Title: Discovery and Identification of s-channel Resonances at the LHC

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Abstract: s-channel resonances are predicted by many models of Physics Beyond the Standard Model and it is quite possible that such an object will be discovered in the early years of the LHC program. If this occurs, the task will be to understand its origins. A brief survey of models that predict s-channel resonances will be given, concentrating mainly on extra neutral gauge bosons (Z' 's) arising from extended gauge theories. This will be followed by a description of how to search for a Z' and the resulting Z' discovery reach of the LHC. I will describe various diagnostic measurements to study Z' 's and describe some new observables we have proposed that can distinguish between models that take advantage of the ability to tag 3rd generation fermions.

Carleton
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ada's Capital University

Discovery and Identification of s-channel Resonances at the LHC

Stephen Godfrey

Carleton University

Outline

1. Models of Physics Beyond the Standard Model
2. Discovery Reach of Z' at the LHC
3. Identification of Z' at the LHC
4. Using 3rd Generation Fermions to ID a Z'
5. Summary

Some reviews on Z' 's:

- T. Rizzo, hep-ph/0610104
- A. Leike, Phys. Rept. 183, 193 (1989)
- M. Cvetic & S. Godfrey, hep-ph/9504216

Why New Physics at TeV ?

- Believe standard model is low energy effective theory
- Expect some form of new physics to exist beyond the SM
- Don't know what it is
- Need experiments to to show the way

Many Models of New Physics

Extended gauge sectors

- Extra U(1) factors: $E_6 \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
- Left-Right symmetric model: $SU(2)_L \times SU(2)_R \times U(1)$

Little Higgs $W_H^\pm \quad Z_H \quad B_H$

Extra dimensions (ADD, RS, UED...): KK excitations

- ADD: Graviton tower exchange effective operators: $i\frac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$
- Randall-Sundrum Gravitons: Discrete KK graviton spectrum

SUSY & SUSY GUTS

Technicolour

Topcolour

Unparticles

Many, many models

- How do we discover the new physics?
- How do we identify the new physics?

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Possible Routes:

- Direct Discovery
- Indirect discovery assuming specific models
- Indirect tests of New Physics via L_{eff}

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- Direct Discovery
- Indirect discovery assuming specific models
- Indirect tests of New Physics via L_{eff}

Tools for "direct" measurements:

- Production of exotic particles
- Di-fermion channel
- Anomalous gauge boson couplings
- Anomalous fermion couplings
- Higgs couplings

To sort out the models we need to elucidate and complete the TeV particle spectrum

Many types of new particles:

- Extra gauge bosons
- Vector resonances
- New fermions
- Extended Higgs sector
- Pseudo Goldstone bosons
- Leptoquarks...

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How do we distinguish the models?

Survey of BSM Models

I want to focus on predictions of the models;
NOT the theoretical nitty gritty details

So start with a rather superficial overview of some recent models

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Extended Gauge Theories

Effective Rank-5 Models (ψ, χ, η)

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi \to SM \times U(1)_{\theta_{E6}}$$

The Z' charges are given as

$$g_{Z^0}(g_{Z'}/g_{Z^0})(Q_\chi \cos\theta_{E_6} + Q_\psi \sin\theta_{E_6})$$

Left-Right Symmetric Model (LR)

$$SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

The Z' -fermion couplings are given by

$$g_{Z^0} \frac{1}{\sqrt{\kappa - (1+\kappa)x_W}} [x_W T_{3L} + \kappa(1 - x_W)T_{3R} - x_W Q]$$

$$0.55 \le \kappa^2 \equiv (g_R/g_L)^2 \le 1 - 2$$

Harvard Model (un-unified model) $SU(2)_l \times SU(2)_q \times U(1)_Y$

Z'-fermion couplings

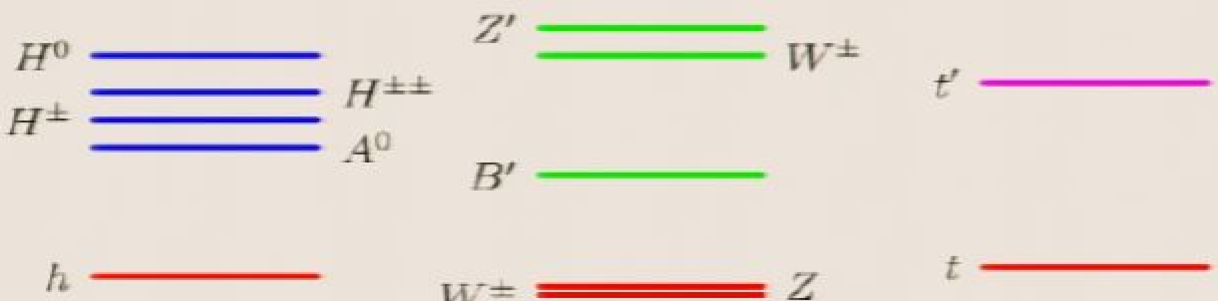
$$g_{Z^0} c_w \left(\frac{T_{3q}}{\tan\phi} - \tan\phi T_{3l} \right)$$

Little Higgs

Arkani-Hamed et al hep-ph/0206021

The little Higgs models are a new approach to stabilize the weak scale against radiative corrections

- **10 TeV**
  - New Strong Dynamics
  - Global Symmetry
- **1 TeV**
  - Symmetries Broken
  - Pseudo-Goldstone Scalars
  - New Gauge Bosons related to SU(2): $W_H^{\pm}$ Z_H B_H
  - New Heavy Top cancels quadratic divergences
- **100 GeV**
  - Light Higgs
  - SM vector bosons & fermions



Parameters:
f~vev
s, s': GB mixing angles

Extra Dimensions

In most scenarios our 3-dimensional space is a 3-brane embedded in a D-dimensional spacetime

Basic signal is KK tower of states corresponding to a particle propagating in the higher dimensional Space-time

The details depend on geometry of extra dimensions

Many variations

ADD Type of Extra Dimensions

(Arkani-Hamed Dimopoulos Dvali)

Have a KK tower of graviton states in 4D which behaves like a continuous spectrum

Graviton tower exchange effective operators: $i\frac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$

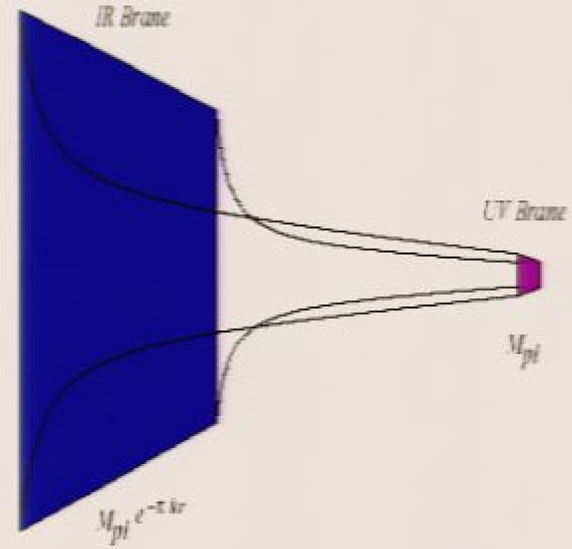
Leads to deviations in $e^+e^- \to f\bar{f}$ dependent on λ and s/M_H

Also predicts graviscalars and gravitensors propagating in extra dimensions

Mixing of graviscalar with Higgs leads to significant invisible width of Higgs

Randall Sundrum Model

2 3+1 dimensional branes separated by a 5th dimension



Predicts existence of the ***radion*** which corresponds to fluctuations in the size of the extra dimension

Radion couplings are very similar to SM Higgs except for anomalous couplings to gluon and photon pairs

- Radion can mix with the Higgs boson
- Results in changes in the Higgs BR's from SM predictions

Also expect large couplings for KK states of fermions

- Expect supression of $h \to WW,\ ZZ$
- Enhancement of $h \to gg,\ \gamma\gamma$

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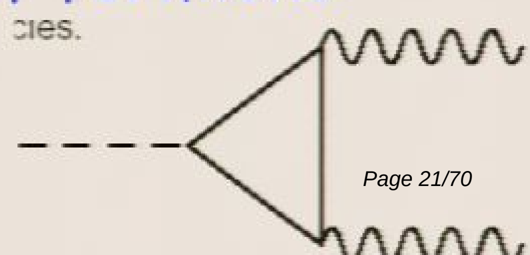
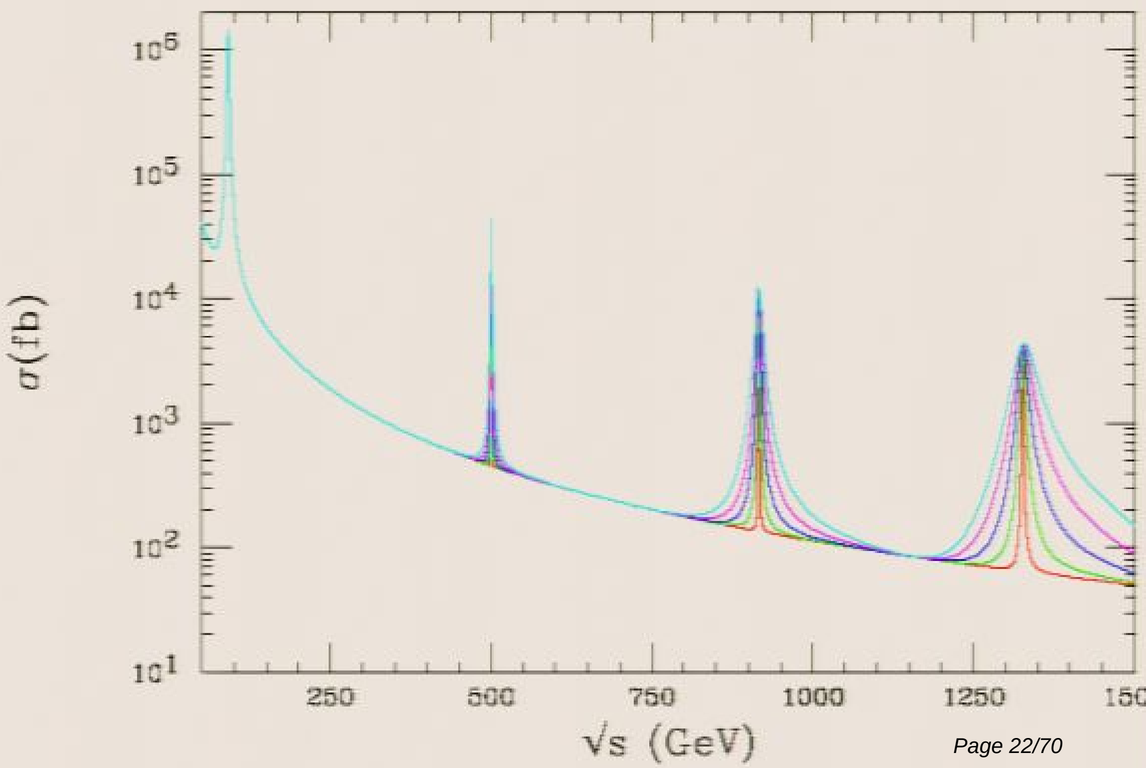


Randall-Sundrum Gravitons:

The spectrum of the graviton KK states is discrete and unevenly spaced

Expect production of TeV scale graviton resonances in 2-fermon channels

has 2 parameters;
mass of the first KK state
coupling strength of the graviton
(controls the width)



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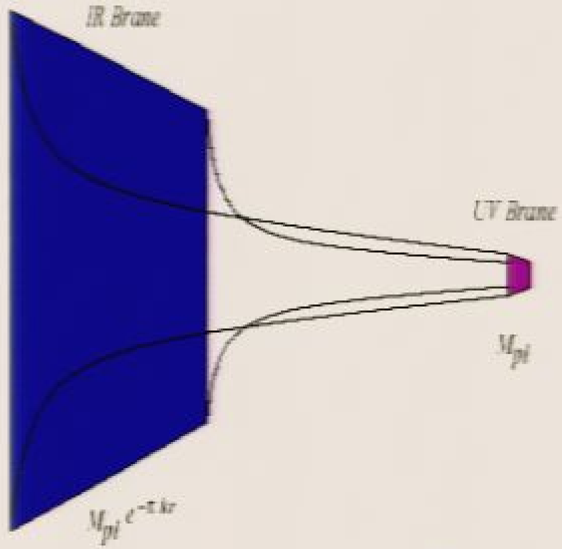
2 3+1 dimensional branes separated by a 5[th] dimension



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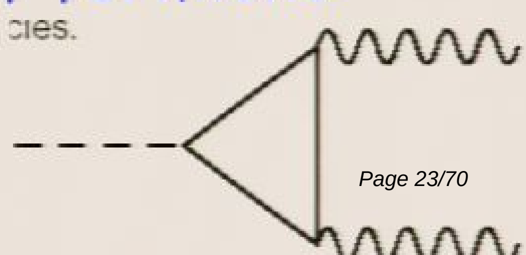
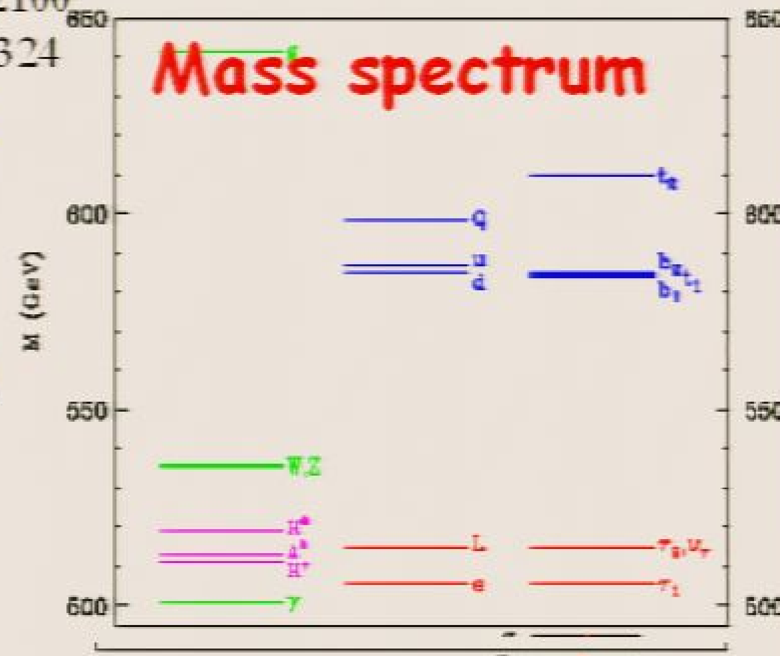
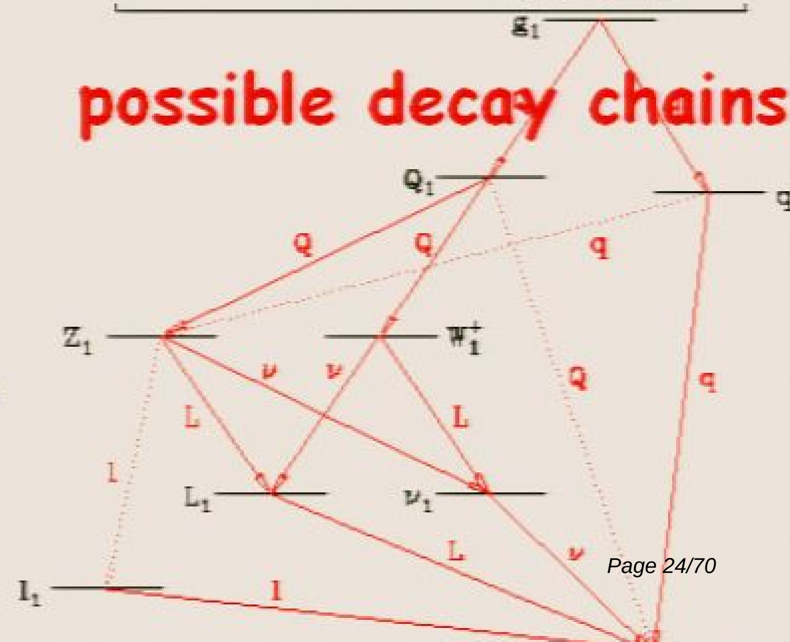


Universal Extra Dimensions

Appelquist, Cheng, Dobrescu, hep-ph/0012100
Cheng, Matchev, Schmaltz, hep-ph/0204324





ll SM particles propagate in the bulk

K towers for SM particles with
spin quantum numbers identical to SM
particles

Spectrum resembles that of SUSY

Have conservation of KK number at
ree level leading to KK parity = $(-1)^n$

Ensures that lightest KK partners are
lways pair produced
So lightest KK particle is stable

New s-channel Resonances

New s-channel structure at ~TeV scale appear in almost all models

Spin 1 appear in many models:

- Z' in string inspired models
- Z', W' in extended gauge sectors
- Z_R, W_R in left-right symmetric models
- Z_H, W_H in Little Higgs Models
- Z_{KK}, γ_{KK}, W_{KK}, in theories with extra dimensions

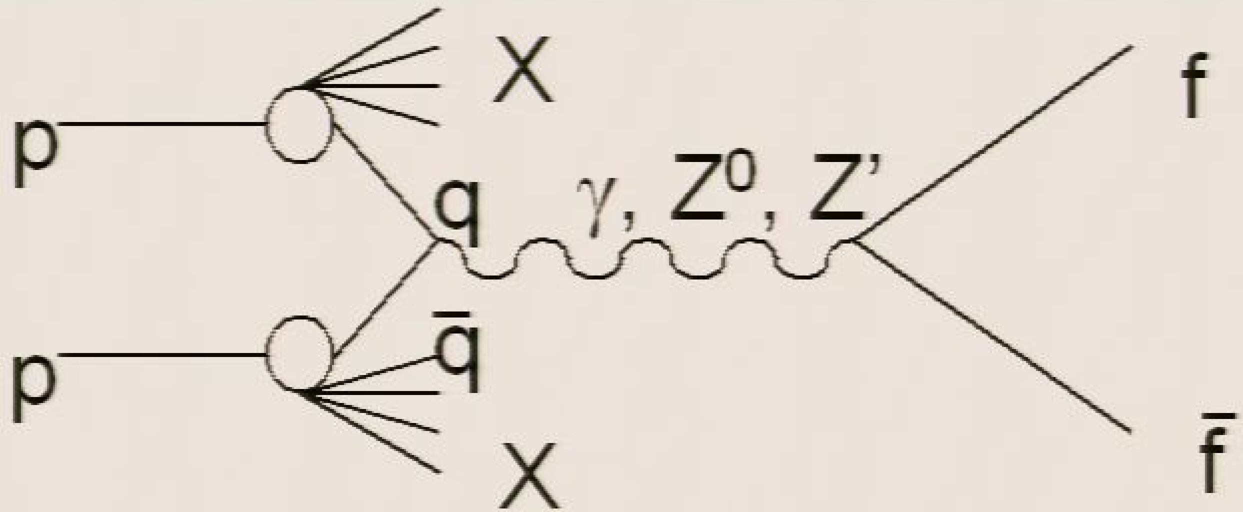
And scalar states:

- Scalars (Higgs bosons)
- Radions
- Graviscalars
- SUSY neutrilino

Also possible higher spin states:

- Gravitons in theories with extra dimensions
- String resonances

Z' Production at Hadron Colliders



$$\frac{d\sigma}{dy\,dM\,d\cos\theta^*} = \frac{2\pi\alpha_{em}^2 x_A x_B}{3M^3}\sum_q [(1+\cos^2\theta^*)S_q G_q^+ + 2\cos\theta^* A_q G_q^-]$$

