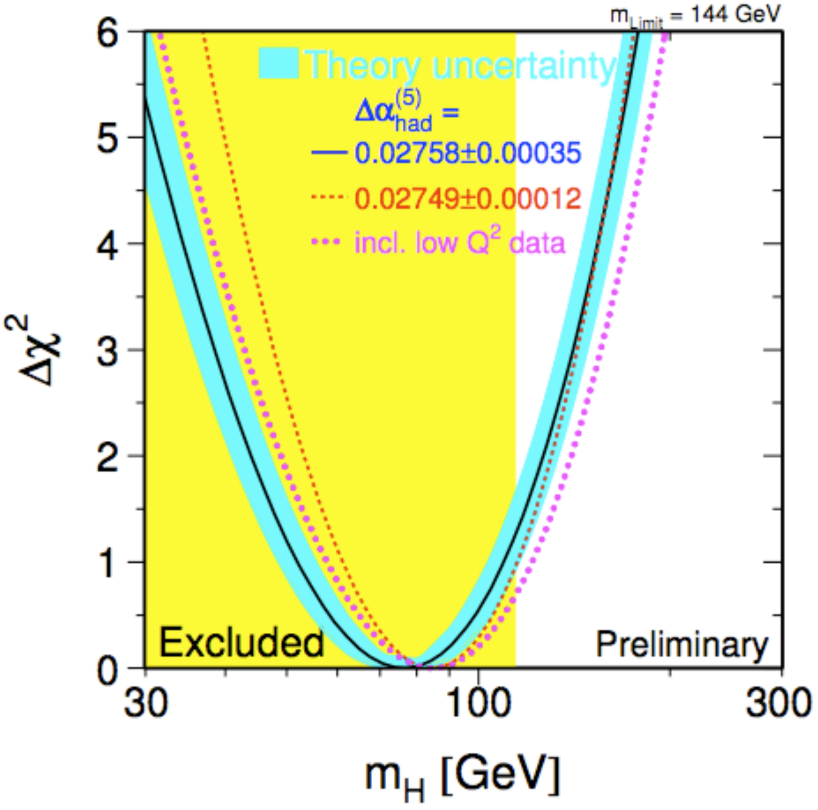
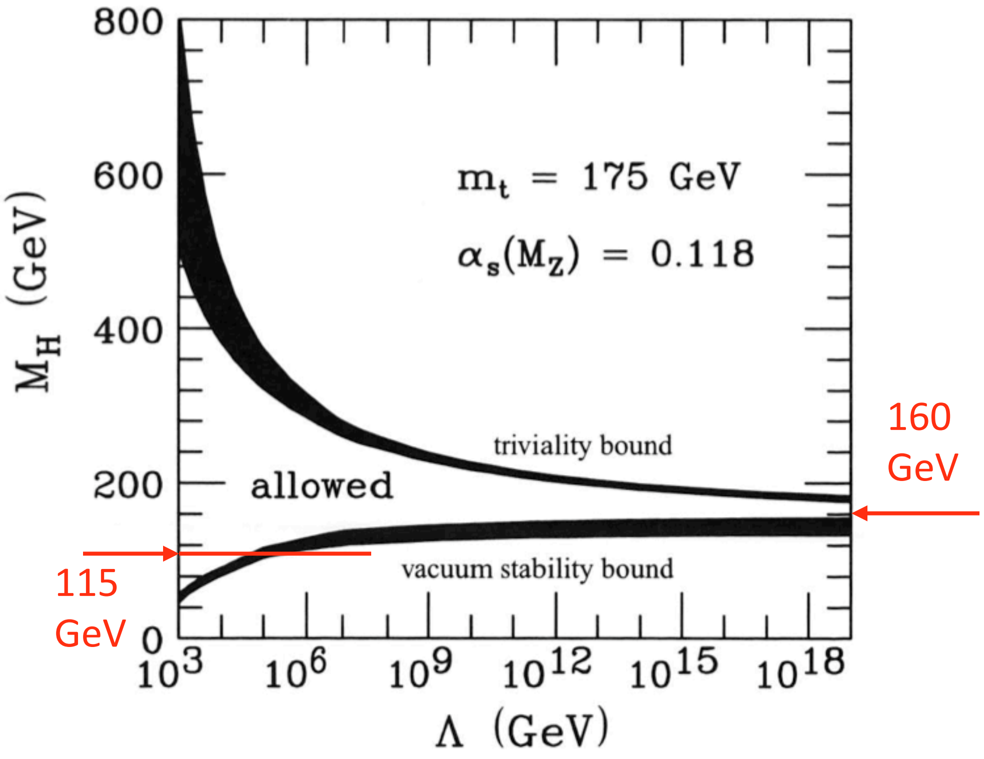
Observation of $Z\gamma\rightarrow\nu\nu\gamma$ at DØ

Yurii Maravin (KSU)

Where is Higgs?

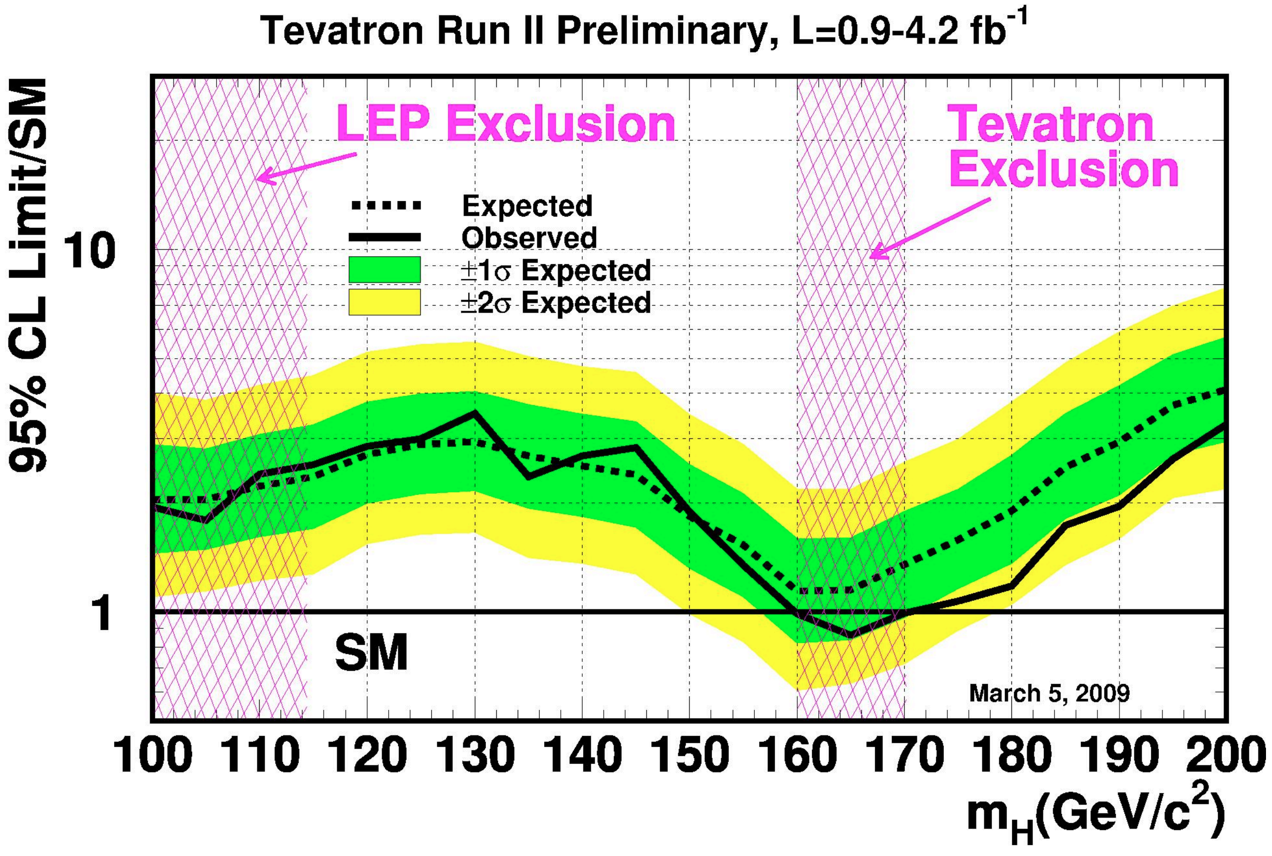
- Artificial add-on to the standard model (is it even there?)
- There is a mounting tension between direct and indirect limits
- SM fits prefer light Higgs that leads to vacuum instabilities at high renormalization scales





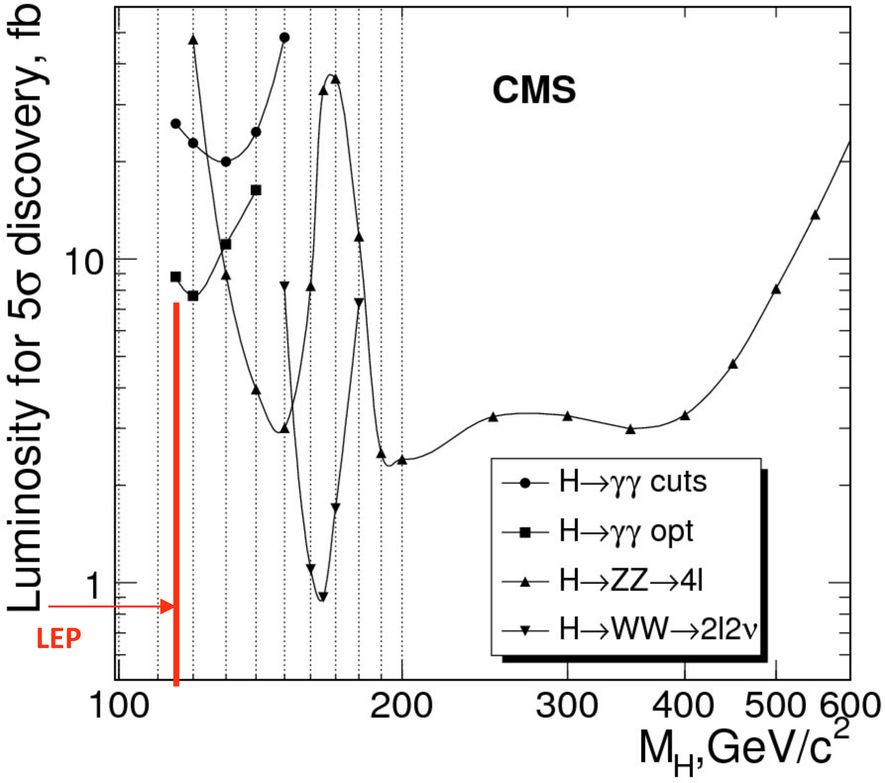
There is no high mass Higgs

- Recent results from Tevatron exclude 160-170 GeV region

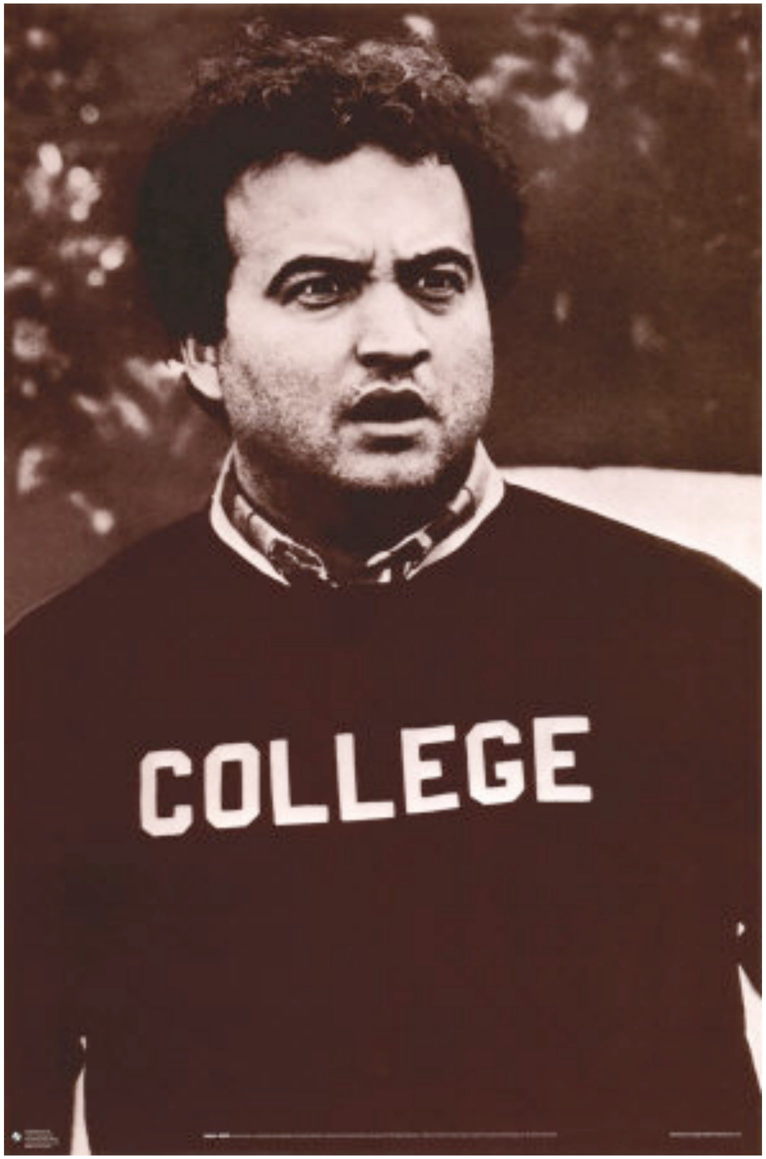


Search for Higgs at LHC

- Low mass Higgs discovery channel is H⟶γγ



Photons?



Yes I see the light!

