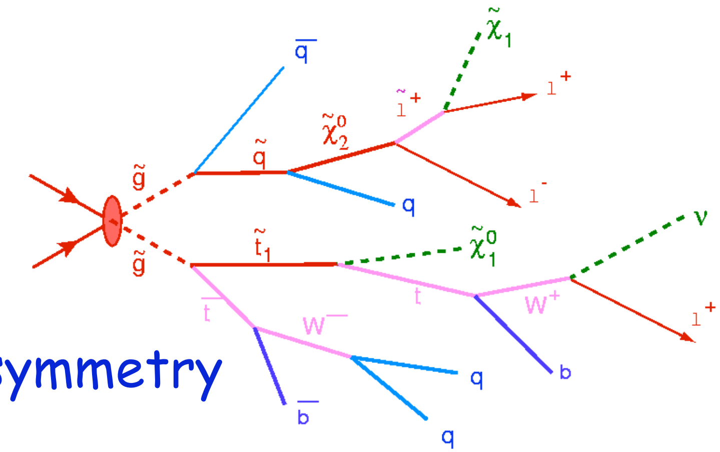
Physics at CMS & ATLAS
Physics Beyond the Standard Model

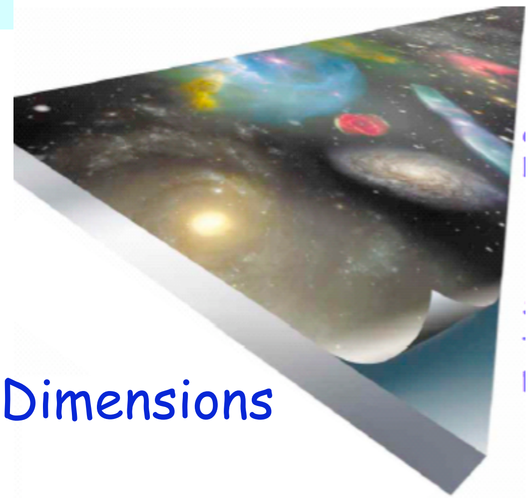
LHC Physics Workshop

Tata Institute of Fundamental Research (TIFR)
21 - 27 October 2009

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



Supersymmetry



Extra Dimensions

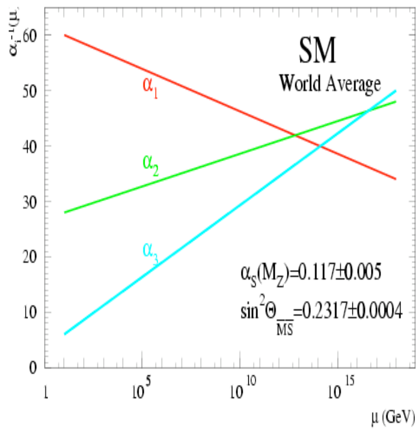
..and more

Physics case for new High Energy Machines

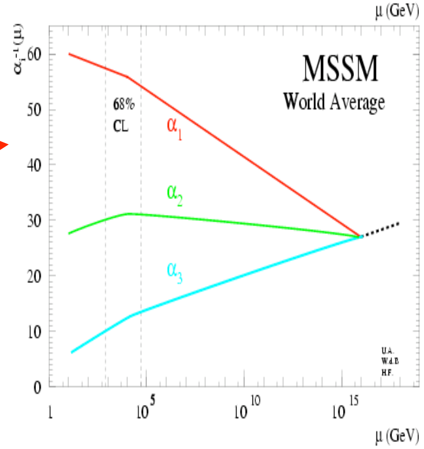
Understand the mechanism Electroweak Symmetry Breaking

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



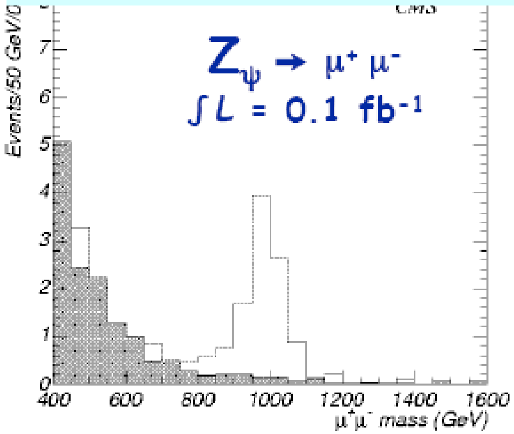
If a Higgs field exists:
- Supersymmetry
- Extra space dimensions

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

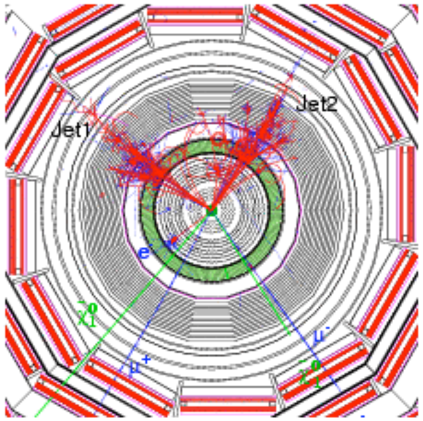
Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models, Technicolor…

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

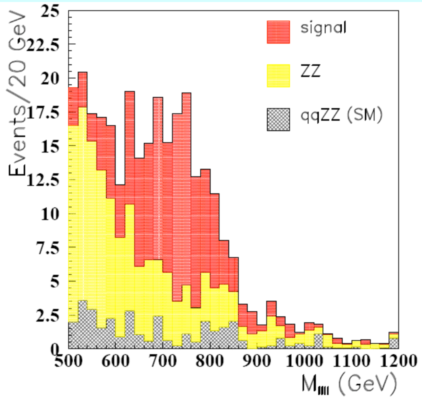
New Gauge Bosons?



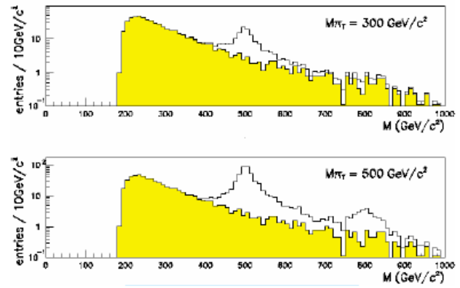
Supersymmetry



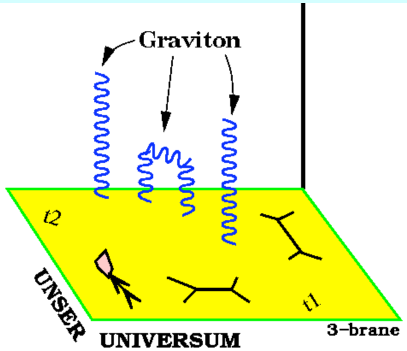
ZZ/WW resonances?



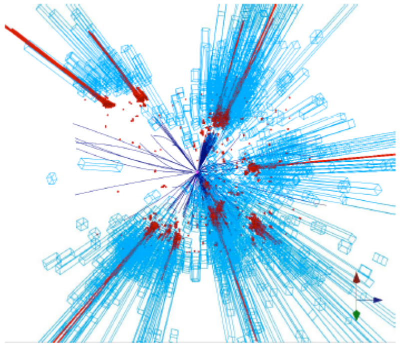
Technicolor?



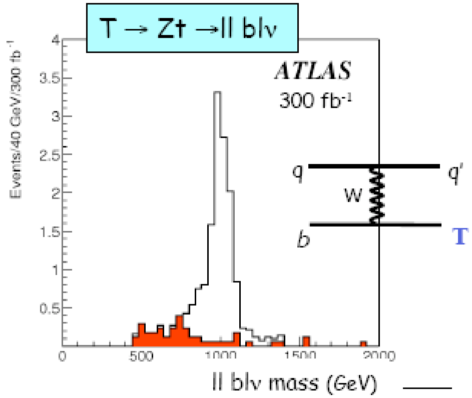
Extra Dimensions?



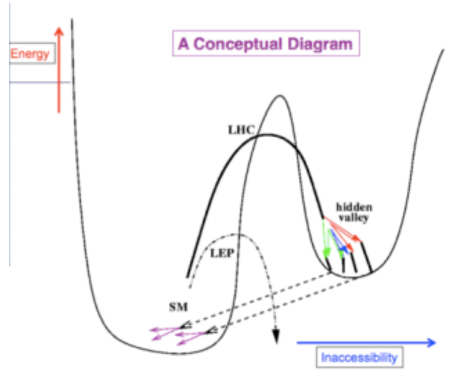
Black Holes???



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

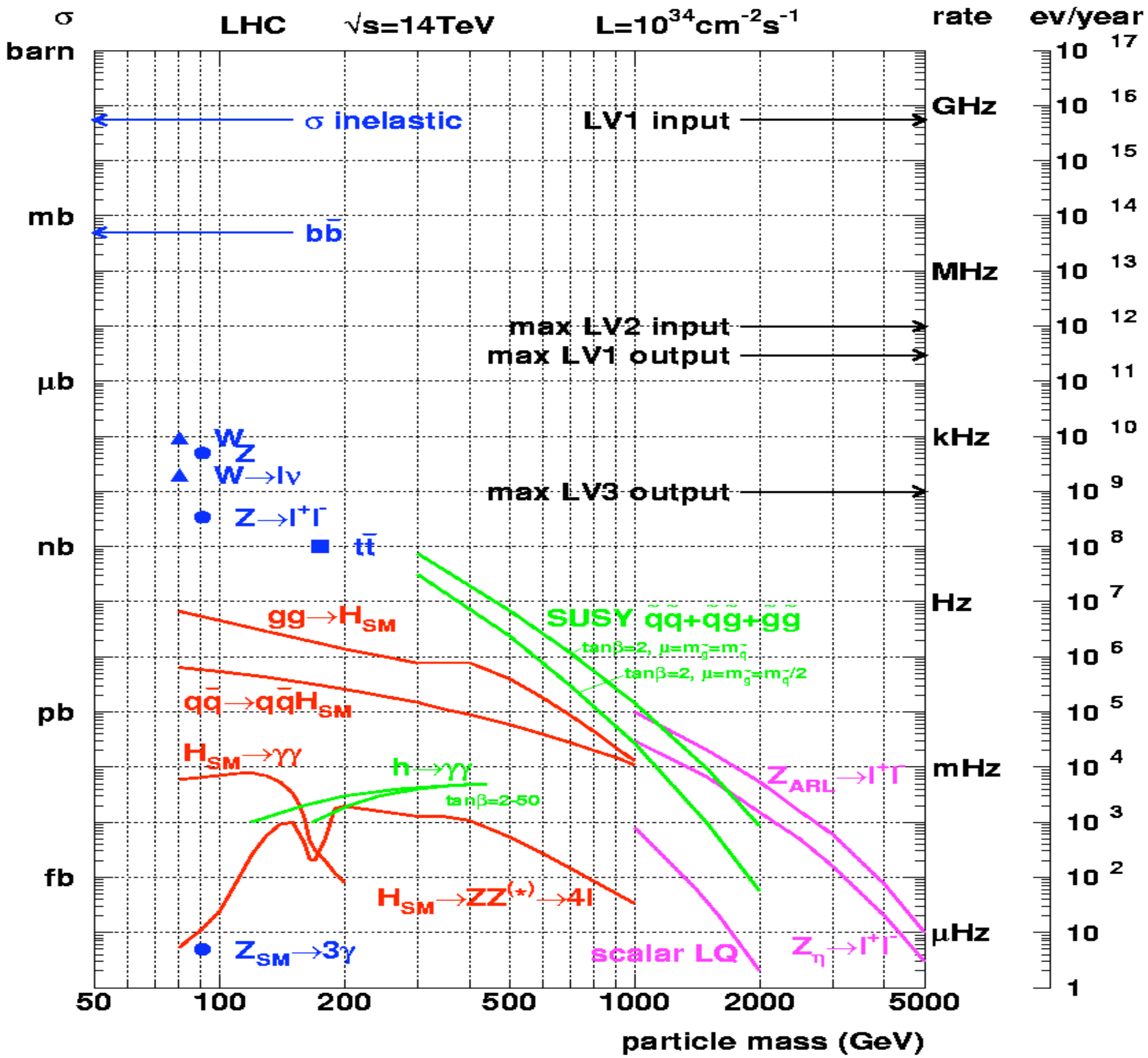
- Many channels in New Physics :Typical signals
  - Di-leptons   resonance/non-resonance, like sign/oposite sign
  - Leptons + MET (=Missing transverse momentum/energy)
  - Photons + MET
  - Multi-jets (2 → ~10)
  - Mono/Multi-jets +MET (few 10 → few 100 GeV)
  - Multi jets + leptons + MET…
  - B/τ final 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

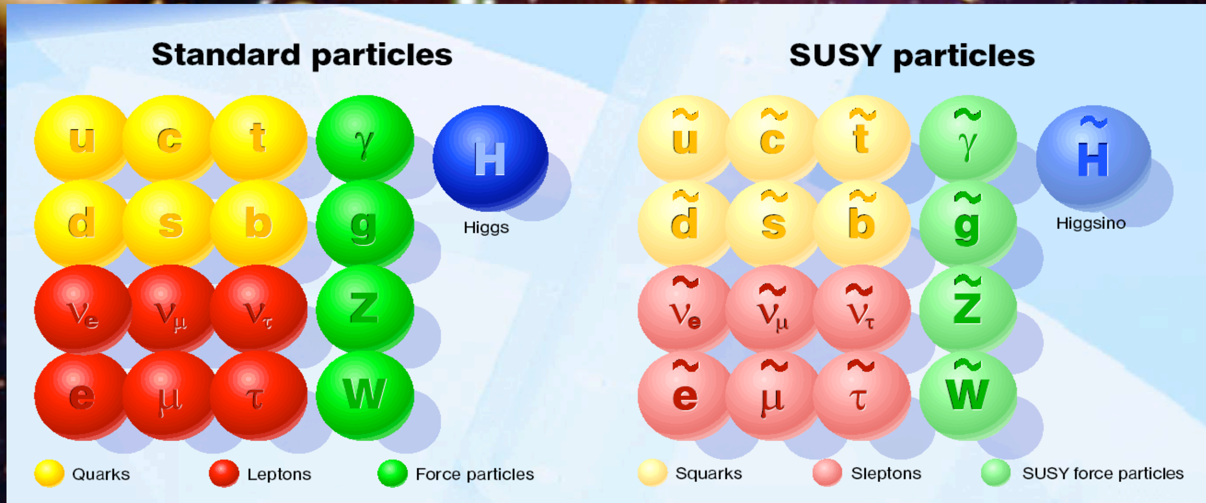


"Well known" processes, don't need to keep all of them …

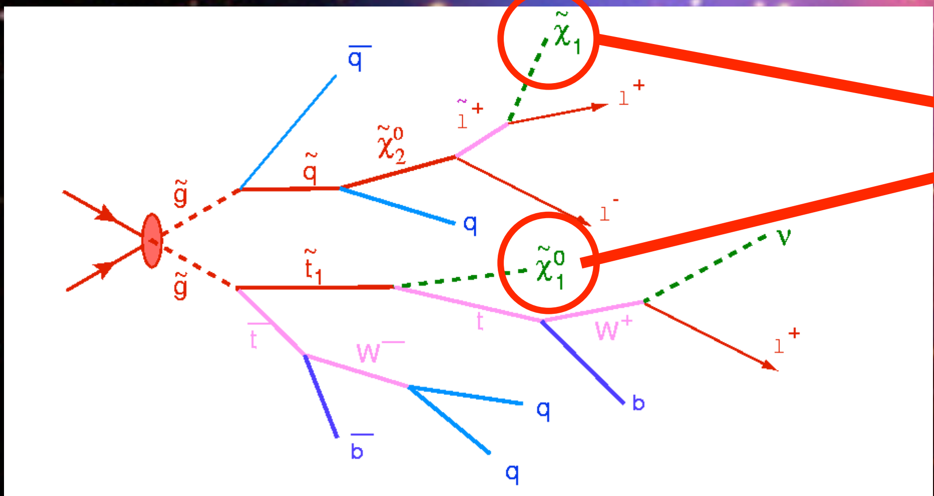
New Physics!!

This we want to keep!!

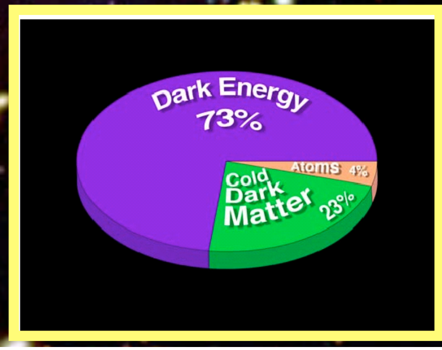
Supersymmetry: a new symmetry in Nature



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



SUSY particle production at the LHC



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!!

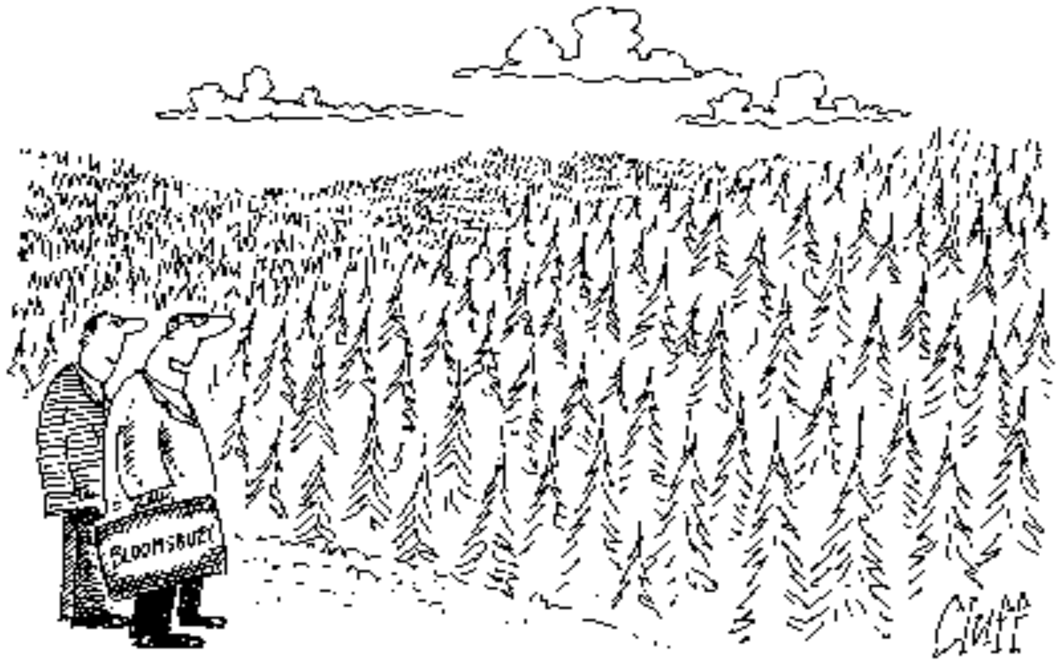
- the outcome of LHC is far more important than any other in the past
- all future projects: ILC, superB, super..., depend on LHC discoveries
- huge responsibility to provide quick and reliable answers

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"

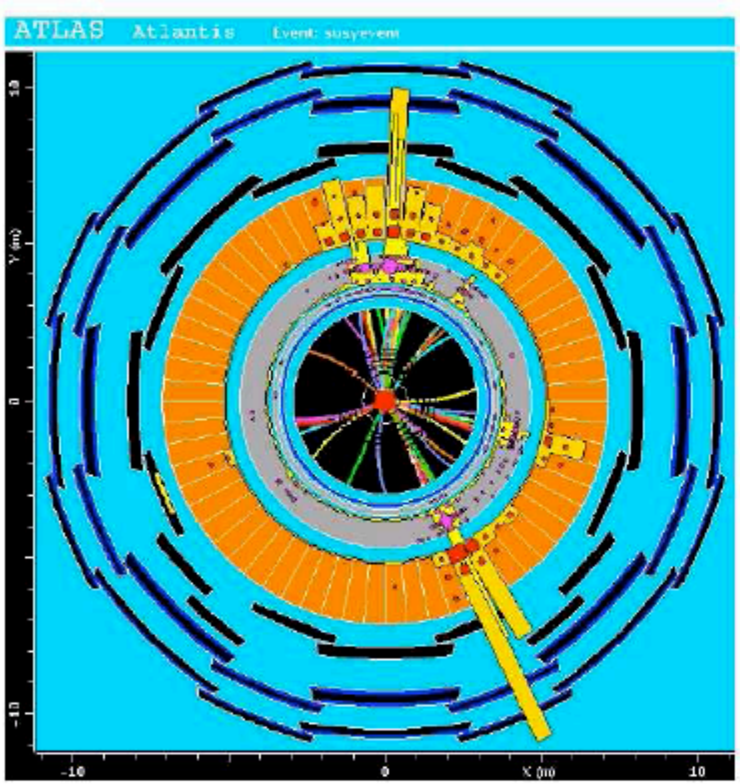
Considered as a benchmark for a large class of new physics models

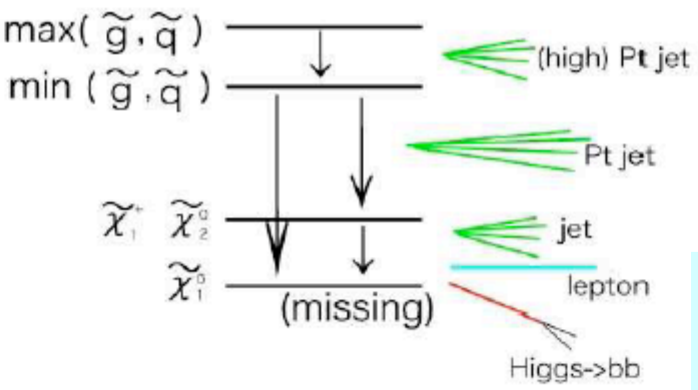
Early Supersymmetry?

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

$10 fb^{-1}$





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

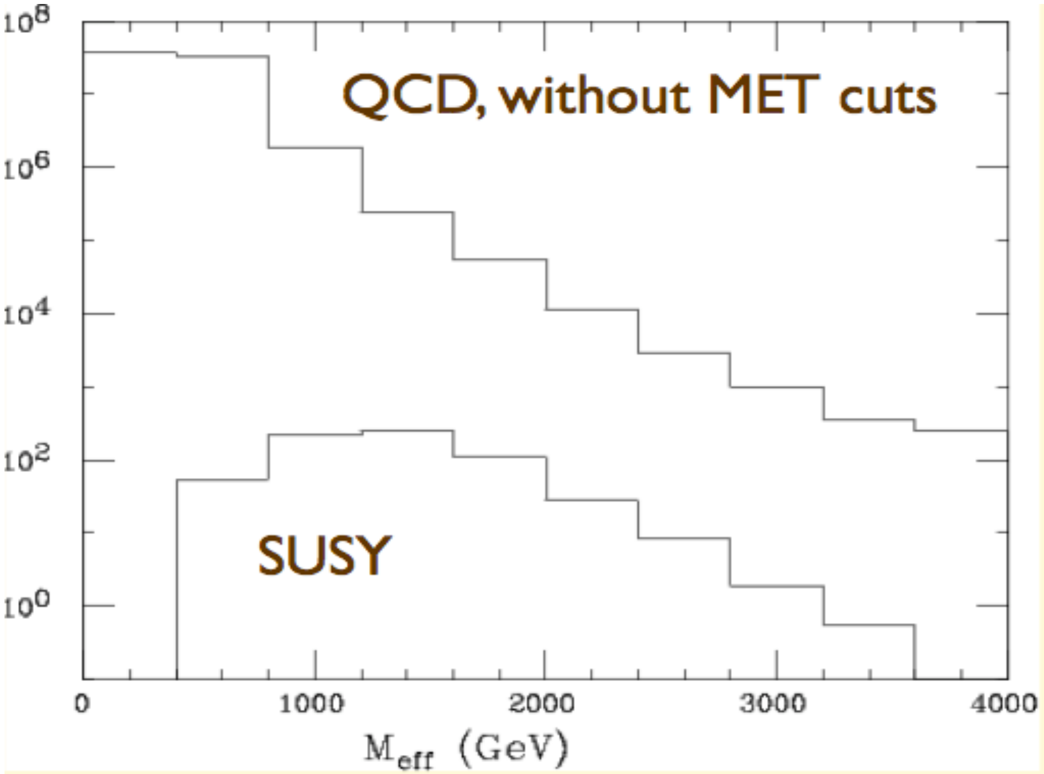
Main signal: lots of activity (jets, leptons, taus, missing E_T)

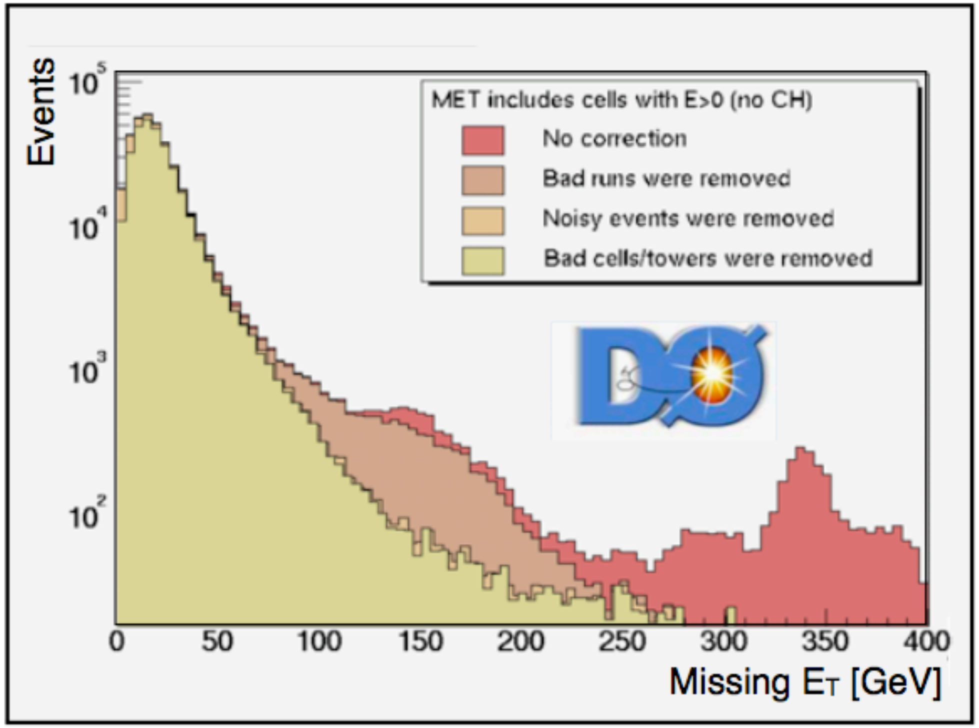
Needs an excellent understanding of the detector and SM backgrounds

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

Missing Transverse Energy

A difficult quantity to measure!



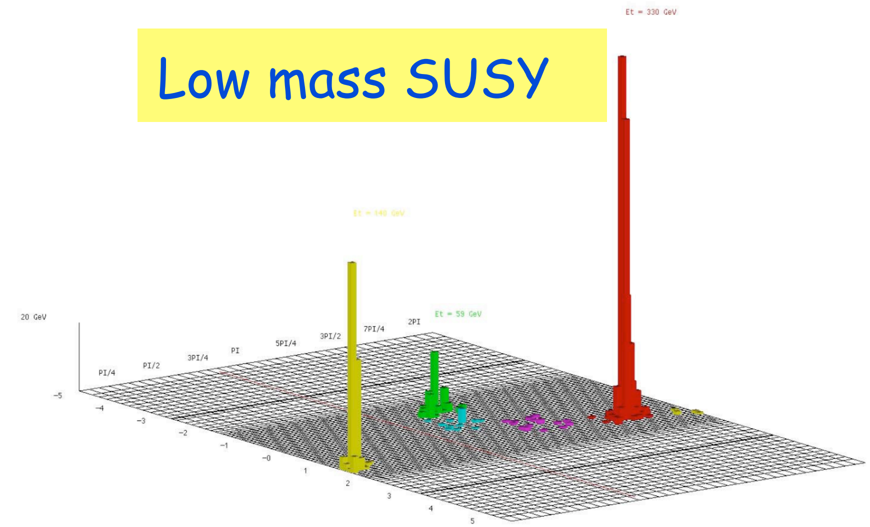


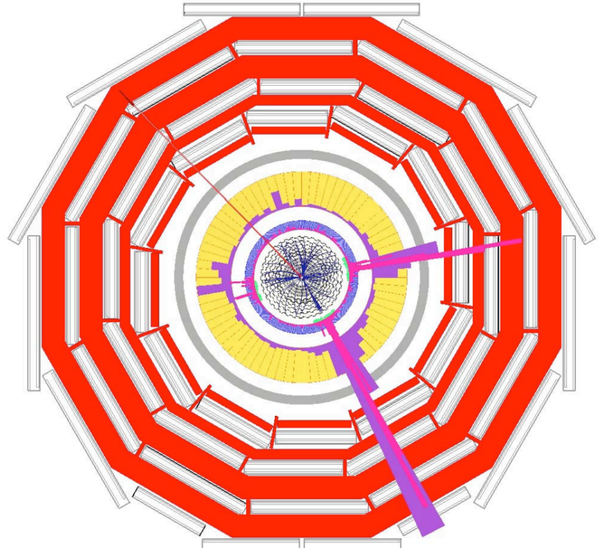
Tevatron experience!

