Detection of Z′ Gauge Bosons in the Di-muon Decay Mode in CMS

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Introduction

- Z':
  - Generic name for additional heavy neutral gauge bosons.
  - Appear in many models beyond the SM: GUTs, dynamical symmetry breaking, "little Higgs", etc.
  - Might be light enough to be accessible at the LHC.
- Experimentally, $Z' \to \mu^+\mu^-$ channel is one of most promising.
- Main $Z' \to \mu^+\mu^-$ physics goals:
  - Understand discovery potential and optimize the search strategy
    - main observable: $M_{\mu+\mu-}$. This talk
  - Work out algorithms to distinguish among models (including graviton) and study properties, once discovered Work in progress
    - main observables: A_{FB} on- and off-peak, y, $\sigma \cdot Br$, Γ.

$Z' \rightarrow \mu^+\mu^-$ studies in CMS

- Rich history of studies of Z' discovery potential in CMS:
  - Pioneered by C.-E. Wulz in 1993-96.
  - Later studied by D. Bourilkov (2000), JINR group (S. Shmatov et al., 2002-03) and ETH group (M. Dittmar et al., 2003).
- Motivations to do more work <u>now</u>:
  - More realistic estimates can be obtained thanks to new tools available:
    - Move from event-generator-level studies to full simulation, reconstruction, and trigger emulation; study systematic uncertainties.
    - Use well-defined statistical techniques to quantify the mass reach.
  - $Z' \rightarrow \mu^+\mu^-$ is a good benchmark channel for the muon detector, largely complementary to other channels (like $H \rightarrow 4\mu$, $H \rightarrow 2\mu 2\nu$, etc.):
    - Reconstruction of very-high-p_T muons.
    - Study of detector misalignment, B field uncertainties, calibration uncertainties, etc.

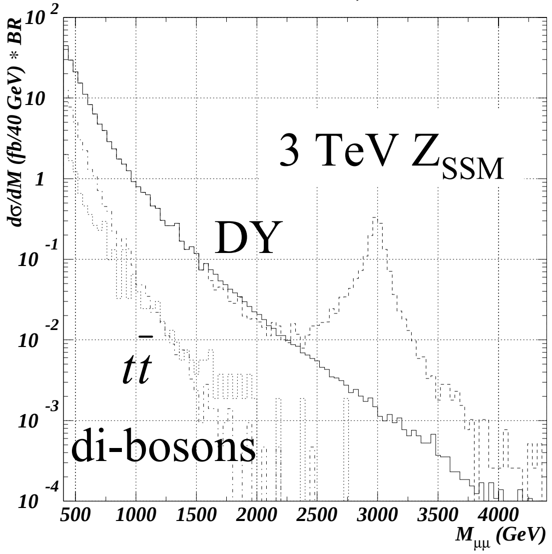
Chosen to be studied extensively for CMS Physics TDR (late 2005)

$Z' \rightarrow \mu^+\mu^-$: signal and backgrounds

- Z's arise in many models; we studied six frequently discussed:
  - Z_{SSM} in sequential standard model (benchmark toy model);
  - $Z' = Z_\psi \cos\theta_{E6} + Z_\chi \sin\theta_{E6}$ in E_6 and/or SO(10) models: Z_ψ, Z_χ and Z_η ($\theta_{E6} = 37.78°$);
  - Z_{LRM} and Z_{ALRM} in left-right symmetric models.
- Limits on the mass:
  - Current: 600-800 GeV;
  - Expected by LHC start-up: $\leq$ 1 TeV.
- $Br(Z' \rightarrow \mu^+\mu^-)$: 2-8%

  (if no exotic decay channels are open)

PYTHIA cross-sections; no added *K*-factors



- Dominant (and irreducible) background: Drell-Yan production of muon pairs $pp \rightarrow \gamma/Z^0 \rightarrow \mu^+\mu^-$.
- Other sources: ZZ, WZ, WW, $t\bar{t}$, $b\bar{b}$, pile-up, etc.

