Indirect Studies of Electroweakly Interacting Particles at 100 TeV Hadron Colliders

So Chigusa

Department of Physics, University of Tokyo

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SC, Yohei Ema, and Takeo Moroi
PLB **789** (2019) 106 [arXiv:1810.07349]
Tomohiro Abe, SC, Yohei Ema, and Takeo Moroi
[arXiv:1904.11162]

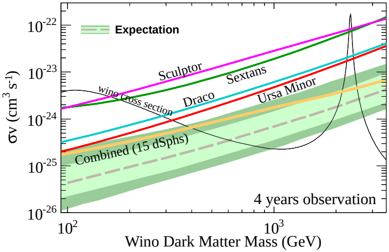
ElectroWeakly Interacting Massive Particle (EWIMP)

- EWIMP : massive particle with non-zero weak charges
- Good dark matter (DM) candidate $\cdots$ “WIMP miracle”

ex) Higgsino, Wino, Minimal Dark Matter

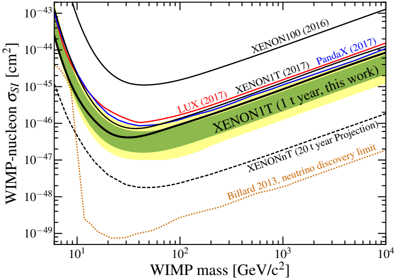
Detection methods of EWIMPs

Indirect detection



B. Bhattacherjee^{+} ’14

Direct detection



XENON1T ’18

Disappearing track search @ LHC (mono-X search)

Difficulty with Higgsino

Higgsino detection may be difficult (model dependent)

Indirect / Direct detection

Higgsino annihilation / scattering cross section is too small

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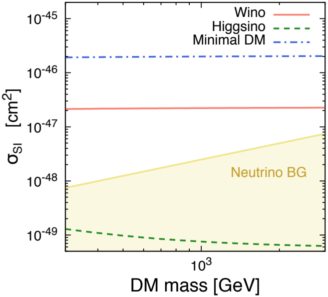


Disappearing track search

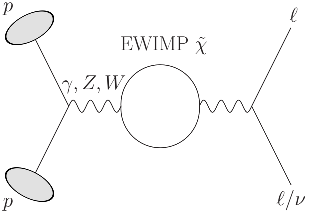
Tiny gaugino fraction (= "almost pure" Higgsino) makes Higgsino short lifetime with $c\tau \ll \mathcal{O}\,(\mathrm{cm})$

How can we search for short lifetime Higgsino?

Invitation : indirect study using colliders

Today I introduce

Indirect search with $\ell\ell/\ell\nu$ production @ 100 TeV collider



Features

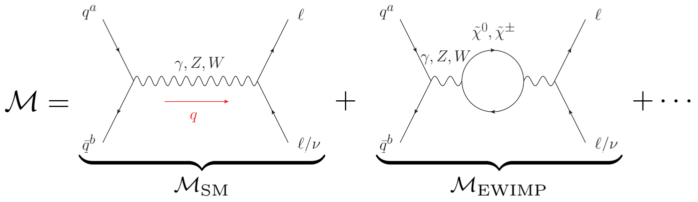
- ✓ Independent of EWIMP lifetime ⇒ Good for Higgsino
- ✓ Clean, tremendous events : 2 energetic leptons (+ jet)

⇒ Signal shape as a func. of lepton inv. mass is usable

  - ✓ to control systematic errors
  - ✓ to determine EWIMP mass and charges

Neutral current (NC) / Charged current (CC)

Parton level scattering amplitude for $q^a\bar{q}^b \to \ell\ell$ (NC) / $\ell\nu$ (CC)



Cross section for fixed $q^2 \equiv s'$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\Re\left[\mathcal{M}_{\text{SM}}\mathcal{M}^*_{\text{EWIMP}}\right] + \cdots$$

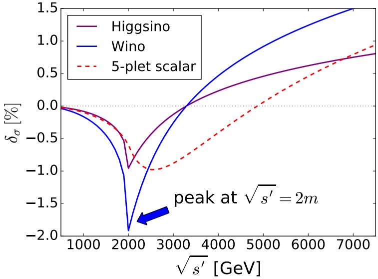
$$\frac{d\sigma^{ab}}{d\sqrt{s'}} \equiv \frac{d\sigma^{ab}_{\text{SM}}}{d\sqrt{s'}} + \frac{d\sigma^{ab}_{\text{EWIMP}}}{d\sqrt{s'}} + \cdots$$