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

Hunting for SUSY @ LHC

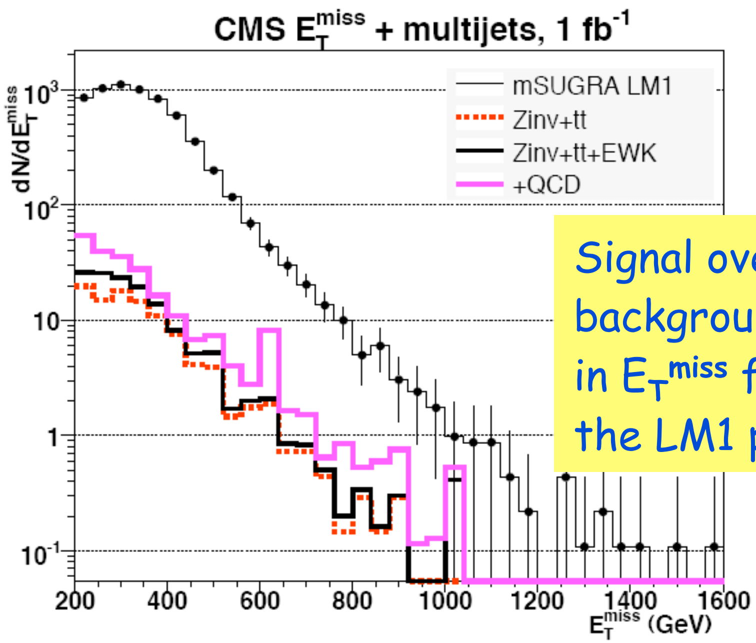
Low mass SUSY



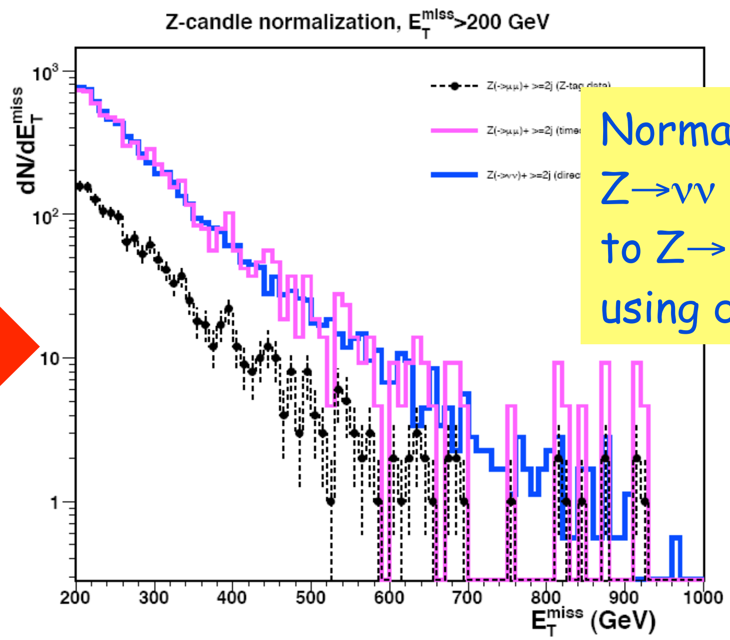


Missing E_T is a difficult measurement for the experiments

CMS PTDR

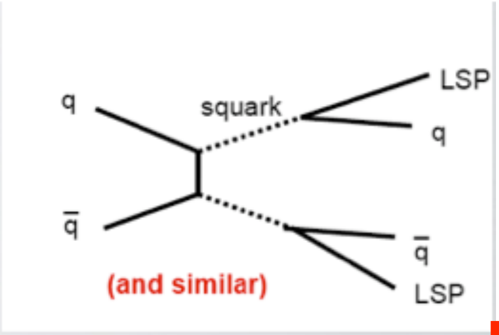


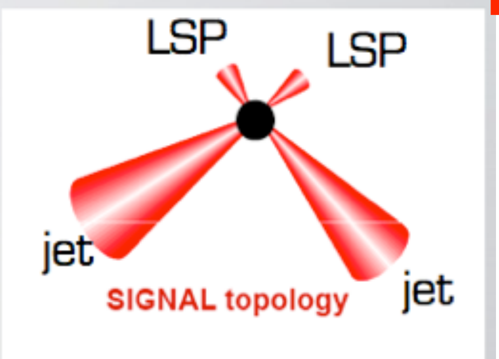
Signal over background in E_T^{miss} for the LM1 point



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

New Data Driven Methods for Backgrounds

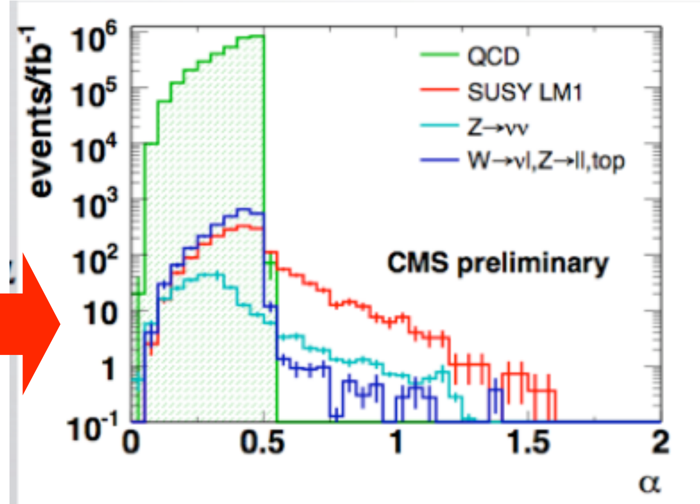




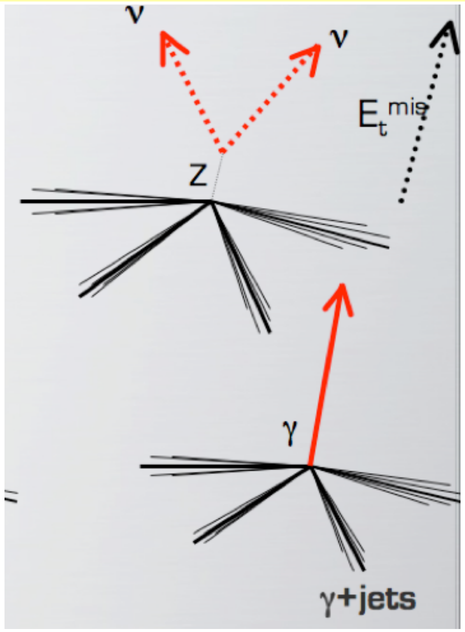
Use kinematics

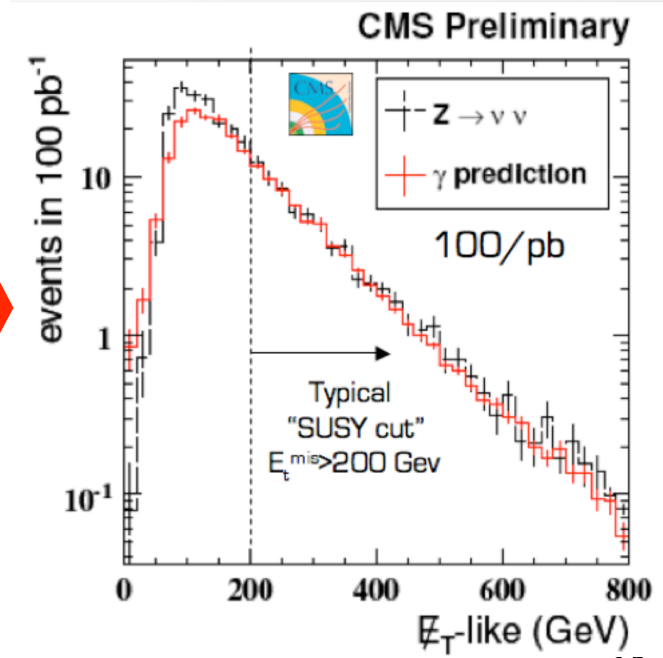
$$\alpha = \frac{E_{T\ j2}}{M_{j1\,j2}} = \frac{E_{T\ j2}}{\sqrt{2E_1E_2(1-\cos\theta)}}$$

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

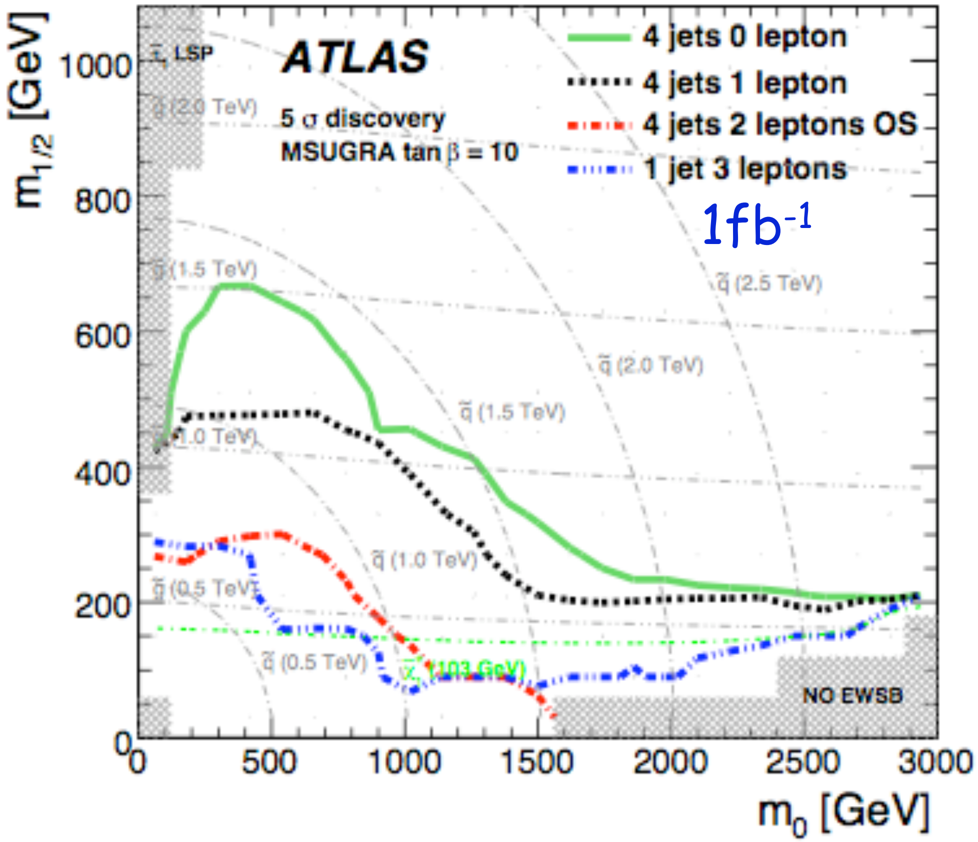


Use photon+jets





Early SUSY Reach



minimal Supergravity (mSUGRA)

$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
tanβ: 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?

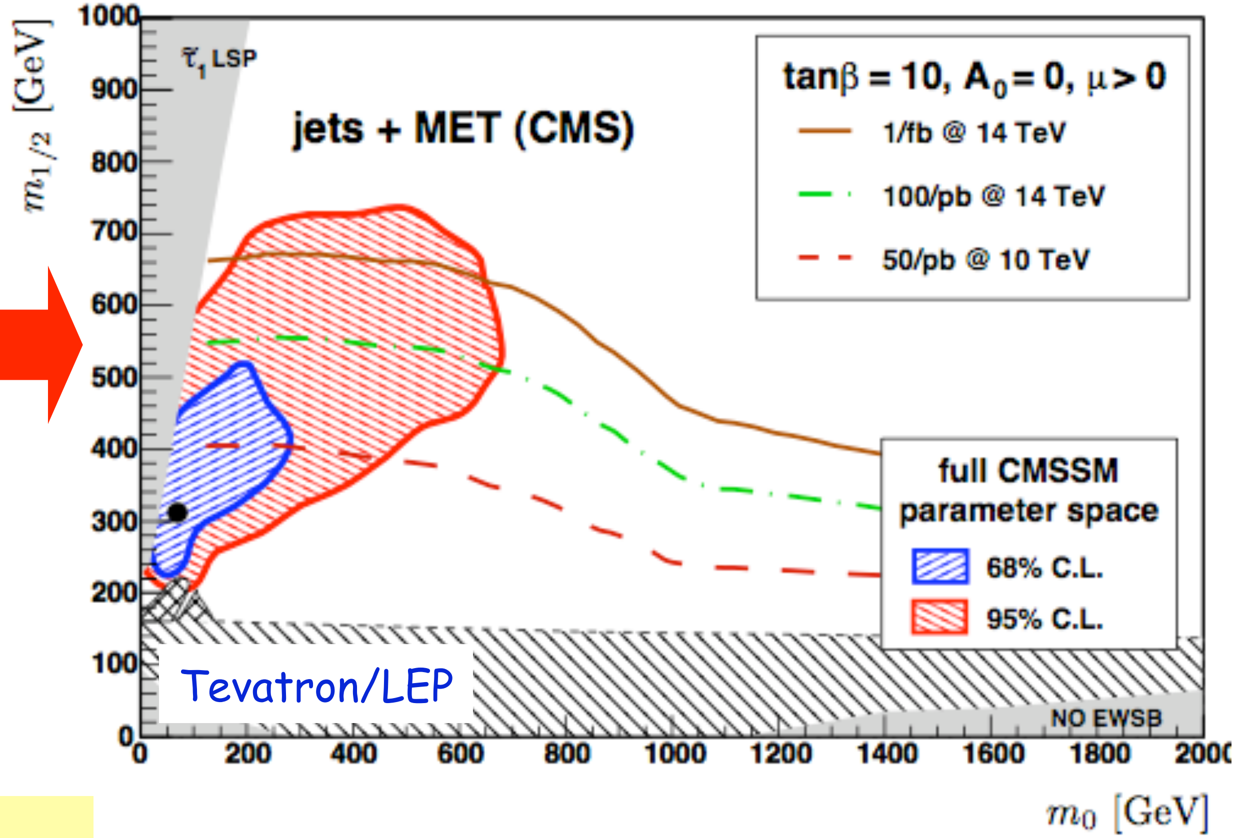
O. Buchmuller et al
arXiv:0808.4128

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_{top}, g-2, BR(B→Xγ), relic density)

"LHC Weather Forecast"



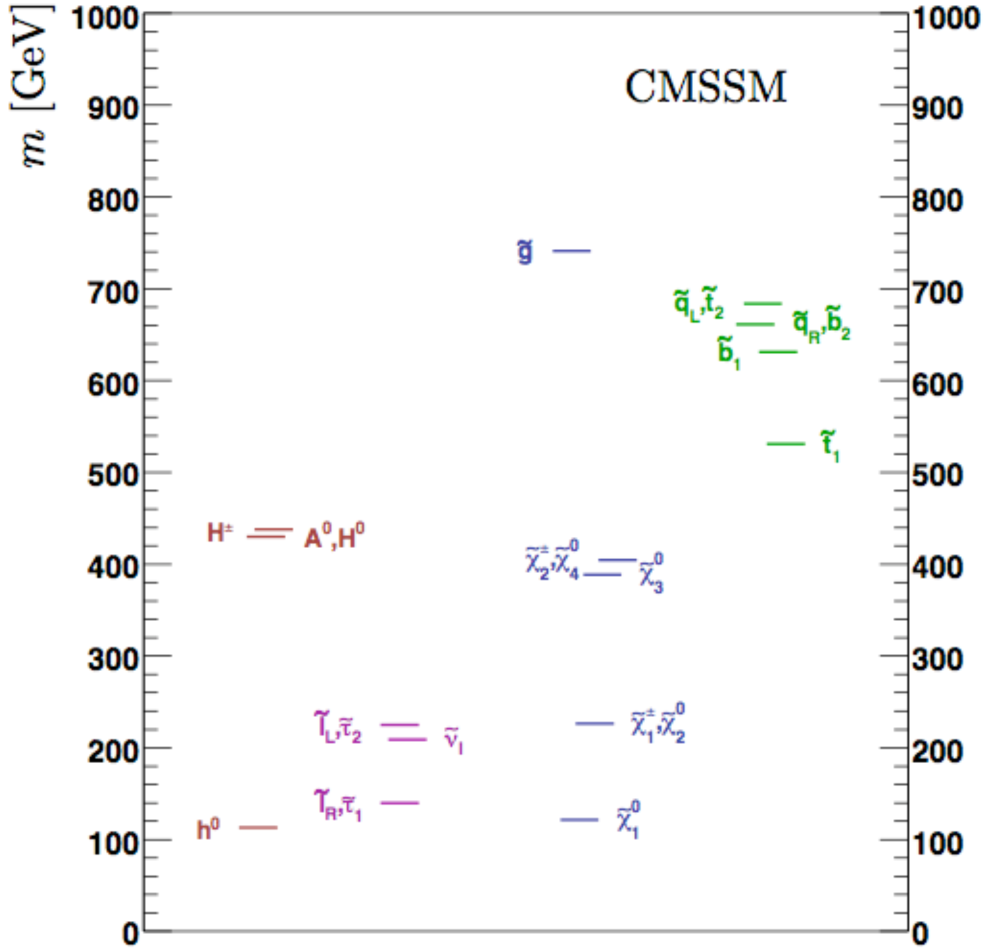
"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

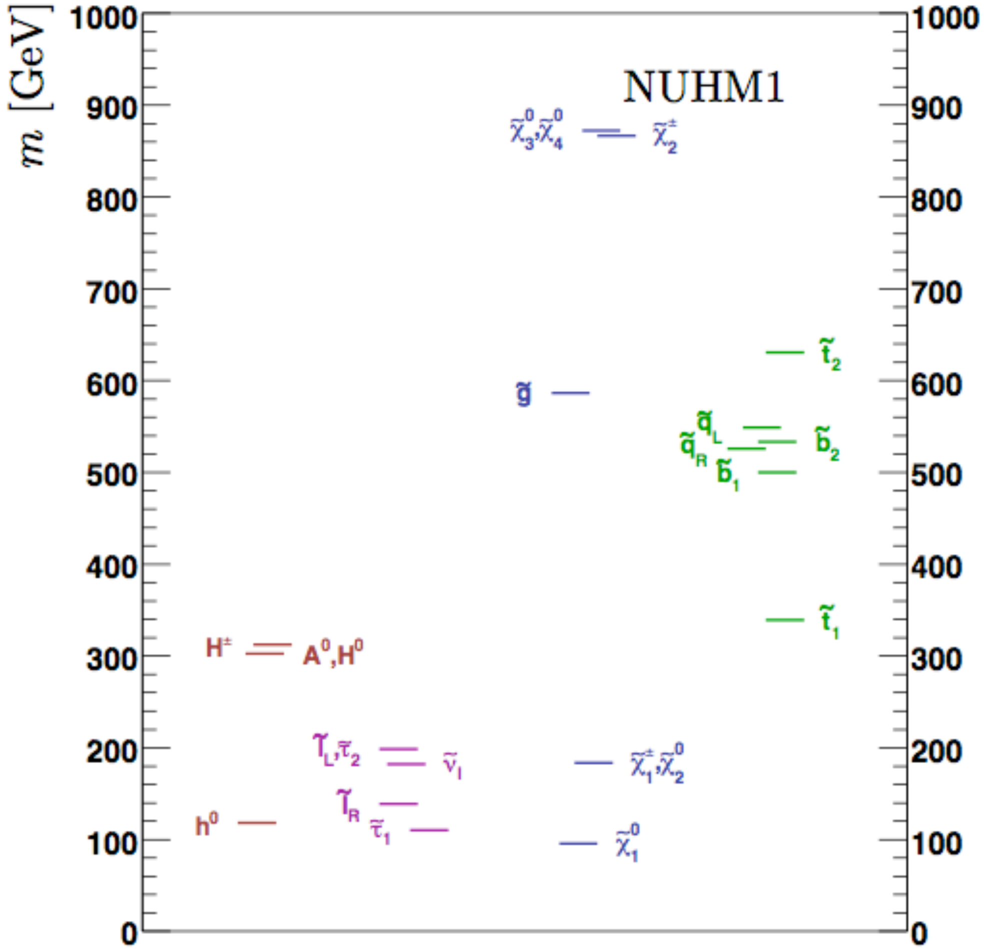
"Predict" on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)

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

SUSY Particle Spectrum

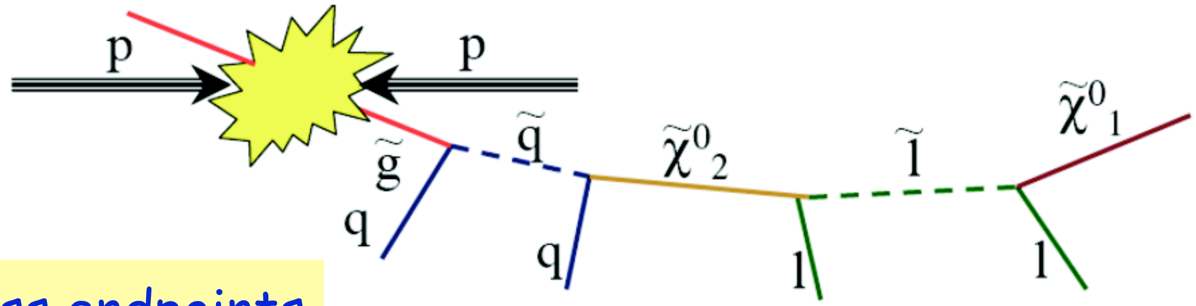
"best" point: Mass spectrum



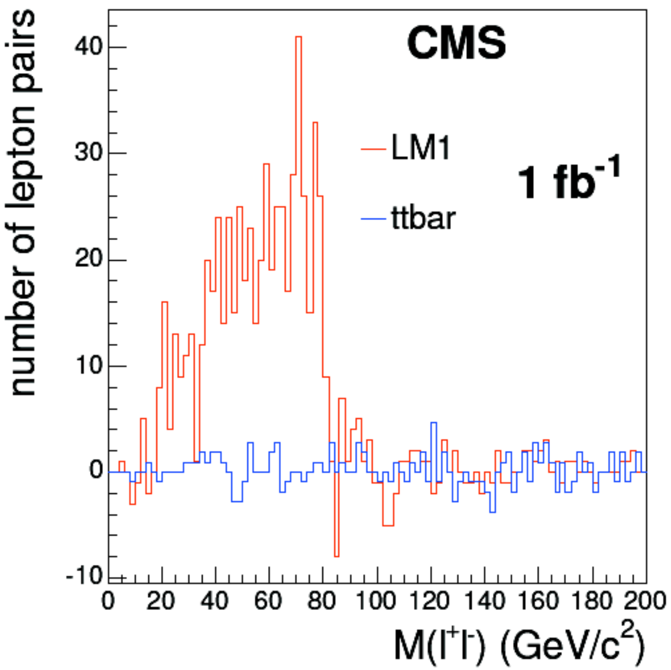


Sparticle Mass Reconstruction

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]

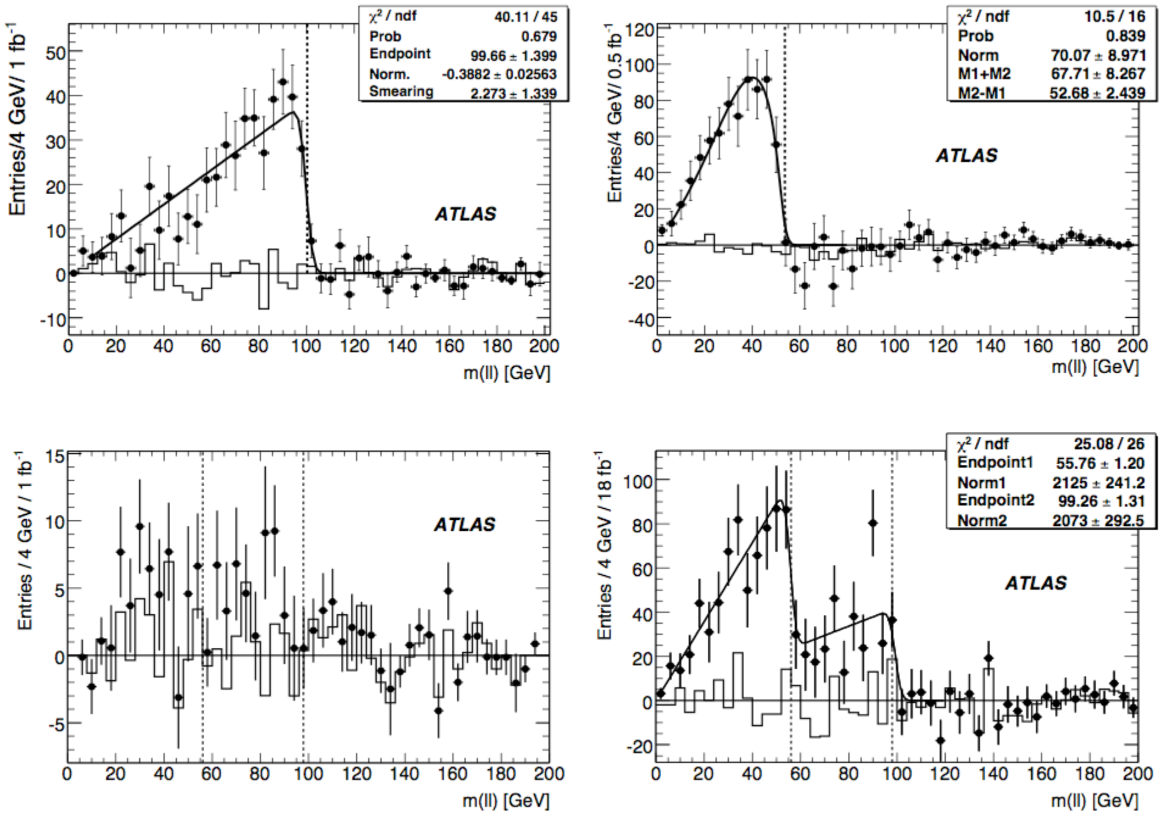
Endpoints: ATLAS Study

Mass Distribution	SU1 end point (GeV)	SU3 end point (GeV)	SU4 end point (GeV)
$m_{\ell\ell}^{\text{edge}}$	56.1, 97.9	100.2	53.6
$m_{\tau\tau}^{\text{edge}}$	77.7, 49.8	98.3	53.6
$m_{\ell\ell q}^{\text{edge}}$	611, 611	501	340
$m_{\ell\ell q}^{\text{thr}}$	133, 235	249	168
$m_{lq(\text{low})}^{\text{max}}$	180, 298	325	240
$m_{lq(\text{high})}^{\text{max}}$	604, 581	418	340

$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

Lepton endpoints

1 fb^{-1}



Overall Result

Observable	SU3 m_{meas} [GeV]	SU3 m_{MC} [GeV]	SU4 m_{meas} [GeV]	SU4 m_{MC} [GeV]
$m_{\tilde{\chi}_1^0}$	$88 \pm 60 \mp 2$	118	$62 \pm 126 \mp 0.4$	60
$m_{\tilde{\chi}_2^0}$	$189 \pm 60 \mp 2$	219	$115 \pm 126 \mp 0.4$	114
$m_{\tilde{q}}$	$614 \pm 91 \pm 11$	634	$406 \pm 180 \pm 9$	416
$m_{\tilde{\ell}}$	$122 \pm 61 \mp 2$	155		
Observable	SU3 Δm_{meas} [GeV]	SU3 Δm_{MC} [GeV]	SU4 Δm_{meas} [GeV]	SU4 Δm_{MC} [GeV]
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7	$52.7 \pm 2.4 \mp 0.0$	53.6
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$	$526 \pm 34 \pm 13$	516.0	$344 \pm 53 \pm 9$	356
$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6		

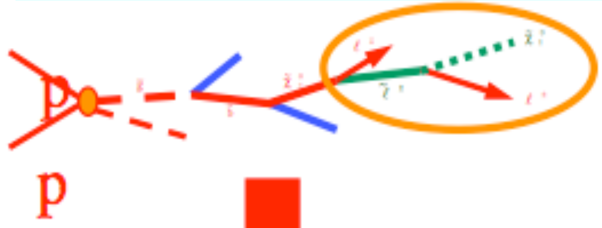
1 fb^{-1}

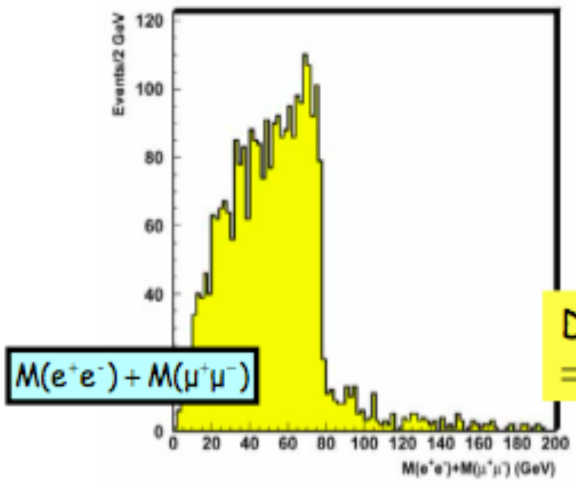
Parameter	SU3 value	fitted value	exp. unc.
	sign$(\mu) = +1$		
$\tan\beta$	6	7.4	4.6
M_0	100 GeV	98.5 GeV	$\pm$9.3 GeV
$M_{1/2}$	300 GeV	317.7 GeV	$\pm$6.9 GeV
A_0	-300 GeV	445 GeV	$\pm$408 GeV
	sign$(\mu) = -1$		
$\tan\beta$		13.9	$\pm$2.8
M_0		104 GeV	$\pm$18 GeV
$M_{1/2}$		309.6 GeV	$\pm$5.9 GeV
A_0		489 GeV	$\pm$189 GeV

