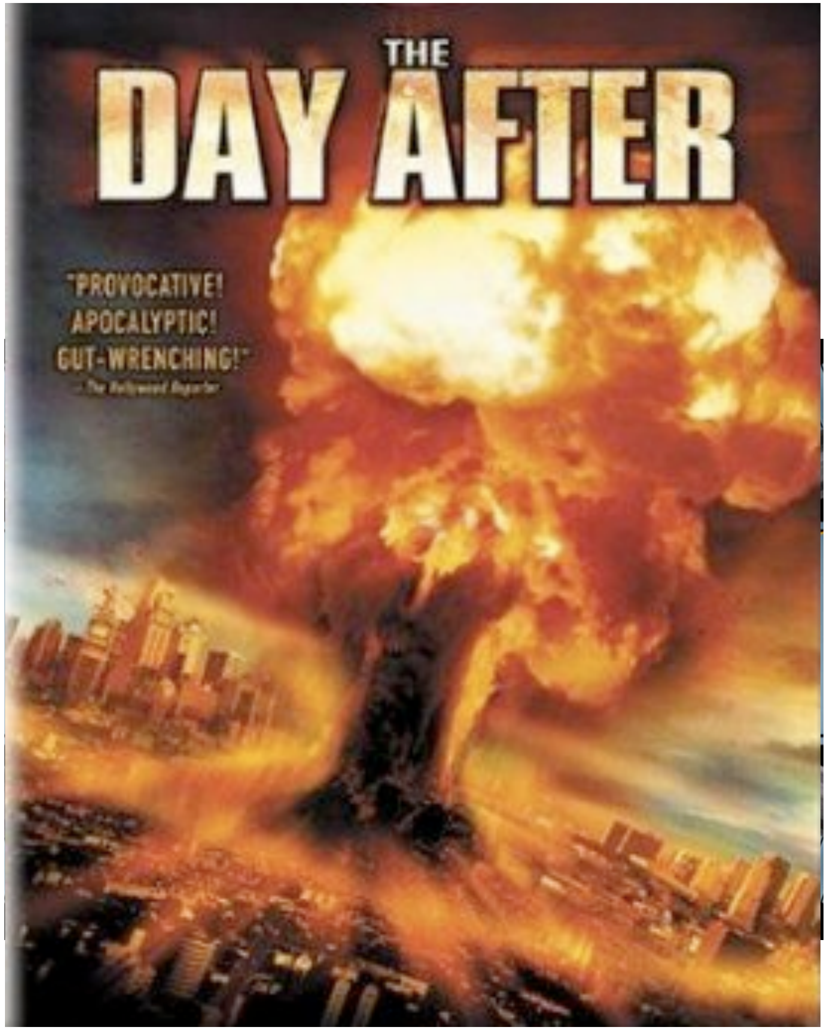
The Day After:
Strategies for Characterizing New Physics

Introduction to the session/discussion

Missing Energy Signals at LHC



HEFTI WORKSHOP

A Cellar of New Ideas

J. Hewett/Lishep09

'67	The Standard Model	a classic! aged to perfection
'77	Vin de Technicolor	better drink now
'70's	Supersymmetry: MSSM	mature, balanced, well developed – the Wino's choice
'90's	SUSY Beyond MSSM	svinters blend
'90's	CP Violating Higgs	all upfront, no finish lacks symmetry
'98	Extra Dimensions	bold, peppery, spicy uncertain terrior
'02	Little Higgs	complex structure
'03	Fat Higgs	young, still tannic needs to develop
'03	Higgsless	sleeper of the vintage what a surprise!
'04	Split Supersymmetry	finely-tuned
'05	Twin Higgs	double the taste

J. Hewett

We have a lot of signatures to look for…

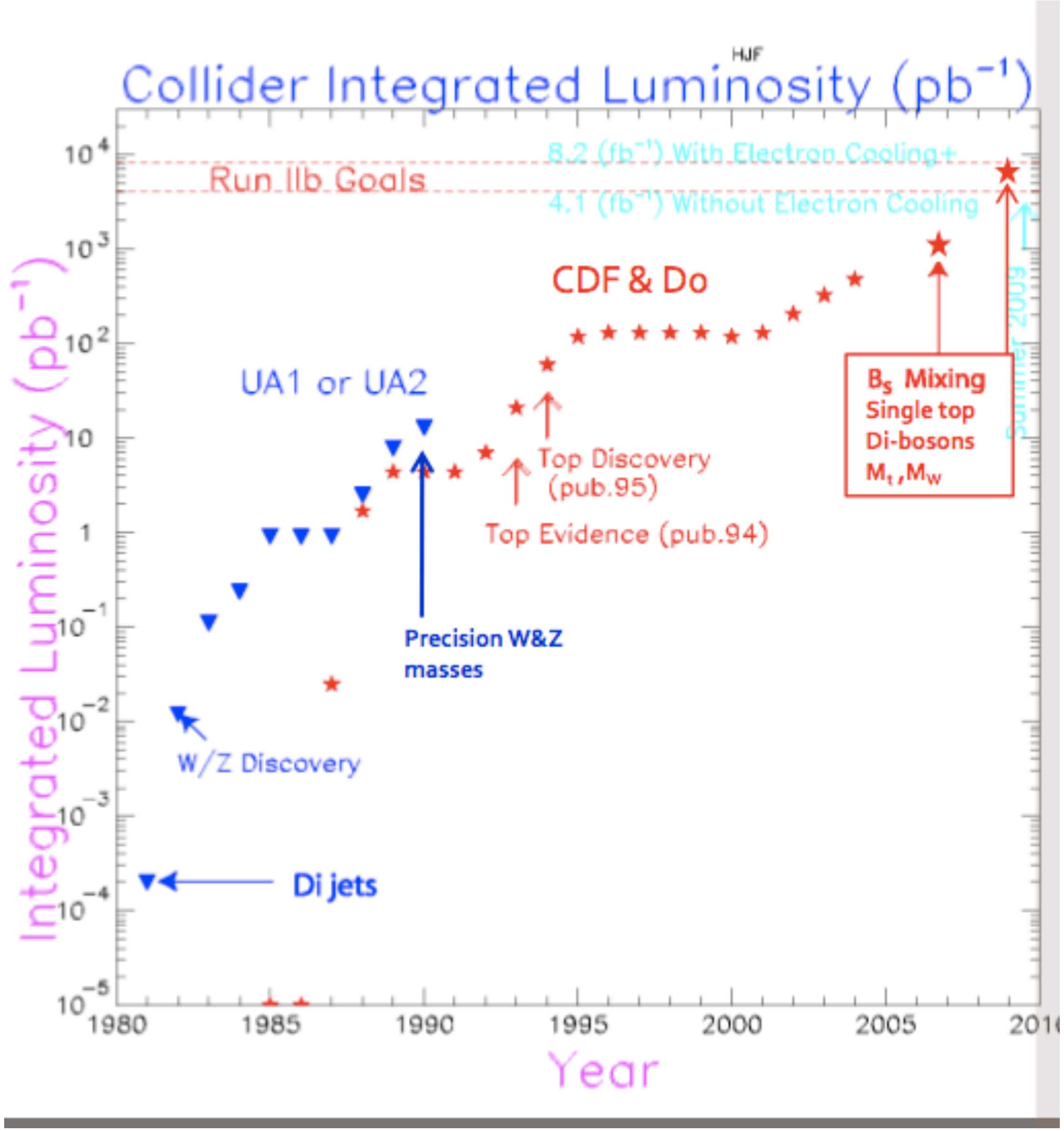
Last Minute Model Building

Anything Goes!

- Non-Communtative Geometries
- Return of the 4th Generation
- Hidden Valleys
- Quirks - Macroscopic Strings
- Lee-Wick Field Theories
- Unparticle Physics
- .....

It is high time we get the data!

Historical Perspective



J. Incandela

SPS turn-on led to quick major discoveries at the start

Tevatron discoveries came as luminosity increased

The Day After…

We just observed a signal 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? If LHC "just" a discovery machine or can we learn much more from the data?

- 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?

