Physics Program

of the experiments at

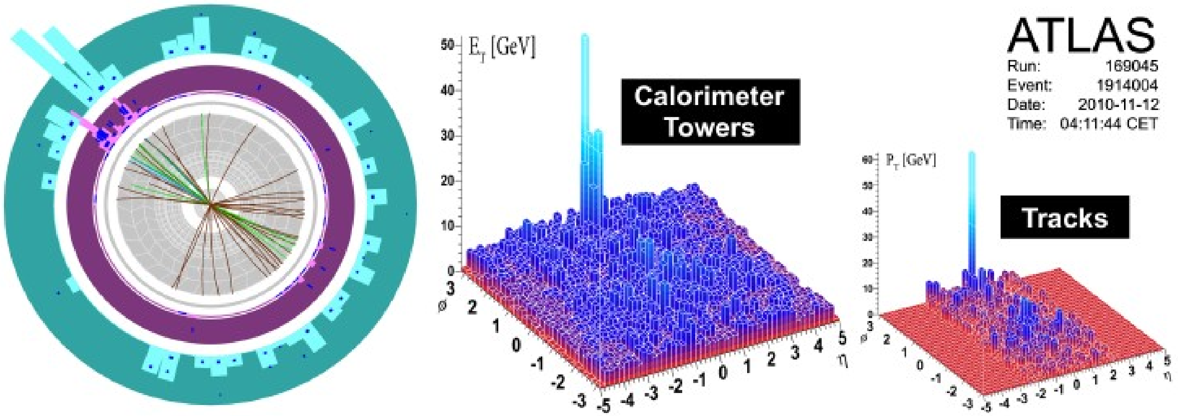
Large Hadron Collider

Lecture 9

- **Bosons properties**
- **Photons**
- **Di-bosons and anomalous couplings**

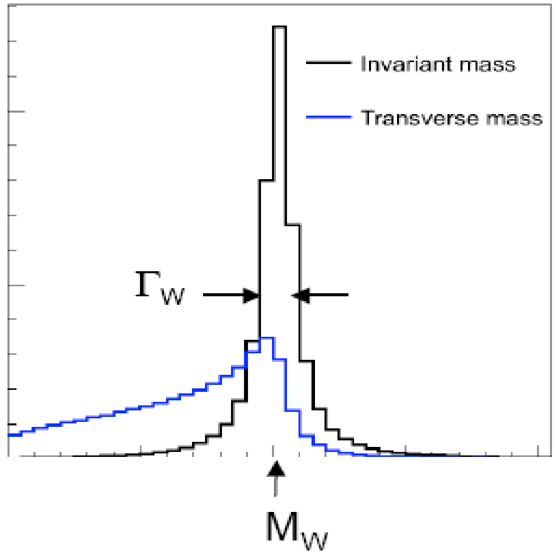
Latest news!!!

- ATLAS experiment published first observation of centrality dependent dijet asymmetry in the collisions of lead ions. **CERN-PH-EP-2010-062**
- This effect is not observed in proton-proton collision, may point to an interpretation in terms of strong jet energy loss in a hot dense medium.
- CMS also observes this effect, publication will follow.



W boson width: introduction

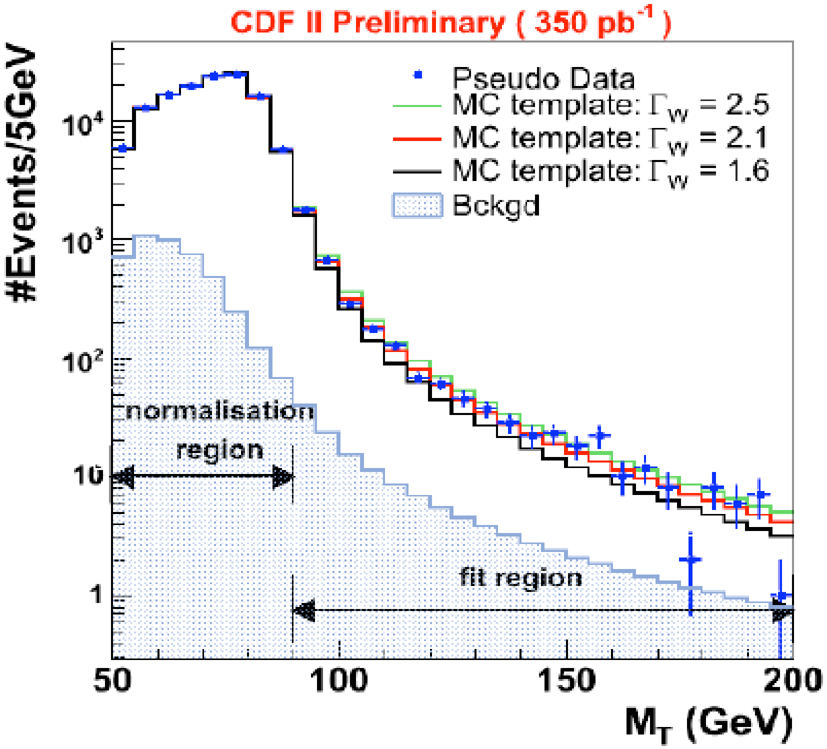
- Predicted very precisely in the Standard Model by assuming the leptonic and hadronic partial width
  - **Γ_W^{SM} = 2091 ± 2MeV [PDG:J.Phys.G33,1] (2007)**
- Deviation from this prediction suggest non-SM decay modes
- Γ_W is an input to the W mass measurement: **$\Delta m_W \sim \Delta\Gamma/7$**



- Ideally we would reconstruct the invariant mass of the decay products to measure Γ_W, since ν isn't detected we reconstruct the transverse mass

$$m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$

W boson width: analysis strategy

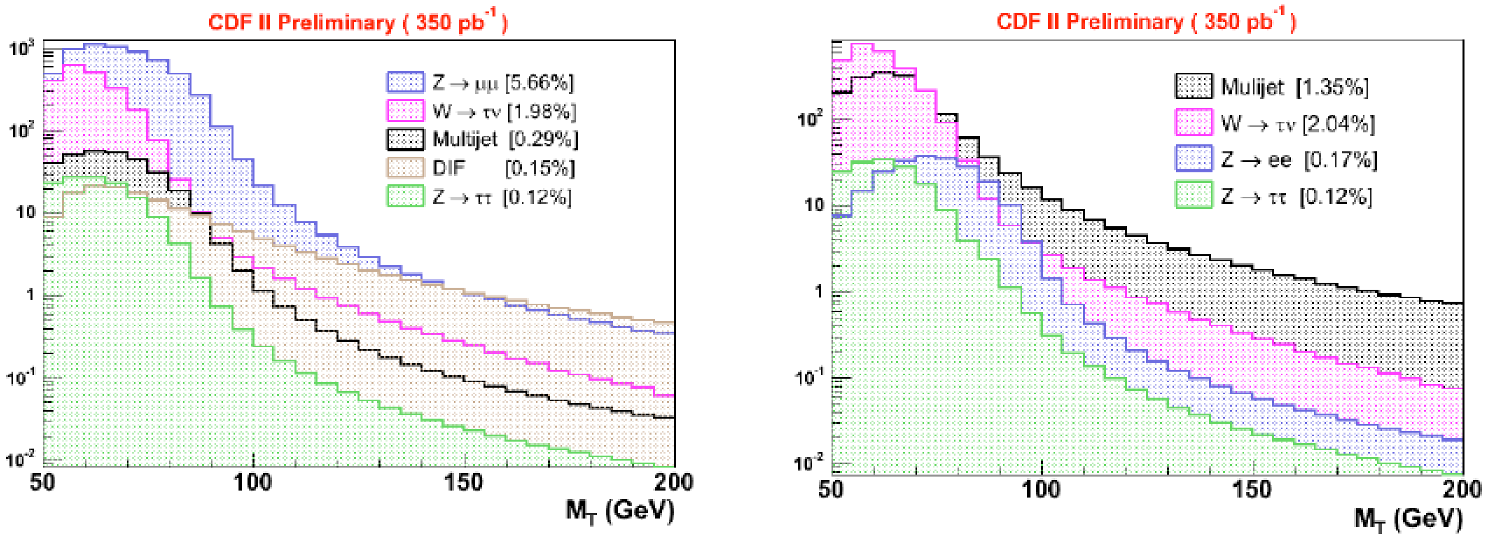


$$m_T = \sqrt{2 p_T{}^{l} p_T{}^{\nu} (1 - \cos\phi_{l\nu})}$$

- Simulate m_T distribution with dedicated fast parametrised MC
- Utilise $Z \rightarrow ll$ (and $W \rightarrow l\nu$) to calibrate the detector to a high precision
- Fit m_T templates (with Γ_W varying) to the data, fit range 90-200 GeV

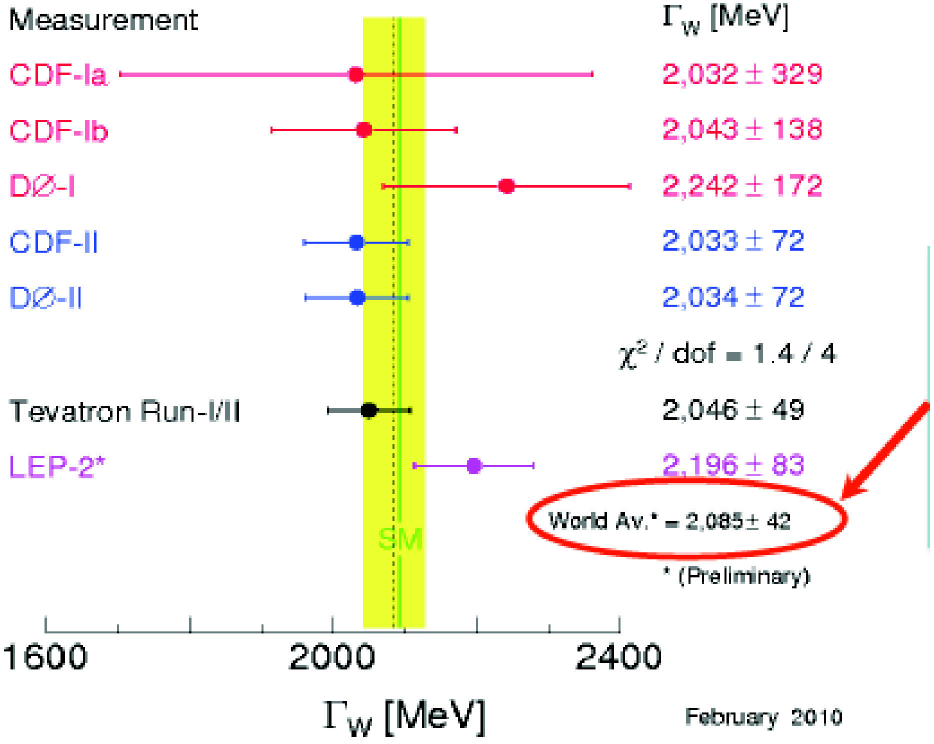
optimised to reduce total uncertainty

W boson width: backgrounds

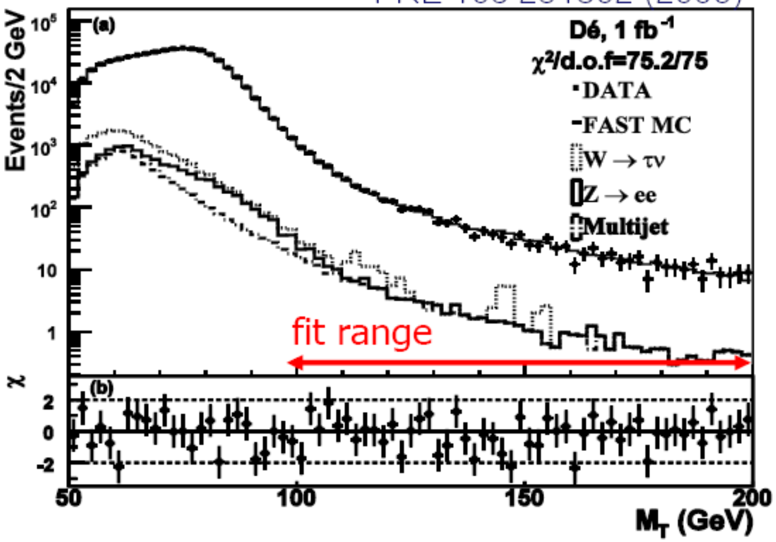


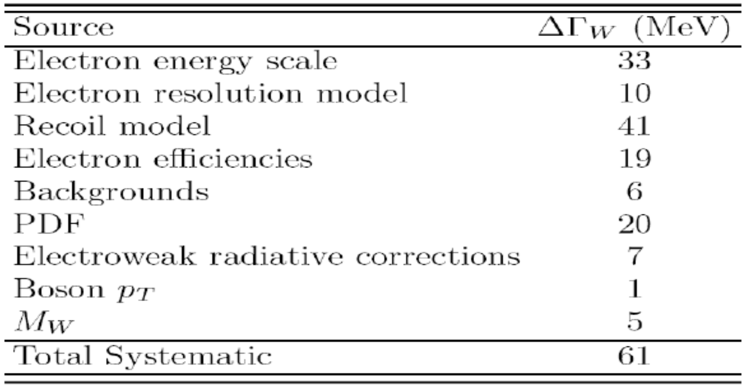
- Composition of processes with different shapes in the fit region

W boson width: measurement



PRL 103 231802 (2009)





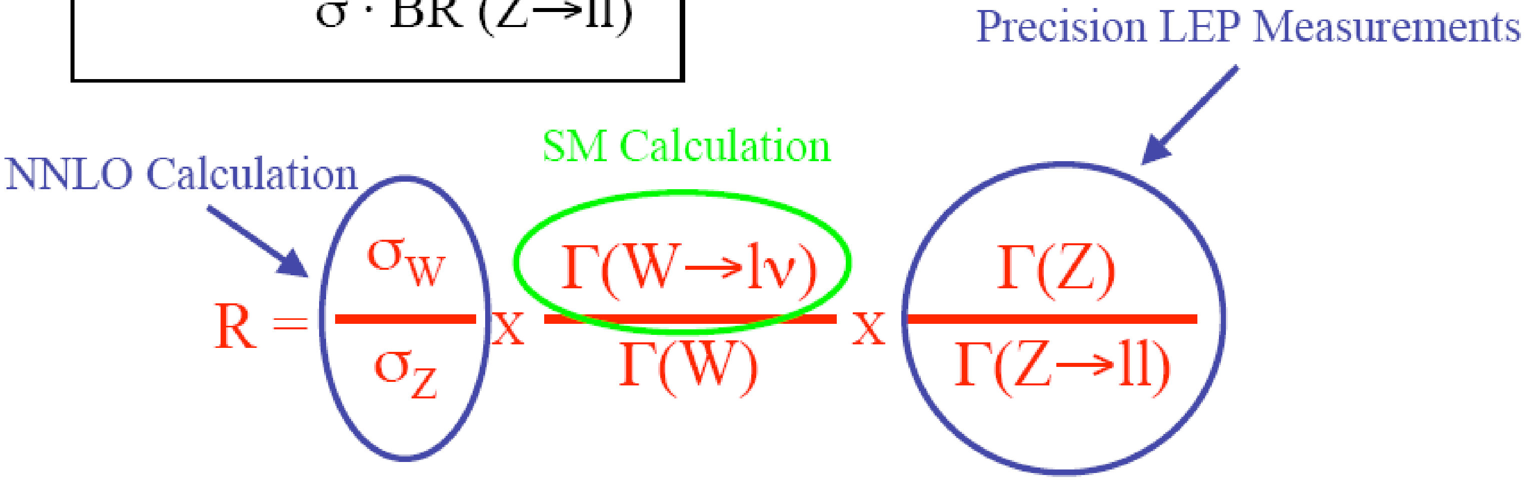
Source	$\Delta\Gamma_W$ (MeV)
Electron energy scale	33
Electron resolution model	10
Recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson p_T	1
M_W	5
Total Systematic	61

World average (Winter 2010):
Γ_W = 2085 ± 42 (stat + syst) MeV

(SM Γ_W = 2.093 ± 0.002 GeV)

Indirect measurement

$$R_{exp} = \frac{\sigma \cdot BR\,(W \rightarrow l\nu)}{\sigma \cdot BR\,(Z \rightarrow ll)}$$



Precision LEP Measurements

SM Calculation

NNLO Calculation

$$R = \frac{\sigma_W}{\sigma_Z} \times \frac{\Gamma(W \rightarrow l\nu)}{\Gamma(W)} \times \frac{\Gamma(Z)}{\Gamma(Z \rightarrow ll)}$$

