Theories Beyond the Standard Model

Lecture # 2

Bogdan Dobrescu (*Fermilab*)

Outline:

- **Probing the unknown**
- **Two Higgs Doublet Models**
- **Supersymmetry, extra dimensions, ...**

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- **Probing the unknown ...**

CMS and ATLAS are exploring physics at distances of $\sim \mathbf{10^{-19}}$*m.*

- **It is hard to make reliable predictions!**

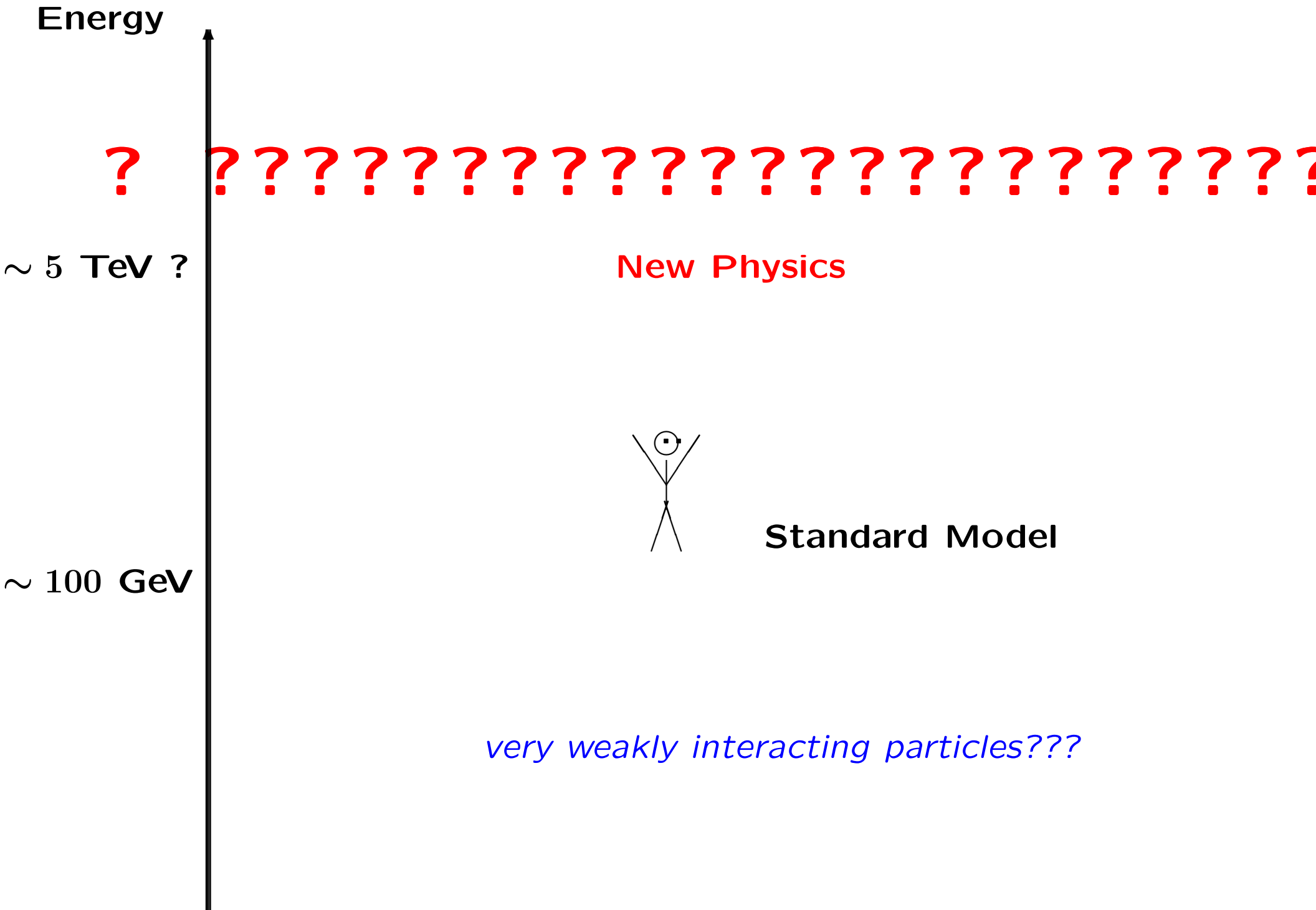
There are many theories for physics beyond the SM.

