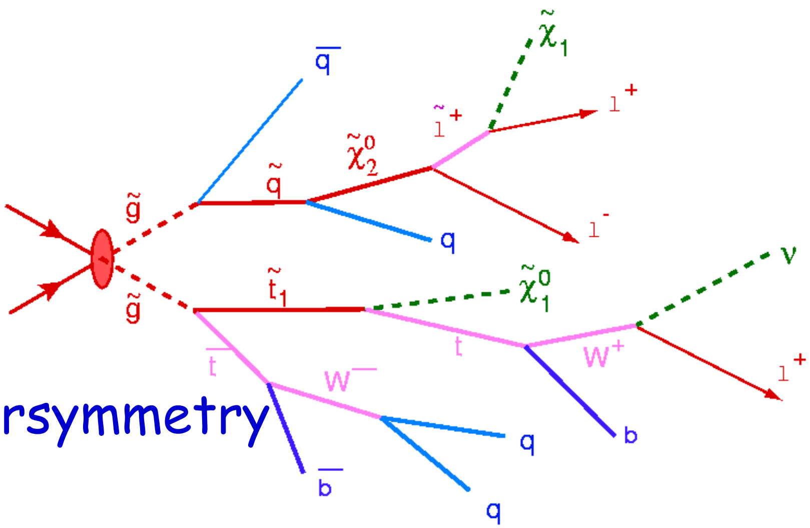
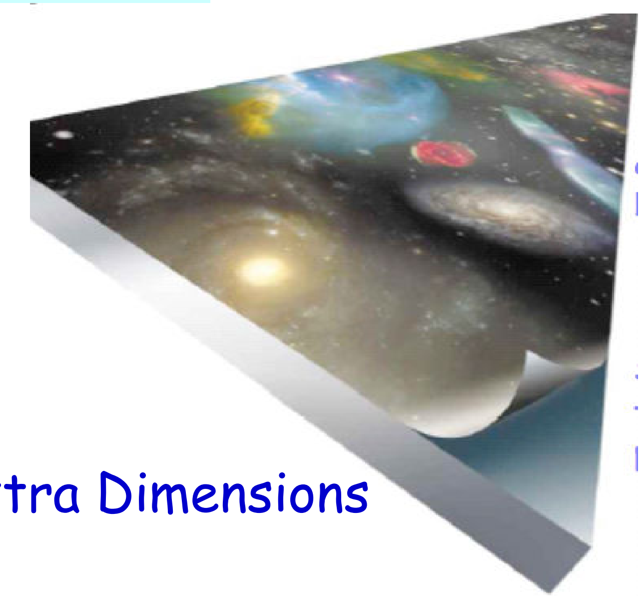
The Search for Physics Beyond the Standard Model

CERN Summer Student Lecture II

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



Supersymmetry



Extra Dimensions

Contents

⇒ Lecture 1

- Introduction: Beyond the Standard Model
- Supersymmetry
- Extra Spatial Dimensions
- Black Holes
- Is the LHC dangerous place?

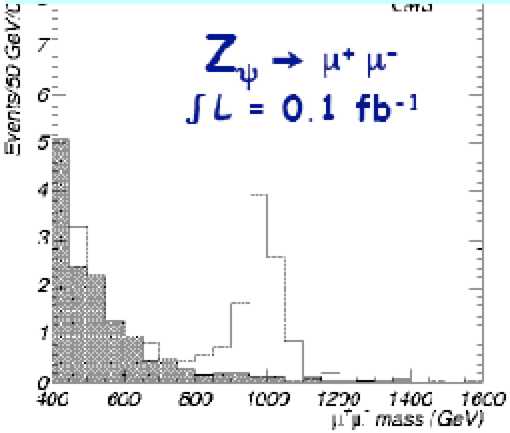
⇒ Lecture 2

- Other models for new physics
- Special exotic signatures
- The task that lies ahead for the LHC
- Summary

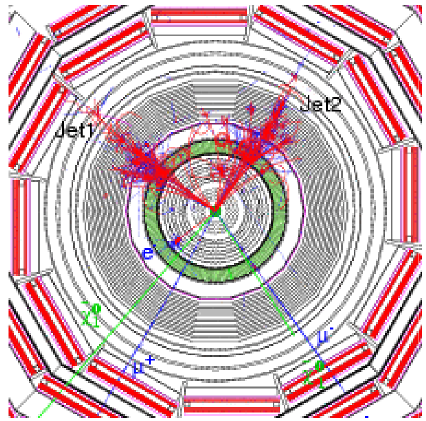
See also lectures of G. Dvali

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

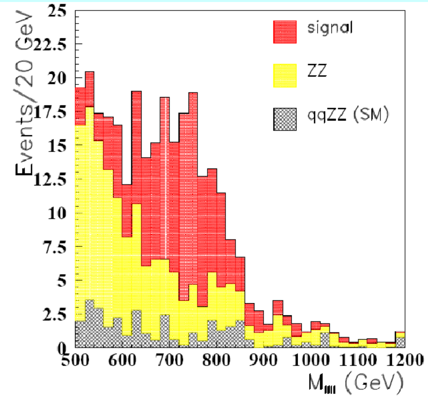
New Gauge Bosons?



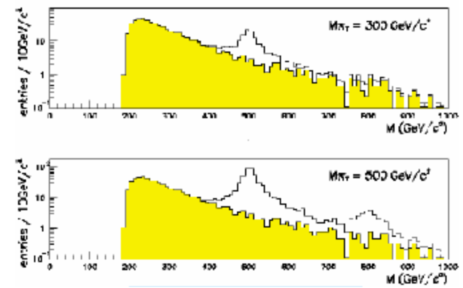
Supersymmetry



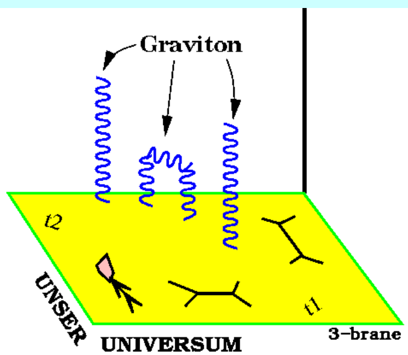
ZZ/WW resonances?



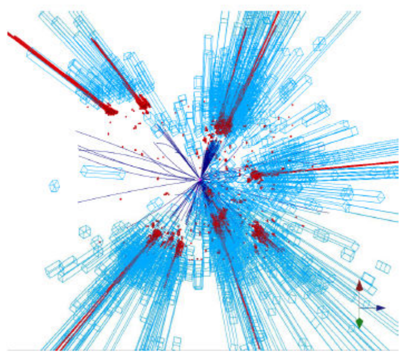
Technicolor?



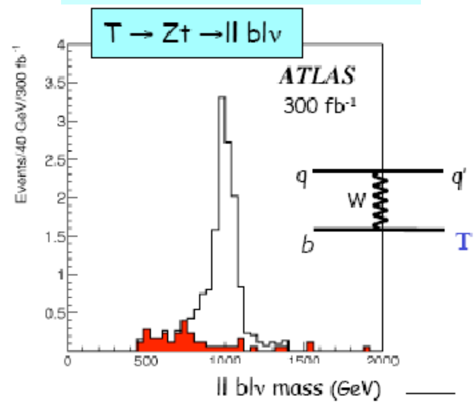
Extra Dimensions?



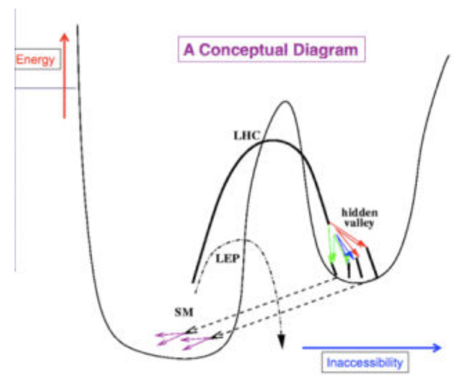
Black Holes???



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

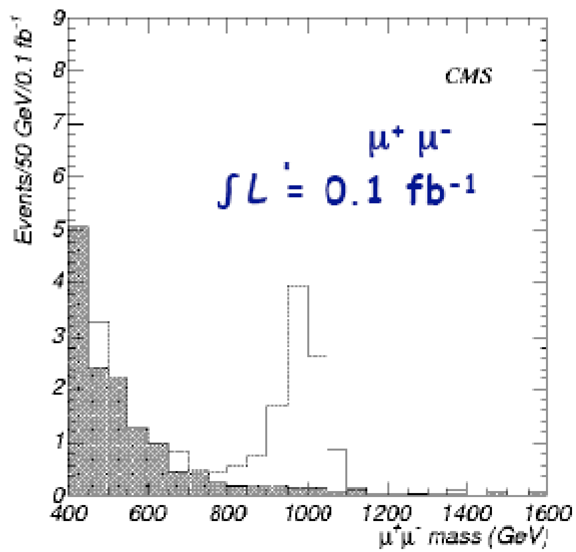
Early Discoveries? E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

A peak!!

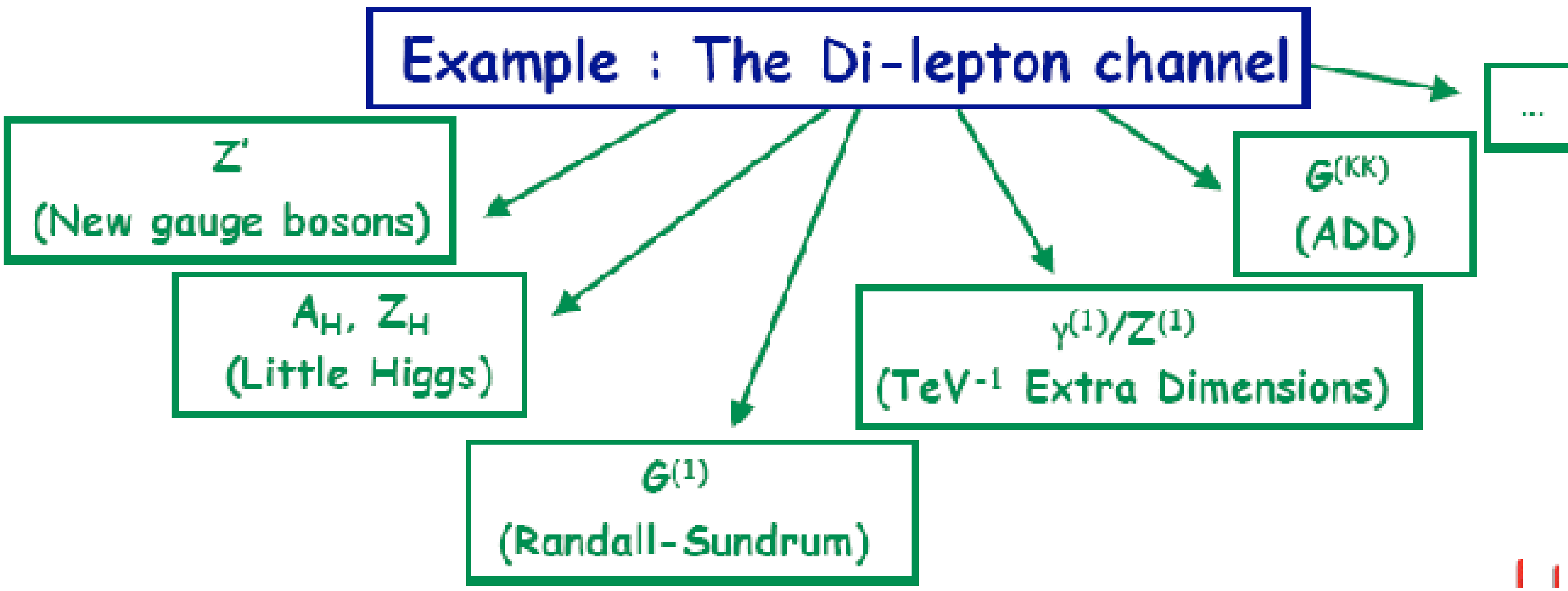
A new particle!!

A discovery!!



$pp \to \mu\mu + X$

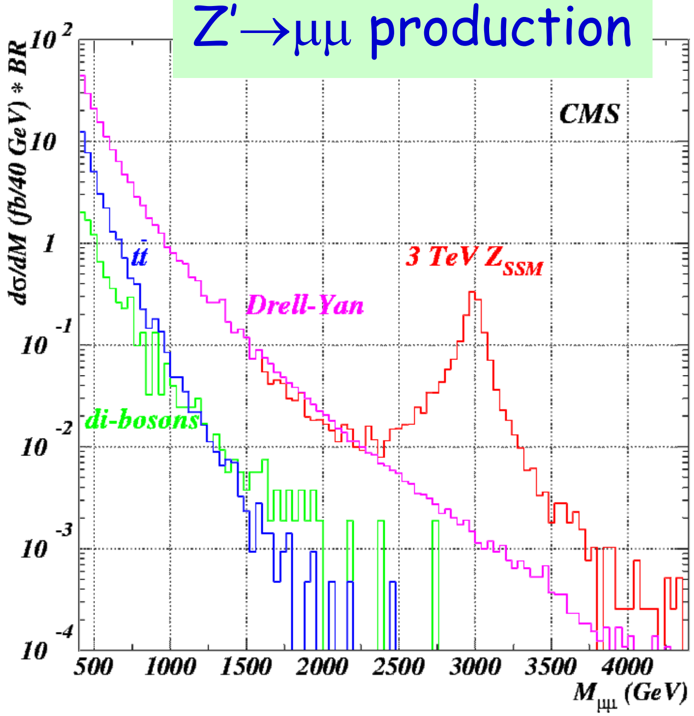
First year of operation

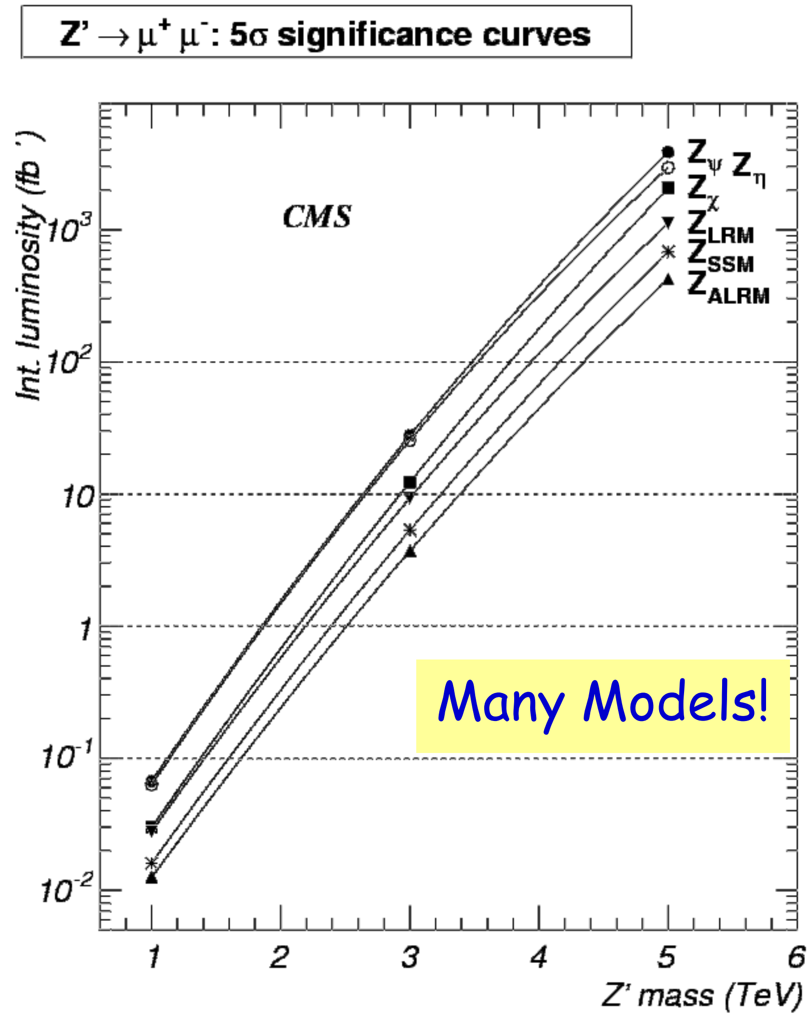


New Heavy Gauge Bosons: Z'

EG due a new symmetry group…

Z'→μμ production





Many Models!