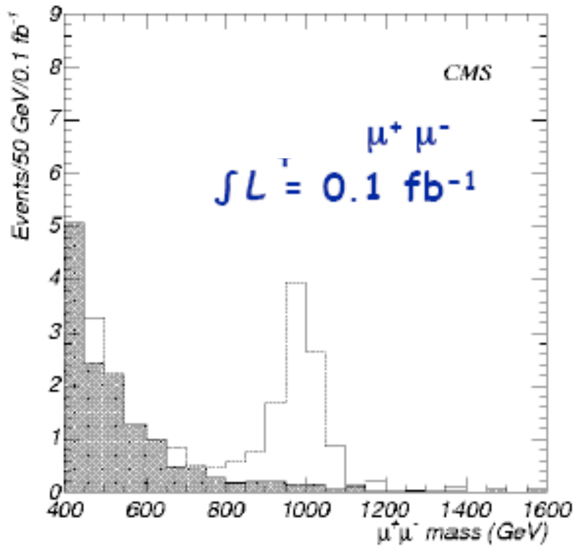
We know that we will have to expect "degeneracies" but we do have many handles at the LHC, which are starting to get explored

The Day After…

- Discovery of an excess!!
- Get detailed information from the data
  - Determine masses or mass related quantities
  - Spin or spin sensitive information
  - Event rates/cross sections
  - Decay patterns
  - Importance of the third generatation
  - Look for special --unusual-- characteristics (eg displaced vertices)
  - Look for (predicted?) other signatures

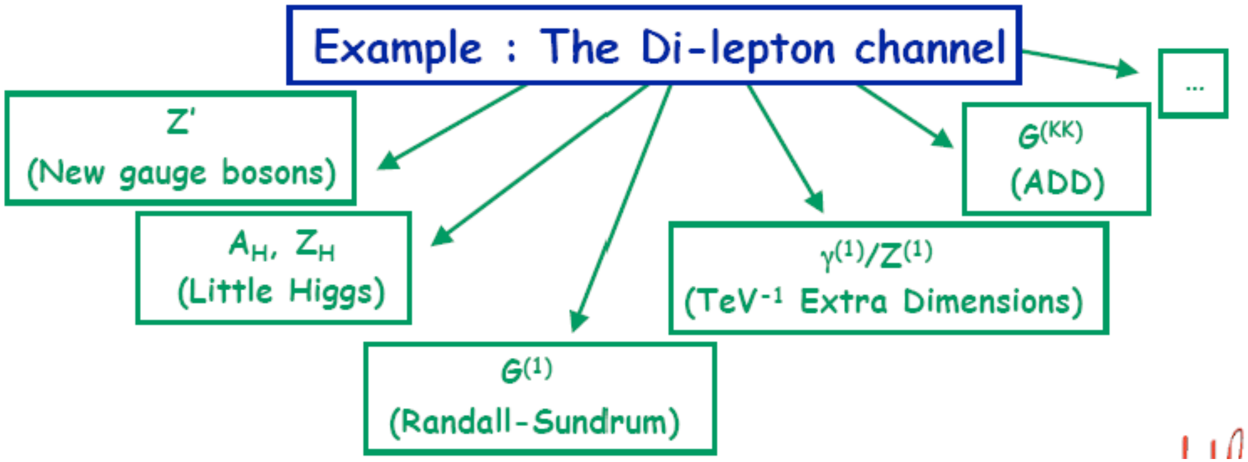
E.g. Di-lepton Resonance

If we are lucky:
a signal could be
seen very early on



$pp \rightarrow \mu\mu + X$

First months of operation

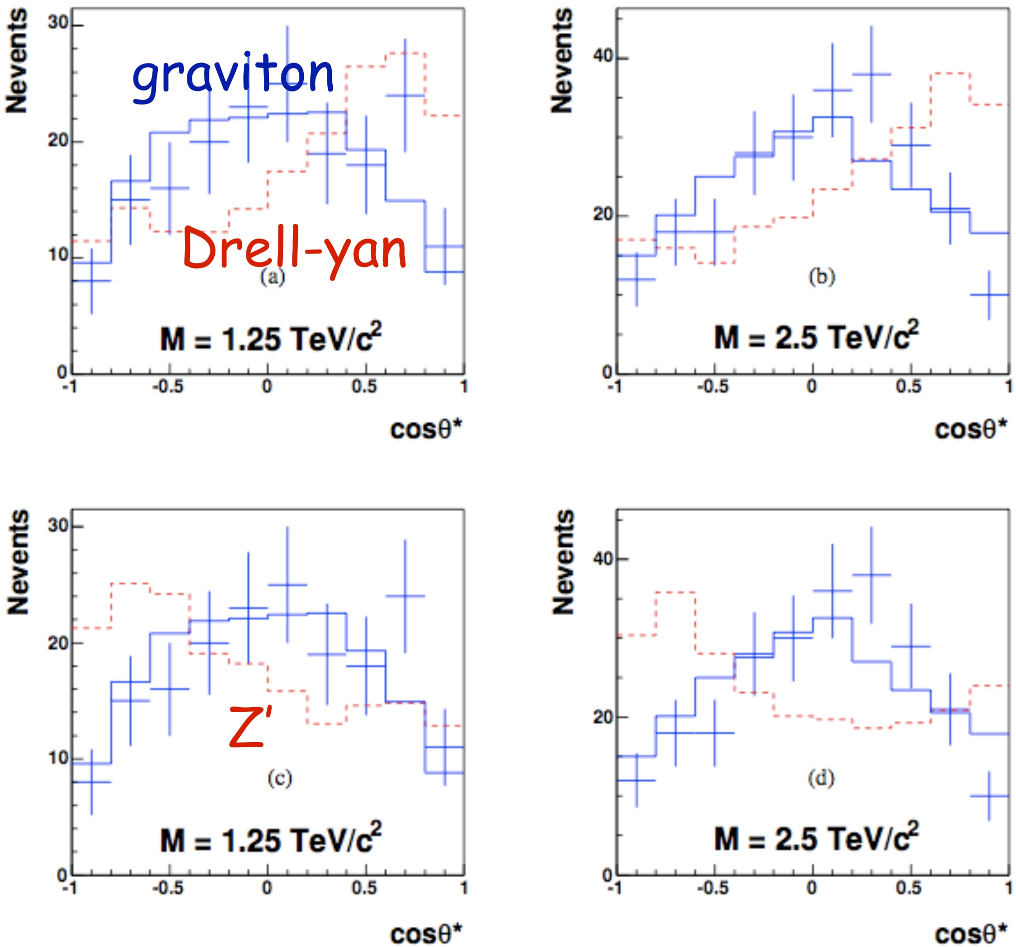


More information wanted
- Other partners? (W'..)
- Other messengers (eg radions/higgs)
- Decay modes and BRs
- Detailed mass & width
- Couplings (T. Rizzo/LHC2FC)
- Spin! high lumi…

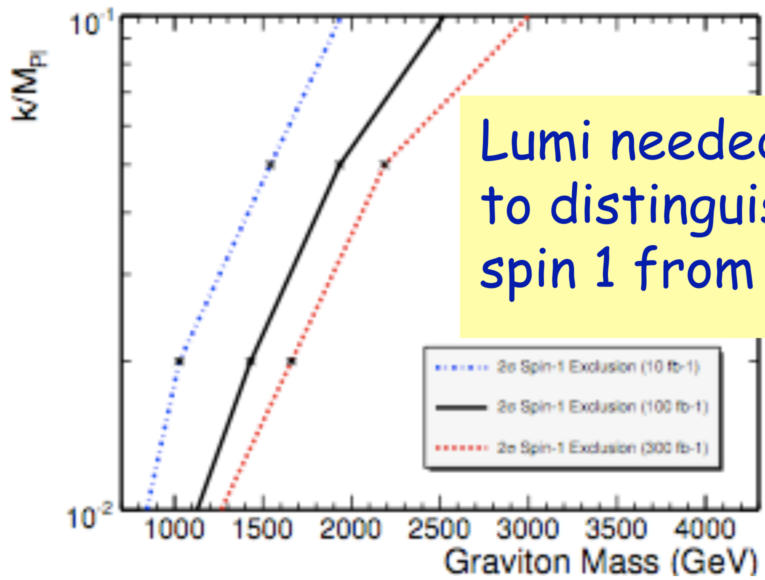
Spin of the Resonances

100 fb^{-1}

CMS PTDR



$\sqrt{s}$, TeV	c	$\int \mathcal{L}dt$, fb^{-1}	N_s	N_b
1.0	0.01	50	200	87
1.0	0.02	10	146	16
1.5	0.02	90	174	41
3.0	0.05	1200	154	22
3.0	0.10	290	148	6



