What's new at the energy frontier

Recent developments in LHC phenomenology

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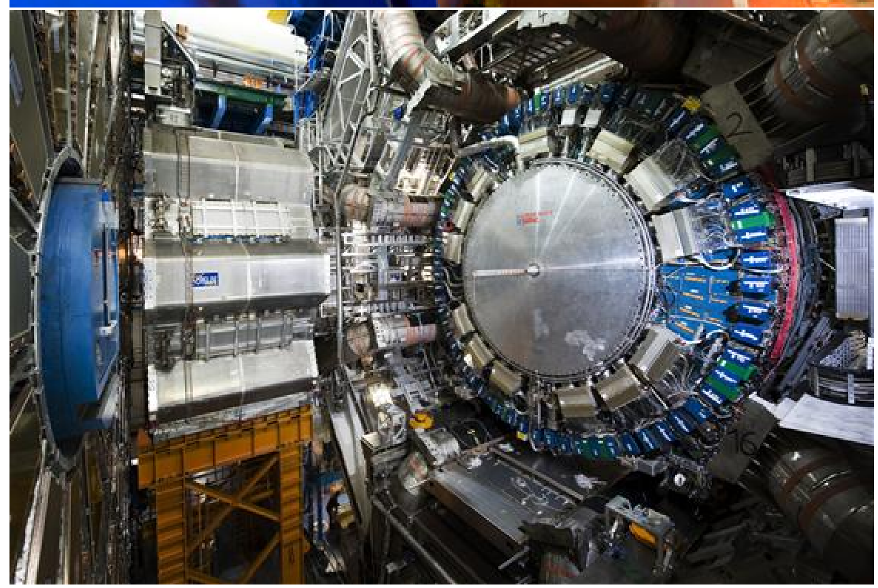
LHC is turning on:
Tremendously exciting time for HEP experimentalists!

Phenomenologists are also very excited:

- New models
- New collider studies
- New analysis method ideas



In this talk I'll sample a few recent developments:

- Walking technicolor at LHC

- "Exotic" multi-Higgs models

- A new method for reconstructing decay chains

Walking technicolor at LHC

Walking technicolor at LHC

Technicolor: born in the late 1970's (Weinberg, Susskind) by analogy to QCD.
Electroweak symmetry breaking caused by strong dynamics.

Heavy top quark mass posed a big difficulty:
solution was "walking" technicolor, in which the strong coupling g_{TC} runs very slowly.
This pushes up the scale where flavour dynamics has to happen and avoids FCNCs.

TC "killed" by precision electroweak constraints...

But news of technicolor's death has been greatly exaggerated!

Technicolor is strongly coupled: can't calculate precision electroweak observables!

Original approach: assume TC is just like QCD, measure hadron stuff, extrapolate to EW precision constraints.

Result: corrections much too big, ruled out by LEP.
But walking technicolor is *not* just like QCD!

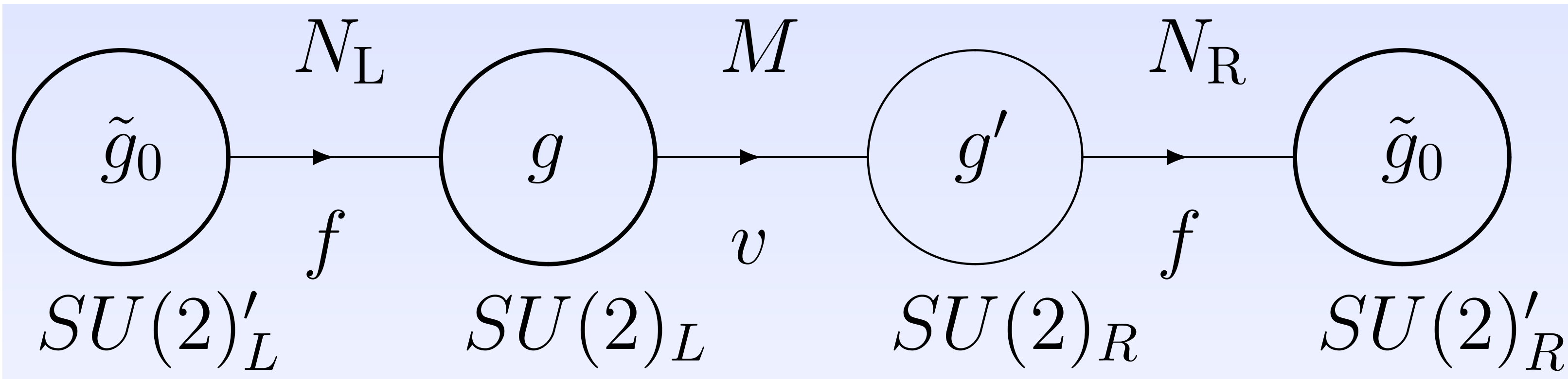
New developments:
Randall-Sundrum warped extra dimensions
+ AdS/CFT correspondence ("holography")
= walking technicolor!

Conformal field theory (CFT): couplings do not run.
Walking technicolor: couplings run very slowly.

"Dual" gravitational theory in 5th dimension is weakly coupled. Can actually compute electroweak precision observables, spectrum, phenomenology, etc.

Technicolor is once more a viable option for EWSB!

Renaissance of technicolor model-building



M. Jarvinen, talk at Pheno 2008 Symposium

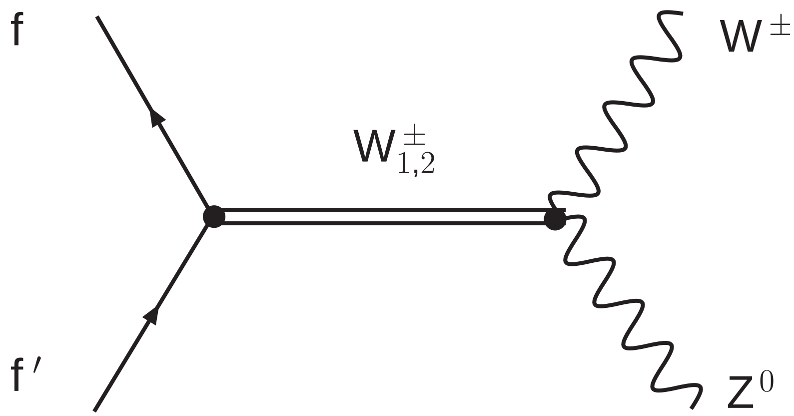
Simple "moose" models; technicolor vector mesons (techni-rho, etc.) modelled as massive vector bosons of broken gauge symmetries.

