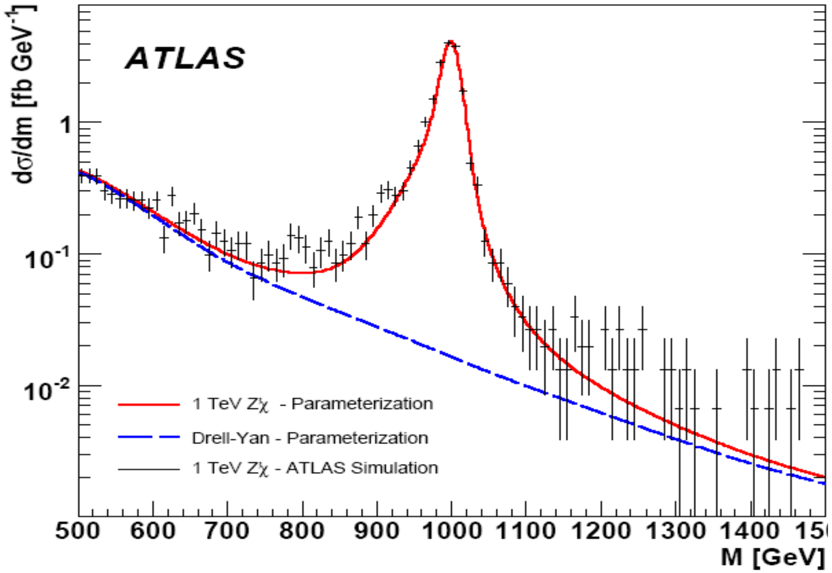
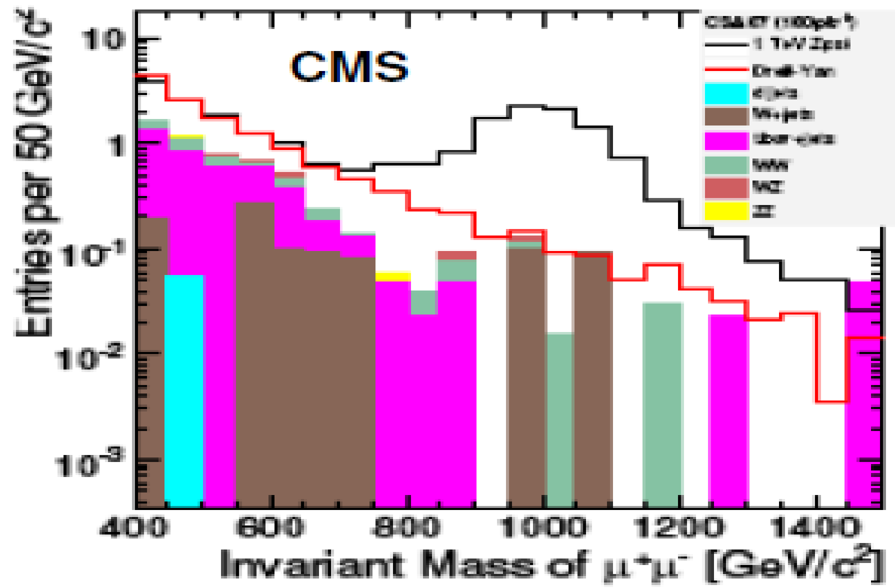
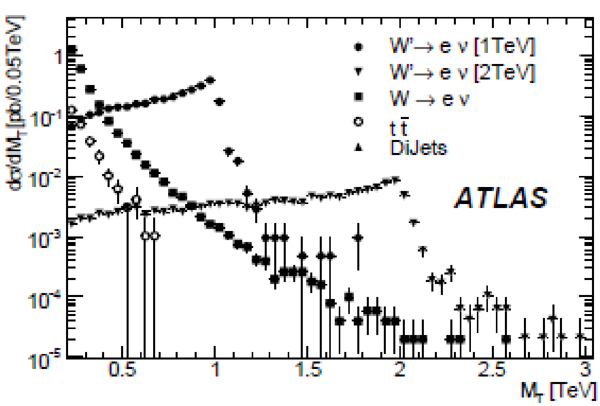
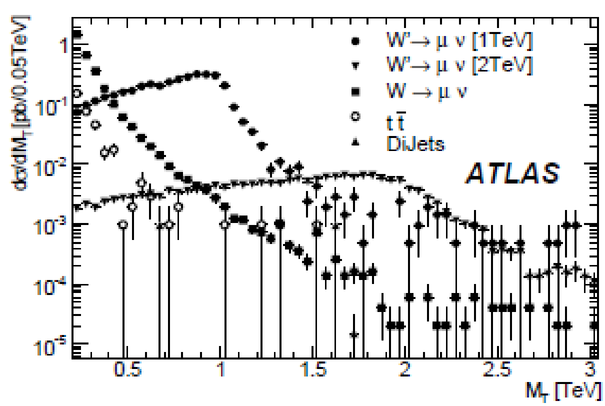
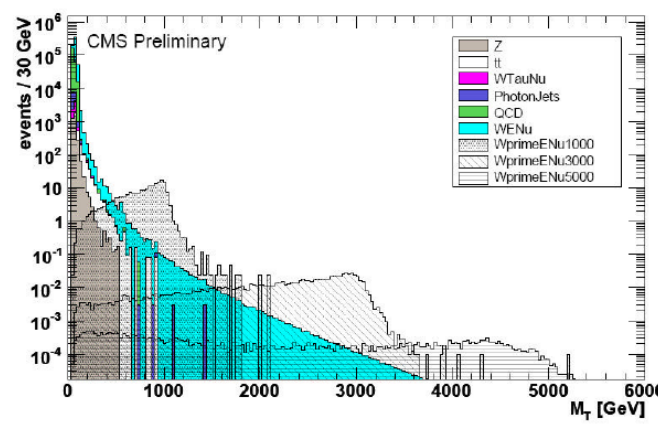
Distinguishing D-Y Resonances @ the LHC











A Z'-like state at the TeV scale in the Drell-Yan channel is a very common prediction in *many* BSM scenarios:

- Extended SUSY-GUT groups
- Sneutrinos in R-Parity violating SUSY
- String constructions/intersecting branes
- Little Higgs models
- Hidden Valley/Sector models
- Extra dimensions: gauge & graviton KK's
- String excitations
- Twin Higgs models
- Unparticles
- Wimponia
- ?????? = all the stuff we haven't though of yet

c/o Kevin Black

The LHC will open up a window to look for such states very soon… *but* how do we know what we've found???

Z Prime

Other / Pop / Electronica

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Dave
Z Prime
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00:32
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Featured Playlist

		ADD	BUY
1. Dave	596 plays		
2. Chris	283 plays		
3. Jumping Beans	200 plays		
4. Jenny and Julia	136 plays		

myspace music

Contacting Z Prime

- **Send Message**
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MySpace URL:
www.myspace.com/zprime

About Z Prime

From the serenity of the scortched sand dunes of the Arabian Deserts. Gushed out the lull of a prepubescent youth: "I want to change my life. And throw it in the garbage can." And God said, "It was good." And thusly, it was. Take your definition of music, (written on a stone slab passed down in the beams of light through the fiery clouds) and shove it in the depths of a blender. That rickity sound of the soon sharded cement blistering the sides of the blender and those electric short

Z Prime: General Info

Member Since	1/12/2005
Band Members	JA-FURY.
Influences	nike 'pump up' shoes and tin

Address http://www.summitpost.org/mountain/rock/154566/peak-s-z-gorgeous-peak-z-prime-.html

Peak's Z "Gorgeous Peak" & "Z-Prime"

Page Type: Mountain/Rock

Location: Colorado, United States, North America

Elevation: 13245 ft / 4037 m

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Created/Edited: Aug 25, 2005 / May 13, 2006

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Page Score: 90.84% - 35 Votes

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Gore Range Overview

Colorado's Gore Range

Address http://www.xtl.ox.ac.uk/zprime.html Go Links »

chem crystnews

21 July 08 >> CRYSTALS Version 12.86c is available as a beta-test

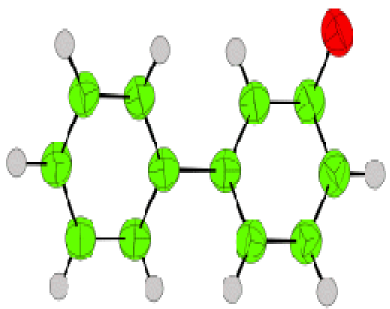
The problems with running CRYSTALS under Vista seem to have been reduced using updates provided by Richard Cooper and Olex Dolomanov. If you continue to have problems, please let us know. Switching from Aero to Classic may provide a temporary workaround. One Thinkpad, in Aero mode, in Australia, reports that the cursor is off-set slightly when pointing into the graphics window. It also seems that there are (independant) problems with ATI

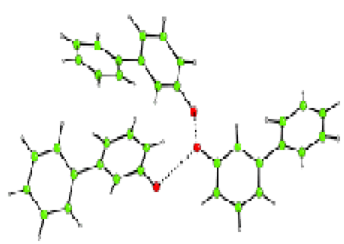
Z'>1 structures:

Just a nuisance, or something more interesting?

For many discrete-molecule materials, the molecules pack together to form crystals in a relatively simple way determined by the Space Group. Such materials are said to have Z'=1 (Z-prime). Increasingly, crystallographers are beginning to find crystals in which the basic building block is not just one molecule, but several molecules taken together. Such materials are said to have Z'>1.

These materials must be studied for two reasons. The most urgent is that they can pose serious problems for the crystallographer, so that new computational tools need to be developed. More fundamental is the question of why these molecules choose to crystallise in such complicated patterns.





3-hydroxybiphenyl is a simple molecule with a complex crystal structure. It turns out that in the crystal, the molecules hang about in groups of three, with the three molecules hydrogen bonded to each other. The hydrogen bonded network cannot extend any further. A fourth molecule cannot get its hydroxyl group sufficiently close to those in the trimer because of steric restrictions.

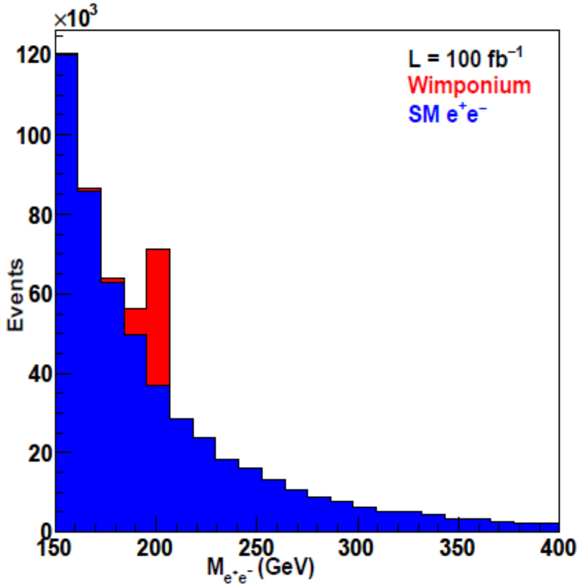
[David Watkin | Keith Prout | X-ray diffraction suite | Z prime | Twins | Mogul]

Crystals Now! Manuals Now!

…this is what we want to know!!

There are many ways to categorize these models but, thinking about their specific aspects, one can broadly classify them in the following way:

0901.2125



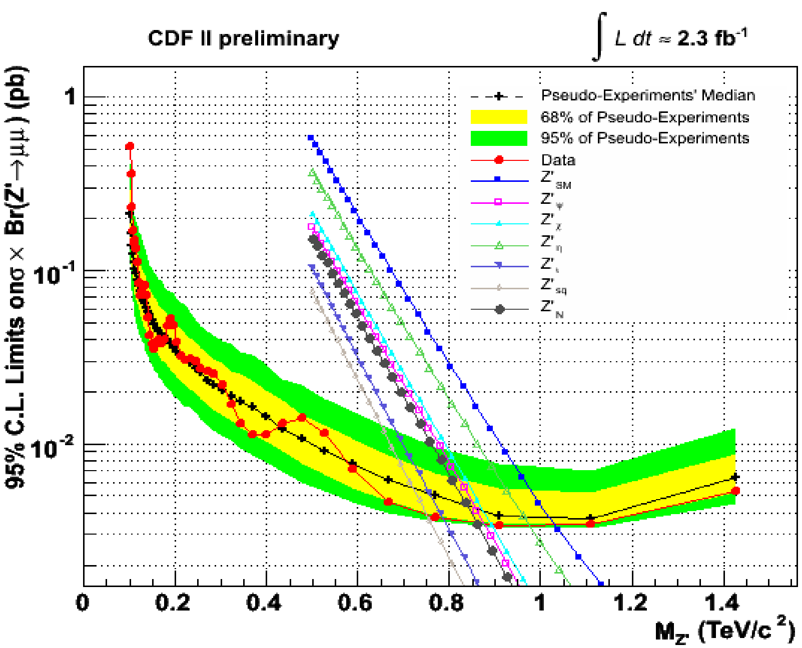
- 'canonical' states
- 'weakly-coupled' states
- 'generation-dependent coupling' states
- 'wrong-spin' states
- 'wrong resonance profile' states

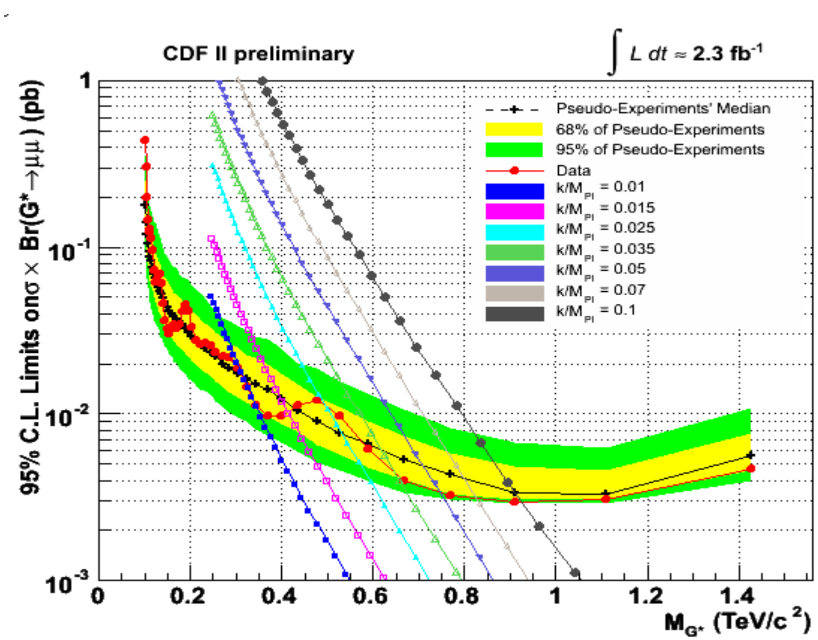
By 'wrong' I mean somewhat 'unusual' in comparison to, e.g., a common, ordinary, 'run-of-the-mill' GUT-inspired Z' we've talked about for many years.

Placing a newly discovered leptonic resonance into one of these bins is the first step towards identifying the underlying theory..

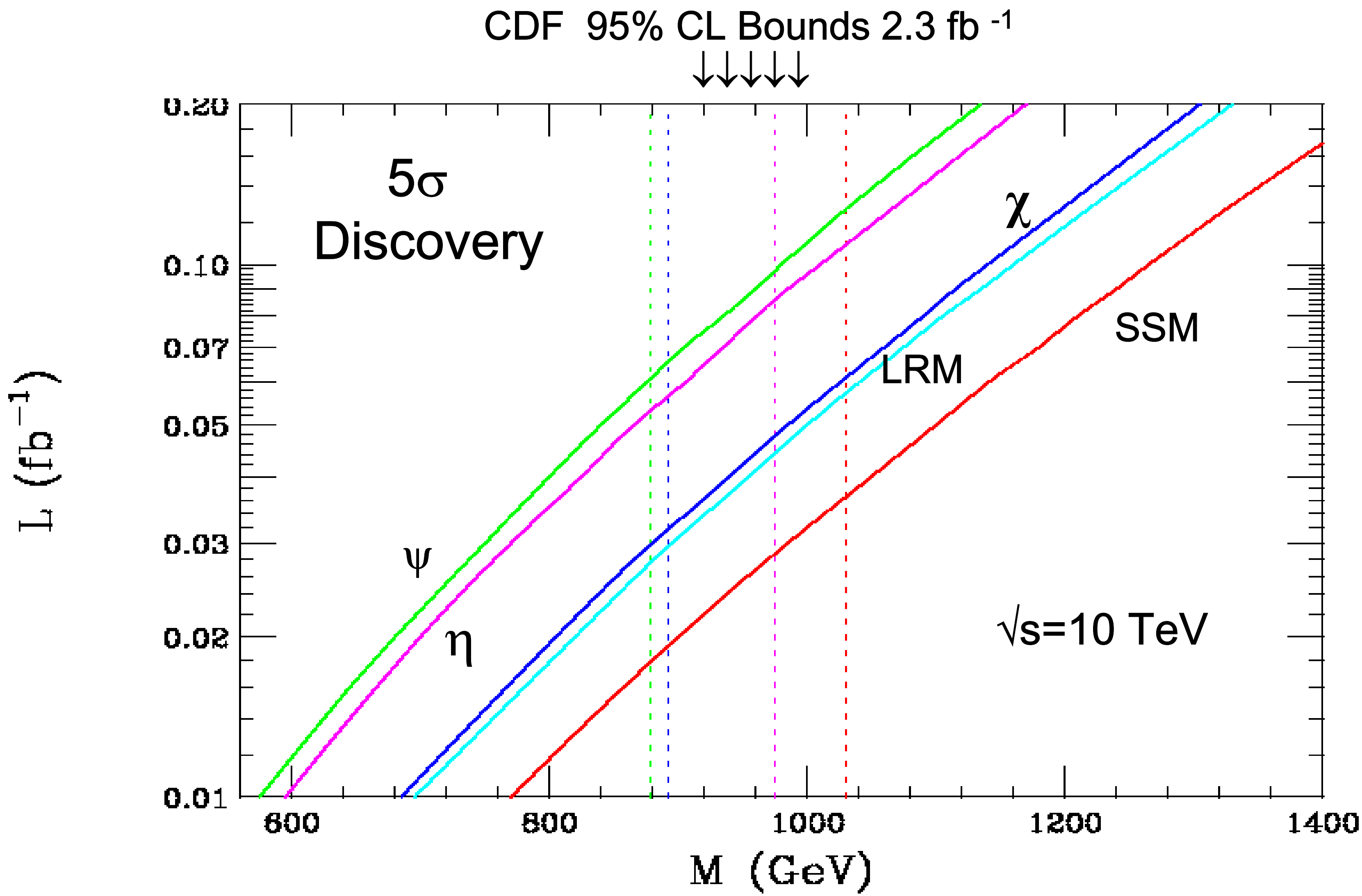
As is well-known, the D-Y channel is a particularly clean one. It is reasonable to expect that enough observables will exist to allow for some restrictions on the underlying theory once such new states are discovered and enough statistics are available.

