Top Quark Spin Correlations at the HL-LHC

Snowmass EF Workshop
February 3 2022

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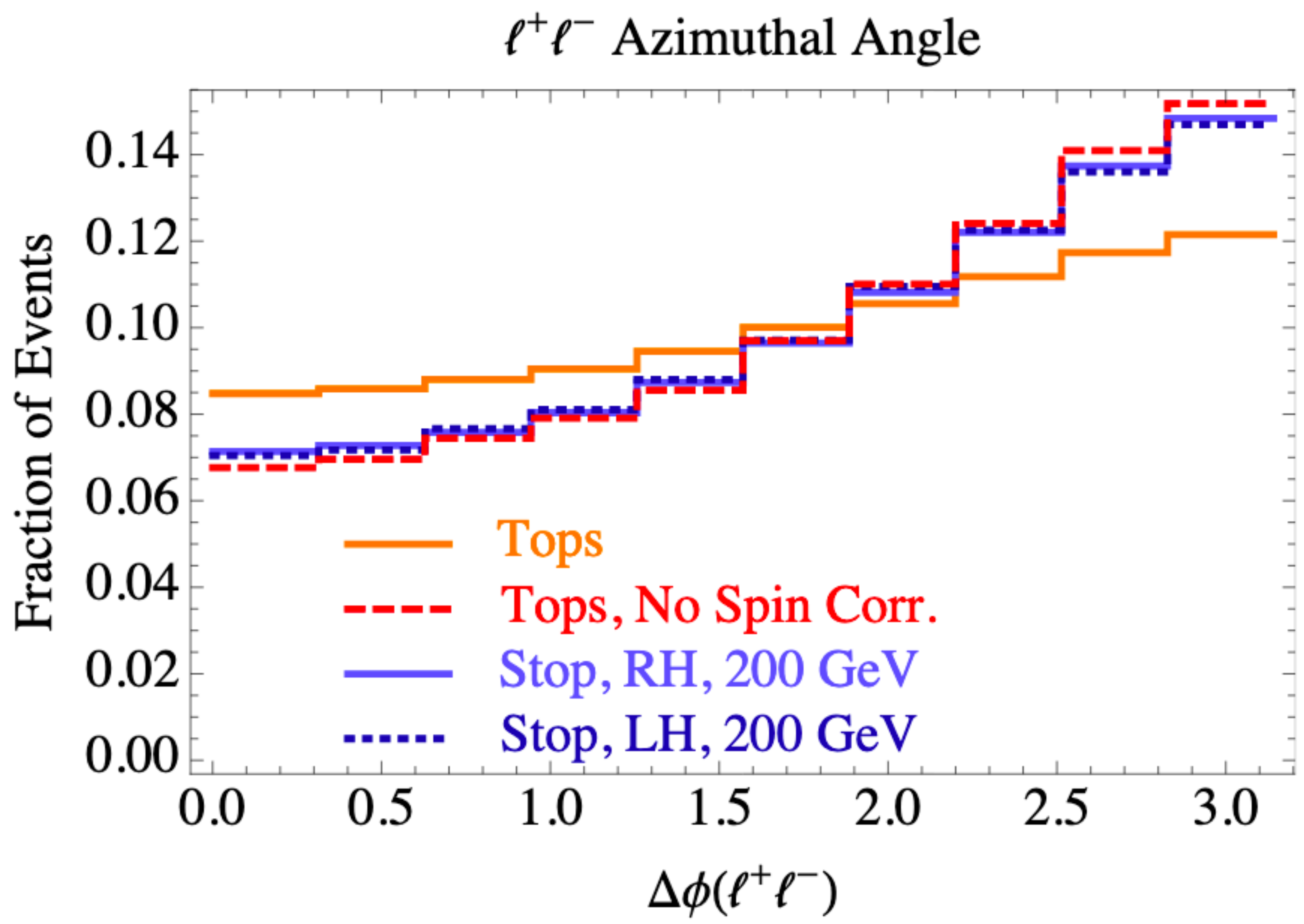
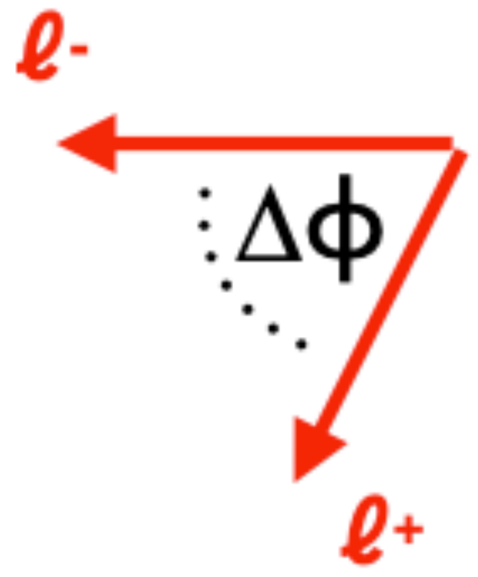
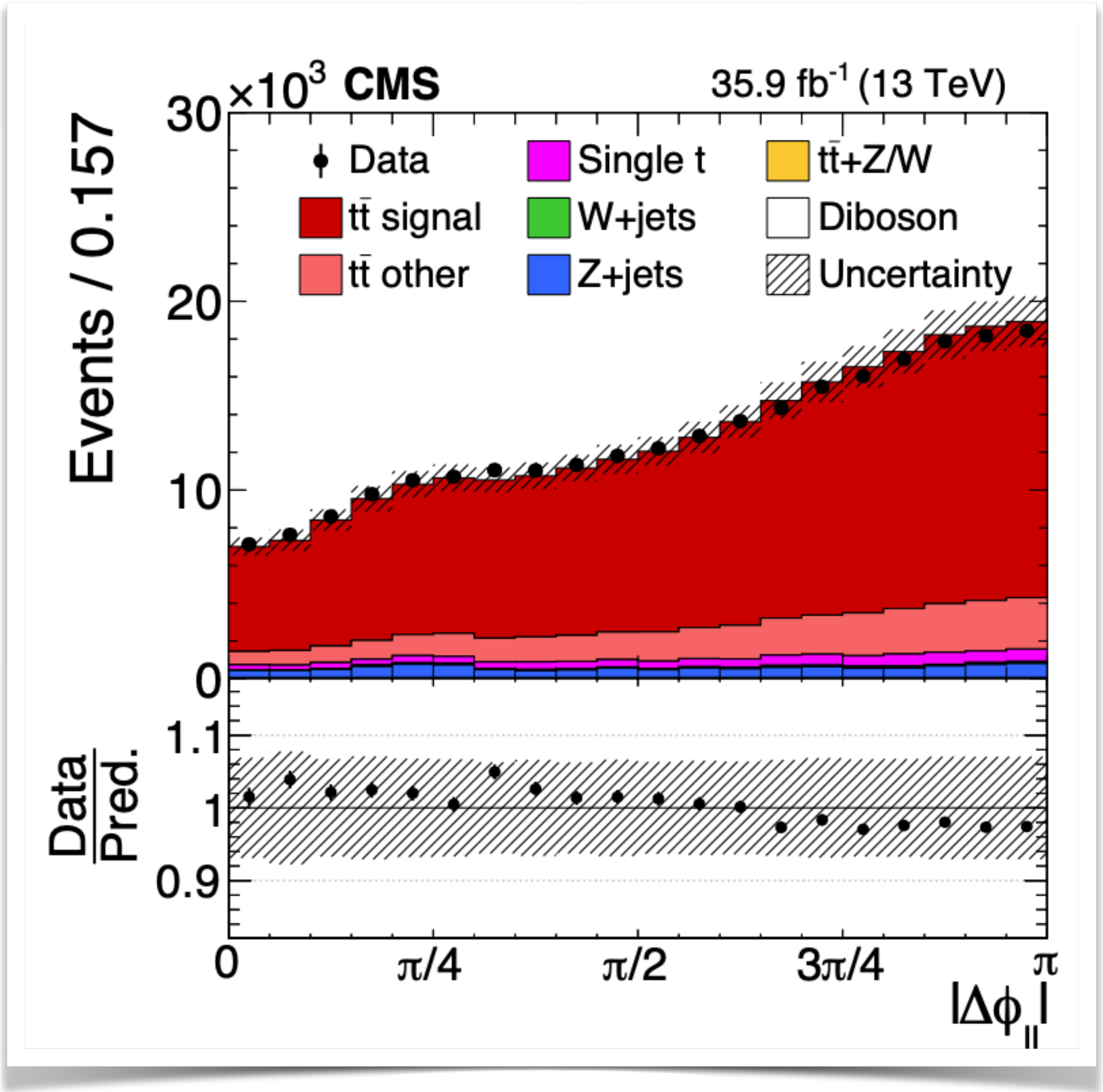
Spin correlations as a probe for BSM

