Studies of Zγ production at DØ and search for physics beyond the standard model

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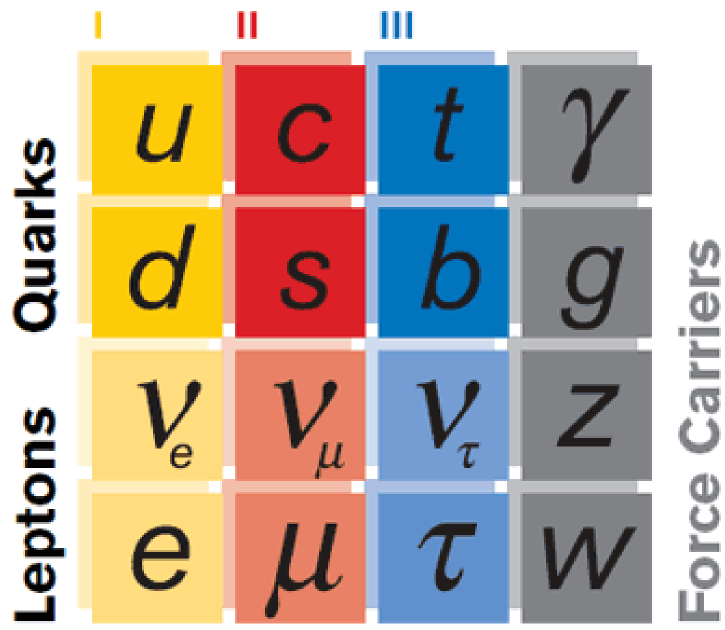
Outline

- **Motivation**
  - standard model
  - diboson physics and anomalous couplings (AC)
- **The experimental apparatus**
  - Tevatron collider and the DØ detector
- **Identification (ID) of signal and background**
- **Cross section measurement and AC limits analyses:**
  - charged leptons channel ($Z\gamma \rightarrow ll\gamma$)
  - neutrino channel ($Z\gamma \rightarrow \nu\nu\gamma$)
  - combination of the results
- **Resonance search**
  - charged leptons channel ($X \rightarrow Z\gamma \rightarrow ll\gamma$)
- **Conclusion and prospects**

The Standard Model

- **The standard model:**
  - describes interactions between the three generations of quarks and leptons
  - vector gauge bosons – force carriers:
    - electroweak: $W^{\pm}$, Z, photon
    - strong: gluons
  - works great at low and moderate energies



Three Generations of Matter

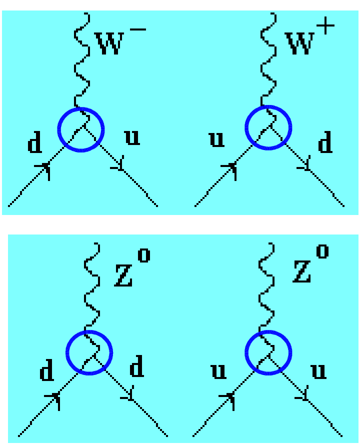
- **Questions ...**
  - gravity: graviton??
    - not included into the SM!
  - why three generations? what is the origin of mass?
  - what is the origin of dark matter – possibly graviton? are there more than 4 space-time dimensions?
  - *etc…*

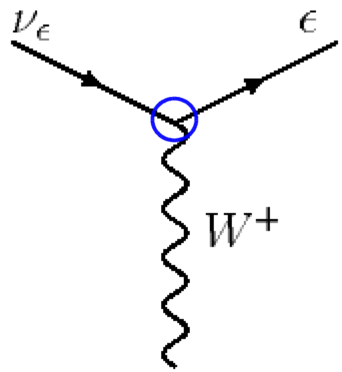
Diboson Physics

Why diboson physics?

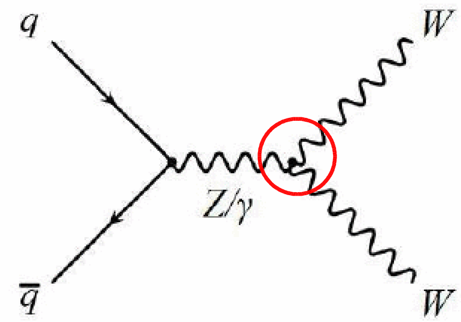
- gauge bosons in the SM have well predicted (and measured!) couplings to leptons and quarks
- diboson production: important decay modes for new phenomena (*e.g.* Higgs, Z' *etc.*)
- search for new physics: explore the least tested sector of the SM
- analysis of vector boson self-interactions provides an important test of the gauge sector of the SM

well known



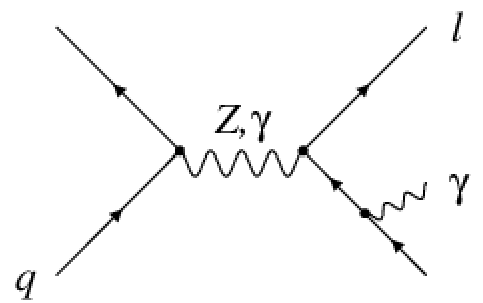


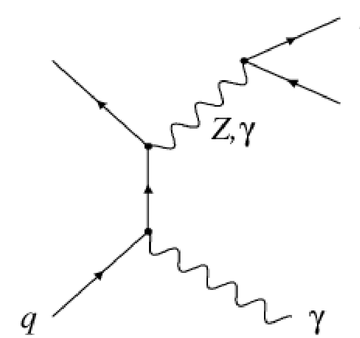
not-so-well tested



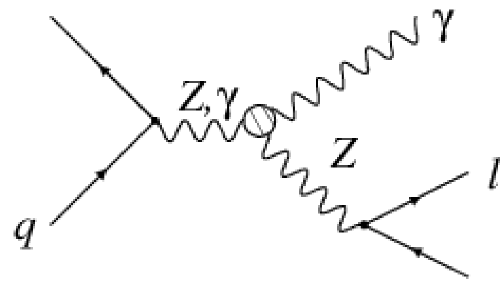
ZZγ and Zγγ Vertices

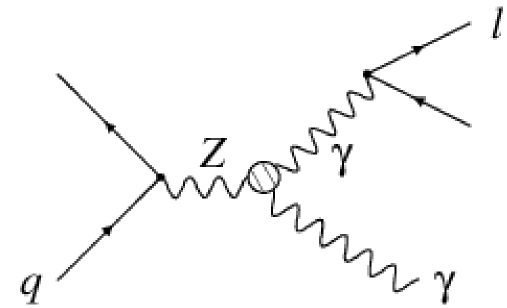
SM allowed:





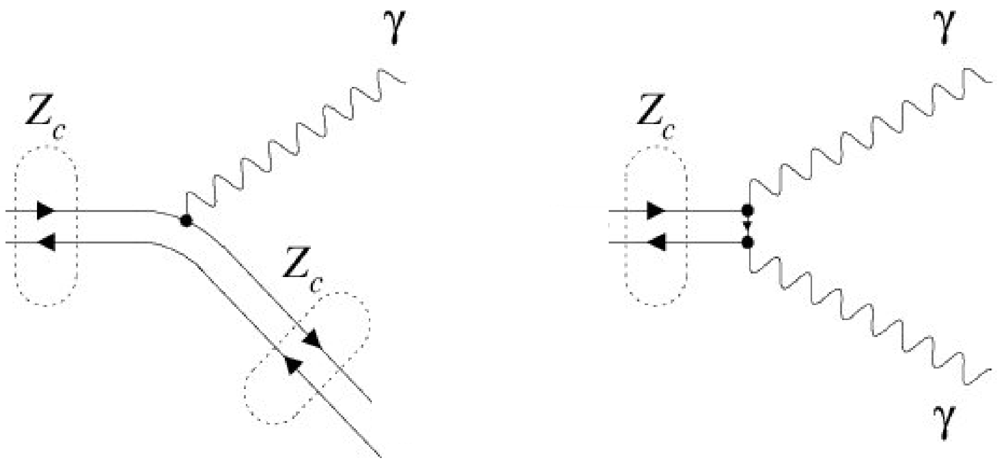
SM forbidden:



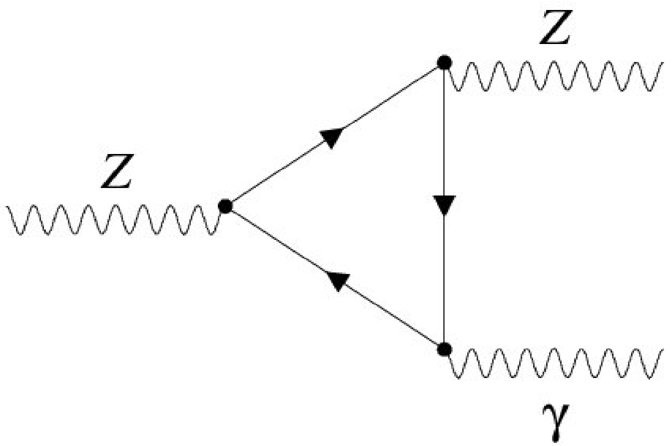


- **In the SM ZZγ and Zγγ couplings are zero at tree level**
  - higher-order corrections contribute at ~O(10^{-4}) level
  - in some extensions of SM couplings may have non-zero values – "anomalous couplings"

- **Compositeness of Z boson:**



- **SUSY:**



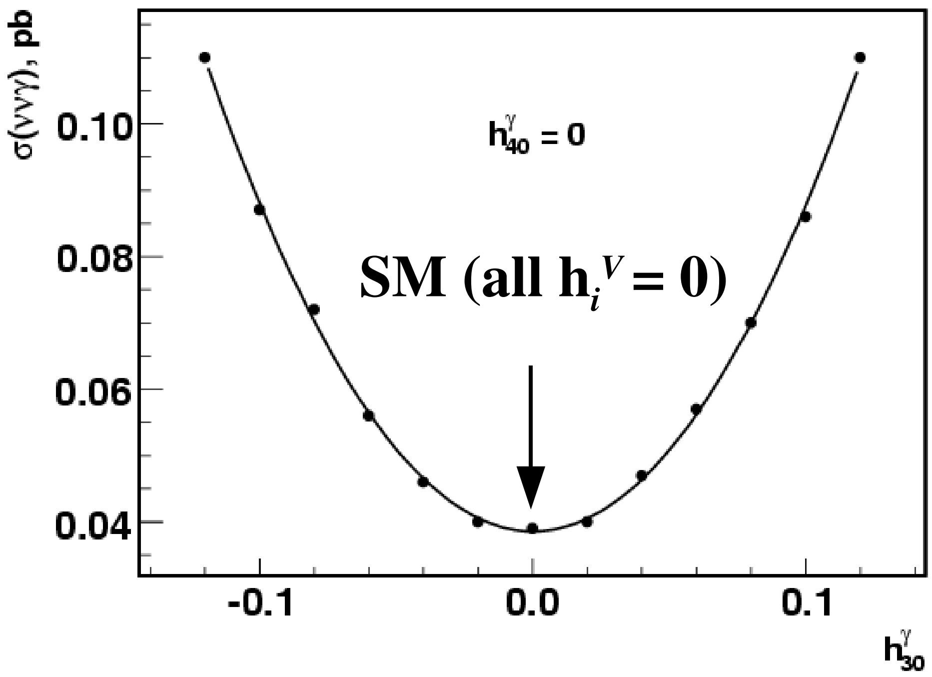
Anomalous Couplings Ansatz

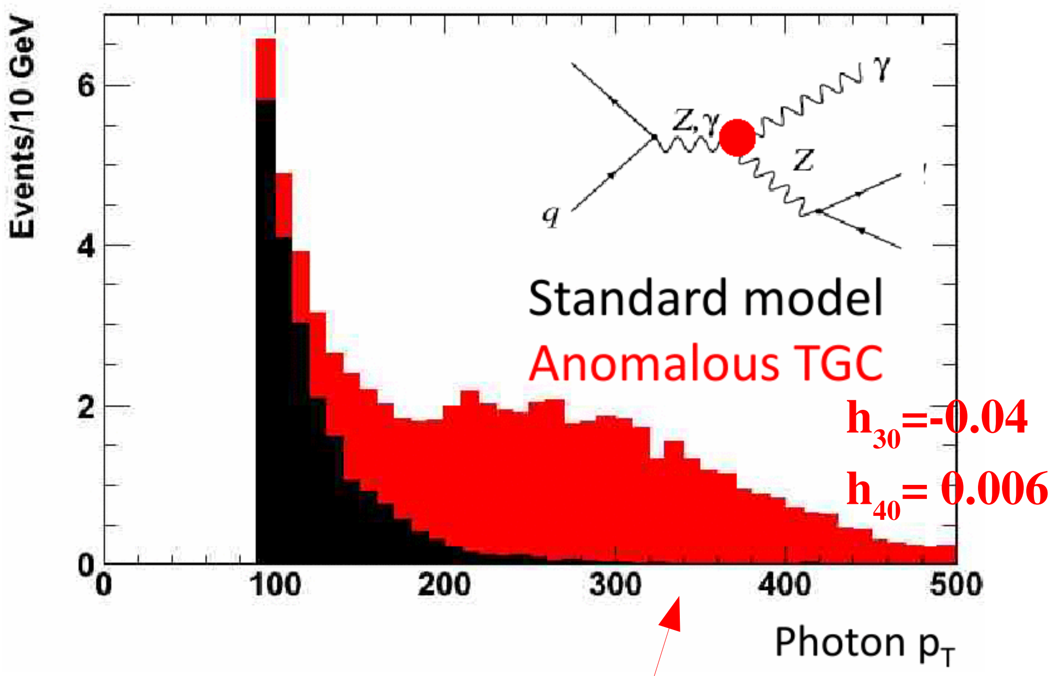
- **ZZγ and Zγγ couplings can be parameterized in general by 8 complex parameters h_i^Z and h_i^γ (i = 1,…,4):**

Low energy approximation

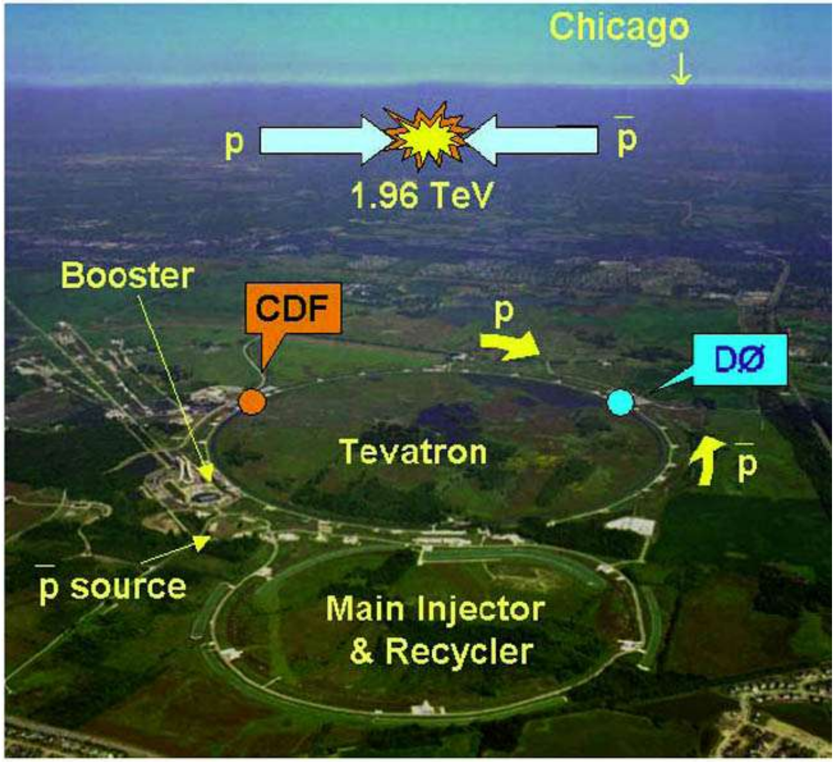
$$h_i^{Z,\gamma} = \frac{h_{i0}^{Z,\gamma}}{(1+\hat{s}/\Lambda^2)^n}$$