Physics with photons

- Higgs!
  - Low mass γγ resonances – *but wit will take time to get there*
- Randall-Sundrum gravitons
  - High mass γγ resonances
- Large extra dimensions
  - Excess of high mass γγ pairs (virtual gravitons)
  - Mono-photons (photon recoils against a graviton that escapes into extra dimension
- GMSB SUSY or UED
  - γγ + missing ET
- Hidden Valley, GMSB SUSY, 4th generation
  - Long lived particles decaying into photons or electrons
- Zγ/Wγ production
  - Measure gauge boson couplings, search for resonances

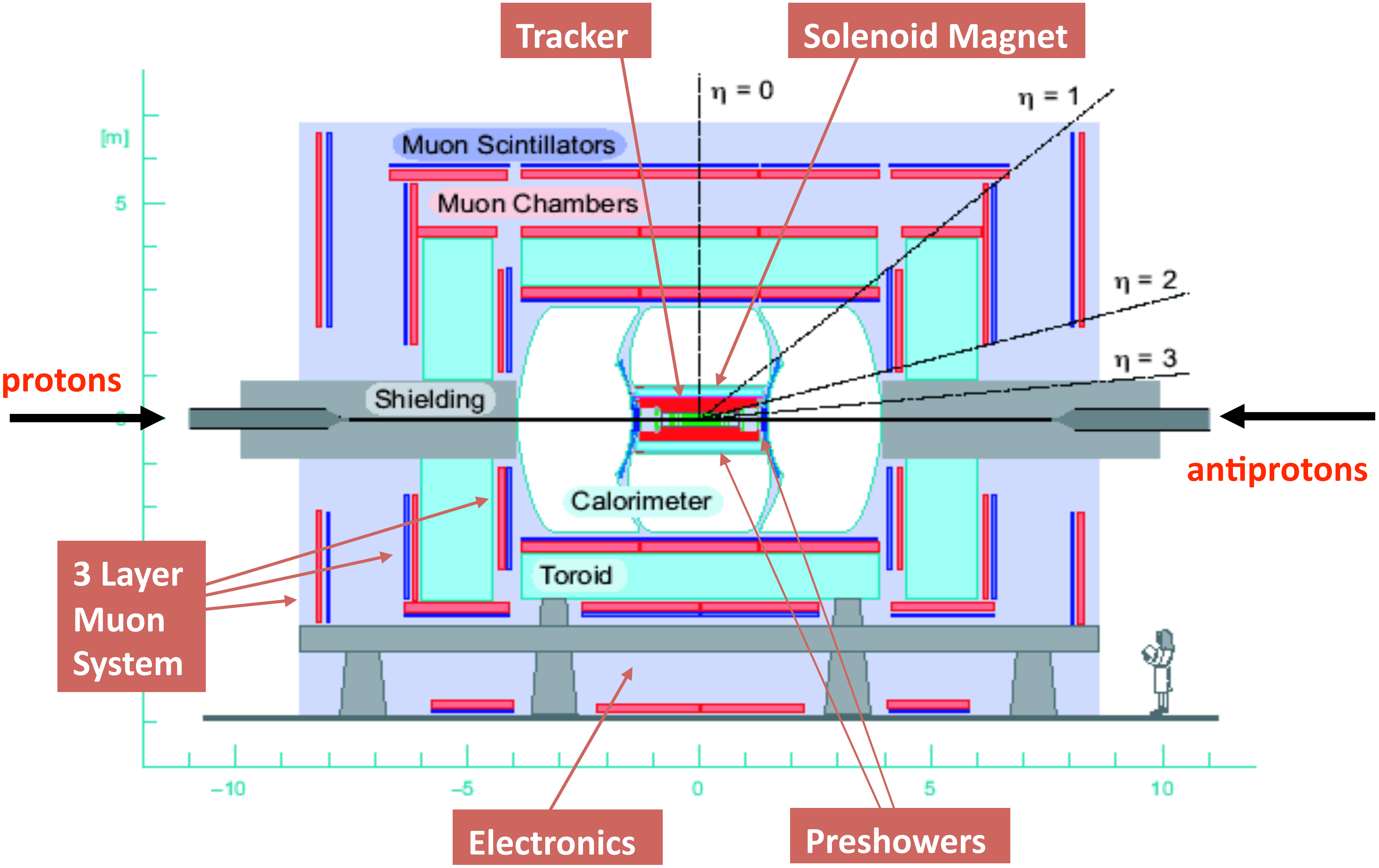
In this talk: photons @ DØ

- Example of a photon physics program at DØ
  - – Photon identification criteria
    - Synergy with CMS
  - – Analysis of mono-photon events with 3.6 /fb
  - – Limits on ZZγ and Z$\gamma\gamma$ anomalous couplings
  - – Observation of Z$\gamma \rightarrow \nu\nu\gamma$

DØ Collaboration

- 18 countries
- 82 institutions
- 500 authors

DØ Detector


Tracker
Solenoid Magnet
η = 0
η = 1
η = 2
η = 3
[m]
5
0
Muon Scintillators
Muon Chambers
protons
Shielding
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Calorimeter
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3 Layer Muon System
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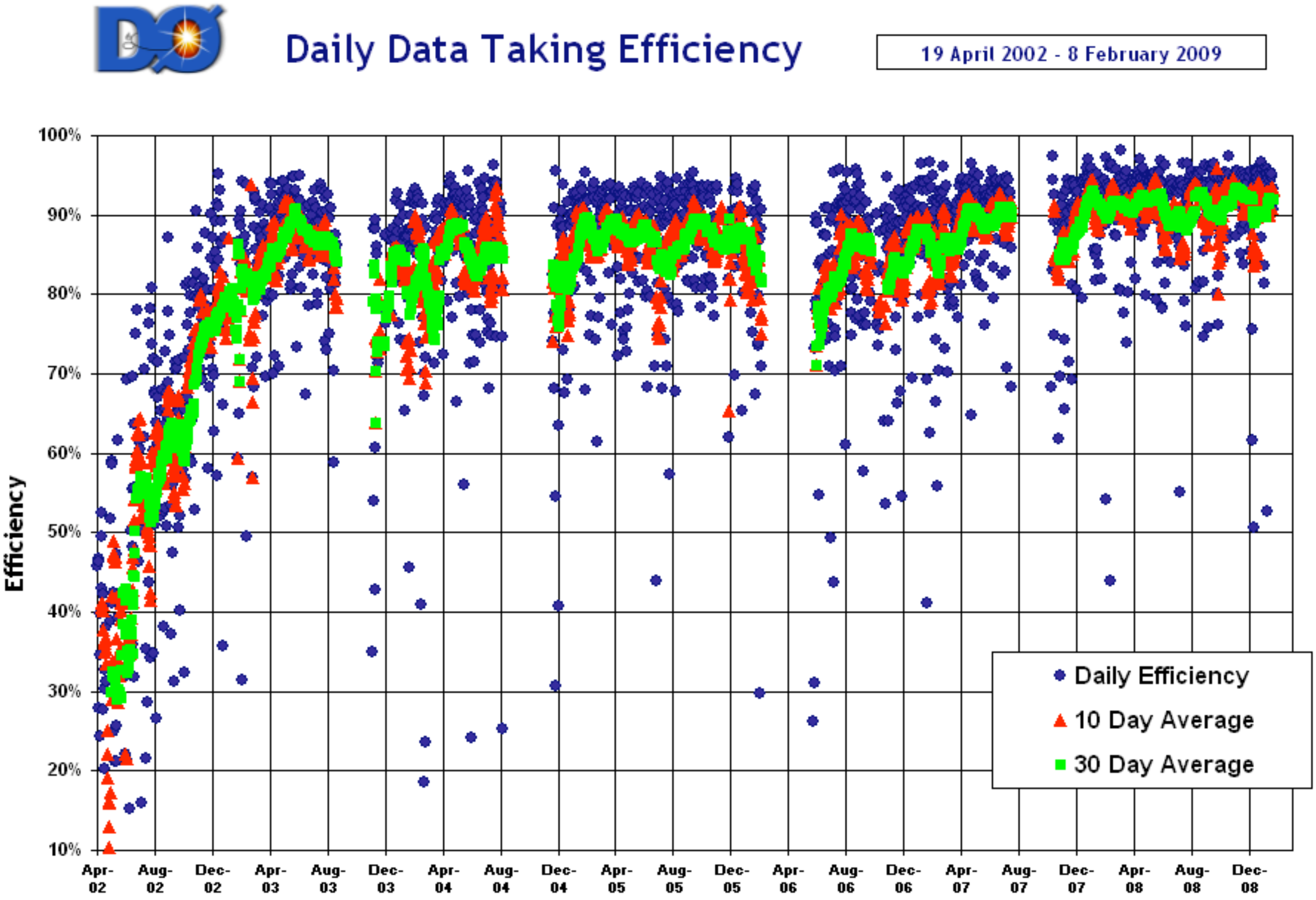
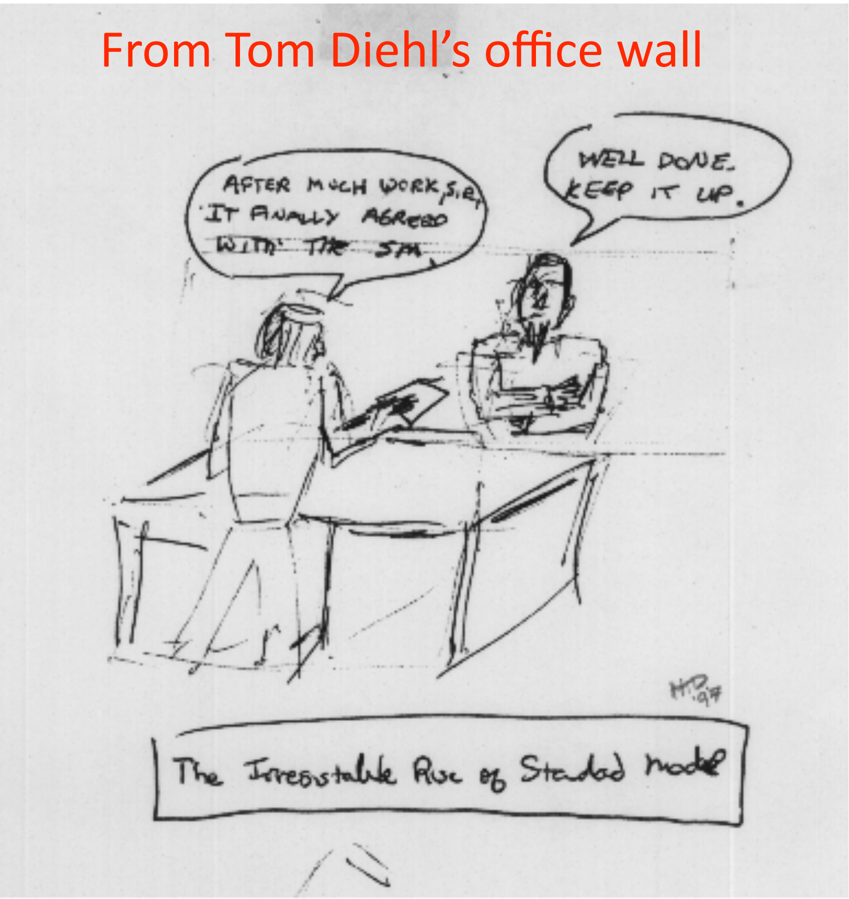
Electronics
Preshowers