- The spin analyzing power of charged leptons, $\kappa_l = +1$ is maximal.
- Can probe top quark spin in 3 dimensions. Also very well reconstructed.
- Very sensitive to BSM physics (s-channel dark matter : more spin correlation, new scalars : less spin correlation)





10.1007/JHEP08(2012)083



PRD 100, 072002
CMS Collaboration

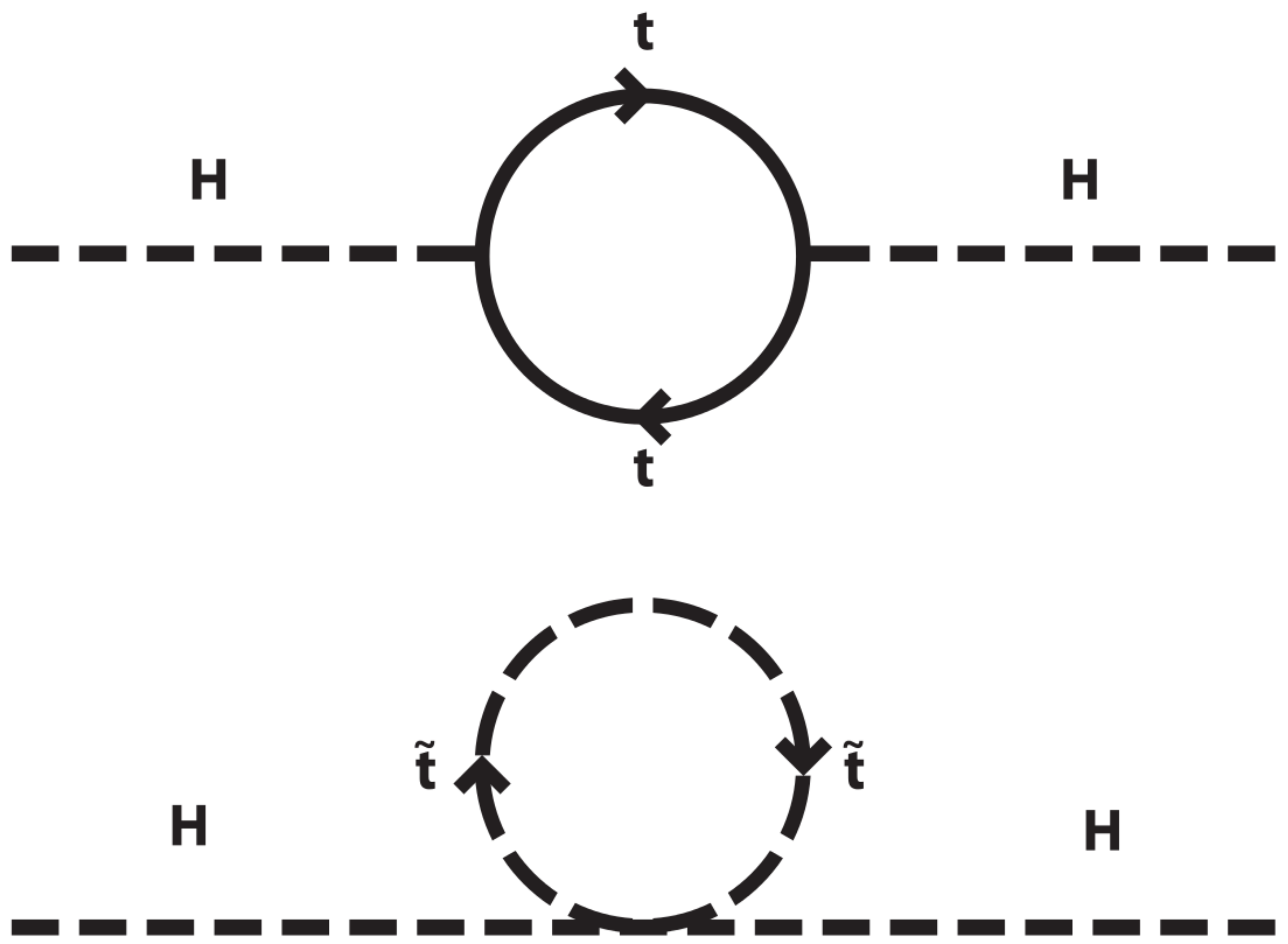
The need for BSM theories

- Fermion loop corrections to the Higgs mass are dominated by its coupling to the top quark (λ_f).

- Corrections to the Higgs mass $\delta M^2(Higgs) \sim \lambda_f^2 \Lambda^2$, where Λ is the cutoff scale.

- These quadratically divergent terms are cancelled by assuming a scalar counterpart to the top (stop).

- Stops with masses close to that of the top quark (stealth stops), require very little fine tuning to the theory, which is motivation to search in this phase space.

