Diboson production with CMS

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Motivation

- Prediction of the non-abelian SM gauge structure:

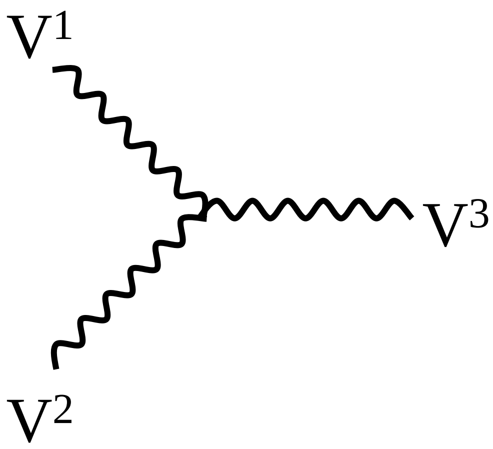
  Couplings between gauge bosons

- Measuring the coupling between the gauge bosons tests a central part of the SM
- Deviations could hint to new physics
- Complementary to direct search for new physics

Manifestation of gauge boson couplings at the LHC:

production of final states with boson pairs (W,Z,γ)

Gauge boson couplings



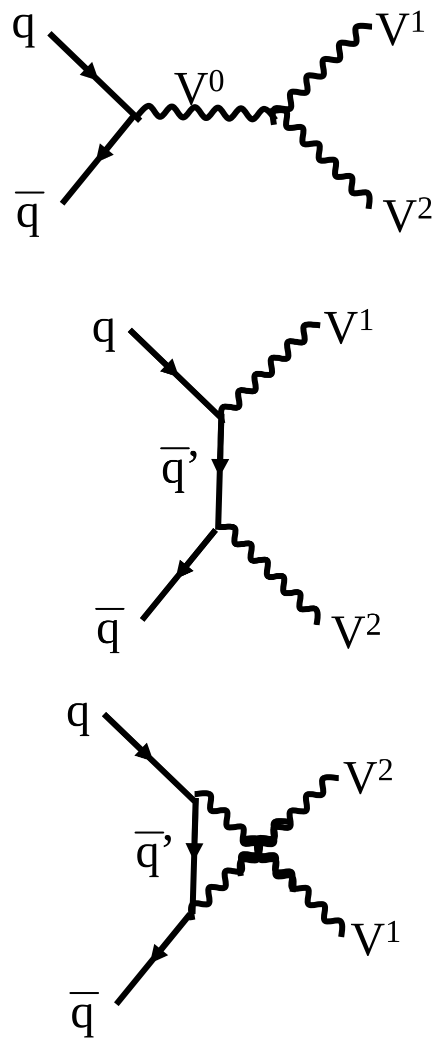
Triple gauge couplings (W,Z,γ)

- Charged couplings WWZ and WWγ
  - Allowed in the SM
- Neutral couplings ZZZ, ZZγ
  - Forbidden in the SM

Diboson production at the LHC

Production Processes at the LHC

- Leading order Feynman diagrams:
- Only s-channel has three boson vertex
- Anomalous couplings tend to manifest in:
  - Cross section enhancement
  - Enhancement at high p_T of $V^{1,2}$.
  - Production angle.



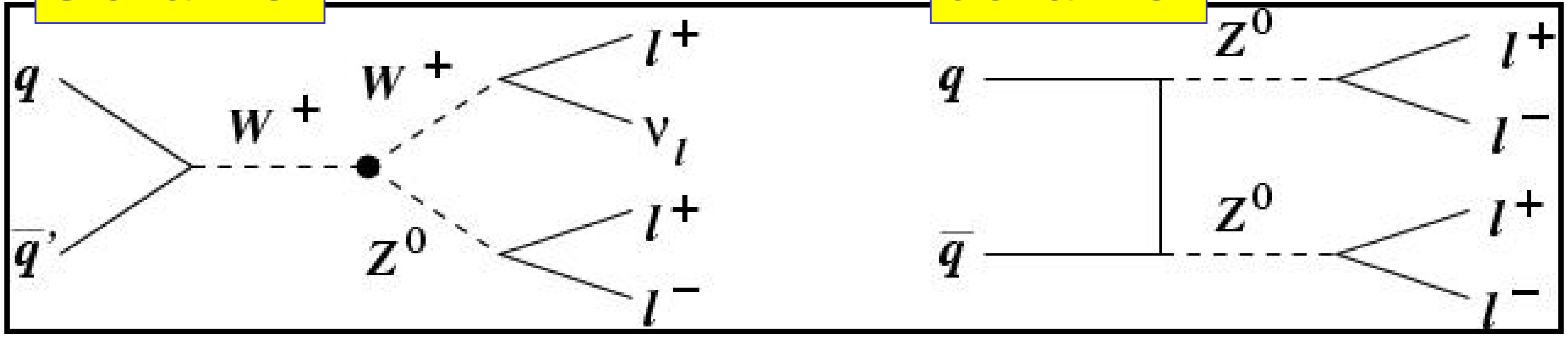
We present here:

Study of discovery potential for WZ and ZZ production

WZ and ZZ production at the LHC

s channel

t channel



WZ

- **s-channel dominates**
- **Sensitive to TGC**

ZZ

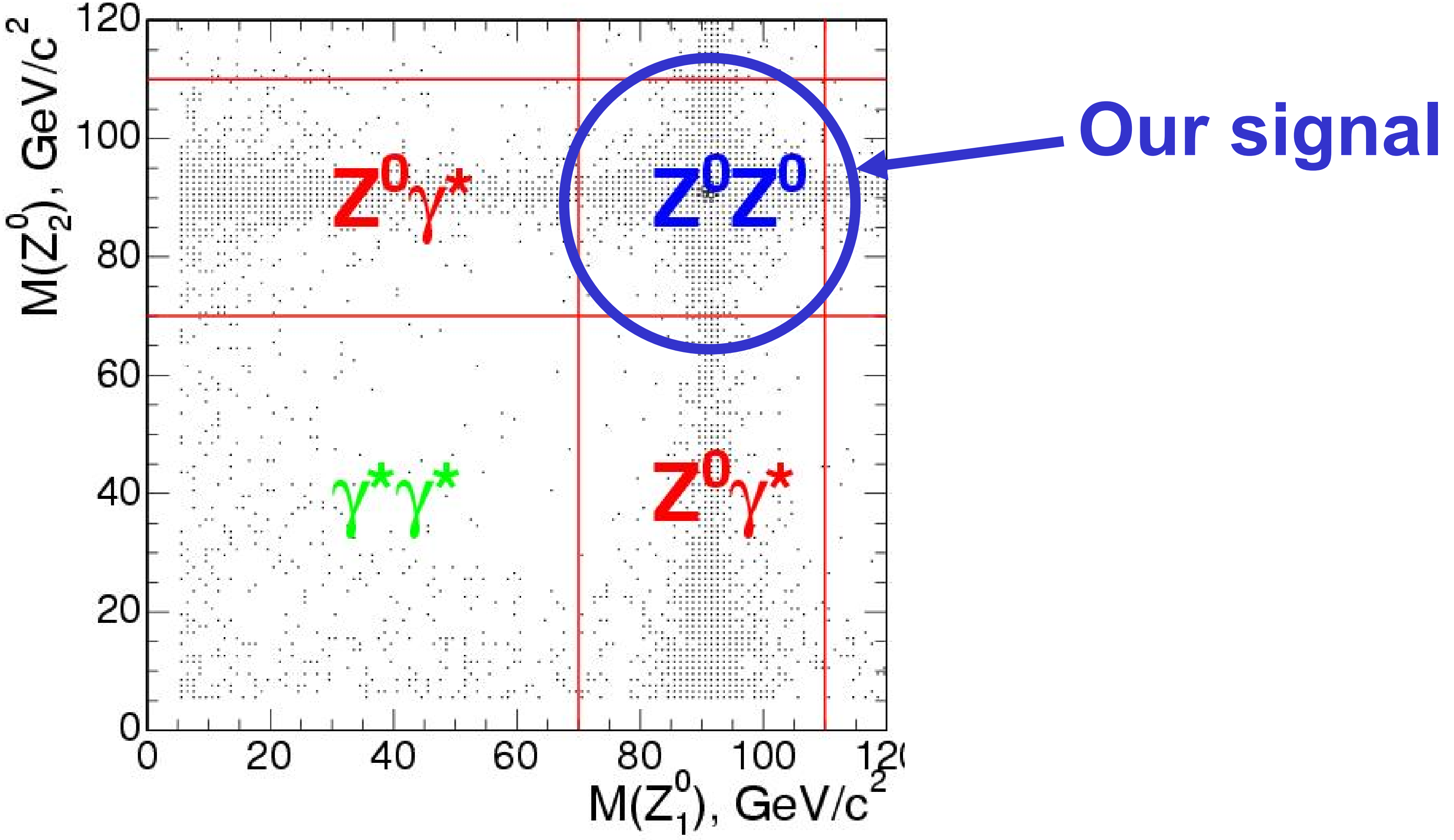
- **Only t-channel at tree level**
- **s-channel suppressed by O(10^{-4})**

  no ZZZ TGC

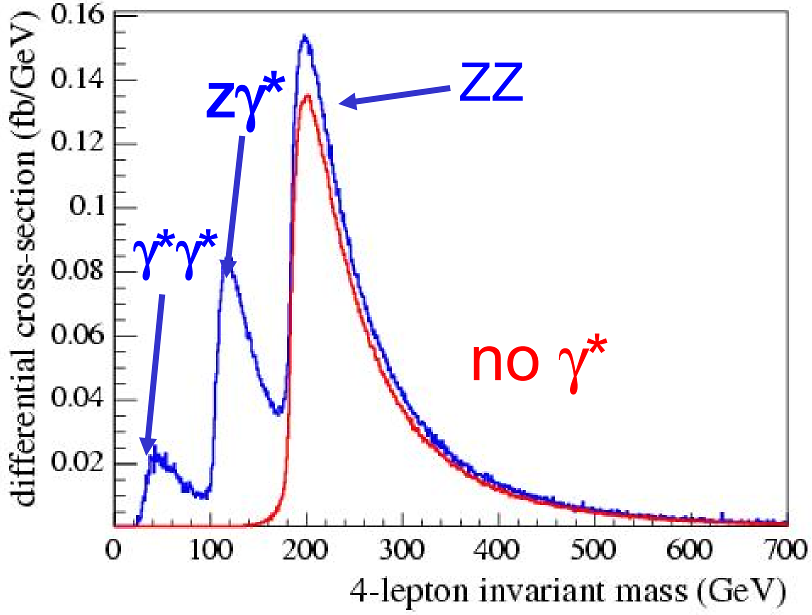
Constitute backgrounds (partly irreducible) for some new physics searches

ZZ signal definition

Need to consider γ* contribution



ZZ signal definition



- Define on-shell Z as:

  70 GeV < M_Z < 110 GeV

- Distinguish 3 states:

  ZZ (72%), Zγ* (26%), γ*γ* (2%)

