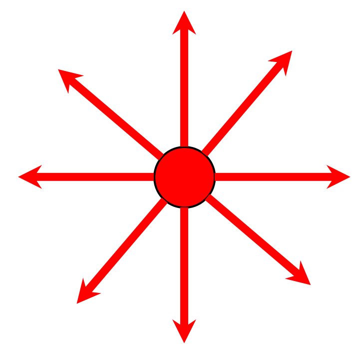
A Search For Magnetic Monopoles at HERA

Stephen Maxfield

THE UNIVERSITY *of* LIVERPOOL

- Introduction
- Experimental Technique and
  Preliminary Results
- Future Plans



D. Milstead, T. Sloan

Introduction: Dirac Monopoles

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \vec{B} = \mu_0 \rho_m$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \mu_0 j_m$$

$$\nabla \times \vec{B} = \mu_0 \vec{j} + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

$$F = e\left(\vec{E} + v \times \vec{B}\right) + g\left(\vec{B} - \frac{1}{c^2}(v \times E)\right)$$

- Magnetic monopoles symmetrize Maxwell's equations
- Duality transformation:

$$\begin{pmatrix} \vec{E} \\ c\vec{B} \end{pmatrix} \mapsto \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \vec{E} \\ c\vec{B} \end{pmatrix}$$

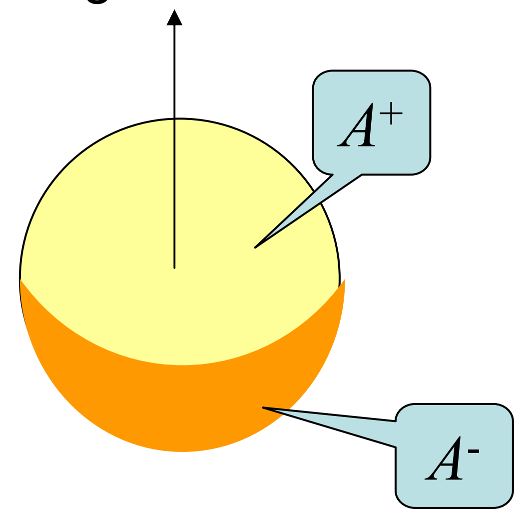
$$\begin{pmatrix} ec \\ g \end{pmatrix} \mapsto \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} ec \\ g \end{pmatrix}$$

- By convention, choose α so $g=0$

- ***Look for particles with different electric/magnetic charge ratio***

•***The Dirac Quantisation Condition***: Wu and Yang's construction

$|q_e - q_p|/e < 10^{-20}$ *Why?*



If there is a monopole…

$$\vec{B} = g\frac{\hat{\vec{r}}}{r^2} \qquad B = \nabla \times \vec{A}$$

•(singular) vector potentials

$$A_r^{\pm} = A_\theta^{\pm} = 0$$

$$A_\phi^{\pm} = \pm \frac{g}{r}\frac{1 \mp \cos\theta}{\sin\theta}$$

•Related by U(1) gauge transformation

$$A^- = A^+ - \tfrac{i}{e} S \nabla_\phi S^{-1}$$

$$S = e^{2ige\phi}$$

•Single-valued as $\phi \rightarrow \phi + 2\pi \;\; \Rightarrow$

$$e = n\frac{1}{2g} \quad \left(= n\frac{\hbar c}{2g} \right)$$

More monopoles…

- Monopoles in U(1) ‘optional’
- Non-Abelian gauge symmetry
  + spontaneous symmetry breaking to U(1) subgroup
  $\Rightarrow$ monopole solutions *t’Hooft Polyakov*
- **Topological** in origin: arise from non-trivial configurations of **Higgs field**. $g = 2g_D$
- Masses typically very large $\sim M_X/\alpha \sim 10^{15+}$ GeV
  - …***but*** 10^4 GeV and lower in some scenarios
- …and ‘classic’ Dirac monopole may have v. low mass:

$$\frac{g^2}{m_M} \approx \frac{e^2}{m_e} \Rightarrow m_M \approx 2.4\text{GeV}$$

Monopole Properties:

m_M anything from few GeV → ~ mass of bacterium!

$$g = n\frac{\hbar c}{2e} \equiv n g_D$$

- Assumes fundamental charge is e – maybe $e/3$, $2e/3$…?
- Maybe restricted to even values – dyons

Schwinger et al

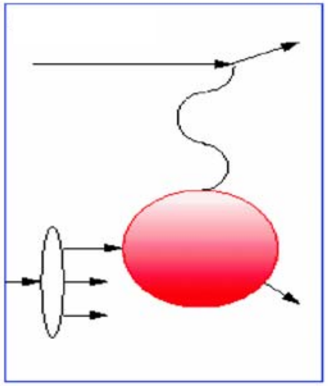
⇒ ***Minimum magnetic charge could be g_D, $2g_D$, $3g_D$, $6g_D$***

$$\alpha_m = \frac{n^2}{4}\frac{1}{\alpha_e} \approx 34n^2$$

$(c.f.\ 1/137)$ ⇒ Coupling huge!

- Perturbation theory not applicable.
- Large ionisation energy losses in material.

Experimental Technique



- ***First search for monopoles in e^+p collisions***
- Monopoles will be stopped in *Al* beam pipe
  - Binding energy expected to be large - permanent trapping.
    Milton et. al.

