Dark Matter and BSM Searches Highlights at ATLAS and CMS

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For the ATLAS and CMS Collaborations

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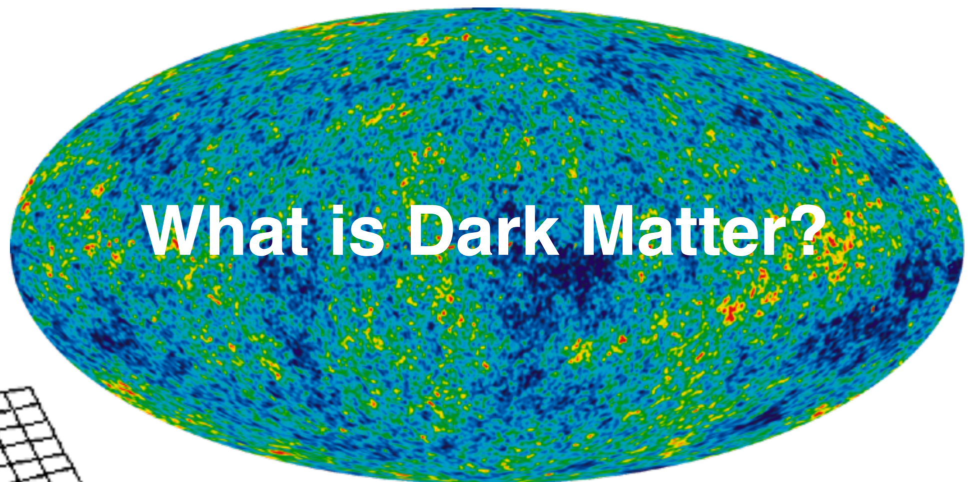
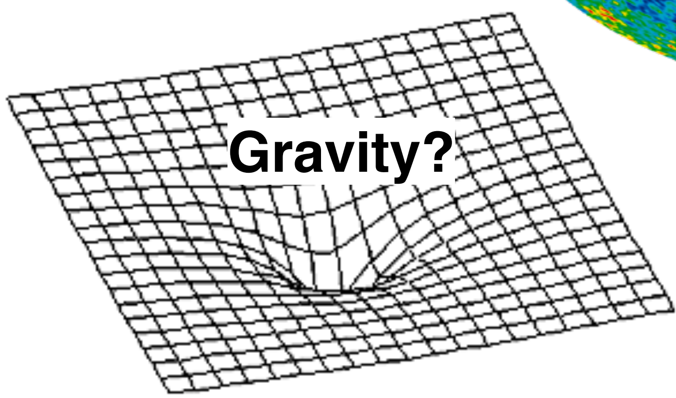
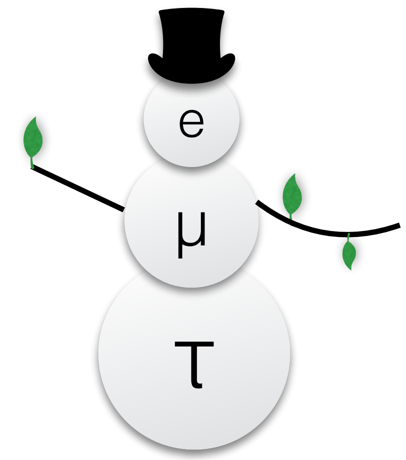
Standard Model Mysteries

Many mysteries remain unexplained by the Standard Model



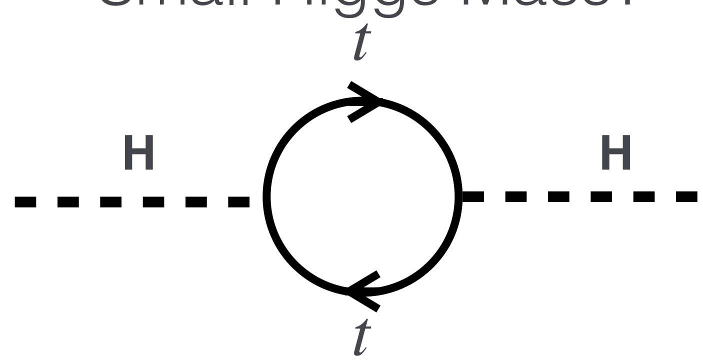


3 fermion generations?

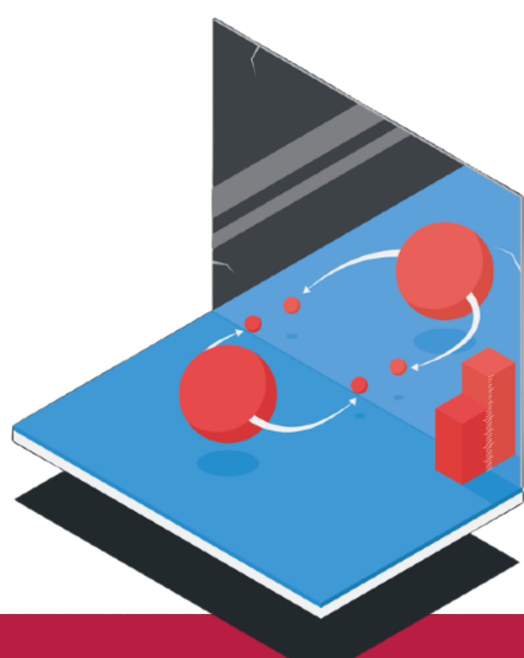


lepton-flavor-universality?

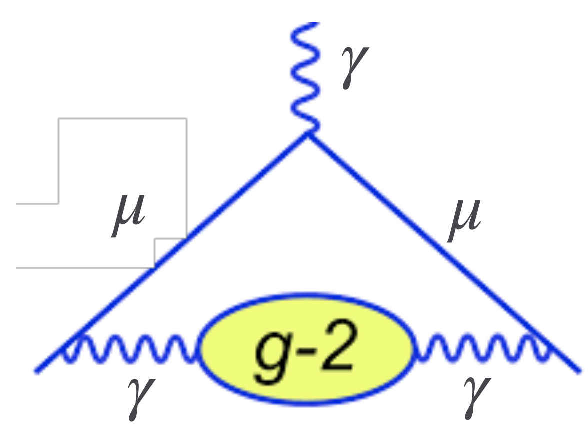
Small Higgs Mass?



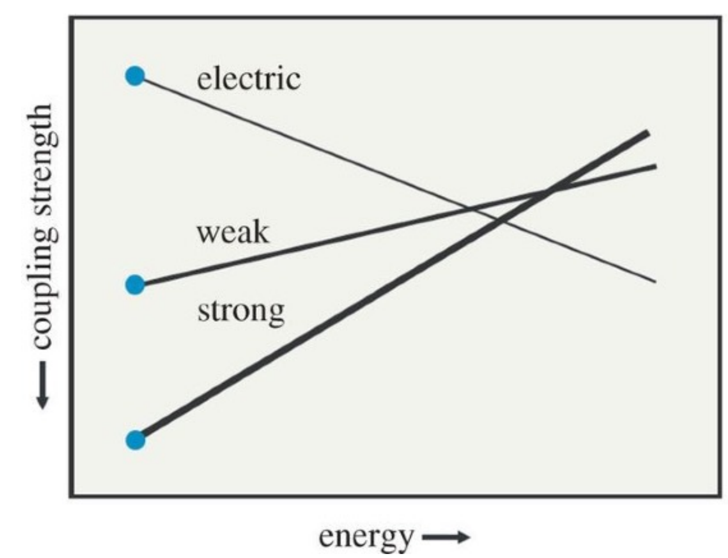
Matter-antimatter asymmetry?



g-2 anomaly?



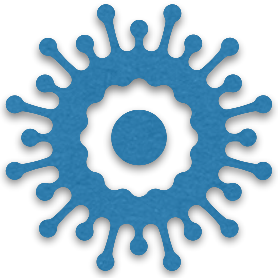
Force unification?



Exciting time for Particle Exploration!

- Massively interesting dataset from LHC between 2015 and 2018
  - Roughly 140 fb^{-1} of $\sqrt{s}$=13 TeV data collected by both ATLAS & CMS, thanks to impressive LHC operation & high data-taking efficiency of both experiments
- Facilitates a rich program of exploration for new physics, even amidst the pandemic

Don't want to discover more of these

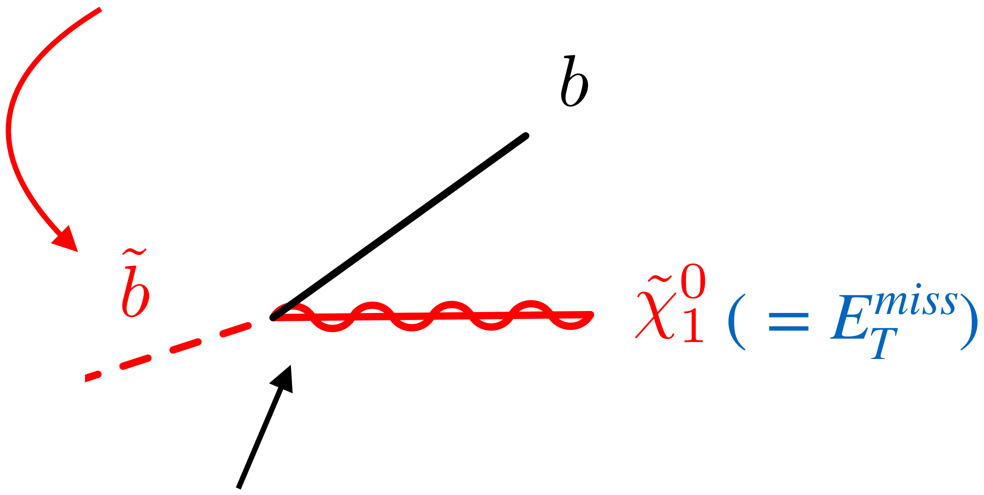


Plentiful Guidance from BSM Models

Supersymmetry

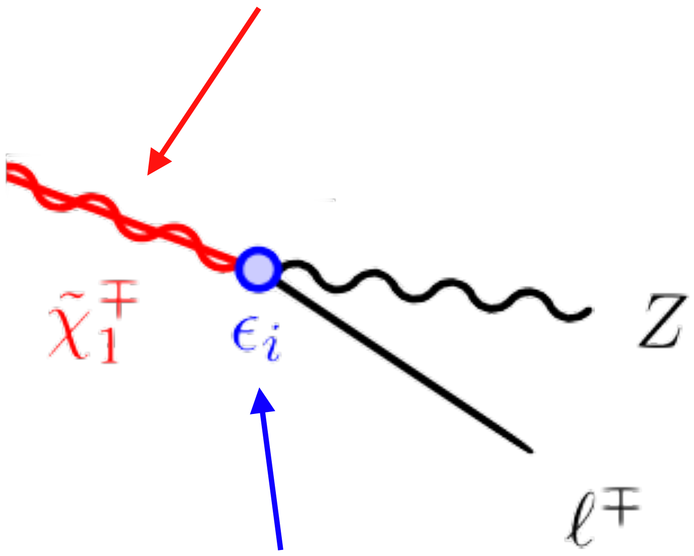
- Elegant solutions to SM mysteries
- Still plenty of phase-space to be hiding

Strong production



R-parity conservation
Stable & invisible LSP (Lightest SUSY Particle)

Electroweak production (rare!)



R-parity violation
Fantastic decays

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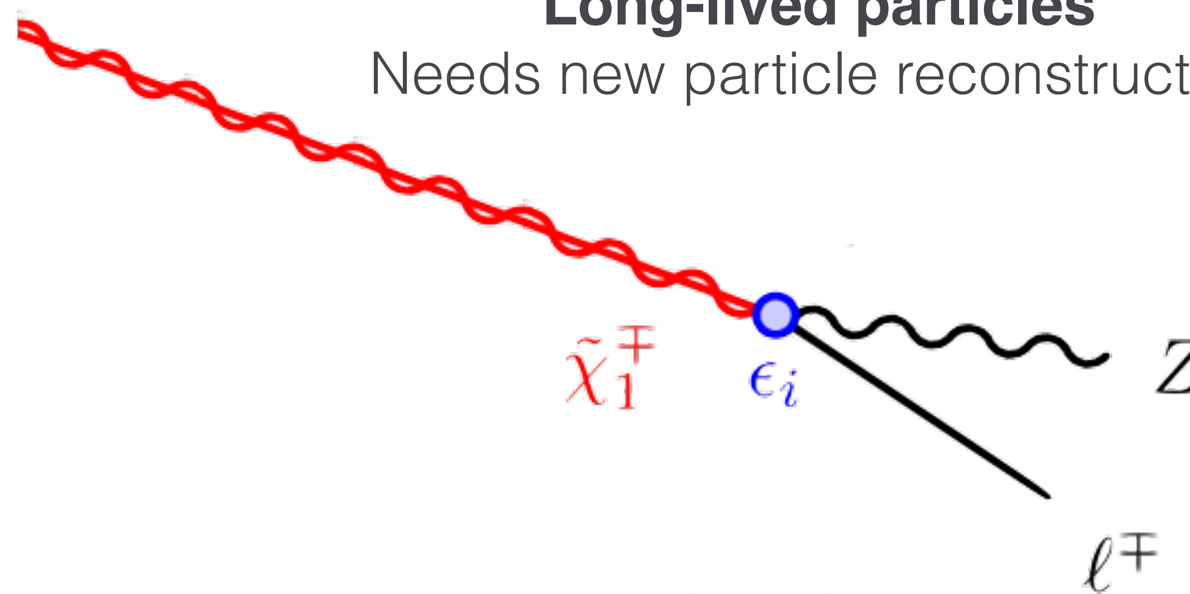
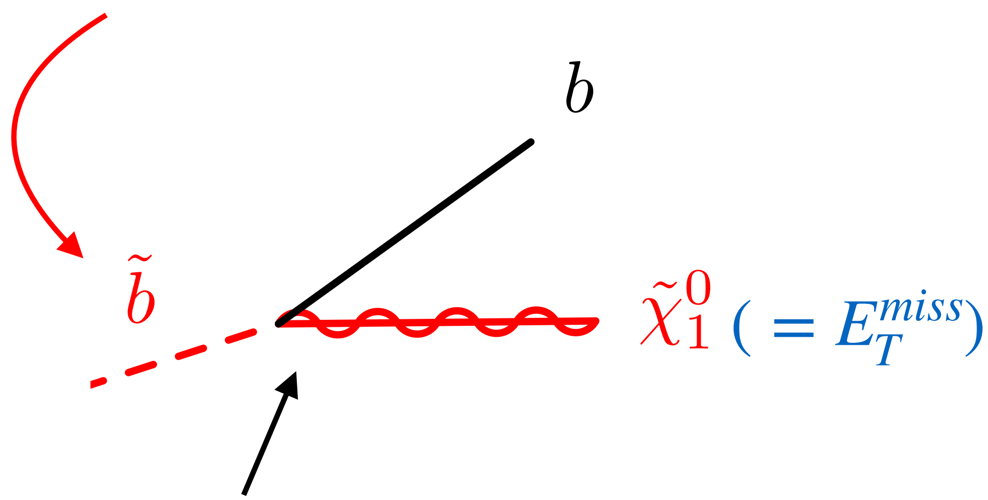
- Elegant solutions to SM mysteries
- Still plenty of phase-space to be hiding

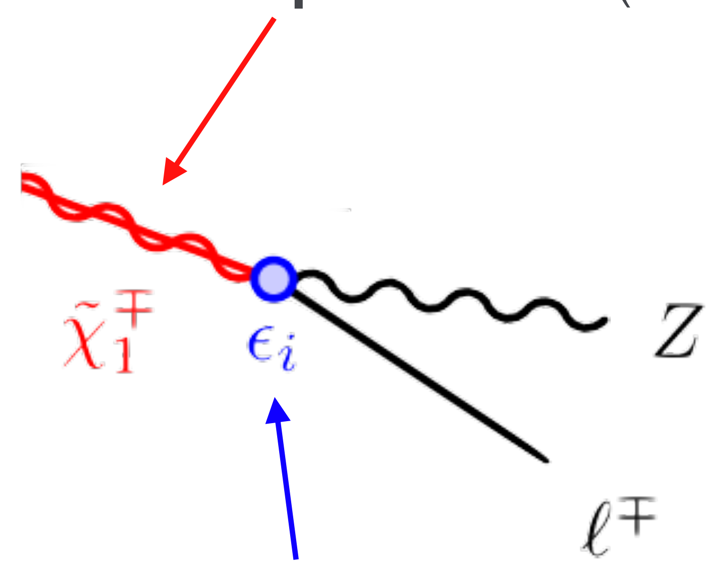
Long-lived particles
Needs new particle reconstruction



Strong production



Electroweak production (rare!)



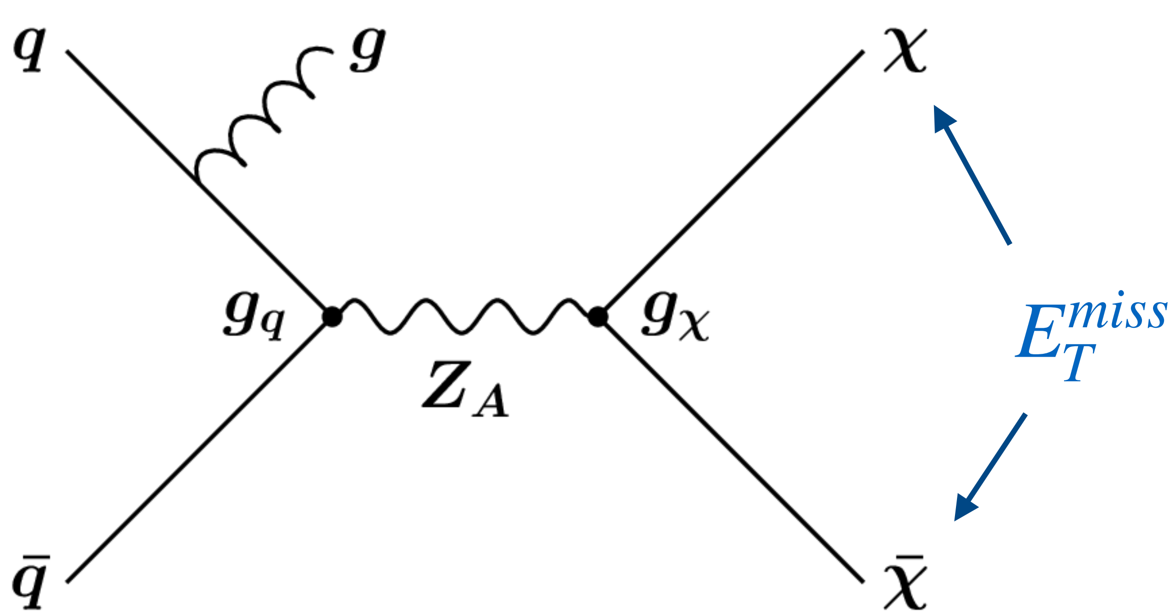
R-parity conservation
Stable & invisible LSP (Lightest SUSY Particle)

R-parity violation
Fantastic decays

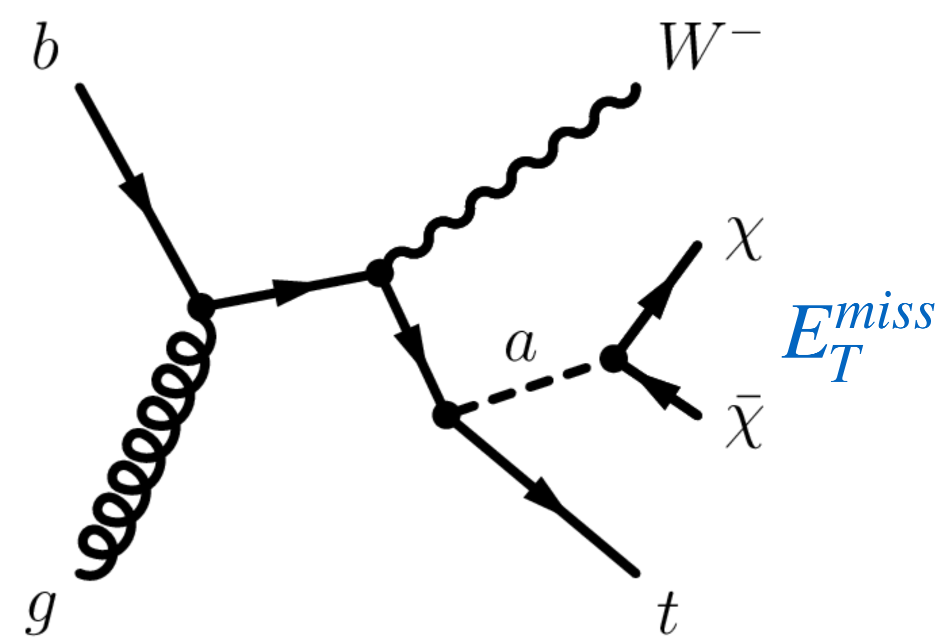
Plentiful Guidance from BSM Models

Exotic Beyond-the-SM Physics

- Immense number of models inspiring many searches



DM+X visible only by initial-state radiation…



…or more complex final-states

Plentiful Guidance from BSM Models

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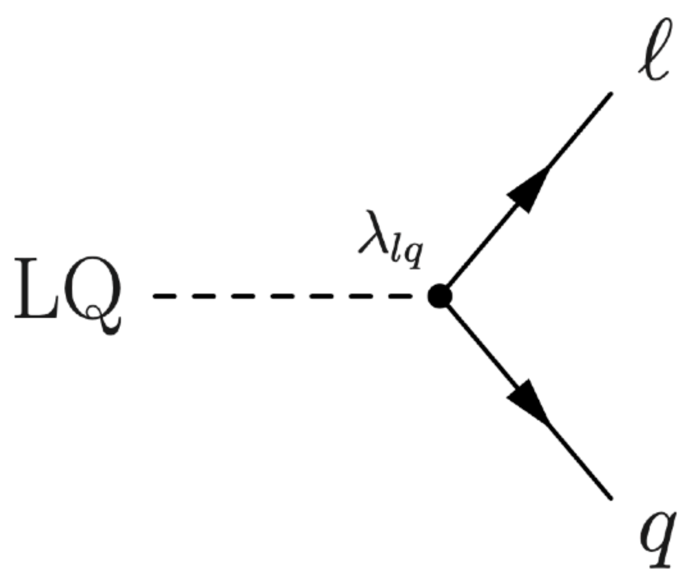
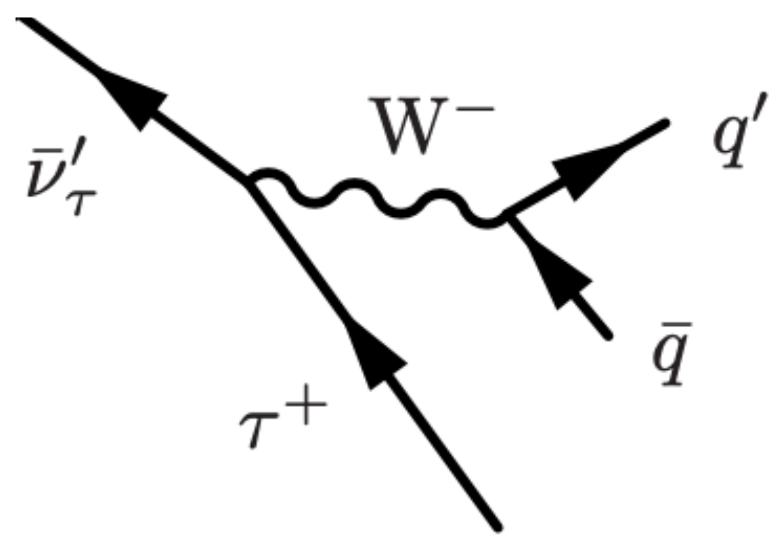


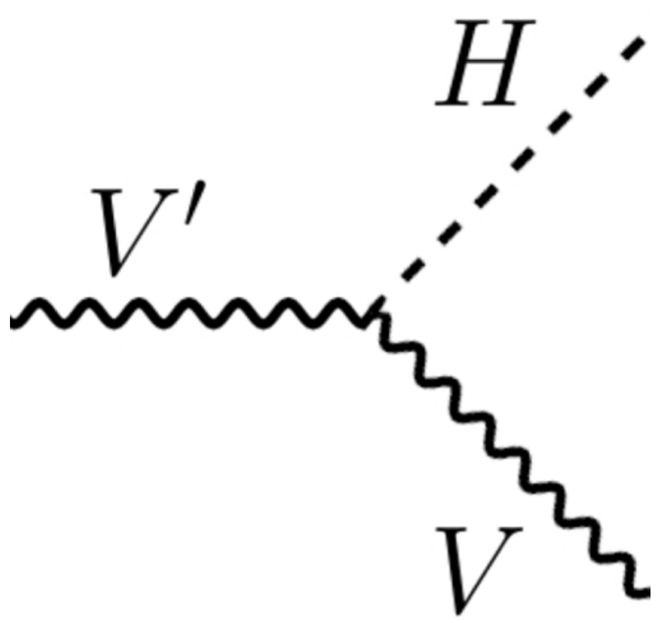
Leptoquarks
Fantastic lepton+quark decays



Vector-like fermions
Fantastic boson + fermion decays

and much more (Composite Fermions, LLPs, Heavy Resonances, …)

Plentiful Guidance from BSM Models

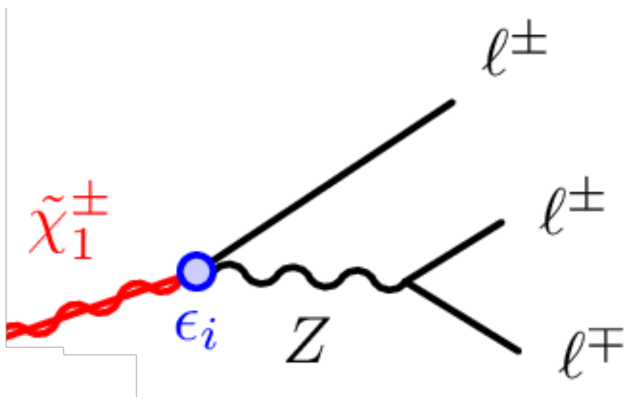


New Resonance Decays to Heavy SM Particles

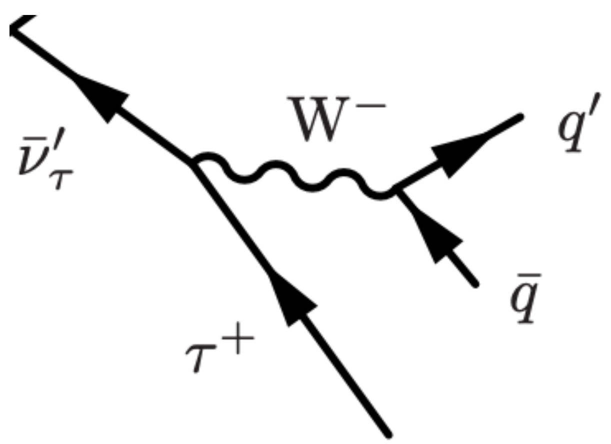
- CMS "Beyond-2-Generations" and ATLAS "Higgs & DiBoson Searches" groups
- Focus on new resonances with **boosted decays to top-quarks, *W*, *Z*, & Higgs**

Plentiful Guidance from BSM Models

Supersymmetry

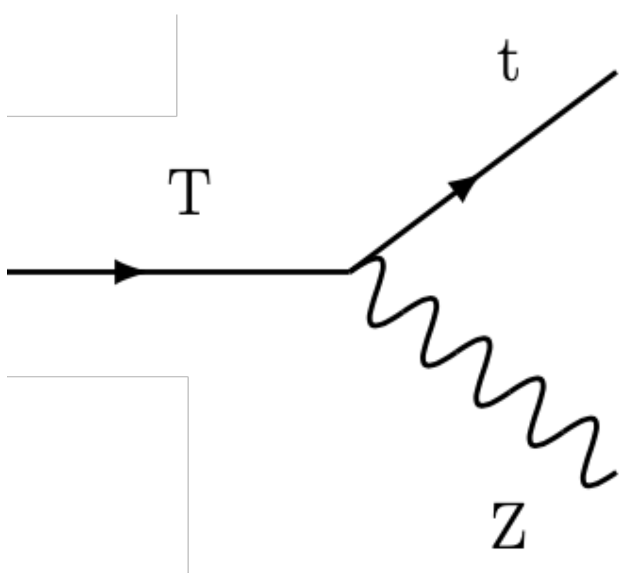


Exotic Beyond-the-SM Physics



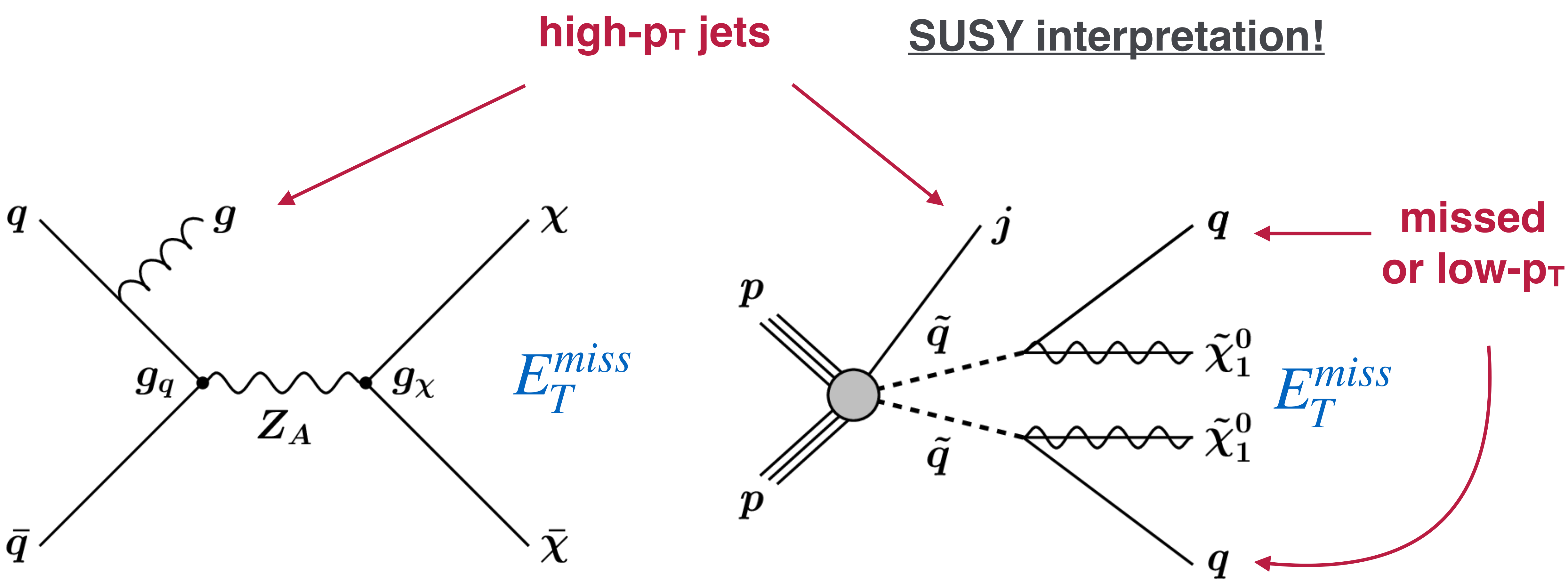
Overlaps ⇒ collaborations, combinations, & reinterpretations

New Resonance Decays to Heavy SM Particles



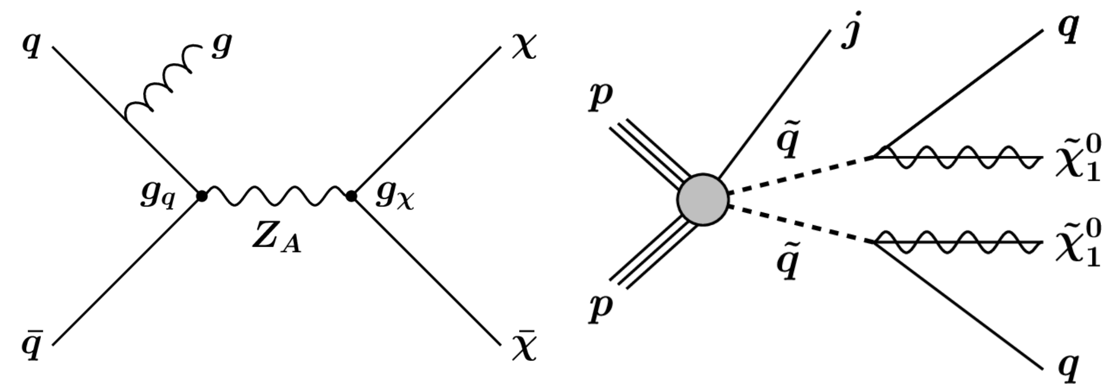
Dark Matter via Monojet

- Extremely energetic jets with no large recoil



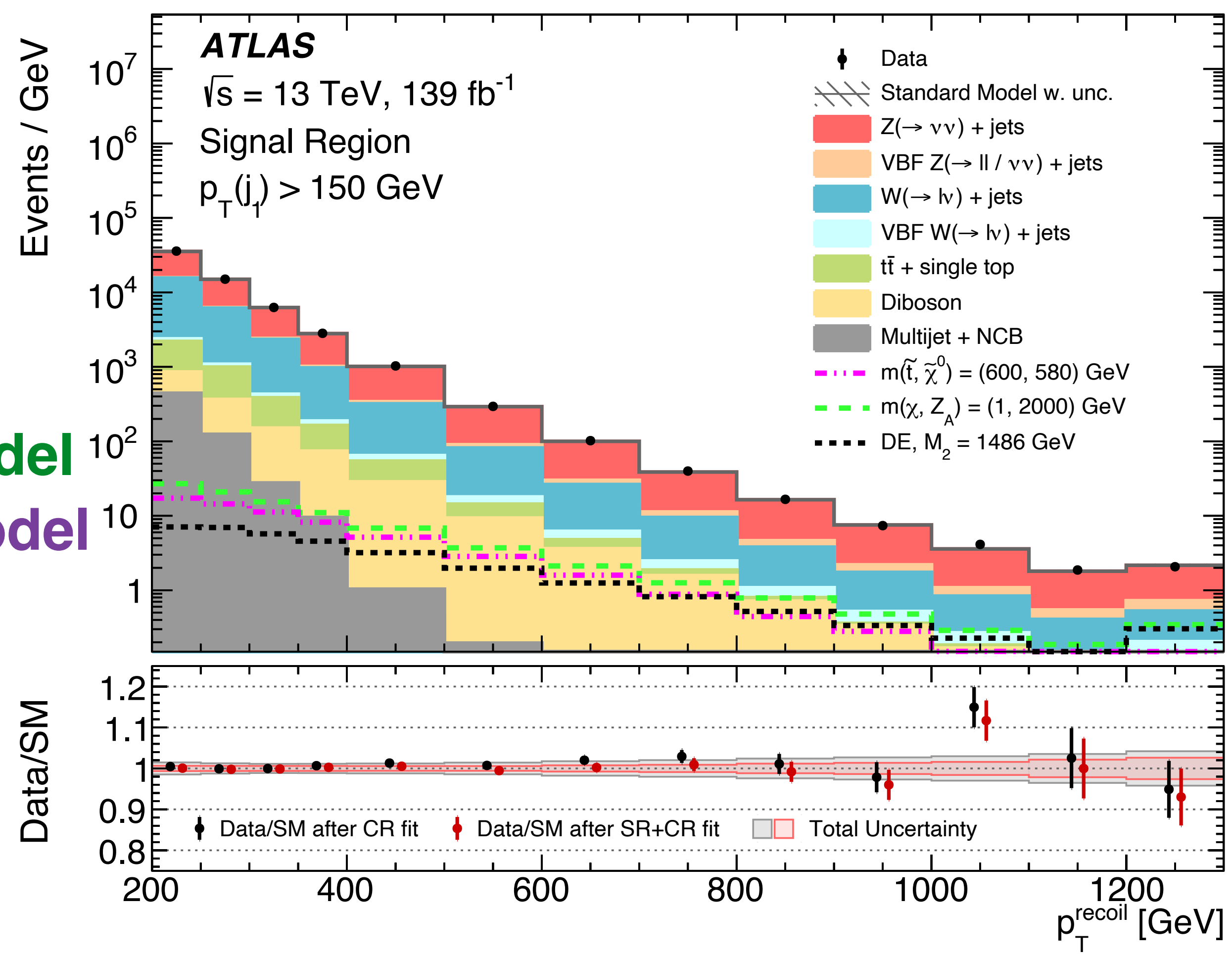
Dark Matter via Monojet

- Extremely energetic jets with no large recoil
- Stronger results with 4x more data & improved background modeling or constraints (particularly **Z→νν**)



