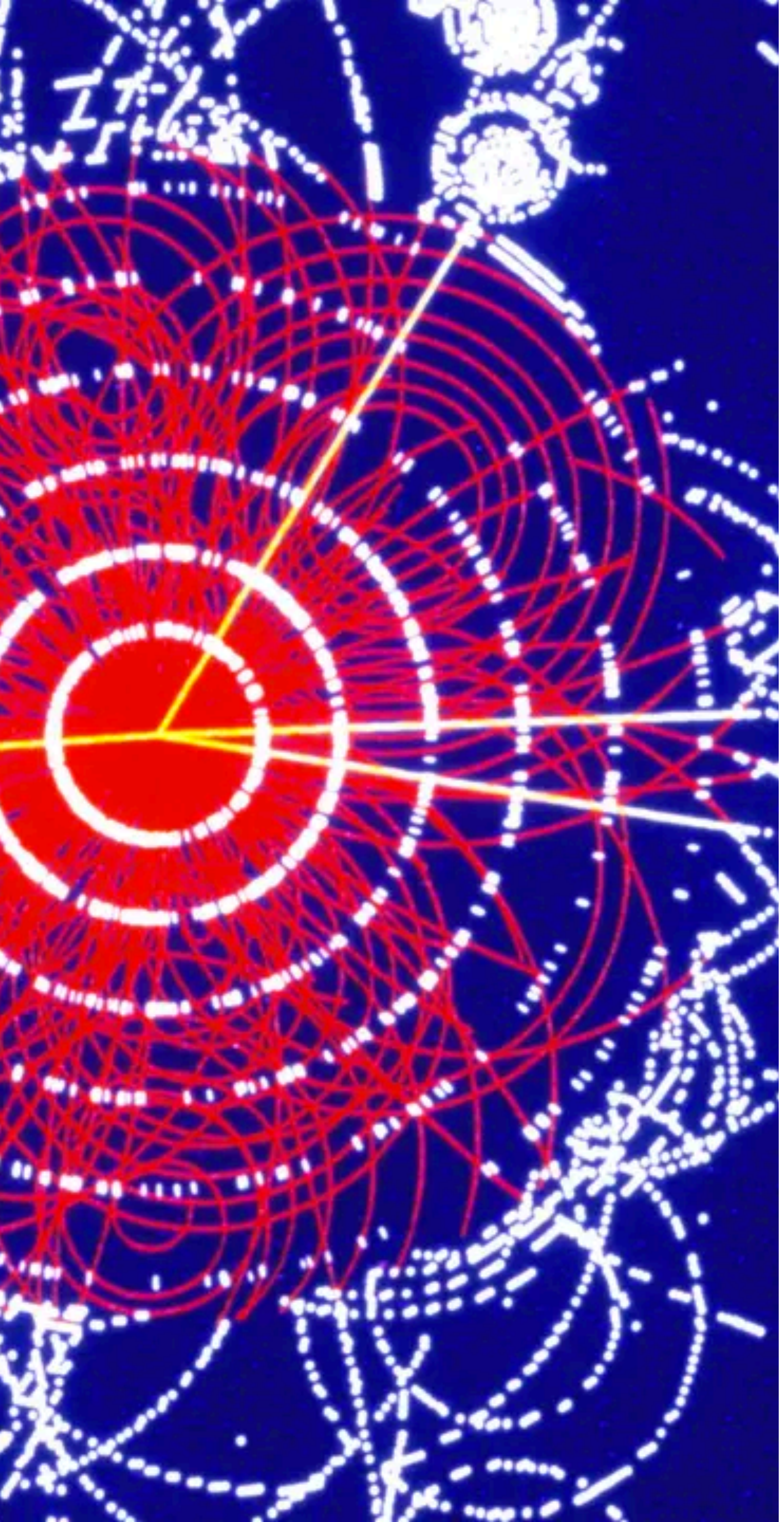

NATIONAL SCIENCE CENTRE POLAND

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

Multiply charged quasi-stable particles at Run-3 and High-Luminosity LHC. Prospects for the discovery.

Rafał Masełek

& M. M. Altakach & P. Lamba & V. Mitsou & K. Sakurai

Planck 2022 02-06-2022

Work supported by
NCN SONATA BIS 7 GRANT
(2017/26/E/ST2/00135)
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(2016/23/G/ST2/04301)

arXiv:2204.03667

Discovery prospects for long-lived highly electrically charged particles at the LHC

Mohammad Altakach[(a)], Priyanka Lamba[(a)], Rafał Masełek[(a)],
Vasiliki A. Mitsou[(b)] and Kazuki Sakurai[(a)]

Submitted to EPJC

Can we discover LLPs at Run-3 LHC/HL-LHC?

Long-lived particles

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Multiply-Charged Particles

Long-lived particles ATLAS

Can we discover LLPs at Run-3 LHC/HL-LHC?

MoEDAL Multiply-Charged Particles

CMS

R. Masełek Planck 2022 02-06-2022

bound states

Long-lived particles ATLAS

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open/closed production CMS

R. Masełek Planck 2022 02-06-2022

simplified models

bound states

lower mass bounds

detection reach

Long-lived particles

ATLAS

Can we discover LLPs at Run-3 LHC/HL-LHC?

MoEDAL

Multiply-Charged Particles

sensitivity

open/closed production

CMS

upper cross-section limits

R. Masełek

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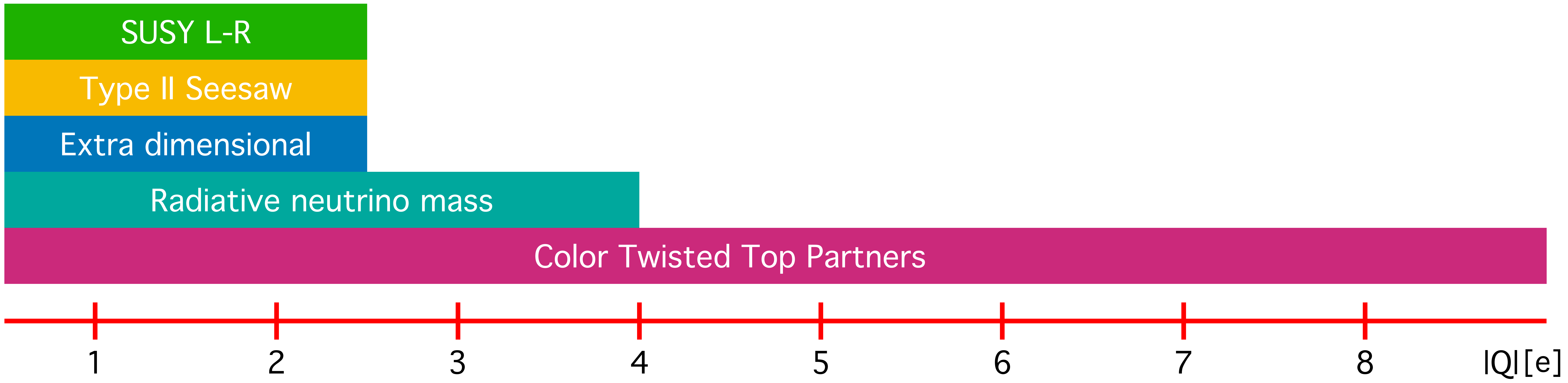
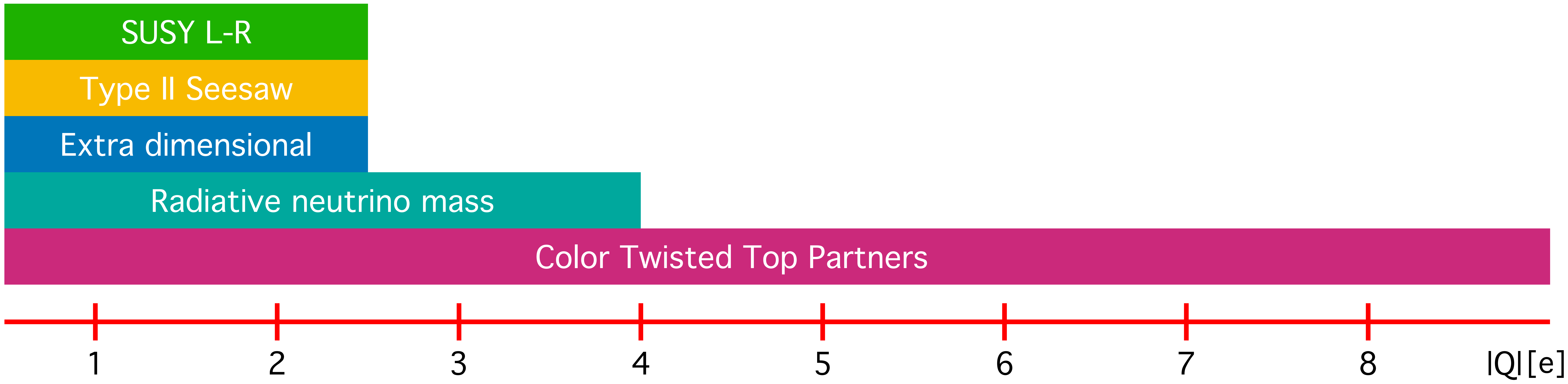
Multiply charged heavy (quasi)stable particles

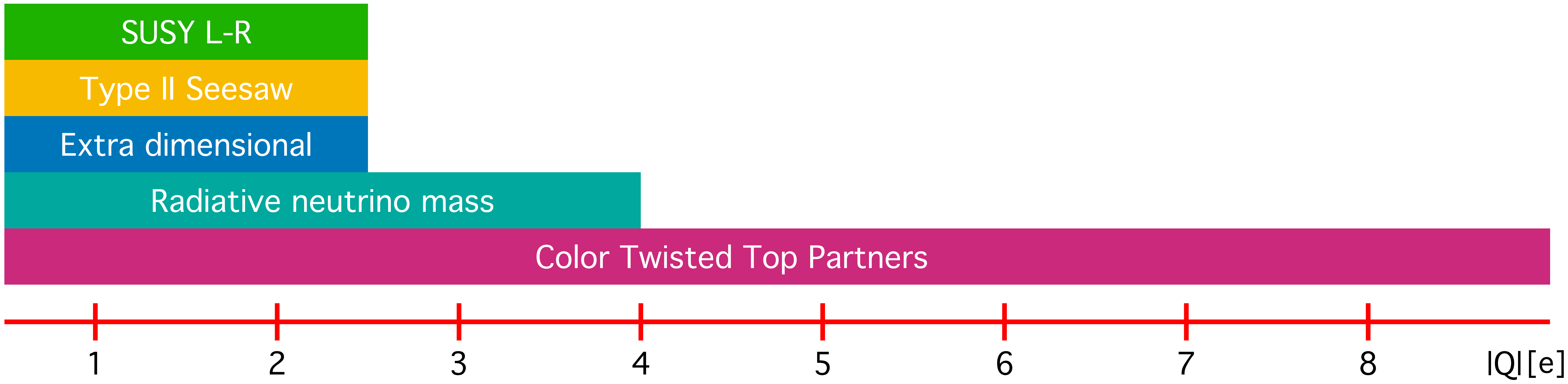


Multiply charged heavy (quasi)stable particles



SU(2) singlet	colour singlet	colour triplet
spin 0	colourless scalar	coloured scalar
spin 1/2	colourless fermion	coloured fermion

Multiply charged heavy (quasi)stable particles



SU(2) singlet	colour singlet	colour triplet
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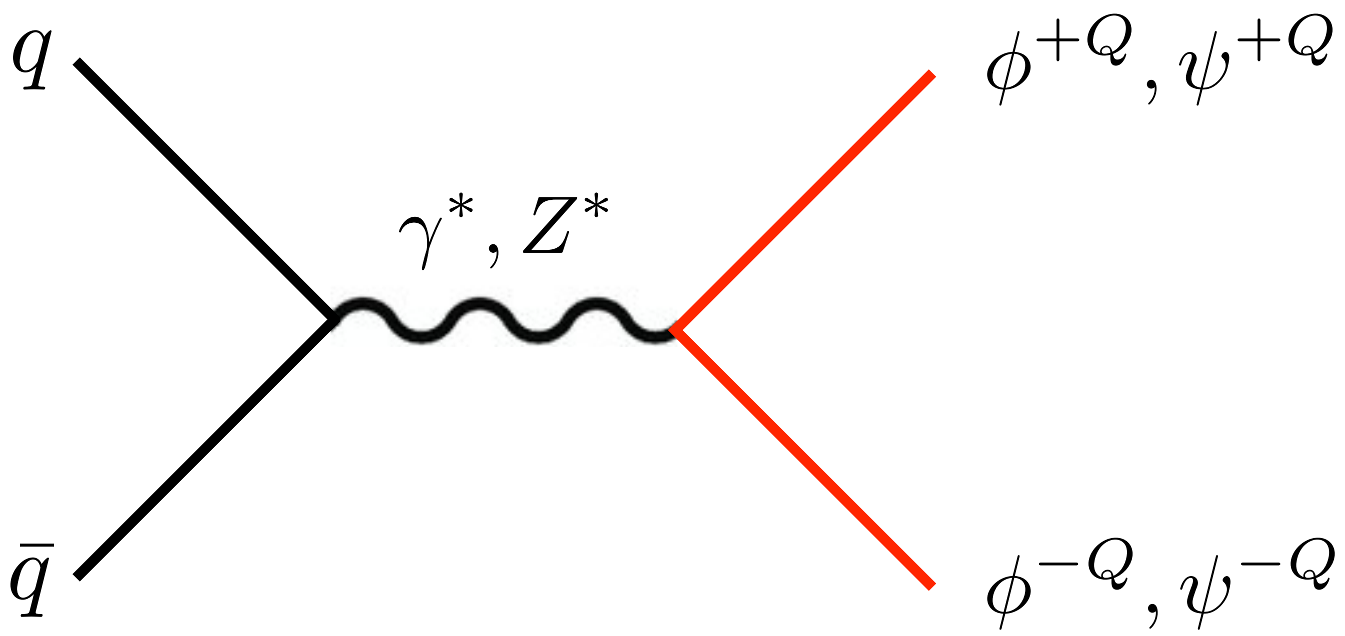
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{KIN}} + \mathscr{L}_{\mathrm{MASS}} + \boxed{\cdots}$$

The particles don't have to be stable, but we do not specify their decays. We treat their decay length as a free parameter or assume they are "collider-stable".

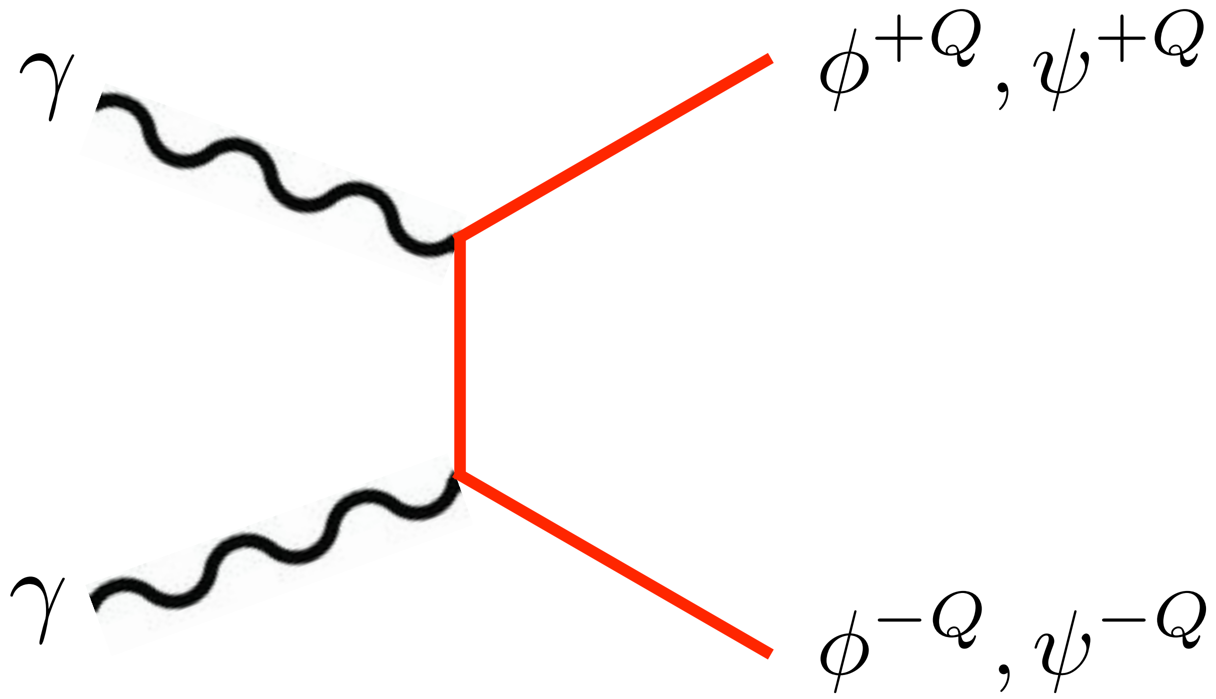
production mechanism

Morskie Oko, Tatra, Poland

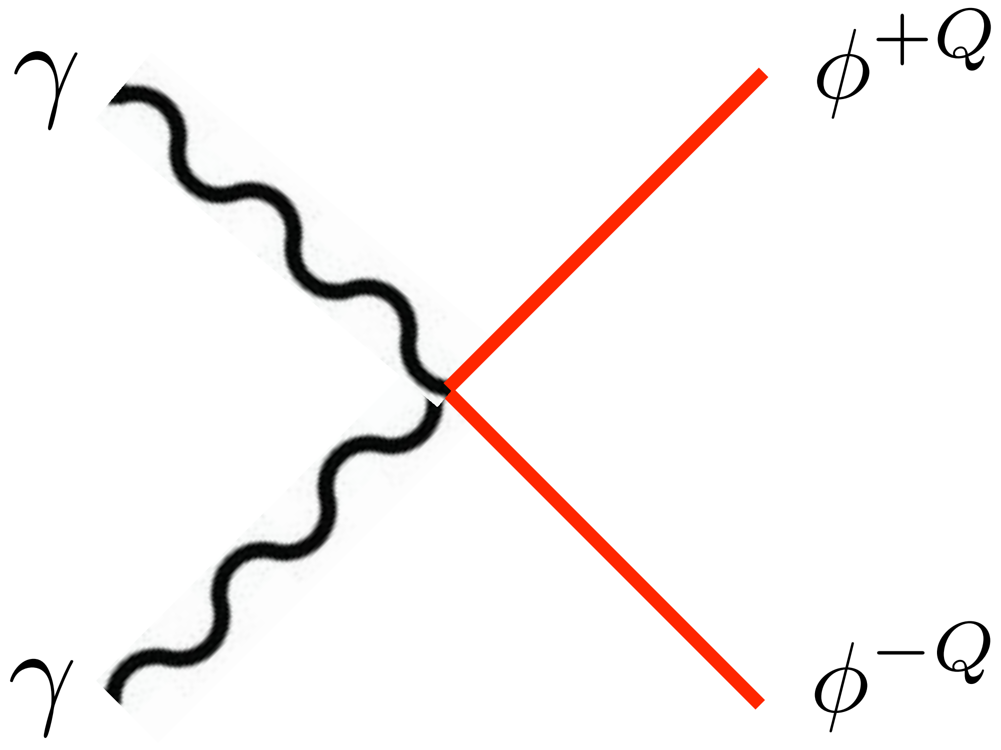
Production mechanism (open channel)



s-channel (DY)

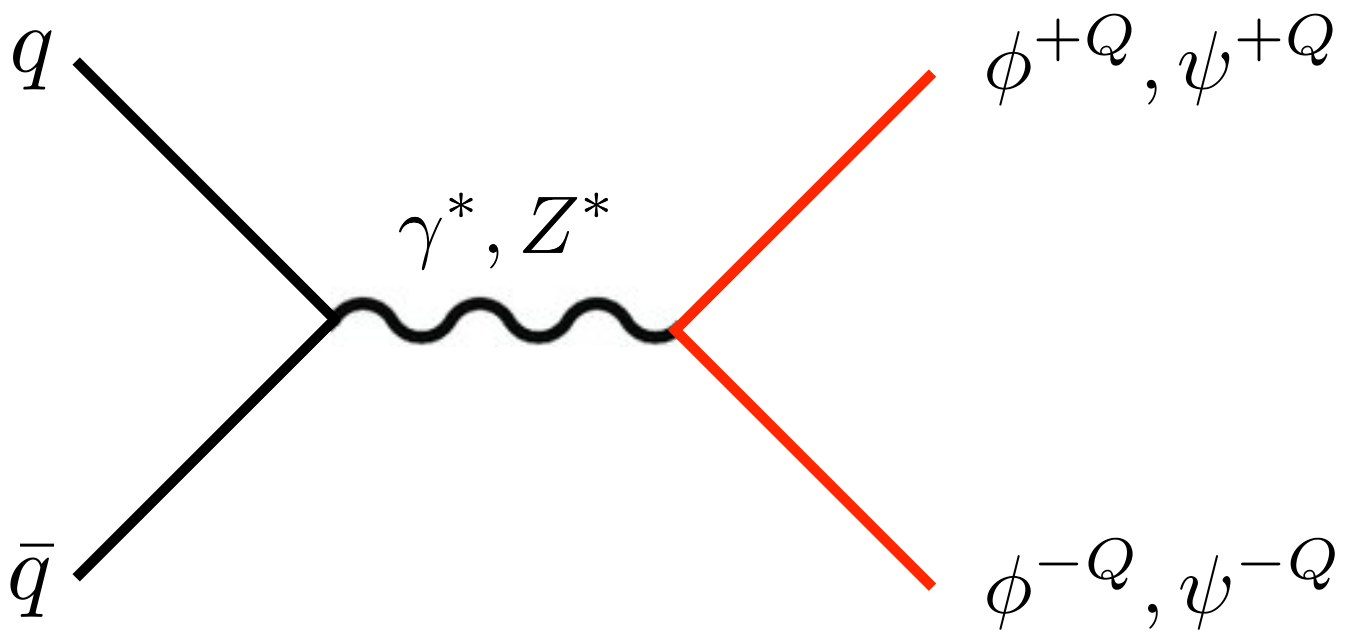


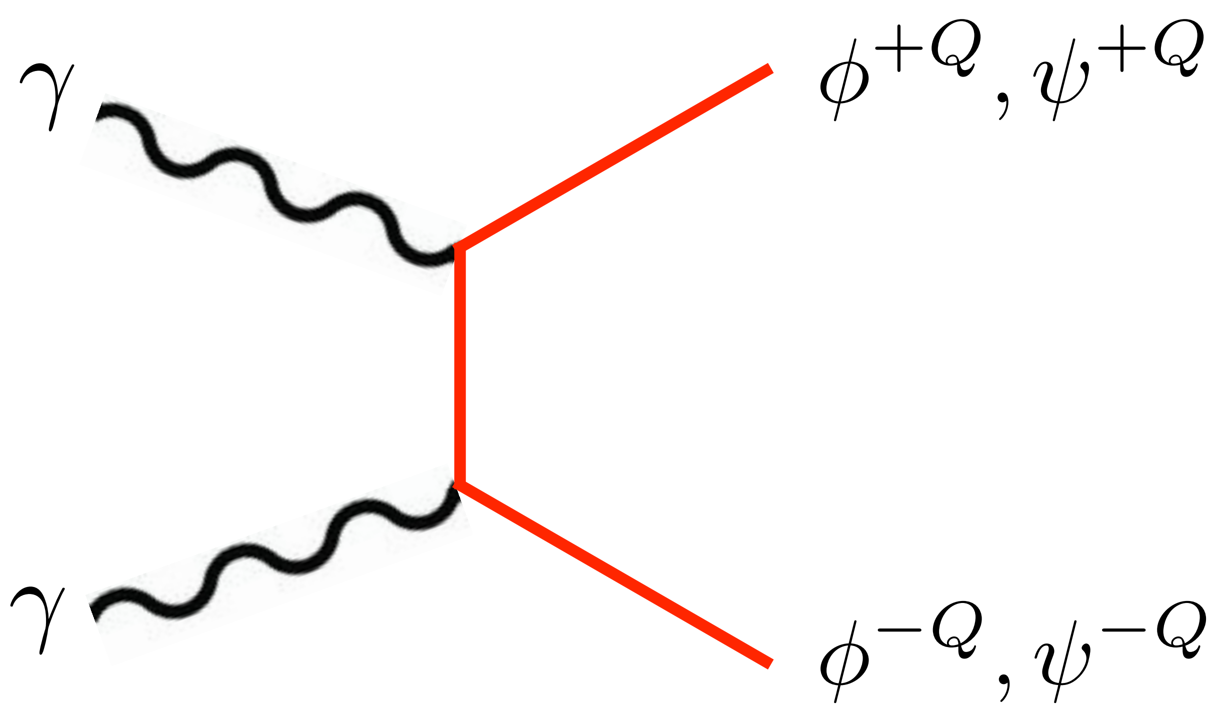
t-channel
photon fusion

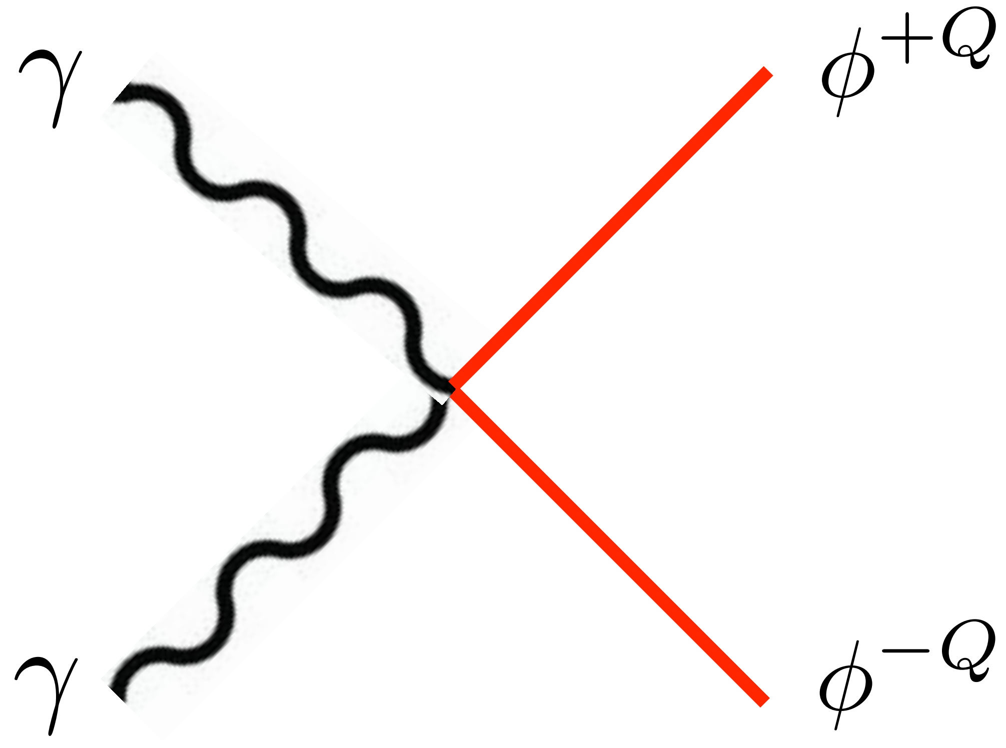


seagull
photon fusion
(scalar only)