Define the size of correction

$$\delta^{ab}_\sigma(\sqrt{s'}) \equiv \frac{d\sigma^{ab}_{\text{EWIMP}}/d\sqrt{s'}}{d\sigma^{ab}_{\text{SM}}/d\sqrt{s'}}$$

Cross section correction from EWIMPs

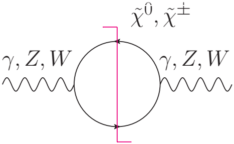
Plot of δ_σ^{ab} for $q^a \bar{q}^b \to \ell\nu$ (CC) with $m = 1$ TeV EWIMPs



Peak structure at $\sqrt{s'} = 2m$ plays an important role

"threshold effect"

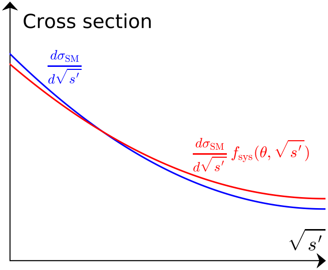
Same for $\ell\ell$ (NC)



Idea of fitting based analysis

Systematic errors may modify theoretical prediction $\dfrac{d\sigma_{\rm SM}}{d\sqrt{s'}}$

- luminosity error
- beam energy error
- choice of renormalization scale
- choice of factorization scale
- choice of PDF
- etc $\cdots$



Idea of fitting based analysis

Absorb above errors into additional parameters $\boldsymbol{\theta}$

(Similar to "side band analysis")

Fitting based analysis

Consider number of events binned by $\sqrt{s'}$

– $\boldsymbol{x} = \{x_i\}$: prediction for SM (i: label of bin)

– $\check{\boldsymbol{x}} = \{\check{x}_i\}$: experimental data (now assume SM+EWIMP)

Define new theoretical prediction $\tilde{x}_i(\boldsymbol{\theta})$

$$\tilde{x}_i(\boldsymbol{\theta}) \equiv x_i \, f_{\mathrm{sys},i}(\boldsymbol{\theta}) \quad ; \quad f_{\mathrm{sys},i}(\mathbf{0}) = 1$$

CDF collaboration '08

– We checked systematic errors successfully absorbed into $\boldsymbol{\theta}$

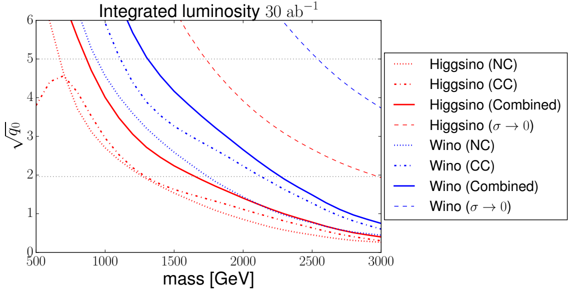
Use a test statistic q_0 that tests the validity of SM

$$q_0 \sim \min_{\boldsymbol{\theta}} \sum_{i:\mathrm{bin}} \frac{\left(\check{x}_i - \tilde{x}_i(\boldsymbol{\theta})\right)^2}{\tilde{x}_i(\boldsymbol{\theta})} \sim \chi^2(1)$$

Result: detection reach

Solid lines : upper bound on the sensitivity

Dashed lines : when statistical errors dominate systematic ones

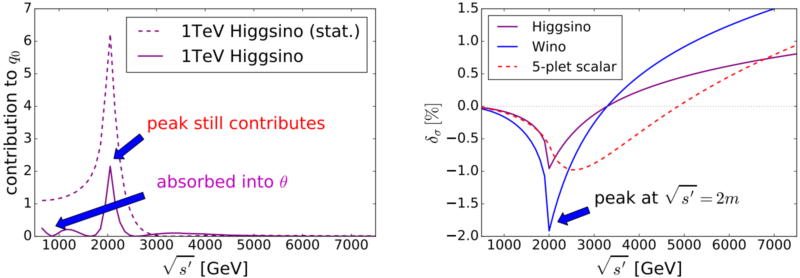


	Higgsino	Wino
5σ	850 GeV	1.6 TeV
5σ (stat.)	1.7 TeV	2.5 TeV

It is important to understand systematic errors

Which bin contributes a lot?

