Non-Simplified SUSY: Stau Coannihilation at LHC and ILC

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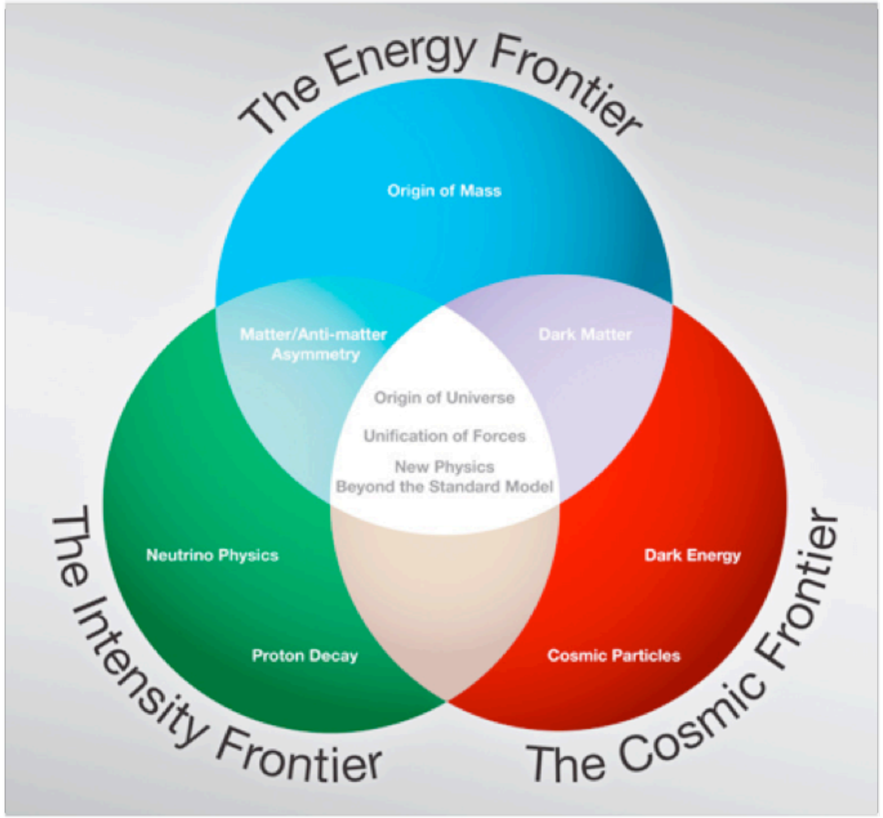
Snowmass 2013
Seattle Workshop

Outline

- **Introduction**
  - LHC Analyses
  - ILC Analyses
  - Summary

Snowmass 2013

- Input from all frontiers:



- Chip Brock: "Accomplish the goals by evaluating the physics… and telling stories"

Snowmass 2013

- Energy Frontier Goals (from Chip Brock)

EF Goals:

Concrete Goals: the science cases

I. What scientific targets can be achieved before ~2018?

at design specifications with $\int \mathcal{L}\, dt$ *~100 fb^{-1})?*

II. What are the scientific cases which motivate HL LHC running:

"Phase 1": circa 2022 with $\int \mathcal{L}\, dt$ *of approximately 300 fb^{-1}*

"Phase 2": circa 2030 with $\int \mathcal{L}\, dt$ *of approximately 3000 fb^{-1}*

How do the envisioned upgrade paths inform those goals?
Specifically, to what extent is precision Higgs Boson physics possible?

III. Is there a scientific necessity for a "Higgs Factory"?

IV. Is there a scientific case today for experiments at higher energies beyond 2030?

A high energy LHC?
High energy lepton collider?
Lepton-hadron collider?
VLHC?

Snowmass 2013

- Energy Frontier Goals (from Chip Brock)

EF Goals:

Community Goals: the context for this science

I. **Articulate to scientific audiences**

   To other Particle Physicists:

   EF science in the context of the Intensity and Cosmic Frontiers' goals

   To other scientists

II. **Justify to governmental audiences**

   OHEP, EPP, OSTP, Congress...beyond our direct agencies

   Not only science, but the internationalization of science

III. **Explain to non-specialist audiences**

   Universities

   Public

   Lectures
   Written documentation
   Attractive on-line presence

Storyline

- What if LHC sees some kind of signal, but cannot distinguish between
  - Is it SUSY or other BSM models?
  - Is it more than one new particle?
  - What are the masses and other properties of the new particles?
  - Can LHC distinguish between different production processes?
  - Do we see THE dark matter?

- Can ILC add information and see particles that LHC cannot see (or at least not distinguish)?

→ LHC: discovery of colored states

→ ILC: precise measurement of EW states

Storyline

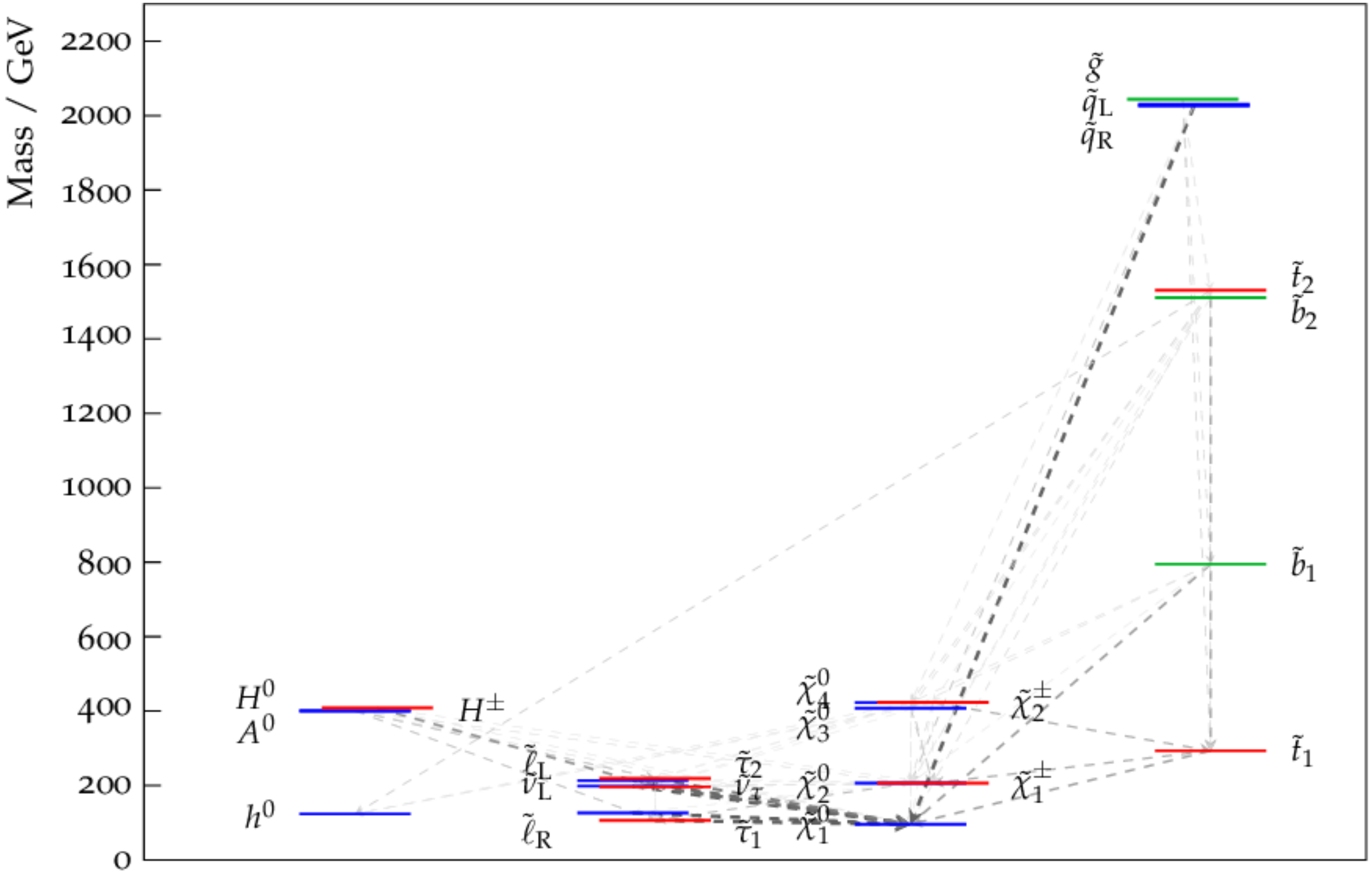
- Choose a full model that is compatible with all recent observations, e.g.:
  - Higgs @ 125 GeV
  - Relic density
  - Latest results of direct dark matter searches

- Full model chosen as example here:
  SUSY pMSSM model with small mass difference (10 GeV) between stau and LSP
  - Four models with differing stop masses:

Model name	Mass parameter of right-handed top quark / GeV	Stop mass / GeV
STC4	400	293
STC5	500	416
STC6	600	527
STC8	800	736