CDF Run II **INDIRECT width ($72\ pb^{-1}$):**

2092 ± 42 MeV

PRL 94, 091803

CDF Run II **DIRECT width ($350\ pb^{-1}$):**

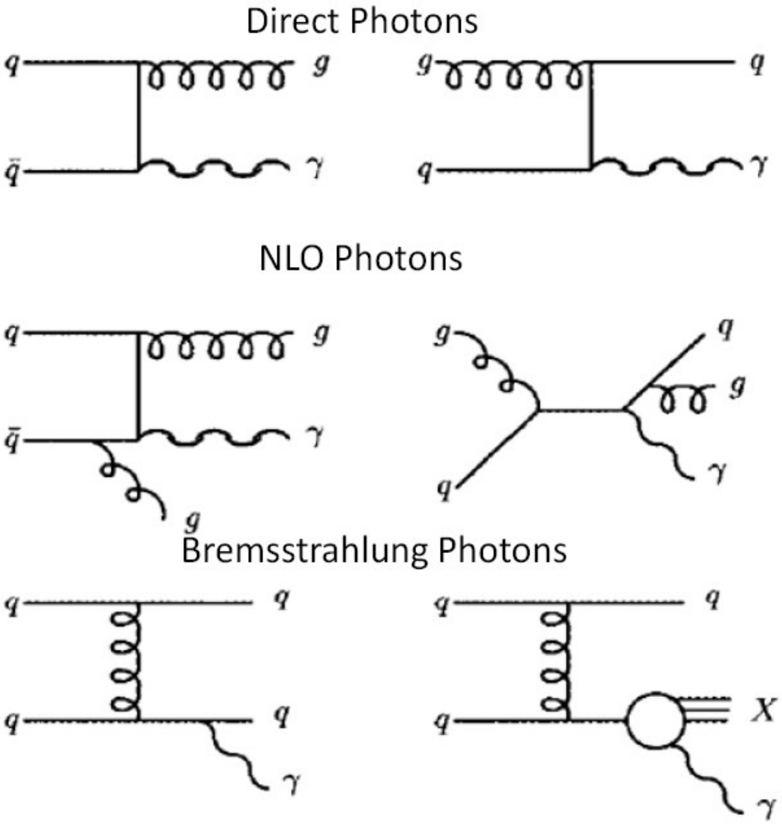
2032 ± 71 MeV

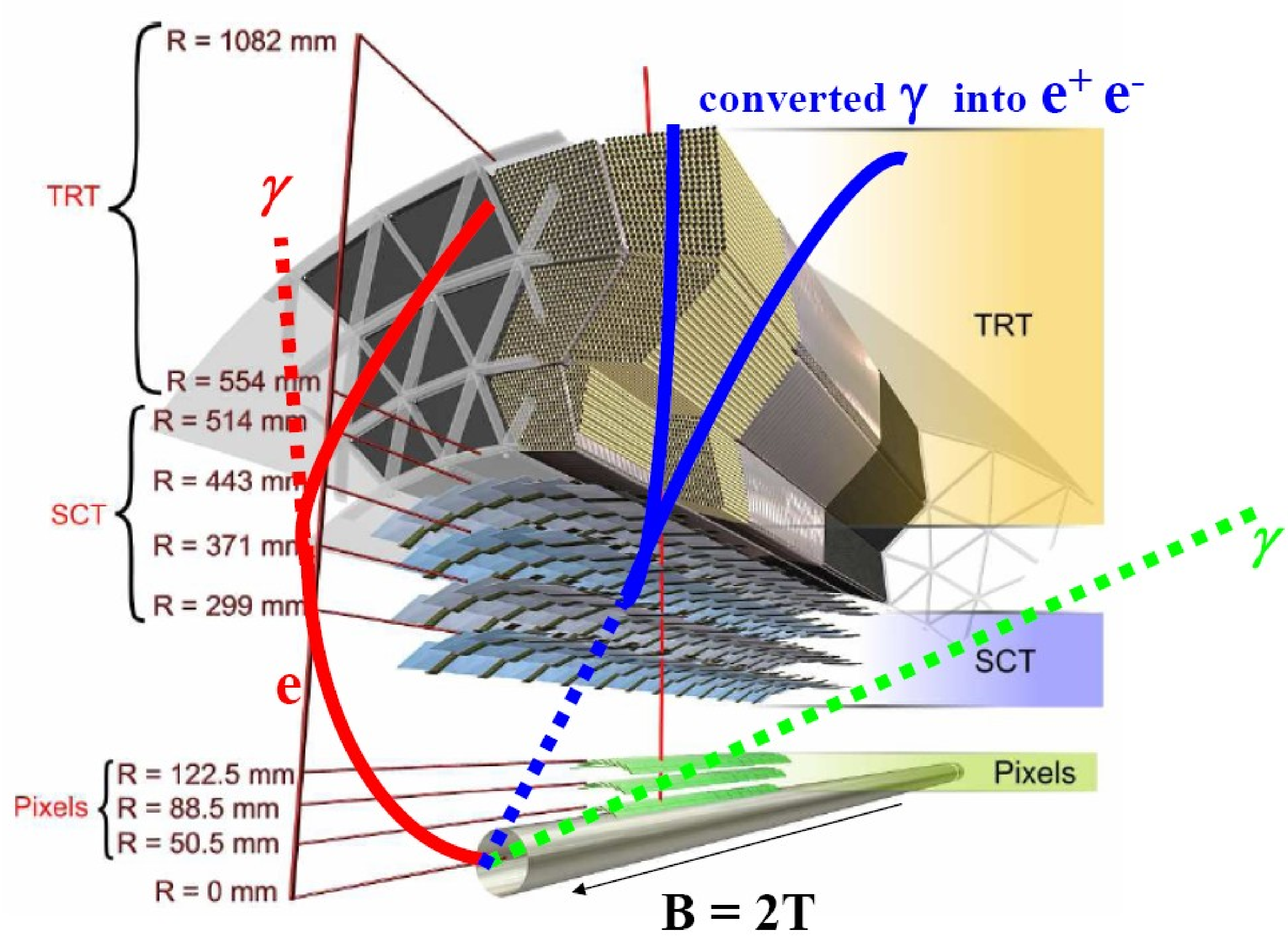
preliminary

Results from 2007, by now updated to $1fb^{-1}$

Direct photon production

- Prompt photon production is an experimental probe of the hard scattering dynamics
    - Study perturbative QCD
    - Jet energy scale calibration
    - Background to searches
- More than 30 years of experimental data available
- Two main leading order contributions
    - Compton scattering
    - Annihilation of quarks
- Background comes from neutral meson decays.

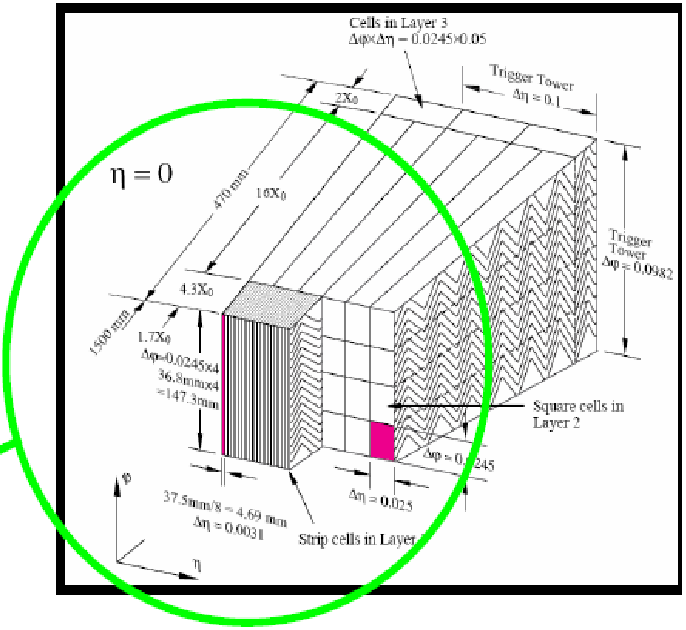


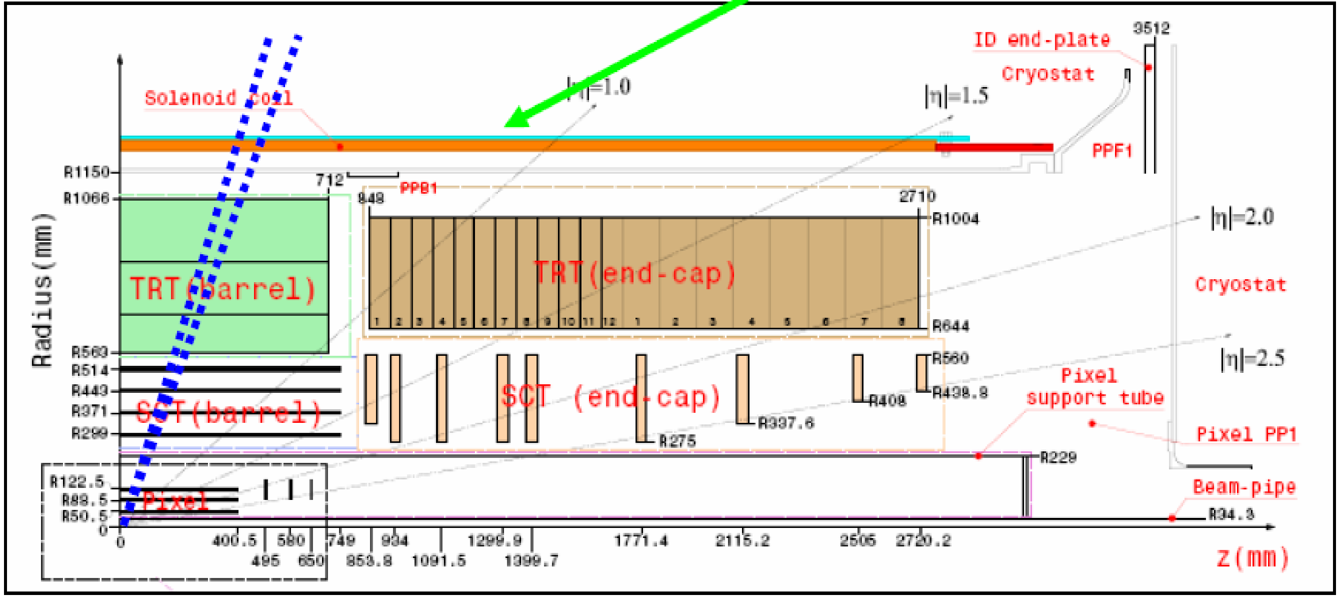

R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
Pixels
R = 122.5 mm
R = 88.5 mm
R = 50.5 mm
R = 0 mm
γ
e
converted γ into e+ e-
TRT
SCT
Pixels
γ
B = 2T

This will be very useful to reject the background from π^0

opening of photons coming from a π^0 (p_T=40 GeV)

$\Delta R > .007$



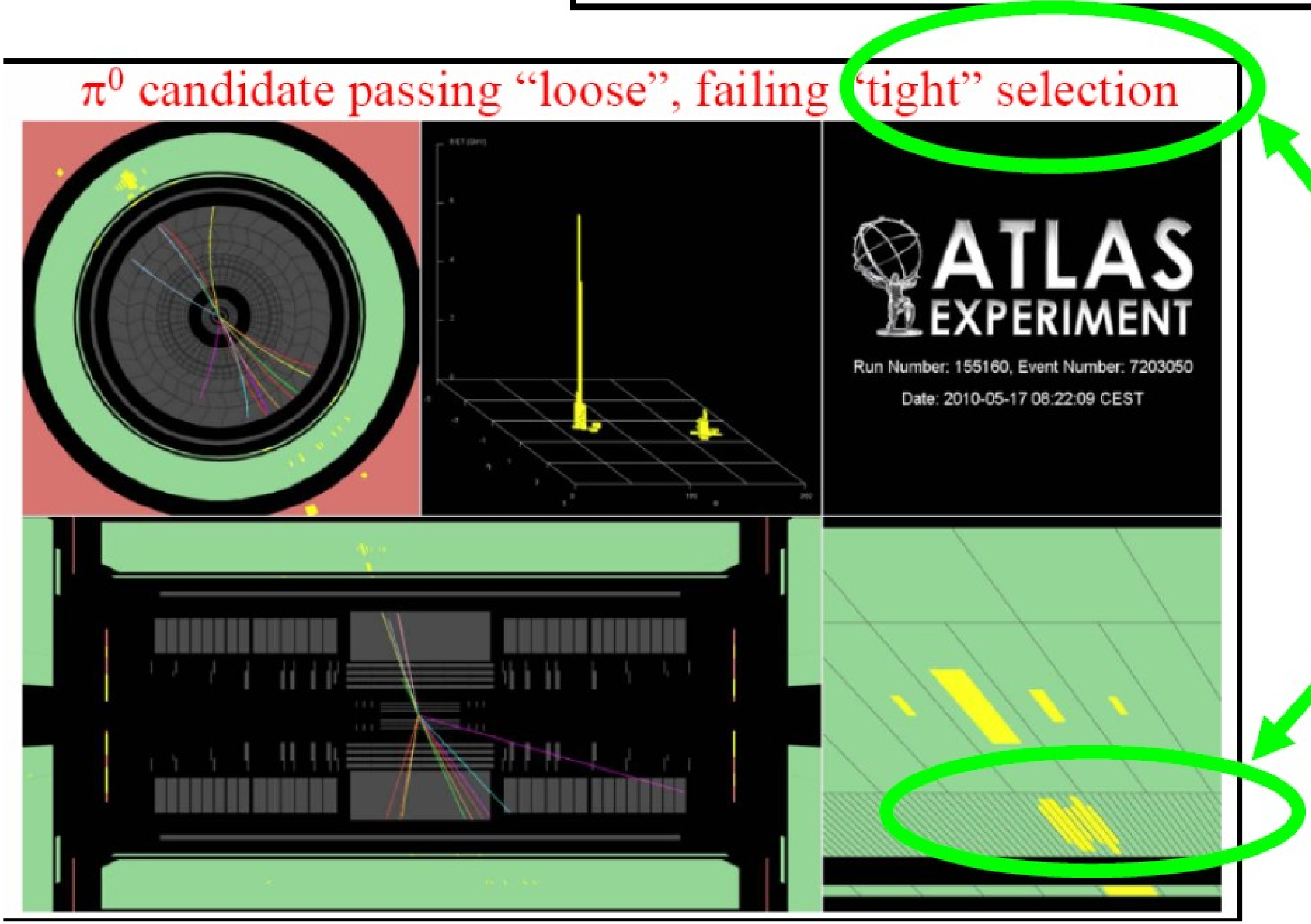


granularity of 1st sampling of calorimeter

$\Delta\eta \sim .003$

Photon identification with shower shapes

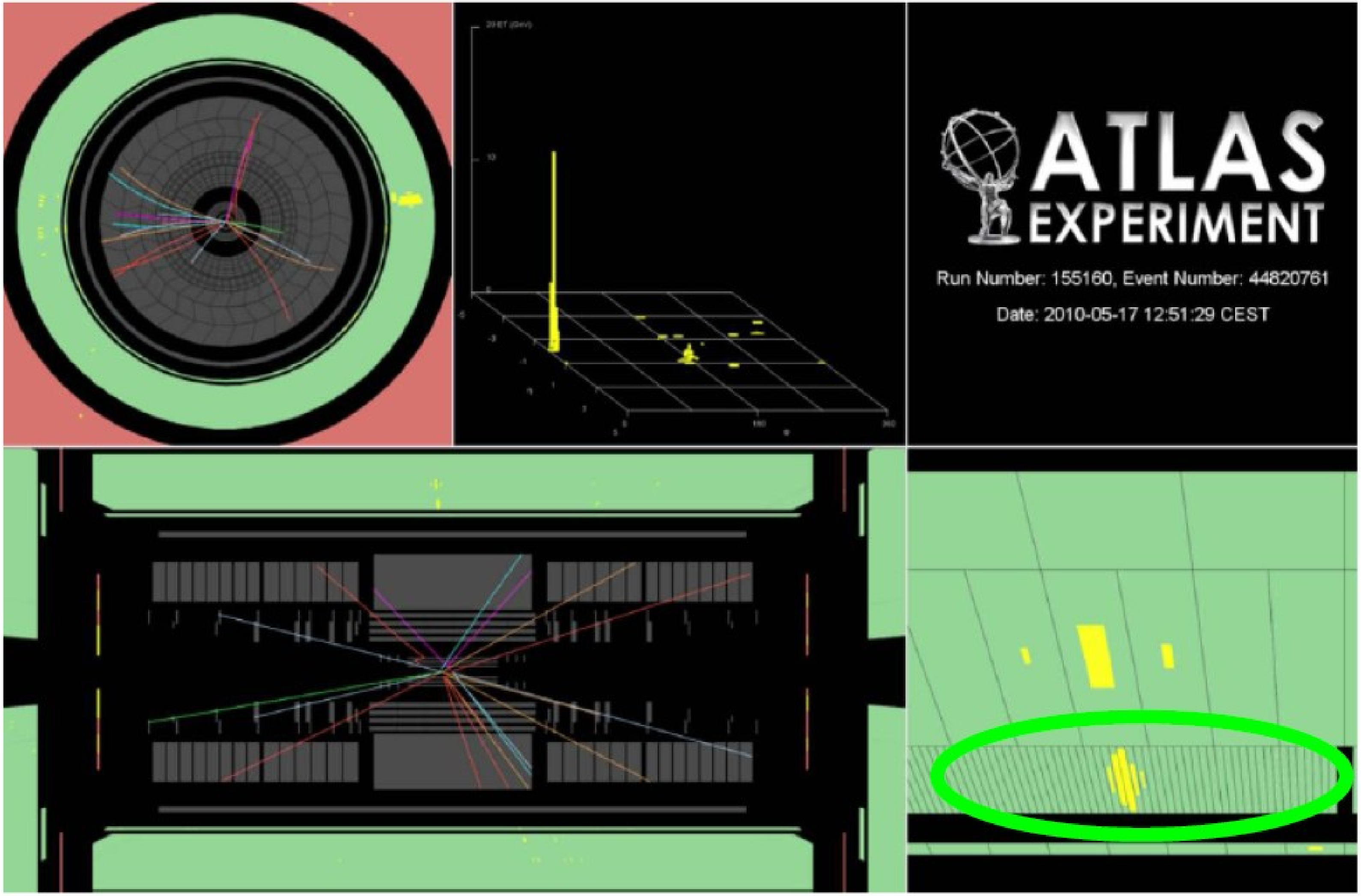
reminder: opening angle between the two photons of a π^0 of p_T =40 GeV ***is > 0.007 to be compared with size of strip calo 1st sampling ~0.003***



