Soft objects for new Physics

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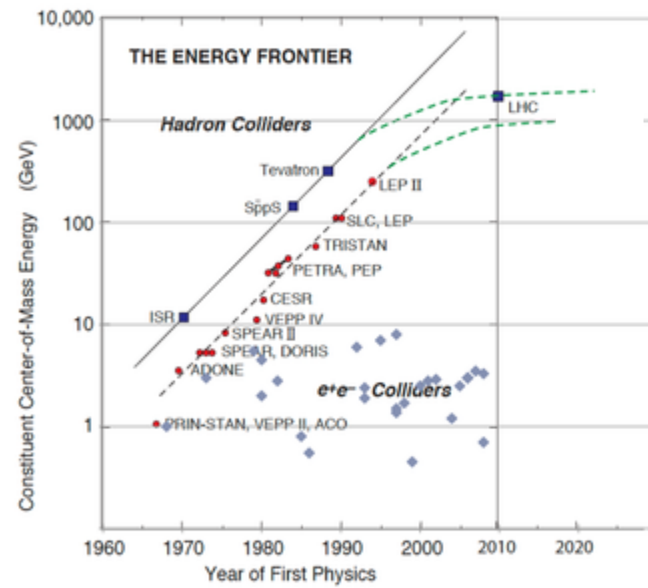
Frozen Energy Frontier

- Over decades energies increased regularly and illuminated new energy regimes

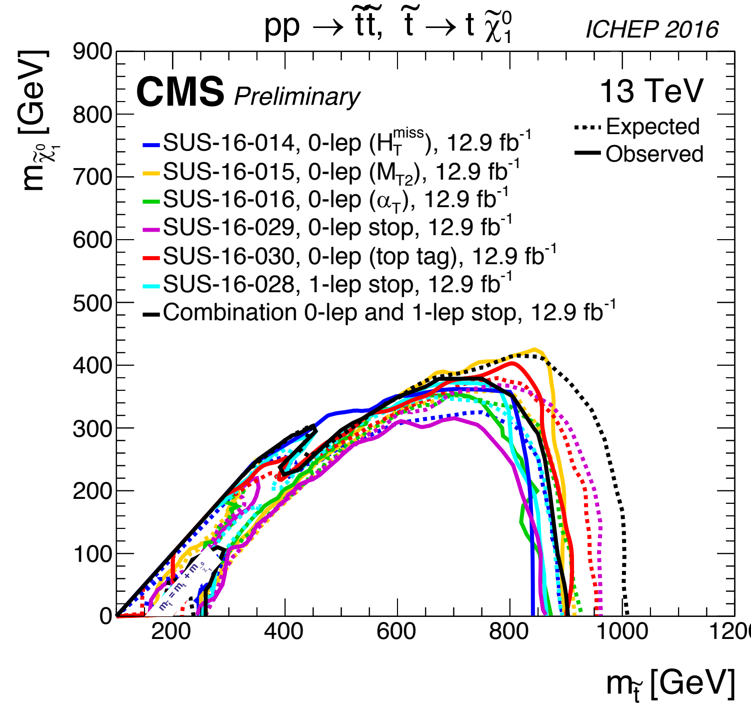
Wikipedia:



Frozen Energy Frontier

- Over decades energies increased regularly and illuminated new energy regimes
- "Standard" analysis were applied to look at the newly illuminated regimes

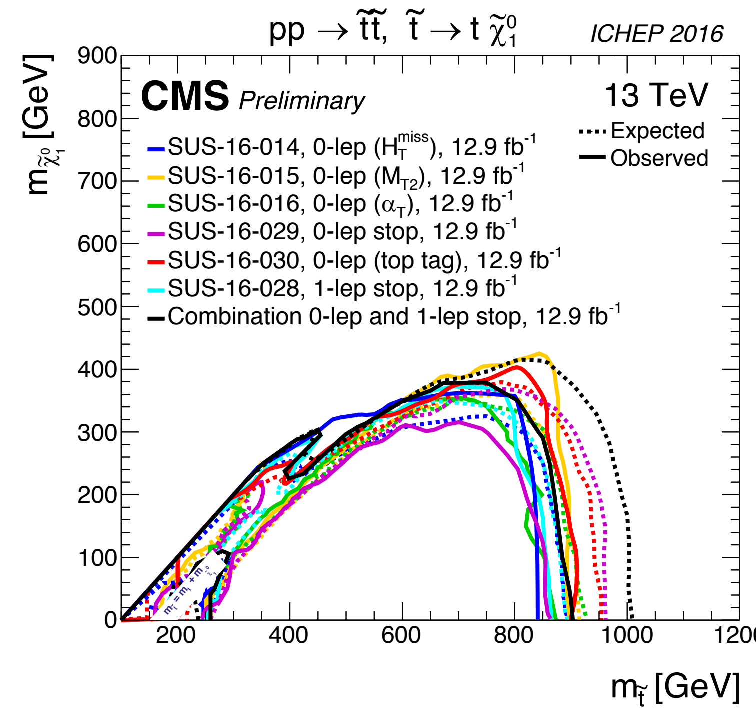
"standard" stops searches



Frozen Energy Frontier

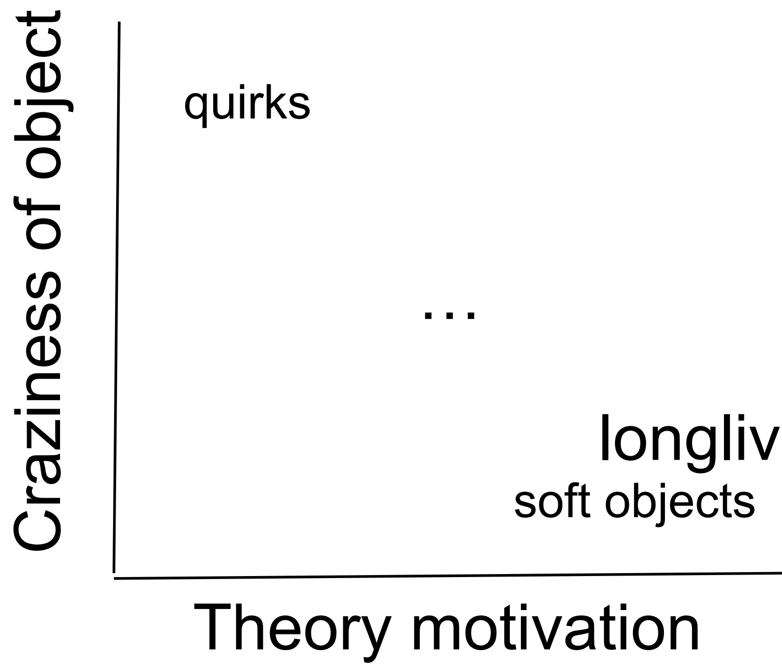
- Over decades energies increased regularly and illuminated new energy regimes
- "Standard" analysis were applied to look at the newly illuminated regimes
- If we cannot extend the energy reach (without waiting a decade), we need extend/improve ways to find new physics instead

"standard" stops searches



Experimentalist's Frontier

- Reconstruction and detector design optimized for standard objects
- Increasing efforts on "out of the box" objects, i.e. longlived, lepton jets, …



