Search for Magnetic Monopoles at Belle II

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Introduction

Monopole Production Cross Section — Accelerator Searches

X-SECT (cm^2)	MASS (GeV)	CHG (g)	ENERGY (GeV)	BEAM	DOCUMENT ID		TECN
<2.5E−37	200–6000	1	13000	pp	[1] ACHARYA	17	INDU
<2E−37	200–6000	2	13000	pp	[1] ACHARYA	17	INDU
<4E−37	200–5000	3	13000	pp	[1] ACHARYA	17	INDU
<1.5E−36	400–4000	4	13000	pp	[1] ACHARYA	17	INDU
<7E−36	1000–3000	5	13000	pp	[1] ACHARYA	17	INDU
<5E−40	200–2500	0.5–2.0	8000	pp	[2] AAD	16AB	ATLS
<2E−37	100–3500	1	8000	pp	[3] ACHARYA	16	INDU
<2E−37	100–3500	2	8000	pp	[3] ACHARYA	16	INDU
<6E−37	500–3000	3	8000	pp	[3] ACHARYA	16	INDU
<7E−36	1000–2000	4	8000	pp	[3] ACHARYA	16	INDU
<1.6E−38	200–1200	1	7000	pp	[4] AAD	12CS	ATLS
<5E−38	45–102	1	206	e^+e^-	[5] ABBIENDI	08	OPAL
<0.2E−36	200–700	1	1960	$p\bar{p}$	[6] ABULENCIA	06K	CNTR
< 2.E−36		1	300	e^+p	[7,8] AKTAS	05A	INDU
< 0.2 E−36		2	300	e^+p	[7,8] AKTAS	05A	INDU
< 0.09E−36		3	300	e^+p	[7,8] AKTAS	05A	INDU
< 0.05E−36		≥ 6	300	e^+p	[7,8] AKTAS	05A	INDU
< 2.E−36		1	300	e^+p	[7,9] AKTAS	05A	INDU
< 0.2E−36		2	300	e^+p	[7,9] AKTAS	05A	INDU
< 0.07E−36		3	300	e^+p	[7,9] AKTAS	05A	INDU
< 0.06E−36		≥ 6	300	e^+p	[7,9] AKTAS	05A	INDU
< 0.6E−36	>265	1	1800	$p\bar{p}$	[10] KALBFLEISCH	04	INDU
< 0.2E−36	>355	2	1800	$p\bar{p}$	[10] KALBFLEISCH	04	INDU
< 0.07E−36	>410	3	1800	$p\bar{p}$	[10] KALBFLEISCH	04	INDU
< 0.2E−36	>375	6	1800	$p\bar{p}$	[10] KALBFLEISCH	04	INDU
< 0.7E−36	>295	1	1800	$p\bar{p}$	[11,12] KALBFLEISCH	00	INDU
< 7.8E−36	>260	2	1800	$p\bar{p}$	[11,12] KALBFLEISCH	00	INDU
< 2.3E−36	>325	3	1800	$p\bar{p}$	[11,13] KALBFLEISCH	00	INDU
< 0.11E−36	>420	6	1800	$p\bar{p}$	[11,13] KALBFLEISCH	00	INDU
<0.65E−33	<3.3	≥ 2	11*A*	^{197}Au	[14] HE	97	
<1.90E−33	<8.1	≥ 2	160*A*	^{208}Pb	[14] HE	97	
<3.E−37	<45.0	1.0	88–94	e^+e^-	PINFOLD	93	PLAS
<3.E−37	<41.6	2.0	88–94	e^+e^-	PINFOLD	93	PLAS
<7.E−35	<44.9	0.2–1.0	89–93	e^+e^-	KINOSHITA	92	PLAS
<2.E−34	<850	≥ 0.5	1800	$p\bar{p}$	BERTANI	90	PLAS
<1.2E−33	<800	≥ 1	1800	$p\bar{p}$	PRICE	90	PLAS
<1.E−37	<29	1	50–61	e^+e^-	KINOSHITA	89	PLAS
<1.E−37	<18	2	50–61	e^+e^-	KINOSHITA	89	PLAS
<1.E−38	<17	<1	35	e^+e^-	BRAUNSCH...	88B	CNTR
<8.E−37	<24	1	50–52	e^+e^-	KINOSHITA	88	PLAS
<1.3E−35	<22	2	50–52	e^+e^-	KINOSHITA	88	PLAS
<9.E−37	<4	<0.15	10.6	e^+e^-	GENTILE	87	CLEO

- A stable particle carrying magnetic charge (dyons have both magnetic and electric charges)
- Proposed by Dirac in 1931 as a way to quantize electric charge
  - $e_0 g_0/\hbar c = n/2$
  - Minimal magnetic charge $g_D = 68.5e$
- Lower charges are not ruled out (e.g composite particles) arXiv:1707.05295

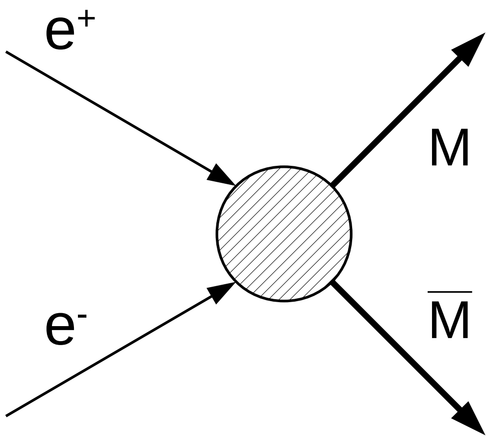
- High magnetic charge 2017
  - MoEDAL – $g \geq g_D$
  - ATLAS – $0.5g_D < g < 2.0g_D$
- Low magnetic charge 1987
  - TASSO – $10e < g < 70e$
  - CLEO – $2e < g < 10e$

Comment on charge limits

- Dirac condition on electric and magnetic charges quantization is obtained from phase properties of a wave-function describing a particle in the EM field which has a static singularity. Such a monopole would be:
  - Point-like
  - Static
- Saha argument gives same condition from quantization of angular momentum in a system of point-like electric and magnetic charges. Such a monopole would be:
  - Point-like
  - Bound to electric charge
- Therefore existence of monopoles of non-Dirac charges $g_D < 68.5e$ are possible, although discouraged
- Belle II have perfect conditions to search for such particles in phase II (Feb-Jun 2017), during which $20fb^{-1}$ (or more) of integrated luminosity is expected.