What so we know so far? The Tevatron has told us that Z'-like states, if they exist, are either reasonably massive or are weakly coupled to the SM…

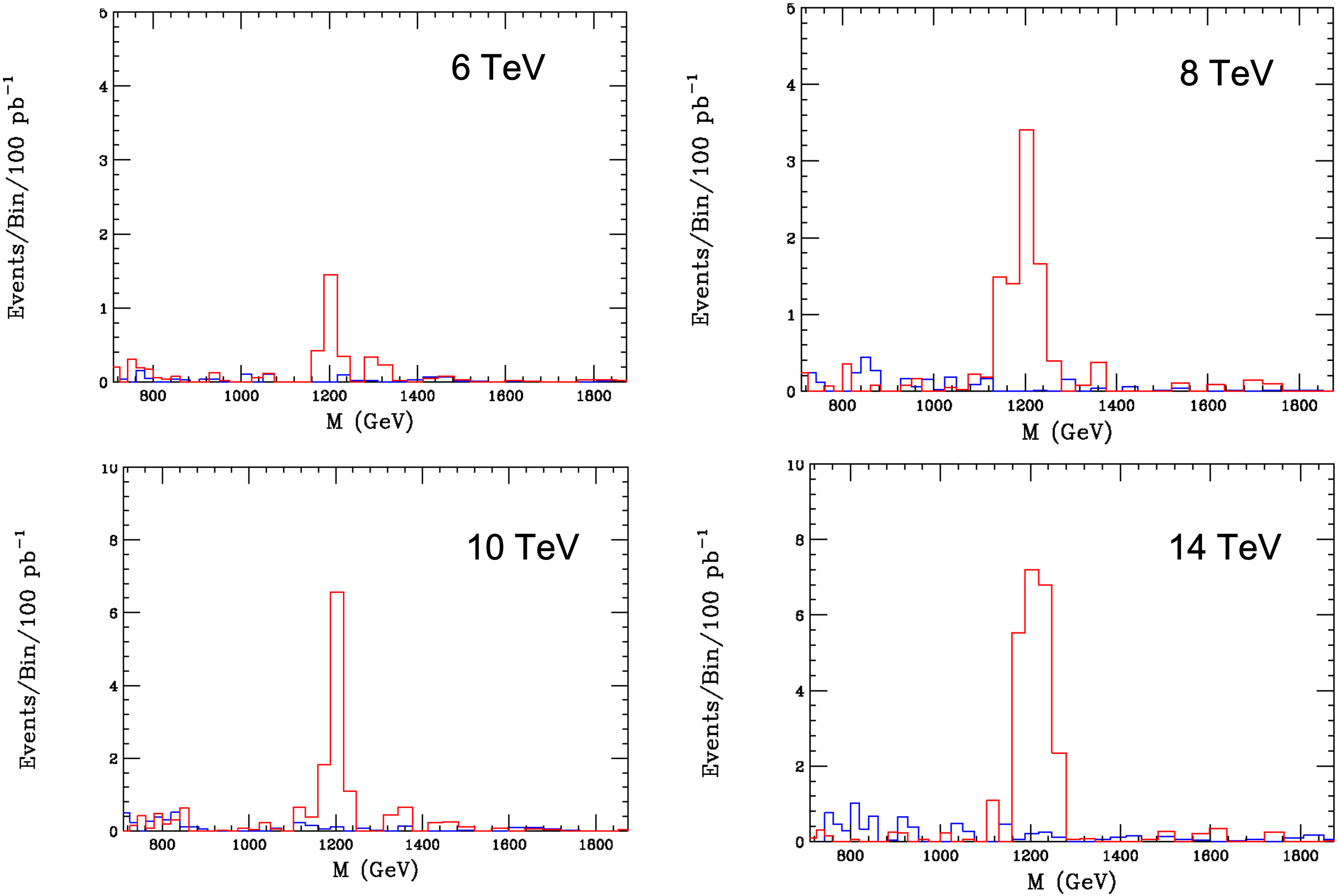


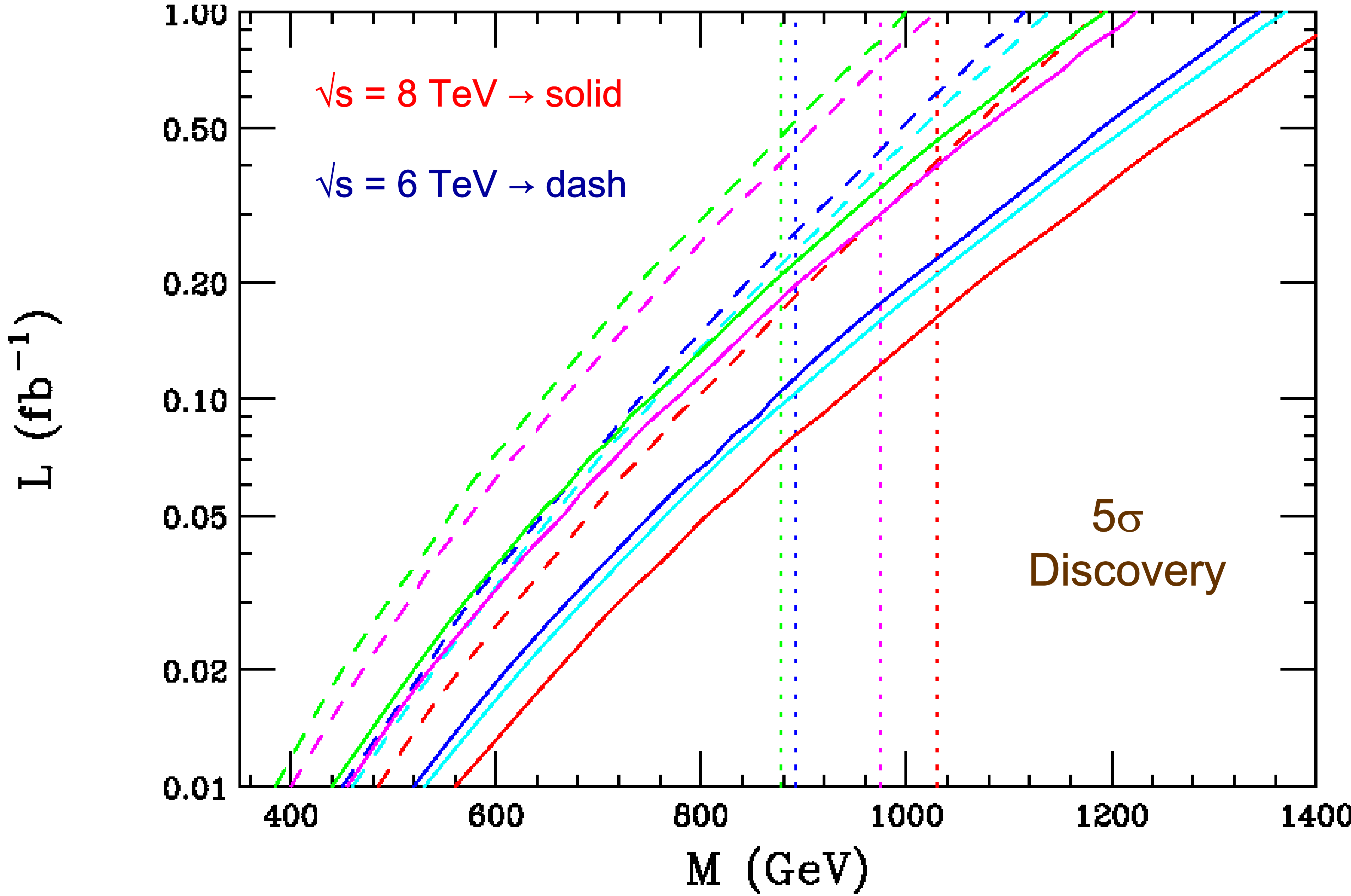


Z'→ leptons is a very clean mode and may provide the first signal of new physics to be observed at the LHC…*even* with √s=10 TeV and a relatively low integrated luminosity ~100-200 pb^{-1}

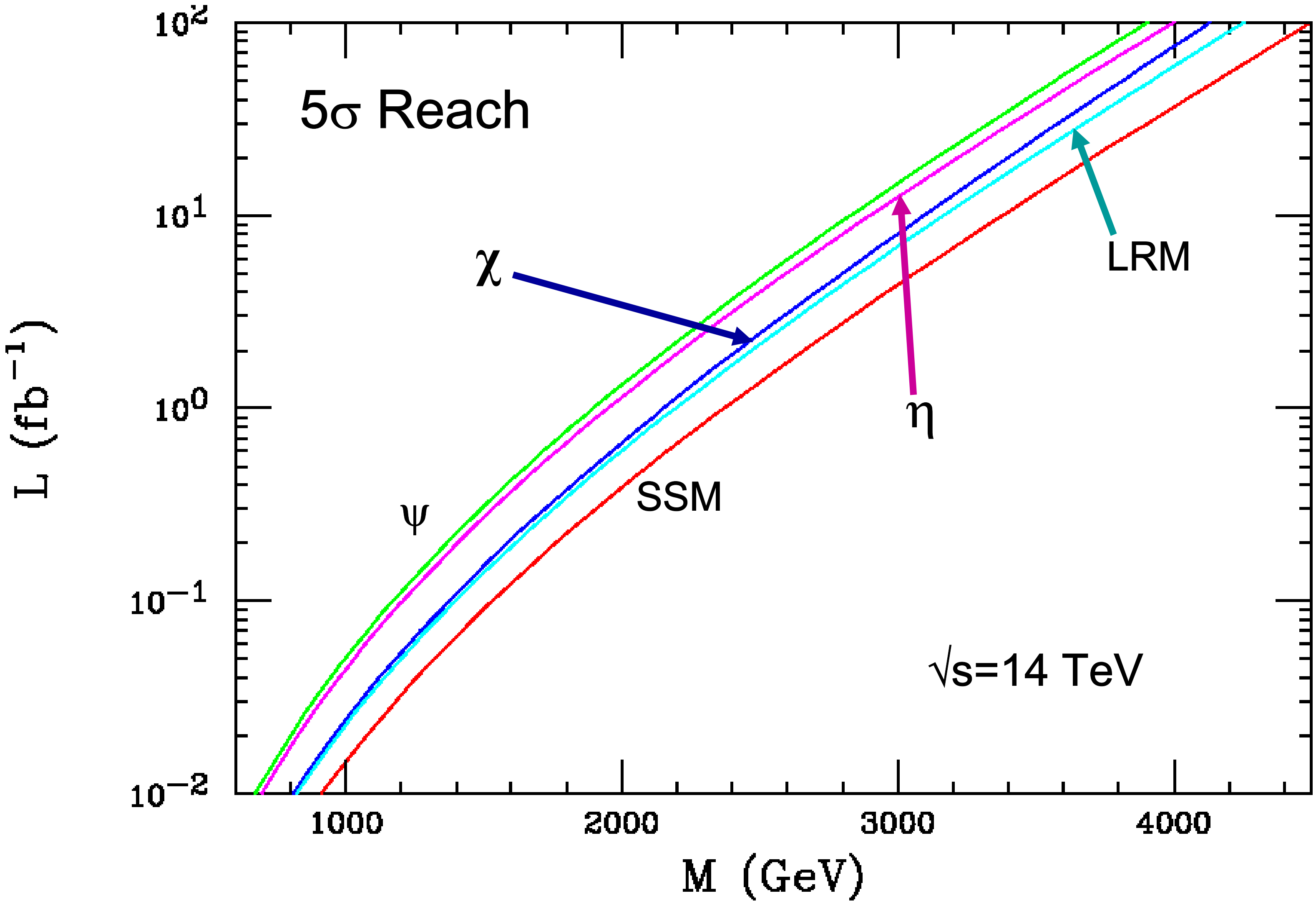


Z'_{SSM} Signal at Different √s With Low Luminosity




√s = 8 TeV → solid
√s = 6 TeV → dash
5σ
Discovery
L (fb^{-1})
M (GeV)
1.00
0.50
0.20
0.10
0.05
0.02
0.01
400
600
800
1000
1200
1400

Eventually the Z' 5σ reach will extend up to ~4-5 TeV and beyond for 'conventional' GUT-inspired models once sufficient lumi is accumulated….



Aside:

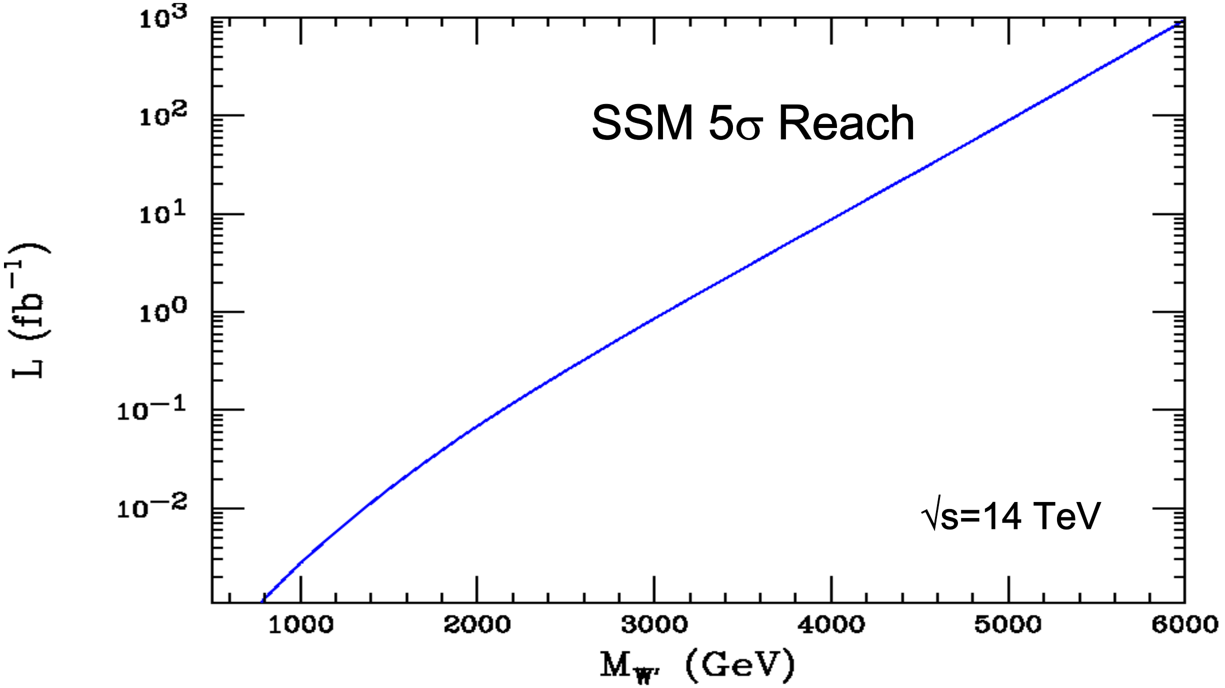
W'-like states are also important!

While we're discussing Z'-like states, let's not forget that there can also be corresponding W'-like states that occur in several of these same models…due to the missing E_T from neutrinos in the conventional Drell-Yan channel there is generally less information available to analyze in these cases (*unless* the RH neutrinos are heavy and their decays are also observed…)

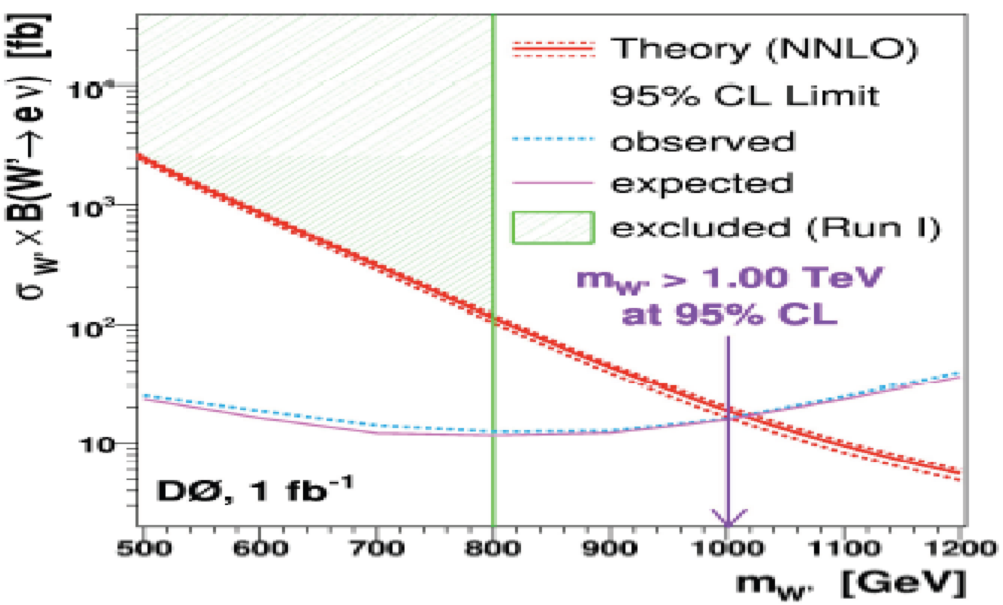
We may further subdivide the Z' classification above by whether or not a corresponding charged state also exists

The interplay of the measured W' and Z' properties, mass ratios etc., may provide critical information about the underlying model

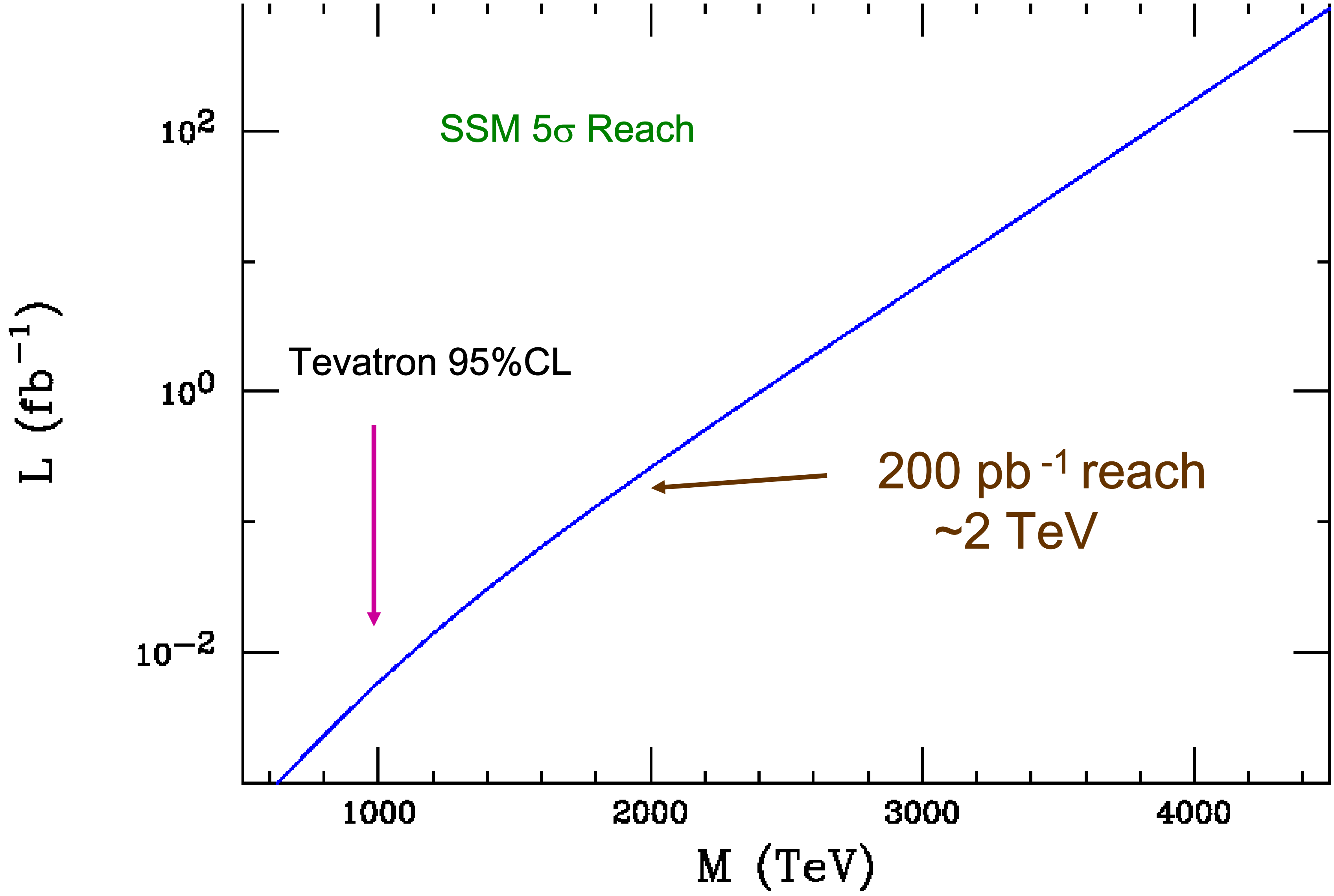
For ‘conventional W’ models’ the reach is even better….