Data taking efficiency



The irresistible rise of the SM

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

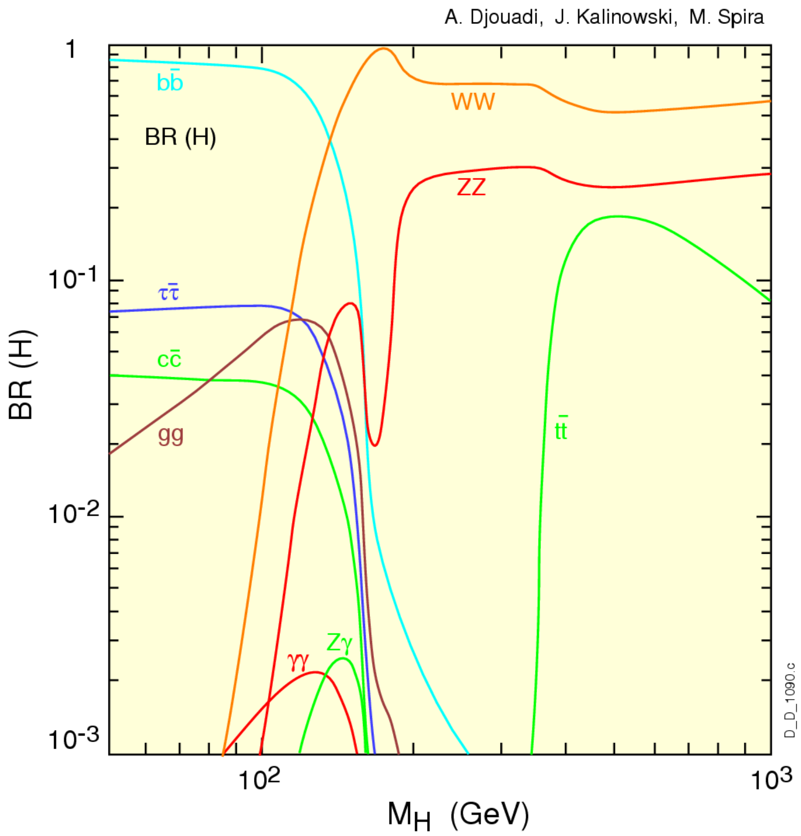


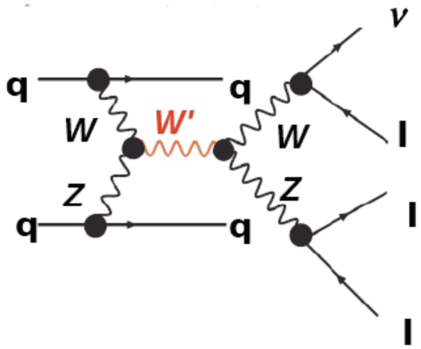
From Tom Diehl's office wall

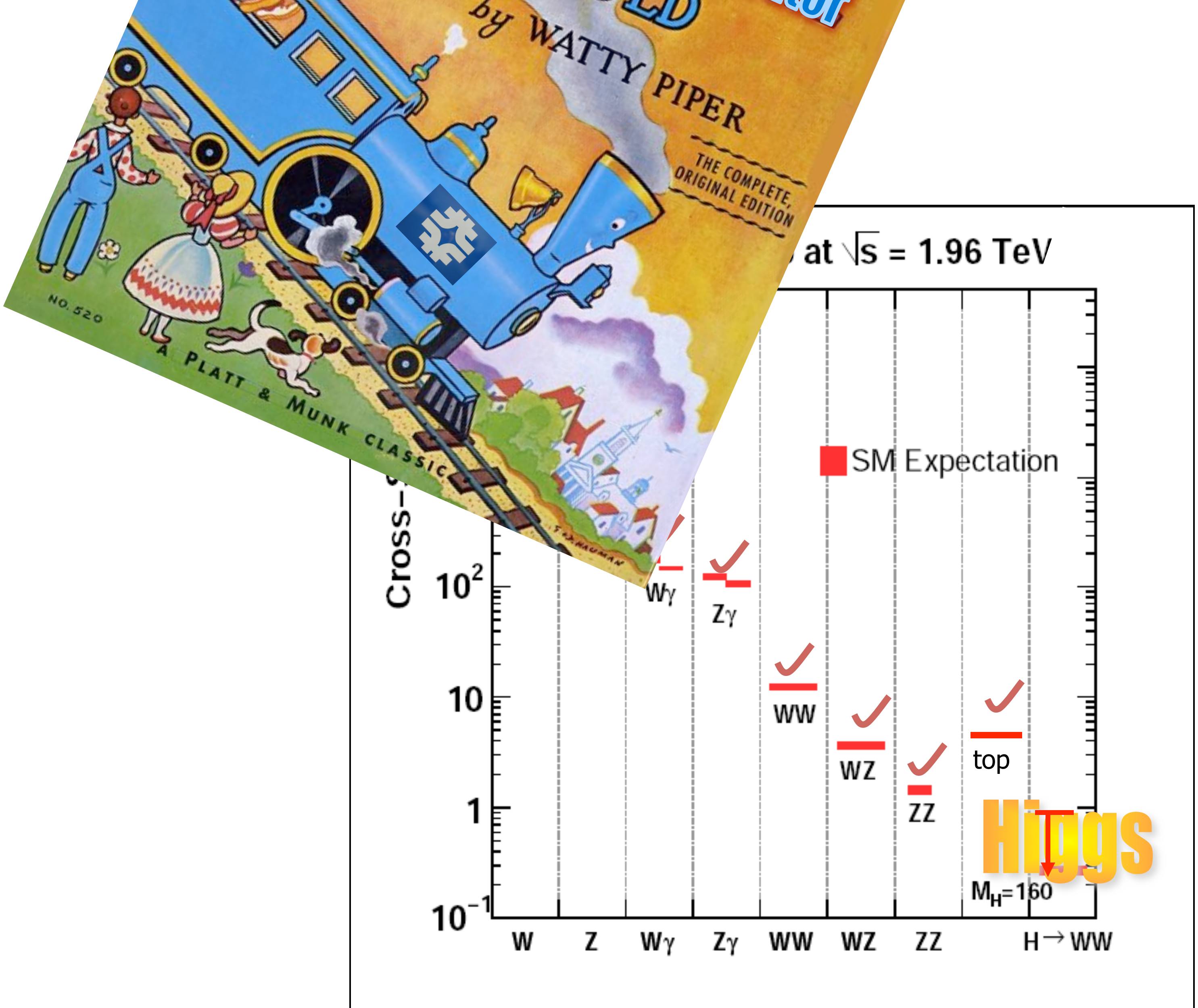
- Wonderful agreement with experimental results
  - What lies ahead?

Diboson physics

- Physics with multiple bosons in the final state
    - Such as WW, WZ, Zγ, γγ, …
- A number of important measurements and searches
    - Cross section
    - Search for resonant production
        - Such as Higgs, or fermiophobic higgs, or whatever…
    - Self-interaction boson couplings are the least well known parameters of the EW sector of the standard model

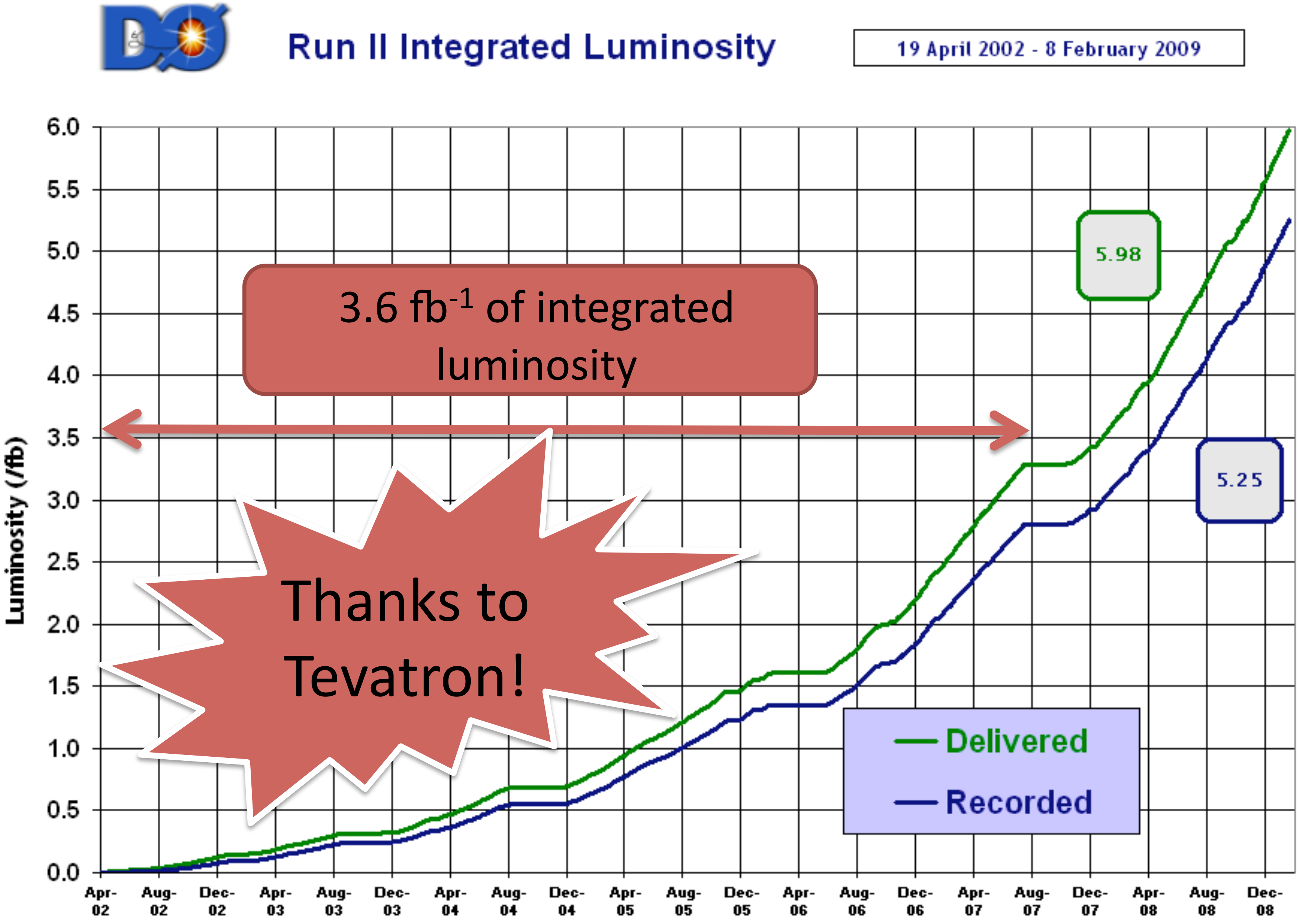






note: this is σ, not $\sigma \times$ BR

Integrated luminosity

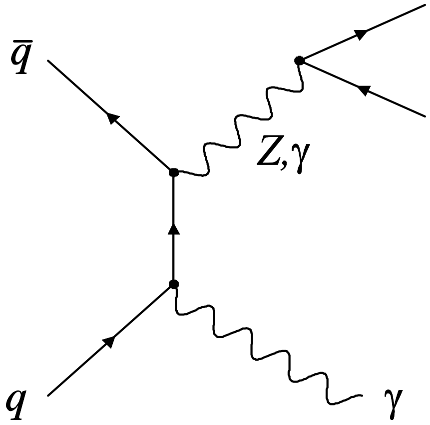


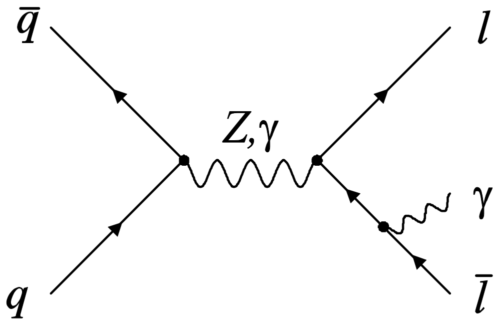
3.6 fb^{-1} of integrated luminosity

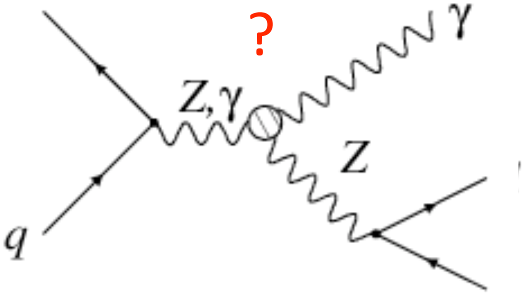
Thanks to Tevatron!

Zγ production

- SM predicts only two tree-level diagram of Zγ via initial and final state radiation
  - No final state radiation in ννγ final state





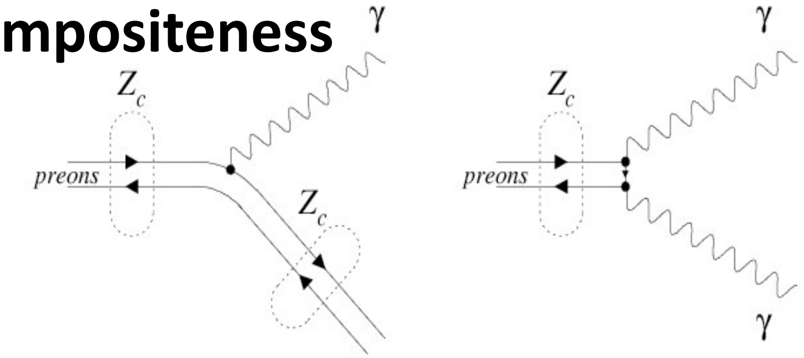


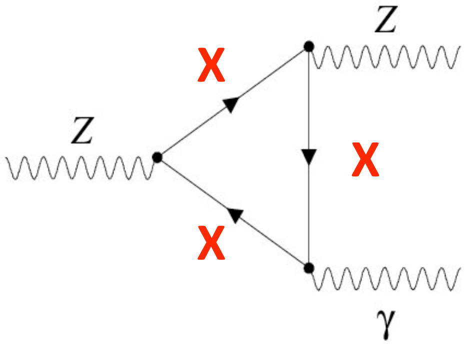
  - ZZγ and Zγγ couplings are almost zero
    - QED corrections are at the 10^{-4} level

New phenomena in Zγ

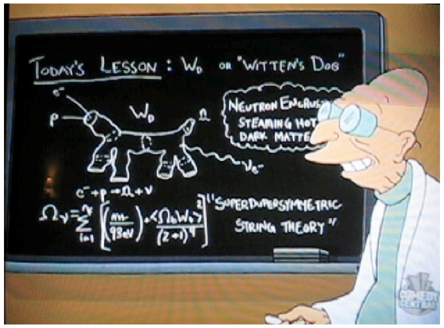
- Numerous possible extensions of the standard model result in non-zero ZZγ and Zγγ couplings

Compositeness





Something else?



- Follow effective Lagrangian approach
  - Parameterize the ZZγ/Zγγ vertex in the most general way

Most general parameterization

Baur & Berger, 1993

- ZVγ vertex can be parameterized by 8 complex couplings h_i^Z and h_i^γ where i is 1-4
  - h$_1$, h$_2$ are CP-odd,
    h$_3$, h$_4$ are CP-even
  - Unitarity is violated at high $\hat{s}$, use form-factor ansatz to enforce good energy behavior

$$d_{Z_T} = -\frac{e}{\sqrt{2}}\frac{k^2}{M_Z^3}(h_{30}^Z - h_{40}^Z)$$

$$\mu_{Z_T} = -\frac{e}{\sqrt{2}}\frac{k^2}{M_Z^3}(h_{10}^Z - h_{20}^Z)$$

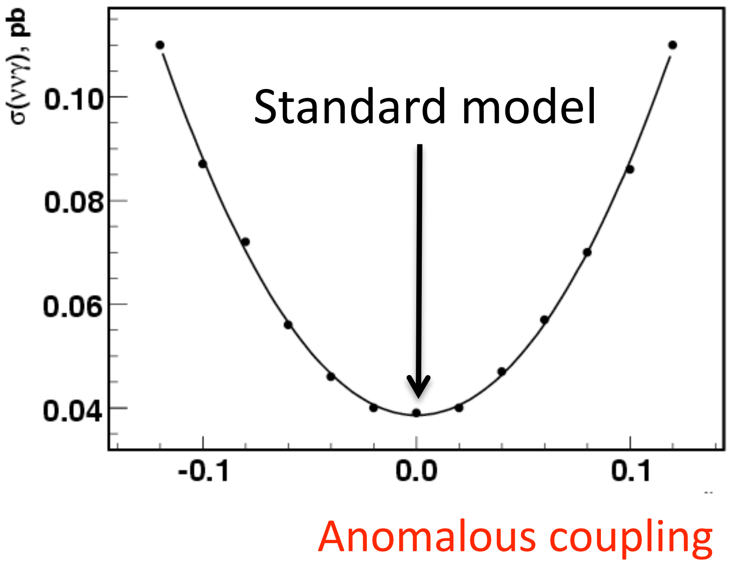
$$h_i^V = \frac{h_{i0}^V}{(1+\hat{s}/\Lambda^2)^n}$$

