Heavy neutral gauge bosons at the LHC

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LHC days 2004

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Outline

- Models predicting new gauge bosons
- Searches for Z' at Tevatron and LEP
- CMS Z' discovery potential
- Observables to identify a Z' and expectations for 100fb^{-1}

  cross section, width, forward backward charge asymmetry, rapidity

The Standard Model

The SM gauge group:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{SSB} SU(3)_c \times U(1)_{em}$$

predicts 3 gauge couplings and $8 + 3 + 1$ gauge bosons

with $\sin^2\theta_W$: free parameter

Why this structure ?
Is it possible to embed the SM gauge group in a unique group ?

(Glashow, Georgi; Pati, Salam; Fritsch, Minkowski)

$$G_{SM} \subset SU(5) \subset SO(10) \subset E_6 ???$$

Extending the SM gauge group: new gauge bosons

Concentrate here on Z'

- Effective Rank-5 models, parameter: β $\quad Z' = Z'_\chi \cos\beta + Z'_\psi \sin\beta$

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

  Models studied: $Z'_\psi, Z'_\chi, Z'_\eta, Z'_d$

- Left-Right symmetric models: parameter: $\alpha_{LR} \equiv \sqrt{\frac{c_W^2}{s_W^2}\frac{g_R^2}{g_L^2} - 1}$

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

  Models studied: Z'_{LR}

- Sequential Standard Model:

  take the SM Z couplings $\to Z'_{SM}$

  (Not gauge invariant but good for comparisons)

Z': already done, a few references

- Z', theoretical point of view

  Robinett, Rosner, *Prospects for a second neutral vector boson at low mass in SO(10)*, Phys. Rev. D25 (1982) 3036

  Del Aguila, Langacker, Cvetič, *Determination of Z' couplings to quarks and leptons at future hadron colliders*, hep-ph/9303299, Phys.Rev.D48

  Cvetič,Godfrey, *Discovery and identification of extra gauge bosons*, hep-ph/9504216

  Djouadi, Leike, Riemann, Schaile, Verzegnassi, *Signals of new gauge bosons at future e^+e^- colliders*, Z.Phys.C56:289-300,1992

- Forward-backward charge asymmetry

  Barger, Deshpande, Rosner, Whisnant,*Production, decay and forward-backward asymmetries of extra gauge bosons in E_6* Phys. Rev. D35 (1987)

  Dittmar, *Neutral current interference in the TeV region; the experimental sensitivity at the LHC*, hep-ex/9606002, Phys.Rev.D55

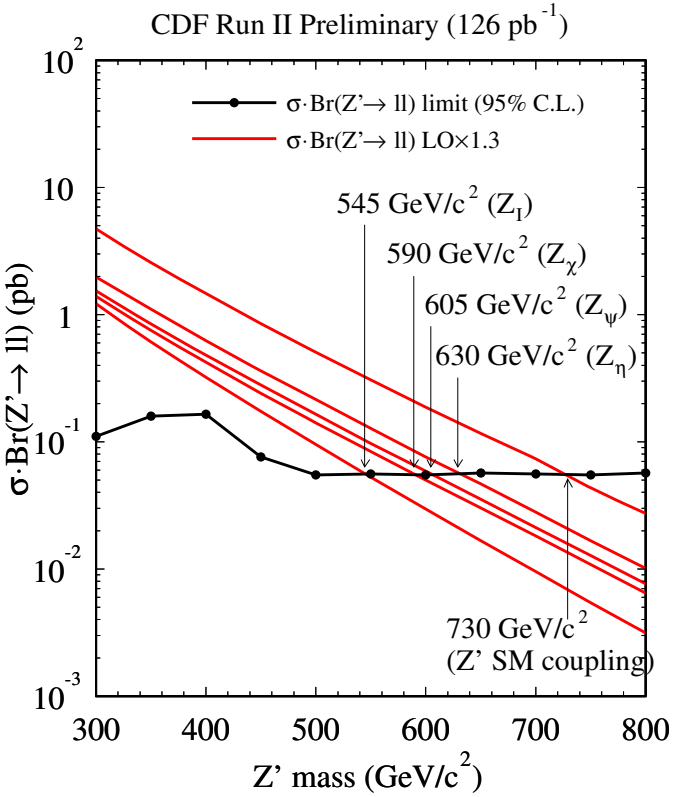
→ Combine all this, update for the LHC, concentrate on the Z′ identifiaction

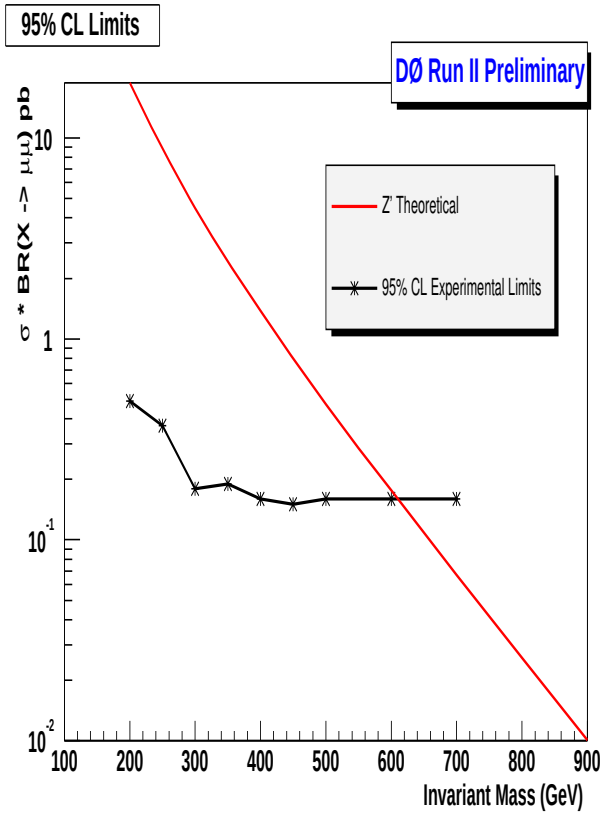
Z' experimental searches

Z' at Tevatron Run II (direct search for a mass peak)

