Monopole production via photon fusion at the LHC

Vasiliki A. Mitsou

In collaboration with
Stephanie Baines, Nick E. Mavromatos,
James L. Pinfold and Arka Santra

Based on arXiv:1808.08942 [hep-ph]

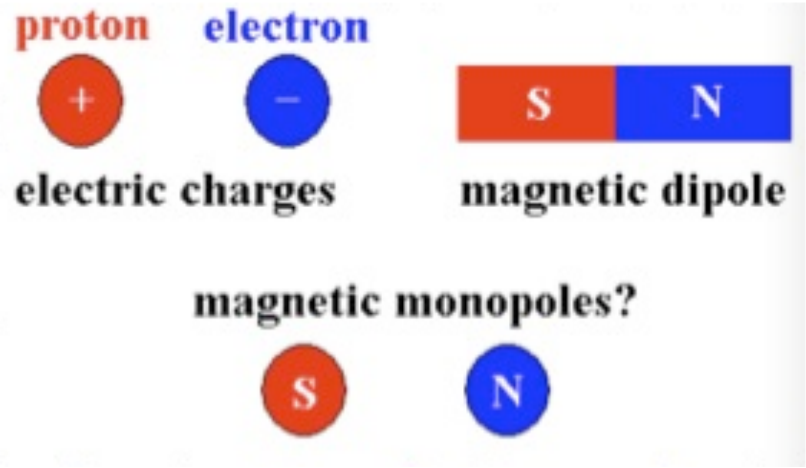
18th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Workshop on the Standard Model and Beyond

August 31 – September 9, 2018, Corfu, Greece

Outline

- Introduction to magnetic monopoles
- Cross-section calculations for colliders
  - **photon fusion** and Drell-Yan processes
  - novel features
    - boost-dependent photon-monopole coupling
    - magnetic-monopole parameter κ
- MadGraph implementation
  - UFO models
- Phenomenology at the LHC
  - kinematic distributions
- Conclusions & outlook



Magnetic monopoles: symmetrising Maxwell

- As no magnetic monopole had ever been seen Maxwell cut isolated magnetic charges from his equations – making them *asymmetric*
- A magnetic monopole restores the symmetry to 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):	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$

- Symmetrised Maxwell's equations invariant under rotations in (E, B) plane of the electric and magnetic field
- Duality ➤ distinction between electric and magnetic charge becomes one of mere definition

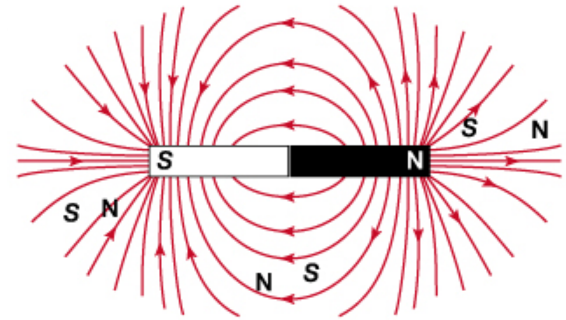
Dirac's Monopole

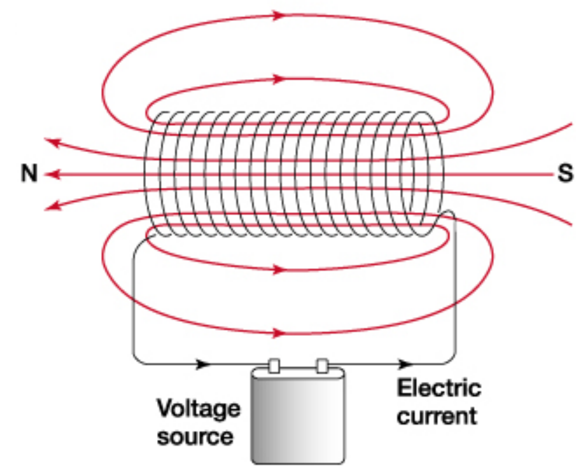
- Paul Dirac in 1931 hypothesised that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

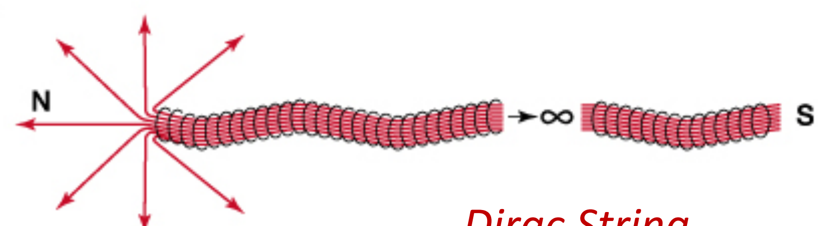
$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \quad \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

  - where g is the "magnetic charge" and α is the fine structure constant 1/137
- This means that **g = 68.5e** (when n=1)!
- If magnetic monopole exists then charge is quantised:

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







Dirac String

Magnetic monopole properties in a nutshell

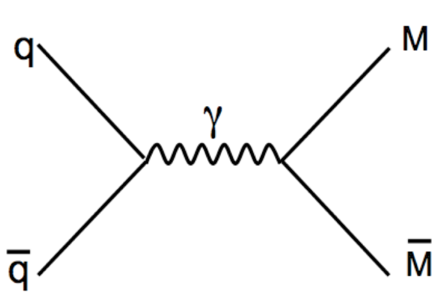
- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - if carries electric charge as well, is called Dyon
- Large coupling constant: $g/\hbar c \sim 34$
- Monopoles would *accelerate* along field lines and *not curve* as electrical charges in a magnetic field - according to the Lorentz equation

$$\vec{F} = g\left(\vec{B} - \vec{v} \times \vec{E}\right)$$

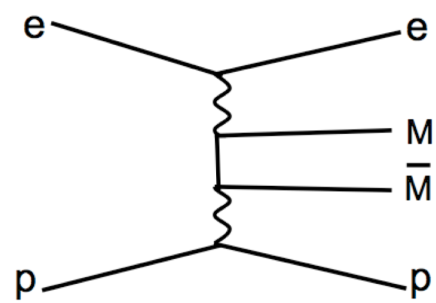
- Energy acquired in a magnetic field: 2.06 MeV/gauss.m
  - monopoles accelerated to ~2 TeV with a 10 m × 10 T magnet!
- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin is not determined by theory
- Monopole mass not predicted within Dirac's theory; other theories predict masses from $\mathcal{O}$(TeV) (electroweak) to $\gtrsim 10^{17}$ GeV (GUT)

Monopole production at colliders

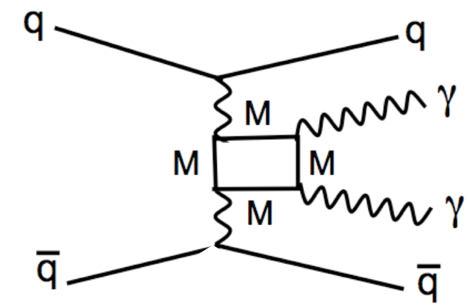
Production mechanisms in colliders



Drell Yan mechanism



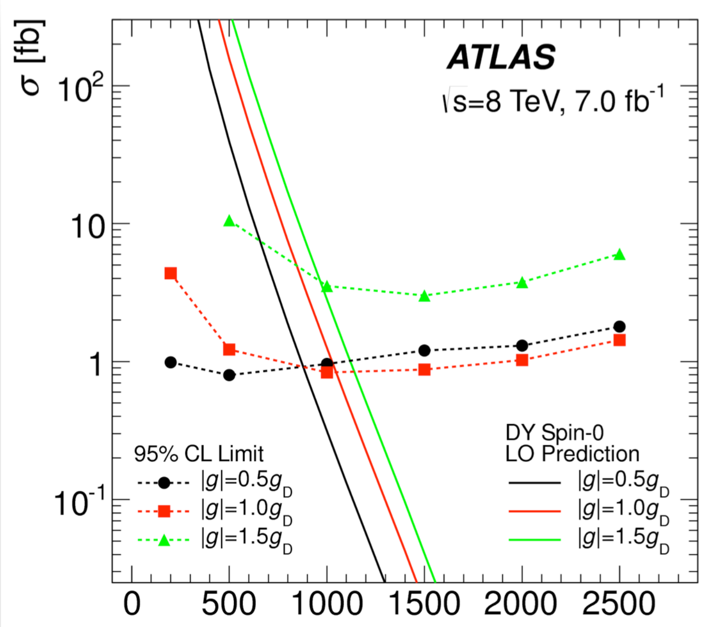
Photon fusion



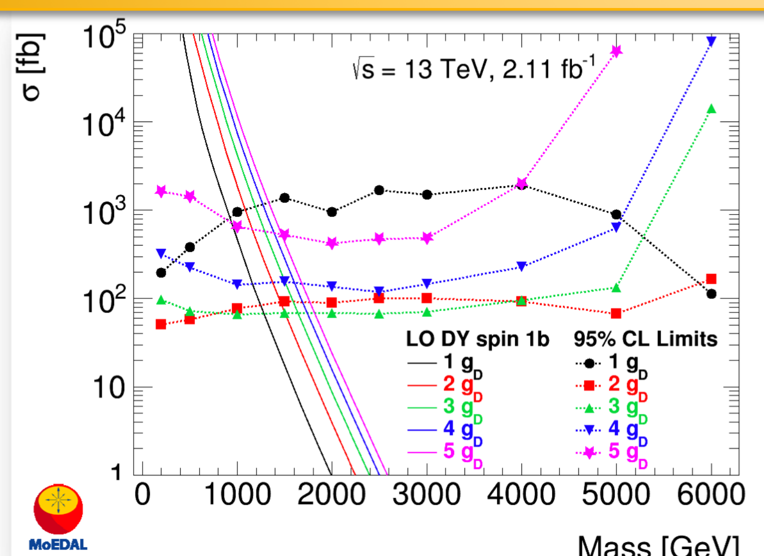
Box diagram

So far, only **Drell-Yan (DY)** has been considered

- CDF, D0, ATLAS & MoEDAL

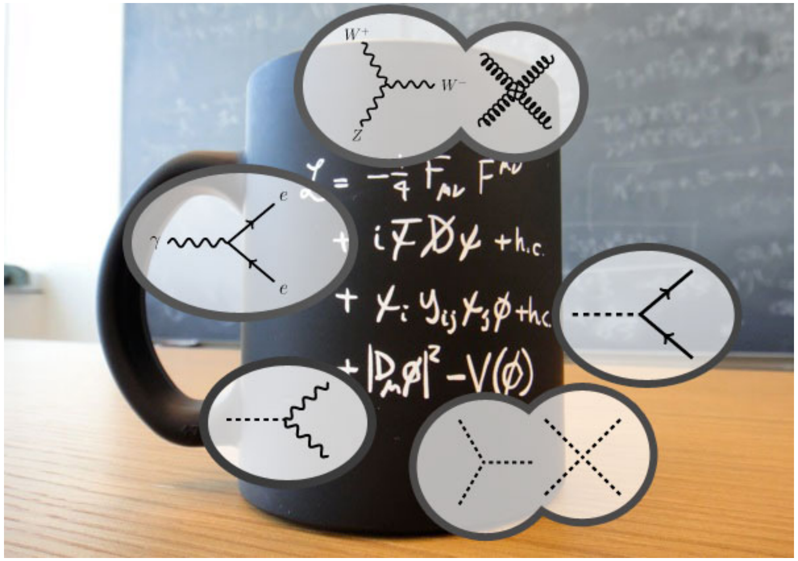


ATLAS, Phys. Rev. D 93, 052009 (2016)