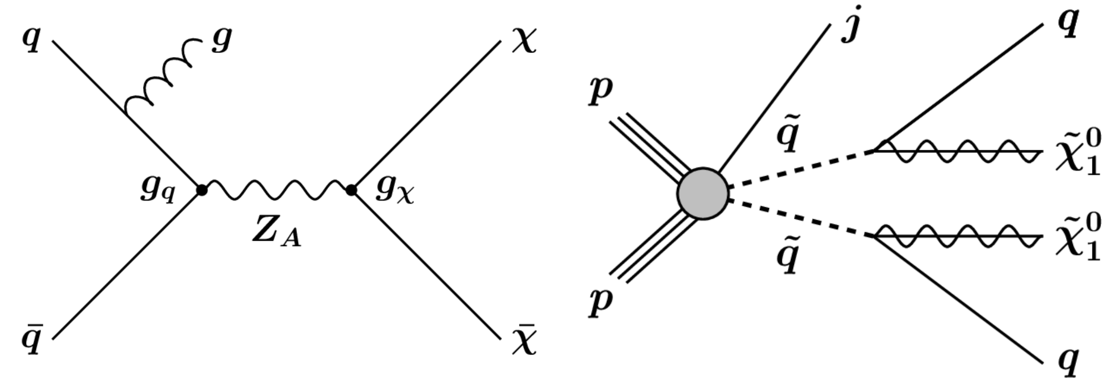
monojet p_T distribution

DM model
SUSY model



Dark Matter via Monojet

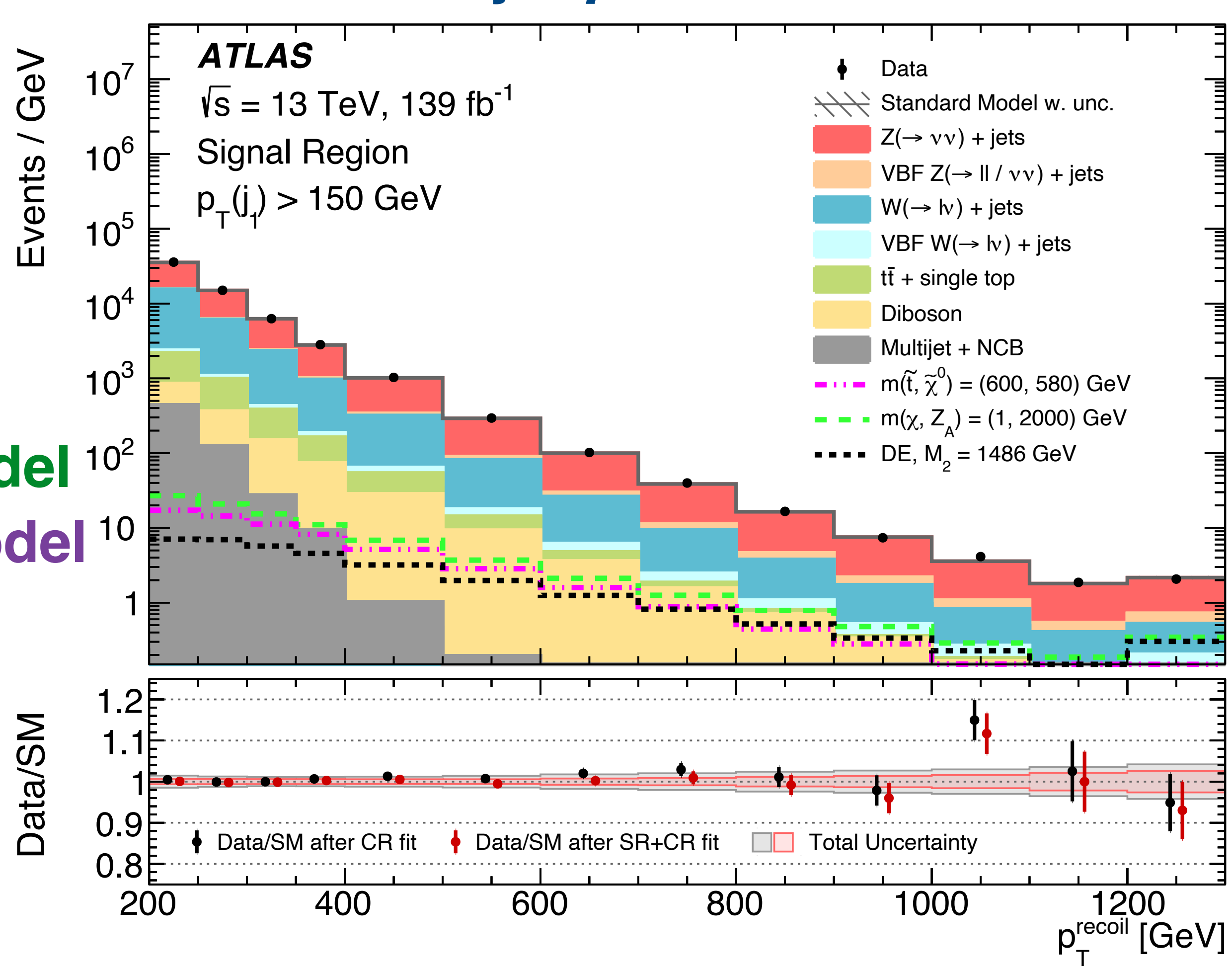
- Extremely energetic jets with no large recoil
- Stronger results with 4x more data & improved background modeling or constraints (particularly **Z→vv**)
- Greatly improved limits for *many* model interpretations
- Similarities with recent [monophoton search]



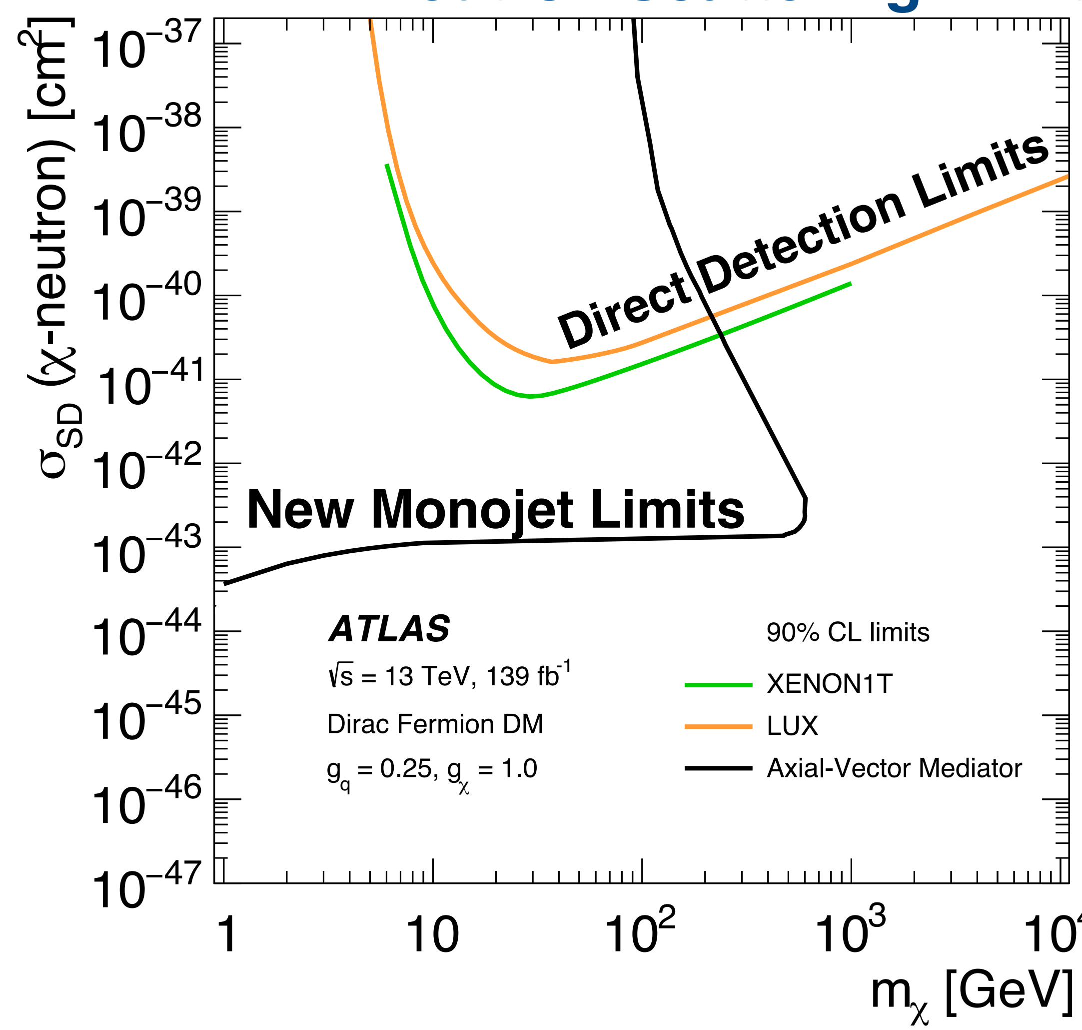
monojet p_T distribution

DM model

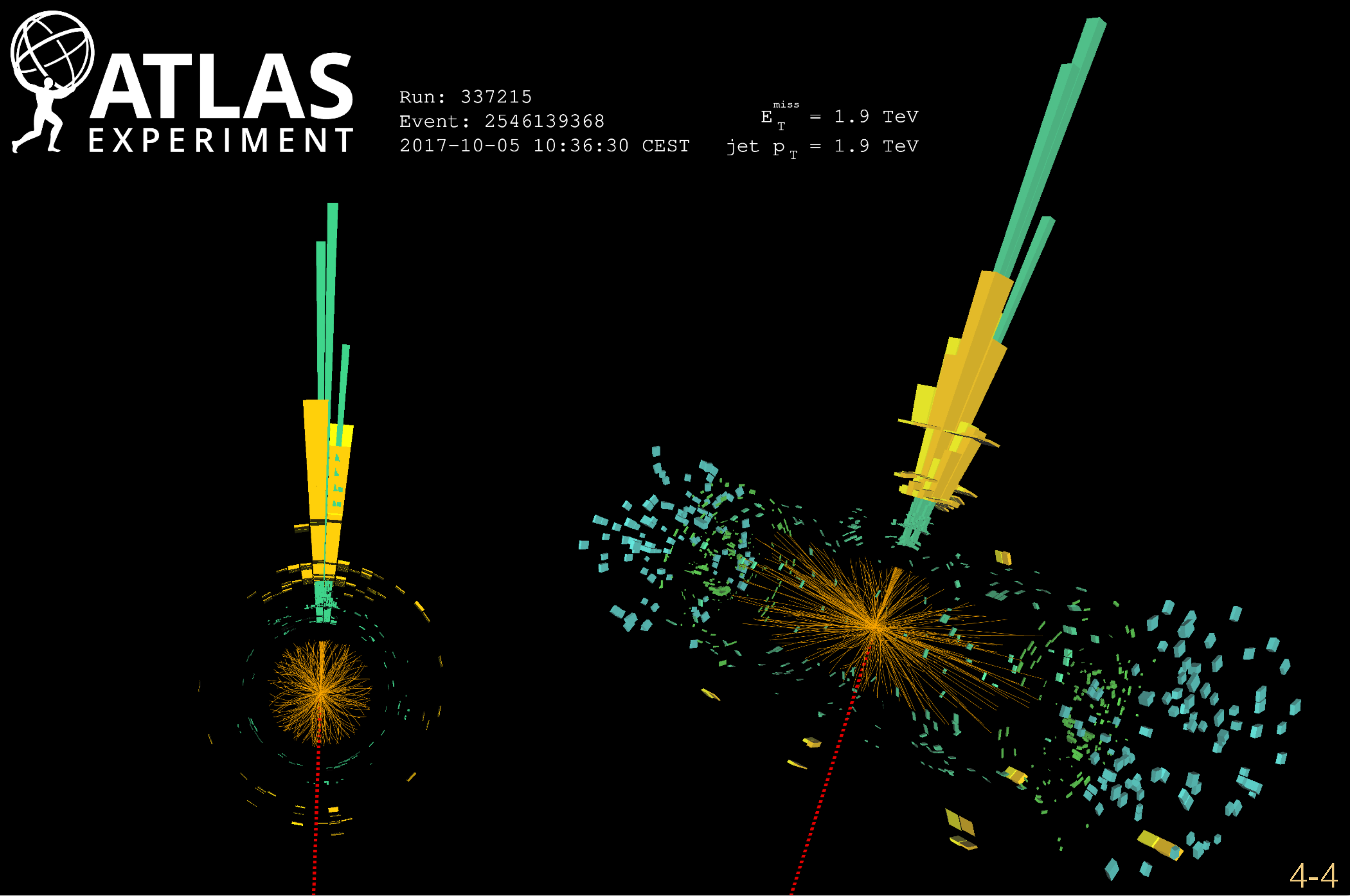
SUSY model



WIMP-neutron Scattering Limits

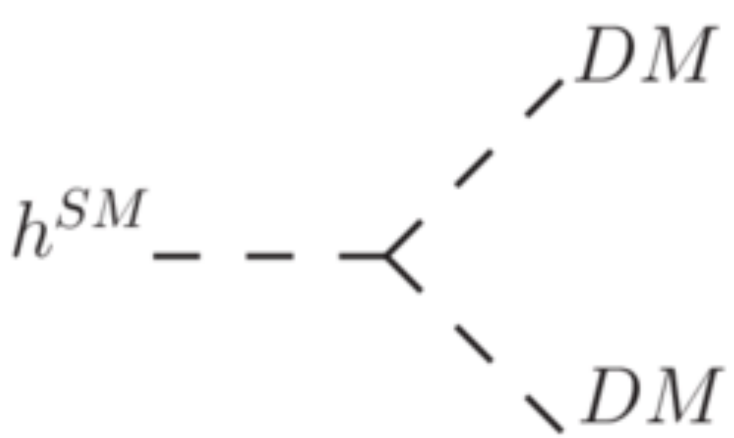


1.9 TeV Monojet Event in Data



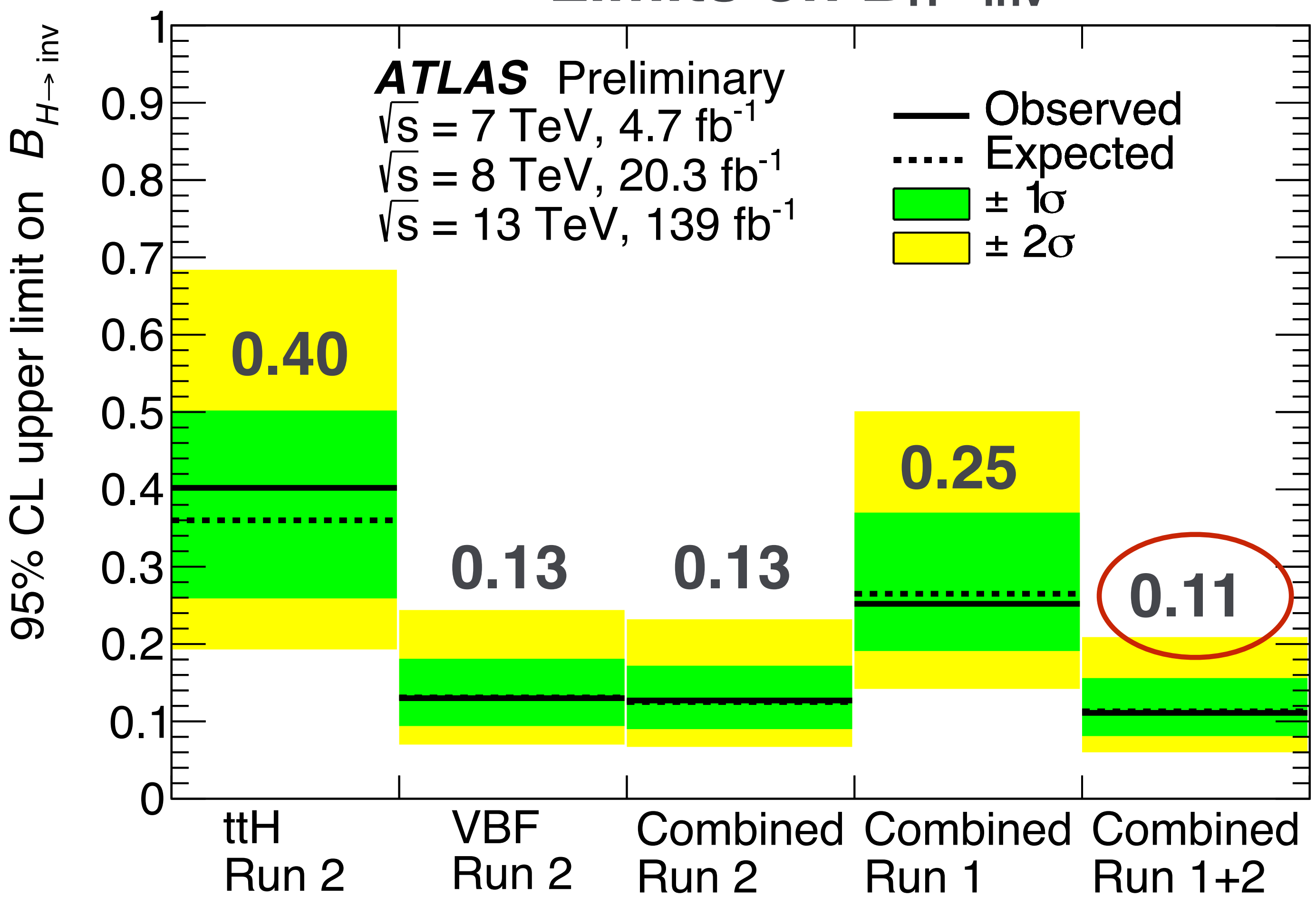
DM via Higgs→Invisible Combo

- Increasing emphasis on combinations to improve limits & identify interesting phase-space
- Combine H→inv channels:
  - **ttH** (0ℓ & 2ℓ) reinterpreted from SUSY top squarks
  - **VBF** (dedicated H→inv search)
  - 7 & 8 TeV combination of **VBF**, **ZH**, & **WH**
- **Uncertainty correlations** carefully considered, and assumptions cross-checked via extreme correlation scenarios



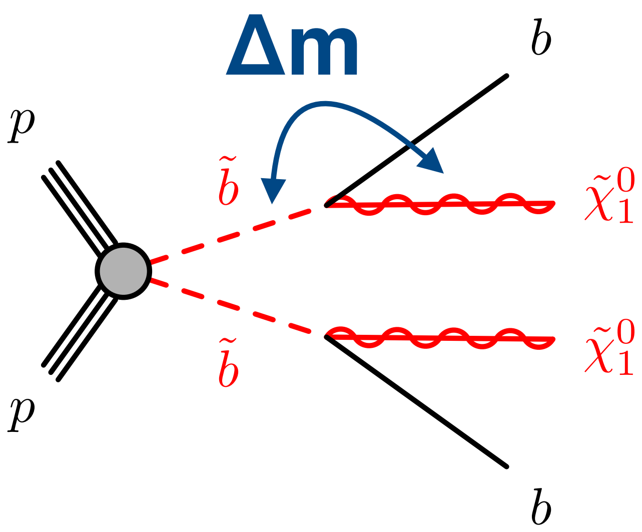
Higgs portal to DM sector

Limits on $B_{H\to inv}$

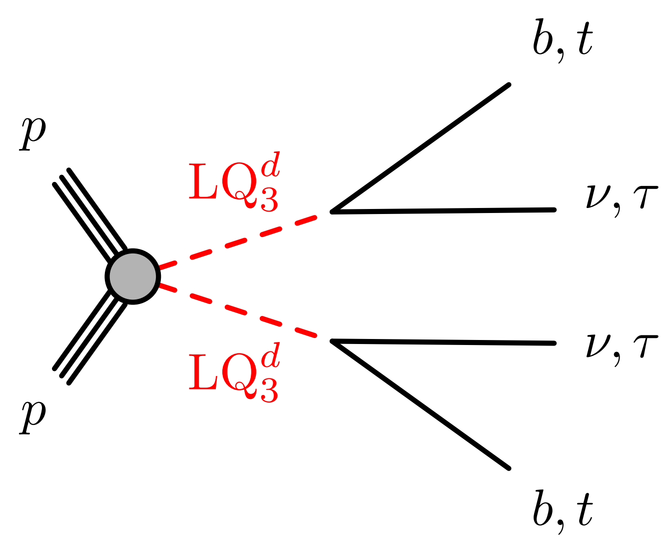


SUSY & more in $bb+E_T^{miss}$

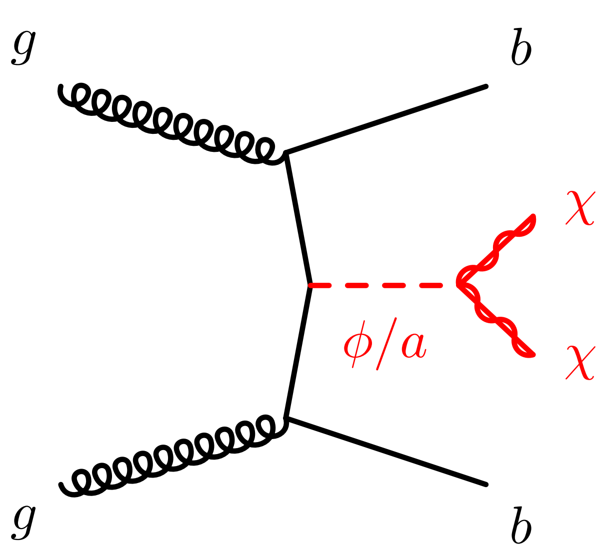
- Rich phenomenology available for final states with *b*-quarks & E_T^{miss}
- *b*-quarks identified by a displaced 2nd decay vertex via deep Neural Network (NN)



SUSY sbottom

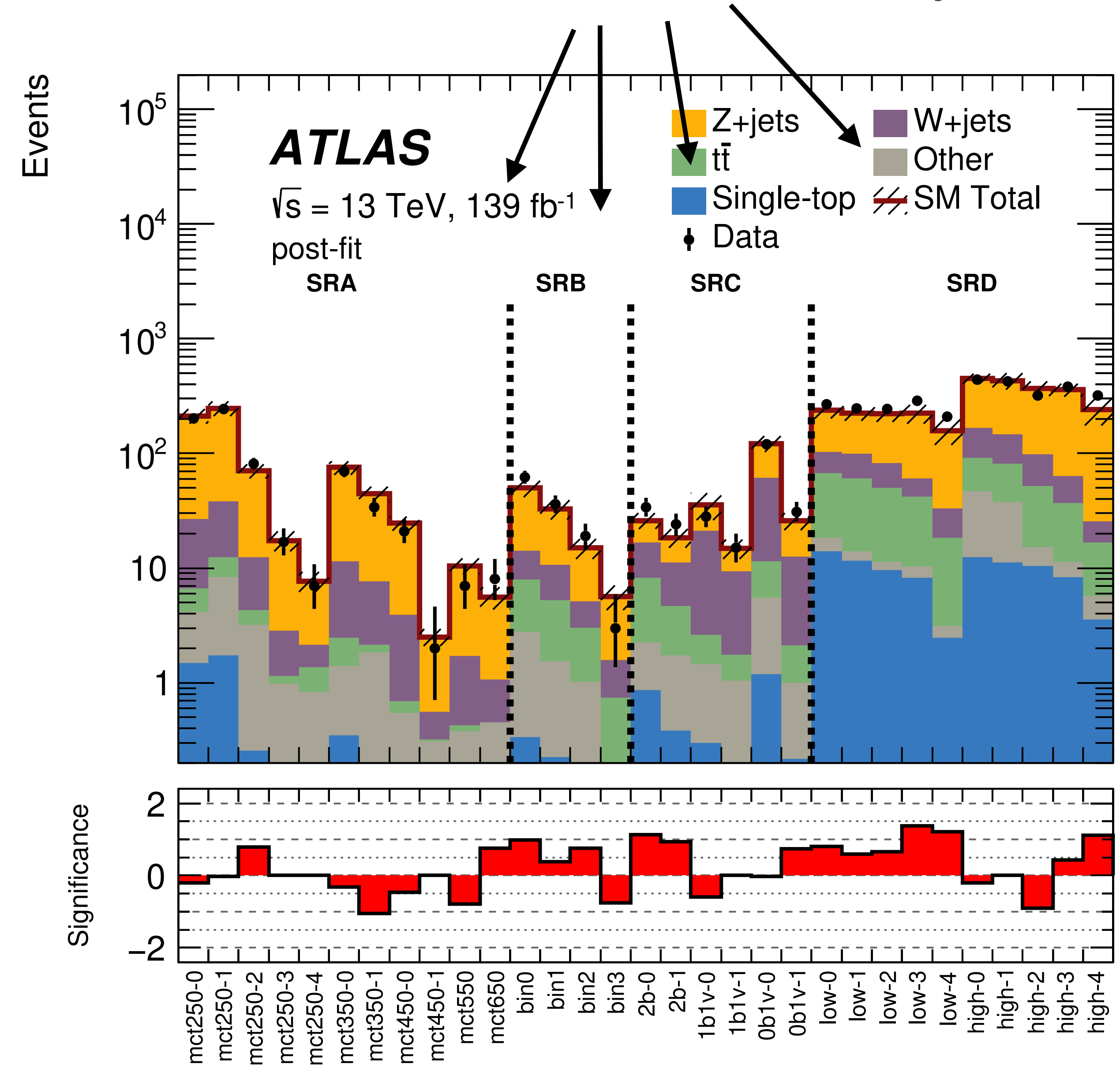


Leptoquarks



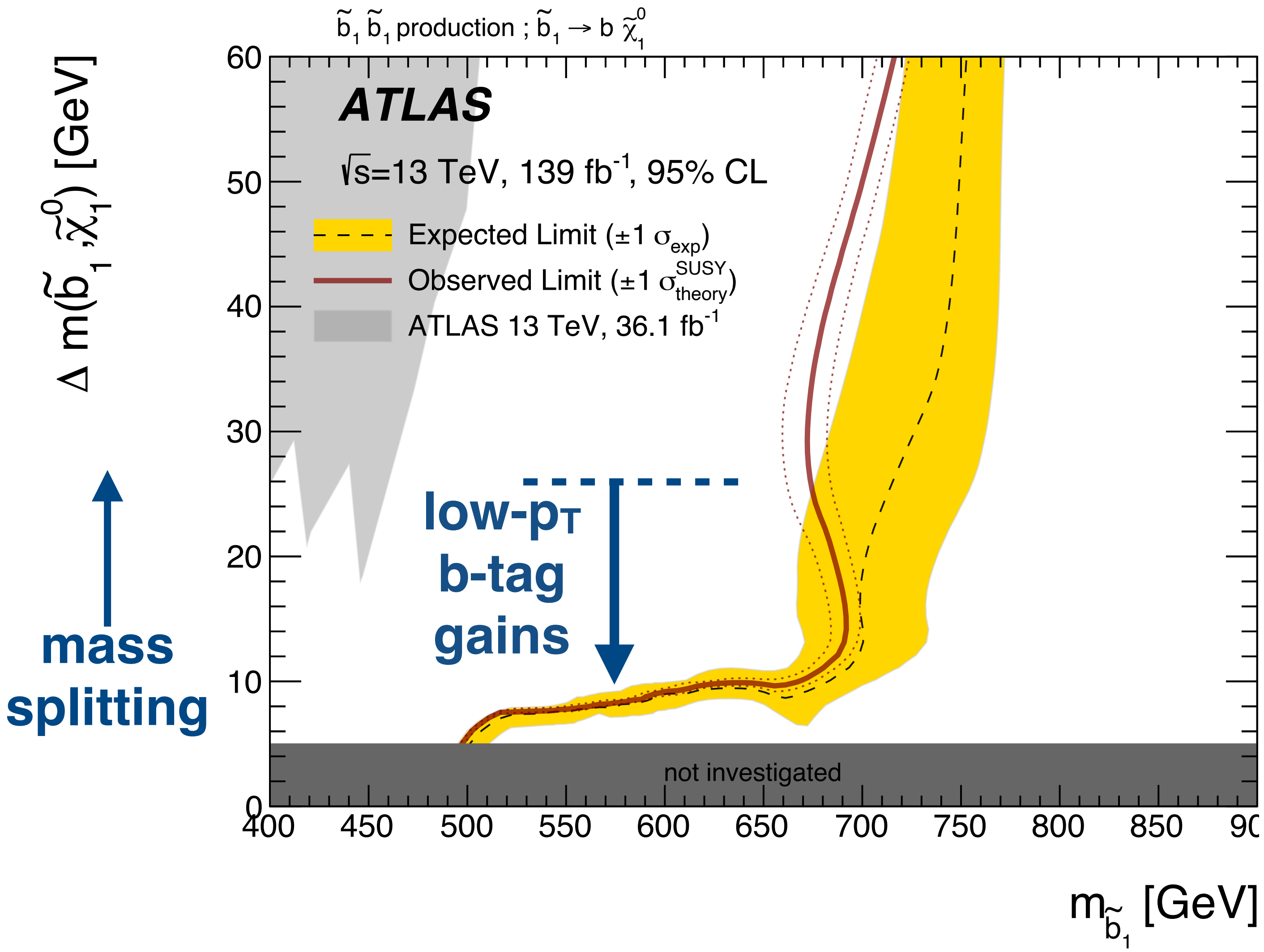
High-or-low mass WIMP

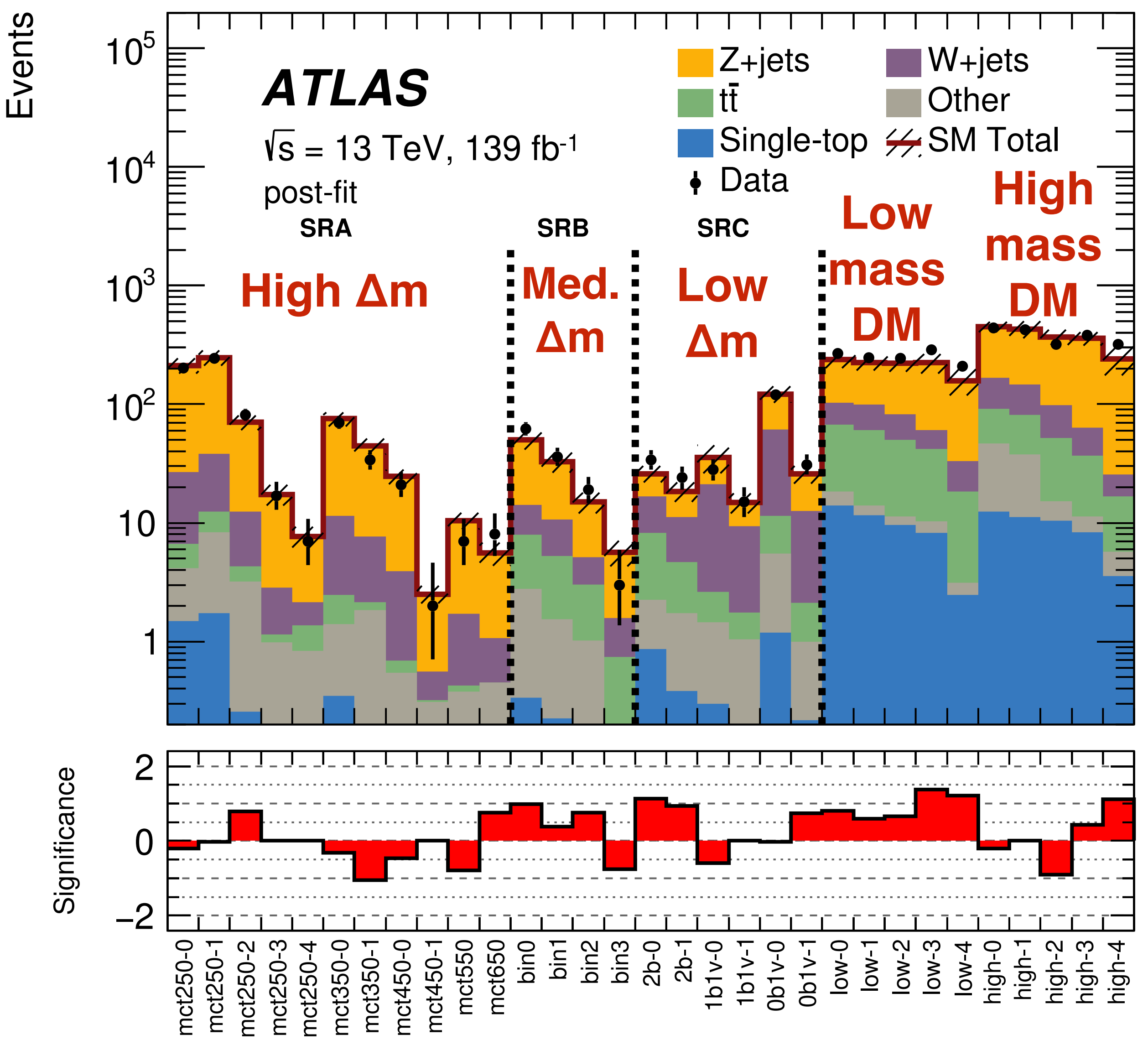
4 broad search regions according to kinematics of the decay



SUSY & more in $bb+E_T^{miss}$

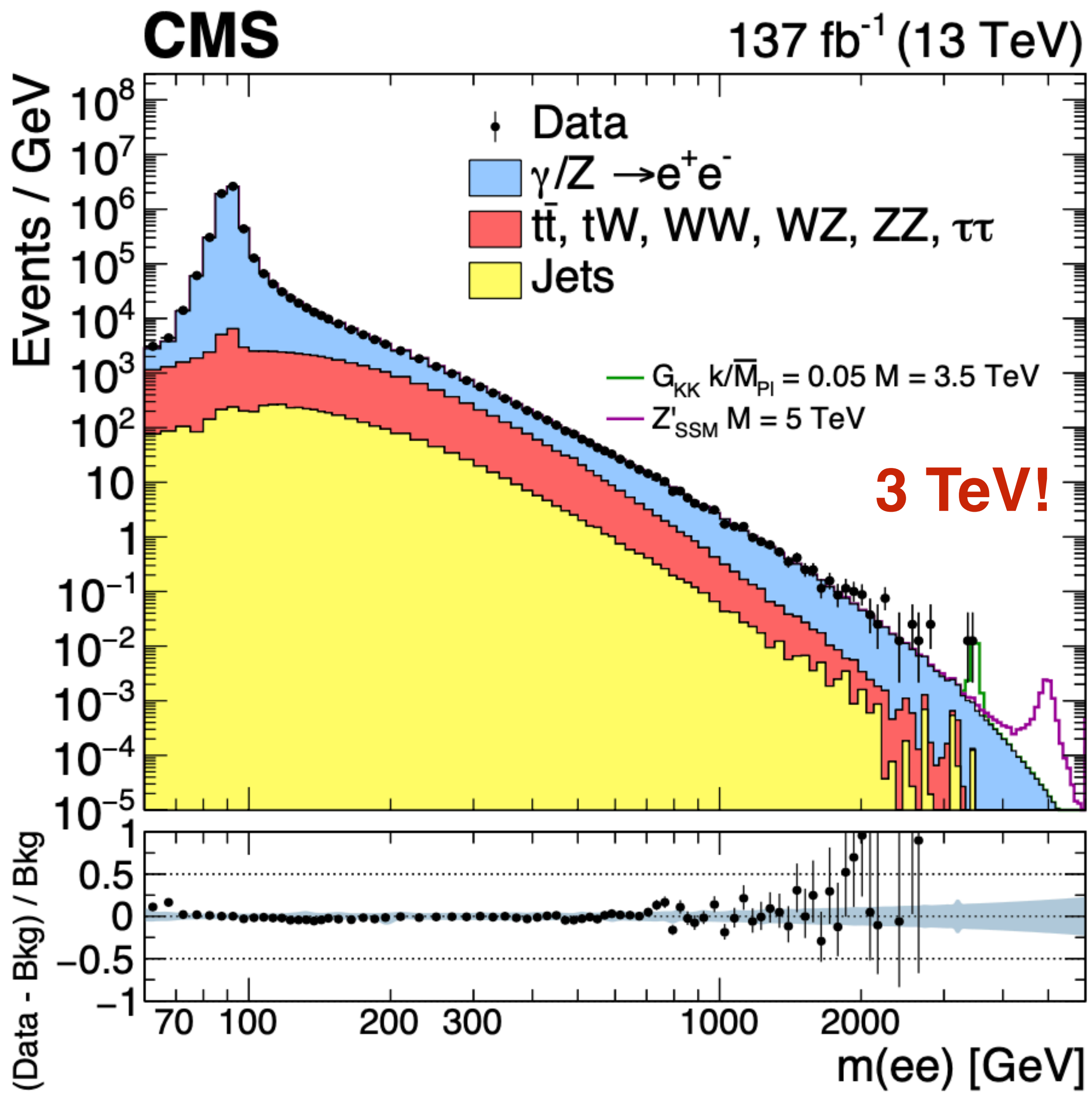
- Cut-&-count across two effective masses (m_{eff} & m_{CT}) for **High Δm**
- BDTs for **Medium Δm** & **High/Low mass DM**
  - Most sensitivity from jet kinematics & angular separations
- **Low Δm** (compressed): low-p_T *b*-tagging through presence of a soft secondary vertex (no associated jet)





Searching for Leptonic Decays

- **Leptons** are powerful handles at the LHC - search targets BSM decays to **ee** and **μμ**
- **Mass resonances** via data-driven sideband fits
  - Heavy bosons, gravitons, DM mediators
  - Exclusions **up to ~5.2 TeV** for generalized *Z`*
- **Non-resonant** enhancements at high mass, new gains using lepton scattering angle
  - Contact interactions via graviton excitations or fermion substructure
  - Exclude enhancements up to Λ cutoff of **~36 TeV**

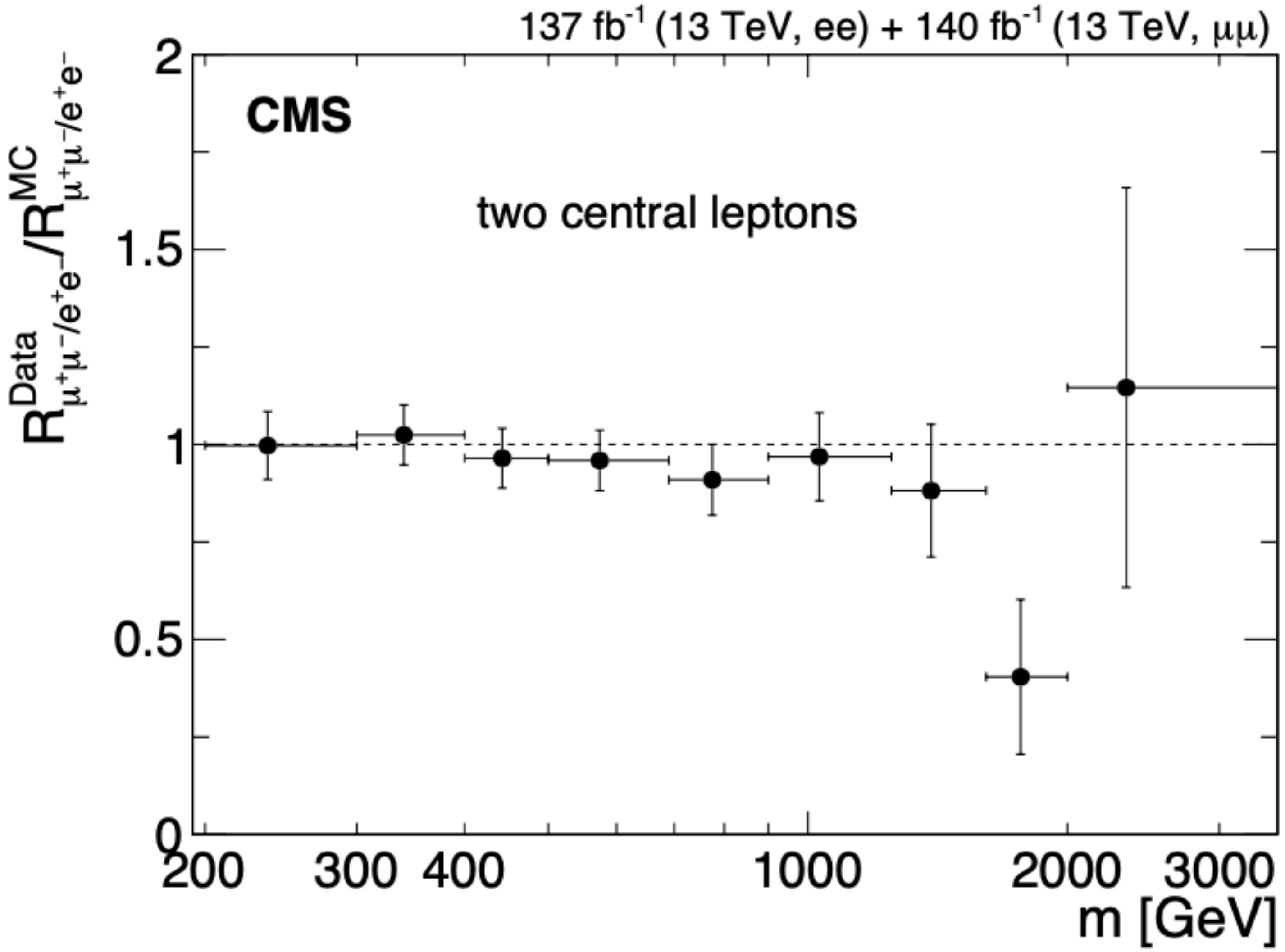


Resonance search in ee channel

Searching for Leptonic Decays

New!