Signal Monte-Carlo

- Currently – simple MC generator of $M\overline{M}$ pairs in CMS with expected angular distribution, boosted to the lab frame

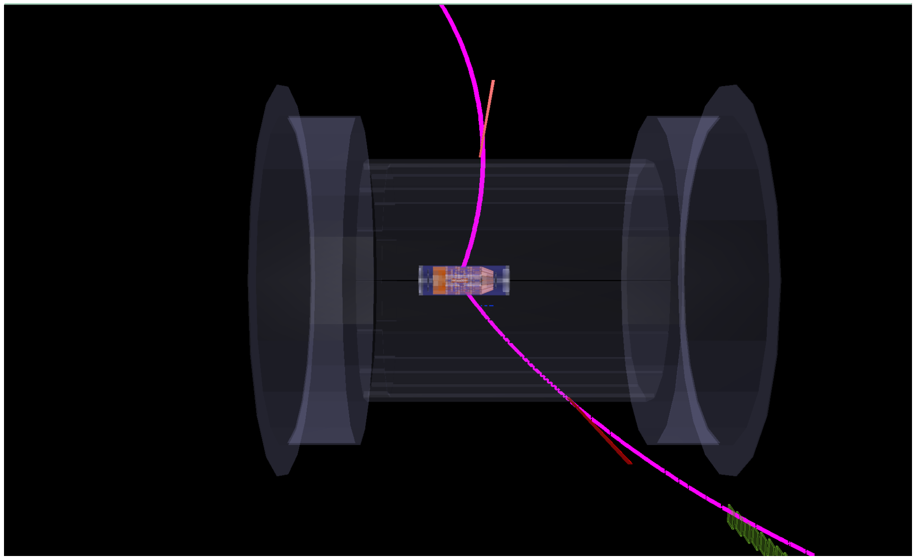


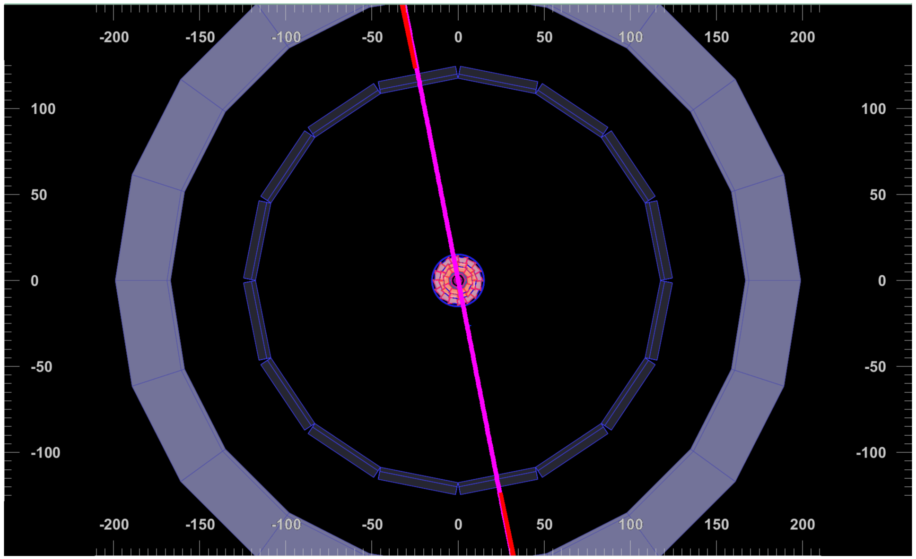
- Monopole parameters:
  - Mass ***m***
  - Magnetic charge ***g***
  - Electric charge ***q***
- Ideally – conventional MC generator (e.g. MadGraph), which will take care of branching ratios and will allow ISR
- $M\overline{M}$ pair differential cross-section

$$\frac{d\sigma_{M\overline{M}}}{d\Omega} = \frac{\alpha\alpha_m(\hbar c)^2\beta^3}{4s}\,(1 + cos^2\Theta)$$

Simulation

- Transportation
  - Magnetic charge is accelerated in B field just like an electric one in E field
  - Boosted parabolas in R-z
  - Straight lines in R-φ
  - Extra curvature in R-φ for dyons





Simulation

- Ionization
  - Based on dE/dx for highly ionising particles (Ahlen 1980) extrapolated to lower charges
  - Bethe-Bloch but with $Ze \rightarrow g\beta$, therefore absence of $1/\beta^2$ dependence

$$-\frac{dE}{dx} = \frac{e^4}{m_u 4\pi\epsilon_0^2 m_e c^2}\frac{Z_{atom}}{A_{atom}}\, g^2\left[ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \frac{1}{2} + \frac{k}{2} - \frac{\delta}{2} - B_m\right]$$

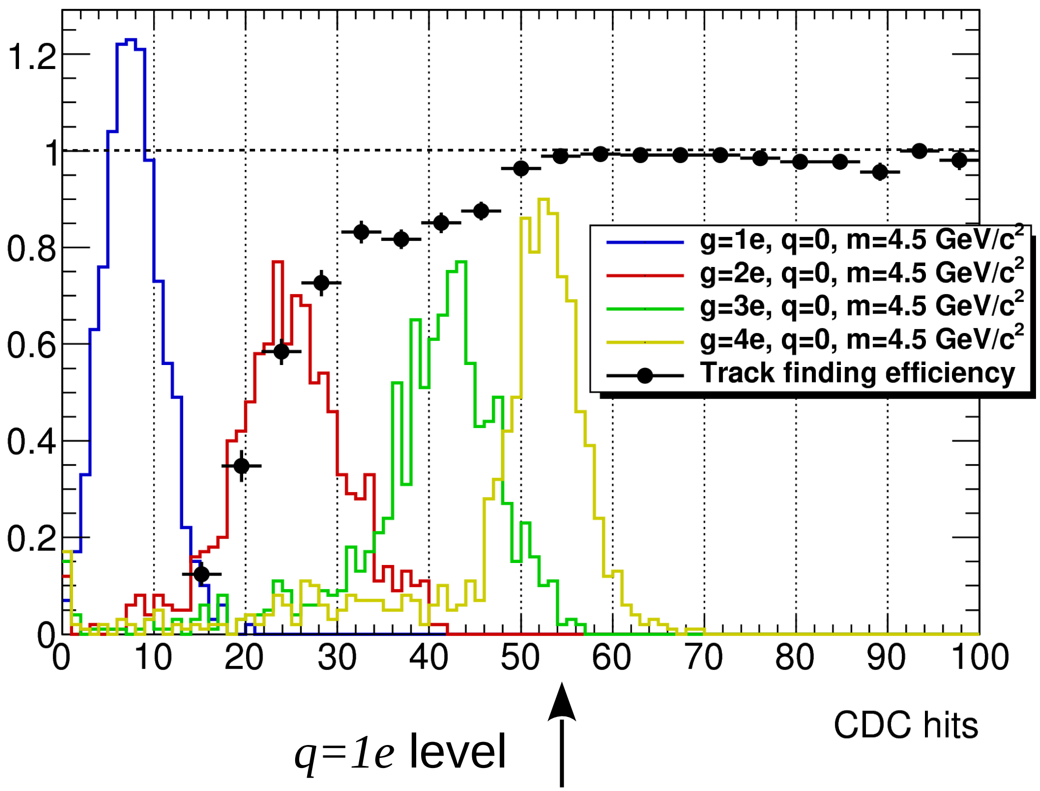
  - K is the QED correction
  - δ is the density effect correction
  - B_m is the Bloch correction

