Weakly coupled Z' bosons at the LHC and ILC

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1. Introduction

2. Search for weakly coupled Z's

3. Parameter determination

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Introduction

Additional neutral gauge bosons expected in many extensions of SM:

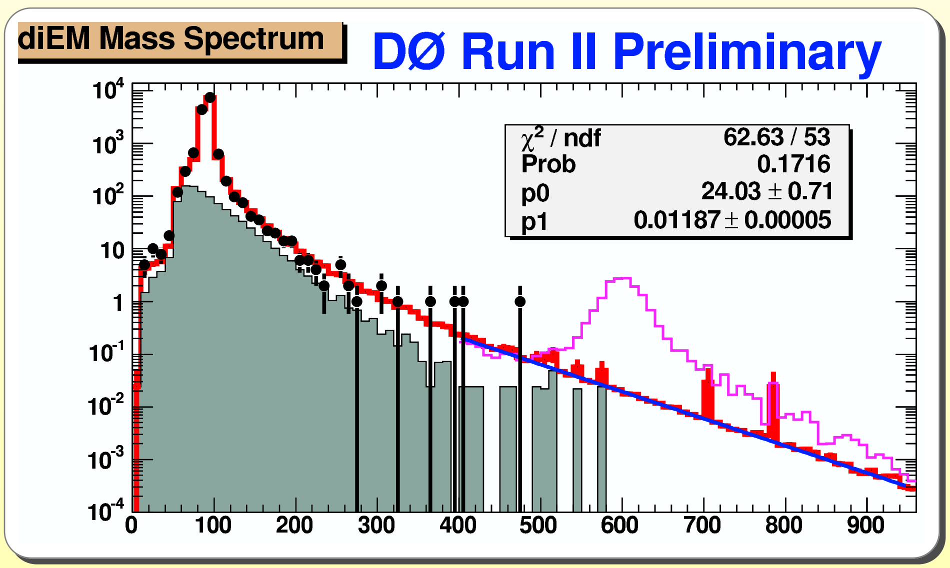
- Unified gauge groups (SU(5), SO(10), E_6, LR-symmetry, ...)
- Dynamical electroweak symmetry breaking
  (Technicolor, Topcolor, ...)
- Little Higgs models
  $\rightarrow$ extra gauge bosons to cancel large radiative corrections to Higgs potential
- Extra dimensions
  KK exitations in models with various geometries and boundary conditions

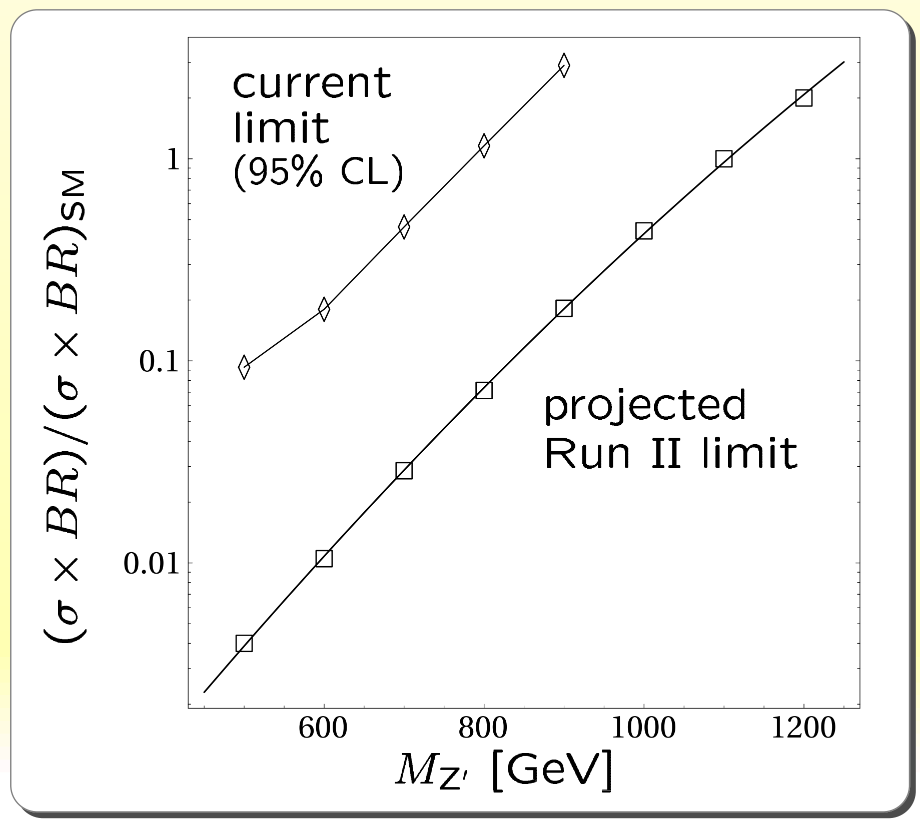
Conclusion: Plethora of new physics models allows wide range of Z' masses and couplings

Existing limits for neutral vector bosons (Z's)

Z' bosons at the Tevatron

- Search for new physics signals in Drell-Yan with lepton final state: $p\bar{p} \to Z' + X \to l^+ l^- + X$
- Main background: $p\bar{p} \to \gamma^*, Z^* + X \to l^+ l^- + X$





Z' bosons at LEP

Heavy Z' bosons $M_{Z'} > 200$ GeV:

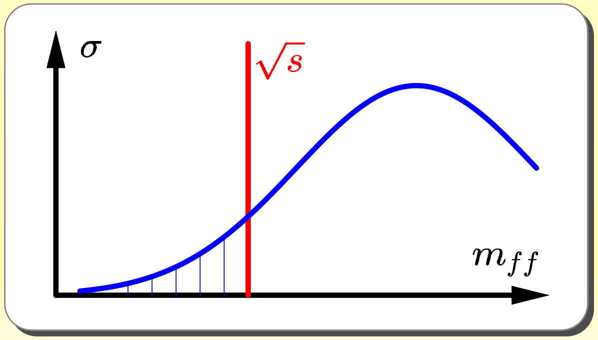
ALEPH '00

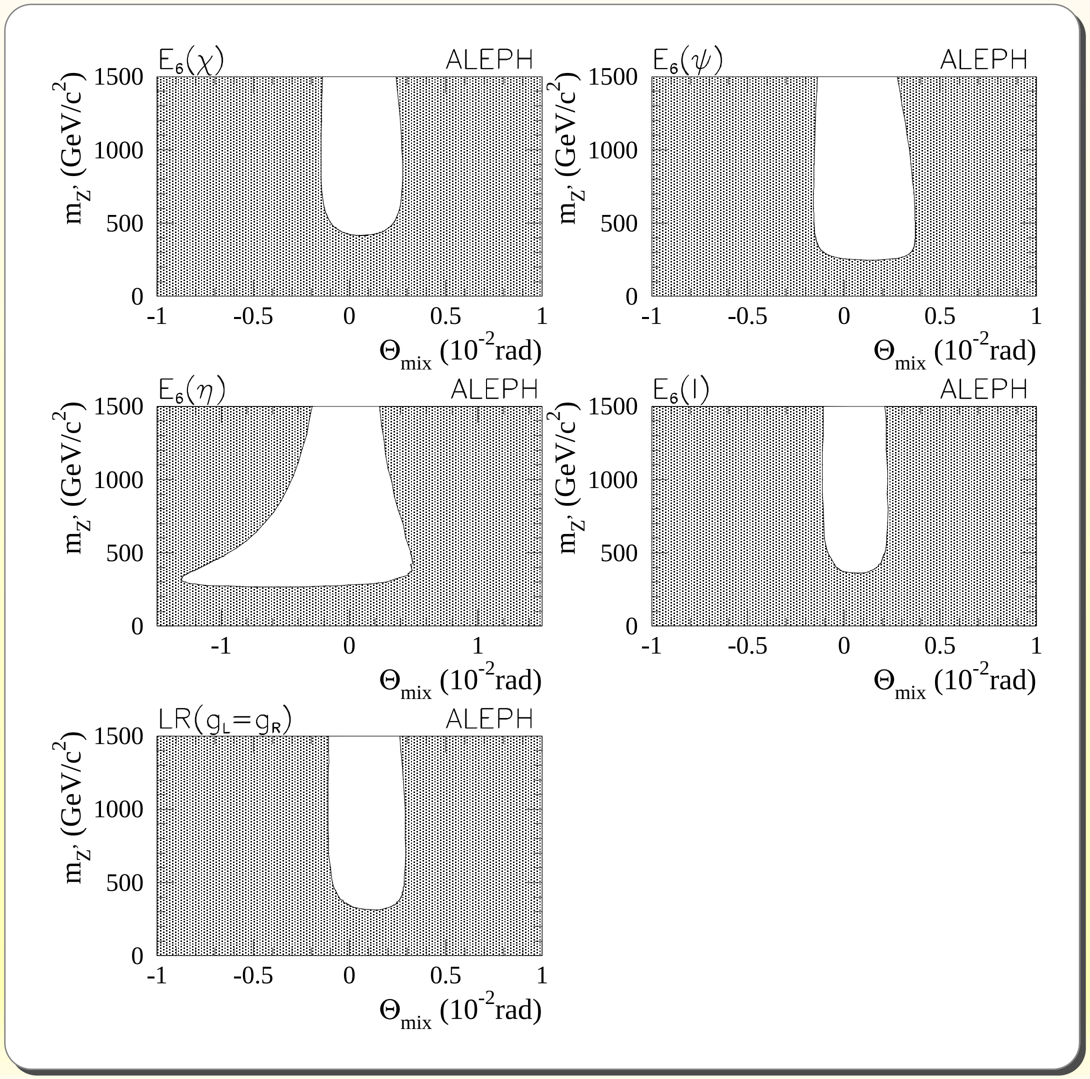
- Z–Z' mixing effects
  $\rightarrow$ measureable at LEP1

- Off-shell propagator effects of Z' modify

$$e^+e^- \xrightarrow{\gamma,Z,Z'} f\bar{f}$$

$\rightarrow$ Sensitivity at LEP2 for $M_{Z'} > \sqrt{s}$



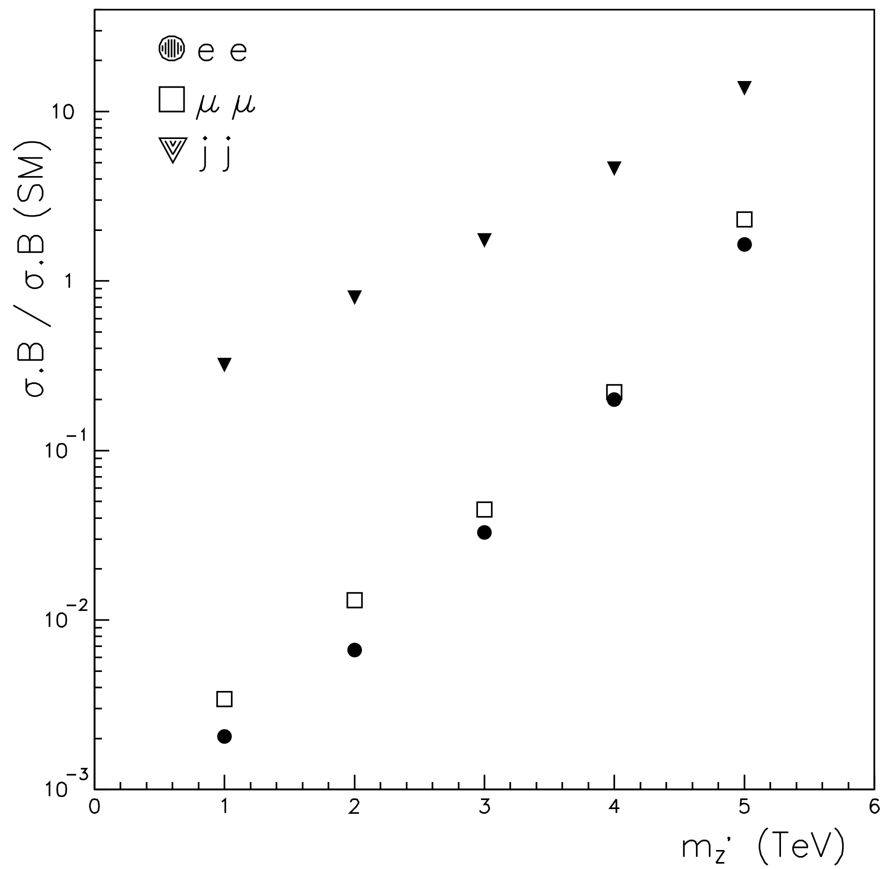


Z' bosons at the LHC

- Higher energy and more statistics than Tevatron
- Discovery in leptonic channels $pp \to Z' + X \to l^+ l^- + X$ up to $M_{Z'} \sim 5$ TeV
- Jet channel also possible, but large QCD background

ATLAS TDR '99

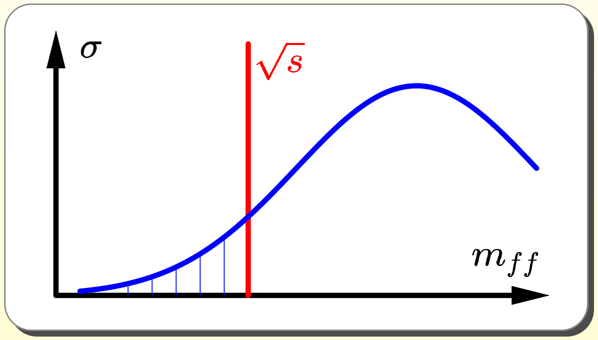
5σ discovery contours:



Z' bosons at a future linear collider

Heavy Z' bosons $M_{Z'} > 1$ TeV:

- Small Z–Z' mixing
  $\rightarrow$ negligible effect on Z-pole data



- Propagator effects of Z' modify

$$e^+e^- \xrightarrow{\gamma, Z, Z'} f\bar{f}$$

$\rightarrow$ High luminosity 500–1000 fb^{-1} allows sensitivity for $M_{Z'} \gg \sqrt{s}$

- Sensitive observables:
  - total cross-section σ_{tot}
  - forward-backward asymmetry A_{FB}
- With e^- beam polarization
  - left-right asymmetry A_{LR}
  - polarization asymmetry A_{pol}