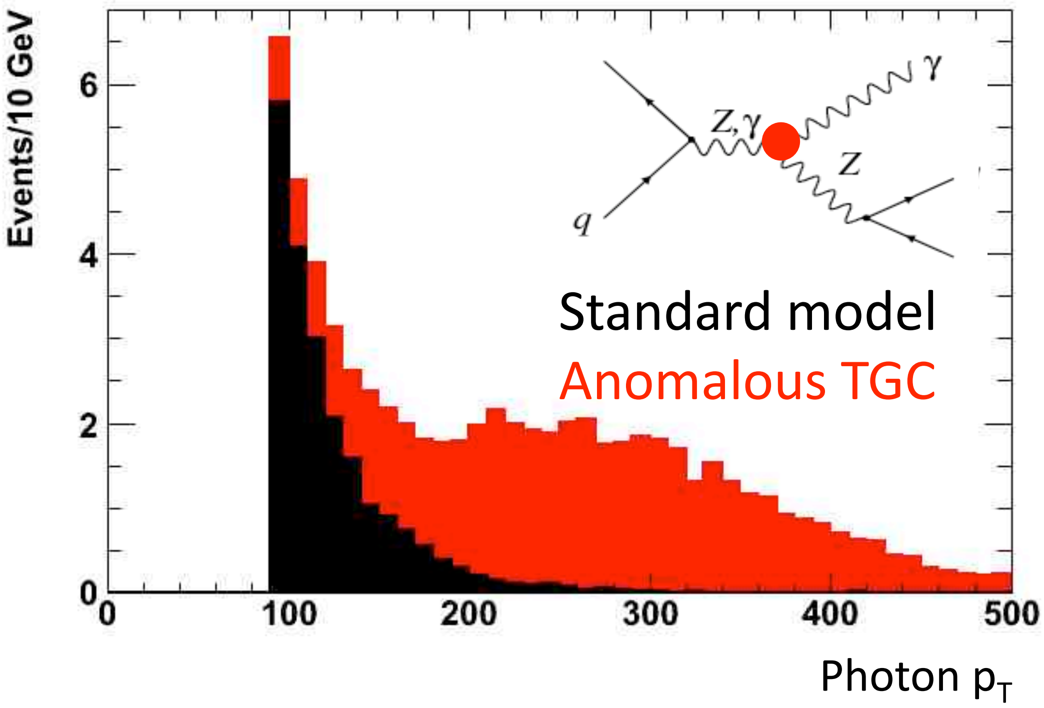
Low energy approximation

- Here, Λ is a new physics scale that is responsible for conserving unitarity at high $\hat{s}$
  - Customary, n = 3 for $h_{1,3}^V$ and, and 4 for $h_{2,4}^V$

Effect of anomalous coupling

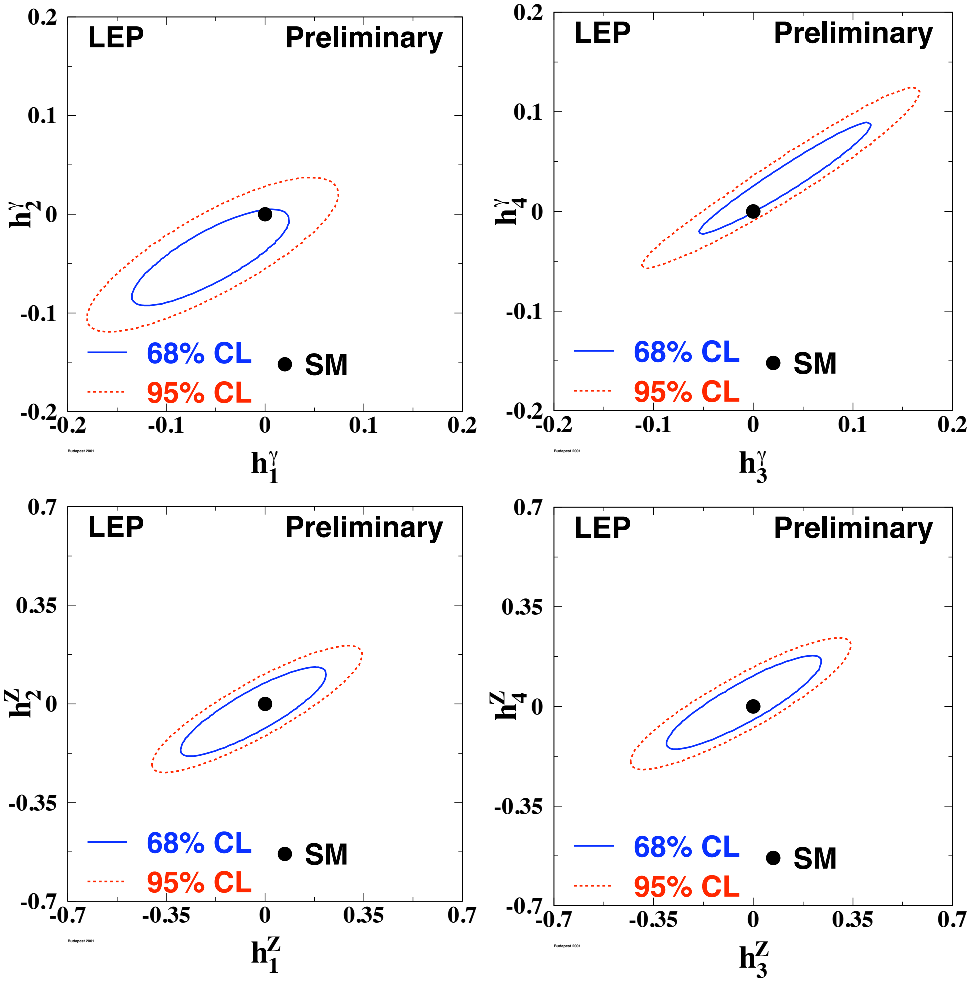
- Any non-zero coupling result in increase of the cross section and harder p_T spectrum of the photon and Z
  - Produced from Baur MC 4-vector output (LO)





Previous results on Zγ: LEP

LEP EWWK 2003, Preliminary



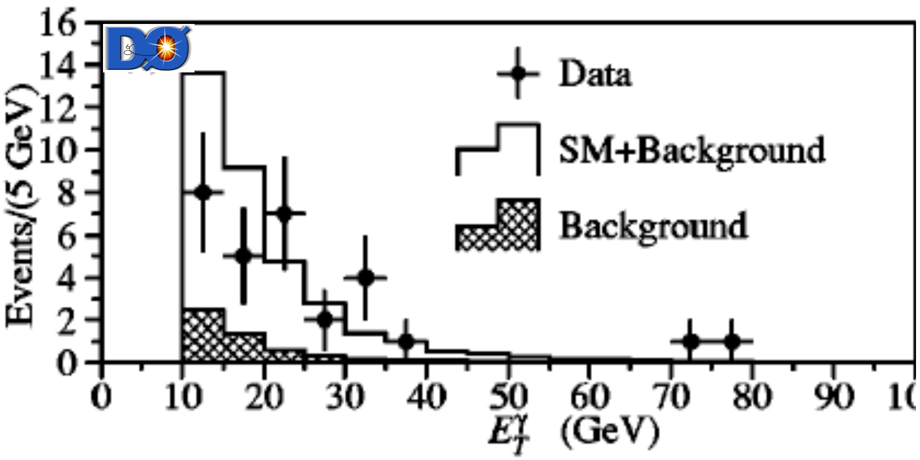
$$-0.056 < h_1^\gamma < 0.055$$
$$-0.045 < h_2^\gamma < 0.025$$
$$-0.049 < h_3^\gamma < -0.008$$
$$-0.002 < h_4^\gamma < 0.034$$

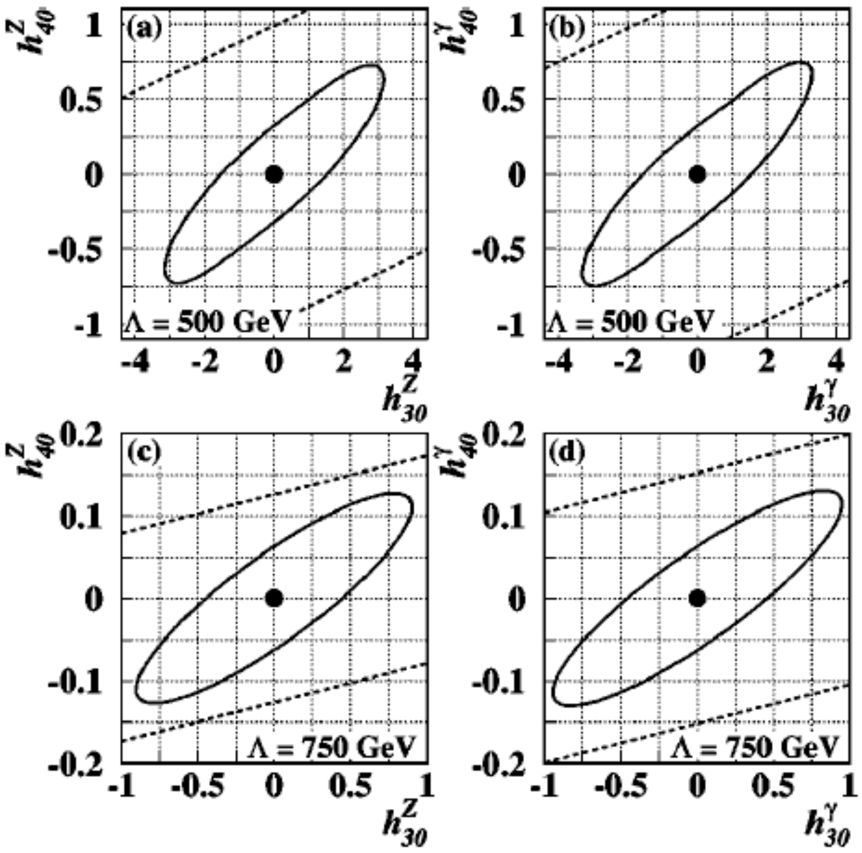
$$-0.13 < h_1^Z < 0.13$$
$$-0.078 < h_2^Z < 0.071$$
$$-0.20 < h_3^Z < 0.07$$
$$-0.05 < h_4^Z < 0.12$$

- Measured ZZγ and Zγγ couplings agree with SM at $10^{-1} – 10^{-2}$ level

Previous Tevatron results $Z\gamma \rightarrow ll\gamma$

- DØ set limits $Z\gamma \rightarrow ll\gamma$ in Run I
  - Observed 29 events
  - The p_T^γ spectrum agree with standard model prediction

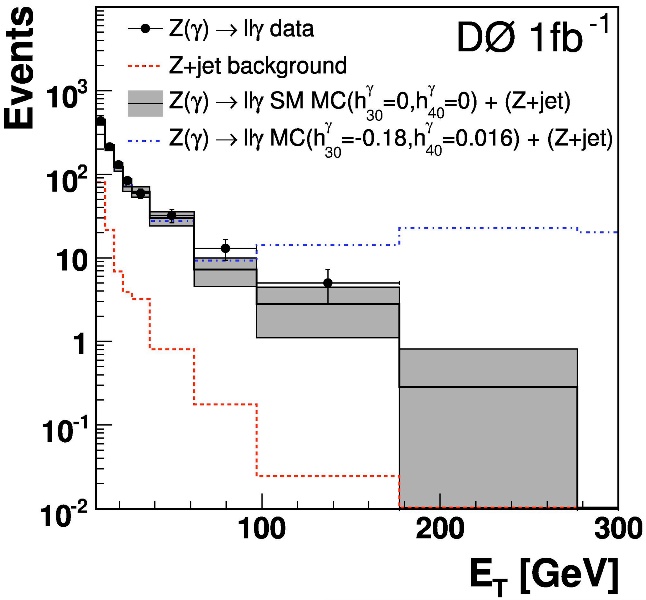


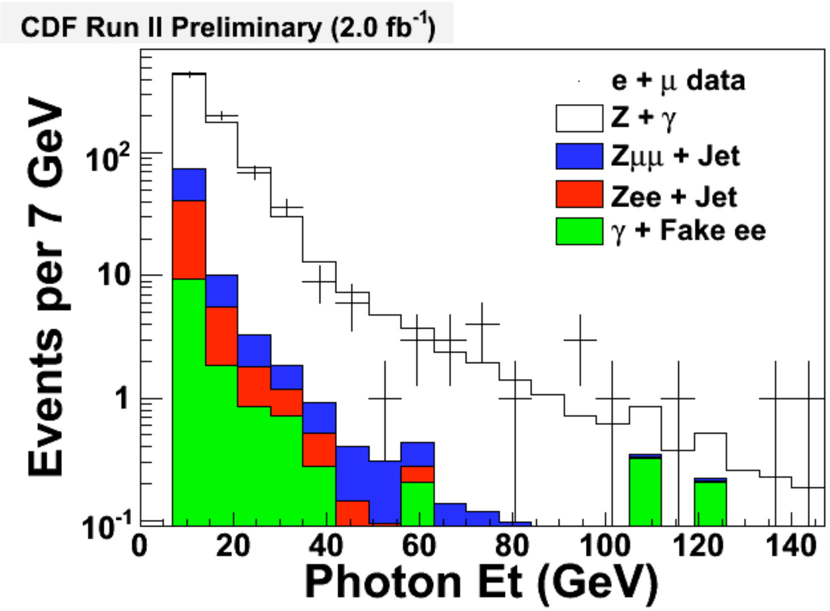


Agreement with SM at $10^{-1} – 10^{-2}$ level

Previous Run II results on Zγ→*ll*γ

- Both CDF and DØ performed extensive studies of the Zγ production in Zγ→*ll*γ
  - Both cross section and p_T^γ spectrum agree with standard model prediction
  - Limits are $\left|h_3^V\right| < 0.085$ $\left|h_4^V\right| < 0.0047$

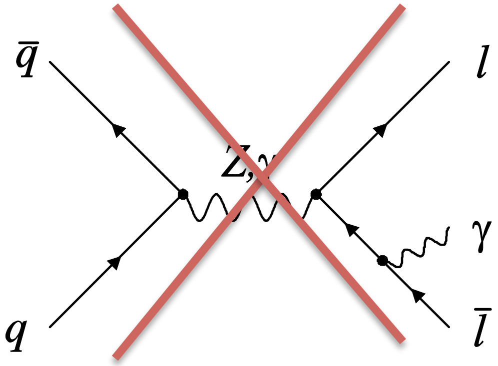




Agreement with SM at 10^{-1} – 10^{-3} level

Can we do better?

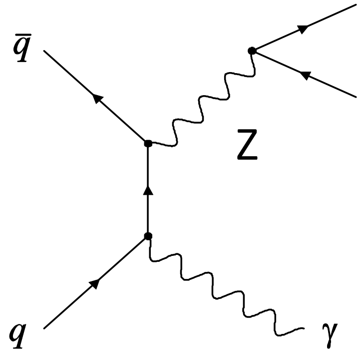
- Precision is still dominated by statistics
  - Sensitivity is in the tail of the p_T^γ distribution
- Major limiting factors:
  - Three particle final state
  - Low Z$\rightarrow ll$ branching fraction



- Challenging alternative: Z$\gamma \rightarrow \nu\nu\gamma$
  - Much higher acceptance
  - No FSR processes!
  - Neutrino branching fraction is three times the Z$\rightarrow ll$

Precision should double for the $\nu\nu\gamma$ channel alone!