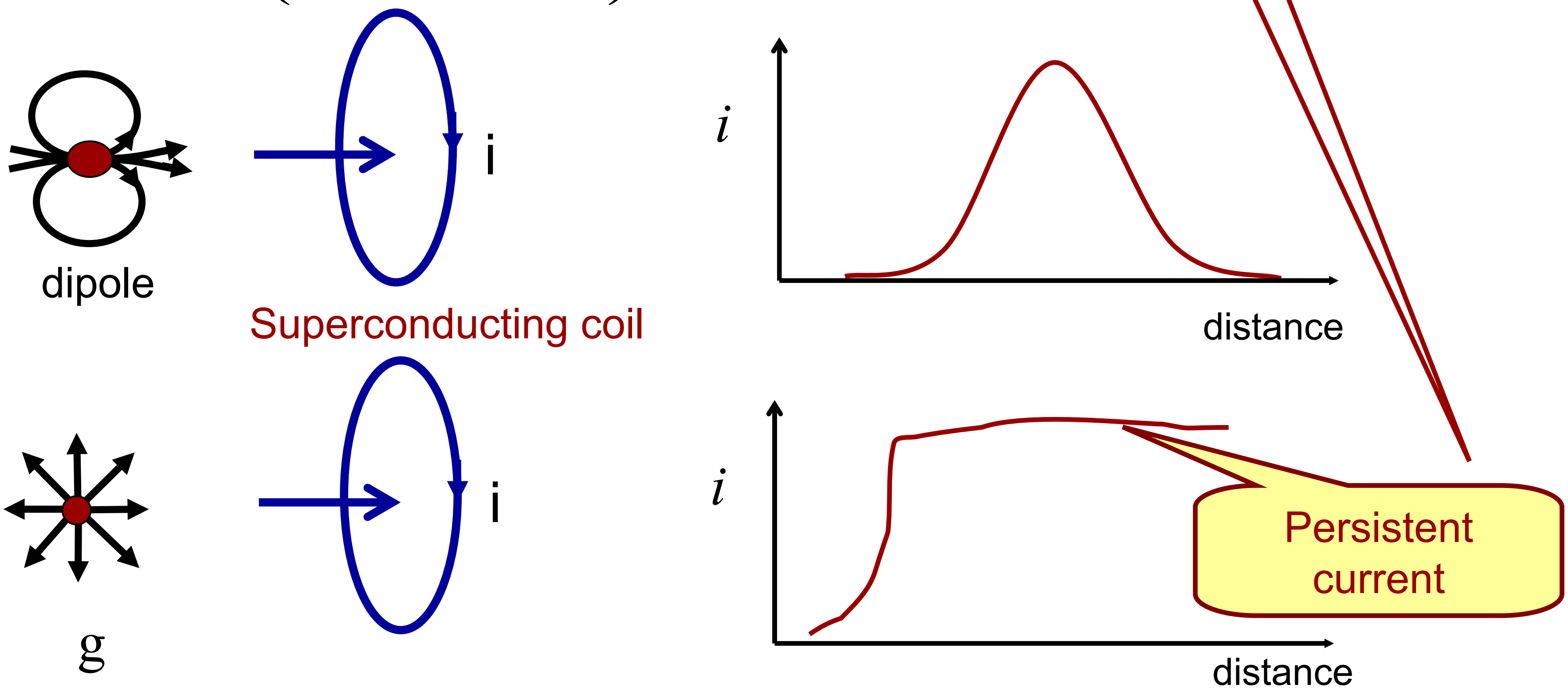
•Use section of **H1 beam-pipe** around interaction zone.
•1995-1997. Exposed to integrated luminosity=60pb-1

60cm long
5cm radius
2mm thick

- Sliced into 15 longitudinal strips
- pass samples through a ***SQUID magnetometer***

Monopole signature

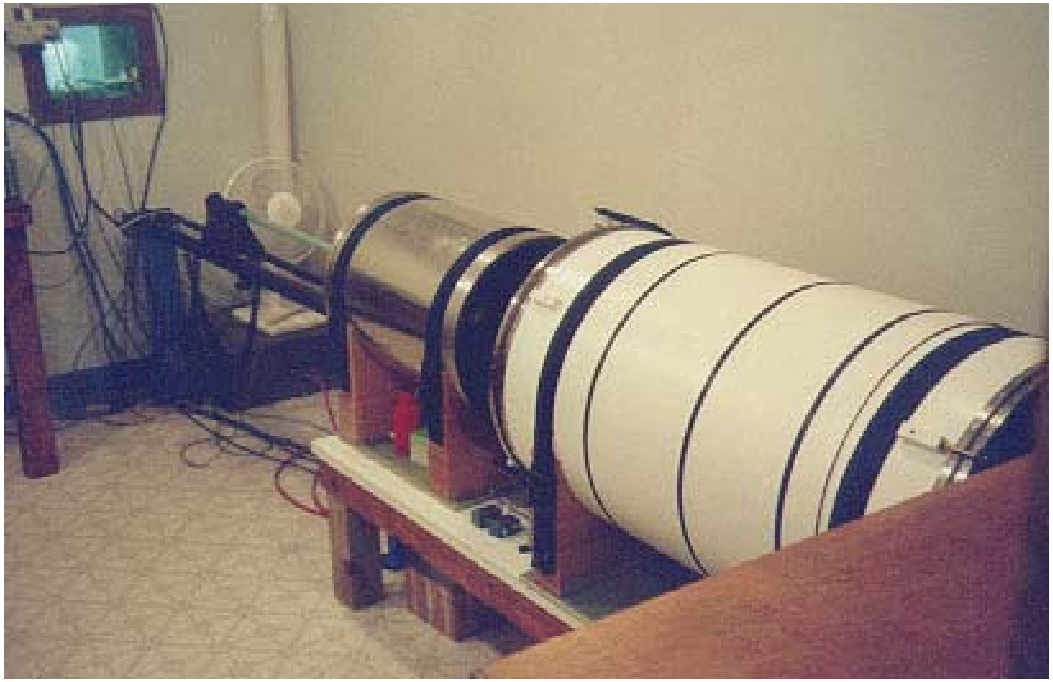
$$\nabla \times \vec{\mathrm{E}} = -\left(\qquad + \frac{\partial \vec{B}}{\partial t} \right) \qquad \Rightarrow i = -\left(\phi + \qquad \right) / L$$



Magnetometer

•2G enterprises type 760 magnetometer at Southampton Oceanography Centre.

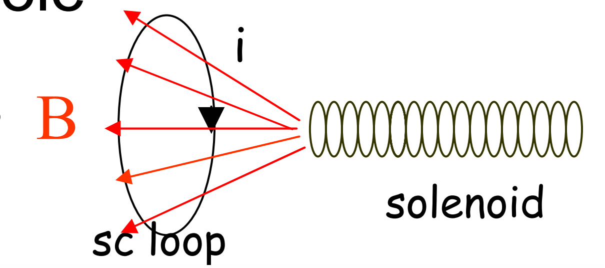
- •Warm bore, high sensitivity low-noise device
- •1/40th fluxon precision from single pass.