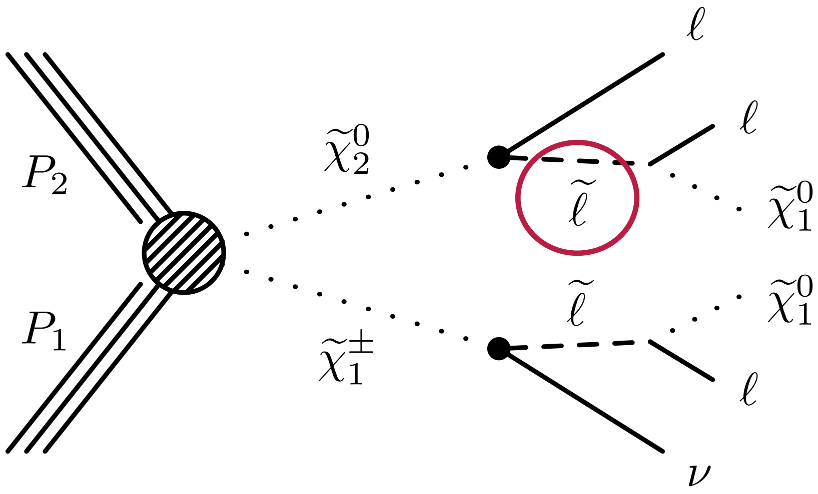
Unfolded ratios of μμ-to-ee production probe lepton-flavor-universality violation

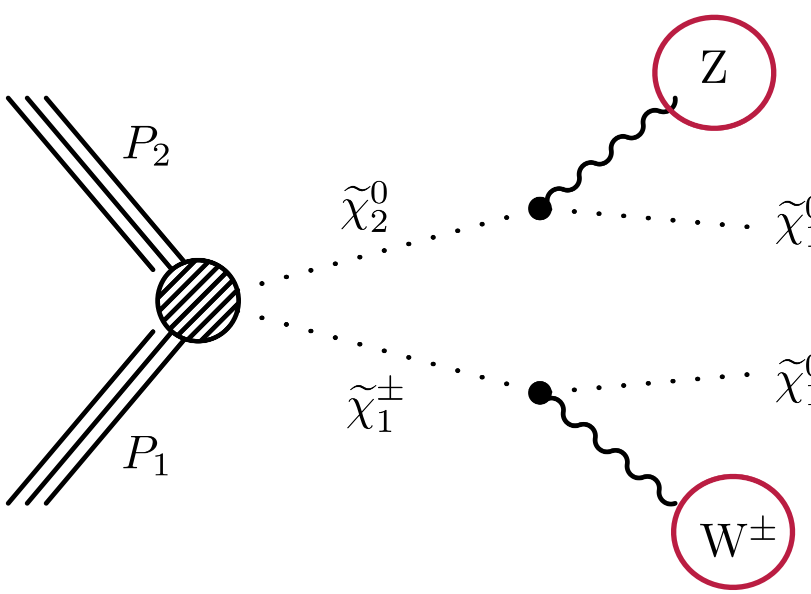


Ratio is Data-MC agreement of μμ-to-ee yields

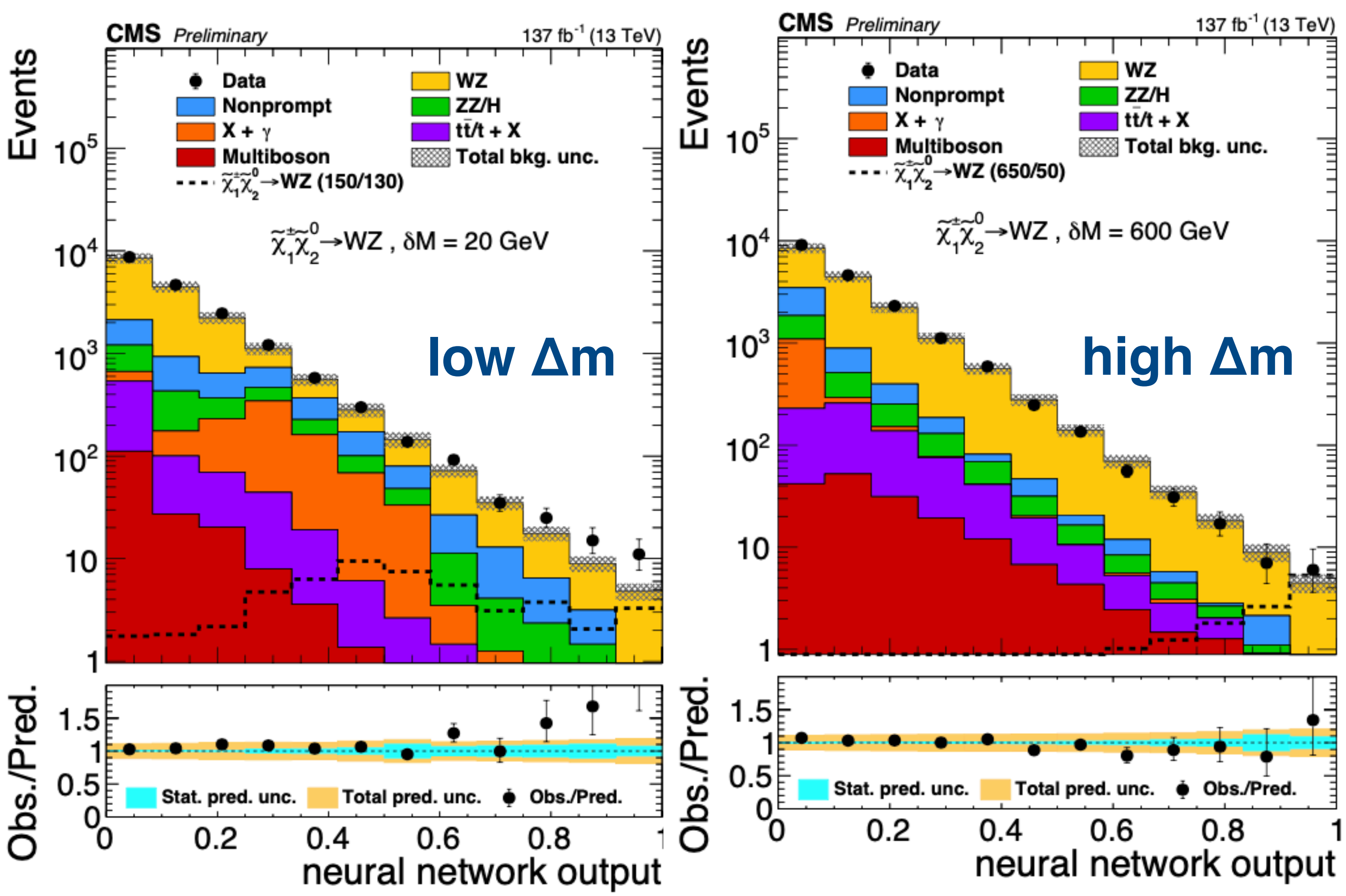
Multilepton SUSY via Neural Networks

- Search for events with 3ℓ, $4\ell+$, & 2ℓ (same-sign)
  - Decays of EWK SUSY via $\tilde{\ell}$ or W, Z, & Higgs bosons

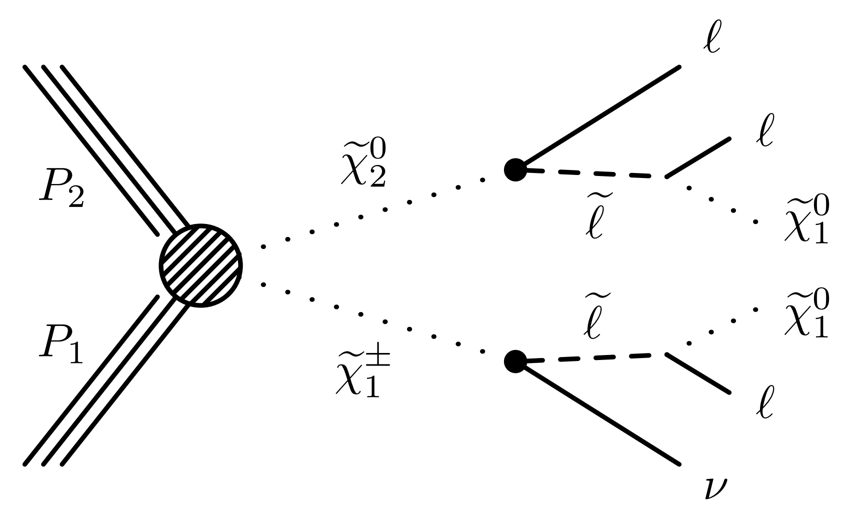


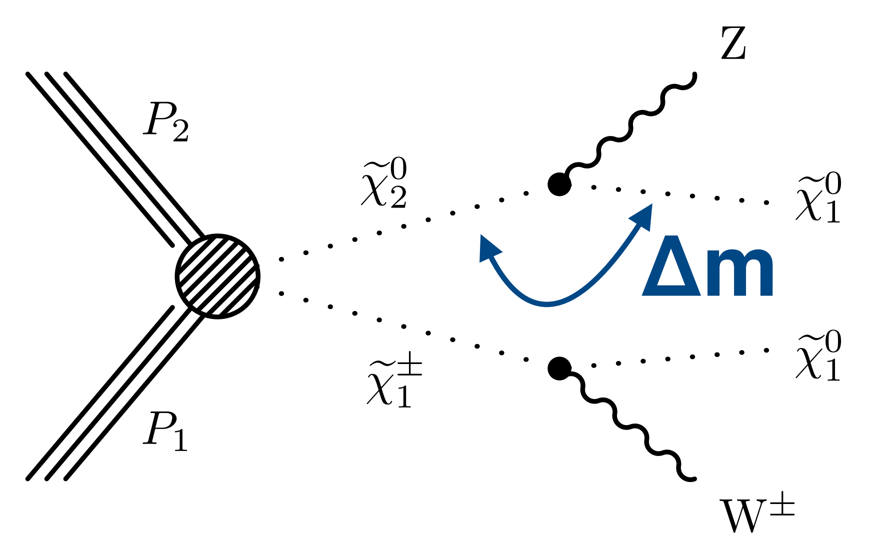


- Search for events with 3ℓ, $4\ell+$, & 2ℓ (same-sign)
  - Decays of EWK SUSY via $\tilde{\ell}$ or W, Z, & Higgs bosons
- Neural network trained on several effective masses and $\sum p_T$ of decay products
  - Training parameteric in mass splitting Δm



NN output for low vs high-mass splitting

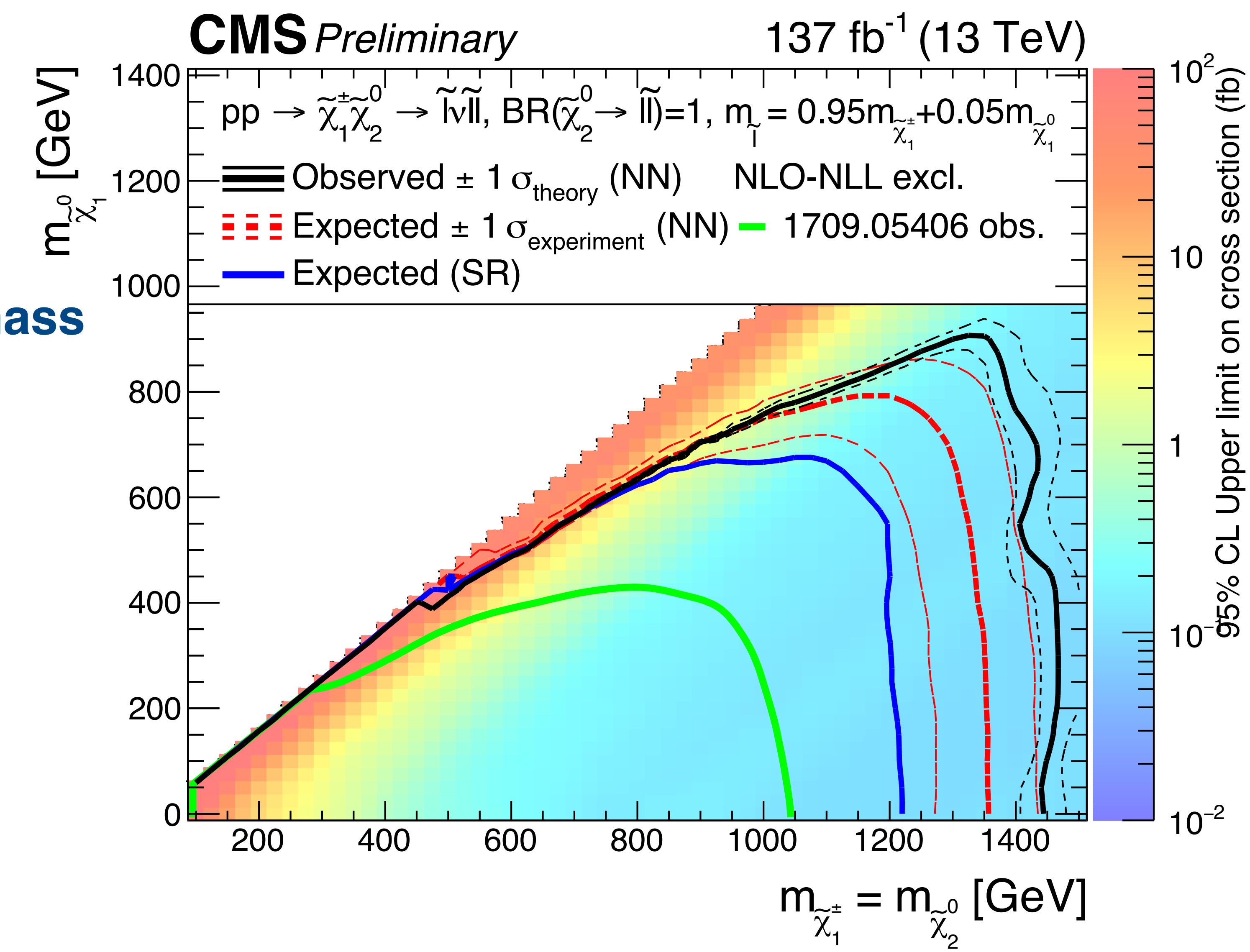




Multilepton SUSY via Neural Networks

- Neural network **compared against cut-&-count method** (>120 search regions)
- NN limits improve up to **150 GeV** over **cut-&-count regions**
  - Mass limits up to 1450 GeV (slepton-mediated) and 650 GeV (boson-mediated)

LSP mass

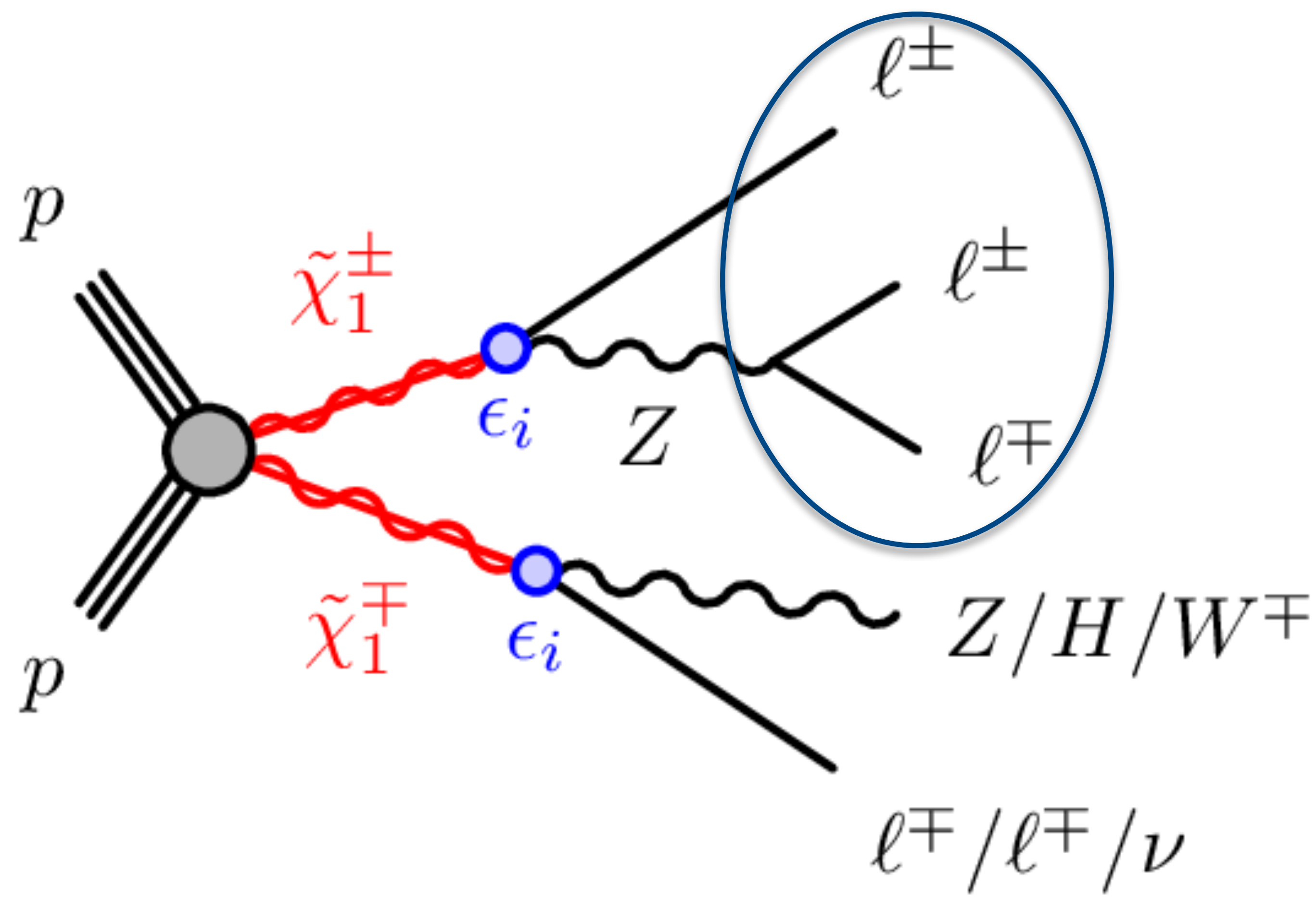


compressed slepton-mediated limits

Mass of directly-produced sparticles

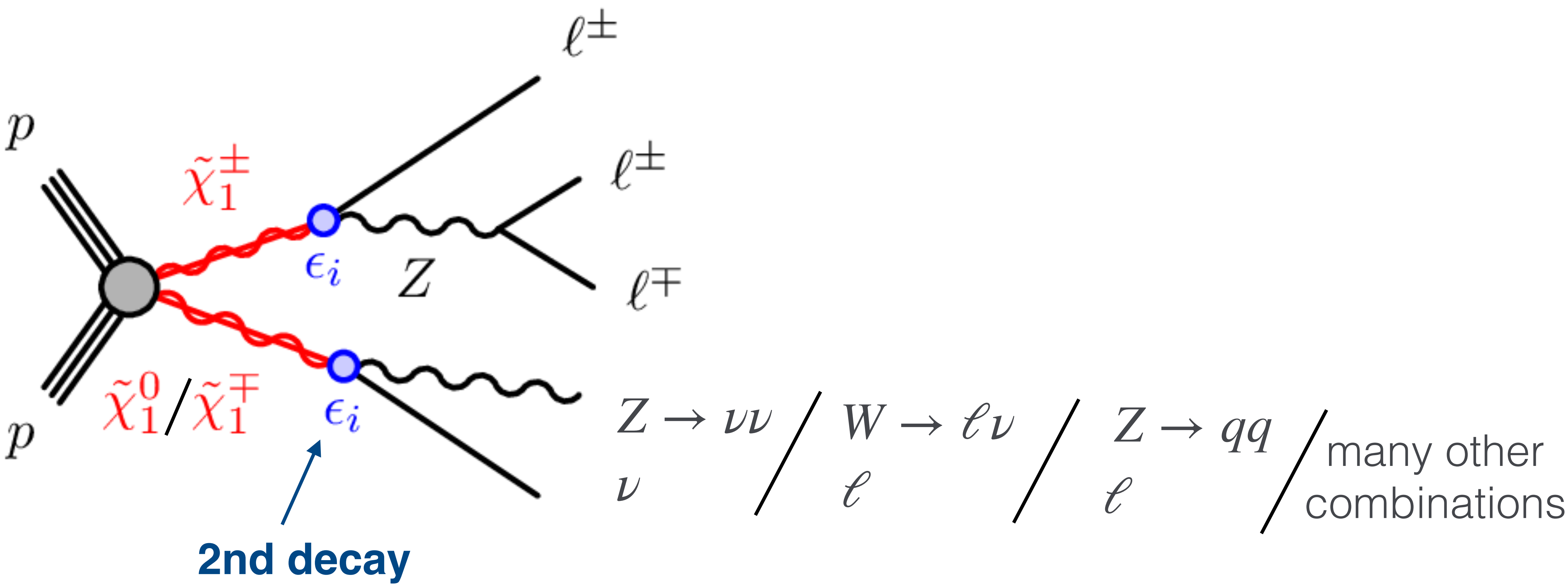
Trilepton Resonances via RPV

- SUSY Lagrangian allows for RPV terms compatible with nature
  - Allows for **spectacular trilepton resonance** via electroweak SUSY

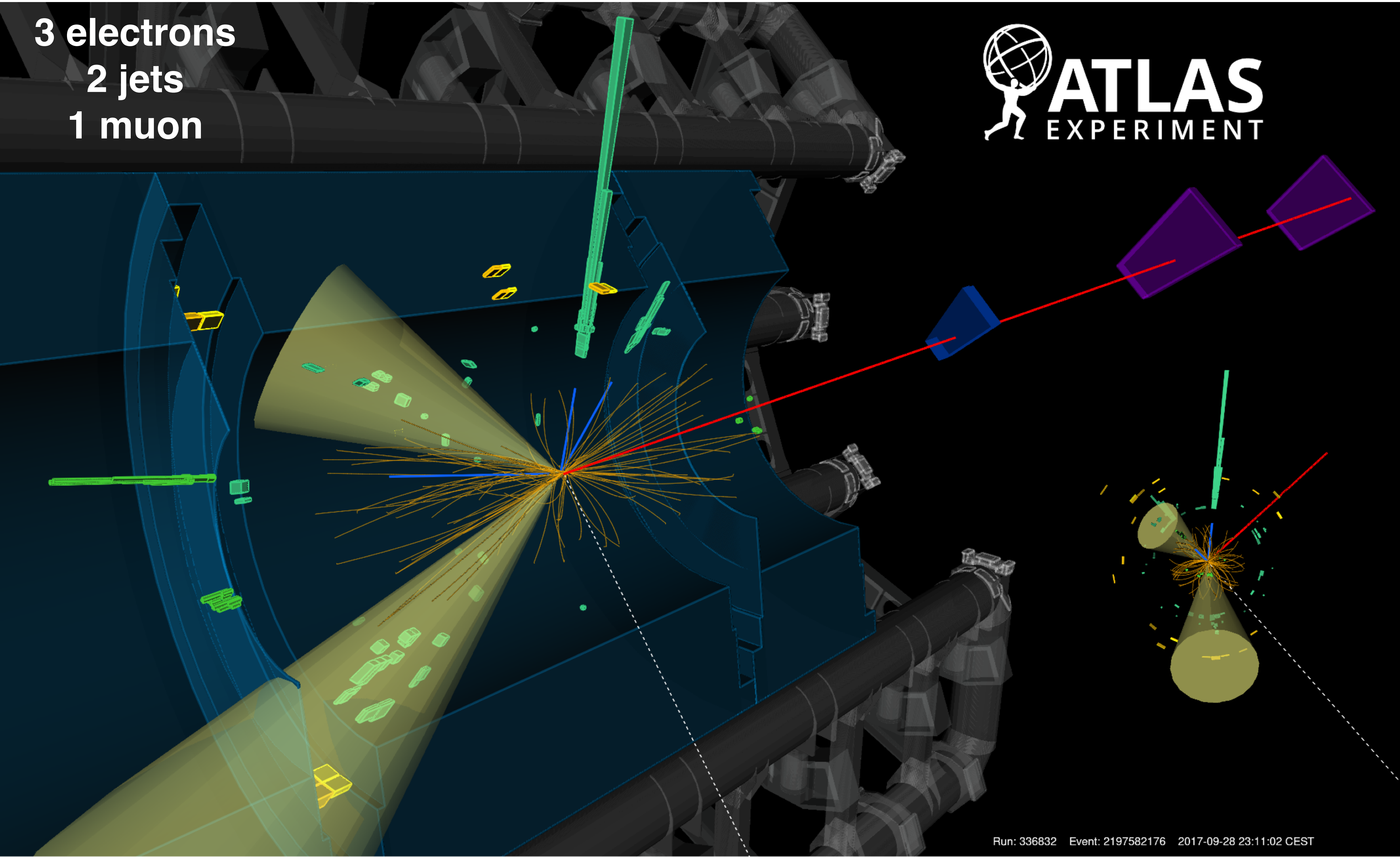


Trilepton Resonances via RPV

- SUSY Lagrangian allows for RPV terms compatible with nature
  - Allows for spectacular trilepton resonance via electroweak SUSY
- Search categorized into 3 regions according visibility of the pair-produced 2nd decay (**invisible**, **partially-visible**, or **fully visible**)
  - Fully visible allows for selection on mass-asymmetry



Trilepton Candidate in Data



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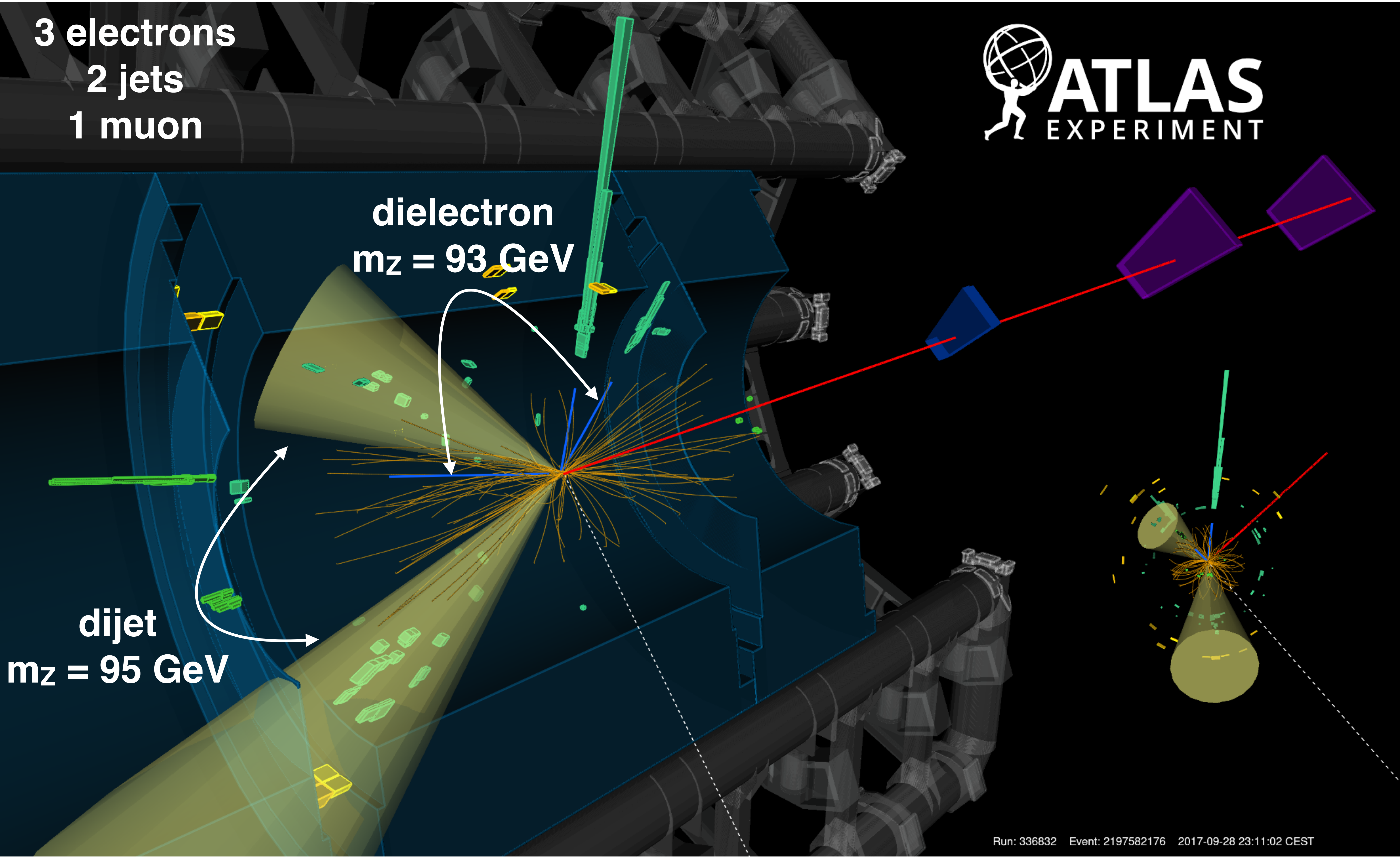

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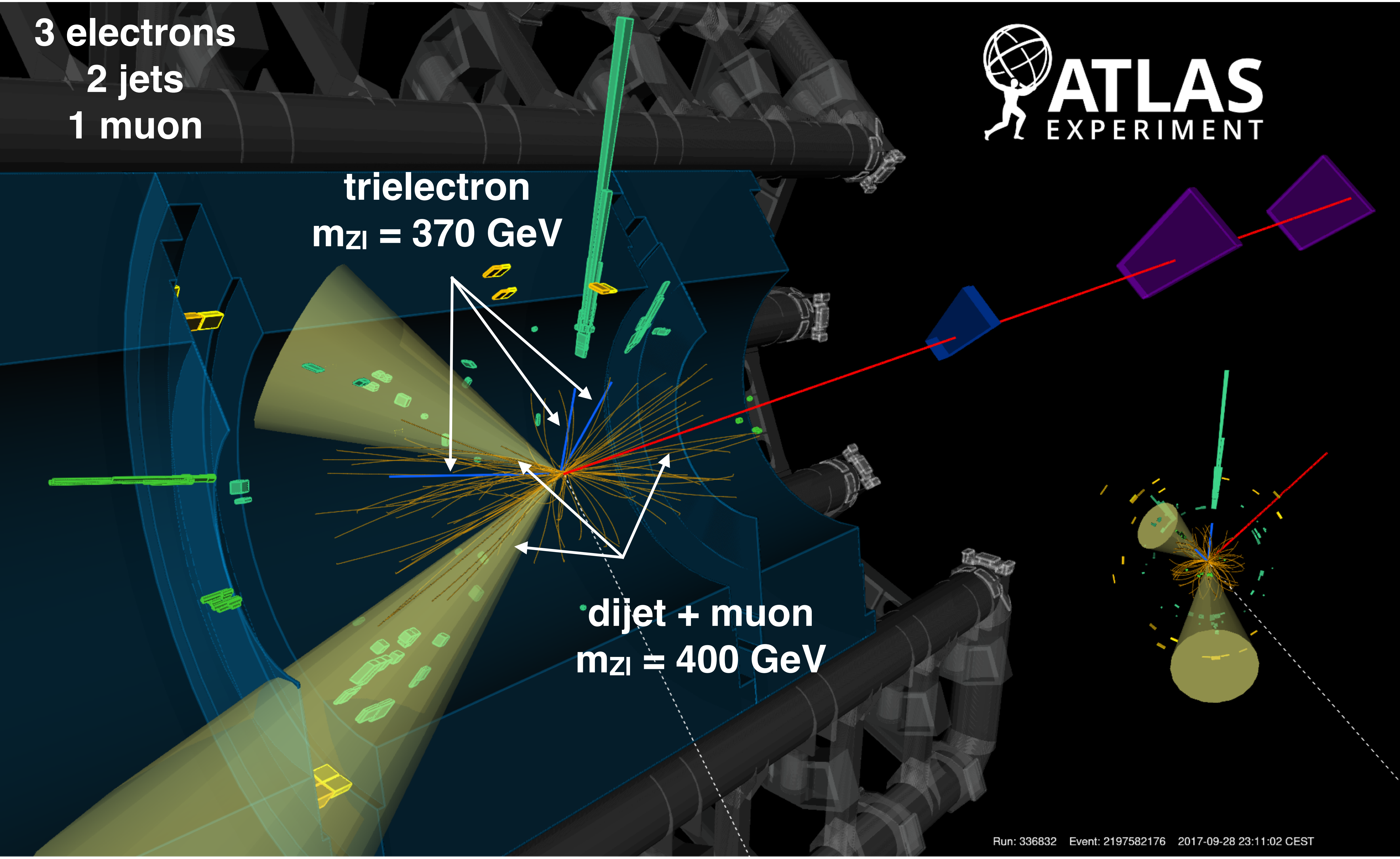
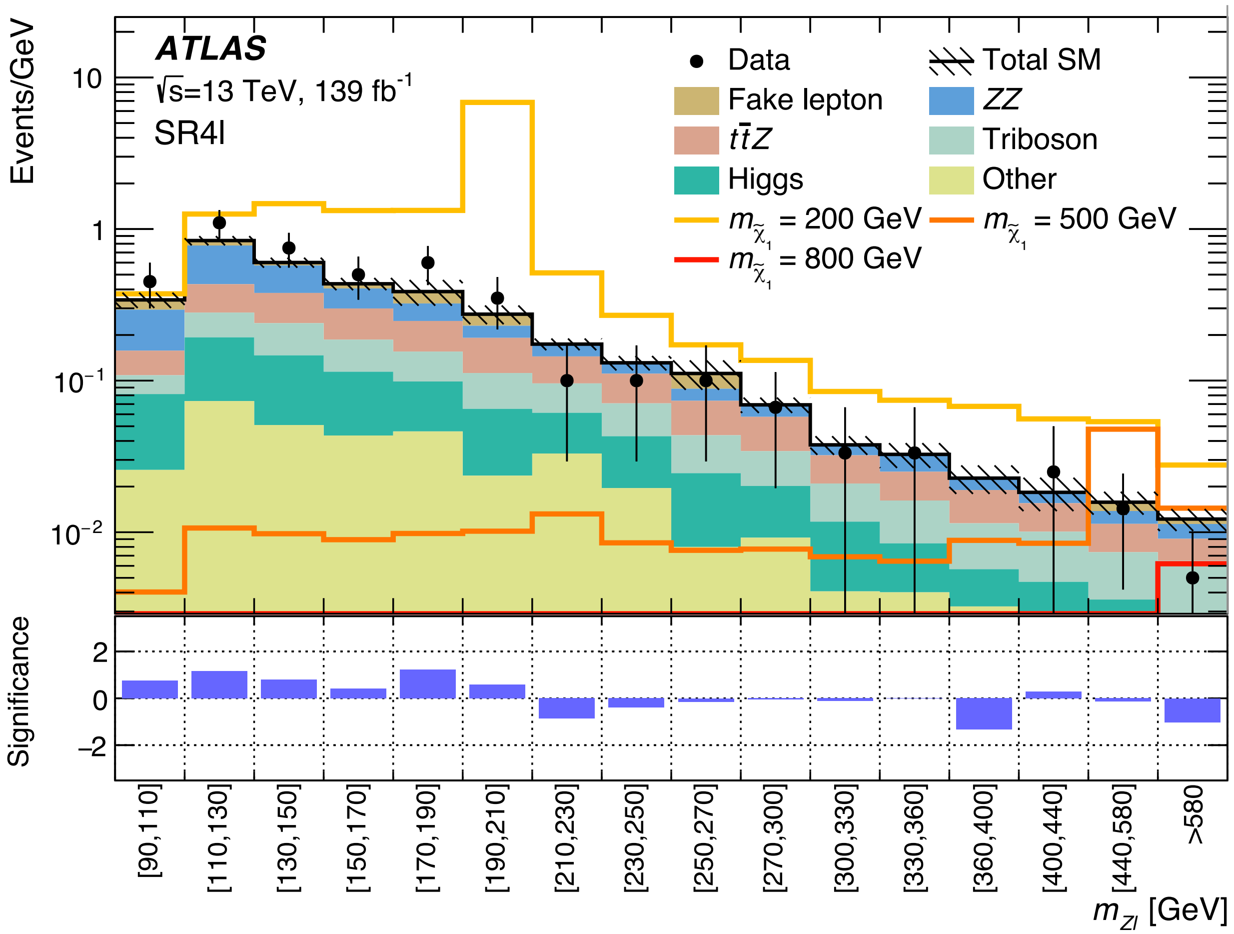


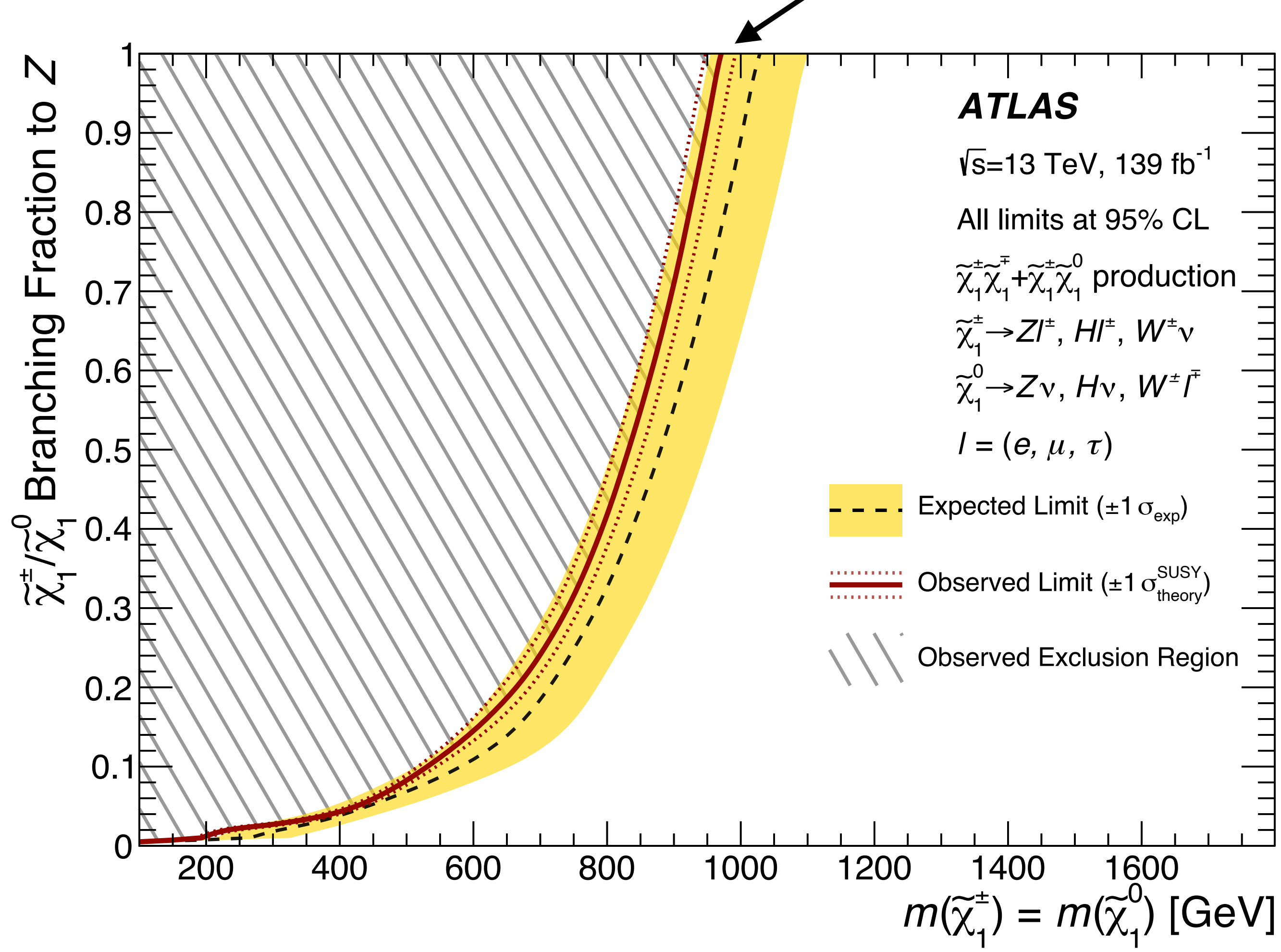
Trilepton Resonances via RPV

- Trilepton invariant mass in data agrees well with SM
- Limits set against *W* / *Z* / Higgs & e / μ / τ branching fractions
  - Full likelihoods (via pyHF) available for reinterpretations

Trilepton mass in 4ℓ+ region

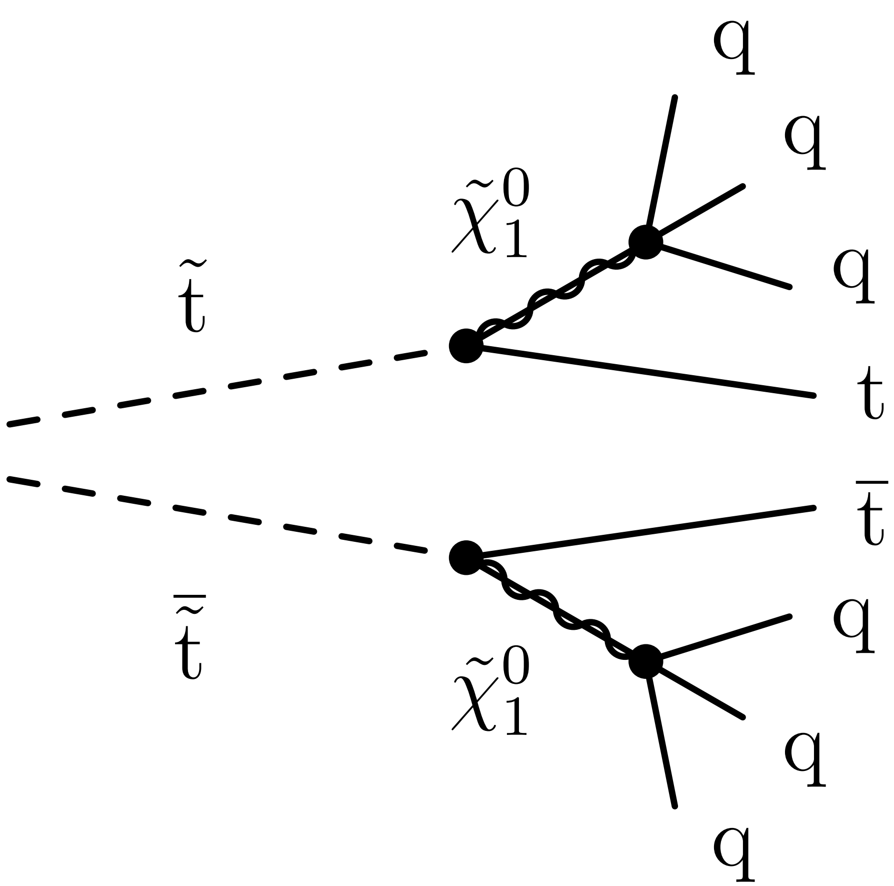


950 GeV limit @ 100% *Z* decays



Multijet Decays via RPV

- Another fantastic & unexplored RPV decay:
  $\tilde{t} \rightarrow$ top + 3 light quarks, giving up to 12 jets!



