Search for Heavy Dirac Monopoles at DØ

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FNAL
Wine & Cheese Seminar

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Outline

- Quantization of Electric Charge
- Theory of Magnetic Monopoles
- Previous Monopole Searches
- Effects of Virtual Monopoles
- Heavy Monopole Search at DØ
  - Data Selection
  - Backgrounds
  - Cross Section Limit
  - Mass Limit
- Elastic Analysis
- Validity of the Theory
- Comparison with Indirect Limits
- Conclusions

100 Years of Particle Physics

1897 - Discovery of Electron (J.J.Thompson)

↓

Symmetries

↓

1995 - Discovery of t-quark (CDF and DØ)

Symmetries → Groups → Transformations (e.g., SO(3) - three-dimensional rotations)

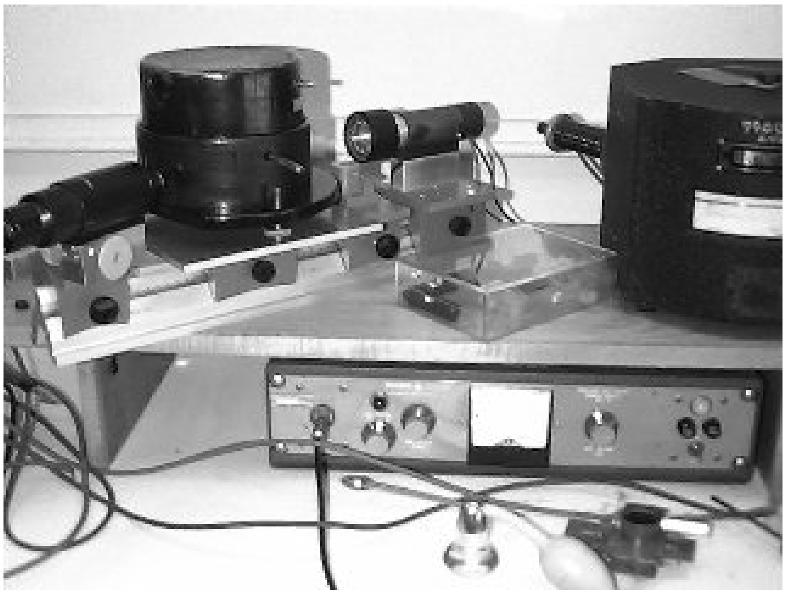
↓ ***<u>Noether's Theorem:</u>***

Symmetries → Invariance → Conservation Laws

↓ ***<u>Higgs Mechanism:</u>***

Symmetries → Approximate Symmetries → Broken Symmetries → Masses

Quantization of the Electric Charge



R.Millikan oil drop experiment (1909):

Electric charge is quantized; the elementary free charge is that of the electron

$e = 1.6\times10^{-19}$ C

We believe that fractional electric charge of e/3 exists (quarks), but multiple experiments similar to the original Millikan experiment show that it seems to be always confined

One way to explain mysterious quantization of the electric charge is to postulate the existence of a free magnetic charge - a MONOPOLE. First introduced by Paul Dirac in 1931 and later extended by J.Schwinger, G.'t Hooft and other founders of QED, they remain hypothetical particles despite numerous attempts to find them

Theory of Magnetic Monopoles

- ***Magnetic monopoles restore symmetry of Maxwell equations:***

$$\left.\begin{aligned}\partial_\nu F^{\mu\nu} &= -j^\mu \\ \partial_\nu \tilde{F}^{\mu\nu} &= 0\end{aligned}\right\} \rightarrow \left\{\begin{aligned}\partial_\nu F^{\mu\nu} &= -j^\mu \\ \partial_\nu \tilde{F}^{\mu\nu} &= -k^\mu\end{aligned}\right.$$

$$\left\{\begin{aligned}F^{\mu\nu} &\rightarrow \tilde{F}^{\mu\nu} \\ \tilde{F}^{\mu\nu} &\rightarrow -F^{\mu\nu}\end{aligned}\right. \qquad \left(\begin{array}{c}\textit{symmetric under} \\ \textit{duality transformations}\end{array}\right)$$

- ***They also explain quantization of the electric charge via famous Dirac quantization rule:***

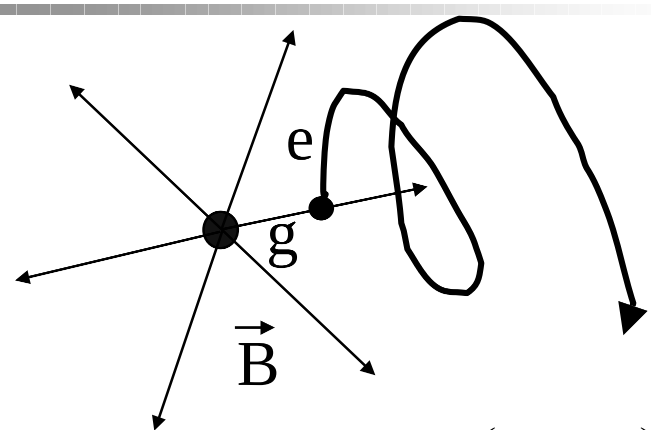
$$\frac{eg}{4\pi} = \frac{1}{2}n$$

(in ħ=c=1 units)

Semiclassical Derivation of Dirac Quantization

$$\vec{B} = \frac{g}{4\pi r^3}\vec{r},$$

$\hbar = c = 1$



$$m\ddot{\vec{r}} = e\dot{\vec{r}} \times \vec{B}, \quad \vec{L} = \vec{r} \times m\dot{\vec{r}}$$

$$\frac{d\vec{L}}{dt} = \frac{d}{dt}(\vec{r} \times m\dot{\vec{r}}) = \vec{r} \times m\ddot{\vec{r}} = \frac{eg}{4\pi r^3}\vec{r} \times \left(\dot{\vec{r}} \times \vec{r}\right) = \frac{d}{dt}\left(\frac{eg}{4\pi r}\vec{r}\right)$$

$$\vec{J} = \vec{r} \times m\dot{\vec{r}} - \frac{eg}{4\pi r}\vec{r}$$

Total angular momentum is the sum of the particle orbital momentum and the angular momentum of the EM field

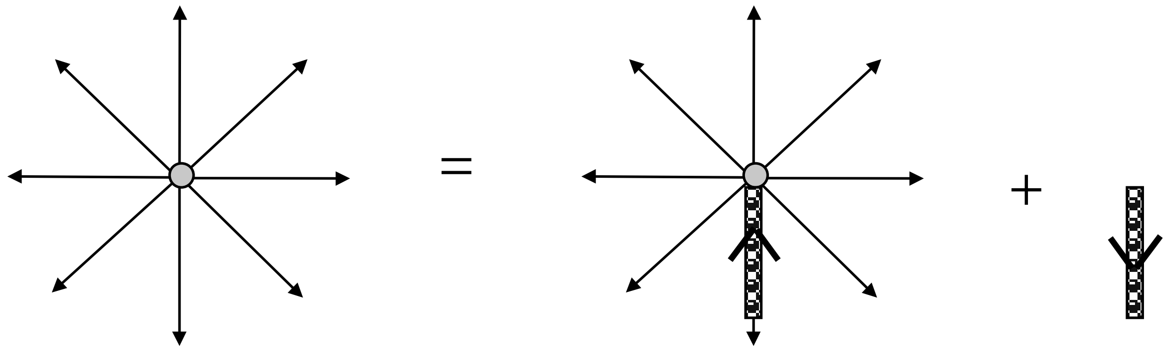
$$\frac{eg}{4\pi} = \frac{1}{2}n$$

Total angular momentum is quantized, hence, second component is quantized!

$$g = \frac{2\pi n}{e}, n = \pm 1, \pm 2, \ldots \text{ (in Schwinger theory } n = \pm 2, \pm 4, \ldots)$$

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137} \Rightarrow \alpha_g = \frac{g^2}{4\pi} = \frac{n^2}{4\alpha} \approx 34n^2$$

Dirac String (Quantum Approach)