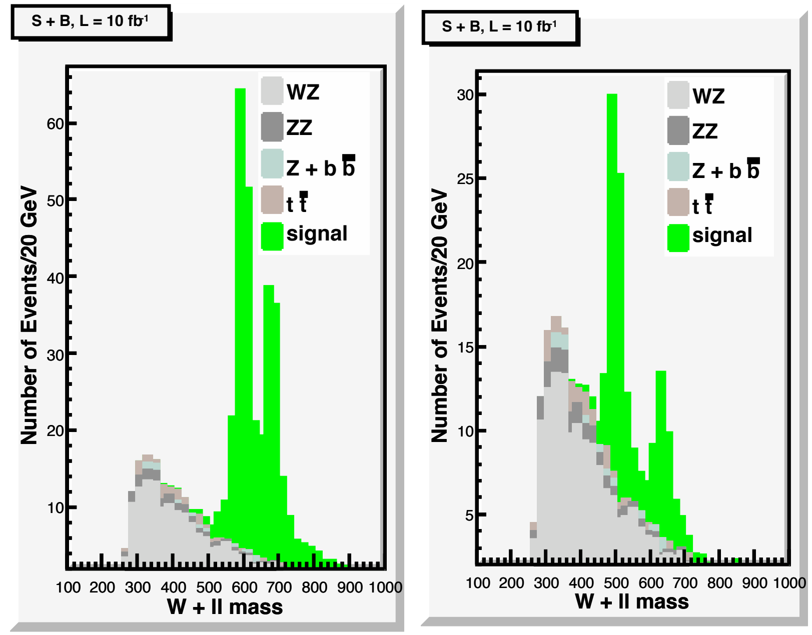
- Higgsless models; Drell-Yan signatures

Recent progress:

Implementation of model Feynman rules into CalcHEP, Sherpa, MadGraph, etc. for efficient collider studies.

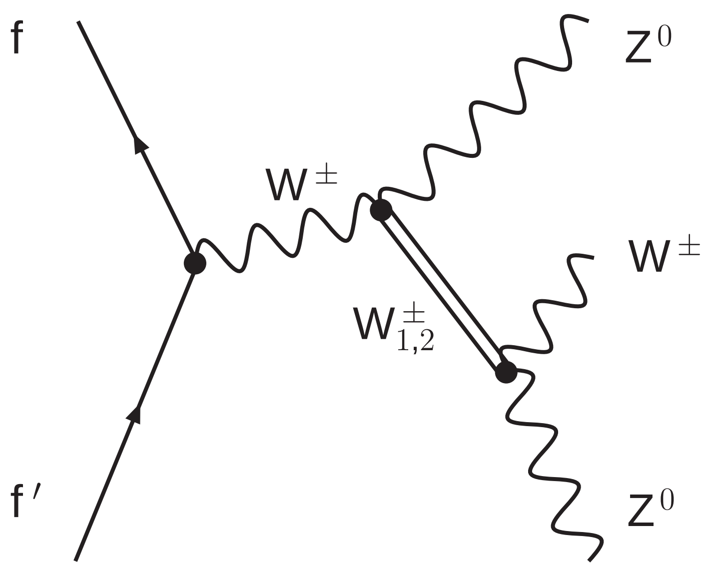
Drell-Yan production of Techni-$W^{\pm}_{1,2}$

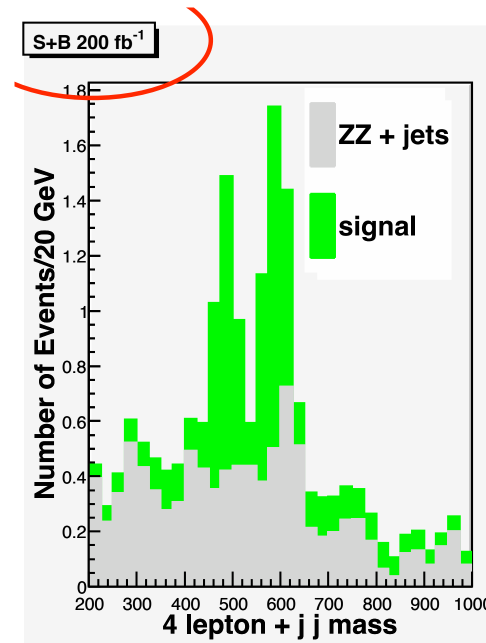




2 plots for different effective warp factors

Fermiophobic Techni-W case:





A. Martin, talk at

Pheno 2008

Symposium

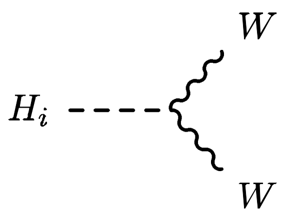
Exotic multi-Higgs models

Exotic multi-Higgs models

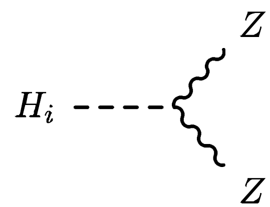
Most familiar models are multi-Higgs-doublet models.

- Couplings of Higgs to WW and ZZ are proportional to that Higgs's contribution to EWSB.

$$v^2 = \sum_i^n v_i^2$$



$$= \frac{g^2 v_i}{2}$$



$$= (g^2 + g'^2)\frac{v_i}{2}$$

- Couplings of Higgs to SM fermions are through Yukawa interactions.

Standard Model

$$y = \frac{m_f}{v}$$

Mixing between mass, gauge eigenstates: C_s

→

Mixing between VEVs: C_v

More Complicated Model

$$y = \left(\frac{C_S}{C_V}\right)\frac{m_f}{v}$$

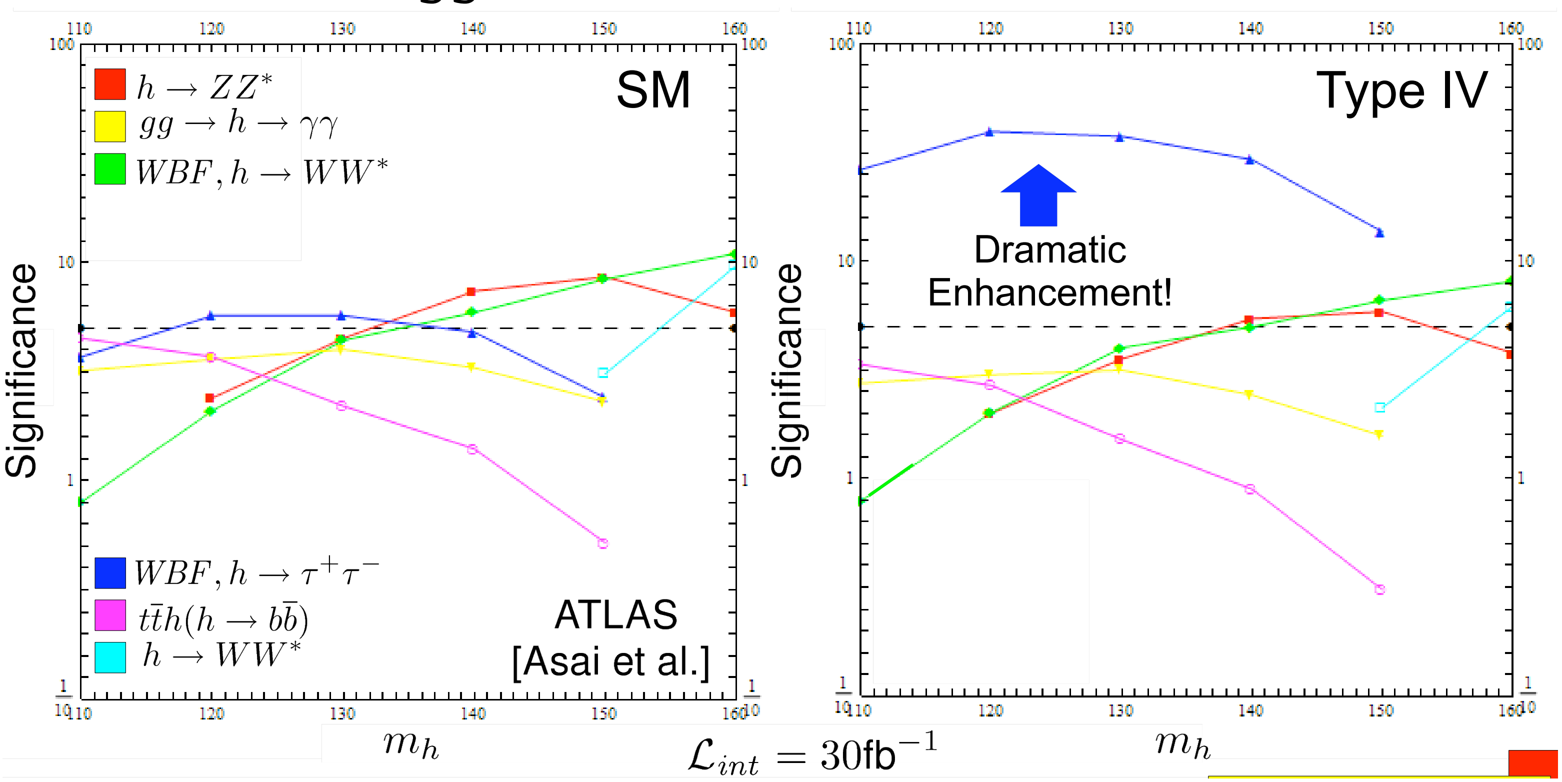
Lots of LHC studies for Type II 2HDM – as found in MSSM.
Not so much for other 2HDMs or more exotic models.
Big territory to explore: surveys of models, general parameterizations of couplings, studies of exotic models.