No theory is sufficiently successful so far in explaining the puzzles of the SM $\longrightarrow$ *we should consider a wide range of theories.*

Even within well defined models, a small change in parameters may lead to widely different collider signatures.

- **Best attitude: search as many final states as possible, try to be "model independent".**

Similar situation for LHCb, Belle, ...


Energy
? ??????????????????????????
~ 5 TeV ?
New Physics
Standard Model
~ 100 GeV
very weakly interacting particles???

Tough questions which could eventually be answered by experiments at hadron colliders:

- *Do the SM particles have substructure?*
- *Are there extra dimensions?*
- *Why is the electroweak scale much smaller than the Planck scale?*
- *Can deviations from quantum field theory be eventually measured?*

More tractable questions that ATLAS and CMS have started addressing:

- *Are there gauge bosons beyond the SM?*
- *Are there any vectorlike quarks or leptons?*
- *Are there 'elementary' spin-0 particles other than* h^0*?*
- *...*

Two Higgs Doublet Model

A straightforward extension of the SM Higgs sector – 2 doublets:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}$$

After the minimization of the Higgs potential, both H_u^0 and H_d^0 acquire VEVs:

$$\langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix} \qquad \langle H_d \rangle = \begin{pmatrix} 0 \\ v_d \end{pmatrix}$$

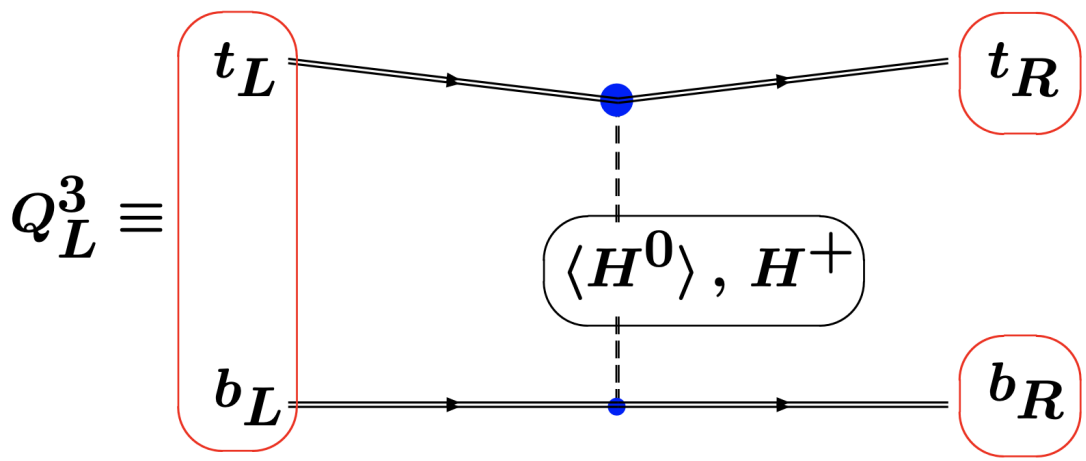
Notation: $\tan\beta = v_u/v_d$

Homework: Show that $M_W^2 = \frac{g^2}{4}\left(v_u^2 + v_d^2\right)$

Spin-0 particles: h^0, H^0, A^0, $H^\pm$.

Two Higgs Doublet Model of Type-I

All SM fermions masses arise from interactions with a single Higgs doublet:



Hierarchy of Yukawa couplings, as in the SM:

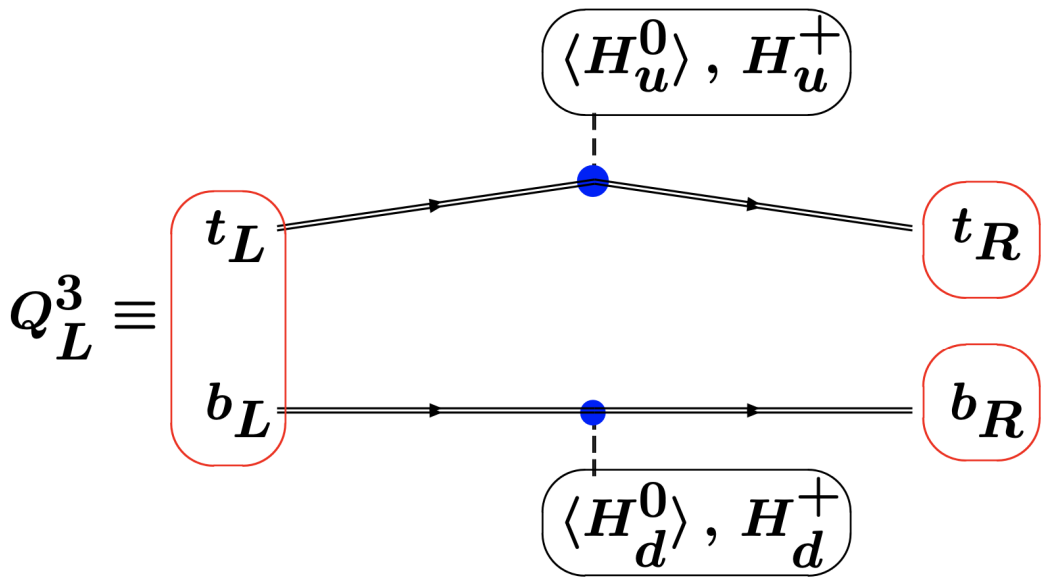
$y_t \approx 1$ (for large scale $\tan\beta$)

$m_b \approx 2.7$ GeV at the weak scale $\Rightarrow$ $y_b \approx 0.016$

Two Higgs Doublet Model of Type-II

only up-type quarks get masses from H_u,

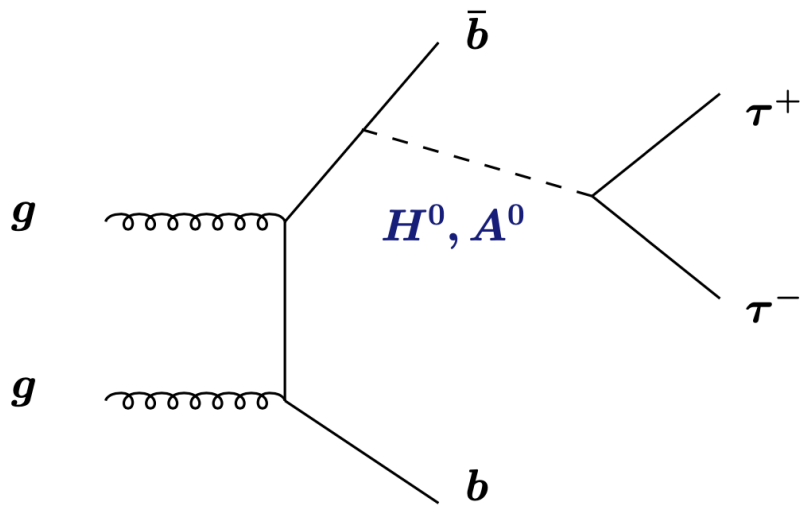
only down-type quarks and charged leptons get masses from H_d.



$y_b = O(1)$ **if** $\tan\beta \equiv \frac{v_u}{v_d} \approx 50.$

Couplings of the heavy neutral Higgs bosons: $\frac{y_b}{\sqrt{2}}\left(A^0 \bar{b}\gamma_5 b - H^0 \bar{b} b\right)$

$b\bar{b}A^0$ and $b\bar{b}H^0$ associated productions at the LHC:

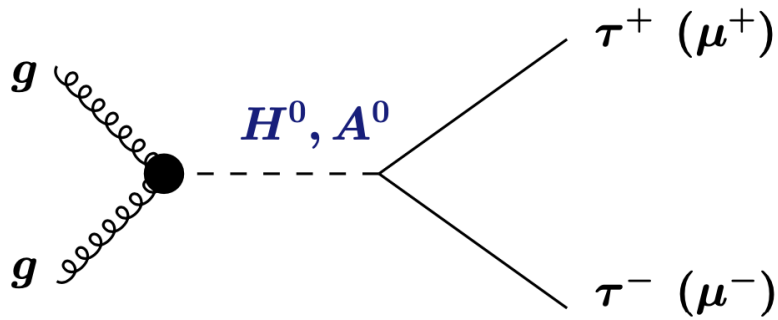


Note: $y_\tau/y_b = m_\tau/m_b$ independent of $\tan\beta$, so that

$$\frac{B(A^0 \to \tau^+\tau^-)}{B(A^0 \to b\bar{b})} \approx \frac{y_\tau^2}{3y_b^2} = \frac{m_\tau^2}{3m_b^2} \approx 10\%$$

