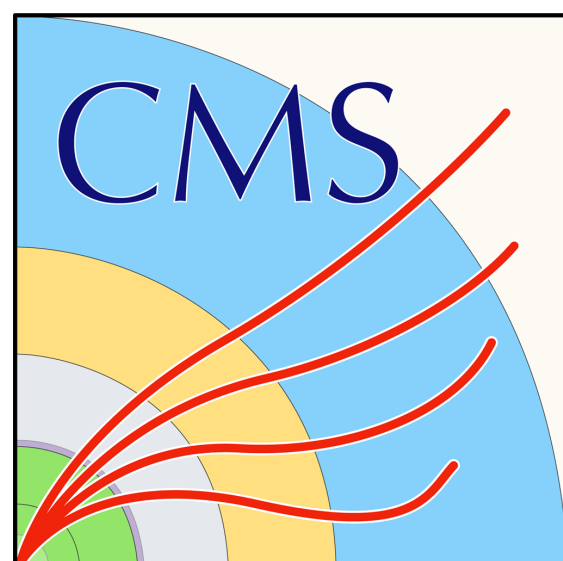# Top Quark Spin Correlations at the HL-LHC

Snowmass EF Workshop
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The top quark

$$m_{top} = 172.44 \pm 0.13 \pm 0.47 \text{ GeV}$$

PRD 93 072004
CMS Collaboration

- The top quark is the heaviest known fundamental particle

- It decays before forming any bound states, thereby relaying the spin information to the daughter particles.

$$\text{lifetime} \quad < \quad \begin{array}{c} \text{QCD} \\ \text{timescale} \end{array} \quad \ll \quad \begin{array}{c} \text{spin-flip} \\ \text{timescale} \end{array}$$

$$10^{-25}\,\text{s} \quad < \quad 10^{-24}\,\text{s} \quad \ll \quad 10^{-21}\,\text{s}$$

- Thus, it is an ideal candidate for spin measurements.

- Top quark spin measurements are a powerful probe for new physics in the $t\bar{t}$ production.
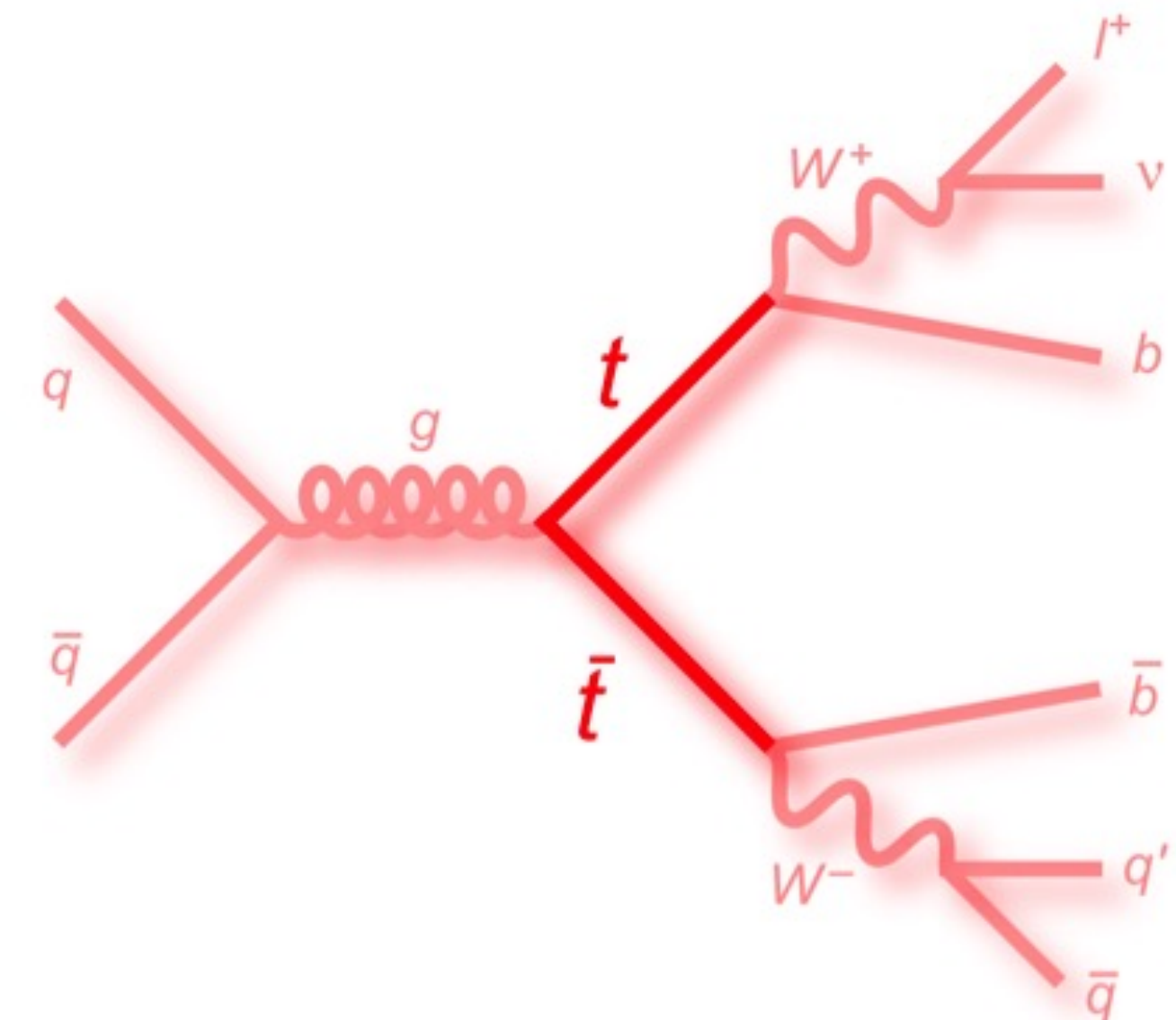
Spin correlations

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

- For a certain choice of reference axis, the spin polarizations are given by the coefficients $B_{1/2}^i$, 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.

