Studying Gauginos in Supersymmetric Model at Future 100 TeV pp Collider

Takeo Moroi (Tokyo)

Asai, Chigusa, Kaji, TM, Saito, Sawada, Tanaka, Terashi & Uno

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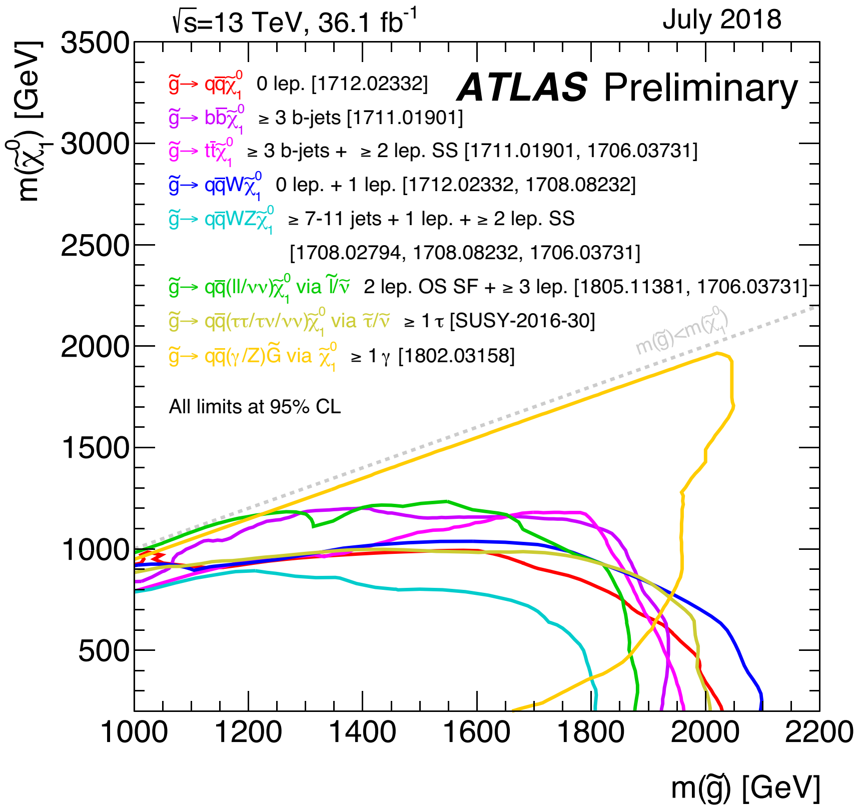
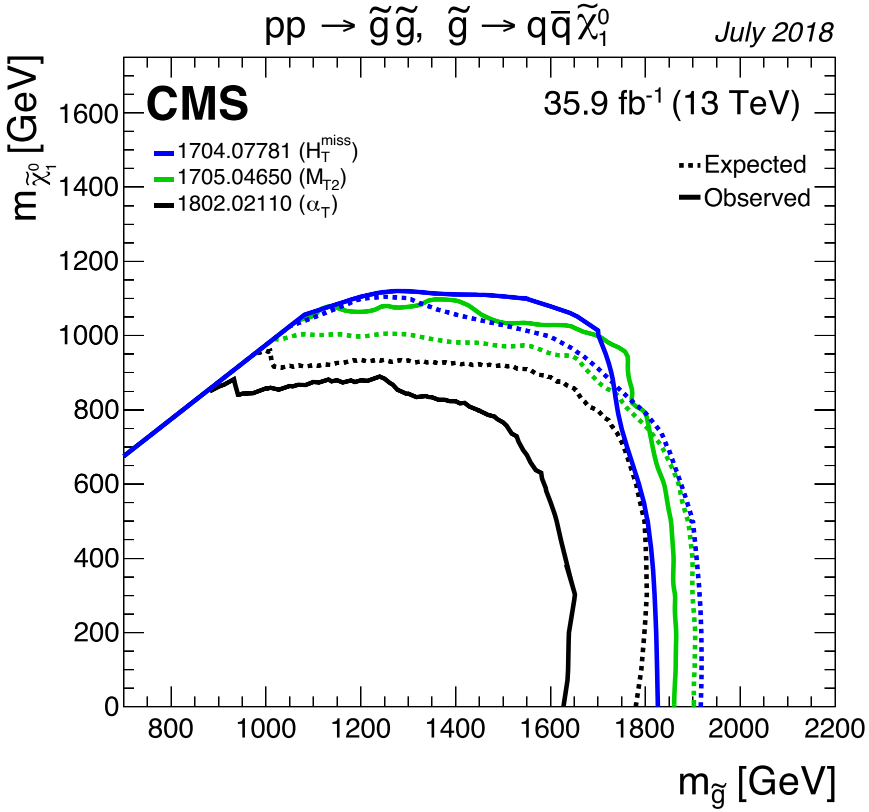
1. Introduction

SUSY particles may be quite heavy (even if they exist)





Do we have a chance to study SUSY particles at colliders?

$\Rightarrow$ Future circular colliders (FCCs) with $E_{\text{CM}} \sim 100$ TeV may be an option

Today, I would like to discuss:

- FCC studies of pure gravity mediation model of SUSY breaking based on anomaly mediation
- In particular, measurements of gaugino masses

Outline

1. Introduction
2. Model
3. Gauginos at FCCs
4. Gaugino Mass Determinations
5. Summary

2. Model

Mass spectrum of our interest

- Sfermion and Higgsino masses are of $O(100)$ TeV

  $\Rightarrow$ Heavy stops are good for $m_h \simeq 125$ GeV

  $\Rightarrow$ SUSY CP / flavor problems are relaxed

- Gaugino masses are loop suppressed, and are of $O(1)$ TeV

  $\Rightarrow$ Wino can be dark matter

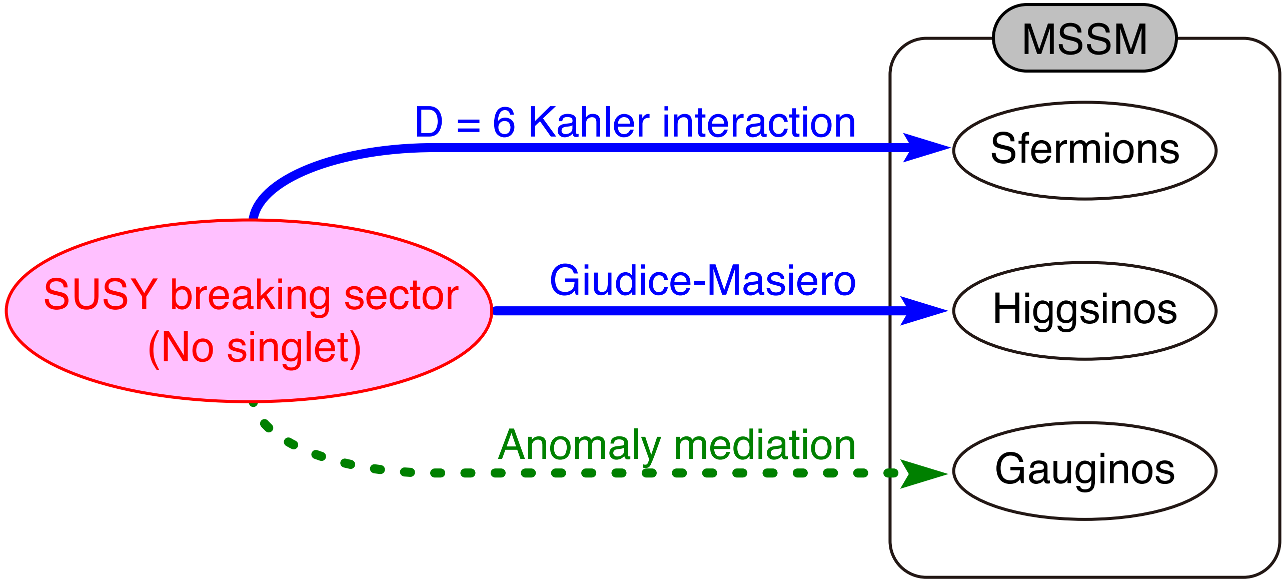
  $\Rightarrow$ Gauginos are primary targets of collider experiments

Such a mass spectrum is phenomenologically viable

$\Rightarrow$ What is the underlying theory?

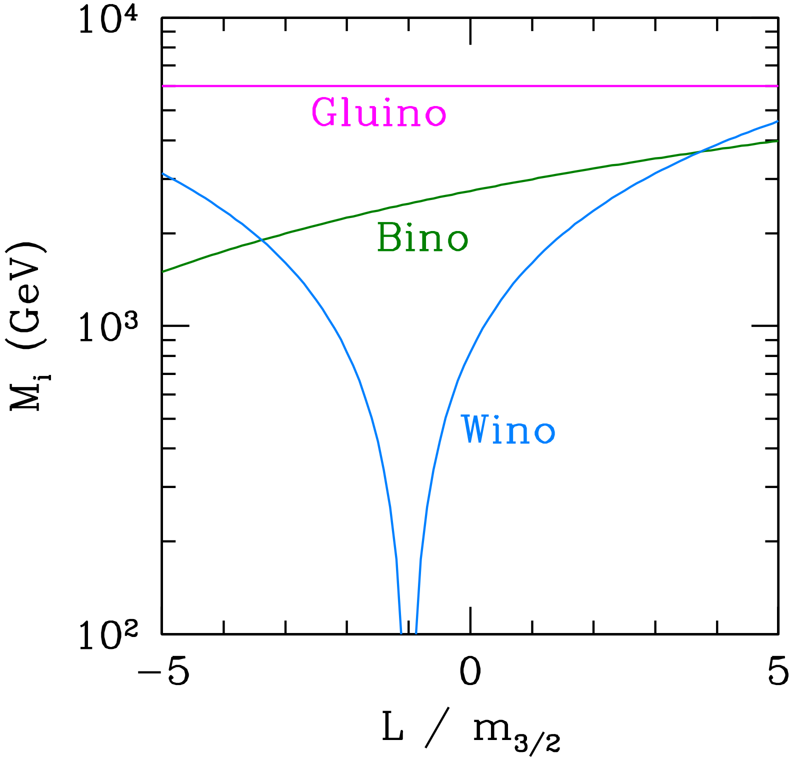
Anomaly mediation + pure gravity mediation

[Giudice, Luty, Murayama & Rattazzi; Randall & Sundrum; Ibe, TM & Yanagida; Ibe & Yanagida; Arkani-Hamed et al.]