There is also s-channel production via gluon fusion:

b and t loops $\Rightarrow$



Cross section depends on $\tan\beta$.

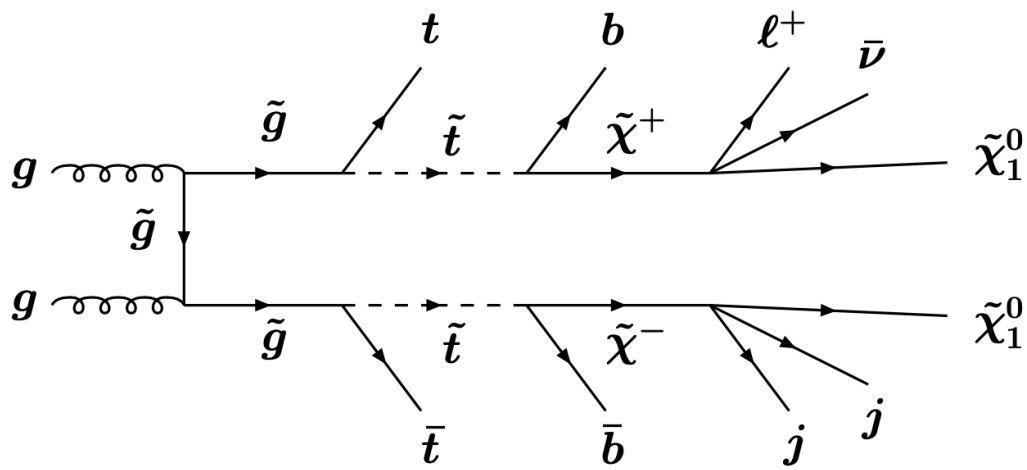
Limits on A^0, H^0 masses from flavor processes ($b \to s\gamma, ...$)

Minimal Supersymmetric Standard Model

Many new particles (33), many new parameters (105)

$\rightarrow$ many interesting signatures.

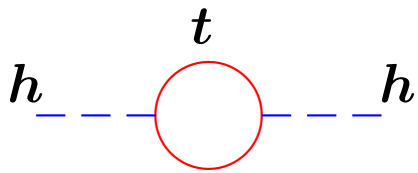
E.g., gluino pair production and cascade decays through stop and chargino:

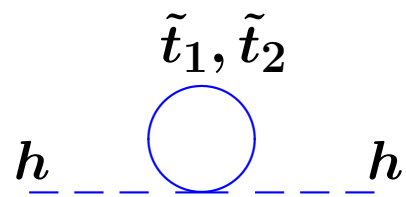


Some nice theoretical features:

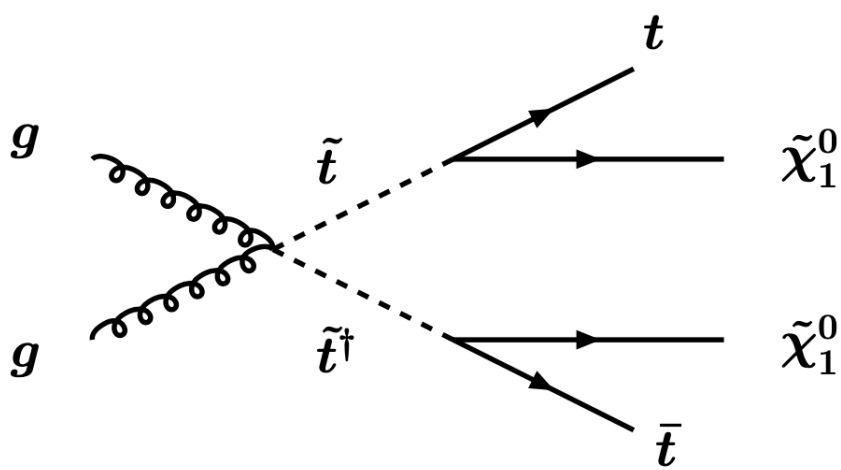
- **No quadratic divergences ($\langle H \rangle \sim M_{\rm SUSY}$, μ)**
- **Gauge couplings unify**
- **Lightest superpartner (LSP) is a dark matter candidate**
- **...**