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)=+



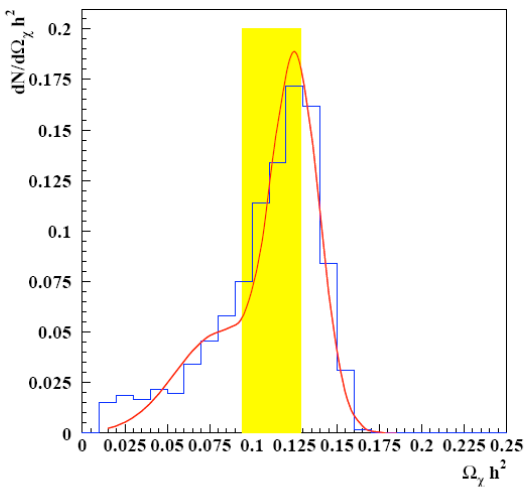


D. Miller et al
⇒Use shapes

hep-ph/0508198

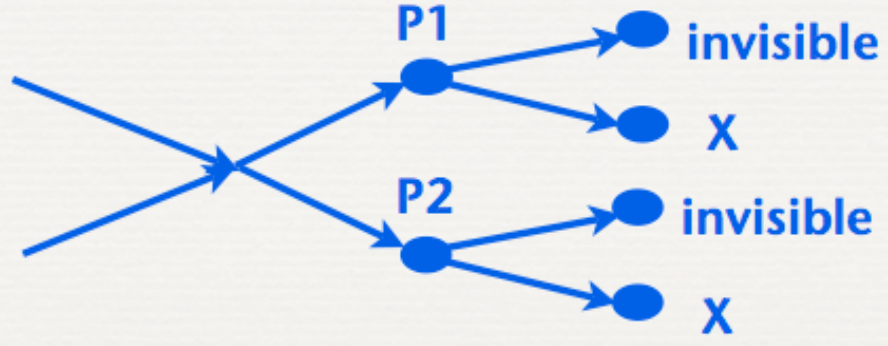
GeV	LHC
$\Delta m_{\tilde{\chi}^0_1}$	4.8
$\Delta m_{\tilde{\chi}^0_2}$	4.7
$\Delta m_{\tilde{\chi}^0_4}$	5.1
$\Delta m_{\tilde{l}_R}$	4.8
$\Delta m_{\tilde{\ell}_L}$	5.0
Δm_{τ_1}	5-8
$\Delta m_{\tilde{q}L}$	8.7
$\Delta m_{\tilde{q}R}$	7-12
$\Delta m_{\tilde{b}_1}$	7.5
$\Delta m_{\tilde{b}_2}$	7.9
$\Delta m_{\tilde{g}}$	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



New Mass Determination Methods

EG MT2

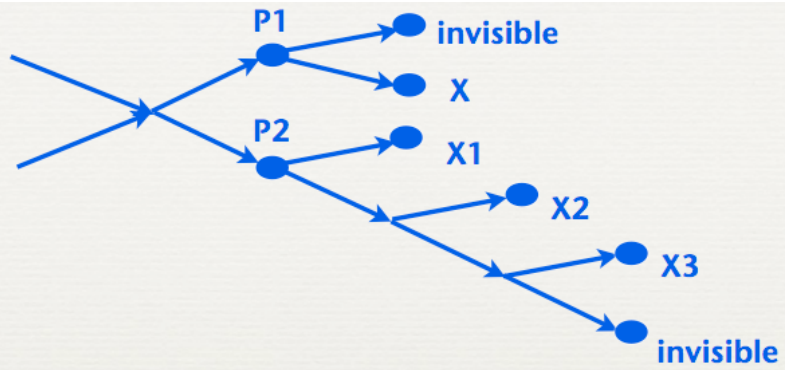


Get information on an ensemble of events when particles go undetected

$$m_{T2}^2 = \min_{p_T^{(1)} + p_T^{(2)} = p_T^{\text{miss}}} \left[\max \left[m_T^2(m_{\text{dm}}; p_T^{(1)}), m_T^2(m_{\text{dm}}; p_T^{(2)}) \right] \right]$$

so $\boxed{m_{T2} \leq m_{\text{P}}}$

Bar, Lester, Stephens



Can be extended
Still much to gain @LHC
by exploring kinematics

Mass Studies using Kinematics

- many improvements of mT2
- the mT2 upper endpoint as a function of m_dm has a "kink"at the true value of m_dm

W.S Cho, K. Choi, Y.G Kim, C.B. Park, arXiv:0709.0288

- can generalize mT2 to intermediate particles in sub-decay chains

M. Burns, KC Kong, K. Matchev, M. Park, arXiv:0810.5576

- can find new mT2-like observables, e.g. shat_min

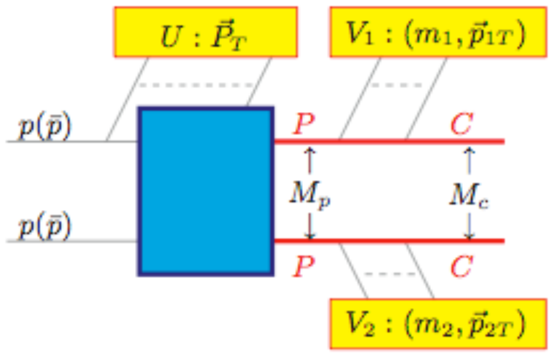
P. Konar, KC Kong, K. Matchev, arXiv:0812.1042

Gains of ~ factor 2 wrt ILC/LHC study reported…

Realism of these methods now being tested at the Tevatron

A general method for determining the masses of semi-invisibly decaying particles at hadron colliders

Konstantin T. Matchev and Myeonghun Park
Physics Department, University of Florida, Gainesville, FL 32611, USA
(Dated: 9 October, 2009)



How well can we measure masses at the LHC using all new techniques? Project?

Is it SUSY?

Example: Universal Extra Dimensions

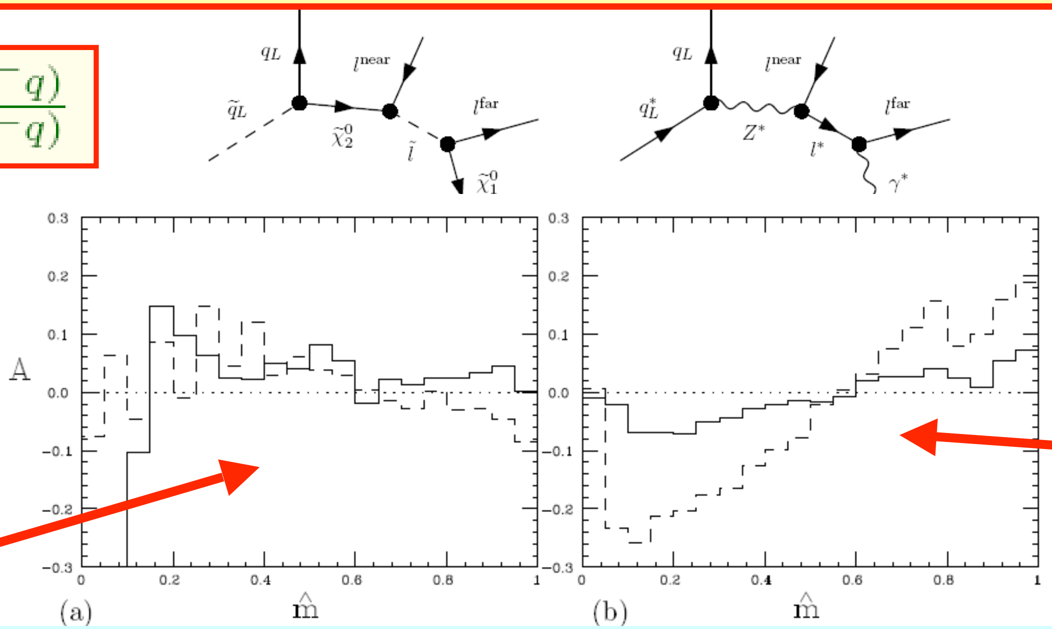
Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:

Can the LHC distinguish?

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

Look for variables sensitive to the particle spin eg. lepton charge asymmetries in squark/KKquark decay chains Barr hep-ph/0405052; Smillie & Webber hep-ph/0507170

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$



Needs 10 fb^{-1} or more.

KK like spectrum (small mass splitting)

SPS1a benchmark type spectrum

Method works better or worse depending on (s)particles spectrum

More discriminating variables needed!!

Spin Measurements

Many new ideas being proposed
Most still need the detailed test of the 'experimental reality'

Kilic-Wang-Yavin:
Spin measurements in cascade decays
Angular correlations in decays...

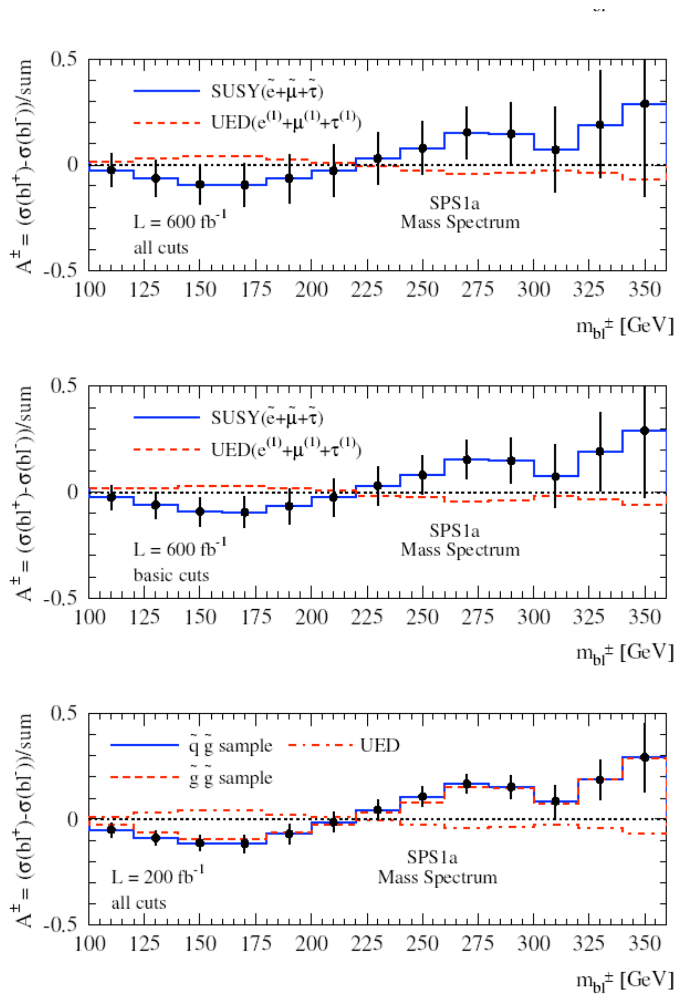
Alves-Eboli
Sbottom spin

Alves-Eboli-Plehn
Spins in Gluino Decays

Athanasiou-Lester-Smillie-Webber
Distinguishing spins in decay chains at the LHC

Choi-Hagiwara-Kim-Mawatari-Zerwas
Tau polarization in SUSY cascade decays

Further: Wang & Yavin, S. Thomas et al,



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")

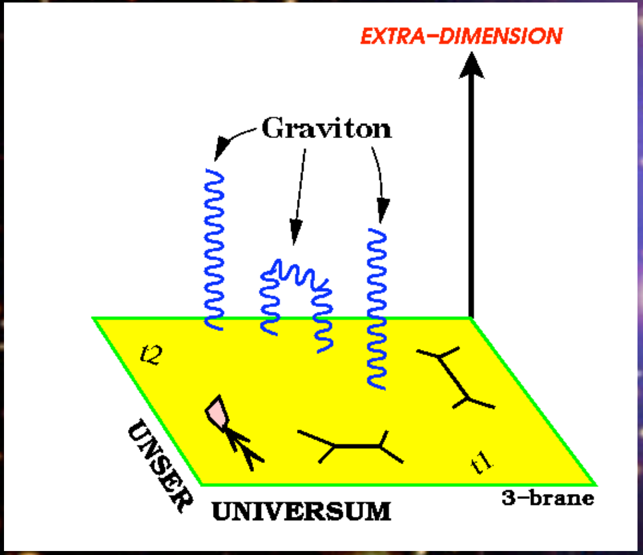
Even for an early discovery it will take years to complete such a program

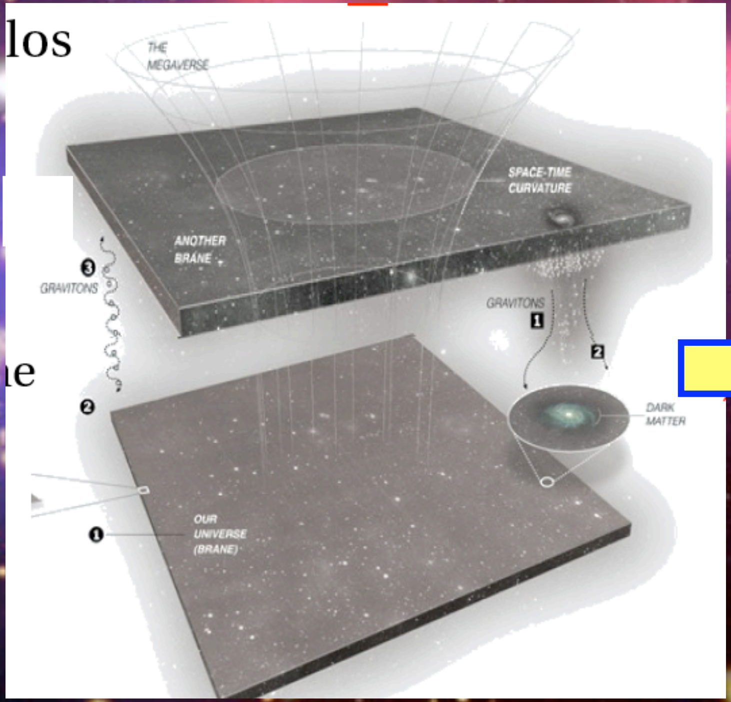
Extra Space Dimensions

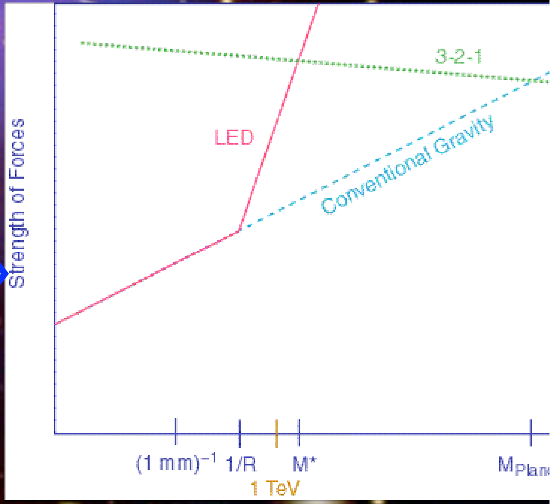
Problem:

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

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







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...

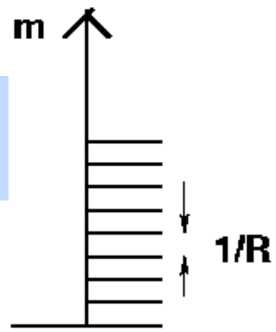
Large Extra Dimension Signatures at LHC

Particles in compact extra dimensions ($2\pi R$)

$\Rightarrow$ Towers of momentum eigenstates

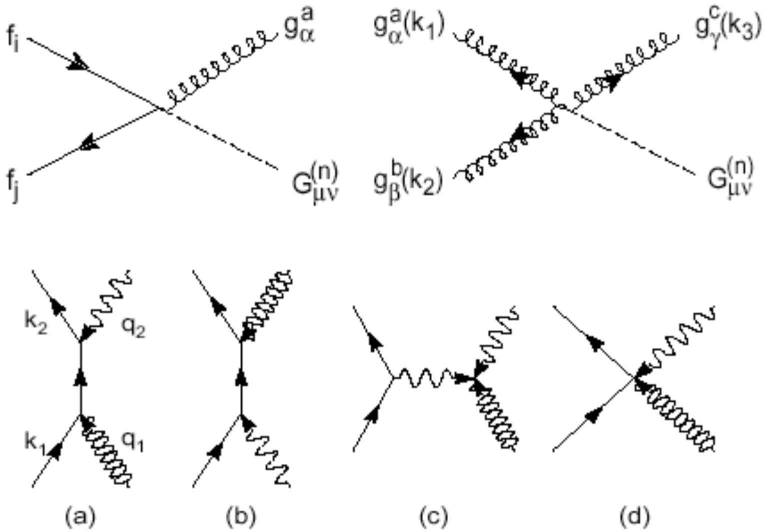
Eg. graviton excitations ($\Delta m = 400$ eV for $\delta = 3$)

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



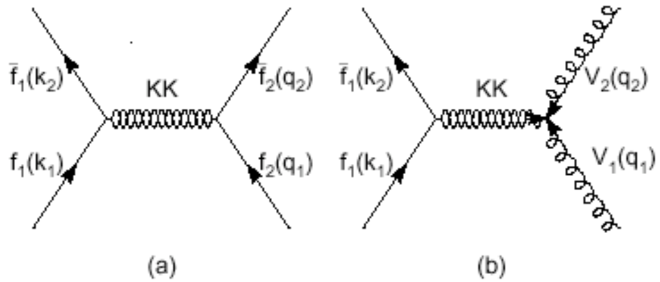
$\Rightarrow$ Strong increase of graviton exchange at high energies

Direct Graviton Emission



- Jets + Missing E_T
- Photon + Missing E_T

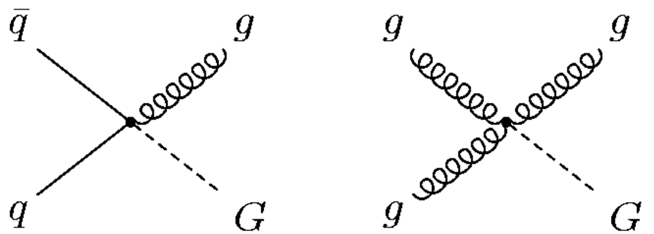
Virtual Graviton Exchange



- Dileptons
- Diphotons

Large Extra Dimension signals at the LHC

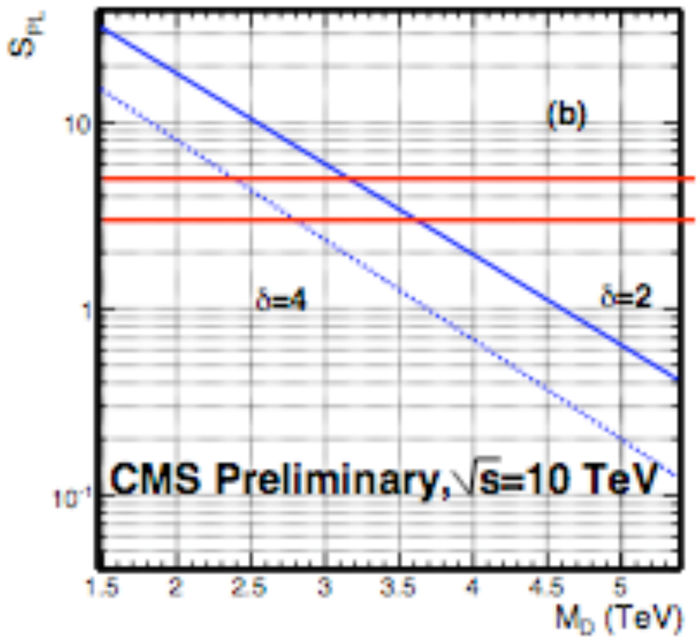
ADD: Arkani –Hamed, Dimopolous,Dvali

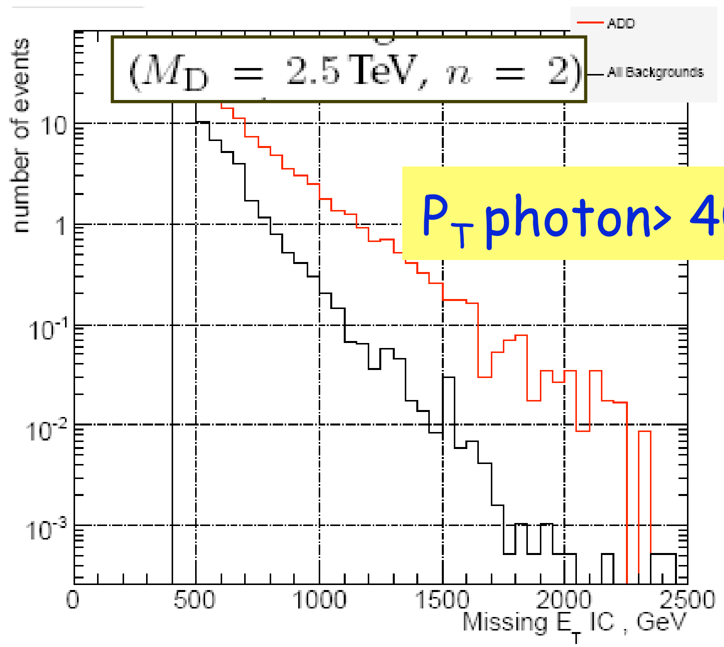


Graviton production!
Graviton escapes detection

Signal: single jet + large missing ET

Signal: single photon + large missing ET





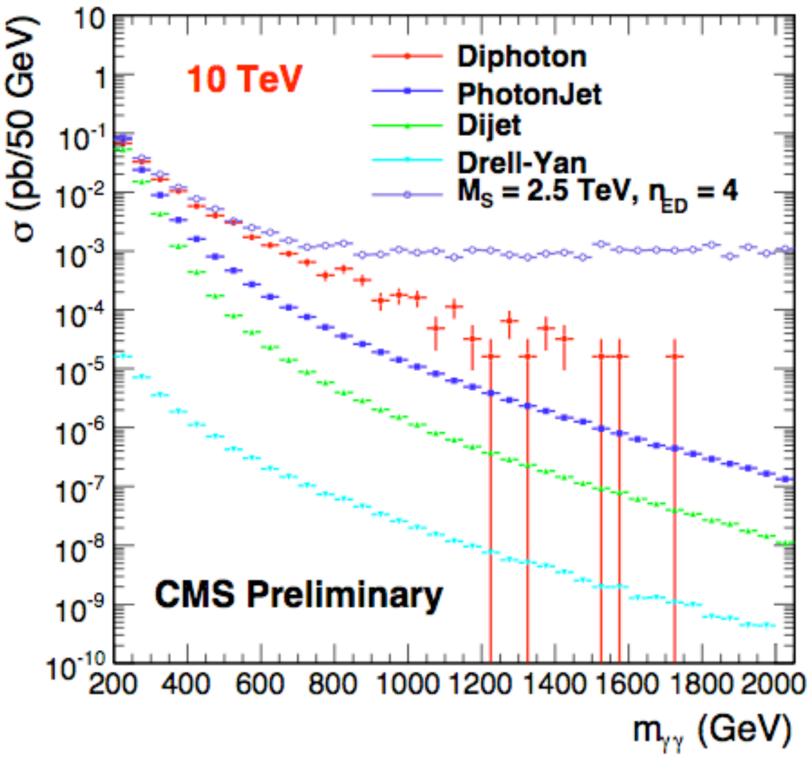
$30 fb^{-1}$

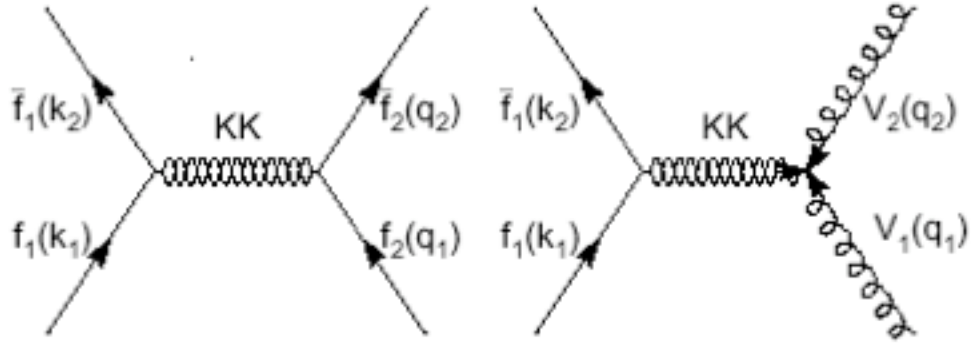
P_T photon> 400 GeV

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 Back Holes

- Schwarzschild radius

Landsberg, Dimopoulos
Giddings, Thomas, Rizzo…

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

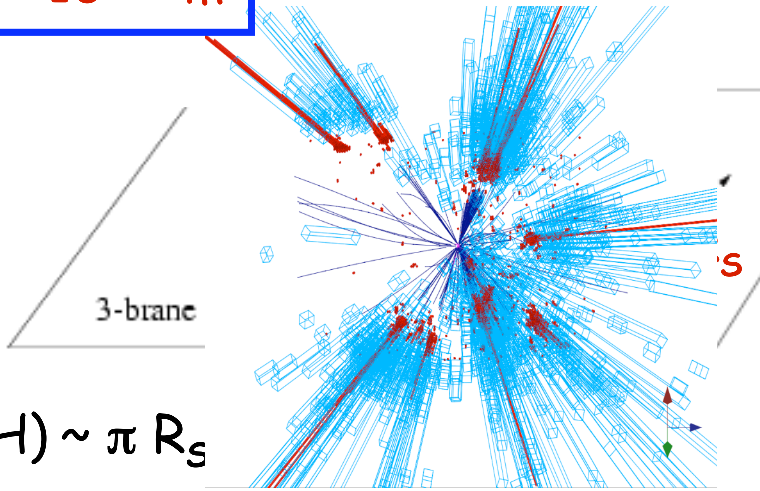
4 + n-dim., $M_{gravity} = M_D \sim$ TeV

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

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

Evaporates in 10^{-27} sec

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 : $\sigma(ij \rightarrow BH) \sim \pi R_S$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

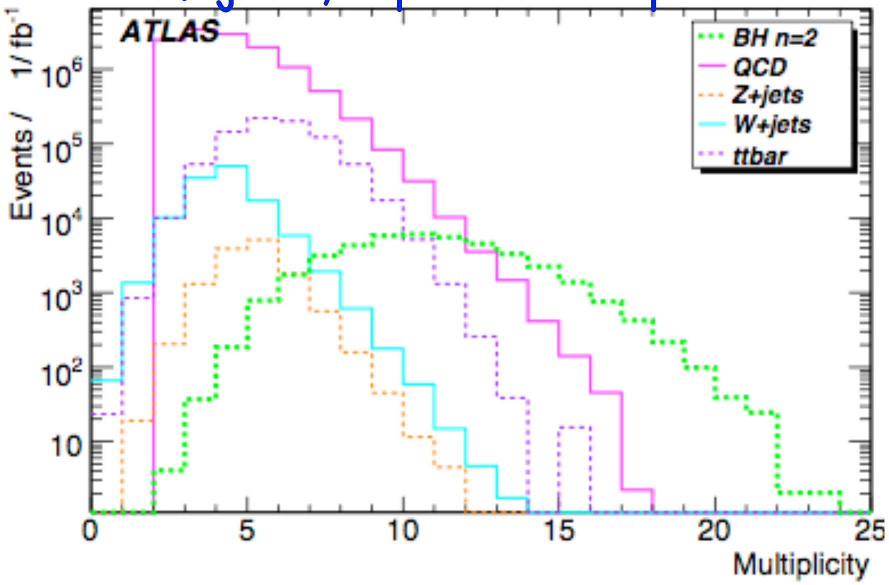
  e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

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

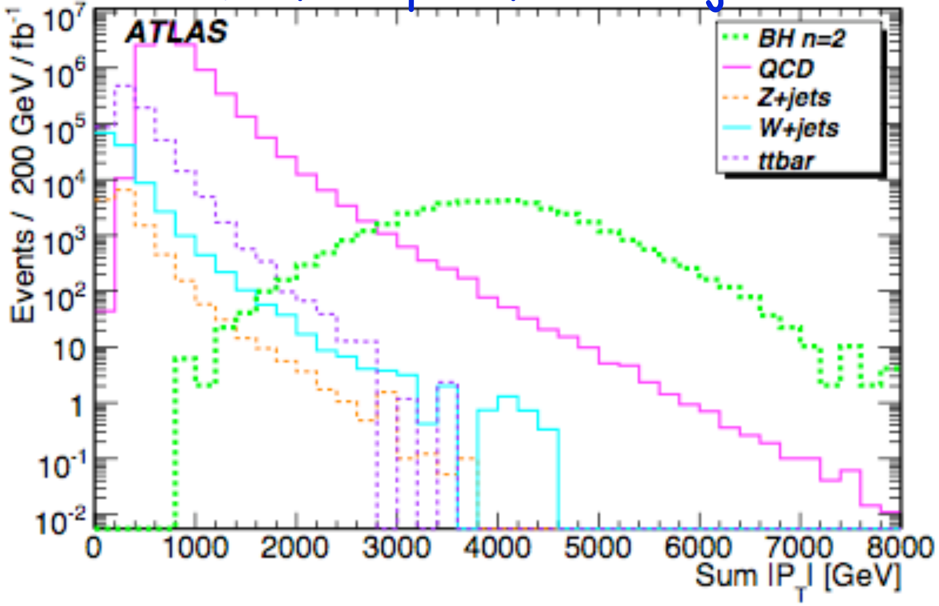
expected signature (quite spectacular …)

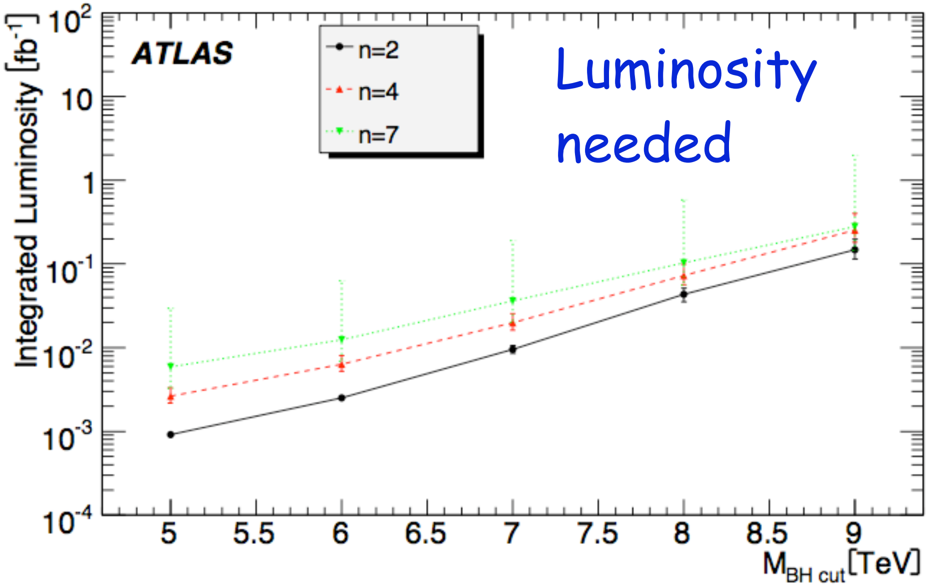
Black Hole Studies

of jets, leptons and photons



Sum of all pt of the objects





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

However cross sections largely unknown (and challenged)

Extra Dimensions: String Balls?

