Higgs Coupling Measurement at FCC-ee with the CLD detector

Colin Bernet

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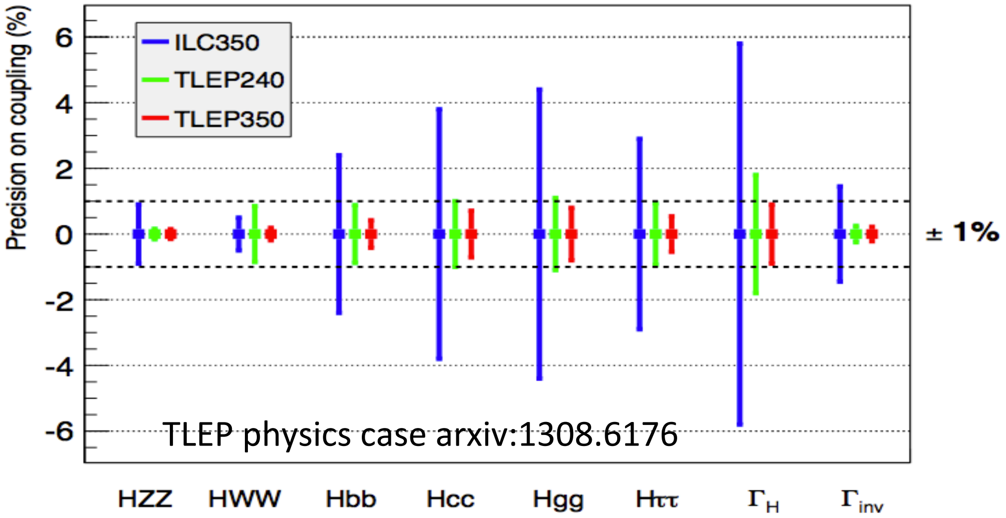
An Indirect Probe of New Physics

- Effective field theory:
  new physics → deviations of the Higgs boson couplings

$$\frac{\delta g_{HXX}}{g_{HXX}^{SM}} \le 5\% \times \left(\frac{1\mathrm{TeV}}{\Lambda}\right)^2$$

- New physics at
  - Λ = 1 TeV → 5% deviation → 1% precision needed for discovery
  - Λ = 3 TeV → 0.5% deviation → **per mille level precision needed! + look for exotic decay modes**



FCC-ee (was TLEP) provides:
- **unprecedented precision**
- **the total width (impossible at hh colliders)**

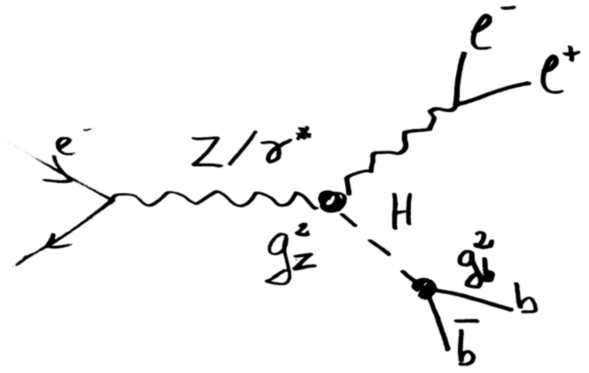
Global Fit: The Kappa Framework

$$\kappa_j \equiv g_j / g_j^{SM}$$

coupling deviation

Deviation of the observed yield w/r SM

$$\frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{SM}} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$



$$\kappa_H^2 \equiv \Gamma / \Gamma_{SM} = \sum_j \kappa_j^2 \mathrm{BR}_{j,SM}$$

Full width deviation assuming no other mode

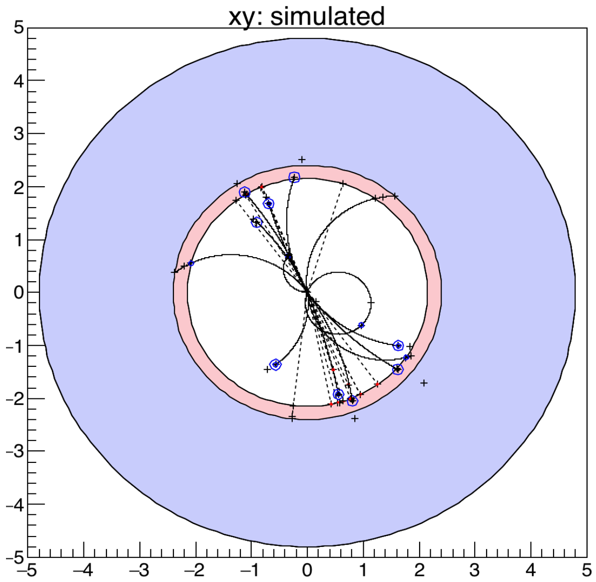
$$\kappa_H^2 \equiv \Gamma / \Gamma_{SM} = \frac{\sum_j \kappa_j^2 \mathrm{BR}_{j,SM}}{1 - \mathrm{BR}_{\mathrm{inv}}}$$

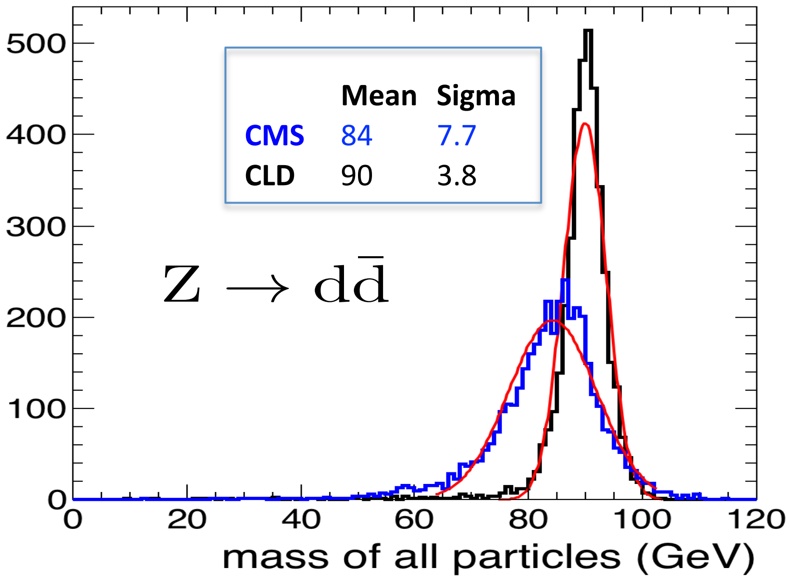
Full width deviation allowing for invisible decay modes