Experimentalists Frontier

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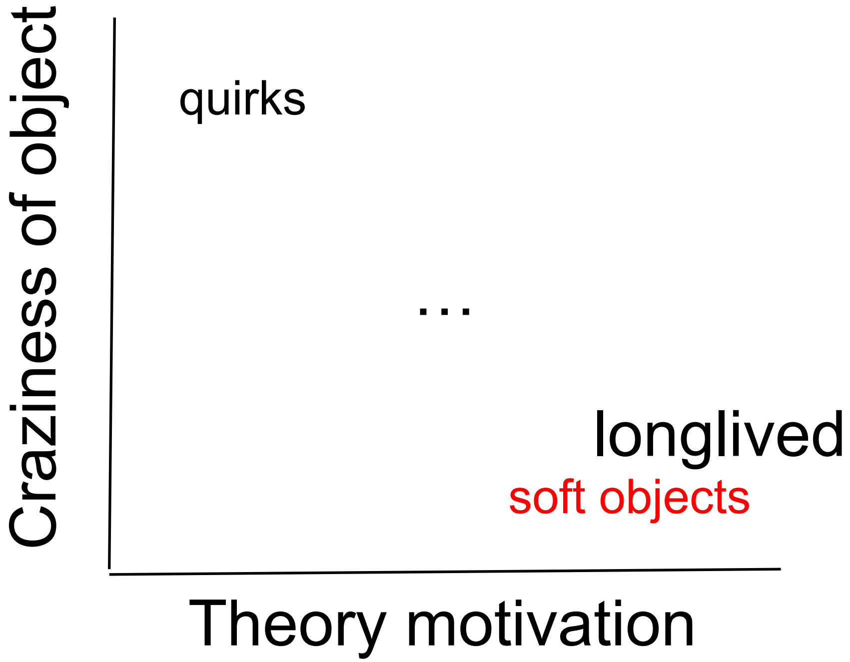
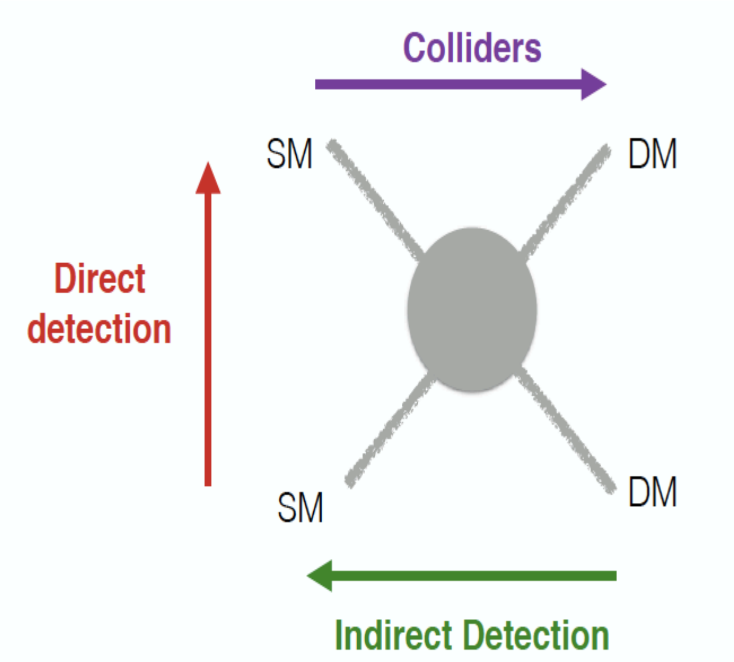


Focus on soft objects in this talk

soft OS leptons + MET

Dark Matter Friends



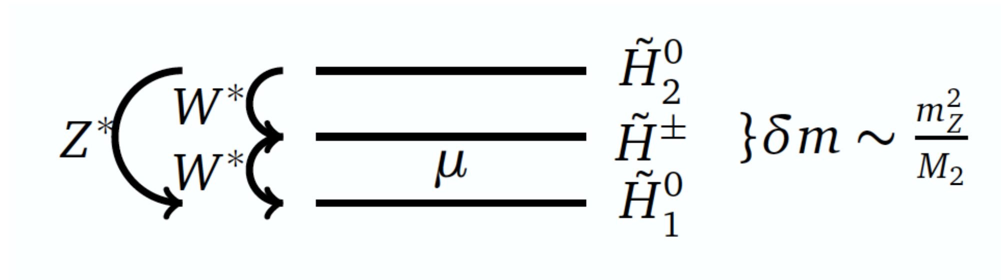
Simple picture suggests:
- Mono + MET
- Overlap of sensitivity

Look at a concrete (not crazy) example:
- SU(2) multiplet Wimp*

*inspired by Matt Reece talk SEARCH16

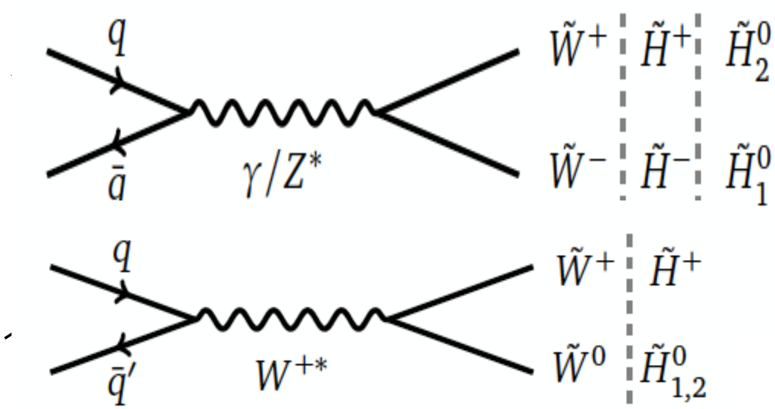
SU (2) multiples

e.g. higgsino



- Naturally *multiple* mass compressed states
- Produce W* and Z* in decay: mono + X +MET

LHC production



- Not acessable to direct detection due to heavier mass eigenstate. (H propagator for dir. dec.)
- No indirect as N2 are missing

- High complementarity between DM approaches

Natural Higgsinos

A "traditional" typical natural spectra

$$m_h^2 \simeq \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$$

Combining dependent terms

μ^2 and $\left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right)$ are $\sim m_Z^2$

"Other" natural spectra

H. Baer, et al. 2013

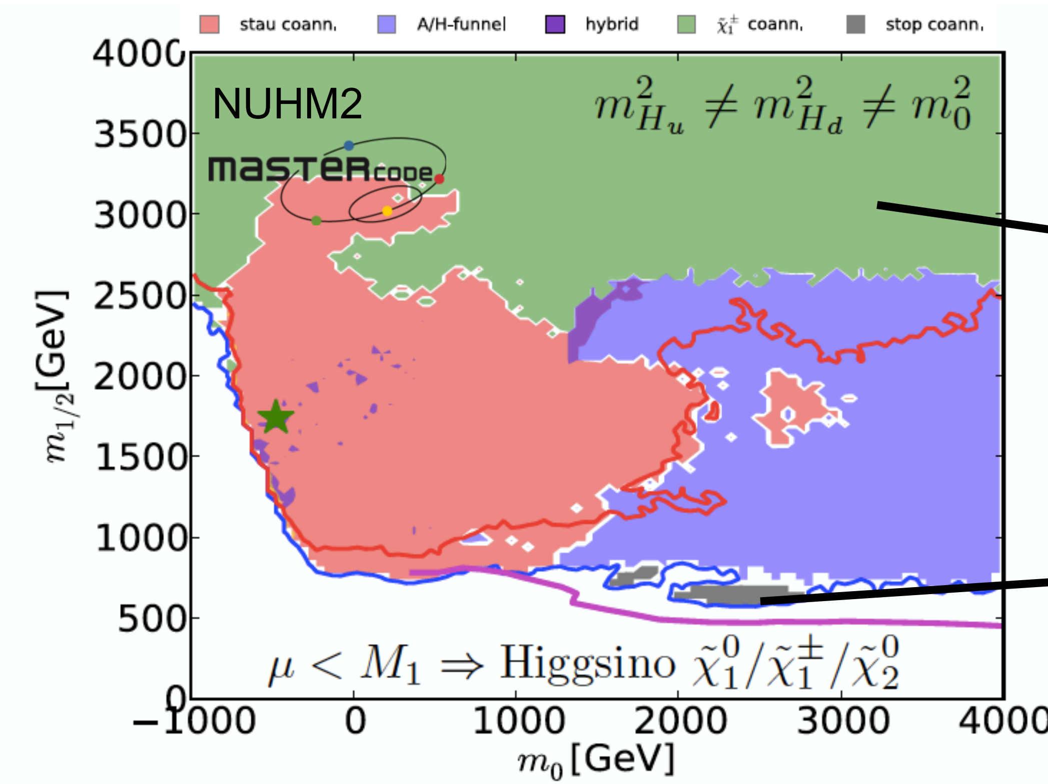
$m(\tilde{g}) < 2\ (4)$ TeV

$m(\tilde{t}) < 1\ (3)$ TeV

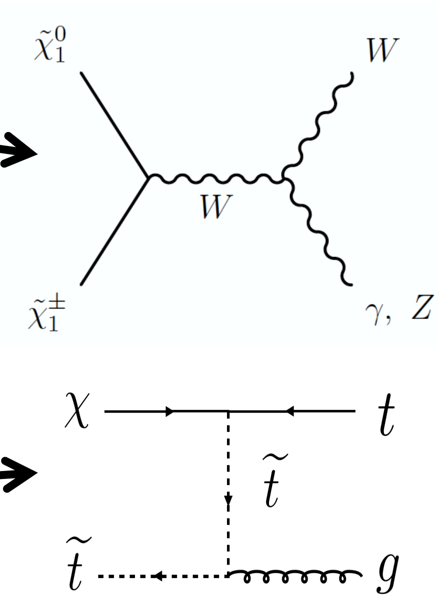
$m(\tilde{h}) < 300$ GeV

- Low $\tilde{h}$ masses are an ingredient of natural SUSY not yet challenged at LHC
- Likely mass-compressed light $\chi^0_2, \chi^\pm_1, \chi^0_1$ in natural SUSY