CDF: $M_{Z'} > 545 - 730$ GeV, 126pb^{-1}
DØ: $M_{Z'_{SM}} > 610$ GeV, 100pb^{-1}

hope to push the limits to $M_{Z'}$ >800-900 GeV with 2 fb^{-1} (CDF TDR)



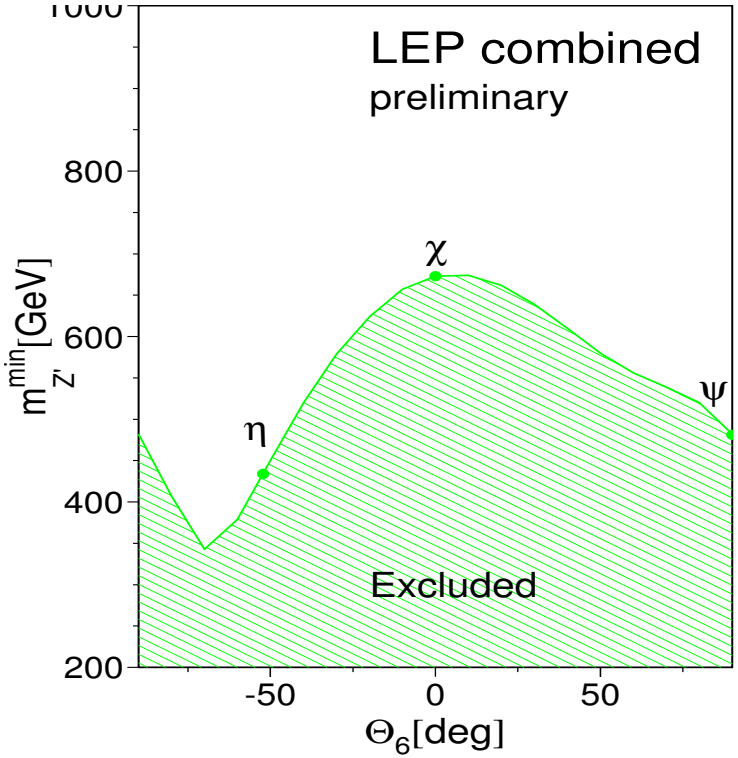


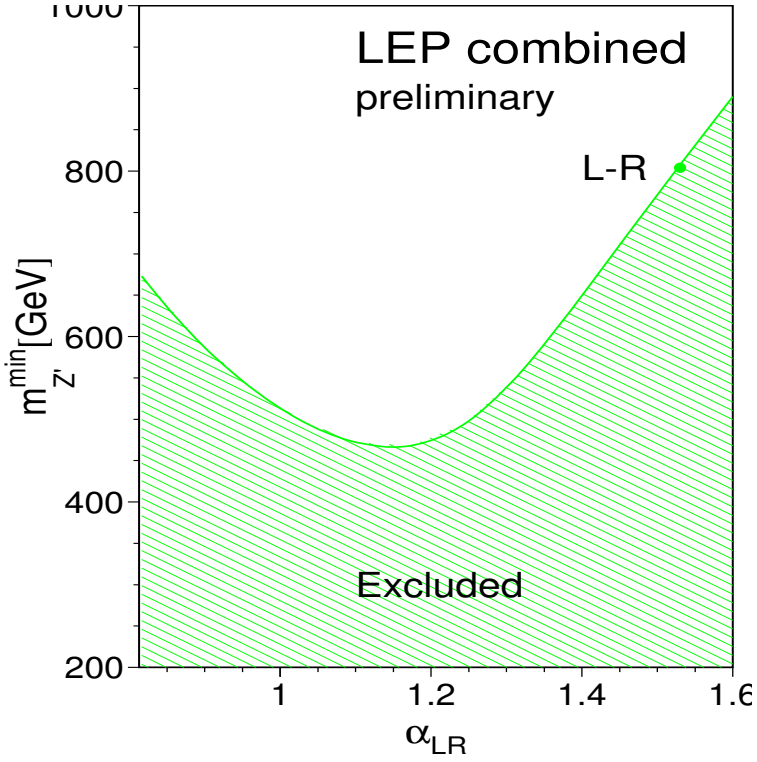
[CDF and DØ public pages]

LEP (indirect search: use A_{FB}^{ℓ} and $\sigma_{\ell\bar{\ell}}$,$\sigma_{q\bar{q}}$)

Upper limits:

Z' model	Z'_χ	Z'_ψ	Z'_η	Z'_{LR}	Z'_{SM}
$M_{Z'}$ [GeV]	673	481	434	804	1787



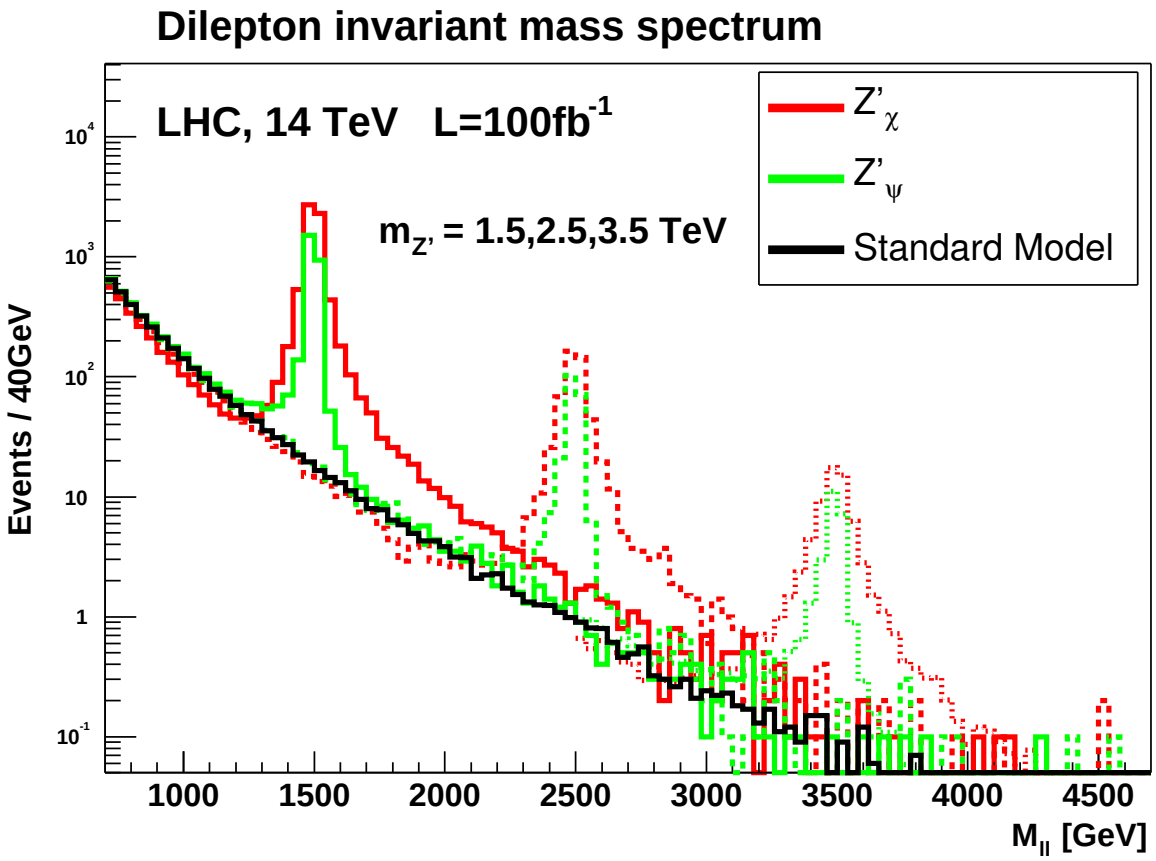


+ small mixing angle between Z and Z' *[hep-ex/0312023]*

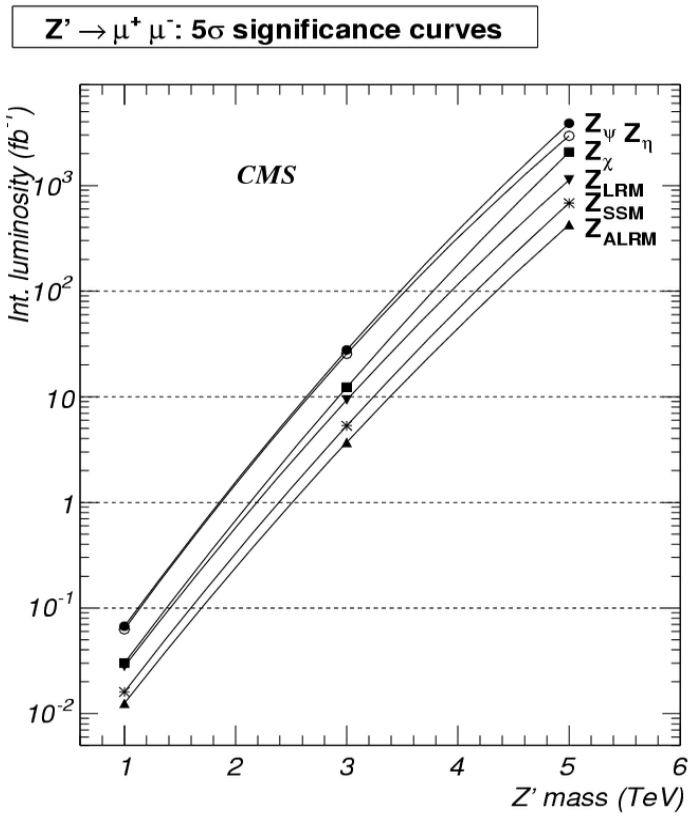
Z′ at LHC/CMS

for Z' **leptonic** decays

Look in dilepton invariant mass



CMS discovery potential for $Z' \to \mu\mu$: 5 TeV



Full simulation

[Cousins et al., CMS Analysis Note 2004/002]

Next step: How to **identify** a Z' ?

Observables to identify a Z′ at the LHC

Fit the mass peak !

- Width: Non relativistic Breit-Wigner fit

- Cross section: Events within 3Γ

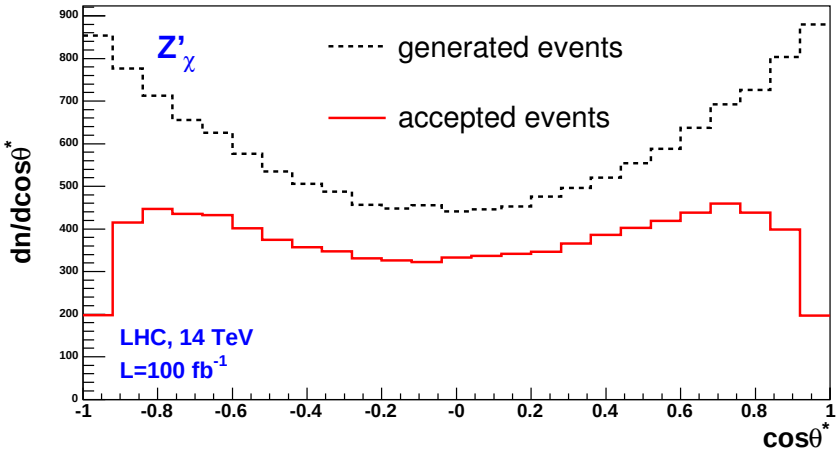
Use $\sigma_{\ell\ell} \cdot \Gamma$

(independent of Z' exotic decays)

- Lepton forward-backward charge asymmetry

  $\cos\theta$ (quark-lepton) distribution in the Z' rest frame:

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



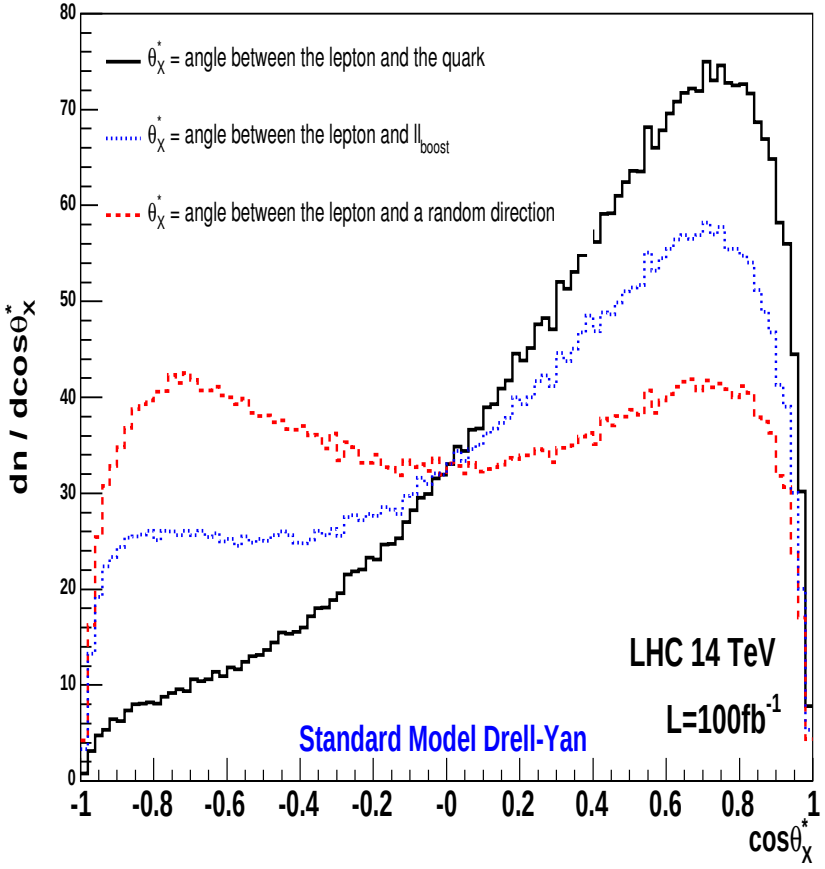
$\Rightarrow$ Unbinned maximum likelihood fit

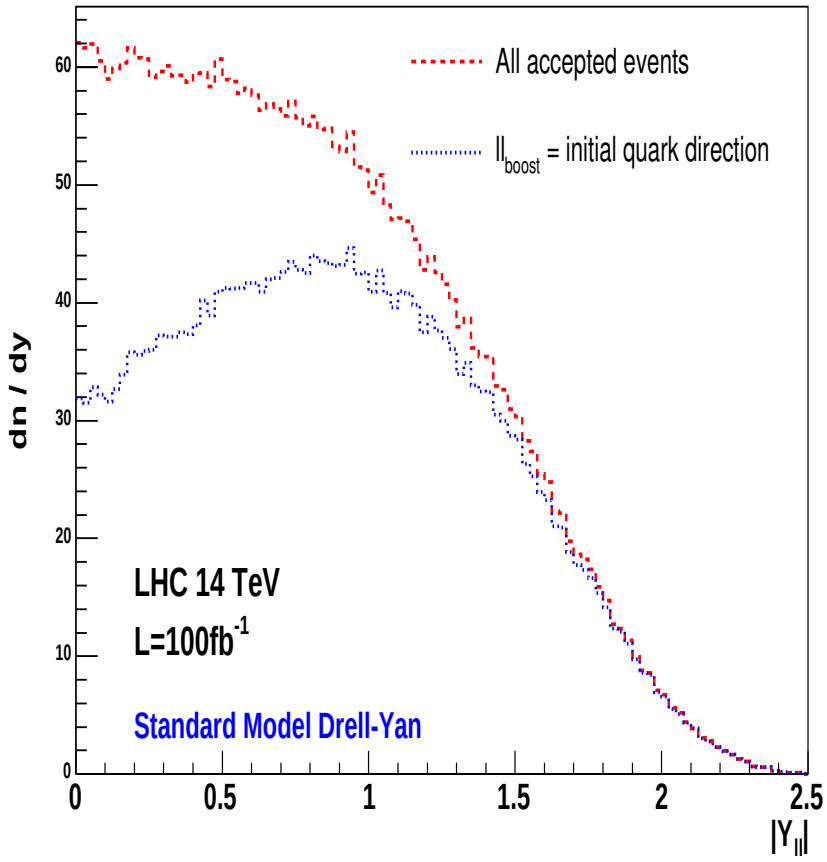
LHC: quark direction not known

$\Rightarrow$ Z' boost $\approx$ initial quark direction

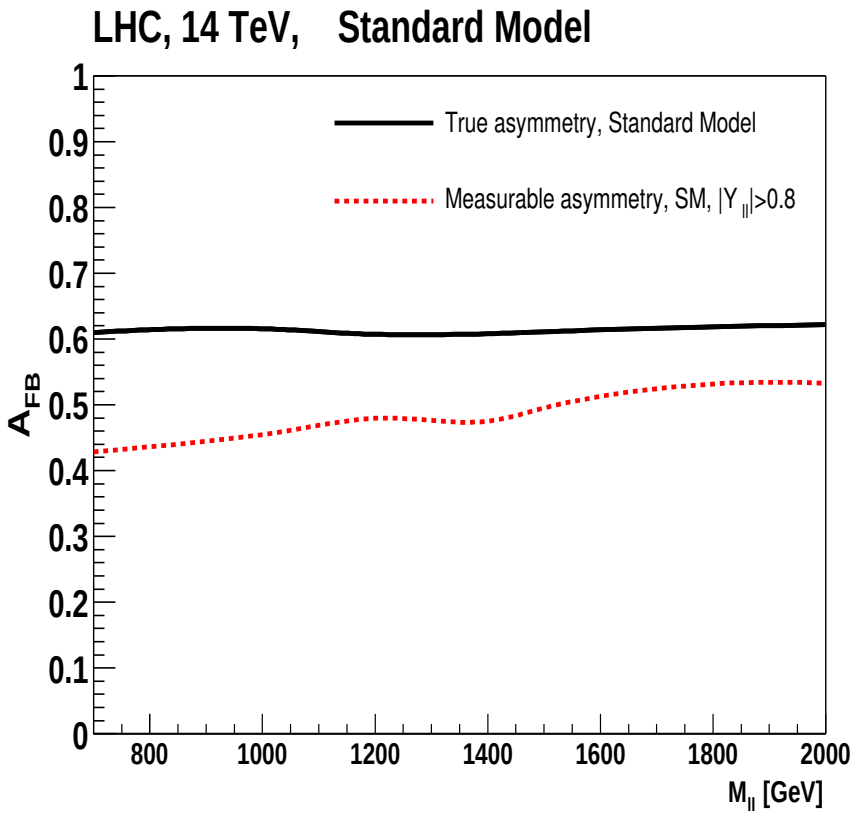
Asymmetry in symmetric collisions ?

