Measurements of WW, ZZ cross section and search for anomalous quartic gauge couplings at D0

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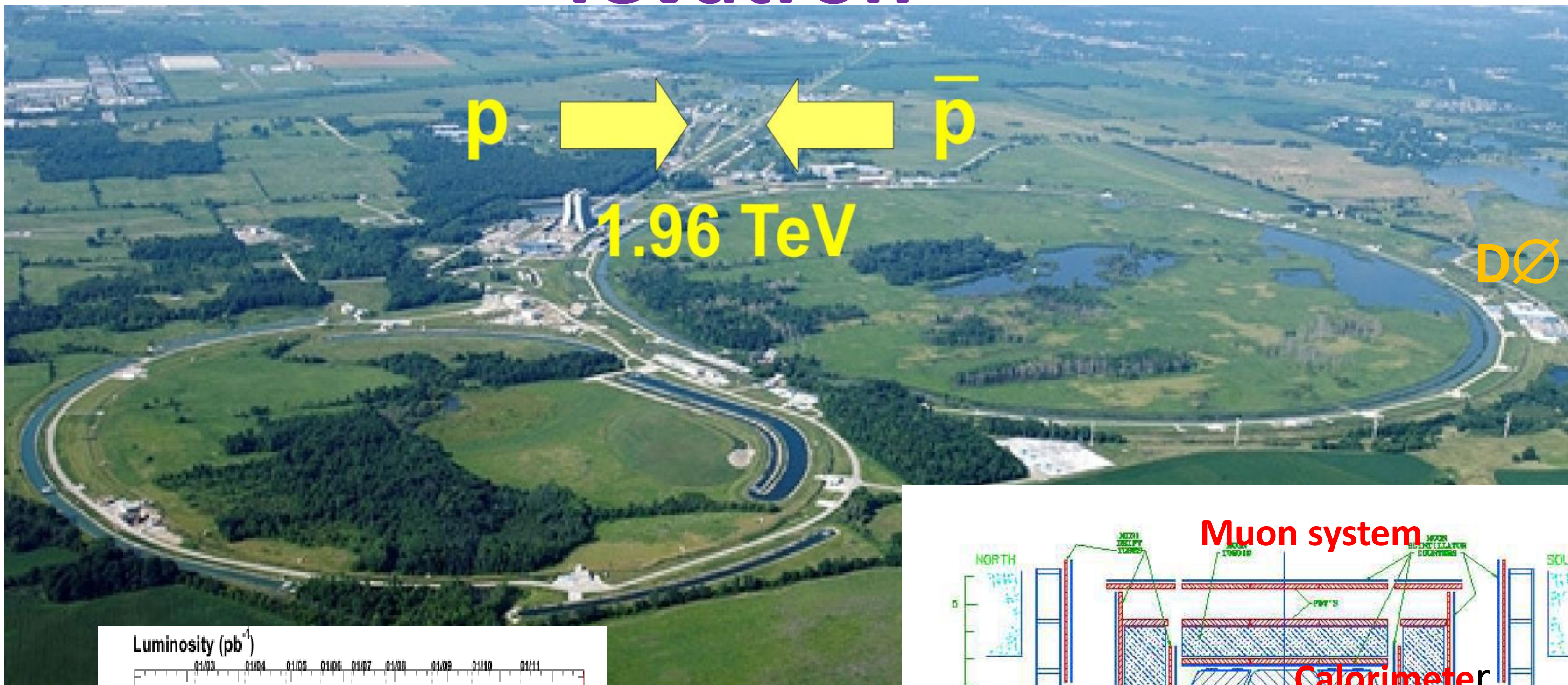
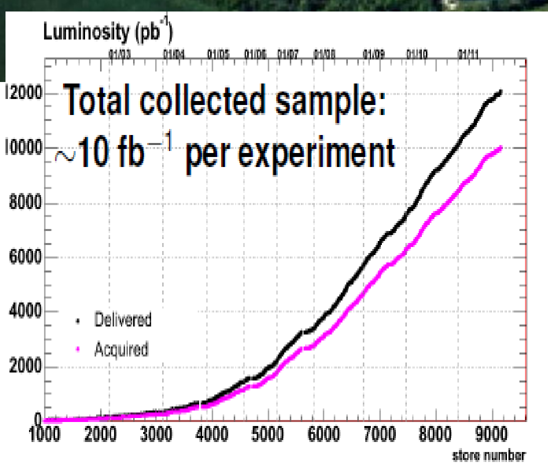
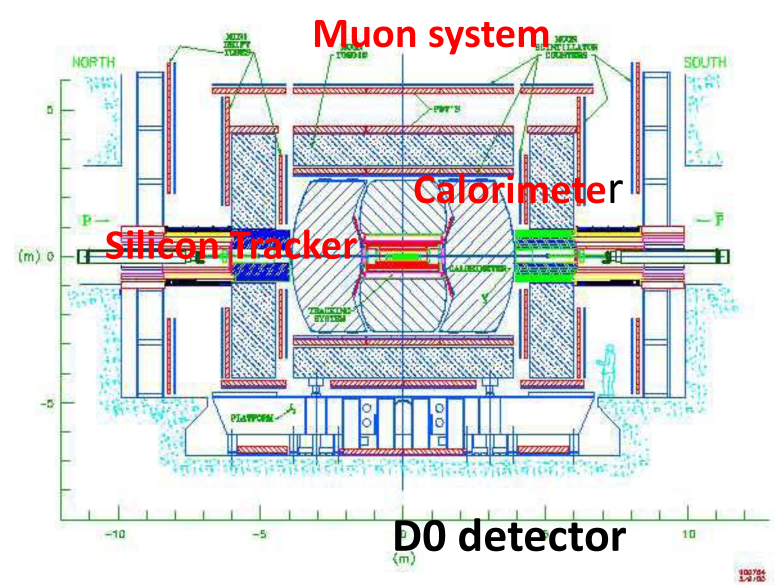
The place where the data was collected

Tevatron



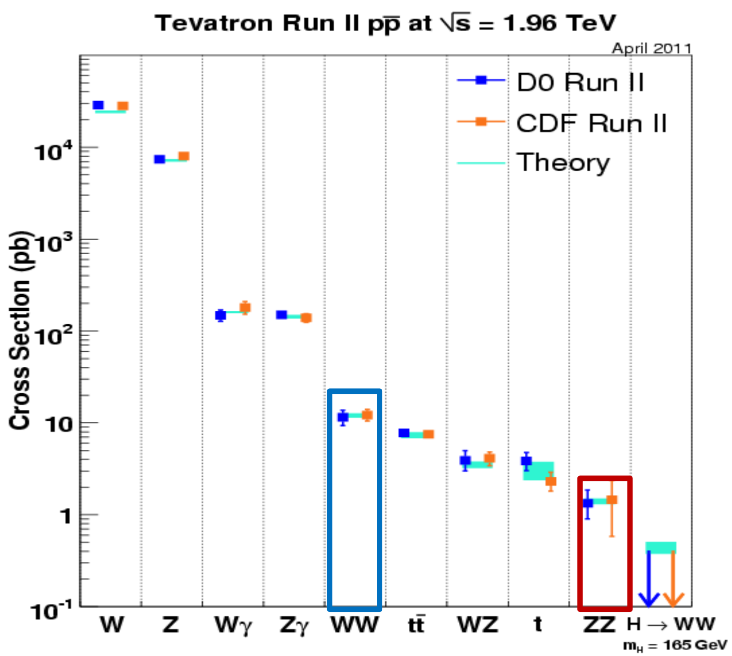




Why WW, ZZ ?

Standard Model (SM) says *W, Z* bosons can be produced in pairs

But less frequently (~10-4) than one *W* or *Z at a time!*

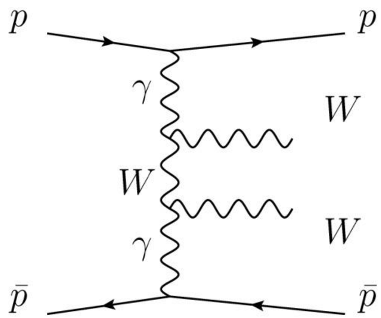


- **Higgs (mH ~ 125 GeV) significant branching fraction to *WW, ZZ's***

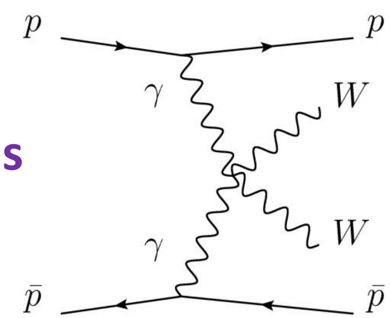
  SM *WW, ZZ* is an important *Higgs* → *WW, ZZ* background

- **Any deviation in the *WW, ZZ* background from SM prediction will mean new physics**

WW production



Two of the many modes



- Probe the existence of trilinear (*VVV*) and quartic (*VVVV*) gauge couplings. ($V=W, Z, \gamma$)
  - A window into electroweak symmetry breaking
  - Signature of new physics
- QED process $p\bar{p} \rightarrow p\bar{p}WW$ can be studied, *W* pair is produced via photon exchange which are directly radiated from p, $\bar{p}$.
- SM : $\sigma(p\bar{p}\rightarrow p\bar{p}WW$ = 3 fb at $\sqrt{s}$ = 1.96 TeV).
- Sensitivity to beyond standard model effects, e.g. anomalous couplings (which can arise from e.g. models with extra dimensions).
- 10-100 times enhancement in cross section with anomalous couplings

- Results are presented here for anomalous quartic gauge couplings (aQGCs)
- It is assumed that triple gauge couplings (TGCs), WWγ are at their SM values (deviations from these values have been constrained by the D0 Collaboration earlier).