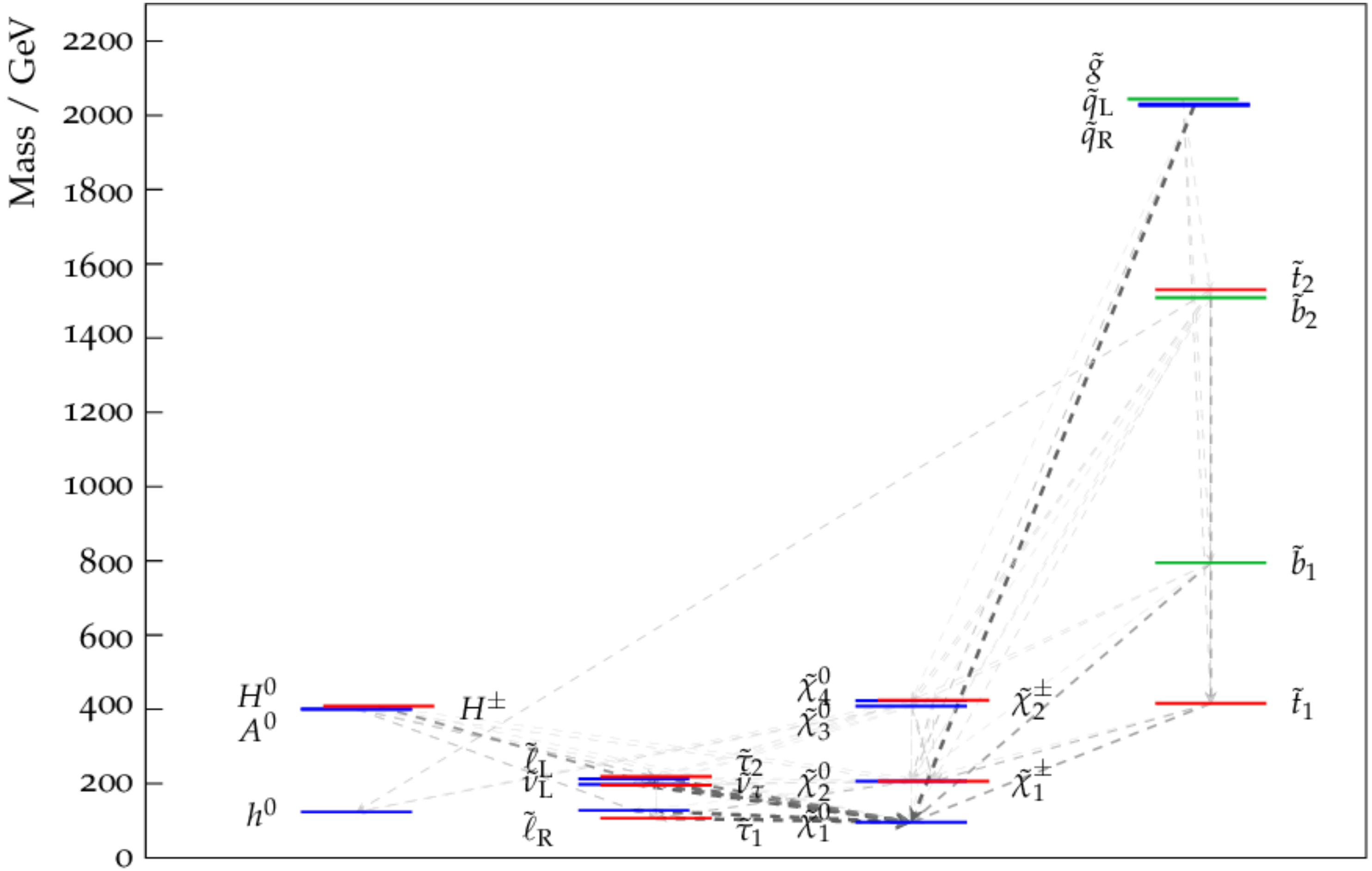
Full Spectrum STC4

- Low stop mass → large direct stop production cross section



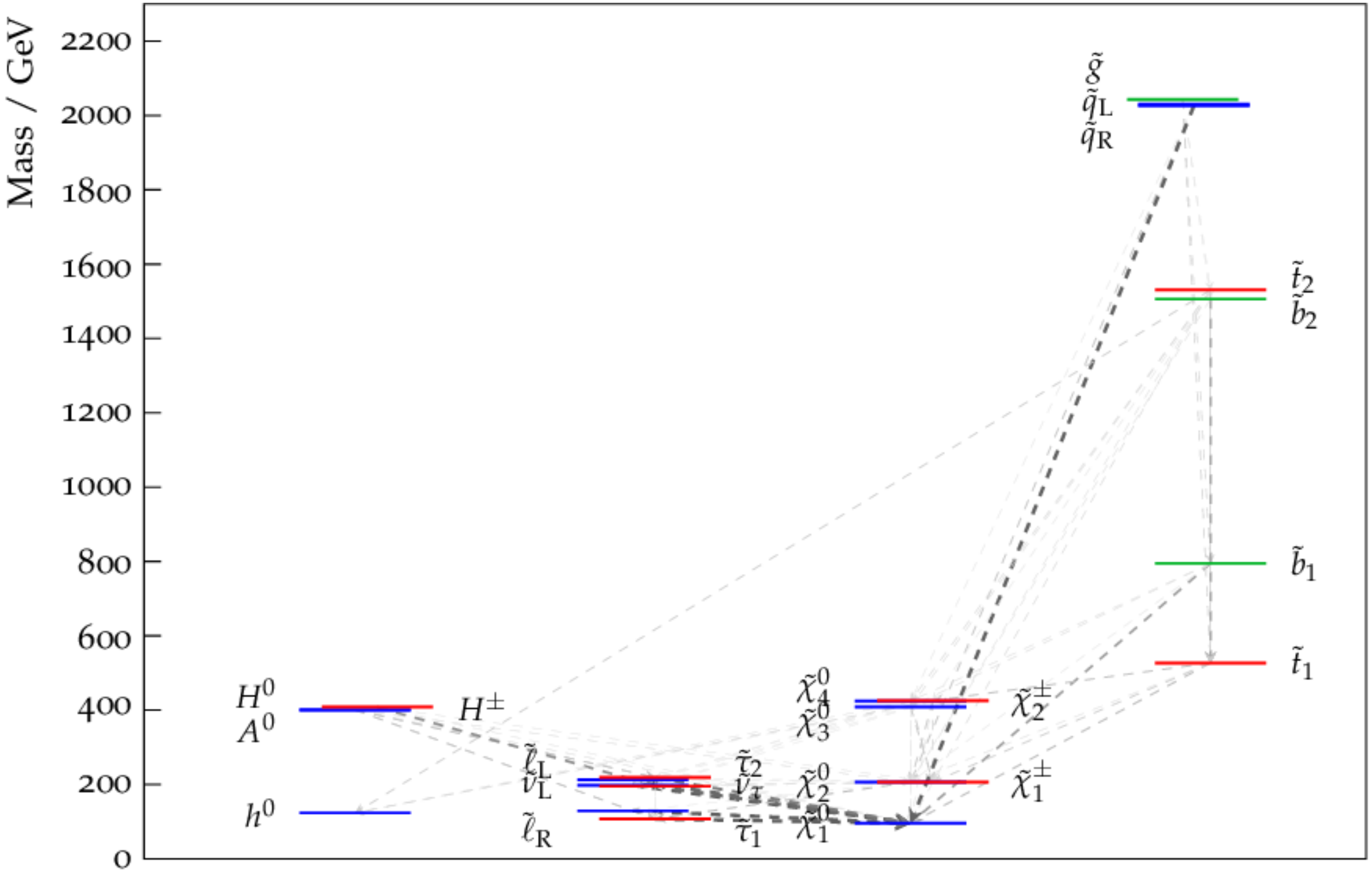
Full Spectrum STC5

- Relatively low stop mass → direct stop production cross section much smaller than in STC4