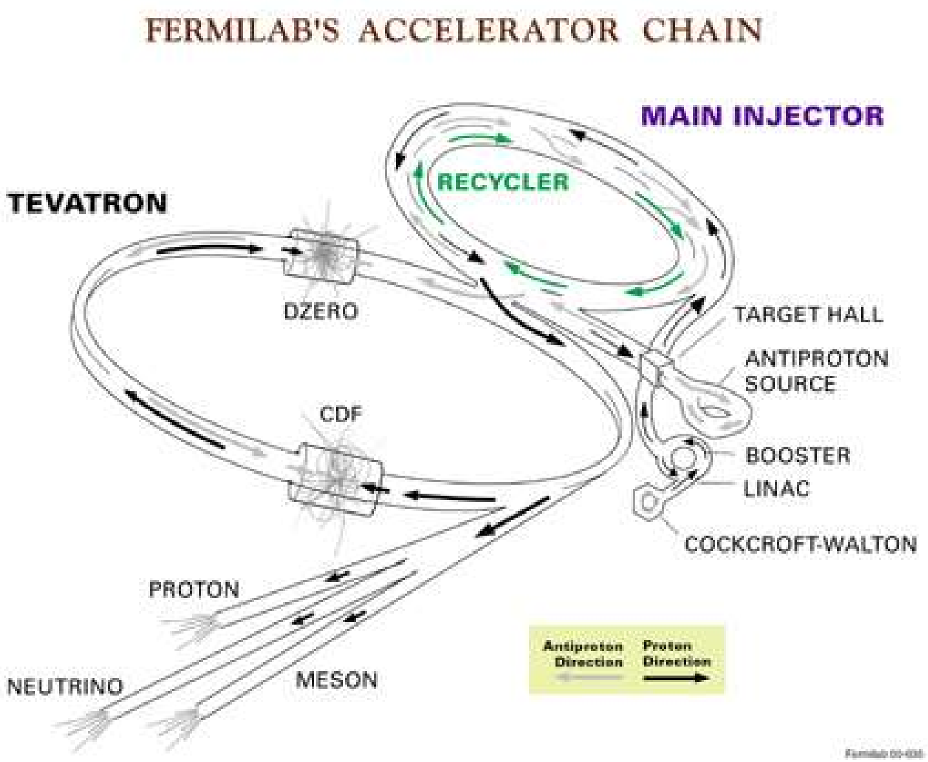
- **Λ is a form-factor scale –** characteristic energy scale above which new physics is no longer negligible, by convention **n = 3** for $\mathbf{h_{1,3}^V}$ and **n = 4** for $\mathbf{h_{2,4}^V}$
- **Usually Λ ≥ 1 TeV**
- **We set limits on real parts of $\mathbf{h_{30}^V}$ and $\mathbf{h_{40}^V}$ (V = Z** or **γ)**





- **Non-zero anomalous couplings lead to:**
  - **Zγ** cross section increase
  - production of photons with anomalously **high transverse momentum**

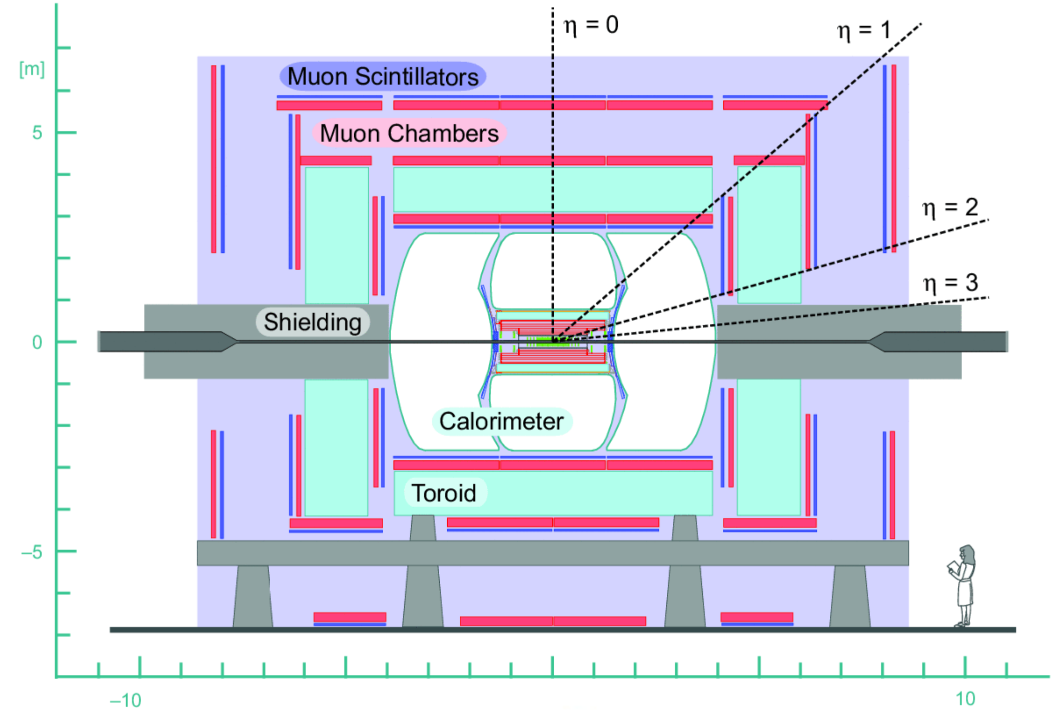


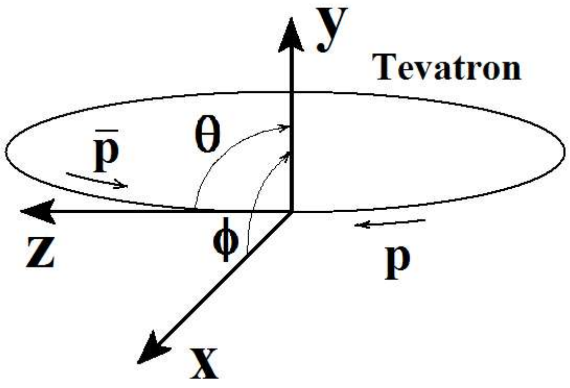


- **Located at Fermilab, Batavia, Illinois**
- **Proton – antiproton interactions**
- **Center-of-mass energy $\sqrt{s} = 1.96$** TeV

- **Tracking system (|η| < 3):**
  - silicon microstrip tracker
  - central fiber tracker
  - superconducting 2 T solenoid
- **EM and hadron calorimeters (|η| < 4):**
  - central calorimeter
  - 2 end calorimeters
- **Muon system (|η| < 2):**
  - central: scintillation counters and proportional drift tubes
  - forward: scintillation counters and mini drift tubes
  - 1.8 T toroids

$$\eta = -\ln(\tan(\Theta/2))$$



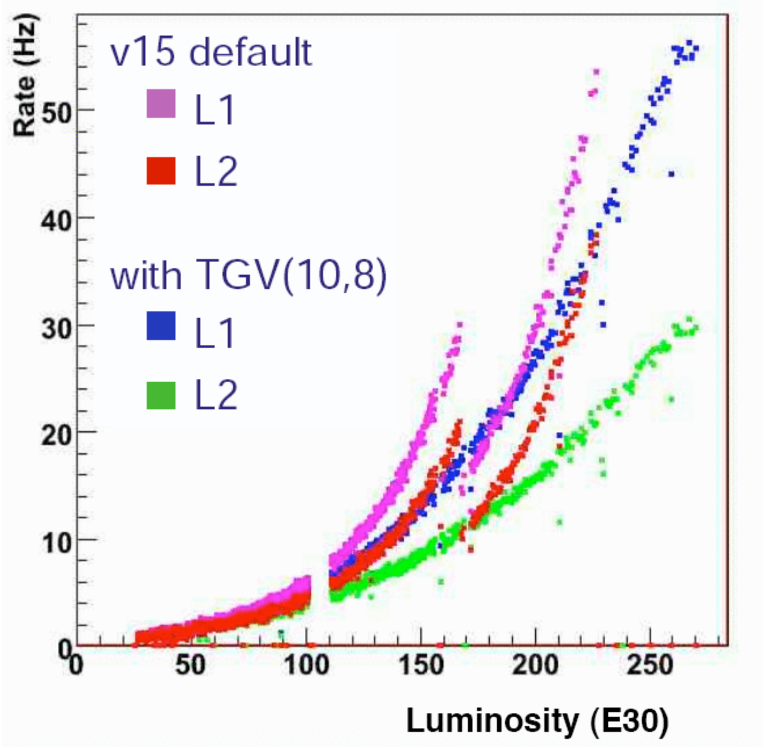


- **Proton-antiproton bunch crossings:**
  - ~1.7×10^{6} evt/sec × 200 kB/evt = 340 GB/sec !!
  - need to quickly analyze events and accept events of interest:
    - Electroweak physics – ≥ 1 high-p_T EM objects or muons

- **3-level trigger system (RED – EM, BLUE – muon)**
  - **L1 – hardware and firmware level:** ≥ 1 EM with cuts on E_T; isolation, track match, preshower confirmation – optional; ≥ 1 mu candidate, cuts on $N_{hits\ scint.}$, $N_{hits\ wire}$; match to a central track (CT) - optional
  - **L2 – simple software, calculate auxiliary variables:** cuts on E_T, calo isolation, likelihood; cuts on local muon p_T, quality info, scintillator timing, confirmed track p_T
  - **L3 – fast object reconstruction:** cuts on available filters – E_T (typically higher than L1), shower shape, likelihood, isolation, EM fraction; cuts on muon p_T (higher than L1), isolation, CT match with certain p_T, ...

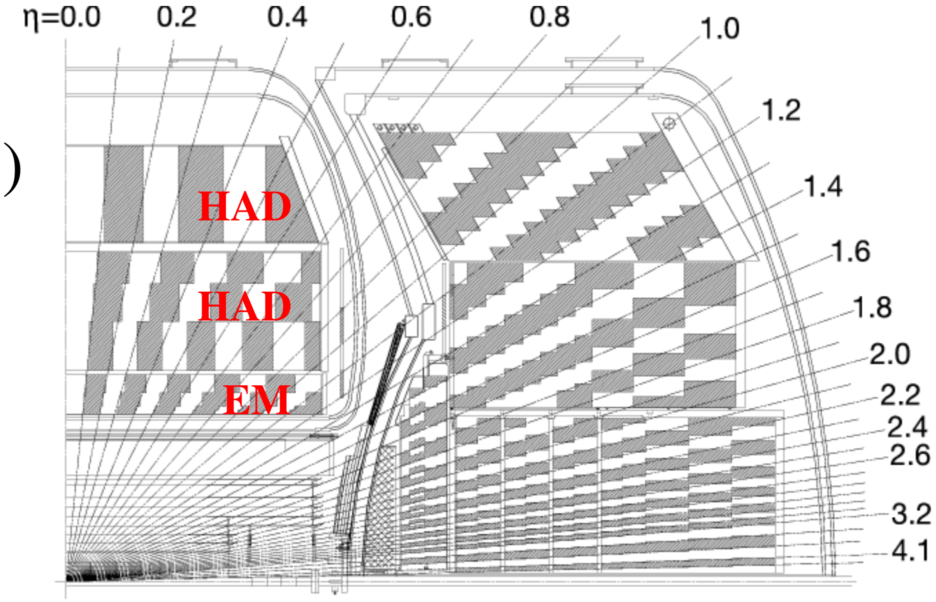
- **Properties:**
  - triggers are combined in trigger suites by L1 condition
  - bandwidth of each trigger (and the suite) is a function of instantaneous luminosity
  - with ever-increasing L_{inst} we accept more events than farms can consume – need to modify triggers to reduce the rates

High-p_T single track matched muon

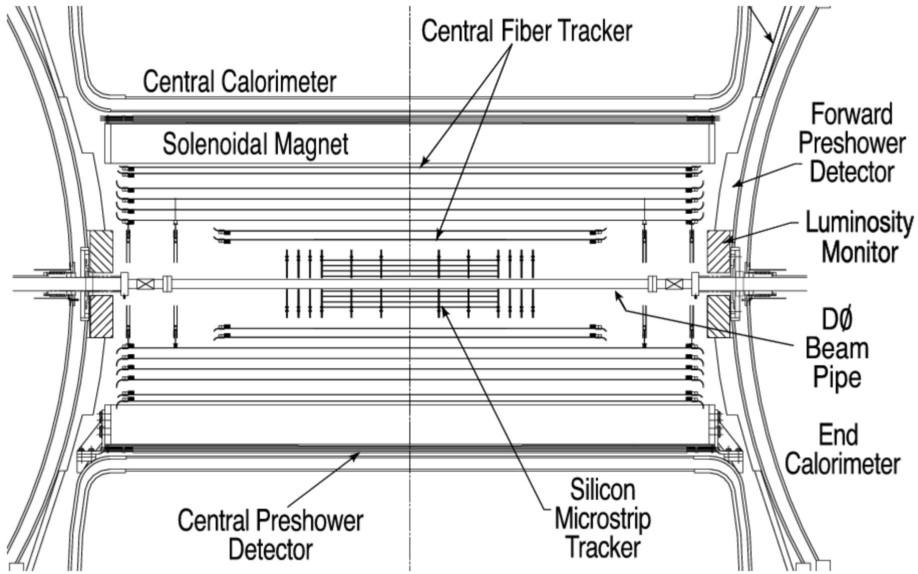


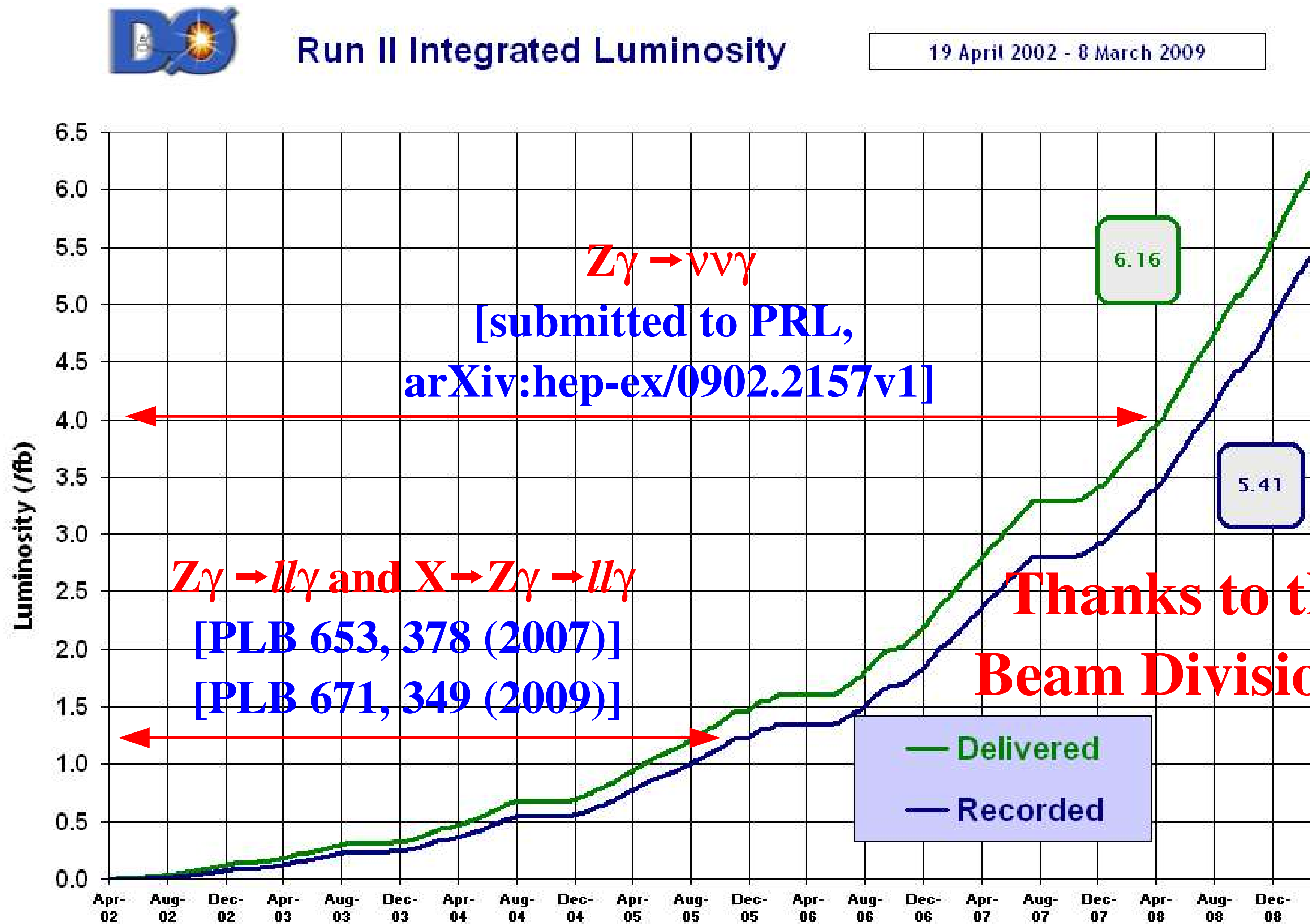
- **Handles:**
  - tighten conditions at trigger levels
  - additional variables at different levels
  - prescales at L1 – pass 1 out X

- **Liquid Ar Calorimeter:**
  - uranium absorber (EM and fine HAD)
  - copper/steel absorber (coarse HAD)
  - 4 signal layers – EM, 3 – fine HAD, 1 – coarse HAD
  - central: $|\eta| < 1.1$, end: $|\eta| < 4$
  - purpose: energy measurement and missing transverse energy estimate



- **Central Preshower (CPS)**
  - triangular scintillator strips
  - coverage: $|\eta| < 1.3$
  - purpose: calorimetry and tracking
  - fast energy and position measurement
  - improve matching between calorimeter showers and tracks





$Z\gamma \rightarrow \nu\nu\gamma$

[submitted to PRL, arXiv:hep-ex/0902.2157v1]

$Z\gamma \rightarrow ll\gamma$ and $X \rightarrow Z\gamma \rightarrow ll\gamma$

[PLB 653, 378 (2007)]

[PLB 671, 349 (2009)]

Thanks to the Beam Division!!