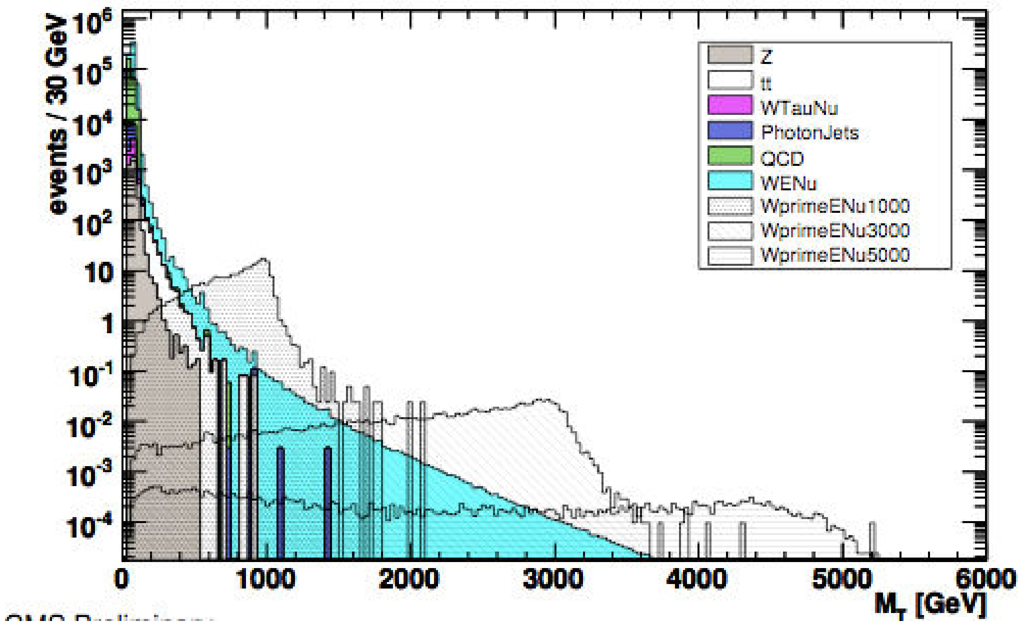
Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

- 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'

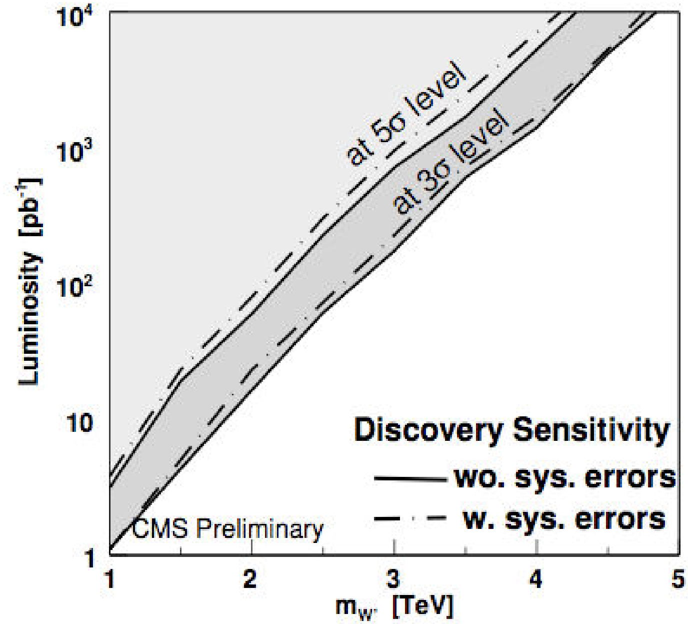
If a Z' exists: what about a W'?

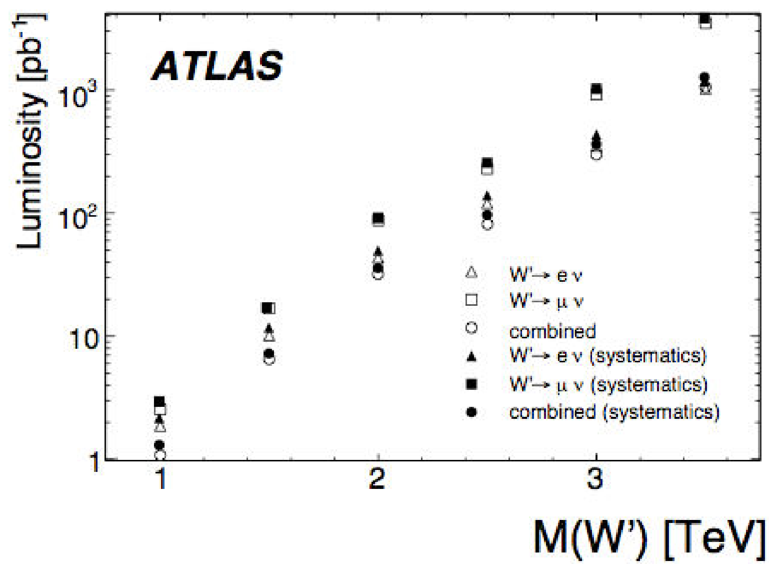
$W \to \mu\nu$, $e\nu$ channels



Tevatron > ~ 1 TeV

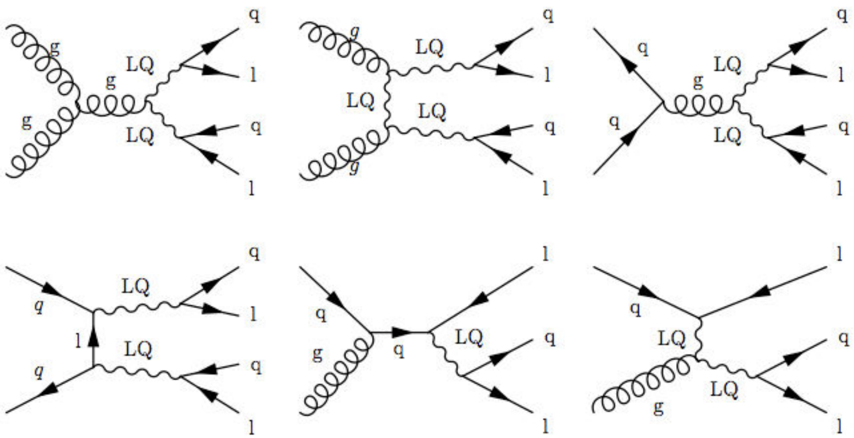
Sensitivity already for 10 pb^{-1}





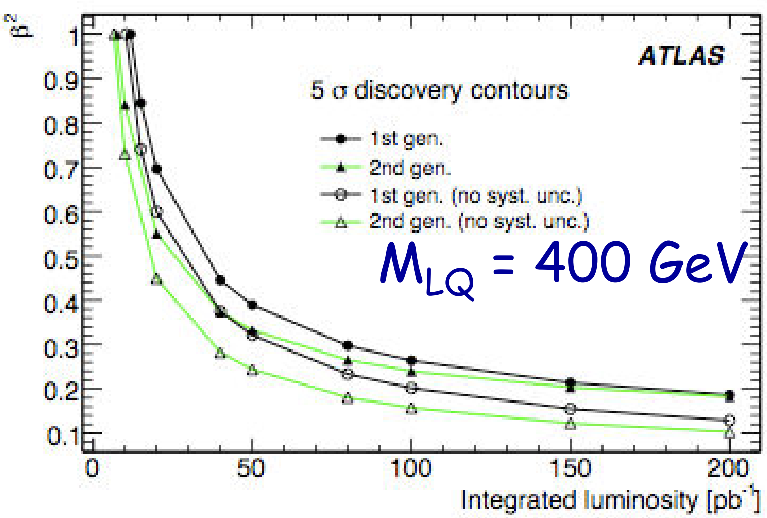
Leptoquark Production

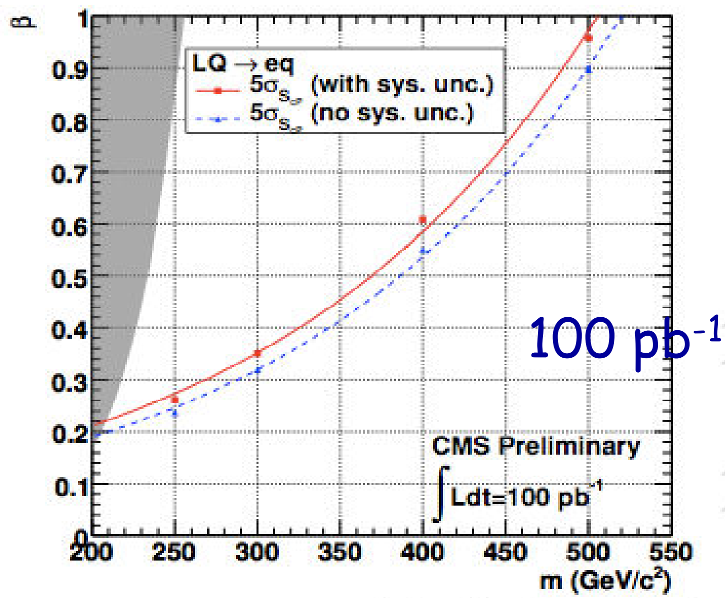
GUT inspired models predict new particles with lepton and quark properties



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}

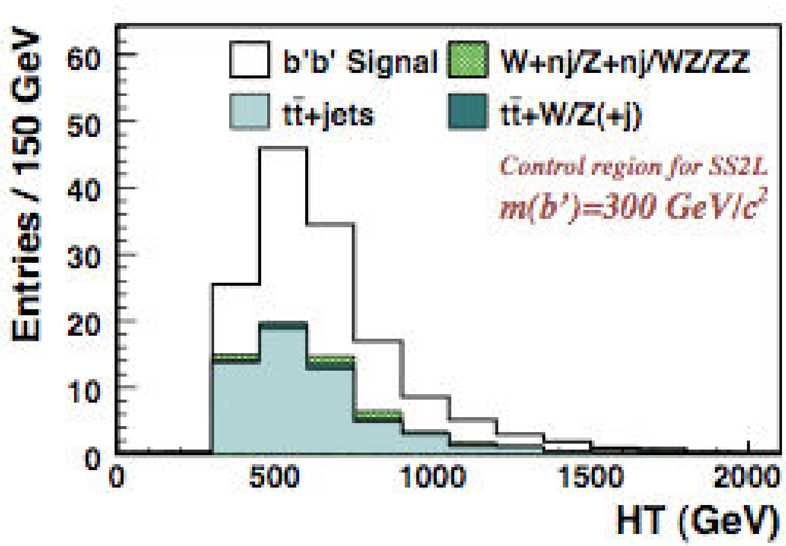


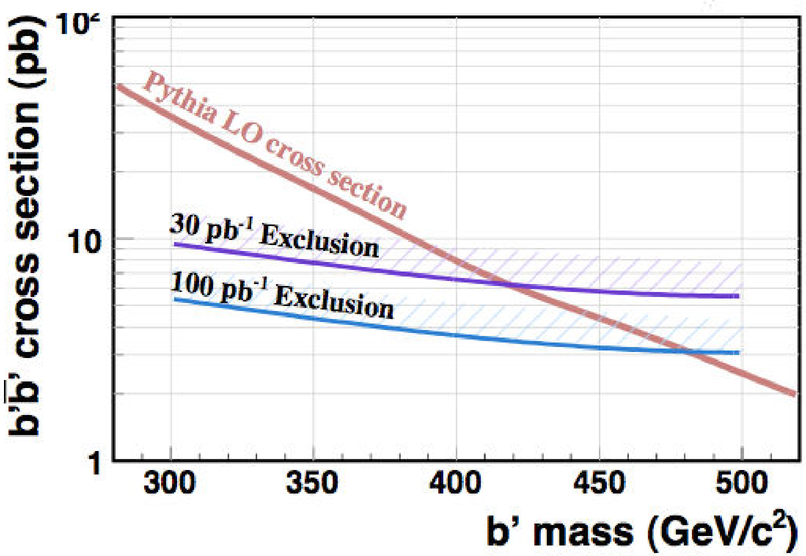


β: fraction decaying into eq (vs νq)

> 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

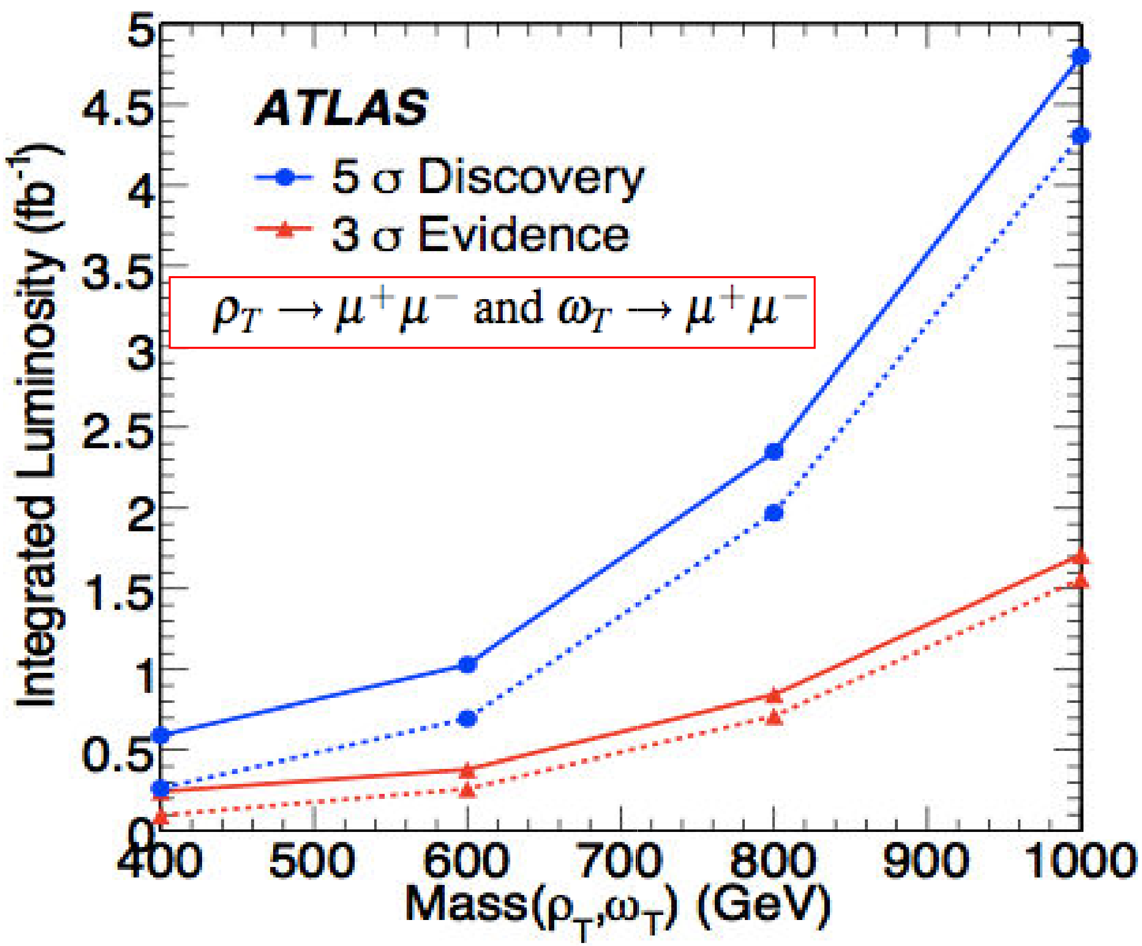
Tevatron Limits

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

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

A new strong force: Technicolor?