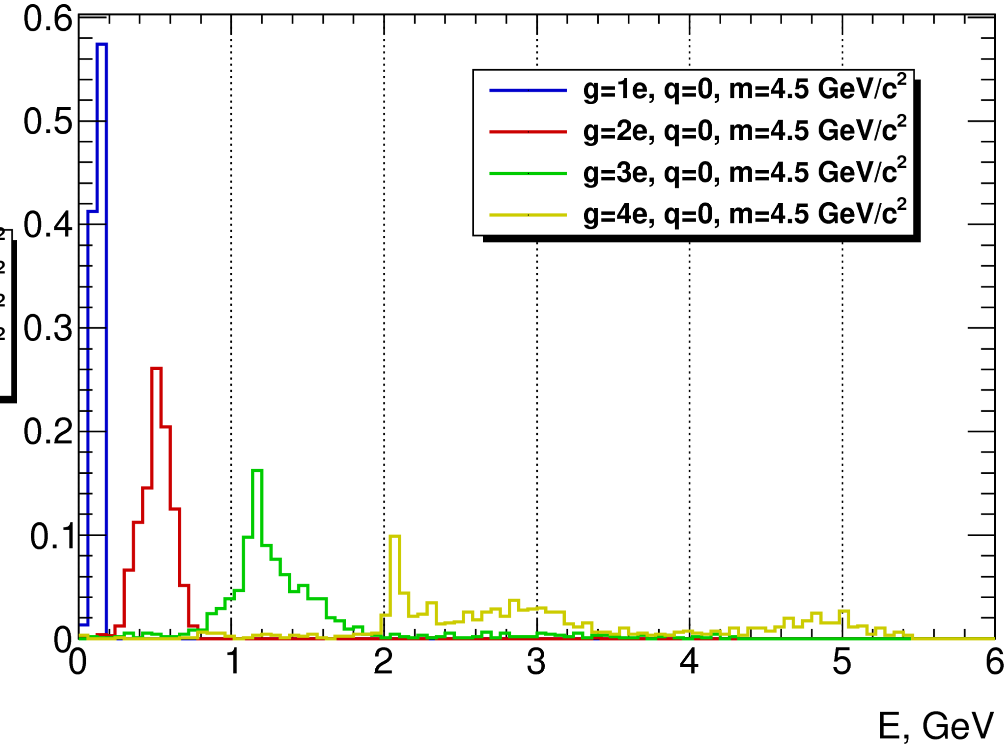
	0.015	1	2	3	6	9
$k(g/g_D)$	0.406	0.406	0.346	0.300	0.300	0.300
$B_m(g/g_D)$	0	0.248	0.672	1.022	1.685	2.085

- Has to be verified and improved, especially for the case of dyons

Single monopole hits

- Example monopoles of $m=4.5$, $q=0$, $g=1,2,3,4e$
- Leaves CDC, ECL, and KLM hits
- Because of $1/\beta^2$ absence in ionisation, heavy (4.5 GeV/c^2) monopoles of low charge give a faint signal





Single monopole reconstruction*

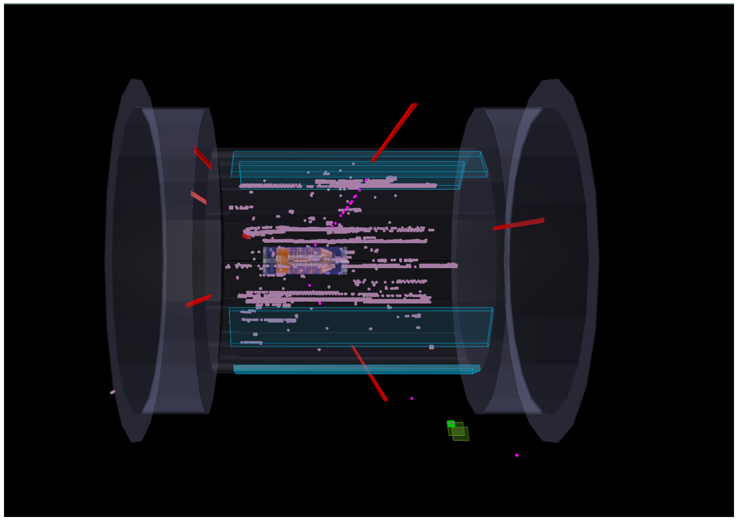
- Under current algorithms reconstructed tracks look like
  - High momentum for monopoles
  - 1, 2 track segments for dyons
- ECL clusters are not assigned to those tracks