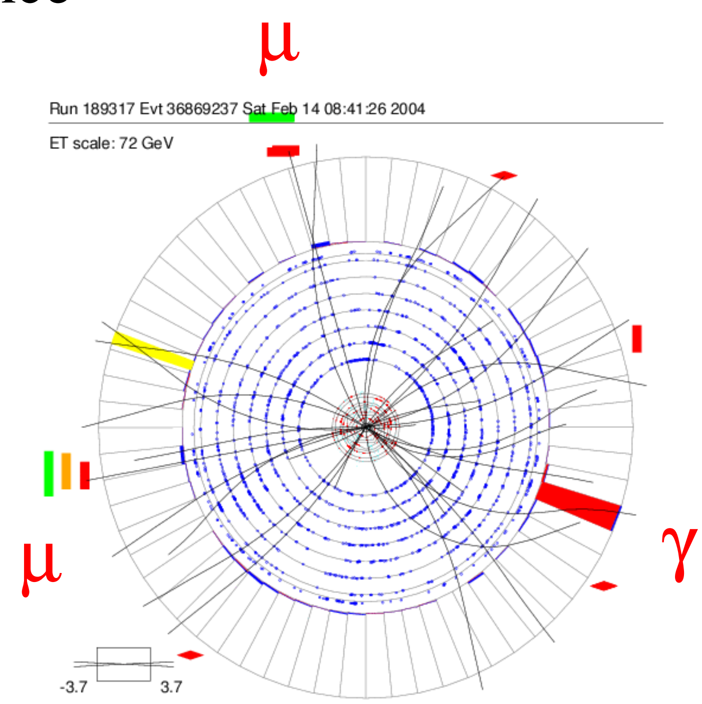
$Z\gamma$ Final State Signatures

- **States of interest (ordered by branching ratio, BR):**
  - ***$Z\gamma \to jets + \gamma$***
    - very large BR (**~70%**)
    - very large contamination from QCD backgrounds
  - **$Z\gamma \to \nu\nu\gamma$ (MET + γ)**
    - smaller BR (**~20%**)
    - only photon to reconstruct: high acceptance
    - Z boson is not reconstructed
  - **$Z\gamma \to ll\gamma$ ($ee\gamma$, $\mu\mu\gamma$, $\tau\tau\gamma$)**
    - even smaller BR (**~10%** with τ lepton mode)
    - very clean signal

- **Objects in the final state:**
  - electrons, muons, photons and neutrinos

Object ID: Muon

- **Hits in the muon system**
  - must be within the muon chambers acceptance
  - matched wire-scintillator hits
- **Matched to a central track**
  - more precise measurement of the p_T
  - use silicon tracker or beamspot to estimate the distance of the muon candidate from the beam line:
    - cosmic muons are less likely to be produced near the interaction point

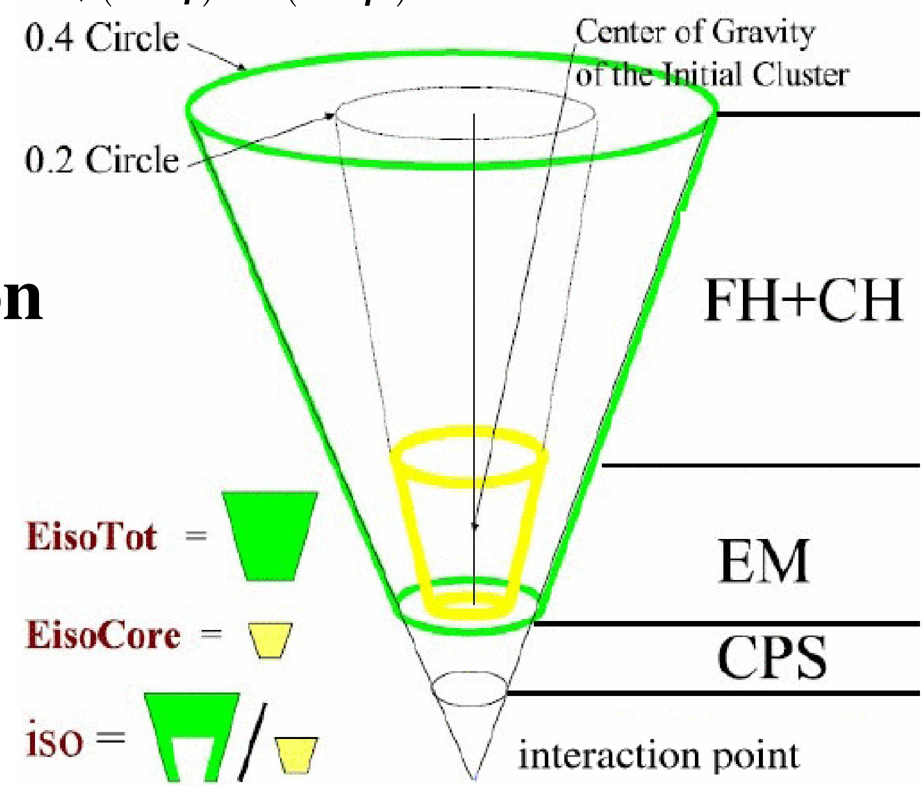


- **Isolation: limited activity in the tracker and calorimeter**
  - sum of tracks p_T in the cone around muon not to exceed **3.5** GeV/*c*
  - sum of calorimeter E_T in the annulus R(0.1,0.4) not to exceed **2.5** GeV

- **Isolated energy deposit in the fiducial region of the calorimeter**
  - most of its energy deposited in the EM calorimeter
  - isolation helps to suppress backgrounds from jets misidentified as electrons

Calorimeter isolation

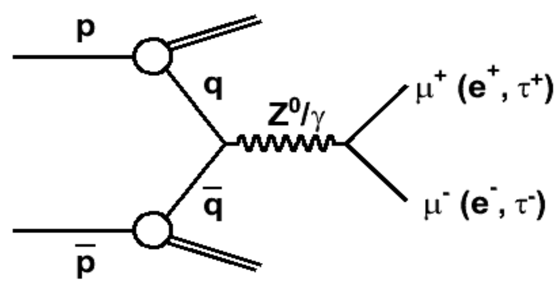
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

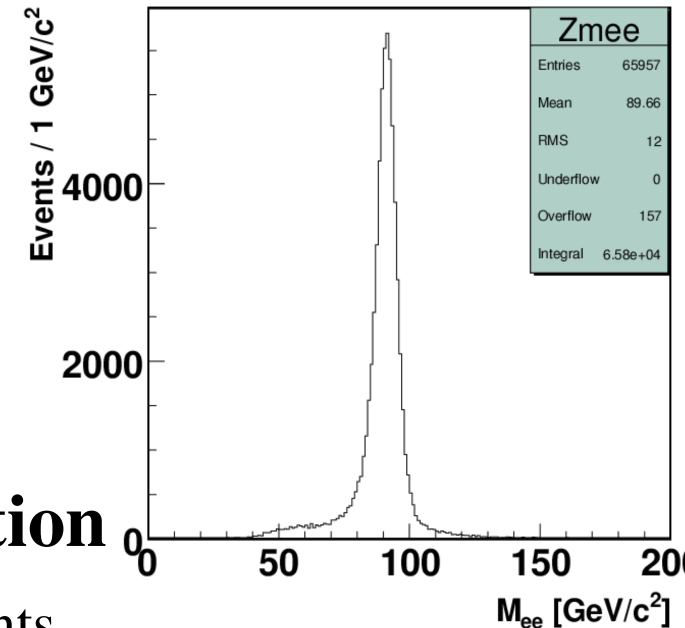


- **Matched to a central track**

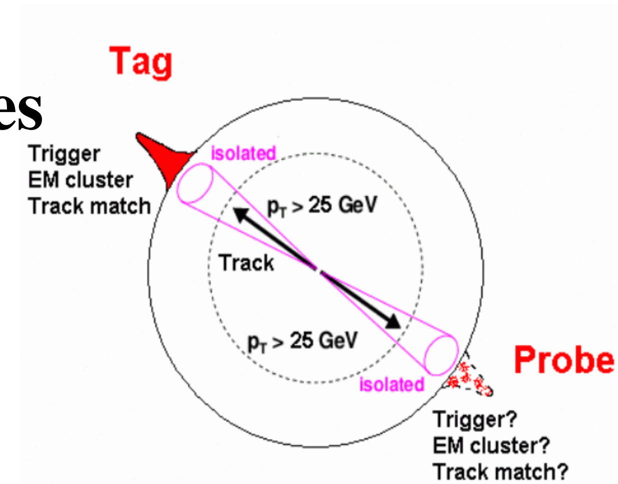
- **Additional cuts on combination of variables to further reduce backgrounds:**
  - combine the following variables:
    - isolation, shower shape
    - quality of the track match, *etc.*

- **Signature of Z boson is 2 high-pt isolated charged leptons and little missing energy:**
  - clean, well known signal, low background





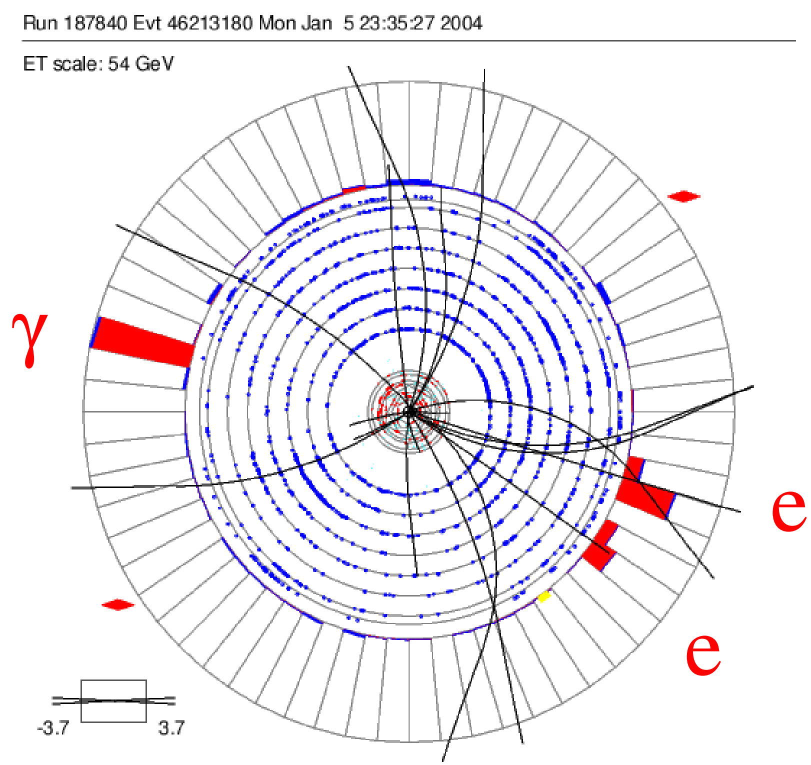
- **One of the best processes for calibration purposes:** *e.g.* cross-check luminosity measurements



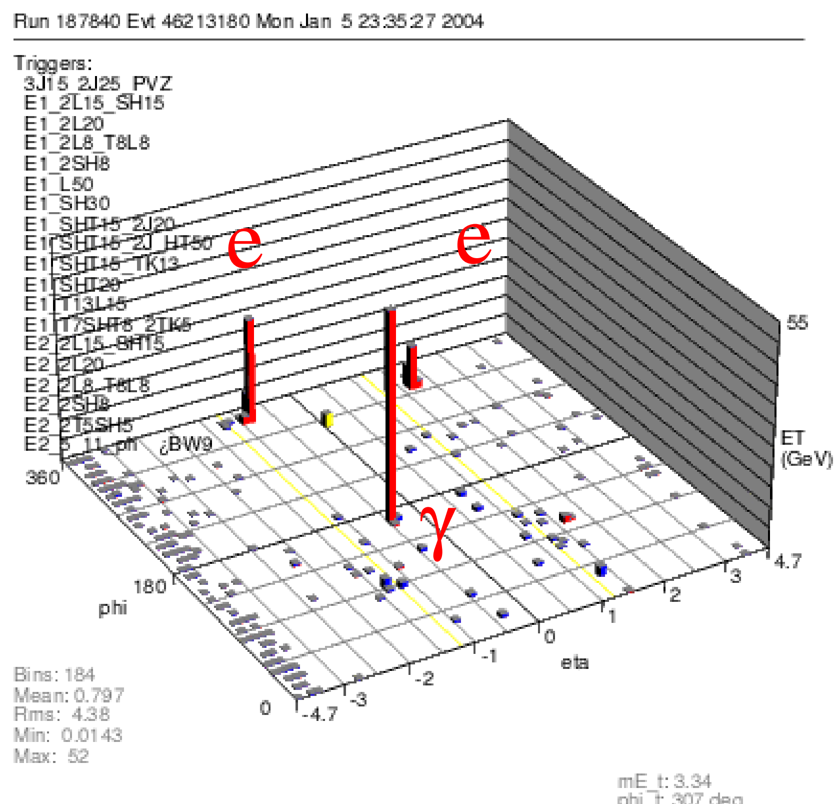
- **Electron and muon identification efficiencies are measured using the tag-and-probe method**
  - develop "collaboration-wide" common tools for electron and photon analyses for that purpose
  - certify electron definitions for out-of-box use

Reconstruction of Zγ: Just Add a Photon!

- **Require an additional photon for the Zγ final state**
- **Photon is reconstructed as an isolated EM cluster in the calorimeter, no track**



Tracker cross section + Cal



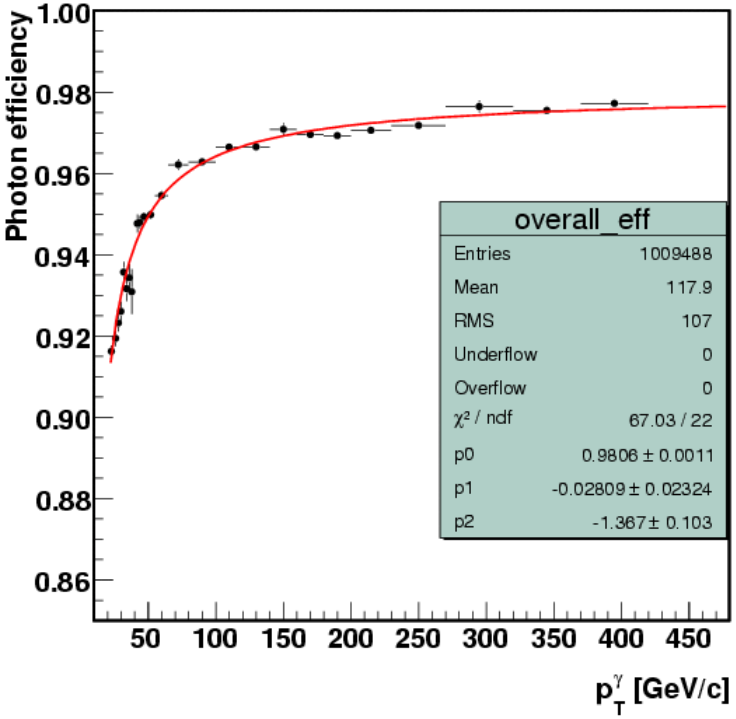
Calorimeter lego plot

Object ID: Photon

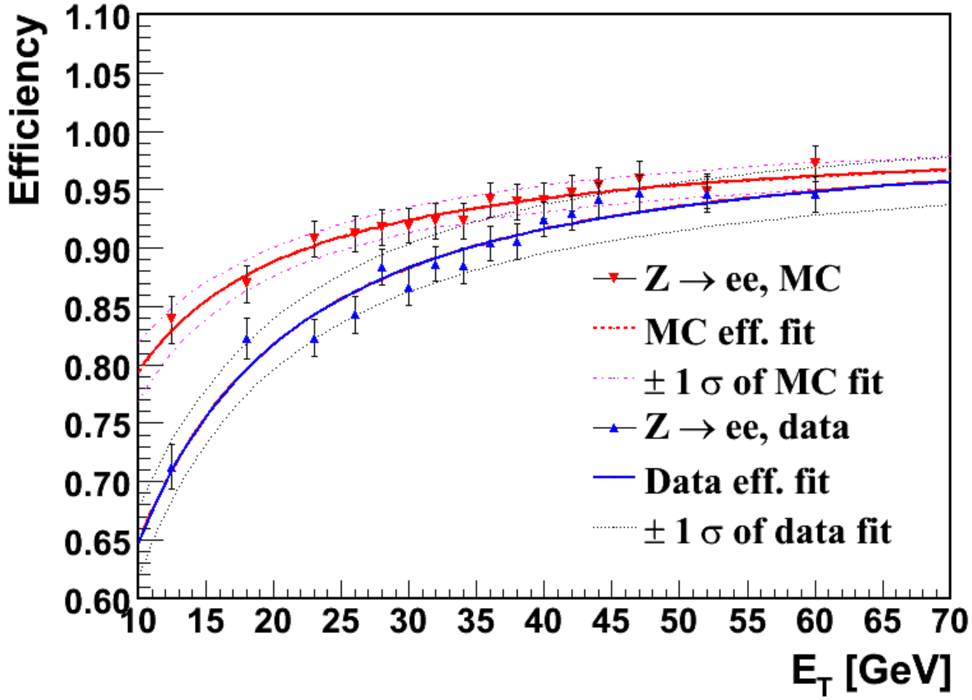
- **The task to reconstruct a photon is challenging –** no track, high QCD and electron background, additional contribution from noise in the DØ Calorimeter