arXiv:1508.0527

- Axis $\hat{r}, \hat{n}$ are defined as :
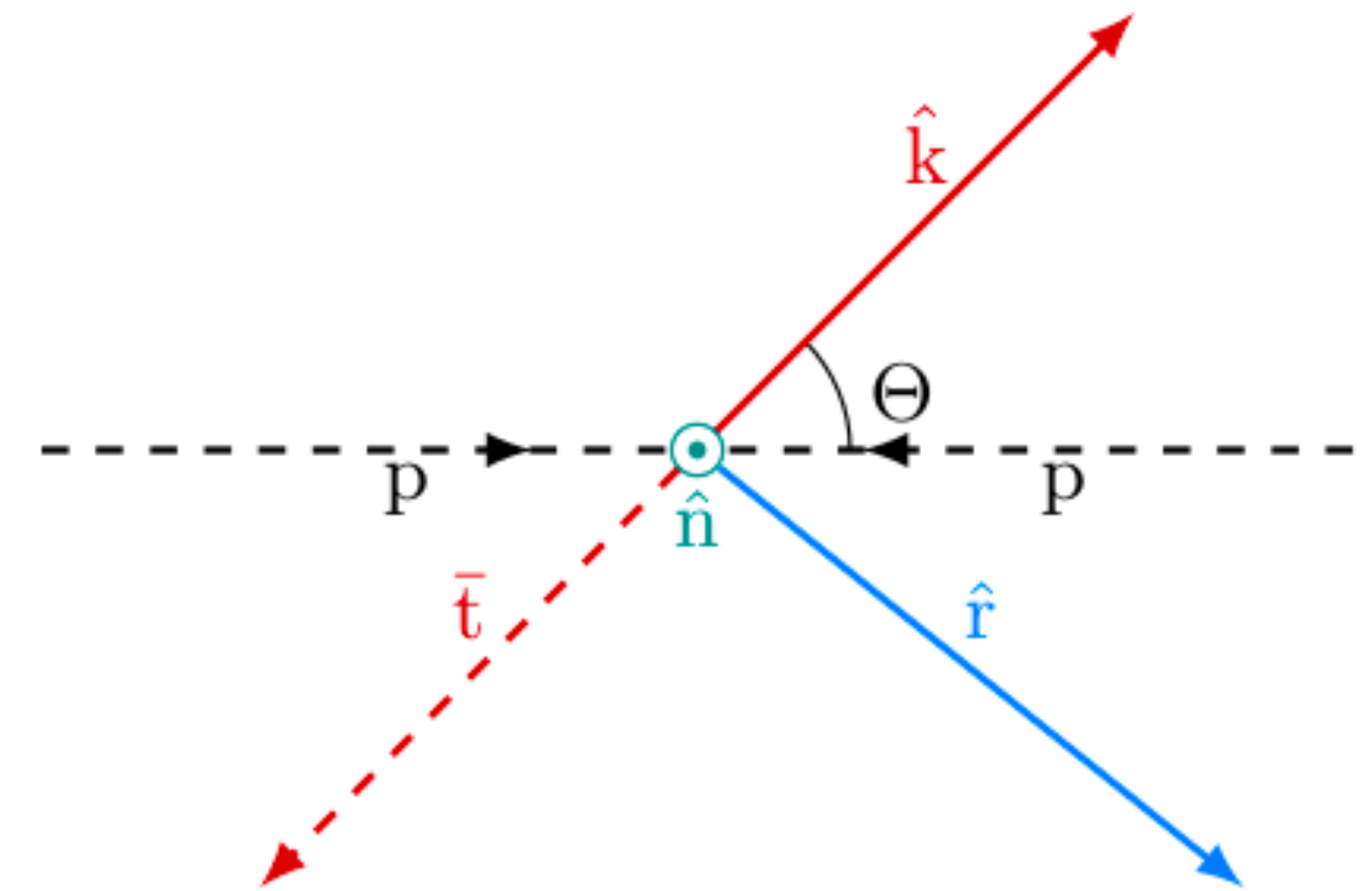
$$\hat{\mathbf{p}}_p = (0,0,1)\,, \quad \hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}})\,, \qquad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,,$$
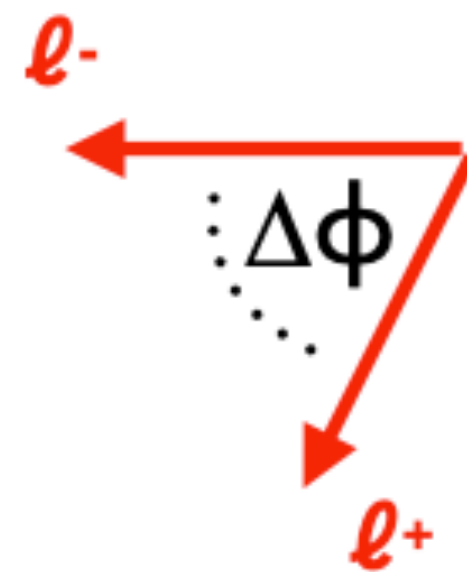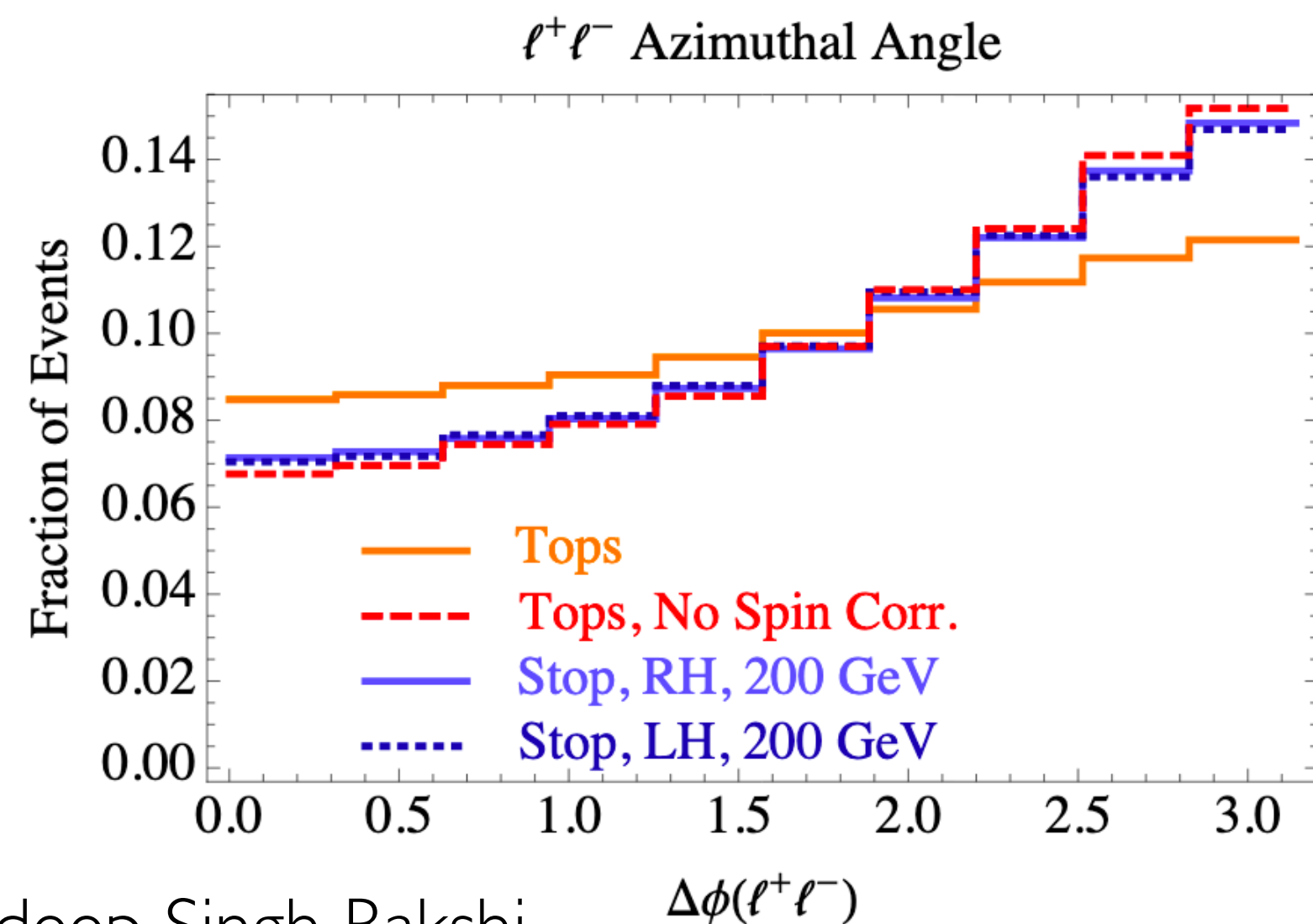
$$y_p = \hat{\mathbf{p}}_p \cdot \hat{\mathbf{k}}\,, \qquad r_p = \sqrt{1-y_p^2}\,.$$
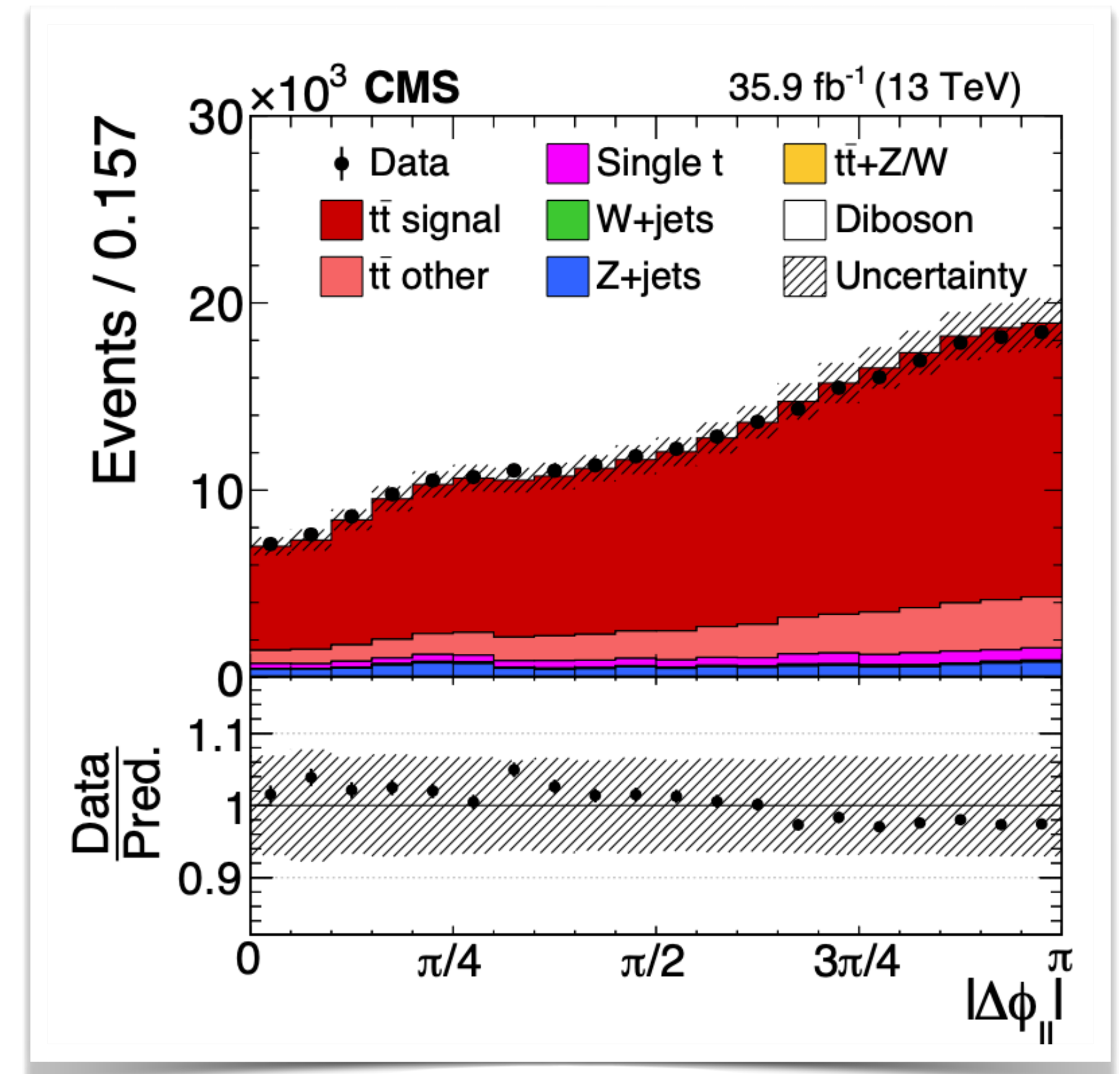
Spin correlations as a probe for BSM