Plot contribution to q_0 from each bin

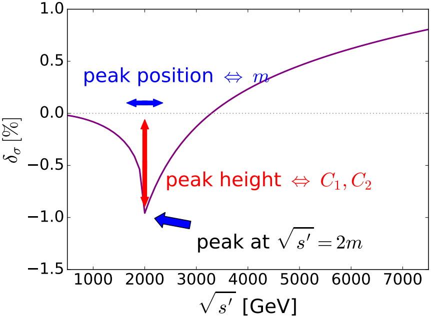


Peak structure at $\sqrt{s'} \sim 2m$ is not fitted.
It is very important for detection.

Determination of EWIMP properties

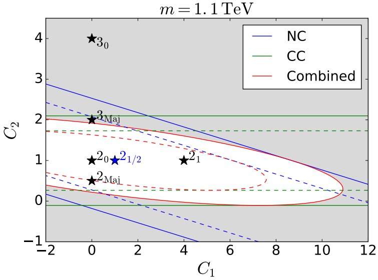
For $SU(2)_L$ n-plet Dirac fermion with $U(1)_Y$ charge Y

$$C_2 \equiv \frac{1}{6}(n^3 - n) \quad ; \quad C_1 \equiv 2nY^2$$



We can extract m, C_1, C_2 from peak structure

Determination of (m, C_1, C_2) for 1.1 TeV Higgsino

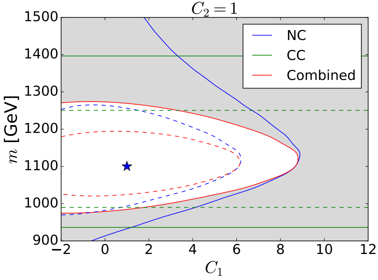


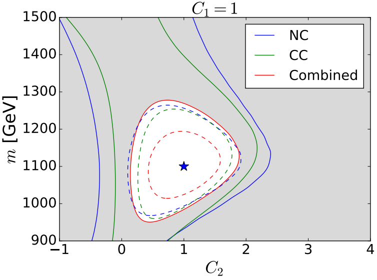
Solid (Dotted) : 2σ (1σ)

n_Y: $SU(2)_L$ n-plet
with $U(1)_Y$ charge Y

– Only doublet is allowed

– $m \sim 1.1$ TeV± 100 GeV





Conclusion

I introduced a way for probing EWIMPs with precision measurement at 100 TeV colliders

I also introduced fitting based analysis, where systematic errors are absorbed into the fit function

- ✓ All the errors we have considered are fitted well
- ✓ Strong discovery potential for short lifetime Higgsino 850 GeV (1.7 TeV) at 5σ (95% C.L.)
- ✓ The peak structure of the EWIMP effect can also be used to determine the EWIMP properties (mass, charge)

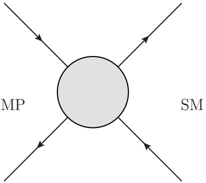
Peak at $\sqrt{s'} = 2m$ is important for all the analysis

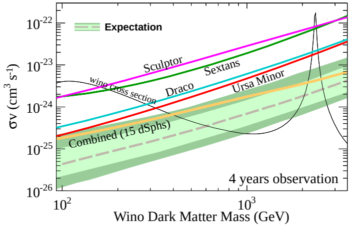
Backup slides

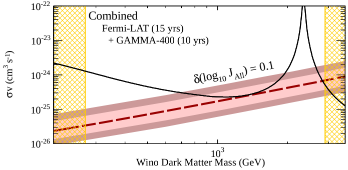
Indirect detection of DM

EWIMP annihilation into SM

γ channel best for EWIMP







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✓ Wino & MDM

Already exclude

$m_{\tilde{W}} < 400$ GeV, ~ 2 TeV

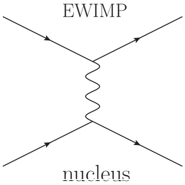
✗ Higgsino

Cross section too small

Direct detection of DM

Collision btw. DM and nucleus

Look for recoiled nuclei

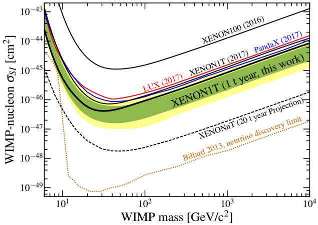


✓ Wino & MDM

Region of future interest

✗ Higgsino

Cross section below νBG



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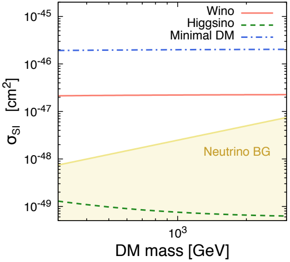


