# Non-Simplified SUSY

Non-Simplified SUSY:

A Stau-Coannihilation model
at LHC and ILC

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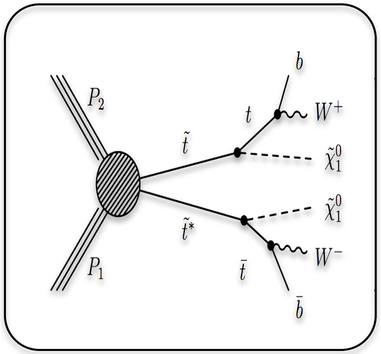
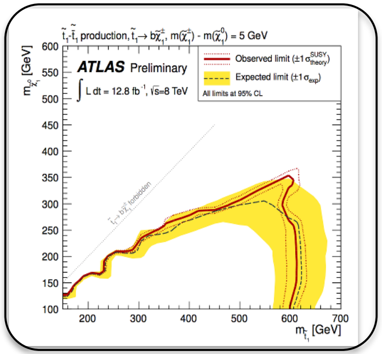
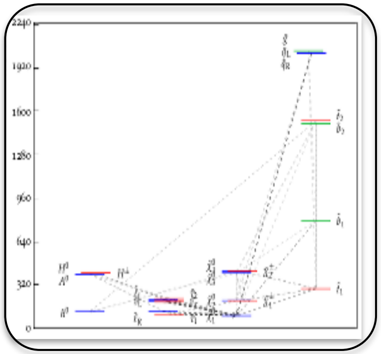
HELMHOLTZ
ASSOCIATION

DESY

# Overview



**Idea:**

In most cases recent SUSY limits are given within simplified models

**Short comings:**

- Typically 100% branching ratio and other assumptions
- No SUSY backgrounds

What happens in **a full model ?**

- Multiple decay chains
- Multiple production modes

What can we **learn** at

**<u>LHC</u> and ILC**

# Considered Models

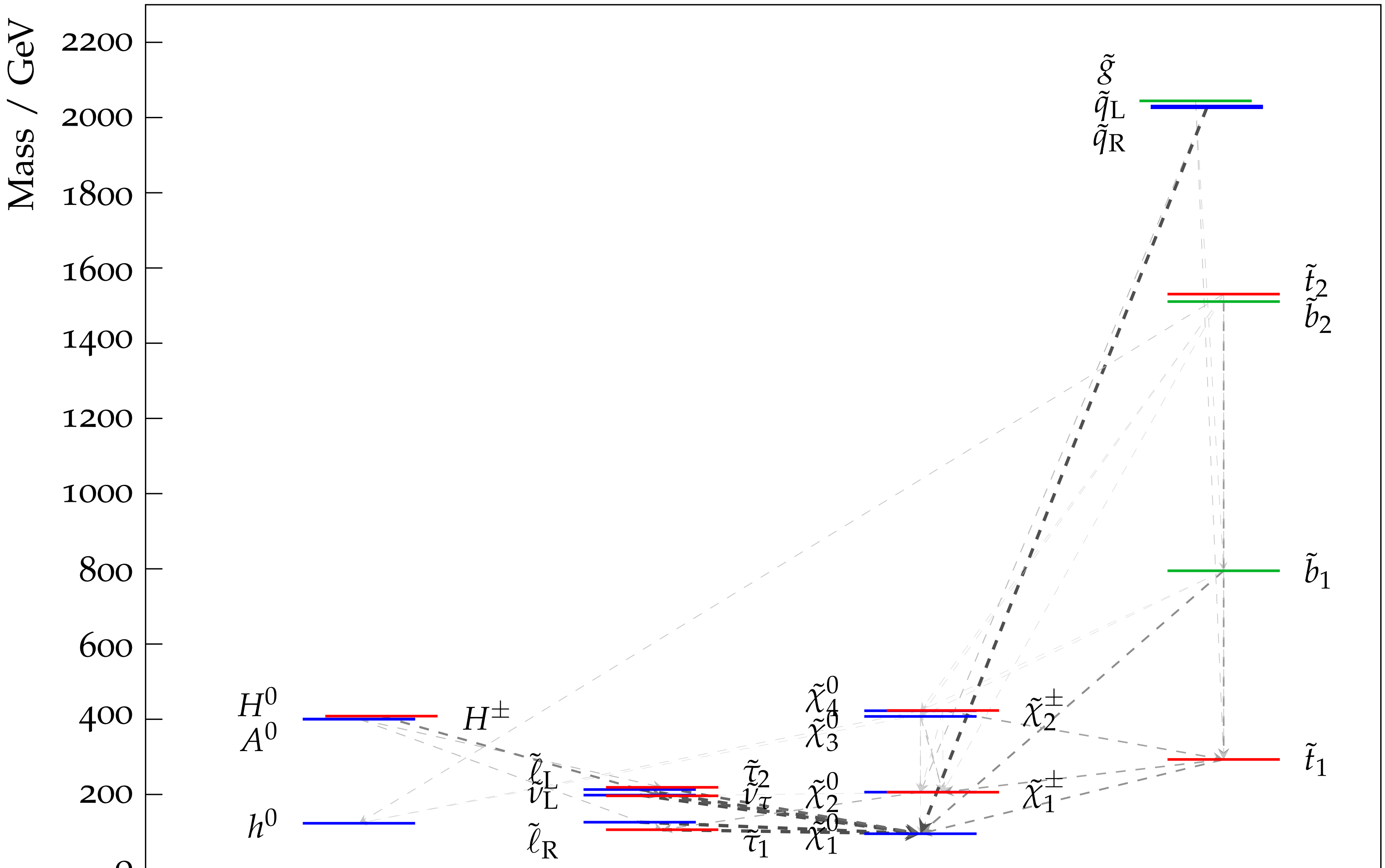
Pick a **full** model

- SUSY model considered here*
  - pMSSM with small $\tilde{\tau} - \chi_1^0$ – mass difference
  
  ➔ $\tilde{\tau}$-coannihilation scenario = **STC**
- Consistent with recent observation e.g.:
  - Relic density
  - Direct dark matter searches
  - Higgs at ~125 GeV
- Choose different $\tilde{\tau}_1$ masses to get 4 models

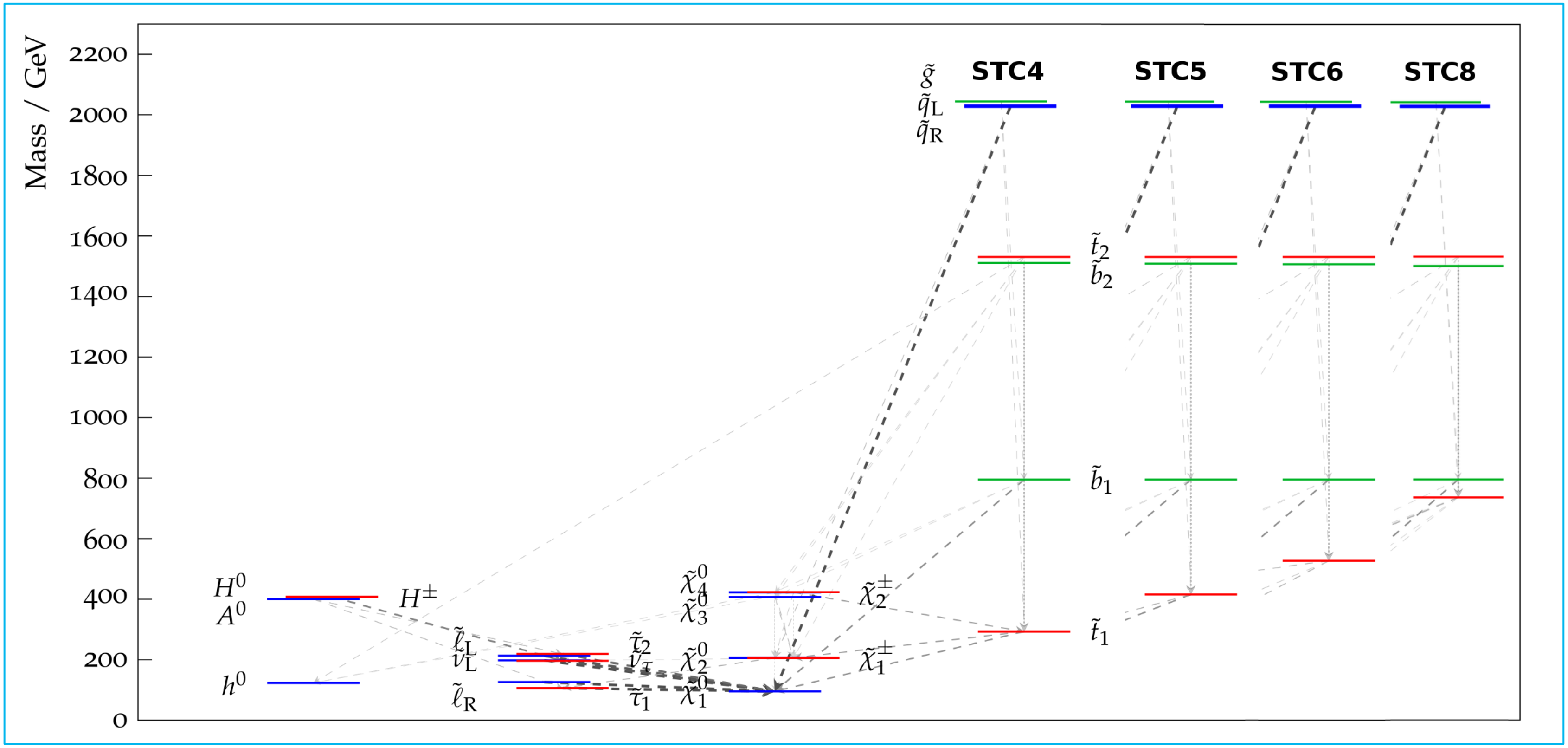
| **Model name** | **Mass parameter/GeV** | $\tilde{\tau}_1$ **mass/GeV** | $\sigma^{NLO}_{pp-14TeV}$ |
|---|---|---|---|
| STC4 | 400 | 293 | 12.7 pb |
| STC5 | 500 | 416 | 3.3 pb |
| STC6 | 600 | 527 | 2.0 pb |
| STC8 | 800 | 736 | 1.6 pb |