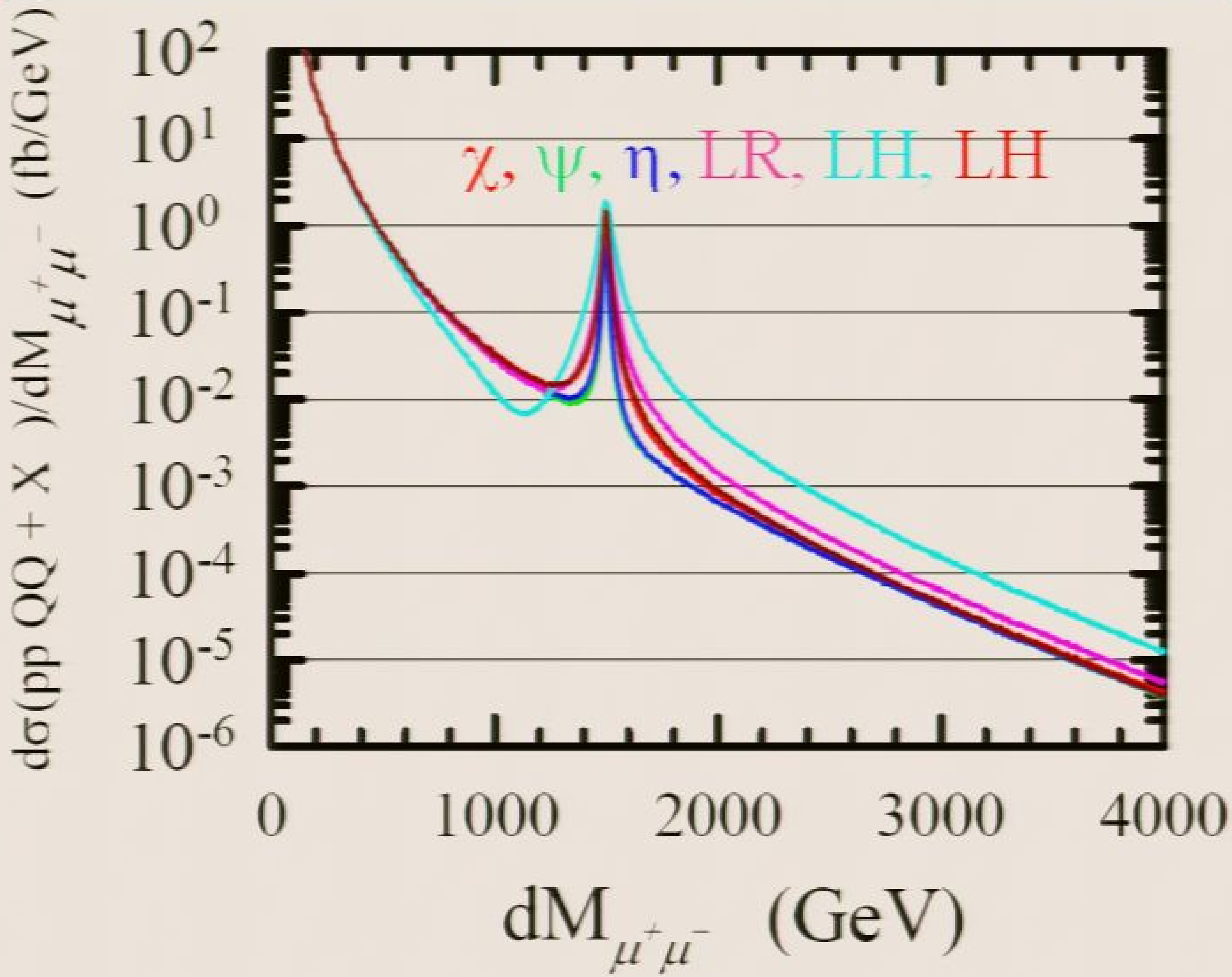
$$S_q, A_q = \left(\frac{g}{e}\right)^4 \frac{\hat{s}^2}{(\hat{s}-M^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}({C_L^f}^2 \pm {C_R^f}^2)({C_L^q}^2 \pm {C_R^q}^2)$$

$$G_a^\pm = [f_{q/A}(x_A) f_{\bar{q}/B}(x_B) \pm f_{\bar{q}/A}(x_A) f_{q/B}(x_B)]$$

$M_{Z'} = 1.5$ TeV

$p_T > 50$ GeV

$|\eta| < 2.5$



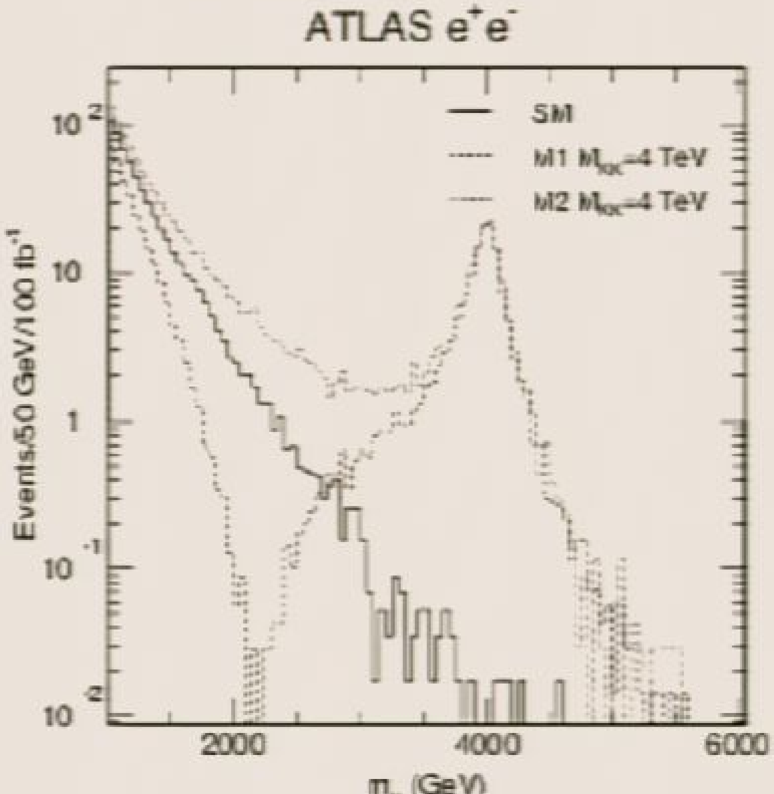
$$\frac{d\sigma}{dy} = \frac{\pi^2 \alpha_{em}^2 x_A x_B}{9 M_{Z'} \Gamma_{Z'}} \left(\frac{g_{Z'}}{e}\right)^4 ({C_L^f}^2 \pm {C_R^f}^2) \sum_q ({C_L^q}^2 \pm {C_R^q}^2) G_q^{\pm}$$

New Z' Gauge Bosons: Di-lepton Resonance Search

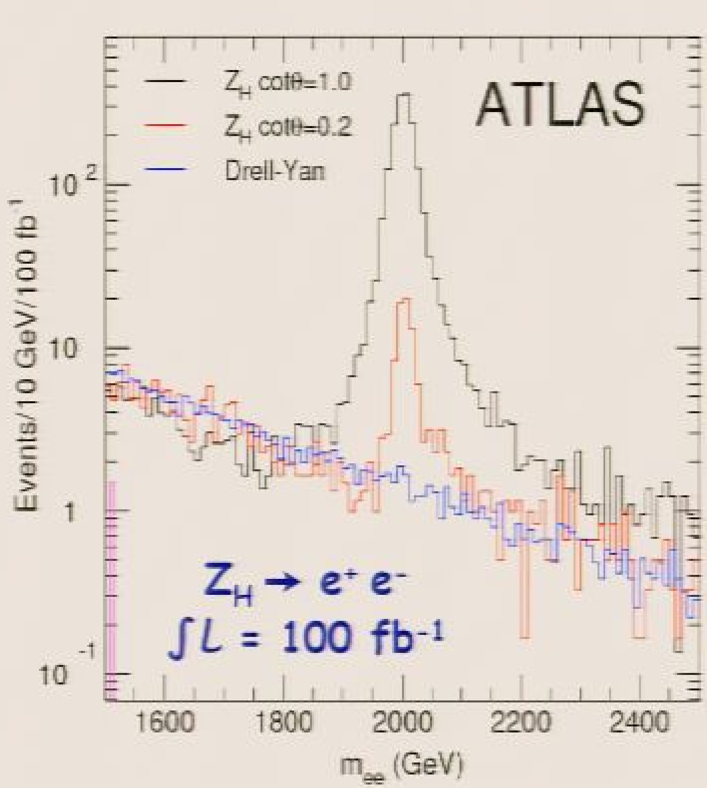
- Select 2 opposite sign high p_T isolated leptons and examine invariant mass distribution

KK in Extra Dimensions

Azuelos & Polesello, Eur. Phys. J C39, s2, s1 (2004)



Little Higgs Model A_H and Z_H



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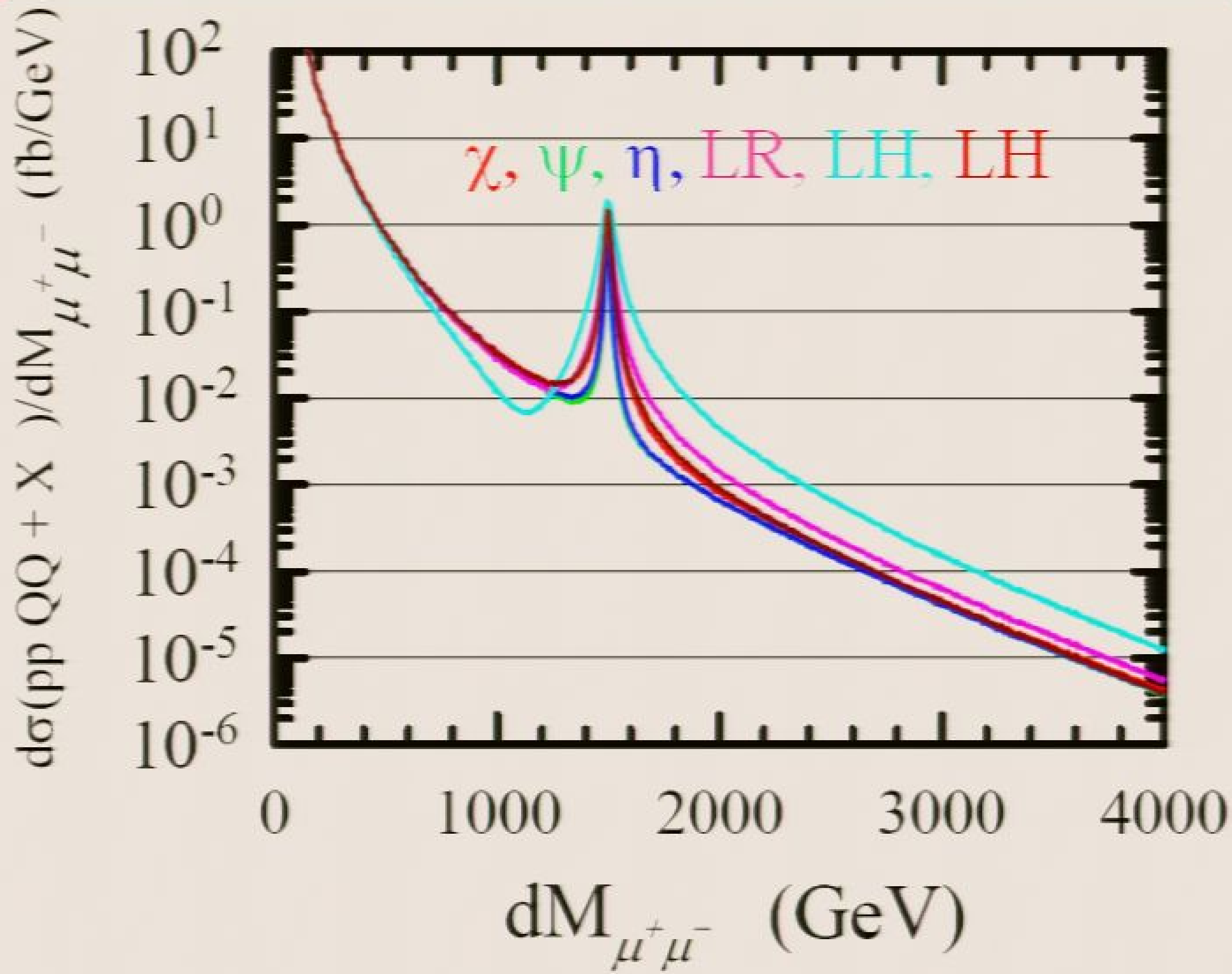

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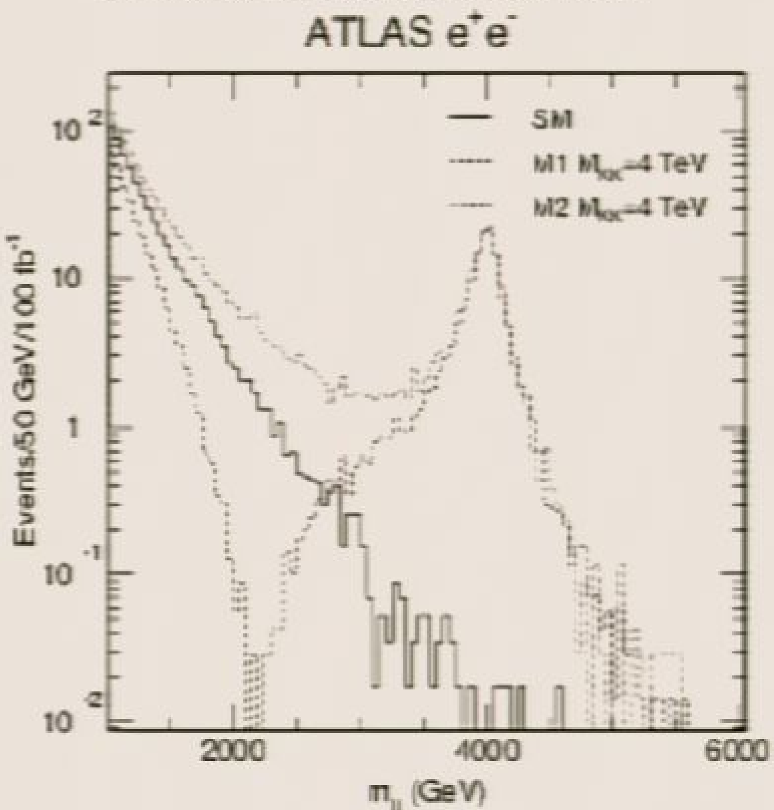

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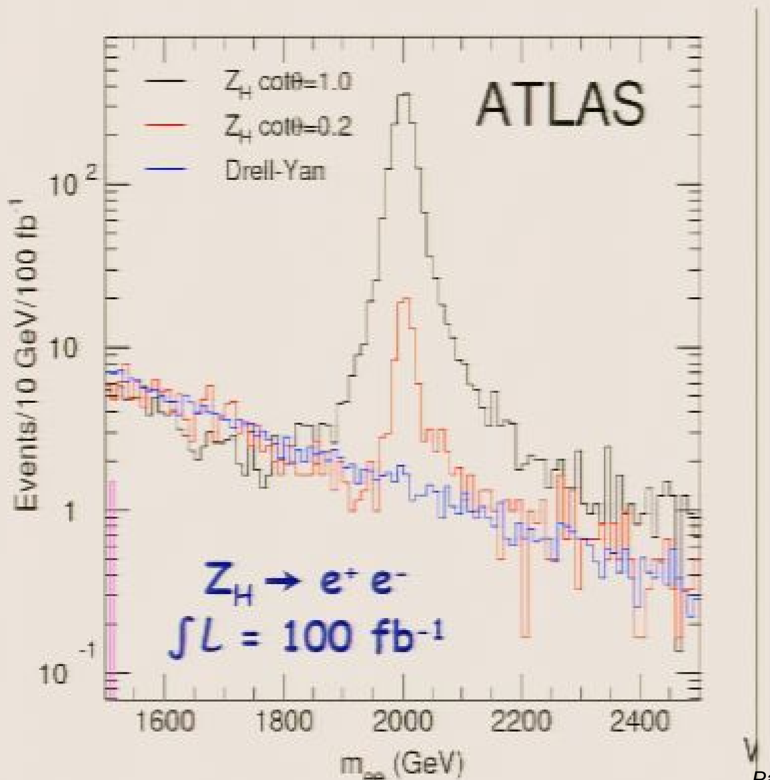
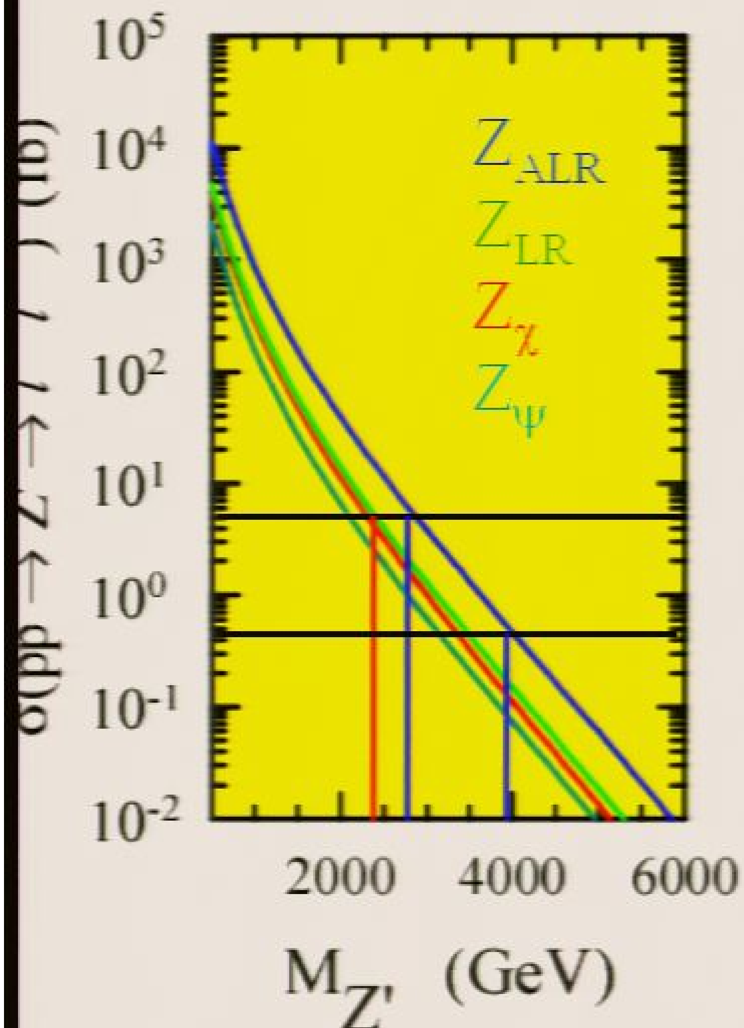
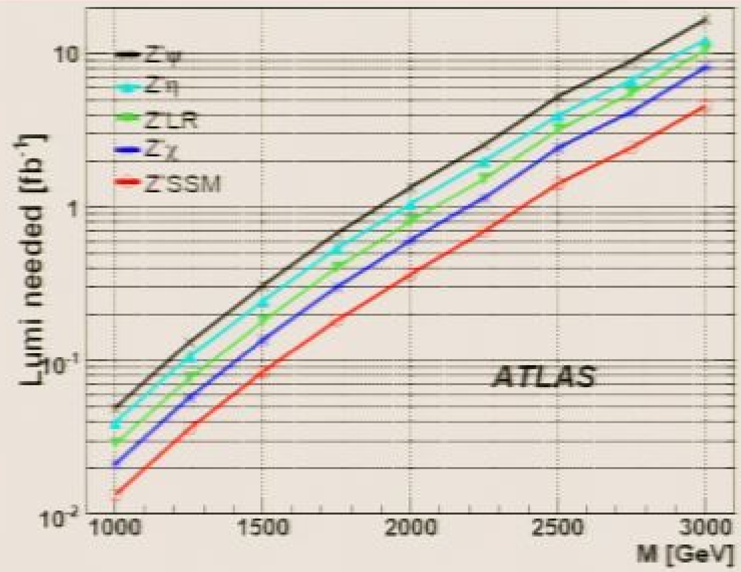
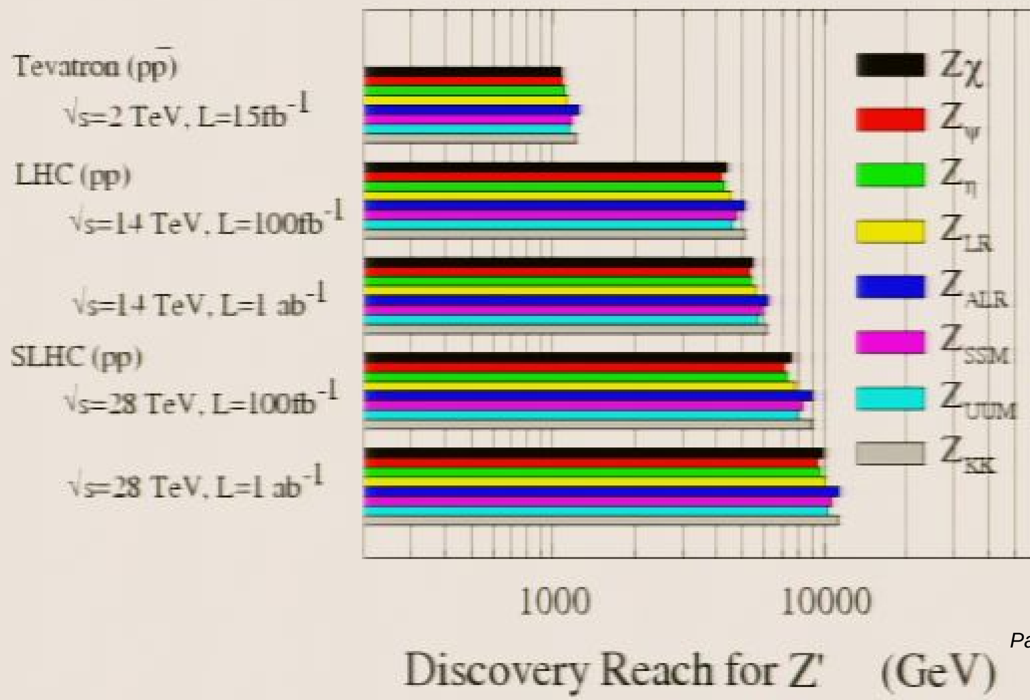