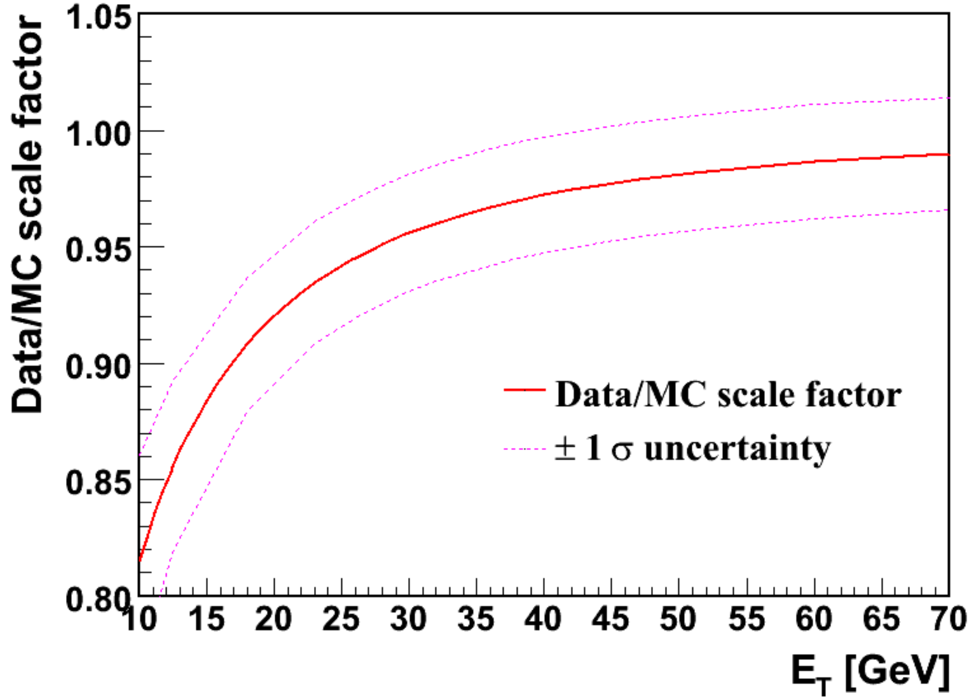
- **It is even more challenging to measure photon efficiency**: no discovered natural source of high-p_T diphoton resonance (e.g. **H→γγ**)

- **We measure photon efficiency using data and Monte Carlo (MC):**
  - common photon analyses tools
  - key point: trust the MC simulation
  - treat photons as electrons, tune selection criteria on **Z→ee** data and MC
  - measure photon efficiency from MC



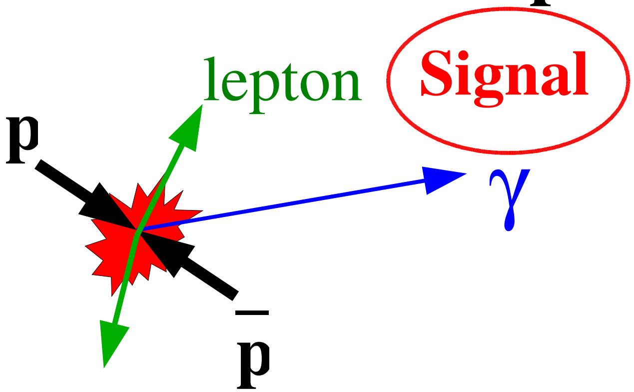
- **Correct the photon efficiency for data/MC difference:**
  - measure the efficiency of the same selection criteria on **Z→ee** data and MC
  - apply the correction factor (ratio of efficiencies in data and MC)

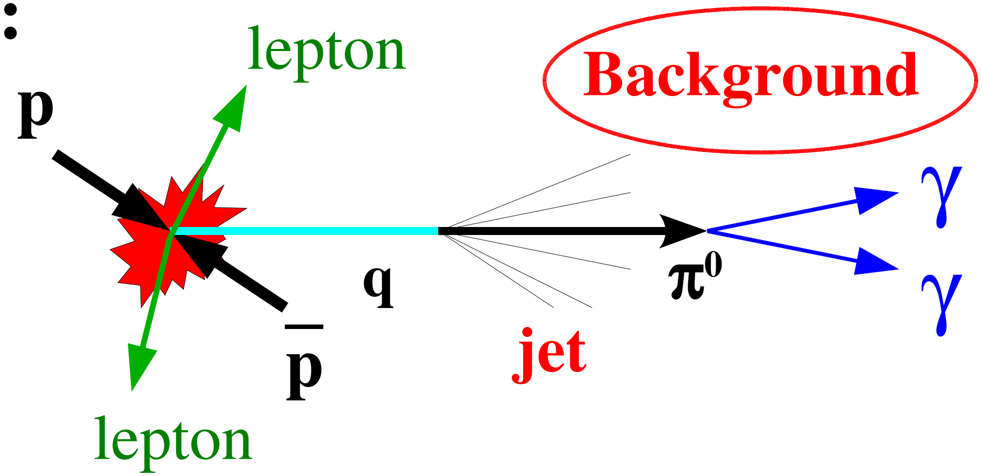




Photon Background: Misidentified Jets

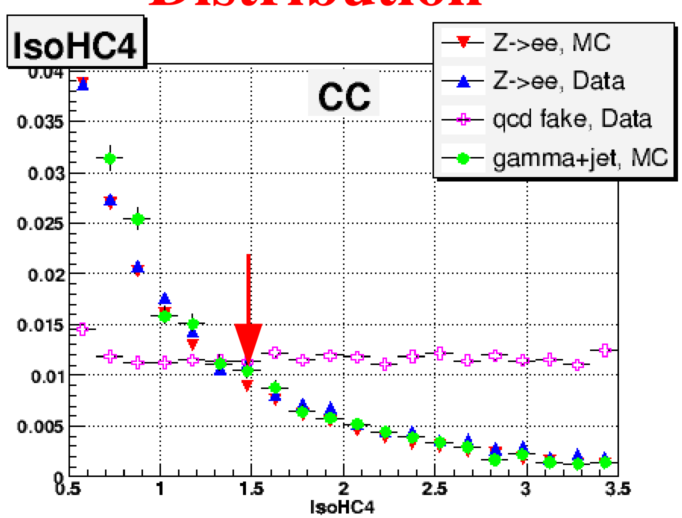
- Important background to $Z\gamma \rightarrow X\gamma$ is Z+jet where a jet is misidentified as a photon:



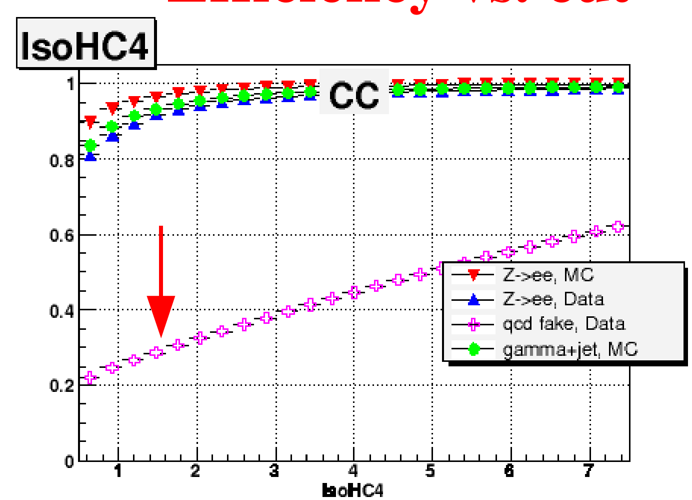


- **Track isolation:** sum of tracks p_T in the hollow cone around a photon < 1.5-2 GeV/*c*

Distribution

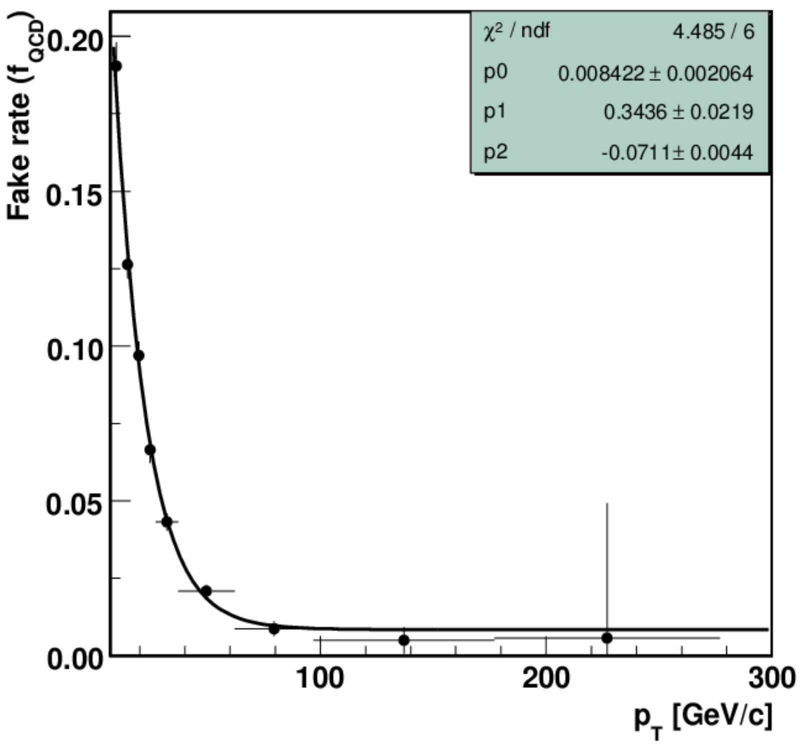


Efficiency vs. cut



- **Measure jet misidentification rate using dijet data sample:**
  - sample: (jets+EM) + good jet (*passed jet triggers*)
  - most photon candidates here are jets that were mis-ID as photons
  - count photon candidates that pass photon selection criteria
  - misidentification rate is:

$$f_{QCD} = \frac{N_{Passed}}{N_{Total}}$$



- **Probability for a jet to be reconstructed as a photon:**
  - **~15-20%** $p_T < 20$ GeV/*c*
  - **<0.5%** $p_T > 100$ GeV/*c*

Non-collision Background

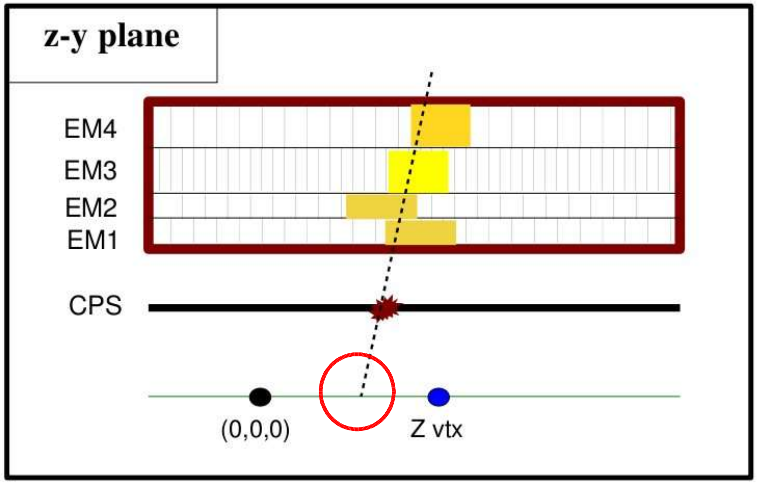
- **Very important for the $Z\gamma \rightarrow \nu\nu\gamma$ analysis**
  - photons from cosmic muons and beam halo muons

- **A couple of handles:**
  - **cosmic muon event:**
    - use timing in the scintillators (< 10 ns)
    - reject events with hits in top and bottom muon system forming one line
  - **beam halo event:**
    - require a reconstructed vertex
    - require more than 3 tracks

- **Still the non-collision background is high**
  - and that's where we use ...

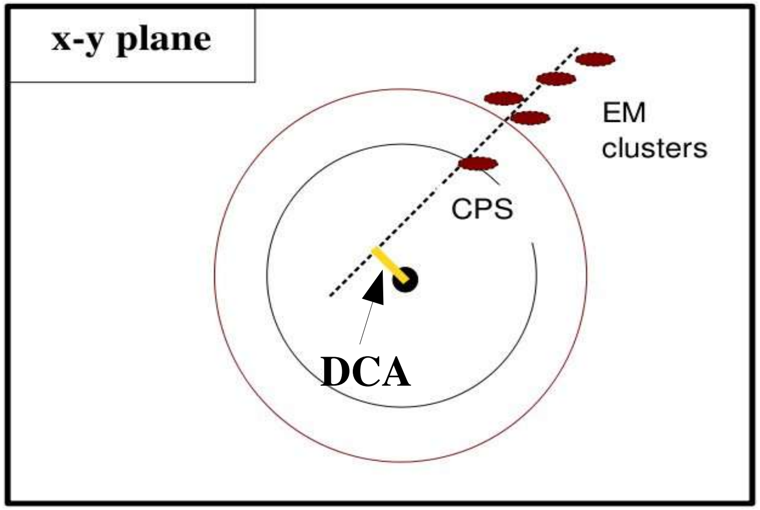
Pointing Algorithm

- **EM cluster pointing algorithm at DØ:**
  - purpose: calculate the direction of the EM showers
  - based on the position of the energy deposits in 4 layers of the EM calorimeter and the central preshower
  - fit all 5 coordinates to a straight line



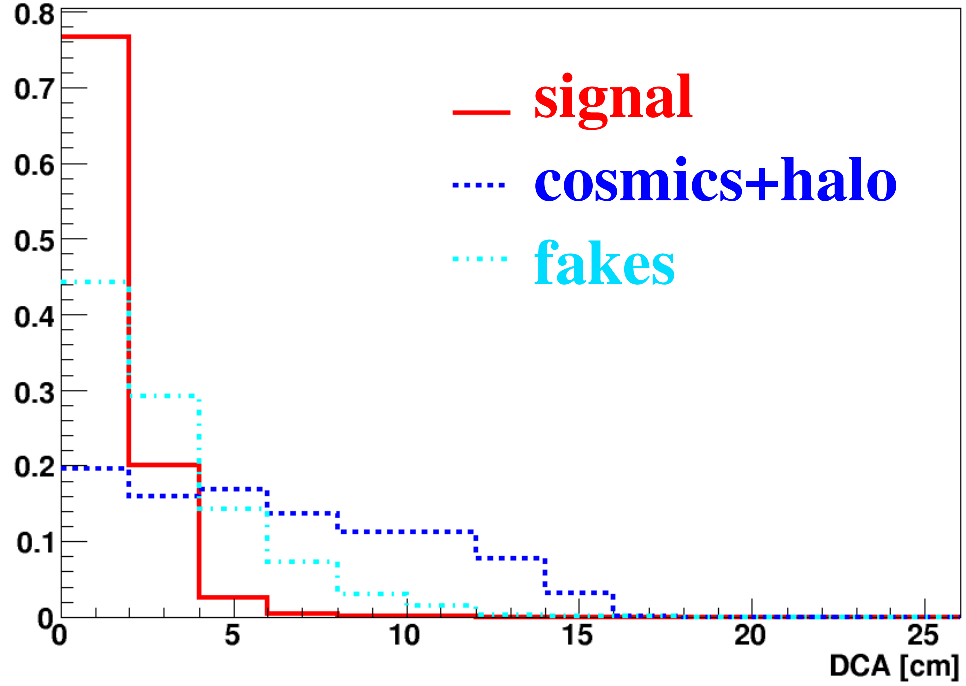
Pointed vertex

- **Extract the z-position of the pointed vertex and the distance of the closest approach (DCA)**
  - resolution is < 3 cm
  - use DCA distributions for background reduction