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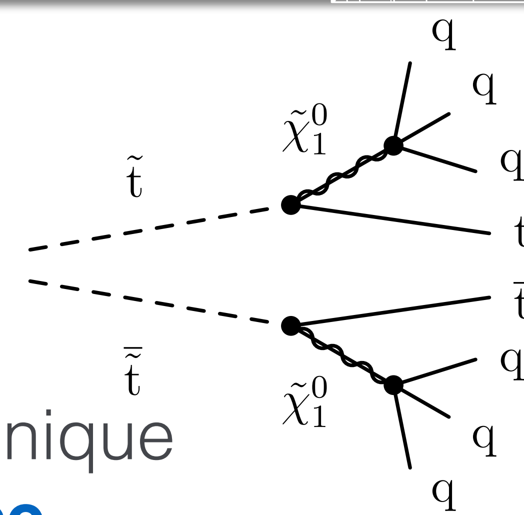
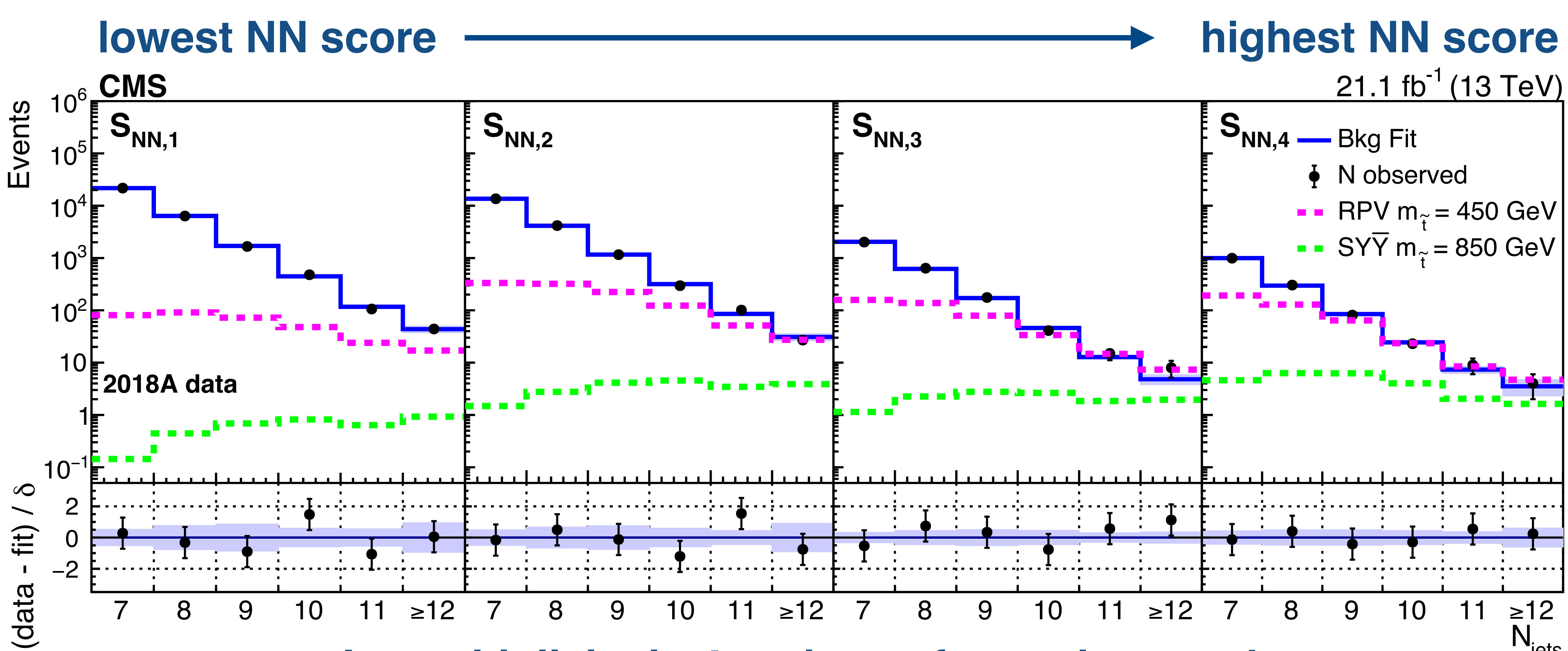


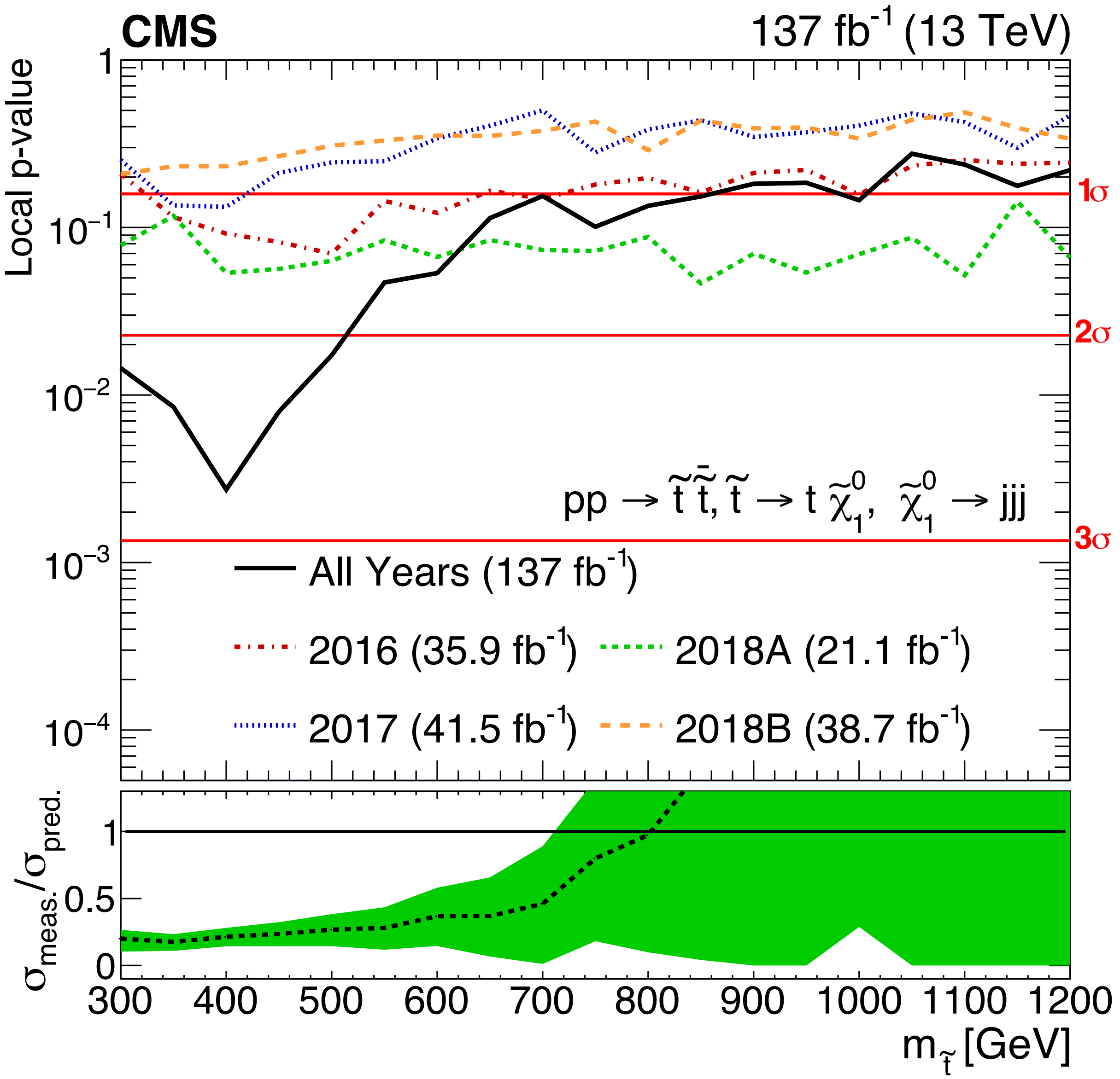
- Search Njets distribution in 4 regions of NN output
  - Remove training dependence on Njets via Gradient Reversal technique & subsequent binning of NN score to give **identical $t\bar{t}$ Njets shape**
  - Reduces sensitivity to uncertainties that don't affect Njets shape



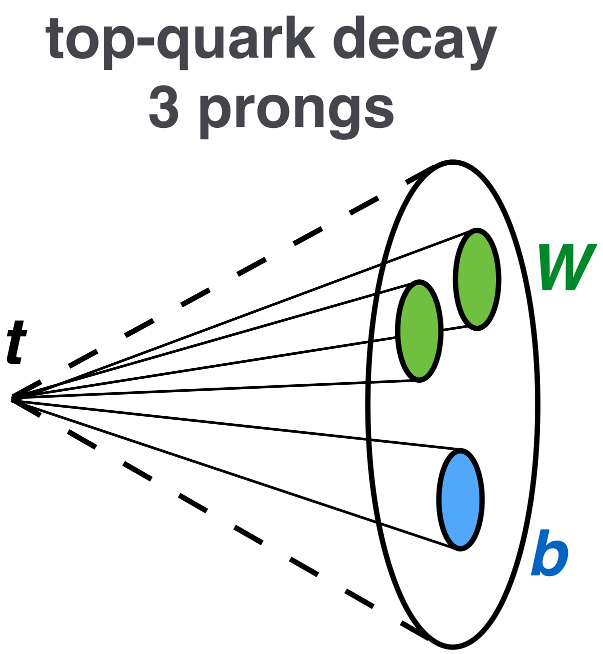
Jet multiplicity in 4 regions of neural-network score

Multijet Decays via RPV

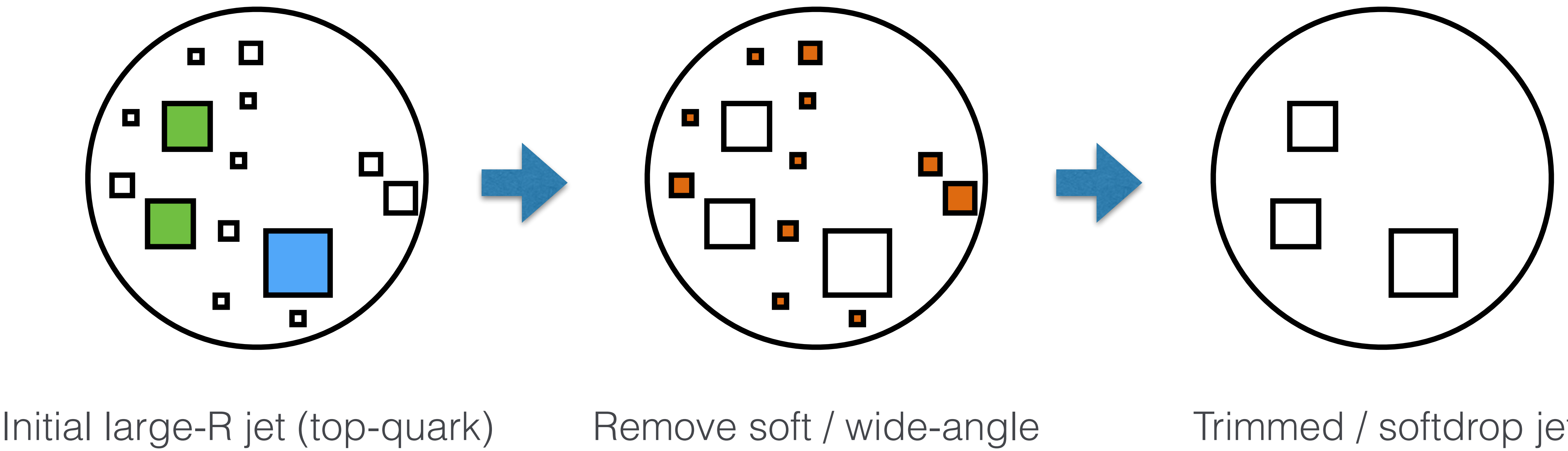
- Limits set on new $\tilde{t}$ decay up to 700 GeV
- Minor preference of 2.8σ (local) for 400 GeV model
  - Includes discussion on source - both minor data excess & reduced tension of uncertainties



Jet Substructure Advances

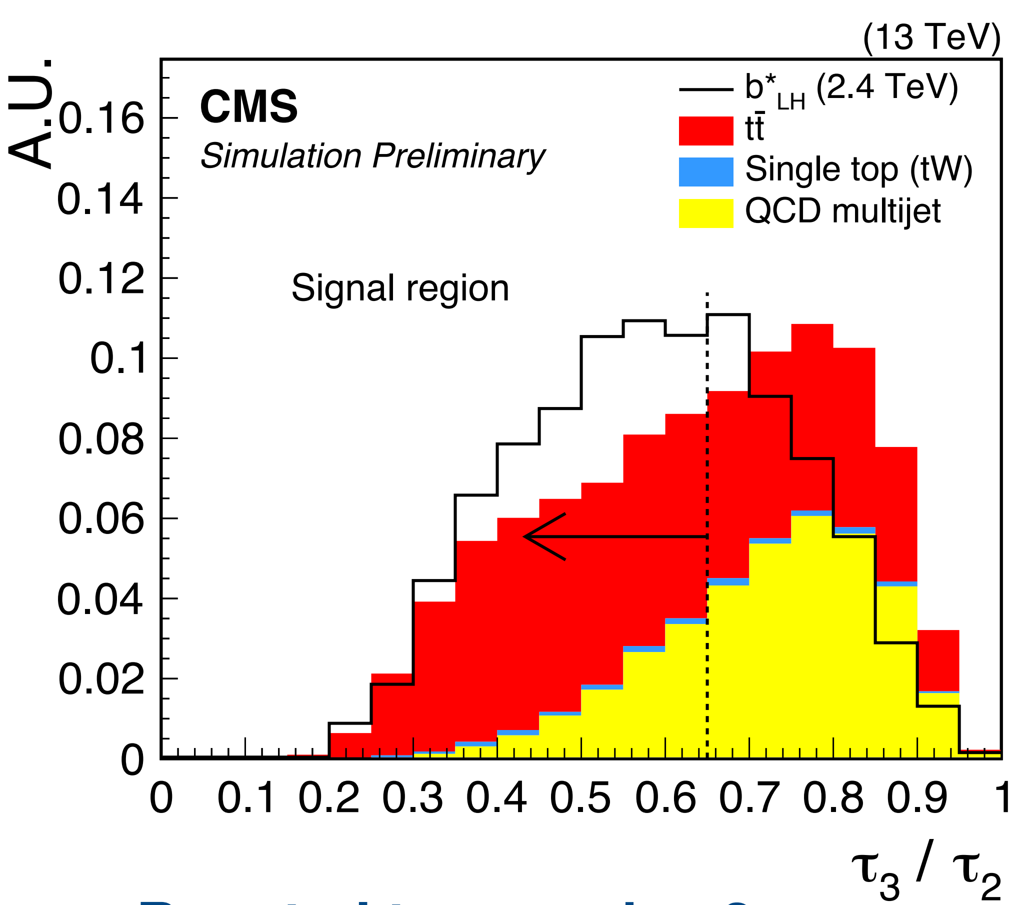


- Many new searches for heavy particles with boosted hadronic decays to ***W***, ***Z***, **Higgs**, and **top quarks**
- **Jet shape** variables such as N-subjettiness (τ_N) - distinguish decays with **1-prong** (QCD), **2-prongs** (*W*/*Z* boson), and **3-prongs** (top quark)
- Iterative **pruning algorithms** (trimmed / softdrop jets)
- Better mass resolution & tagging efficiency

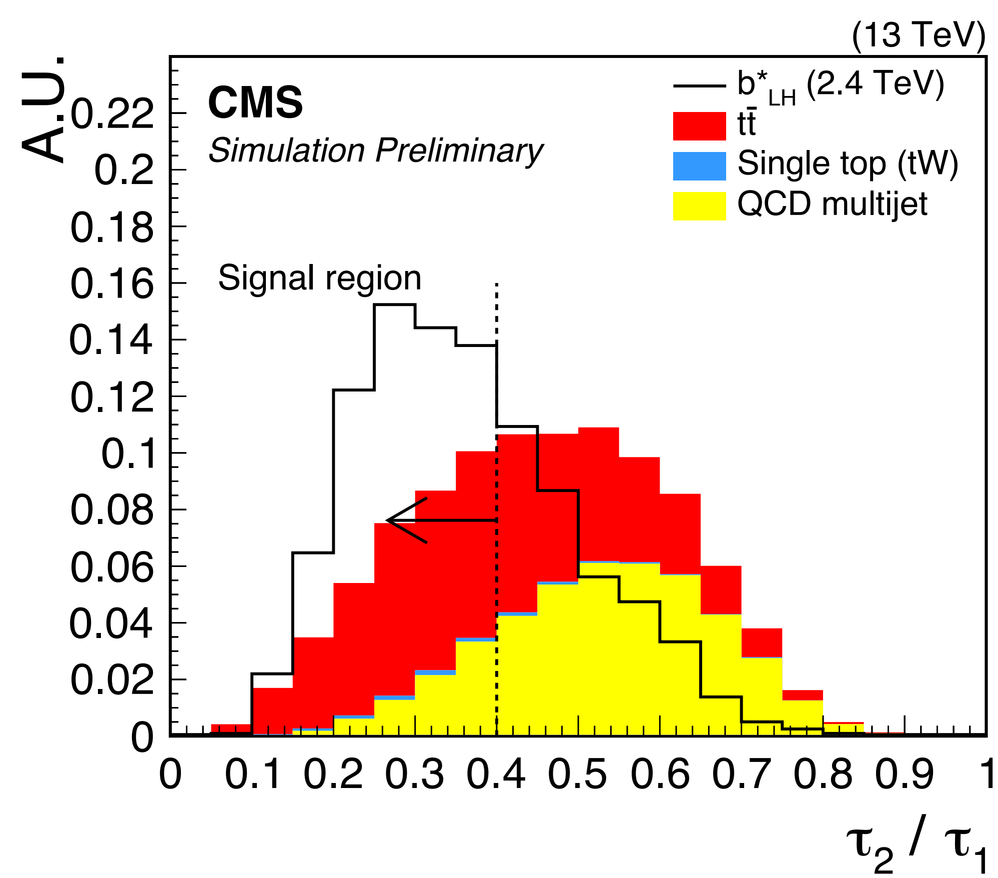


Excited $b^* \to t + W$

- High-mass excited states due to quark compositeness
- Search for back-to-back jets consistent with ***W*** & **top-quarks**
  - Top tagging: τ_3/τ_2, sub-jet ***b*-tagging**, & [105,220] GeV **mass window** → 45% signal efficiency & 3% QCD mistag rate
  - *W*-tagging: τ_2/τ_1 & [65,105] GeV **mass window** → 80% efficiency and 2% mistag rate
- Data-driven estimate of QCD by inverting top tag, and of $t\bar{t}$ by requiring a 2nd top tag



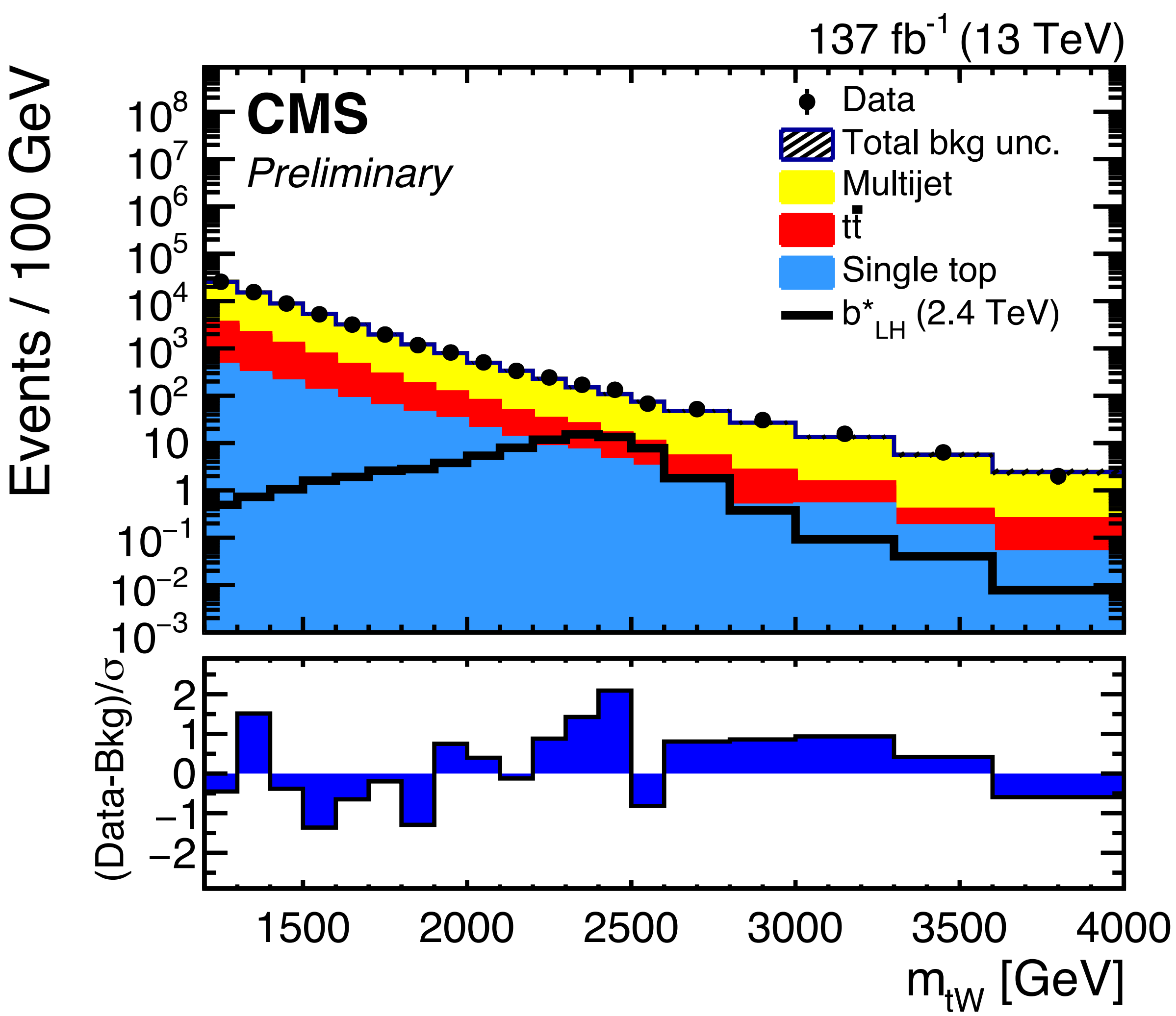
Boosted top quark = 3 prongs



Boosted *W* boson = 2 prongs

Excited $b^* \to t + W$

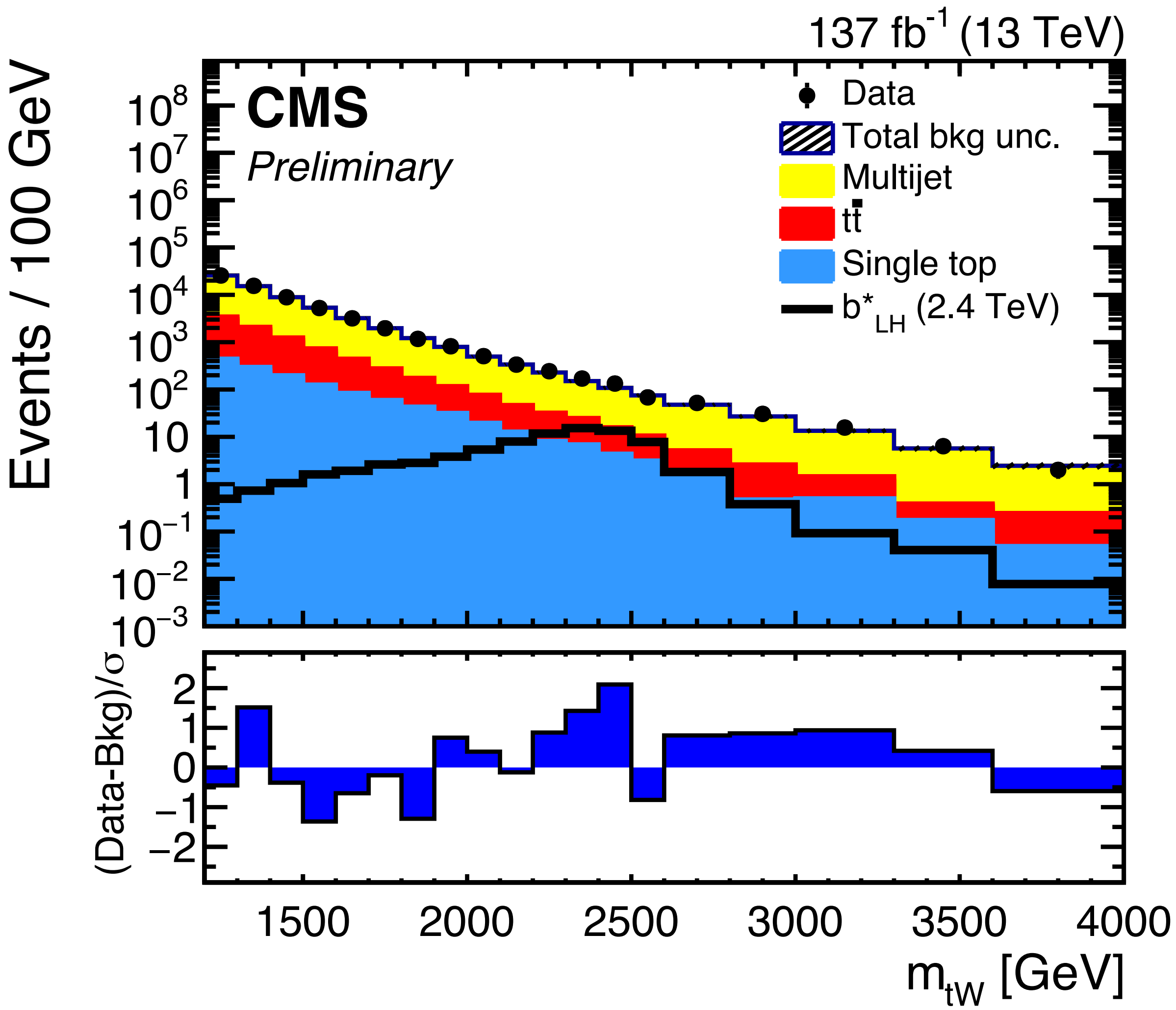
- Perform search in 2D plane of **top**-mass and **top+W** invariant mass
- Good agreement with SM, largest disagreement at 2.4 TeV (2.3σ local)



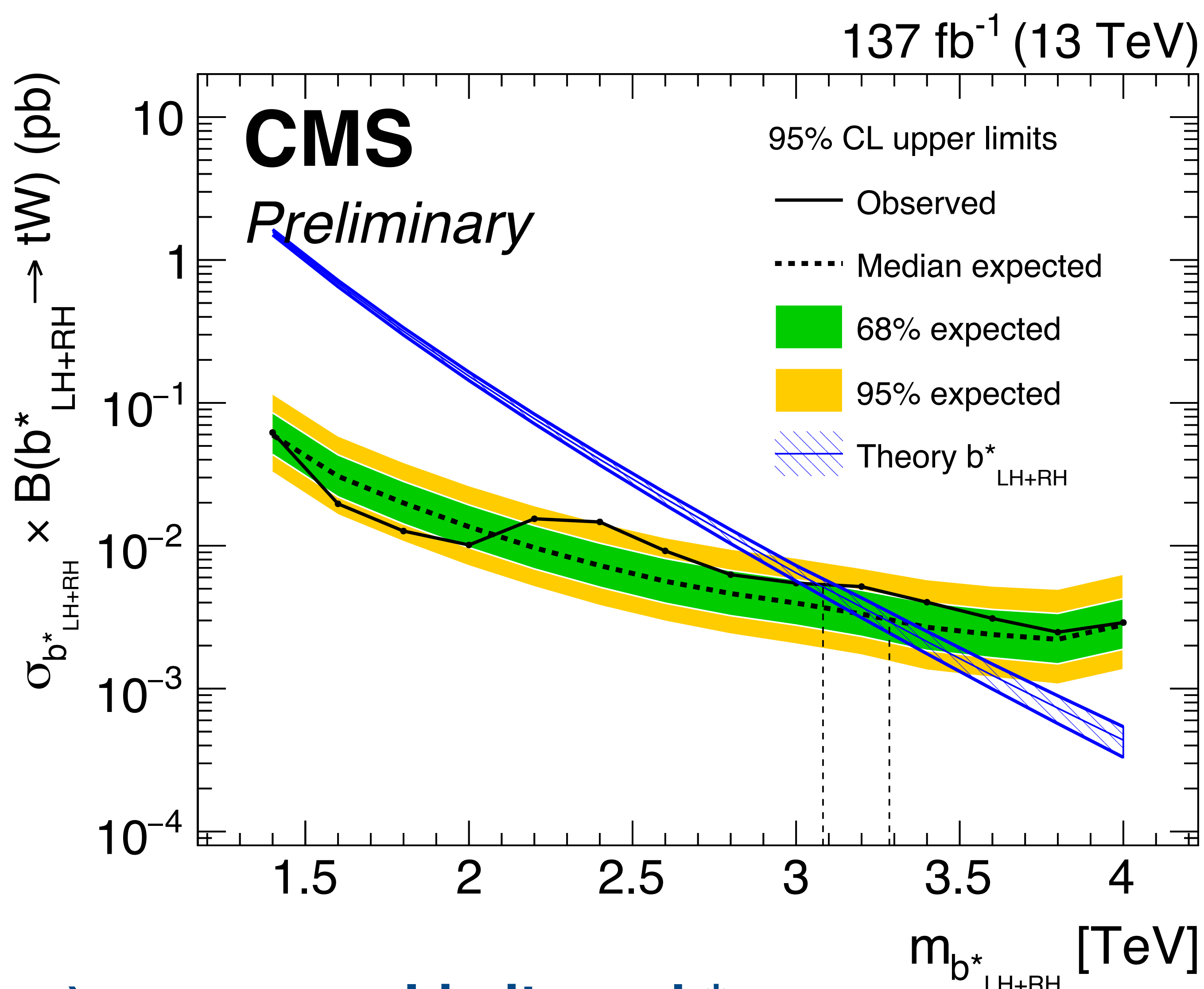
top+W mass (in central top-mass window)

Excited $b^* \to t+W$

- Perform search in 2D plane of top-mass and top+W invariant mass
- Good agreement with SM, largest disagreement at 2.4 TeV (2.3σ local)
- Exclude *b** mass up to 3.1 TeV, 10x more sensitive to *b**→t+W than dijet



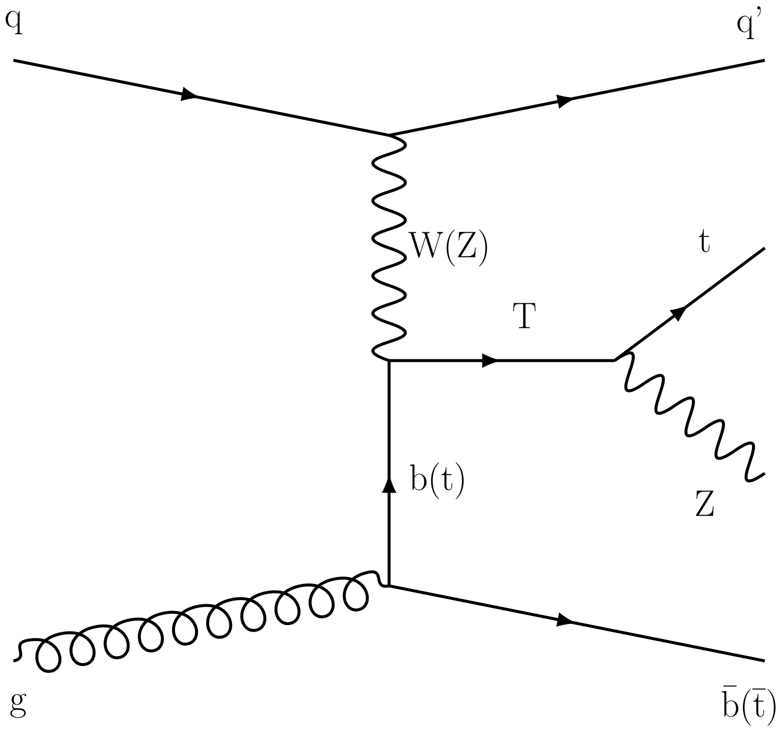
top+W mass (in central top-mass window)



Limits on b*

Vector-like quark T’→t+Z

- Similar tagging techniques for singly-produced T’ with fully-hadronic top & invisible Z→νν decays
  - Top-quark categories: **Merged** (3-prong top), **Partially Merged** (2-prong *W* + *b*-jet), & **Resolved** (3 jets)



