Carleton UNIVERSITY

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Discovery and Identification of s-channel Resonances at the LHC

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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: $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\psi$
  - 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?

Possible Routes:

- 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…

What do these models have in common?

- Almost all of these models have new s-channel structure at ~TeV scale
- Either from extended gauge bosons or new resonances

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

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

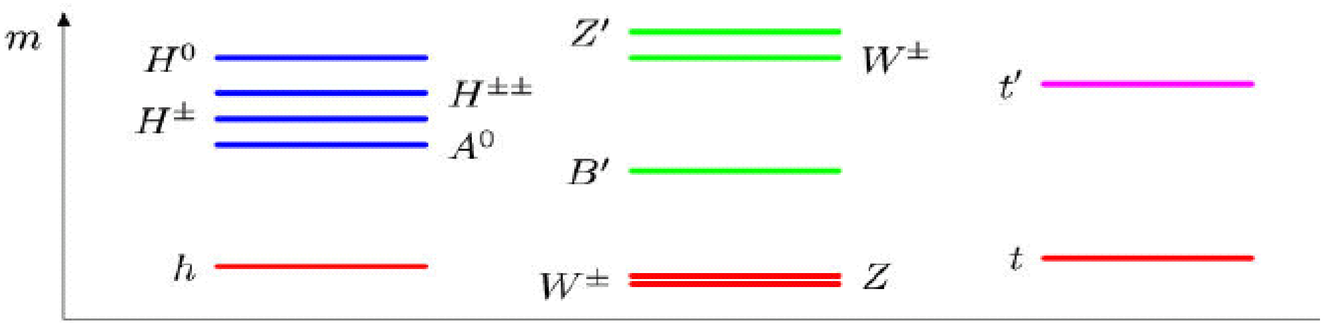
Arkani-Hamed et al hep-ph/0206021

- 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): $W_H^\pm \quad Z_H \quad B_H$
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

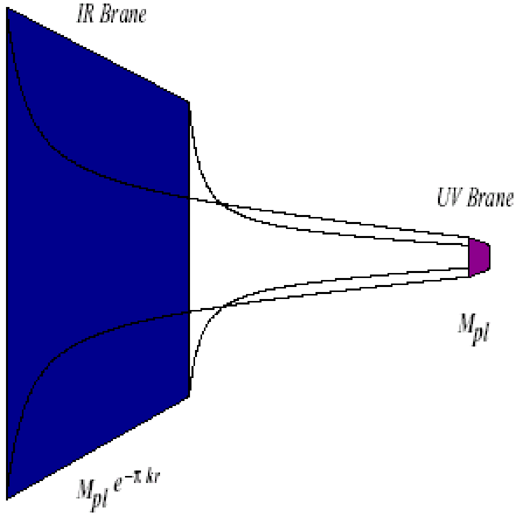
Many variations

ADD Type of Extra Dimensions
(Arkani-Hamed Dimopoulos Dvali)

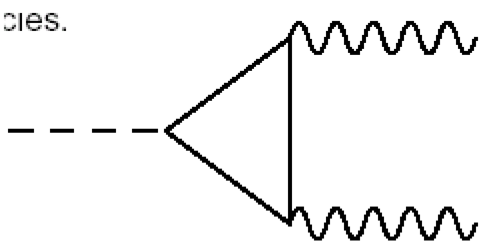
- Have a KK tower of graviton states in 4D which behaves like a continuous spectrum
- Graviton tower exchange effective operators: $i\frac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$
- Leads to deviations in $e^+e^- \to f\bar{f}$ dependent on λ and s/M_H
- Also predicts graviscalars and gravitensors propagating 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 $h \to gg,\ \gamma\gamma$

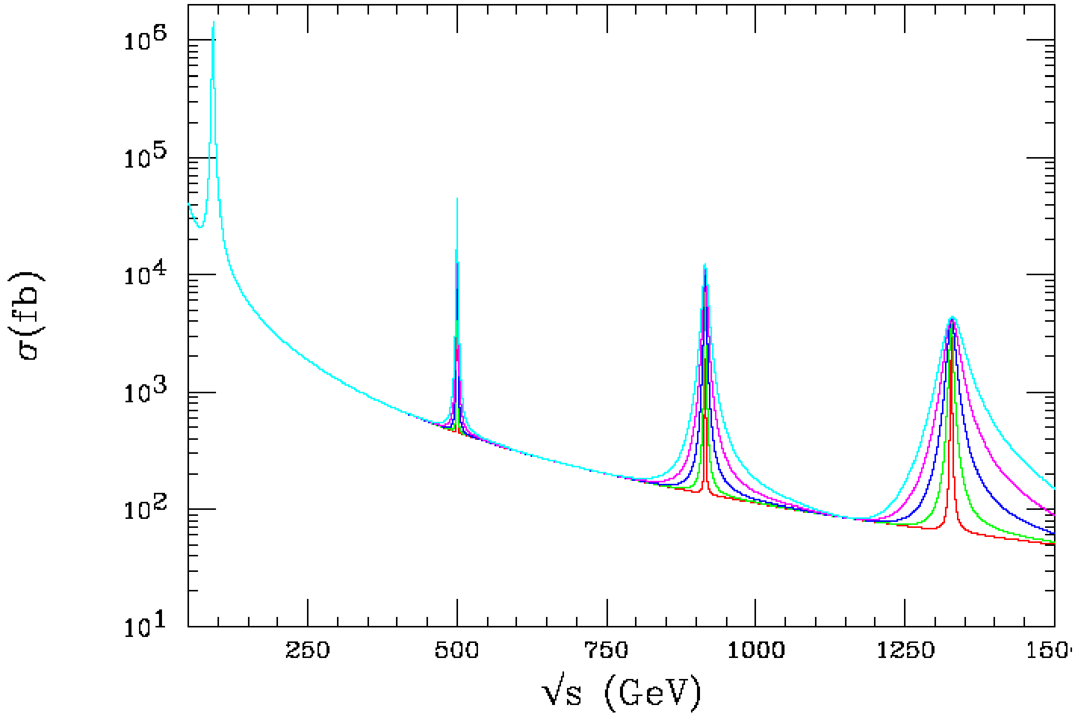


Randall-Sundrum Gravitons:

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

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

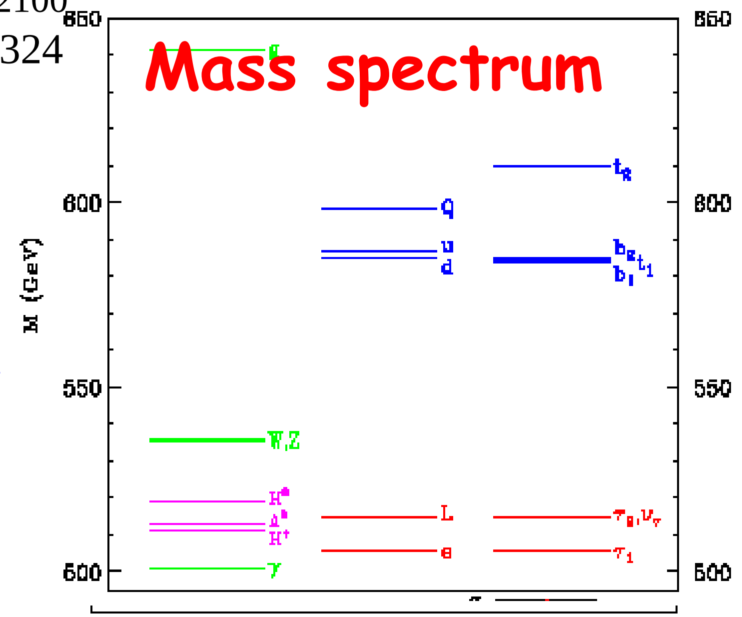
Has 2 parameters;
- mass of the first KK state
- coupling strength of the graviton (controls the width)

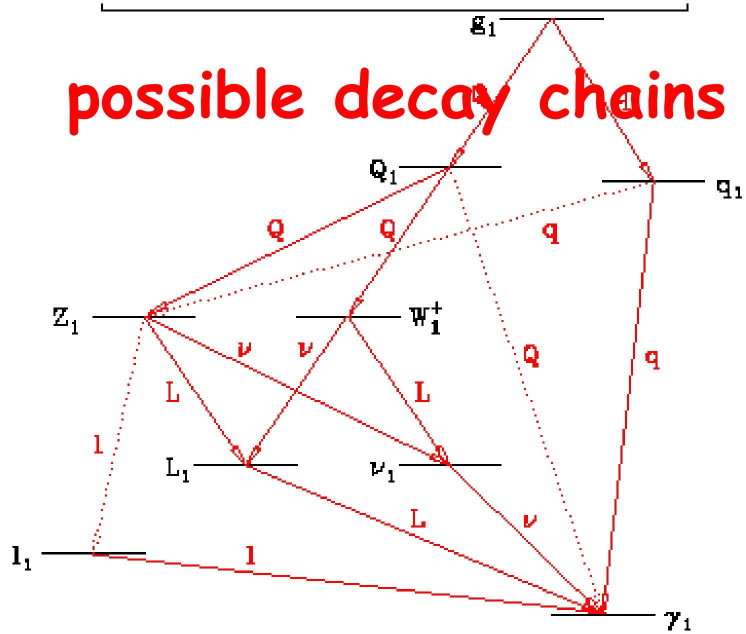


Universal Extra Dimensions

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

- All SM particles propagate in the bulk
- KK towers for SM particles with spin quantum numbers identical to SM particles
- Spectrum resembles that of SUSY
- Have conservation of KK number at tree level leading to KK parity = $(-1)^n$
- Ensures that lightest KK partners are always 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

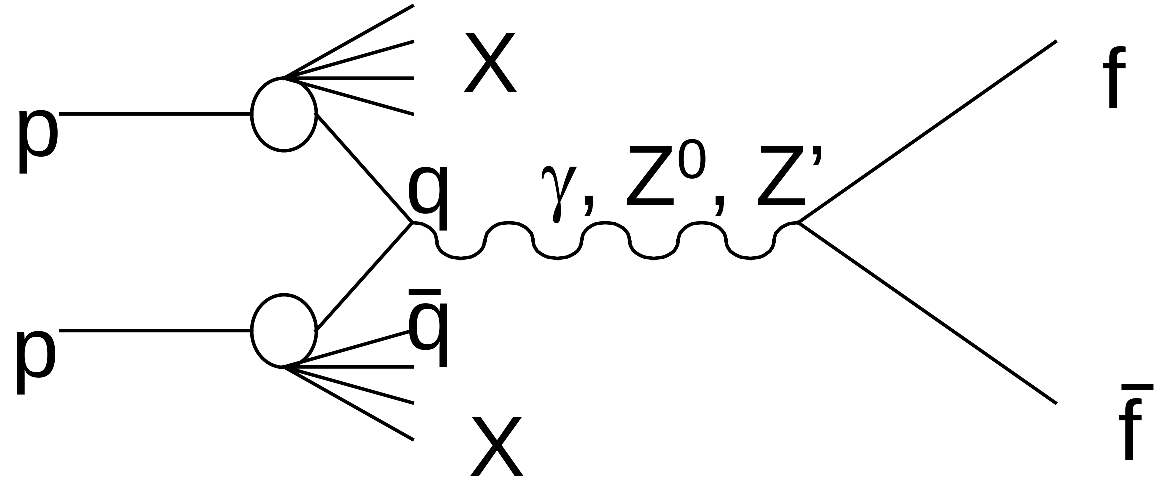
And scalar states:

