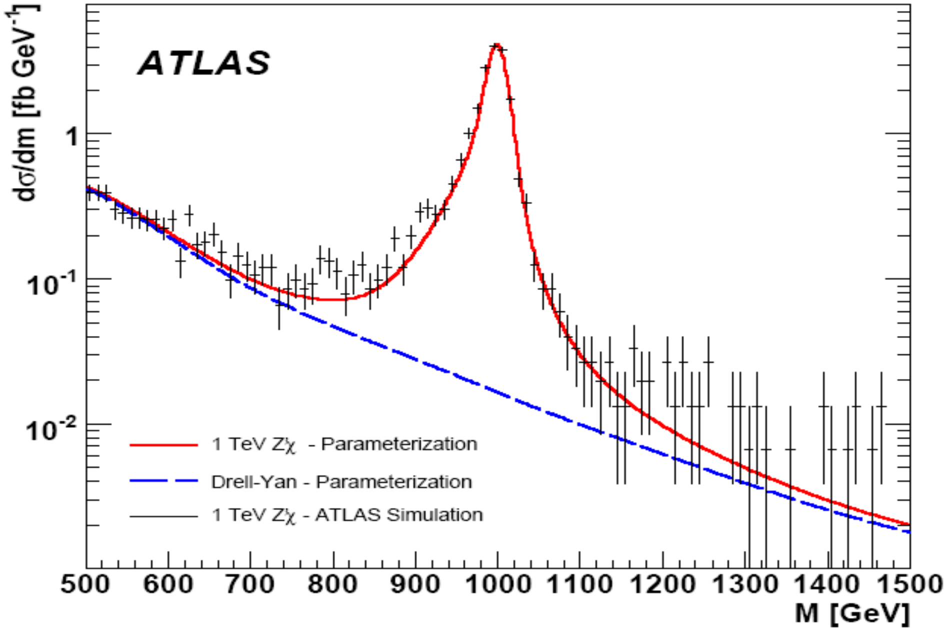
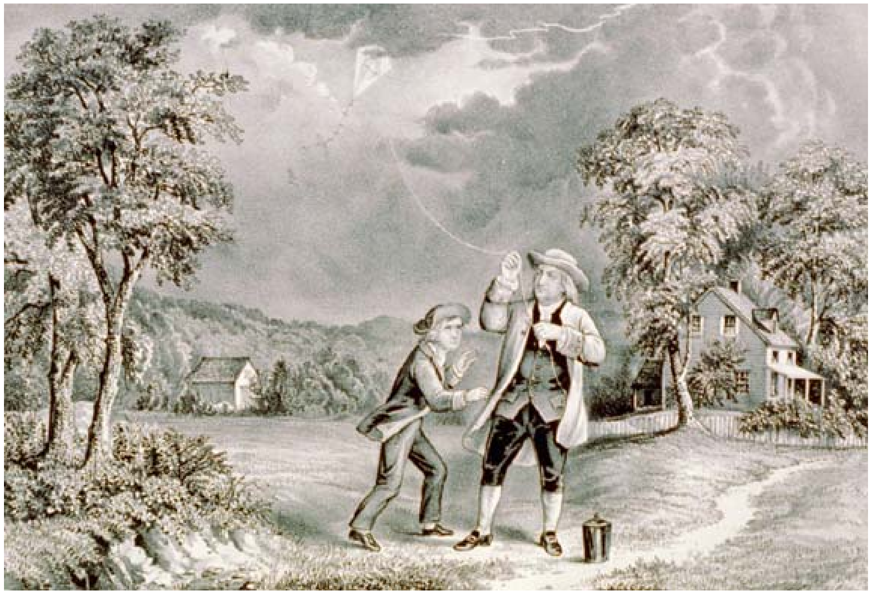
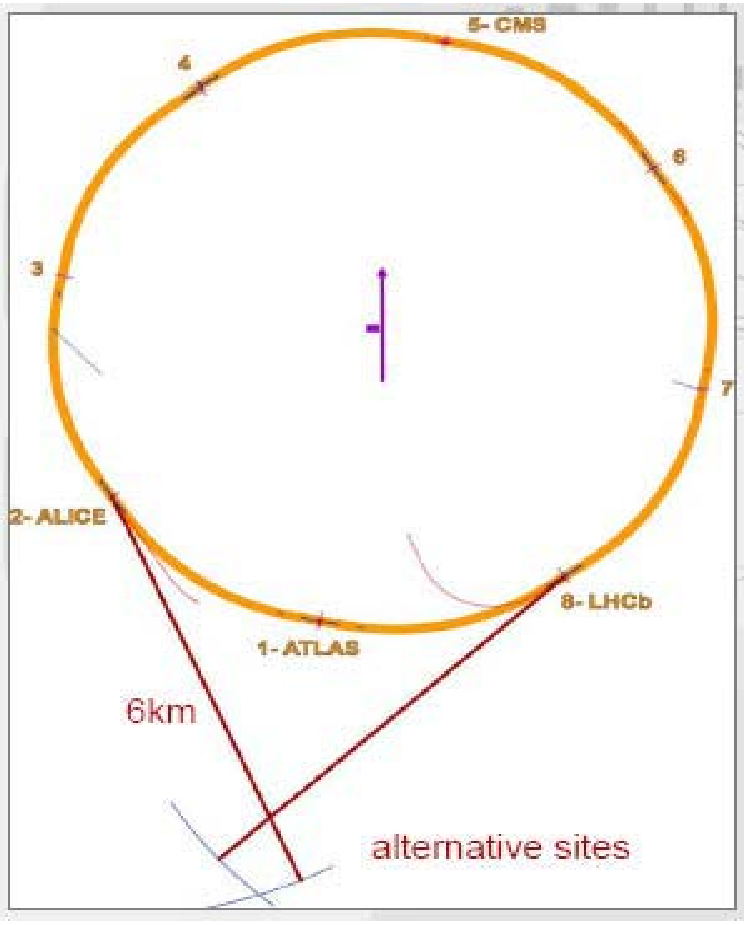
Z’ Physics at LHC & the LHeC







T. Rizzo 08/01/08

arXiv:0804.0081

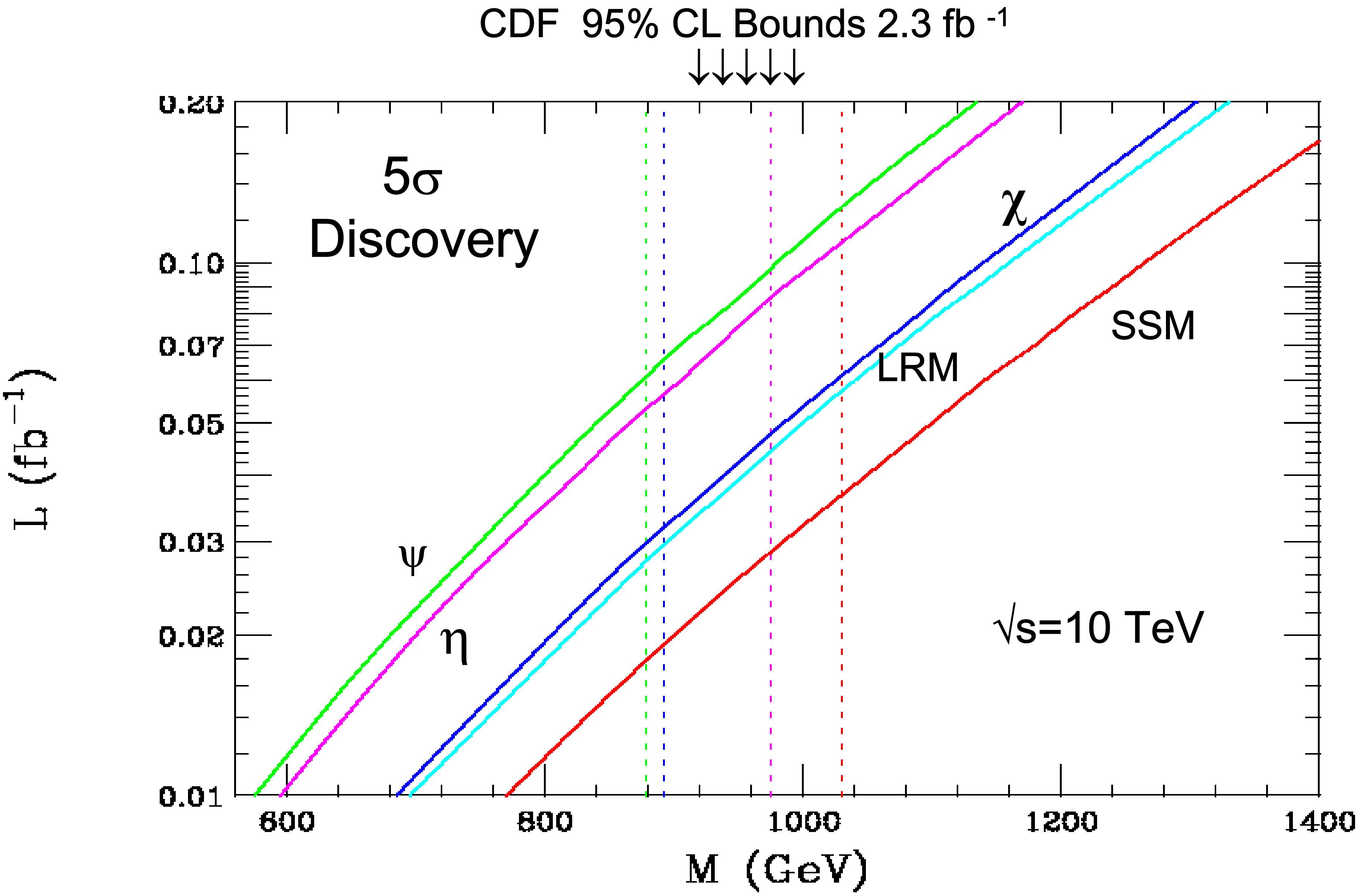
A Z’-like object at the TeV scale in Drell-Yan is a very common prediction in *many* BSM scenarios:

- Extended SUSY-GUT groups
- R-Parity violating SUSY
- String constructions/intersecting branes
- Little Higgs models
- Hidden Valley/mediation models
- Extra dimensions: gauge & graviton KK’s
- String excitations
- Unparticles
-
-

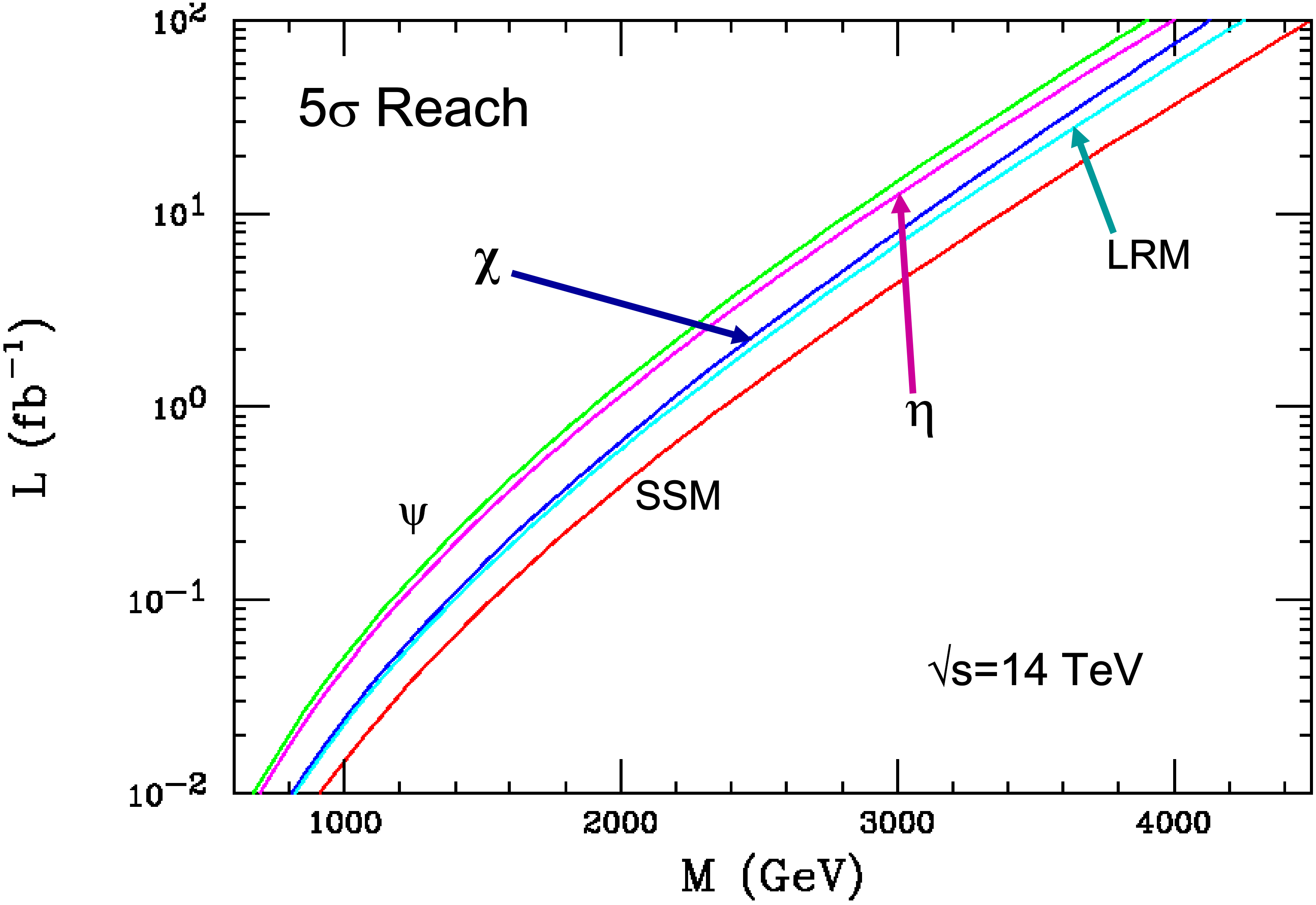
The LHC will open up a window to look for such states very soon now…

hep-ph/ 0610104

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 low integrated luminosity…

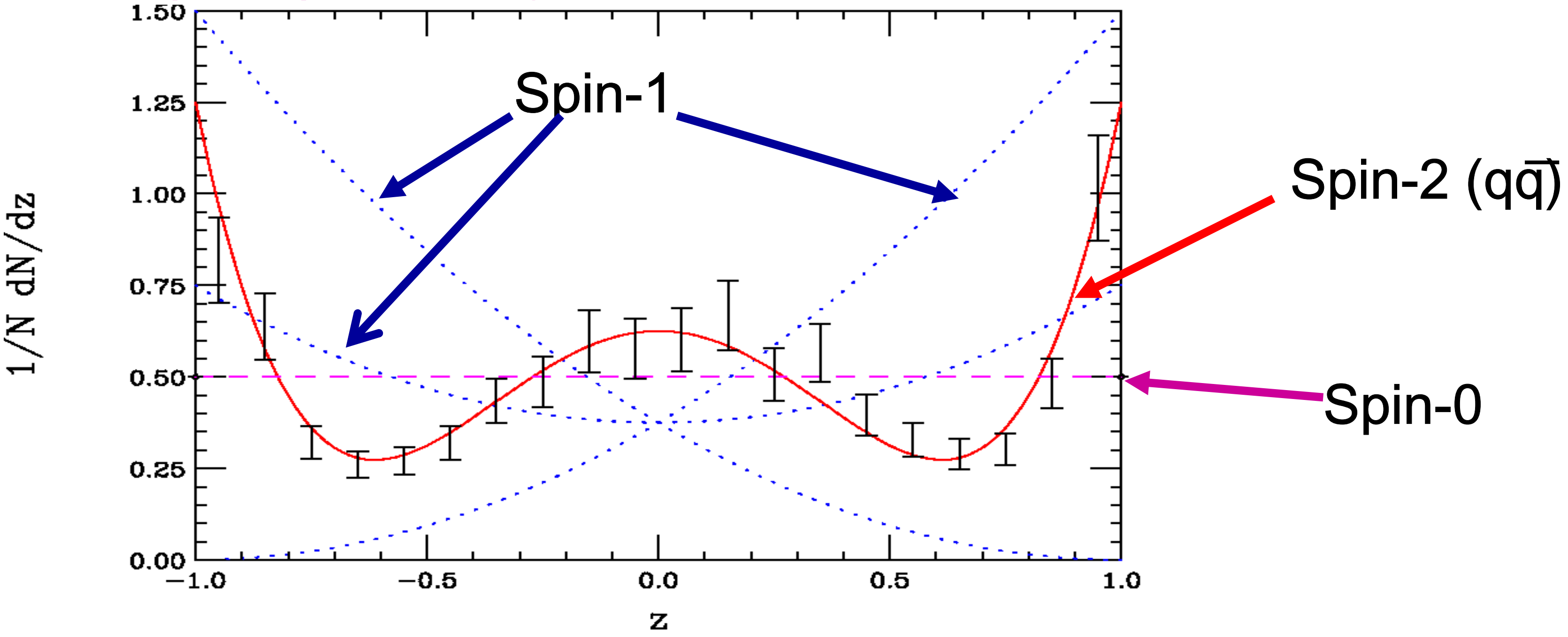


Eventually the Z’ 5σ reach will extend up to 4 TeV and beyond for `conventional’ GUT-inspired models once sufficient lumi is accumulated….



