Searches for direct stop pair production with the ATLAS detector

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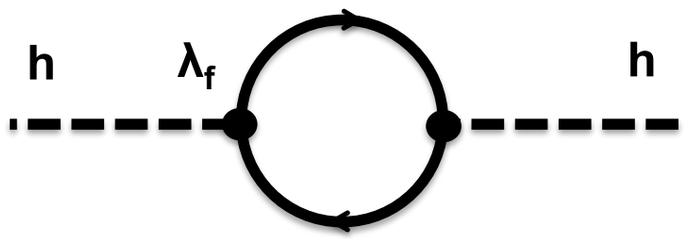
July30 2019 @ Northeastern University

Stop searches

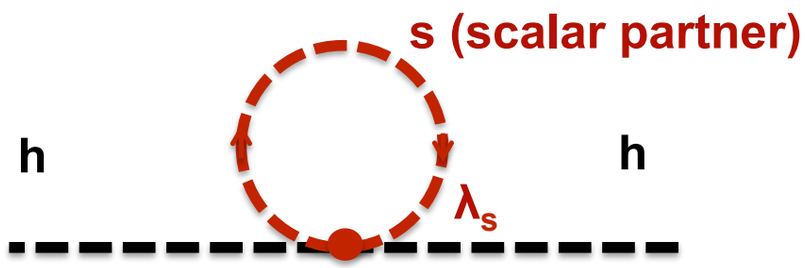
- A key ingredient to solve hierarchy problem
- In R-parity conserved (RPC) scenario, LSP can be a DM candidate



quadratic divergence

$$\Delta m_h{}^2 = -\frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \ldots$$

Λ: UV cut-off ~ Planck scale



$$\Delta m_h{}^2 = \frac{\lambda_s}{16\pi^2}\Lambda^2 + \ldots$$

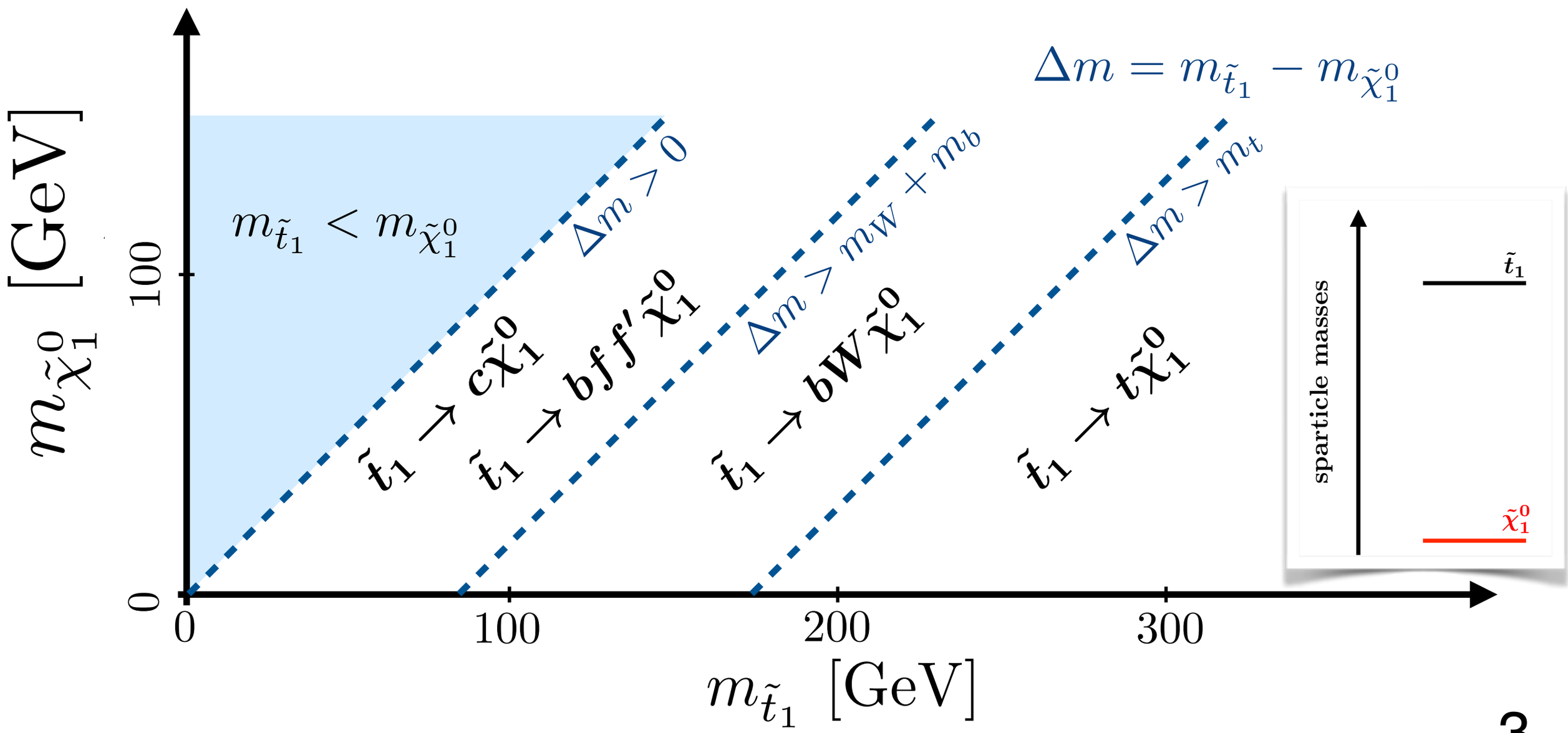
New!

New results (interpretations) with full run-2 data

Analysis	Date	Luminosity	Link
Soft b-hadron ID	**JUL-11-2019**	**139 fb^{-1}**	**ATLAS-CONF-2019-027**
Stop1L	**MAY-19-2019**	**139 fb^{-1}**	**ATLAS-CONF-2019-017**
StopZ/h	**MAY-17-2019**	**139 fb^{-1}**	**ATLAS-CONF-2019-016**
SS/3L (backup)	MAY-17-2019	139 fb^{-1}	ATLAS-CONF-2019-015
Sbottom multi-b (backup)	MAR-26-2019	139 fb^{-1}	ATLAS-CONF-2019-011

Stop searches (pure Bino LSP)

- All SUSY particles are considered to be heavy except for $\tilde{t}_1$ and $\tilde{\chi}_1^0$
- Different analysis techniques are required in different $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ regime



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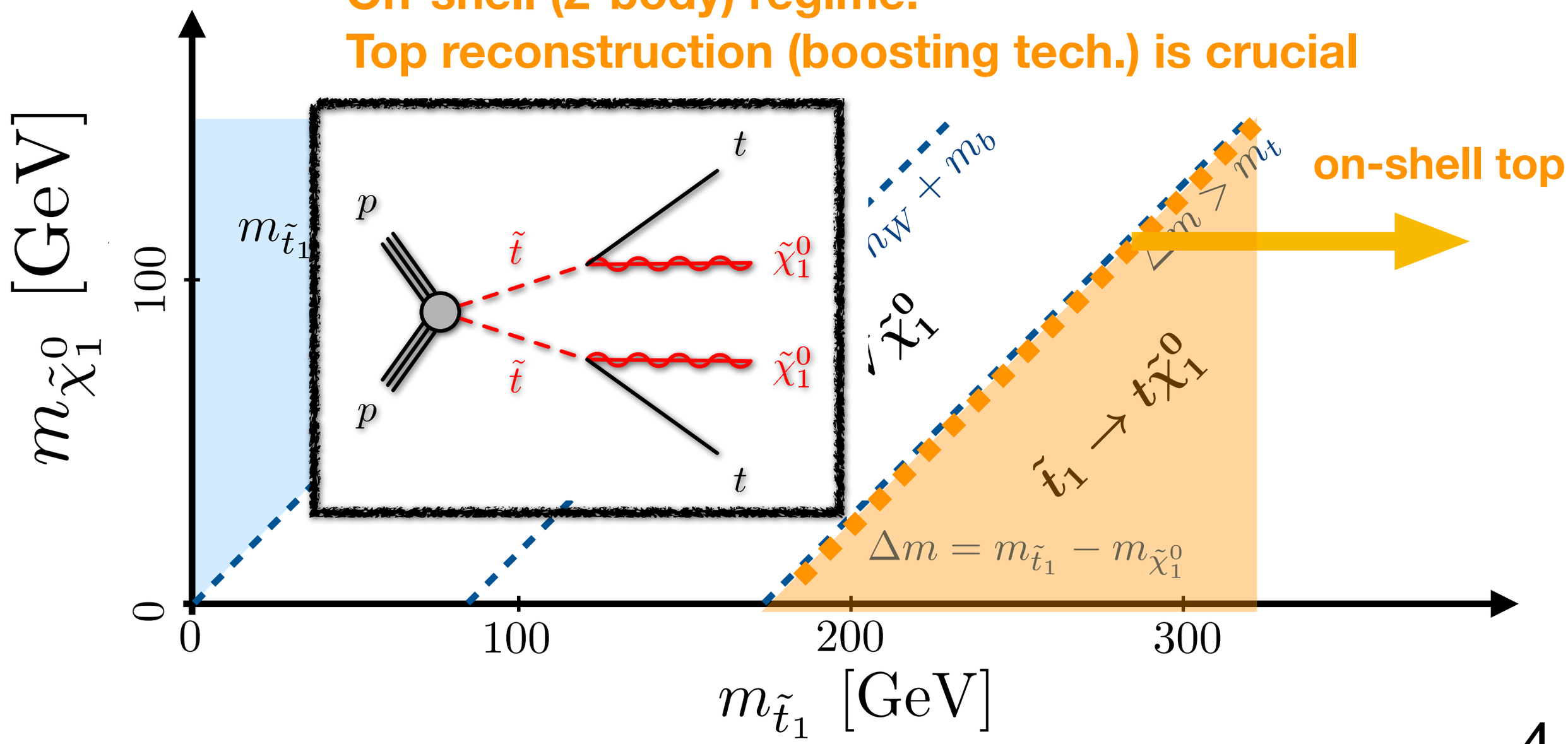
- **On-shell (2-body) regime:**
  Top reconstruction (boosting tech.) is crucial



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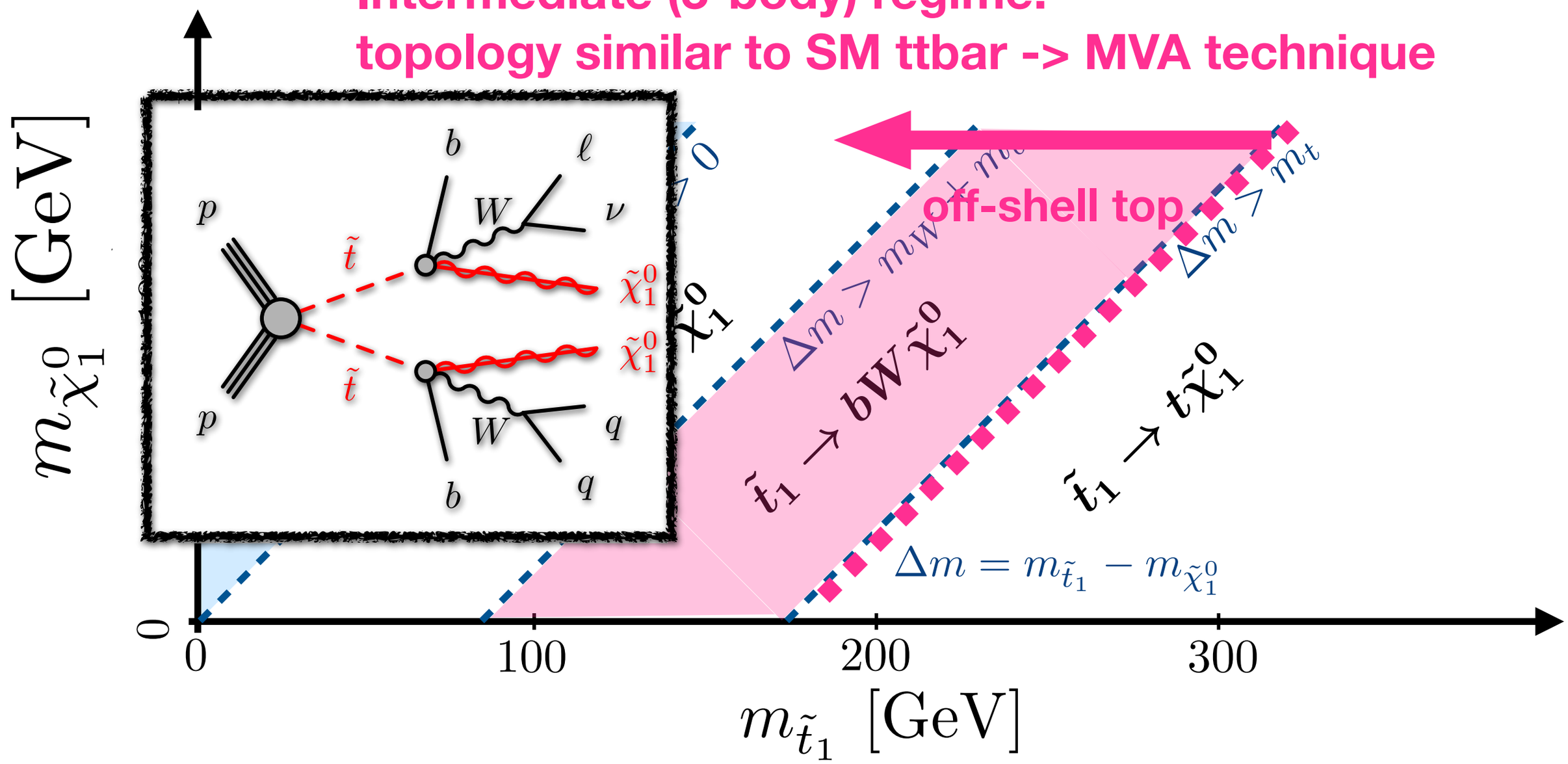
- Different analysis techniques are required in different $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ regime

▸ **Intermediate (3-body) regime: topology similar to SM ttbar -> MVA technique**



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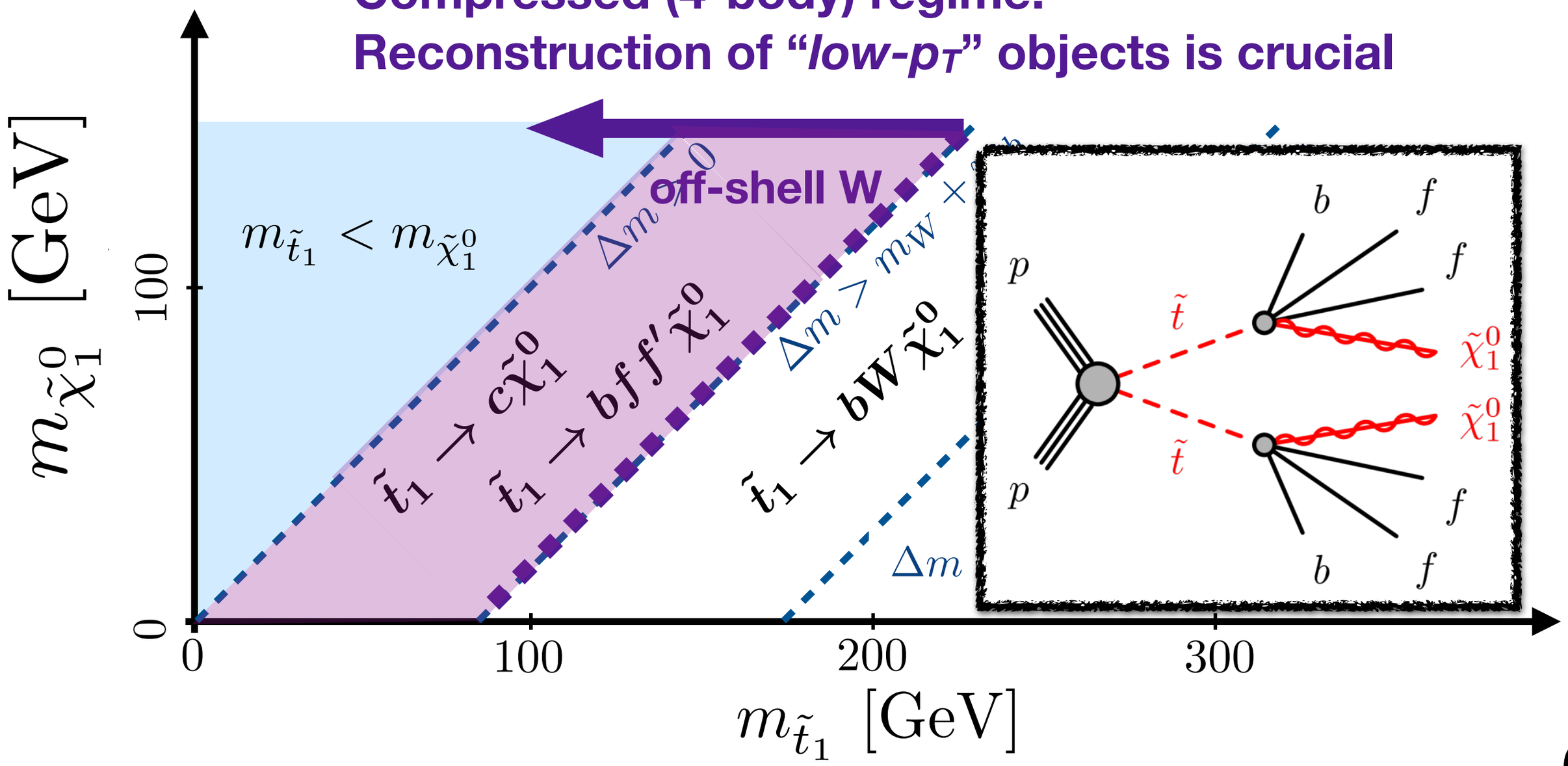
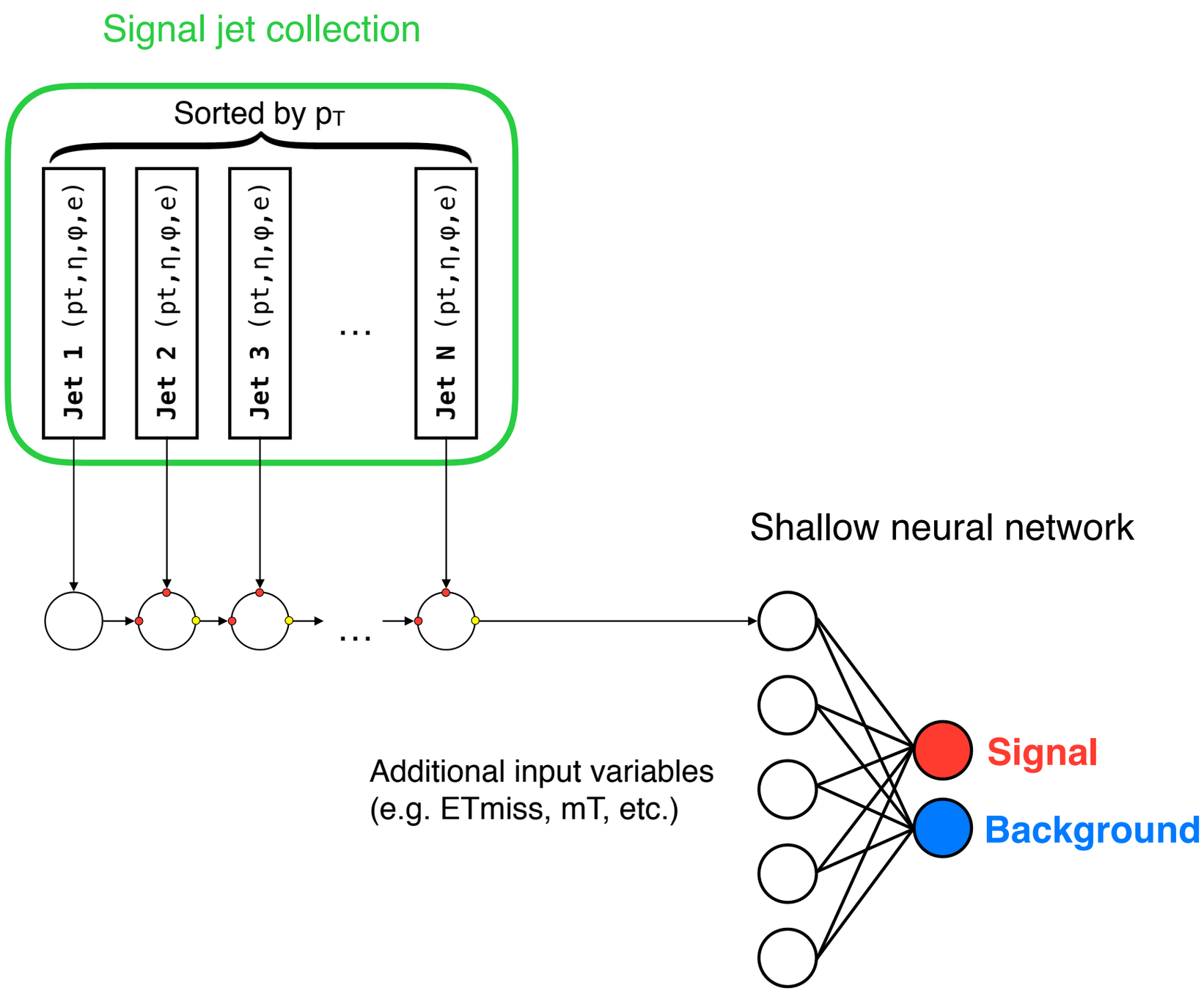
▸ **Compressed (4-body) regime:**
Reconstruction of "*low-p_T*" objects is crucial