Discovery Limits New for Z' Gauge Bosons

Z'→μμ production







Di-lepton Resonance Search at the Tevatron

Select 2 opposite sign high p_T isolated leptons and examine invariant mass distribution

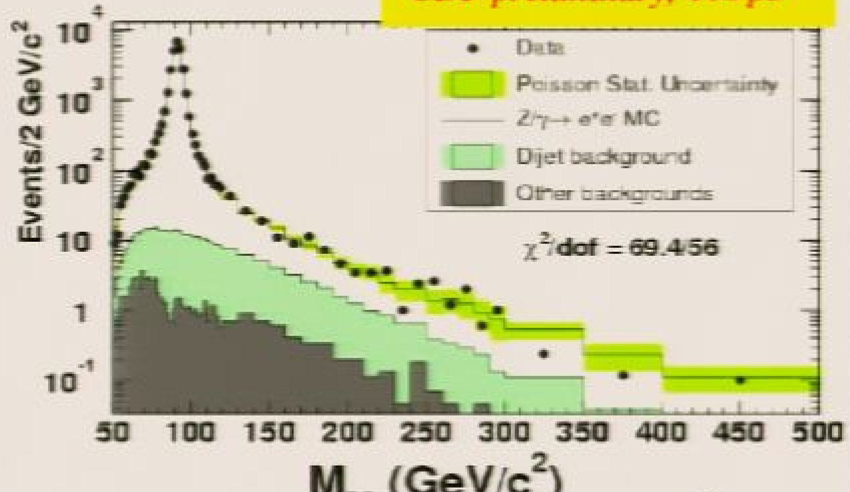
If you find a peak:

- quantify its significance
- Measure its $\sigma \times BR$

If you don't:

- Derive upper limit on $\sigma \times BR$
- Constrain models

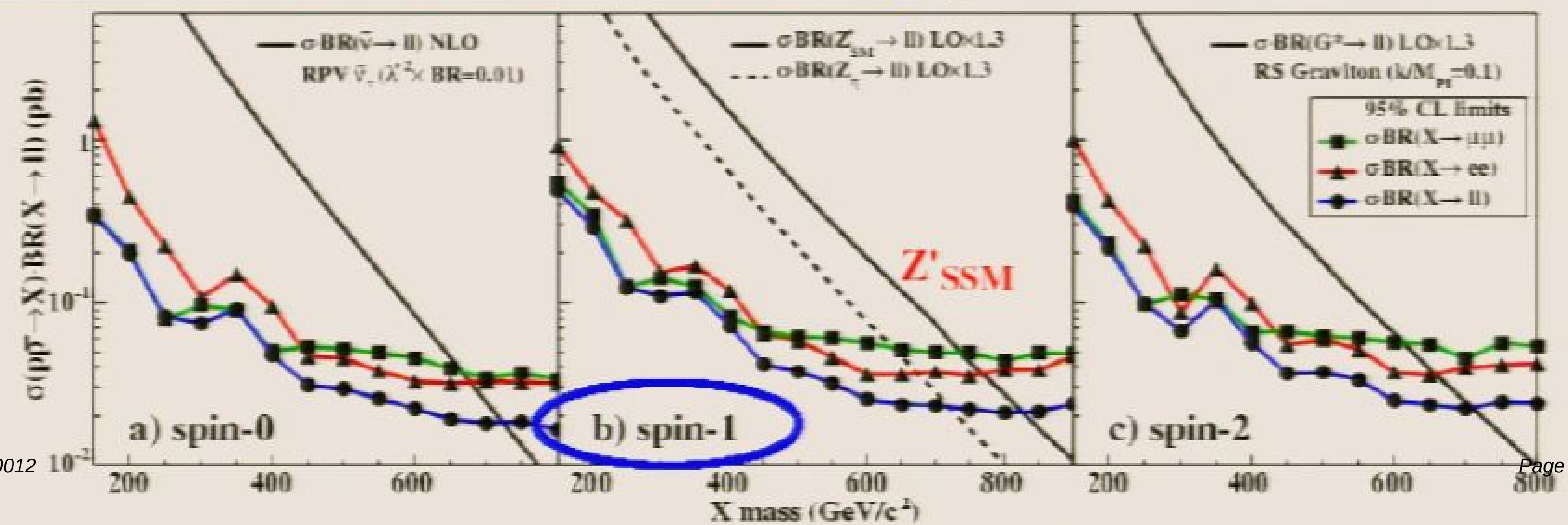
CDF preliminary, 448 pb^{-1}



Z′ Mass[6]

CDF, di-electrons and di-muons combined, 200 pb^{-1}

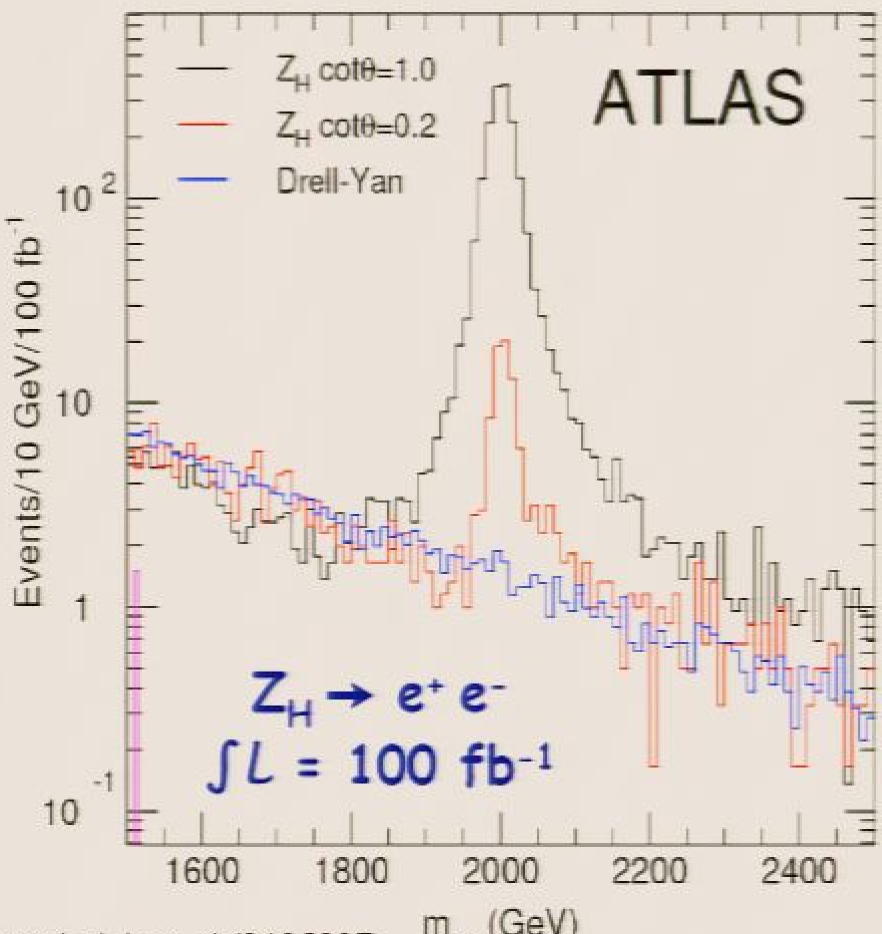
hep-ex/0507104



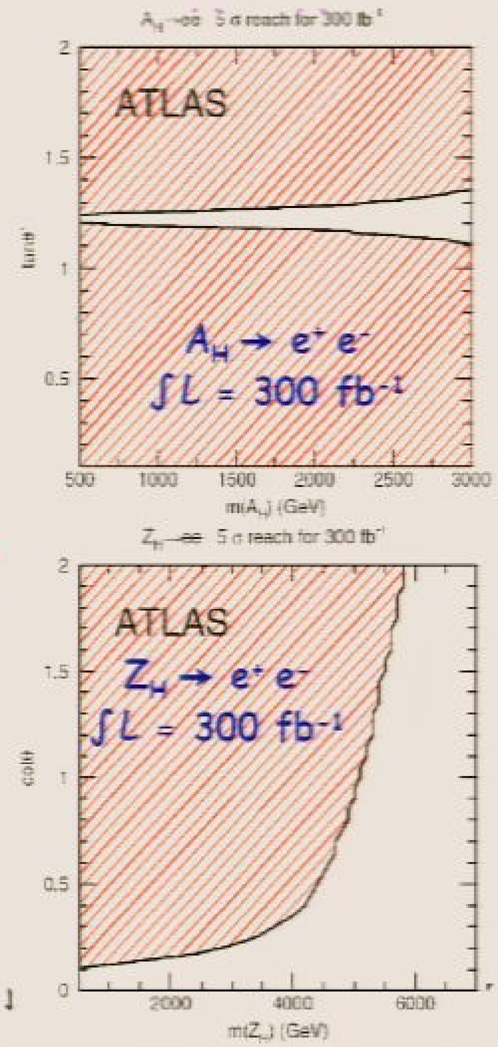
Little Higgs Model A_H and Z_H

Arkani-Hamed et al., Han et al.

Signal : di-lepton resonance



zuelos et al, hep-ph/0402037

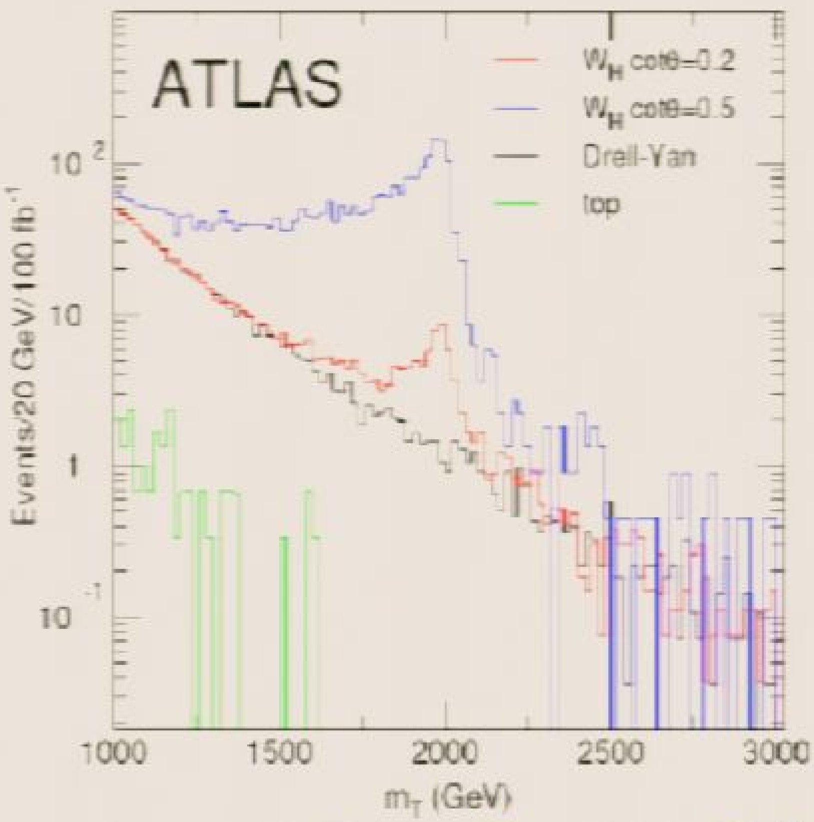


Reach up to 5.7 TeV depending on the θ angle

Little Higgs Model: W_H

$W_H \rightarrow e\upsilon$

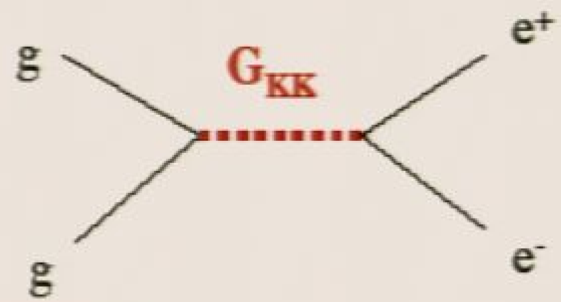
Background: $l\upsilon$ via virtual W, labeled Drell-Yan