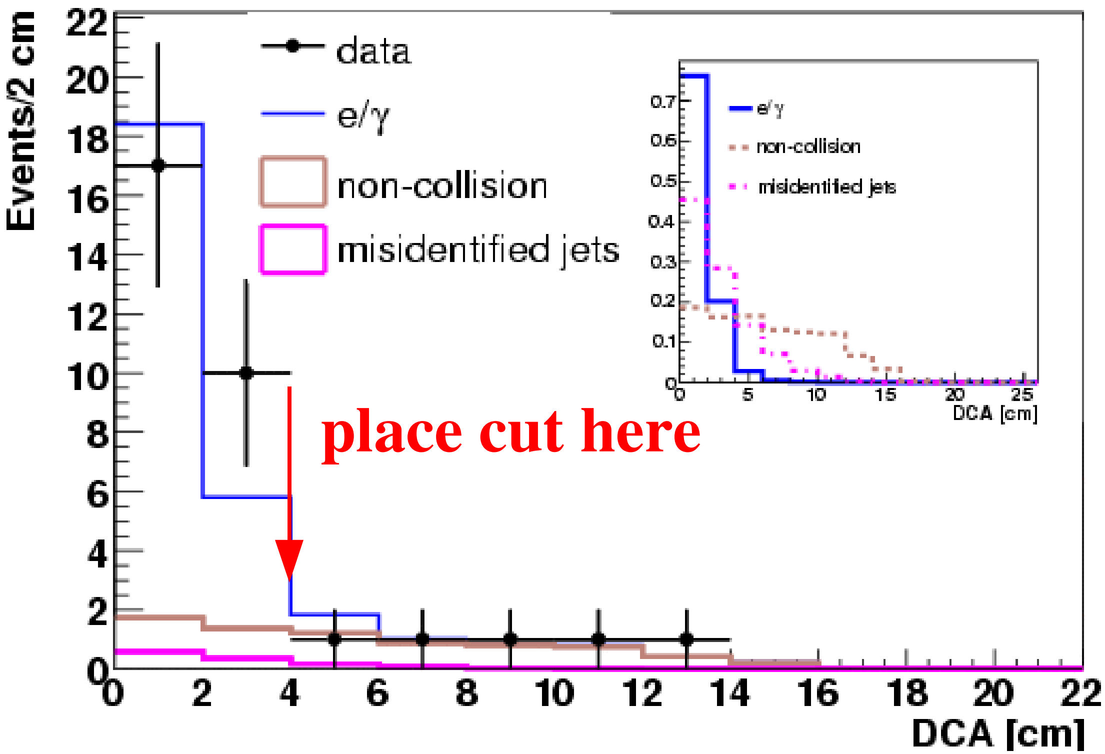


DCA Templates (I)

- **Analysis of DCA distribution is another way to estimate (and suppress) mis-id jets and non-collision backgrounds to photons from data:**
  - signal-like (**e/γ**) – narrow distribution
  - misidentified jets – wider distribution
  - non-collision – widest distribution

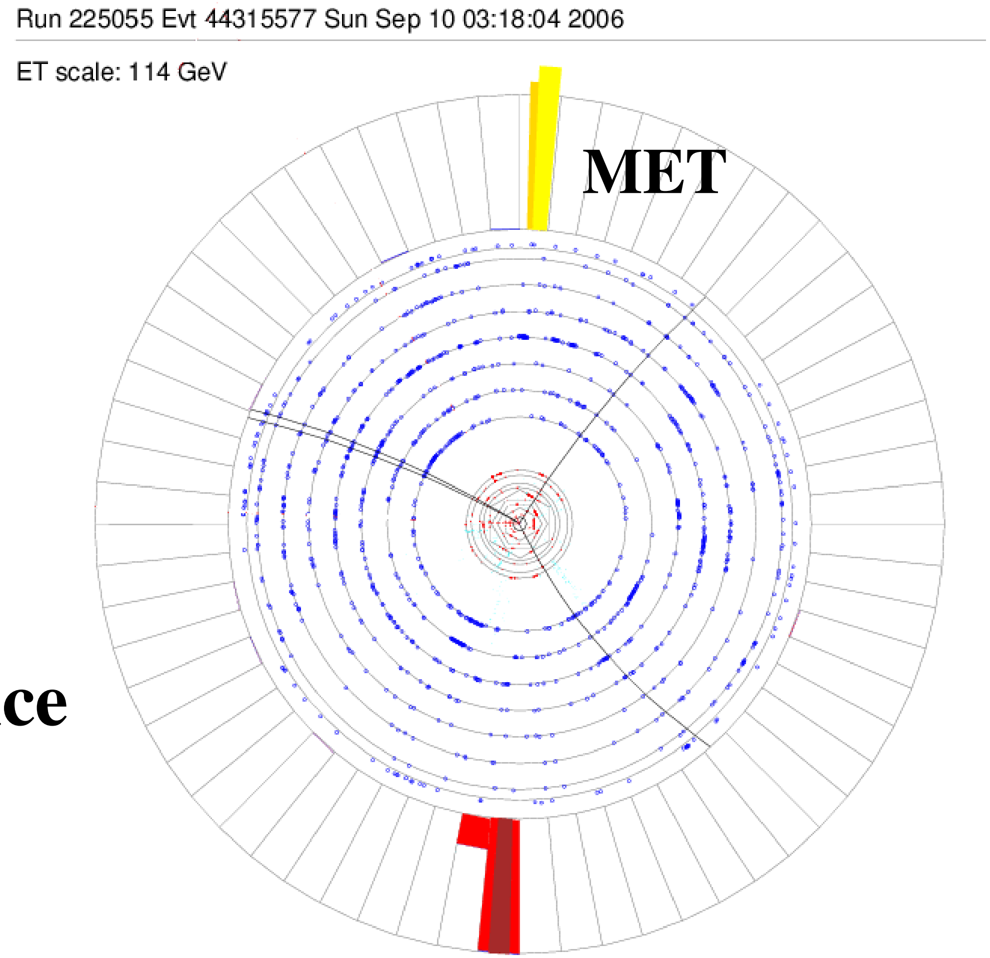


- **The linear sum of all three DCA templates is fitted to the DCA distribution from the final photon candidates sample:**
  - estimate the non-collision and mis-id jets backgrounds
  - cut at DCA < **4** cm to reduce the backgrounds (non-collision by almost a factor of 3!)
  - signal efficiency is still high (~**97%**)



- **Neutrinos are not directly visible in the DØ detector**

- **Use energy conservation law to estimate the missing transverse energy**
  - vector sum of E_T of all objects in the event must be zero: if not, assign the difference as MET
  - we cannot say the same about longitudinal and total energy



- **The substantial MET in the event can indicate presence of neutrinos**

Simulation

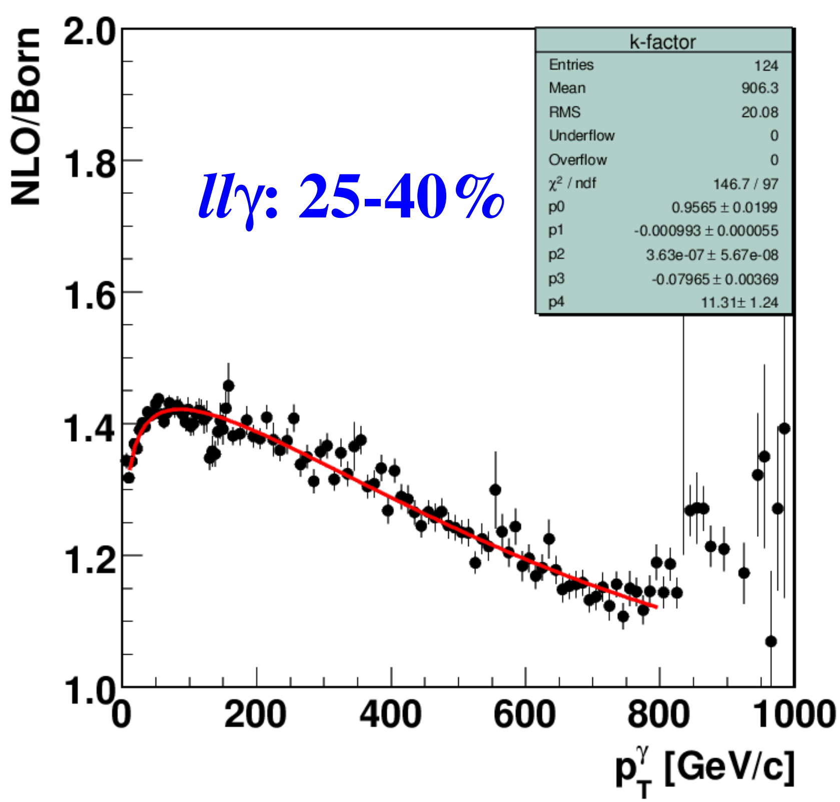
- **We have data, object ID, backgrounds. How do we distinguish the signal?**

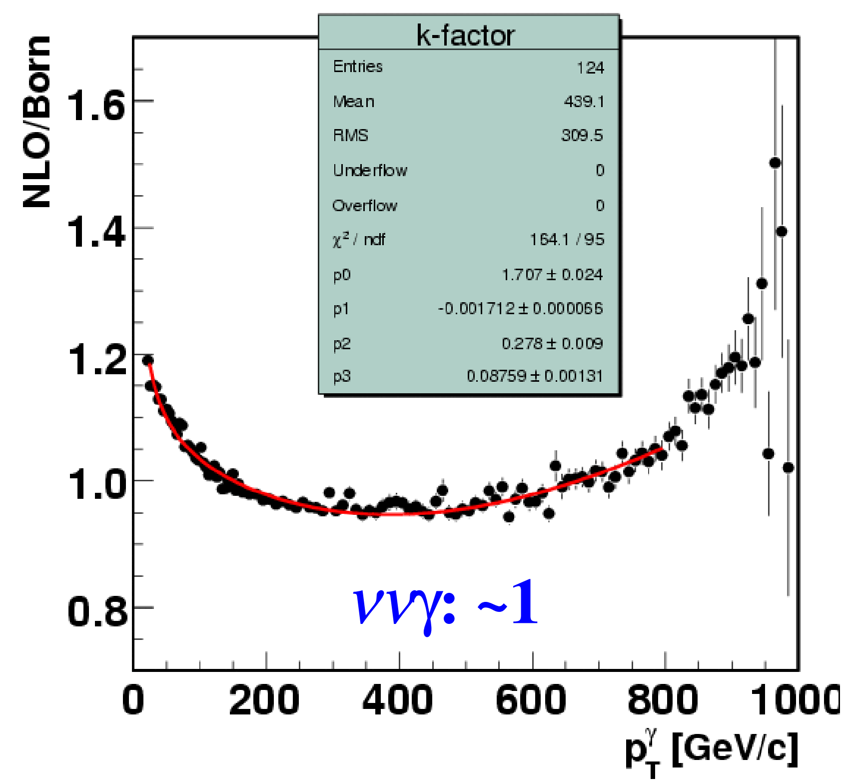
- **We need generators to model the SM process and include new phenomena processes that give the same signature**

- **Need a MC simulation suitable for $Z\gamma$, several options:**
  - Pythia – no anomalous couplings
  - MCFM – not complete for $Z\gamma$ as of v3.0
  - Baur-Berger:
    - designed for SM and anomalous $Z\gamma$ production

Monte Carlo Sample

- **In our studies we use LO Baur-Berger MC Zγ generator:**
  - QCD NLO corrections are important!
  - the magnitude of corrections depends greatly on the number of jets allowed in the final state:
    - *ll*γ analysis: inclusive; ννγ: no jets with p_T > **15** GeV/*c*



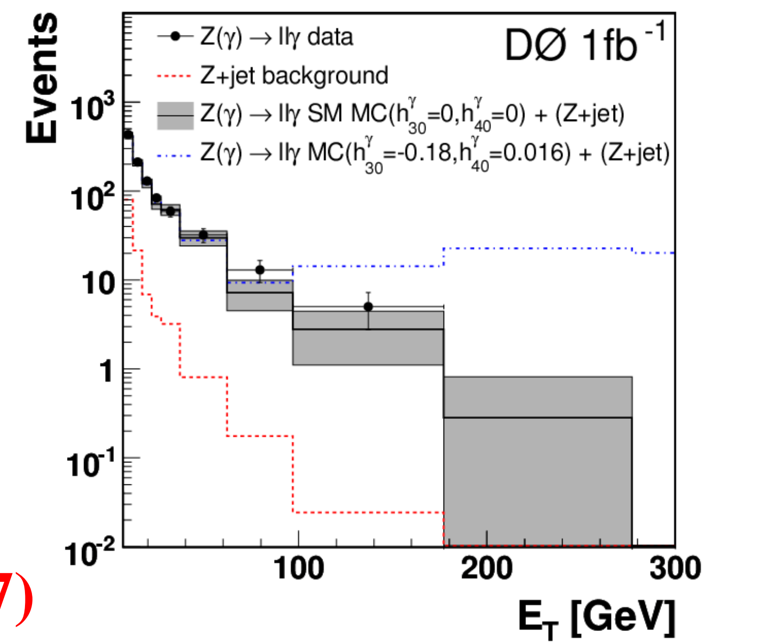


- **Using over 1 fb^{-1} of data in electron and muon channels we observe 968 $Z\gamma \rightarrow ll\gamma$ candidate events:**
  - measure the cross section
  - compare to the SM prediction

$$\sigma \times BR = \frac{N_{cand} - N_{bkg}}{\epsilon_{ll\gamma} L_{Int.}}$$

MAIN CUTS	$ee\gamma + \mu\mu\gamma$
Photon ET, GeV	> 7
Photon $\lvert\eta\rvert$	< 1.1
Electron (muon) pT, GeV/c	15 (20), at least one > 25
dR(l, γ)	> 0.7
M(ll), GeV/c^2	> 30
Background	Z + jet

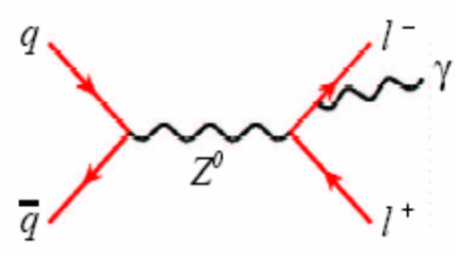
	$ee\gamma + \mu\mu\gamma$
Lumi, 1/fb	1.1
Ncand	968 ± 31.1
SM Predicted	803.9 ± 52.9
Total bkg	116.5 ± 8.9(stat) ± 8.4(syst)
Measured $\sigma\times$Br, pb	4.96 ± 0.30(stat + syst) ± 0.30(lumi)
Predicted $\sigma\times$Br, pb	4.74 ± 0.22



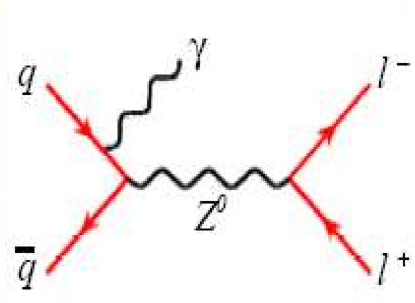
PLB 653, 378 (2007)

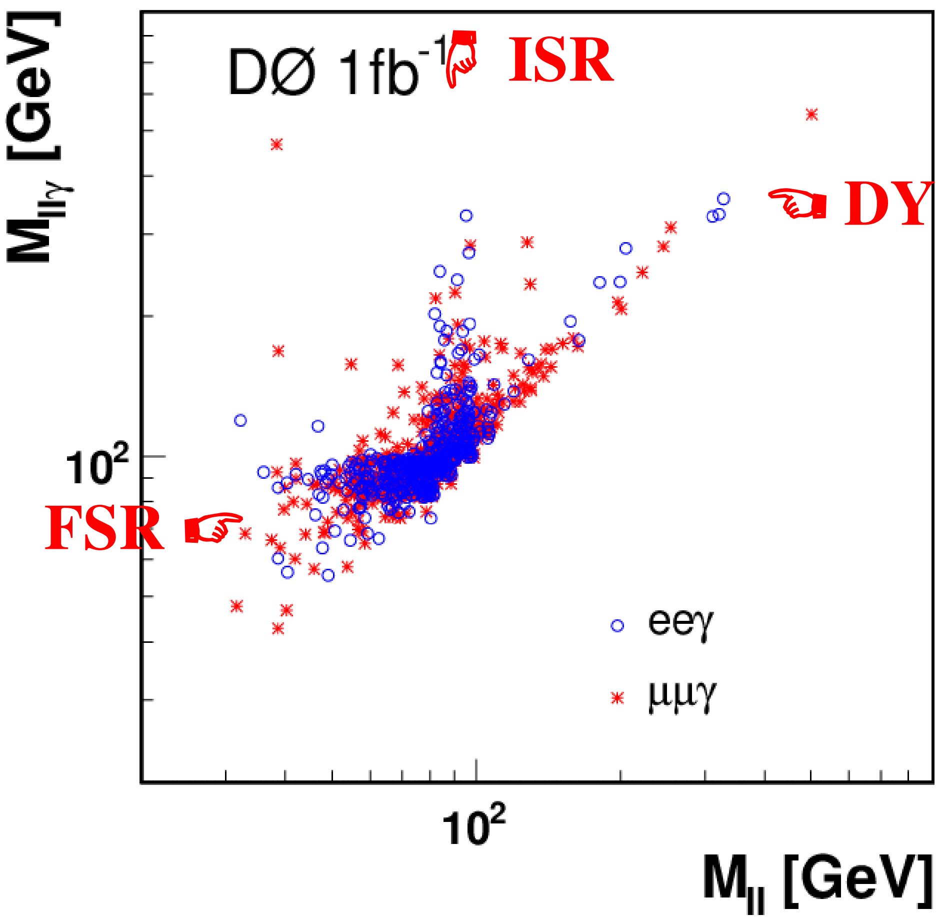
$Z\gamma \rightarrow ll\gamma$ (II): Observed Processes