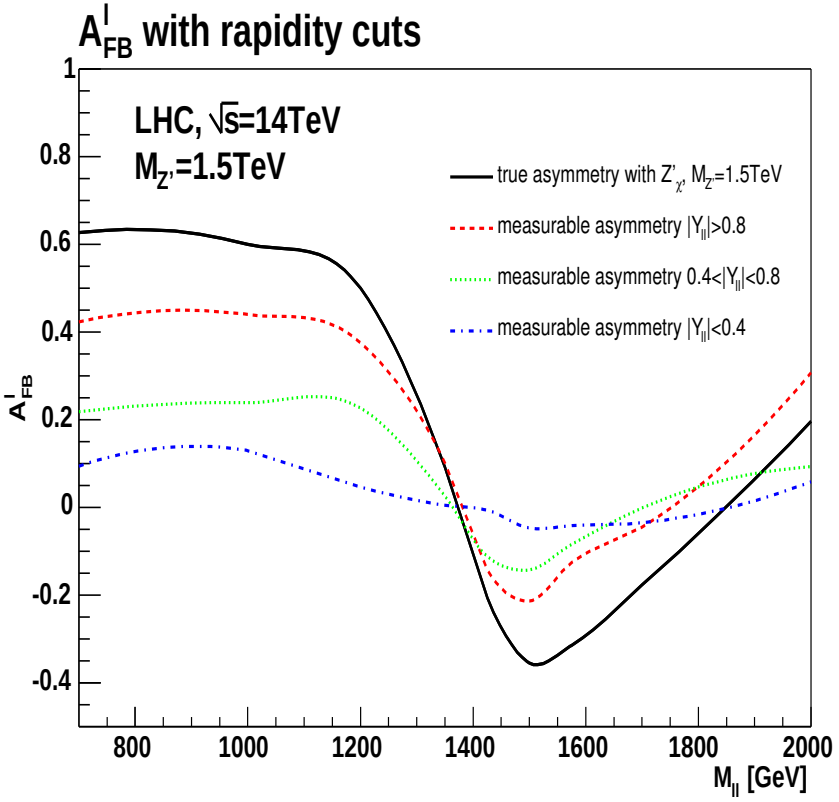
[Dittmar, Phys.Rev.D55]





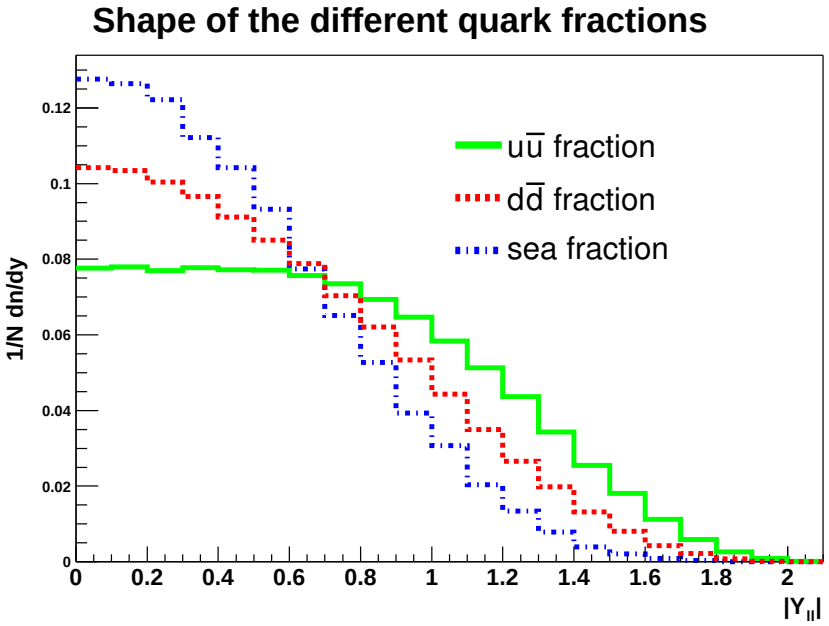
Lepton forward-backward asymmetry (on-peak AND off-peak)





$\Rightarrow$ Require $|Y_{\ell\ell}| > 0.8$ ($\varepsilon_{cut} \approx 40\%$)

- Z' rapidity distribution:
  constrain Z' couplings to u and d



$Y_{Z'}$ depends on Z' couplings to u and d

$\Rightarrow$ Get $Y_{Z'_{u\bar{u}}}$, $Y_{Z'_{d\bar{d}}}$, $Y_{Z'_{sea}}$

$\Rightarrow$ Fit $Y_{\ell\ell}$ in a given Z' model
$\longrightarrow$ relative $u\bar{u}$, $d\bar{d}$ and sea fractions

Standard fast simulation

(easy signature, expect only small efficiency reduction for a real detector)

