FYST11 Lecture 12
BSM II

Thanks to G. Brooijmans, T. Rizzo, L. Covi

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

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		

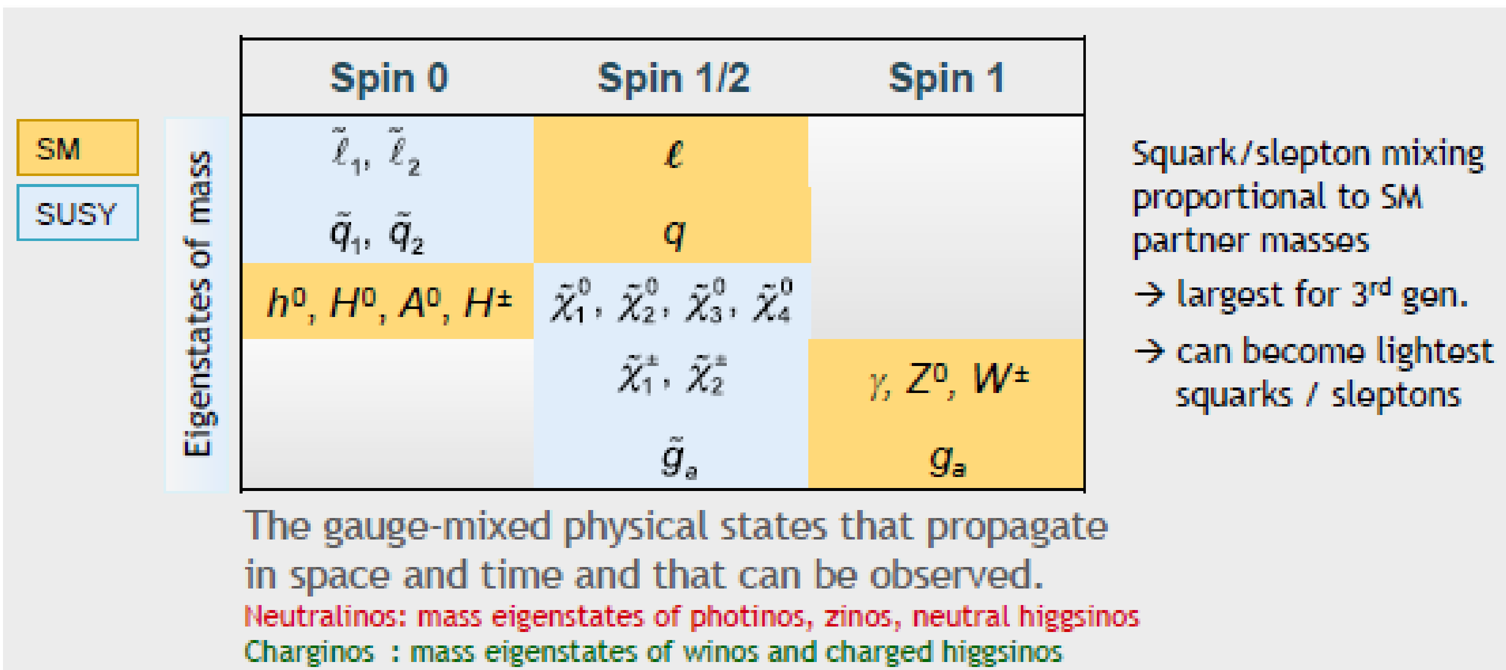
- To create *supermultiplets*, we need to add one *superpartner* to each SM particle
- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side $\Rightarrow$ 5 Higgs bosons

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

Particle spectrum (minimal!)

In reality the new states would *mix*

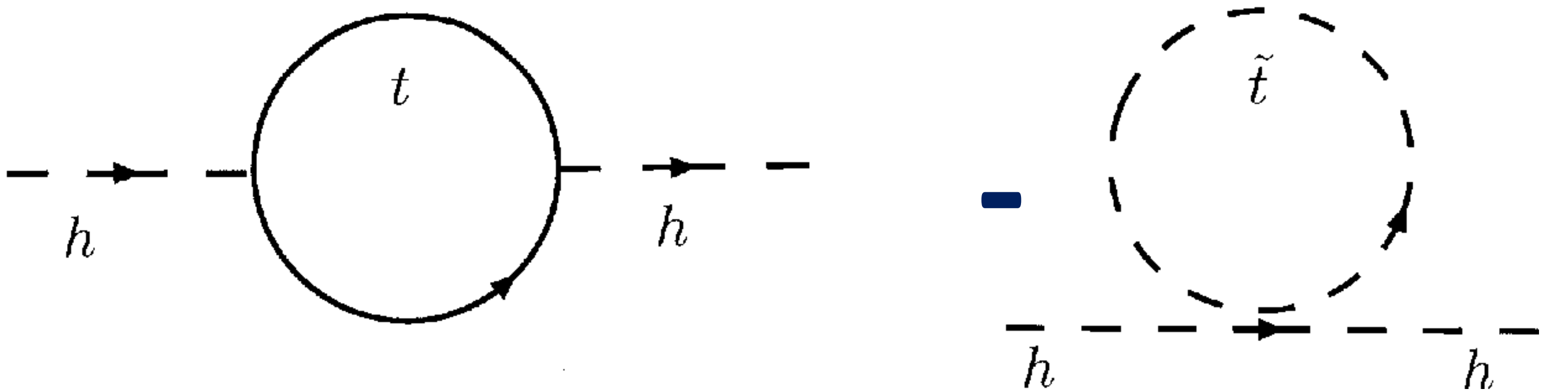
Several ideas of how the supersymmetry is broken – intimately connected with EWK symmetry breaking



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

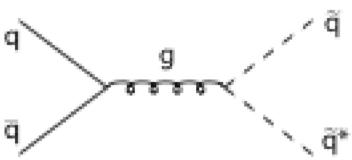
This still gives a decent result if

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

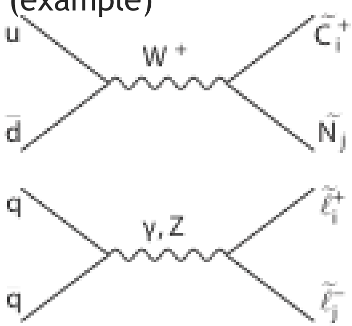
Once mass spectrum fixed, all cross sections predicted

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

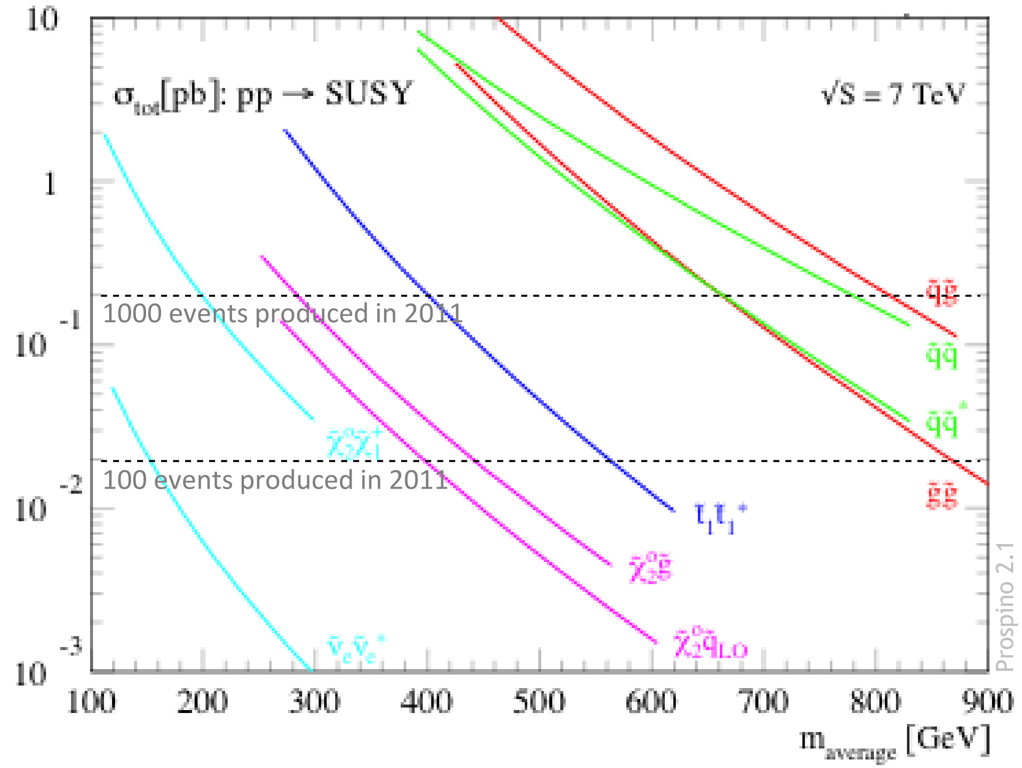
Direct squark pair production (example)



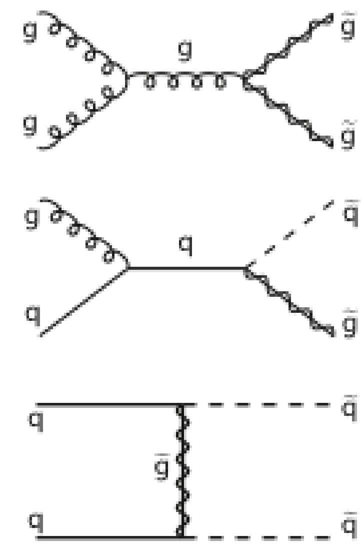
Direct gaugino/slepton pair production (example)