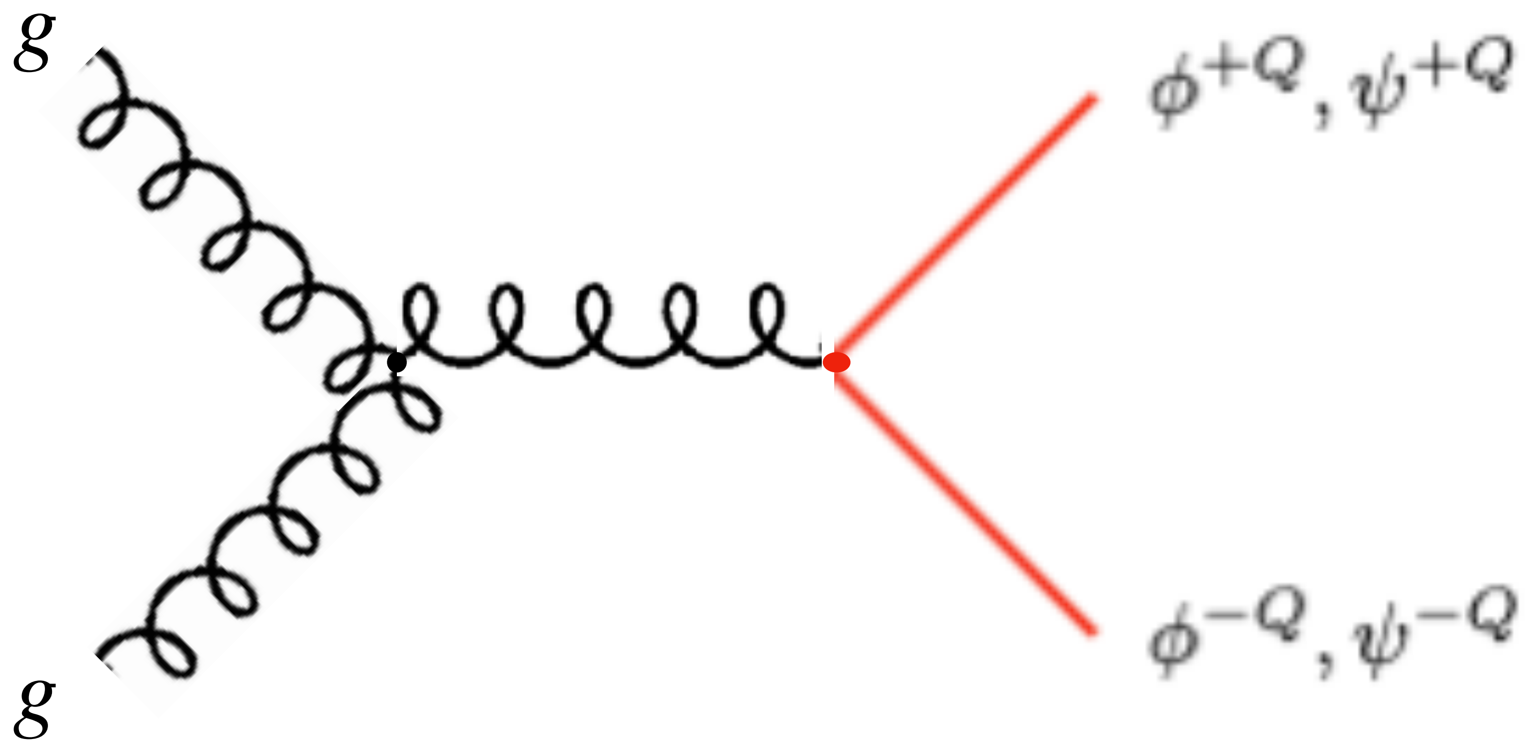
colour singlet/triplet

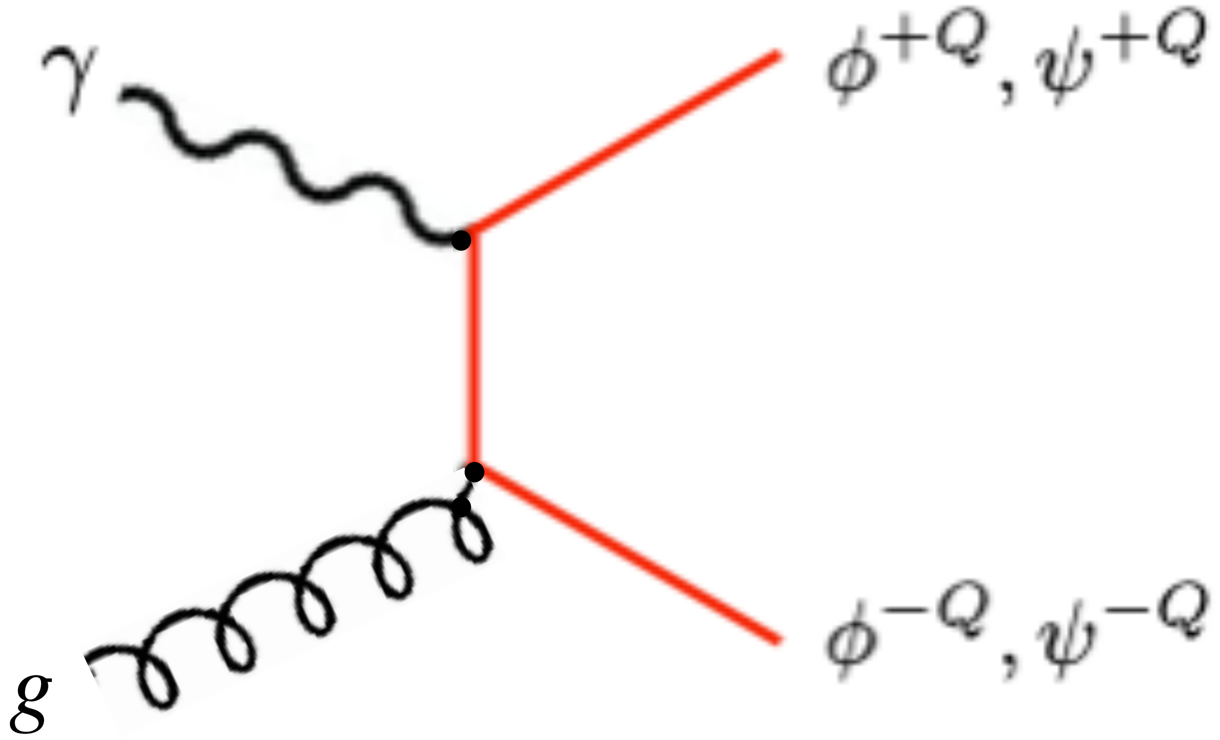


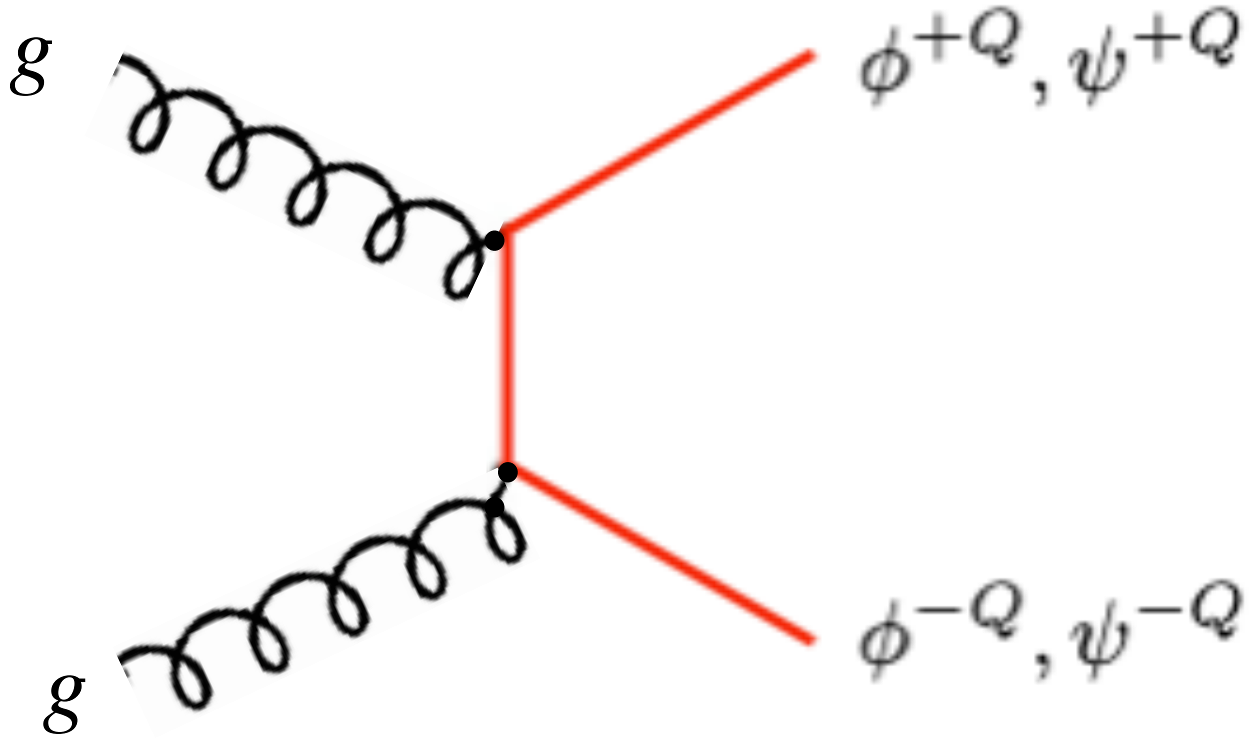




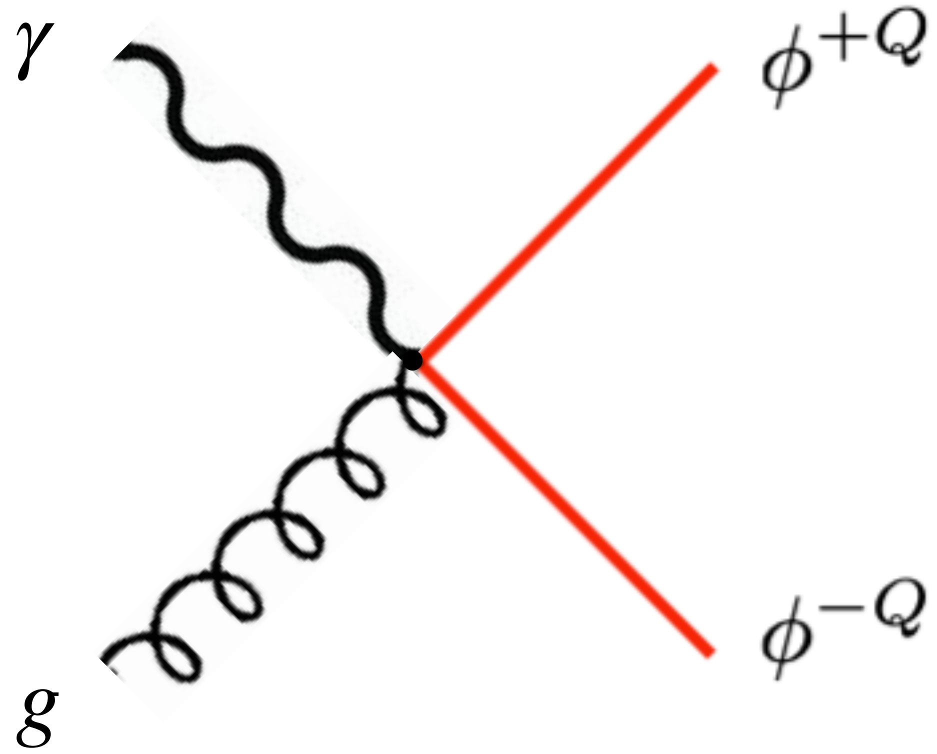
colour triplet

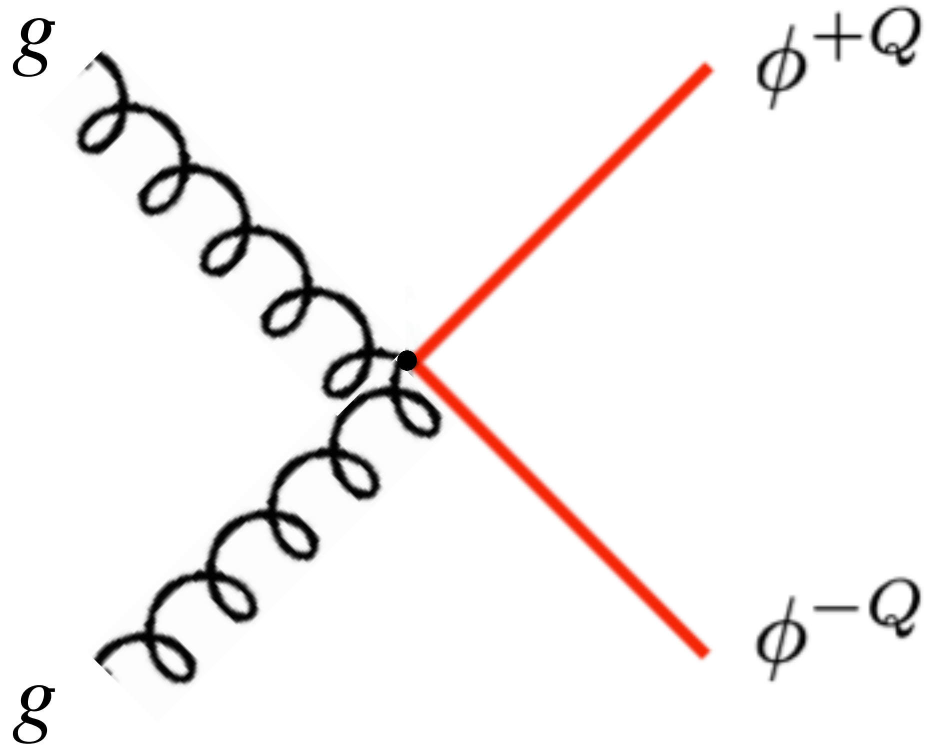






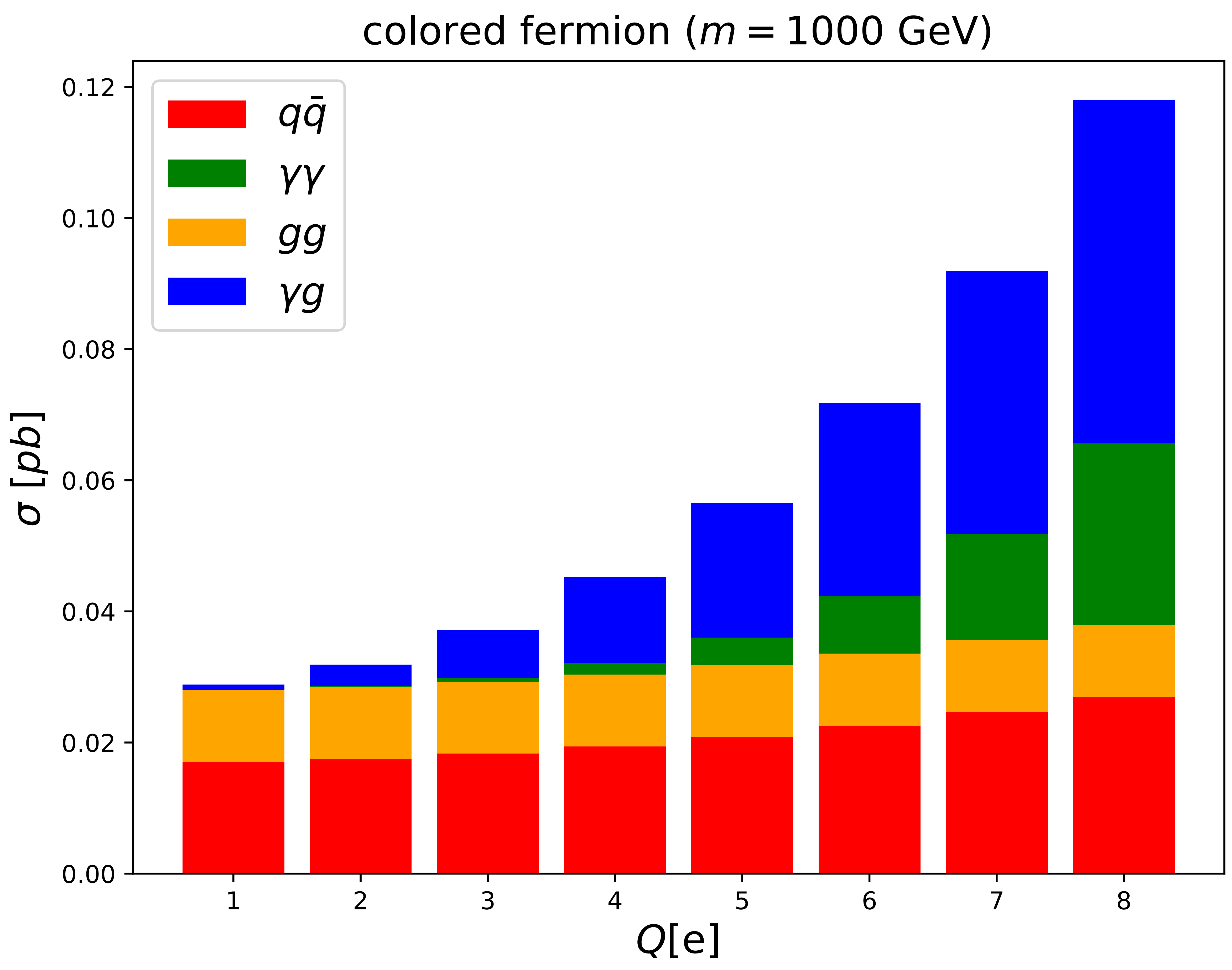
scalars only





Production processes involving photons do matter

Decomposition of pair-production cross-section for color-triplet fermion with 1TeV mass (tree level, MG5)



Production processes involving photons do matter

For low charges DY and gluon fusion processes are dominant.

Experimental searches so far interpret results for DY processes.
[1609.08382;1305.0491;1504.04188]

For larger charges contribution from photon and photon-gluon fusion becomes as relevant as pure QCD production.

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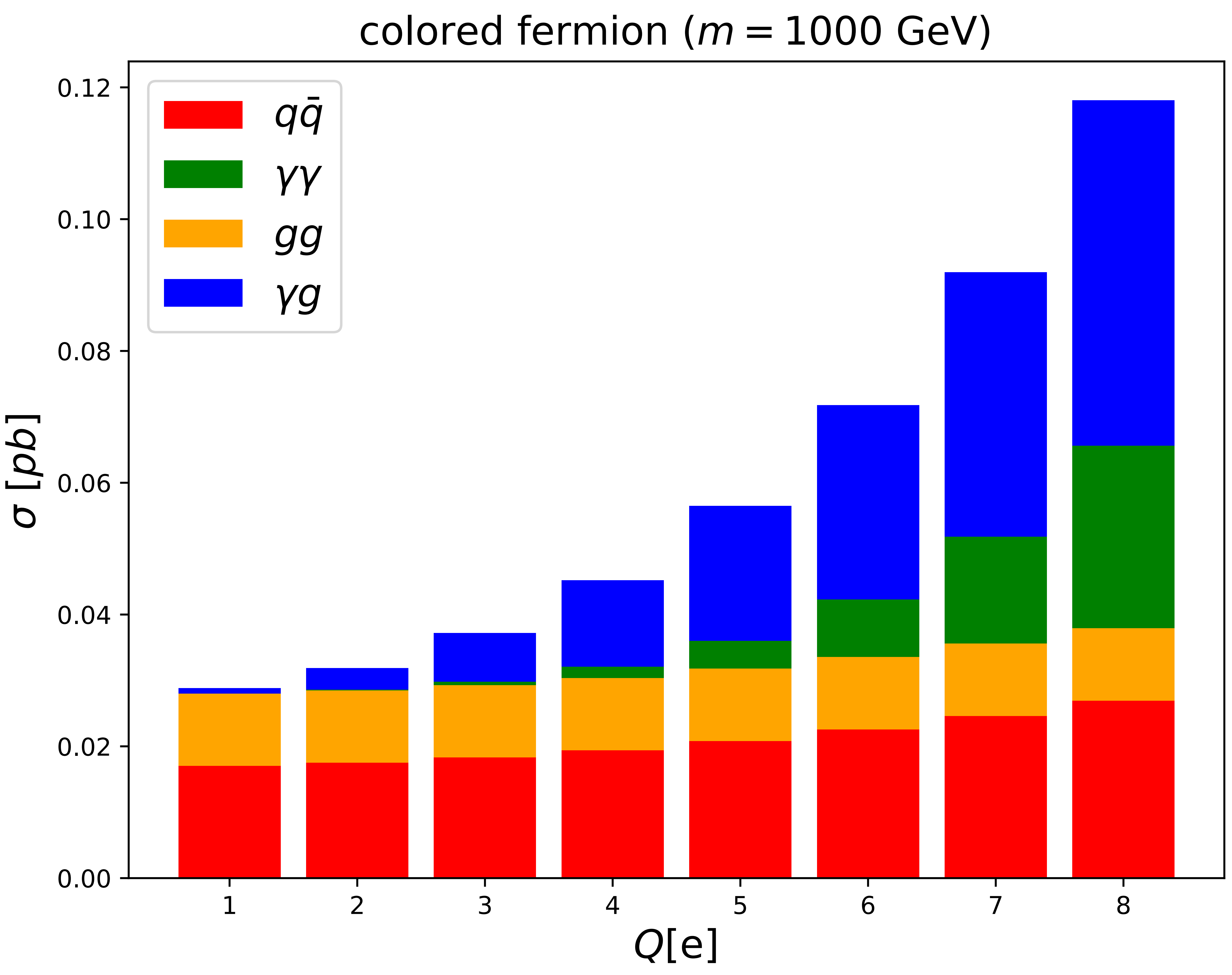