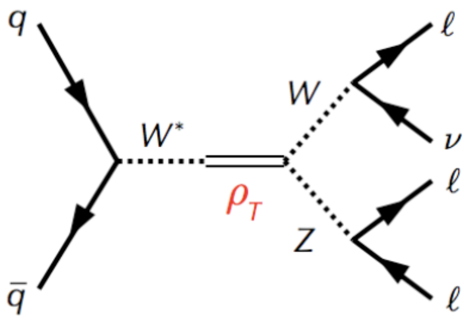
No elementary Higgs but a new type of color-like force, predicting particles called techni-pions, techni-rhos, techni-omegas…with masses ~ few 100 GeV



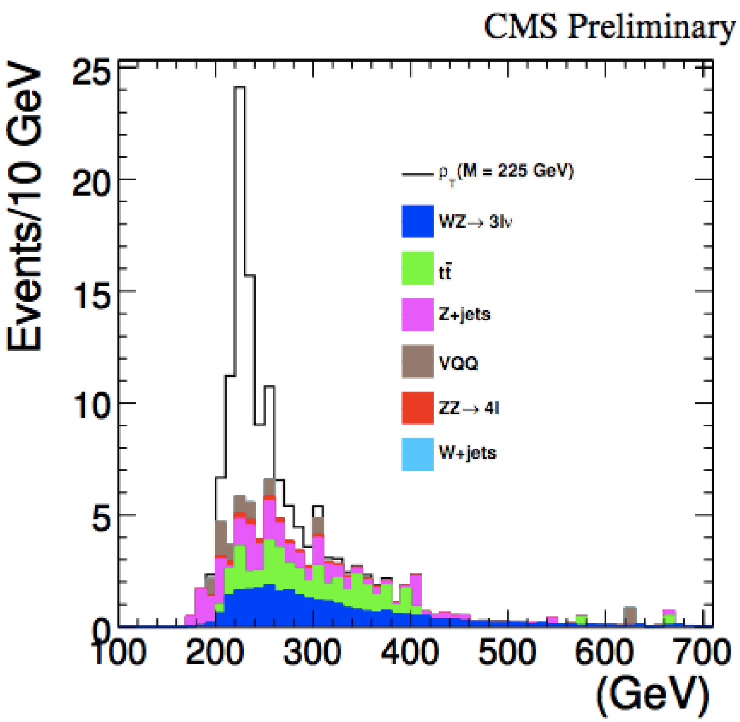
Luminosities of ~ 0.5-1 fb^{-1} or more needed

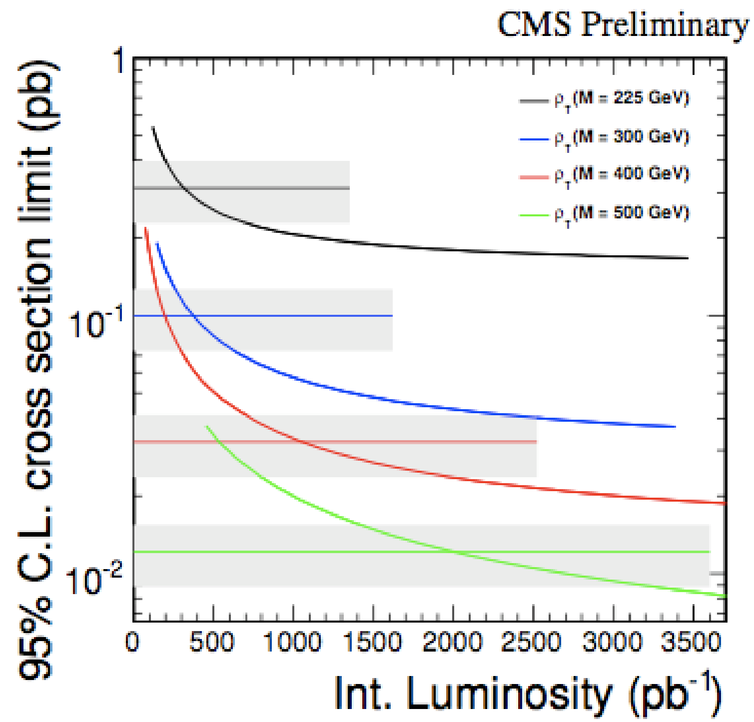
A New Force: Technicolor

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



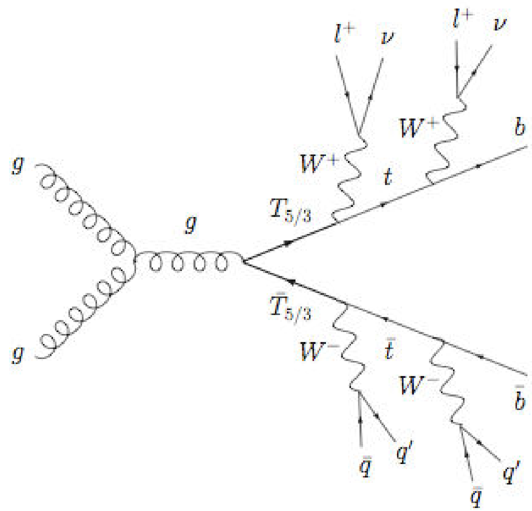
Luminosities of ~ O(0.5) fb^{-1} or more needed

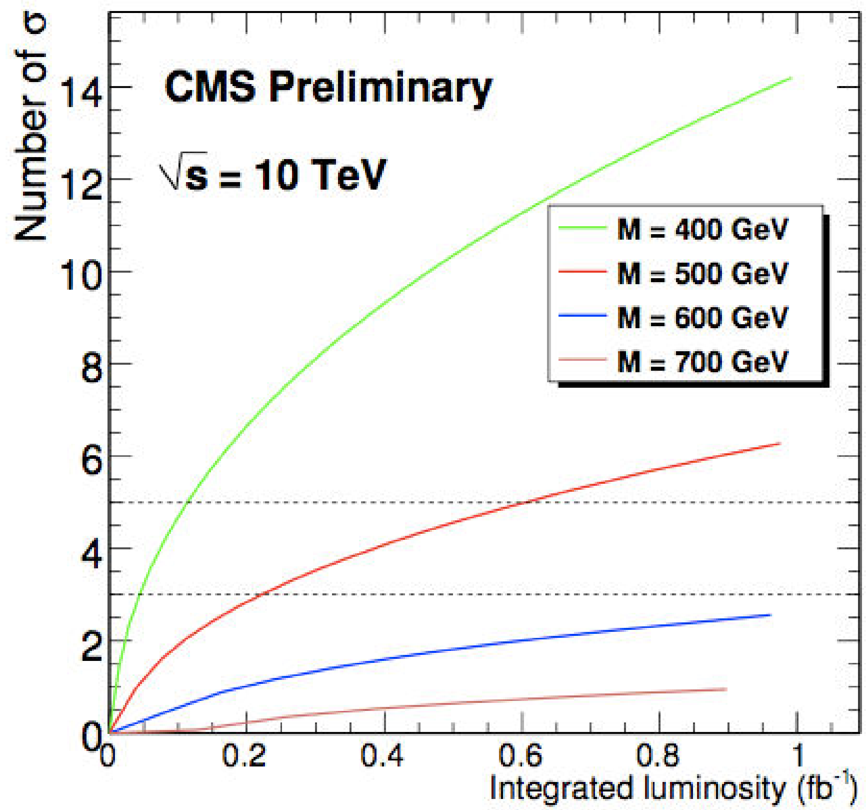




Particles with Unusual Properties

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



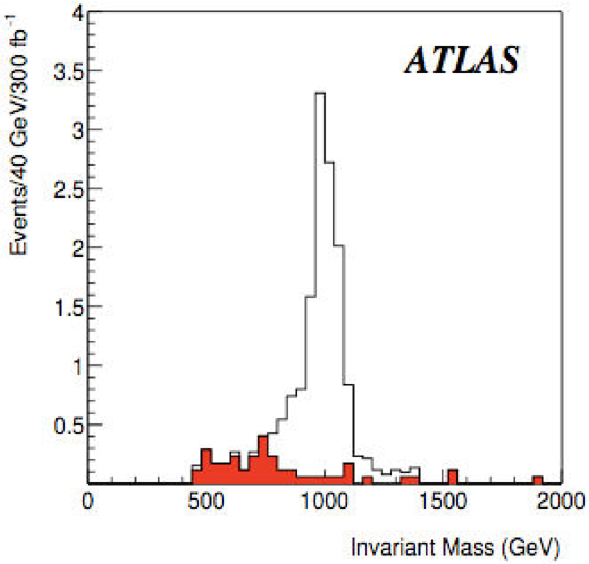


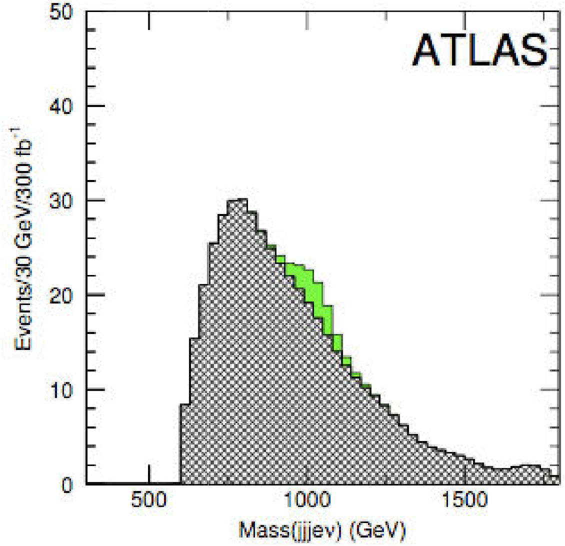
Produced in models with warped space dimensions
Characteristic: like sign leptons in decay

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

Little Higgs Models

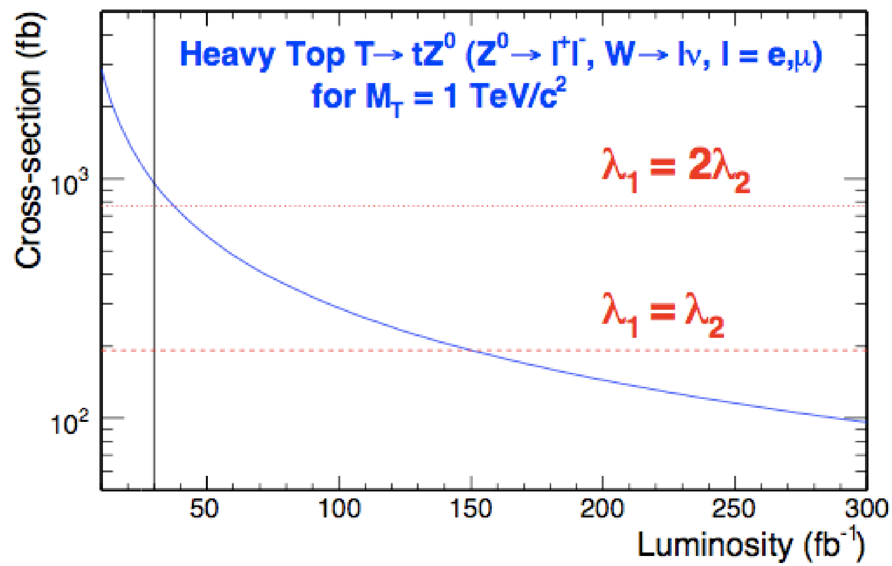
Heavy top partner around 1 TeV ⇒ Decay eg into $T \to tZ$, $T \to tH$



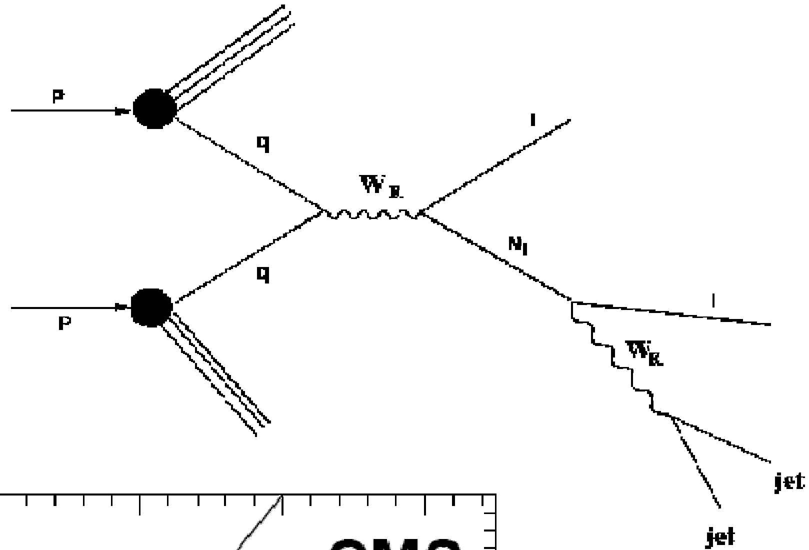


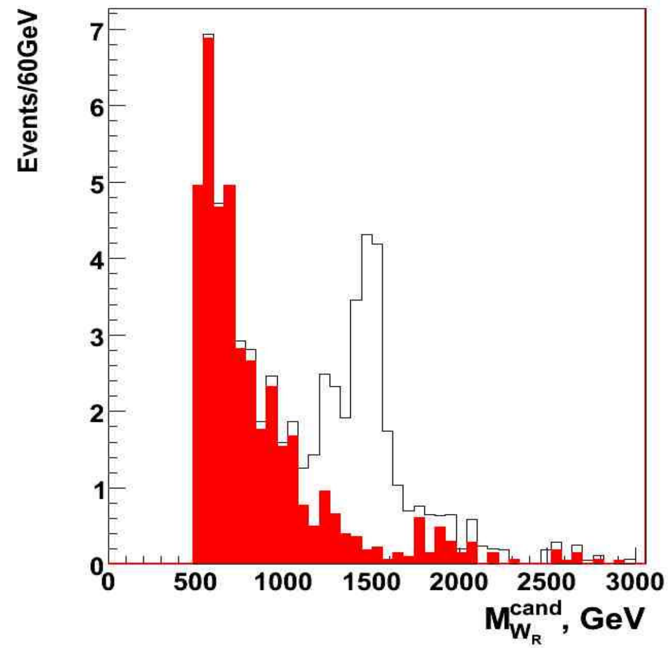
Signals+BG
Needs a lot of luminosity!!

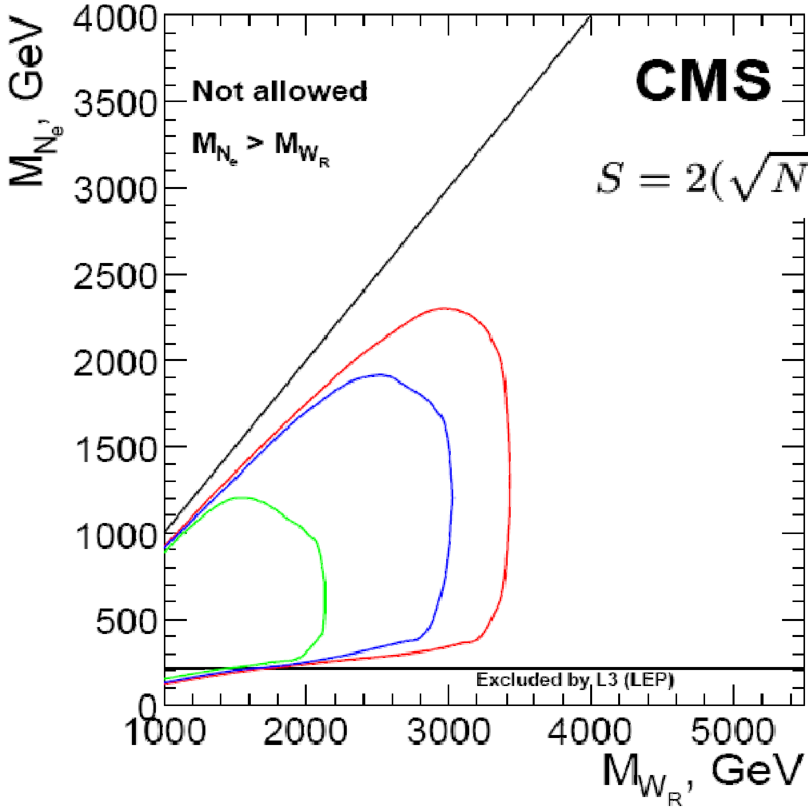
CMS PTDR:
Sensitivity to heavy top cross section