- The most general supergravity Lagrangian with Planck-suppressed interactions
- No singlet in SUSY breaking sector
- Scalar masses are of the order of the gravitino mass $m_{3/2}$

Gaugino masses in the PGM model



$$M_1 \simeq \frac{g_1^2}{16\pi^2}\left(11m_{3/2}+L\right)$$

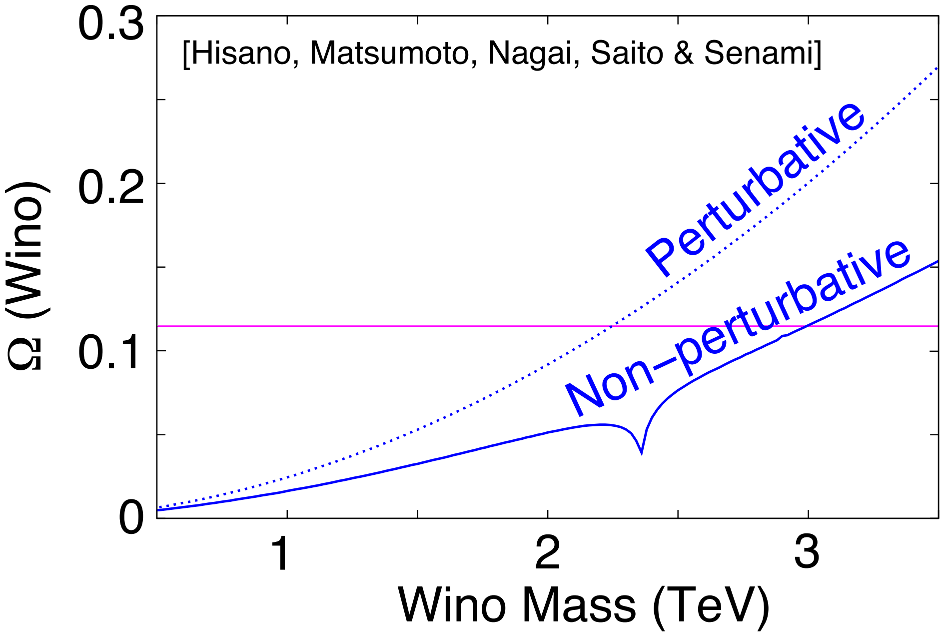
$$M_2 \simeq \frac{g_2^2}{16\pi^2}\left(m_{3/2}+L\right)$$

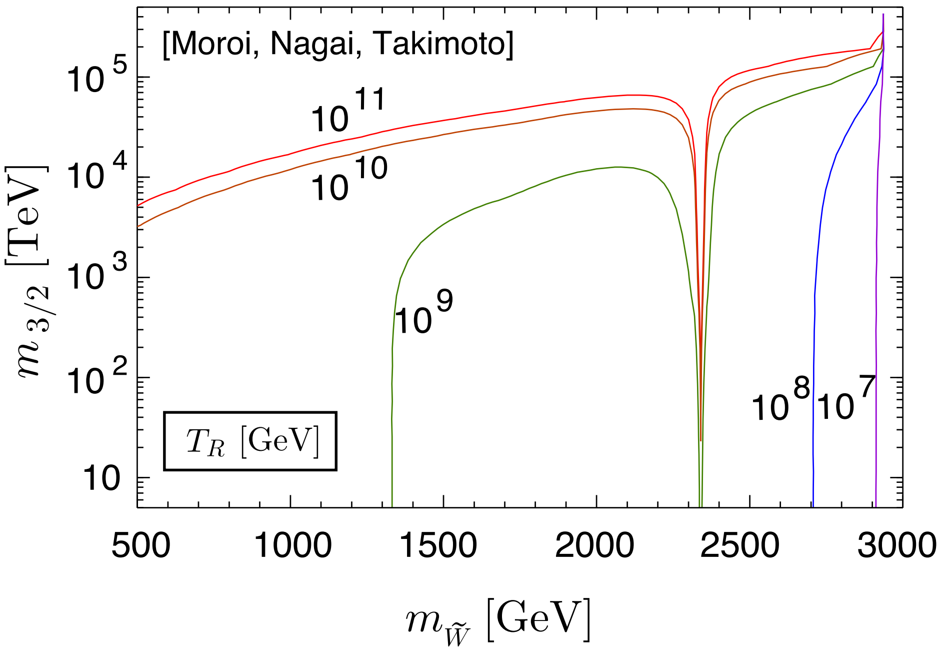
$$M_3 \simeq \frac{g_3^2}{16\pi^2}\left(-3m_{3/2}\right)$$

$$L \equiv \mu \sin 2\beta \frac{m_A^2}{\mu^2 - m_A^2} \ln \frac{\mu^2}{m_A^2}$$

- Wino (gaugino for $SU(2)_L$) is likely to be the LSP
- $\left|\frac{10g_1^2}{3g_3^2}m_{\tilde{g}} - \frac{g_1^2}{g_2^2}m_{\tilde{W}}\right| \lesssim m_{\tilde{B}} \lesssim \frac{10g_1^2}{3g_3^2}m_{\tilde{g}} + \frac{g_1^2}{g_2^2}m_{\tilde{W}}$

Motivation 1: Wino LSP as dark matter





- Thermally produced Wino can be DM, if $m_{\tilde{W}} \simeq 2.9$ TeV

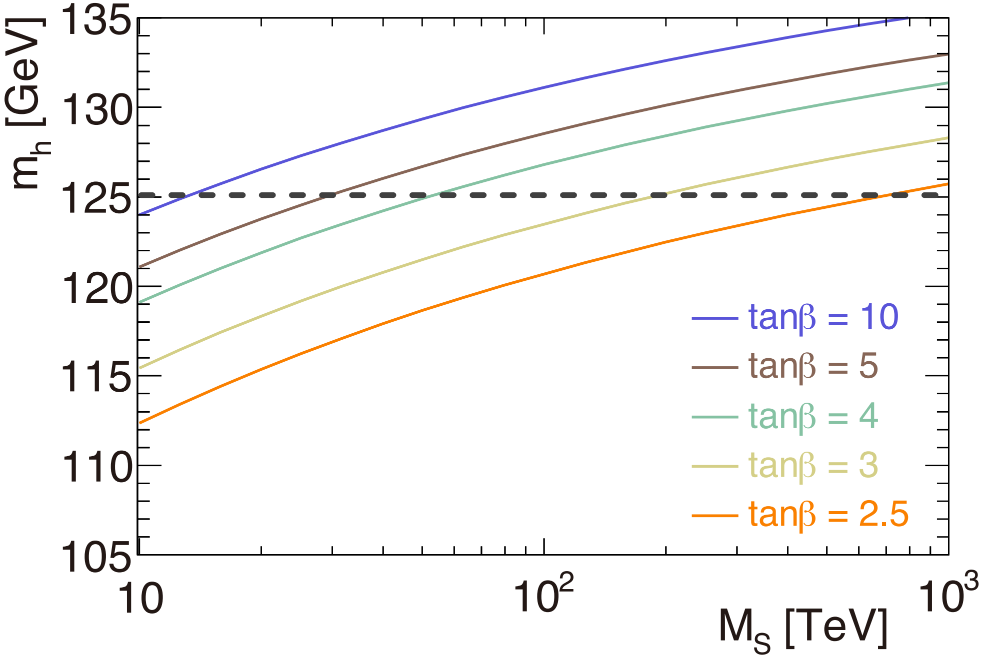
  $\Rightarrow$ Can we test such a Wino at colliders?