Higgs at FCC-ee: A Brief History

- LEP3 arxiv 1208.1662, August 2012
  - ee collider in the LHC tunnel
    500 fb^{-1} @240 GeV
  - σ x BR measurements : analyses based on the CMS full simulation
- TLEP arxiv:1308.6176, August 2013 (plot on 1st slide)
  - 80-100 km tunnel
    10 ab^{-1} @ 240 and
    2.6 ab^{-1} @ 350 GeV
  - scaling of the ILC predictions, back-of-the-envelope calculations
- FCC-ee, Now
  - 5 ab^{-1} @ 240 GeV and
    1.5 ab^{-1} @365 GeV
  - need to confirm the TLEP results with an actual detector model for FCC-ee.
    Here: CLD (CLIC adapted to FCC-ee):
  - need to test various detector hypotheses
    - Can we get a cheaper detector without seriously affecting the physics programme?
- **Setting up full simulation and reconstruction for a given detector hypothesis would take years**
  - except for CLD if we buy it as it is

Papas

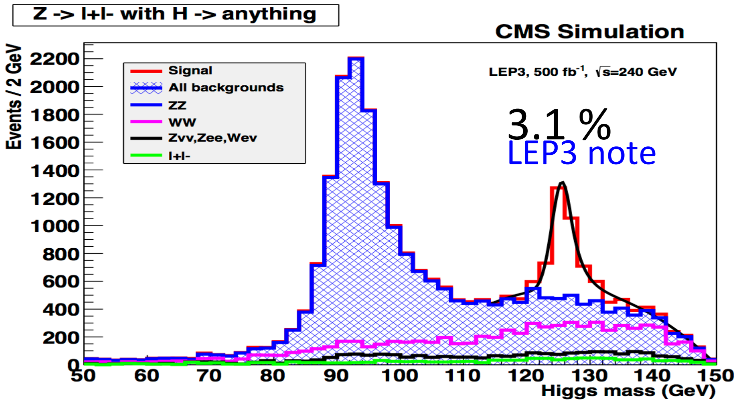


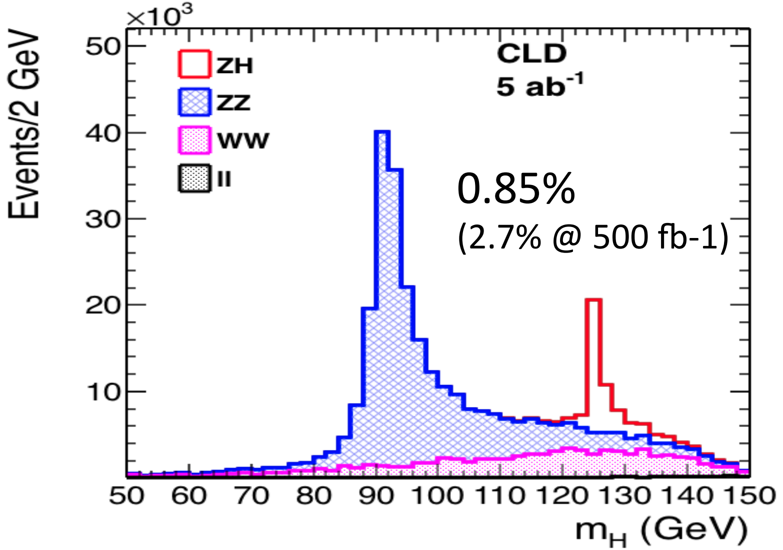


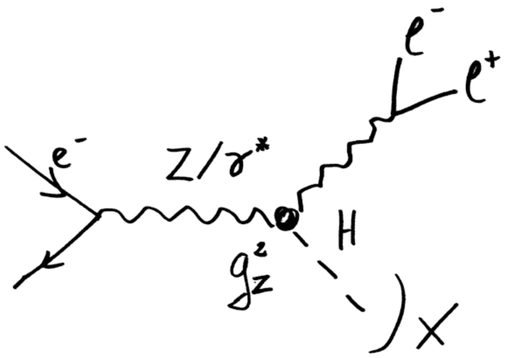
- A fast but accurate simulation of the particle flow
  - c.f. talk at software session
- Inputs from full simulation

- CLD: CLIC adapted to FCC-ee
  - smaller forward acceptance
  - B = 2T, larger radius
  - excellent b tagging
    - eff = 80%, fake = 0.4%

$ZH \to \ell\ell X$







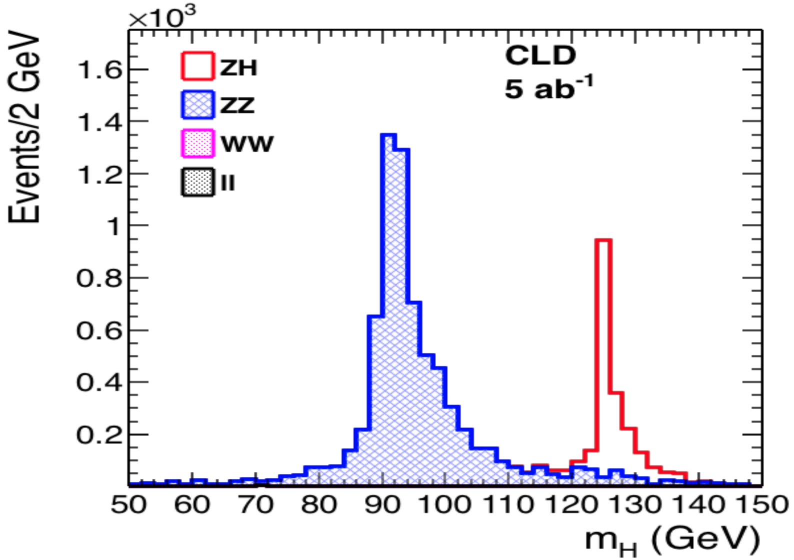
Z→ll : flavour, charge, isolation, mass, …
no photon in acceptance, other kin. cuts
mH = mass recoiling against the two leptons
(Full list of cuts in backup)