Warning: the RH CKM is unknown in the LRM case..



Currently, the bound is M(W’-SSM) > 1.0 TeV from the Tevatron!



W’ Discovery at 10 TeV

If a resonance, X, is observed in the Drell-Yan channel, what do we want to know about it? Plenty!!

THE OBVIOUS BASICS

- lineshape: mass (M), cross section (σ), width (Γ), etc. → Is it really a Breit-Wigner?? → Detector resolution issues!

- spin = ??? Is it a graviton (S=2), a sneutrino (S=0) or a 'gauge boson' (S=1), or 'some combination'? → angular distribution of leptons

- Determine the couplings of X to the fields of the SM. (Note if $X \to \gamma\gamma$ then $S \neq 1$). Is there generation dependence? This is important if we want to access the underlying fundamental theory.

Unparticle Resonances : a non-Breit-Wigner example

$$\frac{1}{\Lambda^{d-1}}\bar{f}\gamma_\mu(c_{fL}P_L + c_{fR}P_R)\tilde{f}\mathcal{O}^\mu$$

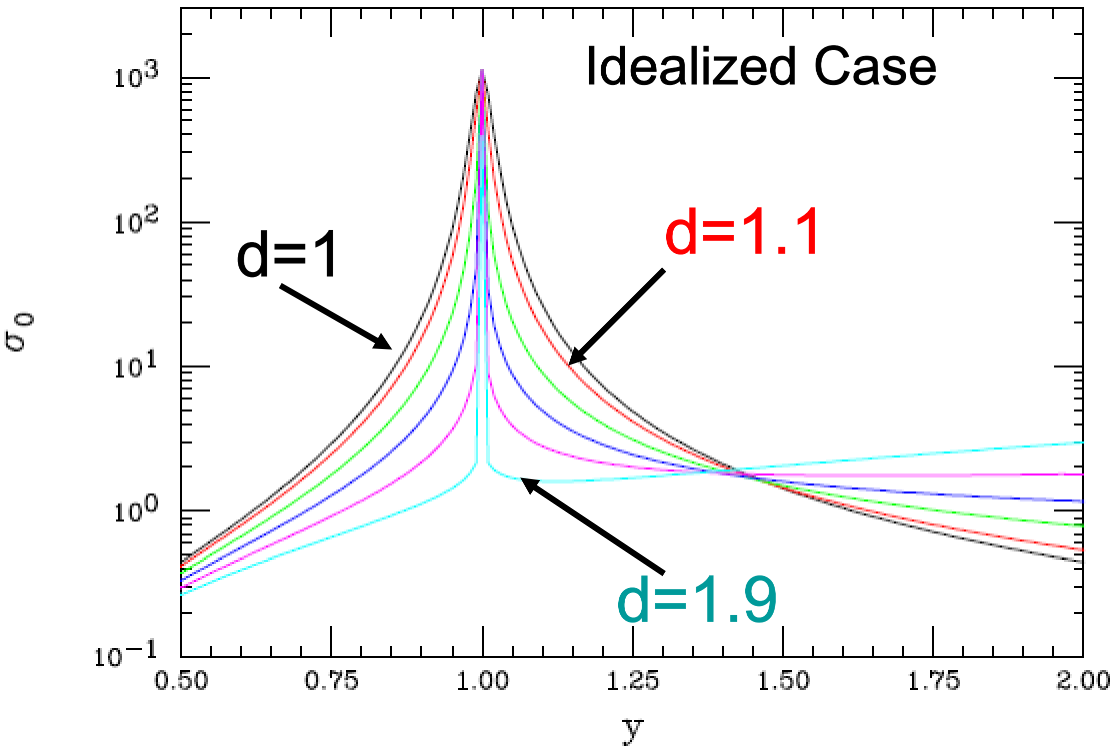
$$U = \frac{X_d P_d}{|\hat{s}-\mu^2|^{2-d} + iX_d P_d \tilde{G}},$$

Note!

$$\tilde{G} = \frac{c^2}{\Lambda^{2(d-1)}}\hat{s}\frac{\tilde{\Gamma}}{\mu}$$

$P_d = [1, e^{-i\pi(d-2)}]$ when $\hat{s}[<,>]\mu^2$,

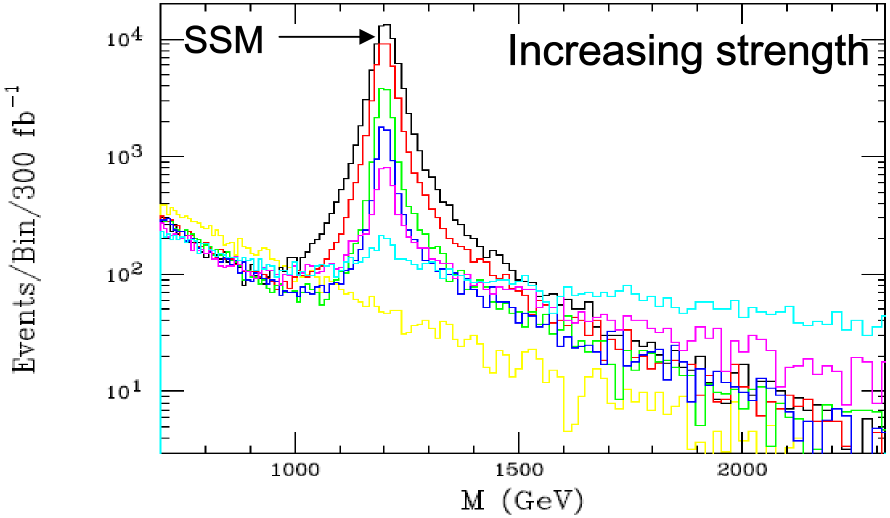
$$X_d = \frac{1}{2\sin d\pi}\,\frac{16\pi^{5/2}\Gamma(d+1/2)}{(2\pi)^{2d}\Gamma(2d)\Gamma(d-1)}$$

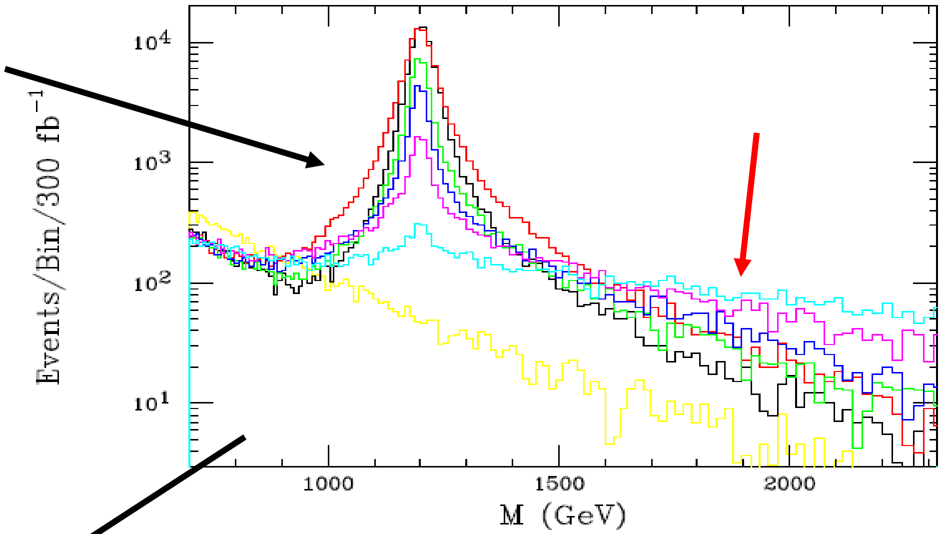


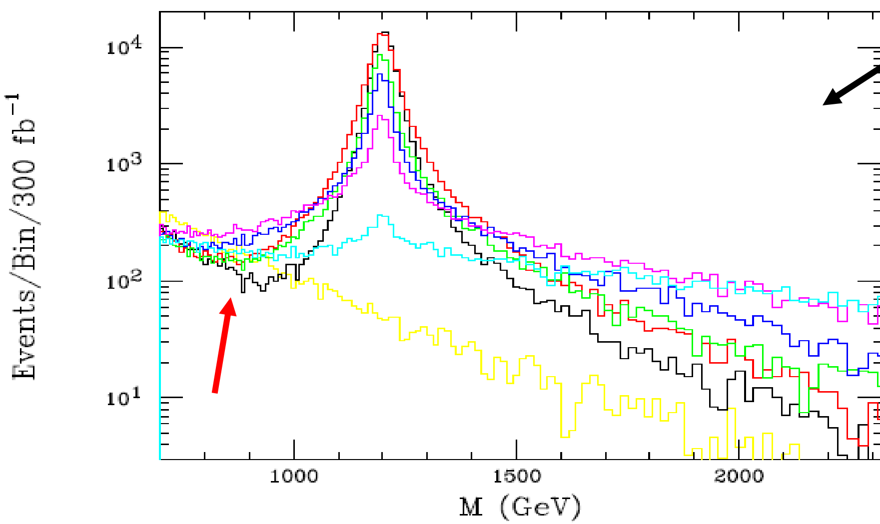
d=1 is a standard gauge boson.. but as d increases the resonance shape becomes distorted away from the familiar B-W….

Can this distortion be seen at the LHC?

arXiv:0809.4659







As the unparticle coupling, c, increases for fixed d, the non-B-W distortion also increases but is mostly visible in the tail after ~1% detector smearing. Note the suppression of interference below the peak for unparticles.

Recall that as d increases the unparticle becomes ‘narrower’ for the same reduced ‘width’ but this effect is washed away to some extent by the finite detector resolution.

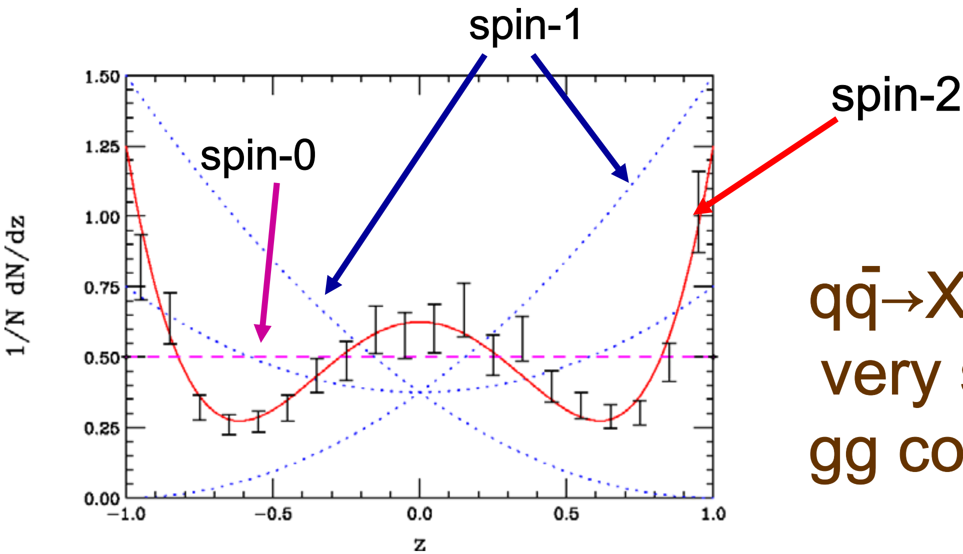
What can we conclude??

With enough luminosity, ~100 fb^{-1}, *if* the unparticle is sufficiently strongly coupled to SM fields and *if* the effective dimension, d, is sufficiently far from unity, it will be possible to state with some confidence that the resonance does not have a B-W lineshape.

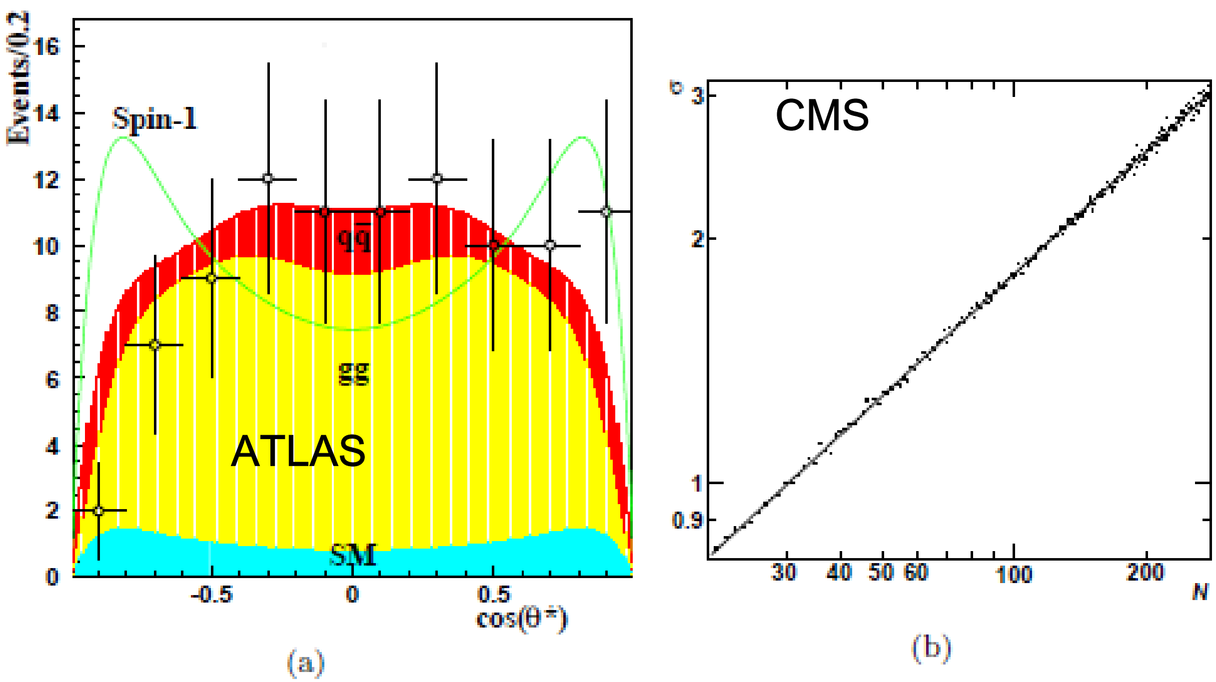
Due to detector resolution, it is possible that much of this information will come from the interference regime below the resonance peak as well as the tail of the distribution above it.

However, to say much more will require a more realistic detector-level study.

Resonance Spin



$q\bar{q} \rightarrow X \rightarrow l^+ l^-$ angular distributions are very sensitive to the spin of X, but gg contributions may be important too.