- Non-thermal production of Wino DM is also possible

Motivation 2: Heavy stops are good for $m_h \simeq 125$ GeV

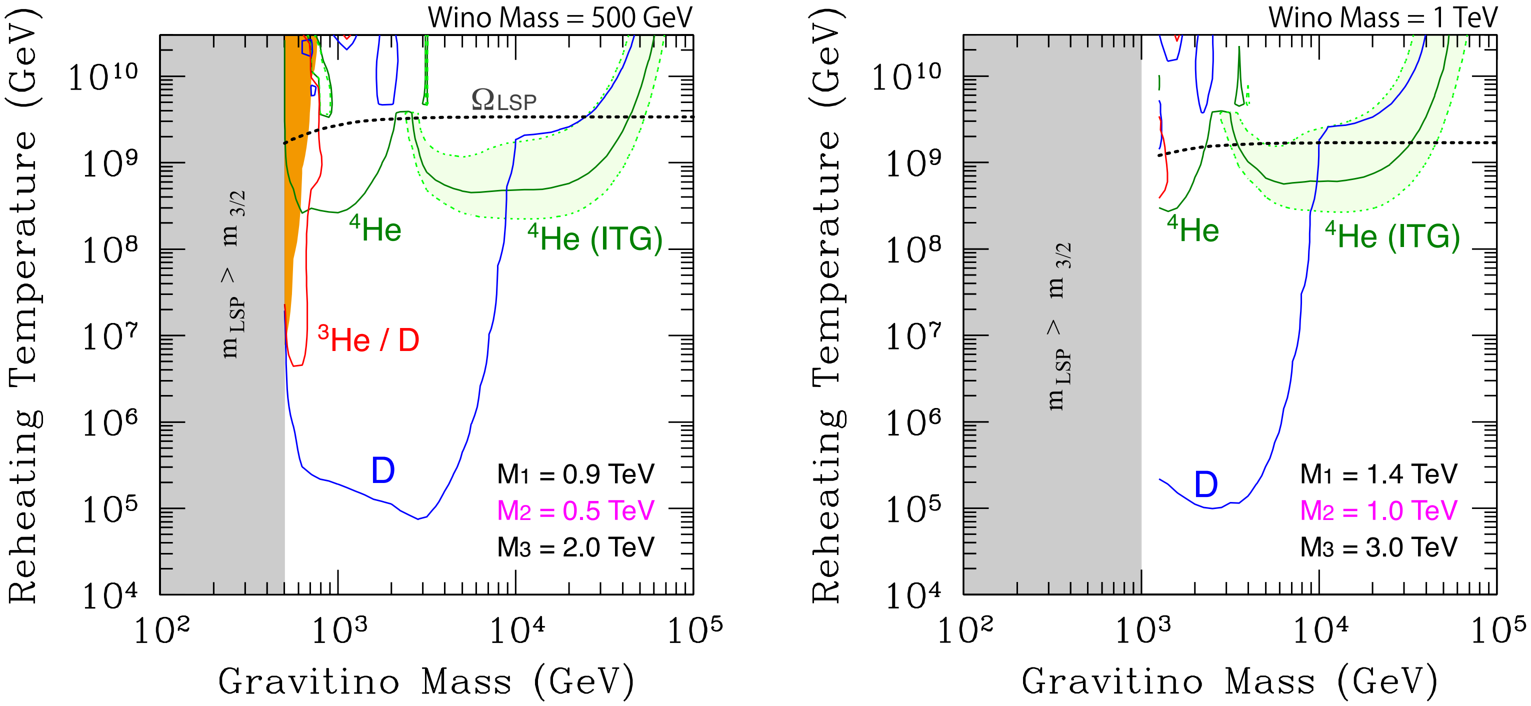
$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

[Okada, Yamaguchi & Yanagida; Ellis, Ridolfi & Zwirner; Haber & Hempfling]



⇒ The stop masses of $O(10 - 1000)$ TeV are suggested

Motivation 3: Cosmological gravitino problem



[Kawasaki, Kohri, TM, Takaesu]

⇒ With $m_{3/2} \gtrsim 10$ TeV, the reheating temperature as high as $T_{\rm R} \gtrsim 10^9$ GeV is possible

⇒ Simple thermal leptogenesis may work

[Buchmuller, Di Bari & Plumacher; Giudice, Notari, Raidal, Riotto & Strumia]

Summary of Motivations

- Higgs mass of $m_h \simeq 125$ GeV is easily realized
- Wino can be the LSP, which is a viable candidate of DM
- Cosmological gravitino problem is easily avoided
- Gauge coupling unification is OK
- SUSY CP / flavor problems may be avoided

Hierarchy between the SUSY scale and the EW scale is sizable

⇒ It's better than the hierarchy between Planck scale and the EW scale

3. Gauginos at FCCs

Let us consider

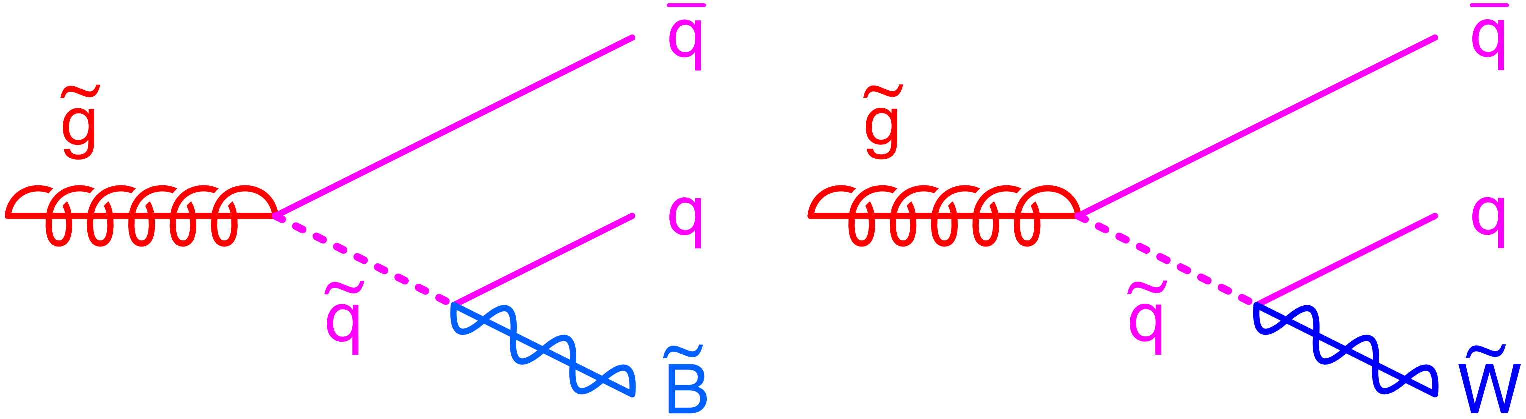
- How and how well we can determine gaugino masses
- Possibility to test the scenario

Sample points for MC studies ($m_{\tilde{W}} < m_{\tilde{B}} < m_{\tilde{g}}$)

	Point 1	Point 2
$m_{3/2}$ [TeV]	250	302
L [TeV]	800	756
$m_{\tilde{B}}$ [TeV]	3.7	4.1
$m_{\tilde{W}}$ [TeV]	2.9	2.9
$m_{\tilde{g}}$ [TeV]	6.0	7.0
$\sigma(pp \to \tilde{g}\tilde{g})$ [fb]	7.9	2.7

Gluino decay

$$\tilde{g} \to \bar{q}q\tilde{B},\ \bar{q}q\tilde{W}$$

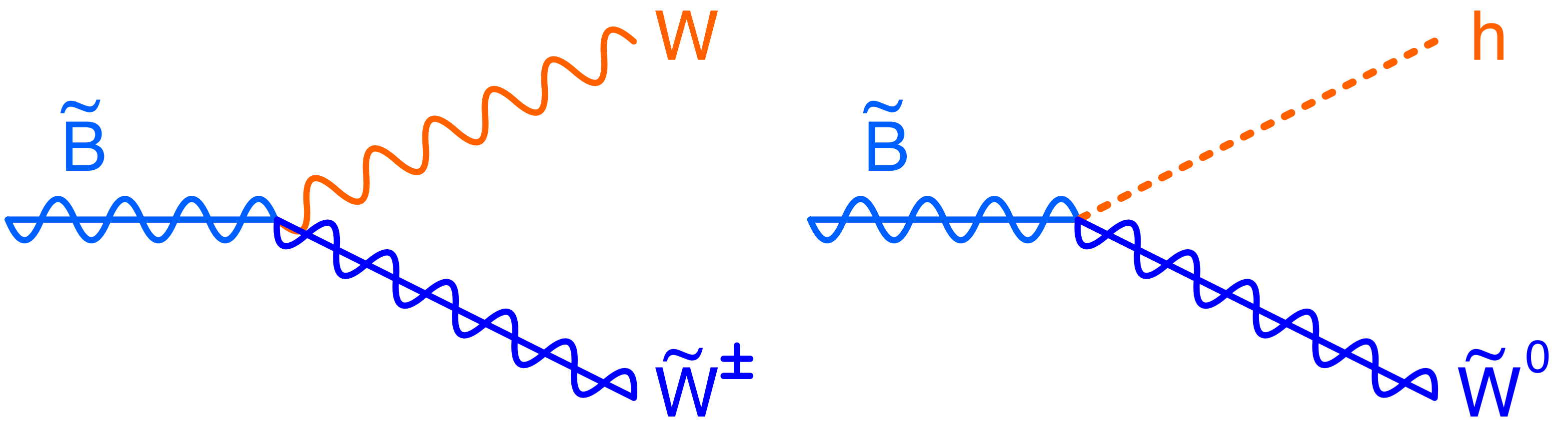


Assumptions:

- $Br(\tilde{g} \to q\bar{q}\tilde{W}) = Br(\tilde{g} \to q\bar{q}\tilde{B}) = 0.5$
- Gluino decays into all the generations universally

Bino decay

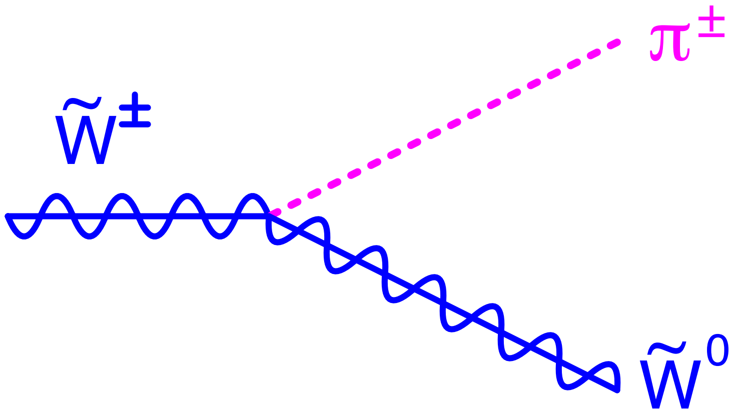
$$\tilde{B} \to W^{\mp}\tilde{W}^{\pm},\ h\tilde{W}^{0}$$



In the sample point of our choice:

- $\tilde{B} \to \tilde{W}^{\pm}W^{\mp}$ dominates
- $\tilde{B} \to f\bar{f}\tilde{W}^{\pm}$ is negligible

