM:"met_shape_boosted_30", FMT:"PDF"
```

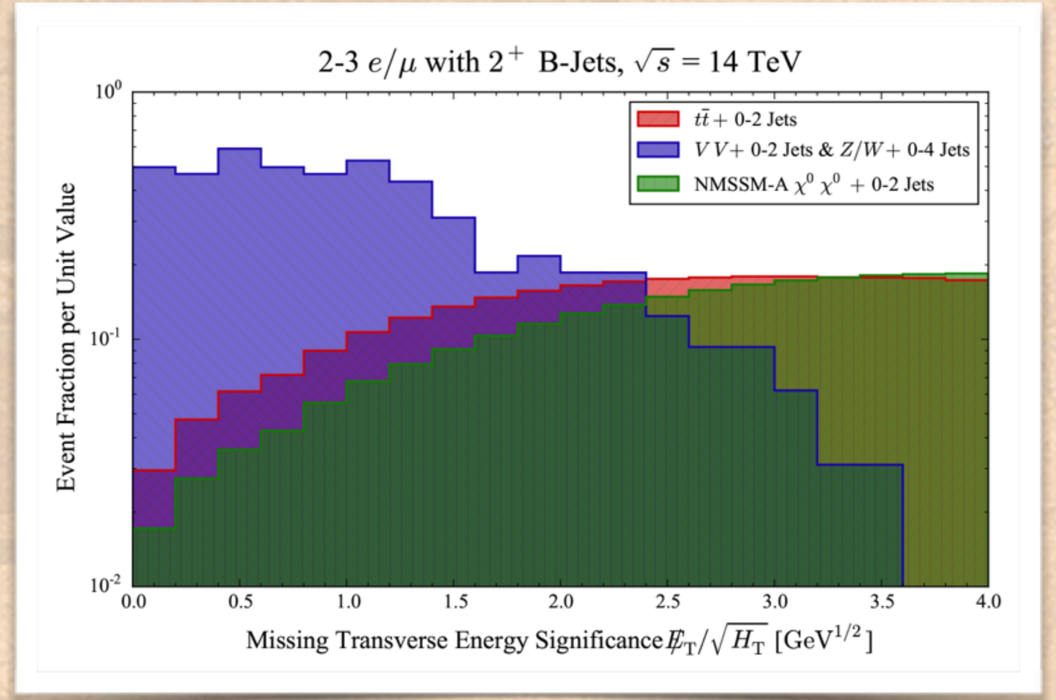
- Shape plots are unit normalized
- Bins are not left/right compounded

Optimize By Shape









Apply Selection Cuts

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"

PLT_ESC_001 = KEY:LEP_002, CUT:[0,0] # Veto Taus
PLT_ESC_002 = KEY:LEP_005, CUT:1     # Force 1 Lepton pair in Z Window
PLT_ESC_003 = KEY:JET_000, CUT:[0,1] # Veto 2+ Jets
PLT_ESC_004 = KEY:JET_003, CUT:[0,0] # Veto B's

PLT_CHN_003 = DAT:[001,002,003], KEY:MET_000, ESC:[+001,+002,+003,+004]
```