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

- lineshape: e.g., mass (M), cross section (σ), width (Γ), etc. → detector resolution!
- spin = ??? Is it a graviton (S=2), a sneutrino (S=0) or a gauge boson (S=1)? → angular distribution of leptons



- Determine the couplings of X to the fields of the SM. (Note if X→$\gamma\gamma$ then S ≠ 1). If X=Z', this is important if we want to expose the underlying fundamental theory

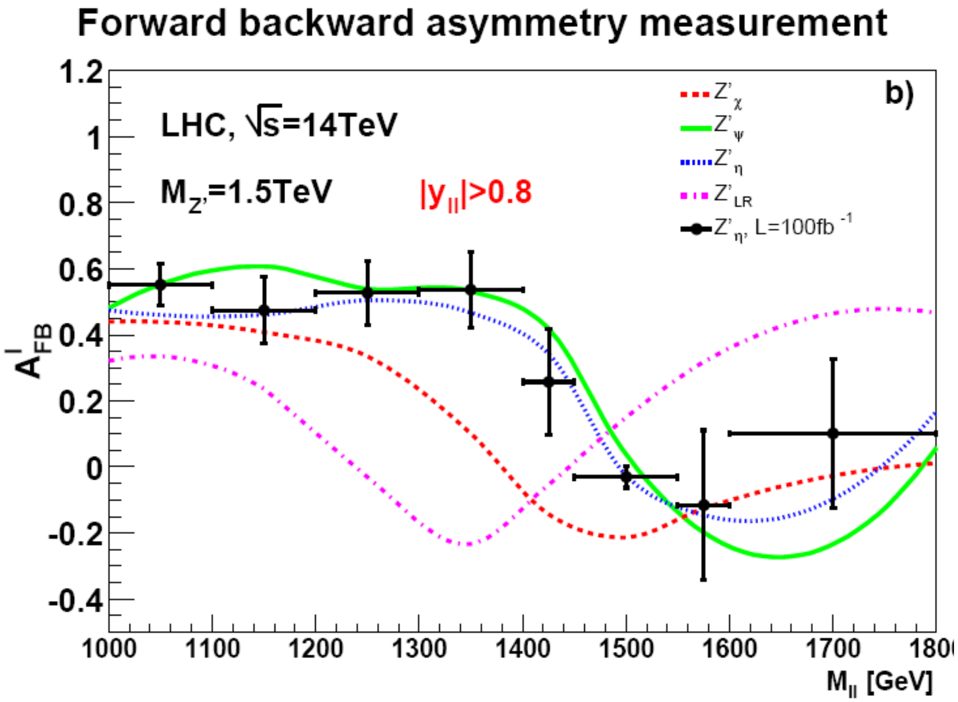
How many independent couplings are there?? Even in the *simplest* possible scenario, where the Z' couples in a generation-independent manner and $[Q_{Z'}, SU(2)_L]=0$, there are 5 coupling constants to determine corresponding to the 5 SM fields Q, L, u^c, d^c & e^c. Are there enough observables at the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

Unfortunately, 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. Then what observables do we have to perform this analysis???

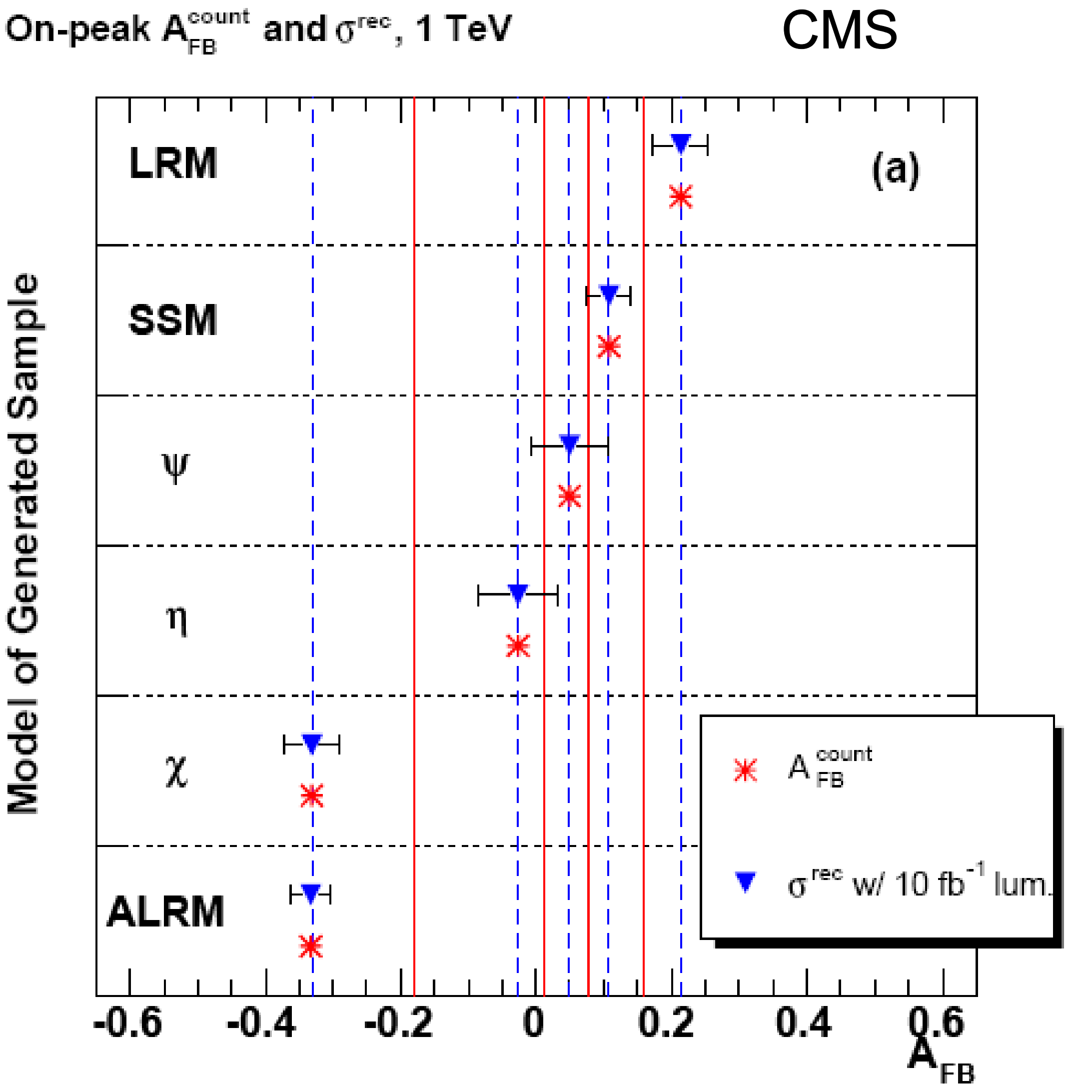
- σ & Γ independently are sensitive to decay assumptions but the product $\sigma\Gamma$ ~ is *not.* This product can be determined at the ~ 5-10% uncertainty level at the LHC with high lumi.

- 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

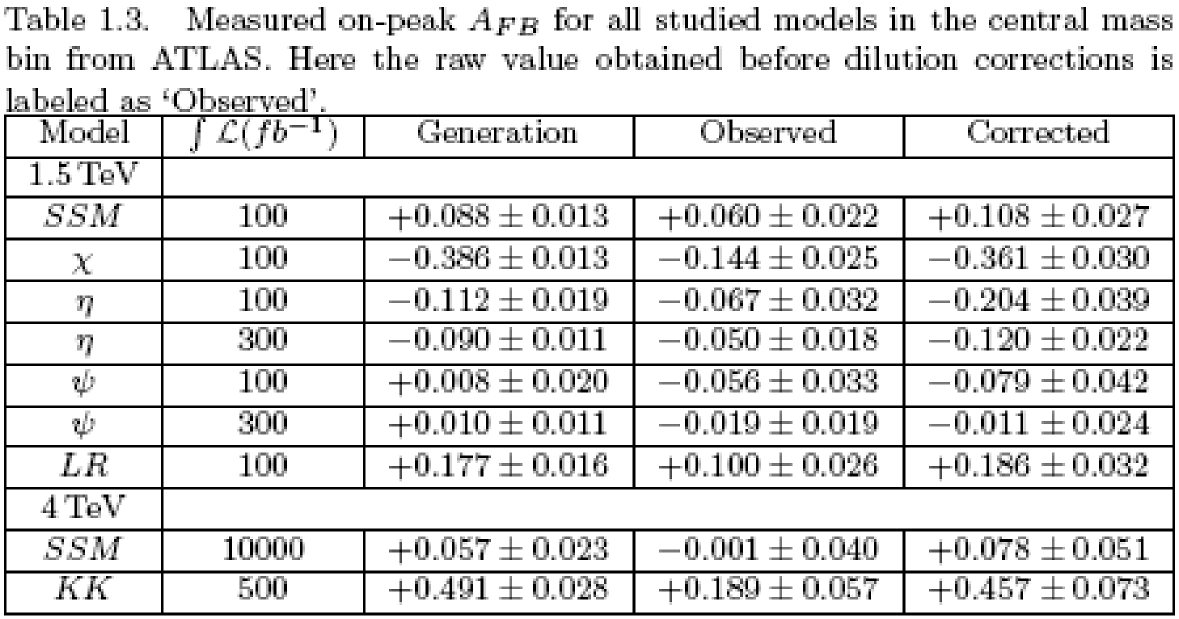


Table 1.3. Measured on-peak A_{FB} for all studied models in the central mass bin from ATLAS. Here the raw value obtained before dilution corrections is labeled as 'Observed'.

