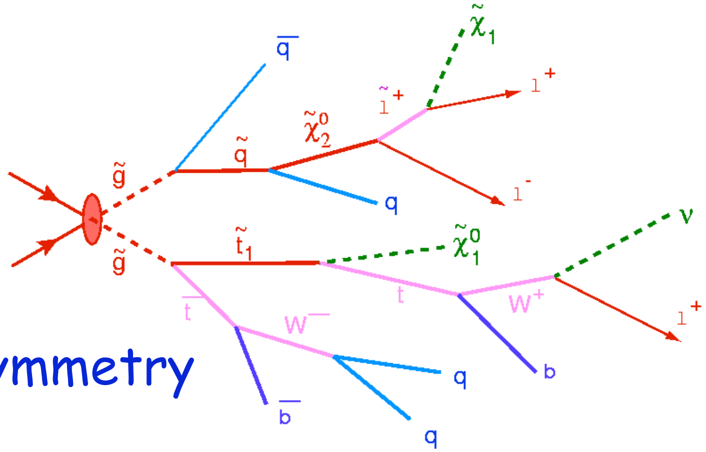
Physics at CMS & ATLAS
Physics Beyond the Standard Model

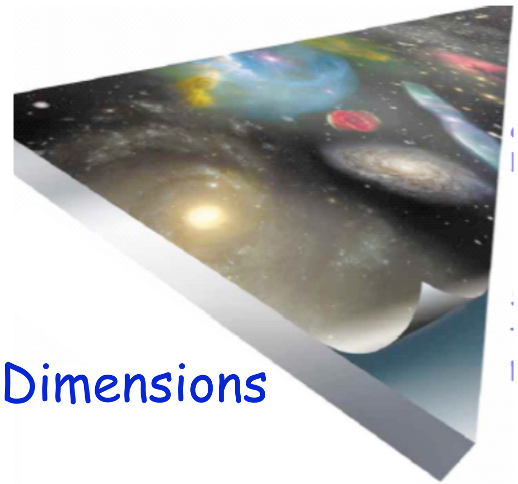
Albert De Roeck
CERN
and University of Antwerp
and the IPPP Durham

Supersymmetry



3 isolated leptons
+ 2 b-jets

Extra Dimensions



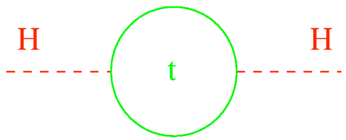
..and more

Why we believe the Standard Model is NOT the Ultimate Theory?

SM predictions confirmed by experiments (at LEP, Tevatron, SLAC, etc.) with precision $\approx 10^{-3}$ or better

So, what is wrong with it ?

- About 20 free parameters (masses of fermions and bosons, couplings
- Higgs: mass $m_H \approx 115$ GeV? Then New Physics for $\Lambda < 10^6$ GeV
- "Naturalness" problem :

  radiative corrections 

  $\delta m_H^2 \sim \Lambda^2$ $\Rightarrow$ diverge for large Λ
  $\Rightarrow$ fine tuning!!
- "Hierarchy" problem: why $M_{EW} / M_{Planck} \sim 10^{-17}$?

+ contribution of EW vacuum to cosmological constant ($\sim v^4$) is ~ 55 orders of magnitudes too large !

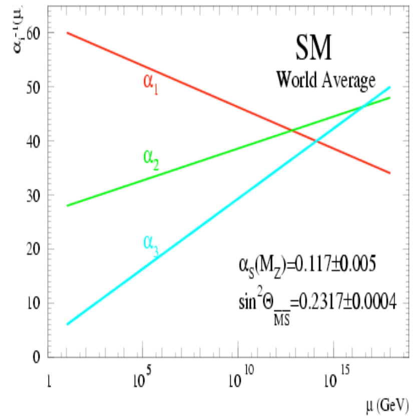
+ flavour/family problem, coupling unification, gravity incorporation, ν masses/oscillations, ... Dark Matter. Dark Energy?

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity. Dark Matter/Energy?
- no unification of the forces at high energy

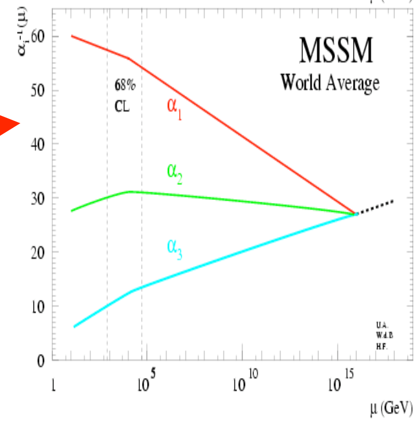


Most popular extensions these days

If a Higgs field exists:
- Supersymmetry
- Extra space dimensions

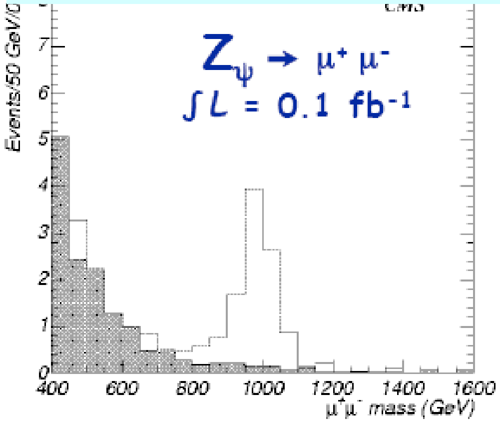
If there is no Higgs below ~ 700 GeV
- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models, Technicolor…

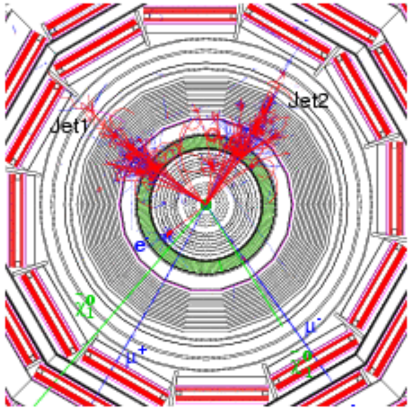


BSM Physics at the LHC: pp @ 10/14 TeV

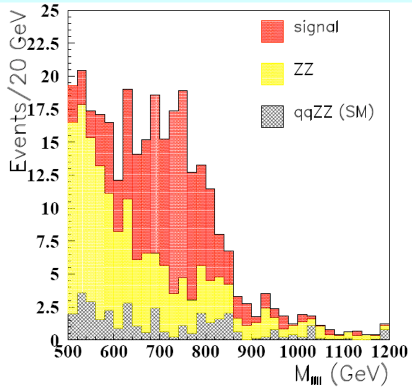
New Gauge Bosons?



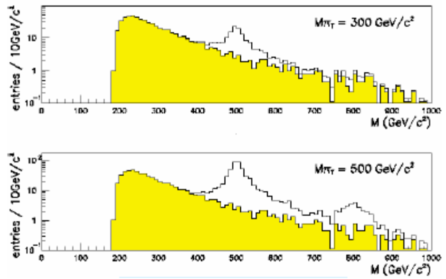
Supersymmetry



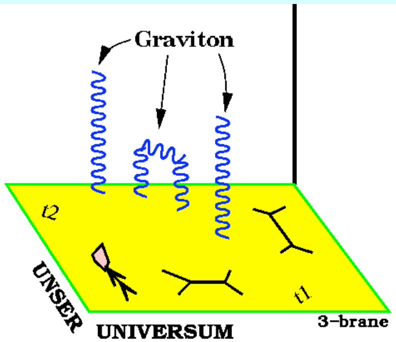
ZZ/WW resonances?



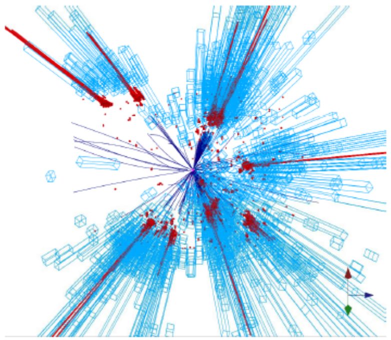
Technicolor?



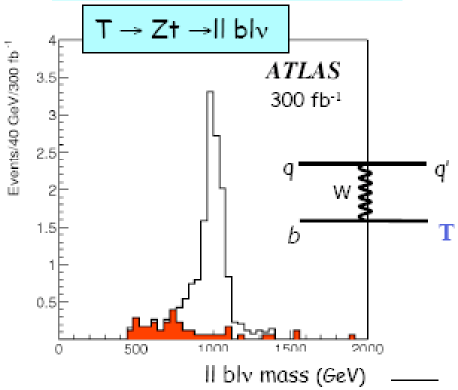
Extra Dimensions?



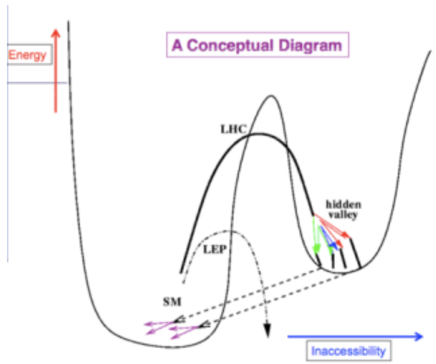
Black Holes???



Little Higgs?



Hidden Valleys?



We do not know what is out there for us…
A large variety of possible signals. We have to be ready for that

Experimental New Physics Signatures

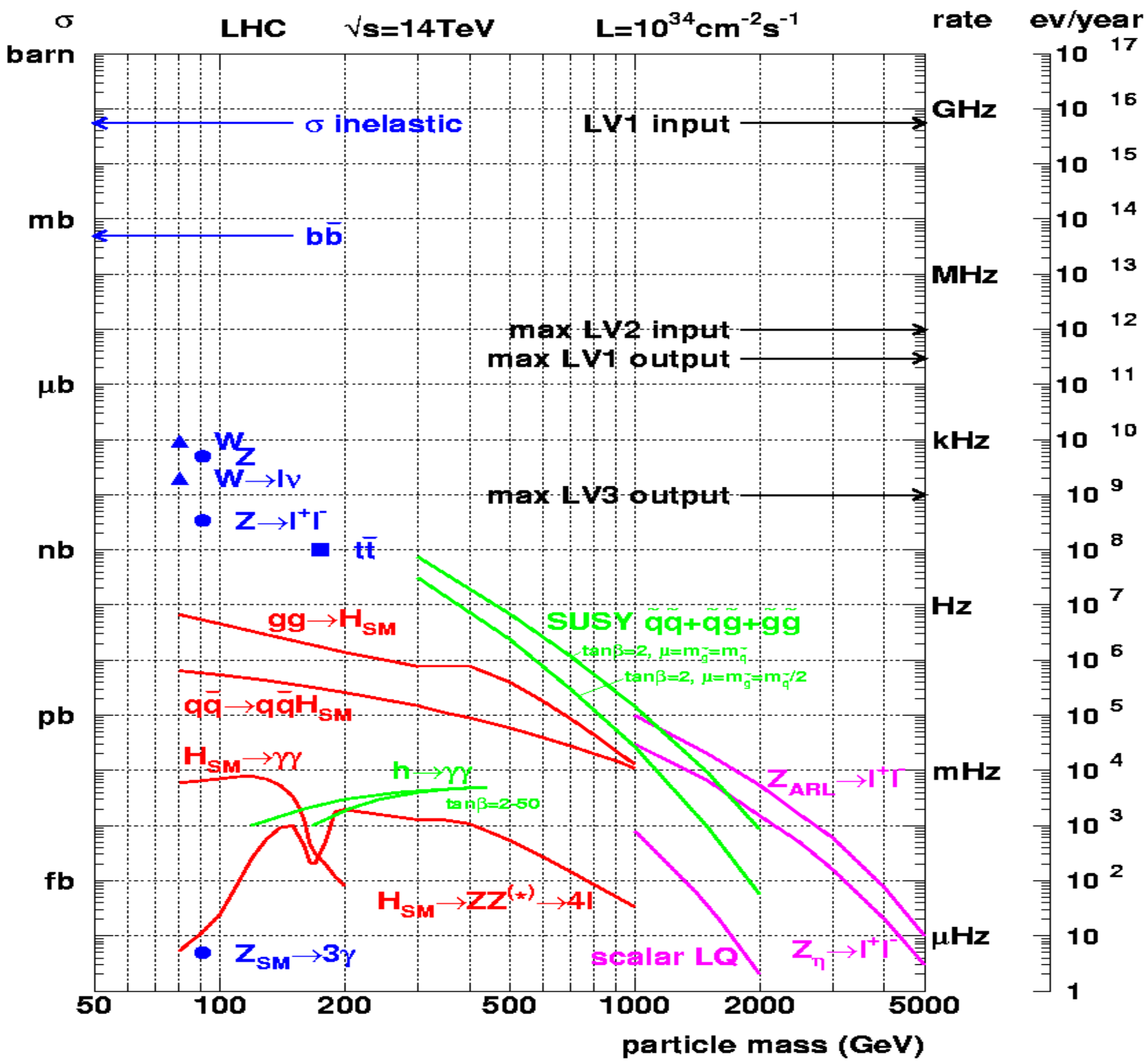
- Many channels in New Physics :Typical signals
  - Di-leptons   resonance/non-resonance, like sign/oposite sign
  - Leptons + MET (=Missing transverse momentum/energy)
  - Photons + MET
  - Multi-jets (2 → ~10)
  - Mono/Multi-jets +MET (few 10 → few 100 GeV)
  - Multi jets + leptons + MET…
  - B/τ final states…
- Also: new unusual signatures
  - Large displaced vertices
  - Heavy ionizing particles (heavy stable charged particles)
  - Non-pointing photons
  - Special showers in the calorimeters
  - Unexpected jet structures
  - Very short tracks (stubs)…

Progress over the last years

- Full simulation/Closer to the real experimental set-up
- Improved signal & backgrounds (More complex MCs, NLO (QCD/EW) corrections)
- Studies for first luminosities (10-100 pb^{-1})
- Studies for detectors with start-up conditions (energy calibration, misalignment of the detectors)
- Special attention to the trigger
- Data driven methods to estimate backgrounds for discoveries.
- In a few cases, real in situ background estimates (cosmics, beam halo)

Sources: CMS Physics TDR Vol II, J. Phys. G34 (2007) 995 + updates
ATLAS CERN-OPEN-2008-20 (December 2008) + updates

Cross Sections at the LHC

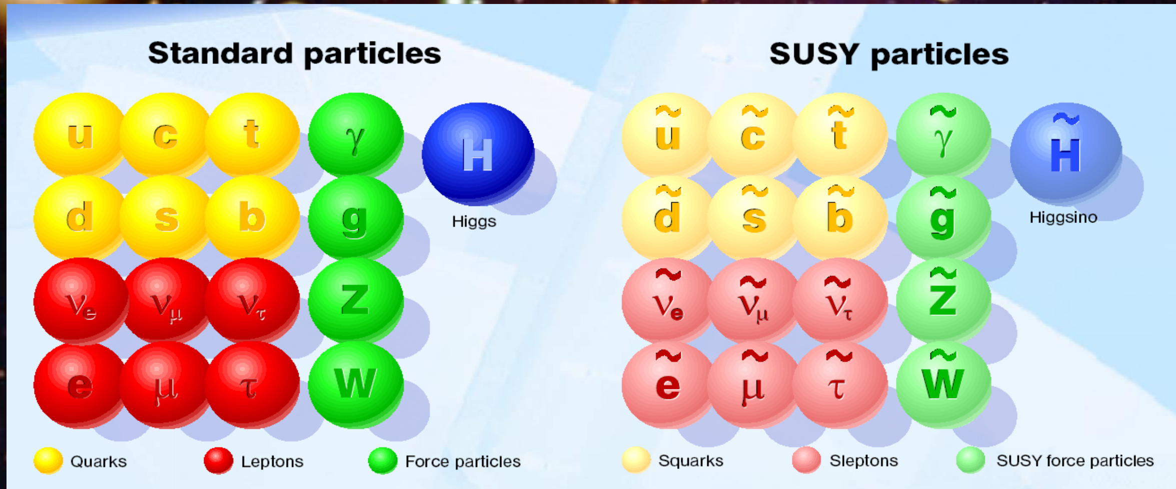


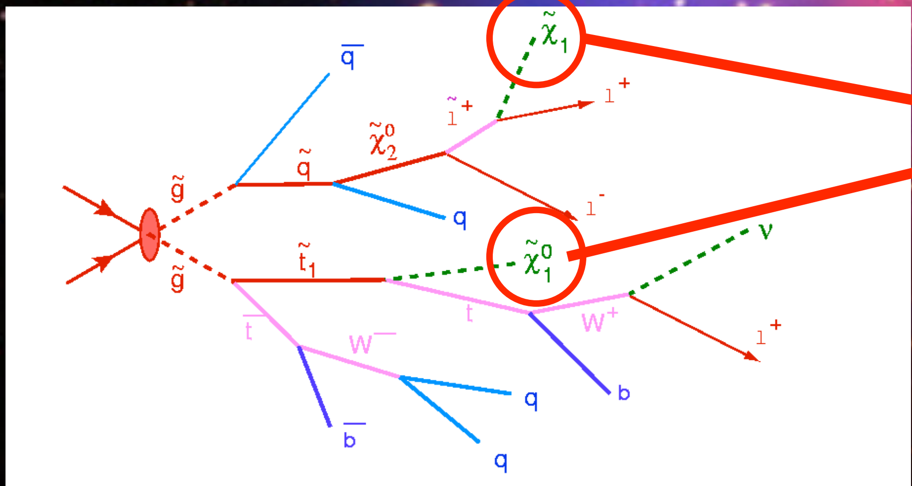
"Well known" processes, don't need to keep all of them …

New Physics!!

This we want to keep!!

Supersymmetry: a new symmetry in Nature





Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

SUSY particle production at the LHC

+ 2 b-jets
+ 4 jets

Why weak-scale SUSY ?

- stabilises the EW scale: $|m_F - m_B| < O(1\text{ TeV})$
- predicts a light Higgs $m_h < 130$ GeV
- predicts gauge unification
- accomodates heavy top quark
- dark matter candidate: neutralino, sneutrino, gravitino, ...
- consistent with Electro-Weak precision data

Discovering SUSY – A revolution in particle physics!!

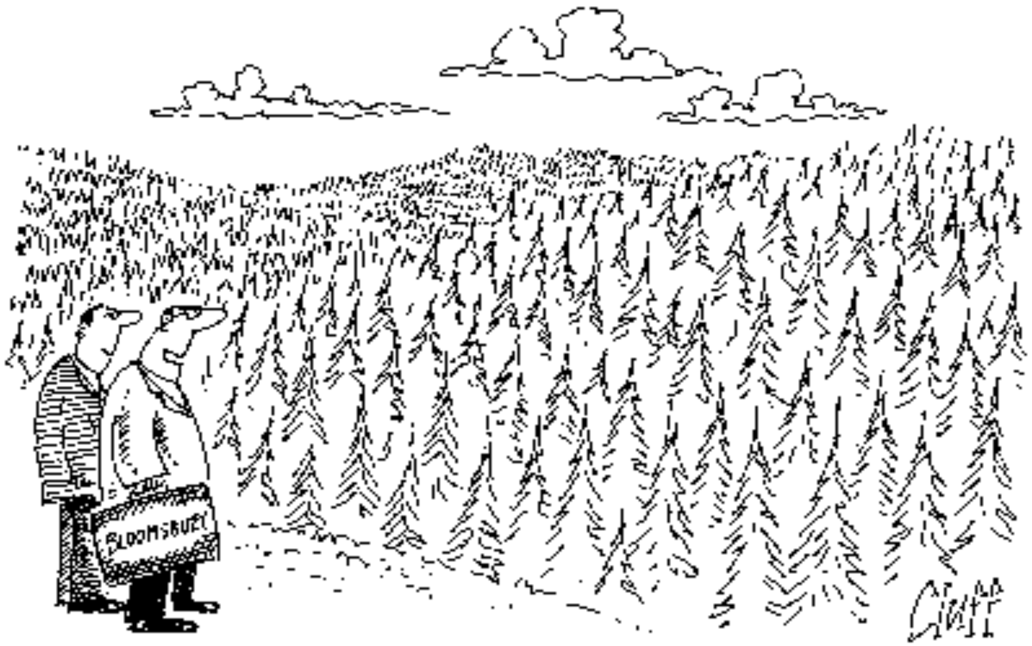
- the outcome of LHC is far more important than any other in the past
- all future projects: ILC, superB, super..., depend on LHC discoveries
- huge responsibility to provide quick and reliable answers

J. Kalinowski, Krakow '06

Supersymmetry

A VERY popular benchmark…

More than 8000 papers since 1990 (Kosower)



"One day all these trees will be SUSY phenomenology papers"

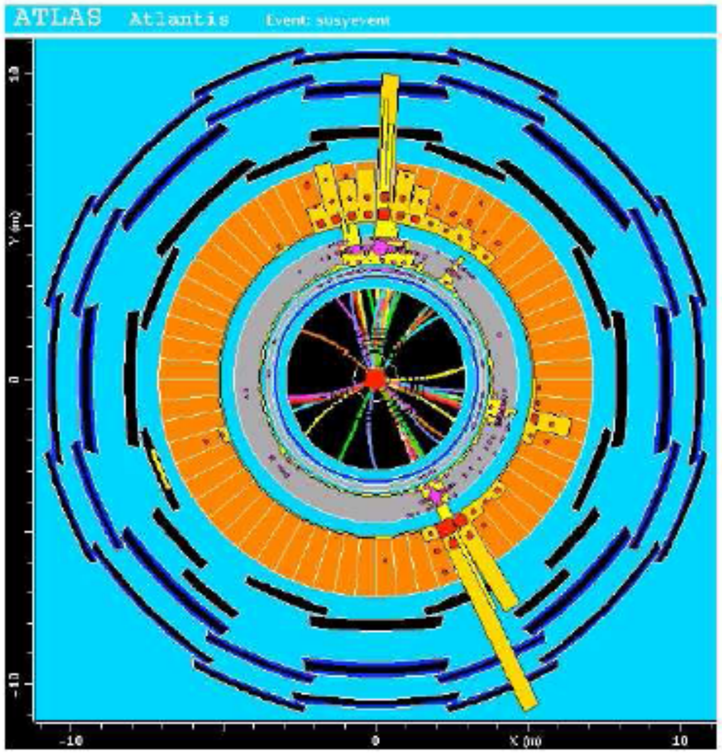
Considered as a benchmark for a large class of new physics models

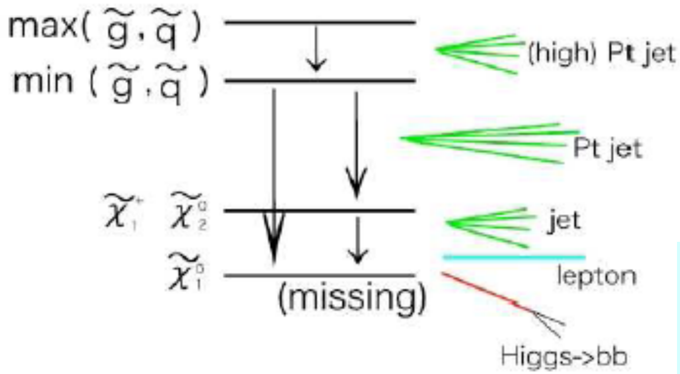
Early Supersymmetry?