3-body ML analysis

ATLAS-CONF-2019-017



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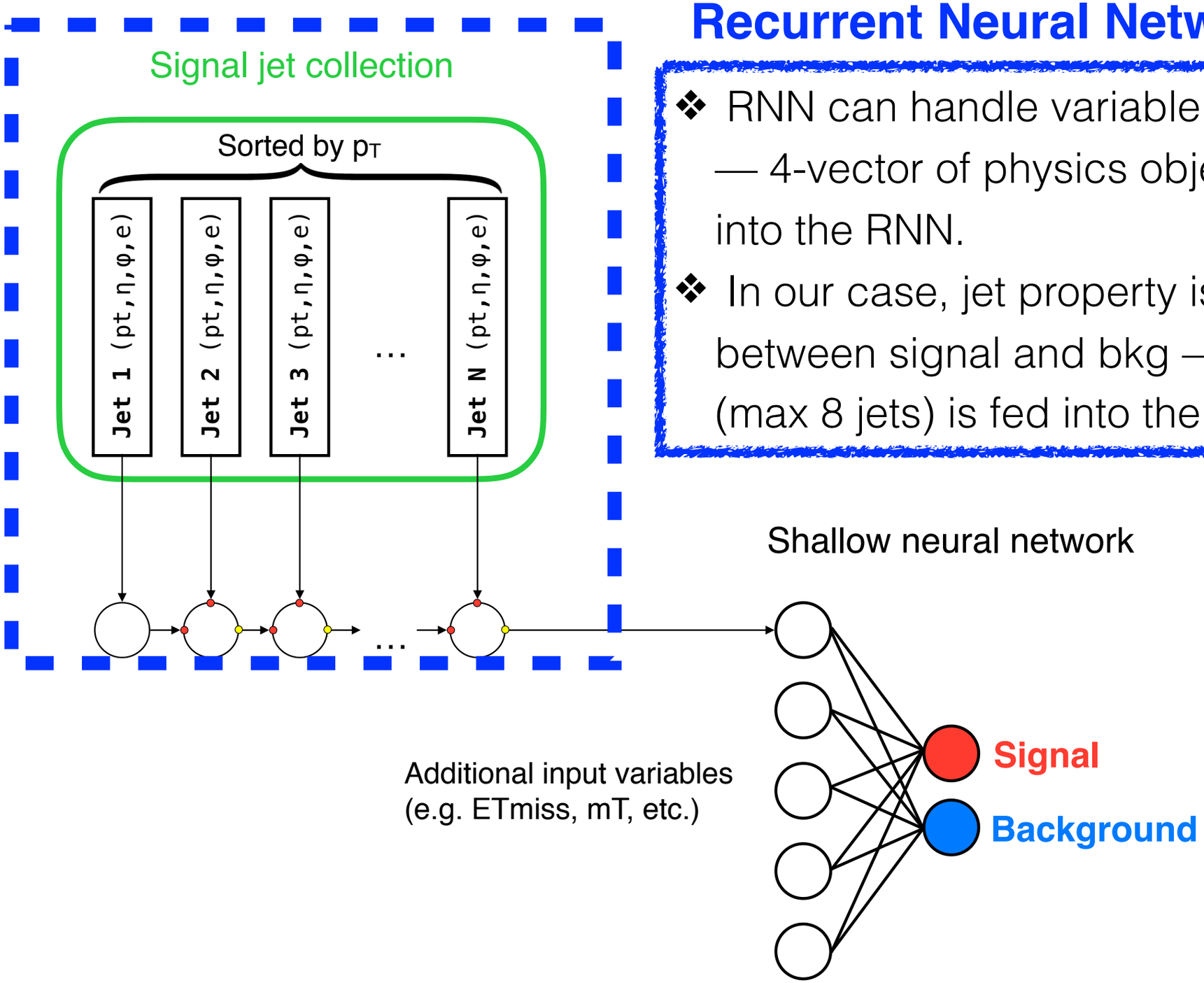

Recurrent Neural Network (RNN)

- ❖ RNN can handle variable length inputs — 4-vector of physics objects can be fed into the RNN.
- ❖ In our case, jet property is different between signal and bkg — jet collection (max 8 jets) is fed into the RNN.

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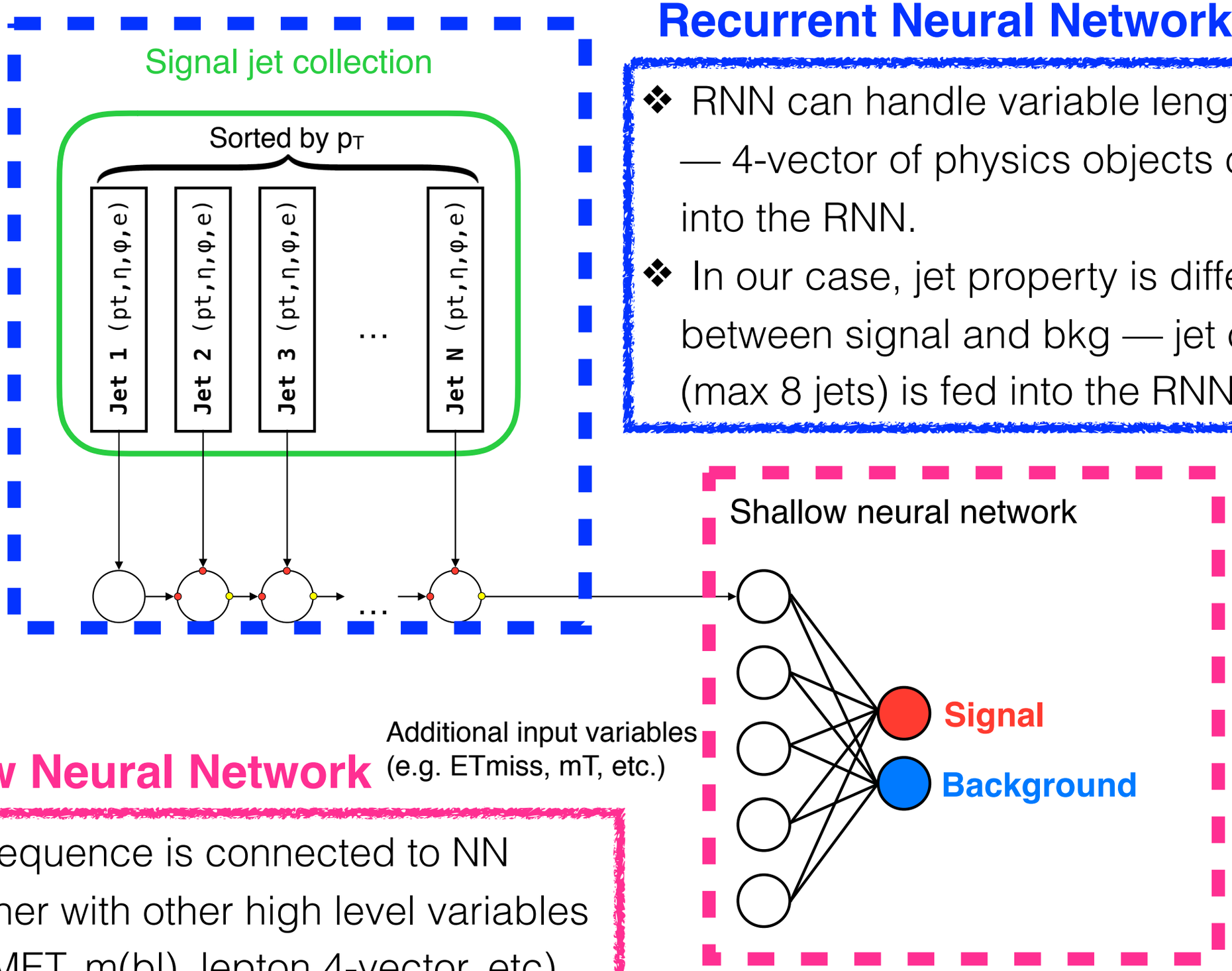

Shallow Neural Network

- Jet sequence is connected to NN together with other high level variables (MT, MET, m(bl), lepton 4-vector, etc)

3-body ML analysis (cont'd)

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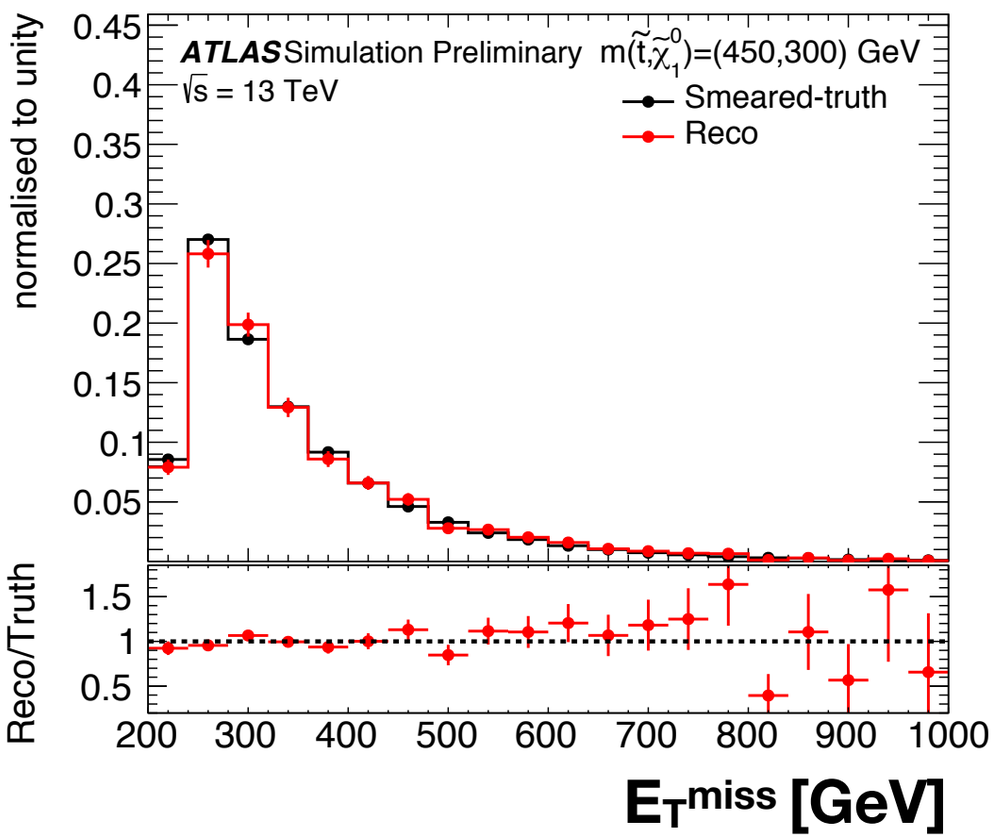
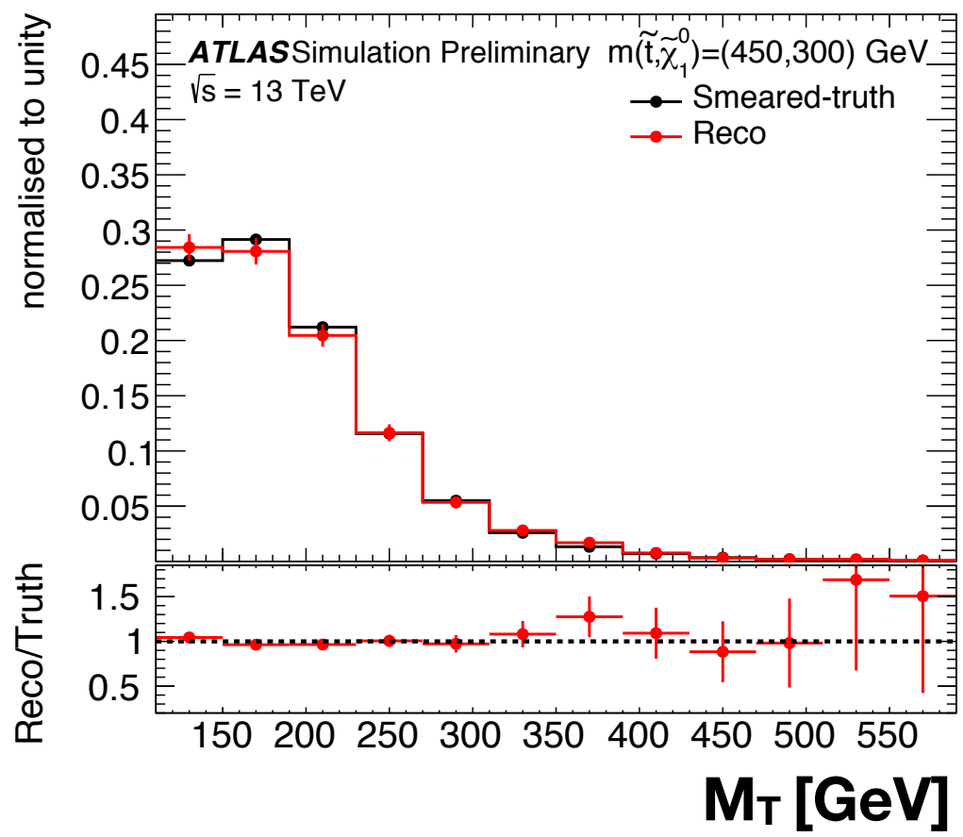
Truth assisted ML training





- **Training statistics was found to be very important!**
- Training performed with particle-level signal events (TRUTH) applying a dedicated smearing procedure. Training statistics enhanced by a factor of 75 (100k -> 7.5M)
- Careful validation for all input variables comparing to "Reco" distributions.