- 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



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

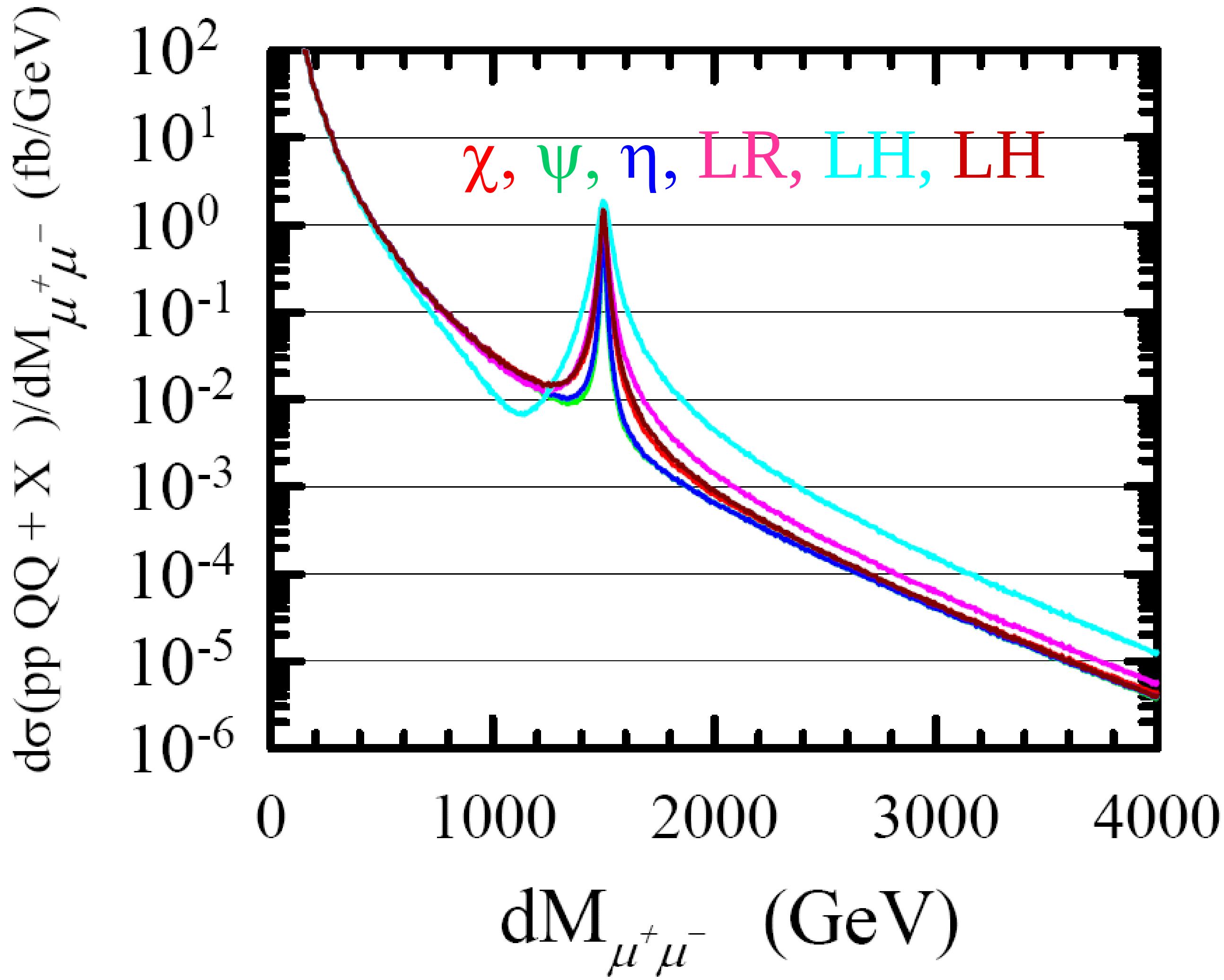
$$S_q, A_q = \left(\frac{g}{e}\right)^4 \frac{\hat{s}^2}{(\hat{s}-M^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}({C_L^f}^2 \pm {C_R^f}^2)({C_L^q}^2 \pm {C_R^q}^2)$$

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

$$M_{Z'} = 1.5 \text{ TeV}$$

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

$$|\eta| < 2.5$$



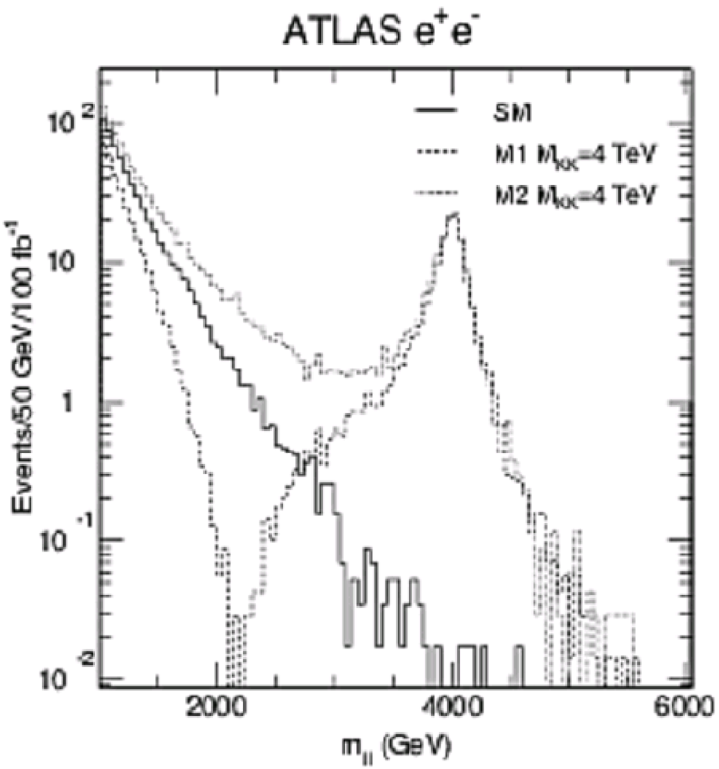
$$\frac{d\sigma}{dy} = \frac{\pi^2 \alpha_{em}^2 x_A x_B}{9 M_{Z'} \Gamma_{Z'}} \left(\frac{g_{Z'}}{e}\right)^4 ({C_L^f}^2 \pm {C_R^f}^2) \sum_q ({C_L^q}^2 \pm {C_R^q}^2) G_q^{\pm}$$

New Z' Gauge Bosons: Di-lepton Resonance Search

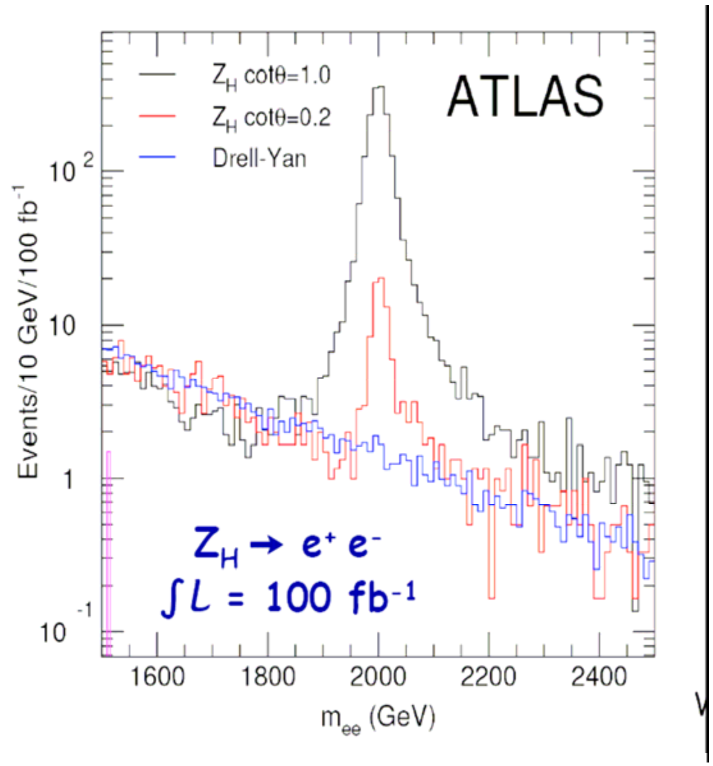
- Select 2 opposite sign high p_T isolated leptons and examine invariant mass distribution

KK in Extra Dimensions

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

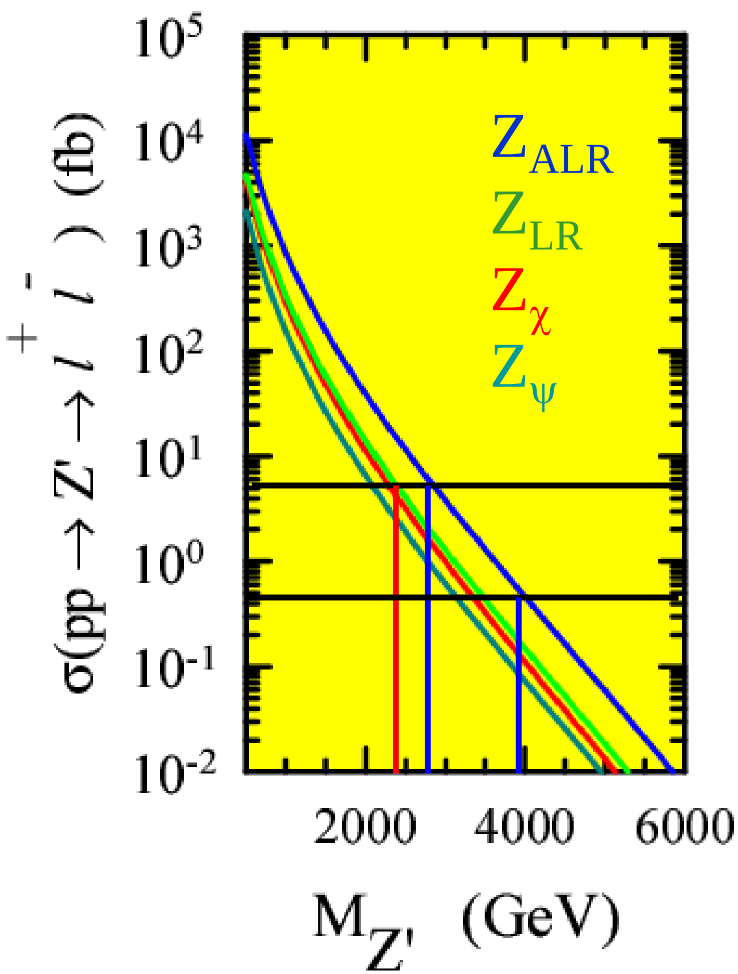


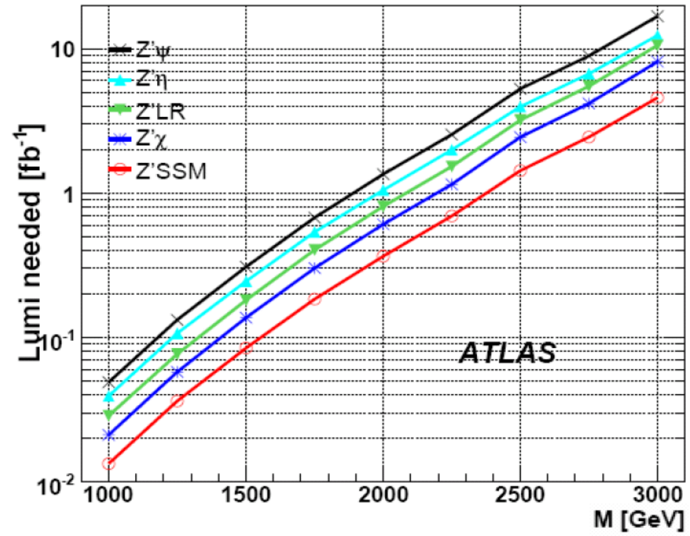
Little Higgs Model A_H and Z_H

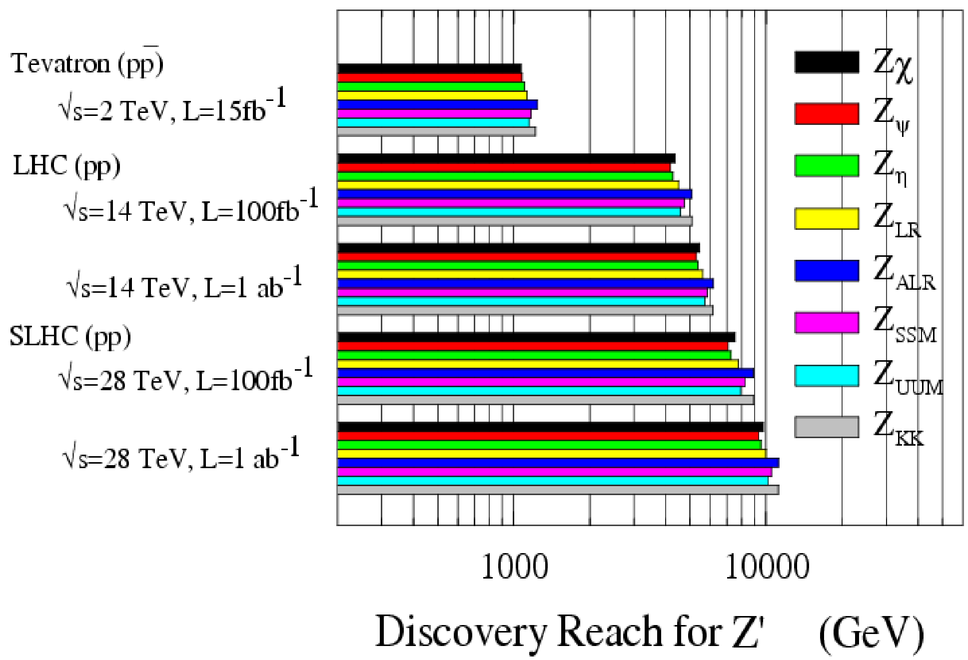


Discovery Limits New for Z' Gauge Bosons

$Z' \to \mu\mu$ production



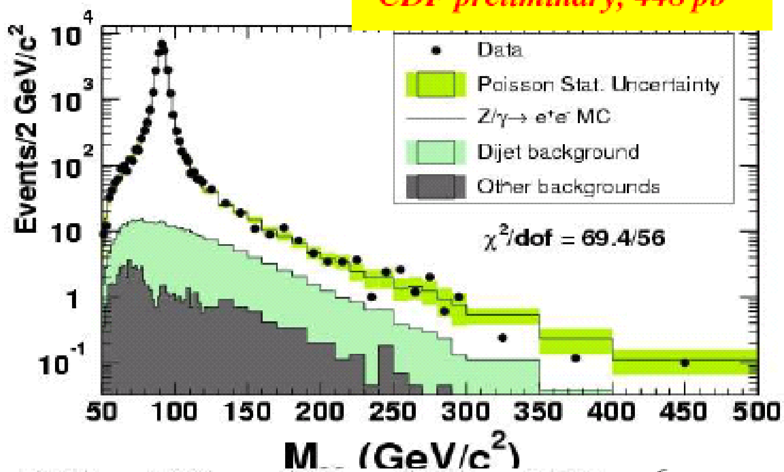




Di-lepton Resonance Search at the Tevatron

- Select 2 opposite sign high p_T isolated leptons and examine invariant mass distribution
- If you find a peak:
  - quantify its significance
  - Measure its σ x BR
- If you don't:
  - Derive upper limit on σ x BR
  - Constrain models