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

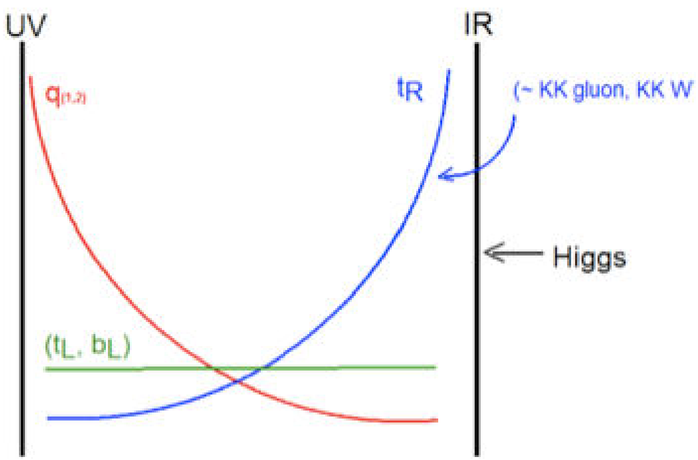
N>0.3 TeV

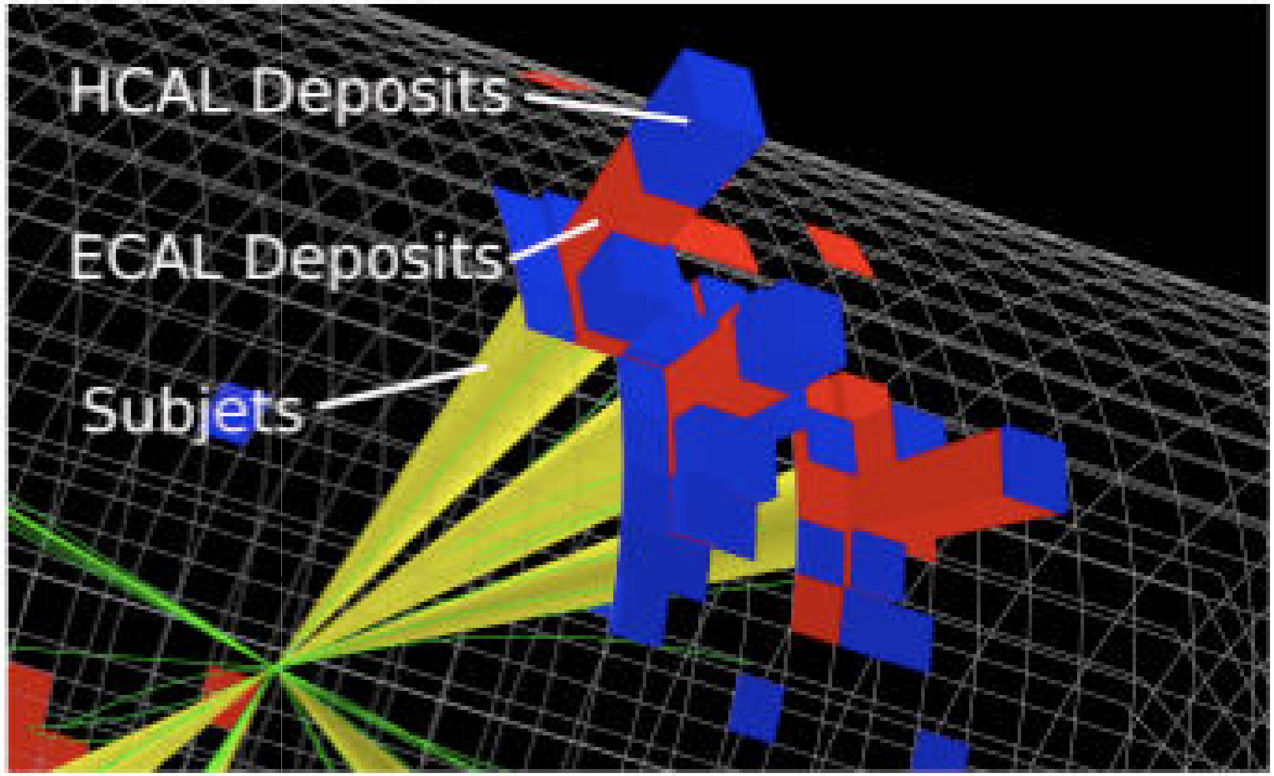
M(WR) = 1.2 TeV, M(Nl) = 500 GeV can be discovered with 40 pb^{-1} @ 10 TeV

TeV Resonances into Top Quark Pairs

Recent developments in models: q 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



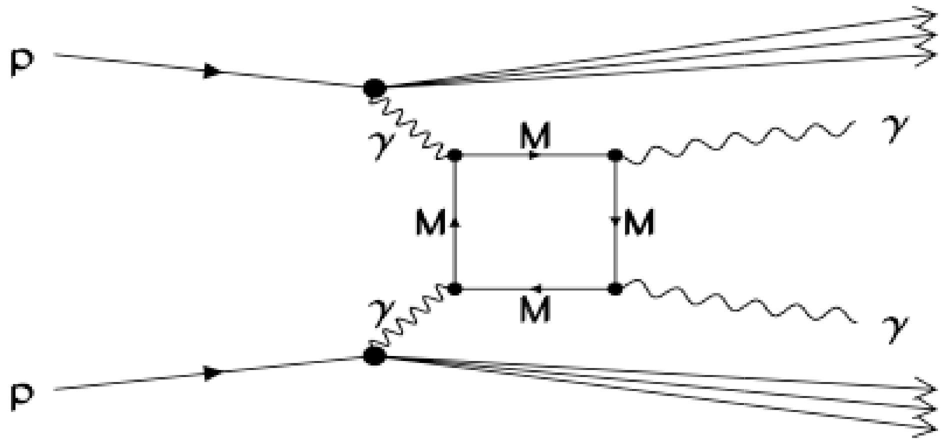


Methods are prepared to tackle the early data

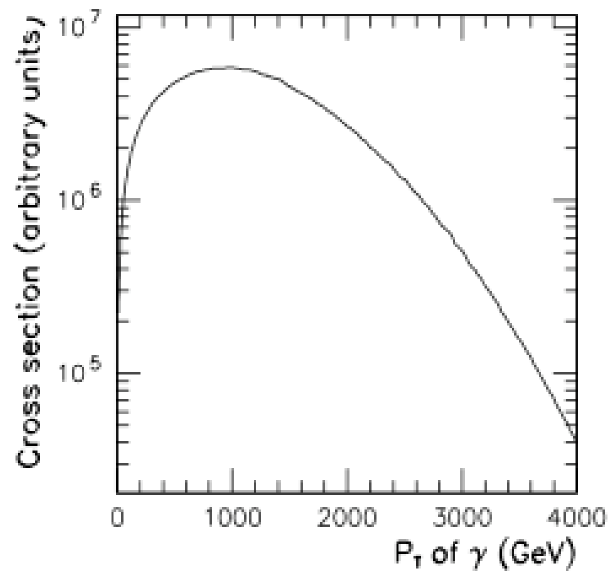
⇒High P_T tops

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

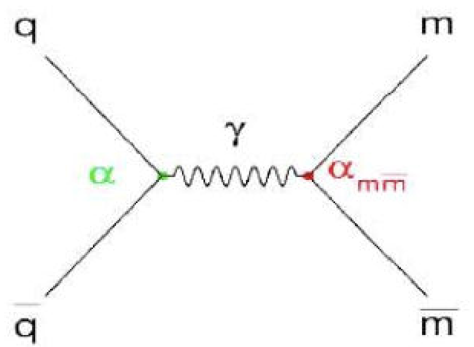


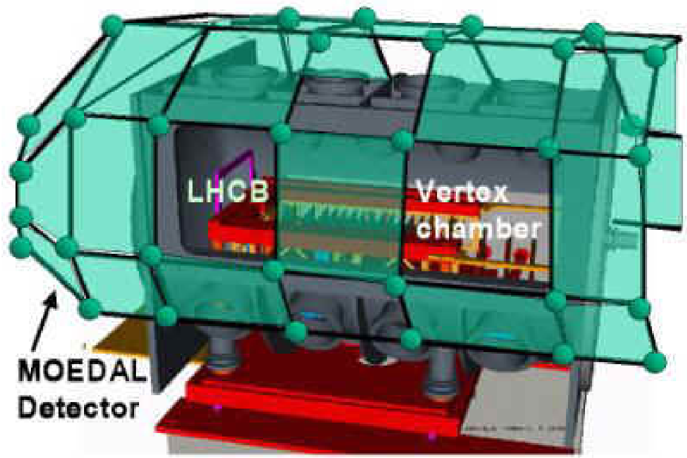
$$\sigma_{pp\to\gamma\gamma X}(E,M,P,n) = 108P\left(\frac{nE}{M}\right)^8\left(\frac{N(E)}{N(1\mathrm{TeV})}\right)^2\left(\frac{1TeV}{E}\right)^2\mathrm{fb}$$

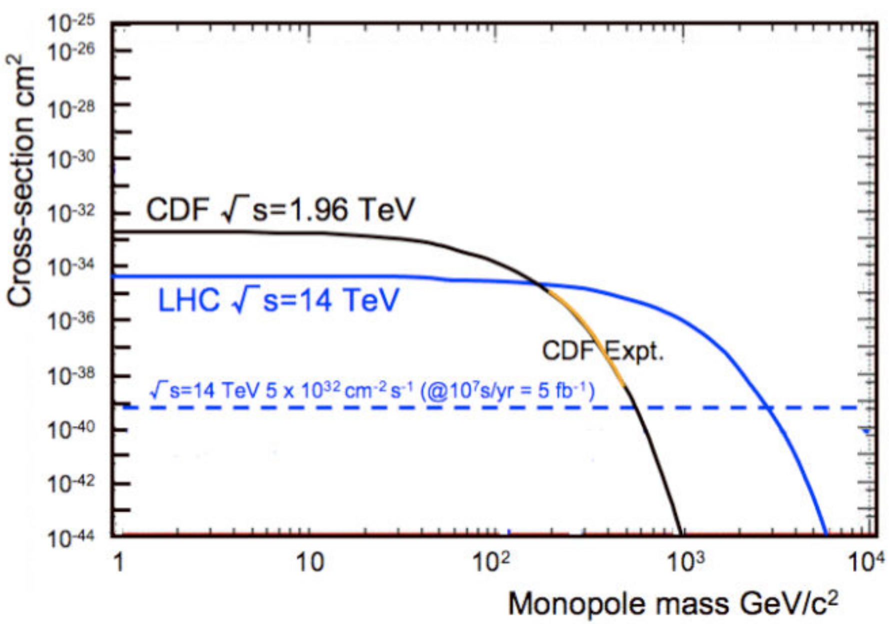
Cross section O(fb)
High luminosity required

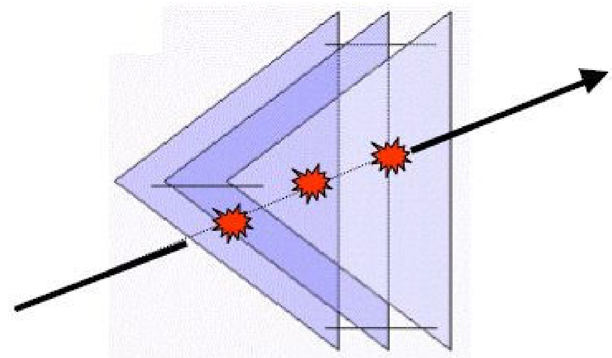
Moedal: MOnopole and Exotics Detector at the LHC

Direct Monopole production









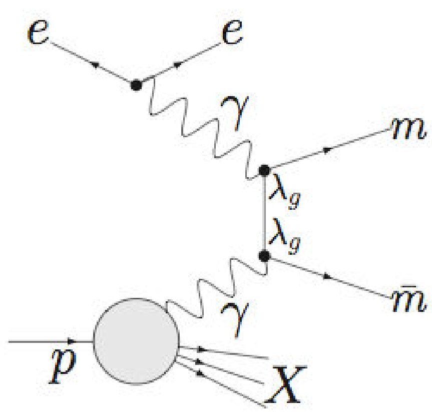
Remove the sheets after some running time and inspect for 'holes'

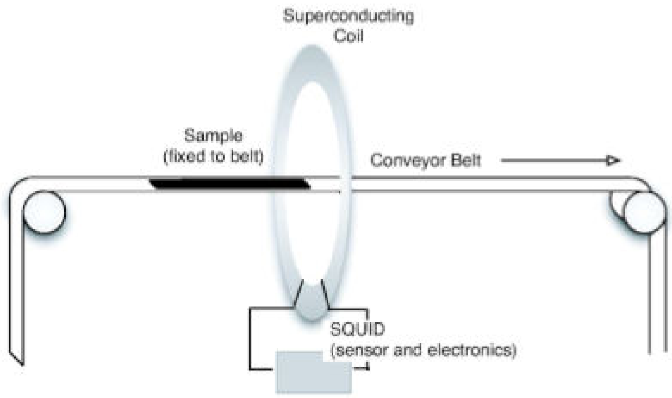
Monopole Search

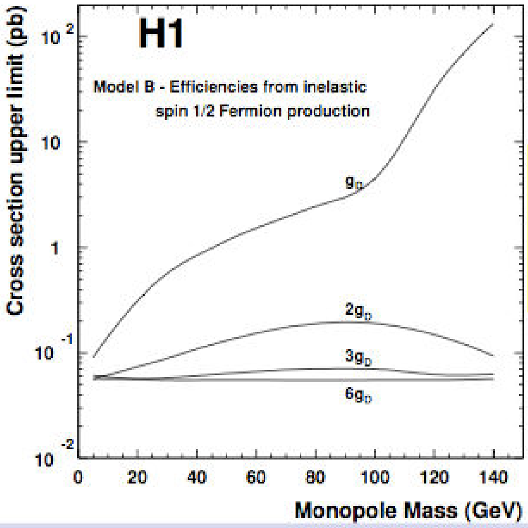
H1 experiment at the ep collider HERA, Hamburg

Magnetic Monopoles stuck in the beampipe?

- Dirac monopoles with large magnetic charge → highly ionizing
- $\lambda_D = \frac{g_D}{\sqrt{4\pi}}$
- Predicted to be light by some models
- Could be trapped in beampipe (Al)
- 1994-97 beampipe was cut into strips and passed through superconducting coil







Also accessible at the LHC

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

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

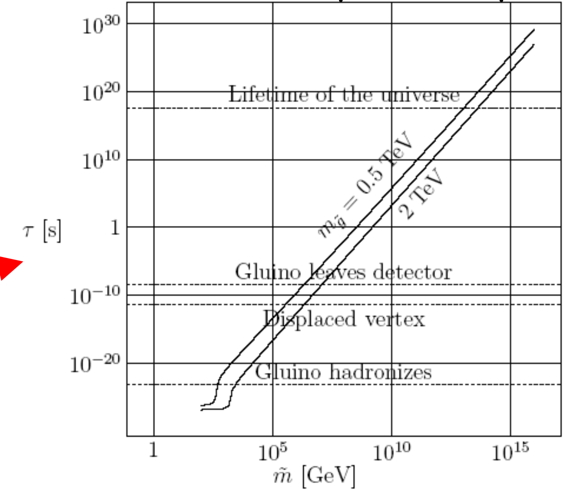
 eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

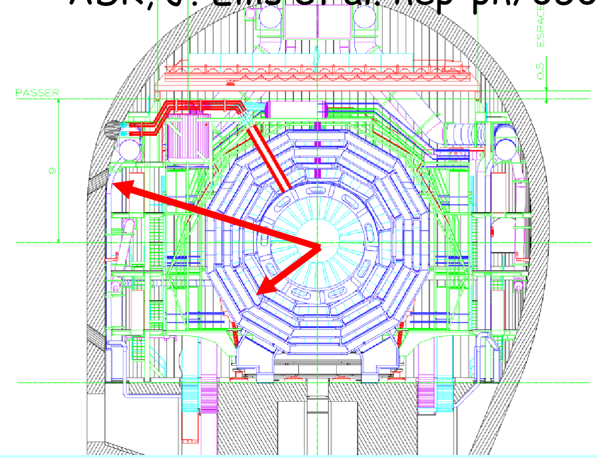
- In some models/phase space the gravitino is the LSP
- $\Rightarrow$ NLSP (neutralino, stau lepton) can live 'long'
- $\Rightarrow$ non-pointing photons