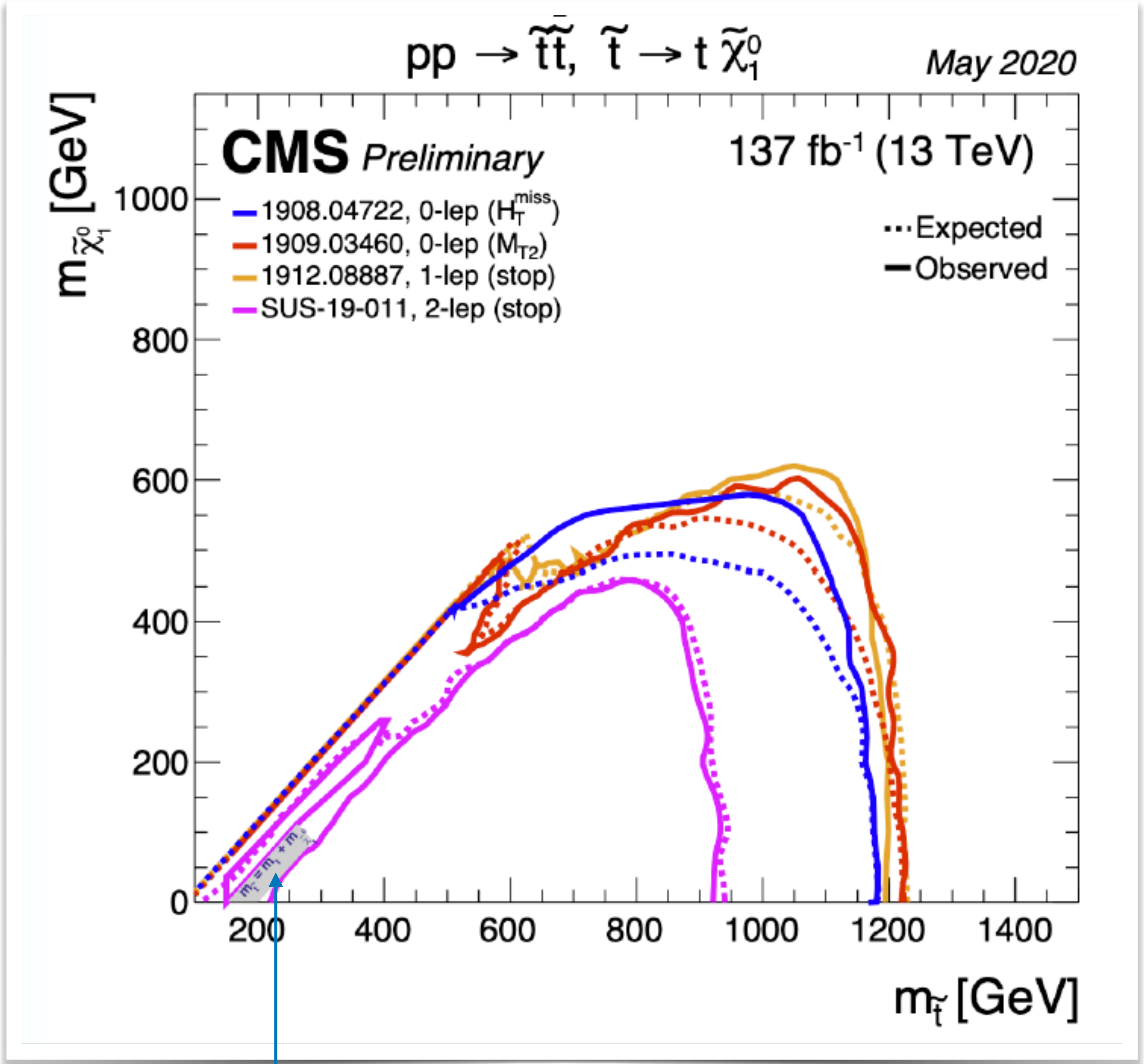


Higgs top loop
and the hypothesized
scalar top loop

Phys.Lett.B 429: 263-272, 1988
Arkani-Hamed et al.

SUSY top quark partners

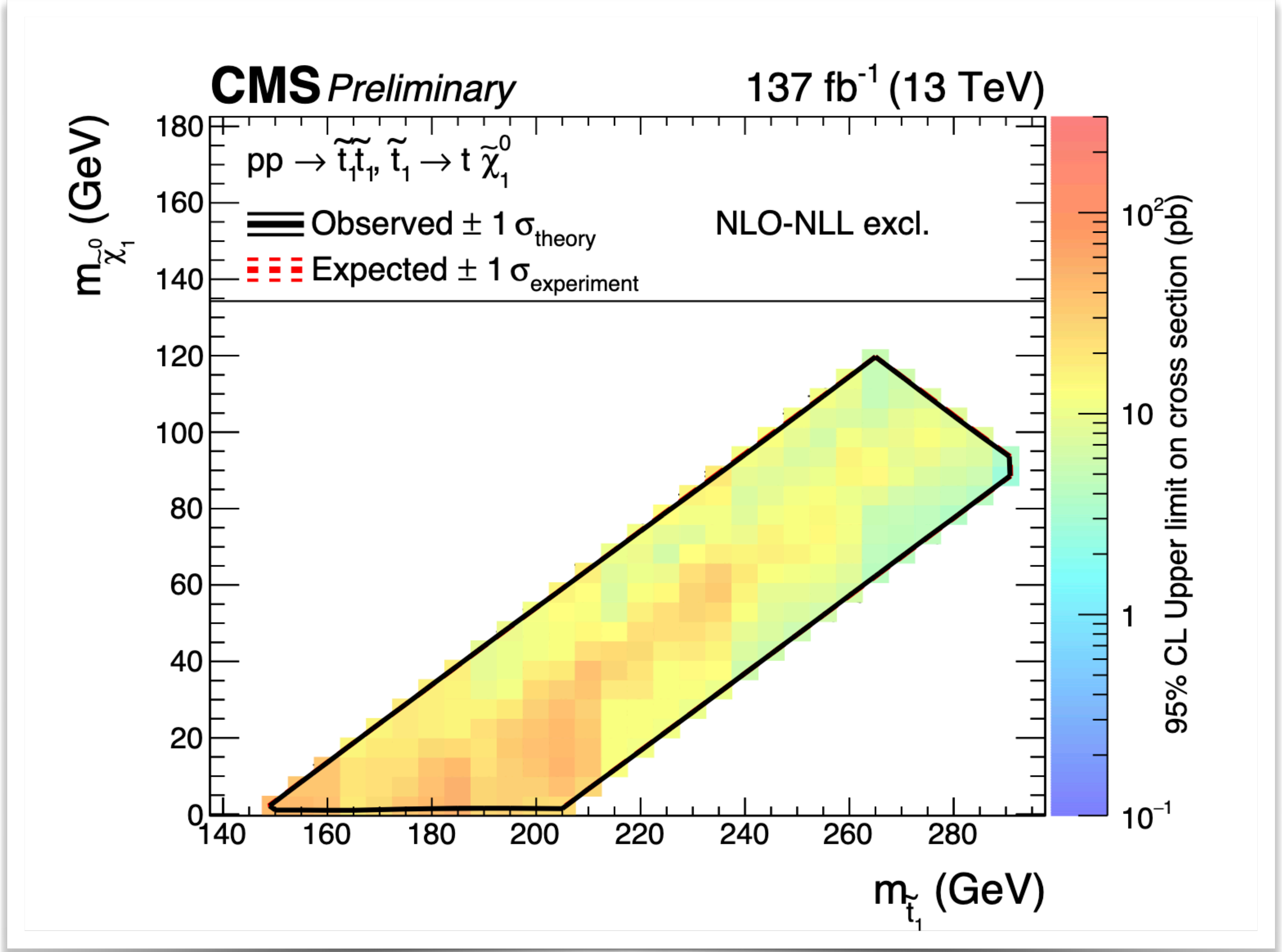
- Of particular interest is the stealth SUSY top corridor.
- This includes mass points such that:
  $M_{stop} \leq 242.5$ GeV, and
  $M_{stop} - M_{\chi_1^0} = M_{top}$
- The acceptance and efficiency change significantly in this region, making exclusion by direct searches harder in this region.