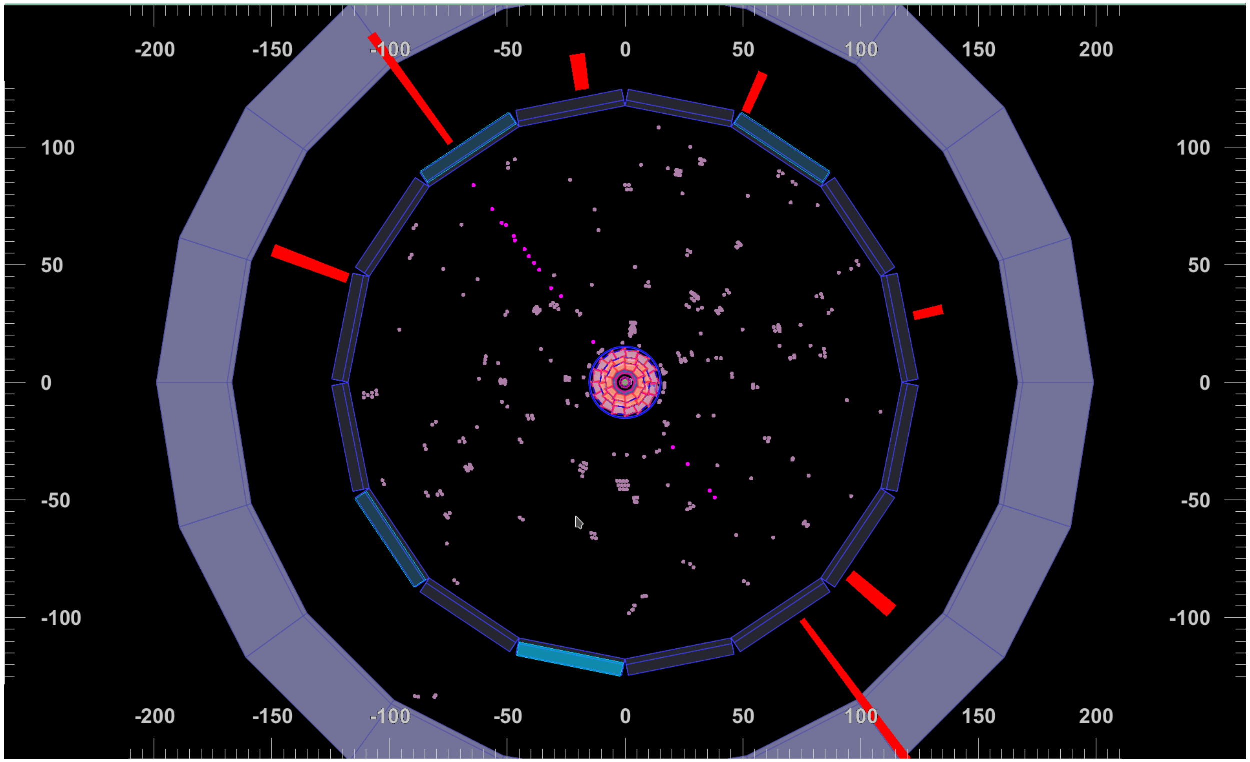
m=4.5 GeV/c^2 **q=0e**	g=1e	g=2e	g=3e	g=4e
Tracking	0.0%	8.6%	69.4%	93%
Clustering	99.1%	99.7%	98.7%	97.7%

m=4.5 GeV/c^2 **q=1e**	g=1e	g=2e	g=3e	g=4e
Tracking	99.9%	99.4%	97.9%	98.8%
Clustering	99.2%	99.8%	98.6%	99.8%

Beam background

- For high-mass, low-charge monopoles even phase II beam background levels are too high for track reconstruction





L1 trigger menu

- Firmware implementation is ongoing with current reconstruction algorithms
- Some small modifications can be proposed to the decision logic

Objects	Description
n_2dfinder_track	#2D finder tracks
n_2dfitter_track	#2D fitter tracks
n_3dfitter_track	#3D fitter tracks
n_NN_track	#Neural Network (NN) tracks
n_2dmatch_track	#2D finder tracks with associated ecl cluster
n_3dmatch_track	#NN tracks with associated ecl cluster
n_cluster	#ecl clusters
n_neutral_cluster	#ecl clusters w/o associated cdc tracks
n_high_300_cluster	#ecl clusters with energy larger than 300 MeV
n_high_1000_cluster	#ecl cluster with energy larger than 1GeV
n_high_2000_cluster	#ecl cluster with energy larger than 2 GeV
n_high_2000_endcap_cluster	#ecl cluster with energy larger than 2 GeV in TC ID 1,17
bbc	#back to back ecl cluster pairs
bbtc	#back to back track-eclcluster pairs
n_klm_track	#klm track
n_klm_hit	#klm hits
bhabhaveto	two track bhabha, 1: bhabha, 0:non-bhabha
sbhabhaveto	single track bhabha, 1:bhabha, 0:non-bhabha
eclbhabhaveto	eclbhabha with ecl information only, 1:bhabha, 0: non-bhabha

Bit	Phase 2 description
0	3 or more 3D tracks
1	2 3D tracks, ≥1 within 25 cm, not a trkBhabha
2	2 3D tracks, not a trkBhabha
3	2 3D tracks, trkBhabha
4	1 track, <25cm, clust same hemi, no 2 GeV clust
5	1 track, <25cm, clust opp hemi, no 2 GeV clust
6	≥3 clusters inc. ≥1 300 MeV, not an eclBhabha
7	2 GeV E* in [4,14], not a trkBhabha
8	2 GeV E* in [4,14], trkBhabha
9	2 GeV E* in 2,3,15,16, not eclBhabha
10	2 GeV E* in 2,3,15 or 16, eclBhabha
11	2 GeV E* in 1 or 17, not eclBhabha
12	2 GeV E* in 1 or 17, eclBhabha
13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]
14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16
15	clusters back-to-back in phi, both >250 MeV, no 2 GeV
16	clusters back-to-back in phi, 1 <250 MeV, no 2 GeV
17	clusters back-to-back in 3D, no 2 GeV

Christopher HEARTY, L1 Trigger menu for phase II and early phase III, 28thB2GM, 9-13 October 2017

Trigger efficiencies

- Using default L1 trigger menu, without acceptance cuts, with phase2 background

m=4.5 GeV/c^2 **q=0e**	g=1e	g=2e	g=3e	g=4e	g=5e
2 Tracks	0.00	0.00	4.80	43.00	32.20
Clusters b2b in φ	38.00	91.60	93.40	39.80	35.80
Total	**39.20**	**97.20**	**98.60**	**88.20**	**88.80**

m=4.5 GeV/c^2 **q=1e**	g=1e	g=2e	g=3e	g=4e	g=5e
2 Tracks	79.20	79.60	71.40	60.20	28.40
Clusters b2b 3D	20.40	31.40	69.40	27.80	28.00
Total	**95.80**	**94.00**	**93.80**	**90.80**	**87.80**

g=1e q=0e	m=4.5	m=2.5	m=1.0	m=0.5	m=0.1
2 Tracks	0.00	0.00	0.00	0.00	0.00
Clusters b2b in φ	38.00	85.60	92.00	91.20	91.40
Total	**39.20**	**87.40**	**93.40**	**93.40**	**93.20**

High level trigger

Realistic strategy of HLT commissioning in Phase 2

1. At the beginning of Phase 2, HLT is operated without any processing. All the events are pass-through to Storage
   * An intensive debugginig of "FastReco(=CDC+ECL recon)" and "Level3" is supposed to be done offline.
   * Also RoI generation is supposed to be debugged.