$\Rightarrow$Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



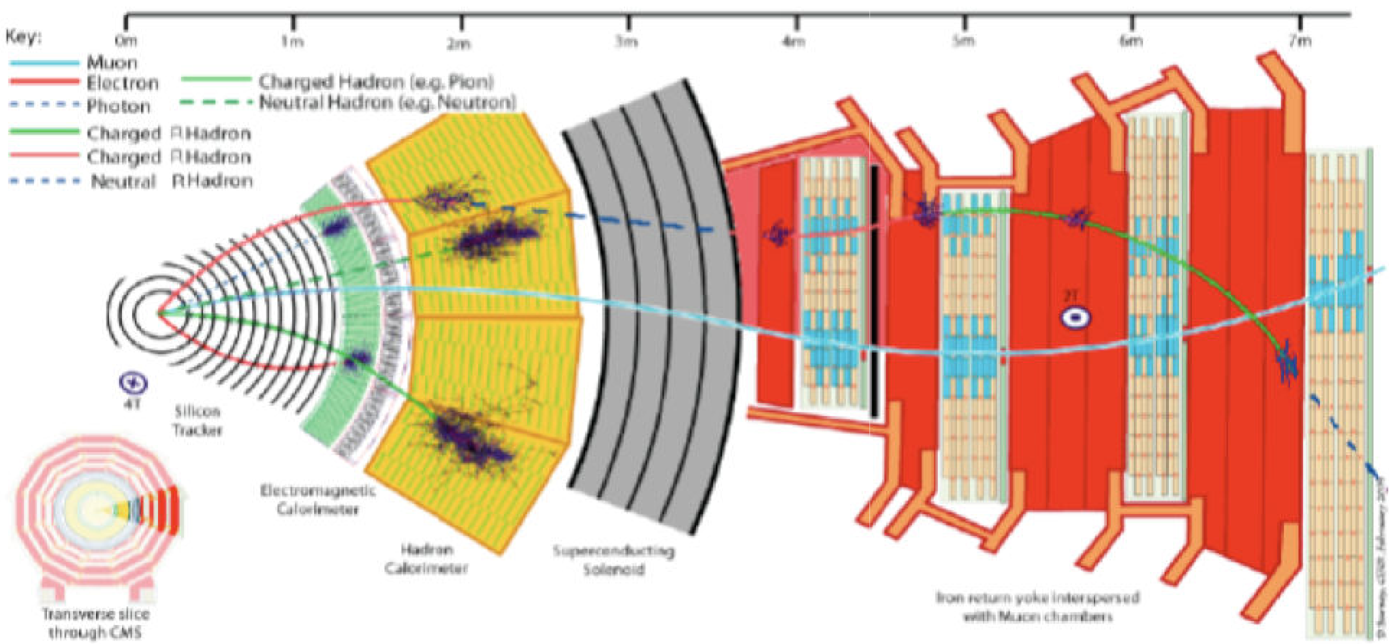
K. Hamaguchi,M Nijori,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198



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)

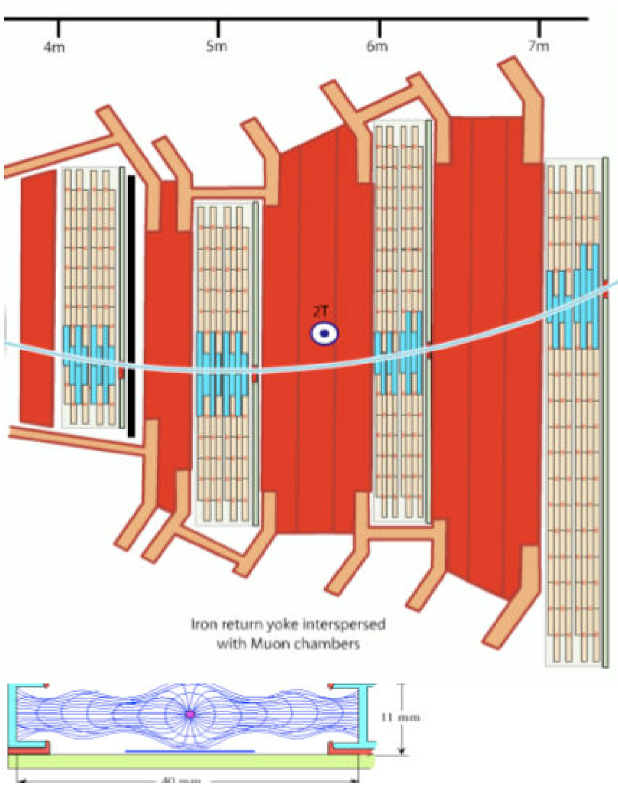


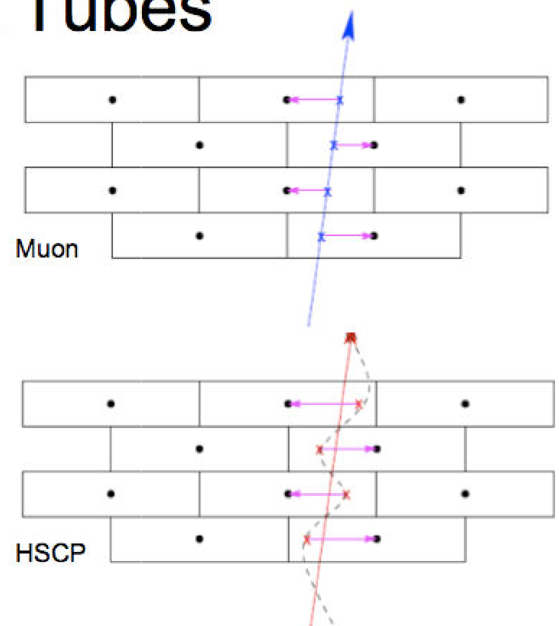
Weird signature!!

Heavy Stable Charged Particles

The heavy particles are moving with less the speed of light, ie. $\beta < 1$
A particle with $\beta = 1$ reaches the muon detectors in CMS after 13 ns
A particle with $\beta < 1$ reaches the muon detectors later than 13 ns

TOF in Drift Tubes





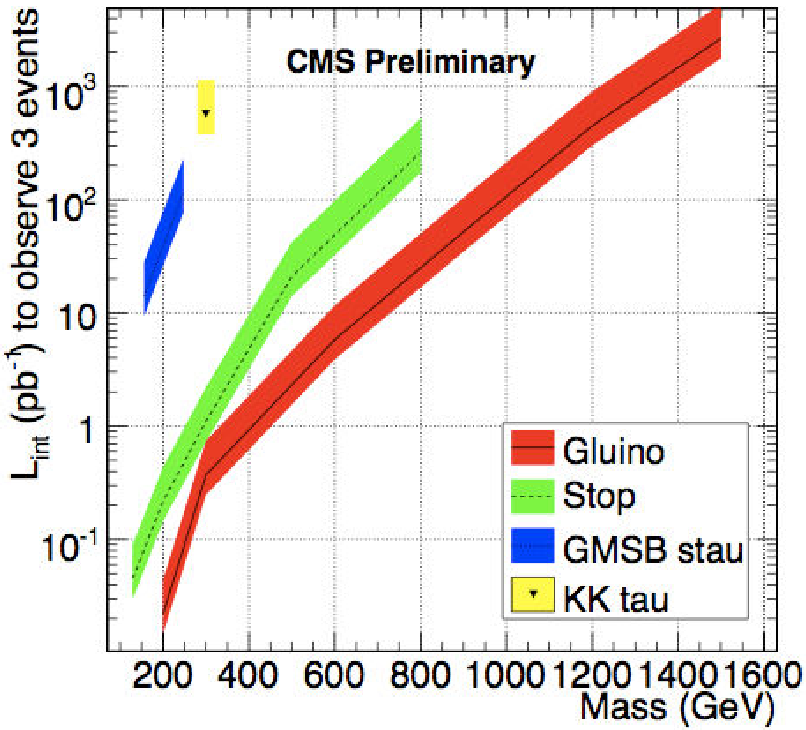
Normally the fit assumes $\beta=1$; here δt is left as a free parameter in the fit
=> TOF measurement
(see extra slides)

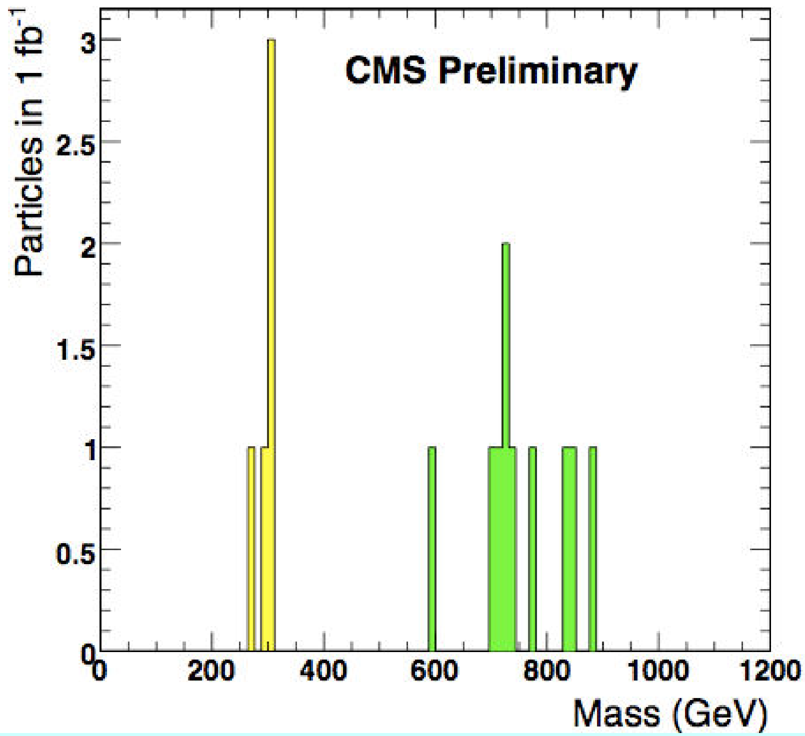
8

Derive the Time-of-flight from hit pattern in the muon chambers
$\Rightarrow$ Measure β of the particle from the time-of-flight!!

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

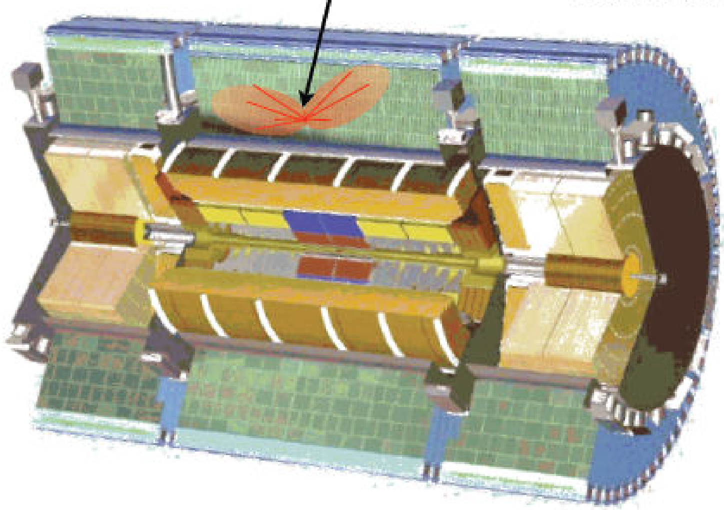
Stopped R-hadrons or Gluinos!

Long Lived Gluinos

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

looking for stopped gluinos that later decay

100s GeV Unbalanced $= \not\!\!E_T$



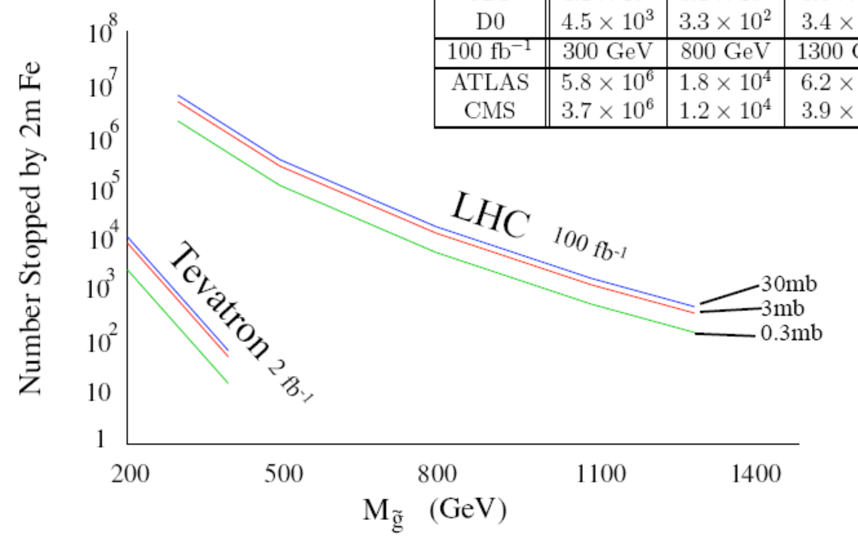
Uncorrelated with any beam crossing
No tracks going to or from activity

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

Total Number of Stopped Gluinos

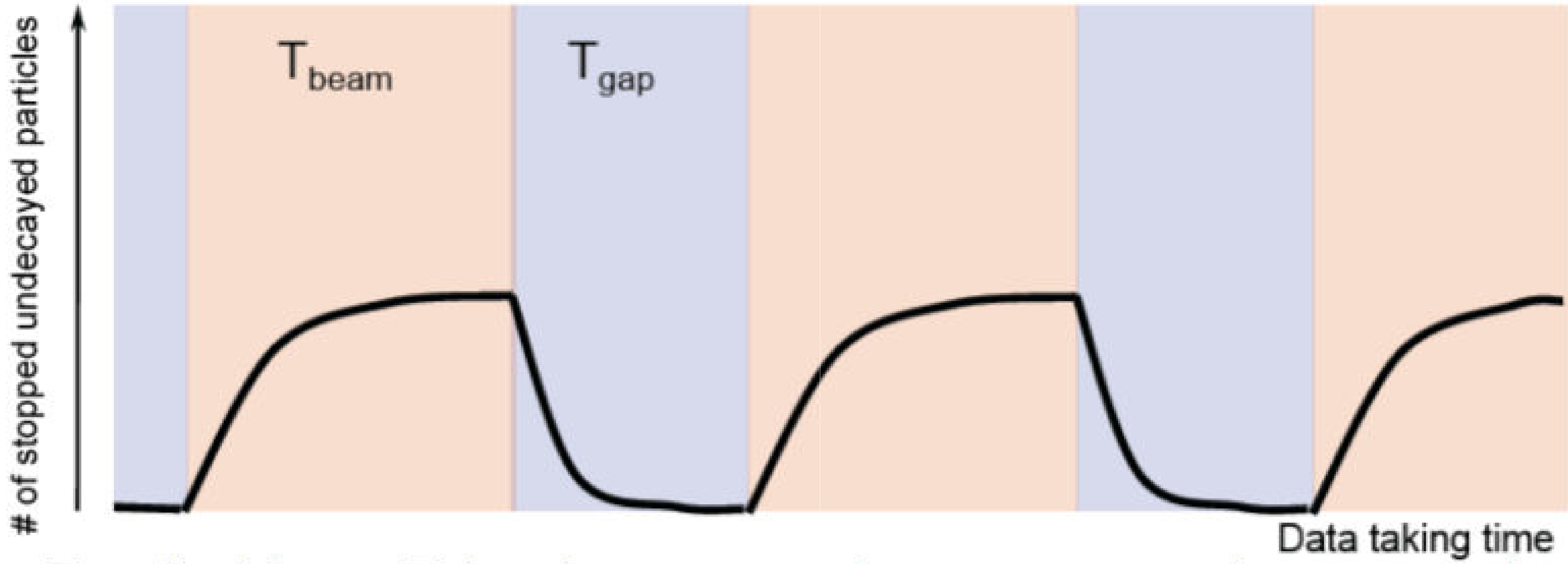
Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242

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



⇒ Special triggers needed, asynchronous with the bunch crossing

Stopped gluinos



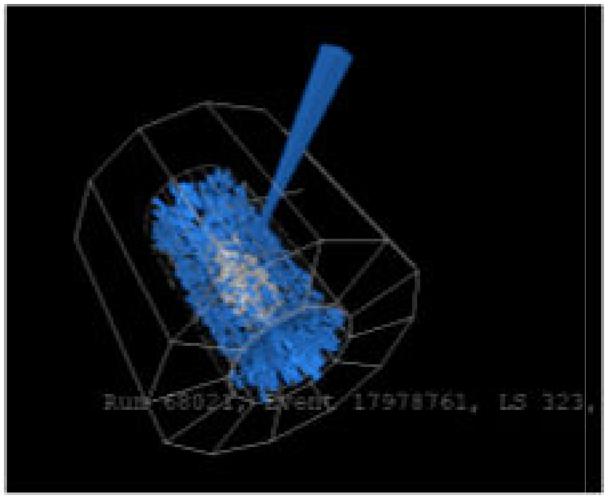
- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay Eg when there is no beam!
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