3-body ML analysis (cont'd)

ATLAS-CONF-2019-017

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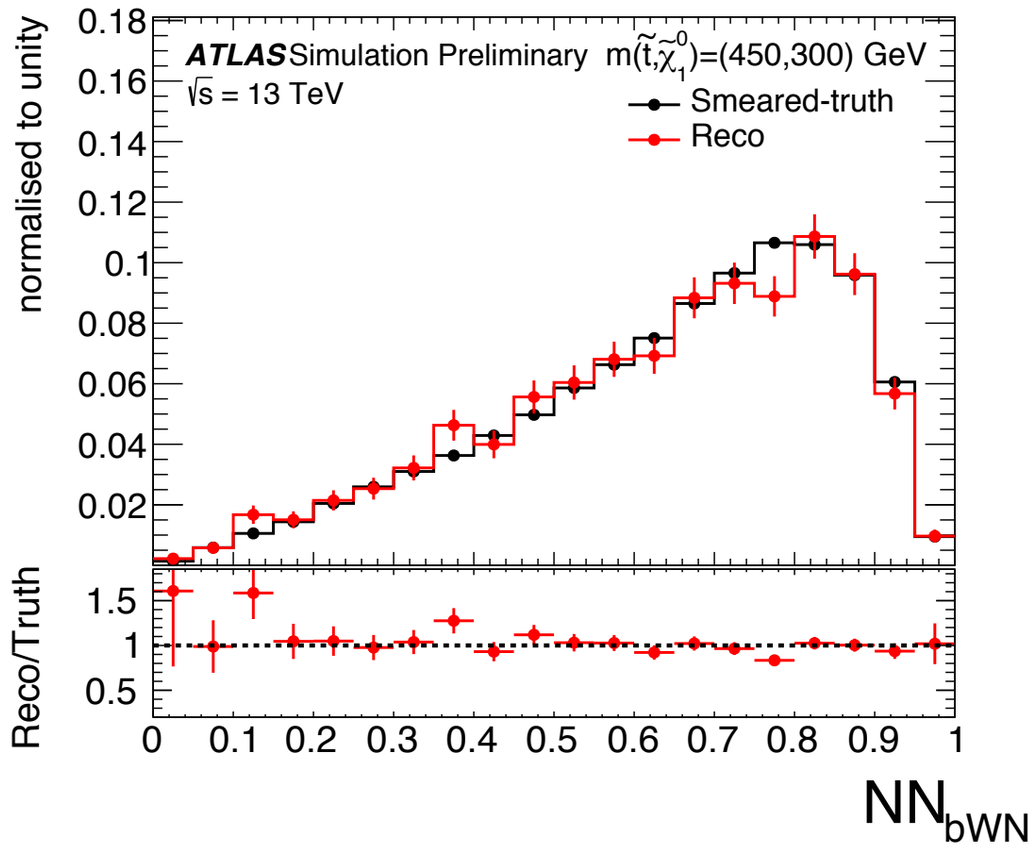

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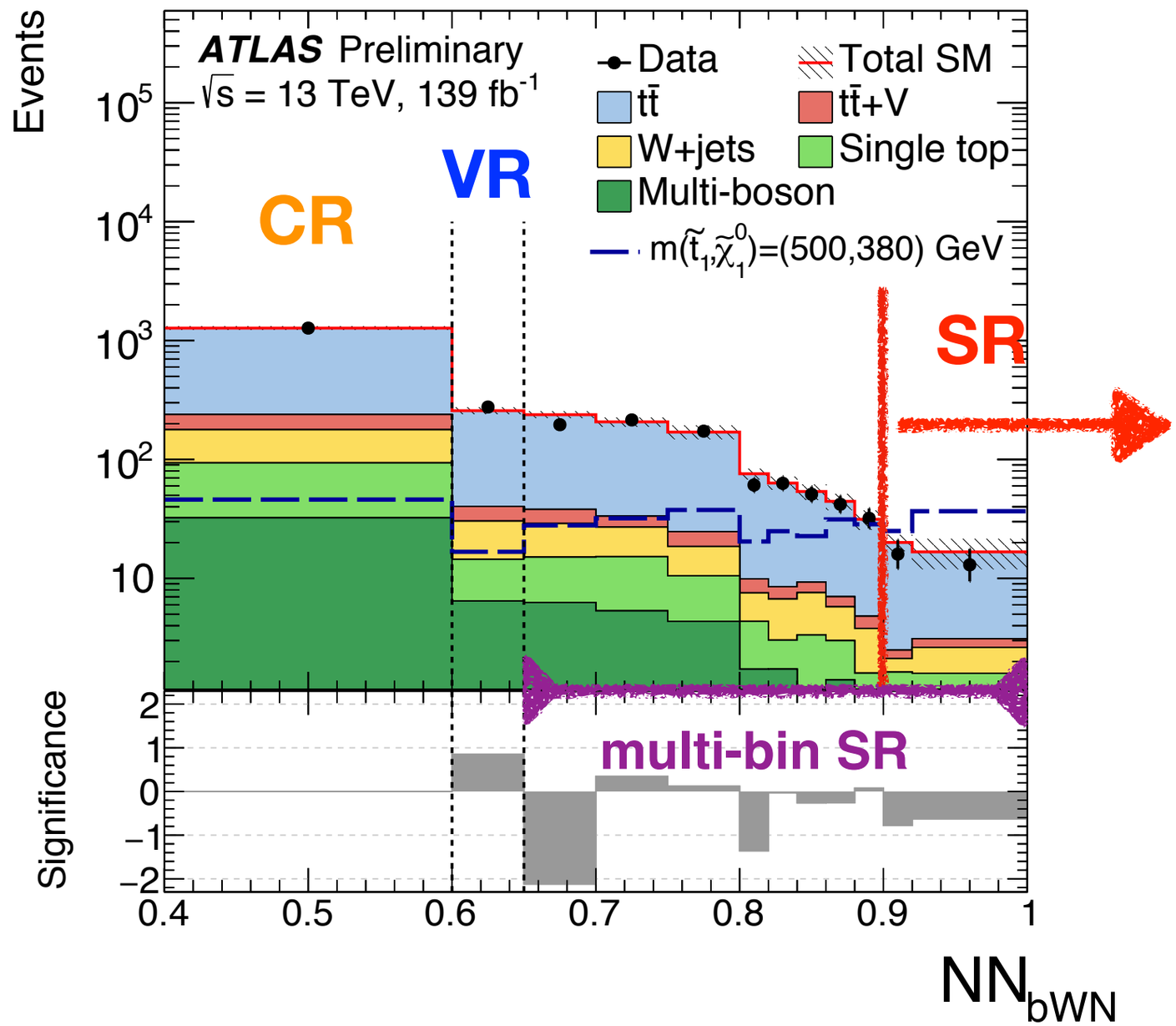
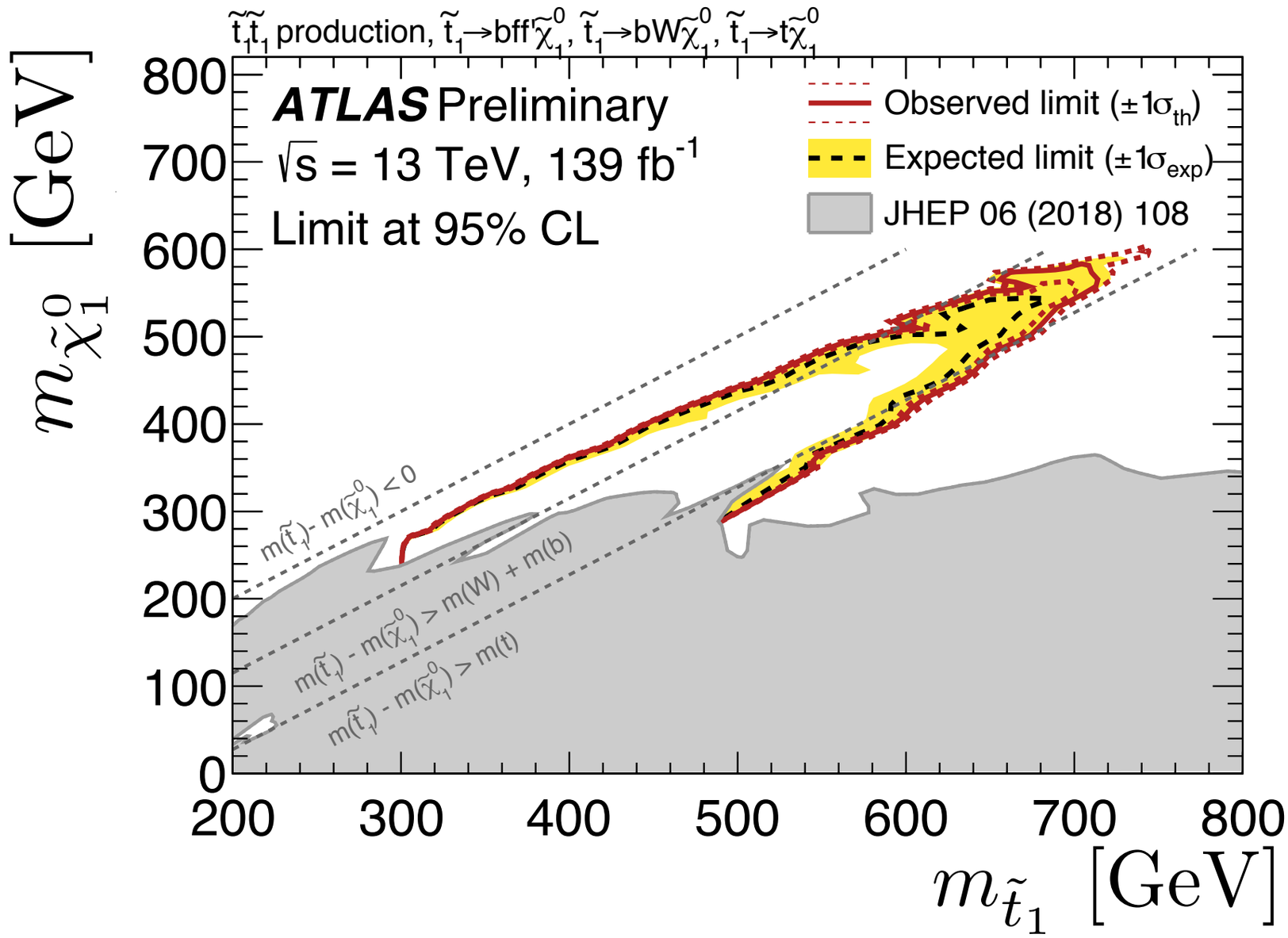


- Signal region (**SR**) defined as the high NN output score (NN_{bWN}>0.9).
- Dileptonic ttbar events are normalized in control region (**CR**), and the variable extrapolation tested in validation region (**VR**).

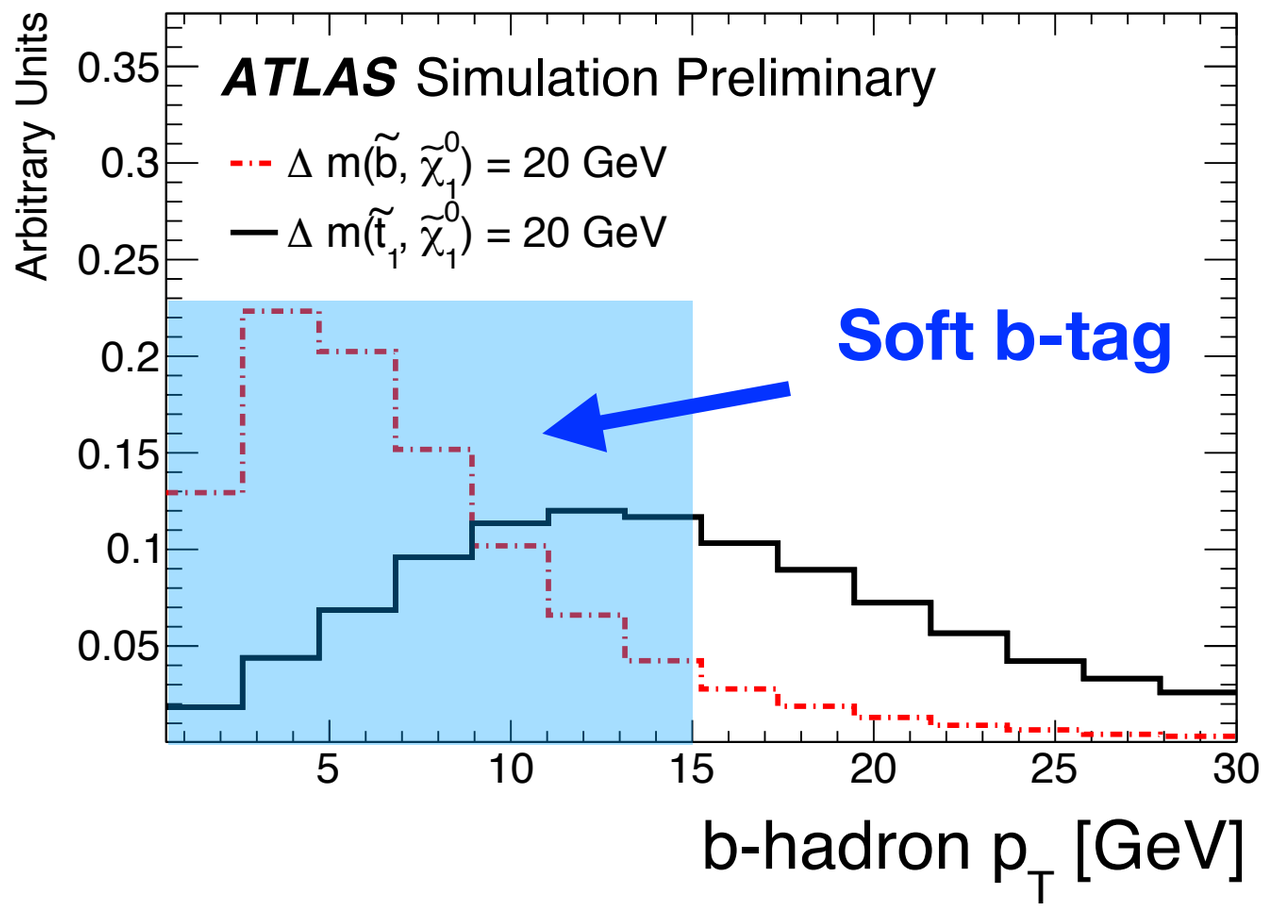
3-body ML analysis (cont'd)

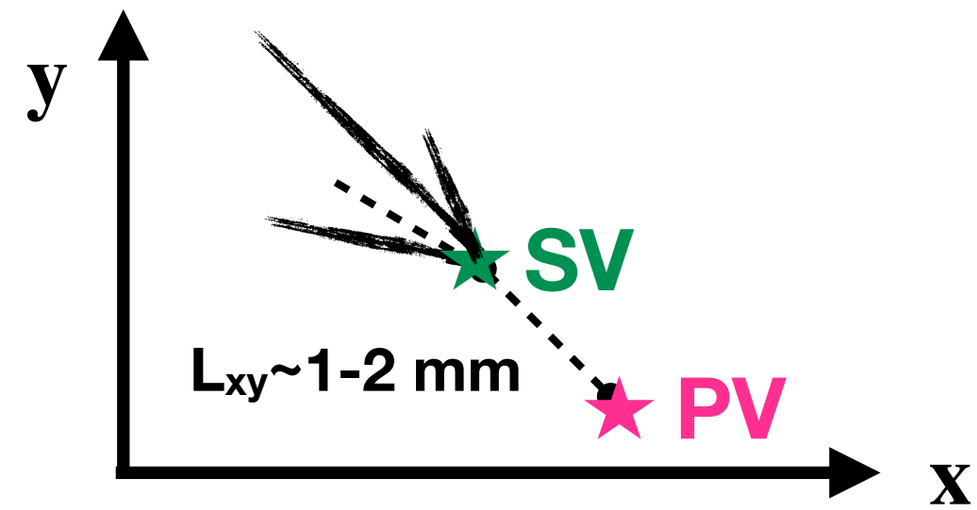


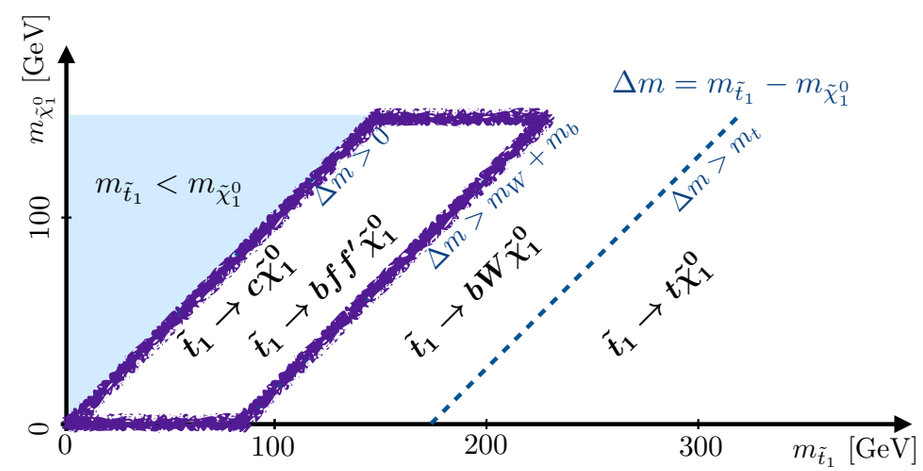
- Set limits to masses of stop and LSP using multi-bin SR (10 bins).
- The limit significantly extended; $m(\tilde{t}_1)$~700GeV.

Soft b-hadron ID for 4-body

ATLAS-CONF-2019-027







- Low-p_T b-hadron reconstruction (out of standard b-tag coverage) provides additional handles to reduce overwhelming V+jets background.
- **Secondary vertex (SV) tagger** developed for soft b-hadron identification starting from track selection, followed by vertex selection.