Charged Wino decay: $\tilde{W}^{\pm} \to \tilde{W}^{0}\pi^{\pm}$



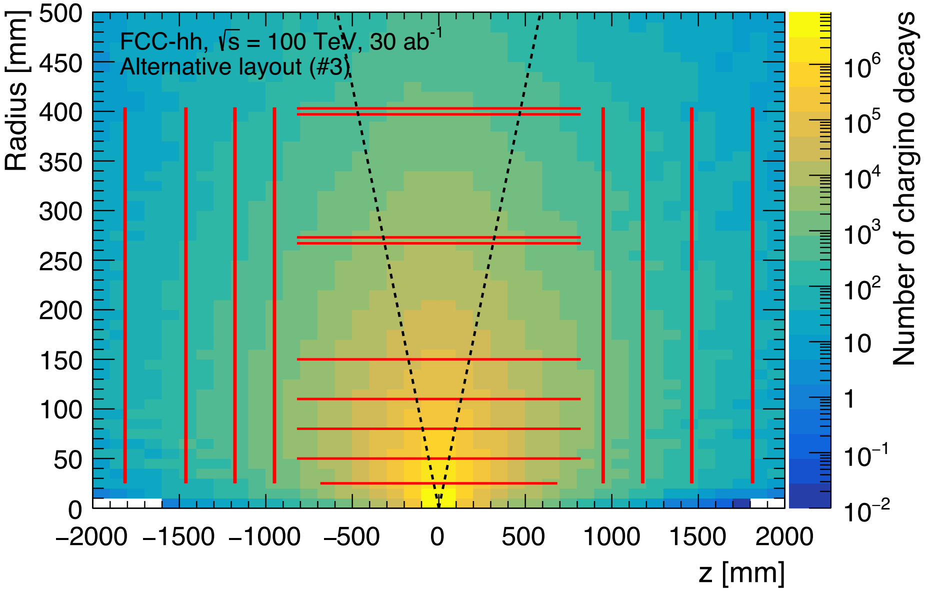
- $\Delta m_{\tilde{W}} \simeq 165$ MeV
- $c\tau_{\tilde{W}^{\pm}\to\tilde{W}^{0}\pi^{\pm}} \simeq 5.8$ cm

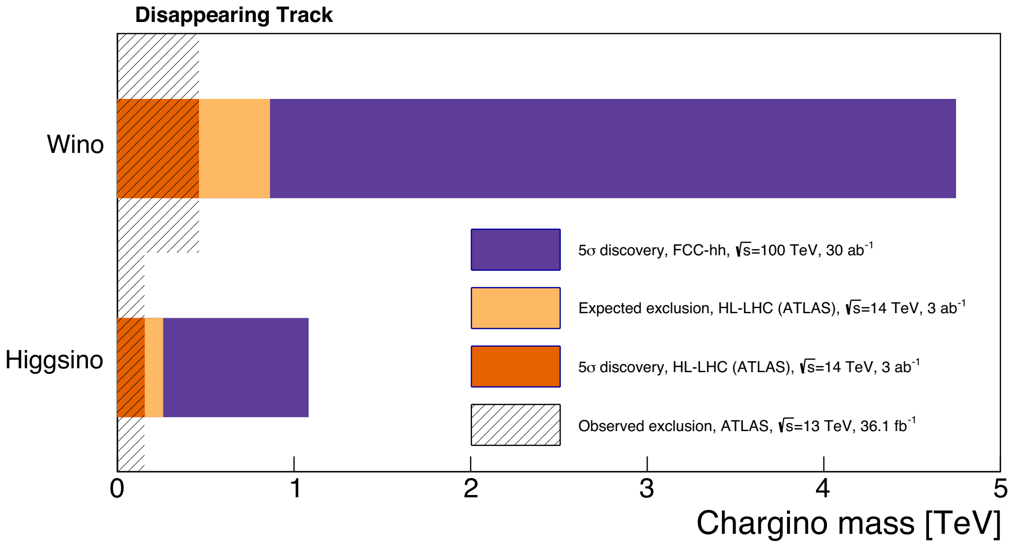
Charged Wino may be identified as short high-p_T track

- $\tilde{W}^{\pm}$-tracks can be reconstructed by inner pixel detector
- Requiring $\tilde{W}^{\pm}$-like tracks, SM background can be reduced

Long-lived $\tilde{W}^{\pm}$ at FCC-hh: case with $pp \to \tilde{W}^{\pm}\tilde{W}^{\pm,0}j$

- Inner pixel detector has several layers at $L_T \lesssim 10 - 15$ cm



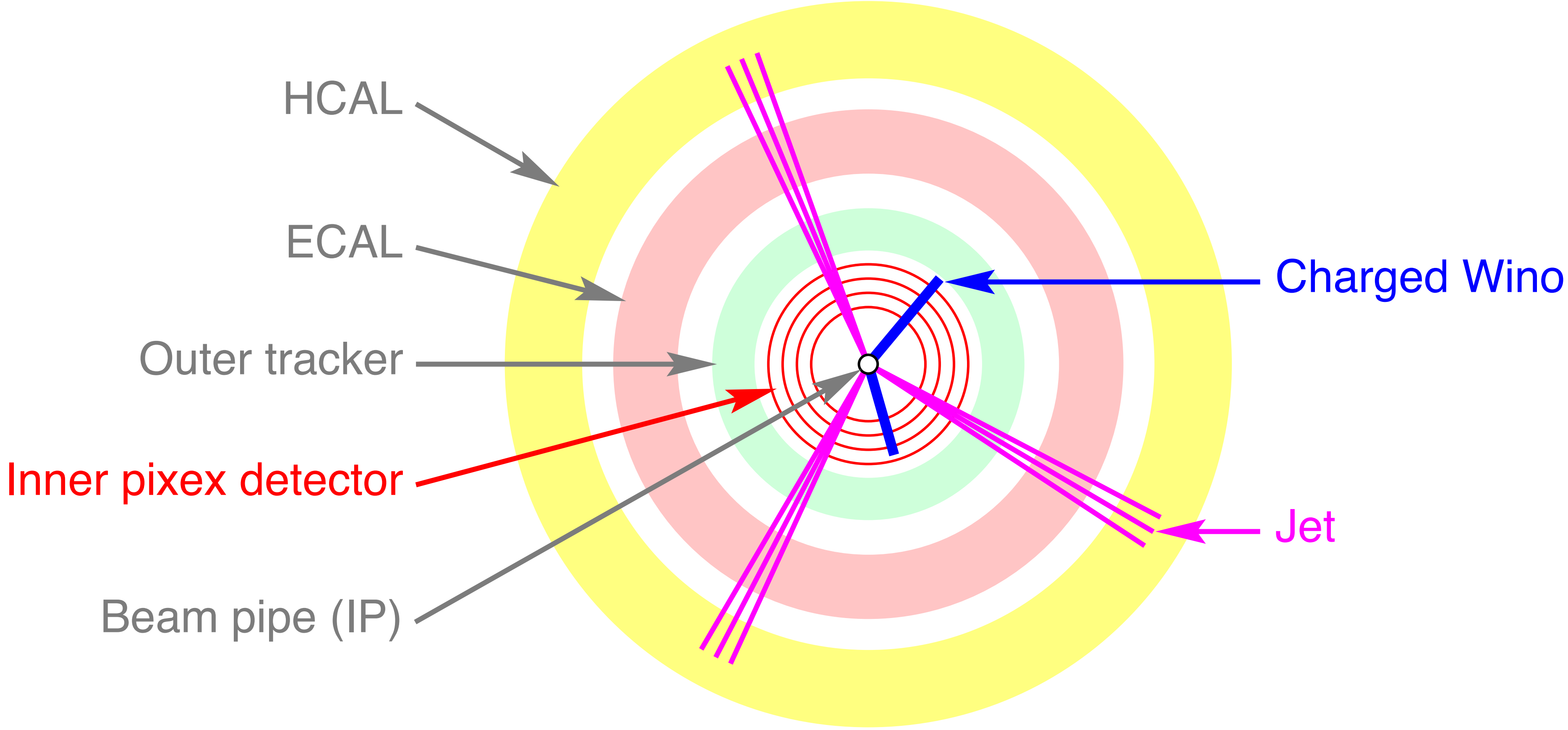


[Saito, Sawada, Terashi & Asai 1901.02987]

- FCC-hh may cover the Wino mass up to $4 - 5$ TeV
- Sensitivity depends on the detector layout

The events of our interest: gluino pair production

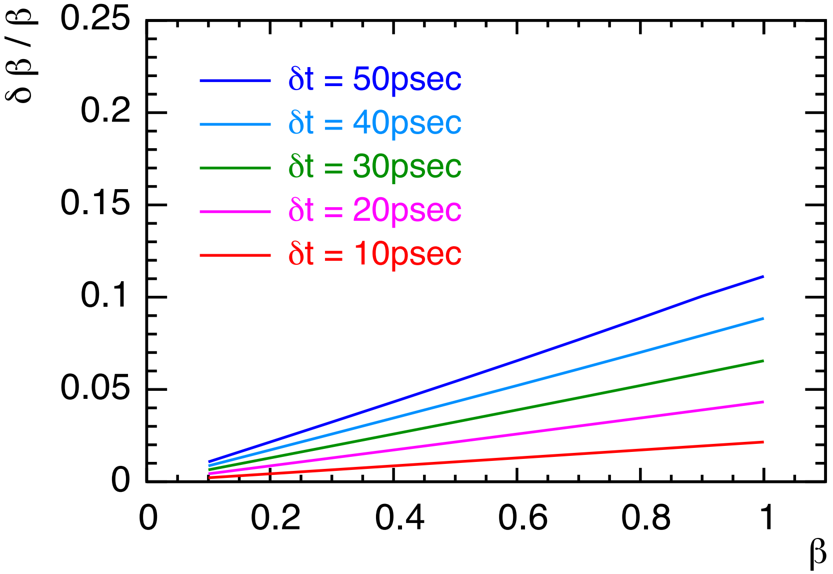
- Multi-jets
- Charged Wino track(s), identified by the pixel detector



