Higgsino LSP / Higgsino DM
— Current Status and Future Prospects —

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Dark matter searches in the 2020s @ Kashiwa, '19.11.11

1. Introduction

Higgsinos: Superpartners of Higgs bosons in SUSY model

- Gauge eigenstates: $\tilde{H}_u = (\tilde{H}_u^+ \ \tilde{H}_u^0)$ and $\tilde{H}_d = (\tilde{H}_d^0 \ \tilde{H}_d^-)$
- Mass eigenstates:

$$\chi_1^0 \simeq \frac{1}{\sqrt{2}} \begin{pmatrix} \tilde{H}_u^0 \pm \tilde{H}_d^0 \\ \bar{\tilde{H}}_u^0 \pm \bar{\tilde{H}}_d^0 \end{pmatrix} \quad \chi_2^0 \simeq \frac{1}{\sqrt{2}} \begin{pmatrix} \tilde{H}_u^0 \mp \tilde{H}_d^0 \\ \bar{\tilde{H}}_u^0 \mp \bar{\tilde{H}}_d^0 \end{pmatrix} \quad \chi_1^+ \simeq \begin{pmatrix} \tilde{H}_u^+ \\ \bar{\tilde{H}}_d^- \end{pmatrix}$$

- χ_1^0 can be DM

I will discuss phenomenology of Higgsino LSP / DM

- Properties of Higgsinos
- Higgsino DM: Relic density and observational constraints
- Higgsino LSP searches at colliders

2. Properties of Higgsinos

Higgsino mass is highly related to the naturalness of EWSB

$$W = \mu \hat{H}_d (i\sigma_2) \hat{H}_u$$

μ is (approximately) equal to masses of Higgsinos

For successful EWSB (tree level):

$$\frac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2 \ (\text{for } \tan\beta \gg 1)$$

$\Rightarrow$ From naturalness point of view, μ is preferred to be close to the EW scale

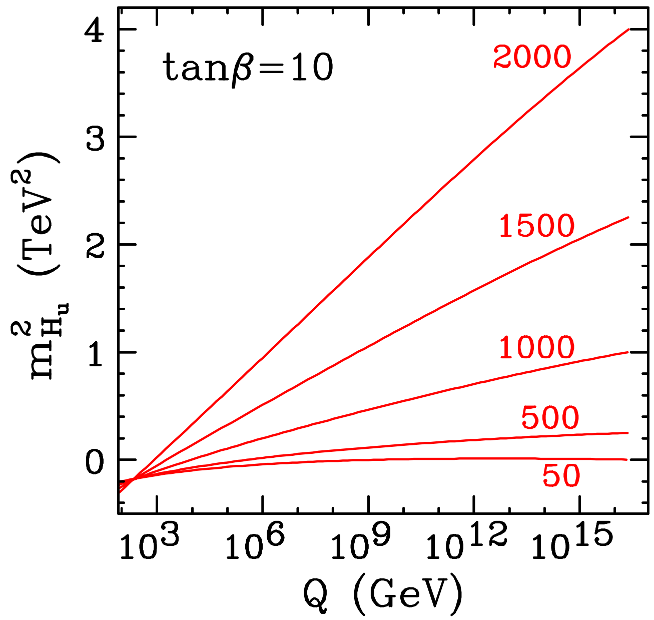
$m_{H_u}^2$ receives renormalization-group effects

$\Rightarrow$ Naively, $|m_{H_u}^2|^{1/2}$ becomes as large as other SUSY breaking parameters

Small μ due to focus-point mechanism

[Feng & TM ('98); Feng, Matchev & TM ('99)]

- $m_{H_u}^2$ becomes insensitive to the scale of SUSY breaking, adopting the universal scalar mass at the GUT scale



$$m_{H_u}^2(m_{\text{weak}}) \simeq c_0 m_0^2 + O(M_{1/2}^2)$$

$$|c_0| \ll 1$$

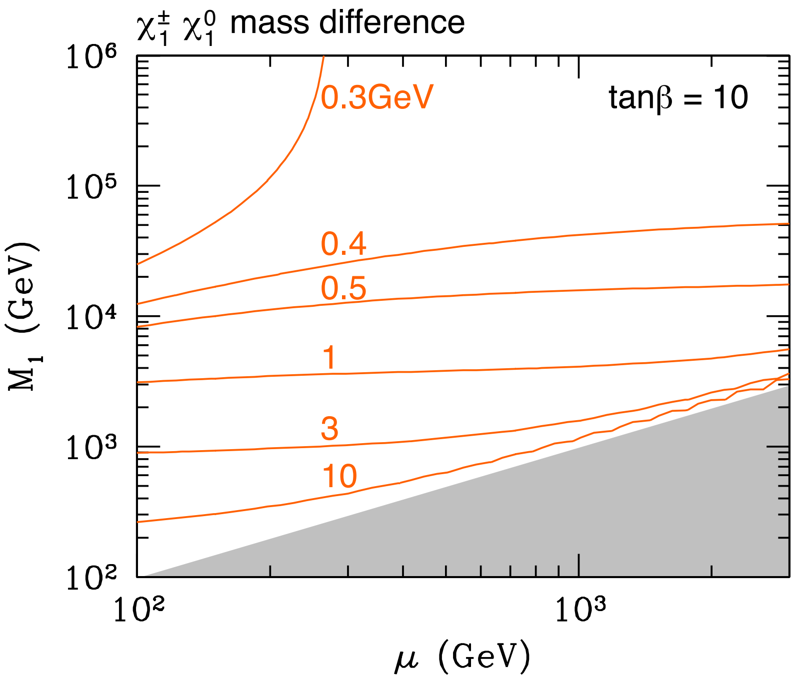
- Gaugino-mediated focus-point scenario is also possible

  [Yanagida & Yokozaki ('13)]

Hereafter, Higgsino is assumed to be the LSP

$\Rightarrow$ Masses of χ_1^0, χ_2^0, $\chi_1^\pm$ are quite degenerate

$\chi_1^\pm$ - χ_1^0 mass difference (with the GUT relation)



- Loop effects
- Mixing with gauginos

$$c\tau_{\tilde{H}^\pm \to \tilde{H}^0 \pi^\pm} \simeq 7\,\mathrm{mm} \times \left(\frac{\Delta m_\pm}{340\ \mathrm{MeV}} \right)^{-3} \left(1 - \frac{m_\pi^2}{\Delta m_\pm^2} \right)^{-1/2}$$

3. Higgsino DM

Thermal relic abundance

$$\Omega_{\tilde{H}}^{(\text{thermal})} = \Omega_{\text{DM}} \text{ requires } \mu \simeq 1.1 - 1.2\,\text{TeV}$$

Results of detailed calculation (for Higgsino-Wino system)

[Beneke, Hellmann & Ruiz-Femen ('14)]

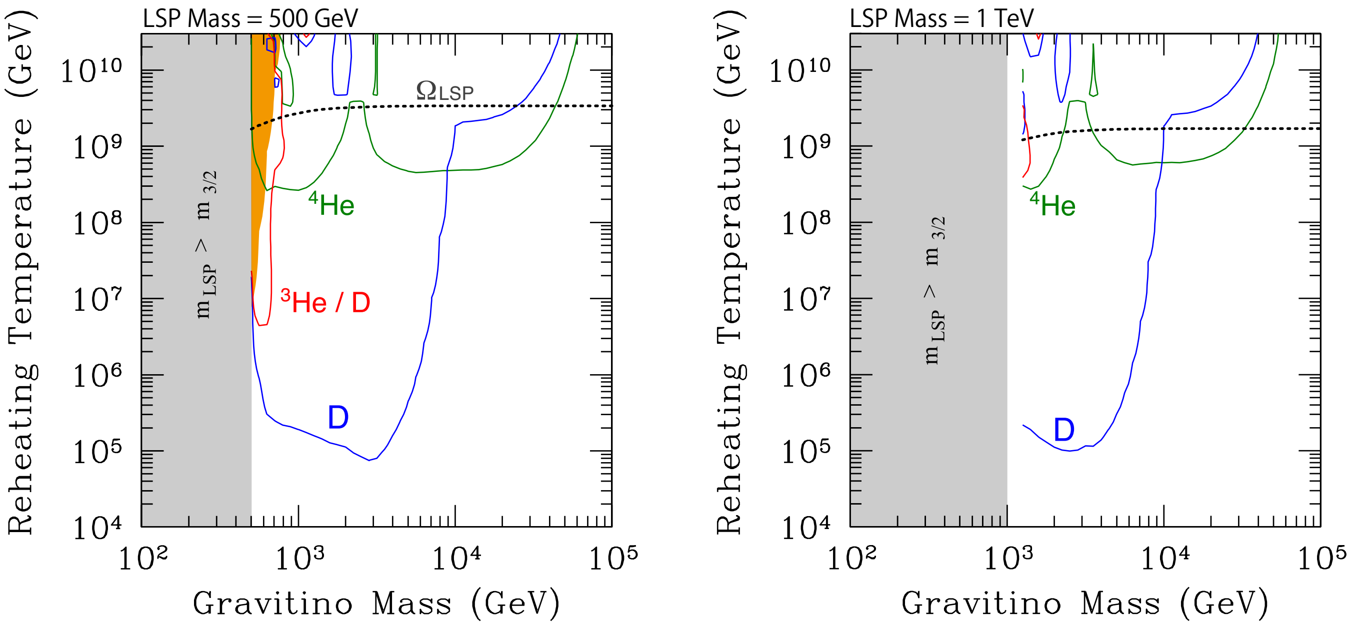
μ	M_2	m_{LSP}	$\Delta m_{\pm}$	$\Omega_{\text{LSP}} h^2$
1172	3300	1170	0.876	0.1157
1185	2800	1169	0.958	0.1129
1208	2300	1205	1.057	0.1136
1233	2000	1229	1.129	0.1119
1300	1661	1290	1.203	0.1074
1400	1593	1382	0.971	0.1016