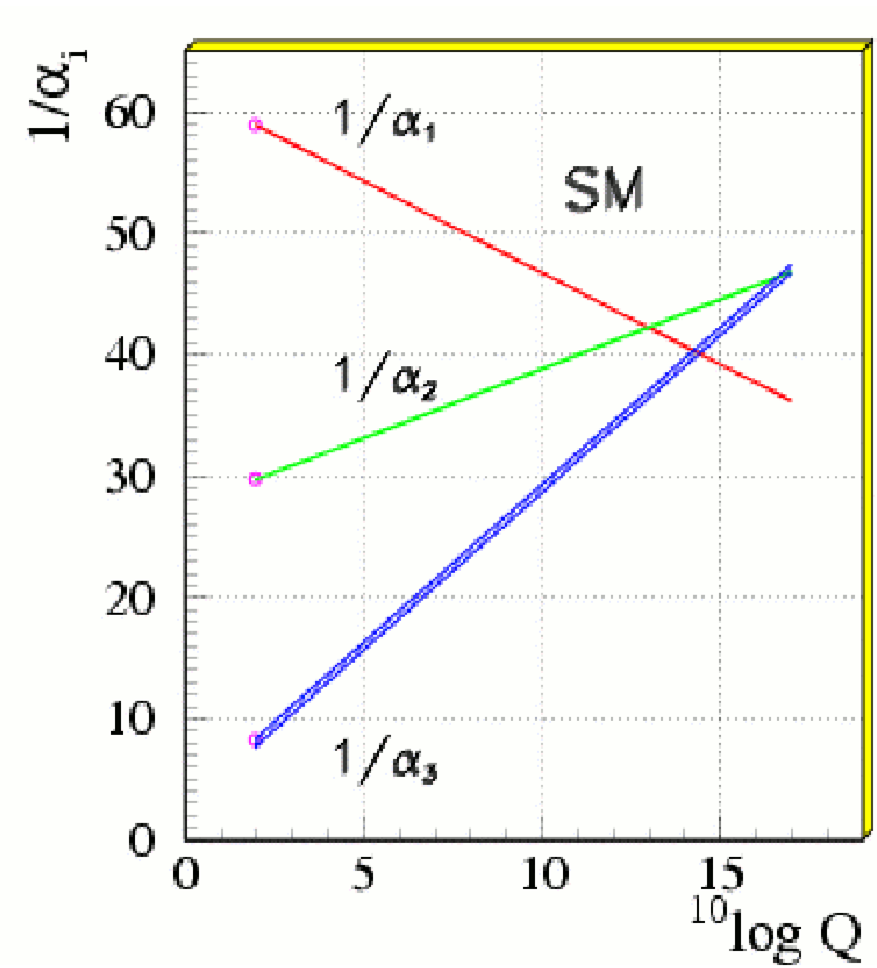
SUSY cross section versus sparticle mass

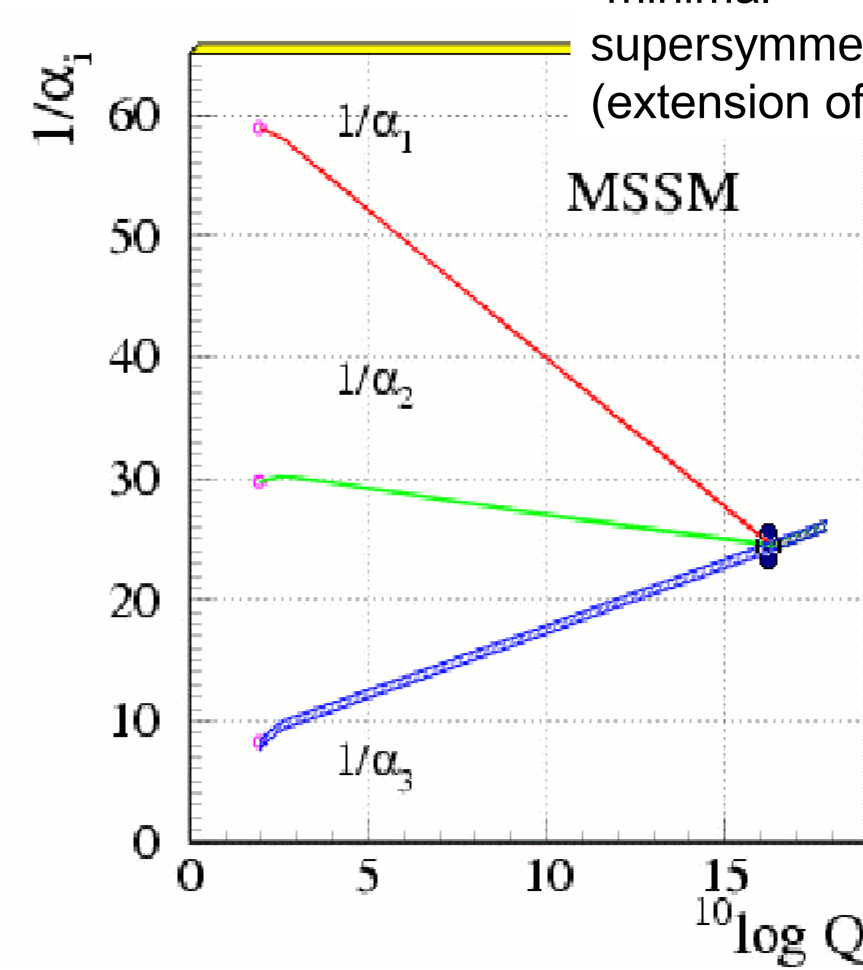


Gluino & squark production (examples)



Unification of coupling constants with supersymmetry





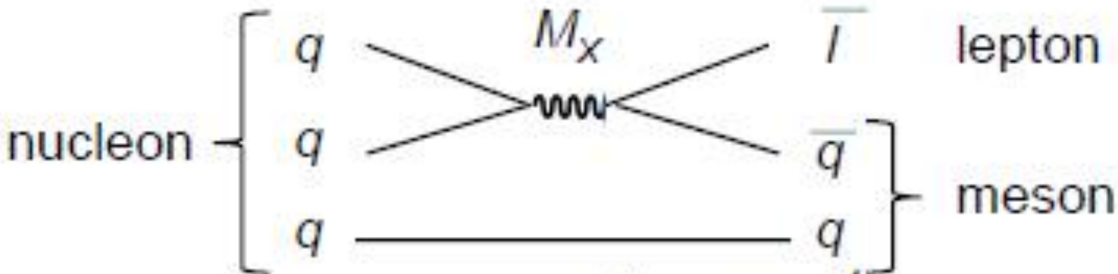
“minimal supersymmetric (extension of) SM”

Proton Decay

(G. Giudice SSLP'15)

in GUT, matter is unstable

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

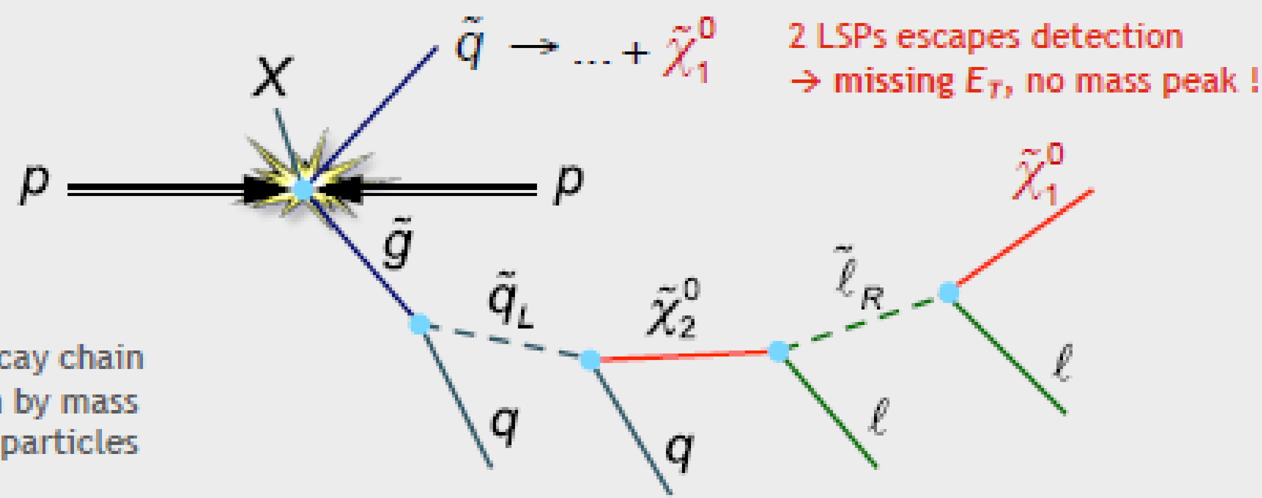


$$\text{GUT: } \tau_p(p \to e^+\pi^0) = \left(\frac{M_X}{10^{15}\ \text{GeV}}\right)^4 10^{31-32}\ \text{yr}$$

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

Characteristic SUSY Decay Cascades

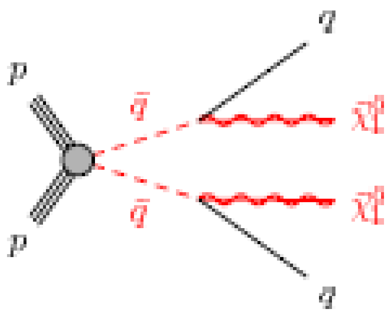
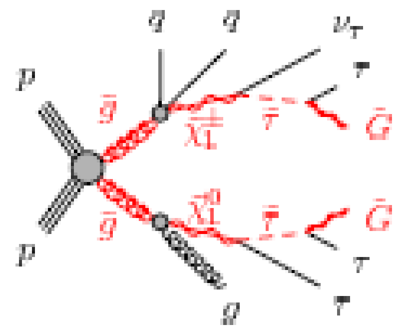
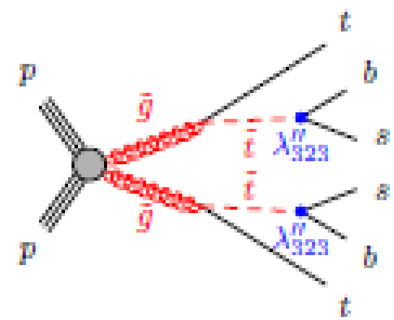
- To avoid proton decay, a new conserved quantum number (R) is introduced, which forces a SUSY particle to decay in at least one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless → WIMP (dark matter candidate)
- Typical **LSP is spin-½ neutralino.**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



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

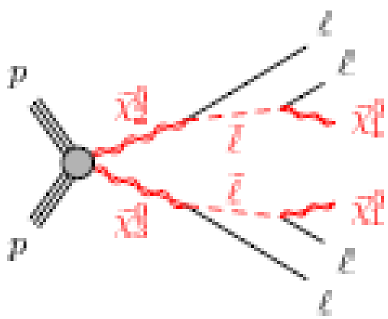
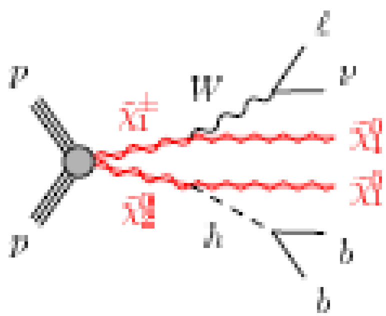
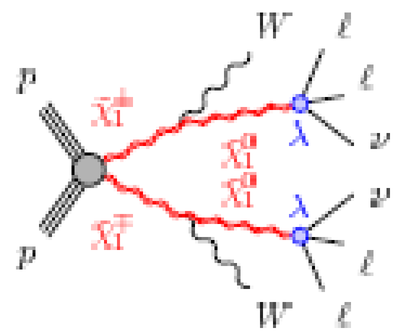
Canonical SUSY