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	$+0.491 \pm 0.028$	$+0.189 \pm 0.057$	$+0.457 \pm 0.073$

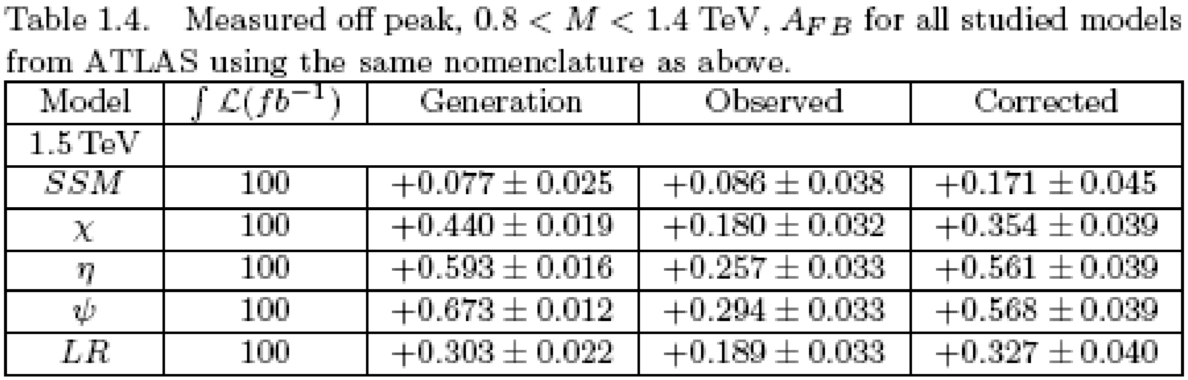


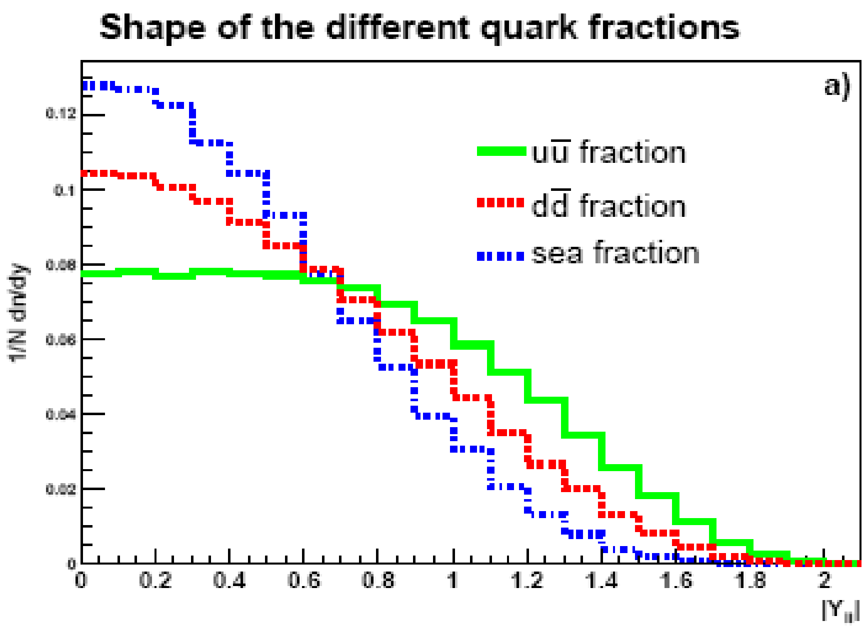
Table 1.4. Measured off peak, $0.8 < M < 1.4$ TeV, A_{FB} for all studied models from ATLAS using the same nomenclature as above.

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	$+0.303 \pm 0.022$	$+0.189 \pm 0.033$	$+0.327 \pm 0.040$

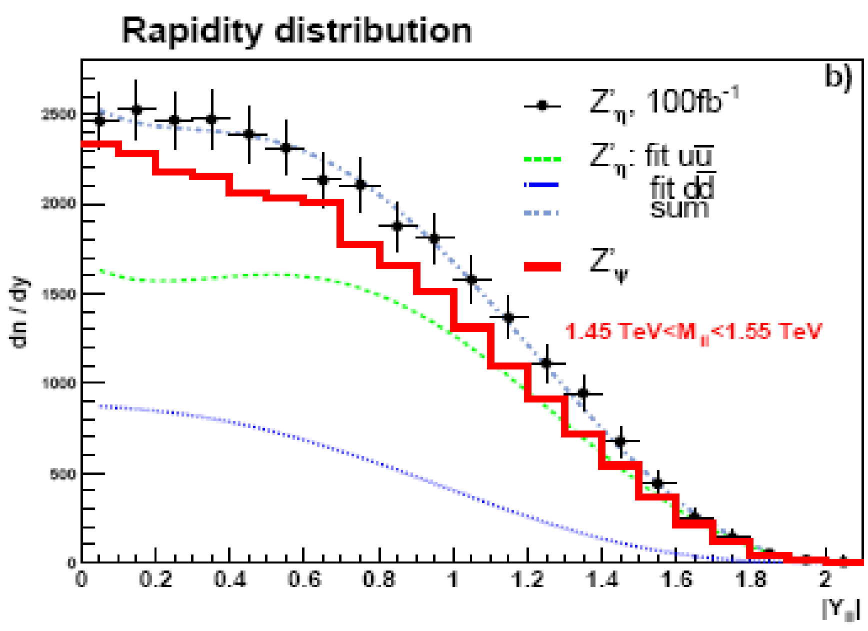
On- & off-peak simulated `measurements' of A_{FB} by ATLAS with large integrated luminosities

- Rapidity distributions

M. Dittmar et al.



(a)

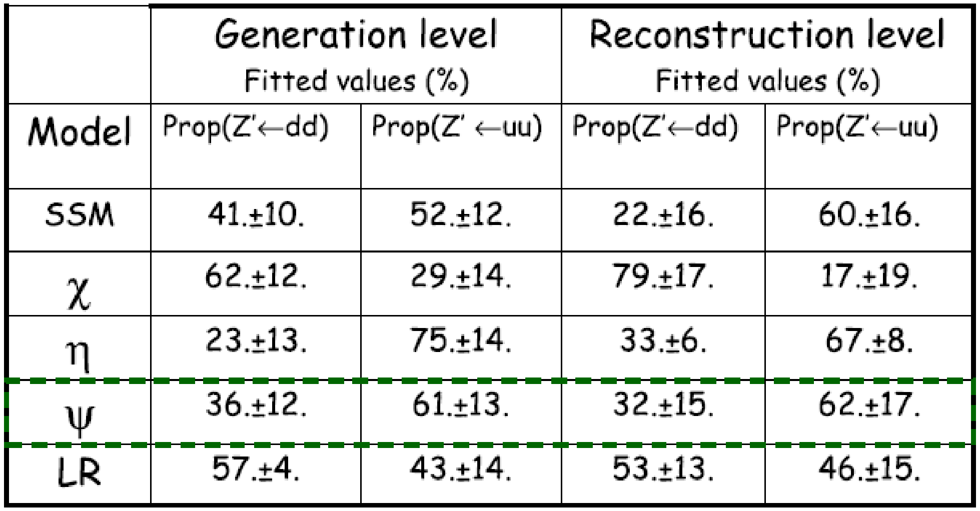


(b)

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

or fit to R_{qq}, the event fraction from a given qq̄ initial state…

ATLAS



Model	Generation level Fitted values (%) Prop(Z'←dd)	Generation level Fitted values (%) Prop(Z' ←uu)	Reconstruction level Fitted values (%) Prop(Z'←dd)	Reconstruction level Fitted values (%) 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.

