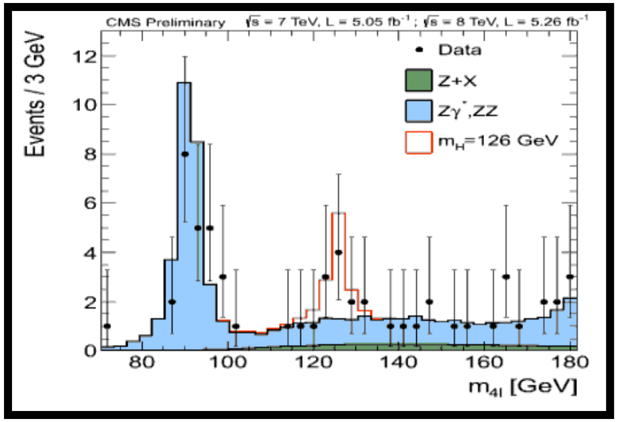
Top squark searches at 100 TeV

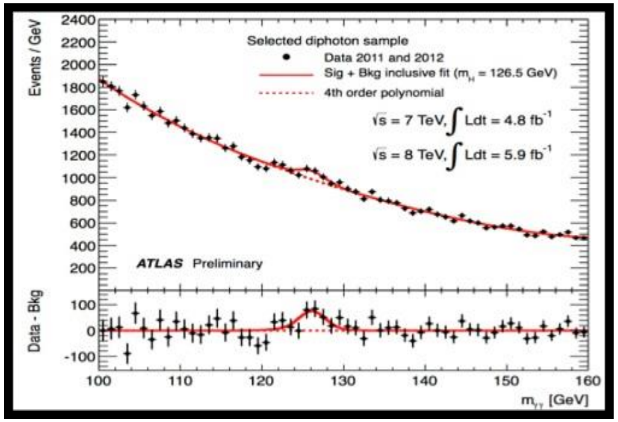
Loukas Gouskos, Allan Sung, Joe Incandela

NB: preliminary version

Physics motivation

- Discovery of the Higgs boson at ~125 GeV completes the SM

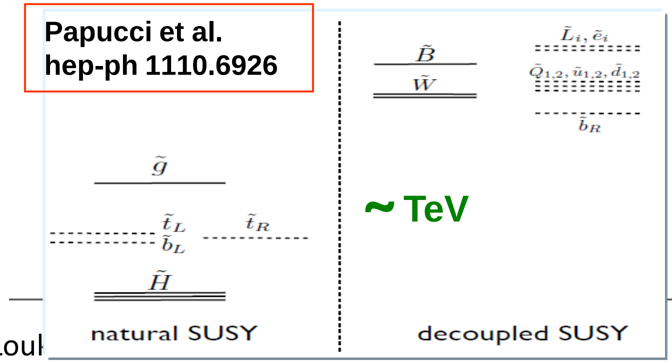


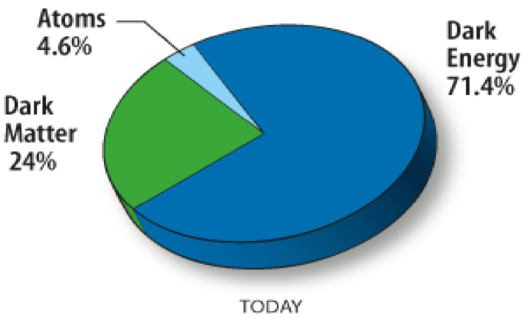


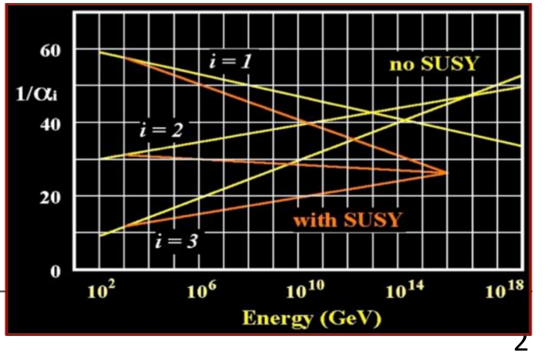
Yet, still many open questions..

- SUSY: one of the most extensively studied BSM theories
  - An excellent answer to:

Hierarchy problem | **Dark Matter** | **Unification**

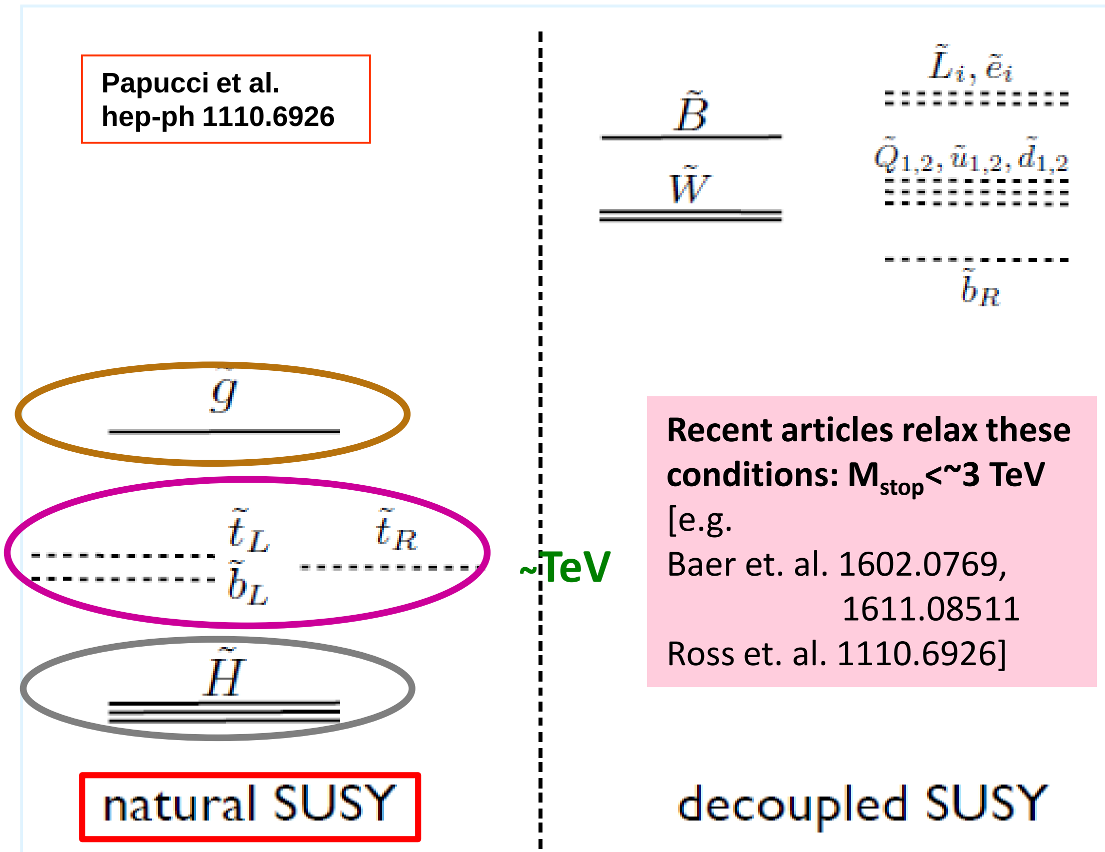






Natural SUSY

- "Natural SUSY" models: attract a lot of attention at the LHC
  - Particularly relevant to address the hierarchy problem / understanding of naturalness of the EWK scale
  - Search for 3rd generation of SUSY particles



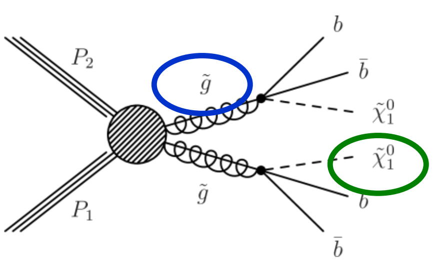
Recent articles relax these conditions: M_{stop}<~3 TeV
[e.g.
Baer et. al. 1602.0769,
1611.08511
Ross et. al. 1110.6926]

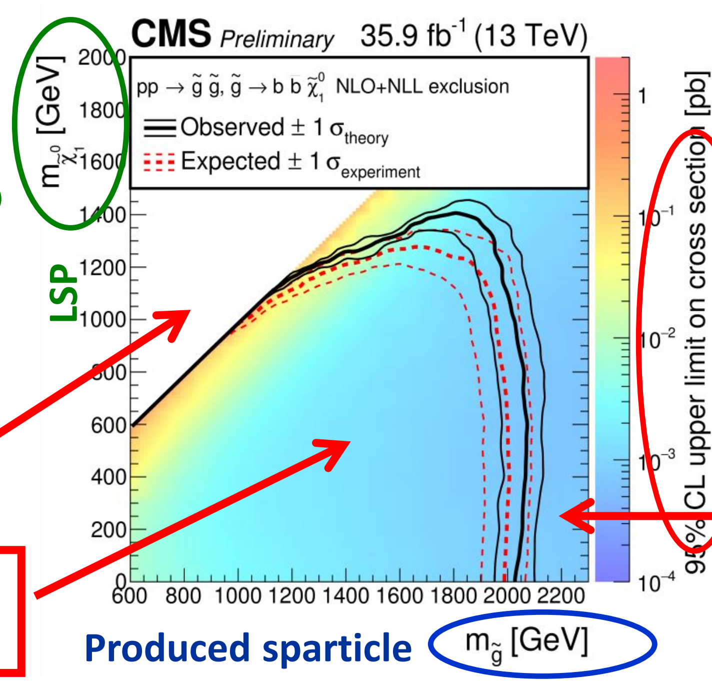
- **Natural SUSY spectrum: higgsinos , stops/sbottoms and gluinos, ~ TeV Scale [maybe within LHC reach]**
- **All other sparticles can be very heavy [decoupled]**

Focus on the search for top squarks

Setting the scene

- SMS: used in SUSY searches (design & result interpretation)
  - Minimal set of free parameters to describe a particular set of decay chains
  - More generic description -> results applicable to other scenarios
- But.. there are some simplifications:
  - eg. full SUSY spectrum not provided; particle properties, (usually) BR=100% for the sparticle decays