Masses are all in units of GeV

Possibility of non-thermal production

$\Rightarrow$ Higgsino DM is possible with $\mu \lesssim 1$ TeV

Example: decay of primordial gravitino



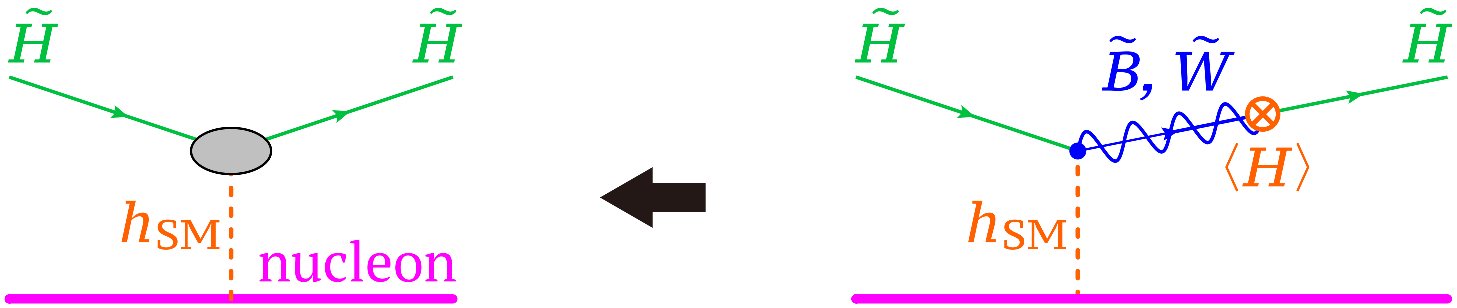
$$\Omega_{\tilde{H}} \simeq \frac{\mu n_{3/2}}{\rho_{\rm crit}}$$

[Kawasaki, Kohri, TM & Takaesu]

- $T_{\rm R} \sim 10^9 - 10^{10}$ GeV for $\Omega_{\tilde{H}}^{(\rm gravitino)} = \Omega_{\rm DM}$
- $m_{3/2} \gtrsim O(10)$ TeV to avoid BBN constraints

Direct detection of the Higgsino DM

Spin-independent (SI) process via Higgs exchange



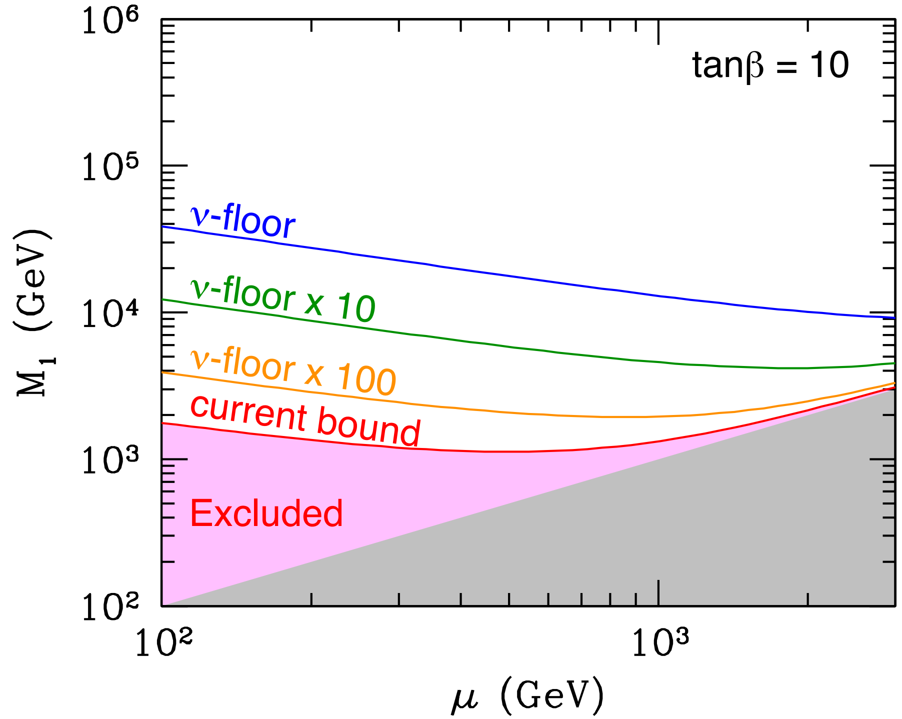
The scattering occurs via diagrams with virtual gauginos

$\Rightarrow$ The SI cross section decreases with heavier gauginos

Z-exchange process is irrelevant if $\Delta m_0 \gtrsim O(100)$ keV

$\Rightarrow$ It can be neglected if $M_{1,2} \lesssim 10^7$ GeV

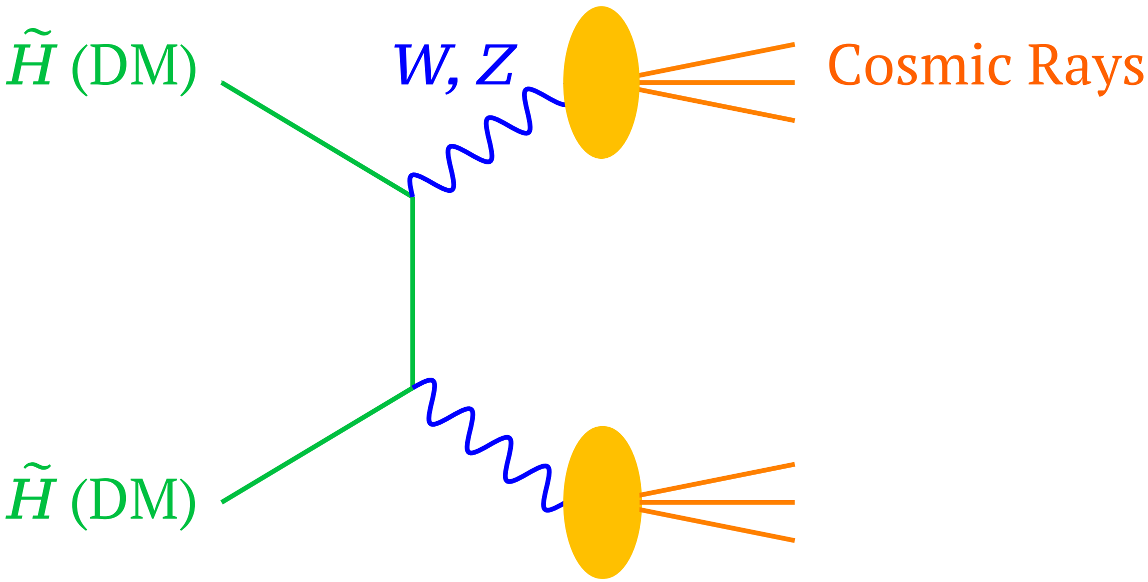
The present bound and future prospects (assuming $\Omega_{\tilde{H}} = \Omega_{\text{DM}}$)



- Current bound already excludes the region with the gaugino masses of $O(1)$ TeV
- The region with the gaugino masses of $O(10)$ TeV can be covered, if we can go down to the neutrino floor

Indirect detection using cosmic rays

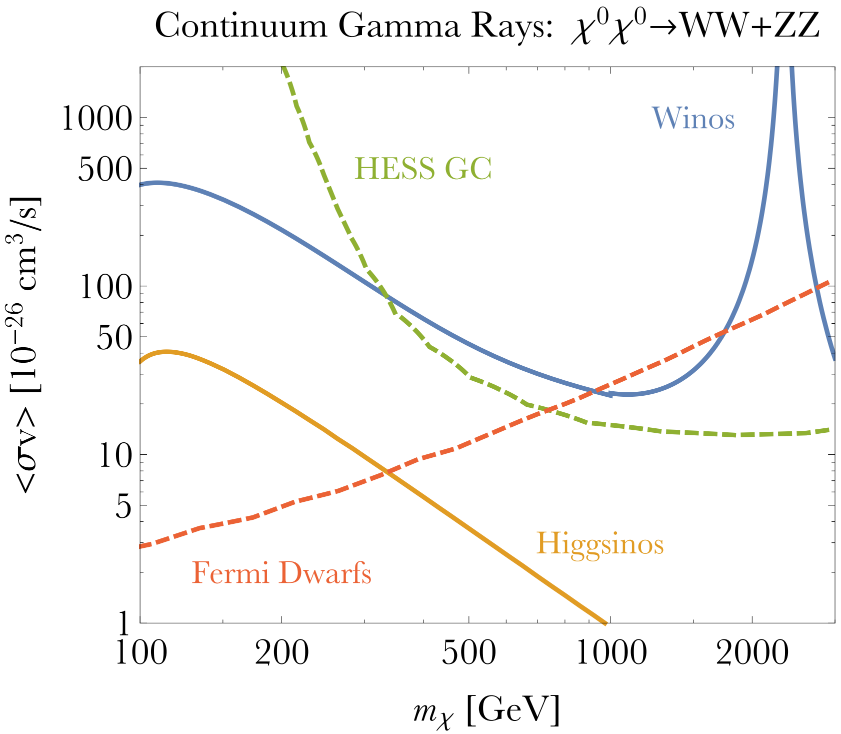
Pair annihilation of DM is a source of cosmic rays