* see **arXiv:1307.0782**

# STC4 Spectrum – Branching Ratio > 10%

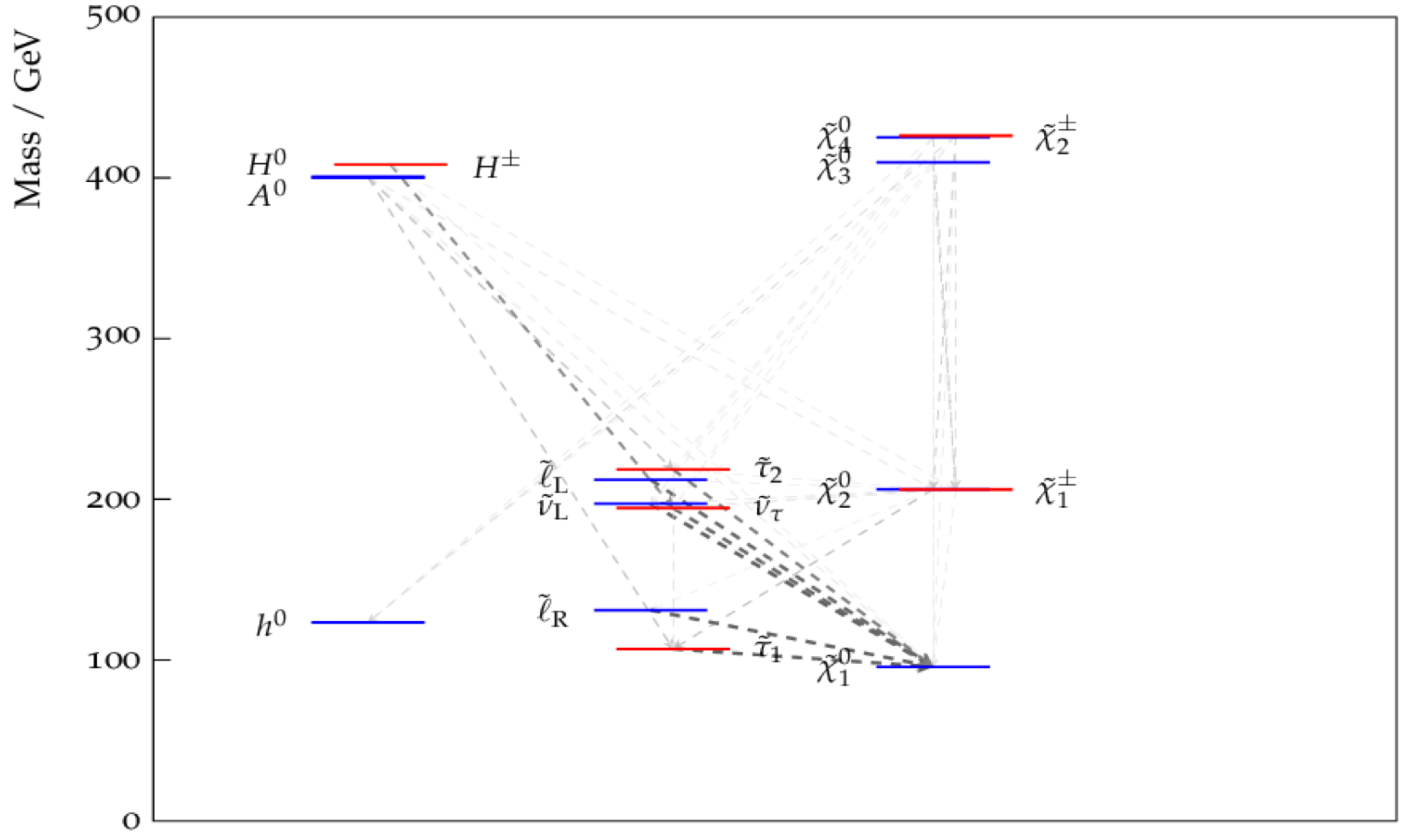


# Considered Models



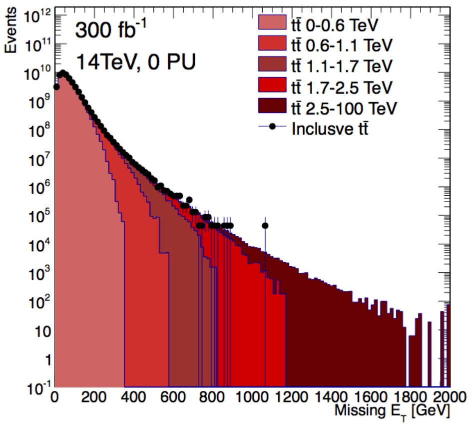

- Models differ only by mass of $\tilde{t}_1$
  - STC4: largest direct stop production cross section
  - STC4-STC8: direct stop becomes equal to ≈2*$\sigma_{sbottom}$
  - STC8: Ewkino production cross section dominates

# STC – Specrtrum below 500 GeV




- Rich pattern of decay channels at low masses

# Used Simulations




DELPHES
fast simulation

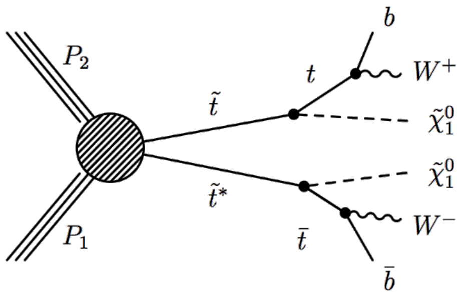
- **Snowmass 2013** studies for an LHC at 14 TeV
  - 3 pile-up scenarios**: no/50/140 pileup** events
  - Massive HT-binned **background** production
    - arXiv:1308.1636

- **Delphes** fast detector simulation
  - Averaged ATLAS and CMS Detector **= Combined Snowmass Detector**
  - arXiv:1309.1057

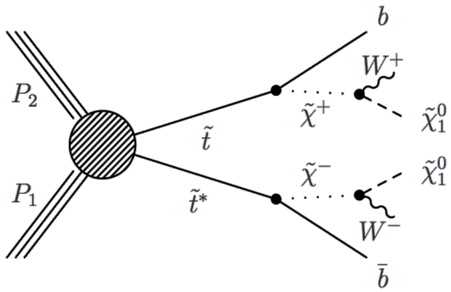
- Private production of STC model points
  - **STC4,5,6** and **8**
  - 1 million events each

# Example LHC Searches @ 8 TeV

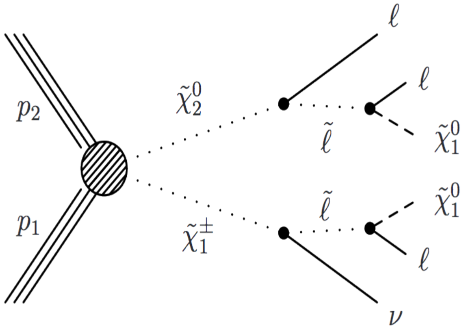
The toy searches are **inspired** by the following LHC analyses:




- Atlas **stop search** with **full-hadronic** final states (*ff'* soft) $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to b\tilde{\chi}_1^0 f f'$ ATLAS-CONF-2013-001 based on ATLAS-CONF-2012-165 $\tilde{b}_1 \to b\tilde{\chi}_1^0$)