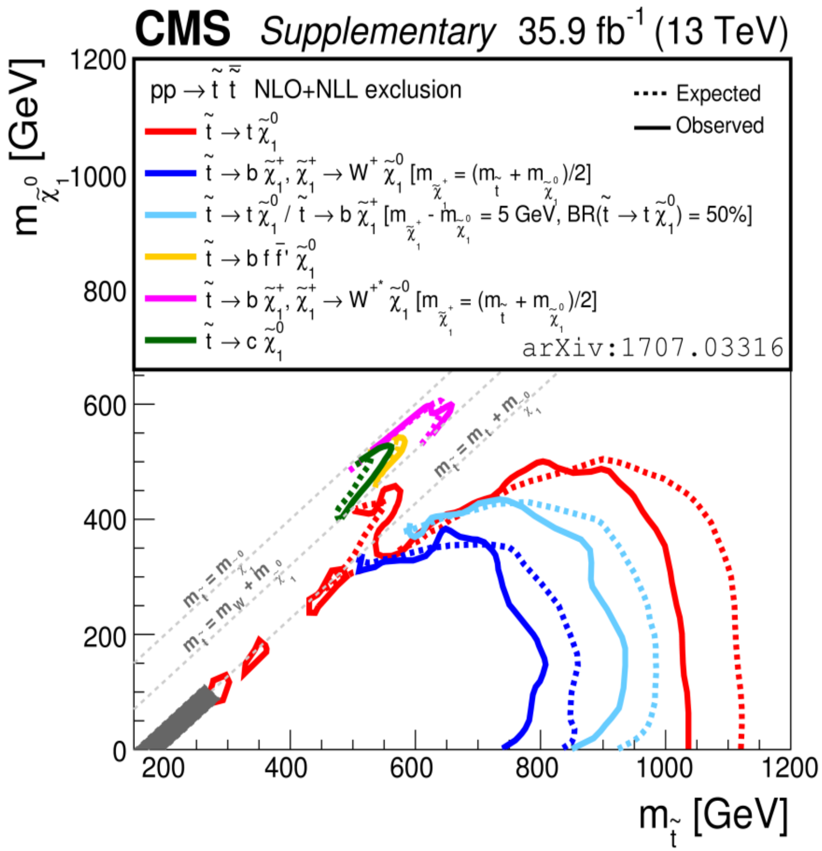
Set Upper Limits in cross-section

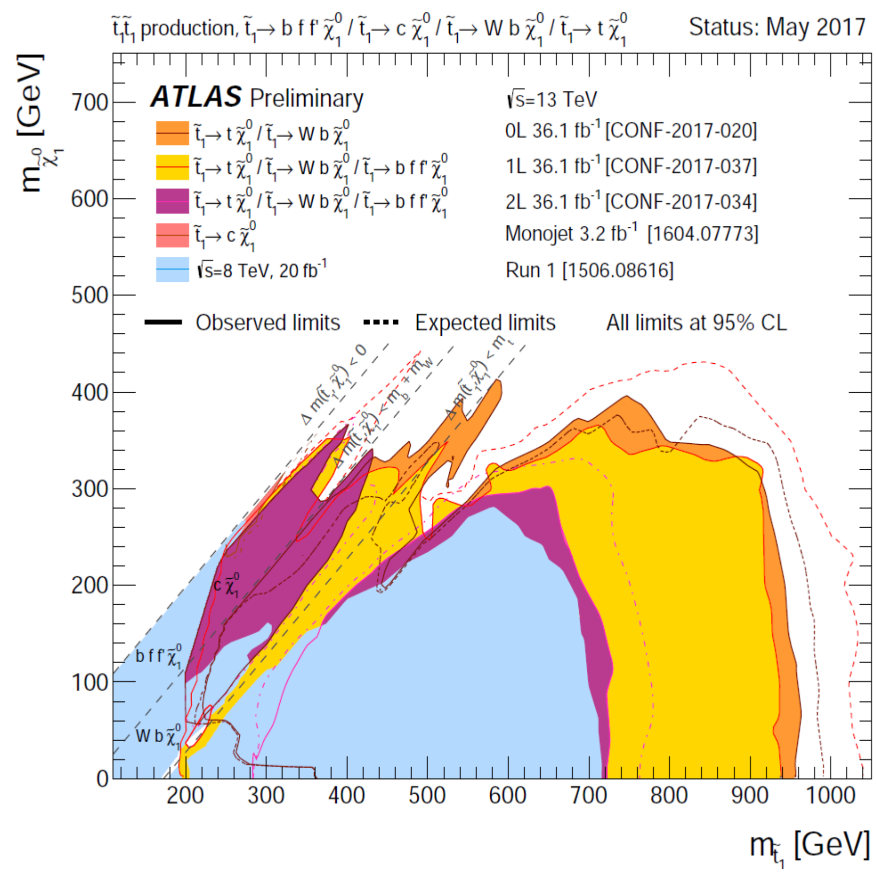
Region kinematically forbidden m[prod. sparticle] < m[LSP]

Excluded parameter space

Observed & Expected mass limits based on the nominal production cross-section

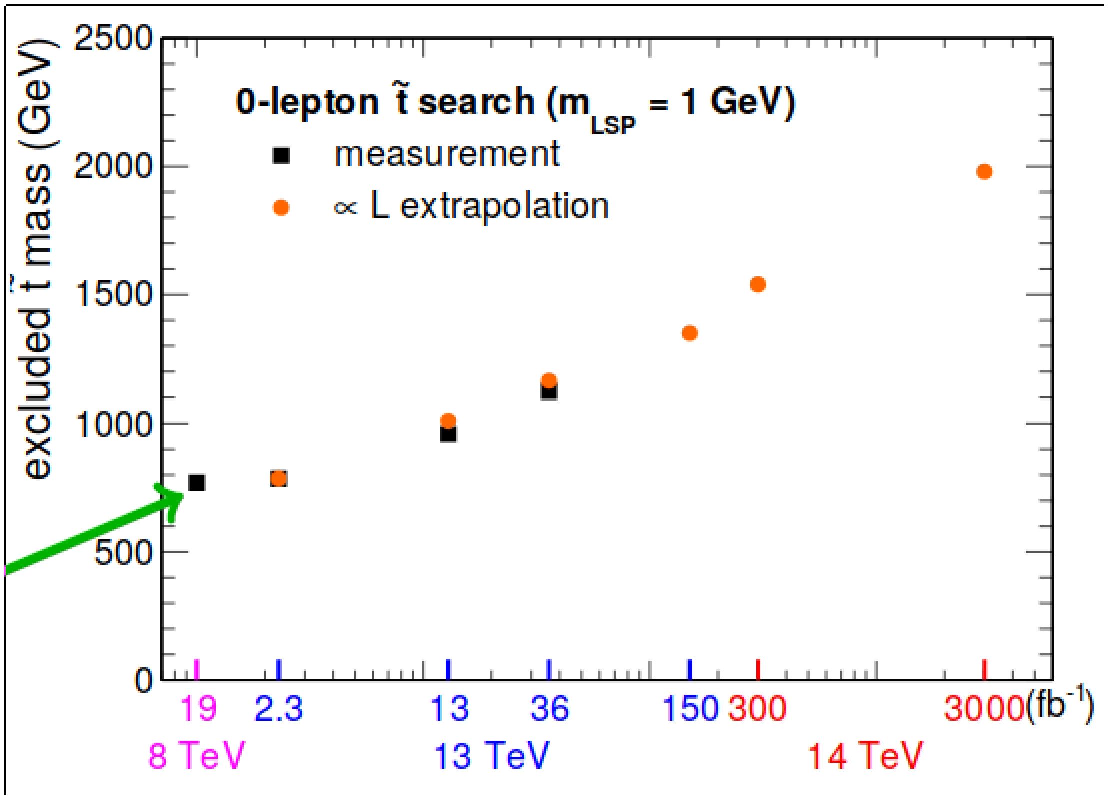
Top squark searches at the LHC





- No hints of SUSY after the first years of LHC operation
- Models with M_{stop} up to ~1 TeV and light LSP are excluded
  - Level of fine tuning ~10^{-2}

Projections at LHC and HL-LHC



Results should be interpreted as indicative of the expected performance

[e.g. no detector aging vs time considered]

- End of HL-LHC Physics program: Exclude top squarks ~ 2 TeV

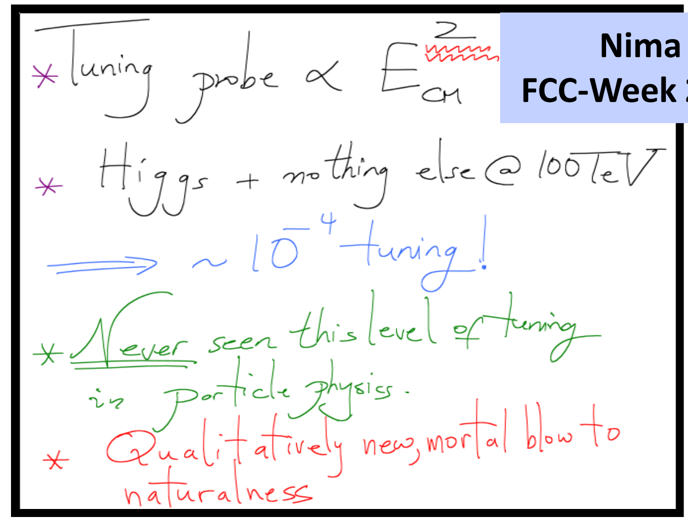
Motivation for FCC-hh @100 TeV

- Both LHC-Run2 & HL-LHC important for SUSY hunting
- Optimistic scenario [or scenario 1]:
  - Discover/Observe top squarks at the LHC [~TeV scale] and then of course get the mechanism for the "hierarchy problem" [and for dark matter if R-Parity Conserving]
  - Need a SUSY-factory to study the properties [mass spectrum, branching fractions, etc..]
  - SUSY-factory: Very High Energy collider [i.e. 100 TeV p-p]
    - e.g. 10^4 increase in prod. x-sec of 2 TeV top squarks wrt 13 TeV
- Pessimistic scenario [or scenario 2]:
  - No hints from SUSY after HL-LHC
    - Natural-SUSY in trouble [though not dead]
    - Other SUSY models alive [i.e. split-SUSY]
    - SUSY mass spectrum very high [top squarks > few TeV]
  - Need a powerful hadronic collider to really explore the FT issue and the viability of SUSY in general
    - And since SUSY is to this day on the most appealing BSM theories, to continue SUSY-hunting

Motivation for FCC-hh @100 TeV (2)

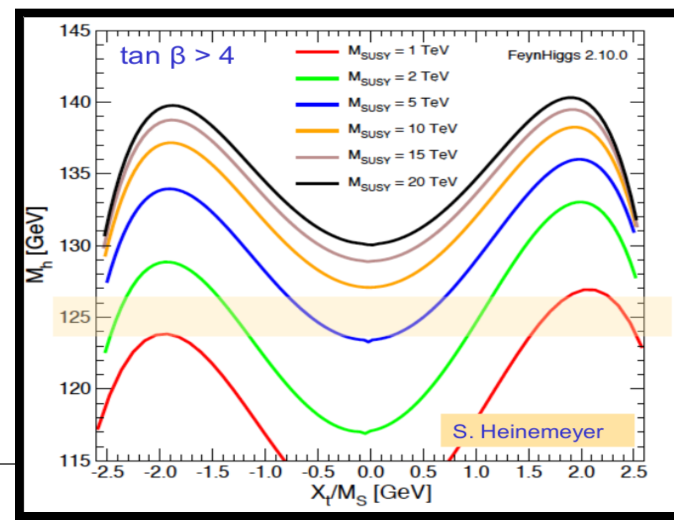
- Can we derive an **upper bound** on the mass of SUSY particles ?

- Understanding the naturalness of the EWK state:
  - "Never seen fine-tuning of 10^{-4} in HEP": FT 10^{-4} -> ~10 TeV top squarks
    - add link
    - Outside (HL-)LHC reach



Nima
FCC-Week 2014

- Can the measured mass of the Higgs be used to set bound to the sparticle masses?
  - Top squarks have the largest contributions to the Higgs mass
  - 1 TeV < m_{stop} < 10 TeV seem to be favored
    - Mostly outside the (HL-)LHC reach



Motivation for FCC-hh @100 TeV (2)

- Can we derive an upper bound on the mass of SUSY particles ?

