FYST17 Lecture 11
BSM I

Thanks to G. Broijmans, C. Grojean

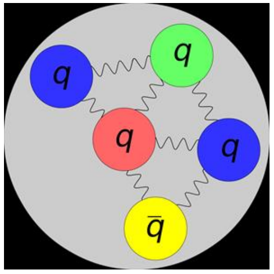
This week's topics

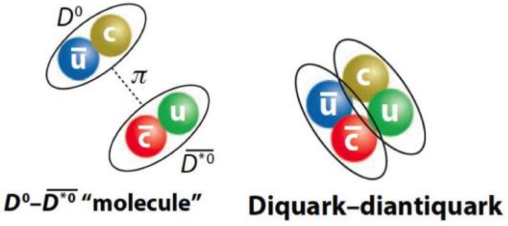
- Why go Beyond the SM?
  - What are the problems with the SM?
  - What direct measurements points to physics BSM
- Some attempts at solutions
  - Supersymmetry
  - Extended Higgs sector
  - Extra dimensions
  - A few others
- Searches for DM

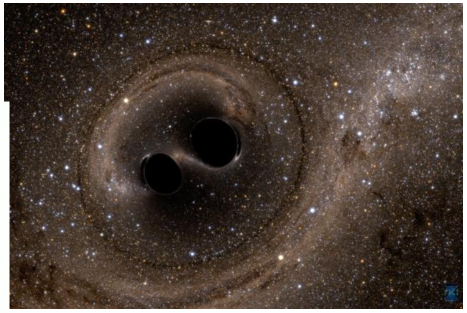
Any direct evidence?

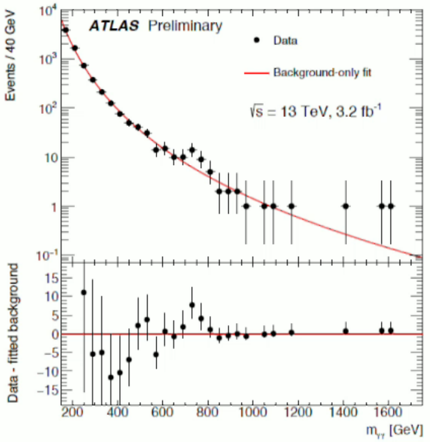
Certainly a few measurements that are not incorporated in the current Standard Model:

- Exotic baryons (X, pentaquarks etc)
- Neutrino masses!
- (Gravitational waves)
- The new $\gamma\gamma$ bump, if it is real









Status of the Standard Model

19 parameters (+ ν masses)

Tested to precision level $10^{-3} - 10^{-12}$

} Extremely successful!

But empirically incomplete

Structure quite complicated

Aesthetically unacceptable

Many problems with naturalness

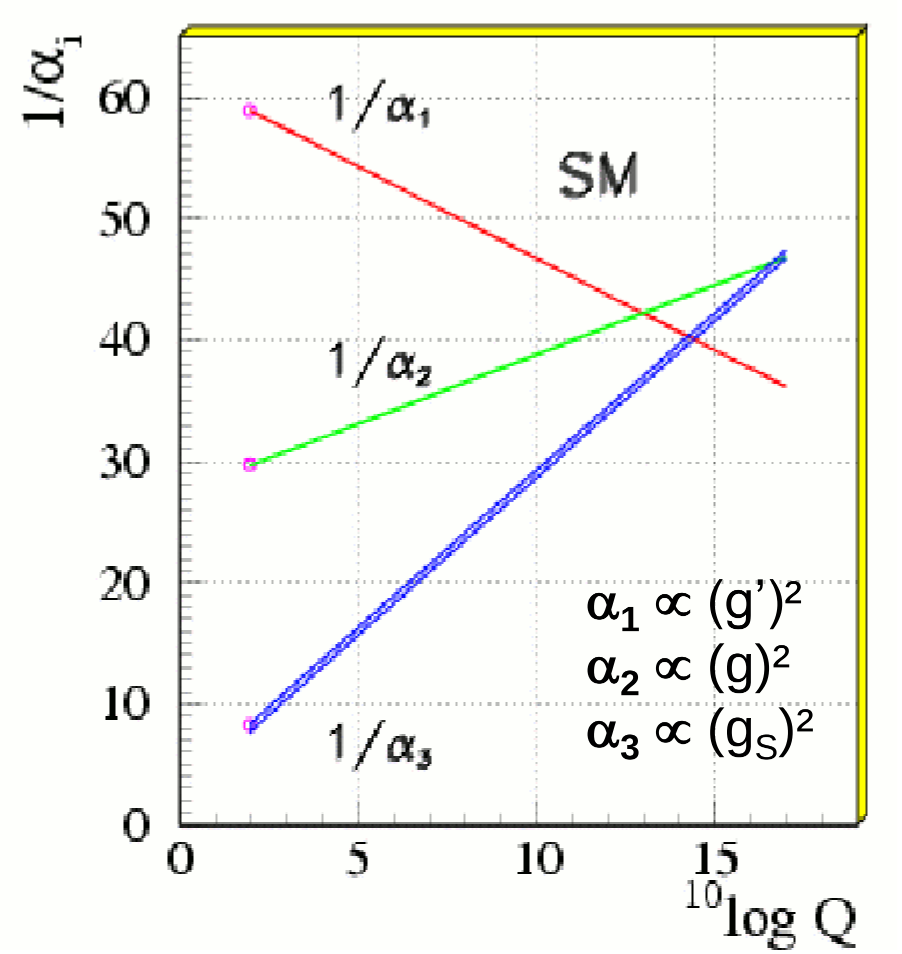
No quantum gravity

Missing answers to ”big” questions

Examples of answers we need

- *What is the origin of CP violation?*
- *What is the origin of the matter/anti-matter asymmetry*
- *Why three gauge forces (so far)? And three generations?*
- *Why is the strong interaction strong? Why only left-handed particles participate in weak force?*
- *Gravity? Is there a unified description of all forces?*
- *Why is mass(W/Z/H) << mass(Planck)? (Hierarchy problem)*
- *Why is charge quantized?*
- *What is Dark Matter and Dark Energy? (and why Dark Energy now?)*
- *What was the Big Bang?*

Unification of coupling constants?