- We consider only ZZ events

  Cut on 4 lepton p_t values:

  p_t > 30, 20, 15, 10 GeV/c

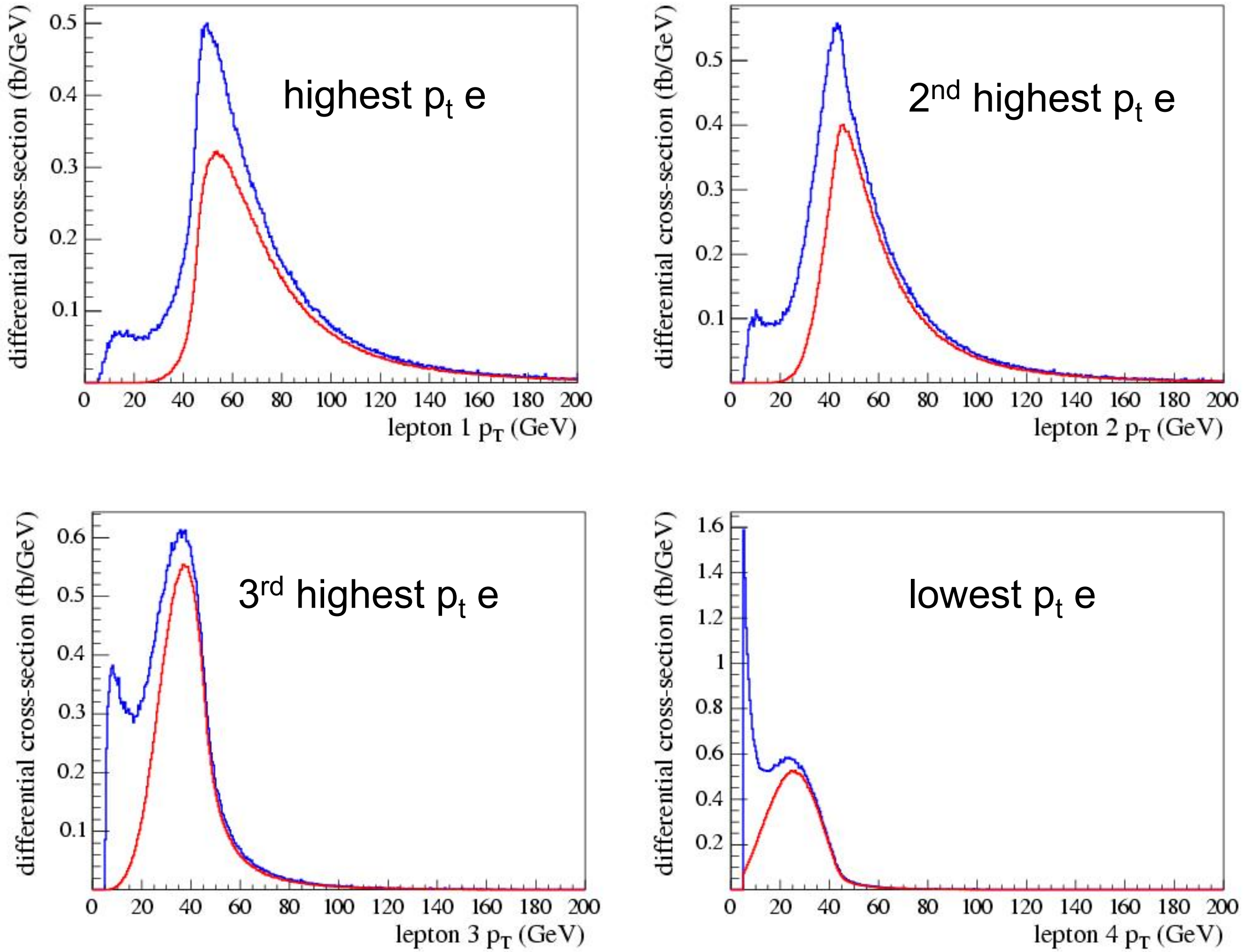
<u>NLO cross section from MCFM</u>:

σ_{LO} (pp → ZZ → 4e) = 13.7 fb

σ_{NLO}(pp → ZZ → 4e) = 18.7 fb

Extract overall *k*-factor

$Z/\gamma^* Z/\gamma^* \rightarrow 4e$ lepton spectra



with γ^*

without γ^*

Cut on leptons p_t :

p^1_t > 30 GeV/c

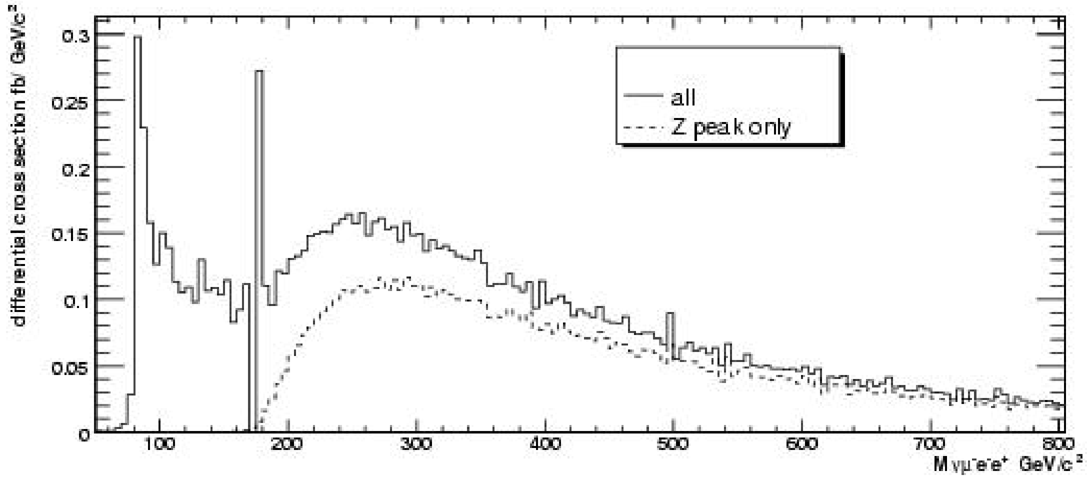
p^2_t > 20 GeV/c

p^3_t > 15 GeV/c

p^4_t > 10 GeV/c

Keep only ZZ!

WZ signal definition



4 lepton invariant mass for process $pp \rightarrow WZ \rightarrow ee\mu\nu_\mu$ (MCFM NLO)

γ^* contribution included

- Restrict to on-shell Z boson: $| M(l^+l^-) - M_Z^{PDG} | < 20$ GeV
- Implicitly forces W on shell

<u>NLO cross section from MCFM</u>

σ_{NLO} ($pp \rightarrow W^-Z \rightarrow 3l$, $l=e,\mu,\tau$) = 0.63 pb

σ_{NLO} ($pp \rightarrow W^+Z \rightarrow 3l$, $l=e,\mu,\tau$) = 1.03 pb

→ Apply overall *k*-factor to Pythia

Studied final states

1. **pp → ZZ → 4e**

2. **pp → WZ → 3l (l=e,μ)**

   4 different event categories:

   1. **"3e"**: W →eν, Z → ee
   2. **"2e1μ"**: W →μν, Z → ee
   3. **"2μ1e"**: W → eν, Z →μμ
   4. **"3μ"**: W → μν, Z →μμ

Effort on Signal efficiency

Effort on Background rejection

Backgrounds

Events with 3 or more (true or fake) leptons and/or real Z:

ttbar, Z+jets (especially Zbb),…

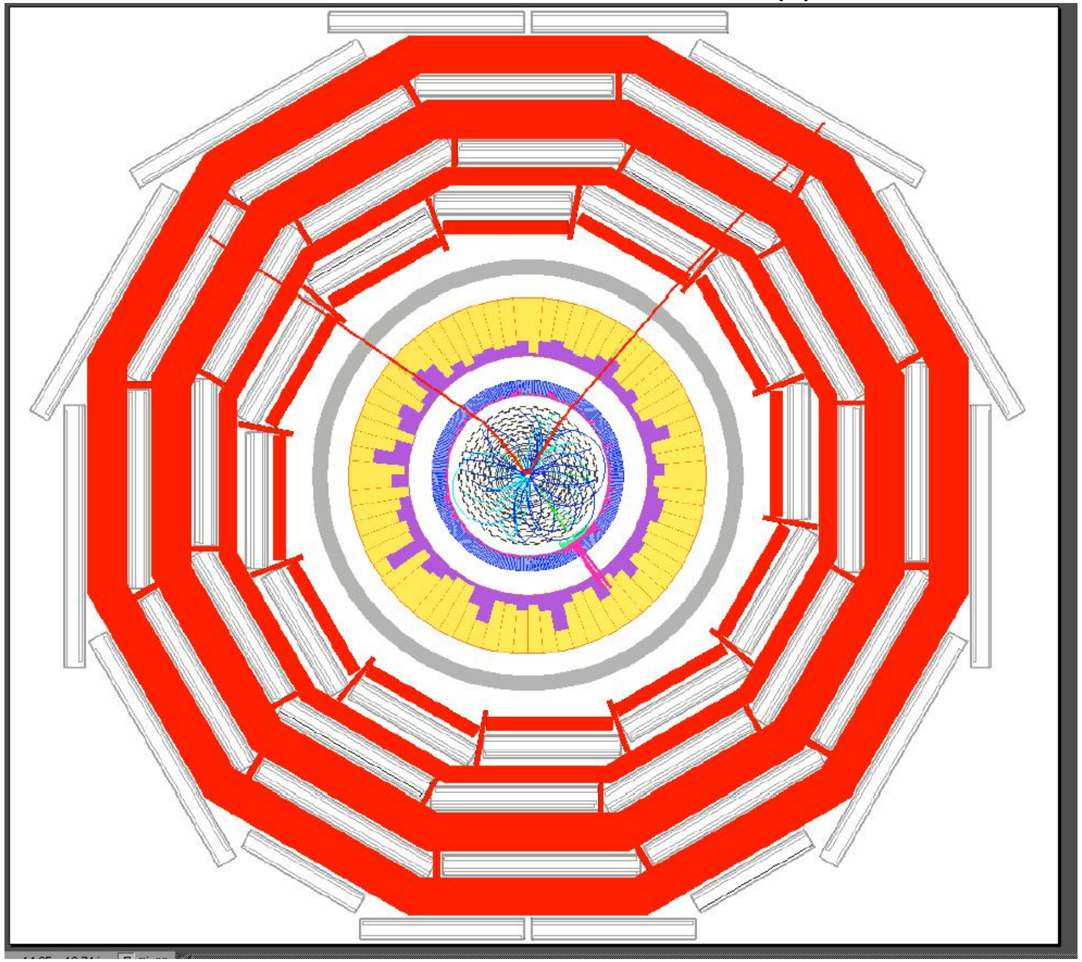
Signal and Background samples

	Cross sections times BR (NLO)	*k*-factor	
Signals			
ZZ(4e)	18.7 fb	1.37	
WZ(3l,l=e,μ,τ)	1.6 pb	1.92	
Main backgrounds			
tt(2l)	62.3 pb	1.6	
Z(ee)bb	60.3 pb	2.4	
Z($\mu\mu$)bb	60.3 pb	2.4	
tt(4e)	194 fb	1.6	
ZZ(2e2μ)	32.3 fb	1.35	(bg. For WZ)

tt(2l) generated with TopReX, Zbb with CompHEP, all others with Pythia

Full detector simulation and reconstruction

WZ event: W → eν, Z →μμ

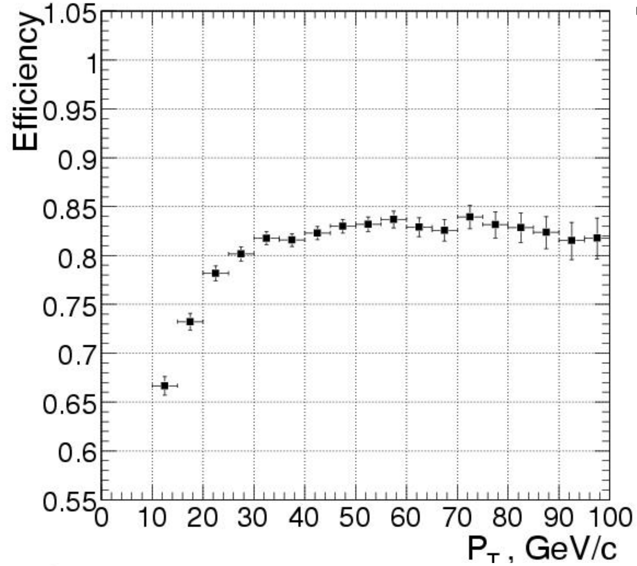


- Signal and backgrounds passed through full detector simulation
- Used reconstructed objects:
  - Tracks
  - ECAL clusters
  - Electrons
    - ECAL clusters + tracks
  - Muons
    - Muon system + tracker
  - Jets
    - For jet veto (WZ)