Top Corridor

SUSY top quark partners

- Hence the need for indirect searches.
- Exclusions can be accomplished via precision measurements of top quark properties, spin correlations in this case.
- Currently results in this region using spin correlations are from ATLAS.
- CMS also has results in the dileptonic channel, but using a direct search.



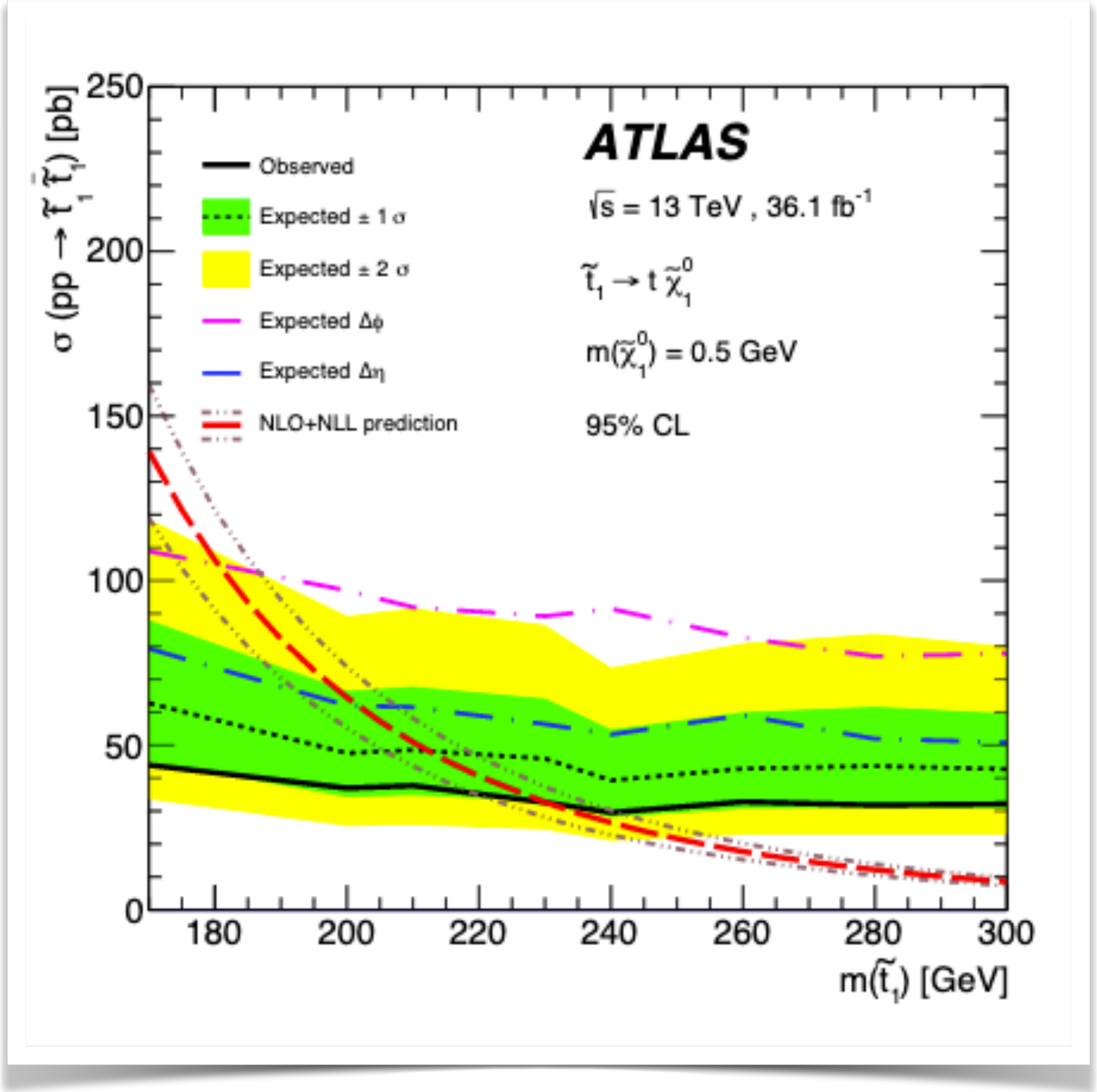
CMS-PAS-SUS-20-002

Strategy for our analysis

- Goal : To perform a sensitivity study on the prospects of the CMS detector for the HL-LHC to exclude top quark partners using top quark spin correlations.
- Kinematic Reconstruction of ttbar system
  - Geometric solver for neutrino momenta + solution smearing within energy resolutions.
- DNN discriminant for SUSY vs SM
  - Develop a SUSY vs all SM backgrounds classifier for all mass points in the sample.
  - The input to the discriminant are spin correlation variables only
- Limit setting
  - Feed DNN outputs into combine to obtain limits on SUSY cross-section.

Plans for Snowmass study

- Set limits in the SUSY top corridor using the spin correlation based DNN.
- Extend phase space beyond stealth corridor region and also study other partners to the top.
- Consider different uncertainty scenarios (full Run2, upcoming Run3 and the HL-LHC) and the impact of major systematics on the limits.
- Our HL-LHC analysis has been pre-approved, **and we expect to be approved by Feb 18th**.
- Could expand into spin density matrix measurement at other colliders/machines: 100 TeV pp, e+e-, muon colliders.