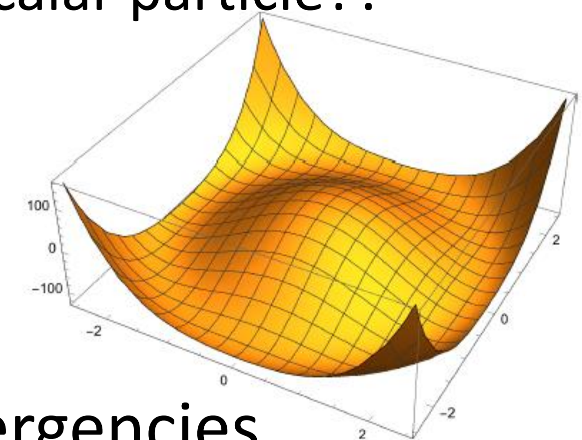


Extrapolating the Standard Model coupling constants to higher energies

http://pdg.lbl.gov

The Higgs discovery just adds to that list…

- What is it, really, a condensate in our Universe?
- Is it elementary?
  - If yes, why is there only 1 fundamental scalar particle??
- Why does it have mass^2 $\mu^2 < 0$?!



- Higgs mechanism gives quadratic divergencies
  - (see later)

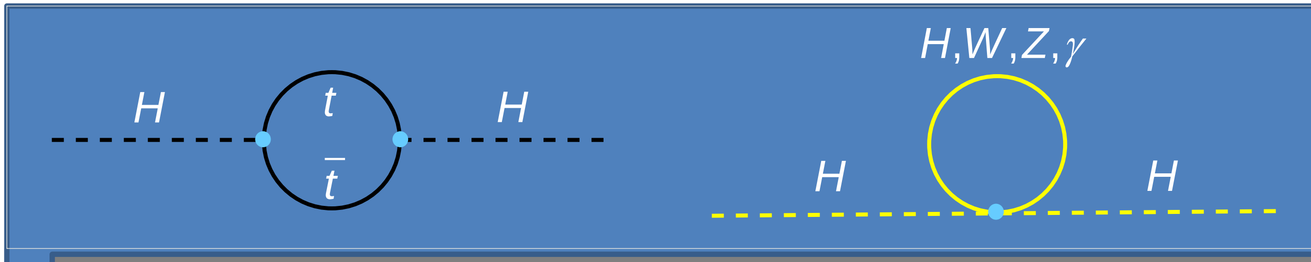
Is the Standard Model really fundamental?

- Does not appear so ($\gtrsim$ 25 parameters?!)
- Evidence of selective processes:
  - For instance, no neutral colored fermions
  - $q_d = q_e /N(\text{colors}) \Rightarrow$ grand unification?
- ***Fragile:*** small changes in parameters $\Rightarrow$ very different physics!
  - If $m_d < m_u$: all protons decay $\Rightarrow$ no atoms
  - If $m_e > 4m_p - m_\alpha \Rightarrow$ Sun doesn't burn $\Rightarrow$ no us
  - If v >> TeV $\Rightarrow |m_n - m_p|$ large , rapid neutron decay $\Rightarrow$ no chemistry nor life

The “Gauge Hierarchy Problem”

Discover of Higgs boson with mass < 1 TeV means the Standard Model is complete !

However, when computing radiative corrections to the bare Higgs mass a problem occurs:



Higgs radiative corrections

$$m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \int_0^{\infty} d^4k \, \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2} + \ldots \xrightarrow{\text{cut-off}} \int_0^{\Lambda_{\text{cut-off}}} (\ldots) \propto \Lambda^2_{\text{cut-off}}$$

Integral quadratically divergent

The cut-off sets the scale where new particles and physical laws must come in

Above the EW scale we only know of two scales: GUT (~10^{16} GeV) and Planck (~10^{19} GeV)

Such a cut-off would require an incredible amount of finetuning to keep m_H light

$$m_H^2 = (125\ GeV)^2 = m_0^2 + C \cdot \Lambda^2_{cut-off}$$

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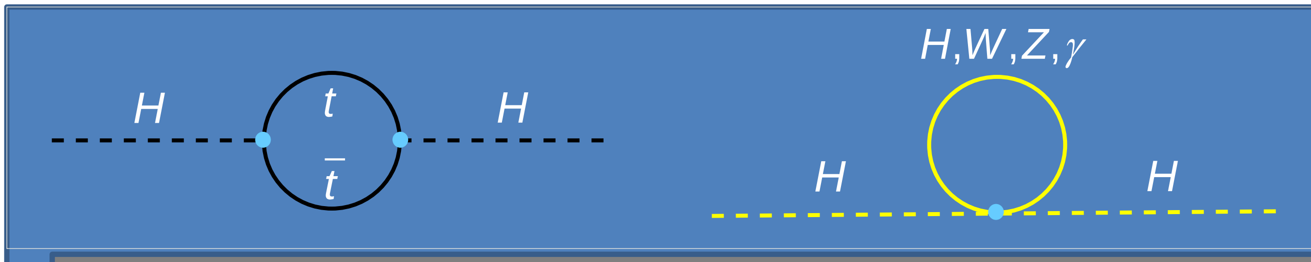