Quadratic divergences in the Higgs self-energy due loops with SM particles are cancelled by those due to loops with superpartners: requires mass of $\tilde{t}$ (and probably of $\tilde{g}$) to be near the weak scale.





A convincing test of the MSSM: $\tilde{t}\tilde{t}^\dagger$ production:



The supersymmetric Higgs sector is a Two-Higgs-Doublet model of type-II *(only up-type quarks get masses from H_u).*

Extra spatial dimensions

4D flat spacetime $\perp$ one dimension of size $L = \pi R$:

A scalar field in the bulk, $\phi(x^\alpha)$, $\alpha = 0, 1, ..., 4$:

$$\mathcal{L}_{5D} = (\partial^\mu \phi)^\dagger \partial_\mu \phi - \left(\partial^4 \phi\right)^\dagger \partial_4 \phi - m_0^2 \phi^\dagger \phi \ , \qquad \mu = 0, 1, 2, 3$$

$\Rightarrow$ **Equation of motion:** $\left(\partial^\mu \partial_\mu - \partial^4 \partial_4\right) \phi = m_0^2 \phi$

m_0 is the 5D mass of ϕ.

Neumann boundary conditions for "even" fields:

$$\frac{\partial}{\partial x^4}\phi(x^\mu, 0) = \frac{\partial}{\partial x^4}\phi(x^\mu, \pi R) = 0$$

Solution to the equation of motion:

$$\phi(x^\mu, x^4) = \frac{1}{\sqrt{\pi R}}\left[\phi^{(0)}(x^\mu) + \sqrt{2}\sum_{j\geq 1}\phi^{(j)}(x^\mu)\cos\left(\frac{jx^4}{R}\right)\right]$$

Kaluza-Klein decomposition

Zero-mode (wave function is constant along x^4)

Kaluza-Klein modes: particles of definite momentum along x^4

4D point of view: a tower of massive particles:

$$\mathcal{L}_{4D} = \int_0^{\pi R} dx^4\, \mathcal{L}_{5D} \qquad \Rightarrow \qquad m_j^2 = m_0^2 + \frac{j^2}{R^2}$$

Kaluza-Klein spectrum of gauge bosons

$A_G^{(j)}(x^\nu)$ *becomes the longitudinal degree of freedom of the spin-1 KK mode* $A_\mu^{(j)}(x^\nu)$.

$$\vdots \qquad \vdots$$

$$A_\mu^{(3)} \;\text{———}\; \frac{3}{R} \;\text{———}\; A_G^{(3)}$$

$$A_\mu^{(2)} \;\text{———}\; \frac{2}{R} \;\text{———}\; A_G^{(2)}$$

$$A_\mu^{(1)} \;\text{———}\; \frac{1}{R} \;\text{———}\; A_G^{(1)}$$

$$A_\mu^{(0)} \;\text{———}$$

Importance of discrete symmetries:

Standard model must be extended in order to include dark matter: a new electrically-neutral stable particle.

Stability of dark matter must be ensured by some symmetry.

Simplest possibility: a new discrete symmetry.