Lagrangians

Effective lagrangian for anomalous quartic gauge couplings $WW\gamma\gamma$ (dim-6):

$$L_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} (W^{+\alpha} W_\alpha^-)$$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_\beta^- + W^{-\alpha} W_\beta^+)$$

$F_{\mu\nu}$ is the electromagnetic field strength tensor and $W_\alpha^\pm$ is the $W^\pm$ boson field

Both anomalous parameters a_0^W and a_C^W are 0 in the SM.

To prevent violation of unitarity at high energies, introduce a form factor:

$$a_0^W / \Lambda^2 \rightarrow \frac{a_0^w / \Lambda^2}{(1 + W_{\gamma\gamma} / \Lambda)^2}$$

, Λ is the scale of new physics

Typical values ~ 0.5 TeV, 1 TeV[a]

[a]e.g. Eboli et al., Phys. Rev. D 63, 075008 (2001)

How can we find the aQGC signal ?

- **Signal:** $p\bar{p} \rightarrow p\bar{p}WW$

  (Scan one of a_0^W or a_C^W with or without form factor)

- **Backgrounds:**
  - **Diffractive:**

    ***WW* and *ll* production through photon exchange or double pomeron exchange.**

    a_c^w

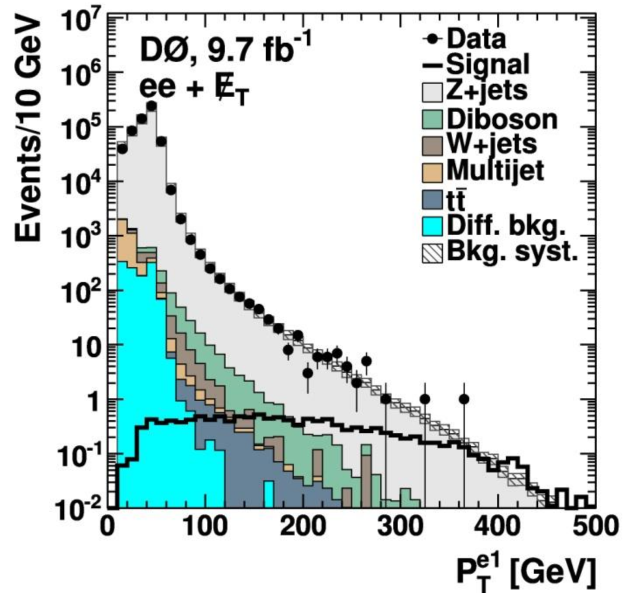
    Signal and diffractive backgrounds are modeled using Forward Physics Monte-Carlo (FPMC) + GEANT3 based detector simulation + D0 reconstruction.

  - **Non-Diffractive backgrounds**
    - **Physics backgrounds: *Z/γ* + jets, $t\bar{t}$, diboson (*WW, WZ, ZZ*)**
    - **Instrumental backgrounds: W+jets, multijets**

    modeled using PYTHIA or ALPGEN+PYTHIA,
    Multijet background is fully determined from data

Features of aQGC

- $p\bar{p} \rightarrow WW$ cross section is measured in the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ analysis
  - This QGC search the same final state ($l\nu l\nu$)[1]
  - Same method as the Higgs search
    - Only the "eνeν" channel is used in this analysis
    - Search for aQGC signal instead of a Higgs signal



Signal features:

The initial and final protons remain intact, but are very forward and are not detected.

Two leptons that are central and very boosted.

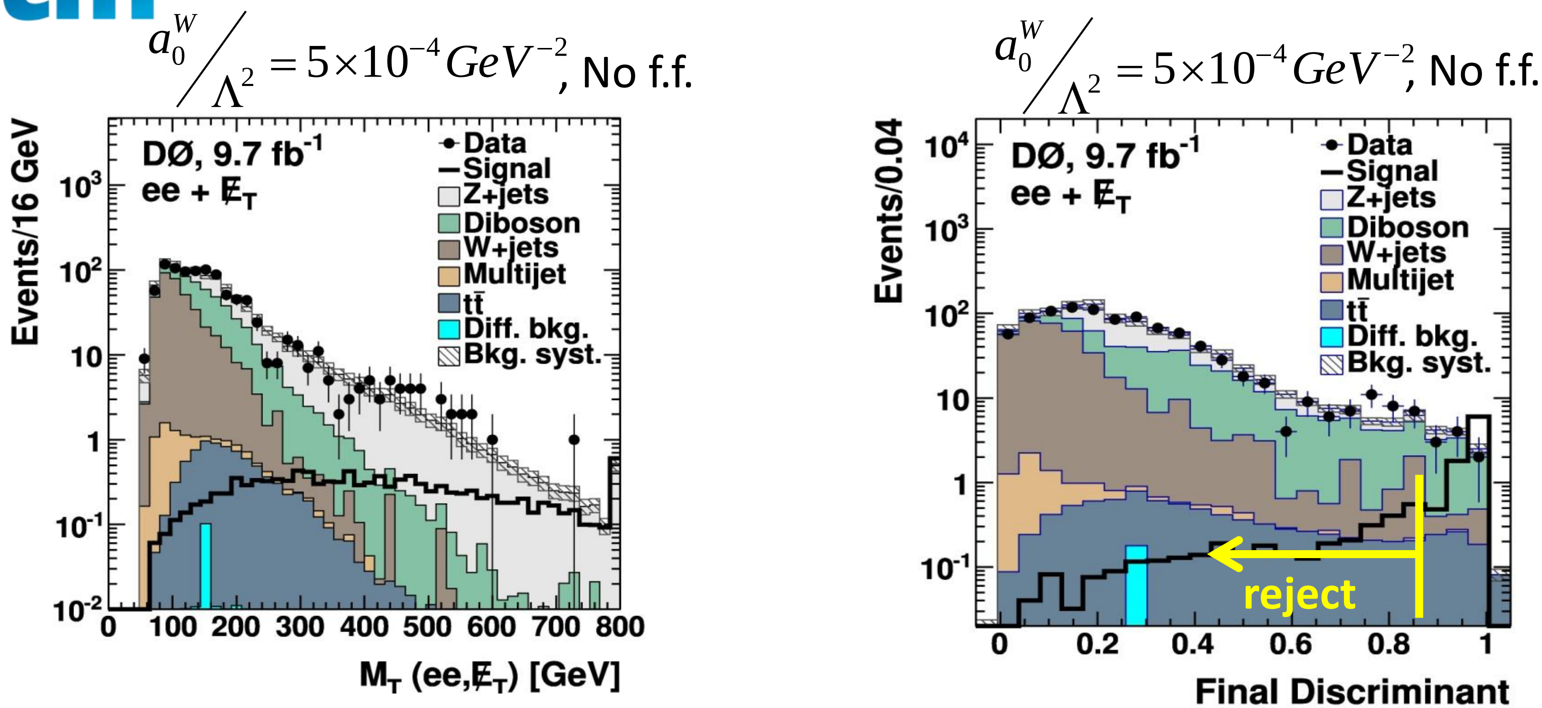
Preselection:

- Two opposite sign electrons, no jet (with $p_T > 20$ GeV, $|\eta|<2.4$).
- $p^1_T > 15$ GeV, $p^2_T > 10$ GeV.
- $M_{ee} > 15$ GeV.
- At least one electron in the CC.

(Plots: $a_0^W/\Lambda^2 = 5 \cdot 10^{-4}$ GeV^{-2})

[1]arXiv:1301.1243 [hep-ex] (2013), to be published in Phys. Rev. D.

aQGC event selection



• A BDT is trained to reject the Z/γ* background.

(All signal points are merged in the training (kinematics are actually close from one point to the other because of the large anomalous couplings considered in all cases).

•A final discriminant is trained against all SM backgrounds.

All signal points are merged together for training.

Signal, Background yields

	Preselection	Final selection
Data	572700	946
Total background	576576 ± 11532	983 ± 108
Signal (a_0^W/Λ^2 = 5 x 10^{-4} GeV^{-2} , no f.f.)	12.2	11.6
$Z/\gamma^* \rightarrow ee$	566800	291
$Z/\gamma^* \rightarrow \tau\tau$	4726	22
$t\bar{t}$	15	8
W+jets	623	370
Diboson	517	287
Multijet	2716	5.4
Diffractive modes	1180	0.2

Systematic Uncertainty

Two classes of systematic uncertainties:

- Flat: affect only normalization of signal and / or background (e.g. theory cross-section error).
- Shape: affect the shape as well as normalization for signal and / or background (e.g. jet energy scale).