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Integral quadratically divergent

Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**. Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model.**

New physics models should address this. M_H should become a deviation from some exact symmetry, and is thus **intrinsically small** !

$$m_H^2 = (125\ GeV)^2 = m_0^2 + C \cdot \Lambda_{cut-off}^2$$

Hunting for Answers

- Get more information
  - Measure particles and their interactions in detail
    - Precision measurements (e.g. LHCb)
  - Observe new particles or interactions
    - Search in new areas in "phase space"
- Find the underlying pattern(s)
  - Hypothesize, build models
    - Internally consistent? Consistent with data?
    - Suggestions on where to look

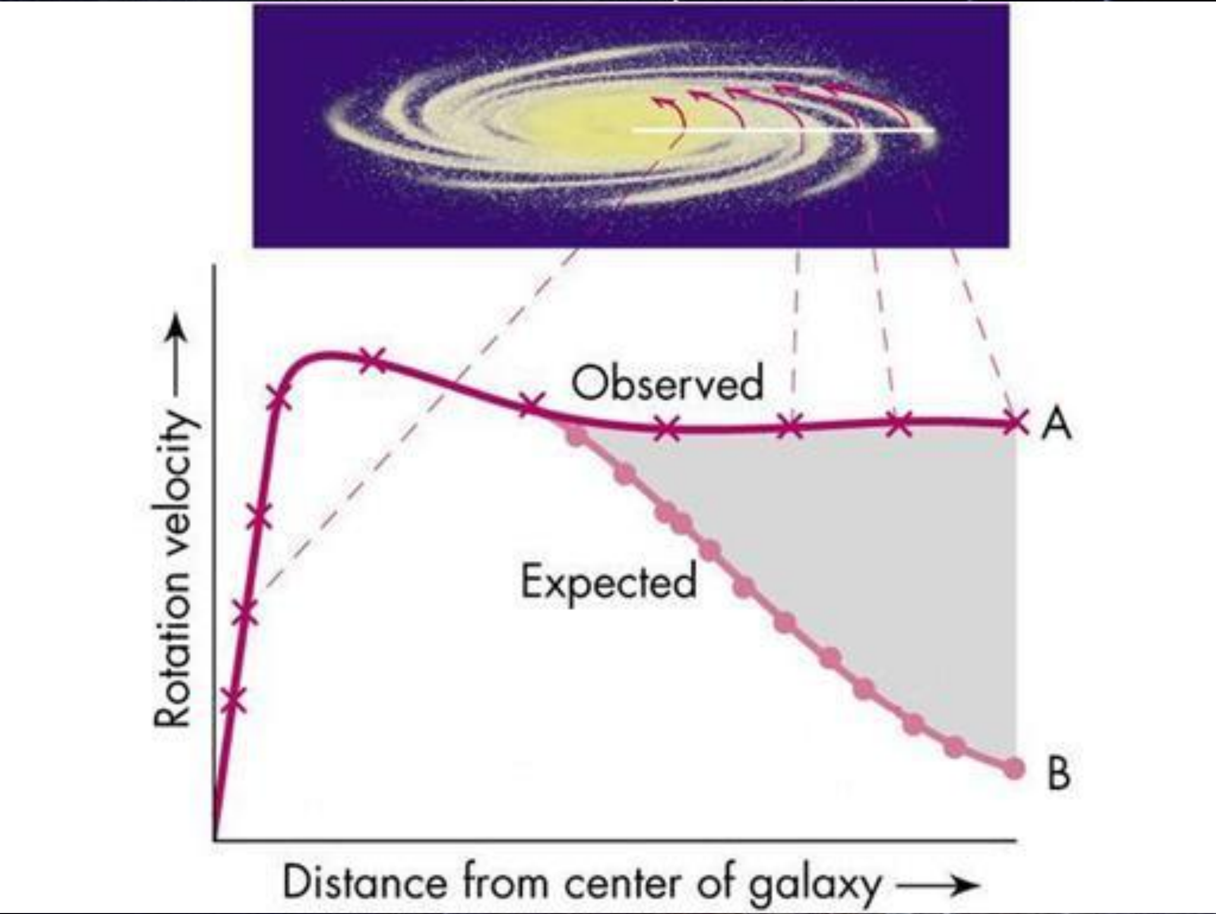
Experiment

Theory

Where to Start?