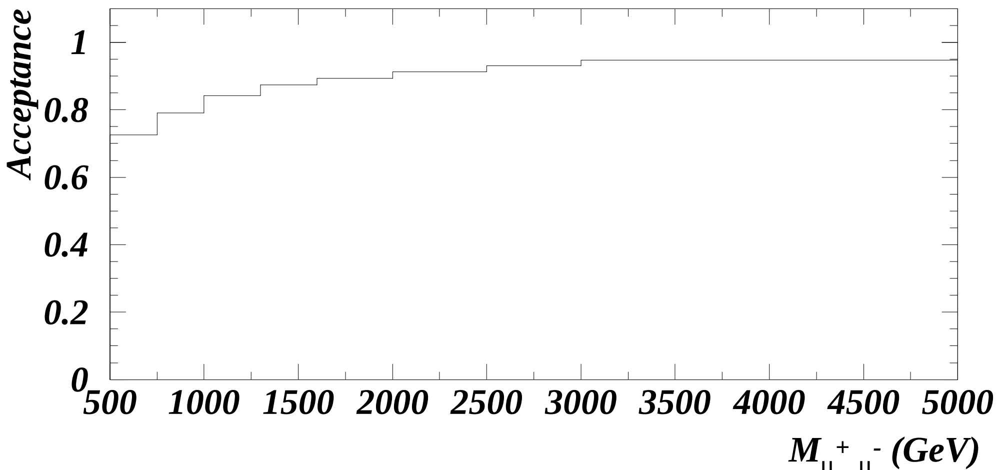
  (much smaller than Drell-Yan and reducible)

Generation and reconstruction

- Event generation: PYTHIA6, CTEQ5 PDF's
  - Z_{SSM}, Z_ψ, Z_η, Z_χ, Z_{LRM}, and Z_{ALRM} at 1, 3 and 5 TeV decaying to $\mu^+\mu^-$
    - Obtain couplings from literature, introduce in PYTHIA.
    - Include the full $\gamma^*/Z^0/Z'$ interference structure.
  - Drell-Yan $\mu^+\mu^-$ pairs in several mass intervals.
- Simulation and reconstruction:
  - Detector response: full GEANT3-based description (CMSIM).
  - Event reconstruction: CMS OO reconstruction package (ORCA). Includes:
    - digitization (detailed simulation of electronic response);
    - emulation of Level-1 and High-Level (HLT) Triggers;
    - off-line reconstruction (our group worked on algorithms capable of improving momentum resolution for very-high-p_T muons).

Event selection

- Both μ^+ and μ^- should be within the geometrical acceptance of the muon system ($|\eta| < 2.4$) and pass the trigger:
  - Acceptance: raises from about 80% at 1 TeV to almost 95% at very high $M_{\mu\mu}$.



  - L1/HLT trigger efficiency: about 98% at 1 TeV, about 95% at 5 TeV.
- Require that there are at least two μ's of opposite charge sign.
- No background-rejection cuts.

Overall efficiency: 70-75% (1-5 TeV).

Fitting procedure

- Generate ensembles of MC experiments:
  - number of events in each experiment fluctuates according to Poisson distribution with a mean of $\sigma \cdot Br \cdot (\int L dt) \cdot \varepsilon$;
  - appropriately add Drell-Yan contribution from lower masses.
- In each experiment, fit $M_{\mu\mu}$ values using an unbinned maximum likelihood:

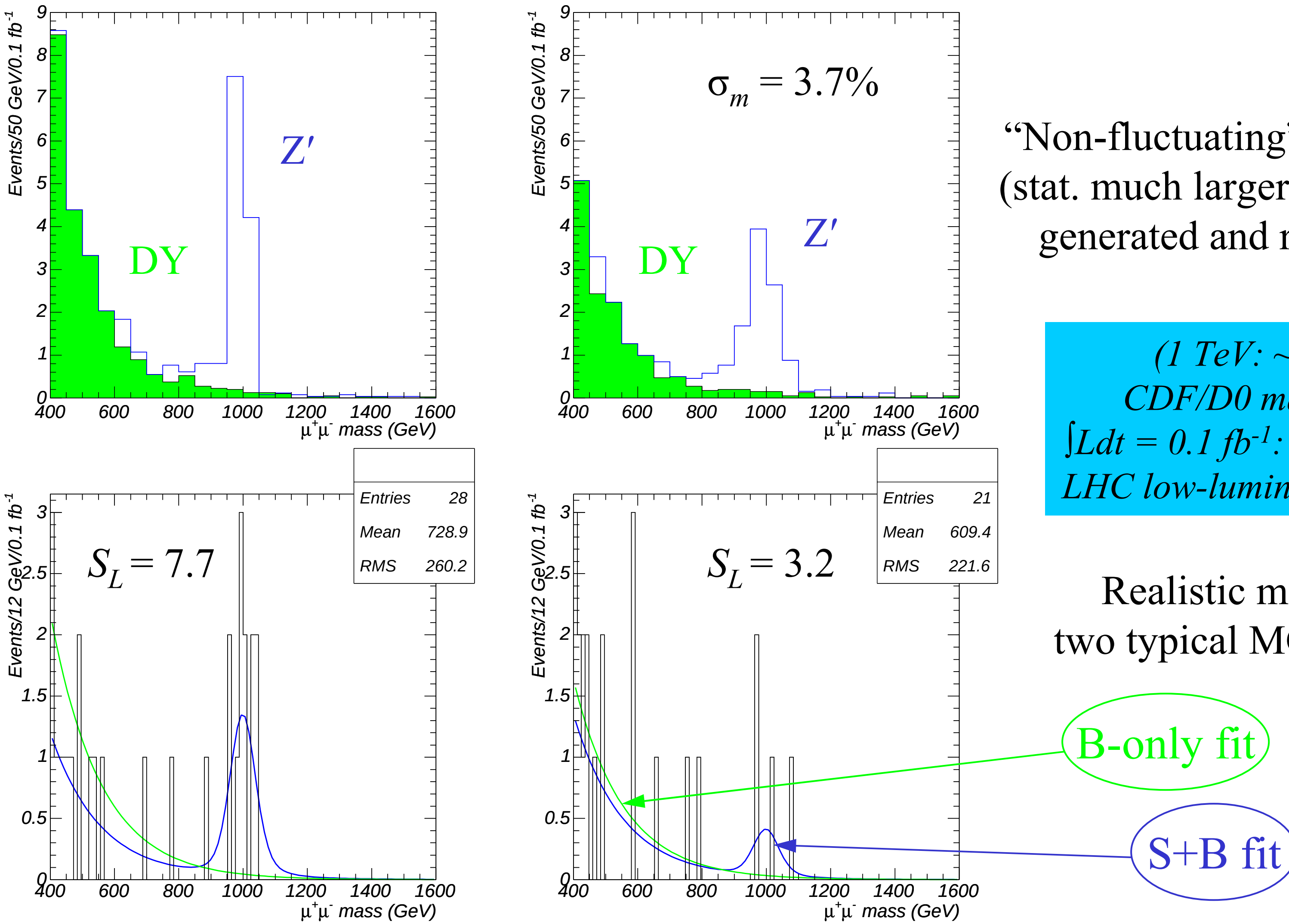
$$p(M_{\mu\mu}) = \frac{N_s}{N_{tot}} \cdot p_s(M_{\mu\mu}; m_0, \Gamma) + \left(1 - \frac{N_s}{N_{tot}}\right) \cdot p_b(M_{\mu\mu})$$

  - p_s (signal pdf) is a convolution of a Breit-Wigner with a Gaussian smearing;
  - p_b (background pdf) is an exponential, with the slope parameter determined from fits to Drell-Yan events.

Up to three free parameters: signal fraction (N_s / N_{tot}), signal mean (m_0), and signal FWHM (Γ).

No constraints on the absolute background level: fit assumes only background shape is known.

Example: Z_ψ at 1 TeV, $\int L dt = 0.1\ fb^{-1}$



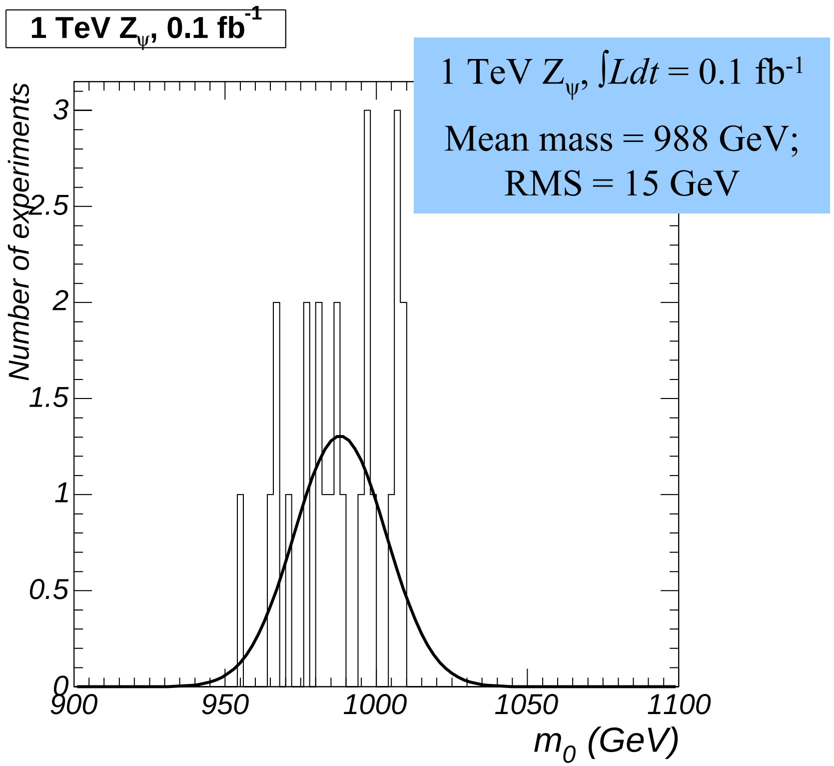
"Non-fluctuating" mass spectra: (stat. much larger than expected) generated and reconstructed