Source	Uncertainty (%)
Z/γ* + jets cross section	6
W+jets cross section	16
Diboson cross section	6
tt cross section	7
Multijet normalization	30
Signal cross section	20
Jet energy scale	4
Jet resolution	0.5
Jet identification	2
Jet primary vertex association	2
W+jets modeling	10
WW modeling	< 1
W, Z, p_T modeling	< 1
E_T modelling	4
Pomeron exchange+DPE norm.	100

aQGC 1-D limits

Cutoff	Expected allowed range [GeV^{-2}]	Observed allowed range [GeV^{-2}]
No form-factor	[-0.00047, 0.00043]	[-0.00046, 0.00043]
= 500 GeV	[-0.0024, 0.0025]	[-0.0024, 0.0025]
= 1000 GeV	[-0.00096, 0.00092]	[-0.00097, 0.00089]

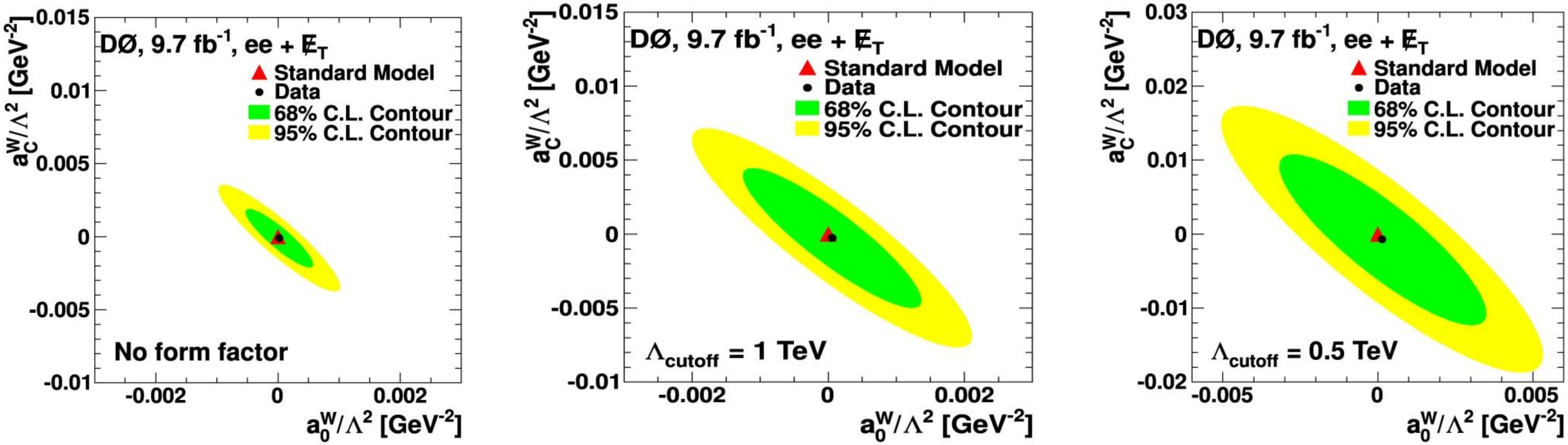
Table: Expected and observed 95% C.L allowed ranges on a_0^W= 2, assuming a_C^W is zero and for different assumptions on the form-factor.

Cutoff	Expected allowed range [GeV^{-2}]	Observed allowed range [GeV^{-2}]
No form-factor	[-0.0016, 0.0016]	[-0.0016, 0.0015]
= 500 GeV	[-0.0092, 0.0090]	[-0.0094, 0.0092]
= 1000 GeV	[-0.0035, 0.0033]	[-0.0035, 0.0033]

Table: Expected and observed 95% C.L allowed ranges on a_C^W =2, assuming a_0^W is zero and for different assumptions on the form-factor.

Constrain New Physics in the EW sector

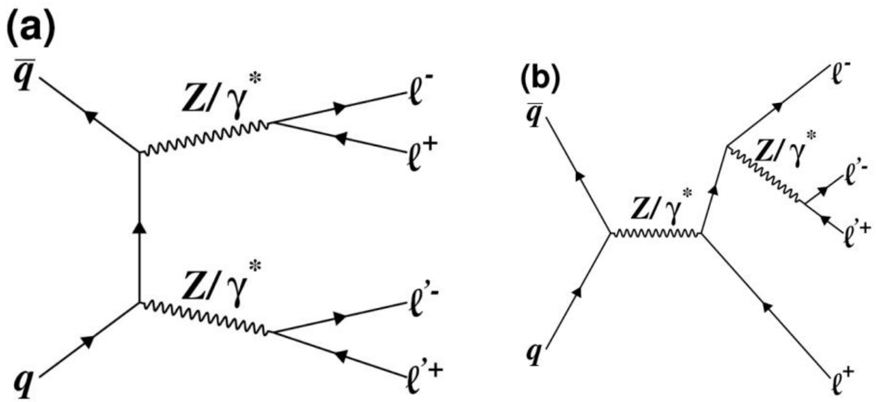
2-D couplings



Limits on single parameters have been converted to simultaneous limits on two parameters using a grid of theoretical predictions for different anomalous parameters.

ZZ search

production and decay



(small contribution)

Focus on the leptonic decays (electrons, muons, taus)

- **Very clean signature**
- **Measurement with the full data set**

(slightly tighter data quality for muons)

Use the whole D0 dataset

$\int \mathscr{L}\, dt = 9.6 - 9.8\ \text{fb}^{-1}$

↑ $ee\mu\mu$, $\mu\mu\mu\mu$ ↑ $eeee$

Event Selection:

- Require M(ll) > 30 GeV for both Z's
  - In $2e2\mu$, use M($\mu\mu$) and M(ee)
  - In 4μ & $4e$ at least one pair of leptons has to pass the cut
  - In 4μ only opposite charged pairs are selected
- In $4e$, need at least two electrons in the central calorimeter
- In 4μ, need at least two muons with hits in the muon chambers
- In $2e2\mu$, dR(eμ) > 0.2 for all e-μ pairs

Signal and Background samples

- **The *ZZ* signal acceptance is estimated with PYTHIA**
- **Three main sources of background**
  - Instrumental – Vector boson events with additional photon or jets misreconstructed as leptons – mostly *Z* + 2 jet events.
  - Migration – $Z/\gamma^* \; Z/\gamma^*$ where at least one Z/γ^* has a mass < 30 GeV but is reconstructed with a mass above 30 GeV.
  - $t\bar{t}$, where the leptons in the b-jets pass the isolation cut

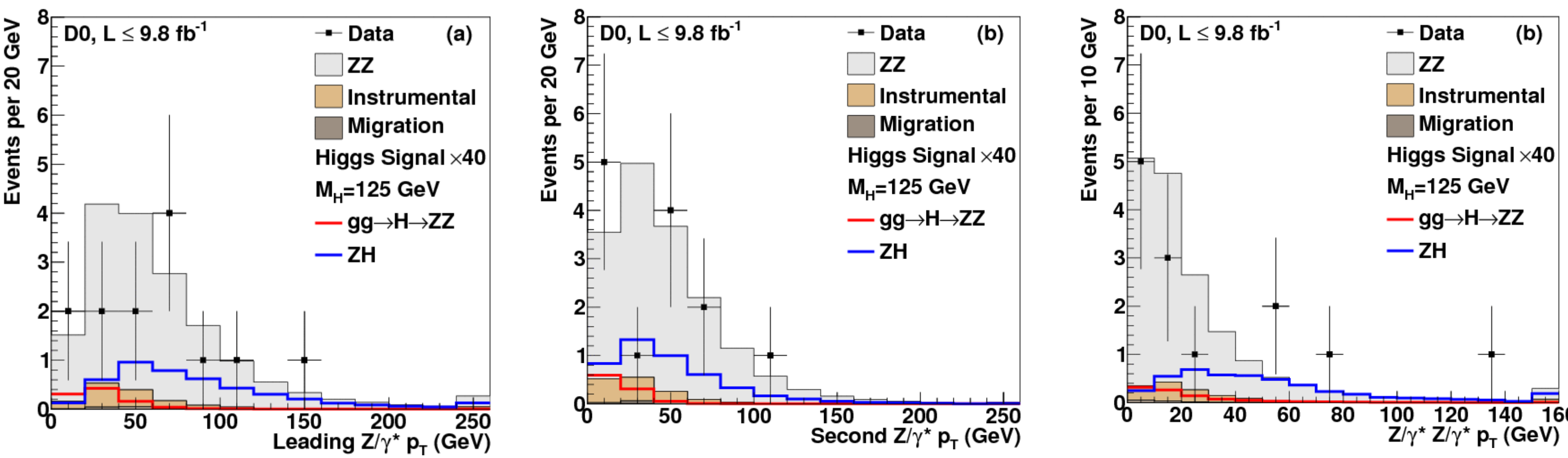
Migration and $t\bar{t}$ are estimated by simulation

Systematic uncertainties:

- 3.7% per CC and EC electron (estimated from Z data) 6% per ICR electron
- 3.2% per muon (estimated from Z data)
- 10%-50% on the instrumental backgrounds (observed variations in the jet-to-lepton rates)
- ~8% uncertainty on the ZZ cross sections used to estimate signal and migration yields
- Luminosity: 6.1%
- PYTHIA system *pT* correction (derived from SHERPA):
  1%-7% for signal, 40% for migration background

Data Analysis

- We divide the analysis into 8 subchannels, four in 4*e*, three in 2*e*2μ *and* 4μ, based on the number of electrons in the central, endcap, and inter-cryostat regions



Process	Candidate events
ZZ	15.3 ± 1.9
Z(γ)+jets	$1.5^{+0.2}_{-0.3}$
Total Expected	16.8 ± 1.9
Data	13