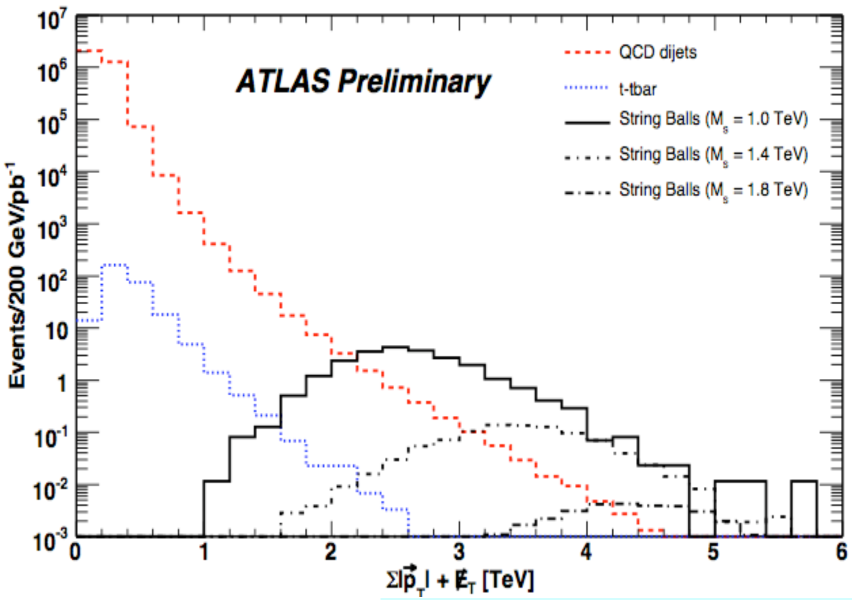
Black Holes: general relativity description only for M_{BH} >> M_D, eg 5•M_D
Weakly-coupled coupled string theory→excited string states?

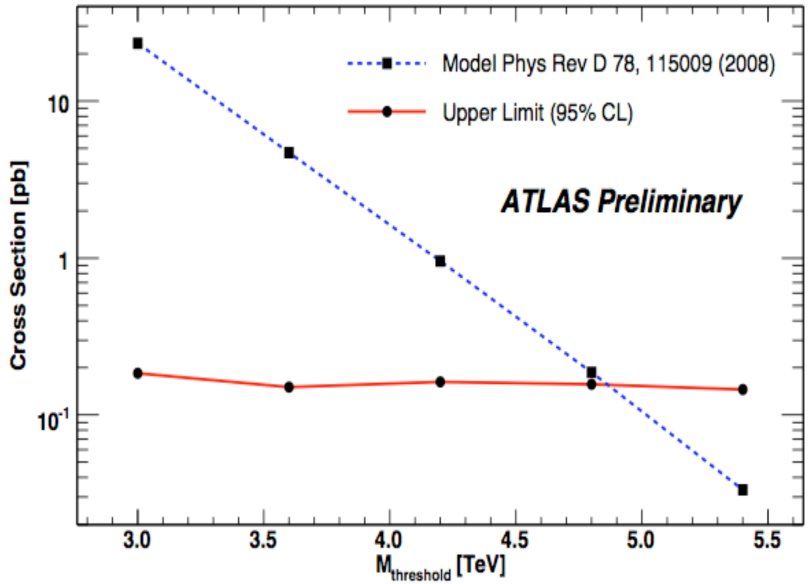
Dimopoulos et al, Ginrich et al.

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

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}

Thermal radiation of jets + leptons



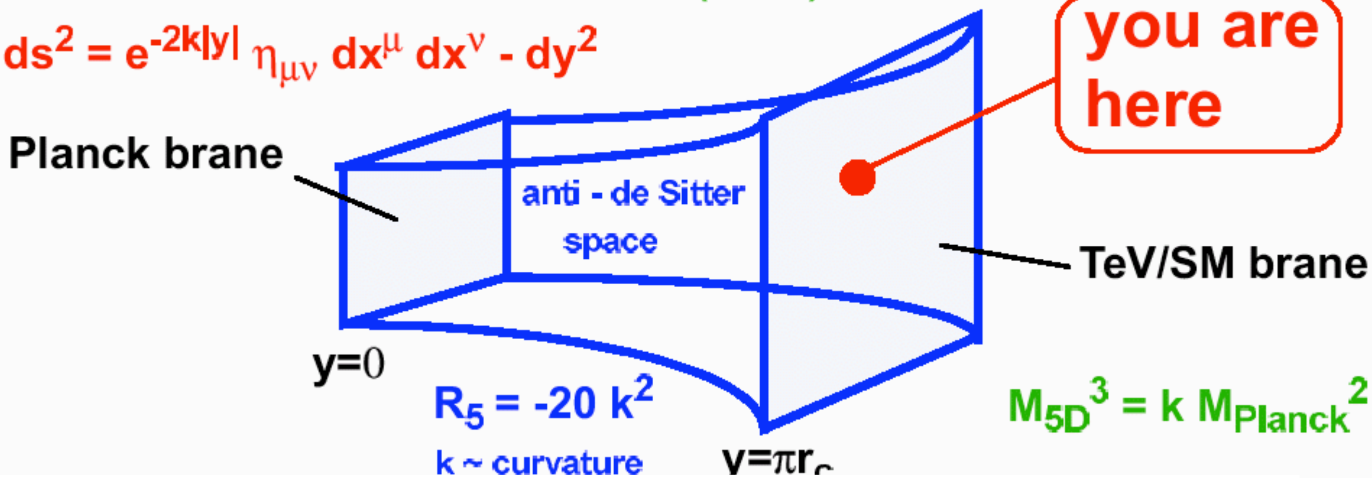


Exclusion of masses of up to ~ 4.8 TeV with 100 pb^{-1}

Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

$ds^2 = e^{-2k|y|}\,\eta_{\mu\nu}\,dx^\mu\,dx^\nu - dy^2$

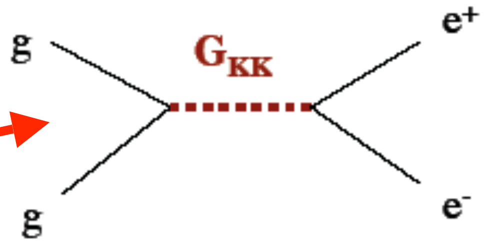


$R_5 = -20\,k^2$

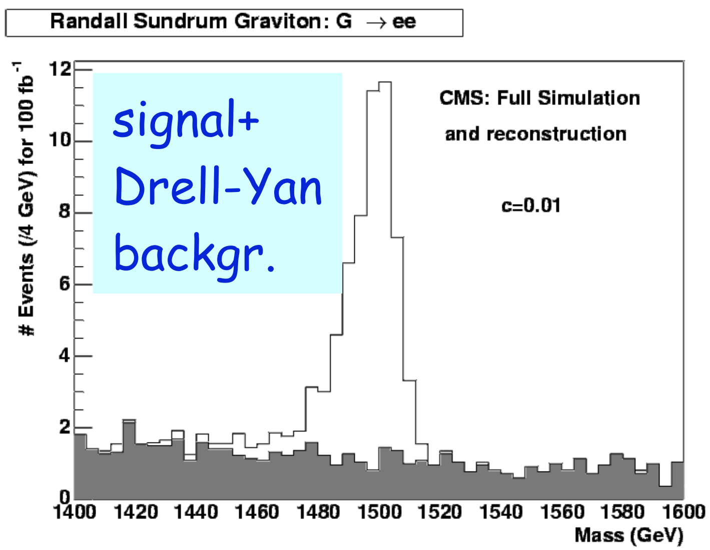
k ~ curvature

$M_{5D}^3 = k\,M_{Planck}^2$

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…

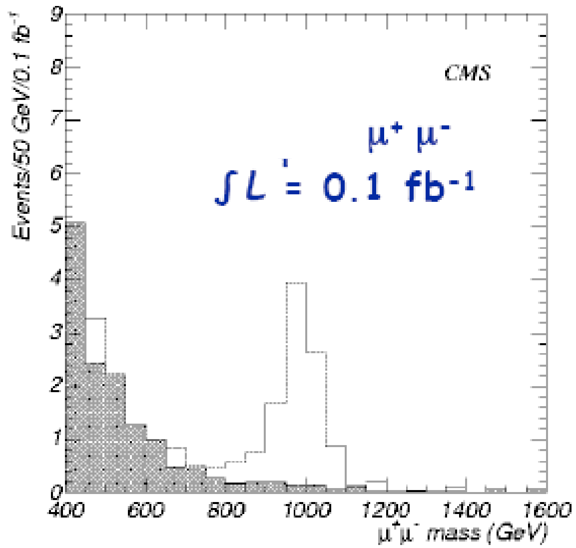
Early Discoveries? E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

A peak!!

A new particle!!

A discovery!!



$pp \rightarrow \mu\mu + X$

First year of operation

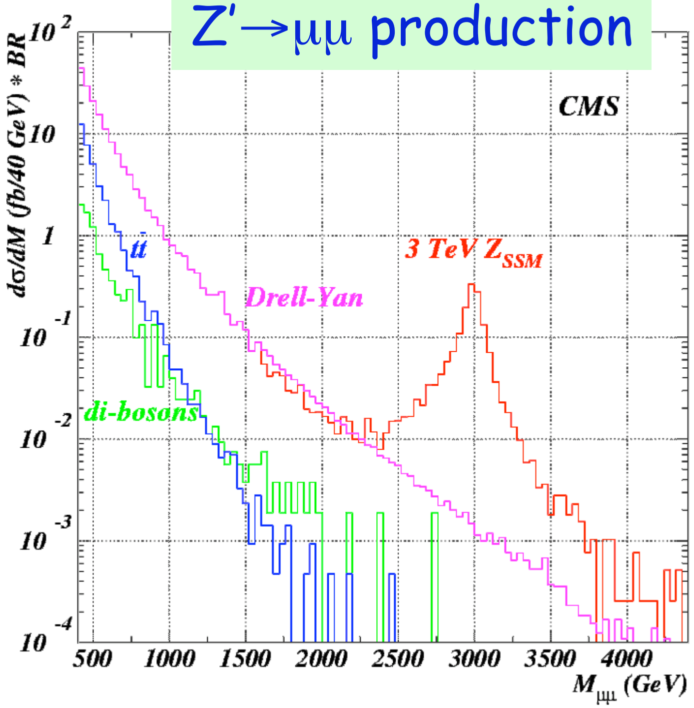
Example : The Di-lepton channel

- 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'

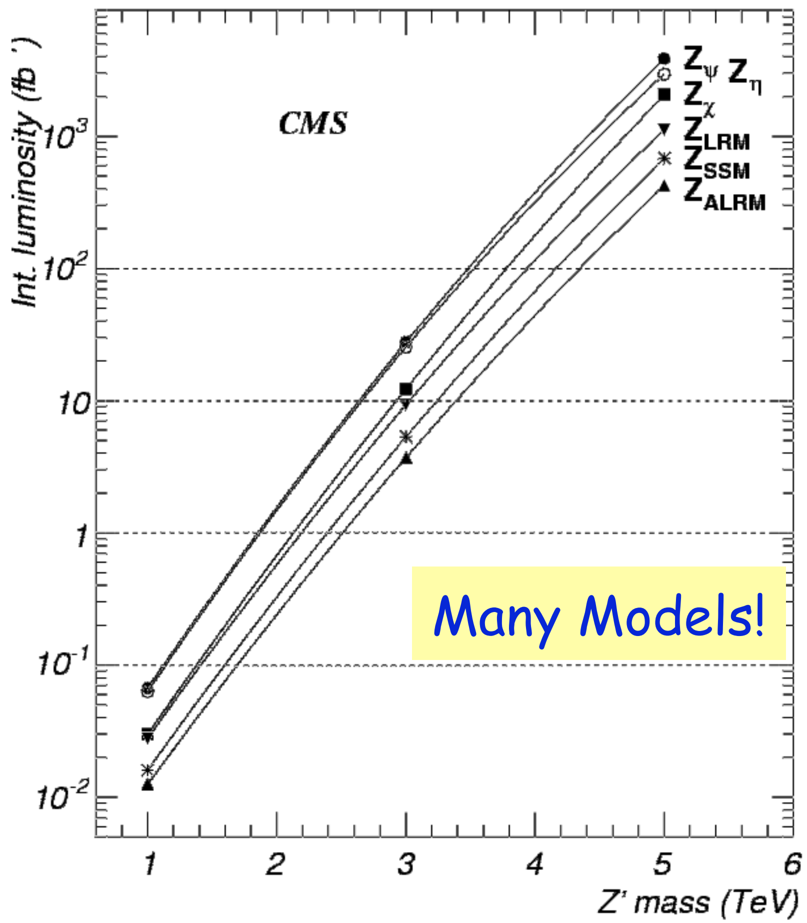
EG due a new symmetry group…

Z'→μμ production



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

$Z' \rightarrow \mu^+\mu^-$: 5σ significance curves

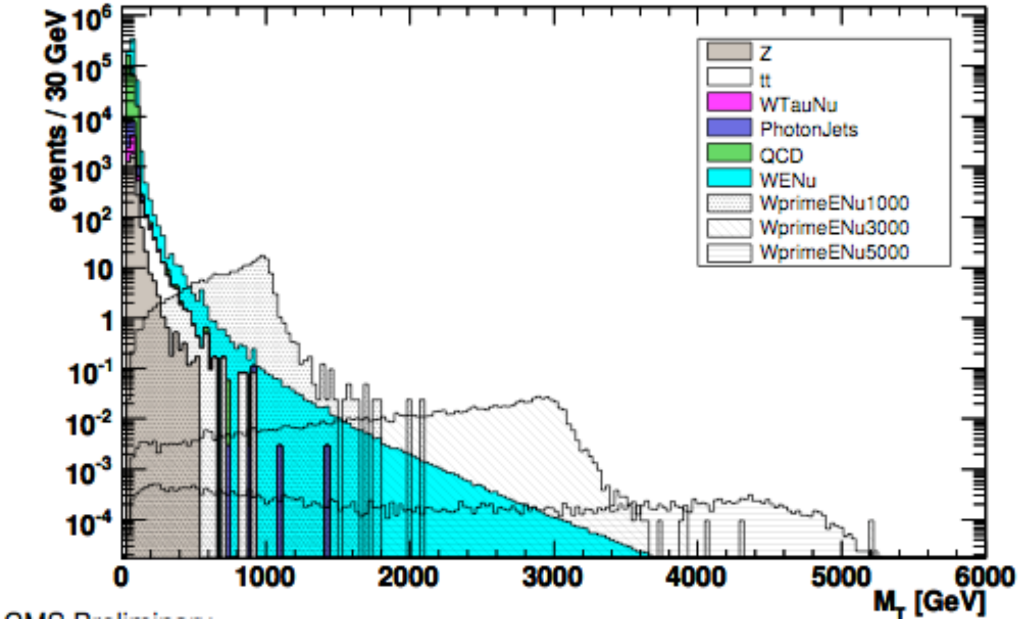


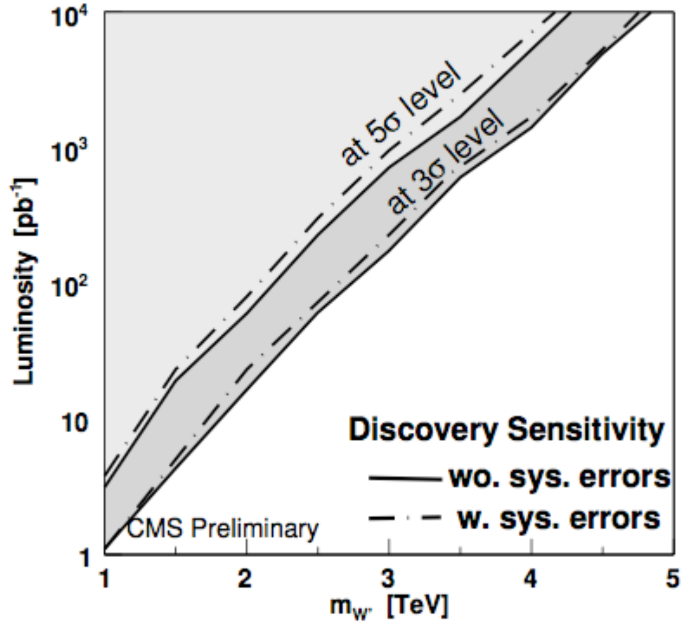
- Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible, beyond Tevatron run-II
- High lumi 100 fb^{-1}: extend range to 3.4-4.3 TeV

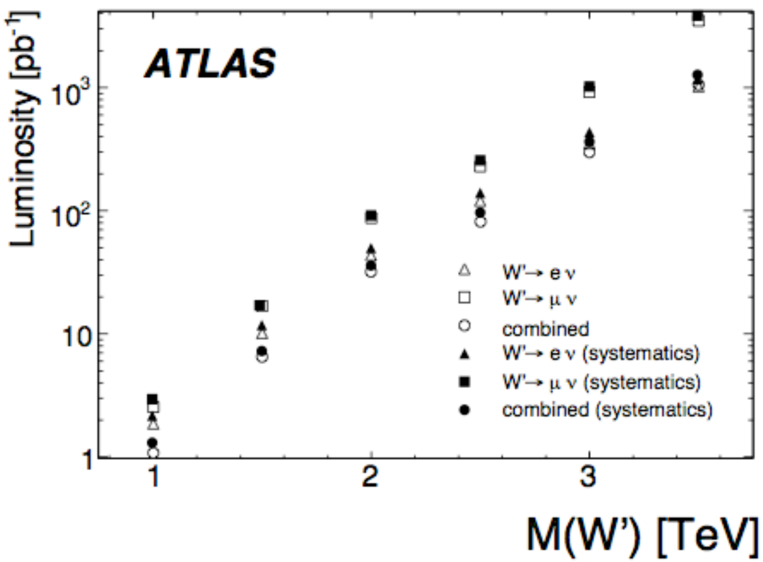
New Heavy Gauge Bosons: W'