- **Final State Radiation:**
  - **Z** production (not **Zγ**)
  - softer photons



- **Initial State Radiation:**
  - **Zγ** production
  - photons are harder, than in FSR
  - ISR is most sensitive to AC





- **Drell-Yan (DY)**

+ low E_T photon

Zγ →ννγ Cross Section Analysis (I)

- **Zγ→ννγ cross section analysis main cuts:**

MAIN CUTS	ννγ
Photon ET, GeV	> 90
Jet veto (pT), GeV/c	< 15
Veto	muons, energetic tracks and EM objects
MET, GeV	> 70
Backgrounds	W→eν, non-collision, W/Z+jet, W+γ

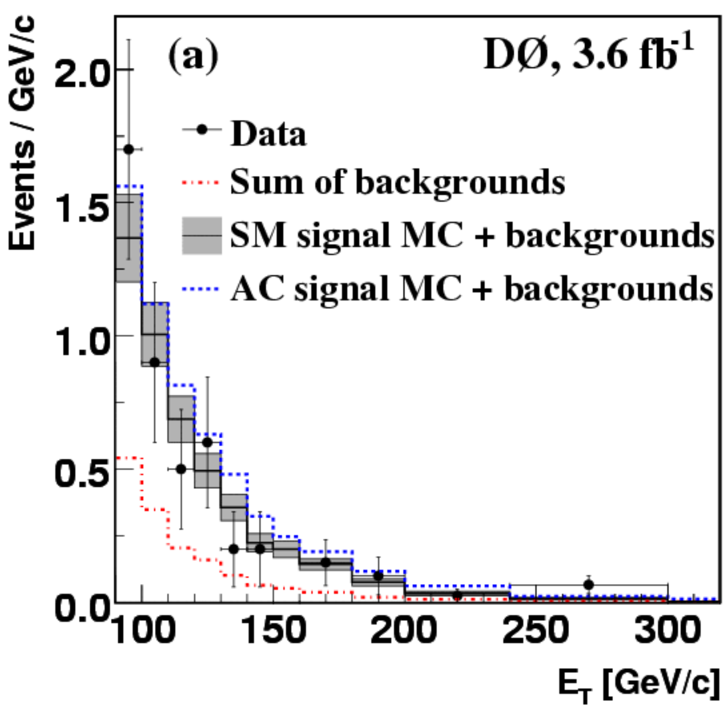
- **Zγ→ννγ additional backgrounds:**
  - **W→eν:** electrons can also be misidentified as photons
    - estimated from a sample of isolated electrons
    - correct for the track match efficiency
  - **Wγ:** lepton is lost
    - estimated from MC

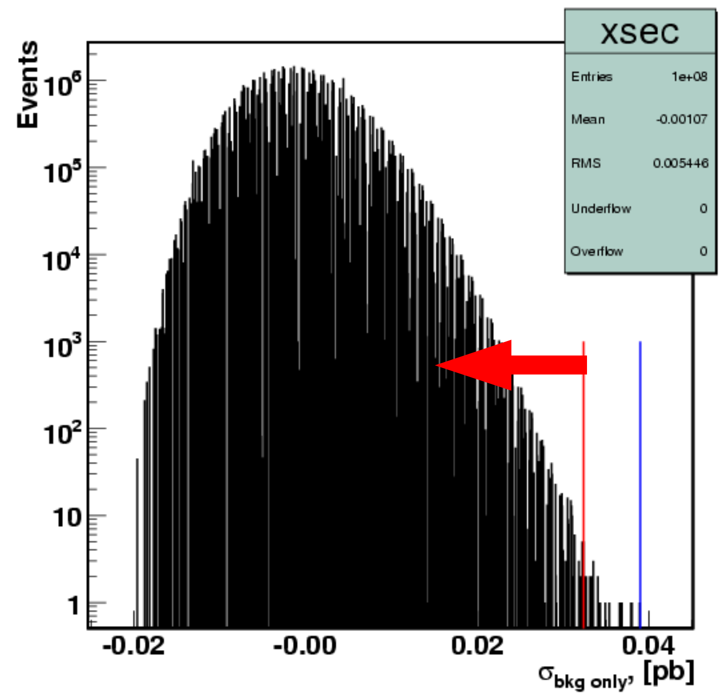
- **Using 3.6 fb^{-1} of data in neutrino channel we observe 51 $Z\gamma \rightarrow \nu\nu\gamma$ candidate events:**
  - measure the cross section
  - compare the measurement with the theoretical prediction

	$\nu\nu\gamma$
Lumi, 1/fb	3.6
Ncand	51 ± 7.1
SM Predicted	33.7 ± 3.4
Total bkg	17.3 ± 0.6(stat) ± 2.3(syst)
Measured $\sigma \times Br$, fb	32 ± 9(stat.+syst.) ± 2(lumi)
Predicted $\sigma \times Br$, fb	39 ± 4

Statistical Significance of the Measurement (ννγ)

- **We perform 100 million pseudoexperiments** to check the consistency of the combined observed data with the **Bkg-only** hypothesis:





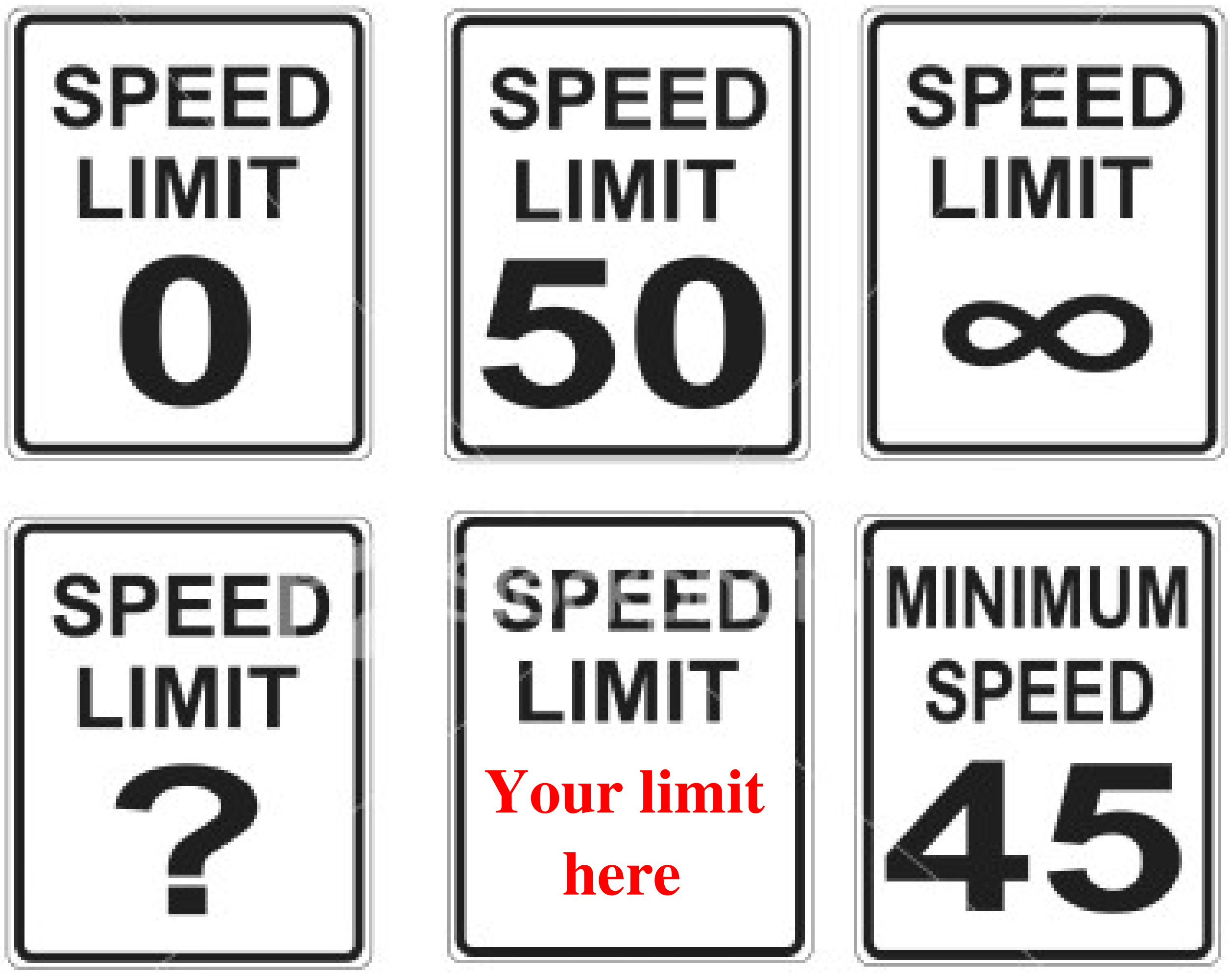
- 3.1×10^{-7} probability of **Xsec(Bkg) > 32 fb**:
  - **5.12 σ** statistical significance
  - first observation of the $Z\gamma \rightarrow \nu\nu\gamma$ production at the Tevatron
    - **arXiv:hep-ex/0902.2157v1**

- **Two cross section measurements in two channels:**
  - $Z\gamma \to \nu\nu\gamma$: corresponds to the Z boson partial decay width Γ_ν
  - combination of $Z\gamma \to ee\gamma$, $Z\gamma \to \mu\mu\gamma$: corresponds to Γ_l
    - photon $E_T > 90$ GeV to match the $Z\gamma \to \nu\nu\gamma$ requirement

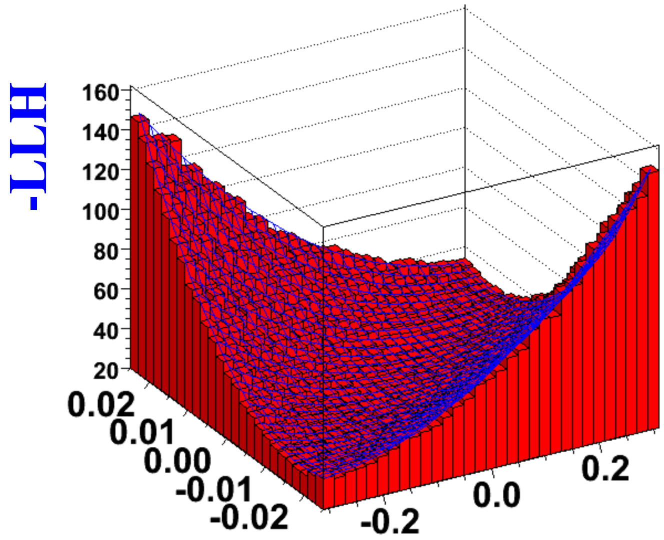
$$\frac{\Gamma_\nu}{\Gamma_l} = \frac{\sigma(Z\gamma)\cdot BR(Z\to\nu\nu)}{\sigma(Z\gamma)\cdot BR(Z\to ll)} \longrightarrow N_\nu = \frac{\Gamma_{invisible}}{\Gamma_\nu}$$

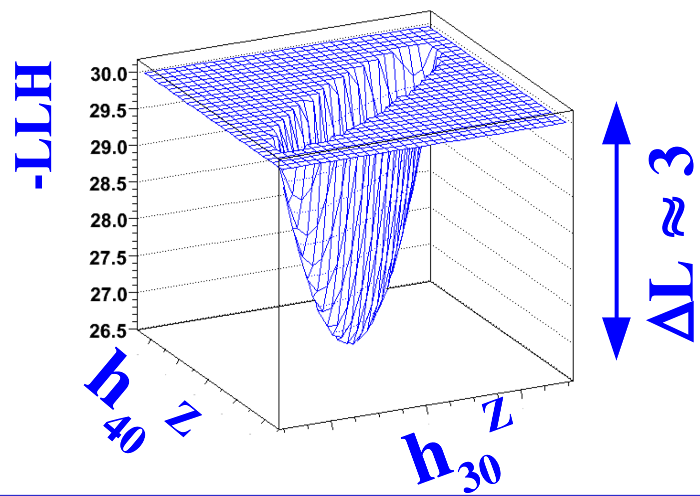
$\sigma\times Br(Z\to\nu\nu)$, fb	32 ± 9(stat+syst) ± 2(lumi)
$\sigma\times Br(Z\to ll)$, fb	16 ± 7(stat+syst) ± 1(lumi)
Γ(invis), MeV	499 ± 1.5 (from PDG08)
Γ(lept), MeV	89.384 ± 0.086 (from PDG08)
Γ(ν), MeV	168 ± 87.4
N(ν), measured	3.0 ± 1.6
N(ν), LEP	2.984 ± 0.008

Observations are consistent with the SM predictions, thus we may set limits on new physics!



- **We generate MC samples of $Z\gamma$ events with non-zero values of $h_{30}^{Z,\gamma}$ and $h_{40}^{Z,\gamma}$ distributed in a 2-D grid:**
  - for each pair of $h_{30}^{Z,\gamma}$ and $h_{40}^{Z,\gamma}$ values of the grid we compare the photon E_T spectrum from data with that from the simulation plus background
  - calculate log likelihood at each point to estimate results of the fit
  - measure **95%** confidence level limits by integrating the likelihood curve (surface) for 1-D (2-D) limits





- **1-D limits on real parts of Zγγ and ZZγ aTGCs: ~1 fb^{-1}**

electron + muon channel, form-factor scale Λ = 1.2 TeV:

$$-0.085 < h_{30}^{\gamma} < 0.084, \quad -0.0053 < h_{40}^{\gamma} < 0.0054$$

$$-0.083 < h_{30}^{Z} < 0.082, \quad -0.0053 < h_{40}^{Z} < 0.0054$$

World's tightest!
(when published)