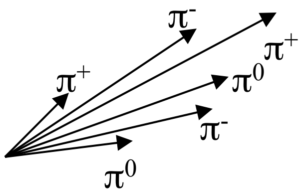
Zγ→ννγ



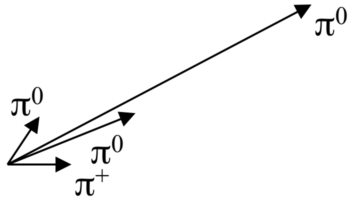
- Very challenging
  - – Has not been seen at Tevatron!
- Final state is a single photon and a missing transverse energy (MET) consistent with Z→νν production
  - – Backgrounds:
    - QCD processes and W production (e → γ)
    - Beam-halo, bremsstrahlung cosmic muons
- A crucial ingredient to this analysis is identification of photons

Photon identification

- Unconverted photons do not have much redundancy: just a shower in the calorimeter
  - Handles to suppress backgrounds:
    - Isolation in tracker and hadron calorimeter
    - Shower profile should be consistent with that of a photon
    - No track pointing to the photon candidate
      - No additional hits in the vicinity of a photon candidate is consistent with not reconstructed track



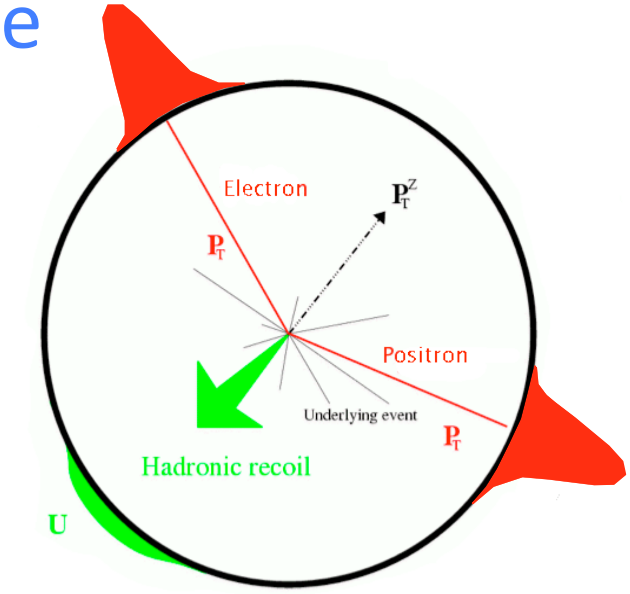
normal jet



fluctuated jet: most energy is carried by π^0

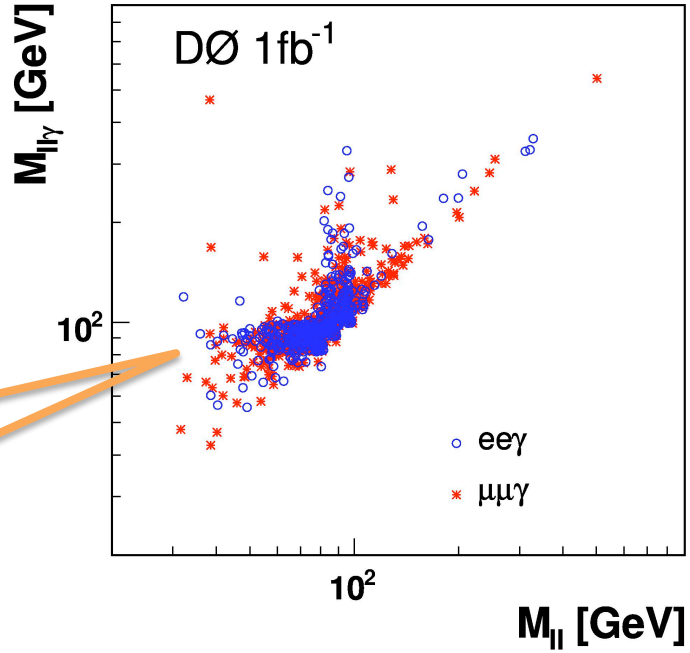
Calibrating photons

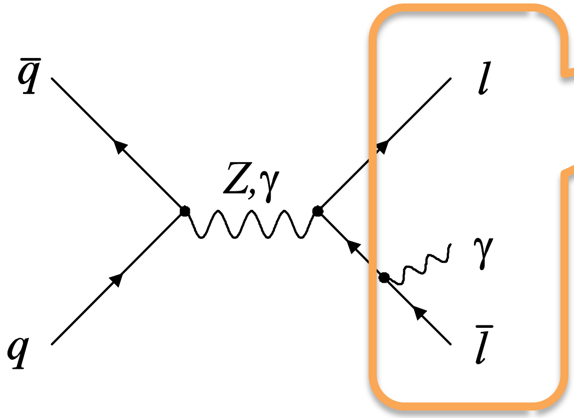
- We must find Higgs to produce a photon calibration signal!
- Use data for calibration: Z→ee
  - Use Monte Carlo to describe the difference between photon and electron shower well
  - Tune Monte Carlo so that it describes electrons well
    - Cross checked in data with FSR Zγ events



Z→$ll\gamma$ as a standard candle

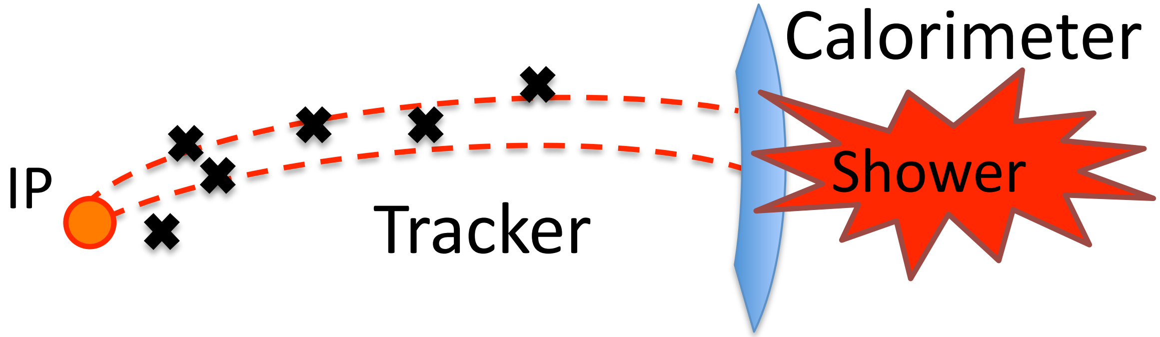
- FSR Zγ is the cleanest source of photons
  - One can use FSR production to make photon sample very clean and to infer photon energy scale!





Suppression of electrons

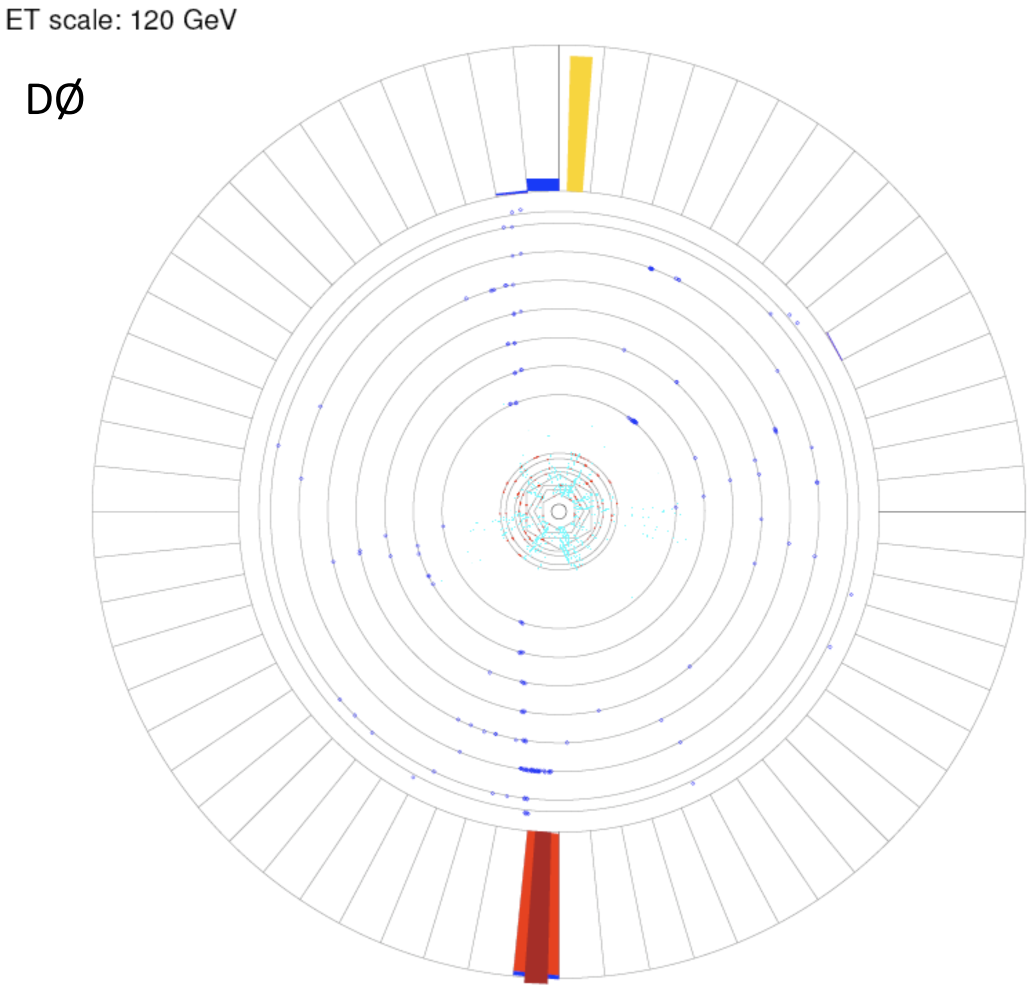
- In addition to the standard matching algorithm in ϕ and η space, require tracker hits density along the EM trajectory to be consistent with noise
  - Hit density and resolution is determined in data

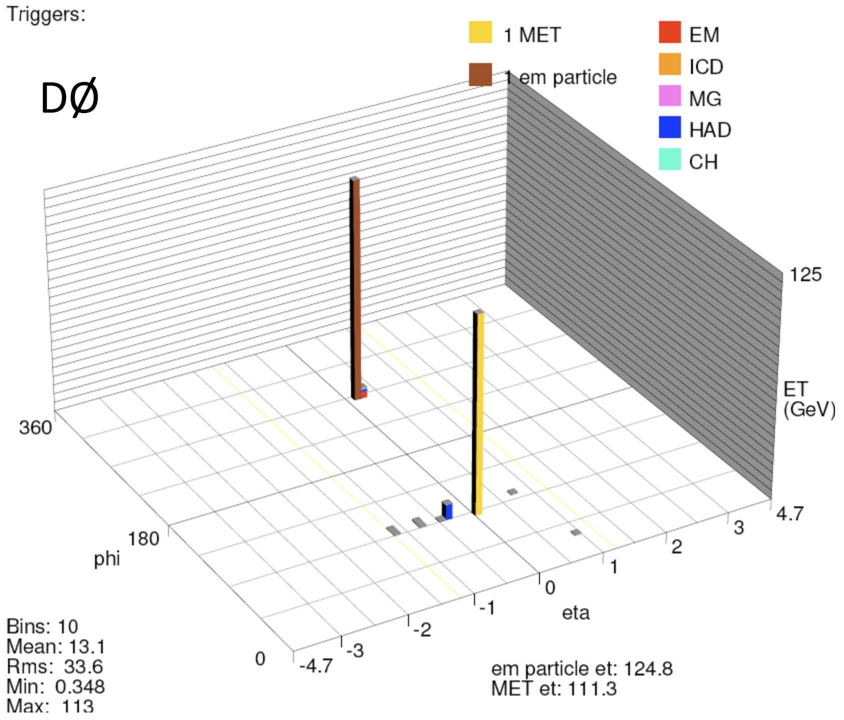


- Improves electron track matching efficiency and decreases the $e \rightarrow \gamma$ misidentification rate by a factor of four!

