Spin Determination @ LHC

Lian-Tao Wang

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A. Hook, L. Wang and I. Yavin To be published
Outline

Motivation

Survey of two approaches

- Initial indication: Rates + simple kinematics
- Spin correlation in cascade decays

Conclusion
The Large Hadron Collider \( p p \) collider, summer 2008

Energy frontier: \( E_{CM} = 14 \) TeV. High intensity

Beginning of a new era. Addressing many fundamental questions.
Focusing on TeV scale

Quantum gravity

Unification

TeV Scale:
- Higgs
- Supersymmetry
- Technicolor
- Black hole

Cold Dark Matter

Naturalness, Flavor...

Standard Model
Elementary Particles

LHC

Spin determination

KITPC, 2008

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What do we expect?

1. Naturalness
2. Cold Dark Matter in the Universe
3. $m_{top} \gg$ Other fermions.
4. Flavor, CP, and more

1. And 2. $\Rightarrow$ Motivations, and challenges for spin measurement
• Mystery of the weak scale, naturalness

Hierarchy problem: \( \Lambda_{EW} \ll \Lambda_{\text{fundamental}} \) (e.g. \( M_{\text{Planck}} \))

a. How to generate a scale very different from the Planck scale

Asymptotic freedom (e.g., QCD) \( \rightarrow \) exponential separation of scales.

\[
\frac{\Lambda_{EW}}{\Lambda_{\text{fundamental}}} \propto e^{-1/g^2}
\]

b. How to stabilize such a scale: quantum corrections \( \sim \frac{1}{16\pi^2} \Lambda_X^2 \)

Two classes of ideas: supersymmetry, compositeness

New physics at \( \Lambda_X \sim 4\pi \times \Lambda_{EW} \)
• **New physics: the partners with similar couplings**

  They typically have same or similar gauge quantum numbers.

  In general, they have different masses and spin.

  Supersymmetry: $\tilde{W}, \tilde{\ell},...$, composite: $W', T',...$

**LHC has enough energy to produce the layer of new physics.**

**Spectacular, complex signals**

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• Dark matter in the universe

Much experimental evidence →
A Promising Candidate for Dark Matter

WIMP

A weakly interacting particle, \( m \sim 10^2 \text{ GeV} \) to \( \text{TeV} \),

→ roughly correct dark matter abundance.

non-trivial, many very different scales, \( \Lambda_{\text{EW}}, M_P, \text{Hubble}, \ldots \), are involved.

A typical implementation in new physics models:

Some Discrete symmetry: new physics particles are odd.

Suppress corrections to SM particle couplings.
  → Improve consistency with precision tests.

Important consequence for LHC signal: \( E_T \)
• Generic “partner” signal.

Dominated by colored NP production.
Rate: $\sim$ pb for $\sim$ TeV NP.
Spin measurement:
Crucial to understand new physics

Spin? $\Rightarrow$ SUSY!

Simulation of a SUSY event at CMS. Taken from Iguana CMS.
Why is spin measurement at LHC challenging?

Leading order features:

\[
\sum \left( \frac{\text{Parton densities}}{2} \right)^2 \times \text{Threshold} \times ? \times \text{matrix elements} \times \text{phase-space}
\]

At \(< 10 \, fb^{-1}\), we are mostly sensitive to

- Gauge quantum number: e.g., colored or not?
- How hard (approximately)? \(\Delta M, P_T\)... Rate \(\times\) BR

\(\Rightarrow\) Degeneracies.

Matrix element information?

1. Angular information in production.

- Many initial state partial waves \((qq, gg, q\bar{q}, \ldots)\).
  \(s, t, u\) channels.
- Unlike \(e^+e^- \to Z \to \ell^+\ell^-\)
  No clean threshold behavior.
- With missing neutral particle in the subsequent decay (cannot reconstruct the rest frame), directional information of the initial particle suffer significant loss.
2. Angular information in decay.

- Detailed shape, requires high statistics.

- Miss pairing,
  \[ \tilde{g}_1 \tilde{g}_2 \rightarrow j_1 j_2 j_3 j_4 + \ldots, \] which ones are from \( \tilde{g}_1(\tilde{g}_2) \)?