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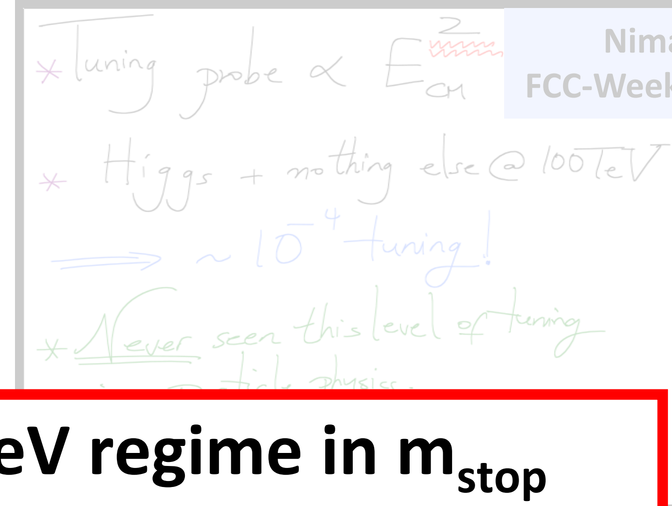
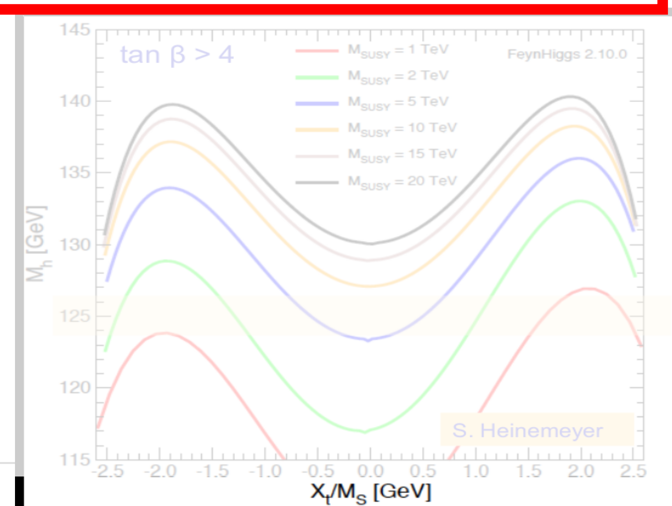
  - "Never seen fine-tuning of 10^{-4} in HEP": FT 10^{-4} -> ~10 TeV top squarks
    - Nima's: add link



Nima
FCC-Week 2014

GOAL: Probe up to the ~10 TeV regime in m_{stop} with FCC-hh @ 100 TeV

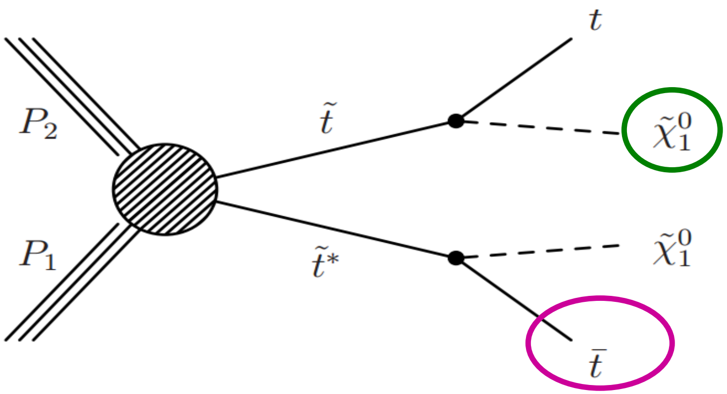
- Can the measured mass of the Higgs be used to set bound to the sparticle masses?
  - Top squarks have the largest contributions to the Higgs mass
  - 1 TeV < m[stop] < 10 TeV seem to be favored
    - Mostly outside the (HL-)LHC reach



Search design

Signal characteristics

- Design a search for top squarks in the all hadronic channel
  - Largest branching fraction (~45%)
  - Very distinct signature

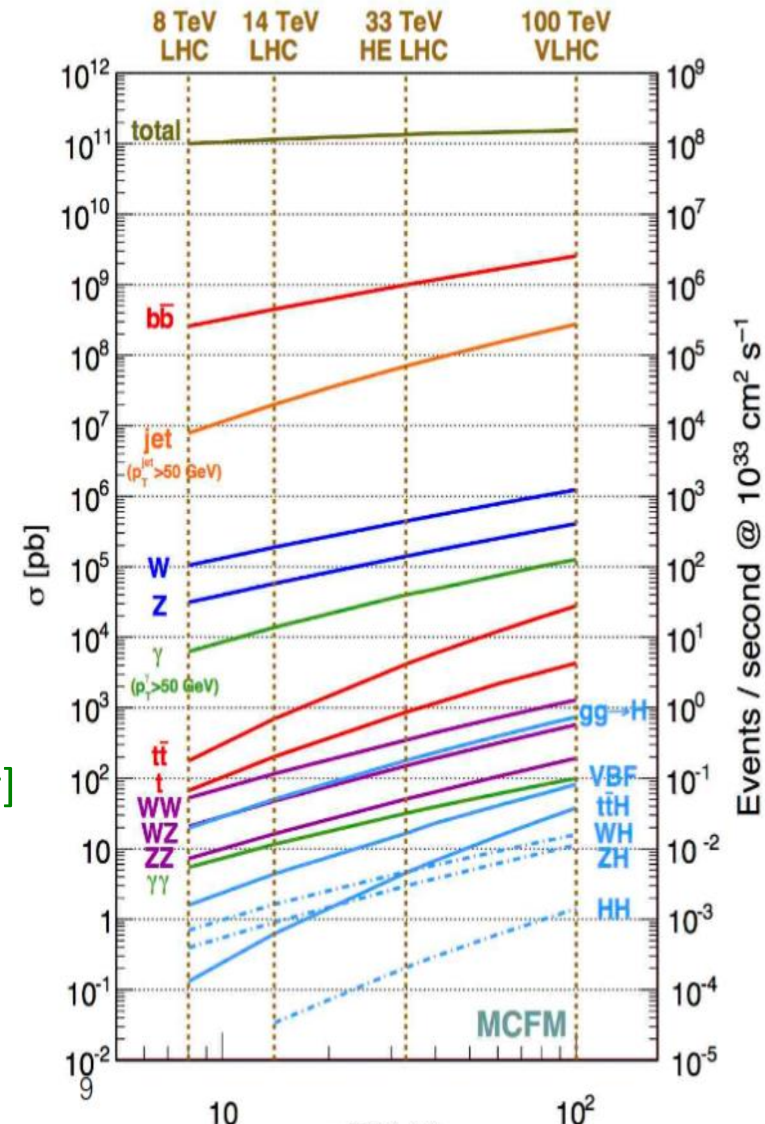


- **Multiple jets**
- **2 b-jets**
- **On-shell top quarks**
- **Large ME_T [from the two LSPs]**

- Baseline selection:
  - Veto leptons with p_T>30 GeV & |η|<4
  - N_j>=2 with p_T>1000 GeV & |η|<4 ; N_b>=1 with p_T>1000 GeV & |η|<4
  - ME_T> 2 TeV
  - Δϕ ($j_{1,2}$; ME_T) > 0.5 ; Δϕ (j_3 ; ME_T) > 0.3 [QCD killers]

Background processes

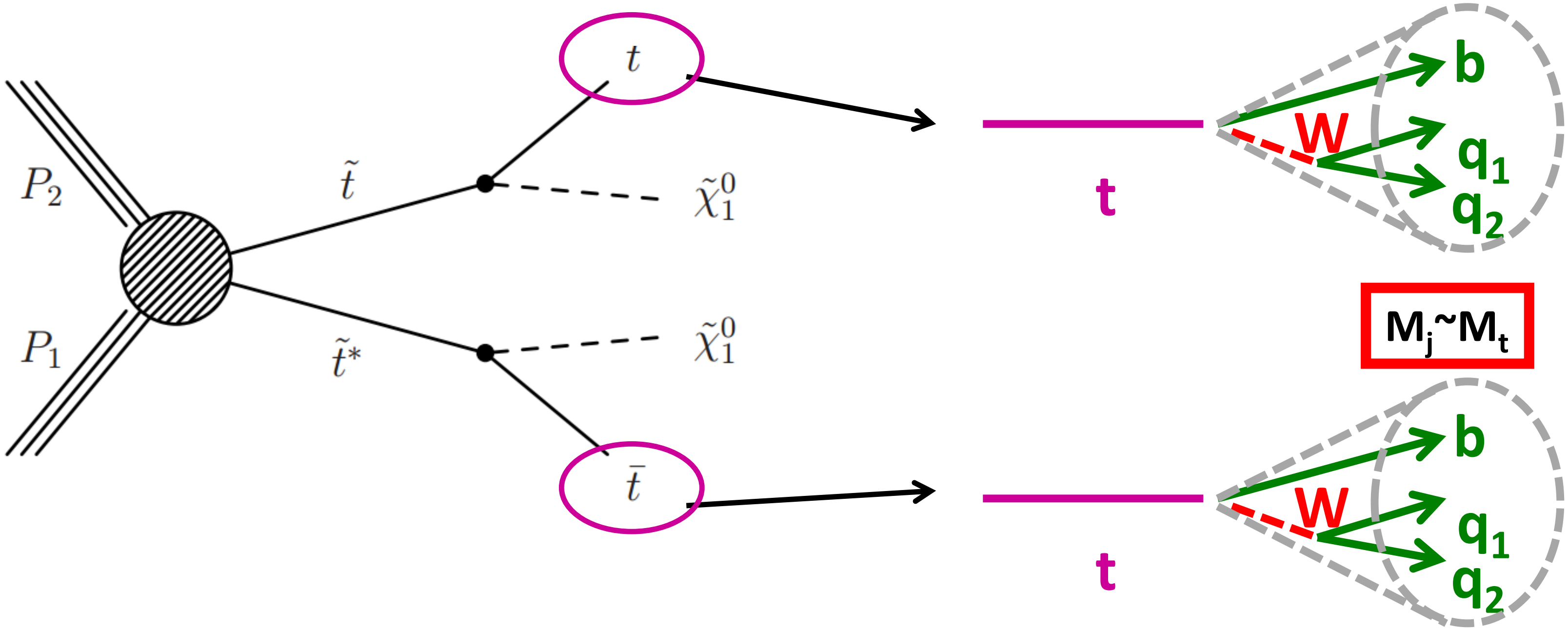
- **Relevant backgrounds:**
  - **"Lost Lepton" (LL) backgrounds:**
    - Stemming from leptonic decays of W with the lepton escaping detection -> large MET
    - ttbar dominates, important contributions from ttW/ttH
  - **ttZ(Z->vv) background:**
    - Similar characteristics with signal
    - σ(100 TeV)/σ(14 TeV) ~60
  - **"Rare" backgrounds:**
    - ttVV, tttt, …
    - Largely irreducible background [but small σ]
    - Very small contribution from V+jets
- **Technical details:**
  - BKG and signal generated using MadGraph
  - NLO k-factors applied