Non-pointing background

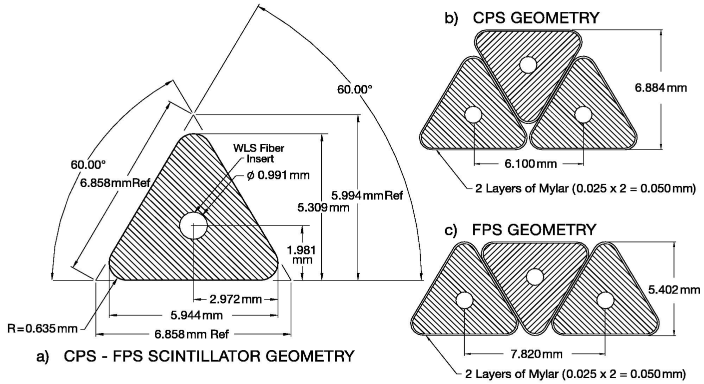
- One of the major backgrounds to the $\nu\nu\gamma$ final state is cosmic muon that radiated a photon in the calorimeter

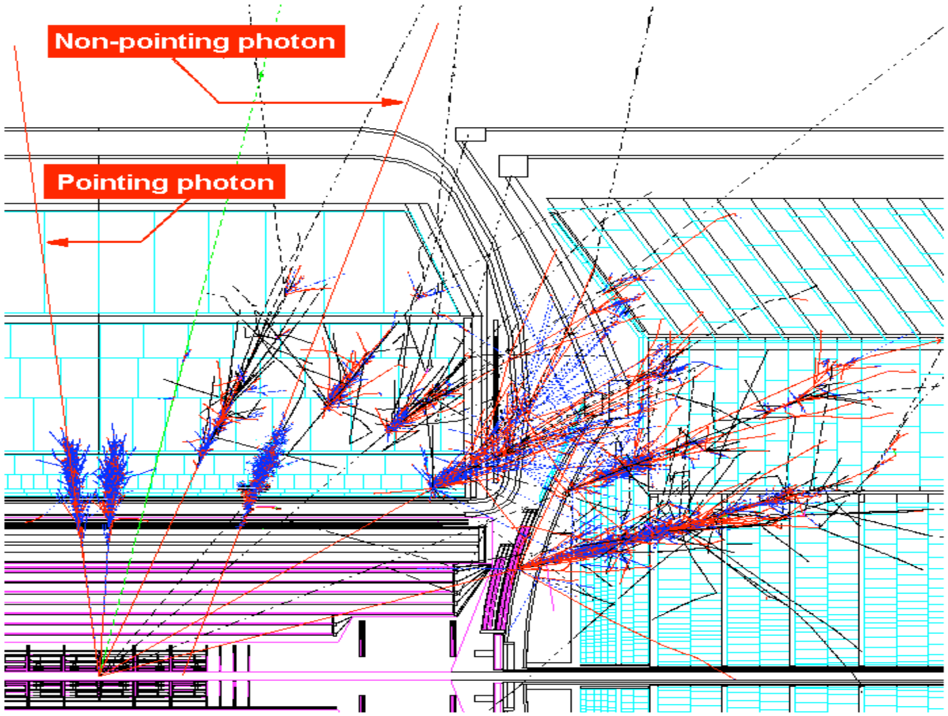


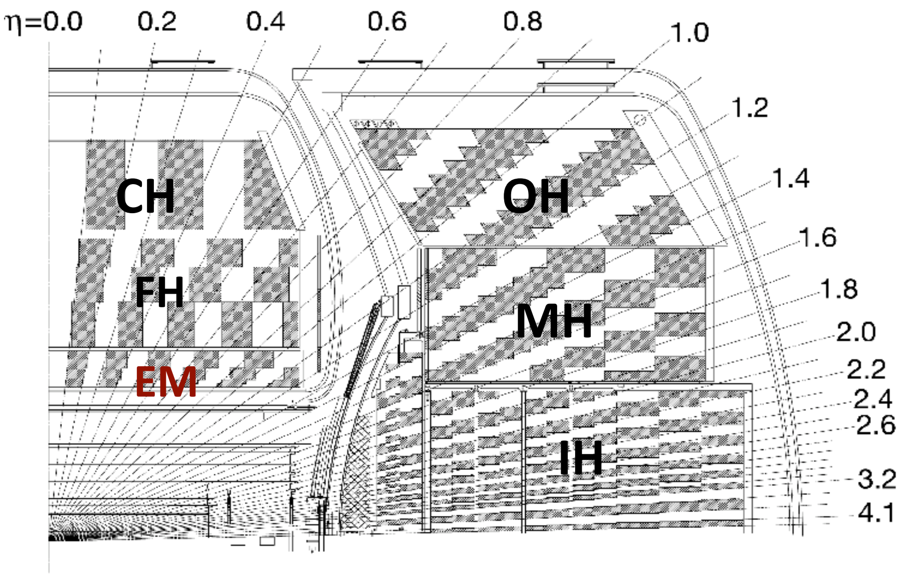


DØ Calorimetry

- DØ calorimeter is highly segmented
  - Use it to pinpoint the shower direction in 3D!

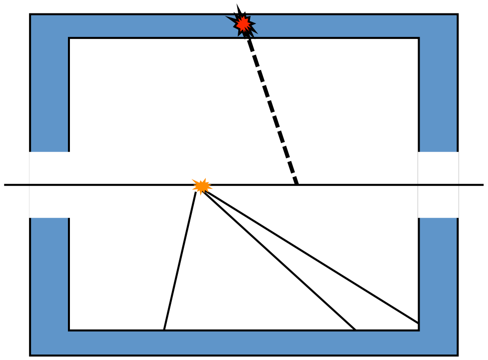


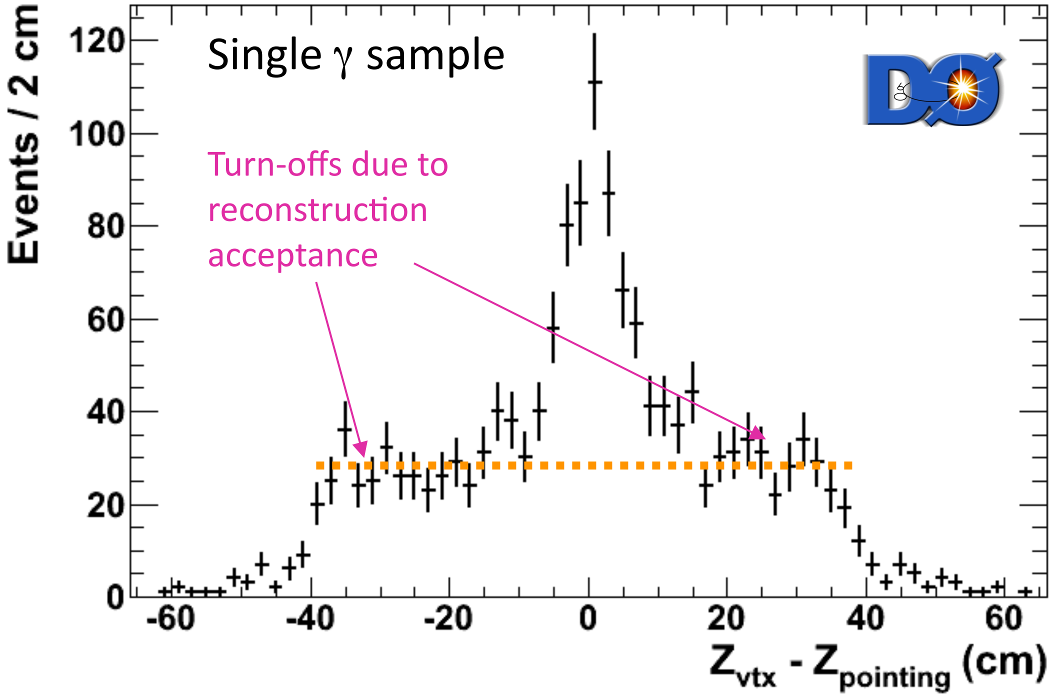




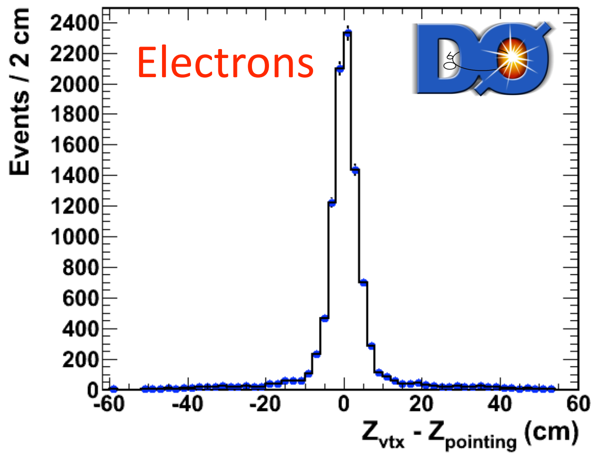
Pointing in *z*-coordinate

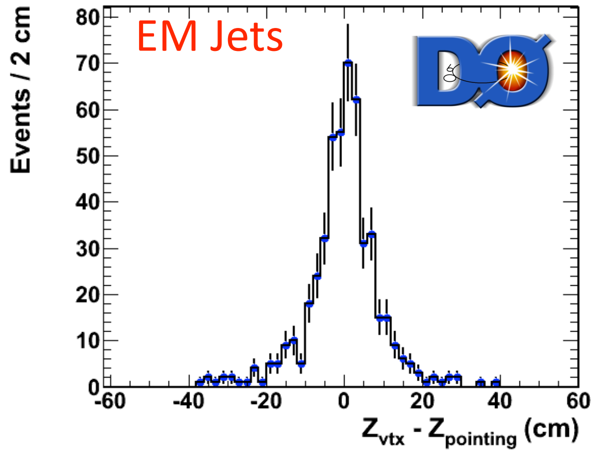
- Cosmics and beam-halo photons would not point to the primary vertex of the event
  - – Exploit this to identify and reject non-collision backgrounds

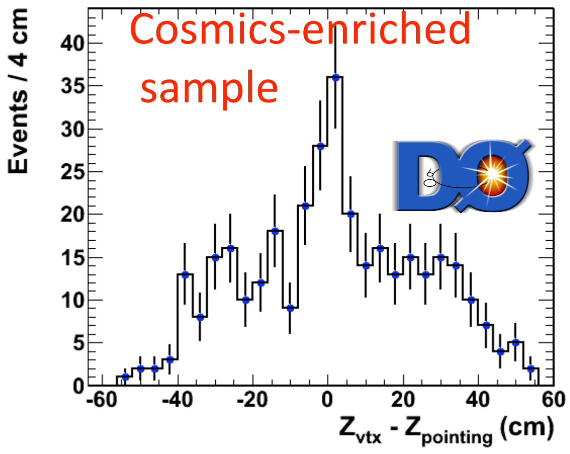




- Δz distributions from data
  - Extremely important for the MET measurement
  - Electrons and photons have narrow showers and thus small Δz resolution
    - Use Z→ee sample
  - Misidentified jets have wider shower profile and thus larger pointing resolution
    - Use "bad" EM sample and γ+jet
  - Non-collision is pretty flat
    - Use cosmics-enriched data



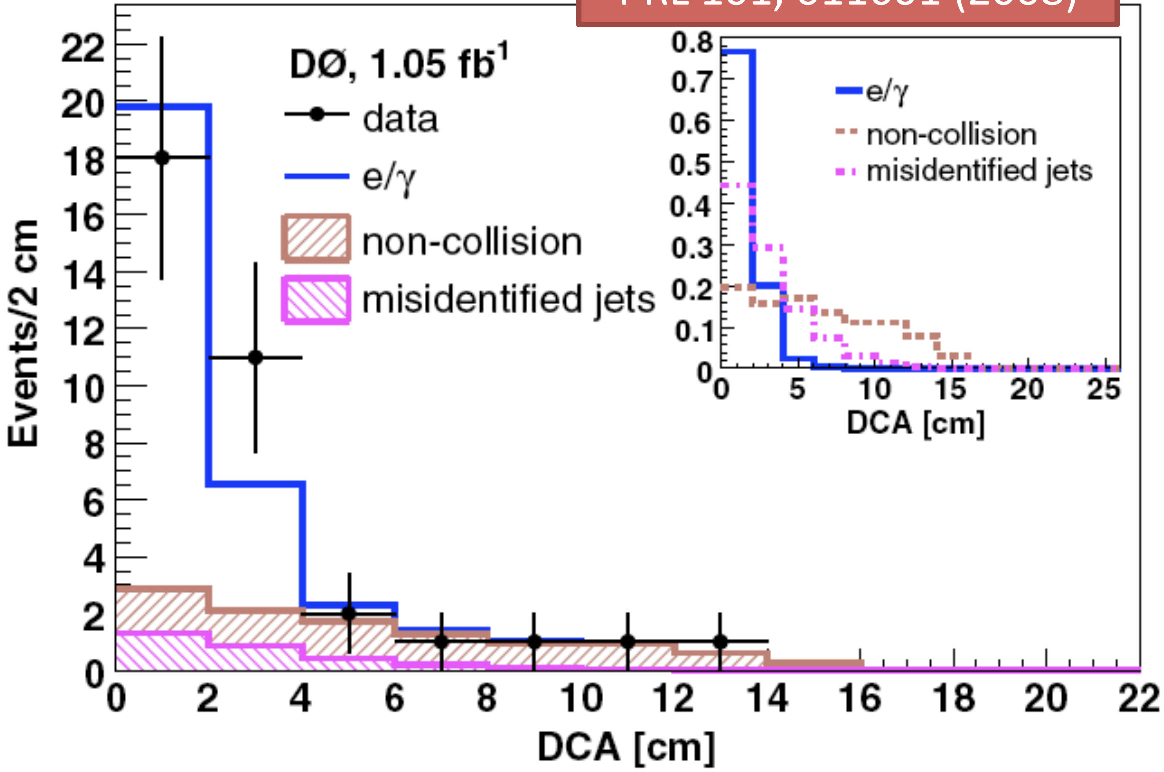


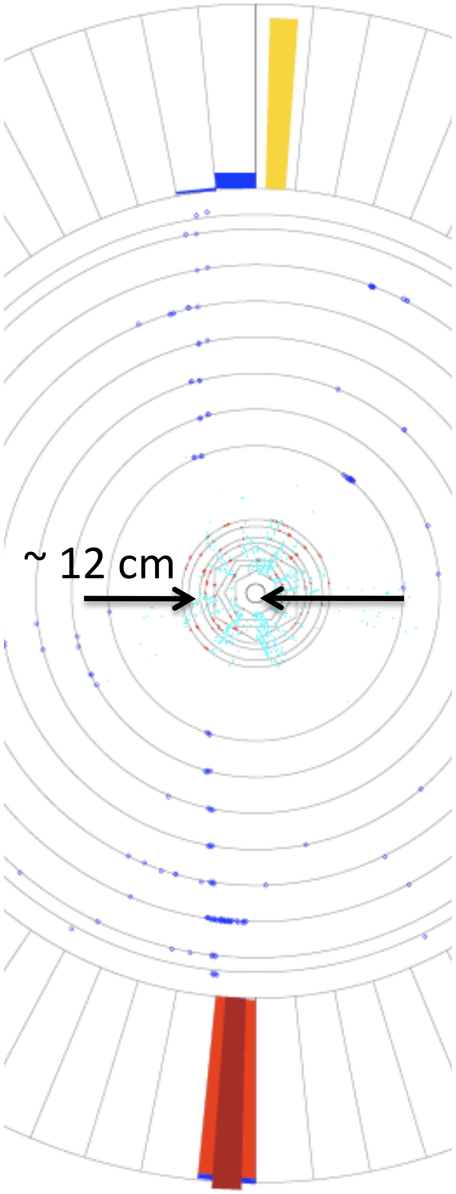


Identification of non-pointing γ

- Determine DCA distributions from data

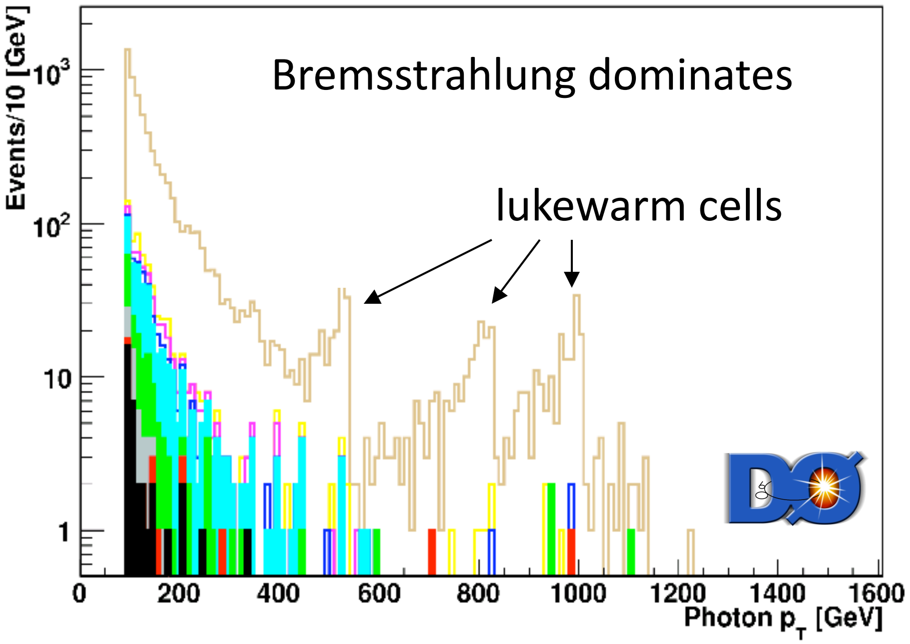
PRL 101, 011601 (2008)





Applying the pointing algorithm

- Select data sample with photon $p_T > 90$ GeV
  - Sample is dominated by muon Bremsstrahlung
  - Applying pointing requirements reduces cosmics and beam-halo considerably!