Moreover, interpretation of angular distribution need gauge quantum number and mass information*:

\[ \Delta m, \] chirality of couplings, etc.

More detail later in the talk.
This talk: survey of two approaches

1. Early indications: rate + kinematical info.

2. Angular correlation in decay.

A relatively new direction.
Many more detailed, and fully realistic study necessary
Focusing on methods here, with only results in special cases.
Early indication: Rate + simple kinematics

G. Kane, A. Petrov, J. Shao, LW hep-ph/0805.1397

Different spin: Different number of degree of freedom (coupling)
Vector (3), Dirac fermion (4), Complex scalar (2)

Very different rates  e.g. Top production in SM
Similarly, in new physics models

\[ \bar{g} : \text{gluino}, \quad g' : \text{spin 1}, \quad g_\text{s} : \text{spin 0} \]

\[ \bar{q} : \text{squark}, \quad q' : \text{spin 1/2} \]

An independent measurement of mass could be interpreted as a measurement of spin. Some model dep. (BR, quantum number.)
Challenge of mass measurements:

No C.M. frame, no resonances

⇒ Only sensitive to “transverse variables” (initially)

\[ H_T = \mathcal{E}_T + \sum_{alljets} P^a_T \]

Or, similarly, sum of any sub-set of objects

Typically, such observables such as only sensitive to mass differences.

For given rate, choose masses to match the production rate. Choose the mass differences to match kinematics.

⇒ Degeneracy!  
H. Cheng, I. Low and LW.  \texttt{hep-ph/0510225}  
P. Meade and M. Reece  \texttt{hep-ph/0601124}
Comparison: Supersymmetry vs same spin partners

\[ pp \rightarrow \tilde{q}\tilde{q}^* \rightarrow q\bar{q} + 2\text{LSP} \quad \text{vs} \quad pp \rightarrow q'q'^* \rightarrow q\bar{q}AA \]

\[ \tilde{q} \rightarrow q + \text{LSP} \quad \text{vs} \quad q' \rightarrow q + A \]

Left: \[ m_{\tilde{q}} = 549 \text{ GeV}, \ m_{q'} = 900 \text{ GeV}, \ m_{\text{LSP}} = 97 \text{ GeV} \quad m_A = 448 \text{ GeV} \]

Right: \[ m_{\tilde{q}} = 549 \text{ GeV}, \ m_{q'} = 900 \text{ GeV}, \ m_{\text{LSP}} = 97 \text{ GeV} \quad m_A = 548 \text{ GeV} \]

Not necessarily the same mass difference (left).
Degeneracy exists as long as observable depend approximately only on mass differences.
New methods of mass measurements


Challenging since it must be fairly accurate.

\[ \text{Rate} \propto \text{mass}^{-6 \text{ or higher}} \]
Combining several channels:

If we have several channels depending on a small set of mass parameters, we could hope to over constrain the system and lift degeneracy. (e.g. quark and gluon partners)

\[ \sigma_{\tilde{g}\tilde{g}} \approx 4 \text{ pb}, \]
\[ \sigma_{g'g'} \approx 4 \text{ pb}, \]
\[ \sigma_{g\bar{q}} \approx 20 \text{ pb}, \]
\[ \sigma_{g'q'} \approx 20 \text{ pb}, \]
\[ \sigma_{\bar{q}\bar{q}} \approx 8 \text{ pb} \]
\[ \sigma_{q'q'} \approx 19 \text{ pb} \]
Fit to observables:

Overlapping jets, initial and final state radiations

$\Rightarrow$ Difficult to separate channels

Fit to observables, two representative examples:

- Jet counts (1, 2, 3, 4, 5+), “rate”

$\overline{H_T}$ Average, more inclusive. “kinematics”
As a proof of principle example:

SUSY benchmark:

\[ m_{\tilde{q}} = 608 \text{ GeV}, \quad m_{\tilde{q}} = 549 \text{ GeV} \]

\[ m_{\text{LSP}} = 97 \text{ GeV}, \quad \overline{H}_T = 913 \text{ GeV} \]

Total rate: \( \sim 32 \text{ pb} \). Study done with 2000 signal events.

