Looking for Magnetic Monopoles AT The Large Hadron Collider

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• Introduction

In 1884 Pierre Curie suggested that magnetic monopoles could exist

Sur la possibilité d'existence de la conductibilité magnétique et du magnétisme libre;

Par M. P. Curie.

Le parallélisme des phénomènes électriques et magnétiques nous amène naturellement à nous demander si cette analogie est plus complète. Est-il absurde de supposer qu'il existe des corps conducteurs du magnétisme, des courants magnétiques (¹), du magnétisme libre?

About the possibility of existence of magnetic conductivity and free magnetism.

by M. P. Curie

The paralelism between electric and magnetic phenomena leads to question us if this analogy is more complete. Is it absurd to assume that there exist bodies which are conductors of magnetism, of magnetic currents, of free magnetism?

Appealing because: It Restores Electric-Magnetic Symmetry in Maxwell's Equations

Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla} \cdot \vec{E} = 4\pi \rho_e$	$\vec{\nabla} \cdot \vec{E} = 4\pi \rho_e$
Gauss' law for magnetism:	$\vec{\nabla} \cdot \vec{B} = 0$	$\vec{\nabla} \cdot \vec{B} = 4\pi \rho_m$
Faraday's law of induction:	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$

Note: the Bivector notation embodies the sign swap, and these four equations can be written as only one equation.

Monopoles

Dirac 1931 : Monopole and Quantum Mechanics: Magnetic Coulomb Field:

$$\vec{B} = g\,\vec{r} / r^2$$

Conflict when defining the vector potential

$\longrightarrow$

The solution of a Genius

A particle with charge, say an electron, traveling around some path P in a region with zero magnetic field ($\mathbf{B} = 0 = \nabla \times \mathbf{A}$) must acquire a phase ϕ; given by: $\phi = \frac{e}{\hbar}\oint_p A.dr$.

The only way we would NOT see the Dirac string is if the wave function of the electron only acquired a "trivial phase" i.e. $\Delta\Phi = 2\pi N$ ($n = 1,2,3..$). That is, if:

$$\Psi \Rightarrow e^{\frac{-ie}{\hbar c}\int A.dr} = e^{\frac{-i4g\pi e}{\hbar c}} = 1 \longrightarrow ge = \left[\frac{\hbar c}{2}\right]n$$

$$\boxed{e = \left[\frac{\hbar c}{2g}\right]n}$$

Charge Quantization

Monopole Properties

- The Dirac monopole is a point like particle

- magnetic charge g = 68.5 e and no electric charge

- Monopoles accelerate along field lines according to the Equivalent Lorentz Eqn.

$$F = g\bar{B} + e\bar{p} \times \bar{B} / \gamma m_0$$

- The monopole mass is not predicted within the Dirac's theory.

Monopoles and Grand Unification

- Grand Unified gauge theories predict Monopoles: 't Hooft and Polyakov (1974) discovered that monopoles are fundamental solutions to non-Abelian gauge "GUT" theories

- These Monopoles have structure and no string singularity.

- The field of the GUT monopole is $B \sim g/r^2$ outside

- The Mass $m(GUT)_M \geq M_X/g > 10^{17}$ GeV. not producible by particle accelerators

- primordial monopoles present in the Universe

- GUT monopoles can catalyze proton decay!

There are models For "the desert" where monopoles appear in a mass range accessible to the LHC:

- The electroweak Cho-Maison monopole
- The Troost-Vinciarelli monopole
- The model of Weinberg, E. and collaborators
- Superstring models

We shall take a phenomenological approach and assume that the mass is a parameter

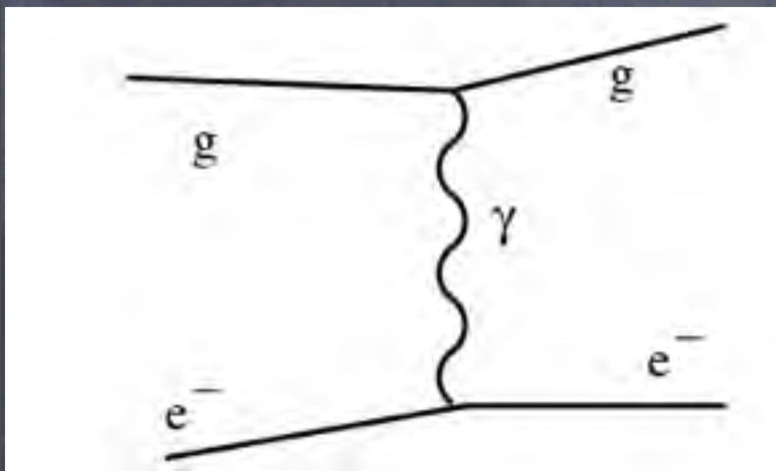
The Monopole is a wishful object

- Dirac felt that he "would be surprised if Nature had made no use of it".

- Witten once asserted in his Loeb Lecture at Harvard, "almost all theoretical physicists believe in the existence of magnetic monopoles, or at least hope that there is one."

- Polchinski described the existence of monopoles as "one of the safest bets that one can make about physics not yet seen" and that "their existence seems inevitable in any framework that explains the quantization of electric charge. Of course their mass scale and abundance are highly uncertain,... "