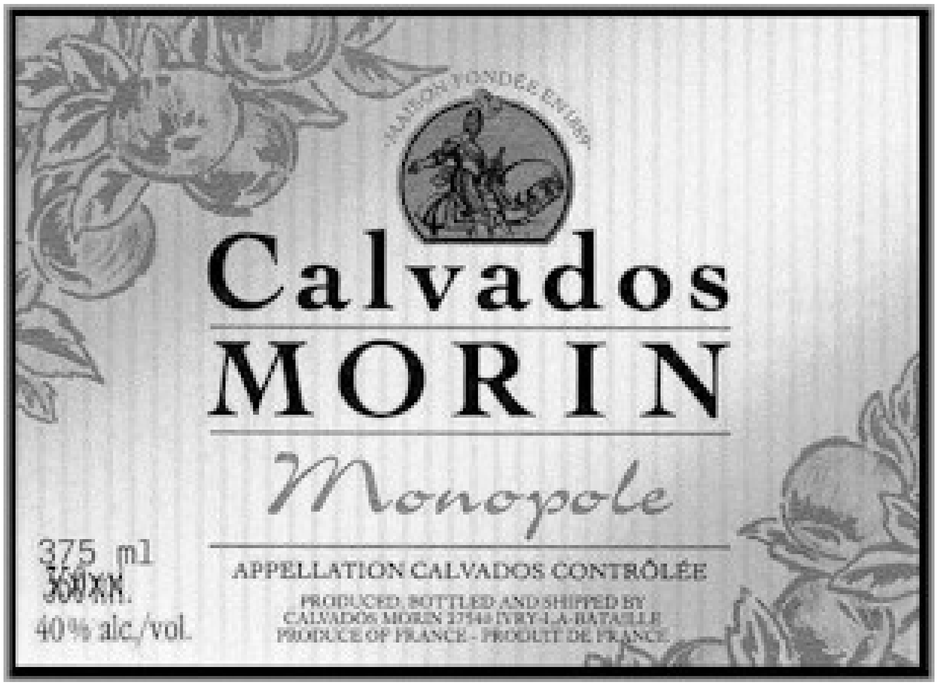


- Need a singularity (Dirac String) to describe the QED in presence of static magnetic charges (otherwise gauge invariance is violated)
- Dirac string can not be observed since it is a mathematical, rather than a physical object (e.g., Aharonov-Bohm effect is absent precisely due to Dirac quantization rule)
- Dirac string is a necessary artifact of gauge invariance requirement

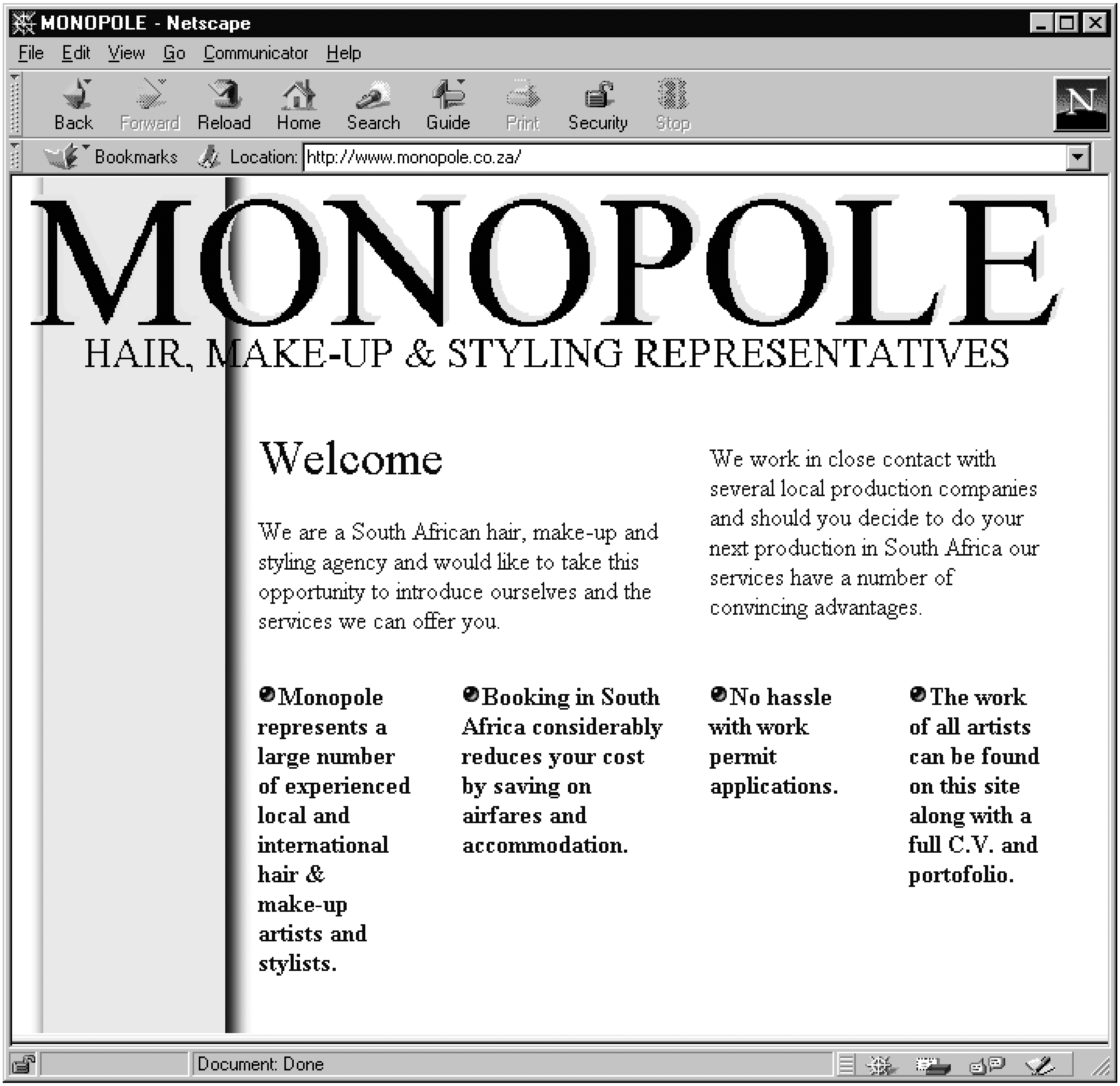
Problems with the Monopole Theory

- ***At the current level of theory we do not know if one can write a fully renormalizable description of magnetic poles: it was never proved either right or wrong***
- ***There are arguments that monopole theory could violate local U(1) or that monopoles have to be heavy (~10^4 TeV) in order not to violate unitarity***
- ***One needs a theory with a Dirac string or its surrogate to describe QED with monopoles***
- ***Definitely more theoretical work on this subject is welcome***

Searches for Monopoles



Searches for Monopoles



Searches for Monopoles

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M14	$1,010.00 each	$52,700.00
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Searches for Monopoles

From THE Journal

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Netscape

http://www.jrnl.com/news/97/Jan/jrn21140197.html

Monopoles: Dominating monstrosities

Idon't want Fairfax County to be dominated by monopoles. I don't want Virginia's natural beauty to be dominated by monopoles.

Go up to New Jersey, a state that is ``wired." The central feature of the New Jersey landscape is the hideous and dominating monopole. There is a monopole every mile, and five above even small towns.

Residents of Fairfax County and Virginia should wake up to what is beginning to happen here. Do we want these ugly intrusions on the beauty of our environment? Do we want to take the health risk living under these monstrosities?

Go and see the one at Lee Highway and Harrison Street in Arlington. If that ugly monopole is the best technology can come up with, I say get back to the drawing board.

EMILIE BRZEZINSKI

McLean

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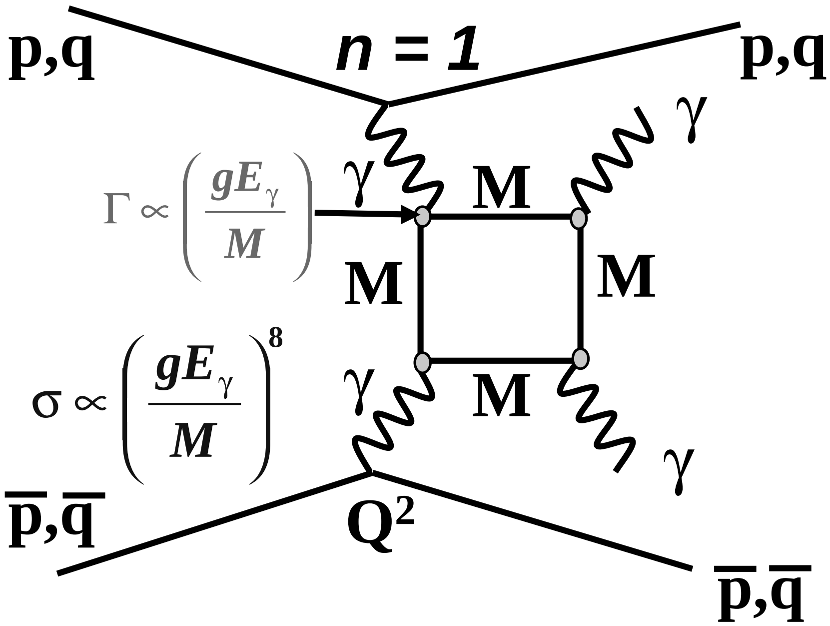
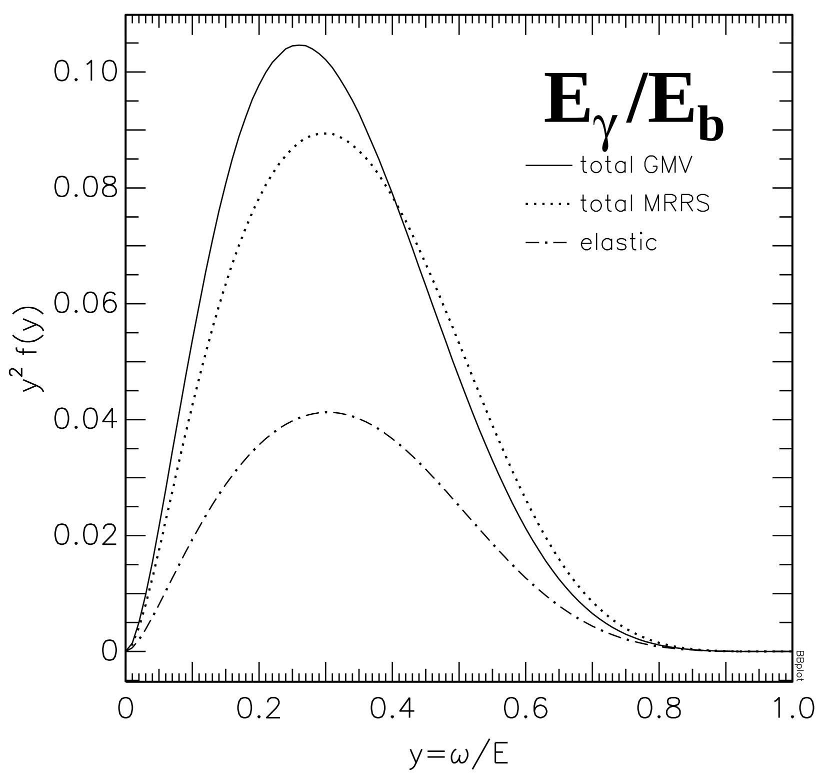
Real Searches for Monopoles