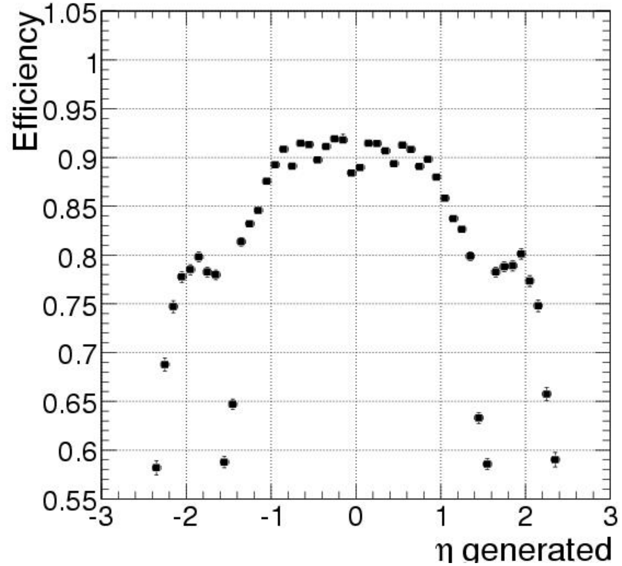
Lepton selection: electrons

Electron candidate selection

- Match ECAL "Supercluster" + track
  - "Supercluster": group of nearby ECAL clusters in narrow η window (Bremsstrahlung recovery)
  - $0.7 < E_{CLUSTER} / P_{track} < 3.$



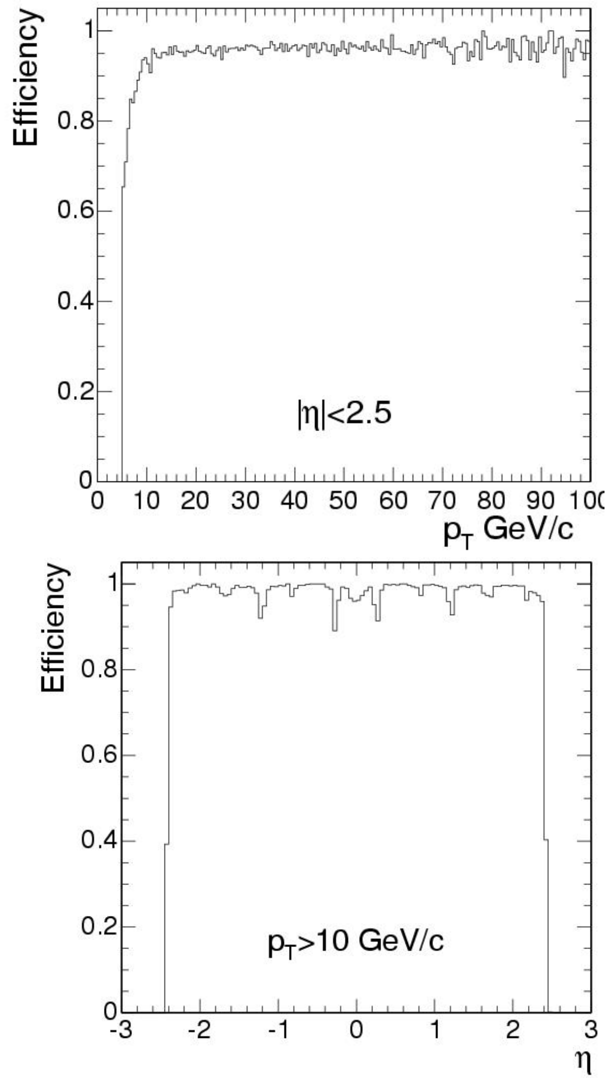
- Isolation requirements in HCAL + tracker:
  - No hadronic activity$E^{HCAL} / E^{ECAL} < 0.08$
  - less than 3 tracks with $p_t > 2$ GeV/c in $\Delta R = 0.15$ cone around candidate
  - Sum(Pt) of all tracks with p_t>2 GeV/c in $\Delta R = 0.2$ cone around candidate must be $< (1+0.34)E_T^{SuperCl.}$



Lepton selection: muons

Muon candidate selection

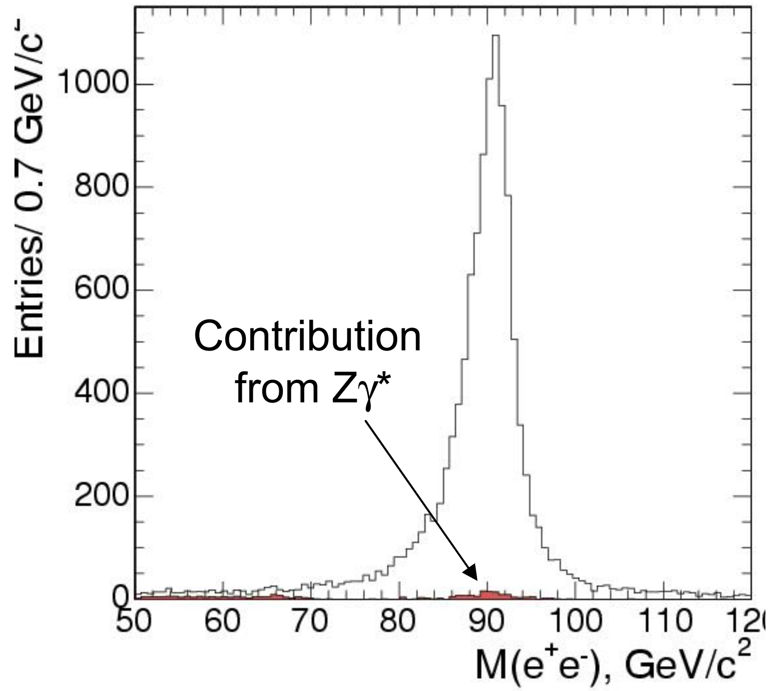
- Match muon track with track in the central tracker
- Require isolation in tracker and calorimeter
  - Sum(Pt) of all tracks in $\Delta R = 0.25$ cone around muon candidate < 2 GeV
  - Energy in calorimeters in $\Delta R = 0.3$ cone around muon candidate < 2 GeV



ZZ Event selection

- Find 4 electron candidates
  - Ordered by P_t, must satisfy: P_t > 30, 20, 15, 10 GeV/c
  - $|\eta|<2.5$
- Form Z candidate:
  - Combine e^+e^- pair
  - 50 GeV < $M(e^+e^-)$ < 120 GeV
  - Order Z's according to nearness to MZ
    - Z1 and Z2
- Form ZZ candidate
  - Combine two non-overlapping Z's

2 entries per event

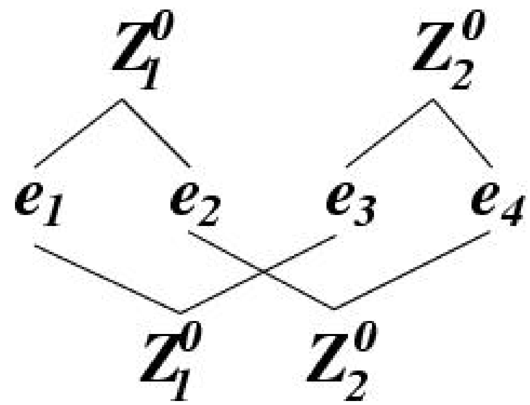


- Z1 biased towards true Z mass and higher p_t lepton
- Consider Z1 and Z2 on equal footing

ZZ best candidate selection

- Best Z association:
  - possible ambiguity in lepton assignment
  - Choose ZZ pairing with masses closest to PDG Z mass

  Correct pairing for ~100% of all on shell ZZ events



- Best ZZ candidate
  - Due to fake electrons more than one ZZ candidate can be formed (2.5 % events)
  - Retain pair with highest p_t non common lepton