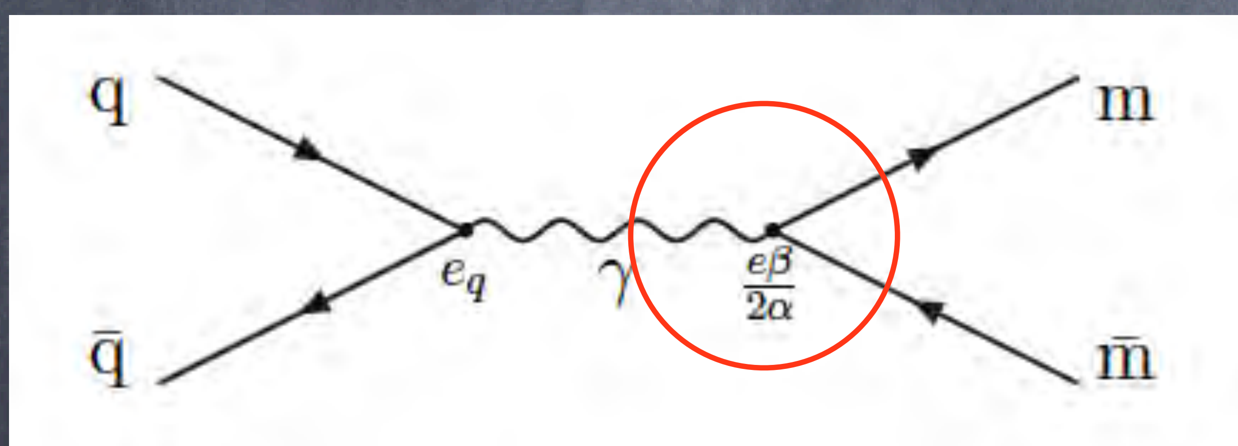
Monopole Production and Detection

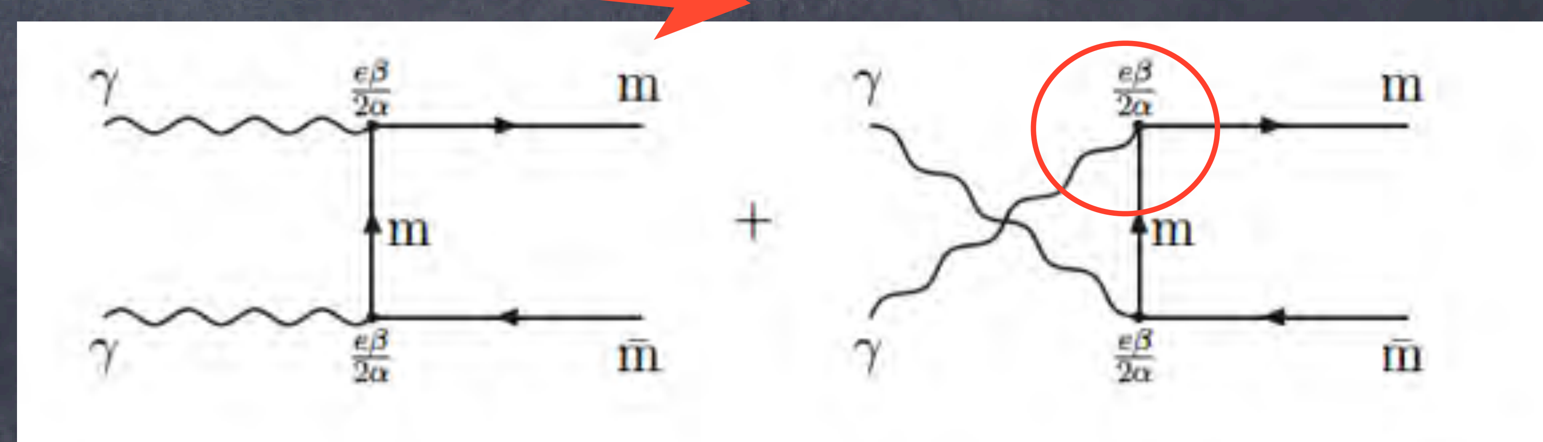


$$E_z^g = -\frac{g\beta d}{(d^2 + (\beta t)^2)^{\frac{3}{2}}}$$

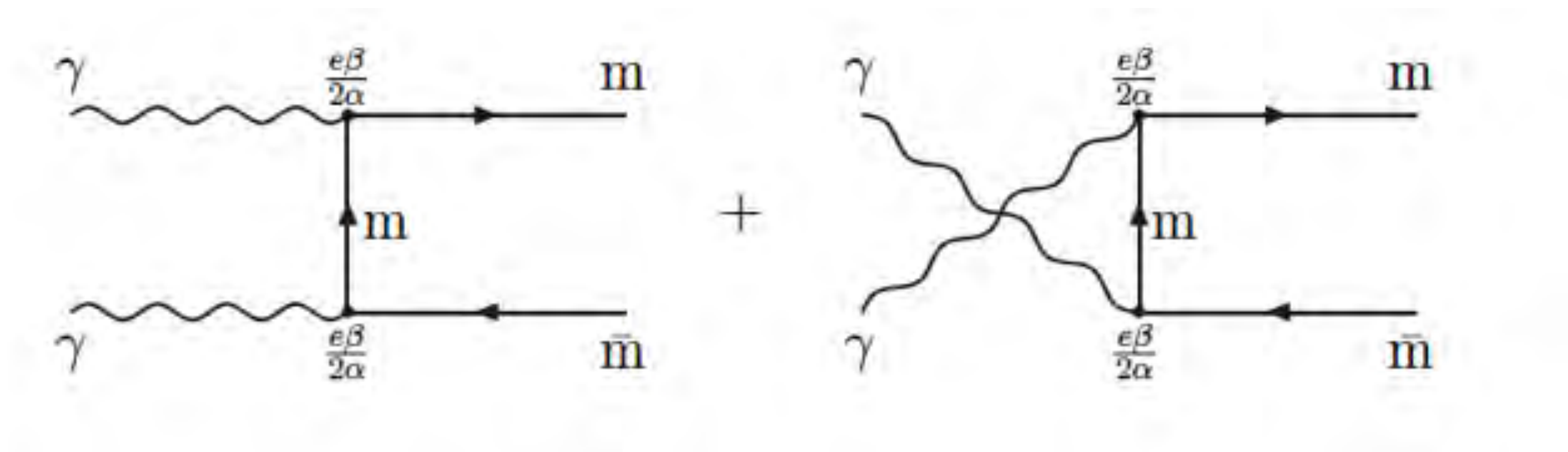
e -> β g

generalization as an s dependent form factor

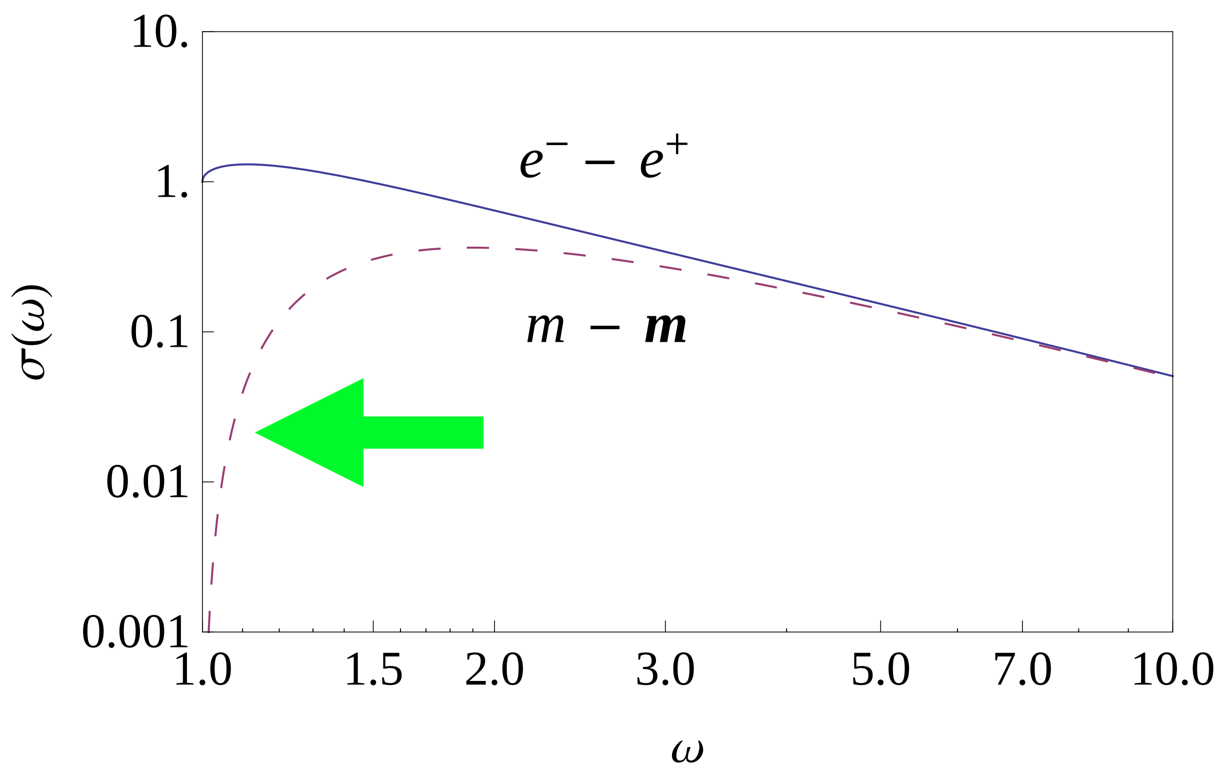




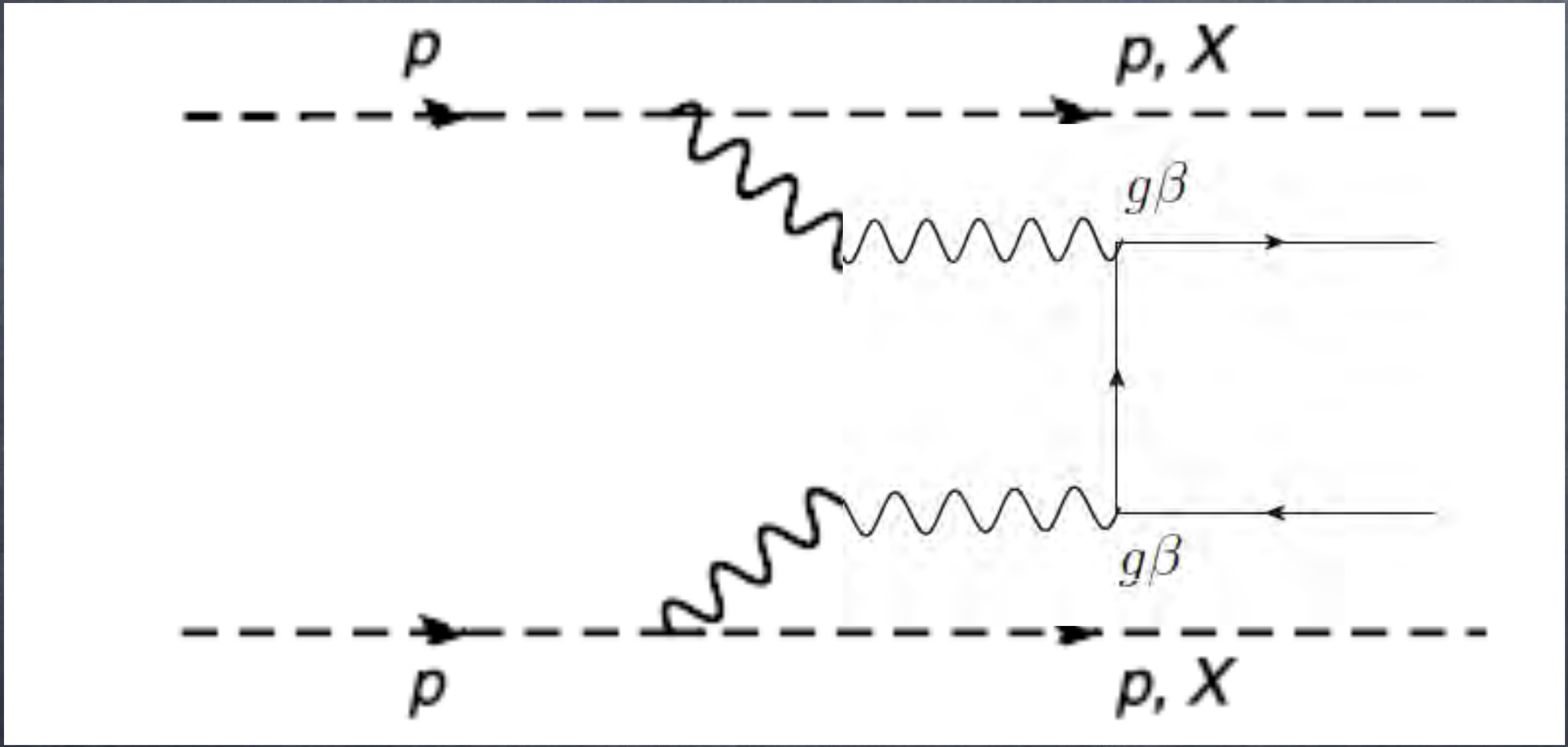
Monopole Production



$$\sigma(\gamma\,\gamma \to m\overline{m}) = \frac{\pi\; g^4\,(1-\beta^2)\,\beta^4}{2\,m^2}\left(\frac{3-\beta^4}{2\beta}\log\left(\frac{1+\beta}{1-\beta}\right) - (2-\beta^2)\right)$$



Production from photon fusion at Large Hadron Collider



i) inelastic $p + p \to X + X + m + m$

(photons radiated from partons)

ii) semielastic $p + p \to p + X + m + m$

(one photon from partons the other from the other proton leaving the proton intact)

iii) elastic $p + p \to p + p + m + m$

(both photons from protons)

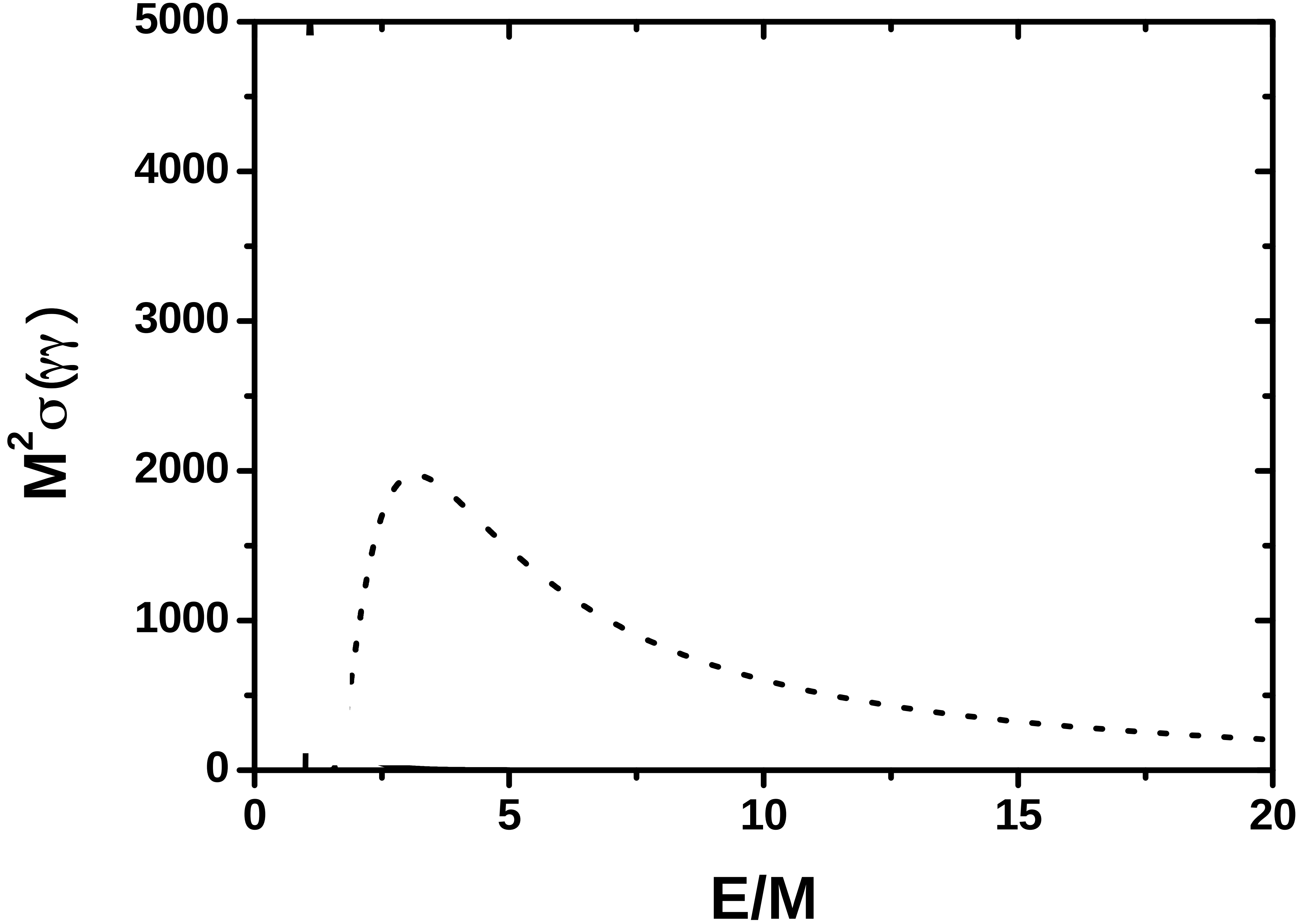
$$\sigma_{pp}^{\text{semiel}}(s)=2\int_{4m^2/s}^{1}dx_1\int_{4m^2/sx_1}^{1}dz_1\int_{4m^2/sx_1z_1}^{1}dz_2\,\frac{1}{x_1}$$

$$F_2^p(x_1,Q^2)f_\gamma(z_1)f_{\gamma/p}^{\text{el}}(z_2)\hat{\sigma}_{\gamma\gamma}(x_1z_1z_2s)$$

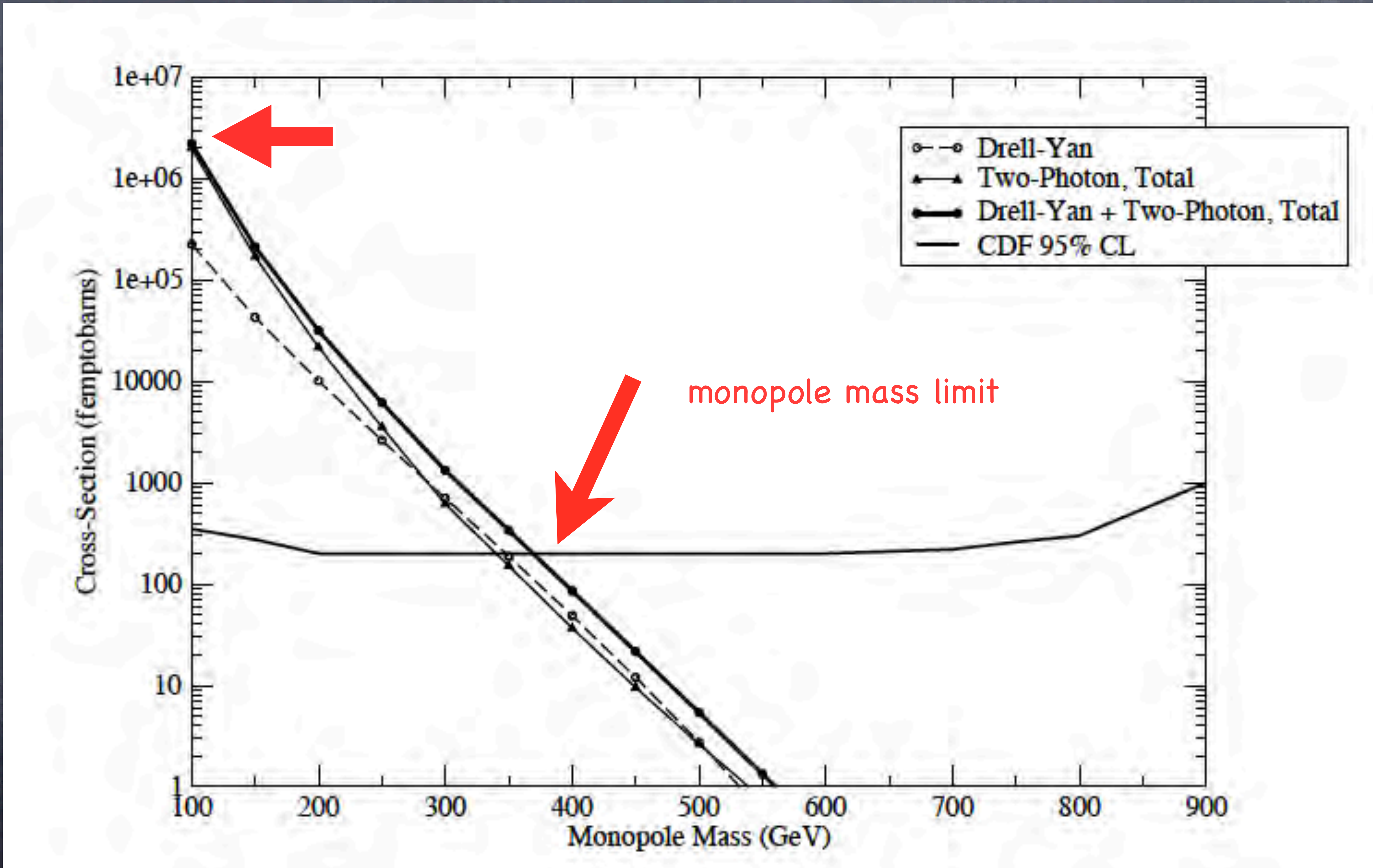
F_2^p is the deep inelastic proton structure function.