- 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.
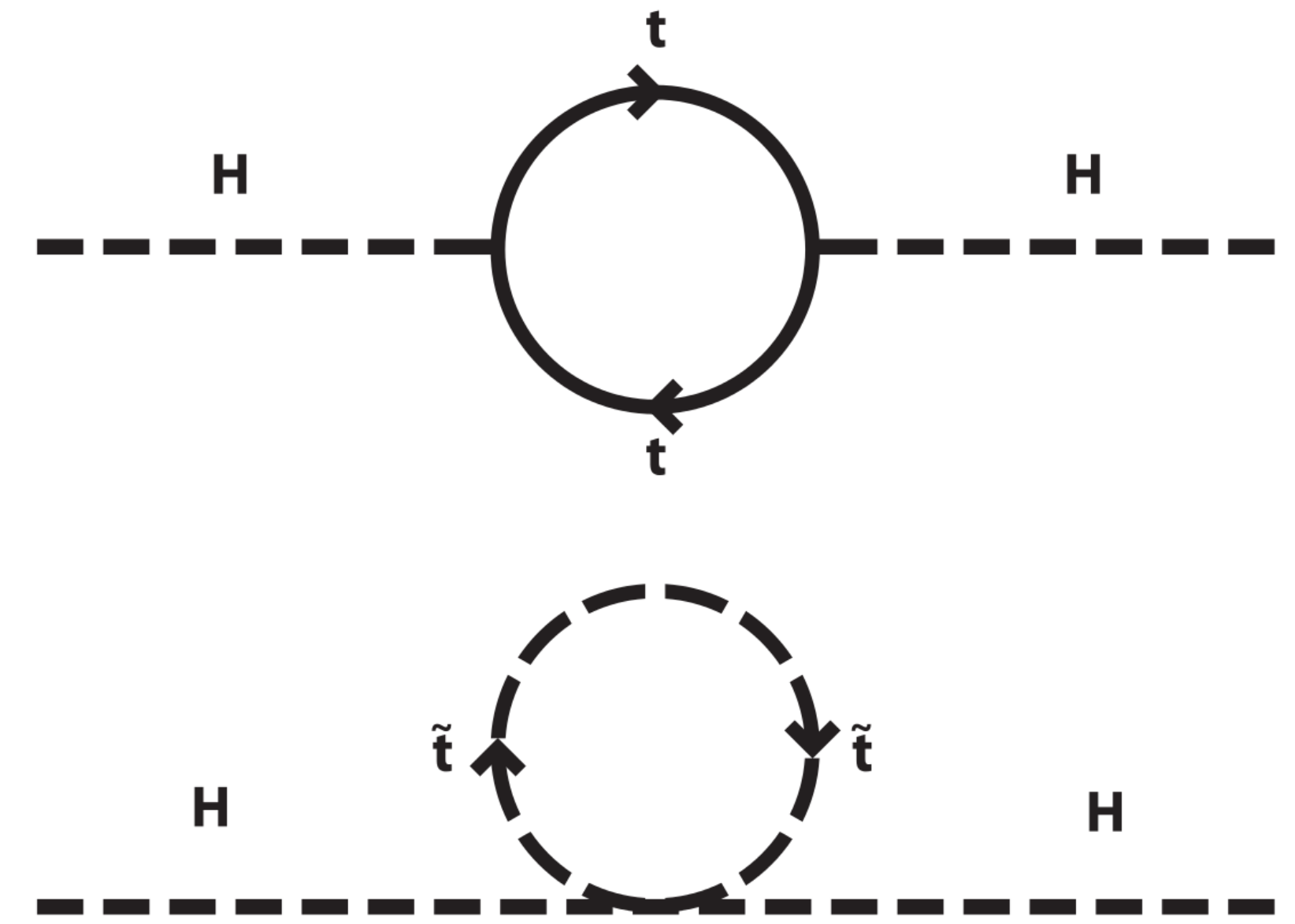
Higgs top loop
and the hypothesized
scalar top loop