  Correct choice for 98.3 % of events

WZ Event Selection

Selection / Background rejection Strategy

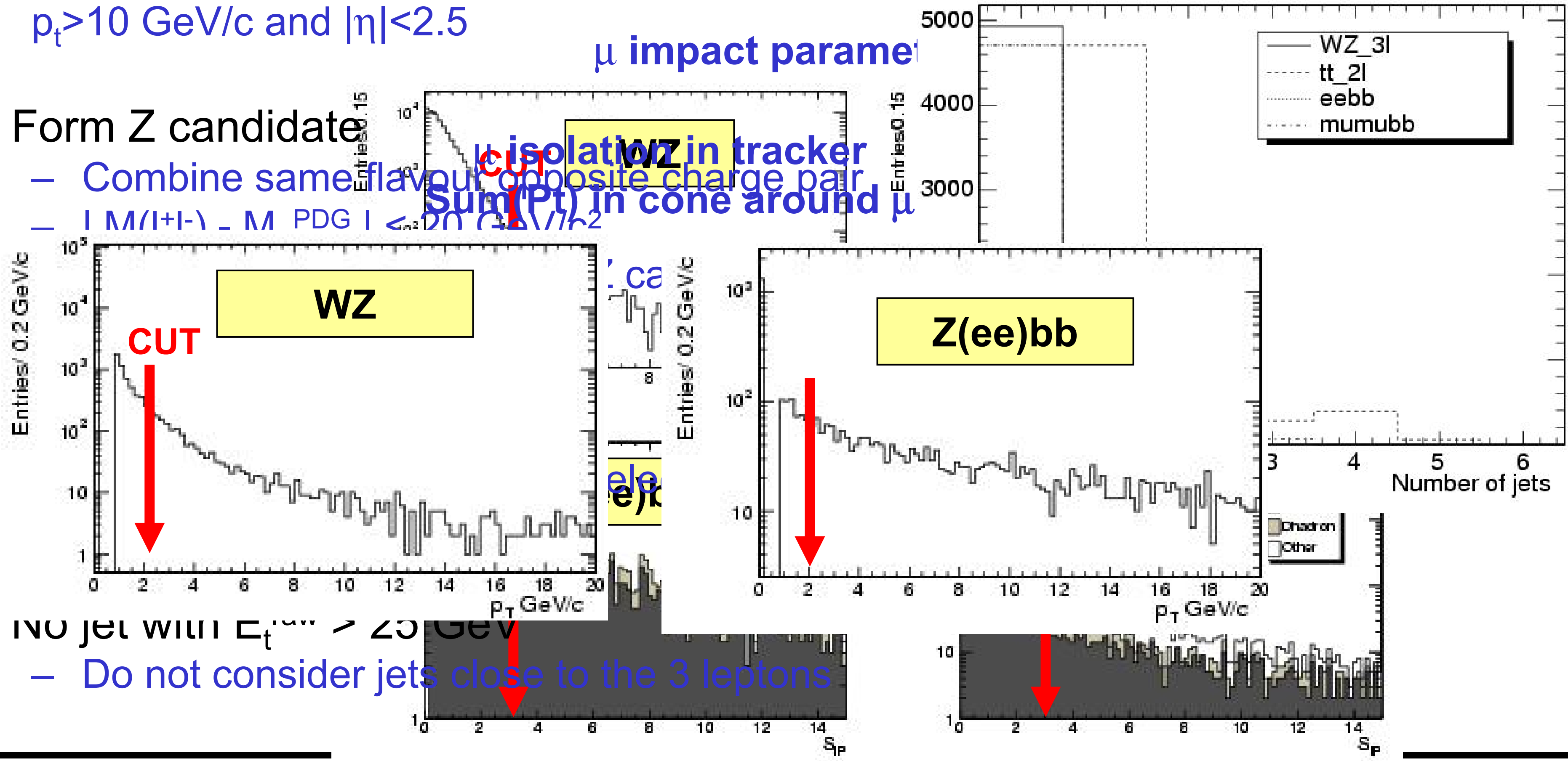
- Find 3 isolated electrons or muons with no lifetime
  - p_t>10 GeV/c and |η|<2.5

μ impact paramet

- Form Z candidate
  - Combine same flavour opposite charge pair
  - | M(l+l-) - M PDG | < 20 GeV/c2

μ isolation in tracker

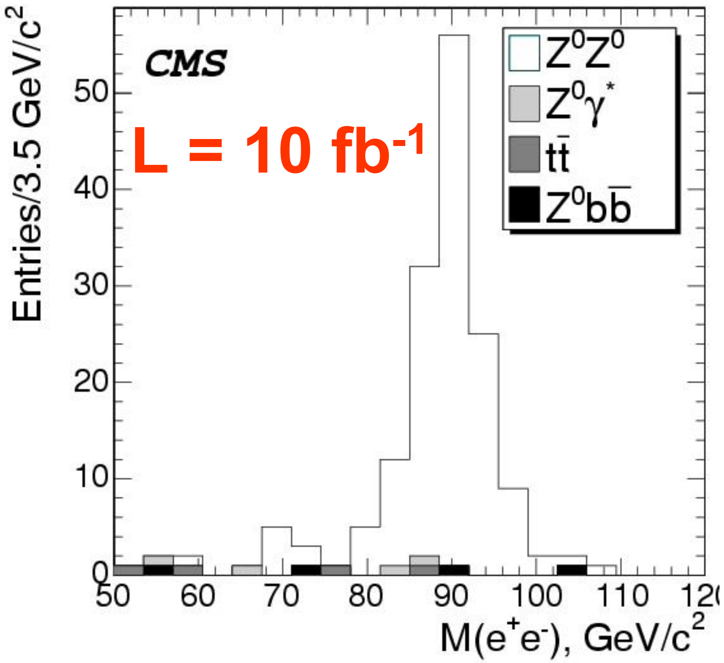
Sum(Pt) in cone around μ



- No jet with E_t^{raw} > 25 GeV
  - Do not consider jets close to the 3 leptons

$ZZ \rightarrow 4e$ expected signal & background

M(e^+e^-) after all cuts
(2 entries per event)

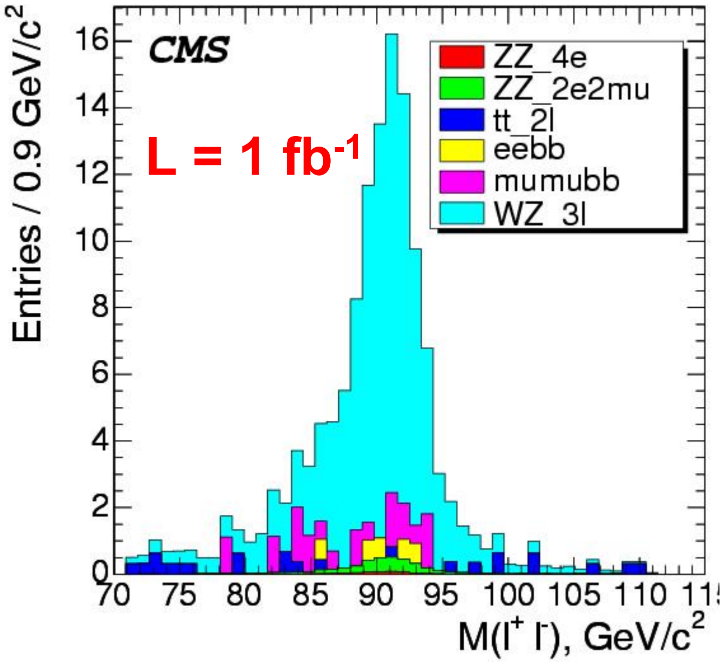


Expected signal and background yields for 1 and 10 fb^{-1}

	Efficiency, %	$N_{events}/1fb^{-1}$	$N_{events}/10fb^{-1}$
Z^0Z^0	38	7.1	71.1
$Z^0\gamma^*$	4.5	0.16	1.60
$Z^0b\bar{b}$	0.07	0.08	0.84
$t\bar{t}$	0.06	0.12	1.22
Total background	–	0.36	3.66
S_L	–	4.8	13.1

Nearly background free!

WZ →3l expected signal & background



M(l^+l^-) after all cuts
4 channels combined
(3e,2e1μ,2μ1e,3μ)

Presence of peaking backgrounds:
- Zbb
- ZZ (irreducible)

Expected signal and background yields for 1 fb^{-1}

	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency, %
$W^\pm Z^0 \to \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1
$Z^0 Z^0$	0.63	1.54	1.50	1.51	5.19	4.7
$t\bar{t}$	0.93	1.55	–	0.31	2.79	0.02
$\mu^+\mu^- b\bar{b}$	–	–	6.54	4.9	11.4	0.005
$e^+e^- b\bar{b}$	1.21	1.82	–	–	3.03	0.005
Total background	2.8	4.9	8.0	6.7	22.5	–
S_L	5.3	7.3	6.5	6.6	12.8	–

High significance in the first fb^{-1} !

Systematic uncertainties

WZ

Systematic source	Cross section	Significance
Luminosity	10.0	–
Trigger efficiency	1.0	1.0
Electron identification	2.6	5.2
Muon identification	3.4	6.8
Jet energy scale	5.0	5.0
$Z^0 b\bar{b}$ subtraction	12.0	12.0
$Z^0 Z^0 \rightarrow 4l$ subtraction	4.0	4.0
PDF uncertainty	–	3.5
Total	17.4	20.8

ZZ

Systematic uncertainties on cross section

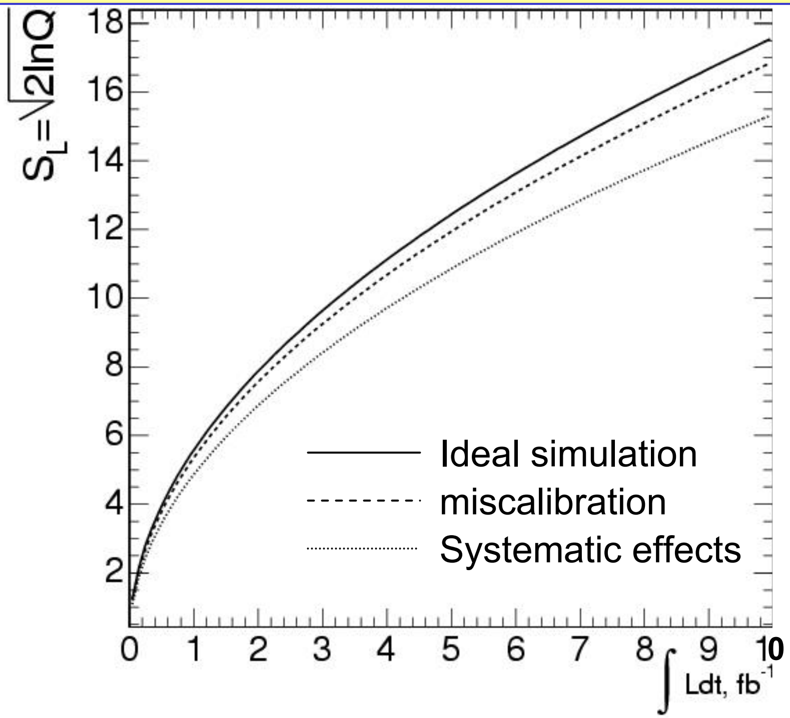
Source of systematic uncertainty	$\int Ldt = 1\,\mathrm{fb}^{-1}$	$\int Ldt = 10\,\mathrm{fb}^{-1}$
Luminosity	10.0	5.0
Trigger efficiency	1.0	1.0
Background subtraction	0.6	0.6
$Z^0\gamma^*$ subtraction	1.2	1.2
Electron identification	4×2.0	4×1.5
Total	12.9	7.9

Systematic uncertainties on significance

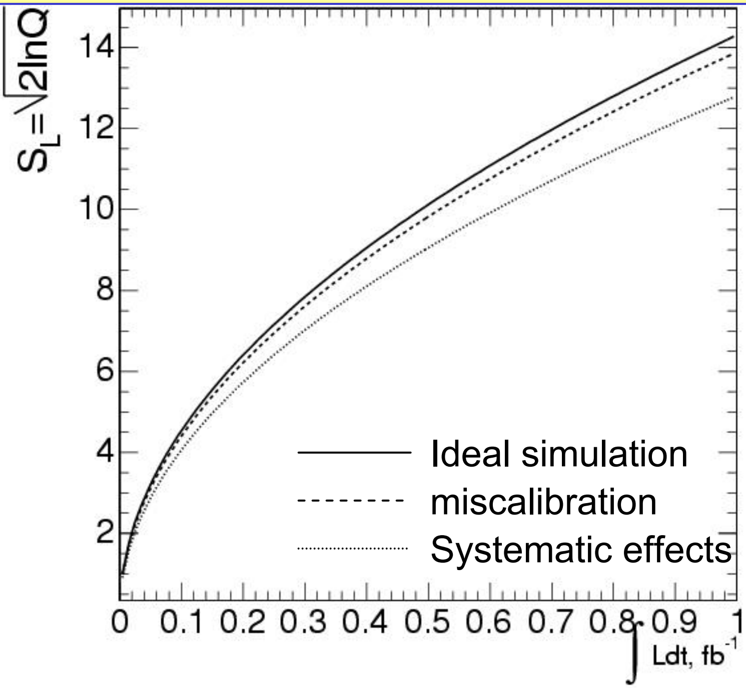
Source	$\int Ldt = 1\,\mathrm{fb}^{-1}$	$\int Ldt = 10\,\mathrm{fb}^{-1}$
Trigger efficiency	1.0	1.0
Background subtraction	0.6	0.6
$Z^0\gamma^*$ subtraction	1.2	1.2
Electron identification	4×2.0	4×1.5
PDF and QCD scale factor	6.4	6.4
Total	18.4	14.9