Soft b-hadron ID for 4-body

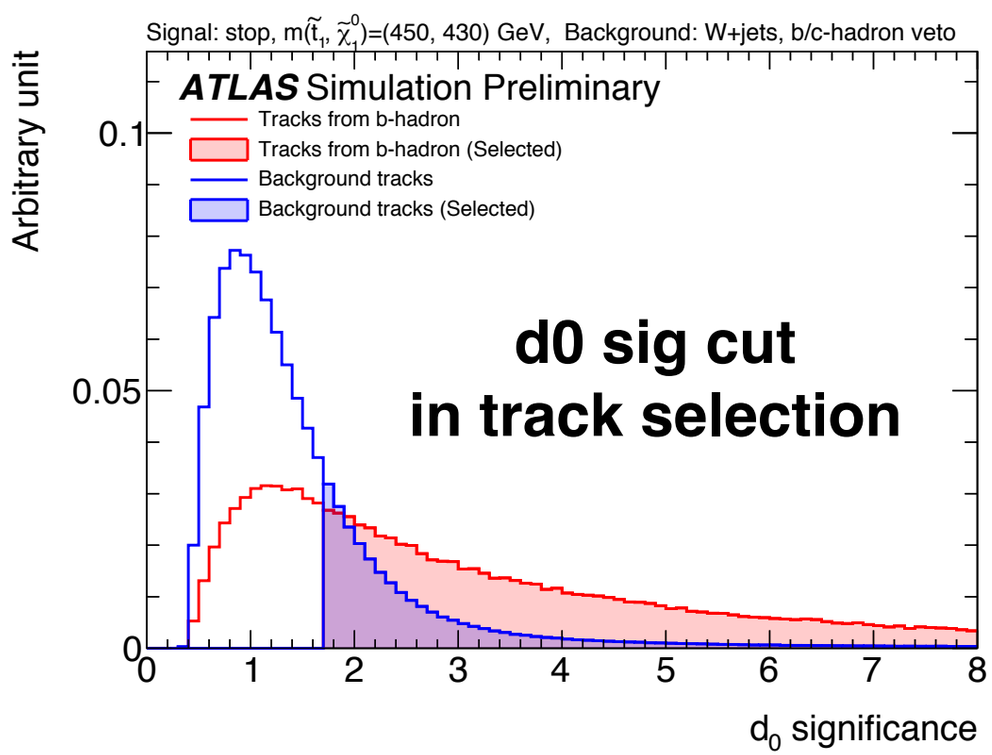
ATLAS-CONF-2019-027

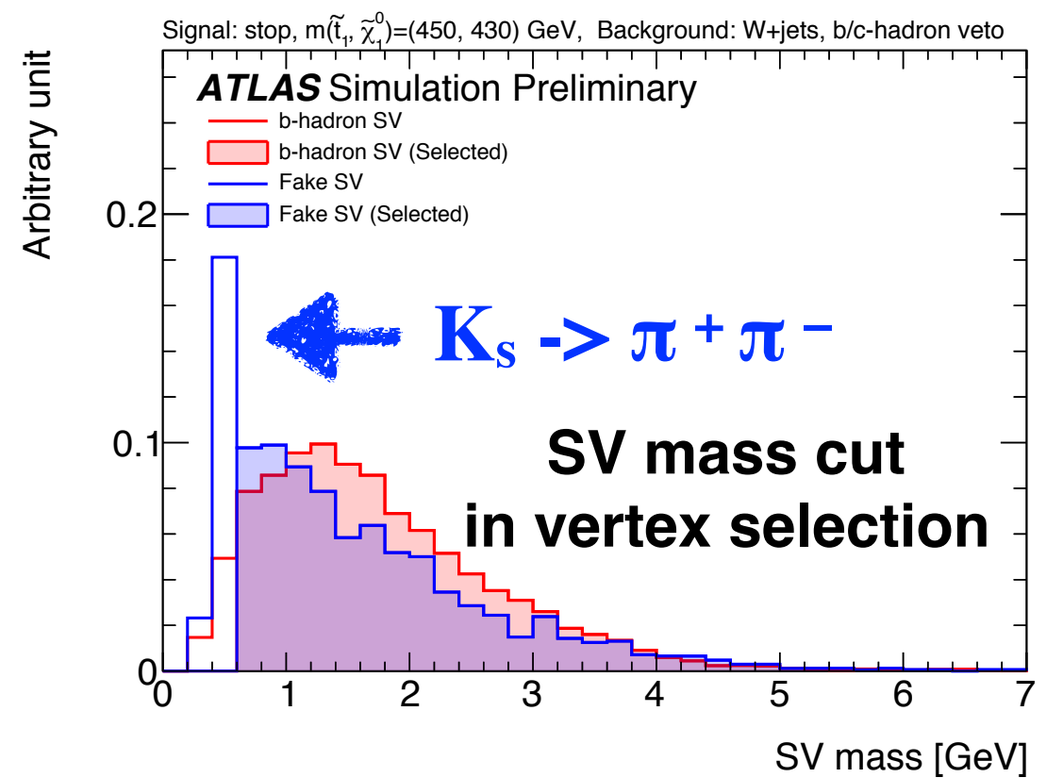
Track selection:

Impossible to check all track combinatorics for vertexing; ~O(500-1k) tracks in an event: remove tracks from PV/pileup, and remove tracks in jets

Vertex reco. and selection:

Perform 2-track vertexing, followed by N-track vertexing. A set of vertex selections is applied further to reduce fake vertices





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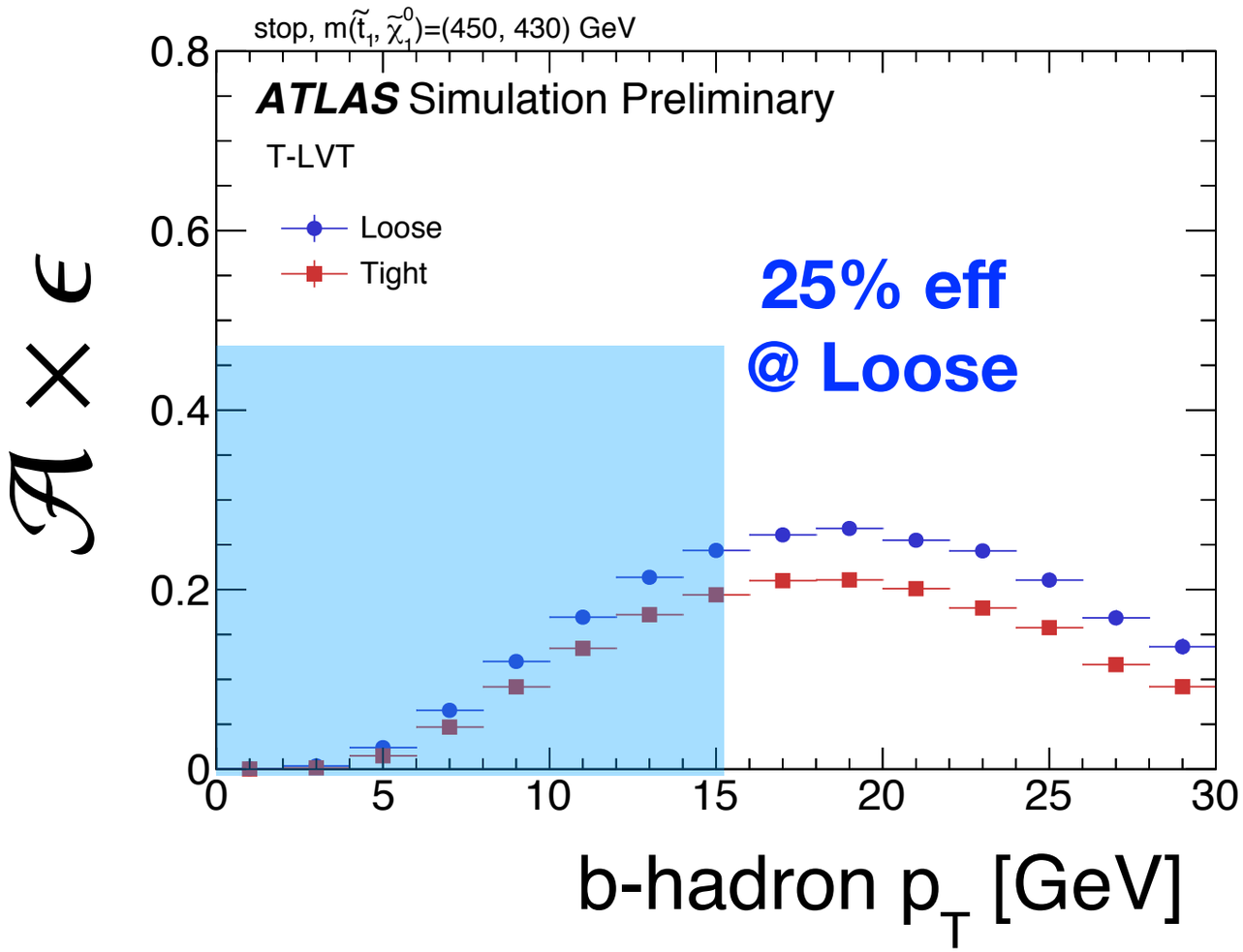
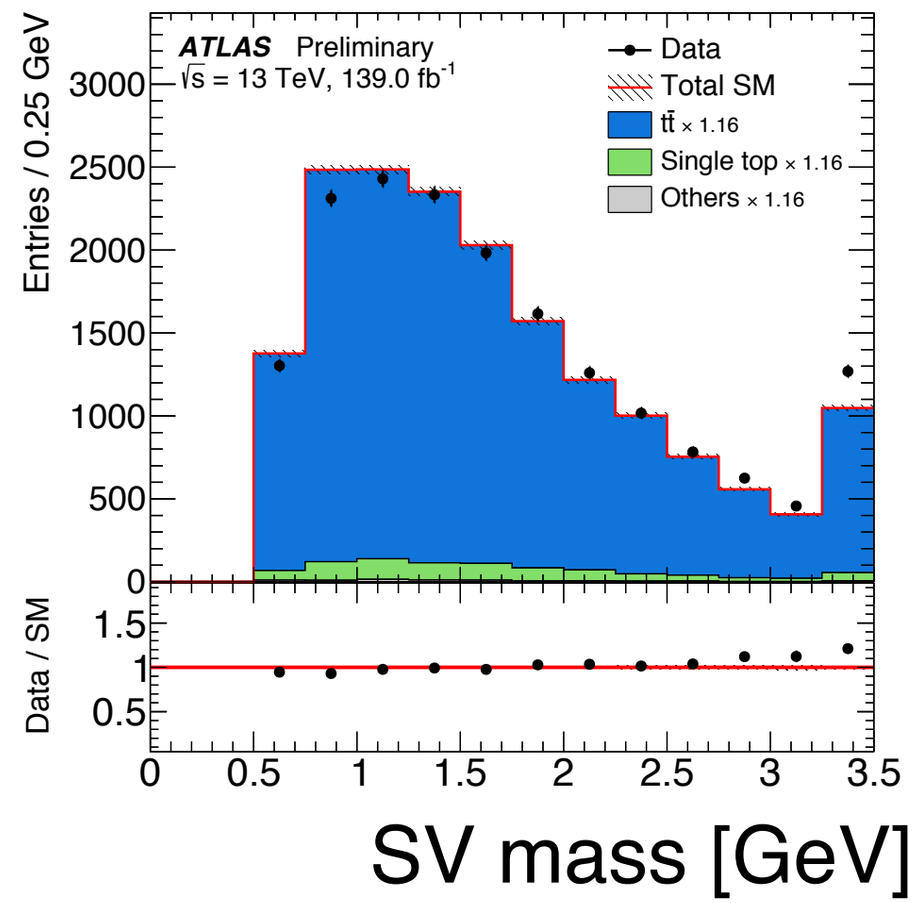


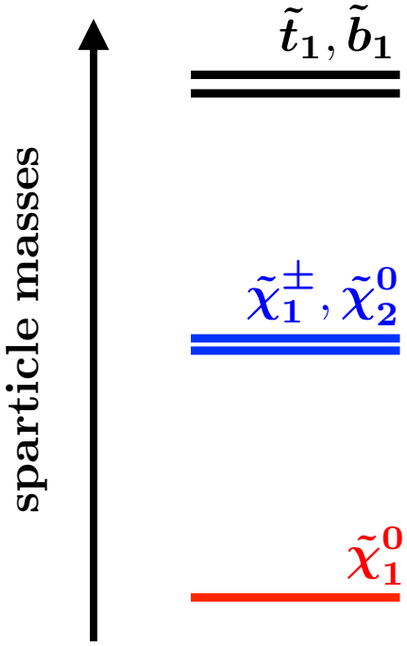


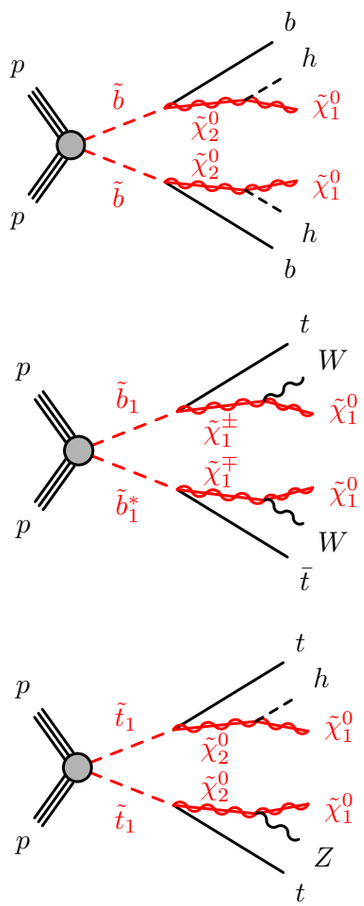
- 25% efficiency is achieved at b-hadron p_T ~15GeV at Loose WP.
- kinematics of SV (including SV mass) is well modeled.

Long decay chains

❖ Stop/sbottom decay may have longer decay chain; **Wino NLSP** or **Bino NLSP**

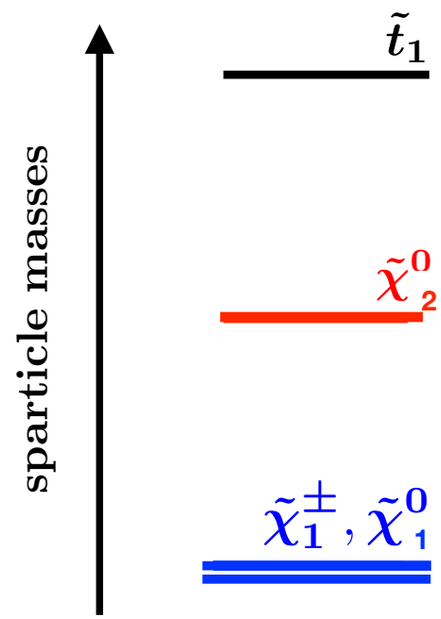
Wino NLSP

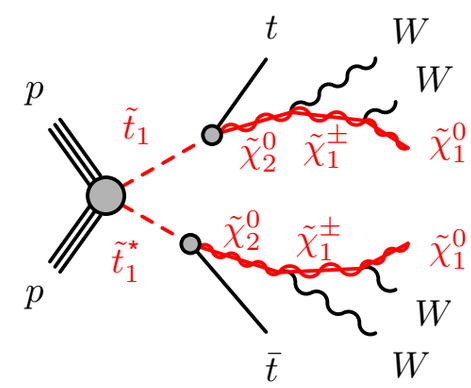




- Simplified model: $\tilde{\chi}_2$ ($\tilde{\chi}_1^{\pm}$) decays into LSP in association with Z/h ($W^{\pm}$) — in MSSM, BR largely depends on sign(μ)

Bino NLSP



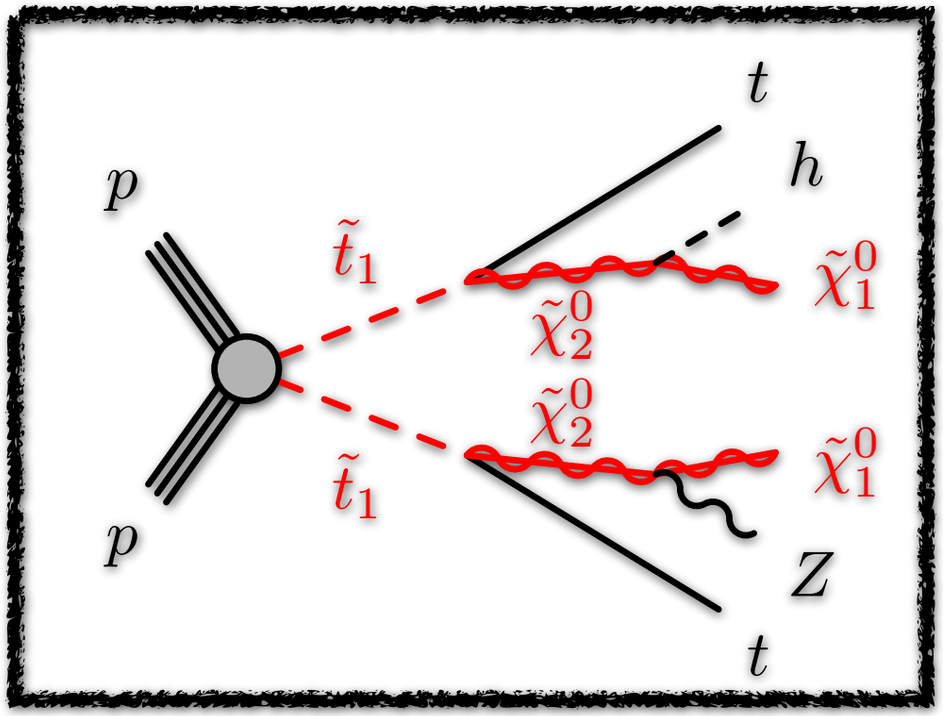


- Simplified model with 100% BR — in MSSM, $\tilde{\chi}_2$ decay is roughly *BR($\tilde{\chi}_2$ ->$W^-\tilde{\chi}_1^+$) = BR($\tilde{\chi}_2$ ->$W^+\tilde{\chi}_1^-$) = BR($\tilde{\chi}_2$ ->$h\tilde{\chi}_1$). BR($\tilde{\chi}_2$ ->$Z\tilde{\chi}_1$) is suppressed (no TGC in the SM)*

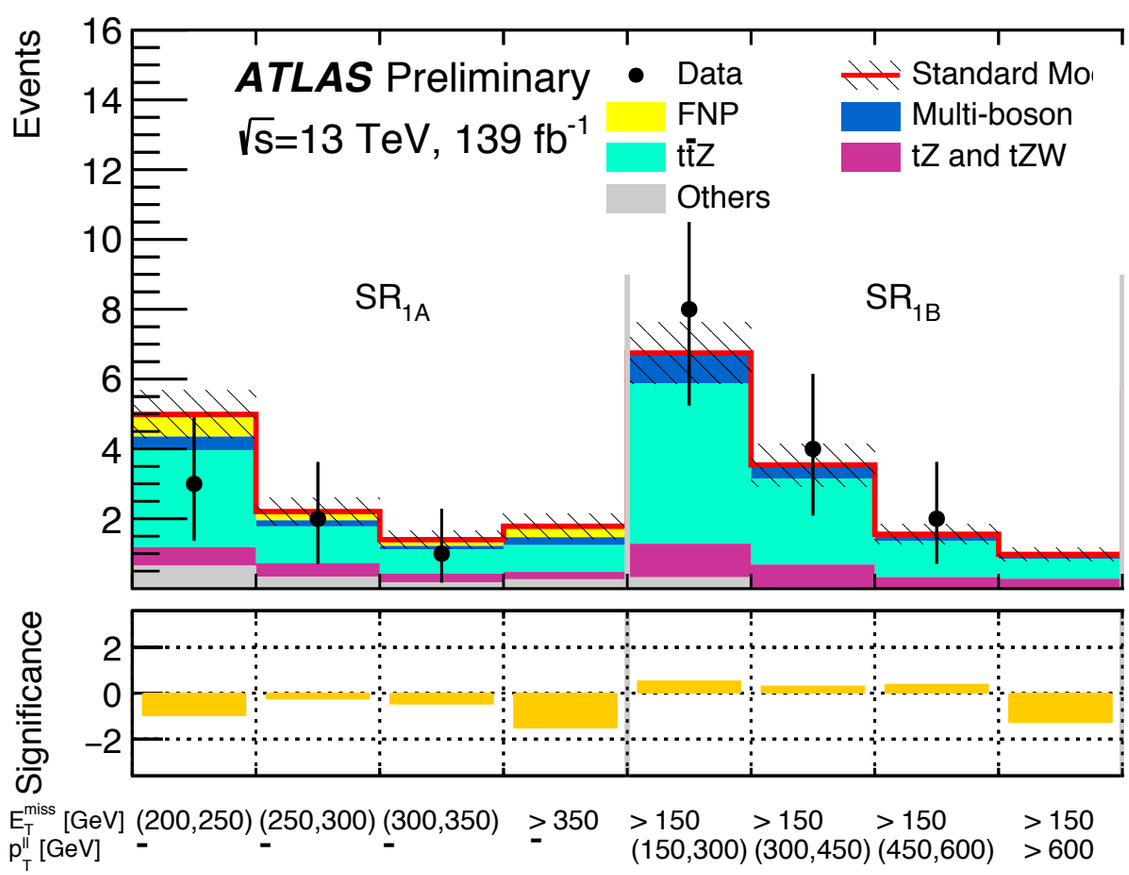
❖ Target signature: **multi-jets (including b-jets) + large E_T^{miss} + 0-3 leptons**