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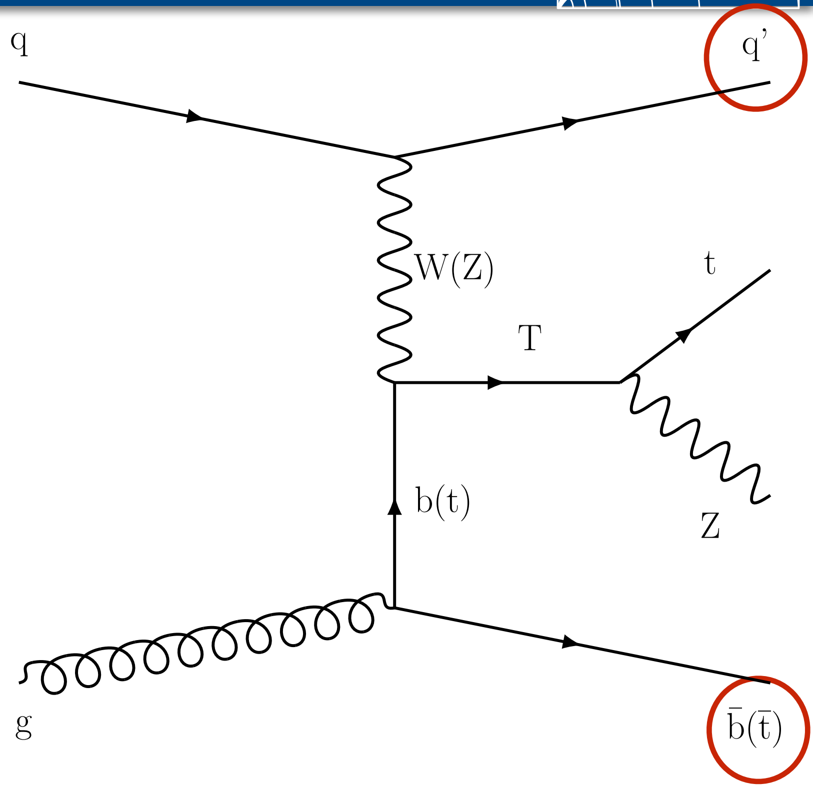
  - Discriminate on presence of **1 or more forward jets**



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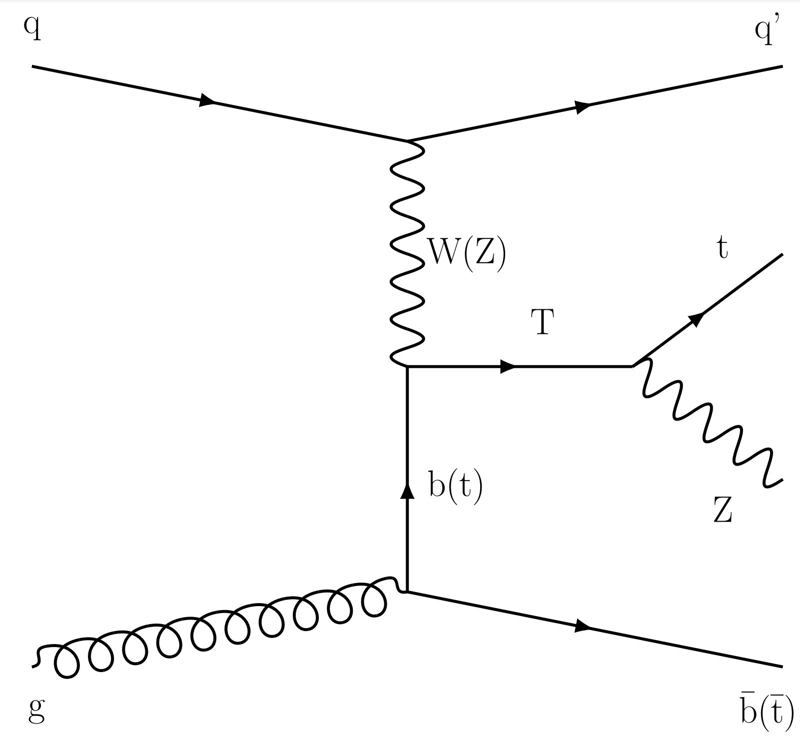
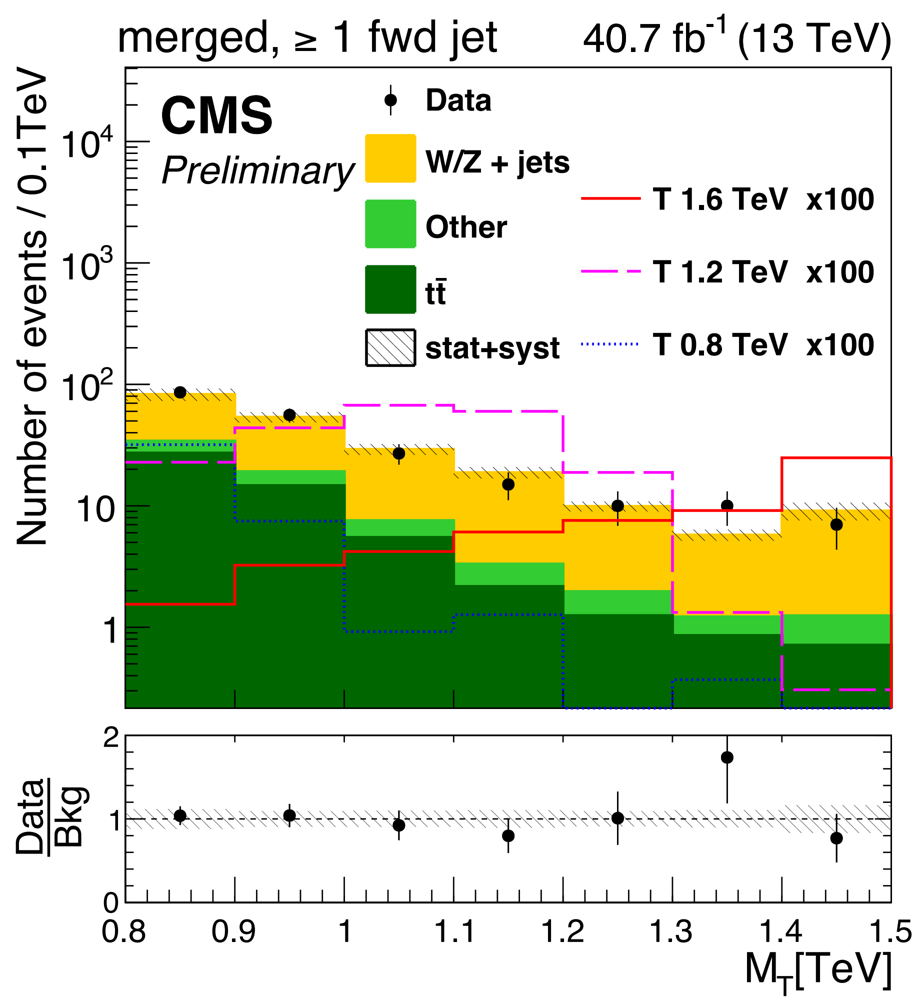
- Search within transverse mass of top + invisible *Z*





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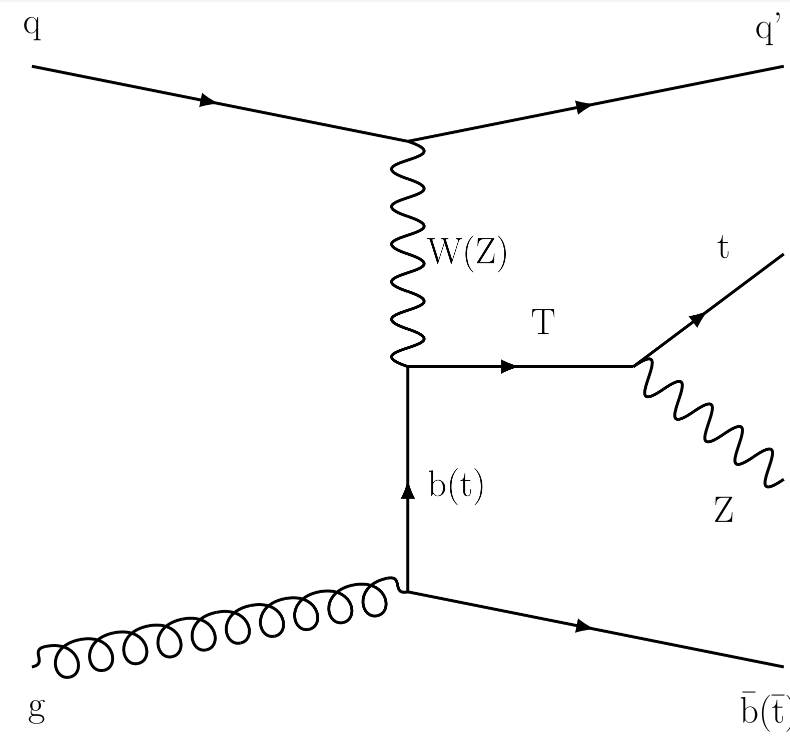
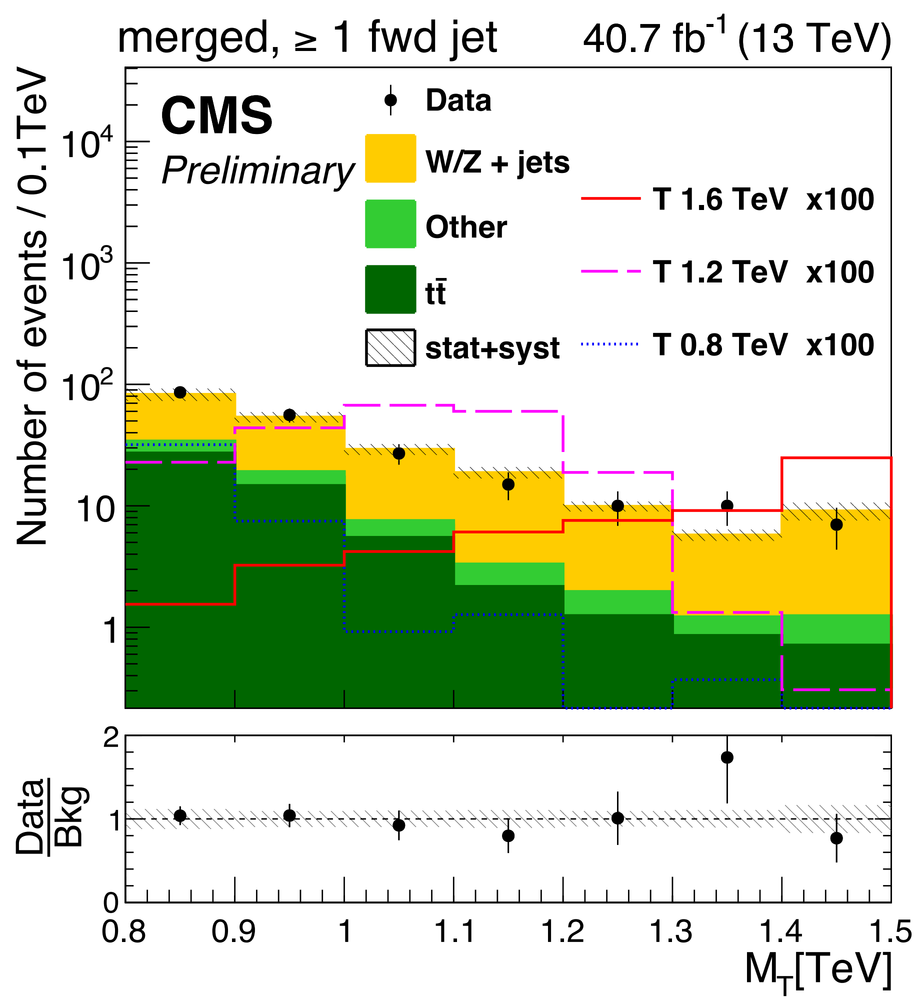
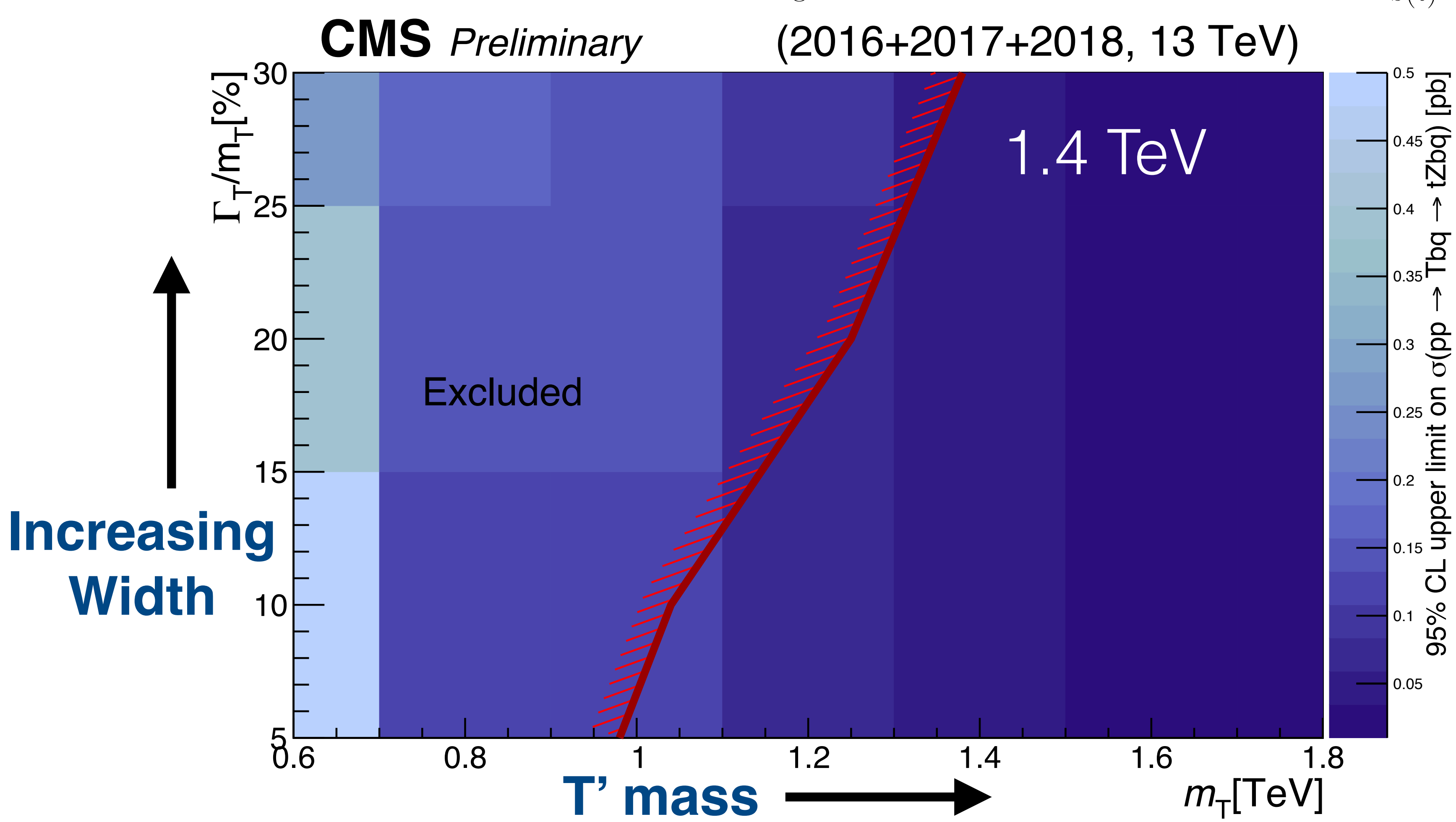
  - Top-quark categories: Merged (3-prong top), Partially Merged (2-prong *W* + *b*-jet), & Resolved (3 jets)
  - Discriminate on presence of 1 or more forward jets
- Search within transverse mass of top + invisible *Z*
- Limits set as a function of resonance width (up to 1.4 TeV)

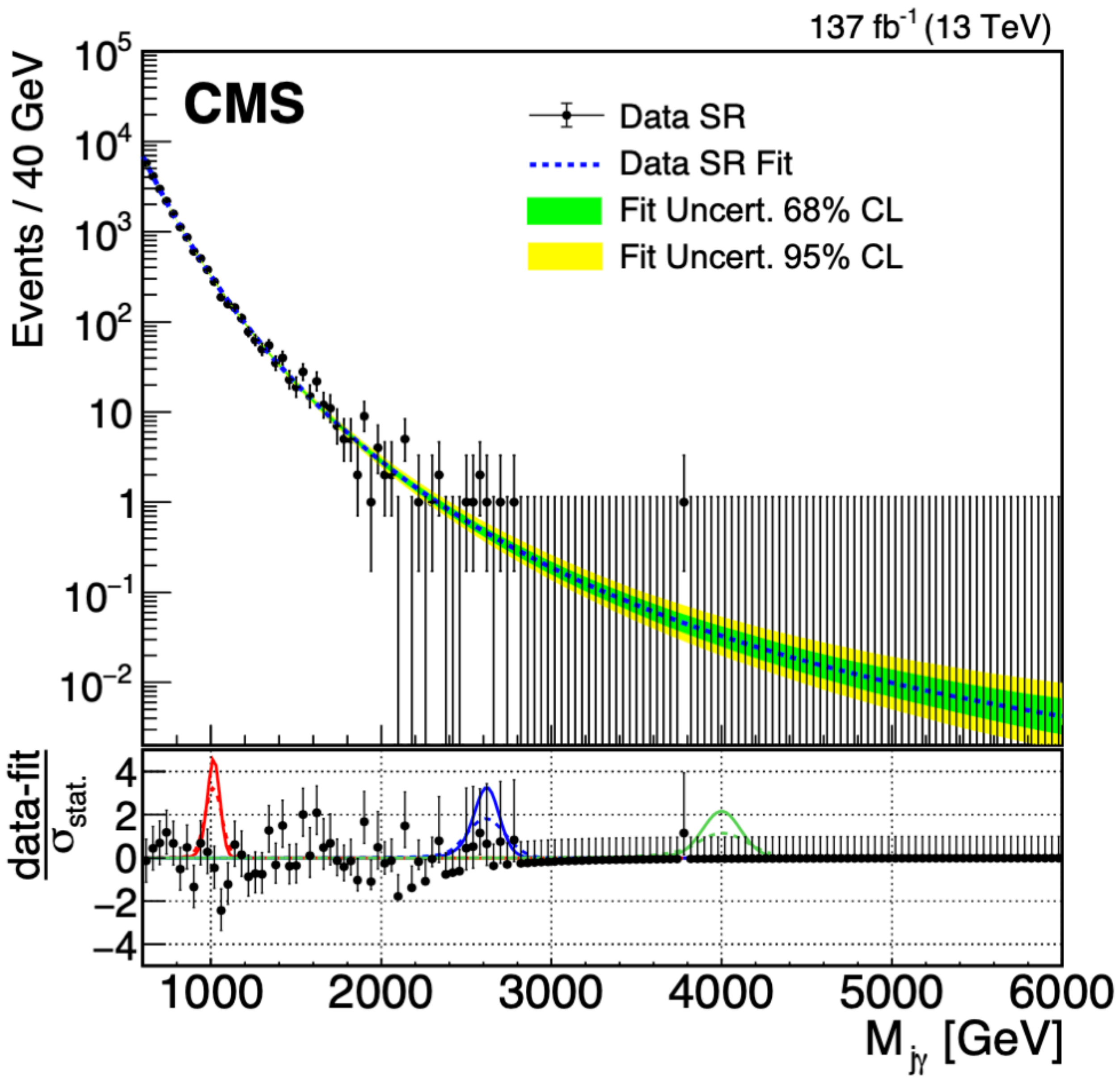






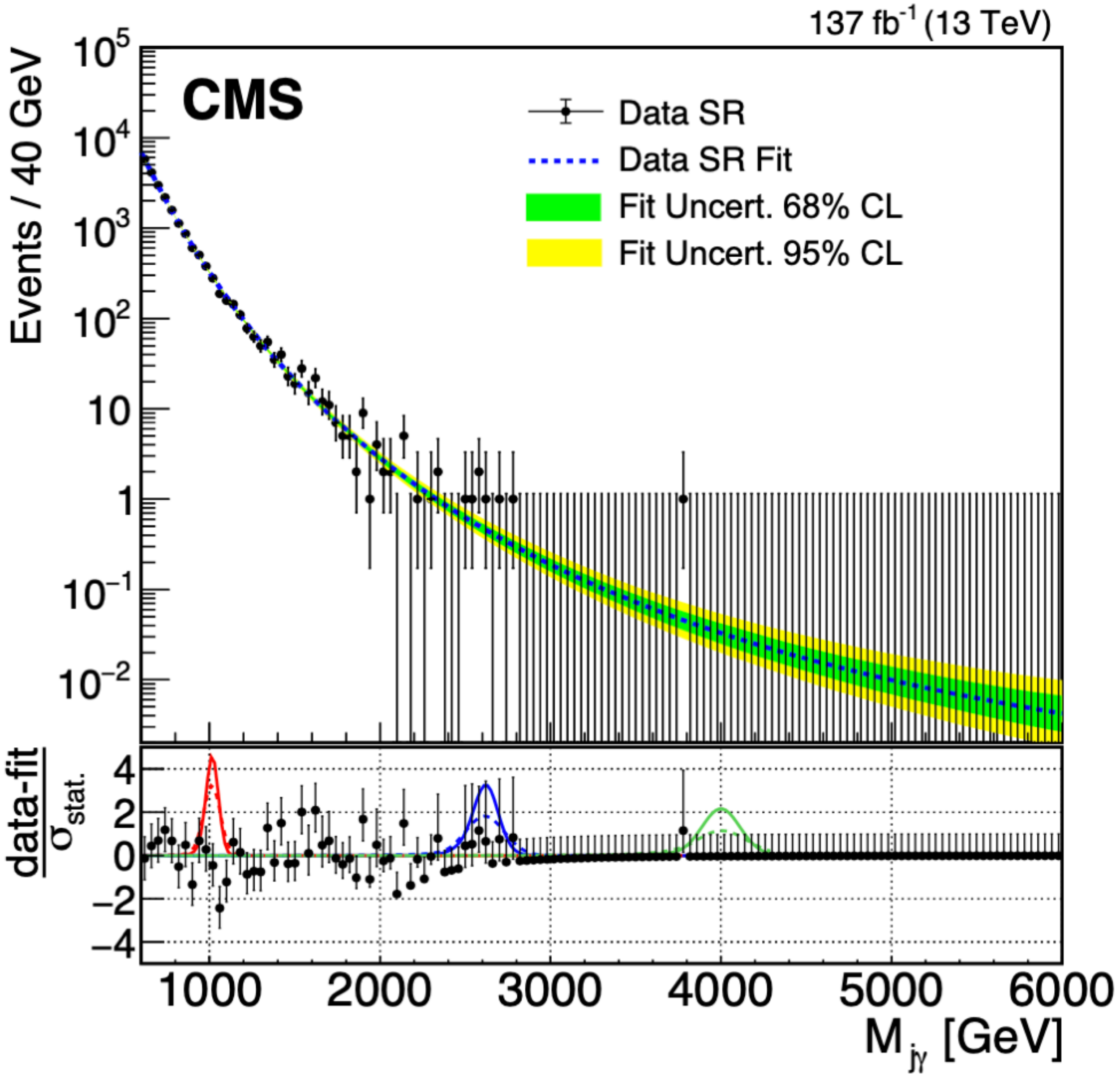
Spin-0/1 Resonances to W+γ

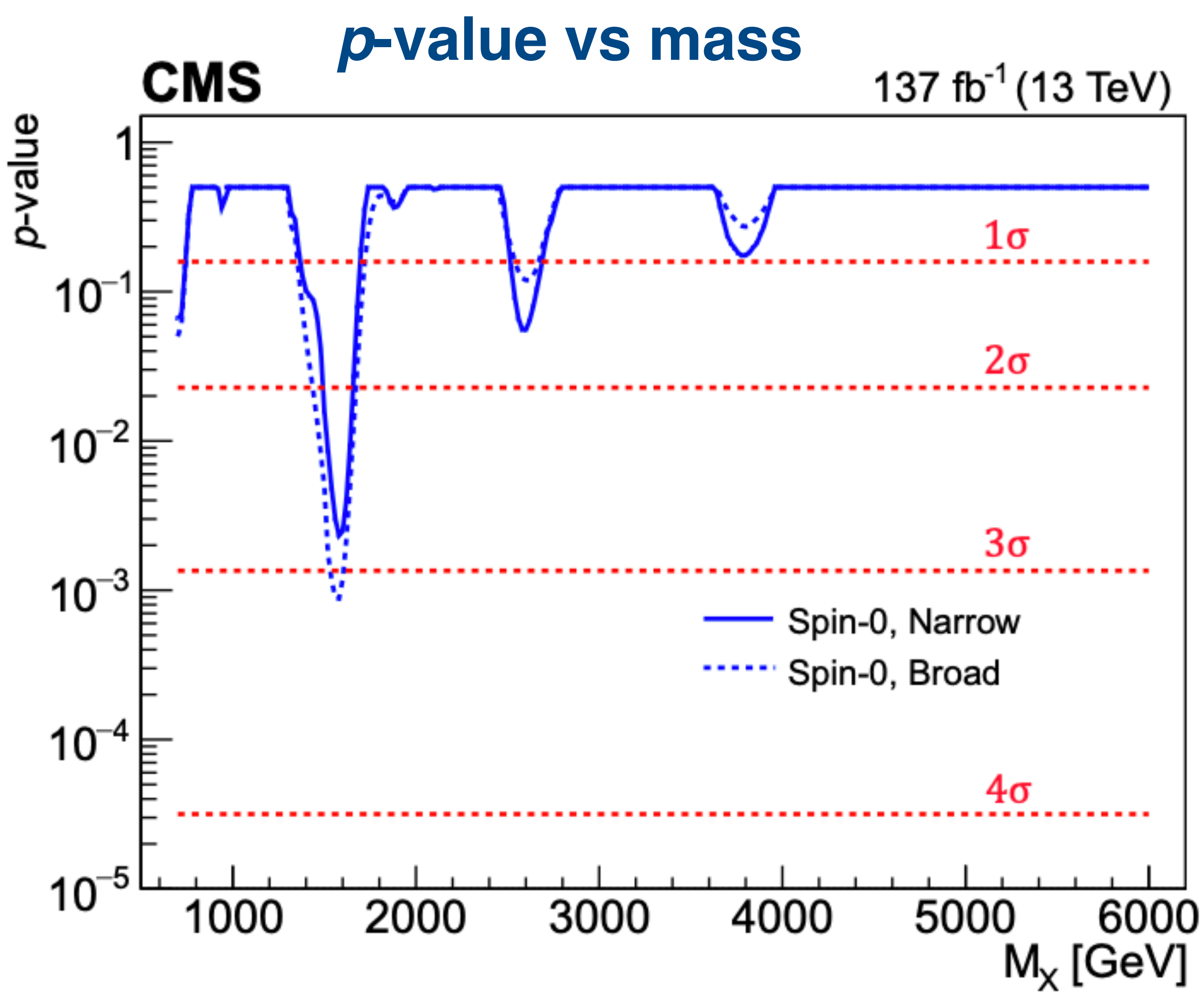
- Resonances (narrow or 5% width) decaying to photon + boosted $W \to qq$ (τ_2/τ_1 tagging)
- Data-driven fit optimized in low M_W sideband



Spin-0/1 Resonances to W+γ

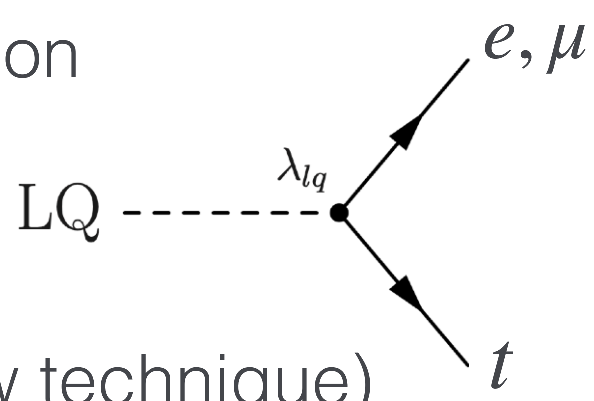
- Resonances (narrow or 5% width) decaying to photon + boosted $W \rightarrow qq$ (τ_2/τ_1 tagging)
- Data-driven fit optimized in low M_W sideband
- Largest excess at ~1.6 TeV (1.7σ global)
  - Limits set on XS of Spin-0 or 1 resonances

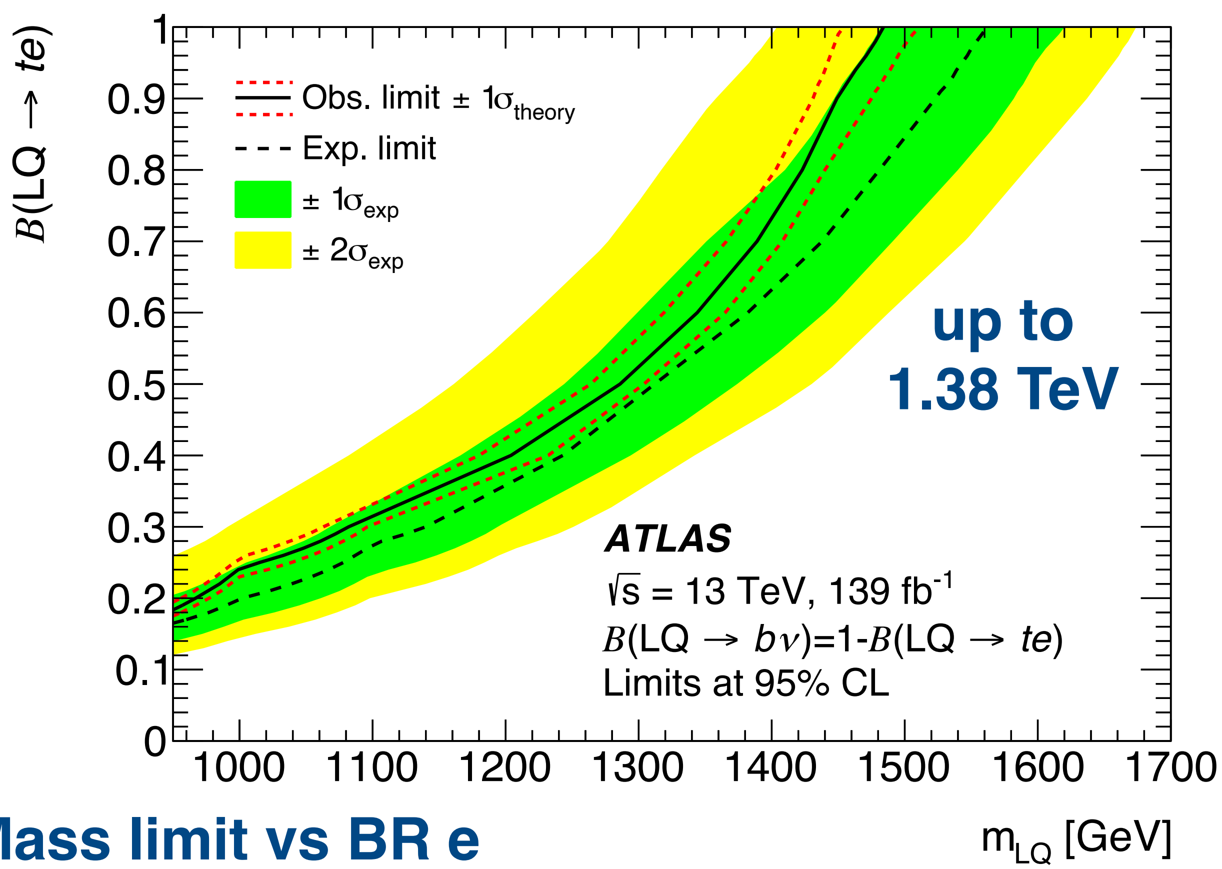




Top-philic Leptoquarks

- Leptoquarks - possible source of lepton-flavor-universality violation
- Cross-generational LQ→t+e/μ identifies boosted tops via τ_3/τ_2 & other splitting-scale observables
  - Input to BDT with kinematics in LQ restframe (Recursive Jigsaw technique)
  - Limits set as a function of decay branching fraction to leptons

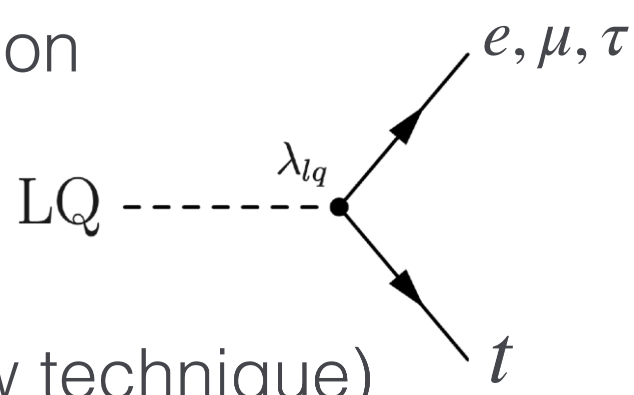


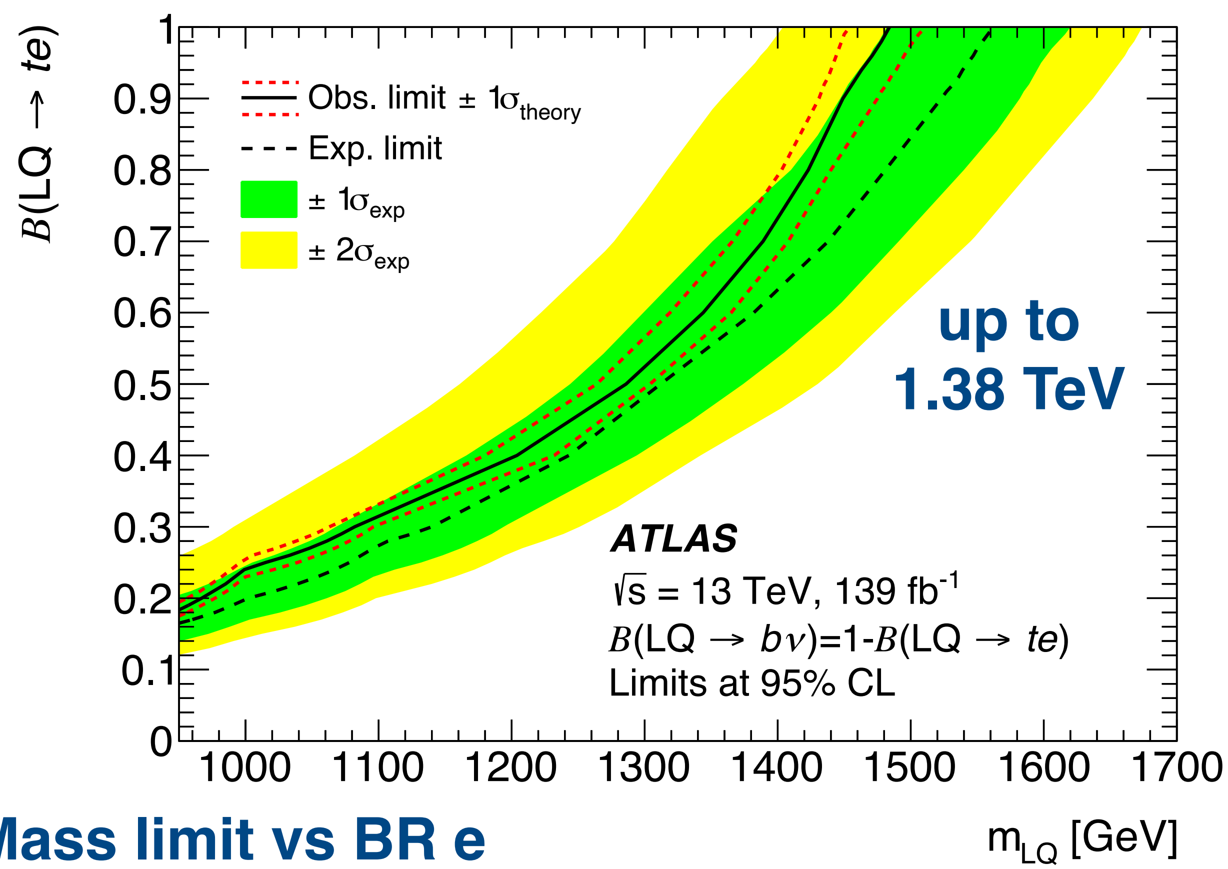


Mass limit vs BR e

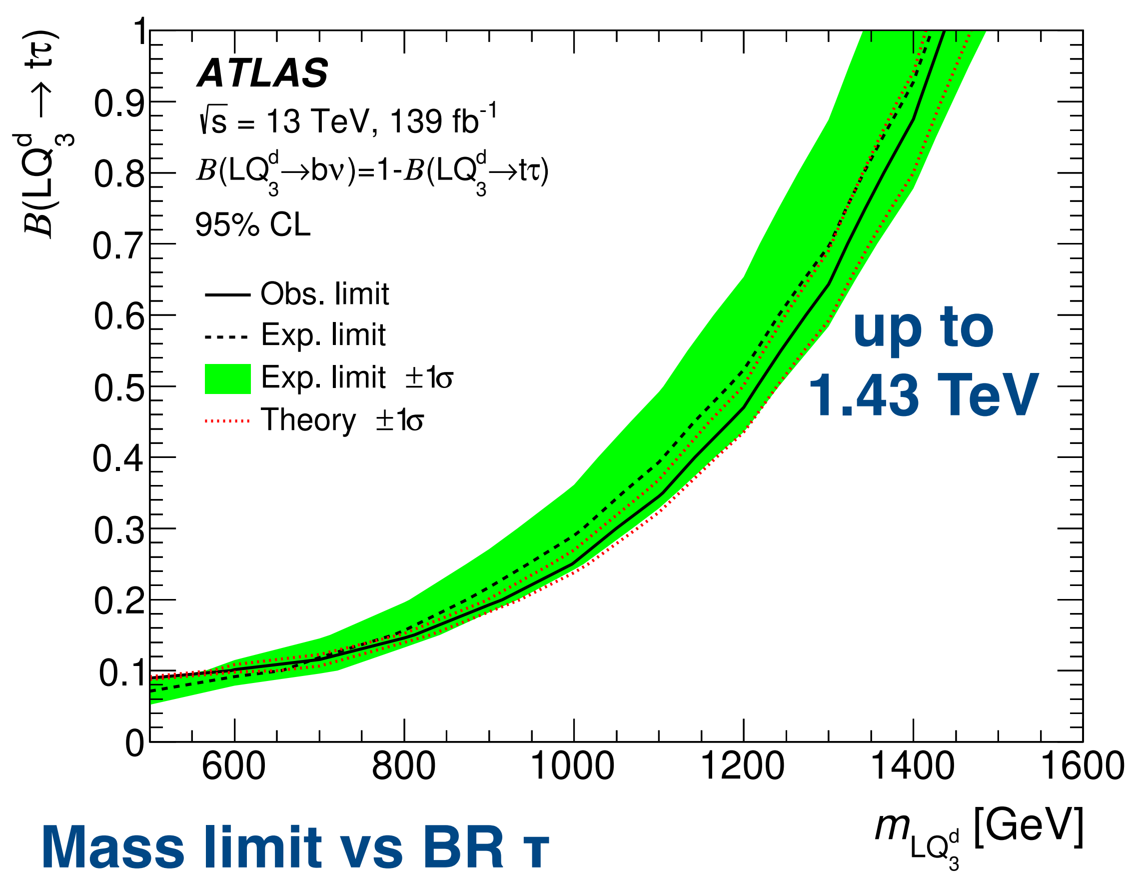
Top-philic Leptoquarks

- Leptoquarks - possible source of lepton-flavor-universality violation
- Cross-generational LQ→t+e/μ identifies boosted tops via τ_3/τ_2 & other splitting-scale observables
  - Input to BDT with kinematics in LQ restframe (Recursive Jigsaw technique)
  - Limits set as a function of decay branching fraction to leptons
- Complements down-type LQ→t+τ search (both hadronic & leptonic decays)
  - Searches within 6 final states according to # of e, μ, or τ_{had} & their charges