J. Hisano$^+$ '15

Higgsino phenomenology

chargino neutralino mass difference H. Fukuda, et al. [1703.09675]

$$\Delta m_+ = \Delta m_{\rm rad} + \Delta m_{\rm tree}$$
$$\Delta m_{\rm rad} \simeq \frac{1}{2}\alpha_2 m_Z s_W^2 \left(1 - \frac{3m_Z}{2\pi m_{\tilde{\chi}^\pm}}\right) \simeq 355\text{MeV},$$
$$\Delta m_{\rm tree} \simeq \frac{v^2}{8|\mu|}\left[|X|\Delta_X + \sin 2\beta\, \Re(Y)\right] \sim 1\,\text{GeV}\left|\frac{\mu}{M_i}\right|,$$

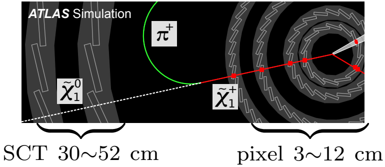
with $X, Y = \mu^*(g_1^2/M_1 \pm g_2^2/M_2)$, $\Delta_X = \sqrt{1 - \sin^2\theta_X \sin^2 2\beta}$

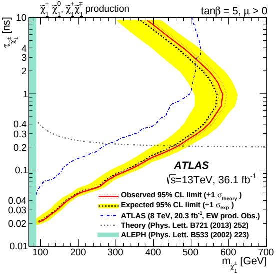
$$c\tau \simeq 0.7\,\text{cm}\left[\left(\frac{\Delta m_+}{340\,\text{MeV}}\right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m_+^2}}\right]^{-1}$$

Production at collider

Difficulty : event recognition

- disappearing track $\Leftarrow$ strict, requires long life time





ATLAS [1712.02118]

CMS [1804.07321]

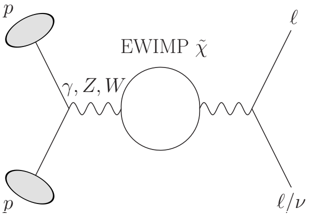
- ✓ $c\tau_{\tilde{W}} \sim 6\,\mathrm{cm}$, $m_{\tilde{W}} < 460$ GeV excluded
- ✓ $c\tau_{\tilde{H}} \sim 1\,\mathrm{cm}$, $m_{\tilde{H}} < 152$ GeV excluded for pure Higgsino
- ✗ Higgsino mixed with gaugino : $c\tau \ll \mathcal{O}(\mathrm{cm})$

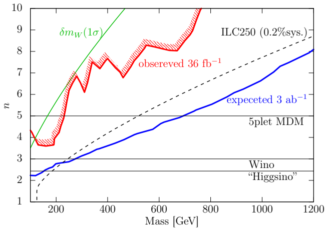
- mono-X search : recognize events with initial state radiation
  no bound on Higgsino @ LHC

H. Baer, et al. [1401.1162]

Studies of indirect search at collider

✓ Applicable to Higgsino independent of life time





S. Matsumoto, et al.

Previous analysis:

D. S. M. Alves, et al. [1410.6810] @ LHC, 100 TeV
C. Gross, et al. [1602.03877] @ LHC
M. Farina, et al. [1609.08157] @ LHC
K. Harigaya, et al. [1504.03402] @ lepton collider
S. Matsumoto, et al. [1711.05449] @ HL-LHC

Up to HL-LHC era
Only a part of allowed region probed

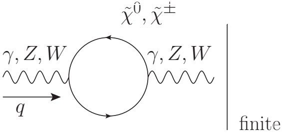
- $m_{\tilde{W}} < 300$ GeV $\ll 3$ TeV
- $m_{\tilde{H}} < 150$ GeV $\ll 1$ TeV

Let’s consider future
100 TeV collider
to cover all the regions!!