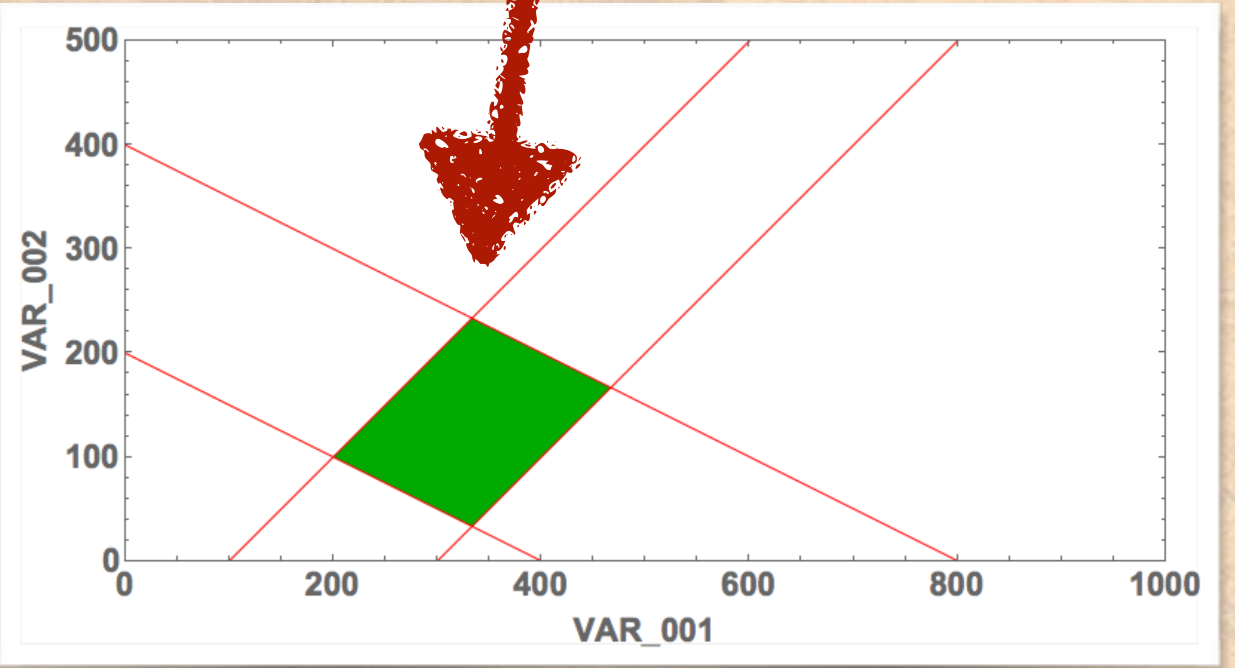
- Event Selection Cuts (ESC) are registered by AEACus key and range
- Channels may subscribe to any number of registered cuts

```
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$, $0\,\tau$, $1^+Z$, 0-1 Jets, 0 B's, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[   "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_OPT_0b_4l_300", FMT:"PDF"
```

Transform Event Keys

```
        # Azimuthal Separation of two 4-vectors in range 0 to Pi
PLT_CHN_001 = DAT:[001,002,003], KEY:{PI()-ABS(PI()-ABS($2-$1)),PHI_001,PHI_002}

        # Compound rhomboid selection region in two variables
PLT_ESC_001 = KEY:{$2-$1,VAR_001,VAR_002}, CUT:[-300,-100]
PLT_ESC_002 = KEY:{$2+$1/2,VAR_001,VAR_002}, CUT:[200,400]
```

- User-defined compound functions of event keys are allowed for event selection and for specification of the independent plotting variable
- Available functions include basic arithmetic, trigonometry, roots, powers, logarithms, exponentials, min, max, integer, modulus, and average



Transform Bin Channels

- User-defined functions of binned channels are allowed for specification of the dependent plotting variable
- Internal histogram object transparently applies the specified functional transformation bin-by-bin
- Channels with multiple data sets iterate automatically
- Single data sets expand to match large dimensionalities