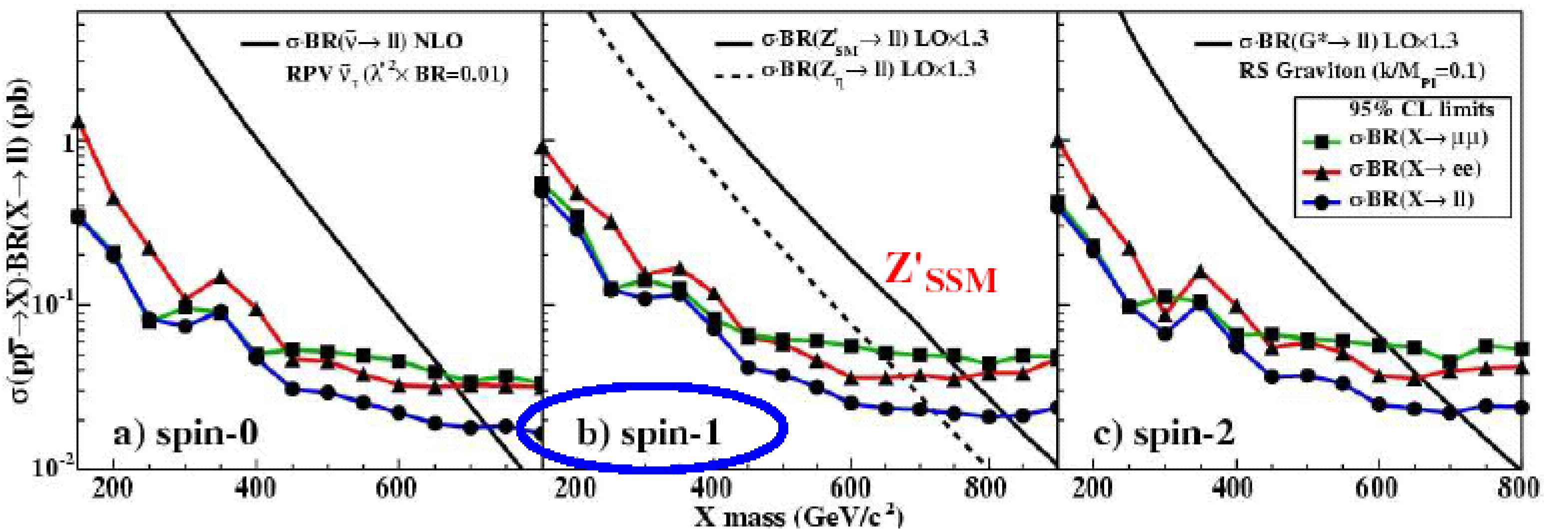
CDF preliminary, 448 pb^{-1}



Z′ Mass[6]

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

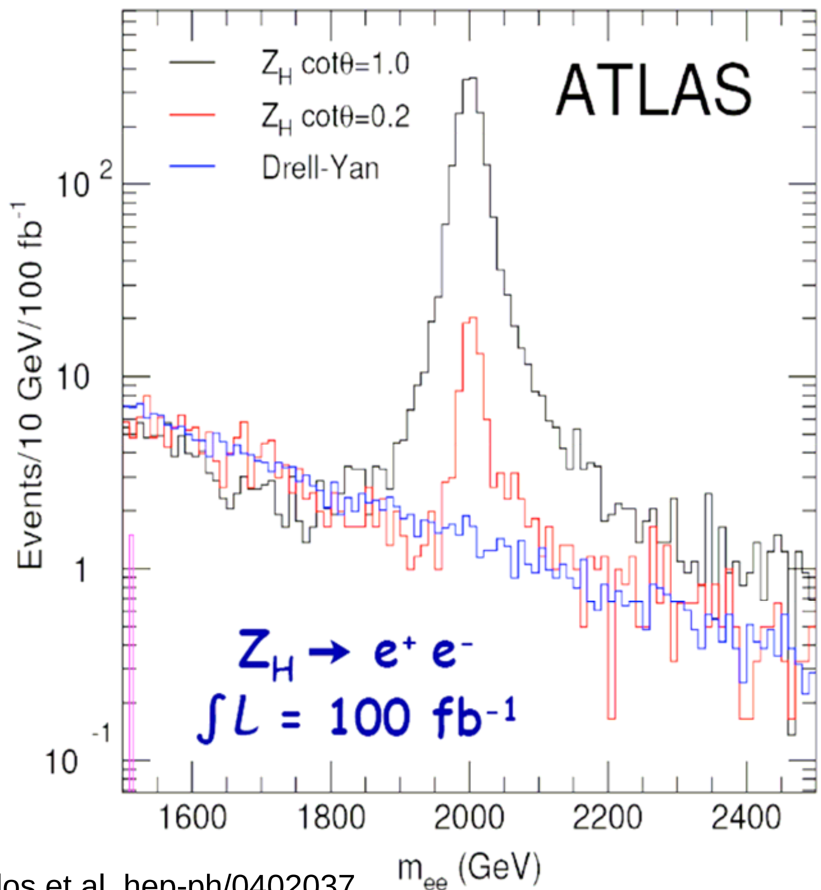
hep-ex/0507104



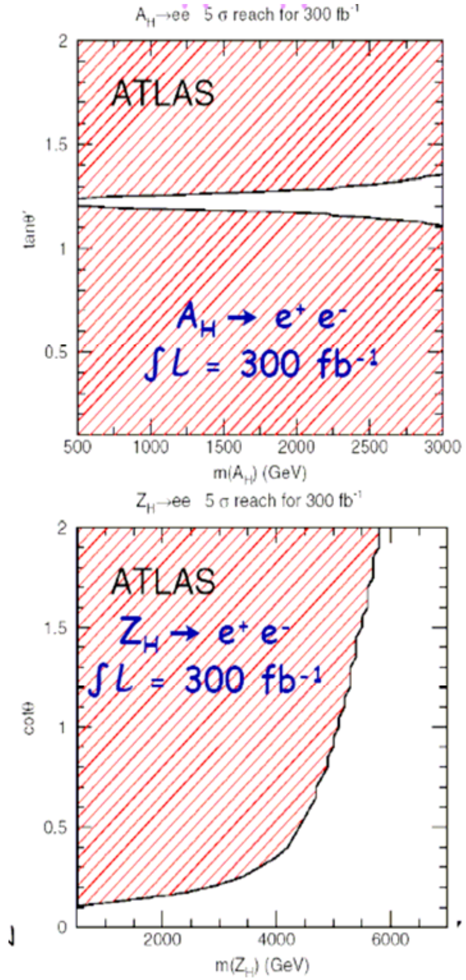
Little Higgs Model A_H and Z_H

Arkani-Hamed et al., Han et al.

Signal : di-lepton resonance



Azuelos et al, hep-ph/0402037

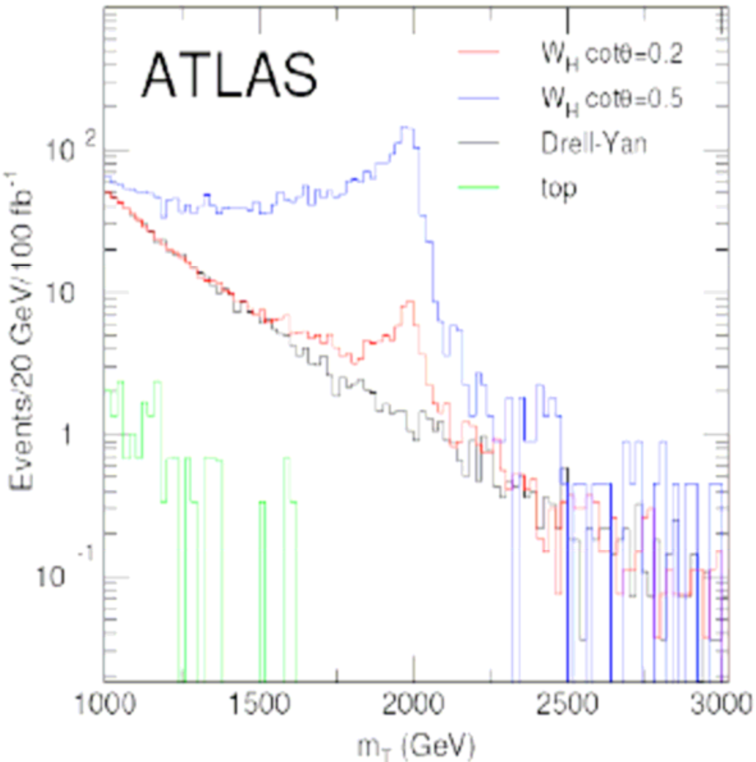


Reach up to 5.7 TeV depending on the θ angle

Little Higgs Model: W_H

$W_H \rightarrow e\nu$

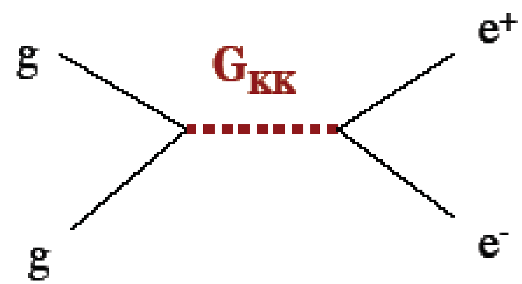
Background: $l\nu$ via virtual W, labeled Drell-Yan