- ***Flux measurement experiments:***
  - ***Always set limits on the flux of the relic monopoles travelling through the universe***
  - ***EM induction in superconducting coils***
  - ***Scanning materials for ionization traces (minerals, meteorites, moon rocks, huge detector volumes)***
- ***Accelerator experiments:***
  - ***Can set limits on monopole mass***
  - ***Production of monopoles in the lab: mass reach is inherently restricted by the machine energy***
- ***Current limits:***
  - ***c.s.< 200 pb for M < 850 GeV (EØ)***
  - ***M > 510 GeV (L3, 1995, $Z \to \gamma\gamma\gamma$, based on a similar idea)***

Effects of the Virtual Monopoles

I.F.Ginzburg, A.Schiller, hep-ph/9802310
(original idea by I.F.Ginzburg, S.L.Panfil, 1982)





Production features:

- ***Low Q^2 of the beams ("γγ-collider")***
- ***Roughly isotropic scattering angle in the CM frame, ergo central photons***
- ***Energetic photons:*** **<E> ≈ $0.3E_b$**
- ***Cross section drops as the monopole mass to the 8^{th} power - no thorough optimization is required***
- ***About a third of the cross section is due to the elastic collisions***

Theoretical Assumptions

- ***Theory is applicable to local, or pointlike, monopoles and not Polyakov-'t Hooft GUT monopoles***
- ***Calculations are based on the perturbation theory with the effective parameter*** $g_{eff} \sim E^{\gamma}/M$ ***and are valid for*** $g_{eff} < 1$
- ***Theory assumes under-threshold production of monopoles, which is equivalent to perturbativity assumption***
- ***Unitarity requirement is automatically satisfied in the perturbative region***

Production Cross Section

At the Tevatron operating at $\sqrt{s}$ = 1.8* TeV *the cross section is given by:

$$\sigma(p\bar{p} \to \gamma\gamma X) = 57 \cdot P\left(\frac{n}{M[\mathrm{TeV}]}\right)^8 \mathrm{fb}$$

Significant spin dependence!

$$\mathrm{P} = \begin{cases} 0.085, & S = 0 \\ 1.39, & S = 1/2 \\ 159, & S = 1 \end{cases}$$

M = 1 TeV, n = 1:
σ = 4.8 fb (S = 0)
σ = 79 fb (S = 1/2)
σ = 9.1 pb (S = 1)

Differential cross section under the assumption of* $E_T(\gamma_1) = E_T(\gamma_2)$ *is given by:

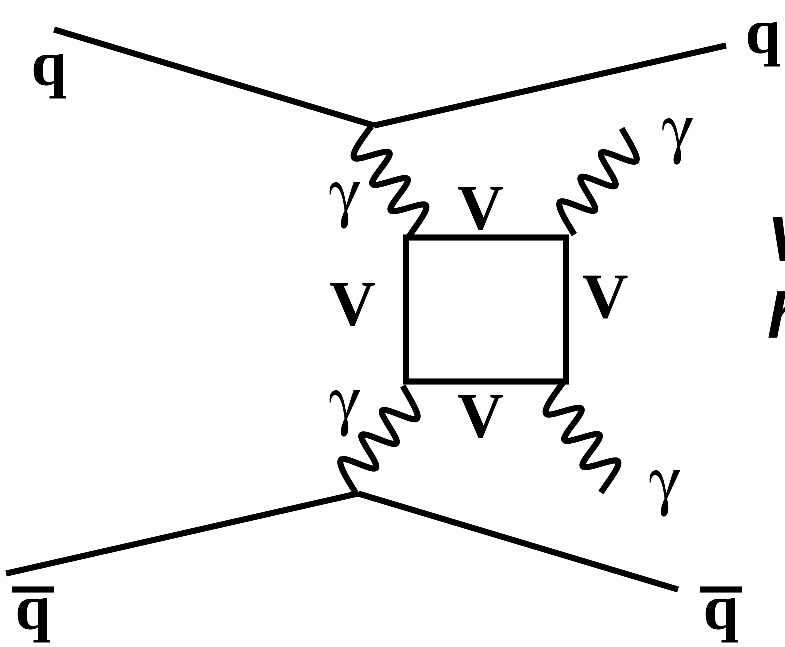
$$\underbrace{\frac{d^3\sigma}{d\eta_3 d\eta_4 dE_T}}_{\textit{observables}} = 2E_T\left(\frac{\alpha_e}{\pi}\right)^2 y_1^2 f(y_1) y_2^2 f(y_2) \frac{5RE_b^4}{112}\Phi$$

$$\Phi = \left(4 - \frac{1}{\cosh^2\left(\frac{\eta_3 - \eta_4}{2}\right)}\right)^2, \; y_{1,2} = \frac{E_T}{2E_b}\left(e^{\pm\eta_3} + e^{\pm\eta_4}\right)$$

$$R = \frac{28P}{405\pi}\left(\frac{n}{2\sqrt{\alpha_e}M}\right)^8$$

Diphoton Backgrounds

(1) *Other $\gamma\gamma$-scattering diagrams:*



V=W has the highest contribution

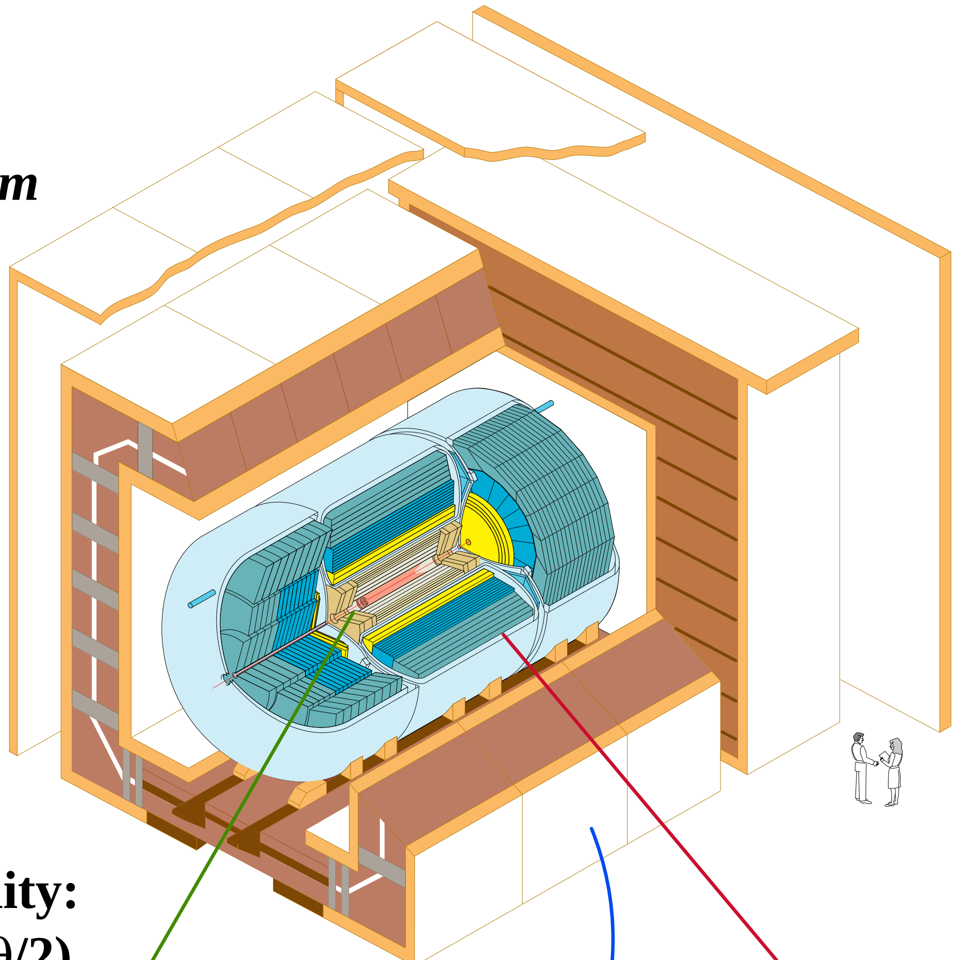
Negligible
[*Jikia,Tkabaladze*
PL ***B323*** *(1994) 453****]***