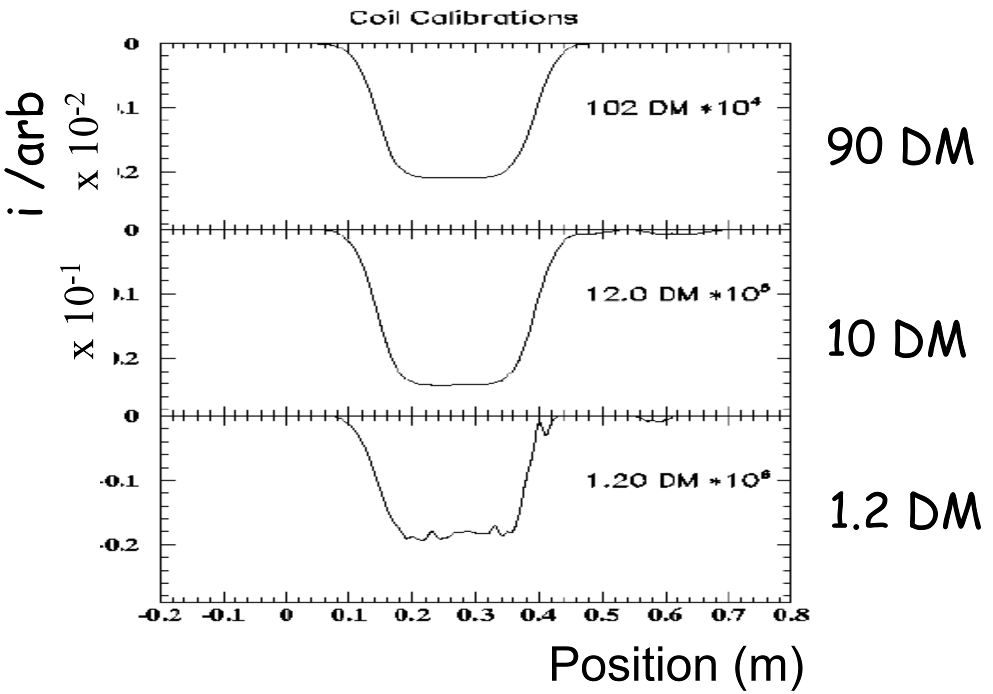


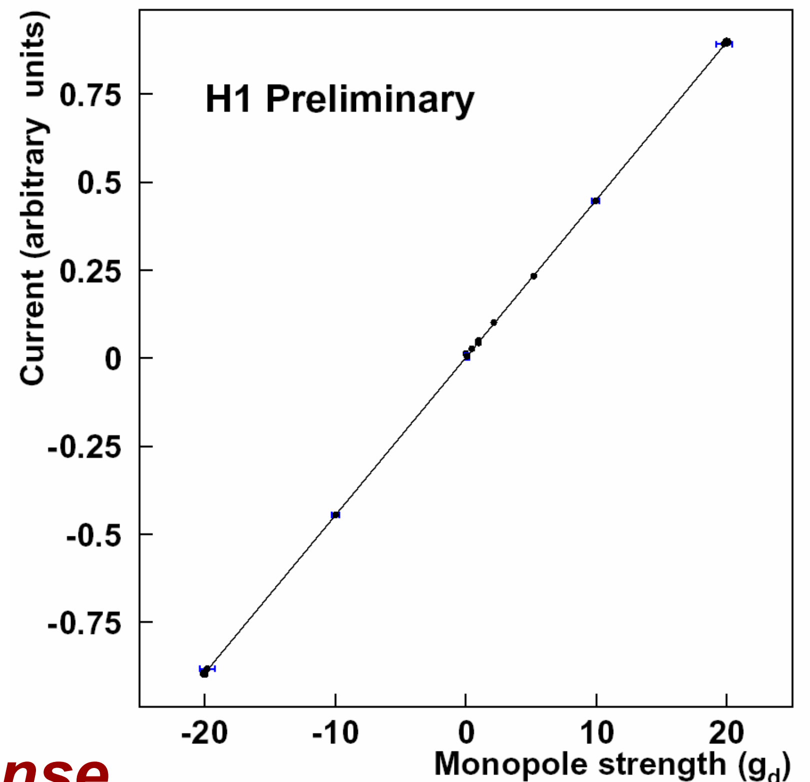
Calibration

- Use long thin solenoids to simulate monopole
- vary current ⇒various monopole strengths

$g = NidS$ (good to 3%)





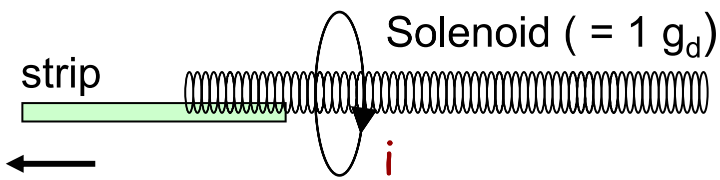


⇒ linear, well-understood response

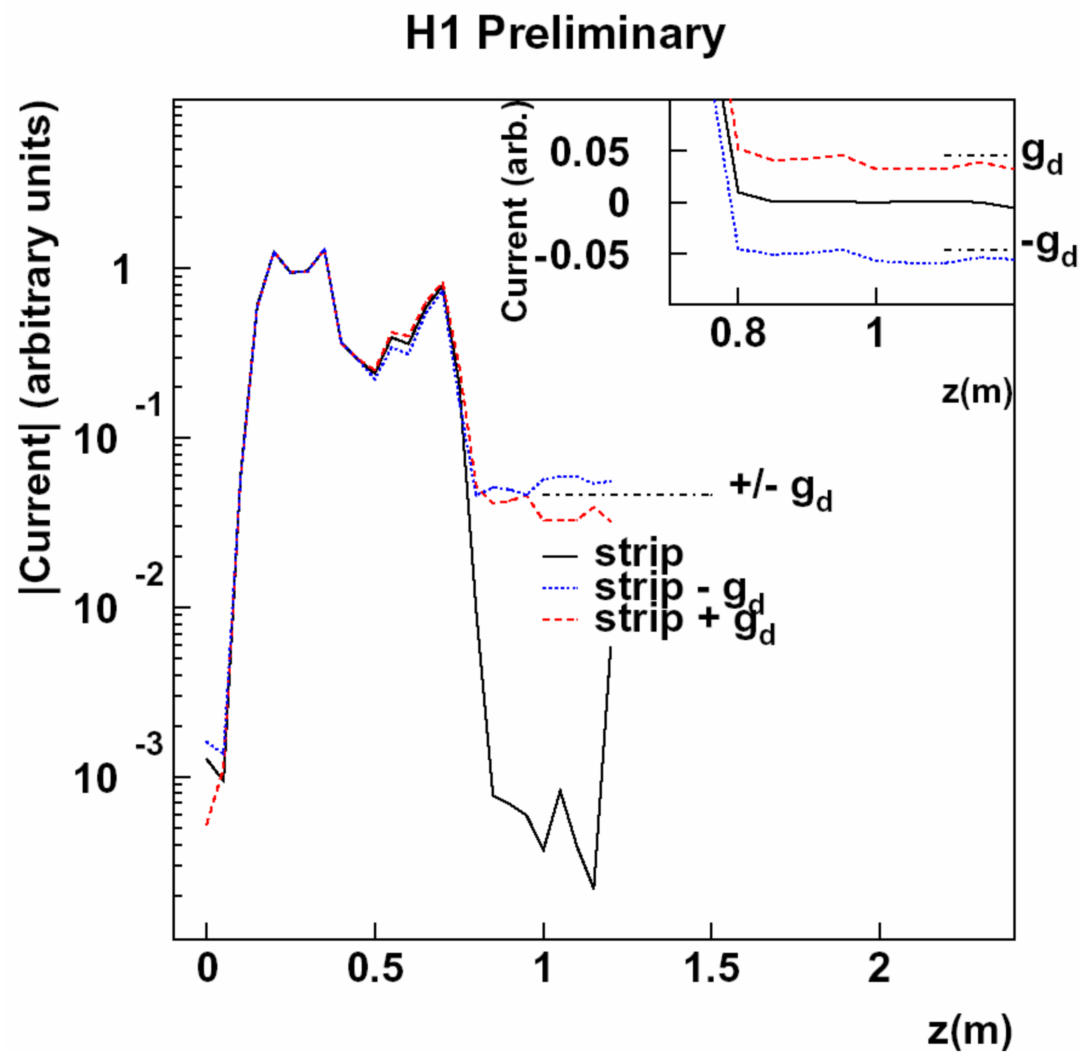
Calibration (2)