WZ and ZZ Discovery Potential

ZZ→4e signal significance



WZ →3l signal significance



$$S_L = \sqrt{2\ln Q}, \qquad Q = \left(1 + \frac{N_S}{N_B}\right)^{N_S+N_B} e^{-N_S}$$

5 σ discovery at:

- **ZZ : ~1 fb^{-1}**
- **WZ : ~150 pb^{-1}**

Summary

- We have investigated the discovery potential for the SM reactions $pp \rightarrow ZZ \rightarrow 4e$ and $pp \rightarrow WZ \rightarrow 3l$ ($l=e,\mu$)

- Signal and background samples were processed through the full simulation, reconstruction analysis chain of the CMS detector

- For 1 fb^{-1} we expect:
  - 7.1 signal and 0.4 background events for $ZZ \rightarrow 4e$
  - 97 signal and 23 background events for $WZ \rightarrow 3l$

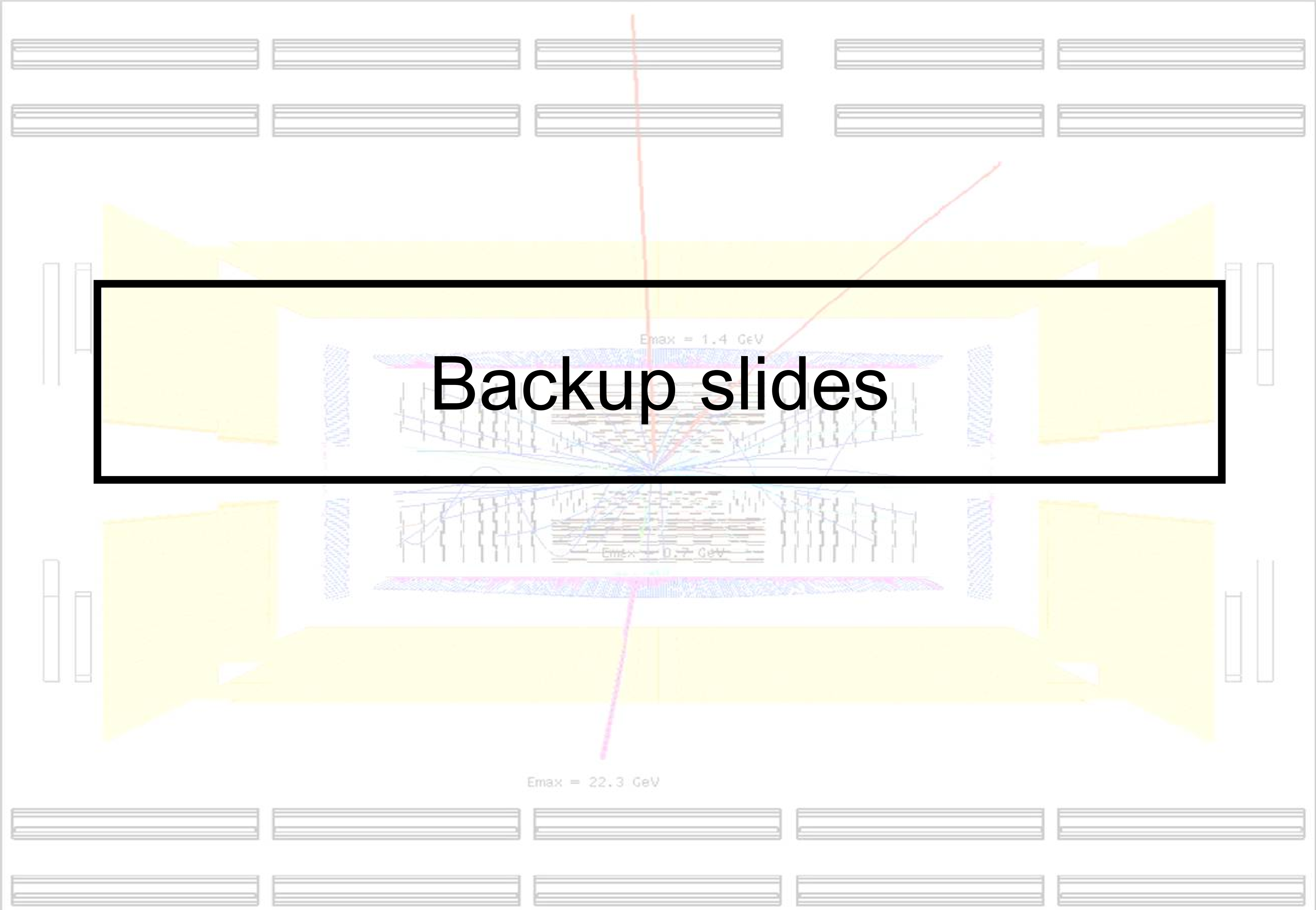
  Expect to establish those signals already in the first run

- Possibility to probe anomalous gauge couplings already with a few fb^{-1}

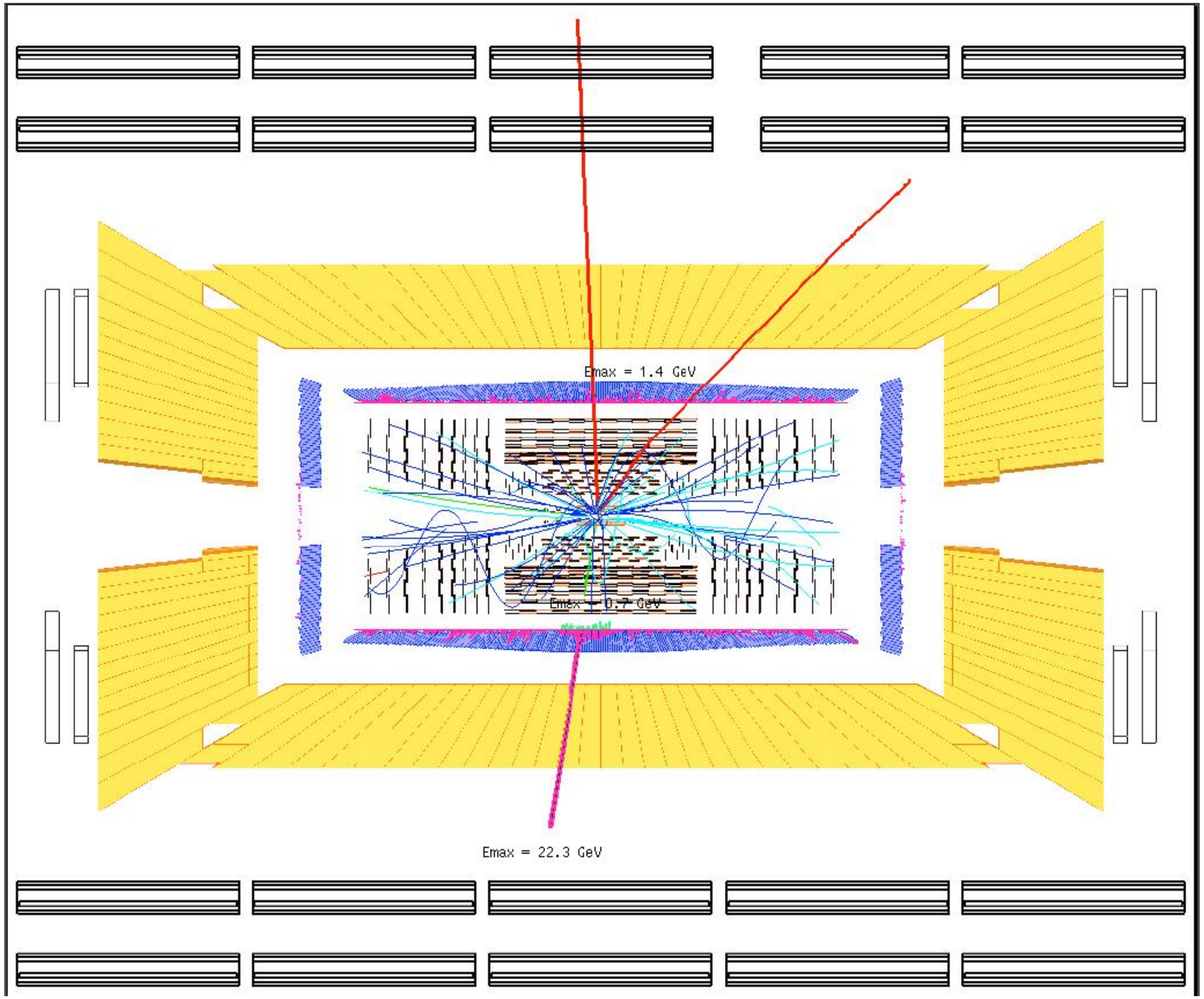
Reference

Study of Di-Boson Production
with the CMS Detector at LHC,
CERN-CMS Note 2006/108