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

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





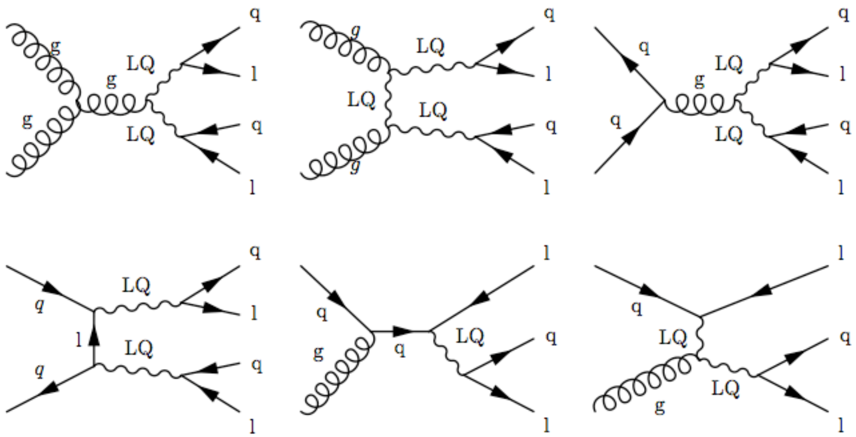


Tevatron > ~ 1 TeV

Sensitivity already for 10 pb^{-1}

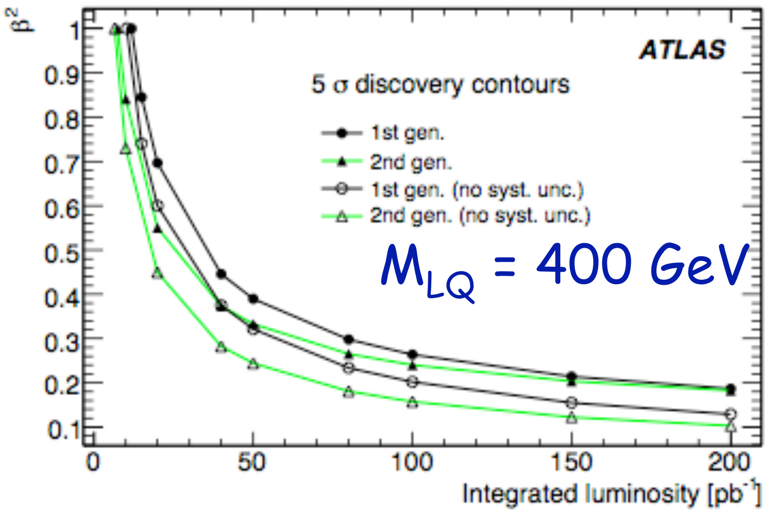
Leptoquark Production

GUT inspired models predict new particles with lepton and quark properties

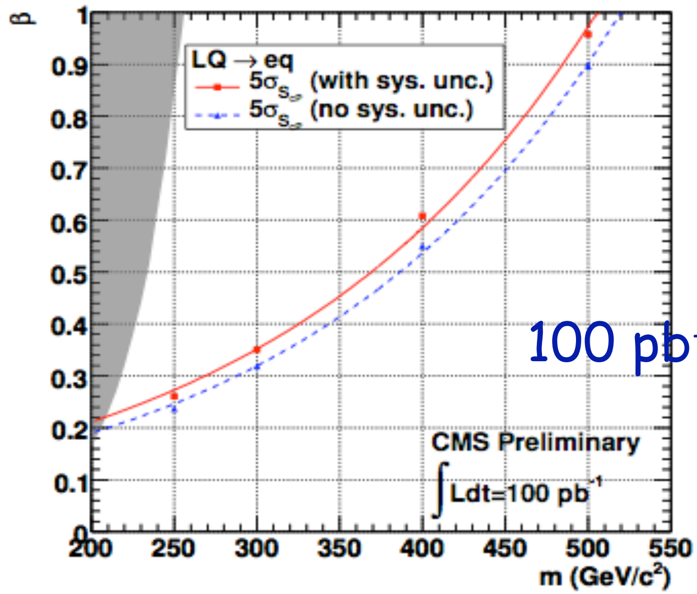


Tevatron limits ~ 300 GeV

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}



M_{LQ} = 400 GeV

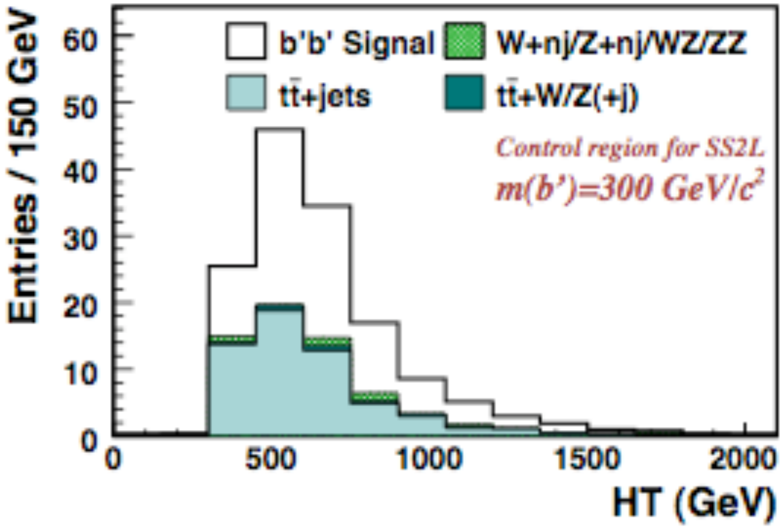


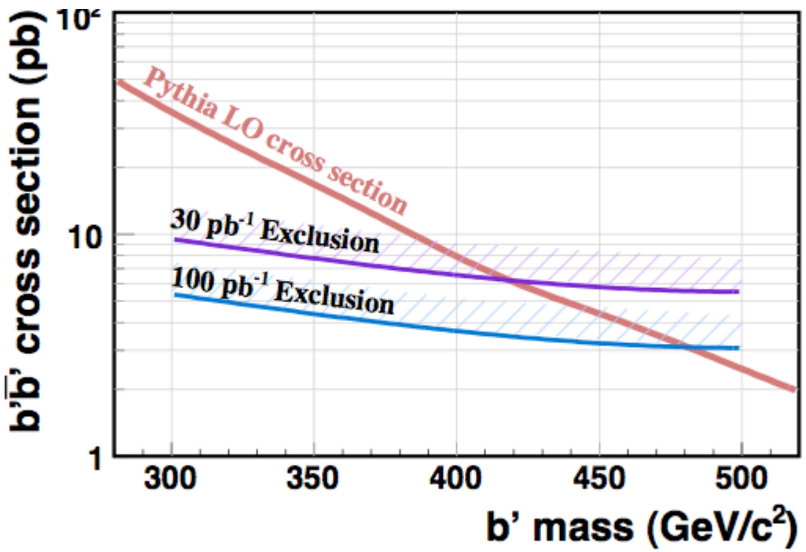
100 pb^{-1}

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'→ tW decays

Present limits ~ 200 GeV

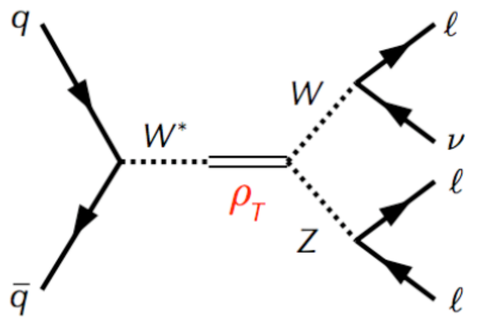
Tevatron Limits

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

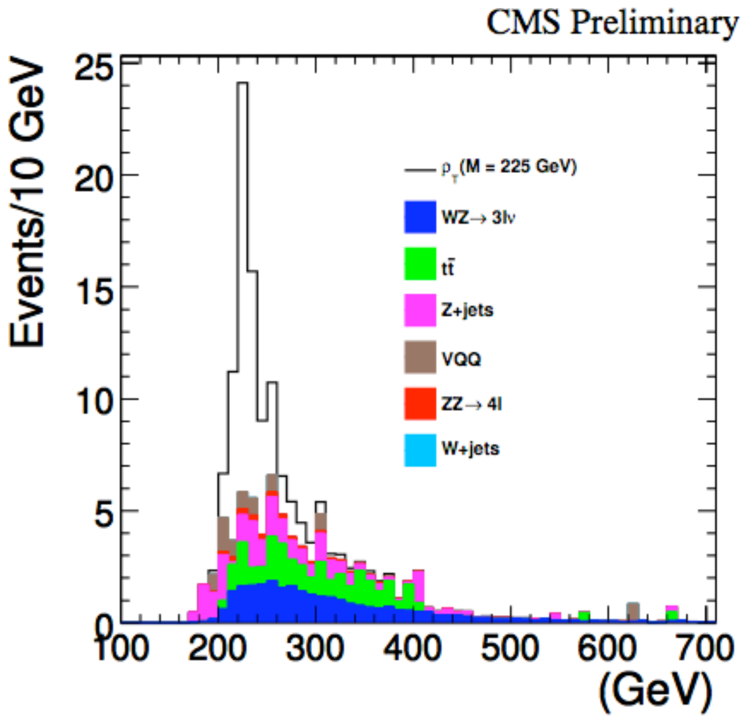
Senstivity ~400 GeV with 100 pb^{-1}

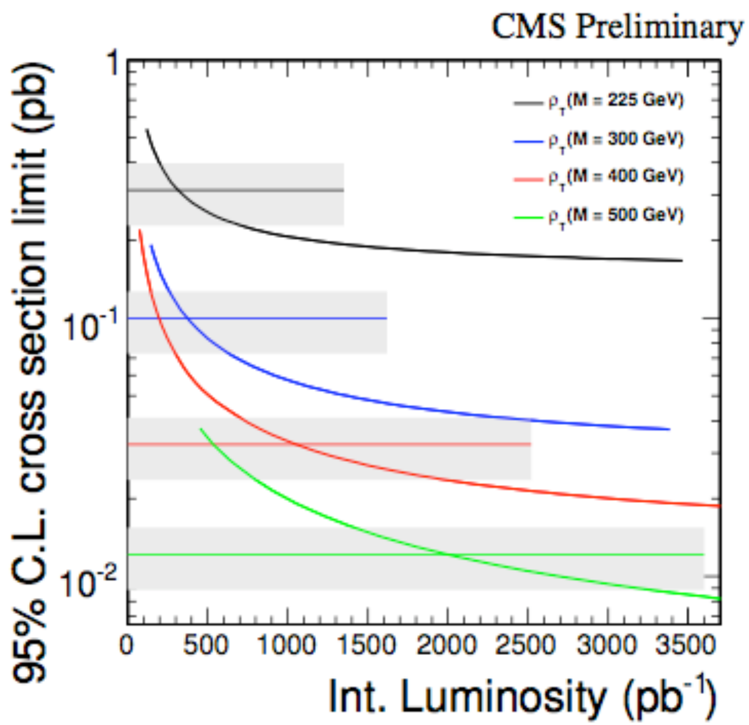
A New Strong Force: Technicolor

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





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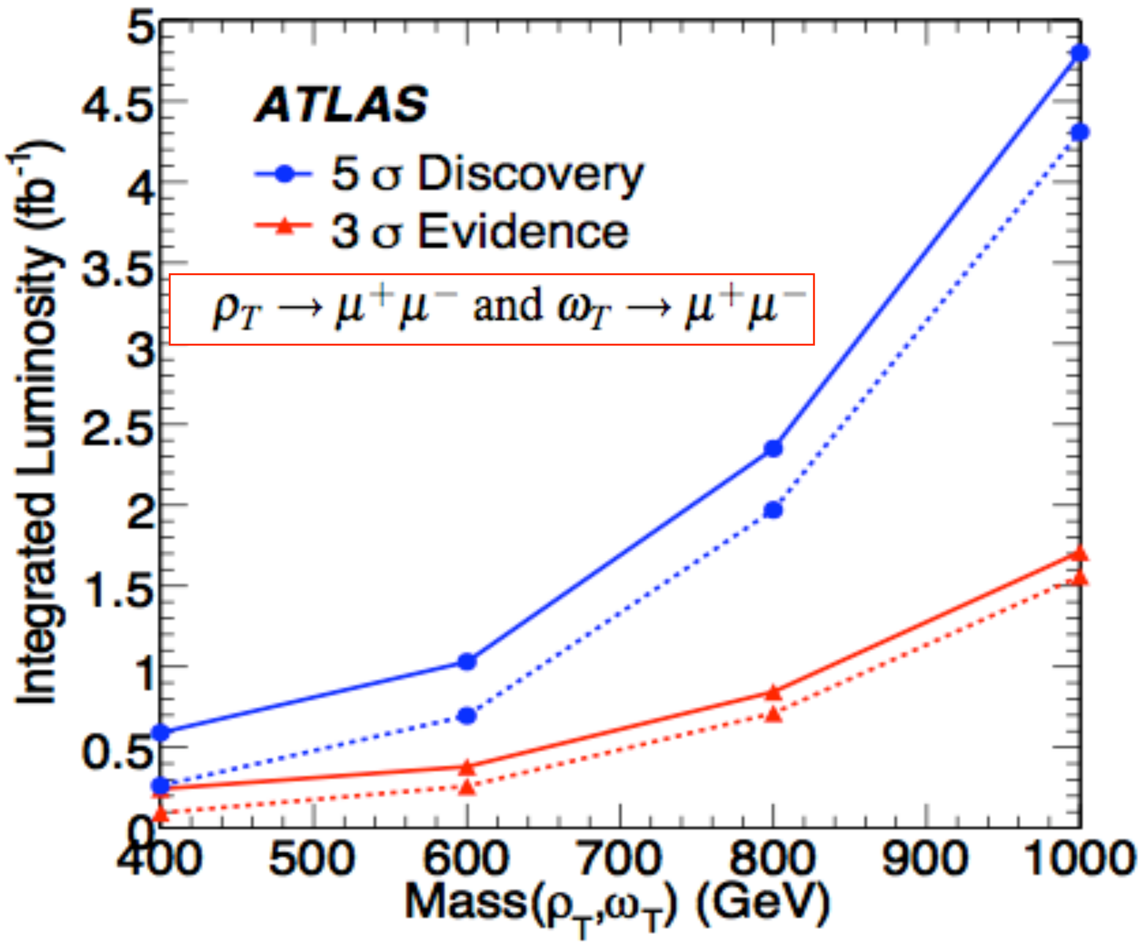
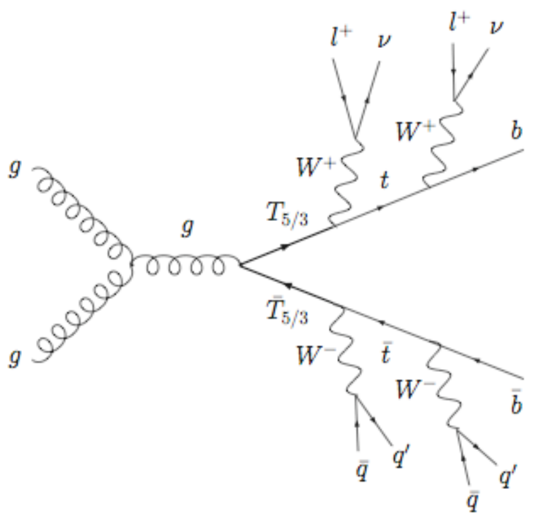


Luminosities of ~ 0.5-1 fb^{-1} or more needed

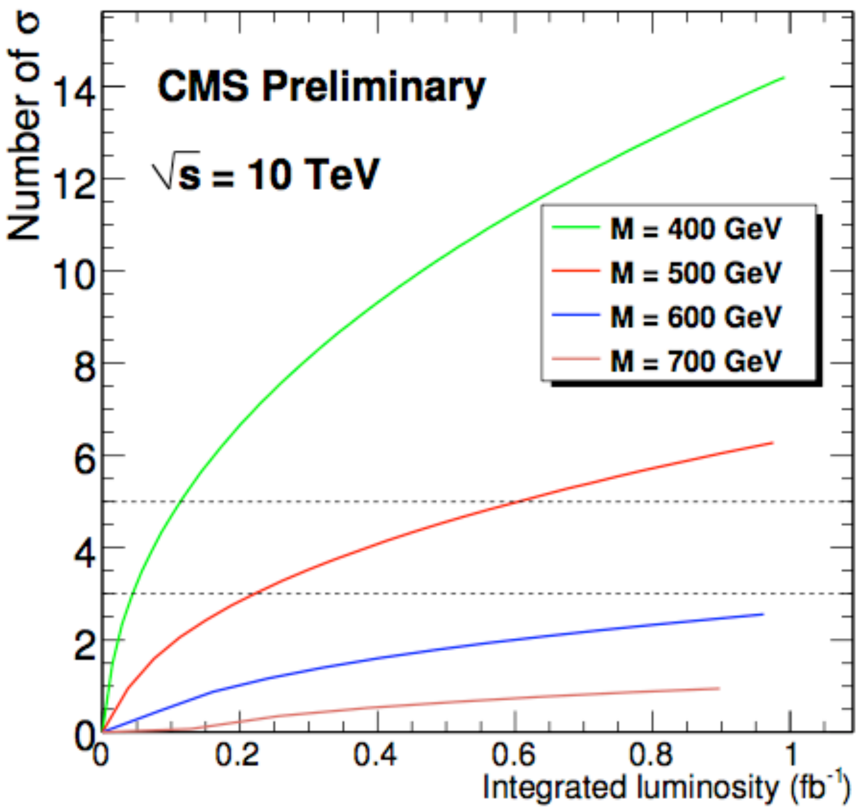
Particles with Unusual Properties

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



Produced in models with warped space dimensions

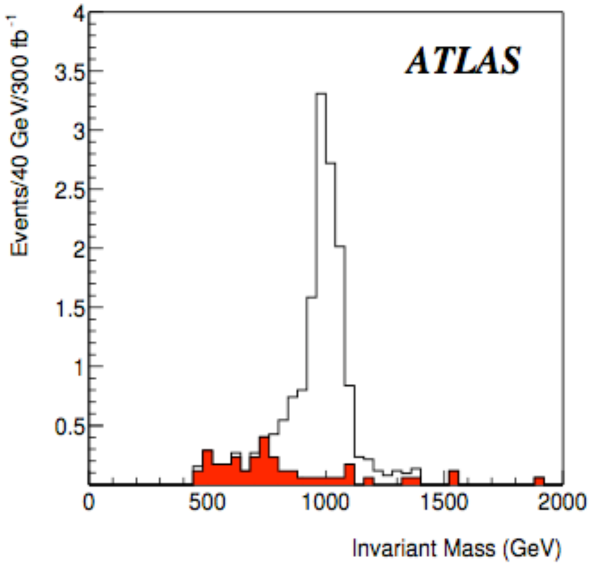
Characteristic: like sign leptons in decay

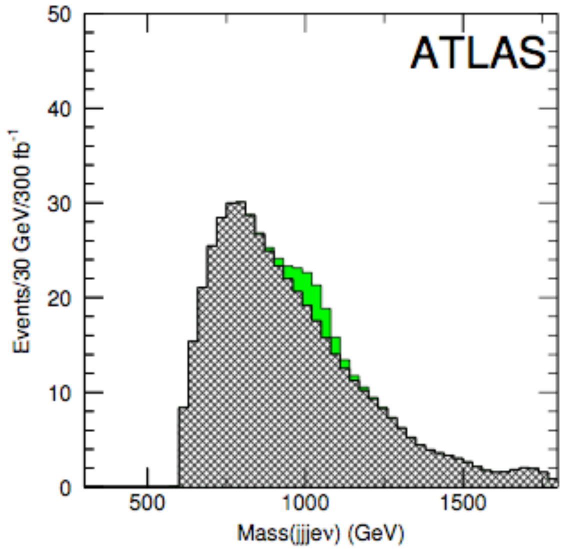


Reach up to 400 GeV with 100 pb^{-1}

Little Higgs Models

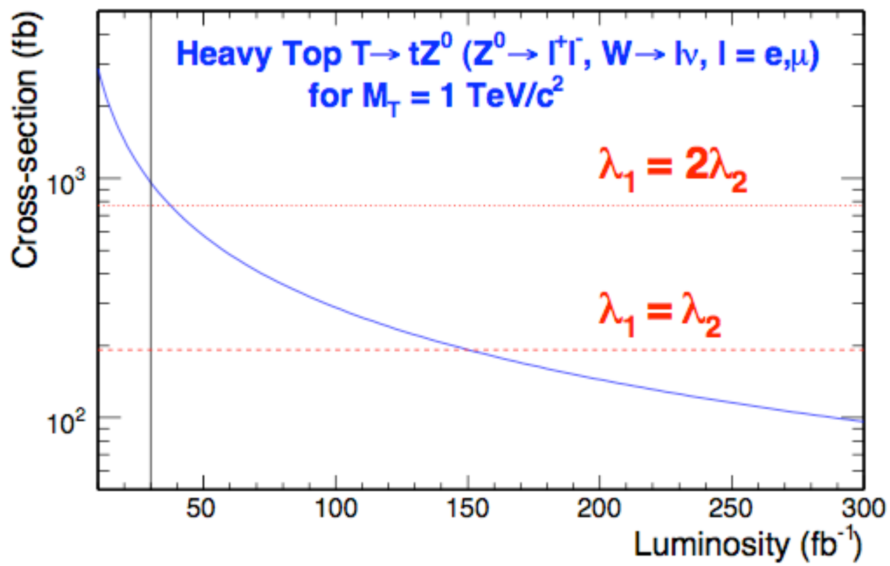
Heavy top partner around 1 TeV ⇒ Decay eg into $T \rightarrow tZ$, $T \rightarrow tH$



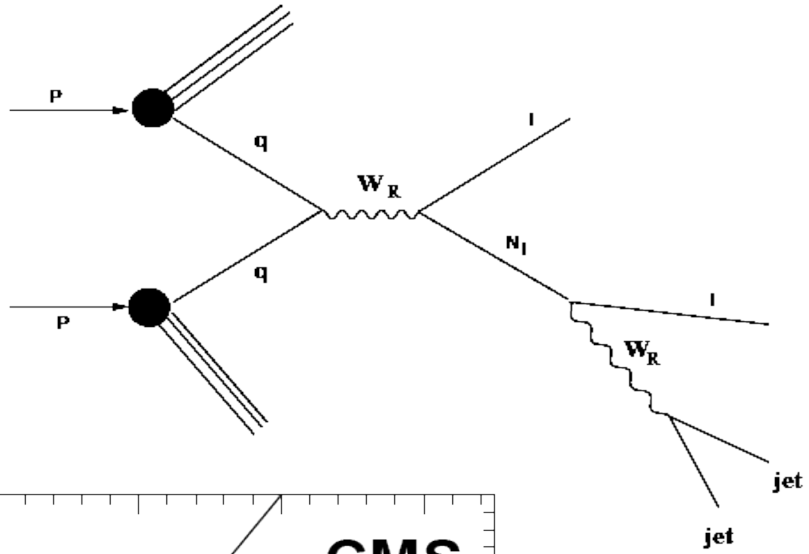


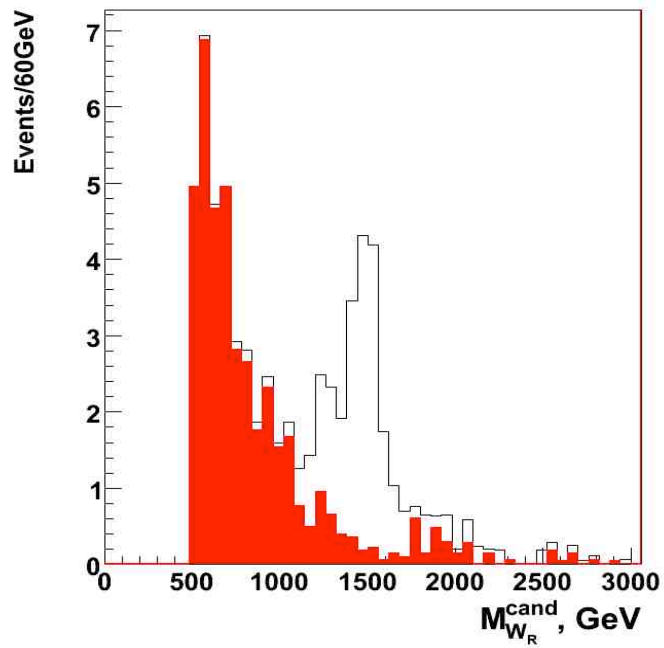
Signals+BG
Needs a lot of luminosity!!
>> fb^{-1}

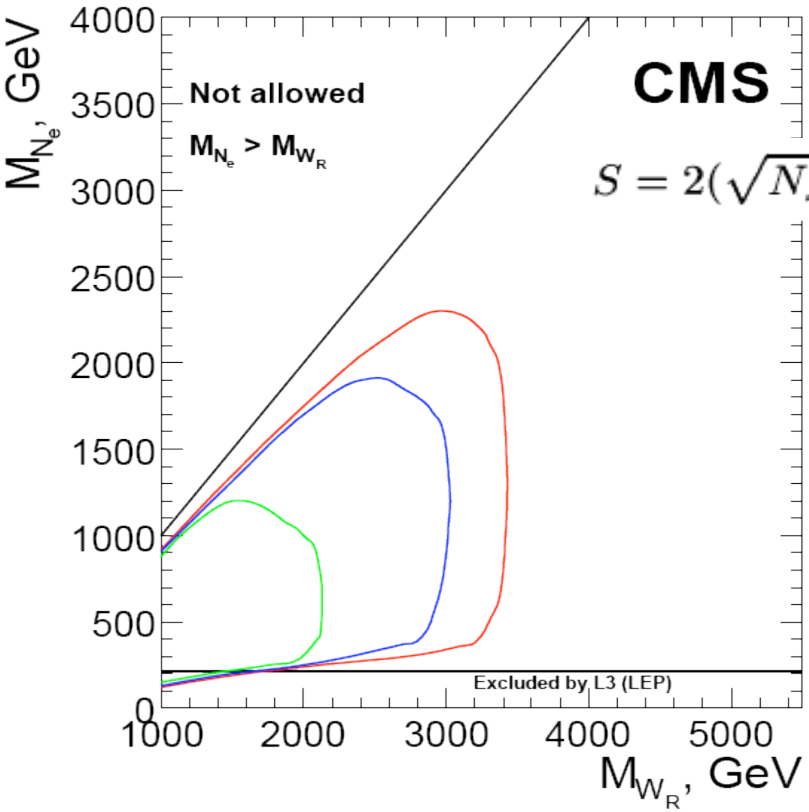
CMS PTDR:
Sensitivity to heavy top cross section



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

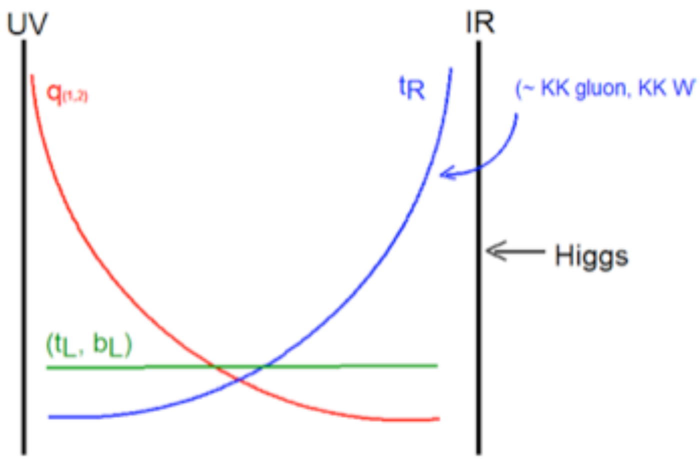
N>0.3 TeV

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

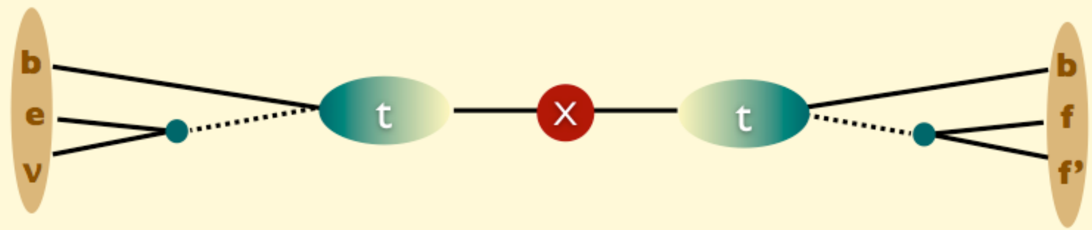
TeV Resonances into Top Quark Pairs

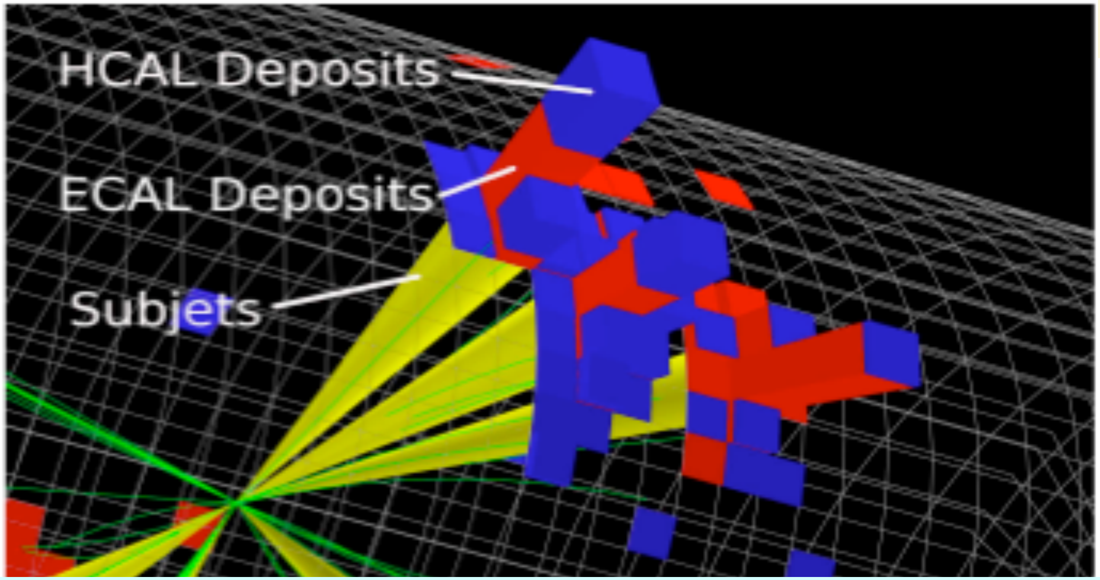
Recent developments in models: a prominent role of top production
-light SM fermions live near Planck brane, heavy (top) near TeV brane
-decay of Randall Sundrum gravitons into top pairs!!

- Eg RS → t tbar



⇒High P_T tops

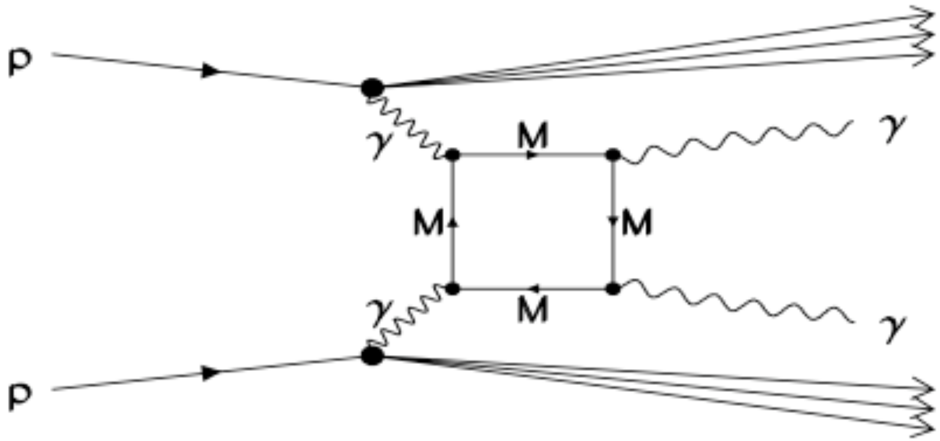




Methods are prepared to tackle the early data

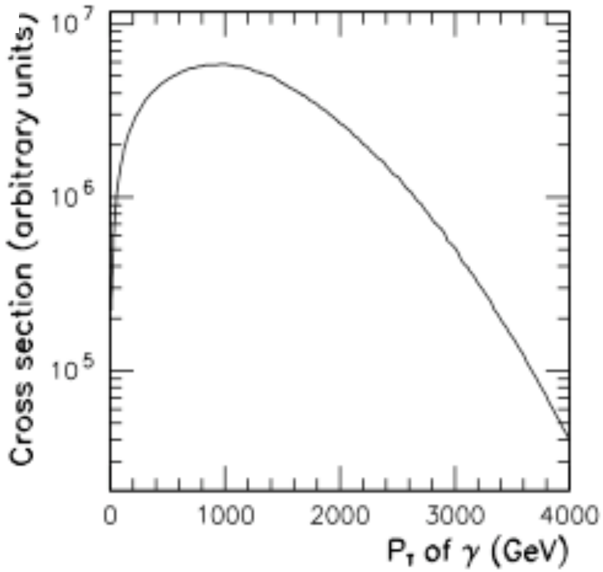
Magnetic Monopoles

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



Virtual production:
Look eg into di-photon final state

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



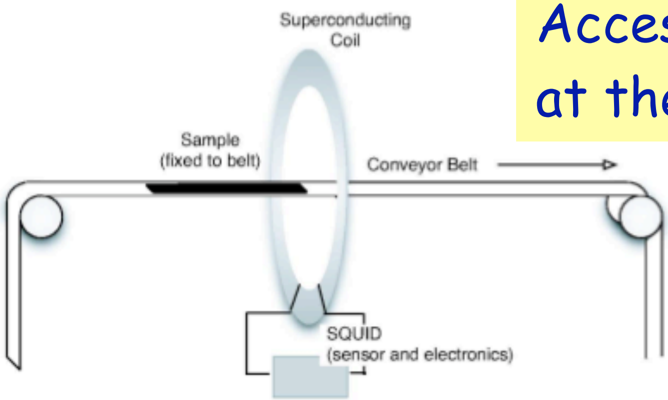
Cross section O(fb)
High luminosity required

Monopole Search

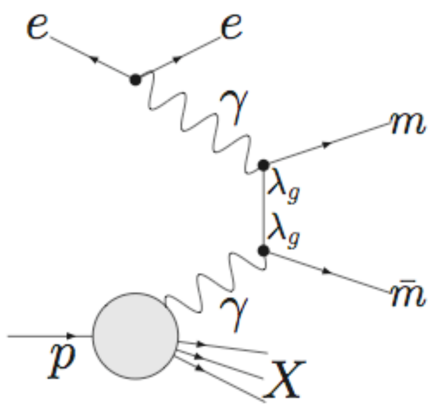
H1 experiment at the ep collider HERA, Hamburg

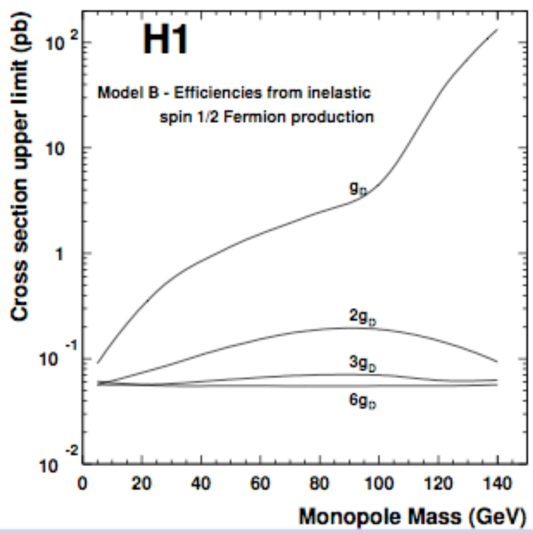
Magnetic Monopoles stuck in the beampipe?

- 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



Accessible at the LHC!





Also: unusual tracks in the CMS detector

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

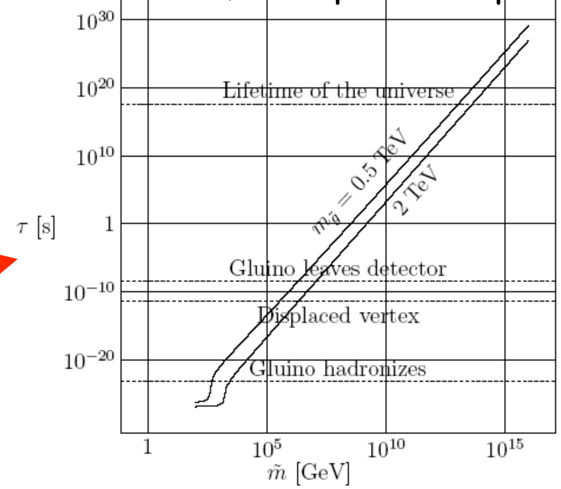
  eg. with the calorimeters of the experiments!