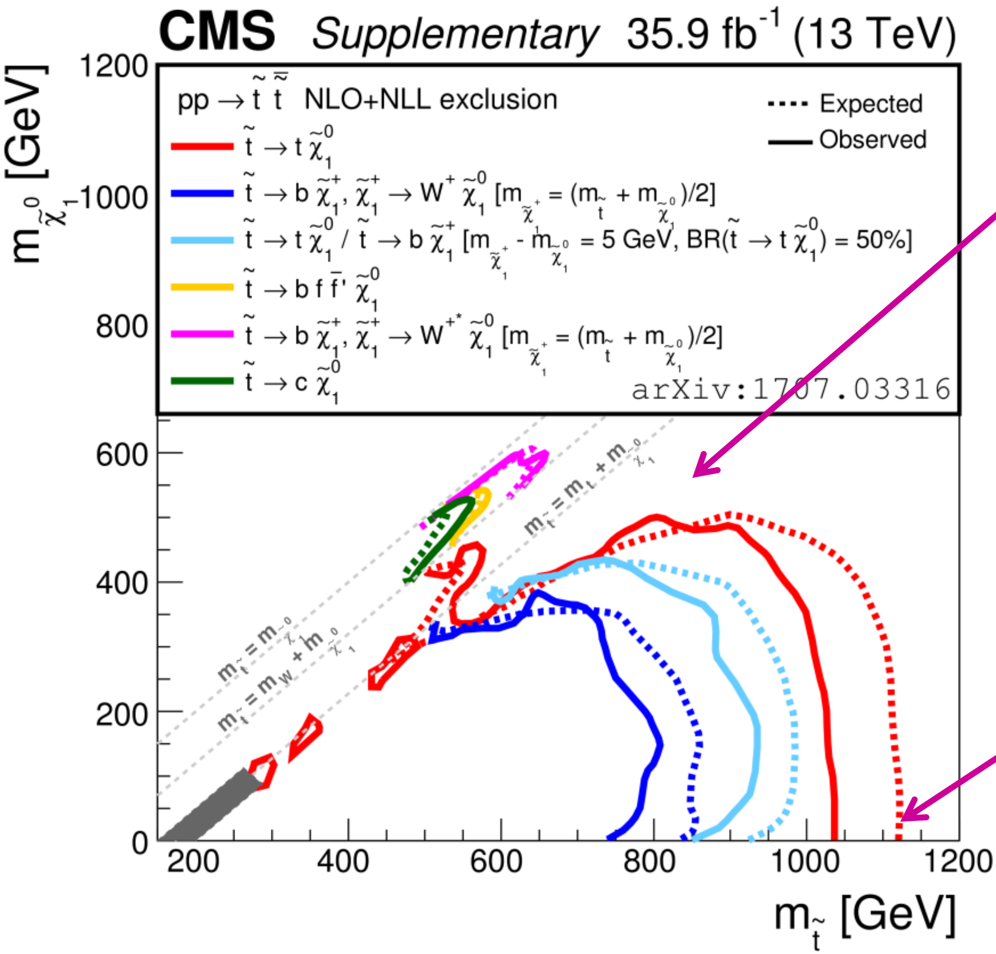
$\sigma(m_{stop}$~7 TeV) ~10^{-4} [NLO]

Top tagging at 100 TeV

- Key player for top squark searches: **identification of hadronic top quarks**
  - Provides a powerful handle to suppress many of the SM backgrounds
    - NB: 2 hadronic top quarks in signal
- Top quarks are typically boosted in signal
  - Top decay products merged into a single jet [$\Delta R \sim 2 x m_{top}/p_T(top)$]



Top tagging at 100 TeV



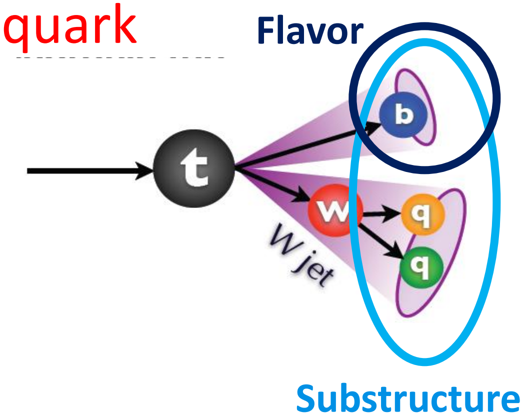
<u>Signals with moderate Δm</u>
top quarks with moderate p_T
~TeV [similar to LHC]

<u>Signals with large Δm</u>
top quarks with very high p_T
~5-10 TeV

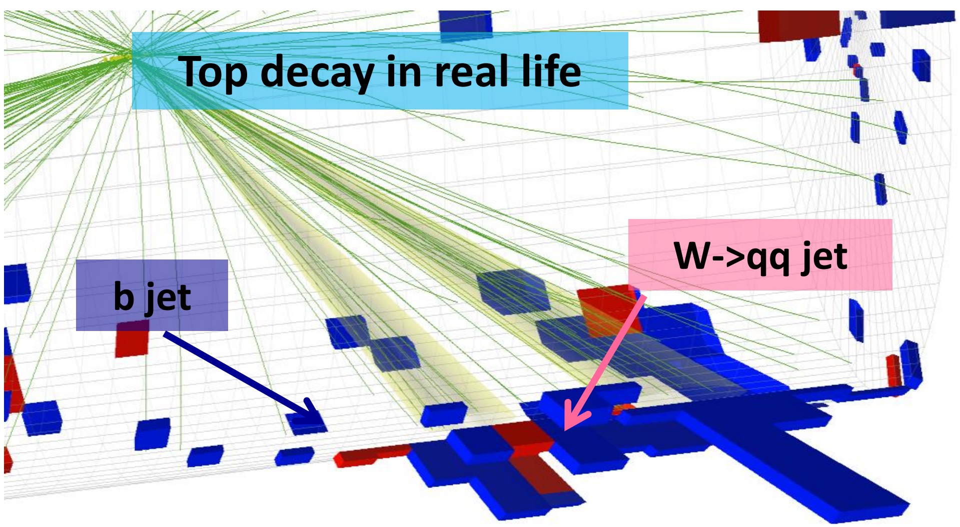
- Boost of the top depends on characteristics of the signal model
  - Need top tagging over a wide range of p_T [challenging]

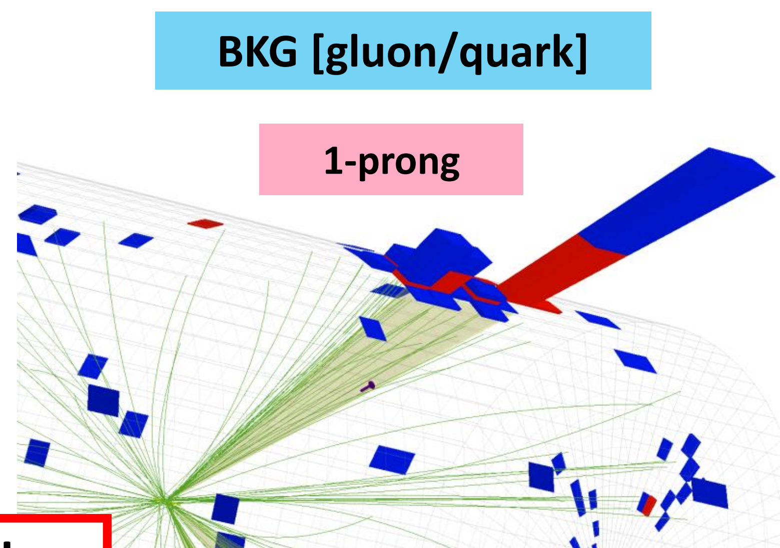
Top tagging at 100 TeV (2)

- **In theory:** A top quark decays to a W boson and a b quark -> 3 quarks in total
  - **Substructure:** identify the 3-prong structure
  - **Flavor:** Identify the b quark [or even W->cX]



- **In practice:** Jet is a cone of reconstructed particles in the detector
  - With a mass and kinematics consistent with the top decay

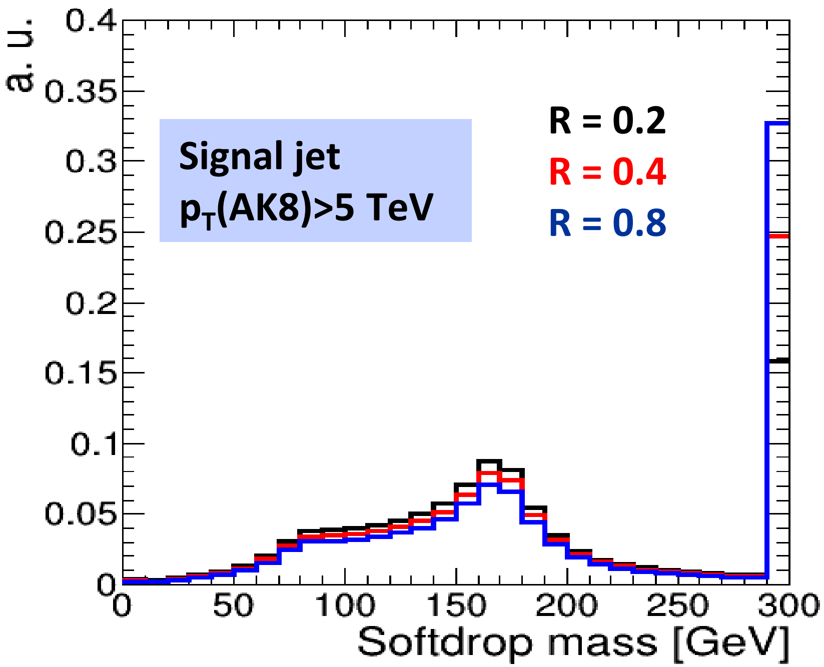


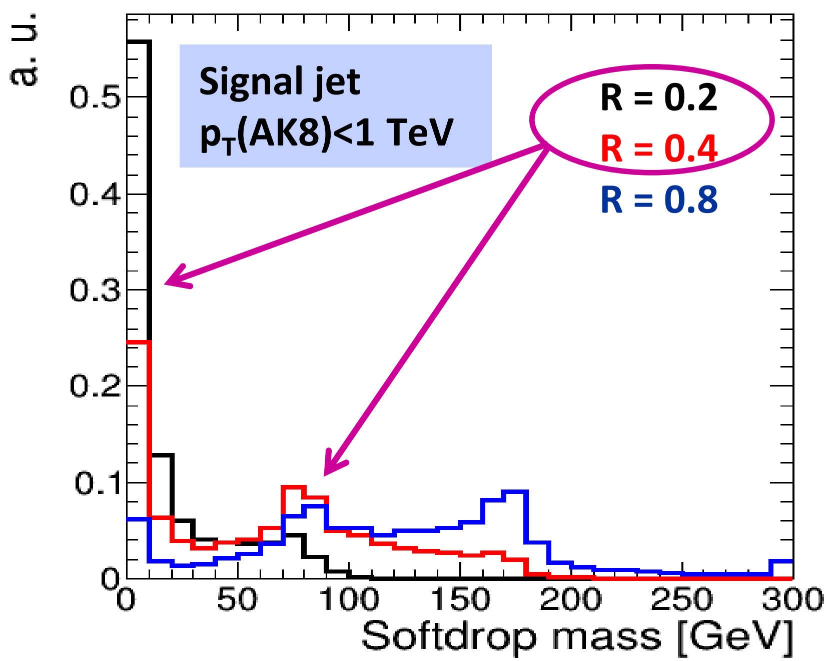


Difficult to distinguish

Top tagging: Multi-R tagger

- The choice of the jet distance parameter (*R*) is important:
  - Large enough to contain the top decay products