Lumi needed to distinguish spin 1 from 2

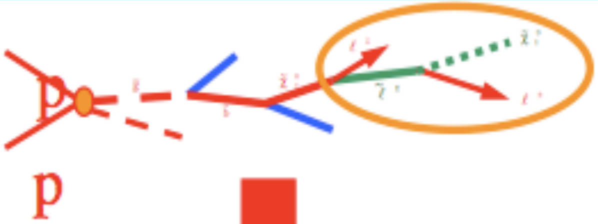
Muon study based on cosθ* analysis

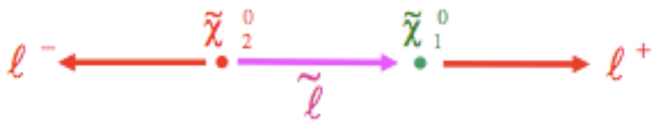
Electron study (mass resolution ~ 0.6% at 2 TeV)

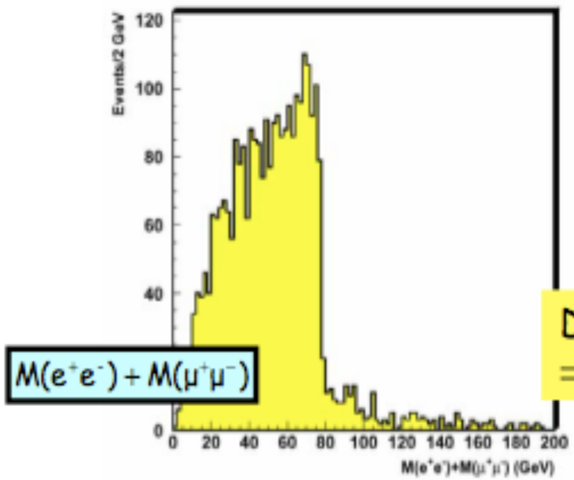
Sparticle Detection & Reconstruction

Mass precision for a favorable benchmark point at the LHC
LCC1~ SPS1a~ point B' (this is a favorable scenario)

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







D. Miller et al
⇒Use shapes

300 fb^{-1}

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

LHC-ILC Phys.Rept.426 47,2006
hep-ph/0508198

More this afternoon from
K Matchev et al.

Is it SUSY?

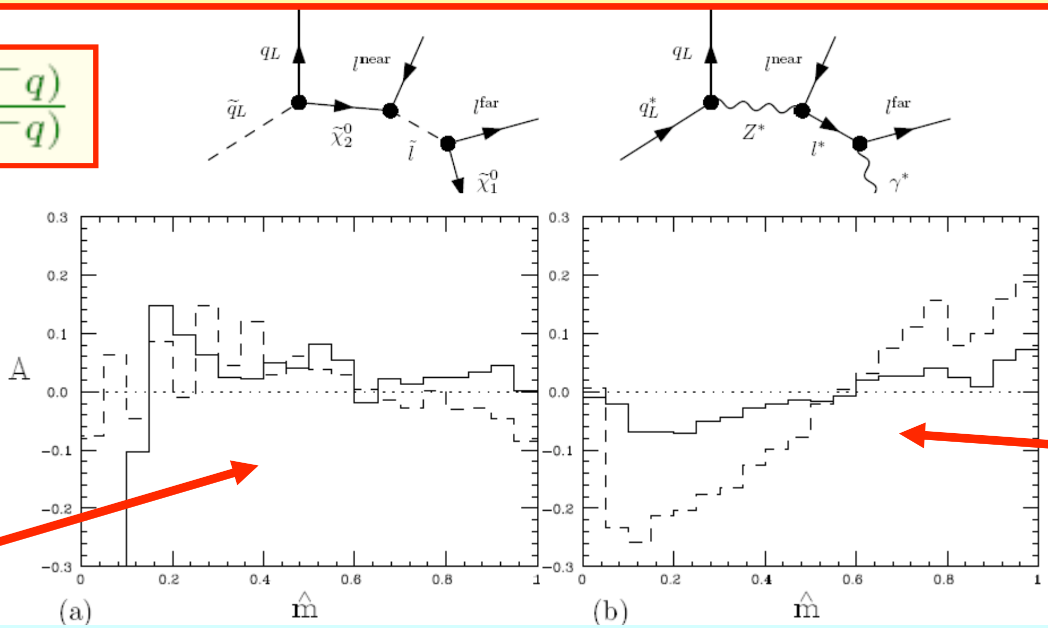
Example: Universal Extra Dimensions
Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:
Can the LHC distinguish?

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

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

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

Last few years: lot of new ideas being proposed
Most still need the detailed test of the 'experimental reality'

$\Rightarrow$ Special session today

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

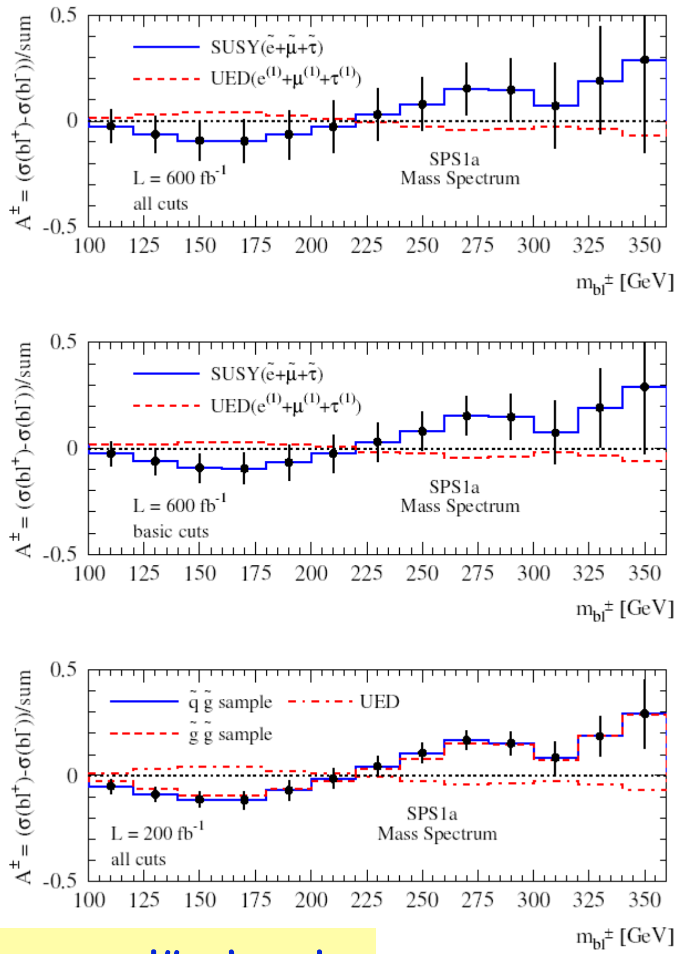
Alves-Eboli
Sbottom spin

Alves-Eboli-Plehn
Spins in Gluino Decays

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

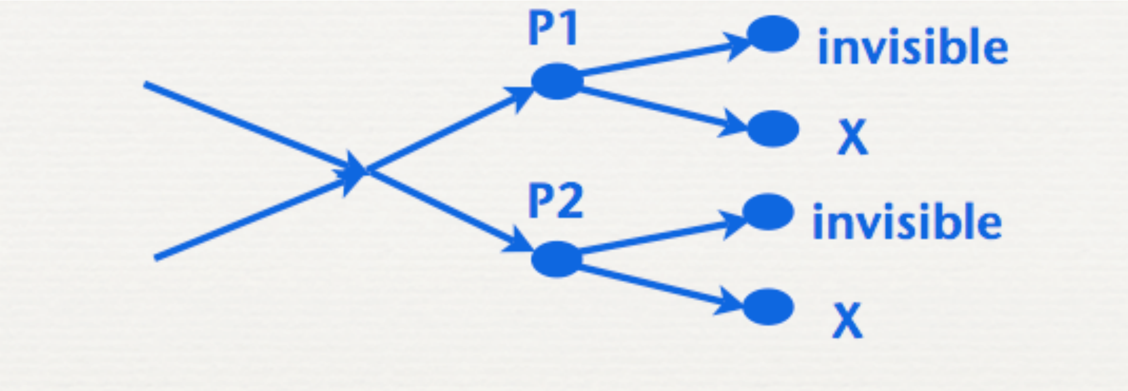
Choi-Hagiwara-Kim-Mawatari-Zerwas
Tau polarization in SUSY cascade decays