Expectation for the pixel detector

- 4th or 5th layer at $L_T \sim 10 - 15$ cm
- Timing information is available: $\delta t \sim O(10 \text{ ps})$

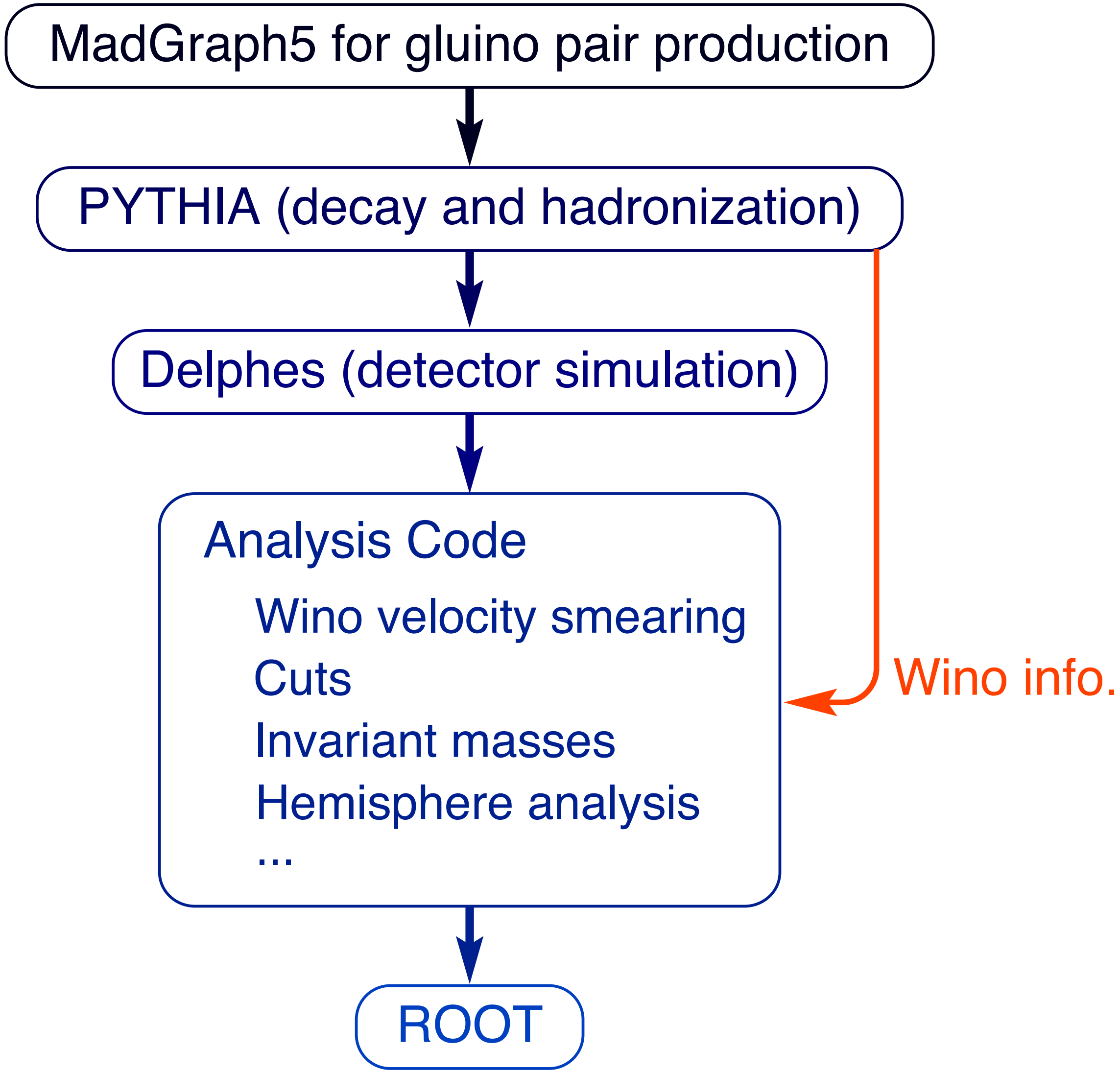
Timing information can be converted to the Wino velocity



$$\Rightarrow \frac{\delta\beta}{\beta} \sim (\text{a few} - 10)\ \% \times \beta^{(\text{true})}$$

4. Gaugino Mass Determinations

Flow-chart of our MC study



MadGraph5 for gluino pair production

PYTHIA (decay and hadronization)

Delphes (detector simulation)

Analysis Code

- Wino velocity smearing
- Cuts
- Invariant masses
- Hemisphere analysis
- ...

ROOT

Wino info.

Requirements on signal events:

- Two $\tilde{W}^{\pm}$-tracks with $L_T > 10$ cm and $|\eta| < 1.5$
- $p_T^{\text{(miss)}} > 1$ TeV

  $p_T^{\text{(miss)}}$: Missing p_T evaluated only from jets

We assume:

- Charged Wino can be identified if $L_T > 10$ cm
- Velocity resolution of $\tilde{W}^{\pm}$ is $6\ \%$
- There is no error in the charged Wino direction

Wino track can also be used to eliminate SM backgrounds

$\Rightarrow$ Fake track rate $\sim O(10^{-5})$ per track

$\Rightarrow$ SM backgrounds are negligible

Measurement 1: Wino mass

- Wino velocity may be determined with timing information
- Momenta of Winos can be estimated using MET information (if two Wino tracks are observed)

  $\Leftrightarrow$ Momentum is assumed to be carried away by jets and Winos

We determine Wino momenta by solving:

$$c_1 \vec{n}_{\tilde{W}_1,T} + c_2 \vec{n}_{\tilde{W}_2,T} = -\vec{p}_{\text{miss}} \equiv - \sum_{i:\text{jets}} \vec{p}_{i,T}$$

$$\vec{p}_{\tilde{W}_1} = c_1 \vec{n}_{\tilde{W}_1}$$

$$\vec{p}_{\tilde{W}_2} = c_2 \vec{n}_{\tilde{W}_2}$$

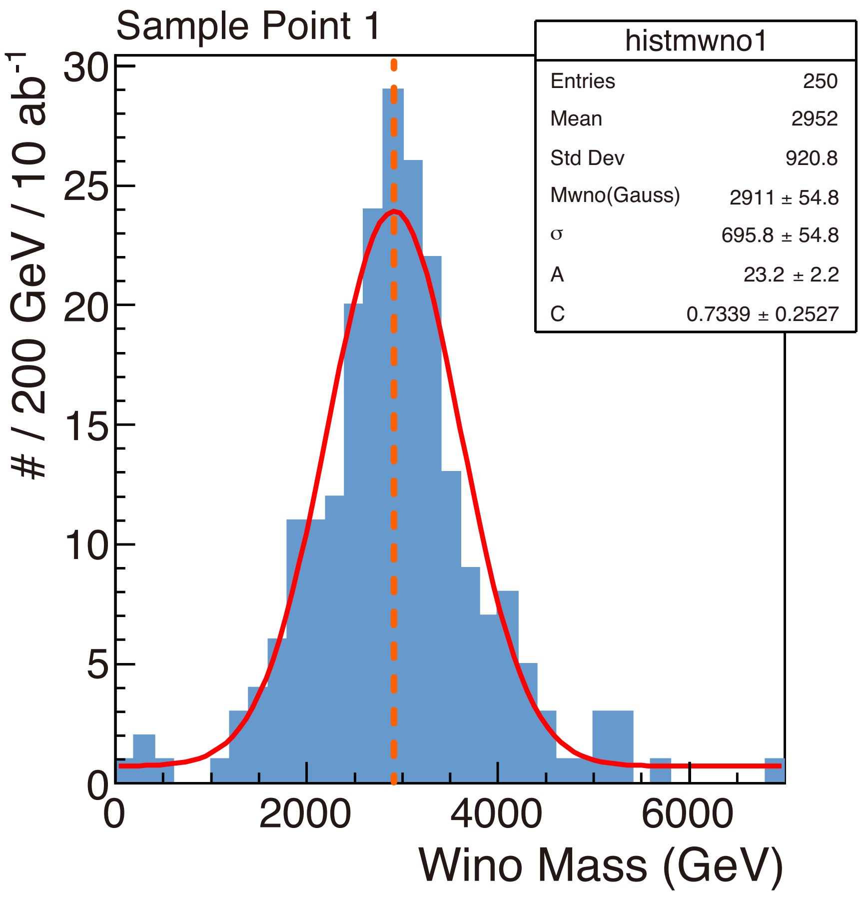
Wino mass in terms of observables:

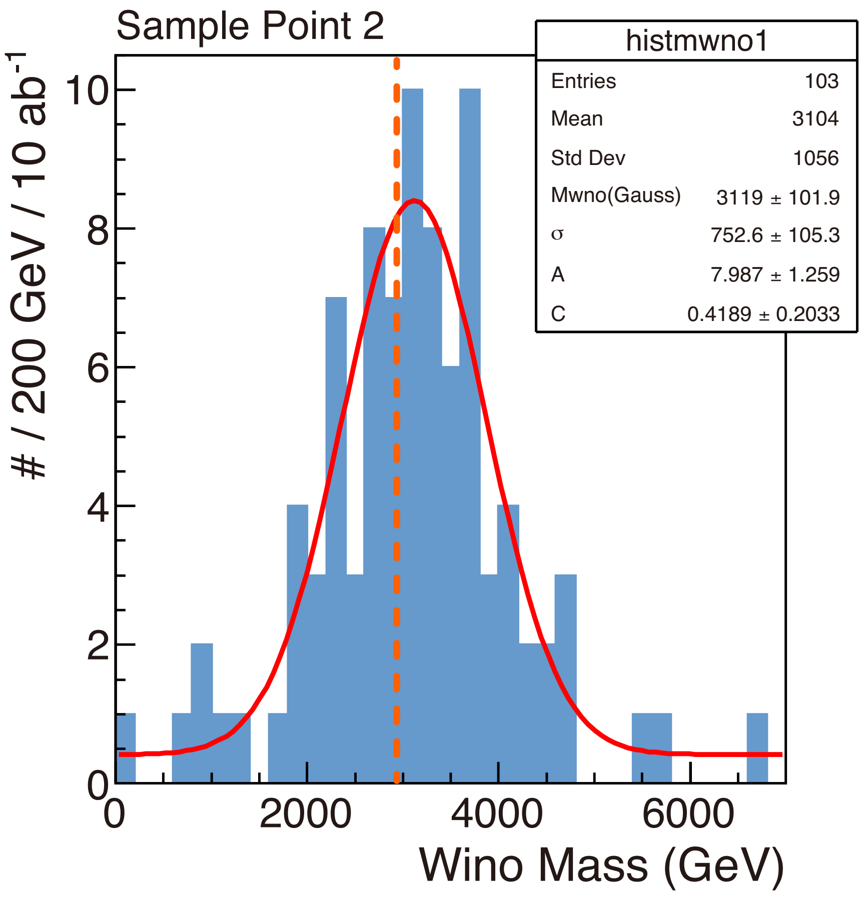
$$m_{\tilde{W}}^{(\text{rec})} = \frac{1}{\beta_{\tilde{W}^\pm}\gamma_{\tilde{W}^\pm}} |\vec{p}_{\tilde{W}^\pm}| \equiv \frac{\sqrt{1-\beta_{\tilde{W}^\pm}^2}}{\beta_{\tilde{W}^\pm}} |\vec{p}_{\tilde{W}^\pm}|$$

We use the events with:

- $\tilde{W}^\pm$ with $L_T > 10$ cm and $\beta^{(\text{obs})} < 0.8$ for reconstruction
- 2nd $\tilde{W}^\pm$ track for background reduction
- No isolated lepton

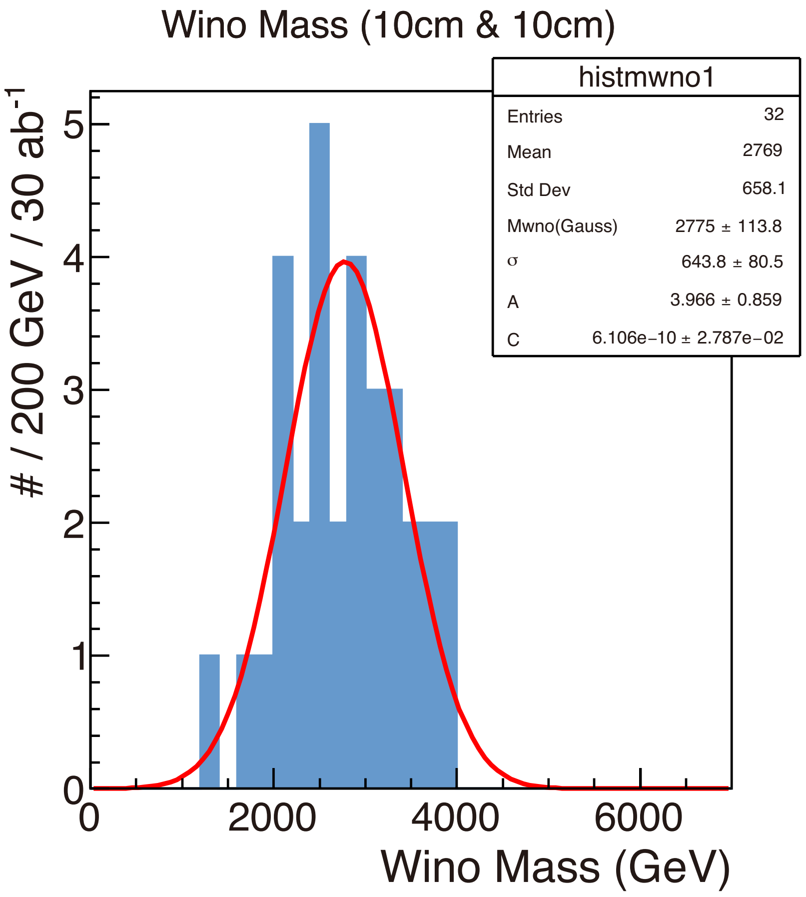
Reconstructed Wino mass





- True value: 2900 GeV
- Fit: Gaussian + constant

Reconstructed Wino mass: $pp \to \tilde{W}^+\tilde{W}^- j$

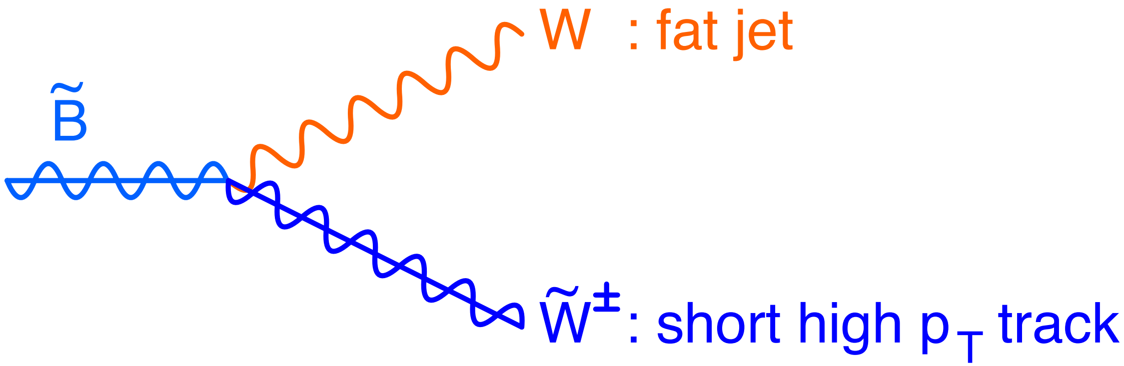


- True Wino mass: 2900 GeV

- $\beta_{\tilde{W}^{\pm}} < 0.8$
- $p_T^{(\text{miss})} > 1$ TeV

$$\Rightarrow \delta m_{\tilde{W}}^{(\text{obs})} \simeq 130 \text{ GeV (with } \mathcal{L} = 30 \text{ ab}^{-1})$$

Measurement 2: Bino mass



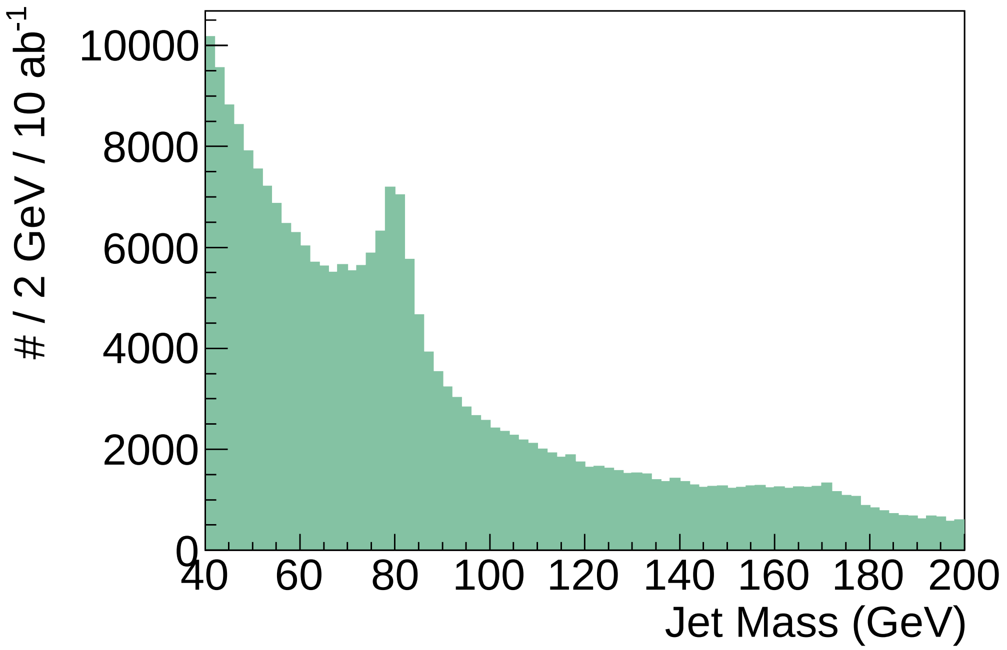
- Wino momentum is known (if L_T is long enough)
- W-jet may be identified as a fat jet

  $\Rightarrow$ We use jets with $m_j \sim m_W$

Reconstructed Bino mass (assuming $m_{\tilde{W}}$ is known)

$$m_{\tilde{B}}^{(\text{rec})} = \sqrt{(m_{\tilde{W}} u_{\tilde{W}^{\pm}} + p_W)^2} \quad \text{with} \quad u_{\tilde{W}^{\pm}} = (\gamma_{\tilde{W}^{\pm}}, \beta_{\tilde{W}^{\pm}} \gamma_{\tilde{W}^{\pm}} \vec{n}_{\tilde{W}^{\pm}})$$