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

Amandeep Singh Bakshi

SUSY top quark partners

- Of particular interest is the stealth SUSY top corridor.

- This includes mass points such that:
$$M_{stop} \leq 242.5 \text{ GeV, and}$$
$$M_{stop} - M_{\chi_1^0} = M_{top}$$

- The acceptance and efficiency change significantly in this region, making exclusion by direct searches harder in this region.
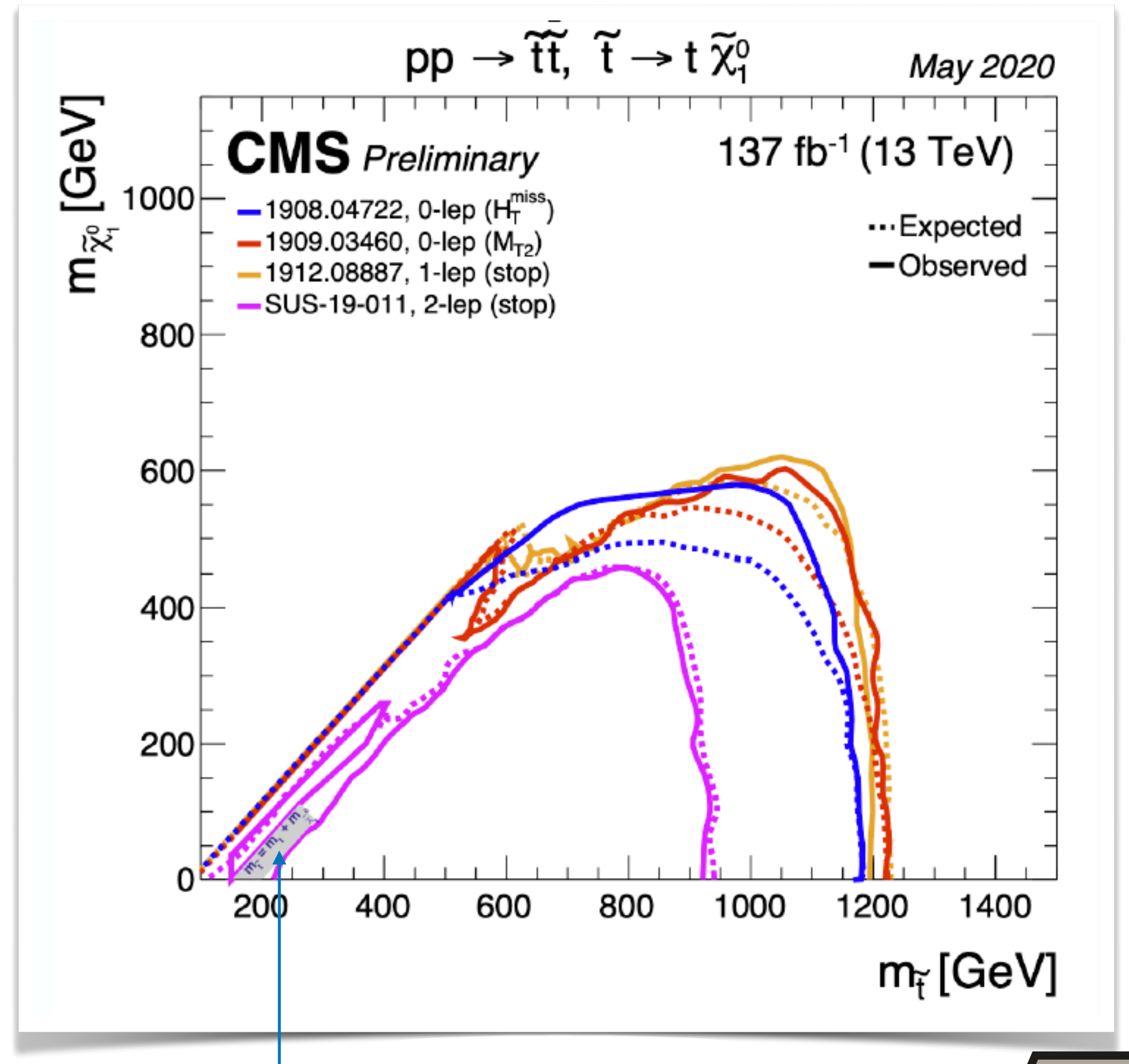
Top Corridor

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 *Preliminary*   137 fb^{-1} (13 TeV)

$pp \to \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \to t \tilde{\chi}_1^0$

Observed $\pm 1\sigma_{theory}$ NLO-NLL excl.
Expected $\pm 1\sigma_{experiment}$

$m_{\tilde{\chi}_1^0}$ (GeV) — vertical axis
$m_{\tilde{t}_1}$ (GeV) — horizontal axis