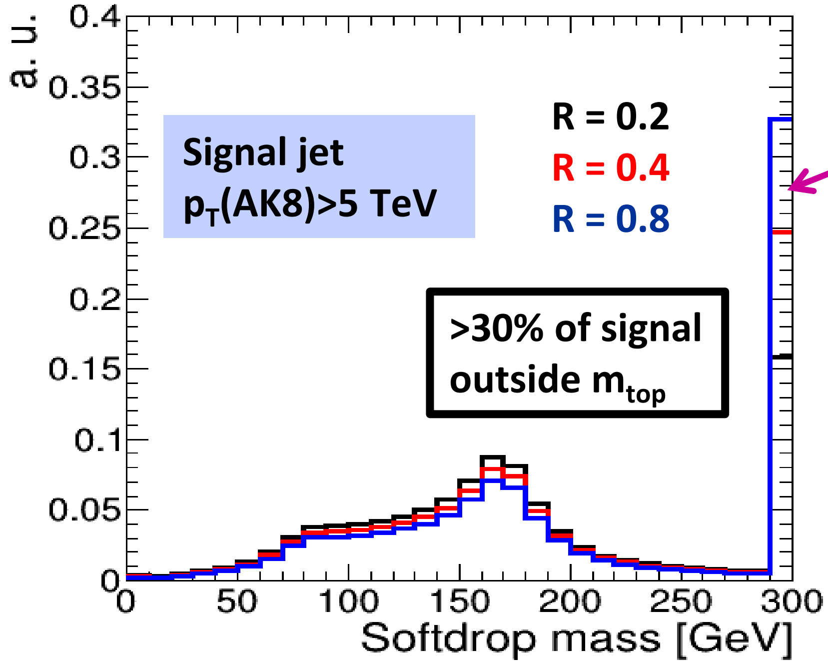


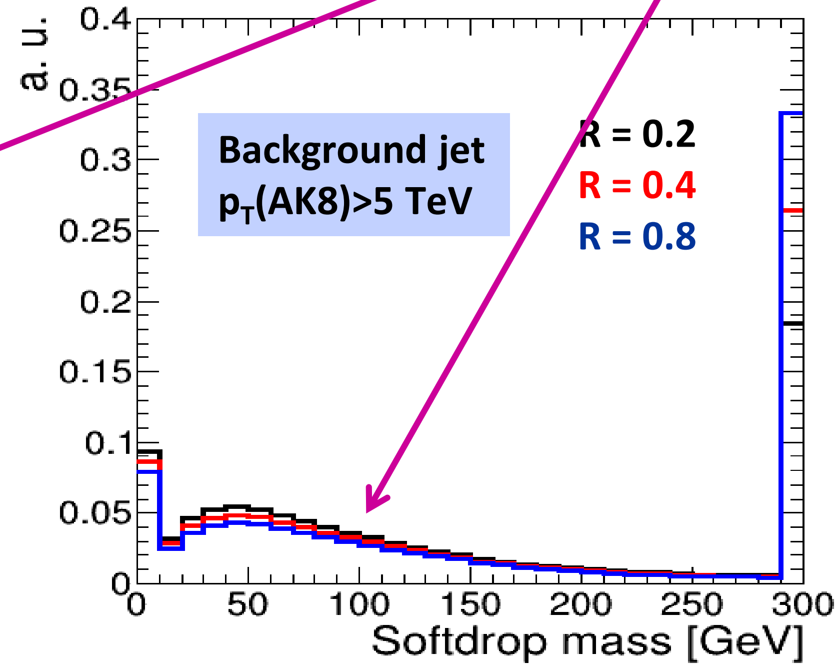


- There is not a single choice: Optimal *R* depends on p_T[top]

Top tagging: Multi-R tagger (2)

- The choice of the jet distance parameter (*R*) is important:
  - Large enough to contain the top decay products
  - But **not too large**…
    - Contributions from the underlying event, pile-up, ISR lead to increased jet mass.





- There is not a single choice: Optimal *R* depends on p_T[top]

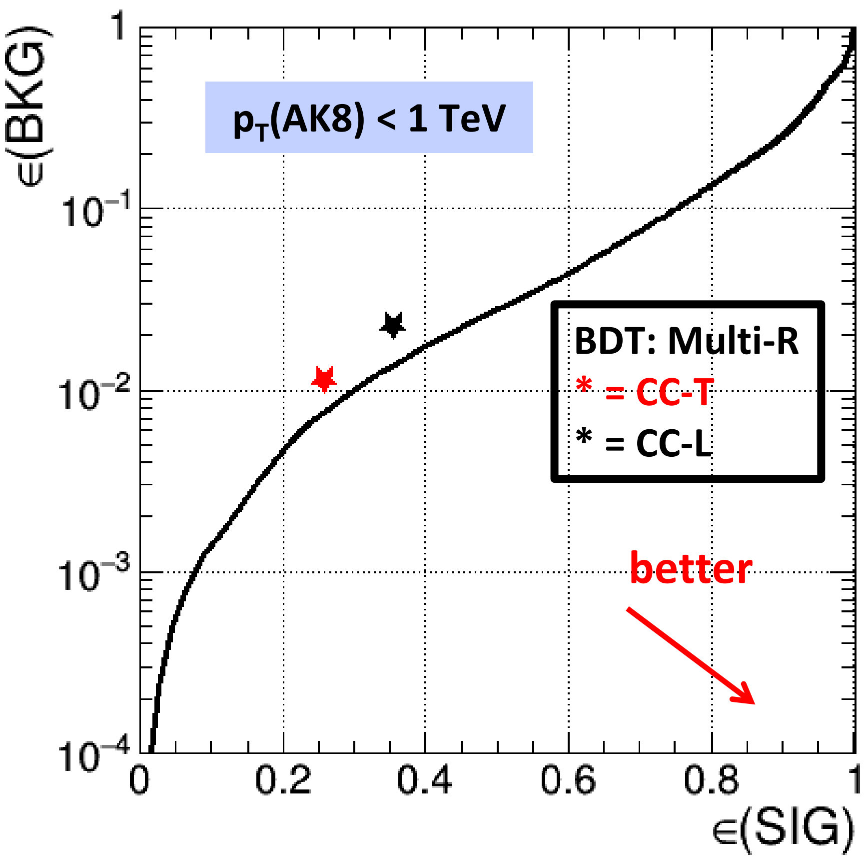
Top tagging: Multi-R tagger (3)

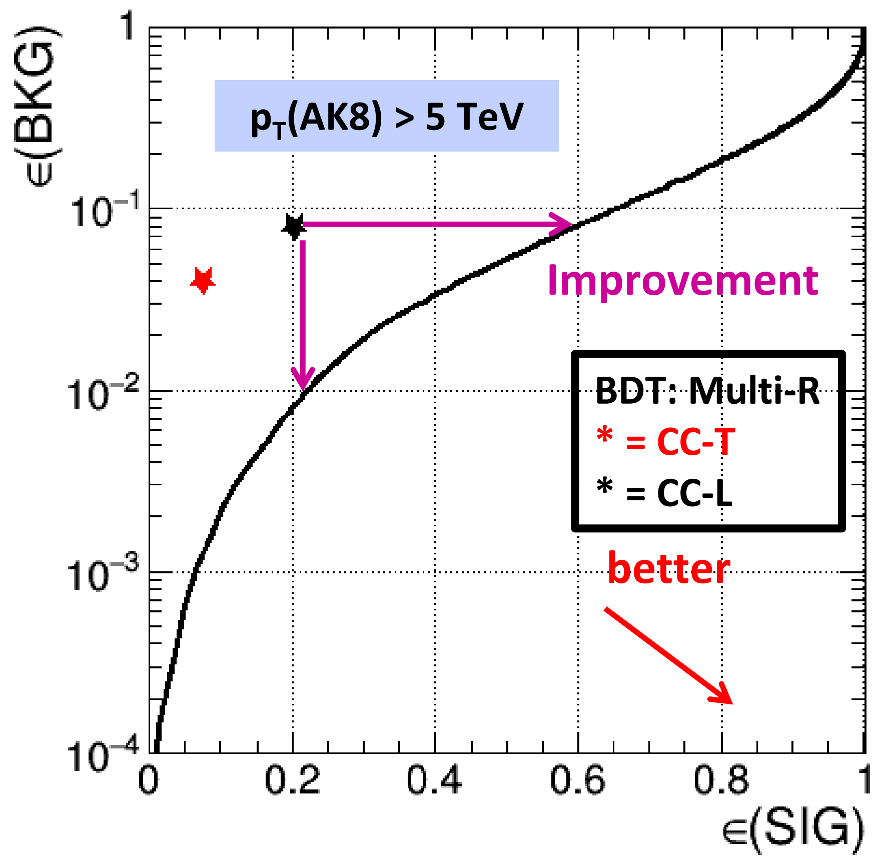
- The choice of the jet distance parameter (*R*) is important

- Develop a "Multi-R" top tagging algorithm:
  - Procedure:
    - Consider all anti-kT PFjets with *R*=0.8 as potential top candidates
    - Remove soft and wide angle radiation ["jet grooming"]
    - Recluster jet constituents with different *R* (=0.2, 0.4)
    - Calculate jet mass and substructure variables (n-jetinness) for each jet variant
  - Expect a very distinct behaviour between Signal and Background

- Utilize multivariate methods [i.e. Boosted Decision Trees, BDT] for the choice of the optimal *R*
  - Input variables for each jet variant:
    - Softdrop mass, p_T, τ32, τ31, τ21

Multi-R tagger: performance





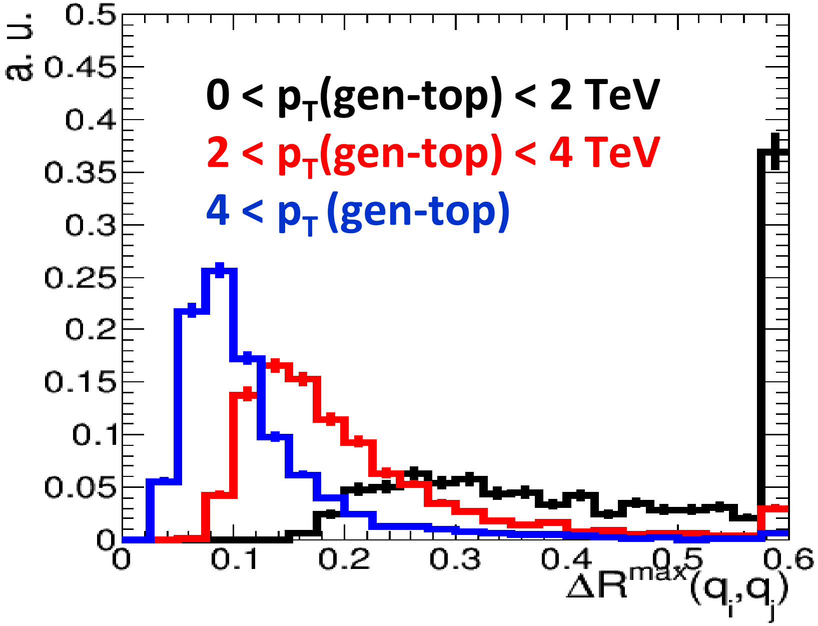
Modest gain wrt cut-based approach [as expected in this p_T regime]