MoEDAL, Phys. Lett. B 782, 510 (2018)

Cross-section calculations



Monopole field theory

- Electric-magnetic duality: The monopole enters the field as a matter field in a U(1) gauge theory

$$\mathcal{L}(\mathcal{A}_\mu, \phi_{(i,\mu)})$$

$$(e, m_e, S = \tfrac{1}{2})$$

Standard QED

$$(g(\beta), M, S = ?)$$

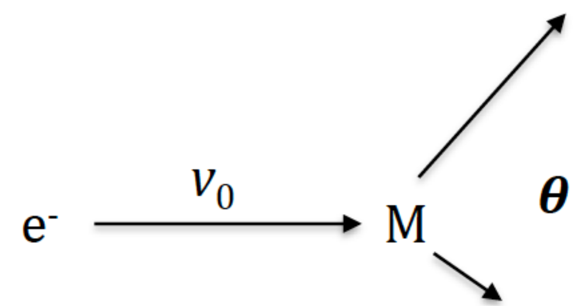
Monopole Field Theory by Analogy

- In a nutshell:
  - S = 0 : Scalar Quantum Electrodynamics
  - S = ½ : Dirac Quantum Electrodynamics
  - S = 1: Lee-Yang Field Theory

β-dependent coupling

- Rutherford (classical) scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{e\,g}{c\,\mu\,v_0}\right)^2 \sum_{\chi} \frac{1}{4\sin^4\left(\frac{\chi}{2}\right)} \left|\frac{\sin(\chi)\,d\chi}{\sin(\theta)\,d\theta}\right|$$



$\theta \ll 1$

$$\frac{d\sigma}{d\Omega} = \left(\frac{e\,g}{2\,\mu\,v_0\,c}\right)^2 \frac{1}{(\theta/2)^4}$$

$$\boxed{\frac{g}{c} \to \frac{e}{v_0}}$$

- It suggests some effective coupling, when monopoles interact with SM matter fields
- Monopole boost expressed by $\beta = \sqrt{1 - \frac{4M^2}{s}}$
- Calculations hold in both the β-dependent (gβ) and β-independent (g) cases

New magnetic-moment parameter κ

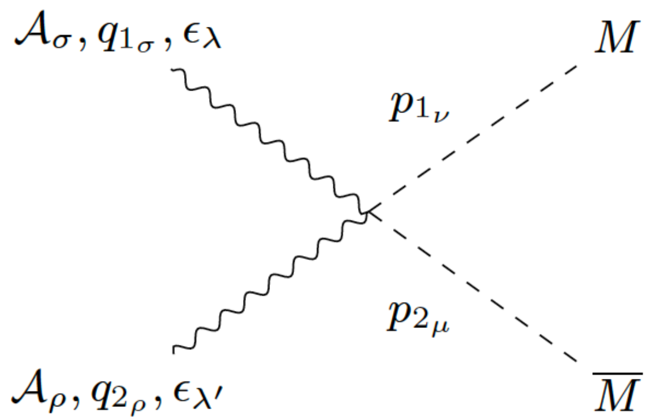
- **Spin ½**: In SM, such a term appears through spin interactions in minimally e$^{\pm}$-γ **QED** coupling
  - SM case: $\tilde{\kappa} = 0$ ($\tilde{\kappa}$ dimensionless parameter)
    - unitary
    - renormalisable

$$\kappa = \frac{\tilde{\kappa}}{M}$$

- **Spin 1:** In SM, such a term appears naturally through the coupling of physical $W^{\pm}$ bosons in rotated **SU(2)×U$_{Y}$(1)/U$_{em}$(1)**
  - SM case: $\kappa = 1$
    - unitary
    - renormalisable
    - no ghosts or gauge fixing
- Impact on observables
  - total cross sections increases with κ
  - kinematic distributions change with κ (at γγ or q$\bar{q}$ scattering)

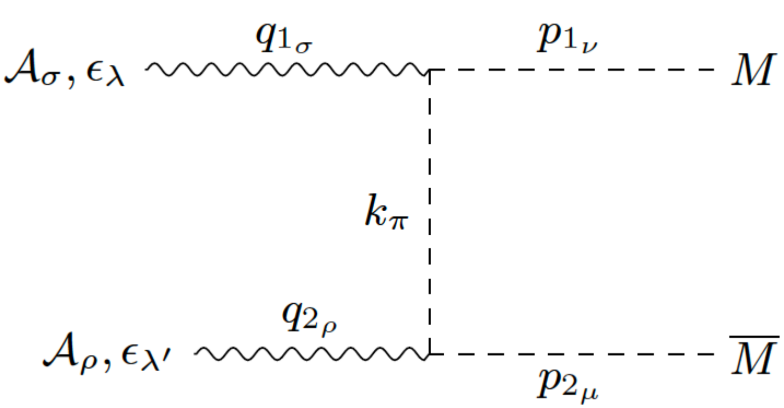
Scalar monopole

- S = 0: **Scalar Quantum Electrodynamics**
  - monopole as a scalar field obeying a U(1)-gauged **Klein Gordon equation**

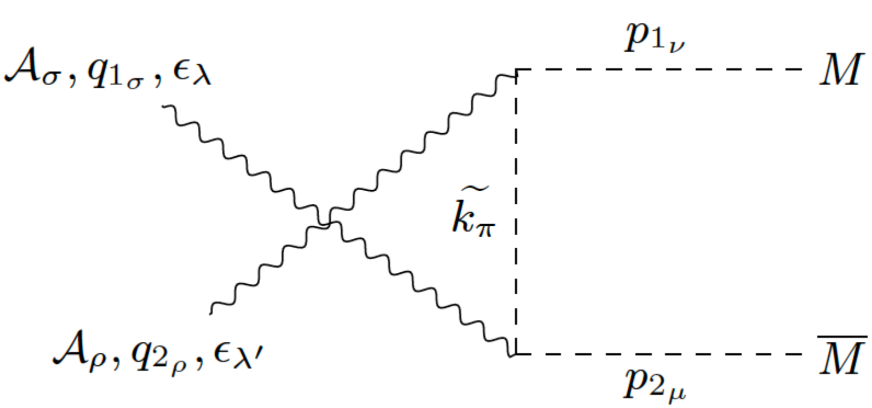


(c) Four-vertex diagram.

$$\boxed{\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + (D^\mu\phi)^\dagger(D_\mu\phi) - M^2\phi^\dagger\phi,}$$



(a) t-channel.



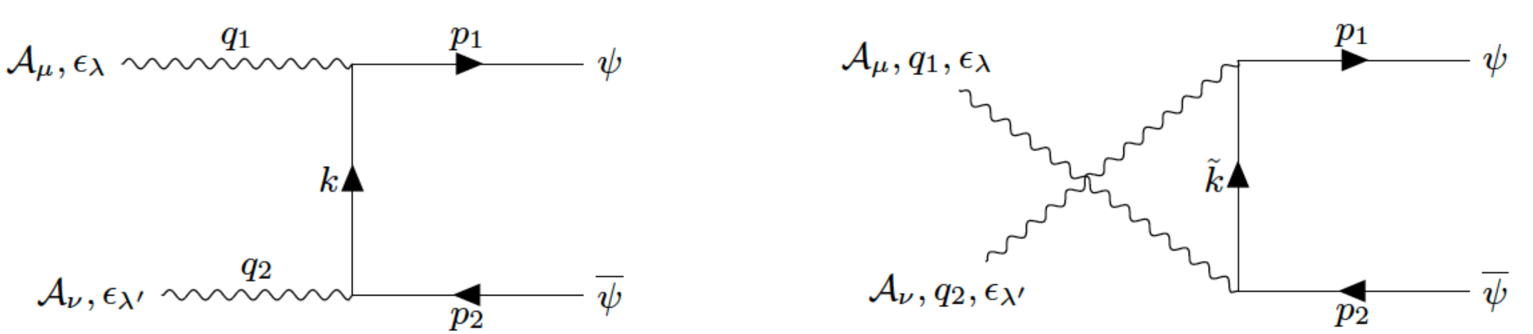
(b) u-channel.

Spinor mopopole

- S = ½ : **Dirac Quantum Electrodynamics**
  - monopole as a spinor field obeying a U(1)-gauged **Dirac equation**
  - magnetic-moment κ
    - κ = 0 ➔ SM case
    - κ̃ dimensionless

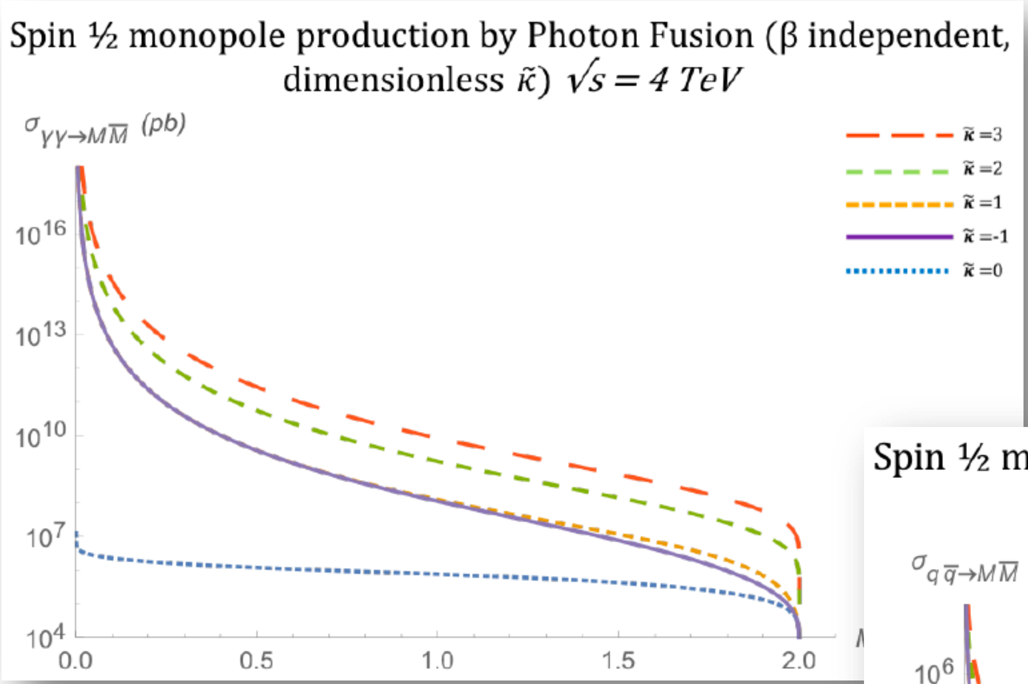
$$\kappa = \frac{\tilde{\kappa}}{M}$$

$$\boxed{\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi}(i \not{D} - m)\psi - i\frac{1}{4}\, g(\beta)\, \kappa\, F_{\mu\nu} \overline{\psi} [\gamma^\mu, \gamma^\nu] \psi,}$$