95% CL Upper limit on cross section (pb)
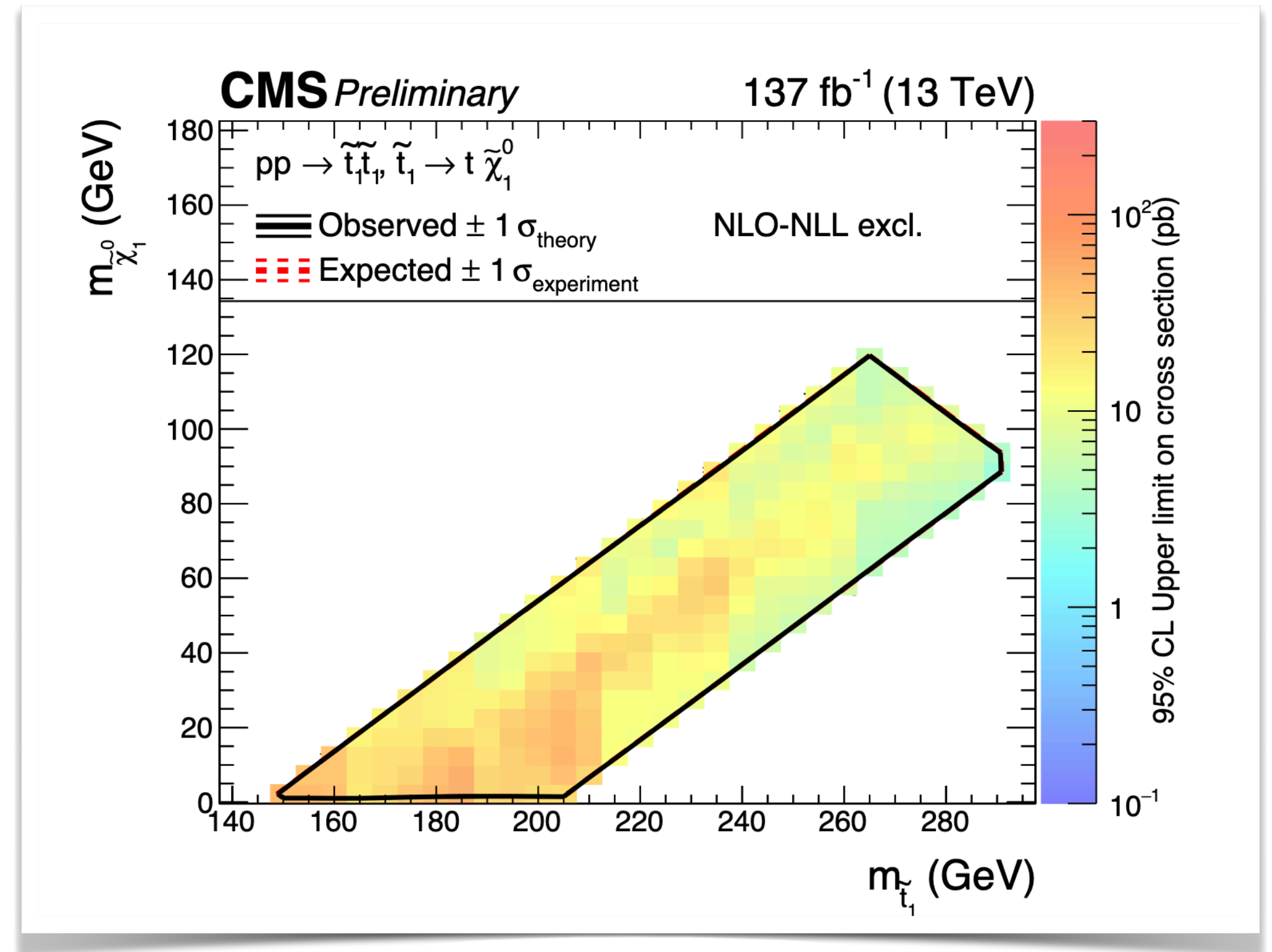
CMS-PAS-SUS-20-002

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).


CMS-PAS-SUS-20-002
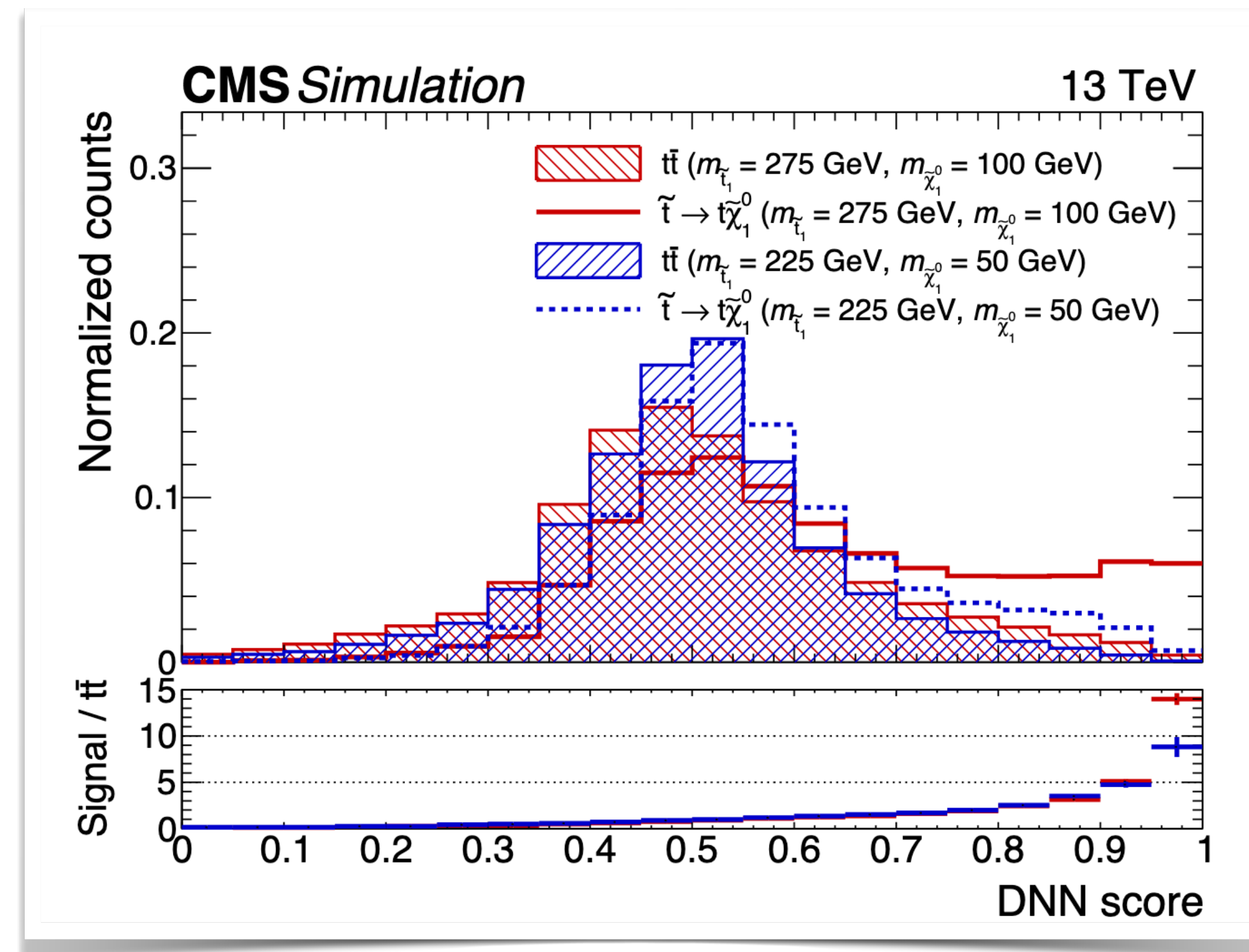
Strategy for our analysis

- <u>Goal</u> : 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.