Significant improvement for ultra-boosted tops

However, performance degrades in the case of very boosted tops

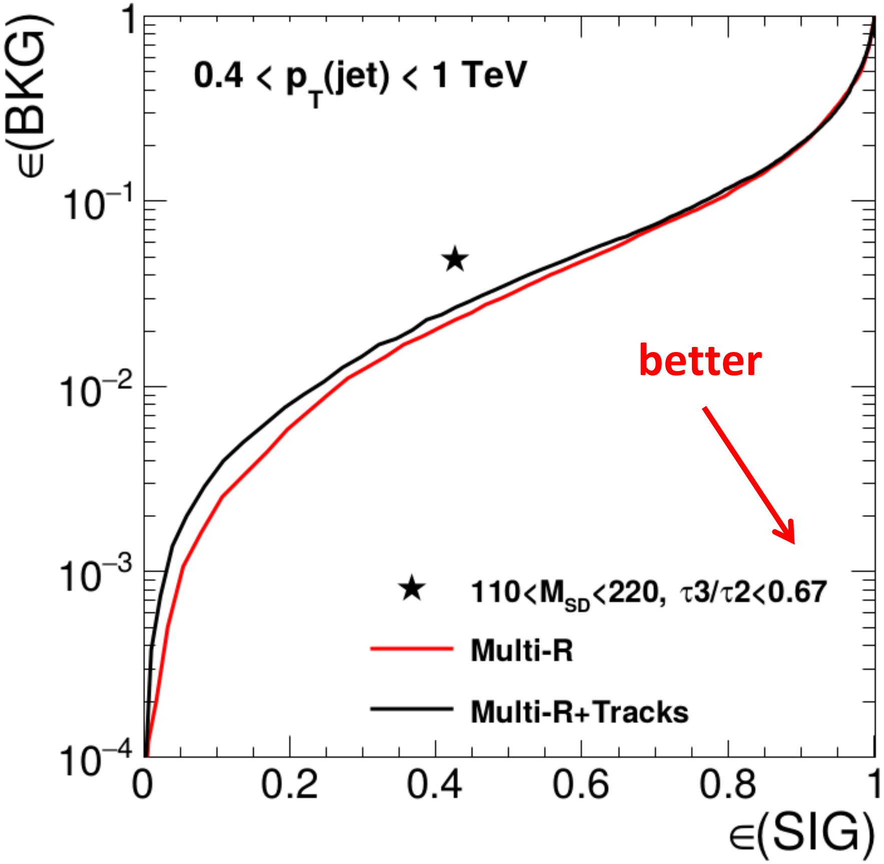
Multi-R tagger + tracks

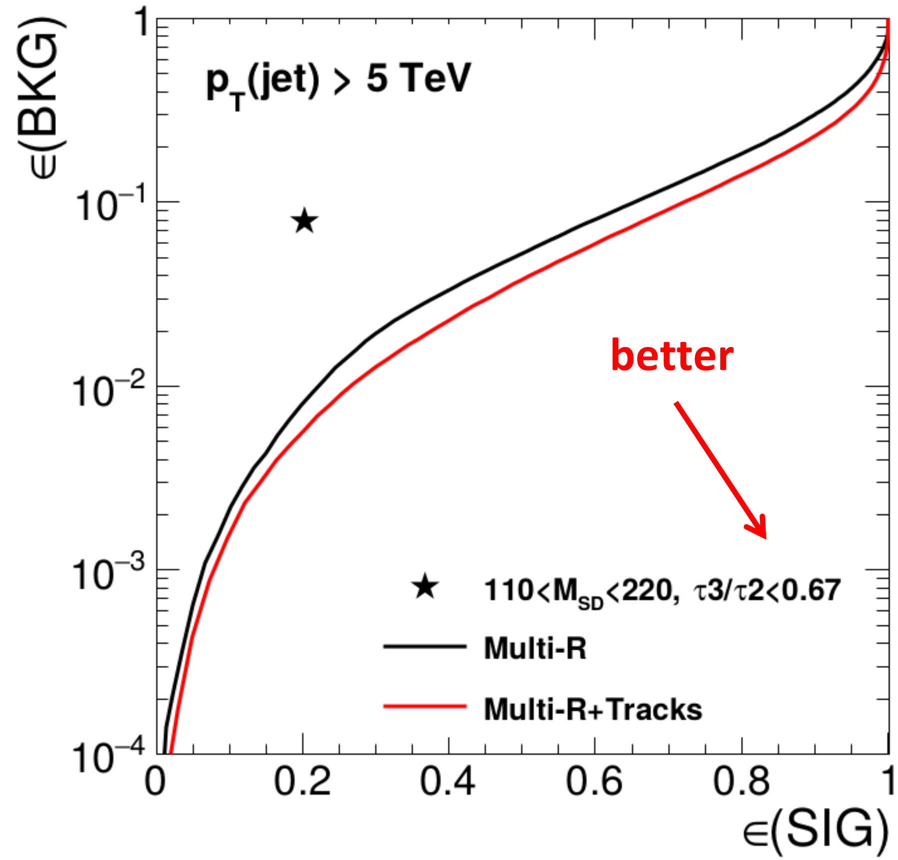
- **Additional challenge:**
  Spatial separation of the decay products of ultra-boosted top quarks
  - Calorimeter granularity not sufficient for efficient identification of boosted tops [i.e. p_T >~4-5 TeV]
  - ΔR (ECAL) ~ 0.02 , ΔR (HCAL) ~ 0.1 vs. $\Delta R_{max}(q_i,q_j)$ ~ 0.05



- Inspired from 1503.03347: Exploit tracking for jet substructure
  - an order of magnitude finer granularity
- Procedure:
  - Consider all anti-kT PFjets with *R*=0.8 as potential top candidates
  - Remove soft and wide angle radiation [“jet grooming”]
  - Recluster jets with *R* (=0.2, 0.4, 0.8) using solely tracks
  - Calculate jet mass and substructure variables [based on tracks] → **Inputs to a BDT**

Multi-R + tracks tagger: performance





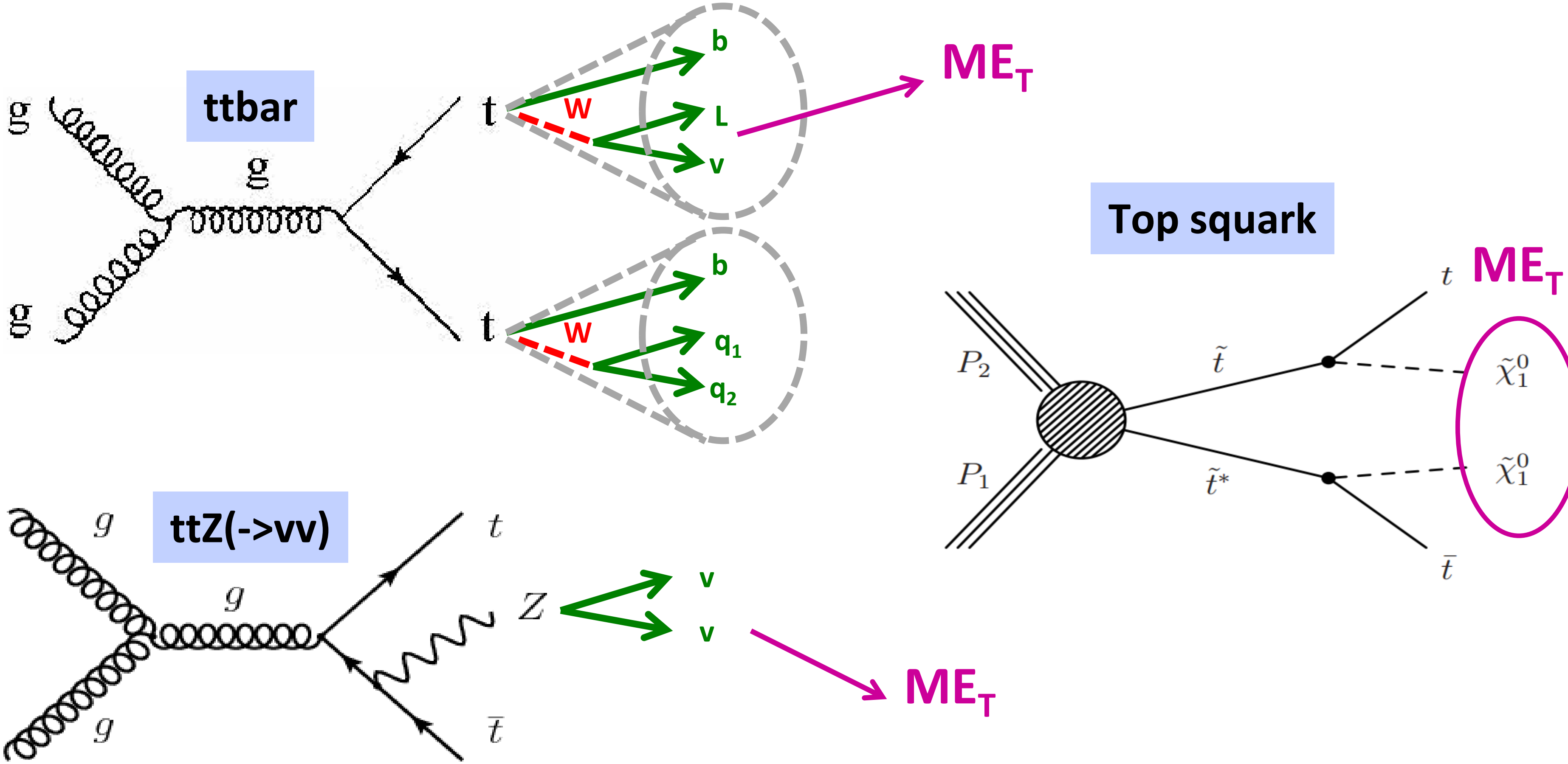
Similar performance to Multi-R version
[as expected in this p_T regime]

Addition of track-based variables recovers loss of performance in the high-pT regime

Proceed with "Multi-R+Tracks" and operate with a working point ~5% mistag

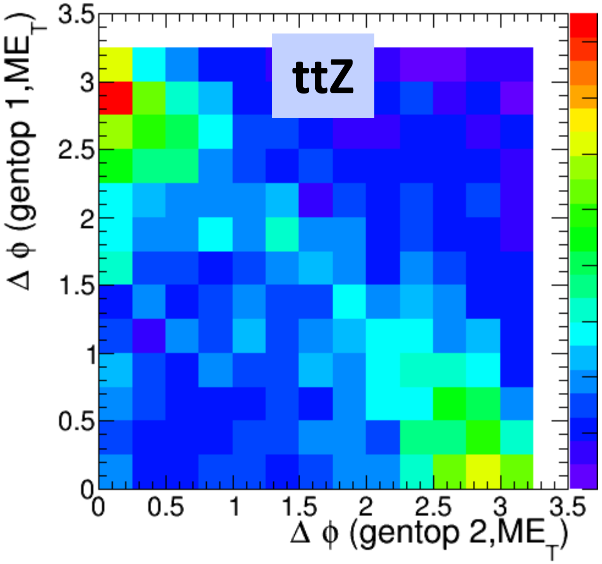
Highlights from the search design

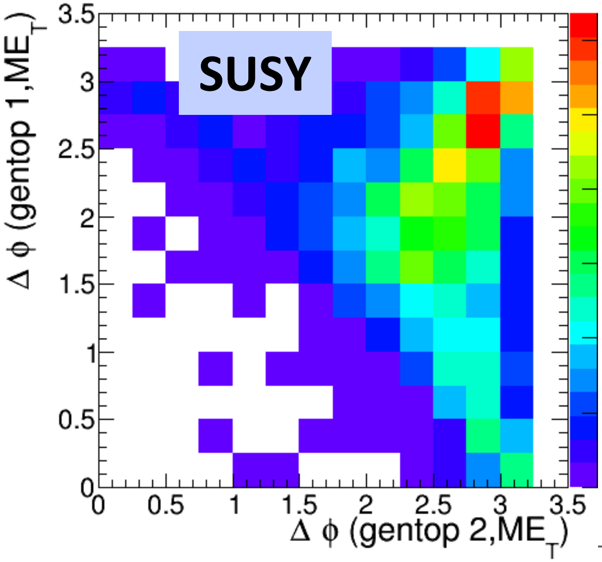
- Dominant BKG after baseline selection + top tagging: **ttbar** & **ttZ**