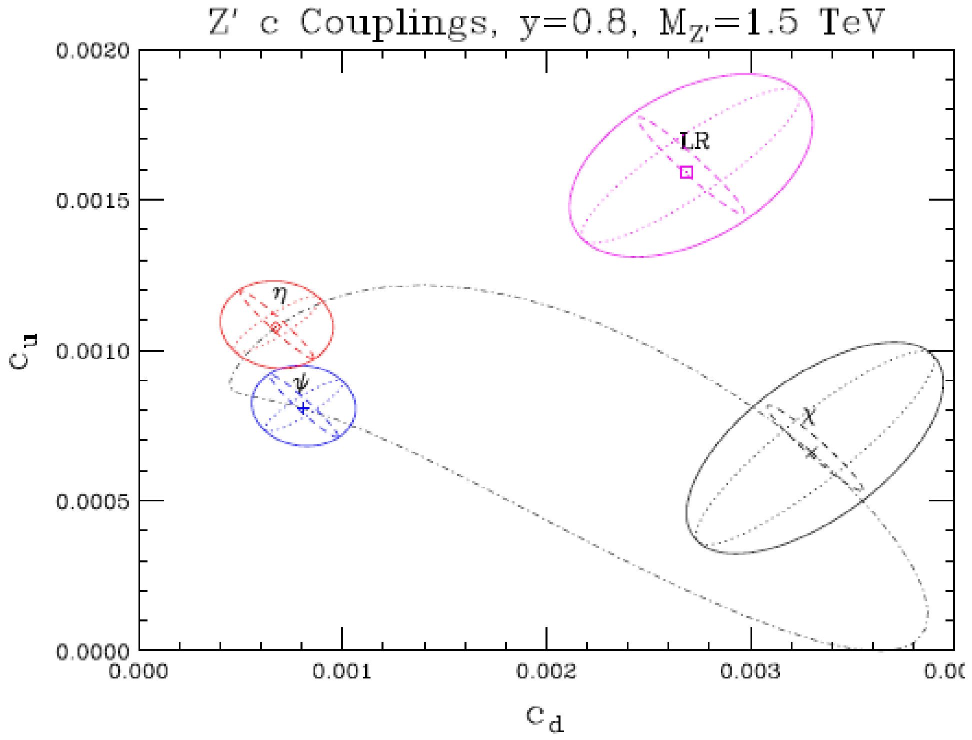
To first approximation these observables really only probe the 4 coupling combinations

Carena et al.

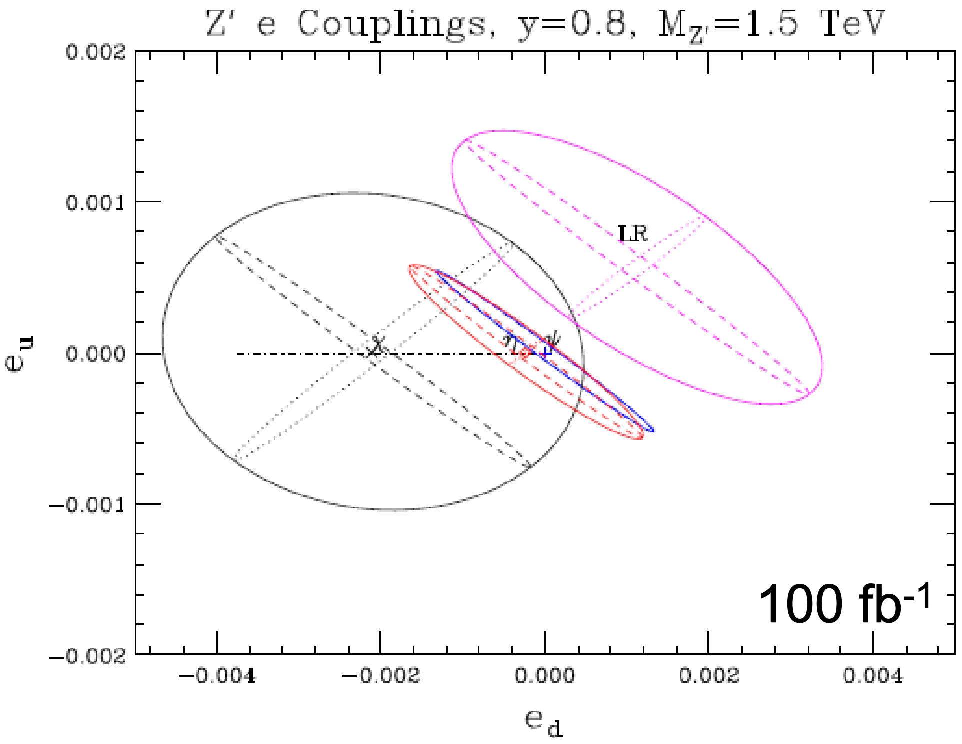
$$c_q = \frac{M_{Z'}}{24\pi\Gamma}(q_R^2 + q_L^2)(e_R^2 + e_L^2)$$

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

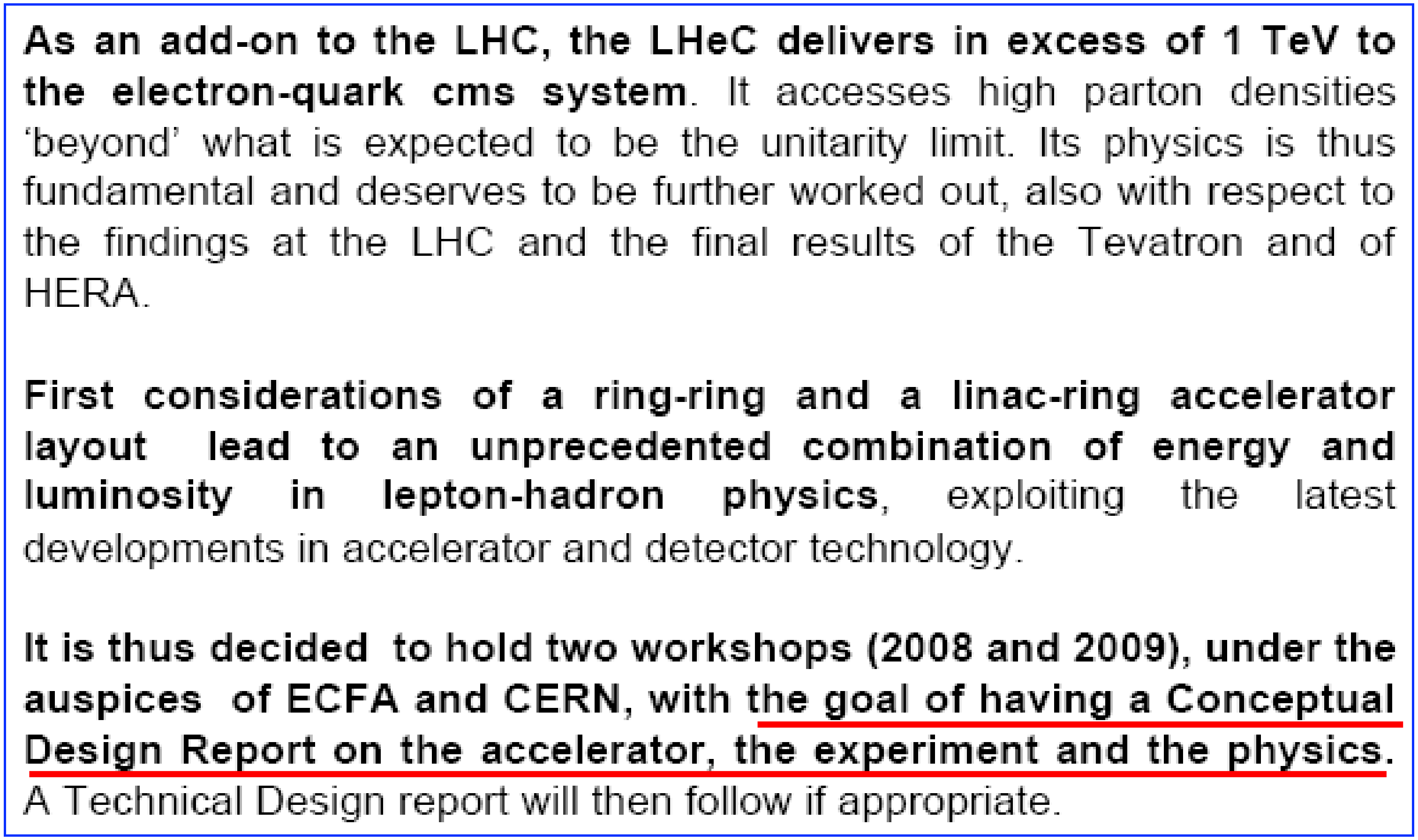


100 fb^{-1}

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

This is good, BUT to determine the *individual* couplings we need more input from ??? There is a proposal to add either an e± ring to the LHC or add a linac so that high energy ep collisions occur :