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

Includes mis-id leptons and taus
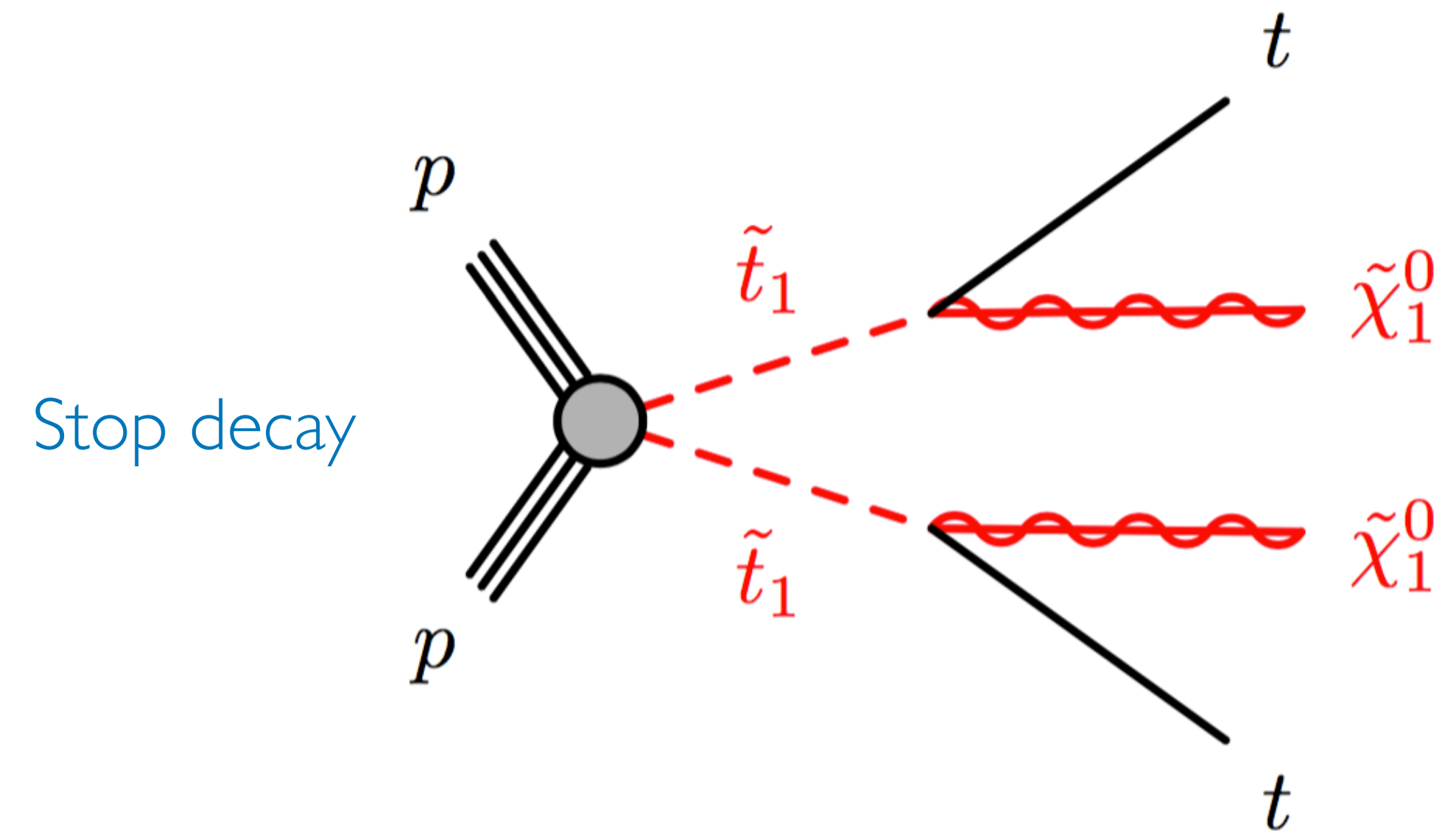
Z+ jets, WW, WZ etc.

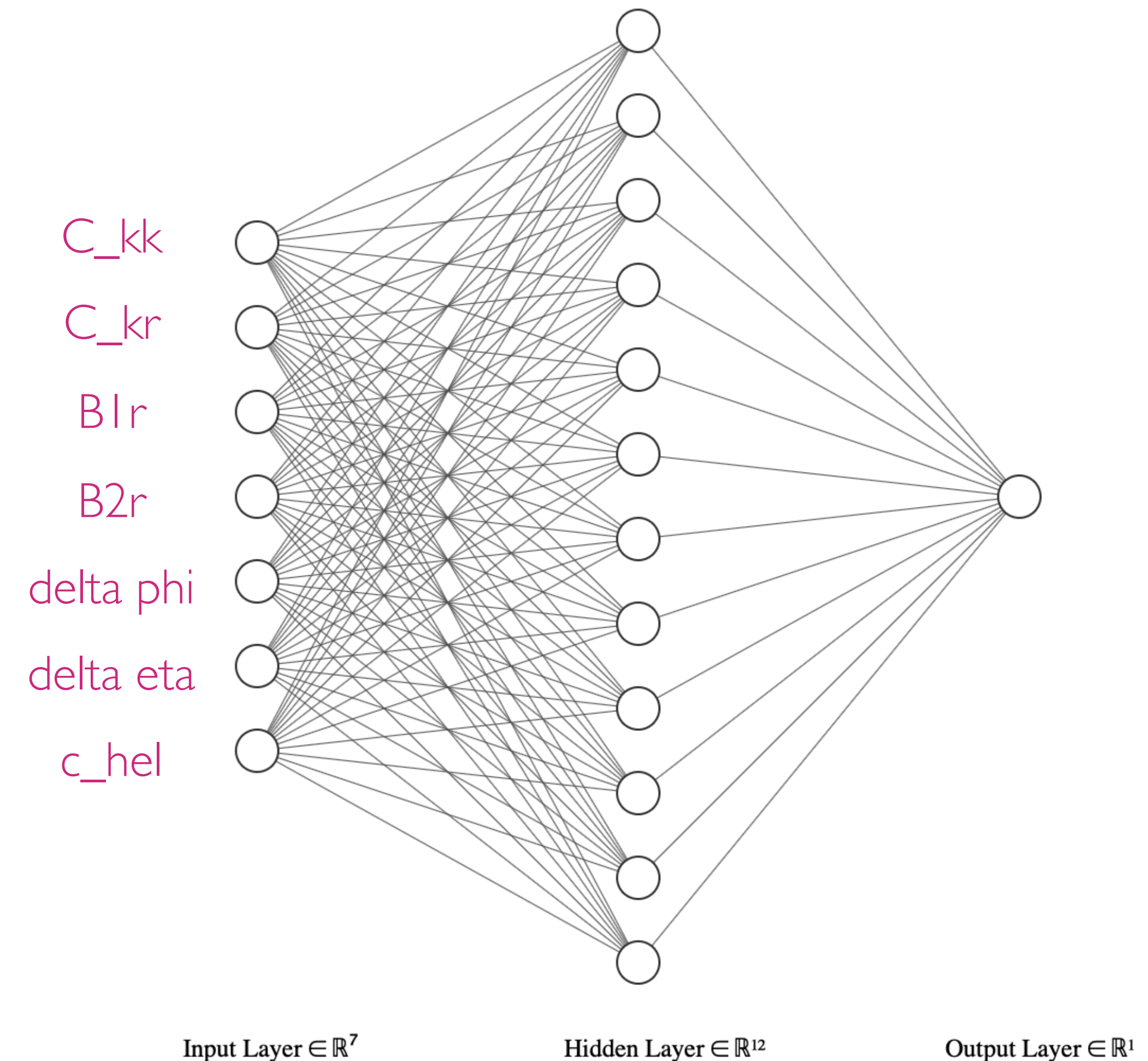| SM background	Fraction
$t\bar{t}$	0.788
$t\bar{t}$ other	0.129
single top	0.049
other	0.034

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.