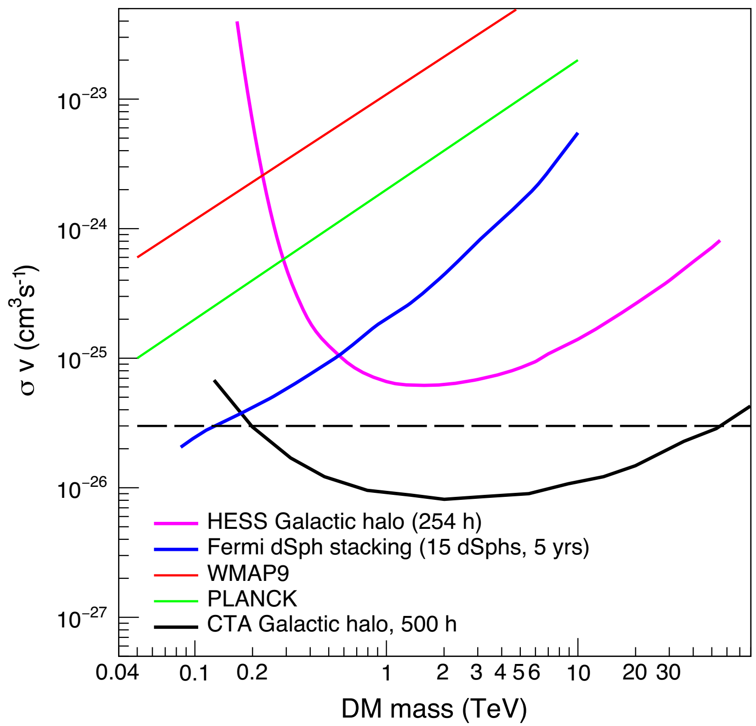
$\Rightarrow$ γ-ray

$\Rightarrow$ Anti-proton

Indirect: γ-ray (present and future)



[Krall & Reece ('17)]



[CTA Collaboration (for WW)]

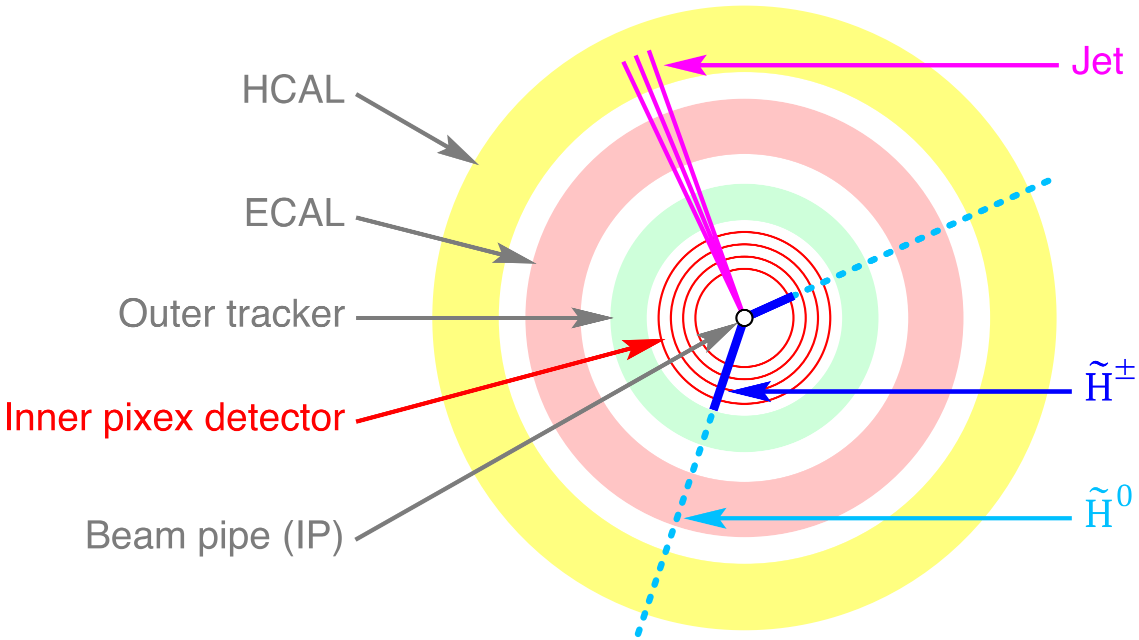
- Currently, $\mu \gtrsim 340$ GeV with Fermi data
- CTA will cover up to $\mu \sim 1$ TeV

4. Higgsino LSP at Colliders

Higgsino-LSP searches at colliders are challenging

- $\chi_1^\pm$ and χ_2^0 decay into soft objects (and χ_1^0)
- $\chi_1^\pm$ is likely to decay before reaching detectors

Events to be used for direct search



$\Rightarrow$ MET + soft $\ell^+\ell^-$

$\Rightarrow$ Mono-jet events

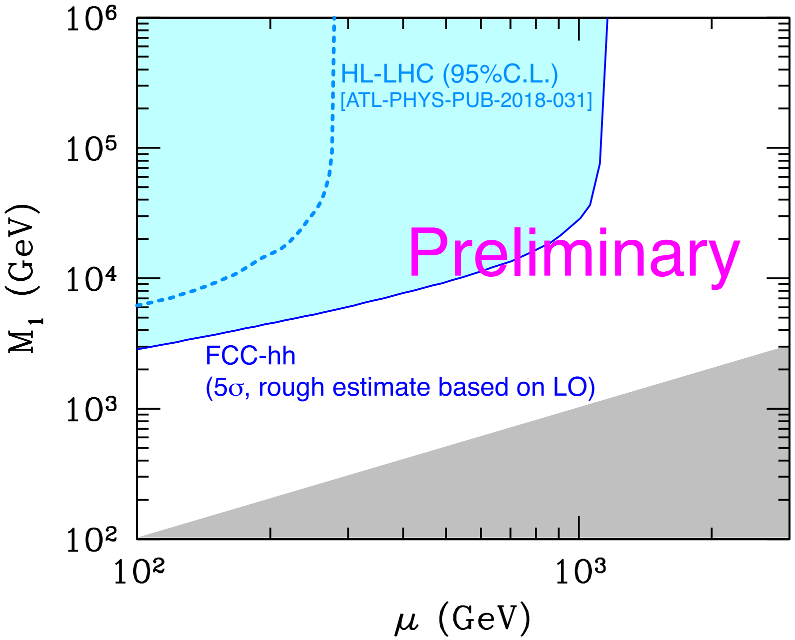
$\Rightarrow$ Disappearing track

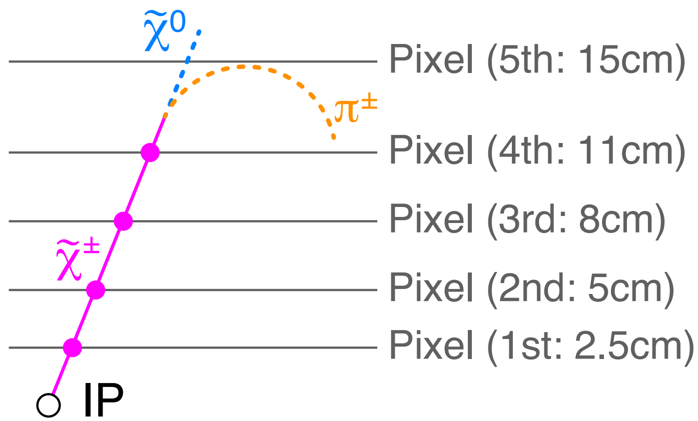
Disappearing track searches with $c\tau_{\tilde{H}^\pm} \simeq 7\,\mathrm{mm}$

[ATL-PHYS-PUB-2018-031; Saito, Sawada, Terashi & Asai ('19)]

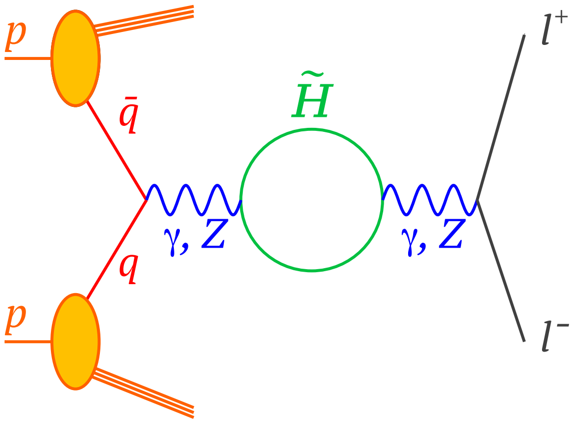
- $\mu \lesssim 260$ GeV at HL-LHC ($95\,\%$ C.L.)
- $\mu \lesssim 1.1$ TeV at FCC-hh (5σ)