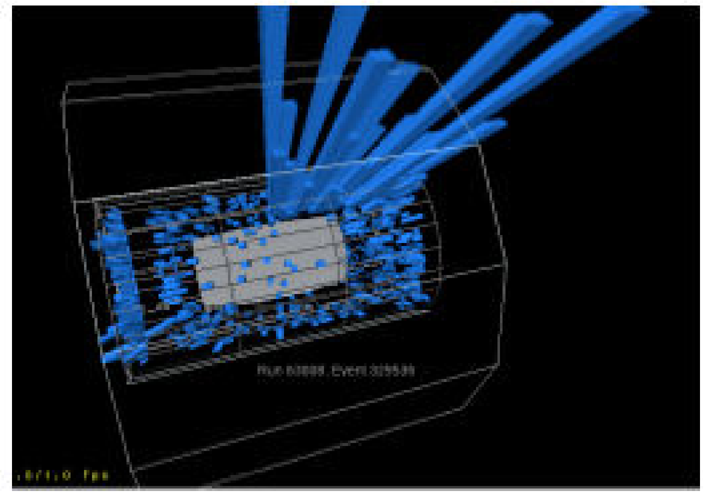
  Can be studied in the experiments NOW with cosmic data

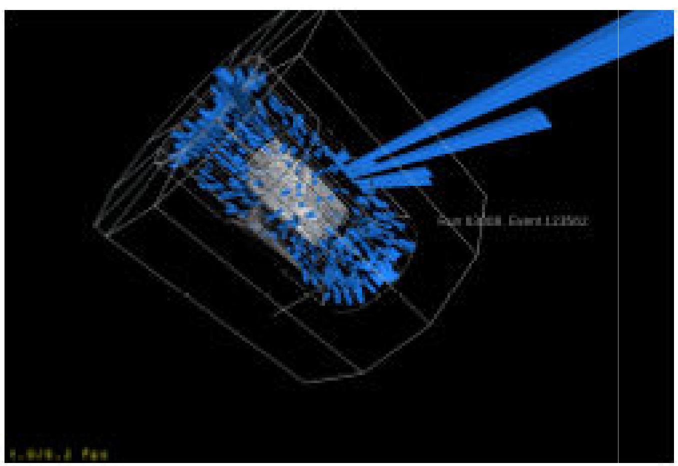
Stopped Gluinos

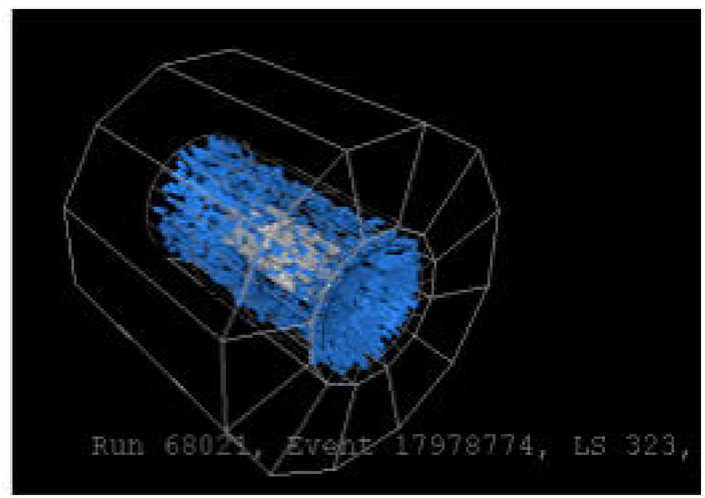
Studies in CMS with the 2008/2009 cosmic data:
All events we find now are background and we can learn how to cut on them!

Find energy splashes with certain topology



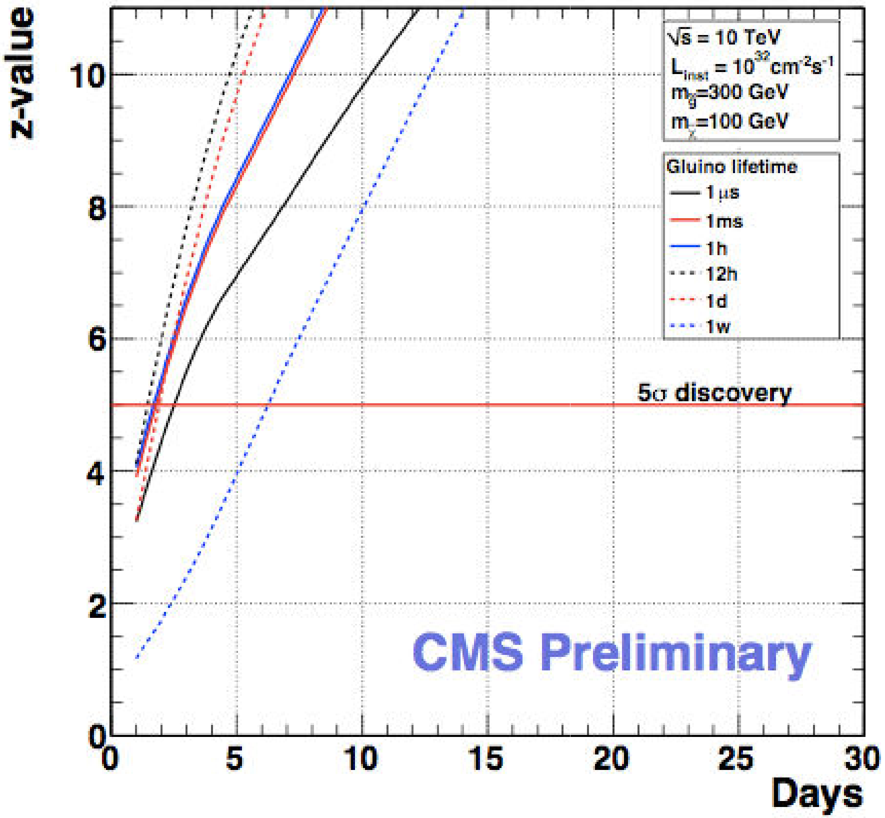






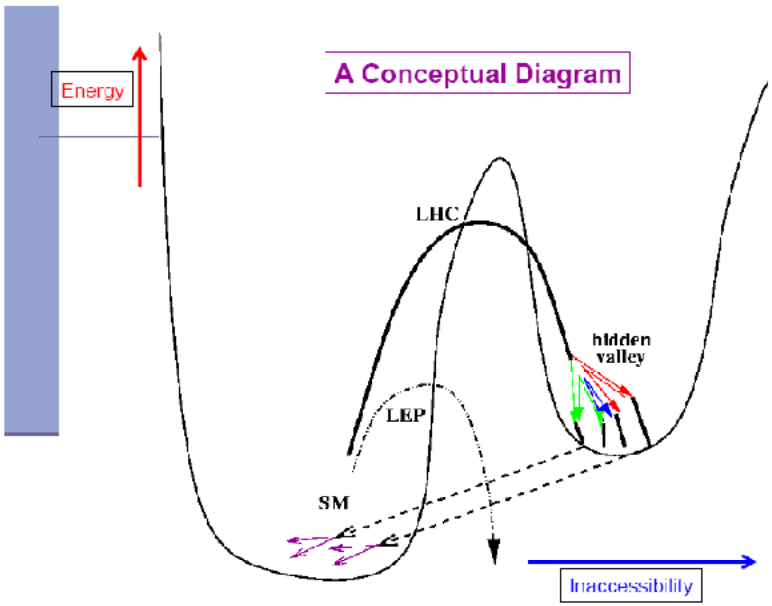
Stopped Gluinos

Expected sensitivity for stopped gluinos
Assuming a luminosity of 10^{32} $cm^{-2}s^{-1}$



We can discover such particles with only a few weeks running!

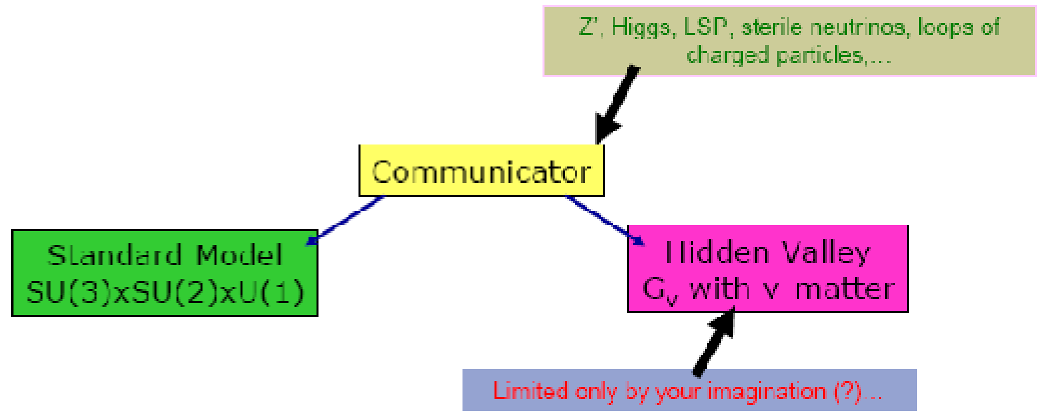
Is there a Hidden Valley?



String Theory inspired

Eg. Strassler & Zurek hep-ph/0604261

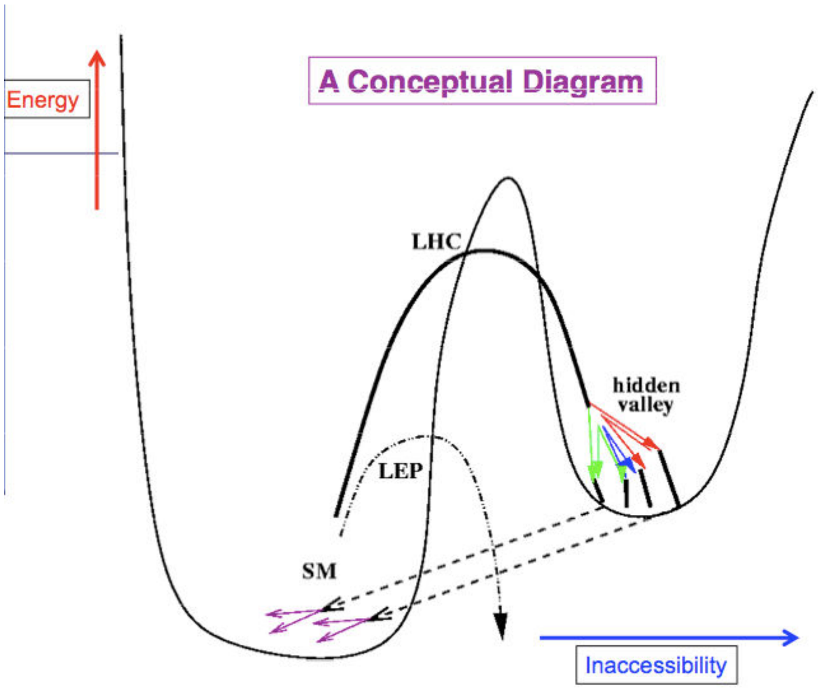
- Basic minimal structure

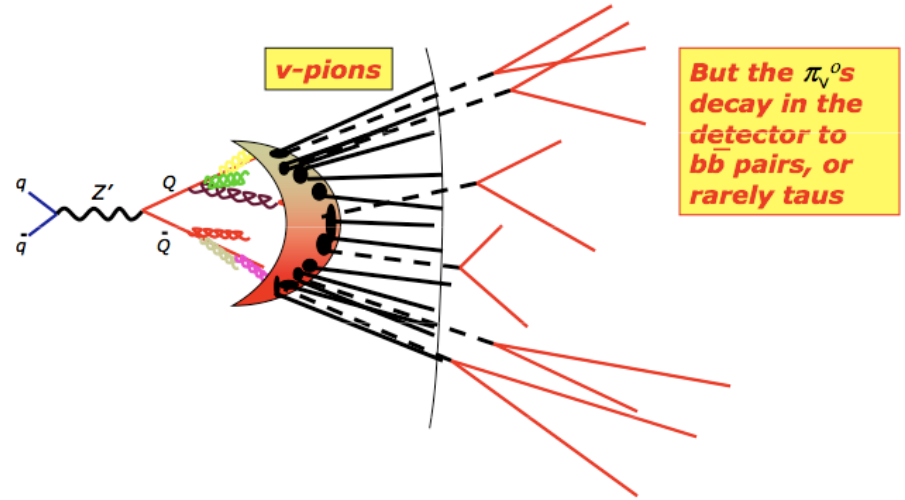


New possible phenomena that could occur in these models

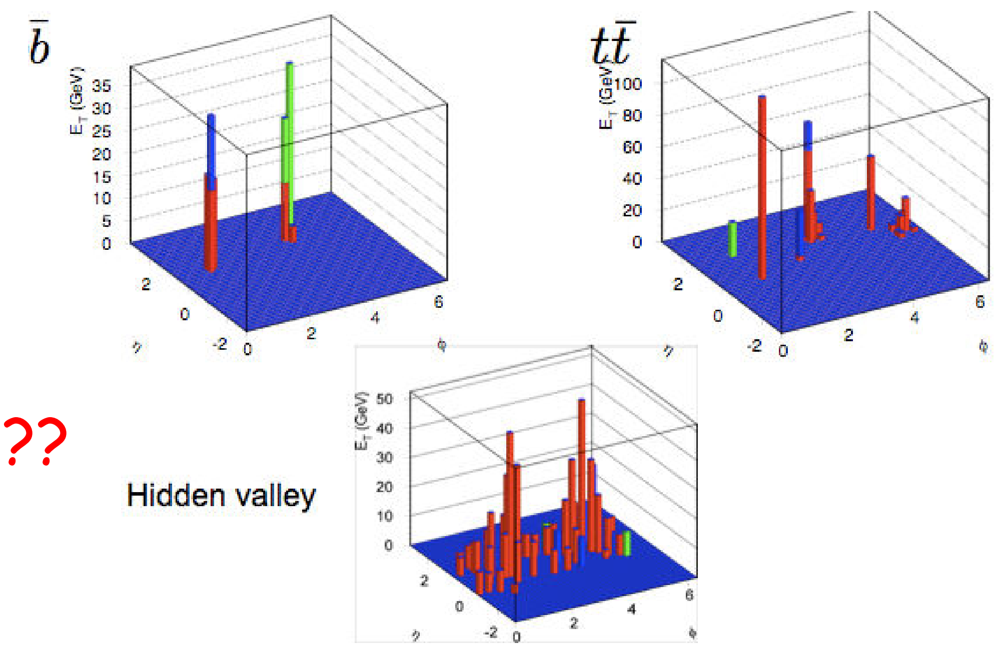
- Higgs decays to two [or more] long-lived particles
  - ***Aside*** *on classes of possible decays of new particles*
- Z' decays to the v-sector:
  - *Final state with many particles, possibly long-lived*
- LSP decays to the v-sector
  - *Degradation of MET signal*
  - *Wide array of complex final states*

Hidden Valley Physics: New Signatures





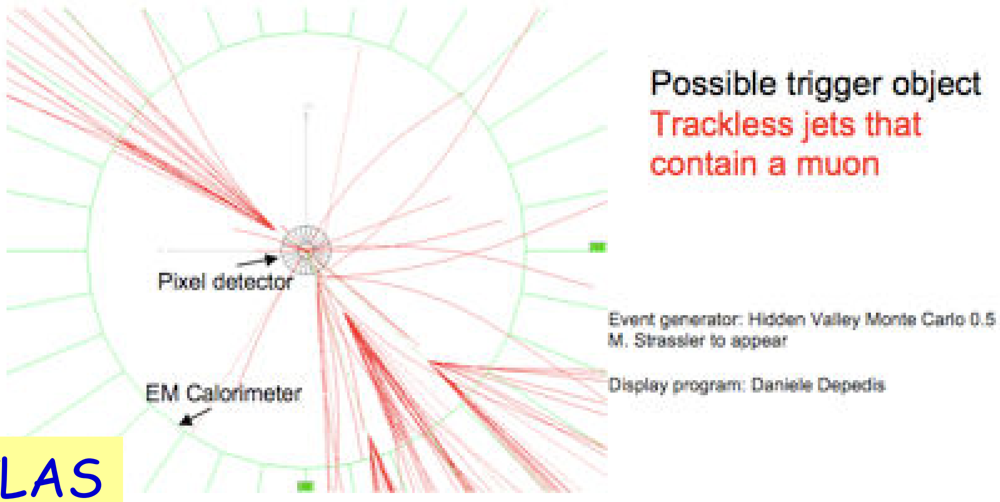
Will produce "Weird Jets" and a lot of secondary vertices



⇒ Difference with QCD jets??