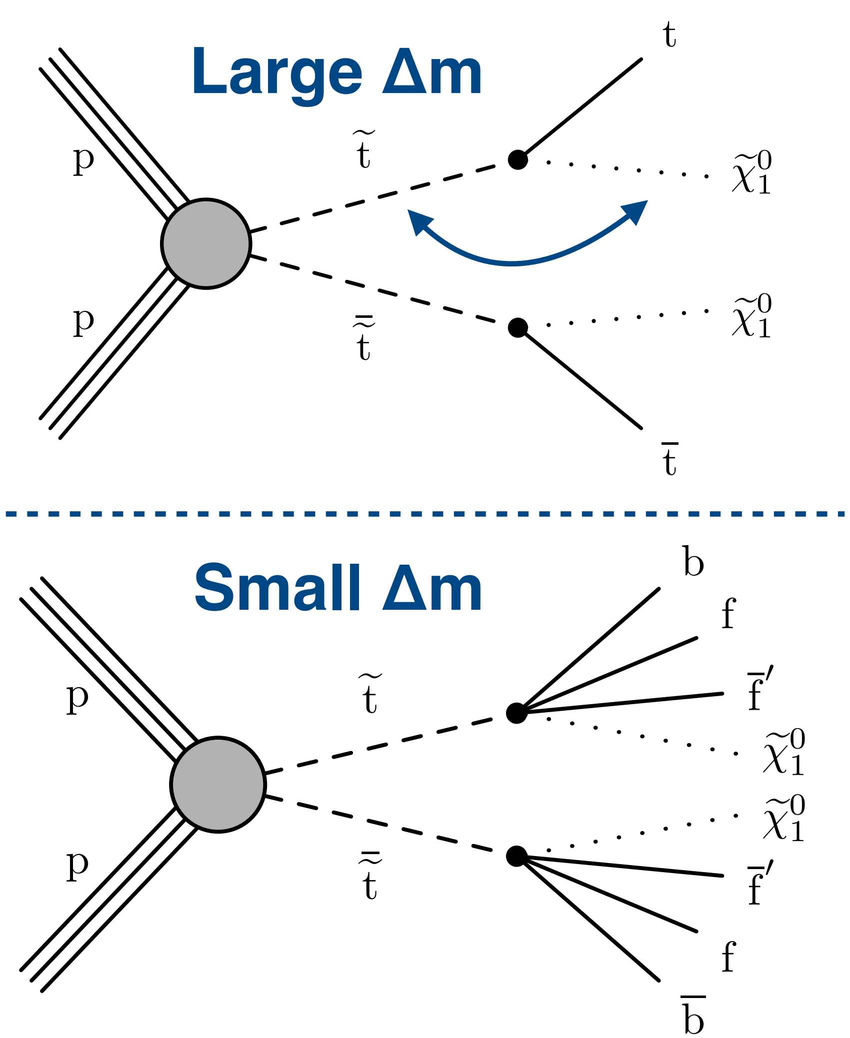
Mass limit vs BR e



Mass limit vs BR τ

Searching Across Mass Splittings

- RPC top squark decay, kinematics depend upon Δm
- Large cut-&-count search using # jets (in tagged categories) & event kinematics



Searching Across Mass Splittings

- RPC top squark decay, kinematics depend upon Δm
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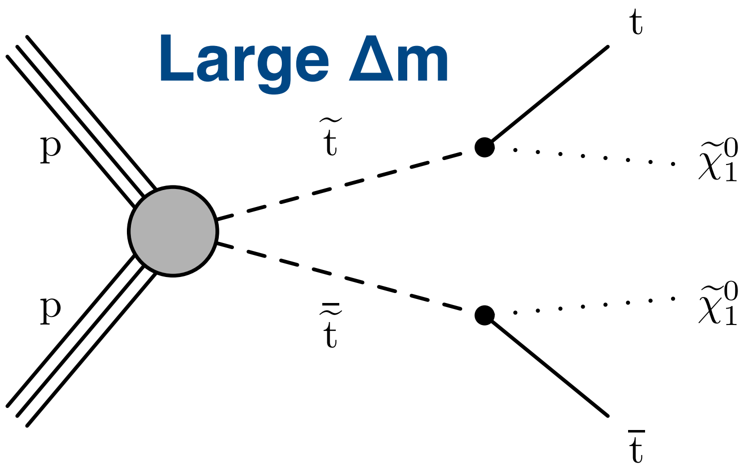
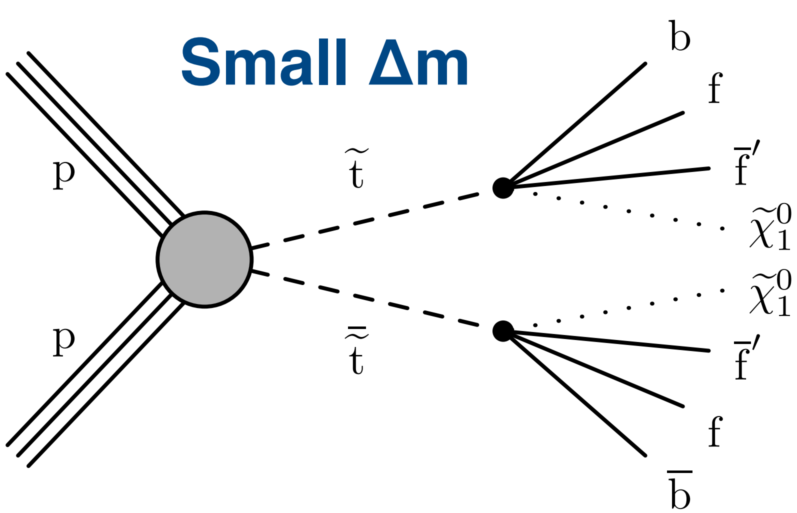
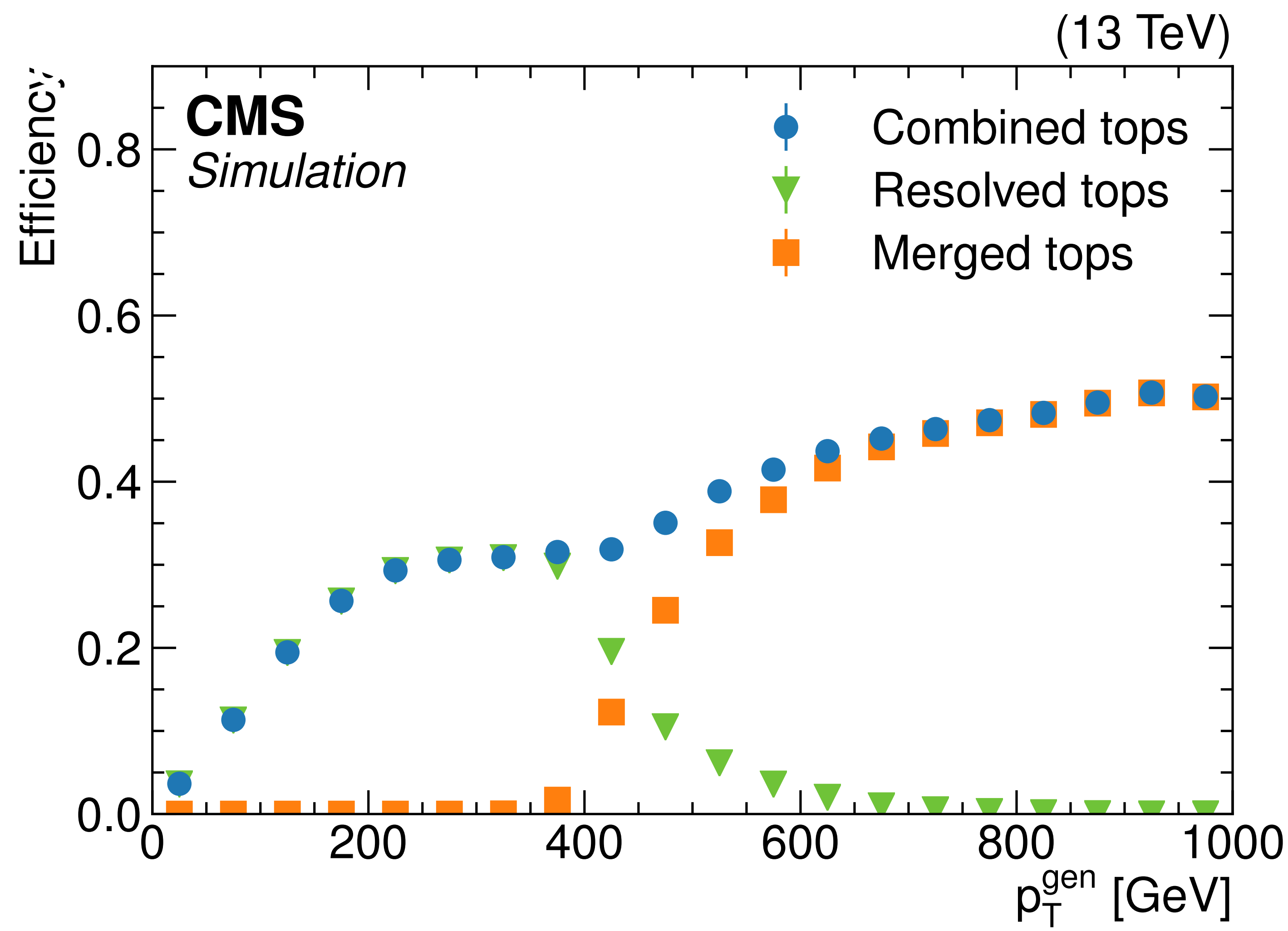
  - 3 distinct deep NNs identify boosted top or W, resolved tops (3 jets), & b-tagged jets
  - Small Δm uses soft secondary-vertex b-tagging & ISR boost to enhance E_T^{miss}





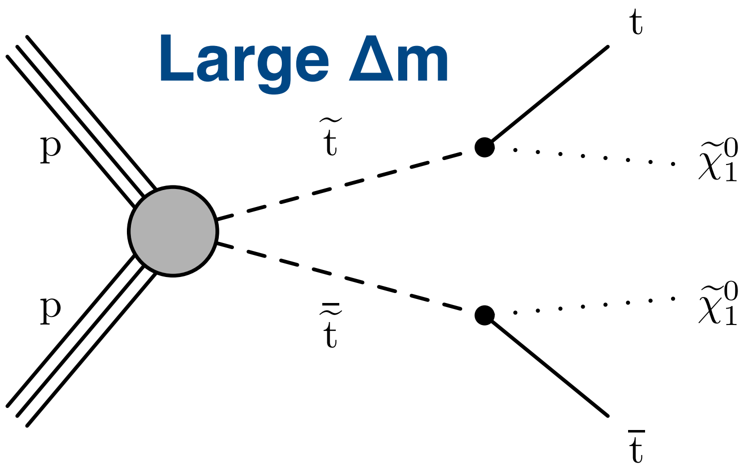


Complementarity of boosted & resolved top-quark DNNs

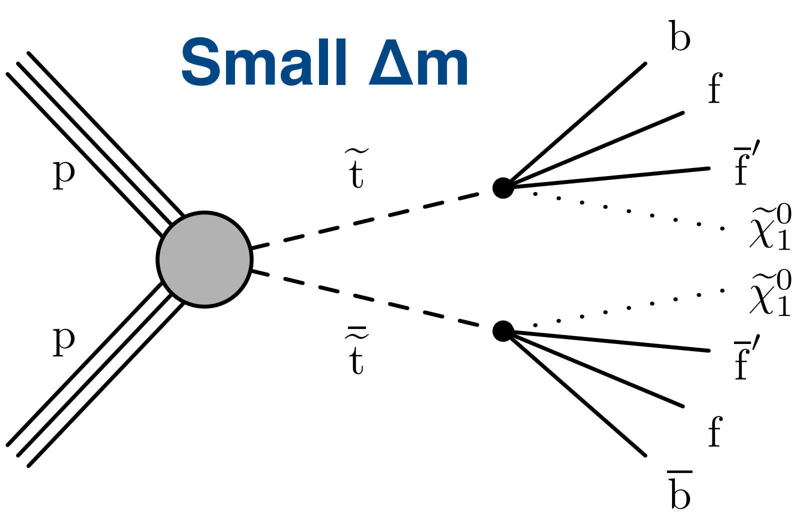
Searching Across Mass Splittings

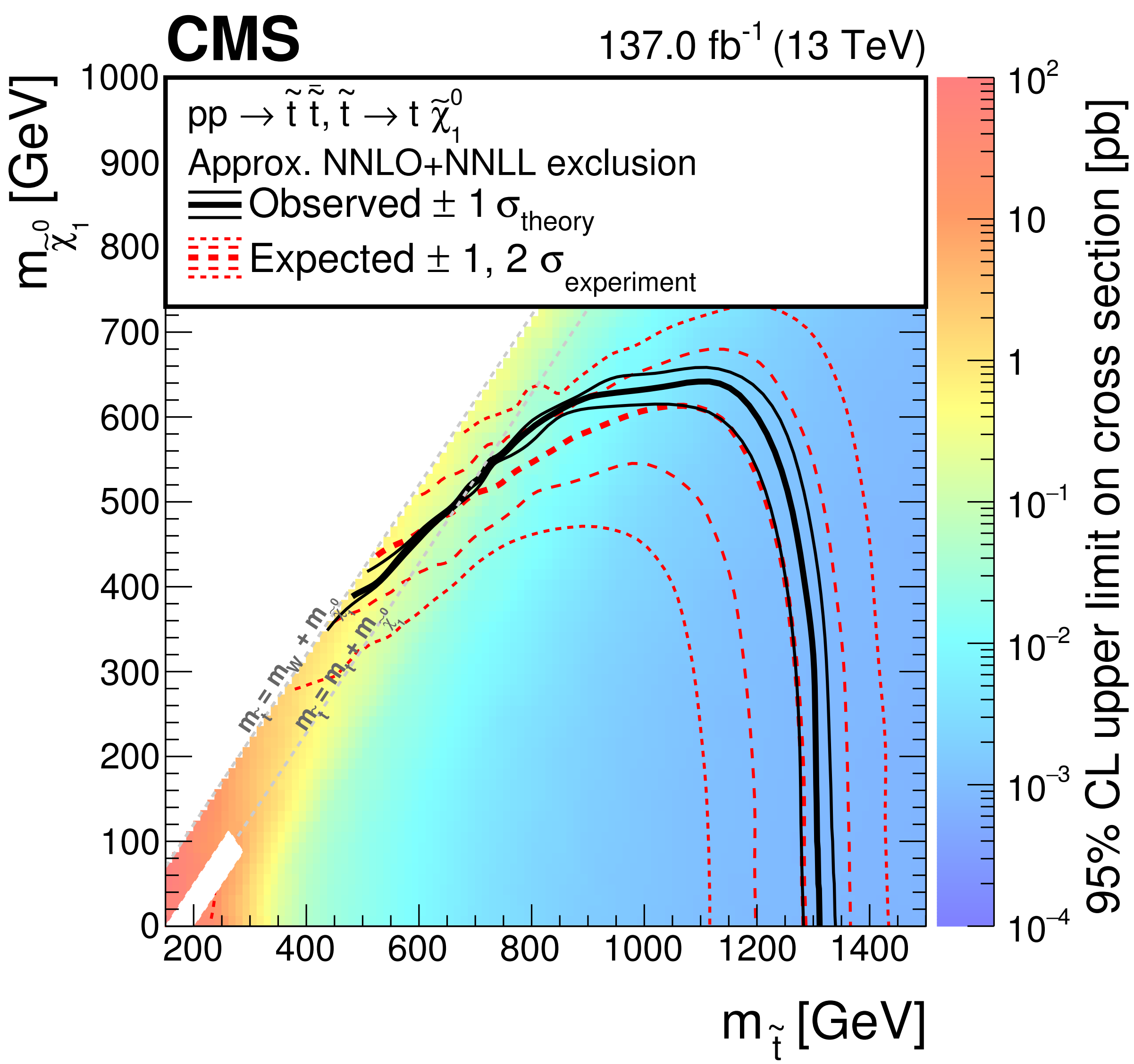
- RPC top squark decay, kinematics depend upon Δm
- Large cut-&-count search using # jets (in tagged categories) & event kinematics
  - 3 distinct deep NNs identify boosted top or W, resolved tops (3 jets), & b-tagged jets
  - Small Δm uses soft secondary-vertex b-tagging & ISR boost to enhance E_T^{miss}
- Mass limits set on gluinos (2.25 TeV) & top squarks (1.31 TeV), **down to Δm of 10 GeV**

Large Δm



Small Δm

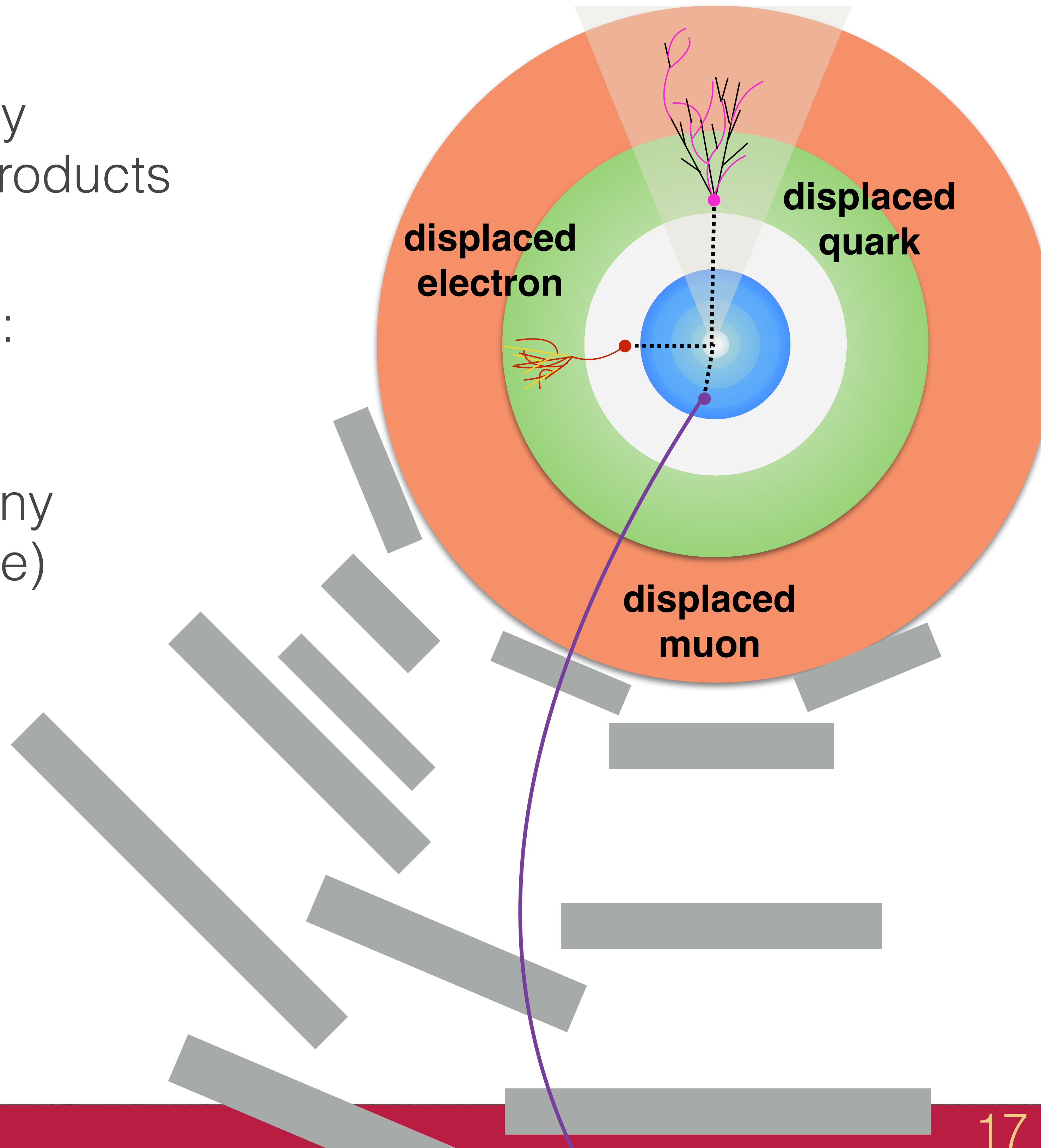




Strong limits on RPC top squarks

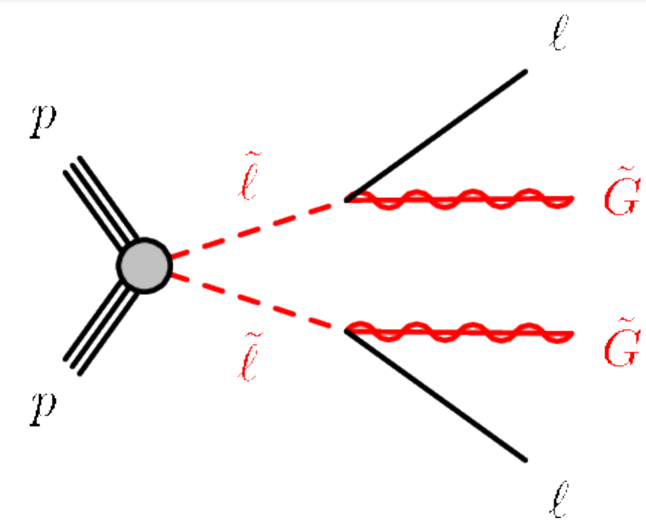
Long-lived Particle Searches

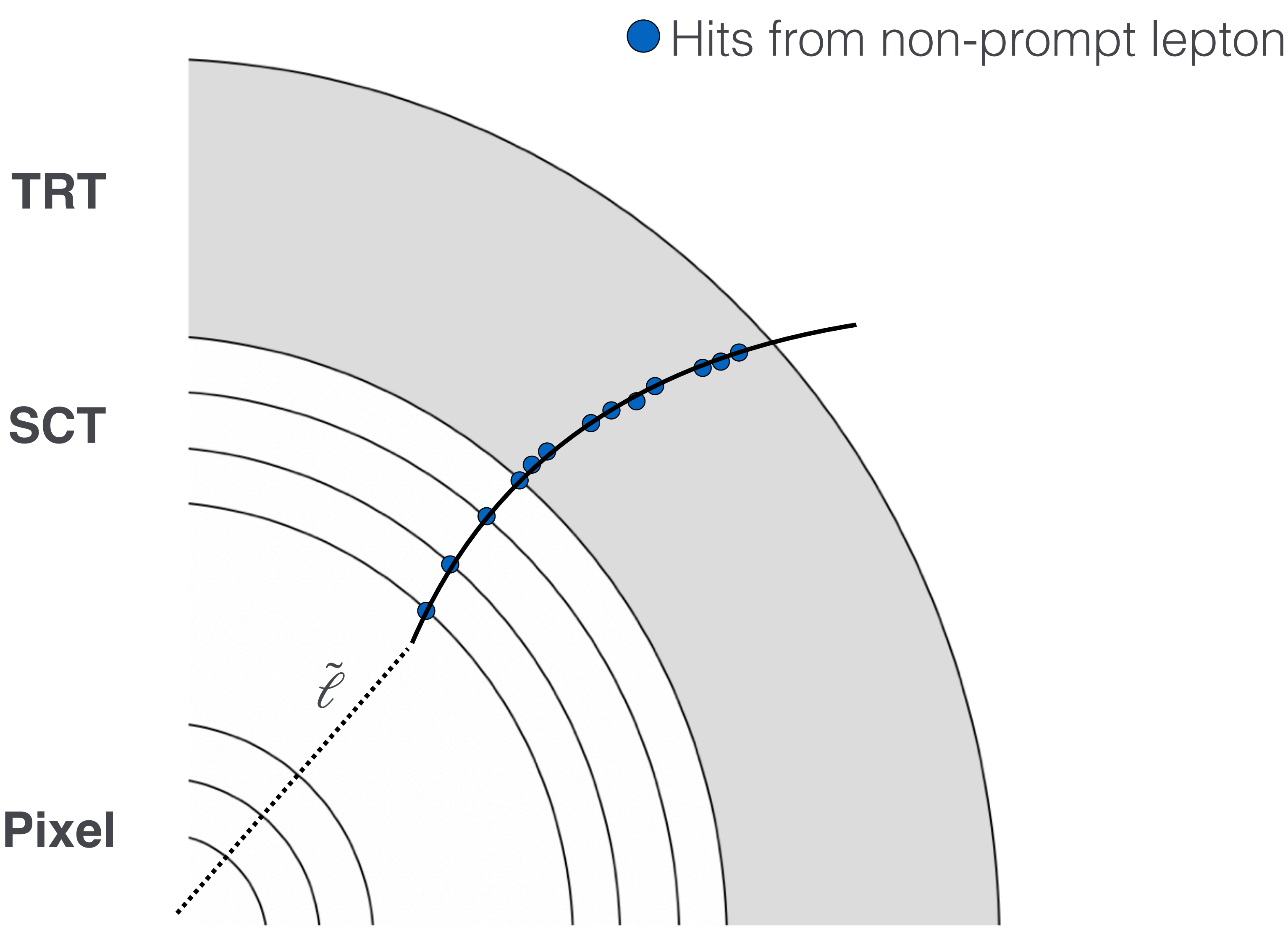
- **New techniques needed** to identify displaced decay vertex & decay products
- **No typical SM backgrounds**, use data-driven techniques to estimate:
    - Cosmic muons
    - Combinatoric backgrounds (many pileup collisions & detector noise)
    - Reconstruction failures



Displaced Leptons

- Long-lived $\tilde{\ell}$ unexplored since LEP (90 GeV limits)
- Extended tracking ignores hits from prompt tracks (<10mm)





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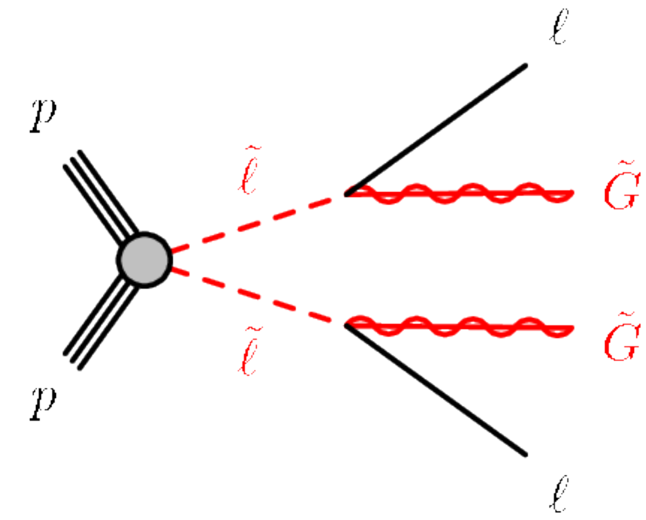

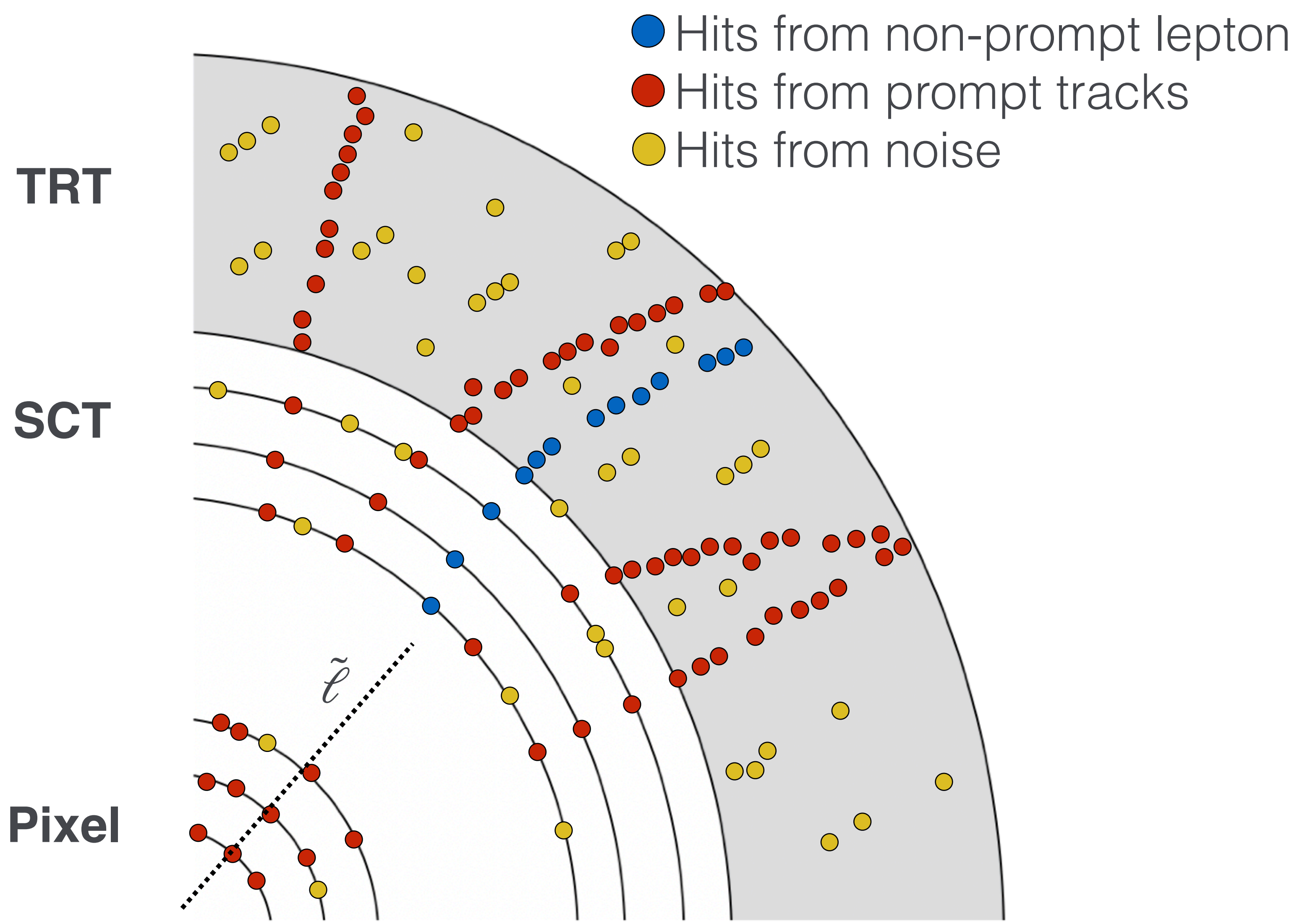

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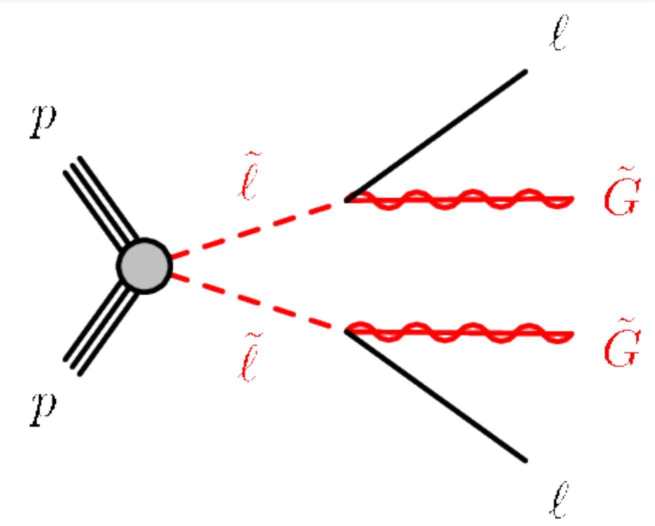

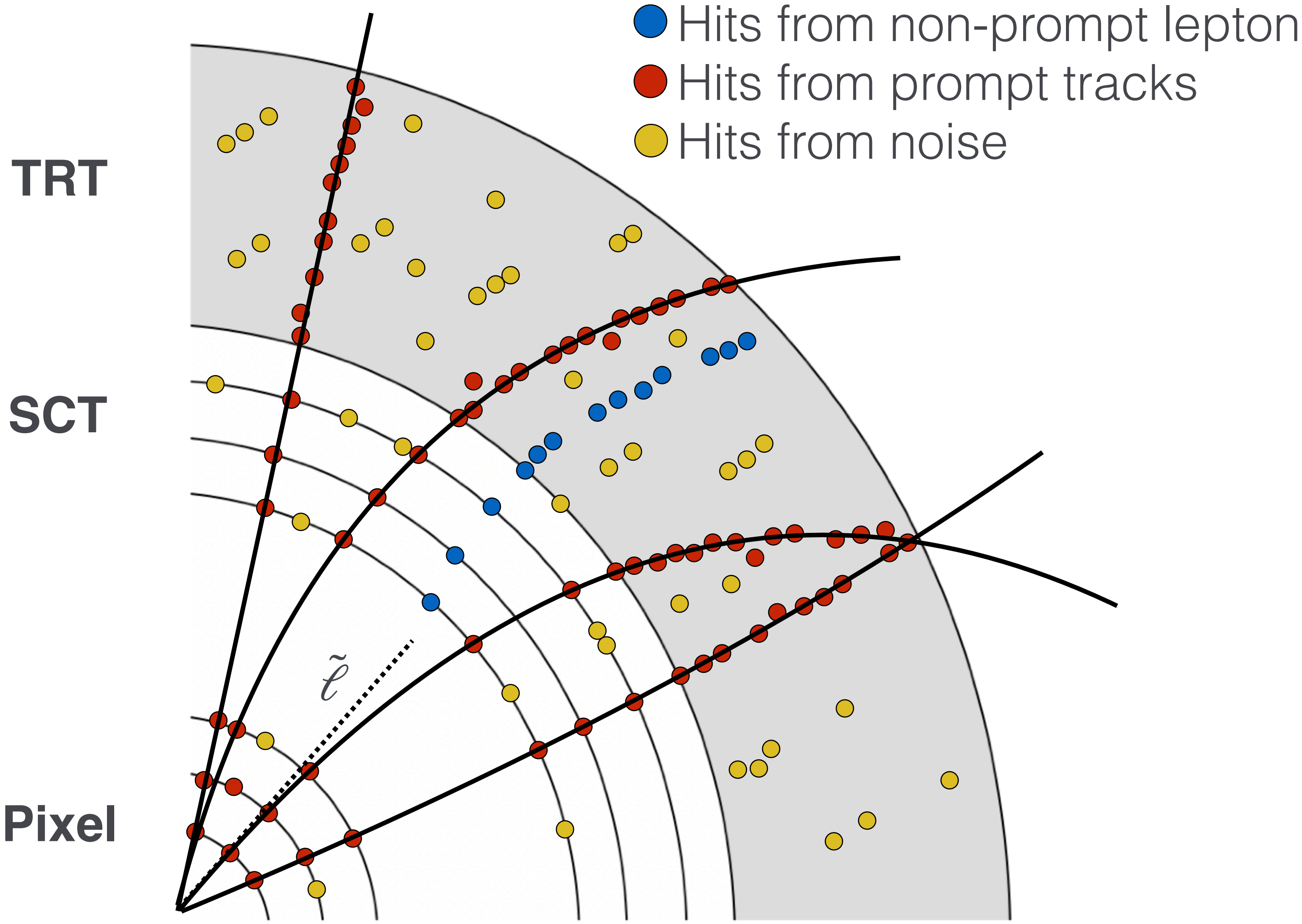

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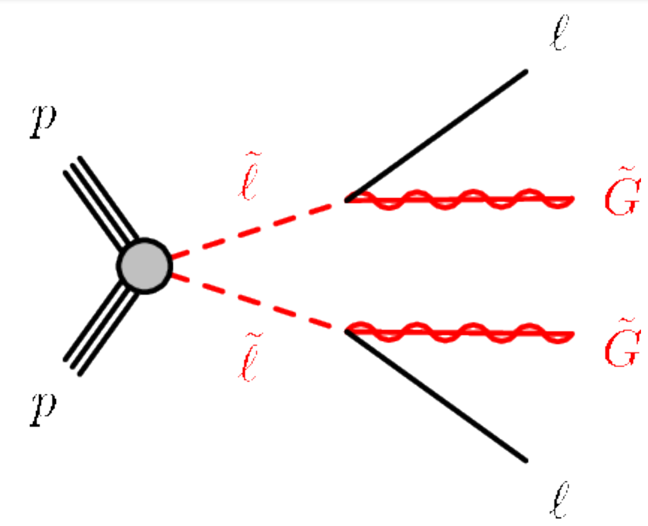
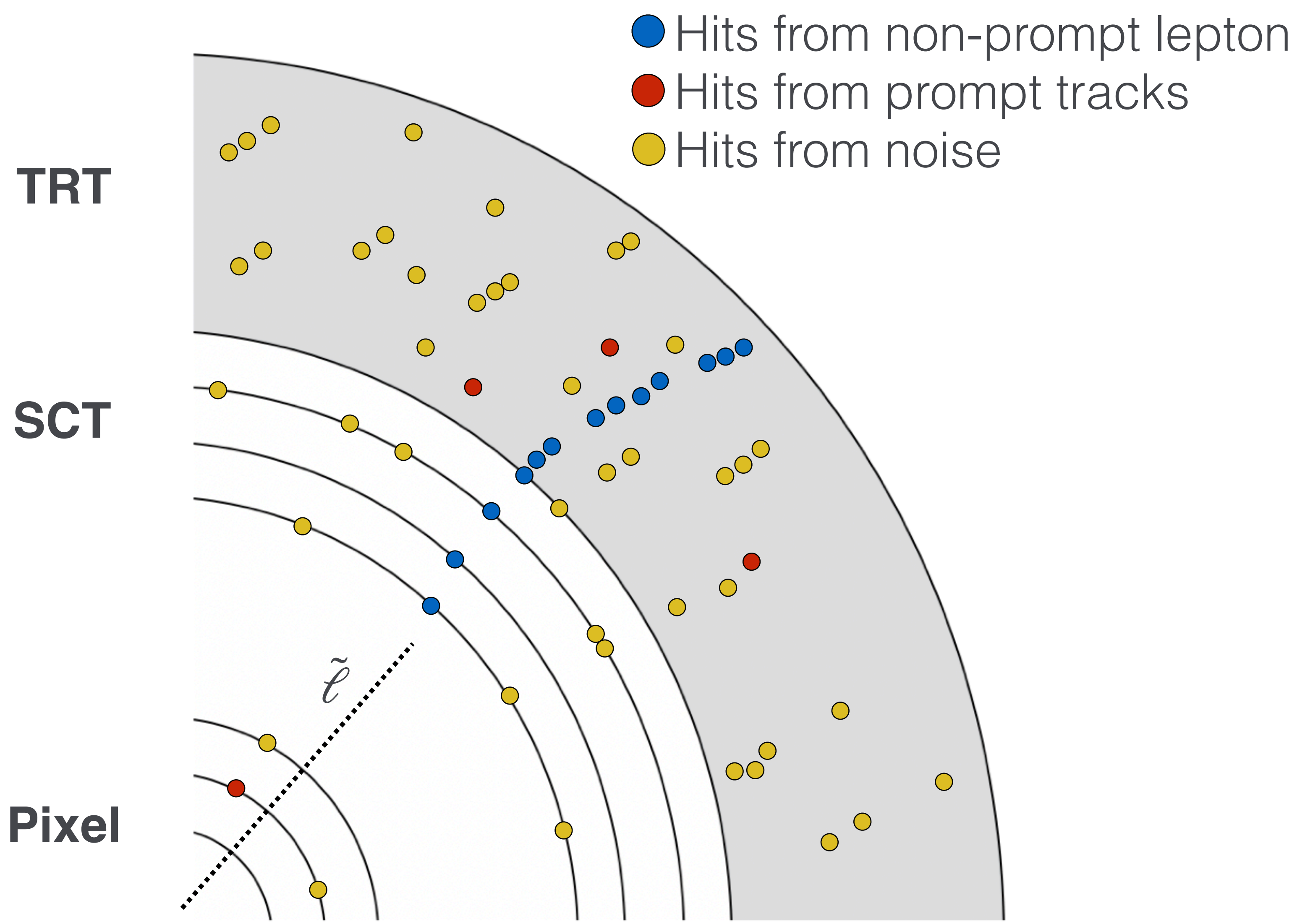
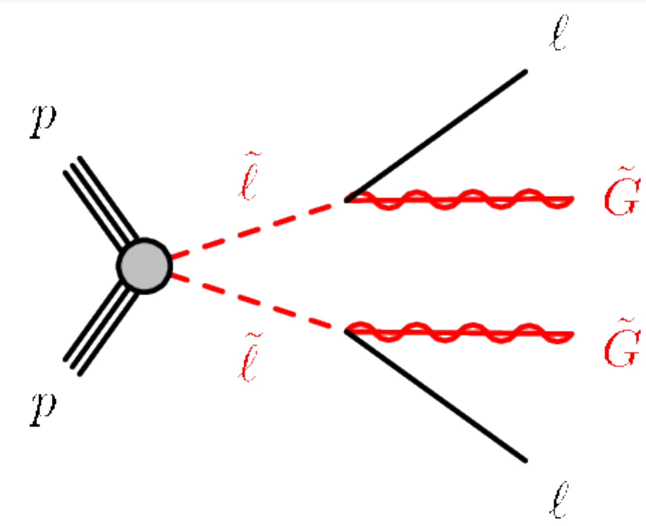