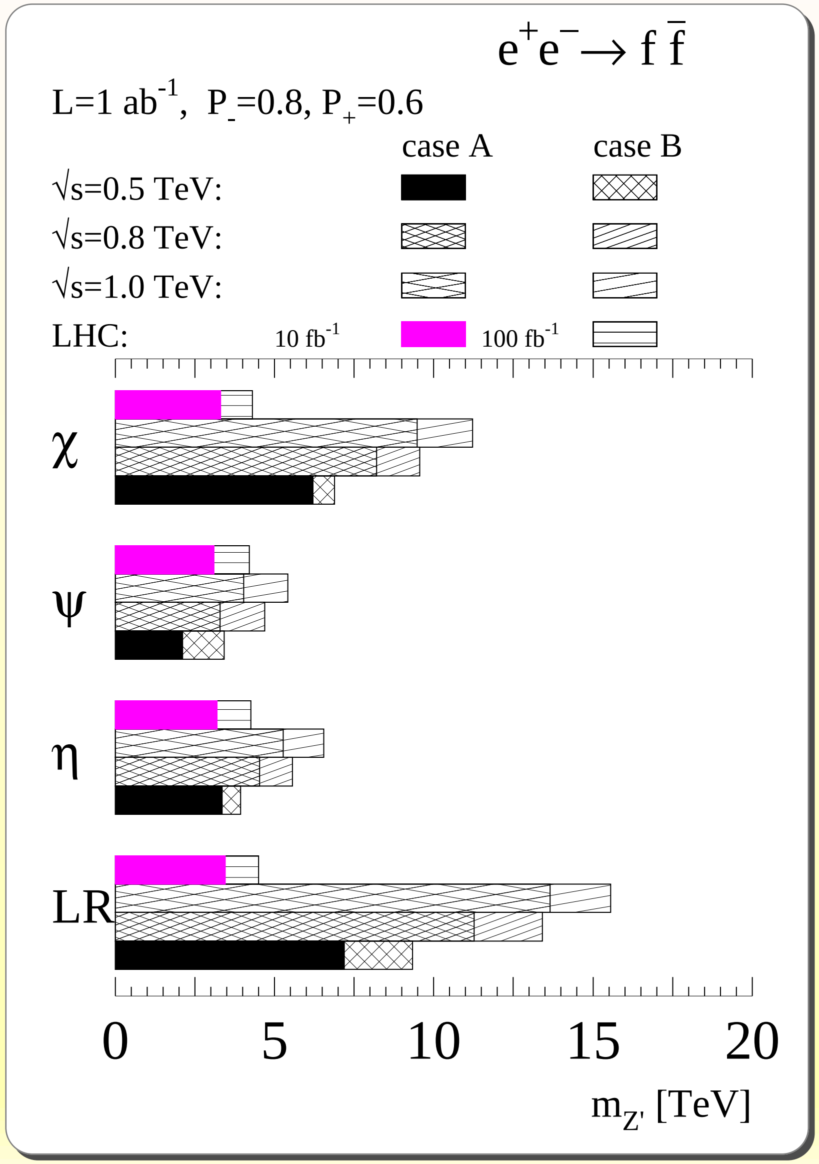
$$A_{\text{FB}} = \frac{\sigma_{\text{F}} - \sigma_{\text{B}}}{\sigma_{\text{tot}}}$$

$$A_{\text{LR}} = \frac{\sigma_{\text{L}} - \sigma_{\text{R}}}{\sigma_{\text{tot}}}$$

$$A_{\text{pol}} = \frac{(\sigma_{\text{L}} - \sigma_{\text{R}})_{\text{F}} - (\sigma_{\text{L}} - \sigma_{\text{R}})_{\text{B}}}{\sigma_{\text{tot}}}$$

Projected sensitivity

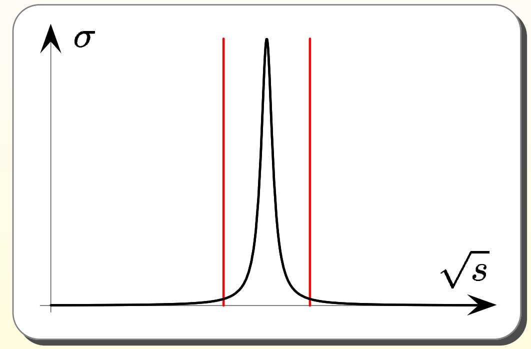
- Look for deviations from SM background
$$e^+e^- \xrightarrow{\gamma^*,Z^*} f\bar{f}$$
- Assume $P(e^-) = 80\%$
$P(e^+) = 60\%$
(slight improvement from e^+ pol.)
- Combine all observables
σ_{tot}, A_{FB}, A_{LR}, A_{pol}



case A,B : different assumptions about sys. errors

S. Riemann '00

Search for weakly coupled neutral vector bosons



Weakly coupled Z' form narrow resonance

$\rightarrow$ Can only be produced in $e^+e^- \to Z' \to f\bar{f}$ for $M_{Z'} \approx \sqrt{s}$

For $\Delta E > \Gamma_{Z'}$:

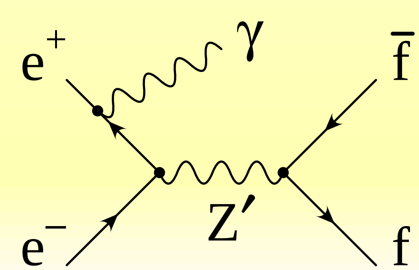
$$\int \mathrm{d}(\sqrt{s})\, \sigma[e^+e^- \to Z' \to f\bar{f}] = \frac{6\pi^2\Gamma_{Z'}}{M_{Z'}^2} \mathrm{Br}(Z' \to e^+e^-)\, \mathrm{Br}(Z' \to f\bar{f}),$$

Most stringent constraints on narrow Z' with $M_{Z'} < \sqrt{s}$ from

$e^+e^- \to Z' + n\gamma \to f\bar{f} + n\gamma$

Leike '99
Appelquist, Dobrescu, Hopper '03

$$\left[e^+e^-\right]_s \xrightarrow{\text{beamstr.}} \left[e^+e^-\right]_{s'<s} \to Z' \to f\bar{f}$$



Initial state-radiation

Leading effects due to initial-state γ radiation collinear to beam

Structure function method: Kuraev, Fadin '85
Altarelli, Martinelli '86

$$\sigma[e^+e^- \to f\bar{f} + n\gamma](s) = \int_0^1 \mathrm{d}x_+ \int_0^1 \mathrm{d}x_- \, \Gamma_{ee}(x_+, s) \, \Gamma_{ee}(x_-, s) \\ \times \; \sigma[e^+e^- \to f\bar{f}](sx_+x_-),$$

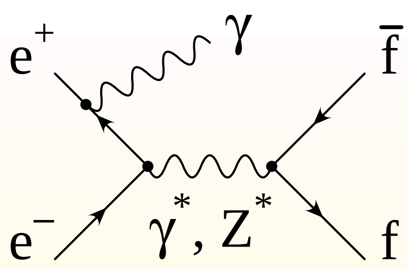
Structure function include large logarithms
$L = \log(s/m_{\mathrm{e}}^2)$, known to $\mathcal{O}(\alpha^5 L^5)$ Przybycień '95

$$\Gamma_{ee}(x, s) = \delta(1-x) \; + \; \frac{\alpha}{2\pi} L \frac{1+x^2}{1-x} \; + \; \left(\frac{\alpha}{2\pi}\right)^2 L^2 \cdots$$

Beamstrahlung:
Beam disruption due to beam-beam interaction

Detailed simulations with *Guinea-Pig* Schulte '99
included in *Circe* ($K\iota\rho\kappa\eta$) Ohl '97

Dominant background:



$e^+e^- \to \gamma^*/Z^* + n\gamma \to f\bar{f} + n\gamma$

$\left[e^+e^-\right]_s \xrightarrow{\text{beamstr.}} \left[e^+e^-\right]_{s'<s} \to \gamma^*/Z^* \to f\bar{f}$

Signal: narrow peak over background in $f\bar{f}$ invariant mass spectrum

$\to$ good momentum resolution crucial to improve S/B

$\mu^+\mu^-$: momentum resolution of central tracker:
$\Delta(1/p) = 5 \cdot 10^{-5}$ GeV^{-1}