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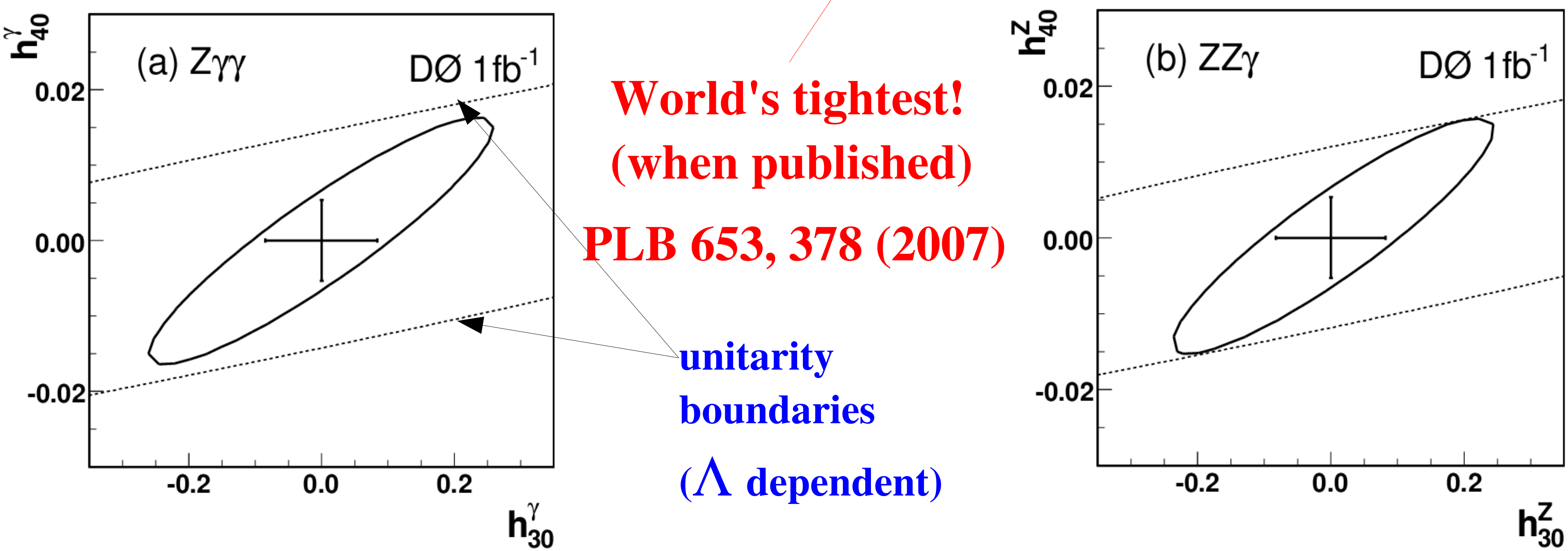
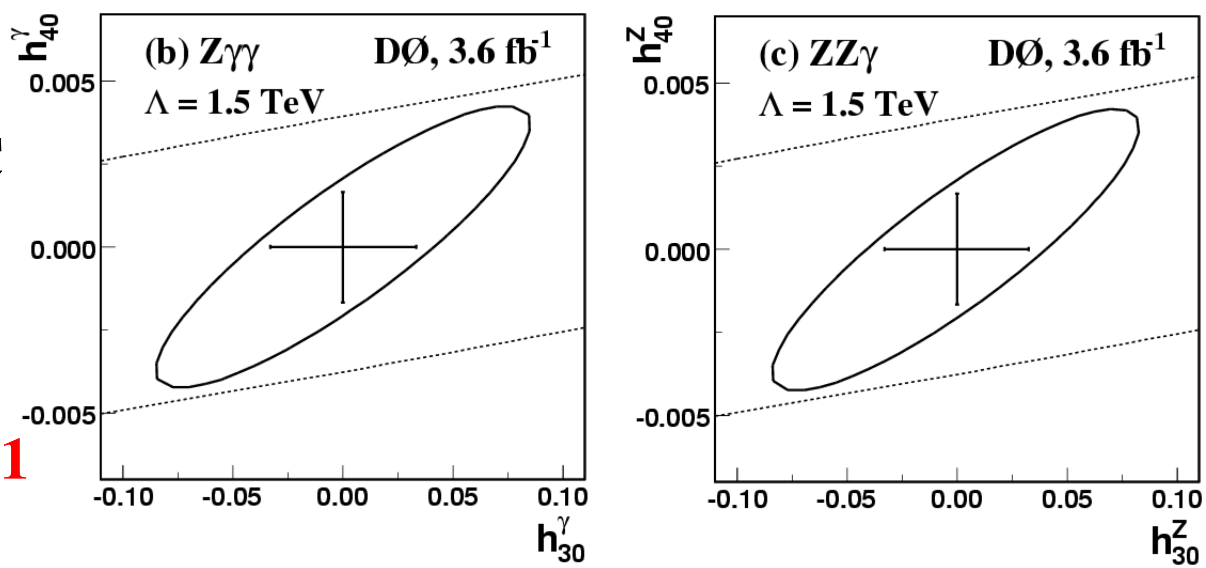


Zγγ and ZZγ Limits: *combined*

	Λ=1.2 TeV	Λ=1.5 TeV
Zγγ el+mu, 1fb-1	|h30| < 0.085, |h40| < 0.0054 (*)	|h30| < 0.079, |h40| < 0.0036
ZZγ el+mu, 1fb-1	|h30| < 0.083, |h40| < 0.0054 (*)	|h30| < 0.075, |h40| < 0.0037
Zγγ neutrino, 3.6fb-1	|h30| < 0.042, |h40| < 0.0029	|h30| < 0.037, |h40| < 0.0020
ZZγ neutrino, 3.6fb-1	|h30| < 0.041, |h40| < 0.0029	|h30| < 0.036, |h40| < 0.0020
Zγγ combination	|h30| < 0.038, |h40| < 0.0025	|h30| < 0.033, |h40| < 0.0017 (**)
ZZγ combination	|h30| < 0.037, |h40| < 0.0025	|h30| < 0.033, |h40| < 0.0017 (**)

- **Current limits (**):**
  - the **tightest limits** on ATGC at hadron collider and are:
    - **3 times tighter** than the prev. published ones (*)
    - **arXiv:hep-ex/0902.2157v1**



- **LEP EWWG results on ATGC:**
  - http://lepewwg.web.cern.ch/LEPEWWG/lepww/tgc/summer03/gc_main2003.ps

LEP	Tevatron
-0.049 < h3_γ < -0.008	-0.033 < h30_γ < 0.033
-0.002 < h4_γ < 0.034	-0.0017 < h40_γ < 0.0017
-0.20 < h3_Z < 0.07	-0.033 < h30_Z < 0.033
-0.05 < h4_Z < 0.12	-0.0017 < h40_Z < 0.0017

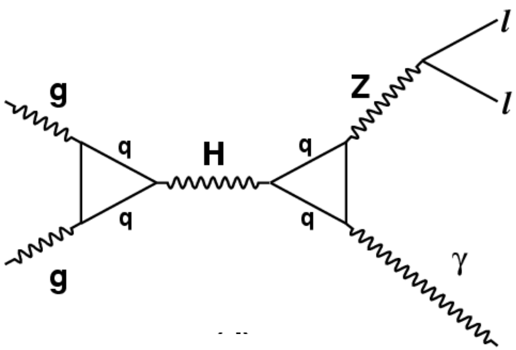
LEP Tevatron

$$h_i^{Z,\gamma} = \frac{h_{i0}^{Z,\gamma}}{(1+\hat{s}/\Lambda^2)^n}$$

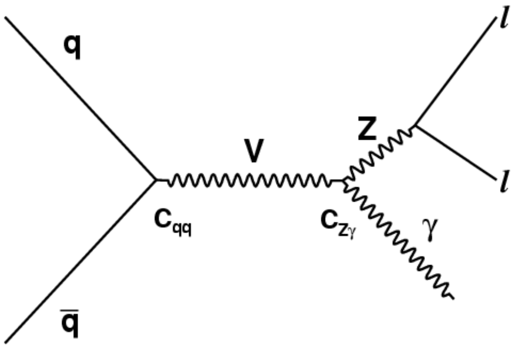
- **Conversion coefficient LEP→Tevatron is $(1+ s/\Lambda^2)^n > 1$**
  - **3 out of 4 CP-conserving limits from Tevatron are more stringent than LEP-II ones (either converted to h_{i0}^V or not):**
    - **h_{30}^Z, h_{40}^Z and h_{40}^γ**

ppbar→X→Zγ Resonance Search (I)

- **The last check to be done is to search for particles that might decay to Zγ**
  - fermiophobic Higgs, Z' , techniparticles



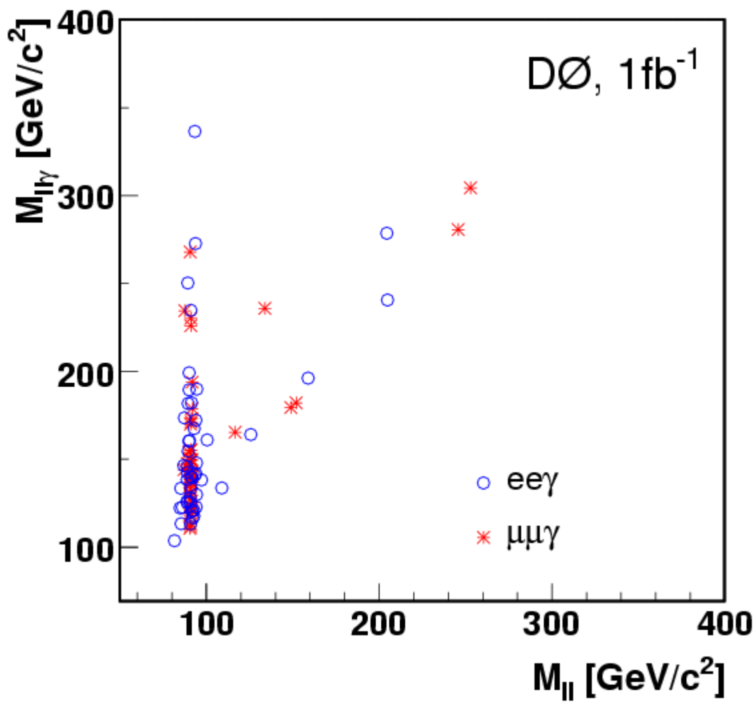
- **Final state**
  - extend the Zγ →*ll*γ analysis
  - 2 charged leptons (e or μ) and a photon
- **Backgrounds:**
  - SM Zγ – LO Baur-Berger generator
    - NLO effects are modeled with the p_T-dependent *K*-factor
  - Z+jet – estimated from data

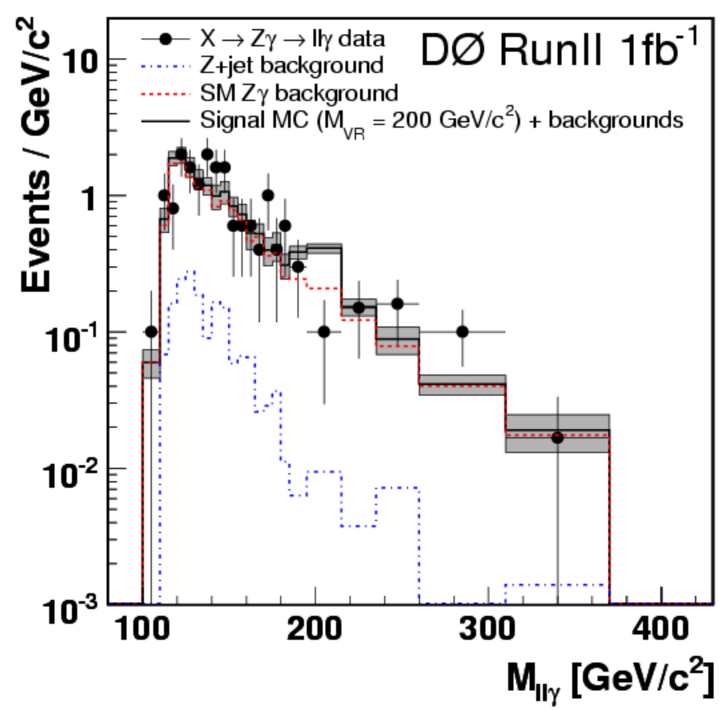


- **Signal (charge and color-singlet):**
  - Scalar – Higgs, generated with PYTHIA
  - Vector – generated with MADEVENT (thanks to Steve Mrenna)

ppbar→X→Zγ Resonance Search (II)

- **Dataset:** **~1fb^{-1}** sample, used in the **Zγ →*ee*(μμ)γ** AC analysis
  - tighter cuts on photon E_T > **20** GeV and M_{ll} > **80** GeV/c^2

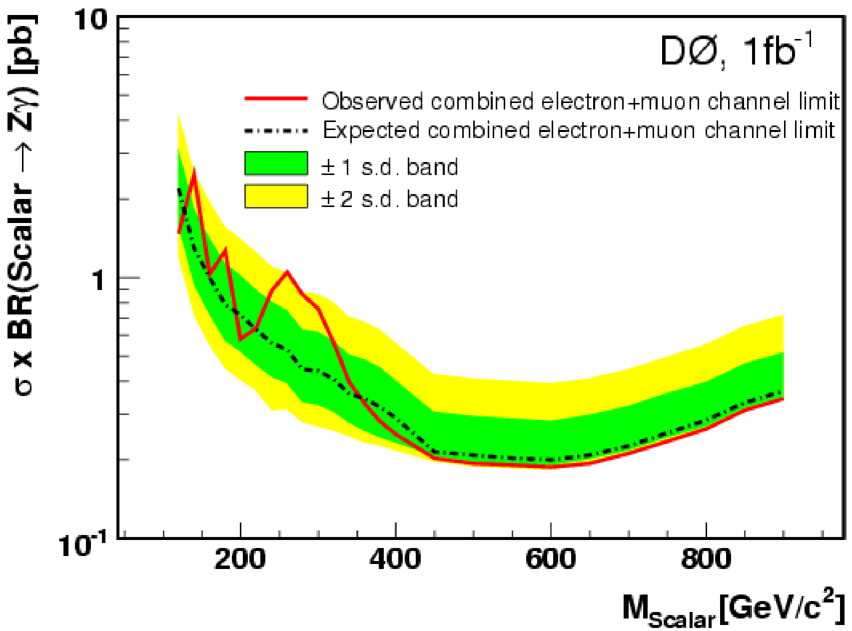


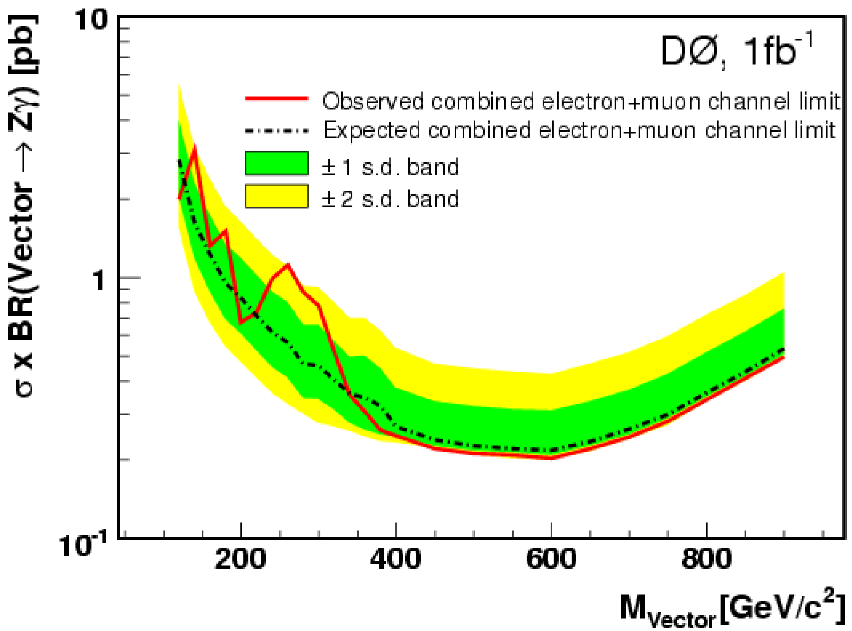


	eeγ+μμγ
Data (candidates)	99 ± 10
SM Zγ background	79 ± 8.9(stat) ± 3.4(syst)
Z+jet background	8.9 ± 1.0(stat) ± 0.9(syst)

ppbar→X→Zγ Resonance Search (III)

- **No significant deviation of data from theory**
- **Hence – set limits on new physics**





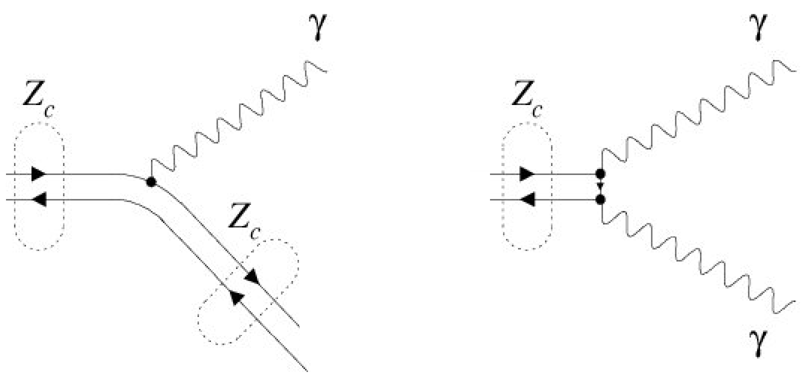
- **$\sigma \times$ BR(X → Zγ) limits:**
  - **0.2** pb @ 600 GeV (Scalar and Vector)
  - **2.5** (**3.1**) pb @ 140 GeV Scalar (Vector)
  - **PLB 671, 349 (2009)**

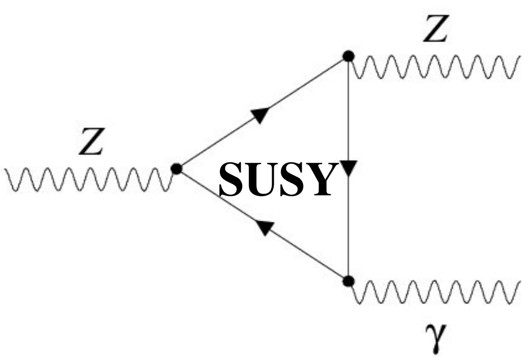
Conclusion

- **We have gained experience in analyses with photons at DØ**
  - developed new "collaboration-wide" tools to certify electrons and photons
  - certified a number of EM and photon definitions to be used out-of-the-box – used in most analyses with electrons and photons at DØ
  - looking forward to apply my knowledge at the LHC
- **We have pioneered the 4 fb^{-1} dataset and studied the $Z\gamma$ final state in various aspects:**
  - measured the the most precise $Z\gamma \rightarrow ll\gamma$ and $Z\gamma \rightarrow \nu\nu\gamma$ cross sections and observed the $Z\gamma \rightarrow \nu\nu\gamma$ process for the first time at hadron colliders
    - **PLB 653, 378 (2007); arXiv:hep-ex/0902.2157v1**
  - set the tightest limits on the $Z\gamma\gamma$ and $ZZ\gamma$ ATGC at hadron colliders to date; three of which are the world's tightest (ever!!)
    - submitted to PRL – **arXiv:hep-ex/0902.2157v1**
  - set upper limits on the production cross section of vector/scalar resonances
    - **PLB 671, 349 (2009)**

- **Tevatron expects to deliver ~10 fb^{-1} of data by end of 2010**
  - still remains world's highest center-of-mass energy collider
  - *enough data to discover new physics?*
  - gives us invaluable understanding of physics at hadron colliders
  - so, everything is ready for...