Vacuum polarization effect from EWIMP

Assume all new physics except EWIMPs are decoupled

Consider vacuum polarization effect from EWIMPs



$$\propto i(q^2 g^{\mu\nu} - q^\mu q^\nu) f(q^2/m^2)$$

f is a loop function

$$f(x) = \begin{cases} \dfrac{1}{16\pi^2} \displaystyle\int_0^1 dy\ y(1-y) \ln(1 - y(1-y)x - i0) & \text{(Fermion)} \\ \dfrac{1}{16\pi^2} \displaystyle\int_0^1 dy\ (1-2y)^2 \ln(1 - y(1-y)x - i0) & \text{(Scalar)} \end{cases}$$

Effective lagrangian (Note: q^2/m^2 expansion NOT performed)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + C_1 {g'}^2 B_{\mu\nu} f\left(-\frac{\partial^2}{m^2}\right) B^{\mu\nu} + C_2 g^2 W^a_{\mu\nu} f\left(-\frac{D^2}{m^2}\right) W^{a\mu\nu}$$

Group theoretical factors C_1, C_2

$SU(2)_L$ n-plet with $U(1)_Y$ charge Y contributes

$$C_1 = \frac{\kappa}{8} n Y^2, \quad C_2 = \frac{\kappa}{96}(n^3 - n),$$

$$\kappa = \begin{cases} 16 & \text{(Dirac fermion)} \\ 8 & \text{(Weyl or Majorana fermion)} \\ 2 & \text{(complex scalar)} \\ 1 & \text{(real scalar)} \end{cases}$$

For popular EWIMPs

	Higgsino	Wino	5-fermion ($Y=0$)	7-scalar ($Y=0$)
C_1	1	0	0	0
C_2	1	2	10	7/2

From parton-level to proton cross section

Proton cross section at $\sqrt{s} = 100$ TeV can be obtained using

$$\frac{dL_{ab}}{dm_{\ell\ell}} \equiv \frac{1}{s}\int_0^1 dx_1 dx_2 \; f_a(x_1) f_b(x_2) \delta(\frac{m_{\ell\ell}^2}{s} - x_1 x_2)$$

$f_a(x)$: parton distribution function (PDF) for a

$$\frac{d\sigma}{dm_{\ell\ell}} = \sum_{a,b} \frac{dL_{ab}}{dm_{\ell\ell}} \frac{d\sigma^{ab}}{dm_{\ell\ell}}$$

Indirect study with precision measurement

Task : Detect $\mathcal{O}(1)\%$ effect through precision measurement

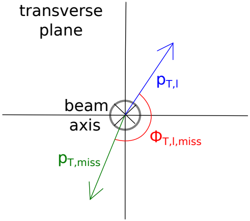
Method : Use functional form of $\delta_\sigma(\sqrt{s'})$

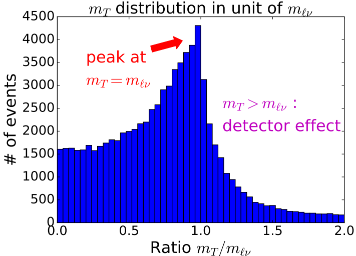
Difficulty :

- For $\ell\ell$ (NC) : $\sqrt{s'} = m_{\ell\ell}$
- For $\ell\nu$ (CC) : Use transverse mass m_T instead

$$m_T^2 \equiv 2p_{T,\ell}\, p_{T,\mathrm{miss}}(1 - \cos\phi_{T,\ell,\mathrm{miss}}) \leq m_{\ell\nu}^2$$

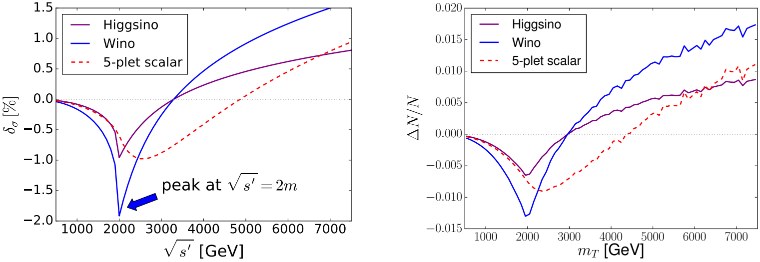
$$(m_T \simeq m_{\ell\nu} \text{ if } p_{\ell,z},\ p_{\nu,z} \text{ are small})$$