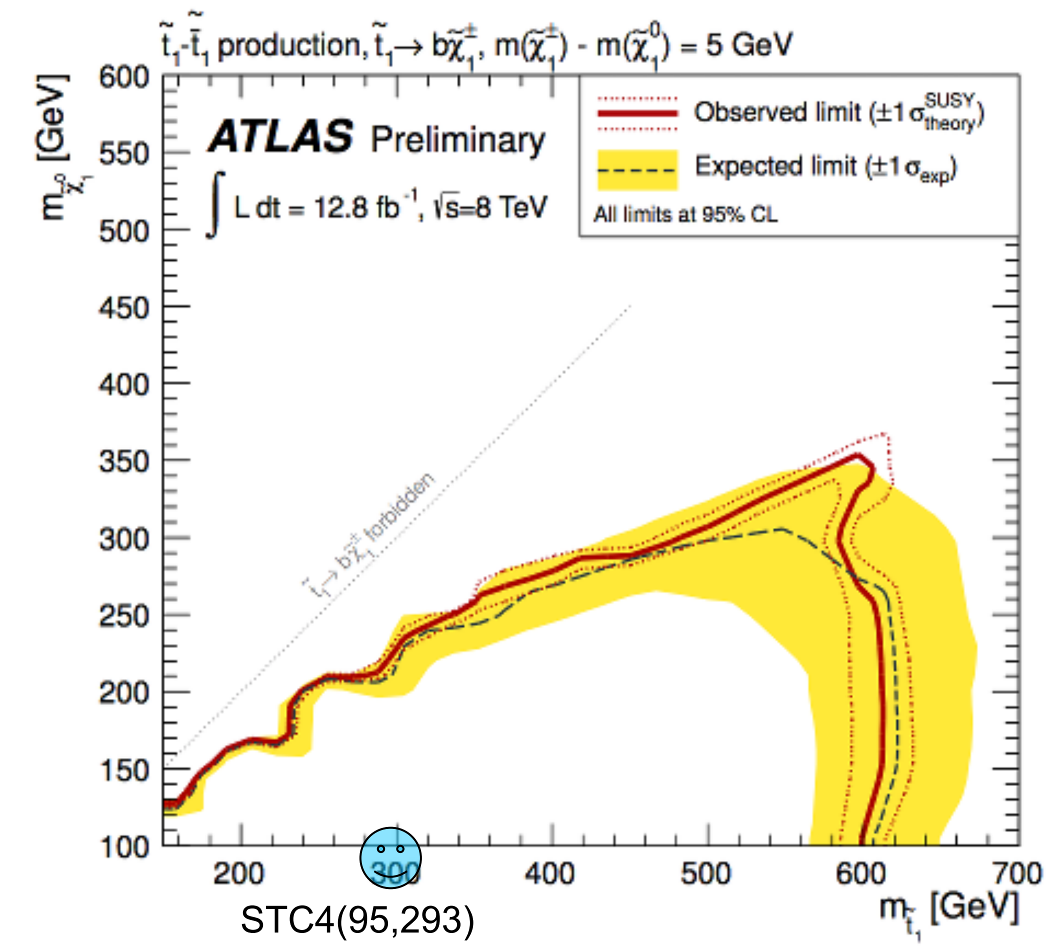

- CMS **stop search** with a **single lepton** final state (CMS-SUS-13-011) $\tilde{t}_1 \to t\tilde{\chi}_1^0 \to b\tilde{\chi}_1^0 l^+ \nu_l$




- **Electroweak production**: $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ **Same-sign lepton** analysis in CMS-PAS-SUS-12-022

# STC4 - Visibility at 8TeV

- Stop at ~300 GeV ?
- Would that have been seen already?




ATLAS-CONF-2013-001

# Full-Hadronic Analyses (0-Leptons) at 14 TeV

- Cut and Count analysis
  - **Lepton veto** (no lepton $p_T$ > 10GeV identified)
  - At least 3 hard jets ($p_T$ >120GeV, >70GeV, >60GeV)
  - At least 2 b-tagged jets
  - ΔΦ(MET,leading jets)>0.5
- Cuts tightened for 14TeV conditions:
  - HT>1000GeV
  - MET/(MET+HT)>0.2
  - MET>750GeV

# STC4 Visibility at 8TeV

| Description | Signal Region | | | | |
|---|---|---|---|---|---|
| | SR1 | | | | SR2 |
| * | $m_{CT} > 150$ | $m_{CT} > 200$ | $m_{CT} > 250$ | $m_{CT} > 300$ | |
| ATLAS observed | 172 | 66 | 16 | 8 | 104 |
| expected SM bgrd. | 176 | 71 | 25 | 7.4 | 95 |
| 95% CL UL on exp. bgrd. | 55 | 25 | 12.5 | 5.5 | 32 |
| STC4 | 18 | 13 | 9.0 | 6.6 | 18 |

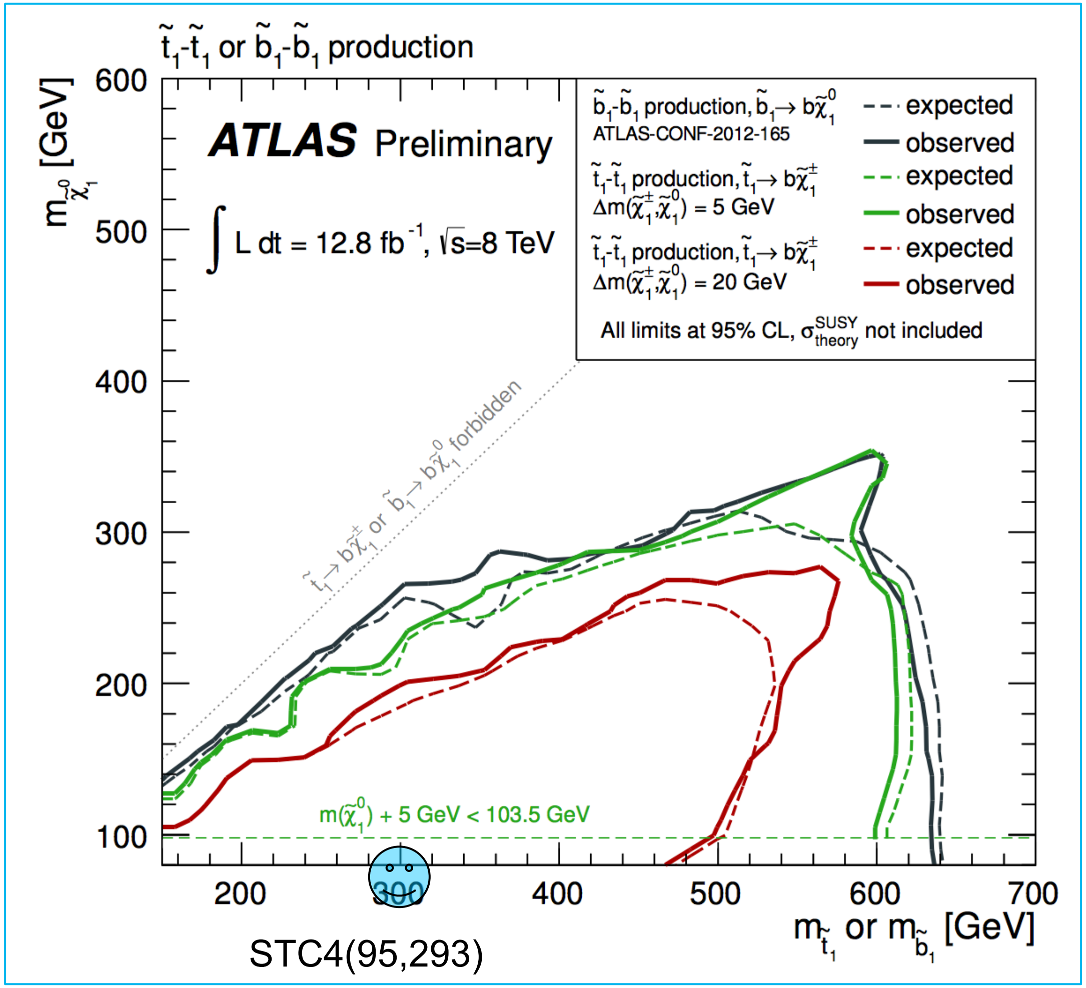
- Our analysis (following ATLAS-CONF-2013-001) sees STC4 at the edge of discovery
- ATLAS interpretation is within
  - A simplified model with 100% branching ratio for $\tilde{t}_1 \to b\chi_1^+$
  - Small mass difference $m_{\chi_1^+} - m_{\chi_1^0}$ = 5 /20 GeV



*Boost corrected cotransverse mass

# STC4 Visibility at 8TeV

- Stop at ~300 GeV ?
- Would that have been seen already?
- Our Δm=105GeV




ATLAS-CONF-2013-001

# Full-Hadronic Analyses (0-Leptons) at 14 TeV

- Cut and Count analysis
  - **Lepton veto** (no lepton $p_T$ > 10GeV identified)
  - At least 3 hard jets ($p_T$ >120GeV, >70GeV, >60GeV)
  - $\Delta\Phi$(MET,leading jets)>0.5
- Cuts tightened for 14TeV conditions:
  - HT>1000GeV
  - MET/(MET+HT)>0.2
  - MET>750GeV
- **Pileup mitigation**:
  - Jet area subtraction
  - Missing transverse energy from pileup corrected objects(jets,leptons)

# Full-Hadronic Analysis (0-Leptons) at 14 TeV

300fb$^{-1}$, 50 pileup events

Cut flow

| Description | ttbar+jets | * boson+jets | *sum bgrds | STC4 | STC5 | STC6 | STC8 |
|---|---|---|---|---|---|---|---|
| preselection | 216124000 | 16842600000 | 17231632200 | 3840000 | 1146000 | 759000 | 657000 |
| lepton veto | 148709000 | 15970700000 | 16264271400 | 2939780 | 858682 | 569011 | 502994 |
| n jets $\geq 3$ | 118324000 | 1987680000 | 2144057800 | 1749960 | 317637 | 103979 | 48157 |
| jet1 > 120 GeV | 54696900 | 668990000 | 740209300 | 1052210 | 259433 | 84595 | 34240 |
| jet2 > 70 GeV | 51083400 | 597564000 | 663634560 | 960943 | 242314 | 78652 | 30258 |
| jet3 > 60 GeV | 41560400 | 359923000 | 411629350 | 774987 | 199271 | 65688 | 23520 |
| bjets *ge2* | 23020600 | 21429600 | 46923485 | 433180 | 121225 | 39601 | 11163 |
| $H_T > 1000$ GeV | 1241760 | 870796 | 2210551 | 59848 | 21130 | 9763 | 4912 |
| $\Delta\Phi > 0.5$ | 800289 | 578069 | 1441010 | 36608 | 15623 | 7720 | 4020 |
| $E_T^{mmiss}/m_{meff} > 0.2$ | 15769 | 12902 | 29869 | 15716 | 7067 | 3854 | 2192 |
| $E_T^{mmiss} > 750$ GeV (50PU) | 334 | 1721 | 2161 | 1920 | 1109 | 815 | 633 |
| FOM: $s/\sqrt{b+(0.25*b)^2}$ | | | | 3.5 | 2.0 | 1.5 | 1.2 |
| FOM: $s/\sqrt{b+(0.15*b)^2}$ | | | | 5.9 | 3.4 | 2.5 | 1.9 |
| $E_T^{mmiss} > 750$ GeV (0 PU) | 331 | 1908 | 2350 | 1843 | 1048 | 775 | 636 |

- #events nicely follows $\tilde{t}_1$ mass – we do indeed select $\tilde{t}$
- No strong dependence on pileup
  - Also true for 140 pileup events (results given in our paper)

*Boson = W and Z,
sum of bgrds = ttbar+jets,Boson+jets,Diboson,Single Top

# Figure of Merit

In the following the sensitivity for 14TeV 300fb$^{-1}$ is shown
For our 4 STC models and the 3 example analyses.