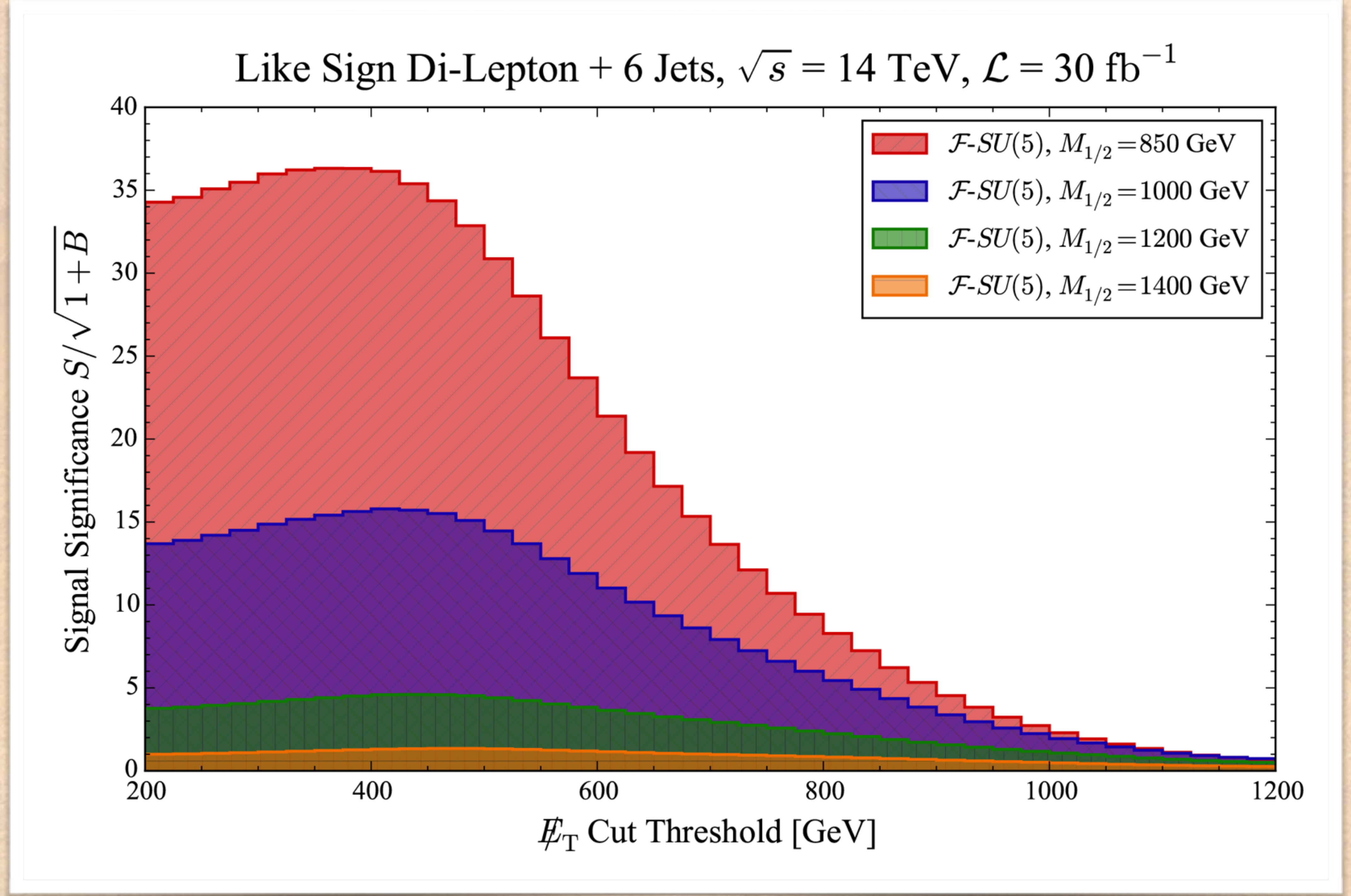
Transform Bin Channels

```
PLT_DAT_001 = DIR:"./Cuts_LSD", FIL:"Jets:BG:MEG:TTBAR_*"
PLT_DAT_002 = DIR:"./Cuts_LSD", FIL:"Jets:FSU5_VBF_25:850_*"
PLT_DAT_003 = DIR:"./Cuts_LSD", FIL:"Jets:FSU5_VBF_25:1000_*"
PLT_DAT_004 = DIR:"./Cuts_LSD", FIL:"Jets:FSU5_VBF_25:1200_*"
PLT_DAT_005 = DIR:"./Cuts_LSD", FIL:"Jets:FSU5_VBF_25:1400_*"

PLT_ESC_001 = KEY:PTM_001, CUT:400
PLT_ESC_002 = KEY:PTM_002, CUT:200
PLT_ESC_003 = KEY:JET_003, CUT:4
PLT_ESC_004 = KEY:JET_004, CUT:2
PLT_ESC_005 = KEY:JET_001, CUT:6

        # One-dimensional background channel
PLT_CHN_001 = DAT:[001], KEY:MET_000, ESC:[+001,+002,+003,+004,+005]
        # Four-dimensional signal channel
PLT_CHN_002 = DAT:[002,003,004,005], KEY:MET_000, ESC:[+001,+002,+003,+004,+005]

PLT_HST_002 =
        IFB:30,
        CHN:{$2/SRT(1+$1),001,002},
        LFT:200, RGT:1200, SPN:25, BNS:UNDEF,
```