f_γ is the photon spectrum inside a quark

$f_{\gamma/p}^{\text{el}}$ elastic photon spectrum

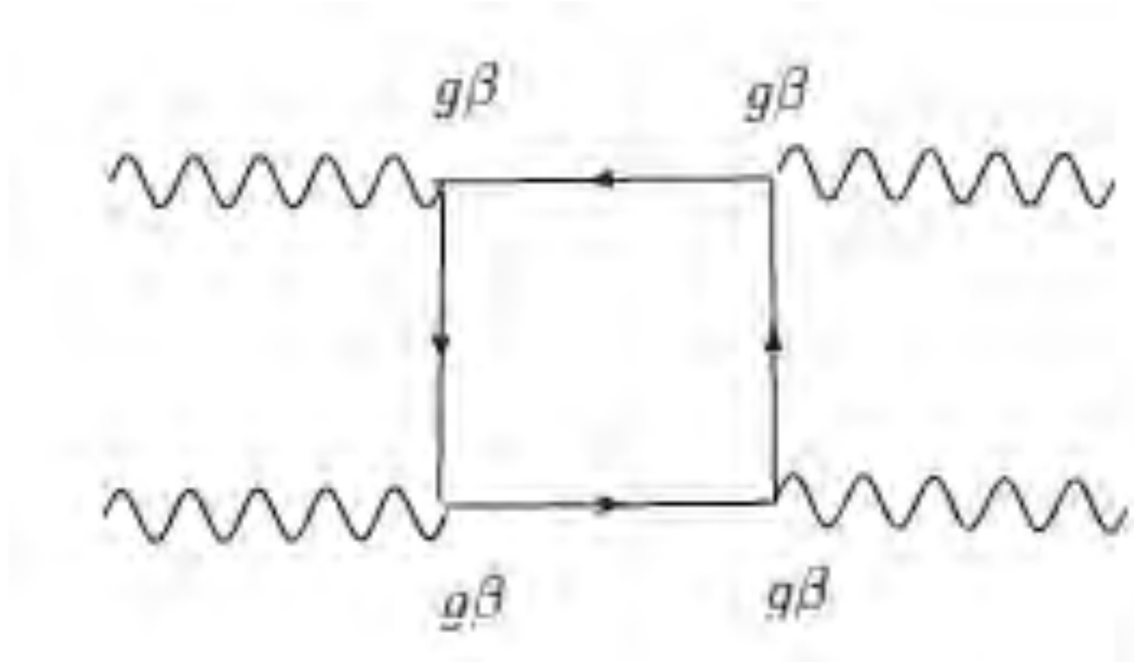


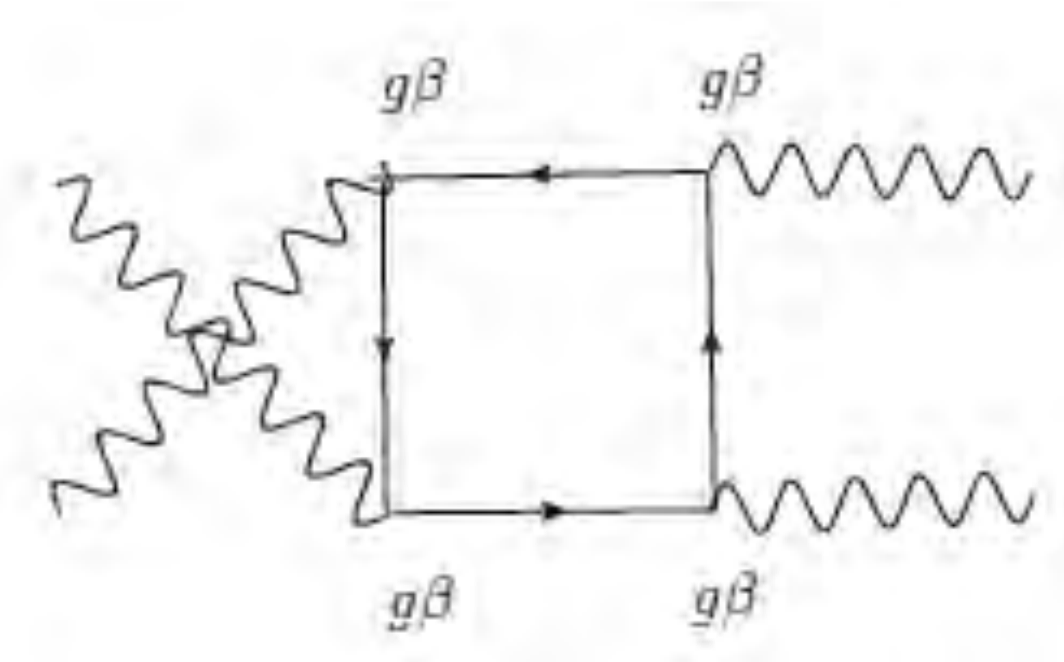
5000
4000
3000
2000
1000
0
0
5
10
15
20
$M^2\sigma(\gamma\gamma)$
E/M

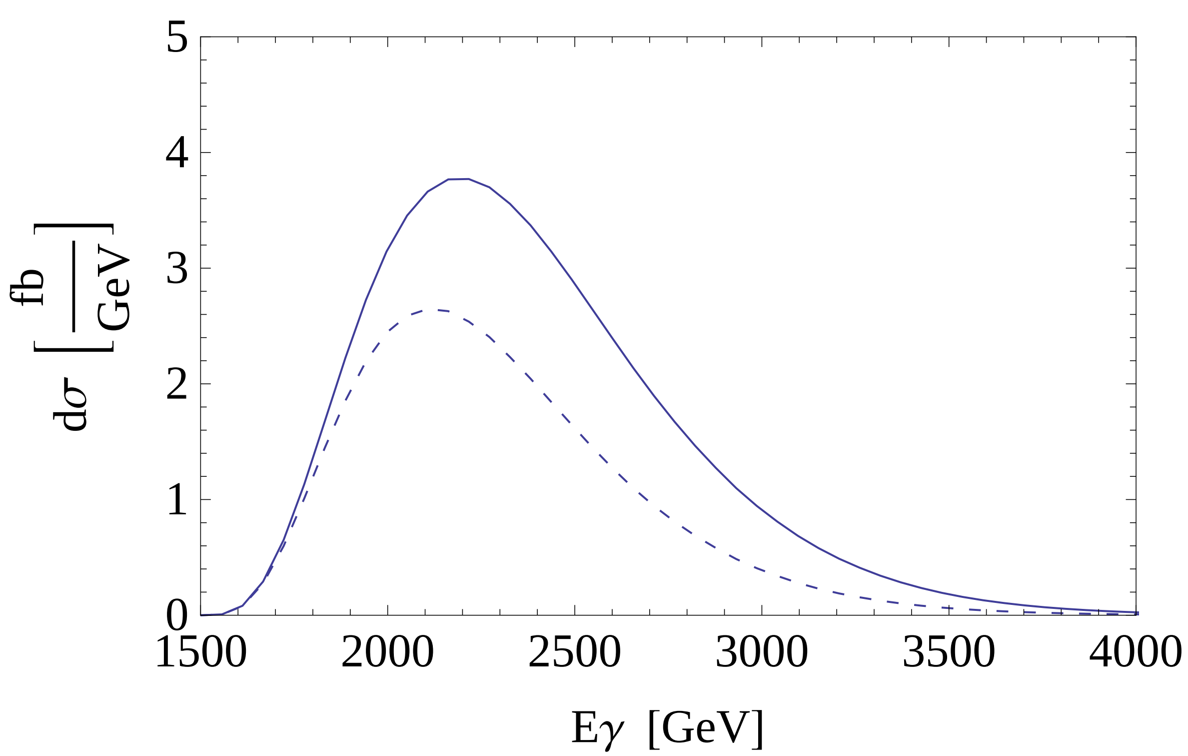


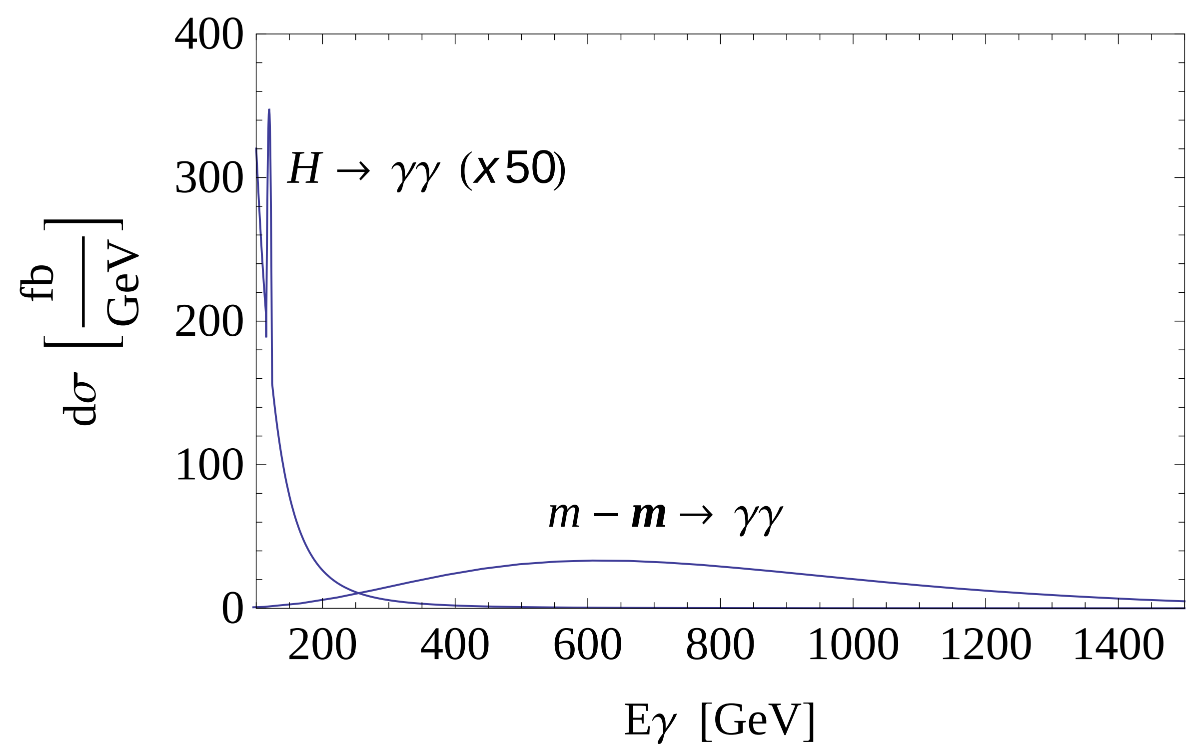
1e+07
1e+06
1e+05
10000
1000
100
10
1
100
200
300
400
500
600
700
800
900
Cross-Section (femptobarns)
Monopole Mass (GeV)
Drell-Yan
Two-Photon, Total
Drell-Yan + Two-Photon, Total
CDF 95% CL
monopole mass limit

Monopole Detection









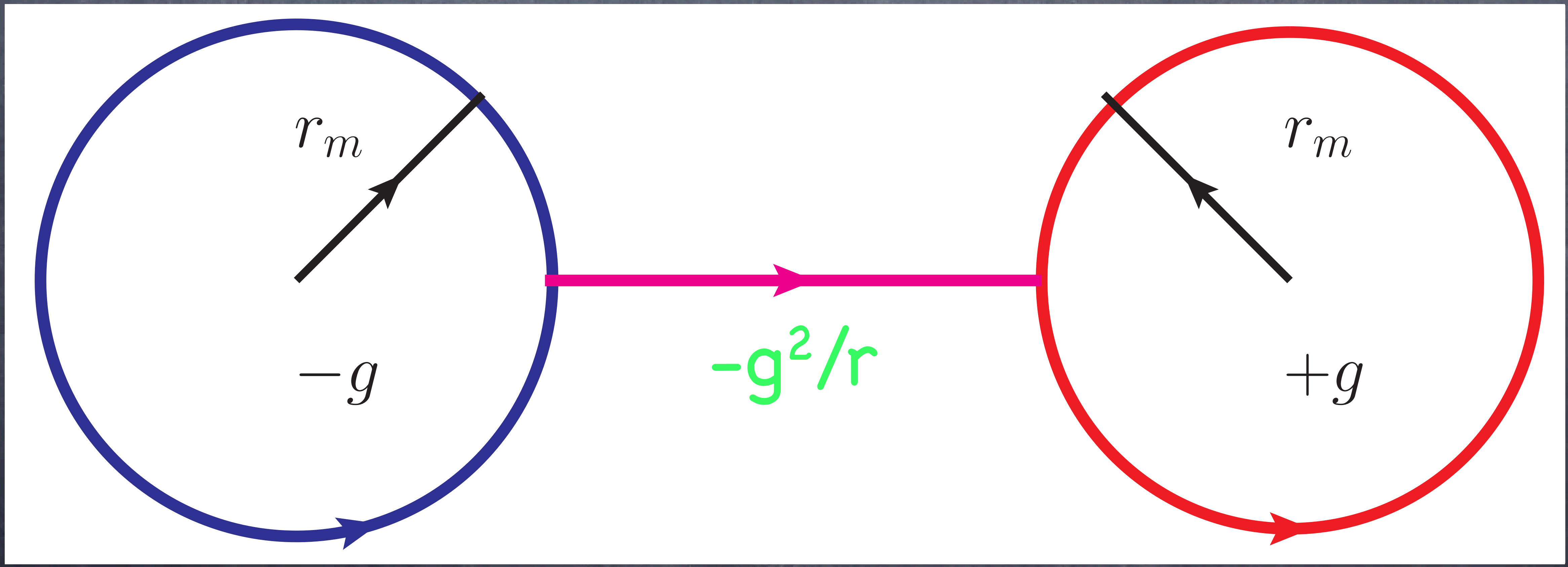
Dirac (1934)

"...The attractive force between two magnetic poles is 4692 1/4 time that between the electron and the proton. This very large force may perhaps account for why the monopoles have never been separated..."