Cross section of $ZZ \rightarrow 4\,l$ events

- **Cross section is obtained by minimizing the –ve log-likelihood**

$$-\ln(L) = \sum_i \sigma \times \mathrm{BR}_i \times \alpha_i \times \epsilon_i \times \int \mathcal{L} \cdot dt + N_i^{bkg} - N_i \ln\left(\sigma \times \mathrm{BR}_i \times \alpha_i \times \epsilon_i \times \int \mathcal{L} \cdot dt\right)$$

- **Include systematics by varying acceptance and backgrounds by $\pm$ 1 s.d. and adding in quadrature**

$$\sigma(p\bar{p} \rightarrow Z/\gamma^* Z/\gamma^*) = 1.26^{+0.44}_{-0.36}(stat.)^{+0.17}_{-0.15}(syst.) \pm 0.08(lumi)$$

Compare to 1.7 $\pm$ 0.1 pb (NLO theory)

(Remove γ^* contribution using MCFM scale factor to get pure *ZZ*

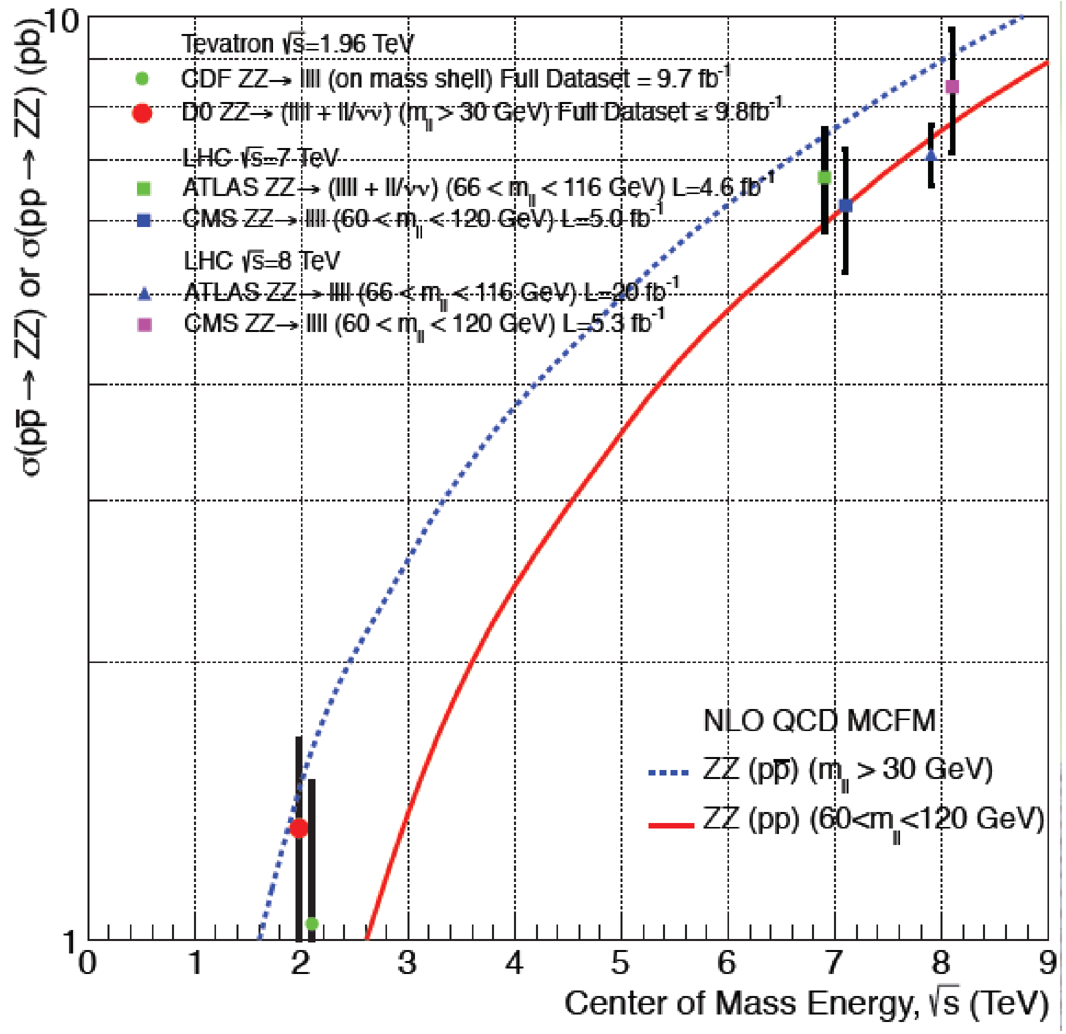
$$\sigma(p\bar{p} \rightarrow Z/\gamma^* Z/\gamma^*) = 1.05^{+0.37}_{-0.30}(stat.)^{+0.14}_{-0.12}(syst.) \pm 0.06(lumi)$$

- **With a combination with the $ZZ \rightarrow ll\ \nu\nu$ cross section measurement,**

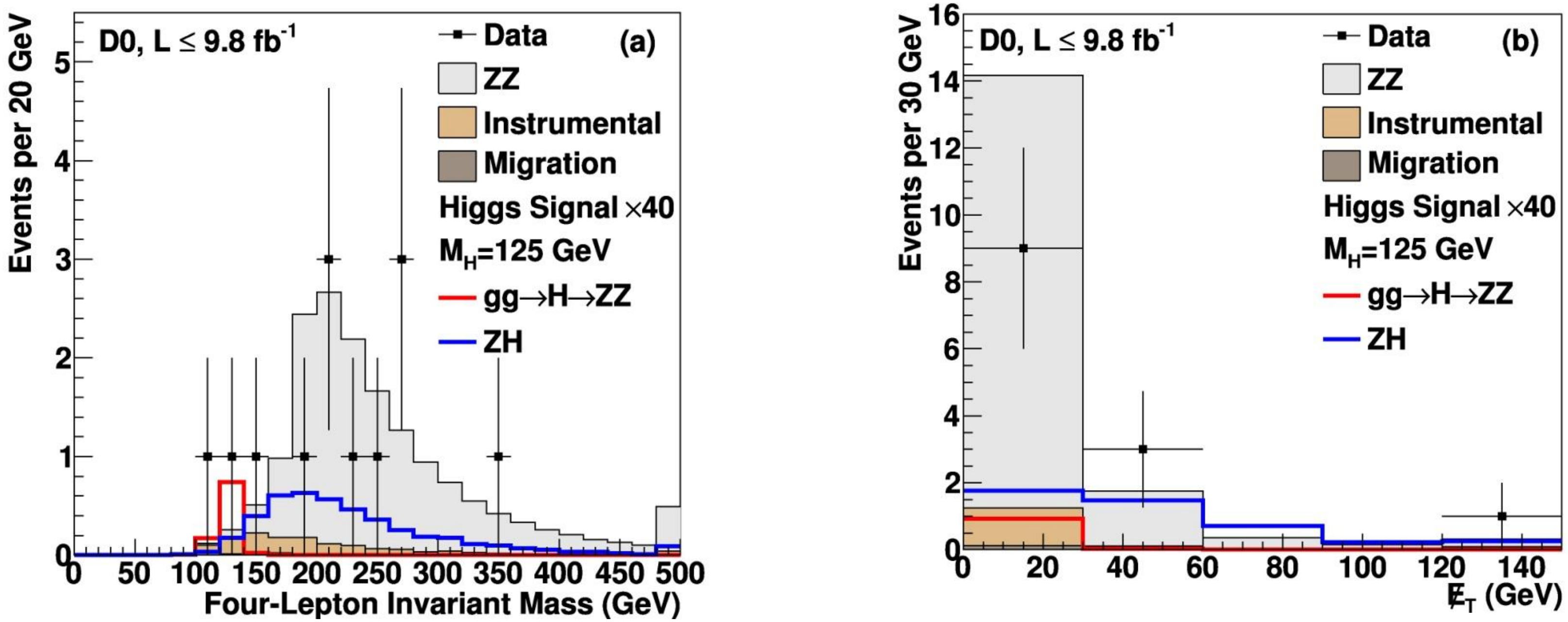
$$\sigma(p\bar{p} \rightarrow Z/\gamma^* Z/\gamma^*) = 1.32^{+0.29}_{-0.25}(stat.) \pm 0.12(syst.) \pm 0.04(lumi)$$

This value is in agreement with S.M. value of 1.4 $\pm$ 0.1 pb (NLO)