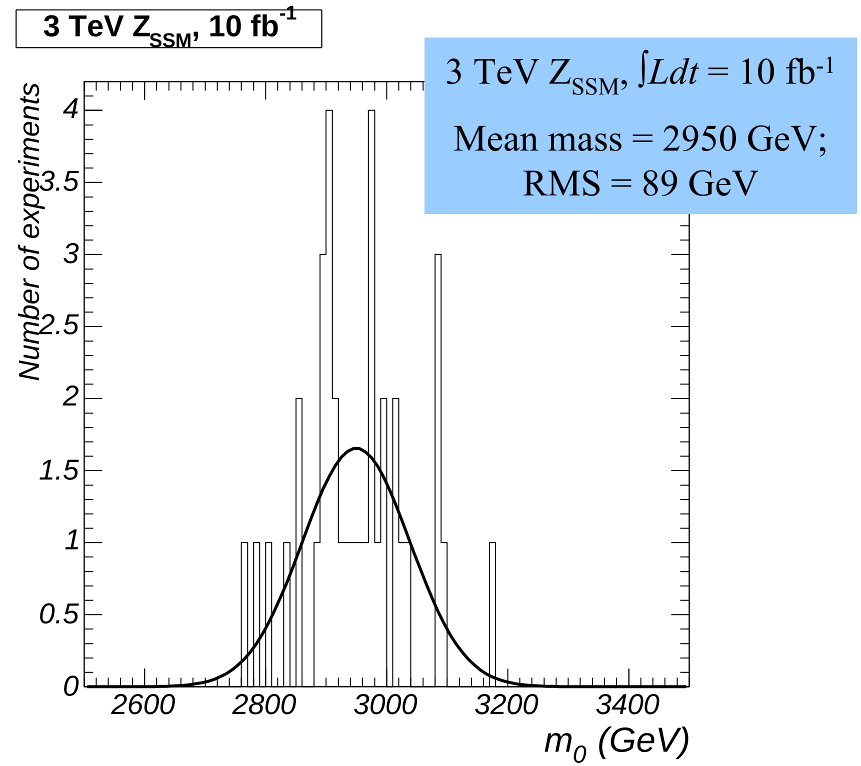
(1 TeV: ~ limit of CDF/D0 mass reach; $\int Ldt = 0.1\ fb^{-1}$: a few days of LHC low-luminosity running)

Realistic mass spectra: two typical MC experiments

Fit results: m_0 and Γ

- Signal mean mass: close to true value, small spread.
  Measured with precision of 5% (at high masses and discovery limit) or better





(Still have to account for the radiative tail in the mass distribution in the fits)

- Signal Γ: hard to reconstruct (FWHM dominated by resolution smearing)

Significance estimators (I)

- Use likelihood-ratio estimator S_L to calculate significance of an observed "signal": (previously used in CMS by Karlsruhe group in H → 4μ studies)

$$S_L = \sqrt{2\ln(L_{S+B}/L_B)},\quad \text{where}$$

  - L_{S+B} is the maximum likelihood from the signal-plus-background fit (p),
  - L_B is the maximum likelihood from the background-only fit (p_b).

Justification:

- In the large-statistics limit, S_L^2 is expected to follow a χ^2-distribution with ndof equal to the difference in the number of free parameters between S+B and B-only hypotheses (theorem proved by S.S. Wilks in 1938).
- If ndof is one, then distribution of S_L is a standard Gaussian.
- Therefore, S_L gives the probability (expressed in number of σ's) that the pure background fakes a signal (i.e. significance).