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

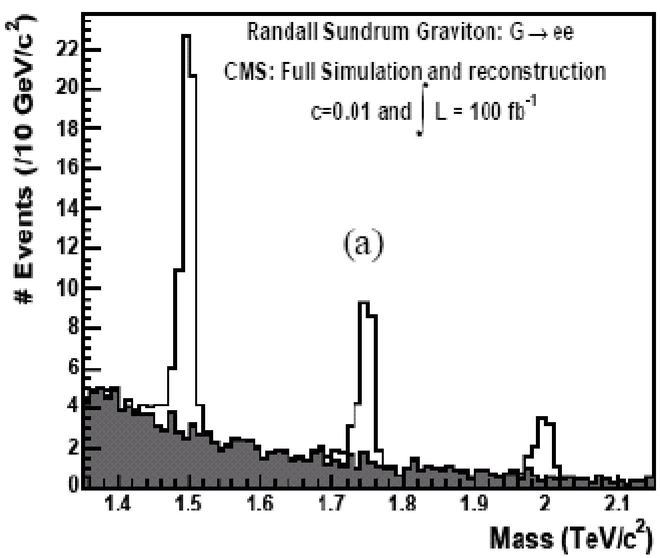
Randall Sundrum Gravitons

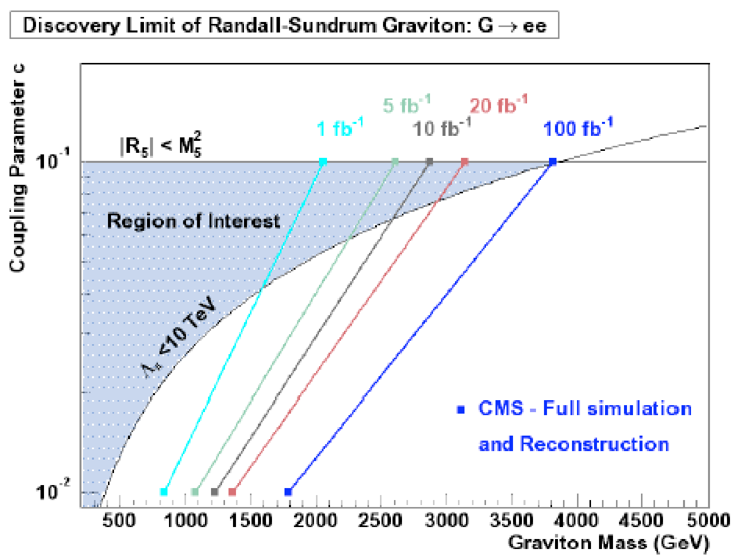
Study the channel pp→Graviton→ e+e-



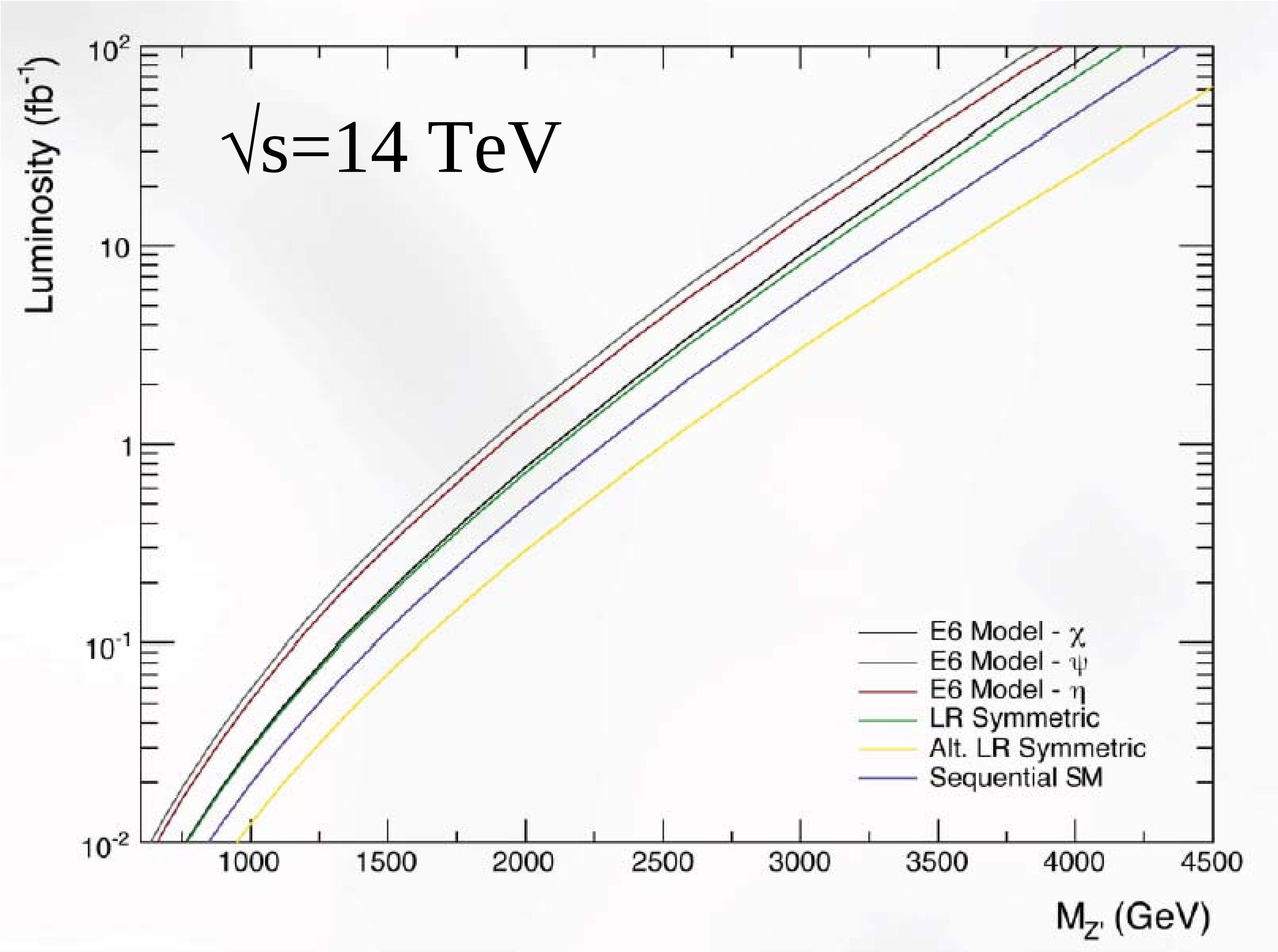
Signal + Drell-Yan background

sensitivity

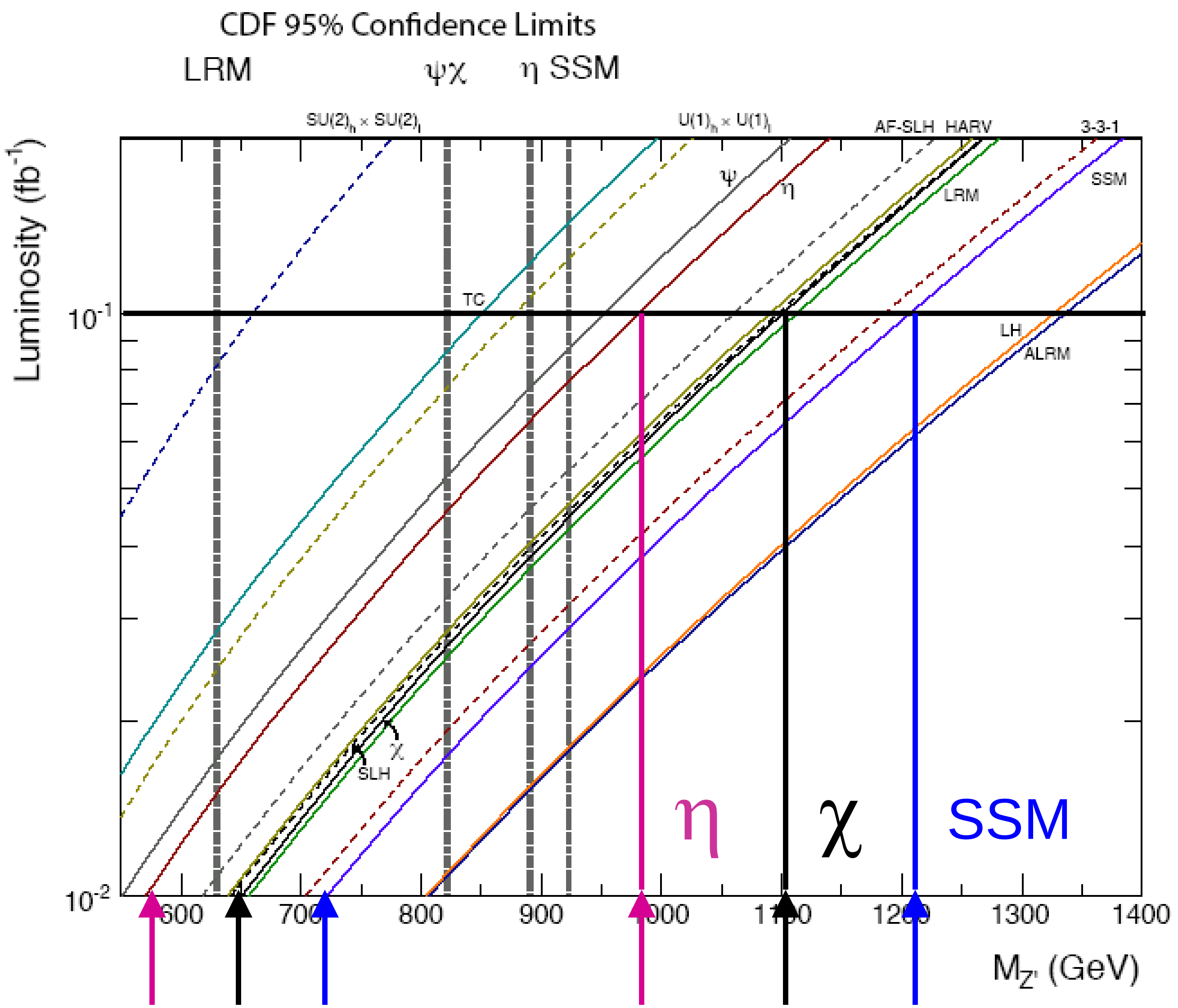




Discovery Reach at the LHC



√s=10 TeV



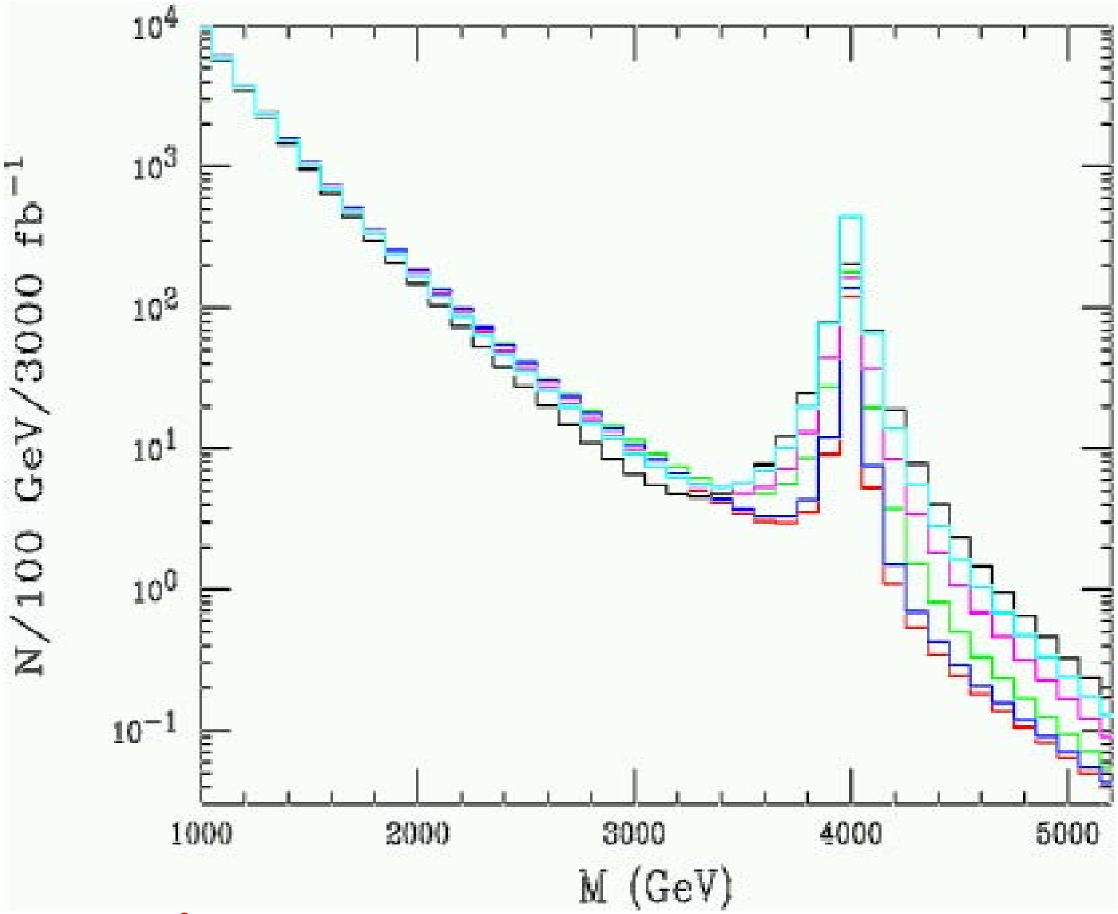
CDF 95% Confidence Limits
LRM
ψχ
η SSM
SU(2)h × SU(2)l
U(1)h × U(1)l
AF-SLH HARV
3-3-1
ψ
η
LRM
SSM
TC
LH
ALRM
χ
SLH
η
χ
SSM
Luminosity (fb-1)
10-1
10-2
600
700
800
900
1000
1100
1200
1300
1400
MZ' (GeV)

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)

LHC Discovers S-channel Resonance !!