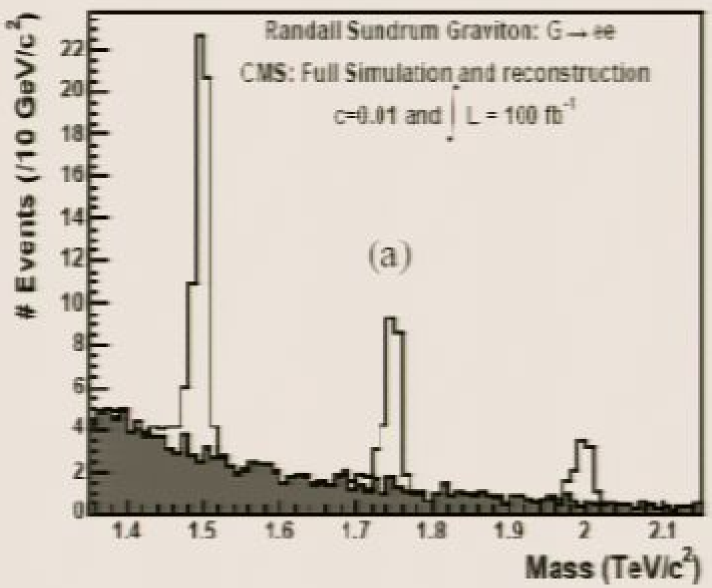
M_{WH} = 2 TeV, $\int L$ = 100 fb^{-1}

Randall Sundrum Gravitons

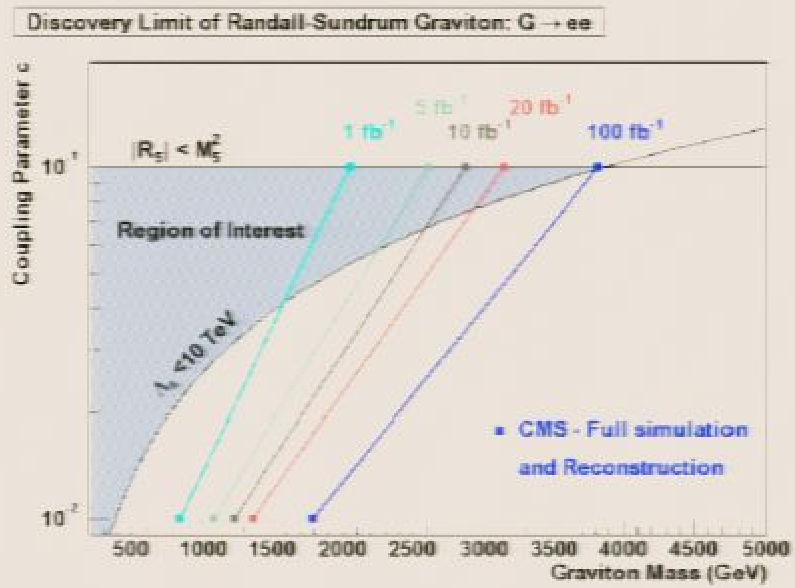
Study the channel pp→Graviton→ e+e-



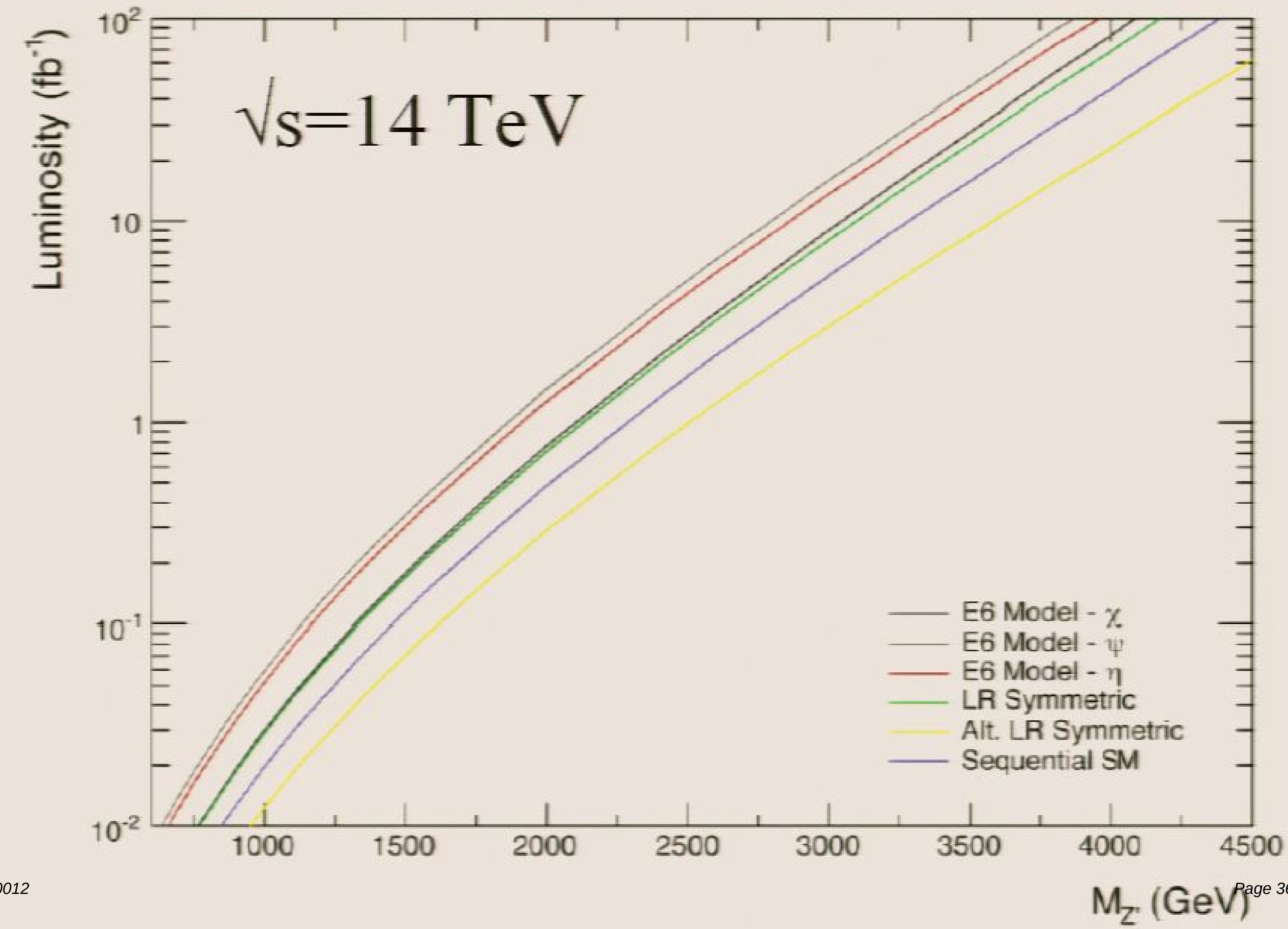
Signal + Drell-Yan background



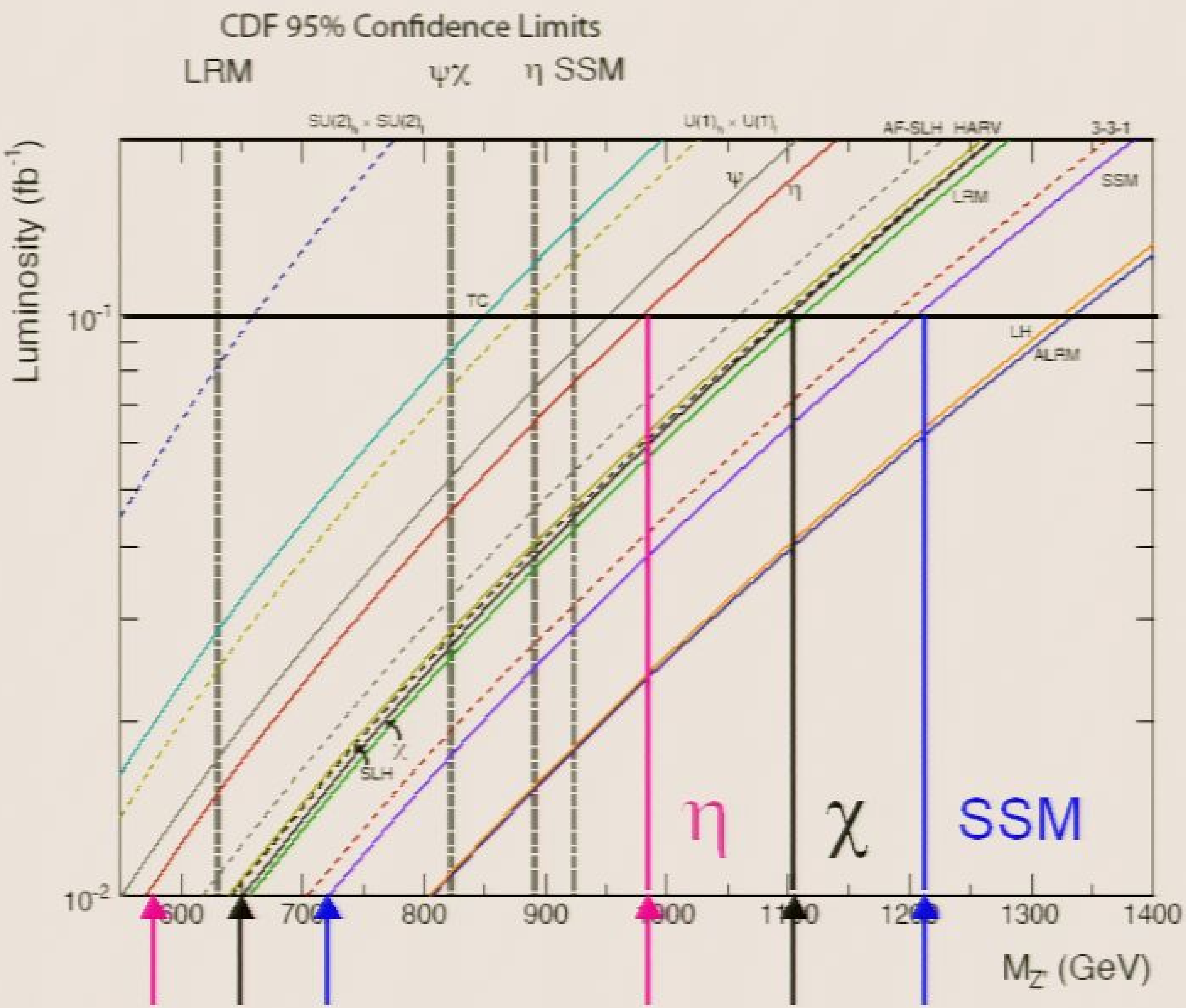
sensitivity



Discovery Reach at the LHC



√s=10 TeV


CDF 95% Confidence Limits
LRM
ψχ
η SSM
SU(2)_h × SU(2)_l
U(1)_h × U(1)_l
AF-SLH HARV
3-3-1
ψ
η
LRM
SSM
TC
LH
ALRM
SLH
χ
Luminosity (fb^-1)
10^-1
10^-2
600
700
800
900
1000
1100
1200
1300
1400
M_Z' (GeV)
η
χ
SSM

Limits on Z'

Model	Electroweak	e^+e^-	pp Tevatron	LHC $L=100fb^{-1}$
SSM	1500	1305	923	4800
LR	860	600	630	4300
χ	680	781	822	4200
ψ	481	475	822	3700
η	619	515	891	3900

PDG Phys. Lett. B667, 1 (2008)

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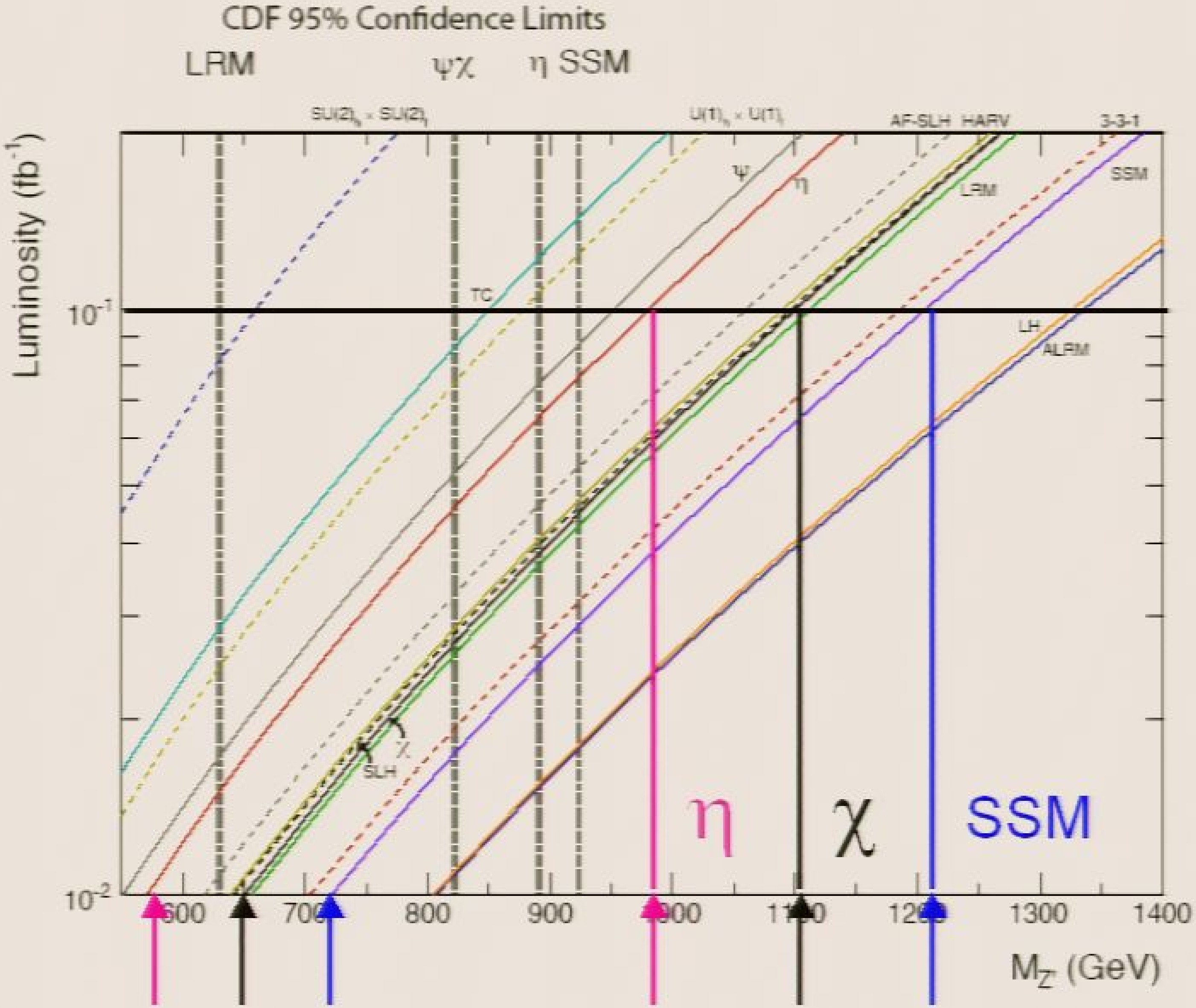

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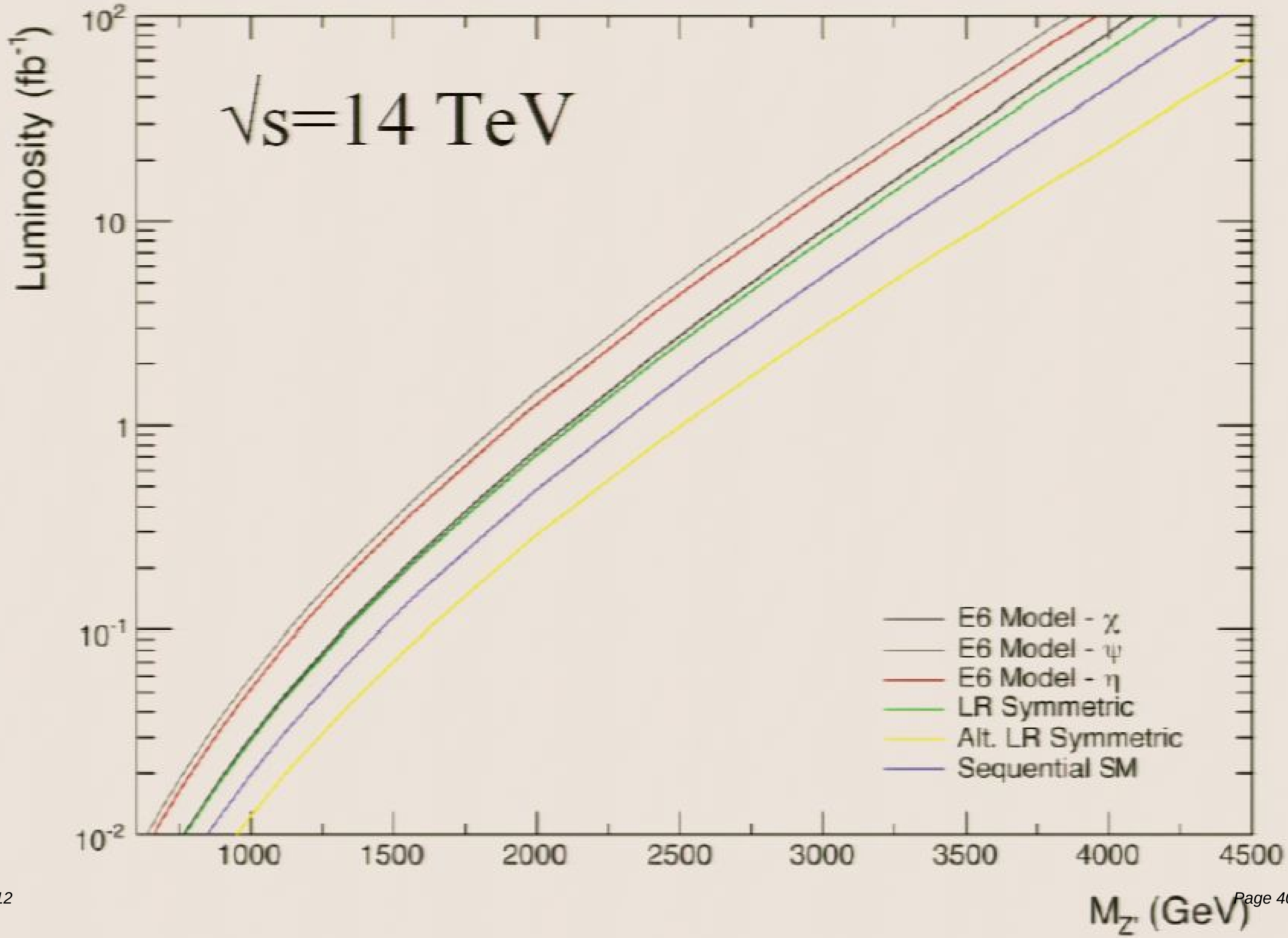

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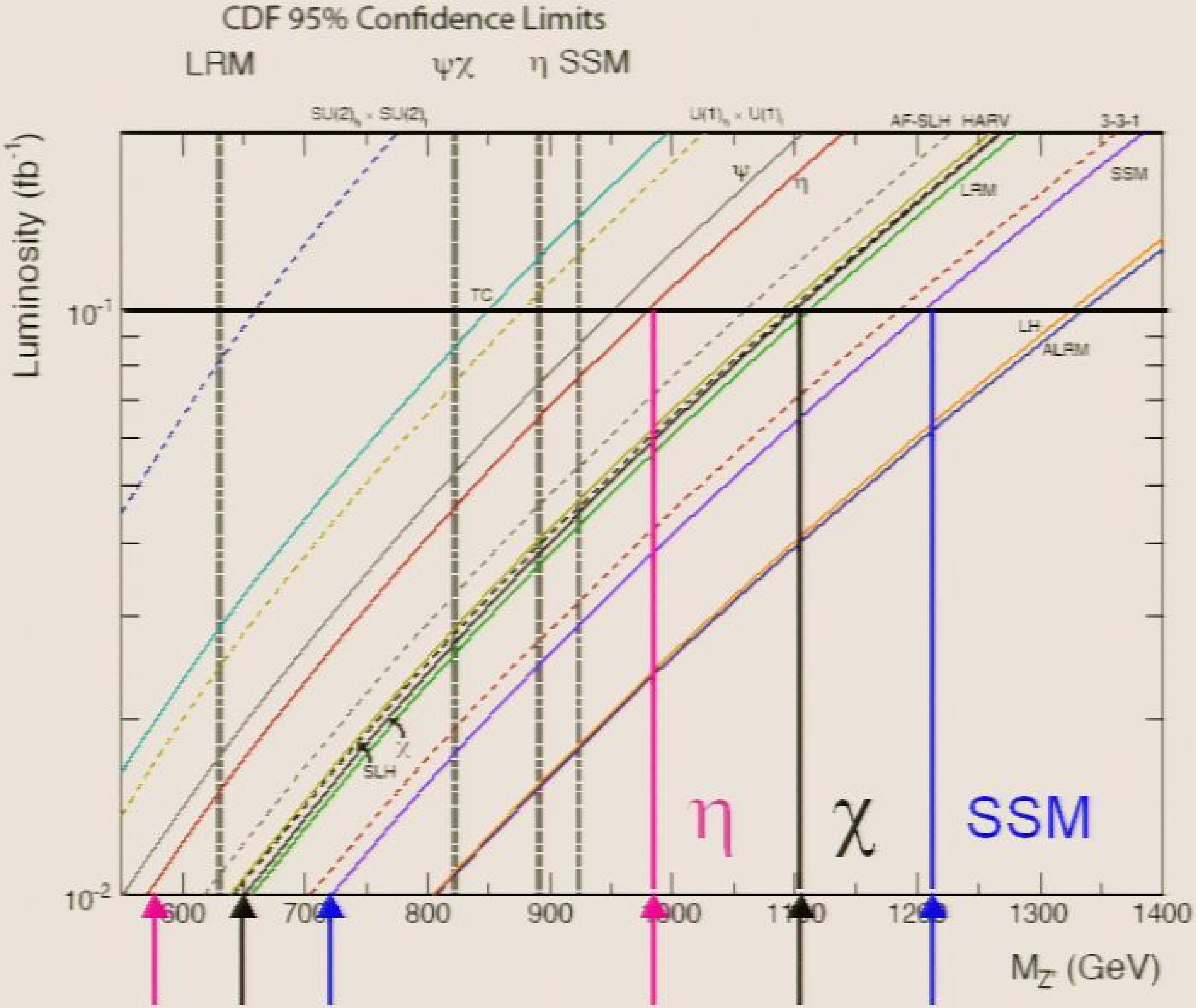
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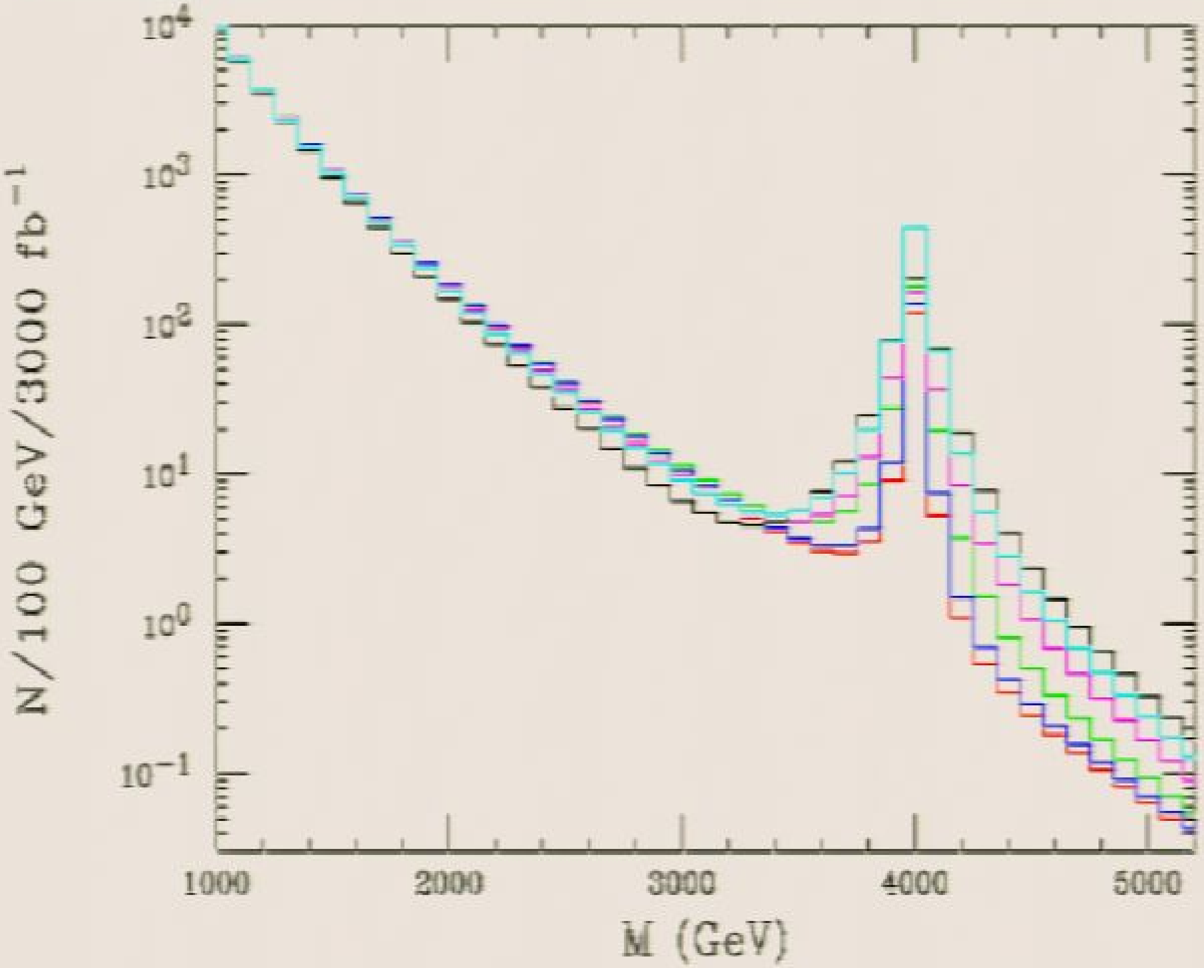
LHC Discovers S-channel Resonance !!