2. After FastReco(Level3) is proven to be stable, we will implement FastReco(Level3) in HLT.
   * The software trigger by FastReco only may be turned on in case the trigger rate is too high.
   * Debugging of full HLT script is done offline.

3. Then the full HLT script is implemented.
   * FastReco trigger is turned on.
   * But final software trigger is not turned on during Phase 2.

Ryosuke ITOH, Current Parallel Processing Implementation, Software workshop and Tutorials, 6-8 October 2017

Towards data taking in phase2

- No time to make tracking modifications (release-01-00-00 on Nov 1st)
- Dedicated HLT can be developed, however HLT failed events will still be stored during phase2
- Monopole simulation need to be finalised to get into release-01-00-00
- Precise trigger efficiency analysis in a wide range of parameters (m, q, g) is required for sensitivity estimations

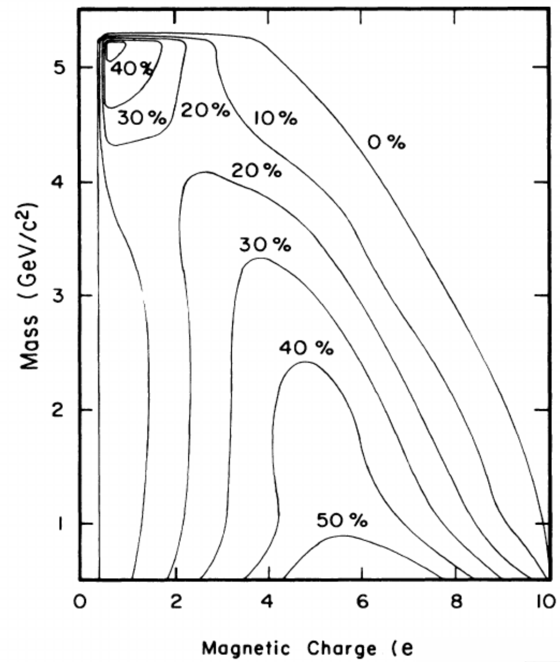
Summary

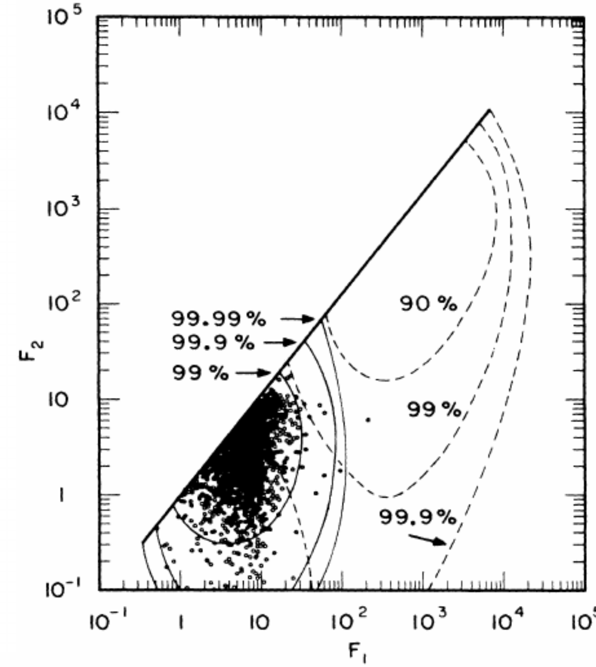
- Previous results are 30 years ago for $2e < g < 10e$
- No limits for $g=1e$ monopole production rates by direct searches
- Monopole simulation is working
- Parasite reconstruction is working
- L1 triggers pickup signal events with high efficiency
- Can be searched for during phase 2
- Require dedicated track reconstruction for analysis
- Virtually no background because of curvature along B field

Thank you for your attention!

Searches in low charge region

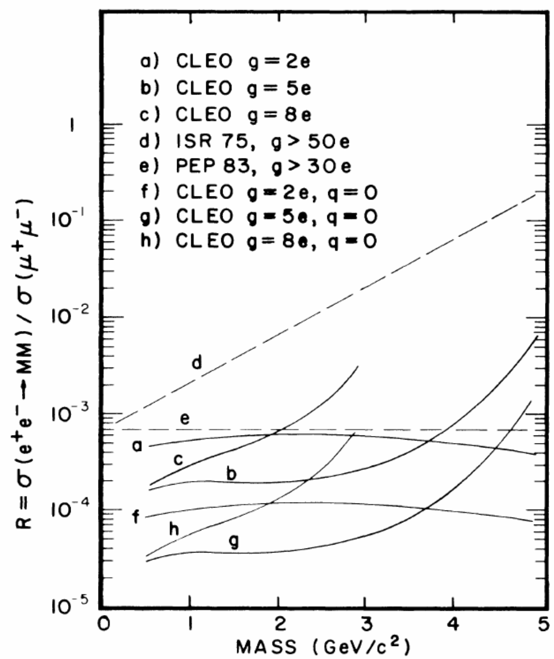
- Trigger – hits in two TOF
- Cuts
  - 4 or less tracks
  - TOF $\Delta t<5$ns
  - $d_0<0.6$cm, $z_0<5$cm
  - Back-to-back tracks





- Method
  - Two types of track fit
    $z=a_0+a_1s$
    $z=a_0+a_1s+a_2s^2$

$$F = \frac{\chi^2_L - \chi^2_Q}{\chi^2_L/(N-3)}$$



- CLEO at CESR in 1987
- Data
  - 25pb^{-1} for dyons at Y(4S)
  - 159pb^{-1} for p>7 GeV/c monopoles at Y(1S), Y(3S) and Y(4S)