- **LHC**
  - will operate at **$\sqrt{s}$ = 14 TeV**
  - will produce a lot of data, many times more than the Tevatron
  - will test the SM
  - *will find physics beyond the SM?*





BACKUP SLIDES

$Z\gamma \rightarrow ll\gamma$ Cross Section

	$ee\gamma$ (CC-CC)	$ee\gamma$ (CC-EC)
Lumi, 1/fb	1.1	1.1
Ncand	308 ± 17.6	145 ± 12.0
Total bkg	29.5 ± 4.8(stat) ± 3.1(syst)	25.7 ± 3.8(stat) ± 2.5(syst)
Total eff	0.0486 ± 0.0031	0.0262 ± 0.0019
Measured $\sigma \times$Br, pb	5.17±0.34(stat)±0.38(syst)±0.31(lumi)	4.11±0.43(stat)±0.33(syst)±0.25(lumi)

	$\mu\mu\gamma$
Lumi, 1/fb	1
Ncand	515 ± 22.7
Total bkg	61.3 ± 6.5(stat) ± 6.2(syst)
Total eff	0.0858 ± 0.0047
Measured $\sigma \times$Br, pb	5.24 ± 0.27(stat) ± 0.30(syst) ± 0.31(lumi)

Combined $\sigma \times$Br, pb	4.96 ± 0.30(stat+syst) ± 0.30(lumi)
Predicted $\sigma \times$Br, pb	4.74 ± 0.22

$Z\gamma \rightarrow \nu\nu\gamma$ Cross Section

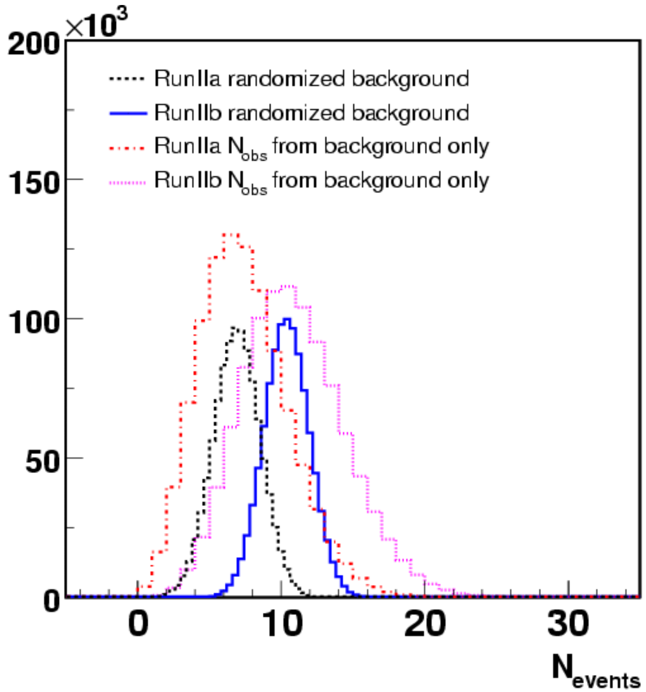
TABLE IV: Summary of backgrounds.

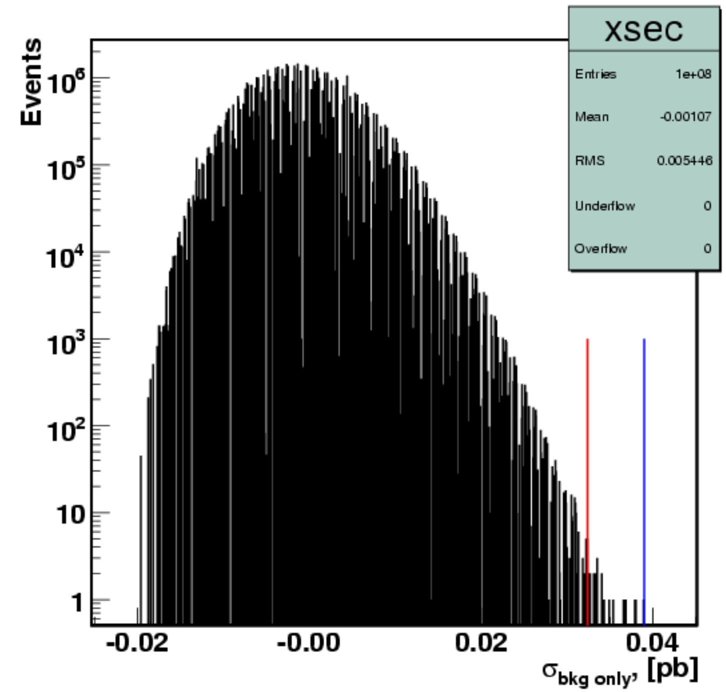
Background	Run IIa (p17)	Run IIb (p20)
$W \rightarrow e\nu$	$3.466 \pm 0.194(\text{stat.}) \pm 0.236(\text{syst.})$	$6.197 \pm 0.233(\text{stat.}) \pm 0.423(\text{syst.})$
$W/Z + jet$	$0.964 \pm 0.186(\text{stat.}) \pm 0.901(\text{syst.})$	$0.409 \pm 0.183(\text{stat.}) \pm 0.100(\text{syst.})$
$non\text{–}collision$	$2.141 \pm 0.227(\text{stat.}) \pm 1.257(\text{syst.})$	$3.191 \pm 0.319(\text{stat.}) \pm 1.440(\text{syst.})$
$W + \gamma$	$0.331 \pm 0.029(\text{stat.}) \pm 0.072(\text{syst.})$	$0.571 \pm 0.062(\text{stat.}) \pm 0.103(\text{syst.})$
Total background	$6.902 \pm 0.353(\text{stat.}) \pm 1.644(\text{syst.})$	$10.368 \pm 0.440(\text{stat.}) \pm 1.588(\text{syst.})$

TABLE V: Summary of the components to the calculation of the cross section for $Z\gamma \rightarrow \nu\nu\gamma$ decay.

Parameter	Value (Run IIa)	Value (Run IIb)
N_{cand}	27 ± 5.2	24 ± 4.9
N_{bkg}	$6.902 \pm 0.353(\text{stat.}) \pm 1.644(\text{syst.})$	$10.368 \pm 0.440(\text{stat.}) \pm 1.588(\text{syst.})$
$\epsilon_{\nu\nu\gamma}$	0.290 ± 0.028	0.216 ± 0.024
$\int \mathcal{L}dt$	1045 ± 63 pb^{-1}	2594 ± 158 pb^{-1}

Run IIa $\sigma\times$Br, pb	$0.067 \pm 0.017(\text{stat}) \pm 0.009(\text{syst}) \pm 0.004(\text{lumi})$
Run IIb $\sigma\times$Br, pb	$0.024 \pm 0.009(\text{stat}) \pm 0.004(\text{syst}) \pm 0.002(\text{lumi})$
Combined $\sigma\times$Br, pb	$0.032 \pm 0.009(\text{stat+syst}) \pm 0.002(\text{lumi})$
Predicted $\sigma\times$Br, pb	0.039 ± 0.004

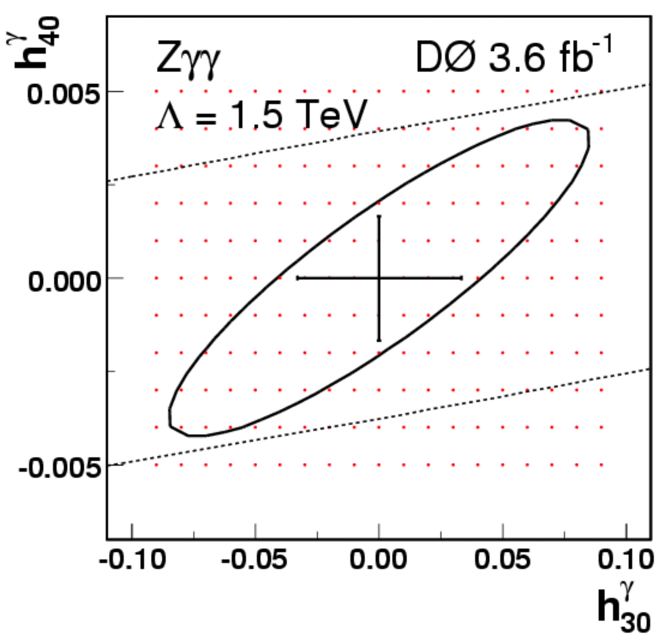


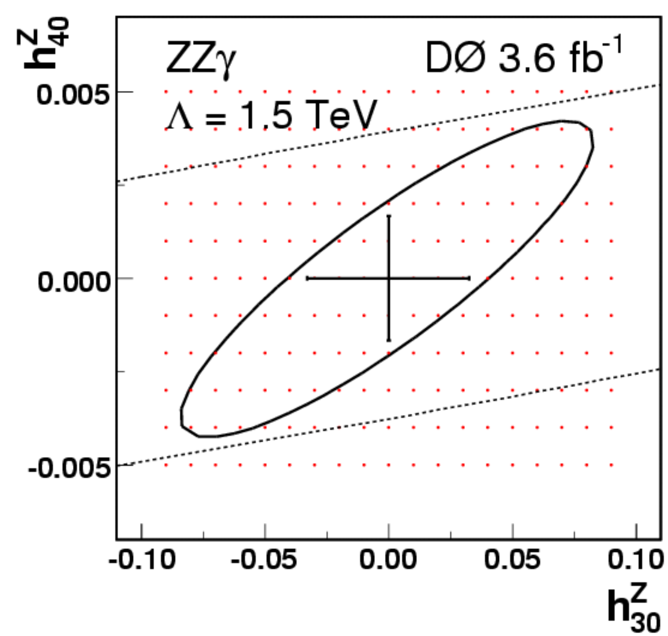


- **4 steps:**
  - throw a random number using estimated bkg. events ($\mathbf{N_{bkg}}$) with the estimated uncert. ($\mathbf{dN_{bkg}}$) using Gaussian statistics, and obtain $\mathbf{N^{*}_{bkg}}$;
  - then for each value of $\mathbf{N^{*}_{bkg}}$ we obtain a number of observed events $\mathbf{N_{obs}}$ that came just from **bkg.** using Poisson statistics
  - then for each new $\mathbf{N_{obs}}$ and fixed $\mathbf{N_{bkg}}$ we calculate the cross section
  - count the number of outcomes below the measured one, and calculate the significance

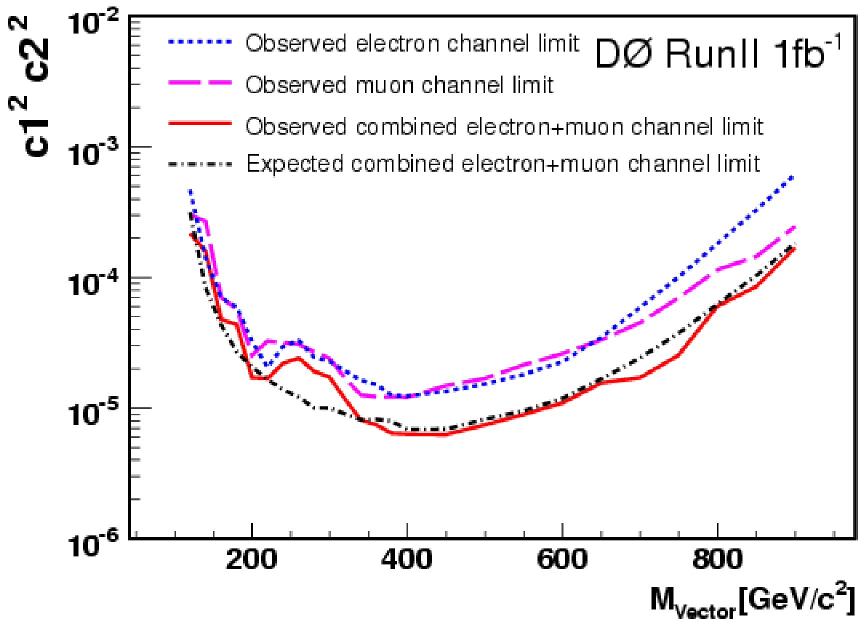
AC Limits Table

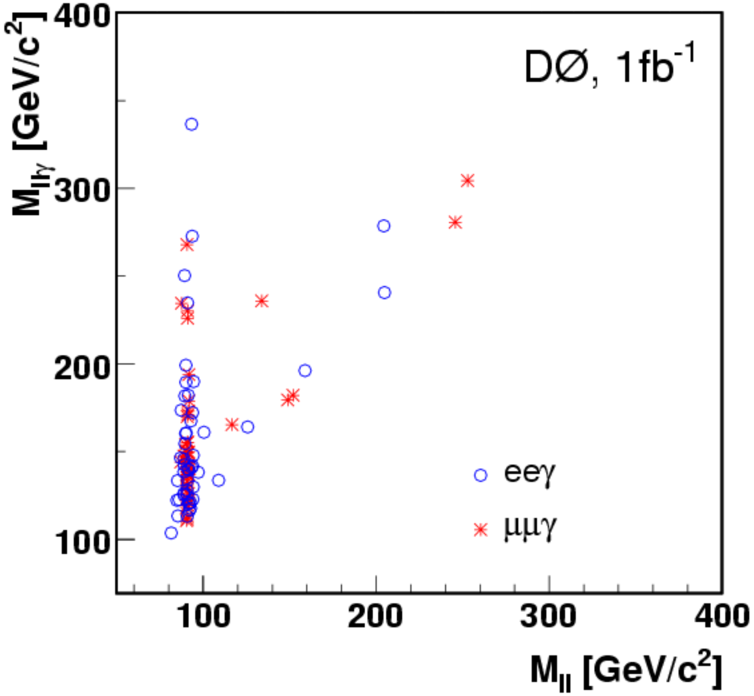
	Λ=1200 GeV	Λ=1500 GeV
Zγγ el+mu, 1fb-1	|h30| < 0.085, |h40| < 0.0054 (*)	|h30| < 0.079, |h40| < 0.0036
ZZγ el+mu, 1fb-1	|h30| < 0.083, |h40| < 0.0054 (*)	|h30| < 0.075, |h40| < 0.0037
Zγγ neutrino, 3.6fb-1	|h30| < 0.042, |h40| < 0.0029	|h30| < 0.037, |h40| < 0.0020
ZZγ neutrino, 3.6fb-1	|h30| < 0.041, |h40| < 0.0029	|h30| < 0.036, |h40| < 0.0020
Zγγ comb. nu + el+ mu	|h30| < 0.038, |h40| < 0.0025	|h30| < 0.033, |h40| < 0.0017 (**)
ZZγ comb. nu + el+ mu	|h30| < 0.037, |h40| < 0.0025	|h30| < 0.033, |h40| < 0.0017 (**)





ppbar→X→Zγ Resonance Search





	eeγ	μμγ
Data (candidates)	49 ± 7.0	50 ± 7.1
SM Zγ background	37.4 ± 6.1(stat) ± 2.6(syst)	41.6 ± 6.5(stat) ± 2.2(syst)
Z+jet background	4.5 ± 0.7(stat) ± 0.6(syst)	4.4 ± 0.7(stat) ± 0.6(syst)
Total eff	0.0026 ± 0.0002	0.0032 ± 0.0002
SM σ×Br, pb	12.85 ± 0.60	12.85 ± 0.60

Backgrounds to Photons

- **Most of backgrounds to the Zγ process are analysis specific:**
  - **W/Z + jet**: jet is misidentified as a photon – most common background to analyses with photons, applicable to ***ll***γ (***l*** = electron or muon) and $\nu\nu\gamma$ analyses
  - ***ll***γ **analysis:** other backgrounds are negligible
    - **WZ→*ll*e**ν, **Z→**$\tau\tau$**,** b-bbar, jets and photons faking electrons
  - $\nu\nu\gamma$ **analysis:** other backgrounds:
    - **W → e**ν: electron is misidentified as a photon
    - **W + γ →** *l*ν + γ: lepton is lost
    - **non-collision**: Bremsstrahlung from cosmic or halo muons