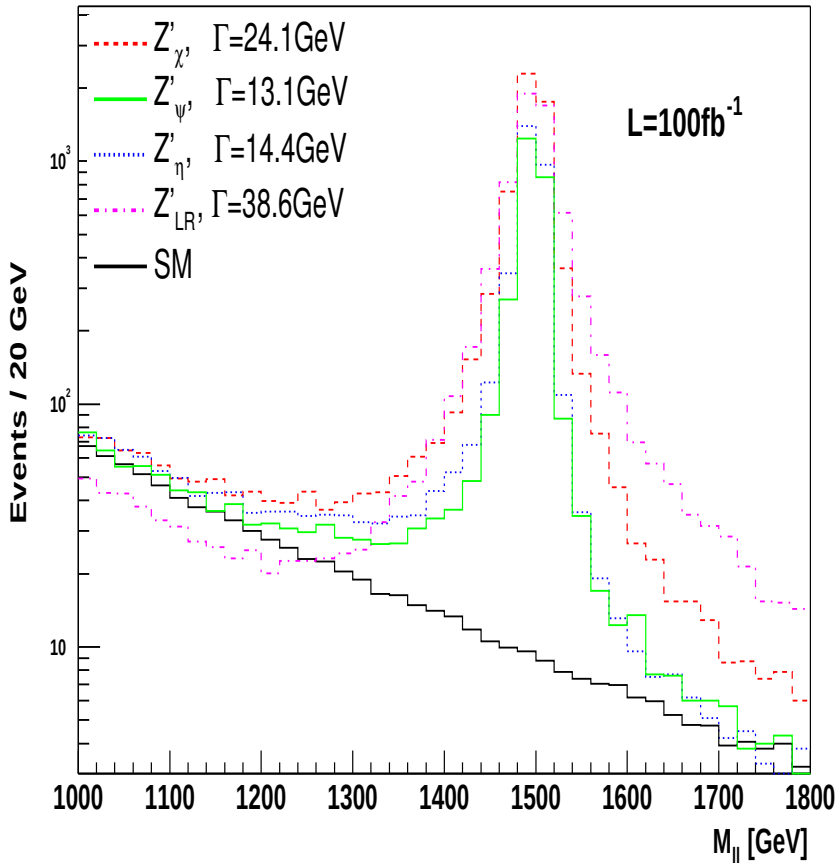
PYTHIA, $pp \rightarrow (Z, \gamma, Z') \rightarrow ee, \mu\mu$
$\sqrt{s}$: 14TeV, pp collisions