Simulate trapped monopole behaviour:

- Attach coil to a strip
- 'pseudopoles' $+g_D$, $-g_D$ and 0



$\Rightarrow$ Expected response



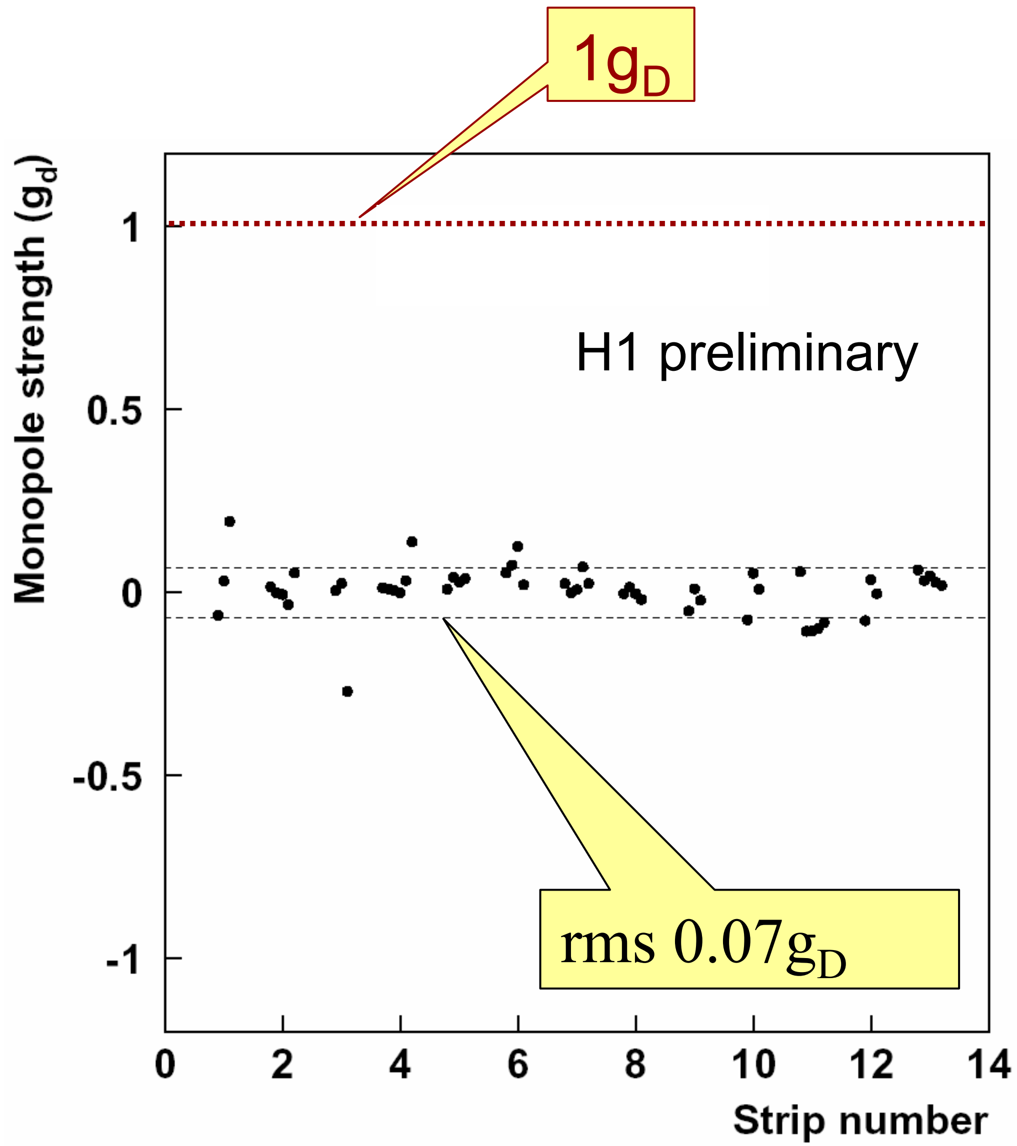
Results

•13 strips measured (several times)

•Care taken to avoid heating and strong magnetising or demagnetising fields

•Magnetometer sensitive to g>~0.2g_D

•No repeatable monopole signal seen



Determination of Upper limits

- Acceptance calculation

- Model an allowed production process $\gamma p \rightarrow M\bar{M}p$
    - ➢relies on perturbation theory!

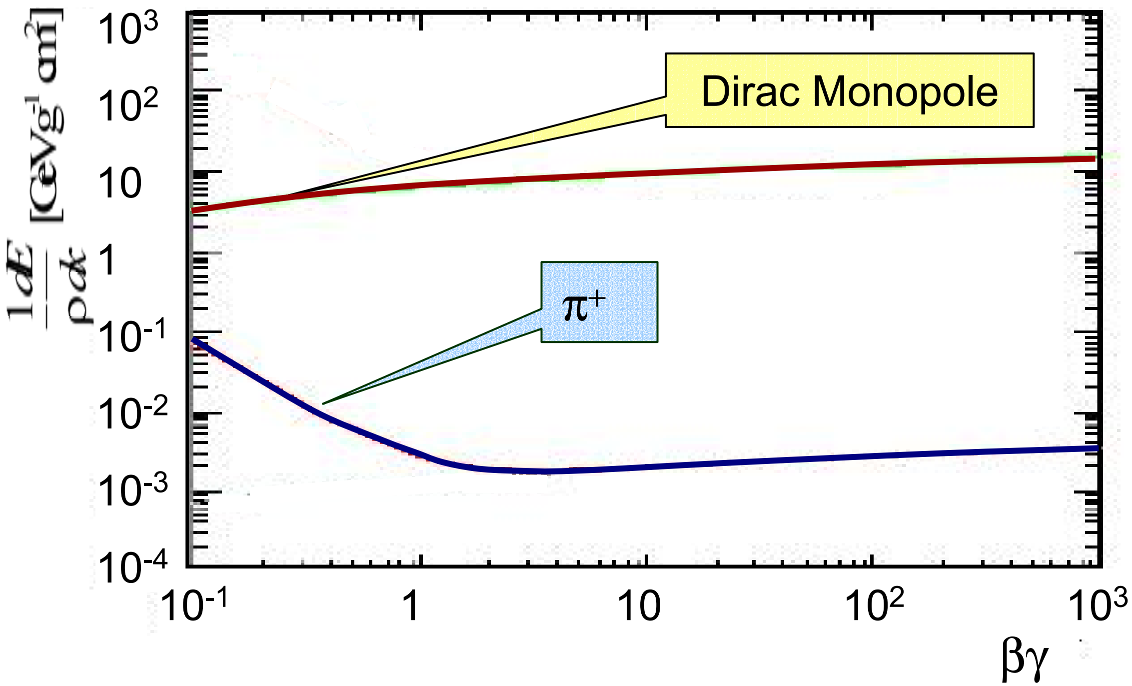
    …but acceptances depend mostly on kinematics

- Track through H1 field (1.15 Tesla) and beampipe.