Scan in the same spin scenario: \( \chi^2 \) fit

<table>
<thead>
<tr>
<th>( m_A ) (GeV)</th>
<th>( m_{\tilde{q}'}, m_{\tilde{q}} ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1000, 640) (950, 720) (900, 800) (850, 880) (800, 960) (750, 1120)</td>
</tr>
<tr>
<td>100</td>
<td>(1218, 6.6) (1271, 7.9) (1307, 7.2) (1373, 7.7) (1399, 13.4) (1474, 16.4)</td>
</tr>
<tr>
<td>250</td>
<td>(1104, 5.8) (1178, 6.4) (1218, 6.2) (1254, 8.0) (1289, 16.8) (1339, 20.0)</td>
</tr>
<tr>
<td>400</td>
<td>(875, 3.2) (984, 5.1) (1036, 4.8) (1057, 7.2) (1072, 17.2) (1103, 18.4)</td>
</tr>
<tr>
<td>550</td>
<td>(584, 6.5) (682, 2.7) (767, 2.5) (776, 3.9) (758, 14.6) (820, 12.0)</td>
</tr>
<tr>
<td>700</td>
<td>– (452, 18.7) (427, 6.0) (410, 7.4) (456, 6.4) (706, 14.2)</td>
</tr>
</tbody>
</table>

Event generated with MadEvent \( \Rightarrow \) PYTHIA \( \Rightarrow \) PGS

With typical trigger thresholds.
Best fit point:

Still distinguishable.
Further study necessary

Standard Model background

More complicated chains BR. Using lepton.

Better signal, lower SM background.

More model dep. Branching ratio to leptons.

G. Kane, J. Shao, LW Work in progress
Second approach: Angular correlations in Cascade decays

Spin ???
Assumptions

We can isolate a subset of events containing new physics.

We have a rough idea of the event topology.

There are invisible particles (LSP, LKP, etc.)
The rest of this talk:

• Rules for the existence of spin information in cascade decays.
  (Using these rules you can simply look at any Feynman diagram and tell whether or not spin correlations exist!!!)

• Gauge-boson partners’ spin.

• Matter partners’ spin.

• Future directions and unresolved issues.
  (The experimental challenges are numerous, but they are at least well-defined and finite).
Angular correlations in fermions decay

Under a rotation a fermion transforms as,

\[ |\uparrow\rangle \rightarrow \cos(\theta/2)|\uparrow\rangle + \sin(\theta/2)|\downarrow\rangle \]

\[ \propto 1 - \cos(\theta) \]

The interaction must be chiral otherwise the angular correlations are washed out!

In addition, the decaying fermion must be polarized as well!
Angular correlations in vector-boson decay

Behaves like,

\[ \sim \cos^2(\theta) \]

No requirements on the vertex, but the vector-boson must be polarized.
Conditions for spin effects

If $X$ is a fermion:

Dirac: Both vertices must be at least partially chiral.

Majorana: also need charge determination

If $X$ is a gauge-boson:

$X$ should be boosted so it is longitudinally enhanced.

Otherwise, spin effects are washed out!!!
Choice of variable

Rest-frame of $X$

Cannot reconstruct rest frame, define Lorentz invariant

$t_{12} = (p_1 + p_2)^2$

$\propto (1 - \cos \theta)$

Therefore:

$$\frac{d\Gamma_{X \rightarrow p_1 p_2} Z}{dt_{12}} = a_0 + \ldots + a_{2s} t_{12}^{2s}$$
Determining the W-boson’s spin in top decays

Define a Lorentz invariant,

\[ t_{bl} = (p_b + p_l)^2 \]

\[ \frac{d\Gamma}{dt_{bl}} = c_2 t_{bl}^2 + c_1 t_{bl} + c_0 \]
Gauge-boson Partner’s Spin
(fermions vs. vector-bosons)