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

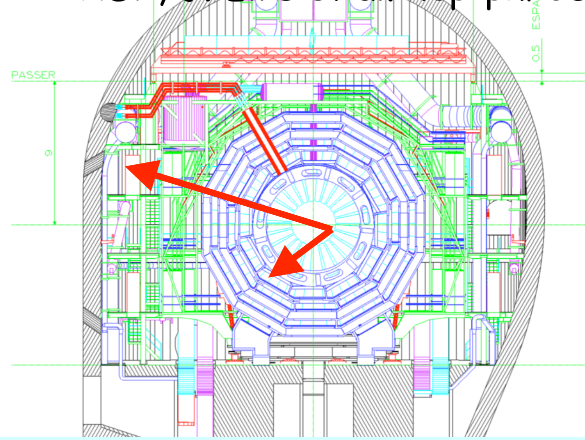
⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



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

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



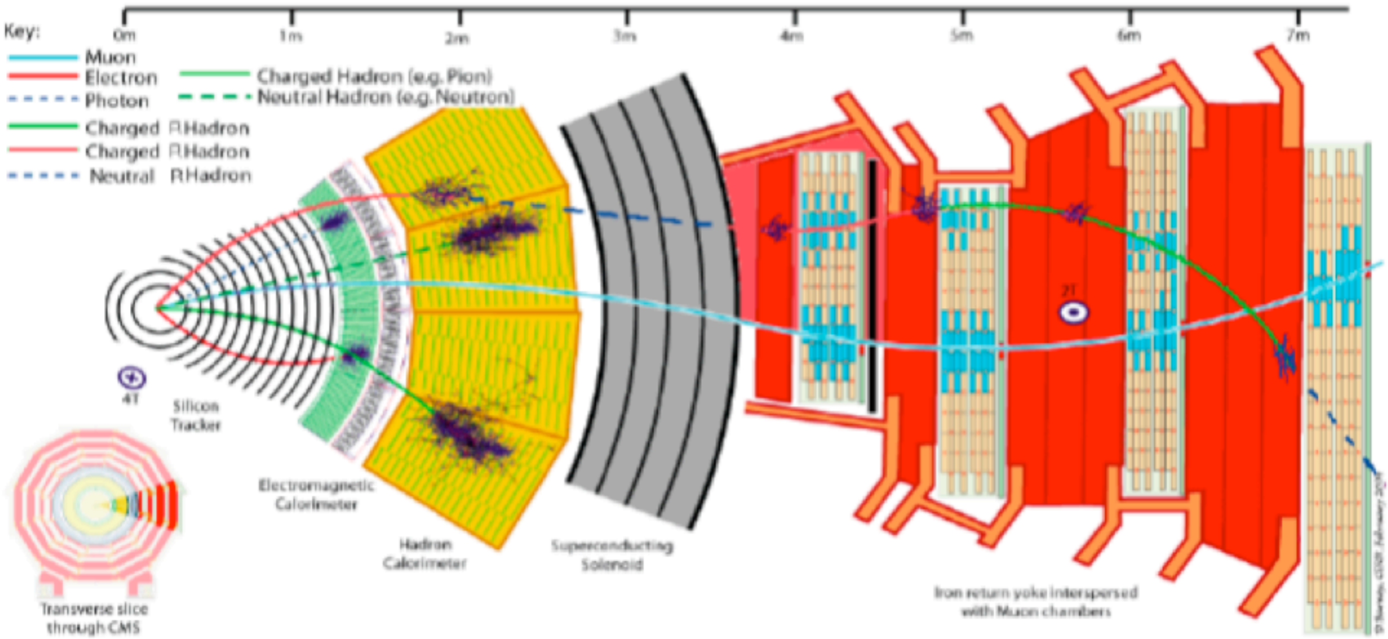
Also eg.
R. Barbieri

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

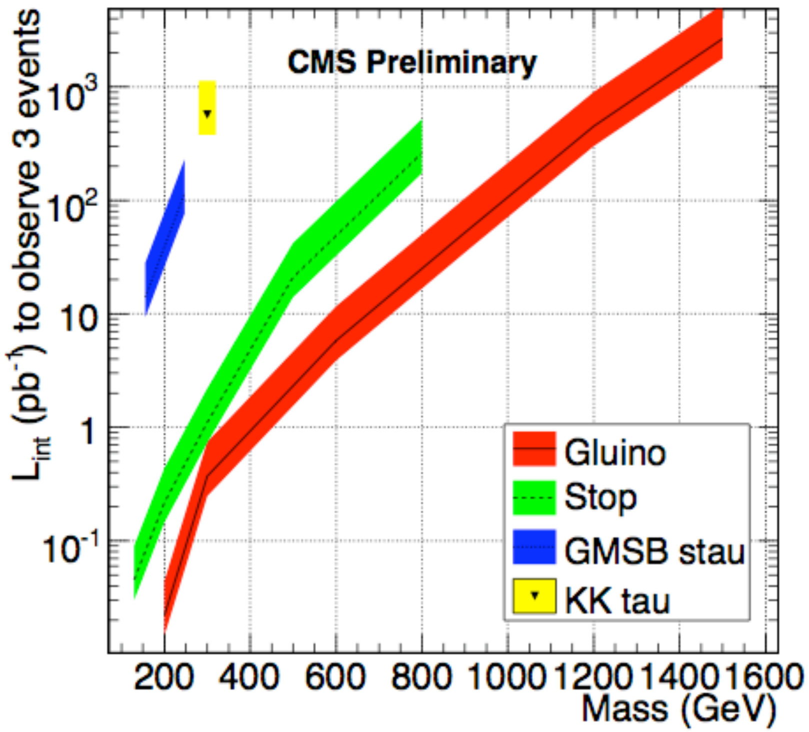
- They 'sail' through the detector like a 'heavy muon'
- In certain (hadronization) models they may change charge on the way
- They also loose a lot of energy when passing the detector (dE/dx)



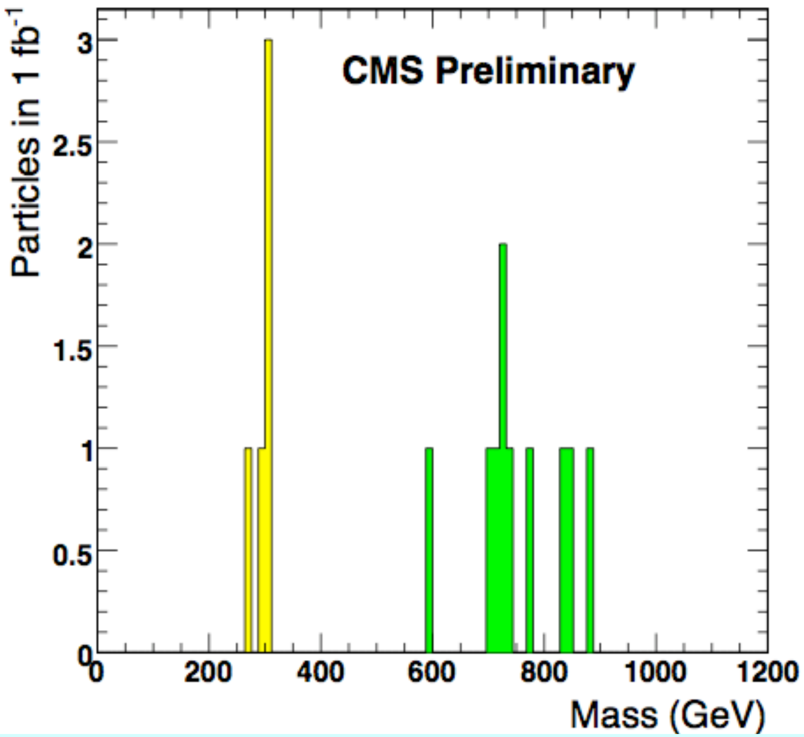
Weird signature!!

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!

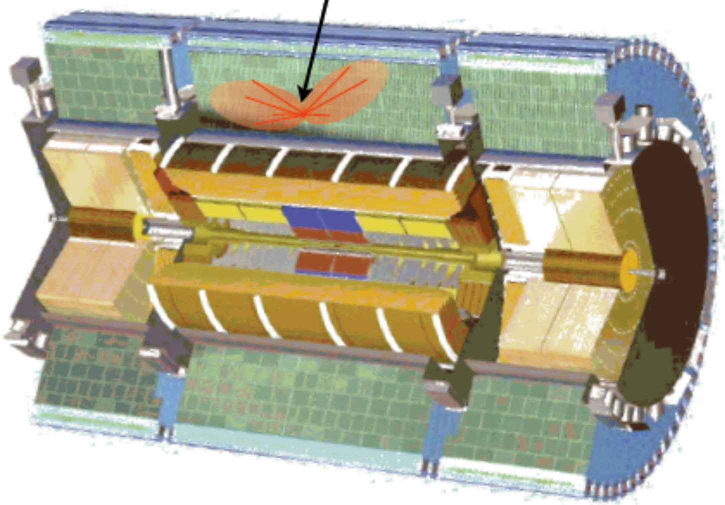
The R-hadrons may loose so much energy that they simply stop in the detector

Long Lived Gluinos

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

looking for stopped gluinos that later decay

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



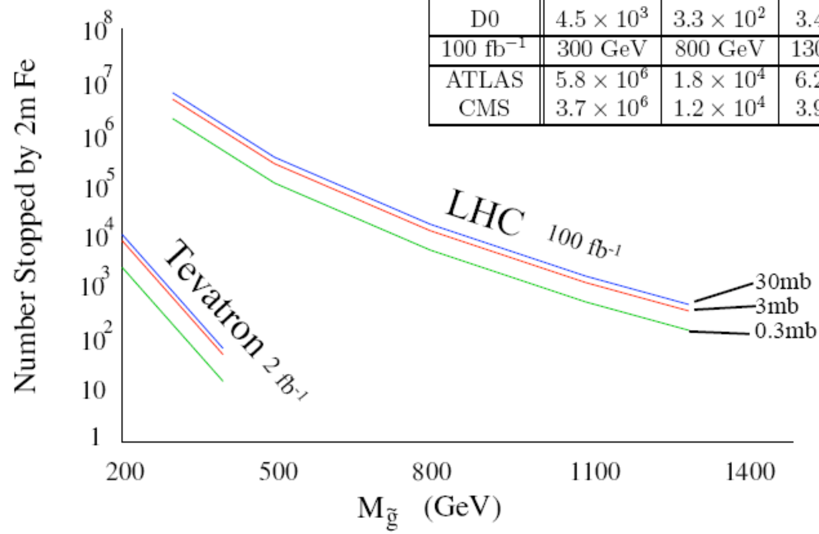
Uncorrelated with any beam crossing

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



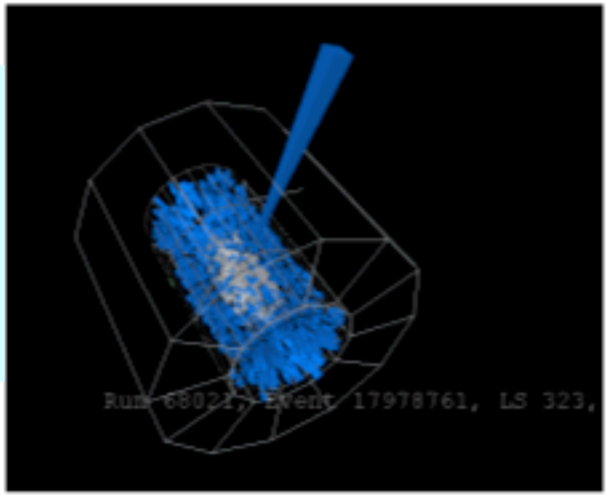
⇒ Special triggers needed, asynchronous with the bunch crossing

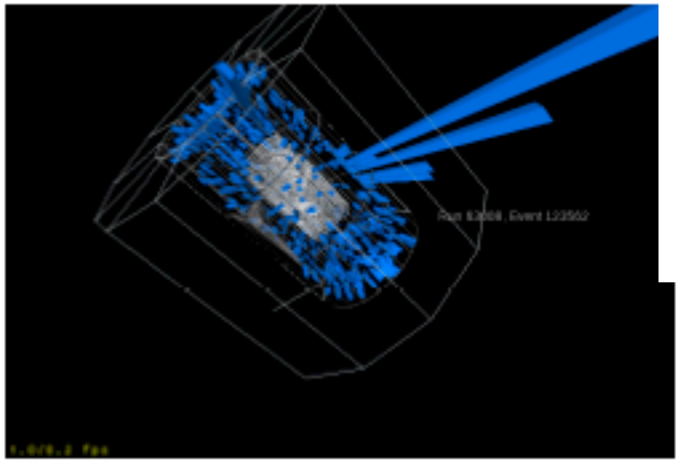
Stopped Gluinos

Studies in CMS with the 2008/2009 cosmic data:

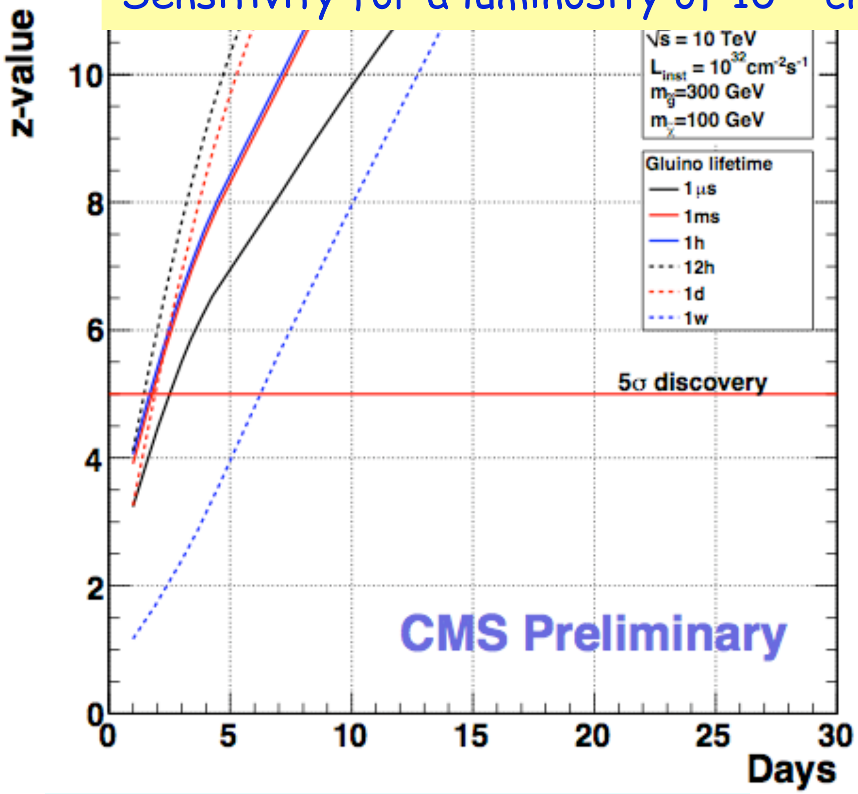
All events we find now are background and we can learn how to cut on them!

Find energy splashes with certain topology



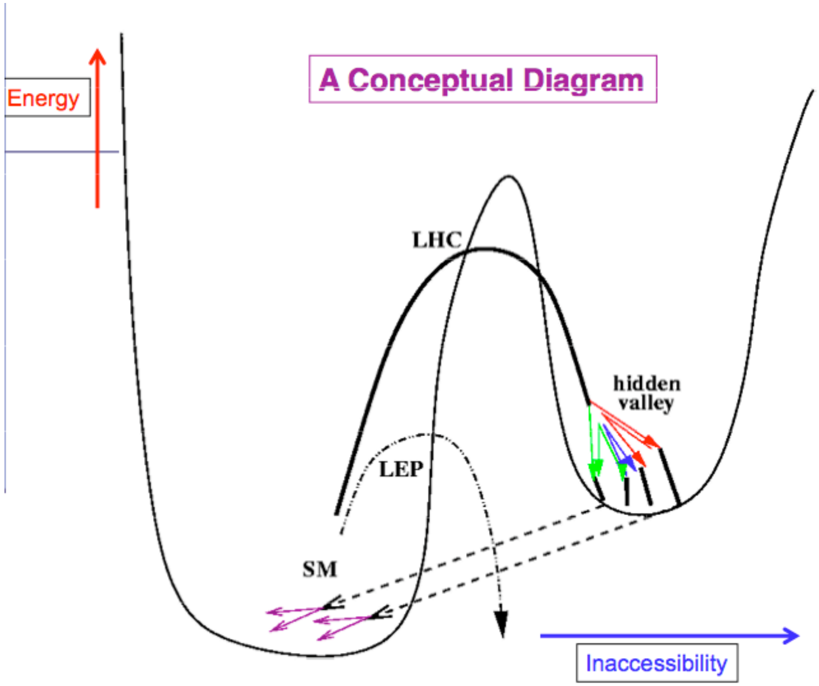


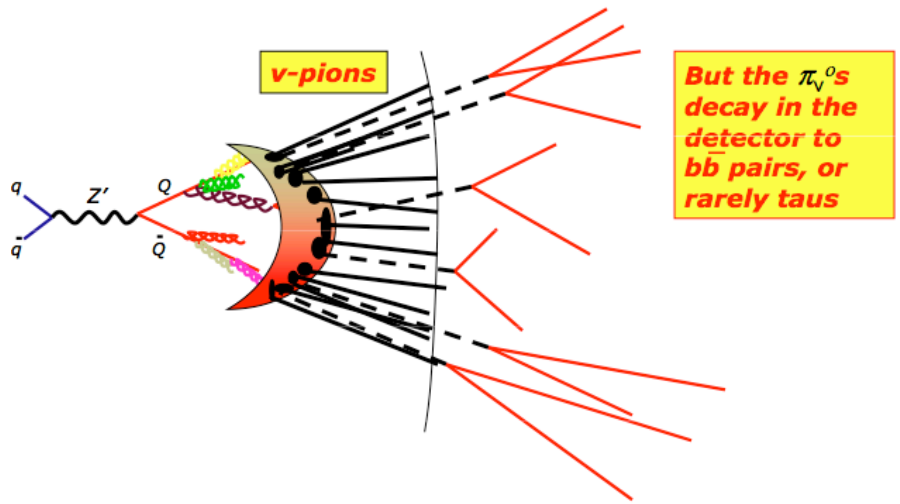
Sensitivity for a luminosity of 10^{32} $cm^{-2}s^{-1}$



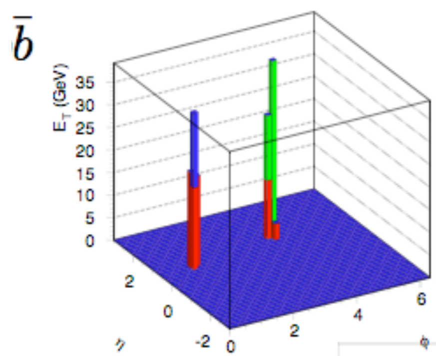
Discovery with only a few weeks running!

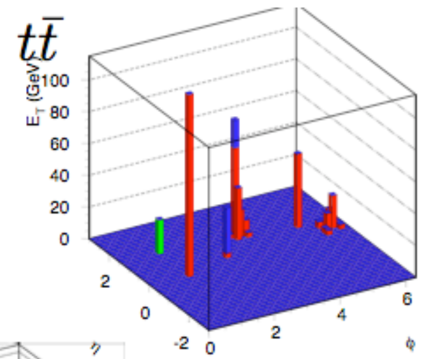
Hidden Valley Physics: New Signatures





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

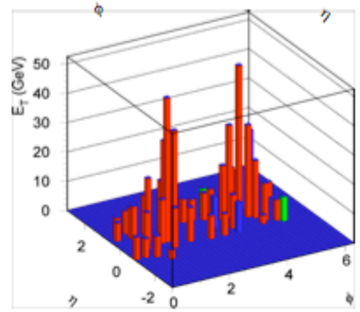




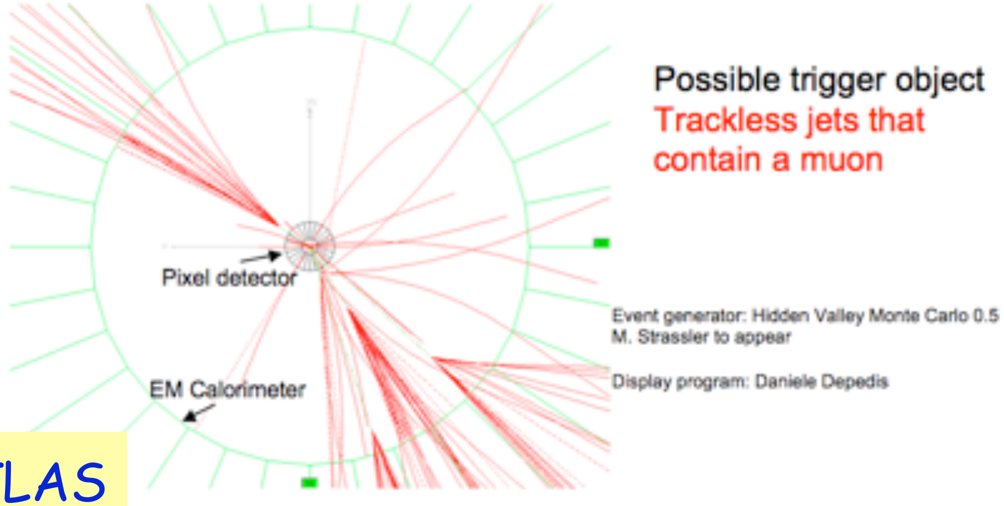
⇒ Difference with QCD jets??

⇒ Study SM jet structure

Hidden valley

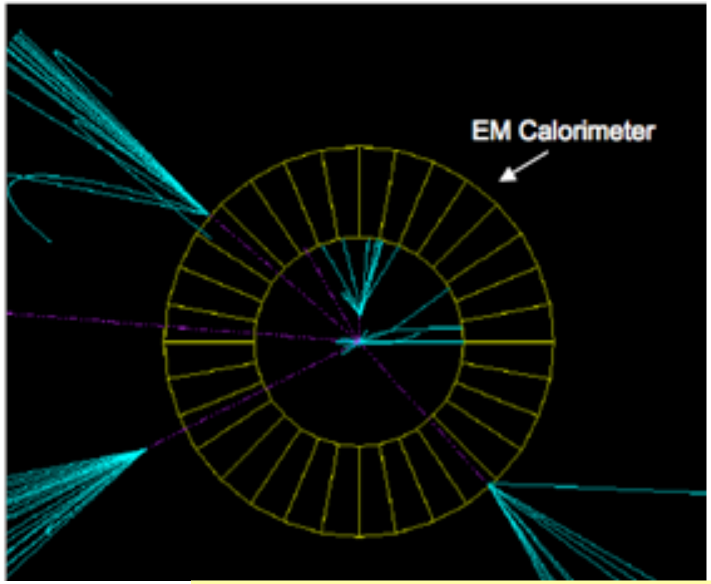


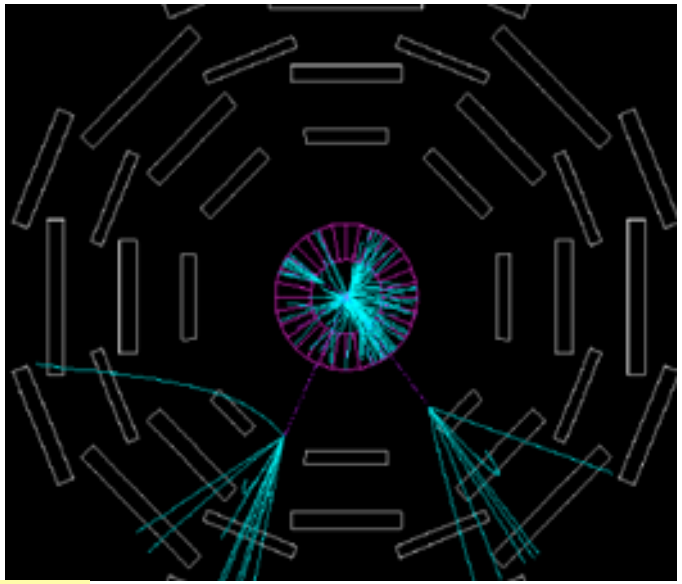
Hidden Valley Events



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

ATLAS



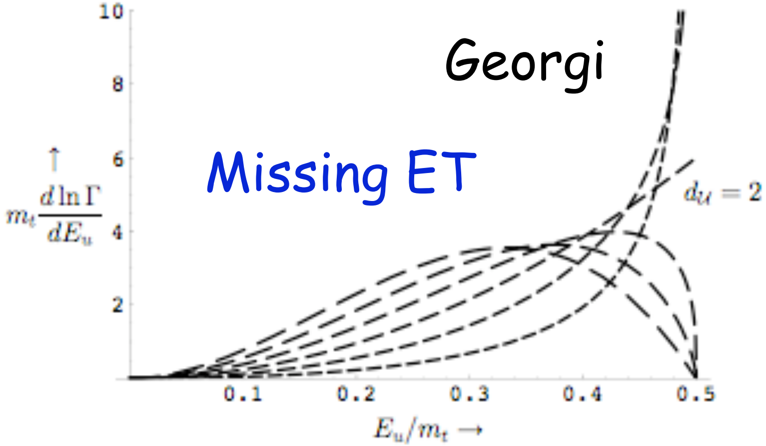


⇒Need special triggers

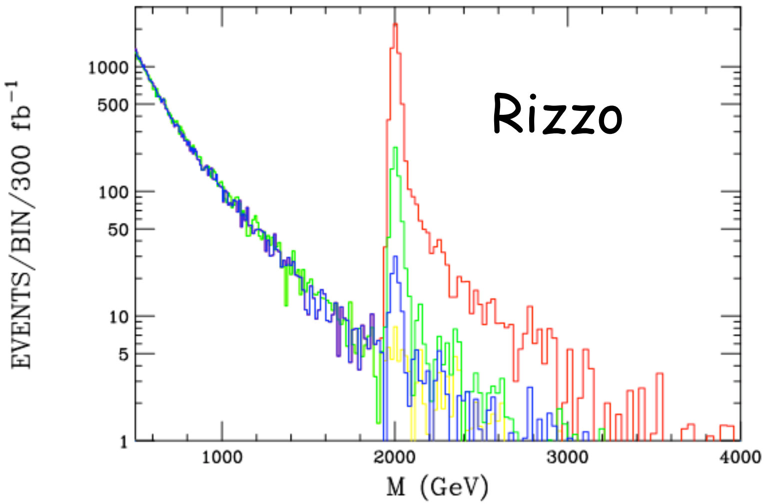
(*) except possibly LHCb

Unparticles

Top decay $t \to u + \mathcal{U}$



Decaying unparticles



•QFT possibility: sector that is scale invariant leading to new physics weakly coupled to SM through heavy mediators

⇒Unparticle stuff (Georgi, '07 + >100 new papers)
arXiv:hep-ph/0703260

•Real unparticle production

–Monophotons at LEP: $e^+e^- \to \gamma$ U

–Monojets at Tevatron, LHC: g g → g U

•Virtual unparticle exchange

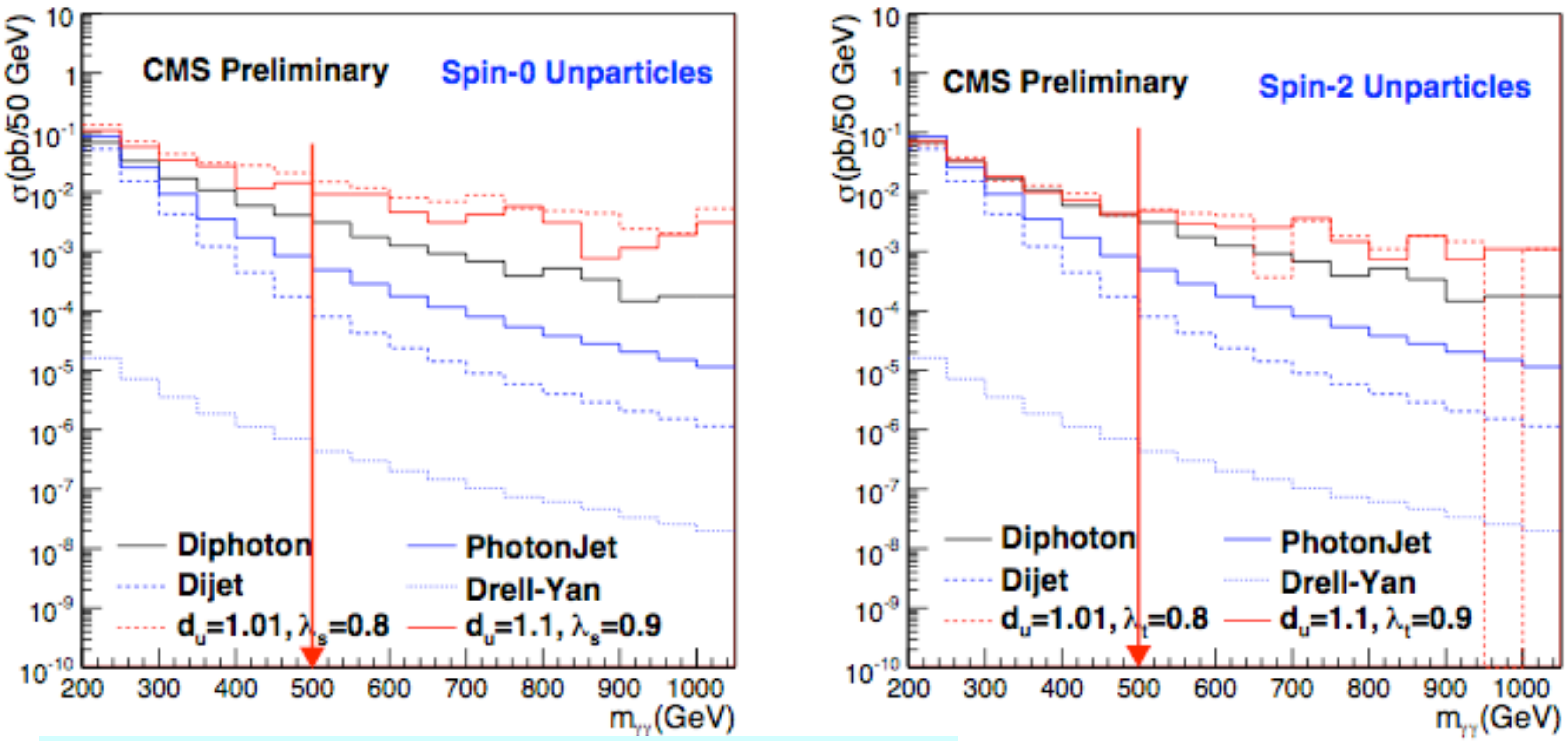
–Scalar unparticles: f f → U → $\mu^+\mu^-$,
g g , ZZ,… [No interference with SM]

–Vector unparticles: $e^+e^- \to U^m \to \mu^+\mu^-$, qq, …

Other signatures: "funny jets"
U→2 or 4 photons
high multiple photon rates

Unparticles

Recycling the diphoton ADD analysis



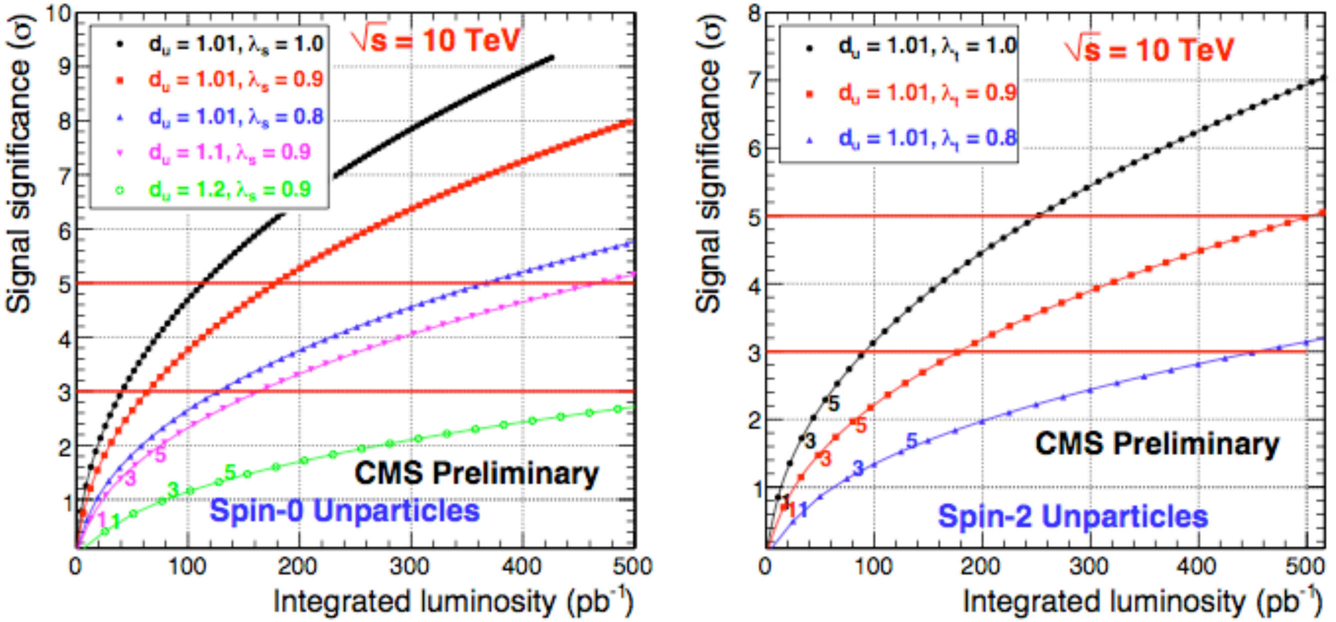
d_U scale dimension parameter

Λ_U renormalization scale (here: 1 TeV)