Further: Wang & Yavin, S. Thomas et al,Kane t al, Kong et al



Most of these proposals still need an "experimental" check

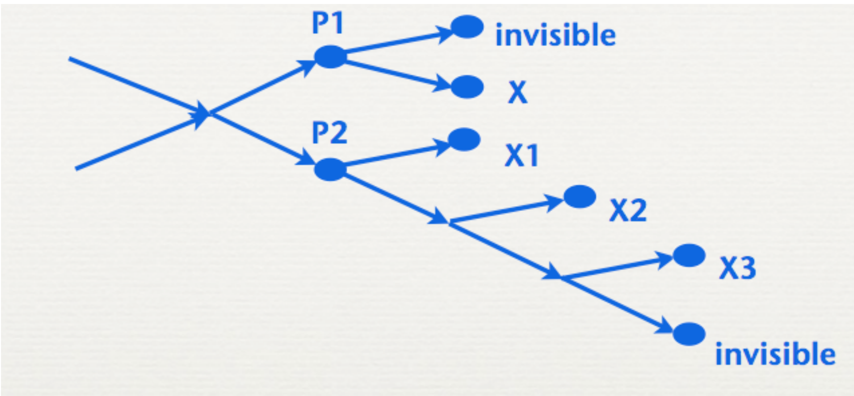
New Variables: eg M_{T2}



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



Can be extended

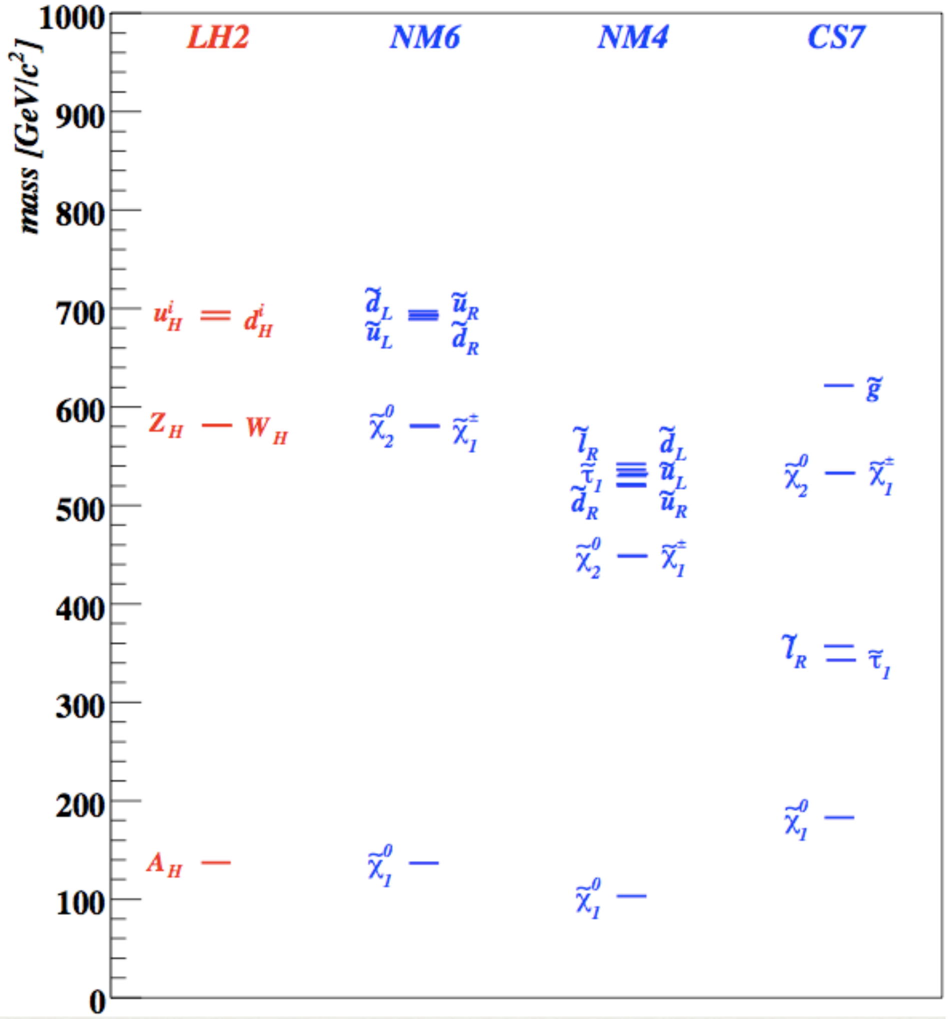
Still much to gain @LHC by exploring kinematics

Missing E_T look alikes

J. Hubisz

Missing energy look-alikes with 100 pb^{-1} at the LHC

Jay Hubisz[1a], Joseph Lykken[2b], Maurizio Pierini[3c], and Maria Spiropulu[3d]



Find SUSY models that give a similar ET signature

Only limited number of observable used.

Situation probably "not so bad"

Note Spins statistics ⇔ Cross sections
Little Higgs, UED >> SUSY for same mass
(ADR, Matchev JHEP '05)
Reverse: use cross sections for spin determination Kane, wang et al arXiv:0805.1397

M_{T2} Variable

J. Lykken/Promoteo Meeting

- 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

Most of these proposals still need an "experimental" check

First Application of M_{T2} to Real Data
CDF (Feb. 2009)

Using Only M_{T2} for the CDF Dilepton $t\bar{t}$ Data ($3\ \text{fb}^{-1}$)

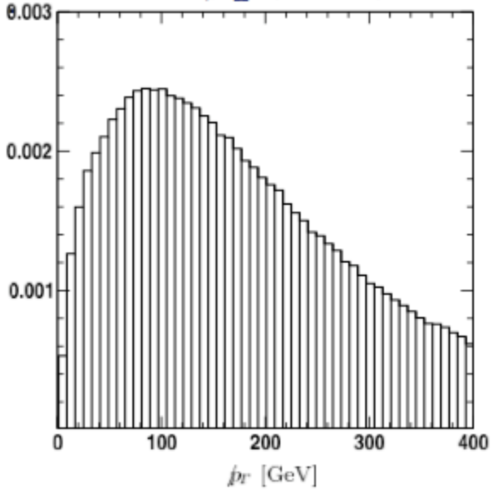
$$m_t = 167.9^{+4.8}_{-4.1}(\text{stat}) \pm 2.9(\text{sys})\ \text{GeV}$$

Missing E_T RPV SUSY

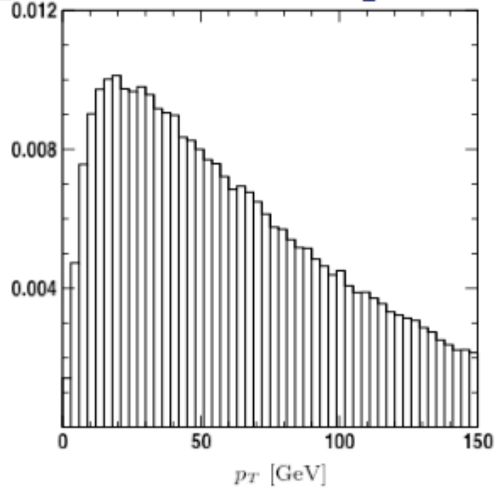
- High p_T muons arise from the direct decays: $\tilde{d}_R \to \mu^- t$; $\tilde{t}_1 \to \mu^+ d$.