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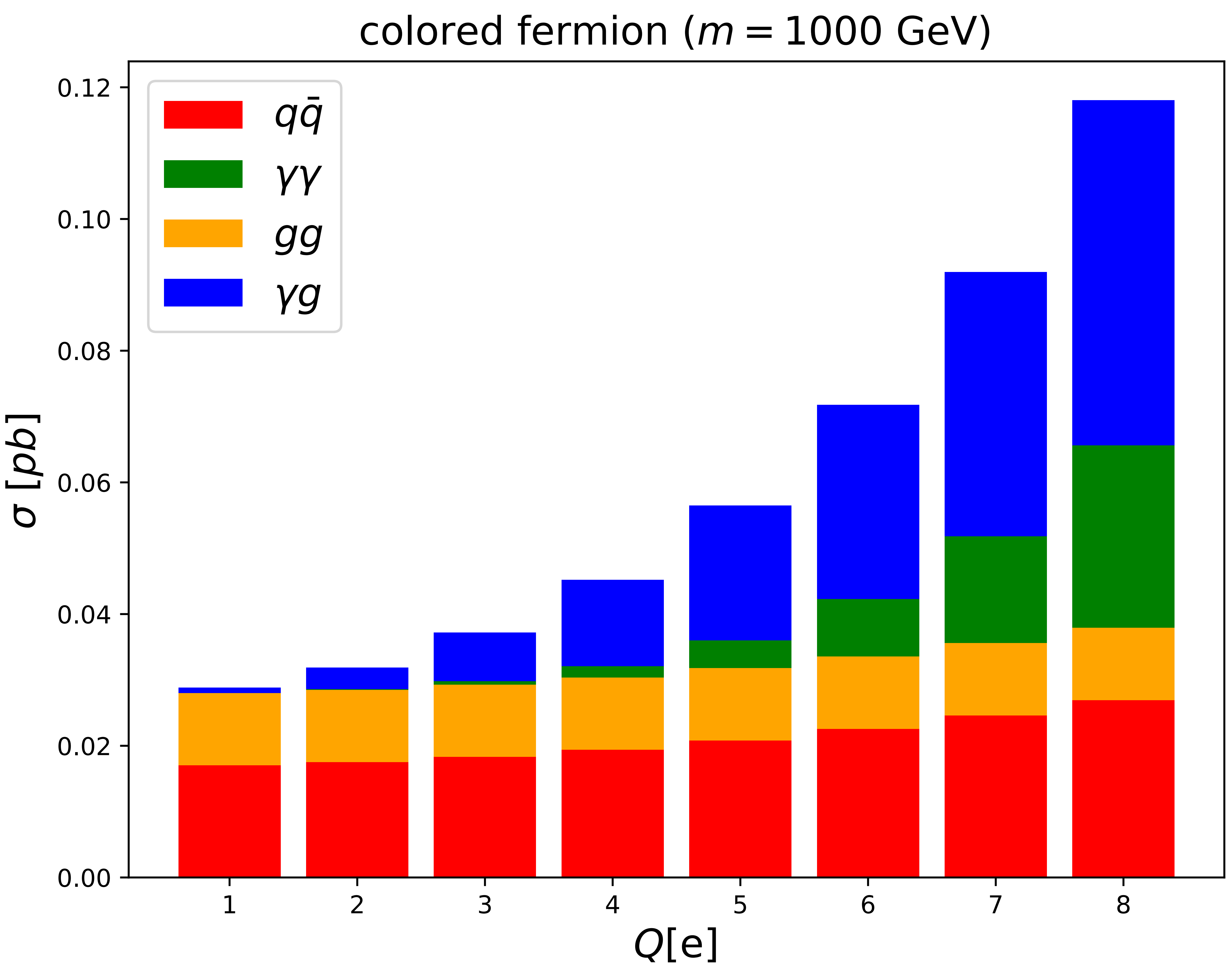
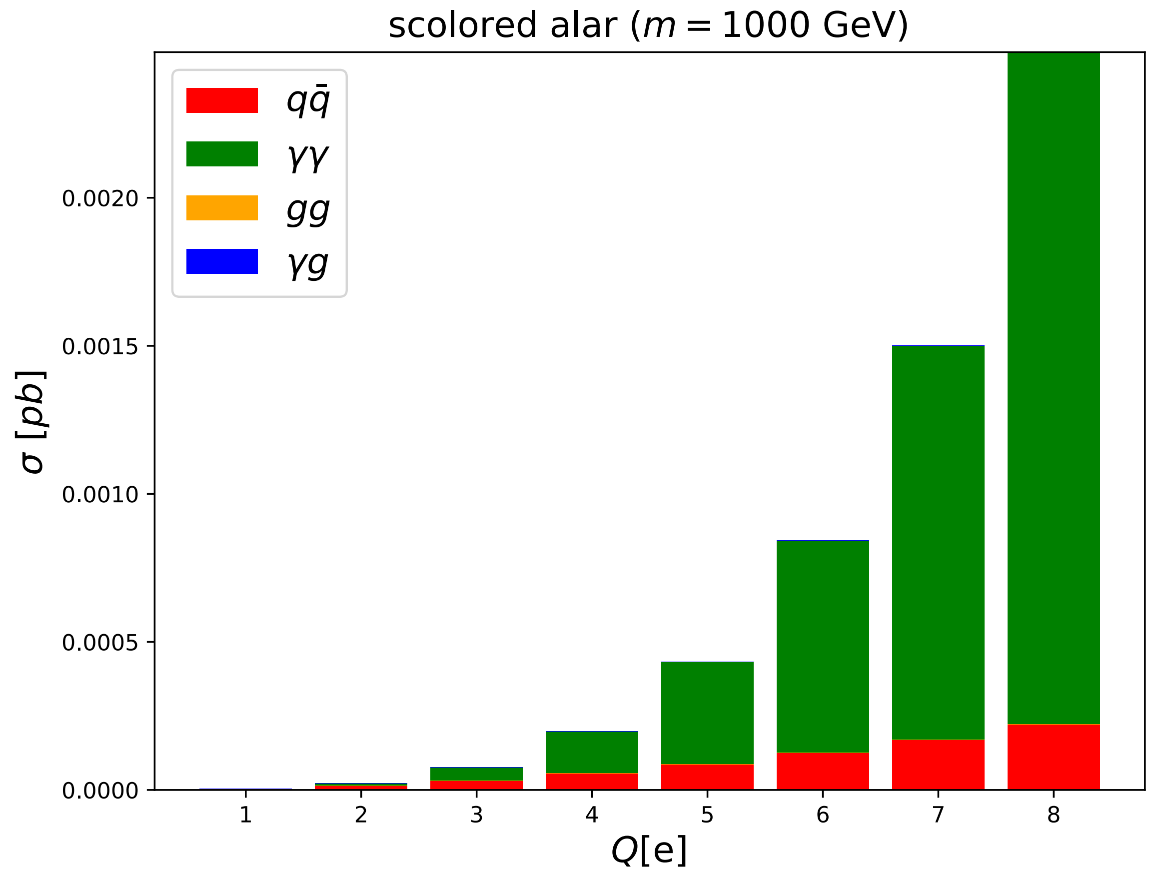
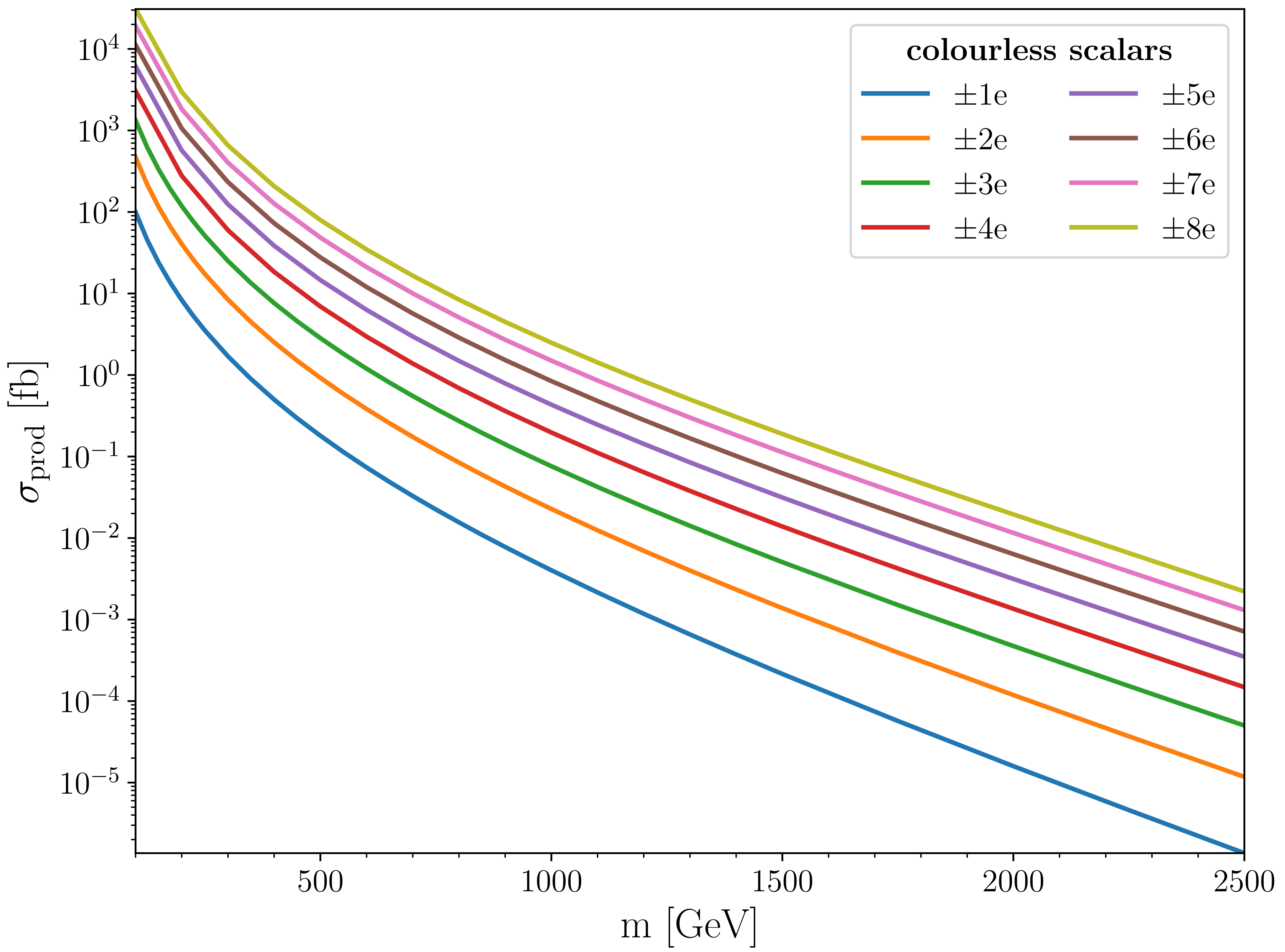


In color singlet case, the impact is also big.

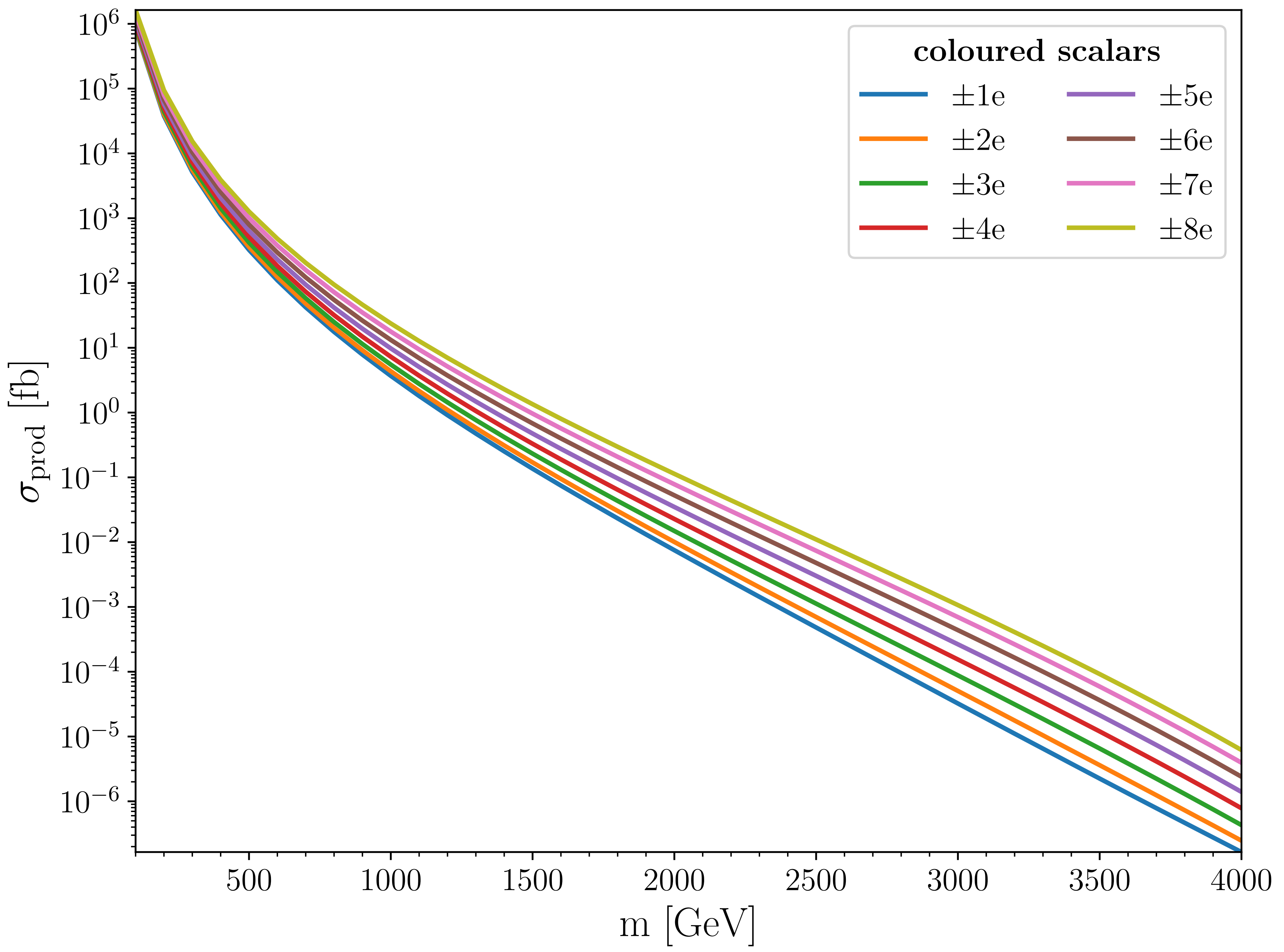


The choice of PDF is crucial! [C. Arbelaez et al.,2003.11494]
(We use LUXqed17)

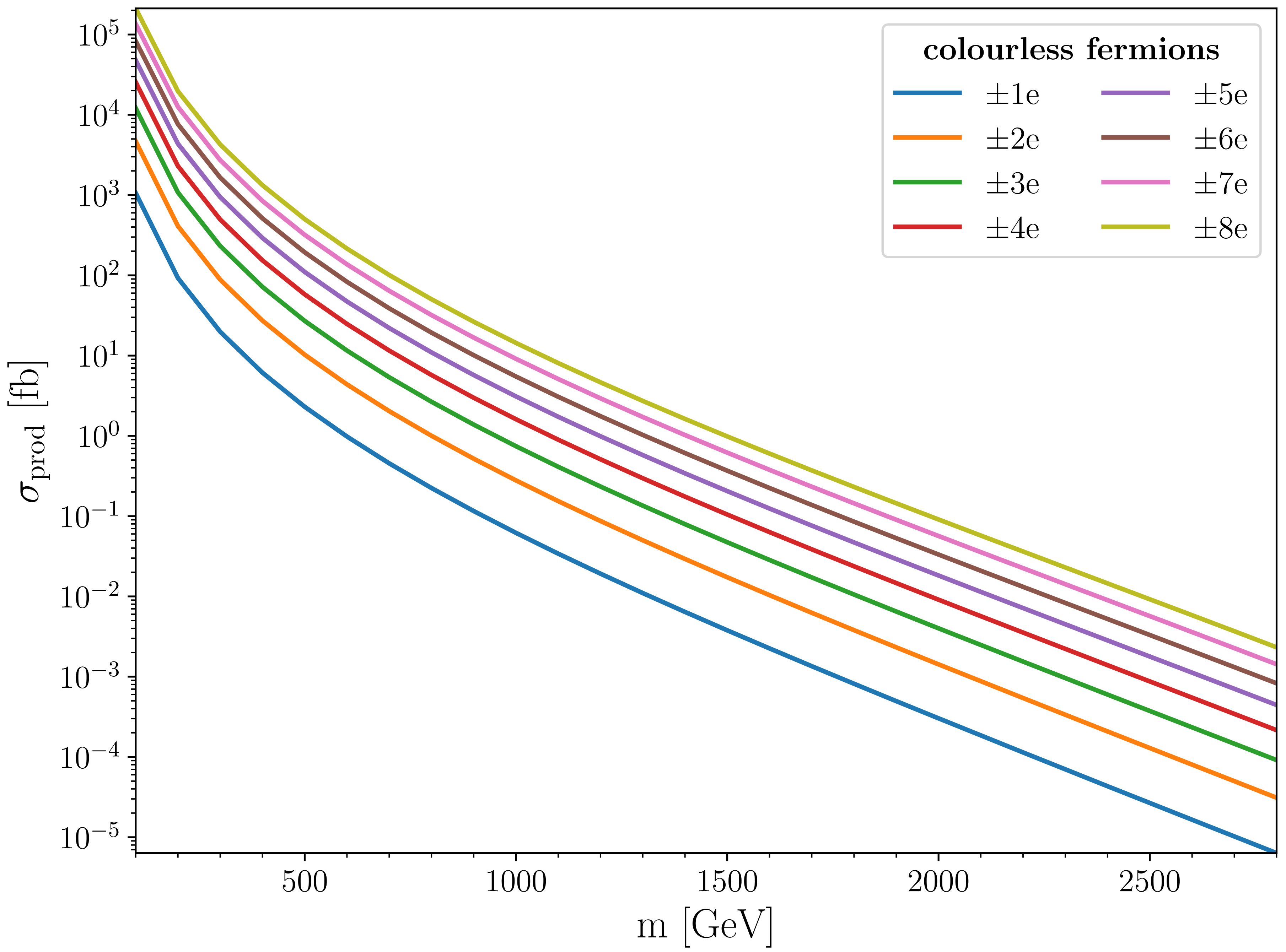
colourless scalars



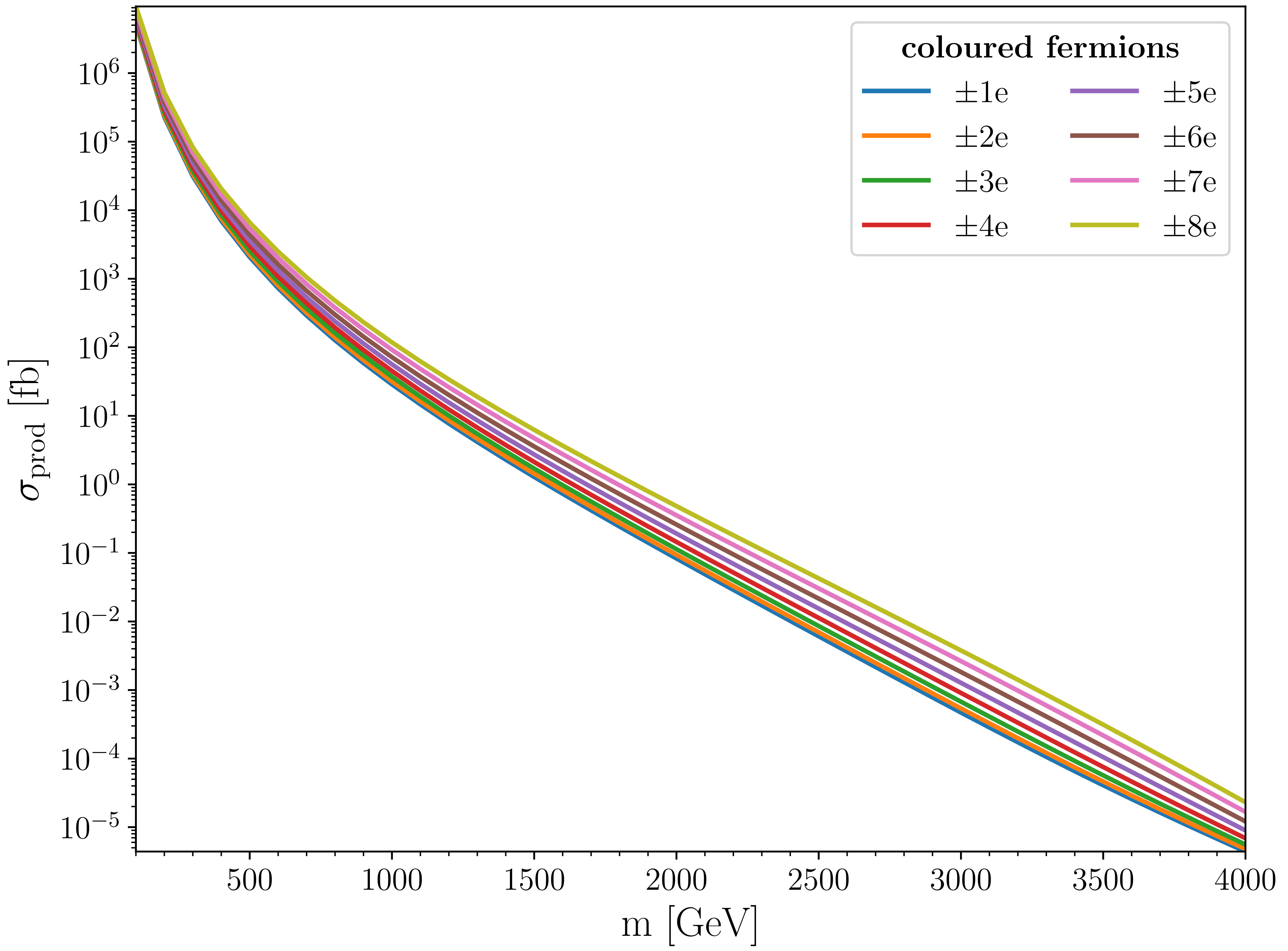
coloured scalars



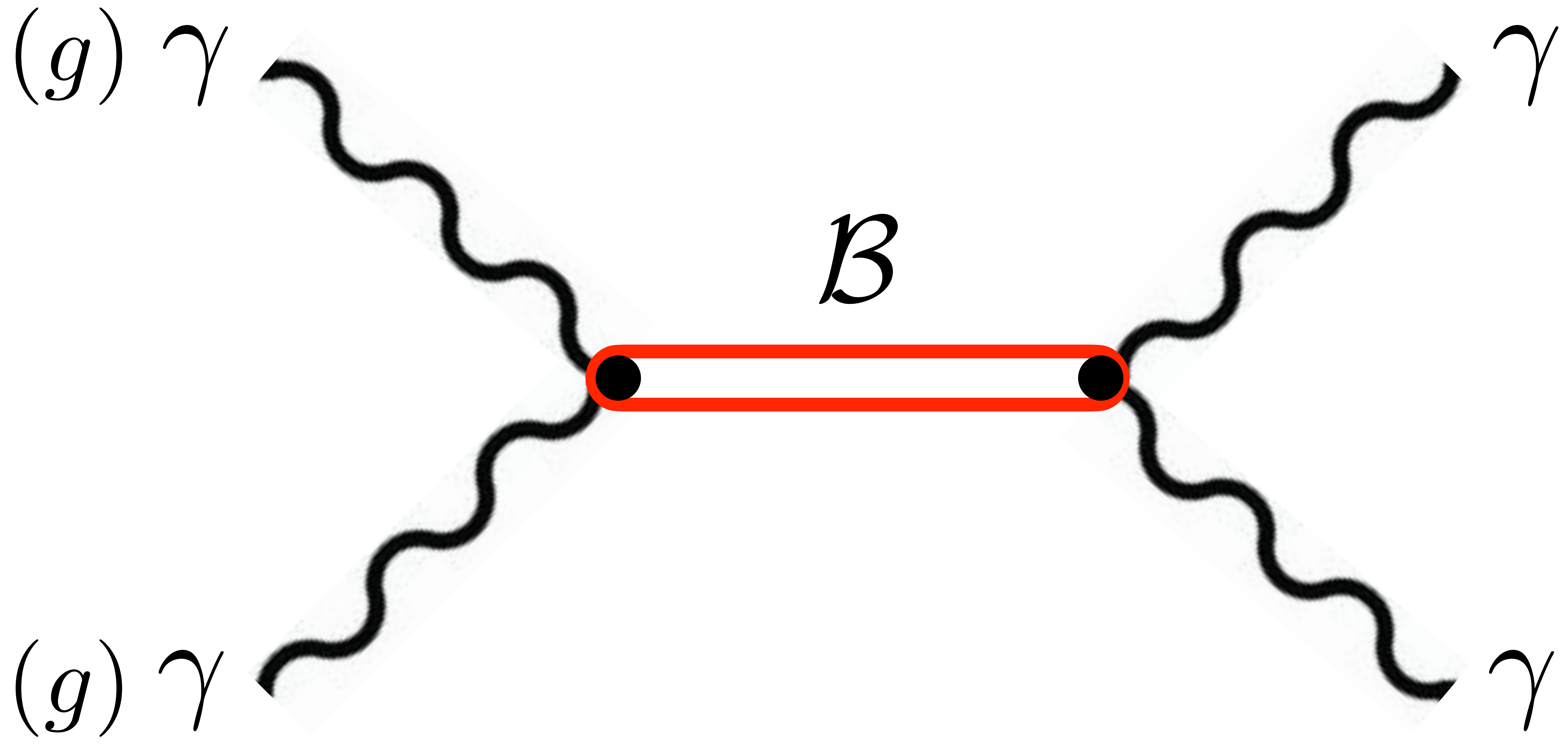
colourless fermions



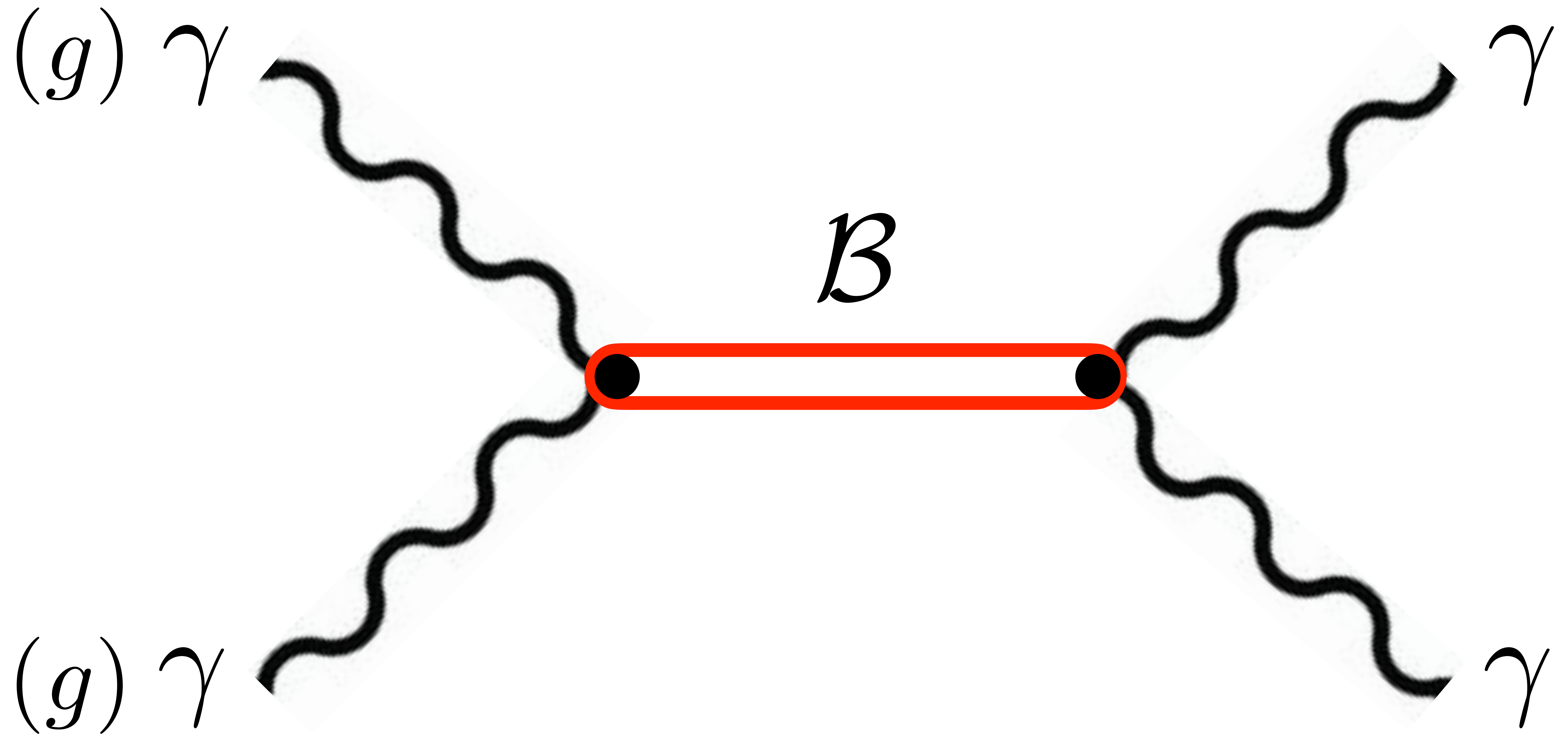
coloured fermions



Bound states



Bound states



- Strong and EM interactions allow to produce a bound state B made of new particles
- B with J=0, 2 can decay to $\gamma\gamma$, γZ, ZZ, (gg)
- B with J=1 can decay to $W^+ W^-$ or $f\bar{f}$
- The di-photon searches are most sensitive, hence we consider only them
- B can be colour singlet or octet, but octet production is subdominant and it cannot decay to di-photon
- We consider only colour singlet J=0, because J=1 cannot decay to 2γ; contribution of J=2 is subdominant.