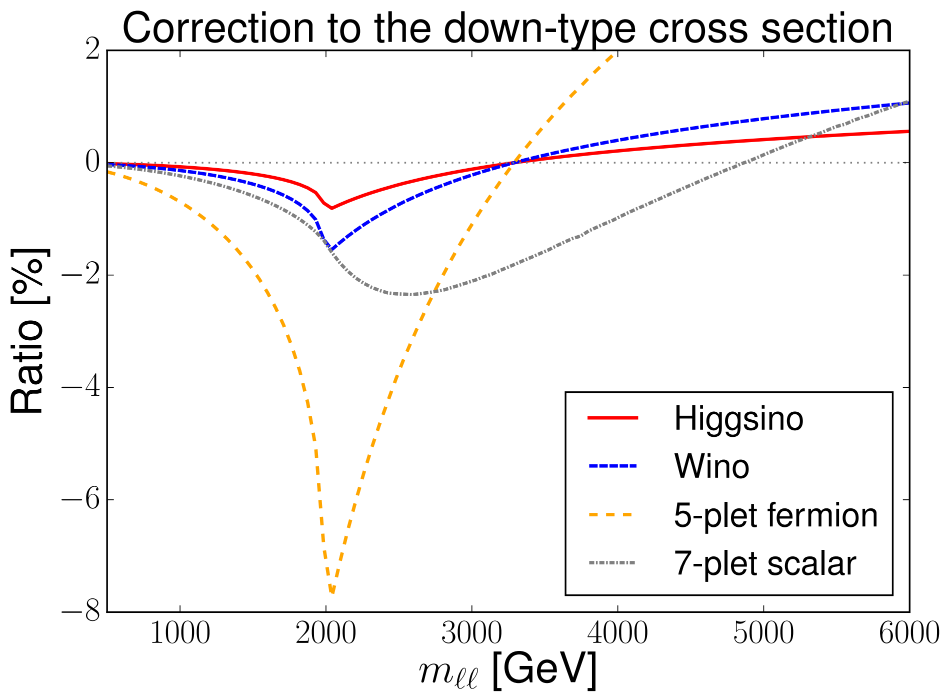
The reach should become worse for shorter lifetime





Indirect search: Higgsinos affect self-energies of EW bosons



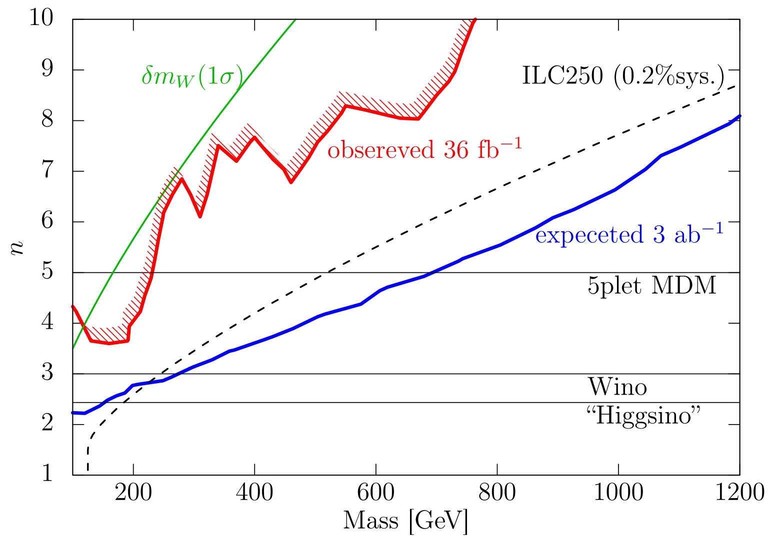


$\Rightarrow$ A "dip" at $m_{\ell\ell} \simeq 2\mu$ for NC (or at $m_T \simeq 2\mu$ for CC)

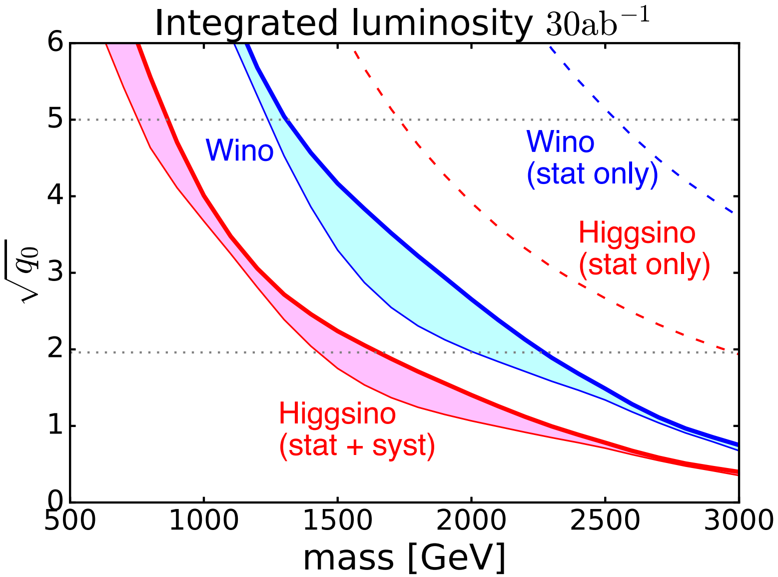
We may study Drell-Yan processes precisely

- Invariant-mass distributions of charged leptons
- Transverse-mass distributions of charged leptons

Future prospects for HL-LHC, ILC, and FCC-hh



[Matsumoto, Shirai & Takeuchi ('17)]



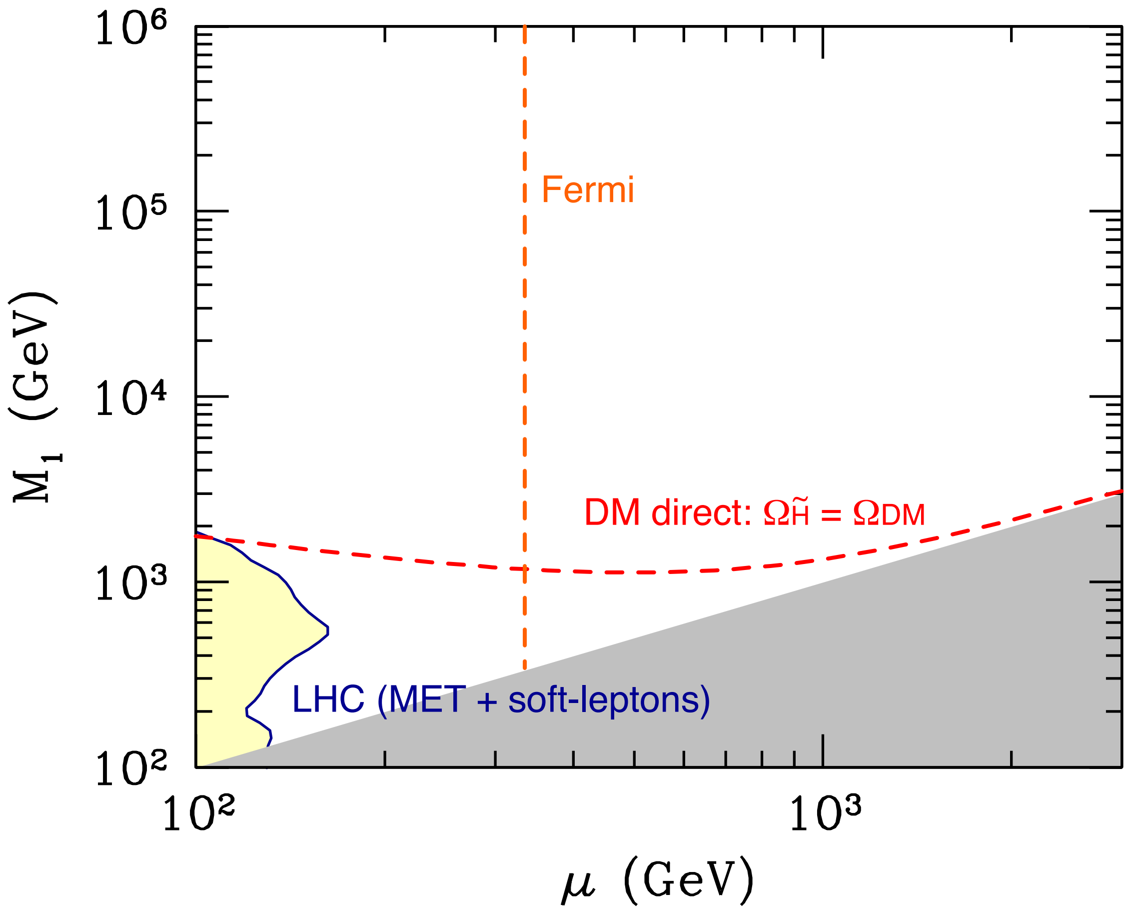
[Abe, Chigusa, Ema & TM ('19)]