(2) *QCD (jj/jγ/$\gamma\gamma$)*

(3) *DØ-specific: Drell-Yan (ee $\rightarrow$ "$\gamma\gamma$")*

DØ Detector

3 Level Trigger System



DØ Detector

Pseudorapidity:
$\eta = -\ln\tan(\theta/2)$

TRACKING

σ(vertex)=6 mm
$\sigma(r\phi)$ = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

$|\eta| < 3.3$

$$\frac{\delta p}{p} = 0.2 \oplus .003p$$

CALORIMETRY

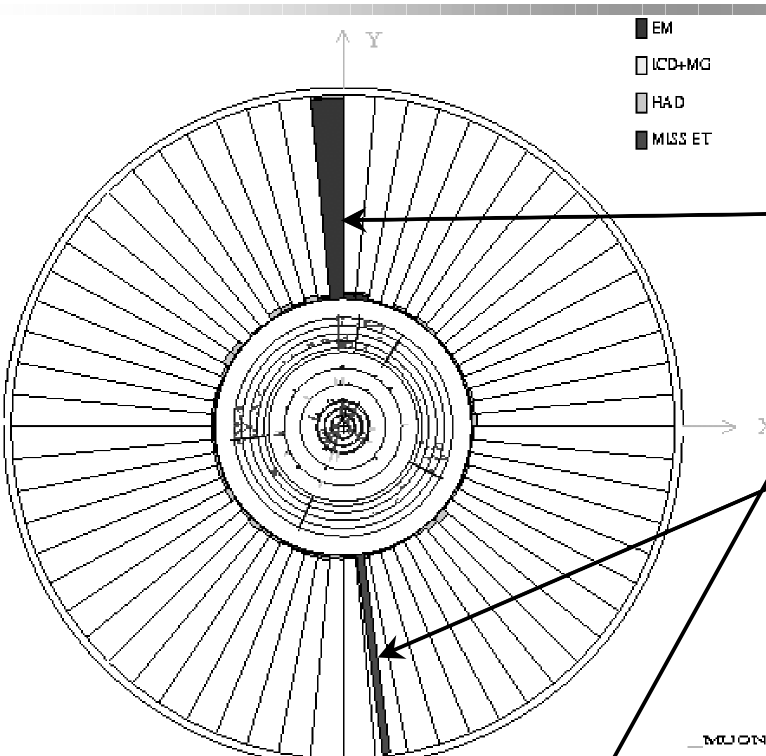
$|\eta|<4$

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

$\sigma(EM) = 15\%/\sqrt{E}$

$\sigma(HAD) = 50\%/\sqrt{E}$

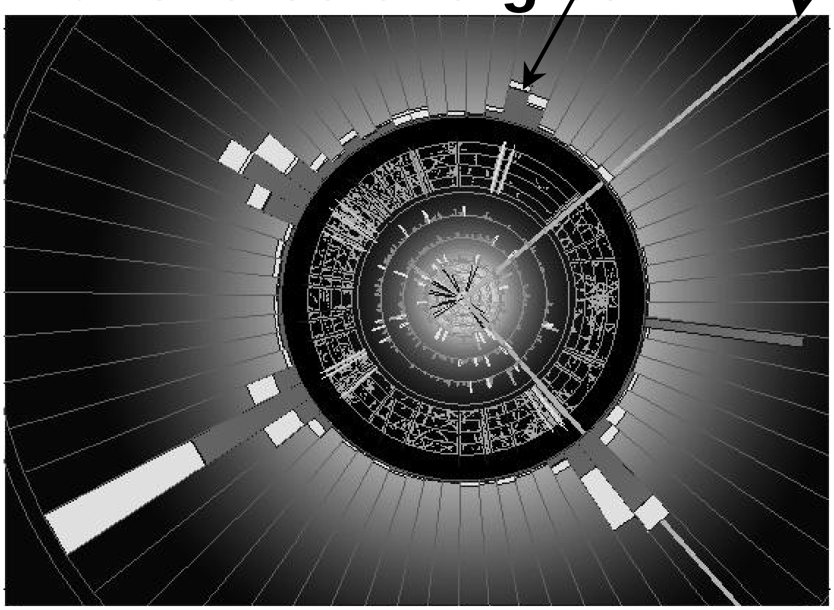
Particle Identification

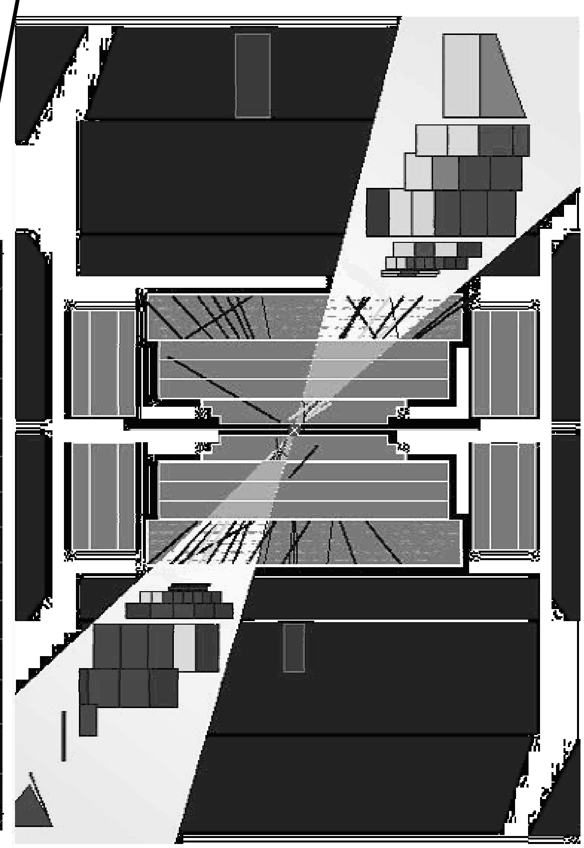


DØ is well suited for identification of:

- *Electrons/Photons*
- *Jets*
- *Muons*
- *Neutrinos (Missing Transverse Energy)*

Mostly work with *transverse* energies





Data Selection

- ***Data Sample:***
  - *Entire Run I data taken with an inclusive single photon trigger with NO inelastic collision requirement (70 ± 4 pb^{-1})*
- ***Data Selection:***
  - *≥ 2 photons (with $E_T^\gamma > 40$ GeV):*

