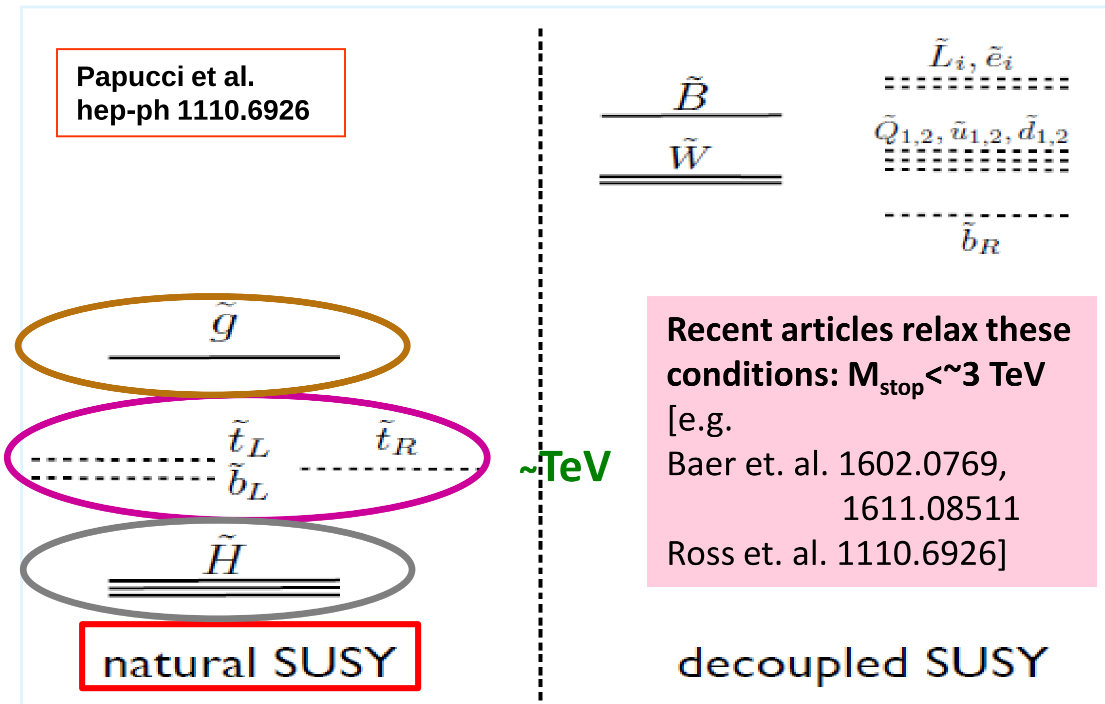
Top squark searches at 100 TeV

Loukas Gouskos, Allan Sung, Joe Incandela

Physics motivation

- SUSY: One of the most extensively studied BSM theories
  - An excellent answer to hierarchy problem, dark matter and unification of couplings
- "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

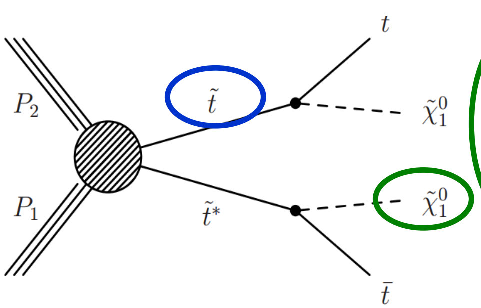


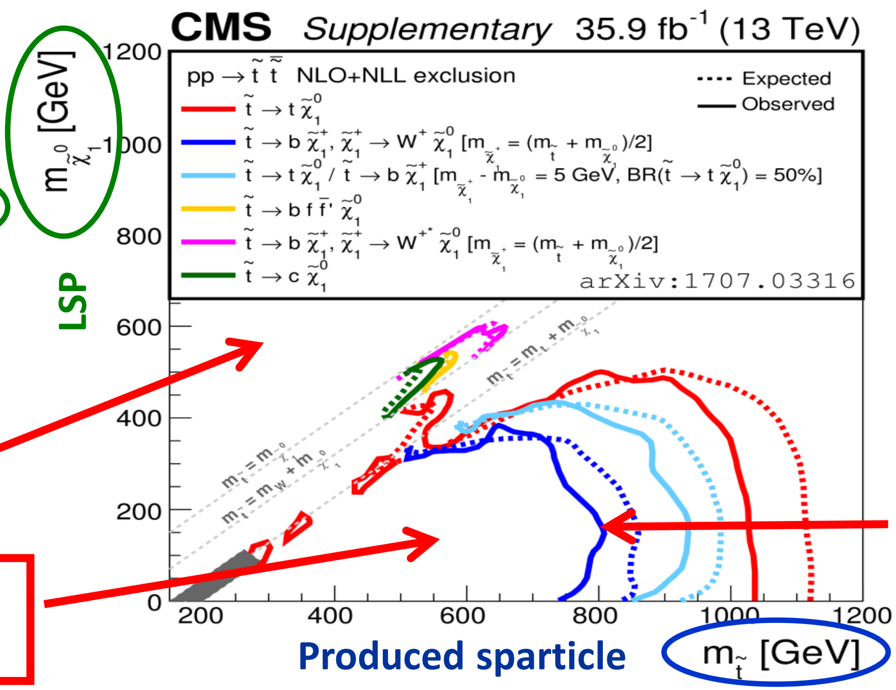
- **Natural SUSY spectrum: higgsinos , stops/sbottoms and gluinos, ~ TeV Scale [maybe within LHC reach]**
- **All other sparticles can be very heavy [decoupled]**

This talk:
Focus on the search for top squarks in models with R-parity conservation

Setting the stage

- **Simplified model spectra [SMS]:** used for 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





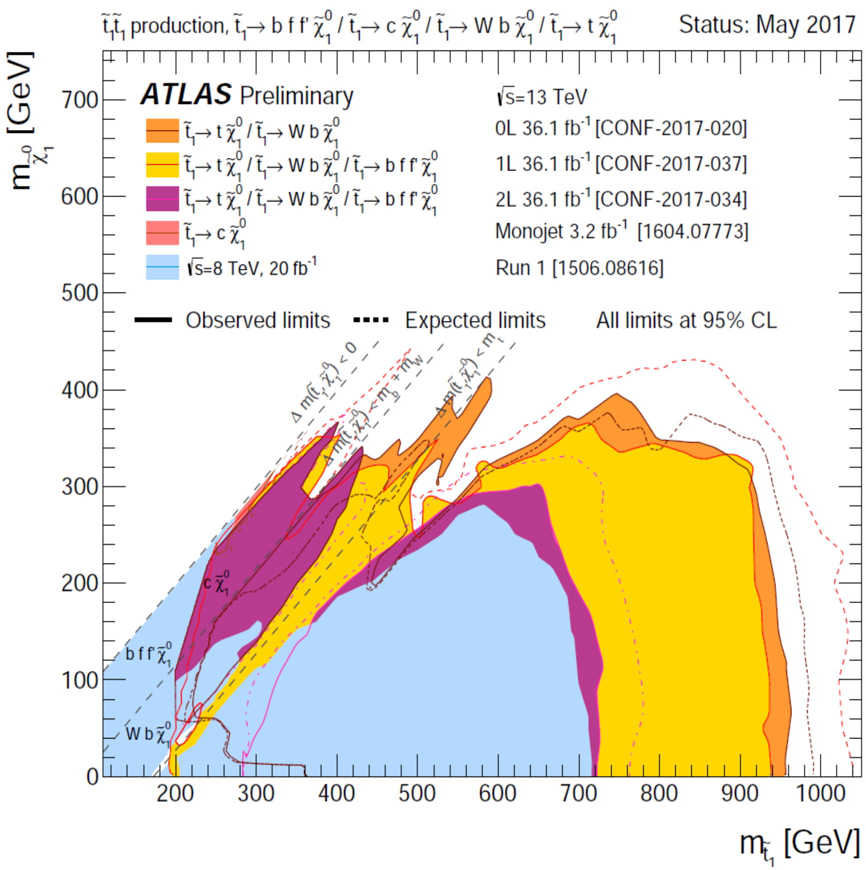
Region kinematically forbidden m[prod. sparticle] < m[LSP]