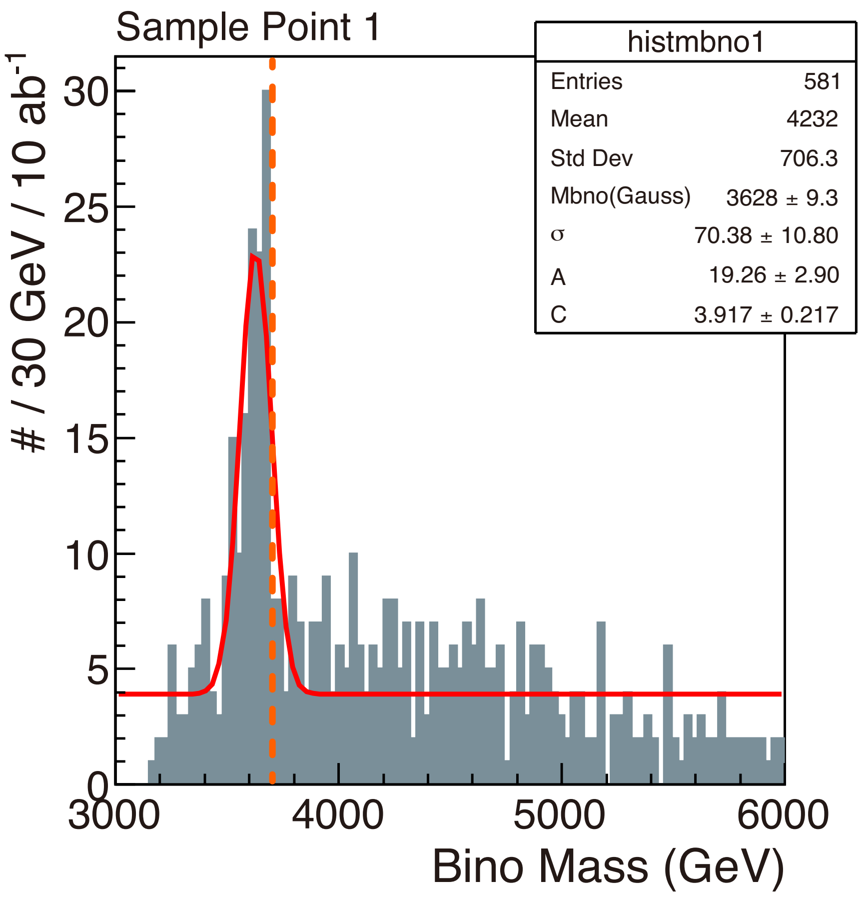
Jet mass distribution (for Point 1)

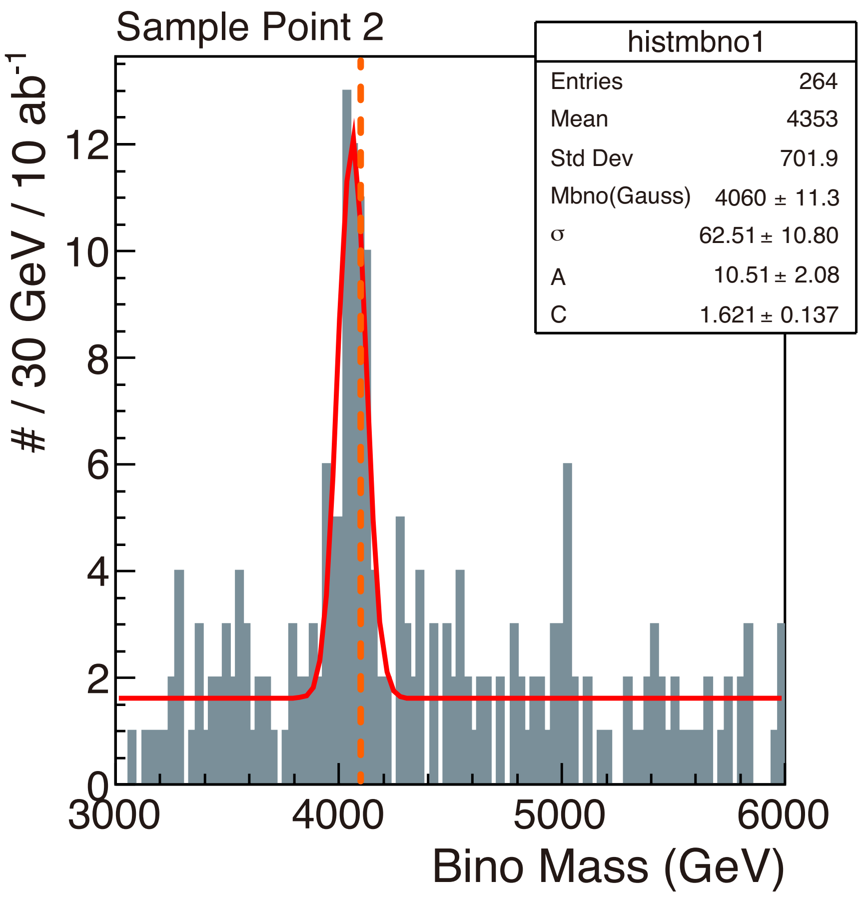


We require:

- $\tilde{W}^{\pm}$ with $L_T > 10$ cm and $\beta^{(\text{obs})} < 0.9$ for reconstruction
- Jet with 70 GeV $< m_j < 90$ GeV

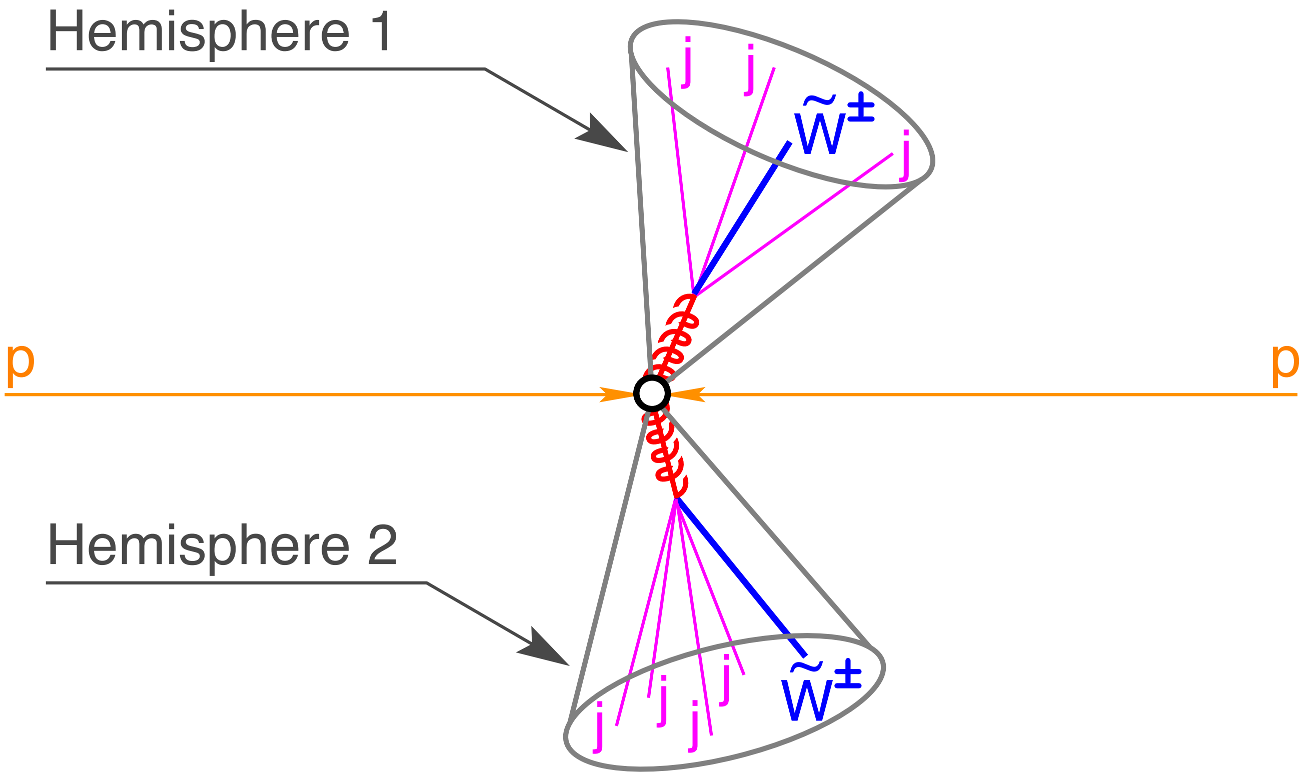
Reconstructed Bino mass (using true Wino mass)





- True value: 3660 GeV (Pt.1) / 4060 GeV (Pt.2)
- Fit: Gaussian + constant

Measurement 3: Gluino mass (with hemisphere analysis)



Reconstructed gluino mass

$$m_{\tilde{g}}^{(\text{rec})} = \sqrt{P^2_{\text{Hemisphere}}} \quad \text{with} \quad P_{\text{Hemisphere}} \equiv P_{\tilde{W}^{\pm}} + \sum_{j\in H} p_j$$

Hemisphere analysis with two observed Wino tracks

- Two charged Winos are assigned to different hemispheres:

$$\tilde{W}^{\pm}_{A} \in H_A \quad (A = 1, 2)$$

- For each high p_T jet:

$$\begin{cases} j_i \in H_1\text{: if } d(p_{H_1}, p_{j_i}) < d(p_{H_2}, p_{j_i}) \\ j_i \in H_2\text{: if } d(p_{H_2}, p_{j_i}) < d(p_{H_1}, p_{j_i}) \end{cases}$$

Momentum of A-th hemisphere H_A

$$p_{H_A} = p_{\tilde{W}^{\pm}_{A}} + \sum_{j_i \in H_A} p_{j_i}$$

Distance function

[See De Roeck (Editor), CMS Physics TDR]

$$d(p_H, p_j) = \frac{(E_H - |\mathbf{p}_H| \cos\theta_{Hj}) E_H}{(E_H + E_j)^2}$$