λ Coupling strength

Inspired by P. Mathews et al

Unparticle Discovery Reach

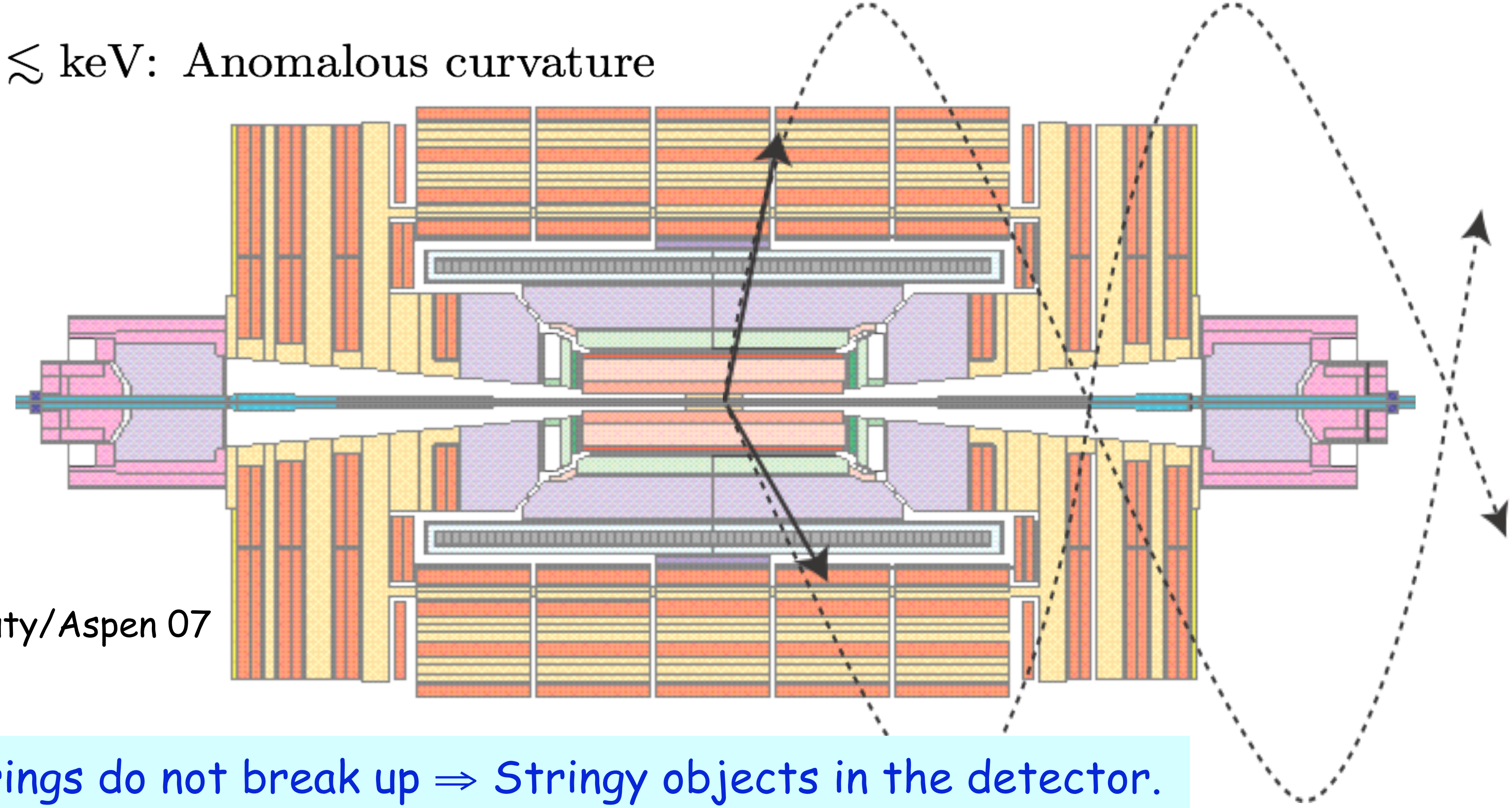


Unparticle parameters	$\int Ldt$ needed for 3σ evidence	$\int Ldt$ needed for 5σ discovery
	Scalar Unparticles	
$d_u = 1.01,\ \lambda_s = 1.0$	$\sim 40pb^{-1}$	$\sim 120pb^{-1}$
$d_u = 1.01,\ \lambda_s = 0.9$	$\sim 70pb^{-1}$	$\sim 180pb^{-1}$
$d_u = 1.01,\ \lambda_s = 0.8$	$\sim 135pb^{-1}$	$\sim 370pb^{-1}$
$d_u = 1.1,\ \lambda_s = 0.9$	$\sim 170pb^{-1}$	$\sim 485pb^{-1}$
$d_u = 1.2,\ \lambda_s = 0.9$	$\sim 640pb^{-1}$	$\sim 2040pb^{-1}$
	Tensor Unparticles	
$d_u = 1.01,\ \lambda_t = 1.0$	$\sim 100pb^{-1}$	$\sim 250pb^{-1}$
$d_u = 1.01,\ \lambda_t = 0.9$	$\sim 180pb^{-1}$	$\sim 520pb^{-1}$
$d_u = 1.01,\ \lambda_t = 0.8$	$\sim 480pb^{-1}$	$\sim 1380pb^{-1}$

Macro-Strings at the LHC?

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

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



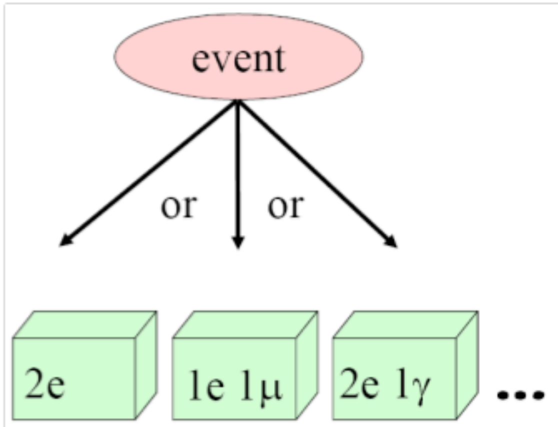
Markus Luty/Aspen 07

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

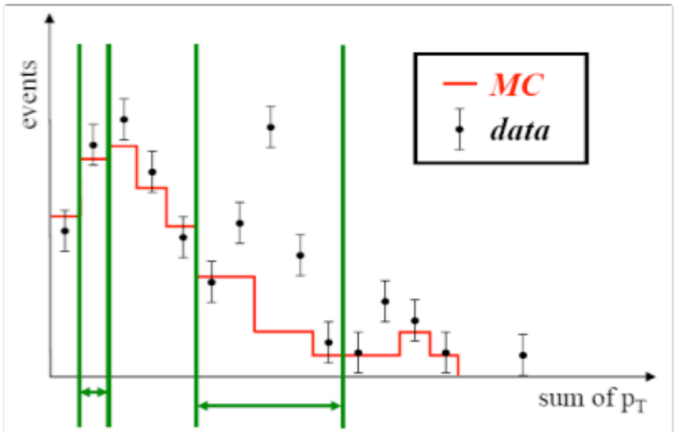
Generic Searches

Eg: MUSiC "Model Unspecified Search in CMS"

- Classify events by particle content
  - Single isolated lepton always required
    → easy trigger, less QCD
  - Exclusive & inclusive final states
    (~ 300 classes each)
  - e, μ, γ, jet, MET

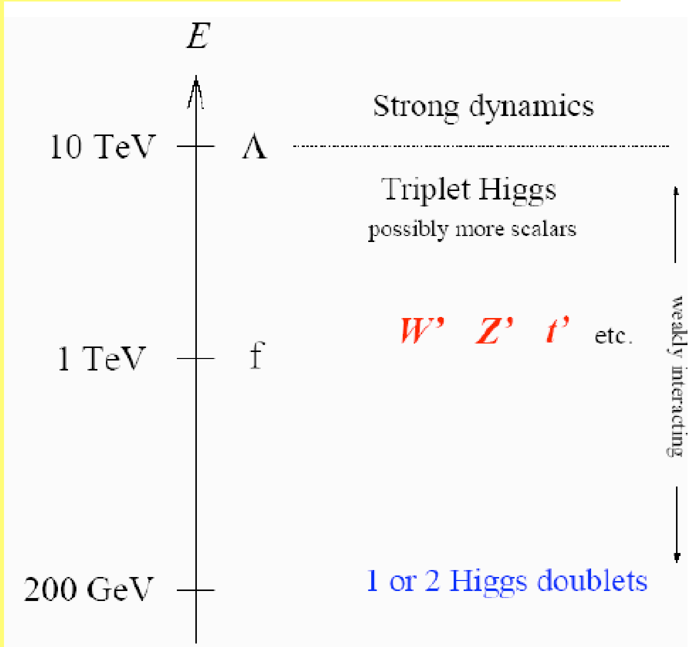


- Scan distributions for statistically significant deviations
  - Presently $\sum p_T$, invariant (transverse) mass, MET
  - Dedicated algorithm searching biggest discrepancy
- Takes systematic uncertainties into account
- A priori sensitive to detector effects and new physics



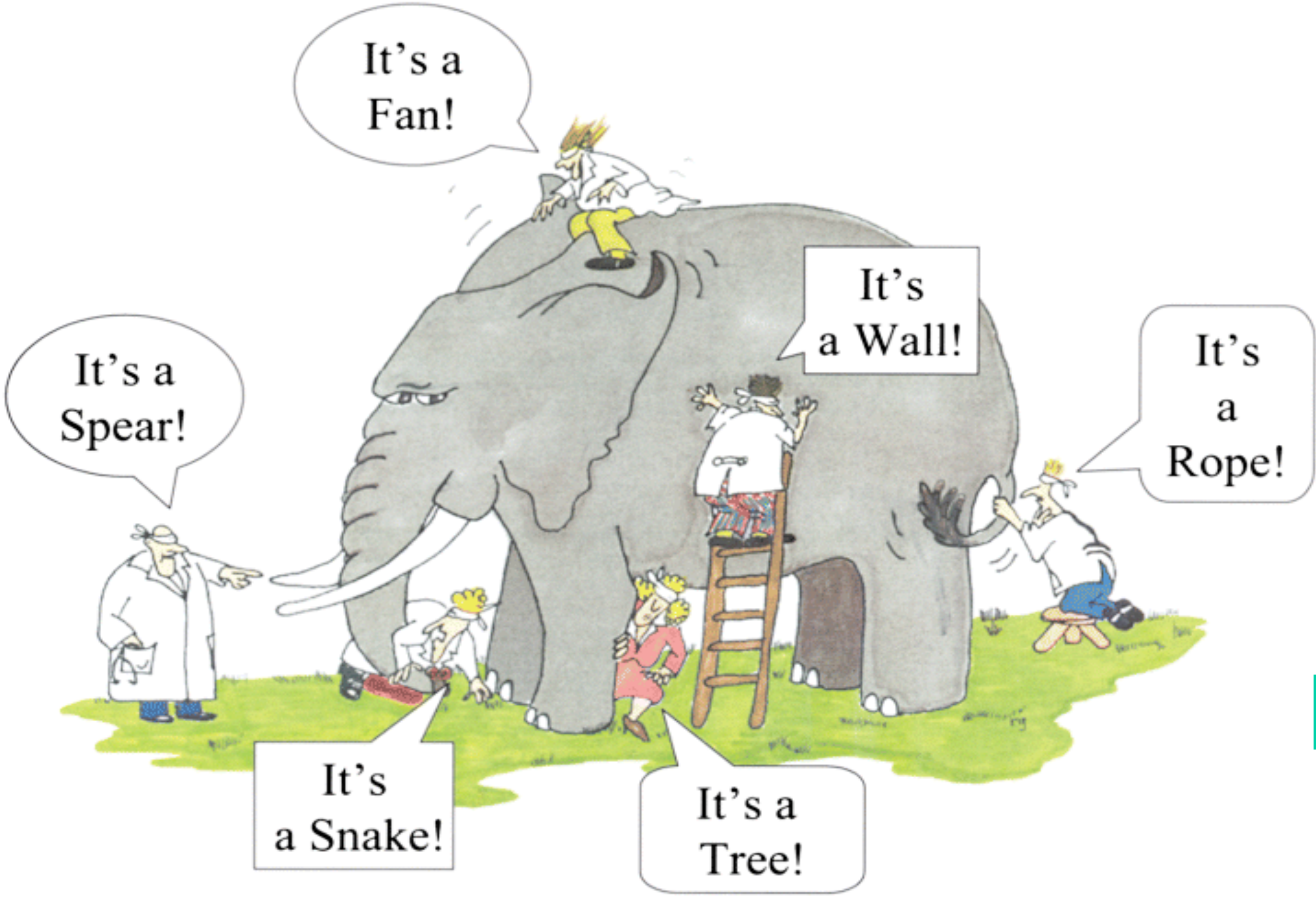
Other New Physics Ideas…

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



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?)
- ...

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
    (Little Higgs….?)
- 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

Backup

Unparticles...?

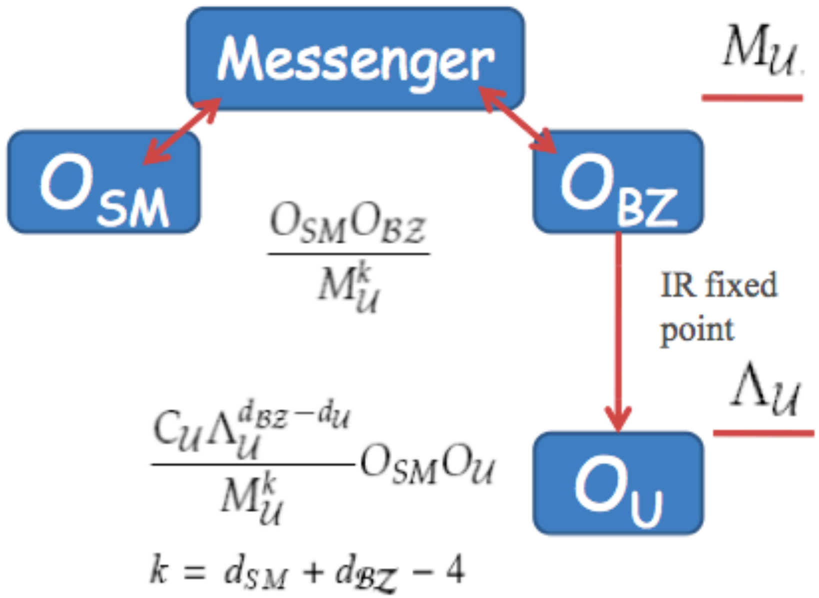
H. Georgi
arXiv:0704.2457

Unparticle Theory

- **Unparticle theory** - assumes that there is scale-invariant sector weakly coupled to the SM.

- At **high energy**, there is a hidden sector that contains both SM and Banks-Zaks (BZ) fields, interacting via the exchange of particles of mass M_u.

- At **low energy**, the hidden sector becomes conformal and the BZ operator flows causing dimensional transmutation to Unparticle operator with dimension d_u.

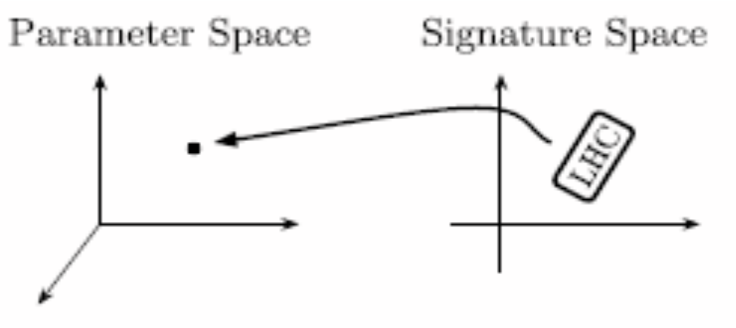


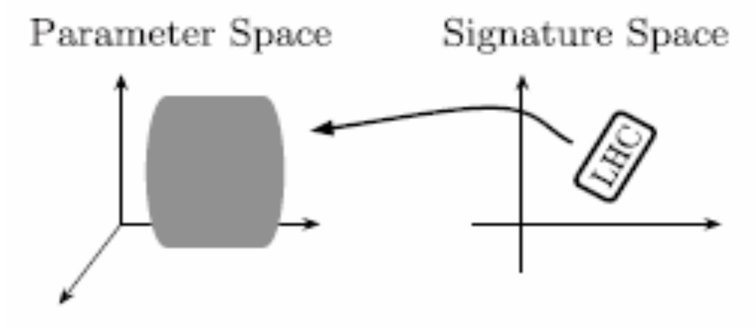
After the Champagne…

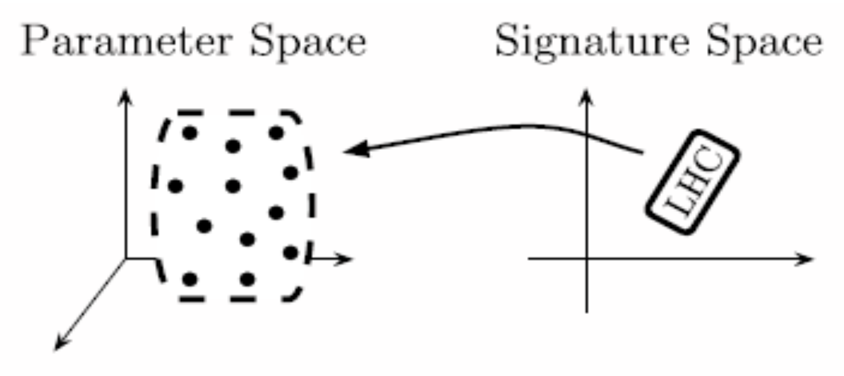
- WHEN new physics is discovered at the LHC, how well can we determine what it is? Does a specific experimental signature map back into a unique theory with a fixed set of parameters?

- 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….







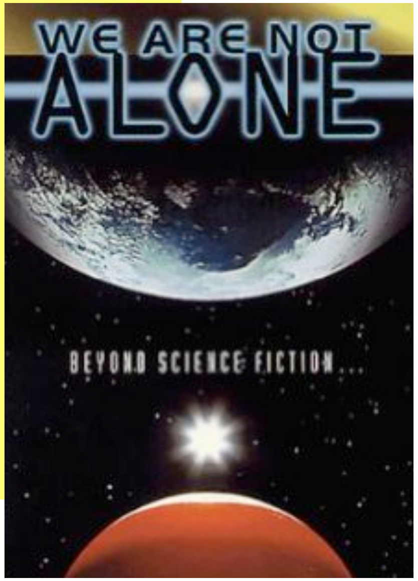
Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space…
→ model degeneracy

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!

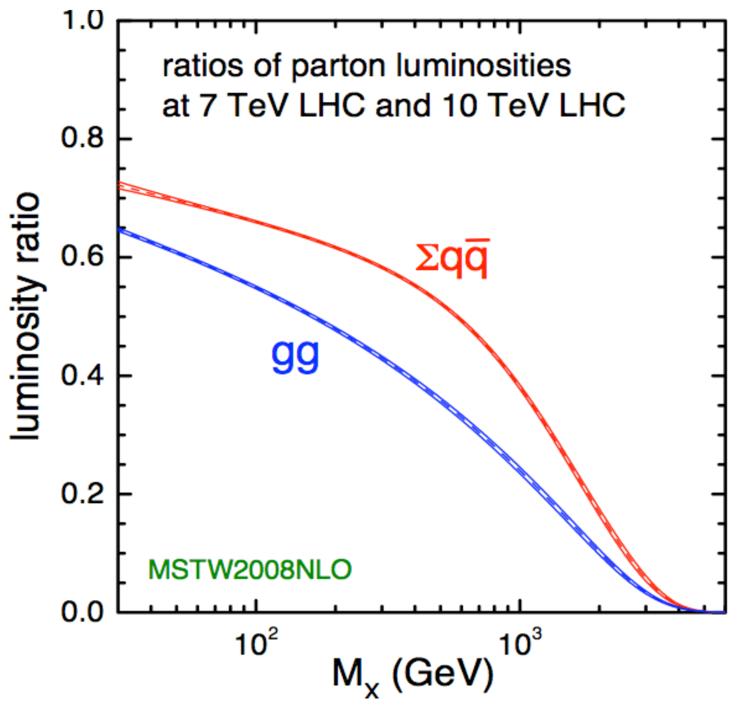
We are not alone!

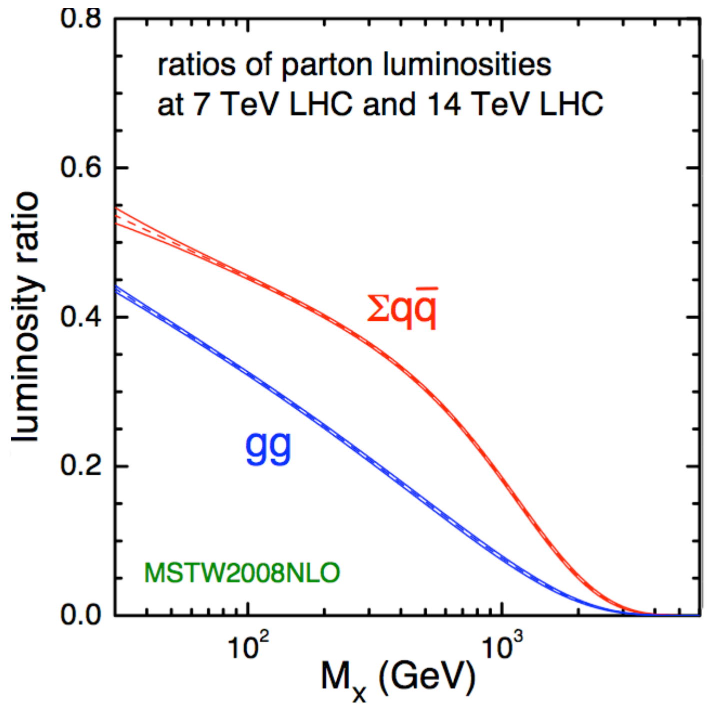
- LHC: LHCb has a complementary sensitivity to CMS/ATLAS for new physics.
  - Not yet explored in a systematic way
- Heavy flavor precision measurements (B-factories)
- g-2 new measurements (factor 5-10 improvement in O(5) years?)
- Dark matter hints from outer space (PAMELA/ATIC GLAST-Fermi..)
  - Wait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



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



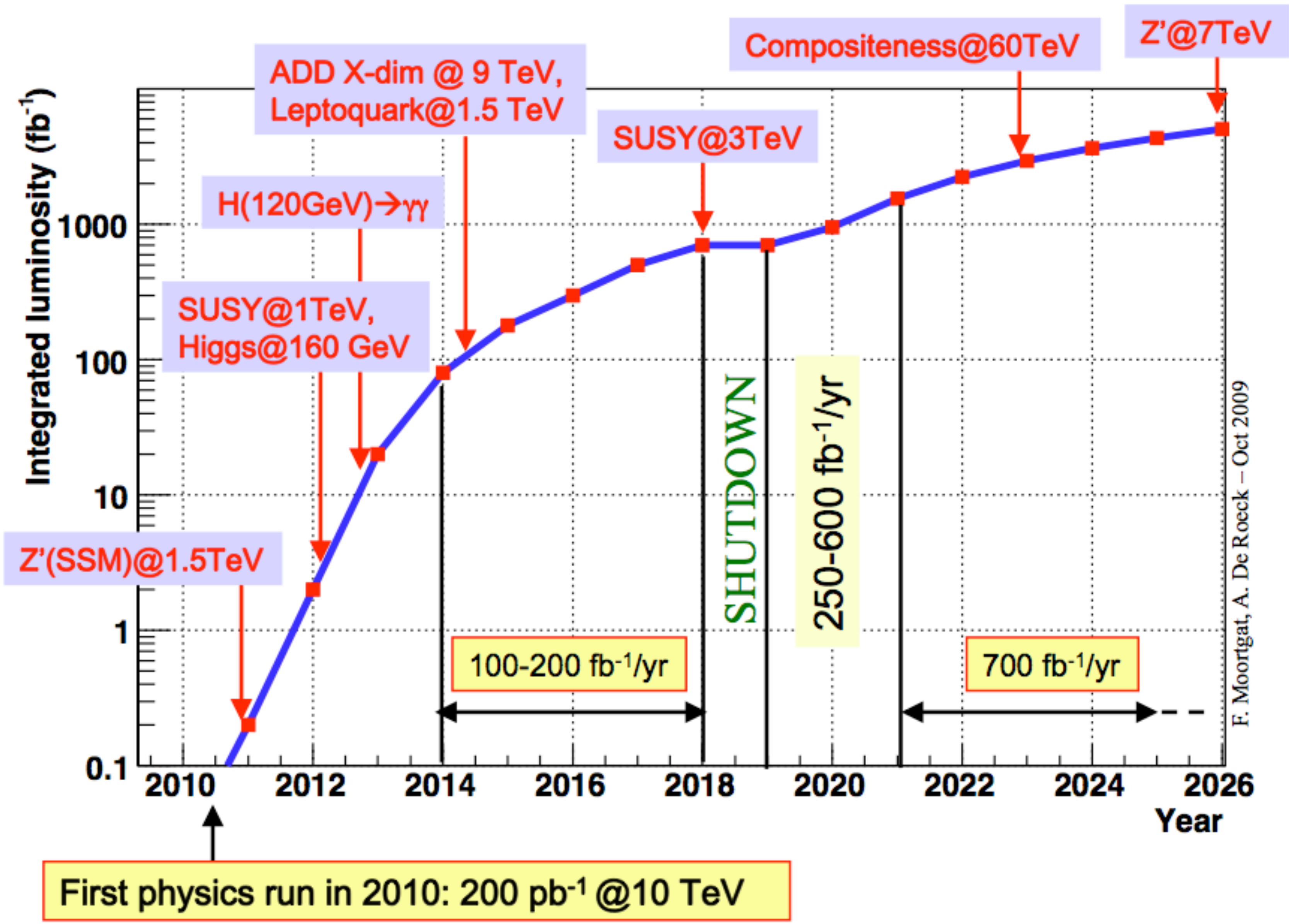


James Stirling

Yesterday 10/8

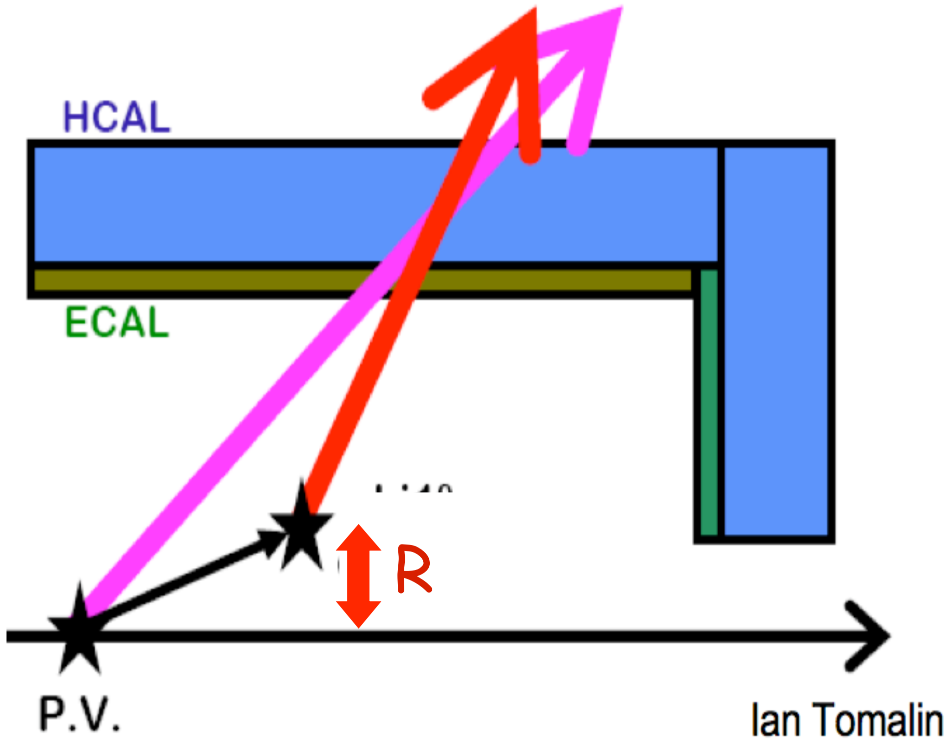
O(10) pb^{-1} @ 7 TeV ⇒ produce 100K $W \to l\nu$, 10K $Z \to ll$, 1000 top pairs…

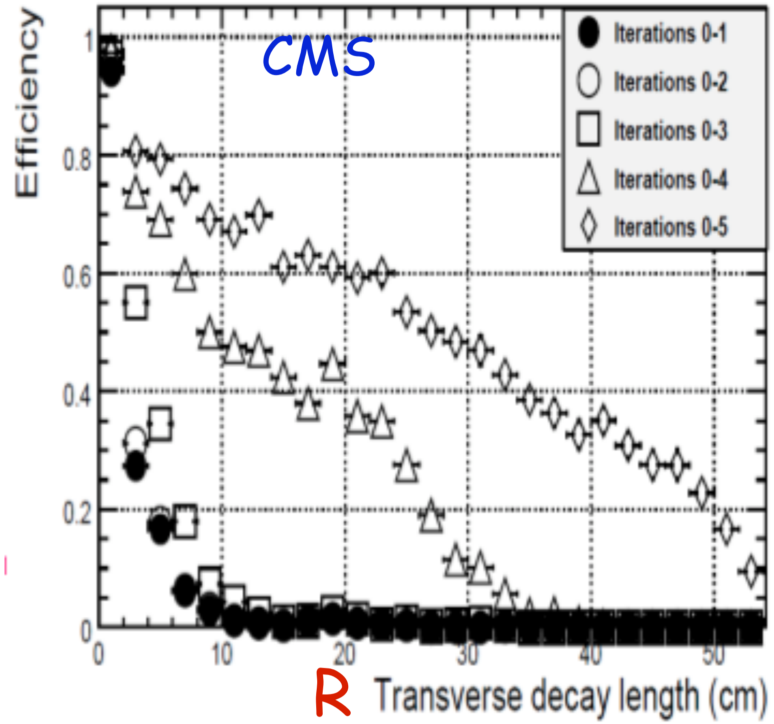
LHC Evolution?