Bound state. Cross-section calculation.

$$V(\vec{r}) = -\frac{C\alpha_s(r^{-1}) + Q^2\alpha}{r}$$

non-relativistic approximation → Schroedinger equation

↓

hydrogen atom-like solutions $\Psi_{nlm}(\vec{r})$

↓

$$P \propto |\Psi_{nlm}(0)|^2$$

non-vanishing only for s-wave (l=m=0)

narrow width approximation ←

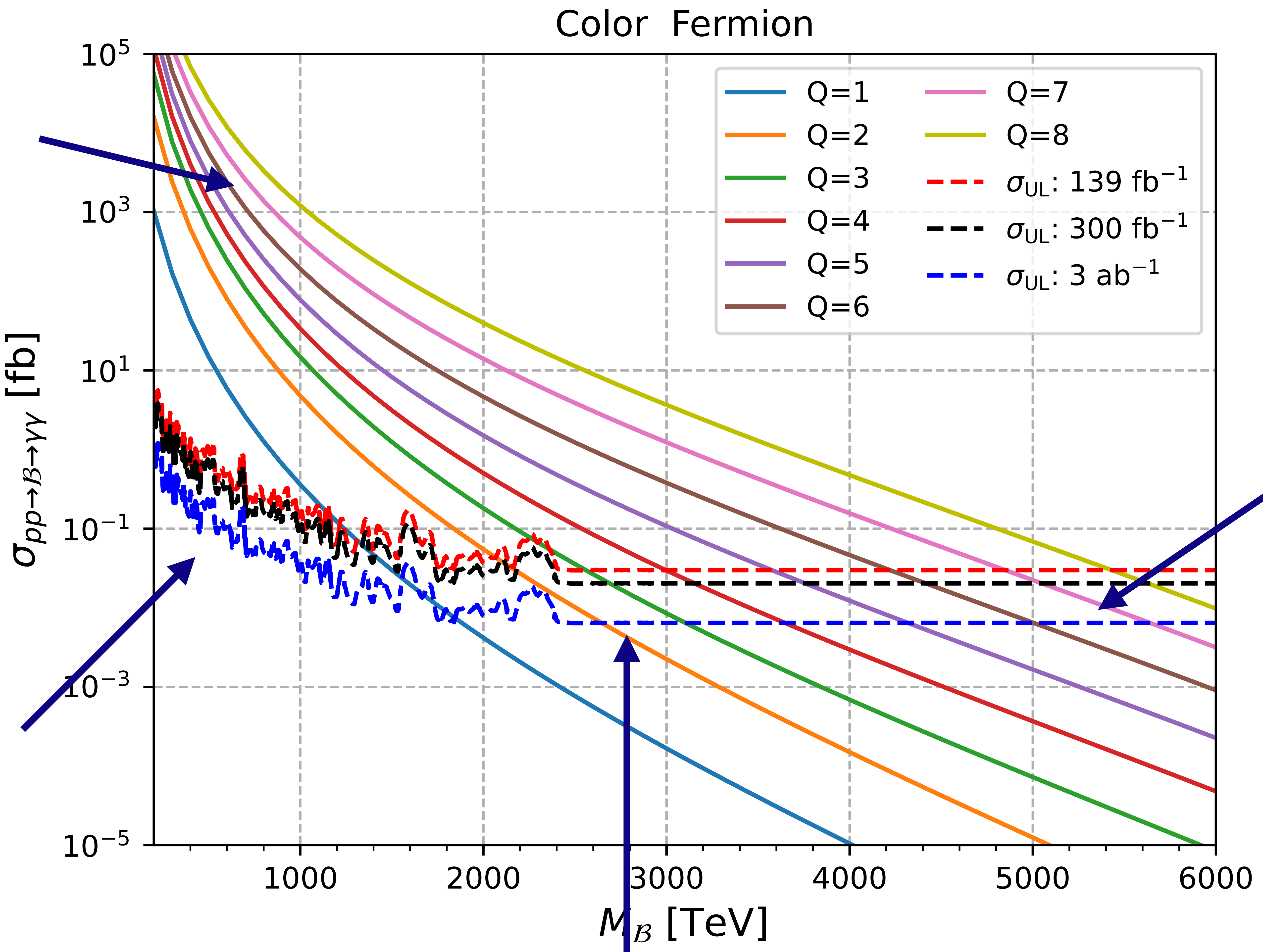
$$\sigma_{pp\to\mathcal{B}\to\gamma\gamma} = \sigma_{pp\to\mathcal{B}} \cdot \mathrm{BR}_{\mathcal{B}\to\gamma\gamma}$$

methodology

Malbork Castle, Poland

Recasting closed channel searches

theoretical cross-section $pp \to \mathscr{B} \to \gamma\gamma$



extrapolation to larger masses

experimental limits from resonance di-photon search

[ATLAS 2102.13405]

search range ends at $M_B = 2.8$ TeV

Recasting open channel searches

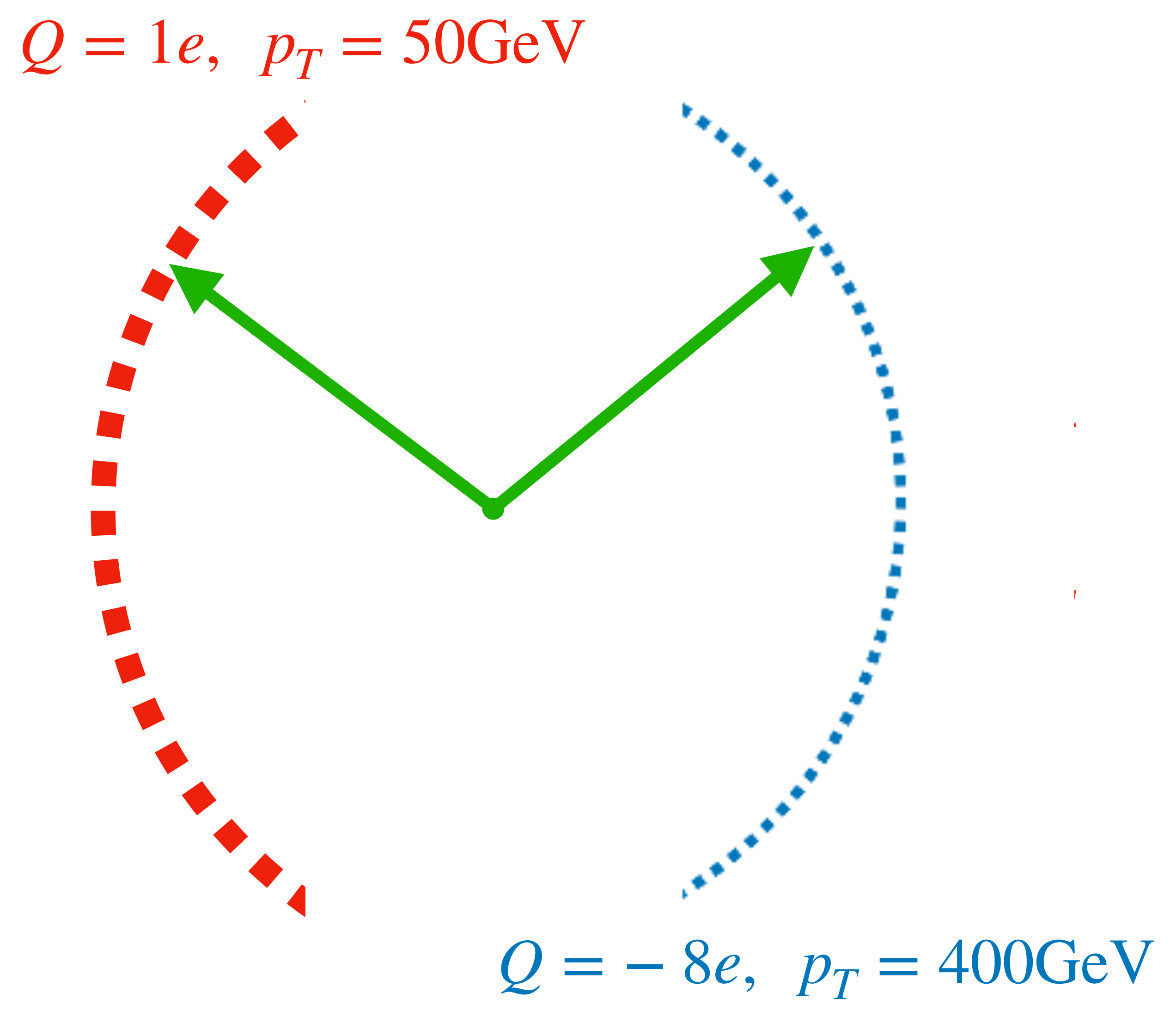
$$\sigma_{\text{eff}} = \left(\epsilon_{\text{online}} \cdot \epsilon_{\text{offline}}\right) \cdot \sigma_{\text{BSM}}$$

$$|\eta| < 2.1$$

$$p_T^{\text{TRUE}} \geq 50 \cdot |Q| \, GeV$$

$$t_{TOF} - \frac{x_{\text{trigger}}}{c} < \begin{cases} 50 \; ns & (|\eta| < 1.6) \\ 25 \; ns & (1.6 \leq |\eta| < 2.1) \end{cases}$$

$$p_T^{\text{MEAS}} = \frac{p_T^{\text{TRUE}}}{|Q|}$$



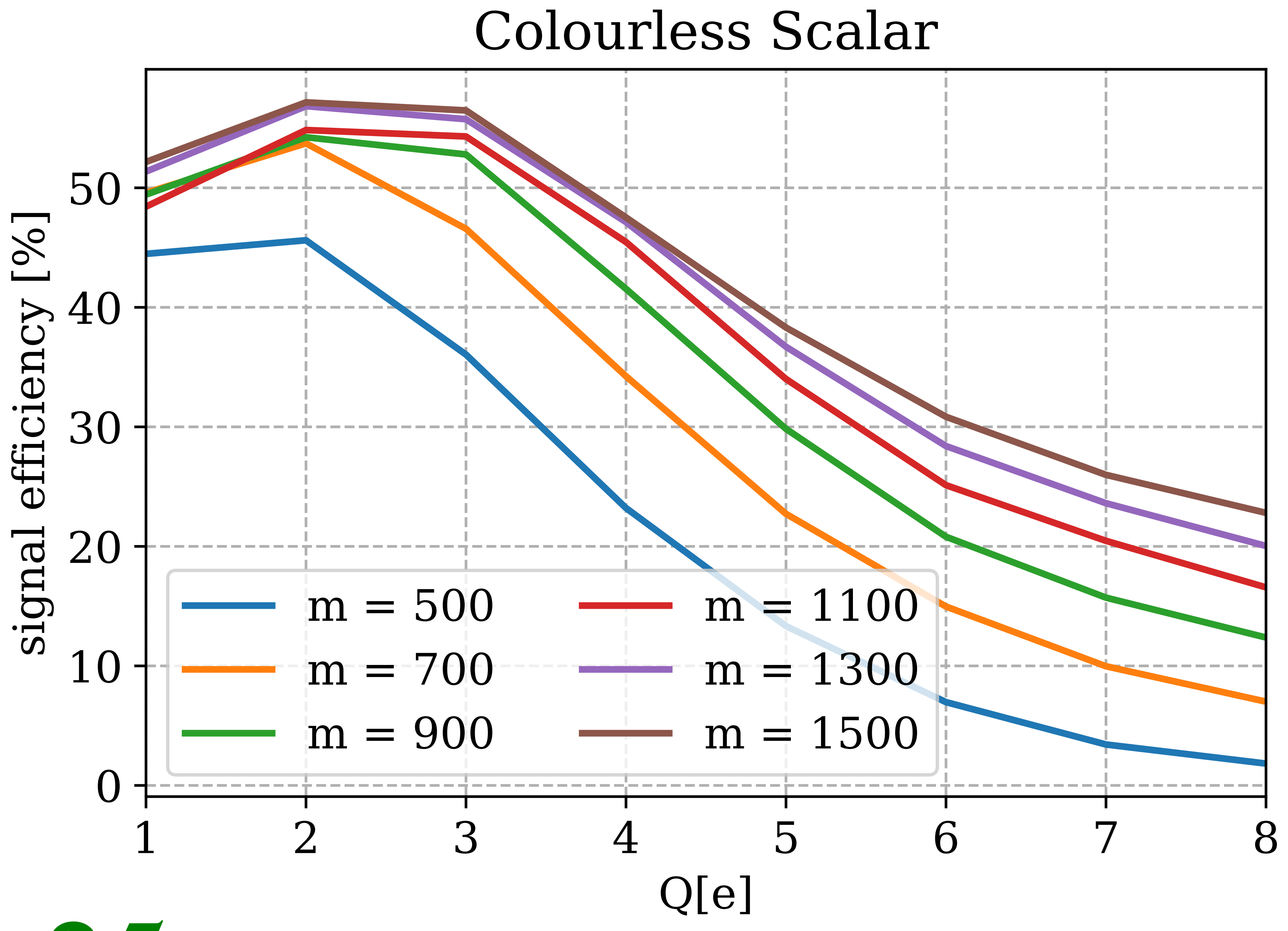
[V. Veeraraghavan, PhD Thesis]
[CMS, 1305.0491 & 1609.08382]

Recasting open channel searches

$$\sigma_{\text{eff}} = \left(\epsilon_{\text{online}} \cdot \epsilon_{\text{offline}}\right) \cdot \sigma_{\text{BSM}}$$

Variable	Type or threshold value
Reconstructed track	Global muon
$\lvert\eta\rvert$	< 2.1
Primary vertex: $\lvert z\rvert$	< 15 cm
Primary vertex: $\sqrt{x^2+y^2}$	< 2 cm
Primary vertex: degrees of freedom	> 3
# Tracker hits (strips and pixels)	> 7
# Pixel hits	> 1
Fraction of valid hits	> 0.80
# $\frac{\Delta E}{\Delta x}$ measurements	> 5
# $1/\beta$ measurements	> 7
# DT- $1/\beta$ OR # CSC- $1/\beta$ measurements	> 5
Global muon track purity	> 1
Global muon track χ^2/dof	< 5.0
p_T	> 45 GeV
I_h	> 3.0 MeV/cm
$\sigma_{\langle 1/\beta\rangle}$	< 0.07
d_{xy}	< 0.5 cm
$\sum_{\Delta R<0.3} p_T$	< 50 GeV
σ_{p_T}/p_T	< 0.25
d_z	< 0.5 cm
$\langle 1/\beta\rangle$	> 1.0

$$p_T^{\text{TRUE}} \geq 65 \cdot |Q/e|\,GeV$$



$$1/\beta_{\text{MS}} > 1.25$$

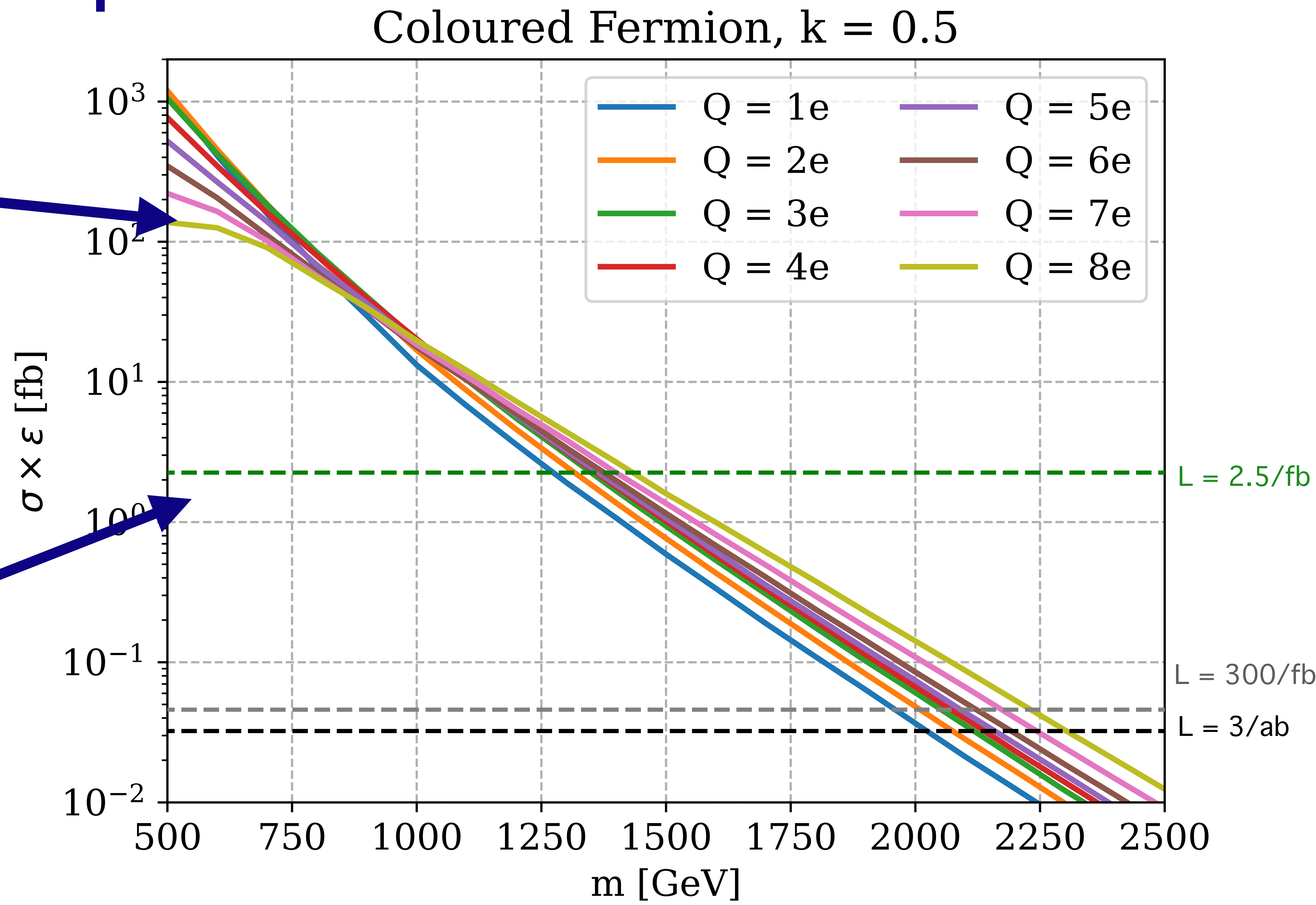
[V. Veeraraghavan, PhD Thesis]

[CMS, 1305.0491 & 1609.08382]

Recasting open channel searches

theoretical effective cross-section

experimental limits (scaled)

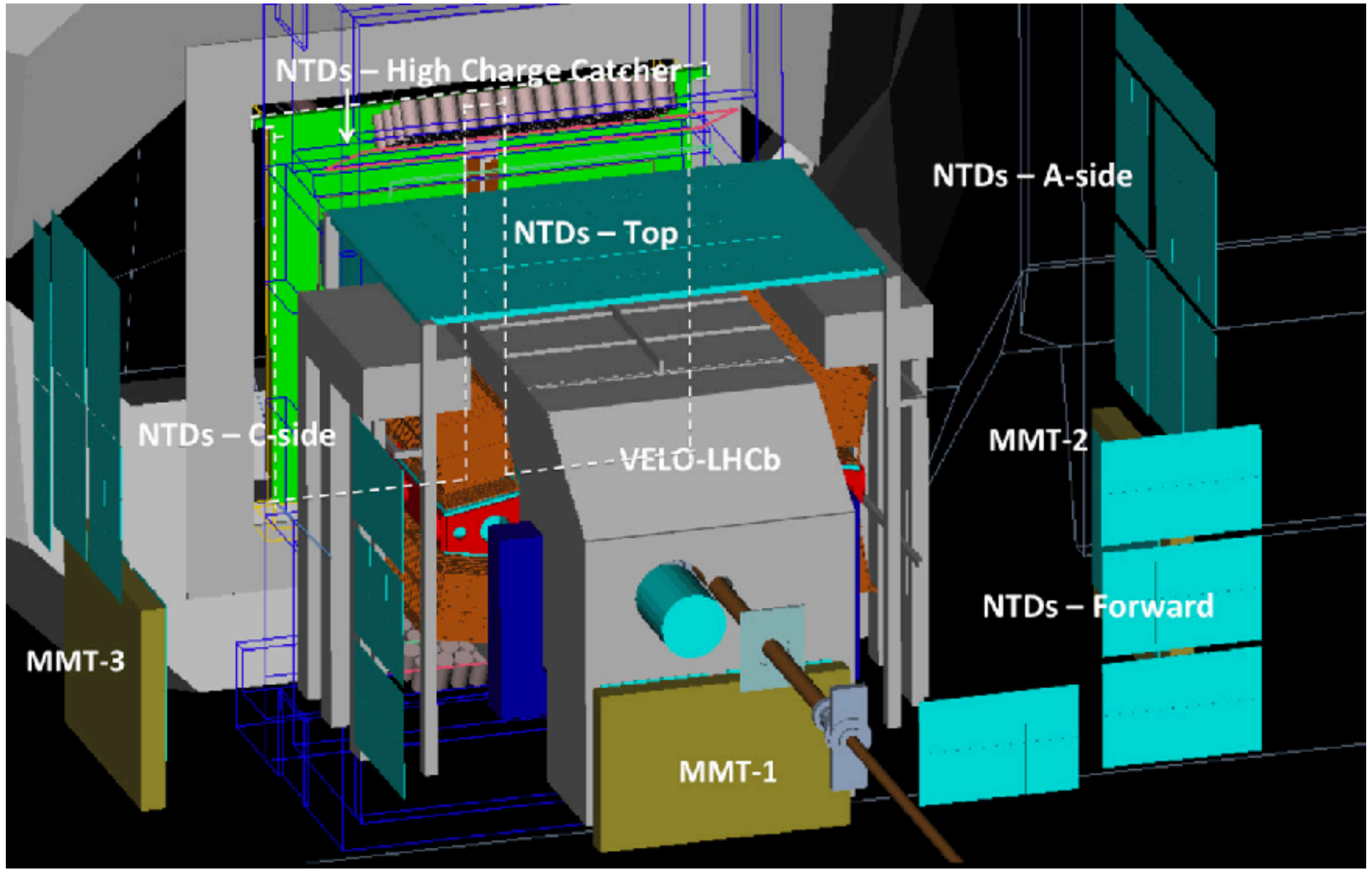


[V. Veeraraghavan, PhD Thesis]

[CMS, 1305.0491 & 1609.08382]

MoEDAL experiment

- MoEDAL is mostly passive detector designed to look for magnetic monopoles
- It is located in LHCb cavern, 2m away from IP8
- For Run-3 luminosity is 30/fb, for HL-LHC it's going to be 300/fb
- MoEDAL is sensitive only to highly-ionising long-lived particles with velocities $\beta \leq 0.15 \cdot |Q|$



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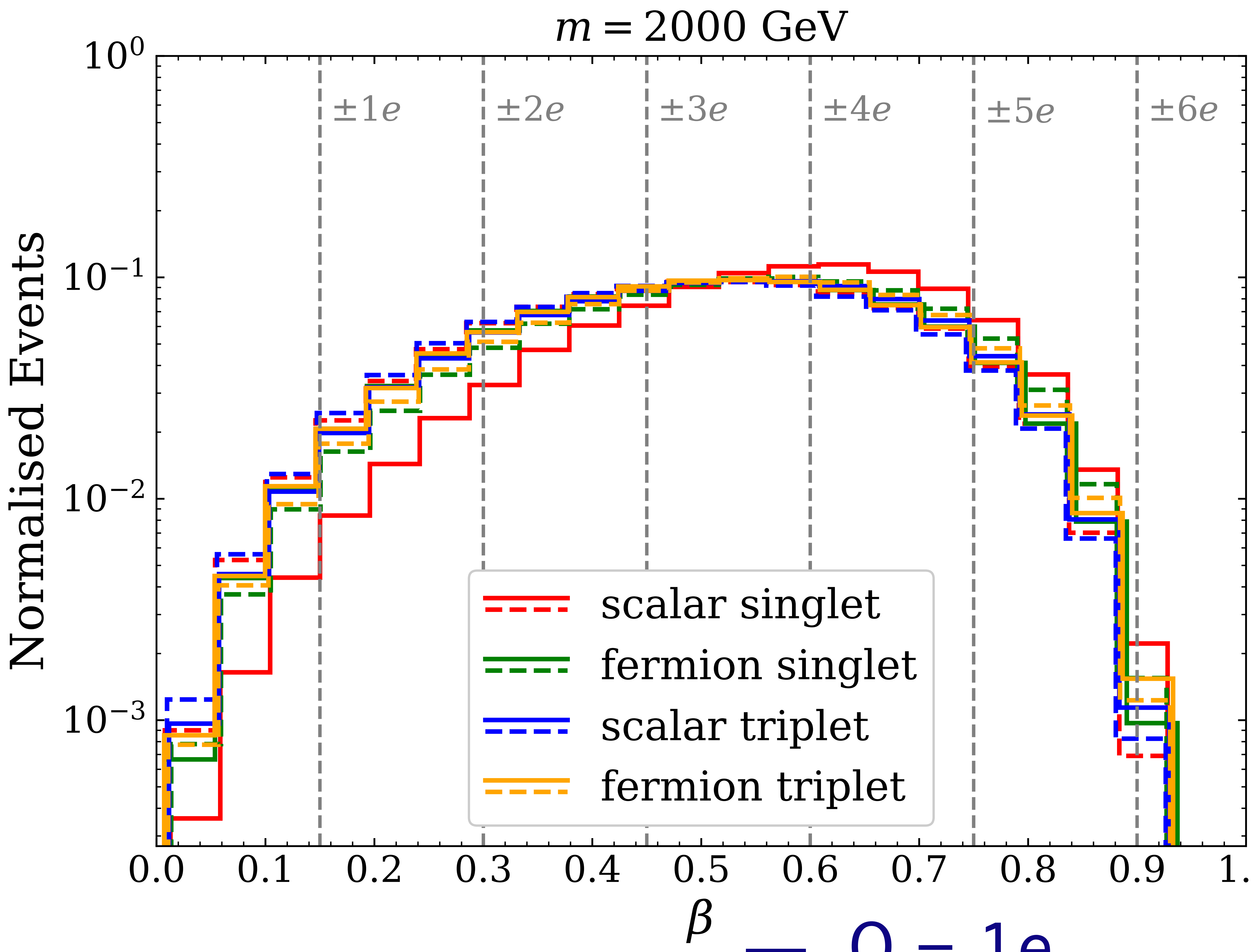
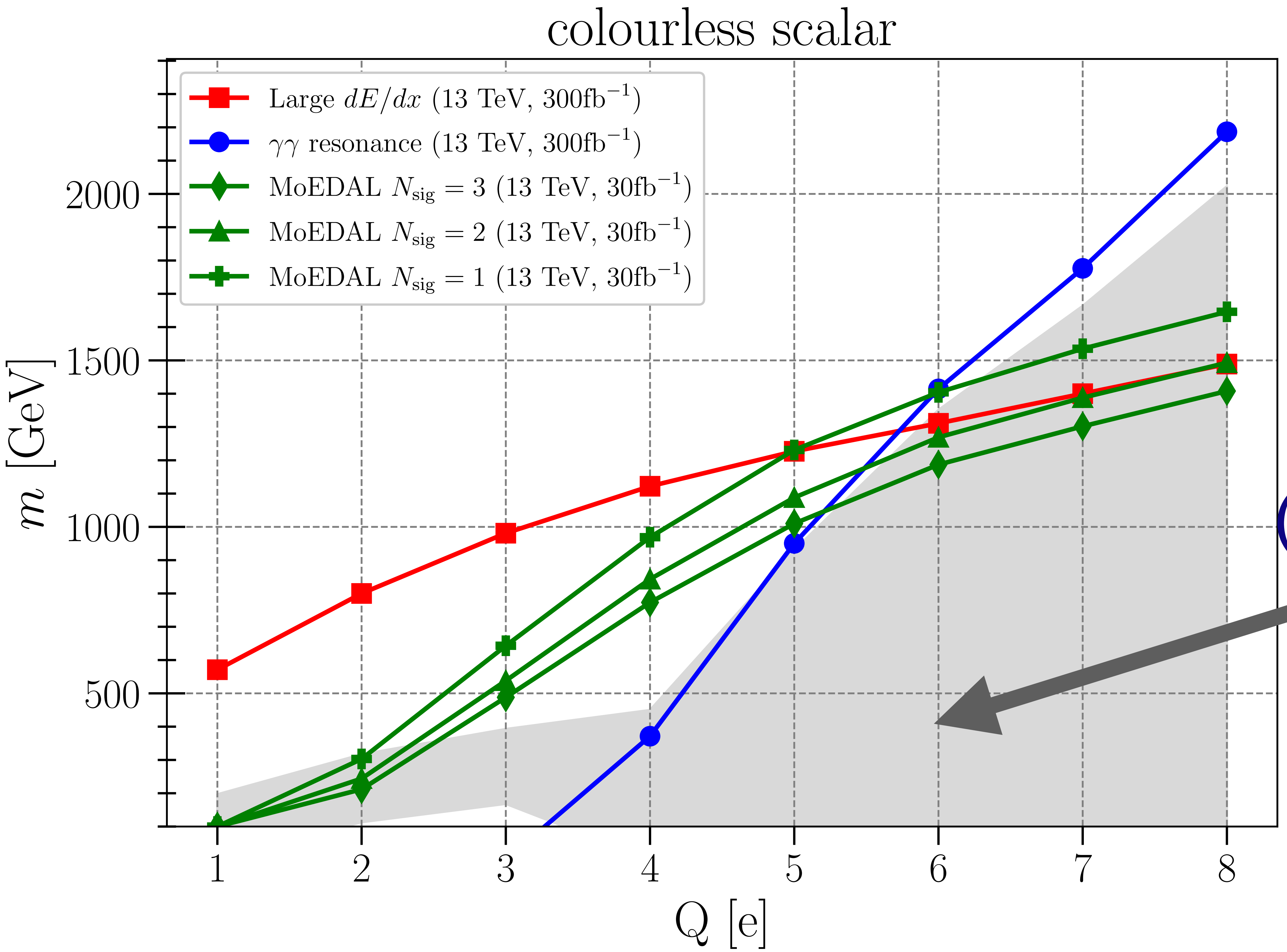
- MoEDAL is sensitive only to highly-ionising long-lived particles with velocities $\beta \leq 0.15 \cdot |Q|$
- For our studies, we treat decay length of our particles as a free parameter
- We calculate expected number of signal events
- Since MoEDAL is background free experiment, detecting few events may mark a discovery
- To compare with ATLAS/CMS we take mass bound in the limit of stable particle