One example from: L. Wang and I. Yavin hep-ph/0605296

A SPSIa-like case (Majorana gaugino, on-shell slepton) has also been studied:


Spin determination KITPC, 2008 Lian-Tao Wang
W-boson partners

e.g. SUSY

\[ d\Gamma/dt_{qW} = c_1 t_{qW} + c_0 \]

Little Higgs, UED, etc.

e.g. same spin

\[ d\Gamma/dt_{qW} = c_2 t_{qW}^2 + c_1 t_{qW} + c_0 \]

Different order polynomials!
Implementation in HERWIG

LW and I. Yavin hep-ph/0605296

We have modified HERWIG to include spin effects for massive spin-1 particles.

\[ t_{qW} = (p_q + p_W)^2 \]
Jet-lepton correlations

If the W-boson decays leptonically then we can form Jet-lepton correlations.

Further study required

$t_{jl}$

Graph with variables:
- $t_{jl}$
- $t^e$
- $J_2$
- $\nu$
- LKP
- $J_1$
- LKP

Equations:
- $M_1 = 100$
- $M_2 = 500$
- $\mu = 800$
- $\tan \beta = 10$
- $m_q = 1000$

$t_{jl}$ (Tev$^2$)

Spin determination

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Reconstructing the W-boson

We may be able to reconstruct the W-boson out of its hadronic decay.

Including $\Delta R$ and $p_T$ cuts and smearing.

Spin determination

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Jet-W correlations

Even after taking combinatorics into account, the difference is very pronounced:

**Same-spin scenario**

**SUSY**

\[ M_1 = 100 \]
\[ M_2 = 500 \]
\[ \mu = 800 \]
\[ \tan \beta = 10 \]
\[ m_q = 1000 \]
W-boson partners, another channel

e.g. SUSY

e.g. Little Higgs, UED, etc.

d\Gamma/dt_{qZ} = c_1 t_{qZ} + c_0

d\Gamma/dt_{qZ} = c_2 t_{qZ}^2 + c_1 t_{qZ} + c_0
Backgrounds and mispairing

Demand: 3 leptons, 2 jets and MET and reconstructing a $Z^0$.
There are only two dominant processes:

There is also the other jet in the event and it is not clear which jet should be paired with which $Z^0$. 
Backgrounds and mispairing

$q_{\text{far}}$ vs $q_{\text{near}}$ resolution: choose the one with smaller $P_T$.

$Z_{\text{far}}$ vs $Z_{\text{near}}$ resolution: choose the one with larger $P_T$.

Possible to reduce mispairing if we know something about the spectrum.

A. Hook, LW and I. Yavin  To be published
Matter Partner’s Spin

(scalars vs. fermions)

C. Kilic, LW and I. Yavin hep-ph/0703085
Conditions for spin effects

*Same spin partner*

*e.g. Little Higgs, UED, etc.*

- X is a fermion, so:
  - Need both vertices to be partially chiral to see angular correlations!

*SUSY*

- X is a scalar, so:
  - No angular correlations between outgoing visible particles!

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Spin determination  KITPC, 2008  Lian-Tao Wang
Matter partners

Supersymmetry: squarks, sleptons. Complex scalars

⇒ Trivial angular correlation

Same spin partners: Dirac fermions

<table>
<thead>
<tr>
<th>SM</th>
<th>Heavy partners</th>
<th>$SU(2) \times U_Y(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_L$</td>
<td>$Q'_L = \begin{pmatrix} u'_L \ d'_L \end{pmatrix}$</td>
<td>$(2, \frac{1}{6})$</td>
</tr>
<tr>
<td>$u_R$</td>
<td>$U'_R$</td>
<td>$(1, \frac{2}{3})$</td>
</tr>
<tr>
<td>$d_R$</td>
<td>$D'_R$</td>
<td>$(1, -\frac{1}{3})$</td>
</tr>
</tbody>
</table>
Couplings of new fermionic matter partners