CERN-EP-2019-034. ATLAS

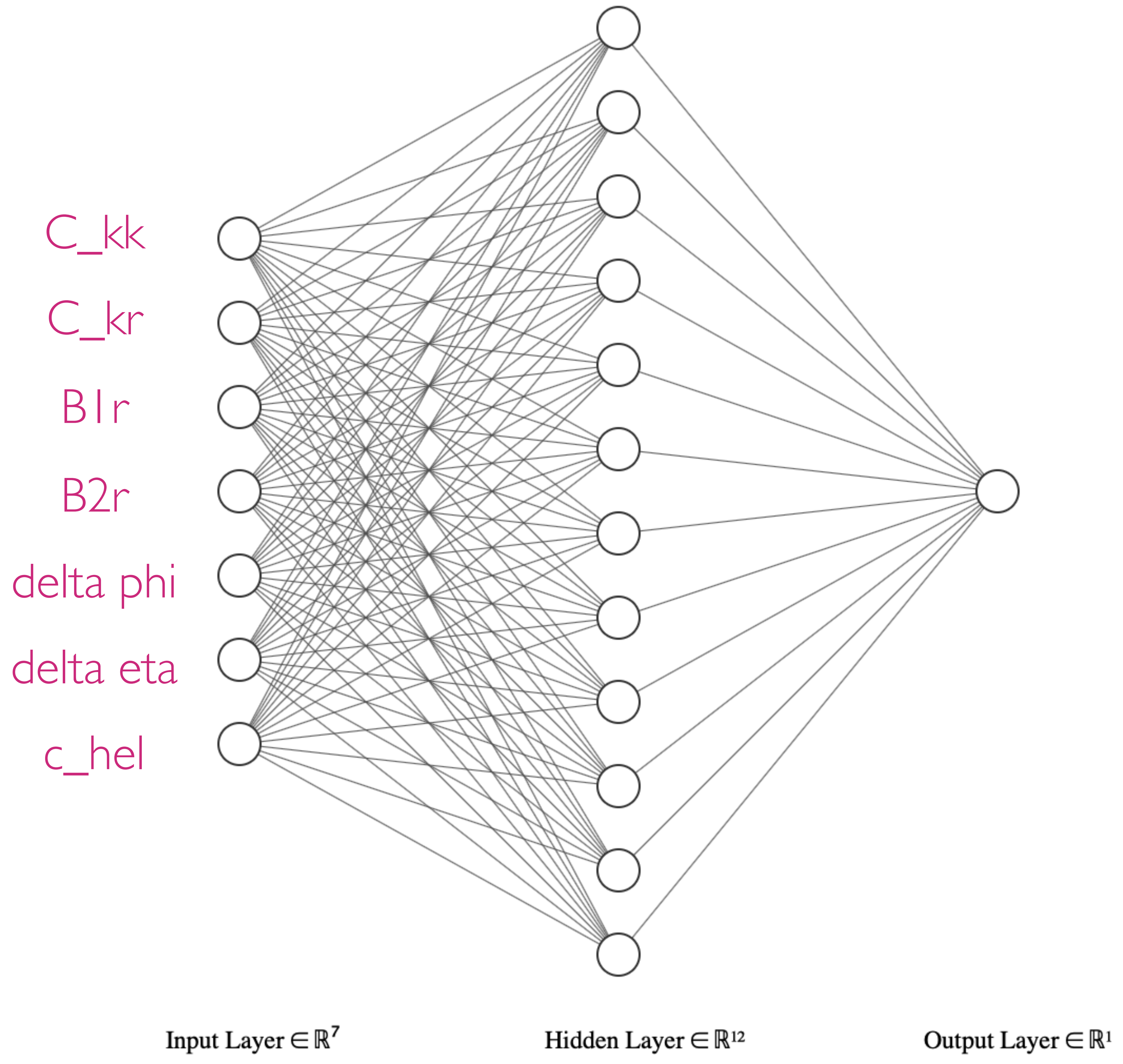
Plans for Snowmass study (beyond HL-LHC)

- Expand into spin density matrix measurement at other colliders/machines: 100 TeV pp, e+e-, muon colliders.
- Rely on the same framework: delphes-based analysis using same framework as for HL-LHC and ideally similar object ID as much as possible
- 100 TeV machine and muon collider appear with a lower threshold for students to get started (e+e- way more advanced with "real" MC)
- Group of UG students is working on 100 TeV and hope to start on muon as well. We hope to update soon on progress…goal: standalone arXiv, if possible connected with the Snowmass process even though past the white paper cut-off.

BACKUP

DNN classifier with spin corr inputs

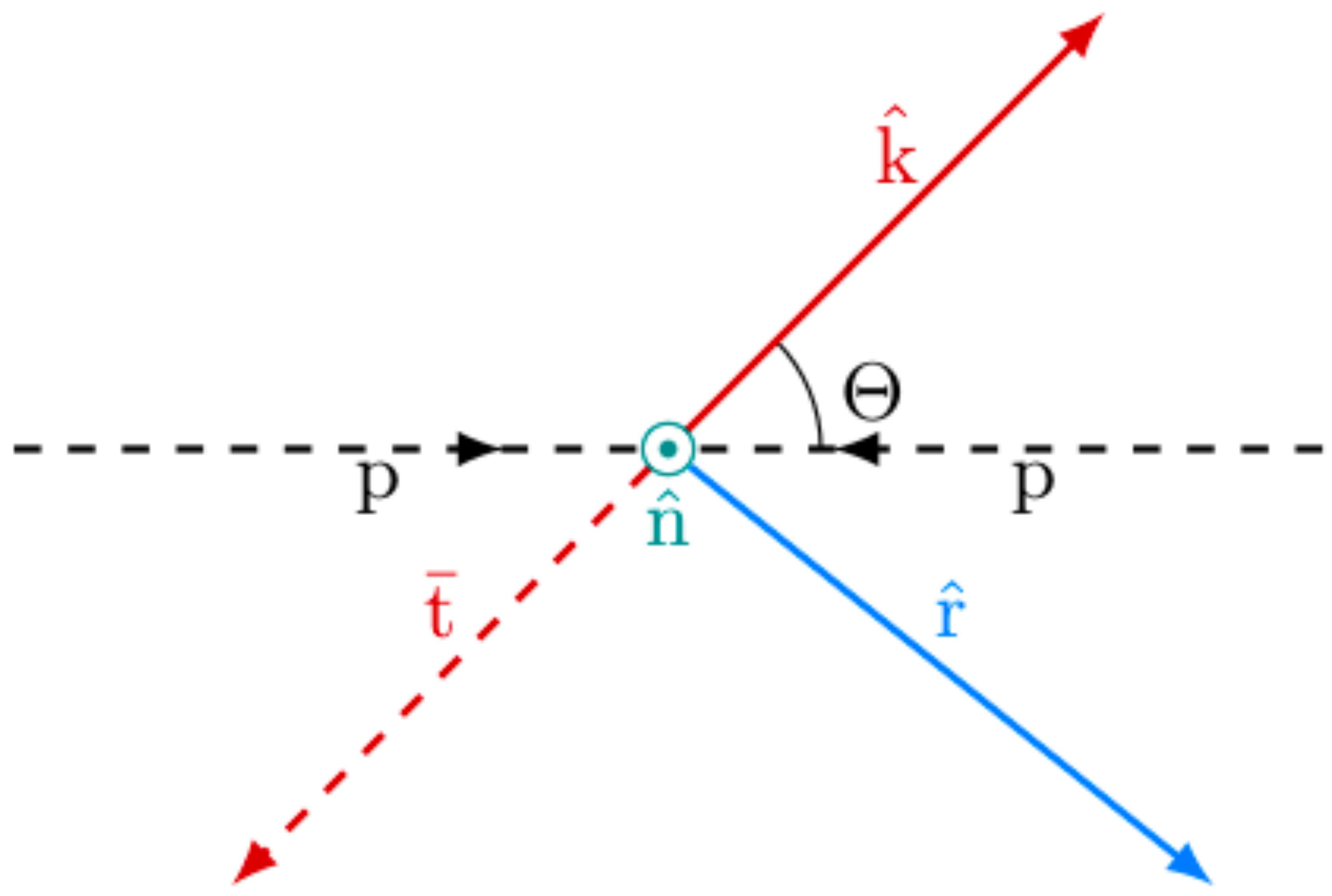
- With these 20 spin correlation variables as input, we use a DNN to construct a discriminant which can help exclude top partners.
- We use a binary classifier with a label of 0 (background) and 1 (signal).
- We develop a classifier for each mass point (signal hypothesis) within the SUSY sample.