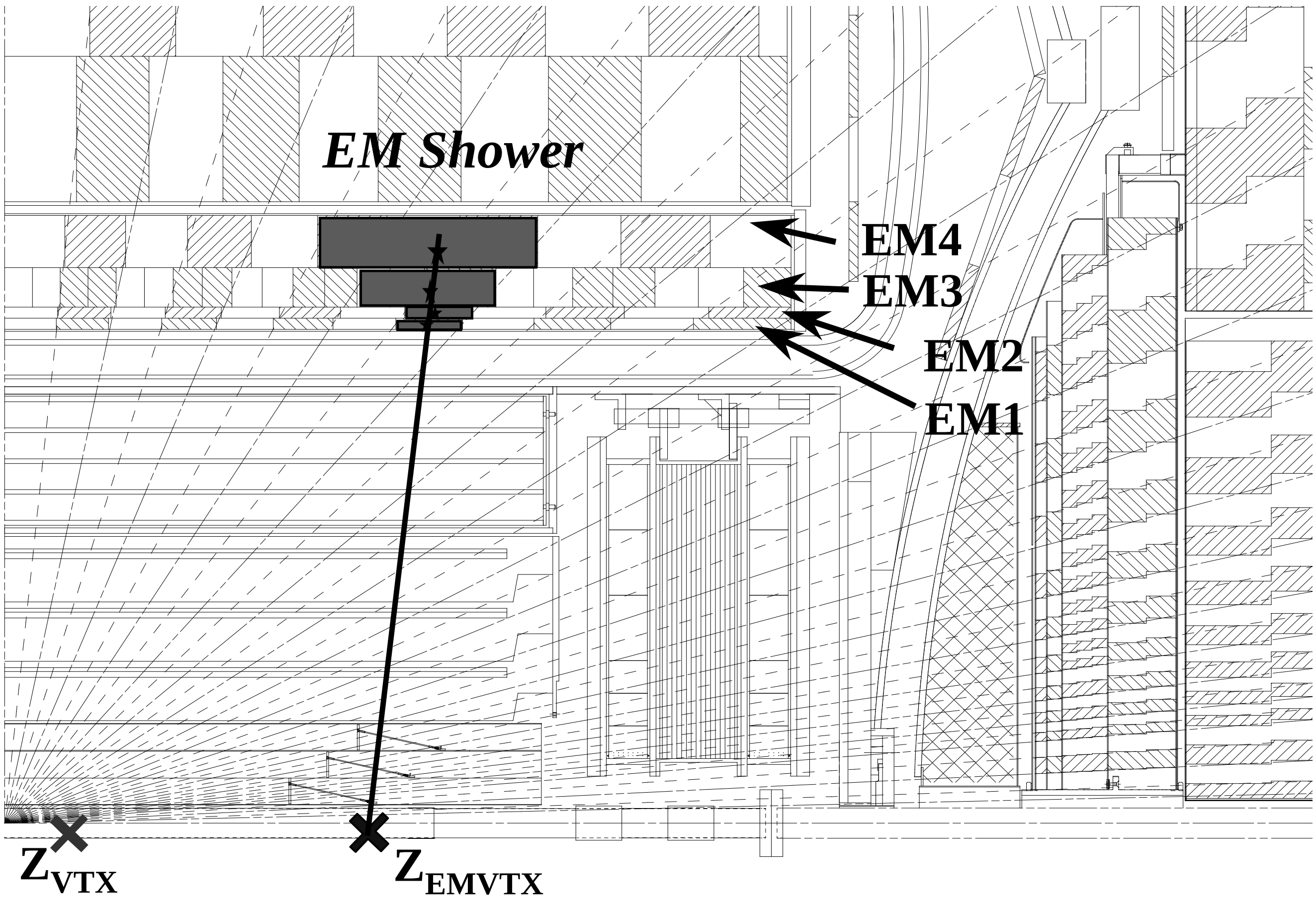
$\lvert\eta_\gamma\rvert < 1.1$	**$\chi^2 < 100$**
ISO < 0.10	**EMF > 0.95**

  - *Jet veto (to select low Q^2 interact.):*

    No jets with $\lvert\eta_j\rvert < 2.5$ and $E_T > 15$ GeV
  - *Transverse Energy Conservation:*

    $\not\!\!E_T < 25$ GeV
- ***Problem:***
  - *What to do about misvertexing?*

EM-Cluster Projection Technique



4-point fit (EM1-EM4): Z_{EMVTX} - calorimeter-based Z-position of the vertex. Typical resolution in RZ per photon is:

$\sigma_{RZ} \sim$ 20 cm (energy and rapidity dependent)

With two photons vertex is known to **~ 14 cm** ***for Z $\rightarrow$ ee events (better for higher E_T^{EM})***

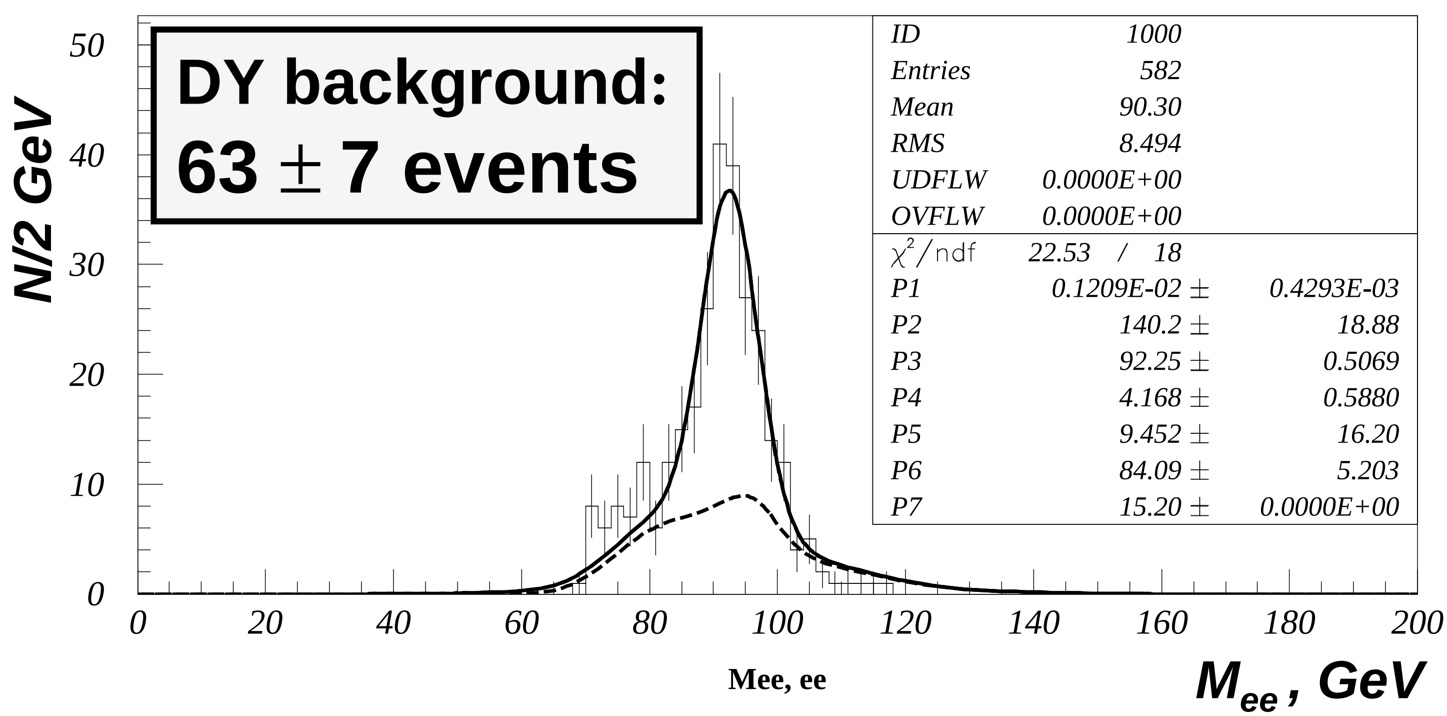
QCD Background

90 candidate events pass basic cuts

- ***Start with*** jγ ***sample collected with the same trigger to calculate QCD background***
- ***Use PYTHIA to obtain fractions of*** jj/jγ/$\gamma\gamma$ ***events as a function of*** E_T^γ ***(do not use cross sections, just the shapes!)***
- $$B_{\gamma\gamma} = N_{jj}P_\gamma^{\,2} + N_{j\gamma}P_\gamma\varepsilon_\gamma + N_{\gamma\gamma}\varepsilon_\gamma^{\,2}$$
  $$B_{j\gamma} = 2N_{jj}P_\gamma + N_{j\gamma}\varepsilon_\gamma$$
- **P(j$\rightarrow\gamma$) = (10.5 $\pm$ 1.4)×10^{-4}**
- **QCD background: 25 $\pm$ 8 events**

Drell-Yan Background

- ***Fit the diphoton mass spectrum for $70 < S_T < 100$ GeV with the sum of a Gaussian and a fixed shape for the QCD background***
- ***Let the two normalizations float***
- **P(ee$\rightarrow$ "$\gamma\gamma$") $=$ 0.110 $\pm$ 0.012**
- ***Use dielectron sample with similar cuts to obtain DY background***