- LH-LHC will cover $\mu \lesssim 150\,\mathrm{GeV}$
- ILC250 may cover $\mu \lesssim 185\,\mathrm{GeV}$

  [See also Harigaya, Ichikawa, Kundu, Matsumoto & Shirai ('15)]
- FCC-hh may cover $\mu \sim 1\,\mathrm{TeV}$

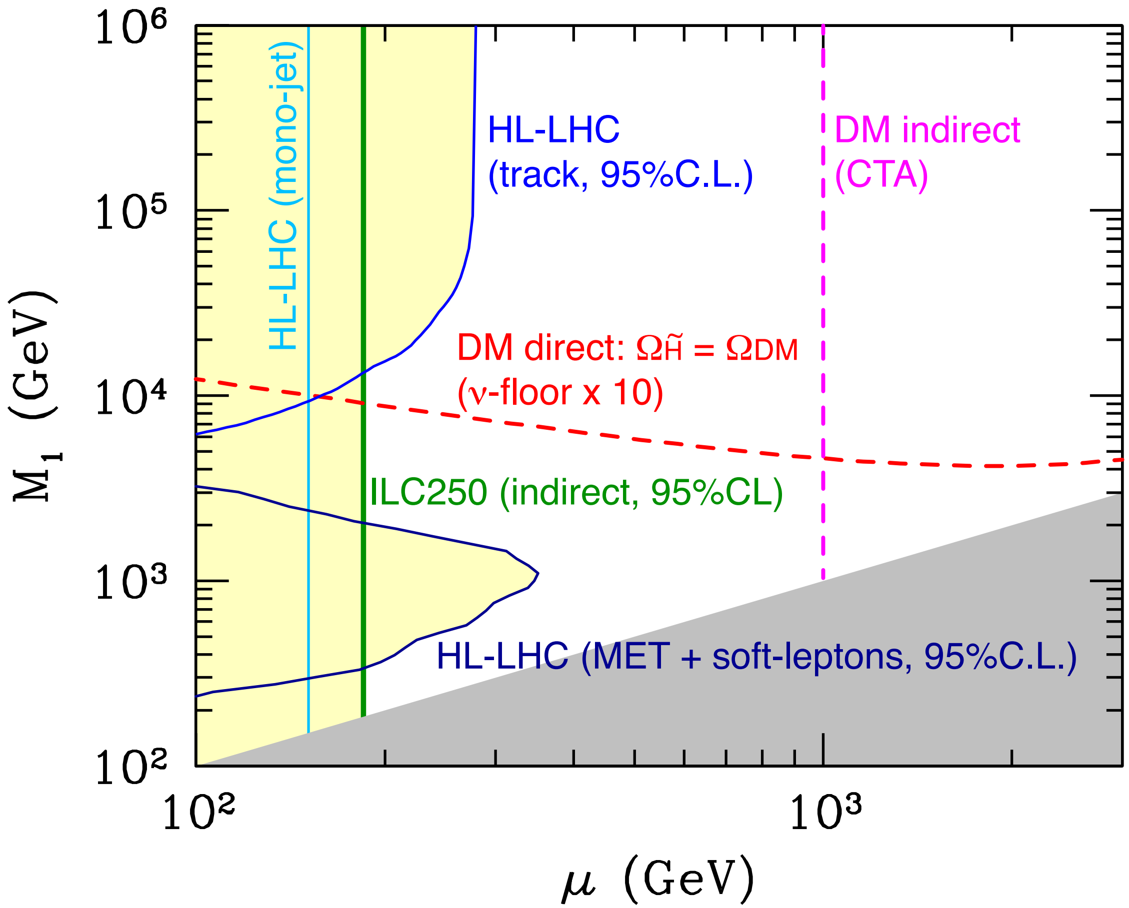
5. Summary (with Three Figures)

Higgsino LSP: current bound



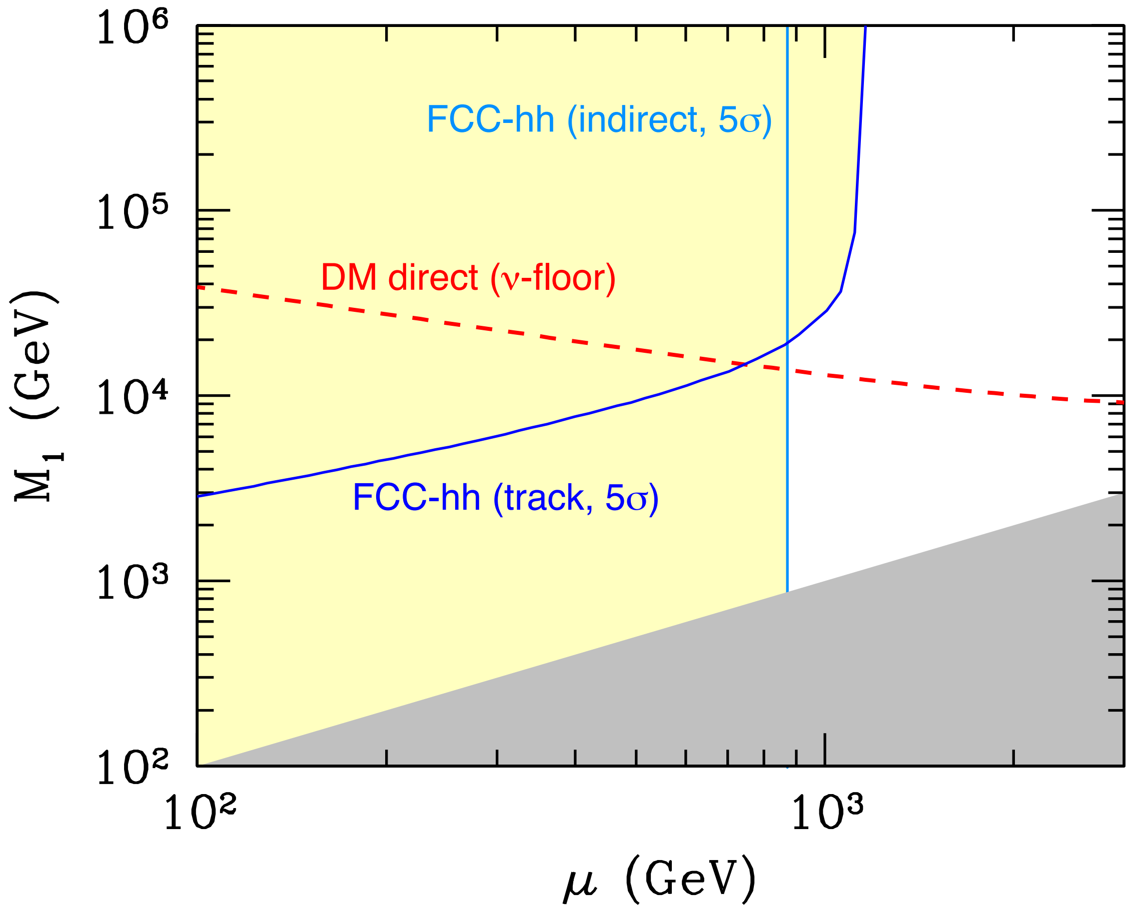
$\Rightarrow$ Large parameter region is still unexplored

Higgsino LSP: future prospect (in a next few decades)



$\Rightarrow$ Significant improvements may be possible in next decades

Higgsino LSP: future prospect (ultimate)



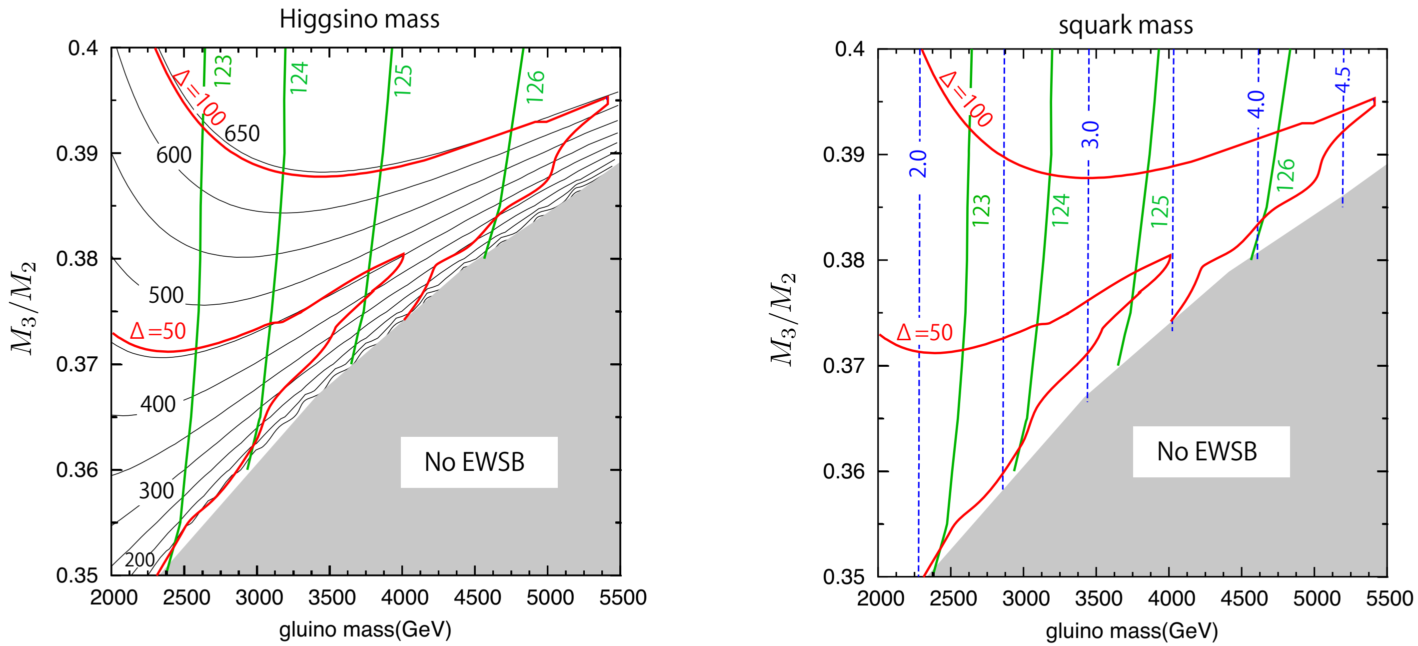
⇒ Collider and DM experiments are both important back ups