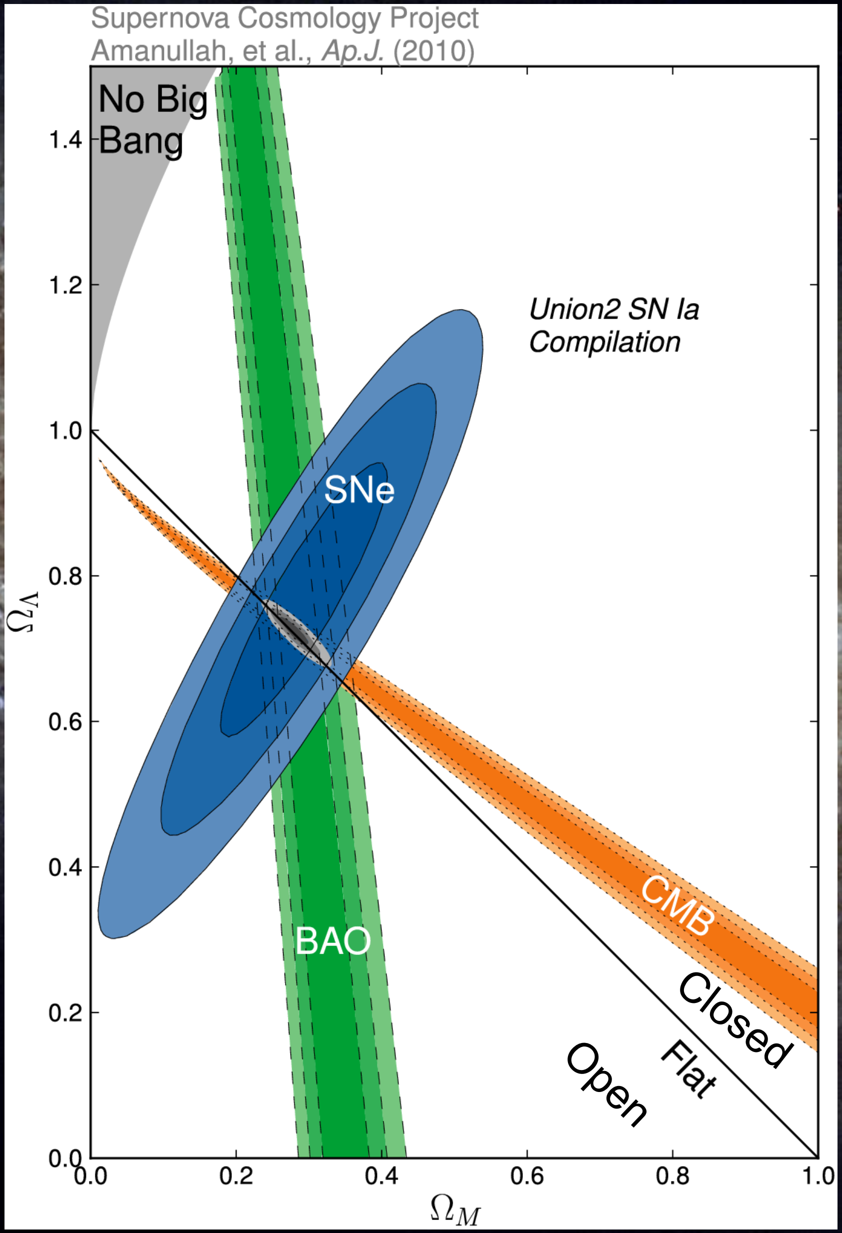
- BSM physics **must** couple to SM (weakly?), but is it
  - Resonant?
    - Does it have new massive particles decaying to electrons, muons, quarks, W, Z,…?
  - "SM-like"?
    - Same but includes some new long-lived particles in the decay chain... (e.g. dark matter candidate)
  - No new "particles" in reach
    - Hidden or too heavy or.... don't exist
  - Are there new interactions?

Galaxy rotation curves



Standard Model only accounts for ~20% of the matter of the Universe!!!

Supernovae data

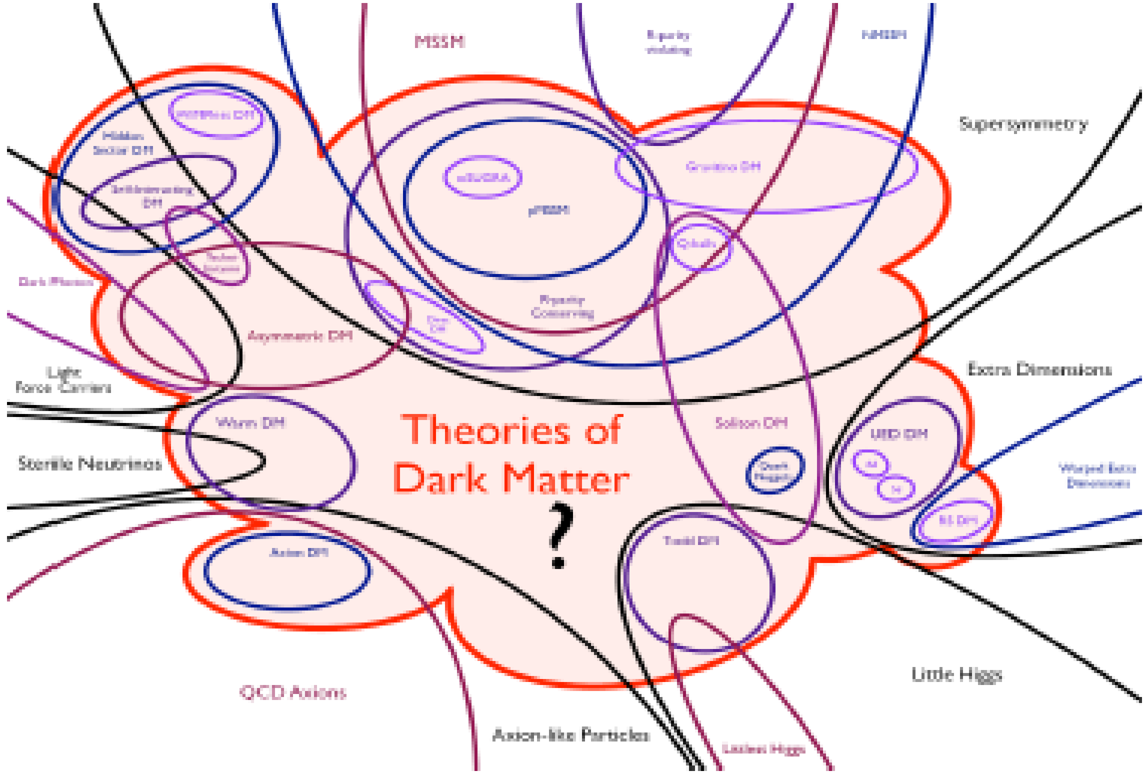


"Cosmological constant" term

"Matter density" term

Matter only accounts for ~30% of the Universe!