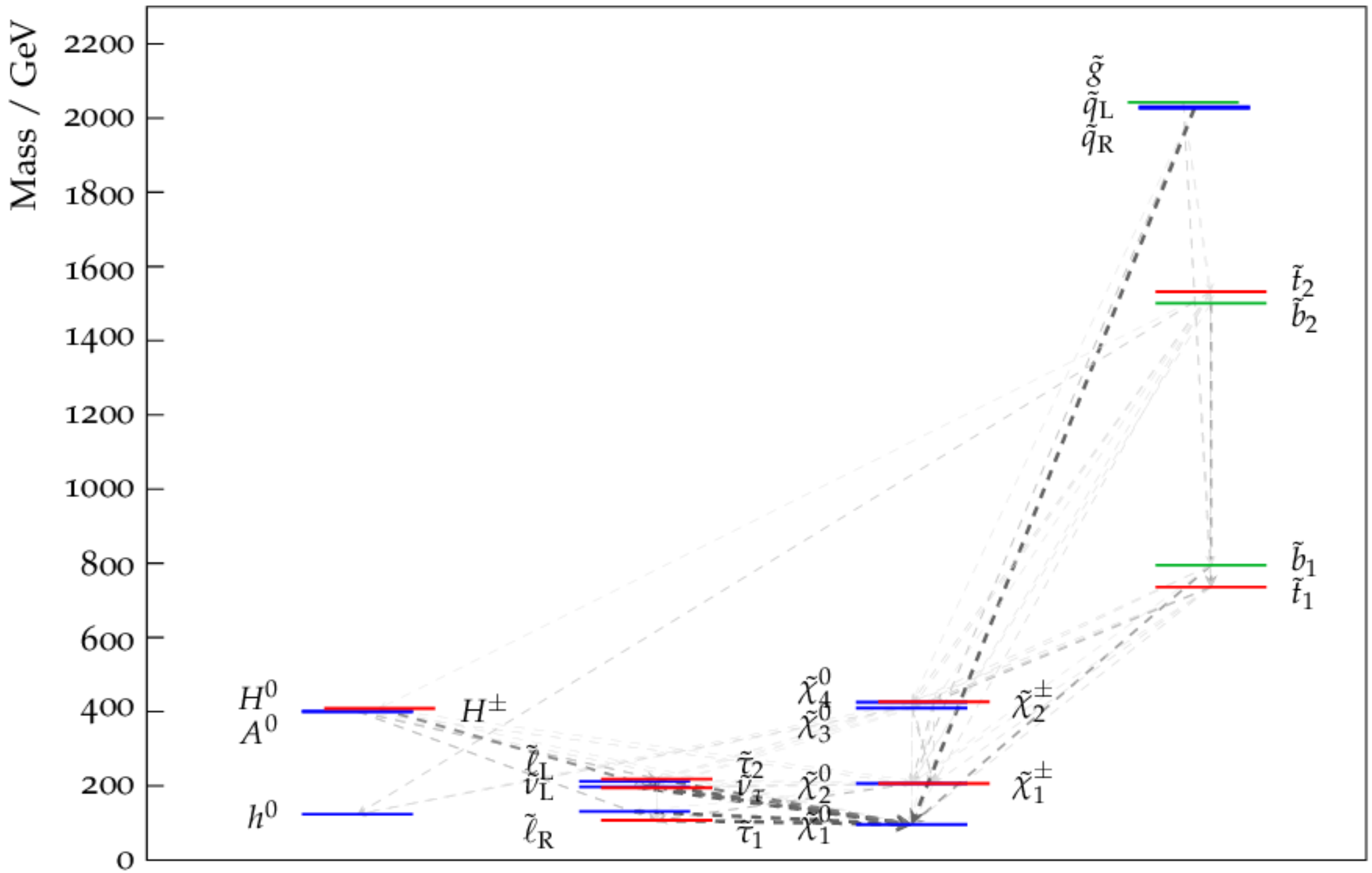
Full Spectrum STC6

- EWkino production gains more weight



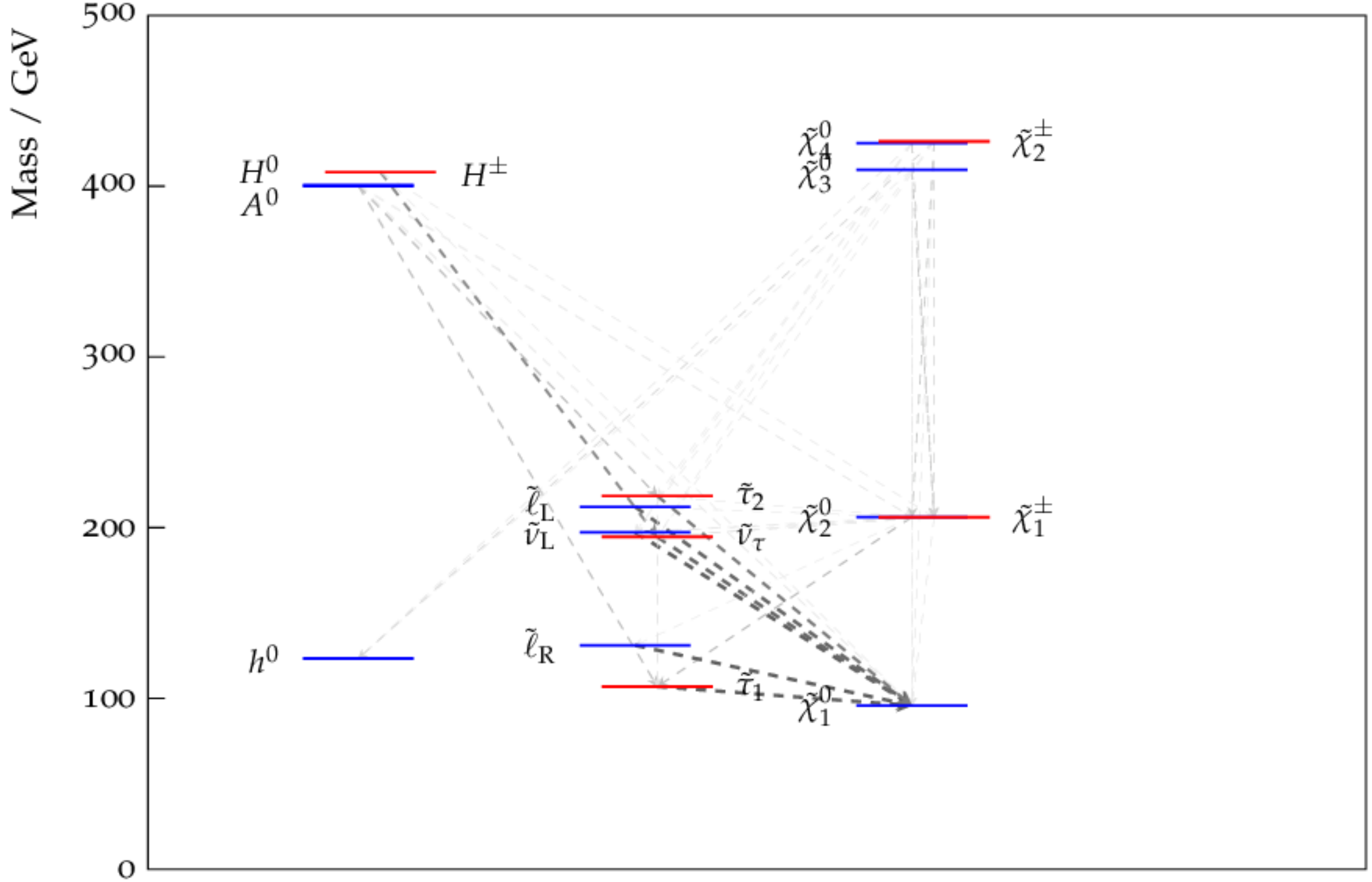
Full Spectrum STC8

- EWkino production has largest cross section



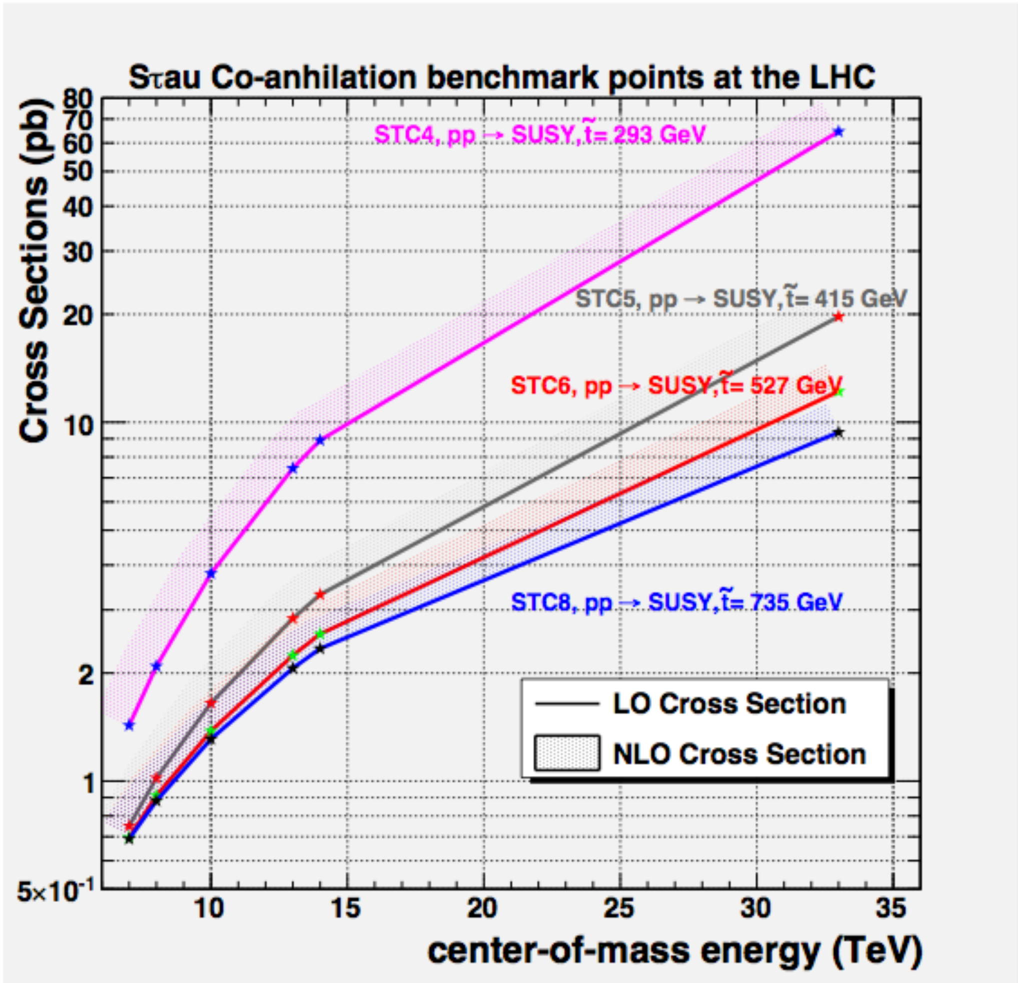
Lower part of STC8 Spectrum

- Many different decays at lower masses



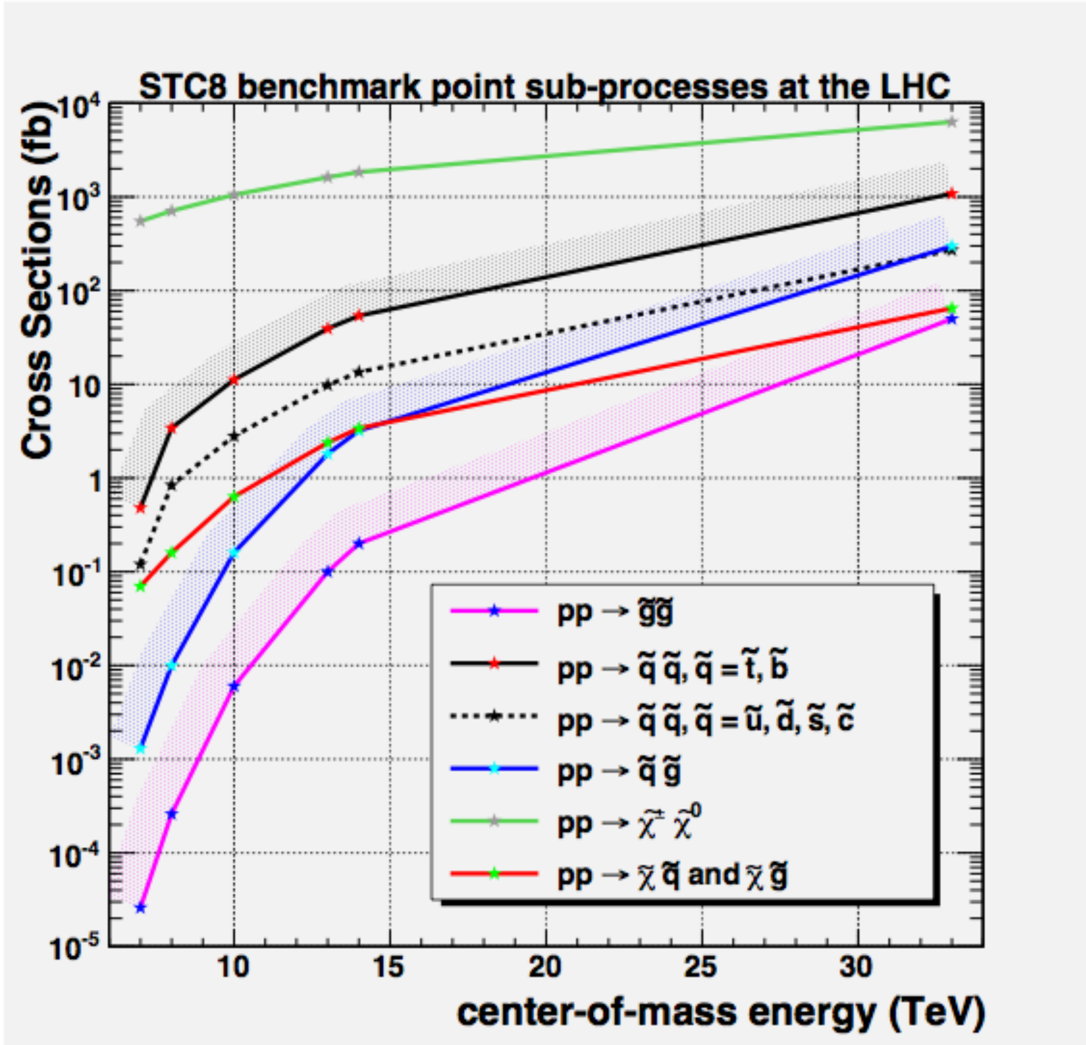
Cross sections for all models

- Inclusive cross sections
  - LO calculated with Pythia6
  - NLO calculated for most sub-processes with Prospino2.1
  - STC4 dominated by direct stop production
  - EWkino cross sections quite dominating in the other scenarios
  - 33 TeV cross section to be taken with some caveat – PDFs not known here…



Sub-process cross sections for STC8

- NLO calculated where possible
- Gluino-gluino production ~0.2 fb
  → expect ~600 events at 3000 fb-1
- 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