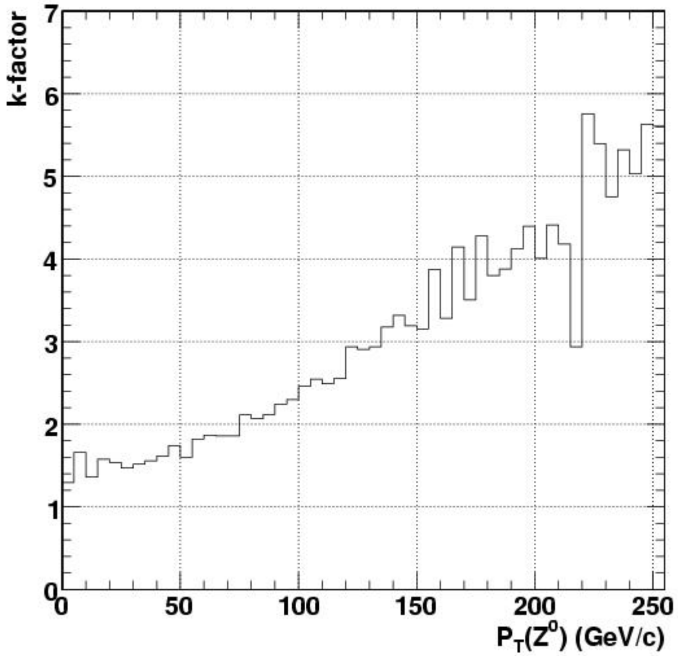
Backup slides

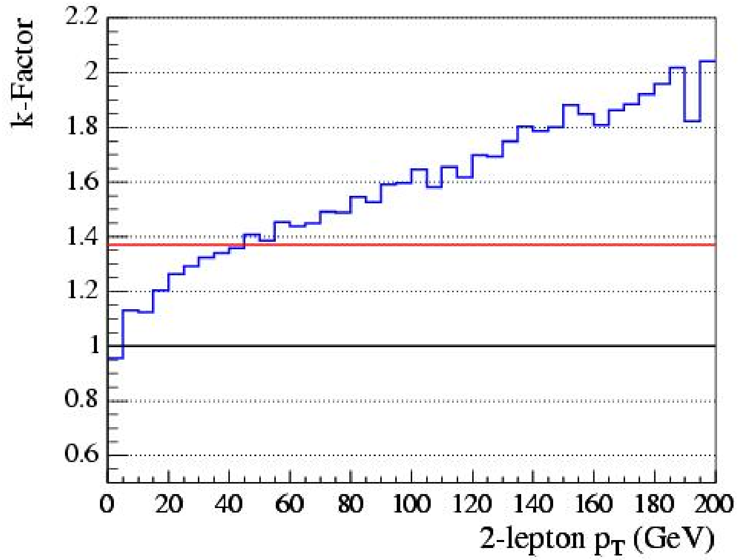


WZ event

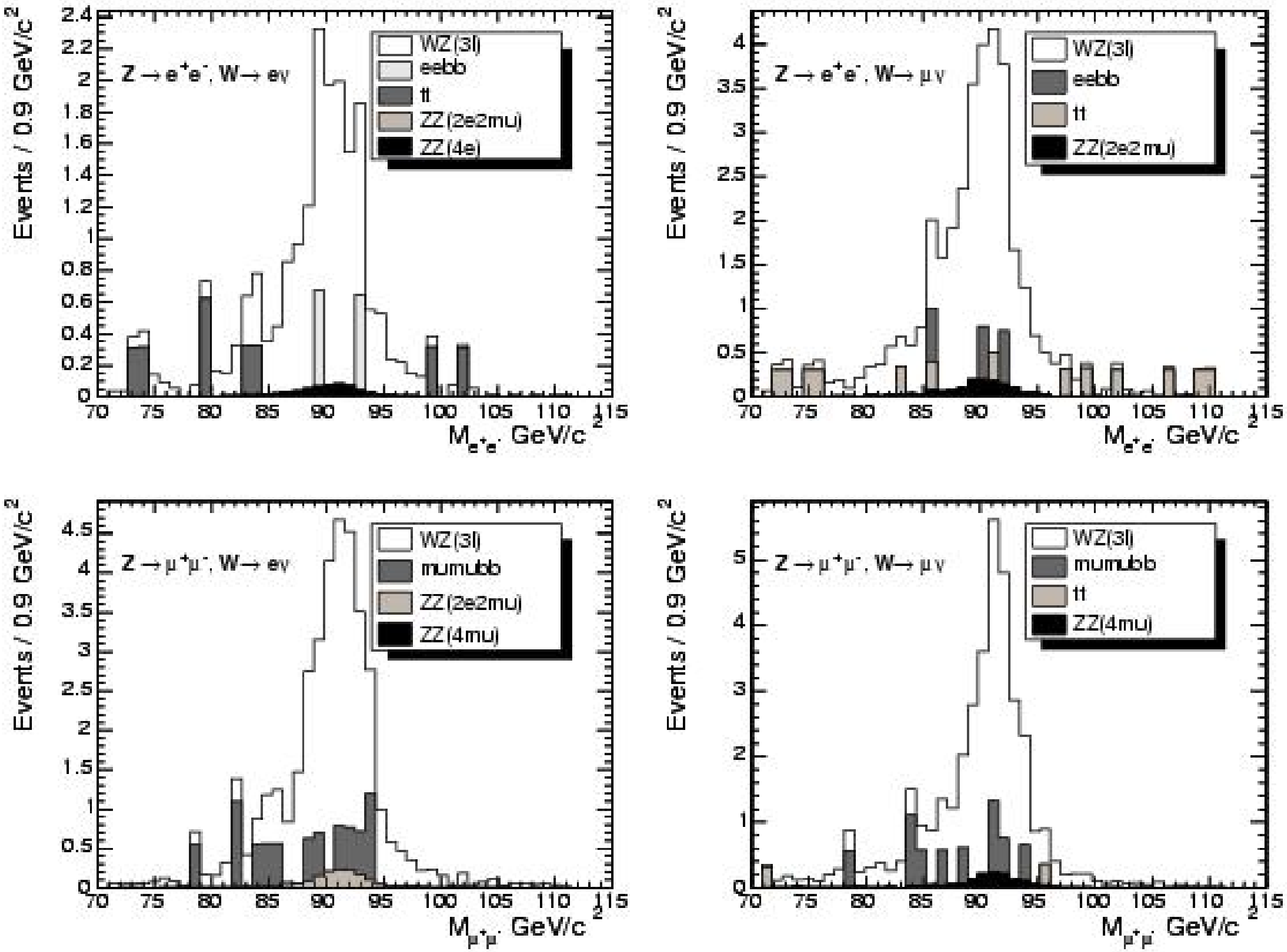


WZ & ZZ k-factors

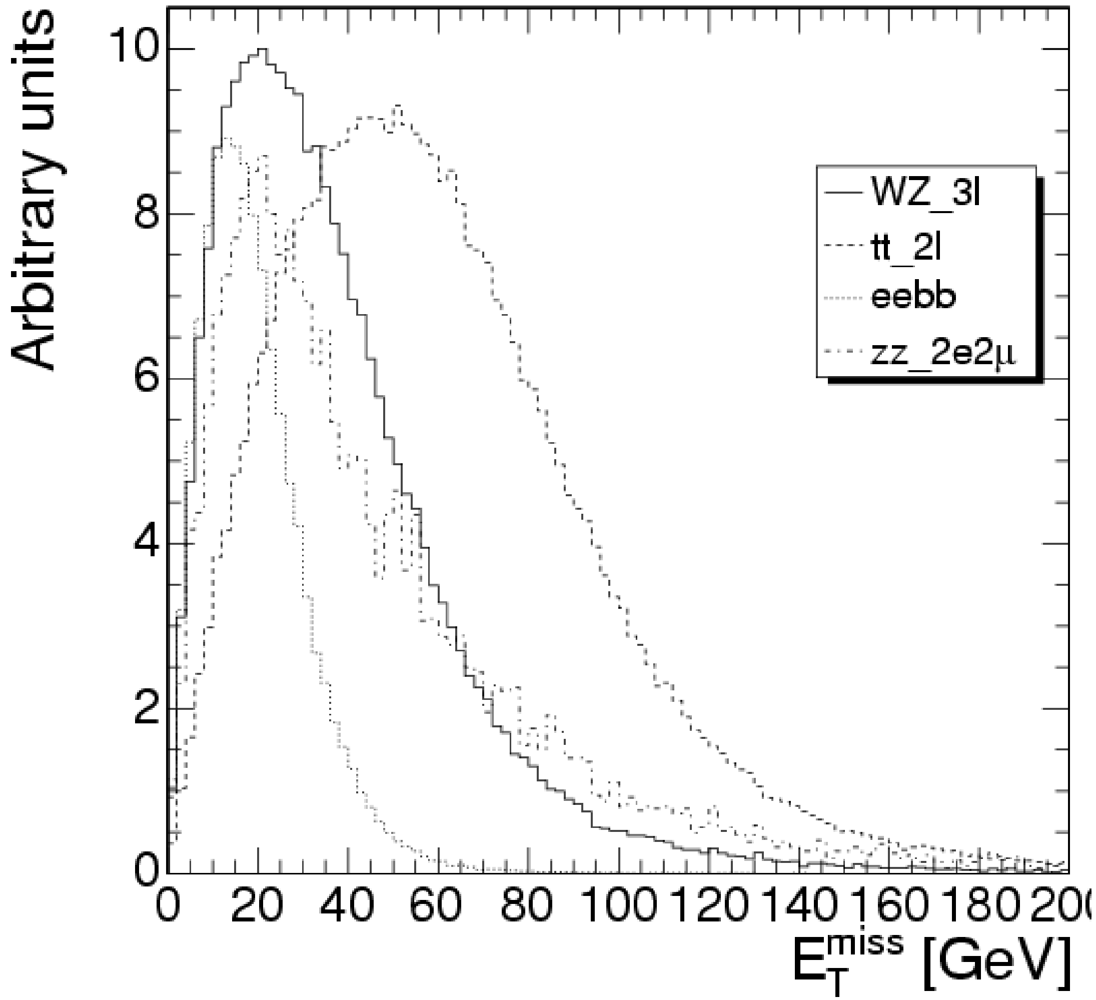




WZ yields by category



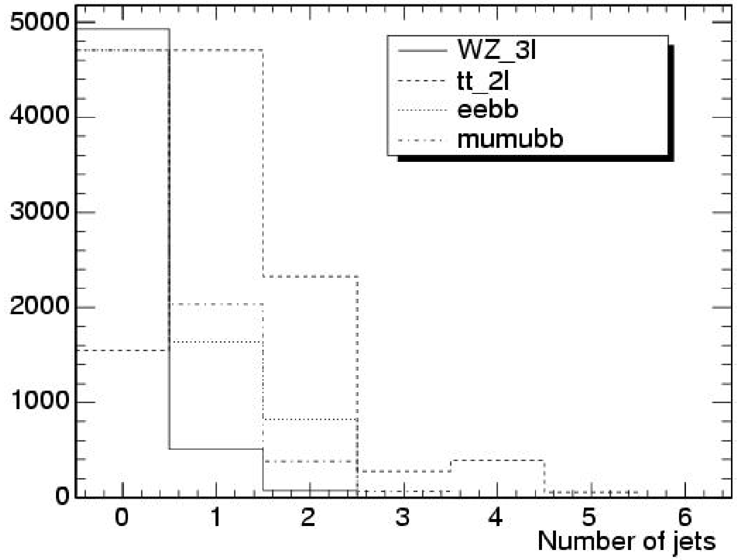
MET: why not use it?