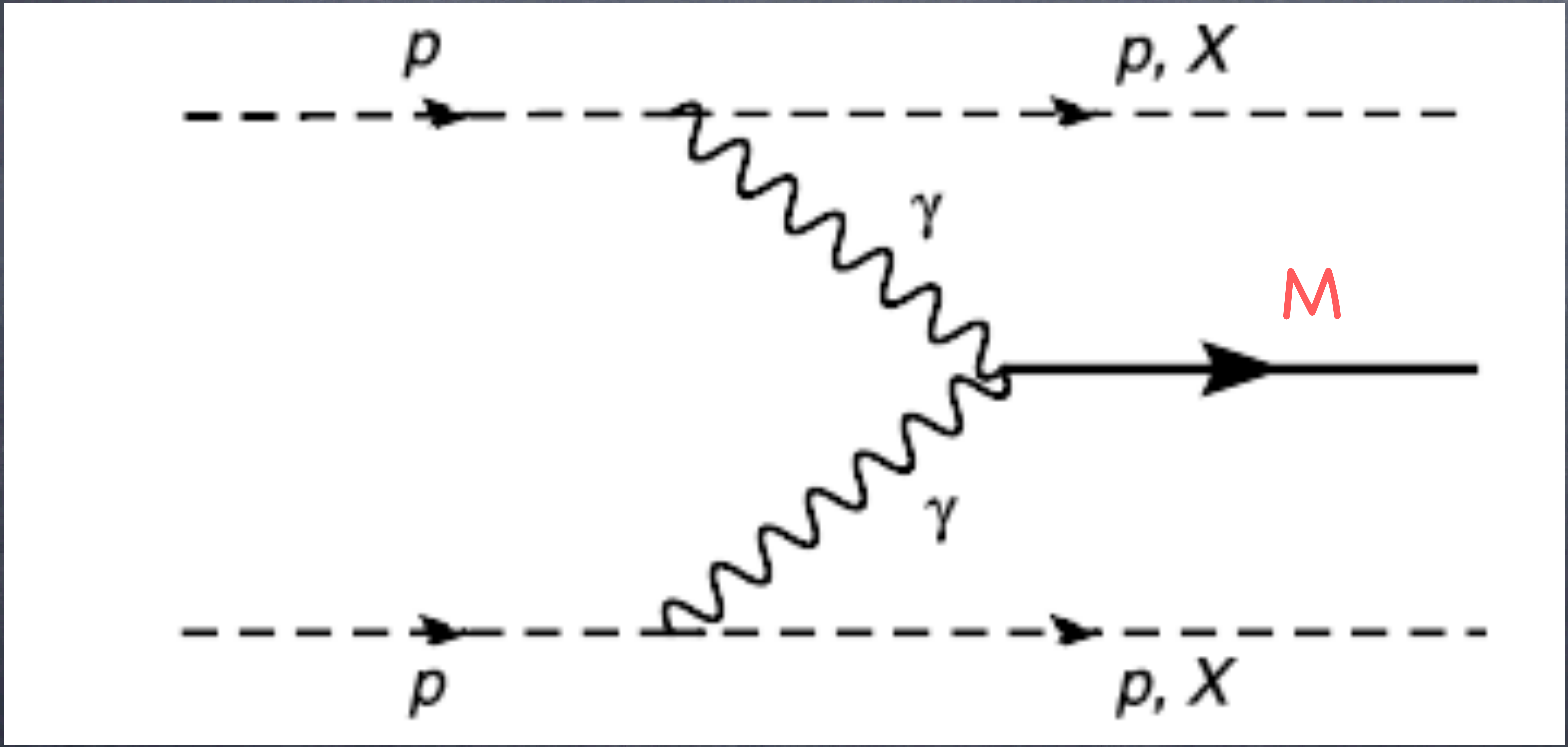
- Monopolium -

Monopolium production

Monopolium is a monopole - antimonopole boundstate



Monopolium production from photon fusion at Large Hadron Collider



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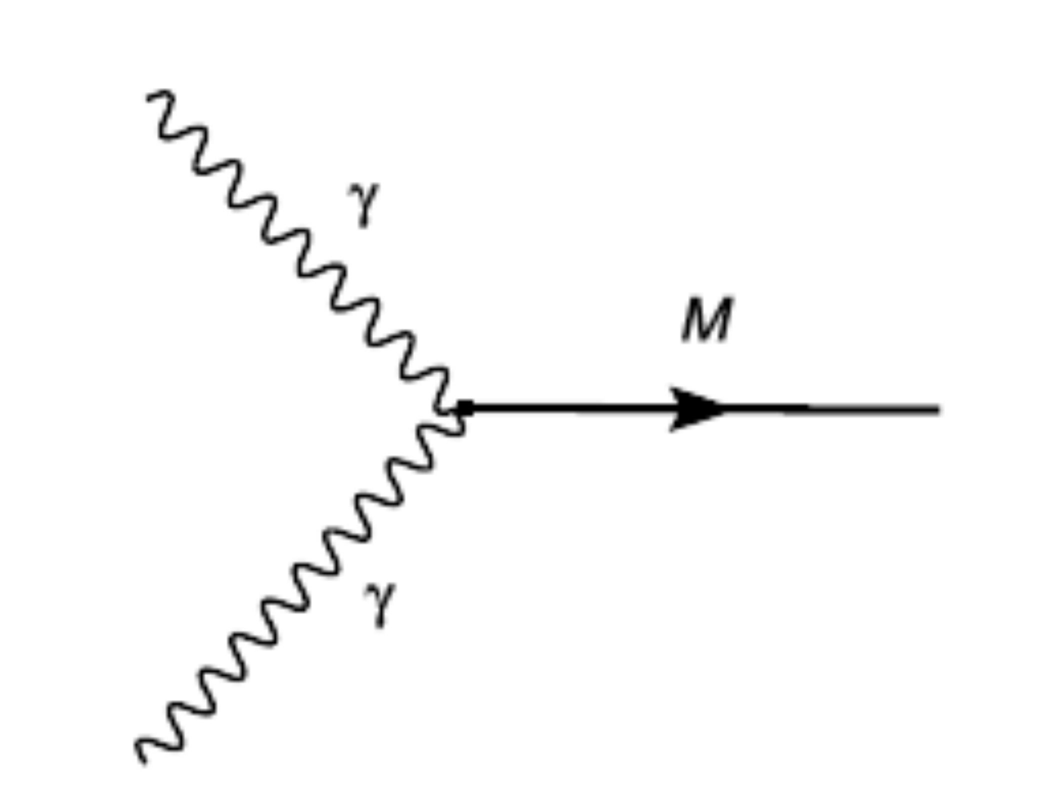
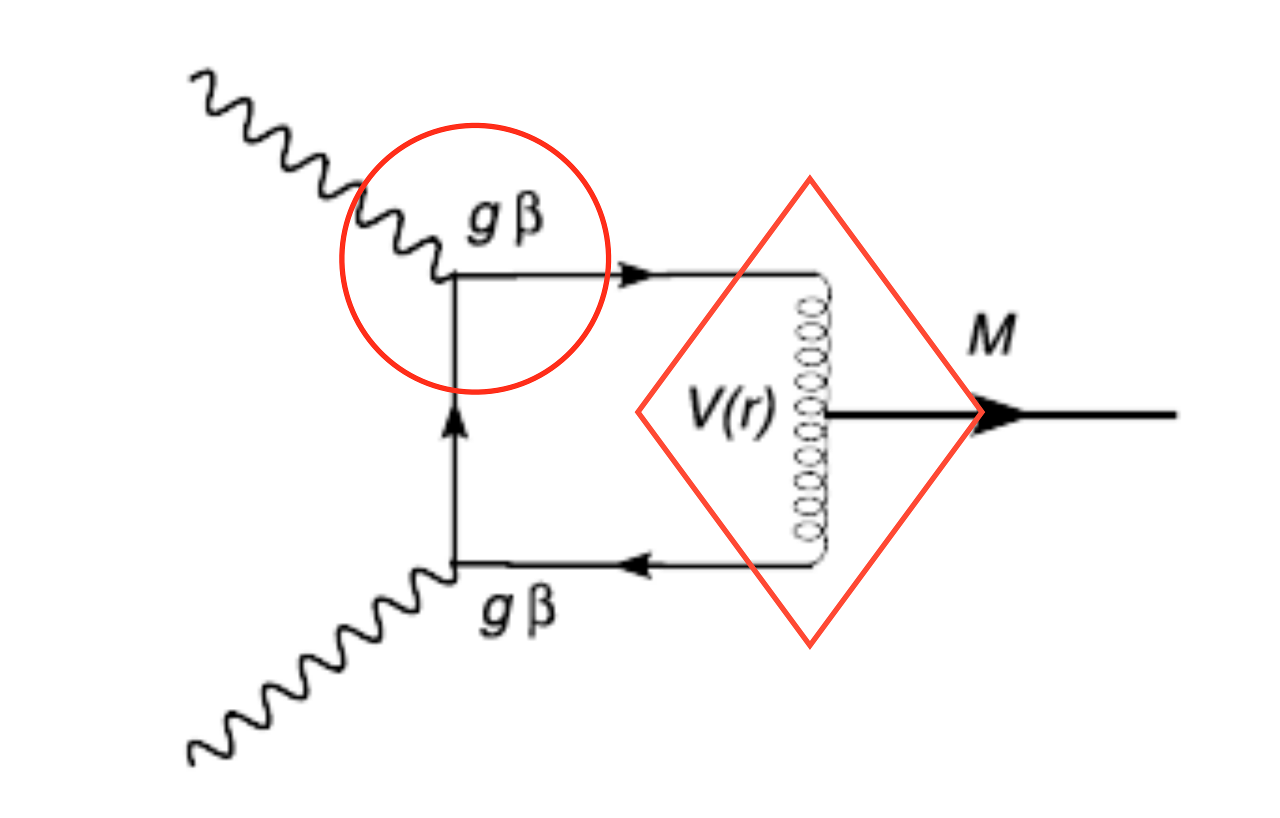
Monopolium photon coupling



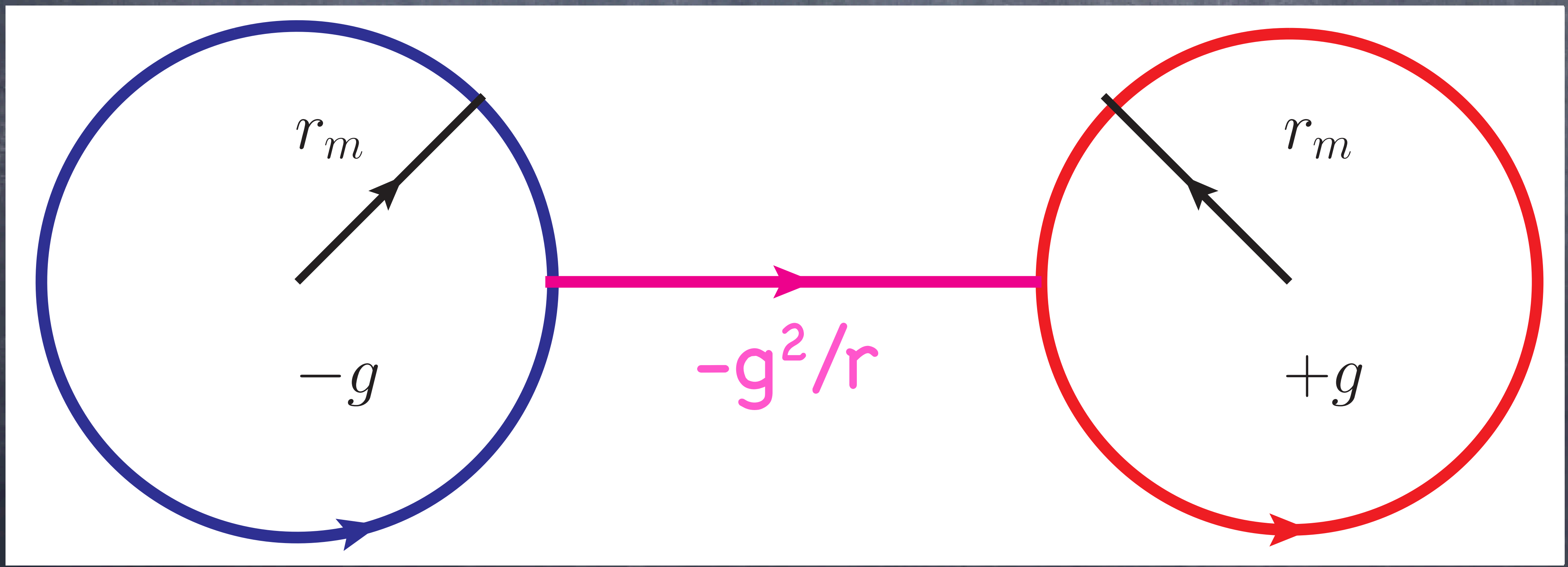
$$\sigma(2\gamma \to M) = \frac{4\pi}{E^2} \frac{M^2 \Gamma(E) \Gamma_M}{(E^2 - M^2)^2 + M^2 \Gamma_M^2}$$