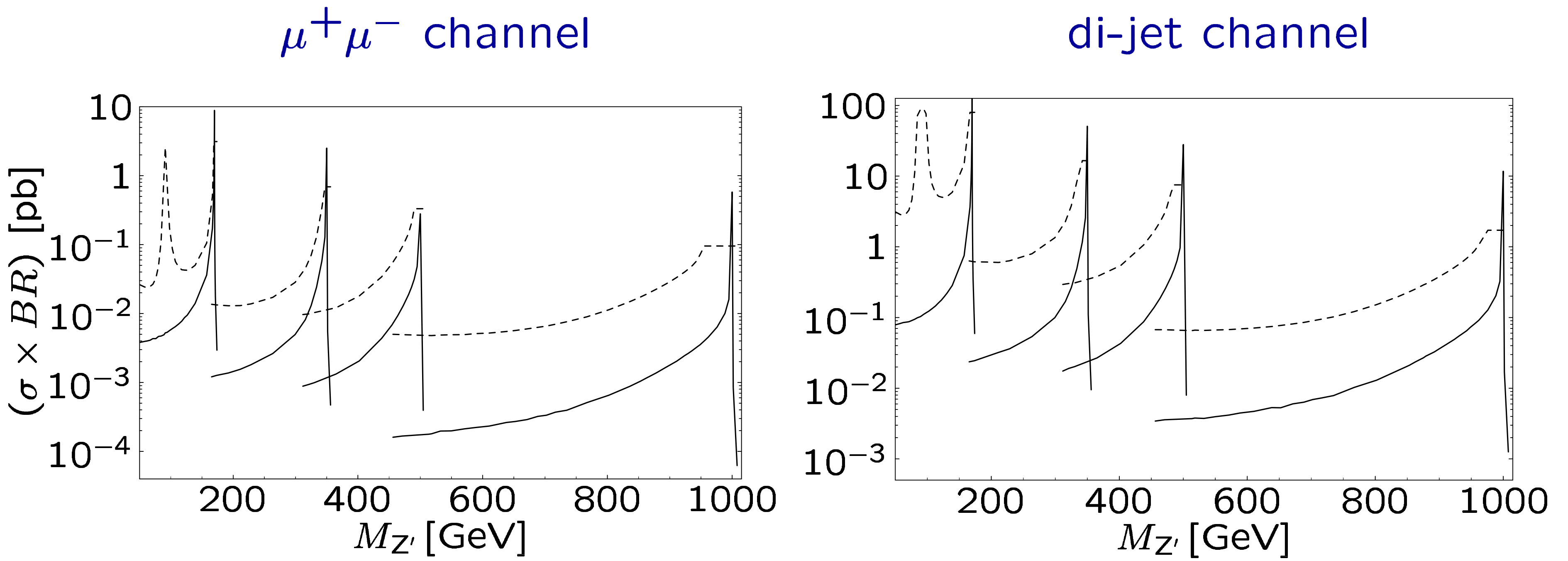
jet–jet: jet energy resolution from hadronic calo.:
$\frac{\Delta E_j}{E_j} \approx \frac{35\%}{\sqrt{E/\text{GeV}}} \oplus 3\%$