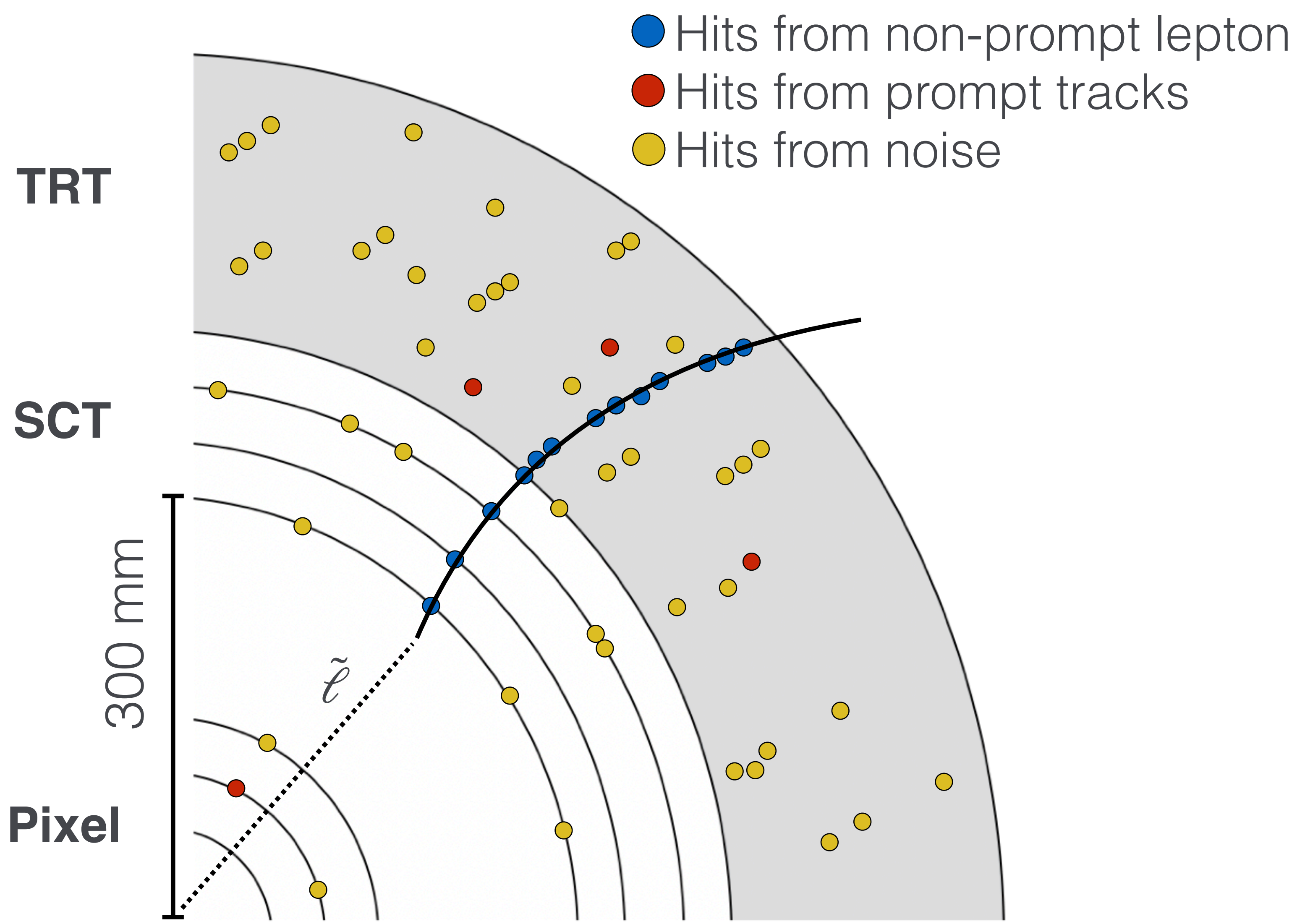


Displaced Leptons

ATLAS EXPERIMENT

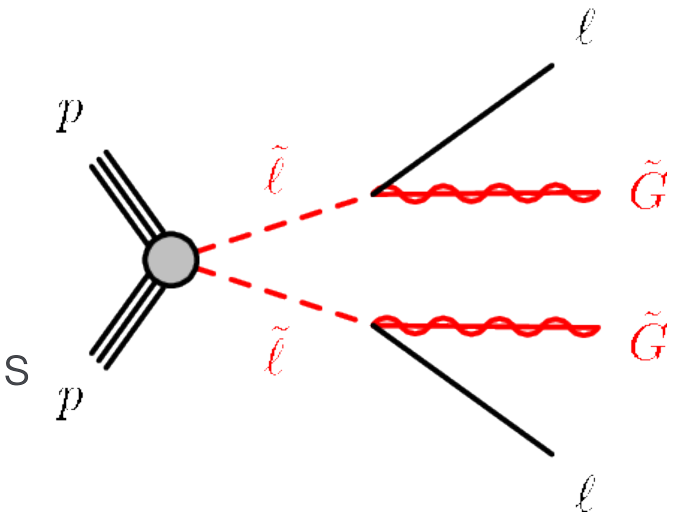
- Long-lived $\tilde{\ell}$ unexplored since LEP (90 GeV limits)
- Extended tracking ignores hits from prompt tracks (<10mm)
  - New lepton identification out to 300 mm

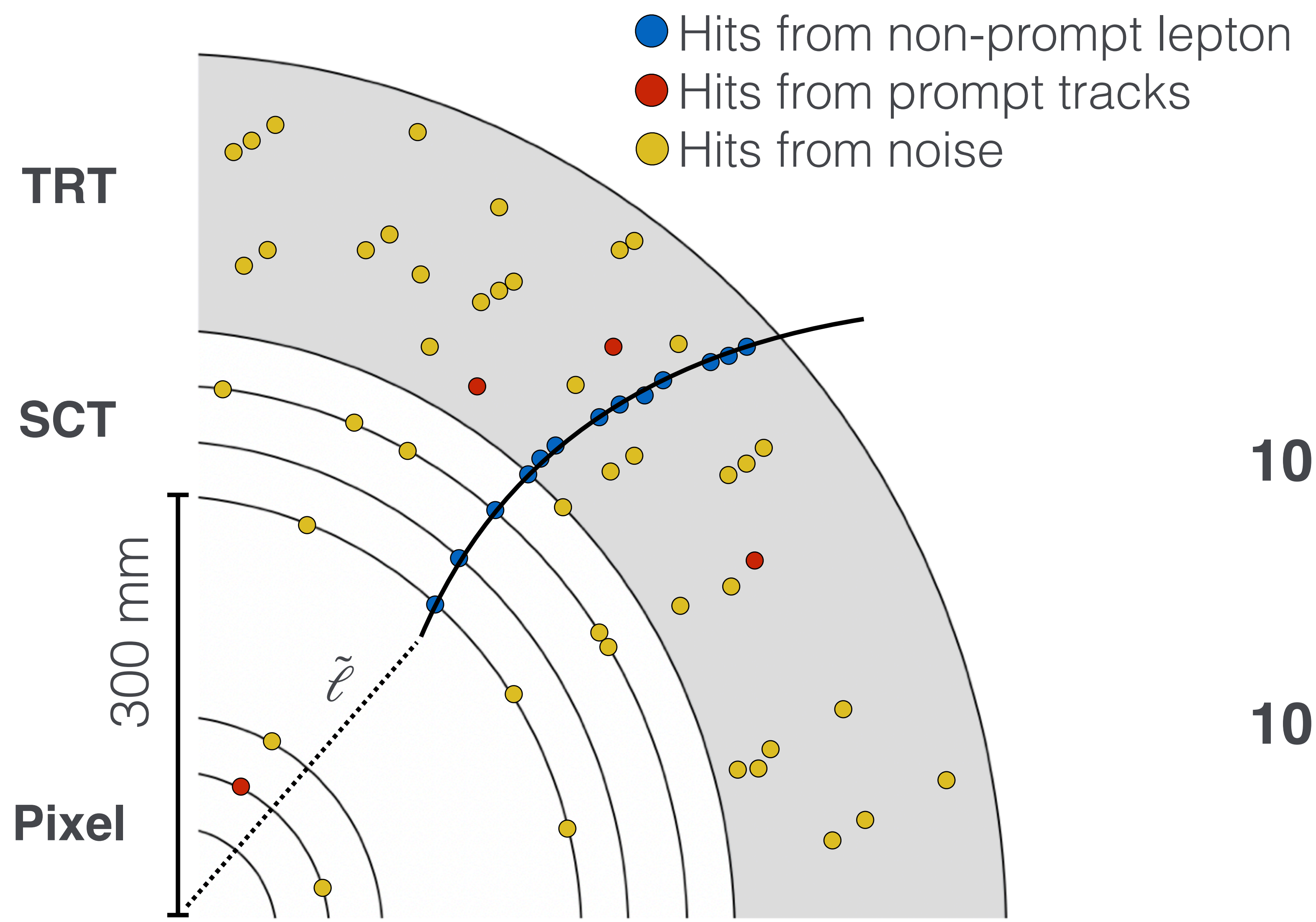


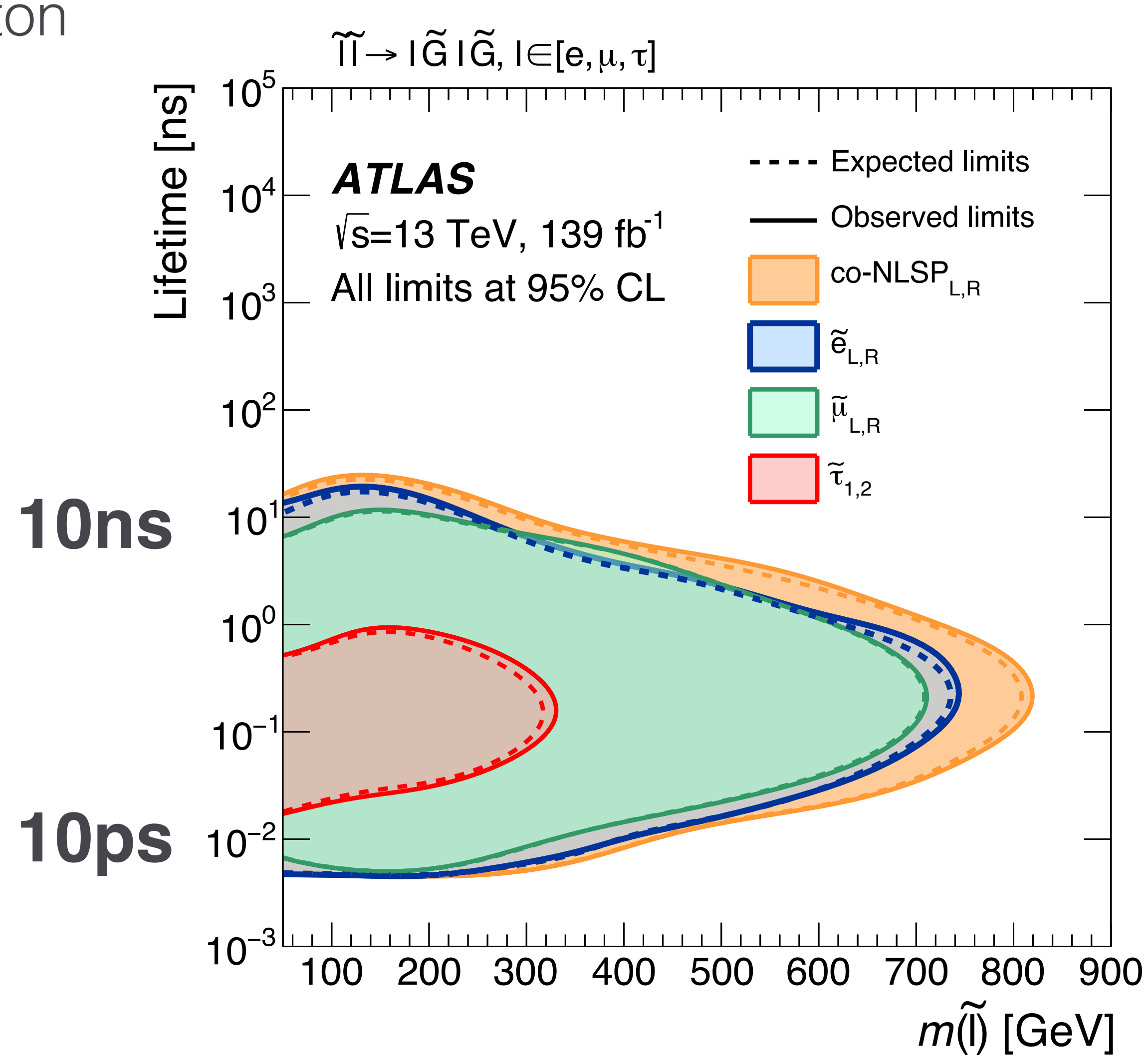


Displaced Leptons

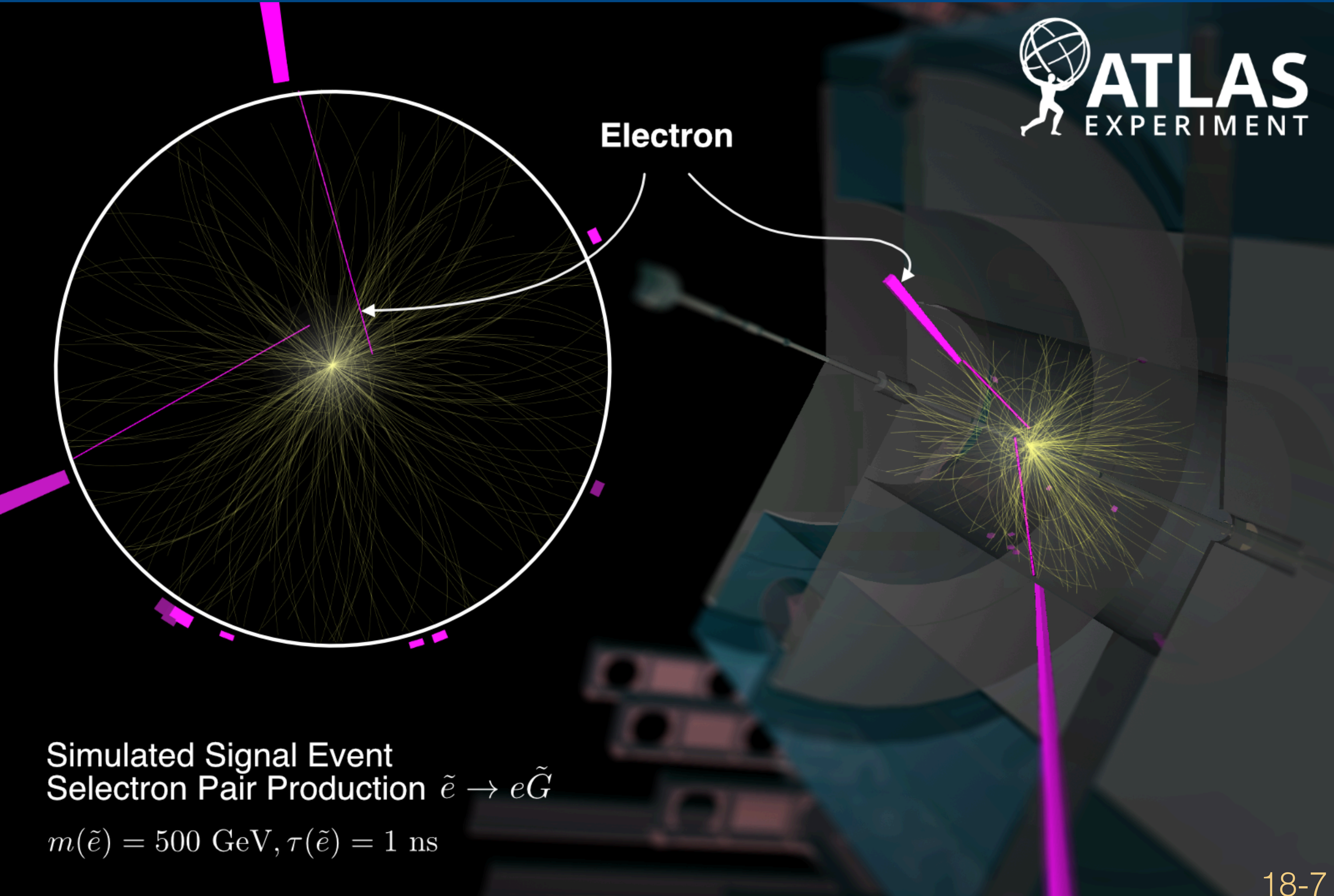
- Long-lived $\tilde{\ell}$ unexplored since LEP (90 GeV limits)
- Extended tracking ignores hits from prompt tracks (<10mm)
  - New lepton identification out to 300 mm
- No events observed → first GMSB $\tilde{\ell}$ limits at LHC with lifetimes of 10 ps to 10 ns
  - Full likelihoods (via pyHF) available for reinterpretations







Displaced Electrons (Simulated Event)

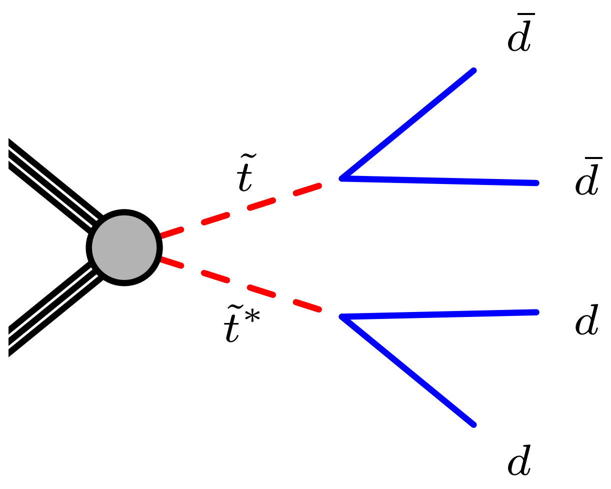


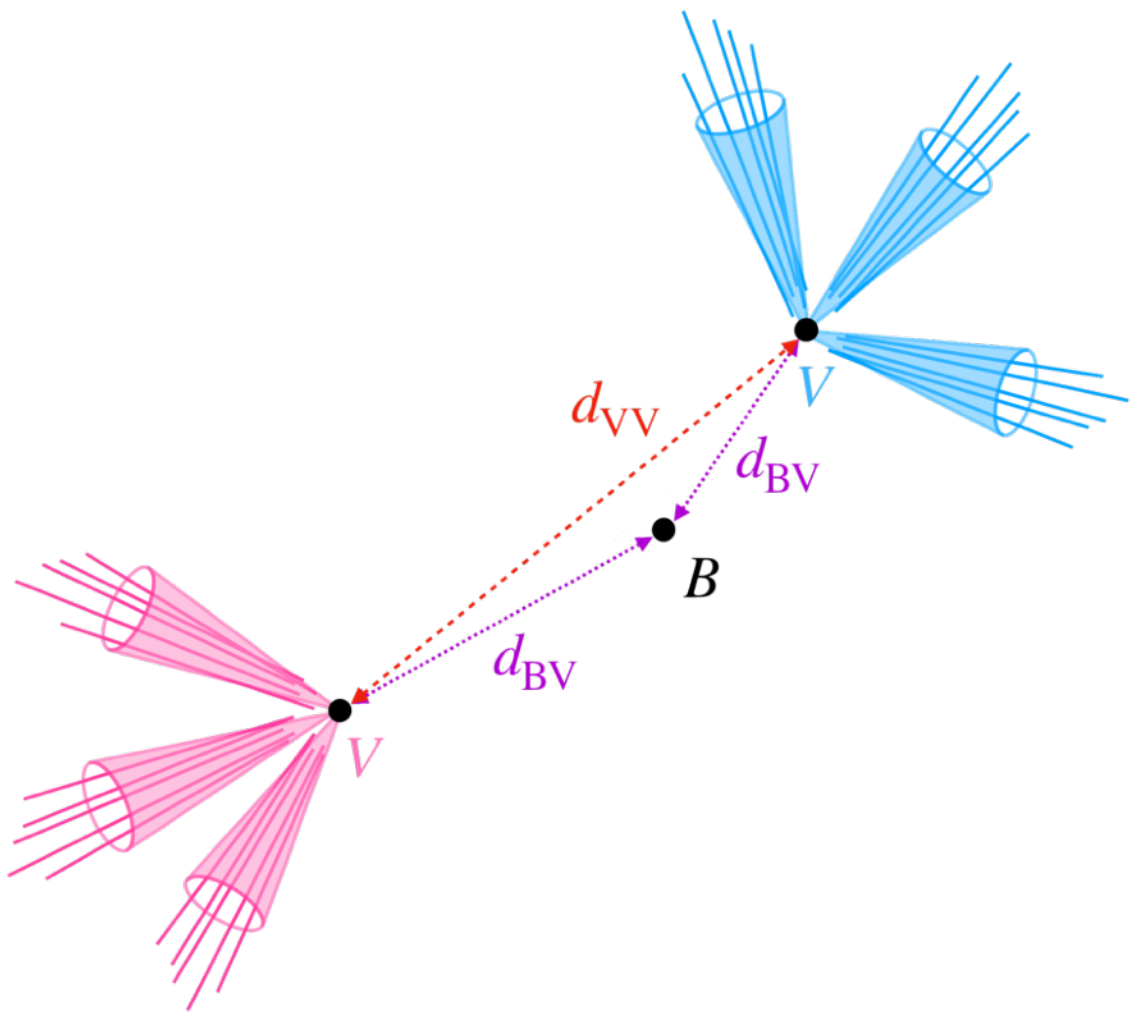
Simulated Signal Event
Selectron Pair Production $\tilde{e} \to e\tilde{G}$

$m(\tilde{e}) = 500\ \mathrm{GeV}, \tau(\tilde{e}) = 1\ \mathrm{ns}$

Jets with Slightly Displaced Vertices

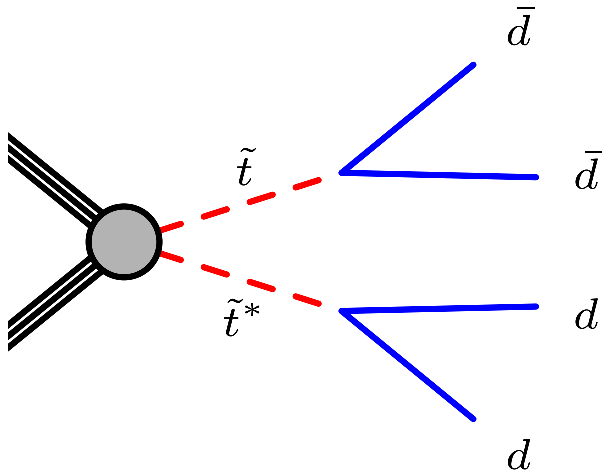
- Long-lived particles decaying to 2 or 3 quarks (**≥5 track vertex**)
- Displaced vertex reconstruction benefits from **upgraded inner detector** & **new pileup rejection** techniques

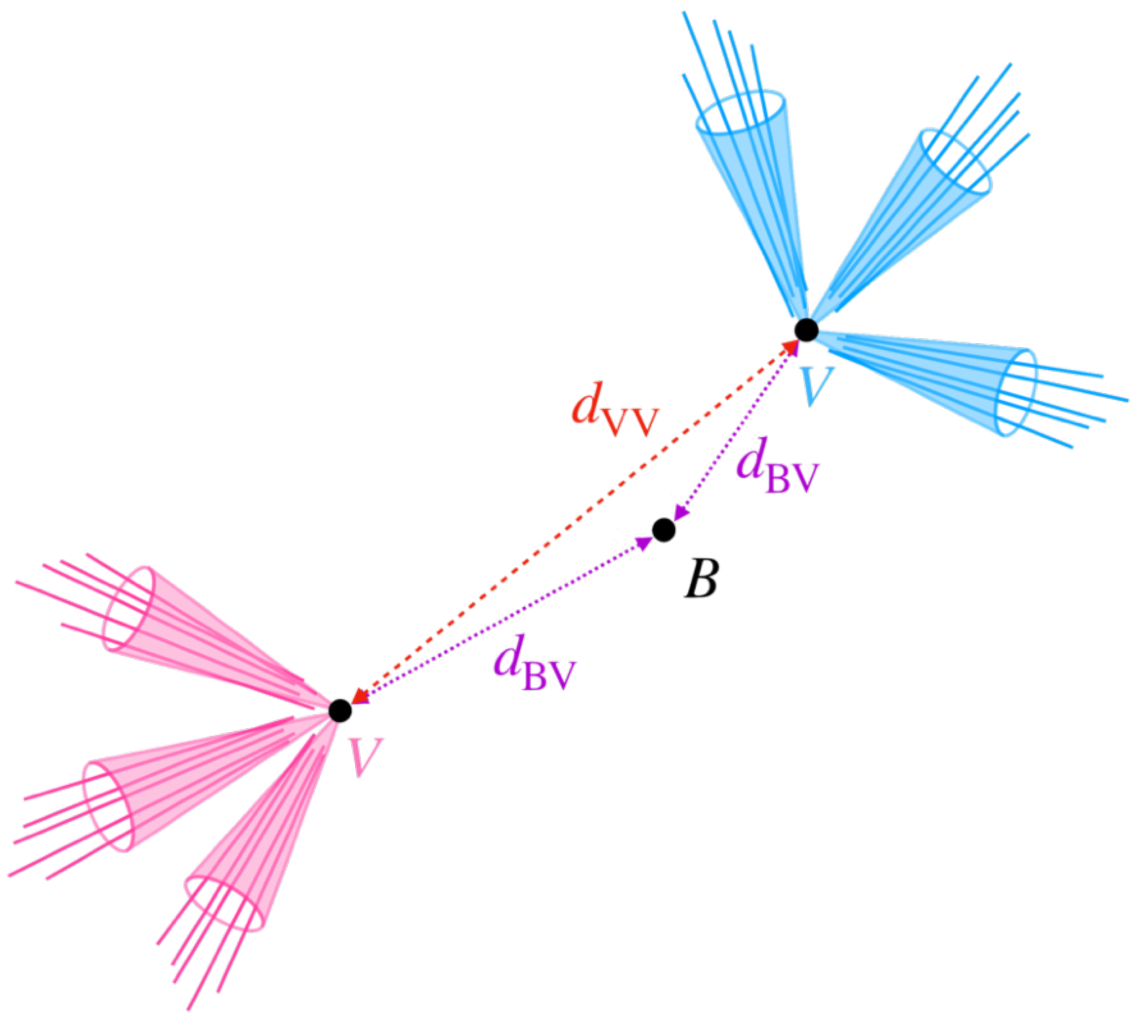


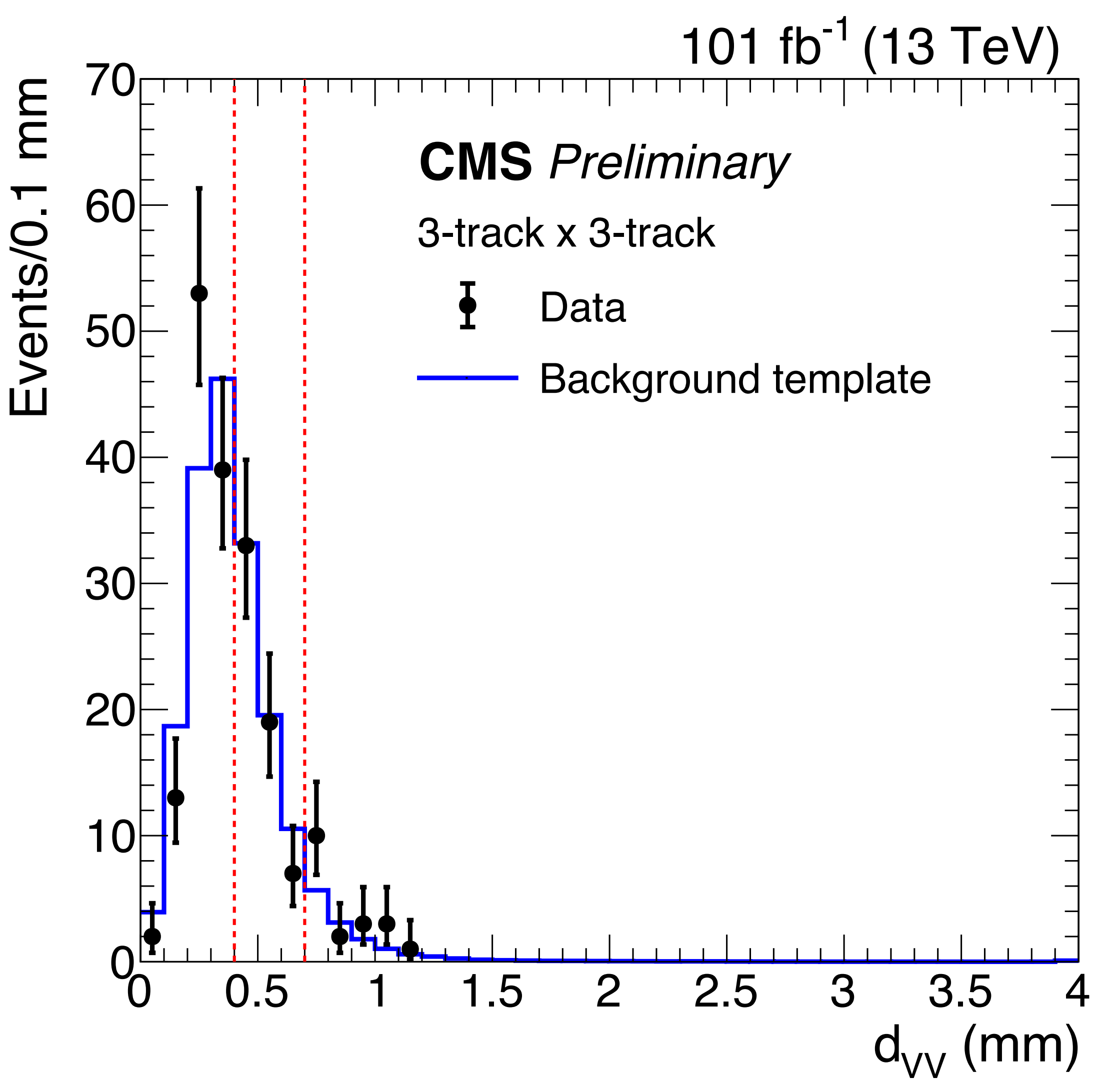


Jets with Slightly Displaced Vertices

- Long-lived particles decaying to 2 or 3 quarks (≥5 track vertex)
- Displaced vertex reconstruction benefits from upgraded inner detector & new pileup rejection techniques
- **Scan d_{VV}**: data-driven background template from 1-vertex events
  - No data events seen in search regions



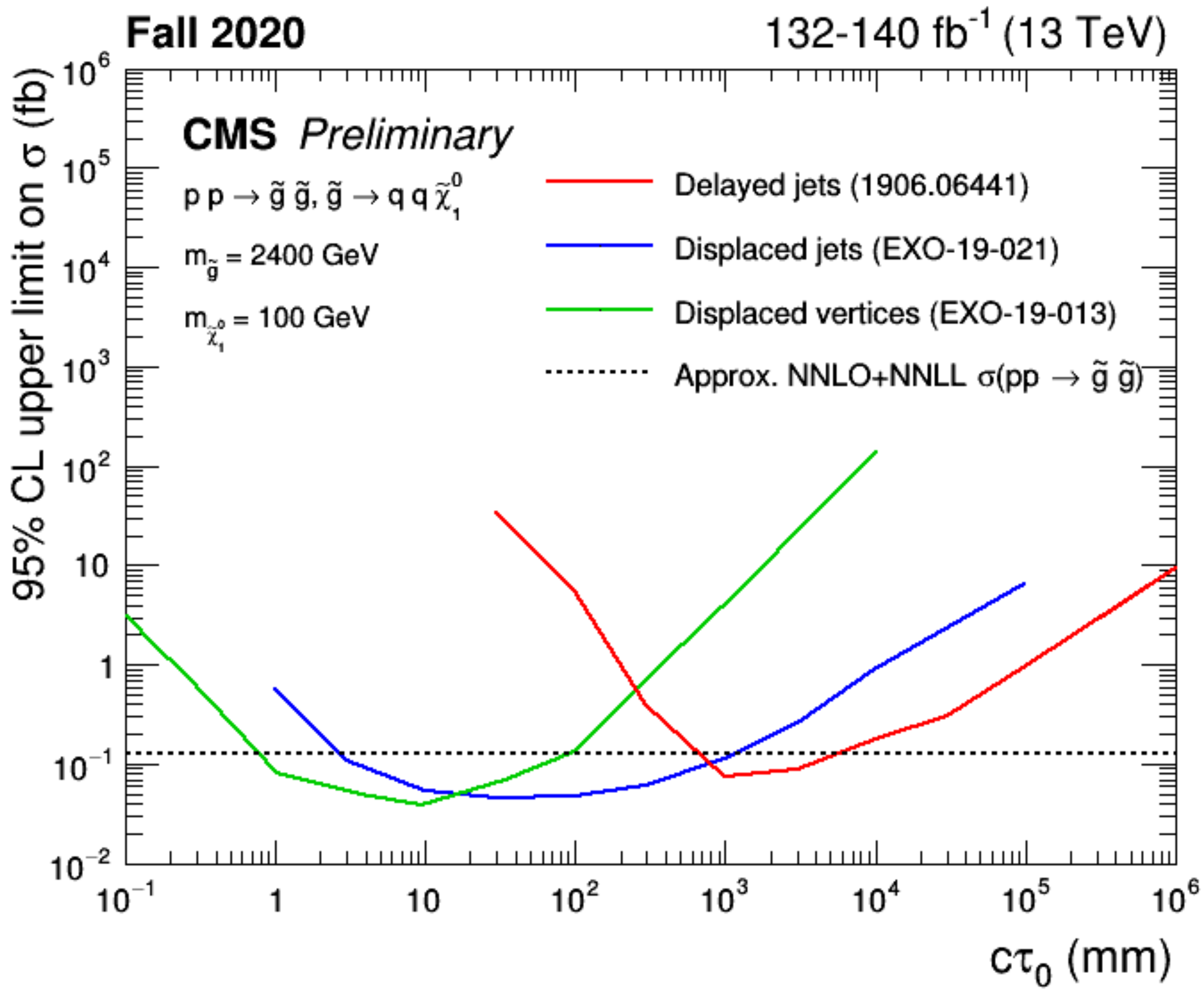




2-vertex template validation (3-track vertices)

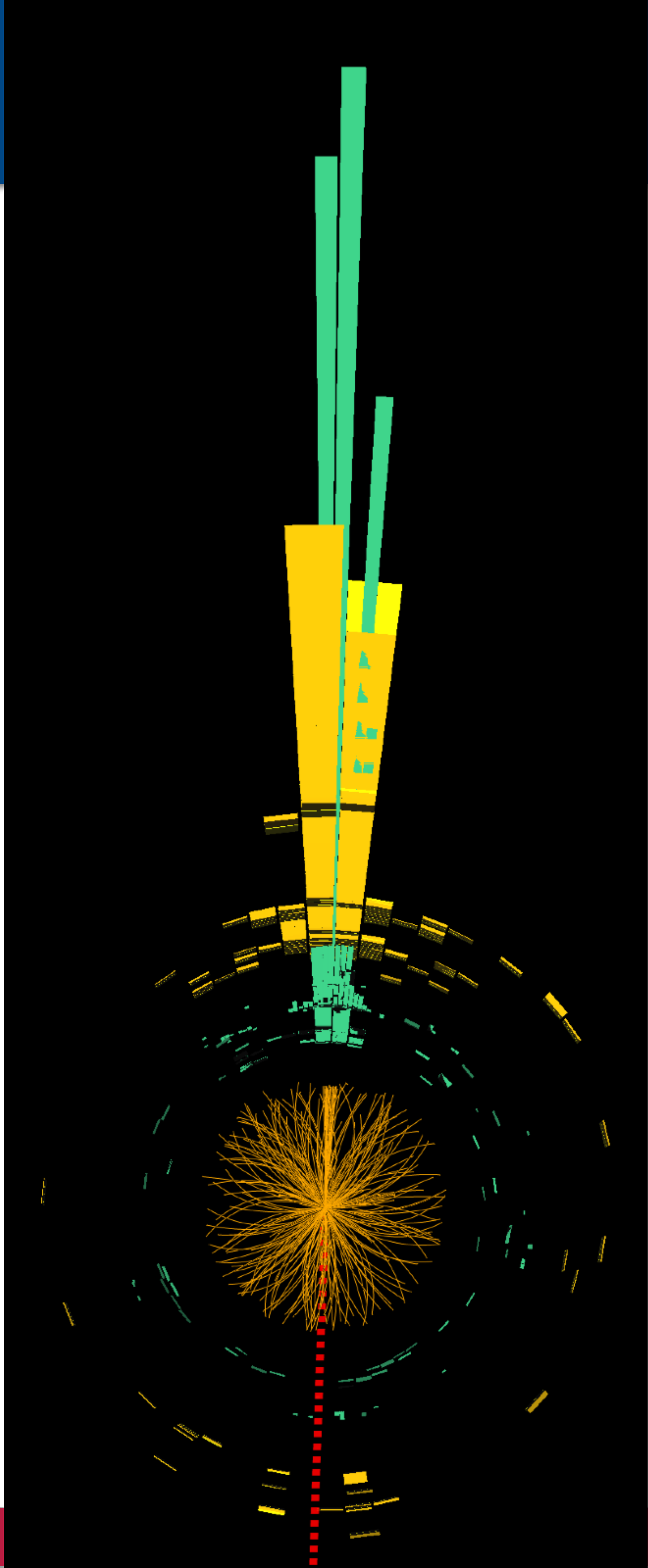
Jets with Slightly Displaced Vertices

- Limits set on long-lived $\tilde{g}$ (2.5 TeV), $\tilde{t}$ (1.5 TeV), & $\tilde{\chi}^0$ (1.1 TeV) with mean lifetimes between 0.1 → 100mm
- **Low-lifetime search** complements limits from **displaced** and **delayed** jet analyses



More on the Way

- Large BSM program to find new physics wherever it is hiding
  - New reconstruction & analysis techniques
  - New searches in uncovered channels
  - New collaborations & emphases on facilitating public reinterpretations
- Run 3 is around the corner and will double the dataset with detector improvements, new triggers, & brand new searches
- Look forward to unparalleled opportunities for discovering new TeV-scale physics!