SUSY could be at the rendez-vous very early on!

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

10fb^{-1}





event topologies of SUSY

multi leptons

$\not{E}_T$ + High P_T jets + b-jets

τ-jets

For low mass SUSY we get O(10,000) events/year even at startup

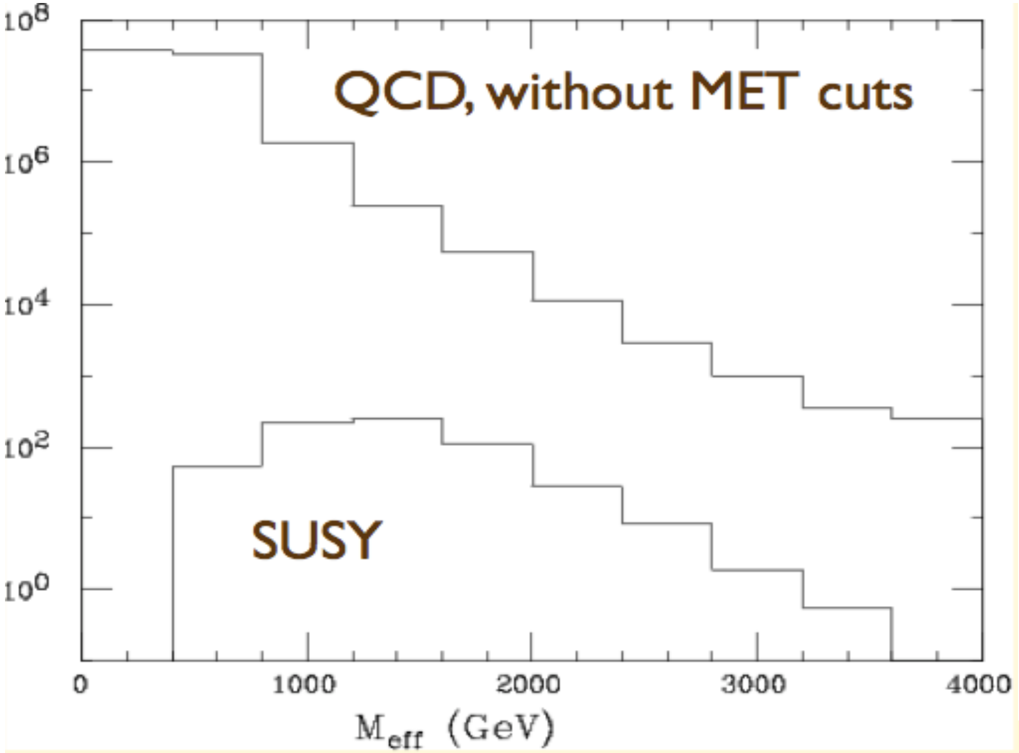
Main signal: lots of activity (jets, leptons, taus, missing E_T)

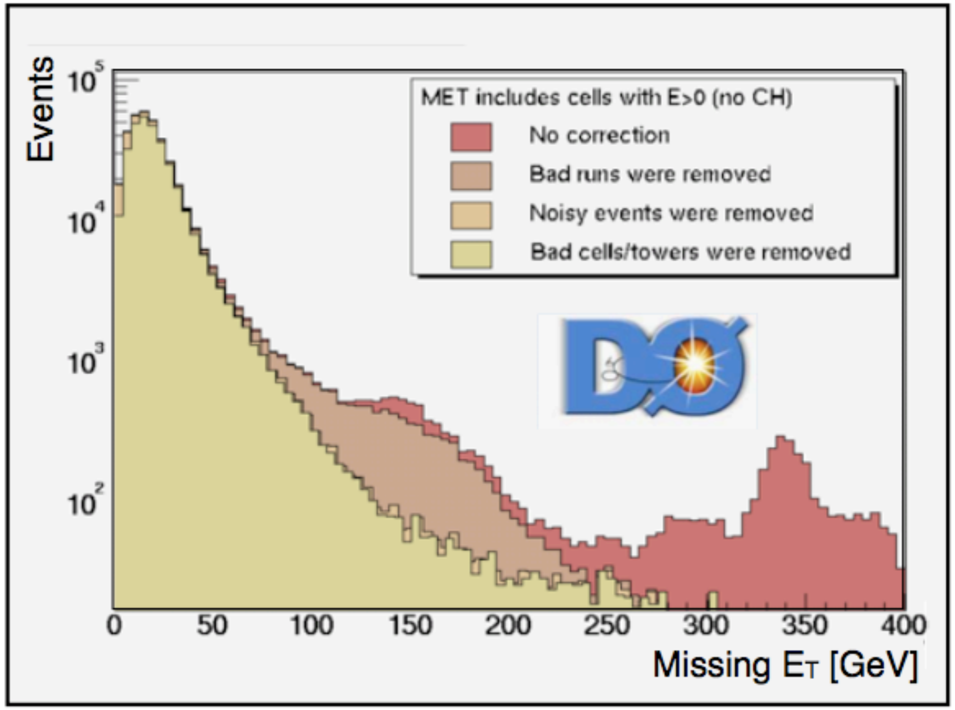
Needs an excellent understanding of the detector and SM backgrounds

Note: establishing that the new signal is SUSY will be more difficult!

Missing Transverse Energy

A difficult quantity to measure!

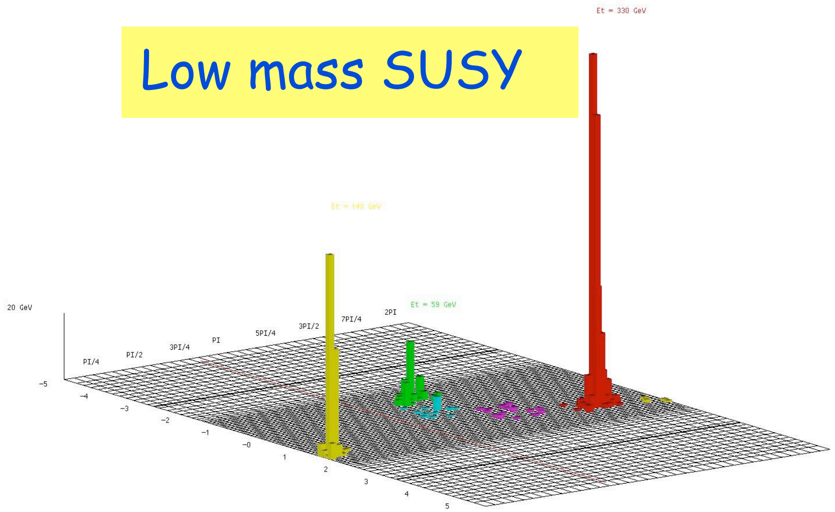


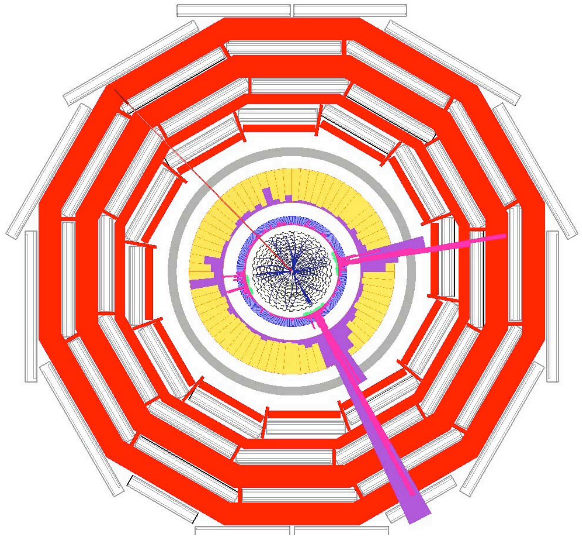


Tevatron experience!
Clean up cuts: cosmics, beam halo, dead channels, QCD background

Hunting for SUSY @ LHC

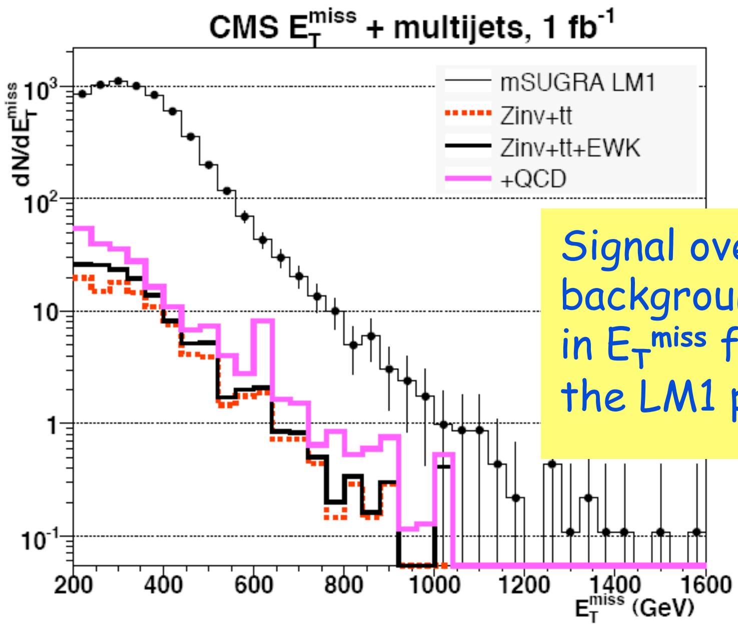
Low mass SUSY



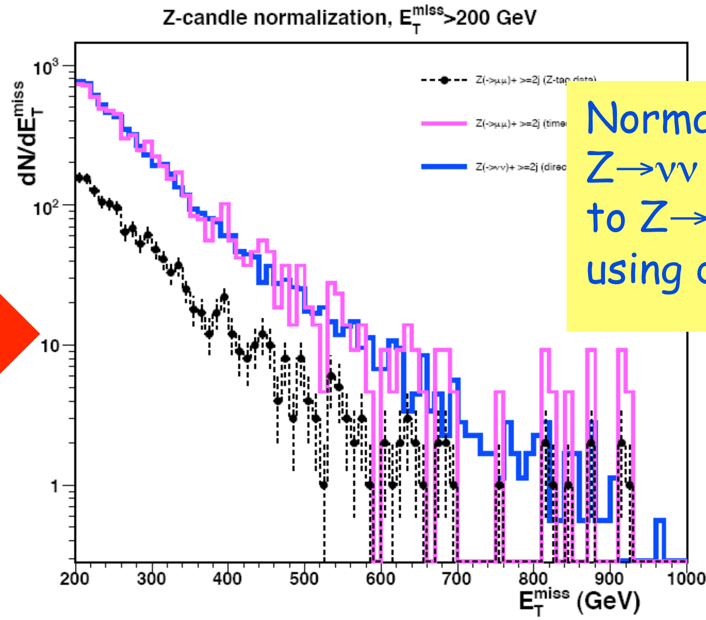


Missing E_T is a difficult measurement for the experiments

CMS PTDR

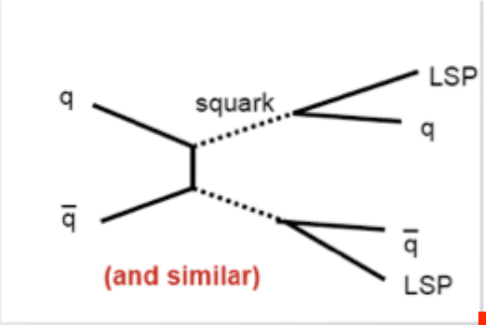


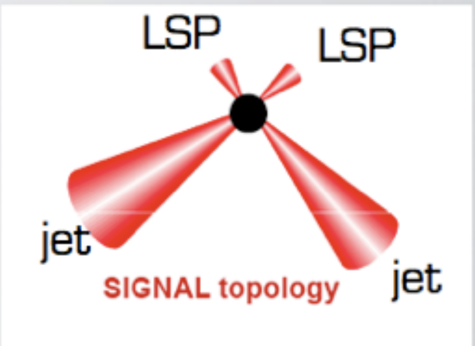
Signal over background in E_T^{miss} for the LM1 point



Normalizing $Z\to\nu\nu$ E_T^{miss} to $Z\to\mu\mu$ using data

New Data Driven Methods for Backgrounds

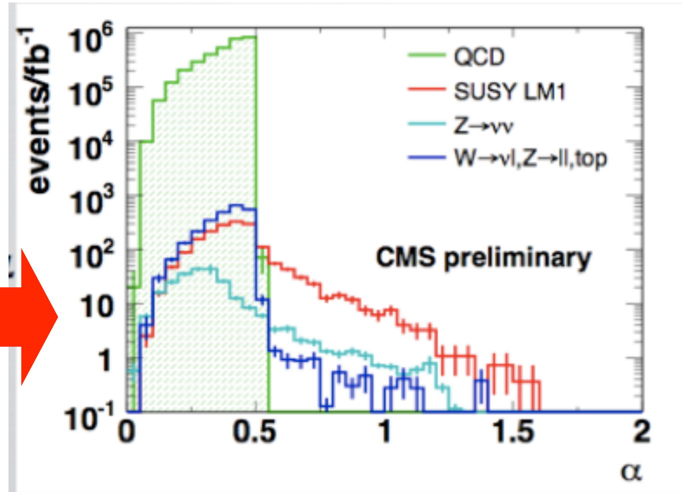




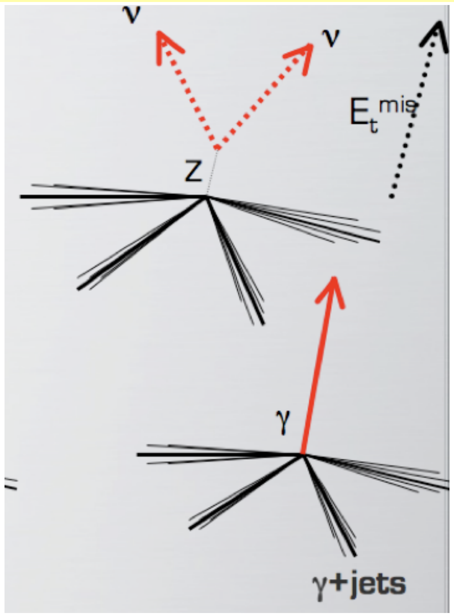
Use kinematics

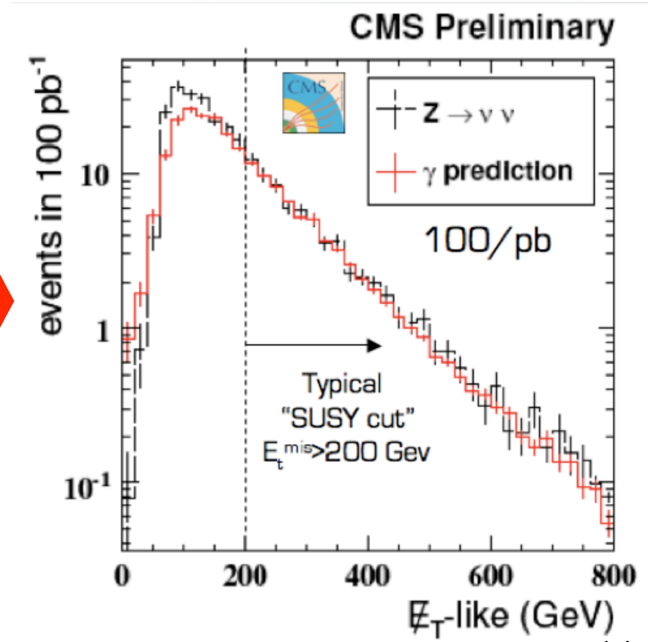
$$\alpha = \frac{E_{T\,j2}}{M_{j1\,j2}} = \frac{E_{T\,j2}}{\sqrt{2E_1E_2(1-\cos\theta)}}$$

- Can be at most 0.5 for QCD, $\alpha < 0.5$
- $\alpha > 0.5$ implies missing momentum

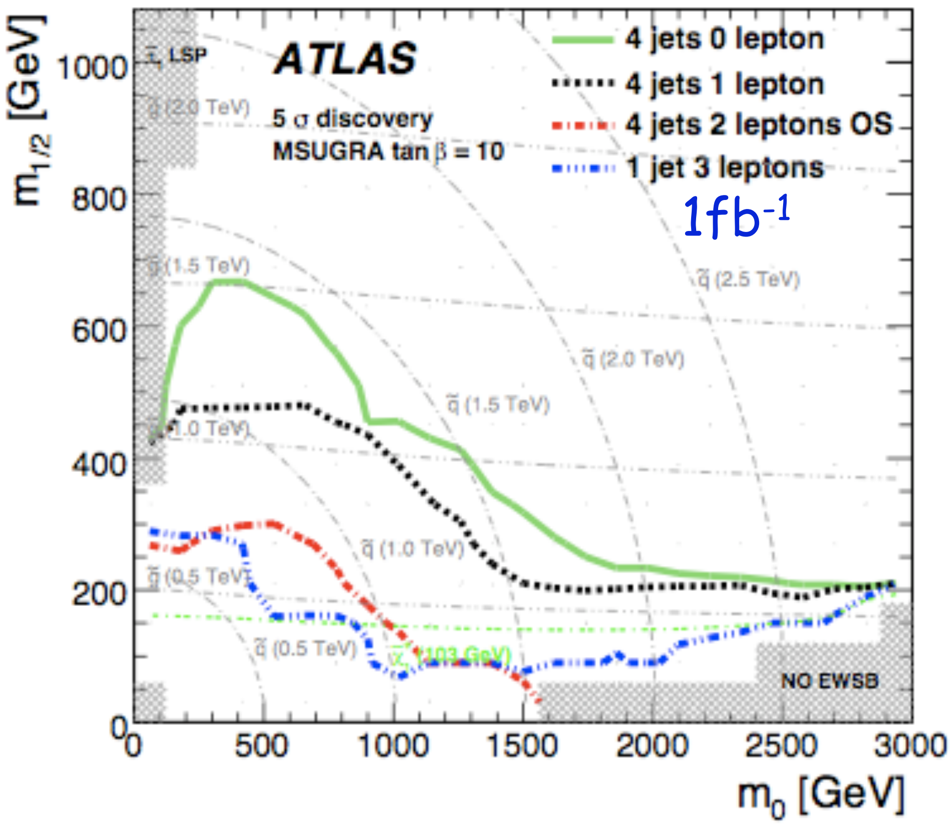


Use photon+jets





Early SUSY Reach



minimal Supergravity (mSUGRA)

$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
$\tan\beta$: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

Low mass SUSY(m_{gluino}~500 GeV) will show an excess for O(100) pb^{-1}

⇒ Time for discovery will be determined by:

- Time needed to understand the detector performance, Etmiss tails,
- Time needed collect SM control samples such as W+jets, Z+jets, top..

Where do we expect SUSY?