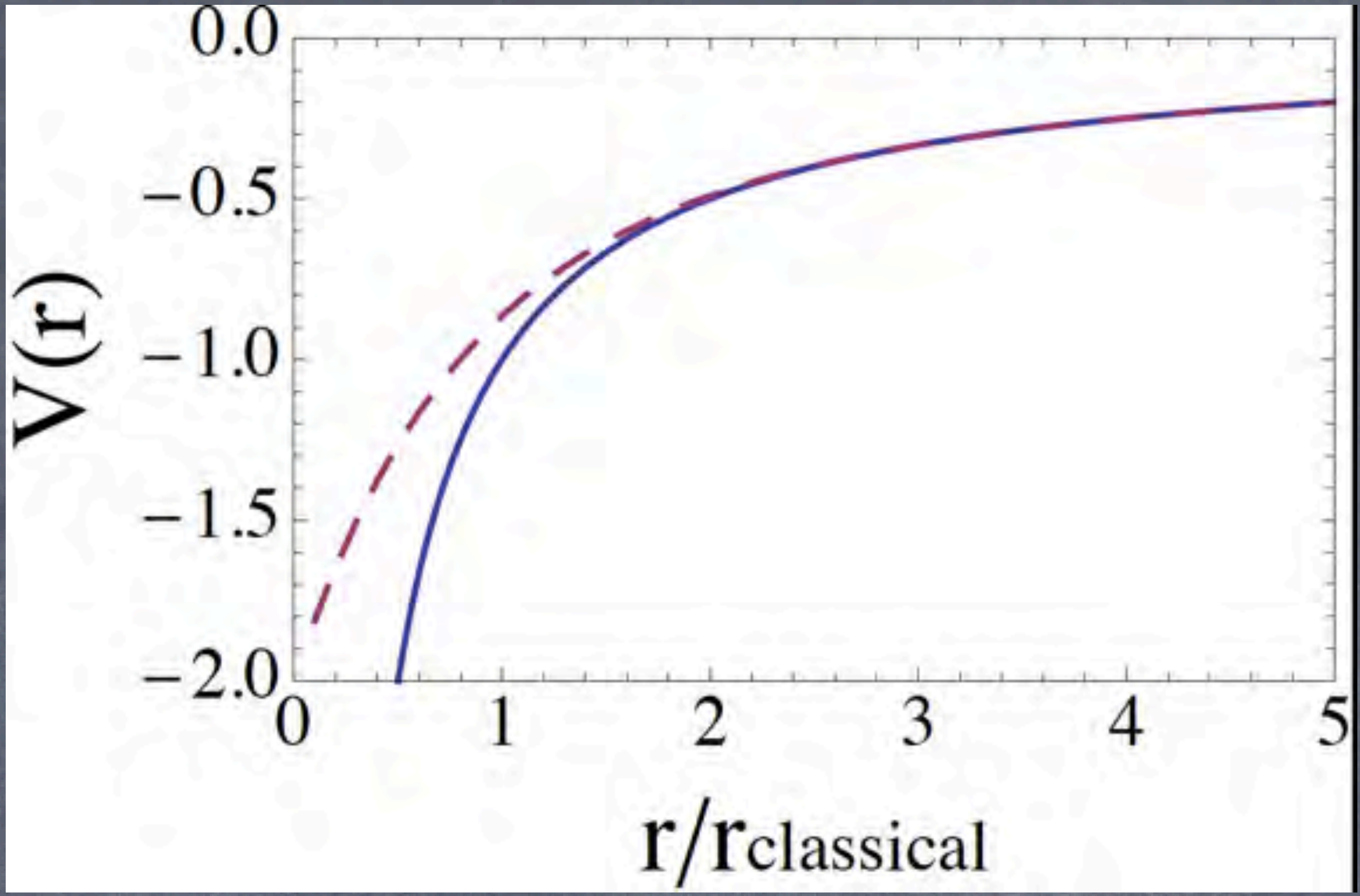
$$\Gamma(E) = \frac{32\pi\alpha_g^2}{M^2} \left|\psi_M(0)\right|^2$$



Monopolium wave function

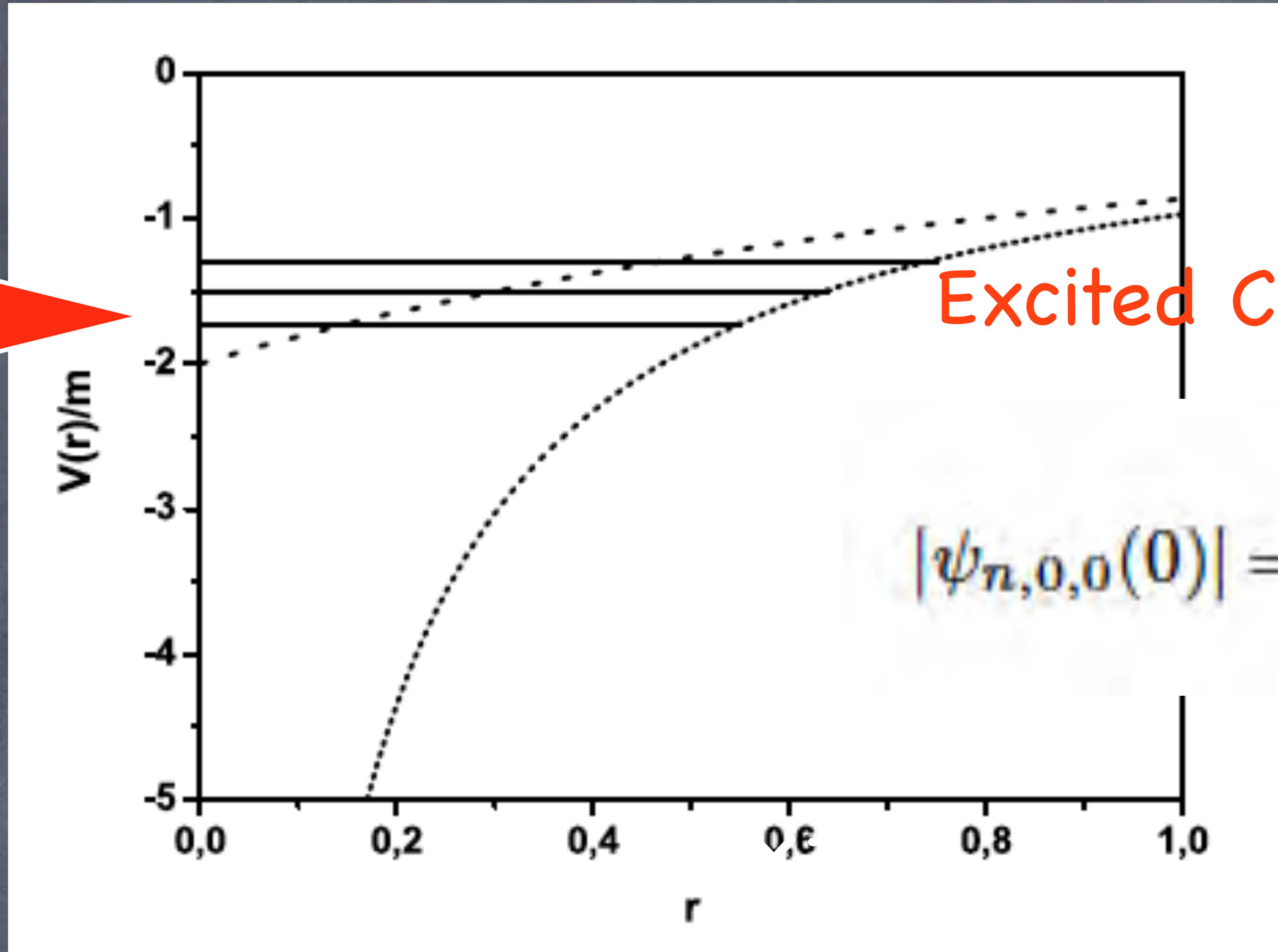
- The monopole can be regarded as possessing some spatial extension that avoids the singularity at the origin.





We have represented this complex scenario by a potential which behaves like a magnetic Coulomb for $r \gg 2\, r_{classical}$ and is finite at the origin.

$$V(r) = -g^2 \frac{1 - \exp\left(-2\frac{r}{r_{\text{classical}}}\right)}{r}$$



Excited Coulomb states

$$|\psi_{n,0,0}(0)| = \frac{1}{\sqrt{\pi}}\left(\frac{\sqrt{3}m}{2\sqrt{\rho}}\right)^{3/2}$$

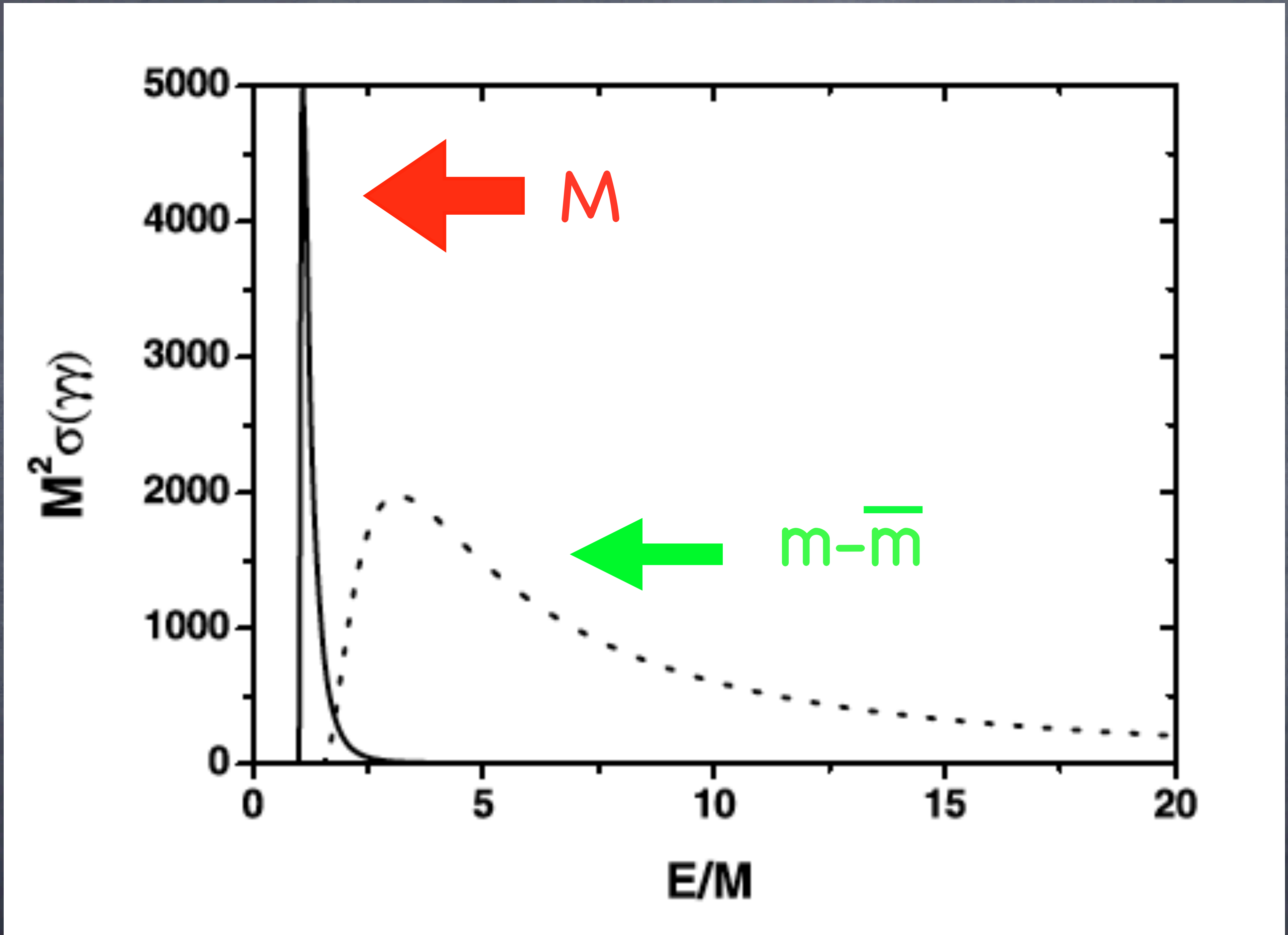
$$M = 2m - \left(\frac{1}{8\alpha}\right)^2 \frac{m}{n^2} > 0,$$