Focus-point scenario with non-universal gaugino masses

[Yanagida & Yokozaki]

$$m_{H_u}^2(m_{\mathrm{weak}}) \simeq -1.21M_3^2 + 0.21M_2^2 - 0.02M_1^2 - 0.10M_2M_3 + \cdots$$

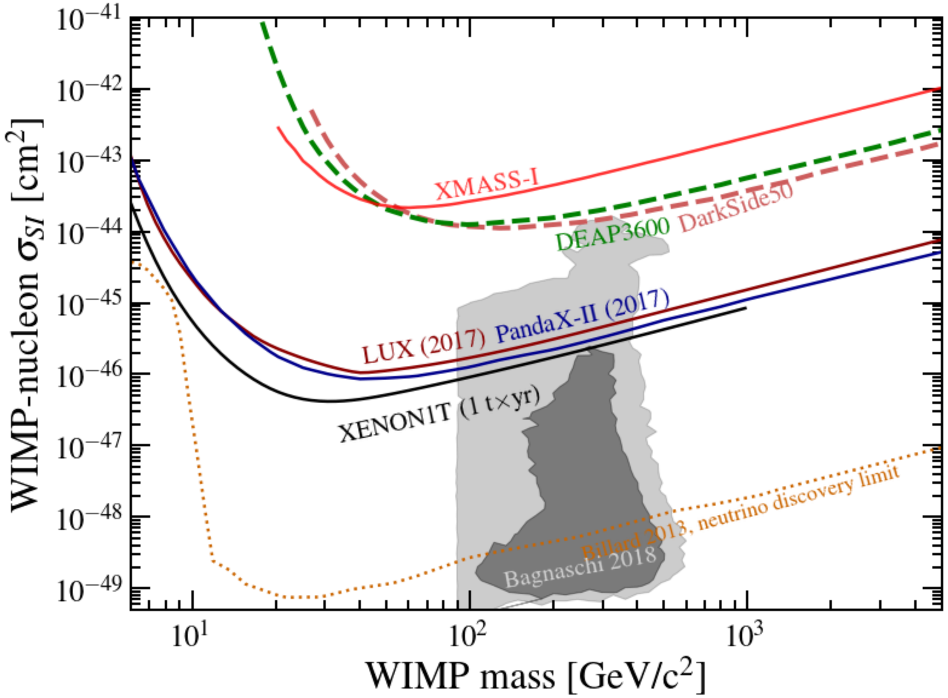
If $M_3 : M_2 : M_1 \simeq 0.4 : 1 : 1$, for e.g., $m_{H_u}^2$ may be suppressed



$M_1 = M_2$

[Yanagida & Yokozaki ('14)]

DM direct detection experiments: summary

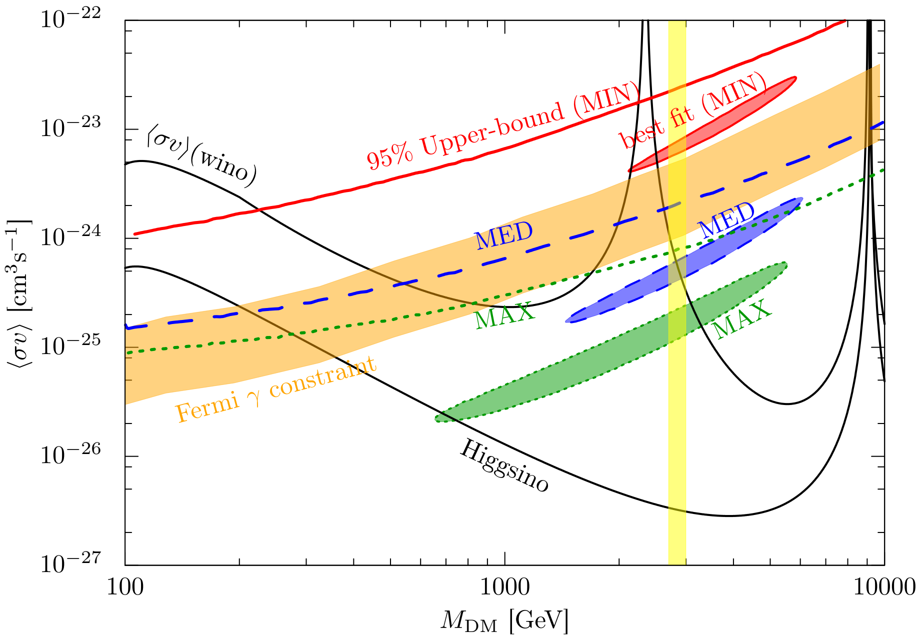


[from T. Yamashita's talk @ TAUP 2019]

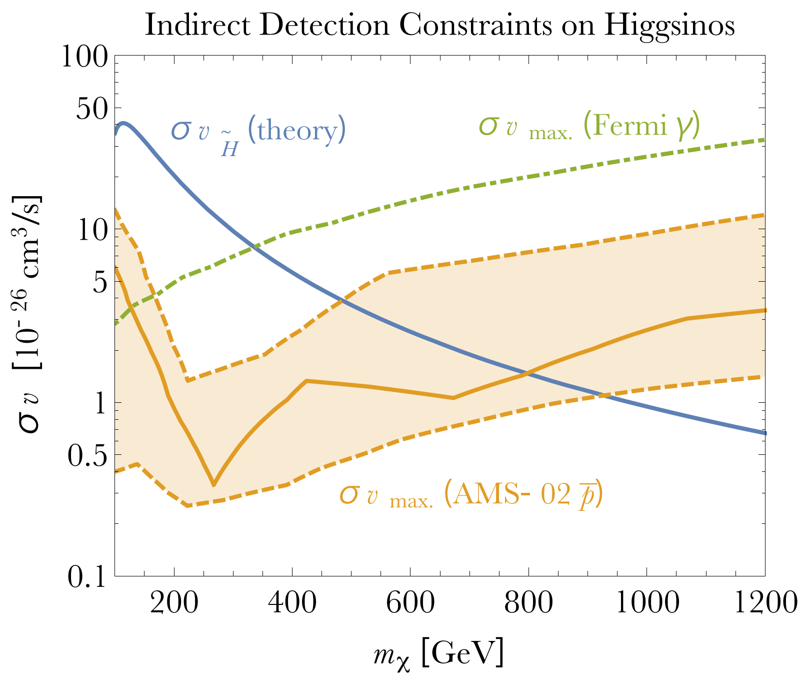
- Current: $\sigma_{\mathsf{SI}} \lesssim 1\times 10^{-45}\,\mathsf{cm}^2 \times \left(\dfrac{m_{\mathsf{WIMP}}}{1\,\mathsf{TeV}}\right)$

- ν floor: $\sigma_{\mathsf{SI}} \sim 2\times 10^{-48}\,\mathsf{cm}^2 \times \left(\dfrac{m_{\mathsf{WIMP}}}{1\,\mathsf{TeV}}\right)$

Indirect: anti-proton (using AMS-02 results)



[Ibe, Matsumoto, Shirai & Yanagida ('15)]