— Q = 1e
-- Q = 8e

Beach in Dębki, Poland

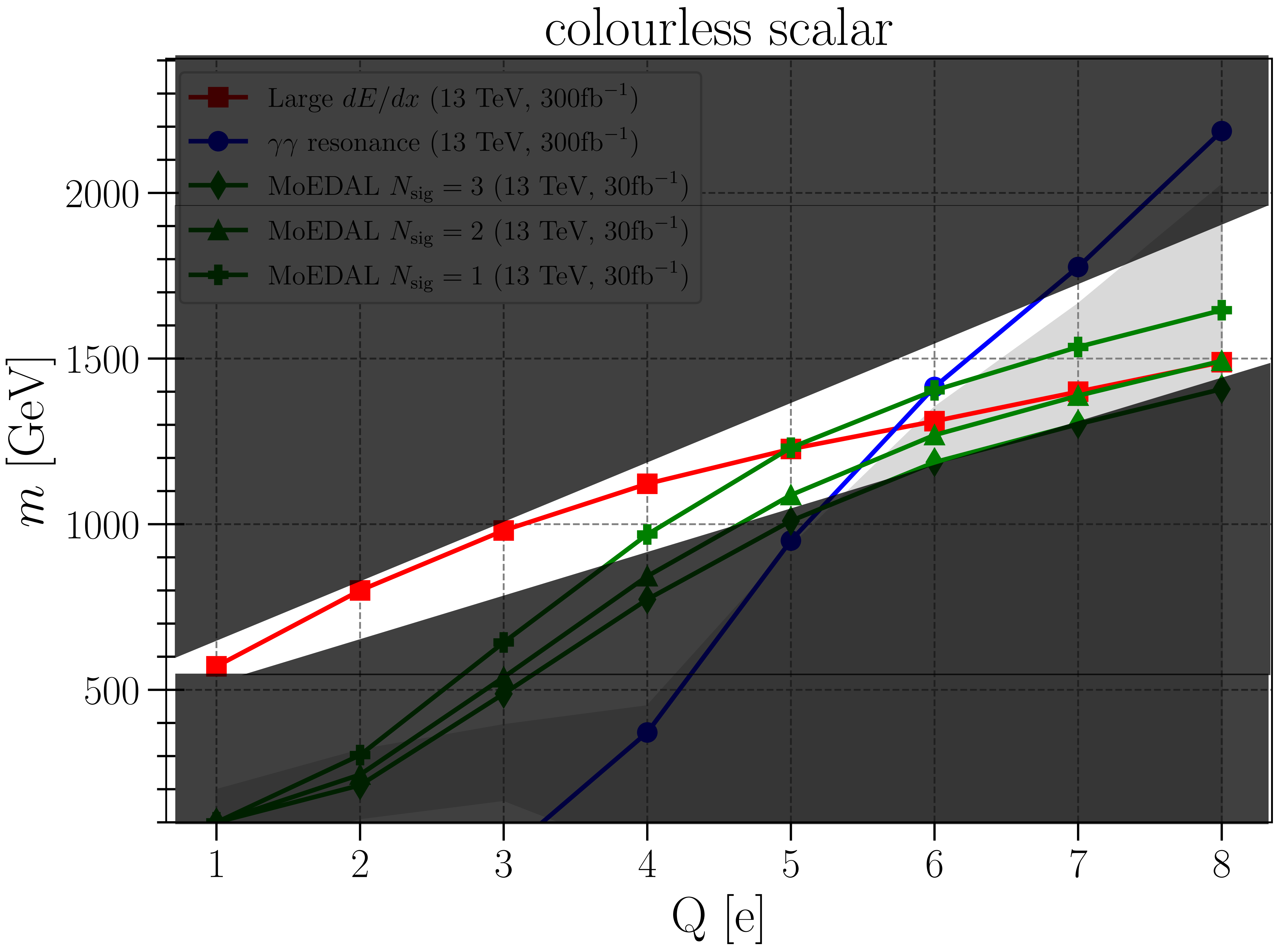
colourless scalars



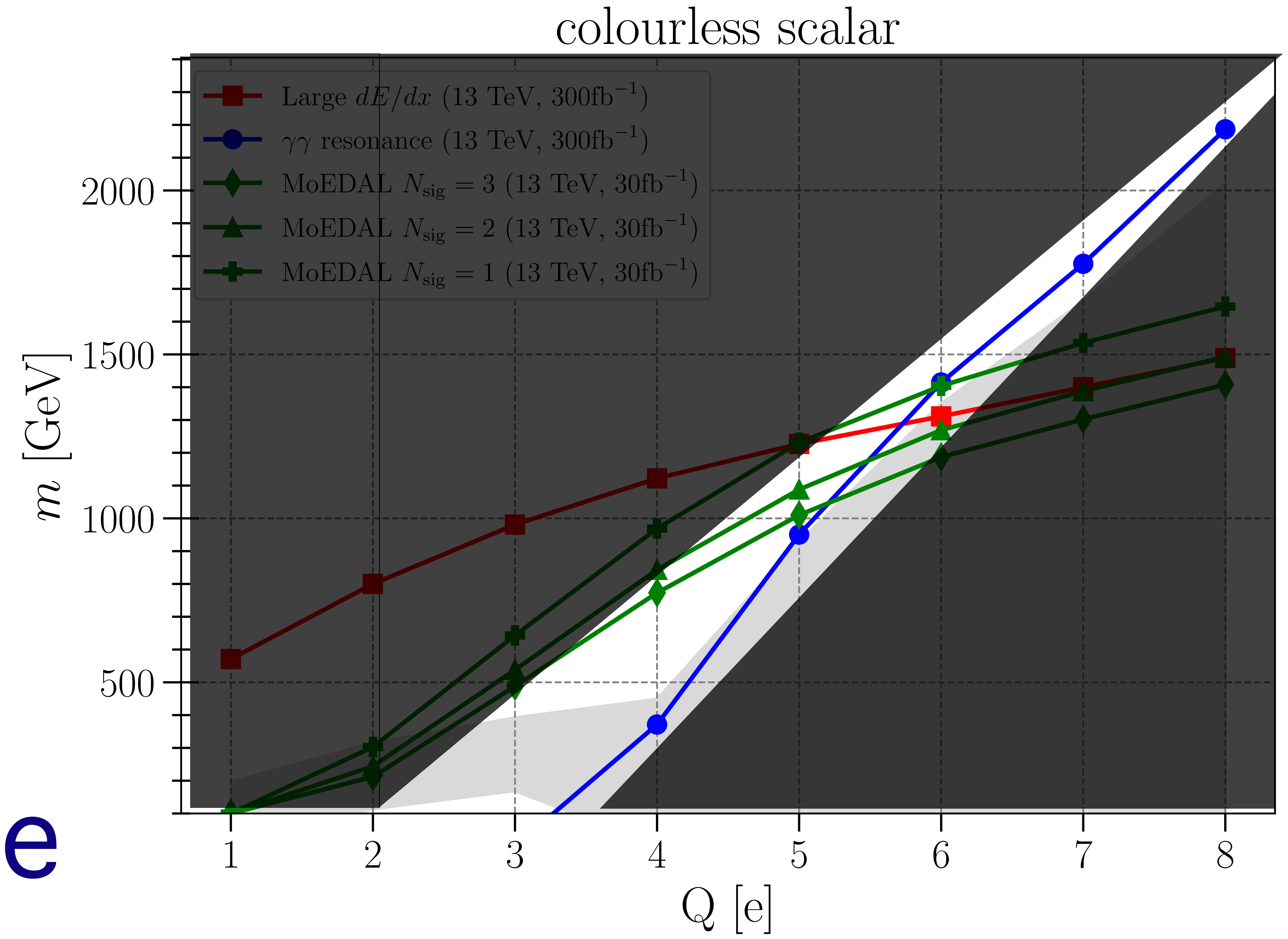
current bound
($\gamma\gamma$ and γg included)

colourless scalars — open channel search

changes moderately with charge



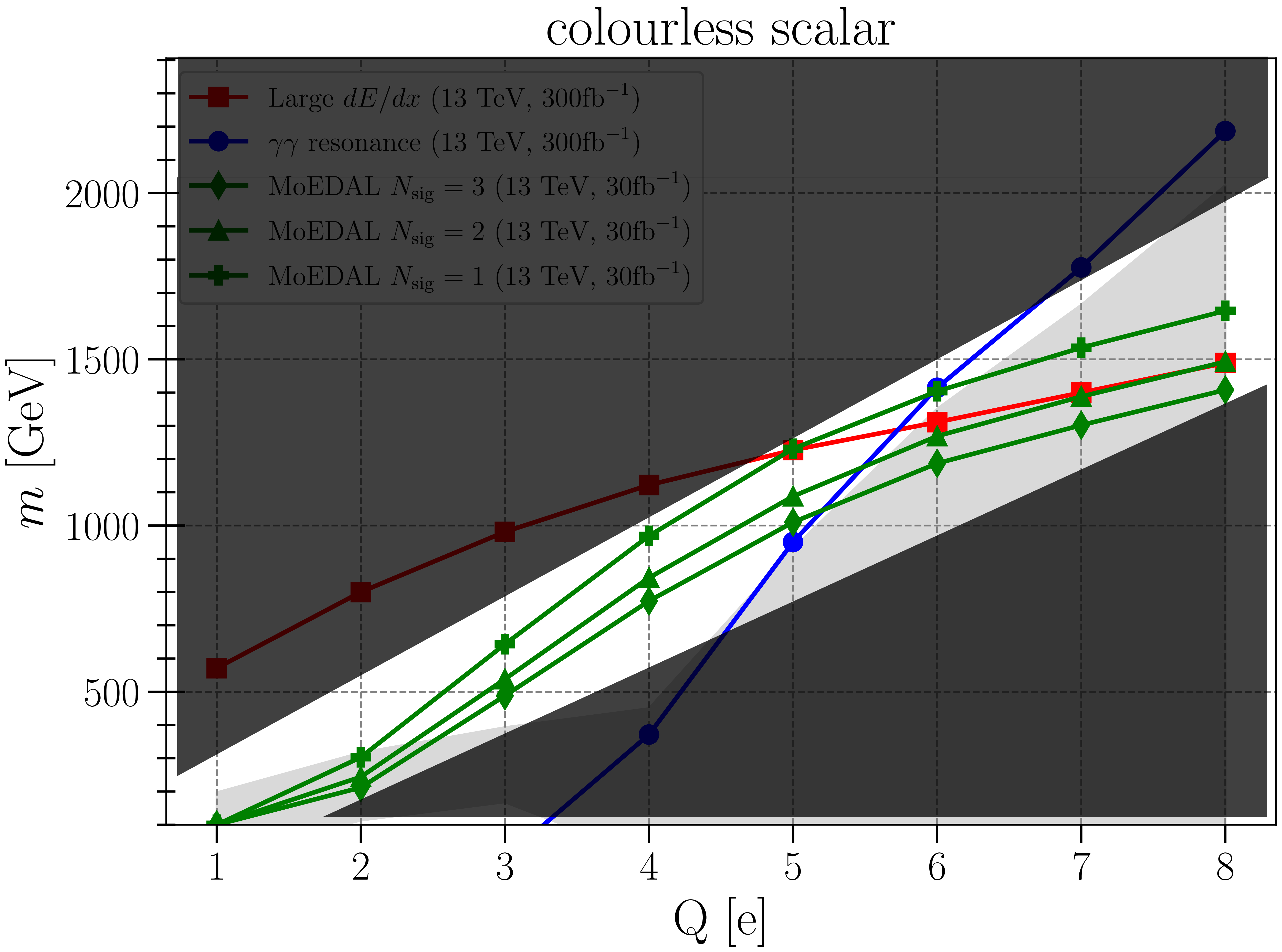
colourless scalars — closed channel search



changes rapidly with charge

not sensitive to low charge

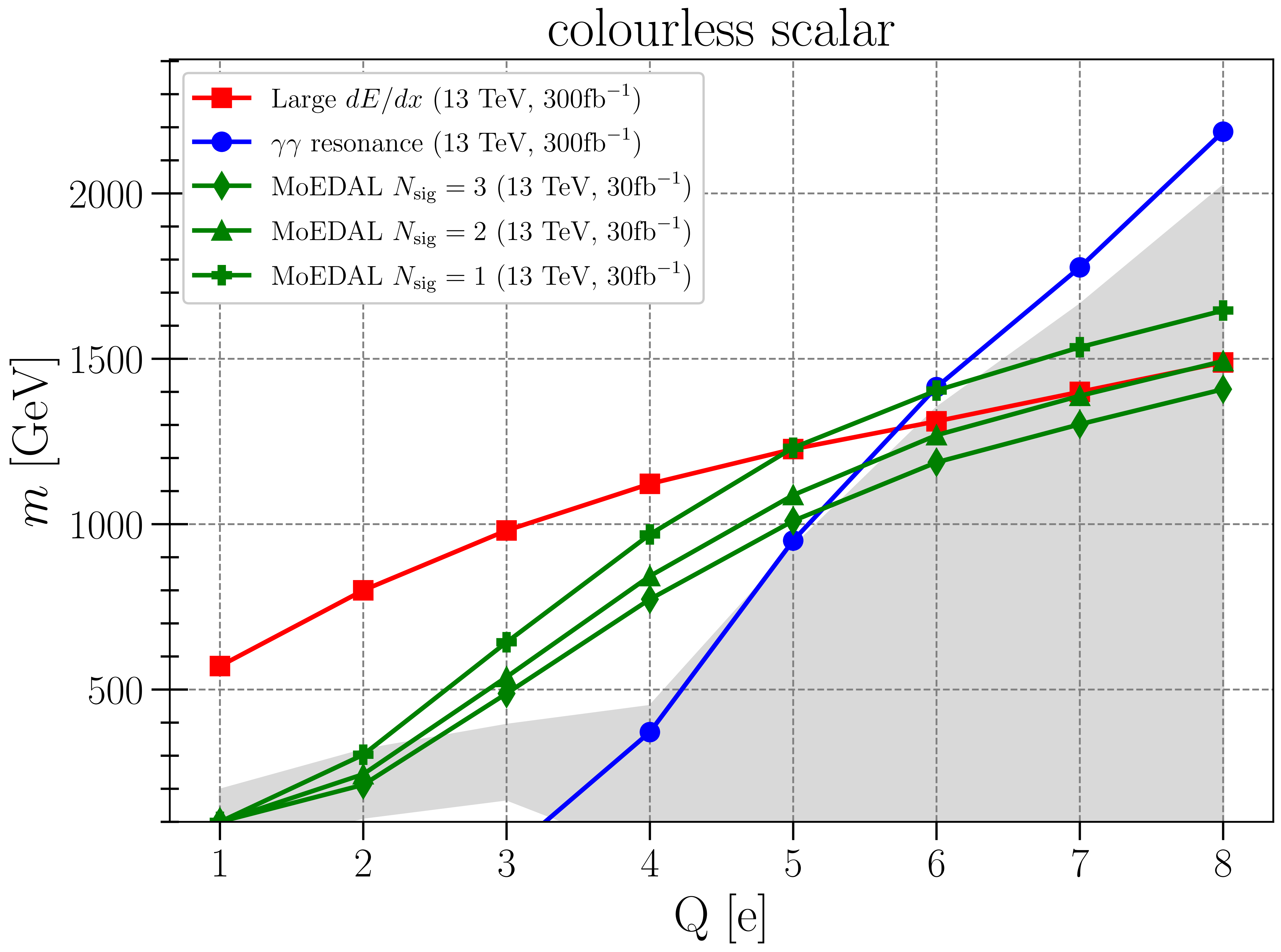
colourless scalars — open channel in MoEDAL