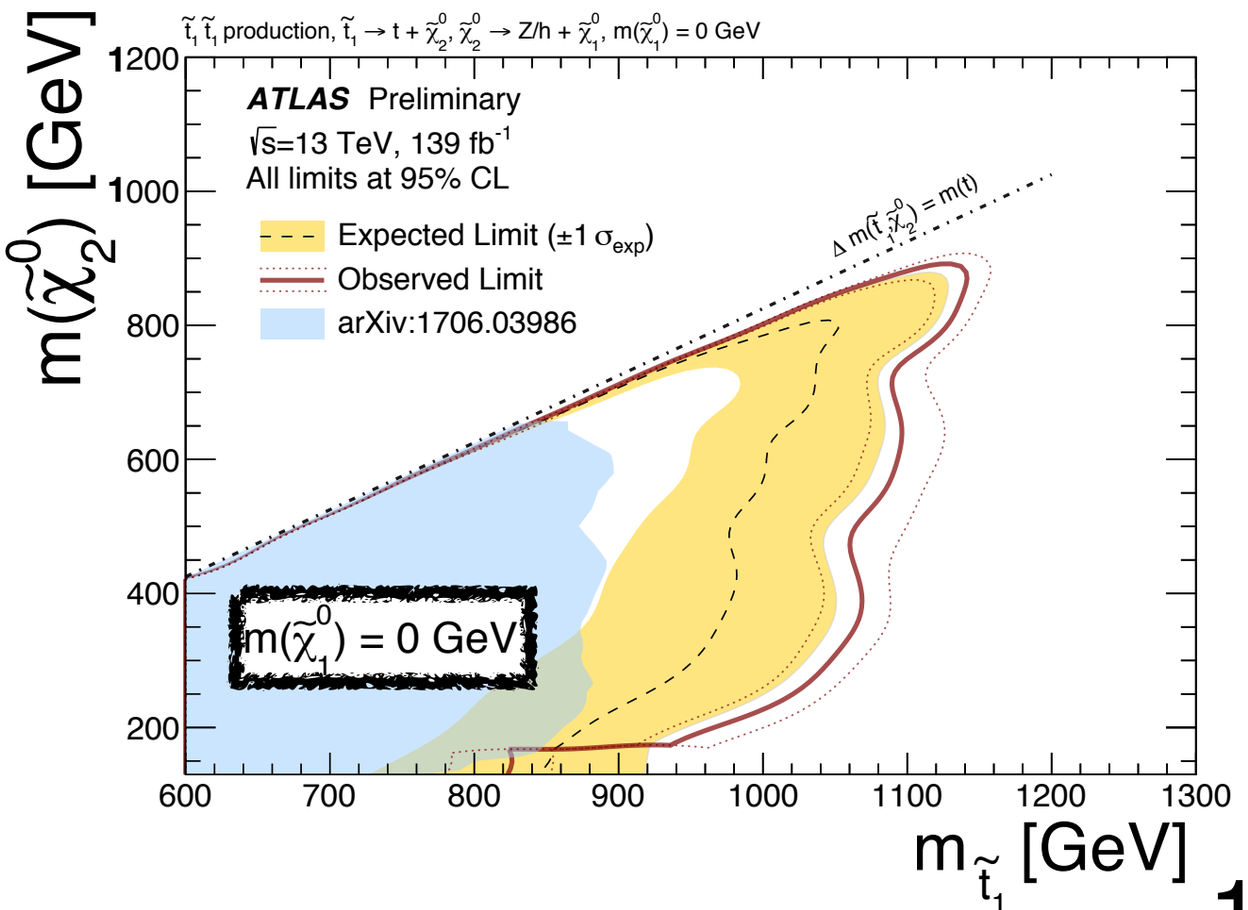
Stop decay w/ Z

ATLAS-CONF-2019-016



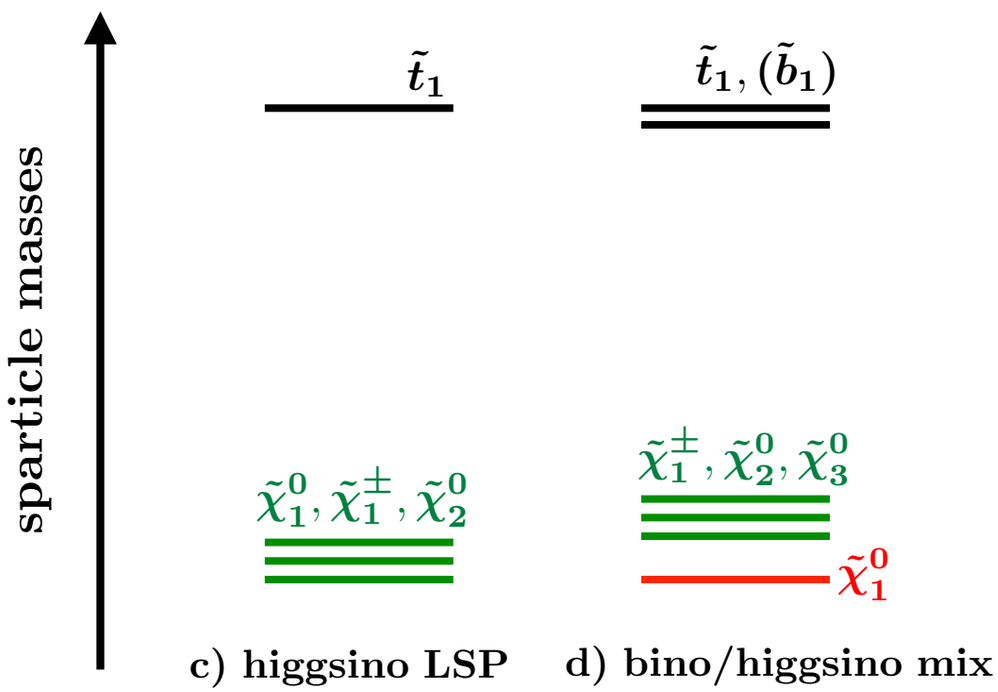
- OS 2-leptons from Z decay and an additional lepton(s) from top decay leads to **multi-leptons** final state.
- ttZ is dominant (irreducible) background
  -- ttZ bkg is normalized to data in CR.



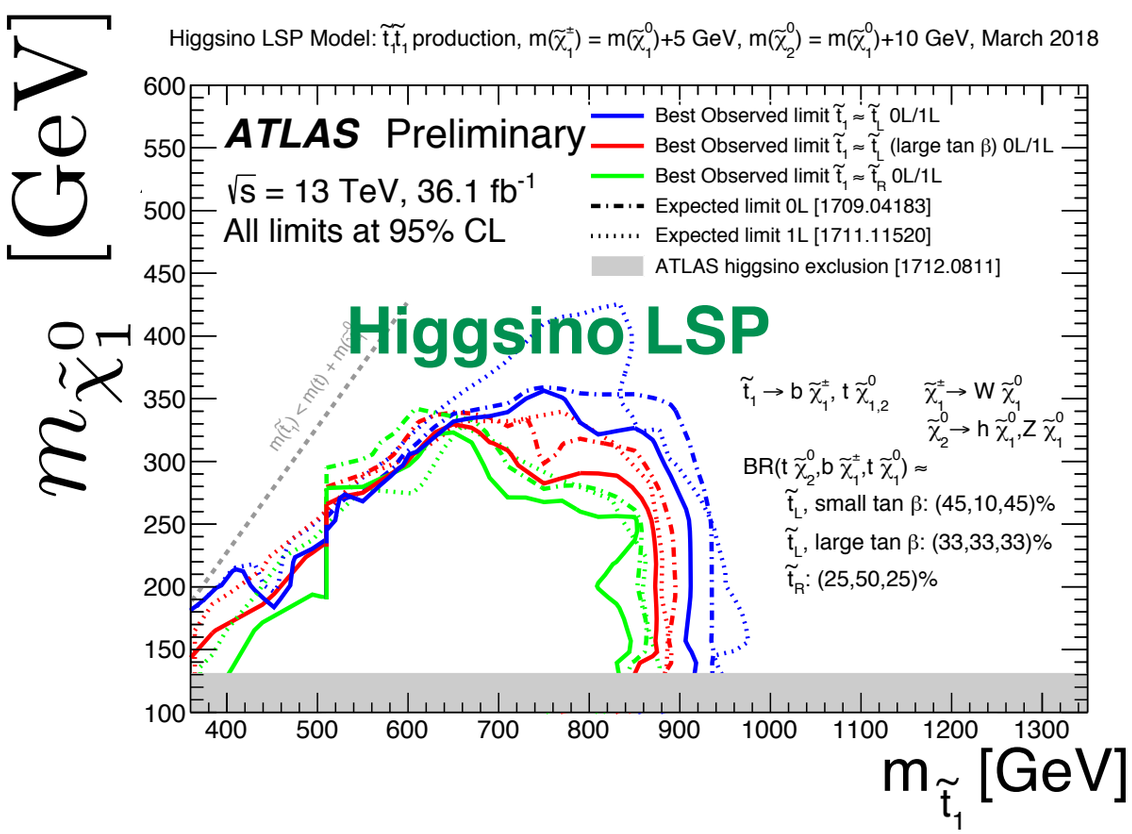


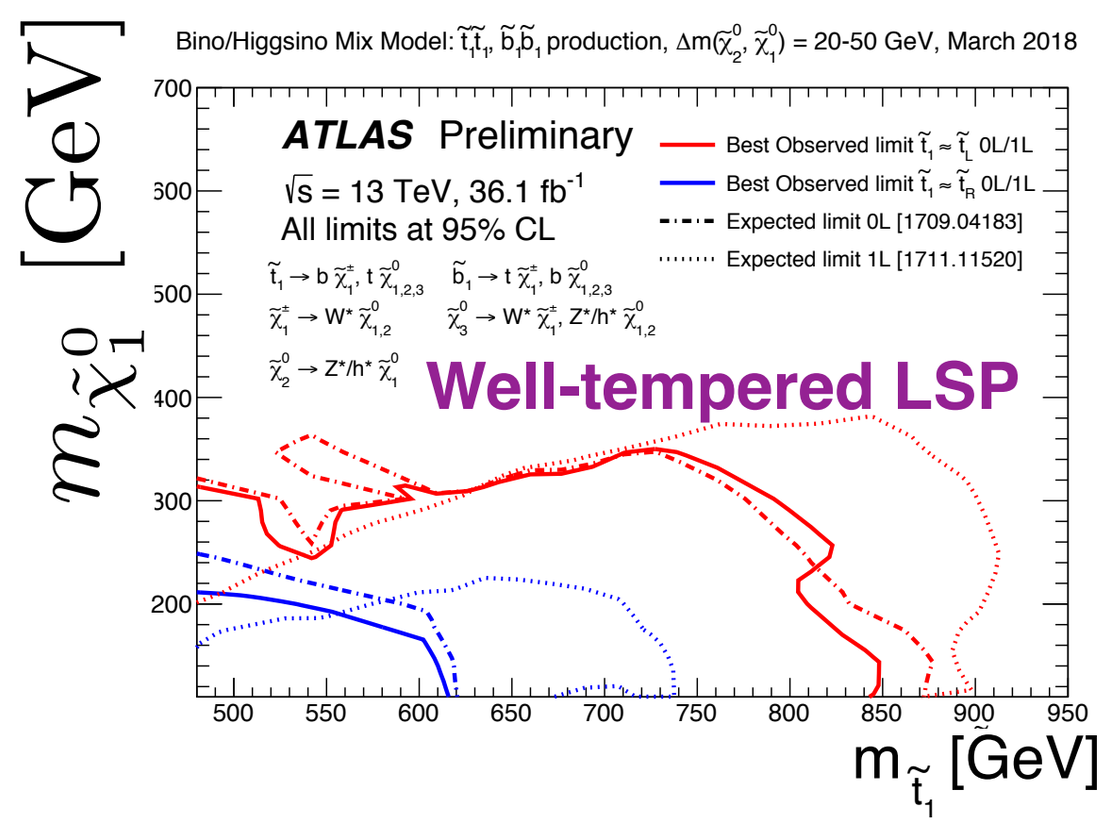
Light higgsino scenarios

ATL-PHYS-PUB-2019-022



- Light higgsino models (pMSSM-inspired) were developed and studied with 36/fb data.
- **Higgsino LSP (natural SUSY):** soft-lepton reco. is crucial
- **Well-tempered neutralino (DM relic):** current analysis turned out to be insensitive due to moderate Δm

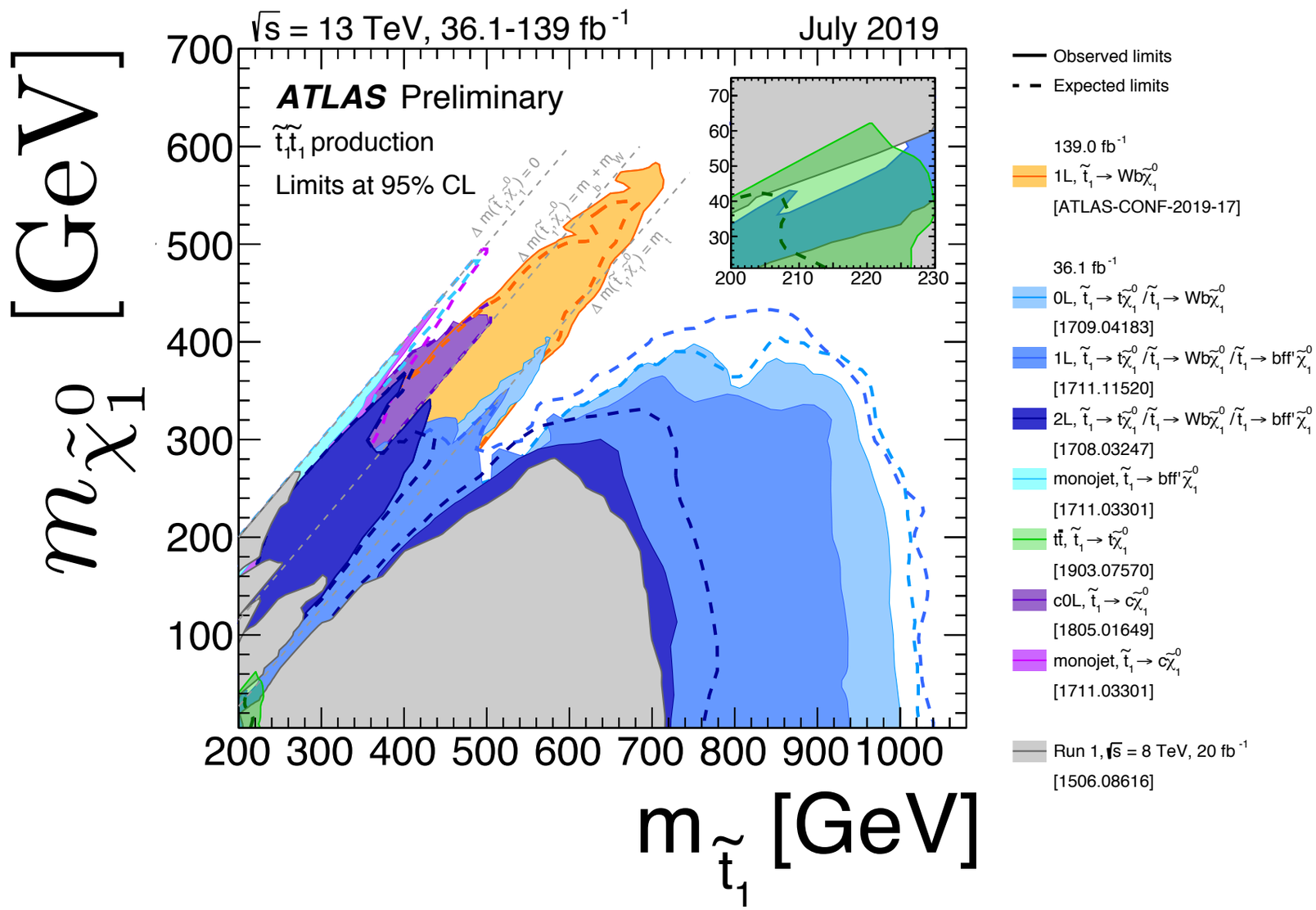




Conclusion

ATL-PHYS-PUB-2019-022

- Extensive search program developed for 3rd gen SUSY in ATLAS (including RPV searches — see backup).
- **No SUSY (just yet)** but many full Run-2 results are in preparation, some of which hopefully(!) give us a hint for new physics 😀



Backup

Some details of ML setup

ATLAS-CONF-2019-017

Table 3: Discriminating variables applied as inputs to the NN to train the classifier. In addition, the output vector of the jet-RNN to transform the variable length jet collection is also applied as an input to the neural network.

Input variable	Description
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse energy
$\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	Azimuthal angle of the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
m_{T}	Transverse mass
$\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	Azimuthal angle between $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$and lepton
m_{bl}	Invariant mass of leading b-tagged jet and lepton
$p_{\mathrm{T}}^{b_{jet}}$	Transverse momentum of the leading b-tagged jet
n_{jet}	Jet multiplicity
$n_{b-\mathrm{tag}}$	Number of b-tagged jets @ 77%
$p_{\mathrm{T}}(\ell)$	Transverse momentum of lepton
$\eta(\ell)$	Pseupdorapidity of lepton
$\phi(\ell)$	Azimuthal angle of lepton
$E(\ell)$	Energy of lepton

Table 4: Architecture and hyperparameters of the neural network.