DM Relic density for SUSY WIMP

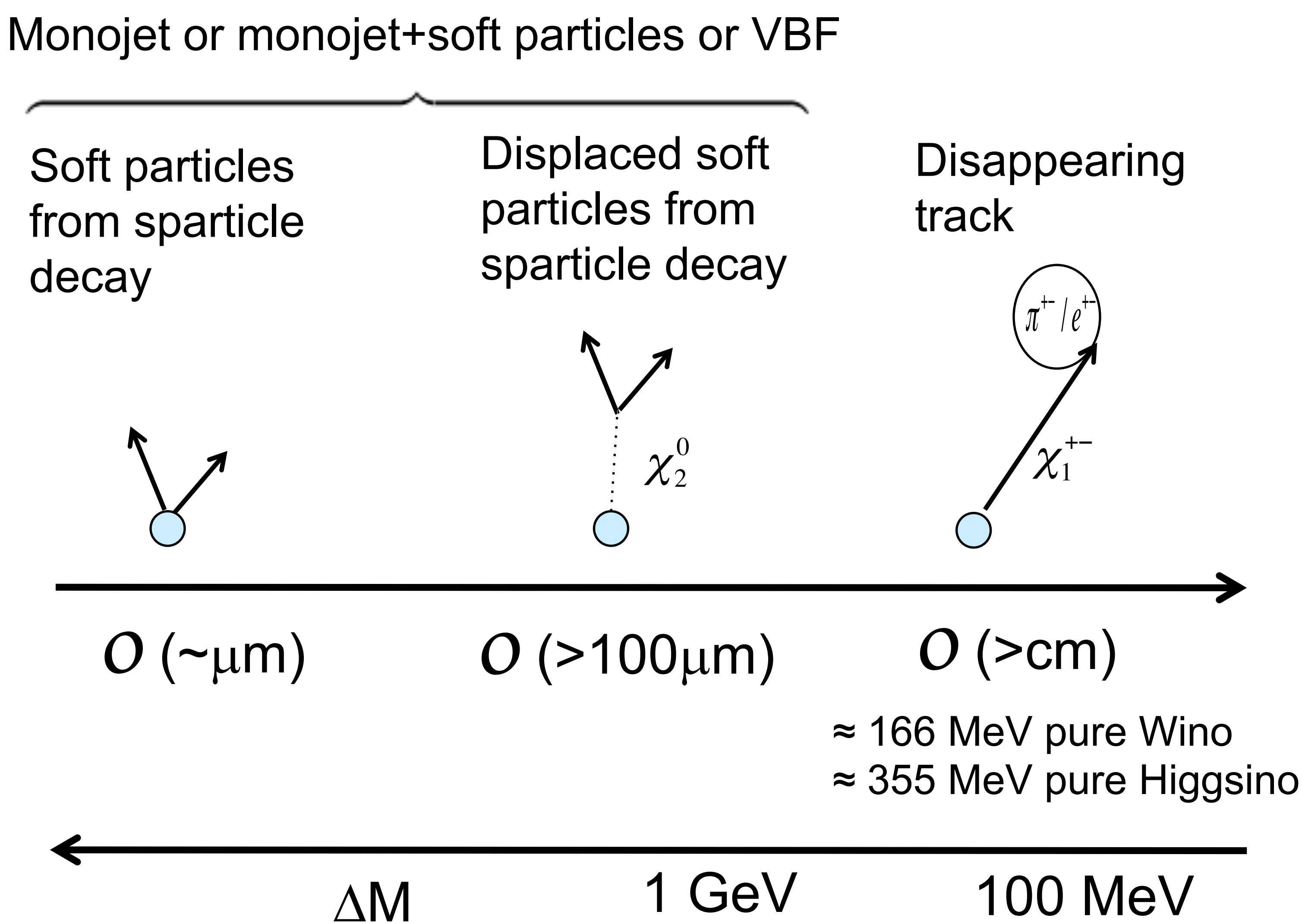


DM coannihilation



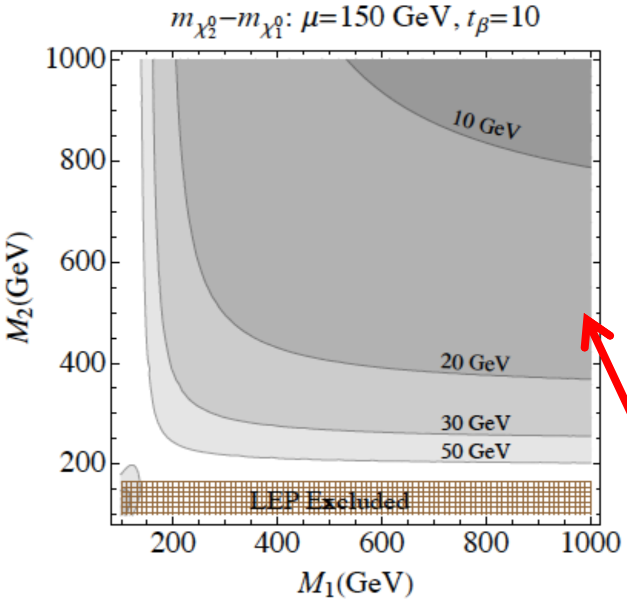
- Coannihilation regions are a mechanism to reduce DM and get right relic density. Occur often in e.g. pMSSM.
- Typically 10-30 GeV mass splitting between coannihilation partners, i.e. compressed spectra