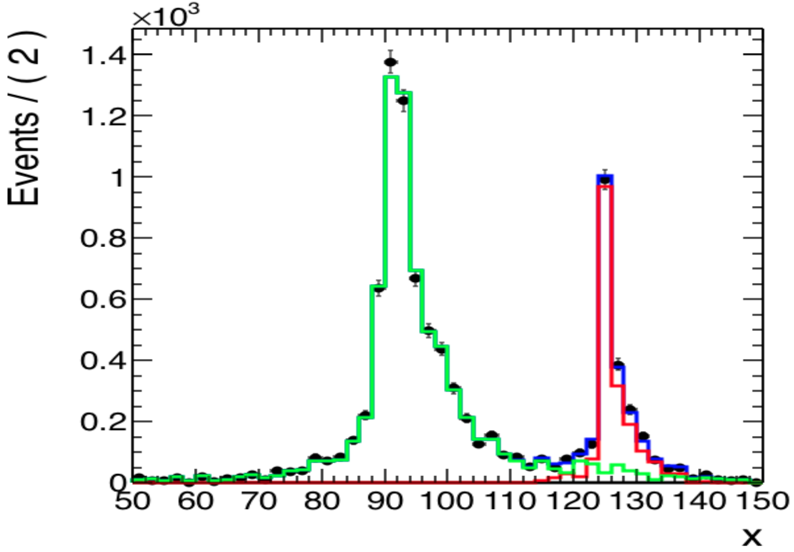
CLD: 15% improvement due to higher lepton efficiency

recoil mass

$$m_H = \sqrt{(p_i - p_{\ell,1} - p_{\ell,2})^2}$$

Yield extraction



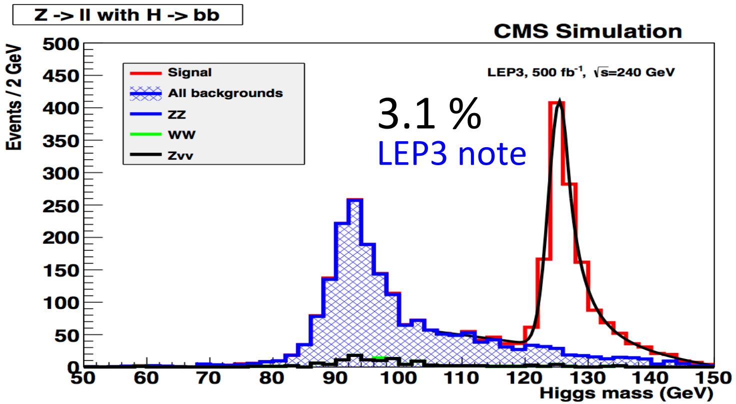


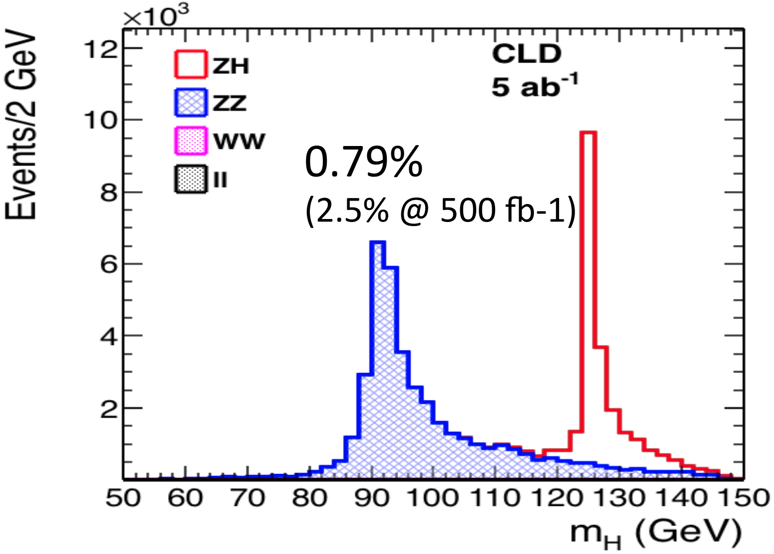
- Use stacked distribution to generate pseudo-data

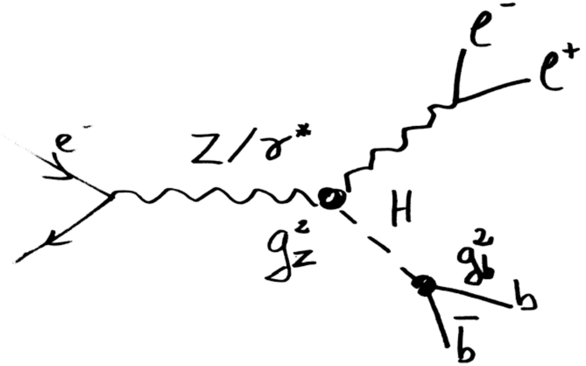
- Use same distributions to fit the yield
  = assume perfect knowledge of template shape
  MC stat uncertainty does not matter
- Get statistical uncertainty on signal yield from the fit