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

RPV

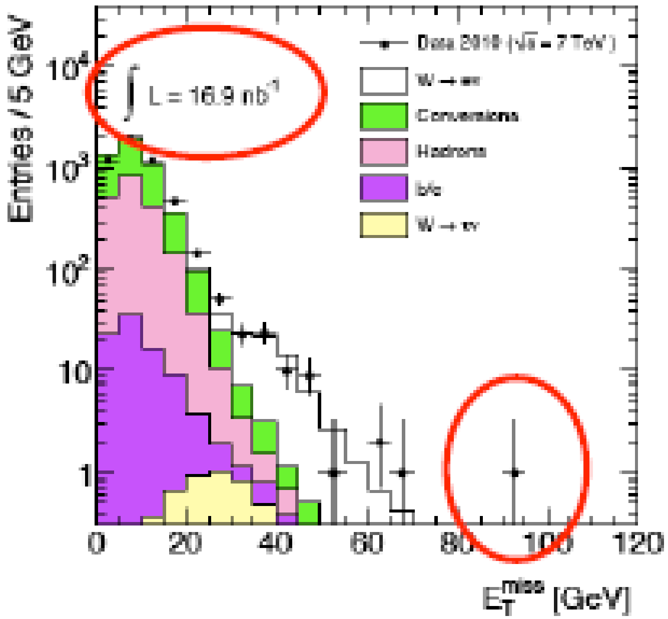
  - … or weak production

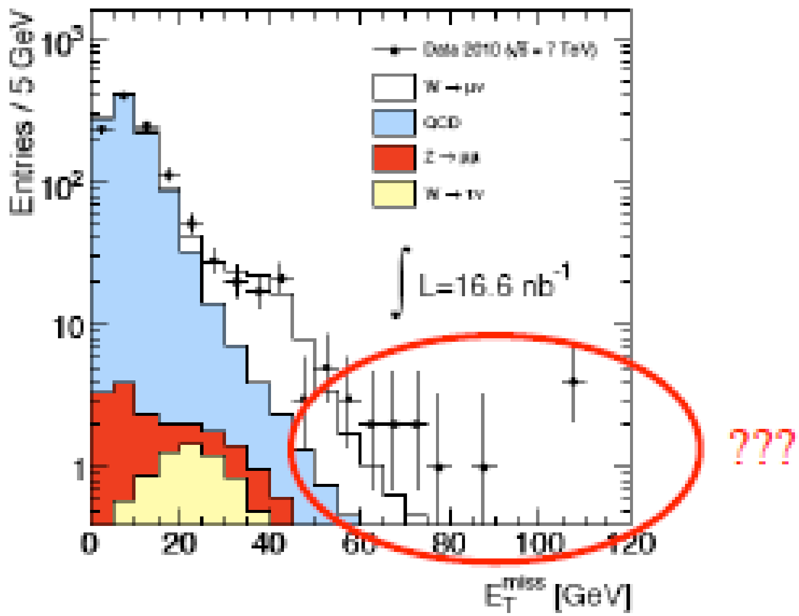




Missing ET

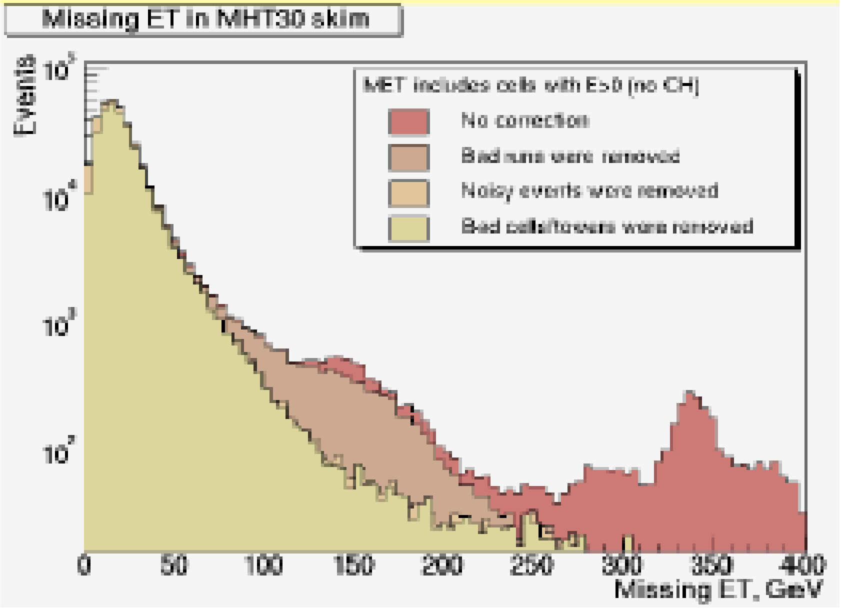
- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

Early 2010

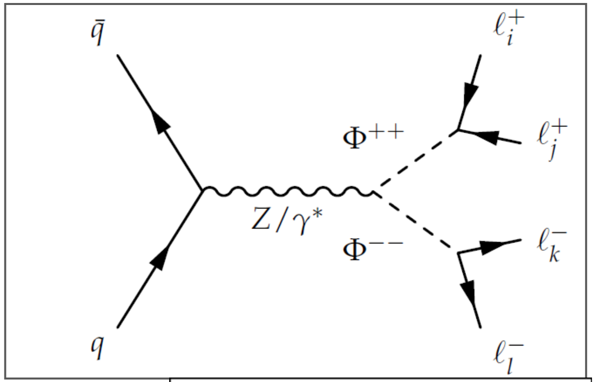




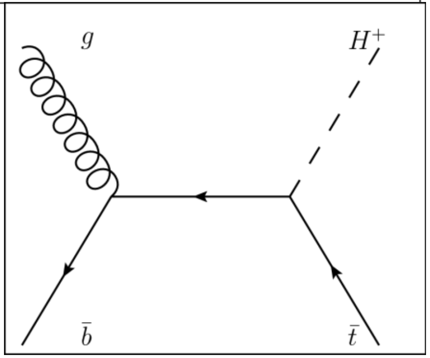
- ❖ Analyses using MET are particularly sensitive
  - Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bits)
  - Easy: basic DQ (high voltage trip, etc.)
  - Hard: low frequency
  - Can't spot a 10^{-5} Hz (once a day) effect online or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



Extended Higgs sector



In the Standard Model single Higgs doublet, often written as $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ or $\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$



Extended: Many choices but a few constraints,

for instance suppression of FCNC and $\frac{M_W}{M_Z} = \cos\theta_W$

- Most successful: 2 Higgs doublet models (2HDMs)
  - Supersymmetry uses this
- See-saw models predict Higgs triplet with $\varphi^0, \varphi^{+/-}, \varphi^{++/--}$

General 2HDM Potential

$$V(\phi_1,\phi_2) = \lambda_1\left(|\phi_1|^2 - v_1^2\right)^2 + \lambda_2\left(|\phi_2|^2 - v_2^2\right)^2$$

$$+\lambda_3\left[\left(|\phi_1|^2 - v_1^2\right)+\left(|\phi_2|^2 - v_2^2\right)\right]^2$$

$$+\lambda_4\left[|\phi_1|^2|\phi_2|^2 - \left(\phi_1^{*T}\phi_2\right)\left(\phi_2^{*T}\phi_1\right)\right]$$

All λ are real.

$$+\lambda_5\left[\mathrm{Re}\left(\phi_1^{*T}\phi_2\right) - v_1 v_2\cos\xi\right]^2$$

$$+\lambda_6\left[\mathrm{Im}\left(\phi_1^{*T}\phi_2\right) - v_1 v_2\sin\xi\right]^2$$

From “Higgs Hunter’s guide”.

$$\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}_1 = \begin{pmatrix}0\\ v_1\end{pmatrix}\frac{1}{\sqrt{2}} \;\; ; \;\; \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}_2 = \begin{pmatrix}0\\ v_2 e^{i\xi}\end{pmatrix}\frac{1}{\sqrt{2}} \;\; ; \quad \tan\beta = \frac{v_2}{v_1}$$

Higgs Boson Spectroscopy

- One Charged Higgs with mass:

$$m_{H^\pm} = \sqrt{\lambda_4 (v_1^2 + v_2^2)}$$

- One CP-odd neutral Higgs with mass:

$$m_{A^0} = \sqrt{\lambda_6 (v_1^2 + v_2^2)}$$

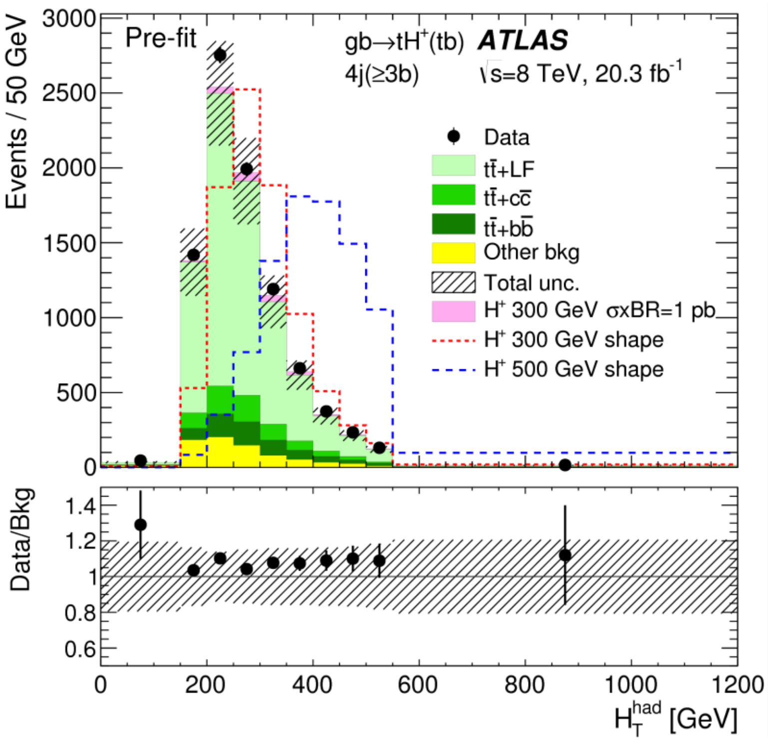
- And two CP-even higgs that mix.

$$M = \begin{pmatrix} 4v_1^2(\lambda_1 + \lambda_3) + v_2^2\lambda_5 & (4\lambda_3 + \lambda_5)v_1 v_2 \\ (4\lambda_3 + \lambda_5)v_1 v_2 & 4v_2^2(\lambda_2 + \lambda_3) + v_1^2\lambda_5 \end{pmatrix}$$