Search strategies for compressed spectra



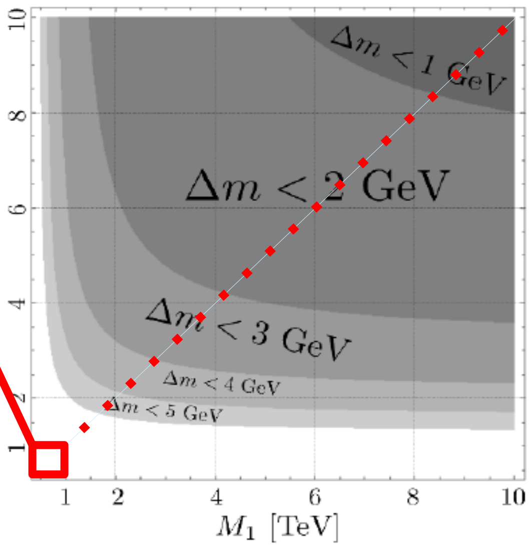
Higgsino spectra

arXiv:1401.1235



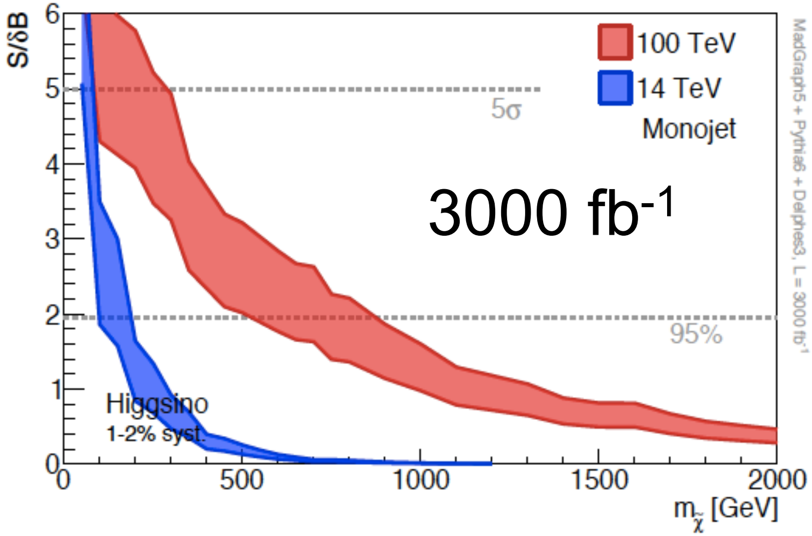
arXiv:1502.03734

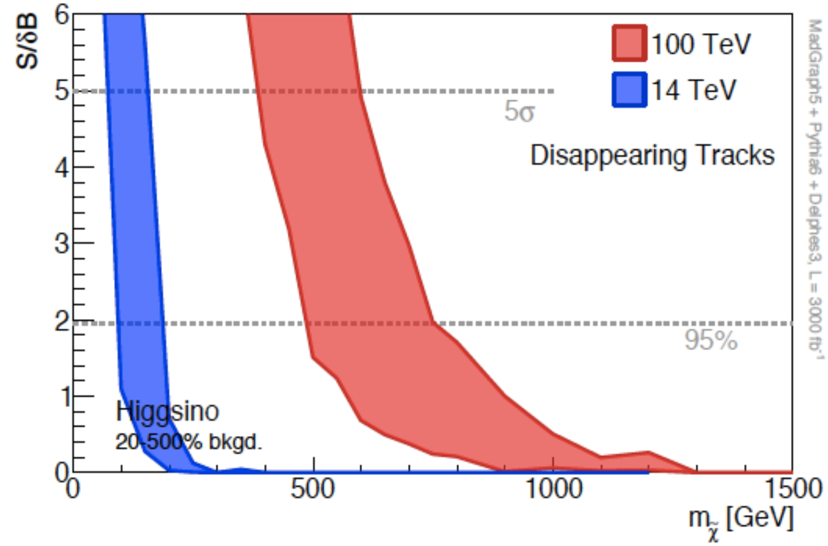
μ = 150 GeV, tan β = 10



Depending on M1 and M2 (Wino/Bino mass) splitting is a of the order few GeV for Higgsinos

Reach of Mono-jet and disa. track





Taking 300 GeV as naturalness boundary, only 100 TeV would seal the deal for pure higgsinos with Mono-jet or disappearing tracks.

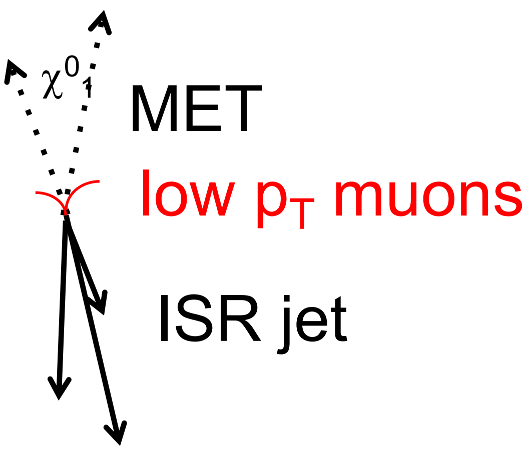
Sharing of the boost

In χ^2_0 restframe, p^* of decay products < $\Delta M/2$

- (N)NLSP heavy and close to LSP
- Soft OS leptons can be produced in NLSP decay(s)

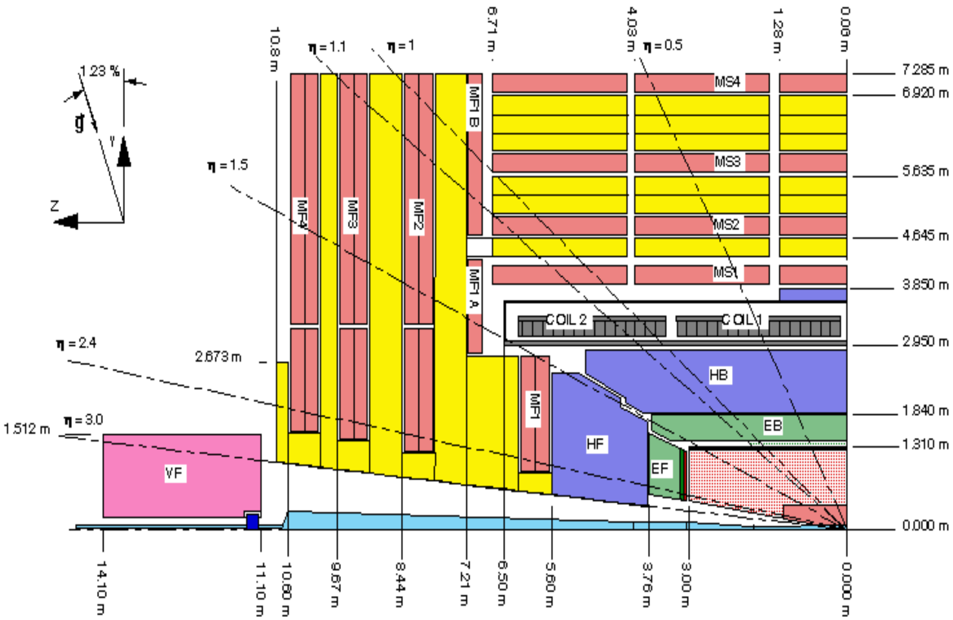
$$p_{\parallel}^{CMS} = \gamma(p_{\parallel}^{*} + \beta E^{*})$$

- Light particle (i.e. lepton): $p^*_{||} \sim E^*$
- Heavy particle (i.e. LSP): $p^*_{||} << E^*$



- Leptons get small boost compared to SU(2) WIMPs
- Requiring SFOS soft leptons with small M(ll) reduces up O(100.000) of background w.r.t mono-jet at same MET cut!

Experimental constraints for muons



Trigger, ***two*** muon stations:
~ 4 GeV in central region
Offline (one muon station):
~ 3.5 GeV in central region

- Magnetic field and energy loss set a minimum P_T to pass the magnet of ~> 3 GeV
- Forward we can go as low at 2 GeV

New soft μ + MET trigger

New trigger:

- MET
- 2 opposite sign muons
- $M(\mu\mu) < 60$ GeV

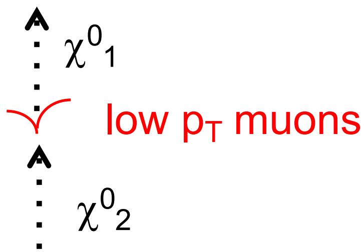
Offline requirements:

- MET > 125 GeV
- $p_T(\mu) > 5$ GeV

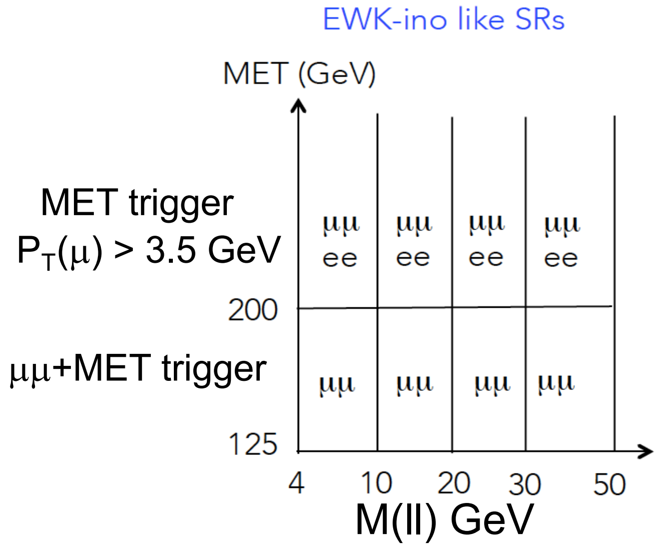
- MET > 125 GeV instead of 200 GeV
- Doubled sensitivity to compressed spectra

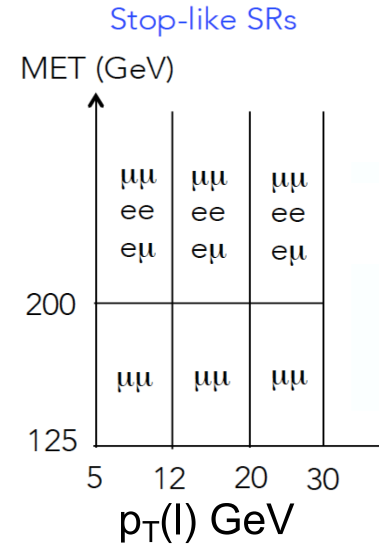
Soft opposite sign lepton search

SUS-016-25



$M(ll) < \Delta M(\chi^0_2, \chi^0_1)$





Search variables EWKino like:

- 0 GeV < $M_{\tau\tau}$ < 160 GeV
- $\max(M_T(l_{12}, MET)) < 70$ GeV
- Impact parameter < 100 μm
- Abs. and rel. isolation
- Veto b-tagged jets