Spin correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

- For a certain choice of reference axis, the spin polarizations are given by the coefficients $B^i_{1/2}$, while the spin correlations are given by C_{ij} in the above expression.
- Indices 1 and 2 are for top and anti-top respectively.
- For our purposes we choose axis $\hat{k}$ as the direction of flight of the top in the ttbar rest frame.
- Axis $\hat{r}, \hat{n}$ are defined as :



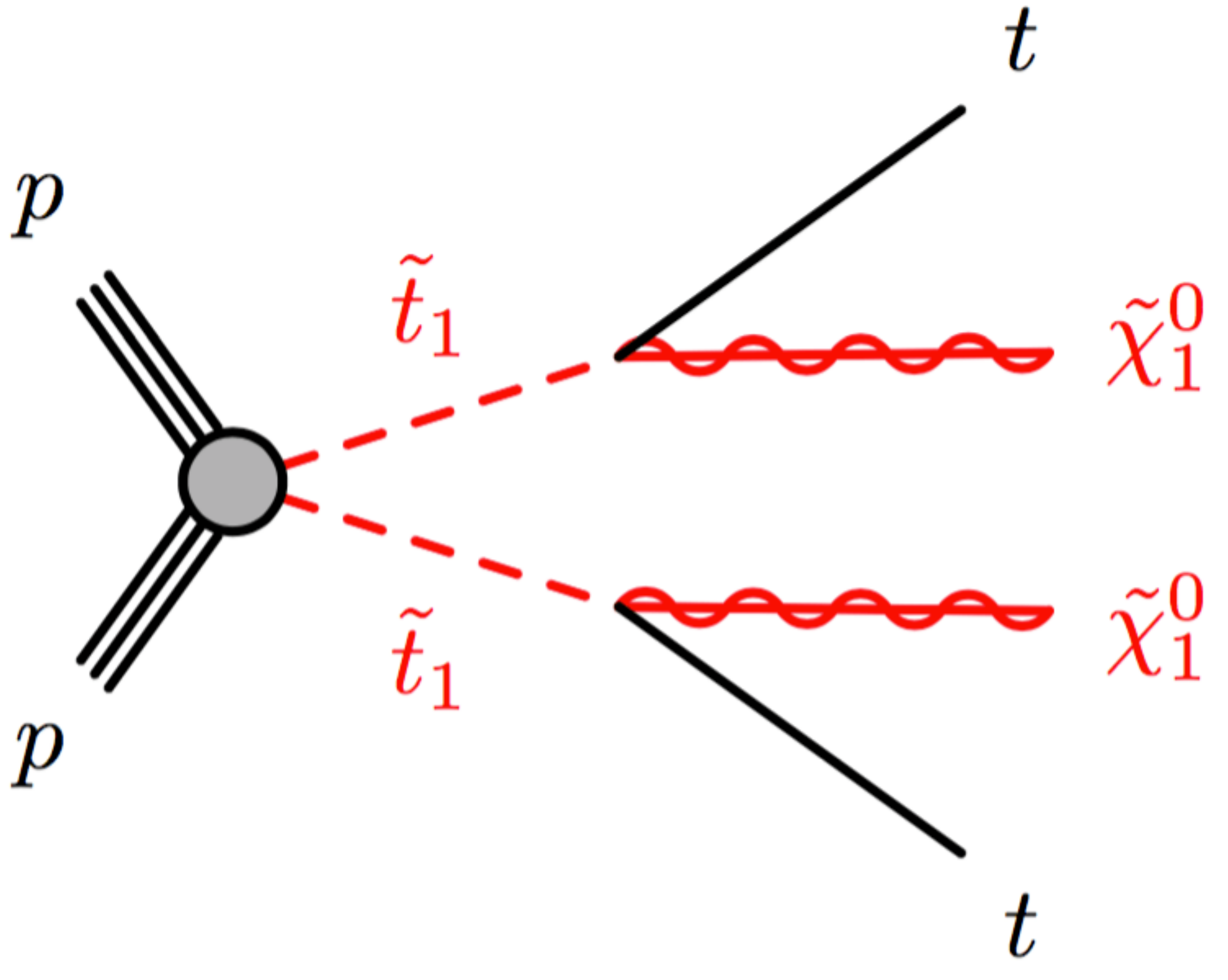
arXiv:1508.0527

$$\hat{\mathbf{p}}_p = (0,0,1)\,,\quad \hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}})\,,\quad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,,$$
$$y_p = \hat{\mathbf{p}}_p \cdot \hat{\mathbf{k}}\,,\quad r_p = \sqrt{1-y_p^2}\,.$$

Signal and background processes

- The scalar stop is assumed to decay into a top and a neutralino 100% of the time.
- We use centrally produced Delphes samples for this study.
- Search for 2 oppositely charged leptons events in the $e\mu$ channel (include semileptonic tau decays).
- Then select events with 2 or more jets, at least one of which is b-tagged.
- $E_T^{miss} > 30$ GeV

Stop decay



SM background	Fraction
$t\bar{t}$	0.788
$t\bar{t}$ other	0.129
single top	0.049
other	0.034

Includes mis-id leptons and taus ← ($t\bar{t}$ other)

Z+ jets, WW, WZ etc. ← (other)

Spin correlation variables

- The spin correlation variables of choice are :
  - $B^i_{1/2}$: Spin polarization of the top (1) or anti-top (2) along the $\hat{k}, \hat{r}, \hat{n}$ axes.
  - C_{ij} : Spin correlation matrix elements for the $\hat{k}, \hat{r}, \hat{n}$ axes.
  - $D = -\frac{1}{3}Tr(C)$.
  - $\Delta\phi$ and $\Delta\eta$ between the leptons.
- All of the above defined variables except $\Delta\phi$ require a reconstruction of the top quark system.