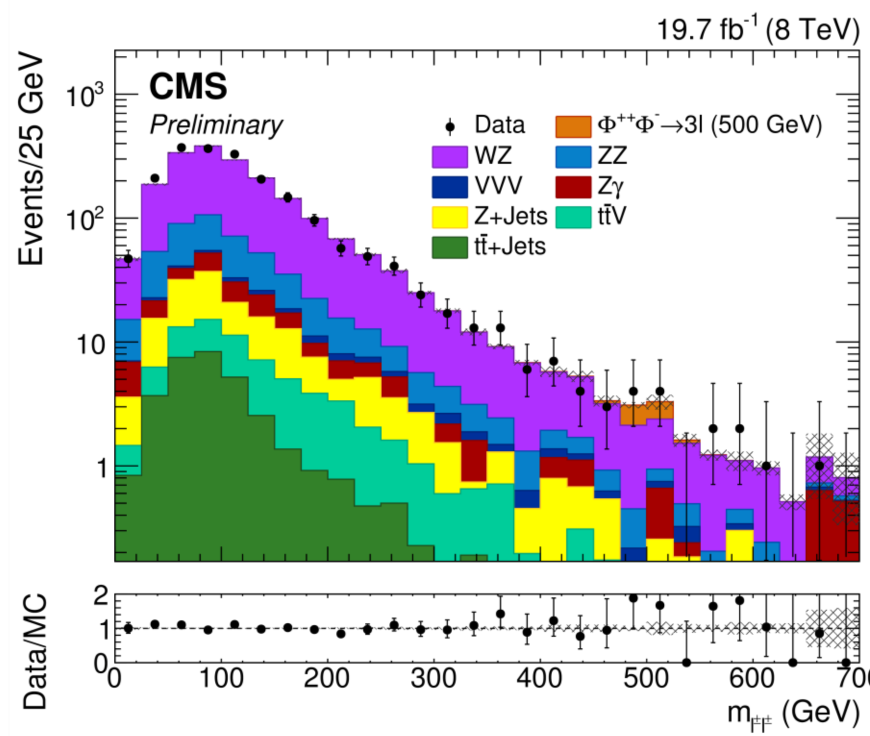
5 Higgs bosons! h, H, A, $H^\pm$

Examples of searches for extra Higgs bosons

Singly-charged



Doubly-charged



Limits around $\mathcal{O}$(200 GeV)

600 GeV

Parity Restoration: Signals

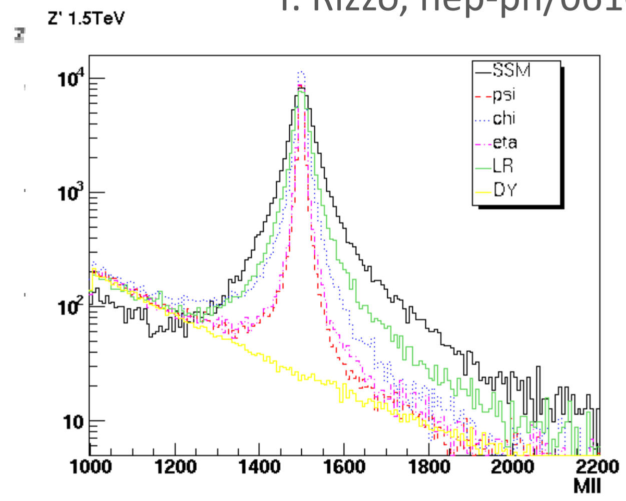
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances (Z') offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p_T
  - $t\bar{t}$ decays visible
  - ν_R is presumably heavy, W' may not decay to leptons
    - Only dijet or diboson
    - If ν_R lighter than W'/Z', ν_R decays become important
- Note: many kinds of Z' - review by Langacker

  arXiv:0801.1345
  - W'/Z' would also require new fermions…

Z' Production and Decay

T. Rizzo, hep-ph/0610104

- Production from u, d quarks is dominant at LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\kappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes ν_R heavier



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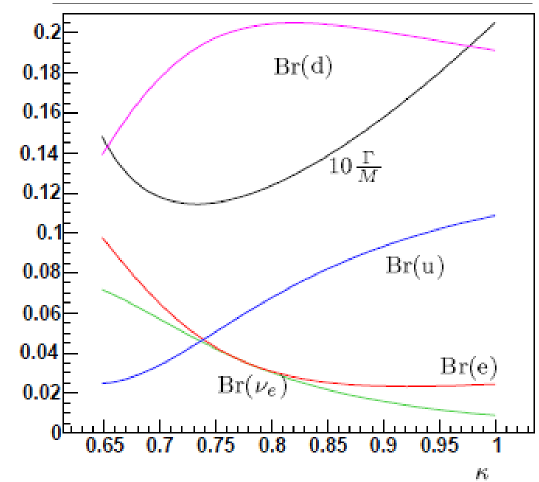
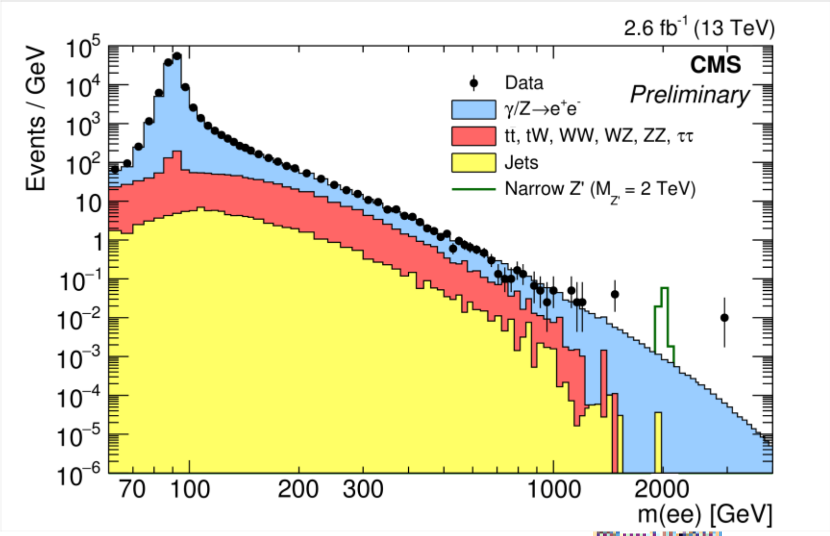
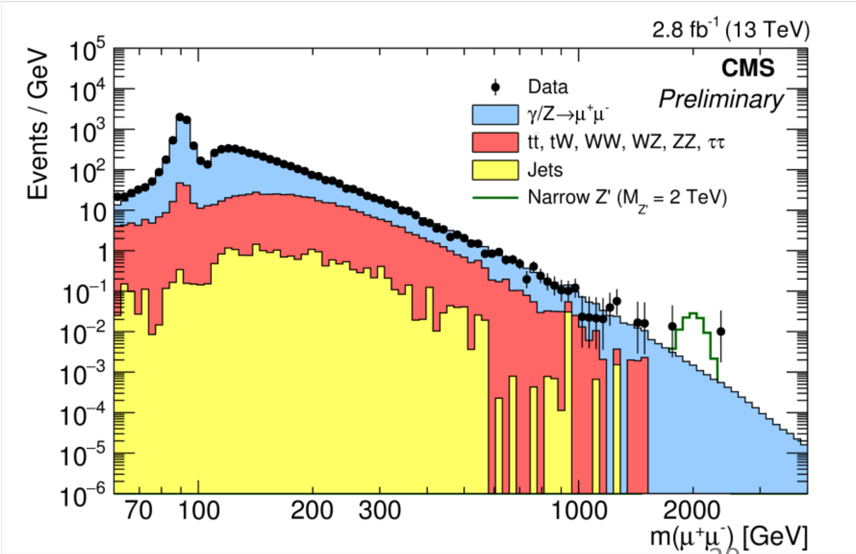


Z’ → ee/μμ

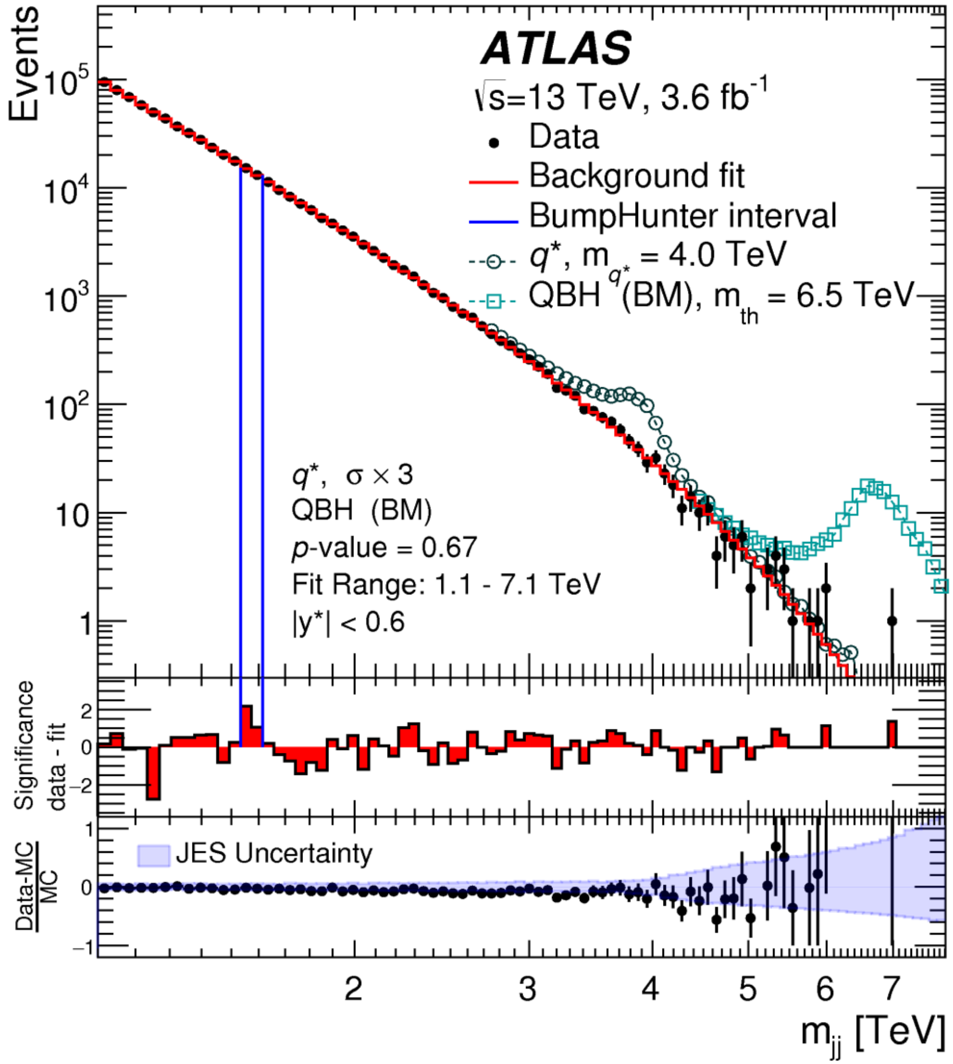
- ❖ Most promising channels:
  - Backgrounds very low!
  - “Self-calibrating”
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- ❖ LHC extended Tevatron reach immediately!