π^0 candidate passing "loose", failing "tight" selection

tight selection uses mainly calo 1st sampling

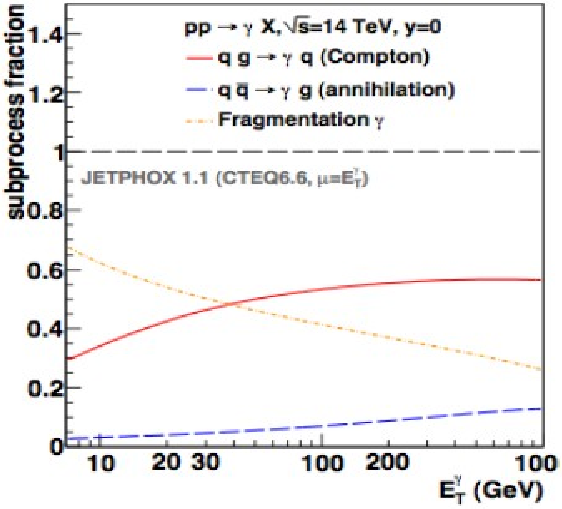
Photon candidate passing "tight" selection

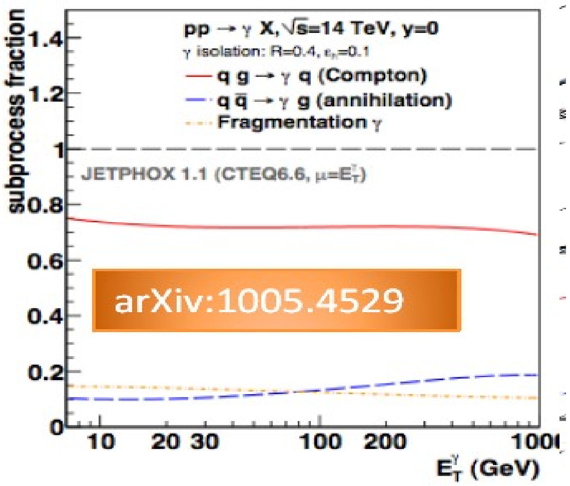


Nice shape in first sampling of EM calormeter

Definition of isolated photons

- Measuring prompt photons experimentally
  - Isolation criterion around the photon candidates is applied to suppress the background from pi0's etc.
  - Requiring isolation also affects the fragmentation contribution
- Theoretical calculations
  - Both the direct and the fragmentation pieces are accounted for
  - Beyond LO, the distinction between the direct and fragmentation becomes dependent on the renormalisation and fragmentation scheme

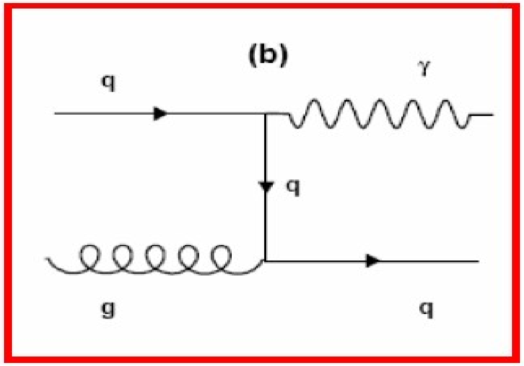


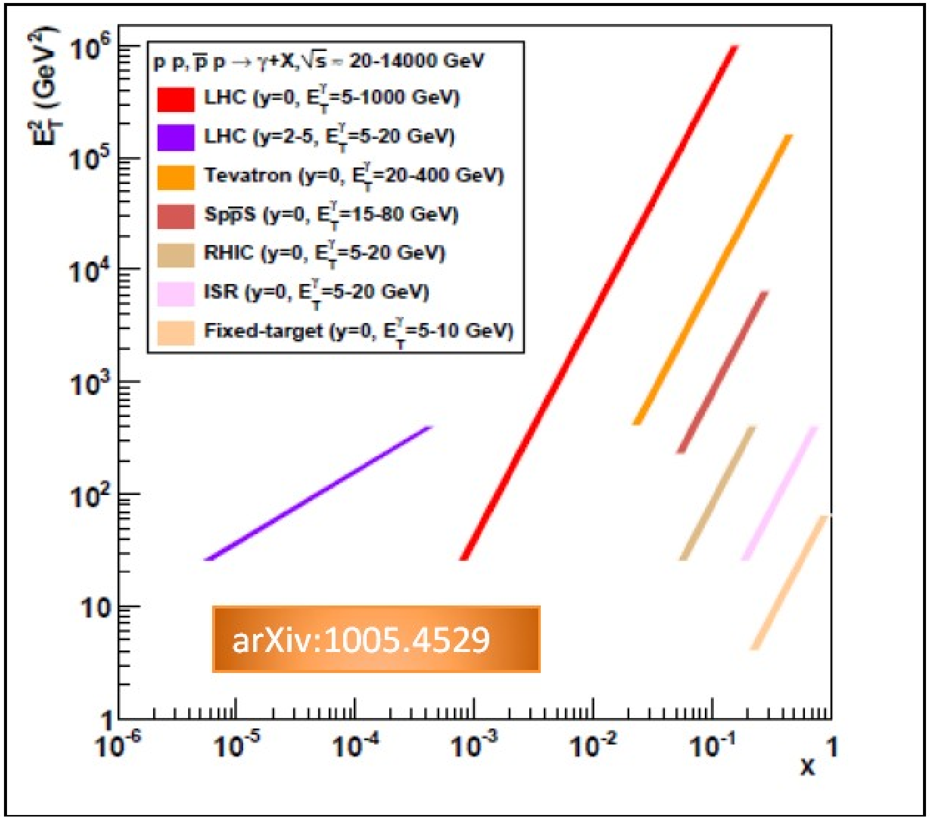


arXiv:1005.4529

Photons at LHC

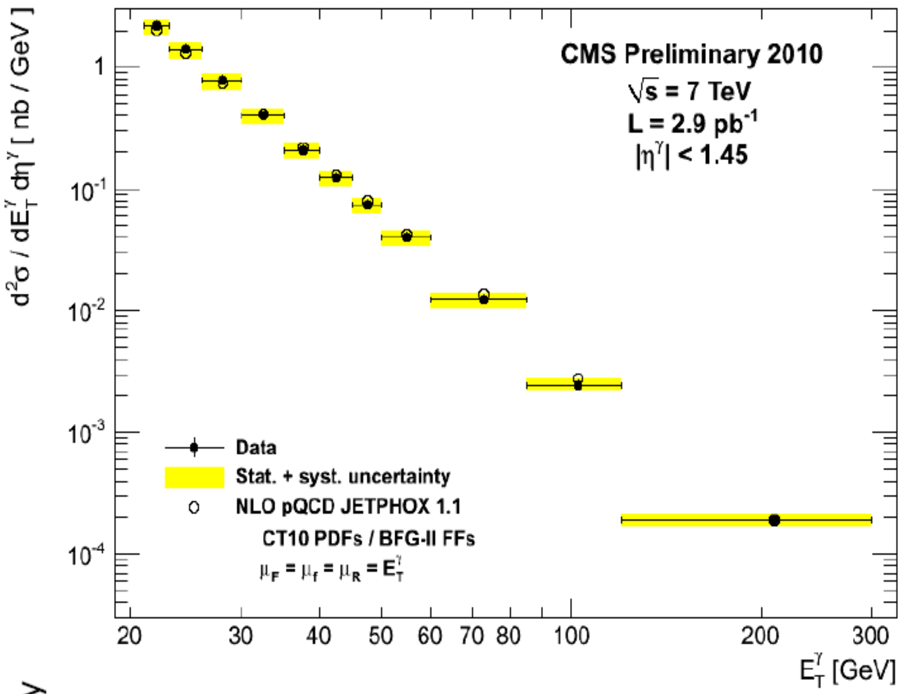
- X reach of photons at LHC is couple of orders of magnitude lower than the previous experiments
- Dominance of the Compton scattering cross-section gives possibility of clean probe to constrain gluon pdf's

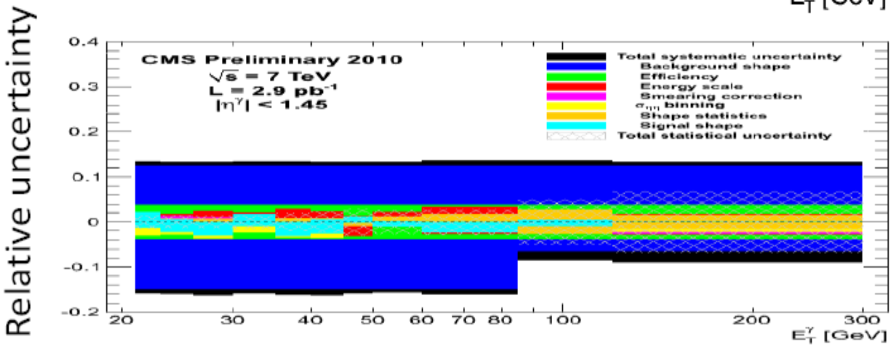




CMS analysis: isolated photon spectrum

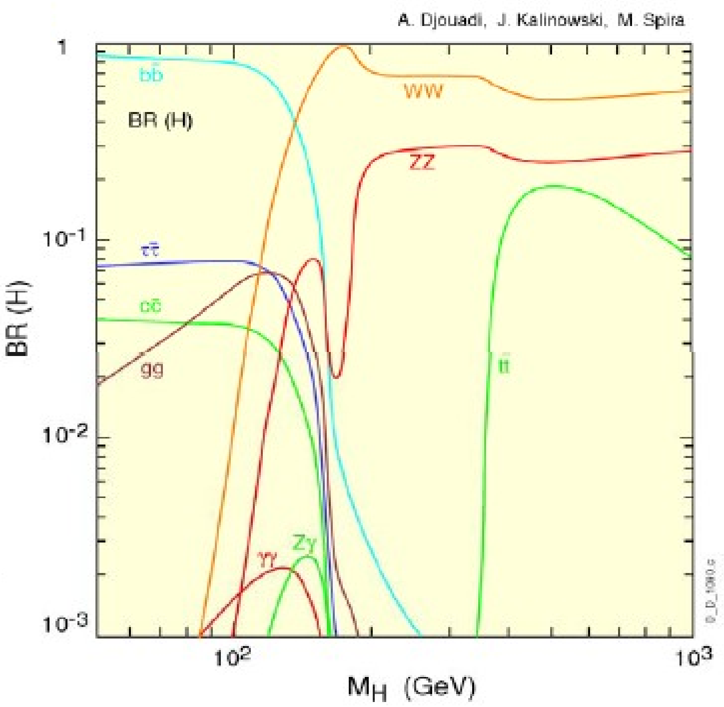
- Good agreement with NLO predictions from JETPHOX is observed
- Total systematics varies from 8.9%-16.3% depending on the transverse momentum bin
- Dominant systematic uncertainty comes from background shape.



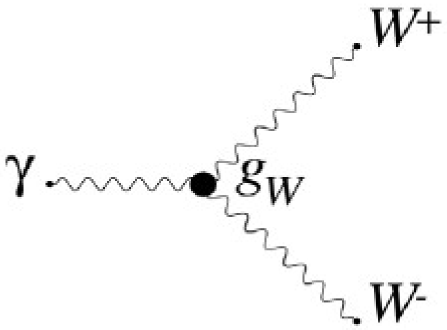


Diboson physics

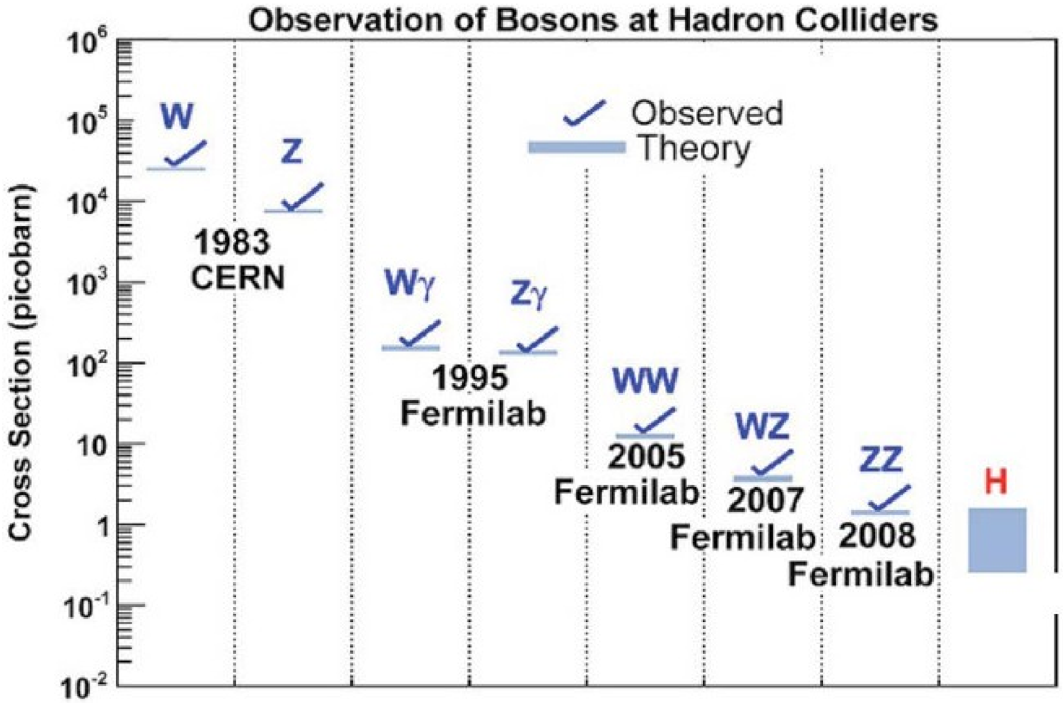
- Physics with multiple bosons in the final state
  - Such as WW, WZ, Zγ, γγ,…
- Number of important measurement and searches
  - Cross section
  - Search for resonant production
    - Such as Higgs or …



- Self-interaction boson couplings are of particular interest as they are precisely measured and can be a very sensitive test of the EWK sector of the standard model.



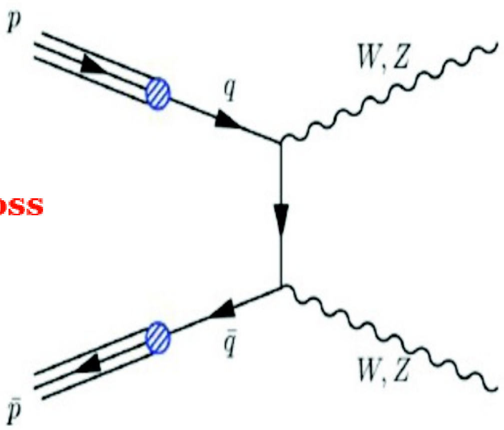
Di-boson cross-sections

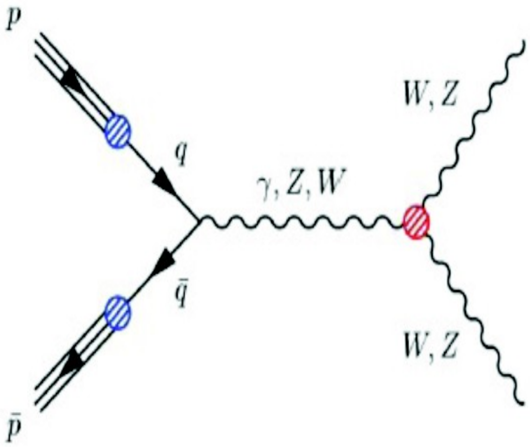


- So far primary measurements in leptonic decays, probed σxBR values orders of magnitude smaller.
- Example:
  - σxBR = 1.5fb^{-1} for ZZ→μμμμ
- In practice measured topologies:
  - lepton+photon+MET (Wγ), di-lepton+photon (Zγ), photon+MET (Zγ),di-leptons+MET(WW), trileptons+MET(WZ), leptons+jets+MET(WW+WZ), jets+MET(WW+WZ+ZZ), four leptons (ZZ).