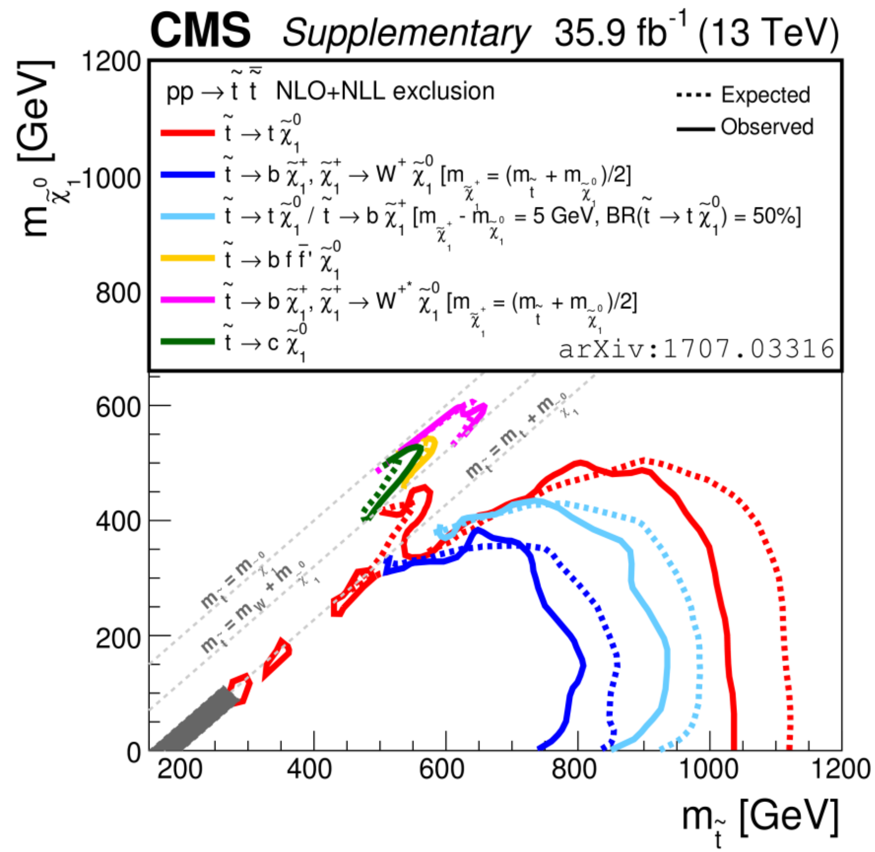
Excluded parameter space

Set Upper Limits in cross-section

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

Top squark searches at the LHC



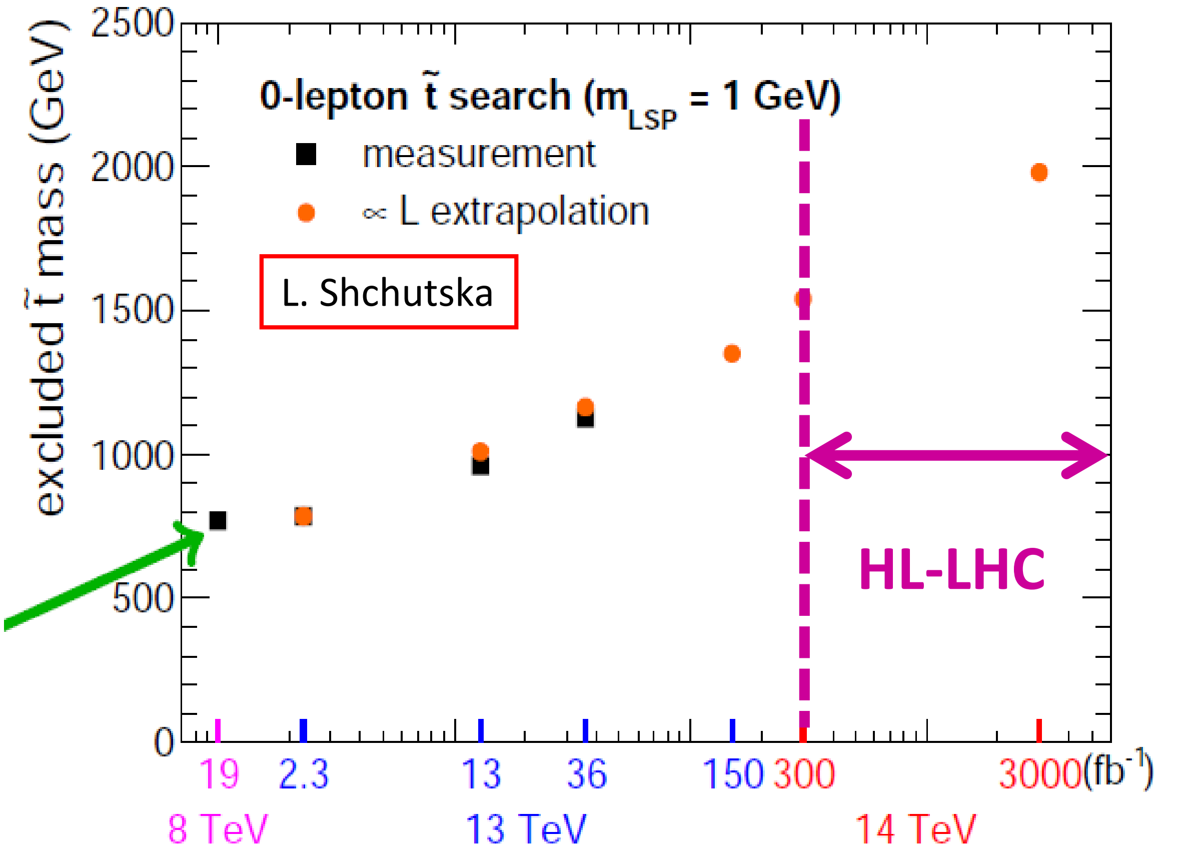


- No hints of SUSY after the first years of LHC operation
- Models with m_{stop} up to ~1 TeV and light LSP are excluded

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

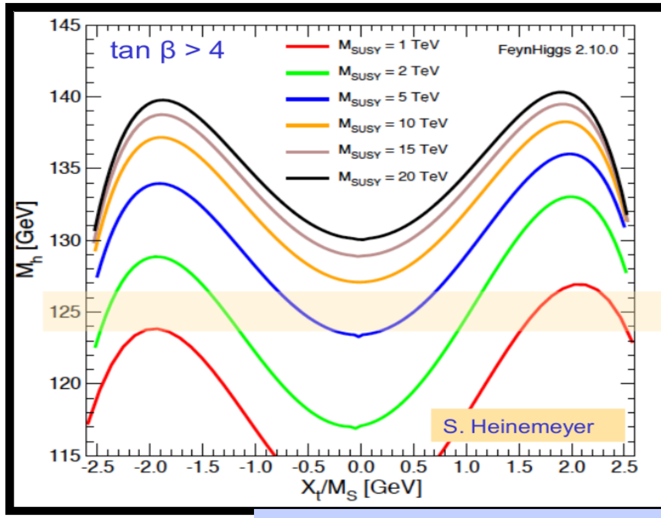
End of HL-LHC program: What's next?