- Observed number of events as test statistic
- Sensitivity for discovery (exclude background-only hypothesis)

$$s_{disc} = S / \sqrt{B + (\delta B)^2_{sys}}$$

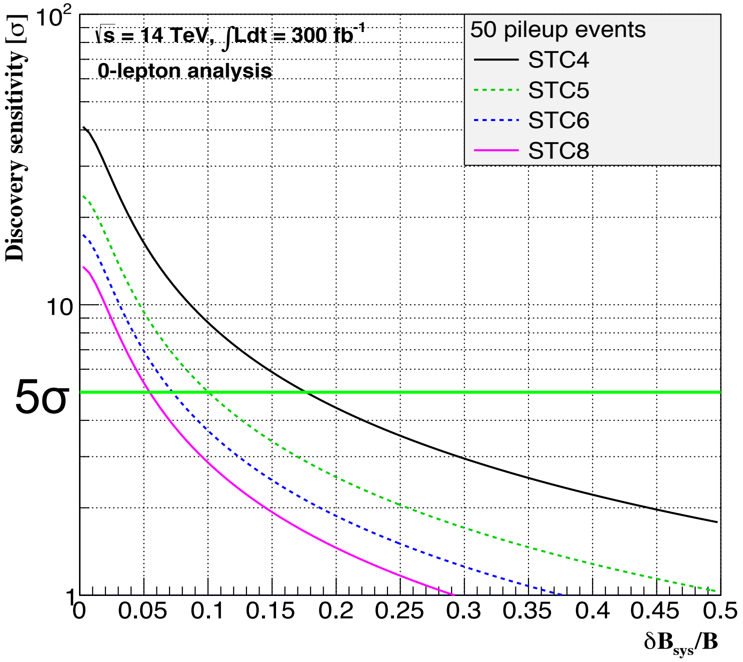
- Sensitivity for exclusion (exclude B+S hypothesis)

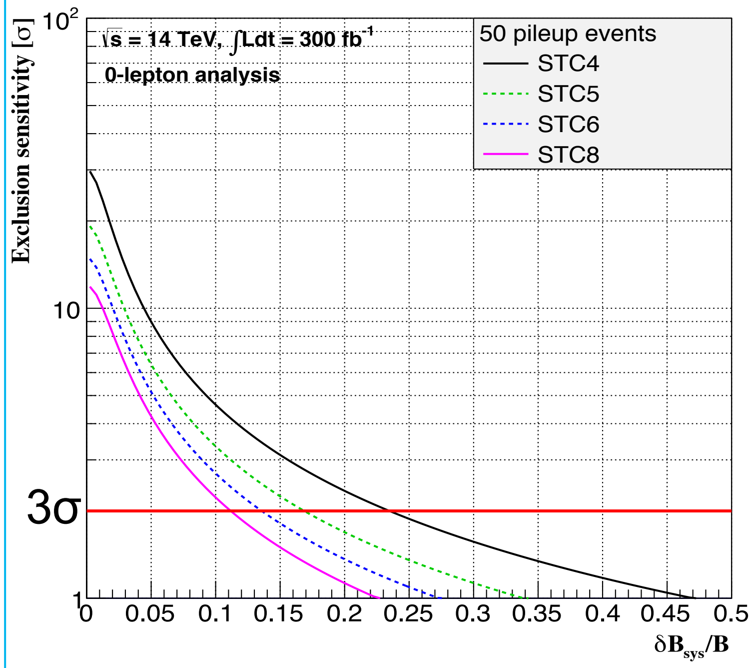
$$s_{excl} = S / \sqrt{S + B + \delta(S+B)^2_{sys}}$$

- We considered for each analysis **a standard and an optimistic** scenario for the systematic uncertainties.
    - Standard = what have been achieved now
    - Optimistic = educated guess
        - A really scientific approach for what will be possible is difficult

# Full-Hadronic Analysis (0-Leptons) at 14 TeV

- Results for $300 fb^{-1}$ with 50 pileup events
- **Systematic uncertainty is crucial** for discovery and exclusion sensitivity



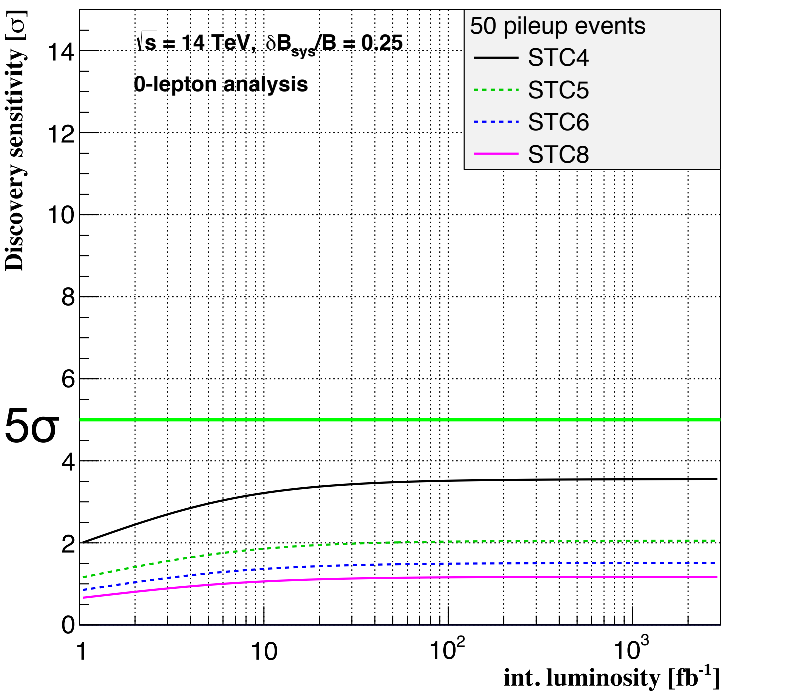




sys. uncertainty

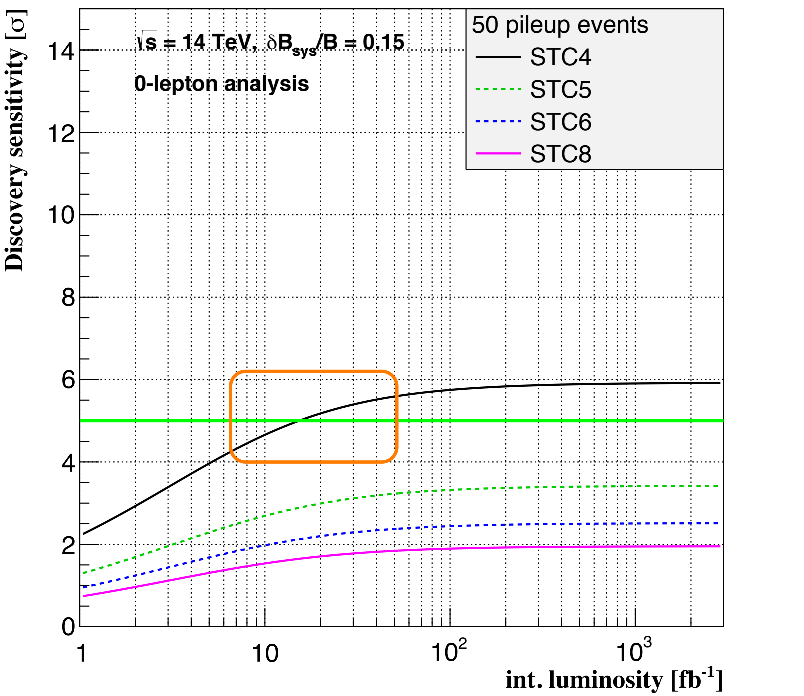
# Full-Hadronic Analysis (0-Leptons) at 14 TeV

- Discovery only at 15% systematic (optimistic scenario)
  - but only STC4 (lowest m)
- The analysis does not profit much from increased luminosity

25% sys. Uncert.