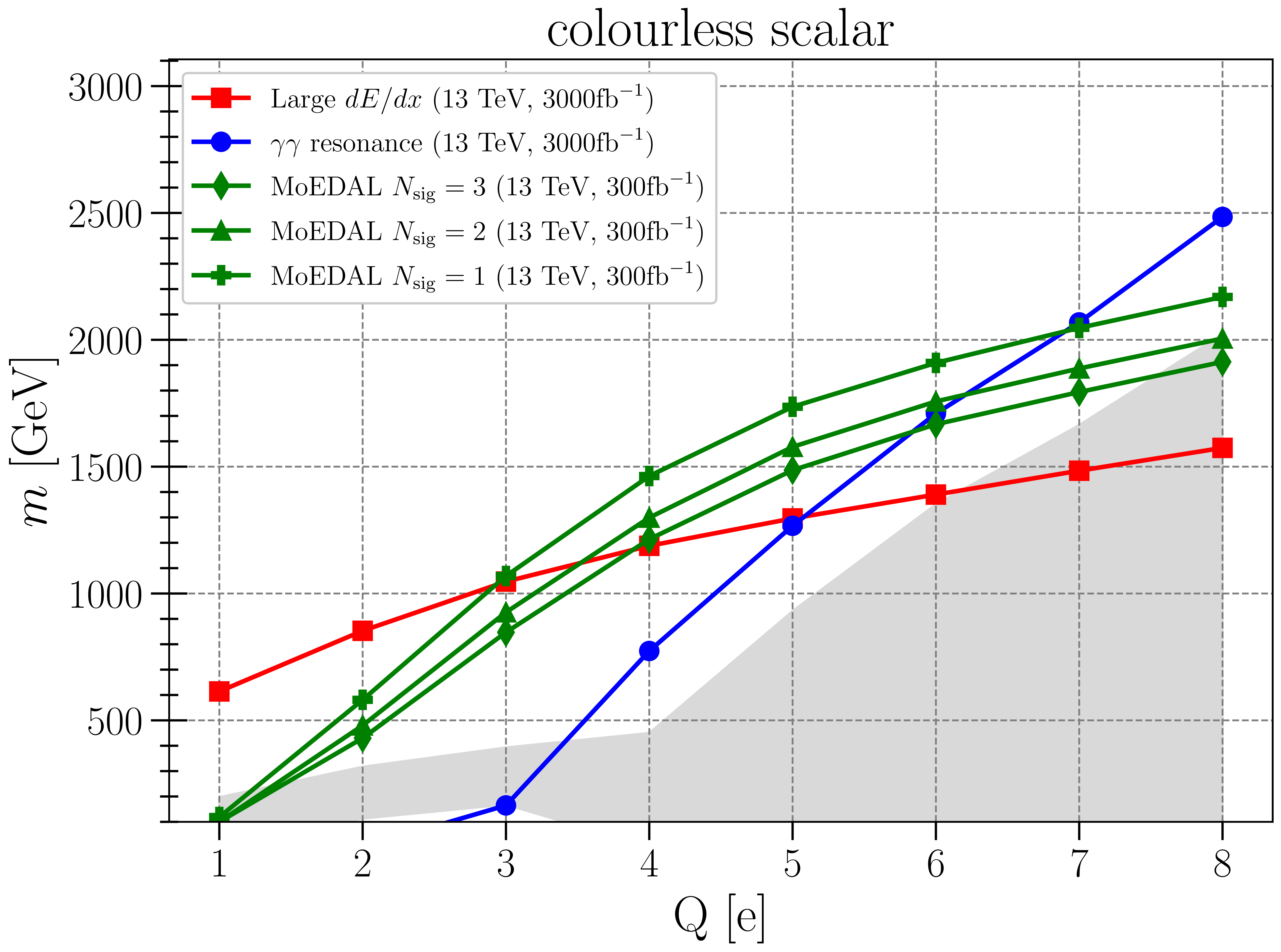


intermediate sensitivity

always increases with charge

colourless scalars

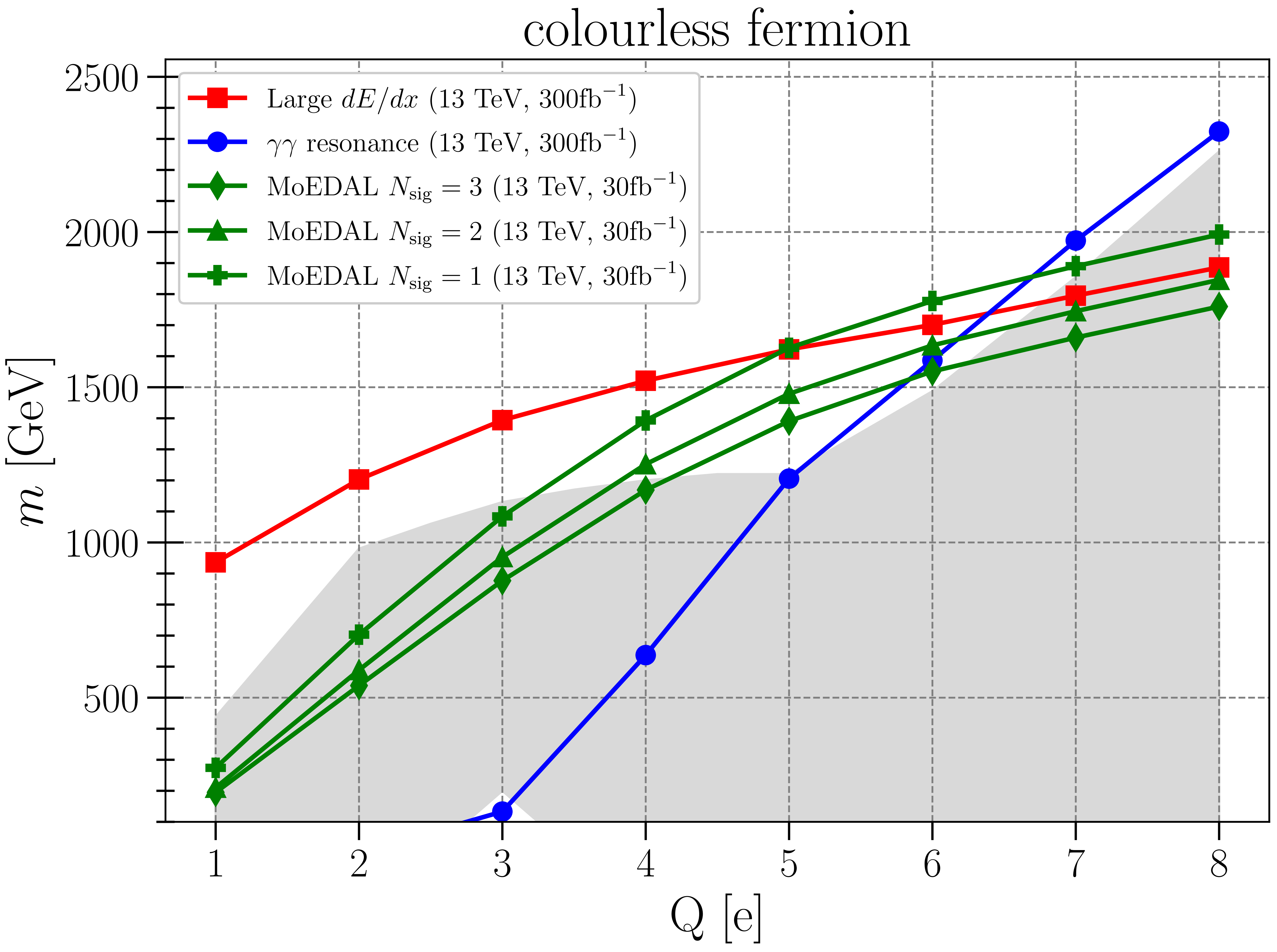


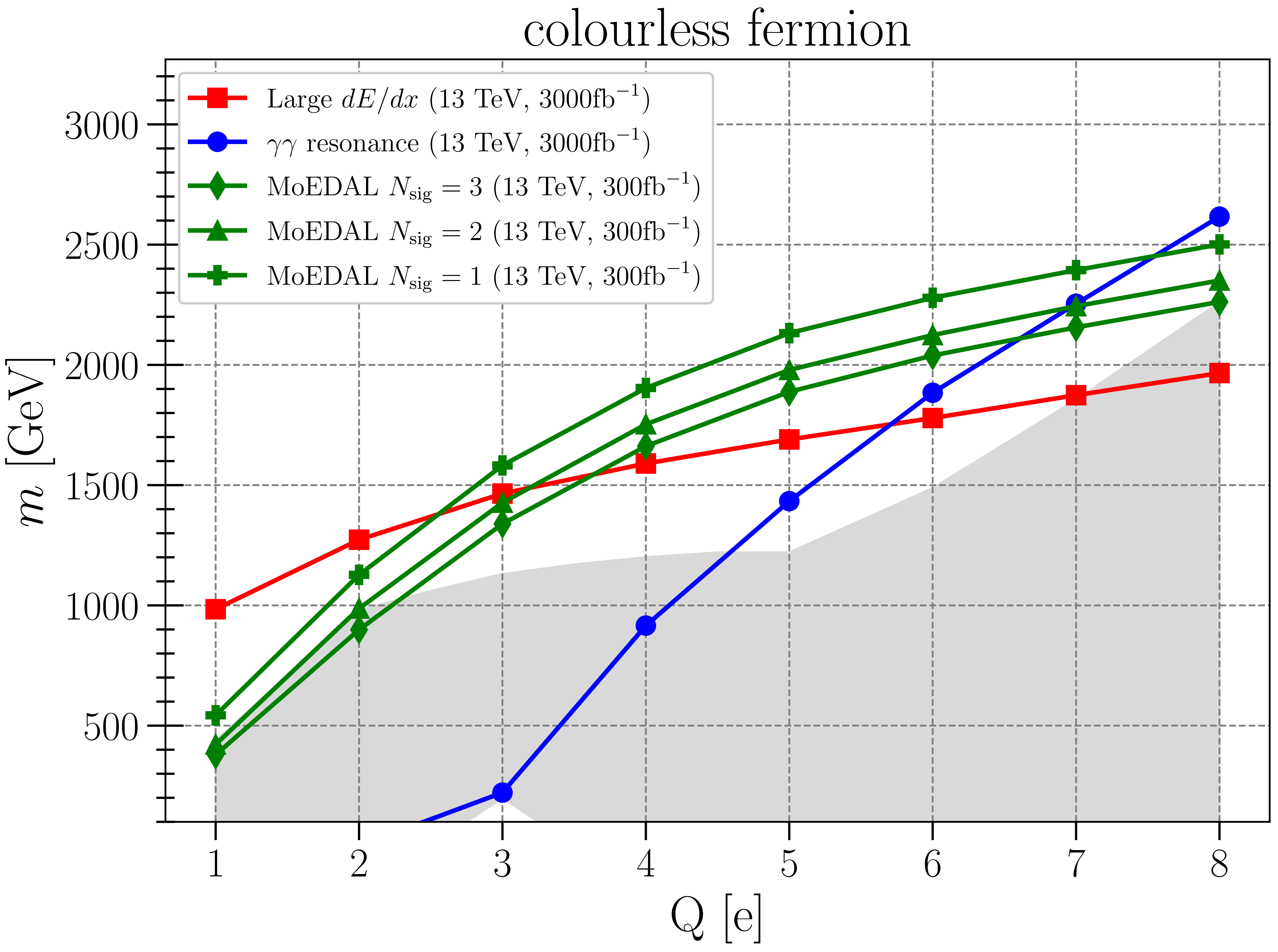


Run 3

HL-LHC

colourless fermions

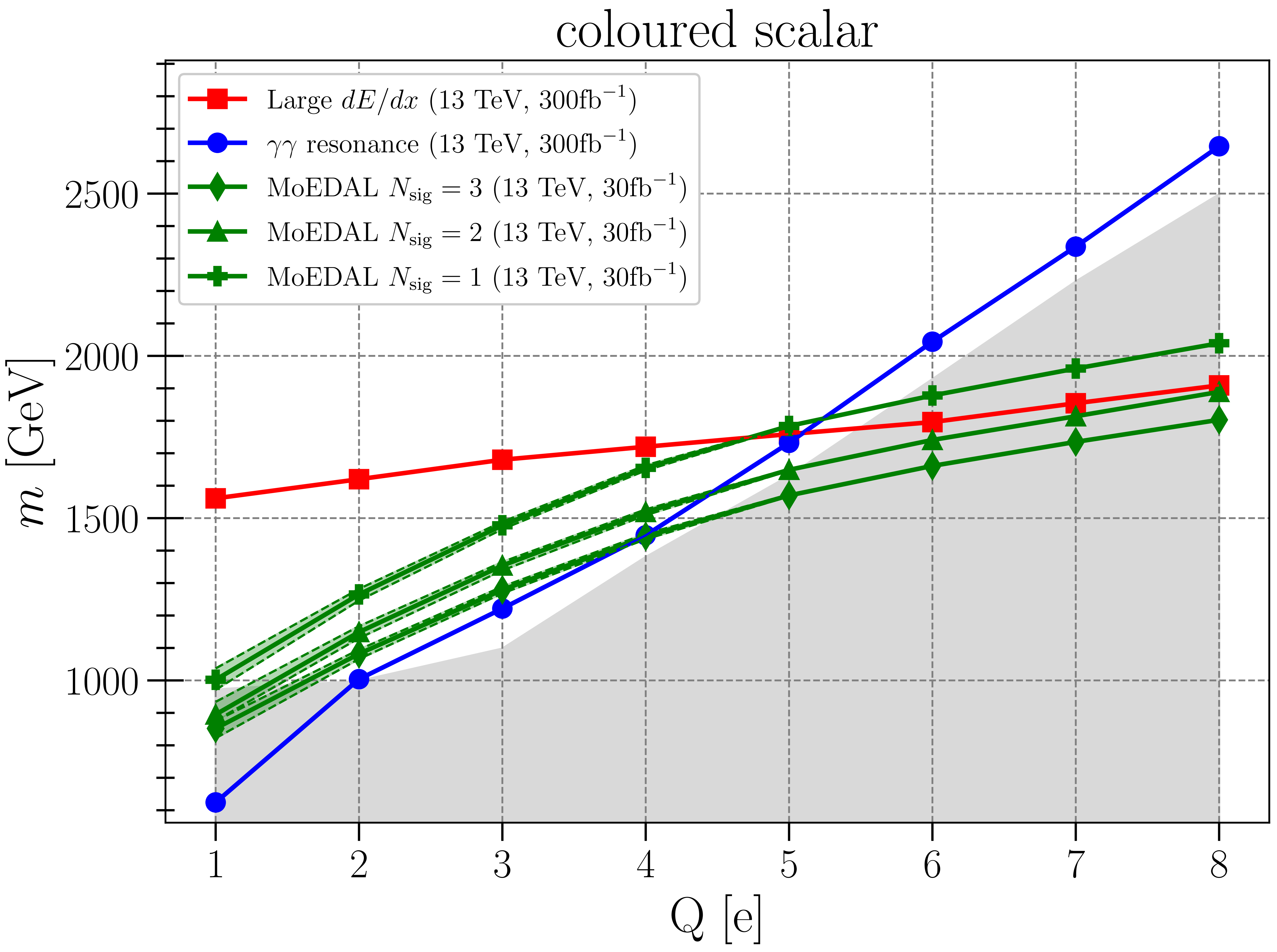


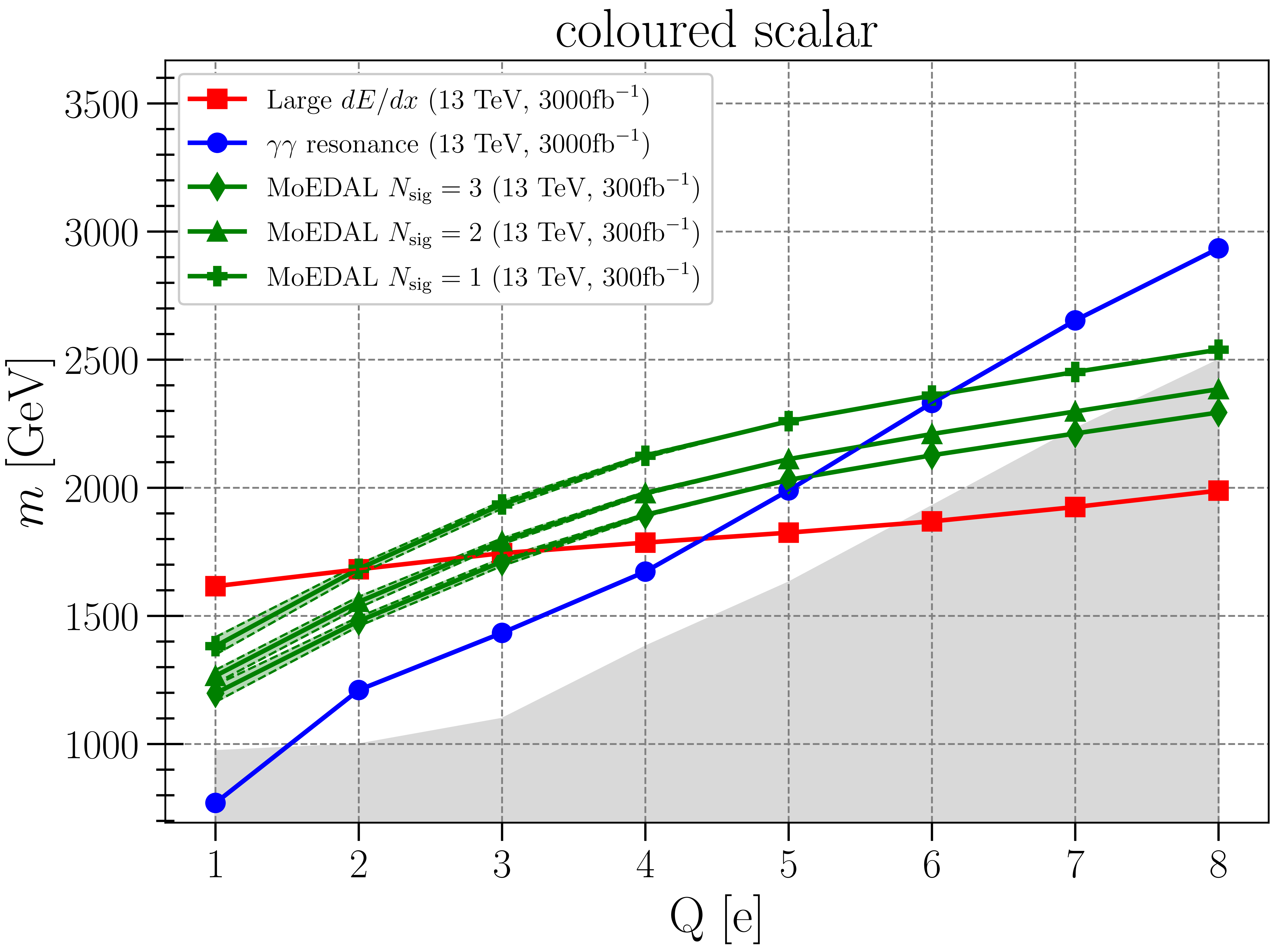


Run 3

HL-LHC

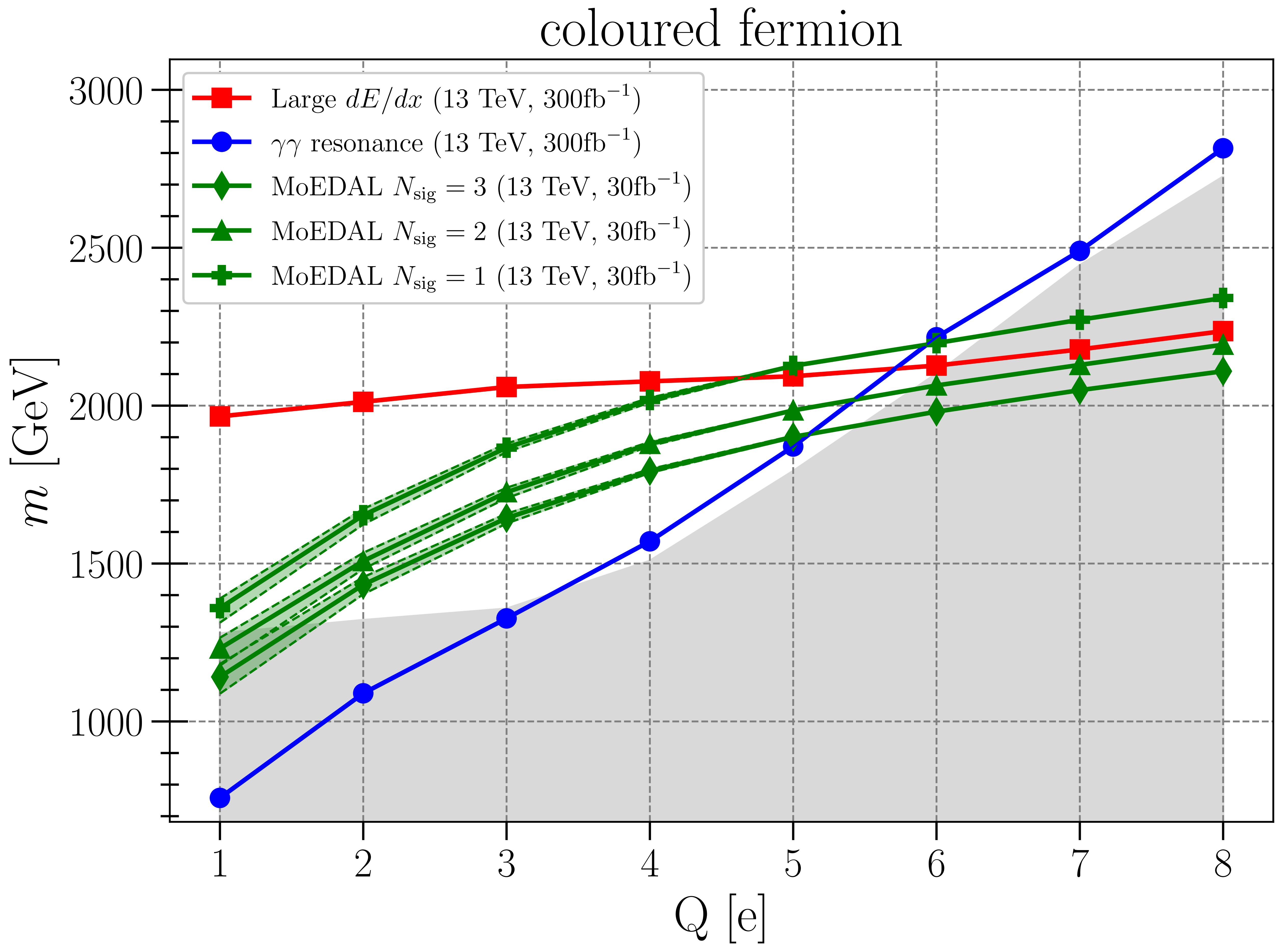
coloured scalars



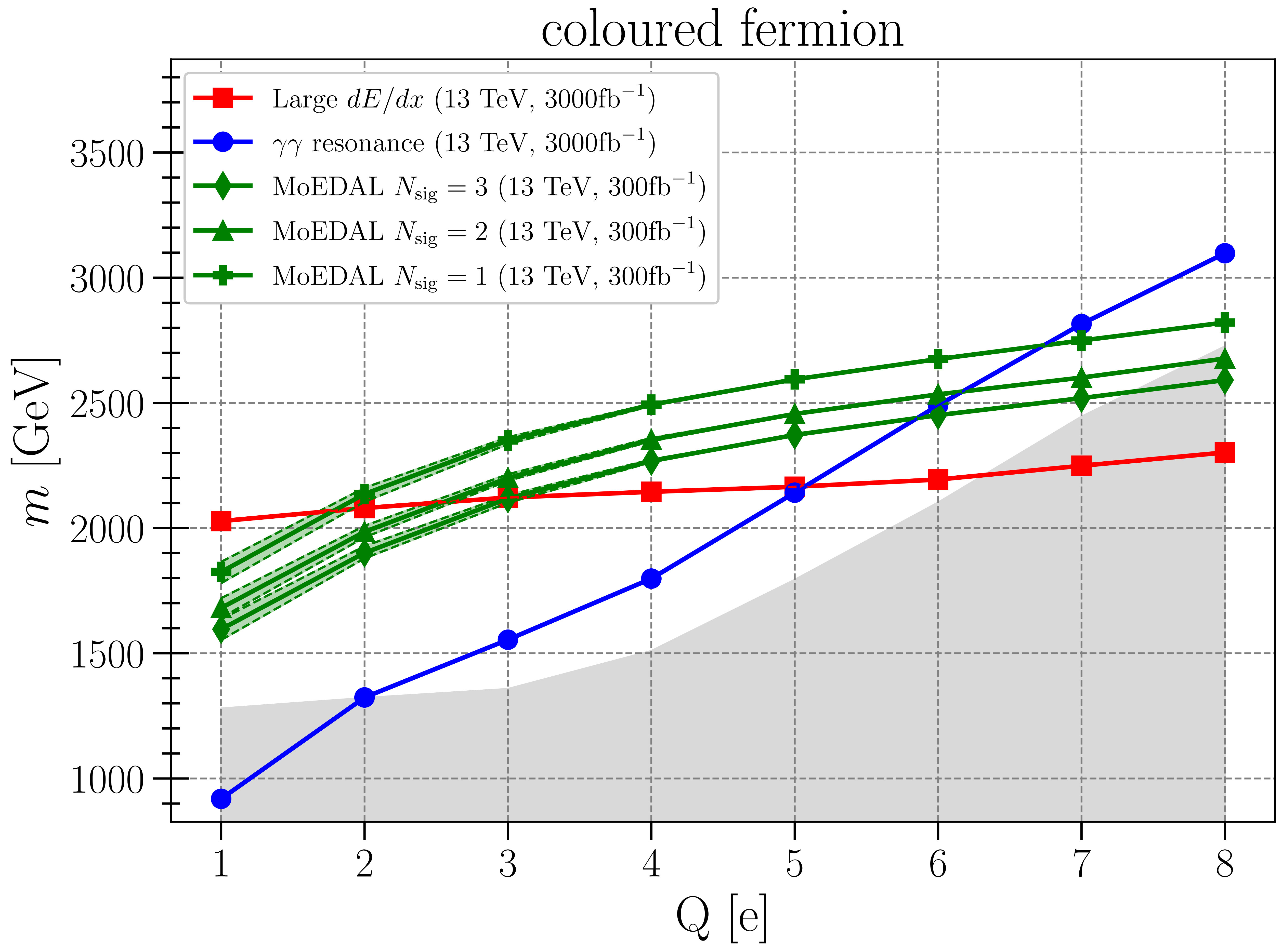


Run 3 HL-LHC

coloured fermions



Run 3

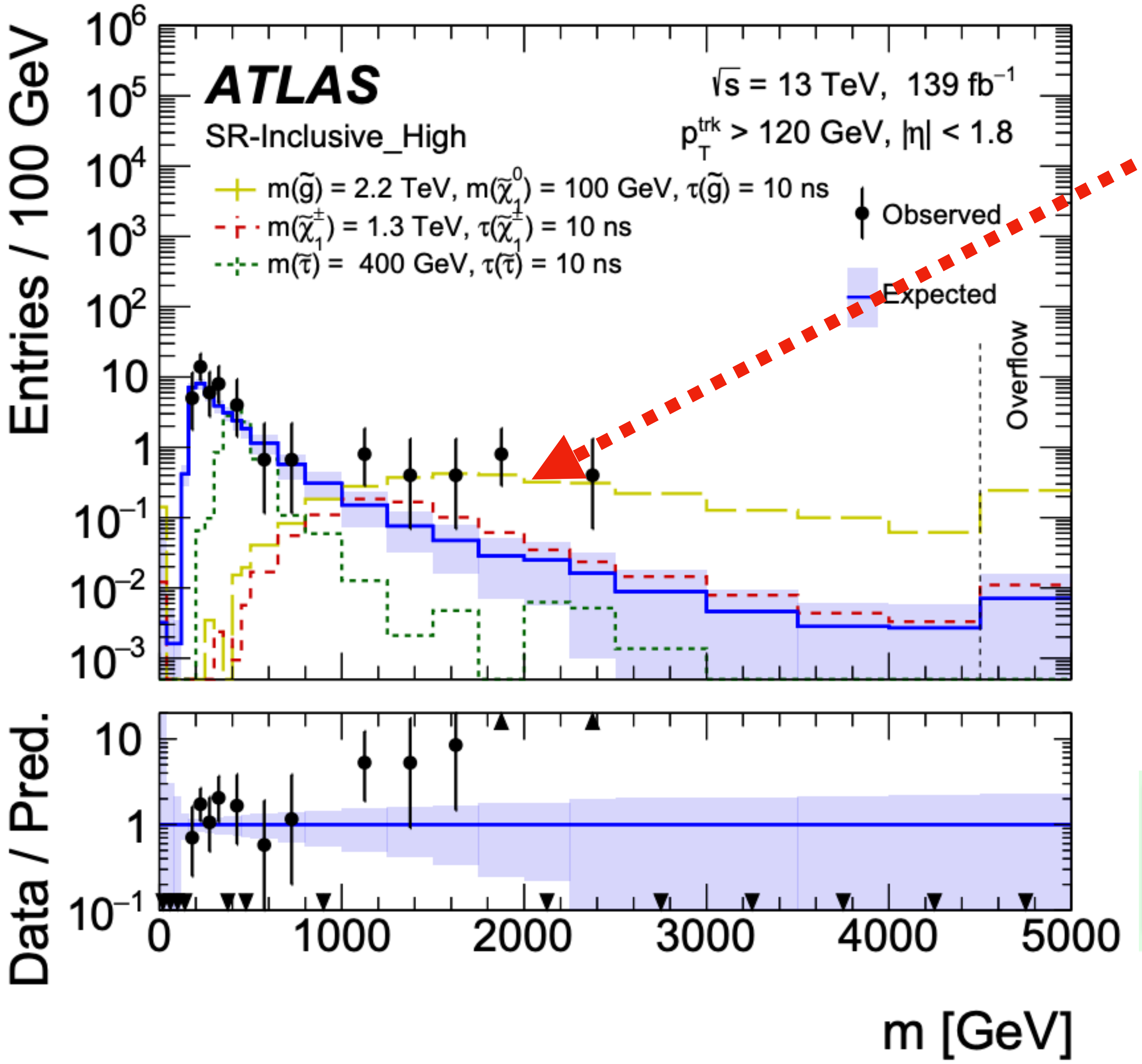


HL-LHC

Conclusion

- Multiply charged heavy long-lived particles can be detected at LHC through open and closed channel searches.
- Including $\gamma\gamma$ and γg fusion with appropriate PDF is crucial for accurate cross-section estimation.
- For charges $1e \leq |Q| \leq 5e$ ATLAS/CMS open channel searches are more sensitive.
- For larger charges di-photon resonance search becomes more sensitive.
- MoEDAL experiment provides independent measurement method.
- It gives intermediate sensitivity for all charges for L=300/fb
- For HL-LHC MoEDAL becomes more senstive than ATLAS & CMS for $3e \leq |Q| \leq 6e$, because it is a background free experiment.
- Combining multiple searches might lead to stronger mass bounds.

One more thing...