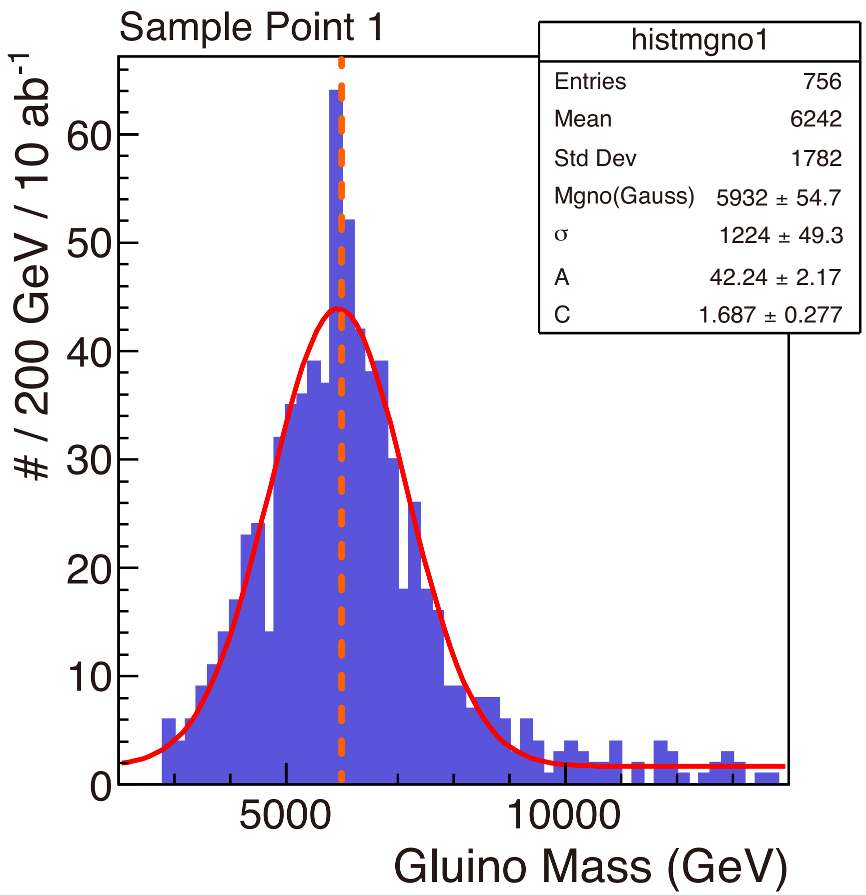
We study the invariant mass of hemispheres containing $\tilde{W}^{\pm}$

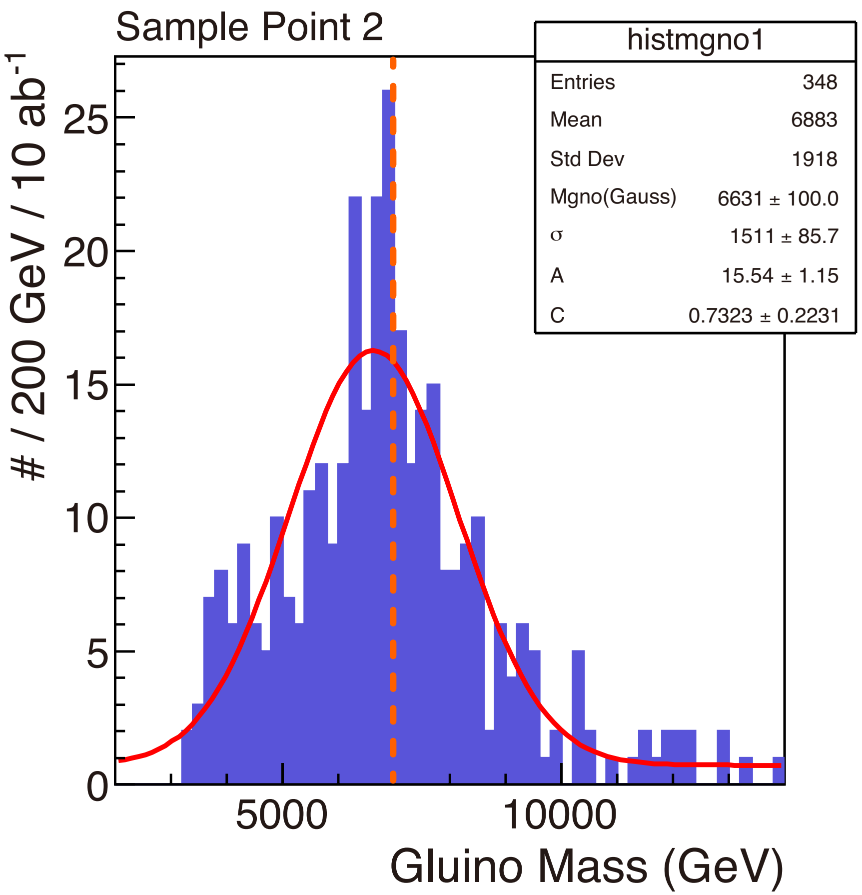
- Two long enough $\tilde{W}^{\pm}$ tracks
- No isolated lepton
- We use jets with $|\eta| < 2$

Hemisphere analysis with two charged Winos

- Momenta of Winos are determined using missing momentum information
- Each hemisphere contains one $\tilde{W}^{\pm}$ (and jets)
- Invariant mass of the hemisphere is regarded as (reconstructed) gluino mass

Reconstructed gluino mass (with true Wino mass):





- True value: 6000 GeV (Pt.1) / 7000 GeV (Pt.2)
- Fit: Gaussian + constant

5. Summary

Gaugino mass determinations may be possible

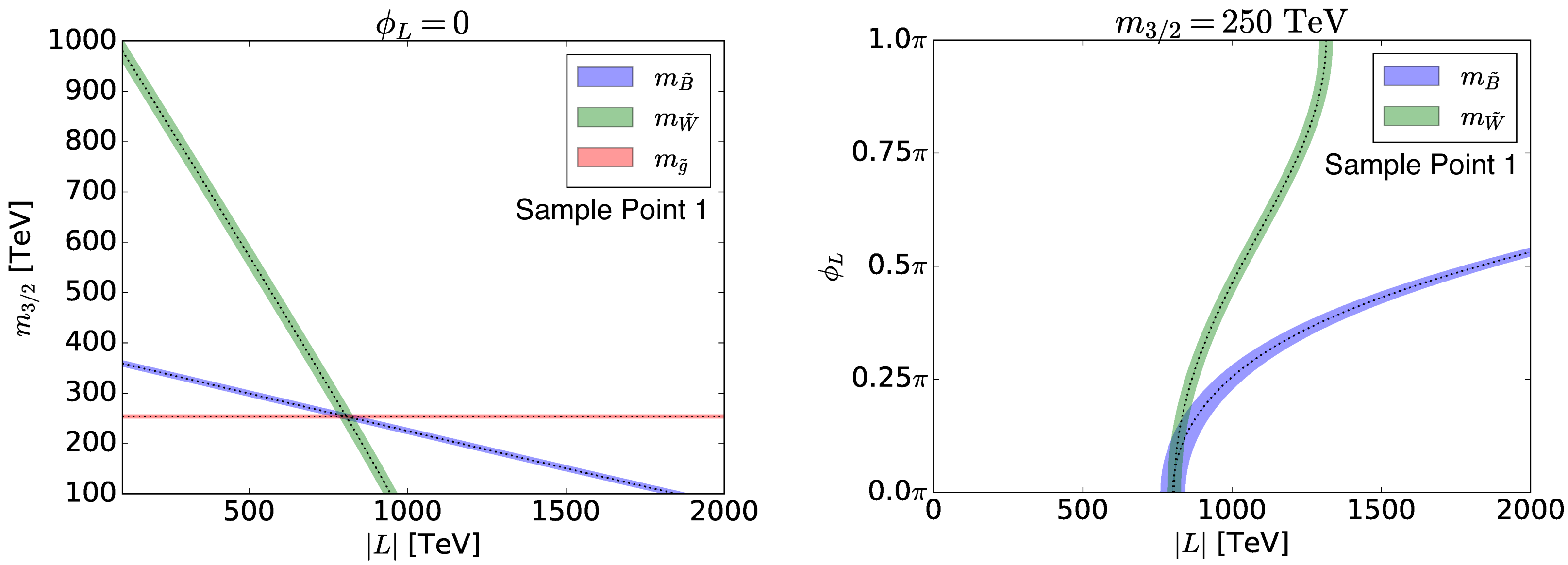
Sample Point 1 (with $\mathcal{L} = 10$ ab^{-1}):

	$\delta m_{\tilde{B}}$	$\delta m_{\tilde{W}}$	$\delta m_{\tilde{g}}$
$\delta m_{\tilde{X}}^{(\mathrm{stat})}$	8 GeV	61 GeV	59 GeV
Due to $\delta m_{\tilde{W}}$	61 GeV	–	61 GeV
Total	62 GeV	61 GeV	85 GeV

⇒ Test of the model

$$\left|\frac{10g_1^2}{3g_3^2}m_{\tilde{g}} - \frac{g_1^2}{g_2^2}m_{\tilde{W}}\right| \lesssim m_{\tilde{B}} \lesssim \frac{10g_1^2}{3g_3^2}m_{\tilde{g}} + \frac{g_1^2}{g_2^2}m_{\tilde{W}}$$

Information about the mechanism of SUSY breaking



$\Rightarrow$ Determination of $m_{3/2}$, $|L|$, $\cdots$

$\Rightarrow$ Impact on cosmology

FCC-hh can have significant impact on BSM studies

- Discovery
- Measurements