Stop like (no Z*):

- No M_T requirement

Backgrounds:

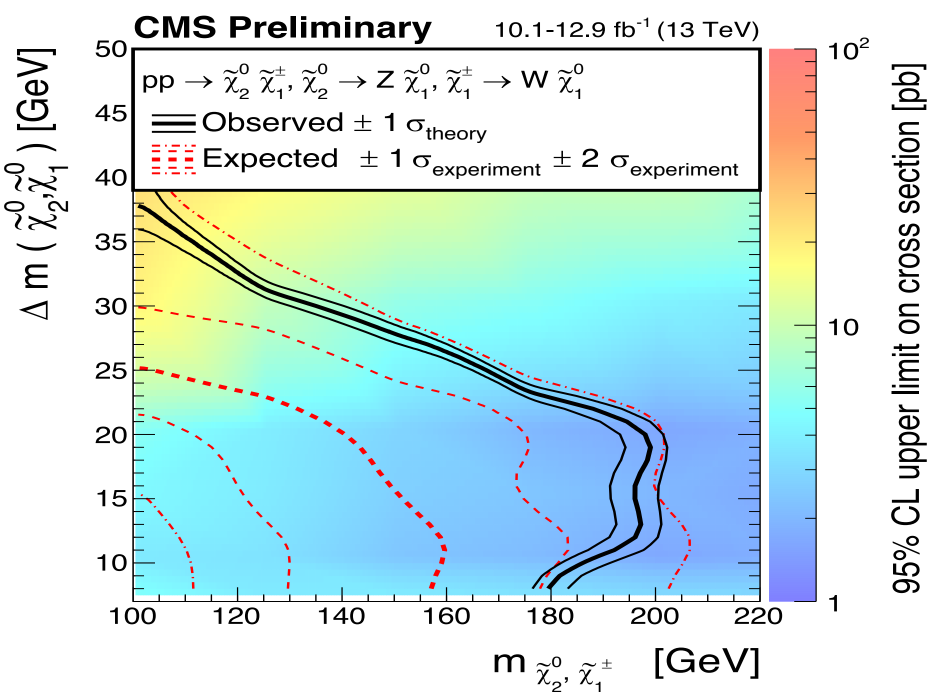
- W+jet (non-prompt), VV, tt(2l), DY->ll$\nu\nu\nu\nu$

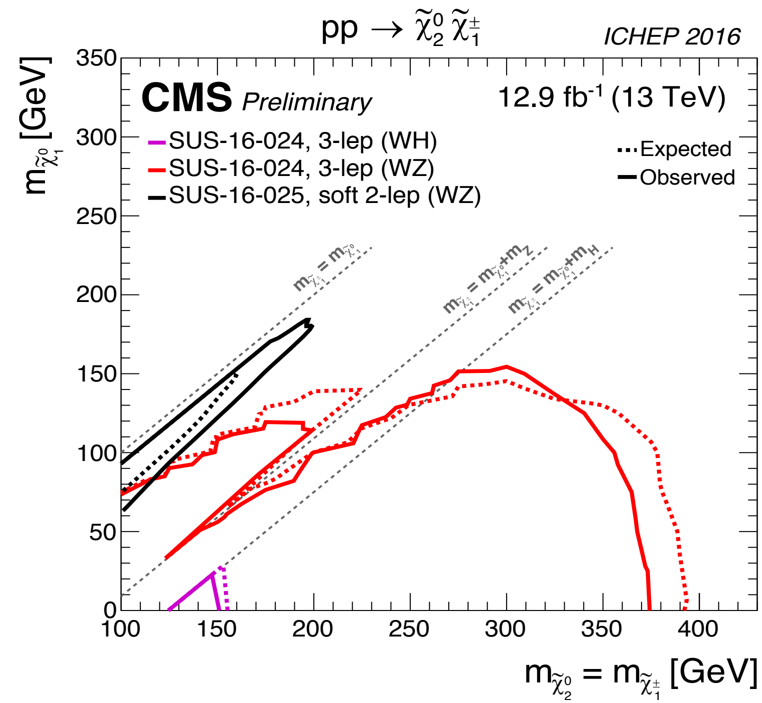
BKG prediction:

- "Tight-to-Loose" for "non-prompt"
- Control regions for tt, DY and validation checks for VV

Soft opposite sign lepton results

Pure Wino production x-sec

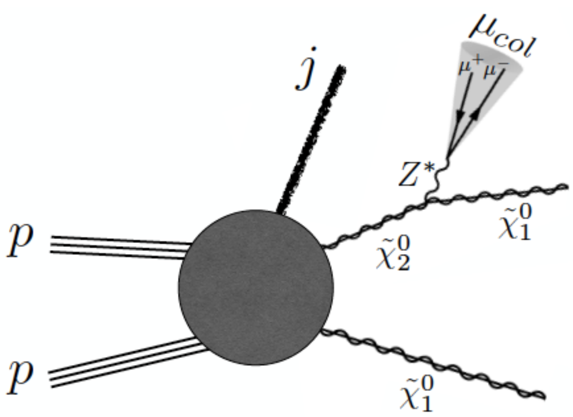


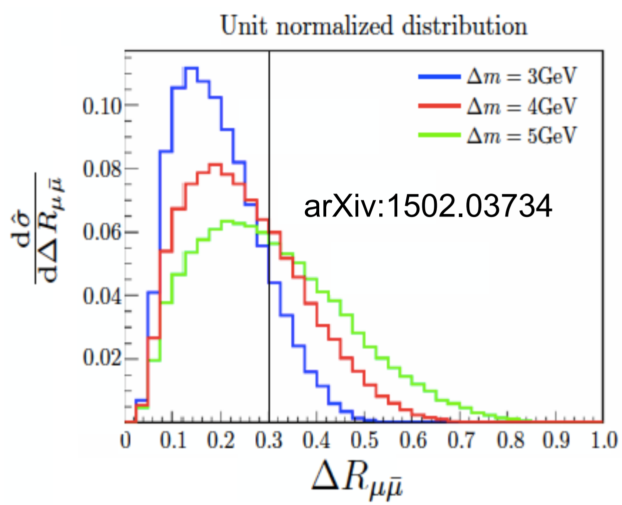


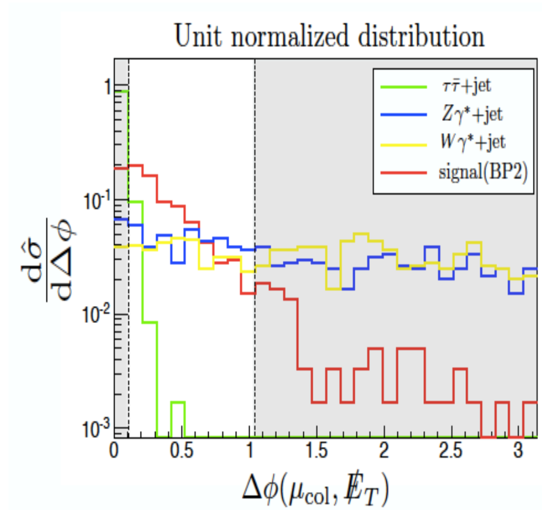
- First coverage of region for Δm from > 5 GeV to ~30 GeV
- Milestone for higgsino searches at the LHC (LEP~100 GeV)
- Preparing Higgsino interpretation for Moriond 2017

Can we go softer?

"Z* lepton jet" tagging







- Pheno studies suggest also for 3-5 GeV mass splitting soft muons similar to mono-jet
- Very complementary approach
- Eventually useful for dark photons

Can we go softer, *really*?

Theorists quite conservative

- Pheno-studies assumed $P_T(\mu)$ > 5 GeV, we go to 3.5 and can go lower in forward region.
- "Z* jet" R fixed, cold be scaled with P_T(boost)
- Do we need two muons, or one muon and a PF candidate (OS, low calorimeter response, P_T>1 GeV)?
- …

Can we go softer, *really*?