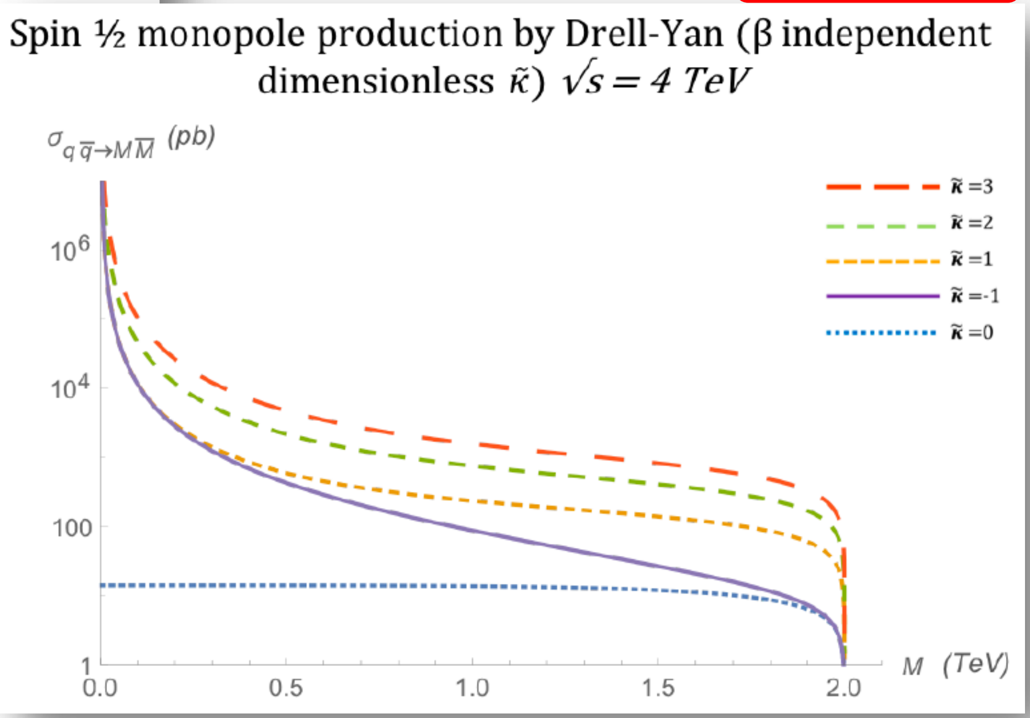
(a) t-channel. (b) u-channel.

Spin ½ – total cross section



γ fusion

Drell-Yan

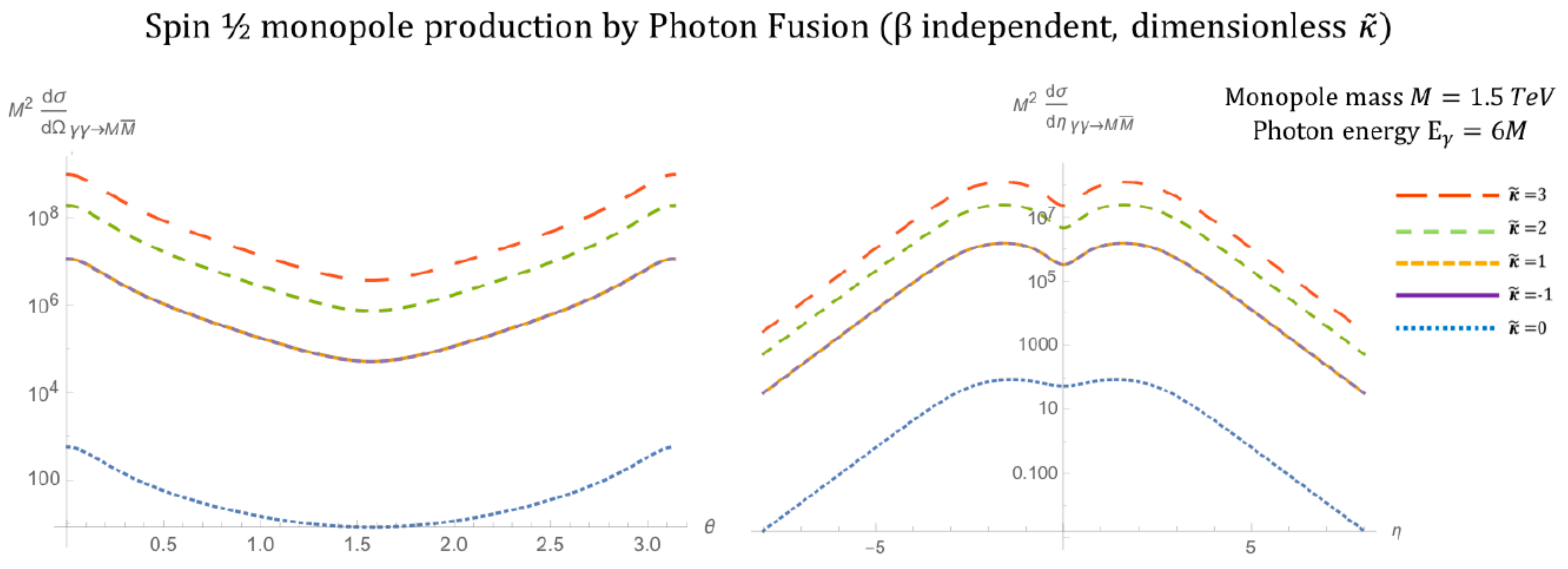


SM case $\tilde{\kappa} = 0$ gives the lower σ, finite at β→0

Spin ½ – differential cross section

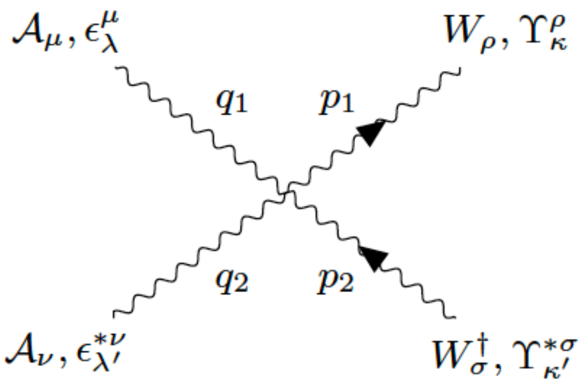
- Distributions quite distinct from the ones for scalar monopoles

γ fusion

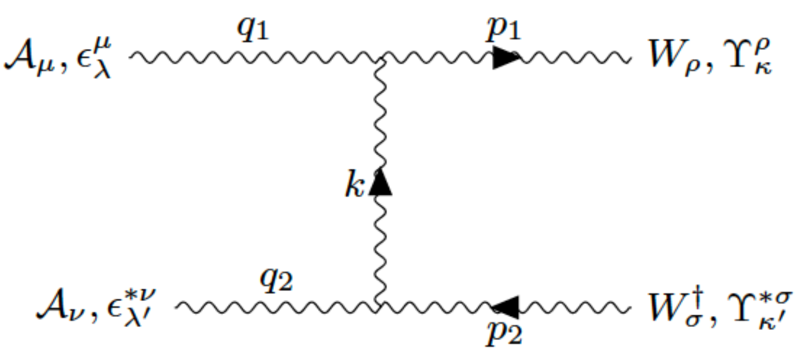


Vector monopole

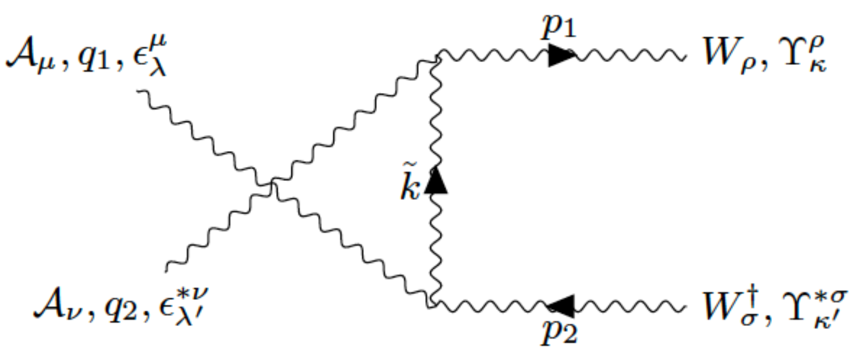
- S = 1: **Lee-Yang Field Theory**
  - monopole as a vector field obeying a U(1)-gauged **Klein Gordon equation** with a gauge fixing parameter and ghosts
  - magnetic-moment κ
    - κ = 1 → SM case



(c) Four-vertex diagram.



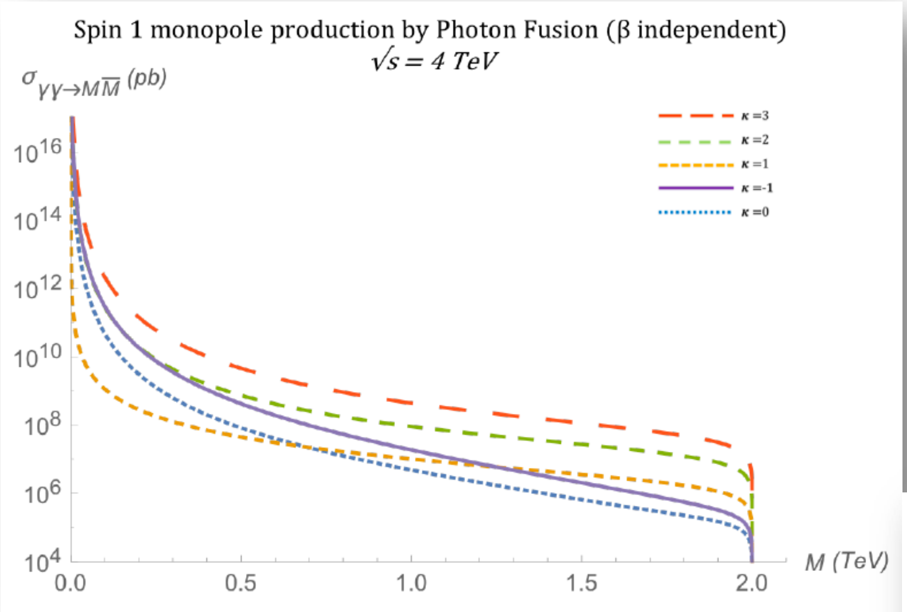
(a) t-channel.