Bremsstrahlung dominates

lukewarm cells

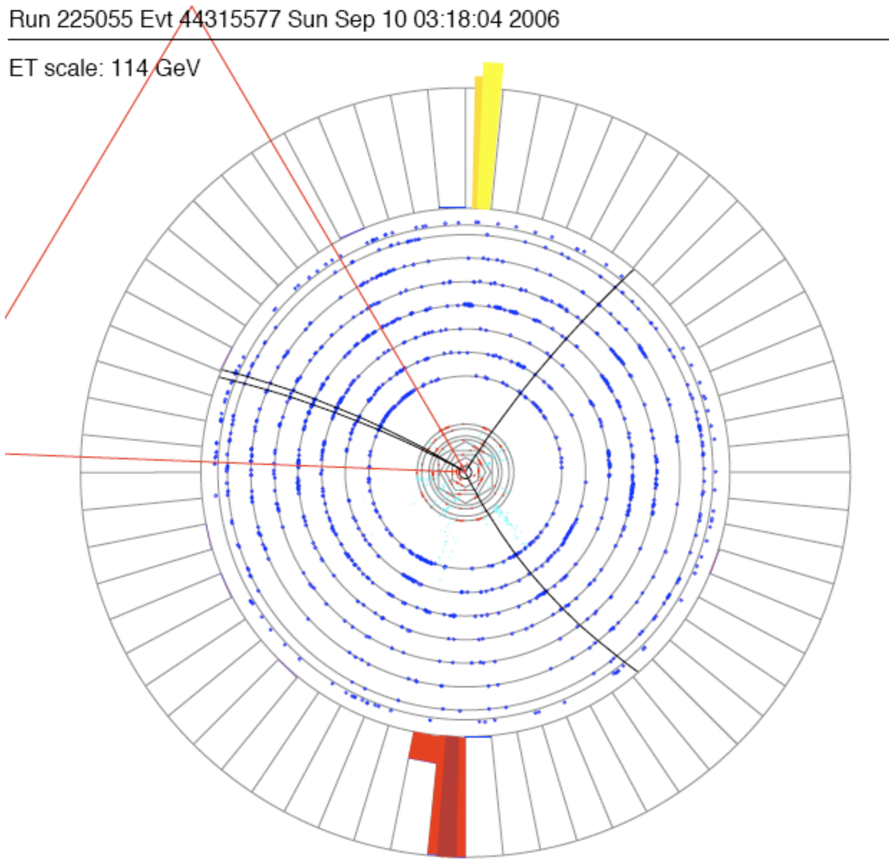
🟧 Kinematics requirements only

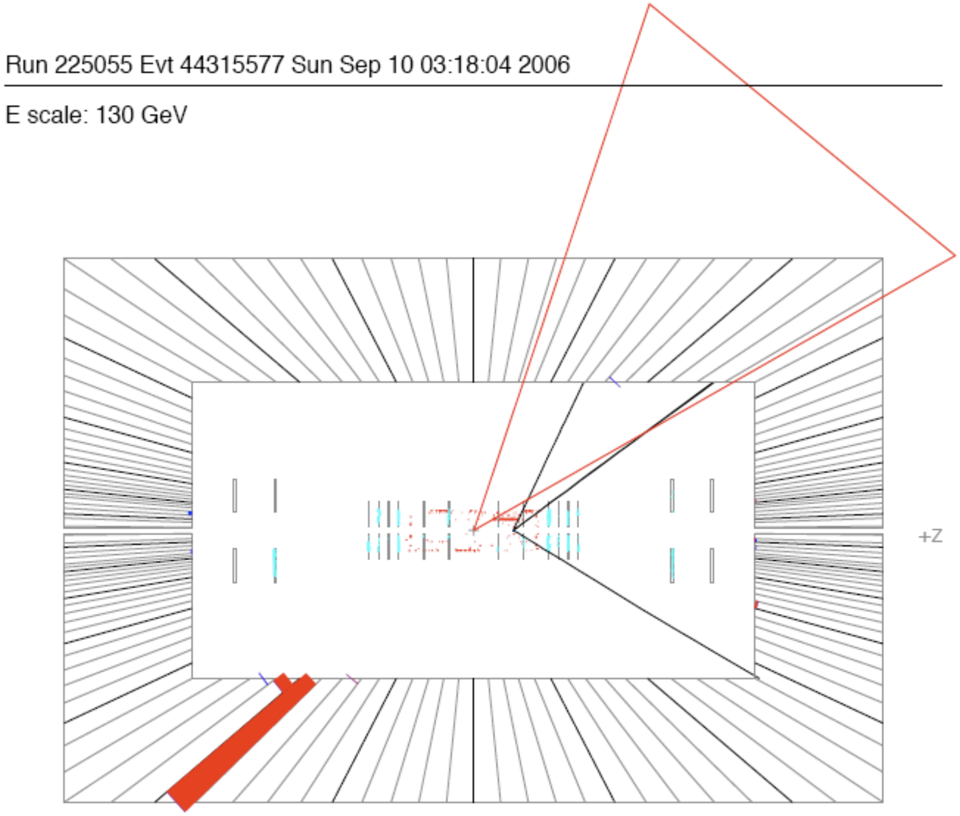
🟦 Applying CPS information

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

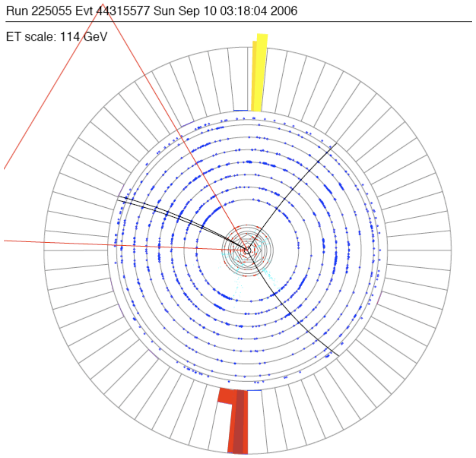
- Select events with single EM triggers
  - Fully efficient at 40 GeV
- Require event to have missing $E_T > 70$ GeV
- Require a clean event
  - No jets with $p_T > 15$ GeV, isolated tracks, cosmic rays, muons…
- Photon candidate has $p_T > 90$ GeV, $|\eta| < 1.1$, isolated, and have shower profile consistent with that of a photon

$\nu\nu\gamma$ candidate event





Backgrounds



- $W \to e\nu$: electron is misidentified as a photon
  - – Estimated from W data sample
- Non-collision: cosmic or halo muon Bremsstrahlung
  - – Estimated from DCA template method
- W or Z + jet: jet is misidentified as a photon
  - – Estimated from the DCA template method
- $W+\gamma \to l\nu + \gamma$: lepton is lost
  - – Small, estimated from Monte Carlo simulation

$W \to e\nu$	9.67 ± 0.30 (stat.) ± 0.48 (syst.)
$non-collision$	5.33 ± 0.39 (stat.) ± 1.91 (syst.)
$W/Z + jet$	1.37 ± 0.26 (stat.) ± 0.91 (syst.)
$W\gamma$	0.90 ± 0.07 (stat.) ± 0.12 (syst.)

Simulation

- There is a number of Monte Carlo generators on the market: use Baur generator
  - – The generator of choice for CDF, DØ, CMS,…
- Use both NLO and LO generators to simulate the process kinematics and acceptance and calculate theoretical cross section
  - – NLO generator is used to calculate NLO *k*-factor
  - – Detector simulation is done by using Parameterized Monte Carlo Simulation (PMCS)
    - Very fast and reliable!

Cross section measurement

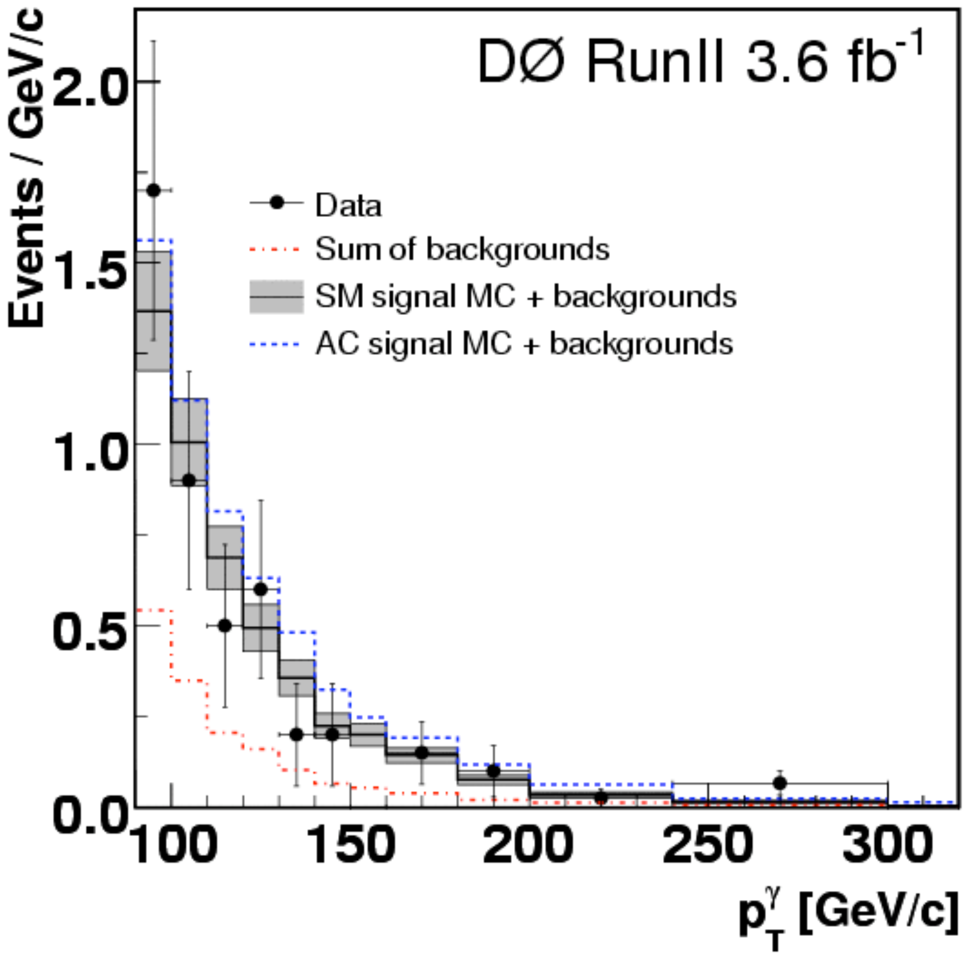
- Using 3.64 fb^{-1} of data we observe 51 $Z\gamma \rightarrow \nu\nu\gamma$ candidate events with an estimated 17.3 ± 0.6 (stat.) ± 2.3 (syst.) background events

$$\sigma \cdot Br(Z \rightarrow \nu\nu) = 32 \pm 9\ (\text{stat+syst}) \pm 2\ (\text{lumi})\ \text{fb}$$

  - Theory predicts 39 ± 4 fb (NLO)
- Perform 10^8 pseudo-experiments with background-only hypothesis to find out that the probability for for background to fluctuate up is 3.1×10^{-7} which corresponds to 5.1σ
  - First observation of $Z\gamma \rightarrow \nu\nu\gamma$ at the Tevatron!