- Optimistic scenario [or scenario 1]:
  - Discovery/Observation top squarks at the LHC [~TeV scale]:
    - mechanism for the "hierarchy problem" [and for dark matter if R_P is conserved]
  - Need a SUSY-factory to study the properties [mass spectrum, BR, etc..]
  - 100 TeV pp collider is a **SUSY-factory** [e.g. m_{stop} = 2 TeV -> $\sigma_{100TeV}/\sigma_{13TeV} \sim 10^4$]

- 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 [?]
  - Need a powerful hadronic collider to really explore the naturalness issue and the viability of SUSY in general
    - SUSY is to this day on the most appealing BSM theories

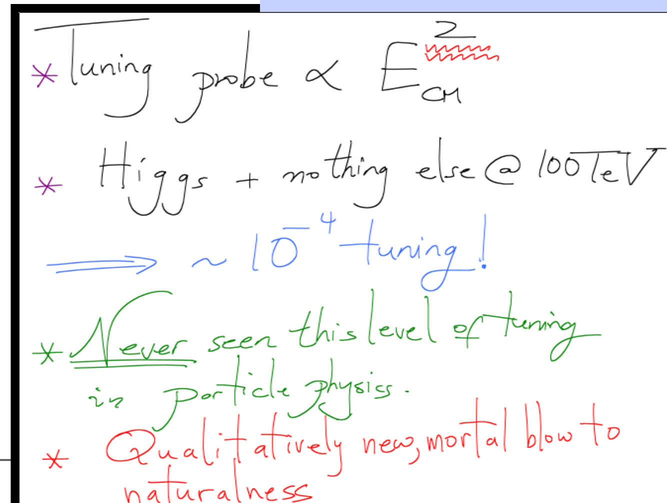
Motivation for FCC-hh @100 TeV

- Theory motivations for superpartner mass upper bounds and the reach of a 100 TeV pp collider:



  - Measured Higgs mass [FCC-hh Yellow report]:
    - Top squarks have the largest contributions to the Higgs mass
    - 1 TeV < m_{stop} < 10 TeV seem to be favored in many models
  - Gauge coupling unification [FCC-hh Yellow report]:
    - Predict superpartners with m_{stop} < 10 TeV
  - Understanding the naturalness of the EWK state:
    - "Never seen fine-tuning of 10^{-4} in HEP": FT 10^{-4} -> ~10 TeV top squarks

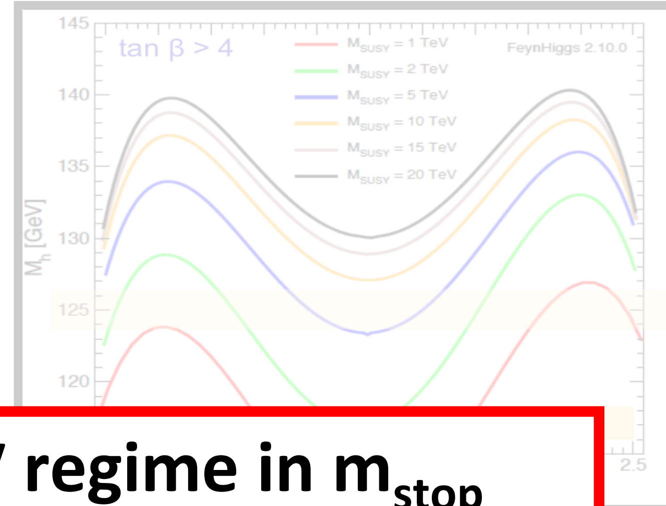
Nima Arkani-Hamed: FCC-Kick-off 2014



Mostly outside the HL-LHC reach; Need for a powerful hadron collider

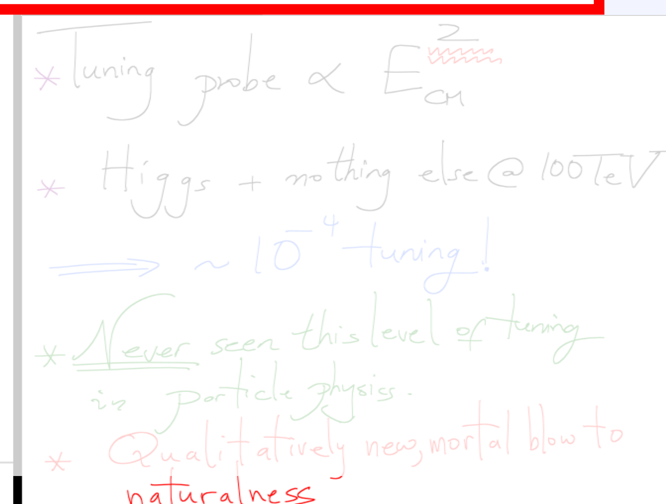
Motivation for FCC-hh @100 TeV

- Theory motivations for superpartner mass upper bounds and the reach of a 100 TeV pp collider:
  - Measured Higgs mass [FCC-hh Yellow report]:
    - Top squarks have the largest contributions to the Higgs mass
    - 1 TeV < m_{stop} < 10 TeV seem to be favored



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

    - “Never seen fine-tuning of 10^{-4} in HEP”: FT 10^{-4} -> ~10 TeV top squarks
  - Gauge coupling unification [FCC-hh Yellow report]:
    - Predict superpartners with m_{stop} < 10 TeV

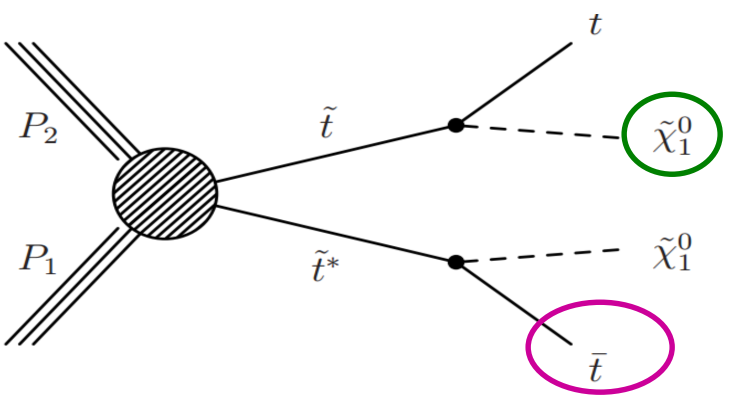


Mostly outside the HL-LHC reach; Need for an FCC-hh @ 100 TeV

Search design

Signal characteristics

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

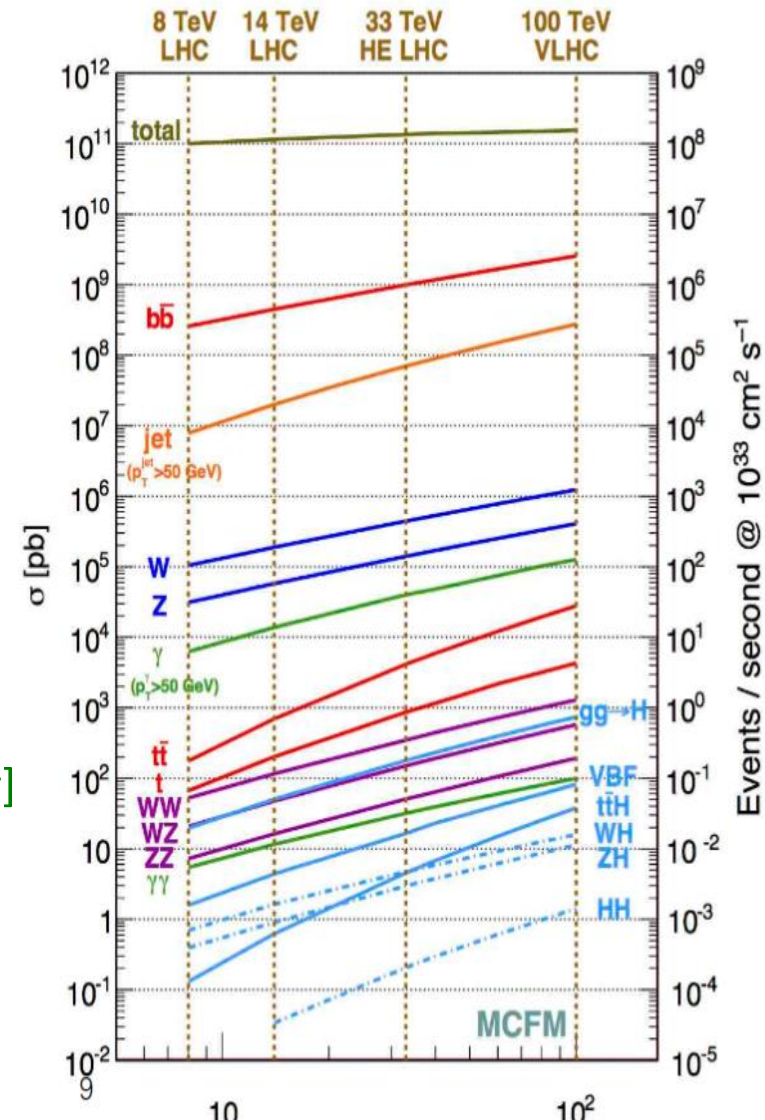


- **Multiple jets**
- **2 b-jets**
- **On-shell top quarks**
- **Large ME_T [from the two LSPs]**