Diboson final states

t-channel dominates cross section



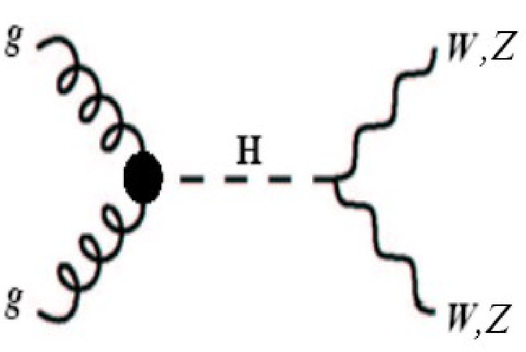


s-channel sensitive to new physics through TGCs

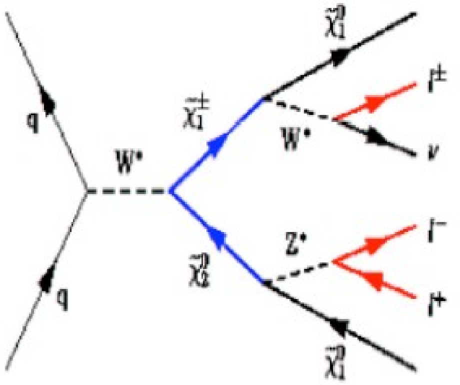
- Charged: WW, WZ, Wγ and neutral ZZ, Zγ and (γγ)
  - Cross-sections, kinematical distributions, gauge-boson couplings
- Verify SM predictions to ~10% (γW,γZ), ~ 25% (WW) and ~50% (WZ,ZZ)
- Until recently measurements at CDF/D0 done in leptonic channel, now new signatures with jets added to the program.

Diboson and searches

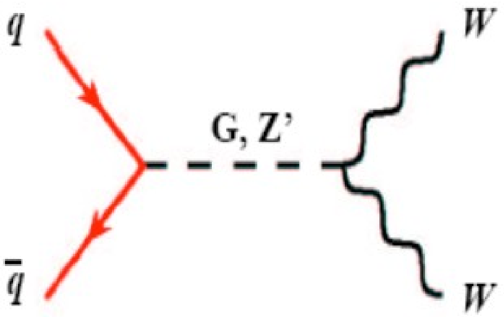
- Diboson productions are also background to New Physics searches
- Important to understand this production process



Higgs

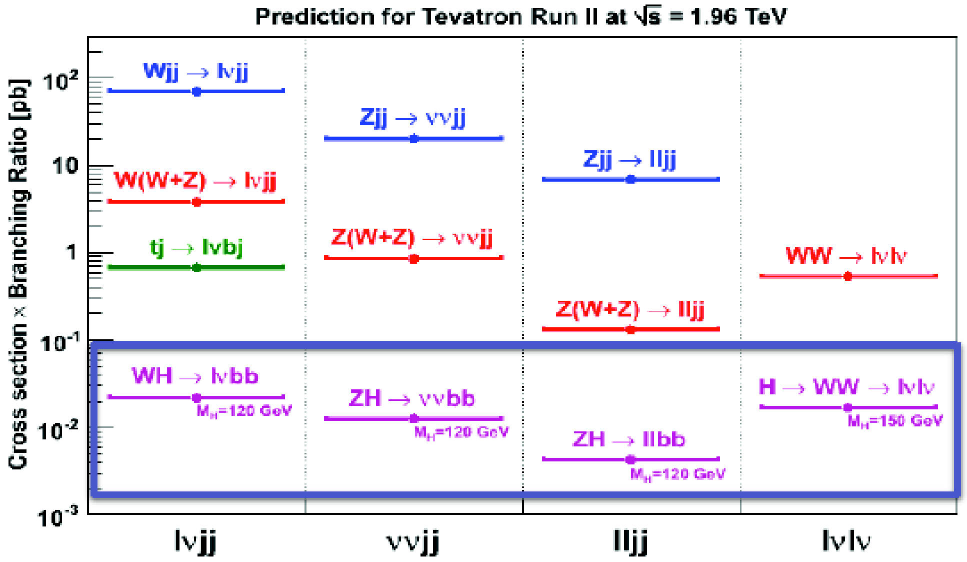


SUSY



New Gauge Boson

Diboson signatures at Tevatron



- Signatures with jets are interesting because they are background to the Higgs boson searches

- Establishing processes in different channels allows to
  - Combine to improve precision
  - Confidence in modeling and techniques
  - Check consistency between channels

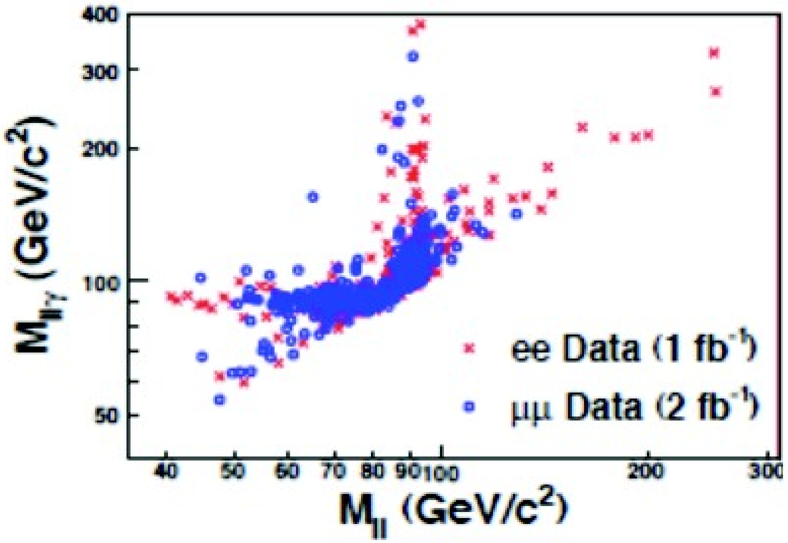
$Z\gamma \to ll\gamma$ (CDF at Tevatron)

- $Z\gamma \to ll\gamma$, produced as ISR and FSR
  - Require $E_T^{\gamma} > 7$ GeV, $m_{ll} > 40$ GeV

CDF (1 and 2 fb^{-1}):

$\sigma(Z \to ll\gamma) = 4.6 \pm 0.2(\text{stat}) \pm 0.3\ (\text{syst}) \pm 0.3\ (\text{lum})$ pb

- Theory: 4.5 ± 0.5 pb(NLO)



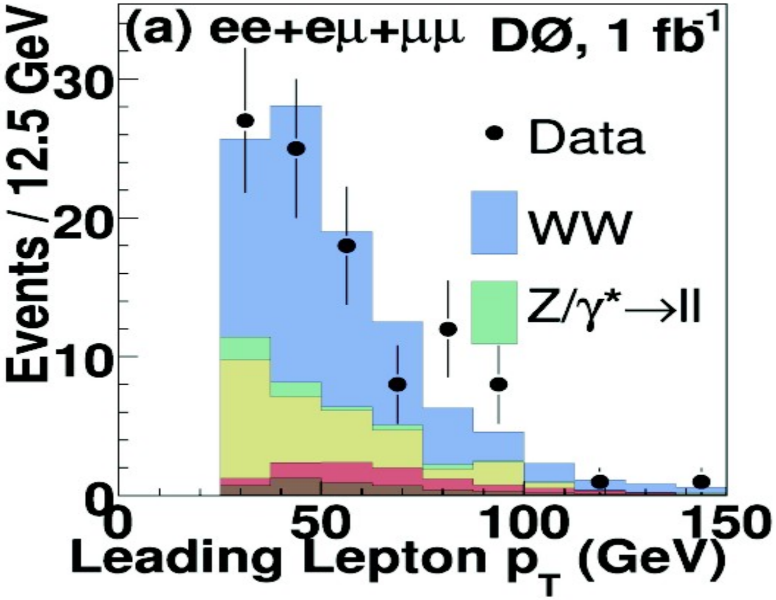
WW→lνlν

- Essential background to understand for Higgs boson searches
- Systematic uncertainties dominated by backgrounds

D0 (1.0 fb^{-1}):
σ(WW->lνlν) =11.5±2.1(stat+syst)±0.7 (lum) pb

CDF (3.6 fb^{-1}):
σ(WW->lνlν) =12.1 ± 0.9(stat) $^{+1.6}_{-1.4}$ (syst) pb

- Theory: 12.0 ±0.7 fb

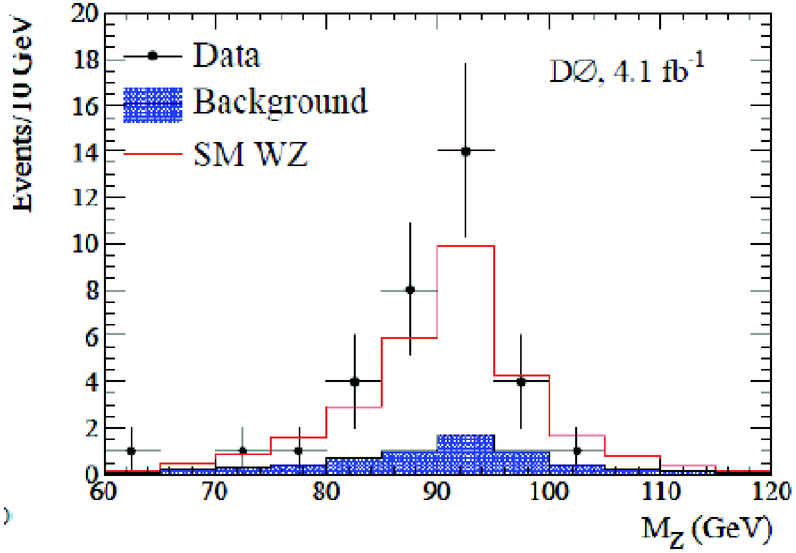


WZ → lνll (at Tevatron)

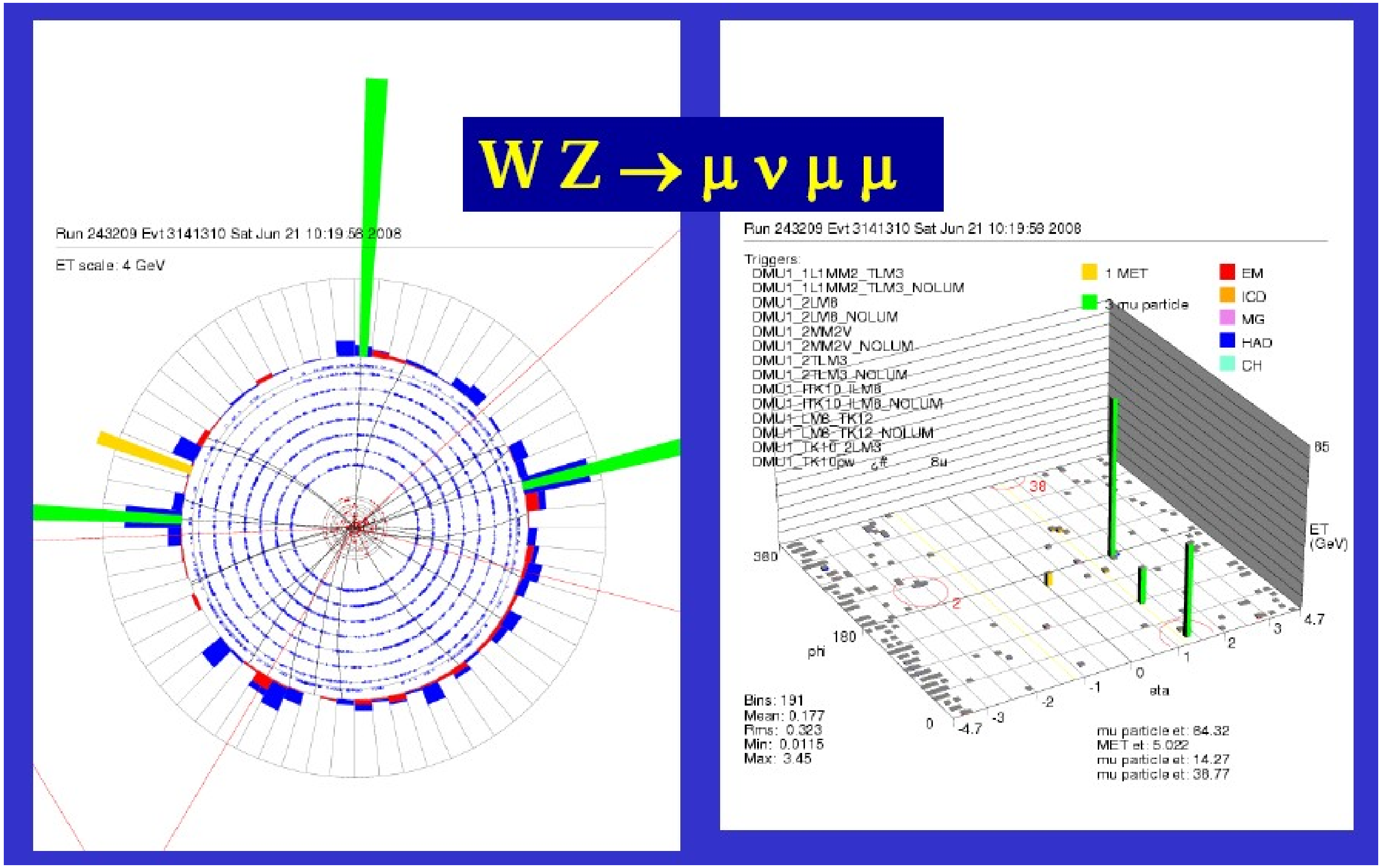
- New measurement:
  - 3 exact leptons p_T > 15 GeV and MET > 20 or 25 GeV

CDF (6 fb^{-1}):
$\sigma(WZ \to l\nu ll) = 4.1 \pm 0.6(stat) \pm 0.4\ (syst)$ pb

D0 (4.1 fb^{-1}):
$\sigma(WZ \to l\nu ll) = 3.9\,^{+1.0}_{-0.8}(stat+sys) \pm 0.3\ (lum)$ pb



WZ candidate event: D0



$WZ \rightarrow \mu \nu \mu \mu$

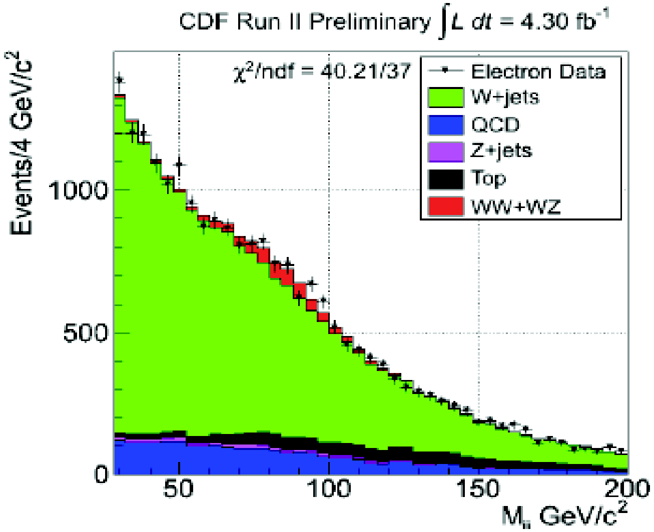
WW/WZ → lνjj (at Tevatron)

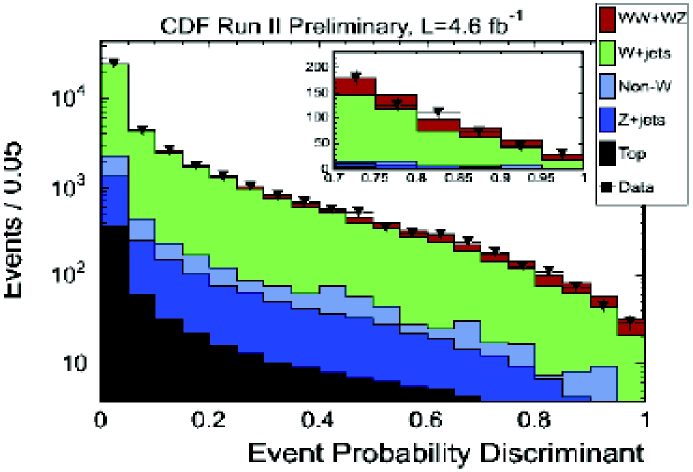
- Dijet mass fit
- Require MET>25 GeV, dijet p_T>40 GeV to produce smoothly falling background in the signal region