The energy scale(s) of new physics



T. Tait, DM@LHC '14

The prediction about the mass scale of DM comes with large error bars:

$$10^{-22}\,\mathrm{eV} < m_{DM} < 10^{20}\,\mathrm{GeV}$$

(ALPs) (Wimpzillas, Q-balls)

Supersymmetry (SUSY)

Idea

New symmetry ***fermions*** $\leftrightarrow$ ***bosons***

This symmetry is the most general extension of Lorentz invariance

SUSY has: N_{dof} (bosons) = N_{dof} (fermions)
[cf. SM: N_{dof} (bosons) << N_{dof} (fermions)]

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sLeptons	Leptons		Gravitino	Graviton
sQuarks	Quarks			
Higgs	Higgsino			
	Photino	Photon		
	Zino	Z		
	Wino	W		
	Gluino	Gluon		

- To create *supermultiplets*, we need to add one *superpartner* to each SM particle
- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side $\rightarrow$ 5 Higgs bosons

But where are these partners?!
Supersymmetry must be broken (if realized)

Particle spectrum (minimal!)

In reality the new states would mix

Several ideas of how the supersymmetry is broken – intimately connected with EWK symmetry breaking

SM

SUSY

Eigenstates of mass

Spin 0	Spin 1/2	Spin 1
$\tilde{\ell}_1, \tilde{\ell}_2$	ℓ	
$\tilde{q}_1, \tilde{q}_2$	q	
$h^0, H^0, A^0, H^\pm$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	
	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\gamma, Z^0, W^\pm$
	$\tilde{g}_a$	g_a

Squark/slepton mixing proportional to SM partner masses

→ largest for 3rd gen.

→ can become lightest squarks / sleptons

The gauge-mixed physical states that propagate in space and time and that can be observed.

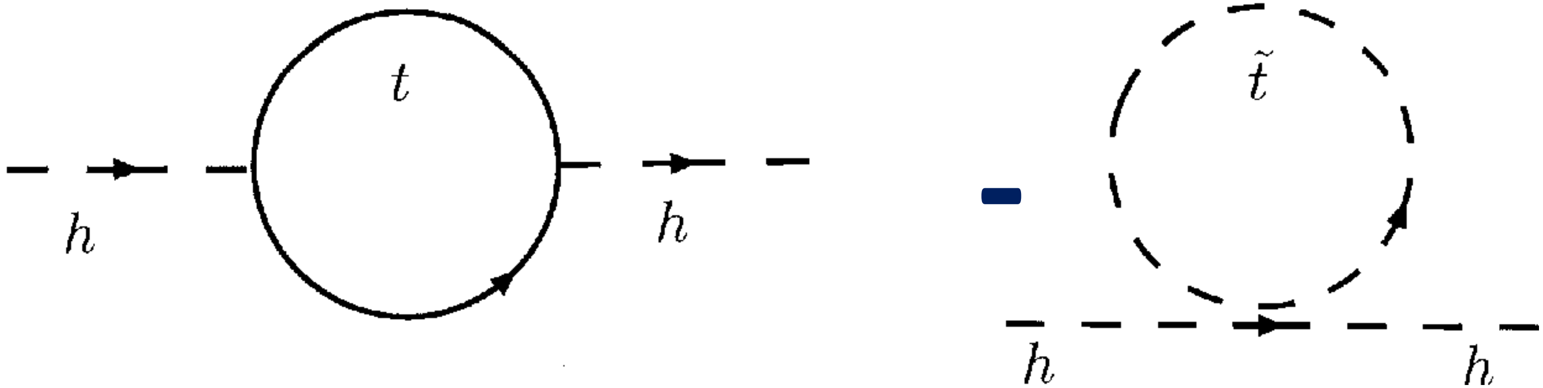
Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

Charginos : mass eigenstates of winos and charged higgsinos

Since we don't know the mechanism, have to introduce $\mathcal{O}(100)$ new parameters

SUSY and the hierachy problem

If Supersymmetry not broken we would have perfect cancellation in the loops!



But as m($\tilde{t}$) ≠ m(t) they do not quite cancel, instead just a suppression

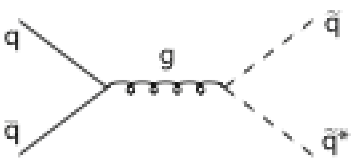
This still gives a decent result if |

m(fermion) – m(boson)| < $\mathcal{O}$(TeV)

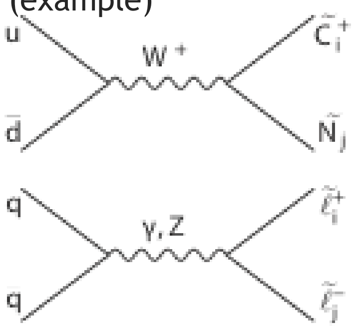
Once mass spectrum fixed, all cross sections predicted

Spin structure of SUSY spectrum: lower σ than other BSM models, harder to find !