- Baseline selection:
  - Veto leptons with p_T>30 GeV
  - N_j>=2 with p_T>1000 GeV; N_b>=1 with p_T>50 GeV
  - ME_T> 2 TeV
  - $\Delta\phi$ ($j_{1,2}$; ME_T) > 0.5 ; $\Delta\phi$ (j_3 ; ME_T) > 0.3 [QCD killers]

Background processes

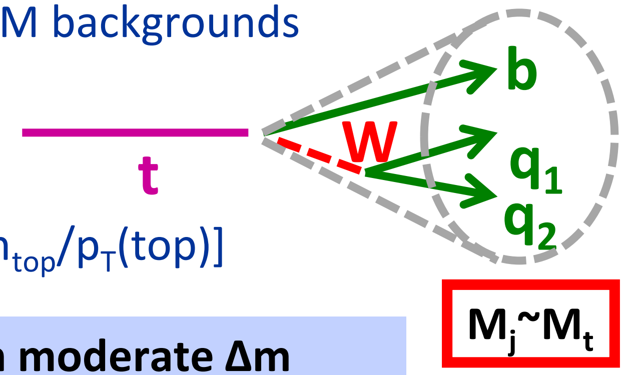
- Relevant backgrounds:
  - **"Lost Lepton" (LL) backgrounds:**
    - Stemming from leptonic decays of W with the lepton escaping detection -> large MET
    - ttbar dominates, important contributions from ttW/ttH
  - **ttZ(Z->vv) background:**
    - Similar characteristics with signal
    - σ(100 TeV)/σ(14 TeV) ~50
  - **"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
  - Events simulated using FCC detector & Delphes

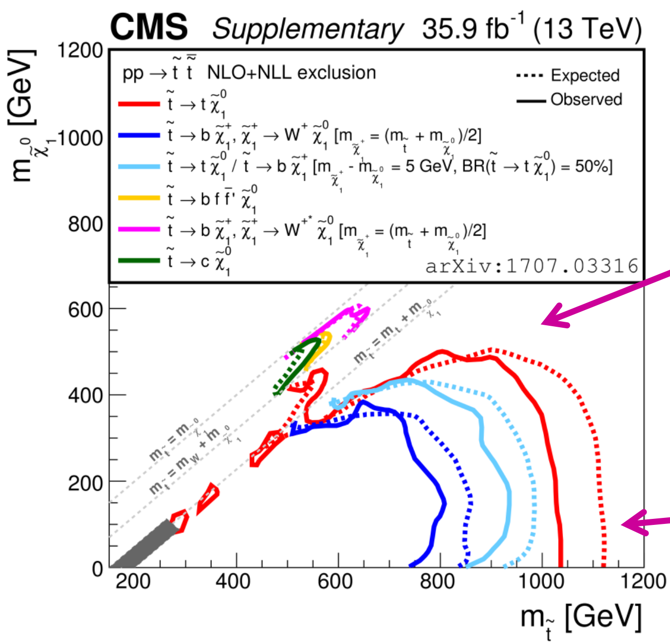


σ(m_{stop}~7 TeV) ~10^{-4} [NLO]

Top tagging in top squark searches

- 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 [$\Delta R \sim 2 x m_{top}/p_T(top)$]





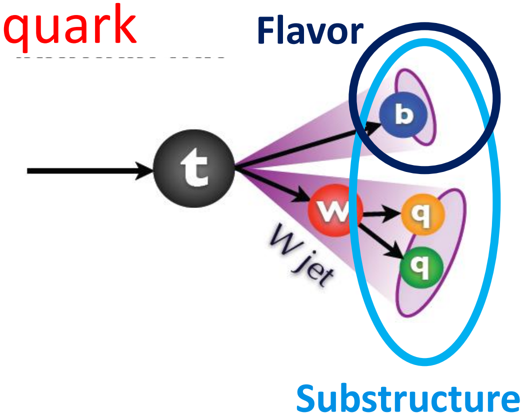
Signals with moderate Δm
top quarks with moderate p_T
~TeV [similar to LHC]

Signals with large Δm
top quarks with very high p_T
~5-10 TeV

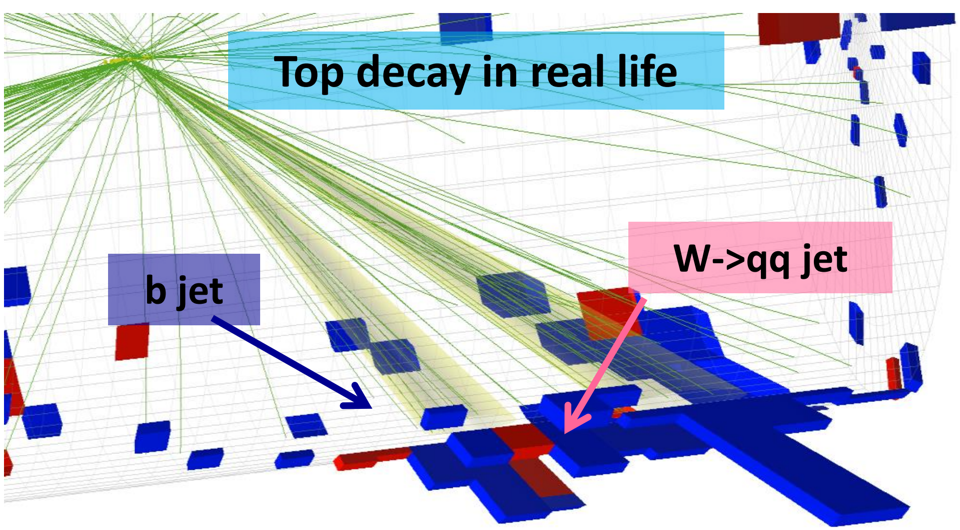
- Boost of the top depends on characteristics of the signal model
  - Need top tagging over a wide range of p_T [challenging]