Architecture	Parameter set
Number of hidden layers	1
Neurons per hidden layer	128
Activation function	leaky relu ($\epsilon = 0.1$) [121]
Learning rate	10^{-3} [120]
Regularisation	$L2$ ($\lambda = 10^{-2}$) [116]
Weight initialisation	Glorot normal [122]
Batch size	32 [116]
Batch normalisation [123]	Yes

- NN is trained using Keras framework with TensorFlow (as a backend)
- The Adam optimizer with a learning rate of 10e-3 was used to optimize the error function.
- 12 input variables used for NN training: lepton 4-vector, jet 4-vector (RNN), E_T^{miss}, and their angular variables, etc
- Long-short term memory (LSTM) algorithm allows you to simultaneously train and optimize the consequent NNs.

T-LVT

VertSecInclusive

Track selection

Vertex reconstruction

Vertex selection

DAOD

Offline selection

Track selection

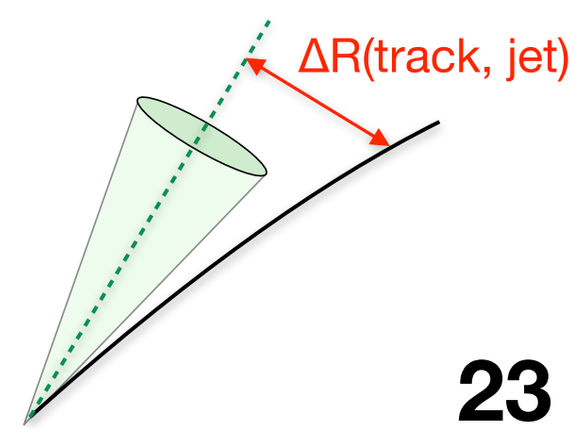
Impossible to check all track combinatorics for vertexing — ~O(500-1k) tracks in an event in ***InDetTrackParticle*** container

Remove tracks from PV or pileup

- d0/sigma(d0) > 1.7
- z0/sigma(z0) > 0.5
- |z0sinθ| < 1.5mm
- other selections (**VertSecInclusive code**)

Remove tracks in AntiKt4EMTopo jets

- ΔR(track, jet) > 0.4 [*]



[*] Standard b-tagging is used when AntiKt4EM jets (p_T>30GeV) available

T-LVT

VertSecInclusive

Track selection

Vertex reconstruction

Vertex selection

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Offline selection

Vertex reconstruction

2-track vertexing

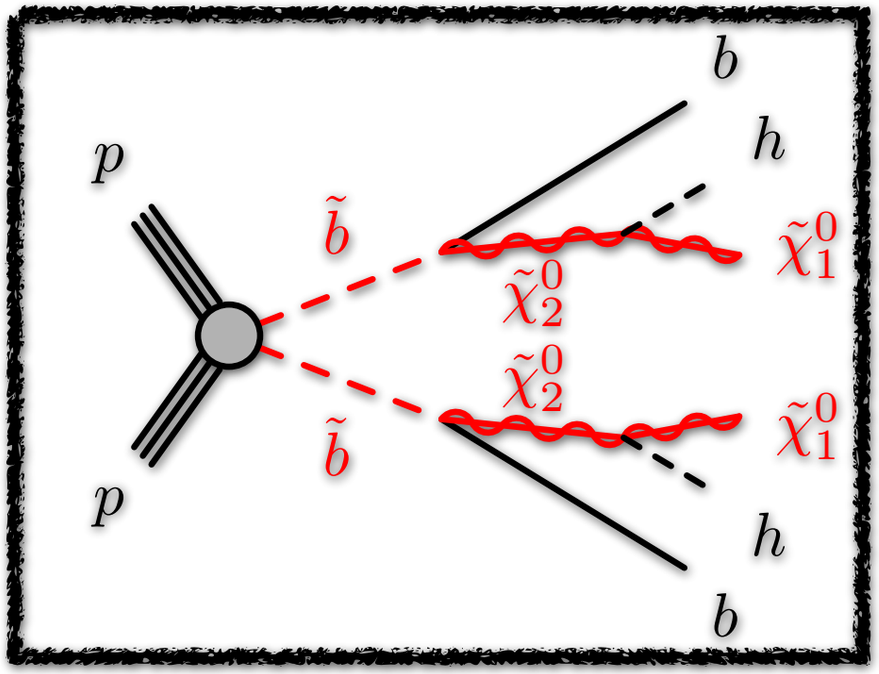
- all possible combinations are tested;
- 2-track seeds retained based on the vertex position
- compatibility check between vertex position and the sum of the momenta of associated tracks

N-track vertexing

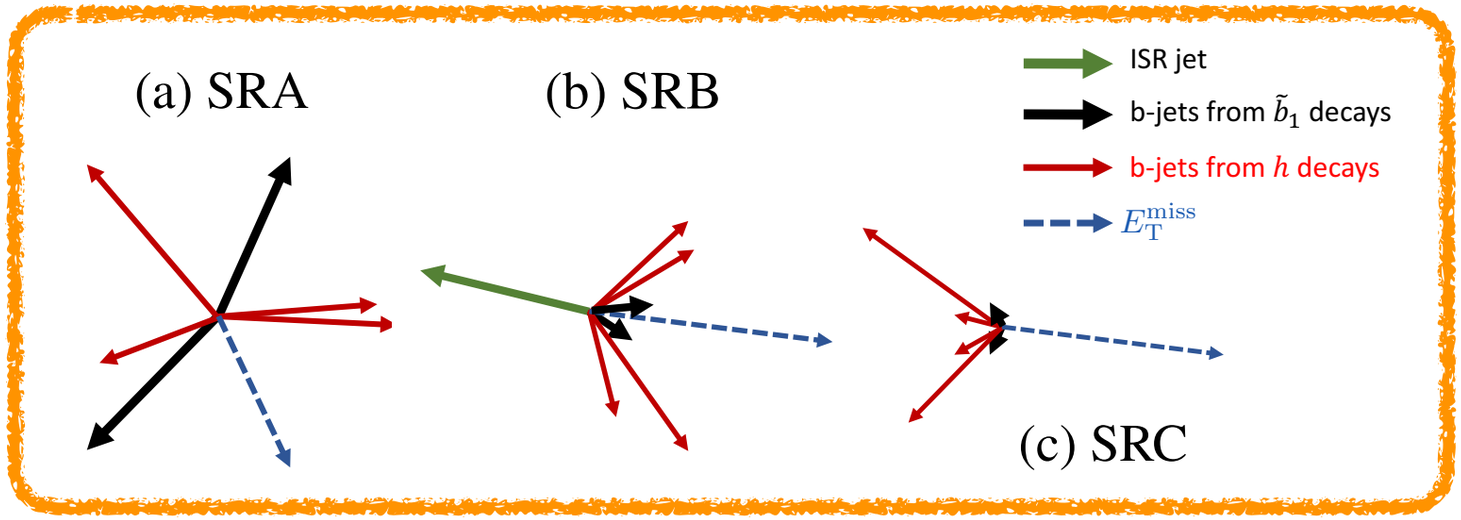
- starting from the list of 2-track seeds, n-track vertexing is performed
- ambiguities arising from track association to multiple vertices resolved

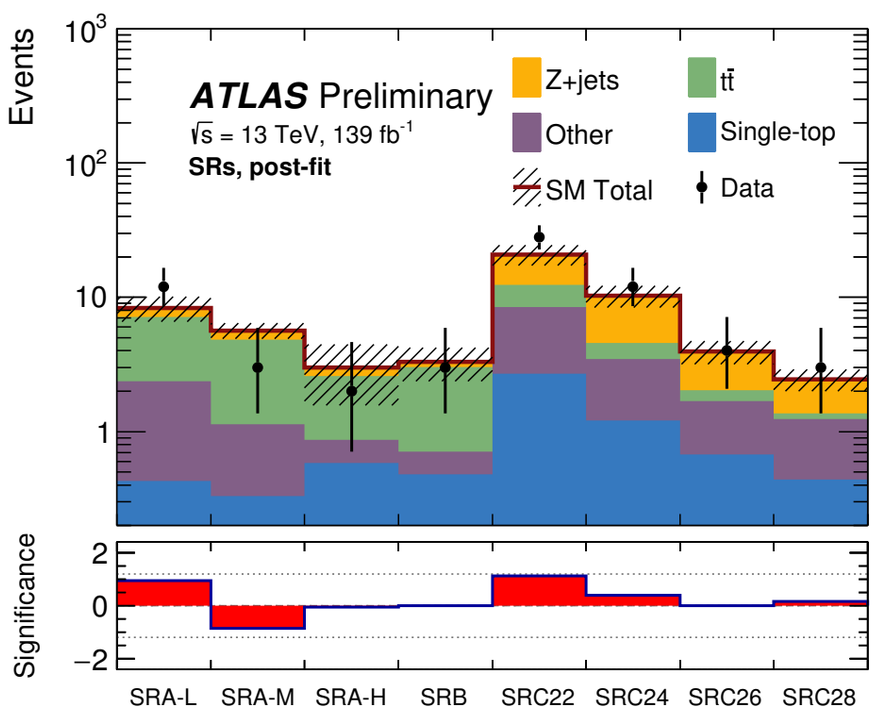
Sbottom decay w/ Higgs

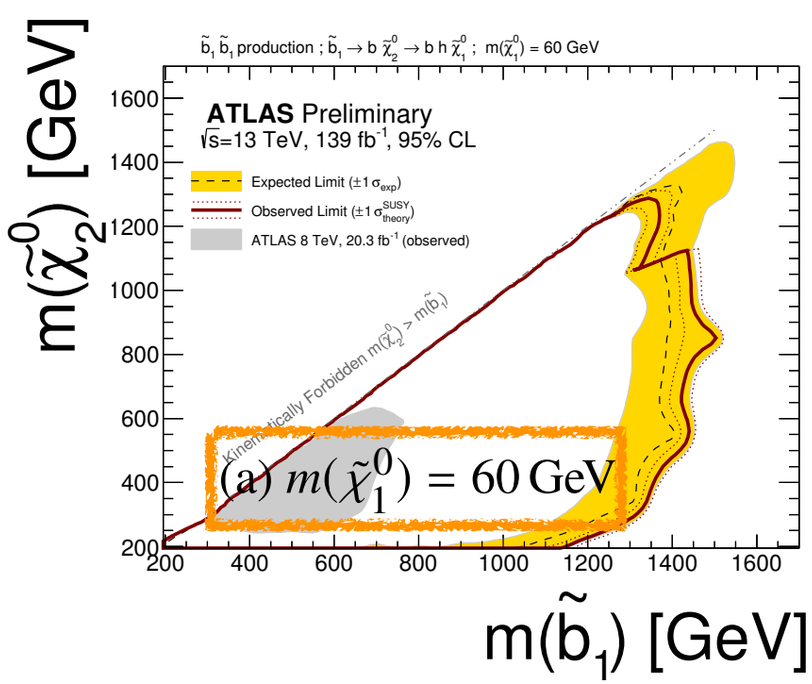
ATLAS-CONF-2019-011

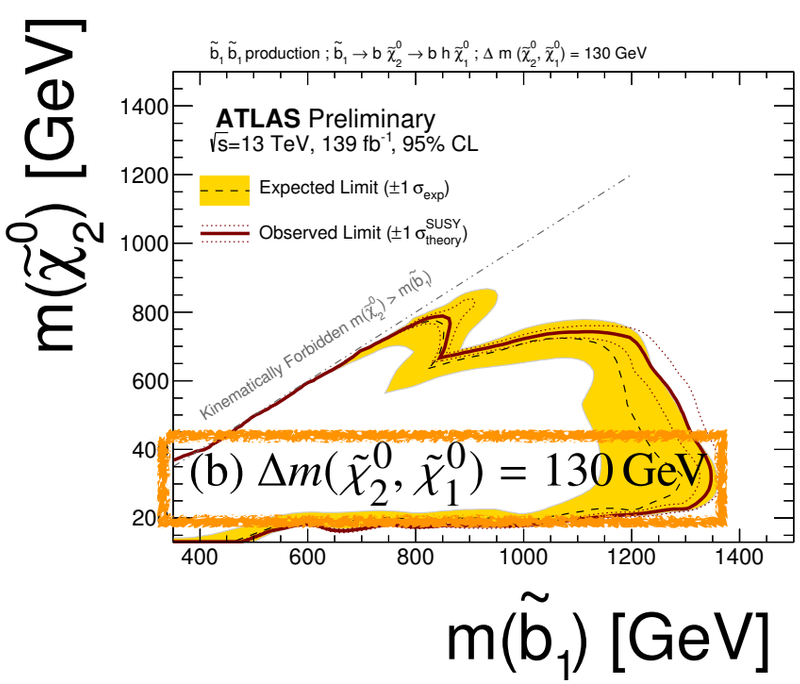


- *h* -> *bb* decay leads to **multi b-jets** final state.
- Depending on Δm, **b-jets from $\tilde{b}_1$** may have different kinematics from **ones from *h***.