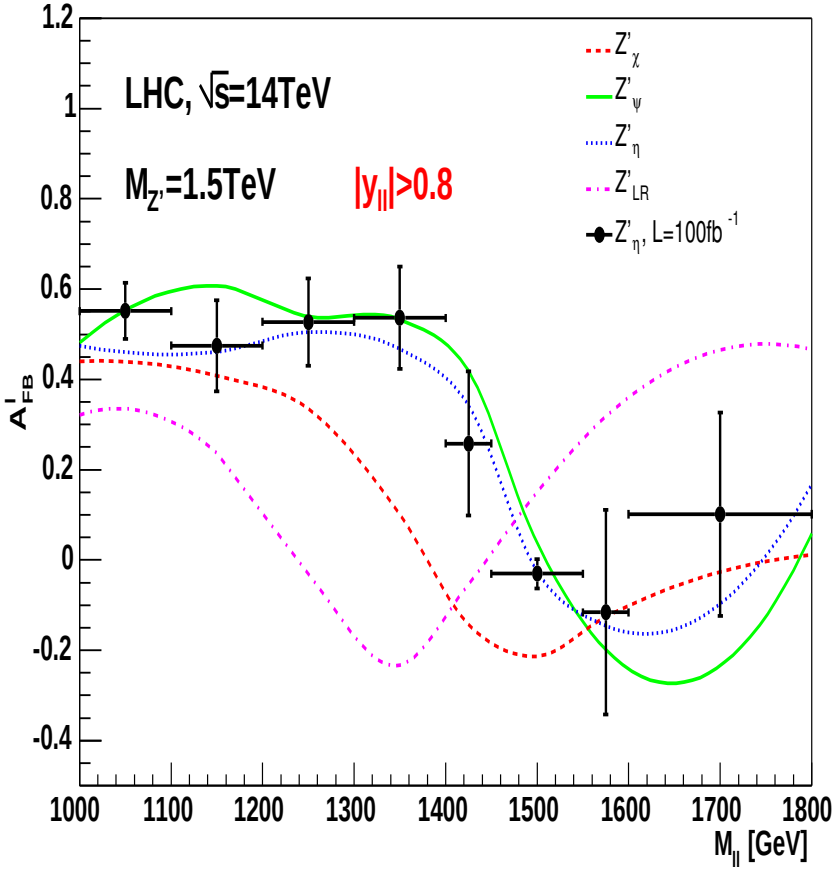
Reconstructing the events

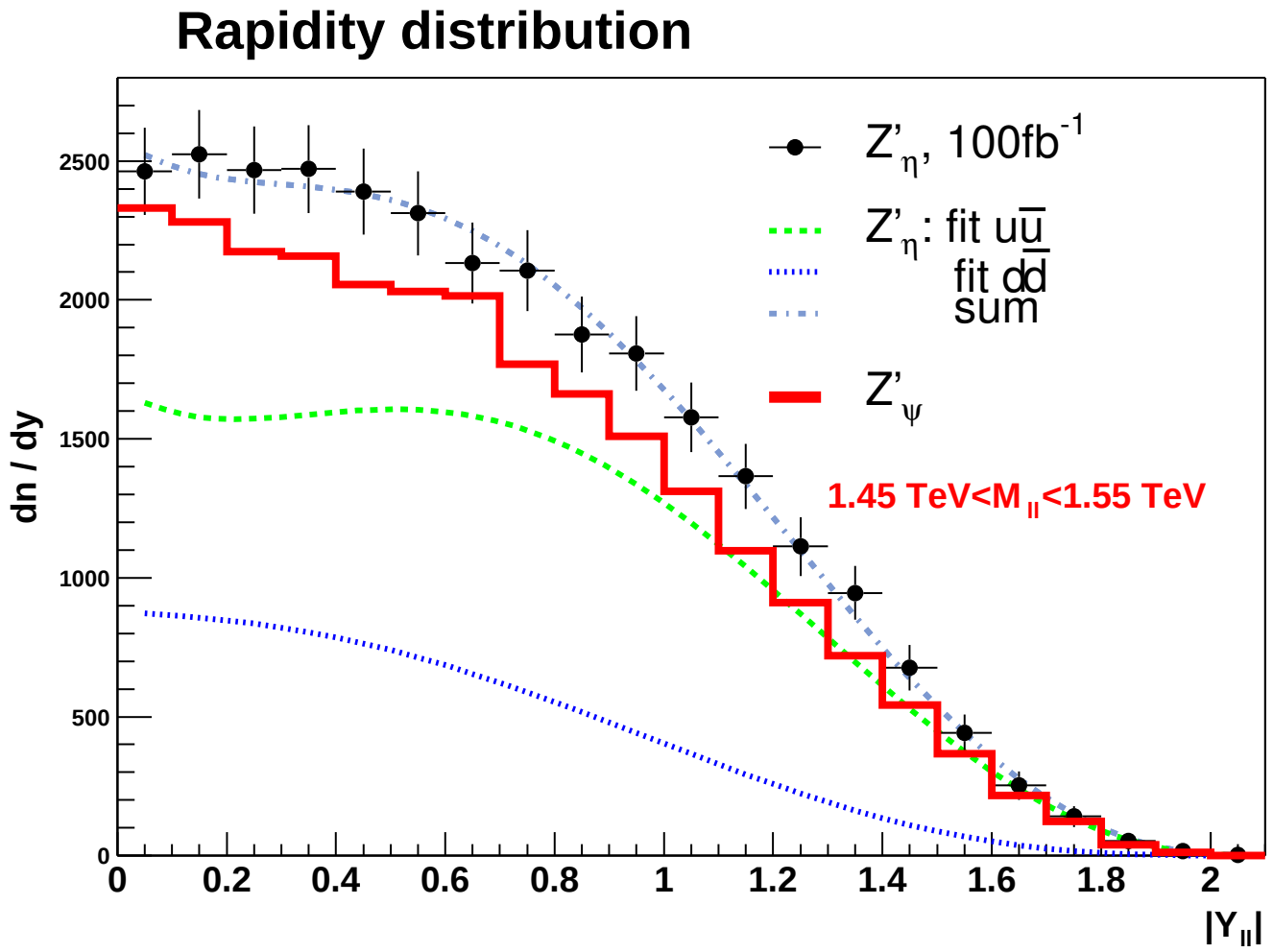
$\rightarrow$ CMS/ATLAS $e^{\pm}$, $\mu^{\pm}$ acceptance

- Two isolated leptons with opposite charge
- $p_t^{min}(\ell) > 20$ GeV
- $|\eta|(\ell) < 2.5$
- Coplanar lepton pairs: $|\phi| > 160^{\circ} (\sum p_t \approx 0)$

Discriminating the models

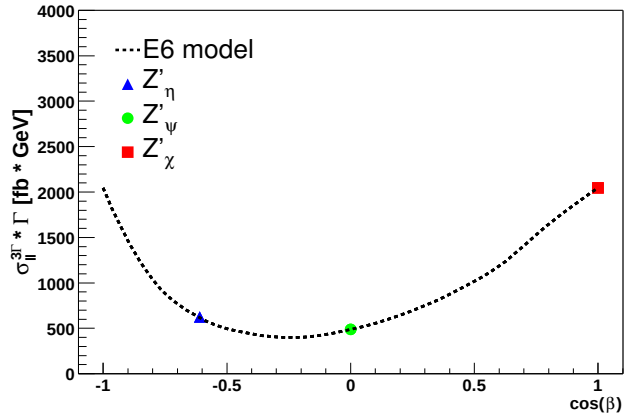


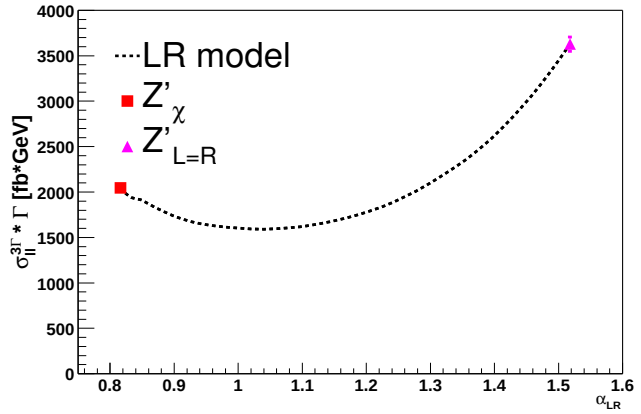


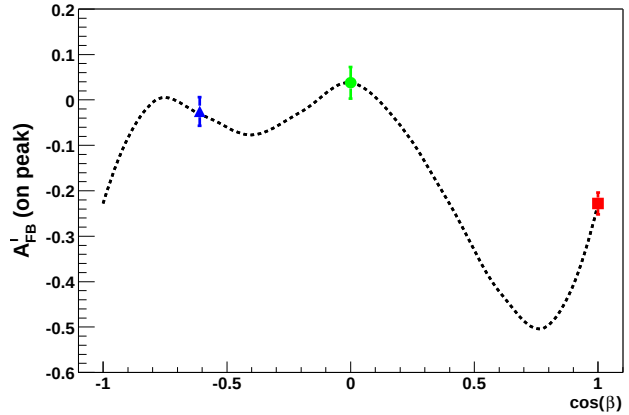


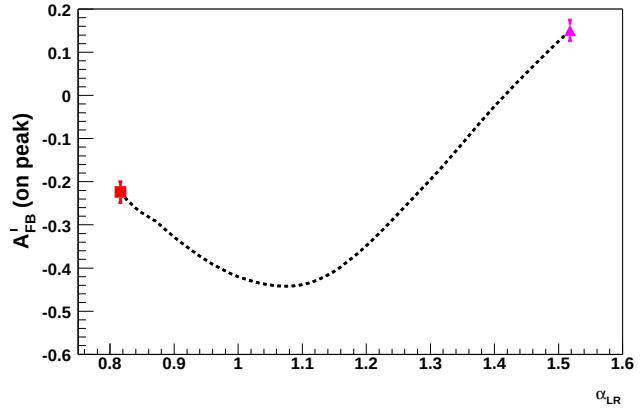
$\Rightarrow$ Combine these observables !