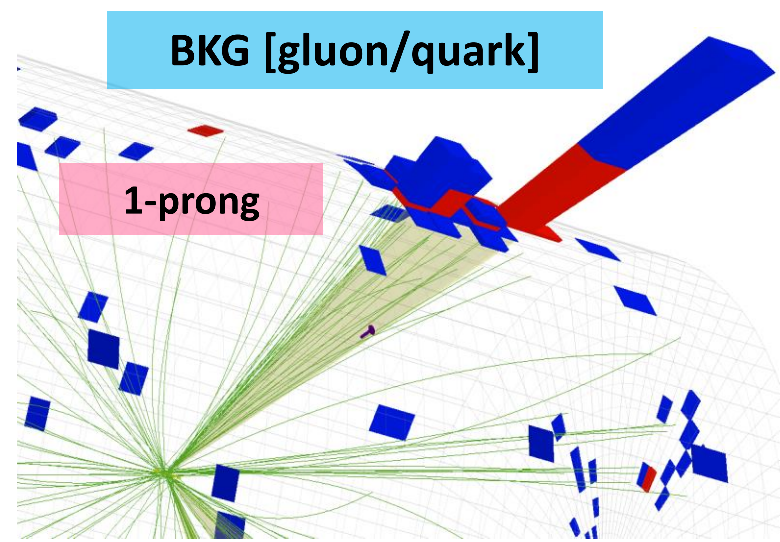
Hadronic top tagging

- **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

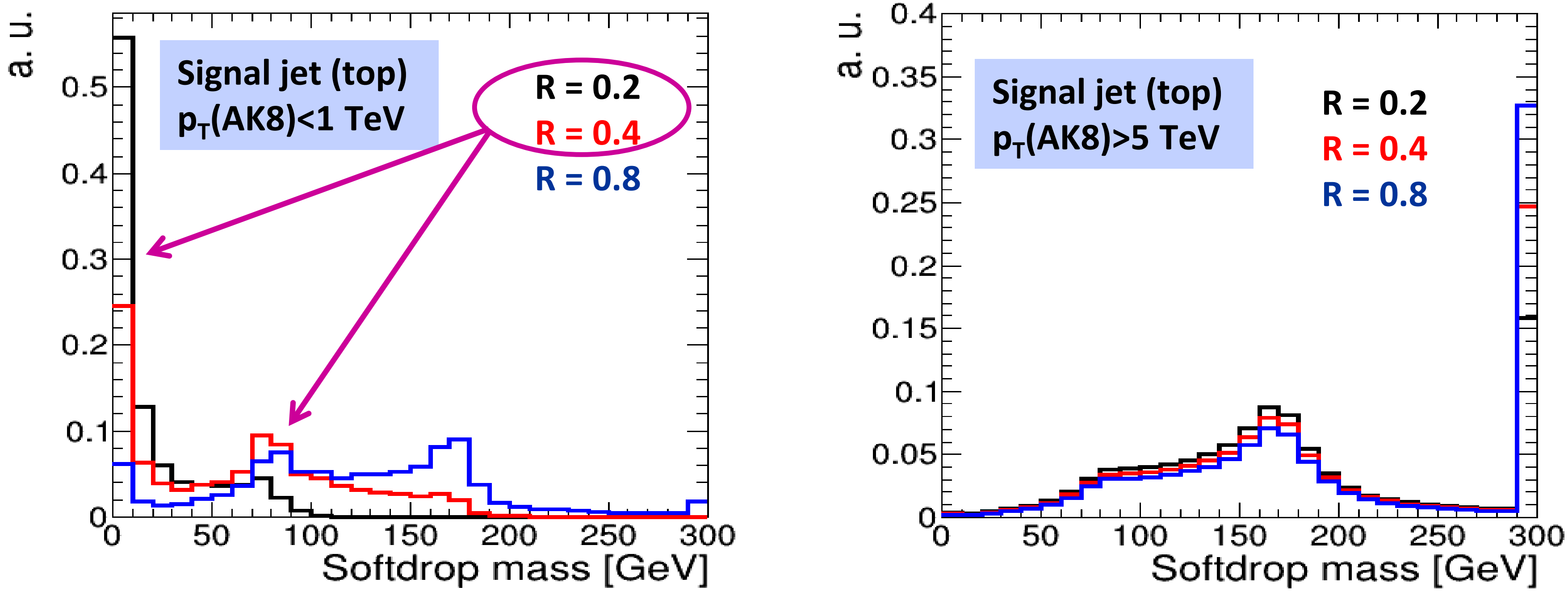




Challenging..

Top tagging at 100 TeV: Challenge 1

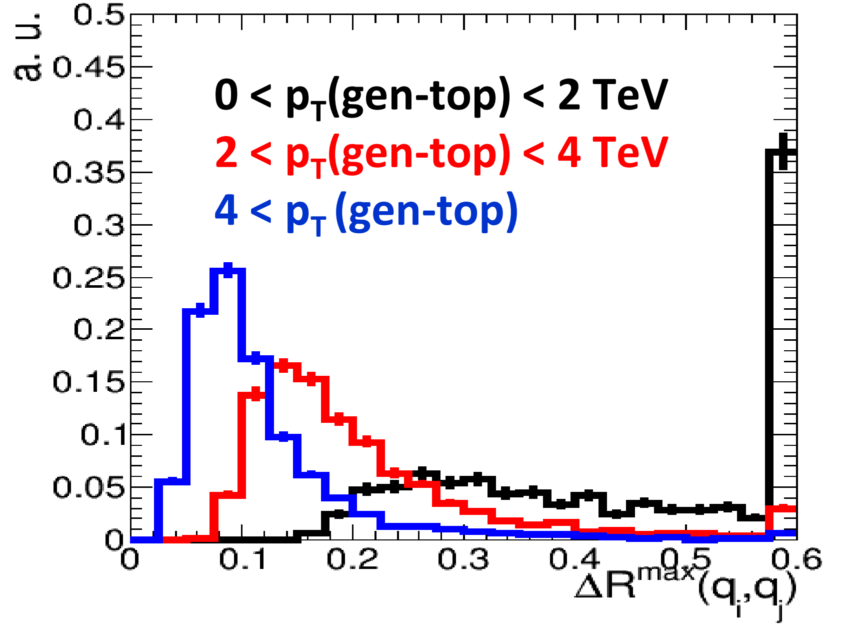
- Choice of the jet distance parameter (*R*)
  - Large enough to contain the top decay products
  - But **not too large**…
    - Contributions from the underlying event, pile-up, ISR lead to increased jet mass.



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

Top tagging at 100 TeV: Challenge 2

- Spatial separation of the decay products of ultra-boosted top quarks
  - ΔR (ECAL) ~ 0.02 , ΔR (HCAL) ~ 0.1
    4x better wrt CMS/ATLAS
  - CALO granularity not sufficient for efficient identification of ultra-boosted tops
- Inspired from 1503.03347:
  - Exploit tracking for jet substructure