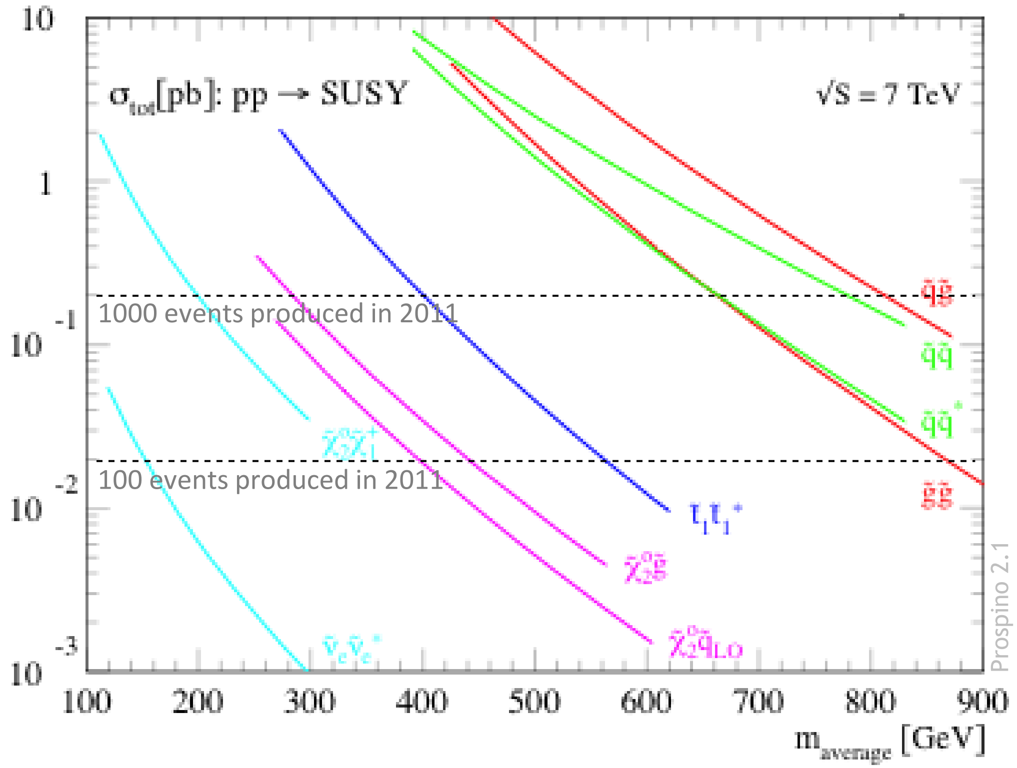
Direct squark pair production (example)



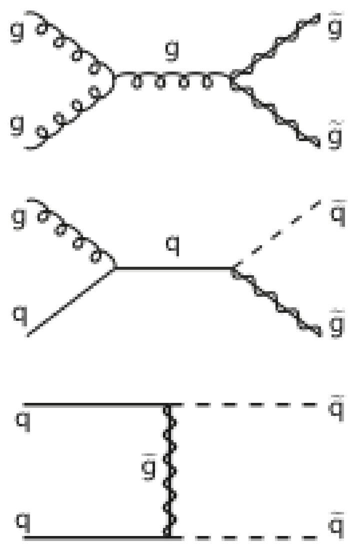
Direct gaugino/slepton pair production (example)