Since the SM is chiral, new fermionic heavy matter partners must couple chirally

\[ L_{mass} = M_Q \bar{Q}_L Q_R + e^{i\phi} M_U \bar{U}_L U_R + \lambda \bar{Q}_L h U_R + \lambda \bar{U}_L h Q_R \]

\[ L_{coupling} = \bar{Q}_L g' q_L + \bar{U} g' u_R + \ldots \]

So, are the interactions always chiral ??
Mixing

After EWSB, $Q_1$ and $U_L$ mix, as well as $U_R$ and $Q_R$, the amount of mixing depends on the mass matrix:

$$
\begin{pmatrix}
M_Q & \lambda v \\
\lambda v & e^{i\phi} M_U
\end{pmatrix}
$$

1) Non-degenerate: $M_Q \gg M_U$ or v.v, mixing is very small.

2) Degenerate: $M_Q \sim M_U$ depends on $\phi$.
   - $\phi = 0$ mixing is maximal.
   - $\phi = \pi$ mixing is very small.

UED predicts $\phi = \pi$
5D Lorentz inv. and sign of fermion mass

A 3-site deconstruction of 5D. Fermion interactions

\[ \mathcal{L}_Q = \text{kinetic terms} + \frac{1}{a} (\overline{Q}_{1R}, \overline{Q}_{2R}, \overline{Q}_{3R}) \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix} \begin{pmatrix} Q_{1L} \\ Q_{2L} \\ Q_{3L} \end{pmatrix} + h.c. \]

SM chiral: \[ \Rightarrow \] Doublet and singlet have different b.c.

\[ \mathcal{L}_Q = \text{kinetic terms} + m \overline{Q}_R^{(\text{sin})} Q_L^{(\text{cos})} + h.c. \]

\[ \mathcal{L}_U = \text{kinetic terms} - m \overline{U}_R^{(\text{sin})} U_L^{(\text{cos})} + h.c. \]

However, not true in general site+link models

\[ \mathcal{L}_U = \text{kinetic terms} + e^{i\phi} \ m \overline{U}_R^{(\text{sin})} U_L^{(\text{cos})} + h.c. \]
Example: dilepton correlations

A histogram of $t_{ff}$ with no cuts applied
Effect of isolation cuts

\[
\Delta R > 0.3
\]

\[
\Delta R > 0.7
\]
Information in the slope

\[ M_Q / M_{\gamma'} = 2 \]

\[ M_Q / M_{\gamma'} = 1.2 \]
Interpreting information in the slope:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Slope $C'_1$</th>
<th>Intercept $C'_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(2M_{g'}^2 - M_Q^2) \left(M_Q^2 - 2M_{\gamma}^2\right)$</td>
<td>$(M_Q^4 + 4M_{g'}^2 M_{\gamma}^2) t_{ff}^{(edge)}$</td>
</tr>
<tr>
<td></td>
<td>$- (M_Q^2 - 2M_{\gamma}^2)$</td>
<td>$M_Q^2 t_{ff}^{(edge)}$</td>
</tr>
<tr>
<td></td>
<td>$(2M_{g'}^2 - M_Q^2)$</td>
<td>$M_Q^2 t_{ff}^{(edge)}$</td>
</tr>
<tr>
<td></td>
<td>$-1$</td>
<td>$t_{ff}^{(edge)}$</td>
</tr>
</tbody>
</table>

Clear interpretation only possible after approximate Measurements of the mass hierarchy.....
Possible to determining all the spins in a cascade

Suppose one measures the slope of the b-b pair to be negative with $M_{B'}^2/M_{Z'}^2 < 2$ and that of the dilepton pair to be negative with $M_{L'}^2/M_{\gamma}^2 < 2$ as well. Then, either all three partners, $g'$, $Z'$ and $\gamma'$, are vector-bosons, or all three are scalars. Hence, with a single spin measurement of the $Z'$, one can determine all the spins in the event.
Off-shell decays

The requirement for chiral vertices can be formulated as the requirement that the intermediate propagator has the mass term dominating over the momentum term or vice-versa.

As was pointed out in LW and I. Yavin hep-ph/0605296 and investigated in detail by Csaki et al, hep-ph/0707.0014 this also happens when the intermediate fermion is off-shell.