Closest evidence

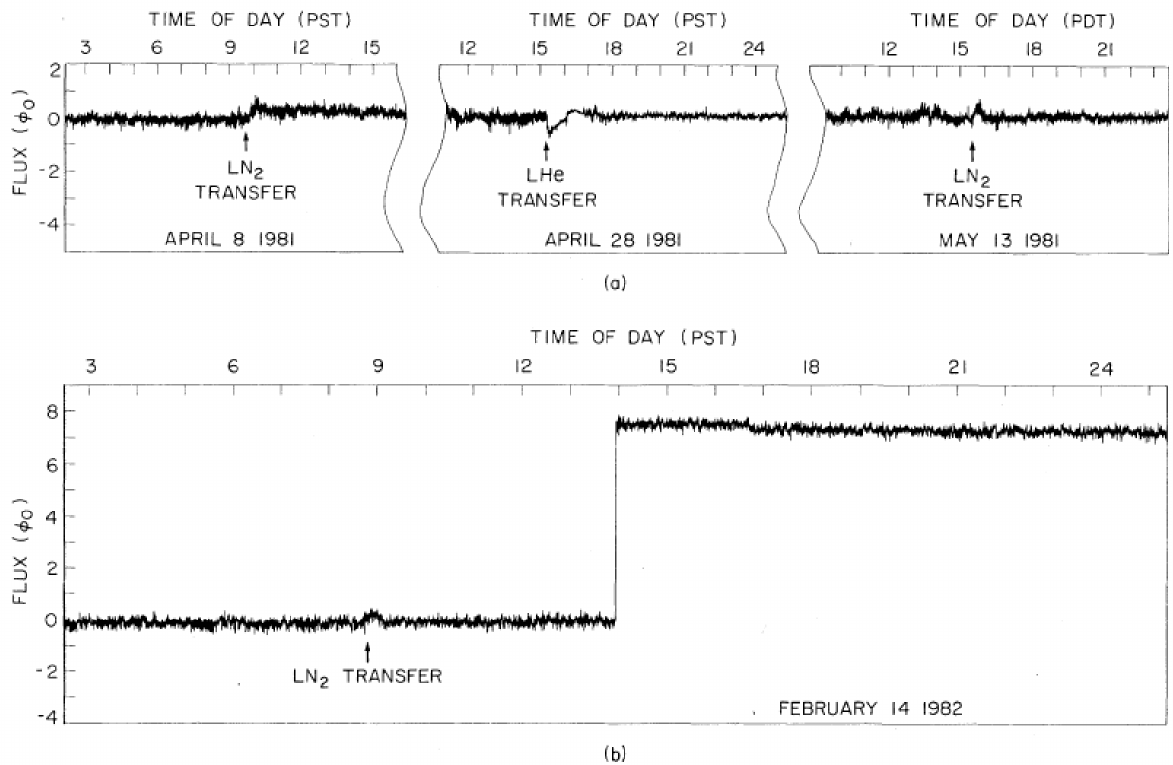
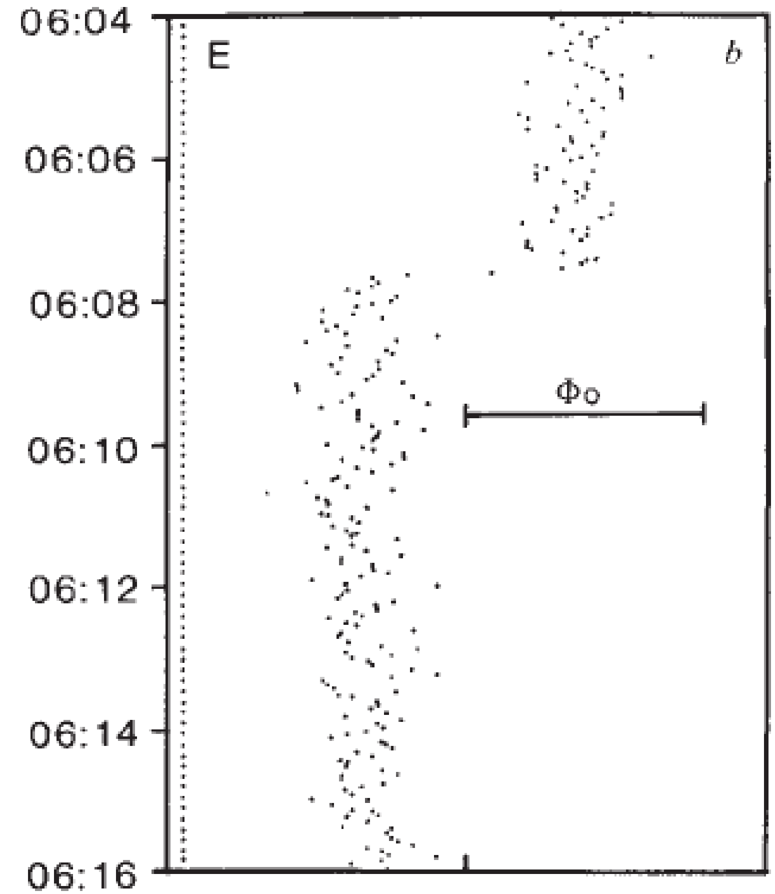


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.



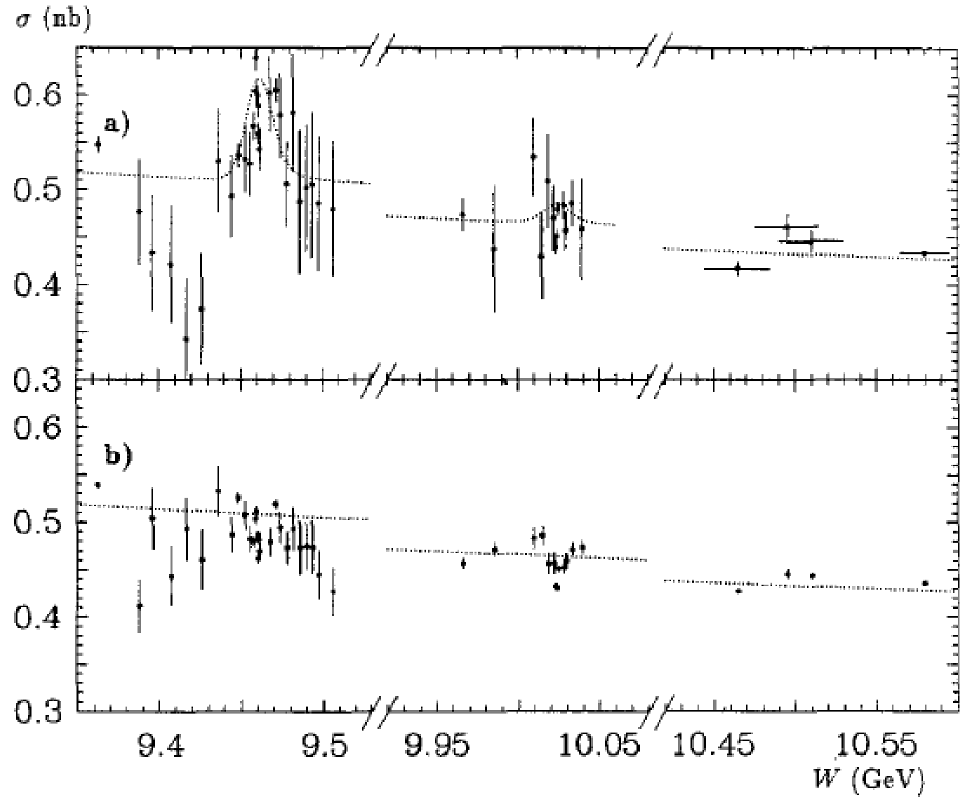
Two unexplained perfect Dirac monopole candidates were observed in 1982 and 1985 using superconducting rings