New D0 Measurement



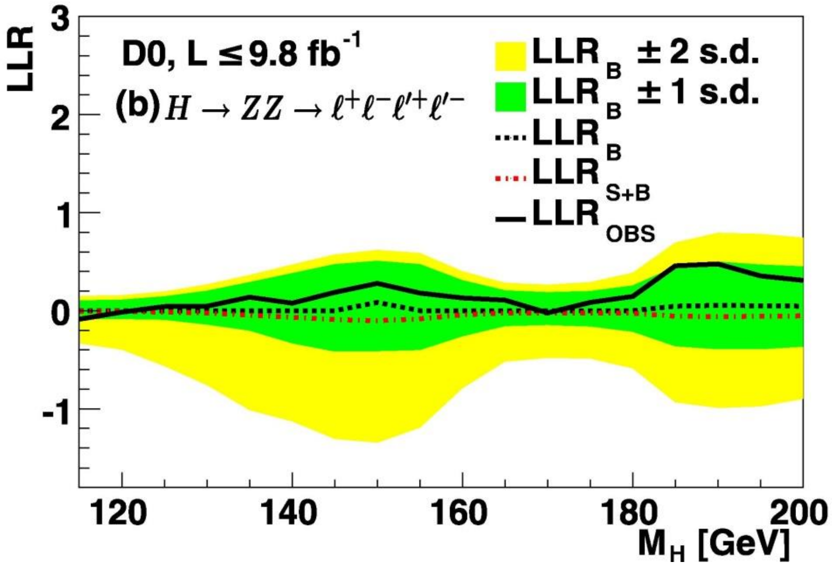
Use ZZ measurement to search for Higgs



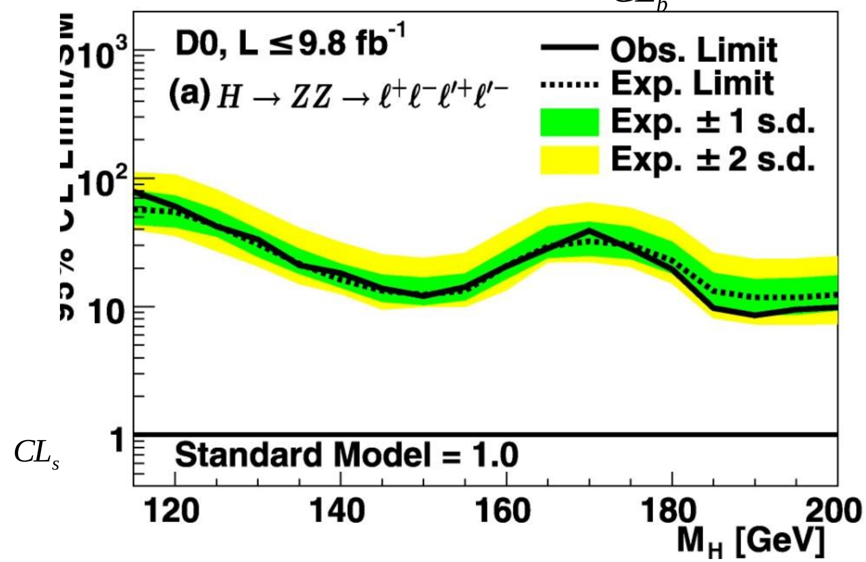
- A new particle (Higgs ?) has been discovered by the ATLAS and CMS experiments at 125 GeV in $H \to ZZ$ and $H \to \gamma\gamma$ decay modes.
- The D0 *ZZ* cross section measurement can be used to search for the Higgs boson
- For events with small $\not{E}_T$ (< 30 GeV) use the 4-lepton mass as discriminant
Else use $\not{E}_T$

Extension to Higgs boson search

Construct Log-Likelihood ratio LLR



95% Exclusion contours when $\frac{CL_{s+b}}{CL_b} = CL_s \leq$ **0.05**



- **At 125 GeV, 0.14 Higgs boson events are expected**
- **Set limits using modified frequentist approach**
  - ❖Log-likelihood ratio test statistic

- **At 125 GeV, find an observed (expected) limit of 42.3 × SM (42.8 x SM)**

M_H (GeV)	Expected	Observed
115	57.3	78.9
120	54.9	60.6
125	42.8	42.3

Conclusions

Using the entire dataset collected by D0

- **Place new constraints on anomalous $WW\gamma\gamma$ quartic gauge boson couplings**

  4 to 8 times more stringent than the current best limits

$$\left| a_0^W / \Lambda^2 \right| < 0.0025 \text{ GeV}^{-2} \qquad a_C^W / \Lambda^2 = 0, \ \Lambda = 0.5 \text{ TeV}$$

$$\left| a_C^W / \Lambda^2 \right| < 0.0092 \text{ GeV}^{-2} \qquad a_0^W / \Lambda^2 = 0, \ \Lambda = 0.5 \text{ TeV}$$

1305.1258 [hep-ex] (submitted to Phys. Rev. D { Rapid Communications)

- **Improved measurement of the cross section**

$$\sigma(p\bar{p} \to Z/\gamma^* Z/\gamma^*) = 1.26^{+0.44}_{-0.36}(stat.)^{+0.17}_{-0.15}(syst.) \pm 0.08(lumi)$$

Backup

Measurements available :

Current best published limits: OPAL

$-0{:}020 < a^W_0 / \Lambda^2 < 0{:}020 \mathrm{GeV}^{-2}$
$-0{:}052 < a^W_0 / \Lambda^2 < 0{:}037 \mathrm{GeV}^{-2}$
OPAL Collaboration, Phys. Rev. D 70, 032005 (2004) [arXiv:hep-ex/0402021].

Current best limits: CMS Preliminary

Without form-factor:
$-2{:}8 \times 10^{-6} < a^W_0 / \Lambda^2 < 2{:}8 \times 10^{-6} \mathrm{GeV}^{-2}$
$-1{:}02 \times 10^{-5} < a^W_0 / \Lambda^2 < 1{:}02 \times 10^{-5} \mathrm{GeV}^{-2}$

With a form-factor with Λ = 500 GeV:
$-0{:}00017 < a^W_0 / \Lambda^2 < 0{:}00017 \mathrm{GeV}^{-2}$
$-0{:}0006 < a^W_0 / \Lambda^2 < 0{:}0006 \mathrm{GeV}^{-2}$
(CMS-PAS-FSQ-12-010)

Diffractive background

QED (photon exchange) $pp \to pp\, e^+e^-$	529
QED (photon exchange) $pp \to pp+\tau^+\tau^-$	6
QED (photon exchange) $pp \to ppW^+W^-$	0.2
QCD (pomeron exchange) $pp \to ppe^+e^-$	2564
QCD (pomeron exchange) $pp \to ppW^+W^-$	0.2

Table: Cross-section of the different processes considered, after requiring two electrons or muons with $p_T > 5$ GeV in the final state.

Cross-check

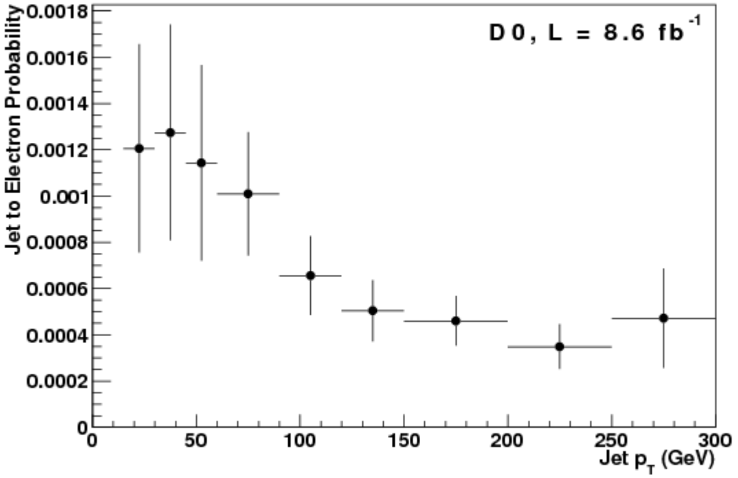
CDF quotes $\sigma_{e+e-;exclusive}(|\eta(e)| < 1; E_T(e) > 2:5\ \text{GeV}) = 3:25 \pm 0:07$ pb[a],

FPMC quotes 3:33 0:09 pb: consistent.

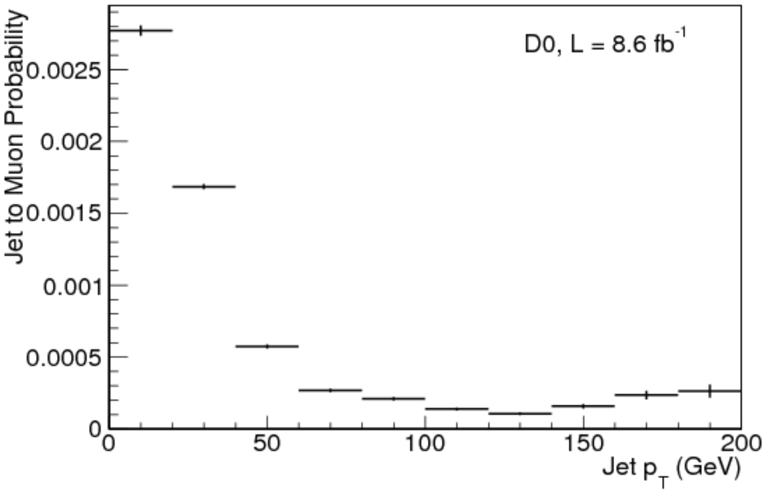
[a]T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 108, 081801 (2012) [arXiv:1112.0858]

Estimation of Instrumental background

Estimate jet → lepton misreconstruction
probability.
(use events triggered by a high pT jet).



Apply rates to 2l + ≥ 2jets events or
To 3l + ≥ 1 jet events.