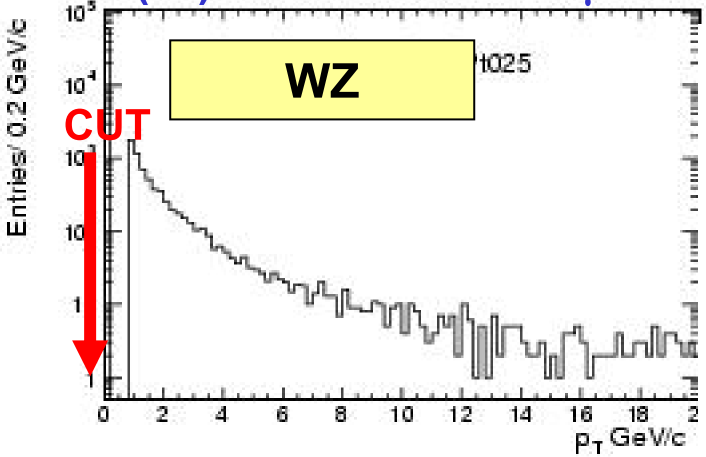
No clear
Signal / Background
separation

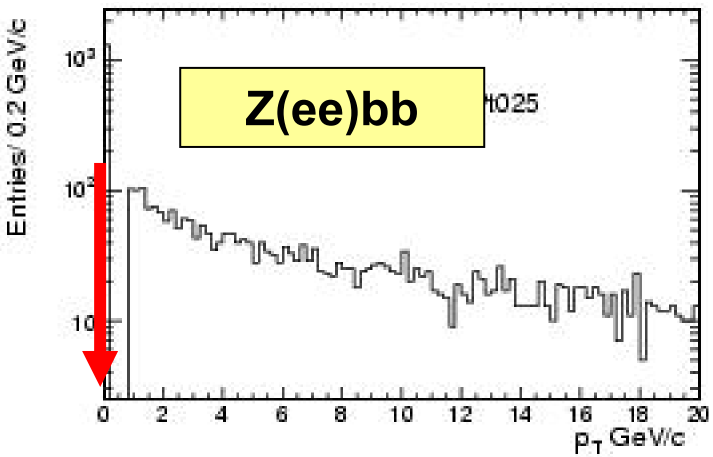
WZ Event Selection

- Find 3 isolated electrons or muons
  p_t>10 GeV/c and |η|<2.5
- Form Z candidate
  - Combine same flavour opposite charge pair
  - $| M(l^+l^-) - M_Z^{PDG} | < 20$ GeV/c^2
  - Veto event if more than one Z candidate
- Find third lepton (from W)
  - $P_t > 20$ GeV/c
  - If more than one candidate, select the one
- No jet with $E_t^{raw} > 25$ GeV
  - Do not consider jets close to the 3 leptons

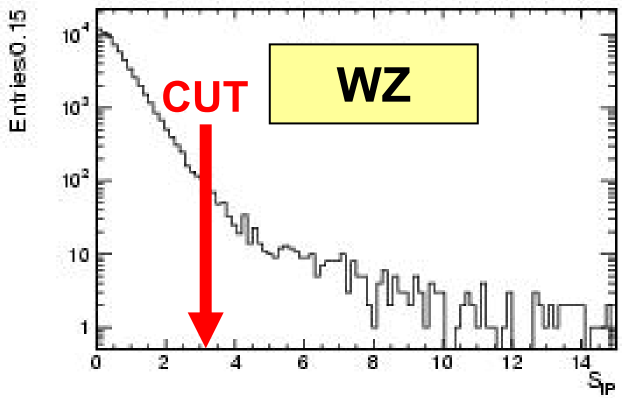


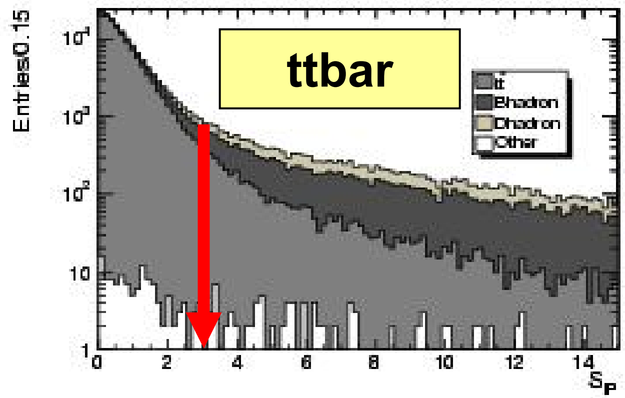
μ isolation in tracker
Sum(Pt) in cone around μ

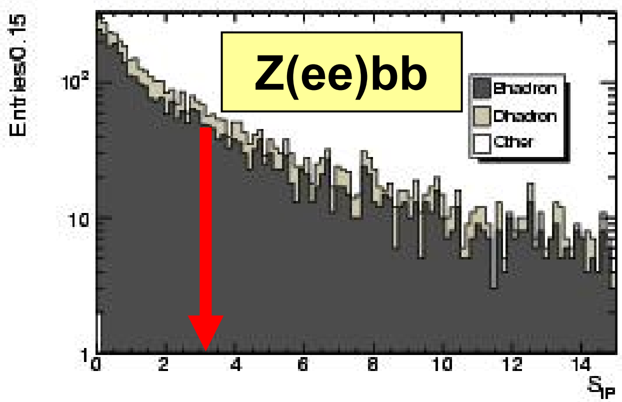


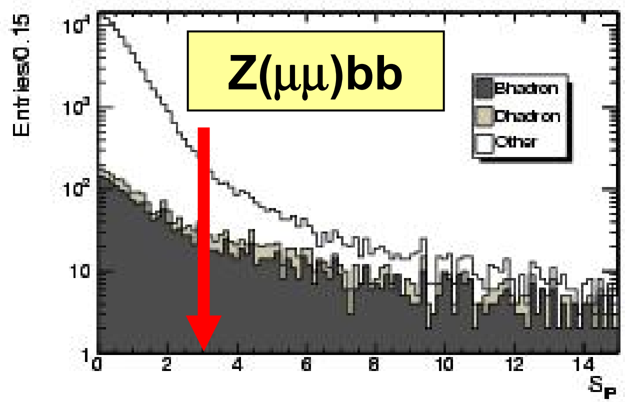


μ impact parameter significance



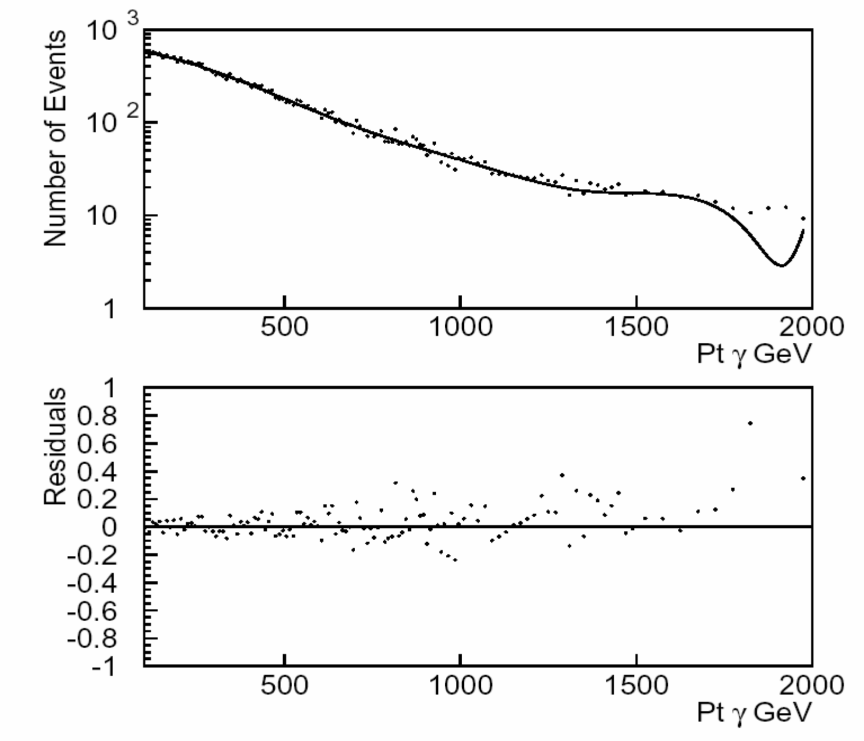






Alex Oh's presentation
"Physics at LHC "
Vienna 2004

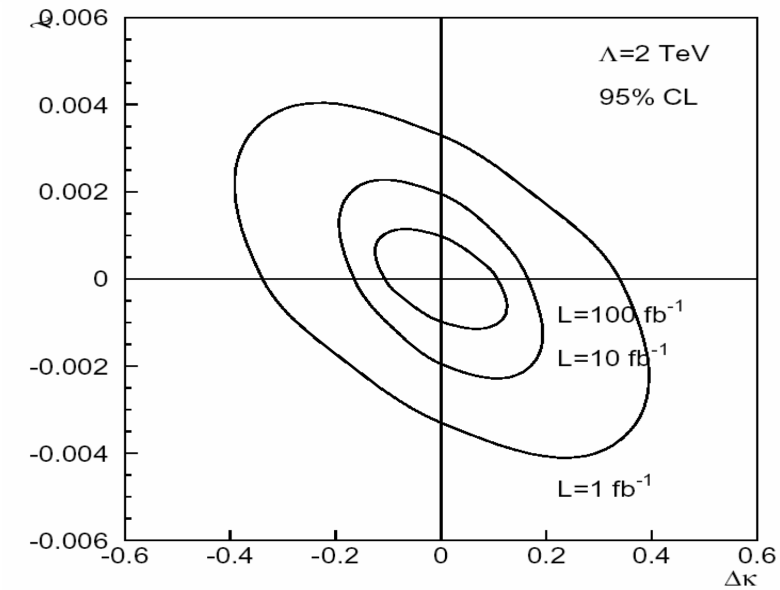
charged TGC



- Strategy Wγ
  - Binned log likelihood fit to $p_T(\gamma)$ distribution.
  - Use parametrised p_T spectrum ($\Delta\kappa$, λ) from BHO NLO generator.

Luminosity (fb^{-1})	CMS Predictions		TeV2000 Predictions	
	$\Delta\kappa$	λ	$\Delta\kappa$	λ
1	± 0.34	± 0.0034	± 0.4	± 0.12
10	± 0.17	± 0.0019	± 0.2	± 0.06
100	± 0.10	± 0.0009	-	-

Λ_{FF}=2TeV



CMS NOTE 2001/056

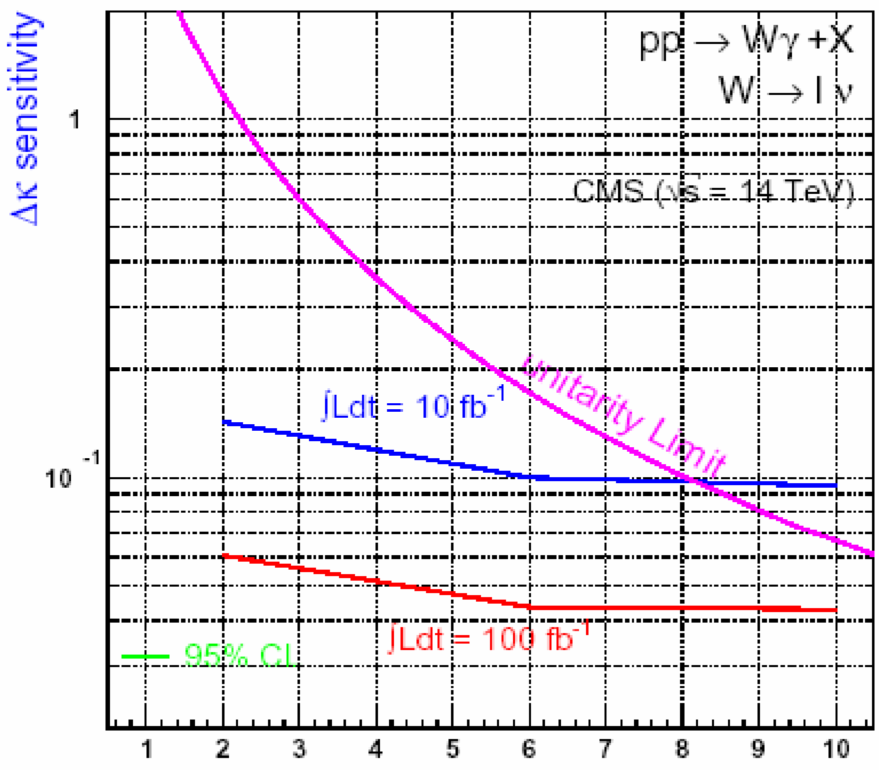
LEP2 combined:

Parameter	68% C.L.	95% C.L.
g_1^Z	$0.991^{+0.022}_{-0.021}$	[0.949, 1.034]
κ_γ	$0.984^{+0.042}_{-0.047}$	[0.895, 1.069]
λ_γ	$-0.016^{+0.021}_{-0.023}$	[−0.059, 0.026]

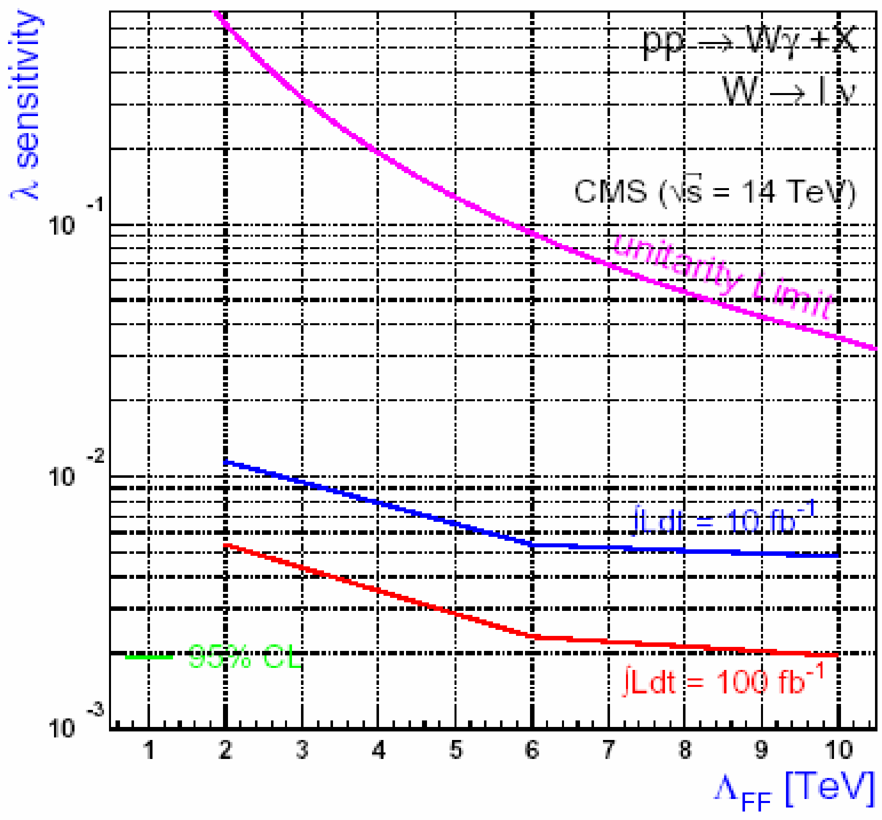
Limits with L=100fb^{-1} improve by two orders of magnitude for λ_γ.

charged TGC

- Λ_{FF} dependence

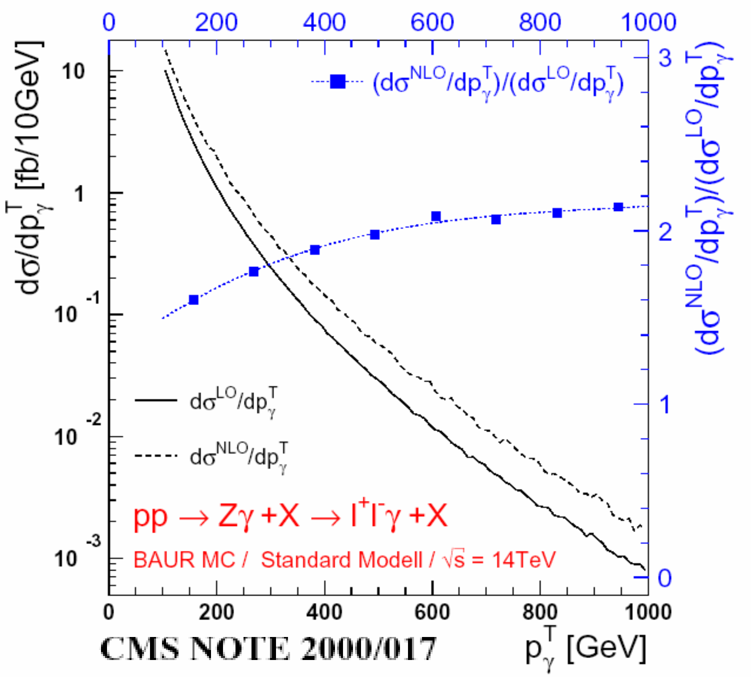


CMS NOTE 2000/017



Alex Oh's presentation
"Physics at LHC"
Vienna 2004

neutral TGC

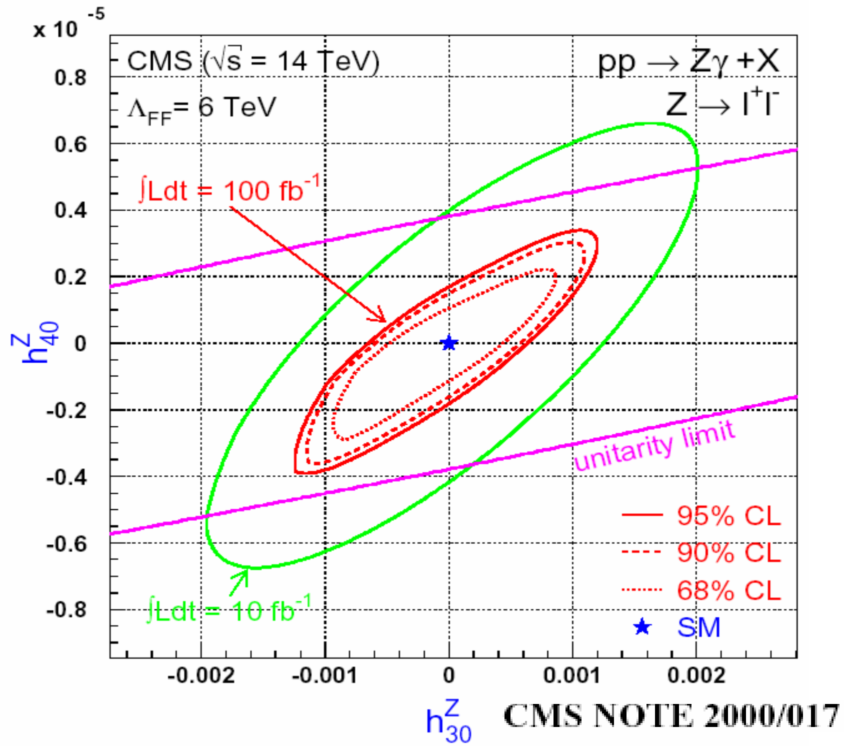


LEP2 combined:

h_3^Z	$[-0.20, \quad +0.07]$
h_4^Z	$[-0.05, \quad +0.12]$

Limits with L=100fb^{-1} improve by 3(5) orders of magnitude for $h_3(h_4)$.

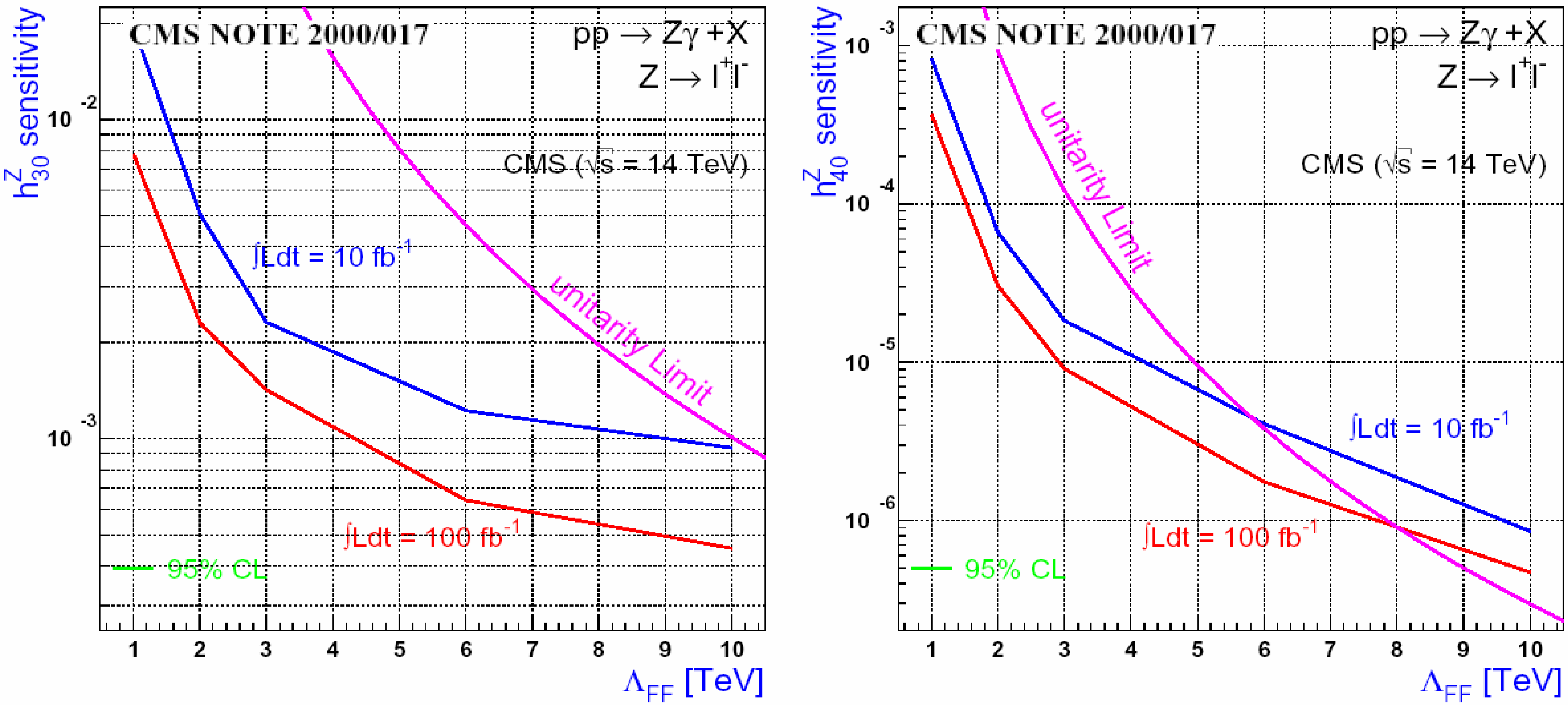
- $Z\gamma$ channel
  - binned log likelihood fit to $p_T(\gamma)$ distribution.
  - NLO taken into account



$$-6.5 \cdot 10^{-4} < h_{30}^Z < 6.4 \cdot 10^{-4}$$
$$-1.8 \cdot 10^{-6} < h_{40}^Z < 1.7 \cdot 10^{-6}$$

neutral TGC

- Λ_{FF} dependence



CMS NOTE 2000/017