3.3σ excess observed by ATLAS
[2205.06013]

1.5σ excess observed by ATLAS
for Q=2 (preliminary)
[Y. Smirnov, LLP11]

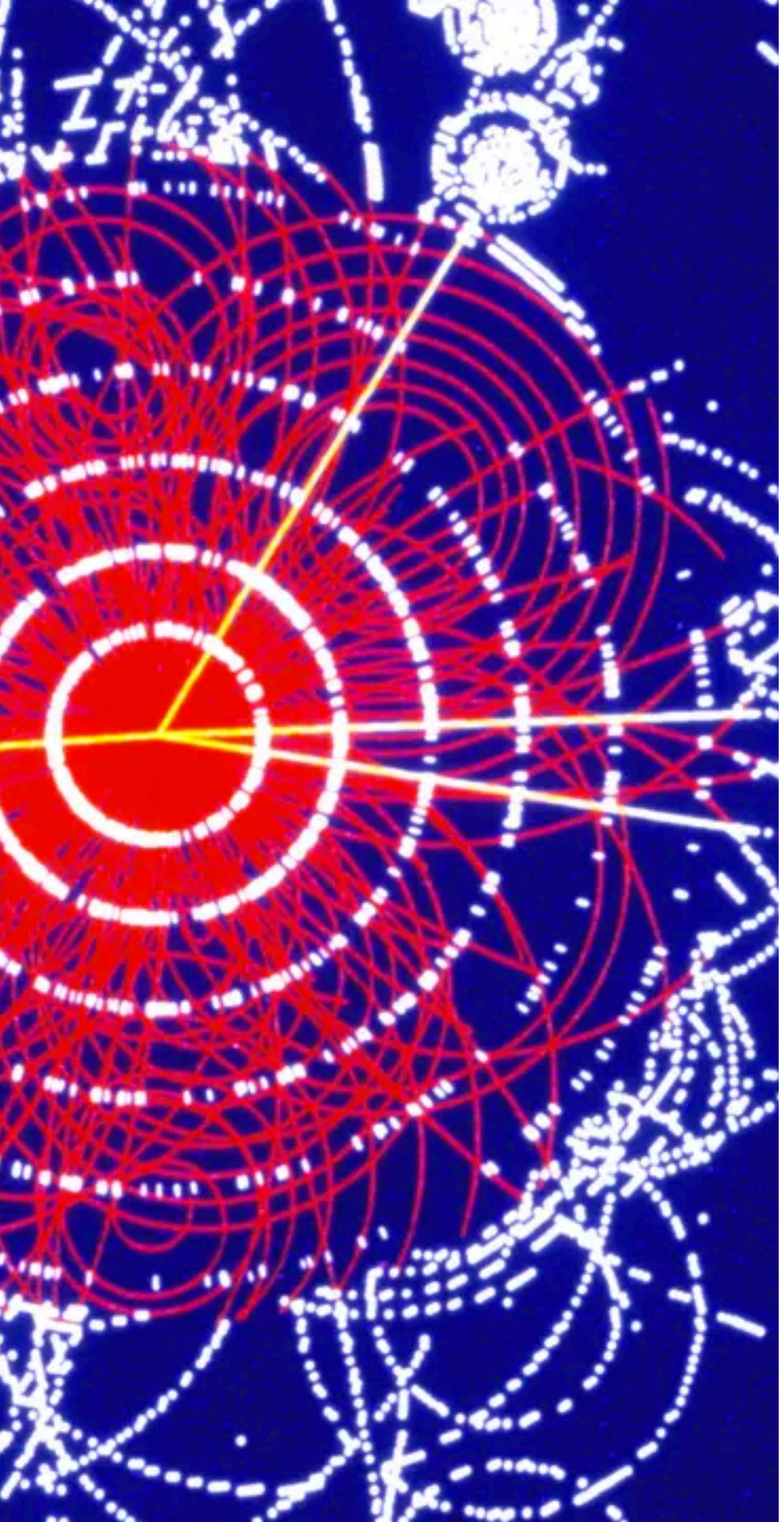
Category	Expectation	Observation
$z = 2$	$1.5 \pm 0.5\,(stat.) \pm 0.5\,(syst.)$ events	4 events
$z > 2$	$0.034 \pm 0.002\,(stat.) \pm 0.004\,(syst.)$ events	0 events

1.5σ excess, p_0 value is 0.06

Thank you for attention!

r.maselek@uw.edu.pl

Dolina Chochołowska, Poland
photo by Piotr Kałuża



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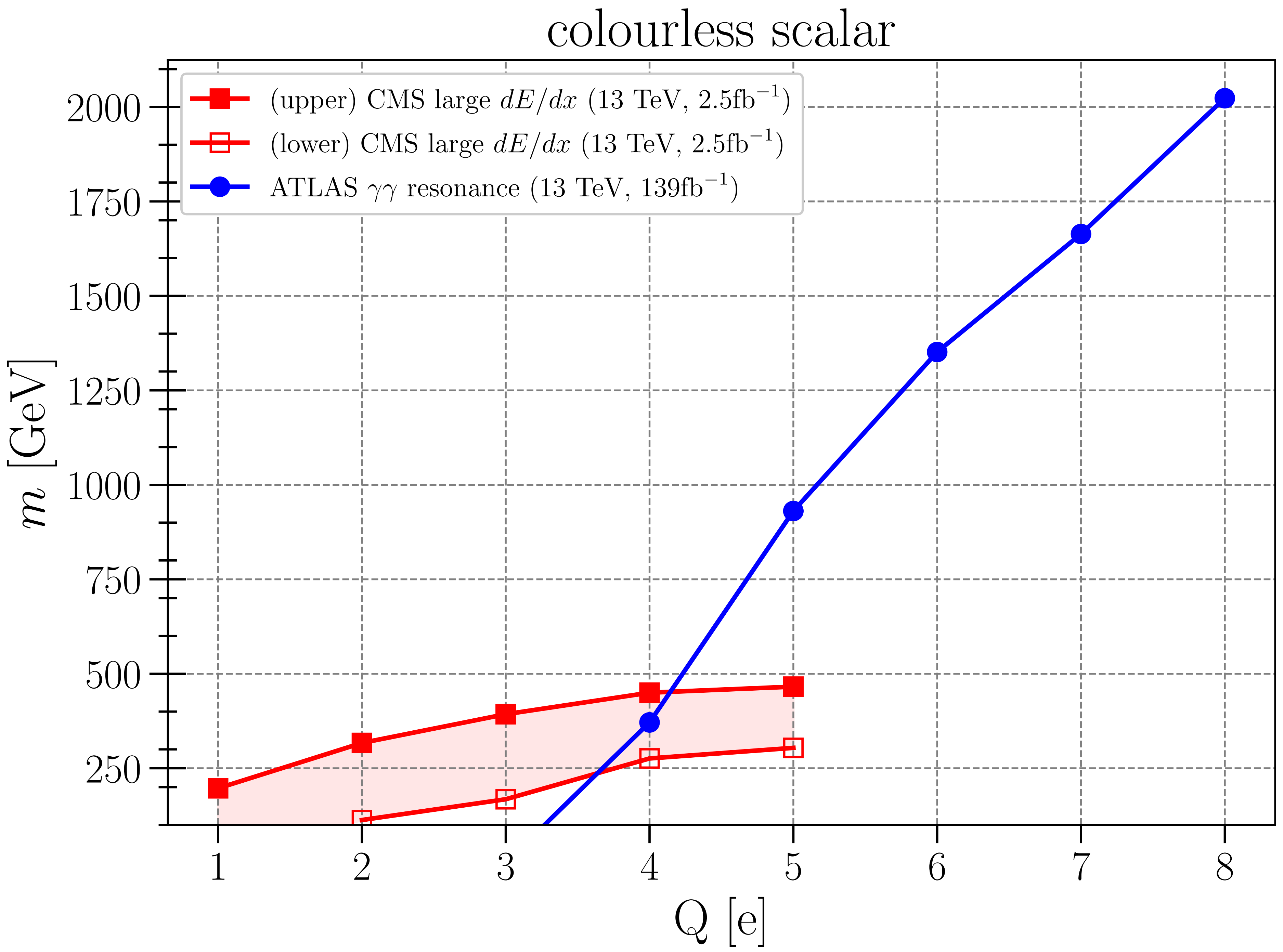
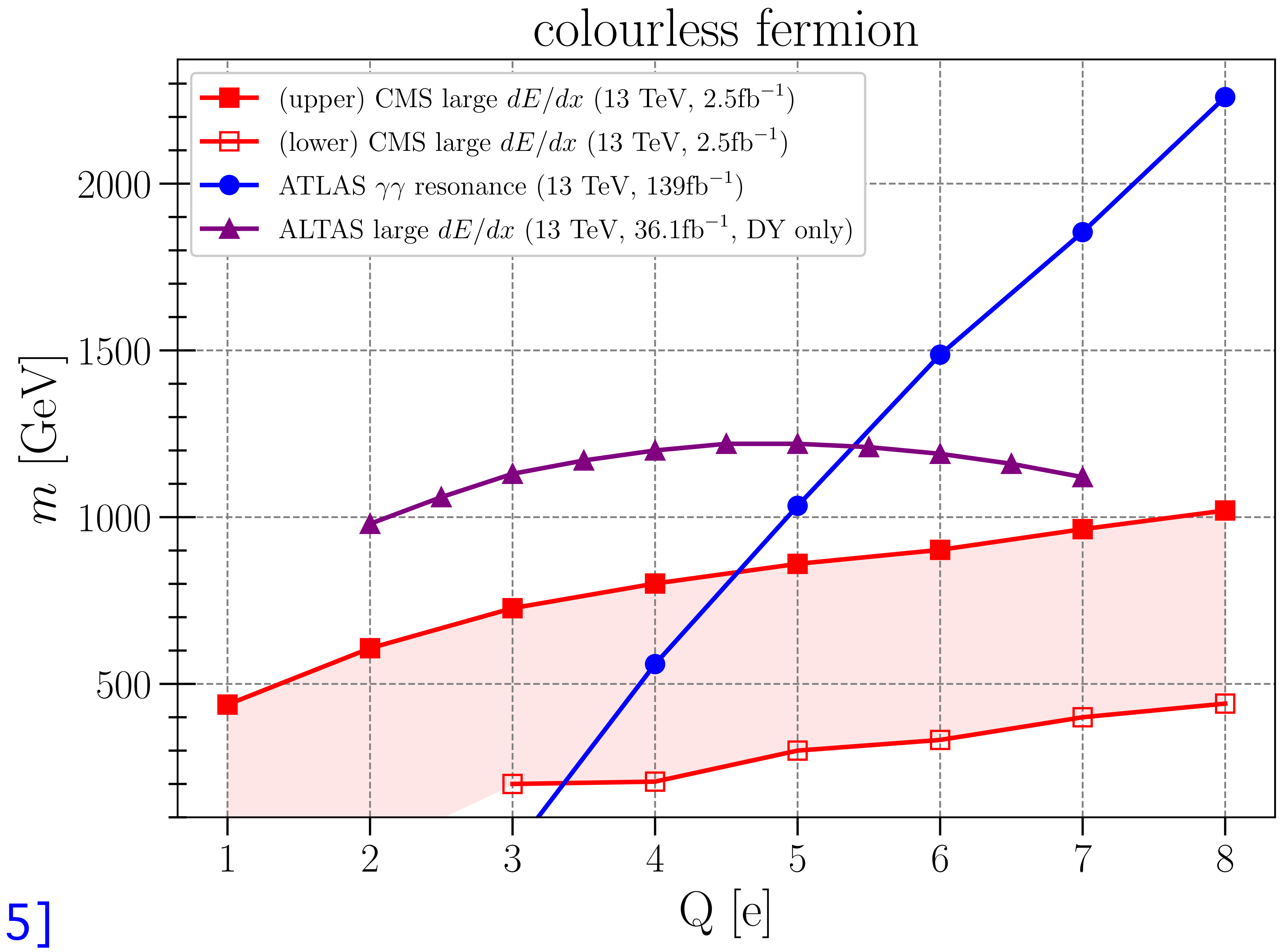
Backup slides

Rafał Masełek



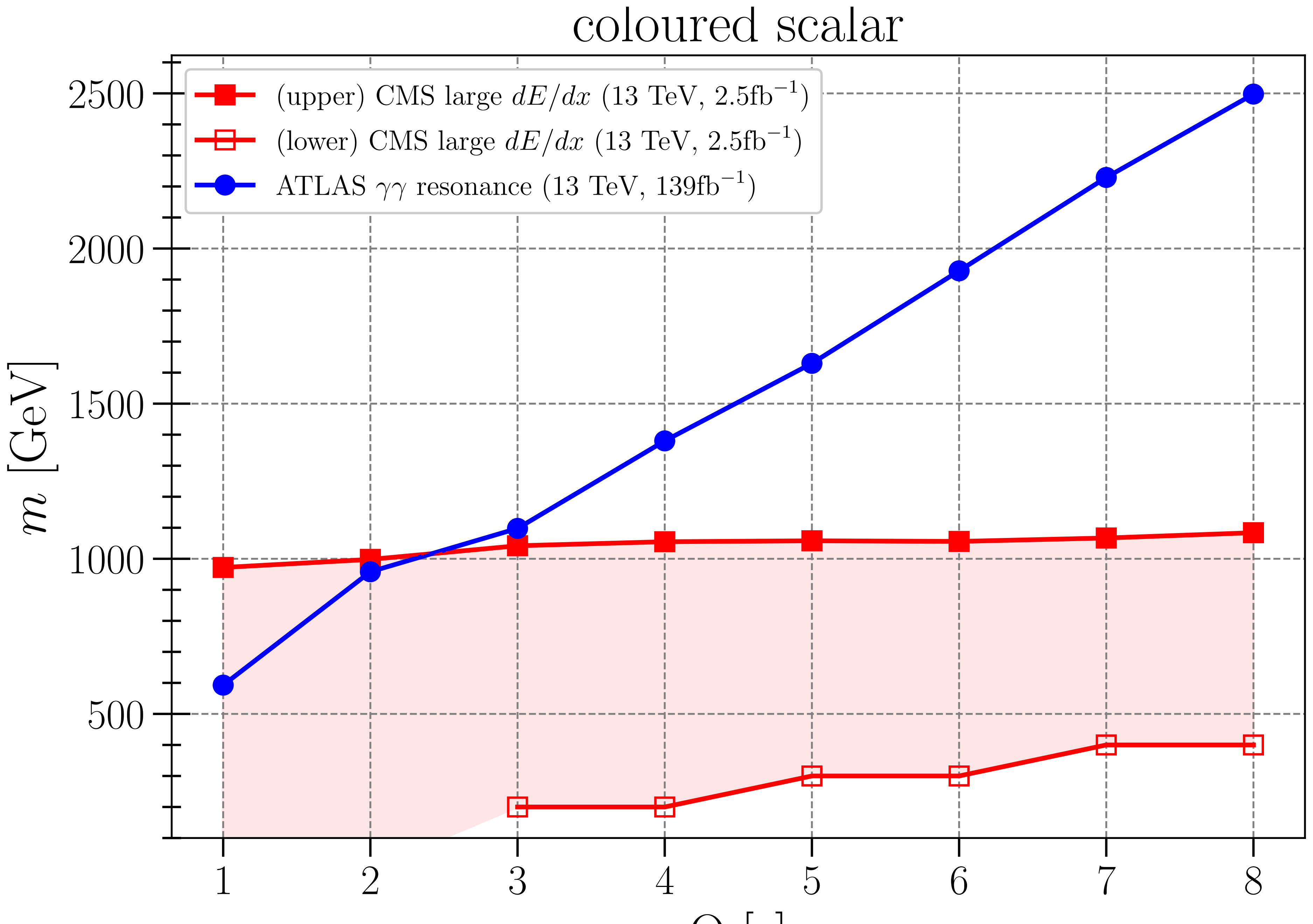


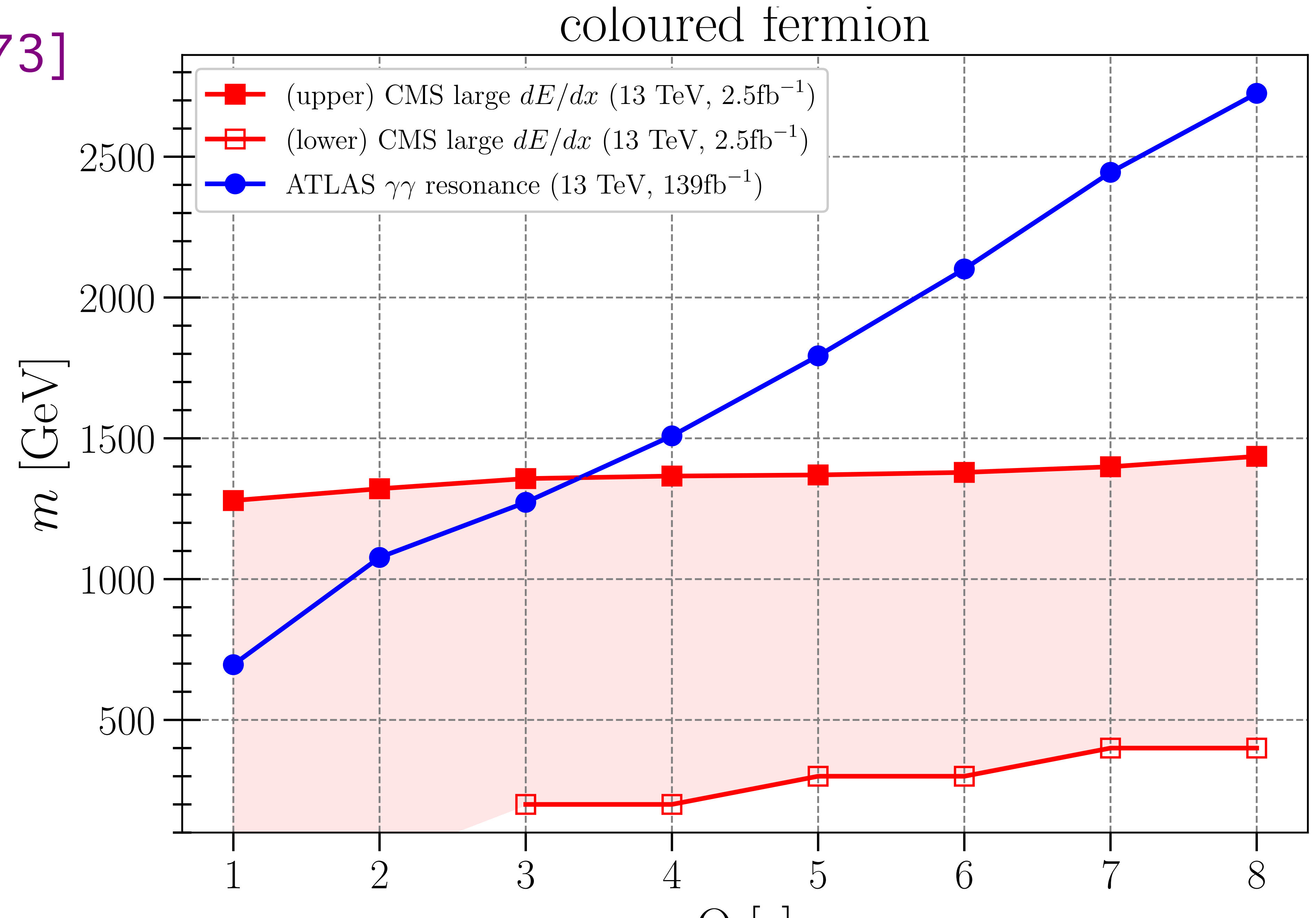
Run 2 (recasted)

[CMS 2.5/fb, 1609.08382]

[ATLAS 139/fb, 2102.13405]

[ATLAS 36.1/fb, 1812.03673]

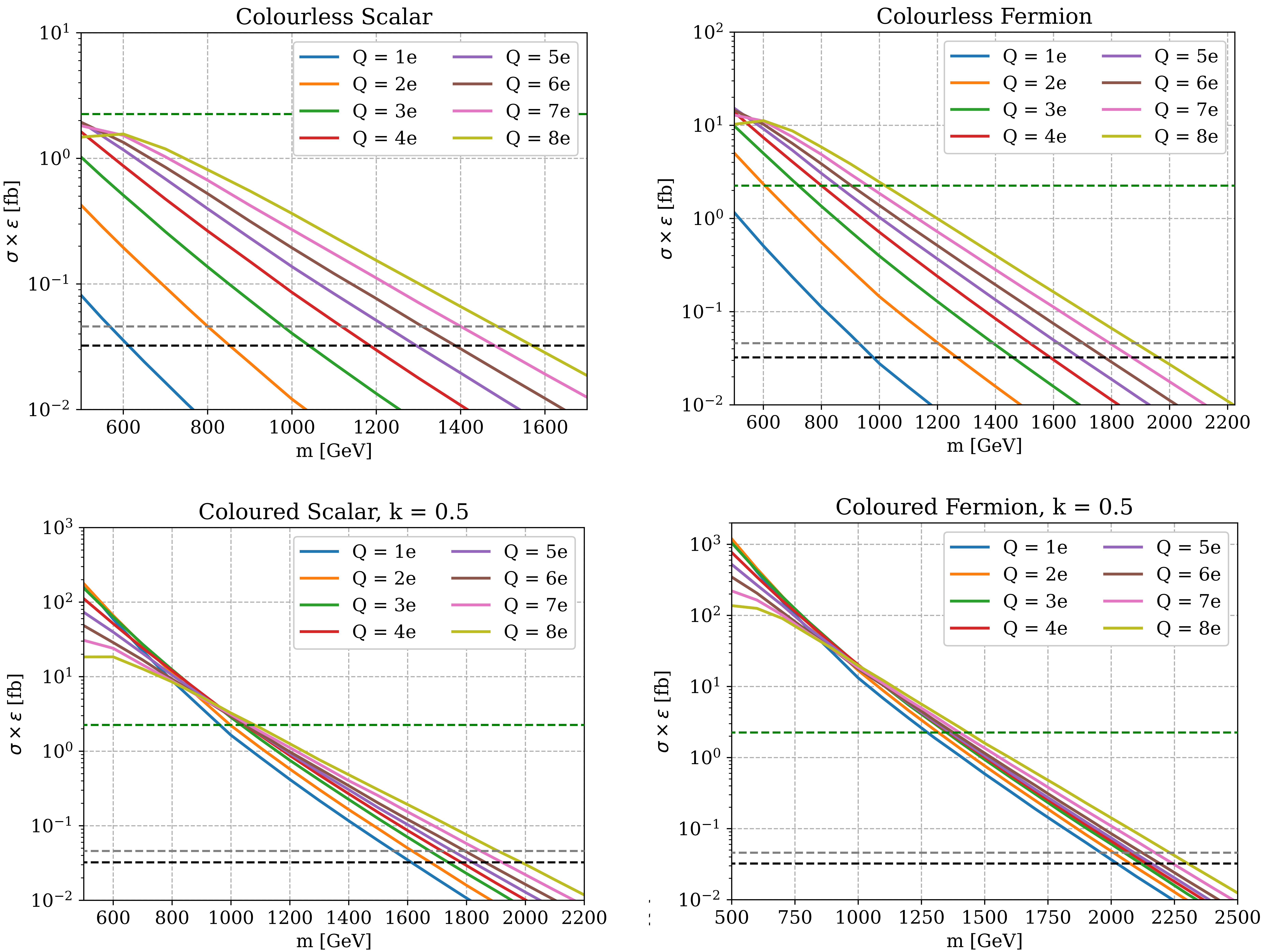


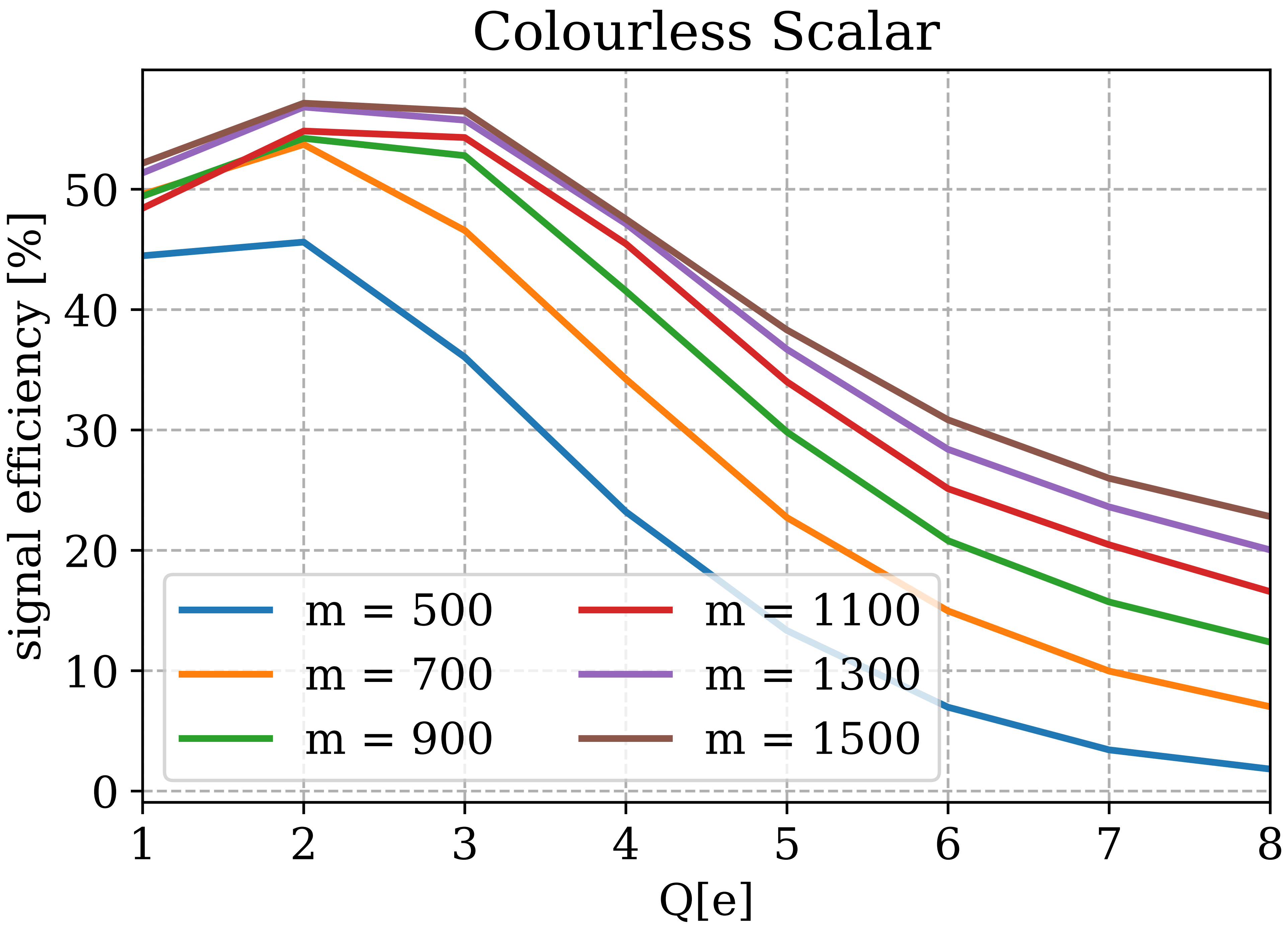


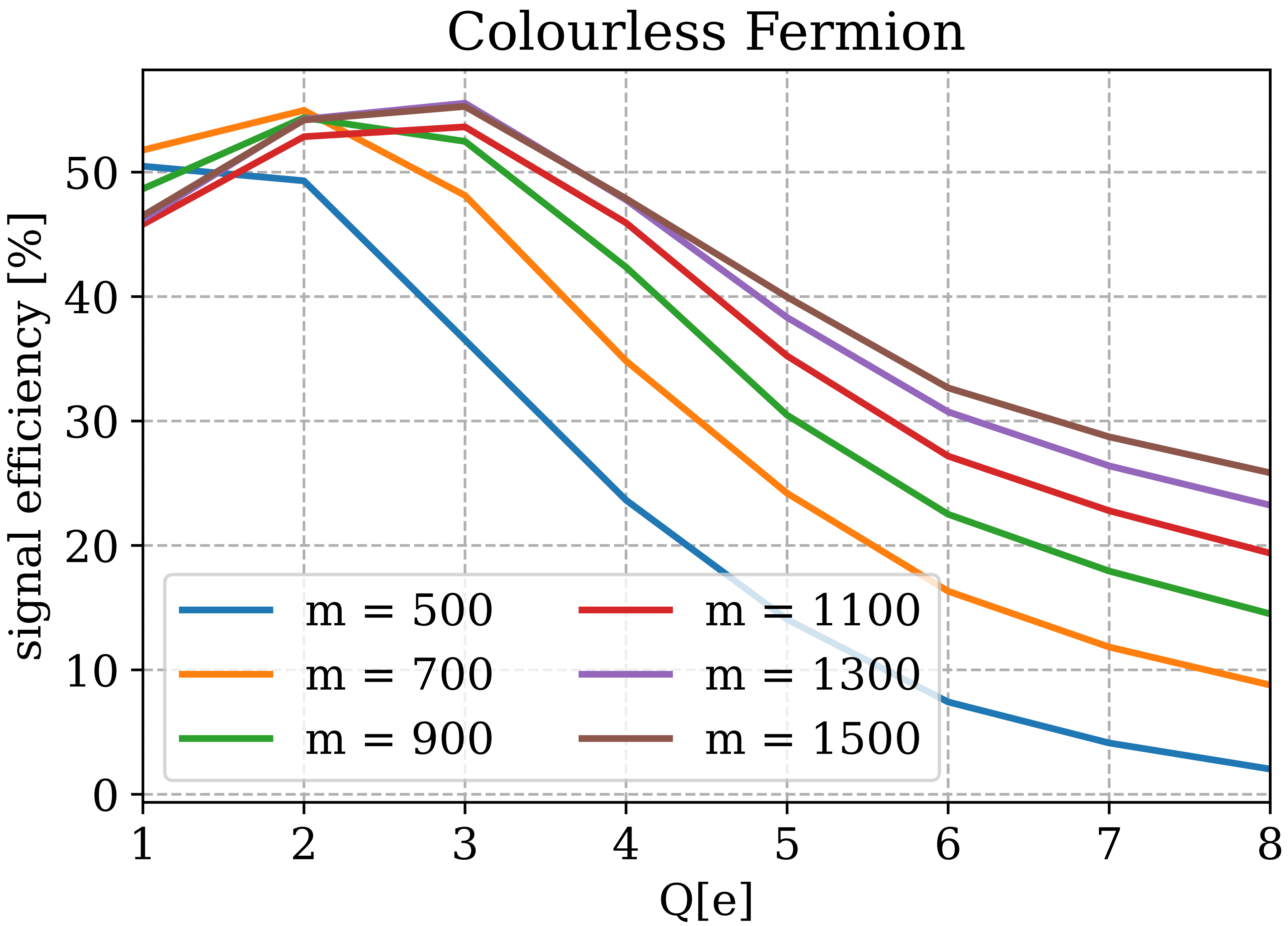
L = 2.5/fb

L = 300/fb

L = 3/ab




Colourless Scalar
signal efficiency [%]
Q[e]
m = 500
m = 700
m = 900
m = 1100
m = 1300
m = 1500