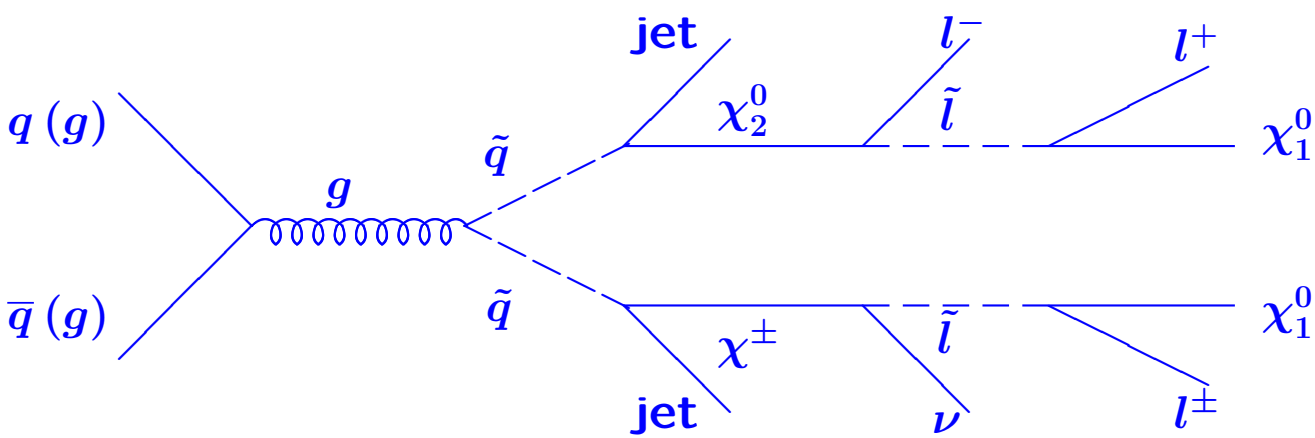
Examples:

- **Supersymmetry with R parity**
- **Universal extra dimensions (KK parity)**
- **Little Higgs models with T parity**

Pair production of colored odd particles at the LHC, followed by cascade decays through lighter odd particles, until a pair of dark matter candidates escapes the detector.

$\Rightarrow$ Generic signal: missing E_T + jets + leptons

E.g., squark production and cascade decays to neutralinos:



Look for: **3 leptons + 2 jets + $\not{E}_T$**

Similarity between supersymmetry, little Higgs with KK parity, and one universal extra dimension is not accidental:

- $N = 1$ **supersymmetry is an extra dimension with anticommuting coordinate**

- **Little Higgs with T parity is a deconstructed extra dimension.**

An important distinction: spins of partners are different

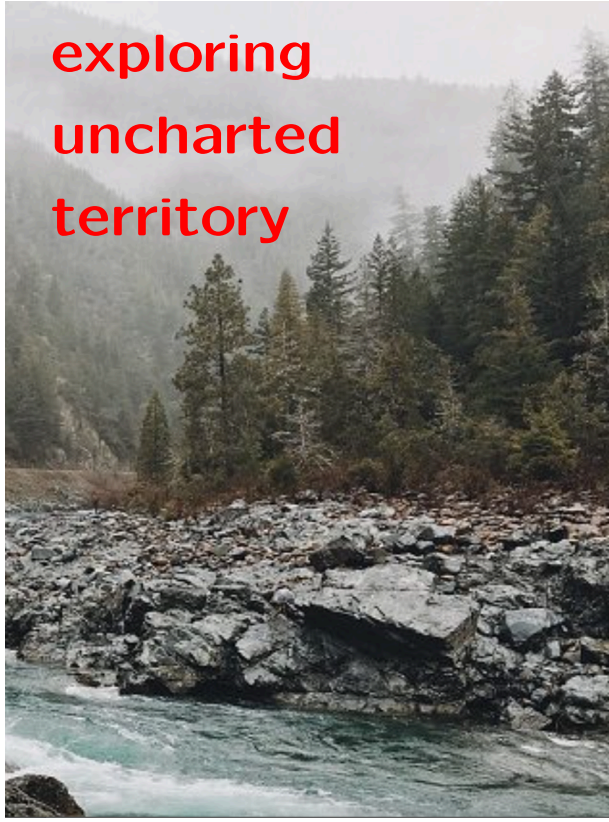
(squarks have spin 0, KK quarks have spin 1/2, etc.)

Measuring spins of new particles at the LHC can be done using angular distributions.