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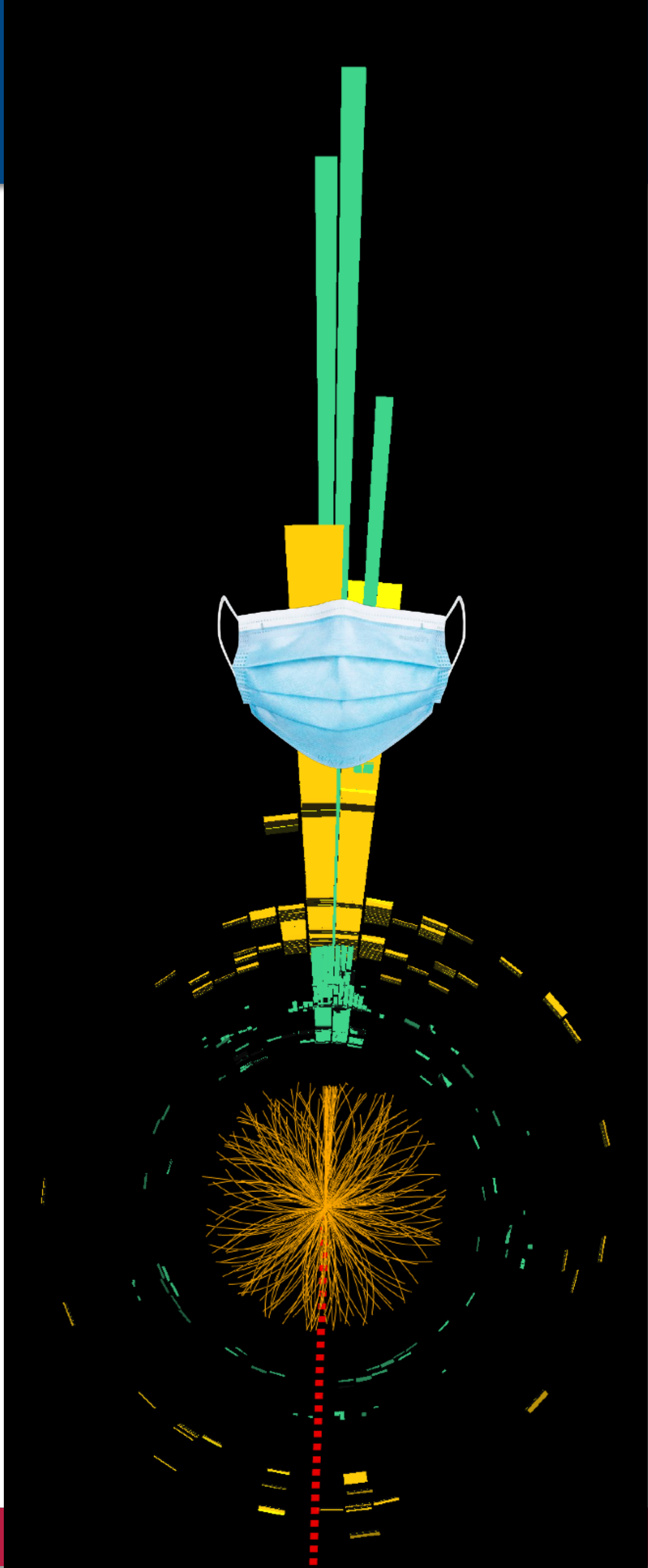
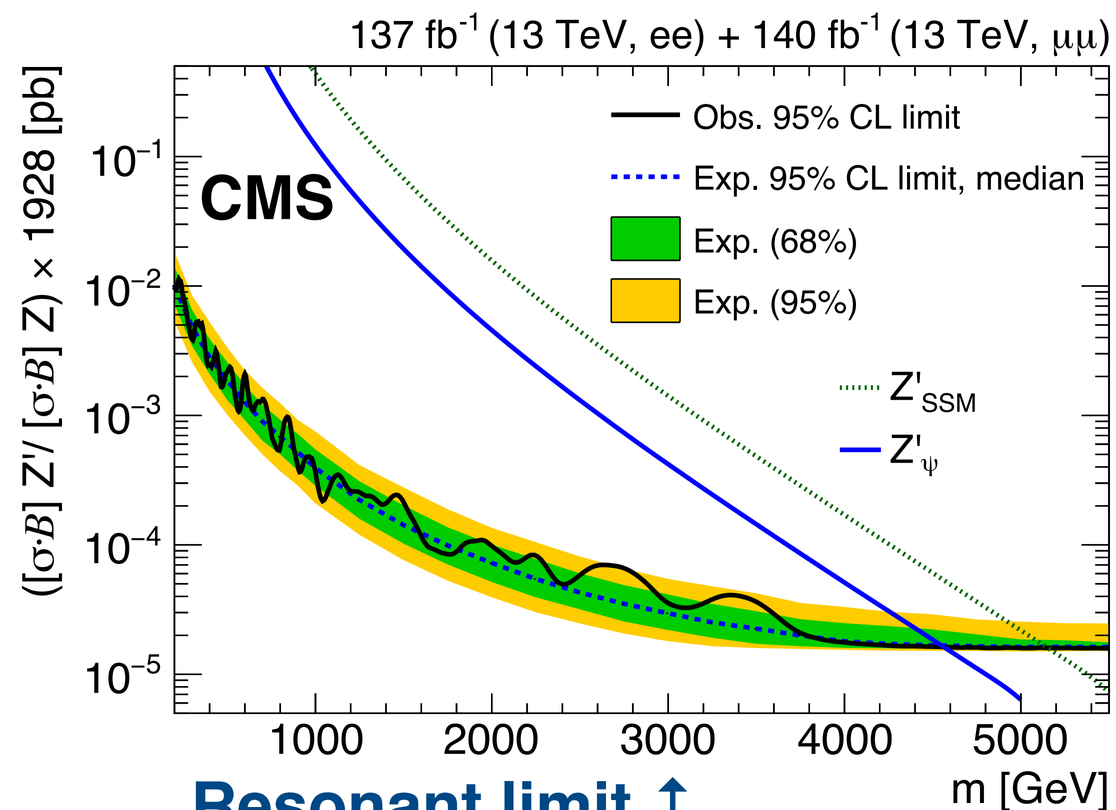


Backup

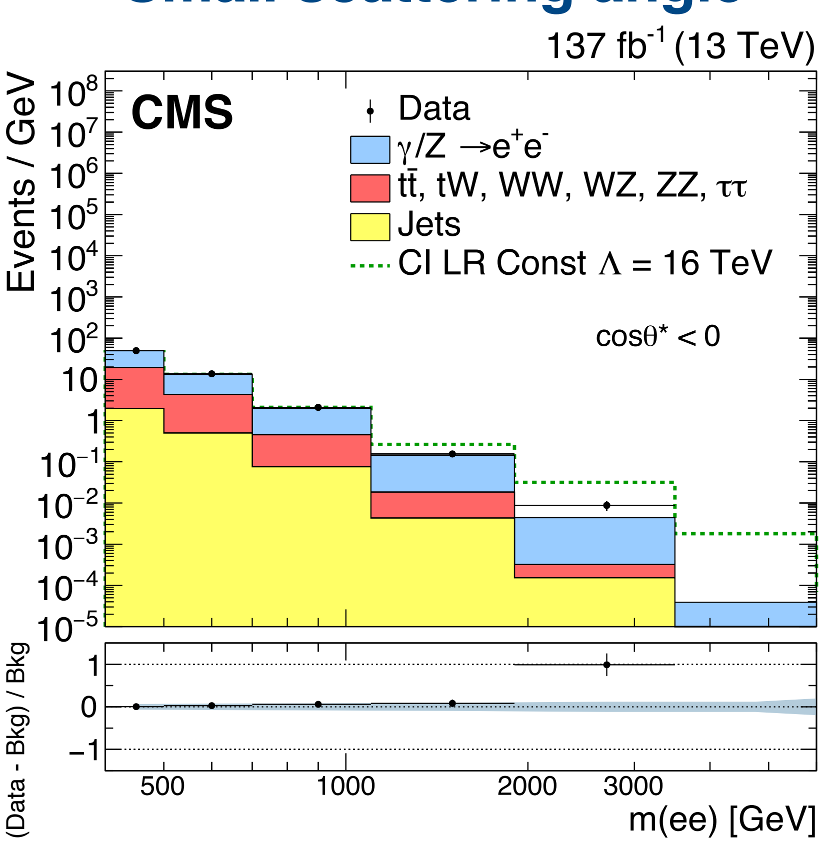
Searching for Leptonic Decays

- **Mass resonance** exclusions **up to ~5.2 TeV** for generalized $Z`$
- **Non-resonant** enhancements at high mass exclude enhancements up to Λ cutoff of **~36 TeV**
  - New gains using lepton scattering angle - angle of negatively charged lepton w.r.t. z-axis in Collins-Soper frame

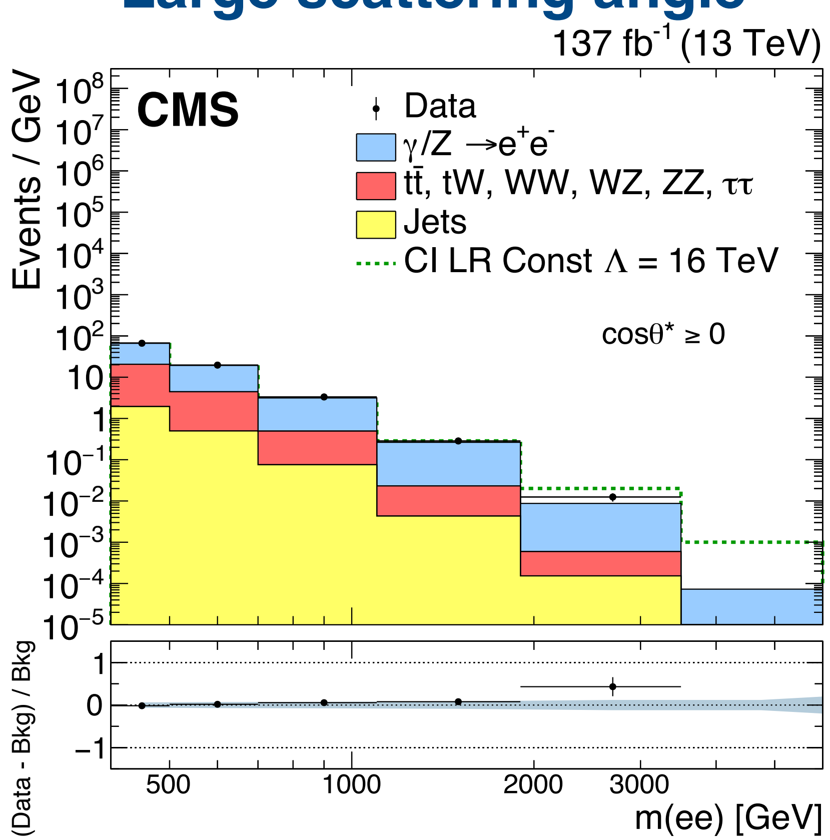


Resonant limit ↑

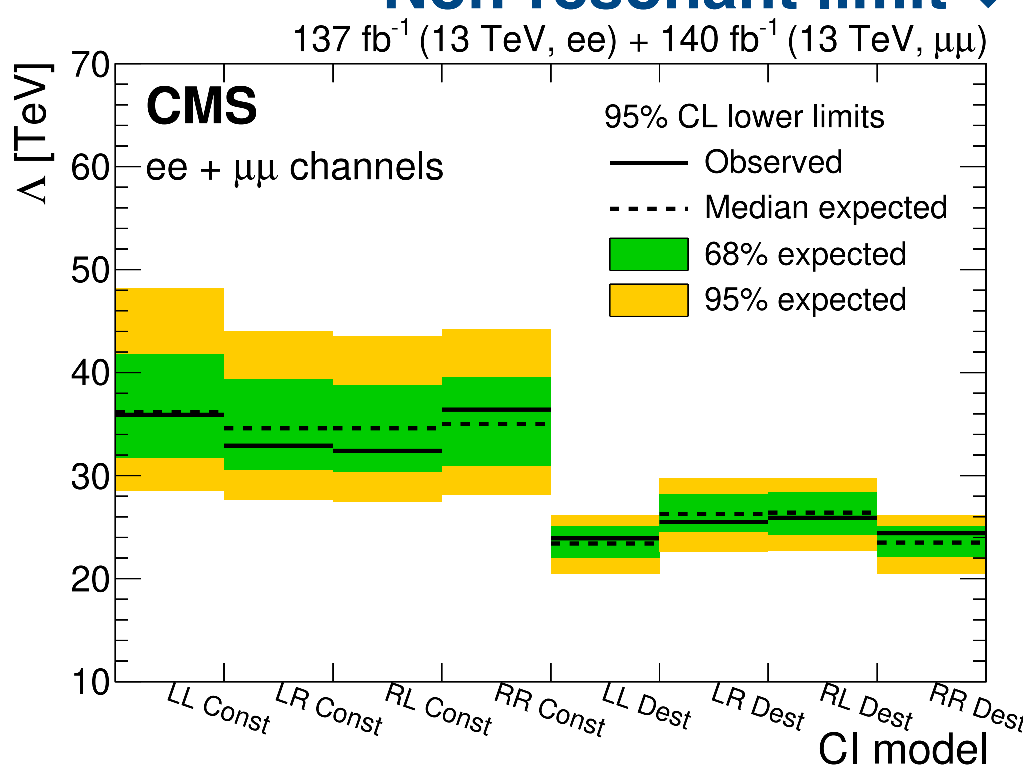
Small scattering angle



Large scattering angle

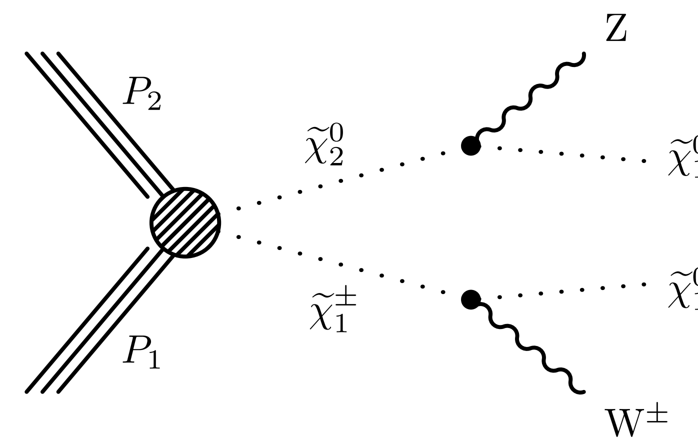


Non-resonant limit ↓

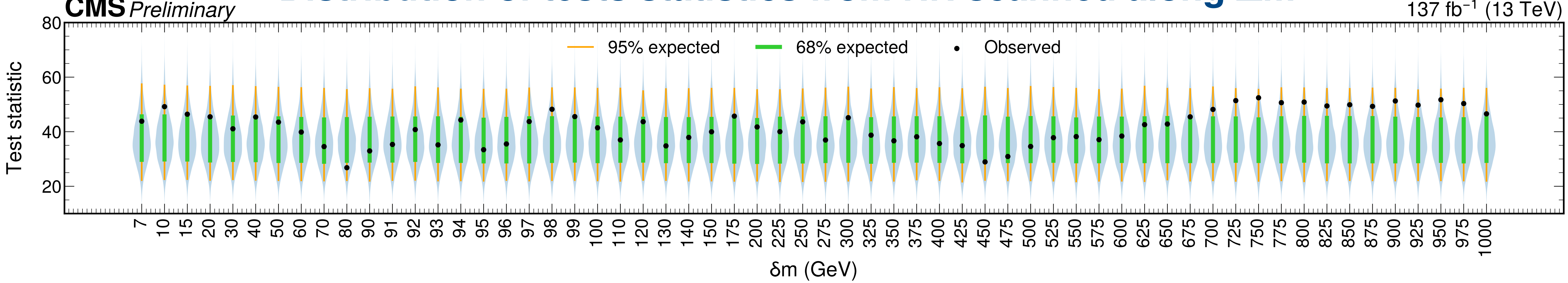


EWK SUSY via Neural Networks

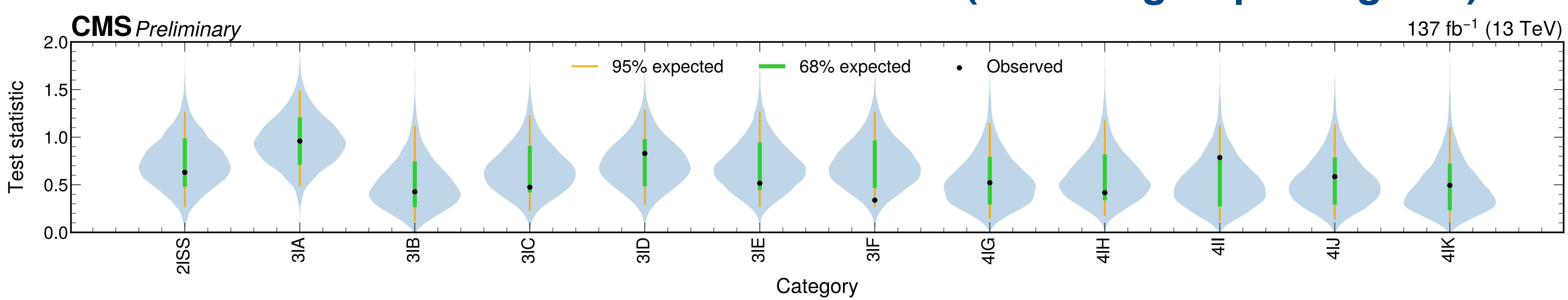
- Search for events with 3ℓ, 4ℓ+, & 2ℓ (same-sign)
  - Decays of EWK SUSY through $\tilde{\ell}$ or W, Z, & Higgs bosons
- Neural network trained on several effective masses and $\sum p_T$ of decay products
  - Training parameteric in mass splitting Δm
- Neural network **compared against cut-&-count method** (>120 search regions)



Distribution of tests statistics from NN scanned along Δm

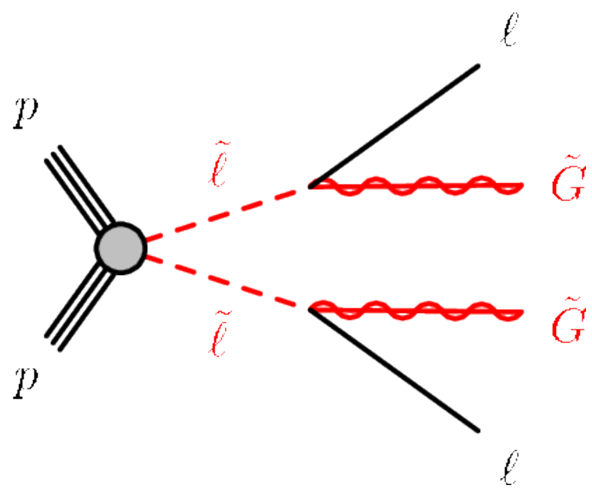


Distribution of tests statistics from cut-&-count (show in grouped regions)

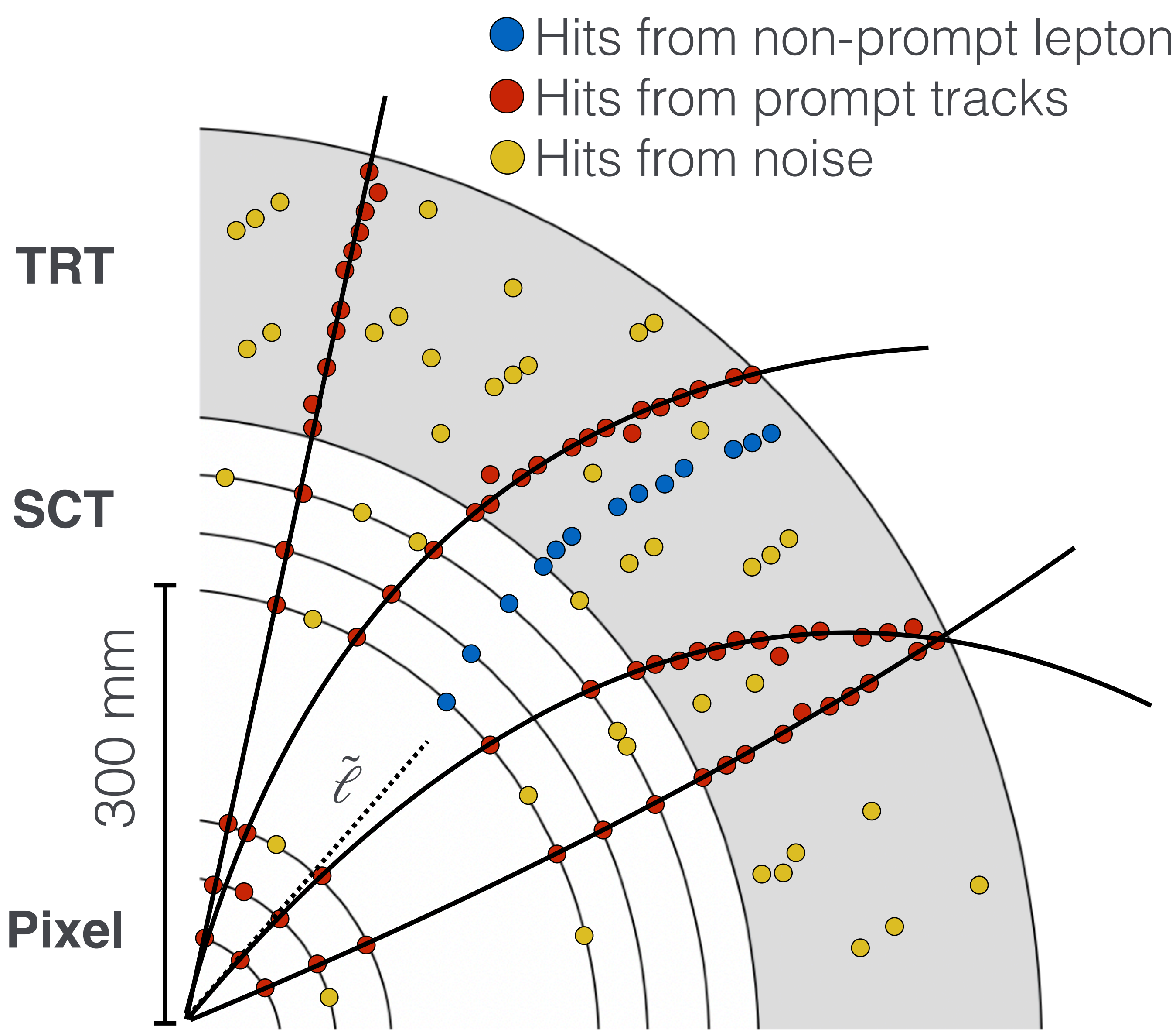


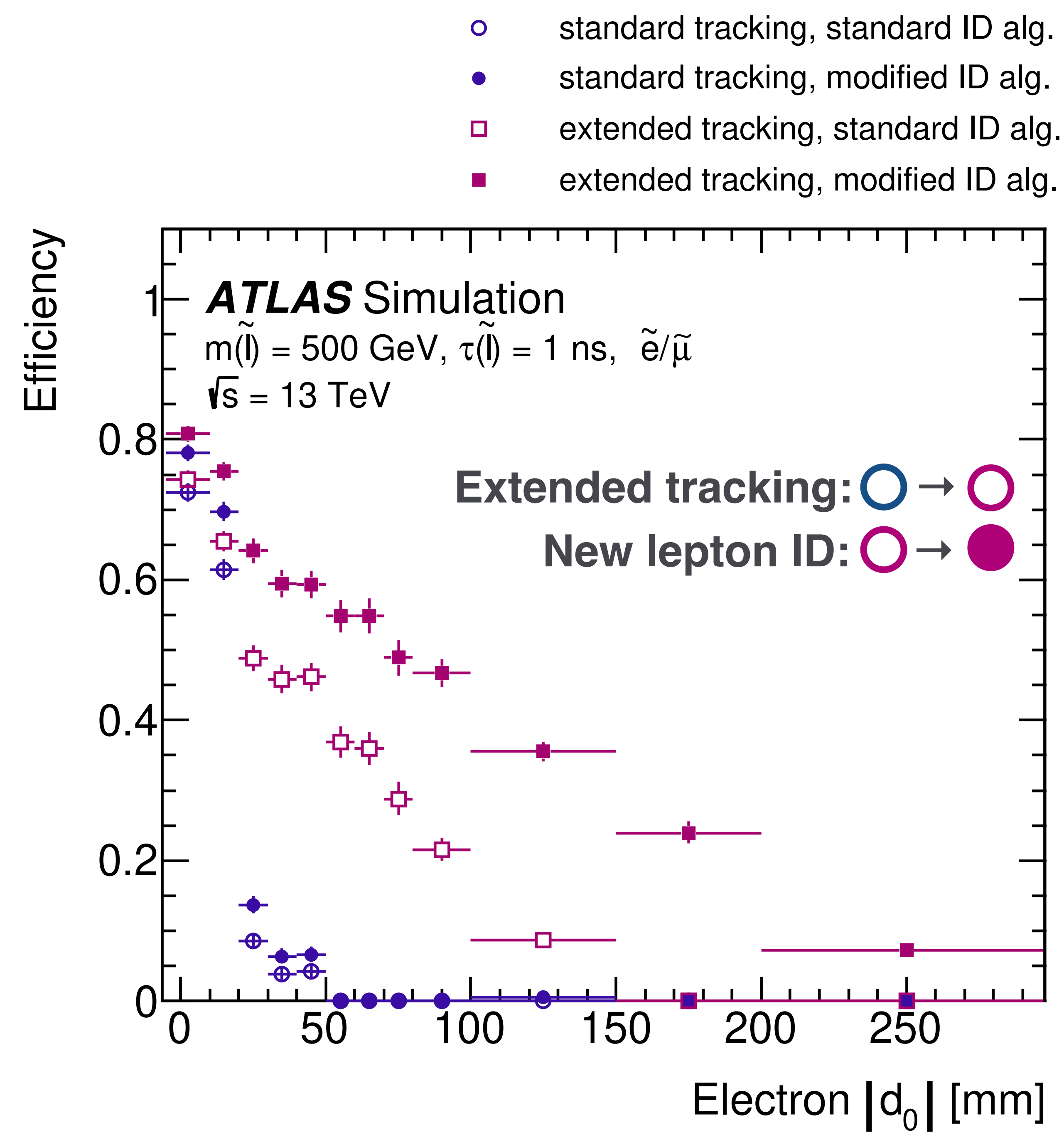
Displaced Leptons

ATLAS EXPERIMENT



- Extended tracking ignores hits from prompt tracks (<10mm)
  - New lepton identification out to 300 mm

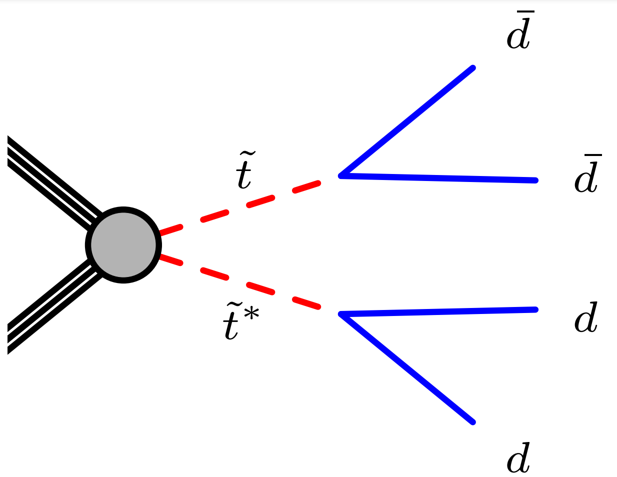


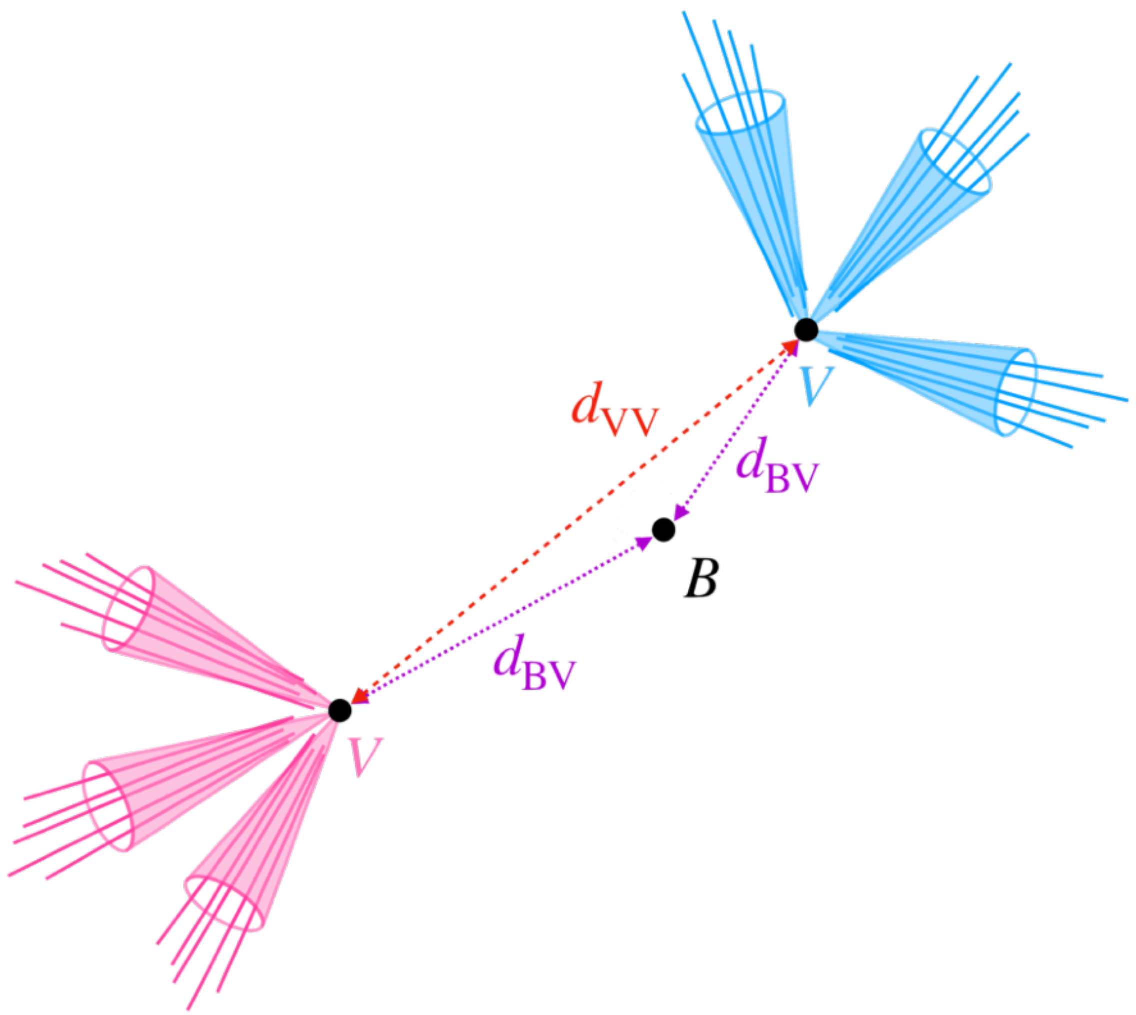


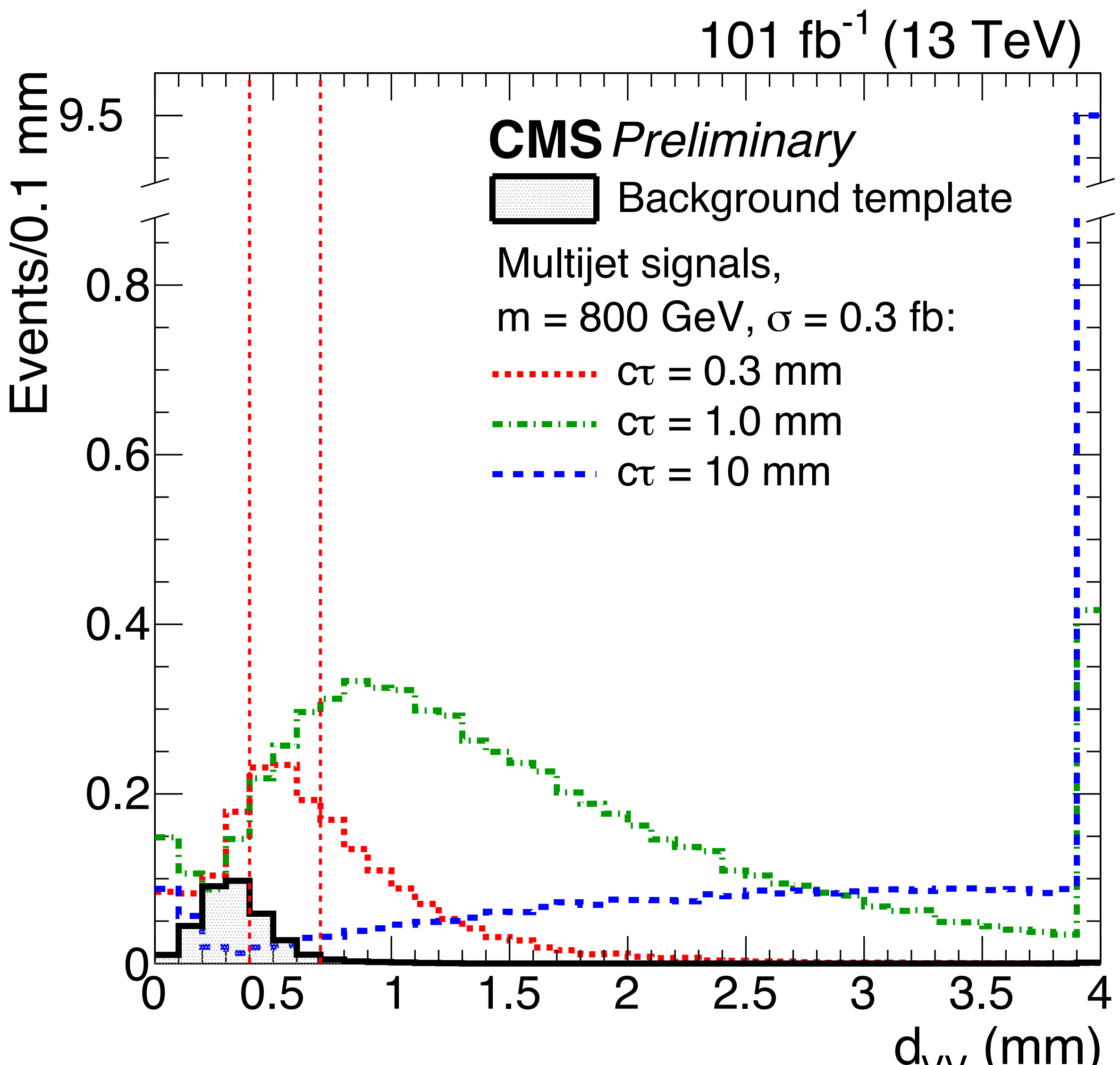
Displaced electron ID efficiency

Jets with Slightly Displaced Vertices

- Long-lived particles decaying to 2 or 3 quarks (≥5 track vertex)
- **Scan d_{VV}**: data-driven background template from 1-vertex events
- Low expected background, no 2-vertex events seen in data







5-track d_{VV} distribution