Measuring ZZγ/Zγγ couplings

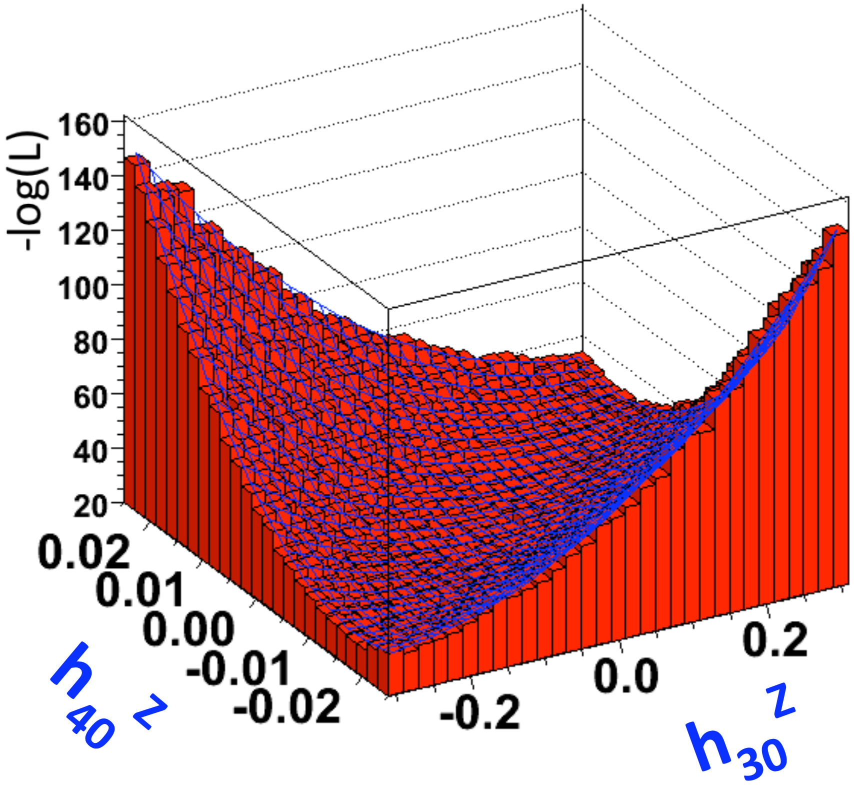
- Data are consistent with standard model production
  - Proceed with setting limits on anomalous couplings

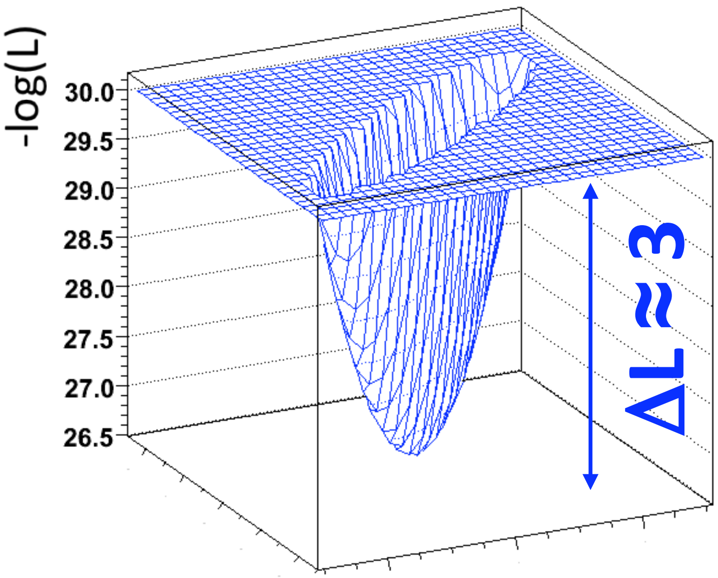


Setting limits on $ZZ\gamma$ and $Z\gamma\gamma$

- The observable (photon p_T) is sensitive to the strength of the coupling
  - We present results for CP-even couplings: sensitivity to h_1 is similar to h_3, and similarly h_2 is similar to h_4
- Generate a 2D grid of simulation with different values of couplings (h_{30} and h_{40})
  - Set CP-odd couplings to zero

- Assume Poisson statistics for signal and Gaussian statistics for systematic uncertainties and background, calculate the likelihood of data to be described by aTGC simulation and background
  - Repeat for every point of the generated grid





Limits on anomalous couplings

Submitted to PRL

- Set 1D limits by setting all the other aTGCs to zero

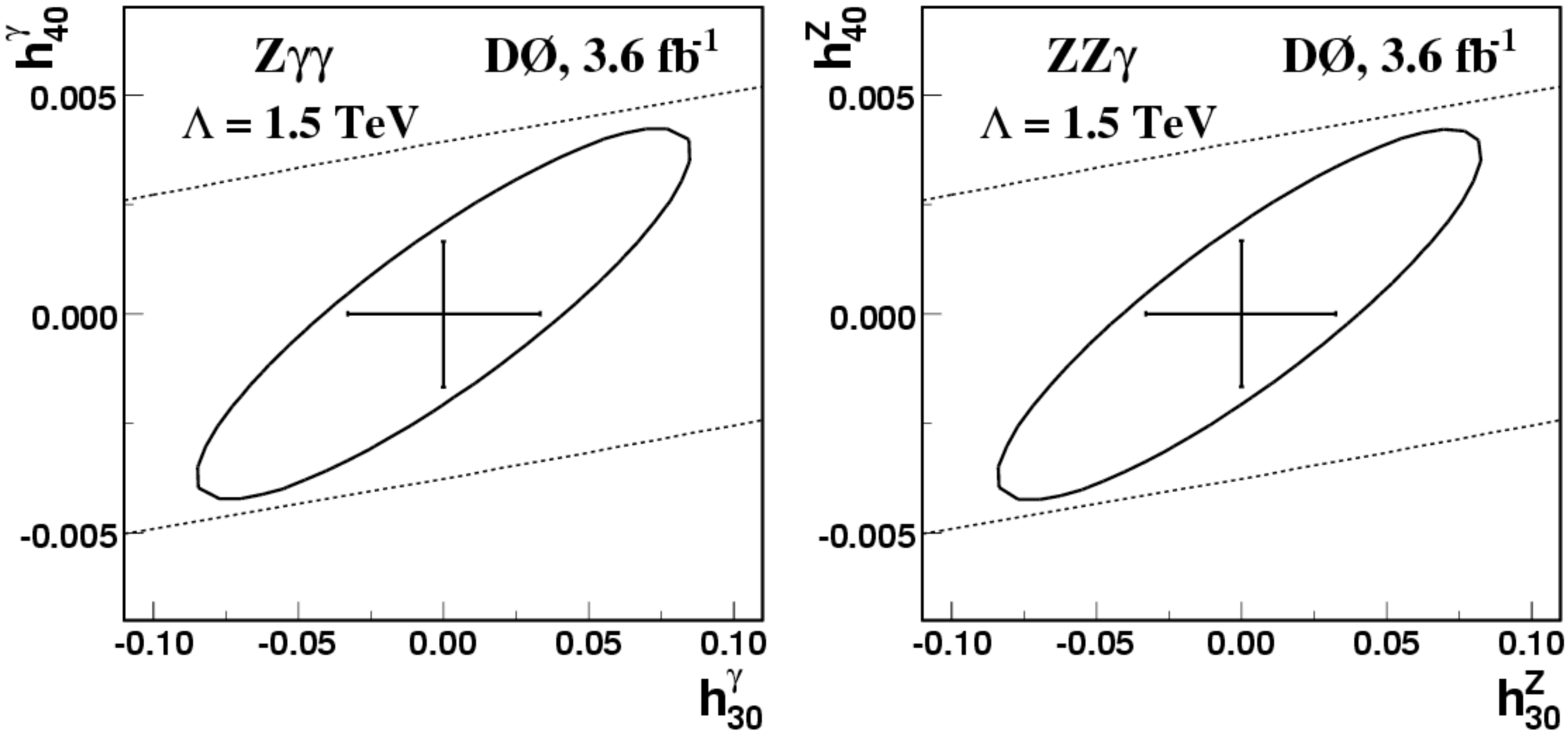
Old DØ result!	Λ = 1.2 TeV	Λ = 1.5 TeV
$Z\gamma \rightarrow ll\gamma$ 1 fb^{-1}	$\lvert h_{30}^{\gamma}\rvert<0.085$ $\lvert h_{40}^{\gamma}\rvert<0.0054$	$\lvert h_{30}^{\gamma}\rvert<0.079$ $\lvert h_{40}^{\gamma}\rvert<0.0036$
$Z\gamma \rightarrow ll\gamma$ 1 fb^{-1}	$\lvert h_{30}^{Z}\rvert<0.083$ $\lvert h_{40}^{Z}\rvert<0.0054$	$\lvert h_{30}^{Z}\rvert<0.075$ $\lvert h_{40}^{Z}\rvert<0.0037$
$Z\gamma \rightarrow \nu\nu\gamma$ 3.6 fb^{-1}	$\lvert h_{30}^{\gamma}\rvert<0.042$ $\lvert h_{40}^{\gamma}\rvert<0.0029$	$\lvert h_{30}^{\gamma}\rvert<0.037$ $\lvert h_{40}^{\gamma}\rvert<0.0020$
$Z\gamma \rightarrow \nu\nu\gamma$ 3.6 fb^{-1}	$\lvert h_{30}^{Z}\rvert<0.041$ $\lvert h_{40}^{Z}\rvert<0.0029$	$\lvert h_{30}^{Z}\rvert<0.036$ $\lvert h_{40}^{Z}\rvert<0.0020$
$Z\gamma$ combination	$\lvert h_{30}^{\gamma}\rvert<0.038$ $\lvert h_{40}^{\gamma}\rvert<0.0025$	$\lvert h_{30}^{\gamma}\rvert<0.033$ $\lvert h_{40}^{\gamma}\rvert<0.0017$
$Z\gamma$ combination	$\lvert h_{30}^{Z}\rvert<0.037$ $\lvert h_{40}^{Z}\rvert<0.0025$	$\lvert h_{30}^{Z}\rvert<0.033$ $\lvert h_{40}^{Z}\rvert<0.0017$

This result!

- Best limits from Tevatron!

Limits on anomalous couplings

- The most probable values of the ZZγ and Zγγ couplings is at the standard model predictions



Comparison with LEP

- These results: $|h_{30}^V| < 0.033$, $|h_{40}^V| < 0.0017$
  - Similar results for CP-odd couplings
- LEP results

$$\begin{array}{ll} -0.056 < h_1^\gamma < 0.055 & -0.13 < h_1^Z < 0.13 \\ -0.045 < h_2^\gamma < 0.025 & -0.078 < h_2^Z < 0.071 \\ \boxed{-0.049 < h_3^\gamma < -0.008} & -0.20 < h_3^Z < 0.07 \\ -0.002 < h_4^\gamma < 0.034 & -0.05 < h_4^Z < 0.12 \end{array}$$

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

  - LEP does not scale couplings with the form-factor, which makes direct comparison more complex
    - Additional $e^{i\pi/2}$ factor from Baur MC

Summary of these results

- We observed $Z\gamma \rightarrow \nu\nu\gamma$ for the first time at the Tevatron and measured the cross section to be in excellent agreement with the standard model
- We set the tightest limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings at the Tevatron

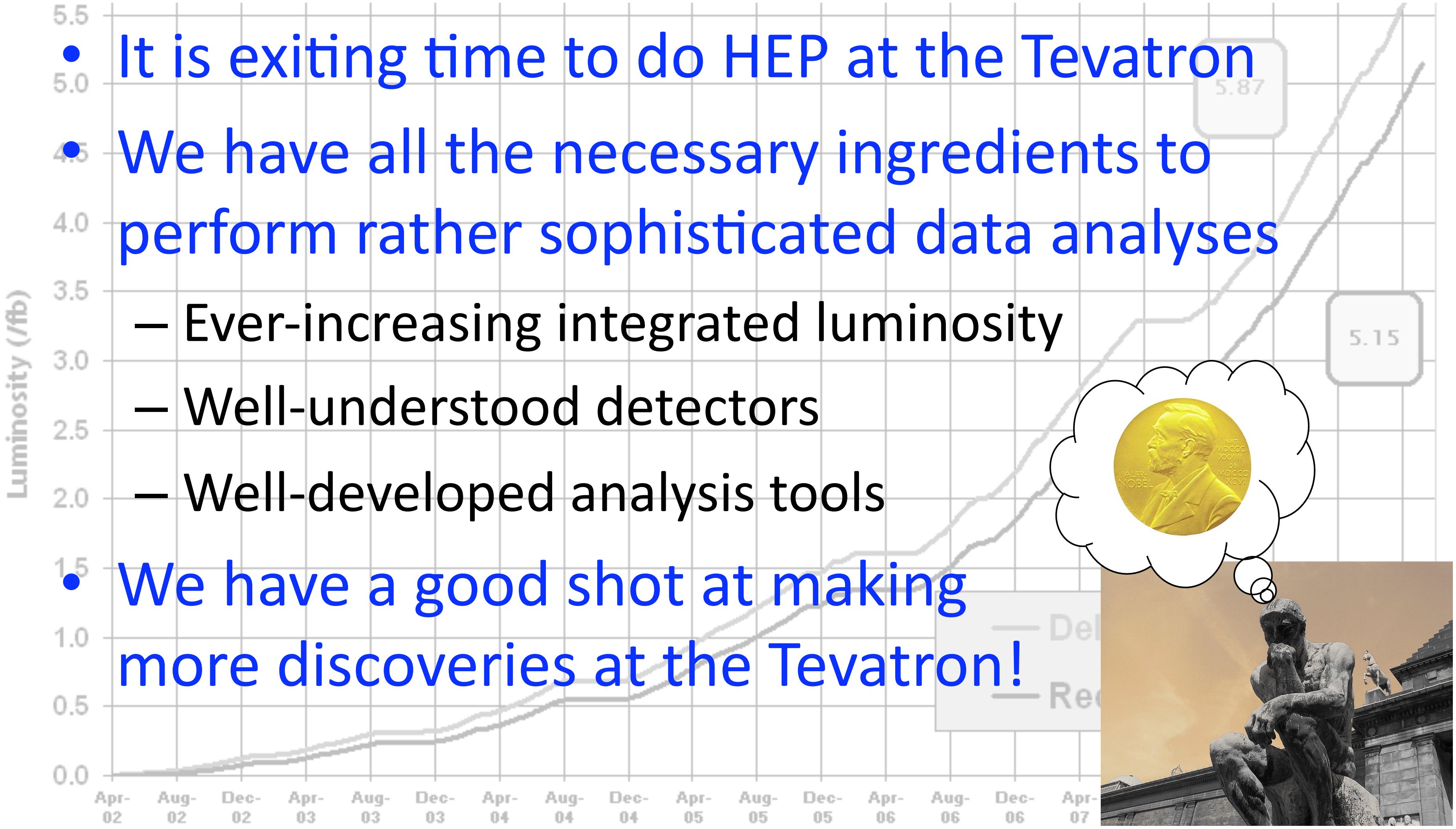
$|h_{30}^{\gamma}|<0.033$ $|h_{40}^{\gamma}|<0.0017$

$|h_{30}^{Z}|<0.033$ $|h_{40}^{Z}|<0.0017$

What comes next?

Prediction is very difficult, especially if it is about the future

Mark Twain, Niels Bohr, Yogi Berra



- It is exiting time to do HEP at the Tevatron
- We have all the necessary ingredients to perform rather sophisticated data analyses
  - – Ever-increasing integrated luminosity
  - – Well-understood detectors
  - – Well-developed analysis tools
- We have a good shot at making more discoveries at the Tevatron!