- Compute acceptance as:
 (geometrical acceptance) x (stopping efficiency)

Ionisation Loss.

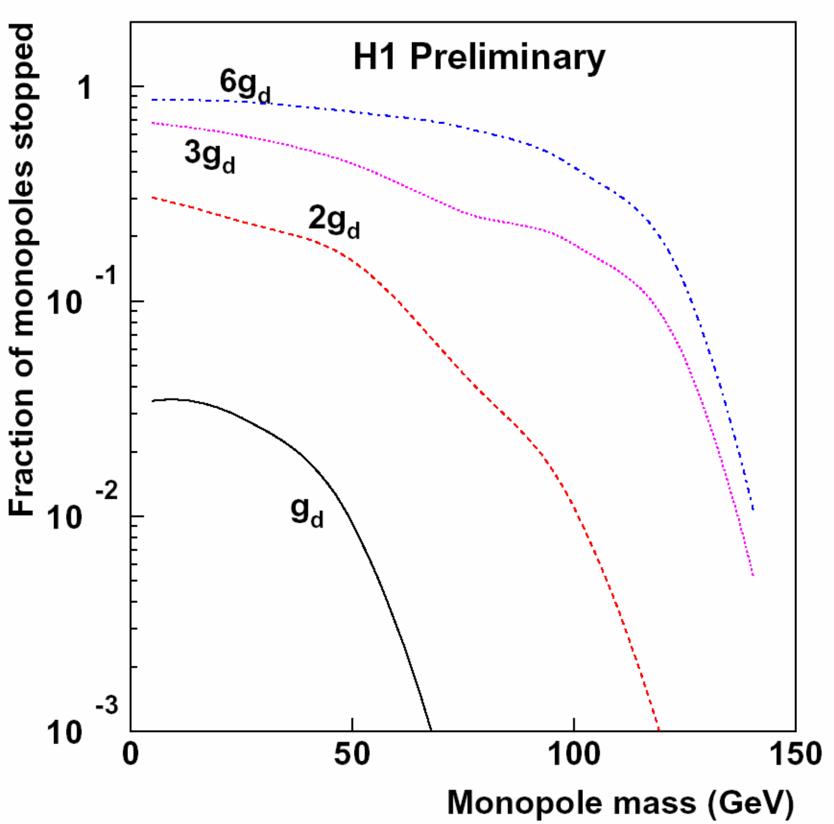
- Modified Bethe-Block formula for magnetic charge.
- dE/dx (g) = (137βn/2)2 dE/dx (q)   (*S.P. Ahlen*)
  - no rise at low β
  - Classical calculation - long-range interactions with atomic electrons



Acceptance

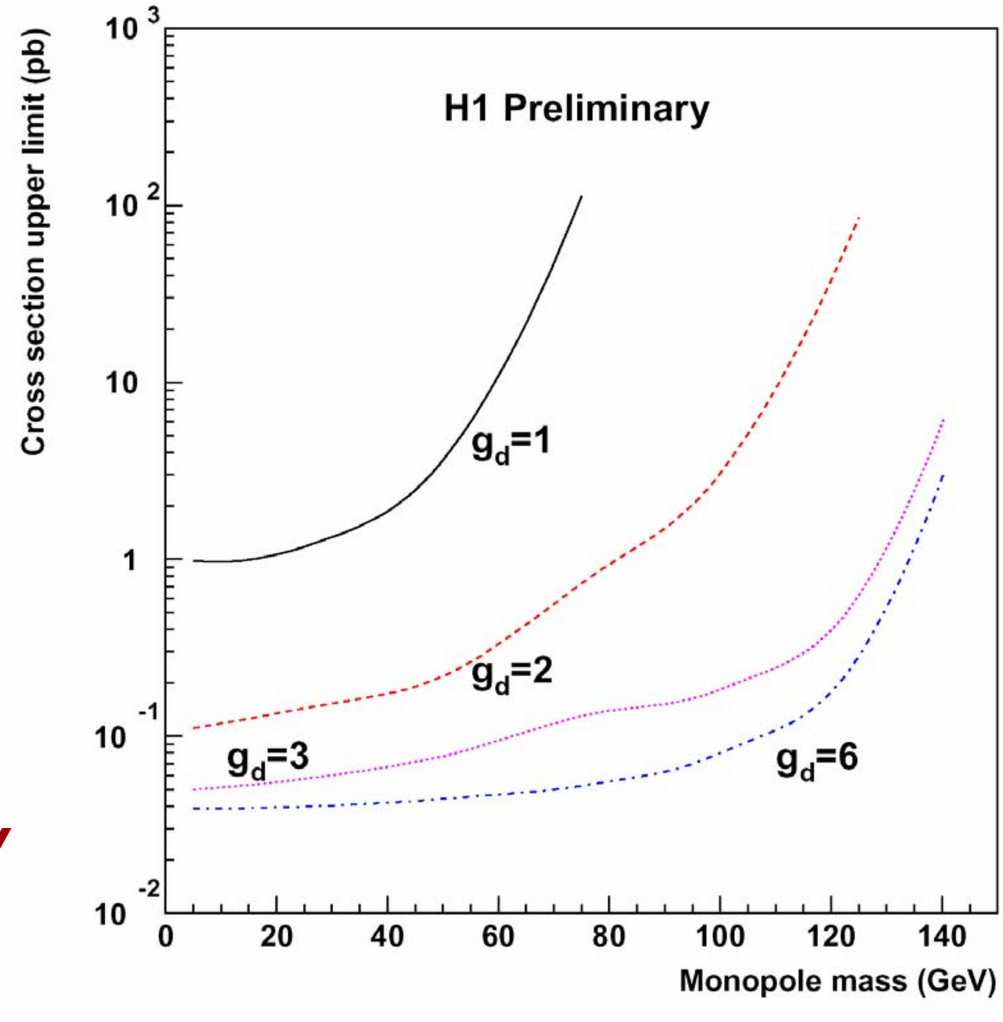
- Integrate dE/dx to get range for $1g_D$ monopoles in Aluminium
- ***Fraction of monopoles stopped vs. monopole mass:***

- Extends to ~ 140 GeV
- For $g > 6g_D$ limited by geometric acceptance



Upper limit for monopole production

- No monopoles detected
- 60 pb^{-1}
- Acceptance calculated as above
- 95% confidence level limits
- Assume flux small so no cancellation between monopoles and anti-monopoles in same strip



•Exclusion up to ~140 GeV

Comparison with other measurements

- Exist limits from diverse processes:

  $e^+p, \quad p\bar{p}, \quad e^+e^-$, cosmic rays ($pN$)