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

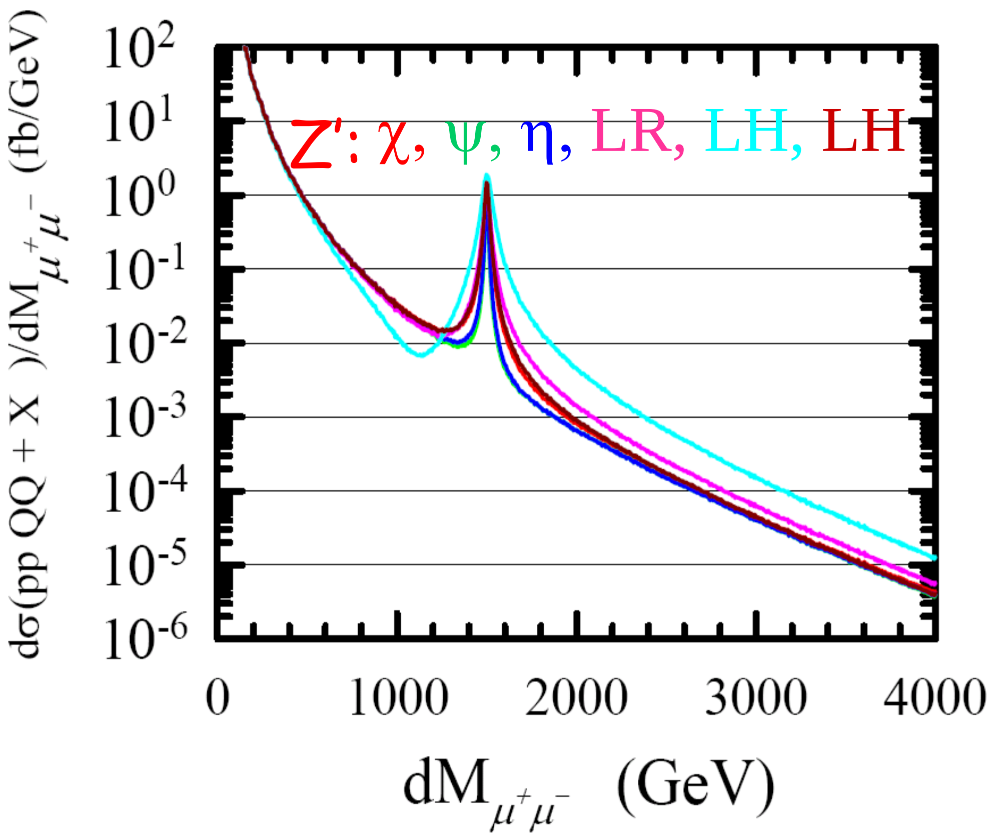
$$\sigma(pp \to Z' \to l^+ l^-) \simeq \sigma(pp \to Z')B(Z' \to l^+ l^0)$$

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

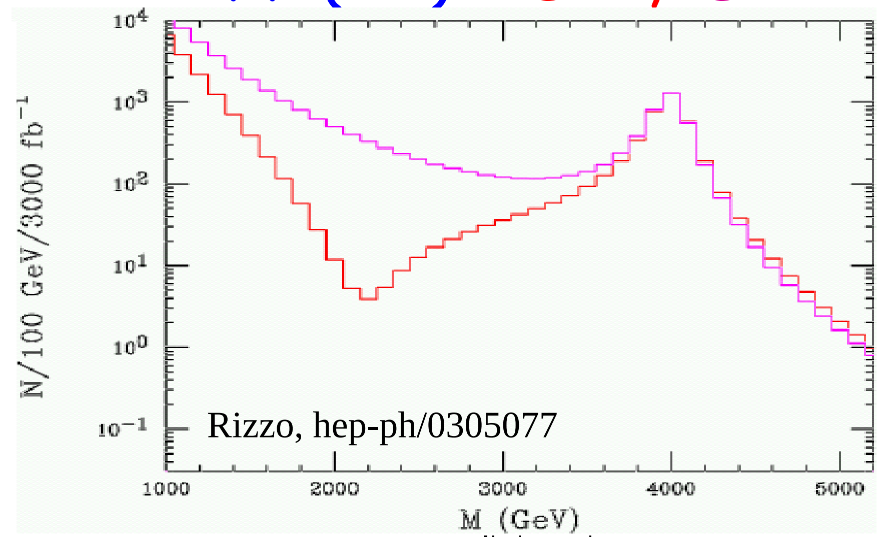
$$\Gamma(Z' \to f\bar{f}) = M_{Z'} g_{Z'}^2 ({C_L^f}^2 + {C_R^f}^2)/24\pi$$

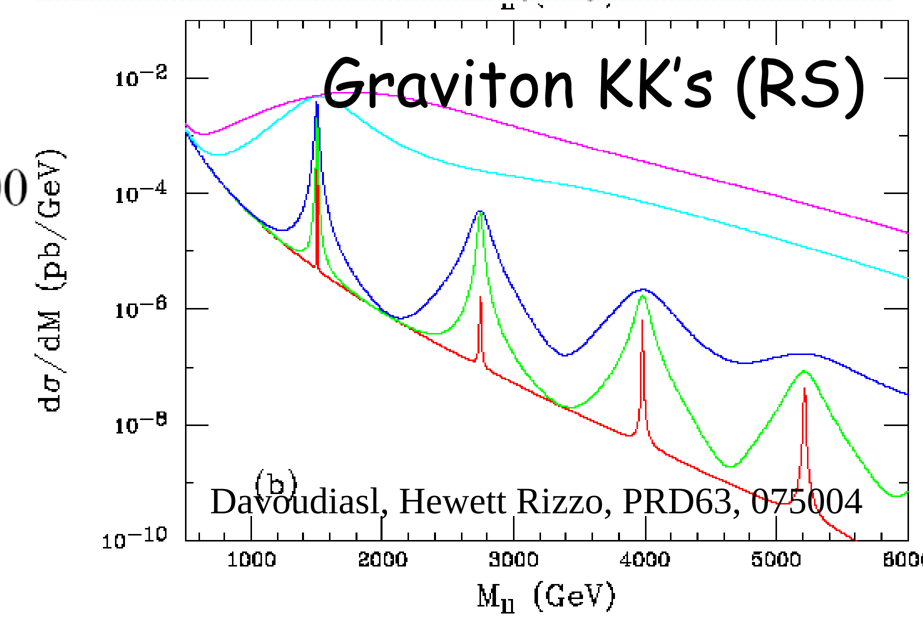
- Angular Distributions
- Rapidity Distributions
- Couplings (decays, polarization…)
- *etc*

M_{ll} distribution gives some information



KK (RS): D=0, D=πR



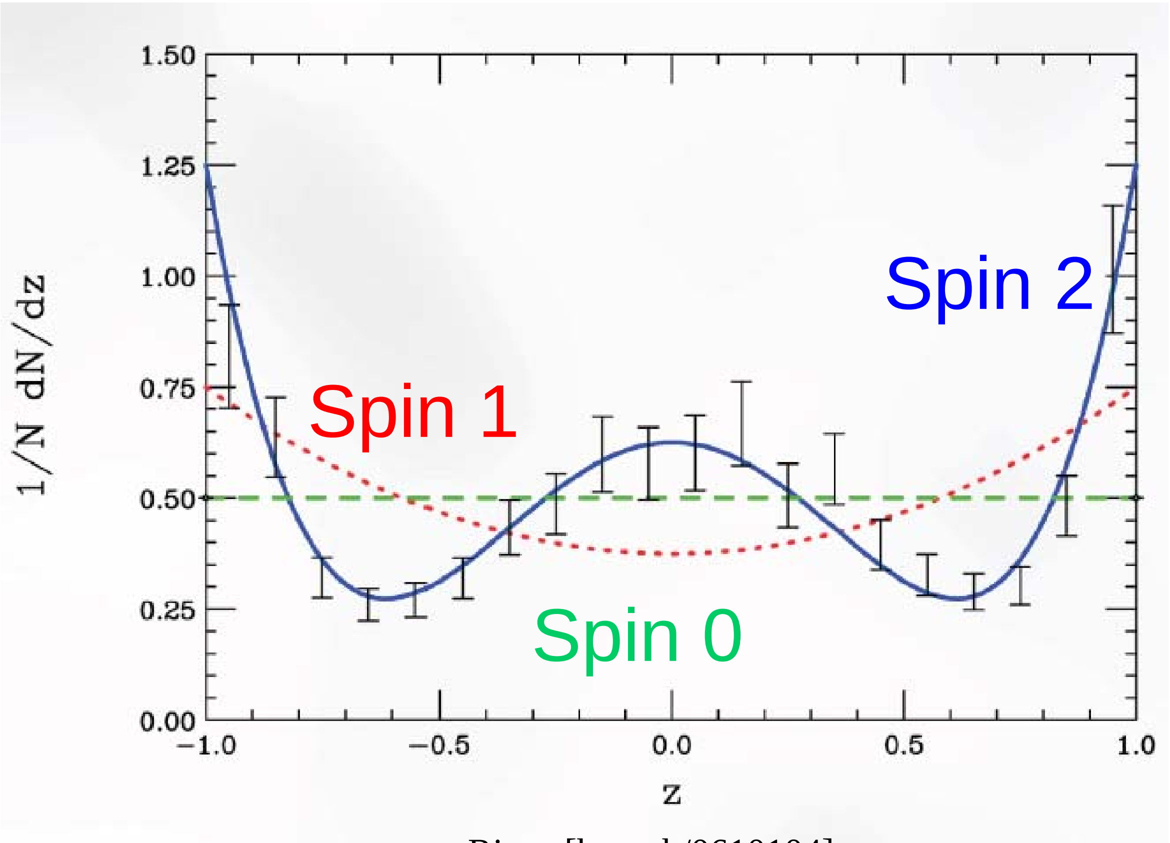


Use angular distributions to determine spin

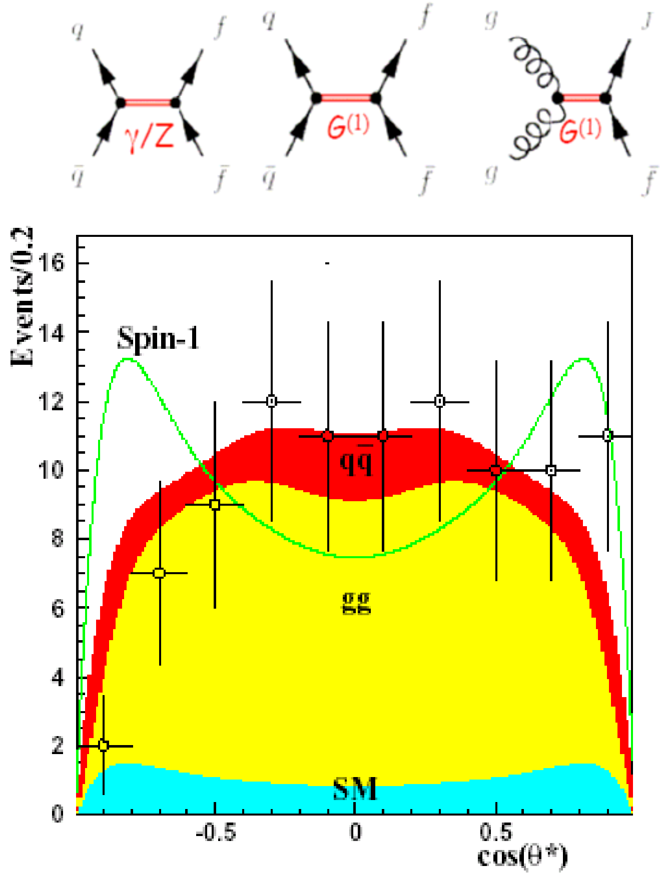
We observe a peak in di-lepton spectrum

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

$\Rightarrow$ Use angular distributions to study the spin of the object



Rizzo [hep-ph/0610104]



Allanach et al [hep-ph/0006114]

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

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

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

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

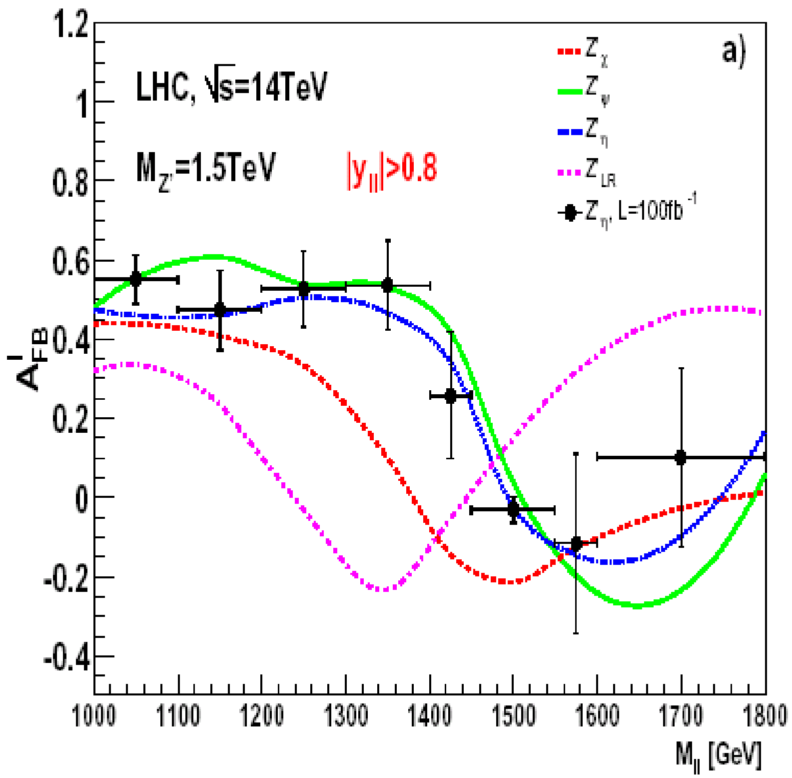
In narrow width approximation:

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

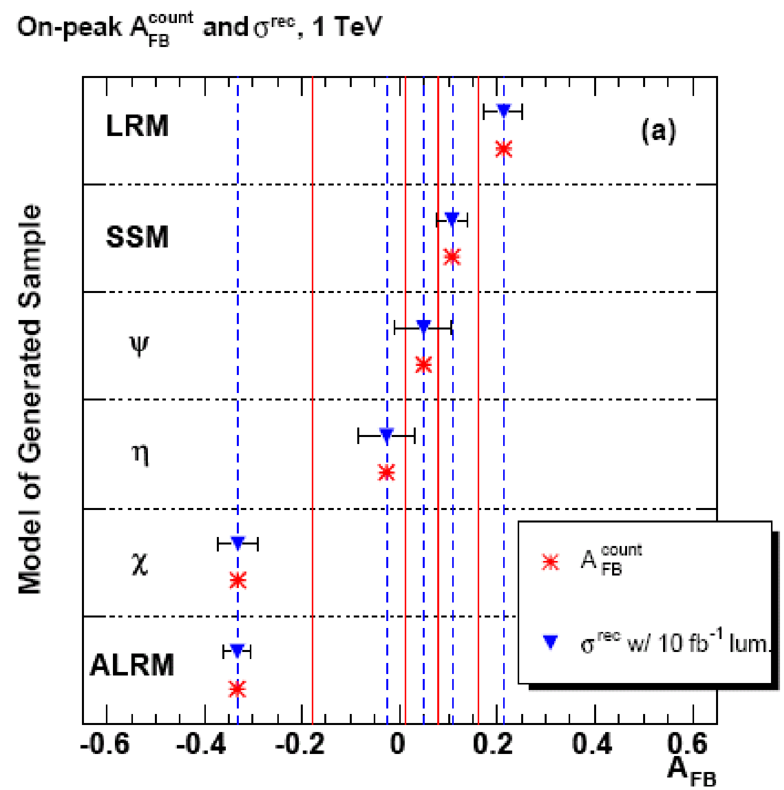
y is the rapidity of the Z′, M the invariant mass of final state fermions

Forward Backward Asymmetry: A_{FB}

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



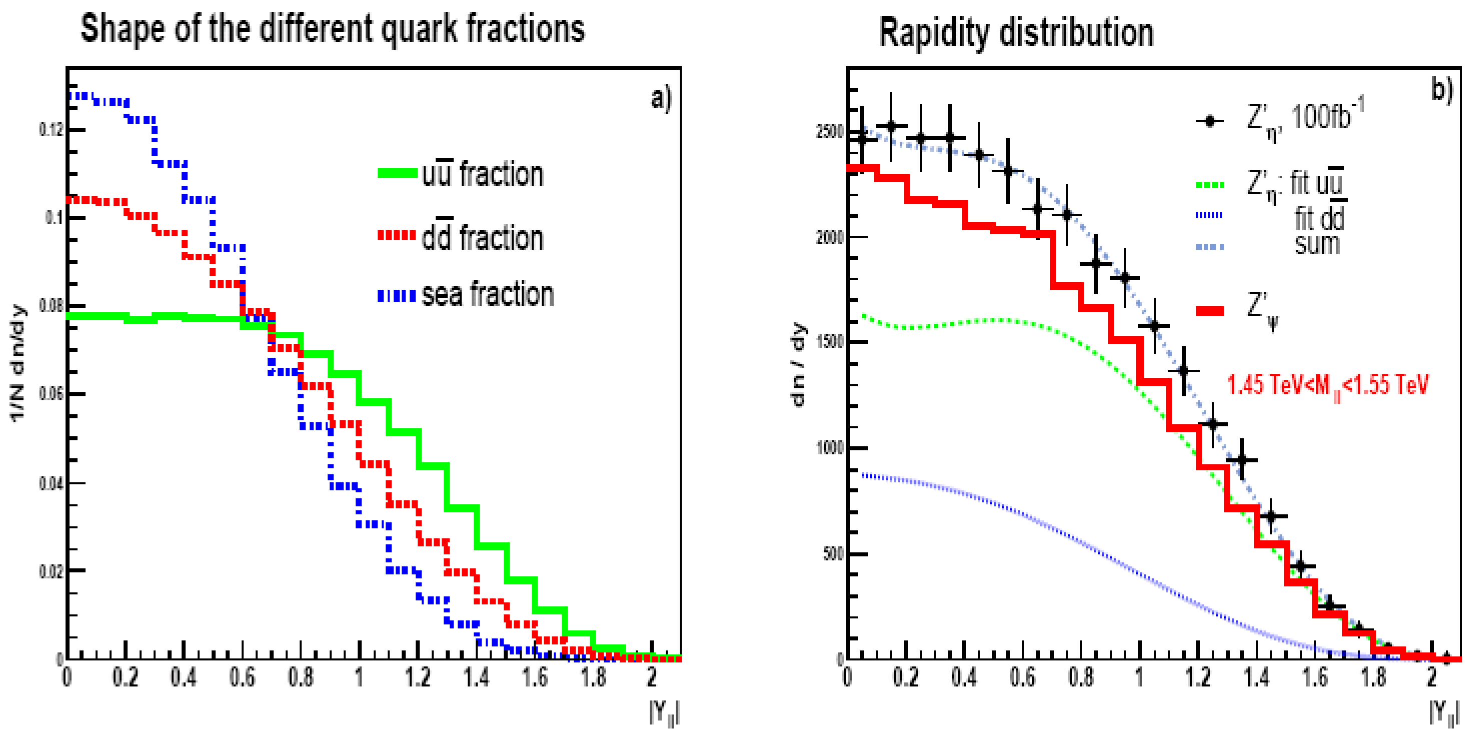
Dittmar, Nicollerat, Djouadi, hep-ph/0307020



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

LHC can resolve to some extent

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

Petriello & 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

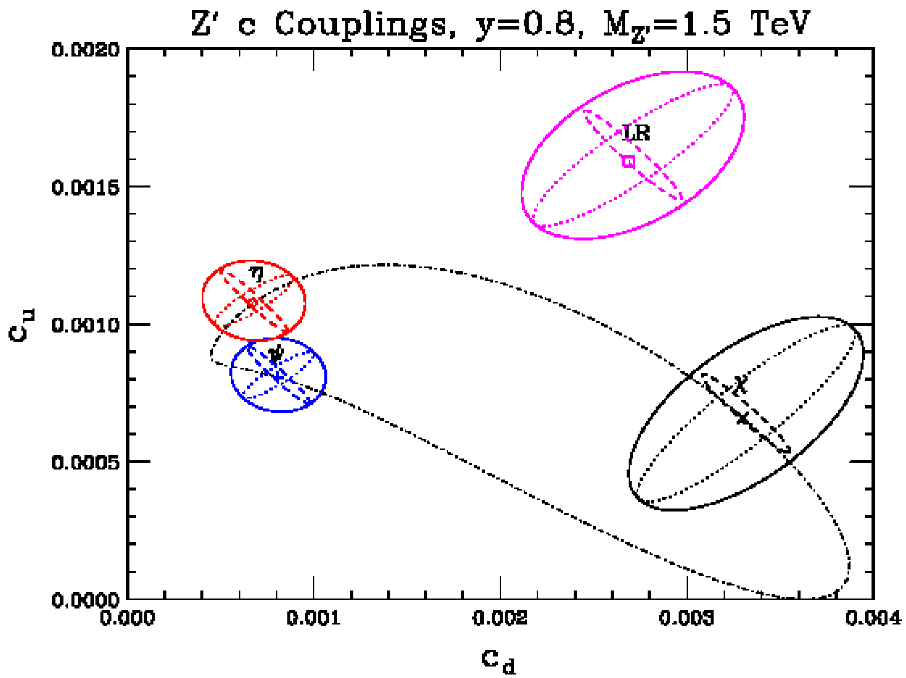
$$F_< = \int_{-y_1}^{y_1}\int_0^1 \frac{d\sigma}{dy\,d\cos\theta^*}dy$$

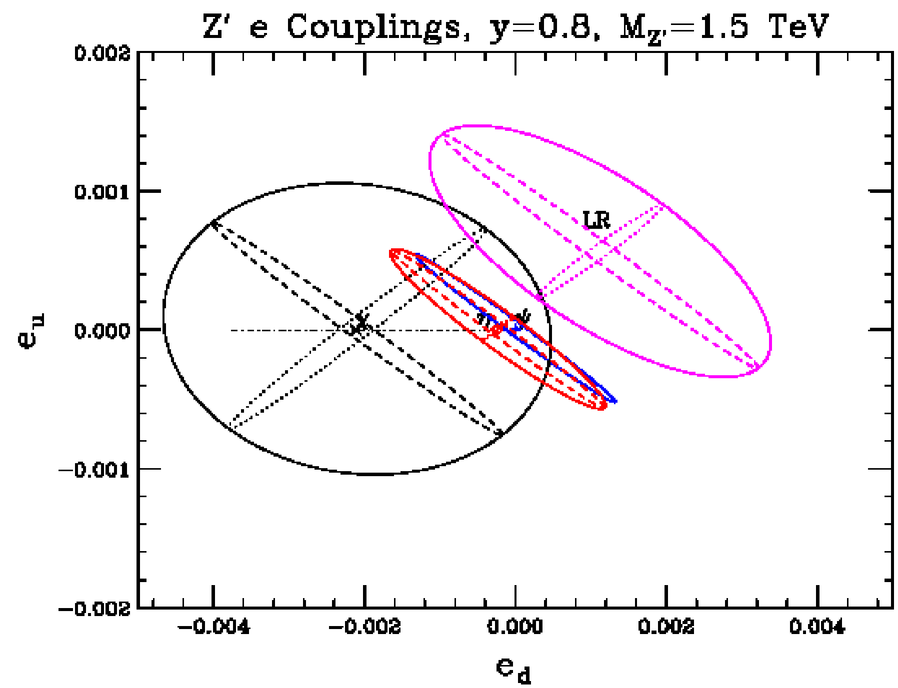
$$B_< = \int_{-y_1}^{y_1}\int_{-1}^0 \frac{d\sigma}{dy\,d\cos\theta^*}dy$$