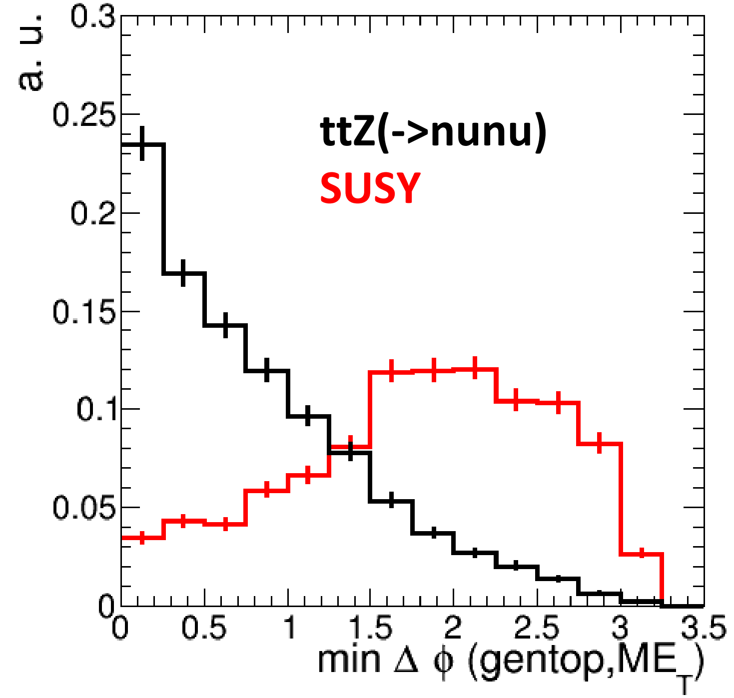
- **ME_T in ttbar & ttZ:** aligned with one of the 2 tops
- **MET in top squarks:** more democratically distributed between the 2 tops

Highlights from search design (2)





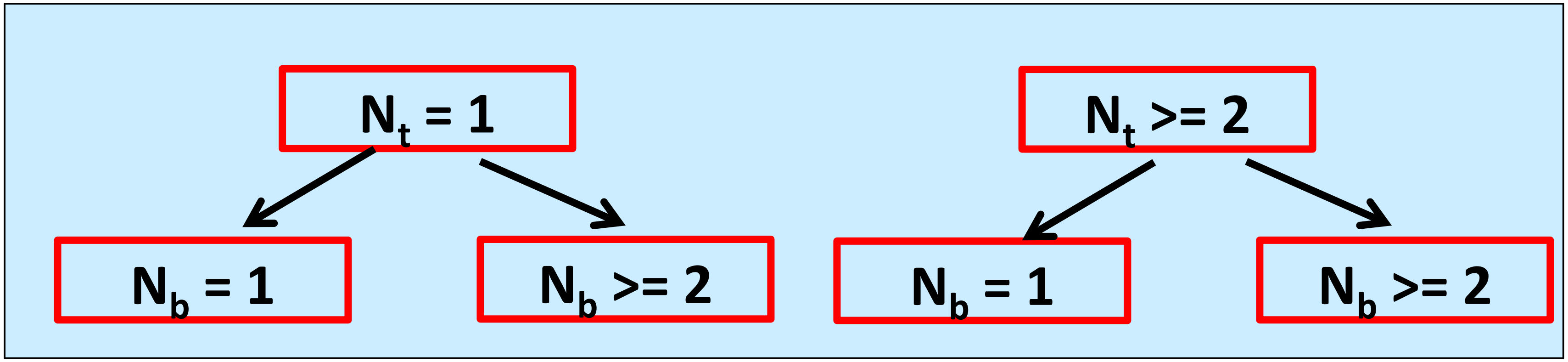
Minimum angle between reconstructed tops and MET



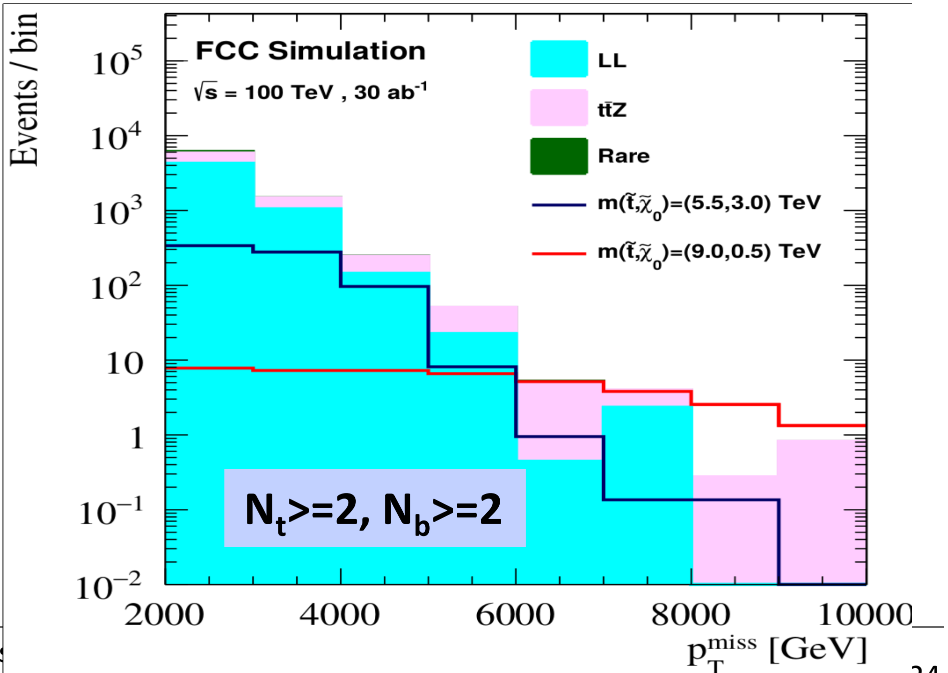
Powerful handle
[~60% BKG for ~10% SIG]

Event categorization

- On top of the baseline, categorize events based on N_t and N_b:



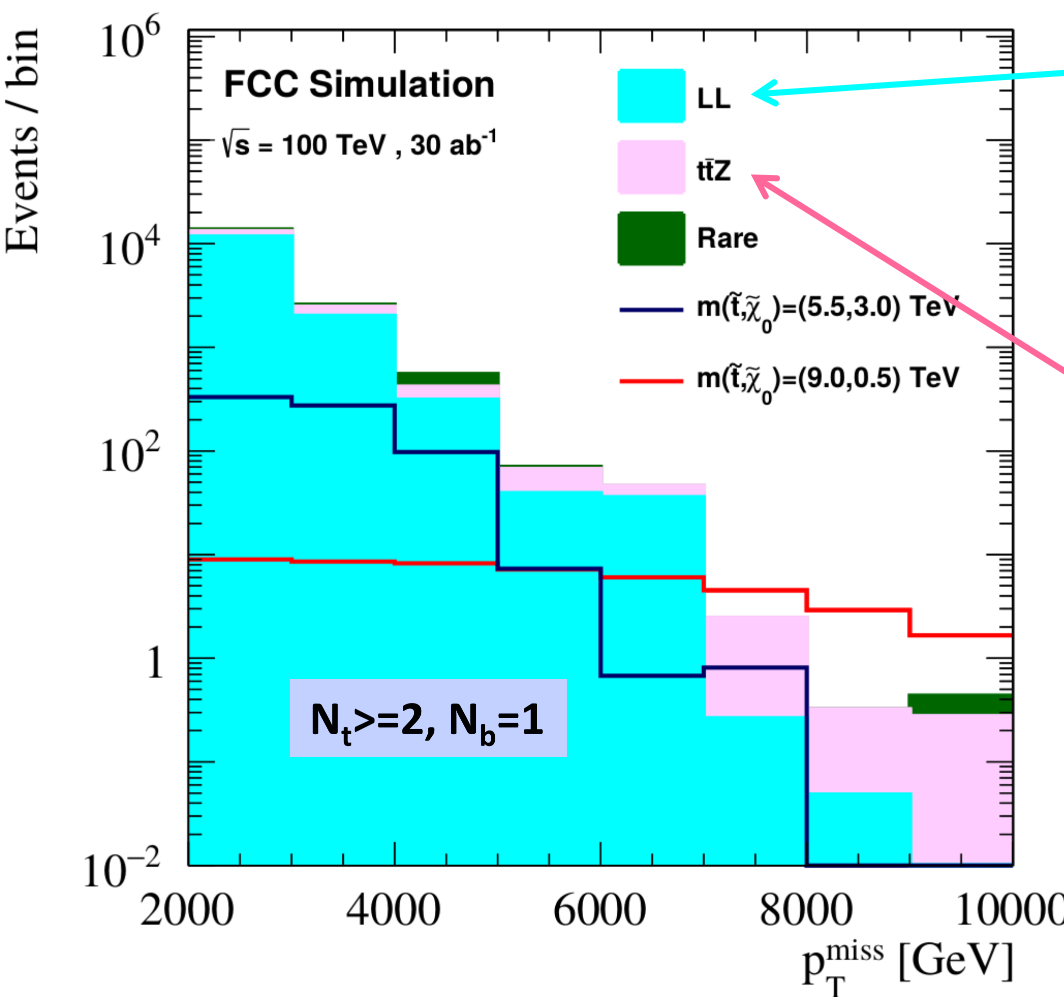
- ME_T traditionally powerful var to separate SIG from BKG
- ME_T spectrum depends strongly on the signal model
  - Fit ME_T shape



Challenge: Background estimation

- We will enter in the regime of very small SUSY production x-sections [very massive sparticles]
  - σ(SUSY) orders of magnitude smaller wrt σ(SM)
- SUSY signal is mainly searched for in the tails of the distributions
  - BKG: very good control of the tails needed
- Strategy:
  - Main backgrounds [LL & ttZ] estimated using data-driven methods:
    - Use dedicated "data" control samples [with kinematics similar to the signal] to measure each process
    - Translate the measurement to a BKG prediction with the aid of simulation
  - Rare backgrounds:
    - Estimated from simulation with generous uncertainties [100%]

Challenge: Background estimation (2)