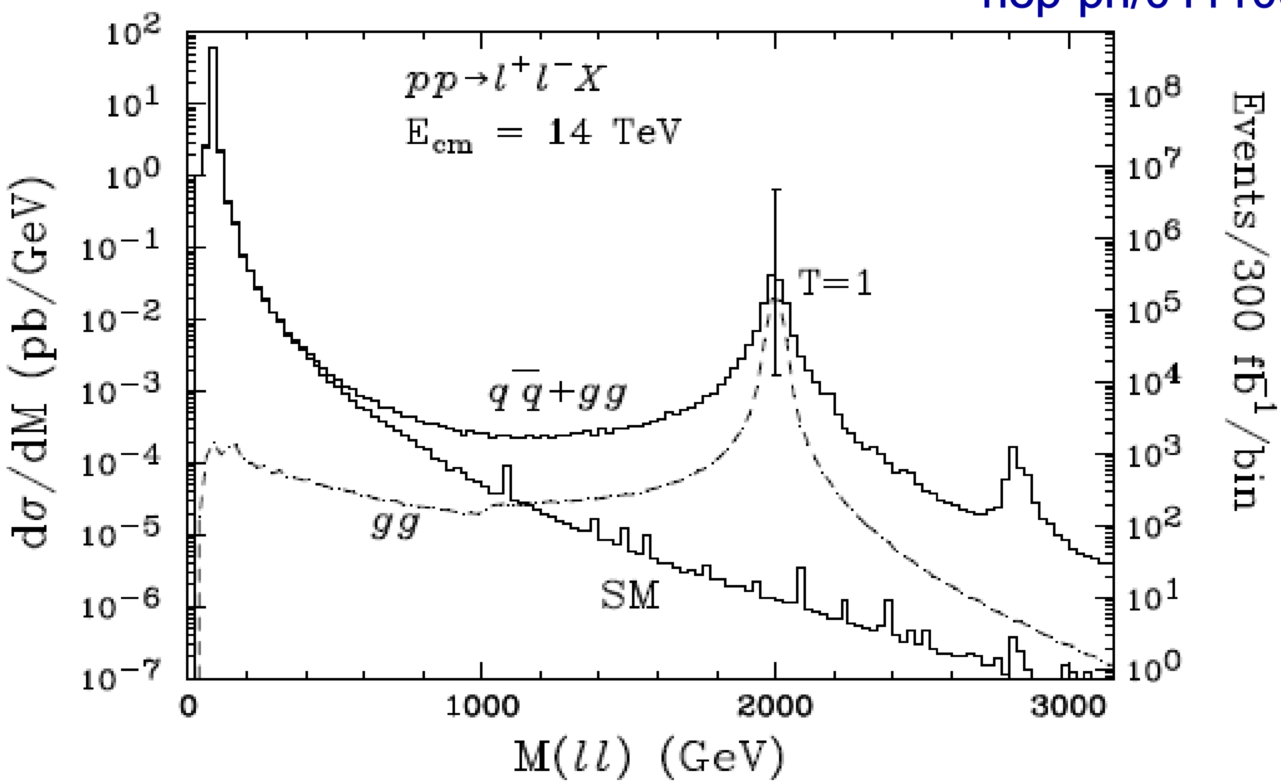


Differentiation of Z' vs KK-graviton at 1.5 TeV

Clearly, this is just a matter of statistics once a resonance is actually found requiring ~ 300-500 signal events. This may be difficult to obtain for heavy states above ~3 TeV

Careful!

hep-ph/0411094



String resonances, e.g., may be a 'combination' of several spin states being produced *simultaneously* with a complex weighting so that the angular distribution of the final state leptons may be more complicated….

If a spin-1, B-W object is found, what's next?

COUPLING DETERMINATIONS

How many independent couplings are there?? Even in the *simplest* possible scenario, where the Z' couples in a generation-independent manner and $[Q_{Z'}, SU(2)_L]=0$, there are 5 coupling constants to determine corresponding to the 5 SM fields Q, L, u^c, d^c & e^c. Are there enough observables at the LHC to uniquely determine these 5 quantities independently??

Unfortunately, it appears the answer is likely 'No'!!!

Remember also that we want to do this coupling determination with as few additional assumptions as possible, e.g., allowing for the possible decay of the Z' into non-SM final states.

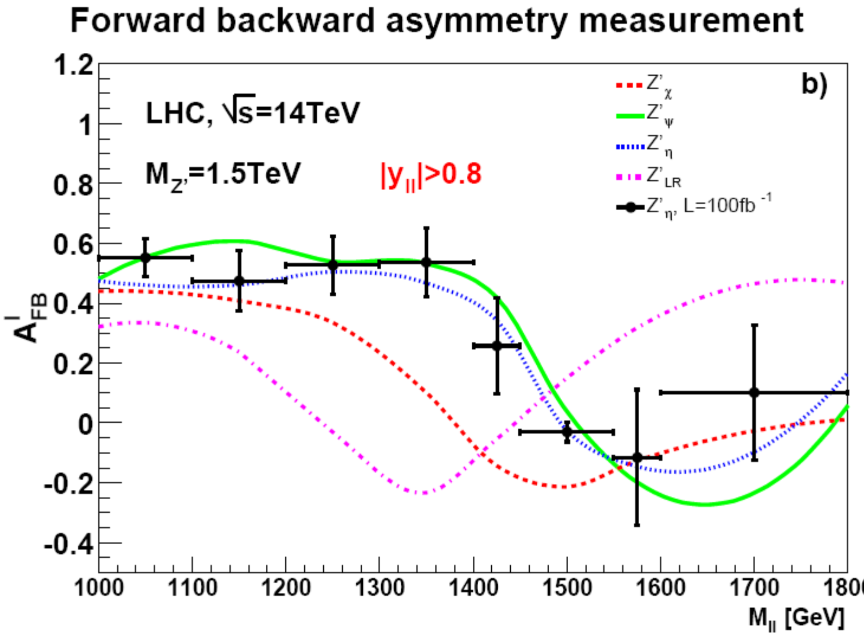
What observables do we have to perform this analysis???

• σ & Γ independently are sensitive to decay assumptions but the product σΓ ~ is *not.* This product can be determined at the ~ 5-10% uncertainty level at the LHC with high lumi for conventional models….

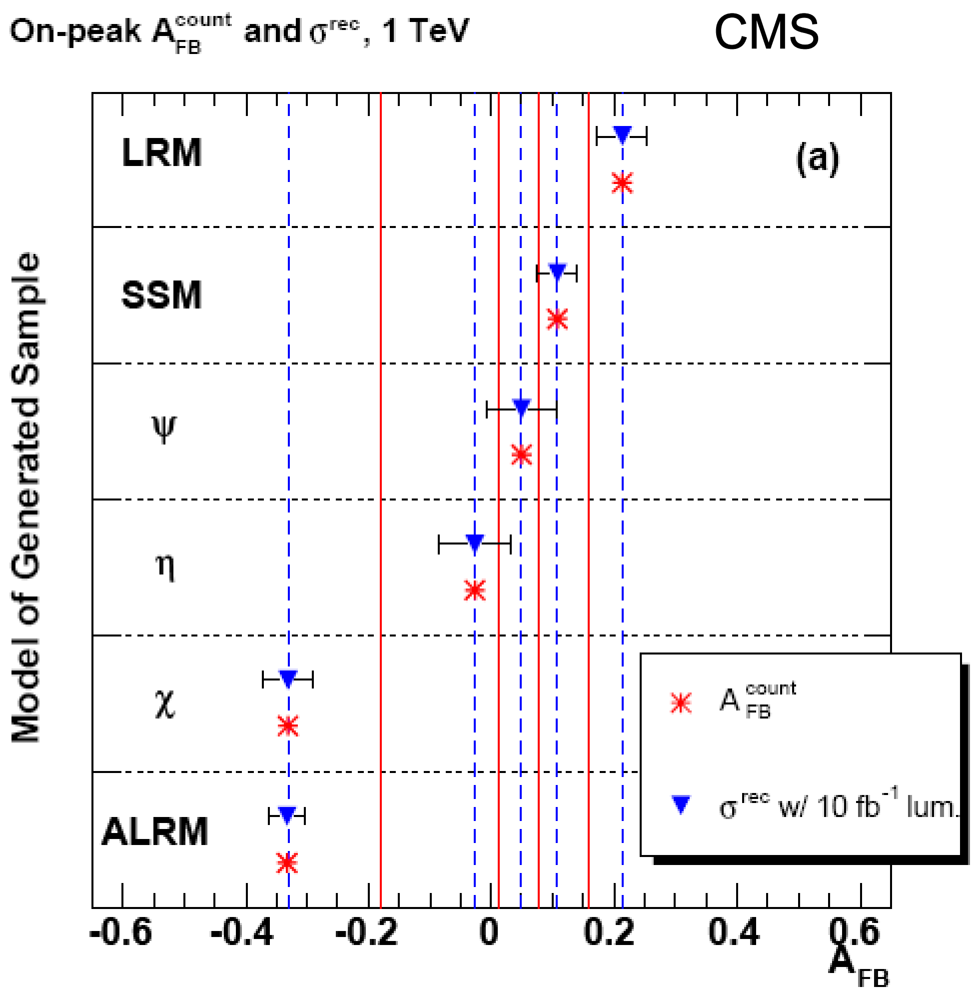
Table 1.2. Results on σ_{ll} and $\sigma_{ll} \times \Gamma_{Z'}$ for all studied models from ATLAS. Here one compares the input values from the generator with the reconstructed values obtained after full detector simulation.

		σ_{ll}^{gen} (fb)	σ_{ll}^{rec}(fb)	$\sigma_{ll}^{rec} \times \Gamma_{rec}$ (fb.GeV)
$M = 1.5$ TeV	SSM	78.4±0.8	78.5±1.8	3550±137
	ψ	22.6±0.3	22.7±0.6	166±15
	χ	47.5±0.6	48.4±1.3	800±47
	η	26.2±0.3	24.6±0.6	212±16
	LR	50.8±0.6	51.1±1.3	1495±72
$M = 4$ TeV	SSM	0.16±0.002	0.16±0.004	19±1
	KK	2.2±0.07	2.2±0.12	331±35

• A_{FB} both on- & off- resonance



M. Dittmar et al.



$$\frac{d\sigma}{d\cos\theta} \sim \frac{3}{8}(1+\cos^2\theta) + A_{FB}\cos\theta$$

ATLAS/CMS simulations indicate these can be reasonably well measured at the LHC:

ATLAS

Table 1.3. Measured on-peak A_{FB} for all studied models in the central mass bin from ATLAS. Here the raw value obtained before dilution corrections is labeled as 'Observed'.

Model	$\int \mathcal{L}(fb^{-1})$	Generation	Observed	Corrected
1.5 TeV				
SSM	100	$+0.088 \pm 0.013$	$+0.060 \pm 0.022$	$+0.108 \pm 0.027$
χ	100	-0.386 ± 0.013	-0.144 ± 0.025	-0.361 ± 0.030
η	100	-0.112 ± 0.019	-0.067 ± 0.032	-0.204 ± 0.039
η	300	-0.090 ± 0.011	-0.050 ± 0.018	-0.120 ± 0.022
ψ	100	$+0.008 \pm 0.020$	-0.056 ± 0.033	-0.079 ± 0.042
ψ	300	$+0.010 \pm 0.011$	-0.019 ± 0.019	-0.011 ± 0.024
LR	100	$+0.177 \pm 0.016$	$+0.100 \pm 0.026$	$+0.186 \pm 0.032$
4 TeV				
SSM	10000	$+0.057 \pm 0.023$	-0.001 ± 0.040	$+0.078 \pm 0.051$
KK	500	$+0.491 \pm 0.028$	$+0.189 \pm 0.057$	$+0.457 \pm 0.073$

On- & off-peak 'measurements' of A_{FB} by ATLAS with large integrated luminosities

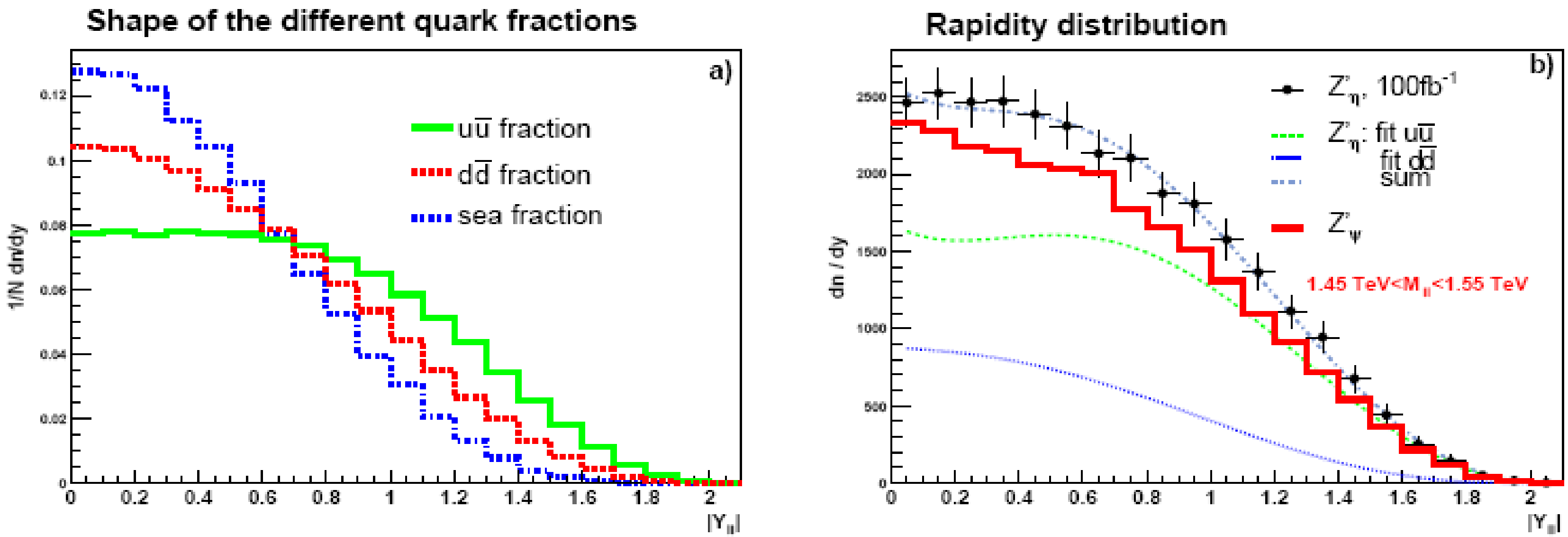
Table 1.4. Measured off peak, $0.8 < M < 1.4$ TeV, A_{FB} for all studied models from ATLAS using the same nomenclature as above.

Model	$\int \mathcal{L}(fb^{-1})$	Generation	Observed	Corrected
1.5 TeV				
SSM	100	$+0.077 \pm 0.025$	$+0.086 \pm 0.038$	$+0.171 \pm 0.045$
χ	100	$+0.440 \pm 0.019$	$+0.180 \pm 0.032$	$+0.354 \pm 0.039$
η	100	$+0.593 \pm 0.016$	$+0.257 \pm 0.033$	$+0.561 \pm 0.039$
ψ	100	$+0.673 \pm 0.012$	$+0.294 \pm 0.033$	$+0.568 \pm 0.039$
LR	100	$+0.303 \pm 0.022$	$+0.189 \pm 0.033$	$+0.327 \pm 0.040$

Note the large errors in the off-peak values due to small statistics

- Rapidity distributions

M. Dittmar et al.



(a) (b)

$$R = \frac{\int_{-y_1}^{y_1} \frac{d\sigma}{dy}\, dy}{\left[\int_{y_1}^{Y} + \int_{-Y}^{-y_1} \frac{d\sigma}{dy}\, dy\right]}.$$

or fit to R_{qq}, the event fraction from a given $q\bar{q}$ initial state…

ATLAS

	Generation level Fitted values (%)		Reconstruction level Fitted values (%)	
Model	Prop(Z'←dd)	Prop(Z' ←uu)	Prop(Z'←dd)	Prop(Z'←uu)
SSM	41.±10.	52.±12.	22.±16.	60.±16.
χ	62.±12.	29.±14.	79.±17.	17.±19.
η	23.±13.	75.±14.	33.±6.	67.±8.
ψ	36.±12.	61.±13.	32.±15.	62.±17.
LR	57.±4.	43.±14.	53.±13.	46.±15.

Fig. 1.13. Comparison of $R_{q\bar{q}}$ values determined at the generator level and after detector simulation by ATLAS.

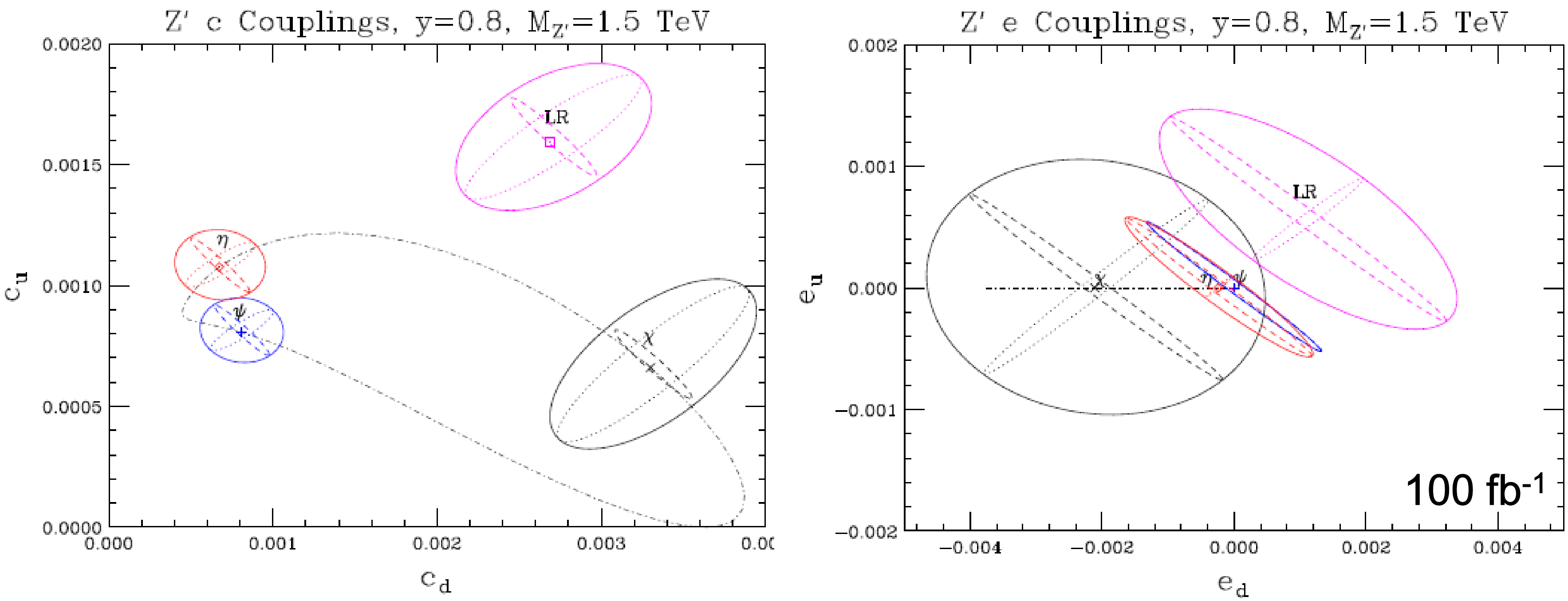
To first approximation these observables really *only* probe the 4 coupling combinations

Carena et al.

$$c_q = \frac{M_{Z'}}{24\pi\Gamma}(q_R^2 + q_L^2)(e_R^2 + e_L^2) \qquad \text{for } q=u,d$$

$$e_q = \frac{M_{Z'}}{24\pi\Gamma}(q_R^2 - q_L^2)(e_R^2 - e_L^2)$$

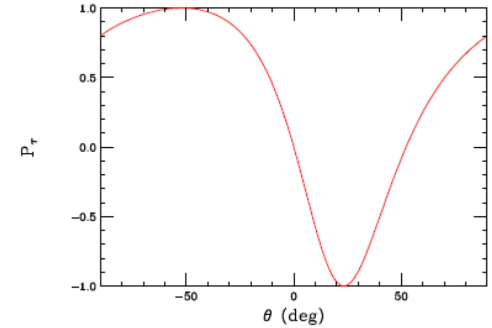
Petriello & Quackenbush



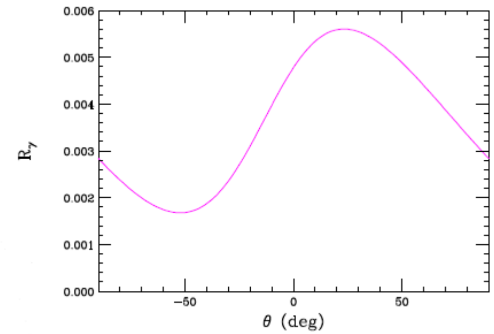
which can be reasonably well determined in a simultaneous fit ...even including NLO QCD contributions