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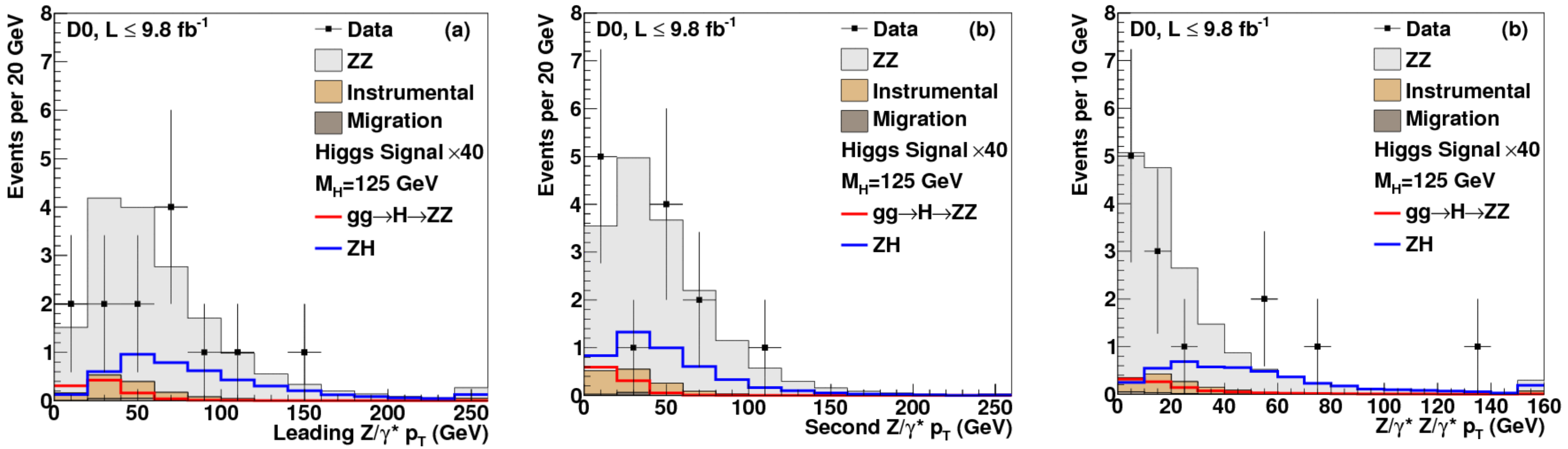

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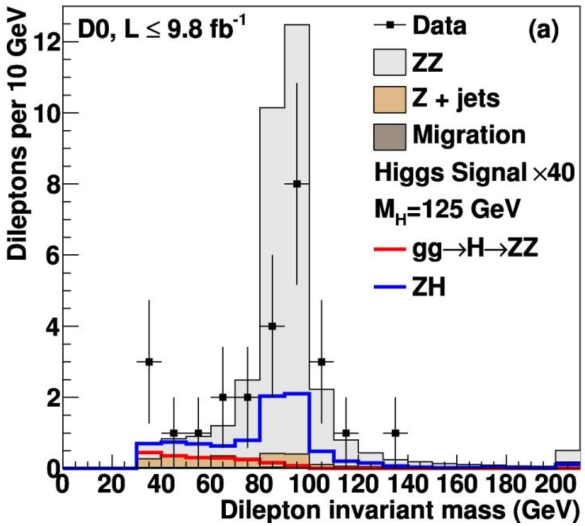
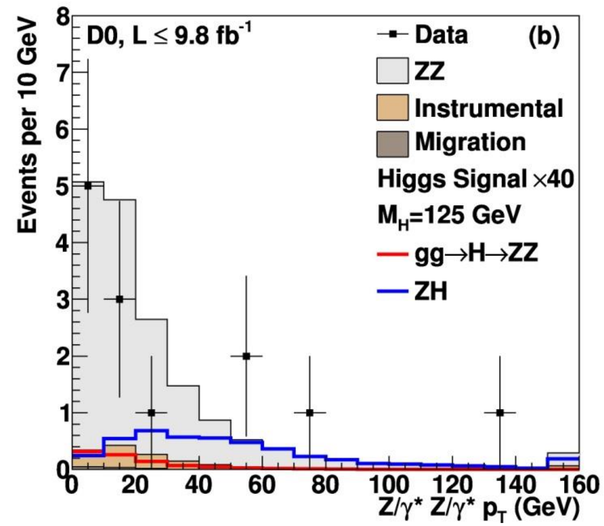
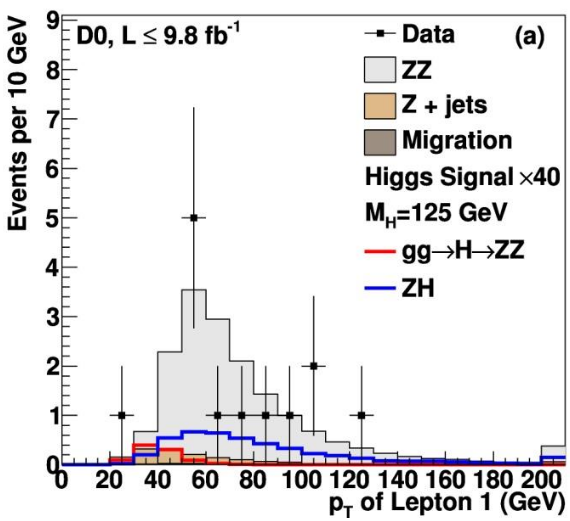
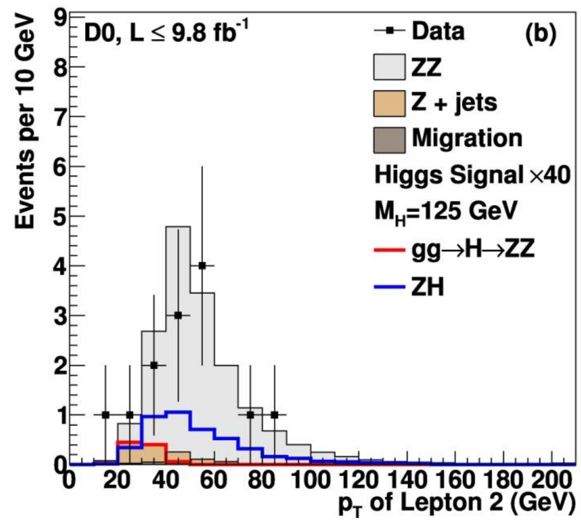
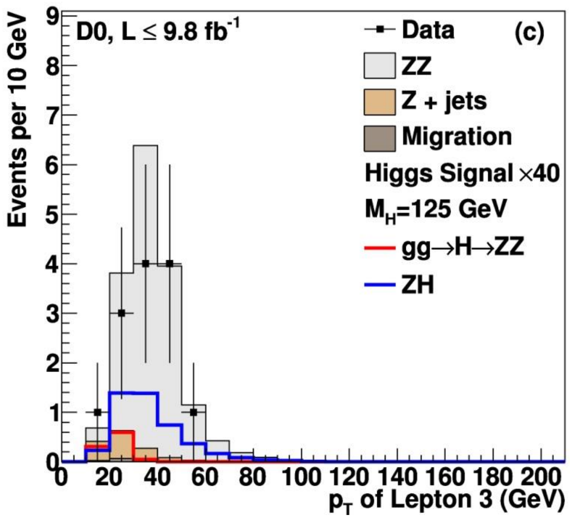
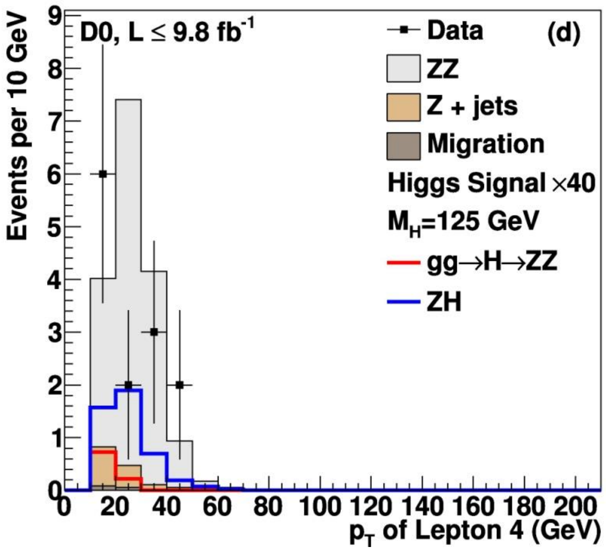

D0, L ≤ 9.8 fb^{-1}
(a)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Dileptons per 10 GeV
Dilepton invariant mass (GeV)

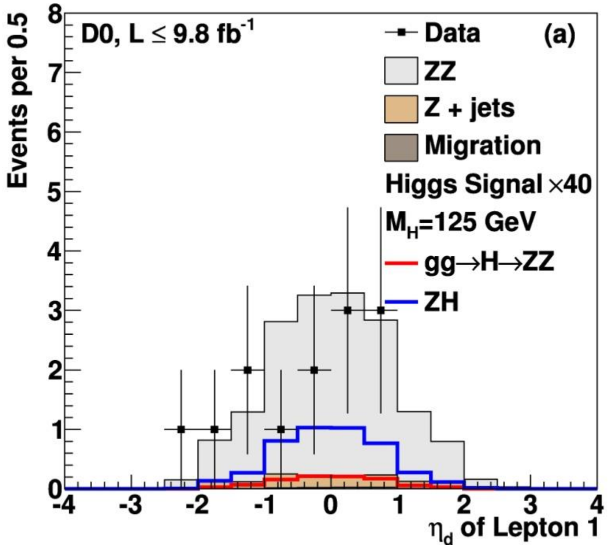

D0, L ≤ 9.8 fb^{-1}
(b)
Data
ZZ
Instrumental
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 10 GeV
Z/γ* Z/γ* p_T (GeV)