CDF (4.3 fb^{-1}):
σ(WW/WZ) =18.1 ± 3.3(stat) ± 2.5 (syst) pb

- Build event PDF using matrix element ME probability to predict background shapes

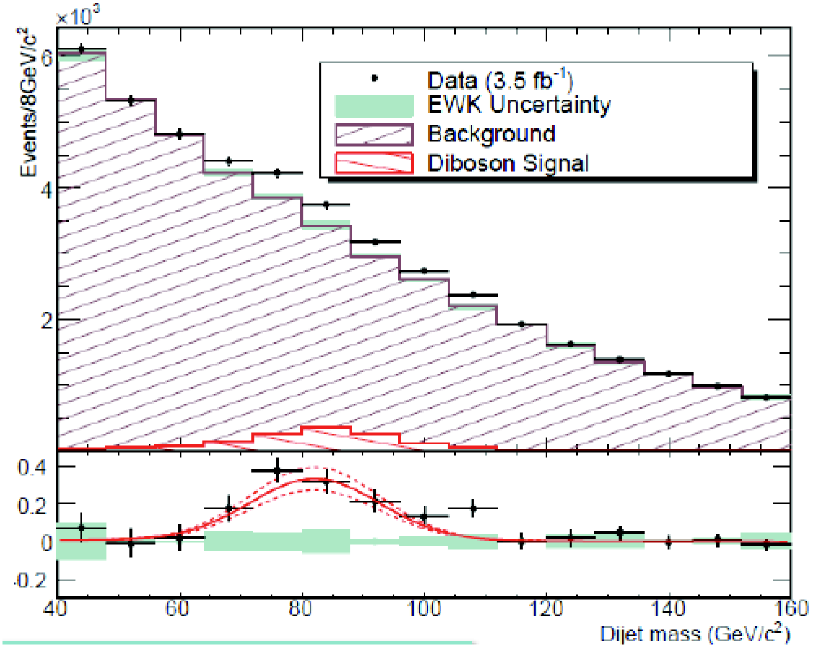
CDF (4.6 fb^{-1}):
σ(WW/WZ) =16.5 ± 3.3(stat) ± 3.0 (syst) pb





WW/WZ/ZZ→ jets + MET (at Tevatron)

- Search for VV (V = W,Z) where one boson decays hadronically
- Signal/Background ~ 3%
  - EWK background: V+jets+top (~85%)
  - QCD background: instrumental (~15%)
- No charged lepton requirement
- Includes ννqq' as well as lνqq' final states



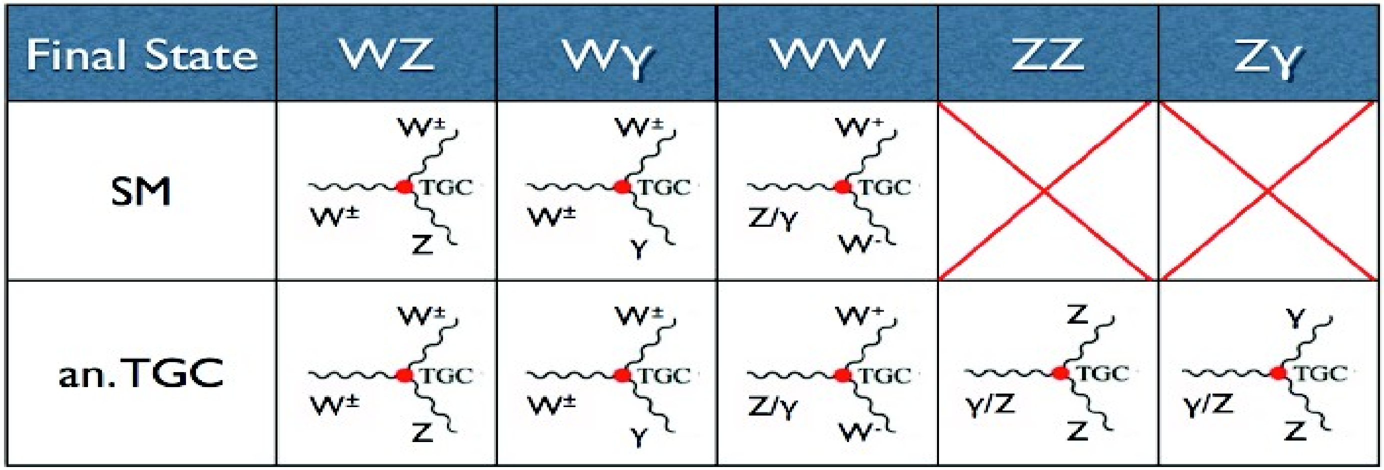
CDF (3.5 fb^{-1}):
σ(WW/WZ/ZZ) =18.0 ± 2.8(stat) ± 2.6(syst) pb

Gauge couplings

- In Standard Model (SM) non-abelian nature of $SU(2)_L$ x $U(1)_Y$ allow gauge bosons to interact with one another
  - Coupling between 3 gauge bosons=> triple Gauge-Boson Coupling (TGC)
- SM only allows charged coupling (WWZ, WWγ), does not allow pure neutral coupling (ZZZ,ZZγ,Z$\gamma\gamma$,$\gamma\gamma\gamma$) since Z/γ has no charge nor weak isospin.
- Physics beyond SM can introduce anomalous TGCs which may allow neutral couplings or increase the charged TGCs couplings strenght.

Diboson at LHC

- At the LHC one can study TGC through the measurement of diboson production
  - Each can probe one or more TGC
    - WZ: WWZ vertex
    - WW: WWZ, WWγ vertex
  - Measures the anomalous coupling parameters



Final State	WZ	Wγ	WW	ZZ	Zγ
SM	W± W± TGC Z	W± W± TGC γ	W+ Z/γ TGC W-		
an.TGC	W± W± TGC Z	W± W± TGC γ	W+ Z/γ TGC W-	Z γ/Z TGC Z	γ γ/Z TGC Z

Anomalous TGC charged

Effective Lagrangian for charged TGC

$$L/g_{WWV} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{*\mu}V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu}W^\mu_\nu V^{\nu\rho}$$

Anomalous coupling aparameters

Parameter / Process	W^+W^-	$W^\pm Z/\gamma$
$\Delta\kappa_Z \equiv \kappa_Z - 1$	proportional to $\hat{s}$	proportional to $\sqrt{\hat{s}}$
$\Delta\kappa_\gamma \equiv \kappa_\gamma - 1$	proportional to $\hat{s}$	proportional to $\sqrt{\hat{s}}$
$\Delta g_1^Z \equiv g_1^Z - 1$	proportional to $\sqrt{\hat{s}}$	proportional to $\hat{s}$
λ_γ	proportional to $\hat{s}$	proportional to $\hat{s}$
λ_Z	proportional to $\hat{s}$	proportional to $\hat{s}$

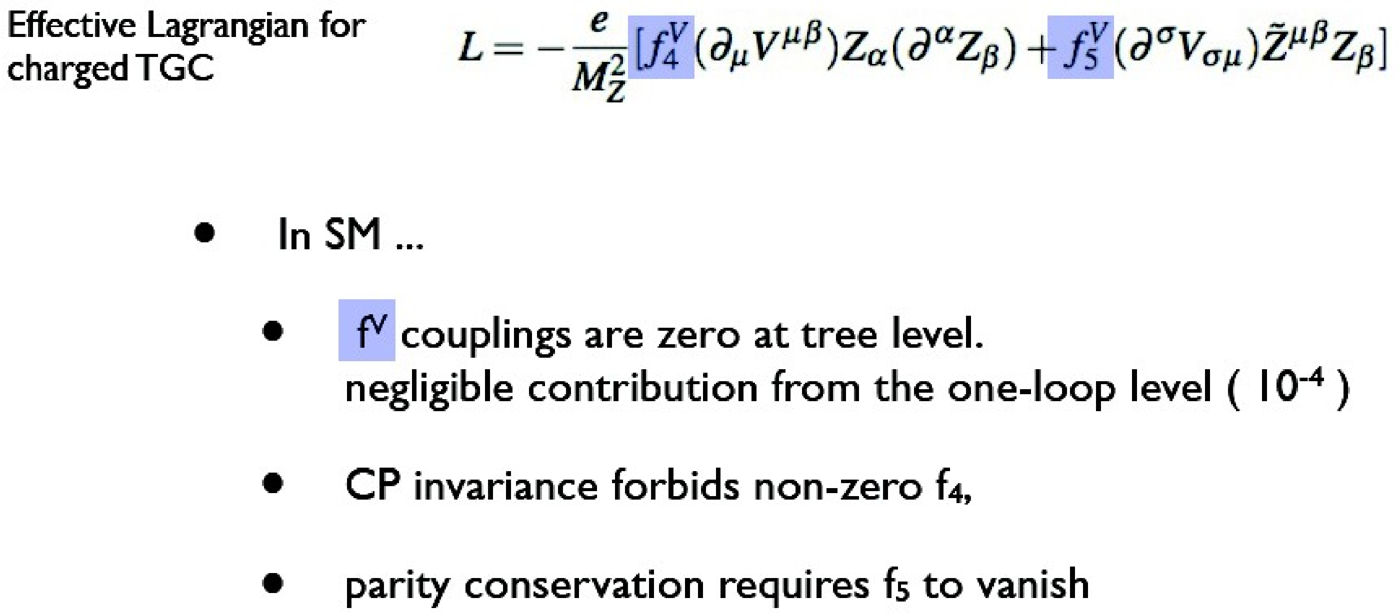
$g_1^\gamma = 1$ or $\Delta g_1^\gamma = 0.$ gauge invariance requires this!

$\hat{s}$: invariant mass of produced bosons

Amplitudes grow with energy and eventually violate tree level unitarity! Avoided by effective cutoff scale:

$$\Delta\kappa(\hat{s}) = \frac{\Delta\kappa}{(1+\hat{s}/\Lambda^2)^n}$$

Anomalous TGC neutral



Effective Lagrangian for charged TGC

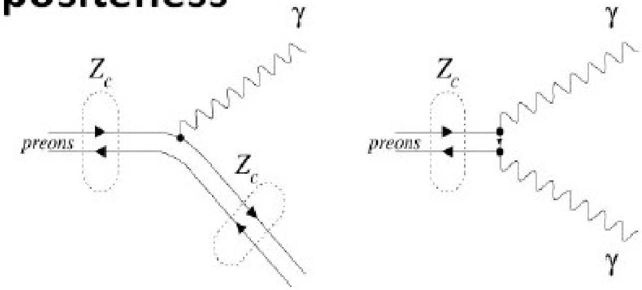
$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

- In SM ...
  - f^V couplings are zero at tree level.
    negligible contribution from the one-loop level (10^{-4})
  - CP invariance forbids non-zero f_4,
  - parity conservation requires f_5 to vanish

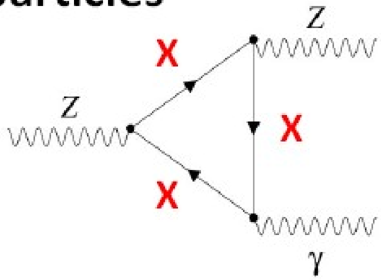
TGCs and new physics

- Numerous possible extensions of the Standard Model result in anomalous couplings
  - Example: neutral TGCs: ZZγ and Zγγ

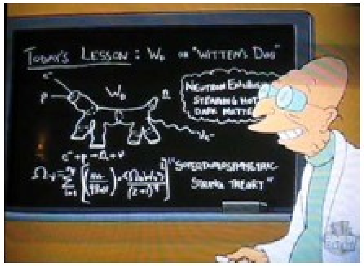
Compositeness



New particles



Something else?



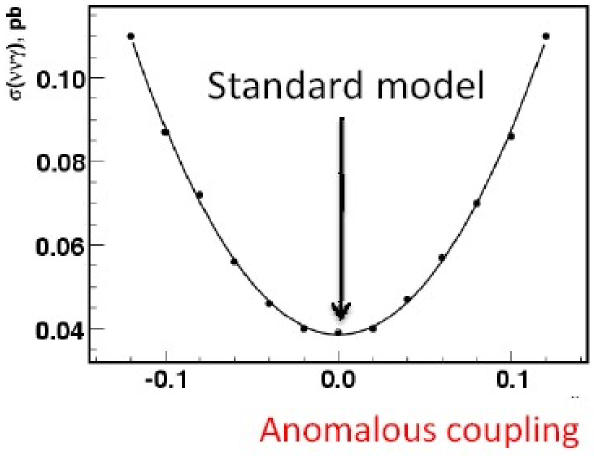
- Follow effective Lagrangian approach
  - Parametrize the ZZγ/Zγγ vertex in the most general way
  - One coupling is usually described in terms of many parameters

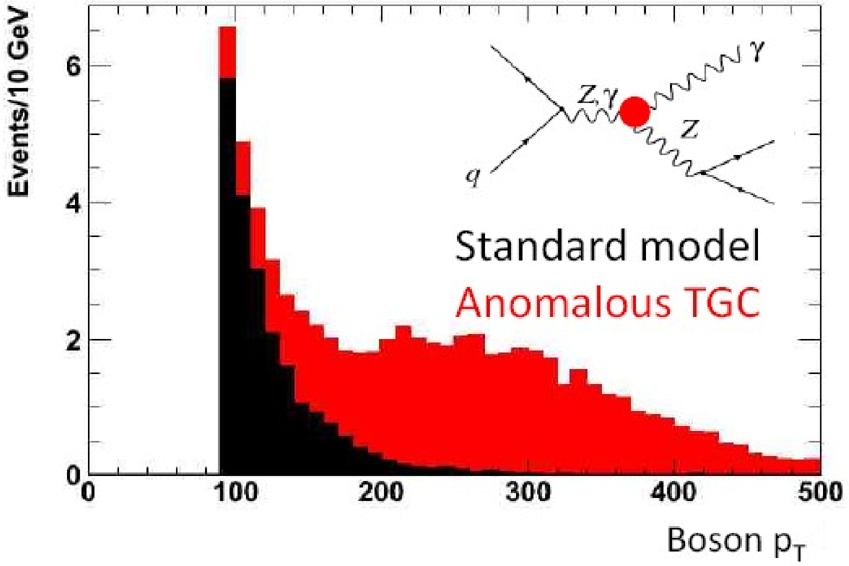
Characteristic of the triple gauge-boson couplings

- Sensitivity to TGCs comes from four different types of information
  - Cross section: parabolic increase of cross-section with TGC due to the linear Lagrangian: $\sigma \sim (\mathrm{TGC})^2$
  - Energy behaviour: TGC lead to a broad increase in the differential cross-section at large invariant mass $M_{WV,ZV}$ $(V=Z,\gamma)$ and transverse momentum $P_T(V)$ $(V=W,Z,\gamma)$
  - Production angle: angular information of the bosons
  - Polarisation: different TGCs contribute to different boson helicity states. Decay angular information enhance sensitivity to individual TGCs.

Effect of anomalous coupling

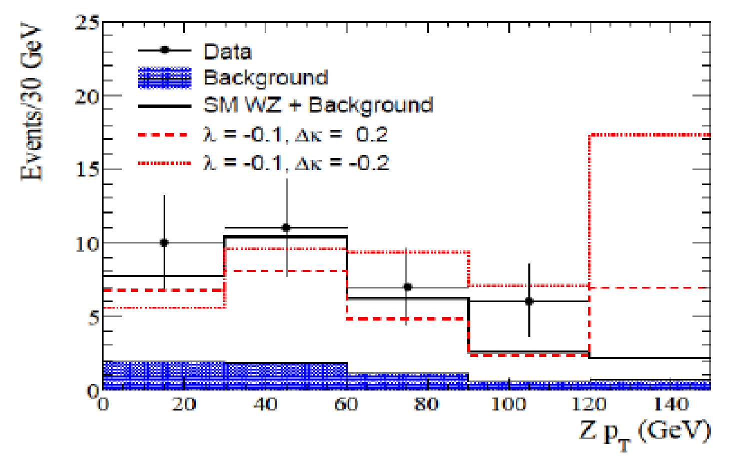
- Any non-zero coupling result in in crease of the cross-section and harder p_T spectrum of the outgoing boson.
  - Can be simulated by a number of generators, such as Sherpa, MCFM, Baur, etc.