δ_σ as function of m_T

$\ell\nu$ (CC) events are binned by m_T

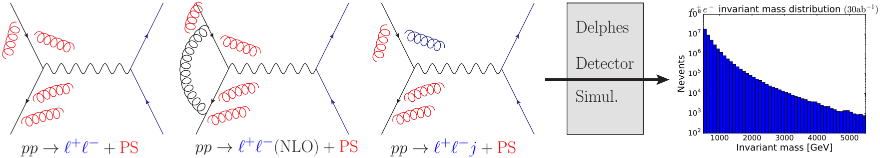


- ✓ Peak structure remains though smeared to lower peak height

Event generation

$\sqrt{s} = 100\,\text{TeV}$, $\mathcal{L} = 30\ \text{ab}^{-1}$ for SM, binned by $m_\text{char} = m_{\ell\ell}$, m_T

- `MadGraph5_aMC@NLO` : hard process @ NLO
- `Pythia8` : parton shower (PS), hadronization
- `Delphes3` : detector simulation



$pp \to \ell^+\ell^- + \text{PS}$ $\quad$ $pp \to \ell^+\ell^-(\text{NLO}) + \text{PS}$ $\quad$ $pp \to \ell^+\ell^- j + \text{PS}$

EWIMP effect is included by rescaling

$$N_{\text{SM+EWIMP}} = \sum_{\text{events}}^{N_{\text{SM}}} \left[1 + \delta_\sigma^{ab}(\sqrt{s'}) \right]$$

Event generation in detail

EWIMP effect can be included with $\delta_\sigma^{ab}(m_{\ell\ell})$

Number of events $\tilde{x}_i$ in i-th bin $m_{\ell\ell}^{\min} < m_{\ell\ell} < m_{\ell\ell}^{\max}$

For SM, $$\tilde{x}_i = \sum_{m_{\ell\ell}^{\min} < {\color{blue} m_{\ell\ell}^{\text{obs}}} < m_{\ell\ell}^{\max}} 1$$

For SM + EWIMP, $$\tilde{x}_i = \sum_{m_{\ell\ell}^{\min} < {\color{blue} m_{\ell\ell}^{\text{obs}}} < m_{\ell\ell}^{\max}} \left[1 + \delta_\sigma^{\color{cyan} ab}({\color{red} m_{\ell\ell}^{\text{true}}})\right]$$

Each event in SM data set has $\{{\color{blue} m_{\ell\ell}^{\text{obs}}}, {\color{red} m_{\ell\ell}^{\text{true}}}, {\color{cyan} a, b}\}$

- ${\color{blue} m_{\ell\ell}^{\text{obs}}}$: observed $m_{\ell\ell}$ from `Delphes3` output
- ${\color{red} m_{\ell\ell}^{\text{true}}}$: true $m_{\ell\ell}$ from `MadGraph5_aMC@NLO` output
- ${\color{cyan} a, b}$: initial partons from `MadGraph5_aMC@NLO` output

∗ Detector effect causes ${\color{blue} m_{\ell\ell}^{\text{obs}}} \neq {\color{red} m_{\ell\ell}^{\text{true}}}$

Statistical treatment in our analysis

$$x_i(\mu) \equiv \sum_{\text{events}} \left[1 + \mu\, \delta_\sigma^{ab}(m_{\text{char}})\right] \quad ; \quad \tilde{x}_i(\boldsymbol{\theta}, \mu) \equiv x_i(\mu) f_i(\boldsymbol{\theta})$$

Definition of q_0 in fitting based analysis Wilk '38

$$q_0 = -2 \ln \frac{L(\check{\boldsymbol{x}}; \hat{\hat{\boldsymbol{\theta}}}, \mu = 0)}{L(\check{\boldsymbol{x}}; \hat{\boldsymbol{\theta}}, \hat{\mu})} \sim \chi^2(1)$$

$$L(\check{\boldsymbol{x}}; \boldsymbol{\theta}, \mu) \equiv \prod_i \exp\left[-\frac{(\check{x}_i - \tilde{x}_i(\boldsymbol{\theta}, \mu))^2}{2\tilde{x}_i(\boldsymbol{\theta}, \mu)}\right] \prod_\alpha \exp\left[-\frac{\theta_\alpha^2}{2\sigma_\alpha^2}\right]$$