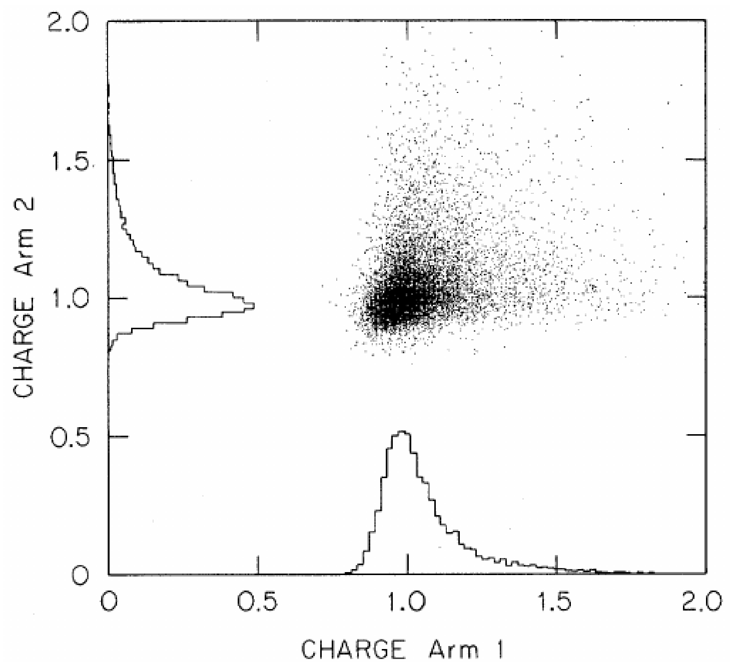
PhysRevLett.48.1378 (1982) Cabrera
Nature vol. 321 (1986) Caplin et. al.

Other experiments

- Crystall ball measured Υ → $\mu^+\mu^-$ branching fraction
- Correction coefficient from MC was 0.999±0.006

- No excess of muons





- FQS search might have been sensitive to slow monopoles

- No candidates

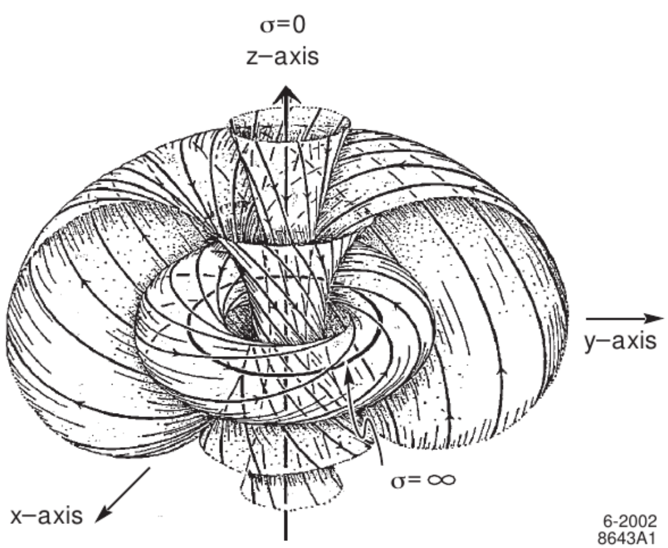
D.Fryberger vorton theory

$$\vec{\nabla}\cdot\vec{D}=4\pi\rho_e, \qquad \vec{\nabla}\times\vec{H}-\frac{1}{c}\frac{\partial\vec{D}}{\partial t}=\frac{4\pi}{c}\vec{j_e},$$

and

$$\vec{\nabla}\cdot\vec{B}=4\pi\rho_m, \qquad -\vec{\nabla}\times\vec{E}-\frac{1}{c}\frac{\partial\vec{B}}{\partial t}=\frac{4\pi}{c}\vec{j_m}$$

In addition to the symmetry of Maxwell equations in Minkowski space, symmetrized Maxwell equations are invariant under rotations in (e, g) plane → dyality angle