Particle Reconstruction: Charged

Particles from displaced vertices need an adapted reconstruction

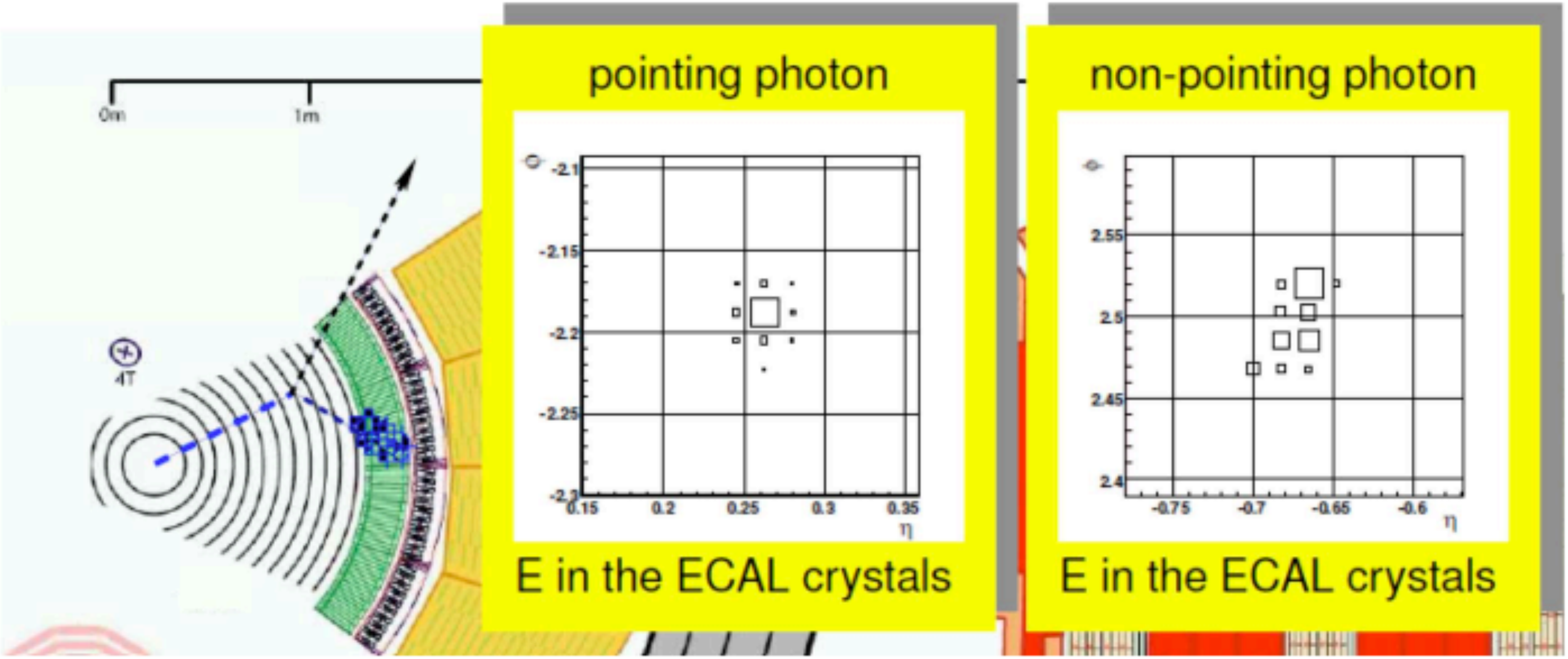




High efficiency possible for charged particles (max R ~ 50 cm)…

Particle Reconstruction: Neutral

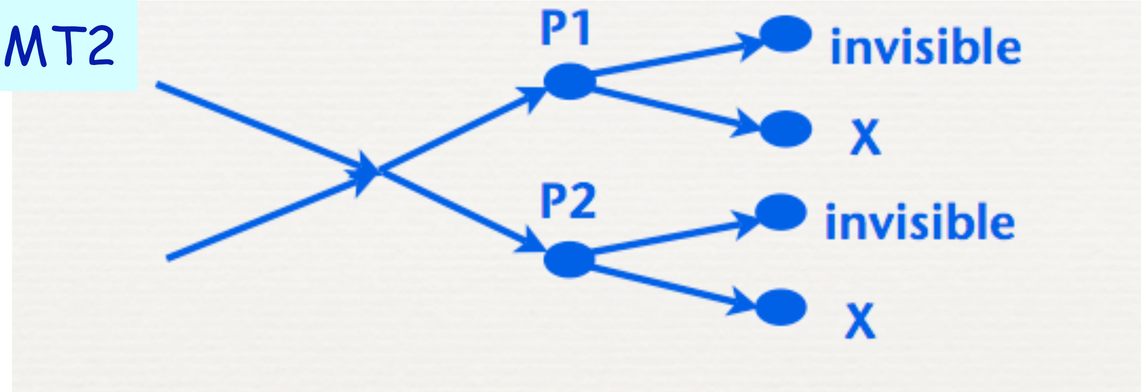
More difficult: non-pointing photons (also in GMSB SUSY models)



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

New Mass Determination Methods

EG MT2

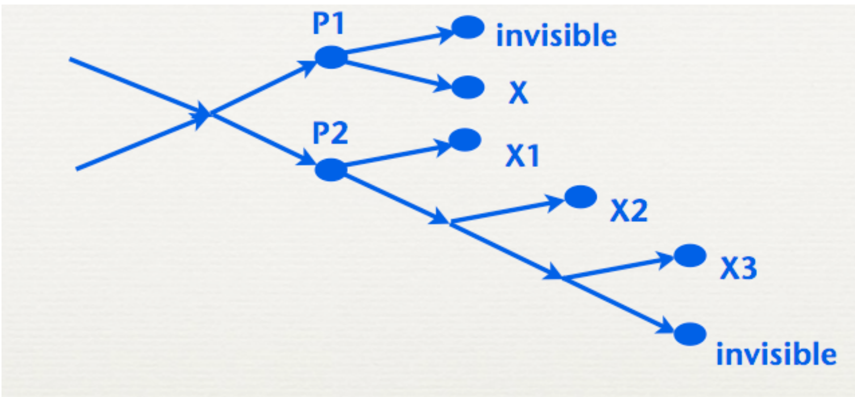


Get information on an ensemble of events when particles go undetected

$$m_{T2}^2 = \min_{p_T^{(1)} + p_T^{(2)} = p_T^{\rm miss}} \left[\max \left[m_T^2(m_{\rm dm}; p_T^{(1)}), m_T^2(m_{\rm dm}; p_T^{(2)}) \right] \right]$$

so $\boxed{m_{T2} \leq m_{\rm P}}$

Bar, Lester, Stephens



Can be extended
Still much to gain @LHC
by exploring kinematics

Mass Studies using Kinematics

- many improvements of mT2
- the mT2 upper endpoint as a function of m_dm has a "kink"at the true value of m_dm

  W.S Cho, K. Choi, Y.G Kim, C.B. Park, arXiv:0709.0288
- can generalize mT2 to intermediate particles in sub-decay chains

  M. Burns, KC Kong, K. Matchev, M. Park, arXiv:0810.5576
- can find new mT2-like observables, e.g. shat_min

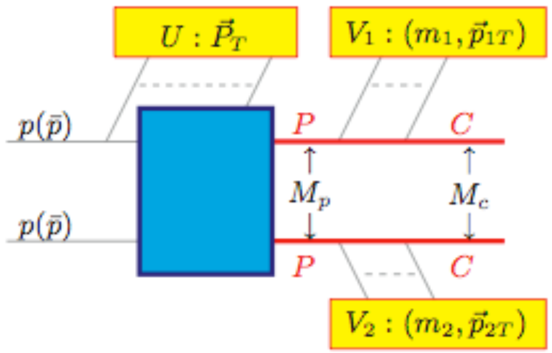
  P. Konar, KC Kong, K. Matchev, arXiv:0812.1042

Gains of ~ factor 2 wrt ILC/LHC study reported…

Realism of these methods now being tested at the Tevatron

A general method for determining the masses of semi-invisibly decaying particles at hadron colliders

Konstantin T. Matchev and Myeonghun Park
Physics Department, University of Florida, Gainesville, FL 32611, USA
(Dated: 9 October, 2009)



How well can we measure masses at the LHC using all new techniques? Project?

Is it SUSY?

Example: Universal Extra Dimensions

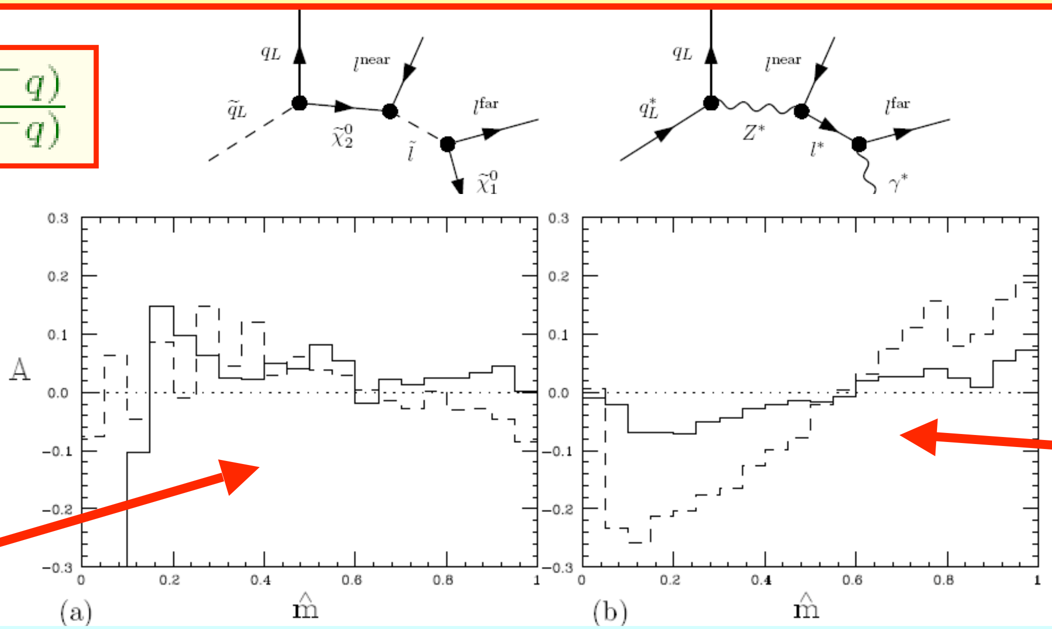
Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:

Can the LHC distinguish?

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

Look for variables sensitive to the particle spin eg. lepton charge asymmetries in squark/KKquark decay chains Barr hep-ph/0405052; Smillie & Webber hep-ph/0507170

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$



Needs 10 fb^{-1} or more.

KK like spectrum (small mass splitting)

SPS1a benchmark type spectrum

Method works better or worse depending on (s)particles spectrum

More discriminating variables needed!!

Spin Measurements

Many new ideas being proposed
Most still need the detailed test of the 'experimental reality'

Kilic-Wang-Yavin:
Spin measurements in cascade decays
Angular correlations in decays...

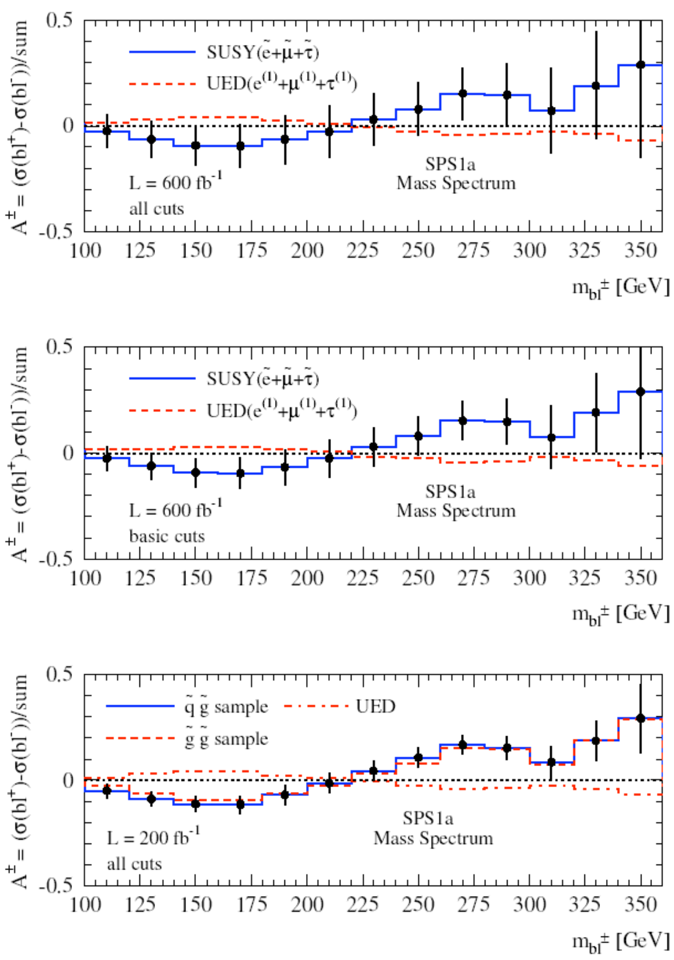
Alves-Eboli
Sbottom spin

Alves-Eboli-Plehn
Spins in Gluino Decays

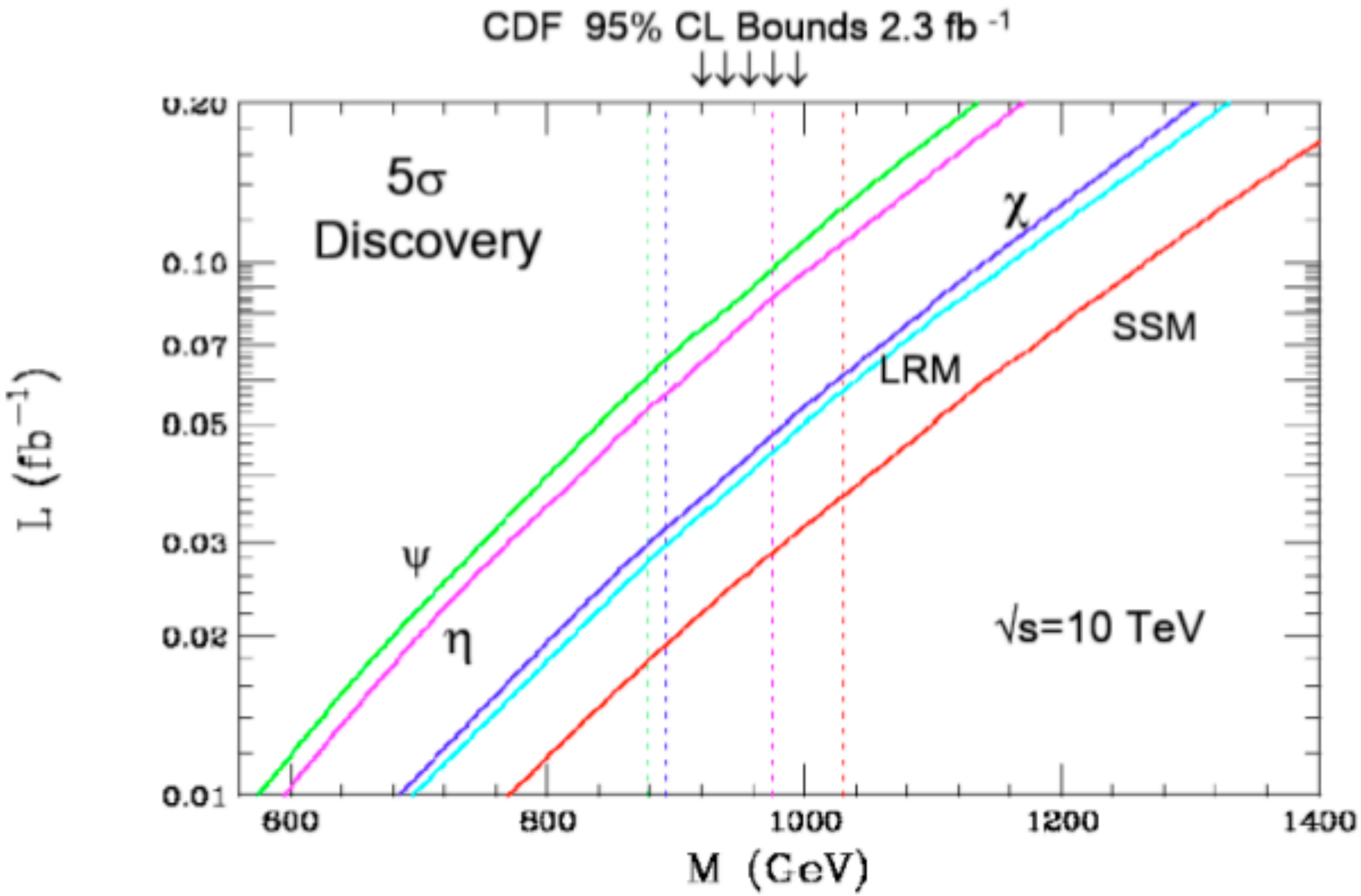
Athanasiou-Lester-Smillie-Webber
Distinguishing spins in decay chains at the LHC

Choi-Hagiwara-Kim-Mawatari-Zerwas
Tau polarization in SUSY cascade decays

Further: Wang & Yavin, S. Thomas et al,



Z' Reach

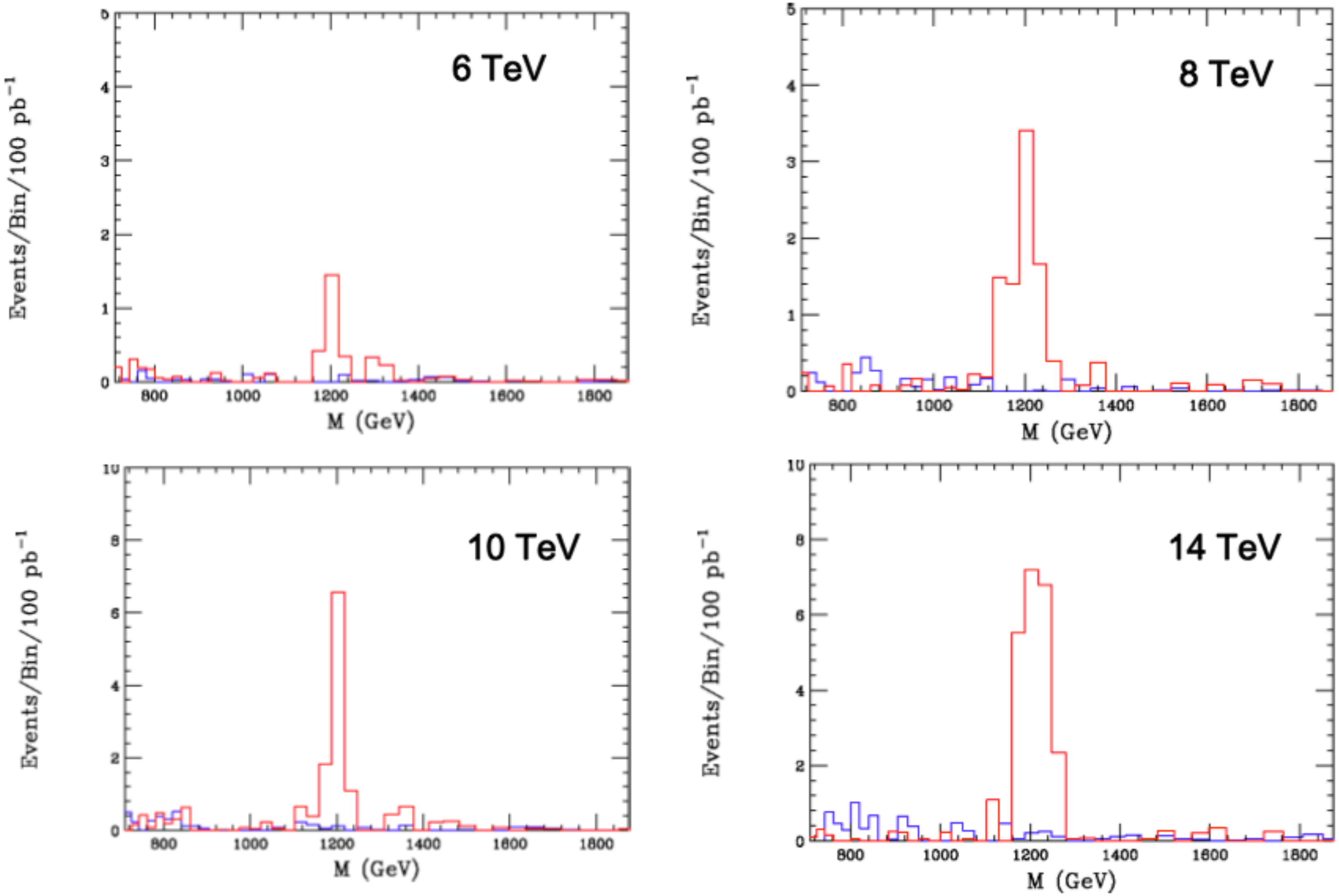


Rizzo

Enter new region even with 100 pb^{-1} and 10 TeV

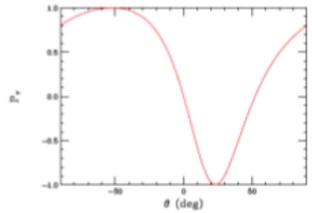
Zprime

Z’$_{SSM}$ Signal at Different √s With Low Luminosity

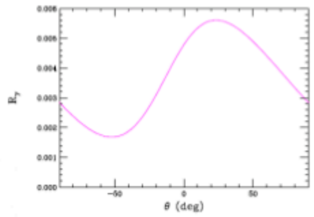


Z' Couplings

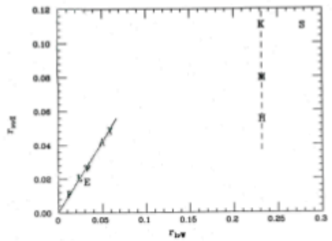
Other Possible Z' Observables For Coupling Determinations



- Z' →ττ polarization measurement



- Associated on-shell Z' + (W,Z,γ) production
- Rare Decays: Z' → $\bar{f}$ f 'V (V = W,Z; f = l,ν)



- Z' → WW, Zh
- Z' →$\bar{b}$b, $\bar{t}$ t

These have not been studied in any detail for the LHC but all will require quite high luminosity even for a light Z'

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Options for LHC

Not yet fully worked out

LHeC?

- With CLIC it may be possible to sit on the resonance peak & extract **all** of the coupling information with high precision as was done by LEP/SLC. The discovery of a 2-3 TeV resonance at the LHC would be a **very strong motivation** to go as quickly as possible to this energy range.

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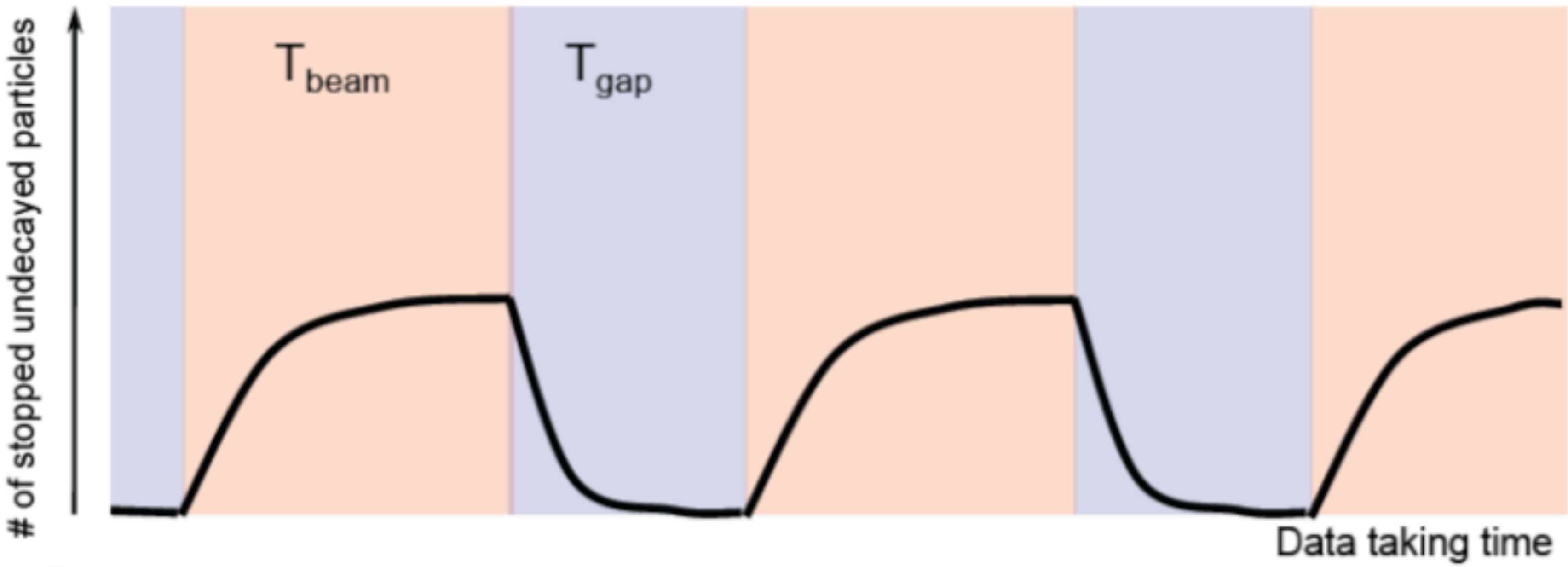
Stopped gluinos



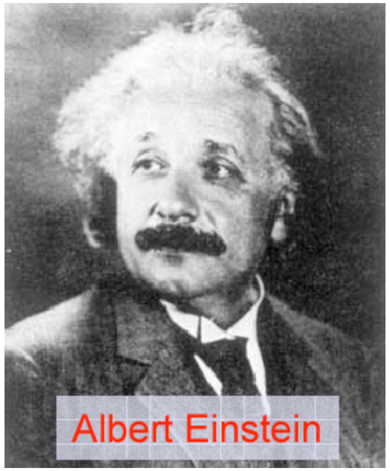
- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay Eg when there is no beam!
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

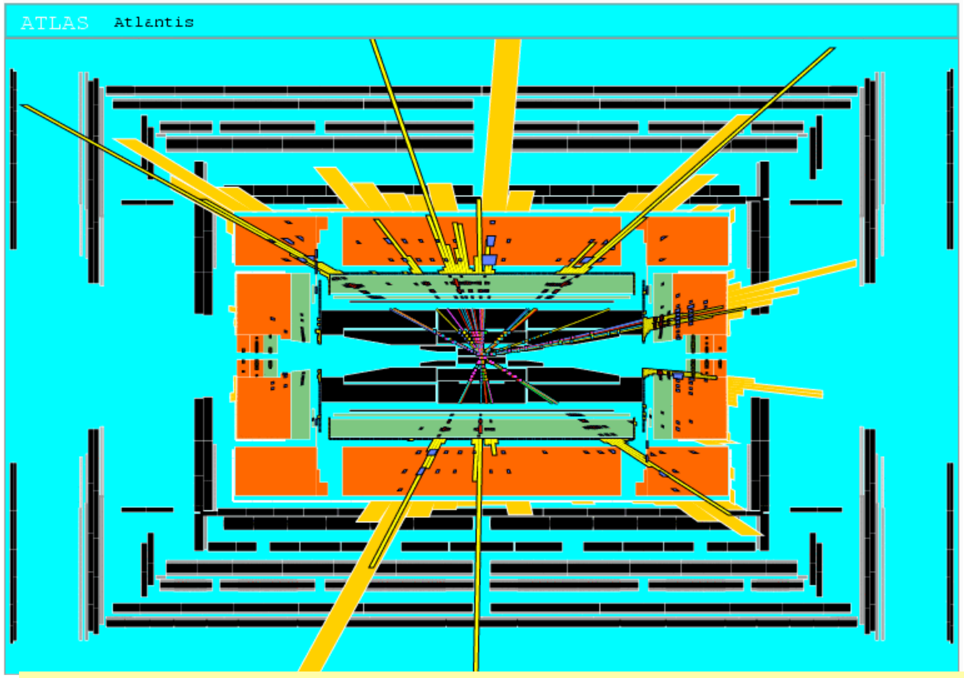
Can be studied in the experiments NOW with cosmic data

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!

Black Holes Hunters at the LHC…