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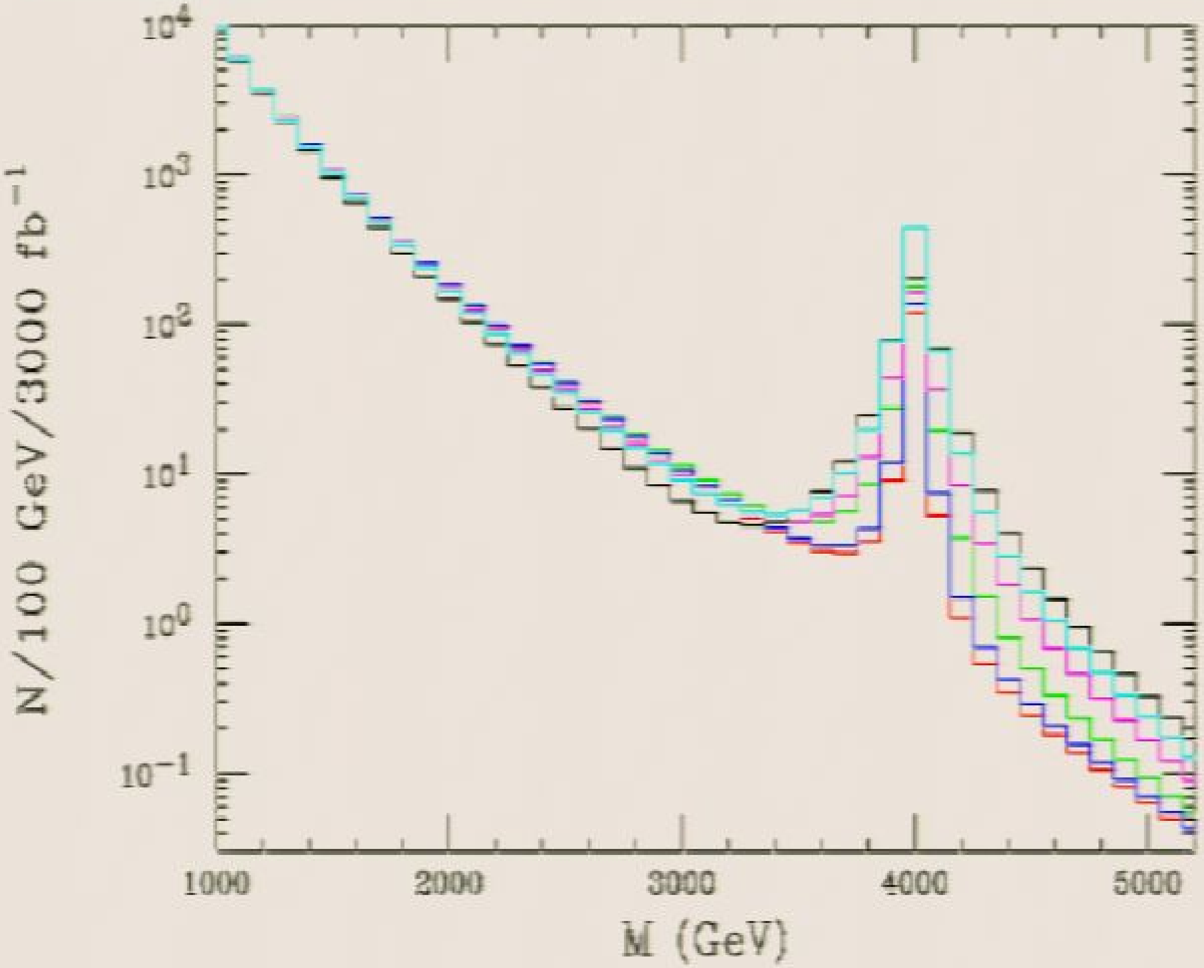

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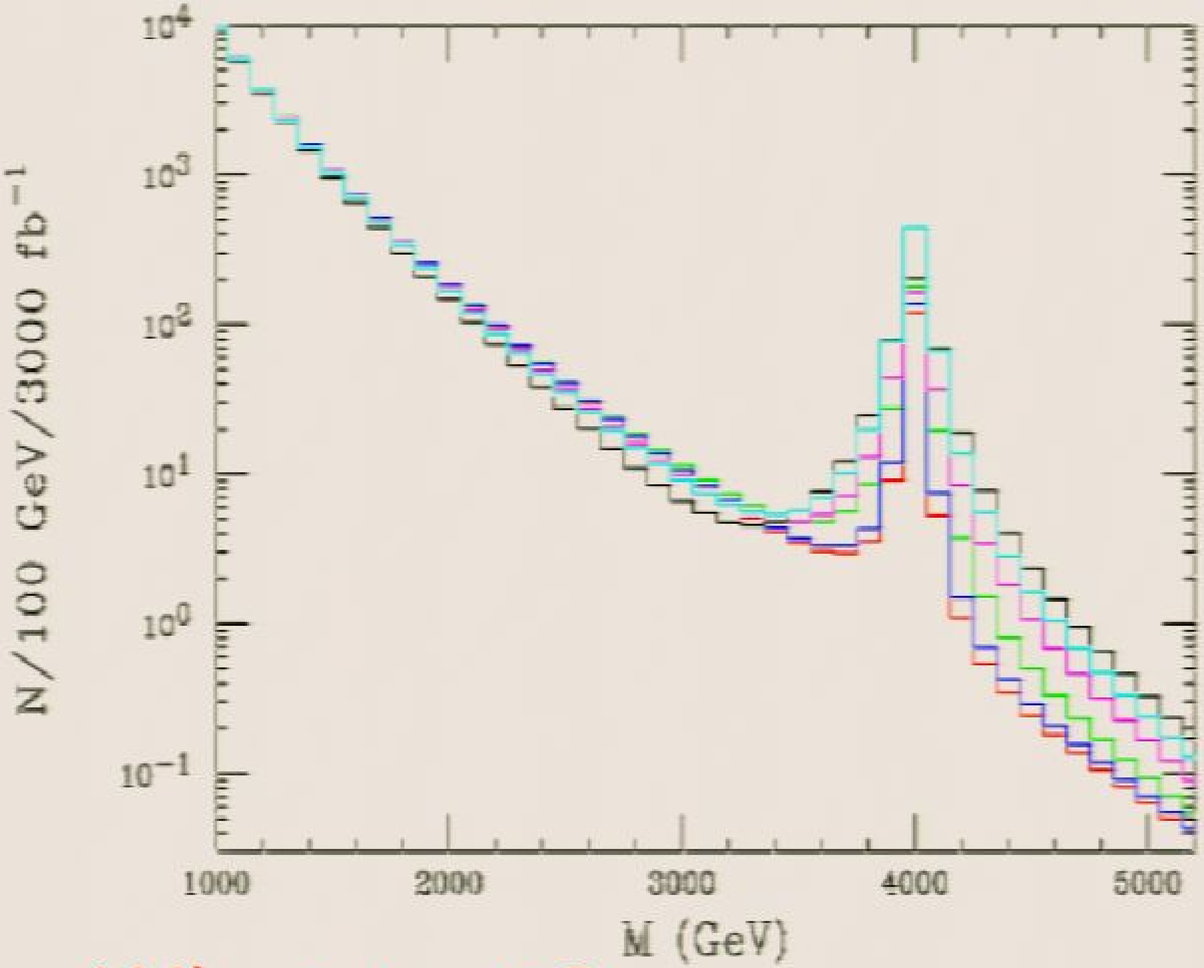


What is it?

Many possibilities for an s-channel resonances:

Z', A_H, Z_H, graviton, KK excitations, ...

How do we distinguish them?

Start by assuming the LHC discovers single rather heavy resonance

What is it?

Tools are:

- Cross sections & Widths

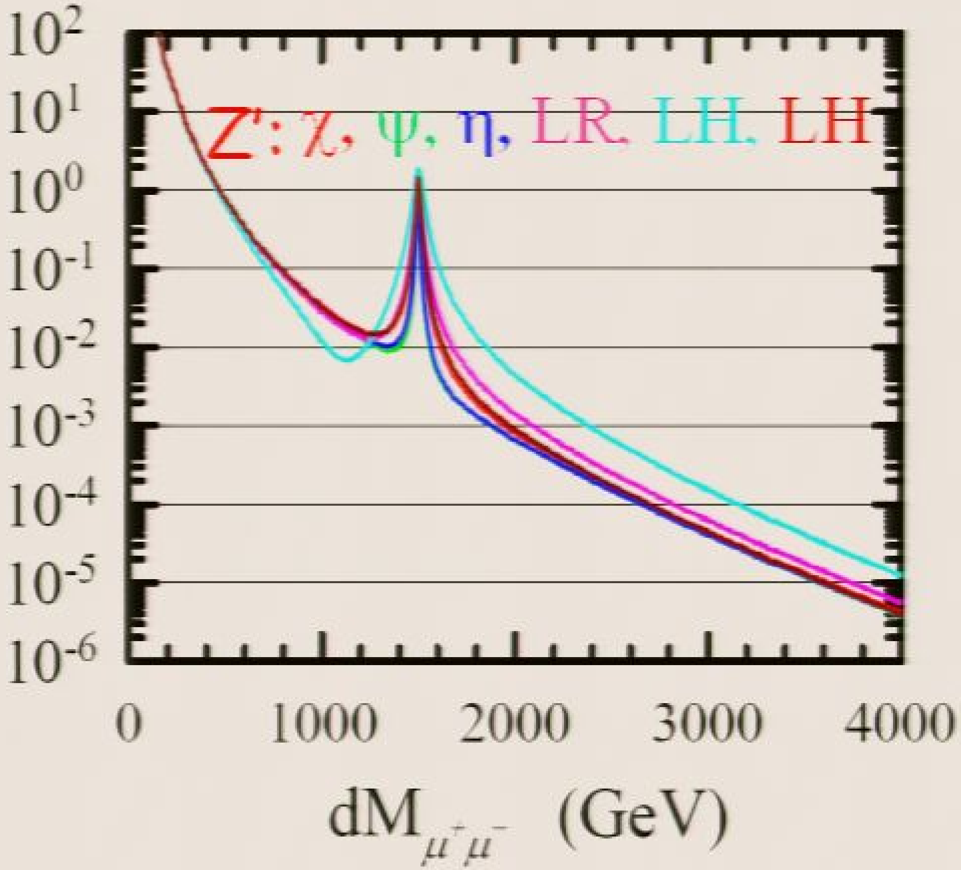
$$\sigma(pp \to Z' \to l^+l^-) \simeq \sigma(pp \to Z')B(Z' \to l^+l^0)$$

$$\sigma(pp \to Z' \to l^+l^-)\Gamma_{Z'} \text{ is independent of B}$$

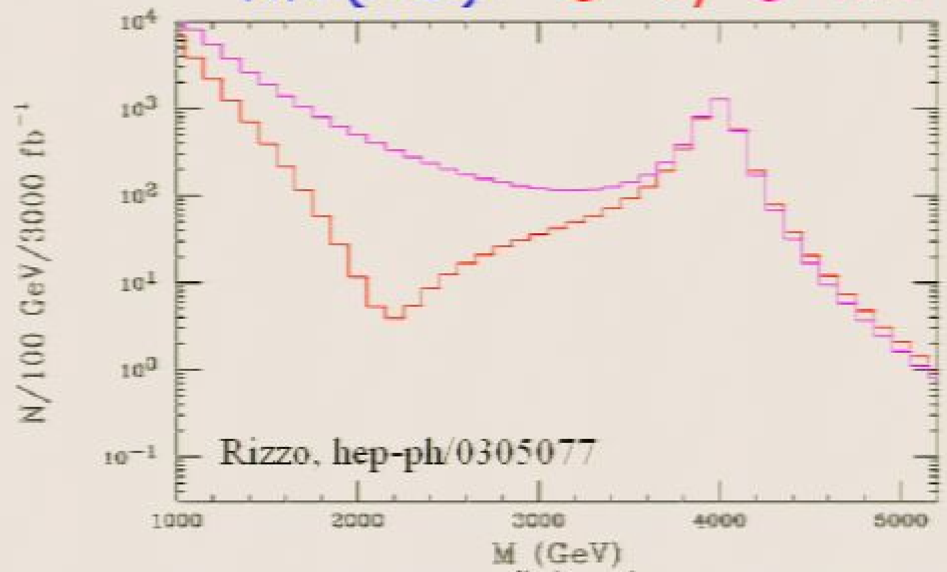
$$\Gamma(Z' \to f\bar{f}) = M_{Z'}g_{Z'}^2({C_L^f}^2 + {C_R^f}^2)/24\pi$$

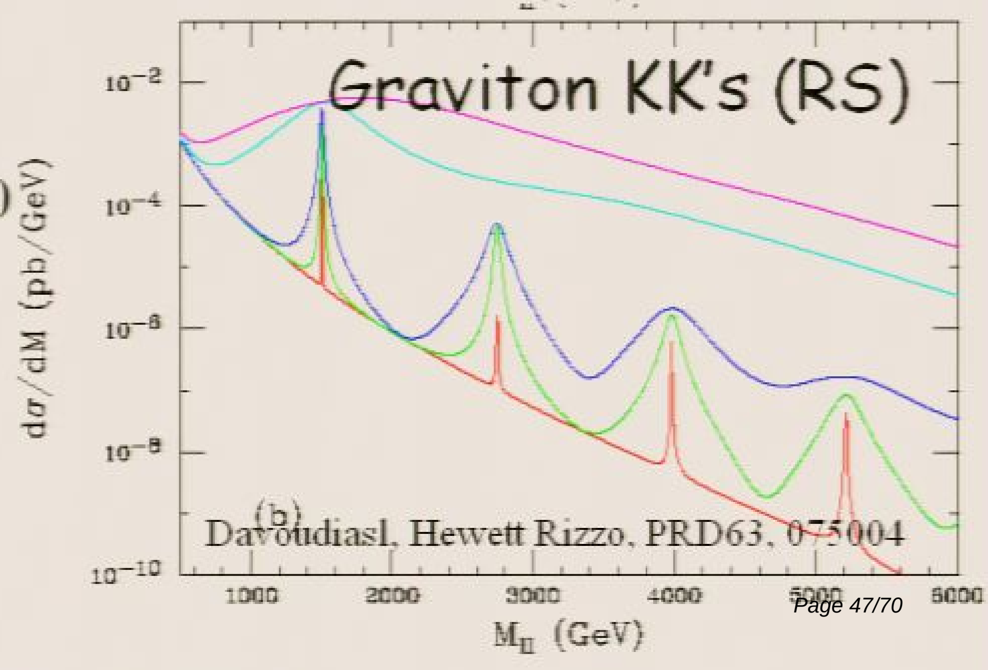
- Angular Distributions
- Rapidity Distributions
- Couplings (decays, polarization...)
- etc

M_{ll} distribution gives some information



KK (RS): D=0, D=πR



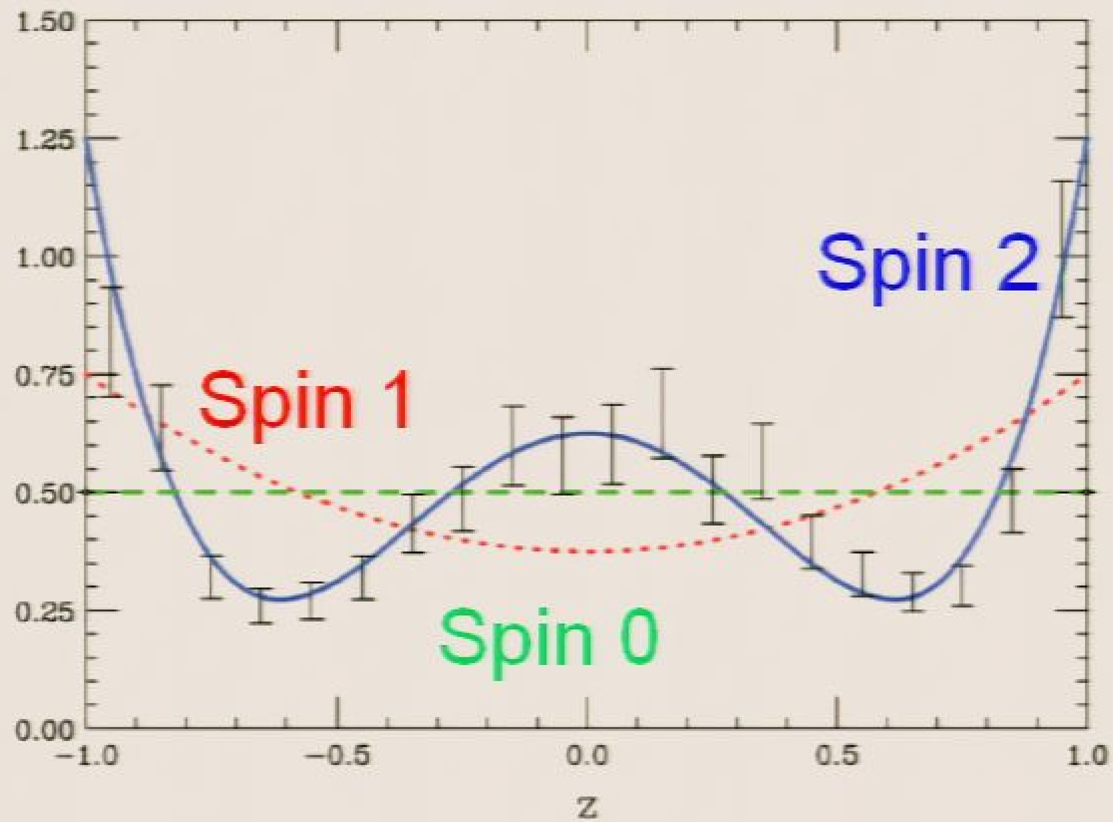


Use angular distributions to determine spin

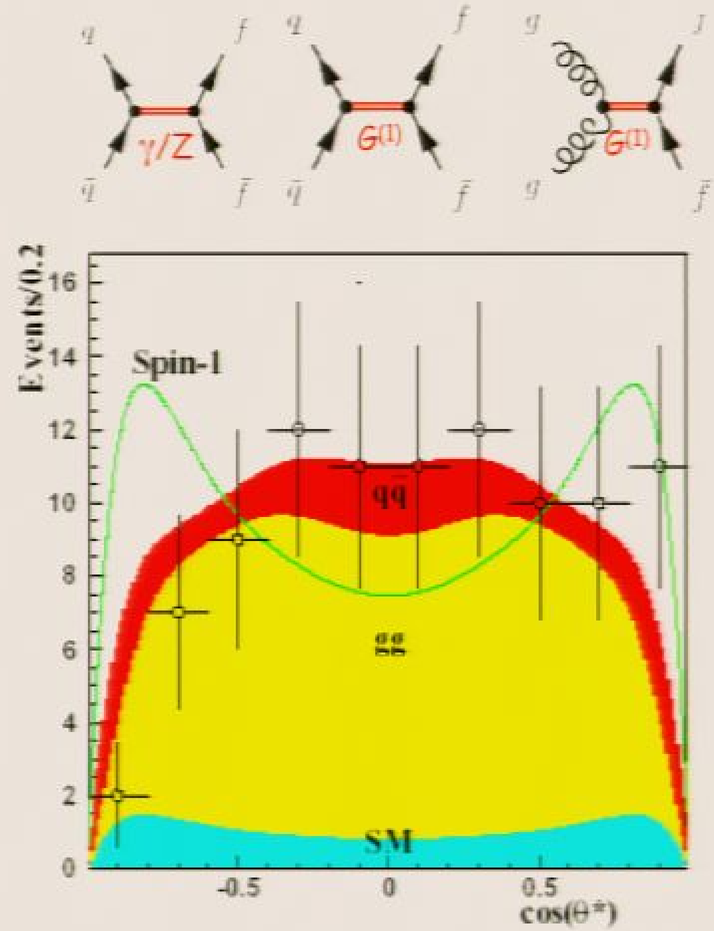
We observe a peak in di-lepton spectrum

- Is it a new gauge boson or a RS KK excitation?