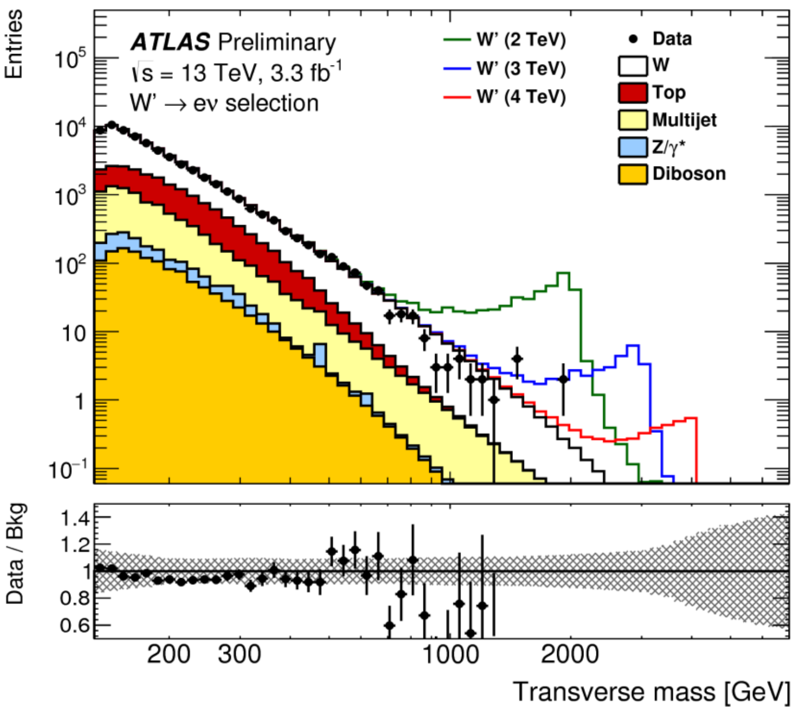
Dijets

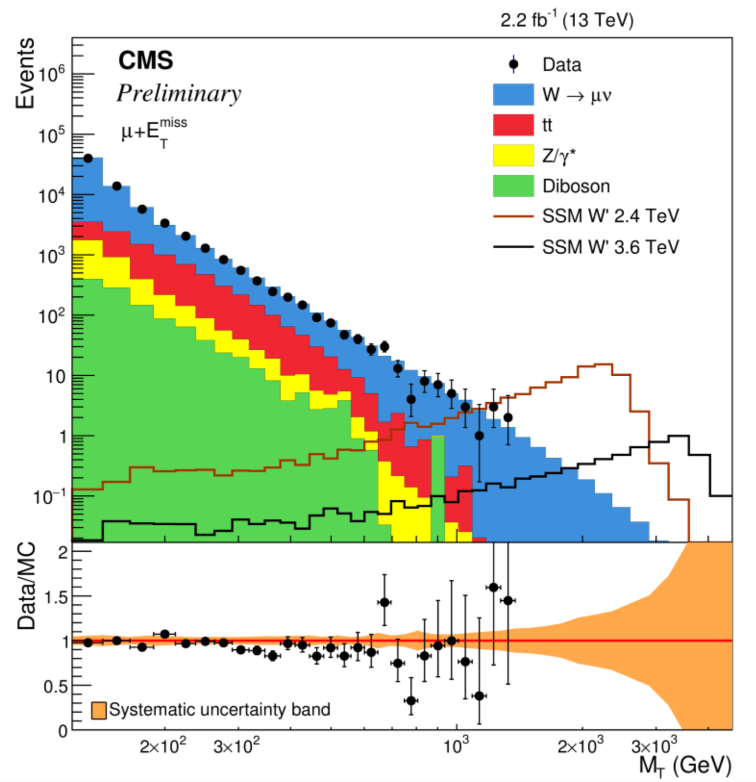
- SM background obviously much larger
  - But single source
  - And opens the door to strongly interacting objects



W’ → μν / eν

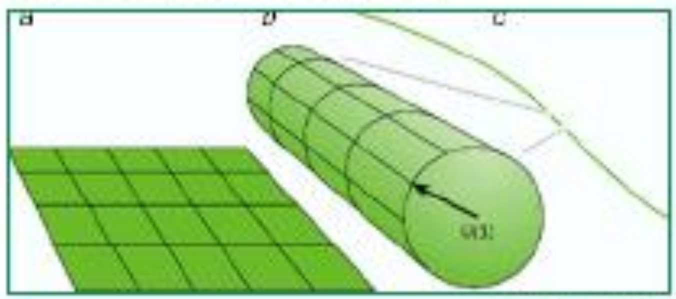
Another very simple selection: lepton + MET





Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified



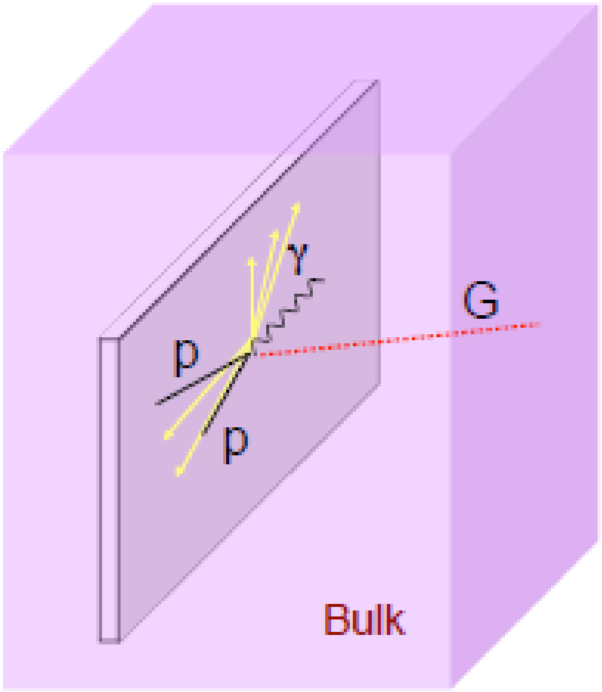
Source: PhysicsWorld

- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger…

Phys Lett B246:377-384 1990

ADD extra dimensions

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali): Phys.Lett. B429 (1998) 263-272
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

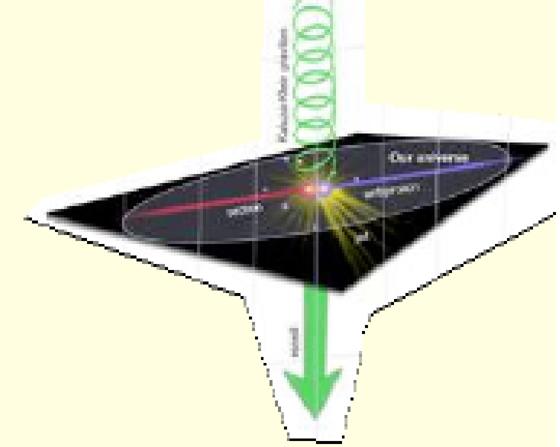


Drawing by K. Loureiro

ADD signatures

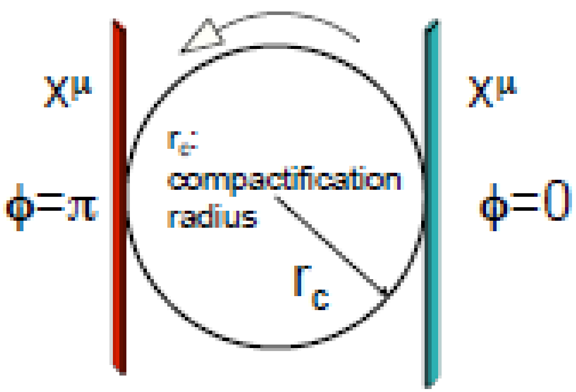
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantized
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

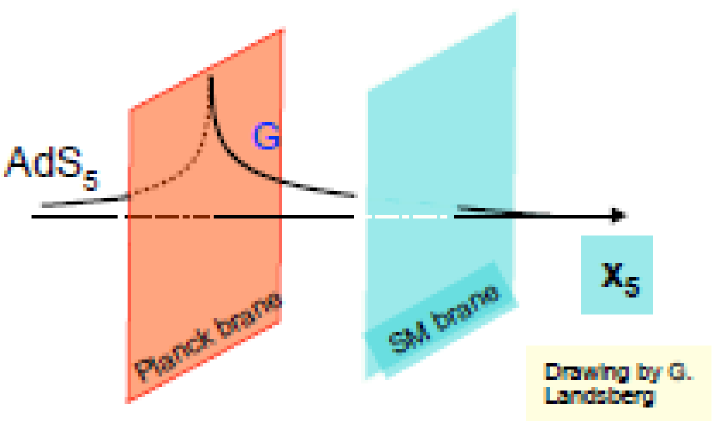
- Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!