O. Buchmuller et al
arXiv:0808.4128

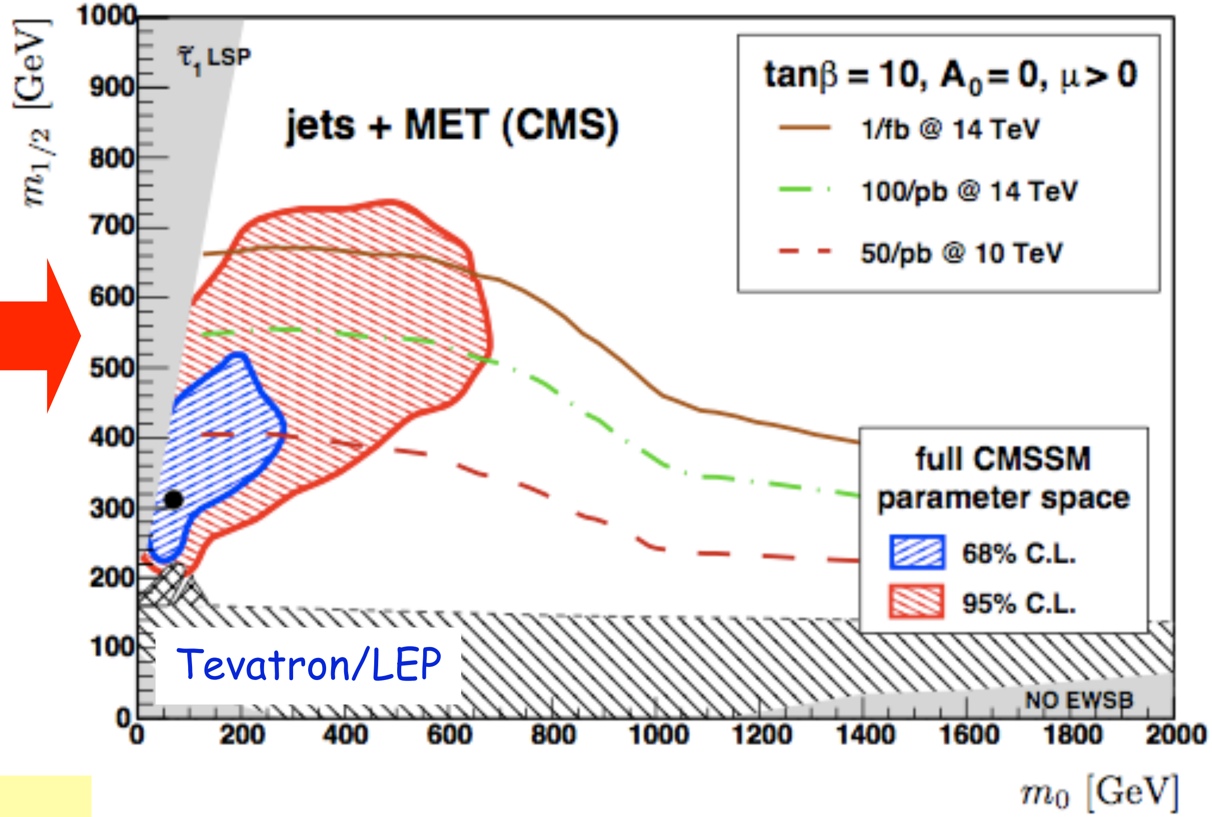
OB, R.Cavanaugh, A.De Roeck,
J.R.Ellis, H.~Flaecher, S.~Heineme
G.Isidor, K.A.Olive, P.Paradisi,
F.J.Ronga, G.Weiglein

Precision measurements
Heavy flavour observables

Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, tan (μ>0) to more than 30 collide and cosmology data (e.g. M_W, M_{top}, g-2, BR(B→Xγ), relic density)

"Predict" on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)

"LHC Weather Forecast"

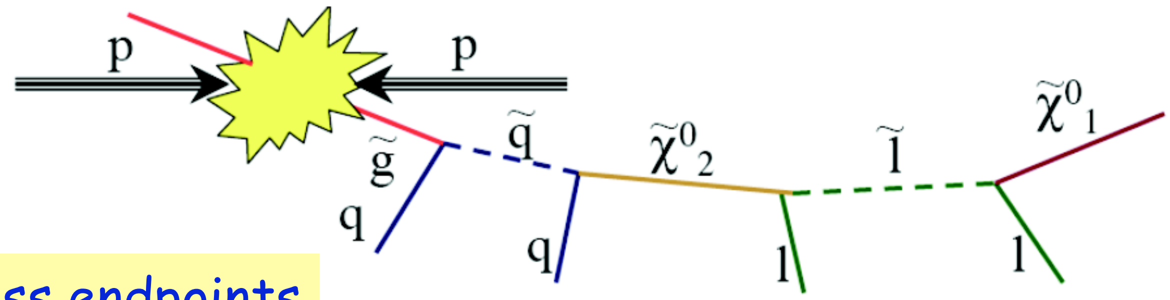


"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

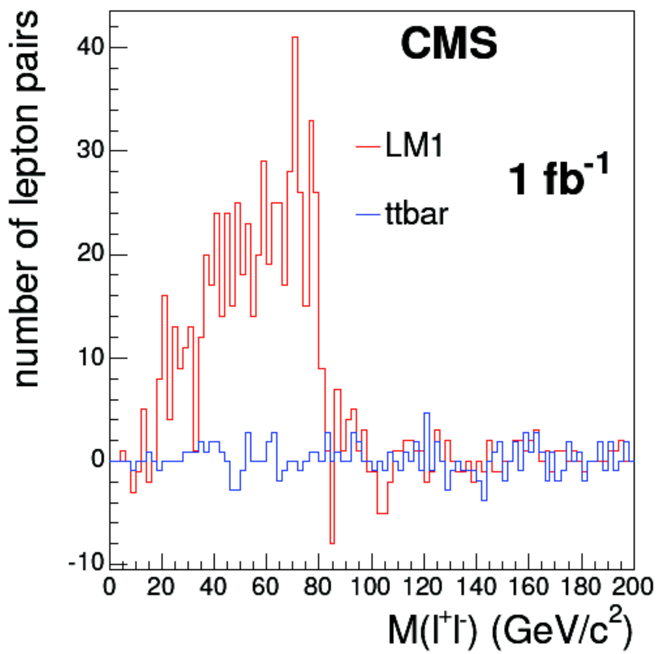
Many other groups attempt
to make similar predictions
See eg R. Trotta tonight

Sparticle Mass Reconstruction

First Mass Clues (dileptons)



Invariant mass endpoints

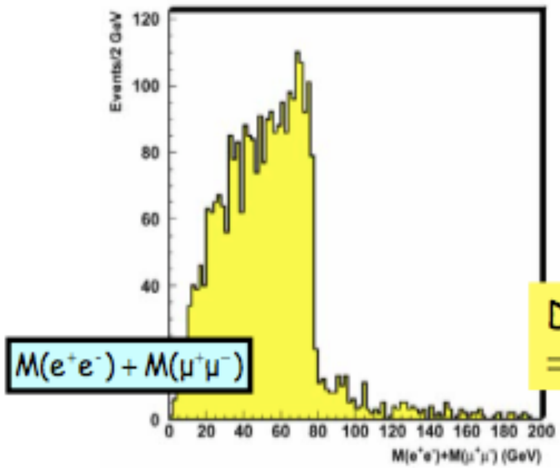


- $M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0)\sqrt{1 - \frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$
- $M_{\ell\ell}^{max}$(meas)= 80.42 ± 0.48 GeV/c^2, *cfr* with
- expected $M_{\ell\ell}^{max}$= 81 GeV/c^2 [given $M(\tilde{\chi}_1^0)$ = 95, $M(\tilde{\chi}_2^0)$= 180 and $M(\tilde{\ell}_R)$ = 119 GeV/c^2]

Sparticle Detection & Reconstruction

Mass precision for a favorable benchmark point at the LHC
LCC1~ SPS1a~ point B' with 100 fb^{-1}

m_0=100 GeV
$m_{1/2}$= 250 GeV
A_0=-100
$\tan\beta$ = 10
sign(μ)=+

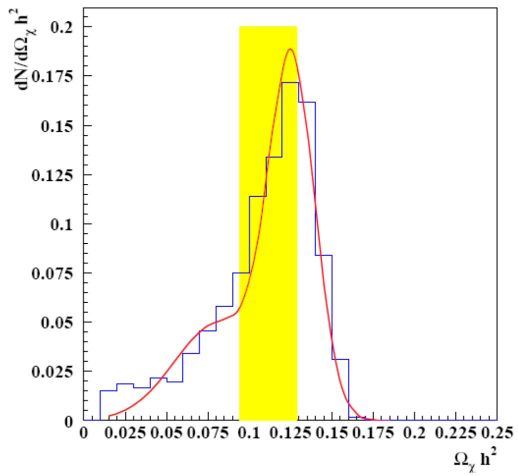


D. Miller et al
⇒Use shapes

hep-ph/0508198

GeV	LHC
$\Delta m_{\tilde\chi^0_1}$	4.8
$\Delta m_{\tilde\chi^0_2}$	4.7
$\Delta m_{\tilde\chi^0_4}$	5.1
$\Delta m_{\tilde l_R}$	4.8
$\Delta m_{\tilde\ell_L}$	5.0
Δm_{τ_1}	5-8
$\Delta m_{\tilde q L}$	8.7
$\Delta m_{\tilde q R}$	7-12
$\Delta m_{\tilde b_1}$	7.5
$\Delta m_{\tilde b_2}$	7.9
$\Delta m_{\tilde g}$	8.0

Lightest neutralino → Dark Matter?
Fit SUSY model parameters to the measured SUSY particle masses to extract $\Omega\chi h^2$ ⇒ O(10%) for LCC1



SUSY Program for an Experimentalist

- Understand the detector and the Standard Model Backgrounds
- Establish an excess ⇒ Discover a signal compatible with supersymmetry
- Measure sparticle masses/ mass differences
- Measure sparticle production cross sections, branching ratios, couplings
- Look for more difficult sparticle signatures hidden in the data
- Is it really SUSY? Check eg. the spin of the new particles. Compatible with present/future data on precision measurements (LHCb, B-fact…)
- Turn the pole mass measurements into MSSM Lagrangian parameters of the model
- Map the measurements to the SUSY space to select possible underlying theory at the high scale and SUSY breaking mechanism (Eg. Nature May06, "theorists try to guess what the theory is from pseudo-data")

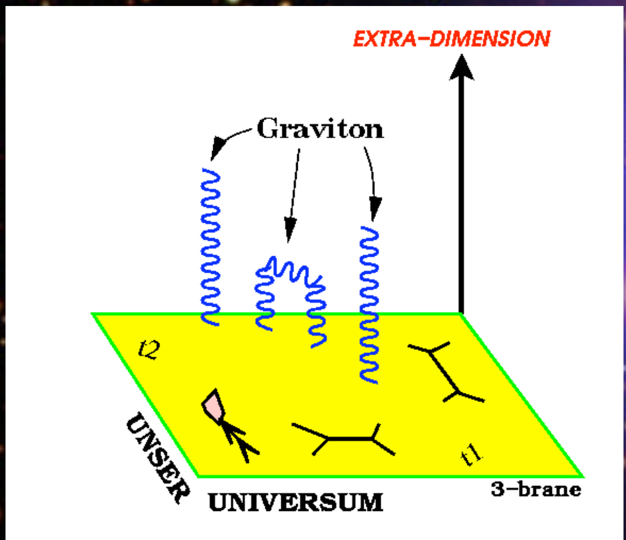
Even for an early discovery it will take years to complete such a program

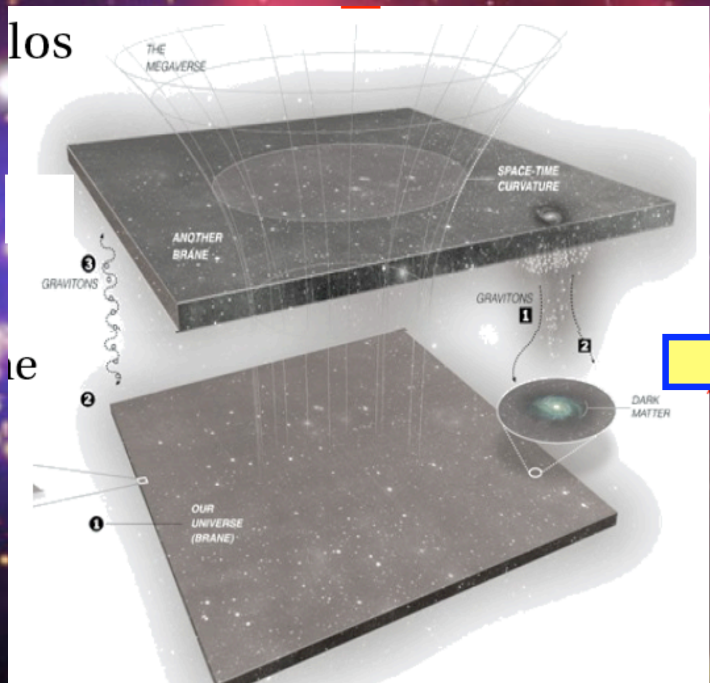
Extra Space Dimensions

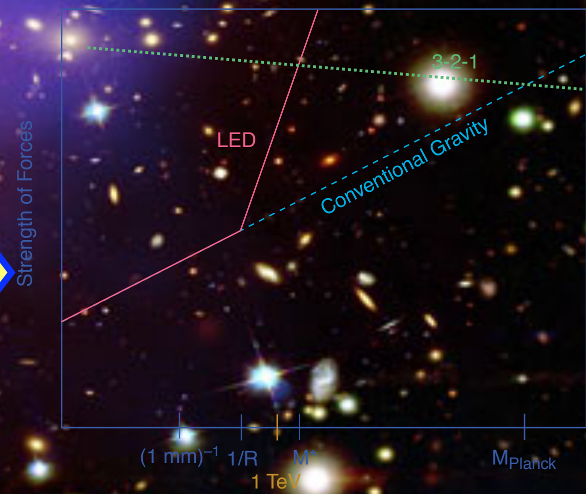
Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$







The Gravity force becomes strong!

Models with Extra Dimensions

Large Extra Dimensions

Planck scale (M_D) ~ TeV

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk

KK-towers (small spacing); KK-exchange; graviton prod.

Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

Warped Extra Dimensions

5-dimensional spacetime with warped geometry

Graviton KK-modes (large spacing); graviton resonances

Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions

look-like SUSY

SM particles allowed to propagate in ED of size TeV^{-1}

[scenarios: gauge fields only (nUED) or all SM particles (UED)]

nUED : KK excitations of gauge bosons

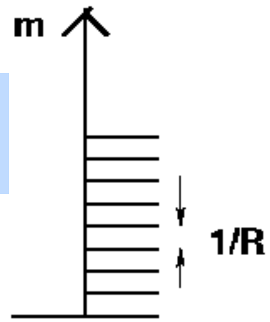
UED : KK number conservation; KK states pair produced (at tree-level) ...

Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

Large Extra Dimension Signatures at LHC

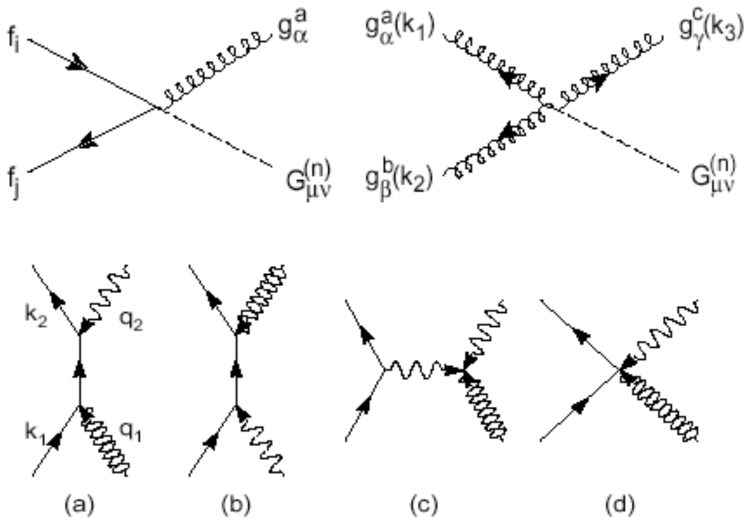
Particles in compact extra dimensions (2πR)
⇒ Towers of momentum eigenstates
Eg. graviton excitations (Δm=400 eV for δ =3)

$$\Delta m_{G_{KK}} \sim \frac{1}{R}$$



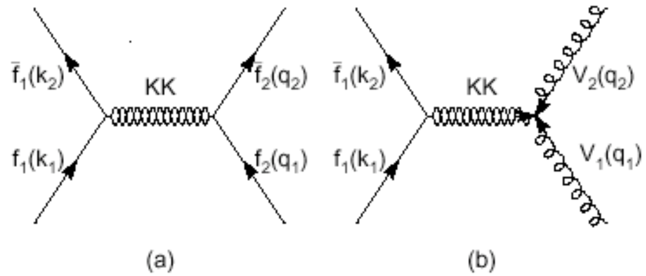
⇒ Strong increase of graviton exchange at high energies

Direct Graviton Emission



- Jets + Missing E_T
- Photon + Missing E_T

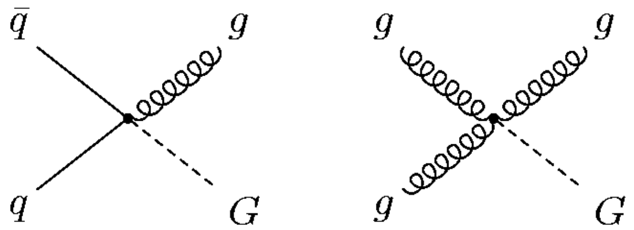
Virtual Graviton Exchange



- Dileptons
- Diphotons

Large Extra Dimension signals at the LHC

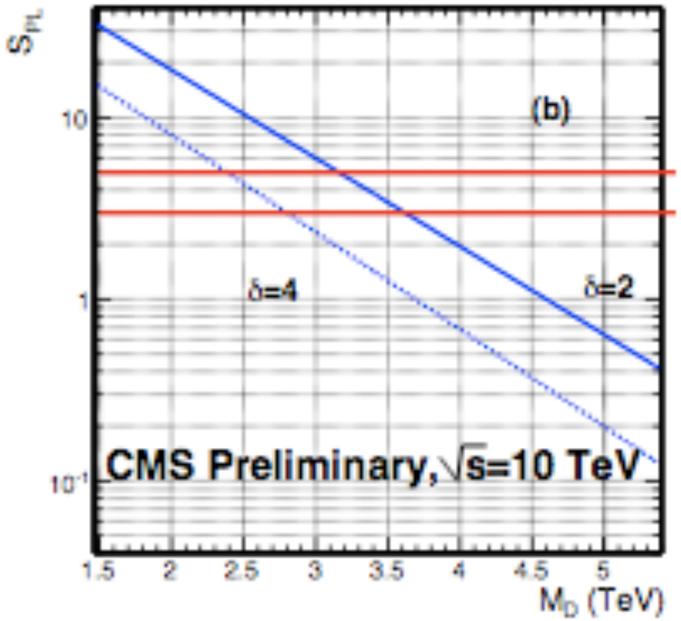
ADD: Arkani –Hamed, Dimopolous,Dvali

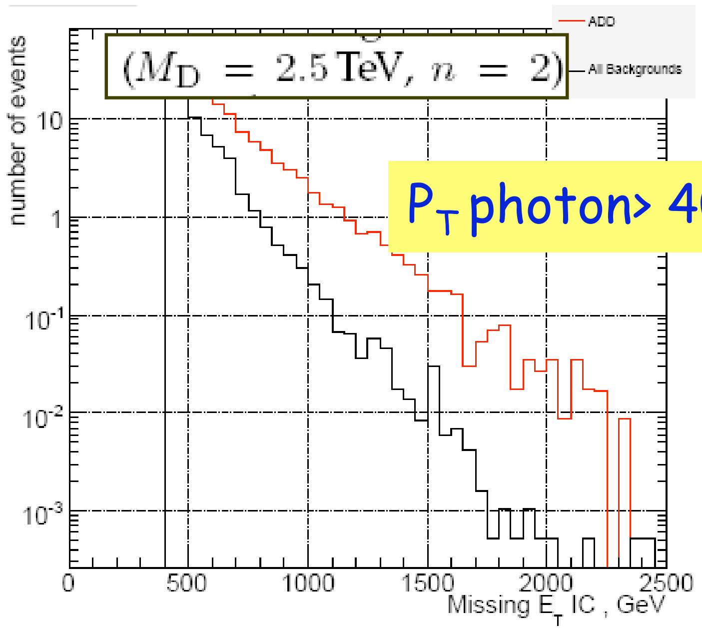


Graviton production!
Graviton escapes detection

Signal: single jet + large missing ET

Signal: single photon + large missing ET





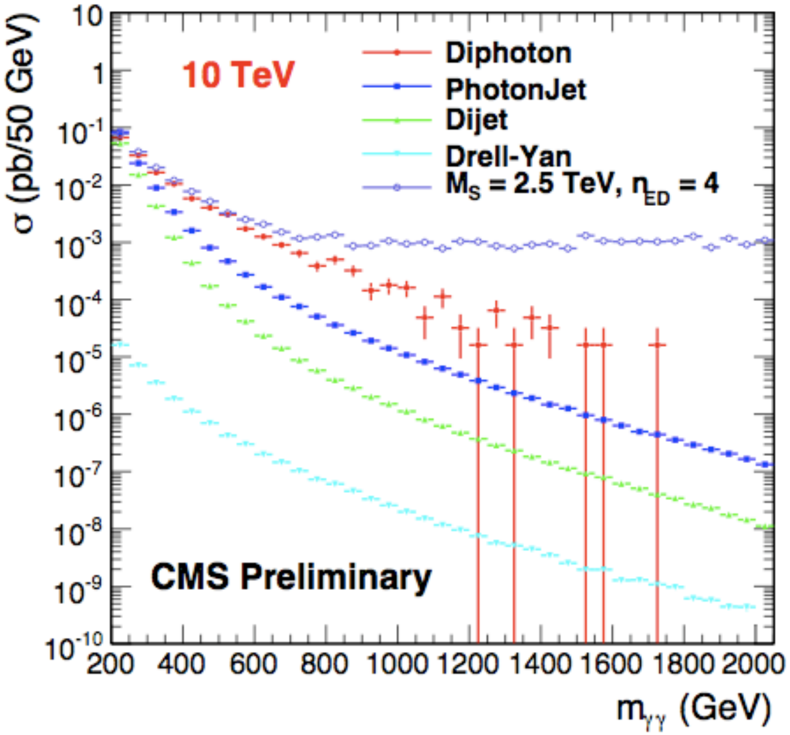
$30 fb^{-1}$

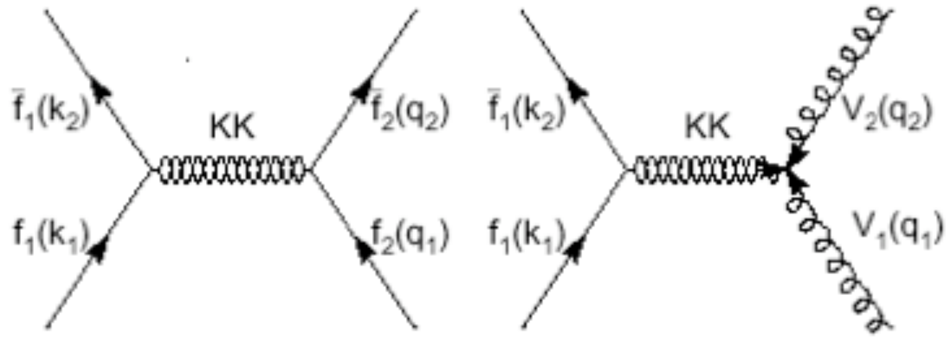
P_T photon> 400 GeV

Test M_D to 2.5-3 TeV for 100 pb^{-1}
Test M_D to 7-9 TeV for 100 fb^{-1}

Test M_D to ~ 2 TeV for O(300) pb^{-1}
Test M_D to ~ 4 TeV for 100 fb^{-1}

Large Extra Dimensions: Diphotons





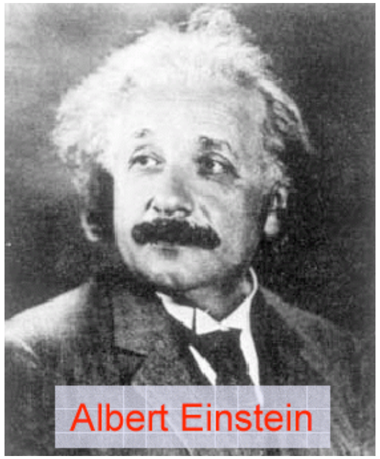
n_{ED}	95% CL Limit on M_S		
	50 pb^{-1}	100 pb^{-1}	200 pb^{-1}
2	2.5 TeV	2.7 TeV	2.9 TeV
3	3.0 TeV	3.3 TeV	3.5 TeV
4	2.6 TeV	2.8 TeV	3.0 TeV
5	2.3 TeV	2.5 TeV	2.7 TeV
6	2.1 TeV	2.3 TeV	2.5 TeV
7	2.0 TeV	2.2 TeV	2.4 TeV