15% sys. Uncert.




int. luminosity →

# Single Lepton Final State (1-Leptons) at 14 TeV

Cut and Count analysis with typical cuts for a leptonic search

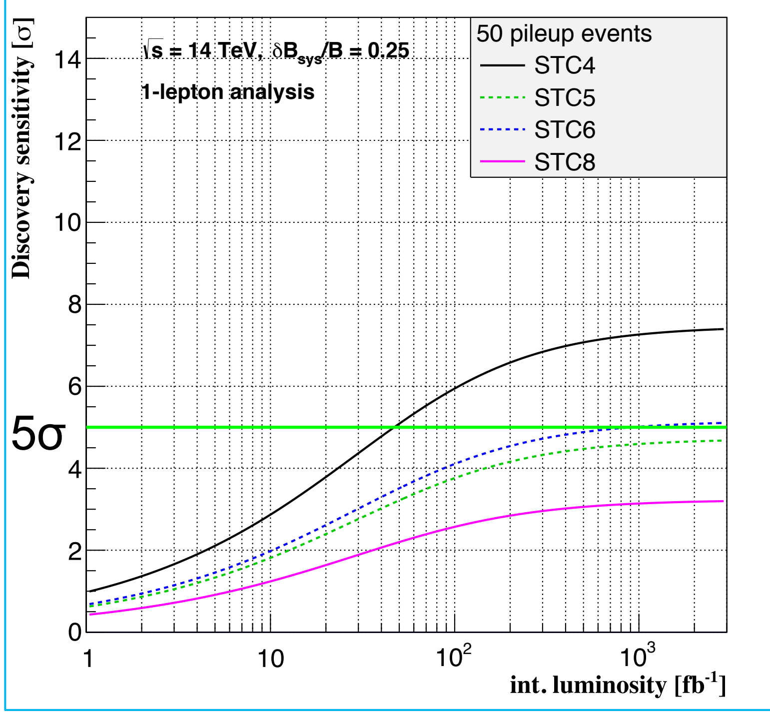
- **Lepton(e/μ)** $p_T > 10$ GeV
- At least 3 jets with $p_T > 40$ GeV
- 1 or 2 b-tagged jets
- $\Delta\Phi$(MET,leading 2 jets) > 0.5
- $M_T > 120$ GeV
- To protect against di-leptonic $t\bar{t}$ bgrd.:
  - $\mathbf{M_{T2}^{W}}$ > 250 GeV (arXiv:1203.4813) – had been used by CMS
  - **Topness** > 9.5 (arXiv:1212.4495) - turns out to be most efficient
- Cuts tightened for 14TeV conditions:
  - HT>500 GeV
  - MET>500 GeV

- Our most successful analysis

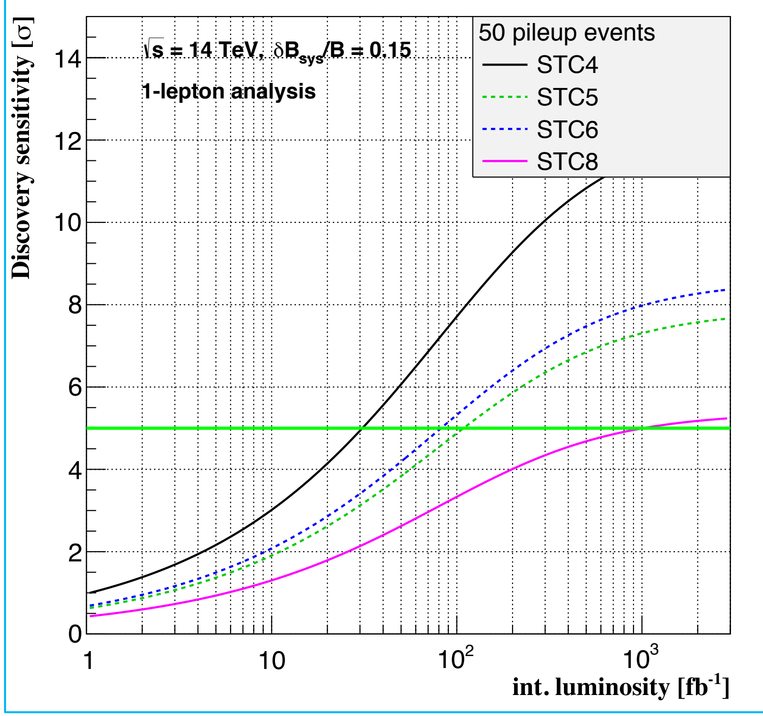
# Single Lepton Final State (1-Leptons) at 14 TeV

- Results for 50 pileup events
- Discovery already at 25% systematic uncert. for STC4/5
- With improved systematic uncertainties all STC models visible

25% sys. Uncert.




15% sys. Uncert.




int. luminosity

# LHC: Search for EWkinos (2-Leptons) at 14 TeV

- Search for same-sign leptons coming from:
  - $pp \to \chi_2^0 \chi_1^\pm$

    $\chi_2^0 \to \tilde{\tau}\tau \to \tau\tau\chi_1^0$ (STC4-8: ~75%)

    $\chi_1^\pm \to \tilde{\tau}\upsilon_\tau$ (STC4-8: ~69%)
  - Leptonic τ decays: at least a same-sign lepton pair + additional lepton
  - Selection: Z-veto & b-jet veto & Missing Energy Cut
- Rough comparison to same-sign analysis in PAS-CMS-12-022:
  - CMS gives complex set of interpretation in simplified models
    - Flavour(eμτ) democratic , τ enriched, τ dominated
    - Slepton mass relative to $\chi_2^0, \chi_1^\pm$ mass (0.05,0.5,0.95)
  - Becomes simple if we reproduce the analysis:
    - At 8 TeV STC4 signal yields less than 10 events
    - 11 are observed in data (compatible with bgrd. expectation)

# LHC: Search for EWkinos (2-Leptons) at 14 TeV

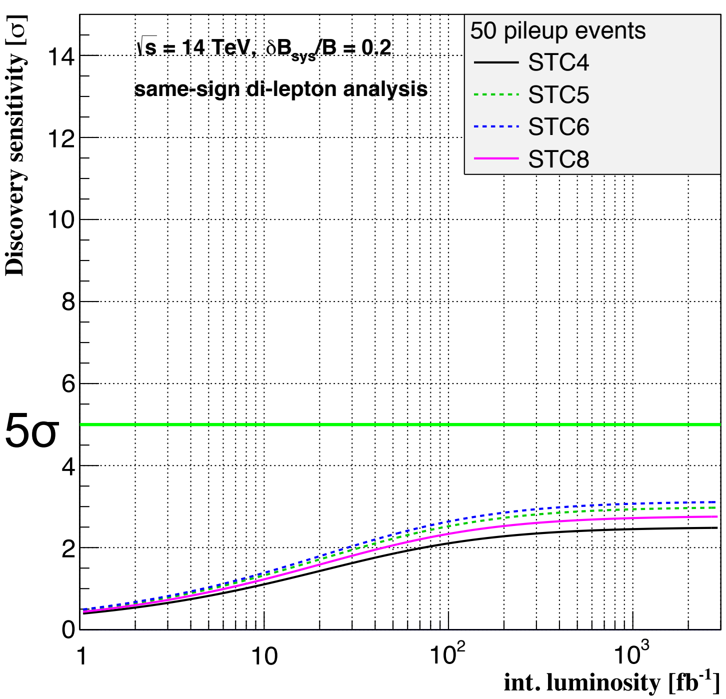
| Description | diboson | ttbar+jets | boson+jets | sum bgrds | STC4 | STC5 | STC6 | STC8 | |
|---|---|---|---|---|---|---|---|---|---|
| preselection | 110822000 | 216124000 | 16842600000 | 17231632200 | 3840000 | 1146000 | 759000 | 657000 | |
| 2 lepton req. | 1914290 | 6745420 | 50864800 | 59591013 | 80459 | 40117 | 30936 | 23903 | |
| $E_T^{miss} > 120$ GeV | 125330 | 1203360 | 883404 | 2220621 | 39799 | 22116 | 16700 | 11604 | |
| same-sign req. | 7920 | 7424 | 2511 | 18405 | 1385 | 2431 | 2284 | 1659 | |
| Z veto | 3546 | 7356 | 2115 | 13565 | 1121 | 1988 | 1829 | 1335 | |
| b-jet veto | 3071 | 2183 | 1172 | 6629 | 701 | 930 | 838 | 740 | |
| $E_T^{miss} > 200$ GeV | 783 | 413 | 414 | 1657 | 378 | 526 | 460 | 424 | |
| $E_T^{miss} > 400$ GeV | 90 | 21 | 66 | 182 | 91 | 109 | 114 | 101 | 50 PU |
| $s/\sqrt{b + (0.3 * b)^2}$ | | | | | 1.6 | 1.9 | 2.0 | 1.8 | |
| $s/\sqrt{b + (0.2 * b)^2}$ | | | | | 2.4 | 2.8 | 2.9 | 2.6 | |
| $E_T^{miss} > 400$ GeV | 88 | 4 | 17 | 110 | 86 | 116 | 131 | 115 | 0 PU |

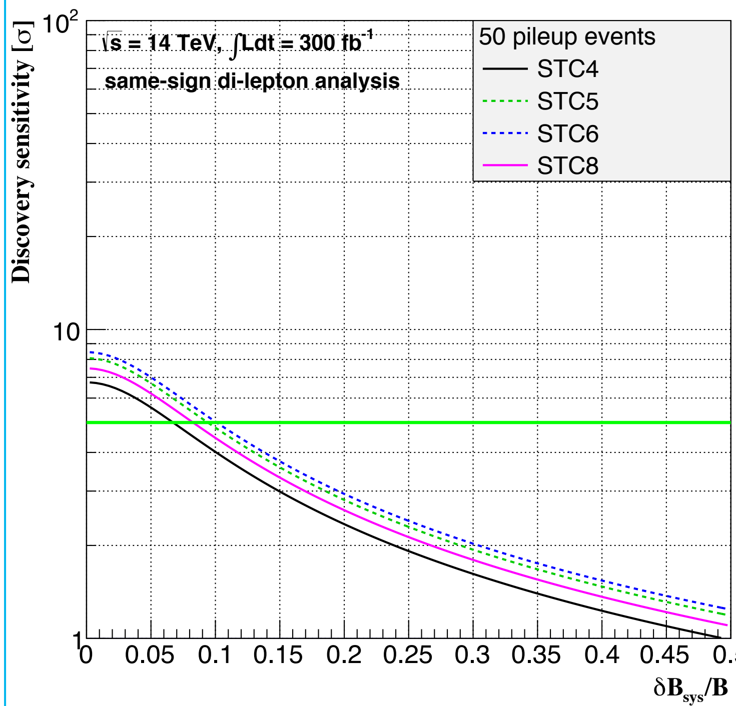
- #events independent of $\tilde{t}_1$ mass – we do indeed select Ewkino part
- No strong dependence on pileup
  - Also true for 140 pileup events (results in paper)