"Lepton-specific Higgs"

Consider a 2HDM in which one doublet couples only to quarks (both up- and down-type) and the other couples only to leptons.

$$\mathcal{L}_{\text{Yuk}} = y_u^{ij} \bar{Q}_i \tilde{\Phi}_q u_j + y_d^{ij} \bar{Q}_i \Phi_q d_j + y_\ell^{ij} \bar{L}_i \Phi_\ell e_j + \text{h.c.}$$

Can get enhancement of Higgs coupling to leptons.
Affects LHC Higgs search channels!



B. Thomas, talk at Pheno 2008 Symposium

“Lepton-specific Higgs”

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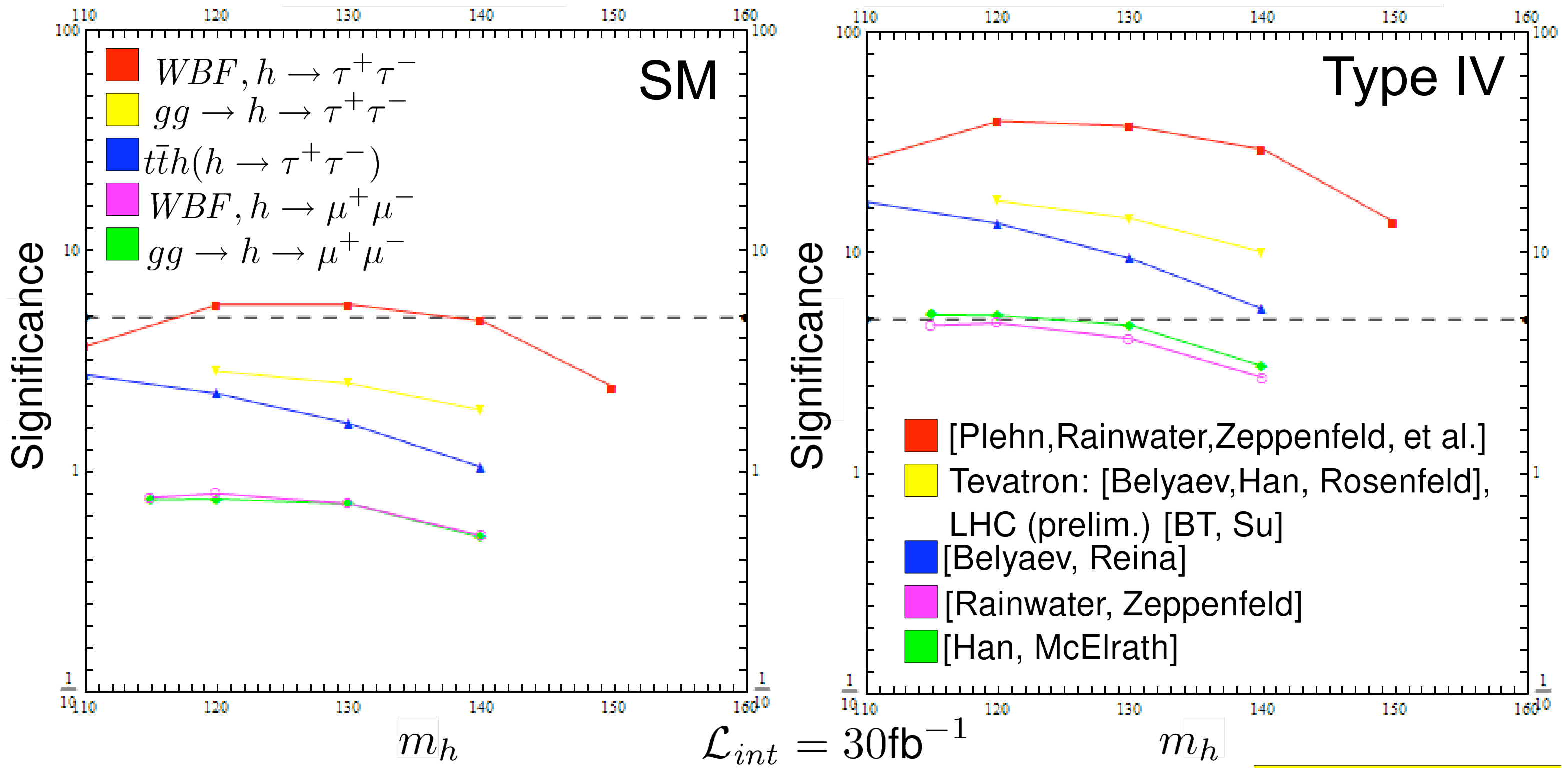
Can get enhancement of Higgs coupling to leptons.

Affects LHC Higgs search channels! Unusual channels become interesting.