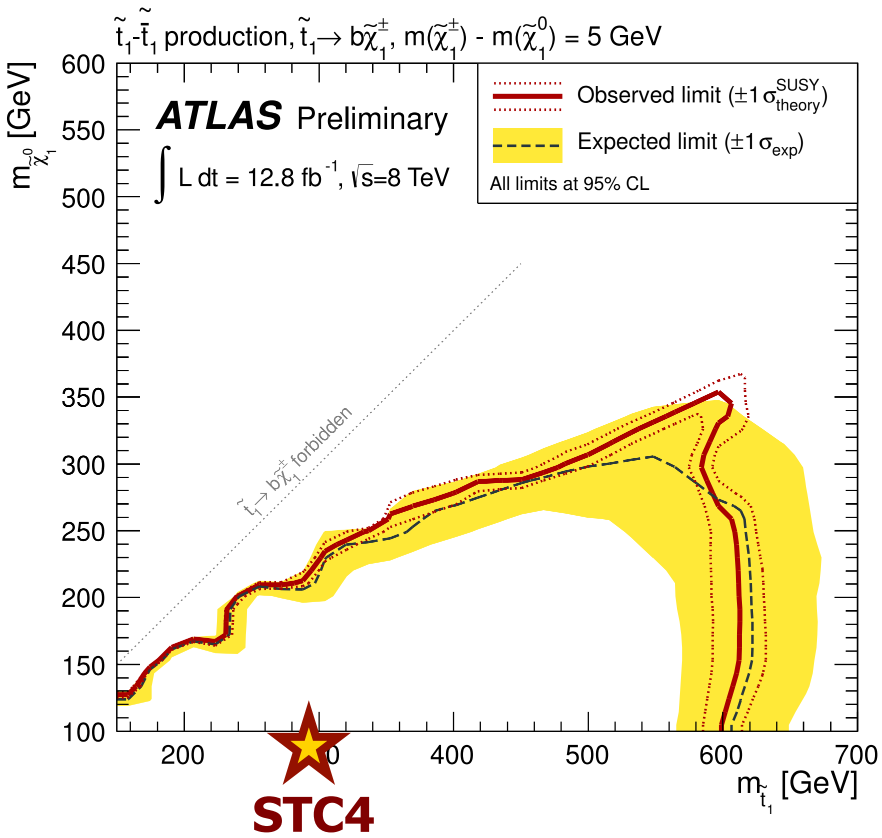


Where we are...

- Introduction
- **LHC Analyses**
- ILC Analyses
- Summary

Reach of current 8 TeV Analyses

- Full-hadronic analysis from ATLAS: ATLAS-CONF-2013-001
- m_stop = 293 GeV and m_N1 = 95 GeV lies in excluded region, but…



Reach of current 8 TeV Analyses

- Full-hadronic analysis from ATLAS: ATLAS-CONF-2013-001

Cut flow from ATLAS

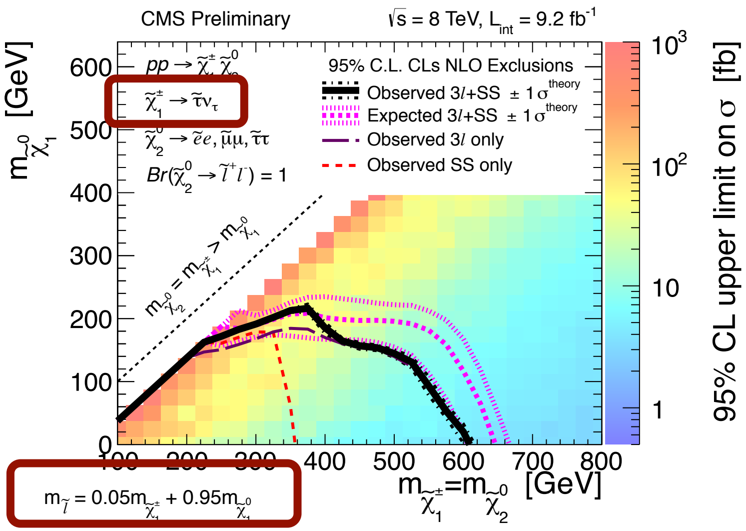
Description	Signal region			
	SR1	SR2	SR3a	SR3b
Trigger	E_T^{miss} trigger > 99% efficient for $E_T^{miss} > 150$ GeV			
Event cleaning	Common to all SR			
Lepton veto	No e/μ with $p_T > 10$ GeV			
E_T^{miss}	> 150 GeV	> 200 GeV	> 150 GeV	> 250 GeV
Leading jet $p_T(j_1)$	> 130 GeV, $\|\eta\| < 2.8$	> 60 GeV, $\|\eta\| < 2.8$	> 130 GeV, $\|\eta\| < 2.8$	> 150 GeV, $\|\eta\| < 2.8$
Second jet $p_T(j_2)$	> 50 GeV, $\|\eta\| < 2.8$	> 60 GeV, $\|\eta\| < 2.8$	> 30 GeV, < 110 GeV, $\|\eta\| < 2.8$	
Third jet $p_T(j_3)$	veto event if $p_T(j_3) > 50$ GeV, $\|\eta\| < 2.8$		> 30 GeV, $\|\eta\| < 2.8$	
$\Delta\phi(E_T^{miss}, j_1)$	-		> 2.5	
jet b-tagging ($\|\eta\| < 2.5$)	j_1 and j_2 tagged		j_1 anti-tagged, j_2 and j_3 tagged	
$\Delta\phi_{min}(n)$	> 0.4 ($n = 2$)		> 0.4 ($n = 3$)	
$E_T^{miss}/m_{eff}(j_1, j_2, j_3)$	> 0.25			
m_{CT}	> 150, 200, 250, 300 GeV	> 100 GeV	-	
$H_{T,x}$	-	< 50 GeV, $x = 2$	< 50 GeV, $x = 3$	

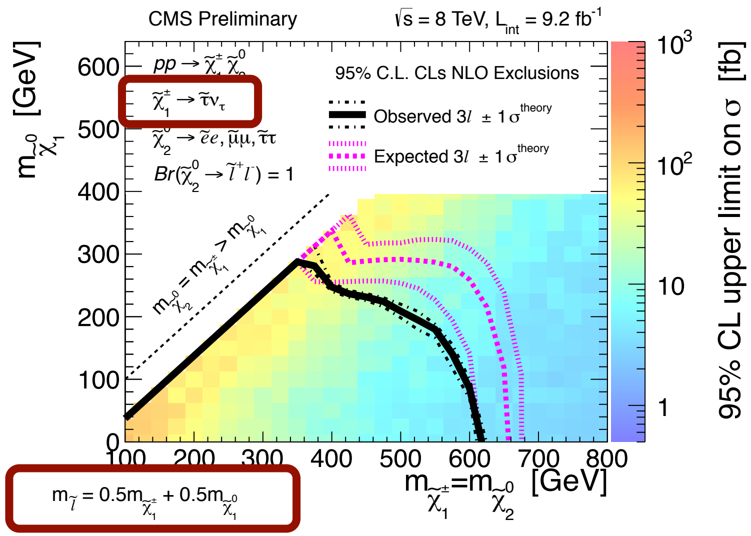
expected number of signal events for STC4 as generated with Delphes Snowmass det.

Description	Signal Region			
	SR1	SR2	SR3	SR4
Preselection	8576			
Lepton Veto	6628			
E_T^{miss}	285	249	507	131
N_{jets}	198	215	427	115
Leading jet p_T	173	215	339	111
Second jet p_T	138	137	339	111
Third jet p_T	85	74	176	49
jet b-tagging	4	3	2	1
$\Delta\phi_{min}$	1	1	1	1
E_T^{miss}/m_{eff}	1	1	1	1
M_{CT}	1	1	1	1
$H_{T,x}$	1	1	0	0