n > 13 well defined

$$\rho = \frac{r_{\mathrm{M}}}{r_{\mathrm{classical}}} = 48\alpha^2 n^2$$

$$M = m\left(2 - \frac{3}{4\rho}\right)$$

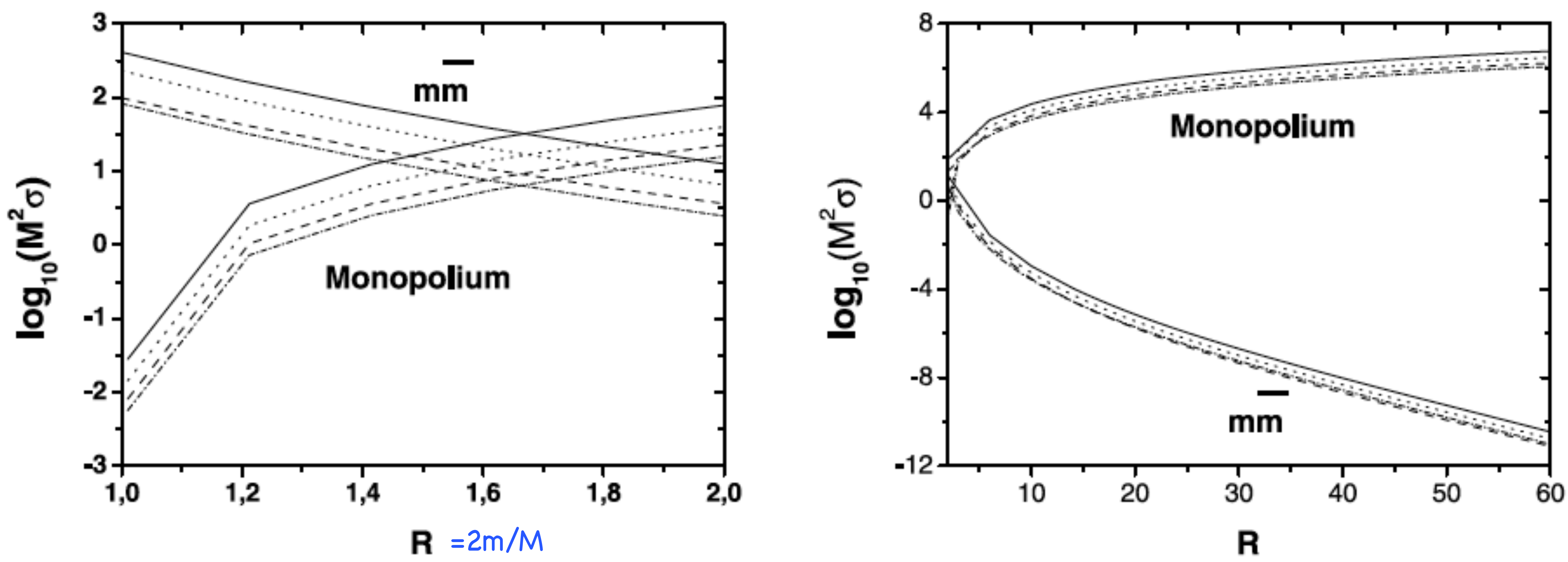
Two parameters : M , m



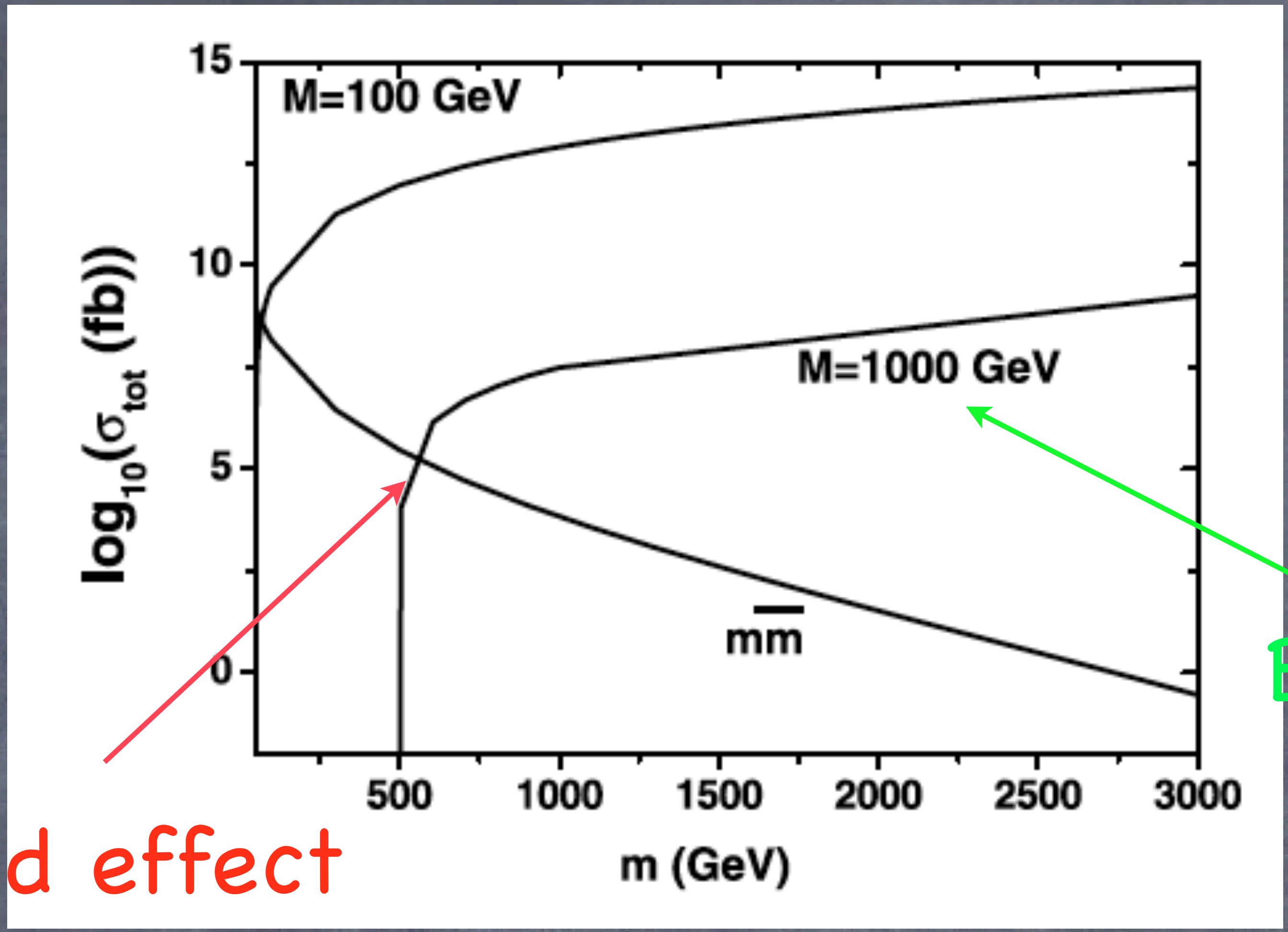
M
m-m̄
$M^2\sigma(\gamma\gamma)$
E/M
0
1000
2000
3000
4000
5000
5
10
15
20

Small Binding

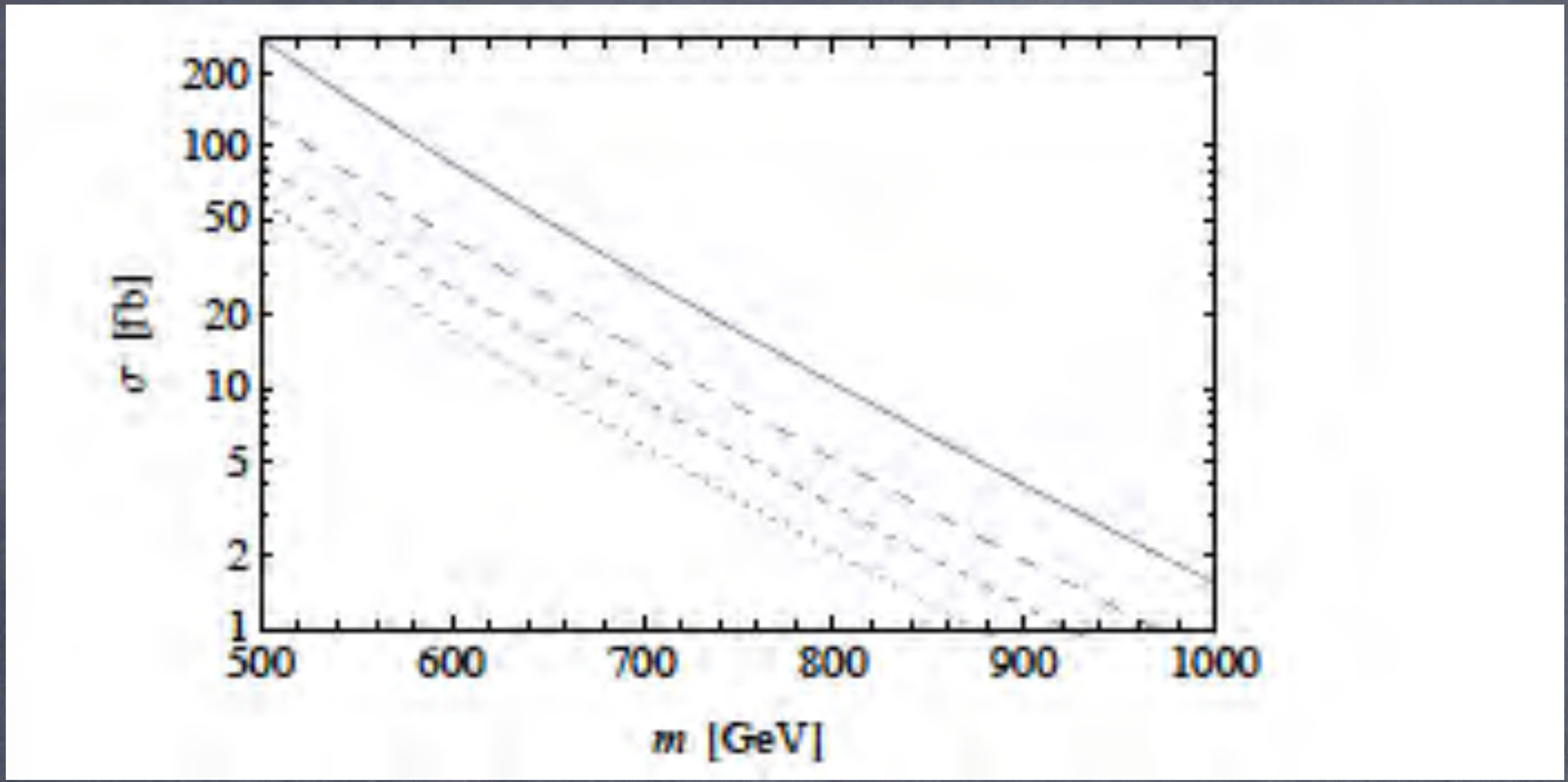
Large Binding



Lower mass threshold M < 2m

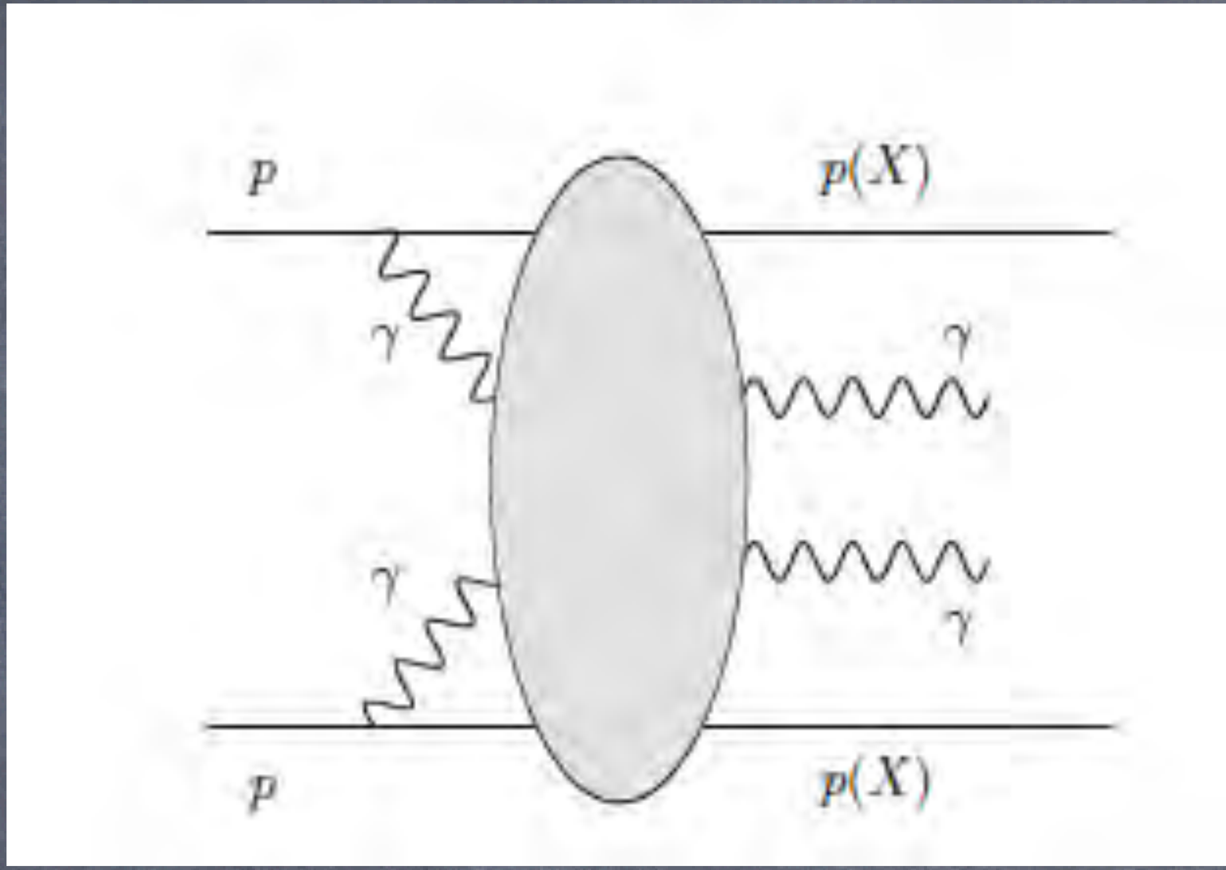


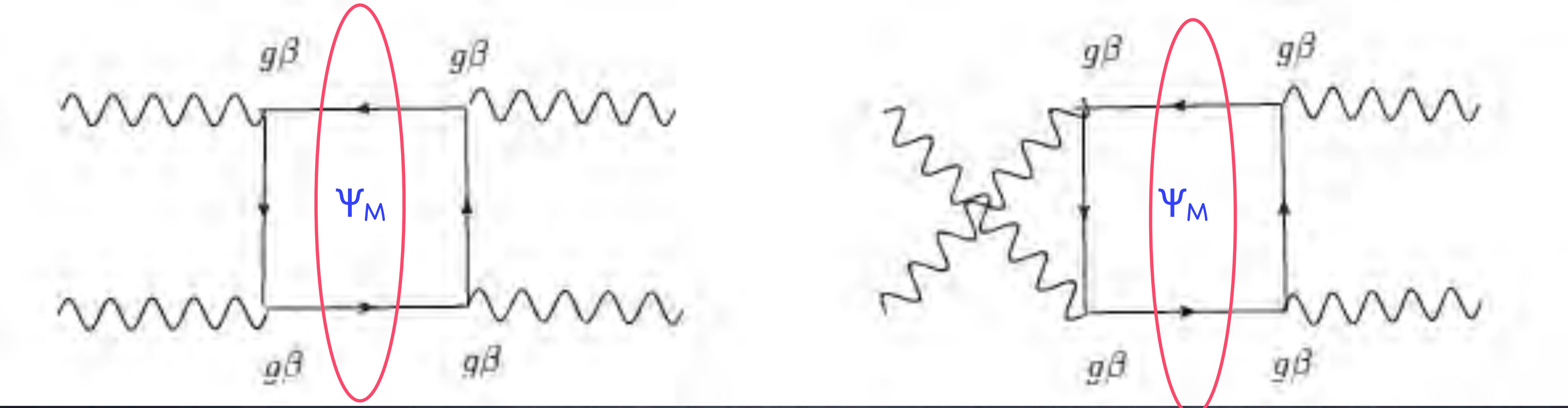
Example: for m = 1 TeV and M= 1 TeV at LHC for 100 fb^{-1} 10^6 monopoles and 10^8 monopolia.