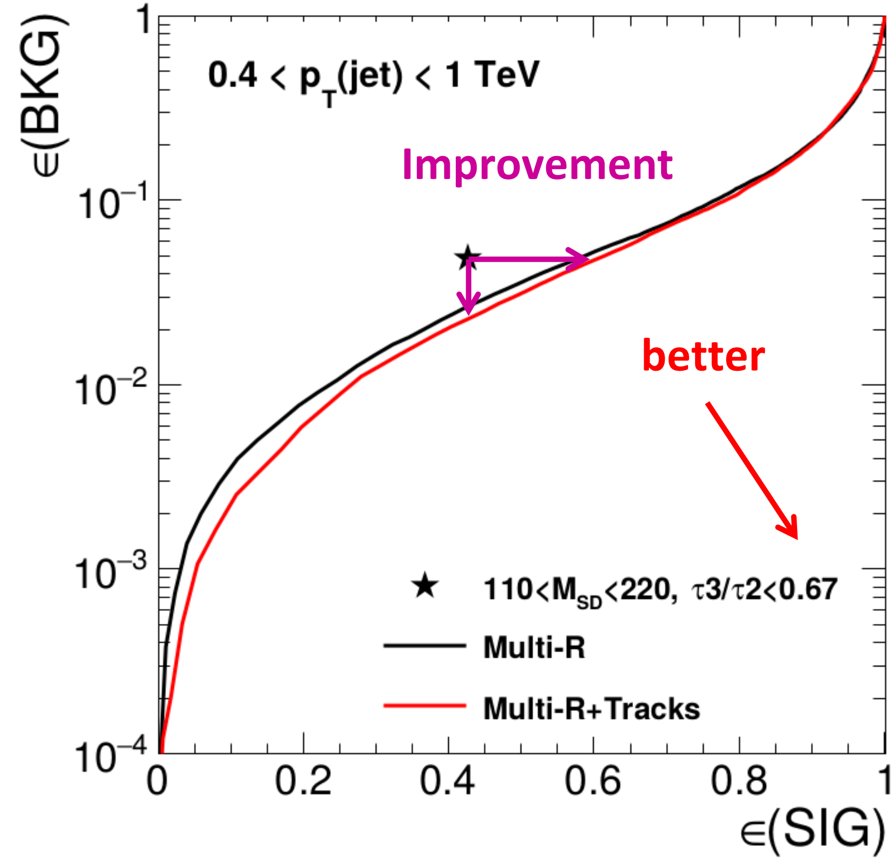


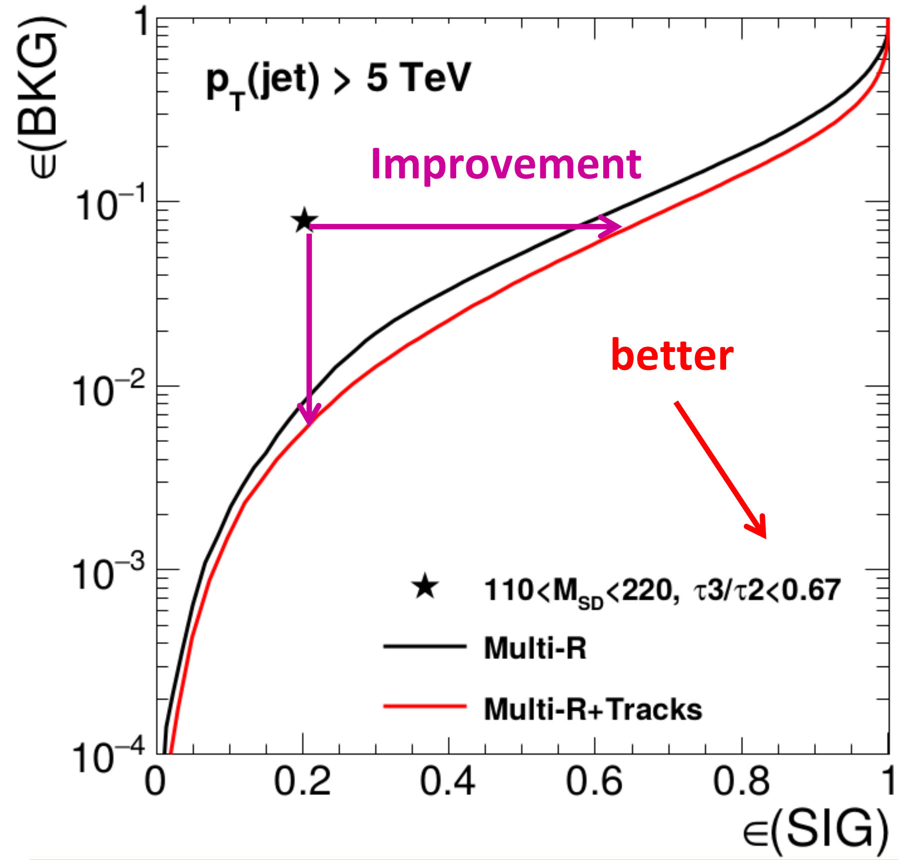
<u>Putting pieces together</u>

-> top candidate: anti-kT PF-Jets with *R*=0.8
-> iteratively reduce *R* and exploit jet substructure
-> Repeat using jets made solely from tracks
-> Utilize Multivariate methods [i.e. BDT] to suppress fake rate

"Multi-R + Tracks" top tagging algorithm

Multi-R + tracks tagger: performance





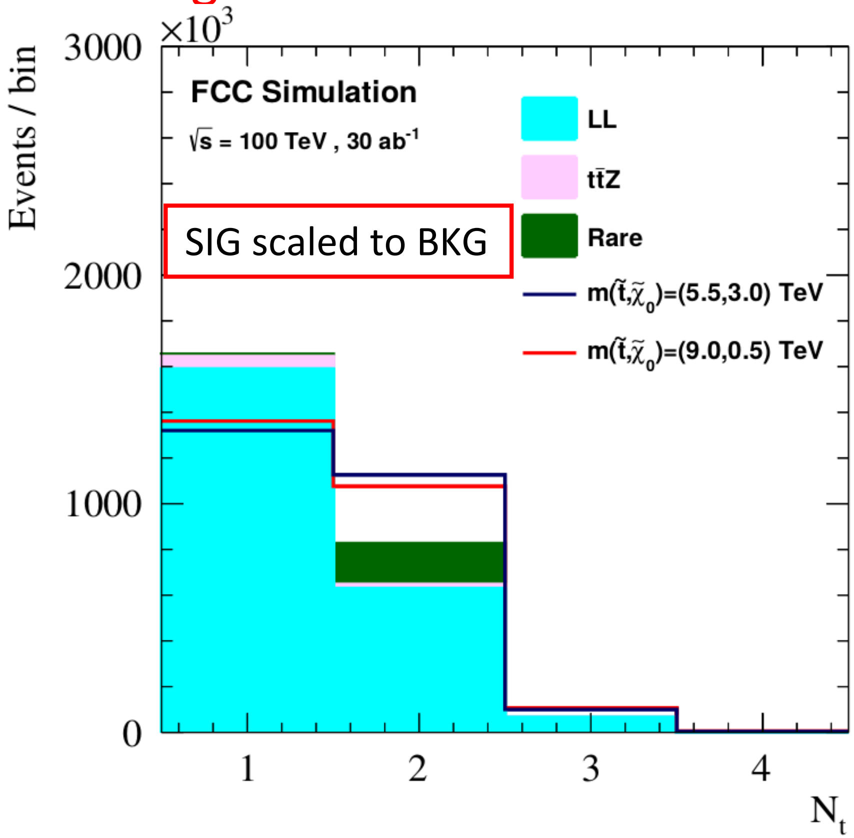
-> modest improvement wrt cut-based tagger
-> “Multi-R+Tracks”: Similar performance to Multi-R version [as expected in this p_T regime]

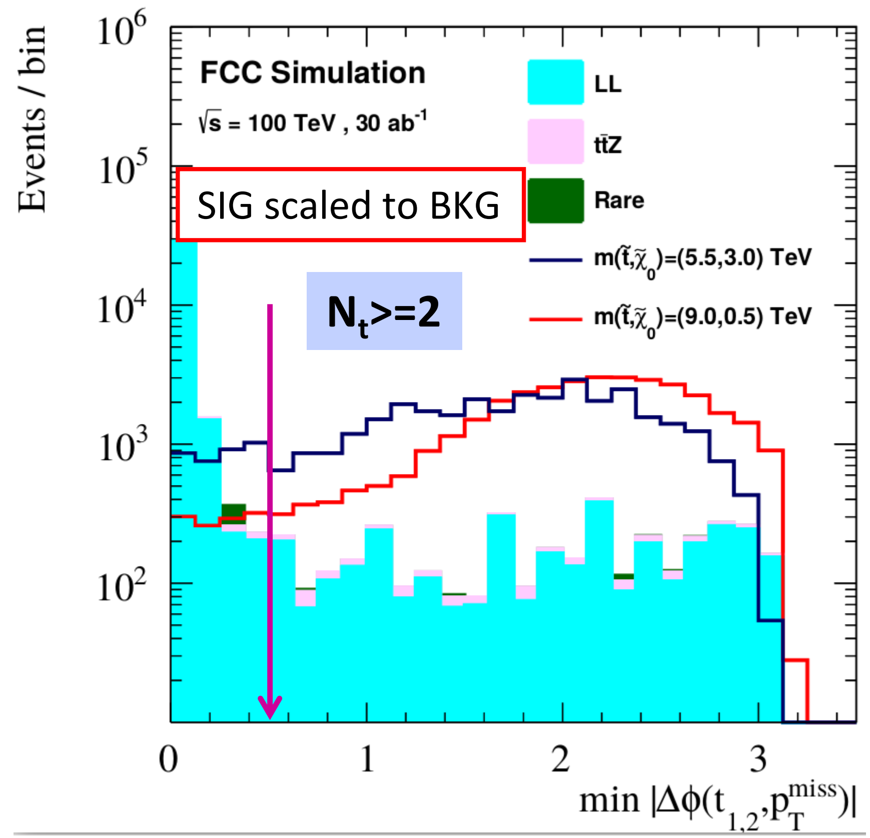
-> significant gain wrt to the cut based tagger
-> Addition of track-based variables recovers loss of performance in the high-pT regime

Work in progress: Study performance with improved calorimeters [e.g. HGC]

Highlights from the search design

- “Multi-*R* + Tracks” provides a powerful handle to suppress many backgrounds:



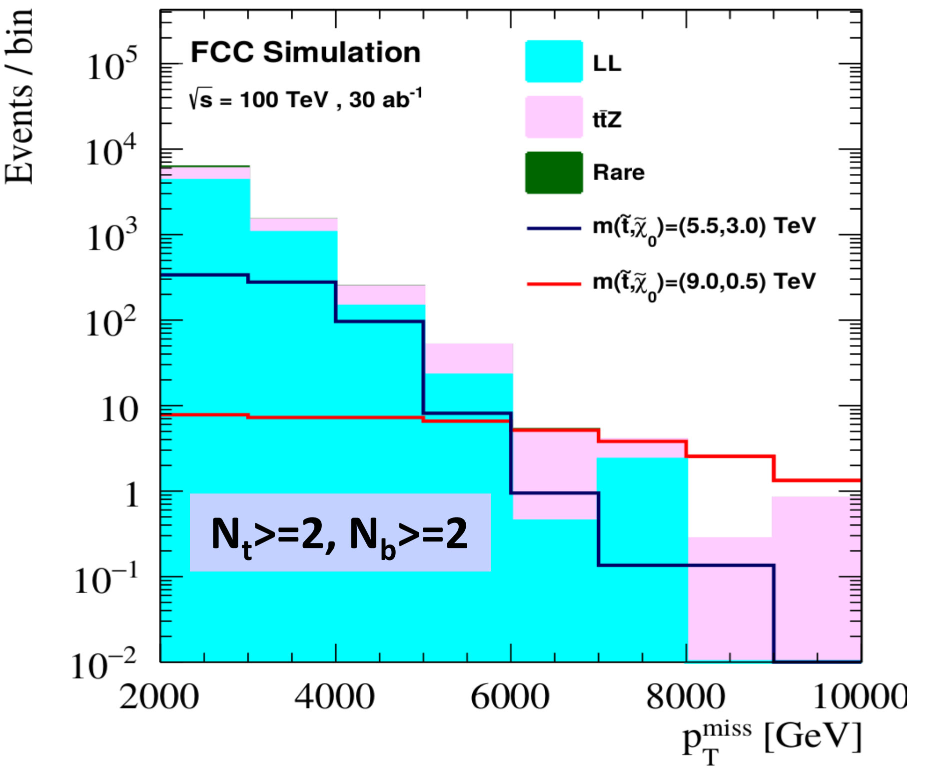


Working point:
~5% mistagging rate

Powerful observable:
[up to 90% BKG for <10% SIG]

Highlights from the search design (2)

- On top of the baseline, categorize events based on N_t and N_b
- ME_T traditionally powerful variable to separate signal from background
- ME_T spectrum depends strongly on the signal model:
  - Fit ME_T shape



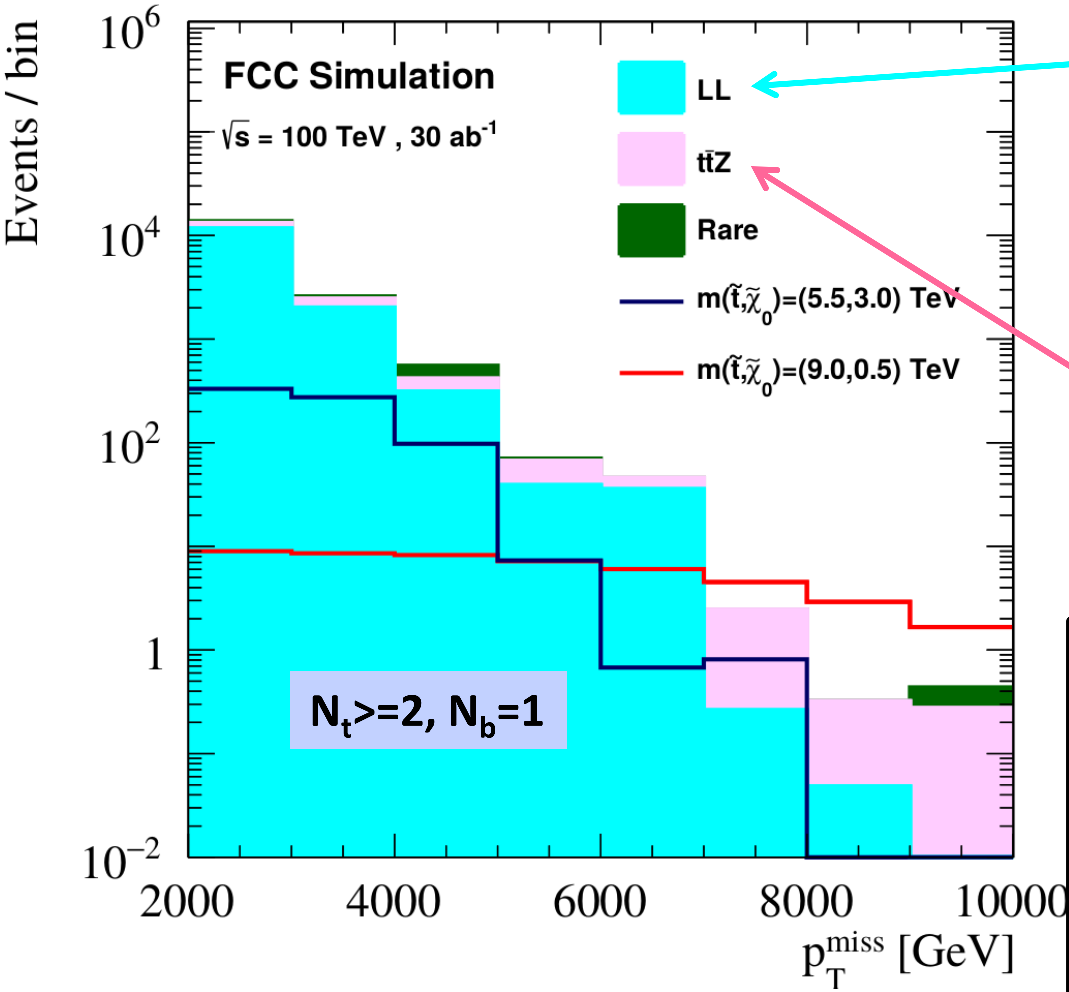
Challenge: Background estimation

- 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 [propagated to the final results]
- Two scenarios to account for additional sources:

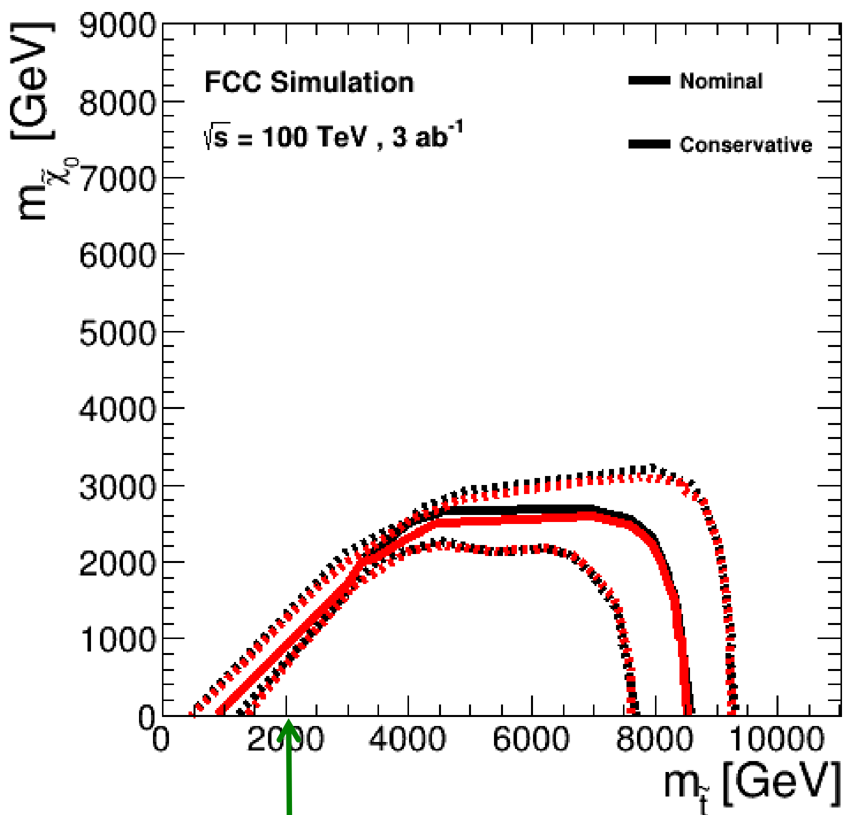
-> “**nominal**”: 20% (*)