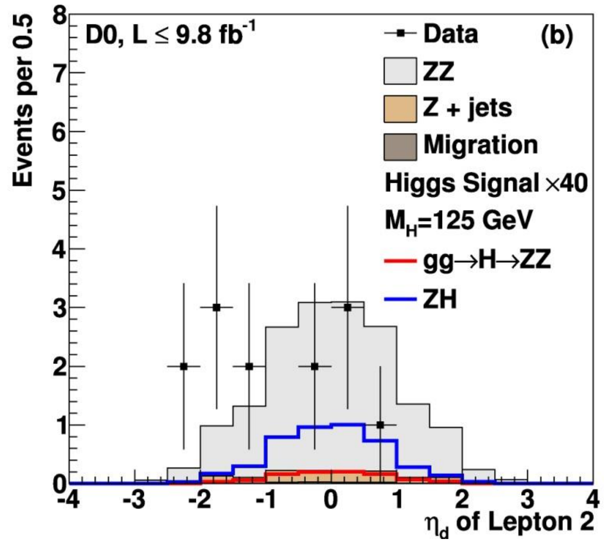

D0, L ≤ 9.8 fb^{-1}
(a)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 10 GeV
p_T of Lepton 1 (GeV)

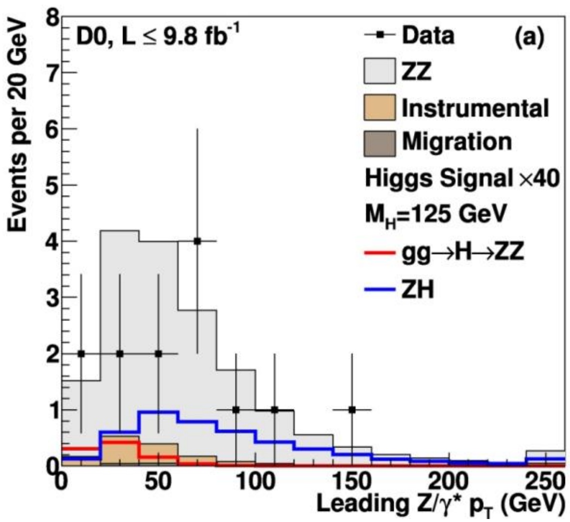

D0, L ≤ 9.8 fb^{-1}
(b)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 10 GeV
p_T of Lepton 2 (GeV)

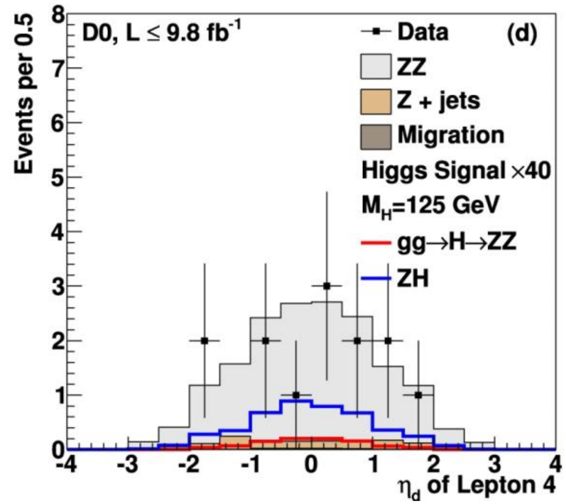

D0, L ≤ 9.8 fb^{-1}
(c)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 10 GeV
p_T of Lepton 3 (GeV)

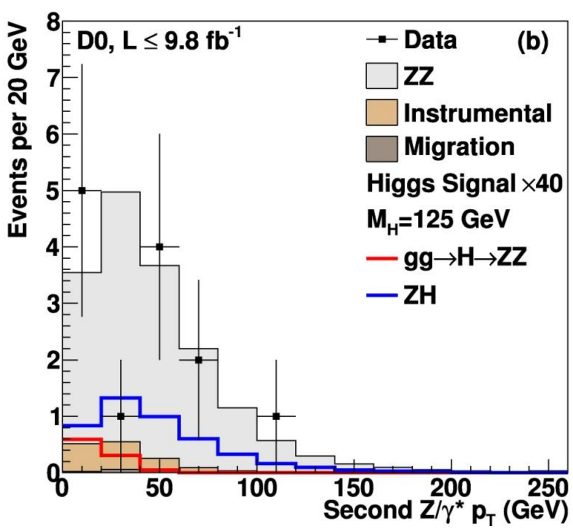

D0, L ≤ 9.8 fb^{-1}
(d)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 10 GeV
p_T of Lepton 4 (GeV)

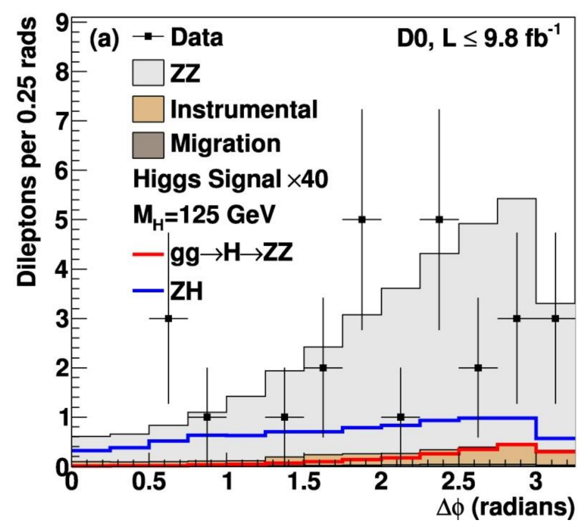

D0, L ≤ 9.8 fb^{-1}
(a)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 0.5
η_d of Lepton 1

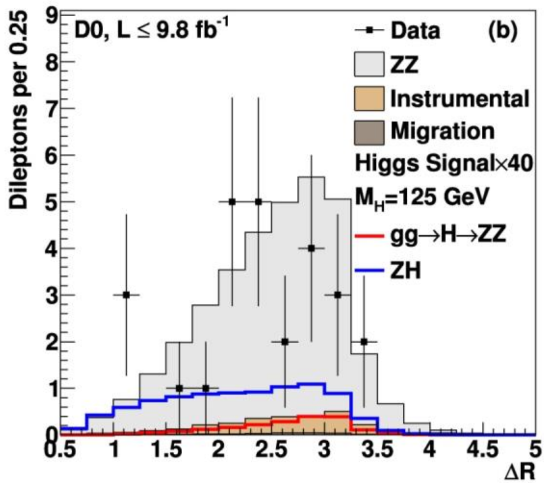

D0, L ≤ 9.8 fb^{-1}
(b)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 0.5
η_d of Lepton 2

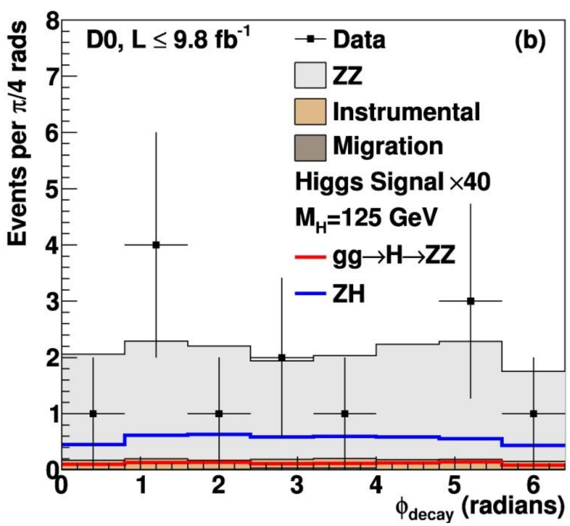

D0, L ≤ 9.8 fb^{-1}
(a)
Data
ZZ
Instrumental
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 20 GeV
Leading Z/γ* p_T (GeV)

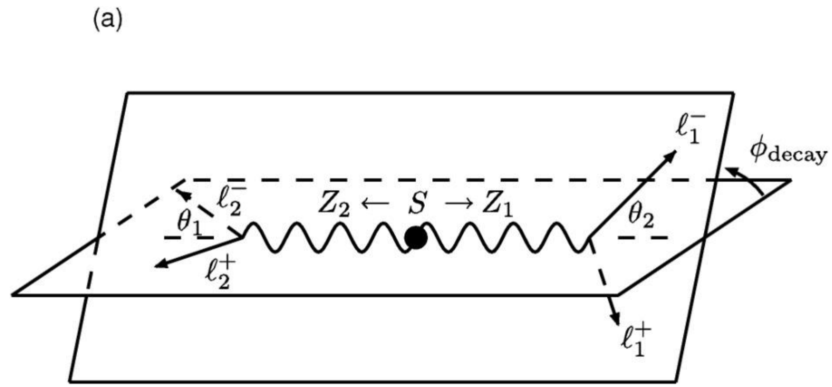

D0, L ≤ 9.8 fb^{-1}
(d)
Data
ZZ
Z + jets
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 0.5
η_d of Lepton 4


D0, L ≤ 9.8 fb^{-1}
(b)
Data
ZZ
Instrumental
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per 20 GeV
Second Z/γ* p_T (GeV)