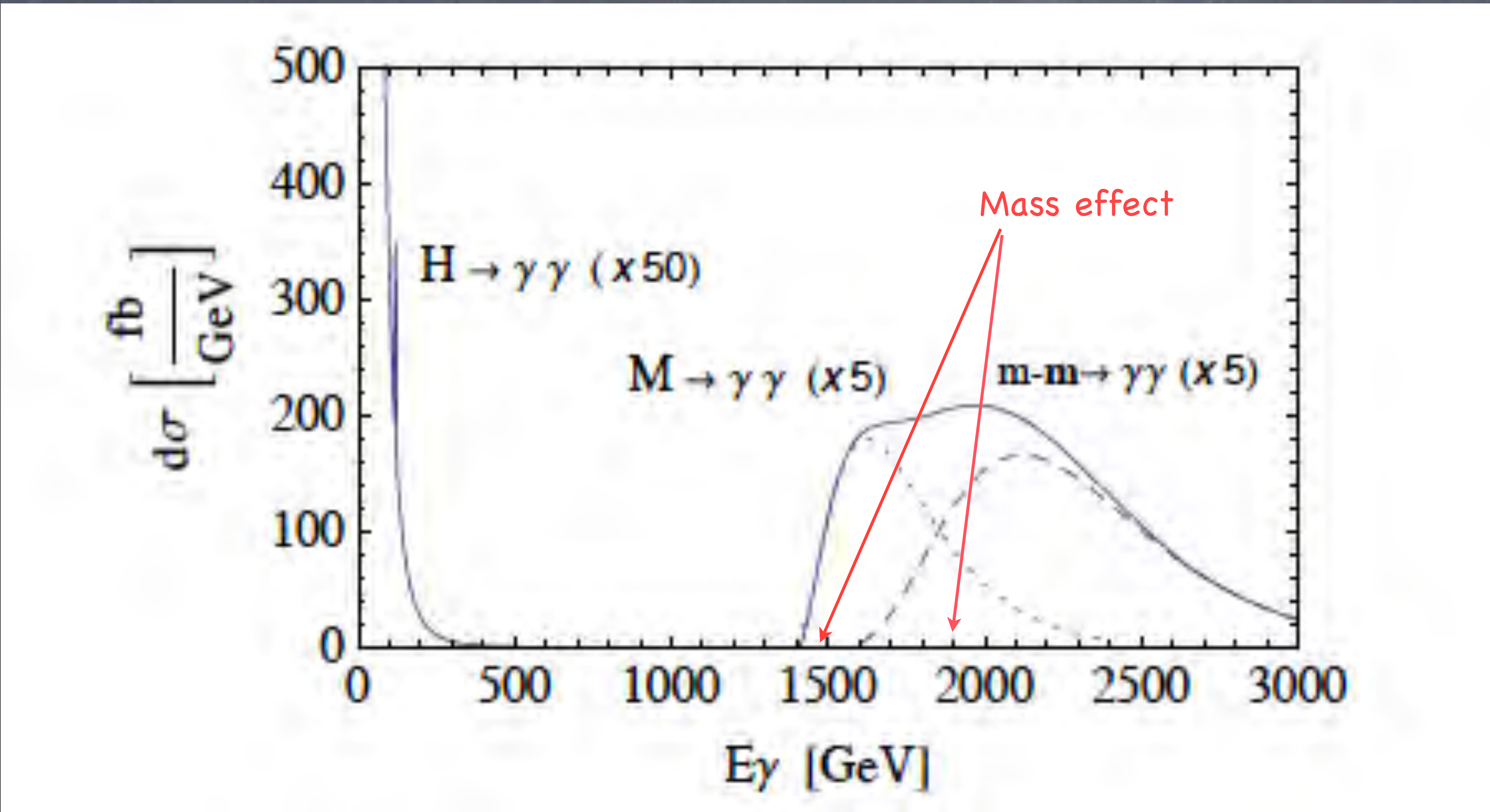


Total cross section for monopolium production at LHC with 3.5 TeV beams and monopole masses ranging from 500 to 1000 GeV, with binding energies 2 m/15 and widths 10 GeV.