- Mass-charge exclusion regions largely from kinematics

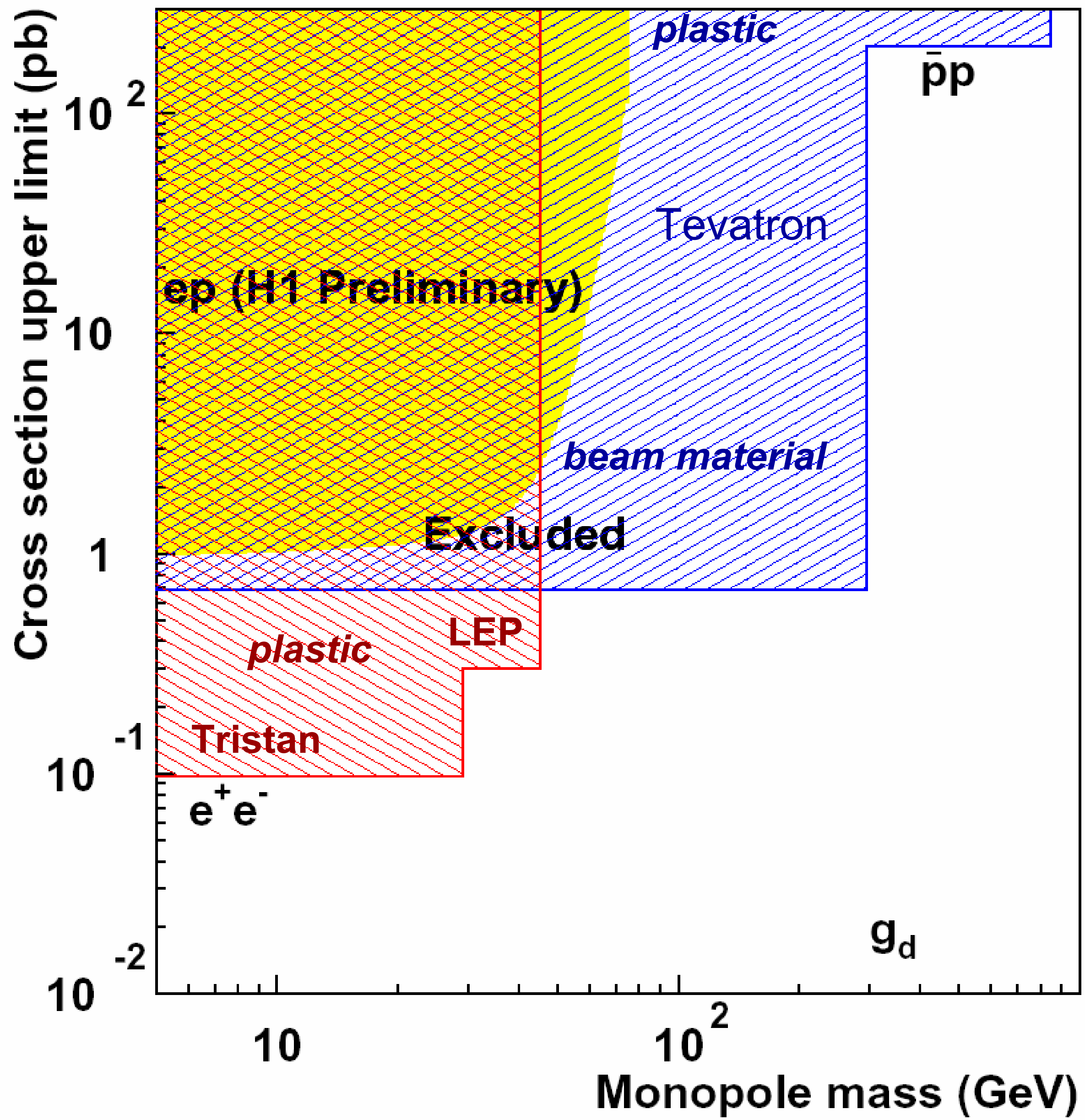
- ***Model-dependent cross-section limits*** – different assumptions made

For low charge monopoles:

- H1 mass limits similar to LEP, lower than Tevatron

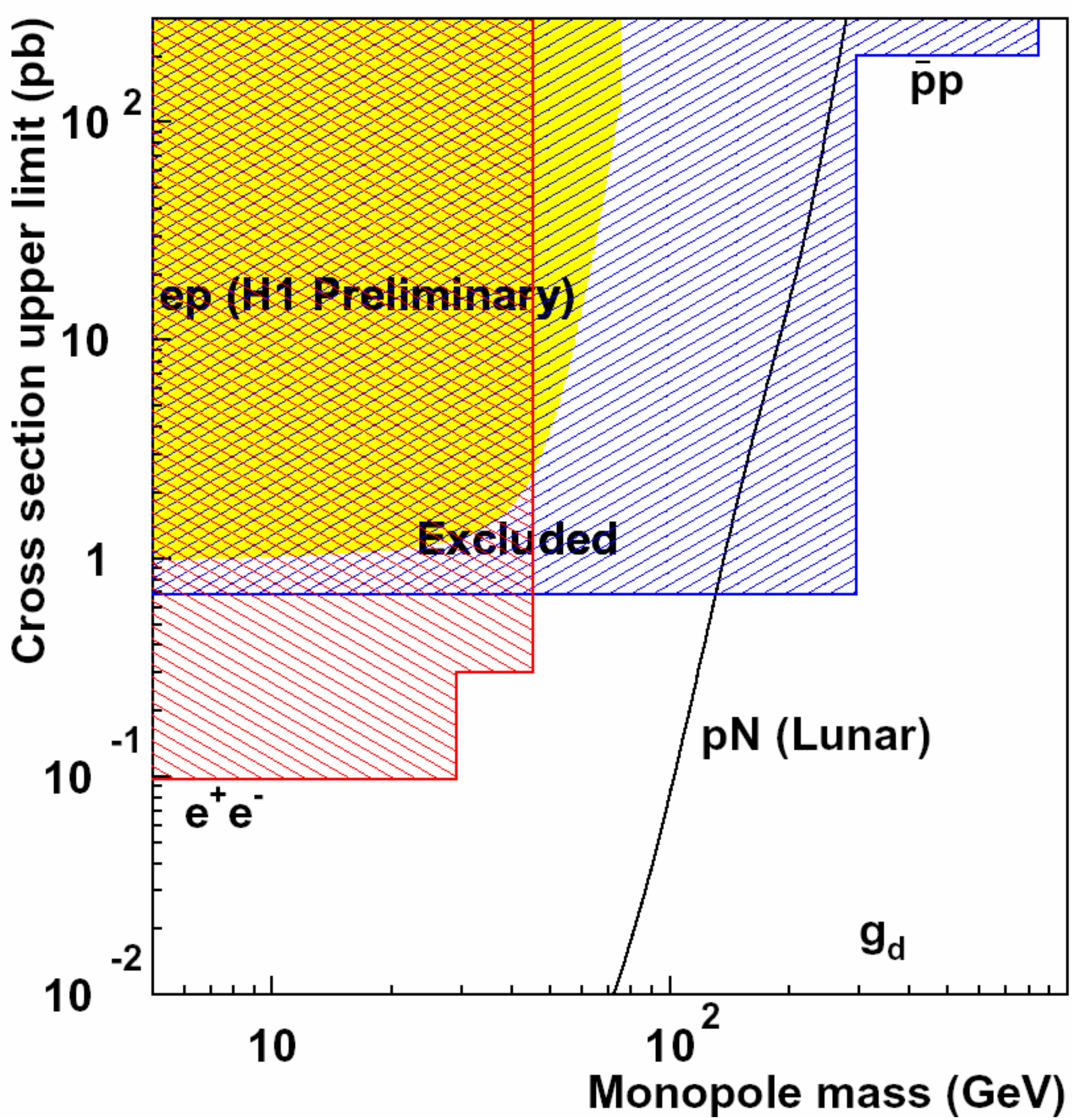
But

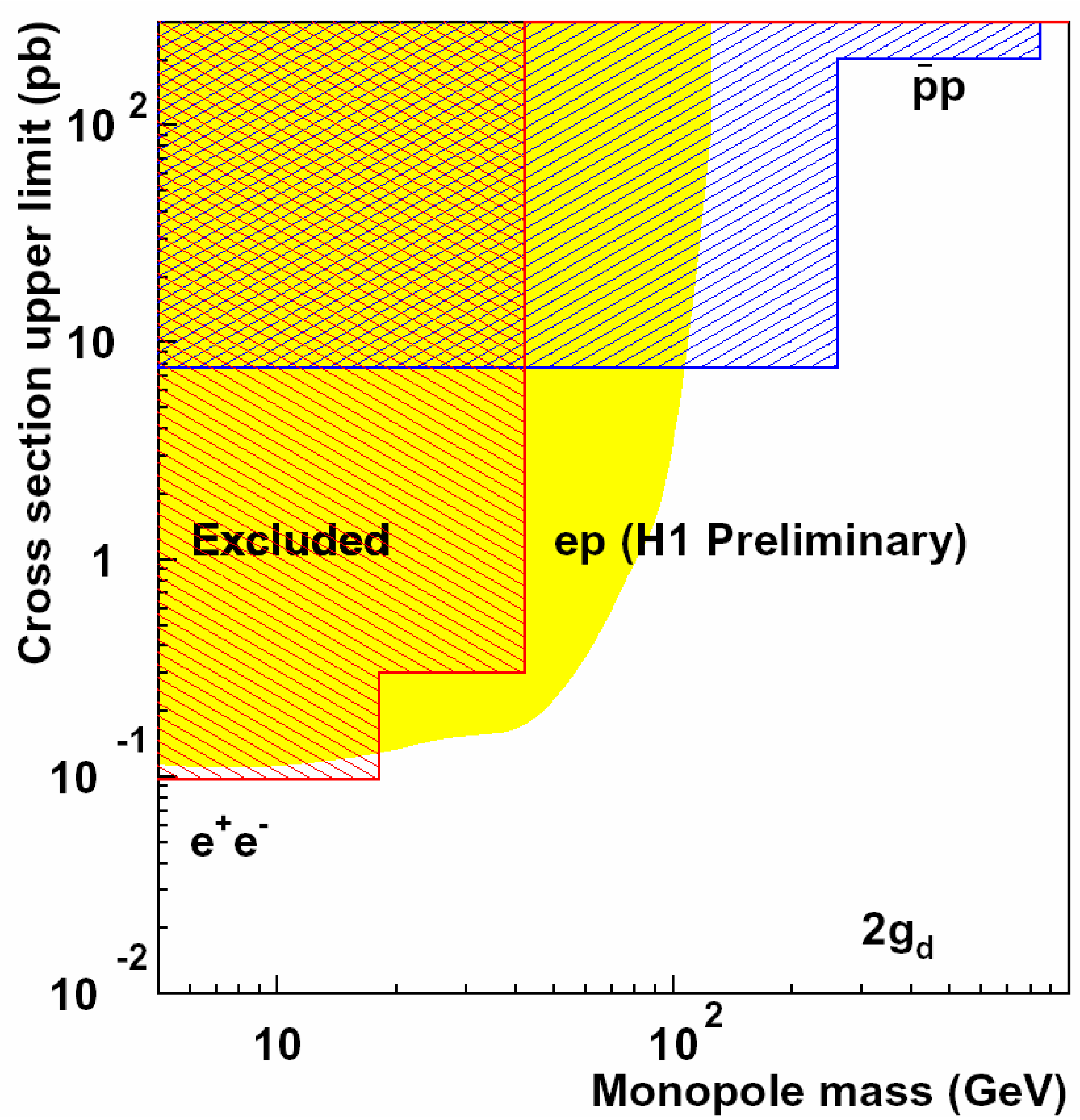
- Different cross sections, different assumptions