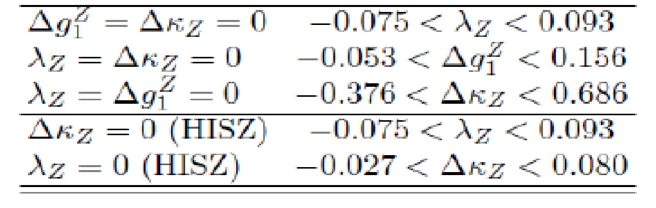




WZ → lνll at D0

Use Z p_T distribution to test TGCs

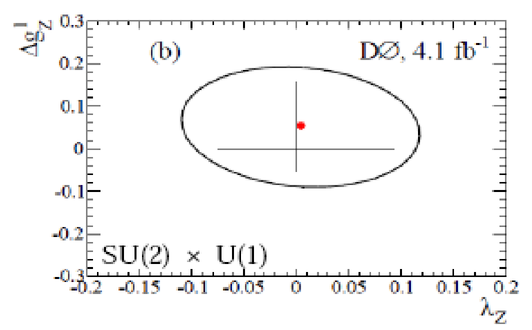


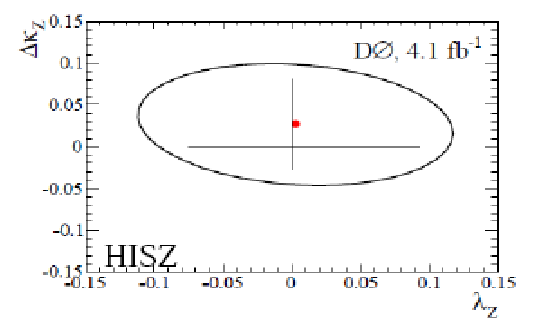


Coupling relation	95% C.L. Limit
$\Delta g_1^Z = \Delta\kappa_Z = 0$	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = \Delta\kappa_Z = 0$	$-0.053 < \Delta g_1^Z < 0.156$
$\lambda_Z = \Delta g_1^Z = 0$	$-0.376 < \Delta\kappa_Z < 0.686$
$\Delta\kappa_Z = 0$ (HISZ)	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = 0$ (HISZ)	$-0.027 < \Delta\kappa_Z < 0.080$

Λ=2TeV

Set 95%CL limits in 2D and 1-D





WWV coupling

- WWV (V=γ or Z) can be parametrized by seven independent parameters as such

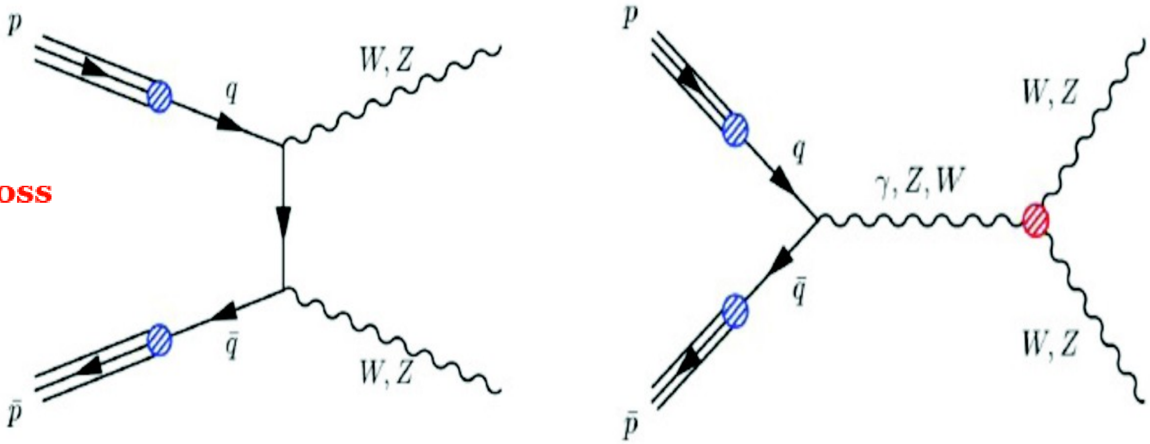
$$\mathcal{L}_{WWV}/g_{wwv} = i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} -$$

$$g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) + g_5^V \epsilon^{\mu\nu\rho\alpha} \left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right) V_\alpha + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}.$$

  - For WWγ, only two, CP even couplings are generally considered: λ_γ and $\Delta k_\gamma = k_\gamma - 1$
  - For WWZ, another CP even variable is used g_1^Z
- In SM unitarity is conserved at all energies, anomalous couplings violate it at some energy.
  - Usually analyses follow form-factor parametrisation of couplings as function of energy scale

$$\lambda_V = \frac{\lambda_V^0}{\left(1+\hat{s}/\Lambda^2\right)^2} \qquad \Delta\kappa_V = \frac{\Delta\kappa_V^0}{\left(1+\hat{s}/\Lambda^2\right)^2}$$

Anomalous TGC measurements



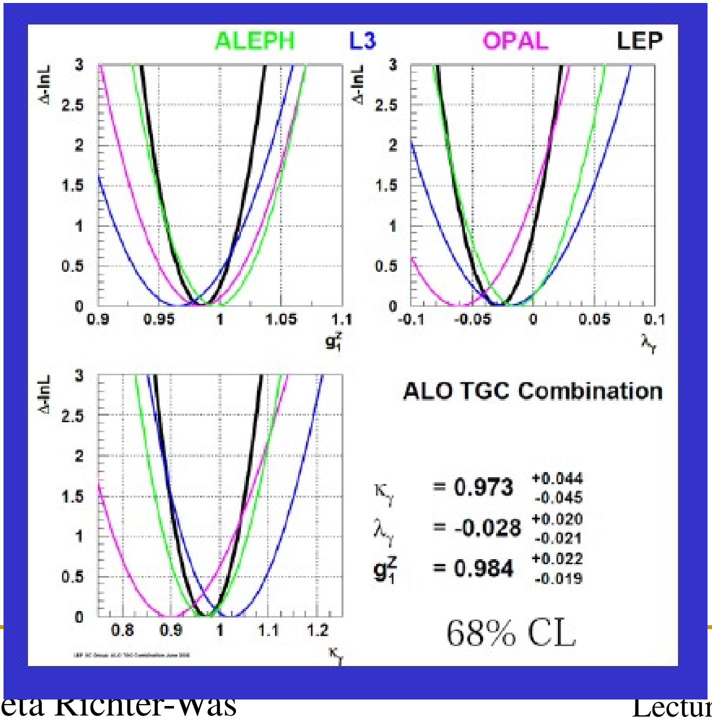
t-channel dominates cross section

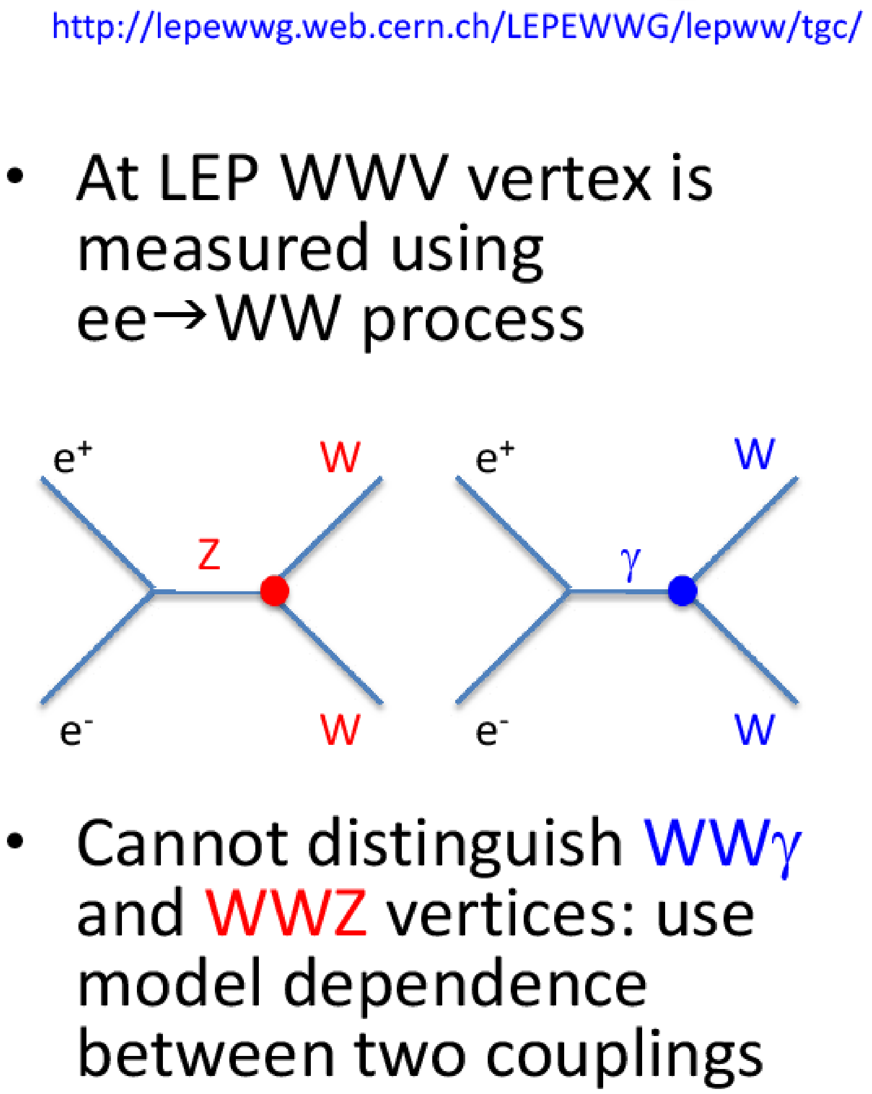
s-channel sensitive to new physics through TGCs

- Diboson channels are used to test the SM description for gauge bosons interations
  - Tevatron (LHC) results complementary to LEP
    - Sensitive to deviations at higher Q^2
    - Separately probe WWZ and WWγ vertices

Complementarity to LEP

- Experiments at LEP2 primarily tested a combination of WWγ and WWZ TGC's in ee→ WW by full reconstruction of event kinematics and cross-section measurements at sqrt(s) < 2009 GeV



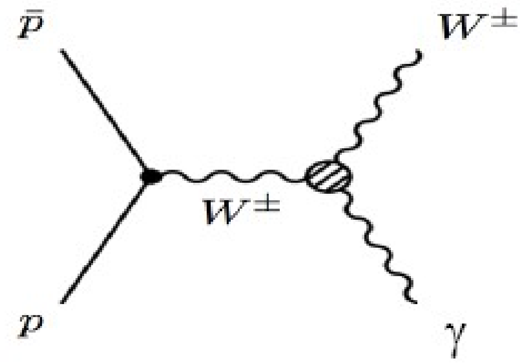


http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc/

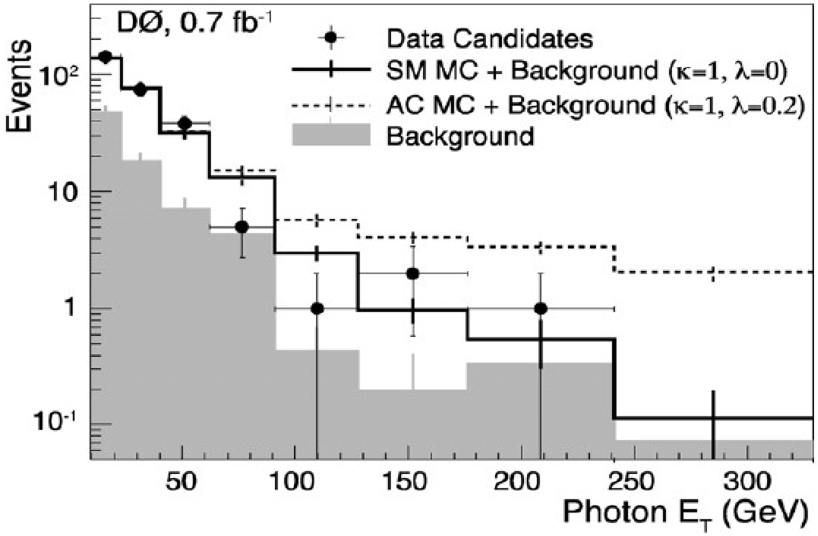
- At LEP WWV vertex is measured using ee→WW process

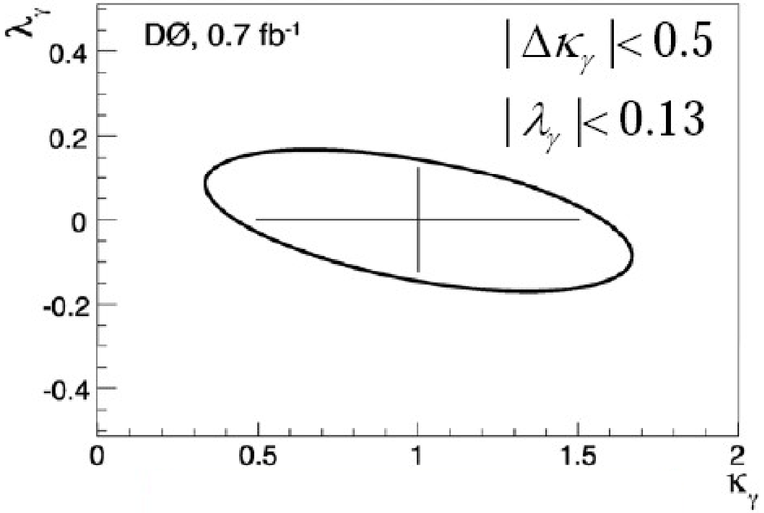
- Cannot distinguish WWγ and WWZ vertices: use model dependence between two couplings

WWγ coupling

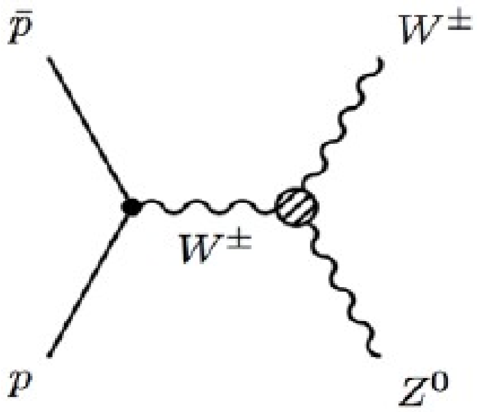


- WWγ coupling can be directly probed in Wγ production
  - Require standard photon and lepton identification criteria
  - $p_T(\gamma) > 8$ GeV, $\Delta R > 0.7$
- Use MC generator to simulate effect of anomalous coupling

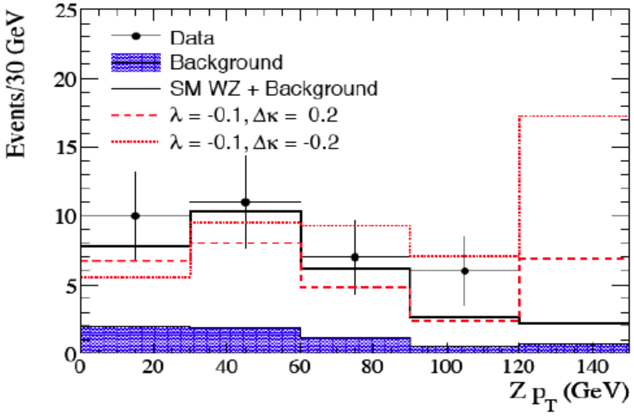


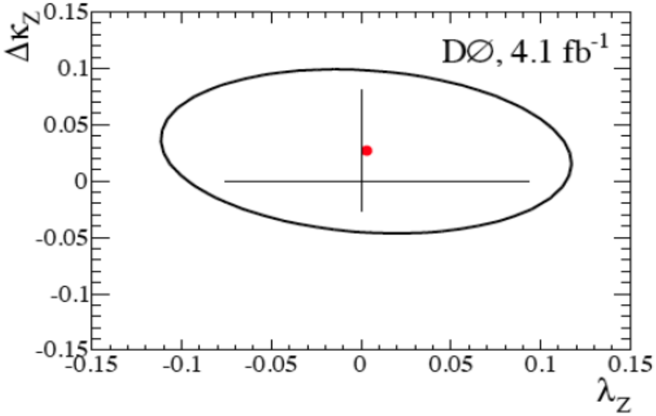


WWZ coupling



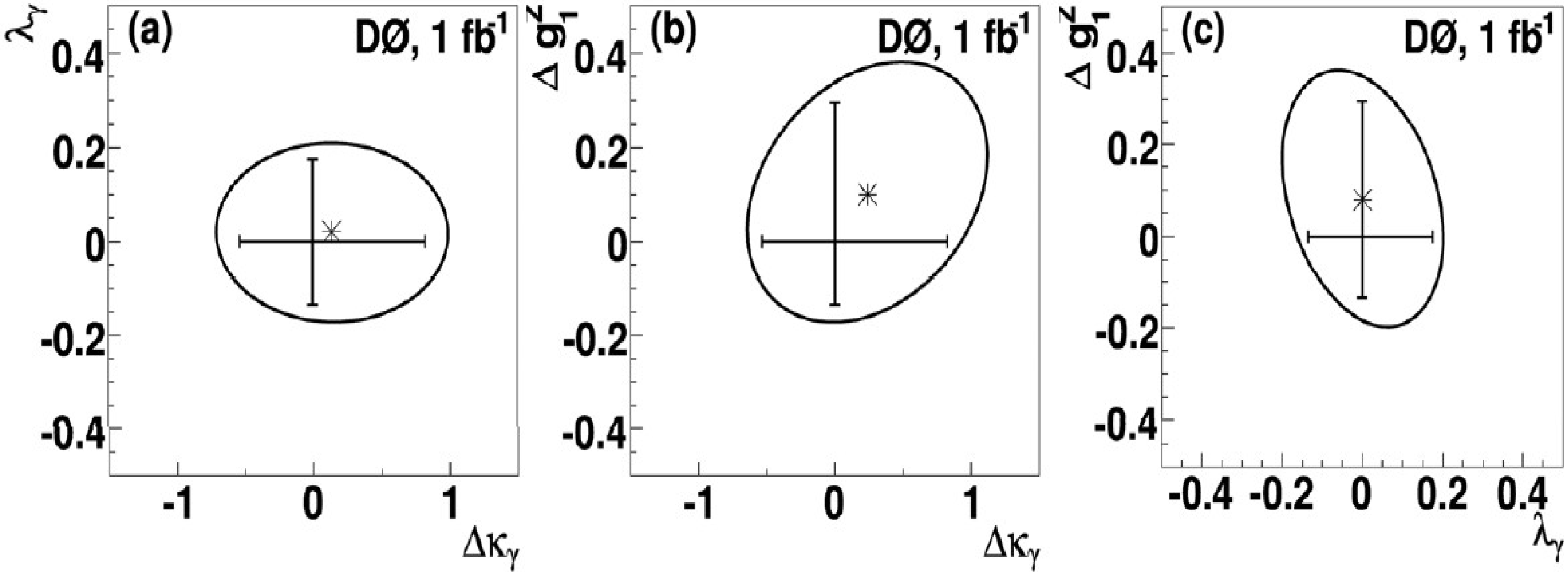
- Two processes can be used to probe this coupling: WW and WZ
  - WZ production is unique to directly check WWZ coupling
  - Tevatron is using leptonic decay channels