Other Possible Z' Observables For Coupling Determinations

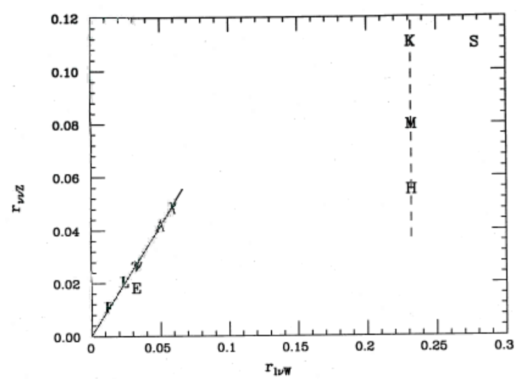
- Z' $\to \tau\tau$ polarization measurement



- Associated on-shell Z' + (W,Z,γ) production



- Rare Decays: Z' $\to \bar{f} f' V$ (V = W,Z; f = l,ν)
- Z' $\to$ WW, Zh
- Z' $\to \bar{b}b$, $\bar{t}t$



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

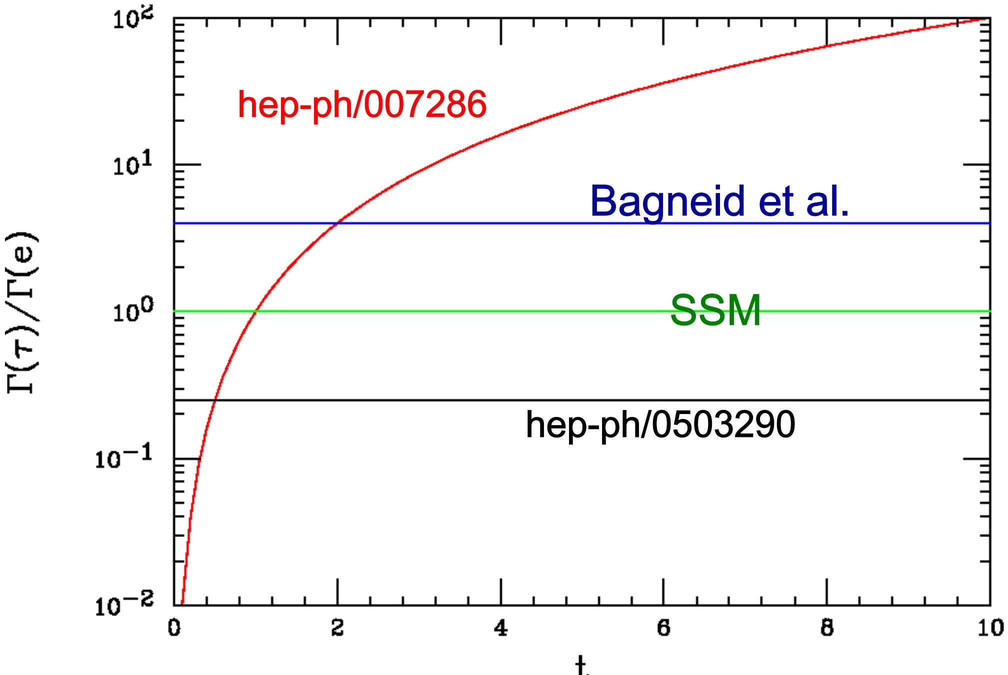
Generation-Dependent Couplings

- These are common, e.g., for KKs in ED setups (i.e., RS)

- It is very likely that e-μ universality will be reasonably well satisfied by any new resonances but will be easily tested.

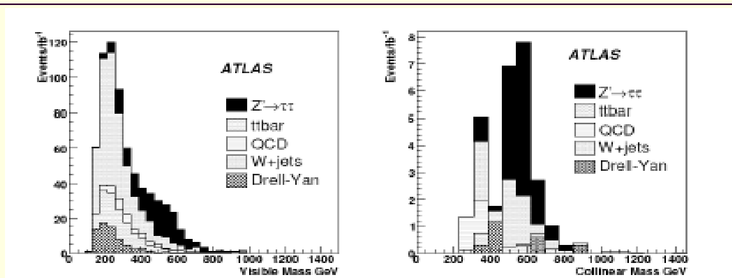
- The real issue is with the models which treat the third generation, i.e., τ's, differently. These are more difficult to see due to both reduced efficiencies as well as the larger SM backgrounds

- It is important to measure how badly universality is violated, is it ~10% or is it O(1) as these can possibly point to very different classes of underlying models.



Various models predict a wide range of values for the ratio of 3rd to 1st generation branching fractions.. Both enhancements and suppressions are possible.

$Z' \rightarrow \tau\tau \rightarrow \ell h$: ATLAS studied the case of 600 GeV Z' with 1 fb^{-1} collected data



Once an excess is observed, the collinear approximation helps to measure the mass of the resonance

Selection	Signal	$t\bar{t}$	Drell-Yan	Multijet	W+jet
Trigger	1356.	213600.	2.3950 10^7	4.19000 10^6	6.69400 10^6
Lepton	905.	150900.	1.2600 10^7	1.08230 10^6	120400.
τ selection	368.	7818.	145680	40080	4587.
Opposite charge	315.	2498.	5306	23240	771.
$\not{E}_T > 30$ GeV	270.	2040.	2562	835	162.
$m_T < 35$ GeV	203.2	302.4	388.0	436.4	83.8
$p_T^{tot} < 70$ GeV	155.0	106.7	331.5	221.6	28.4
$m_{vis} > 300$ GeV	132.5	26.2	105.6	33.8	15.0
$\cos\Delta\phi_{\ell h} > -.99$	13.3	2.1	5.5	2.3	2.7

$$S/\sqrt{B} = 9.9$$

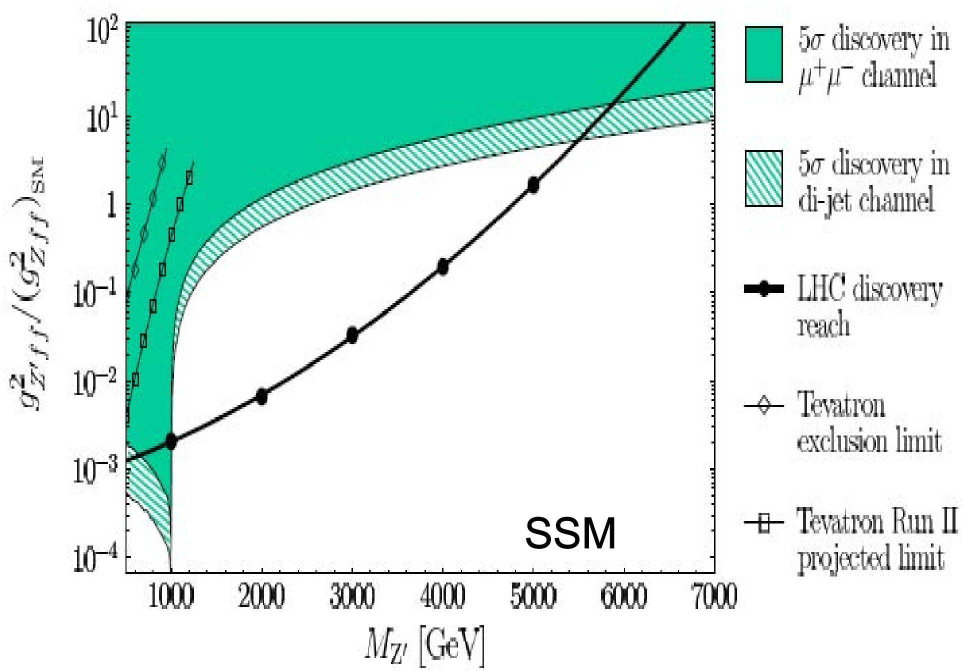
1 August 2008 ICHEP08 Paolo SPAGNOLO 8

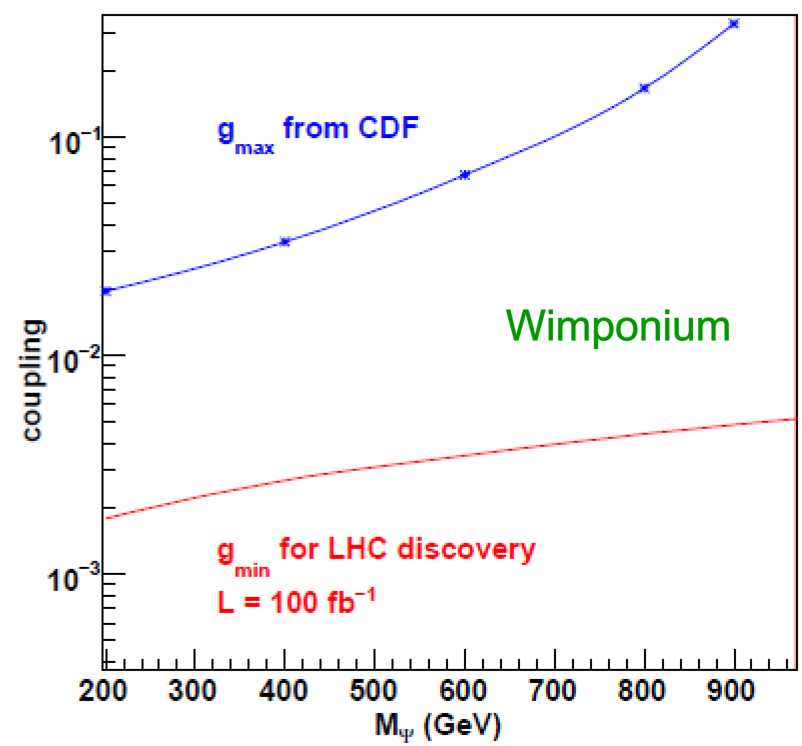
LHC studies indicate that Z' to τ pairs is not always so easy but lots of statistics is helpful. The relative branching fraction for this mode may then be difficult to determine for heavy states

Weakly Coupled (to the SM) Resonances

Lighter DY resonant states may exist with masses below ~1 TeV that are so weakly coupled that they get missed at the Tevatron due to poor S/√B but can still can show up at the LHC…

0901.2125





hep-ph/0403288

- Generally weakly coupled → narrow with small cross section, e.g., 2nd KKs in UED, Stueckelberg Z' or Wimponia

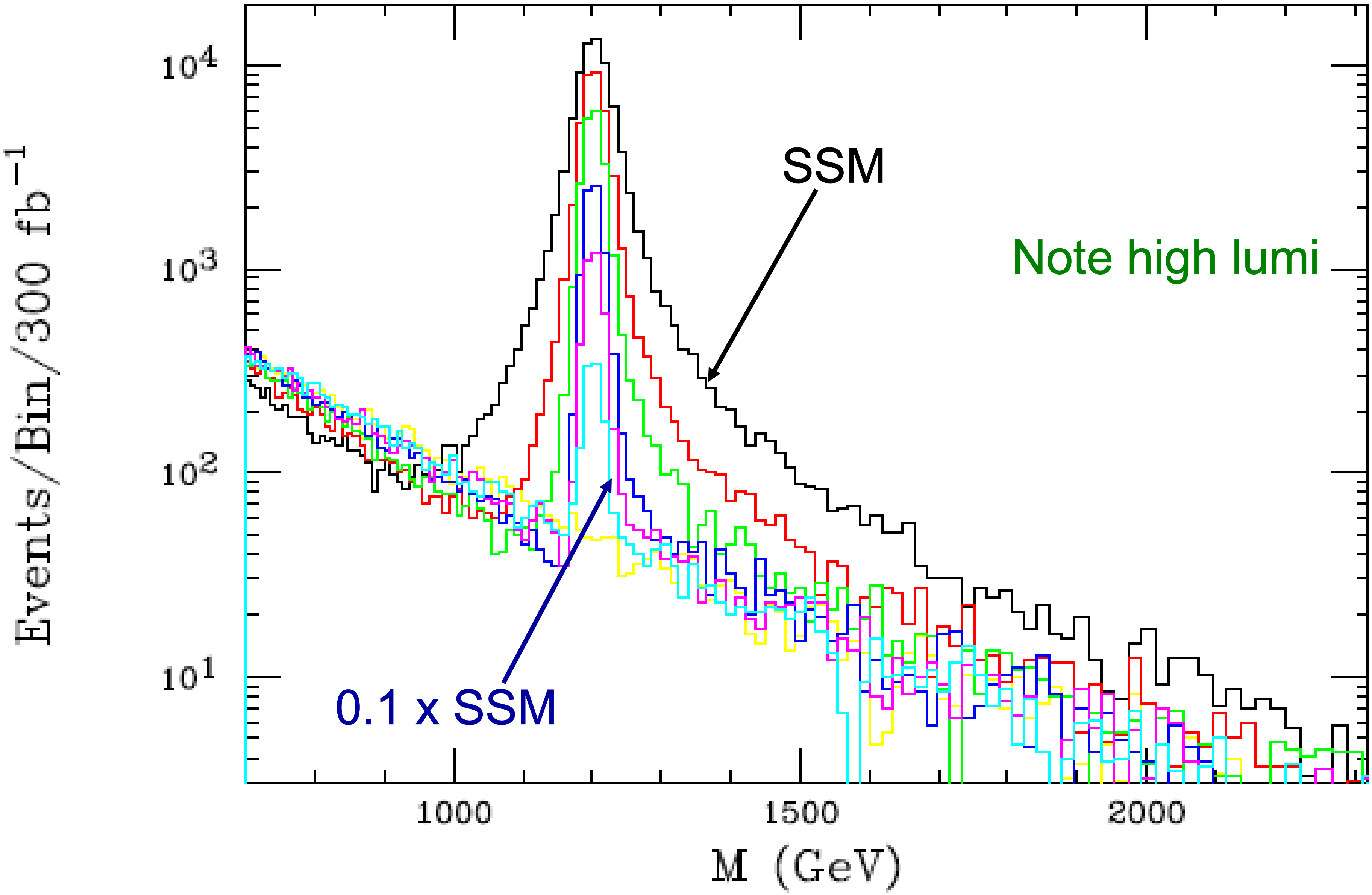
- 'Normally' coupled to a hidden sector → 'standard' width but small cross section, e.g., Hidden Valley models

In many cases the SM couplings are induced by either mass mixing via Higgs fields, in which case the resonance looks like a SSM Z' with scaled-down couplings, or via gauge kinetic mixing:

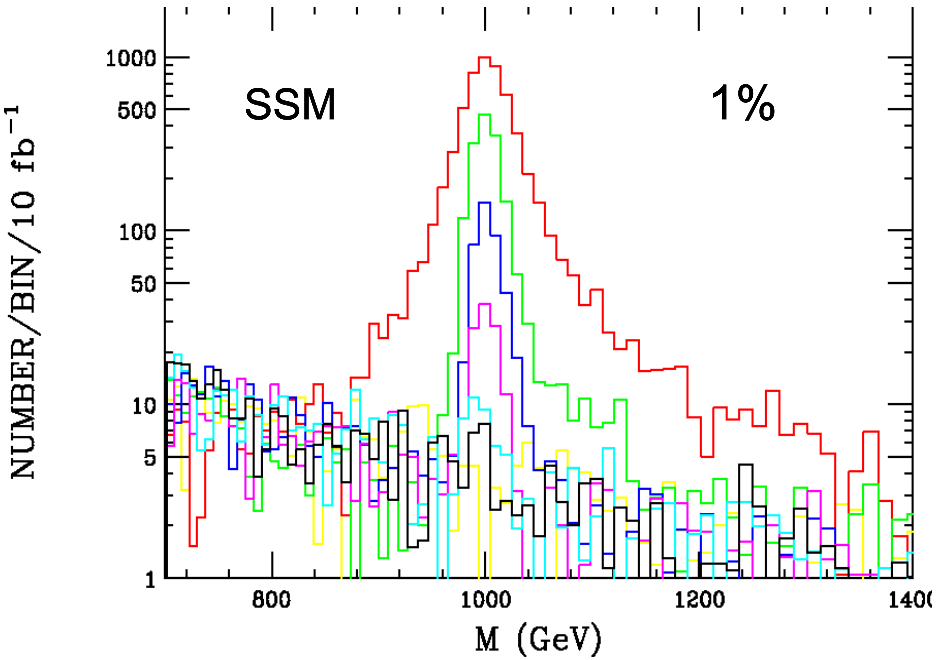
$$\mathcal{L}_K = -\frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}\bar{B}_{\mu\nu}\bar{B}^{\mu\nu} - \frac{1}{4}\bar{Z}'_{\mu\nu}\bar{Z}'^{\mu\nu} - \frac{\sin\chi}{2}\bar{Z}'_{\mu\nu}\bar{B}^{\mu\nu}$$

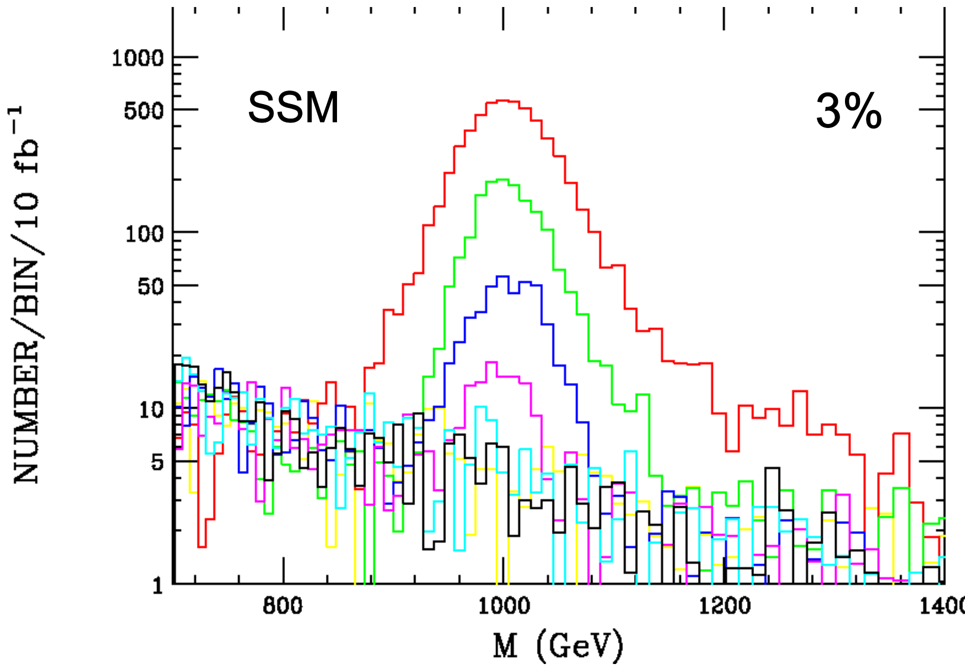
The coupling is then ~ $g_Y Y \sin\chi$, i.e., weakly coupled to hypercharge. This also happens for the Stueckelberg Z'.