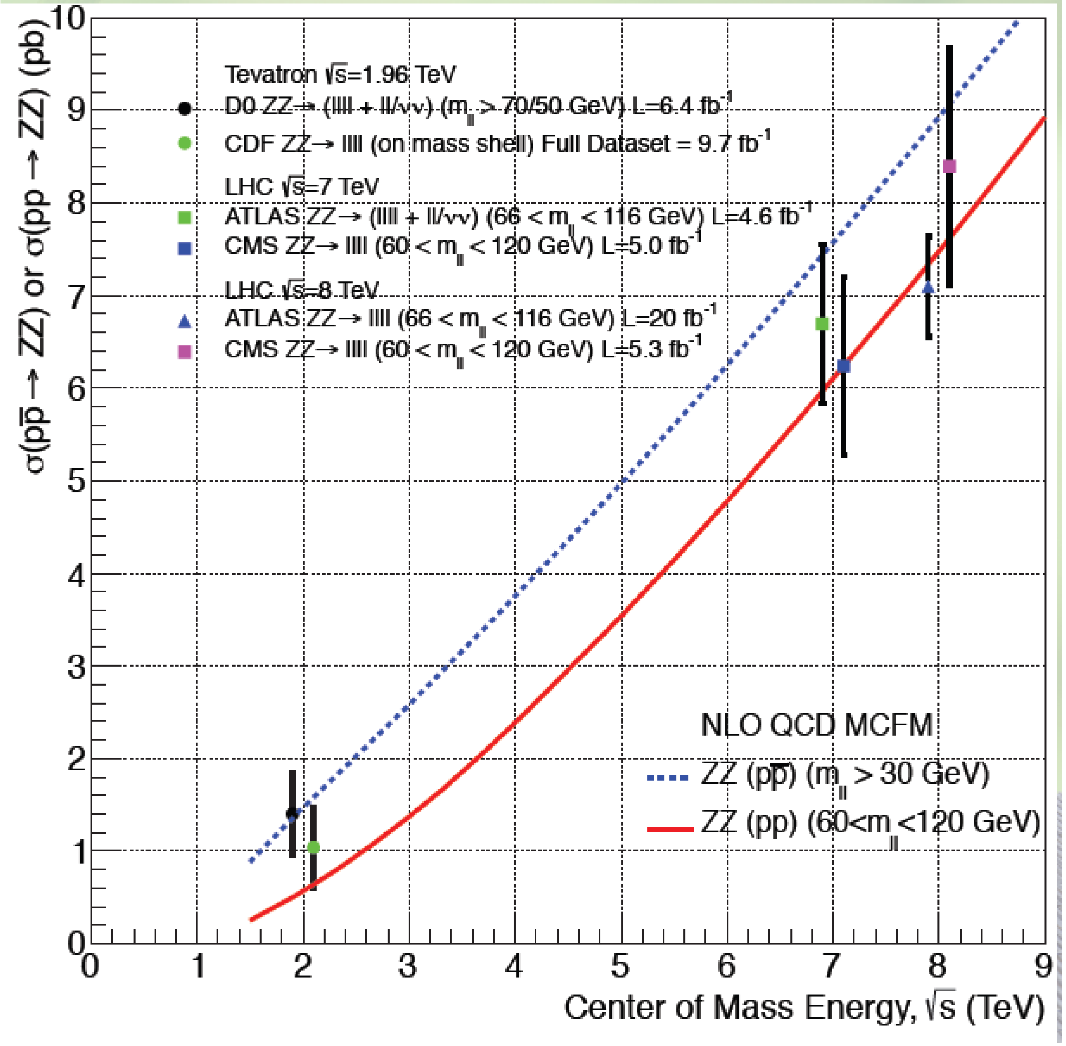

(a)
Data
D0, L ≤ 9.8 fb^{-1}
ZZ
Instrumental
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Dileptons per 0.25 rads
Δφ (radians)


D0, L ≤ 9.8 fb^{-1}
(b)
Data
ZZ
Instrumental
Migration
Higgs Signal×40
M_H=125 GeV
gg→H→ZZ
ZH
Dileptons per 0.25
ΔR

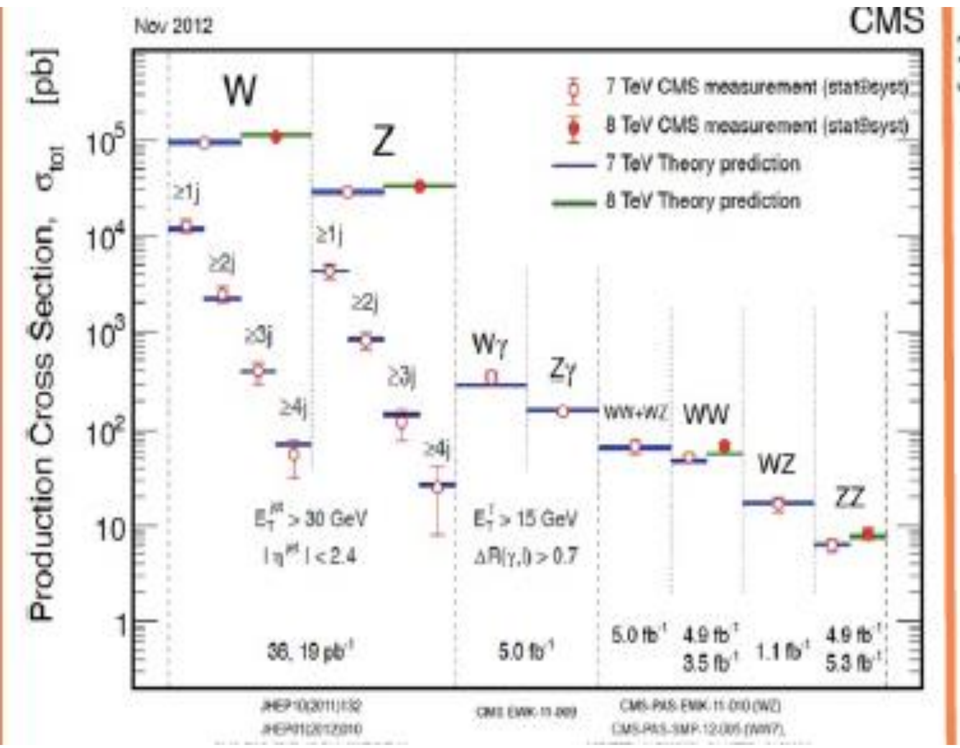

D0, L ≤ 9.8 fb^{-1}
(b)
Data
ZZ
Instrumental
Migration
Higgs Signal ×40
M_H=125 GeV
gg→H→ZZ
ZH
Events per π/4 rads
ϕ_{decay} (radians)

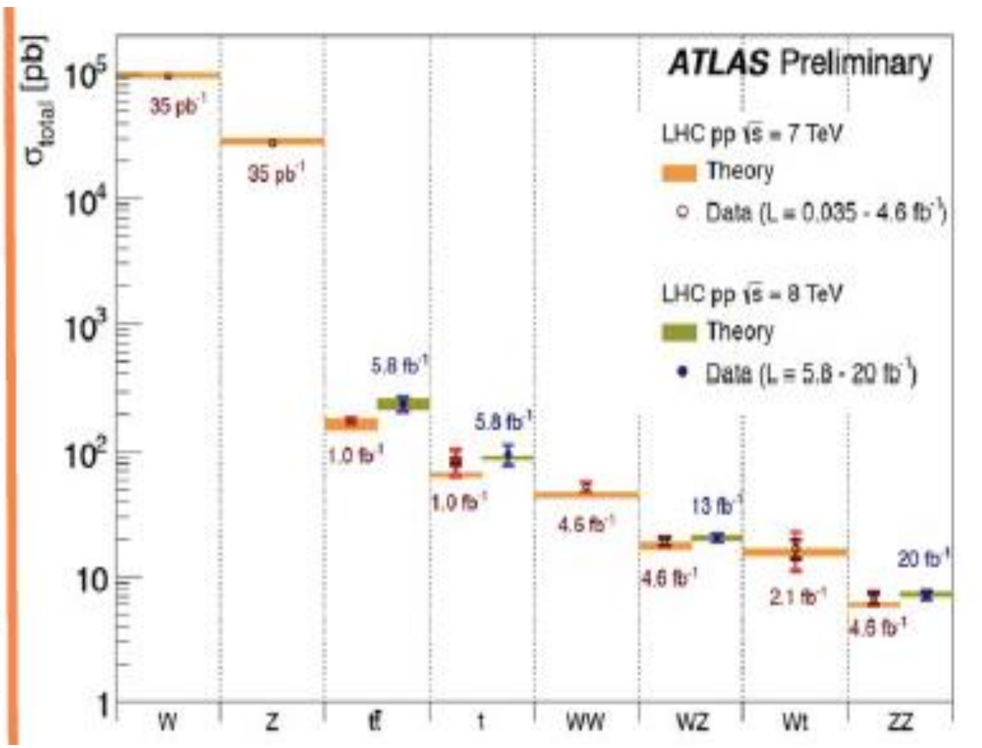

(a)
ℓ_1^-
$\phi_{\rm decay}$
ℓ_2^-
$Z_2 \leftarrow S \rightarrow Z_1$
θ_1
θ_2
ℓ_2^+
ℓ_1^+

Current Status



WW, ZZ cross sections, ATLAS, CMS





Heavy di-boson decays