  $\longrightarrow$ Plot

Neutrino $\not{p}_T$ (GeV)

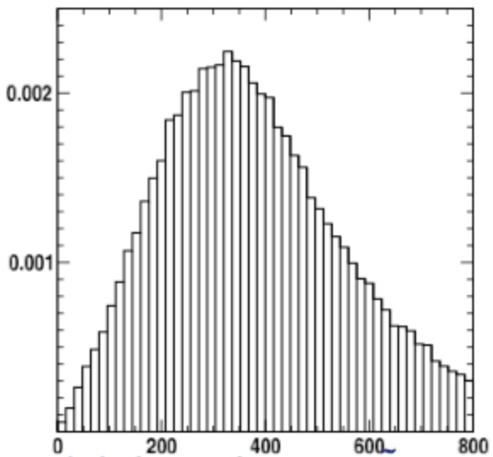


$p_T(\mu)$ (GeV) from $\tilde{\chi}_1^0 \to \tilde{\mu}\mu$

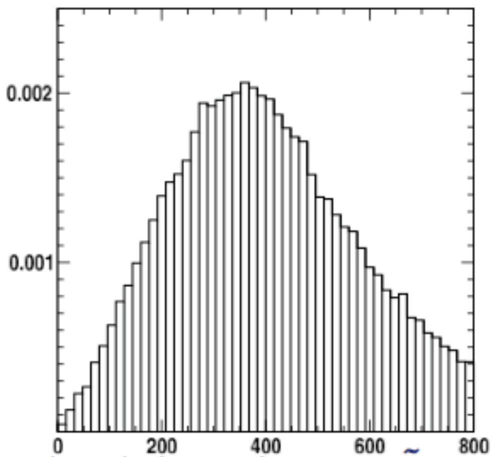


H. Dreiner
LHC2FC

Missing ET can be large in these events too



$p_T(\mu)$ (GeV) from $\tilde{d}_R \to \mu t$,



$p_T(\mathrm{top})$ (GeV) from $\tilde{d}_R \to \mu t$

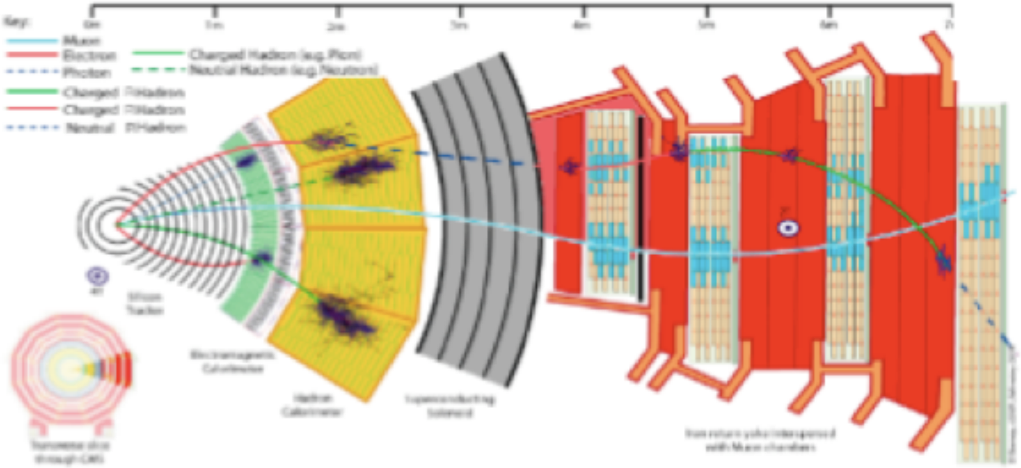
Special Signatures

- Recent developements: unusual signatures in the detectors
  - Large displaced vertices (Hidden Valleys,…)
  - Heavy ionizing particles & heavy stable charged particles (GMSB, Spilt SUSY, Gravitino DM SUSY. Monopoles…)
  - Stable particles that get stopped and decay with time delay in the detector (Split SUSY…)
  - Boomerang particles (ie get stuck outside the detector and return in detector after decay…)
  - Non-pointing photons (GMSB)
  - Special showers in the calorimeters (Split SUSY…)
  - Unexpected jet structures (Hidden Valley, Unparticles…)
  - Very short tracks (stubs)… (AMSB G2-SUSY models)

Experiment/analyses need to be prepared (trigger…)

New Signatures

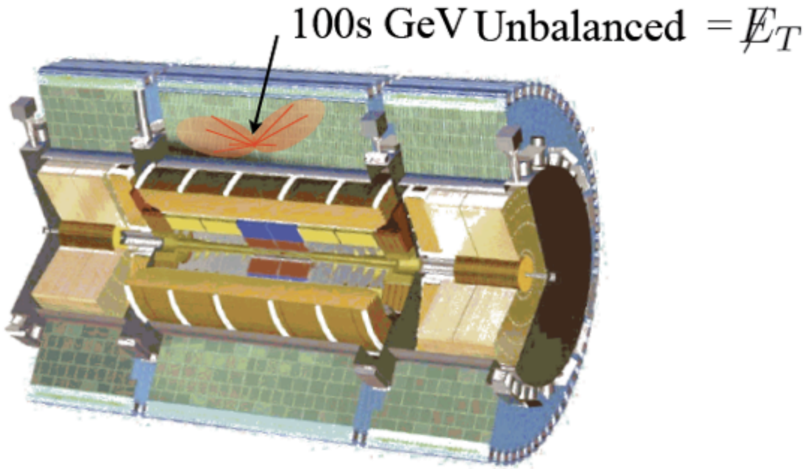
Heavy stable particles



Long Lived Gluinos

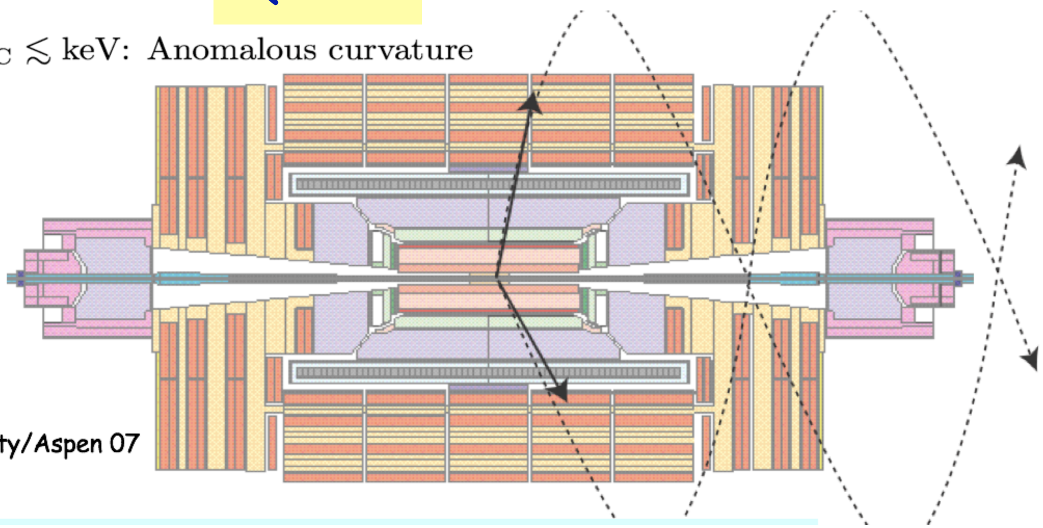
$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay



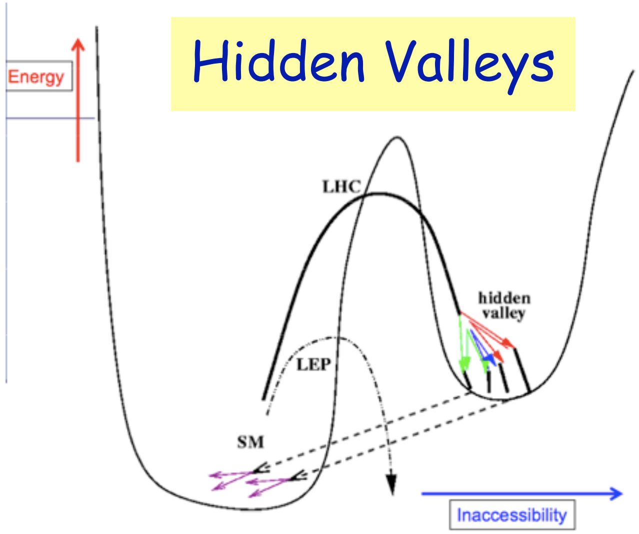
Quirks

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



Markus Luty/Aspen 07

Hidden Valleys



New Physics Search Challenges…

4th LHC Workshop

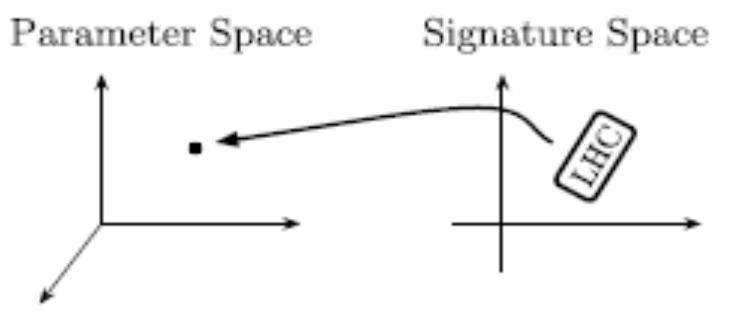
Princeton, 22 March, 2007

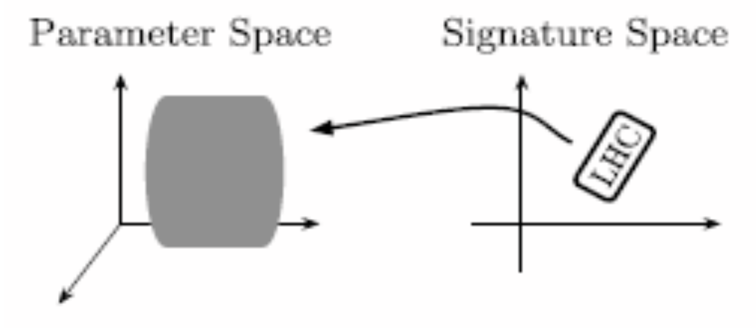
Blind SUSY Analysis
Lyon Workshop

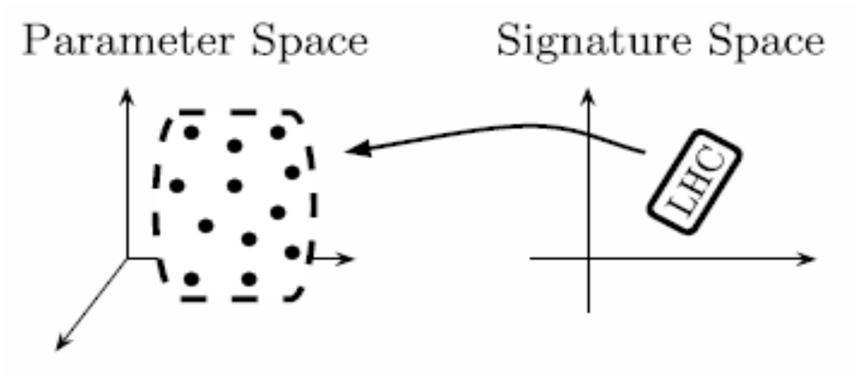
(last week)

- Project details: http://www-clued0.fnal.gov/~muanza/Blind_SUSY_Analysis.html

The Inverse Problem: Strategies







Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190
Kane, Kumar and Shao, arXiv:0709.4259

⇒ **Worked out MSSM Example**
Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space…
→ model degeneracy but not too large (~ 10-100)

Follow up by Berger, Hewett, Gainer, Lillie & Rizzo for the ILC **arXiv:0711.1374**

The Inverse Problem

Other

Lester et al., hep-ph/0508143

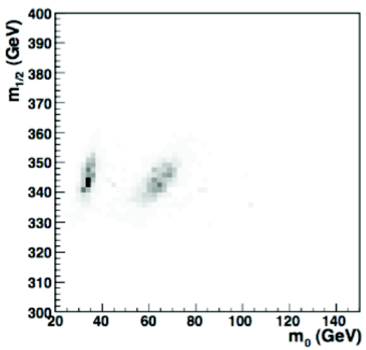
Kane et al., arXiv:0709.4259

Attempts to Map Measurements to the Parameter Space

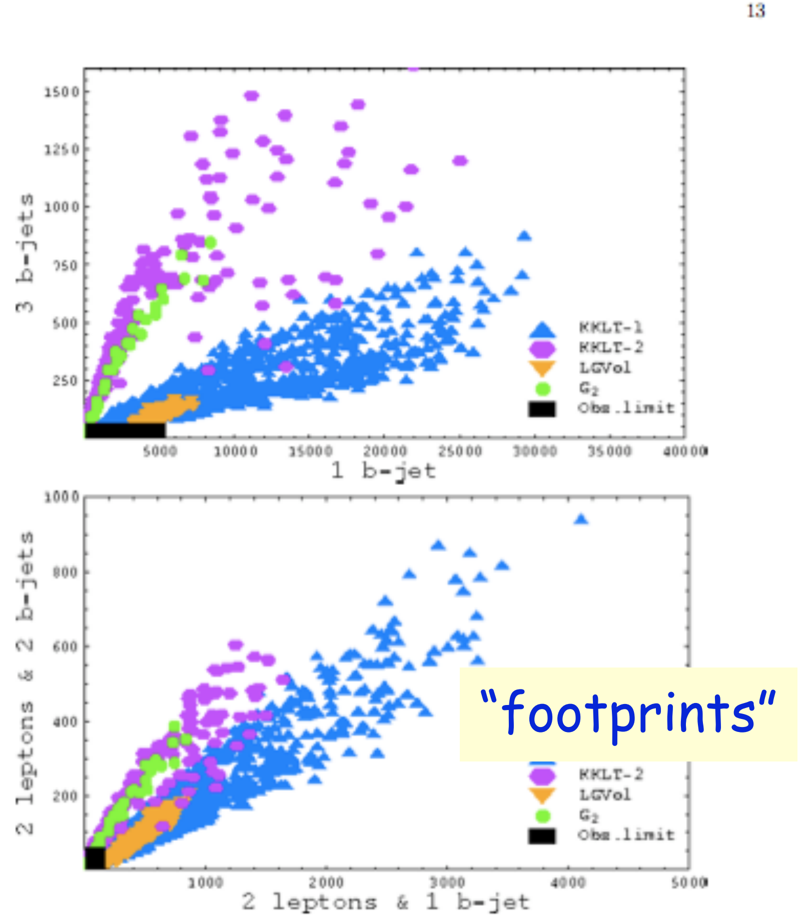
Inclusive+Exclusive

Inclusive [counting/cross section] and exclusive [end-point type] of measurements ⟶ a-posteriori probabilities of mapping back to the parameter space (*cf* references last slide and "Olympics" series)

Example



[3] a-posteriori probability distribution of mSUGRA parameters using cross-section + end-point measurements in a Markov Chain Monte Carlo sampling of the parameter space. The two regions reflect the lack of knowledge of which slepton is involved in the decay chain.

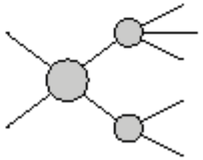


"footprints"

⇒ Studies of different variables/separating power

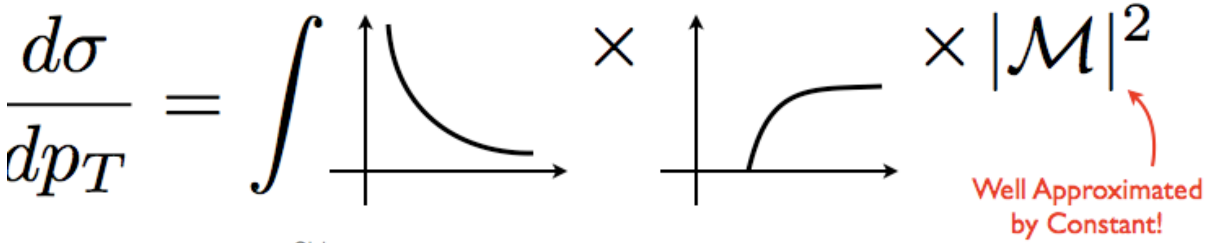
OSETs

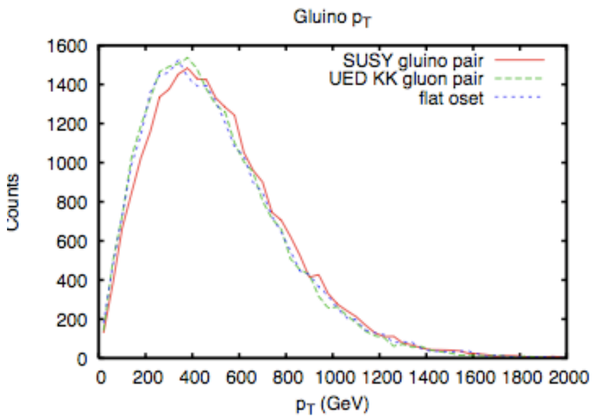
N. Toro

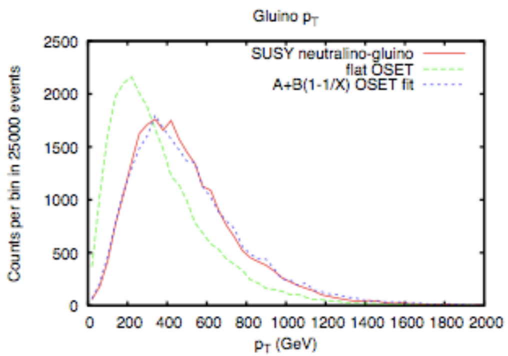
LHC Signatures $\Leftrightarrow$ **OSET**  $\Leftrightarrow$ $\mathcal{L}$