If the coupling is not too small the Z’ will still be easily seen provided it is not too massive..

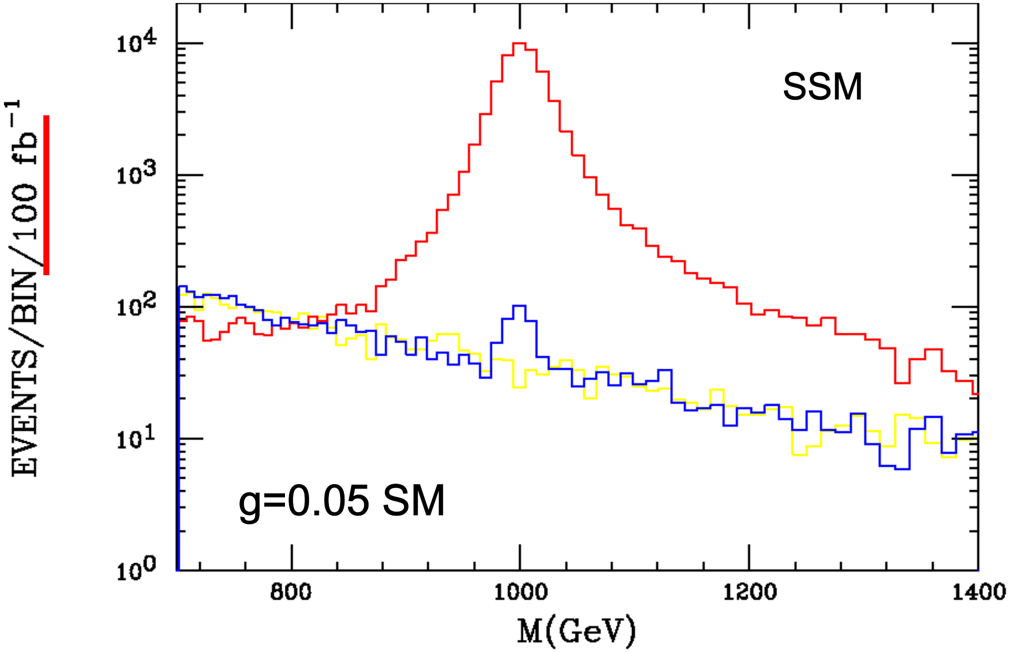


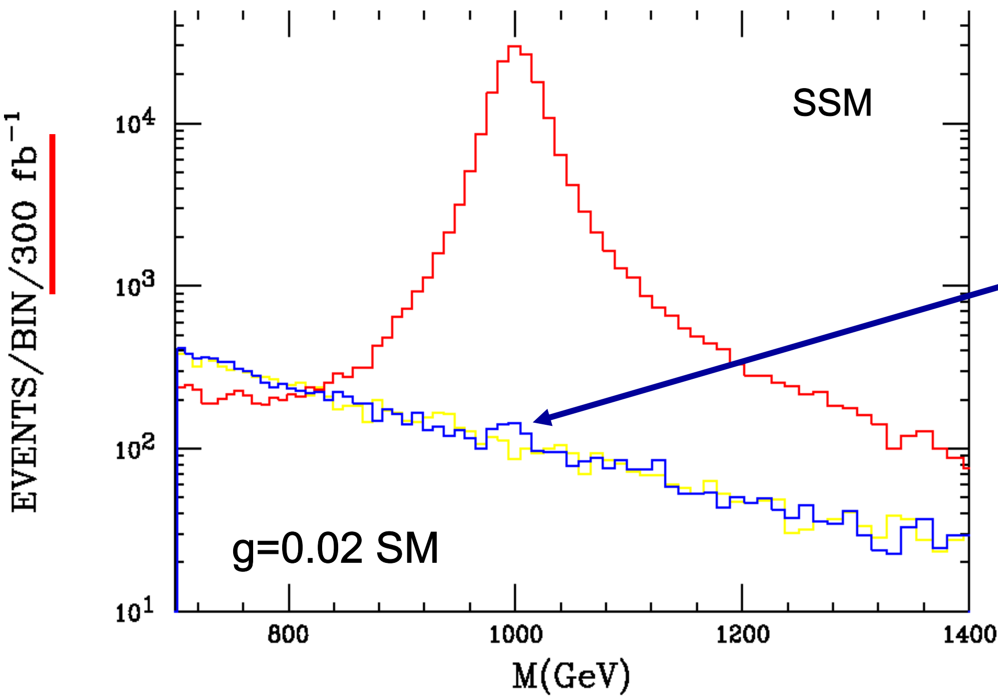
For low lumi the situation is much more difficult especially if the dilepton mass resolution is poor..





SSM with each lower histogram coupling ½ of the previous one. One can argue whether or not the 1/16 case is visible assuming this lumi & a 1% mass resolution (no), but it clearly is not in the 3% case.





Looking at this another way..

at high luminosity rather small values of scaled SSM couplings can be accessible if the Z’ is not too heavy.

But at some point we just run out of steam

The problem can much more severe for even smaller couplings or for heavier states…

hep-ph/0606183

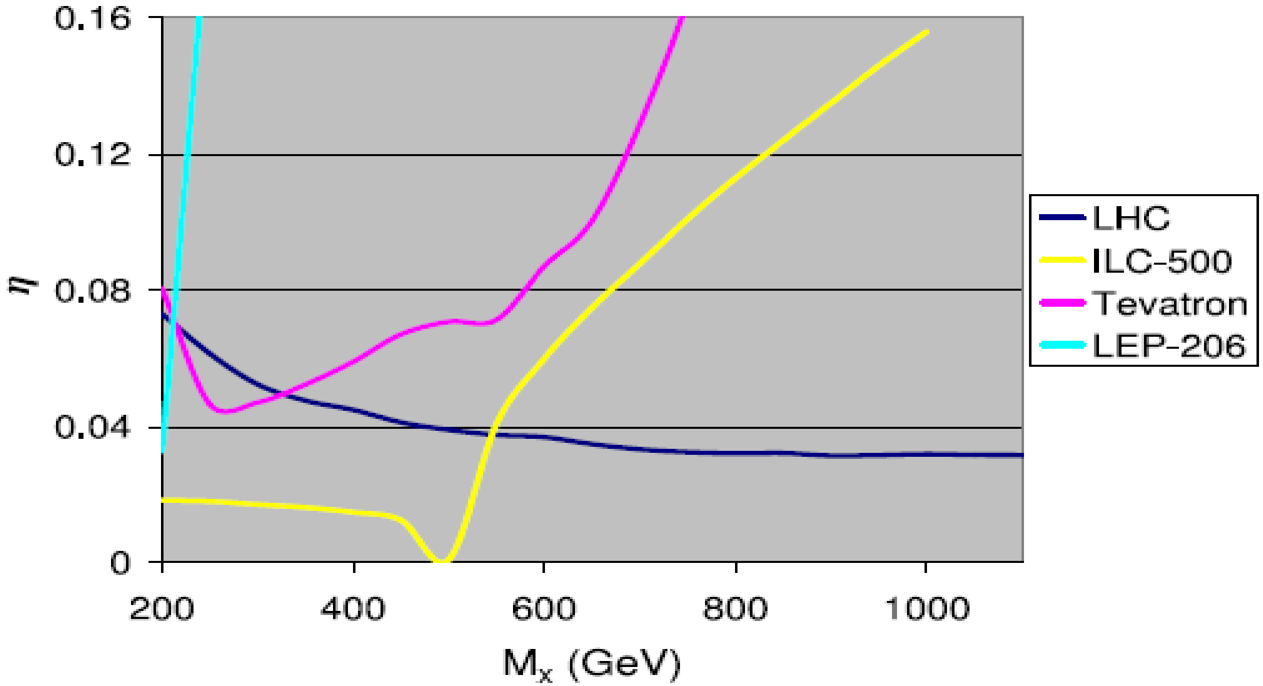
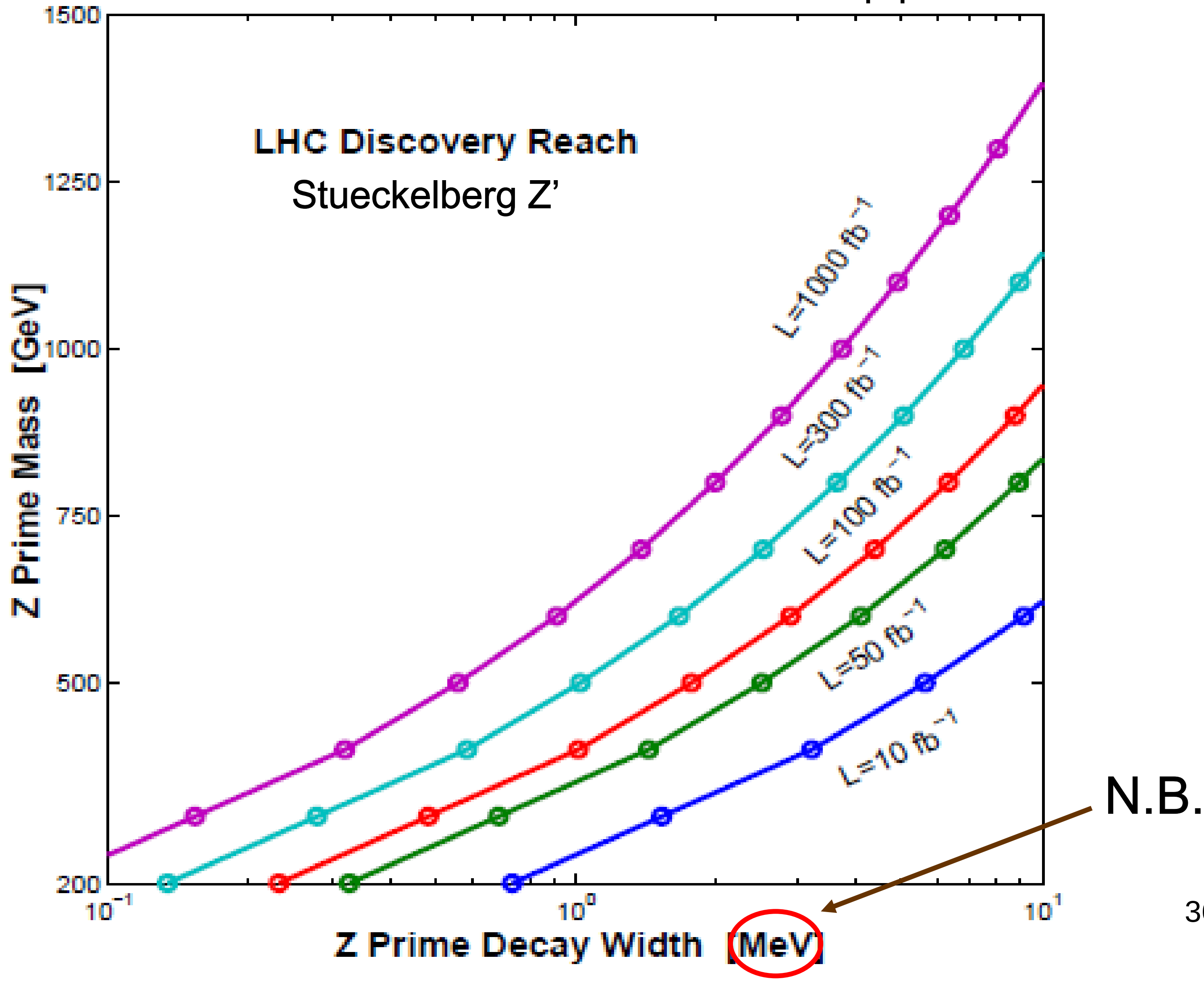


FIG. 4: Detection plot of estimated 5σ confidence level of X-boson that kinetically mixes with hypercharge. Detection for Tevatron ($8\,\mathrm{fb}^{-1}$), LHC ($100\,\mathrm{fb}^{-1}$), LEP ($\sqrt{s} = 206\,\mathrm{GeV}$ and $725\,\mathrm{pb}^{-1}$), and ILC ($\sqrt{s} = 500\,\mathrm{GeV}$ and $500\,\mathrm{fb}^{-1}$) can occur at points above their respective lines.

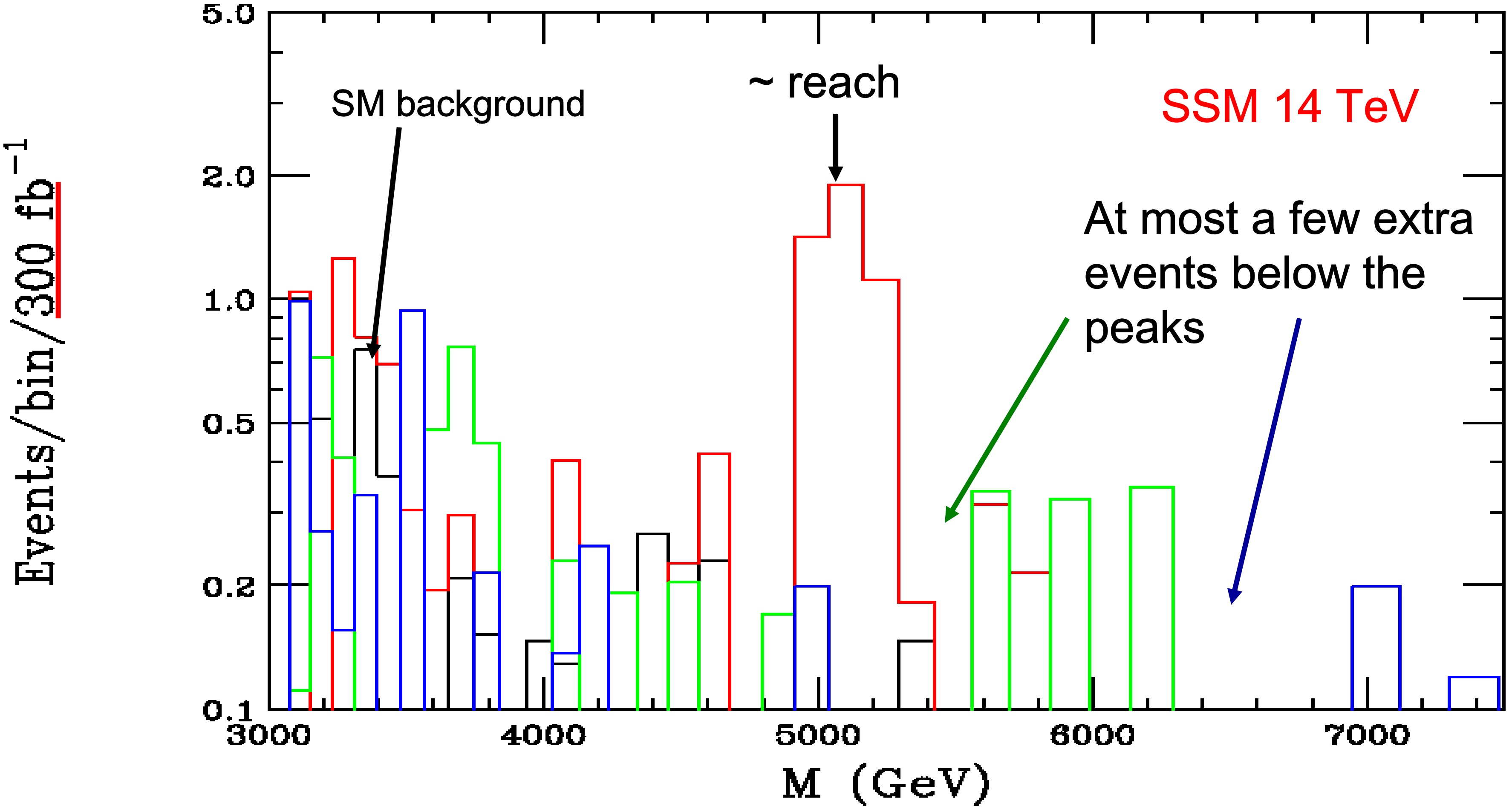
…and similarly..

hep-ph/0606249



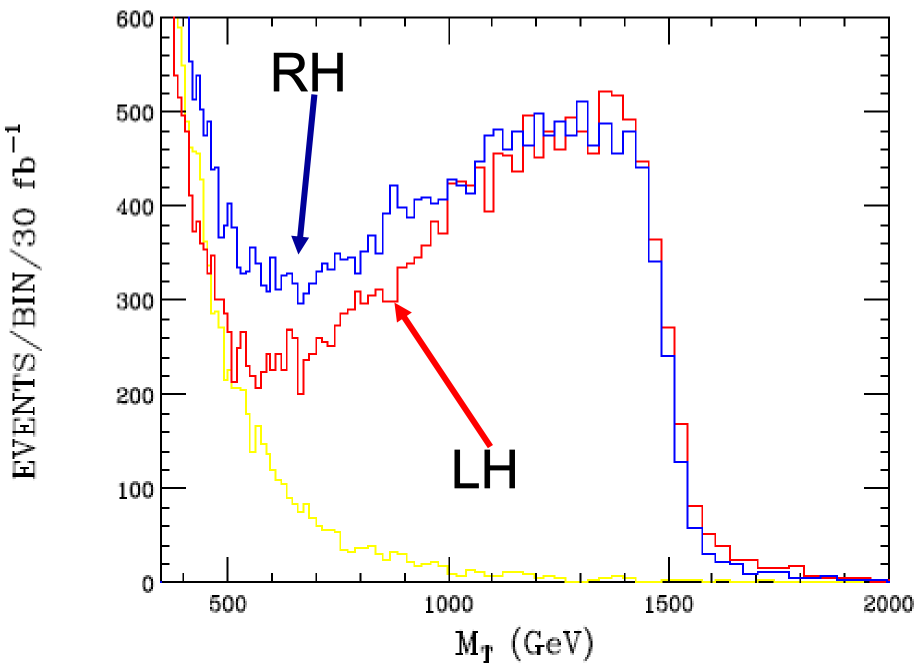
Indirect Z' Searches at LHC??