# LHC: Search for EWkinos (2-Leptons) at 14 TeV

- Results for 300$fb^{-1}$ with 50 pileup events
- **No sensitivity**
  - Not even in optimistic scenario with 20% sys. uncert.
  - **Needs control of sys. uncert. in the order of a few%**

Optimistic scenario

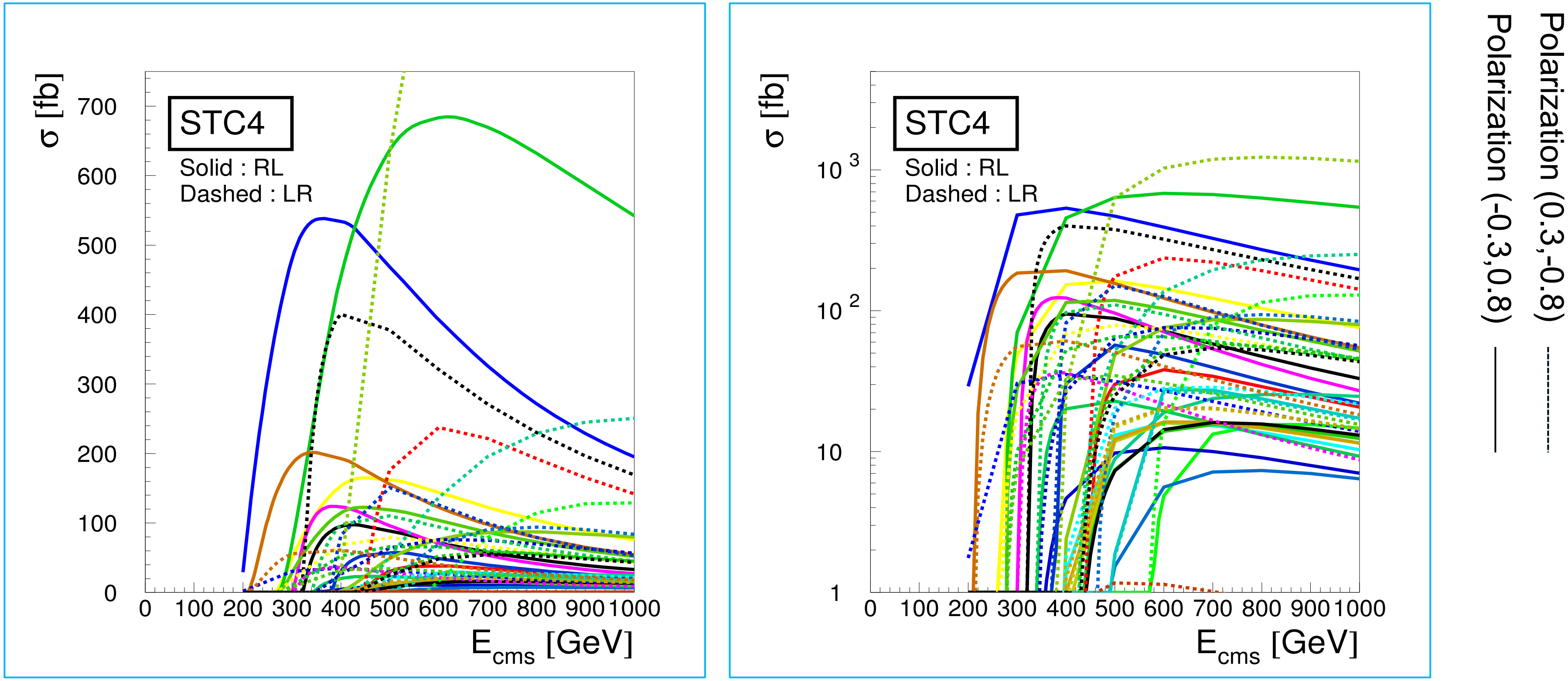



int. luminosity

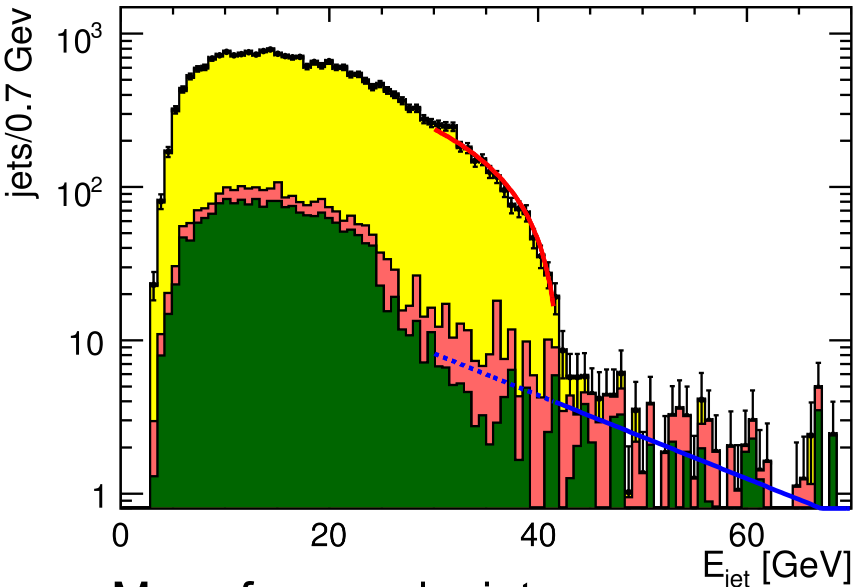
sys. uncertainty

# ILC: Precision Analyses – Example $\tilde{\tau}$

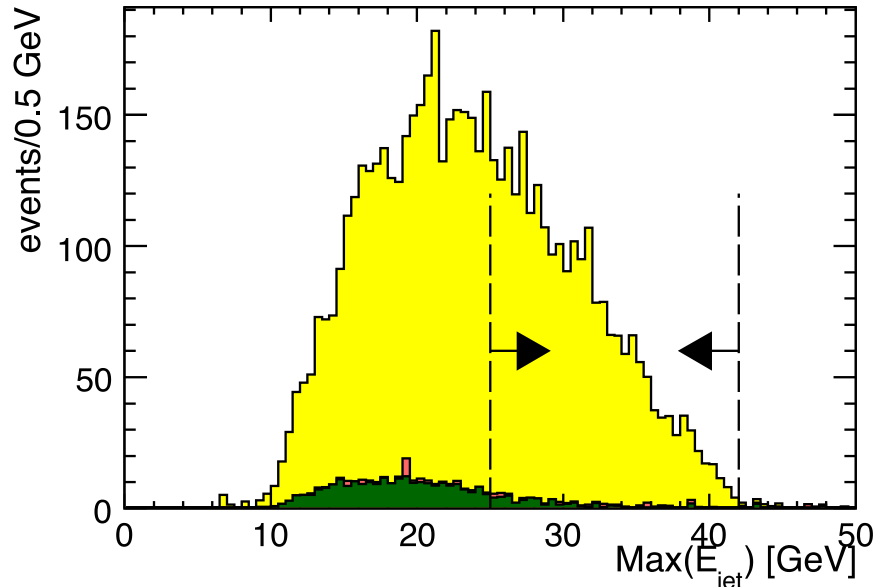



- Cross section **ILC@500GeV:**
  - All sleptons and bosinos can be produced with reasonable cross section (inclusive for both polarization about 3 pb)