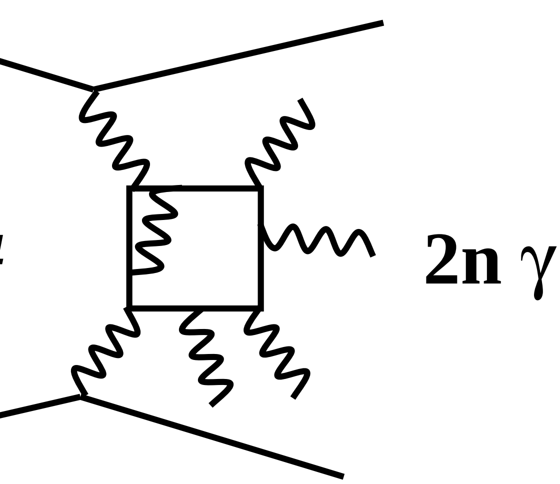


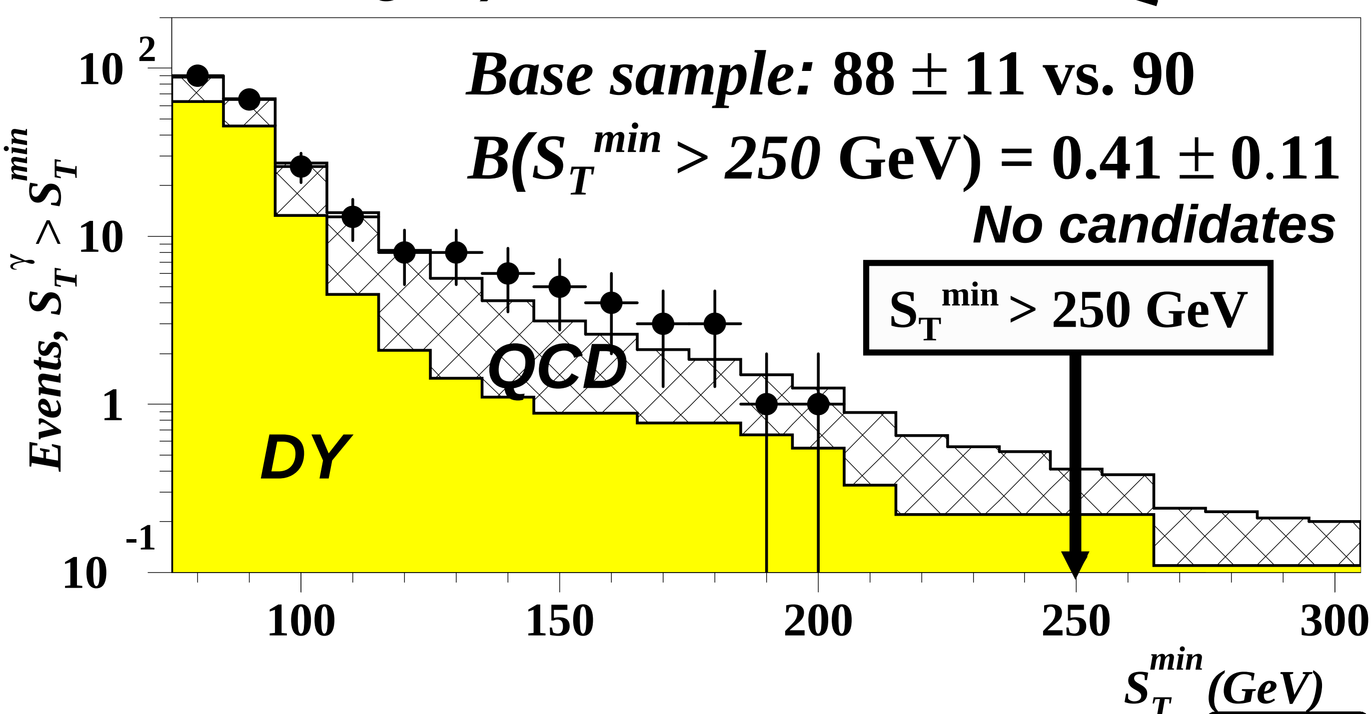
S_T Analysis

S_T approach takes care of possible NLO QED effects which result in partial cross section “leak” into the final states with higher photon multiplicity:

$$S_T = \sum E_T^{\gamma} > S_T^{min}$$

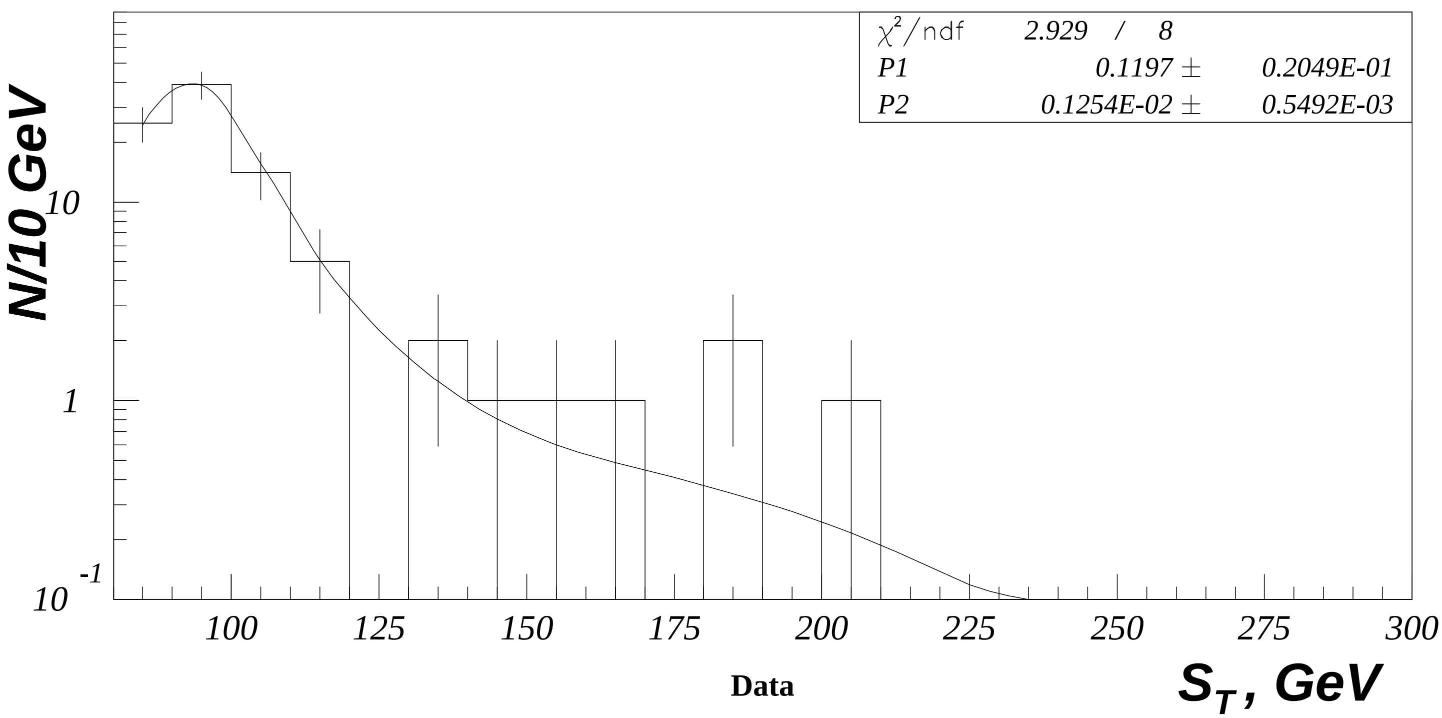
Choose background level of 0.4 events (70% probability of not seeing any events if there is no signal)





S_T-Distribution Fit

- ***A cross check was done by fitting the differential S_T distribution with the sum of two backgrounds with the two misidentification probabilities as fit parameters***
- ***Excellent agreement with the direct method***



Efficiency and Cross Section Limit

Chosen cut: $S_T > 250$ GeV
Background: 0.41 ± 0.11 events
Candidates: None
Efficiency:

ISO < 0.10:	0.93 ± 0.01	per photon
EMF > 0.95:	0.99 ± 0.01	
$\chi^2 < 100$:	0.95 ± 0.01	
No tracks:	0.91 ± 0.01	
No convrsns:	0.92 ± 0.01	
Total:	0.73 ± 0.01	(per photon)
$\not{E}_T$<25 GeV:	0.99 ± 0.01	} per event
Overall:	0.53 ± 0.01	(per event)

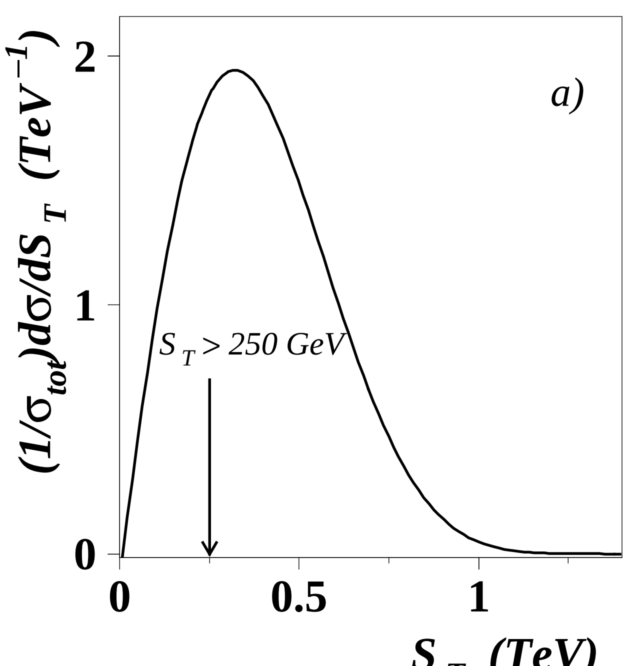
95% CL upper cross section limit: 83 fb (includes systematic errors on the efficiency and integrated luminosity)