SUSY cross section versus sparticle mass

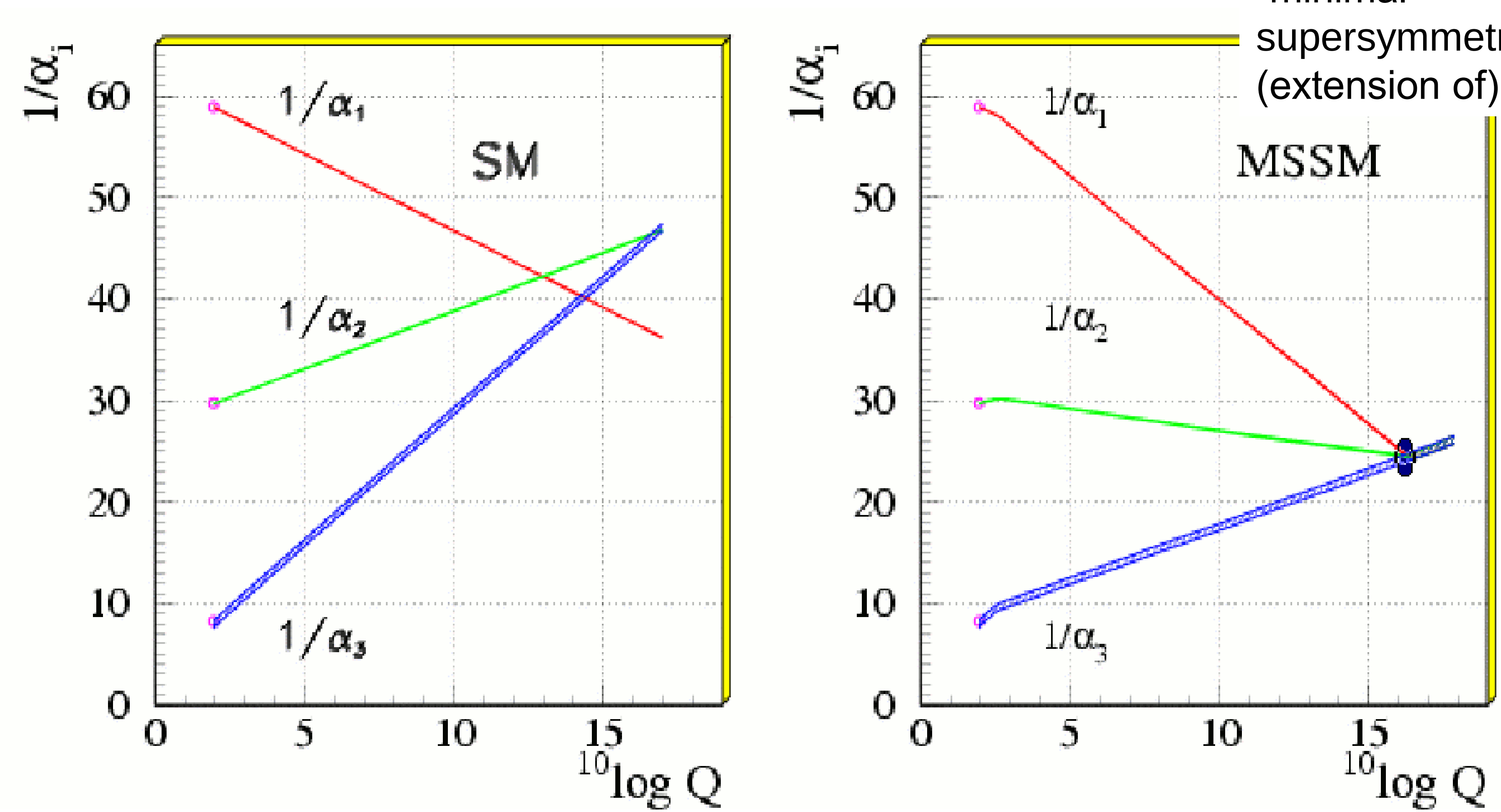


Gluino & squark production (examples)



Unification of coupling constants with supersymmetry

“minimal supersymmetric (extension of) SM”

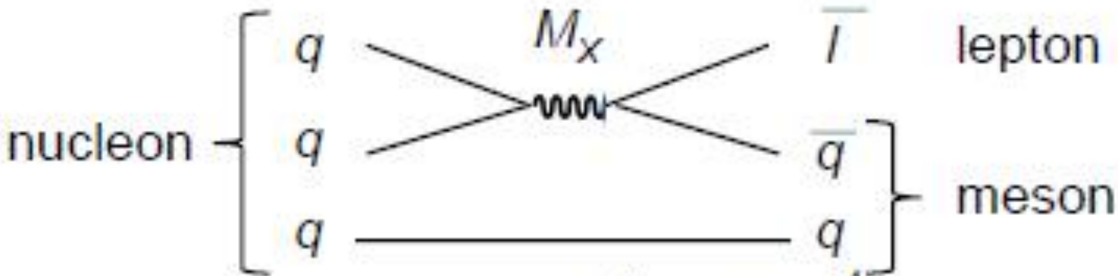


Proton Decay

(G. Giudice SSLP'15)

in GUT, matter is unstable

decay of proton mediated by new SU(5)/SO(10) gauge bosons

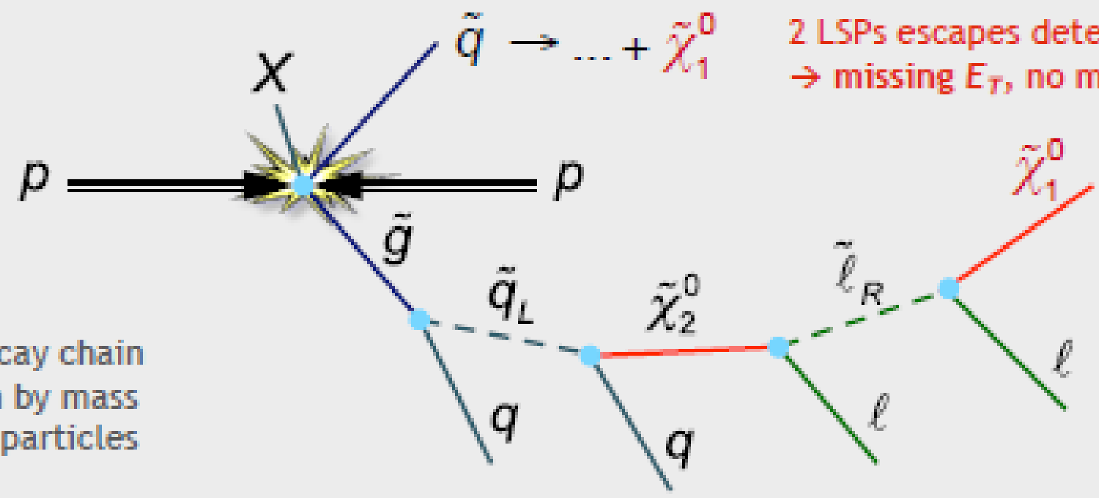


$$\text{GUT: } \tau_p(p \rightarrow e^+\pi^0) = \left(\frac{M_X}{10^{15}\text{ GeV}}\right)^4 10^{31-32}\text{ yr}$$

$$\text{Exp: } \tau_p(p \rightarrow e^+\pi^0) > 8.2 \times 10^{33}\text{ yr}$$

Characteristic SUSY Decay Cascades

- To avoid proton decay, a new conserved quantum number (R) is introduced, which forces a SUSY particle to decay in at least one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless → WIMP (dark matter candidate)
- Typical **LSP is spin-½ neutralino.** It could also be a gravitino
- With R parity: SUSY production in pairs only → requires energy 2 × SUSY mass !

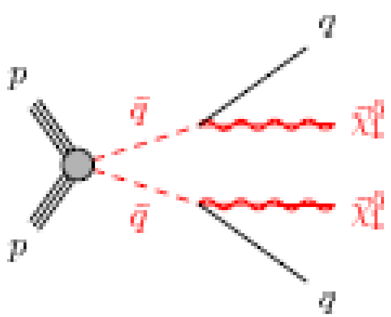


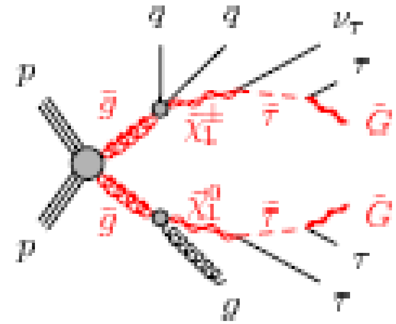
2 LSPs escapes detection
→ missing E_T, no mass peak !