$\hat{\hat{\boldsymbol{\theta}}}$ maximizes numerator $L(\check{\boldsymbol{x}}; \hat{\hat{\boldsymbol{\theta}}}, \mu = 0)$

$\{\hat{\boldsymbol{\theta}}, \hat{\mu}\}$ maximizes denominator $L(\check{\boldsymbol{x}}; \hat{\boldsymbol{\theta}}, \hat{\mu})$

Within our analysis, $\check{x} = x_i(\mu = 1)$ and

$\{\hat{\boldsymbol{\theta}}, \hat{\mu}\} = \{0, 1\}$ with $L(\check{\boldsymbol{x}}; \hat{\boldsymbol{\theta}}, \hat{\mu}) = 1$

Statistical treatment : (I) Fit systematic errors

Consider number of events in i-th bin of $m_{\rm char} = m_{\ell\ell}$ or m_T

– $\boldsymbol{y} = \{y_i\}$: prediction for SM $\cdots$ deformed $\tilde{y}_i(\boldsymbol{\theta}) \equiv y_i f_{{\rm sys},i}(\boldsymbol{\theta})$

– $\check{\boldsymbol{y}} = \{\check{y}_i\}$: data with one of errors included

List of errors considered

- Luminosity ±5%
- Beam energy ±1%
- Renormalization scale $2Q$, $Q/2$
- Factorization scale $2Q$, $Q/2$
- PDF choice (101 variants of `NNPDF2.3QED` $\alpha_s(M_Z) = 0.118$)

Perform chi-squared fit and evaluate

$$\chi^2 = \min_{\boldsymbol{\theta}} \sum_{i:{\rm bin}} \frac{(\check{y}_i - \tilde{y}_i(\boldsymbol{\theta}))^2}{\tilde{y}_i(\boldsymbol{\theta})}$$

Statistical treatment : (II) Fit result and $\boldsymbol{\sigma}$

All errors fitted well : Best fit values for $\ell\ell$ (NC)

Sources of systematic errors	θ_1	θ_2	θ_3	θ_4	θ_5
Luminosity: ±5 %	0.07	0	0	0	0
Beam energy: ±1 %	negligible				
Renormalization scale: $2Q, Q/2$	0.6	0.9	0.4	0.08	0.006
Factorization scale: $2Q, Q/2$	0.5	0.7	0.3	0.07	0.007
PDF choice	0.4	0.7	0.3	0.06	0.004
Total	0.9	1.3	0.5	0.1	0.01

Each value can be interpreted as possible size of $|\theta|$ within SM

Let's call them as "σ" $\cdots$ deviation of $|\theta|$ from 0

Assuming each source is independent, take squared sum :

$$\sigma_\alpha^{\text{total}} = \sqrt{(\sigma_\alpha^{\text{lumi.}})^2 + (\sigma_\alpha^{\text{ren.}})^2 + (\sigma_\alpha^{\text{fac.}})^2 + (\sigma_\alpha^{\text{PDF}})^2}$$

Statistical treatment : (III) profile likelihood method

Fit function

$$f_{\mathrm{sys},i}(\boldsymbol{\theta}) = e^{\theta_1}(1+\theta_2 p_i)p_i^{(\theta_3+\theta_4\ln p_i+\theta_5\ln^2 p_i)}$$

$$p_i = 2m_{\mathrm{char},i}/\sqrt{s}$$

Definition of test statistic q_0

$$q_0 \equiv \min_{\boldsymbol{\theta}}\left[\underbrace{\sum_{i:\mathrm{bin}}\frac{(\check{x}_i-\tilde{x}_i(\boldsymbol{\theta}))^2}{\tilde{x}_i(\boldsymbol{\theta})}}_{\text{try to fit data}} + \underbrace{\sum_{\alpha=1}^{5}}_{\text{control size of }\boldsymbol{\theta}}\frac{\theta_\alpha^2}{\sigma_\alpha^2}\right]$$

q_0 tests validity of SM and obeys $\chi^2(1)$

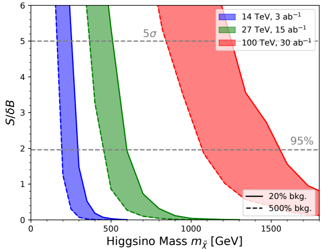
Wilk '38

Comparison with other approaches

Higgsino production at $\sqrt{s} = 100$ TeV, $\mathcal{L} = 30$ ab^{-1}

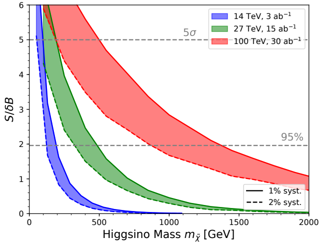
- disappearing track search

  (for pure Higgsino $c\tau_{\tilde{H}} \sim 1\,\mathrm{cm}$)