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

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

Calculate the model independent stuff then fit to 4 coupling factors





L=100 fb^{-1}

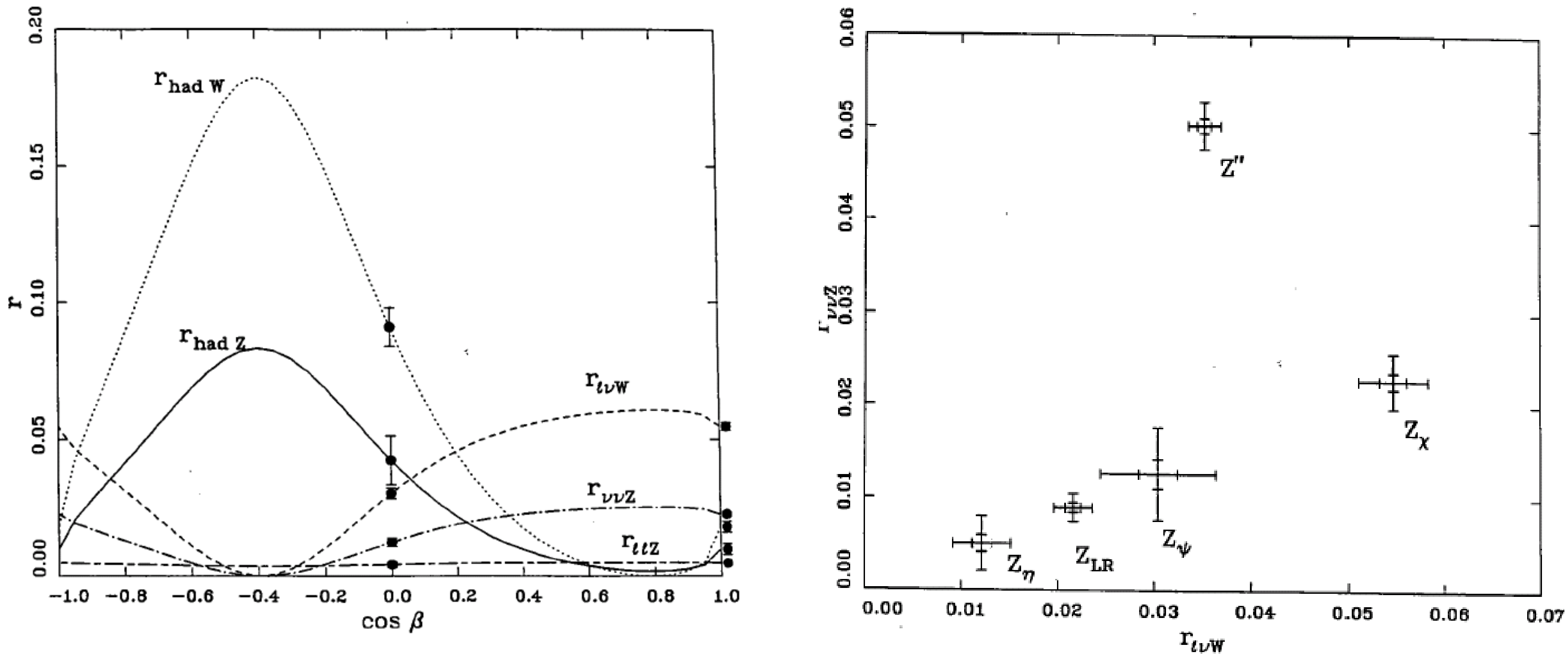
Dashed ellipses are statistical errors

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

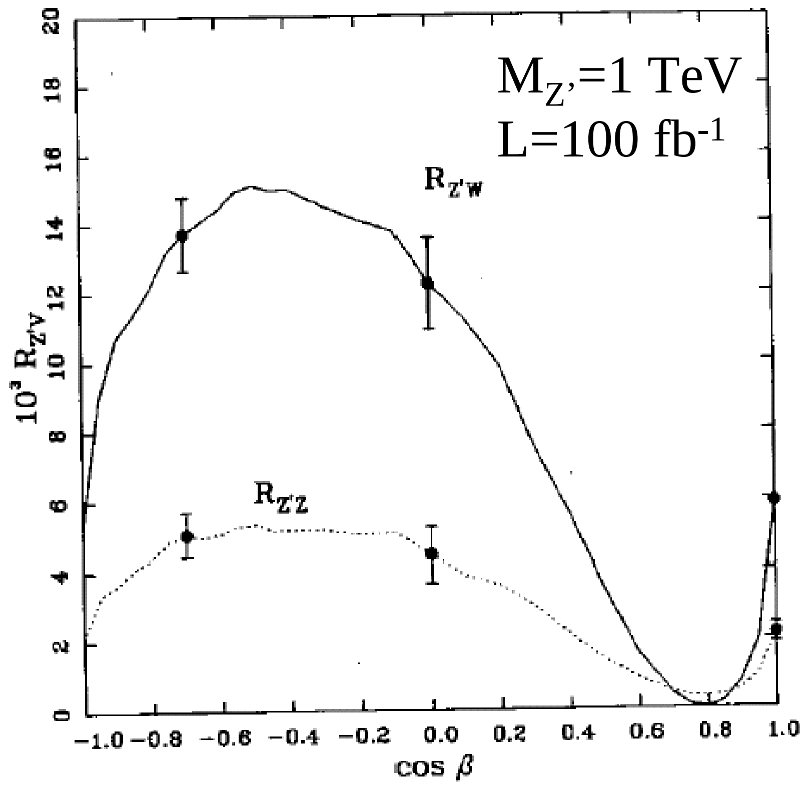


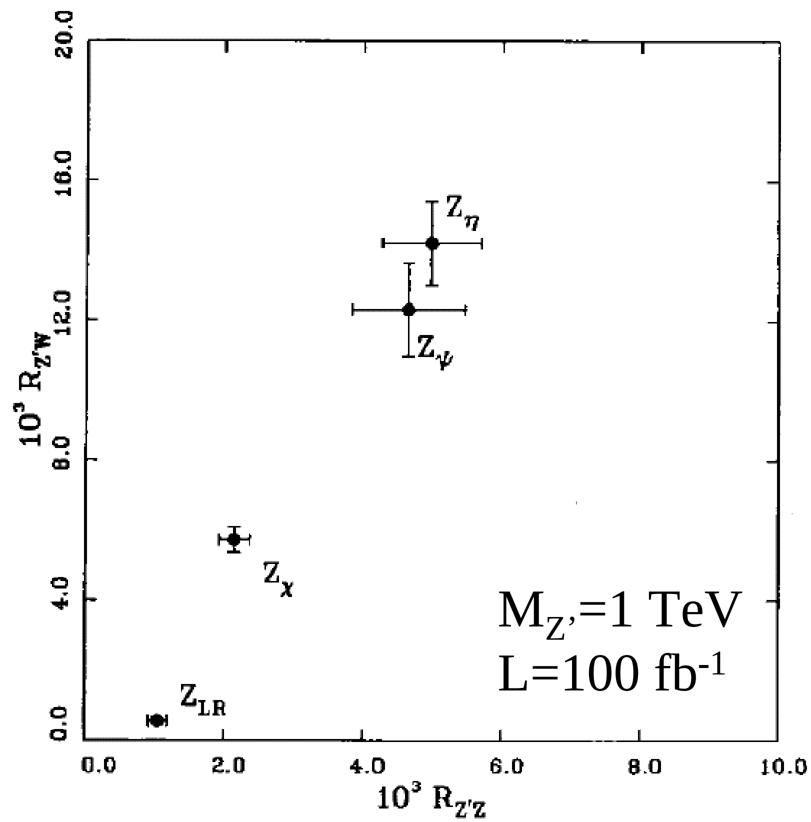
From Cvetic and Langacker PRD46, 14 (1992)

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

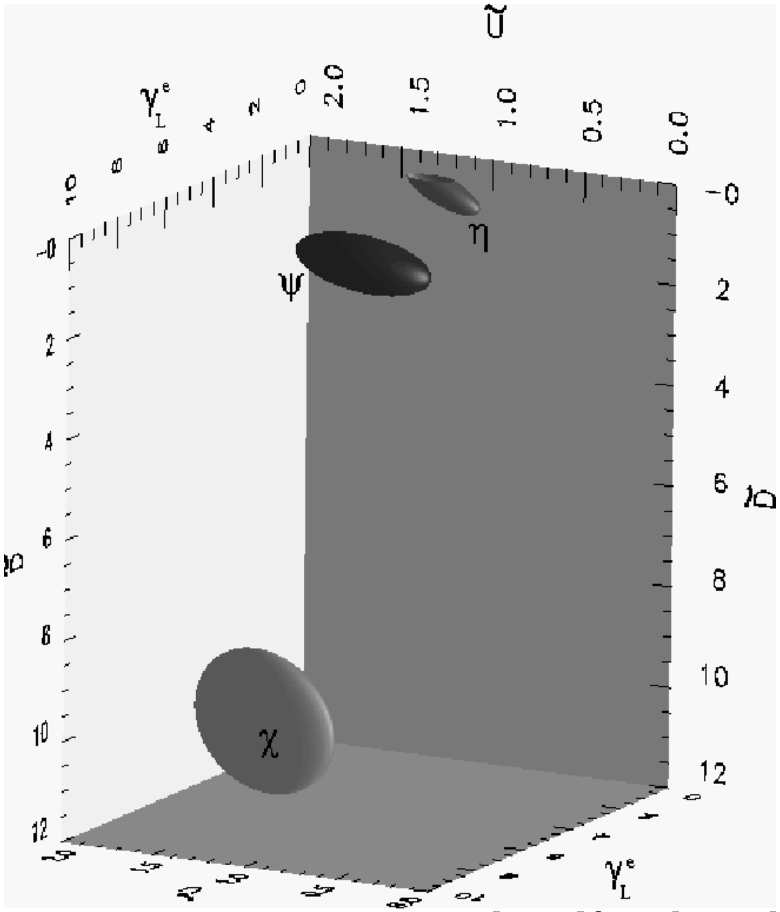




From Cvetic and Langacker PRD46, 4943 (1992)

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

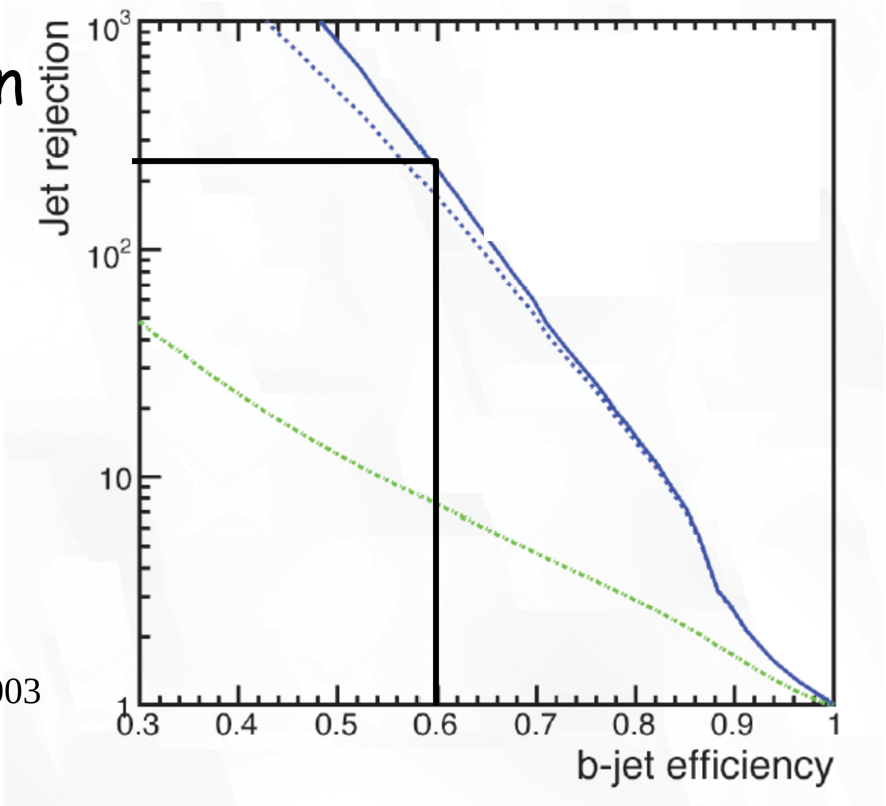
b & t identification efficiency

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

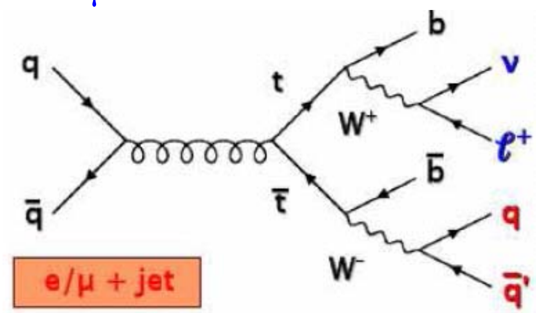
b & t identification efficiency

t-quark

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

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

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%

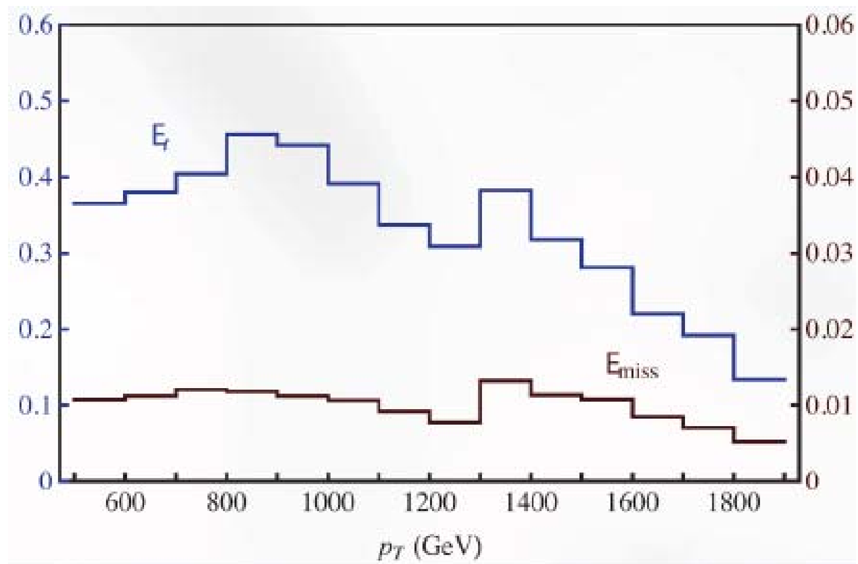
Purely hadronic modes

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

See also:

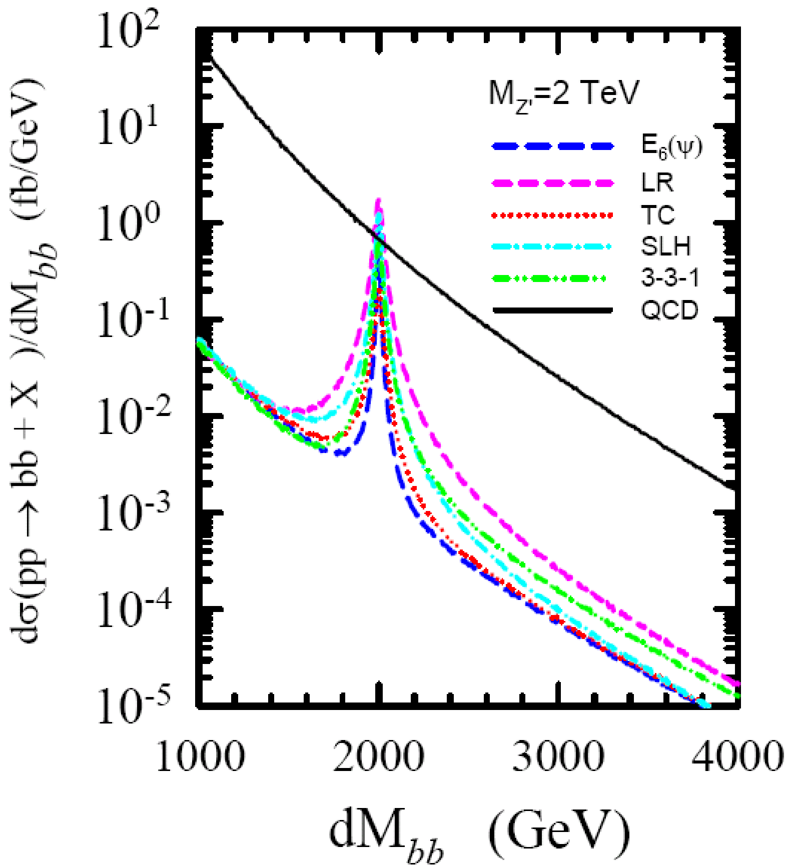
Orr and Baur [hep-ph/0707.2066]