  - $D = -\dfrac{1}{3}Tr(C).$

  - $\Delta\phi$ 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
$\cos\theta^k_1$	B^k_1	b^+_k
$\cos\theta^k_2$	B^k_2	b^-_k
$\cos\theta^r_1$	B^r_1	b^+_r
$\cos\theta^r_2$	B^r_2	b^-_r
$\cos\theta^n_1$	B^n_1	b^+_n
$\cos\theta^n_2$	B^n_2	b^-_n
$\cos\theta^k_1\cos\theta^k_2$	C_{kk}	c_{kk}
$\cos\theta^r_1\cos\theta^r_2$	C_{rr}	c_{rr}
$\cos\theta^n_1\cos\theta^n_2$	C_{nn}	c_{nn}
$\cos\theta^r_1\cos\theta^k_2 + \cos\theta^k_1\cos\theta^r_2$	$C_{rk} + C_{kr}$	c_{rk}
$\cos\theta^r_1\cos\theta^k_2 - \cos\theta^k_1\cos\theta^r_2$	$C_{rk} - C_{kr}$	c_n
$\cos\theta^n_1\cos\theta^r_2 + \cos\theta^r_1\cos\theta^n_2$	$C_{nr} + C_{rn}$	c_{nr}
$\cos\theta^n_1\cos\theta^r_2 - \cos\theta^r_1\cos\theta^n_2$	$C_{nr} - C_{rn}$	c_k
$\cos\theta^n_1\cos\theta^k_2 + \cos\theta^k_1\cos\theta^n_2$	$C_{nk} + C_{kn}$	c_{kn}
$\cos\theta^n_1\cos\theta^k_2 - \cos\theta^k_1\cos\theta^n_2$	$C_{nk} - C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$
$|\Delta\phi_{\ell\ell}|$	$|\Delta\phi_{\ell\ell}|$	$-$
$|\Delta\eta_{\ell\ell}|$	$|\Delta\eta_{\ell\ell}|$	$-$

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.

C_kk

C_kr

B1r

B2r

delta phi

delta eta

c_hel

Input Layer $\in \mathbb{R}^7$ Hidden Layer $\in \mathbb{R}^{12}$ Output Layer $\in \mathbb{R}^1$

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.