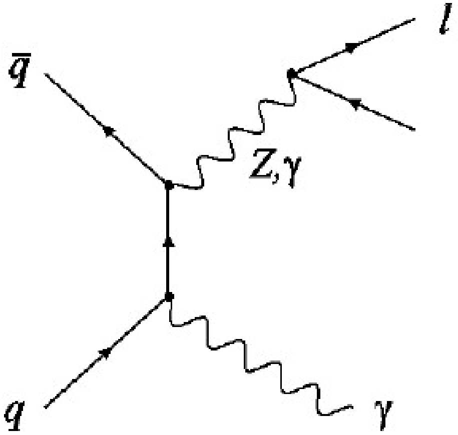
WWγ – WWZ coupling

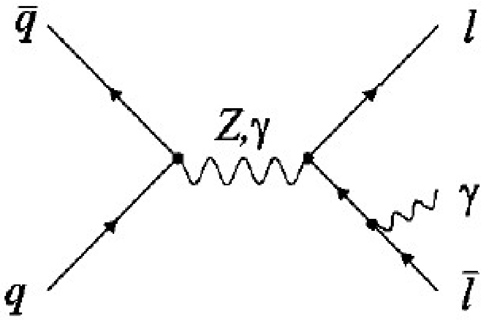
- Results are consistent with SM predictions
  - Limits on TGC's are ~0.2 at 95% CL

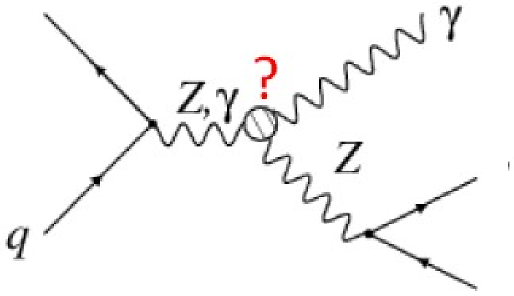


Neutral TGC: $ZZ\gamma$ and $Z\gamma\gamma$

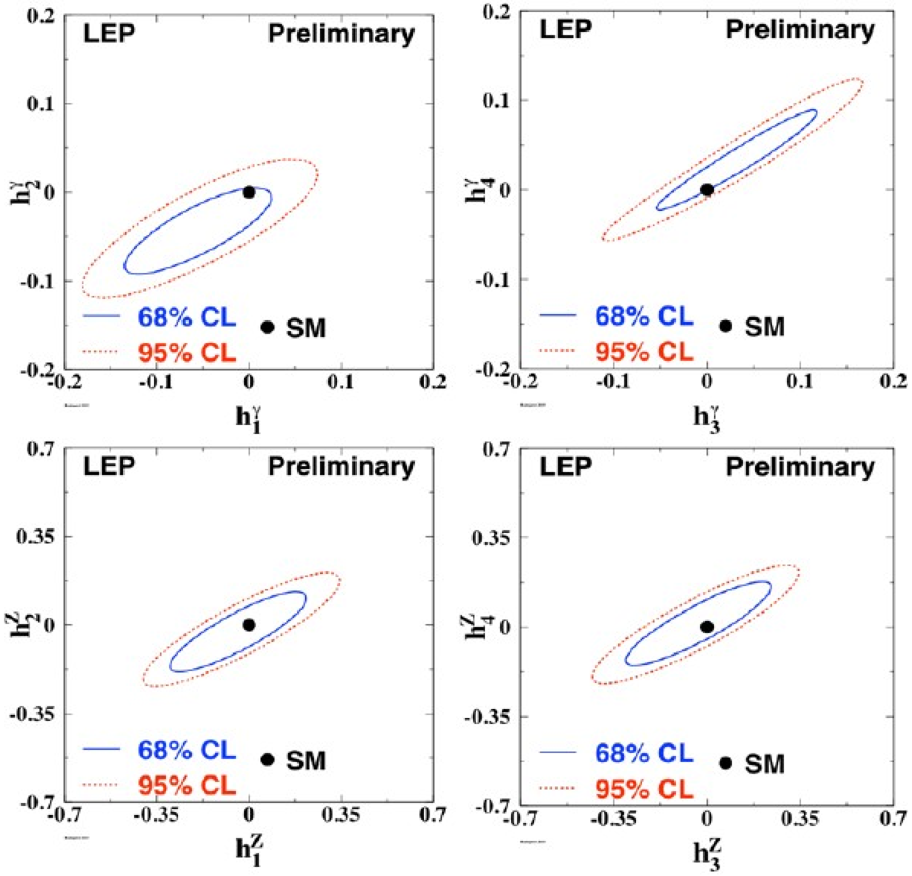
- SM predicts only two three-level diagrams of $Z\gamma$ via initial and final state radiation
  - Events with charged leptons are very clean but less sensitive to TGC's
  - $ZZ\gamma$ and $Z\gamma\gamma$ couplings are almost zero







Previous results on Zγ: LEP



LEP EWWK 2003, Preliminary

$$-0.056 < h_1^\gamma < 0.055$$

$$-0.045 < h_2^\gamma < 0.025$$

$$-0.049 < h_3^\gamma < -0.008$$

$$-0.002 < h_4^\gamma < 0.034$$

$$-0.13 < h_1^Z < 0.13$$

$$-0.078 < h_2^Z < 0.071$$

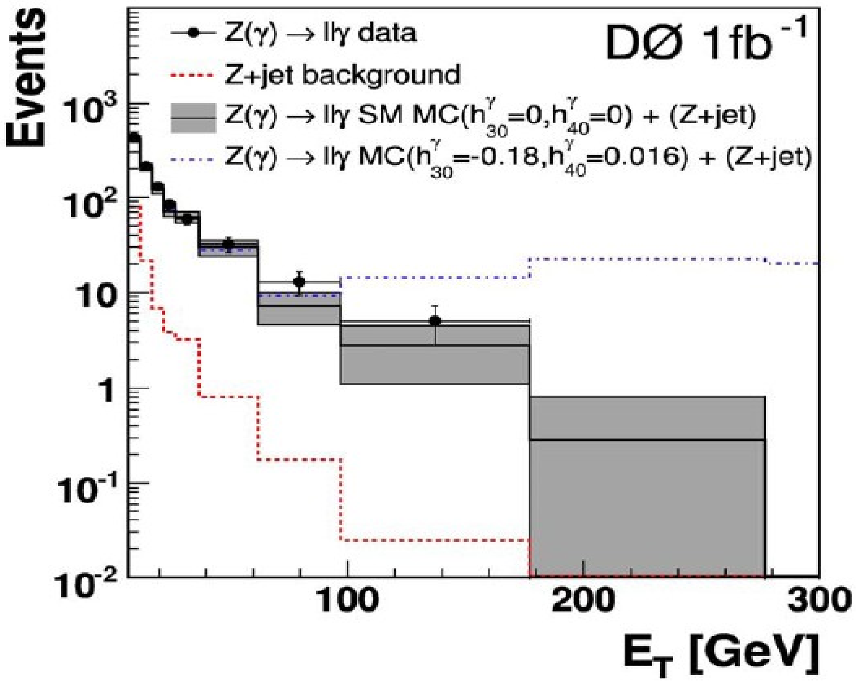
$$-0.20 < h_3^Z < 0.07$$

$$-0.05 < h_4^Z < 0.12$$

- Measured ZZγ and Z$\gamma\gamma$ couplings agree with SM at 10^{-1} – 10^{-2} level.

Search for a TGCs in $Z\gamma$

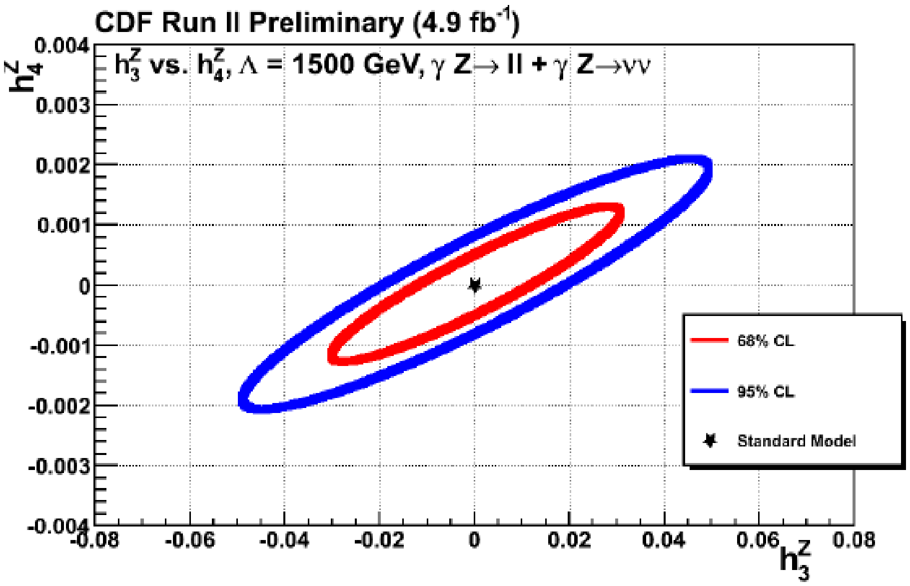
- Use both $Z\gamma \to ll\gamma$ and $Z\gamma \to \nu\nu\gamma$ productions to search for anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.

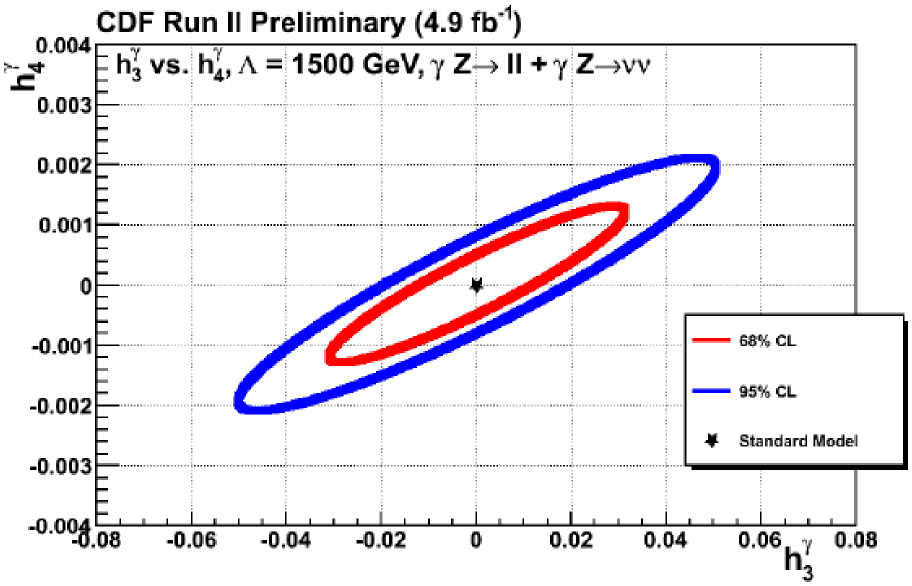


- Cross-section and p_T^γ spectrum agrees well with SM predictions

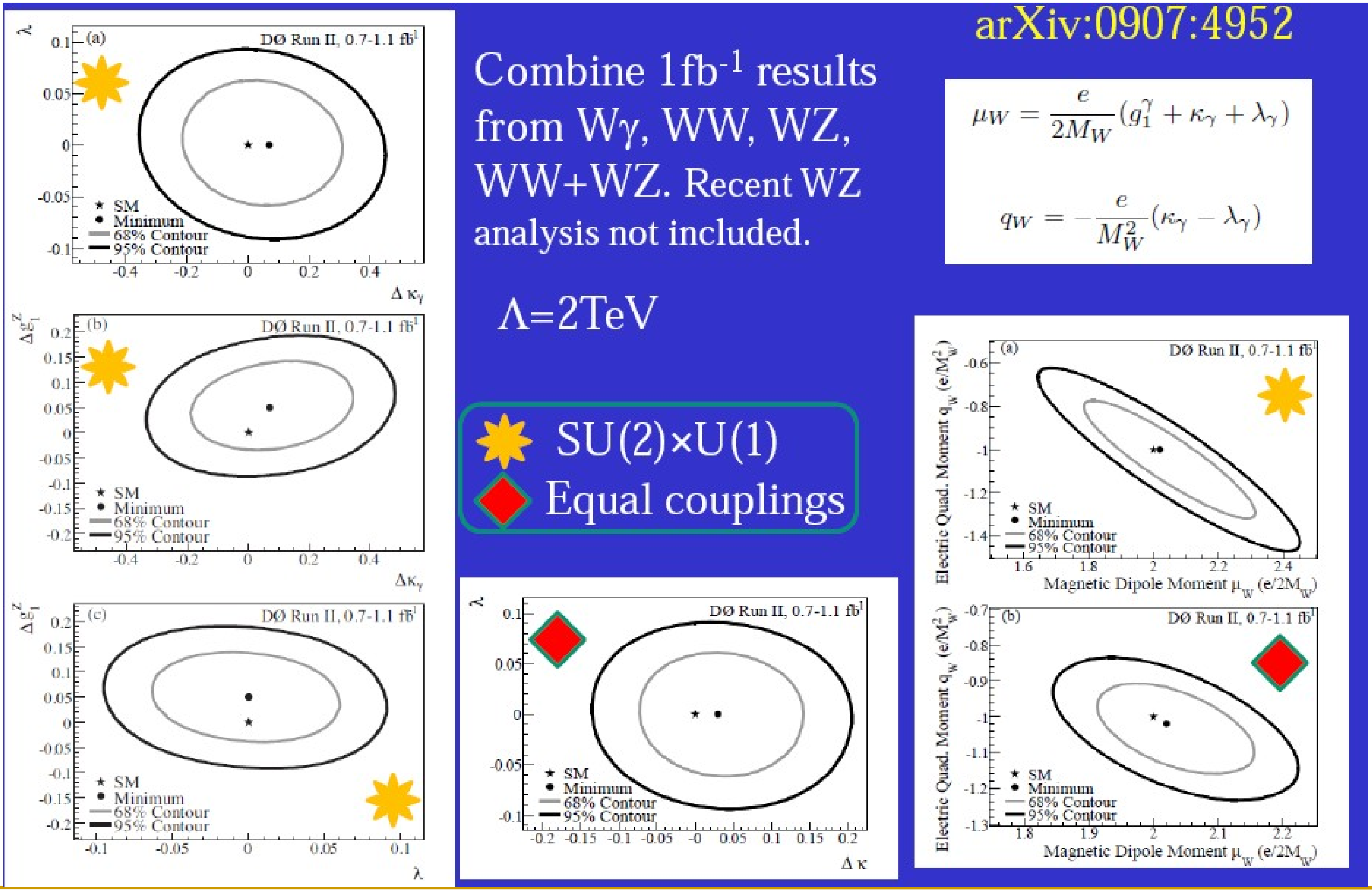
Combined limits

- The most stringent limits on ZZγ and Zγγ anomalous couplings
  - $|h_3^V| < 0.016$, $|h_4^V| < 0.0006$ at 95% C.L.