We want to see the ultimate performance → no systematic uncertainty

$\mathrm{ZH} \rightarrow \ell\ell bb$





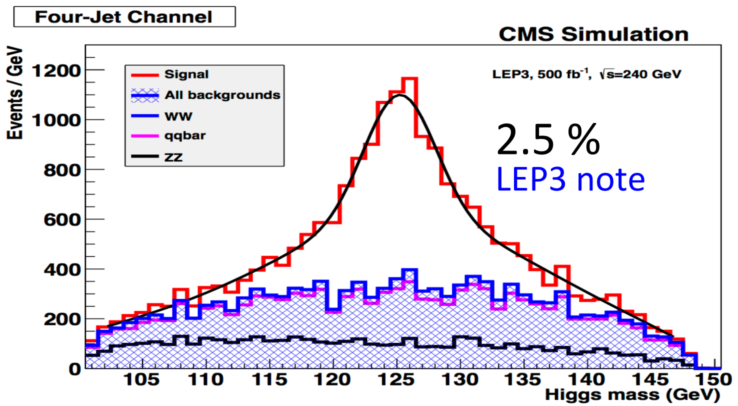


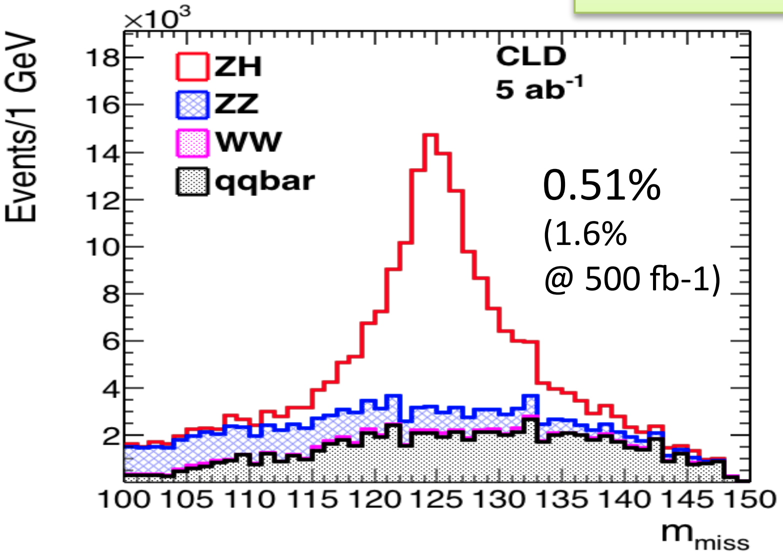
Z→ll, m_H = same as before
exclusive 2 jet reconstruction, at least 1 b

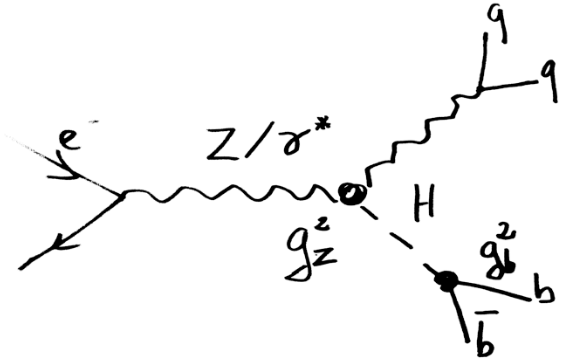
CLD: 20% improvement due to higher lepton efficiency and better b tagging

$\mathrm{ZH} \rightarrow qqbb$

Jonas Neundorf
(DESY)





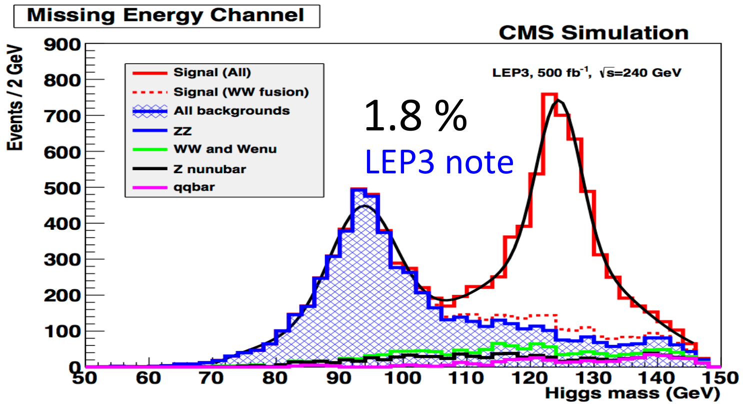


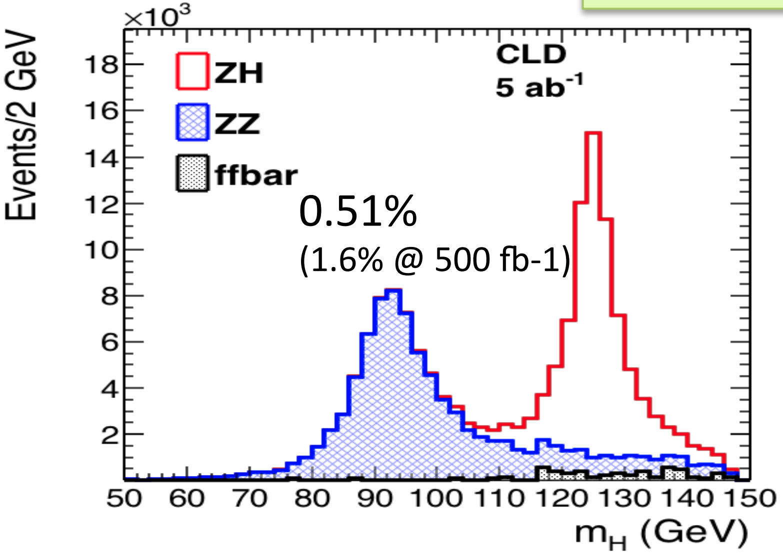
exclusive 4 jet reconstruction,
rescale jet energies for p4 conservation
reject combinations compatible with ZZ and WW
select best combination for H→bb (b tag)

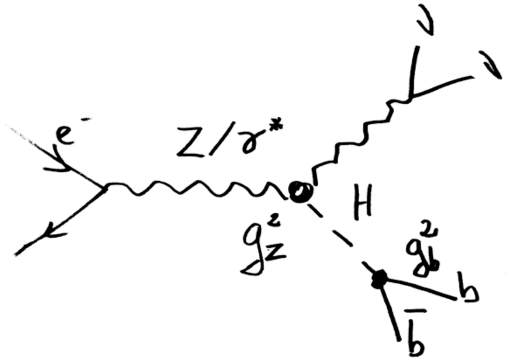
CLD: 35% improvement due to better b tagging and particle flow

$\mathrm{ZH} \rightarrow \nu\nu bb$

Janik Von Ahnen
(DESY)