100 pb^{-1} ⇒ exclude M_S in range of 2.2-3.3 TeV

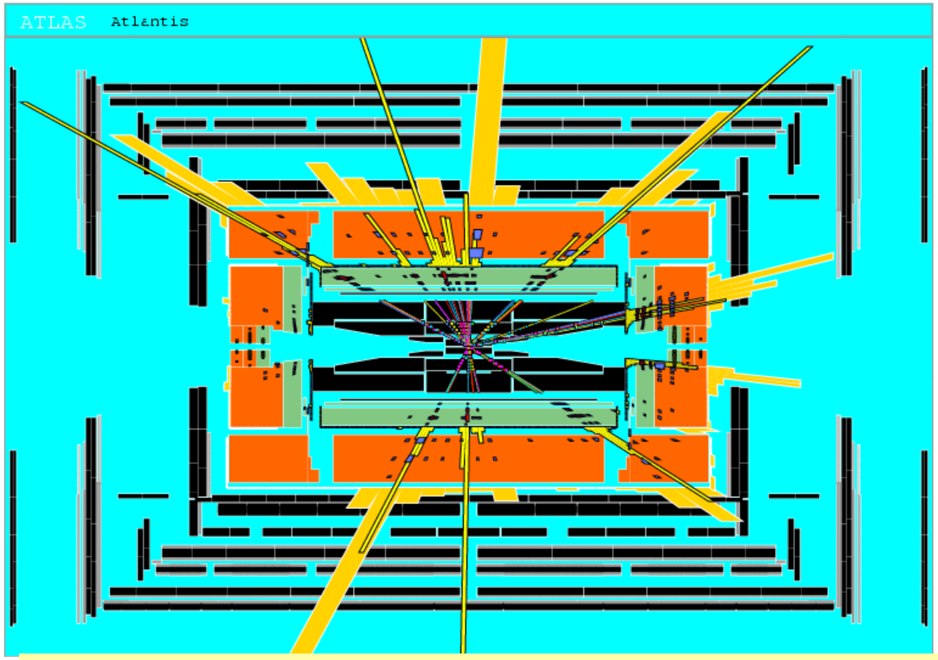
Probe M_S = 2-2.5 TeV with O(100) pb^{-1}

Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein's general theory on relativity



If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production



Simulation of a Quantum Black Hole event

Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

Quantum Back Holes

- Schwarzschild radius

Landsberg, Dimopoulos
Giddings, Thomas, Rizzo…

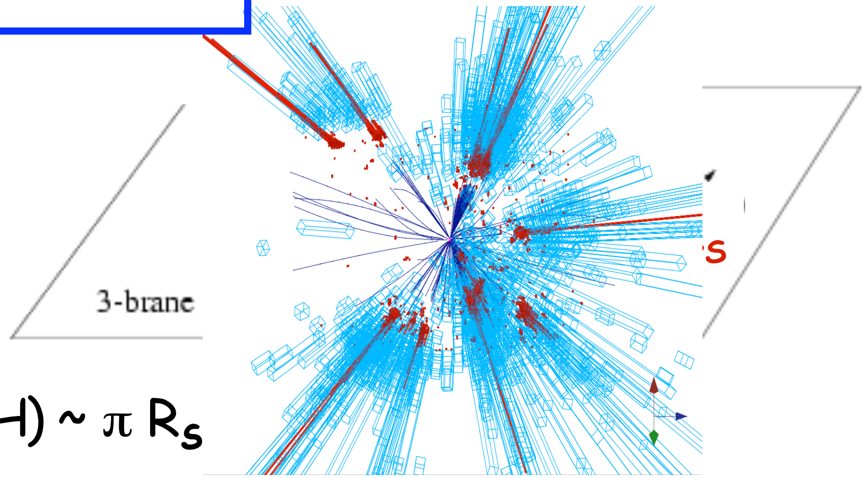
4-dim., $M_{gravity} = M_{Planck}$ (:10^{19}GeV)

$R_s \to \ll 10^{-35}$ m

4 + n-dim., $M_{gravity} = M_D \sim$ TeV

$R_s \to \sim 10^{-19}$ m

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S



- Large partonic cross-section : $\sigma(ij \to BH) \sim \pi R_S$
- $\sigma(pp \to BH)$ is in the range of 1 nb – 1 fb

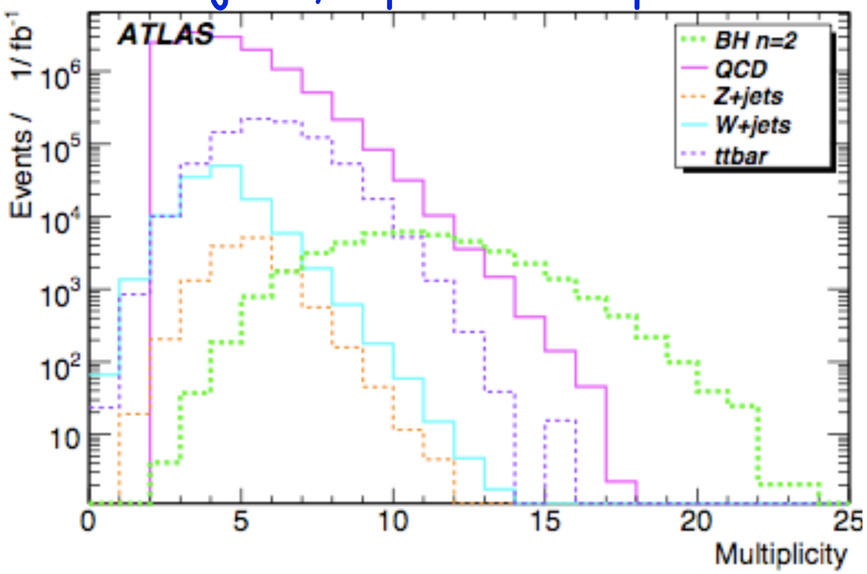
e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

- Black holes decay immediately by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

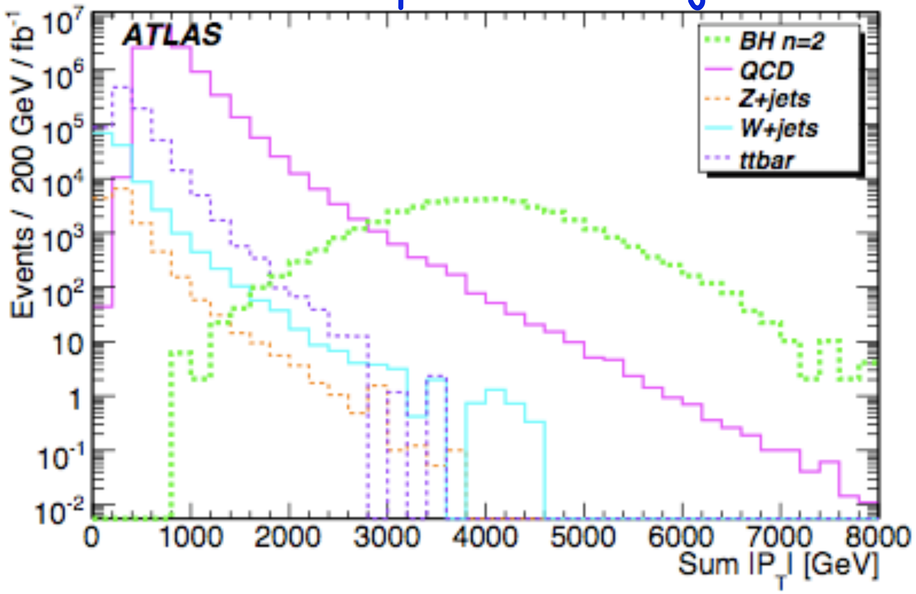
expected signature (quite spectacular …)

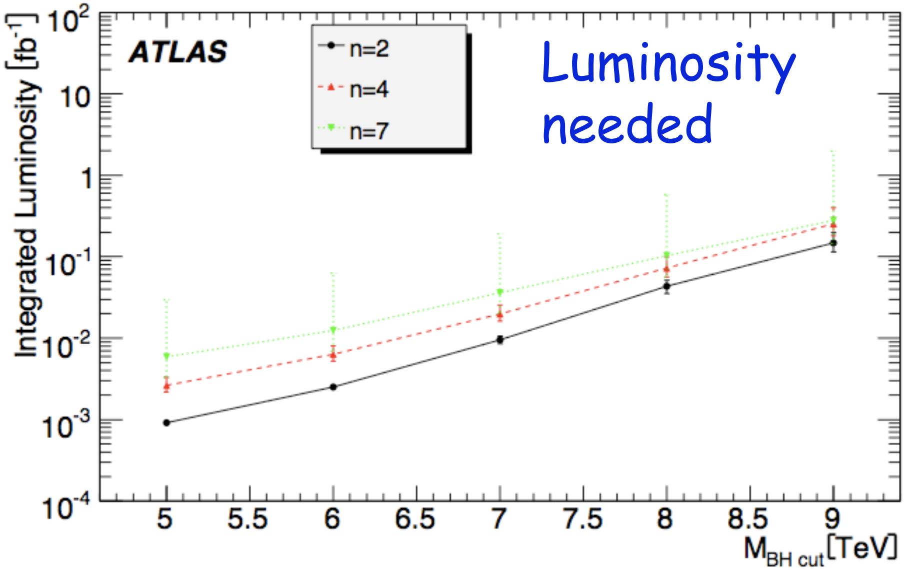
Black Hole Studies

of jets, leptons and photons



Sum of all pt of the objects





Luminosity needed

Already possible to discover with 1 pb^{-1}!!!

However cross sections largely unknown (and challenged)

Black Holes Hunters at the LHC…

Extra Dimensions: String Balls?

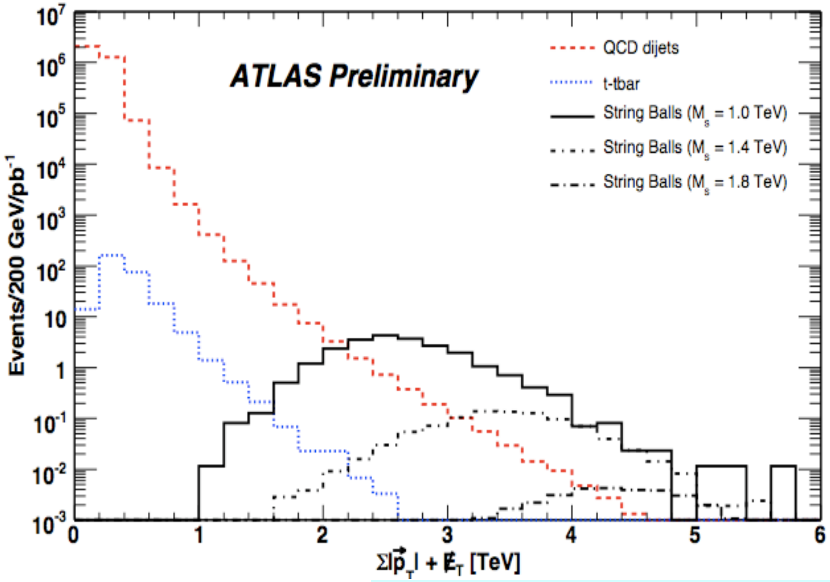
Black Holes: general relativity description only for $M_{BH} >> M_D$, eg $5 \bullet M_D$
Weakly-coupled coupled string theory→excited string states?

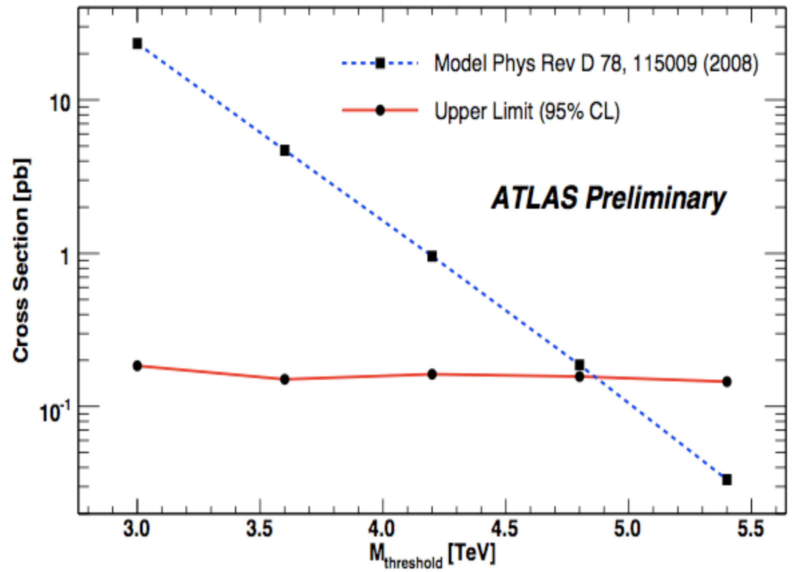
Dimopoulos et al, Ginrich et al.

$$M_s < M_D < \frac{M_s}{g_s^2}$$

Thermal radiation of jets + leptons

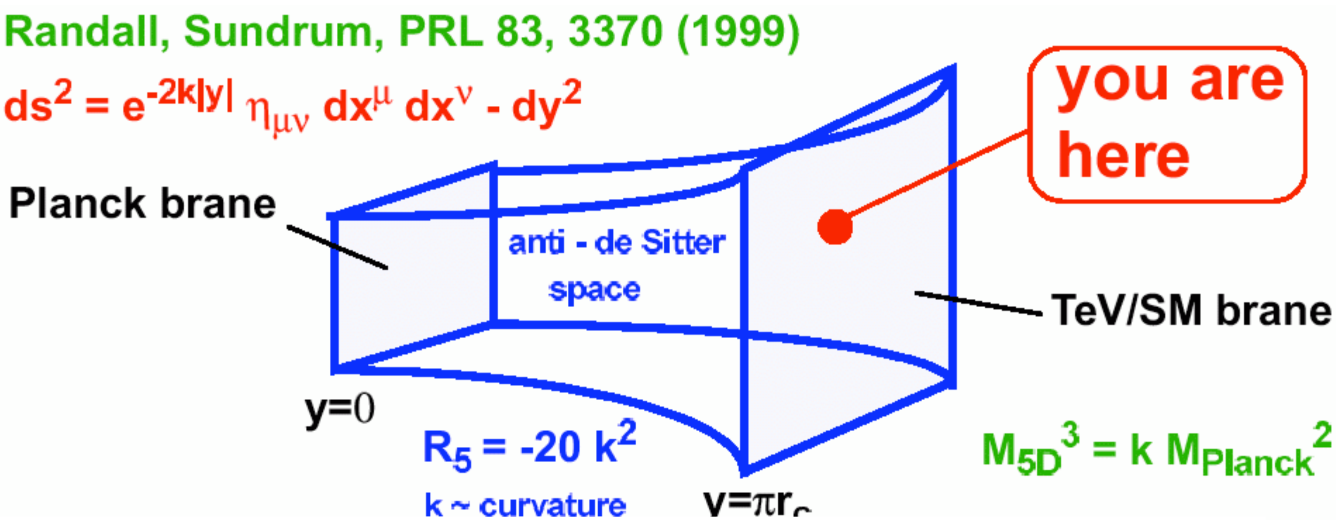
M_s (TeV)	M_D (TeV)	M_{thresh} (TeV)	σ (pb)
1.0	1.5	3.0	$2.3 \times 10^{+1}$
1.2	1.8	3.6	$4.7 \times 10^{+0}$
1.4	2.1	4.2	9.6×10^{-1}
1.6	2.4	4.8	1.9×10^{-1}
1.8	2.7	5.4	3.3×10^{-2}



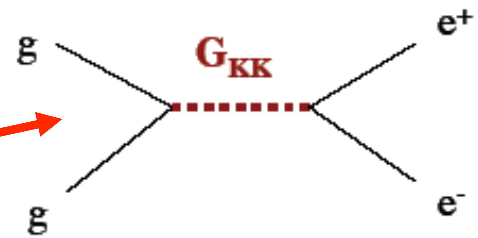


Exclusion of masses of up to ~ 4.8 TeV with 100 pb^{-1}

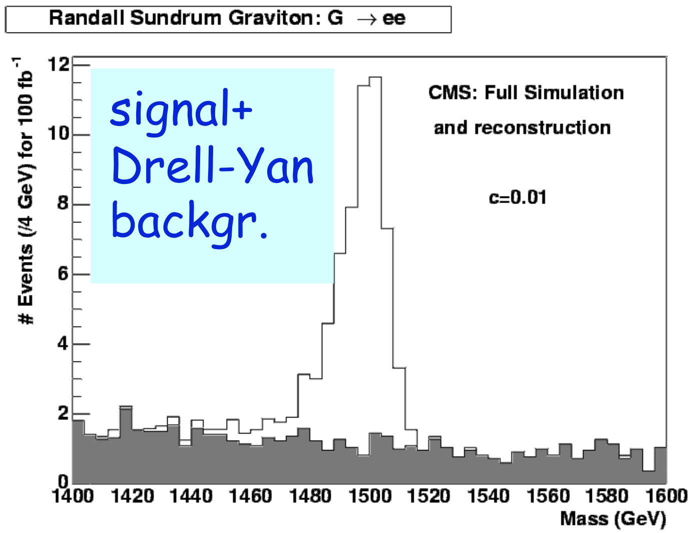
Curved Space: RS Extra Dimensions



phenomenology



Study the channel pp→Graviton→ e+e-



Signature: a resonance in the di-electron or di-muon final state a priori easy for the experiments

Caveat: new developments suggest that G_{KK} would couple dominantly to top anti-top…

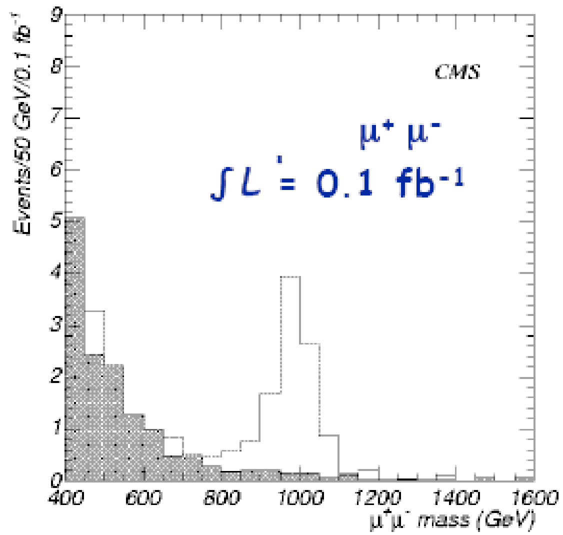
Early Discoveries? E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

A peak!!

A new particle!!

A discovery!!



$pp \rightarrow \mu\mu + X$

First year of operation

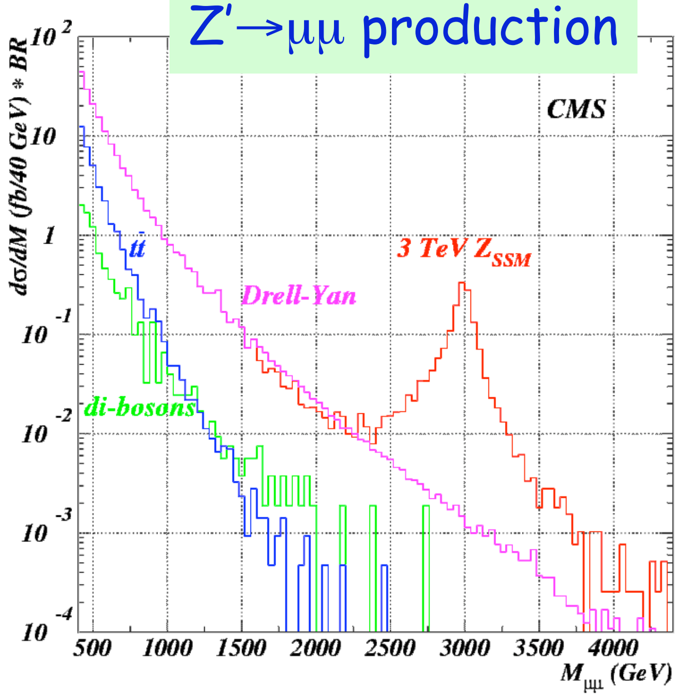
Example : The Di-lepton channel

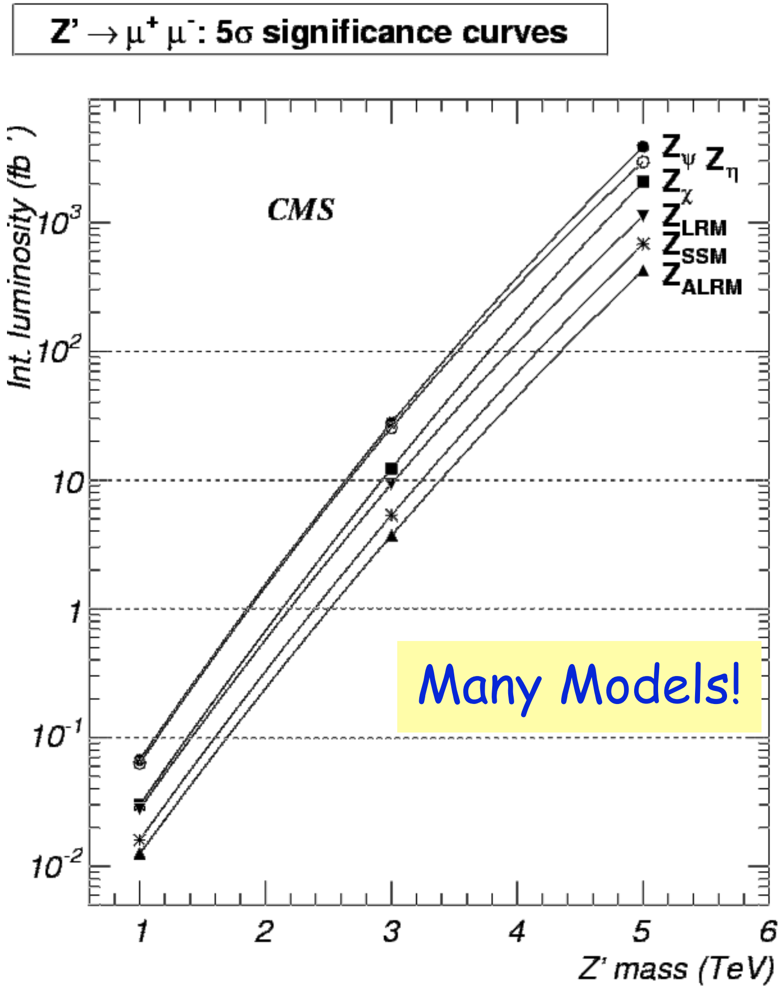
- Z' (New gauge bosons)
- A_H, Z_H (Little Higgs)
- $G^{(1)}$ (Randall-Sundrum)
- $\gamma^{(1)}/Z^{(1)}$ (TeV^{-1} Extra Dimensions)
- $G^{(KK)}$ (ADD)
- ...

New Heavy Gauge Bosons: Z'

EG due a new symmetry group…

Z'→μμ production





Many Models!