Theorists quite conservative

- Pheno-studies assumed $P_T(\mu)$ > 5 GeV, we go to 3.5 and can go lower in forward region.
- "Z* jet" R fixed, cold be scaled with MET (boost)
- Do we need two muons, or one muon and a PF candidate (OS, low MS, few calorimeter response, P_T>1 GeV)?
- …

My personal expermentalist's view (yes, we can):

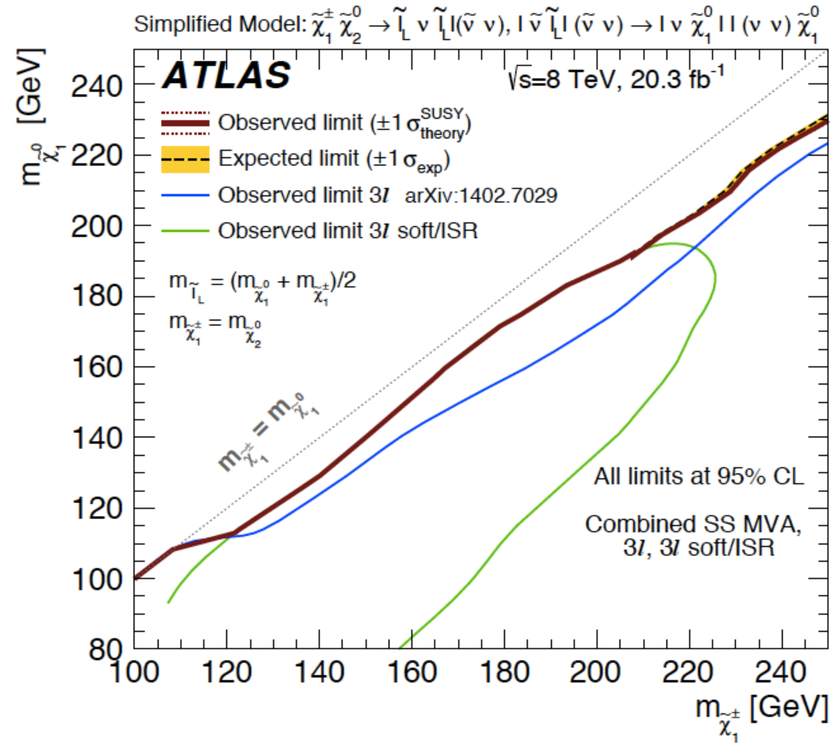
- We have a beautiful detector with track reconstruction starting at a few 100 MeV, muons of a few GeV …
- Modern machine learning simplifies reconstruction algorithm development (see e.g. b-tagging)
- Both, especially combined, I think we still have significant improvement potential

Multiple soft leptons

EWKinos

ATLAS EWKino search with three soft leptons

		Common		
ℓ flavor/sign		$\ell^{\pm}\ell^{\mp}\ell$, $\ell^{\pm}\ell^{\mp}\ell'$		
$p_{\mathrm{T}}^{\mathrm{lep}\,1}$		< 30 GeV		
b-jet		veto		
$E_{\mathrm{T}}^{\mathrm{miss}}$		> 50 GeV		
m_{SFOS}		veto 8.4–10.4 GeV		
SR	SR3ℓ-0a	SR3ℓ-0b	SR3ℓ-1a	SR3ℓ-1b
Central jets	no jets $p_{\mathrm{T}} > 50$ GeV		≥ 1 jet $p_{\mathrm{T}} > 50$ GeV	
$m_{\mathrm{SFOS}}^{\mathrm{min}}$	4–15 GeV	15–25 GeV	5–15 GeV	15–25 GeV
Other	$30 < m_{\ell\ell\ell} < 60$ GeV $m_{\mathrm{T}} < 20$ GeV	$30 < m_{\ell\ell\ell} < 60$ GeV	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}\,1) > 2.7$ rad $p_{\mathrm{T}}^{\mathrm{lep}\,1}/p_{\mathrm{T}}^{\mathrm{jet}\,1} < 0.2$	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, 3\ell) > 0.7\pi$ rad



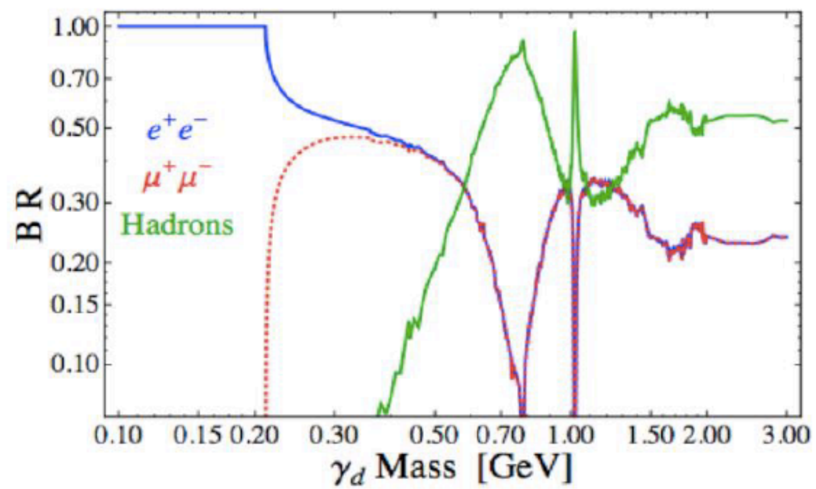
Soft tri-muon trigger helped:

- Only 7 fb^{-1} taken with soft tri-muon trigger at CMS in 2016
- ATLAS has soft tri-muon trigger

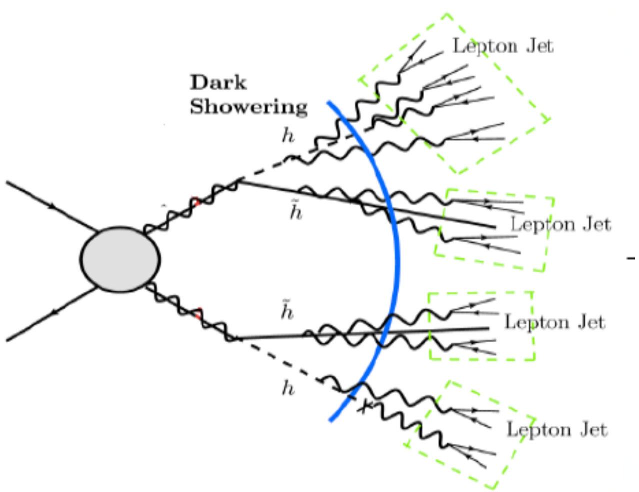
dark photons, … ?

Various BSM model predict few or many soft lepton:

- Soft OS lepton, eventually displaces (dark photon)
- Many lepton in shower that are than naturally soft (e.g. from dark pions/photons in dark showers)
- …



[arXiv:1002.2952]

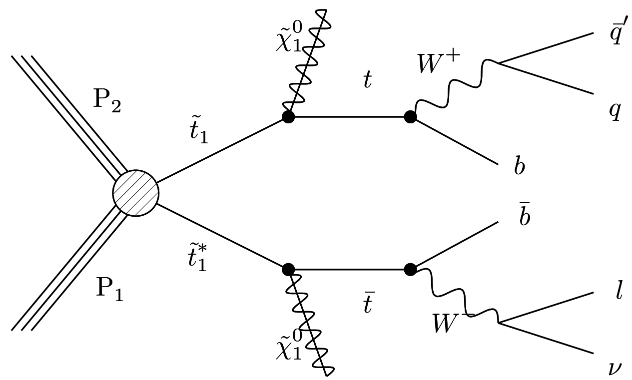


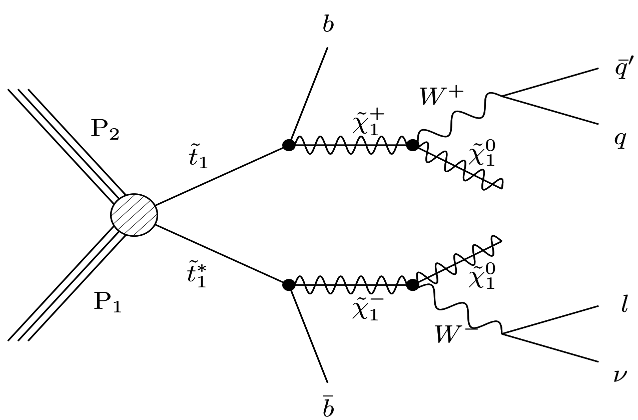
- Z*,W*,γ_d similar in dectetor
- Going soft might help also here (tri-soft-muon trigger for ATLAS)

soft b-tagging

$\tilde{t}$ searches

Strongly motivated by natural SUSY





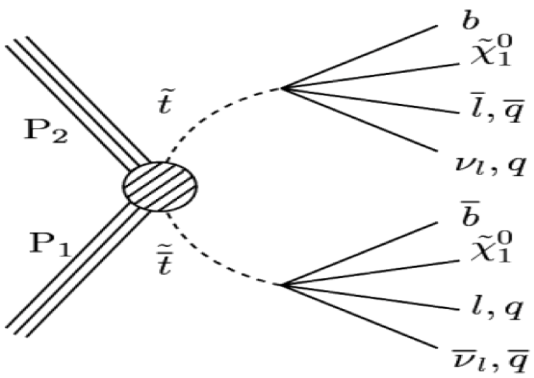
Strong motivation:

- Optimized targeted searches
- Difficult low MET regions:
  - $\Delta m(\tilde{t},\chi^0_1)$ small
  - $\Delta m(\tilde{t},\chi^0_1) \sim m(t)$
  - ➢ motivates special approaches

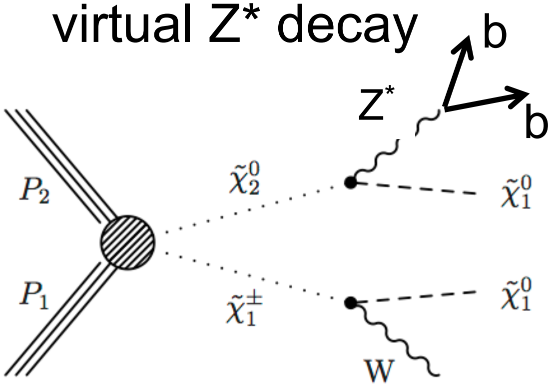
Low p_T(b)

SUS-016-29 (small Δm selection)

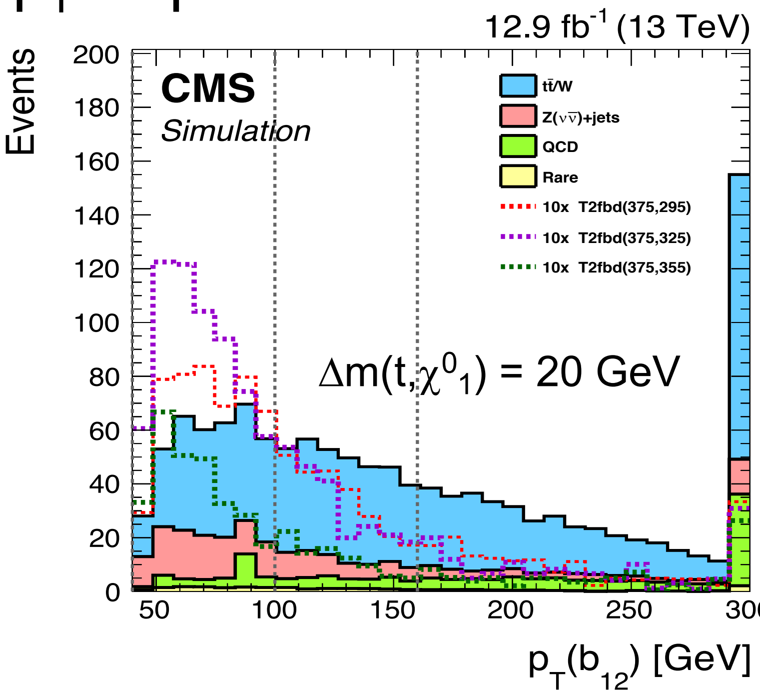
$\tilde{t}$ 4-body decay



virtual Z* decay

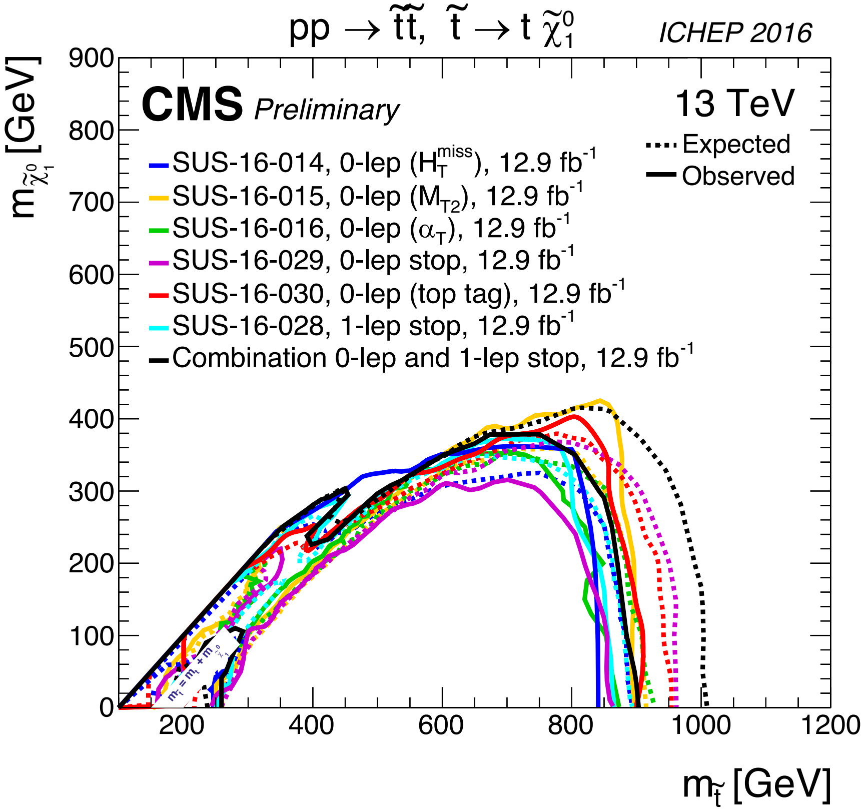


Small $\Delta m(t,\chi^0_1)$ or $\Delta m(\chi^0_1,\chi^0_2)$ can lead to low p_T b-quarks