TESLA TDR '01

Typical cross-sections

Consider Z' boson with same coupling quantum numbers as Z

$g_{Z'} = g_Z/30$

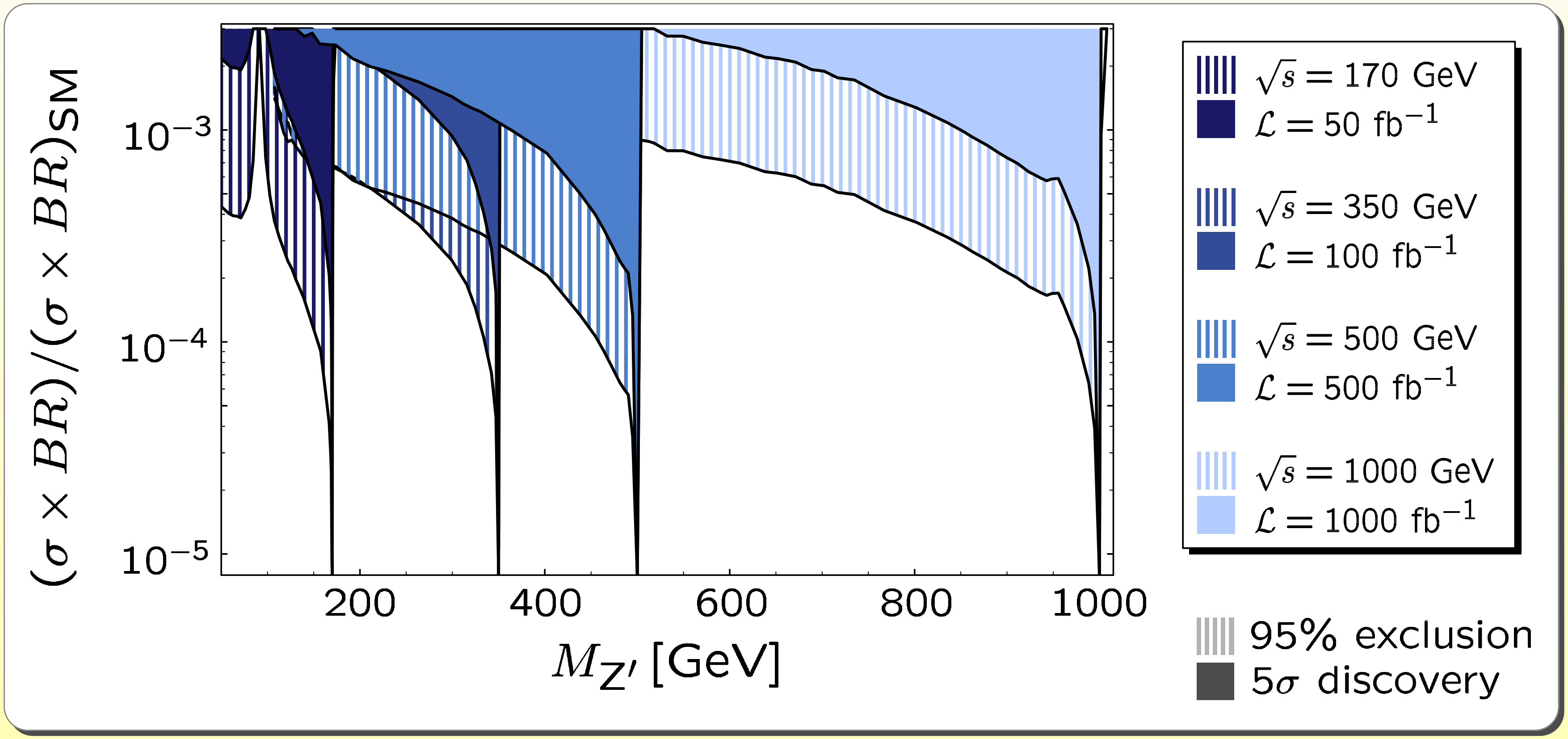


—— signal

- - - SM background

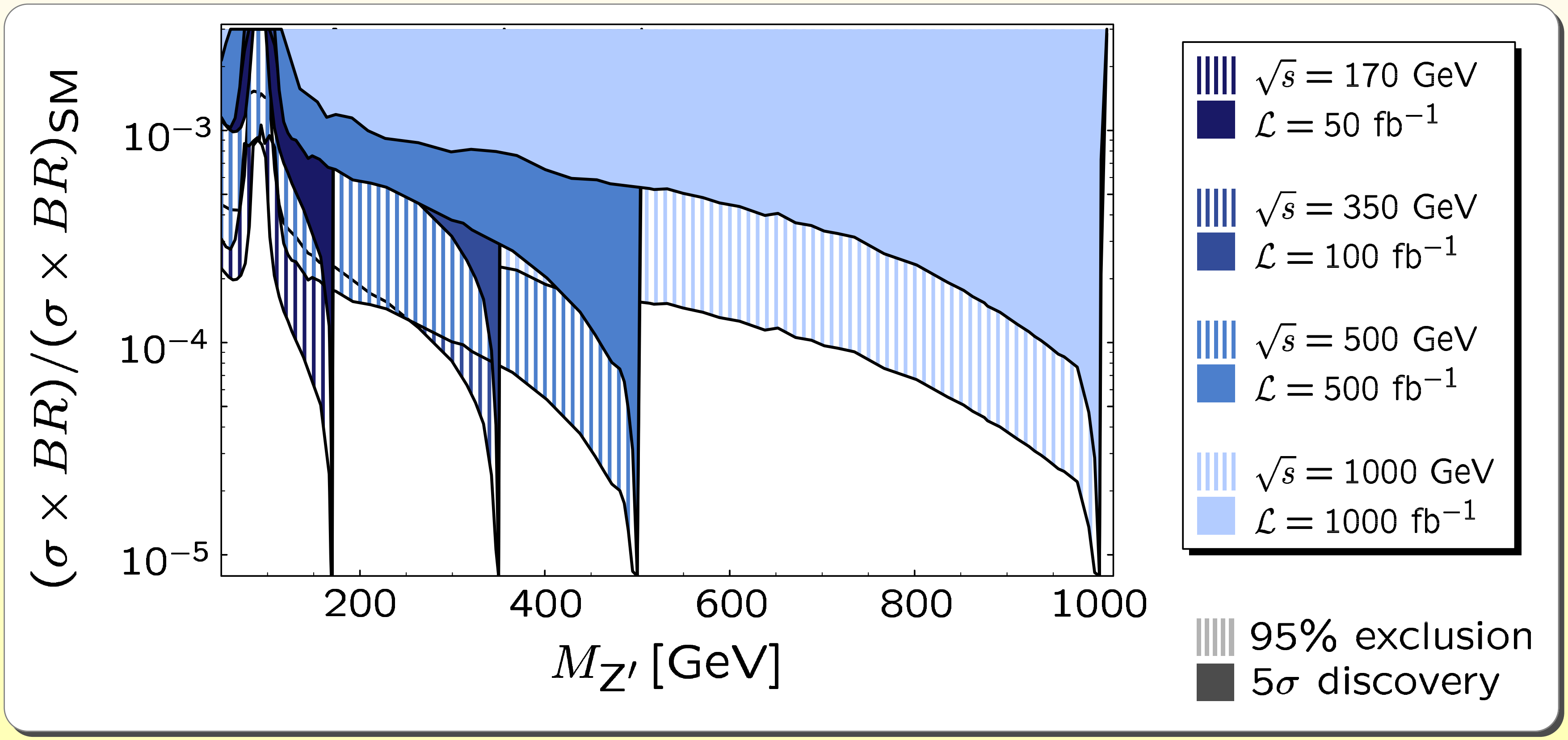
Results for $\mu^+\mu^-$ channel

Cuts: $\cos\theta_\mu \leq 0.94$ $\Delta E_{\mu\mu} \approx 5 \cdot 10^{-5}\ \text{GeV}^{-1} \cdot s$



Results for di-jet channel

Cuts: $\cos\theta_\mu \le 0.94$ $\Delta E_{jj} = 2\sqrt{0.06125\ \text{GeV} \cdot \sqrt{s} + 0.000225\, s}$

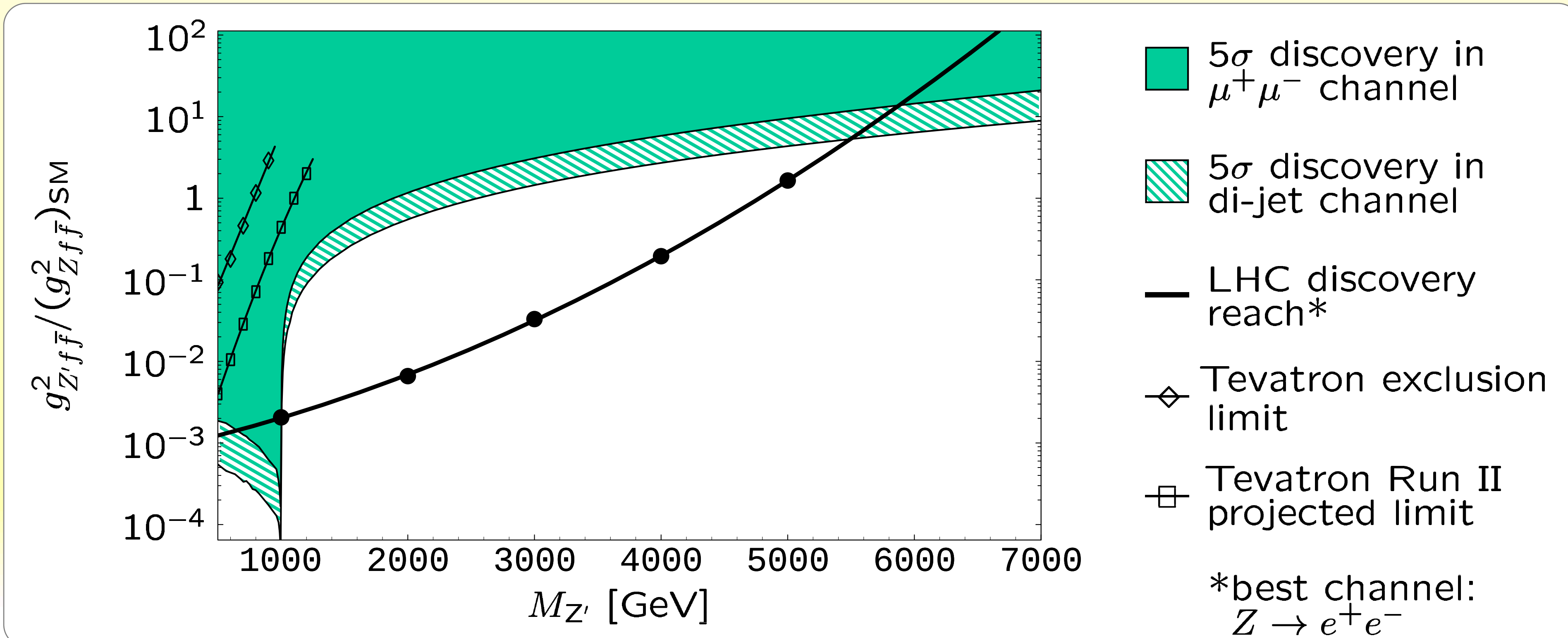


Comparison with hadron colliders

Combination of searches with radiative-return method for $M_{Z'} < \sqrt{s}$ and contact-interaction method for $M_{Z'} > \sqrt{s}$:

Sensitivity to high masses $M_{Z'}$, but only moderate coupling strength $g^2_{Z'f\bar{f}}/(g^2_{Zf\bar{f}})_{\rm SM}$

Example for BR = $\mathrm{BR_{SM}}$: $\sqrt{s}$ = 1000 GeV, $\int \mathcal{L}$ = 1000 fb^{-1}