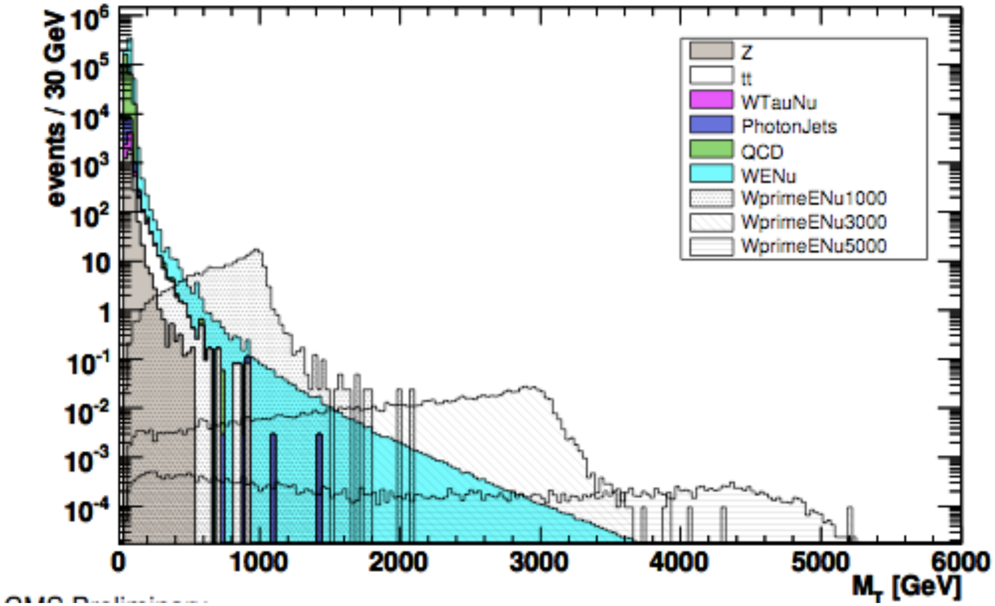
Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

- Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible, beyond Tevatron run-II
- High lumi 100 fb^{-1}: extend range to 3.4-4.3 TeV

New Heavy Gauge Bosons: W'

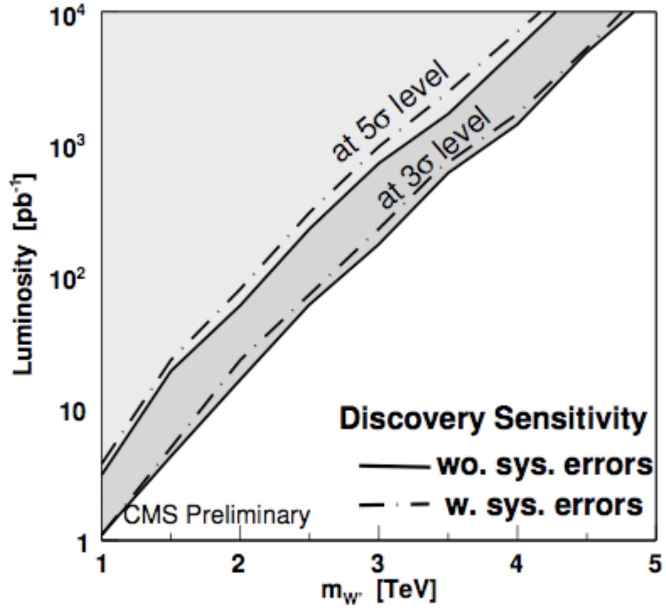
If a Z' exists: what about a W'?

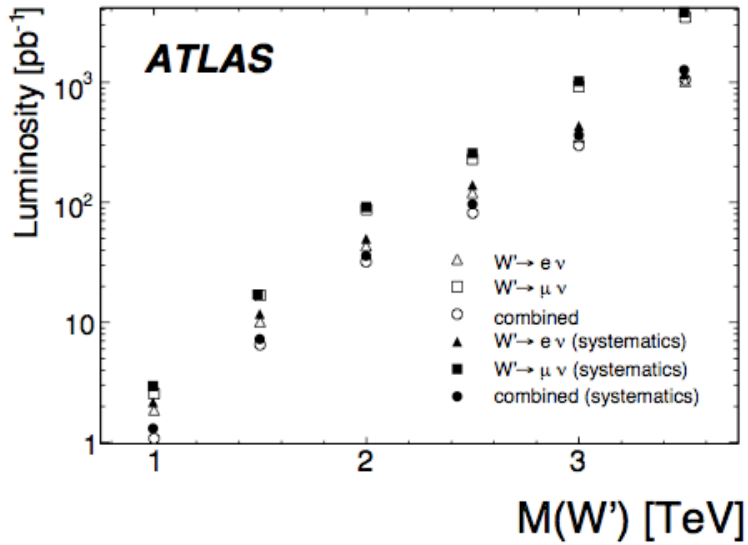
$W \rightarrow \mu\nu$, $e\nu$ channels



Tevatron > ~ 1 TeV

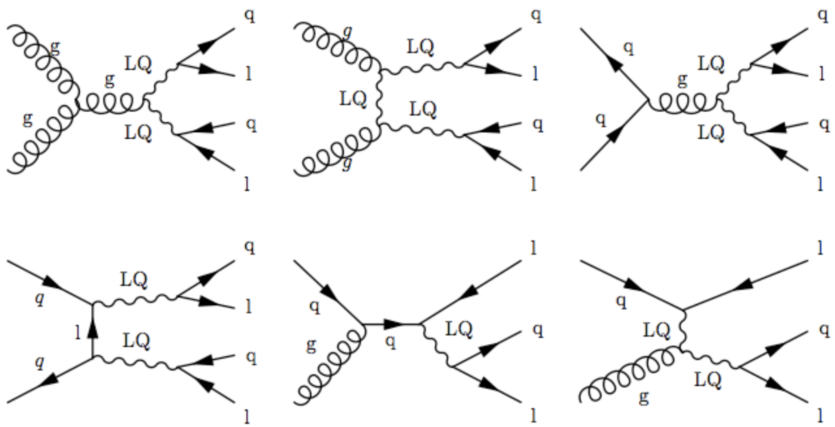
Sensitivity already for 10 pb^{-1}





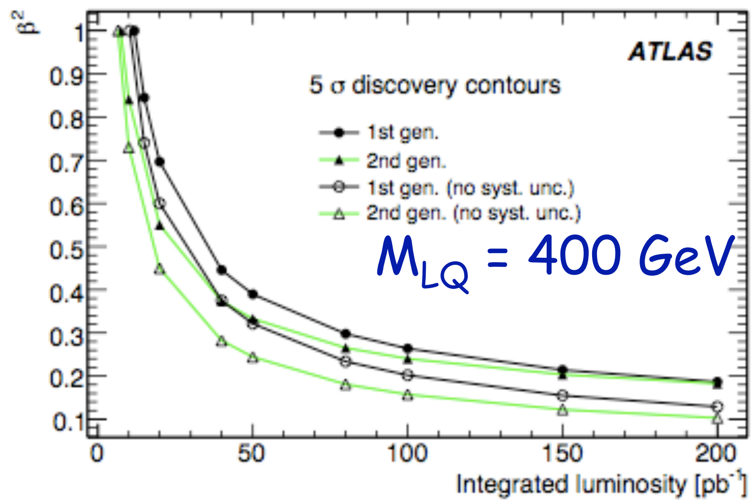
Leptoquark Production

GUT inspired models predict new particles with lepton and quark properties

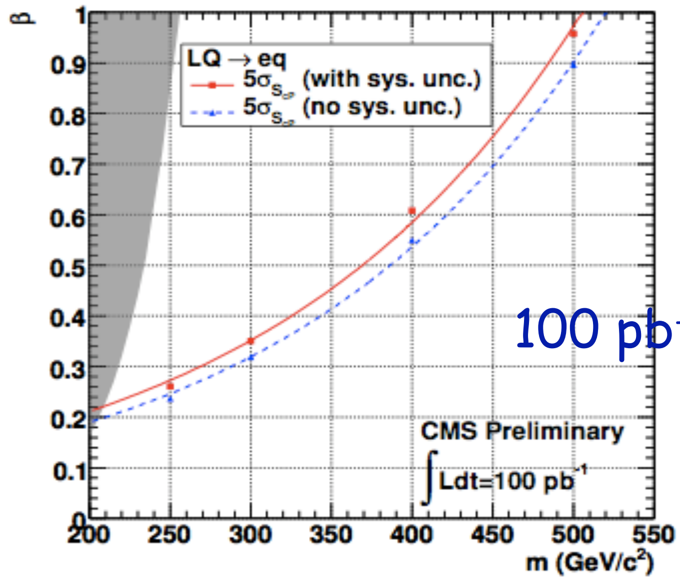


Tevatron limits ~ 300 GeV

Leptoquark mass	Expected luminosity needed for a 5σ discovery	
	1st gen.	2nd gen.
300 GeV	2.8 pb^{-1}	1.6 pb^{-1}
400 GeV	11.8 pb^{-1}	7.7 pb^{-1}
600 GeV	123 pb^{-1}	103 pb^{-1}
800 GeV	1094 pb^{-1}	664 pb^{-1}



M_{LQ} = 400 GeV

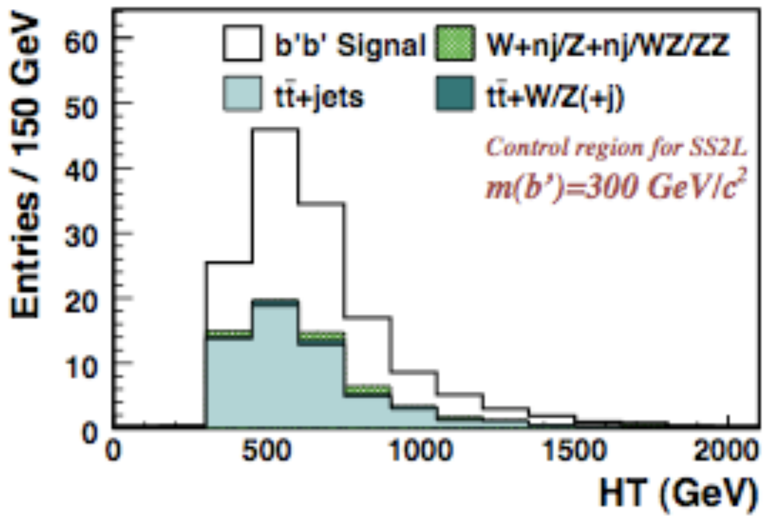


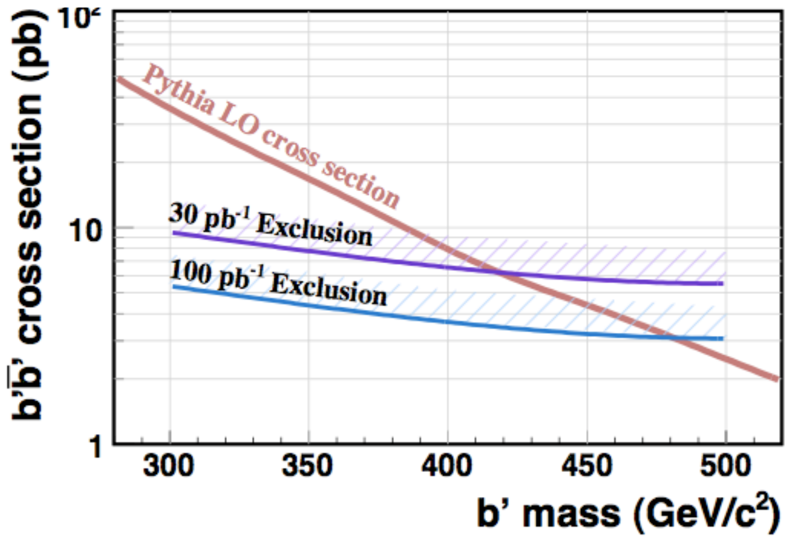
100 pb^{-1}

β: fraction decaying into eq (vs νq)

> 10 pb^{-1} to enter a new mass domain

A Fourth Quark Flavor Generation?





We can't be sure that there are only 3 generations (u,d) (s,c) (b,t)
A possible new generation should be heavy!

Look for b′ and t′ quarks
This channel: $b' \to tW$ decays

Present limits ~ 200 GeV

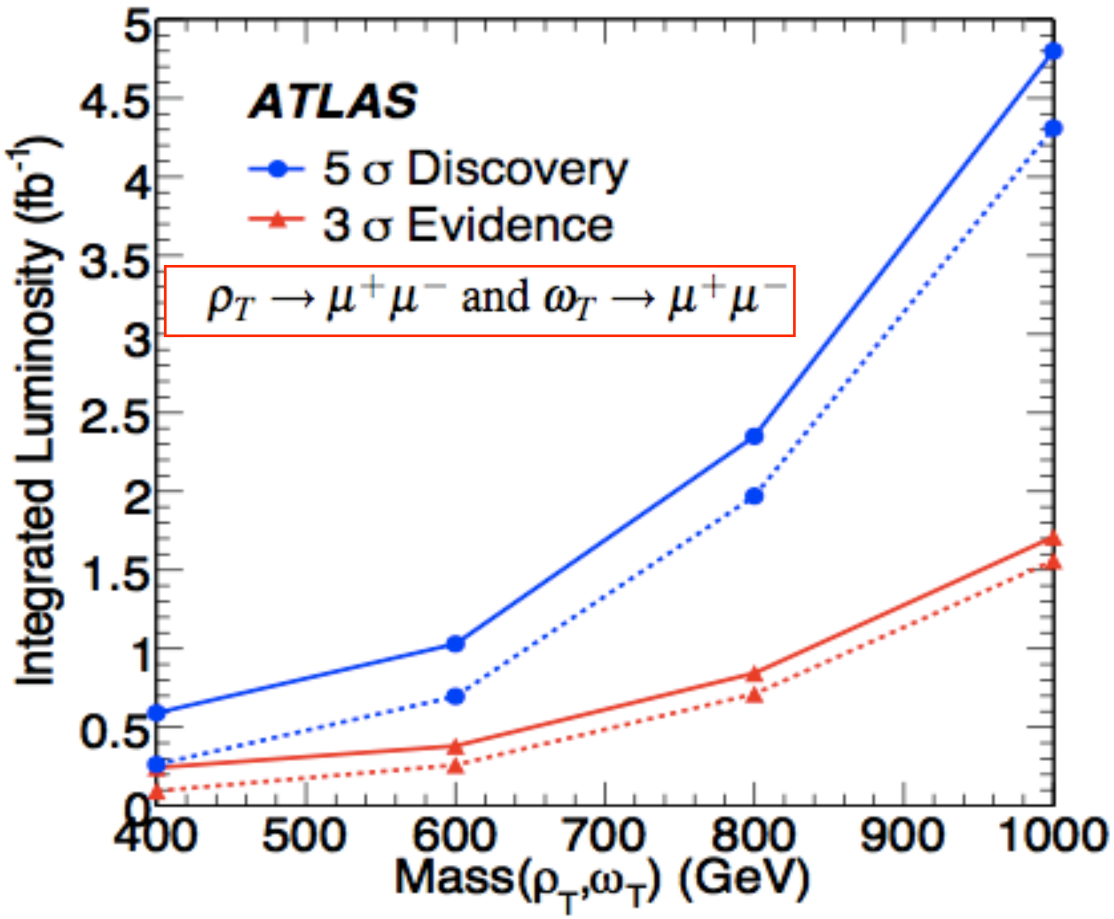
Tevatron Limits

$m_{t'} > 311$ GeV ($t' \to bW$) $m_{b'} > 199$ GeV ($b' \to bZ$)

Senstivity ~400 GeV with 100 pb^{-1}

A new strong force: Technicolor?

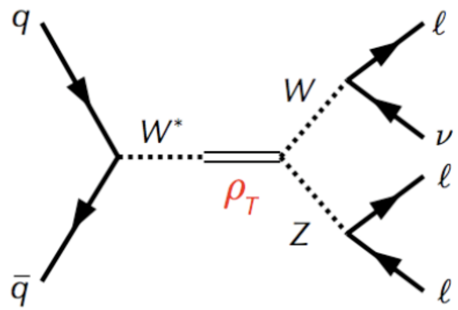
No elementary Higgs but a new type of color-like force, predicting particles called techni-pions, techni-rhos, techni-omegas…with masses ~ few 100 GeV



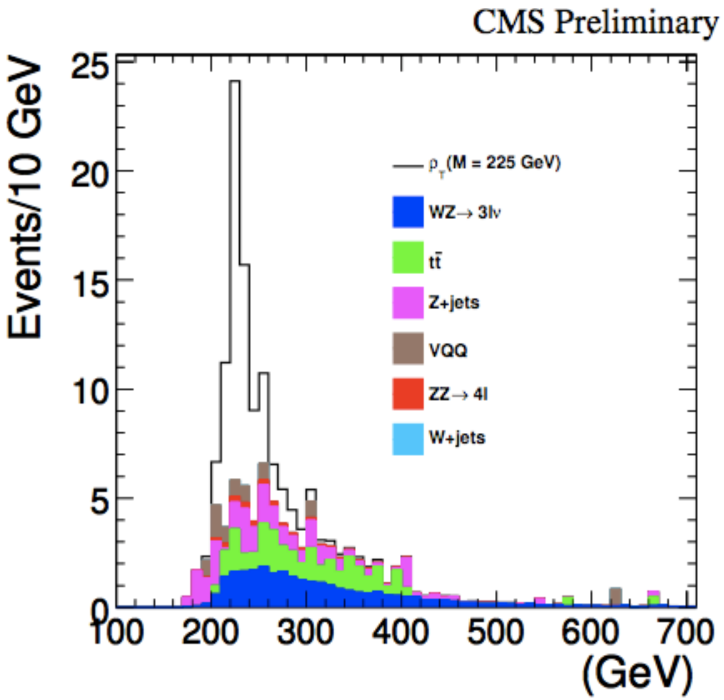
Luminosities of ~ 0.5-1 fb^{-1} or more needed

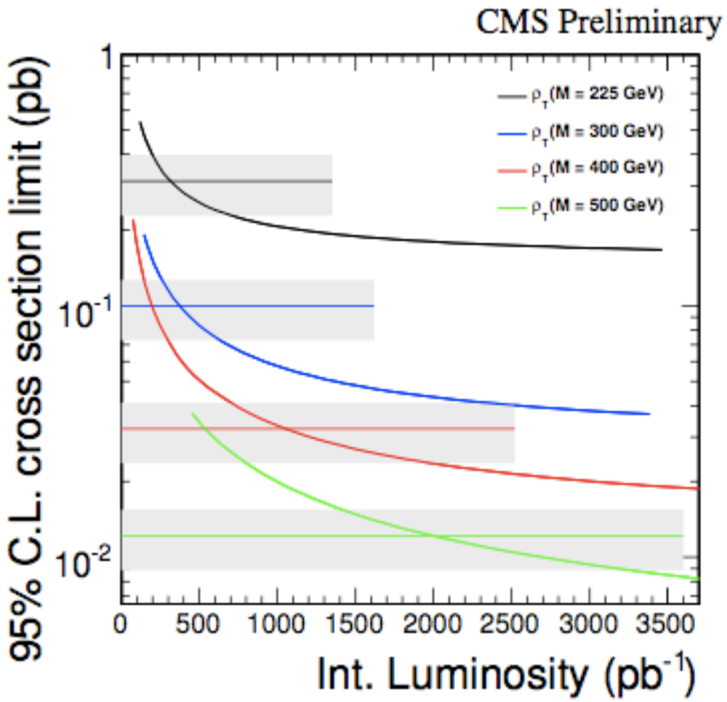
A New Force: Technicolor

No elementary Higgs but a new type of color-like force, predicting particles called tehni-pions, techni-rhos, techni-omegas…with masses ~ few 100 GeV



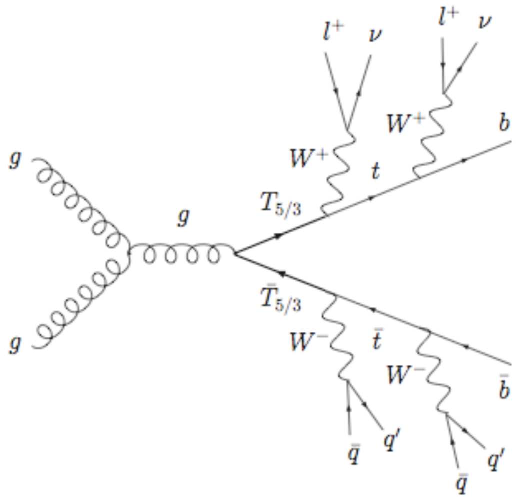
Luminosities of ~ O(0.5) fb^{-1} or more needed