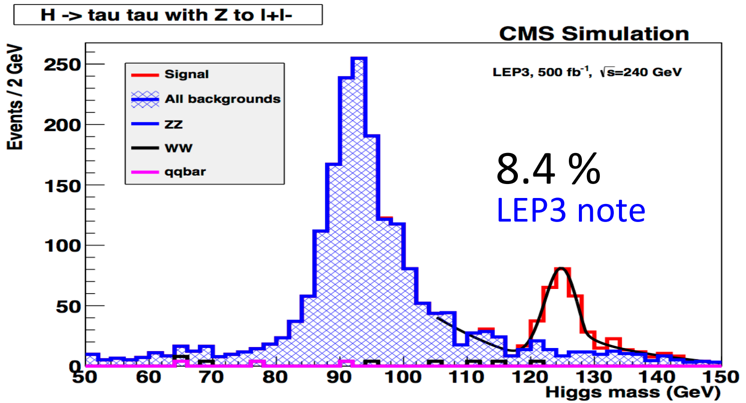


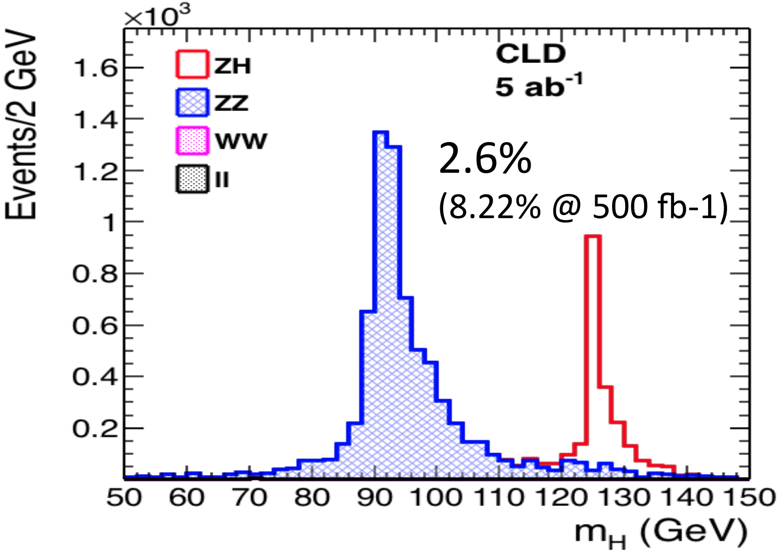


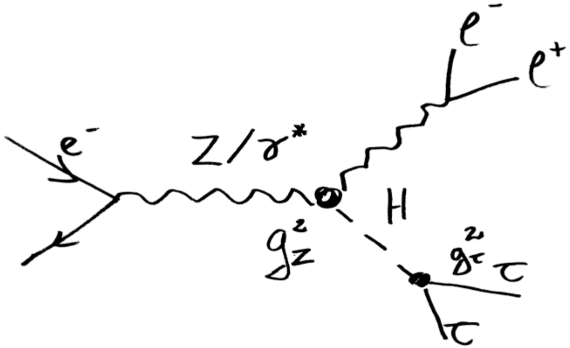
exclusive 2 jet reconstruction, at least 1 b
80 < missing mass < 135
rescale jet p4 to bring missing mass to mZ
plot mass of the 2-jet system

CLD: 12% improvement due better b tagging and particle flow

$\mathrm{ZH} \to \ell\ell\tau\tau$



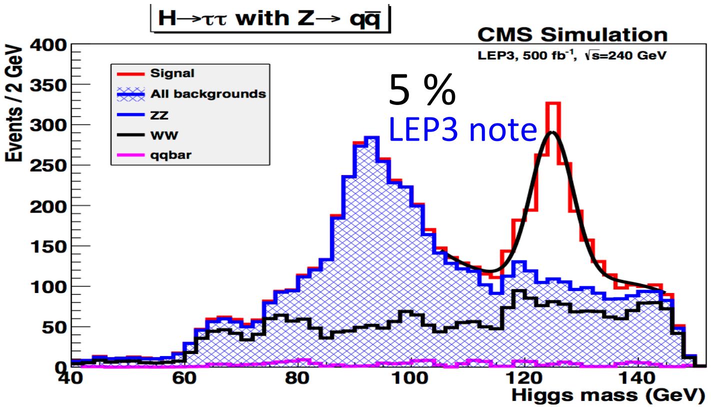


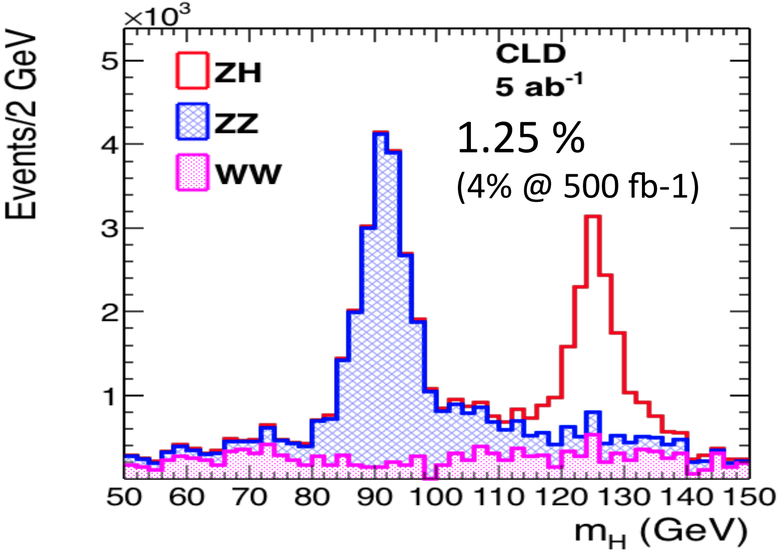


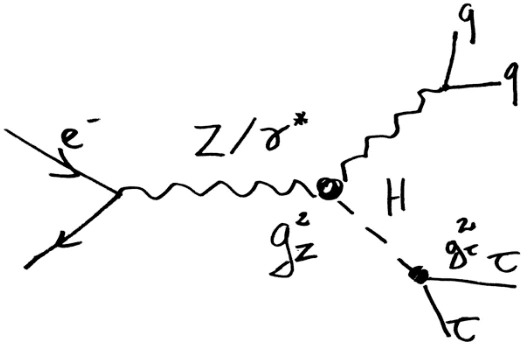
Z→ll, m_H = same as before
inclusive jet reconstruction (narrow, R=0.3)
exactly 2 jets: taus (1 or 3 charged particles)
rescale lepton and tau energies for p4 conservation (ν)
m_H and ττ mass agree (H→WW down to 3%)