(b) t-channel.

$$\boxed{\mathcal{L} = -\xi(\partial_\mu W^{\dagger\mu})(\partial_\nu W^\nu) - \frac{1}{2}(\partial_\mu \mathcal{A}_\nu)(\partial^\nu \mathcal{A}_\mu) - \frac{1}{2}G^\dagger_{\mu\nu}G^{\mu\nu} - M^2 W^\dagger_\mu W^\mu - ig(\beta)\kappa F^{\mu\nu}W^\dagger_\mu W_\nu}$$

Spin 1 – total cross section

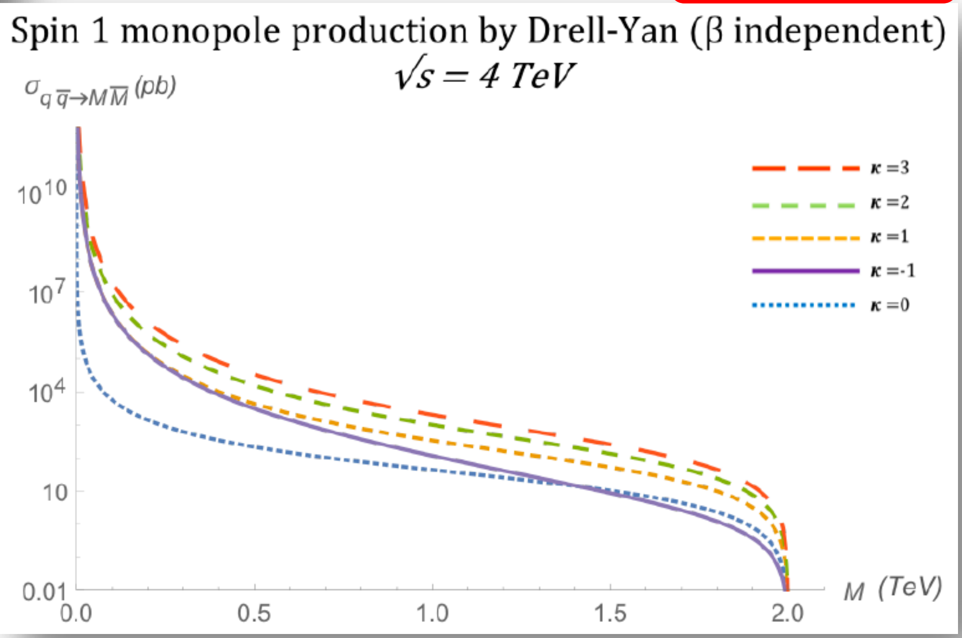


γ fusion

Distinct cross-section evolution

- γγ: SM case κ = 1
- DY: κ = 0

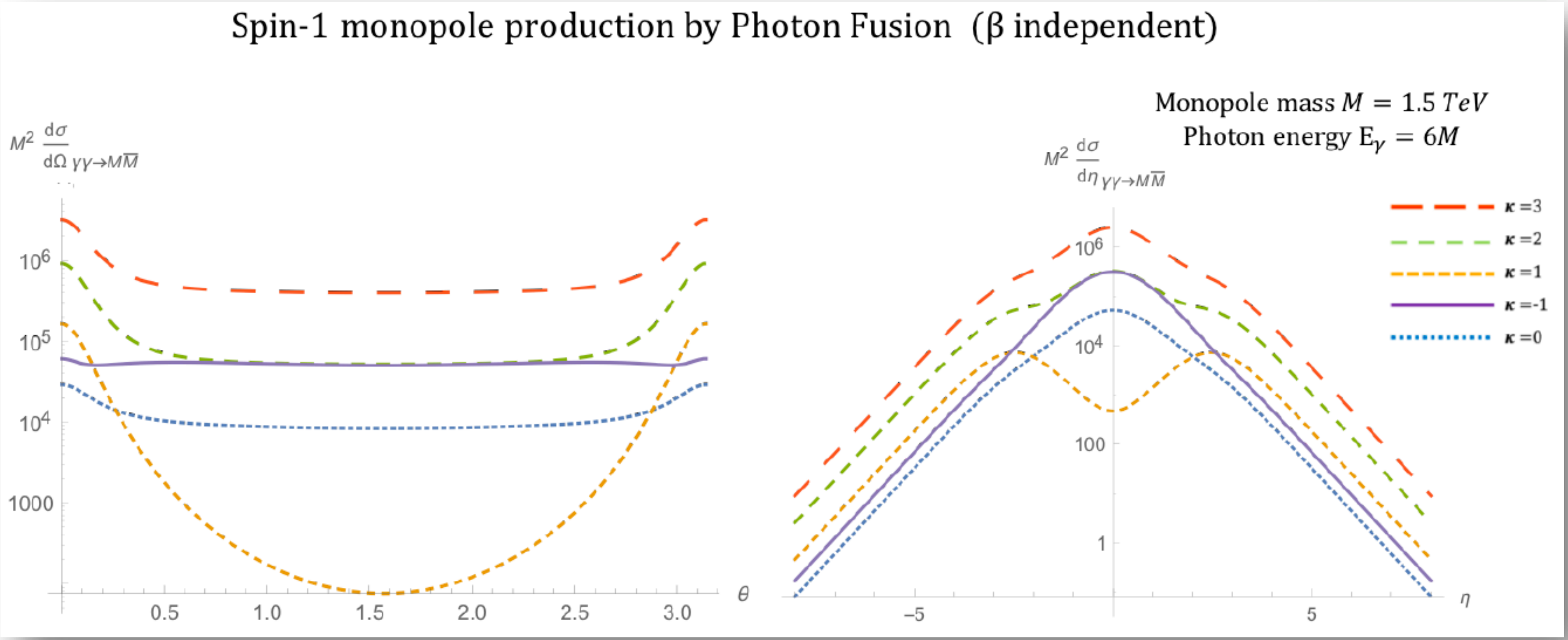
Drell-Yan



Spin 1 – differential cross section

SM case κ = 1 gives a distinct angular distribution w.r.t. non-SM cases

γ fusion



Perturbativity issues

- Both photon fusion and Drell-Yan processes suffer from a large photon-monopole coupling that makes perturbative calculations problematic
- This situation may be resolved if
  - very slow monopoles, $\beta \to 0$
  - parameter κ becomes very large, $\kappa \to \infty$
  - condition for perturbative coupling:

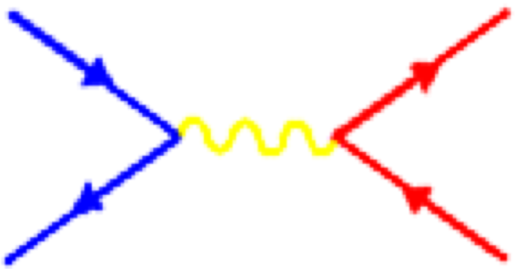
$$\boldsymbol{g\kappa'\beta^2 < 1}$$

$$\kappa' = \begin{cases} \tilde{\kappa}, & \text{spin } 1/2 \\ \kappa, & \text{spin } 1 \end{cases}$$

- Cross section remains finite at this limit for photon fusion while it vanishes for DY

MadGraph implementation

- UFO models
- Validation



Photon fusion (& DY) in MG5

- Drell-Yan was implemented in MADGRAPH5 (MG5) using FORTRAN-code setup
  - only three-particle vertex
  - used in ATLAS & MoEDAL analyses
- We implemented at modeling photon fusion process in MG5
- HOW?
- Fortran models inadequate to describe four-particle vertex as required in bosonic monopole production through photon fusion
- Future MG5 models will be usable only through PYTHON, hence old models need to be transferred to PYTHON
- Solution: implement photon fusion as a UFO model written in PYTHON

- Bonus: also transfer old FORTRAN models for DY to new scheme

UFO models

- UFO: Universal FEYNRULES Output
  - FEYNRULES: MATHEMATICA package for describing Feynman rules.
  - Based on PYTHON objects
  - Requires the model Lagrangian as an input in MATHEMATICA format
  - Model parameters (mass, spin, coupling, magnetic charge) are kept in a text file
- For β-dependent coupling, β is introduced as a FORTRAN form factor
  - definition: $\beta = \sqrt{1 - \frac{4M^2}{\hat{s}}}$ with $\hat{s} = 2P_1 \cdot P_2$ where P_i are the 4-momenta of colliding particles

MadGraph validation

- **Total cross section**: For all considered spins, processes and range of masses, very good agreement between MG5 simulations and theoretical calculations

Mass (GeV)	Spin 0 $\gamma\gamma \to M\bar{M},\ \sigma$ (pb) UFO model	Spin 0 Theory	Spin 0 Ratio UFO/th.	Spin 1/2 $\gamma\gamma \to M\bar{M},\ \sigma$ (pb) UFO model	Spin 1/2 Theory	Spin 1/2 Ratio UFO/th.	Spin 1 $\gamma\gamma \to M\bar{M},\ \sigma$ (pb) UFO model	Spin 1 Theory	Spin 1 Ratio UFO/th.
1000	1.4493×10^4	1.4336×10^4	0.99	1.364×10^5	1.358×10^5	1.004	1.078×10^7	1.0781×10^7	0.999
2000	9.851×10^3	9.791×10^3	1.006	8.341×10^4	8.2551×10^4	1.010	2.277×10^6	2.2520×10^6	1.011
3000	5.685×10^3	5.640×10^3	1.007	4.803×10^4	4.7554×10^4	1.010	7.214×10^5	7.1290×10^5	1.012
4000	2847	2810.5	1.013	2.251×10^4	2.2156×10^4	1.012	2.275×10^5	2.2523×10^5	1.010
5000	1094	1087	1.006	6362	6331	1.005	5.256×10^4	5.1833×10^4	1.014
6000	117.8	116.53	1.011	370	365.5	1.012	3.034×10^3	3.014×10^3	1.007

γ fusion

Mass (GeV)	Spin 0 $q\bar{q} \to M\bar{M},\ \sigma$ (pb) UFO model	Spin 0 Theory	Spin 0 Ratio UFO/th.	Spin 1/2 $q\bar{q} \to M\bar{M},\ \sigma$ (pb) UFO model	Spin 1/2 Theory	Spin 1/2 Ratio UFO/th.	Spin 1 $q\bar{q} \to M\bar{M},\ \sigma$ (pb) UFO model	Spin 1 Theory	Spin 1 Ratio UFO/th.
1000	0.4223	0.4184	1.009	1.747	1.735	1.007	3362	3343.05	1.006
2000	0.3484	0.3465	1.005	1.614	1.603	1.007	230.6	228.872	1.007
3000	0.2463	0.2441	1.009	1.373	1.373	1.000	45.43	45.173	1.006
4000	0.1361	0.1352	1.007	1.039	1.0352	1.004	11.38	11.3162	1.006
5000	0.04724	0.0473	0.999	0.6029	0.601	1.003	2.299	2.282	1.007
6000	0.003745	0.00373	1.004	0.1454	0.1442	1.008	0.1206	0.1196	1.008

Drell-Yan

- **Kinematic distributions:** Good agreement also observed with MG5-simulated events without PDF (no-PDF option), i.e. direct γγ and $q\bar{q}$ scattering