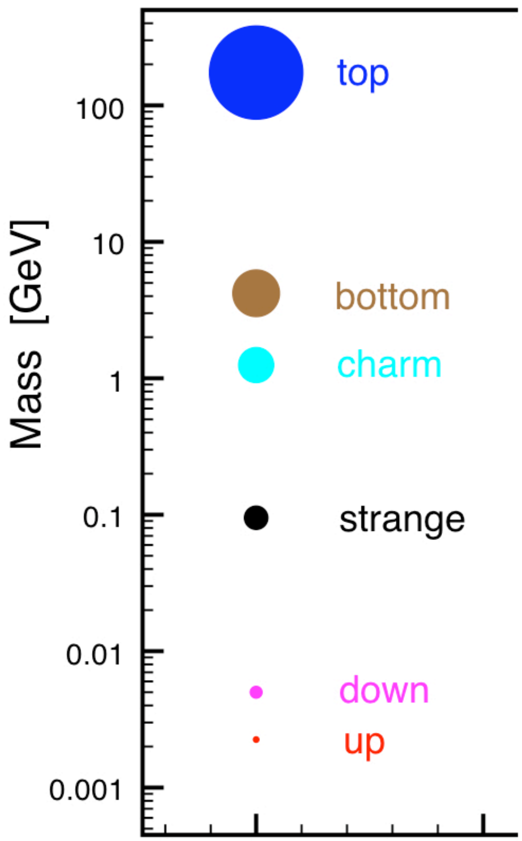


B. Thomas, talk at Pheno 2008 Symposium

“Private Higgs” R.A. Porto & A. Zee, arXiv:0712.0448 [hep-ph]

Aim to explain quark mass hierarchy

Introduce one Higgs doublet *for each quark*!
- Top quark’s “private Higgs” responsible for W, Z masses
- Light quark masses explained by small vevs; seesaw between M_{H_i} and v_i



Singlets with discrete symmetries provide dark matter candidate
- Talk to rest of particles via Higgs exchange
- Good potential for indirect detection from $SS \to \gamma\gamma$ C.B. Jackson, arXiv:0804.3792 [hep-ph]

Neutrino masses from a Higgs triplet

Introduce a hypercharge-2 Higgs triplet:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

Couple it to lepton doublet and to Higgs doublet:

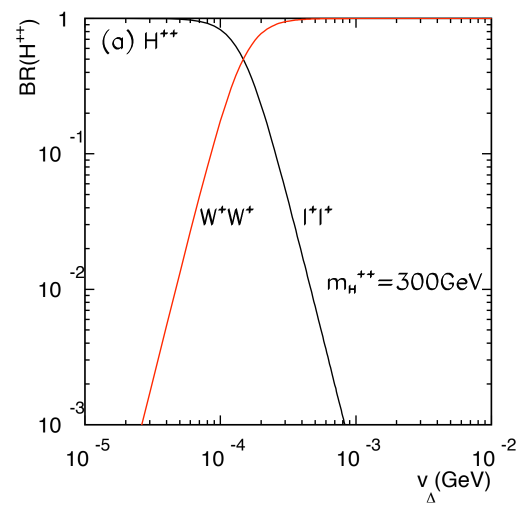
$$\mathcal{L} = -y_\nu^{ij} L_i^T C i\sigma_2 \Delta \, L_j + m H^T i\sigma_2 \Delta^\dagger H + \text{h.c.} + \cdots$$

SM Higgs vev triggers triplet vev; triplet vev gives Majorana neutrino masses:

$$v_\Delta = \frac{m v_H^2}{\sqrt{2} M_\Delta^2} \qquad\qquad M_\nu \sim \sqrt{2} v_\Delta y_\nu$$

Phenomenology: doubly-charged Higgs!

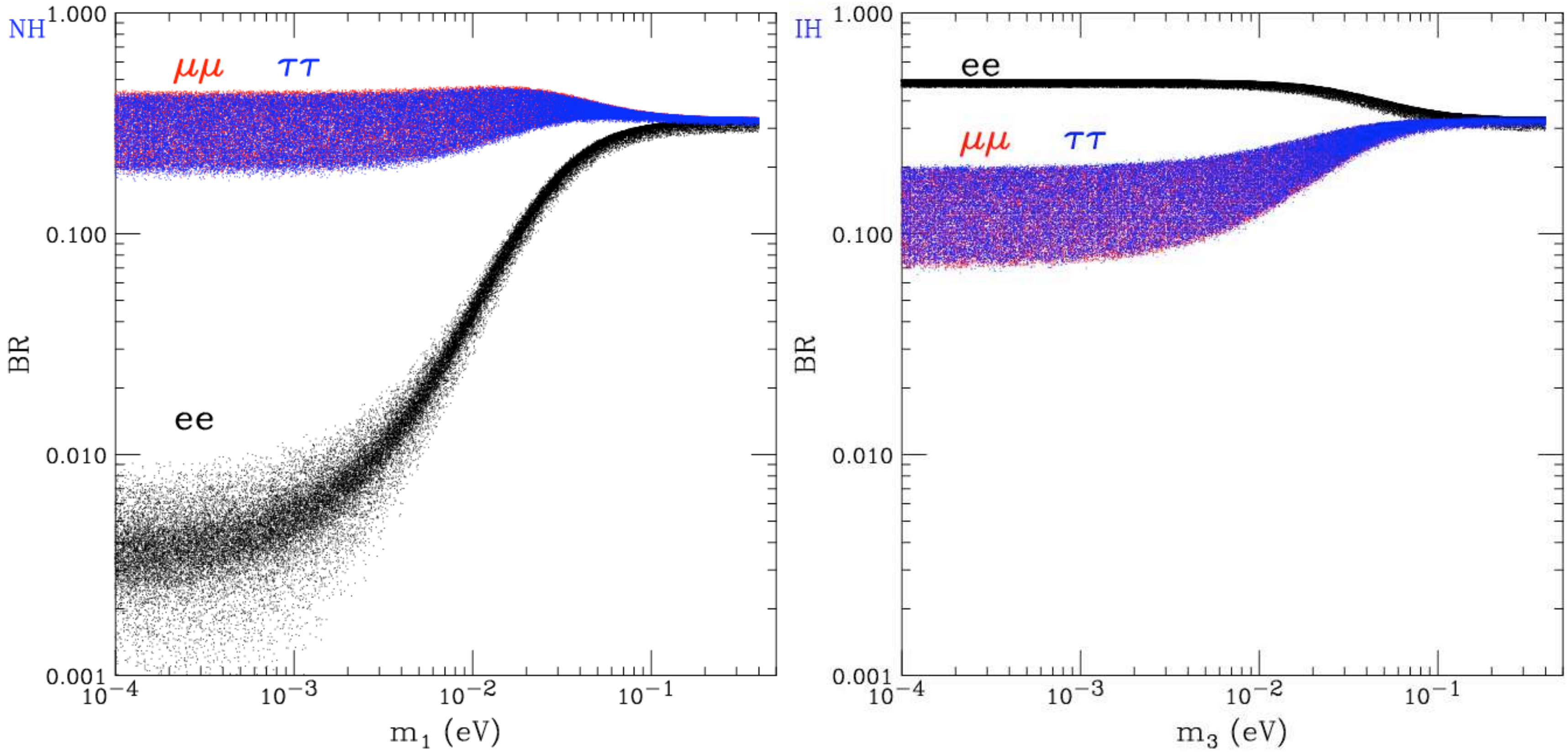
$H^{++} \to \ell^+\ell^+$ for small v_Δ
$H^{++} \to W^+W^+$ for large v_Δ



Tong Li, talk at Pheno 2008 Symposium

Perez, Han, Huang, Li & Wang, arXiv:0803.3450, 0805.3536

Decays of $H^{++} \leftrightarrow$ neutrino mass matrix!