⇒ Use angular distributions to study the spin of the object



Rizzo [hep-ph/0610104]



Allanach et al [hep-ph/0006114]

$$\frac{d\sigma}{dydMd\cos\theta^*} = \frac{2\pi\alpha_{em}^2 x_A x_B}{3M^3}\sum_q [(1+\cos^2\theta^*)S_q G_q^+ + 2\cos\theta^* A_q G_q^-]$$

$$S_q, A_q = \left(\frac{q}{e}\right)^4 \frac{\hat{s}^2}{(\hat{s}-M^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}(C_L^{f\,2} \pm C_R^{f\,2})(C_L^{q\,2} \pm C_R^{q\,2})$$

$$G_a^\pm = [f_{q/A}(x_A) f_{\bar{q}/B}(x_B) \pm f_{\bar{q}/A}(x_A) f_{q/B}(x_B)]$$

$$\frac{d\sigma^\pm}{dydM} = \frac{d\sigma^F}{dydM} \pm \frac{d\sigma^B}{dydM} = \left[\int_0^1 \pm \int_{-1}^0\right] d\cos\theta^* \frac{d\sigma}{dydMd\cos\theta^*}$$

narrow width approximation:

$$\frac{d\sigma^\pm}{dy} \sim (C_L^{f\,2} \pm C_R^{f\,2})\sum_q (C_L^{q\,2} \pm C_R^{q\,2}) G_q^\pm$$

is the rapidity of the Z', M the invariant mass of final state ermions

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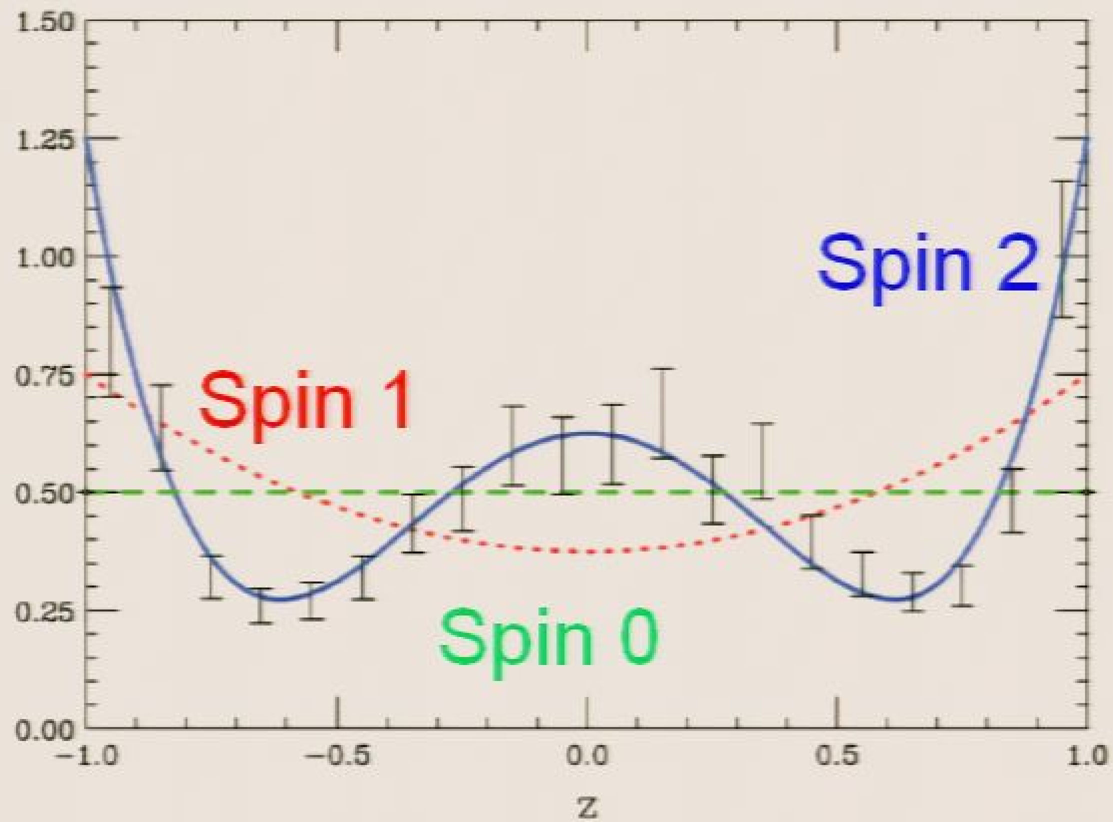

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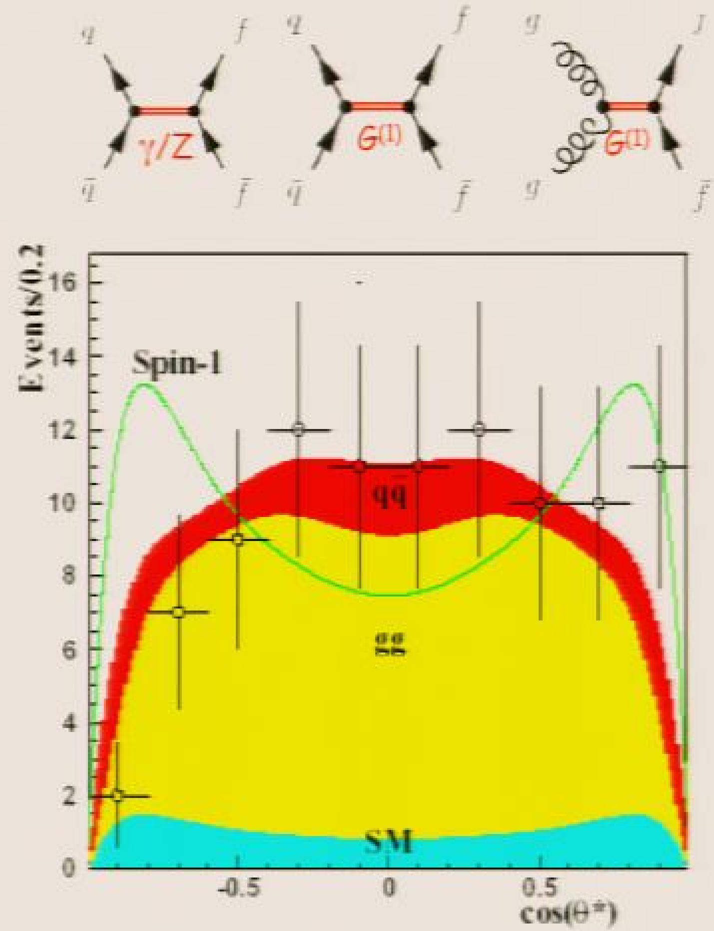

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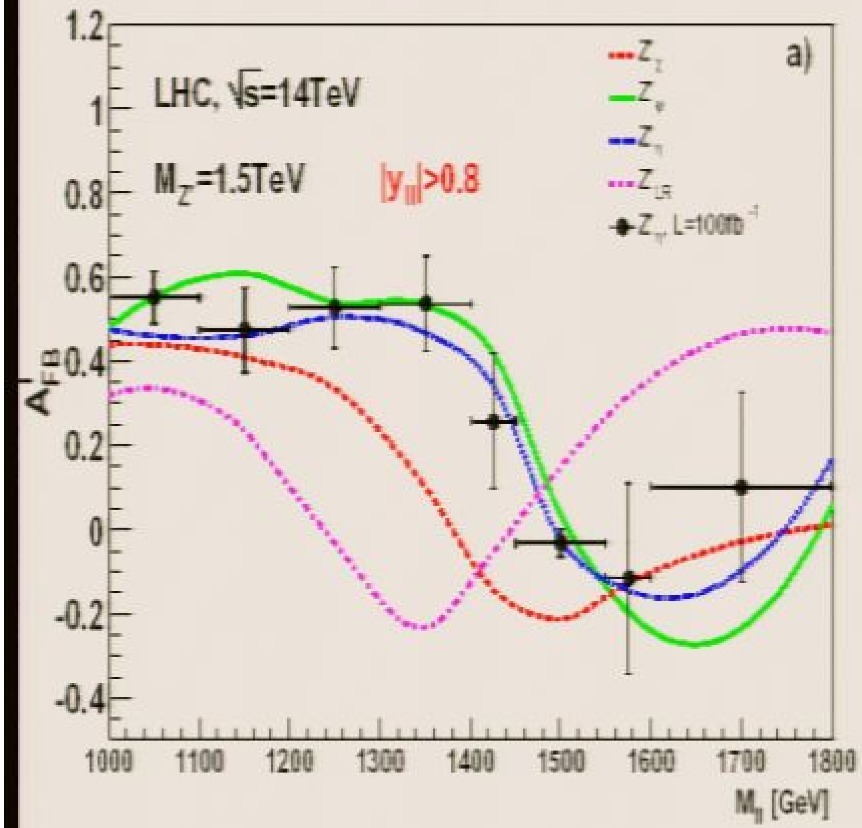
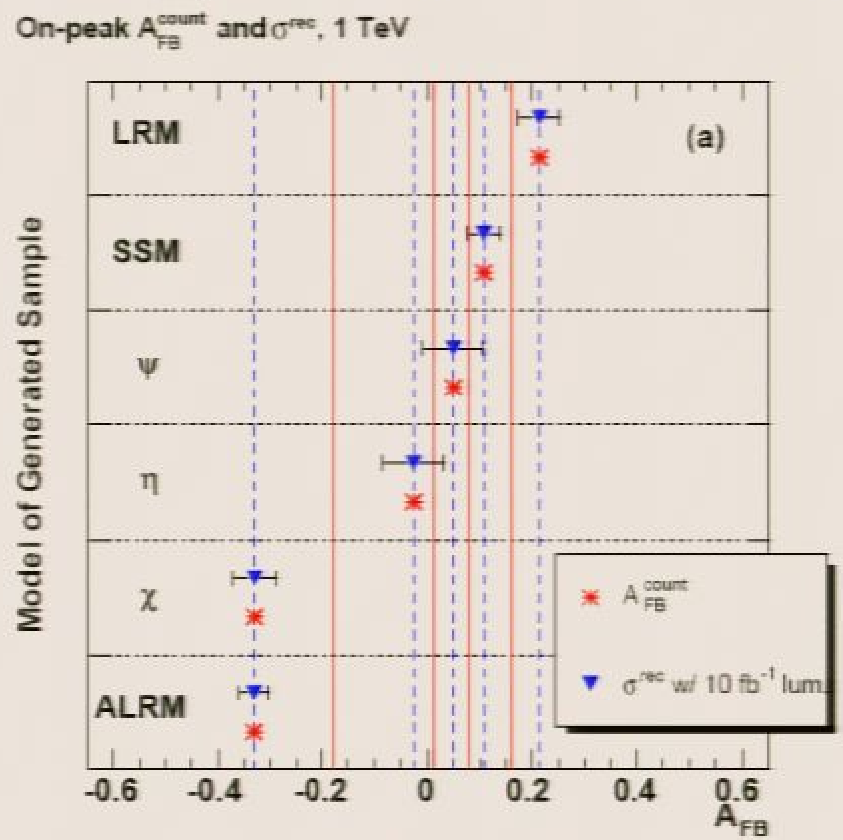
Forward Backward Asymmetry: A_{FB}

$$A_{FB} = \frac{\left[\int_o^{y_{max}} - \int_{-y_{max}}^{0}\right] \frac{d\sigma^-}{dy} dy}{\int_{-y_{max}}^{y_{max}} \frac{d\sigma^+}{dy} dy} \sim \left(\frac{C_L^{f\,2} - C_R^{f\,2}}{C_L^{f\,2} + C_R^{f\,2}}\right) \left(\frac{\sum_q G_q^-(C_L^{f\,2} - C_R^{f\,2})}{\sum_q G_q^+(C_L^{f\,2} + C_R^{f\,2})}\right)$$



Dittmar, Nicollerat, Djouadi, hep-ph/0307020



Cousings, Mumford, Tucker, Valuev CMS Note 2006/070

LHC can resolve to some extent

$$\frac{d\sigma}{dydMd\cos\theta^*} = \frac{2\pi\alpha_{em}^2 x_A x_B}{3M^3}\sum_q[(1+\cos^2\theta^*)S_q G_q^+ + 2\cos\theta^* A_q G_q^-]$$

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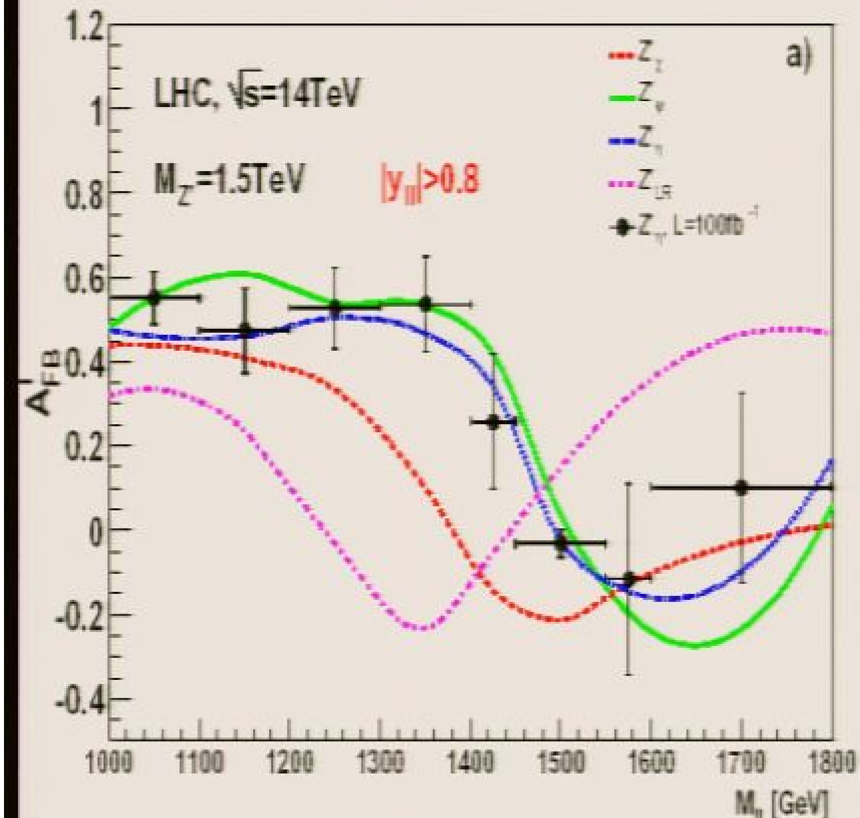
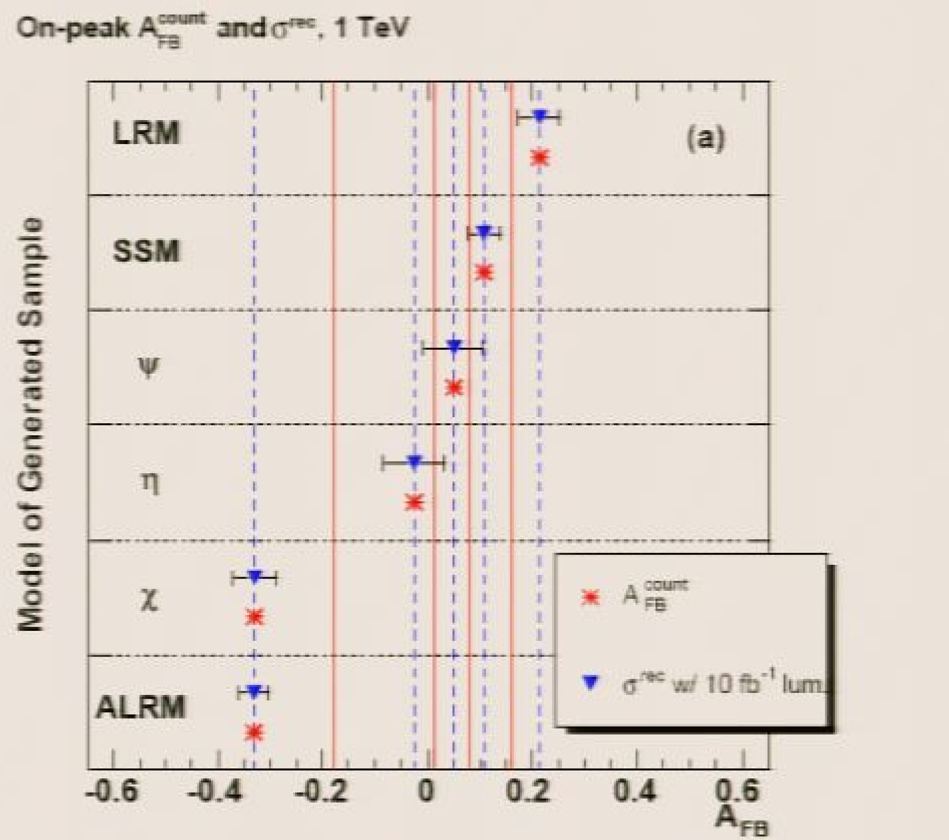


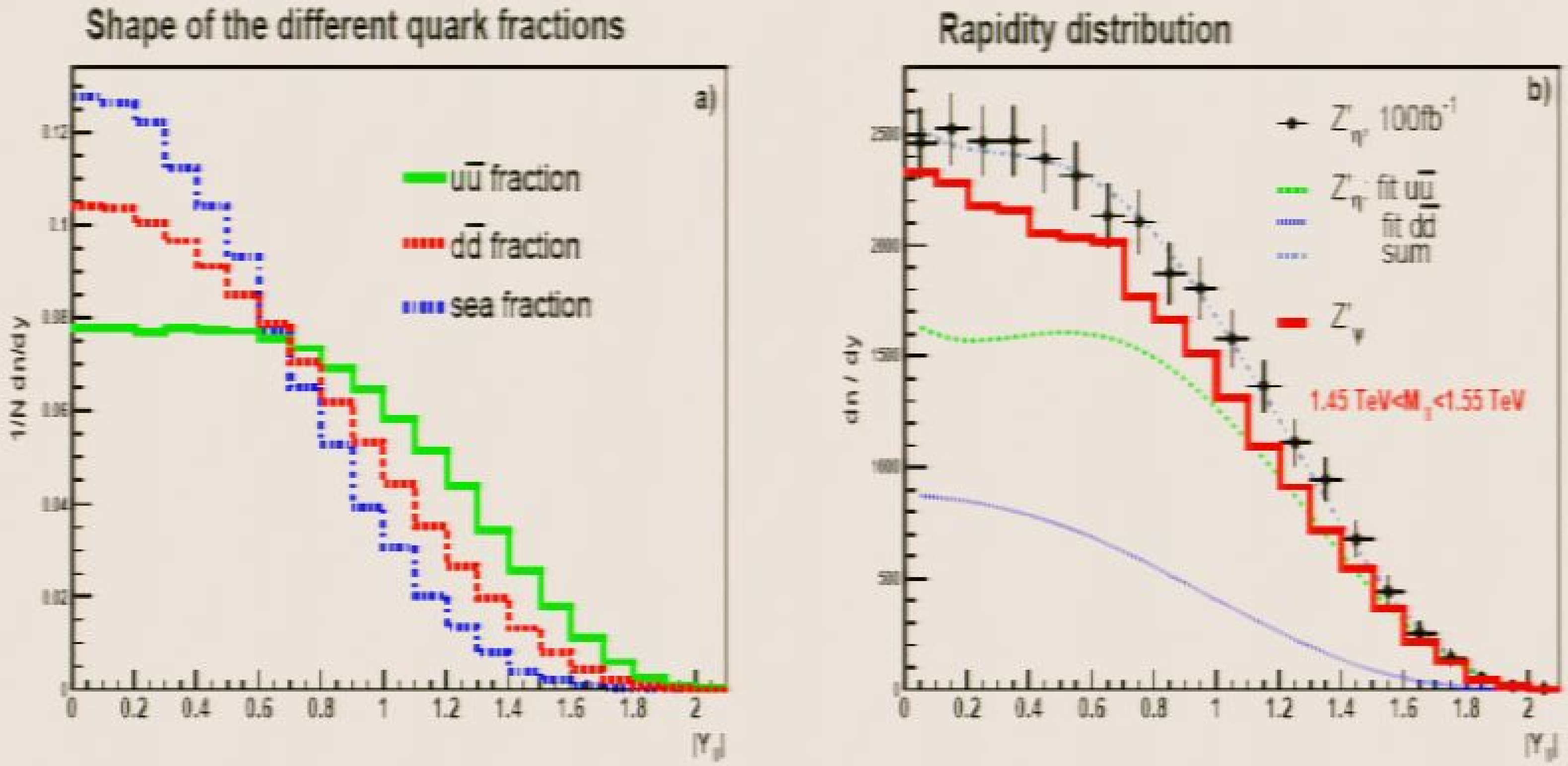
Dittmar, Nicollerat, Djouadi, hep-ph/0307020



Cousings, Mumford, Tucker, Valuev CMS Note 2006/070

LHC can resolve to some extent

Rapidity Binning: r_{y1}



Dittmar, Nicollerat, Djouadi, hep-ph/0307020

$$r_{y_1} = \frac{\int_{-y_1}^{y_1} \frac{d\sigma^+}{dy} dy}{\left[\int_{-y_{max}}^{-y_1} + \int_{y_1}^{y_{max}}\right] \frac{d\sigma^+}{dy} dy}$$

Combined Fits 1st Approach

etriello & Quackenbush PRD77, 115004 (2008) [see also Carena et al, PRD70, 093009 (2004)]

4 model dependent factors to determine:

$$c_q = \frac{M_{Z'}}{24\pi\Gamma}({C_R^q}^2 + {C_L^q}^2)({C_R^e}^2 + {C_L^e}^2) \quad q=u,d$$

$$e_q = \frac{M_{Z'}}{24\pi\Gamma}({C_R^q}^2 - {C_L^q}^2)({C_R^e}^2 - {C_L^e}^2)$$

Divide phase space into 4 regions in y and θ

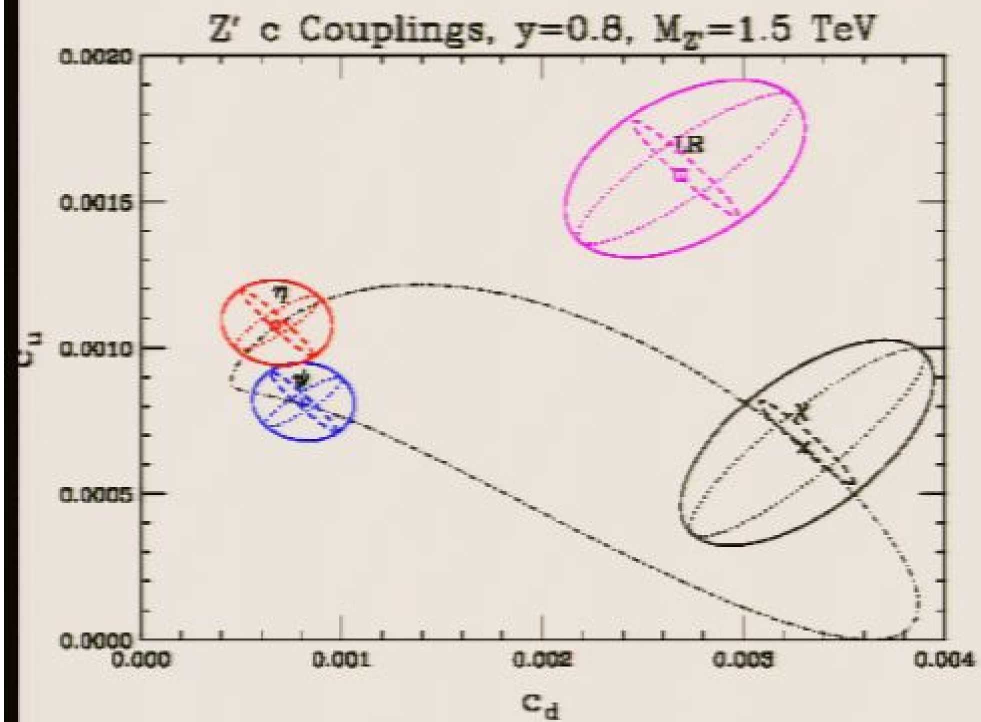
$$F_< = \int_{-y_1}^{y_1}\int_0^1 \frac{d\sigma}{dy\,d\cos\theta^*}dy$$