LHC phenomenology

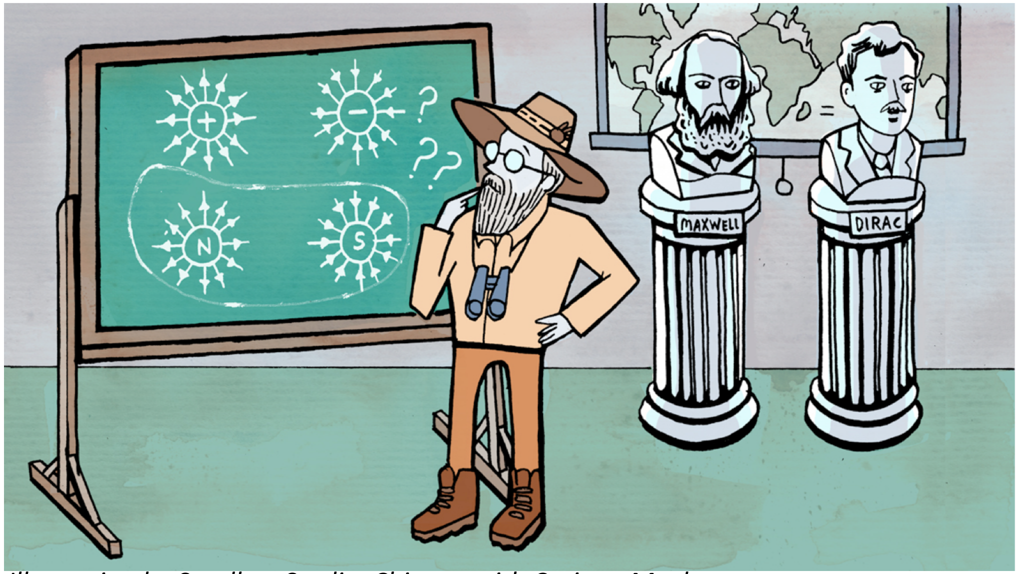
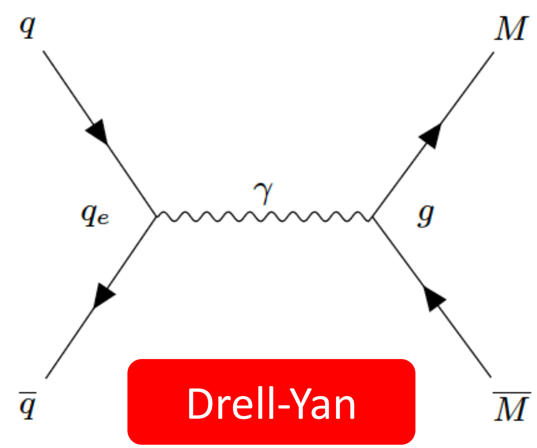


Illustration by Sandbox Studio, Chicago with Corinne Mucha

Simulation setup

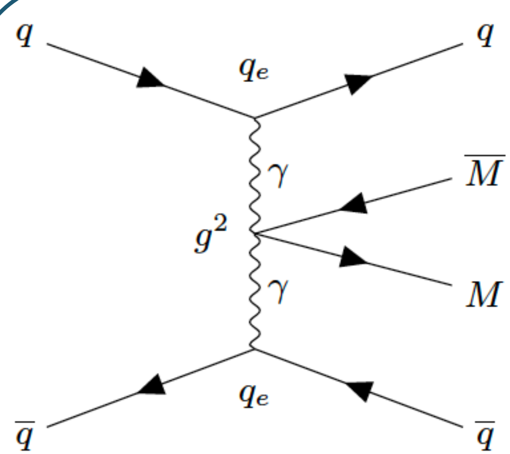
- Proton-to-proton collisions at **√s = 13 TeV**
- Monopole mass **M=1.5 TeV**
- All three spin cases considered
- Magnetic charge set to minimum: **1 g_D**
- Parton distribution functions (PDFs)
  - NNPDF23 at LO for $q\bar{q}$ (Drell Yan)
  - LUXqed for γγ