D0 charged TGC combination



arXiv:0907:4952

Combine 1fb^{-1} results from Wγ, WW, WZ, WW+WZ. Recent WZ analysis not included.

$$\mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$

$$q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$

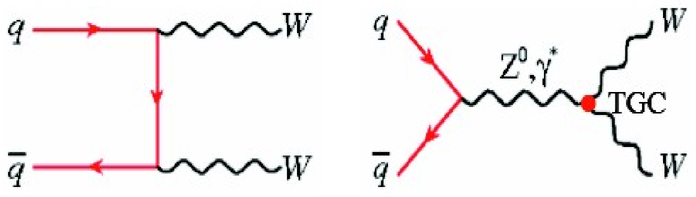
Λ=2TeV

✸ SU(2)×U(1)

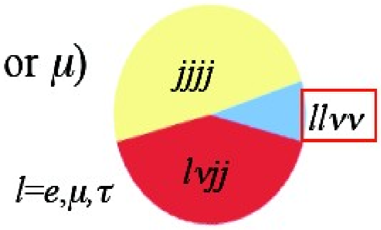
◆ Equal couplings

Examples from ATLAS and CMS:

$WW \rightarrow l\nu l\nu$

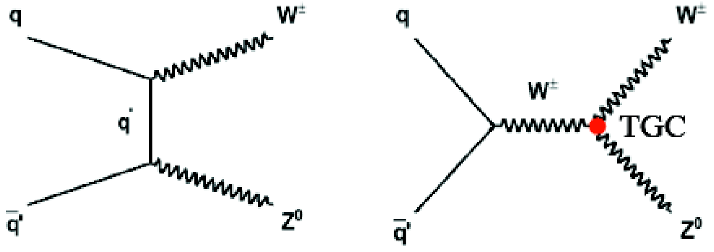


- Small BR: ~5-6% (l=e or μ)
- Clean sample

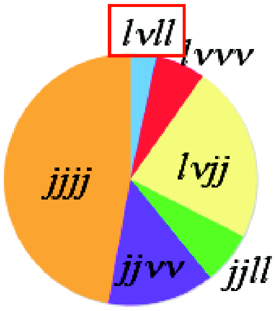


- Probes WWγ & WWZ TGC

$WZ \rightarrow l\nu ll$

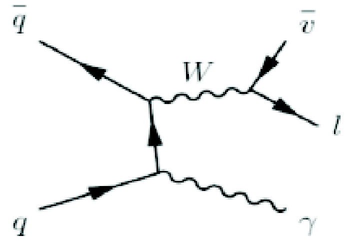


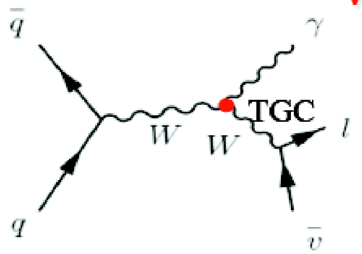
- Small BR:~2% (l=e or μ)
- Clean final state



- Probe WWZ TGC

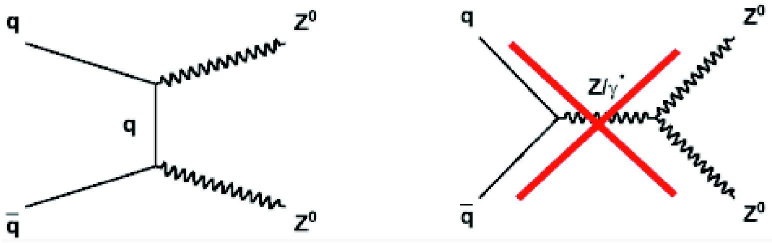
Examples from ATLAS and CMS:





$W\gamma \to l\nu\gamma$

- Wγ measurement can probe WWγ TGC
- Events selected with 1 isolated lepton (e,μ) , 1 isolated photon, large E_T^{miss}



$ZZ \to llll,\ \nu\nu ll$

- *llll* : BR ~ 0.5%
- *ννll* : BR ~ 3%
- ZZZ and ZZγ couplings forbidden in SM

LHC prospects

ATLAS TGC sensitivity for 1.0 fb^{-1}

95% CL intervals for anomalous TGCs, cutoff $\Lambda = 2$ TeV

Diboson	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
WZ(ATLAS) 1.0 fb^{-1}	[-0.028,0.024]	[-0.203,0.339]	[-0.021,0.054]		
WZ(D0) 1.0 fb^{-1}	[-0.17,0.21]	[-0.12,0.29]	$\Delta g_1^Z = \Delta\kappa_Z$		
WW(ATLAS) 1.0 fb^{-1}	[-0.108,0.111]	[-0.117,0.187]	[-0.355,0.616]	[-0.240,0.251]	[-0.259,0.421]
WW(LEP)	$\lambda_Z = \lambda_\gamma$	$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$	[-0.051,0.034]	[-0.105,0.069]	[-0.059,0.026]
Wγ(ATLAS) 1.0 fb^{-1}				[-0.43,0.20]	[-0.09,0.04]
Wγ(D0) 0.16 fb^{-1}				[-0.88, 0.96]	[-0.2,0.2]

LHC prospects

WW, WZ, Wγ and Zγ signal can be established with statistical sensitivity better than 5σ for the first 0.1 fb^{-1} integrated luminosity, and ZZ signal can be established with 1.0 fb^{-1} data.

The anomalous triple gauge boson coupling sensitivities from LHC/ATLAS can be significant improved over the results from Tevatron and LEP using the first 1.0 fb^{-1} data.

SM Diboson productions are important control samples for Higgs, SUSY, Technicolor, G, Z' particle searches with diboson final states.

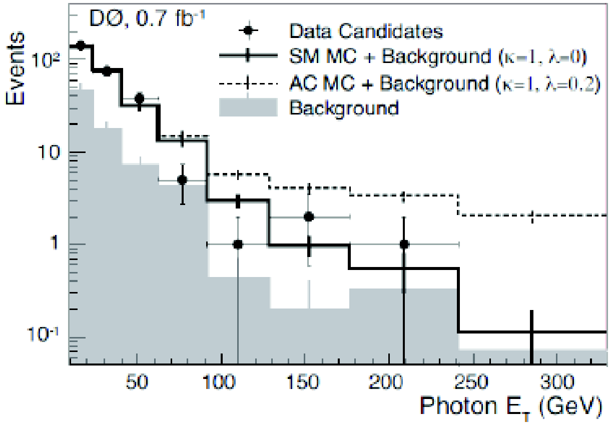
Next topics

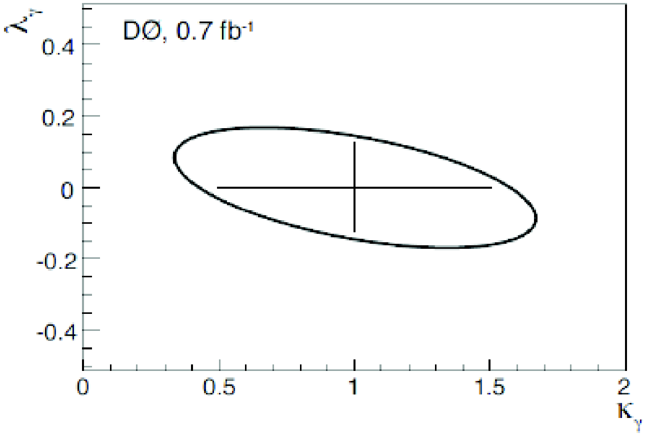
- 8.12, 15.12 – Higgs (SM)
- 5.01 - Searches: new exclusion limits
- 12.01 - Higgs (MSSM)
- 19.01, 26.01 - SUSY

Anomalous TGC measurements (at Tevatron)

- **$W\gamma \rightarrow l\nu\gamma$**
- $Z\gamma \rightarrow ll\gamma$
- $Z\gamma \rightarrow \nu\nu\gamma$
- $WW \rightarrow ll\nu\nu$
- $WW \rightarrow l\nu qq$
- $WZ \rightarrow l\nu qq$
- $WZ \rightarrow lll\nu$
- $WZ \rightarrow qq\nu\nu$
- $ZZ \rightarrow qq\nu\nu$
- $ZZ \rightarrow llll$
- $ZZ \rightarrow ll\nu\nu$
- $ZZ \rightarrow llqq$

Photon E_T sensitive variable





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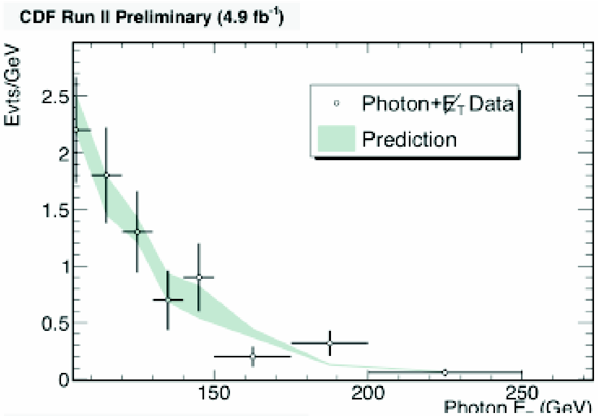

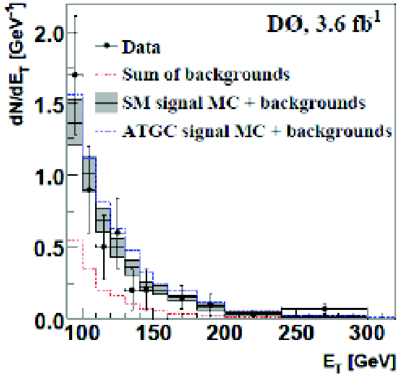

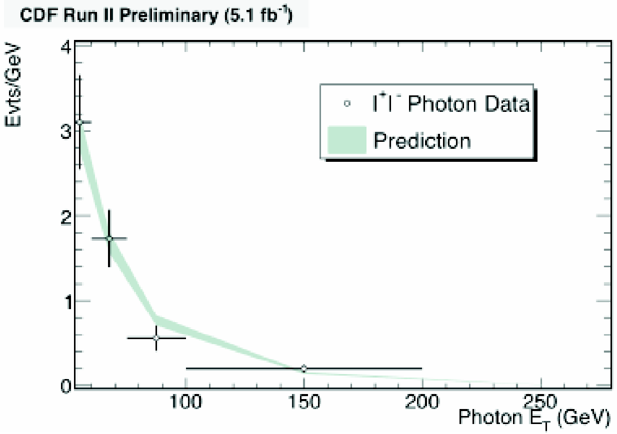

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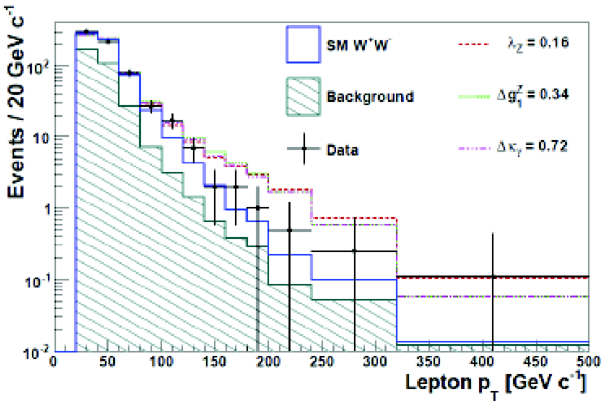
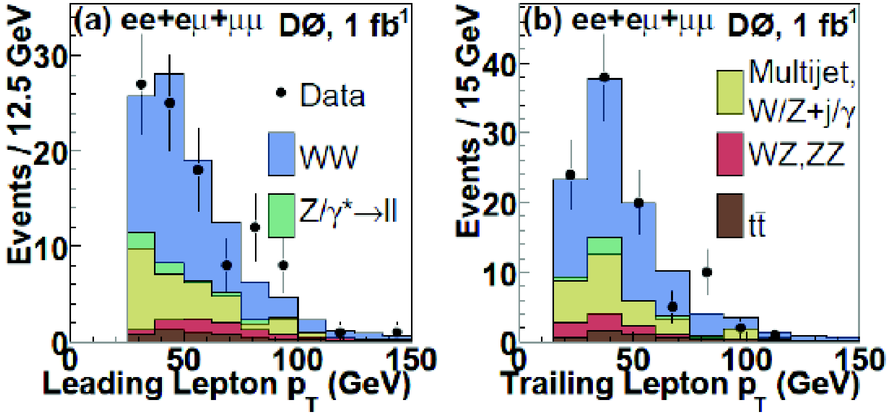
- $ZZ \to ll\nu\nu$
- $ZZ \to llqq$

Lepton p_T sensitive variable





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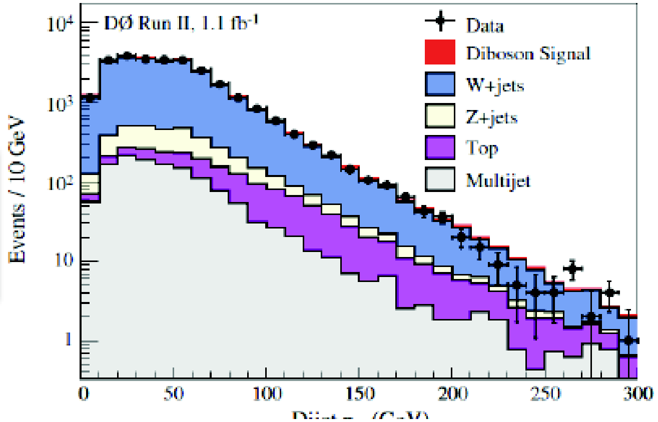
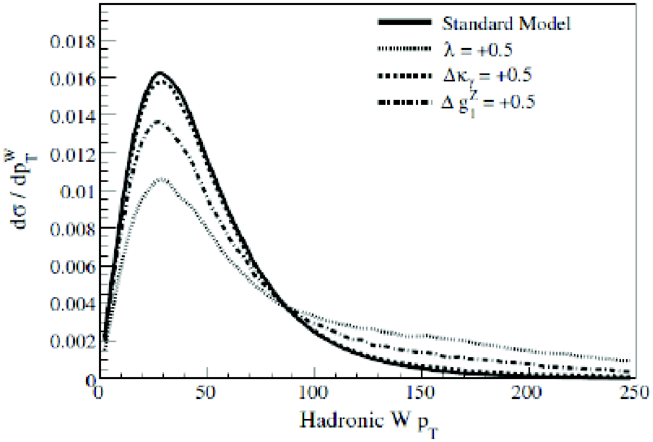
Dijet p_T sensitive variable





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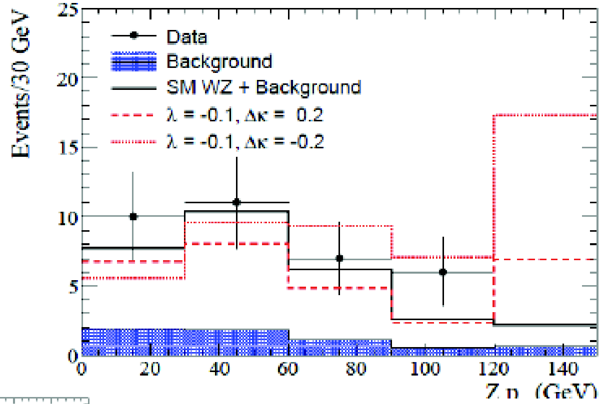
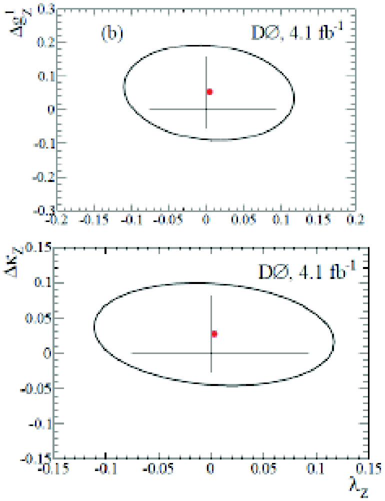
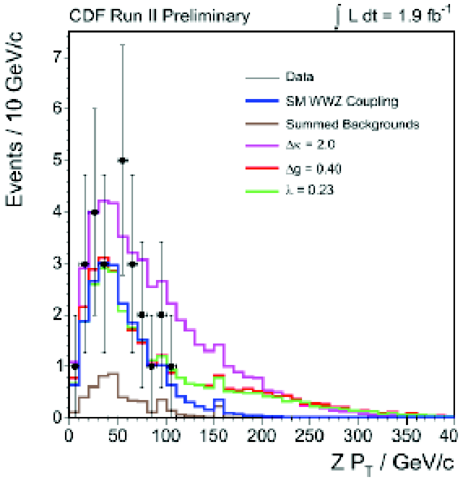
Z p_T sensitive variable







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- $ZZ \to ll\nu\nu$
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