Conclusions to Lecture #2

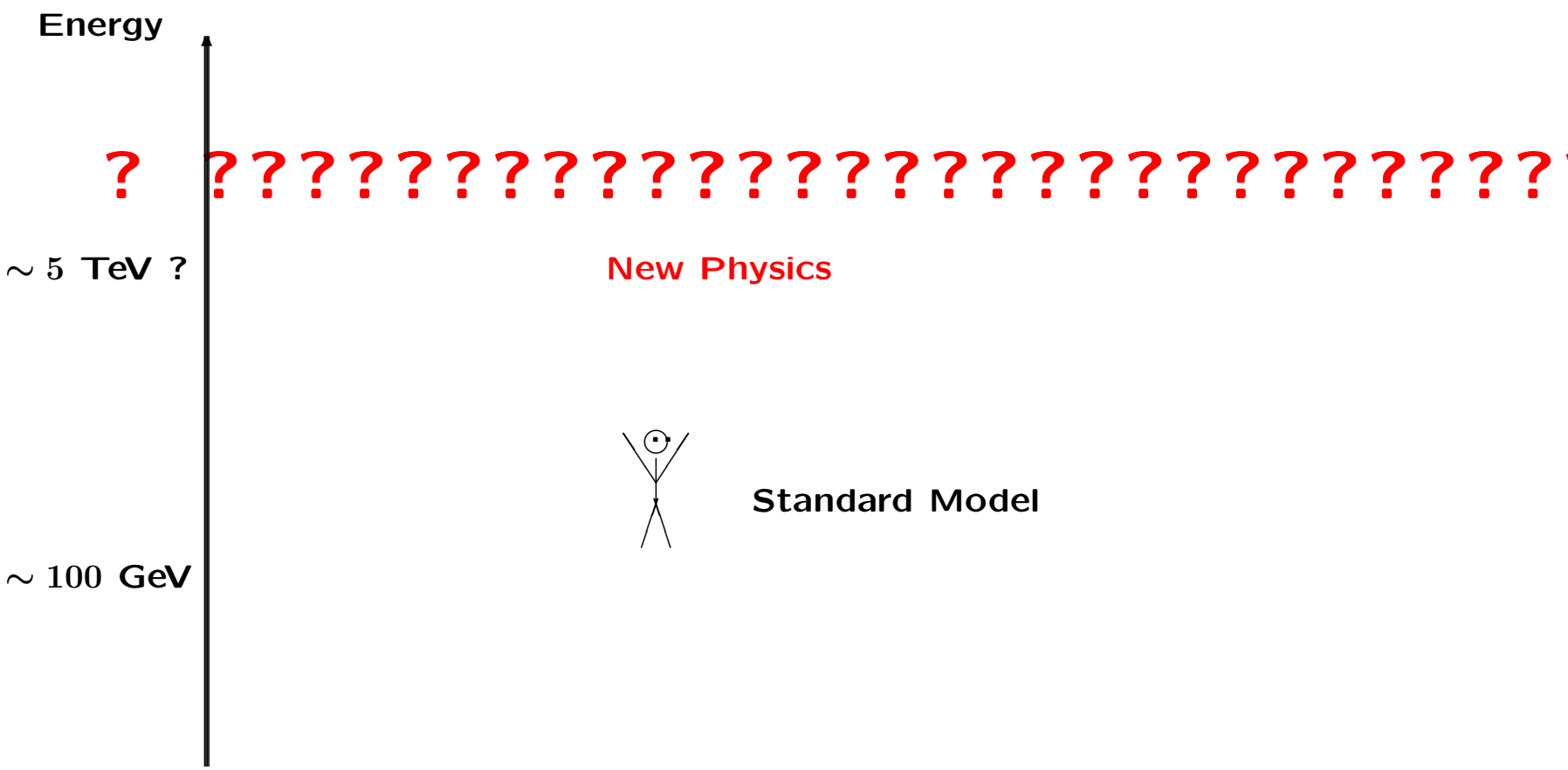
Run 3 and the HL-LHC will increase the reach of searches for:

- vectorlike quarks and leptons
- Z' and W' bosons
- color-octet scalars, colorons
- diquark scalars, leptoquarks
- supersymmetric particles
- heavy Higgs bosons
- right-handed neutrinos
- ... other new particles



There are also many searches that have never been performed

$\longrightarrow$ potential for discoveries even with Run 2 data!

Final Exam

Find out what theory describes physics at the ~ 5 TeV scale.