In the SUSY case the intermediate off-shell particle is just a scalar and the correlations just follow that of 3-body phase-space. However, in the case of an intermediate off-shell fermion, the situation is more interesting:
Spin determination

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Future directions

• Experimental difficulties:
  o Background
  o Can the correct pairing be determined and combinatorics reduced?
  o How well will b-tagging (charge) work?

• New methods
  o Can, and how much, new mass determination methods help in determining the spin? (rate, reconstruction of kinematics.)
  o Methods using rate information are important and should be pursued further. Are there more model independent statements one can make?
Conclusions:
A roadmap for spin measurements at the LHC

**Initial stage (soon after discovery):** \( O(1-10) fb^{-1} \)

Combine rate and simple kinematical information to obtain initial indication of spin.

**In the process of accumulating data:**

- Measure masses, quantum numbers (color, SU(2)...),
- couplings (chiral...). Event topology.

Crucial for detailed, model independent, spin measurement.

**High statistics and good knowledge of spectrum:** \( O(10^2) fb^{-1} \)

Spin measurement: angular correlations
Other new methods: mass + reconstruction, ...

Spin determination

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PGS Thresholds:

- Inclusive $E_T$ 90 GeV
- Inclusive single-jet 400 GeV
- Jet plus $E_T$ (180 GeV, 80 GeV)
- Accoplanar jet and $E_T$ (100 GeV, 80 GeV, $1 < \Delta \phi < 2$)
- Accoplanar dijets (200 GeV, $\Delta \phi < 2$)
SUSY cascade decays

\[ t_{q_l \pm} = (p_q + p_{l \pm})^2 \]

Define an asymmetry var.

Invisible. cannot reconstruct rest frame of neutralino.

Barr, Datta, Kong & Matchev
Smillie & Webber
Alves, Eboli & Plehn

Spin determination: KITPC, 2008
Lian-Tao Wang
Reconstructing the W-boson

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Barr, Datta, Kong & Matchev
Smillie & Webber
Alves, Eboli & Plehn

\[ t_{ql^{\pm}} = (p_q + p_{l^{\pm}})^2 \]

Define an asymmetry var.

\[ A = \frac{s_+ - s_-}{s_+ + s_-} \]

\[ s_{\pm} = \frac{d\Gamma}{dt_{ql^{\pm}}} \]
The Questions to address

Is there any spin information to begin with?

What are the conditions for spin effects to manifest themselves?

Can spin be determined @ LHC ? ?
More ref.

H. Cheng, I. Low and LW.  hep-ph/0510225

P. Meade and M. Reece  hep-ph/0601124


P. Richardson  hep-ph/0110108
Many scenarios, Models, Variations

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Supersymmetry</th>
<th>Compositeness, low $\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V(h)$?</td>
<td>Opp. stat.</td>
<td>Same stat.</td>
</tr>
<tr>
<td>NP partners</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W-W$</td>
<td>$h$</td>
<td>$h$</td>
</tr>
<tr>
<td>Models</td>
<td>string comp.</td>
<td>Georgi-Kaplan</td>
</tr>
<tr>
<td>grav-MSB</td>
<td></td>
<td>Simple Group</td>
</tr>
<tr>
<td>AMSB</td>
<td></td>
<td>Minimal moose</td>
</tr>
<tr>
<td>GMSB</td>
<td>AntiSym-</td>
<td>Condensate</td>
</tr>
<tr>
<td>$\tilde{g}$MSB</td>
<td></td>
<td>Littlest</td>
</tr>
<tr>
<td>super-soft</td>
<td>focus point</td>
<td>RS/Holographic</td>
</tr>
<tr>
<td>mirage</td>
<td>$\mu$-driven</td>
<td>Twin</td>
</tr>
<tr>
<td>....</td>
<td></td>
<td>UED($A_5$-Higgs)</td>
</tr>
</tbody>
</table>

Combinations: Little-supersymmetry, Twin SUSY, Folded SUSY, fat Higgs...
However, many constraints → None works straightforwardly.

The new physics is likely to be subtle and unexpected.