Warped extra dimensions

- "Simple" Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is "warped" by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)

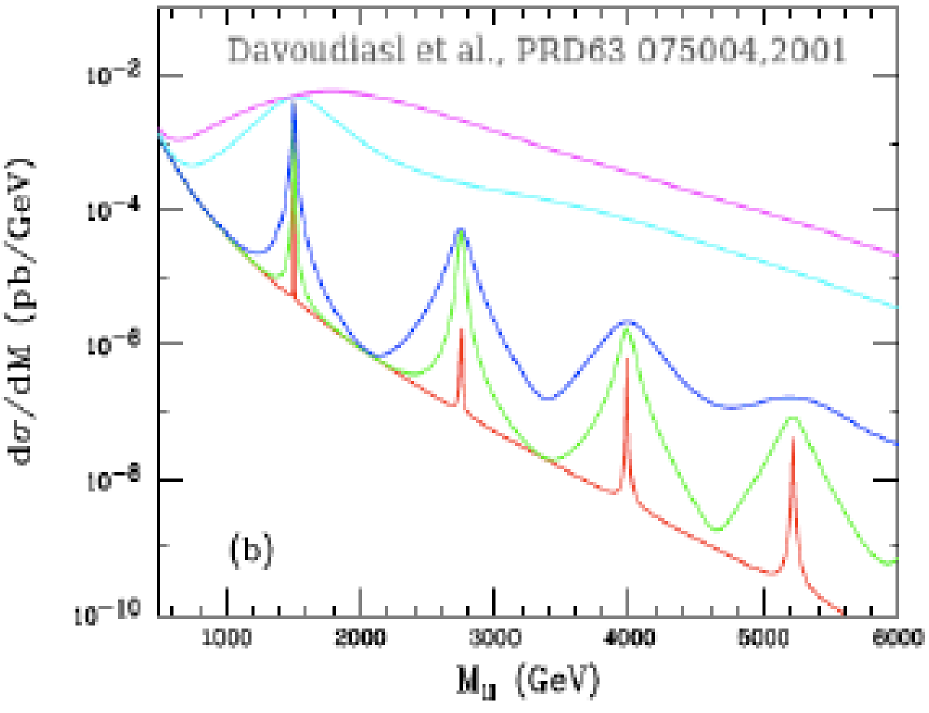




Graviton excitations

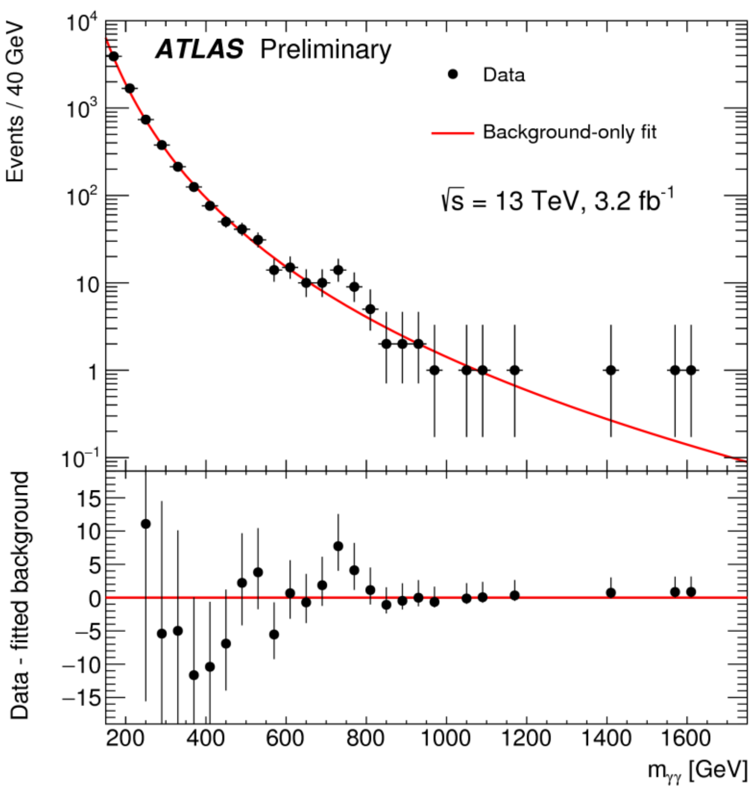
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function
    - ➡ Smoking gun!

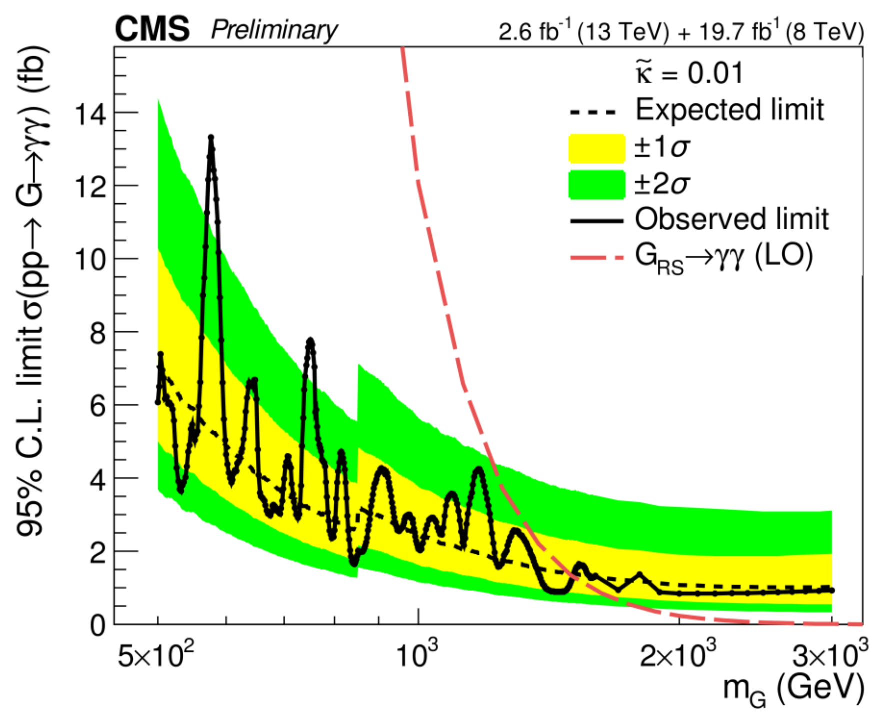
(BRs also different than Z':
e.g. γγ allowed)



Example

The infamous $\gamma\gamma$ bump is an example of a search for RS gravitons:

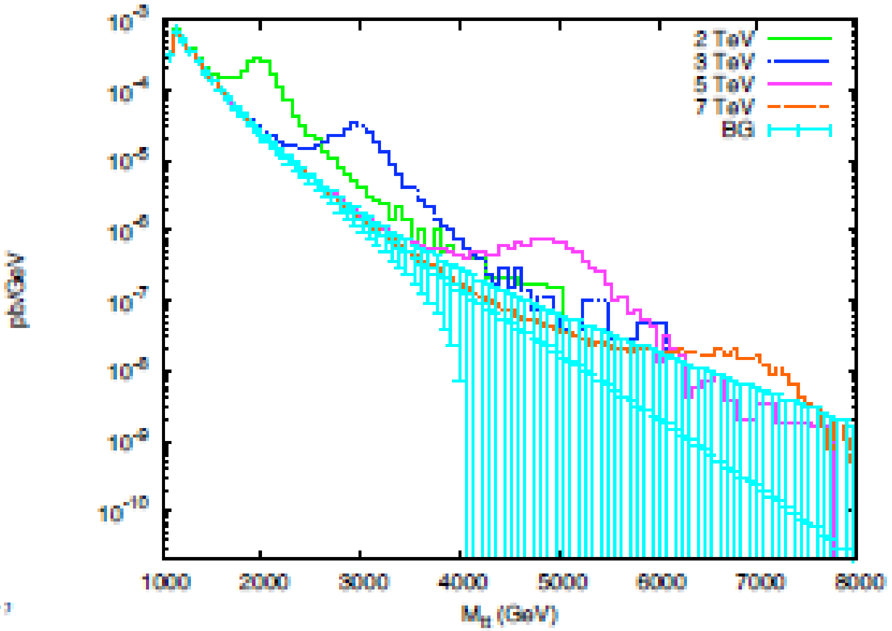




Gauge boson excitations

- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

B. Lillie et al., JHEP 0709:074,2007

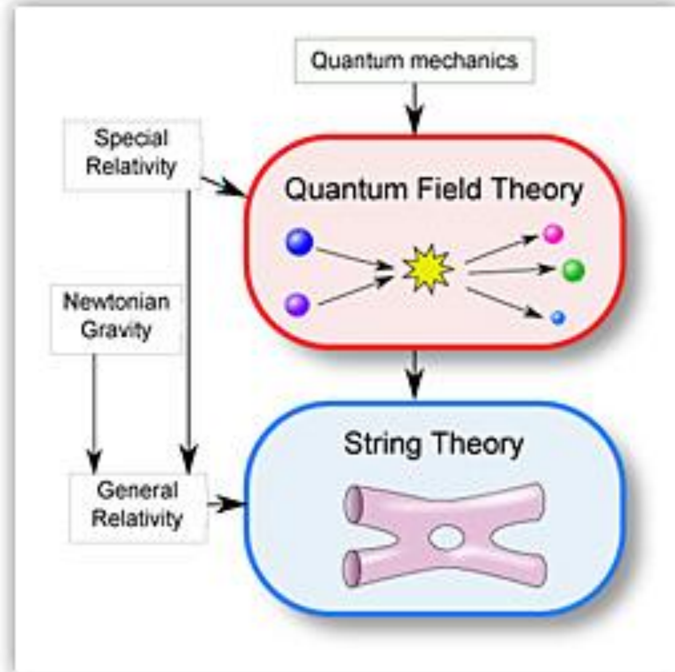


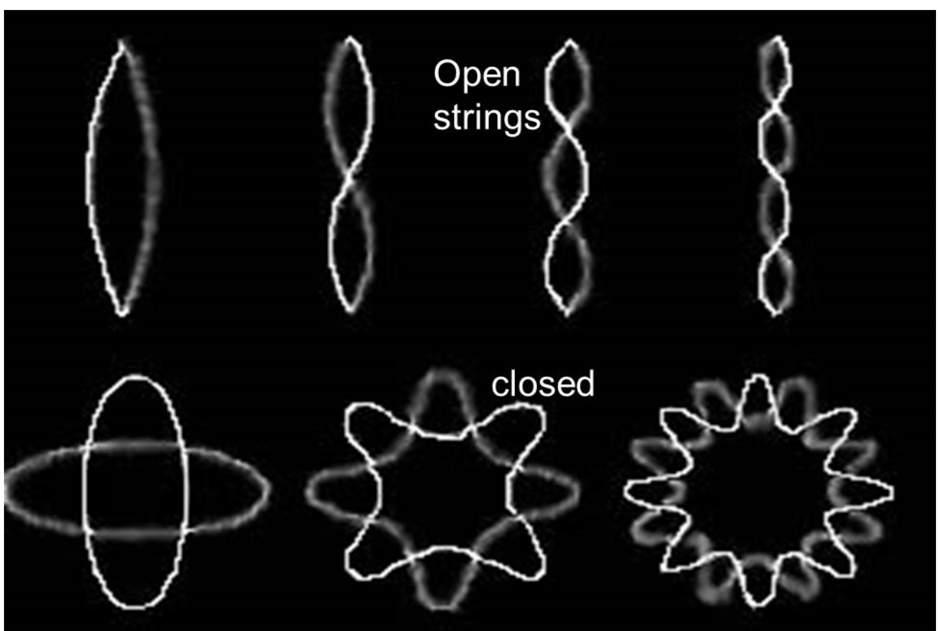
(super)Strings

Avoid infinities from point-like particles

Different vibration modes = different particles

One fundamental parameter: *string size*





Great idea but we have not yet understood how to test it at current "low" energies