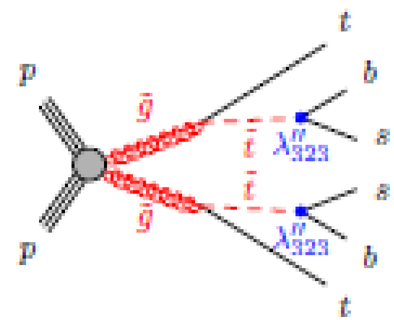
"Typical" SUSY decay chain at the LHC, driven by mass hierarchy of SUSY particles

Canonical SUSY

- Wide range of signatures
  - Strong production… (large cross-section)

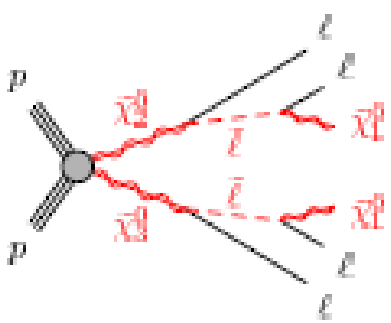


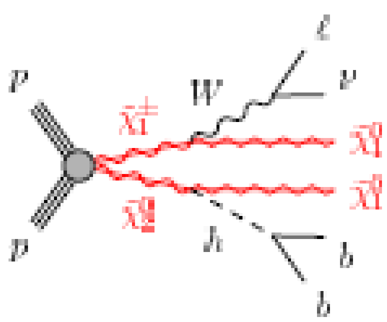


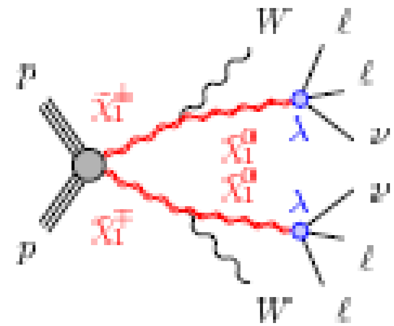


RPV

  - … or weak production



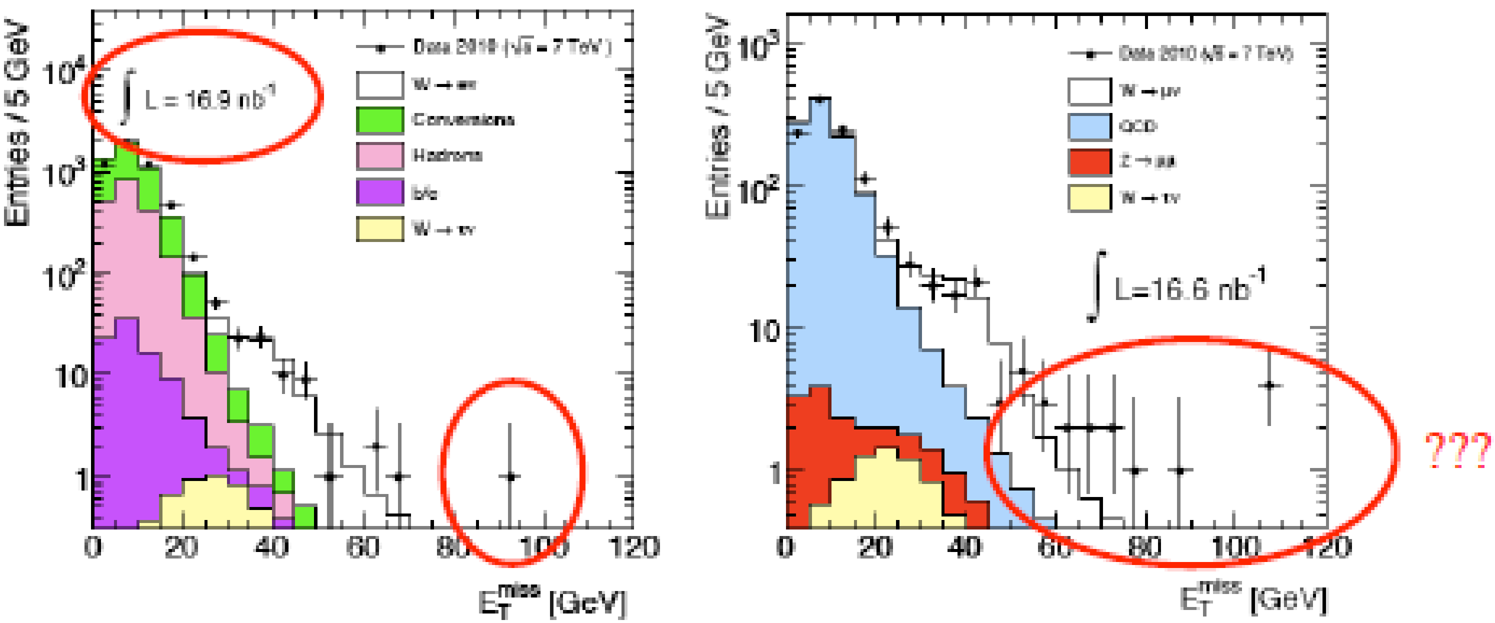




Missing ET

- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

Early 2010



- Analyses using MET are particularly sensitive
  - Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bits)
  - Easy: basic DQ (high voltage trip, etc.)
  - Hard: low frequency
  - Can't spot a 10^{-5} Hz (once a day) effect online or in first pass DQ
    - But can be biggest part of dataset after cuts!