Monopolium detection at LHC with diphoton events

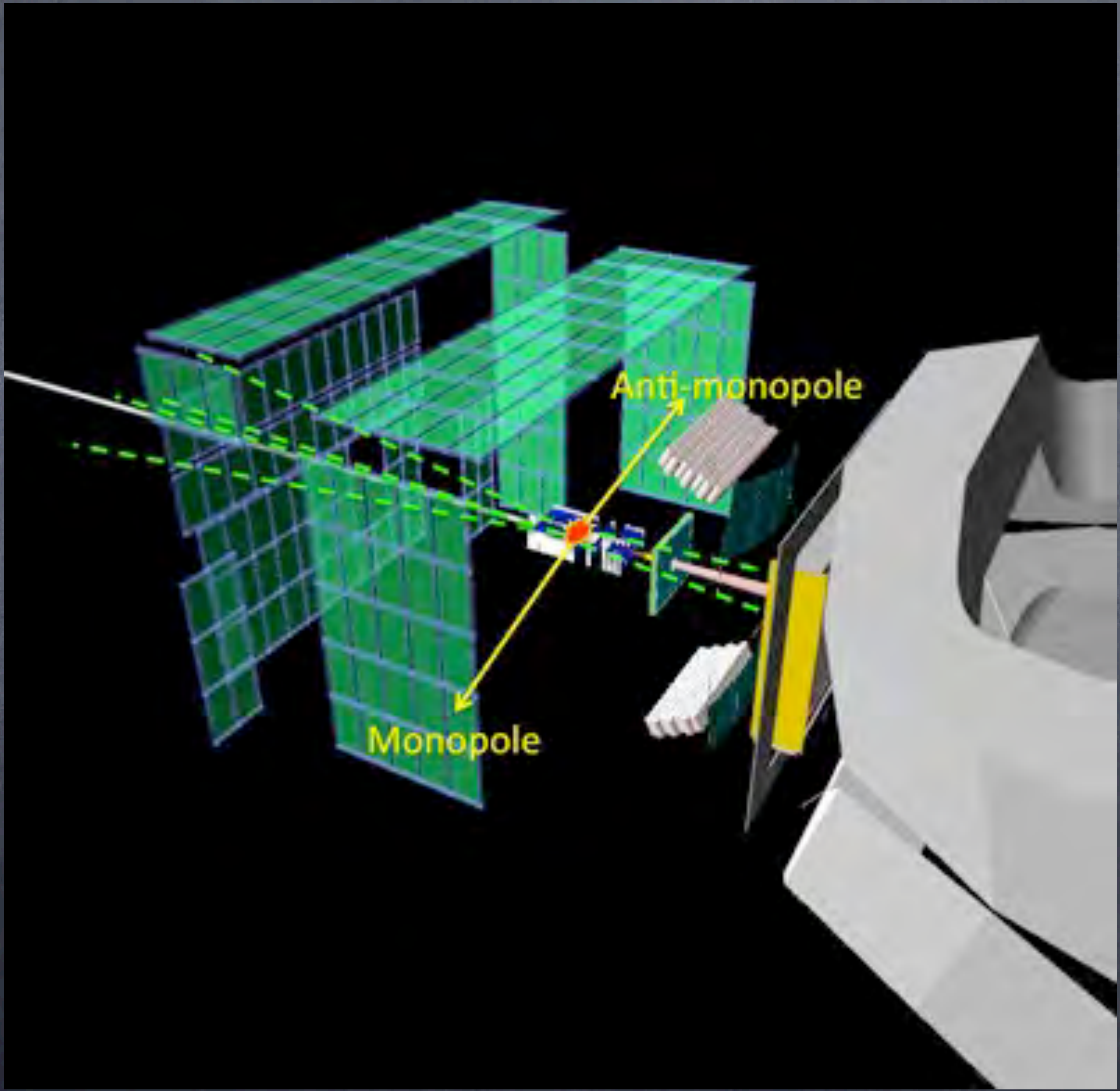


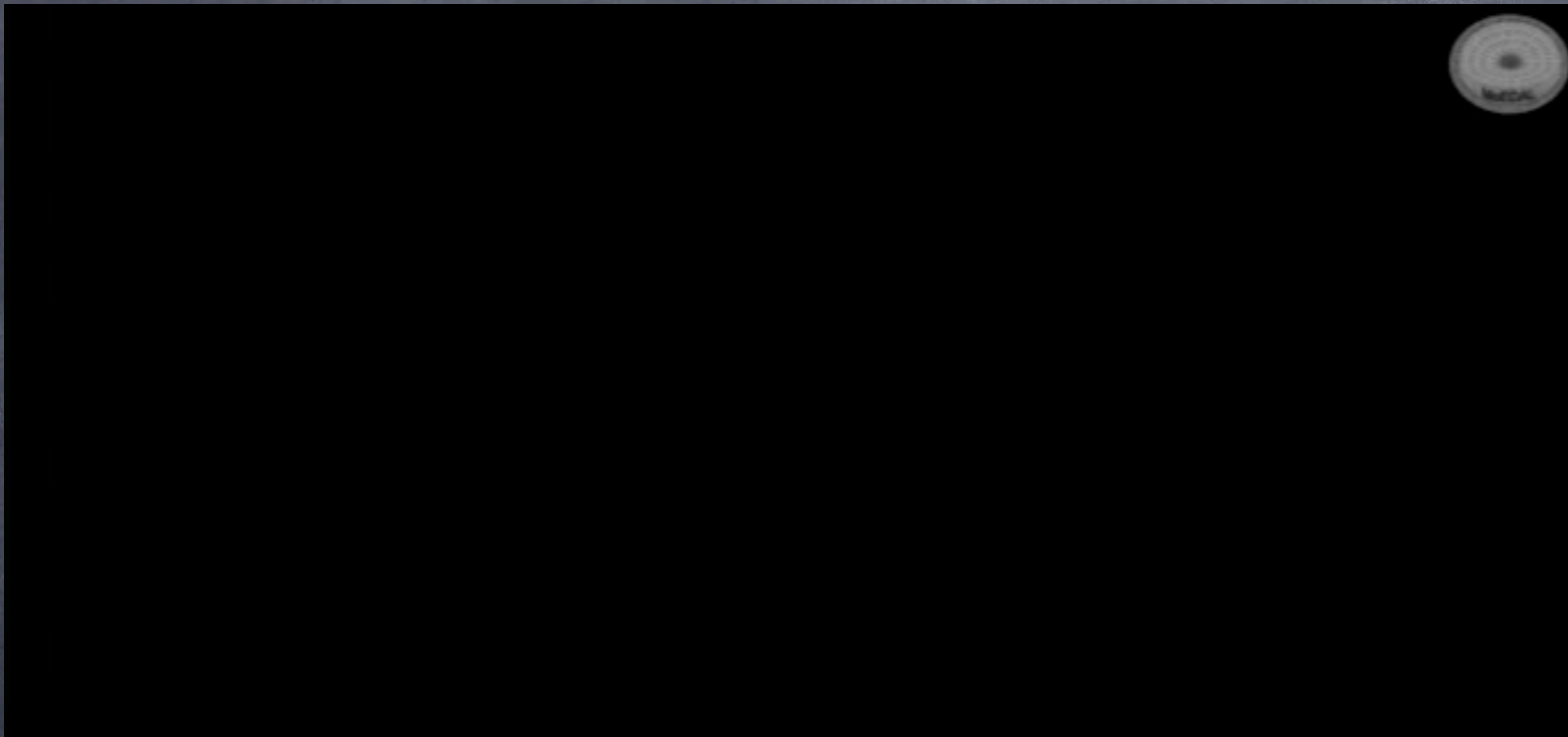




m= 750 GeV   M= 1400 GeV Γ_M = 10 GeV

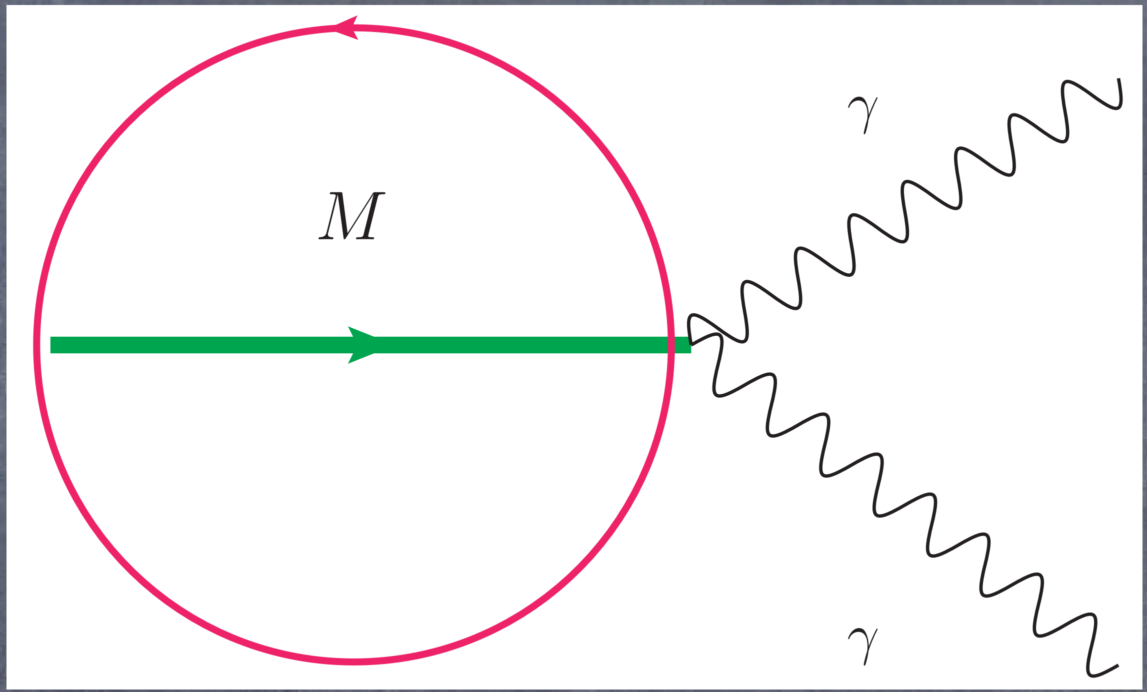
Moedal





Some toughts for monopolium detection

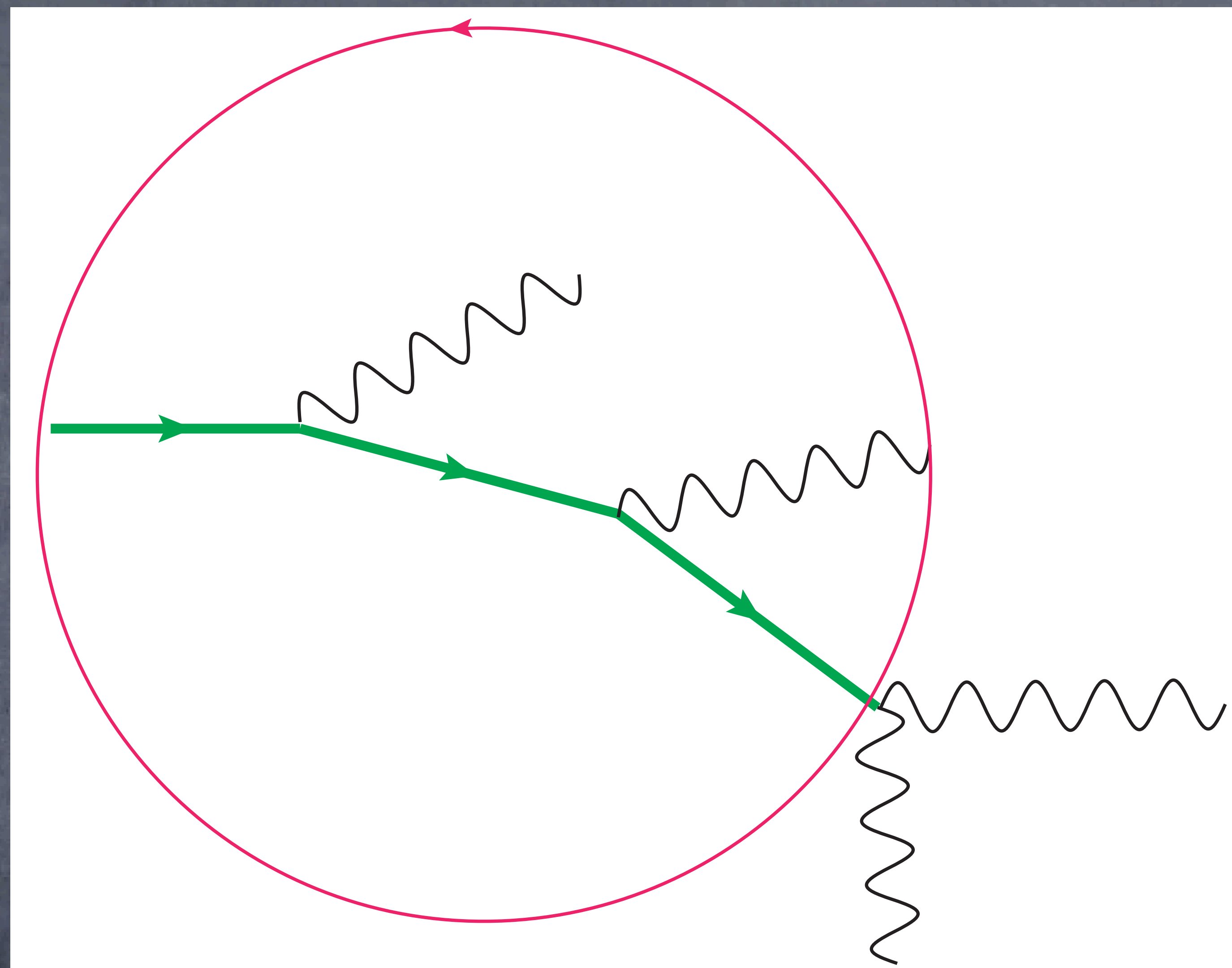
i) near threshold (grounstate -> l= 0)



- β small -> elastic multiparticle collisions
- In presence of magnetic fields huge polarizability

  $d \sim r_M^3\ B \sim (\alpha\ E_{binding})^{-3}\ B$

ii) boundstate -> excited states -> l > 0

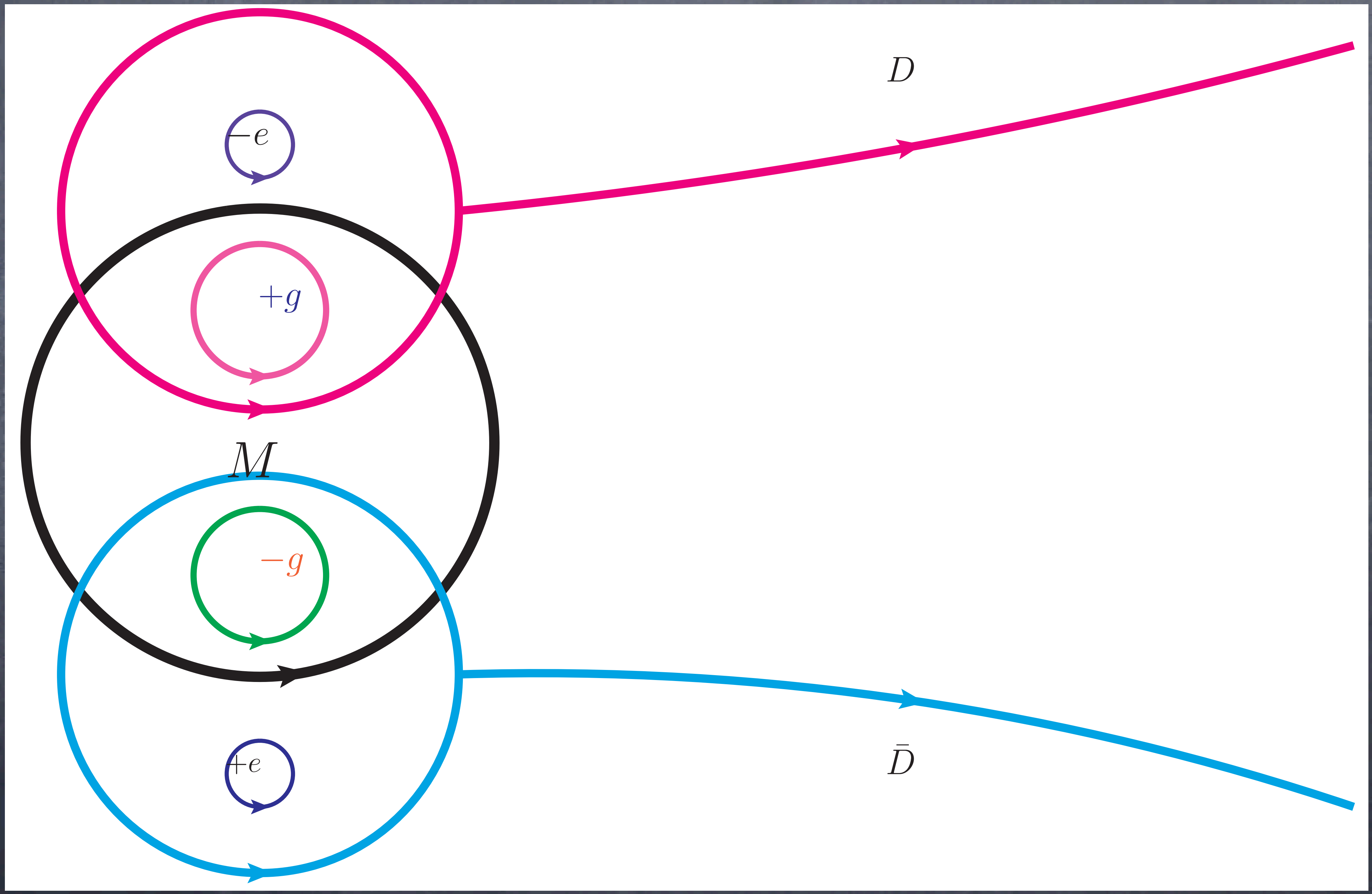


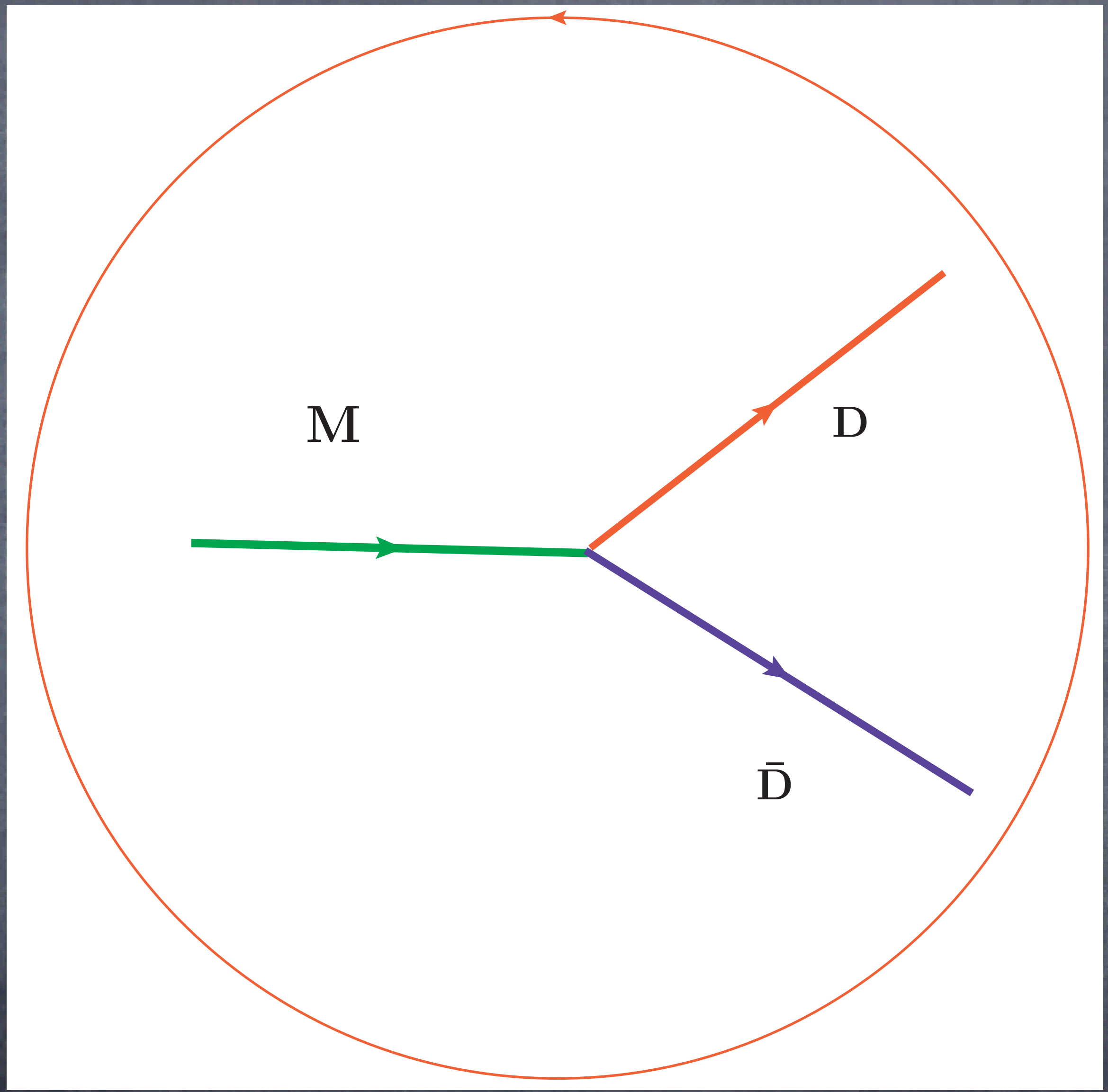
multipoles

-> bending (photon emission)

-> excitation and ionization

iii) Monopolium (weak binding and/or excited states) -> (capturing electrons or protons) -> Dions




M
D
D̄

Concluding remarks

- We have shown that if non relic monopoles exist and their masses are in the TeV region they are soon to be found either as

  m - m pairs or monopolium

  much effort is going to go both in the more traditional schemes, Atlas and CMS, but also in a dedicated experiment Moedal.

- Magnetic monopoles can be detected by their high ionization, their binding to conventional particles and nuclei, diphoton events, ...

- Monopolium groud state is a very heavy neutral object
    - -> good diphoton signal (Z_0, $W^{\pm}$, ...)
    - -> large magnetic polarizability (in the presence of large B-fields)
    - -> naively : difficult object for Moedal (?? elastic collisions)
- Monopolium excitations
    - -> multiphoton processes (pseudo-polynomial trajectories)
    - -> excitation and ionization (multipole interactions)
- Dion formation
    - -> good Moedal candidates

Thank you for your attention!