Extra dimensions a must
Supersymmetry a plus

Dark Matter Searches

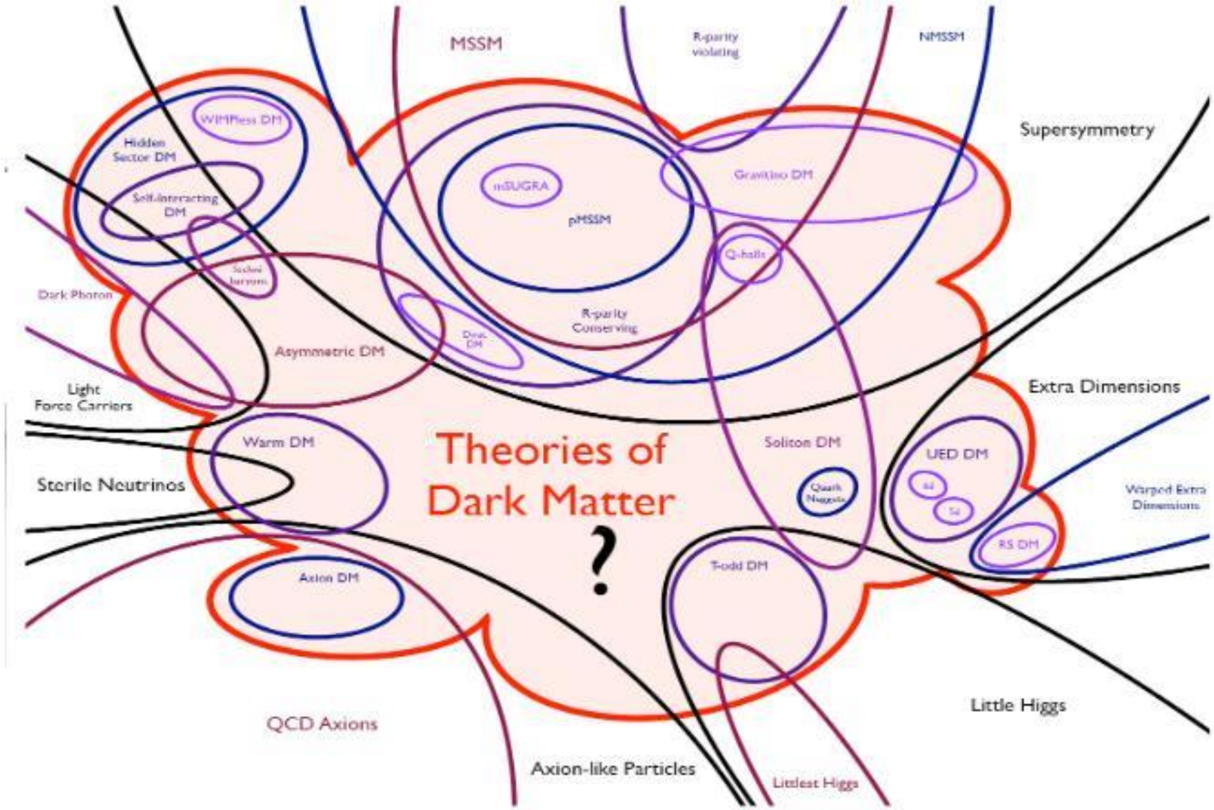
Lots of models, this is not a unique search!

Typically divided in two ”classes”:

WIMP: weakly interacting massive particle
(≈ elementary particle)

MACHO: Massive Compact Halo Objects
(planets, dwarf stars, something large)

The energy scale(s) of new physics



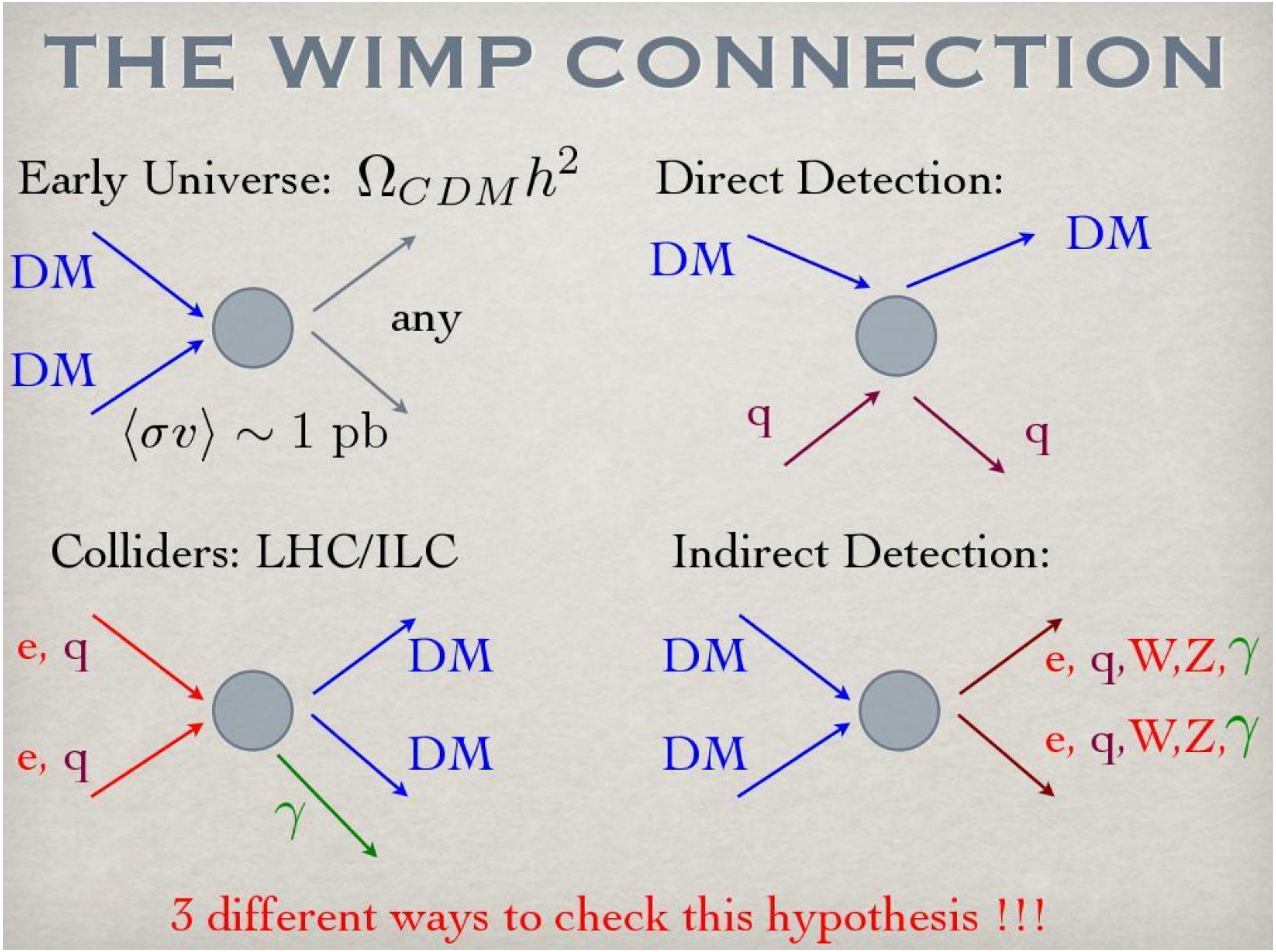
T. Tait, DM@LHC '14

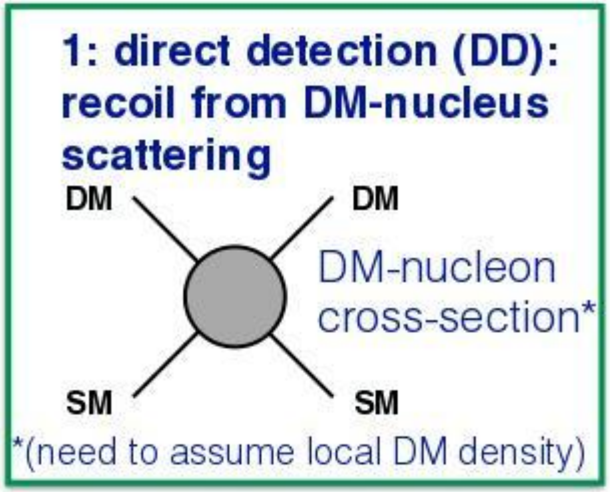
The prediction about the mass scale of DM comes with large error bars:

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

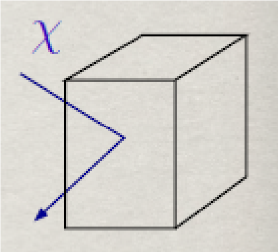
(ALPs) (Wimpzillas, Q-balls)

or even black holes ~10000 x M_{Sun}

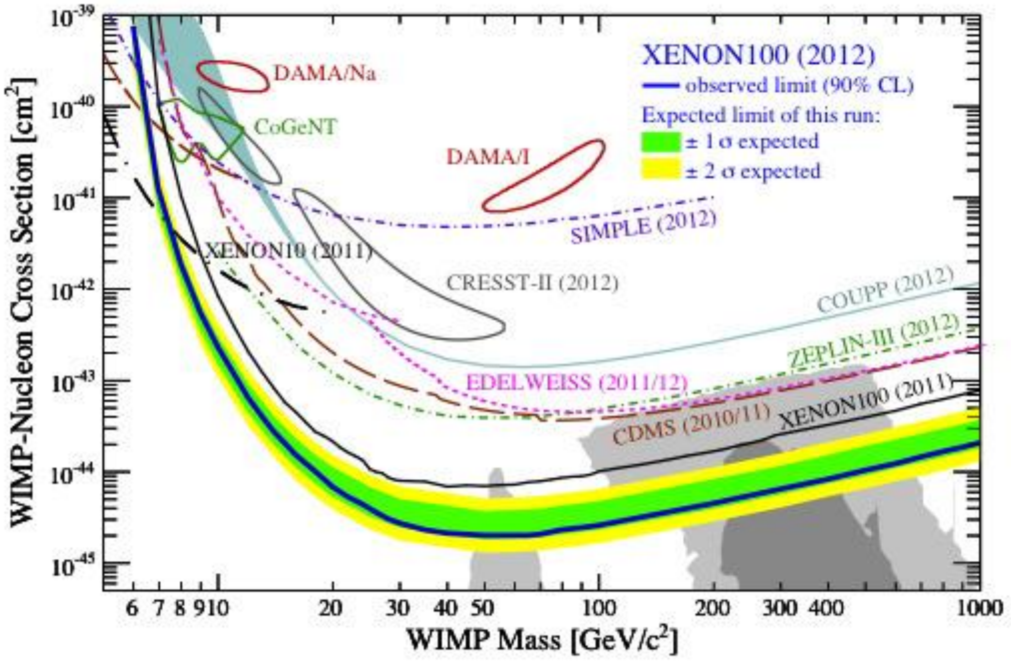

THE WIMP CONNECTION
Early Universe: $\Omega_{CDM}h^2$
DM
DM
any
$\langle\sigma v\rangle \sim 1$ pb
Direct Detection:
DM
DM
q
q
Colliders: LHC/ILC
e, q
e, q
DM
DM
γ
Indirect Detection:
DM
DM
e, q,W,Z,γ
e, q,W,Z,γ
3 different ways to check this hypothesis !!!