2→2 Folk Theorem

hep-ph/0703088, N. Arkani-Ahmed et al







...or simple parametrization in extreme cases

Has been exercised in CMS

$\Rightarrow$

- Quick turn around cycle
- Understand basic pattern of the data
- Predictions to check in data

Model Characterization

Dictionary of LHC signatures

A. Belyaev, I.A. Christidi, A. De Roeck, R.M. Godbole, B. Mellado, A. Nyffeler, C. Petridou, D.P. Roy

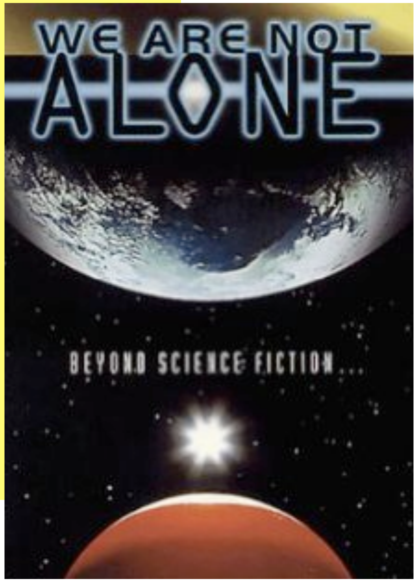
WHEPPX Proceedings
arXiv:0806.2838

Table 1. Discriminating signatures between SUSY (MSSM), LHT and UED. See description in the text. "YES" or "NO" mean presence or absence of the particular signature respectively, "SS" stands for "like-sign leptons".

Variables		SUSY (MSSM)	LHT (littlest)	UED(MUED)
Spin		heavy partners are spin 1/2 different	heavy partners have the same spin, no heavy gluon	heavy partners have the same spin
Higher level modes		NO heavy partners	NO heavy partners	YES heavy partners
$N_{l^+l^+}/N_{l^-l^-}$		$< 4:1$	$4:1$	4:1
SS leptons rates		from several channels: SS heavy fermions, Majorana fermions	only from SS heavy fermions	only from SS heavy fermions
$R = \frac{N(\not{E}_T + jets)}{N(l's + \not{E}_T + \text{jets})}$		$R_{\rm SUSY}$	$R_{\rm LHT} < R_{\rm SUSY}$	$R_{\rm UED}$ to be studied
b-jet multiplicity		enhanced (FP)	not enhanced	not enhanced
Single heavy top		NO NO	YES YES	YES via KK2 decay
polarization effects	$tt + \not{E}_T$	to be studied	to be studied	to be studied
	$\tau\tau + \not{E}_T$	to be studied	to be studied	to be studied
Direct DM detection rate		high (FP) low (coann)	low (Bino-like LTP)	typically low for γ_1(5D) DM [20] typically high for γ_H(6D) DM [20]

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 variables (precision measurements)
- 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



Heavy Flavor ↔ High p_T Interplay

The most interesting observables in the MSSM with MFV:

G. Isodori
LHC2FC

$B(B_s \to \mu\mu)_{SM} \approx 3.5 \times 10^{-9}$

$B(B_d \to \mu\mu)_{SM} \approx 1.3 \times 10^{-10}$

e channels suppressed by $(m_e/m_\mu)^2$

τ channles enhanced by $(m_\tau/m_\mu)^2$

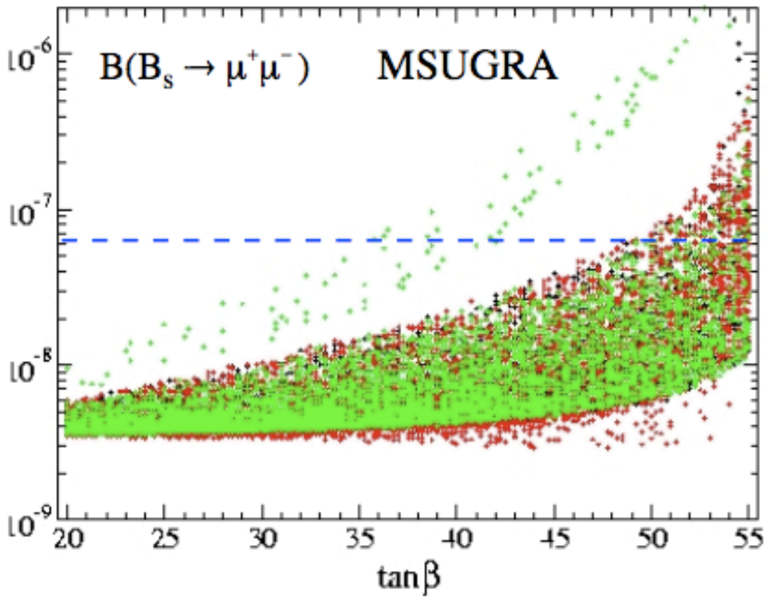
Most interesting bound set by:

$B(B_s \to \mu\mu) < 5.8 \times 10^{-8}$ (95%CL)

CDF+D0 '07

Significant constraint, but a good fraction of the parameter space is still allowed

N.B.: the $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV



Kane *et al.* '03

Unfortunately no systematic comparison between the LHCb and ATLAS/CMS New Physics reach yet…

Where do we expect SUSY?

O. Buchmuller et al
arXiv:0808.4128

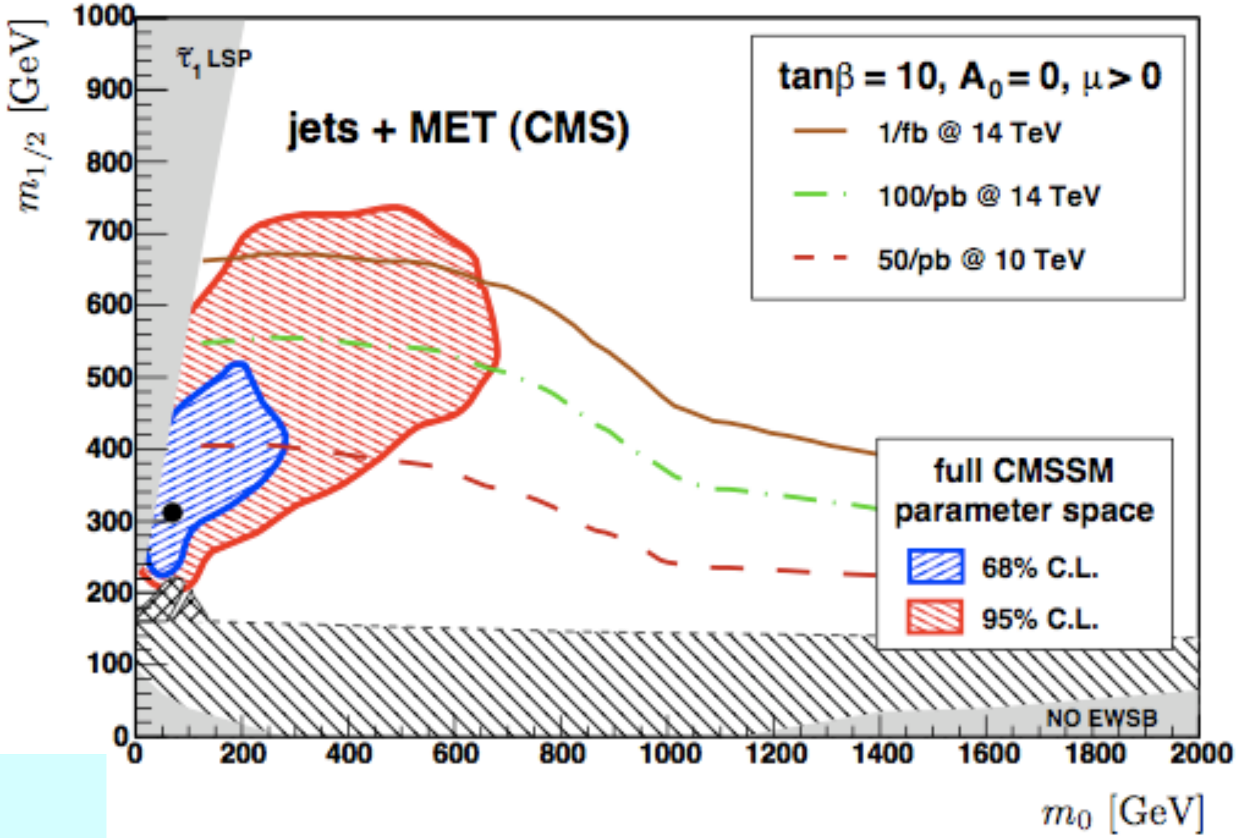
OB, R.Cavanaugh, A.De Roeck,
J.R.Ellis, H.~Flaecher, S.~Heinemeye
G.Isidor, K.A.Olive, P.Paradisi,
F.J.Ronga, G.Weiglein