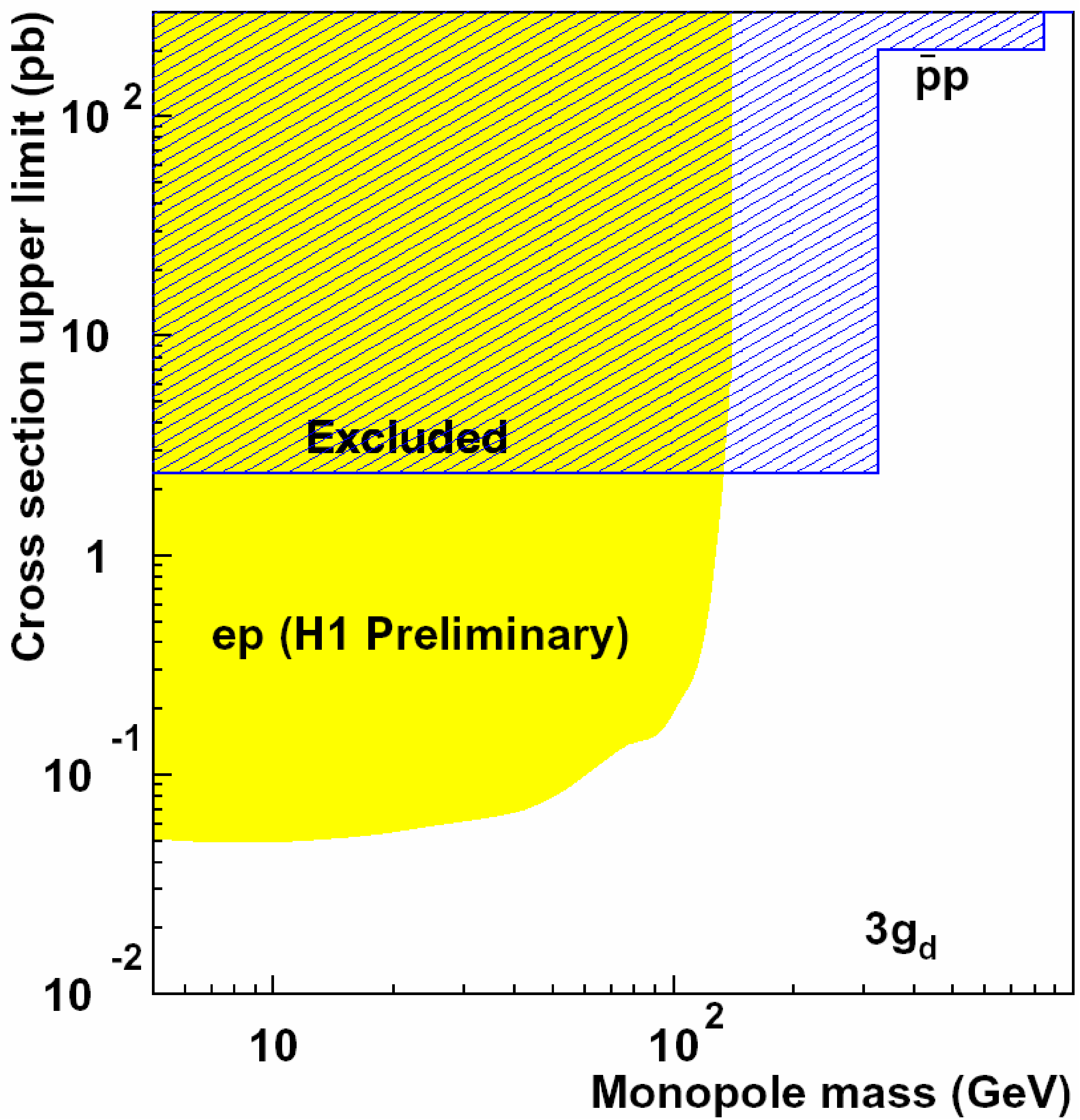
Moon rock

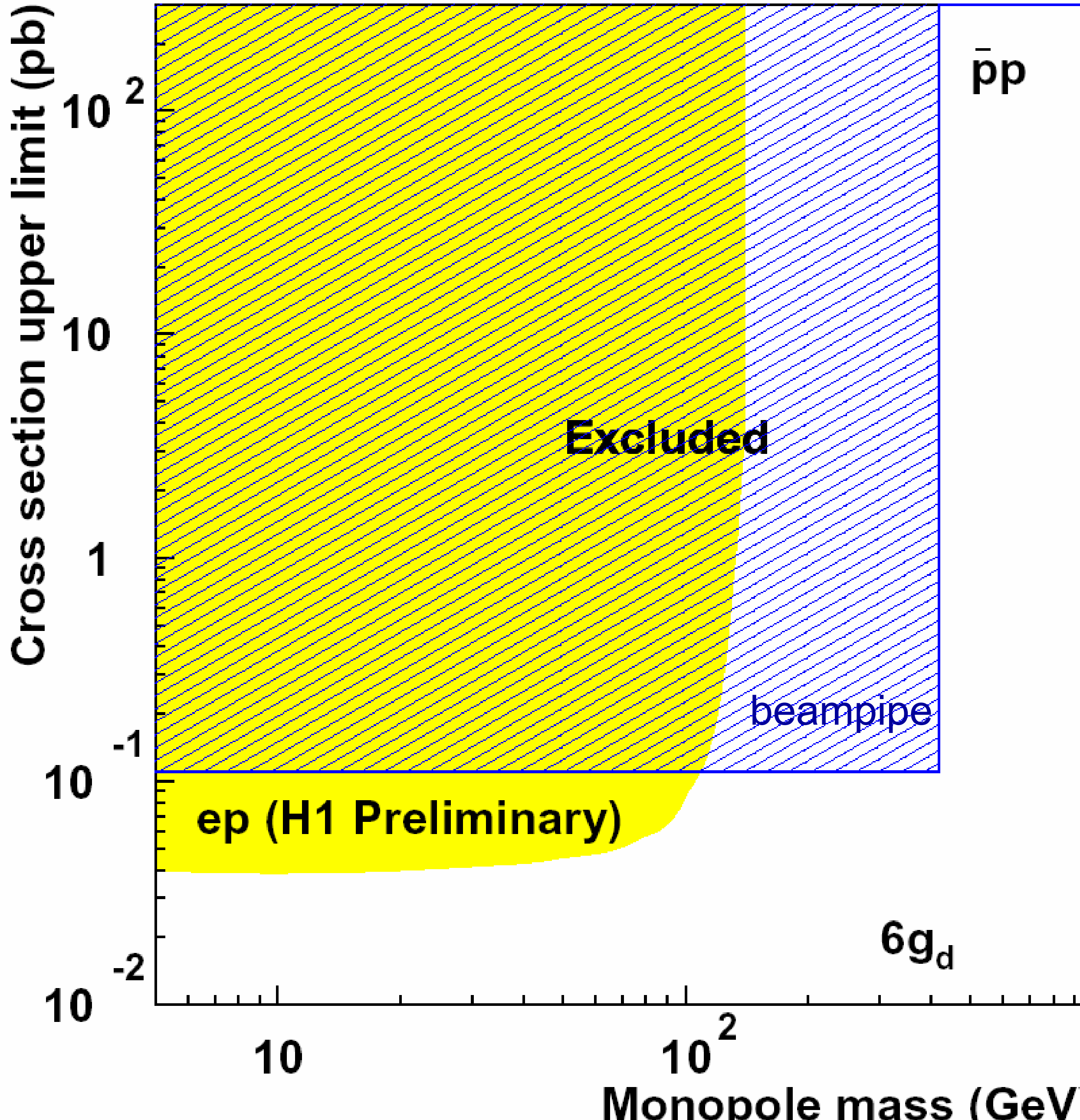
- Fixed target pN!
- 500 Myrs exposure
- assumes:
  - cosmic ray flux stable
  - no churning




Cross section upper limit (pb)
10^2
10
1
10^-1
10^-2
p̄p
Excluded
ep (H1 Preliminary)
e+e-
2g_d
10
10^2
Monopole mass (GeV)

H1 not so limited by geometrical acceptance





Cross section upper limit (pb)
10 2
10
1
10 -1
10 -2
10
10 2
Monopole mass (GeV)
p̄p
Excluded
beampipe
ep (H1 Preliminary)
6g_d

Conclusions and Future Prospects

- ***First search for magnetic monopoles in e^+p collisions***
- Upper limits set for monopole pair production for monopoles with m <150 GeV and charge $1g_D - 6g_D$
- Sensitive to larger range of mass and charge than e^+e^-
- $p\overline{p}$ higher mass limits but more assumptions

Future plans

- Additional models
- Analyse more sections of beampipe (more forward)
- Complement with dE/dx measurements in trackers