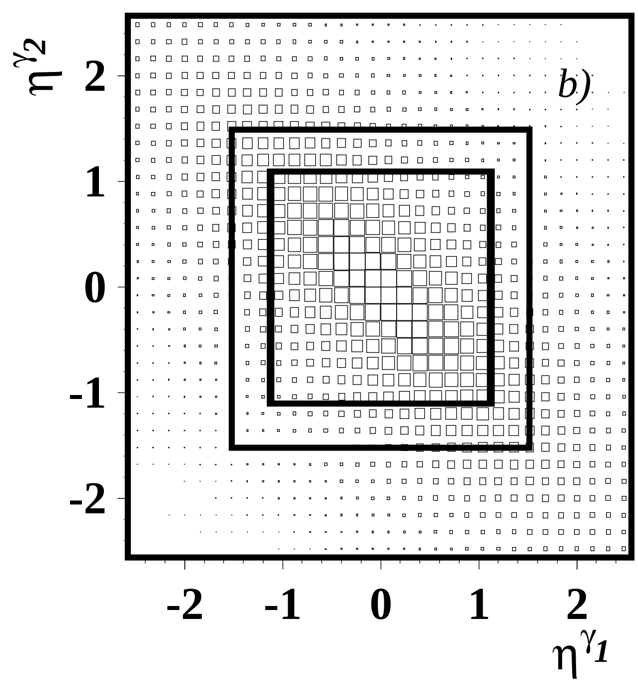
Monopole Parametric Monte Carlo

Includes:

- ***Interaction point smearing σ = 30 cm***
- ***Vertex position resolution***
- ***EM energy smearing***
- ***Detector acceptance***
- ***Photon flux via p.d.f. (CTEQ4L, GRV)***

A = 0.50 ± 0.01



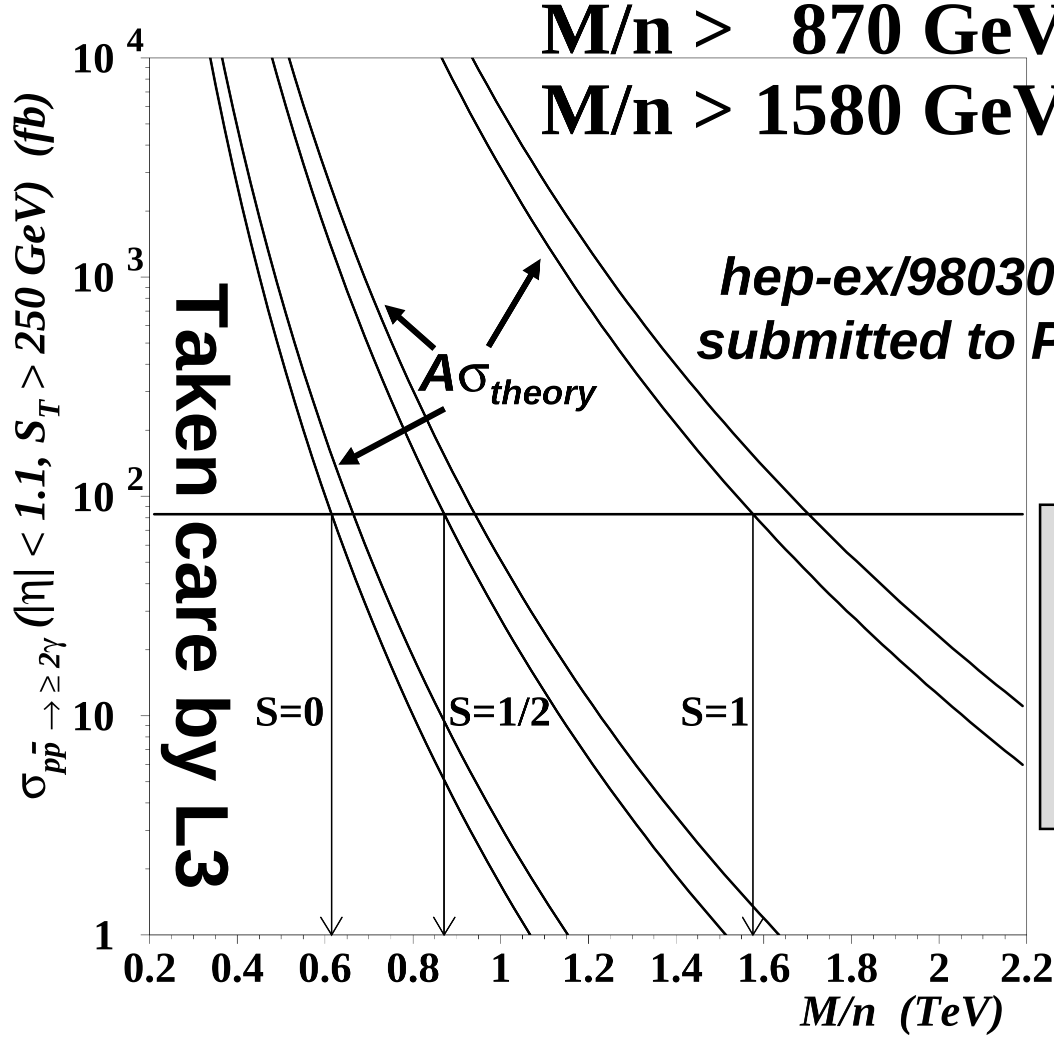


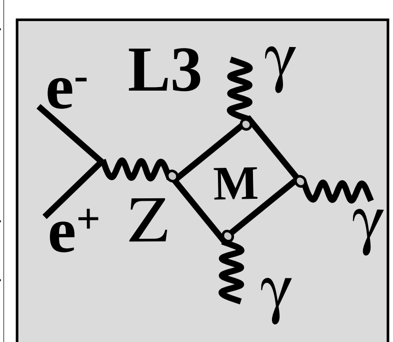
N.B. max A = 0.56 ± 0.01 (less than 2% in limits)!

Limits on Heavy Monopole Mass

- ***Bayesian approach with flat prior and Gaussian uncertainties on the efficiency, integrated luminosity and acceptance***
- ***30% uncertainty on the theory; use low theory band***