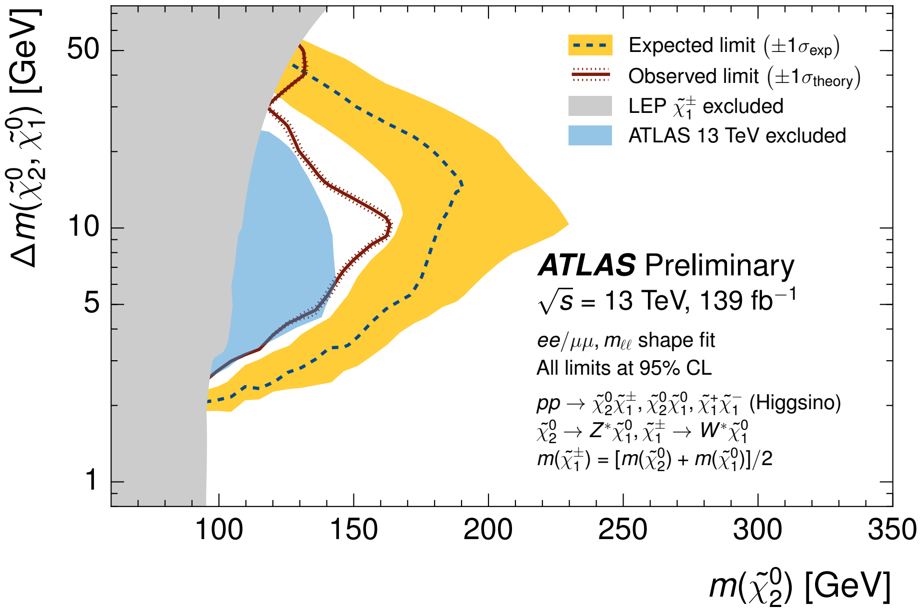


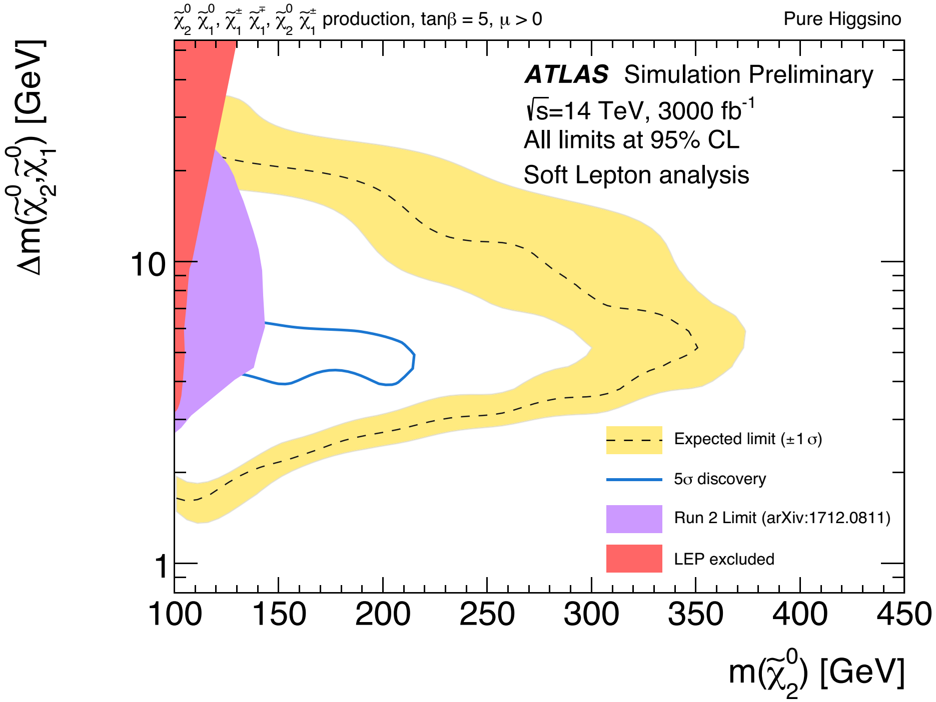
[Krall & Reece ('17), based on Cuoco, Kramer& Korsmeiner ('17)]

$\Rightarrow$ Anti-proton constraint is sensitive to the propagation model

Current and future bounds with MET + soft $\ell^+\ell^-$

[ATLAS-CONF-2019-014, ATL-PHYS-PUB-2018-031]

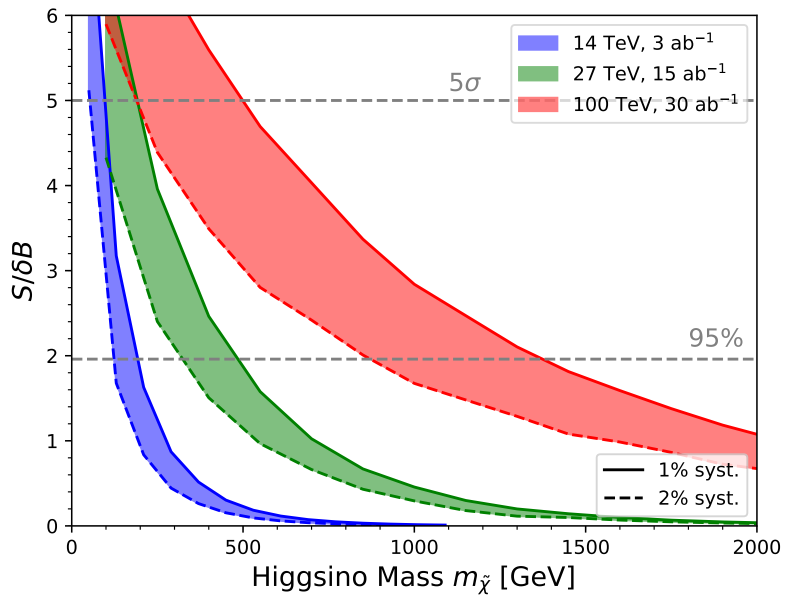




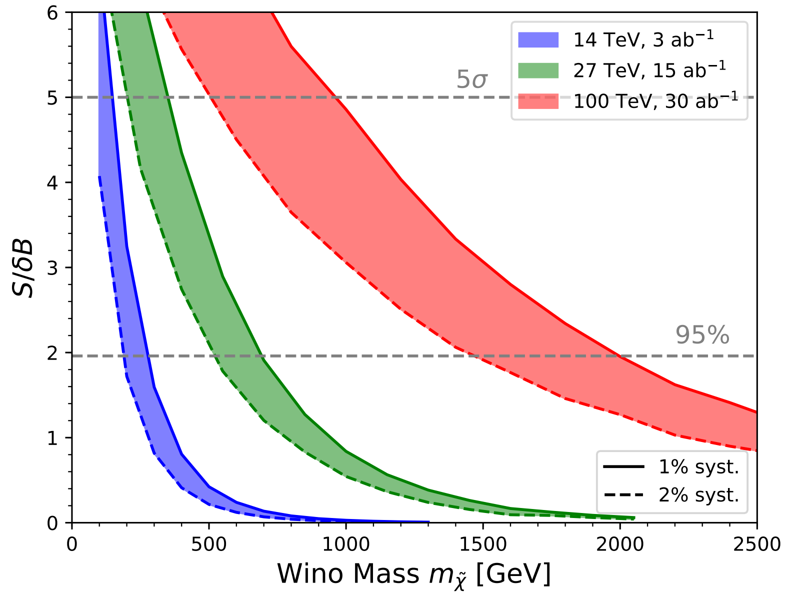
- High p_T jet(s) and MET
- Soft $\ell^+\ell^-$ pair, with $m_{\ell\ell} \sim O(1-10)$ GeV

Mono-jet: future prospect

Higgsino



Wino

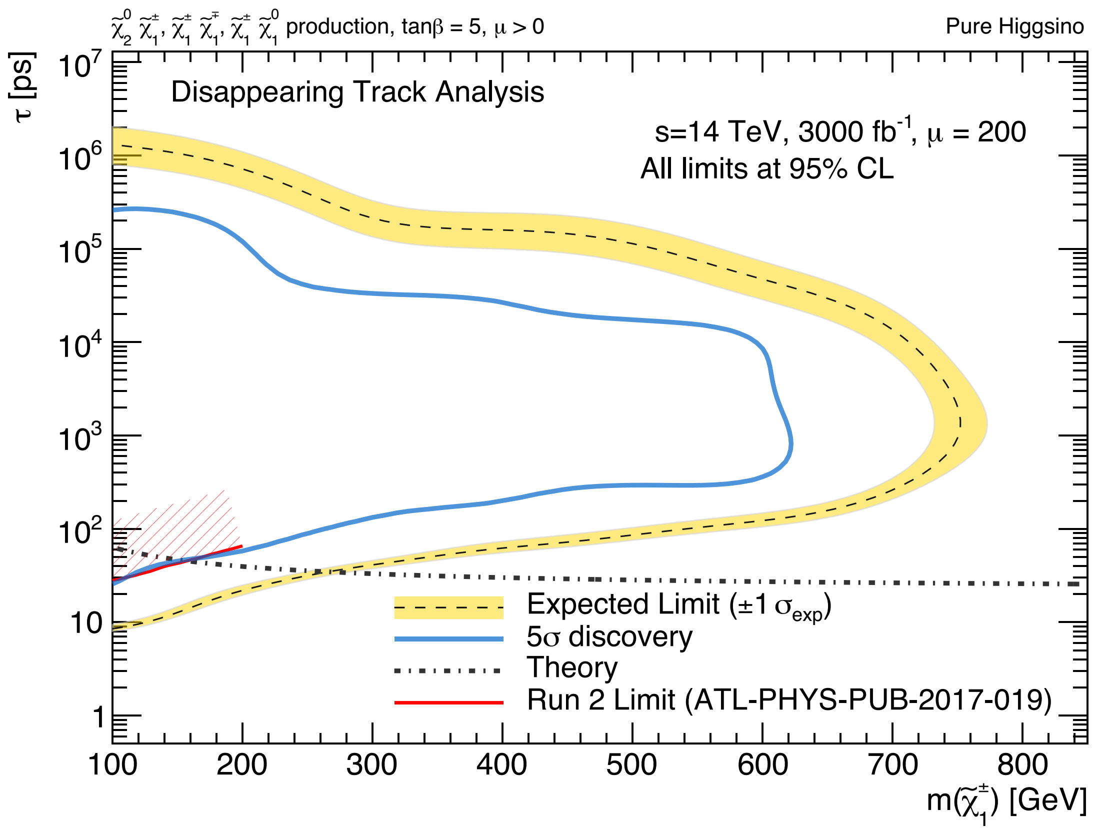


[Han, Mukhopadhyay & Wang ('18)]