Perez, Han, Huang, Li & Wang, arXiv:0805.3536 [hep-ph]

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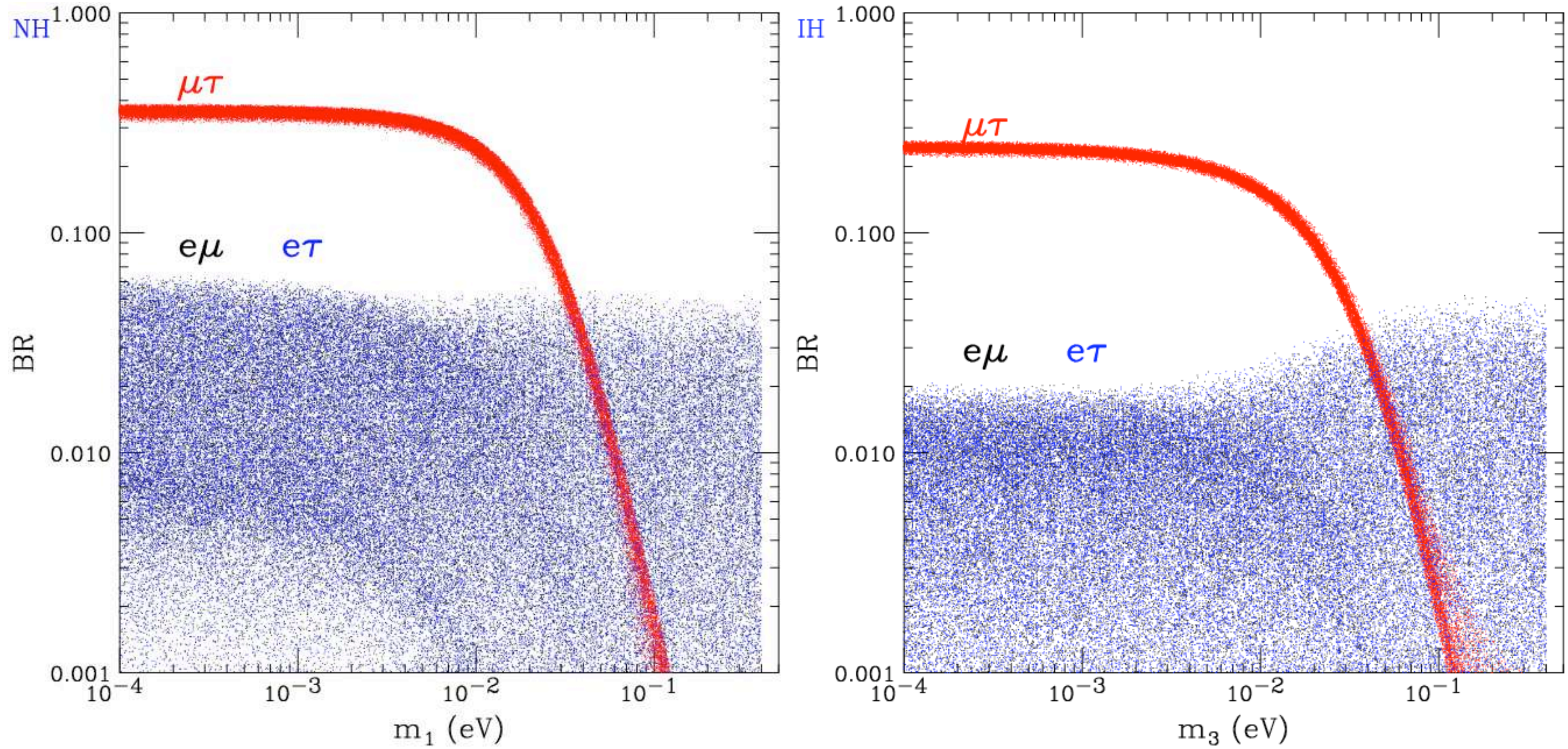


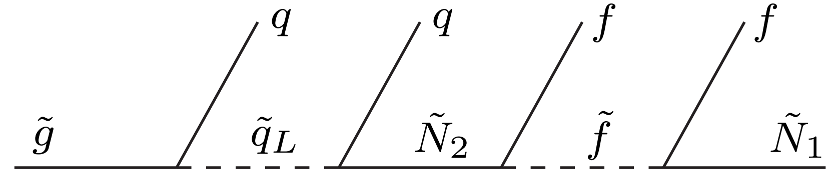
Perez, Han, Huang, Li & Wang, arXiv:0805.3536 [hep-ph]

Neutrino mixing matrix $\rightarrow$ flavour-nondiagonal decays.

Interesting LHC opportunity to probe neutrino physics.

New method for reconstructing decay chains

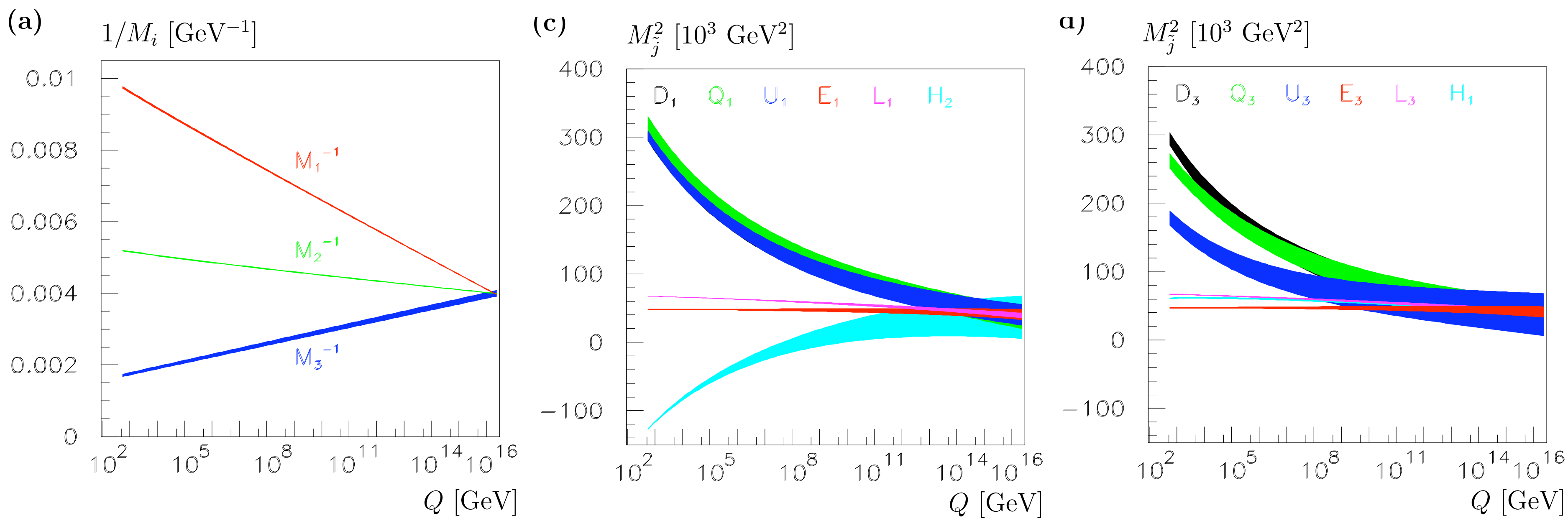
New method for reconstructing decay chains



SUSY particles pair-produced
Decay in a cascade down to LSP
LSPs escape the detector (2 per event)

2 missing particles $\longrightarrow$ reconstructing SUSY masses is not so easy!