CLD: 7% improvement

$\mathrm{ZH} \rightarrow qq\tau\tau$



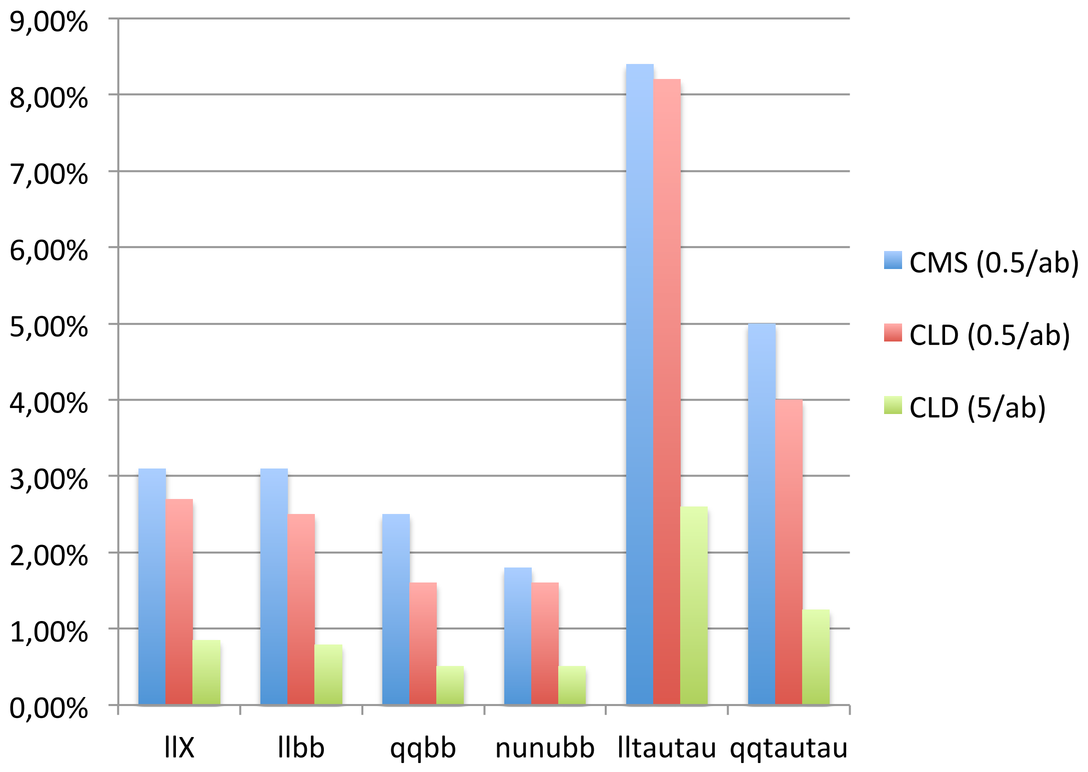




inclusive jet reconstruction (R=0.3), at least 2 taus
other particles forced to 2 jets
rescale jets and taus for p4 conservation
choose combination with 2-jet mass closest to mZ
two taus isolated, $m_{qq} > 80$ → WW down

CLD: 20% improvement (new analysis strategy)

Summary



Precision 7-35% better with CLD than with CMS

Equivalent to +15-140% integrated luminosity

Outlook

- Set up the missing analysis channels
  - $H \rightarrow WW$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow cc$, $H \rightarrow gg$
    - major improvements expected in all channels except $H \rightarrow \gamma\gamma$
  - $WW \rightarrow H$ @ 365 GeV (Janik, almost ready)

- Run the kappa fit
  EFT interpretation (Jorge de Blas)

- Study variations in the detector design
  - cost / benefit analysis

Back-up

```
cut_lepiso          ((zeds_1_iso_e/zeds_1_e<0.2) && (zeds_2_iso_e/zeds_2_e<0.2) && zeds_1_e>0 && zeds_2_e>0)
cut_z_mass          (abs(zeds_m-91)<10)
cut_z_kine          (zeds_pt>10 && zeds_pz<50 && zeds_acol>100 && zeds_cross>10)
cut_z_flavour       (zeds_1_pdgid==-zeds_2_pdgid)
cut_rad2            (jets_1_e>0 || (jets_1_e<0 && n_particles_not_zed==0))
cut_rad             (((jets_1_e<0 || jets_1_22_e/jets_1_e<0.8) && (jets_2_e<0 || jets_2_22_e/jets_2_e<0.8)))
cut_rm4l            !((second_zeds_1_pdgid==-second_zeds_2_pdgid) && (abs(second_zeds_1_pdgid)==13 ||
abs(second_zeds_1_pdgid)==11))
```

Counter WW :

Preselection	107160	1.00	1.0000
cut_lepiso	102566	0.96	0.9571
cut_z_mass	11997	0.12	0.1120
cut_z_kine	6654	0.55	0.0621
cut_z_flavour	6651	1.00	0.0621
cut_rad2	4532	0.68	0.0423
cut_rad	3916	0.86	0.0365
cut_rm4l	3916	1.00	0.0365

Counter ZH :

Preselection	35252	1.00	1.0000
cut_lepiso	31891	0.90	0.9047
cut_z_mass	24418	0.77	0.6927
cut_z_kine	17598	0.72	0.4992
cut_z_flavour	17442	0.99	0.4948
cut_rad2	17347	0.99	0.4921
cut_rad	16813	0.97	0.4769
cut_rm4l	16603	0.99	0.4710

Counter ZZ :

Preselection	284155	1.00	1.0000
cut_lepiso	266559	0.94	0.9381
cut_z_mass	171636	0.64	0.6040
cut_z_kine	84104	0.49	0.2960
cut_z_flavour	83162	0.99	0.2927
cut_rad2	77406	0.93	0.2724
cut_rad	72795	0.94	0.2562
cut_rm4l	69071	0.95	0.2431

Counter ll :