→ **No observation with current analysis expected**

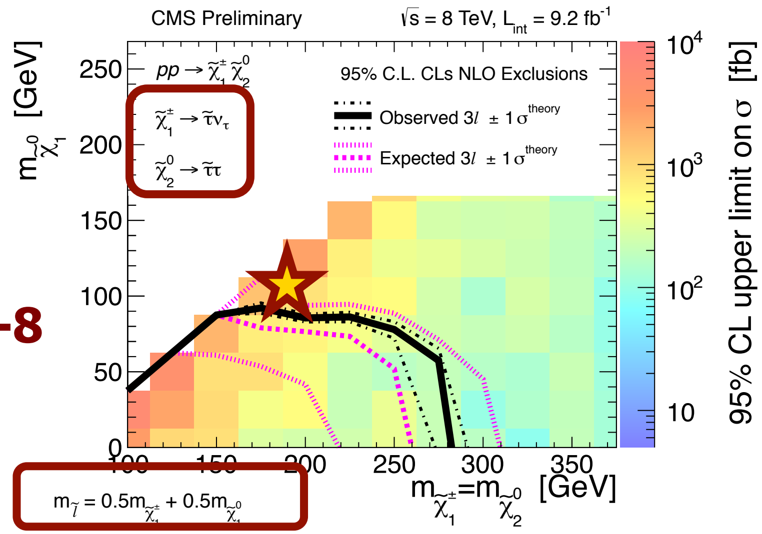
Reach of current 8 TeV Analyses





- 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

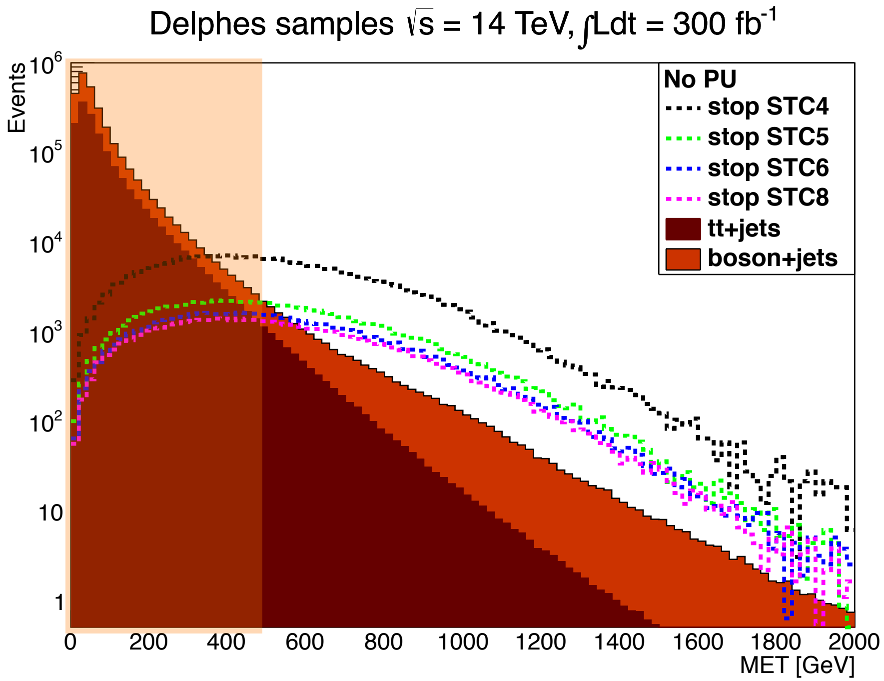


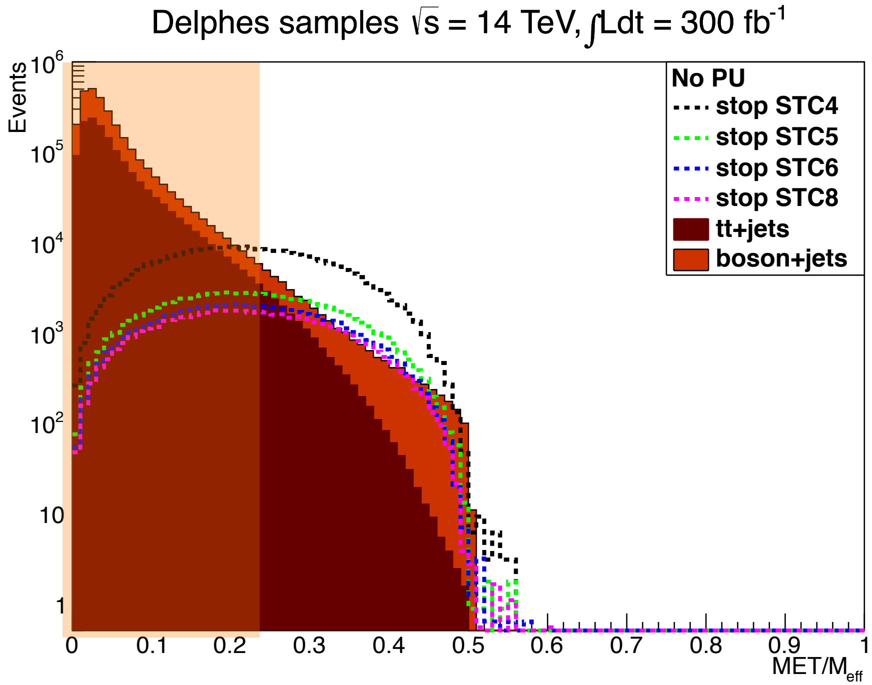
LHC: Search for Stops

- Simple cut-and-count analysis, inspired by ATLAS 8 TeV full-hadronic analysis:
  - Lepton veto (no identified lepton with p_T > 10 GeV)
  - N_jets > 3
    - Jet1: p_T > 120 GeV
    - Jet2: p_T > 80 GeV
    - Jet3: p_T > 70 GeV
  - N_btag >= 2
  - dPhi(MET, $Jet_{1,2}$) > 0.5
  - MET/M_{eff} > 0.25
  - H_T > 1000 GeV
  - MET > 500 GeV

LHC: Search for Stops

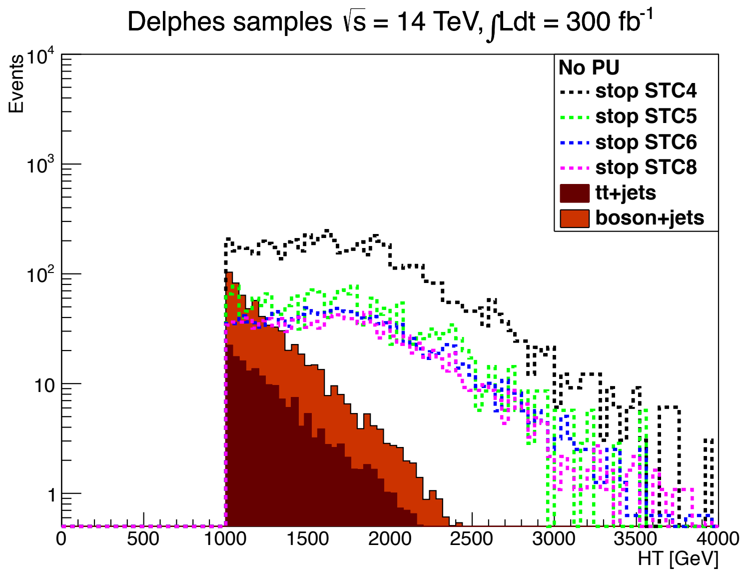
- Control plots before cut on MET, MET/Meff, Δφ(Jet1,2 and MET):

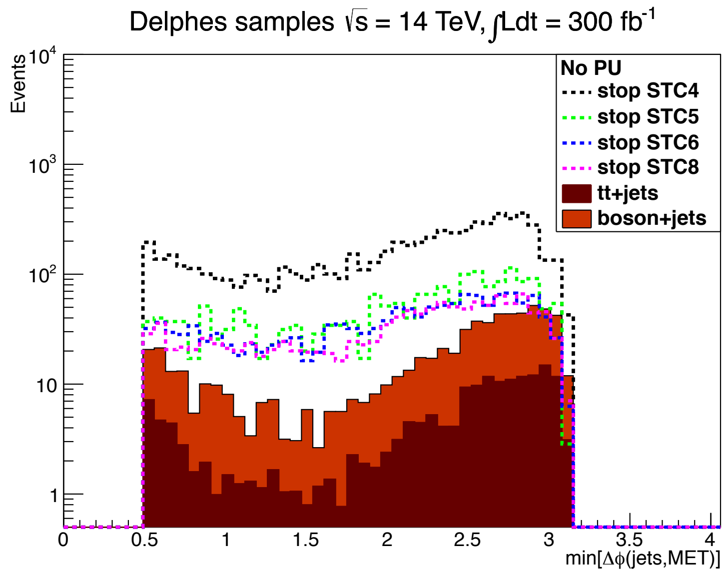




LHC: Search for Stops

Cut	STC4	STC5	STC6	STC8	tt+jets	boson+jets
Presel	2703890	856200	617099	538800	1.80002e+08	1.58575e+10
Lepton Veto	2425610	768130	553643	483258	1.55928e+08	2.25747e+10
nJets >= 3	737193	233168	168517	146843	1.27979e+08	2.32575e+09
P_T^{J1} > 120GeV	708440	224098	161879	141136	5.92435e+07	9.11032e+08
P_T^{J2} > 70GeV	685382	216777	156634	136497	5.57657e+07	8.25922e+08
P_T^{J3} > 60GeV	600203	189834	137302	119709	4.56697e+07	5.25214e+08
btags >= 2	416927	131541	95454	83011	2.56063e+07	3.25545e+07
HT>1000GeV	244239	76559	56190	48563	1.40112e+06	1.39993e+06
min($\Delta\Phi$) > 0.5	11642	3633	2662	2351	36665	21128
MET/M_{eff} > 0.2	7601	2306	1739	1528	1087	1053
MET > 500	6243	1875	1409	1253	177	496





LHC: Search for Stops

- Good visibility for all four models!
- Expect same sensitivity for direct stop search with one lepton
- Full-hadronic search has better sensitivity to direct sbottom production (decay without leptons), while semi-leptonic search is expected to yield best sensitivity for stop → top N1
- Possibility to distinguish between stop and sbottom by comparison of these two analyses and measured cross sections
- Sensitivity to production of 1st and 2nd generation squarks enhanced by requiring no b-jet, but we expect SUSY background from 3rd generation squarks (to be checked)!
- More methods for mass measurements etc. for a different spectrum described in: http://arxiv.org/pdf/hep-ph/0410364v1.pdf

LHC: Search for EWkinos

- Search for same-sign leptons coming from:
  - N2 C1 production, where
    - N2→ stau tau → tau tau N1
    - C1 → tau N1
  - expect at least same-sign + additional lepton

- Rough comparison to same-sign analysis in PAS CMS-12-022
  - 8 TeV signal yields less than 10 Events for STC4 (where 11 are observed in data and compatible with BG expectation)

LHC: Search for EWkinos

- Result for 300 fb^{-1} and 14 TeV:

Cut	$\tilde{\chi}^{\pm}\tilde{\chi}_2^0$ Production only	Inclusive signal	Vectorboson+jets
Presel	552000	702000	127910741
2lepton req	10625	13725	891459
$E_T^{miss} > 120$ GeV	5606	7330	44378
SS req	921	1193	2908
Z veto	723	958	1552
120 GeV $< E_T^{miss} <$ 200 GeV no b-jet, $N_{jet} \leq 2$	187	224	854
120 GeV $< E_T^{miss} <$ 200 GeV no b-jet, $N_{jet} \leq 2$ no third lepton	150	171	849
$E_T^{miss} > 200$ GeV	394	519	402
$E_T^{miss} > 200$ GeV, no third lepton	280	384	401

- EWkino production expected to be visible
- Depending on selection SUSY background or SM background larger
- An optimized selection is of course necessary to further distinguish the new particles

LHC Search – Conclusion

- LHC will be able access all four models, but:
  - it will be difficult to identify the nature of the access
  - EWkino identification partly lacking SUSY background
  - staus very difficult for LHC

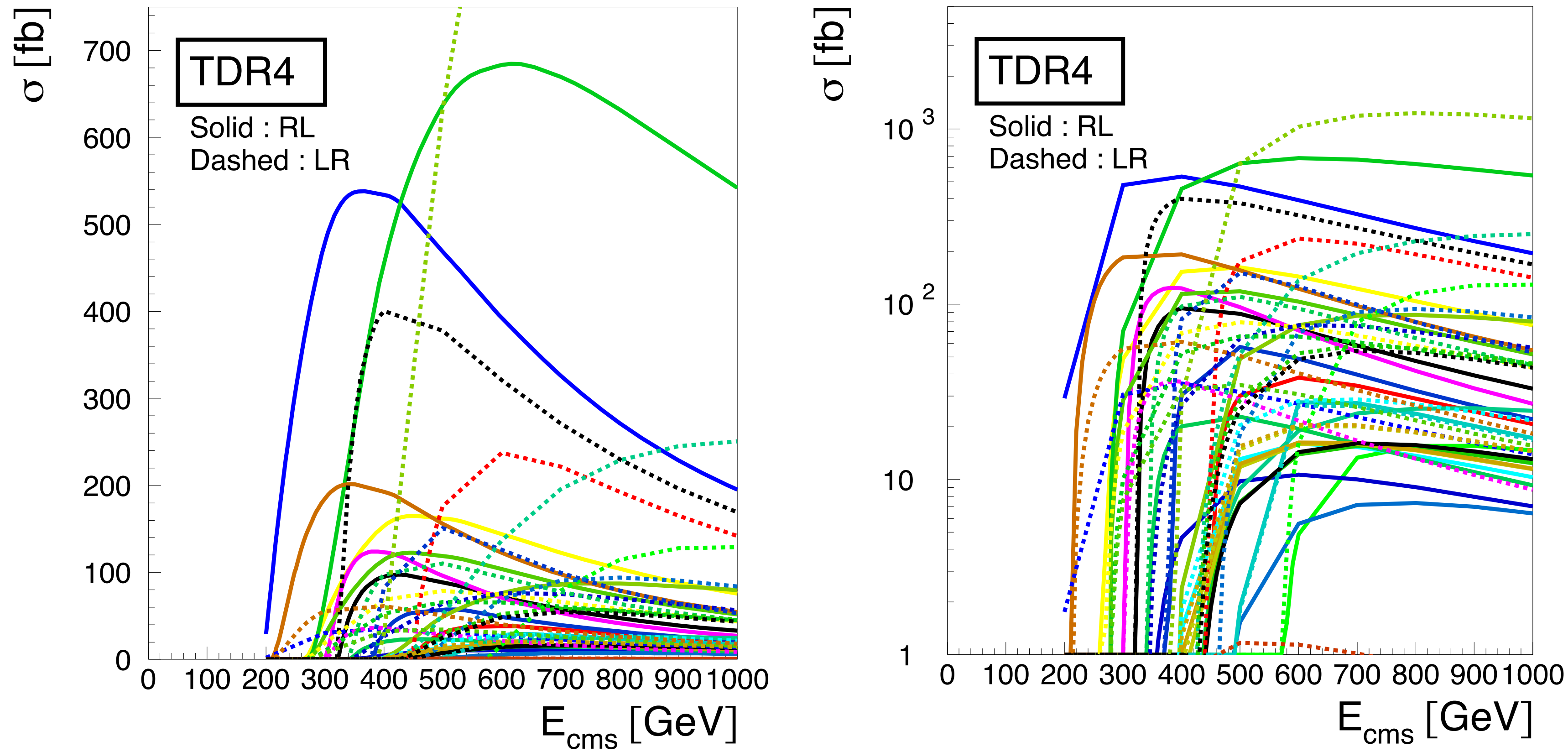
  - will need ILC to further identify particle masses etc.