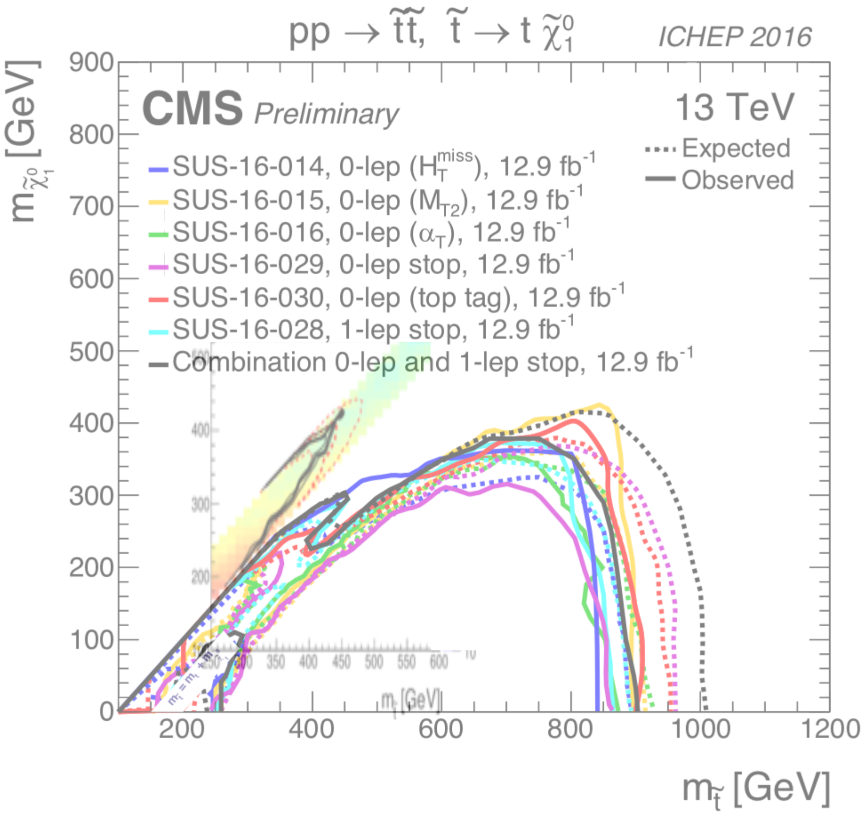


b-tagging used starts at **20** GeV

Small Δm $\tilde{t}$ results



Small $\Delta m\ \tilde{t}$ results



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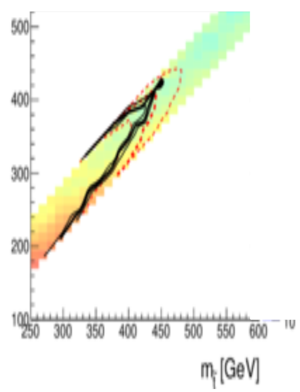
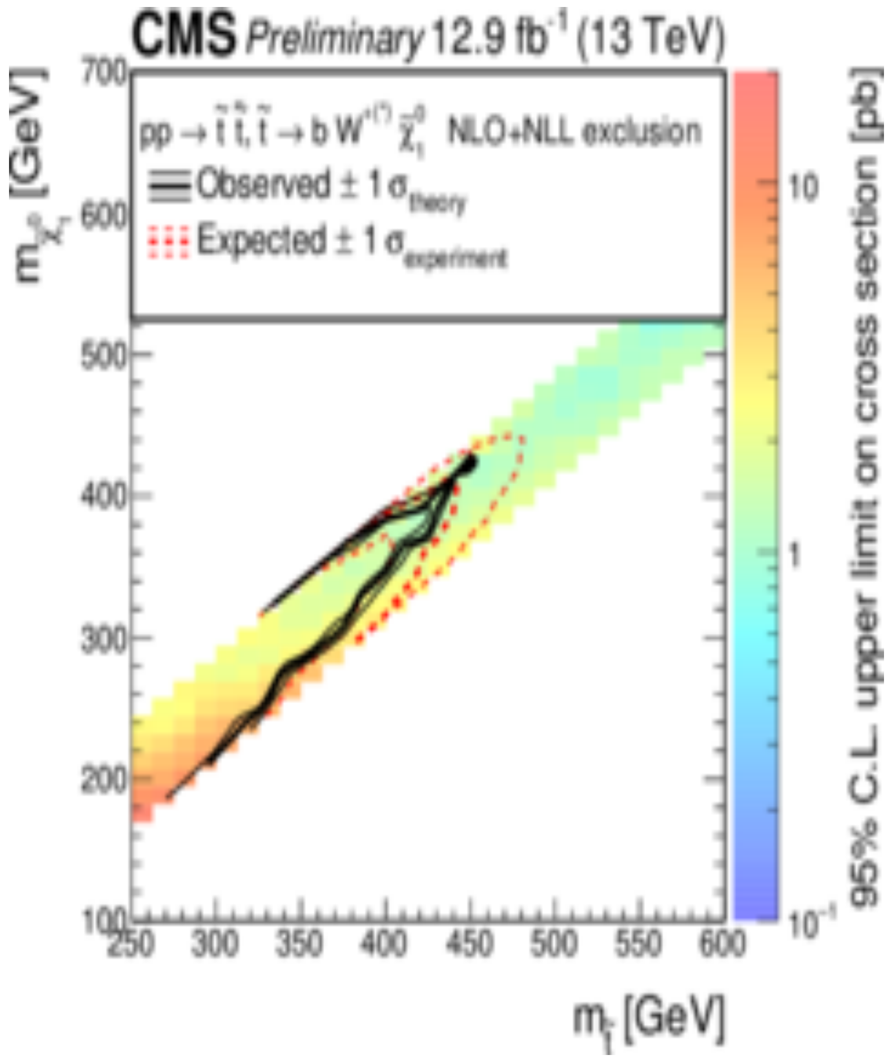


Small $\Delta m\ \tilde{t}$ results



- Significant Improvement w.r.t. default selection
- $m(\chi^0{}_1)$ excluded up to 400 GeV in $\tilde{t}$ to 4-body

Can we go softer

- Currently b-tagging used only down to **20** GeV
- Vertex and track identification in principle would allow to go significantly lower
- E.g. Track pre-selection for b-tagging tuned to 20 > GeV jets
- P_T cut off mainly by commissioning and historical aspects
- B-tagging can be done significantly lower in P_T

Summary

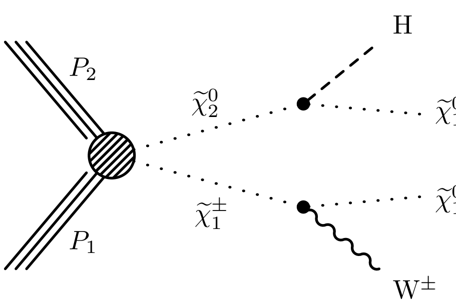
- One way to extend the reach to new physics is to extend reconstructed objects phase-space and type
- Various (non-crazy, higgsinos) SM extension lead to soft objects
- Using soft objects reaches new physics regions that else are not covered.
- The CMS detector capabilities allow still further improvements/triggers: softer multiple leptons, soft and eventually displaced lepton jets, softer b-tagging, …
- Extending the phase-space (extreme high or low P_T) is not only useful, but fun. It operates on the border of feasibility and is challenging.

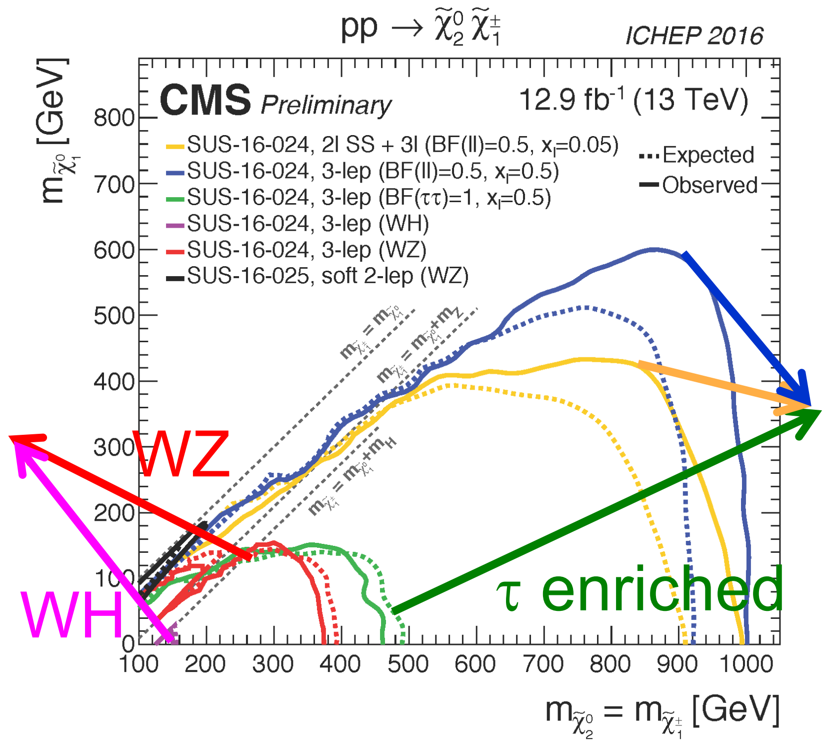
BACKUP

EWKino searches interpretation

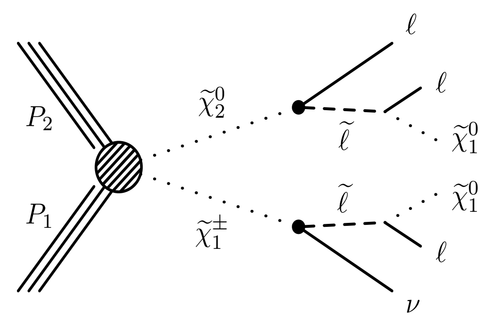
- Pure wino production cross-sections assumed
- Pure higgsino cross-section significantly smaller

Lower BR to l: decay via bosons, e.g.





High BR to l: decay via $\tilde{l}$, e.g.



Depending on scenario exclusions from small regions to 1 TeV

Targeted hadronic $\tilde{t}$ searches

Two hadronic searches

Search variables (SUS-16-029):

- Reject M_T(l-like,MET) < 100 GeV
- Top/W tagging (within 0.8 cone jets in R)
- Tagging start at p_T 400 (200) GeV for top (W)
- 4 categories [0,0],[0,1≥],[1≥,0], and [1≥,1≥] for [W,t]]tag
- Further binned in N_{btag}, N_{jet}, MET, $M_T(b_{12,}$MET)

Search variables (SUS-16-029):

- Reject M_T(l-like, MET) < 100 GeV
- Top tagging (1.5 cone in R)
- Tagging uses from ak4 jets
- Tagging binned from 1 to ≥ 3 top tags (i.e. gluino induced production)
- Further binned in N_{btag}, MET, and M_{T2}(tagged tops)

More focused in covering more decay modes and $\Delta m(\tilde{t},\chi^0_1)$ in $\tilde{t}$ pair production

More focused on top tagging and aiming at more $\tilde{t}$ production mechanism