Preselection	7466664	1.00	1.0000
cut_lepiso	7180552	0.96	0.9617
cut_z_mass	2501058	0.35	0.3350
cut_z_kine	105240	0.04	0.0141
cut_z_flavour	105069	1.00	0.0141
cut_rad2	43171	0.41	0.0058
cut_rad	830	0.02	0.0001
cut_rm4l	724	0.87	0.0001

$$\mathrm{ZH} \rightarrow \ell\ell X$$

```
cut_lepiso          ((zeds_1_iso_e/zeds_1_e<0.2) && (zeds_2_iso_e/zeds_2_e<0.2) && zeds_1_e>0 && zeds_2_e>0)
cut_z_mass          (abs(zeds_m-91)<10)
cut_z_kine          (zeds_pt>10 && zeds_pz<50 && zeds_acol>100 && zeds_cross>10)
cut_z_flavour       (zeds_1_pdgid==-zeds_2_pdgid)
cut_rad2            (jets_1_e>0 || (jets_1_e<0 && n_particles_not_zed==0))
cut_rad             (((jets_1_e<0 || jets_1_22_e/jets_1_e<0.8) && (jets_2_e<0 || jets_2_22_e/jets_2_e<0.8)))
cut_rm4l            !((second_zeds_1_pdgid==-second_zeds_2_pdgid) && (abs(second_zeds_1_pdgid)==13 ||
abs(second_zeds_1_pdgid)==11))
cut_hbb             (((jets_1_bmatch==1 && rndm<0.8) || (jets_1_bmatch==0 && rndm<0.004))  ||  ((jets_2_bmatch==1 &&
rndm<0.8) || (jets_2_bmatch==0 && rndm<0.004)))
```

Counter WW :

Preselection	107160	1.00	1.0000
cut_lepiso	102566	0.96	0.9571
cut_z_mass	11997	0.12	0.1120
cut_z_kine	6654	0.55	0.0621
cut_z_flavour	6651	1.00	0.0621
cut_rad2	4532	0.68	0.0423
cut_rad	3916	0.86	0.0365
cut_rm4l	3916	1.00	0.0365
cut_hbb	0	0.00	0.0000

Counter ZH :

Preselection	35252	1.00	1.0000
cut_lepiso	31891	0.90	0.9047
cut_z_mass	24418	0.77	0.6927
cut_z_kine	17598	0.72	0.4992
cut_z_flavour	17442	0.99	0.4948
cut_rad2	17347	0.99	0.4921
cut_rad	16813	0.97	0.4769
cut_rm4l	16603	0.99	0.4710
cut_hbb	9761	0.59	0.2769

Counter ZZ :

Preselection	284155	1.00	1.0000
cut_lepiso	266559	0.94	0.9381
cut_z_mass	171636	0.64	0.6040
cut_z_kine	84104	0.49	0.2960
cut_z_flavour	83162	0.99	0.2927
cut_rad2	77406	0.93	0.2724
cut_rad	72795	0.94	0.2562
cut_rm4l	69071	0.95	0.2431
cut_hbb	12031	0.17	0.0423

Counter ll :

Preselection	7466664	1.00	1.0000
cut_lepiso	7180552	0.96	0.9617
cut_z_mass	2501058	0.35	0.3350
cut_z_kine	105240	0.04	0.0141
cut_z_flavour	105069	1.00	0.0141
cut_rad2	43171	0.41	0.0058
cut_rad	830	0.02	0.0001
cut_rm4l	724	0.87	0.0001
cut_hbb	5	0.01	0.0000

$\mathrm{ZH} \rightarrow \ell\ell bb$

```
cut_hbb             (((jets_1_bmatch==1 && rndm<0.8) || (jets_1_bmatch==0 && rndm<0.004))  ||
((jets_2_bmatch==1 && rndm<0.8) || (jets_2_bmatch==0 && rndm<0.004)))
cut_h_pz            (abs(missing_energy_pz)<50.)
cut_h_pt            (missing_energy_pt>10.)
cut_h_acol          (higgses_acol>100.)
cut_h_cross         (higgses_cross>10.)
cut_missmass        (missing_energy_m>80. && missing_energy_m<135.)
cut_ffbar_hpm       (jets_1_211_num>3. && jets_2_211_num>3.)
```

Counter ZH :

Preselection	492622	1.00	1.0000
cut_hbb	307182	0.62	0.6236
cut_h_pz	303506	0.99	0.6161
cut_h_pt	145926	0.48	0.2962
cut_h_acol	145774	1.00	0.2959
cut_h_cross	53462	0.37	0.1085
cut_missmass	36537	0.68	0.0742
cut_ffbar_hpm	34938	0.96	0.0709

Counter ZZ :

Preselection	1964236	1.00	1.0000
cut_hbb	486585	0.25	0.2477
cut_h_pz	432490	0.89	0.2202
cut_h_pt	180279	0.42	0.0918
cut_h_acol	164553	0.91	0.0838
cut_h_cross	50307	0.31	0.0256
cut_missmass	26874	0.53	0.0137
cut_ffbar_hpm	24247	0.90	0.0123

Counter ffbar :

Preselection	4893855	1.00	1.0000
cut_hbb	639762	0.13	0.1307
cut_h_pz	281141	0.44	0.0574
cut_h_pt	78388	0.28	0.0160
cut_h_acol	76920	0.98	0.0157
cut_h_cross	1443	0.02	0.0003
cut_missmass	105	0.07	0.0000
cut_ffbar_hpm	66	0.63	0.0000