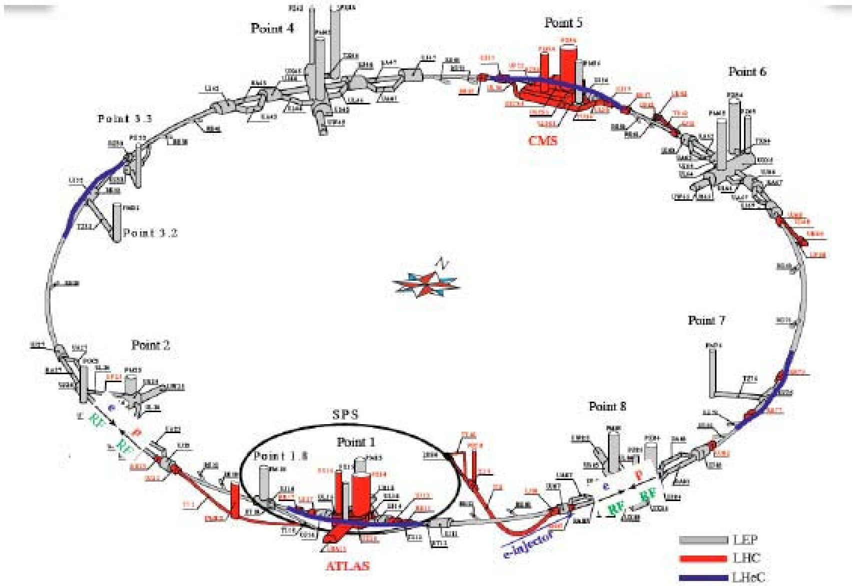
Summary and Proposal endorsed by ECFA 30.11.07



As an add-on to the LHC, the LHeC delivers in excess of 1 TeV to the electron-quark cms system. It accesses high parton densities ‘beyond’ what is expected to be the unitarity limit. Its physics is thus fundamental and deserves to be further worked out, also with respect to the findings at the LHC and the final results of the Tevatron and of HERA.

First considerations of a ring-ring and a linac-ring accelerator layout lead to an unprecedented combination of energy and luminosity in lepton-hadron physics, exploiting the latest developments in accelerator and detector technology.

It is thus decided to hold two workshops (2008 and 2009), under the auspices of ECFA and CERN, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.



Max Klein LHeC DIS08 London 11.4.08

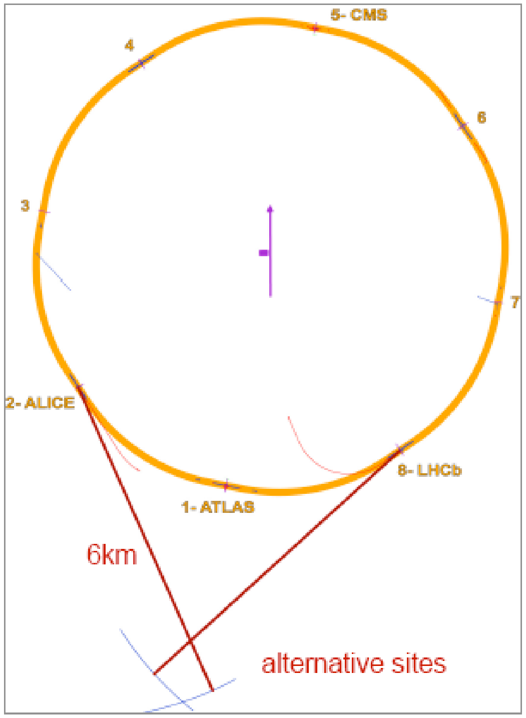
Comparison Linac-Ring and Ring-Ring

Energy / GeV	40-140	40-80
Luminosity / 10^{32} cm^{-2} s^{-1}	0.5	10
Mean Luminosity, relative	2	1 [dump at L_{peak} /e]
Lepton Polarisation	60-80%	30% [?]
Tunnel / km	6	2.5=0.5 * 5 bypasses
Biggest challenge	CW cavities	Civil Engineering Ring+Rf installation
Biggest limitation	luminosity (ERL,CW)	maximum energy
IR	not considered yet one design? (eRHIC)	allows ep+pp 2 configurations [lox, hiq]

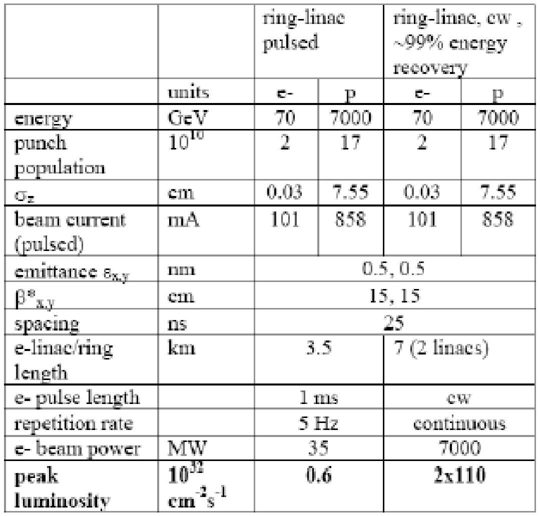
LHeC

Two possible scenarios..
each with its own strengths
and weaknesses

For more details, see
www.ep.ph.bham.ac.uk/exp/LHeC/



e$^{\pm}$ Linac - p/A Ring



		ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
	units	e-	p	e-	p
energy	GeV	70	7000	70	7000
punch population	10^{10}	2	17	2	17
σ_z	cm	0.03	7.55	0.03	7.55
beam current (pulsed)	mA	101	858	101	858
emittance $\varepsilon_{x,y}$	nm	0.5, 0.5			
$\beta^*_{x,y}$	cm	15, 15			
spacing	ns	25			
e-linac/ring length	km	3.5		7 (2 linacs)	
e- pulse length		1 ms		cw	
repetition rate		5 Hz		continuous	
e- beam power	MW	35		7000	
peak luminosity	**10^{32} cm^{-2}s^{-1}**	**0.6**		**2x110**	

S. Chattopadhyay (Cockcroft), F.Zimmermann (CERN), et al.

Bottom line: 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?

Let's see what such a machine can do to address our problem..

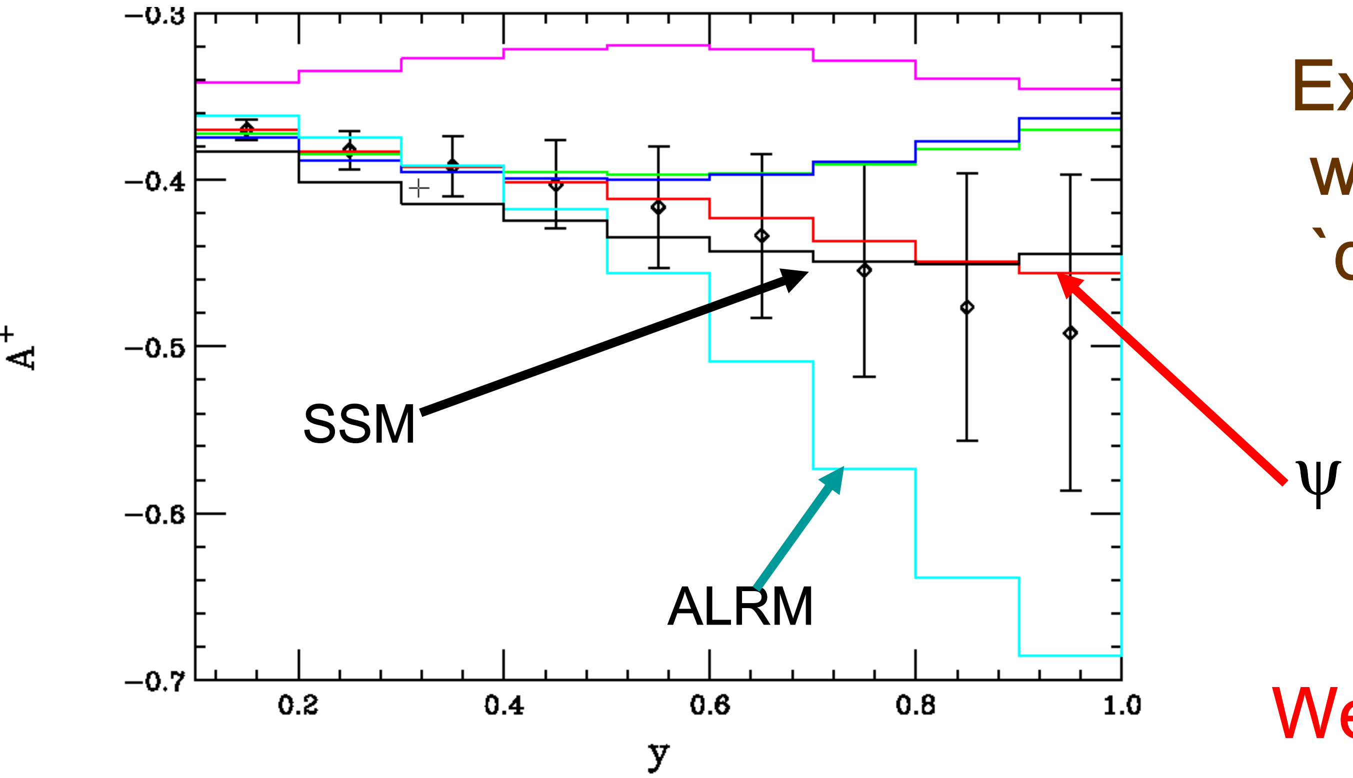
Technique: form polarization asymmetries to reduce systematics & PDF uncertainties. Apply (x,y,Q^2) cuts to increase sensitivity & then integrate over the remaining x range.