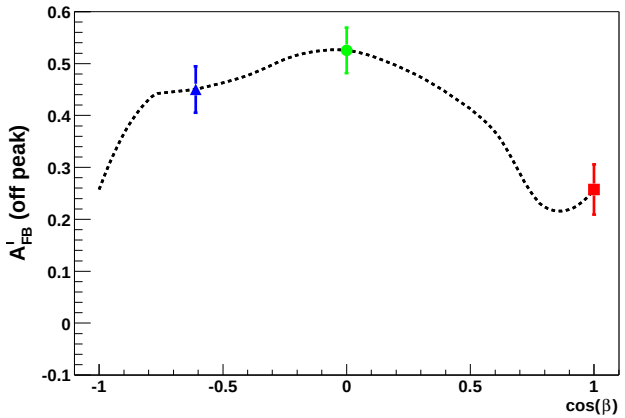
Observables vs. model parameters

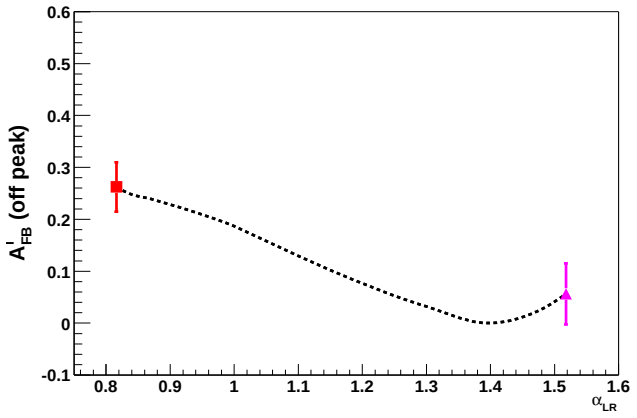


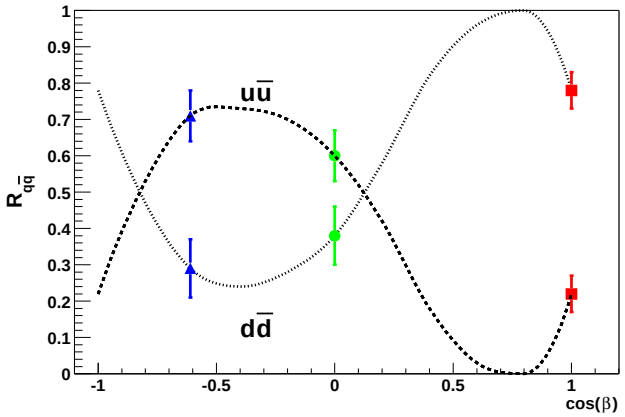


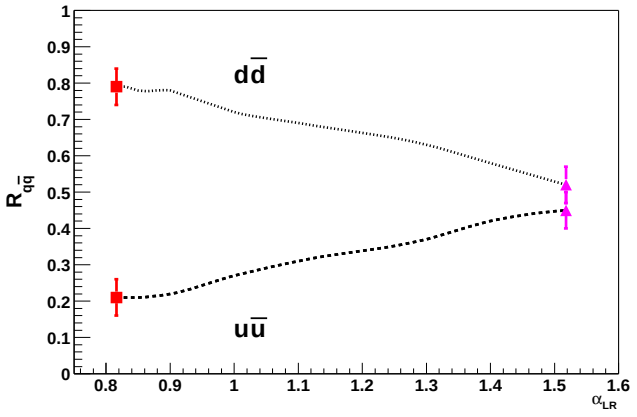





A'_{FB} (off peak)
cos(β)


A'_{FB} (off peak)
α_{LR}


$R_{q\bar{q}}$
$u\bar{u}$
$d\bar{d}$
cos(β)


$R_{q\bar{q}}$
$d\bar{d}$
$u\bar{u}$
α_{LR}

Summary

LHC potential for Z' study:

Discovery: up to 5 TeV

Identification: up to 2-2.5TeV with 100fb^{-1}

Results of this study published in
Phys.Lett.B583:111-120,2004, hep-ph/0307020
coauthors: M. Dittmar, A. Djouadi

Backup slides

The 4 observables for a 1.5 TeV Z'

for $\mathcal{L} = 100\text{fb}^{-1}$

Model	$\sigma^{3\Gamma}_{\ell\ell} \times \Gamma$ [fb·GeV]	$A_{FB}^{\text{on-peak}}$	$A_{FB}^{\text{off-peak}}$	$R_{u\bar{u}}$
Z'_ψ	487 ± 5	0.04 ± 0.03	0.53 ± 0.04	0.60 ± 0.07
Z'_η	630 ± 20	-0.03 ± 0.03	0.45 ± 0.04	0.71 ± 0.07
Z'_d	1520 ± 40	-0.50 ± 0.02	0.26 ± 0.05	0.00 ± 0.01
Z'_χ	2050 ± 40	-0.23 ± 0.02	0.26 ± 0.05	0.22 ± 0.05
Z'_{LR}	3630 ± 80	0.15 ± 0.02	0.06 ± 0.06	0.45 ± 0.05
Z'_{SM}	8000 ± 140	0.07 ± 0.02	0.18 ± 0.03	0.05 ± 0.04

Potential accuracies for 100 fb^{-1}

- $\Delta\sigma^{3\Gamma}_{\ell\ell}\cdot\Gamma/\sigma^{3\Gamma}_{\ell\ell}\cdot\Gamma$

  $\sim 0.1-0.3\%$ (stat.) $\oplus$ 1% ??(syst.) ($M_{Z'}=1.5$ TeV)

  $\sim 8-10\%$ (stat.) $\oplus$ 1% ??(syst.) ($M_{Z'}=2.5$ TeV)

- ΔA_{FB}^{onpeak}

  $\sim 0.02-0.03$ (stat.) ($M_{Z'}=1.5$ TeV)

  $\sim 0.07-0.1$ (stat.) ($M_{Z'}=2.5$ TeV)

- $\Delta A_{FB}^{interference}$

  $\sim 0.04-0.06$ (stat.) ($M_{Z'}=1.5$ TeV)

  $\sim 0.1-0.2$ (stat.) ($M_{Z'}=2.5$ TeV)

- $\Delta R_{u\bar{u}}$

  $\sim 5-8\%$ (stat.) ($M_{Z'}=1.5$ TeV)

  $\sim 10-30\%$ (stat.) ($M_{Z'}=2.5$ TeV)