Where we are...

- Introduction
- LHC Analyses
- **ILC Analyses**
- Summary

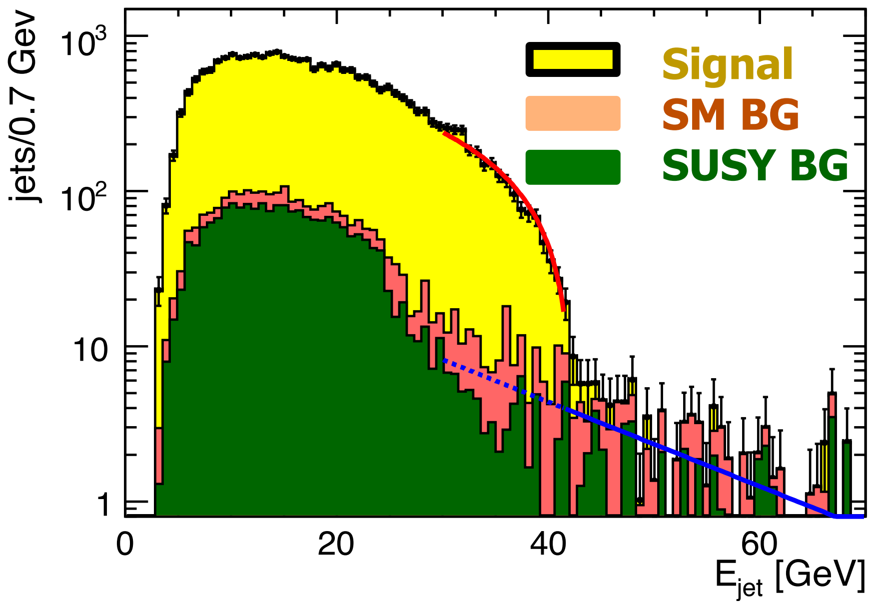
ILC: Precision Measurement

- At ILC (@ 500 GeV), all sleptons and bosinos can be produced with reasonable cross section (inclusive for both polarizations about 3pb)

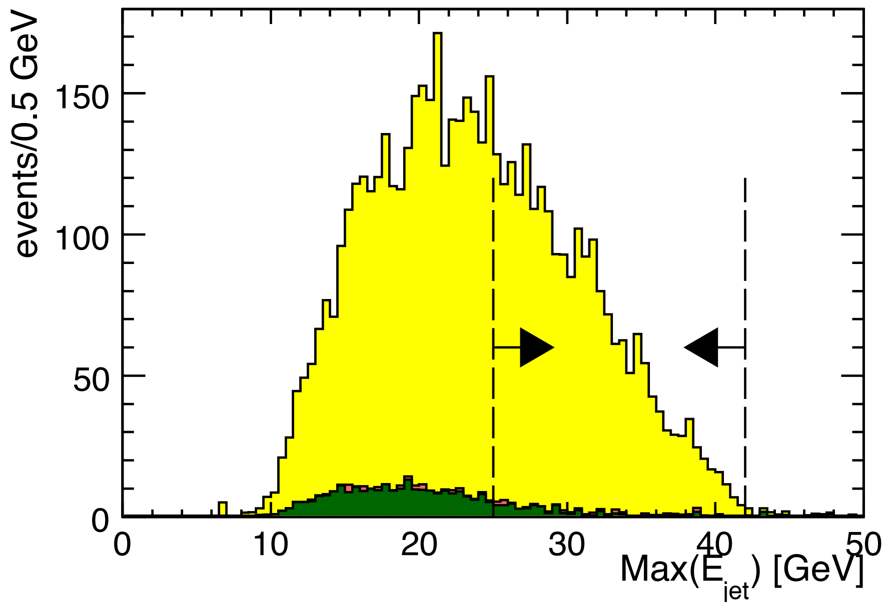


ILC: Stau_1 Measurement

- Very clean signal after few cleaning cuts
- Stau_1 can be measured with precision of 200 MeV



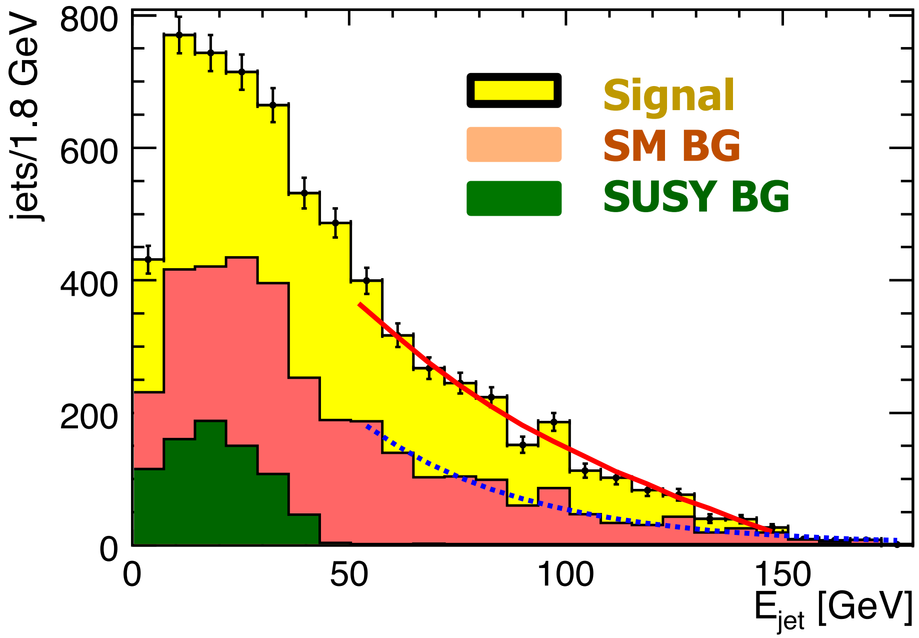
endpoint determination



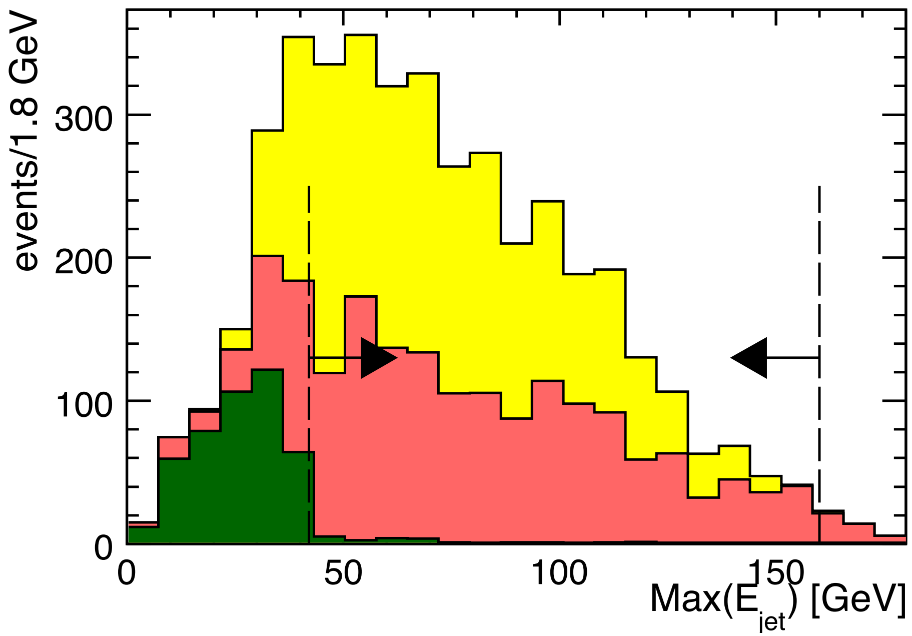
cross section determination
using region between arrows

ILC: Stau_2 Measurement

- Not only stau_1, but also stau_2 can be measured with high precision up to 5 GeV:



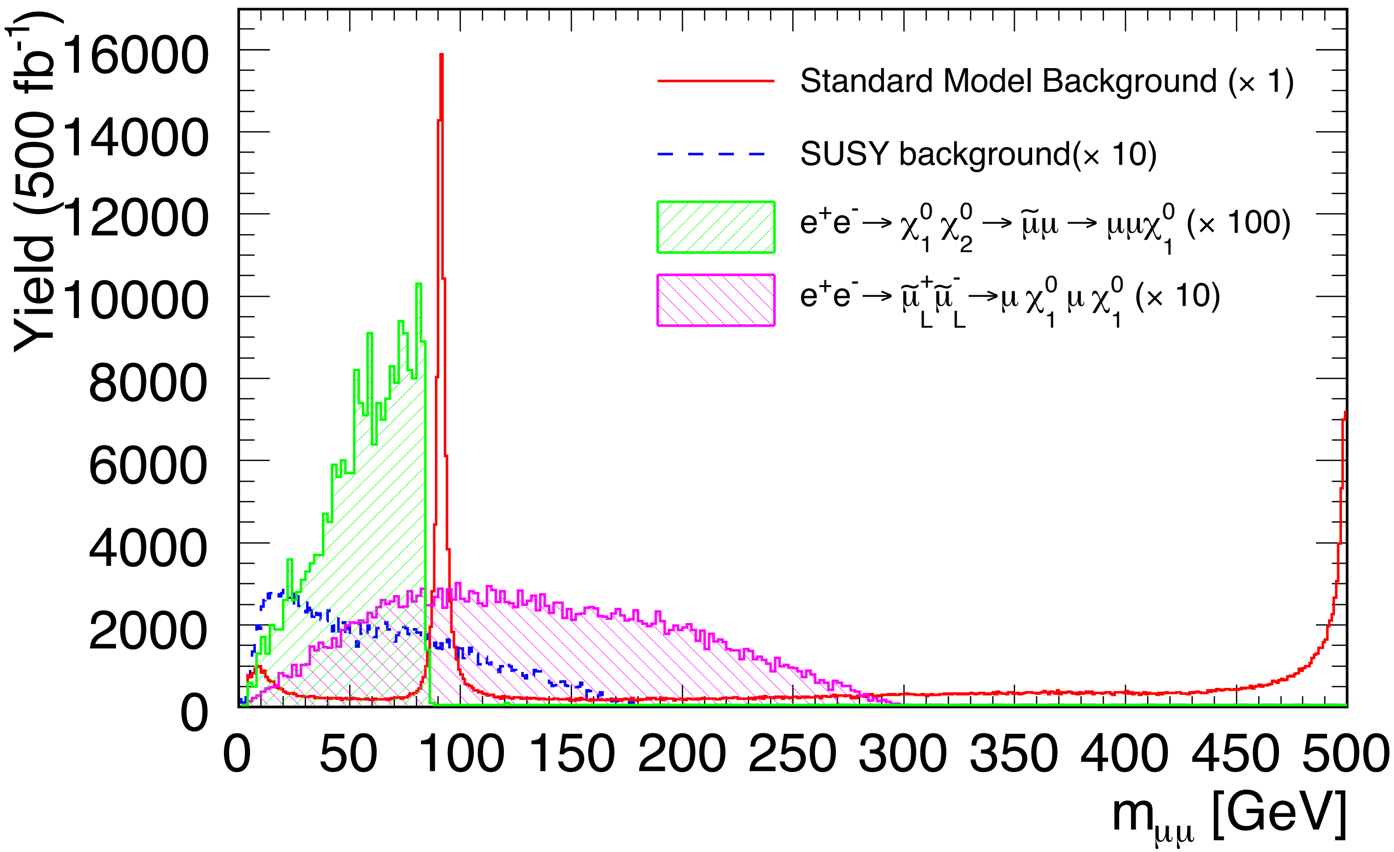
endpoint determination



cross section determination using region between arrows

ILC: Measurement of smuon

- Reconstruction of invariant di-muon mass → edge for smuon



ILC: Measurement of smuon

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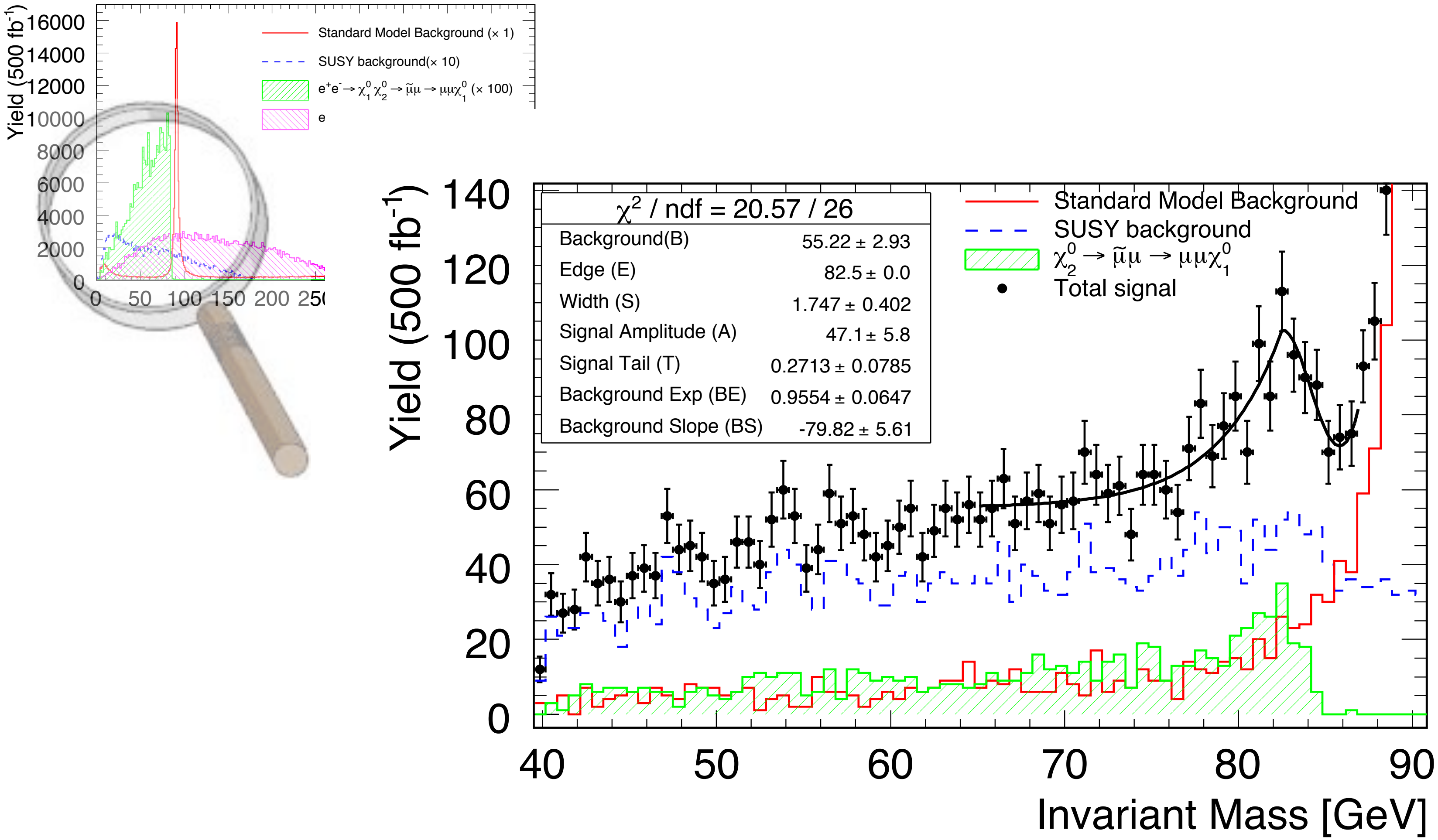
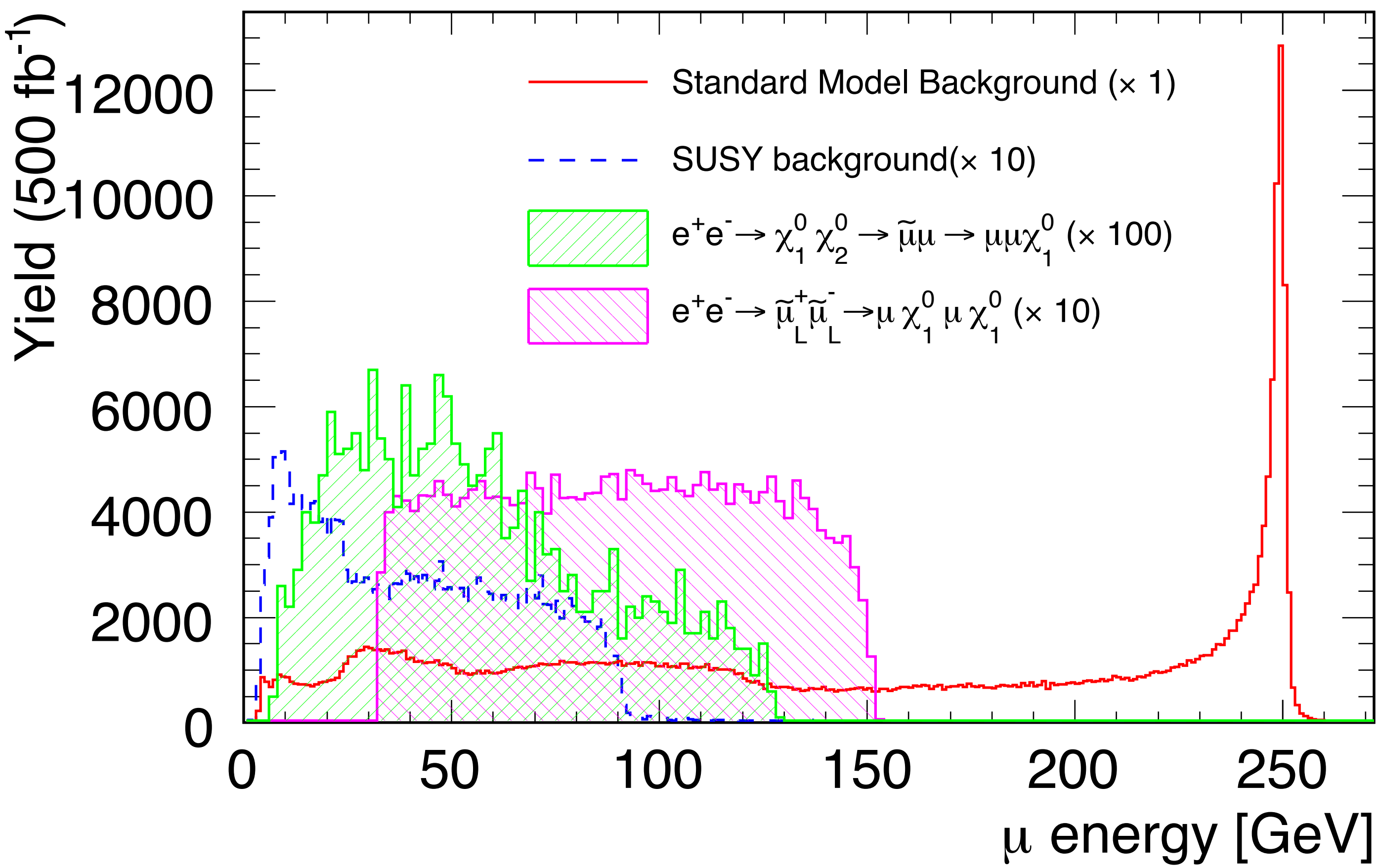