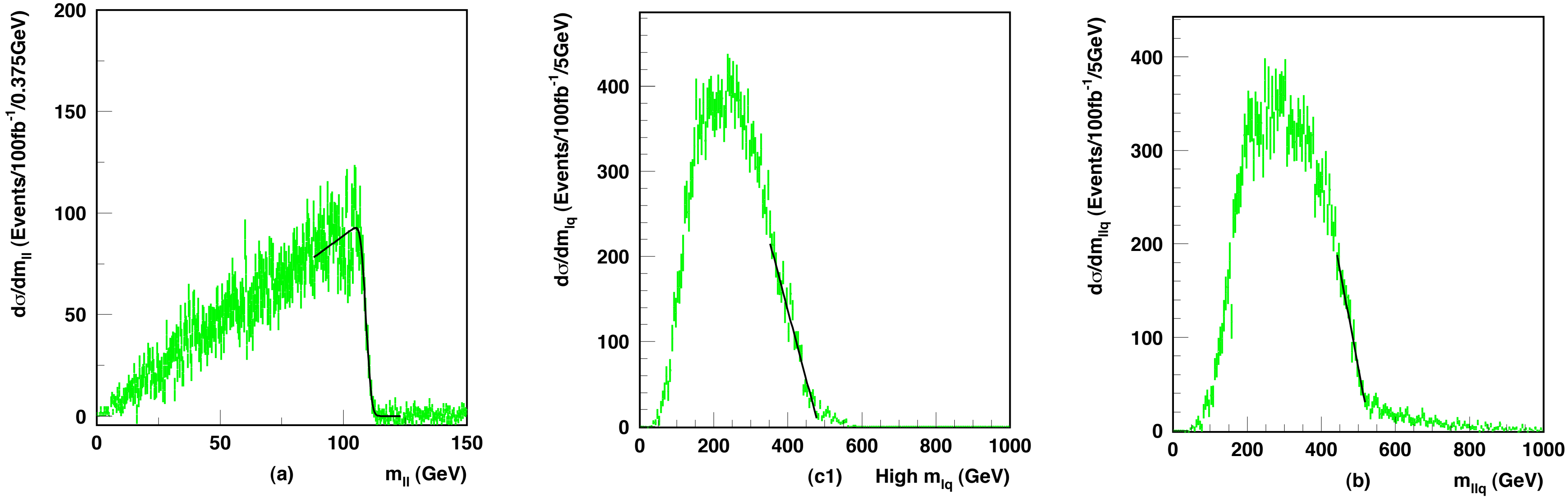
But we need to measure those masses in order to do this:



Blair, Porod & Zerwas, hep-ph/0210058 [mSUGRA]

Classic method:

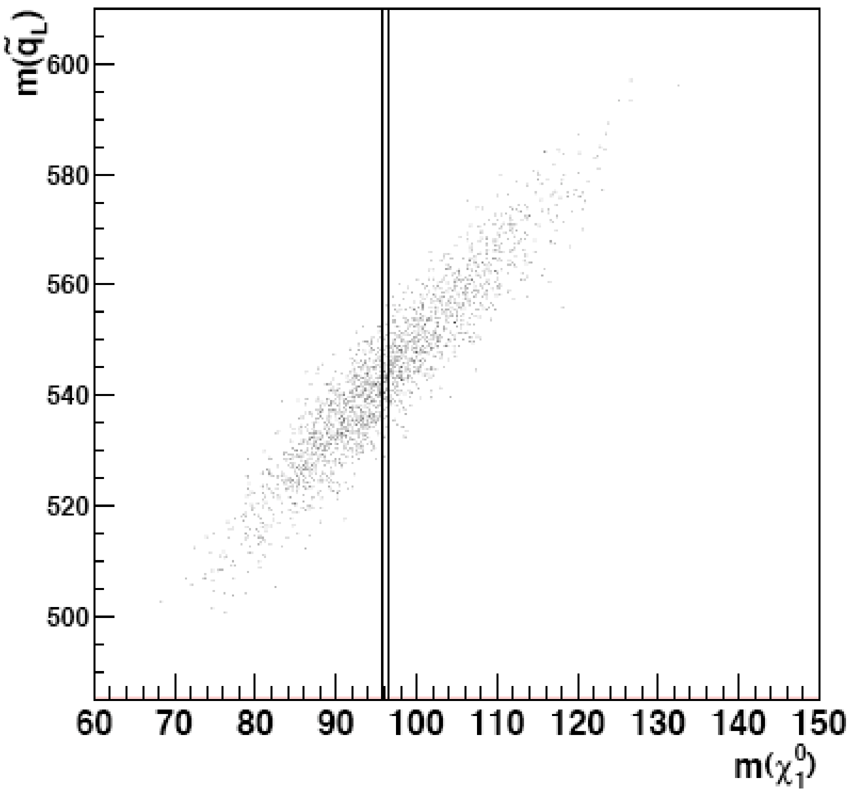
Use kinematic edges to get mass differences in decay chain.



Paige, hep-ph/0211017

Mass uncertainties highly correlated; uncertainties fairly large.

SPS1a



SPS1a′

Particle	Mass	"LHC"	"ILC"	"LHC+ILC"
h^0	116.0	0.25	0.05	0.05
H^0	425.0		1.5	1.5
$\tilde{\chi}_1^0$	97.7	4.8	0.05	0.05
$\tilde{\chi}_2^0$	183.9	4.7	1.2	0.08
$\tilde{\chi}_4^0$	413.9	5.1	$3-5$	2.5
$\tilde{\chi}_1^\pm$	183.7		0.55	0.55
$\tilde{e}_R$	125.3	4.8	0.05	0.05
$\tilde{e}_L$	189.9	5.0	0.18	0.18
$\tilde{\tau}_1$	107.9	$5-8$	0.24	0.24
$\tilde{q}_R$	547.2	$7-12$	–	$5-11$
$\tilde{q}_L$	564.7	8.7	–	4.9
$\tilde{t}_1$	366.5		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.1	8.0	–	6.5

[Left] M. Chiorboli et al., in hep-ph/0410364; dots are LHC, vertical bands are ILC

[Right] Supersymmetry Parameter Analysis group report, hep-ph/0511344; all masses in GeV

Kinematic endpoint method "throws away" lots of events.
Can we do better?

Method of Kawagoe, Nojiri & Polesello, PRD 71, 035008 (2005):

Consider a long decay chain, e.g.
$\tilde{g} \to \tilde{b} b_2 \to \tilde{\chi}_2^0 b_1 b_2 \to \tilde{\ell} b_1 b_2 \ell_2 \to \tilde{\chi}_1^0 b_1 b_2 \ell_1 \ell_2$
5 mass-shell constraints
4 unknown components of neutralino 4-momentum

Each event defines a *different* 4-dim hypersurface in the 5-dim parameter space of masses.