- mono-jet search

  (for any $c\tau_{\tilde{H}}$)



T. Han^{+} '18

- indirect study

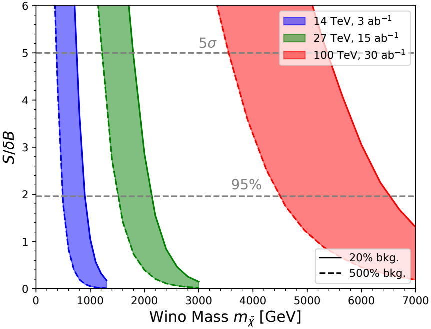
Probe $m_{\tilde{H}} <$ 850 GeV (1.7 TeV)
at 5σ (95% C.L.) level

Our method provides

— comparable reach for pure Higgsino

— better for short lifetime Higgsino

Disappearing track search of Wino



Other sources of systematic errors

Smooth correction seems to be well absorbed into $\boldsymbol{\theta}$: Then,

- estimation error in detector effect

may also be absorbed : our method can be applied!!

- higher order loop effect within SM
- background process

in principle possible to take account of (future task)

Yet remaining sources:

- pile-up effect
- underlying event

negligible thanks to clean signal with two energetic leptons

Statistical treatment for properties determination

Fix $\mu = 1$ (SM+EWIMP) and consider (m, C_1, C_2) dependence

$$x_i(m, C_1, C_2) \equiv \sum_{\text{events}} \left[1 + \delta_\sigma^{ab}(m, C_1, C_2; \sqrt{s'})\right]$$

Assume $\check{\boldsymbol{x}}$ for 1.1 TeV Higgsino as example:

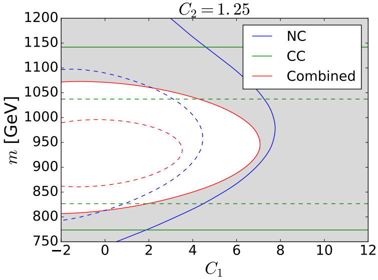
$$\check{x}_i = x_i(m = 1.1\,\mathrm{TeV}, C_1 = 1, C_2 = 1)$$

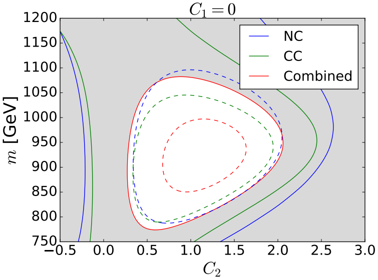
Although still 3.5σ hint we try...

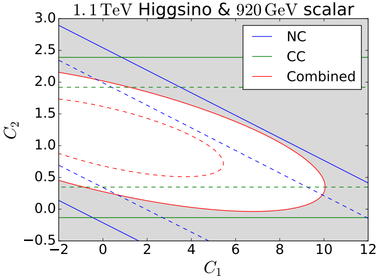
$$q(m, C_1, C_2) \equiv \min_{\boldsymbol{\theta}} \left[\sum_{i:\text{bin}} \frac{(\check{x}_i - \tilde{x}_i(\boldsymbol{\theta}, m, C_1, C_2))^2}{\tilde{x}_i(\boldsymbol{\theta}, m, C_1, C_2)} + \sum_{\alpha=1}^{5} \frac{\theta_\alpha^2}{\sigma_\alpha^2}\right]$$

q tests validity of model (m, C_1, C_2)

Determination of spin







Solid (Dotted) : 2σ (1σ)

– Best fit:

$(m, C_1, C_2) = (920\,\mathrm{GeV}, 0, 1.2)$

– Bosonic EWIMP allowed

– For lighter (e.g. $m = 800\,\mathrm{GeV}$) Higgsino, only fermion allowed