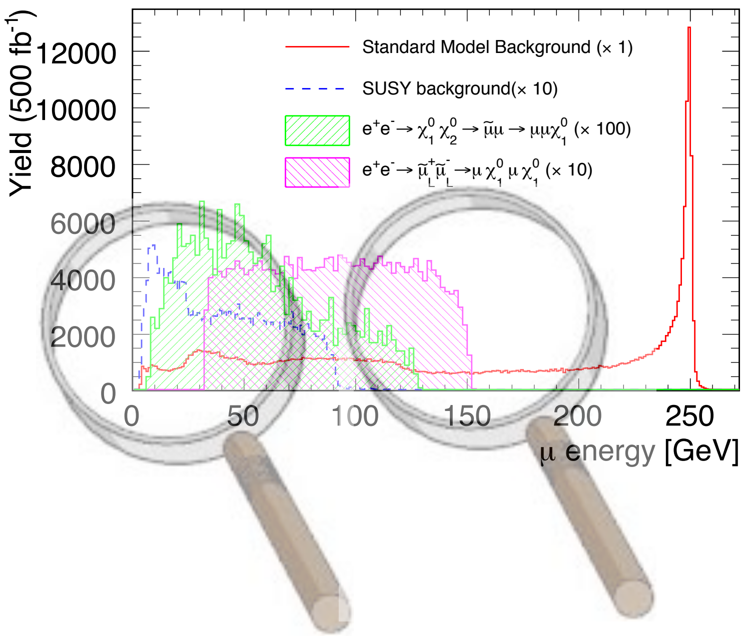
ILC: Measurement of smuon

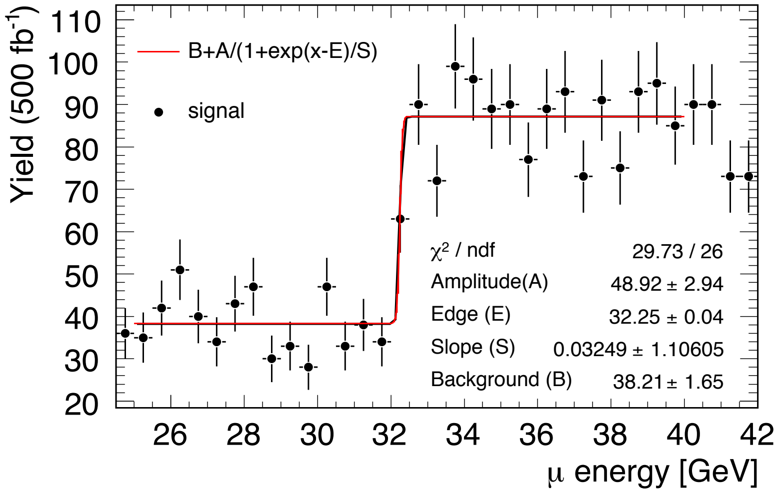
- Mu energy spectrum (smu_L)

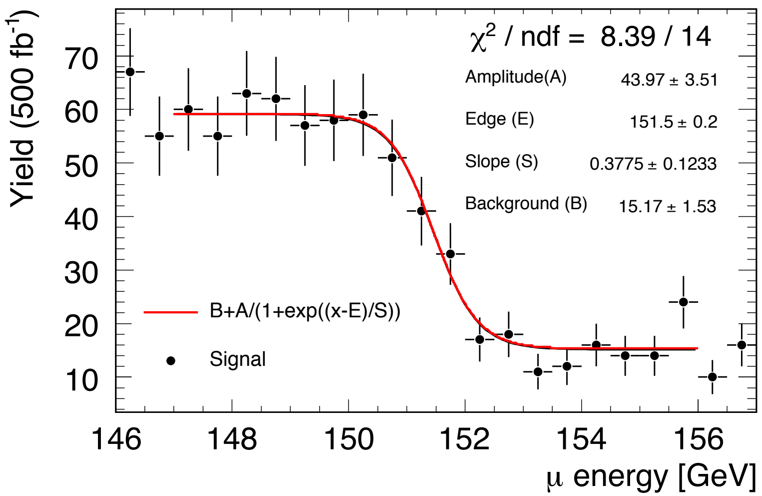


ILC: Measurement of smuon_L

- Mu energy spectrum (smuon_L)





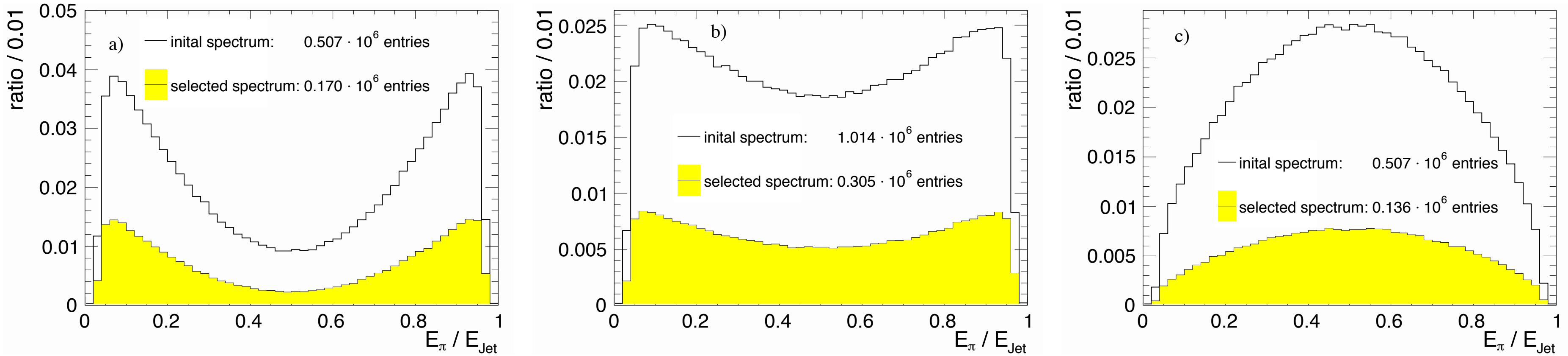


ILC: Measurement of Stau Helicity

- Stau polarization: depends on
  - mixing angle θ_{stau} of the chiral eigenstates to mass eigenstates
  - amount of Higgsino and gaugino eigenstates of N1 (gaugino and fermions: conserving chirality; Higgsino: Yukawa coupling flips chirality)

- Ratio of pion over jet energy differs for different stau helicity

both stau leptons right-handed | opposite helicity | both stau leptons left-handed



Where we are...

- Introduction
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- ILC Analyses
- **Summary**

Summary and Conclusion

- LHC capable to see all four studied models, especially the light third generation squarks
- Expect sensitivity to distinguish between stop and sbottom due to different decays
- Gluino measurement difficult due to low cross section
- Sensitivity to EW sector at LHC very low due to stau decays – analysis still ongoing…

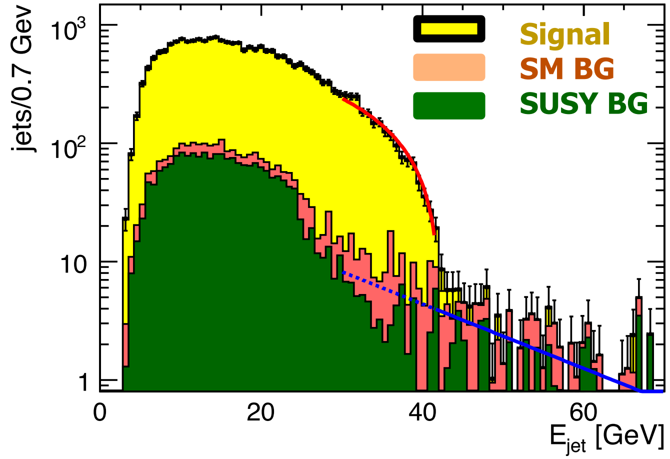
→ Need ILC for precision measurements of the EW sector

→ At ILC all sleptons and bosinos with masses low enough to be produced with ILC energy have reasonable cross section to be measured, e.g.:

→ Mass measurements of stau_1 and stau_2

→ Mass measurements of smuons

→ Measurement of stau helicity

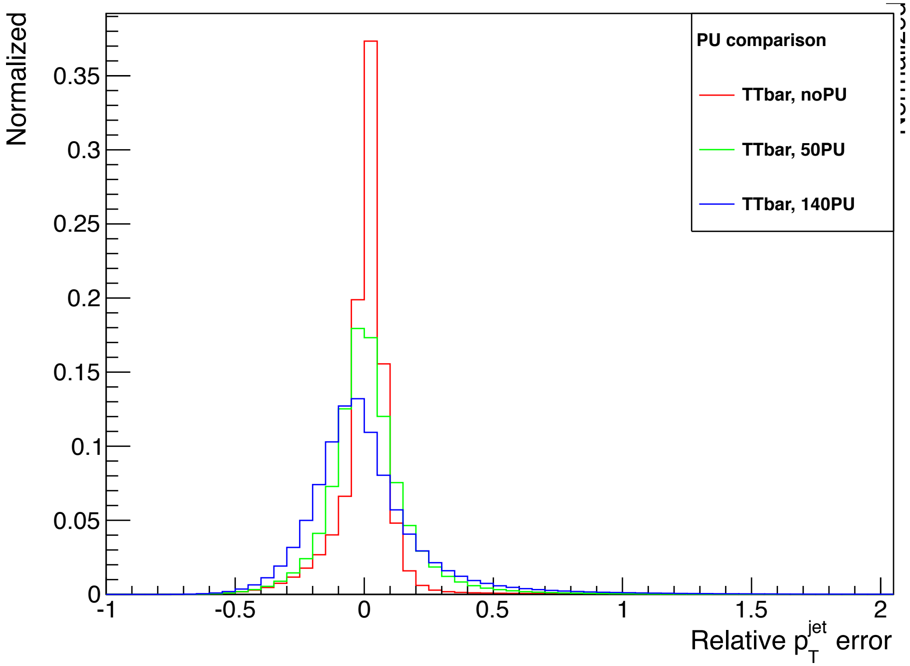


Thank you for listening

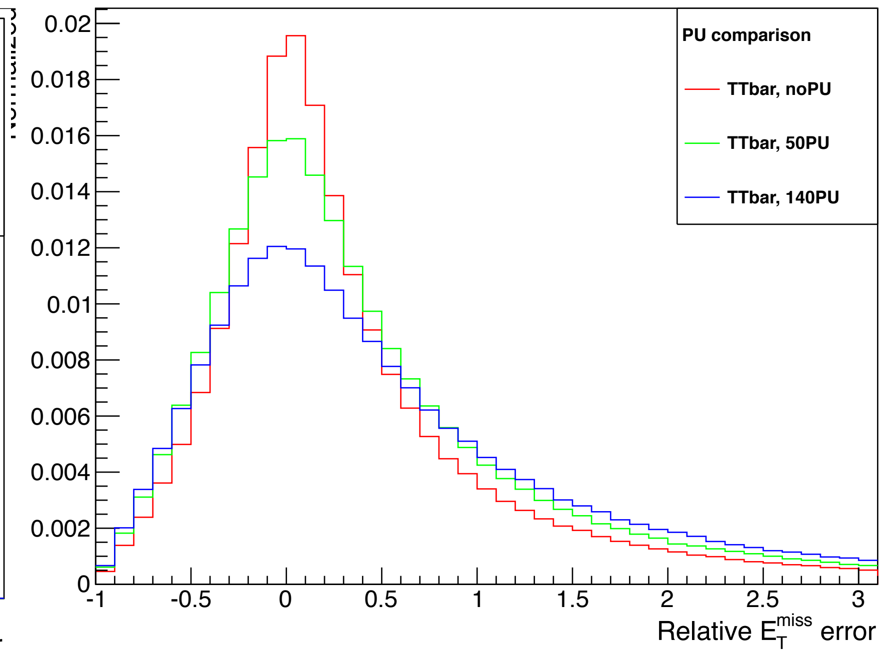
Backup slides follow…

PU dependence

Jet energy resolution



MET resolution



Resolution degrades with higher PU (as expected)