For Higgsino:

- 2σ exclusion at HL-LHC: $m_{\tilde{H}} \lesssim 100 - 200$ GeV
- 5σ discovery at FCC-hh: $m_{\tilde{H}} \lesssim 200 - 500$ GeV

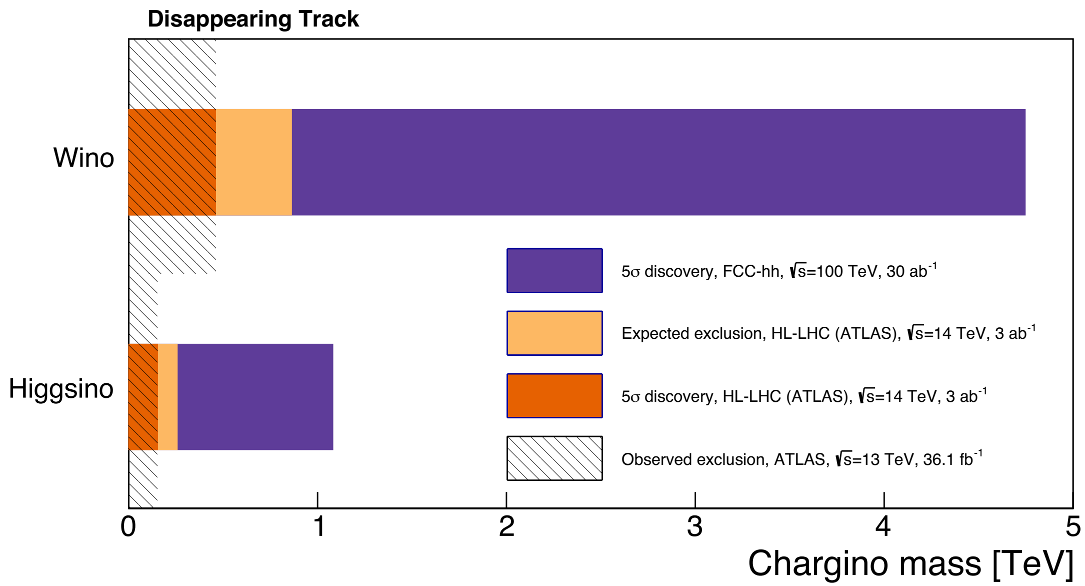
Disappearing track search: HL-LHC (future prospect)

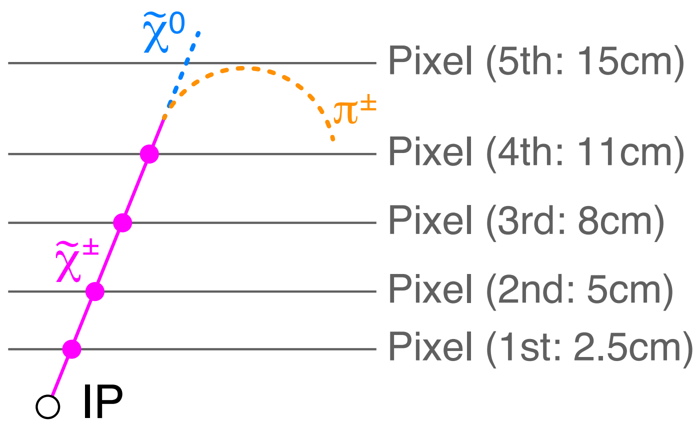


[ATL-PHYS-PUB-2018-031]

Disappearing track searches at the HL-LHC and FCC-hh

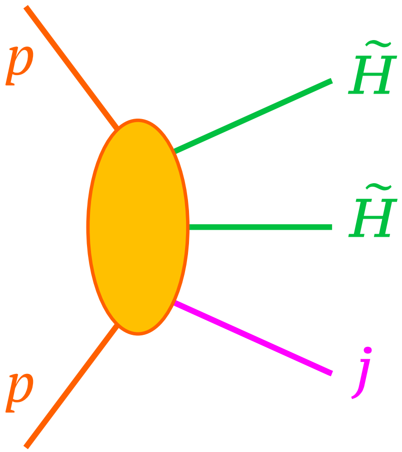
[Saito, Sawada, Terashi & Asai ('19); see also ATL-PHYS-PUB-2018-031]

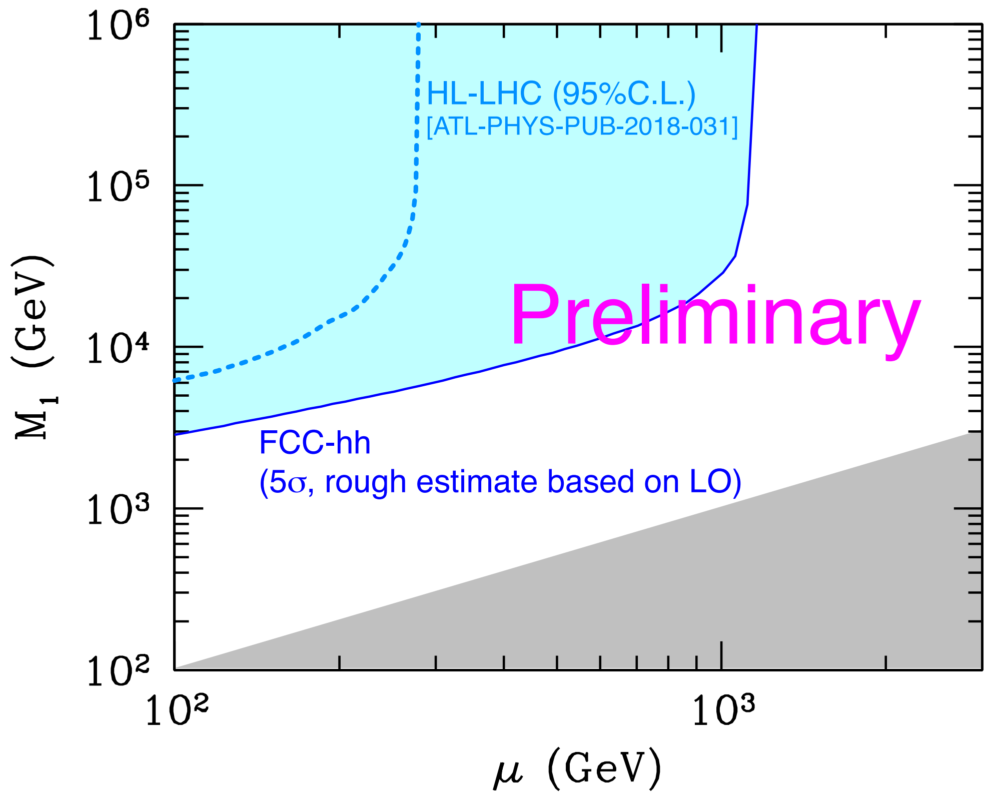




- Reaches for Higgsino with $\tau_{\tilde{H}^\pm} = 0.023\,\text{ns}$ (i.e., $c\tau_{\tilde{H}^\pm} \simeq 7\,\text{mm}$)
  - $\mu \lesssim 260$ GeV at HL-LHC ($95\,\%$ C.L.)
  - $\mu \lesssim 1.1$ TeV at FCC-hh (5σ)
- The reach should become worse for shorter lifetime

Disappearing track search for $c\tau_{\tilde{H}^\pm} < 7\,\mathrm{mm}$ (a rough estimate)





- $\tilde{H}^\pm$ with $L_T^{\tilde{H}^\pm} > 11\,\mathrm{cm}$
- MET $> 4\,\mathrm{TeV}$

$\Rightarrow$ Disappearing track search cannot access the region of relatively small gaugino masses

Systematic errors in our FCC-hh analysis

- Systematic effects are assumed to be smooth

Real number of events in i-th bin in the SM ($p = m_{\ell\ell}$ or m_T)

$$N_i^{(\text{true})} = N_i^{(\text{MC})} \times e^{\theta_1}(1-p_i)^{\theta_2} p_i^{(\theta_3+\theta_4 \ln p_i + \theta_5 \ln^2 p_i)}$$

$\Rightarrow$ θ's absorb systematic uncertainties

Sources of systematic uncertainties

- Luminosity
- Renormalization and factorization scales
- PDF choice
- (Lepton ID)