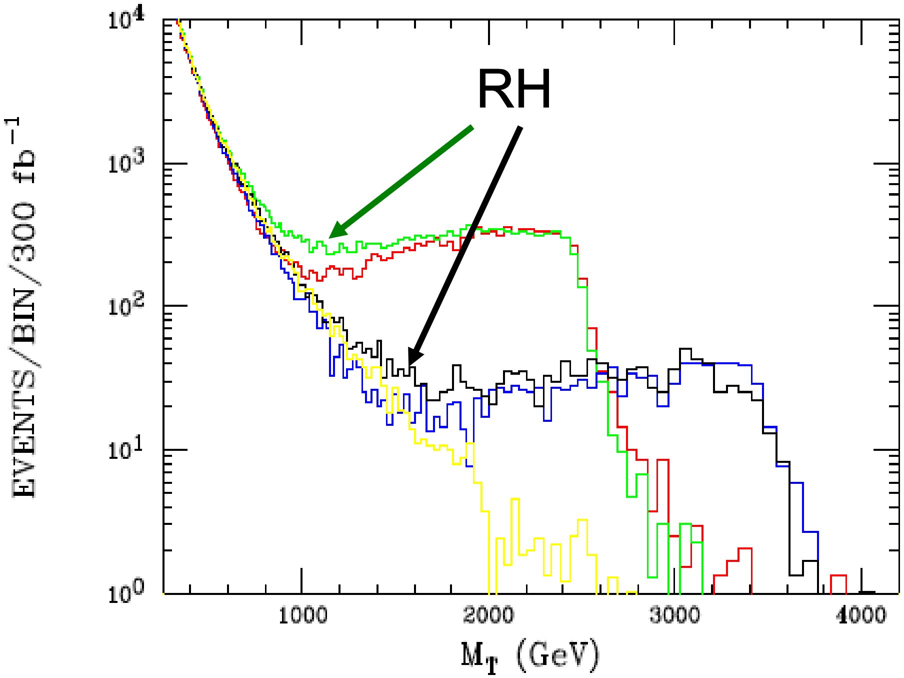
Can we observe a Z' below threshold at the LHC by 'contact-interaction-like' deviations in the cross section?? No statistics there to see any effect!



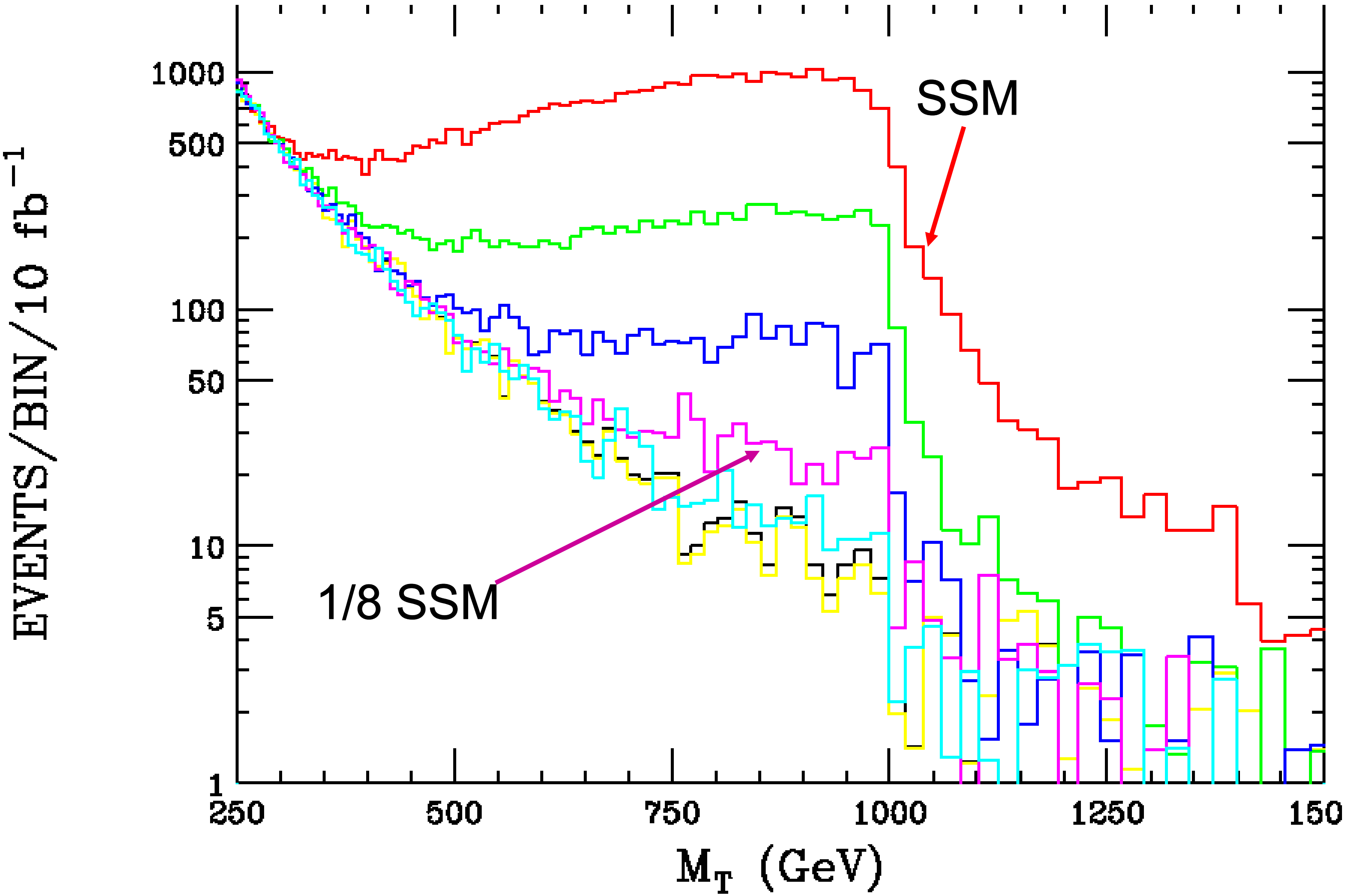
W' Coupling Helicity

- W' are usually chiral so the most critical issue is to determine the handedness of its couplings to SM fermions
- This cannot be done on the 'peak' of the transverse mass distribution BUT can be done in the W-W' interference region given enough integrated luminosity





A W' with small couplings will also have some visibility issues…



LHeC

Polarized $e^{\pm}p$ collisions in the $1.5 < \sqrt{s} < 2$ TeV range…
Can these be used to get new coupling info on the Z' while we wait for a linear collider? Is there any Z' coupling sensitivity?

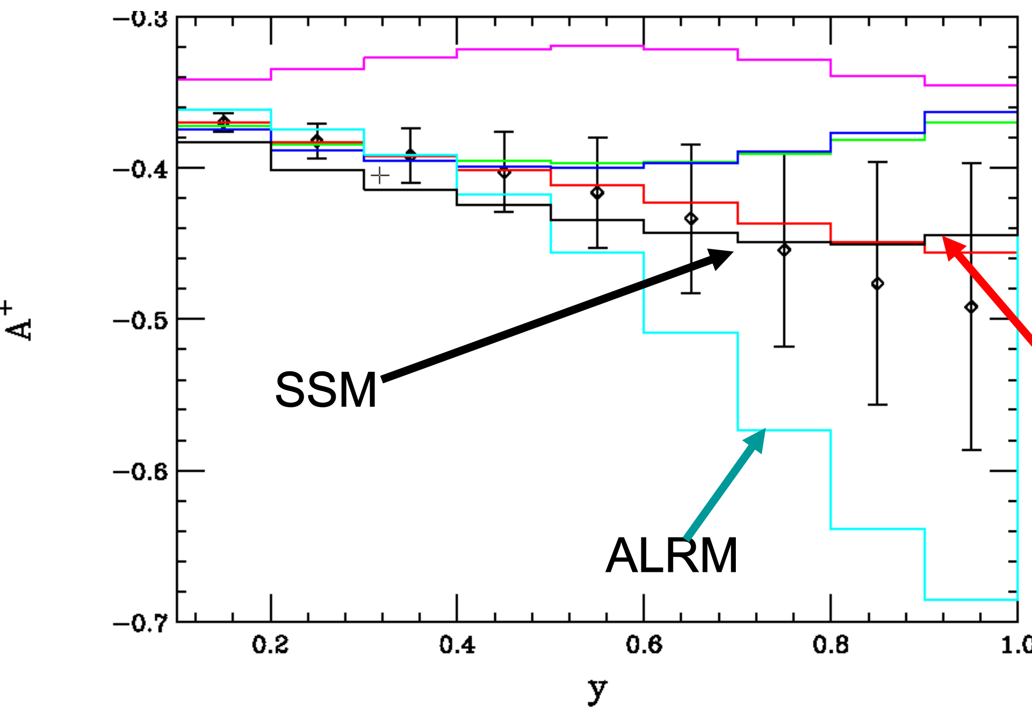
Technique: form polarization asymmetries to reduce systematics & PDF uncertainties. Apply (x,y,Q^2) cuts to increase sensitivity & then integrate over the remaining x range, plot vs y.

$$A^{\pm} = \frac{d\sigma(e^{\pm}_L) - d\sigma(e^{\pm}_R)}{d\sigma(e^{\pm}_L) + d\sigma(e^{\pm}_R)}$$

These asymmetries are found to have a completely different dependence on the Z' couplings than do the Drell-Yan observables at the LHC itself

$$C_{L,R} = \frac{d\sigma(e^{-}_{L,R}) - d\sigma(e^{+}_{L,R})}{d\sigma(e^{-}_{L,R}) + d\sigma(e^{+}_{L,R})}$$

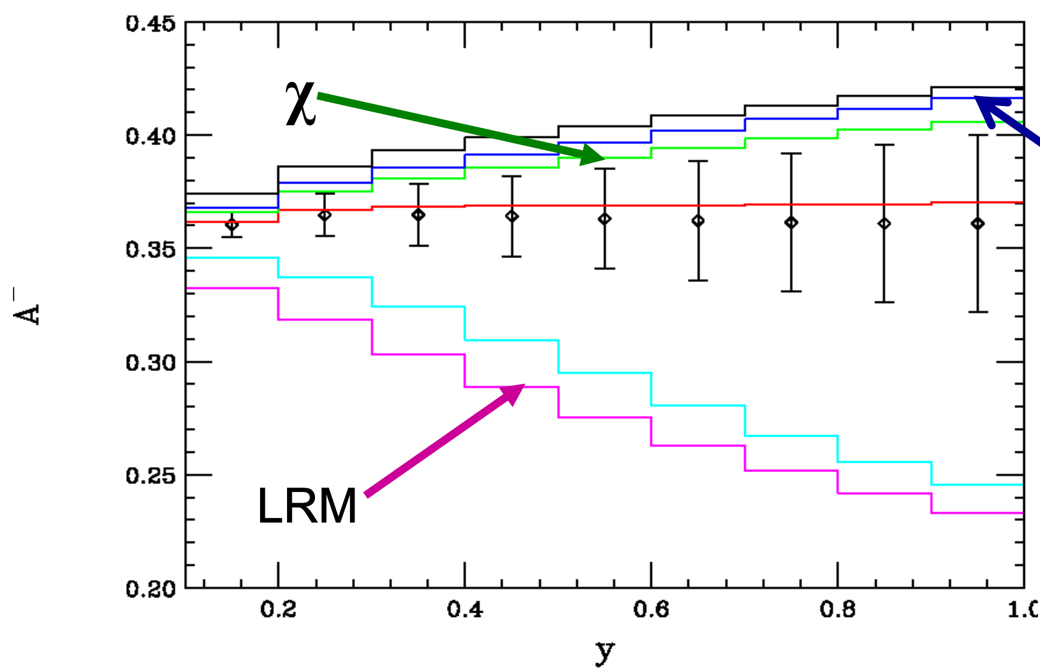
$$B_{1,2} = \frac{d\sigma(e^{-}_{L,R}) - d\sigma(e^{+}_{R,L})}{d\sigma(e^{-}_{L,R}) + d\sigma(e^{+}_{R,L})}$$



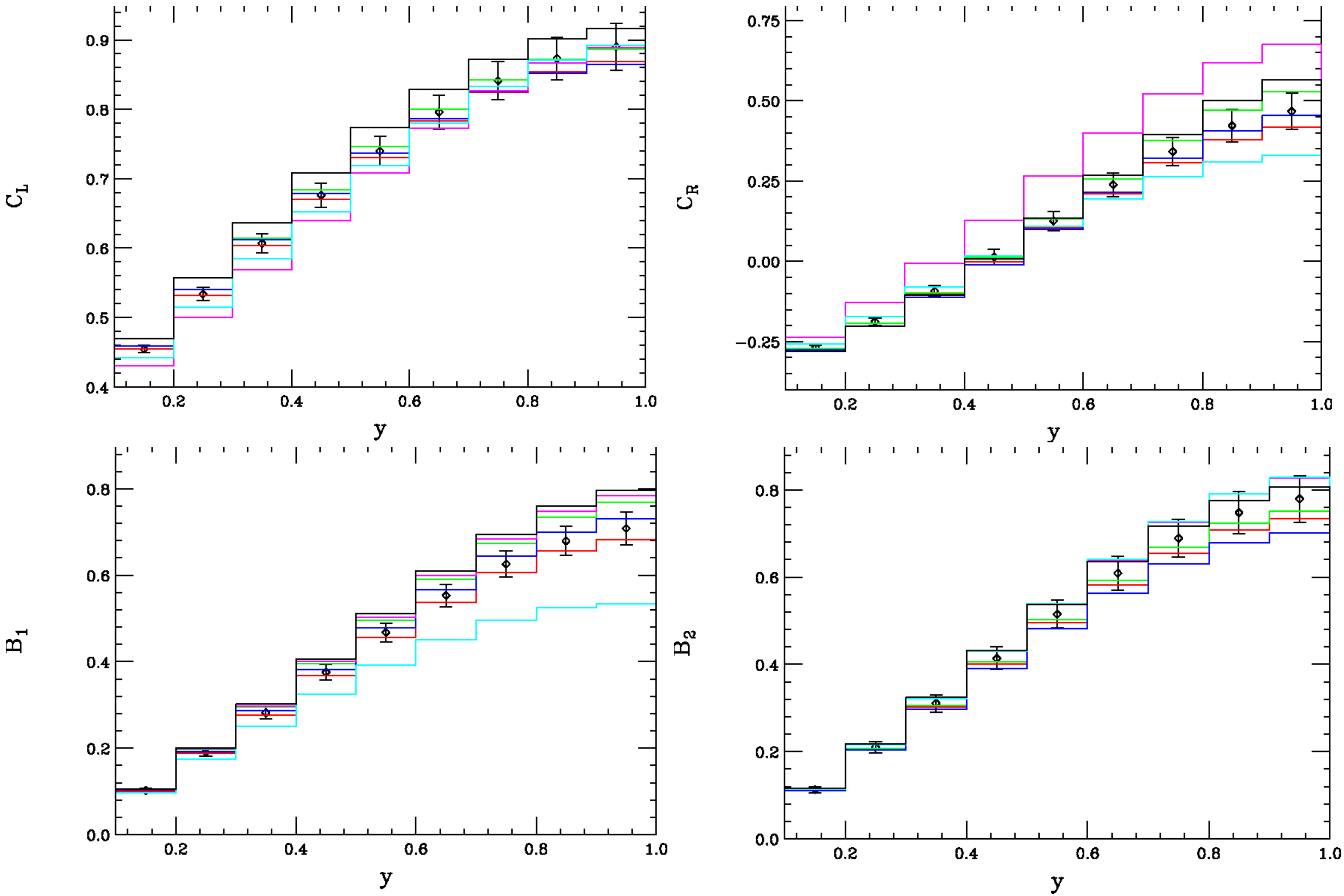
Example: $M_{Z'}$ = 1.2 TeV
with ep @ √s = 1.5 TeV
'data'=SM prediction

Need beam polarization
& high luminosity

We'll use GUT-inspired models for demonstration purposes



Clearly these variables show substantial coupling sensitivity



Different asymmetries show a wide range of various sensitivities to Z' couplings but only 4 of them are independent…

ILC Indirect Search Reach for Z'