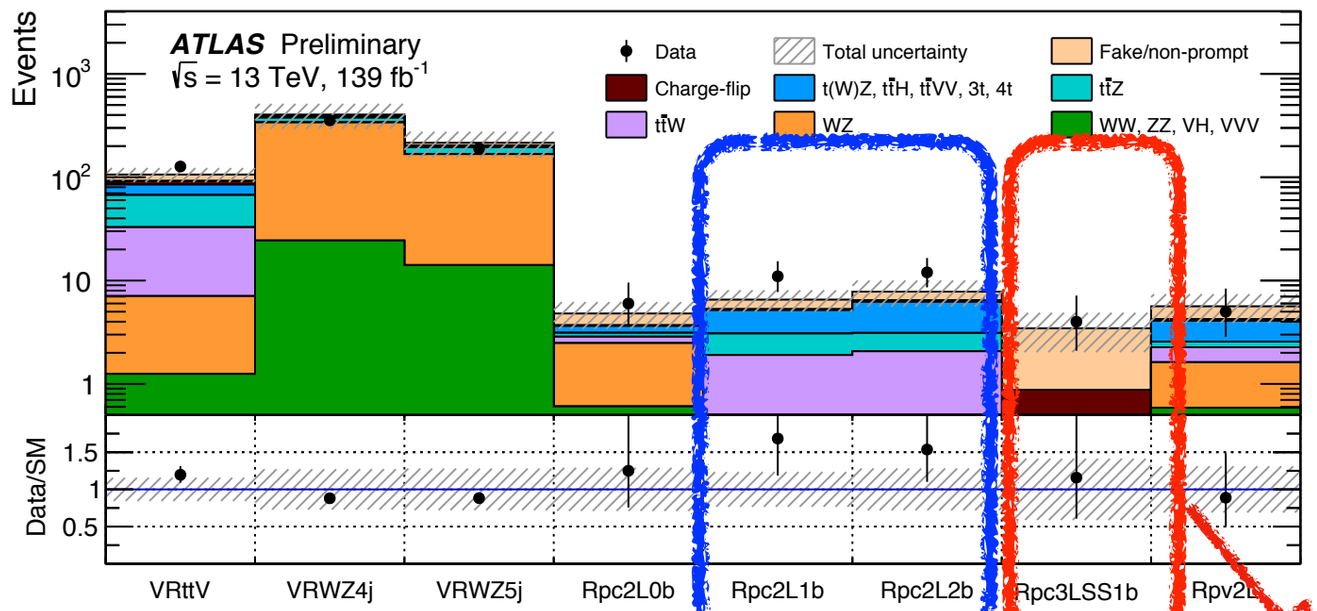




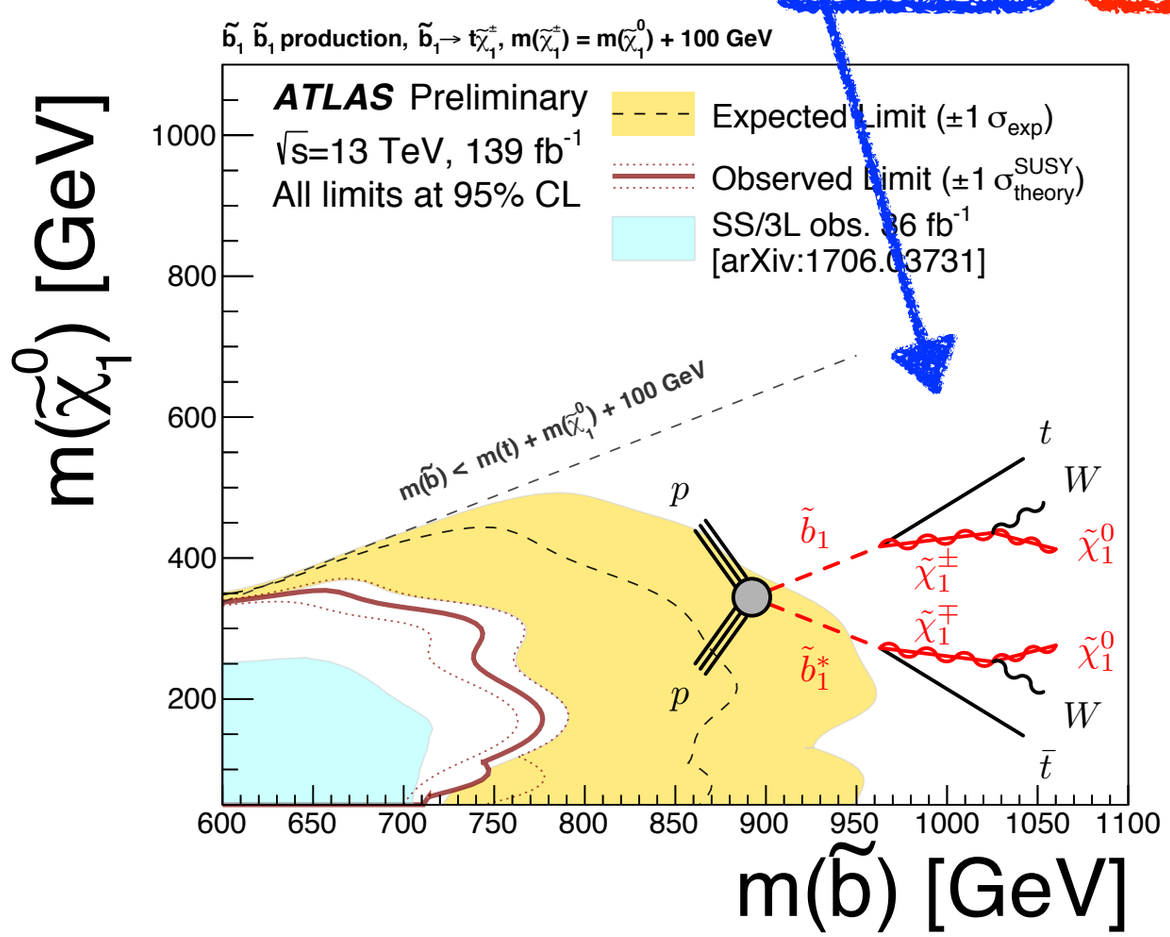
- **ttbar** and **Z+jets** dominant

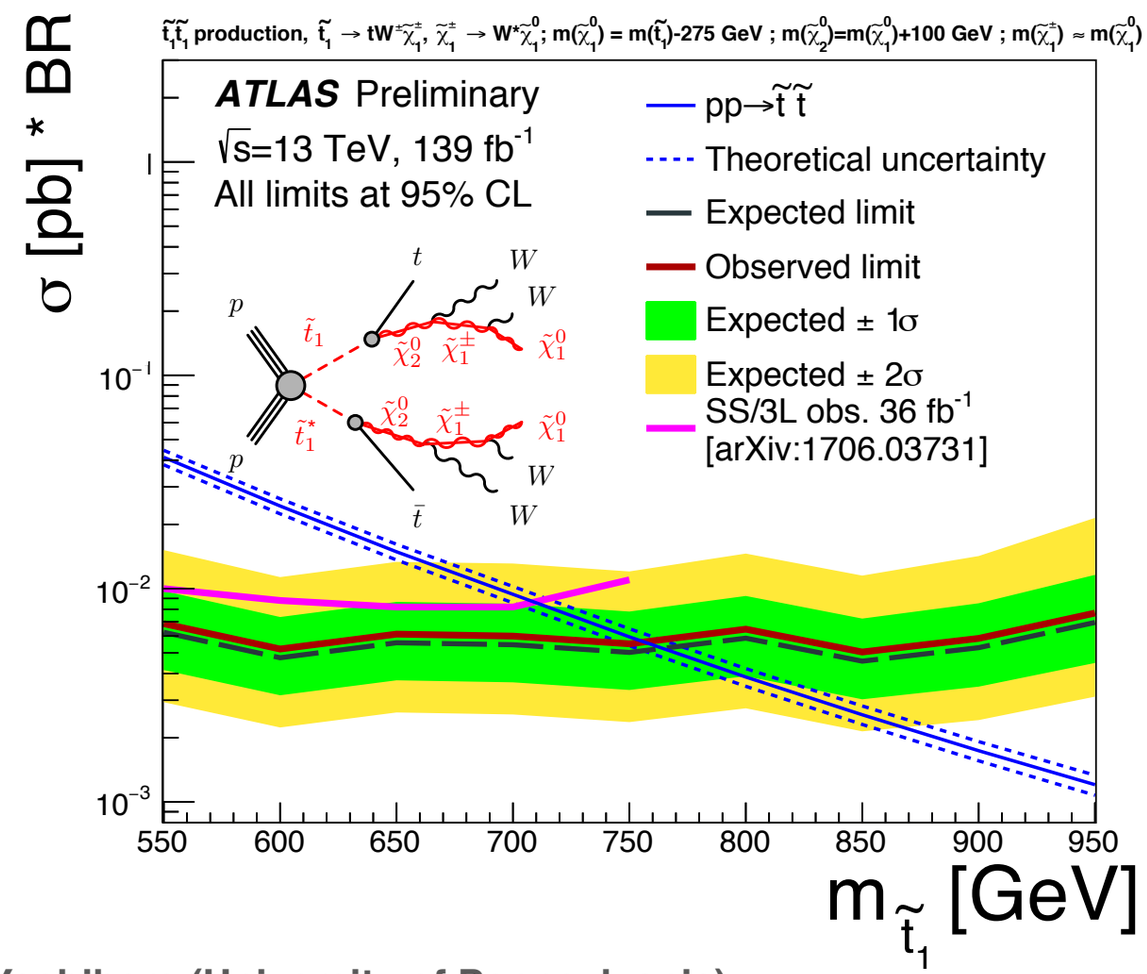
SS and 3L analysis

ATLAS-CONF-2019-015



- **SS 2-leptons or 3-lepton** final state also sensitive to 3rd generation search.
- ttV and fake-lepton are dominant backgrounds — data-driven estimate for the fake-lepton bkg.





Stop decay w/ Z

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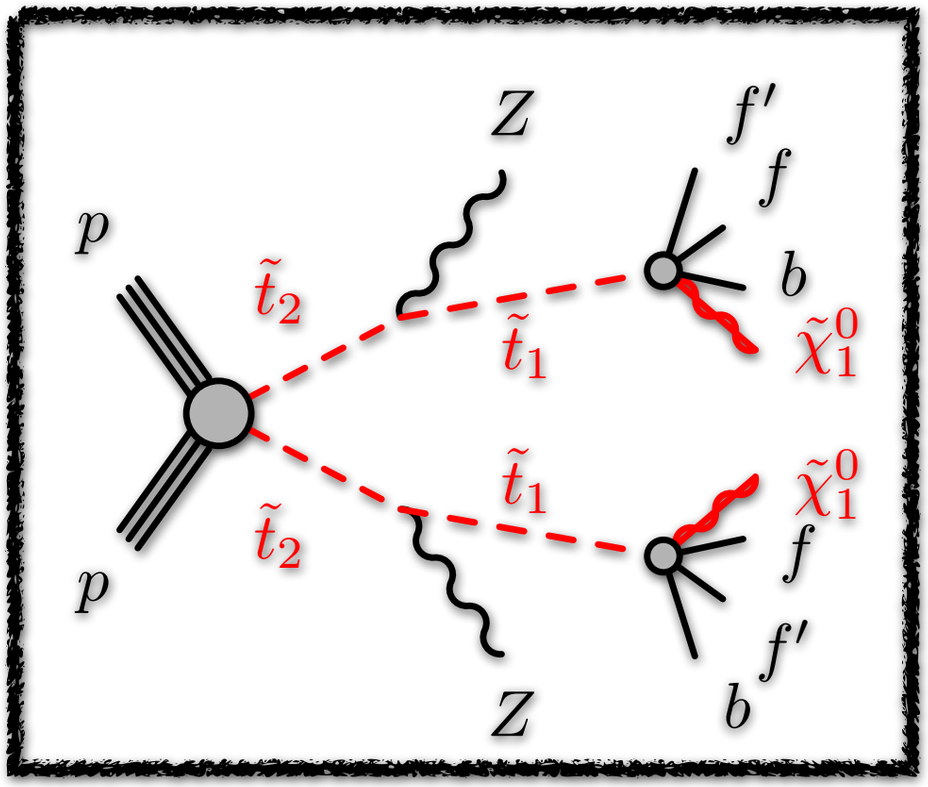

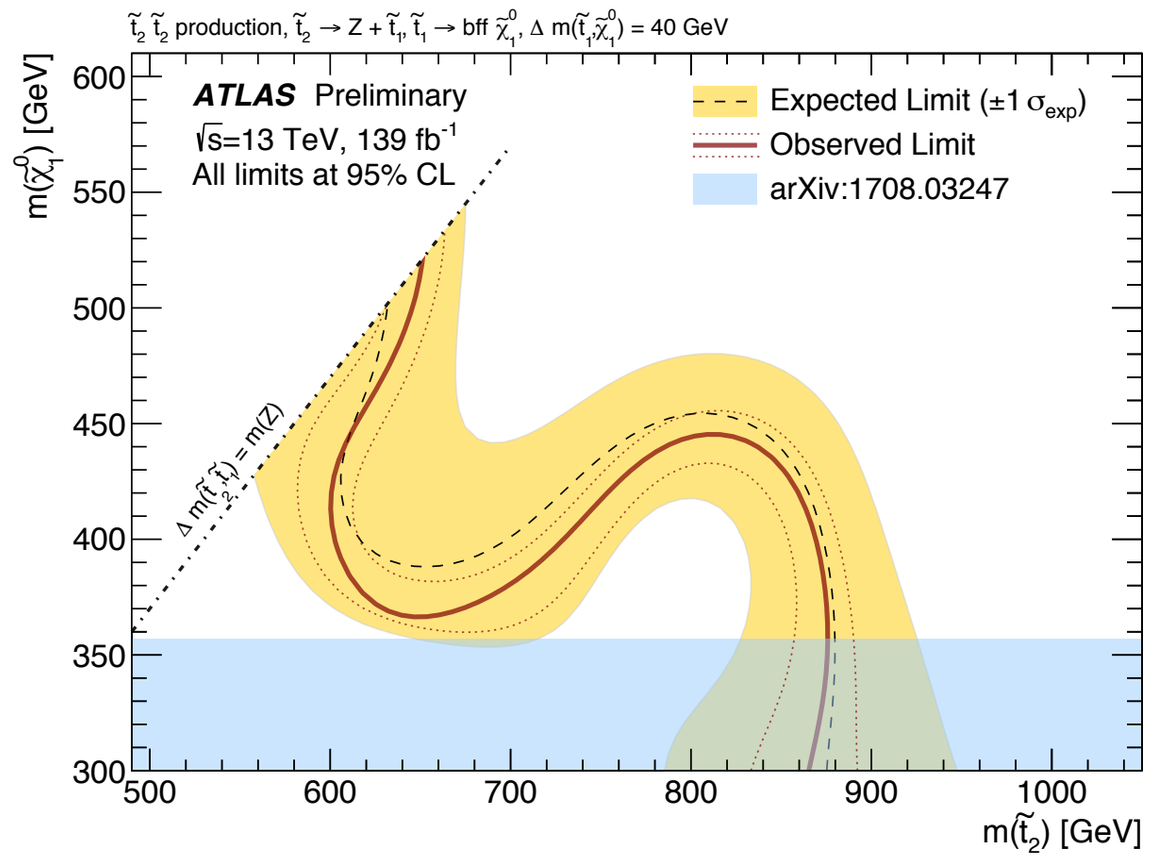

- Analysis is extended to heavy stop ($\tilde{t}_2$) search in the same final state.
- Two SRs optimized for high mass and compressed region

Wino NLSP summary

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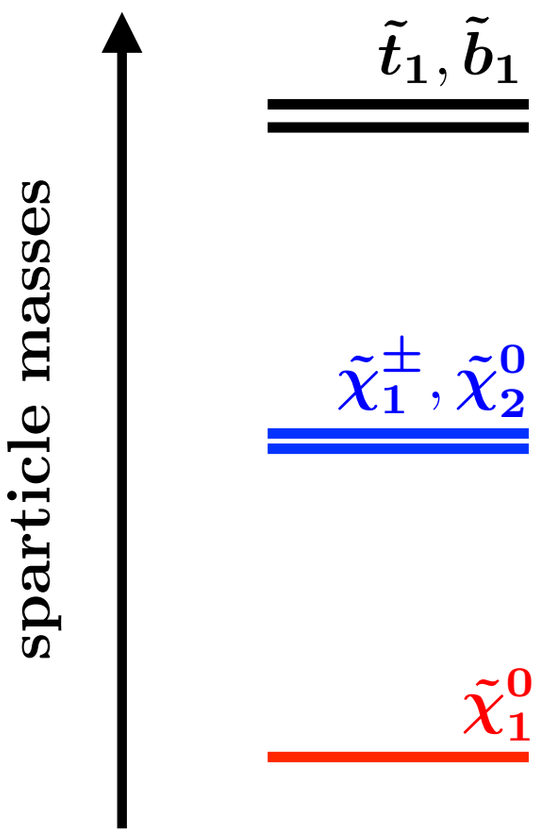
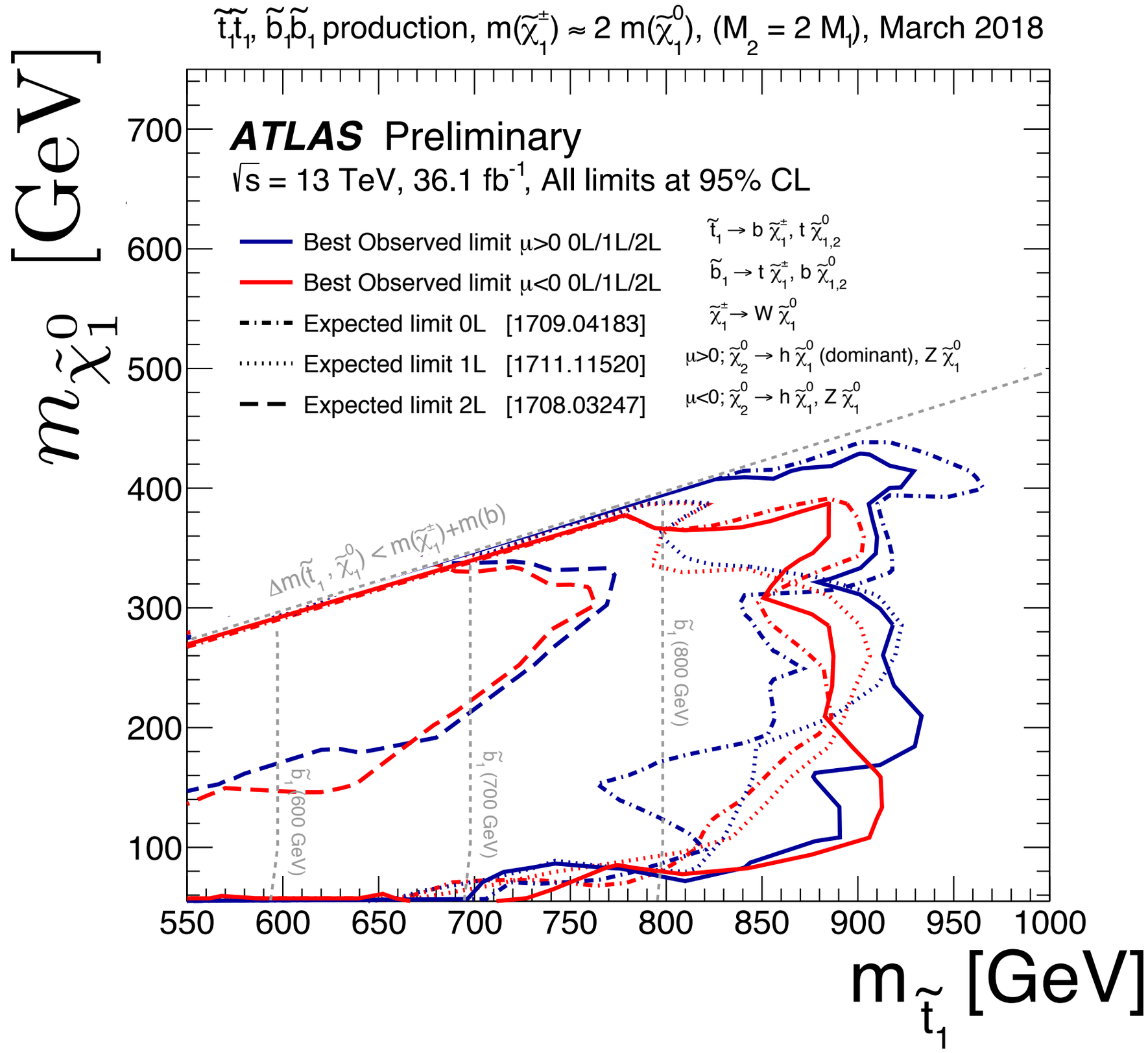
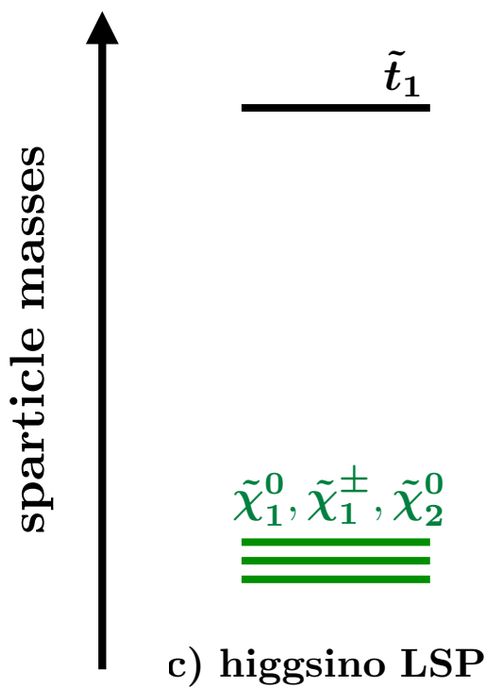
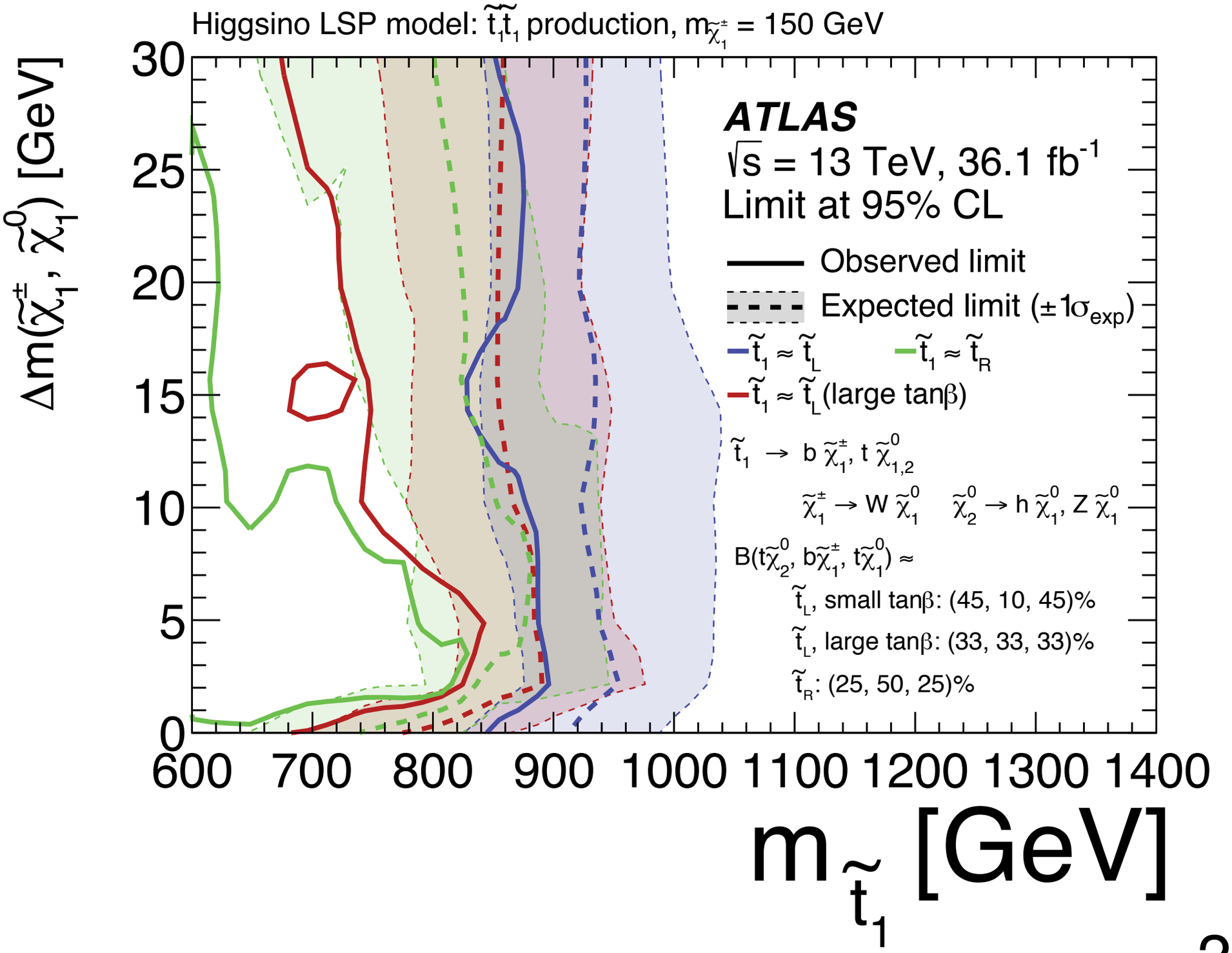