# ILC: $\tilde{\tau}_1$ Measurements



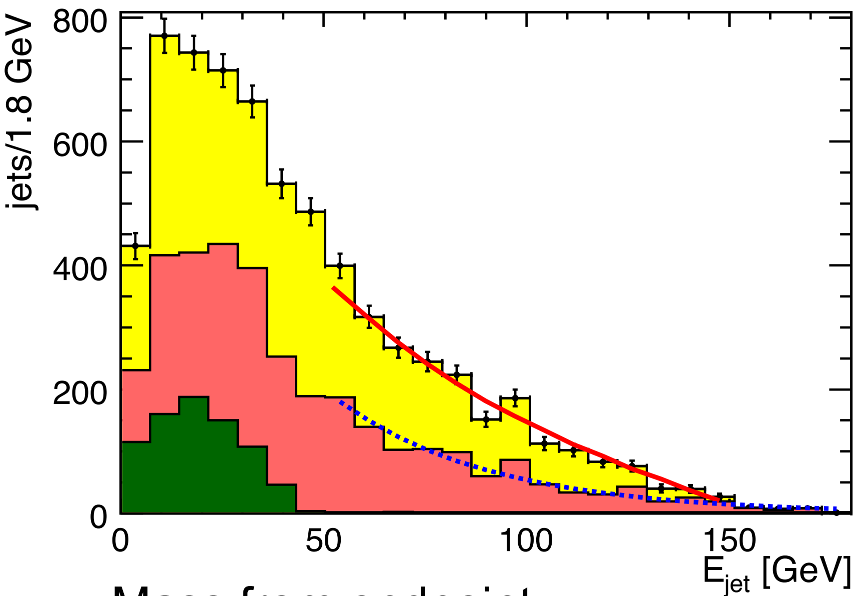

Mass from endpoint



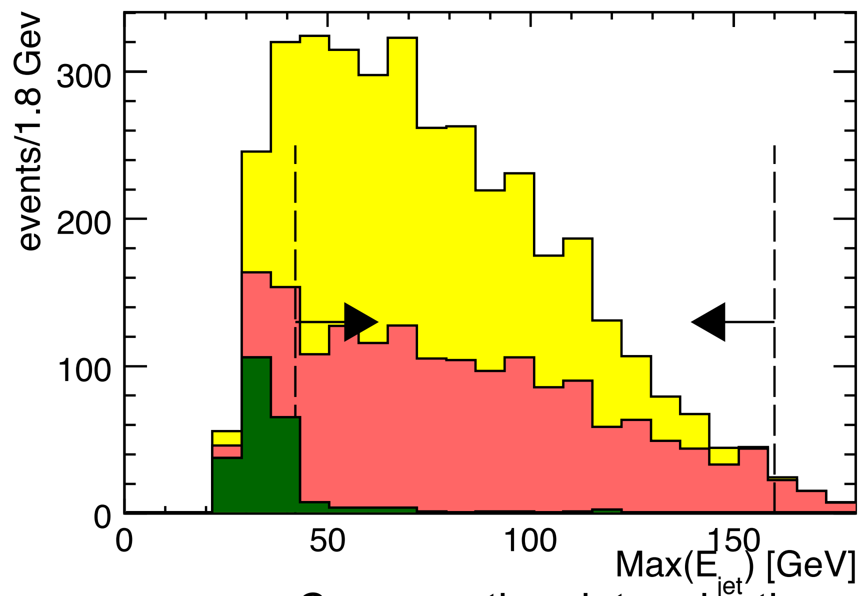

Cross section determination

- Yellow: signal, red: SM bgrd, green: other SUSY bgrd. - ->SUSY bgrd ~free<-
- Very clear signal after few cleaning cuts –
- 4% error for cross section measurement
- $\tilde{\tau}_1$ mass can be measured with precision of 200 MeV

# ILC: $\tilde{\tau}_2$ Measurements




Mass from endpoint

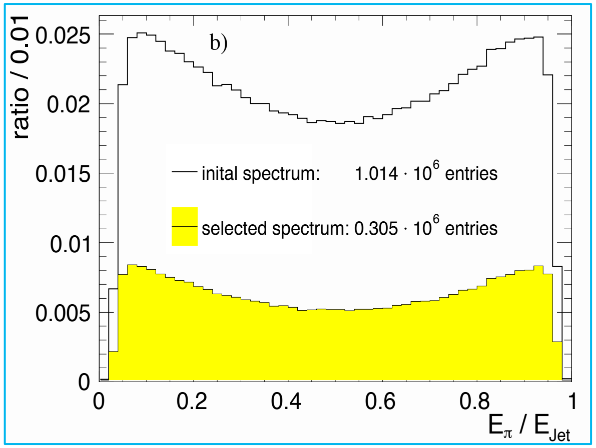



Cross section determination

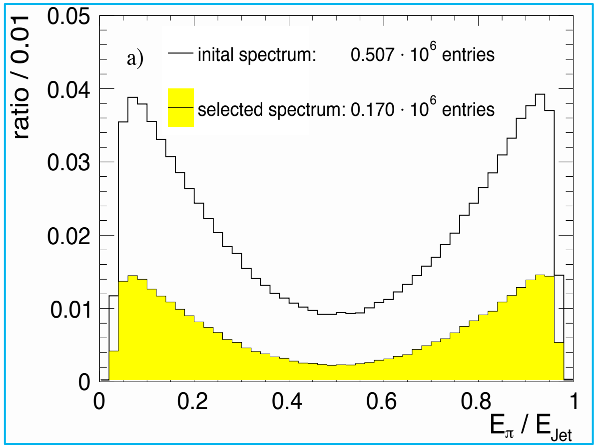
- Yellow: signal, red: SM bgrd, green: other SUSY bgrd.
- $\tilde{\tau}_2$ mass can be measured as well with precision of 5 GeV

# ILC: $\tau$ Helicity

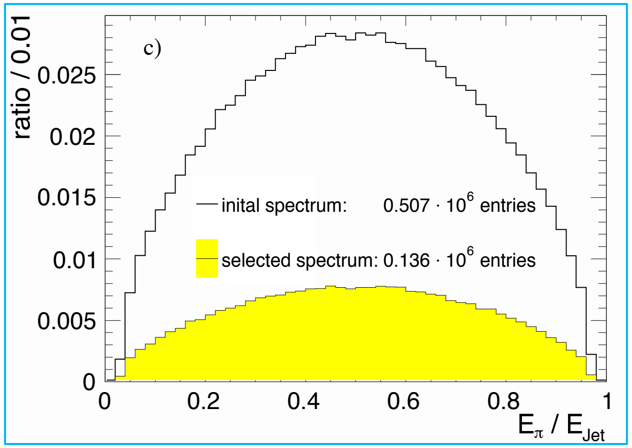
- Pion/jet energy differs for different $\tau$ helicity




Both $\tau$ leptons right-handed




Opposite helicity




Both $\tau$ leptons left-handed

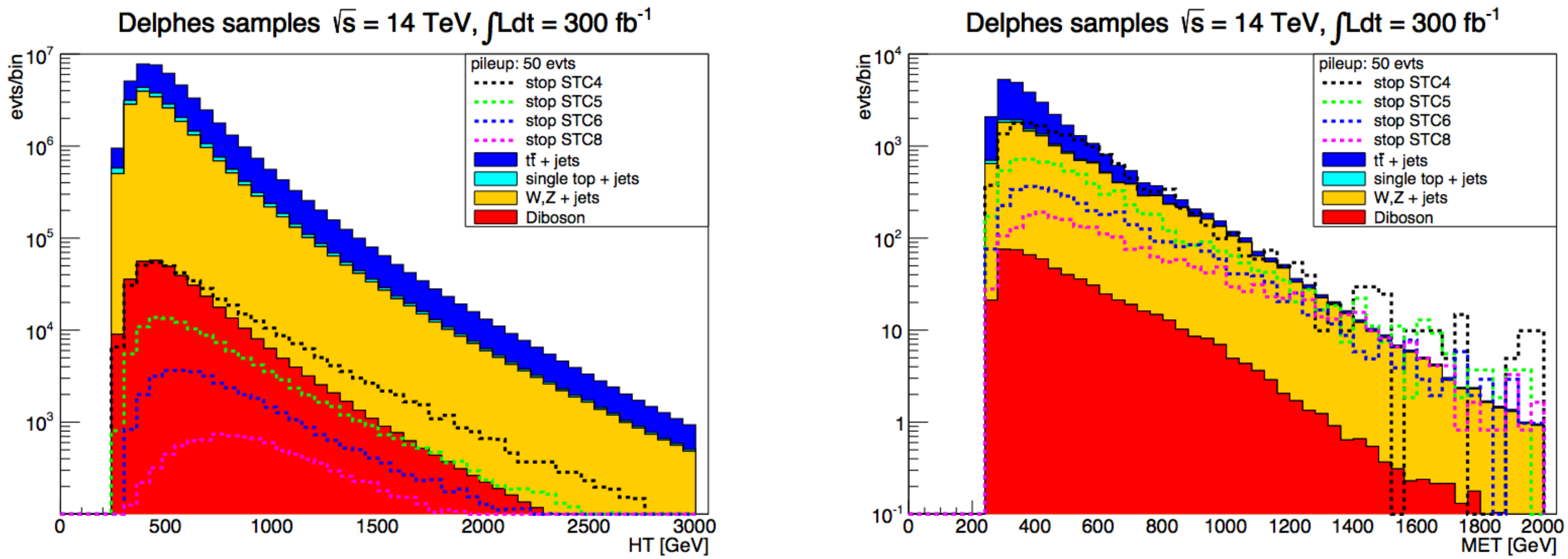
- $E_{\pi}/E_{jet}$
- $\tau$ polarization: depends on mixing angle i.e. amount of higgsino and gaugino eigenstates of $\chi_1^0$
  - Gaugino and sfermions conserve chirality
  - Higgsino: Yukawa coupling flips chirality

# Conclusions – Full Results in arXiv:1307.8076

- Full SUSY 'Real world' models **may escape existing 8TeV limits**
- LHC@14TeV/300fb$^{-1}$ will be able to observe all 4 studied STC models due to the light third generation squarks but
  - Sensitivity strongly depends on how well we will be able **control of systematic uncertainties**
- **Low sensitivity to EW** sector at LHC due to challenging $\tilde{\tau}$ decays
- LHC: good for the discovery of colored states - ILC: precise measurement of EW states
- At ILC@500GeV all sleptons and bosinos with masses low enough to be produced with ILC energy have reasonable cross section to be measured, e.g.:
- $\tilde{\tau}$ coannihilation hypothesis can only be tested with additional measurements from ILC
  - Mass measurements of $\tilde{\tau}_1$ and $\tilde{\tau}_2$
  - Measurement of $\tau$ helicity gives access to $\chi^0$ composition
- **ILC needed for searching Dark Matter**