$$A^\pm = \frac{d\sigma(e_L^\pm) - d\sigma(e_R^\pm)}{d\sigma(e_L^\pm) + d\sigma(e_R^\pm)}$$

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

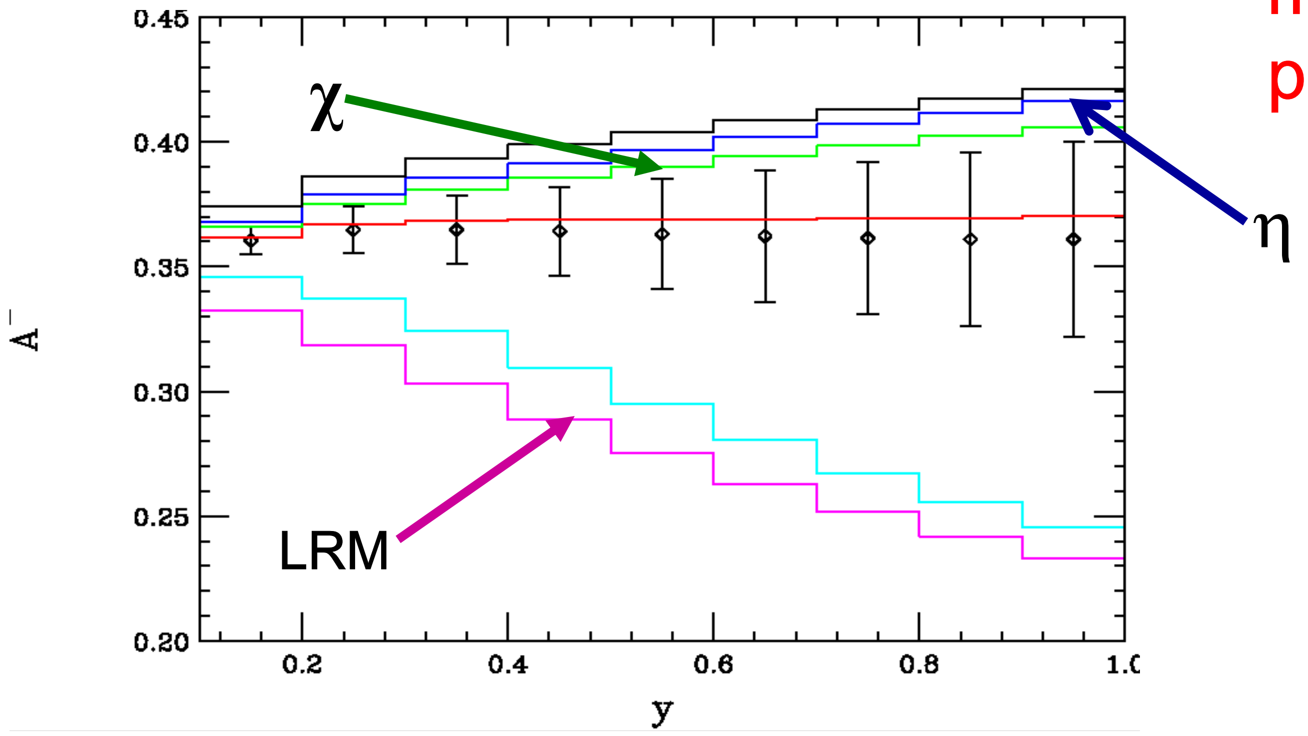
$$C_{L,R} = \frac{d\sigma(e_{L,R}^-) - d\sigma(e_{L,R}^+)}{d\sigma(e_{L,R}^-) + d\sigma(e_{L,R}^+)}$$