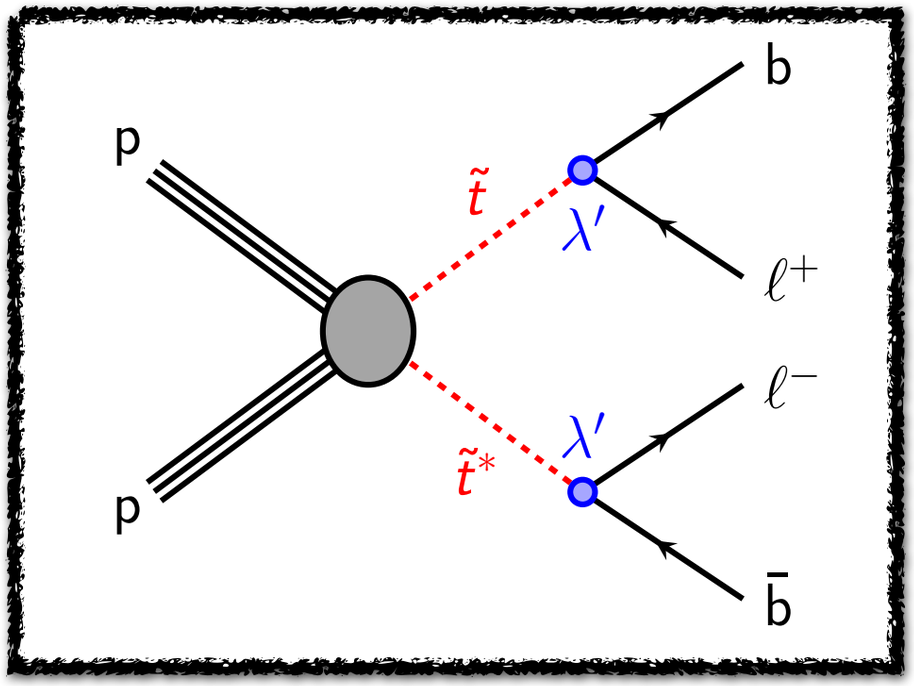
Higgsino LSP: $\Delta m(\chi_1^{\pm}, \chi_1^0)$ vs $m(t_1)$

1711.11520





Stop search in RPV scenario



❖ RPV stop decay, while conserving the baryon number (B) to avoid a prompt proton decay.

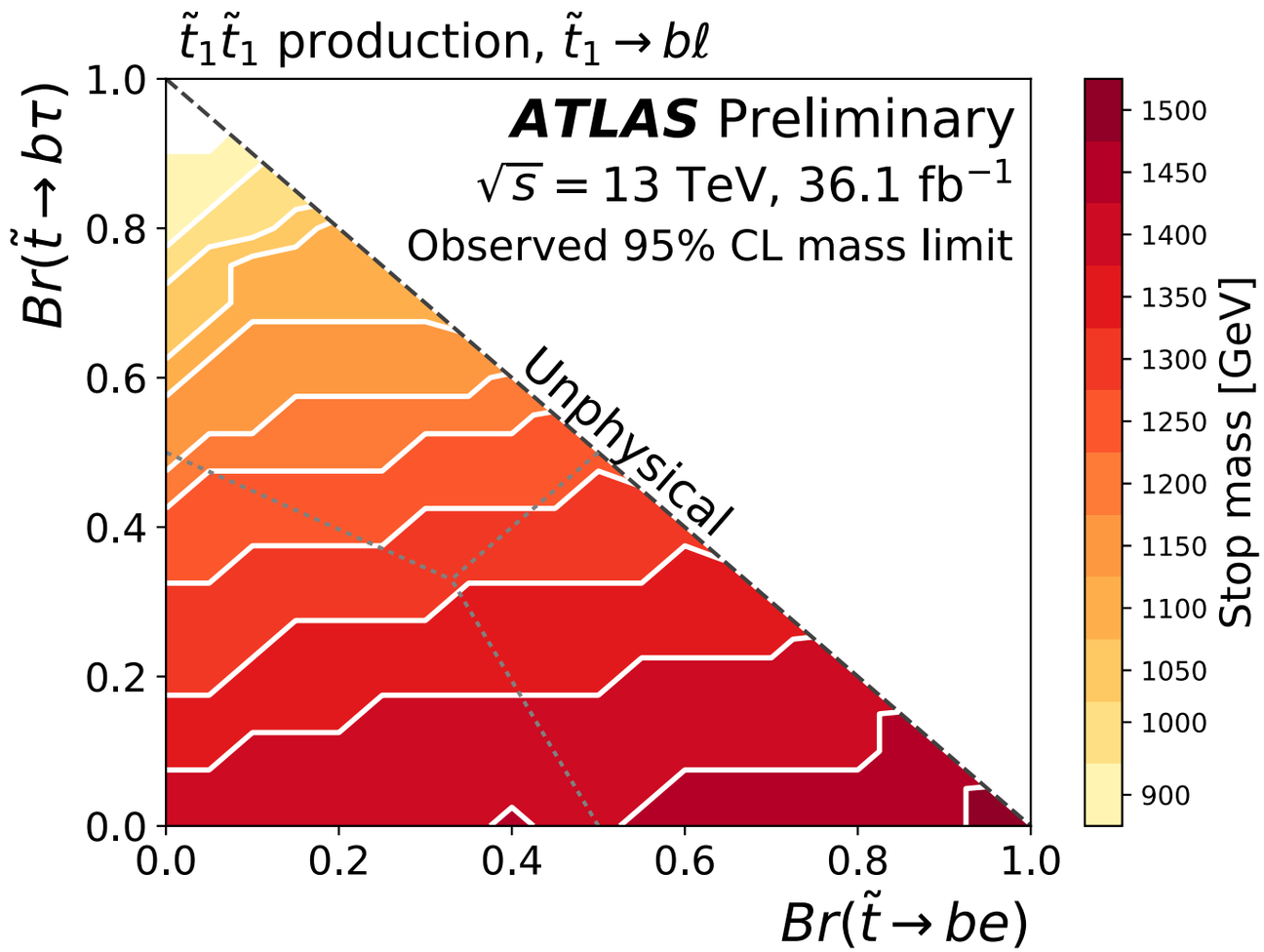
❖ Final state: 2L+2b

❖ Key discriminant: m_{bl} and m_{CT}

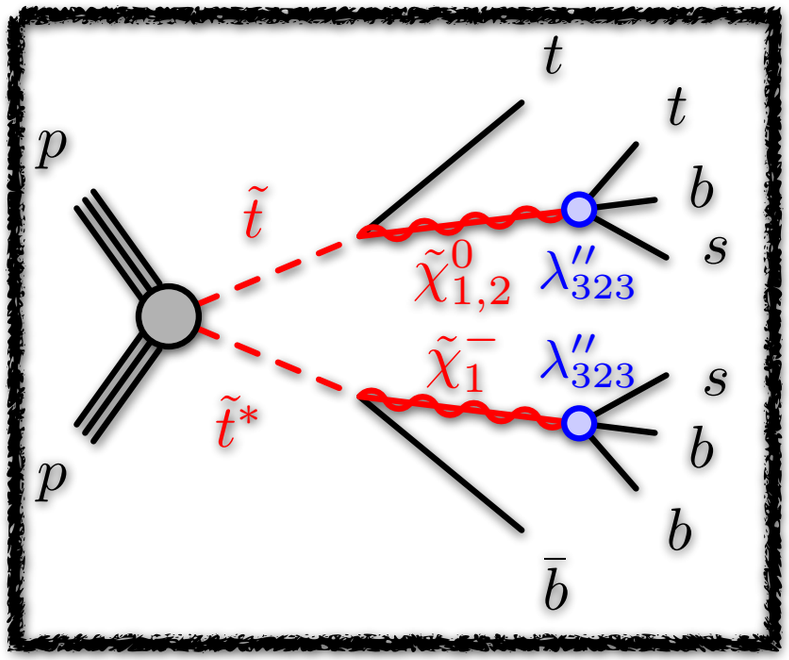
❖ Main backgrounds:

Wt, Z+jets, and ttbar events

❖ Limits are set on various possible BRs (no $\tilde{t}_1$ -> bτ search)

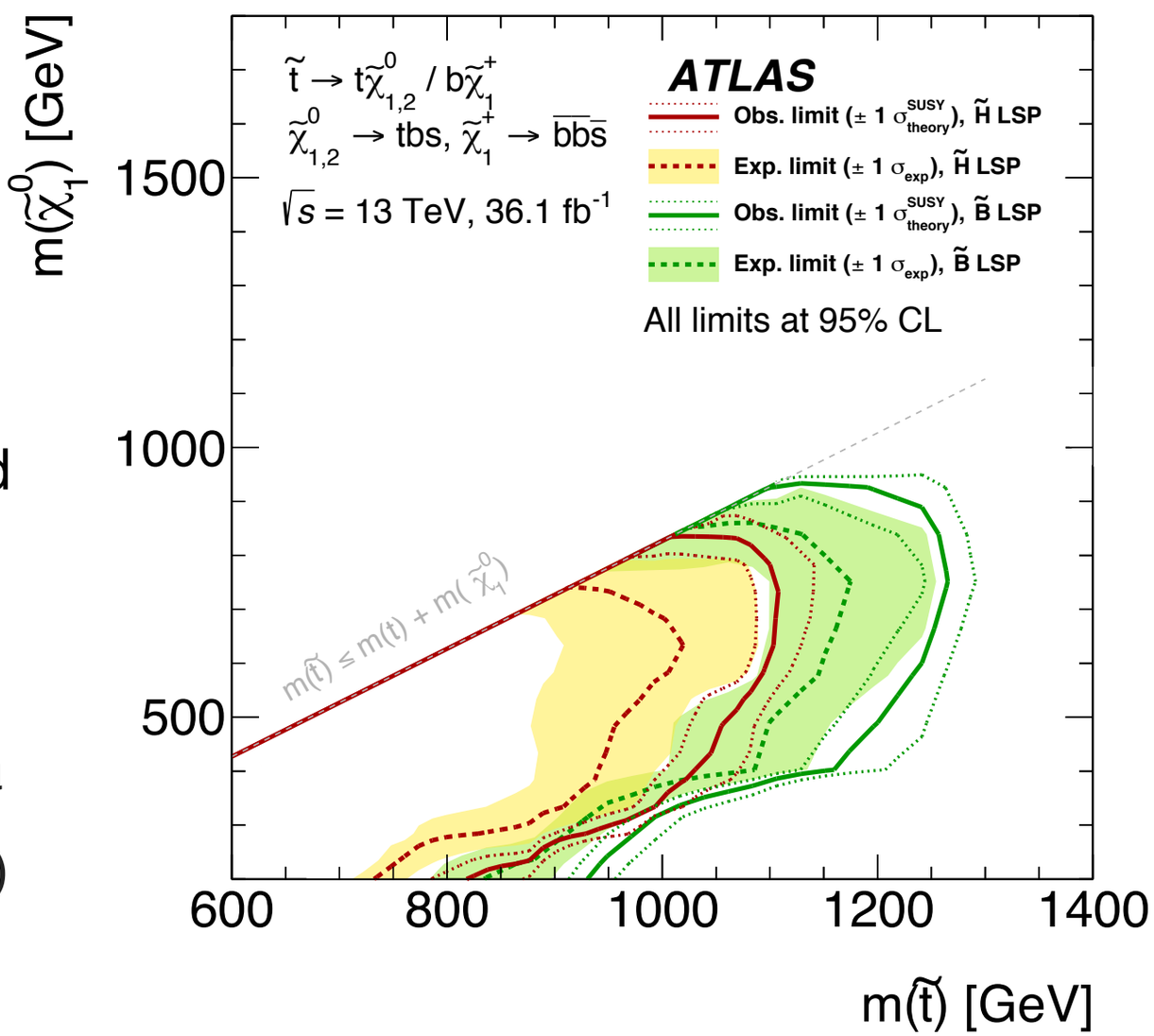


Stop search in RPV scenario (cont'd)



- In RPV models, LSP decays further into quarks, leading to multijets (up to >= 12 jets!) and a lepton (from semi-leptonic top-quark decay) final state.

- Higgsino LSP (with $\tilde{t}_1 \sim \tilde{t}_R$) and Bino LSP scenarios considered.
- $m_{\tilde{t}1}$ up to 1250 GeV (1100 GeV) is excluded for the bino LSP (higgsino LSP) scenario.
- In RPV, LSP decays further into quarks, leading to multijets (up to >= 12 jets!) and a lepton (from semi-leptonic top-quark decay) final state.



RPV stop Summary

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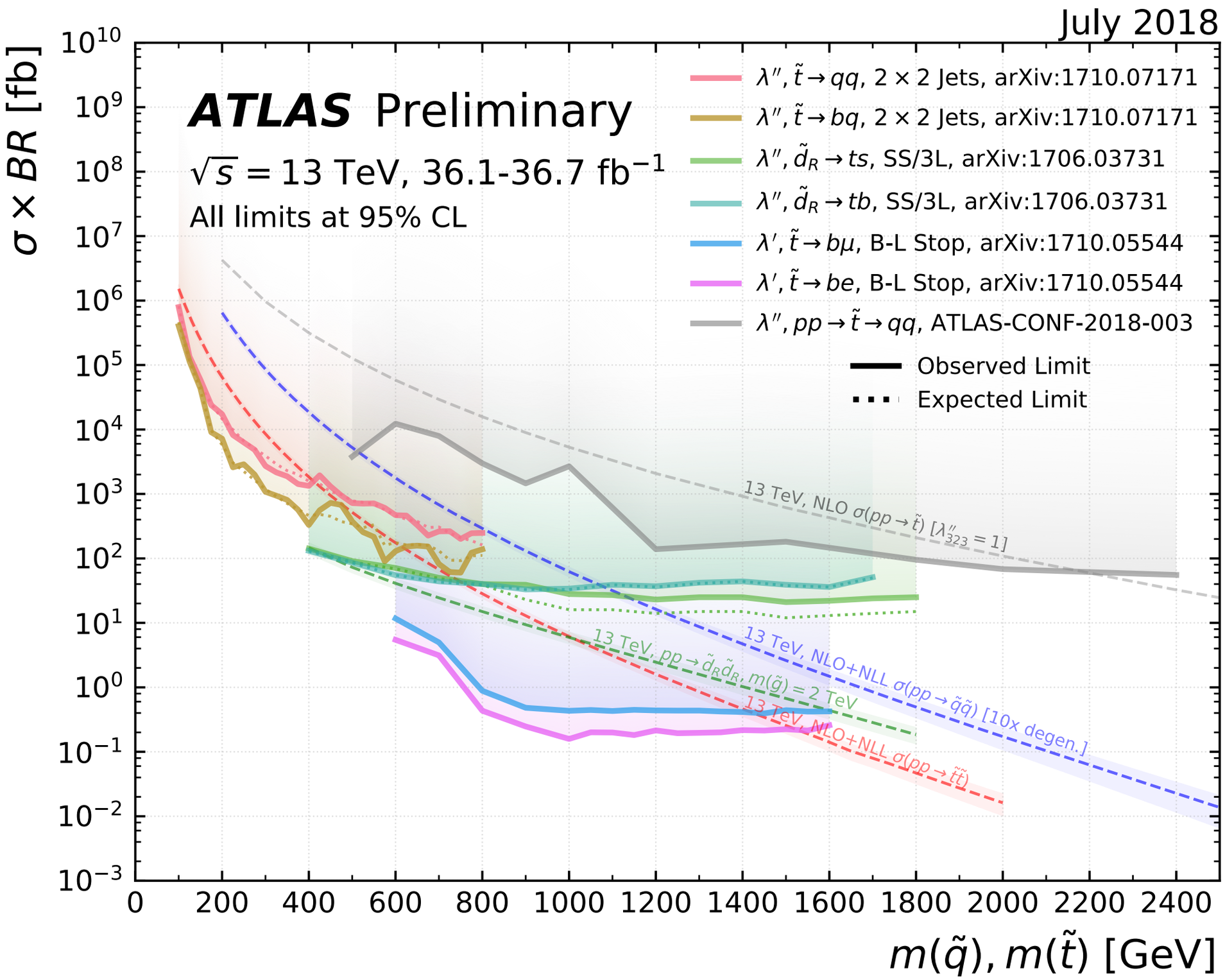

DM + HF summary

1903.01400