-> “**conservative**”: 40% (*)

(*)uncorrelated across all regions/ processes

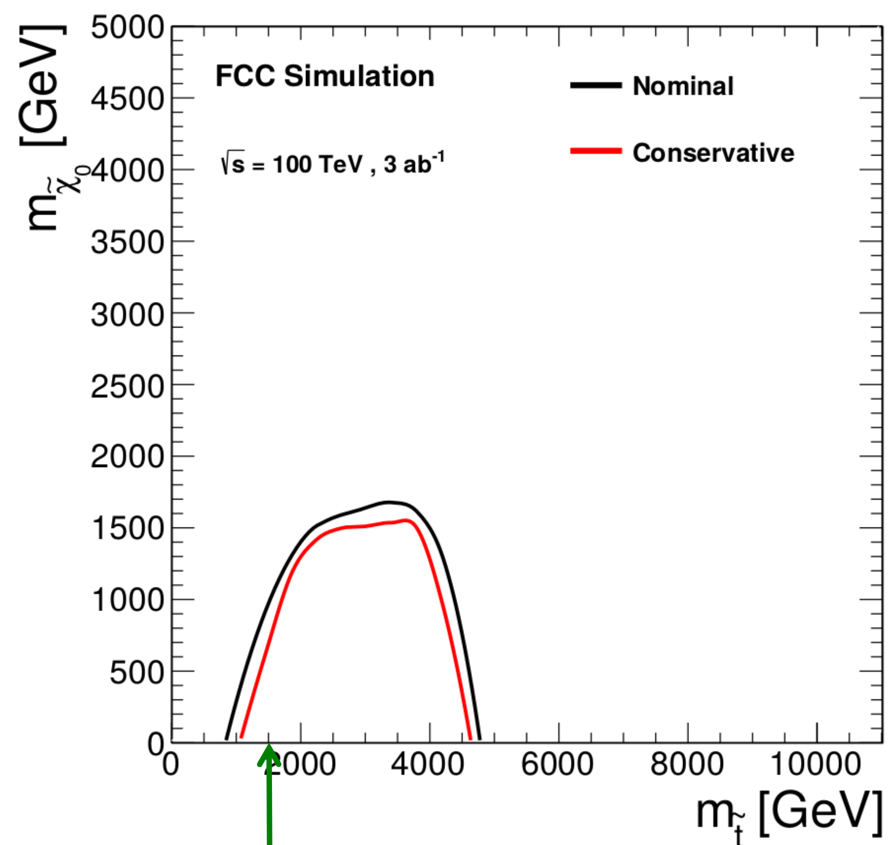
Results

Expected limit @95% CL



~2 TeV
HL-LHC

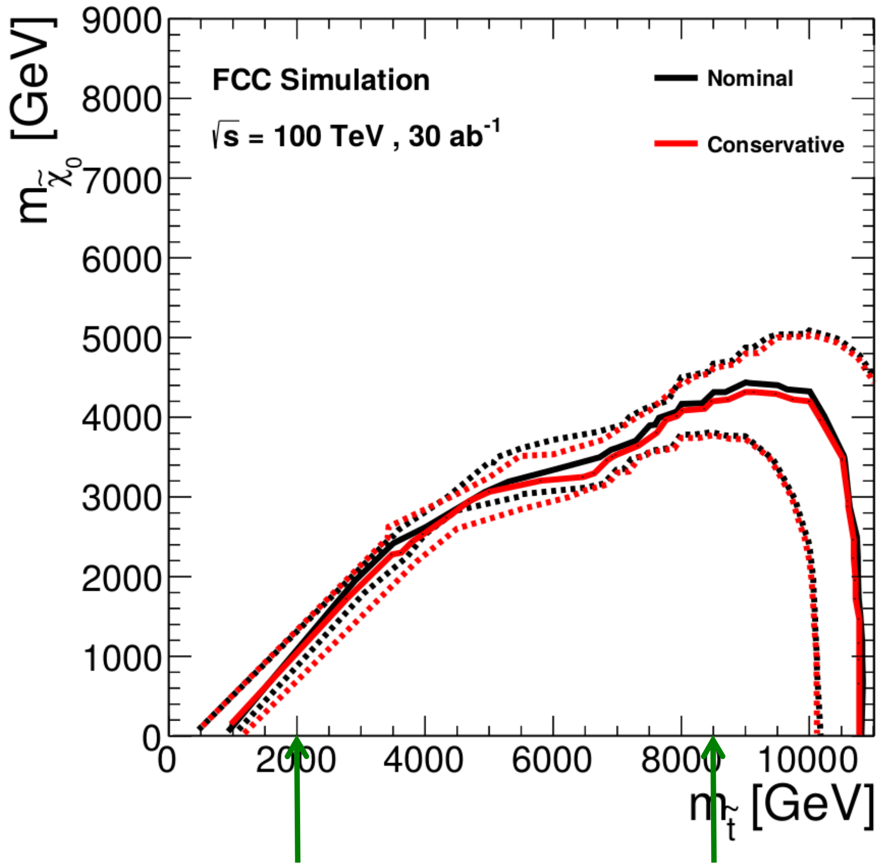
Discovery potential (5σ)



~1.4 TeV
HL-LHC

Results @ 30 ab^{-1}

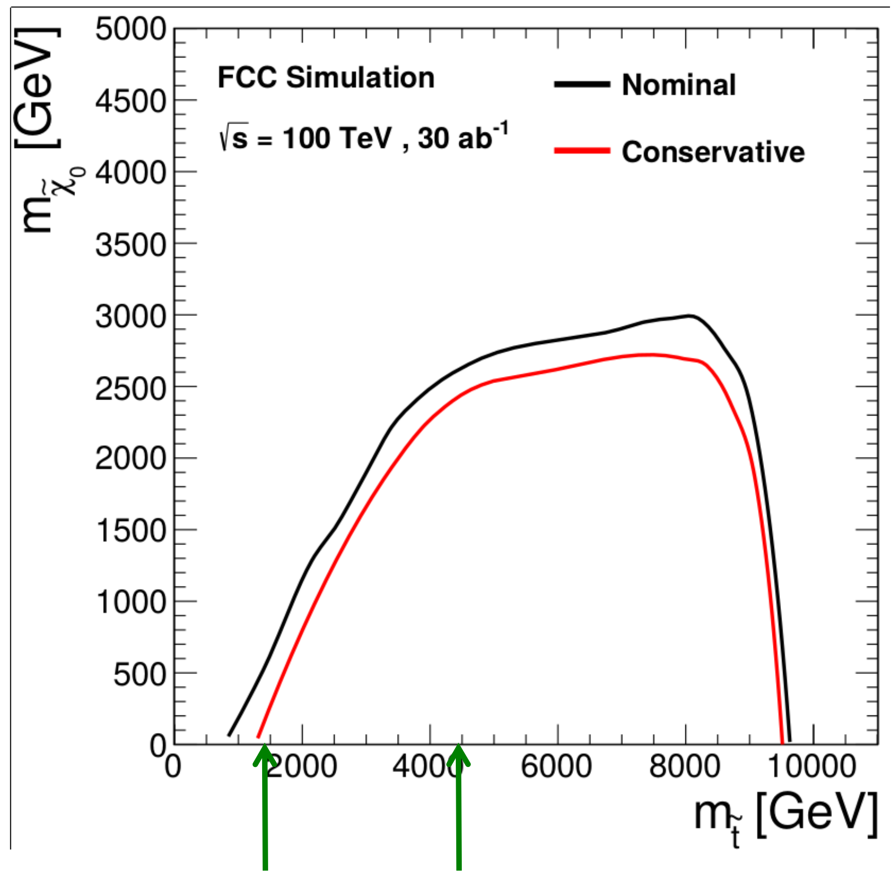
Expected limit @95% CL



~2 TeV
HL-LHC

~8.5 TeV
FCC-hh (3ab^{-1})

Discovery potential (5σ)



~1.4 TeV
HL-LHC

~4.5 TeV
FCC-hh (3ab^{-1})

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}~8.5 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}~9.5 TeV & exclusion up to ~11 TeV

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

Back-ups