# Appendix

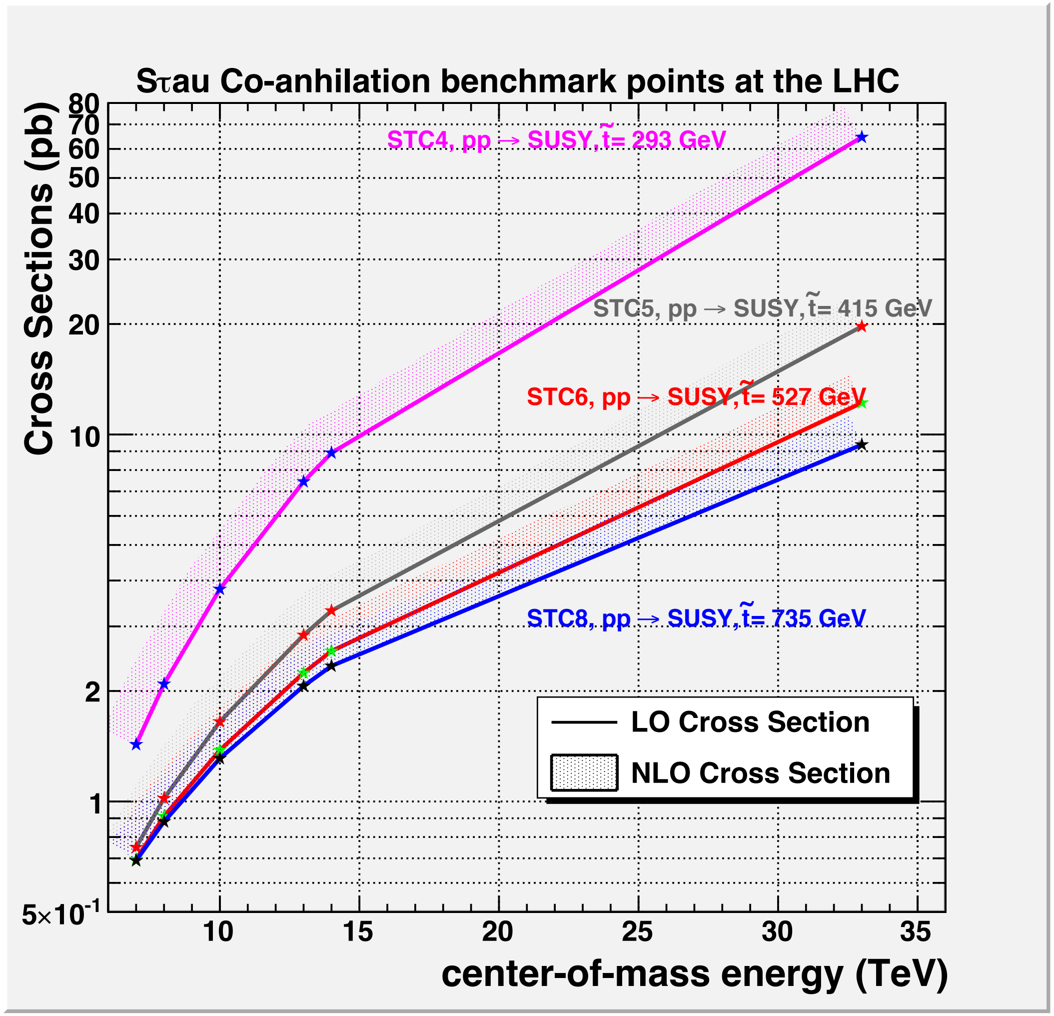
# Example Control Plots




- Full-hadronic analysis
- HT (scalar sum of the jets) and missing transverse energy after jet and b-jet requirements and lepton veto for 50 pileup events
- Typically $t\bar{t}$+ jets is the dominant background for stop searches

# Cross Sections – STC4…STC8

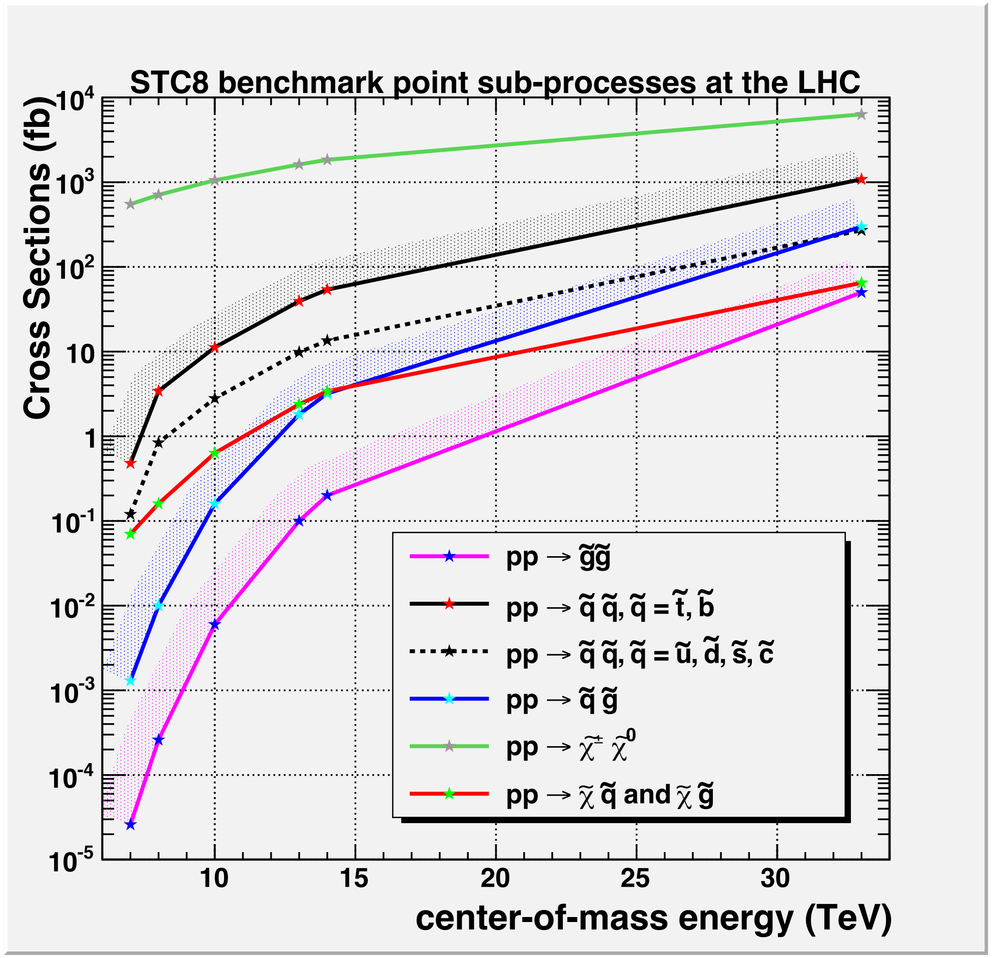
- LO Phythia6,  NLO Prospino*
- STC4 dominant contribution from direct stop
- Ewkino dominates in STC5-8




*Prospino 2.1 with private patch for 33 TeV

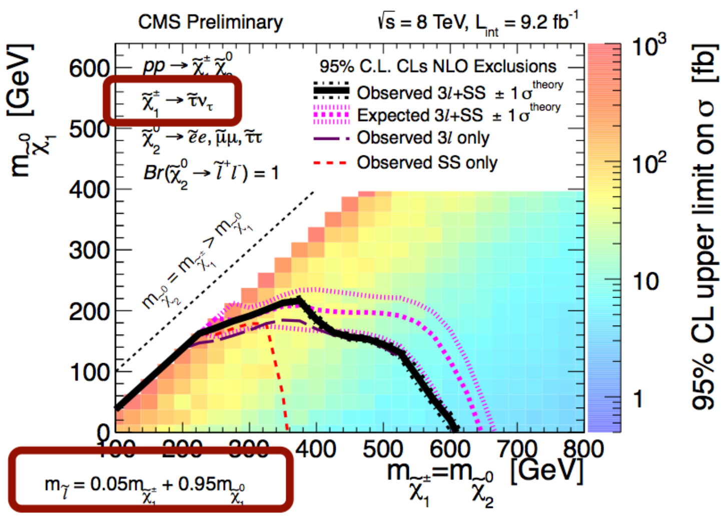
# Sub-process Cross Sections STC8

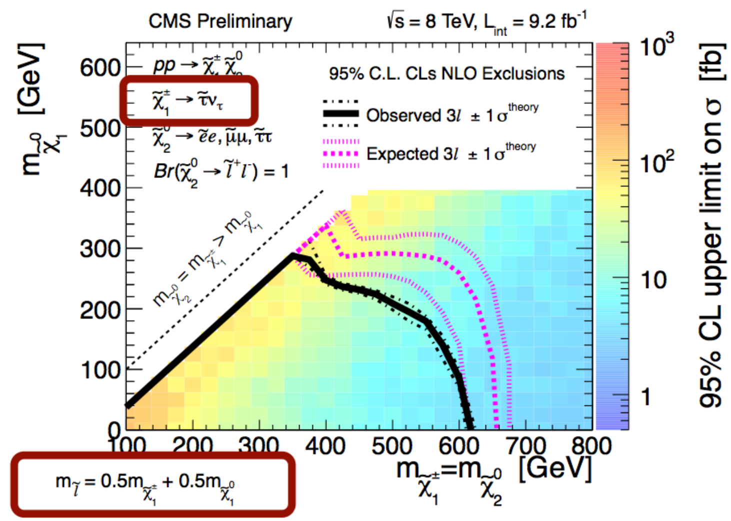
- Gluino-gluino production ~0.2 fb
- Expect ~600 events at 3000/fb
- Direct production of first 2 generations ~20fb
  - 60.000 events
  - expect more sensitivity for these (e.g. search for high-energetic jets and MET, no b-tags)
- Ewkino production dominates




*Prospino 2.1 with private patch for 33 TeV

# STC4-8 in CMS Ewkino Analysis




- CMS EWkino Analysis PAS-SUS-12-022
  - Mass parameters outside excluded region for case with stau mass in middle of C1 and N1 (even worse if stau closer to N1)

**STC4-8**