$$\mathrm{ZH} \to \nu\nu bb$$

```
cut_lepiso          ((sel_zeds_1_iso_e/sel_zeds_1_e<0.2) && (sel_zeds_2_iso_e/sel_zeds_2_e<0.2) && sel_zeds_1_e>0 && sel_zeds_2_e>0)
cut_z_mass          (abs(sel_zeds_m-91)<15)
cut_z_kine          (sel_zeds_pt>10 && sel_zeds_pz<50 && sel_zeds_acol>100 && sel_zeds_cross>10)
cut_z_flavour       (sel_zeds_1_pdgid==-sel_zeds_2_pdgid)
cut_rad2            (jets_1_e>0 || (jets_1_e<0 && n_particles_not_zed==0))
cut_htautau         (((jets_1_211_num+jets_1_11_num+jets_1_13_num)==1 || (jets_1_211_num+jets_1_11_num+jets_1_13_num)==3) &&
((jets_2_211_num+jets_2_11_num+jets_2_13_num)==1 || (jets_2_211_num+jets_2_11_num+jets_2_13_num)==3))
cut_rm4l            !((second_zeds_1_pdgid==-second_zeds_2_pdgid) && (abs(second_zeds_1_pdgid)==13 || abs(second_zeds_1_pdgid)==11))
cut_w_3body         abs(higgses_r_m - recoil_m)<15
cut_not_hbb         !((((jets_1_bmatch==1 && rndm<0.8) || (jets_1_bmatch==0 && rndm<0.004))  ||  ((jets_2_bmatch==1 && rndm<0.8) ||
(jets_2_bmatch==0 && rndm<0.004))))
```

Counter WW :

Preselection	932	1.00	1.0000
cut_lepiso	469	0.50	0.5032
cut_z_mass	82	0.17	0.0880
cut_z_kine	43	0.52	0.0461
cut_z_flavour	43	1.00	0.0461
cut_rad2	43	1.00	0.0461
cut_htautau	0	0.00	0.0000
cut_rm4l	0	-1.00	0.0000
cut_w_3body	0	-1.00	0.0000
cut_not_hbb	0	-1.00	0.0000

Counter ZH :

Preselection	14324	1.00	1.0000
cut_lepiso	13655	0.95	0.9533
cut_z_mass	11187	0.82	0.7810
cut_z_kine	8020	0.72	0.5599
cut_z_flavour	8020	1.00	0.5599
cut_rad2	8020	1.00	0.5599
cut_htautau	1338	0.17	0.0934
cut_rm4l	1190	0.89	0.0831
cut_w_3body	831	0.70	0.0580
cut_not_hbb	786	0.95	0.0549

Counter ZZ :

Preselection	124189	1.00	1.0000
cut_lepiso	119792	0.96	0.9646
cut_z_mass	82761	0.69	0.6664
cut_z_kine	39444	0.48	0.3176
cut_z_flavour	39444	1.00	0.3176
cut_rad2	39444	1.00	0.3176
cut_htautau	6853	0.17	0.0552
cut_rm4l	3206	0.47	0.0258
cut_w_3body	2347	0.73	0.0189
cut_not_hbb	2275	0.97	0.0183

Counter ll :

Preselection	158573	1.00	1.0000
cut_lepiso	109681	0.69	0.6917
cut_z_mass	49933	0.46	0.3149
cut_z_kine	13660	0.27	0.0861
cut_z_flavour	13660	1.00	0.0861
cut_rad2	13660	1.00	0.0861
cut_htautau	27	0.00	0.0002
cut_rm4l	20	0.74	0.0001
cut_w_3body	2	0.10	0.0000
cut_not_hbb	2	1.00	0.0000

H->WW contamination : 3%

$\mathrm{ZH} \rightarrow \ell\ell\tau\tau$

```
cut_zqq             (zedqq2_r_m>75 && zedqq2_r_m<110)
cut_htautau         (((besttaus_1_211_num+besttaus_1_11_num+besttaus_1_13_num)==1 ||
(besttaus_1_211_num+besttaus_1_11_num+besttaus_1_13_num)==3) &&  ((besttaus_2_211_num+besttaus_2_11_num+besttaus_2_13_num)==1 ||
(besttaus_2_211_num+besttaus_2_11_num+besttaus_2_13_num)==3))
cut_htautau_1prong  (((besttaus_1_211_num+besttaus_1_11_num+besttaus_1_13_num)==1) &&
((besttaus_2_211_num+besttaus_2_11_num+besttaus_2_13_num)==1))
cut_zqq_acol        zedqq2_r_acol>110
cut_zqq_acol_2      zedqq2_acol>110
cut_zqq_2_WW        zedqq2_m>80
cut_zqq_jets        (bestjets_1_m>1.5 && bestjets_2_m>1.5)
cut_zedll_2         (!(besttaus_1_11_num==1 && besttaus_2_11_num==1) && !(besttaus_1_13_num==1 && besttaus_2_13_num==1))
cut_tau_iso         ((besttaus_1_iso_e/besttaus_1_e<0.05) && (besttaus_2_iso_e/besttaus_2_e<0.05))
```

Counter WW :

Preselection	1195237	1.00	1.0000
cut_zqq	193492	0.16	0.1619
cut_htautau	193492	1.00	0.1619
cut_htautau_1prong	48116	0.25	0.0403
cut_zqq_acol	13144	0.27	0.0110
cut_zqq_acol_2	7790	0.59	0.0065
cut_zqq_2_WW	4192	0.54	0.0035
cut_zqq_jets	3675	0.88	0.0031
cut_zedll_2	3673	1.00	0.0031
cut_tau_iso	798	0.22	0.0007

Counter ZH :

Preselection	200048	1.00	1.0000
cut_zqq	33940	0.17	0.1697
cut_htautau	33940	1.00	0.1697
cut_htautau_1prong	16292	0.48	0.0814
cut_zqq_acol	12687	0.78	0.0634
cut_zqq_acol_2	12414	0.98	0.0621
cut_zqq_2_WW	10599	0.85	0.0530
cut_zqq_jets	9562	0.90	0.0478
cut_zedll_2	7773	0.81	0.0389
cut_tau_iso	6271	0.81	0.0313

Counter ZZ :

Preselection	652854	1.00	1.0000
cut_zqq	263254	0.40	0.4032
cut_htautau	263254	1.00	0.4032
cut_htautau_1prong	198568	0.75	0.3042
cut_zqq_acol	74646	0.38	0.1143
cut_zqq_acol_2	73717	0.99	0.1129
cut_zqq_2_WW	62579	0.85	0.0959
cut_zqq_jets	56043	0.90	0.0858
cut_zedll_2	12506	0.22	0.0192
cut_tau_iso	9064	0.72	0.0139

H->WW contamination : 8%
H->bb contamination : 3%

$$\mathrm{ZH} \rightarrow qq\tau\tau$$