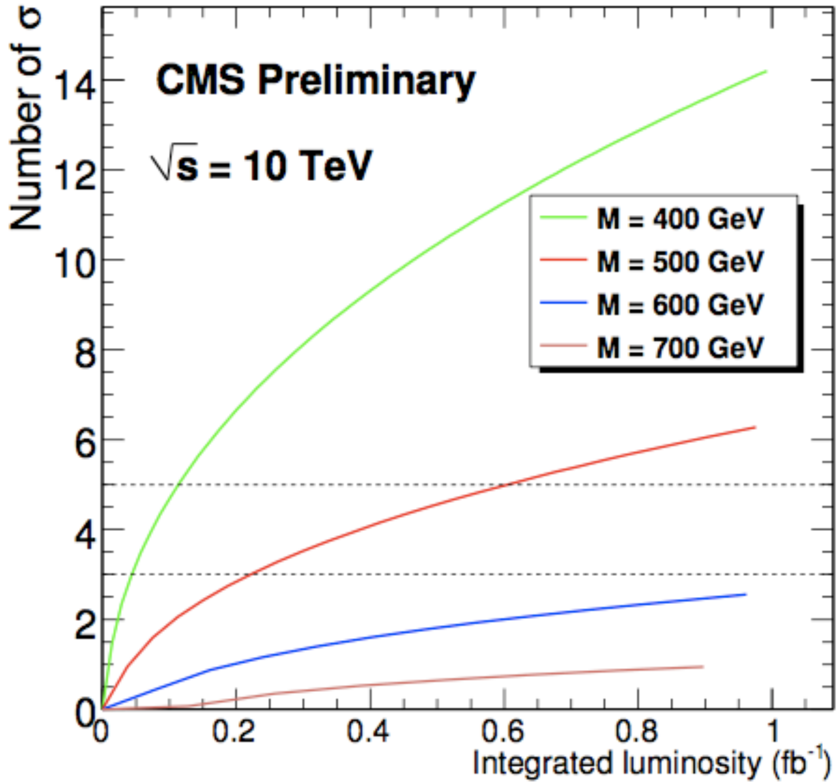




Particles with Unusual Properties

Top partners with exotic quantum numbers, eg Q = 5/3



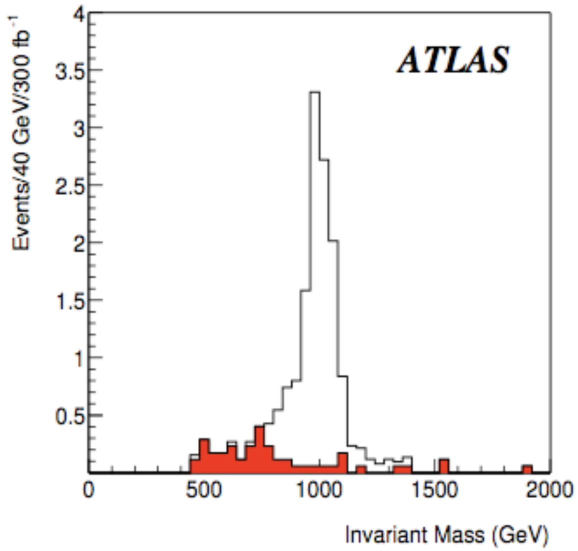


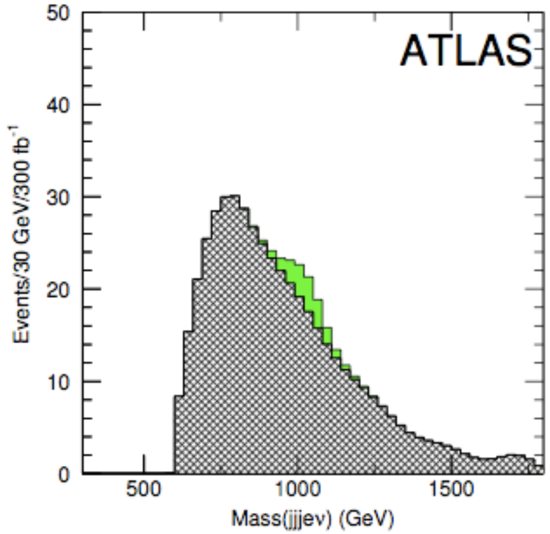
Produced in models with warped space dimensions
Characteristic: like sign leptons in decay

Reach up to 400 GeV with 100 pb^{-1}

Little Higgs Models

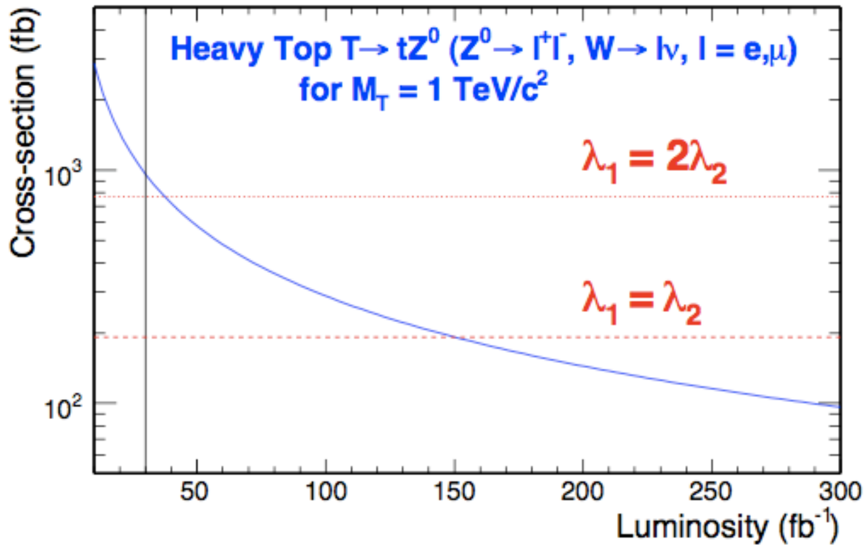
Heavy top partner around 1 TeV ⇒ Decay eg intoT → tZ, T→tH



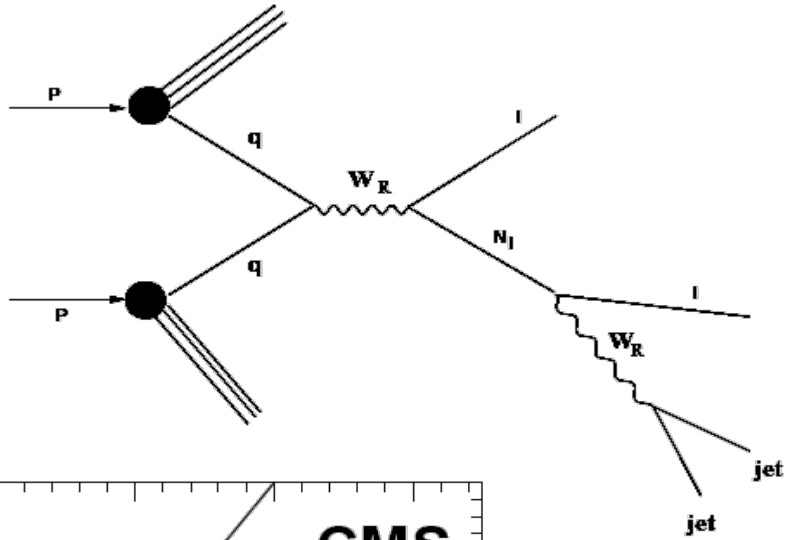


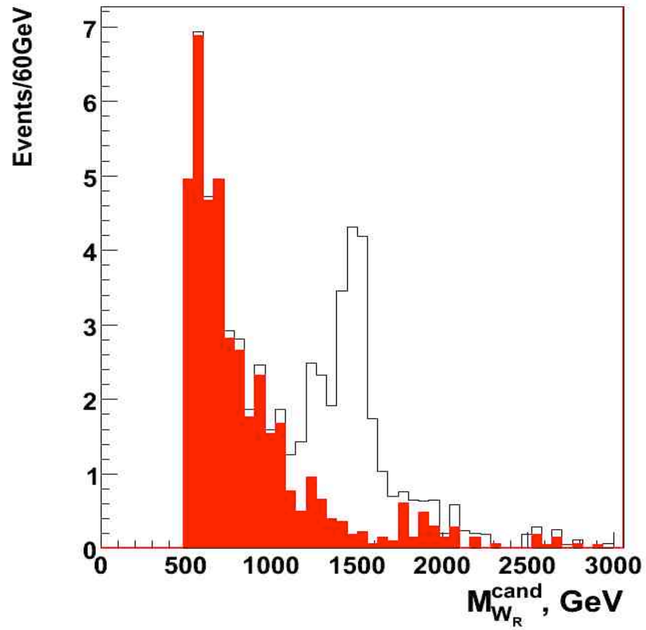
Signals+BG
Needs a lot of luminosity!!

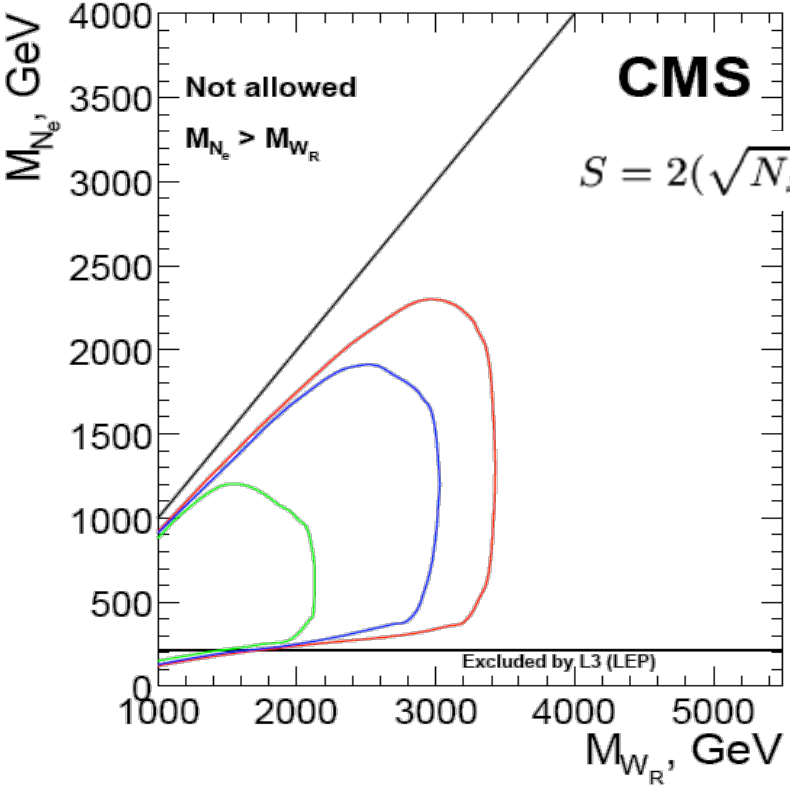
CMS PTDR:
Sensitivity to heavy top cross section



Heavy Neutrinos







$$S = 2(\sqrt{N_S + N_B} - \sqrt{N_B}) \geq 5$$

CMS discovery potential of the W_R boson and right-handed Majorana neutrino for luminosity 30 fb^{-1}, 10 fb^{-1}, 1 fb^{-1}.

Tevatron limits
WR>0.7 TeV

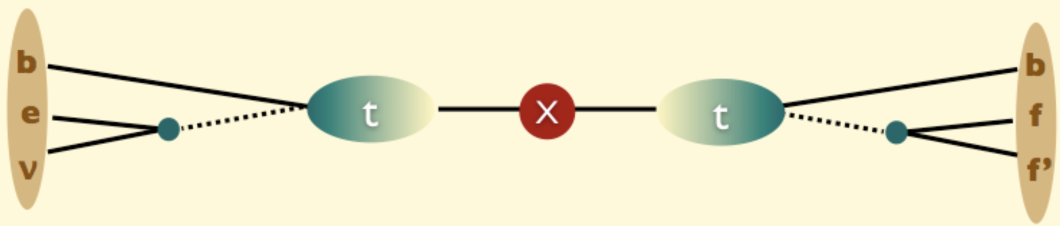
N>0.3 TeV

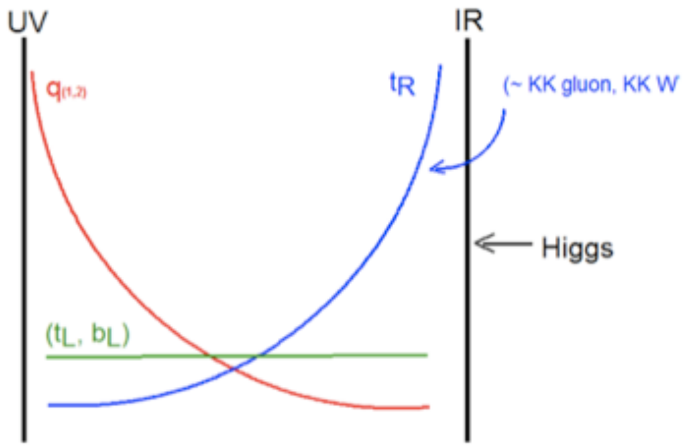
M(WR) = 1.2 TeV, M(Nl) = 500 GeV can be discovered with 40 pb^{-1} @ 10 TeV

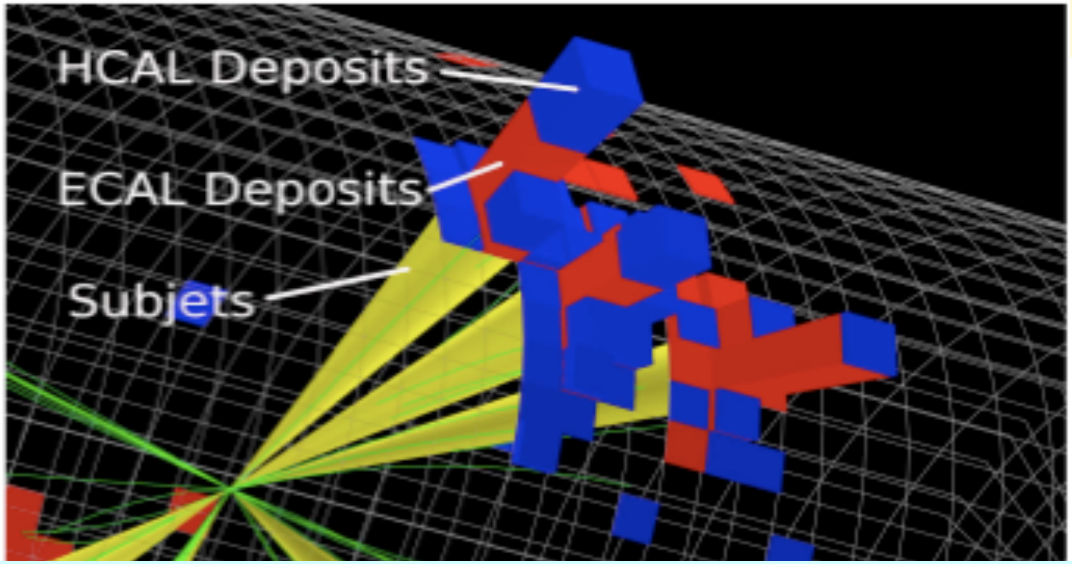
TeV Resonances into Top Quark Pairs

Recent developments in models: a prominent role of top production
-light SM fermions live near Planck brane, heavy (top) near TeV brane
-decay of Randall Sundrum gravitons into top pairs!!

- Eg RS → t tbar





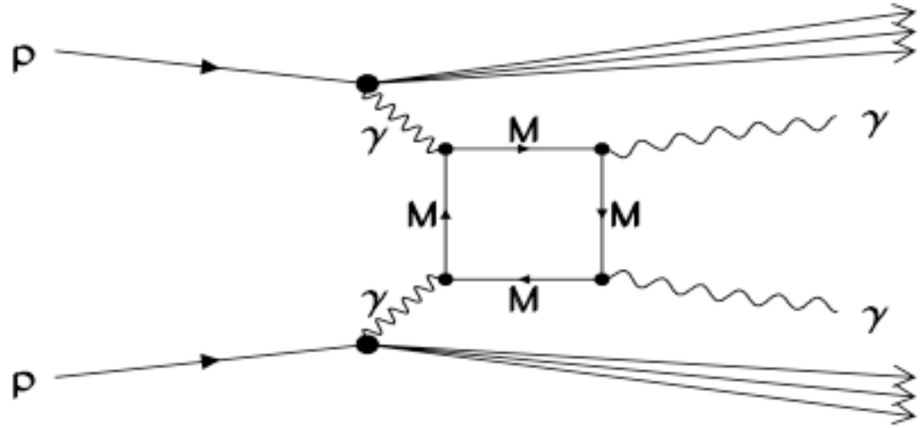


⇒High P_T tops

Methods are prepared to tackle the early data

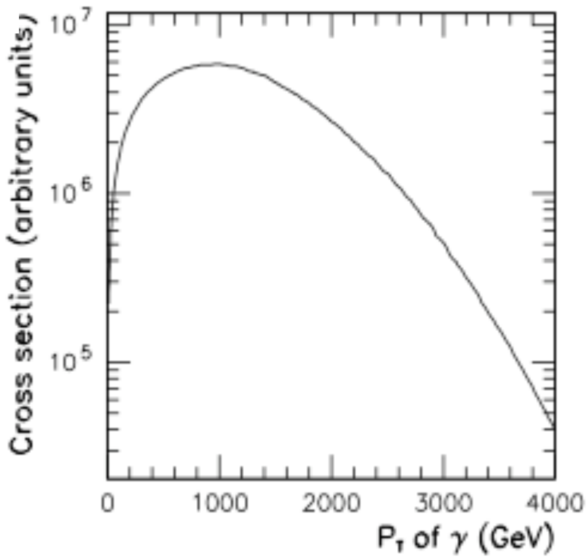
Magnetic Monopoles

Heavy particles which carry "magnetic charge"
Could eg explain why particles have "integer electric charge"



Virtual production:
Look eg into di-photon final state

$$\sigma_{pp \to \gamma\gamma X}(E, M, P, n) = 108 P \left(\frac{nE}{M}\right)^8 \left(\frac{N(E))}{N(1\mathrm{TeV})}\right)^2 \left(\frac{1TeV}{E}\right)^2 \mathrm{fb}$$



Cross section O(fb)
High luminosity required

But maybe the "New World" is far more weird than what we thought so far…

Recent developments in many models lead to the possible existence of heavy particles that have unusual long lifetimes

These can decay in the middle of the detector (nanoseconds) or live even much longer eg seconds, hours, days…

This leads to very special detector signatures!

Long Lived Particles in Supersymmetry

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

  - Gluino can live long: sec, min, years!

  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles containing a heavy gluino.

  Unusual interactions with material

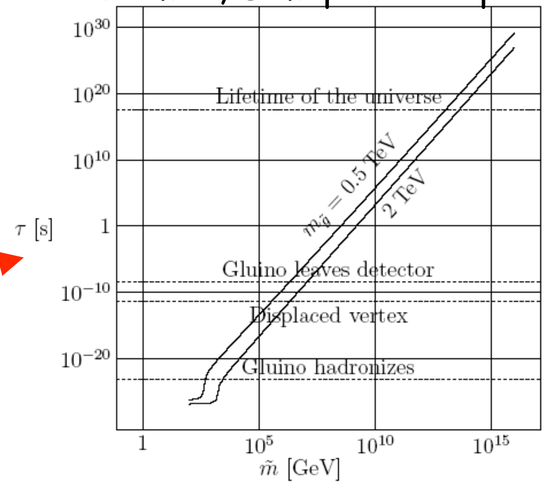
  eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

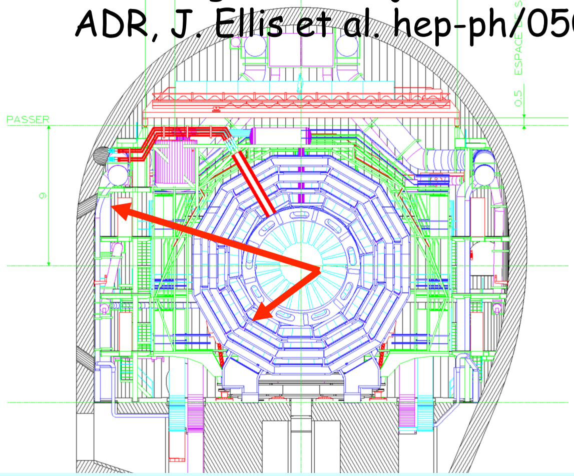
⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



K. Hamaguchi,M Nijori,ADR hep-ph/0612060

ADR, J. Ellis et al. hep-ph/0508198

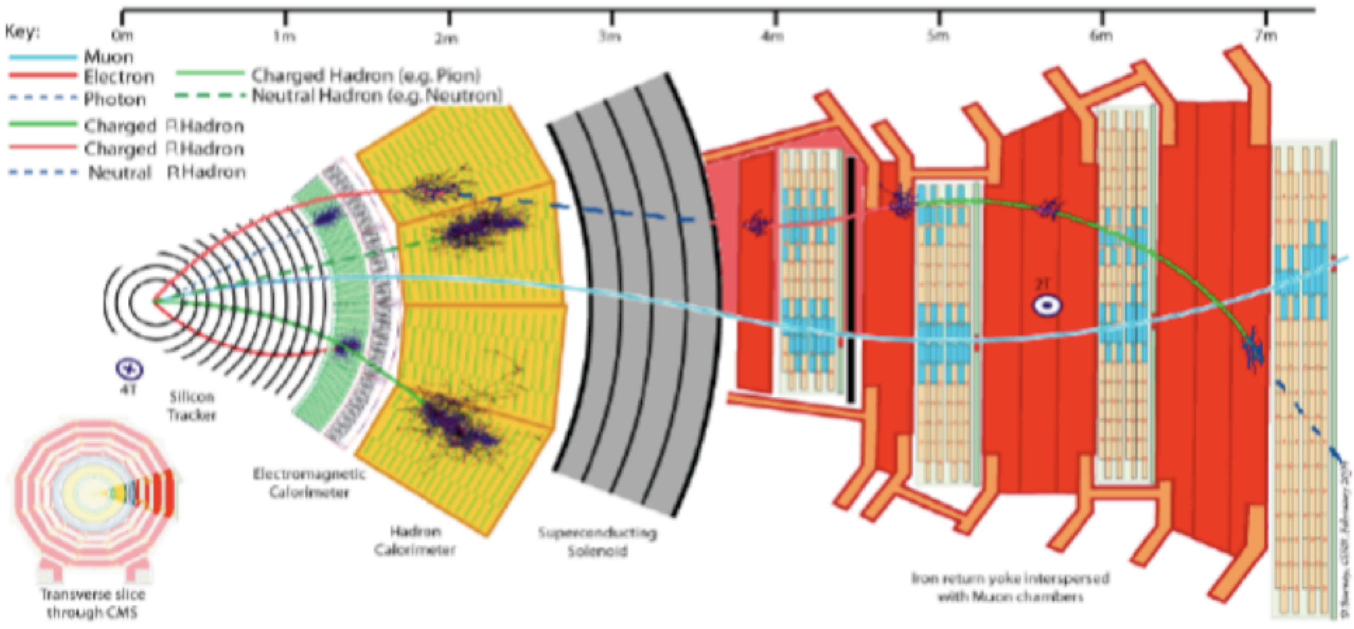


Also eg. R. Barbieri

Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

R-Hadrons Passing Through the Detector

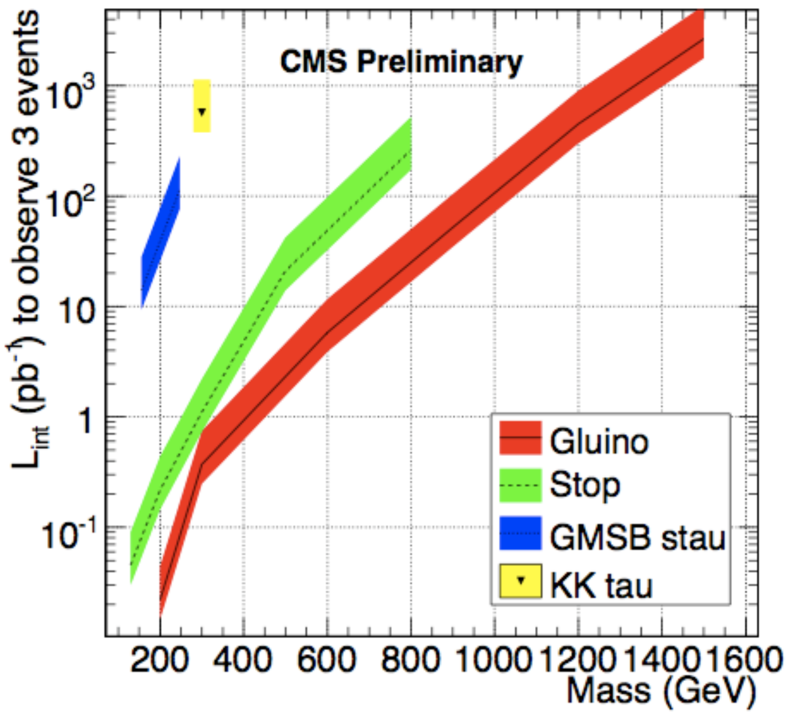
R-hadrons would have a mass of at least a few 100 GeV
- They 'sail' through the detector like a 'heavy muon'
- In certain (hadronization) models they may change charge on the way
- They also loose a lot of energy when passing the detector (dE/dx)



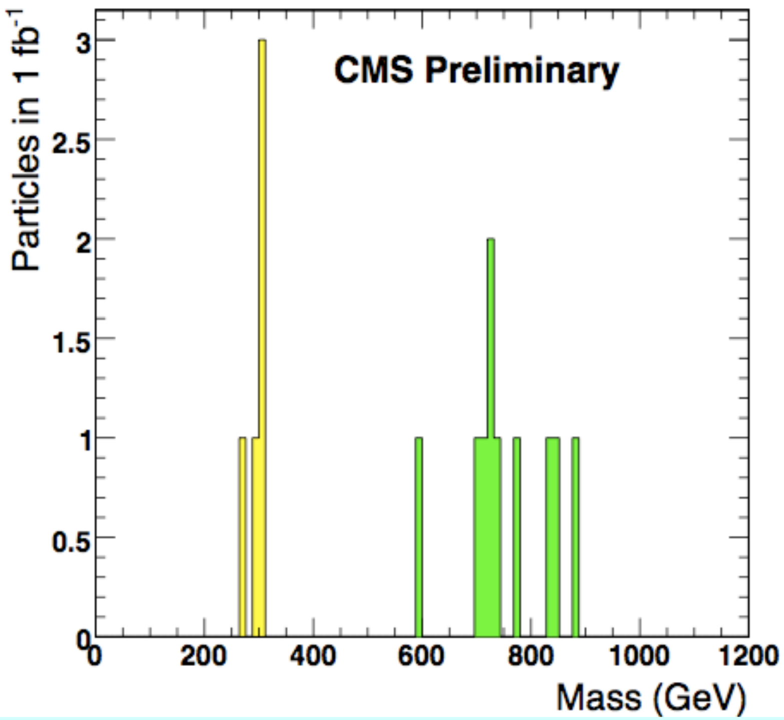
Weird signature!!