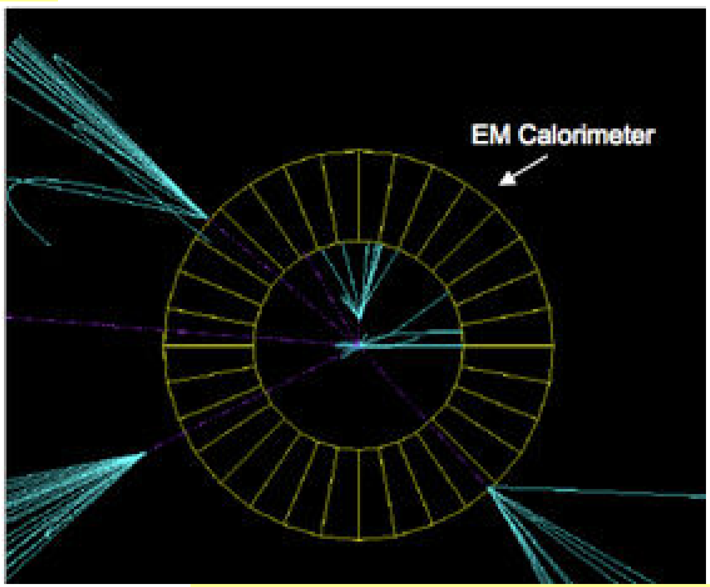
⇒ Study SM jet structure

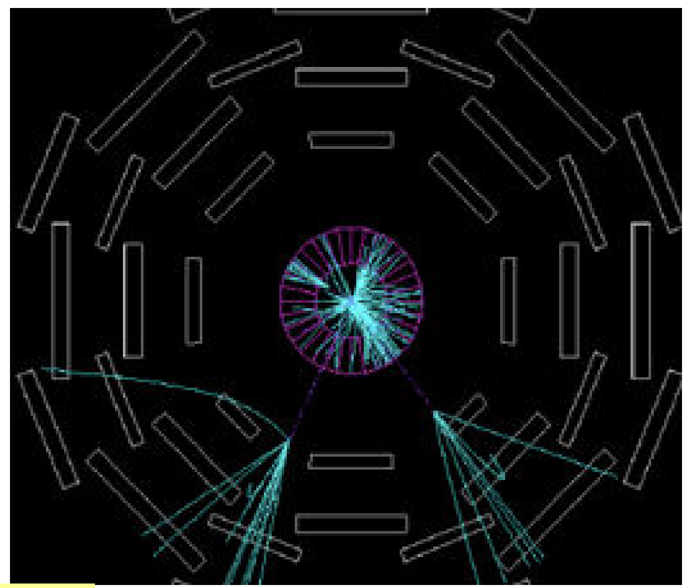
Hidden Valley Events



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

ATLAS



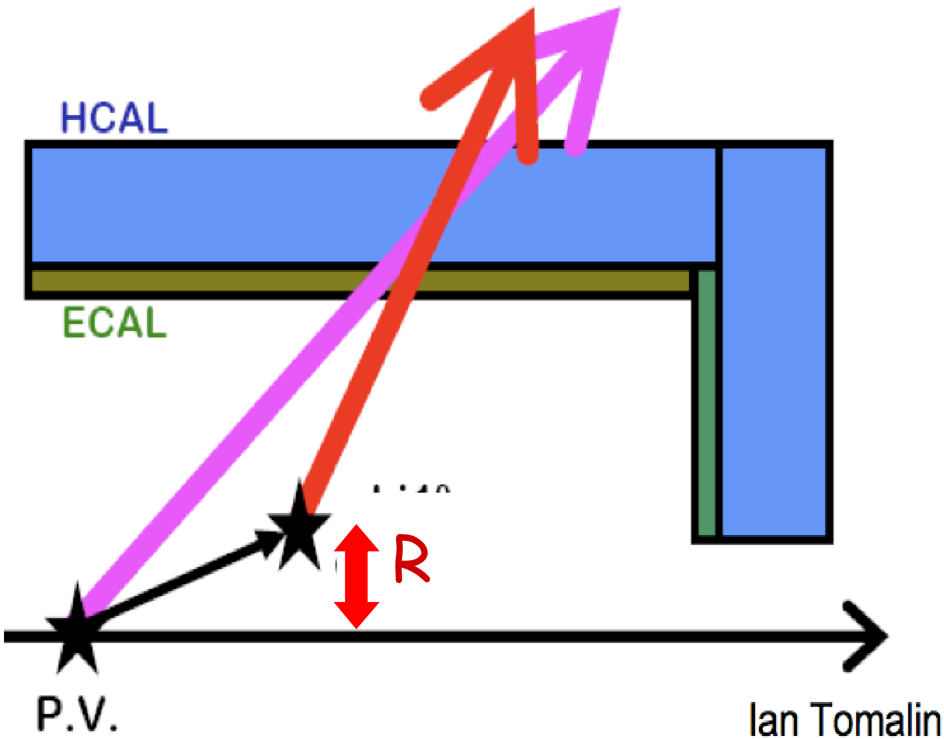


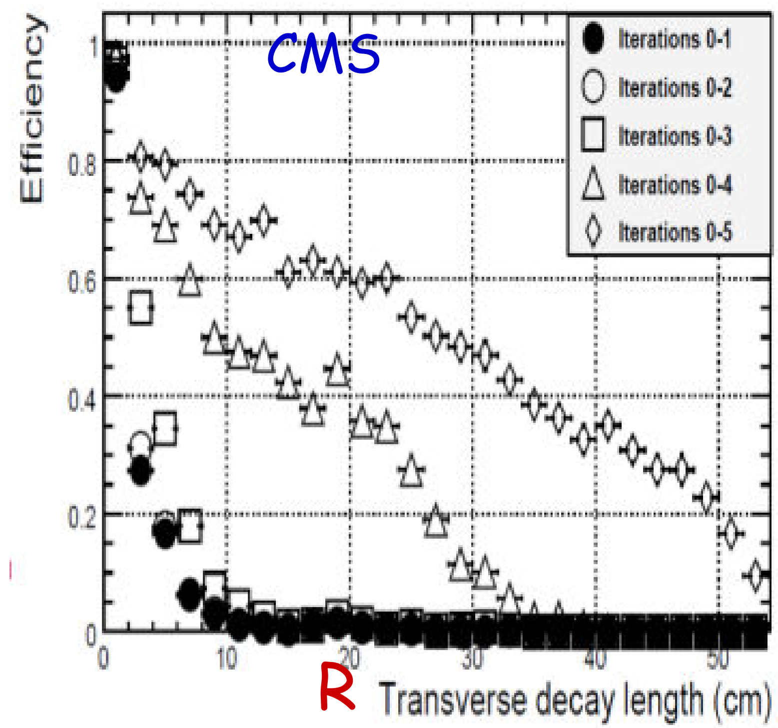
⇒Need special triggers

(*) except possibly LHCb

Particle Reconstruction: Charged

Particles from displaced vertices need an adapted reconstruction

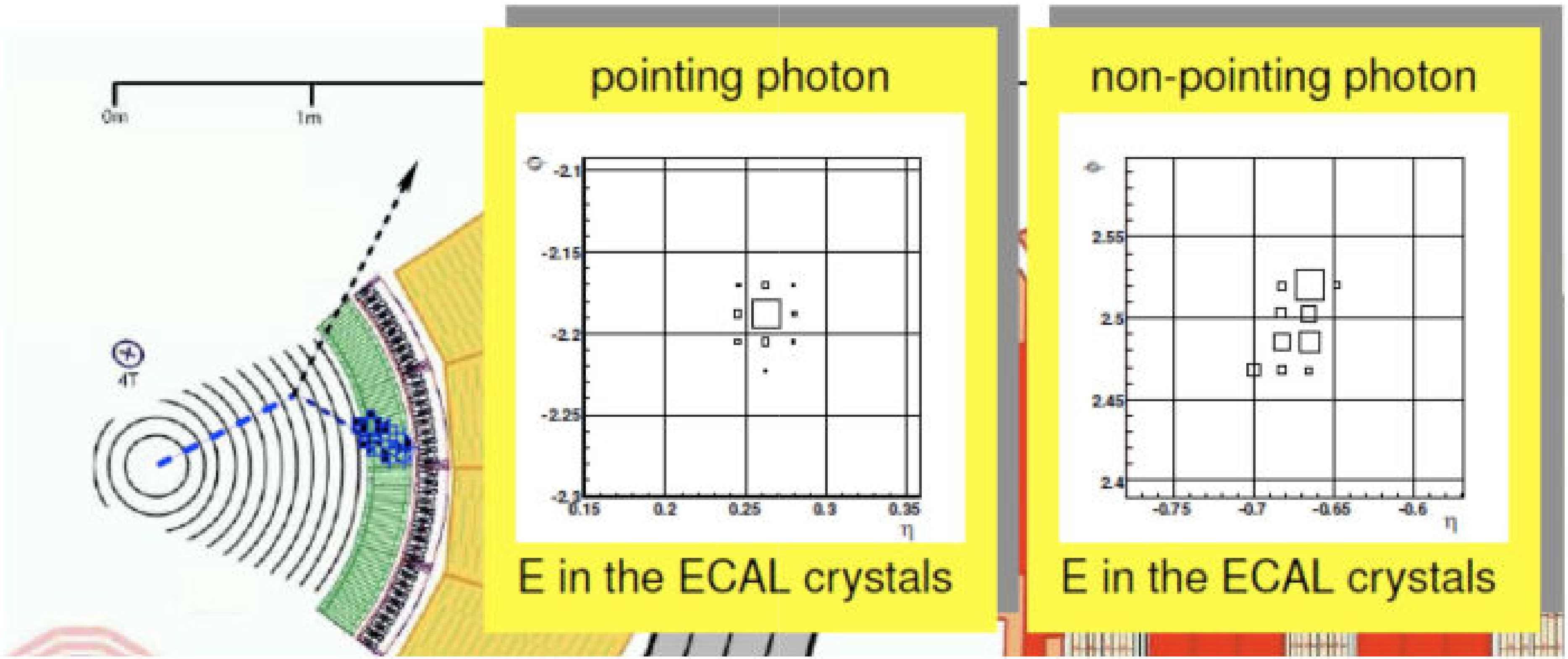




High efficiency possible for charged particles (max R ~ 50 cm)…

Particle Reconstruction: Neutral

More difficult: non-pointing photons (also in GMSB SUSY models)

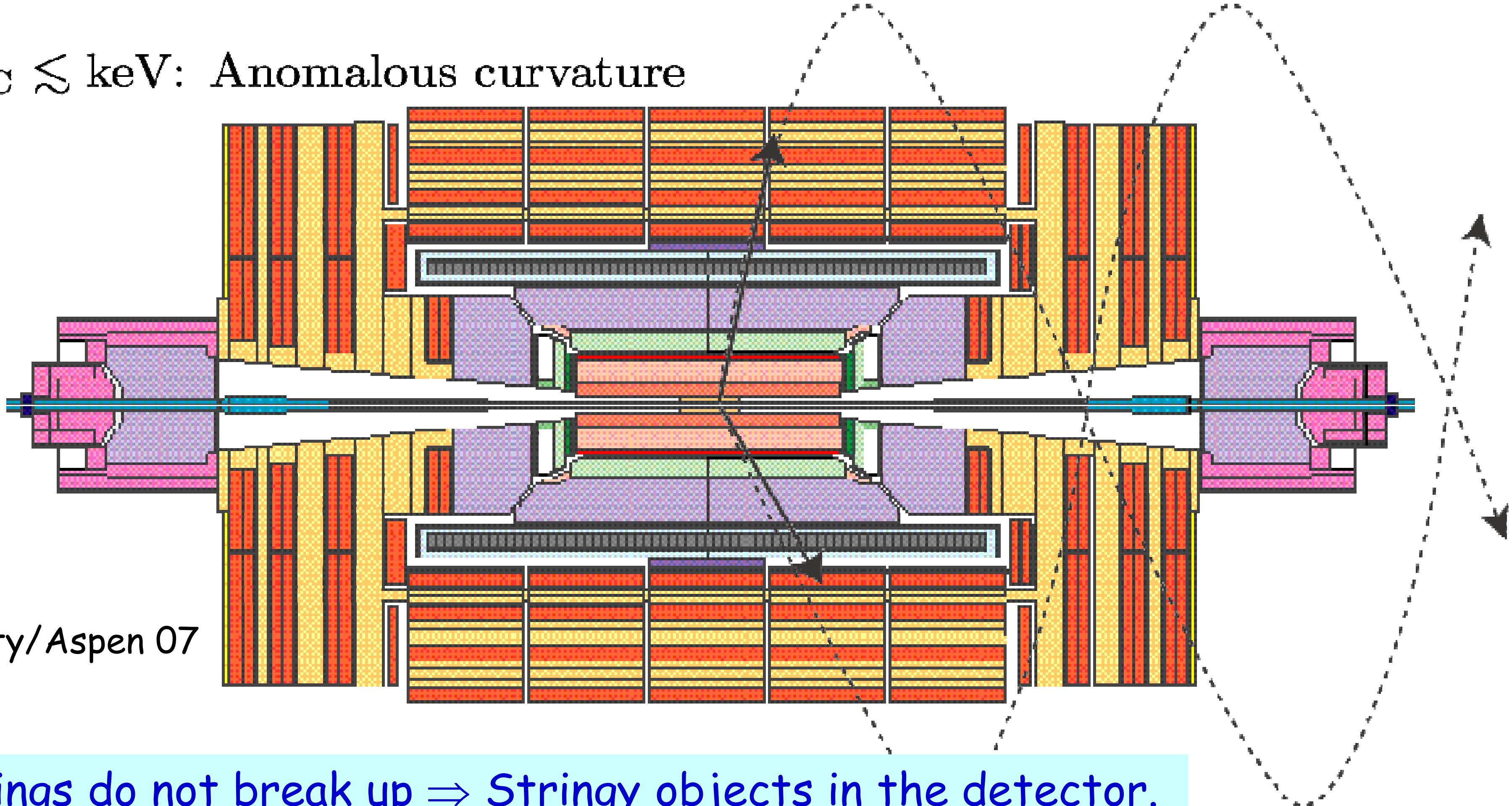


Possible both in CMS and ATLAS from the shower shape in the electromagnetic calorimeters. Example: CMS projective crystal calorimeter

Macro-Strings at the LHC?