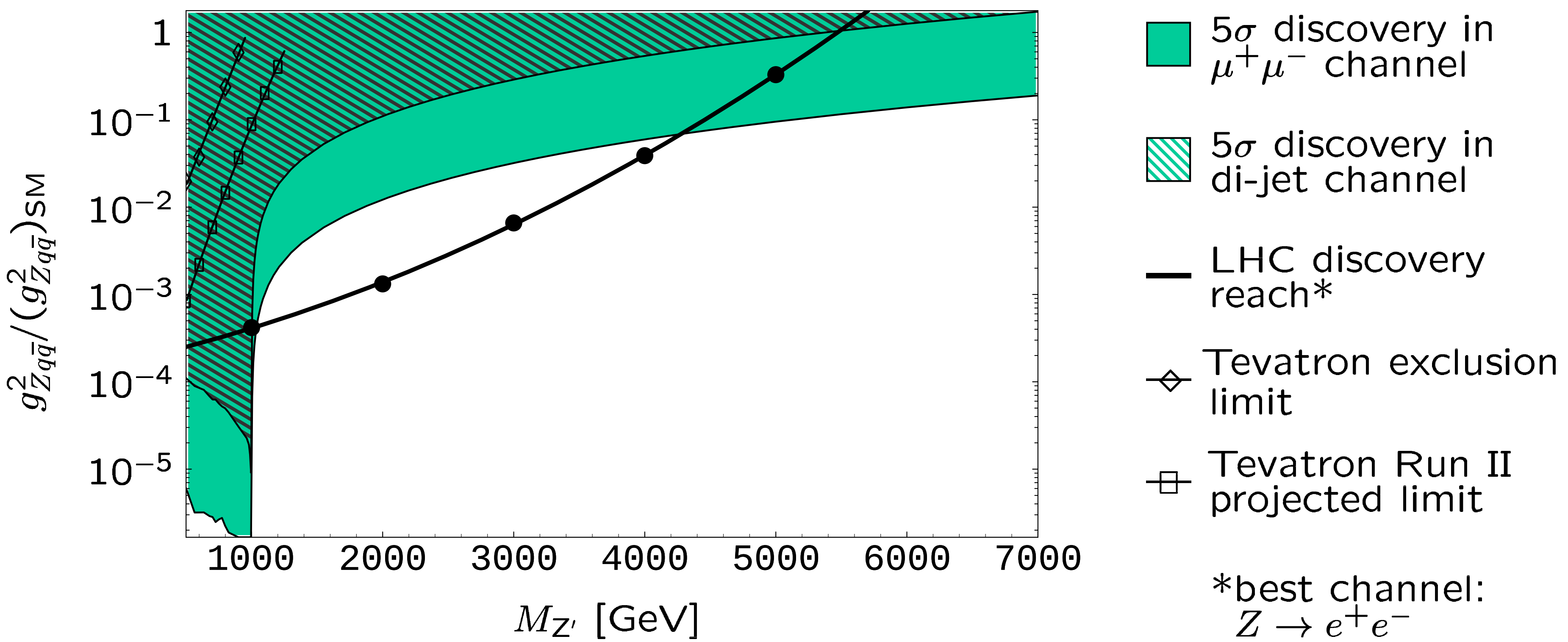


Special case: $Z_{\text{B-L}}$

Z' has pure $B-L$ couplings → corresponding to $z_u = z_q$

⇒ No mixing between Z and Z' (i.e. no constraints from Z-pole)

$\sqrt{s} = 1000$ GeV, $\int \mathcal{L} = 1000$ fb^{-1}



Parameter determination at LHC

Only relative couplings:

$$\gamma^l_{\mathsf{L}} = \frac{(g^l_{\mathsf{L}})^2}{(g^l_{\mathsf{L}})^2 + (g^l_{\mathsf{R}})^2},$$

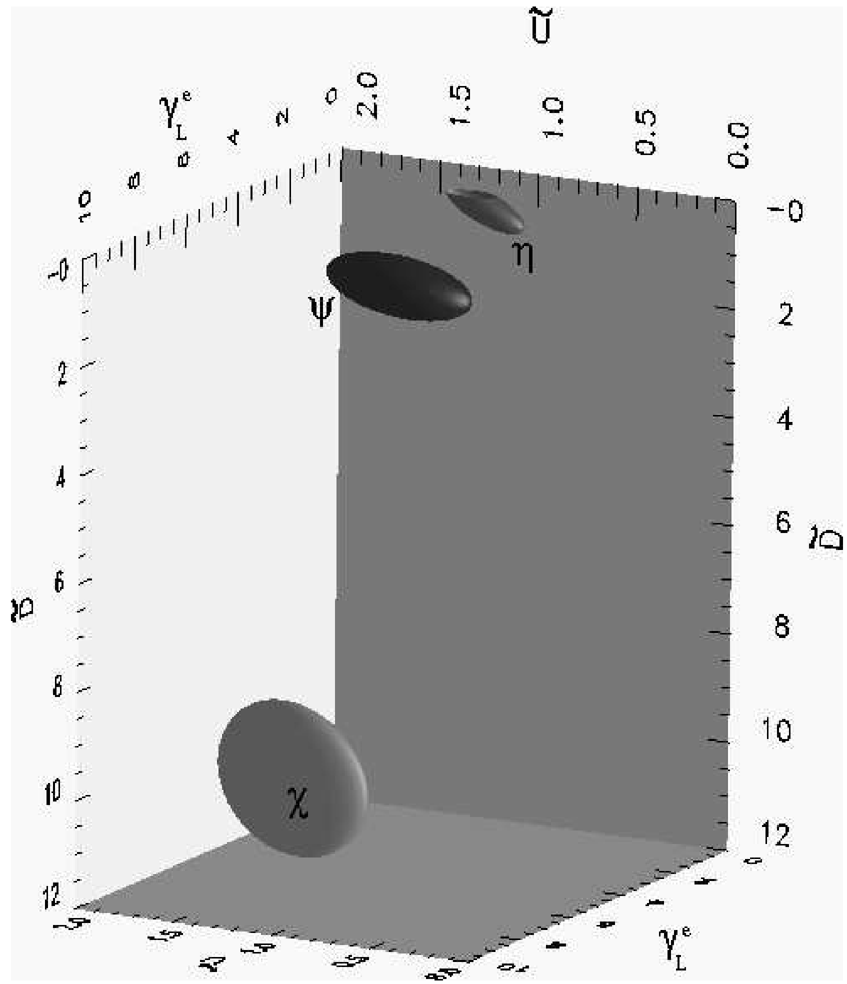
$$\gamma^q_{\mathsf{L}} = \frac{(g^q_{\mathsf{L}})^2}{(g^q_{\mathsf{L}})^2 + (g^q_{\mathsf{R}})^2},$$

$$\tilde{U} = \frac{(g^u_{\mathsf{R}})^2}{(g^q_{\mathsf{L}})^2}, \qquad \tilde{D} = \frac{(g^d_{\mathsf{R}})^2}{(g^q_{\mathsf{L}})^2}$$

Sensitive observables:

- forw.-backw. asymmetry A_{FB}
- rapidity distribution
- associated production $pp \to Z'Z,\ Z'\gamma,\ Z'W^{\pm}$

→ Good accuracy,
but ambiguity in signs



M. Cvetič, S. Godfrey '95

Parameter determination at linear collider

Determination of couplings of heavy Z' bosons $M_{Z'} > 1$ TeV:

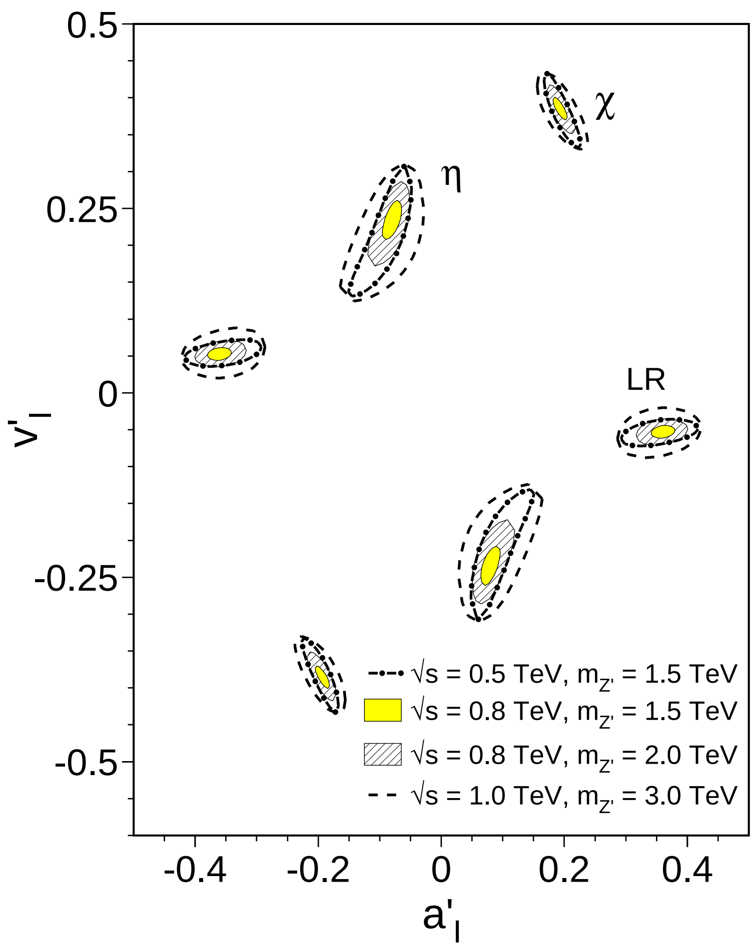
- Measure deviation from SM bkgd. $e^+e^- \to \gamma^*, Z^* \to f\bar{f}$ in cross-section and asymmetries