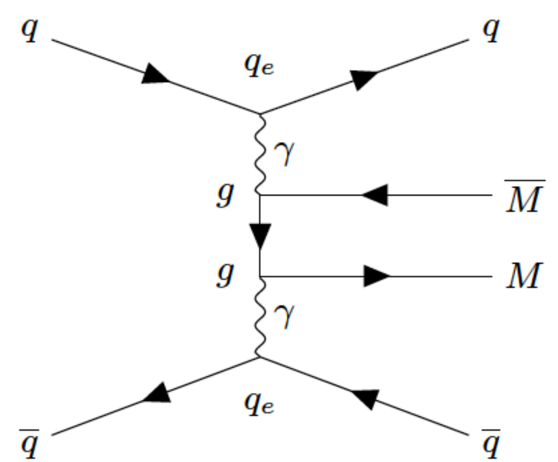
DY monopole production

γ fusion

Only for spin-0 and spin-1 monopoles



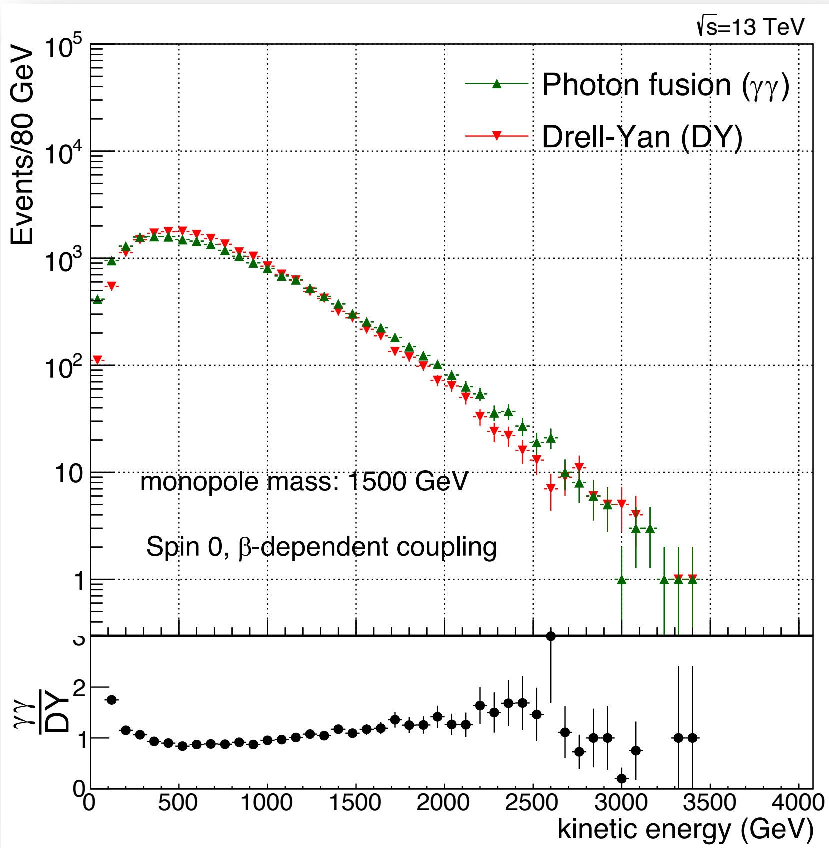
Four-vertex PF process

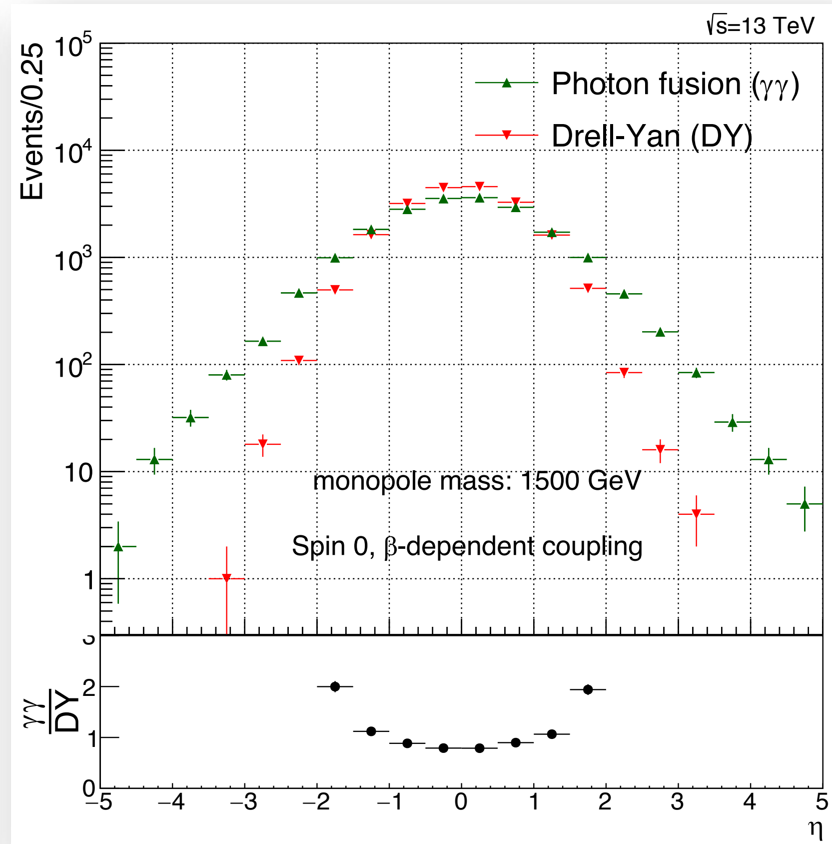


Three-vertex PF process

γ fusion

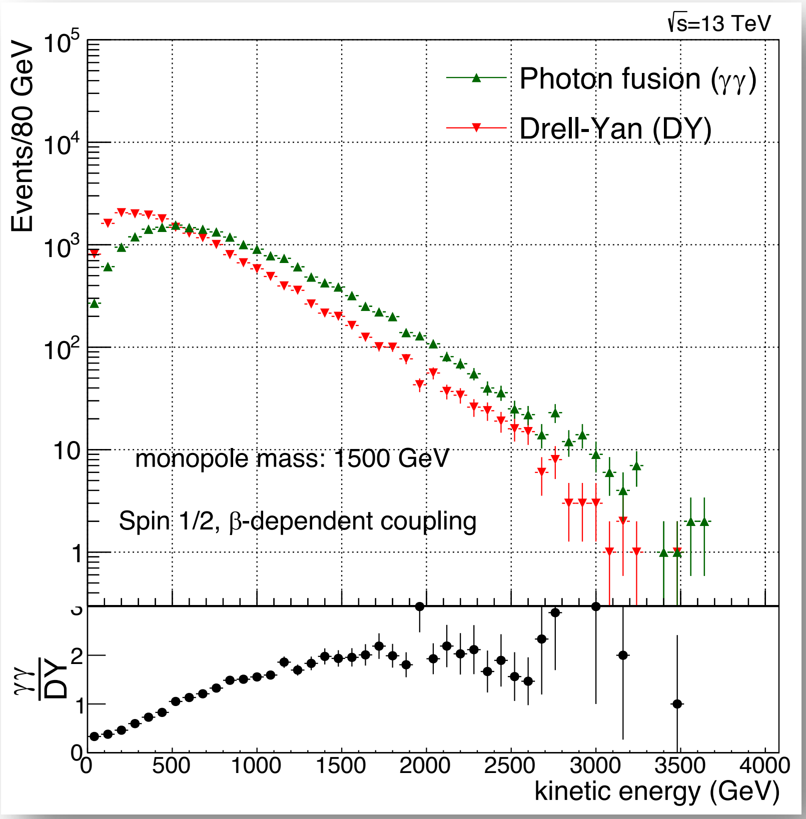
Spin 0: kinematic distributions

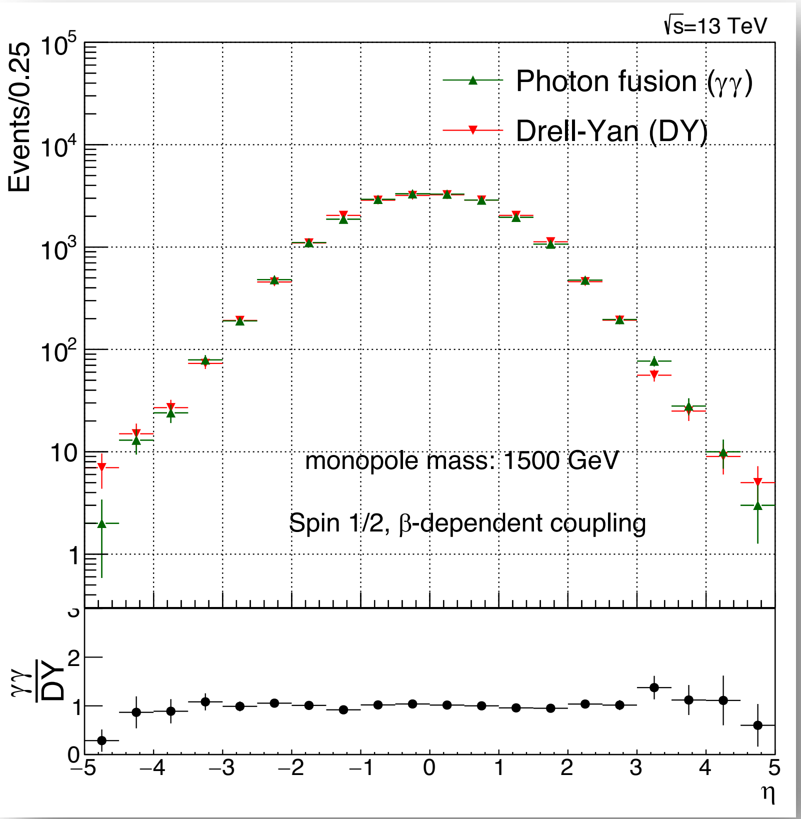




- DY events are characterised be a slightly “harder” spectrum and are more centrally produced than PF

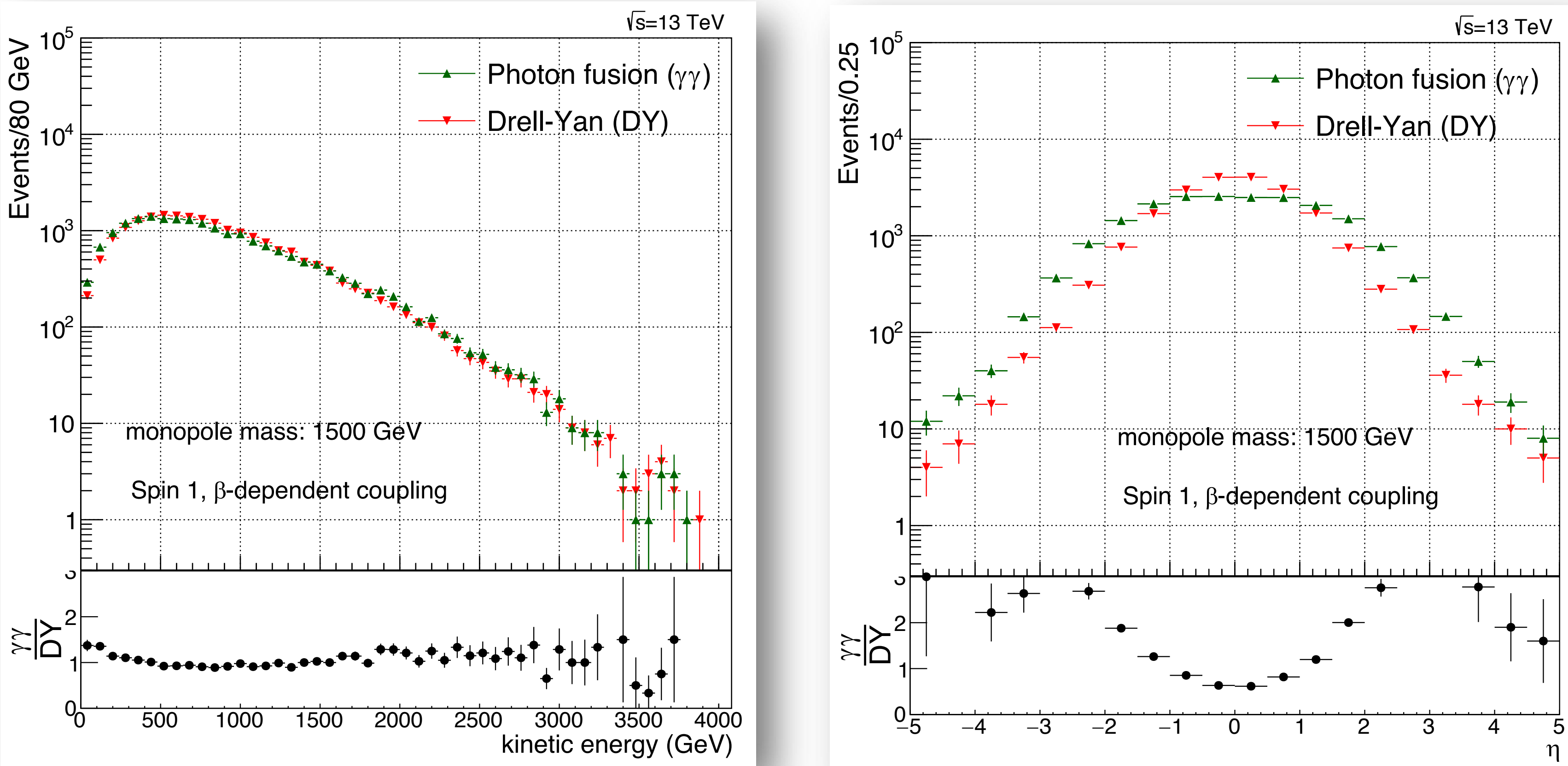
Spin ½: kinematic distributions





- DY events have a significantly "softer" spectrum than PF
- Angular distributions are similar

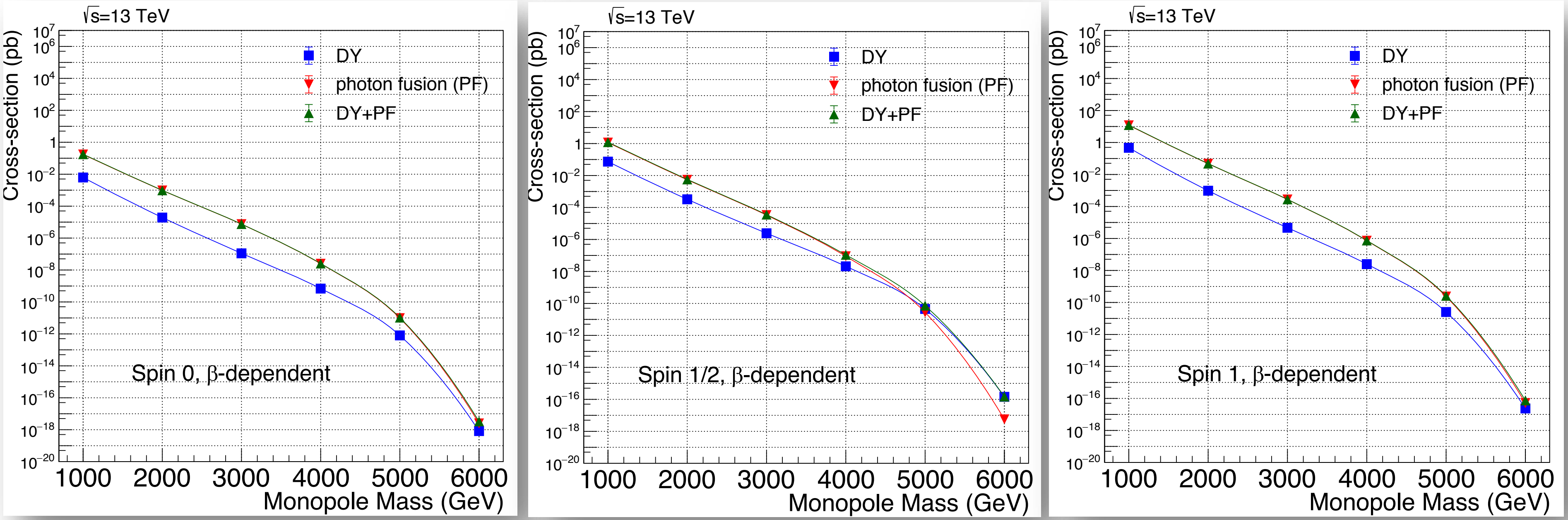
Spin 1: kinematic distributions



- DY events are characterised be a slightly “harder” spectrum and are more centrally produced than PF
- PF-DY comparison similar to scalar monopoles

Cross section comparison

- Photon fusion most abundant than DY for almost the whole mass range at LHC energies
  - important to be included in future interpretations of searches at colliders



Testing perturbativity criterion – spin ½

γ fusion

- Cross sections for γγ direct scattering
- For spin ½ indeed al small monopole velocities and large κ̃ the cross section remains finite