Thaler and Wang [hep-ph/0806.0023]



If can utilize hadronic modes should increase efficiencies significantly

SM QCD Backgrounds



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

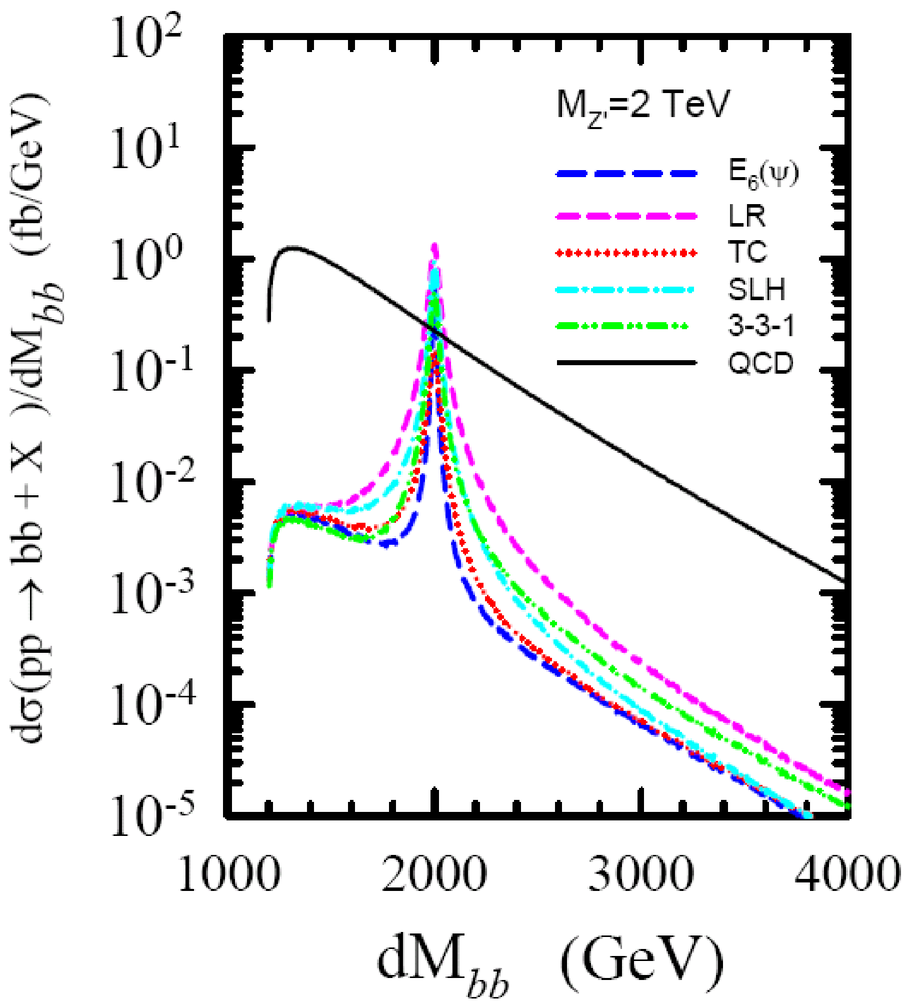
$$P_T > 50 \text{ GeV}$$

- 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:

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

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

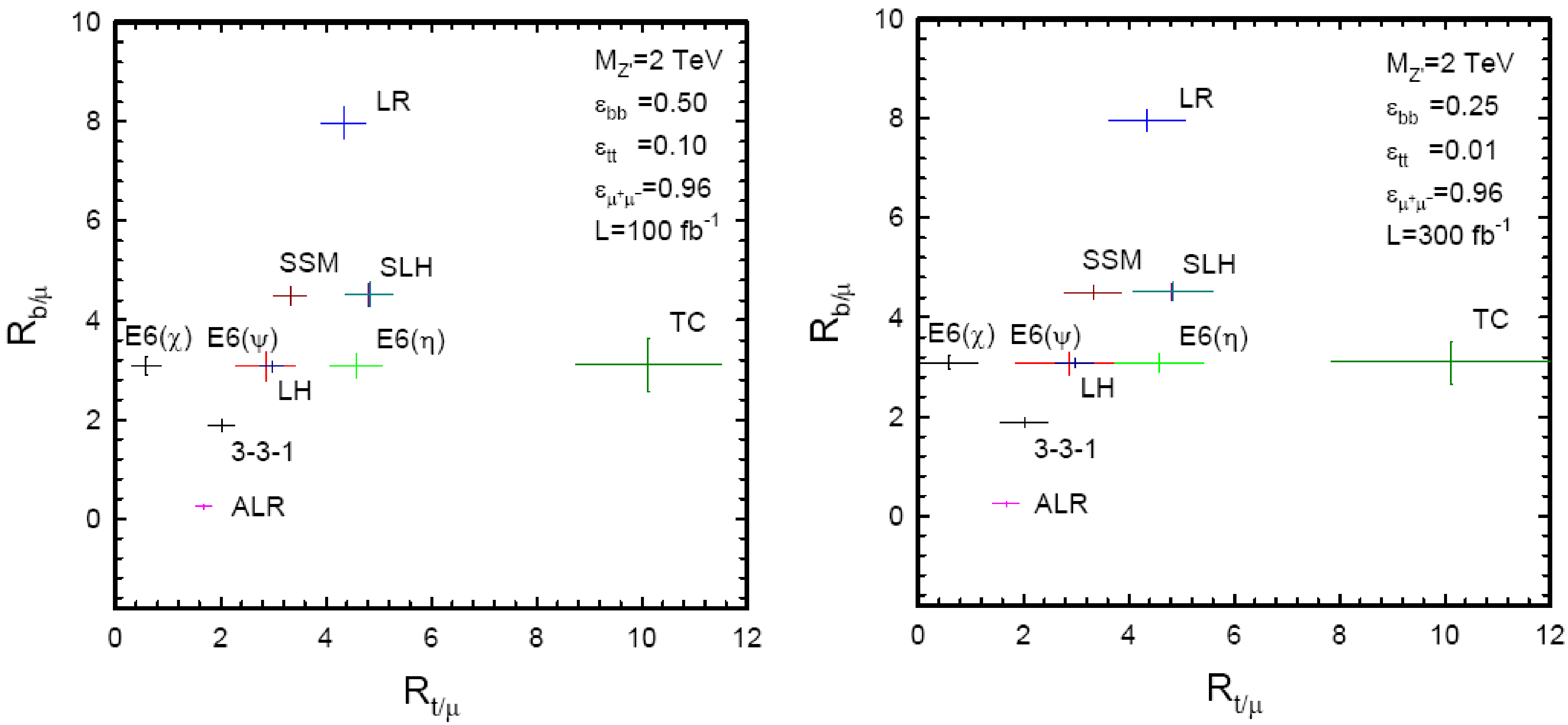
K_q depends on QCD and EW corrections

The ratios depend on model dependent couplings

Can use them to distinguish between models

Assume Z' discovered and mass and width measured

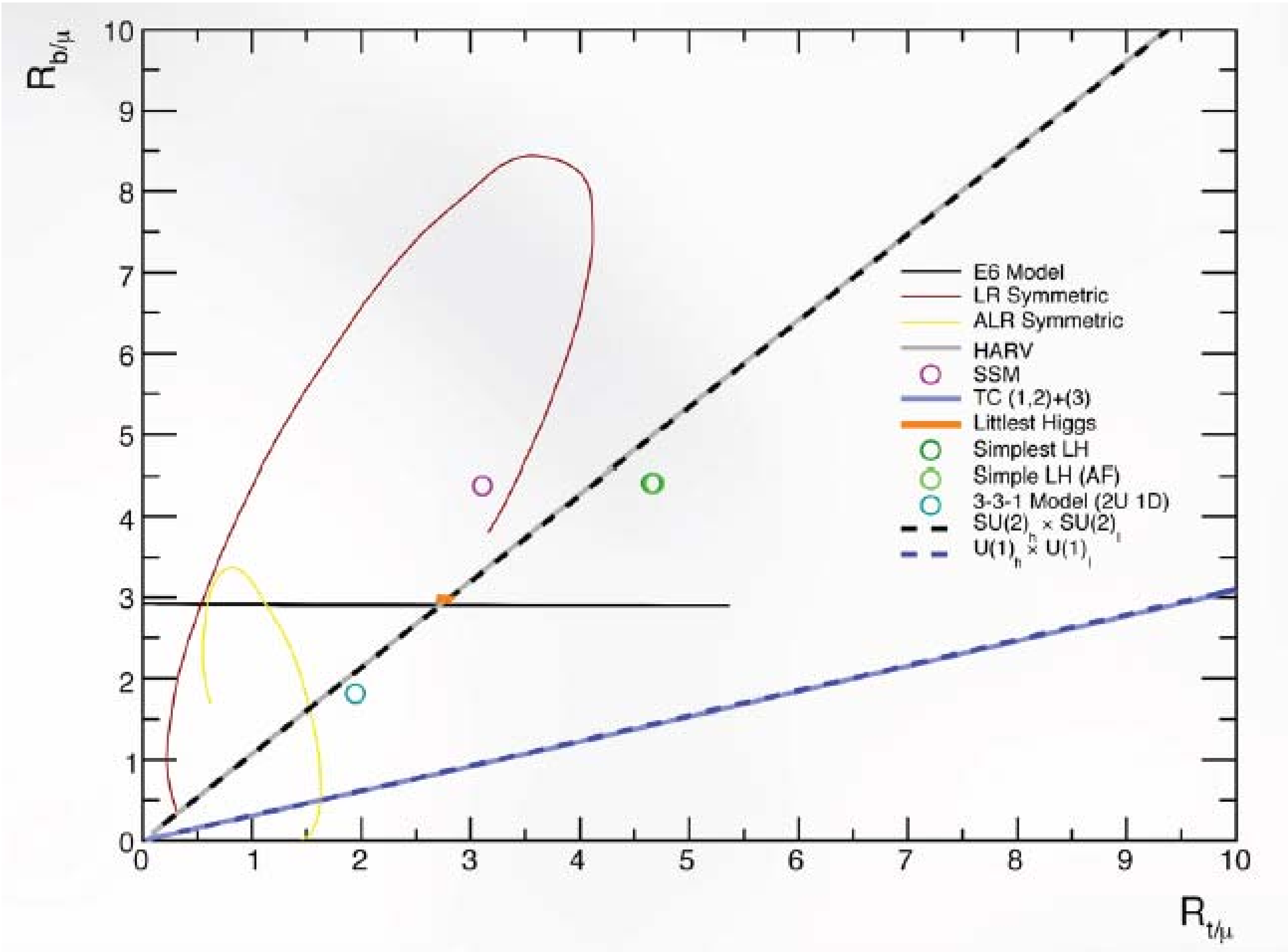
- Statistical error based on signal + background for given luminosity and ε
- Subtract SM backgrounds for predicted # of signal events



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

LHC Physics activities at Carleton

Theory

Steve Godfrey

Pat Kalyniak

Heather Logan

???

Research Interests:

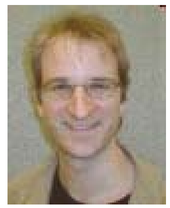
- Particle Physics Phenomenology
- Understanding the Higgs Mechanism
- Supersymmetry
- Searches for new physics

Experiment

David Asner

Gerald Oakham

Manuella Vincter



Alain Bellerive

Research Interests:

- Study of Invisible Higgs
- Search for SUSY
- Top quark properties

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TRIUMF

Workshop on Physics at the LHC: the 1st Year & ATLAS-CanadaWorkshop

Home | Agenda | Travel | Lodging | Registration

The Theory Groups at TRIUMF and Carleton University are organizing a three-day workshop on LHC Physics to be held at TRIUMF, in Vancouver. The ATLAS Group at TRIUMF will be hosting the 10th annual ATLAS-Canada Physics Workshop at TRIUMF immediately afterwards. Joint sessions of the two workshops have been arranged.

Dates	LHC/Theory	April 27th-30th, 2009
	ATLAS	April 30th and May 1st, 2009

Location Auditorium
2nd floor of Main Office Building
TRIUMF
4004 Wesbrook Mall
Vancouver BC
Canada

See TRIUMF Location Maps for more details.

Organizers:

Theory Workshop

- **Steve Godfrey**
- **Pat Kalyniak**
- **Heather Logan**
- **David Morrissey**
- **John Ng**

Theory Workshop Invited Speakers

Sekhar Chivukula (Michigan State)
Hooman Davoudiasl (Brookhaven)
David E. Kaplan (Johns Hopkins)
JoAnne Hewett (SLAC)
Michael Peskin (SLAC)
Frank Petriello (Madison)
Juergen Reuter (Freiburg)
Tom Rizzo (SLAC)
Veronica Sanz (Boston and York U.)
C.-P. Yuan (Michigan State U.)

Important Announcements

Registration **is now open.**

Workshop Sessions

Monday, April 27, 2009
Theory Session
1:00pm - 6:00pm

Tuesday, April 28, 2009
Theory Session