Precision measurements
Heavy flavour observables

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

Reversely: once we have first signals for New Physics at the LHC: use synergy to extract/ learn as much as possible on the New Physics

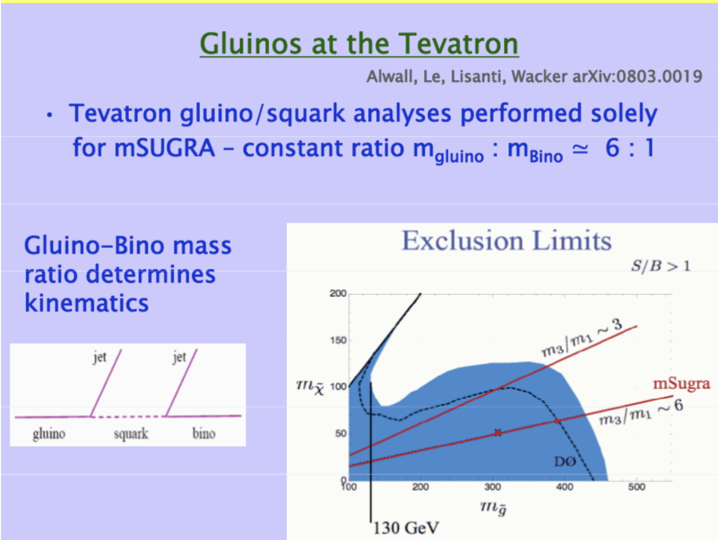
"LHC Weather Forecast"

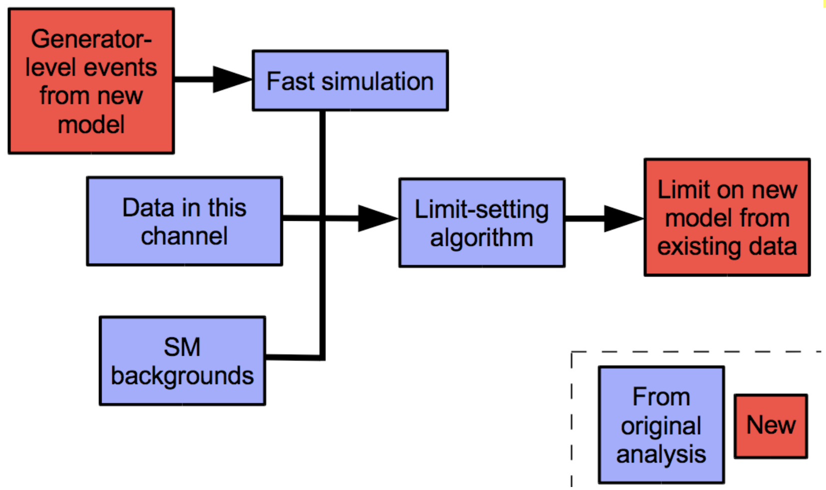


"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

Data presentation/storage discussion

- Often released data are presented under model assumptions, thus making it difficult to interpret in a different context
- How to communicate/catalogue an excess best
- Time overlaps between running of big facilities (Eg LHC/SLC and the LC) could be small. How to bridge that gap so that (S)LHC data is still fully alive when the next machine comes online?

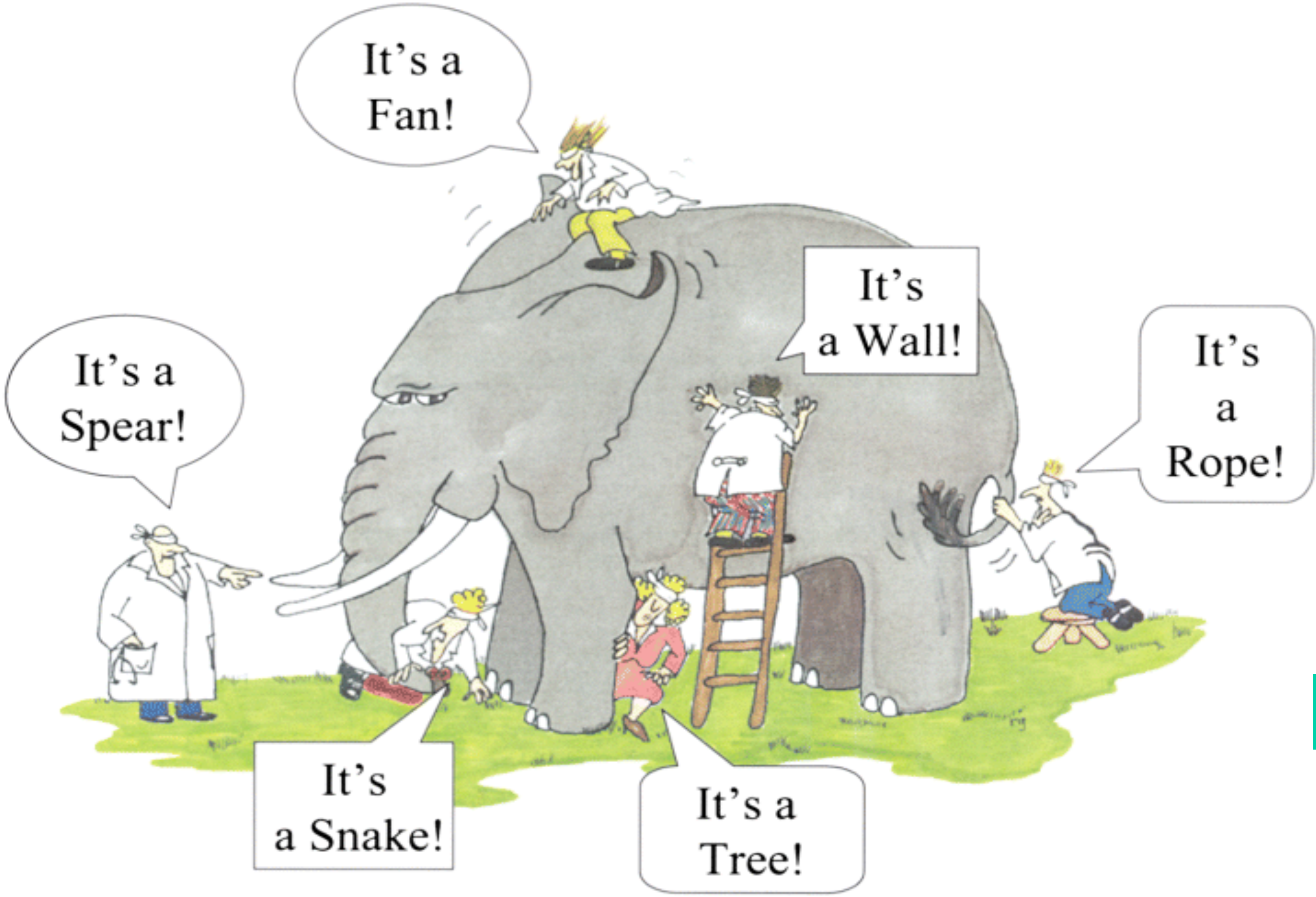




Lively discussion! To be continued

J. Hewett, C. Henderson
J. Incandela

Since we do not know what we will find…



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…we will look at it from all angles….

Close interaction between Experiment and Theory will be important