$\tilde{\kappa} \to \infty$

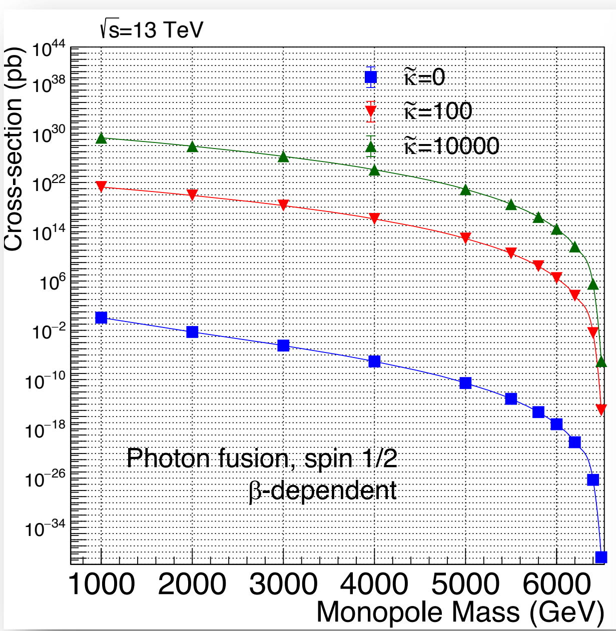
Monopole mass (GeV)	β	$\gamma\gamma \to M\bar{M},\ \sigma$ (pb)			
		$\tilde{\kappa} = 0$	$\tilde{\kappa} = 10$	$\tilde{\kappa} = 100$	$\tilde{\kappa} = 10,000$
1000	0.9881	$1.37 \times 10^5 \pm 4.6 \times 10^2$	$1.639 \times 10^{24} \pm 3.3 \times 10^{21}$	$1.639 \times 10^{28} \pm 3.3 \times 10^{25}$	$1.639 \times 10^{36} \pm 3.3 \times 10^{33}$
2000	0.9515	$8.303 \times 10^4 \pm 4.5 \times 10^2$	$1.61 \times 10^{24} \pm 3.1 \times 10^{21}$	$1.61 \times 10^{28} \pm 3.1 \times 10^{25}$	$1.61 \times 10^{36} \pm 3.1 \times 10^{33}$
3000	0.8871	$4.78 \times 10^4 \pm 3.5 \times 10^2$	$1.356 \times 10^{24} \pm 2.5 \times 10^{21}$	$1.356 \times 10^{28} \pm 2.5 \times 10^{25}$	$1.356 \times 10^{36} \pm 2.5 \times 10^{33}$
4000	0.7882	$2.237 \times 10^4 \pm 1.9 \times 10^2$	$8.612 \times 10^{23} \pm 2.1 \times 10^{21}$	$8.613 \times 10^{27} \pm 2.1 \times 10^{25}$	$8.613 \times 10^{35} \pm 2.1 \times 10^{33}$
5000	0.639	6396 ± 61	$3.154 \times 10^{23} \pm 1.1 \times 10^{21}$	$3.154 \times 10^{27} \pm 1.1 \times 10^{25}$	$3.154 \times 10^{35} \pm 1.1 \times 10^{33}$
5500	0.5329	2256 ± 22	$1.247 \times 10^{23} \pm 4.5 \times 10^{20}$	$1.247 \times 10^{27} \pm 4.5 \times 10^{24}$	$1.247 \times 10^{35} \pm 4.5 \times 10^{32}$
5800	0.4514	886.5 ± 7.8	$5.28 \times 10^{22} \pm 2.5 \times 10^{20}$	$5.28 \times 10^{26} \pm 2.5 \times 10^{24}$	$5.28 \times 10^{34} \pm 2.5 \times 10^{32}$
6000	0.3846	367.2 ± 3	$2.294 \times 10^{22} \pm 7.6 \times 10^{19}$	$2.294 \times 10^{26} \pm 7.6 \times 10^{23}$	$2.294 \times 10^{34} \pm 7.6 \times 10^{31}$
6200	0.3003	97.19 ± 0.77	$6.43 \times 10^{21} \pm 3.3 \times 10^{19}$	$6.43 \times 10^{25} \pm 3.3 \times 10^{23}$	$6.43 \times 10^{33} \pm 3.3 \times 10^{31}$
6400	0.1747	5.846 ± 0.025	$4.065 \times 10^{20} \pm 1.5 \times 10^{18}$	$4.065 \times 10^{24} \pm 1.5 \times 10^{22}$	$4.065 \times 10^{32} \pm 1.5 \times 10^{30}$
6490	0.0554	$0.017 \pm 2.27 \times 10^{-5}$	$1.27 \times 10^{18} \pm 8.74 \times 10^{14}$	$1.27 \times 10^{22} \pm 8.74 \times 10^{18}$	$1.27 \times 10^{30} \pm 8.74 \times 10^{26}$

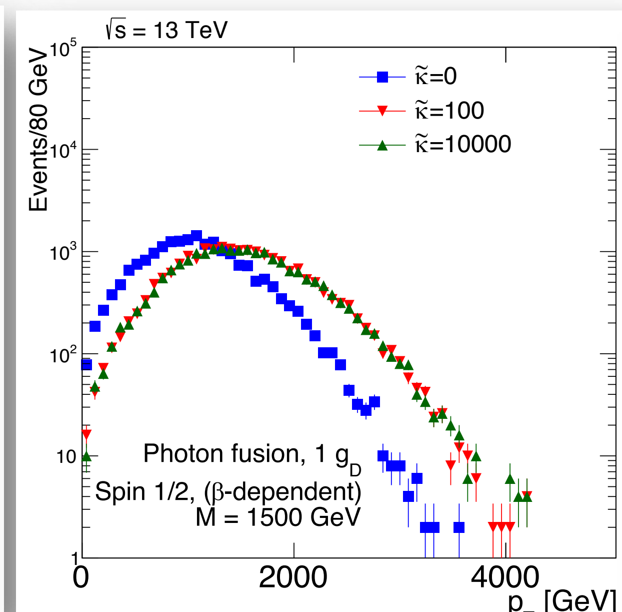
$\beta \to 0$

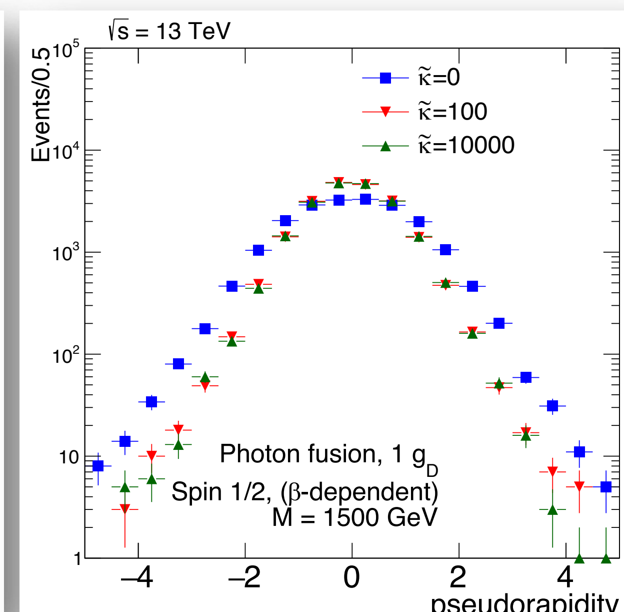
Perturbativity limit – spin ½

- Kinematic distributions different between SM case ($\tilde{\kappa} = 0$) and large $\tilde{\kappa}$
- Similar distributions for large $\tilde{\kappa}$ makes "perturbatively friendly" case easy to test at colliders
- Slow-monopole condition may be satisfied if experiment is sensitive to such monopoles
  - MoEDAL nuclear track detectors can inherently detect highly-ionising particles, such as magnetic monopoles, only if the are slow moving

γ fusion







Testing perturbativity criterion – spin 1

- For spin 1 at small monopole velocities and large κ cross section remains finite
- Just as for spin ½ monopoles

γ fusion

$\kappa \rightarrow \infty$

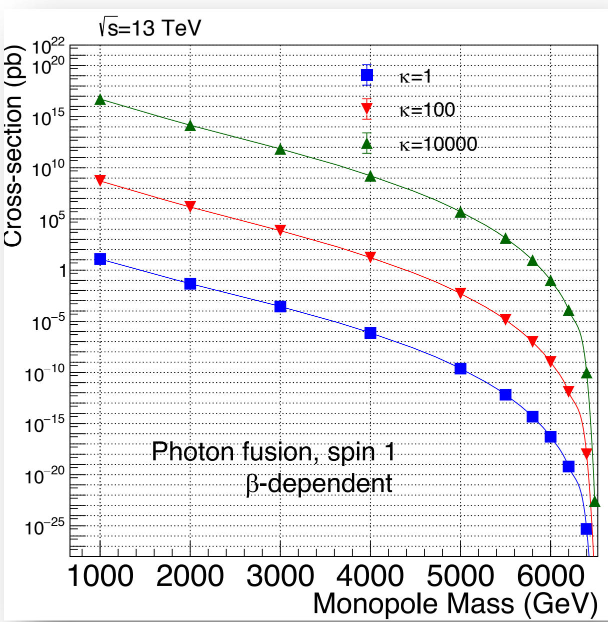
Monopole mass (GeV)	β	$\gamma\gamma \to M\bar{M}$, σ (pb) $\kappa = 1$	$\kappa = 100$	$\kappa = 10,000$
1000	0.9881	$1.086 \times 10^7 \pm 1.4 \times 10^5$	$4.939 \times 10^{15} \pm 1 \times 10^{13}$	$5.033 \times 10^{23} \pm 2.1 \times 10^{21}$
2000	0.9515	$2.275 \times 10^6 \pm 1.6 \times 10^4$	$2.844 \times 10^{14} \pm 4.9 \times 10^{11}$	$2.879 \times 10^{22} \pm 9.8 \times 10^{19}$
3000	0.8871	$7.198 \times 10^5 \pm 6.6 \times 10^3$	$4.518 \times 10^{13} \pm 1.5 \times 10^{11}$	$4.536 \times 10^{21} \pm 1.2 \times 10^{19}$
4000	0.7882	$2.273 \times 10^5 \pm 2.2 \times 10^3$	$9.079 \times 10^{12} \pm 2.7 \times 10^{10}$	$9.002 \times 10^{20} \pm 3.2 \times 10^{18}$
5000	0.639	$5.232 \times 10^4 \pm 4.9 \times 10^2$	$1.513 \times 10^{12} \pm 9.2 \times 10^9$	$1.5 \times 10^{20} \pm 9.3 \times 10^{17}$
5500	0.5329	$1.785 \times 10^4 \pm 1.6 \times 10^2$	$4.49 \times 10^{11} \pm 1.7 \times 10^9$	$4.466 \times 10^{19} \pm 2.9 \times 10^{17}$
5800	0.4514	7118 ± 62	$1.658 \times 10^{11} \pm 1.1 \times 10^9$	$1.624 \times 10^{19} \pm 8.4 \times 10^{16}$
6000	0.3846	3025 ± 24	$6.72 \times 10^{10} \pm 2.5 \times 10^8$	$6.627 \times 10^{18} \pm 3.7 \times 10^{16}$
6200	0.3003	836.9 ± 6.3	$1.764 \times 10^{10} \pm 1 \times 10^8$	$1.733 \times 10^{18} \pm 1 \times 10^{16}$
6400	0.1747	53.42 ± 0.23	$1.066 \times 10^9 \pm 3.9 \times 10^6$	$1.05 \times 10^{17} \pm 3.8 \times 10^{14}$
6490	0.0554	0.1694 ± 0.00065	$3.293 \times 10^6 \pm 5.6 \times 10^3$	$3.244 \times 10^{14} \pm 5.6 \times 10^{11}$