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

$\Lambda_{IC} \lesssim$ keV: Anomalous curvature

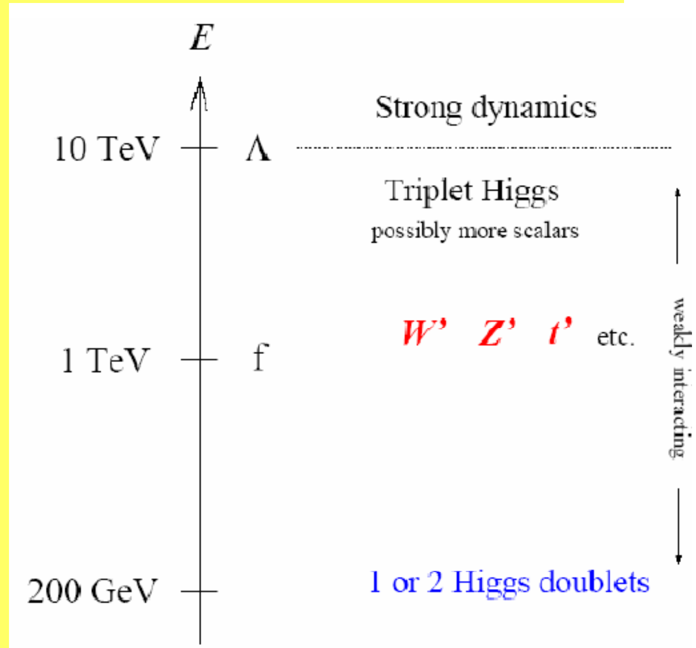


Markus Luty/Aspen 07

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

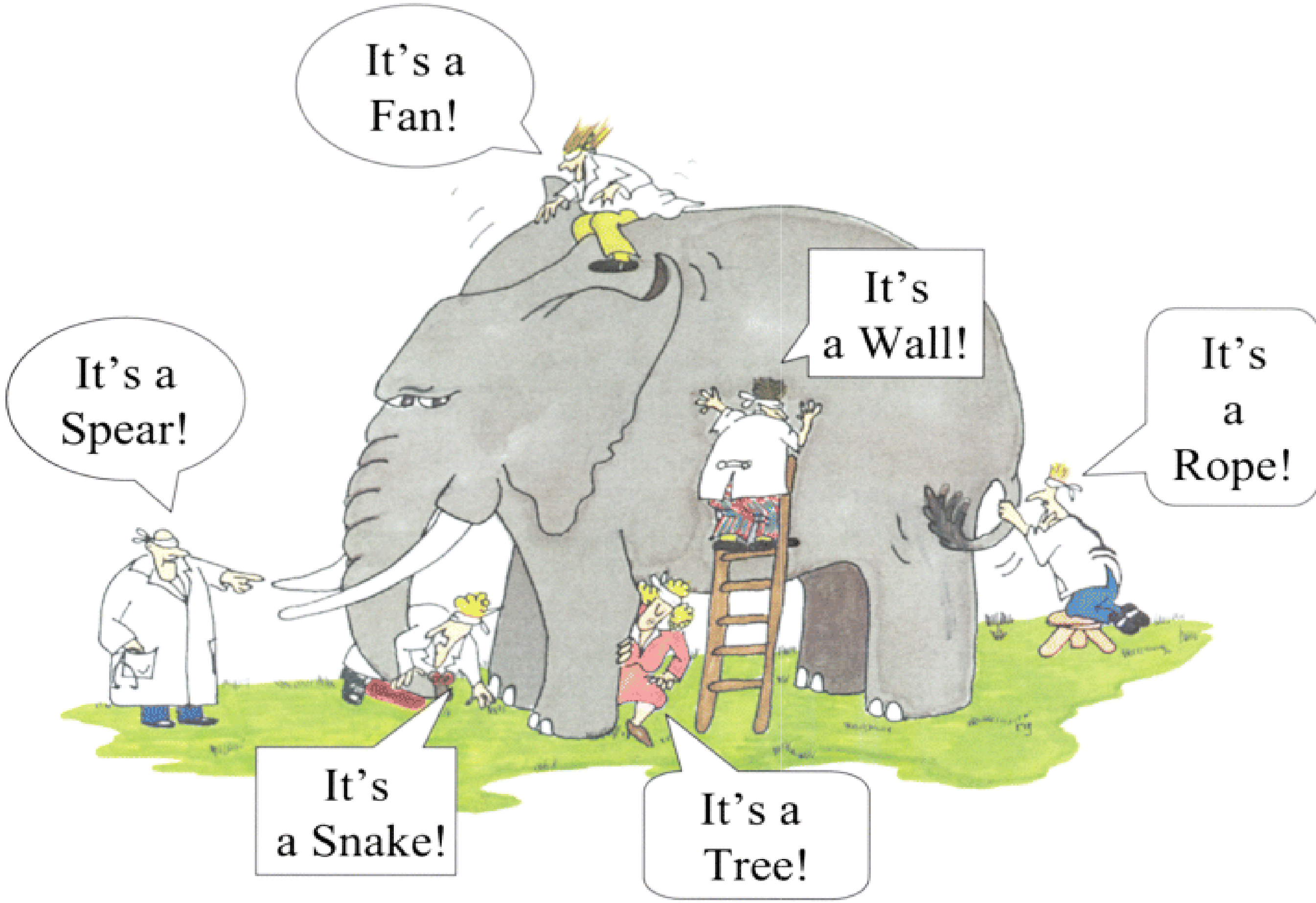
Other New Physics Ideas…

- 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….

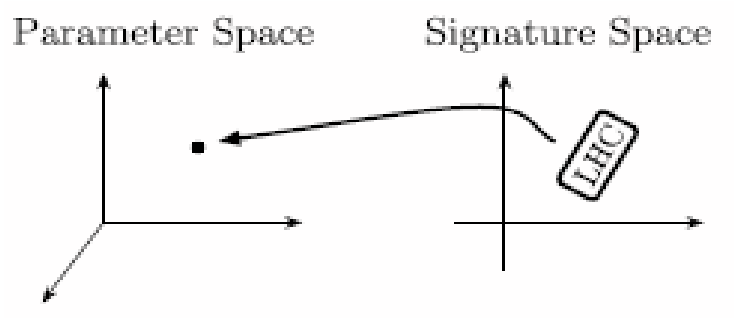
Close interaction between Experiment and Theory will be important

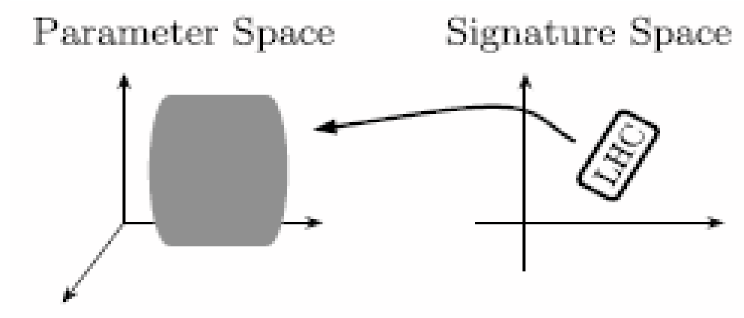
After the Champagne…

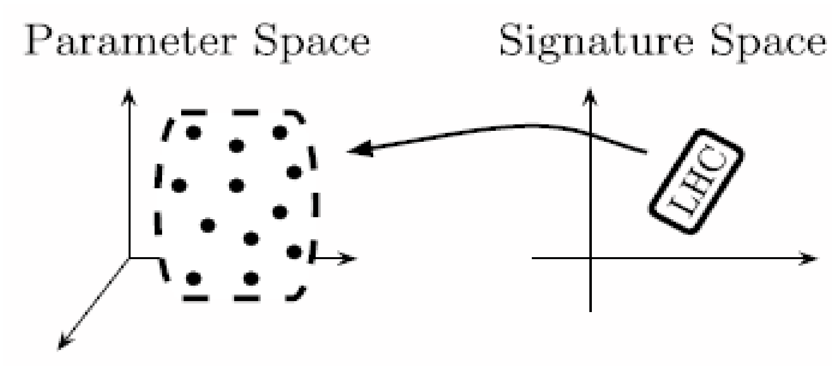
- WHEN new physics is discovered at the LHC, how well can we determine what it is? Does a specific experimental signature map back into a unique theory with a fixed set of parameters?

- 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….







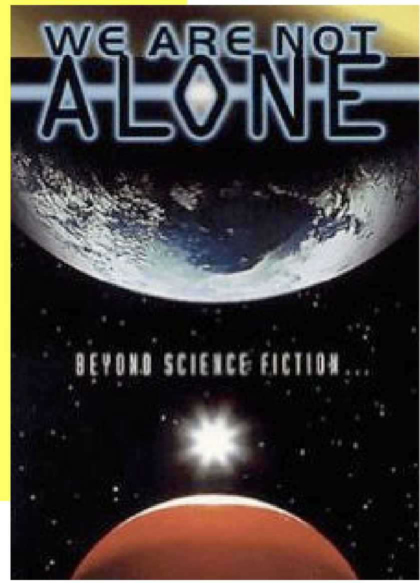
Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space…
→ model degeneracy

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!

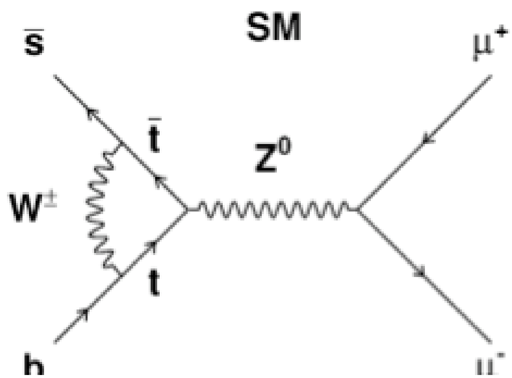
We are not alone!

- 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

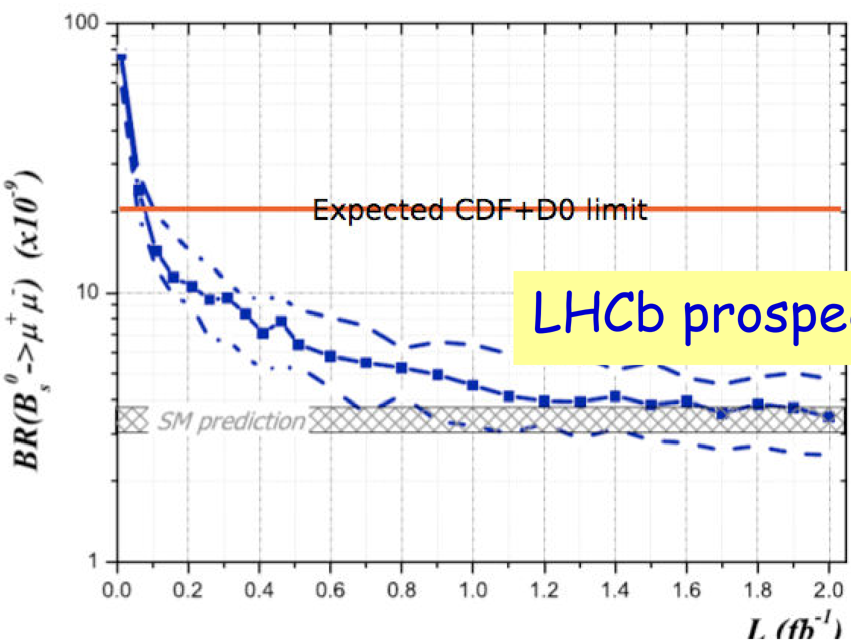


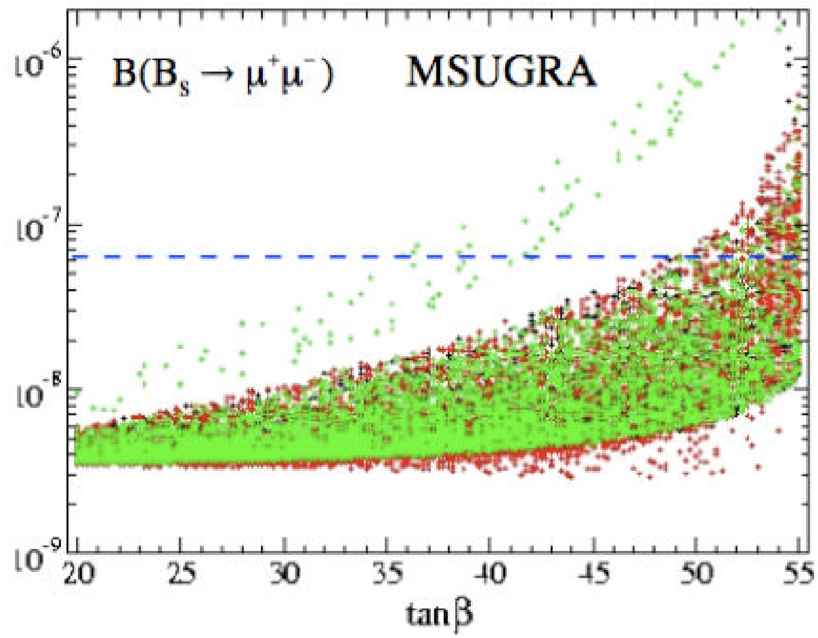
Example: The Rare Decay $B_s \to \mu\mu$

This decay is sensitive to new physics (new heavy particles)

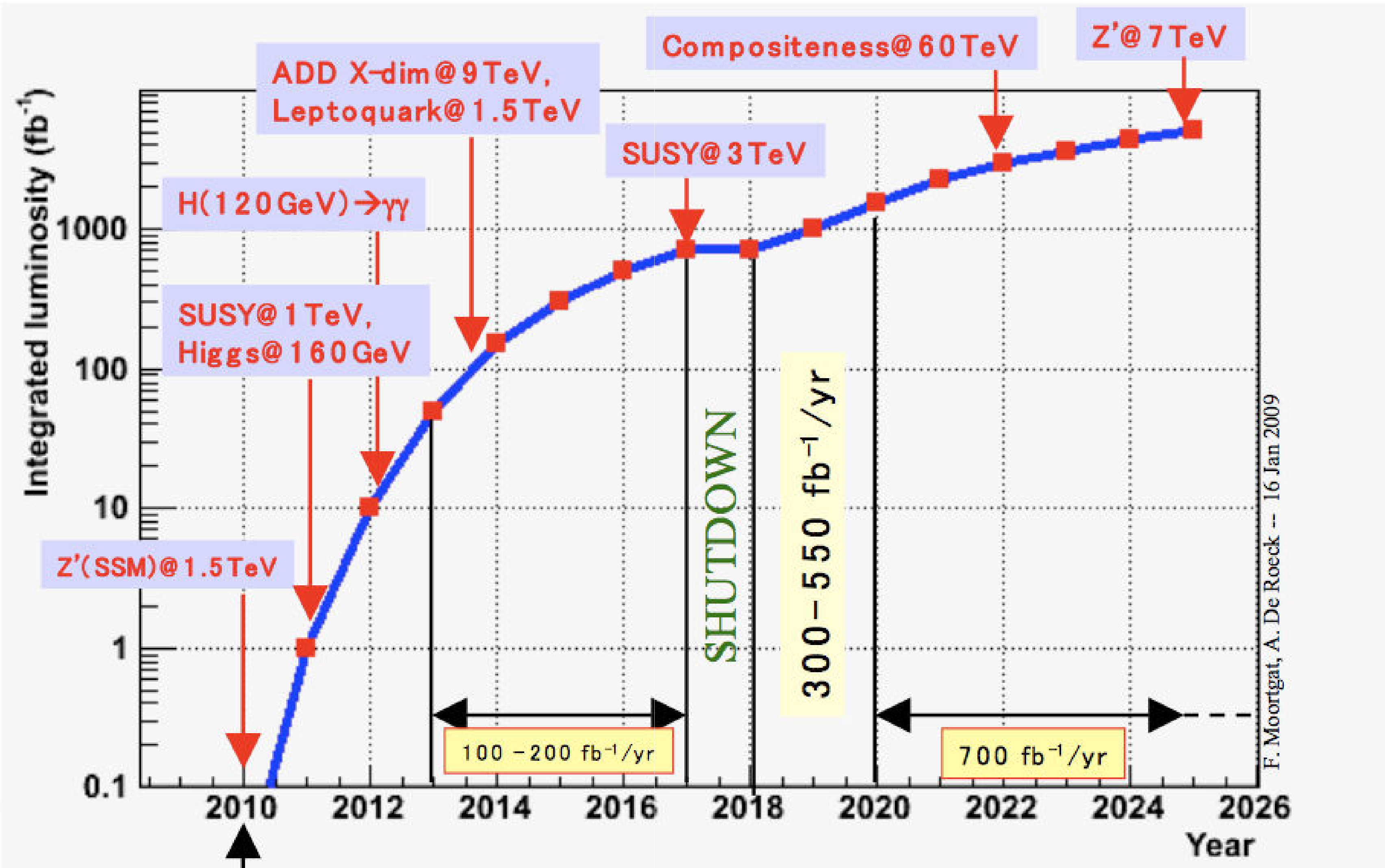


- SM prediction: $BR(B_s \to \mu^+ \mu^-) = (3.35 \pm 0.32) \times 10^{-9}$ [1]
- Current Tevatron limit at 90% CL: $< 4.7 \times 10^{-8}$ $[2\,fb^{-1}]$ [2]





The LHC Outlook



2010

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

End of lecture 2

- 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