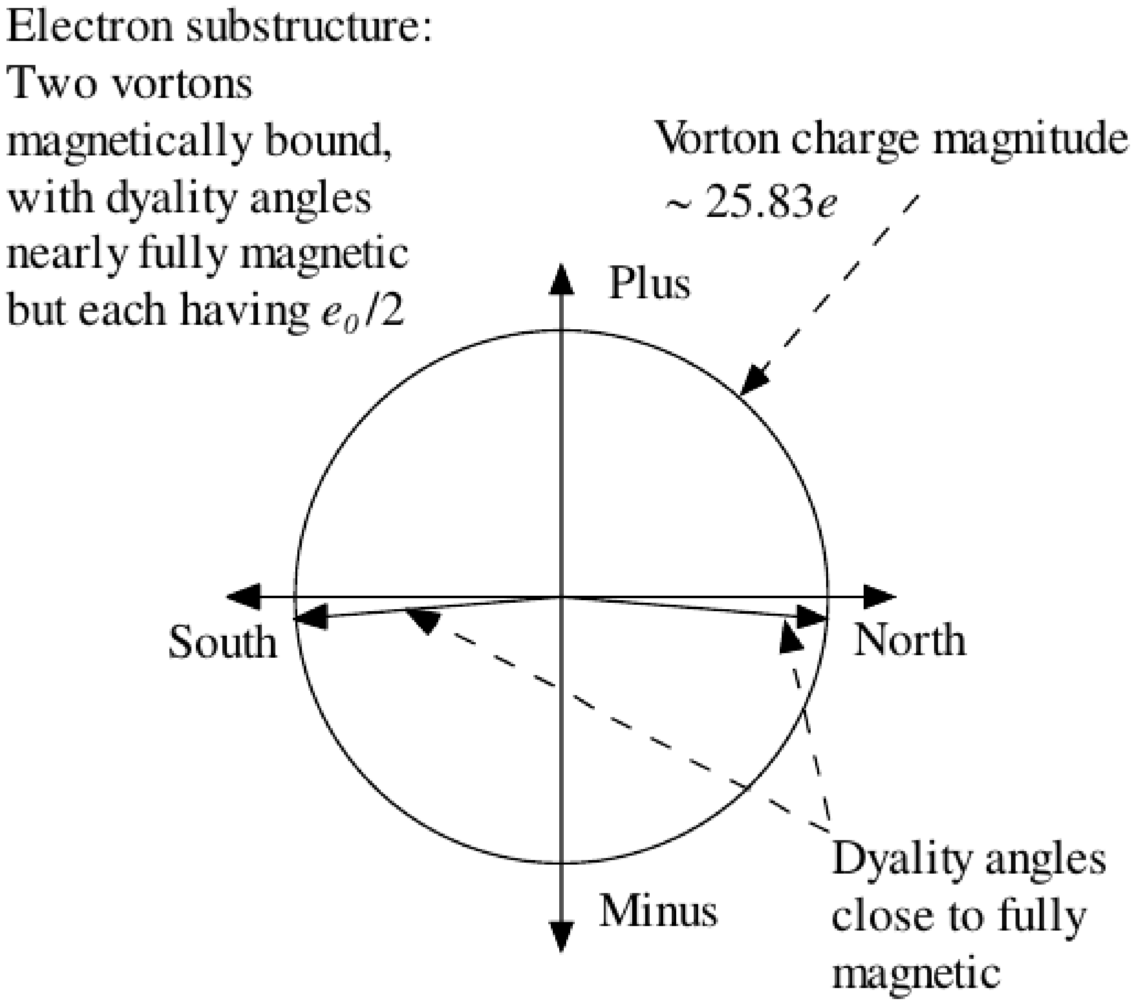


Explicit addition of magnetic charge density + conformal group generators + Bohr-Sommerfeld quantization

Solution – configuration of field:

- No singularities
- Static spherically symmetrical
- Has topological charge → stable
- Minimum electromagnetic charge of ~25.83e, dyality angle is a free parameter
- Another parameter – vorton scale, toroid radius a
- Called vorton

Vorton pairs as particles

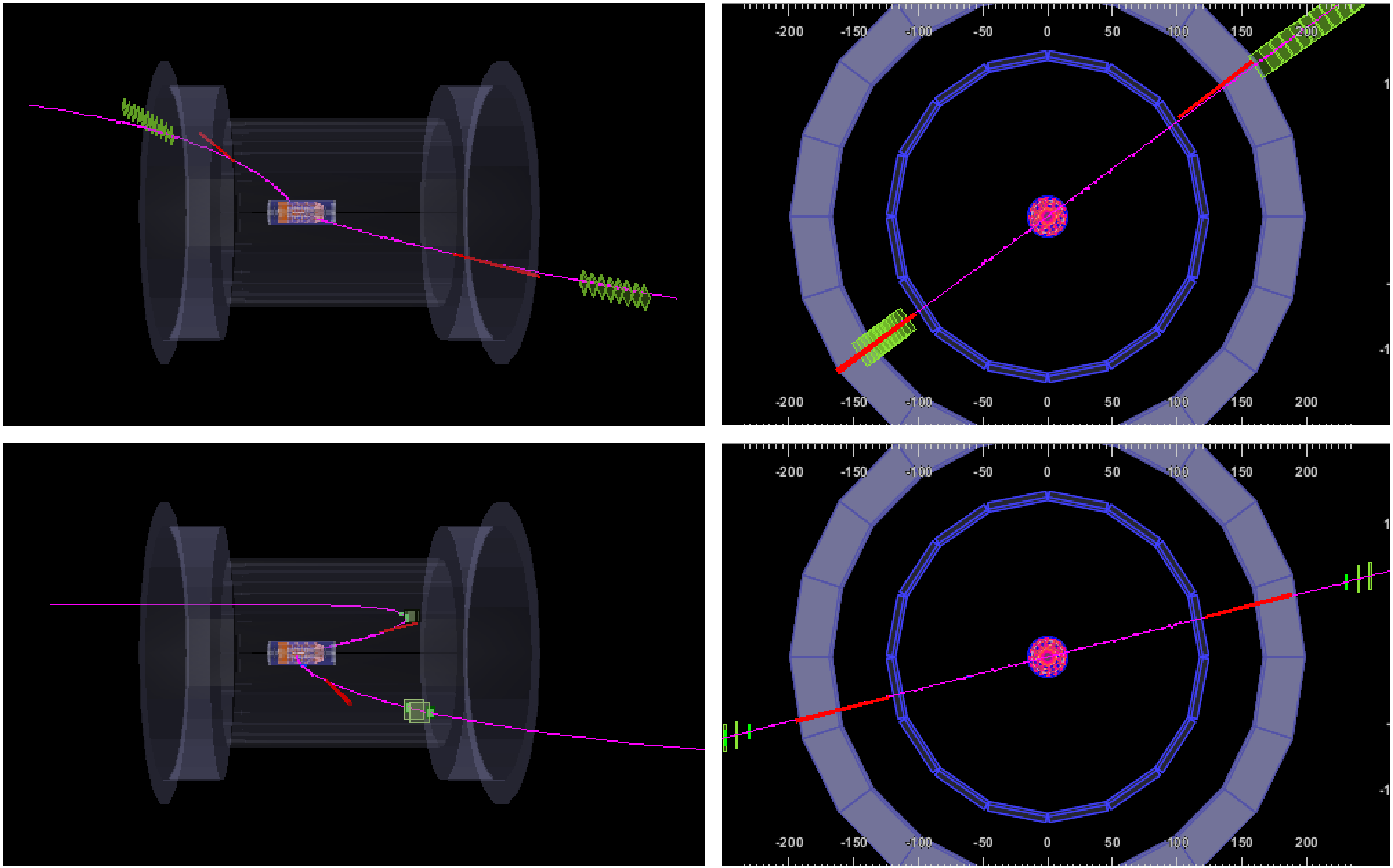


$$\frac{d\sigma_{m\bar{m}}}{d\Omega} = \frac{\alpha\alpha_m (\hbar c)^2 \beta^3}{4s}\left(1+\cos^2\theta\right)$$

- Discrete number of states
- High magnetic charge make the pair tightly bound
- Topological charge prohibits vorton annihilation
- Vorton angular momentum provides the particle spin

Magnetic counterpart of electron - magneticon

Example events, q=0, g=1e



Example events, q=1, g=1e