M/n > 610 GeV for S=0
M/n > 870 GeV for S=1/2
M/n > 1580 GeV for S=1

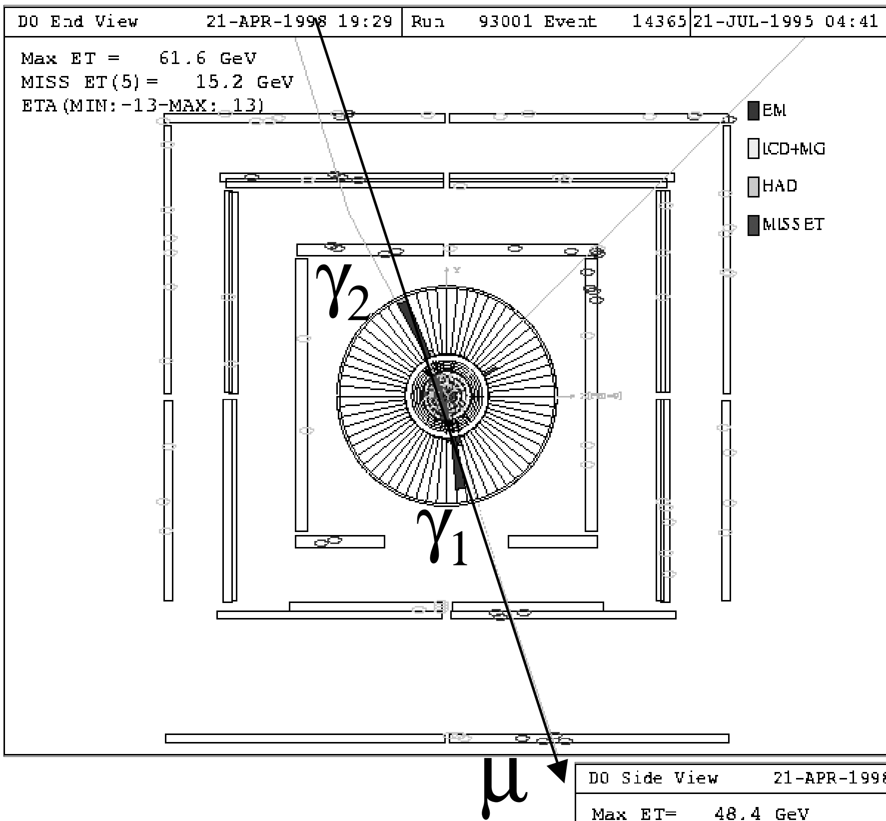




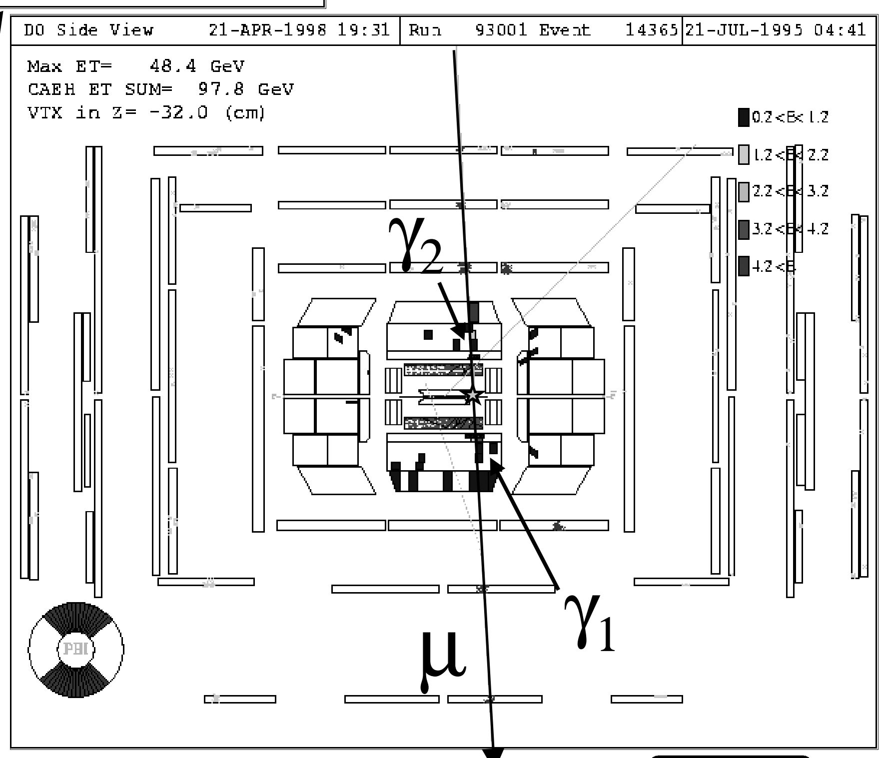
Elastic Analysis

- *An alternative analysis can be done by noting that about 50% of the cross section for the monopole loop is due to (nearly) elastic collisions*
- *DØ is equipped with luminosity monitors (Level 0 trigger) which can be used as an inelastic collision veto*
- *Such a veto corresponds to virtually background-free environment: B = 1.8 $\pm$ 0.4 events (dominated by the diffractive Drell-Yan) and only one candidate (consistent with $Z \rightarrow ee$)*
- *For S_T > 100 GeV cut, background is 0.4 events; no candidate events pass this cut*
- *We use this only as a cross check since the acceptance is small due to multiple interactions effects and additional elasticity requirement*

Double Cosmic Bremsstrahlung



Extremely rare double cosmic bremsstrahlung event (fails the missing E_T cut)



E_{γ_1} = 96 GeV

E_{γ_2} = 93 GeV

Z^{γ}_{vtx} = 45 cm

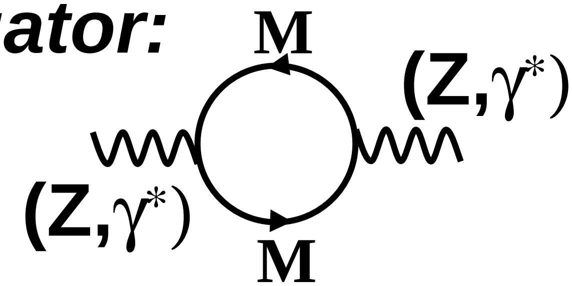
no Level 0 hits

Validity of the Theory

- ***Strictly speaking theory is valid only for under the threshold production, i.e.*** $\langle E_\gamma \rangle < M$
- ***Hence, our limits are valid for M above a few hundred GeV. L3 results cover lower masses.***
- ***If the effective parameter of the perturbation theory*** ($g_{eff} \sim E_\gamma/M$) ***is »1, extra photons will be emitted, but our*** S_T ***analysis accounts for that***
- ***When (and if) the higher order theory is available DØ results could be easily used to set updated limits***

Comparison with Other Indirect Limits

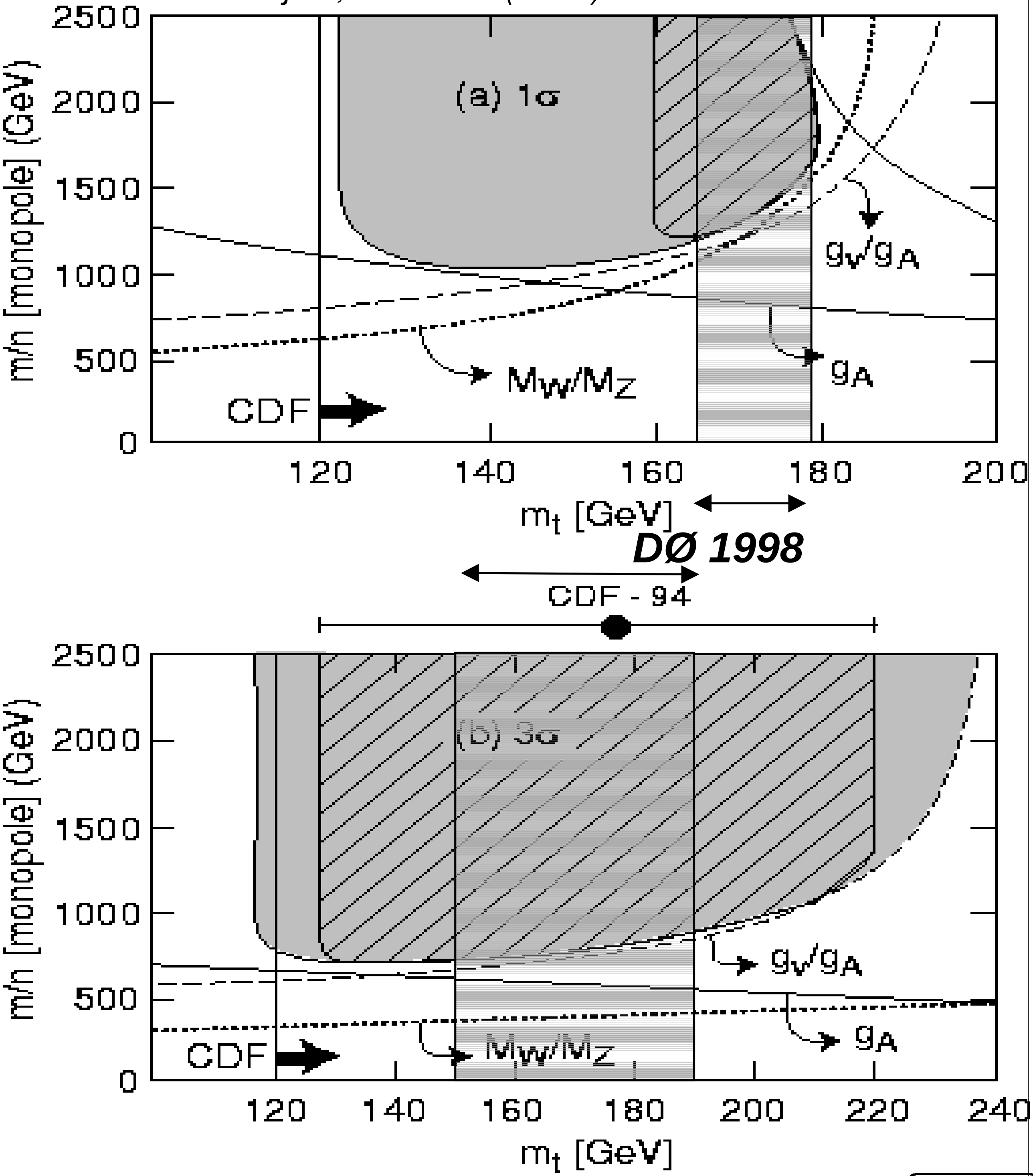
- ***Indirect limits on the monopole mass can be derived from loop corrections to the (Z,γ) propagator:***



- ***The variables most sensitive to this loop diagram are:*** **g_V/g_A, g_A,** ***and*** **M_Z/M_W**
- ***Corrections were calculated by DeRujula [****Nucl. Phys.* **B435** *(1995) 257****] and were shown to give mass limit of about 0.8 TeV for spin 1/2 monopoles, which is somewhat worse than the new DØ limits***
- ***Updated LEP results make these indirect limits slightly less restrictive***

Monopole Mass Limits from EW Results

*A.De Rujula, NP **B435** (1995) 257*



Monopole Search Summary

- ***Experimental upper cross section limit:***

  $\sigma(pp \to \geq 2\gamma + X, S_T > 250$ GeV, $|\eta_\gamma| < 1.1) < 83$ fb (at the 95% CL)

- ***Monopole lower mass limits:***

  M/n > 610 GeV for S=0

  M/n > 870 GeV for S = 1/2

  M/n > 1580 GeV for S = 1

these are the most restrictive mass limits on heavy pointlike Dirac monopoles

- ***Multiple cross checks show that the results are very stable***
- ***Results were submitted to PRL (Fermilab Preprint-98/095-E)***

Conclusions: Future of DØ

- ***Currently, the DØ detector is undergoing a major upgrade***
- ***We expect to accumulate at least 20 times more data in the next Run scheduled to start in the year 2000***
- ***The upgraded DØ detector with improved strengths will be well suited for searches for unknown in the next millenium***
- ***After all, the main reason to do particle physics is to either find something new or prove that it is not there. We hope to find it!***