Dedicated MC study showed that S_L behaves as desired in a small stat. regime

Significance estimators (II)

- For comparison with S_L, also try a few other commonly used ("counting") estimators:

$$S_{c1} = N_S / \sqrt{N_B}\,,$$

$$S_{c2} = N_S / \sqrt{N_S + N_B}\,,$$

$$S_{c12} = 2 \times (\sqrt{N_S + N_B} - \sqrt{N_B}),$$

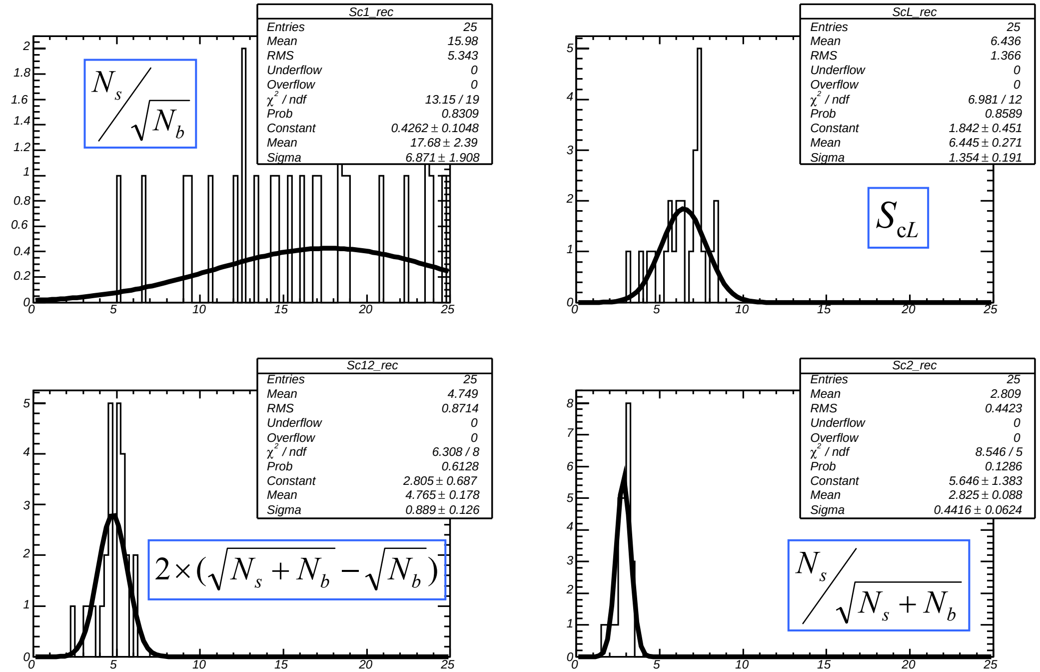
(proposed by S. Bityukov and N. Krasnikov, Mod. Phys. Lett. A13 (1998) 3235)

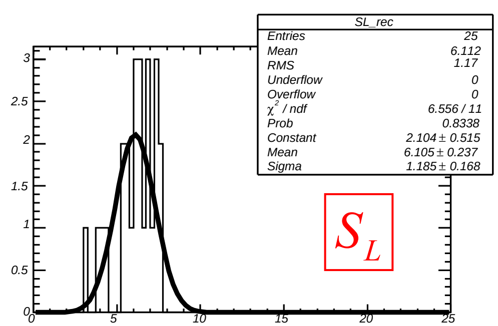
$$S_{cL} = \sqrt{2 \ln\left(\left(1 + N_S / N_B\right)^{N_S + N_B} \exp\left(-N_S\right)\right)}.$$

N_S and N_B – number of signal and background events within $m_0 \pm 2\sigma$.

- Usual convention: $S > 5$ is necessary to establish a discovery
  (probability of $2.9 \cdot 10^{-7}$ that the pure background would mimic a signal)