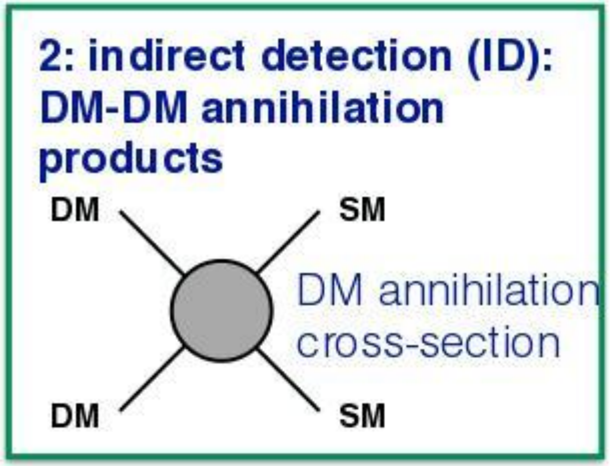
Underground searches (experiments: DAMA, Xenon etc

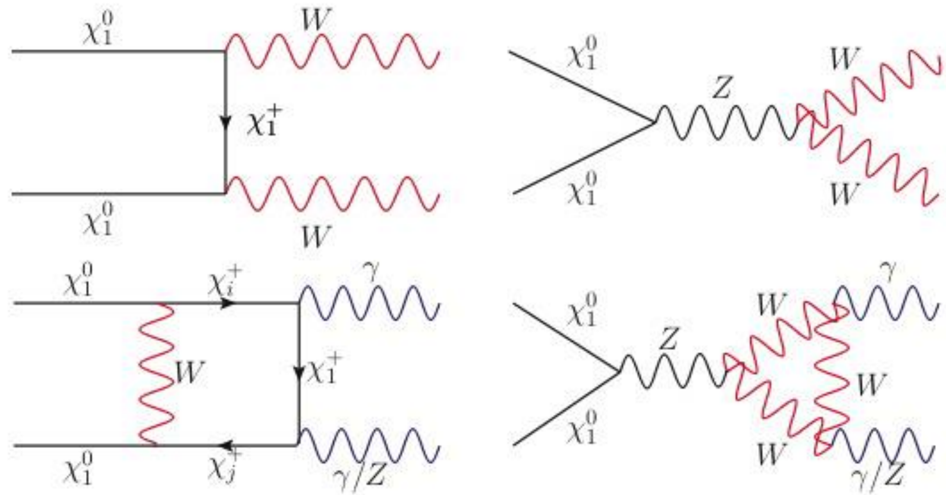


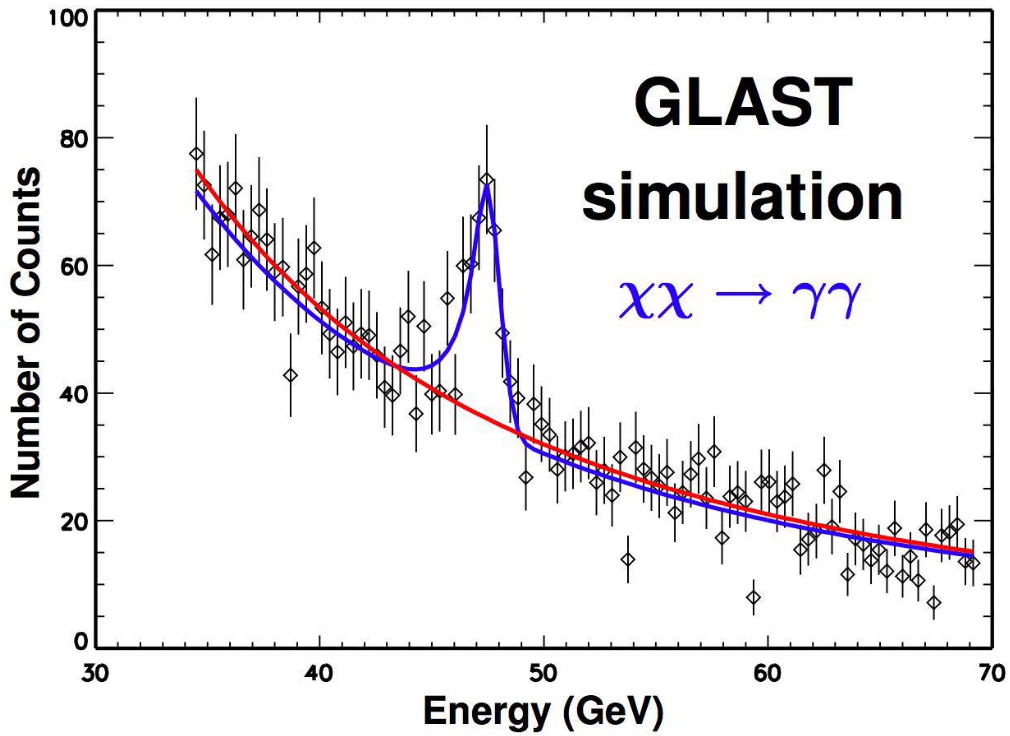
WIMP scatters off nuclei
Looking for annual modulation / DM ”wind”



Cross section depends on exchange particle:
Z exchange ruled out
Now looking for H exchange



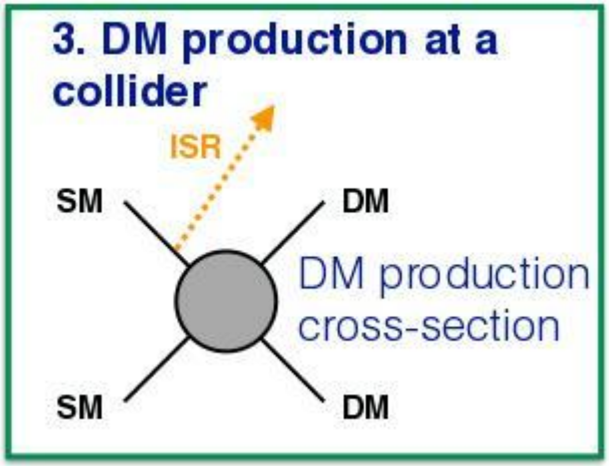




Look for annihilation signals!
Measure decay products

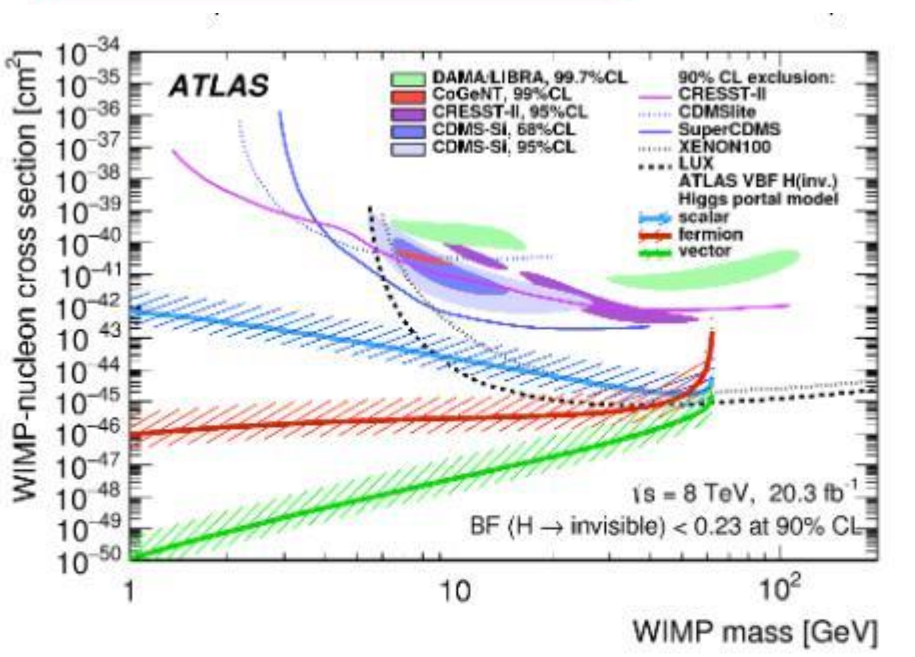
Experiments: FERMI, PAMELA, AMS etc

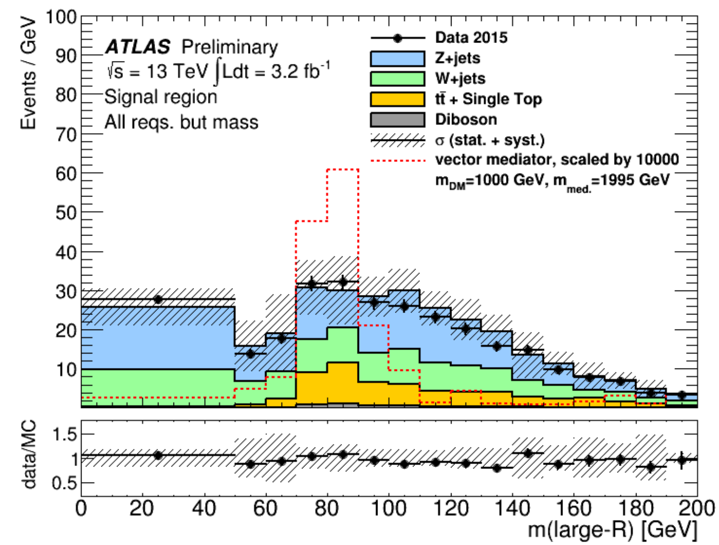
At the LHC



No Dark Matter interaction with the detector ⇒ signature is missing energy

Use initial state radiation (ISR) to detect it! (e.g jets, γ, W, Z, H)





Summary/outlook

- Many problems with current Standard model
- Many new models to take over

  Some important models not mentioned, for instance:
  - GUT models
  - Technicolor
  - Hidden valleys
- The LHC energy scale is tuned to be sensitive to many of these, complementary to other current searches
- Several potential signatures requires new ”objects”, ie lepton-jets, long-lived heavy particles, ”quirks” etc
- Several good ideas but Nature decides which (if any) are true!