- Only sensitive to ratio of Z' couplings and Z' mass

$$a_f^N = a'_f \sqrt{\frac{s}{M_{Z'}^2 - s}},$$

$$v_f^N = v'_f \sqrt{\frac{s}{M_{Z'}^2 - s}}$$

- If Z' discovered at LHC
  $\to$ Use LHC mass measurement as input



S. Riemann '00

Determination of couplings of light Z' bosons $M_{Z'} < 1$ TeV:

Example: $Z_{\mathrm{B-L}}$ boson with $M_{Z'} = 400$ GeV and $\tilde{g}_l = g_{Z'll} = 0.006$

$\Rightarrow$ $(\sigma \times BR)/(\sigma \times BR)_{\mathrm{SM}} \simeq 1.2 \times 10^{-3}$, $\Gamma_{Z'} \simeq 0.6$ MeV

Total width too small to be resolved

$\rightarrow$ Difficult to determine **absolute** coupling strength

$\rightarrow$ Still possible to determine **relative** coupling ratios

- From left-right asymmetry: $A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}}$

Using 80% polarized e^- and
10 fb^{-1} each for L- and R-polarized e^- at $\sqrt{s} = 400$ GeV

$$\left(\frac{g^{\mathrm{L}}_{Z'ee}}{g^{\mathrm{R}}_{Z'ee}}\right)^2 = \frac{P + A_{\mathrm{LR}}}{P - A_{\mathrm{LR}}} \quad \Rightarrow \quad \frac{\delta(g^{\mathrm{L}}_{Z'ee}/g^{\mathrm{R}}_{Z'ee})}{g^{\mathrm{L}}_{Z'ee}/g^{\mathrm{R}}_{Z'ee}} \simeq 0.01$$

P = Polarization degree

- From forward-backward asymmetry: $$A_{\mathsf{FB}} = \frac{\sigma_{\mathsf{F}} - \sigma_{\mathsf{B}}}{\sigma_{\mathsf{F}} + \sigma_{\mathsf{B}}}$$

Consider $e^+e^- \to \mu^+\mu^-$ and assuming lepton universality

Using 20 fb^{-1} at $\sqrt{s} = 400$ GeV

$$\left(\frac{g^{\mathsf{F}}_{Z'll}}{g^{\mathsf{B}}_{Z'll}}\right)^2 = \frac{\sqrt{C} + \sqrt{A_{\mathsf{FB}}}}{\sqrt{C} - \sqrt{A_{\mathsf{FB}}}} \qquad C = \frac{\cos\theta_{\mathsf{max}}}{1 + \frac{1}{3}\cos\theta_{\mathsf{max}}}$$

$$\Rightarrow \quad \frac{\delta(g^{\mathsf{F}}_{Z'll}/g^{\mathsf{B}}_{Z'll})}{g^{\mathsf{F}}_{Z'll}/g^{\mathsf{B}}_{Z'll}} \simeq 0.14.$$

Combining with previous result from A_{LR}, $\frac{\delta(g^{\mathsf{L}}_{Z'ee}/g^{\mathsf{R}}_{Z'ee})}{g^{\mathsf{L}}_{Z'ee}/g^{\mathsf{R}}_{Z'ee}} \simeq 0.01$:

$$\Rightarrow \quad \frac{\delta(g^{\mathsf{F}}_{Z'\mu\mu}/g^{\mathsf{B}}_{Z'\mu\mu})}{g^{\mathsf{F}}_{Z'\mu\mu}/g^{\mathsf{B}}_{Z'\mu\mu}} \simeq 0.01.$$