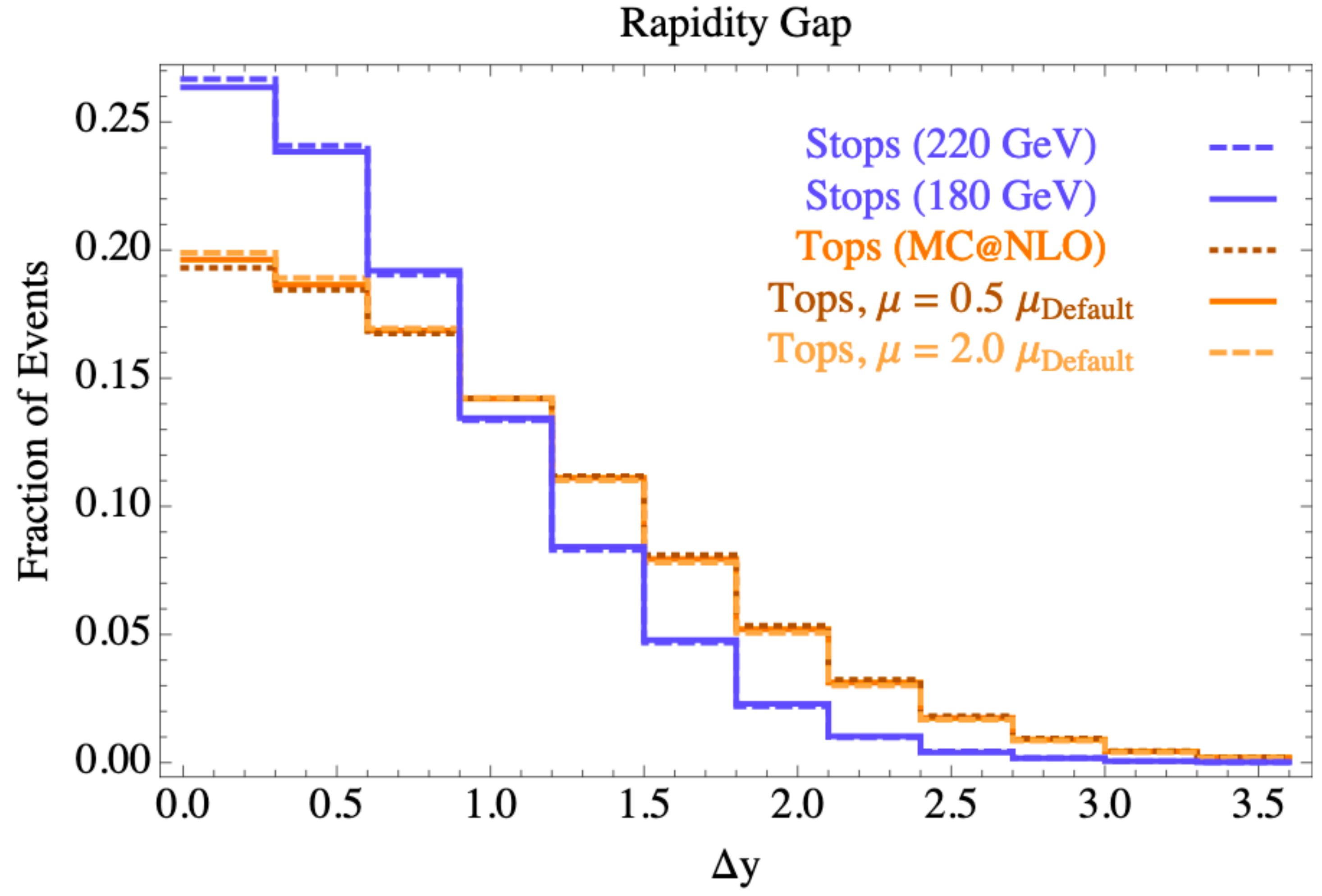
Observable	**Measured coefficient**	**Coefficient function**
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-
$\cos\theta_1^k \cos\theta_2^k$	C_{kk}	c_{kk}
$\cos\theta_1^r \cos\theta_2^r$	C_{rr}	c_{rr}
$\cos\theta_1^n \cos\theta_2^n$	C_{nn}	c_{nn}
$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$	$C_{rk} + C_{kr}$	c_{rk}
$\cos\theta_1^r \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^r$	$C_{rk} - C_{kr}$	c_n
$\cos\theta_1^n \cos\theta_2^r + \cos\theta_1^r \cos\theta_2^n$	$C_{nr} + C_{rn}$	c_{nr}
$\cos\theta_1^n \cos\theta_2^r - \cos\theta_1^r \cos\theta_2^n$	$C_{nr} - C_{rn}$	c_k
$\cos\theta_1^n \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^n$	$C_{nk} + C_{kn}$	c_{kn}
$\cos\theta_1^n \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^n$	$C_{nk} - C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$
$\|\Delta\phi_{\ell\ell}\|$	$\|\Delta\phi_{\ell\ell}\|$	$-$
$\|\Delta\eta_{\ell\ell}\|$	$\|\Delta\eta_{\ell\ell}\|$	$-$

Motivating the choice of features

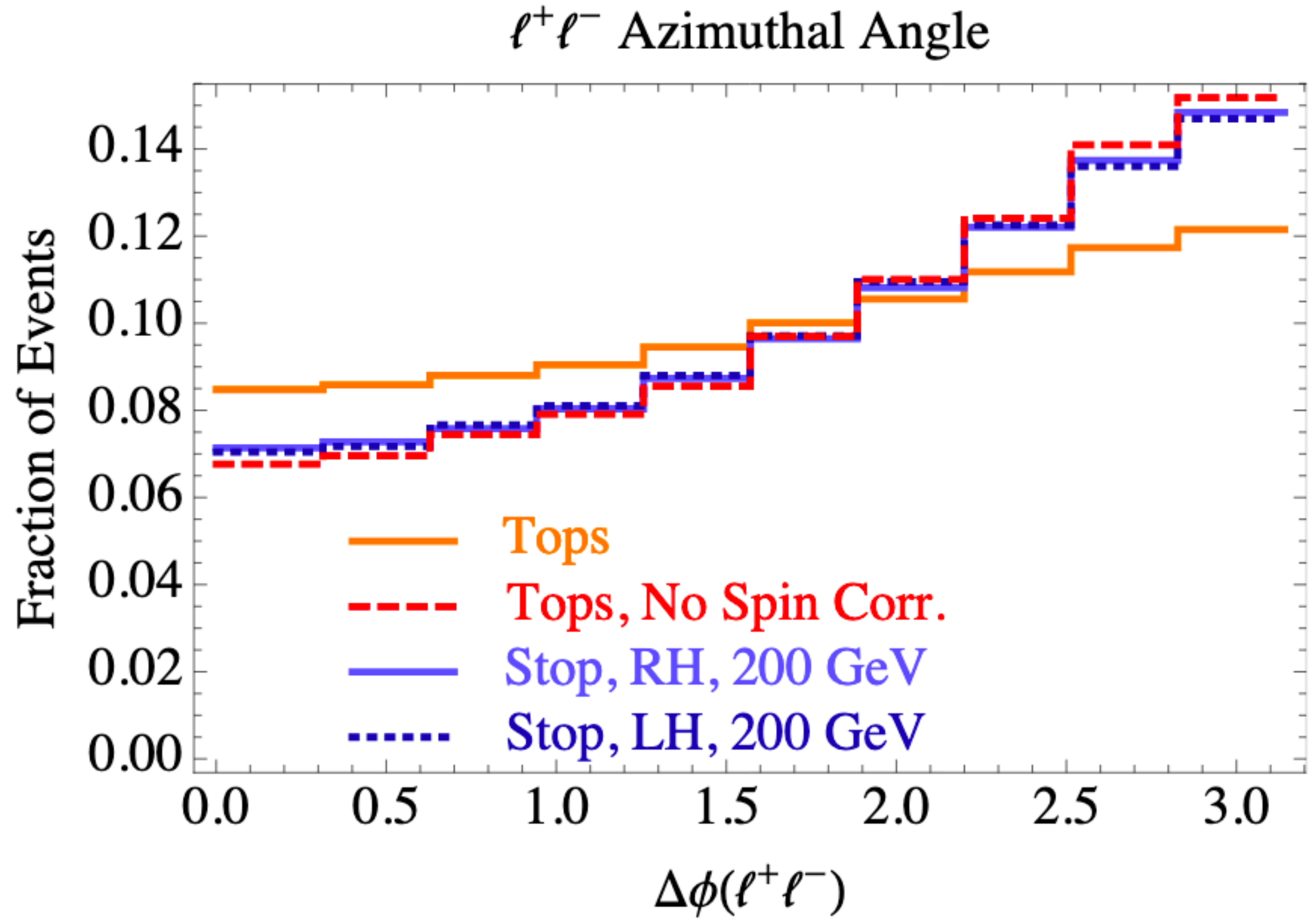
- Because of the difference in the production mechanism, stops being scalars, we see that they behave like tops with close to no spin correlations.