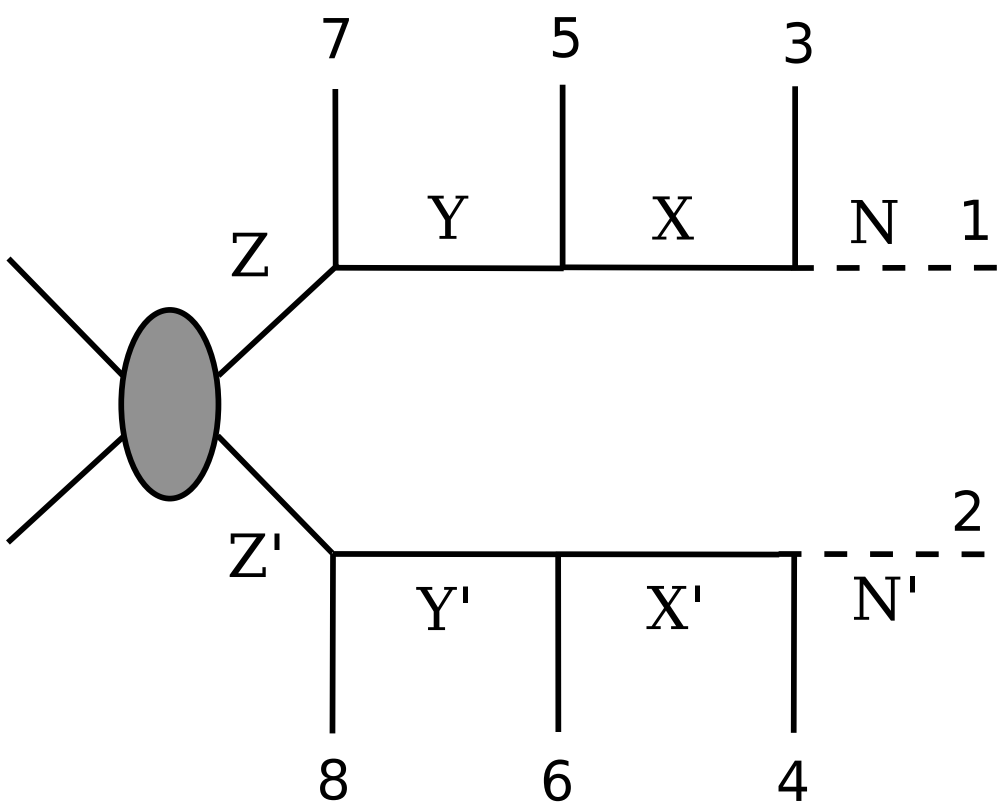
Combine hypersurfaces of ≥ 5 events: all overlap at the true solution point.

* Need at least 5 mass-shell constraints in the decay chain for method to work.

New method:

H.-C. Cheng, Gunion, Z. Han, Marandella & McElrath, JHEP 0712, 076 (2007)

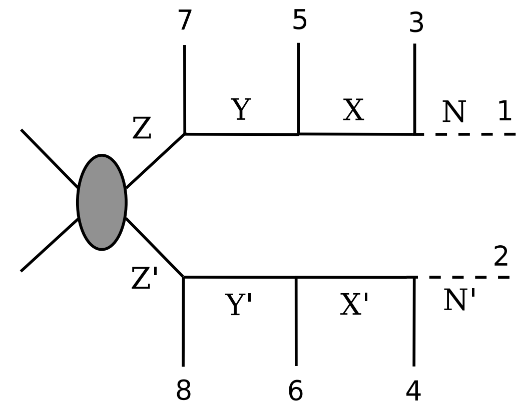
Take advantage of pair production of SUSY particles; look at both sides of the event.



from B. McElrath, talk at Pheno 2008 Symposium

Process depends on 8 final-state 4-momenta ($8 \times 4 = 32$ d.o.f.)
Measure 6 visible final-state 4-momenta ($6 \times 4 = 24$ constraints)
2 components of missing momentum are measured (2 constraints)

$$p_1^x + p_2^x = p_{\rm miss}^x, \qquad p_1^y + p_2^y = p_{\rm miss}^y$$



$32 - 24 - 2 = 6$ unmeasured d.o.f. remain.

We have four further constraints *per event*:

$$\begin{aligned}(p_1+p_3+p_5+p_7)^2 &= (p_2+p_4+p_6+p_8)^2 = M_Z^2 \\ (p_1+p_3+p_5)^2 &= (p_2+p_4+p_6)^2 = M_Y^2 \\ (p_1+p_3)^2 &= (p_2+p_4)^2 = M_X^2 \\ p_1^2 &= p_2^2 = M_N^2\end{aligned}$$

Only $32 - 24 - 2 - 4 = 2$ unconstrained d.o.f. in one event.

Add a second event:

32 more d.o.f.

$32 - 24 - 2 = 6$ unmeasured d.o.f. from second event.

4 further constraint equations *for second event*:

$$\begin{aligned}
(q_1 + q_3 + q_5 + q_7)^2 &= (q_2 + q_4 + q_6 + q_8)^2 = M_Z^2 \\
(q_1 + q_3 + q_5)^2 &= (q_2 + q_4 + q_6)^2 = M_Y^2 \\
(q_1 + q_3)^2 &= (q_2 + q_4)^2 = M_X^2 \\
q_1^2 &= q_2^2 = M_N^2
\end{aligned}$$

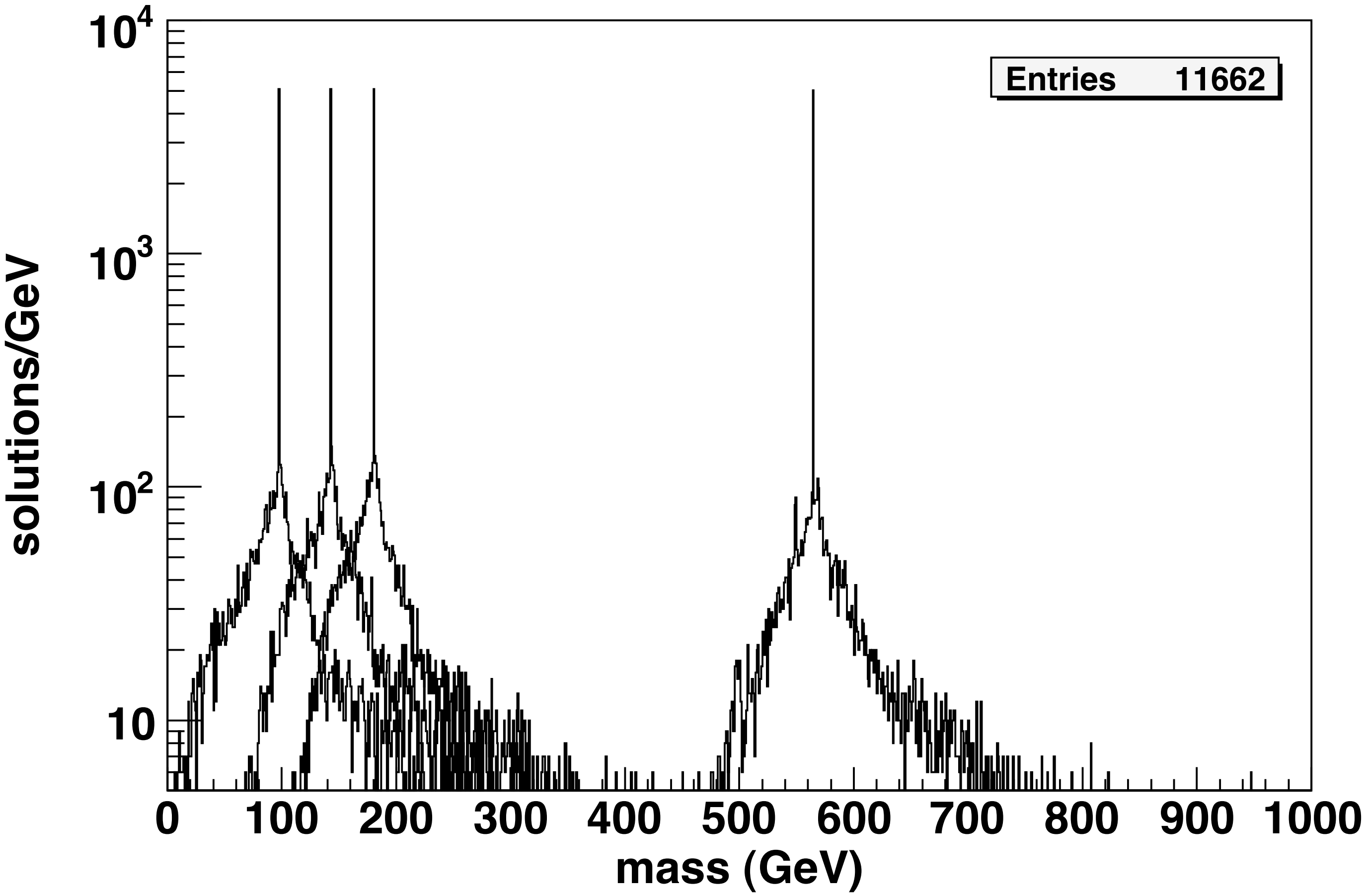
$32 - 24 - 2 - 4 = 2$ unconstrained d.o.f. from second event.