- Signal significance is computed here by combining Signal & BG
- Signal and BG use same key and subscribe to identical event selection cuts
- The single BG Channel is expanded to match four Signal Channels

```
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1200$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1400$ GeV" ],
        OUT:"./Plots", NAM:"met_sig_LSD_30", FMT:"PDF"
```

Transform Bin Channels



Transform Bin Channels

```
PLT_DAT_001 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_25:1000_*"
PLT_DAT_002 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_15:1000_*"
PLT_DAT_003 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_6:990_*"

PLT_ESC_001 = KEY:PTM_001, CUT:400    # Leading P_T Cut
PLT_ESC_002 = KEY:PTM_002, CUT:200    # Sub-leading P_T Cut
PLT_ESC_003 = KEY:MET_000, CUT:700    # MET Cut
PLT_ESC_004 = KEY:DIL_001, CUT:1      # Same Sign Dilepton
PLT_ESC_005 = KEY:DIL_002, CUT:1      # Opposite Sign Dilepton

PLT_CHN_001 = DAT:[001,002,003], KEY:OIM_001, ESC:[+001,+002,+003,+004]
PLT_CHN_002 = DAT:[001,002,003], KEY:OIM_001, ESC:[+001,+002,+003,+005]

PLT_HST_001 =
        IFB:UNDEF,
        CHN:{($2-$1),001,002},

        OUT:"./Plots", NAM:"mtt_OS-LS_shape_DeltaM", FMT:"PDF"
```

- Opposite- minus Like-Sign dilepton counts are binned on invariant mass
- The signal is compared to itself, subscribing to different selection cuts
- The operation is repeated over each of three registered data sets
- There is an internal limiter ensuring positive semi-def bin values