- Because of the neutralino emitted, there is more MET in the SUSY process.

- Also, the stop being more massive leads to different pt distributions.



10.1007/JHEP08(2012)083
M Reece et al.



Mass points

Initial state	$t\bar{t}$	$\tilde{t}\tilde{t}^*$
gg	68 pb	11 pb
$q\bar{q}$	23 pb	1.6 pb

10.1007/JHEP08(2012)083

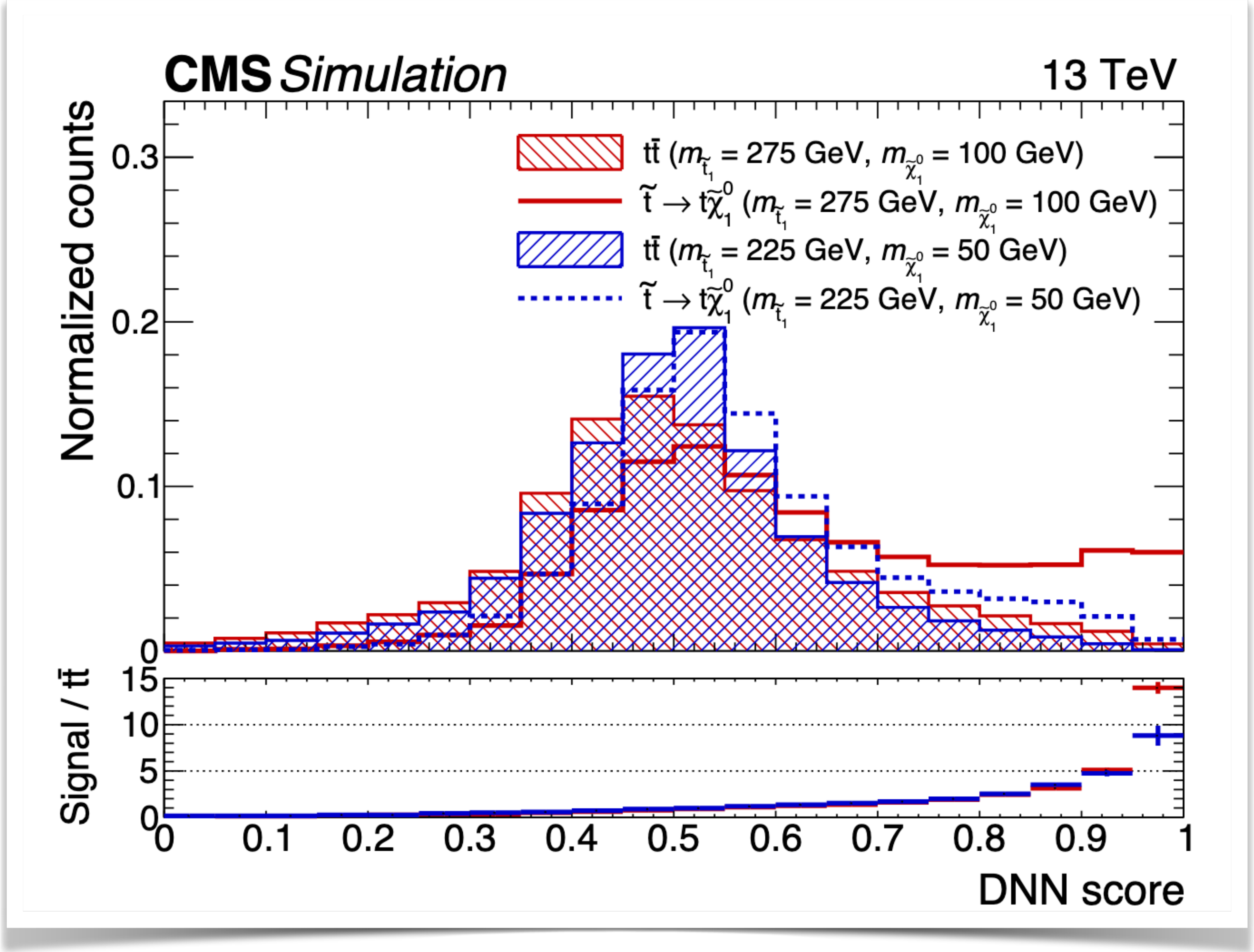
$$C(\hat{\mathbf{a}}, \hat{\mathbf{b}}) = \kappa_\ell^2 \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

https://arxiv.org/pdf/1508.05271.pdf

$\Delta M = 167.5\,\mathrm{GeV}/c^2$	$\Delta M = 175\,\mathrm{GeV}/c^2$	$\Delta M = 182.5\,\mathrm{GeV}/c^2$	Cross Section [pb] $\pm\ \delta$ [%]
167.5, 0	-	-	173.0±14.3%
175, 7.5	175, 0	-	143.4±14.3%
182.5, 15	182.5, 7.5	182.5, 0	108.0±14.3%
190, 22.5	190, 15	190, 7.5	97.7±14.4%
197.5, 30	197.5, 22.5	197.5, 15	80.2±14.3%
205, 37.5	205, 30	205, 22.5	68.3±14.3%
212.5, 45	212.5, 37.5	212.5, 30	53.6±14.2%
220, 52.5	220, 45	220, 37.5	48.6±14.2%
227.5, 60	227.5,52.5	227.5,45	45.6±14.2%
235, 67.5	235, 60	235, 52.5	35.2±14.2%
242.5, 75	242.5, 67.5	242.5, 60	31.3±14.1%

CMS kinematic approach

- Current CMS SUSY analysis uses the full Run2 dataset to set limits in the stealth stop region.
- Kinematic variables including p_T, η of the leptons, $\Delta\phi$, $\Delta\eta$ between the leptons and E_T^{miss} are used.
- A parametric DNN is used to discriminate different physics models (mass points).



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