- Could expand into spin density matrix measurement at other colliders/machines: 100 TeV pp, e+e-, muon colliders.
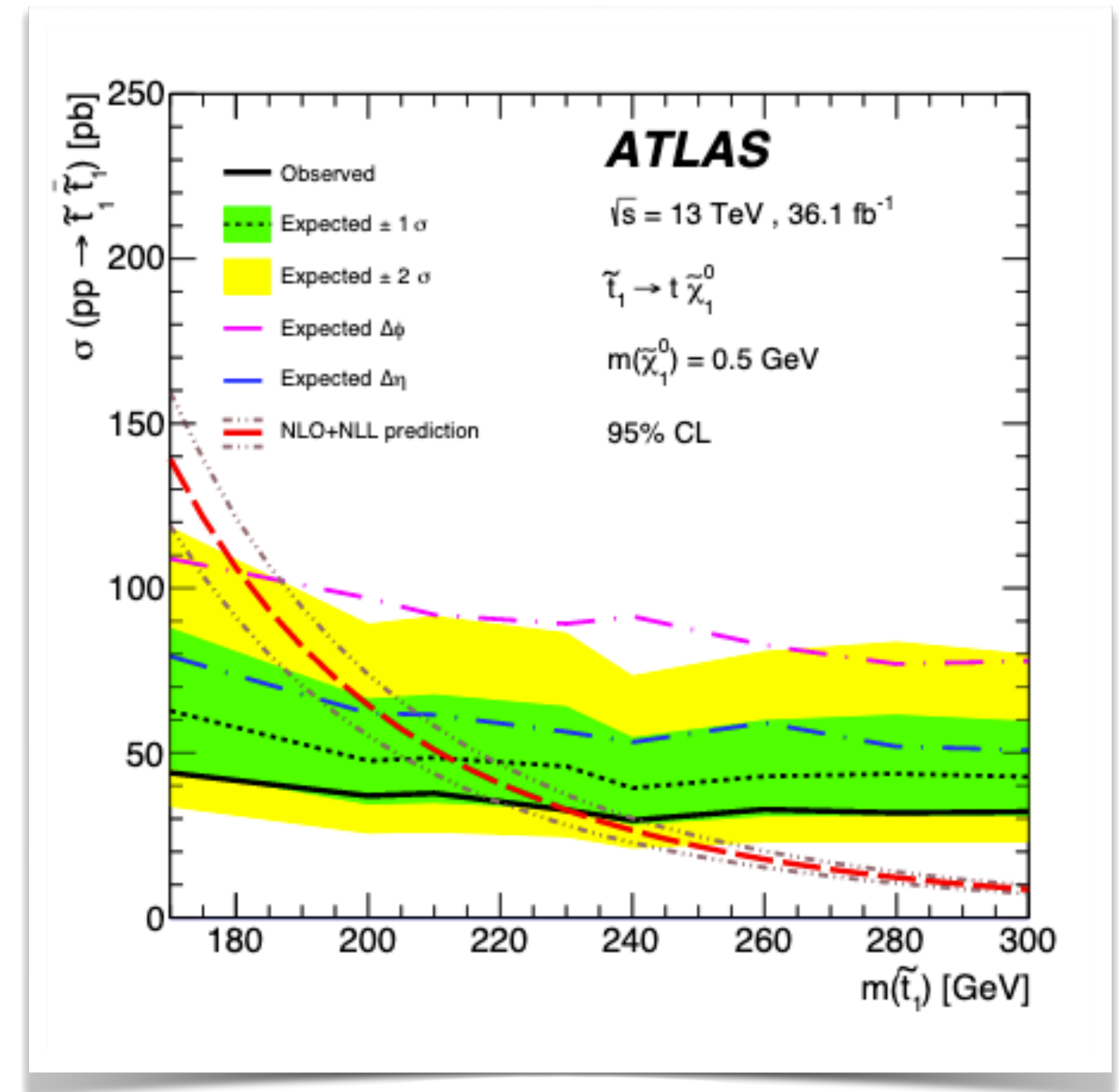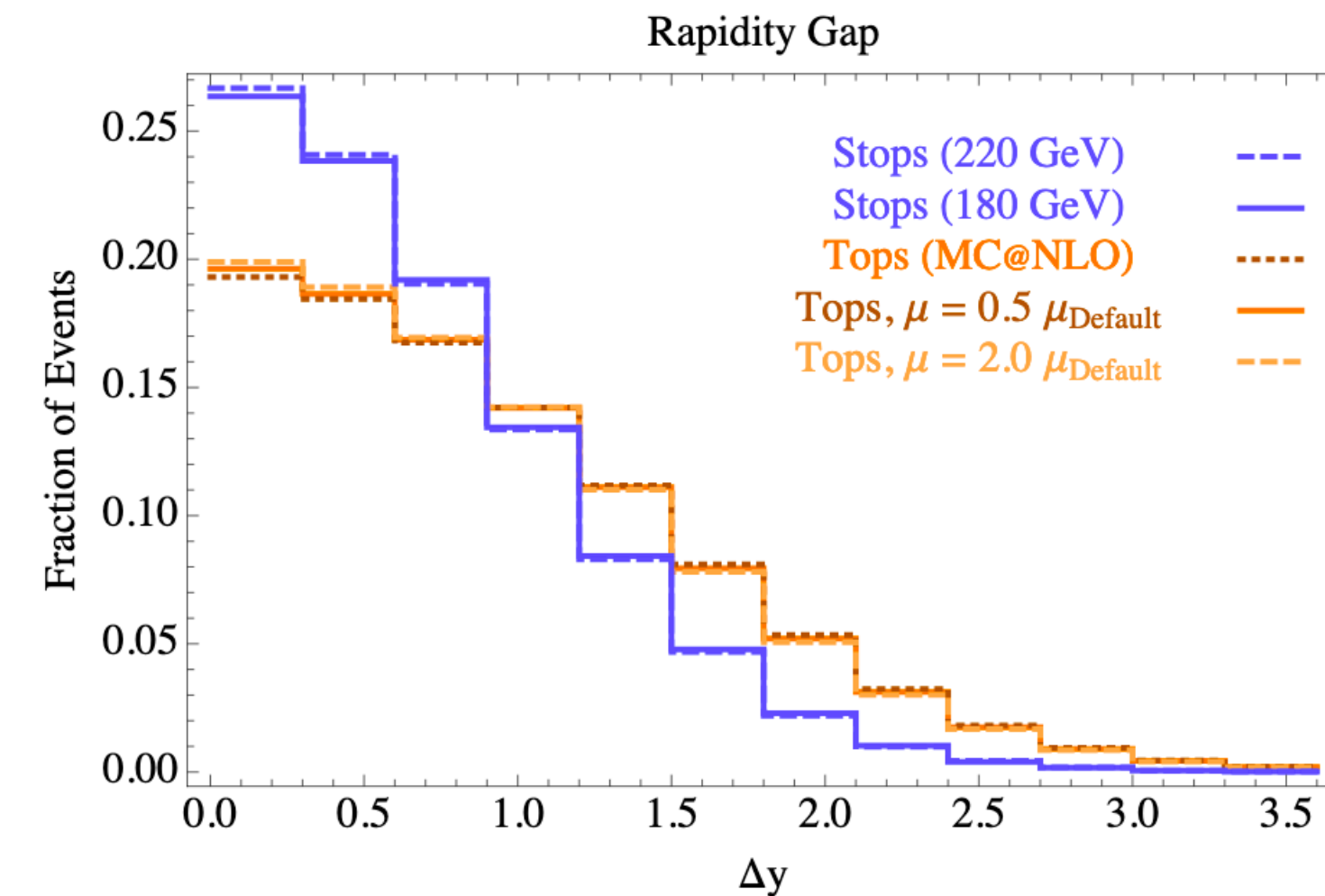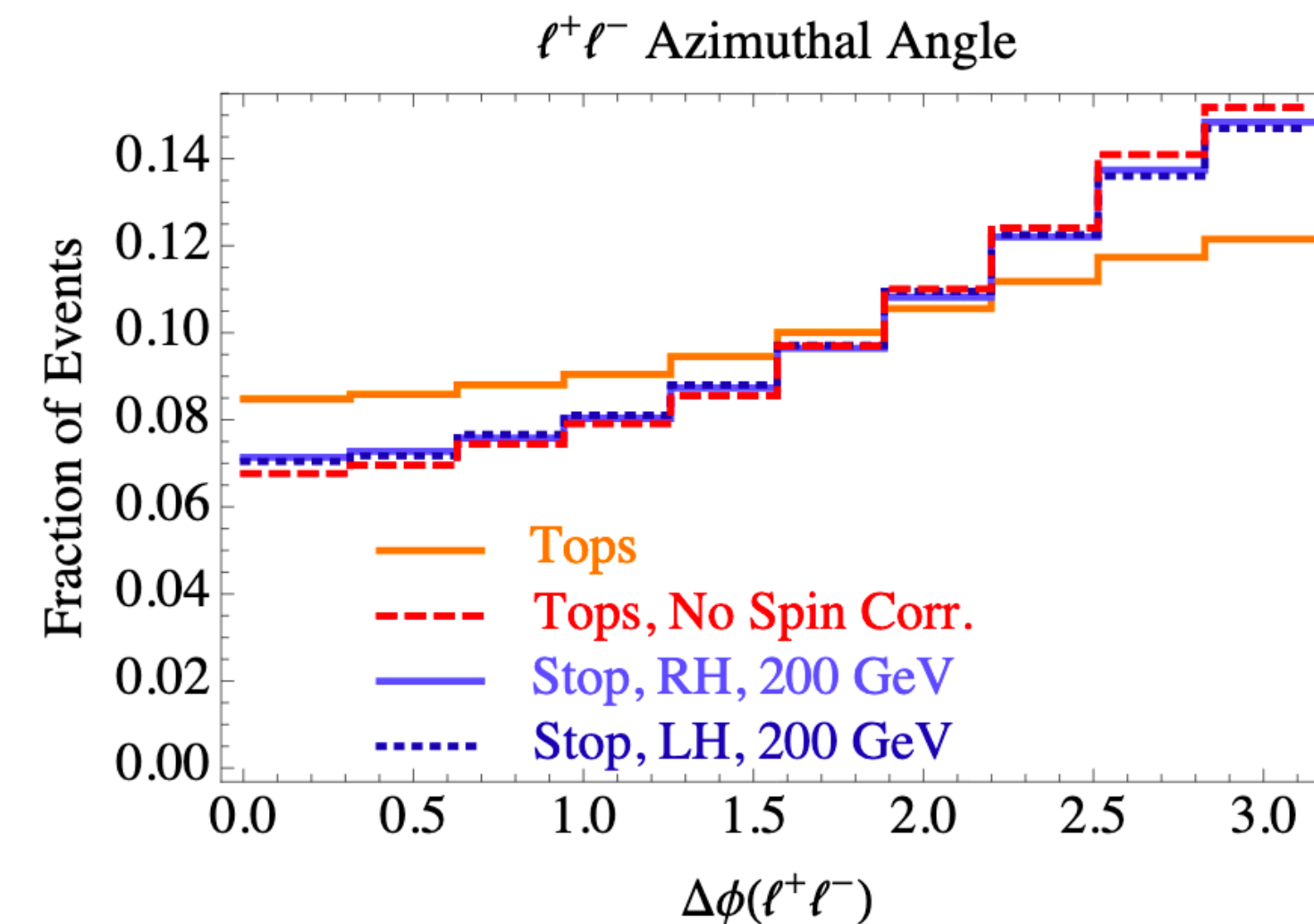

CERN-EP-2019-034. ATLAS

BACKUP

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.

Rapidity Gap

Stops (220 GeV)
Stops (180 GeV)
Tops (MC@NLO)
Tops, $\mu = 0.5\,\mu_{Default}$
Tops, $\mu = 2.0\,\mu_{Default}$

Fraction of Events

Δy

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

$\ell^+\ell^-$ Azimuthal Angle

Fraction of Events

Tops
Tops, No Spin Corr.
Stop, RH, 200 GeV
Stop, LH, 200 GeV

$\Delta\phi(\ell^+\ell^-)$

Mass points

Initial state	$t\bar{t}$	$\widetilde{t}\widetilde{t}^*$
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%