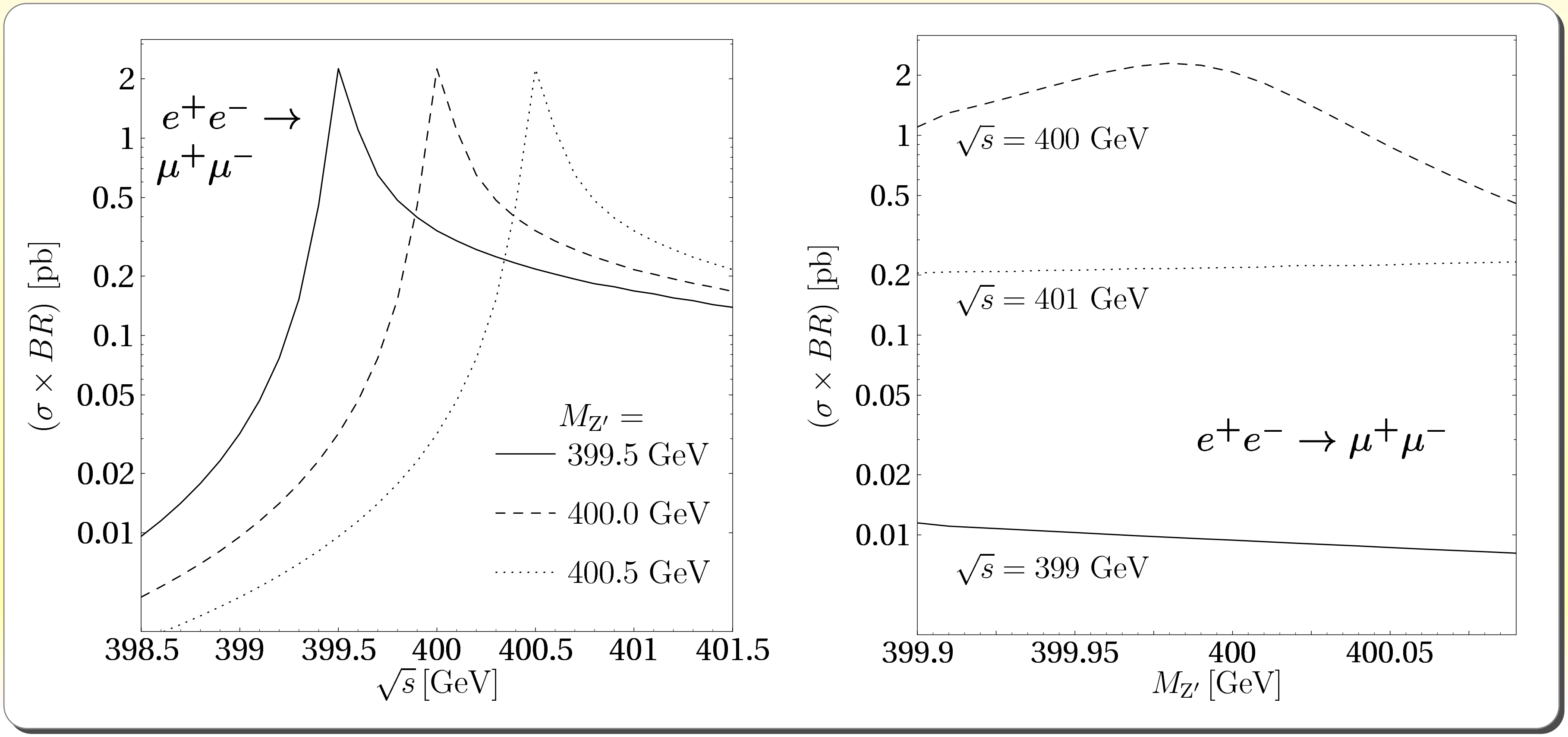
Mass measurement

Precise determination of mass from scan around resonance region

Resonance line-shape distorted due to beam energy spread

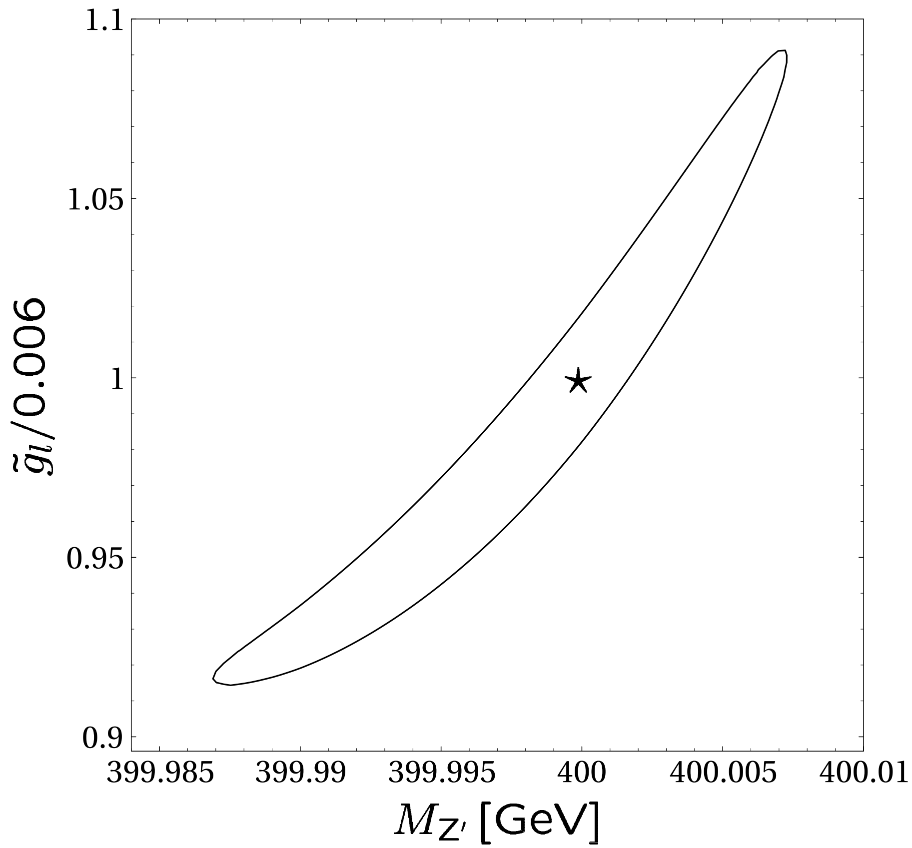
$\rightarrow$ Initial-state radiation calculable to high accuracy

$\rightarrow$ Beamstrahlung determined from measuring Bhabha scattering



Mass measurement from cross-section $e^+e^- \to \mu^+\mu^-$

Scan around resonance:
$\sqrt{s} = 399, 400, 401$ GeV width 10 fb^{-1} each



Beam energy spread causes strong correlation between mass $M_{Z'}$ and coupling $\tilde{g}_l$

Fit result:

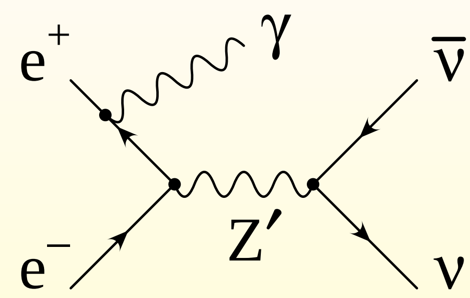
$$M_{Z'} = 400.0^{+0.007+0.040}_{-0.013-0.040} \text{ GeV}$$

↑ Systematics dominated by uncertainty in beam energy

Special case: Invisible Z' decays

Invisible decay modes, e.g. $Z' \to \nu\bar{\nu}$

Experimentally accesible by using
hard photon for tagging
$e^+e^- \to \gamma\nu\bar{\nu}$



Carena, de Gouvêa, Freitas, Schmitt '03

Z' peak translates into peak in E_γ spectrum
$E_\gamma = \sqrt{s}(1 - m_{\nu\bar{\nu}})$

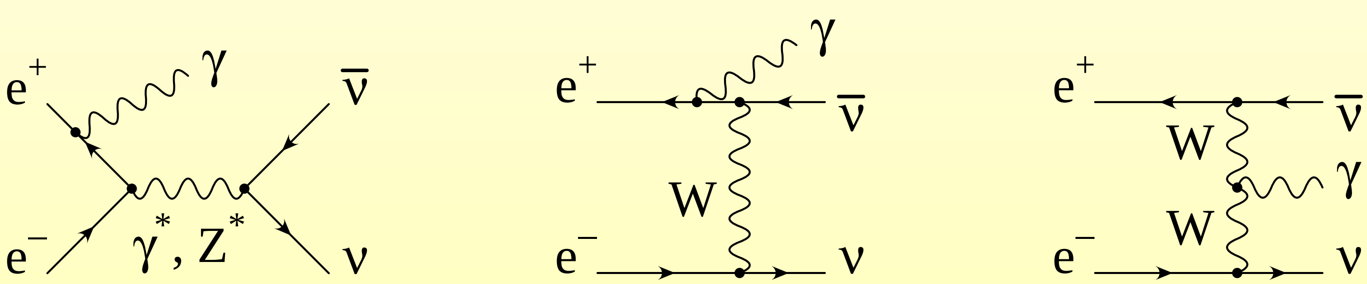
Search limits in $(\sigma \times BR)$ are weaker than in visible channels by roughly a factor $\log(s/m_e^2) \approx$ 25–28

Determination of absolute branching ratios

Measurement of invisible decay channels allows determination of **absolute** BRs

Constraint: Not feasible for very weakly coupled Z' bosons due to photon phase-space
$\rightarrow$ Cannot exploit resonace enhancement

Background: SM contributions to $e^+e^- \rightarrow \gamma\nu\bar{\nu}$



Signal identification: Peak in E_γ spectrum over background

Photon energy resolution:
E_γ resolution from em. calo.: $\frac{\Delta E_\gamma}{E_\gamma} \approx \frac{10\%}{\sqrt{E_\gamma/\mathrm{GeV}}} \oplus 1\%$ TESLA TDR '01

Example: $Z_{\text{B}-\text{L}}$ boson with $M_{Z'} = 400$ GeV and $\tilde{g}_l = g_{Z'll} = 0.1$

Use 100 fb^{-1} at $\sqrt{s} = 420$ GeV

$N_{\text{sig}} = 5700$, $N_{\text{bkgd}} = 20000$

$\rightarrow$ $\delta\sigma_{\nu\bar{\nu}\gamma}/\sigma_{\nu\bar{\nu}\gamma} = 2.8\%$ (stat.)

Subtraction of background and deconvolution of photon spectrum: $\delta(\sigma \times BR_{\nu\bar{\nu}})/(\sigma \times BR_{\nu\bar{\nu}}) = 3.1\%$

Combination with visible modes:

Visible cross-sections from peak measurements $\rightarrow$ negligible error

$\Rightarrow$

Channel	BR measurement	rel. error
l^+l^-	0.469 ± 0.0035	0.8%
$q\bar{q}, q \neq t$	0.261 ± 0.002	0.8%
$t\bar{t}$	0.035 ± 0.0003	0.8%
$\nu\bar{\nu}$	0.235 ± 0.0055	2.5%

Summary

- Possibility of new vector bosons with mass $M_{Z'} \sim 1$ TeV is one standard scenario of physics beyond the Standard Model

- Next generation of colliders can study new neutral vector bosons with masses up to $M_{Z'} \approx 10$ TeV or couplings down to $g_{Z'} \sim 10^{-3}$
  $\rightarrow$ Complementarity between LHC and linear collider

- Linear collider provides unique opportunities for very weakly coupled Z' bosons ($M_{Z'} < \sqrt{s}$)

- Precise determination of Z' parameters possible for $M_{Z'} < \sqrt{s}$
  $\rightarrow$ can be improved by tuning accelerator on Z' resonance and using polarized beams

Backup slides

Projected limits for Tevatron Run II

Extrapolate current limits to end of Run II

- Assume integrated luminosity of 4 fb^{-1}
- Scale signal rates
- Background very low
- Combine experiments