Heavy Stable Charged Particles

Sensitivity for different models:
⇒ Gluinos, stop, stau and KKtau production



Luminosity needed for a discovery



Mass reconstruction for a 200 GeV KKtau and a 800 GeV stop particle

Stopped R-hadrons or Gluinos!

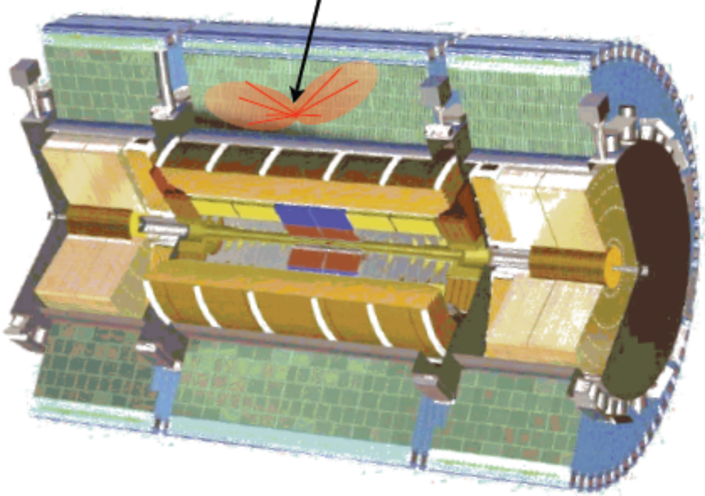
The R-hadrons may loose so much energy that they simply stop in the detector

Long Lived Gluinos

$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay

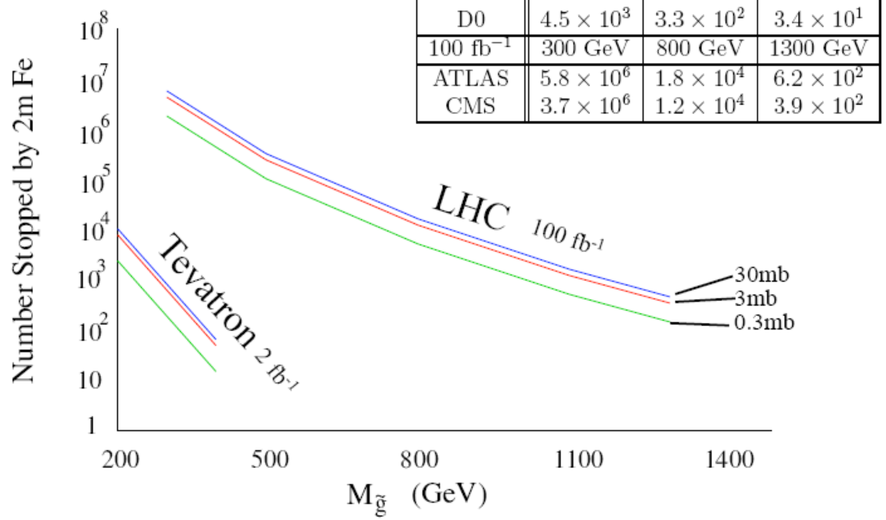
100s GeV Unbalanced $= \not{E}_T$



Uncorrelated with any beam crossing
No tracks going to or from activity

Total Number of Stopped Gluinos

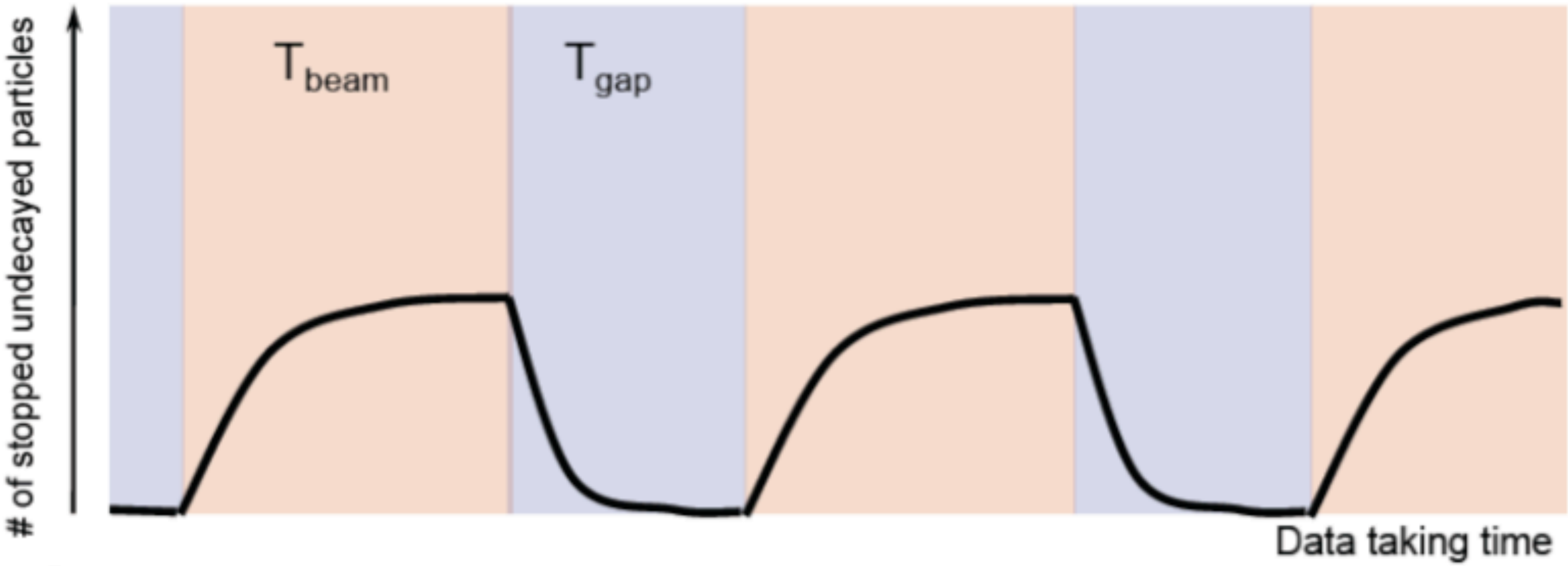
Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242



2 fb^{-1}	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
100 fb^{-1}	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2

$\Rightarrow$ Special triggers needed, asynchronous with the bunch crossing

Stopped gluinos



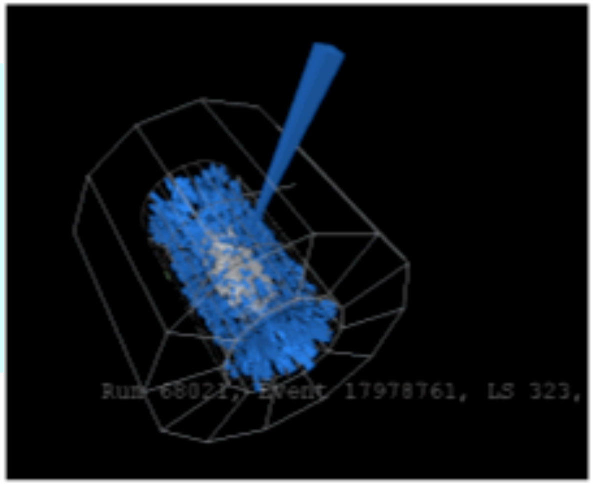
- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay   Eg when there is no beam!
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

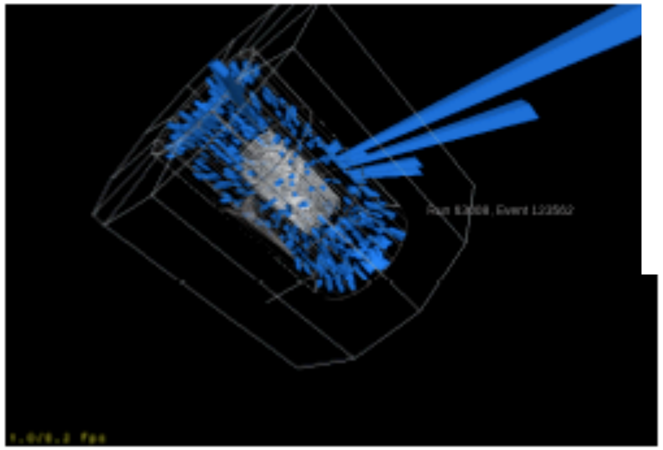
Can be studied in the experiments NOW with cosmic data

Stopped Gluinos

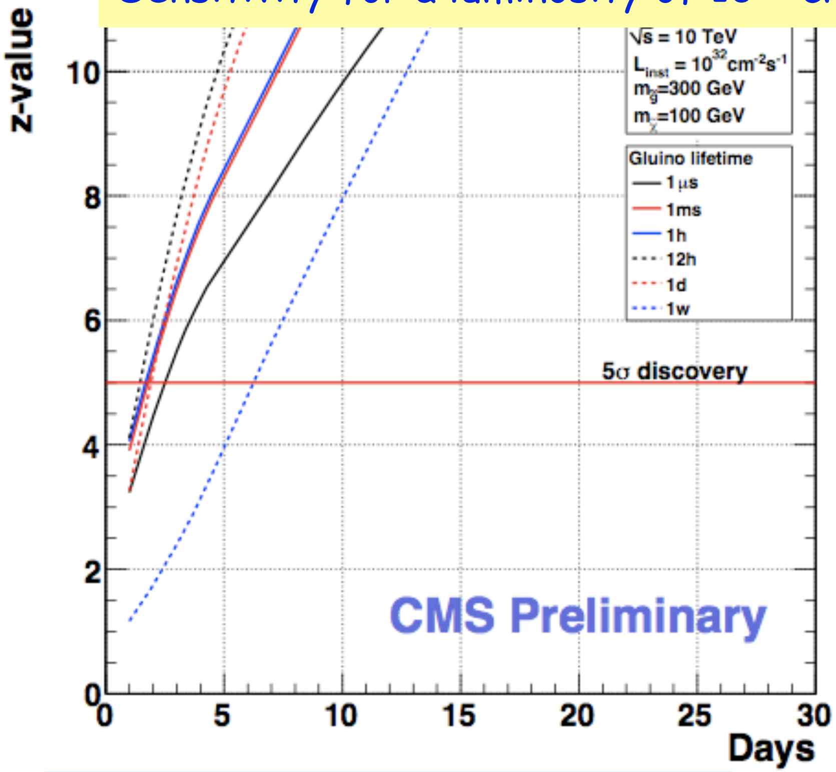
Studies in CMS with the 2008/2009 cosmic data:
All events we find now are background and we can learn how to cut on them!

Find energy splashes with certain topology



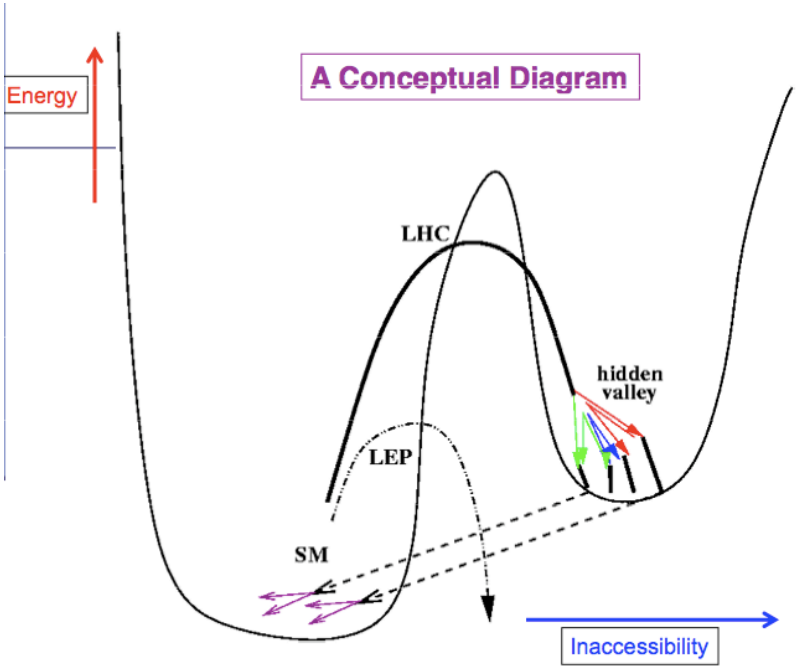


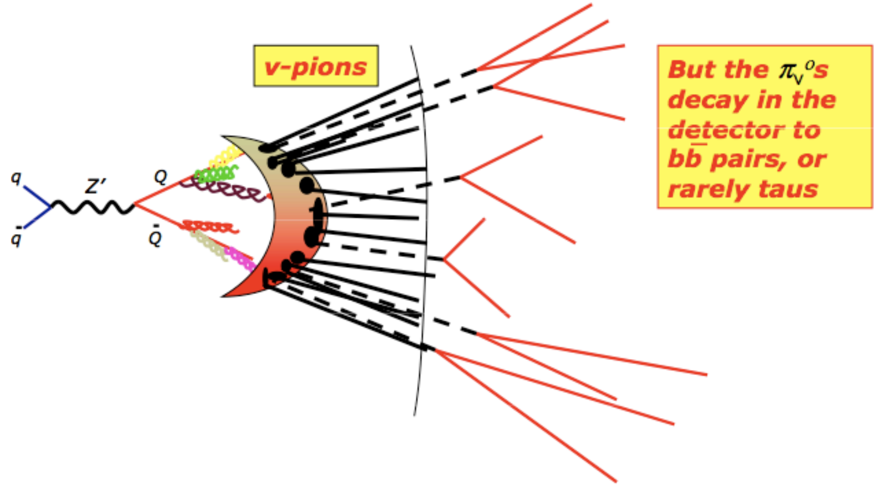
Sensitivity for a luminosity of 10^{32} cm^{-2}s^{-1}



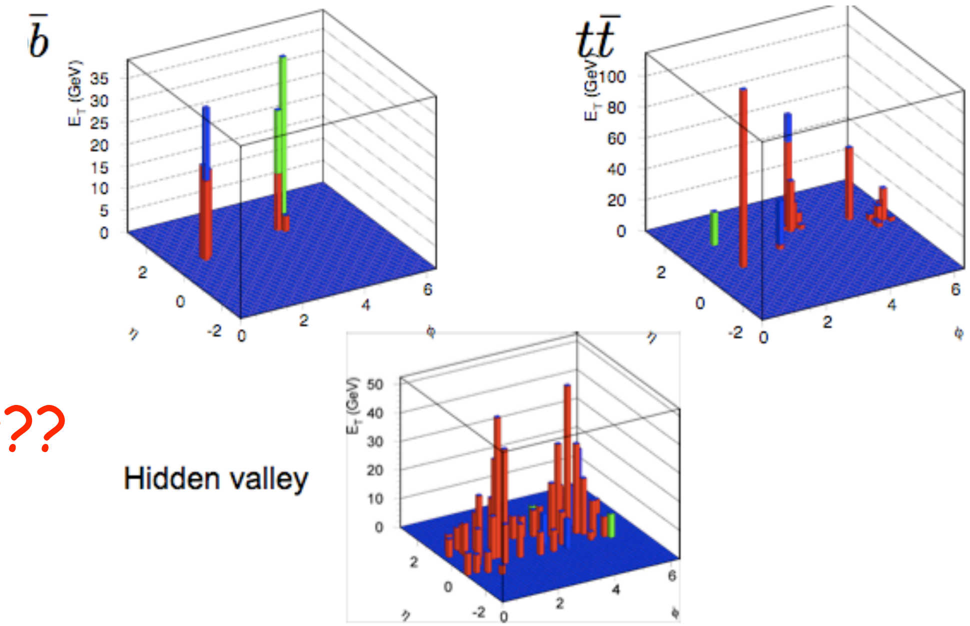
Discovery with only a few weeks running!

Hidden Valley Physics: New Signatures





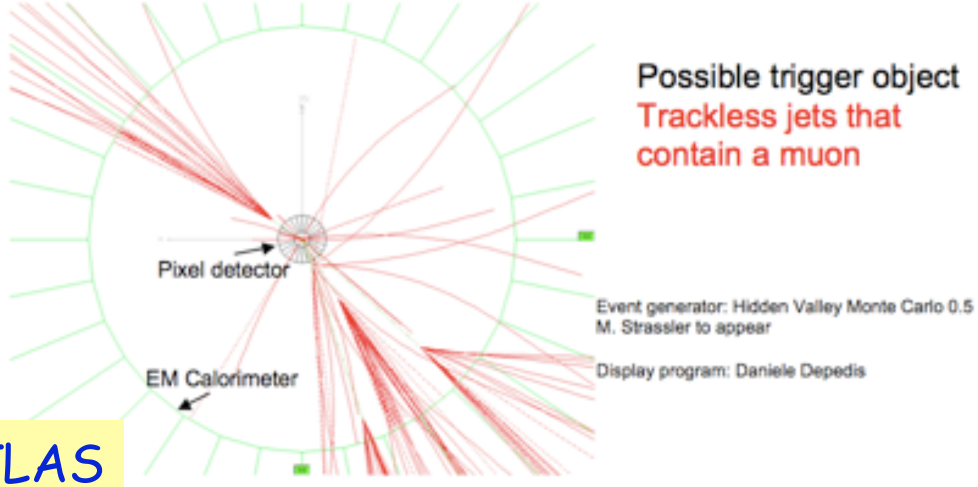
Will produce "Weird Jets" and a lot of secondary vertices



⇒ Difference with QCD jets??