Plus 4 more constraint equations when you require that M_X, M_Y, M_Z, and M_N are the same in the two events.

These are enough to solve the system.

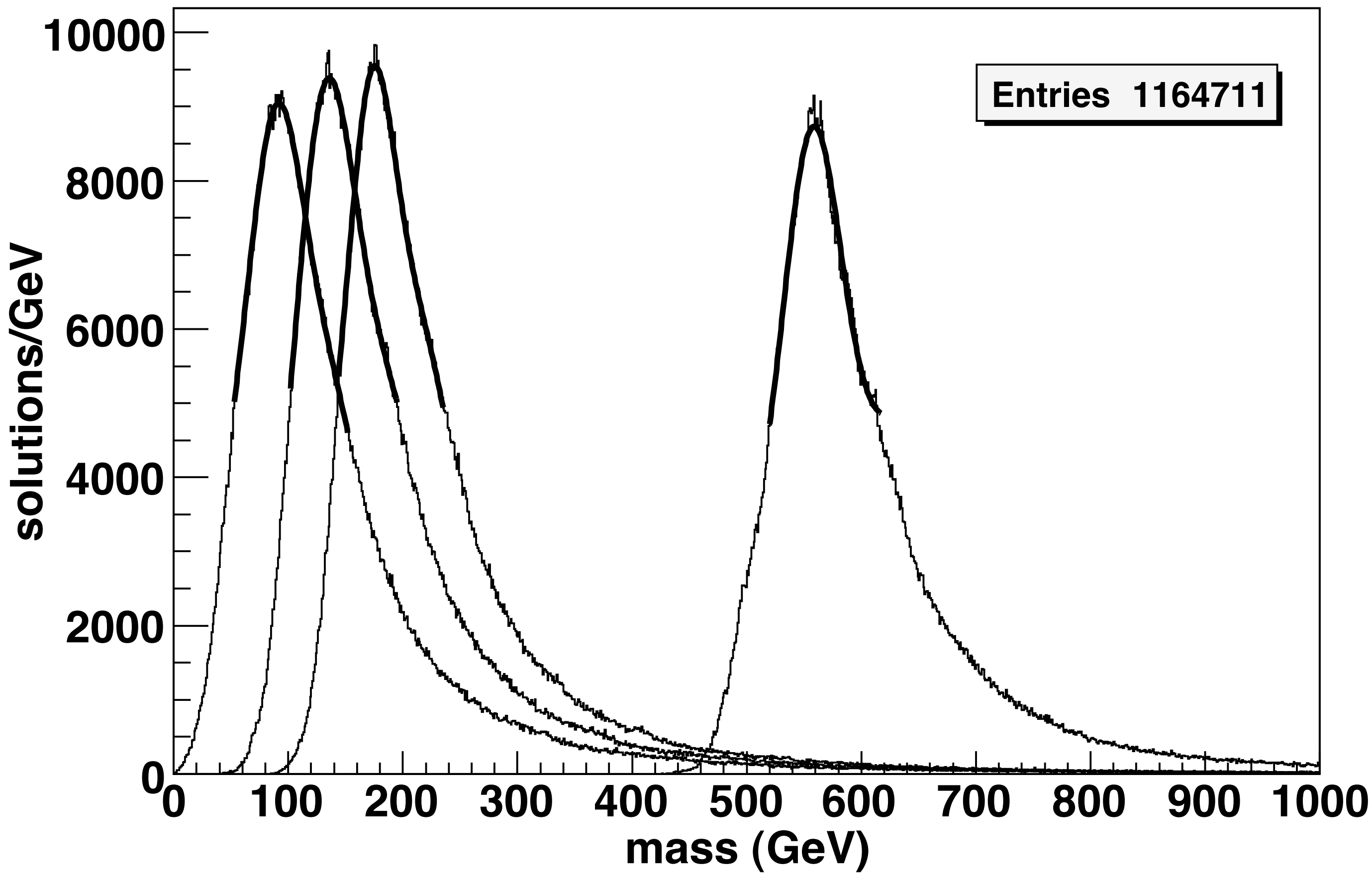
* Need at least 4 mass-shell constraints in the decay chain for method to work.

Example: SPS1a B. McElrath, talk at Pheno 2008 Symposium



Ideal momenta, no combinatorics

Example: SPS1a B. McElrath, talk at Pheno 2008 Symposium



Momenta reconstructed with ATLFAST; combinatorics included with cuts to reduce combinatorics bias

Already better resolution than endpoint method.
Can make mass-bump plots!

Canadian connection

Canadian phenomenology community is small but growing
- New hires at TRIUMF, York U.
- Search this coming year at Carleton

Expertise in wide range of BSM
- Holographic Technicolor phenomenology – Veronica Sanz $\rightarrow$ York 2009
- John Ng (TRIUMF) + postdoc & student – neutrino mass models
- Carleton students – Leptonic 2HDM, similar neutrino mass model
- Many others: faculty, postdocs & students
- Connections outside of Canada

Advertisement:
LHC Phenomenology Workshop Dec 17 at Carleton
("Day 3" of December ATLAS Canada meeting)

Conclusions

Technicolor is alive and kicking
- Active model building
- Parameterization framework for LHC phenomenology
- Implementation into parton-level event generators
- Colldier studies

Broader surveys of two- (or more-) Higgs-doublet models
- Framework for interpreting non-standard Higgs couplings
- Framework for parameterizing $H^{\pm}$, A^0, etc. couplings

Triplet Higgs phenomenology for neutrino mass models
- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

New mass reconstruction techniques for long decay chains ending in dark matter particles

Let's collaborate more!