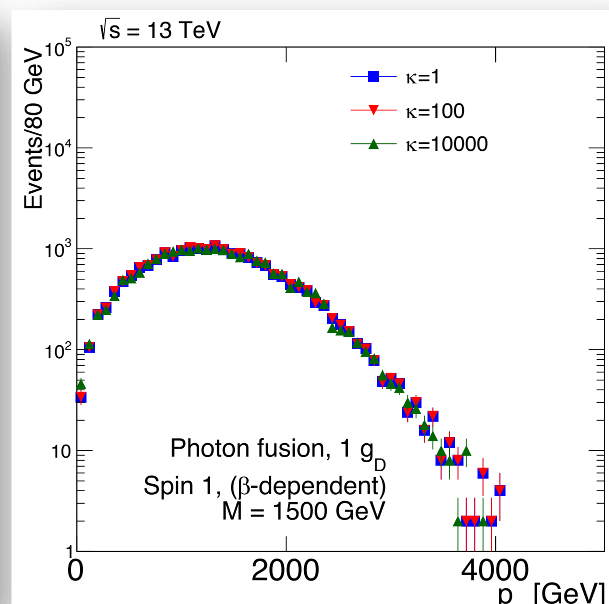
$\beta \rightarrow 0$

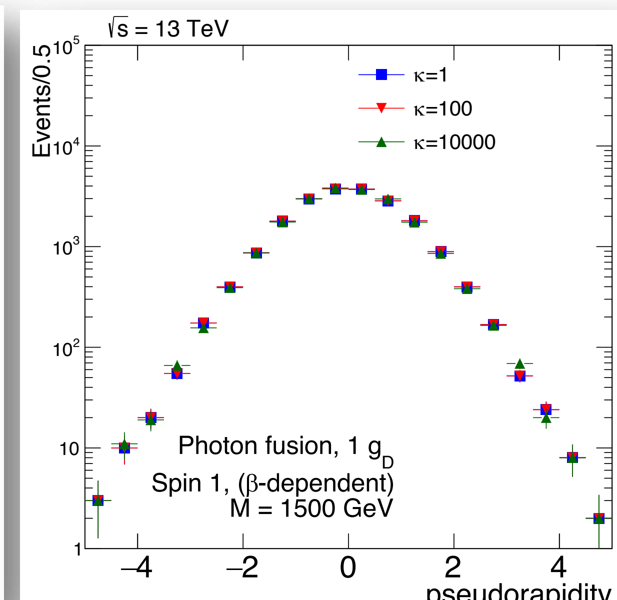
Perturbativity limit – spin 1

- Kinematic distributions *same* between SM case (κ = 0) and large κ (unlike spin ½)
- Similar distributions for large κ makes again "perturbatively friendly" case easy to test at colliders
- Slow-monopole condition may be satisfied if experiment is sensitive to such monopoles
  - MoEDAL nuclear track detectors can inherently detect highly-ionising particles, such as magnetic monopoles, only if the are slow moving

γ fusion





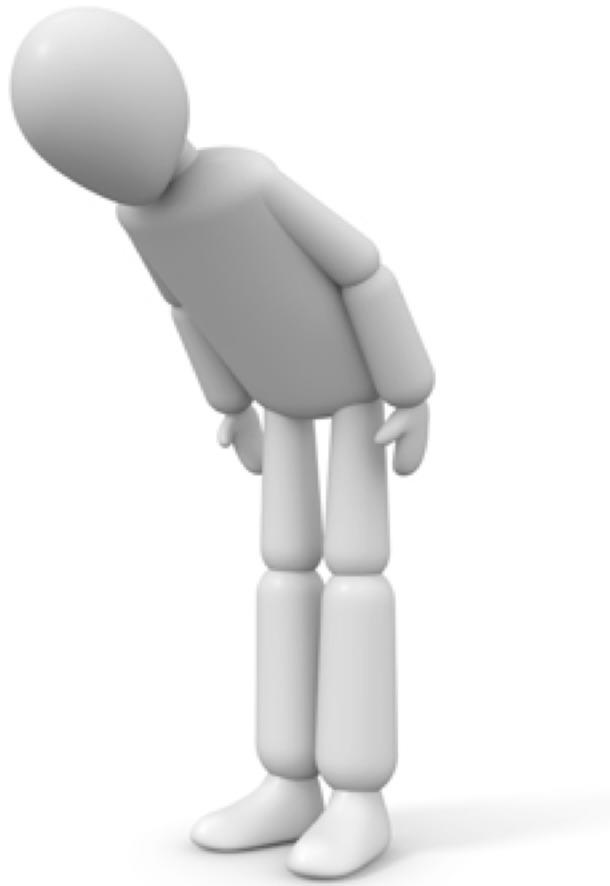


Conclusions & outlook

- Cross-section calculations for colliders have been performed
  - photon fusion and Drell-Yan processes
    - γ fusion least studied and used in searches
    - γ fusion more abundant at LHC than DY
  - novel features
    - boost-dependent photon-monopole coupling
    - magnetic-monopole parameter κ
- MadGraph implementation performed for the first time for photon fusion
- Perturbativity: the photon-fusion cross section remains finite and the coupling is perturbative at the formal limits $\beta \to 0$ and $\kappa \to \infty$
- Possibility to interpret the cross-section bounds set in collider experiments in a proper way, thus yielding sensible monopole-mass limits

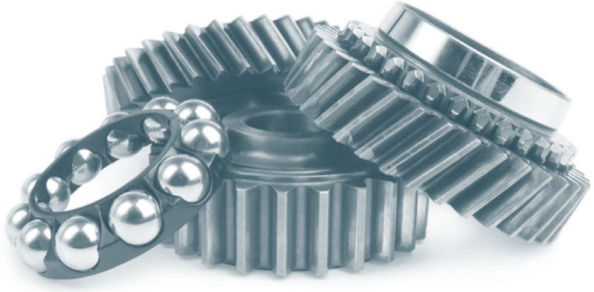
More info at: arXiv:1808.08942 [hep-ph]

Thank you for your attention!

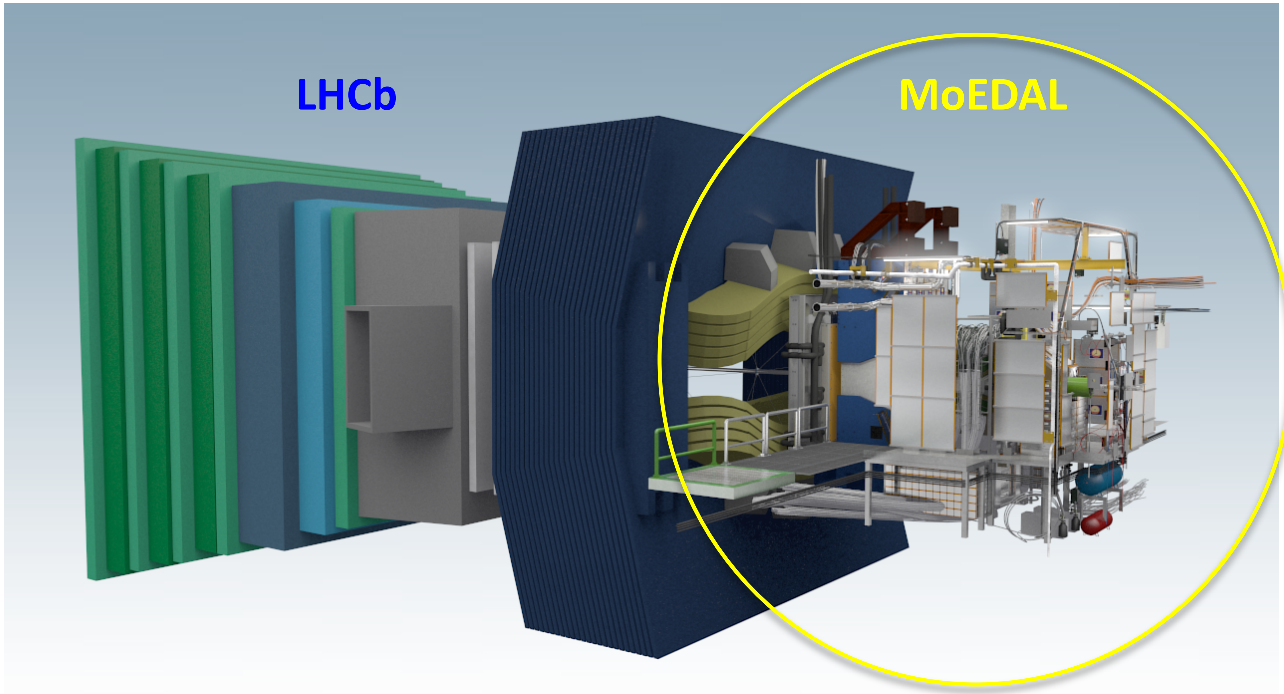


Project supported by a 2017 Leonardo Grant for Researchers and Cultural Creators, BBVA Foundation

Spares



MoEDAL detector



MoEDAL is unlike any other LHC experiment:

- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
  - $z/\beta > \sim 5 - 10$

② Very High Charge Catcher NTD (**HCC-NTD**) array
  - $z/\beta > \sim 50$

③ **TimePix** radiation background monitor

④ Monopole Trapping detector (**MMT**)

Physics program

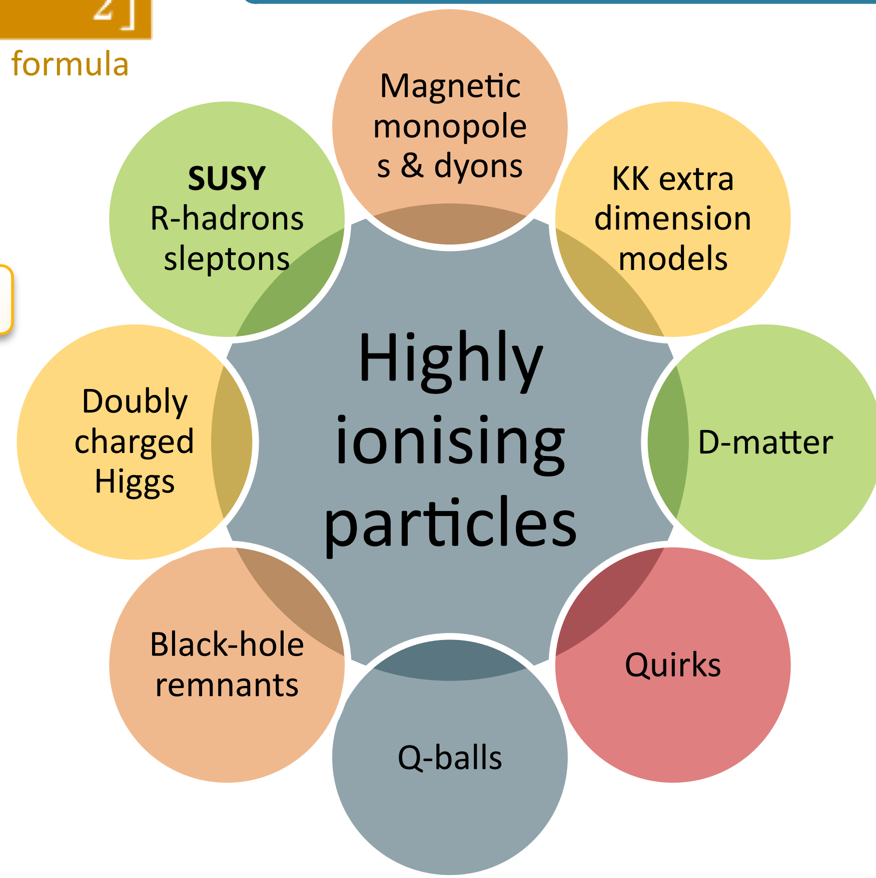
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Bethe-Bloch formula

$$\frac{\text{charge}}{\text{velocity: } \beta = v/c} = z/\beta$$

MoEDAL detectors have a threshold of **z/β ~ 5 – 10**

MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050
[arXiv:1405.7662]



High ionisation (HI) possible when:

- multiple electric charge (H^{++}, Q-balls, etc.)
- very low velocity & electric charge, i.e. Stable Massive Charged Particles (SMCPs)
- magnetic charge (monopoles, dyons) = $ng_D = n \times 68.5 \times e$
  - a singly charged relativistic monopole has ionisation **~4700 times MIP!**

Particles must be *massive*, *long-lived* & *highly ionising* to be detected at *MoEDAL*