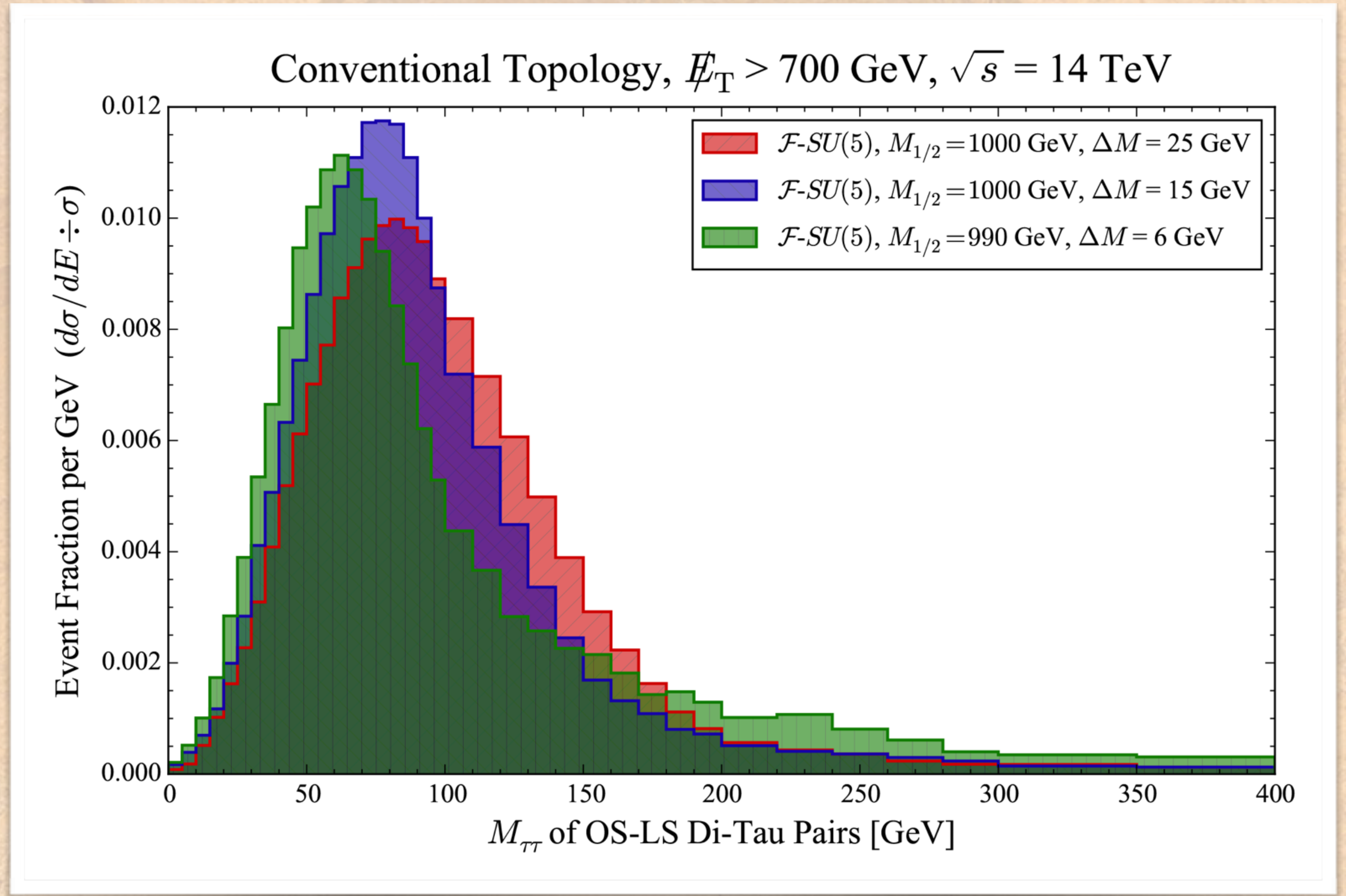
Transform Bin Channels

```
PLT_DAT_001 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_25:1000_*"
PLT_DAT_002 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_15:1000_*"
PLT_DAT_003 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_6:990_*"

PLT_ESC_001 = KEY:PTM_001, CUT:400    # Leading P_T Cut
```

- This example also demonstrates variable width binning
- Counts in wide bins are automatically scaled to preserve axis units
- The bin smoothing width “AVG” is set independent for each data set

```
PLT_HST_001 =
        IFB:UNDEF,
        CHN:{($2-$1),001,002},
        LFT:0, RGT:[100,200,300,400], SPN:[5,10,20,50]
        MIN:0.0, MAX:UNDEF,
        SUM:0, NRM:1, AVG:[3,3,4],
        LOG:0, LOC:0, CLR:0,
        TTL:"Conventional Topology,  <MET> > 700 GeV, <RTS> = 14 TeV",
        LBL:[   "$M_{\tau \tau}$ of OS-LS Di-Tau Pairs [GeV]",
                "Event Fraction per GeV  (<DEF>)" ],
        LGD:[   "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV, $\Delta M$ = 25 GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV, $\Delta M$ = 15 GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 990$ GeV, $\Delta M$ = 6 GeV" ],
        OUT:"./Plots", NAM:"mtt_OS-LS_shape_DeltaM", FMT:"PDF"
```

Transform Bin Channels



RHADAMANTHUS

(Recursively Heuristic Analysis, Display, And MANipulation: The Histogram Utility Suite)

- Heuristic *adjective* \ hyü-'ris-tik \ (www.merriam-webster.com)

  : using experience to learn and improve :

  involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods <*heuristic* techniques> <a *heuristic* assumption>; *also* : of or relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance <a *heuristic* computer program>
- The package is now ready to use - Use address below next week.
- `http://joelwalker.net/code/aeacus.tar.gz`
- Please contact author directly: `jwalker@shsu.edu`
- Full documentation and availability via web are pending

MINOS ?

(Maximally INdependent Optimization of Statistics)

- Analyze sequential cut flows
- Compute correlation metric of high dimension cut space
- Iteratively optimize on specified significance measure
- Automatically converge on event selection with maximal discrimination and minimal covariance
- Stay Tuned …