LL BKG: 1L control sample

- N_L = 1 with $p_T[L] \geq 30$ GeV
- $M_T(L,ME_T)$<100 GeV:

suppress potential signal contamination

ttZ BKG: 3L control sample

- N_L = 3 with $p_T[L] \geq 30$ GeV
- OSSF pair consistent with M_Z
- $p_T(Z)$)> 2 TeV:

Systematics

- Dominant uncertainty from the stats of the control regions

- Two scenarios to account for additional sources:

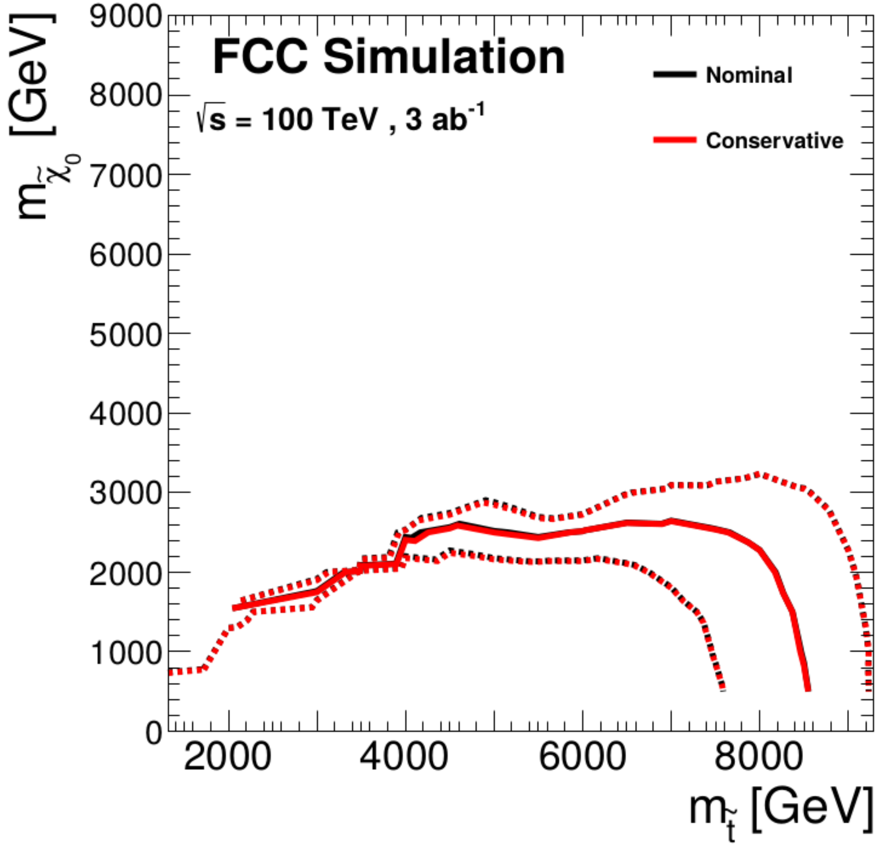
-> “**nominal**”: 20% uncertainty uncorrelated across all regions/ processes

-> “**conservative**”: 40%

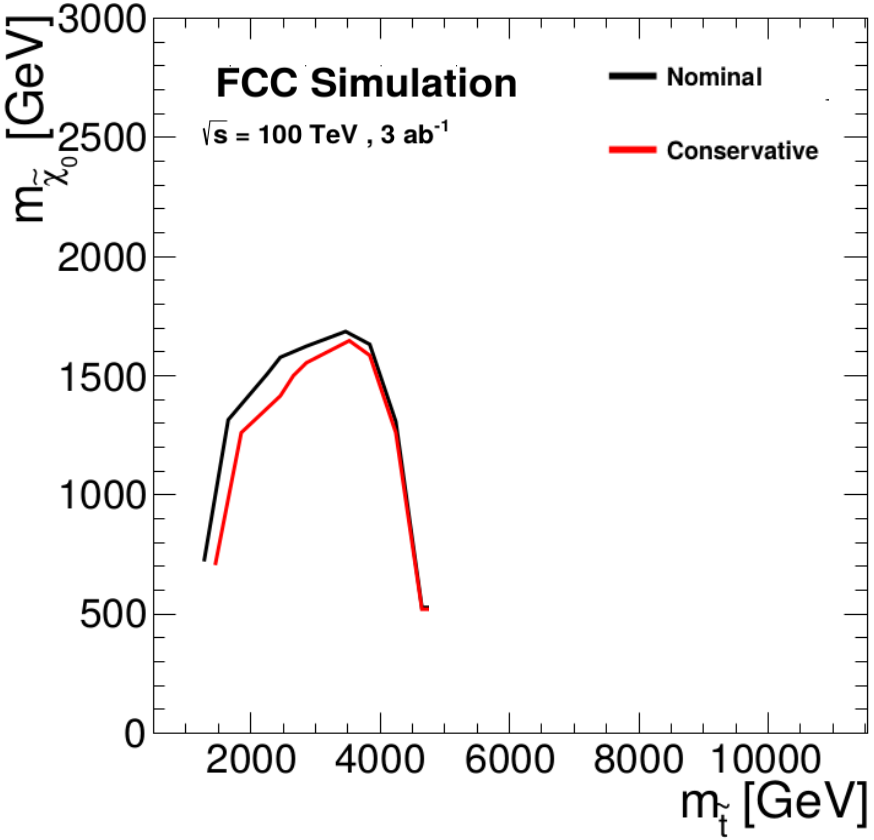
Results

Results @ 3 ab^{-1}

Expected limit



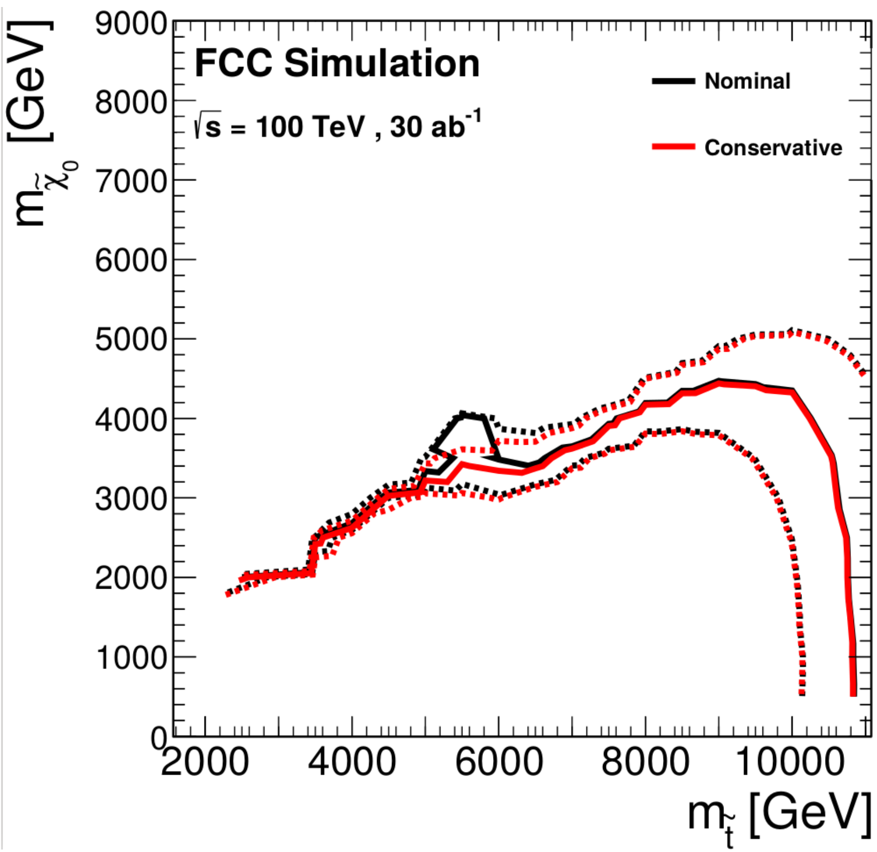
Expected Significance



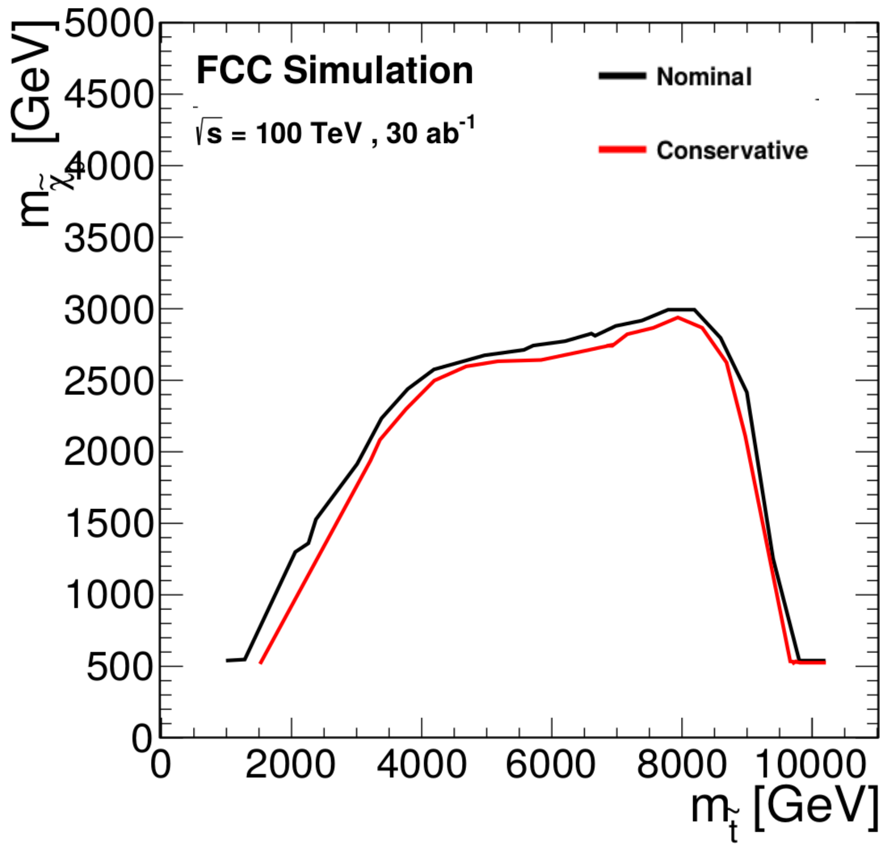
NB: Work on going [smoothing]

Results @ 30 ab^{-1}

Expected limit



Expected Significance



NB: Work on going [smoothing, cosmetics]

Summary

- We have designed a search for top squarks for the FCC-hh at 100 TeV
  - Focus on all hadronic channel -> take advantage of the largest BR
- Tagging ultra-boosted top quarks @ 100 TeV needs detector granularity and improved methods:
  - Multi-R approach
  - Track-based substructure variables

"Multi-R+Tracks"

5-10x improved background rejection wrt to existing approaches

[Still lots of room for improvement]

- **Conclusion:**
  - We can reach the m_{stop}~9-10 TeV barrier already with 3 ab^{-1}
  - Additional luminosity [i.e. 30 ab^{-1}] is important for SUSY hunt:
    - discover top squarks with m_{stop}~9 TeV

NB: for models with $m_{LSP} << m_{stop}$

- An O(100 TeV) hadron collider should be the next step after HL-LHC

The FCC-hh physics program will be critical in our discovery or abandonment of SUSY