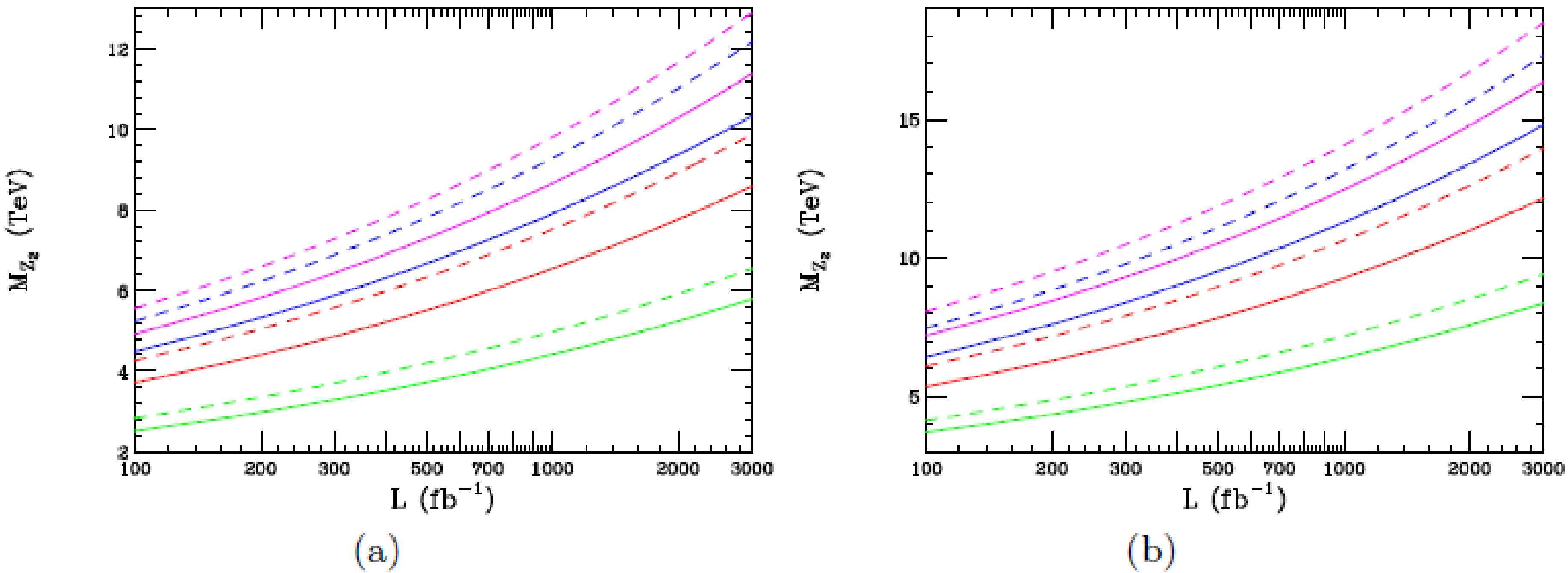
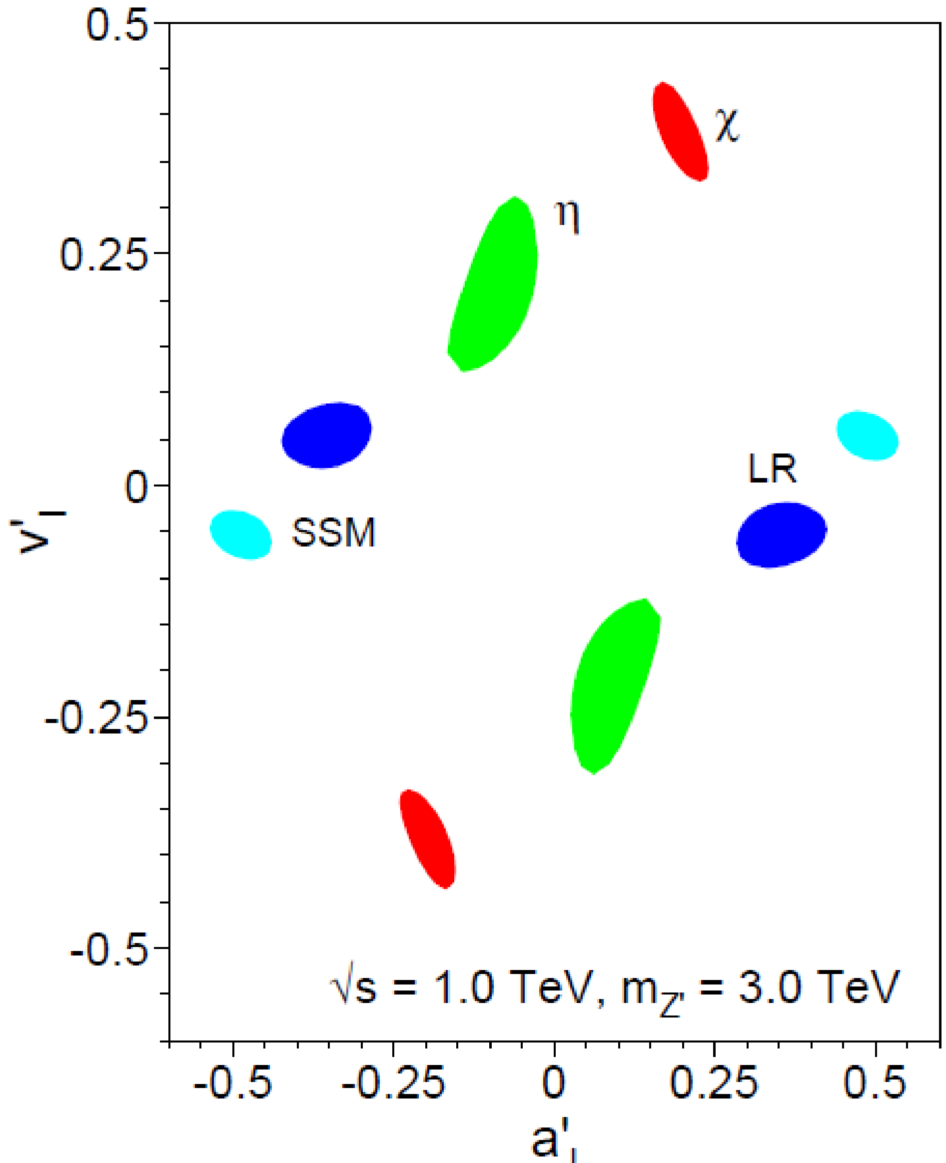


Fig. 1.21. Z' search reach at a $\sqrt{s}$=0.5 TeV(a) or 1 TeV(b) ILC as a function of the integrated luminosity without(solid) or with(dashed) 60% positron beam polarization for models ψ(green), χ(red), SSM(magenta) and LRM with $\kappa = 1$(blue).

ILC Indirect Z' Coupling Determinations



S. Riemann

Summary

- D-Y resonances come in many shapes & sizes but should be easy to spot at the LHC if they are not too heavy or if their couplings to the SM are not too small

- We need to differentiate states with various (combinations of) spins and to identify non-BW resonance line shapes.

- Insufficient info available to uniquely determine Z' couplings?

- More detailed studies of narrow states are required at the detector level to understand what is & is not observable & what properties can be measured.

- The interplay of results from Z'-like & W'-like states may be important in identifying the underlying theory

Summary, Part II

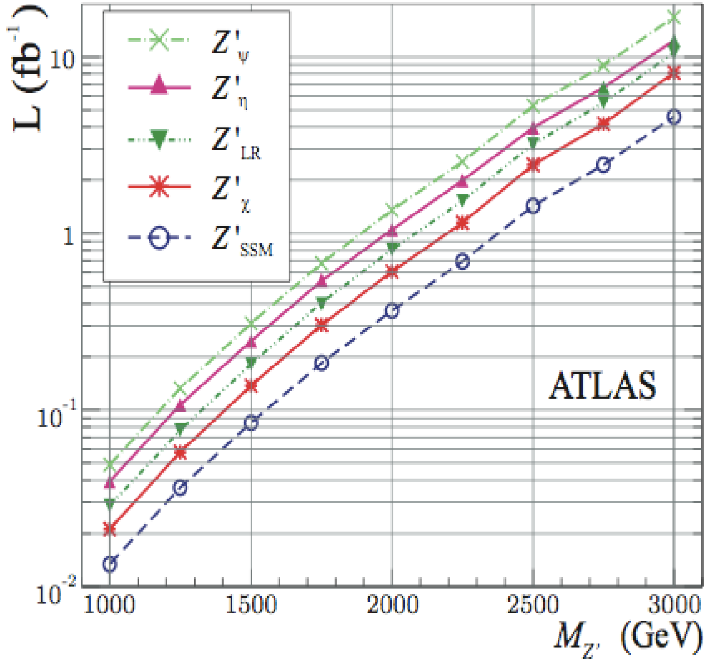
- The LHeC may provide useful coupling info depending upon the Z' mass and the specifics of the machine design: collision energy, luminosity & availability of beam polarization

- Indirect Z' searches at LHC are not likely to be useful

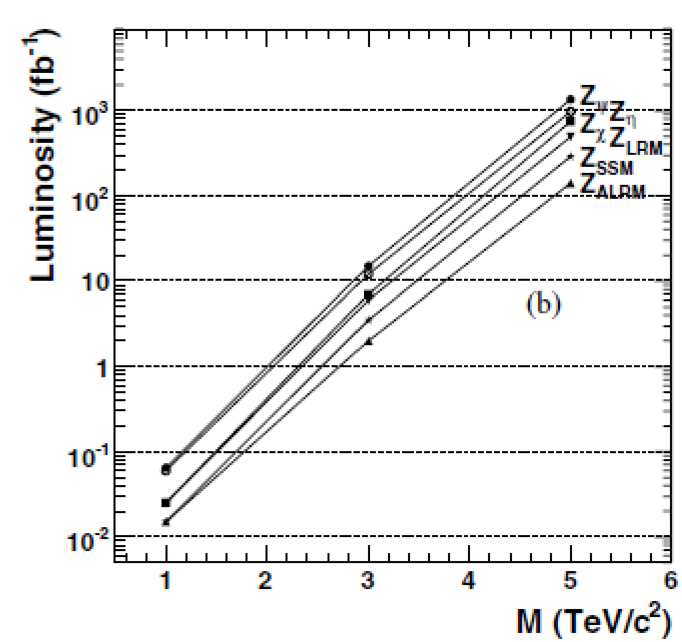
- The ILC may play an important role in coupling determinations provided the Z' is not too heavy, M ~3-4$\sqrt{s}$, with indirect search sensitivity in the ~6-12$\sqrt{s}$ range.

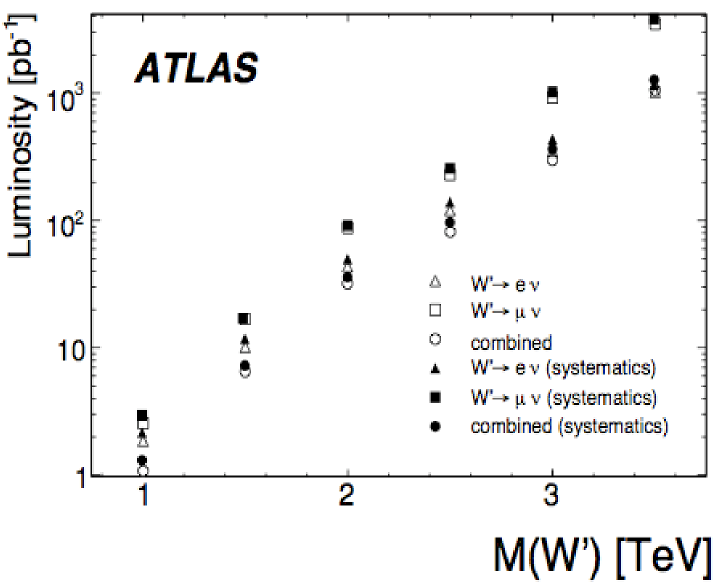
- With CLIC it may be possible to sit on the resonance peak & extract all of the coupling information with high precision as was done by LEP/SLC. The discovery of a 2-3 TeV resonance at the LHC would be a very strong motivation to go as quickly as possible to this energy range.

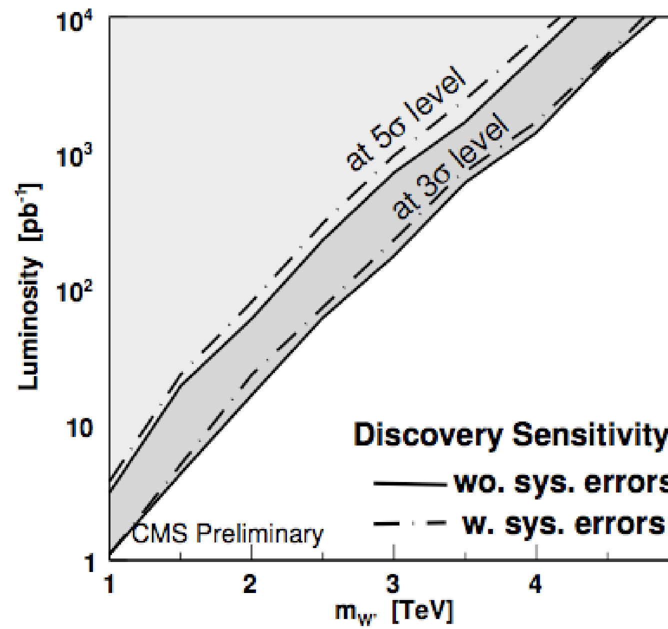
BACKUP SLIDES



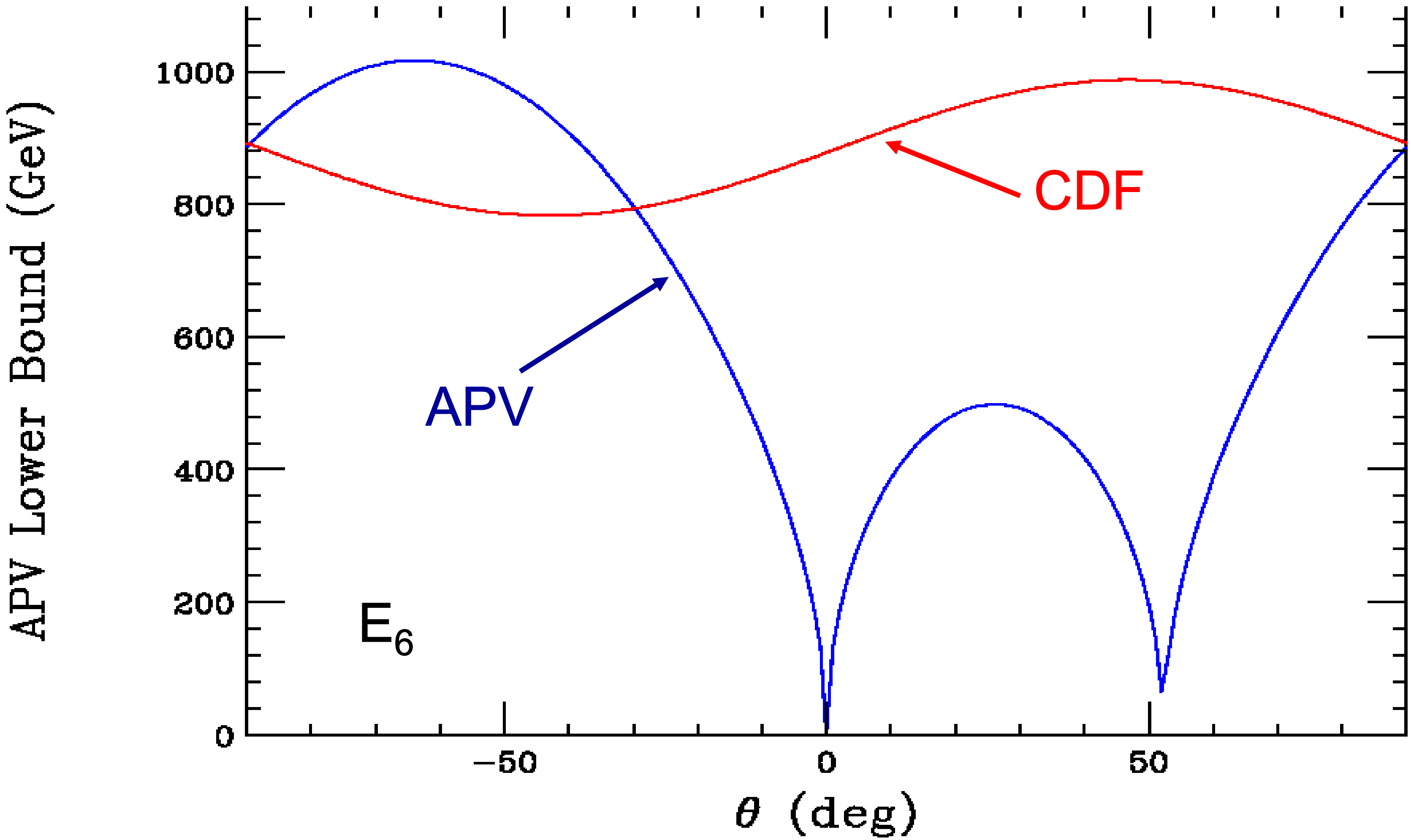
CMS Collaboration



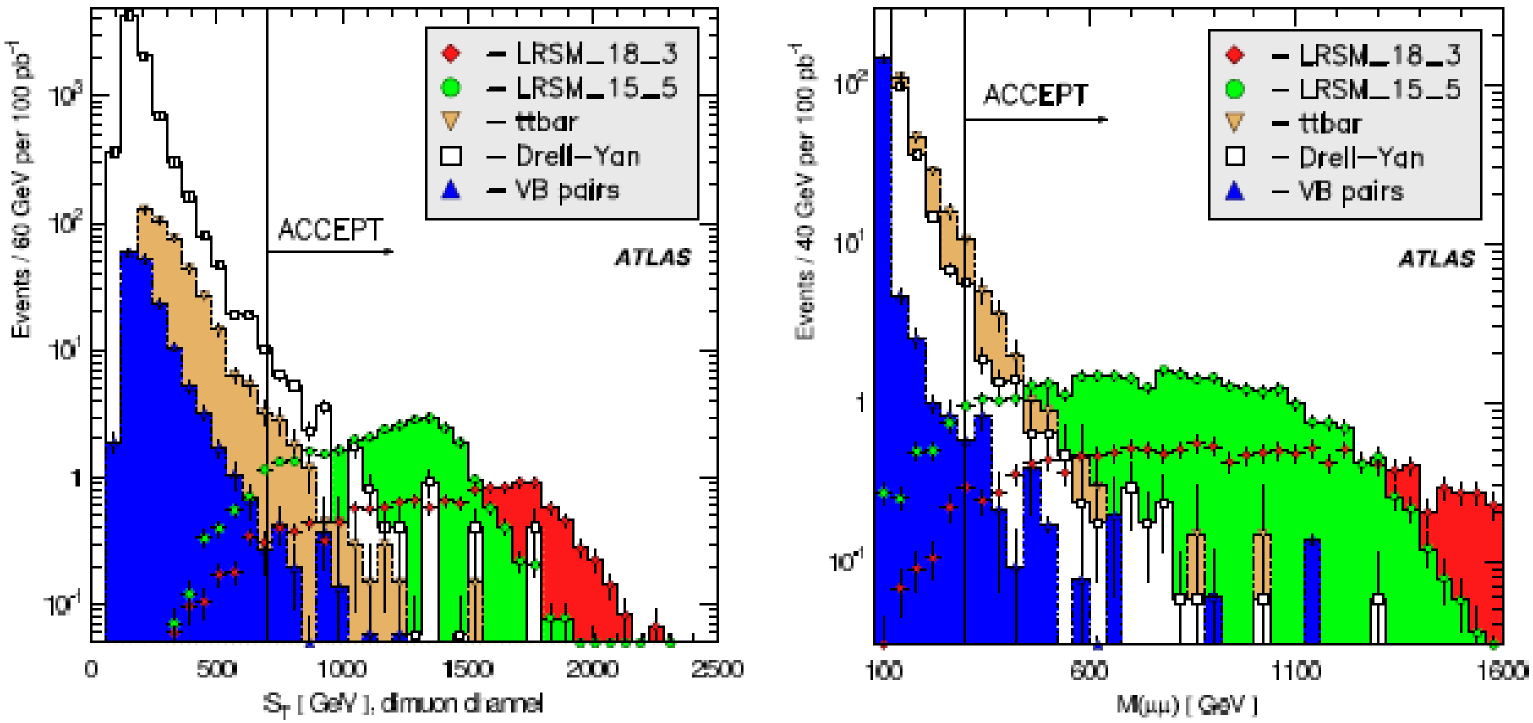




Z’ bounds can also arise from precision measurements, e.g., APV (0902.0335)



W’ → Heavy RH Neutrinos



(a) (b)

Fig. 3. Sum of the transverse energies of the two muons and two leading jets (S_T) (a), and dilepton invariant mass (b) for backgrounds and two signal points in the search for W' bosons decaying following the chain $W' \to \mu N_R, N_R \to \mu W'^*, W'^* \to q\bar{q}'$. The signal points LRSM_18_3 and LRSM_15_5 correspond to masses $m_{W'} = 1800$ GeV, $m_{N_R} = 300$ GeV and $m_{W'} = 1500$ GeV, $m_{N_R} = 500$ GeV respectively.