Z_ψ at 1 TeV, 0.1 fb^{-1}: significance





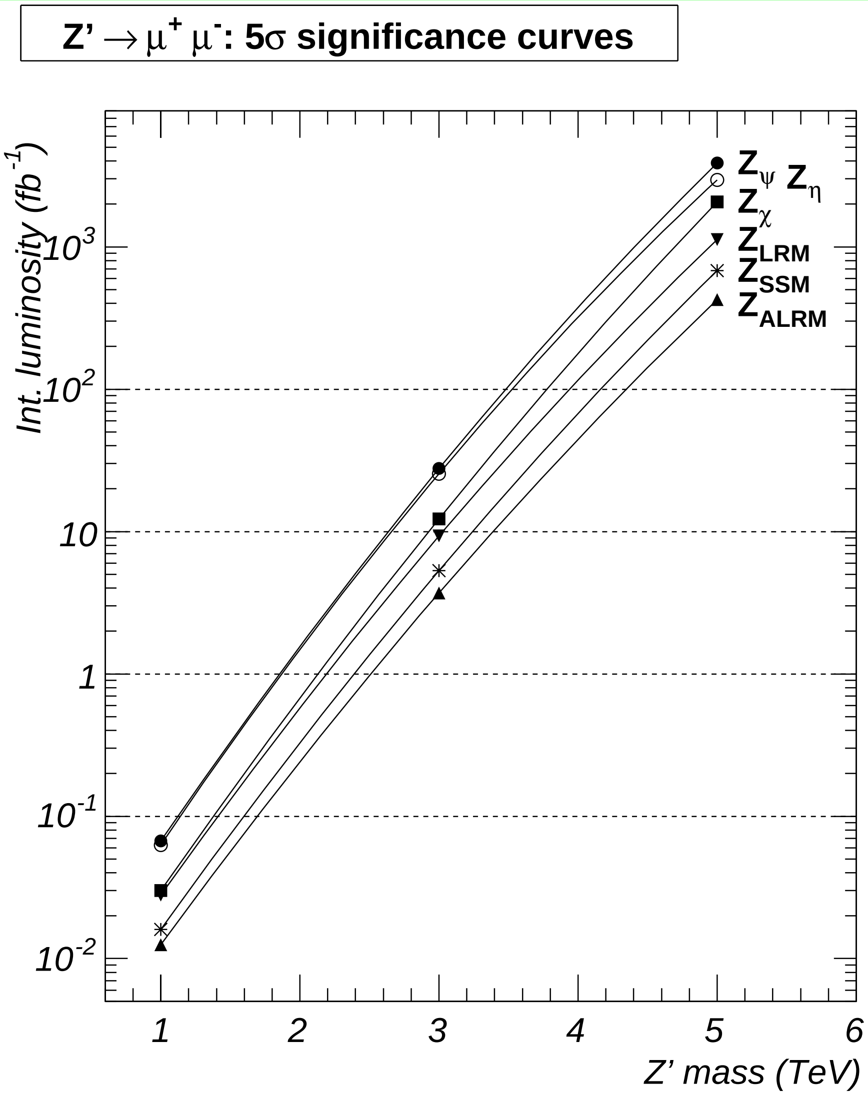
Fix both m_0 and Γ to true values to calculate S_L

- $S_{c1} >> S_L$
- $S_{c2} < S_L$
- $S_{c12} \leq S_L$

(in agreement with other Z' models, masses, luminosities tried)

- In this example, obtain $\langle S_L \rangle = 6.1$.
- For 0.1 fb^{-1}, average S_L is more than 5 at 1 TeV for all the Z' models considered.
- S_L scales very nicely with $\sqrt{\int L dt}$.

$Z' \to \mu^+\mu^-$: CMS discovery potential



$Z' \to \mu^+\mu^-$ mass reach:

- > 1 TeV with 0.1 fb^{-1}
- 2.6 – 3.4 TeV with 10 fb^{-1}
- 3.4 – 4.3 TeV with 100 fb^{-1}

N.B.: syst. uncertainties are not taken into account

- Perfect alignment, calibration, B field, etc.;
- Background shape, functional forms of pdf's, mass resolution perfectly known.

Summary

- We have set up a procedure for studying and quantifying the Z' mass reach. Main points:
  - Full simulation (CMSIM) and reconstruction (ORCA) as input;
  - Unbinned M.L. fits exploring signal and background shapes only;
  - Likelihood-ratio significance estimator, shown to perform as desired.
- We have obtained mass reach estimates in $Z' \rightarrow \mu^+\mu^-$ channel, with systematic uncertainties yet to be accounted for:
  - More than 5σ significance above 1 TeV at the earliest stages of data-taking;
  - Average 5σ significance at a mass of 3.4-4.3 TeV (depending on the model) with an integrated luminosity of 100 fb^{-1}.

Consistent with earlier results, but obtained with above improvements

- Next step: evaluate systematic uncertainties and their impact.