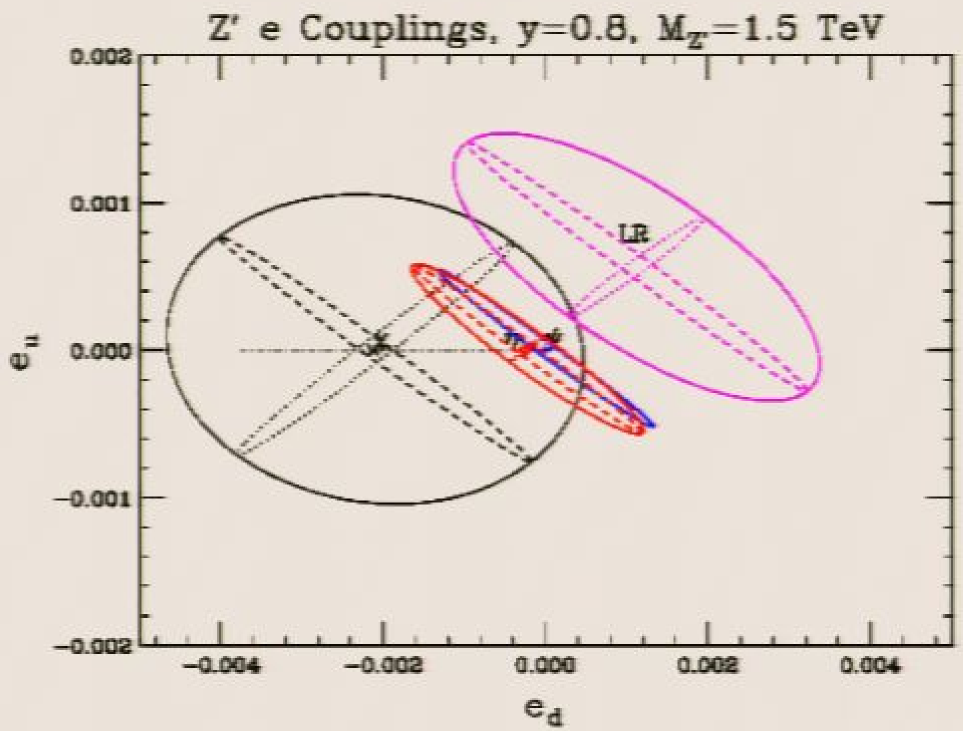
$$B_< = \int_{-y_1}^{y_1}\int_{-1}^0 \frac{d\sigma}{dy\,d\cos\theta^*}dy$$

$$F_> = \left(\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1}\right)\int_0^1 \frac{d\sigma}{dy\,d\cos\theta^*}dy$$

$$B_> = \left(\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1}\right)\int_{-1}^0 \frac{d\sigma}{dy\,d\cos\theta^*}dy$$

Calculate the model independent stuff
then fit to 4 coupling factors





L=100 fb^{-1}

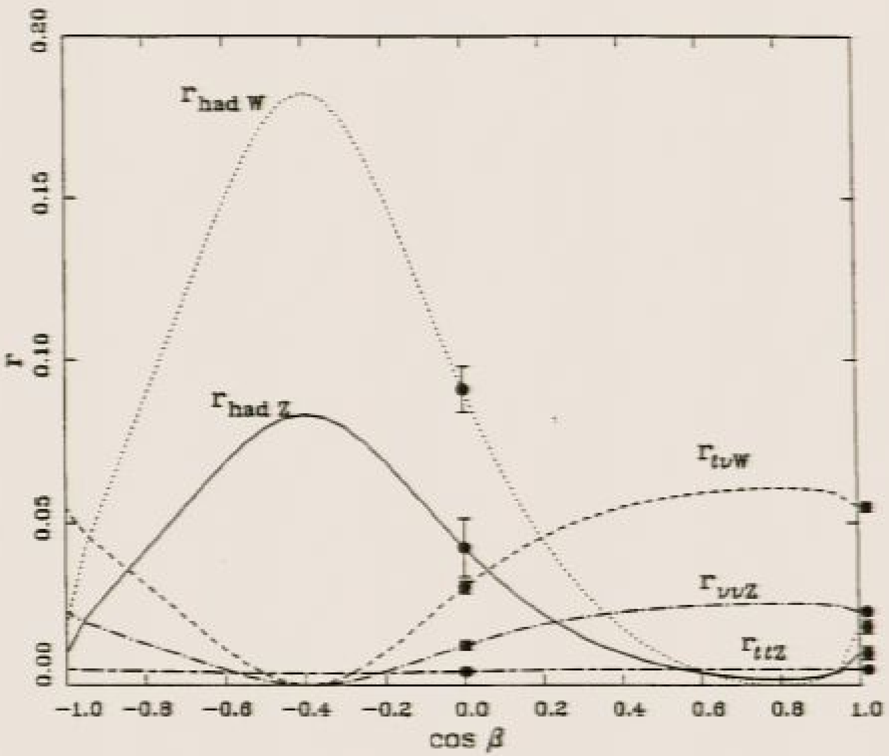
Dashed ellipses are statistical errors

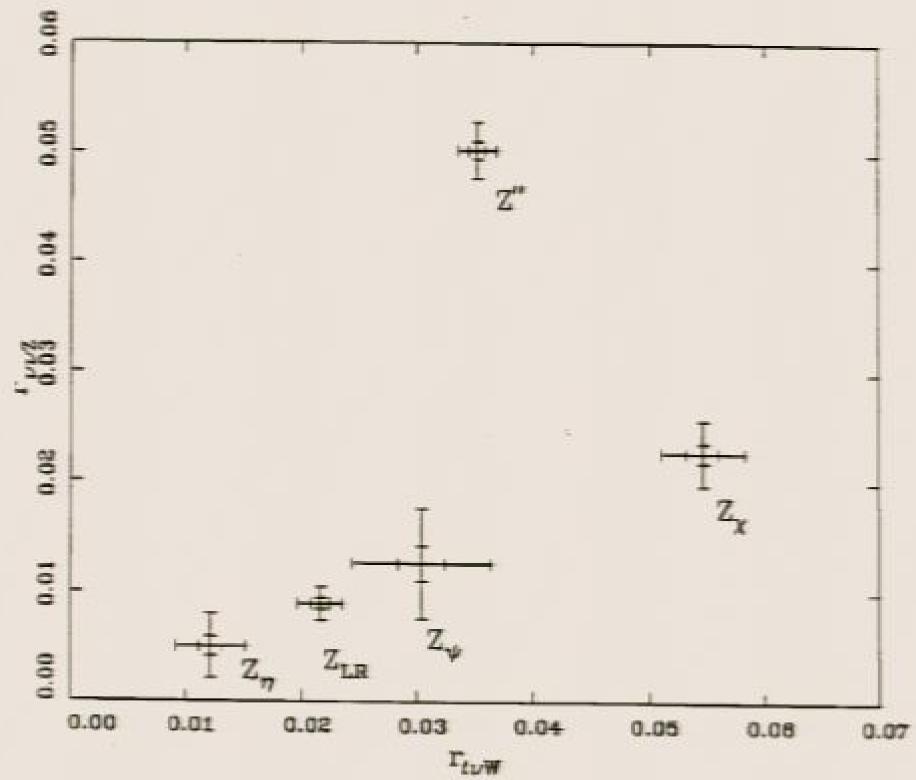
Dotted ellipses are PDF errors

Rare Decays

$$r_{\ell\nu W} \equiv \frac{B(Z' \to W l \nu_l)}{B(Z' \to l^+ l^-)}, \qquad r_{\nu\nu Z} \equiv \frac{B(Z' \to Z \nu \bar{\nu})}{B(Z' \to l^+ l^-)}, \qquad r_{l^+l^- Z} \equiv \frac{B(Z' \to Z l^+ l^-)}{B(Z' \to l^+ l^-)}$$

With analogous expressions for hadronic final states



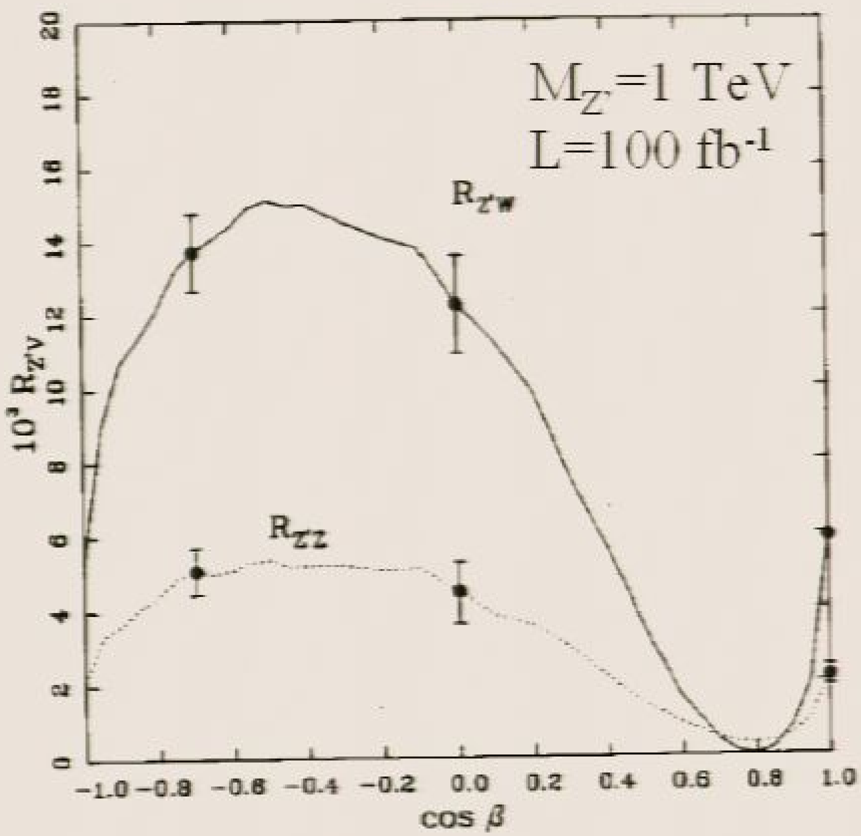


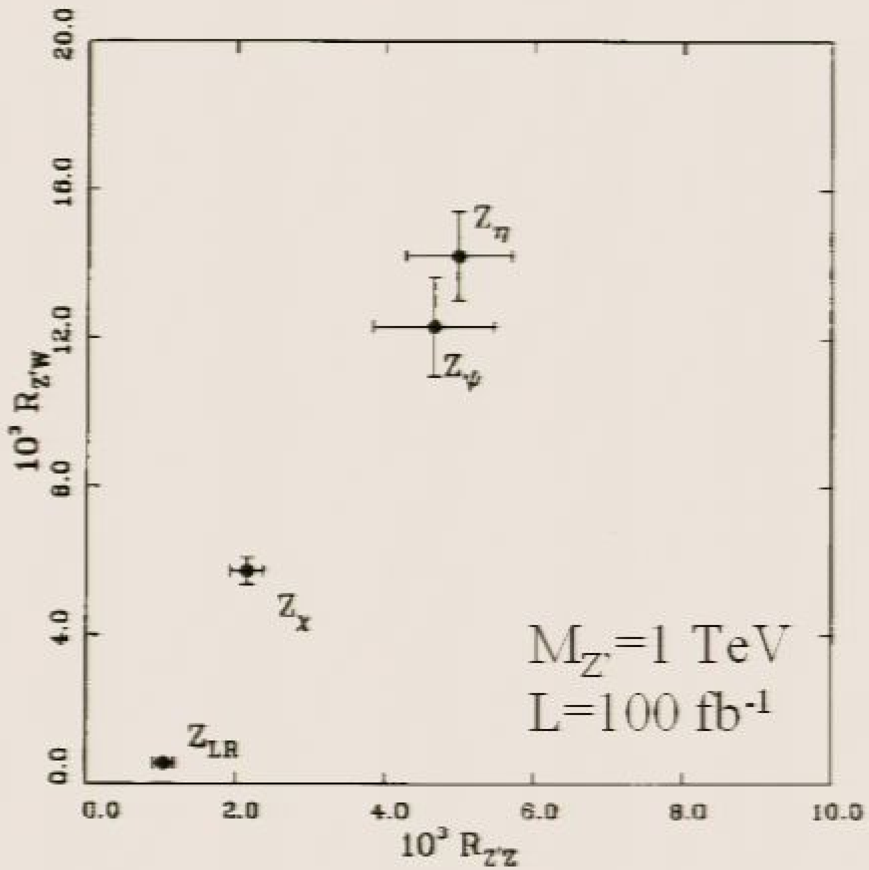
From Cvetic and Langacker PRD46, 14 (1992)

Associated Production

$$R_{Z'V} = \frac{\sigma(pp \to Z'V) \cdot B(Z' \to l^+l^-)}{\sigma(pp \to Z') \cdot B(Z' \to l^+l^-))}$$

Where V=Z,W,γ

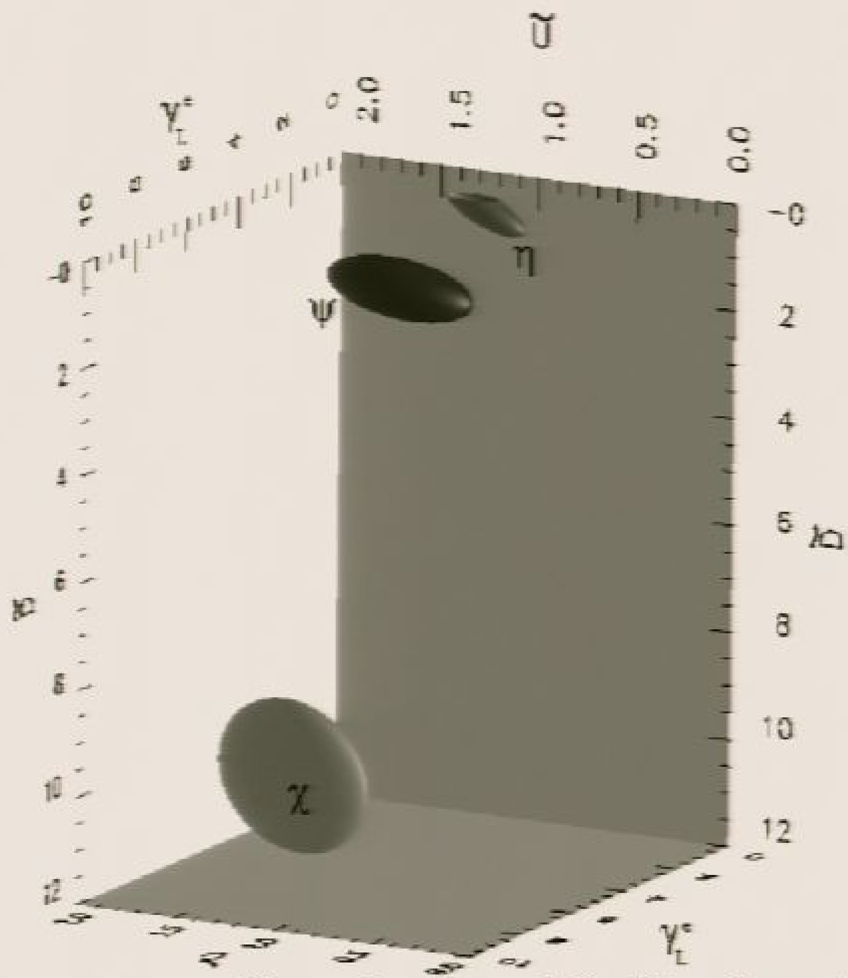




From Cvetic and Langacker PRD46, 4943 (1992)

Combined Fits 2nd Approach

$$\gamma_L^l \equiv \frac{(C_L^\ell)^2}{(C_L^\ell)^2 + (C_R^\ell)^2}, \quad \gamma_L^q \equiv \frac{(C_L^q)^2}{(C_L^\ell)^2 + (C_R^\ell)^2}, \quad \tilde{U} \equiv \frac{(C_R^u)^2}{(C_L^q)^2}, \quad \tilde{D} \equiv \frac{(C_R^d)^2}{(C_L^q)^2}$$



From Cvetic and Godfrey hep-ph/9504216
see also del Aguila, Cvetic, Langacker, PRD48, R969 (1993)

Z' Identification using b & t quarks

SG + T. Martin, PRL101, 151803 (2008).

The problem with quark final states is distinguishing between species and measuring Z'-quark couplings

But b and t quarks can uniquely be identified in the final state (maybe also c-quarks)

We use this property to discriminate between models

The primary issues in this analysis are:

- Identification efficiency
- Standard Model Backgrounds

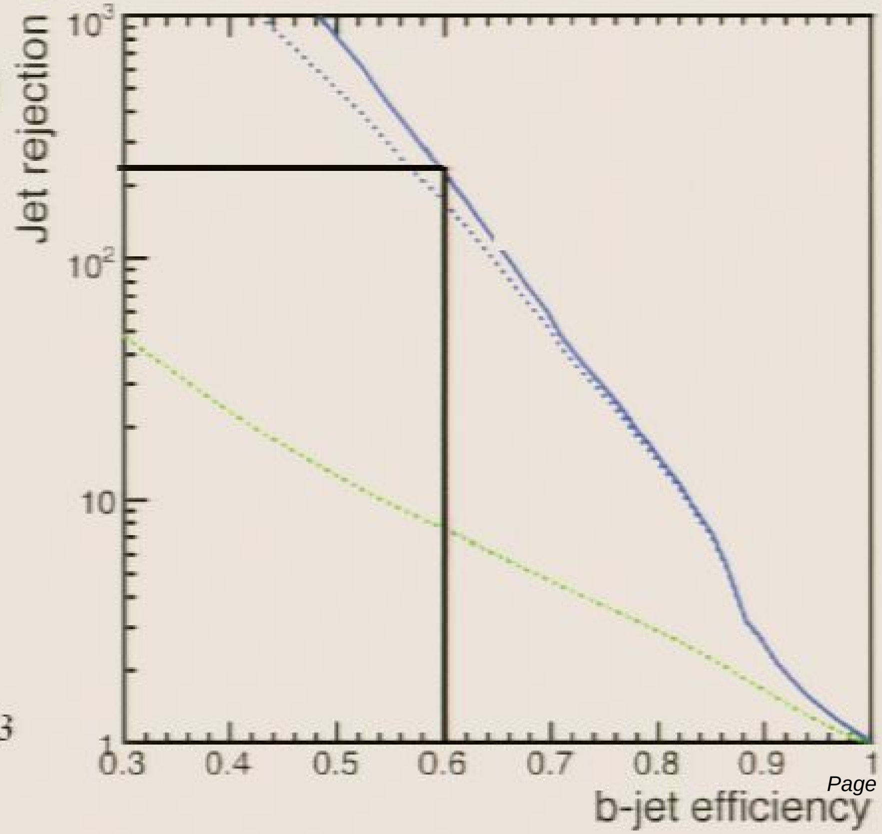
b & t identification efficiency

b-quark

- ATLAS TDR gives ε_b=50% for high luminosity with 100 to 1 rejection against light and c-jets
- Rejection of fakes can be improved by requiring both b and b in which case we use ε_{bb}=25%

b-jet efficiency vs j rejection

ε_b=60% -> ε_{jet}~1/100



The ATLAS Collaboration, G Aad et al JINST 3 S08003

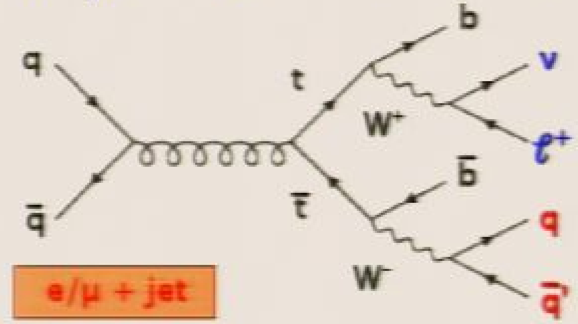
b & t identification efficiency

-quark

- Top decays to b + W^+, with $W \to (e\nu_e, \mu\nu_\mu, \tau\nu_\tau)$ or (ud, cs)
- The single lepton + jets

$$t\bar{t} \to WWb\bar{b} \to (l\nu)(jj)(b\bar{b})$$

has a BR of ~30% and is viewed to have best signal/bgrnd



- CMS & ATLAS estimates ε_{tt}~2-5% but more recent studies give ε_{tt}~10%

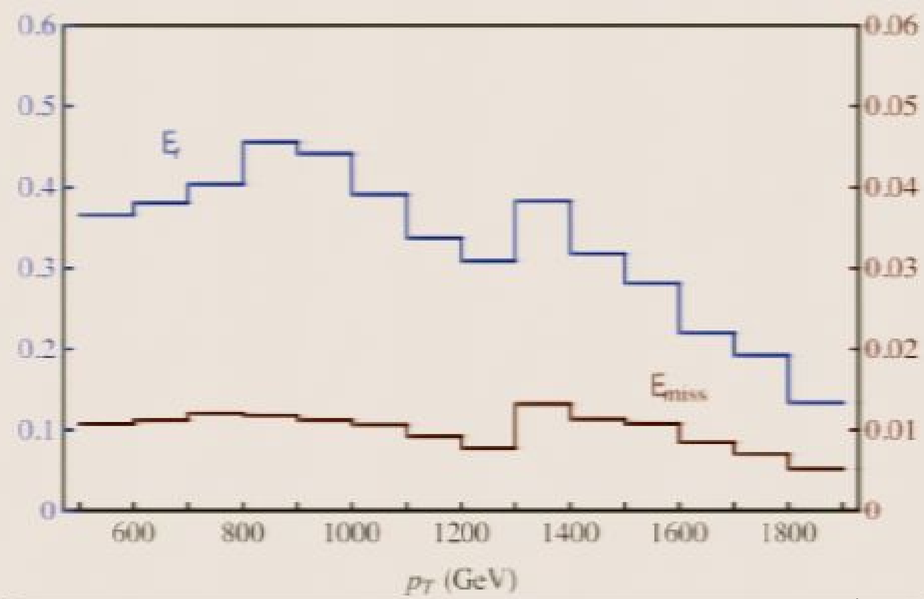
urely hadronic modes

aplan, Rehermann, Schwartz & Tweedie [hep-ph/0806.0848]

ee also:

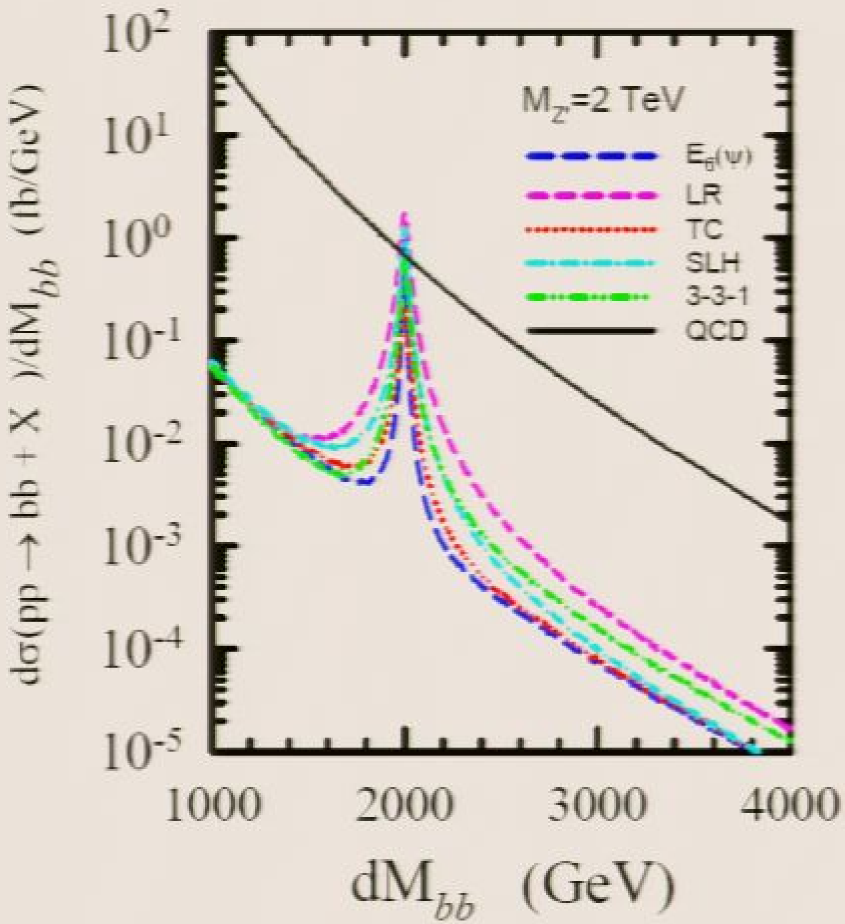
Orr and Baur [hep-ph/0707.2066]

Thaler and Wang [hep-ph/0806.0023]



If can utilize hadronic modes hould increase efficiencies ignificantly

SM QCD Backgrounds



$$M_{Z'} = 2 \text{ TeV}$$

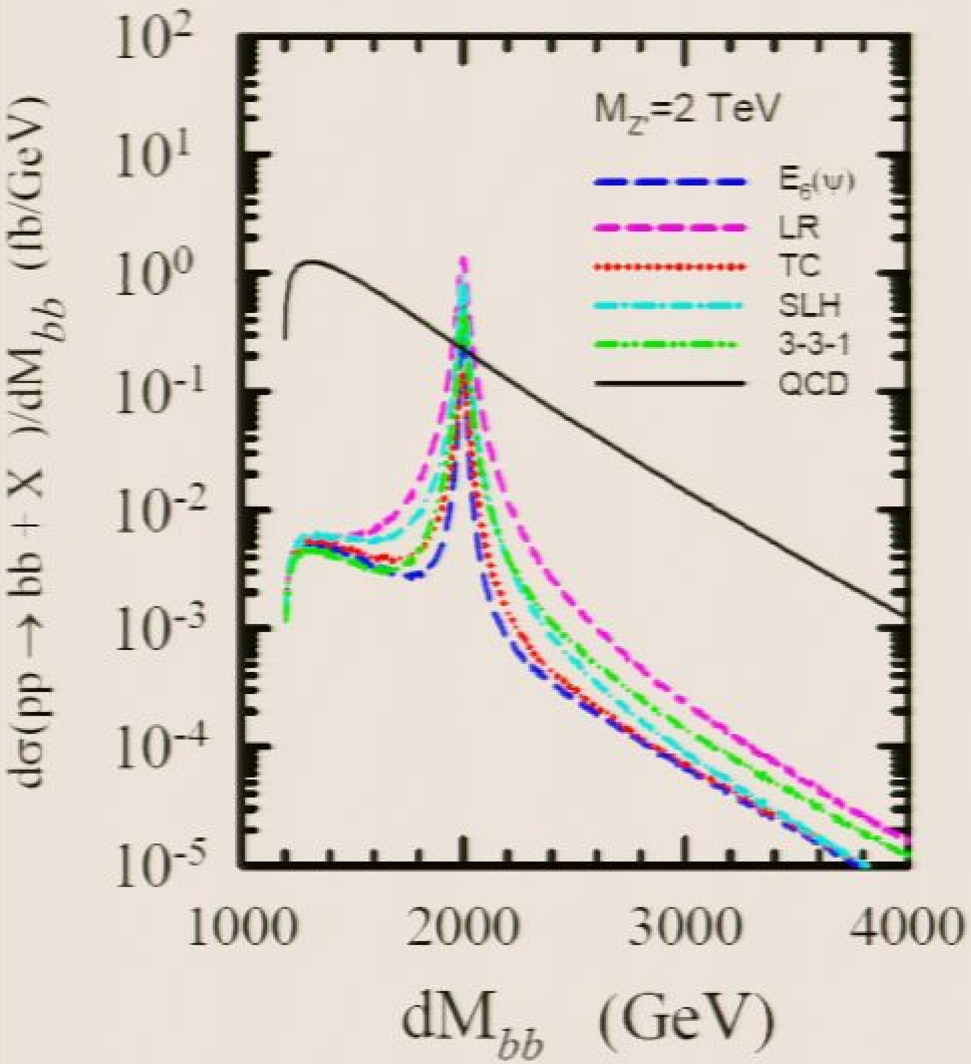
$$P_T > 50 \text{ GeV}$$

- Can reduce background by imposing a p_T cut on the reconstructed t or b
- Found

$$P_T \geq 0.3 M_{Z'}$$

reduces the background significantly

- Balance between improving signal/background vs increasing the statistical uncertainty



Can further reduce improve S/N with

$$|M_{f\bar{f}} - M_{Z'}| \leq 2.5\,\Gamma_{Z'}$$

Other issues:

- Fakes from gluons, light quarks & c-quarks

- Non-QCD SM backgrounds

  eg: $Wb\bar{b} + jets$

  $(Wb + W\bar{b})$

  $W + jets$

Can be controlled by constraints on cluster transverse mass and invariant mass of jets

- Uncertainties in parton distribution functions

Can reduce pdf uncertainties by using ratios:

$$R_{b/\mu} \equiv \frac{\sigma(pp \to Z' \to b\bar{b})}{\sigma(pp \to Z' \to \mu^+\mu^-)} \approx \frac{BR(Z' \to b\bar{b})}{BR(Z' \to \mu^+\mu^-)} = \frac{3K_q\left(g_L^{b2} + g_R^{b2}\right)}{\left(g_L^{\mu 2} + g_R^{\mu 2}\right)}$$

$$R_{t/\mu} \equiv \frac{\sigma(pp \to Z' \to t\bar{t})}{\sigma(pp \to Z' \to \mu^+\mu^-)} \approx \frac{BR(Z' \to t\bar{t})}{BR(Z' \to \mu^+\mu^-)} = \frac{3K_q\left(g_L^{t2} + g_R^{t2}\right)}{\left(g_L^{\mu 2} + g_R^{\mu 2}\right)},$$

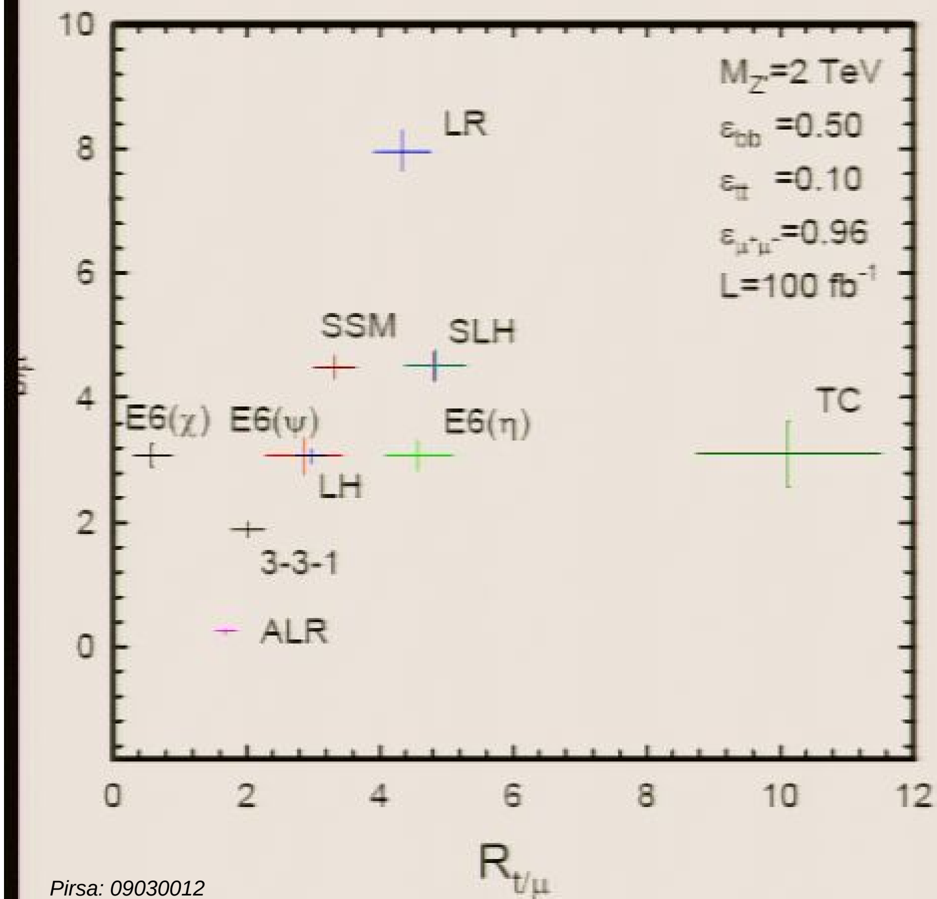
K_q depends on QCD and EW corrections

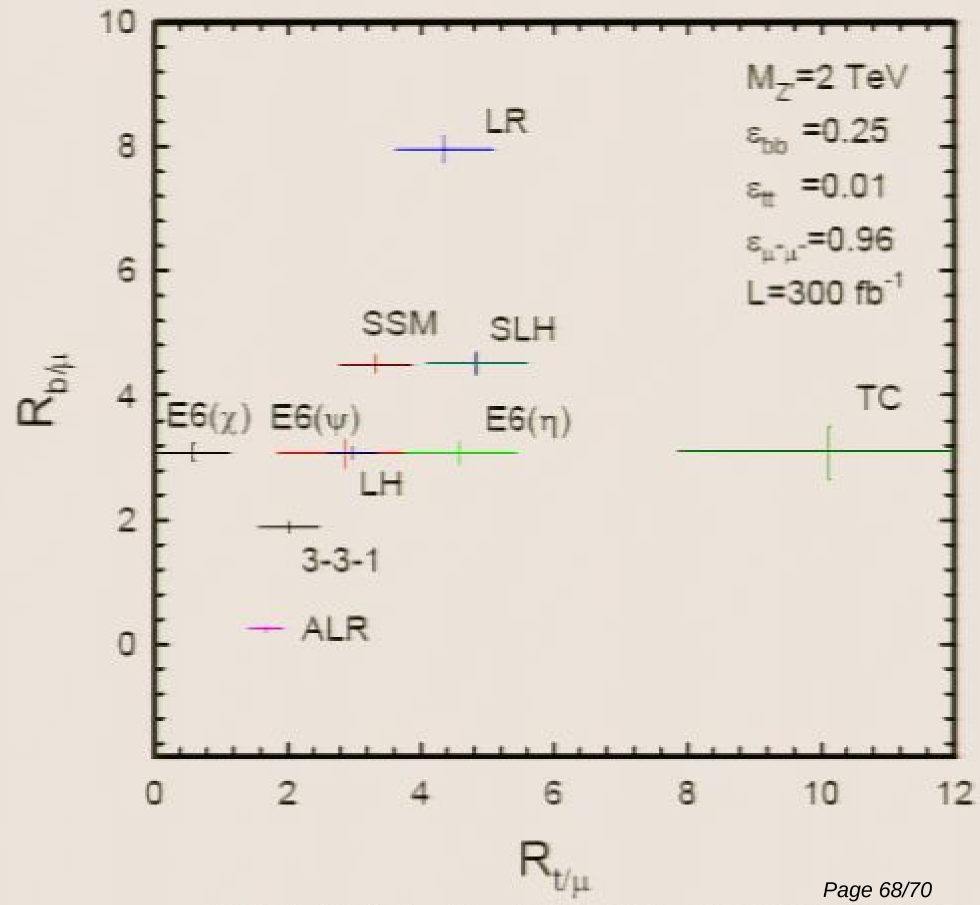
The ratios depend on model dependent couplings

Can use them to distinguish between models

Assume Z' discovered and mass and width measured

Statistical error based on signal + background for given luminosity and ε
Subtract SM backgrounds for predicted # of signal events

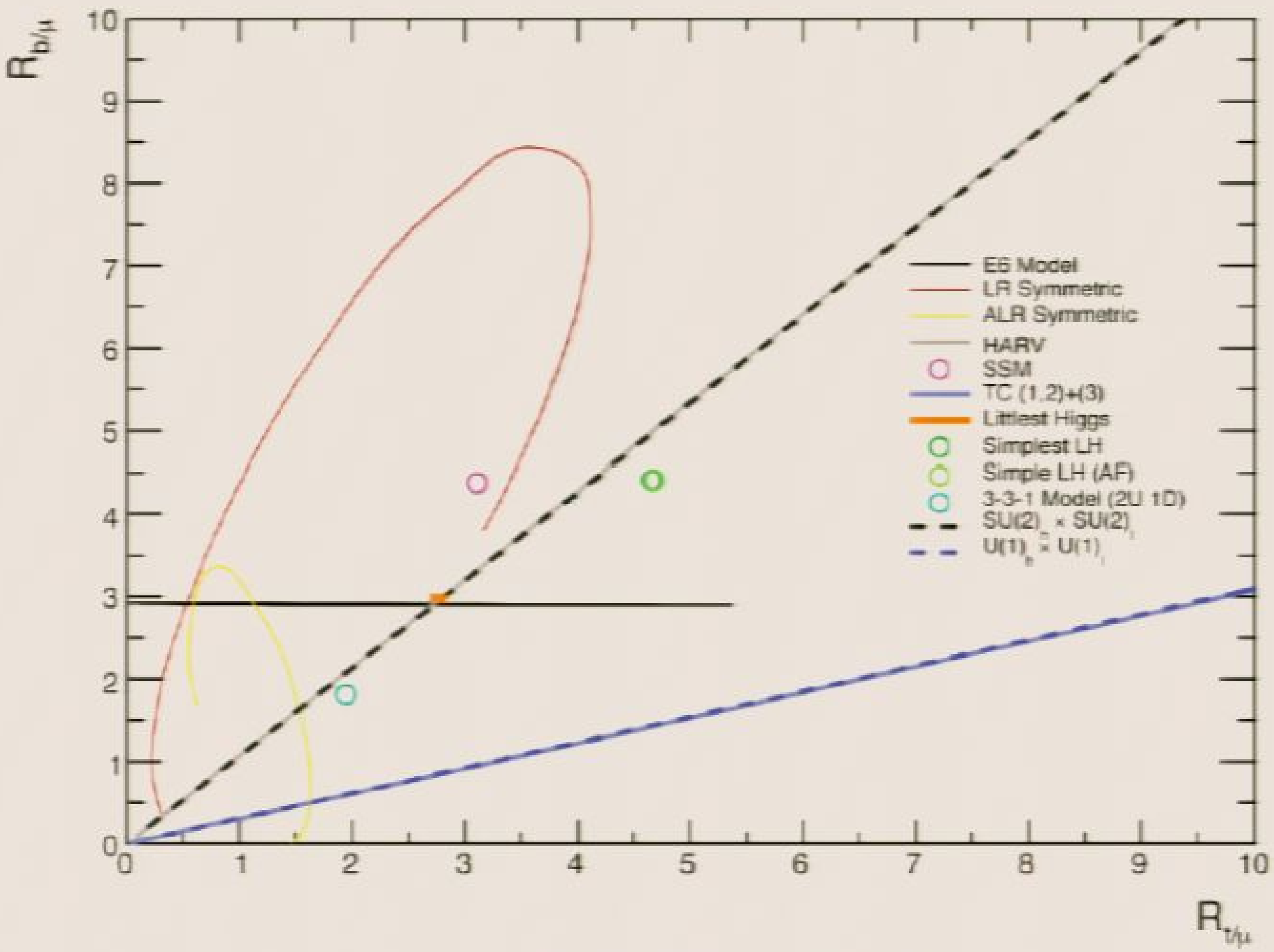




SG + T. Martin, PRL101, 151803 (2008).

But if allow model parameters to vary have ambiguities depending on parameter

Need additional information



Summary

s-channel resonances are predicted by many models of new physics

One might be discovered early in the LHC program, in particulat the LHC can easily find a heavy Z' like state

The challenge will then be to figure out the underlying theory

Numerous observables available to distinguish between models

Showed that flavour tagging of 3rd generation quarks is can be used to distinguish models and measure individual quark couplings to Z'

Look forward to a very exciting LHC era