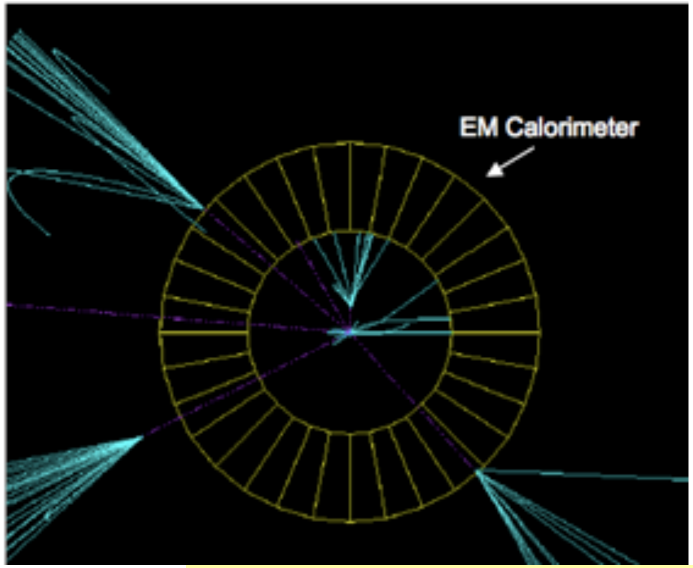
⇒ Study SM jet structure

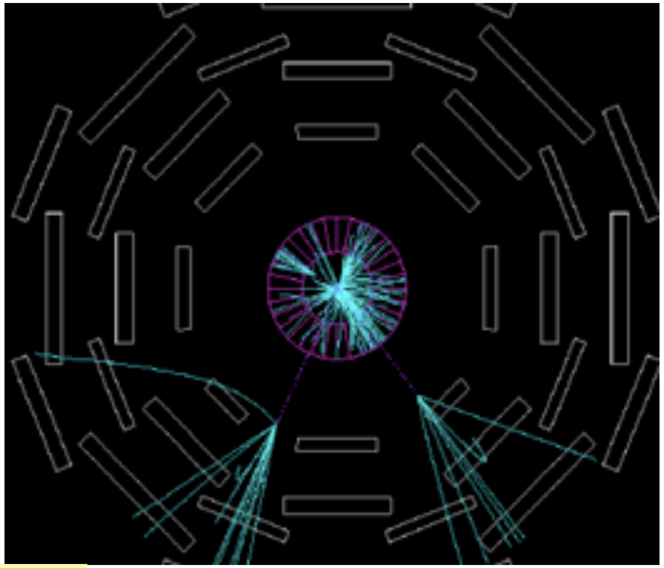
Hidden Valley Events



The experiments are not really prepared for this(*)
For example: Trigger problems for events with large displayed vertices

ATLAS



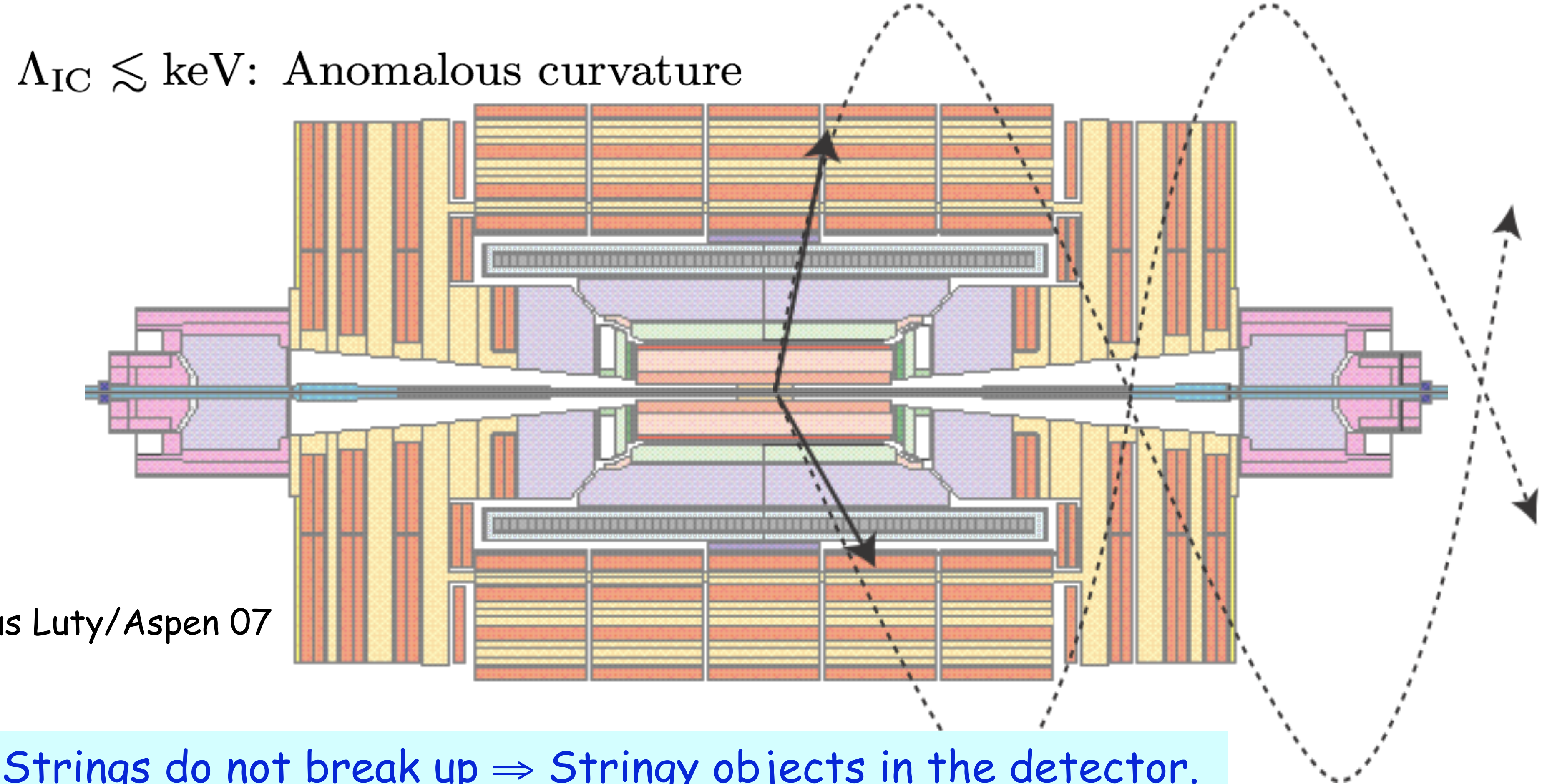


⇒Need special triggers

(*) except possibly LHCb

Macro-Strings at the LHC?

New strong interactions with small Λ & new quarks m_Q> several hundered GeV

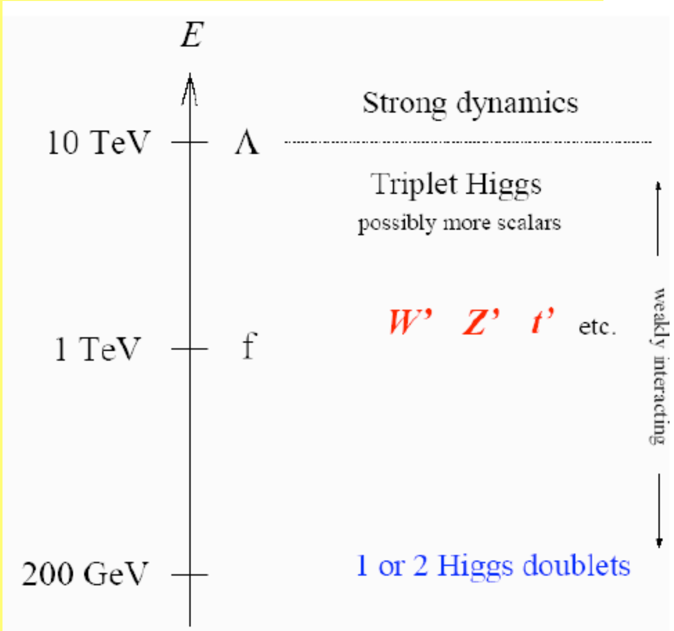


Markus Luty/Aspen 07

- Strings do not break up $\Rightarrow$ Stringy objects in the detector.
- End points are massive quarks (quirks)
- The strings can oscillate$\Rightarrow$ strange signature in detectors

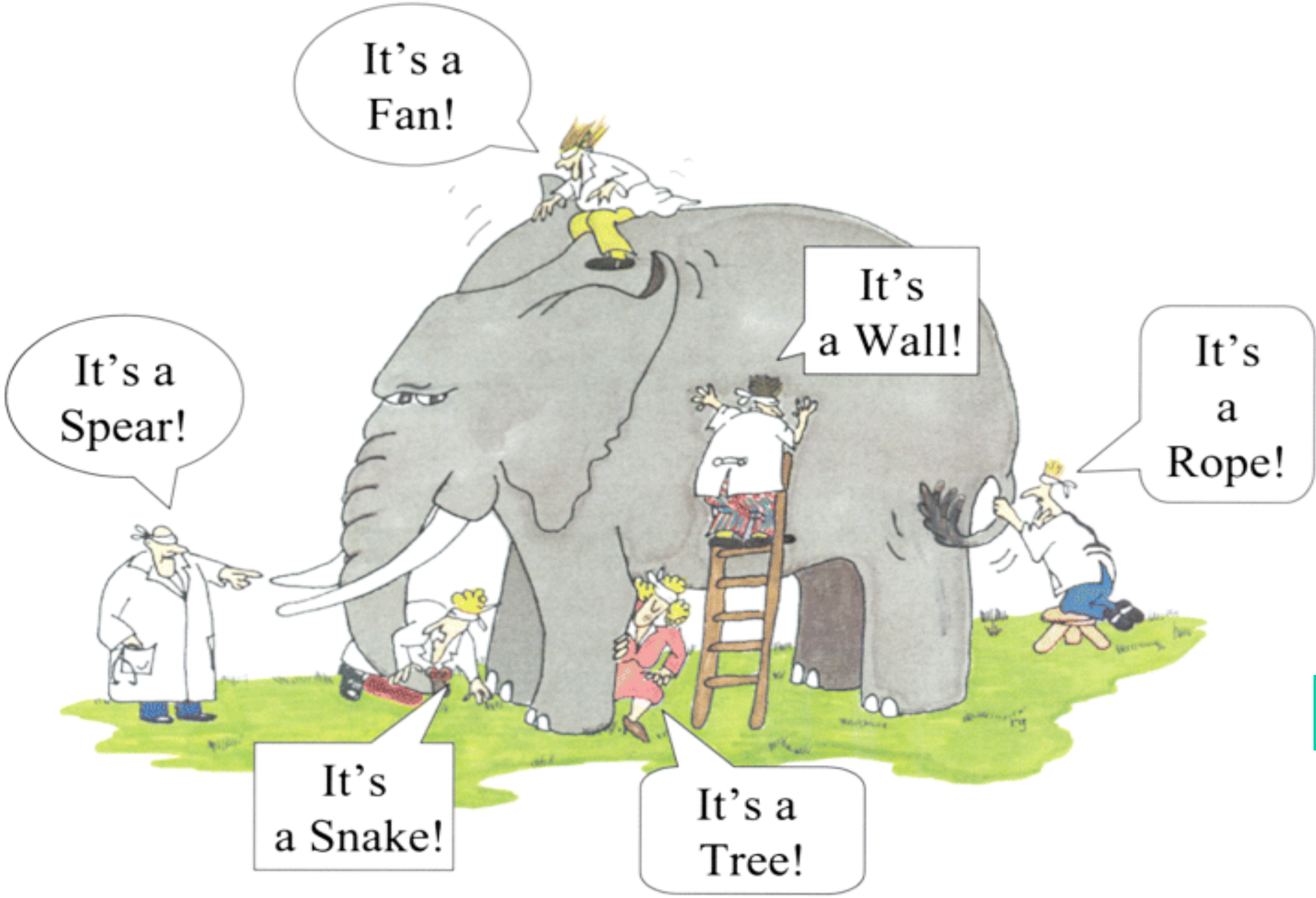
Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Heavy Majorana Neutrinos
  - WW,WZ resonances
  - Unparticles
  - …



Have to keep our eyes open for all possibilities:
Food for many PhD theses!!

Since we do not know what we will find…



Nature.com

…we will look at it from all angles….

Close interaction between Experiment and Theory will be important

Tools & Theoretical Estimates

The LHC will be a precision and hopefully discovery machine
But it needs strong collaboration with theorists

Examples

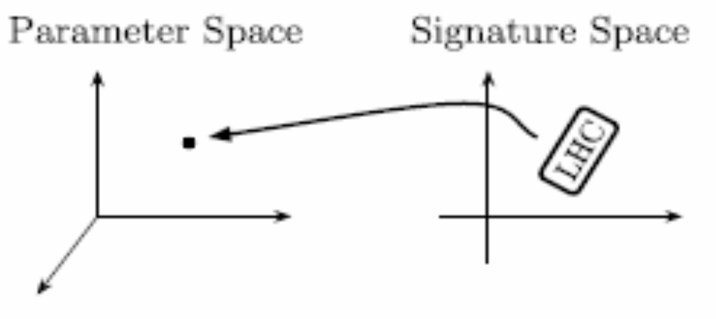
- Precision predictions of cross sections
- Estimates for backgrounds to new physics
- Monte Carlo programs (tuned) for SM processes:
  W,Z,t.. + njets and more..
- Monte Carlo programs for signals (ED's,….)
- Evaluation of systematics due to theory uncertainties
- Higher order calculations
- New phenomenology/signatures to look for
- Discriminating variables among different theories
- Getting spin information from particles
- Tools to interpret the new signals in an as model independent way as possible (MARMOSET, footprints?)
- …

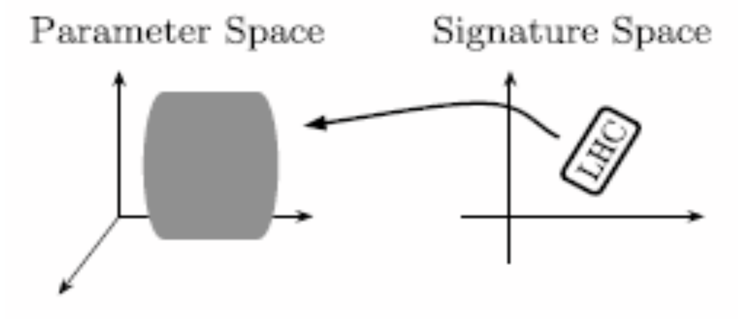
After the Champagne…

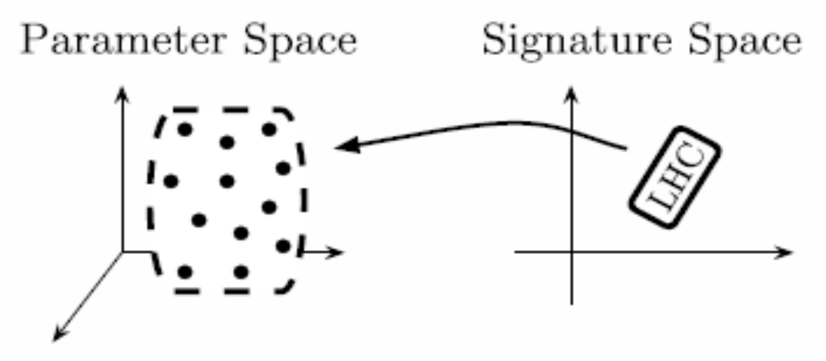
• WHEN new physics is discovered at the LHC, how well can we determine what it is? Does a specific experimental signature map back into a unique theory with a fixed set of parameters?

• Even within a very specific context, e.g., the MSSM, can one uniquely determine the values of, e.g., the weak scale Lagrangian parameters from LHC data alone?

The Inverse Mapping of Data: there are many possible outcomes….







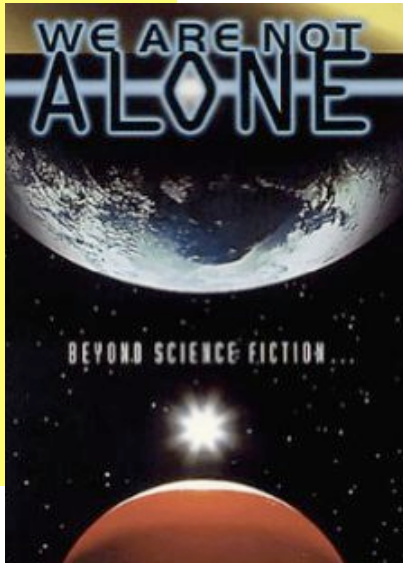
Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space…
→ model degeneracy

Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190 + follow up papers

The efforts to understand the problems and design strategies – even before data– are very important!

We are not alone!

- LHC: LHCb has a complementary sensitivity to CMS/ATLAS for new physics.
  - Not yet explored in a systematic way
- Heavy flavor precision measurements (B-factories)
- g-2 new measurements (factor 5-10 improvement in O(5) years?)
- Dark matter hints from outer space (PAMELA/ATIC GLAST-Fermi..)
  - Wait until the dust settles…!
- New Collider?… not any time soon



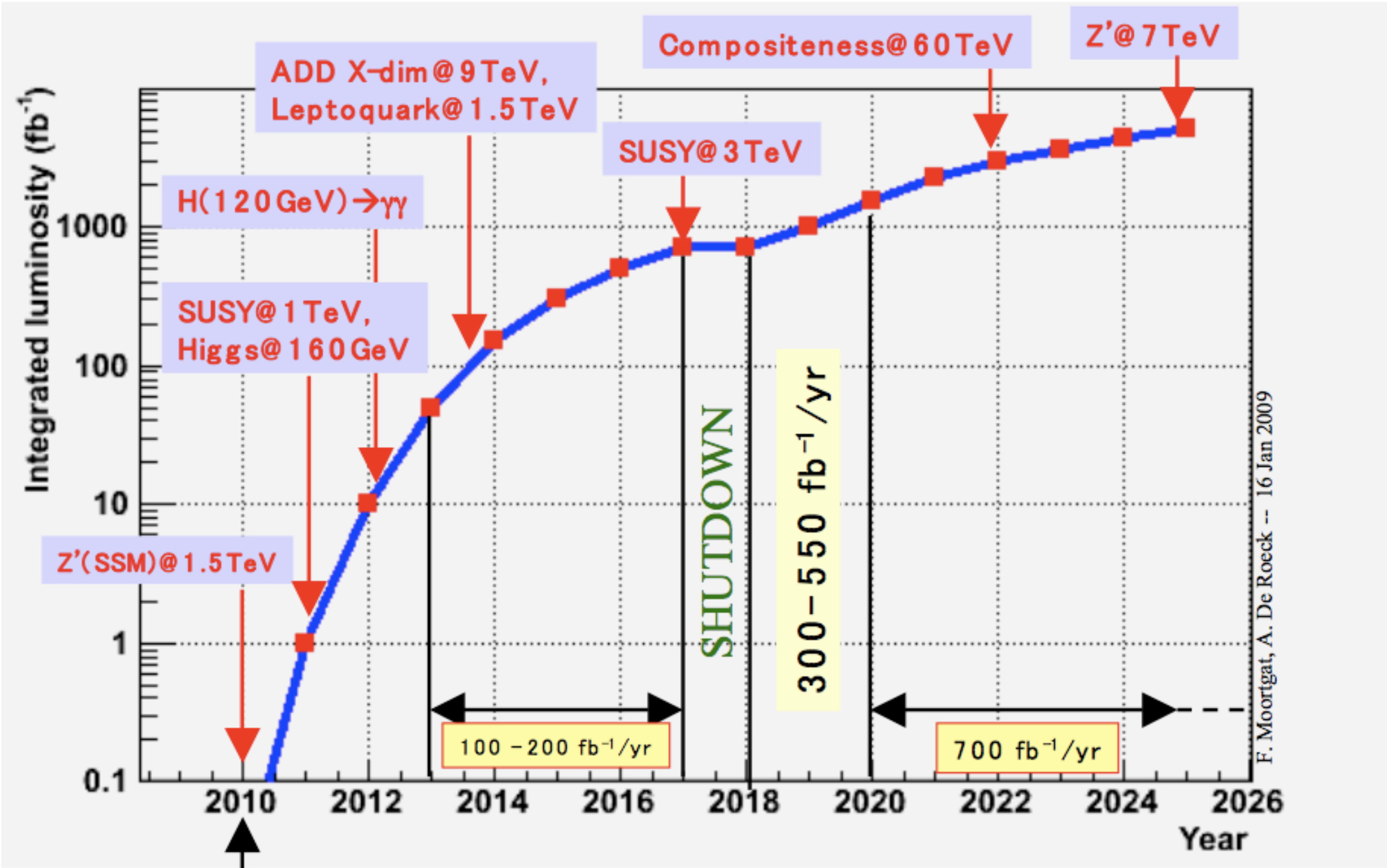
Summary

- There is a plethora of new models for physics Beyond the Standard Model
  - Not all are equally well motivated
  - Main ones still Supersymmetry and Extra Dimensions
- Recent developments lead to expect signatures for which the "general purpose detectors" were not designed for (eg trigger, measurements of timing…)
  - Fear factor! Can we miss the signal??
  - So far:ATLAS and CMS are flexible enough
- Hence: the experiments are ready to go!!

And maybe not long from now ⇒

END

The LHC Outlook

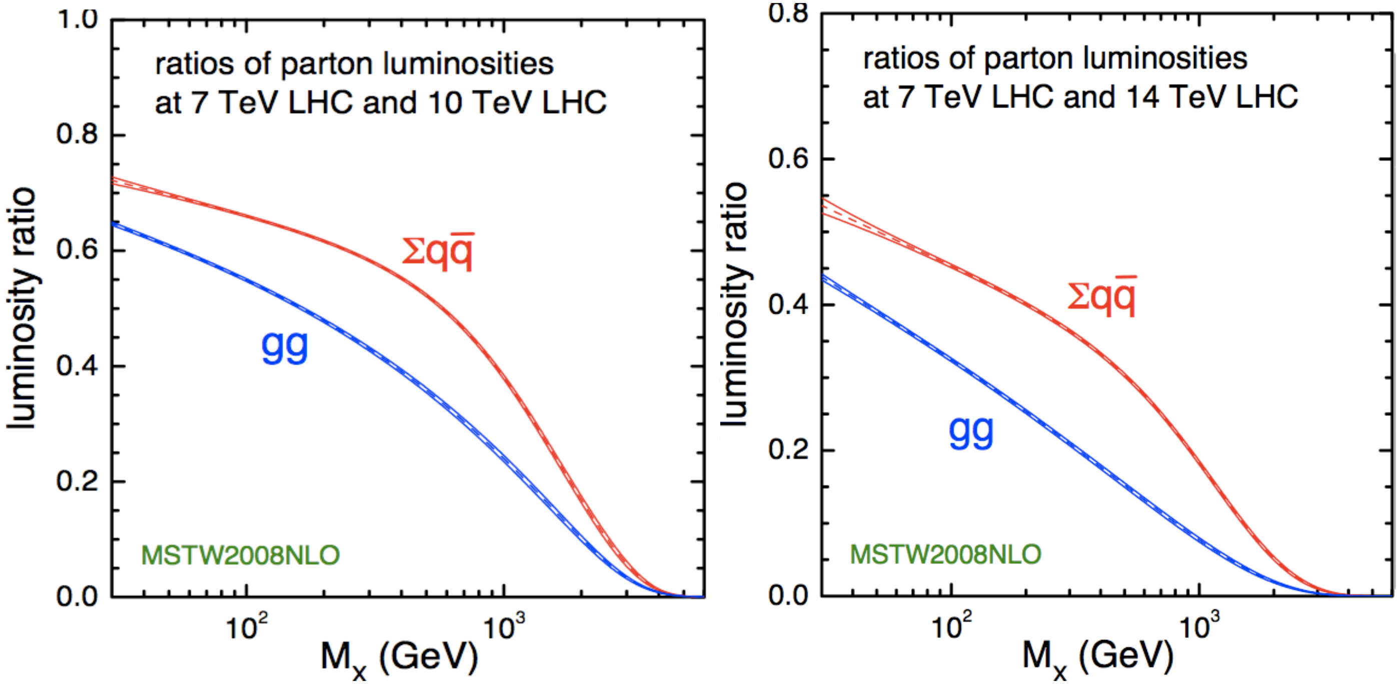


2010

First physics run in 2~~00~~9: 50 pb^{-1}

Startup of the LHC

- Beam energy at startup will be 7 TeV
- Then the energy will be increased possibly to as much as 10 TeV
  - 7 TeV is (most likely) not a discovery energy with O(100) pb^{-1}
  - A good sample of data at 10 TeV (> 100 pb^{-1}) will be needed



James Stirling

Yesterday 10/8

O(10) pb^{-1} @ 7 TeV $\Rightarrow$ produce 100K $W \rightarrow l\nu$, 10K $Z \rightarrow ll$, 1000 top pairs…