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

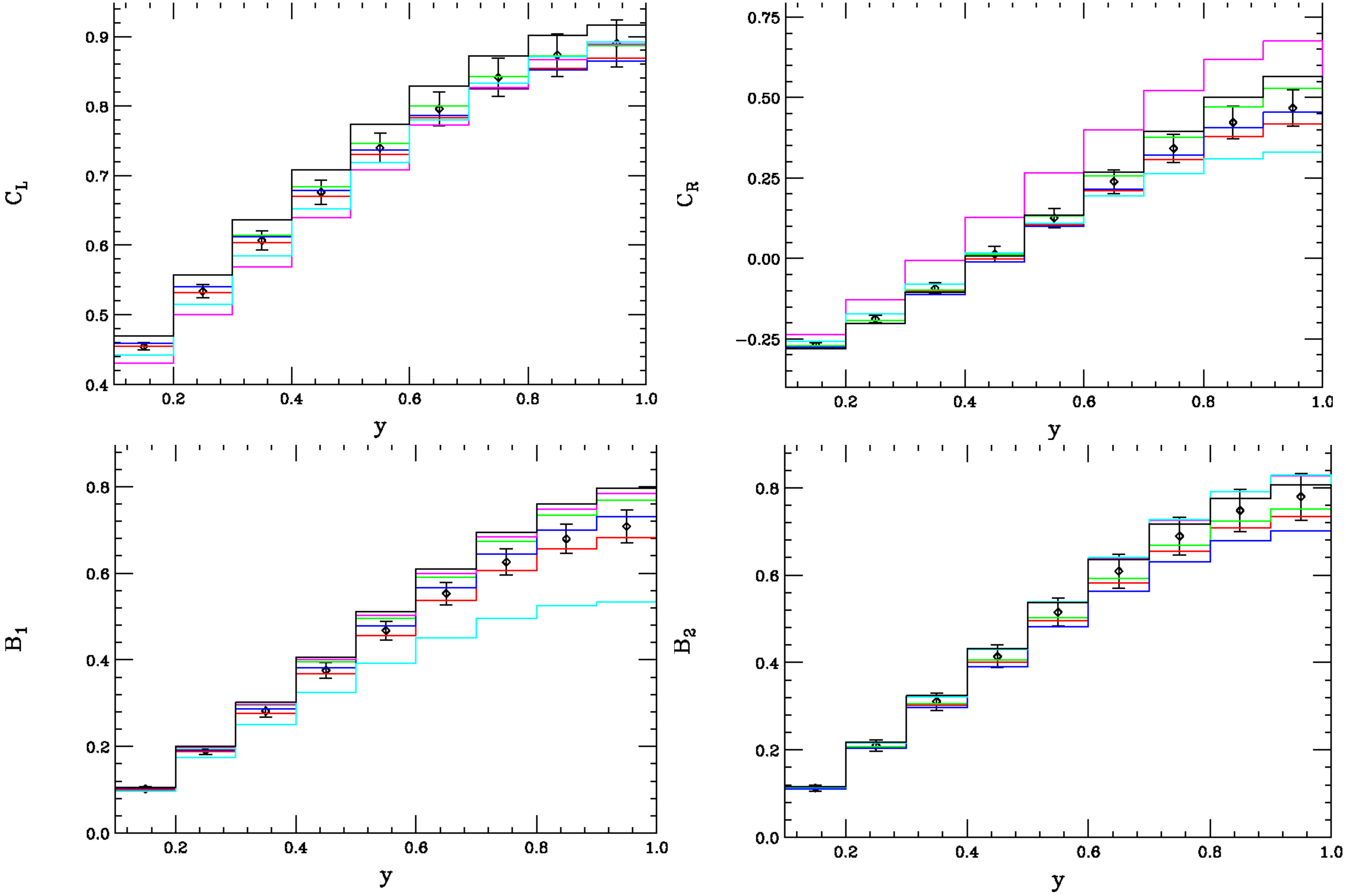


Example: $M_{Z'}$ = 1.2 TeV
with ep @ √s = 1.5 TeV
`data'=SM prediction

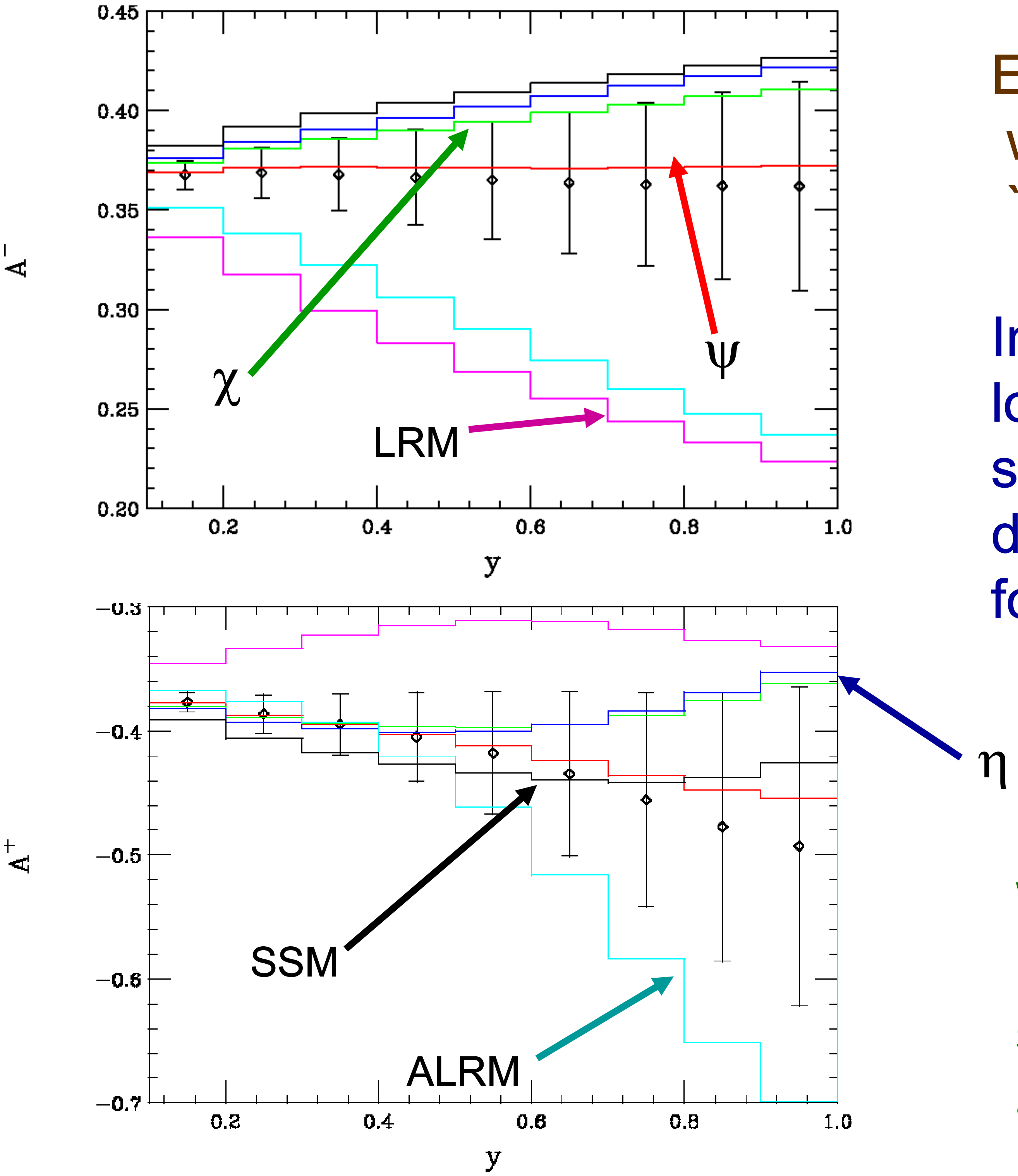
We'll use GUT-inspired models for demonstration purposes



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…



Example: $M_{Z'}$= 1.5 TeV
with ep @ √s = 2 TeV
\`data'=SM prediction

Improved mass reach but lower sensitivity due to smaller cross section… doesn't look very good for much heavier Z' states

We again see that there is substantial model sensitivity in these asymmetries

Summary

- The LHC can easily find heavy Z'-like states but it can only obtain detailed coupling info if they are reasonable light M< 1.5-2 TeV since very high statistics is required

- Even in the best case scenario the LHC cannot uniquely determine the SM fermion couplings to the Z' since there are not enough observables even with the SLHC (though this will help a lot with other potential observables)

- A LC can be used to solve this problem BUT we might be able to get additional information sooner (?) employing the LHeC

- We have shown that LHeC *may* have the desired capability if the Z' is light enough *but* a believable evaluation awaits a realistic design study

BACKUP SLIDES

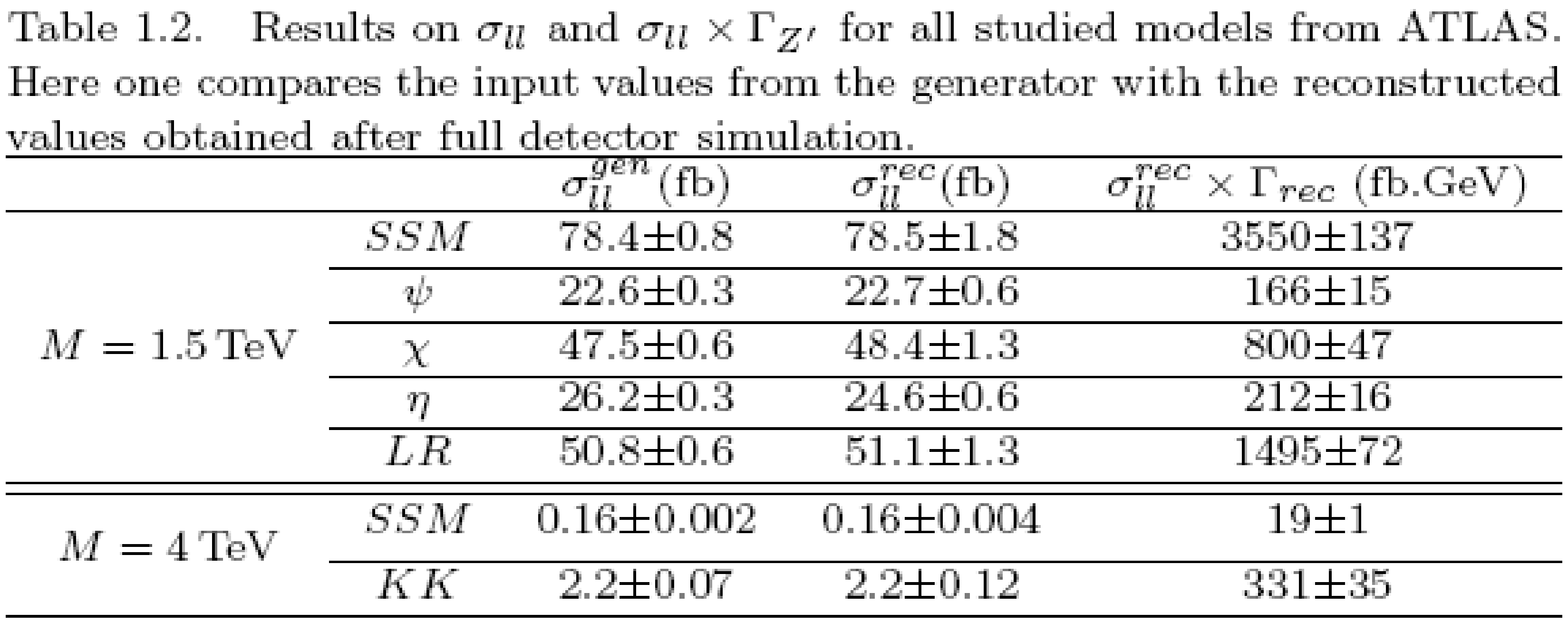


Table 1.2. Results on σ_{ll} and $\sigma_{ll} \times \Gamma_{Z'}$ for all studied models from ATLAS. Here one compares the input values from the generator with the reconstructed values obtained after full detector simulation.

		σ_{ll}^{gen}(fb)	σ_{ll}^{rec}(fb)	$\sigma_{ll}^{rec} \times \Gamma_{rec}$ (fb.GeV)
$M = 1.5\,\mathrm{TeV}$	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
$M = 4\,\mathrm{TeV}$	SSM	0.16±0.002	0.16±0.004	19±1
	KK	2.2±0.07	2.2±0.12	331±35

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
- etc