Colourless Fermion
signal efficiency [%]
Q[e]
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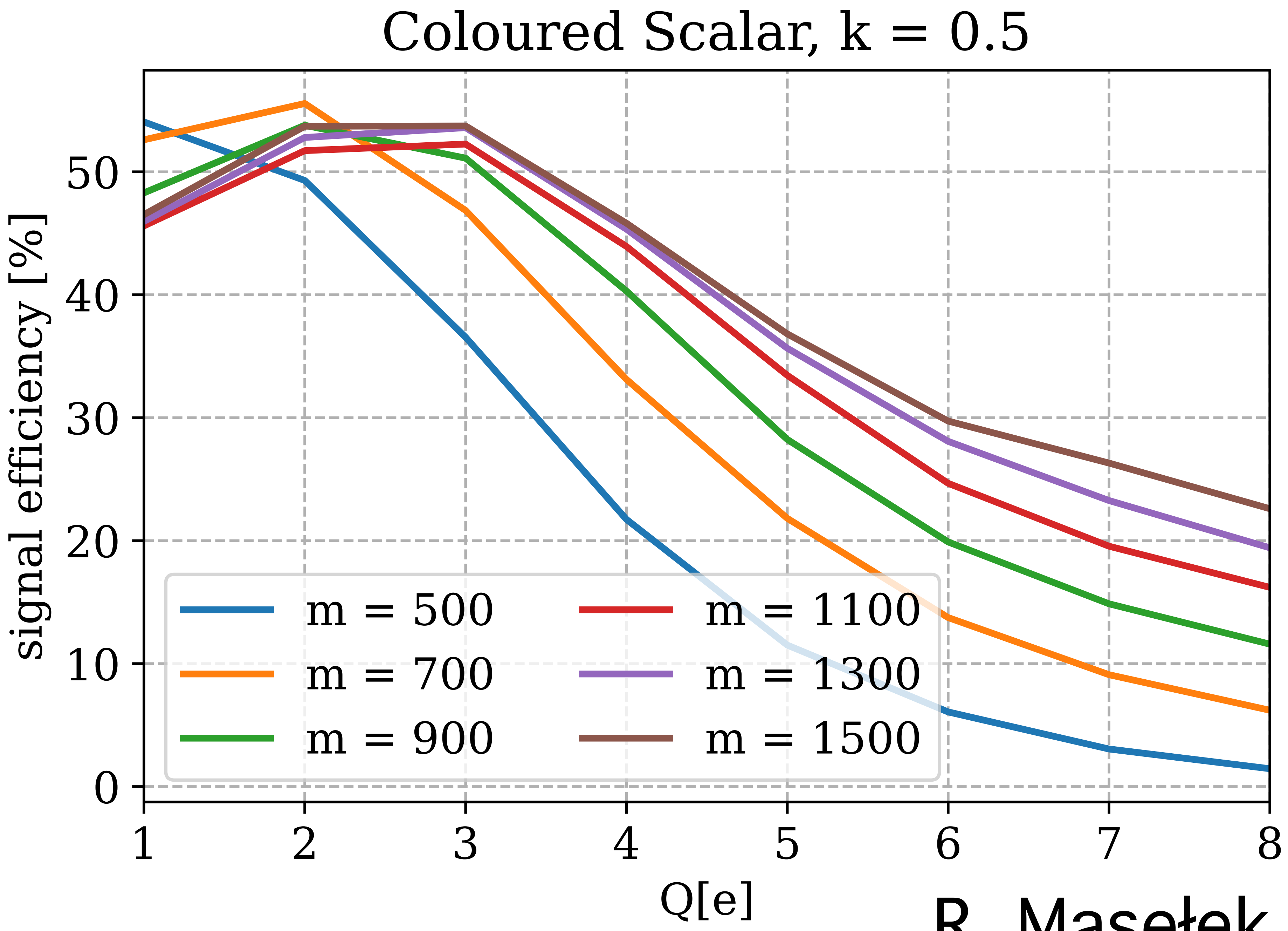
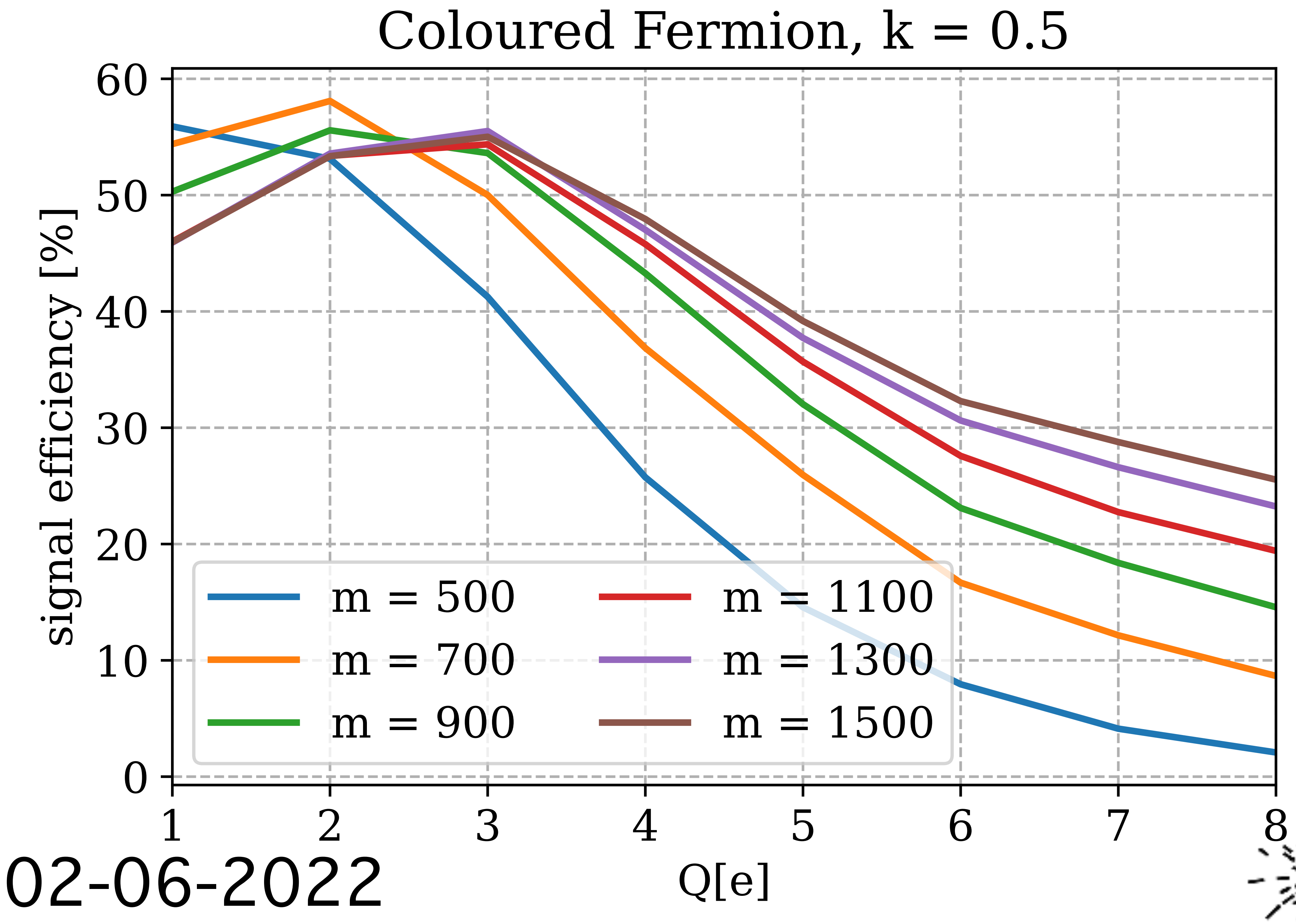
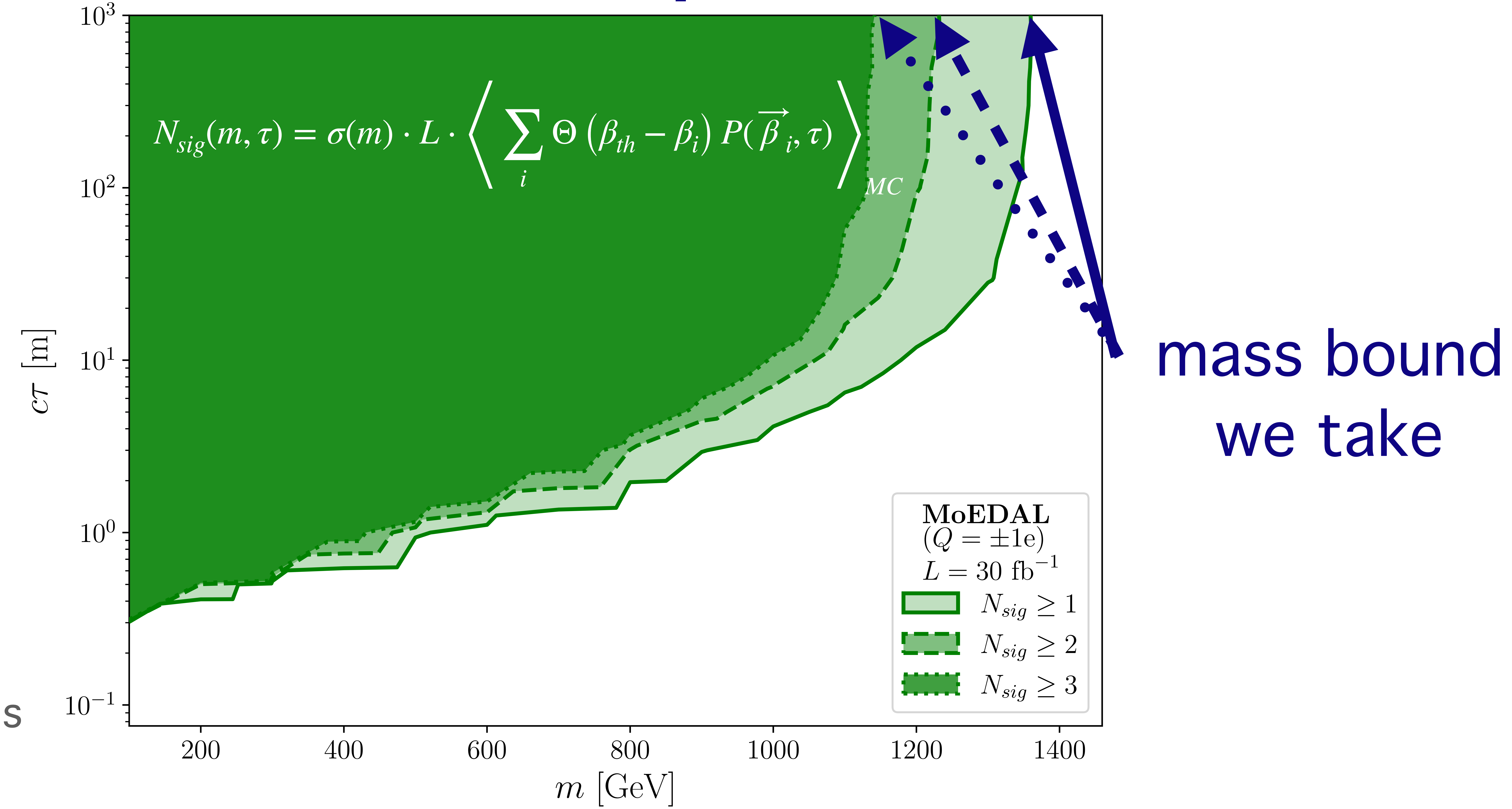
m = 700
m = 900
m = 1100
m = 1300
m = 1500


Coloured Scalar, k = 0.5
signal efficiency [%]
Q[e]
m = 500
m = 700
m = 900
m = 1100
m = 1300
m = 1500


Coloured Fermion, k = 0.5
signal efficiency [%]
Q[e]
m = 500
m = 700
m = 900
m = 1100
m = 1300
m = 1500

MoEDAL experiment



coloured fermions
Q=1e, L=30/fb

Open channel calculations

Hadronisation model

we set k=0.5 in this presentation

Spin-1/2 mesons

State	ΔQ	p
$\phi^{+Q} + \bar{u}_{L/R}$	$-\frac{2}{3}$	$\frac{k}{2}$
$\phi^{+Q} + \bar{d}_{L/R}$	$+\frac{1}{3}$	$\frac{k}{2}$

Spin-0 baryons

State	ΔQ	p
$\phi^{+Q} + u_L u_R$	$+\frac{4}{3}$	$\frac{1-k}{6}$
$\phi^{+Q} + d_L d_R$	$-\frac{2}{3}$	$\frac{1-k}{6}$
$\phi^{+Q} + u_L d_R$	$+\frac{1}{3}$	$\frac{1-k}{6}$
$\phi^{+Q} + d_L u_R$	$+\frac{1}{3}$	$\frac{1-k}{6}$

Spin-1 baryons

State	ΔQ	p
$\phi^{+Q} + u_L d_L$	$+\frac{1}{3}$	$\frac{1-k}{6}$
$\phi^{+Q} + u_R d_R$	$+\frac{1}{3}$	$\frac{1-k}{6}$

Table 3: A hadronization model for a colour-triplet scalar particle (ϕ^{+Q}). The charge shift ΔQ and the probability p assigned to each state are shown in the second and third columns, respectively.

Spin-0 mesons

State	ΔQ	p
$\psi^{+Q} + \bar{u}_L$	$-\frac{2}{3}$	$\frac{k}{4}$
$\psi^{+Q} + \bar{d}_L$	$+\frac{1}{3}$	$\frac{k}{4}$

Spin-1 mesons

State	ΔQ	p
$\psi^{+Q} + \bar{u}_R$	$-\frac{2}{3}$	$\frac{k}{4}$
$\psi^{+Q} + \bar{d}_R$	$+\frac{1}{3}$	$\frac{k}{4}$

Spin-1/2 baryons

State	ΔQ	p
$\psi^{+Q} + u_L u_R$	$+\frac{4}{3}$	$\frac{1-k}{5}$
$\psi^{+Q} + d_L d_R$	$-\frac{2}{3}$	$\frac{1-k}{5}$
$\psi^{+Q} + u_L d_R$	$+\frac{1}{3}$	$\frac{1-k}{5}$
$\psi^{+Q} + d_L u_R$	$+\frac{1}{3}$	$\frac{1-k}{5}$
$\psi^{+Q} + u_L d_L$	$+\frac{1}{3}$	$\frac{1-k}{5}$

Table 4: A hadronization model for a colour-triplet fermionic particle (ψ^{+Q}). The charge shift ΔQ and the probability p assigned to each state are shown in the second and third columns, respectively.

To determine whether a candidate particle is accepted by the muon trigger, we calculate its corresponding TOF by

$$c \cdot t_{\mathrm{TOF}} = \frac{\gamma_0}{\sqrt{\gamma_0^2 - 1}} \cdot x^0_{\mathrm{HCAL}} + \int_0^{x^f_{\mathrm{HCAL}} - x^0_{\mathrm{HCAL}}} \frac{\gamma_{\mathrm{Brass}}}{\sqrt{\gamma^2_{\mathrm{Brass}} - 1}} dx + \frac{\gamma_{\mathrm{Brass}}(x^f_{\mathrm{HCAL}})}{\sqrt{\gamma_{\mathrm{Brass}}(x^f_{\mathrm{HCAL}})^2 - 1}} \cdot (x_{\mathrm{trigger}} - x^f_{\mathrm{HCAL}} - \Delta x_{\mathrm{IY}}) + \int_0^{\Delta x_{\mathrm{IY}}} \frac{\gamma_{\mathrm{Iron}}}{\sqrt{\gamma^2_{\mathrm{Iron}} - 1}} dx \,, \tag{A.1}$$

$\frac{1}{\beta_0}$

where x_{trigger} is the minimal distance a particle must travel, within the trigger time window, in order to be triggered as a muon. As explained in Section 2.2, x_{trigger} is η-dependent and it is presented in Figure. 12(a). x^0_{HCAL}, x^f_{HCAL} are, respectively – the distance a particle would travel to the entrance and to the exit of the hadronic calorimeter (HCAL). The minimal distance a triggering particle would travel in the brass absorber of the HCAL, $x^f_{\mathrm{HCAL}} - x^0_{\mathrm{HCAL}}$, and in the iron absorber of the iron yoke, Δx_{IY}, are also η-dependent and are shown in Fig. 12(b). $\gamma(x)$ is the Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$, and it is calculated by numerically solving

$$\frac{d\gamma_{\mathrm{Brass}}}{dx}(x) = \frac{Q^2}{m} \frac{dE}{dx}_{\mathrm{Brass}}(\gamma), \qquad \gamma_{\mathrm{Brass}}(0) = \gamma_0 \tag{A.2}$$

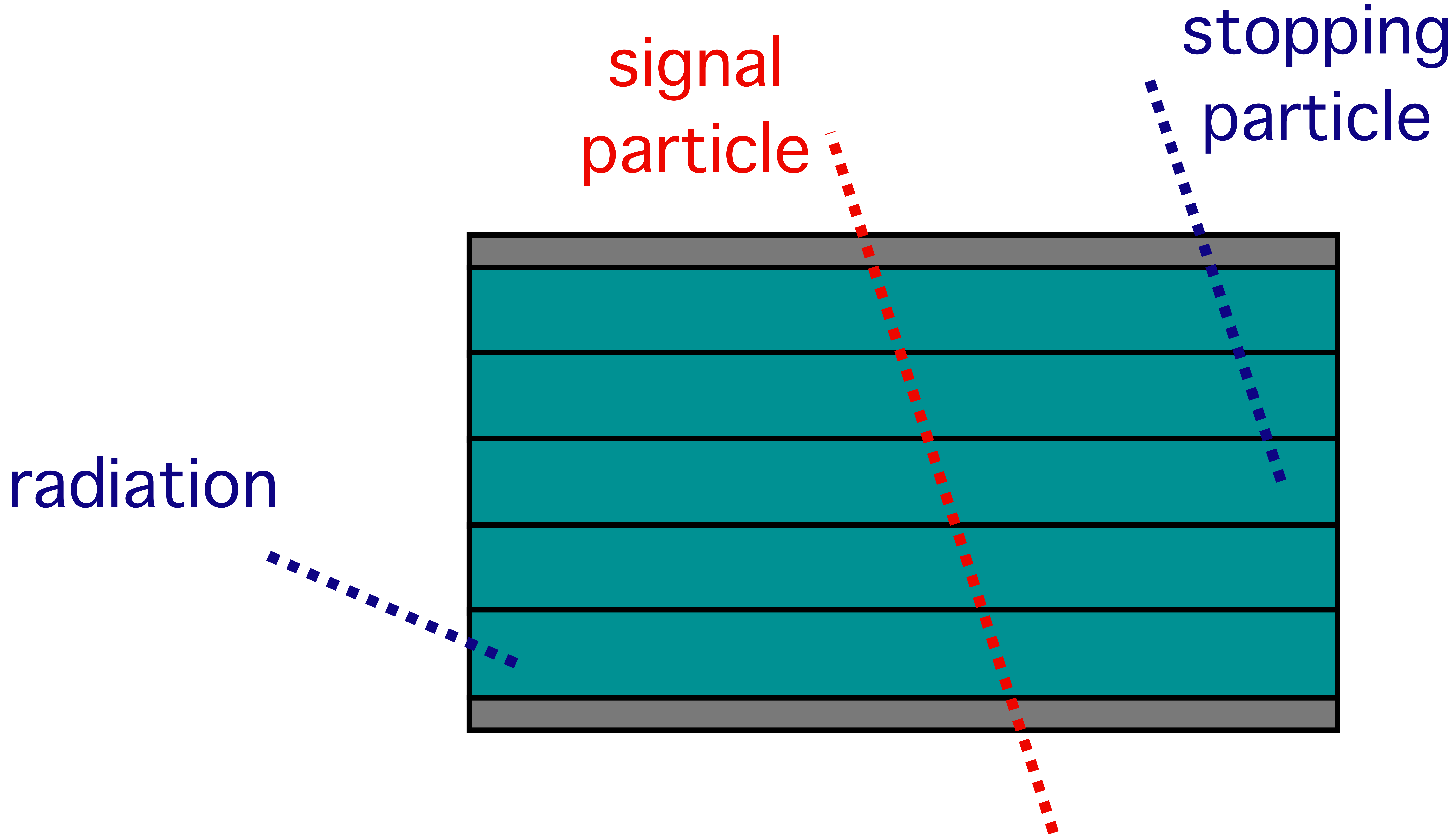
$$\frac{d\gamma_{\mathrm{Iron}}}{dx}(x) = \frac{Q^2}{m} \frac{dE}{dx}_{\mathrm{Iron}}(\gamma), \qquad \gamma_{\mathrm{Iron}}(0) = \gamma_{\mathrm{Brass}}(x^f_{\mathrm{HCAL}} - x^0_{\mathrm{HCAL}}) \,, \tag{A.3}$$

where γ_0 is γ at production, Q is the charge of the particle and m is the mass of the particle. dE/dx is the energy loss function in the appropriate material for $Q = 1$, and is taken from [44] (brass) and [28] (iron).

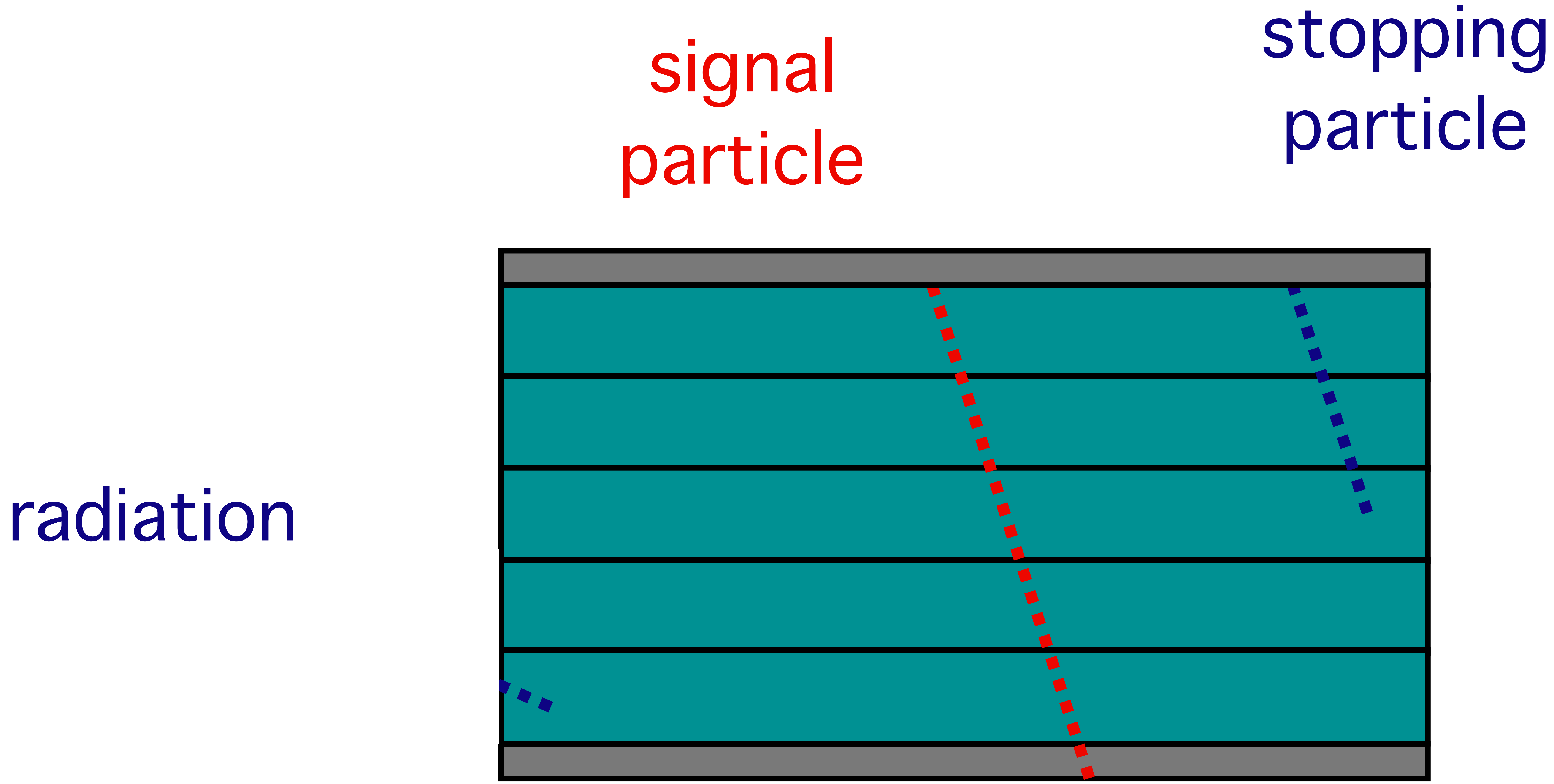
[S.Jaegeret al; 1812:03182]

MoEDAL experiment

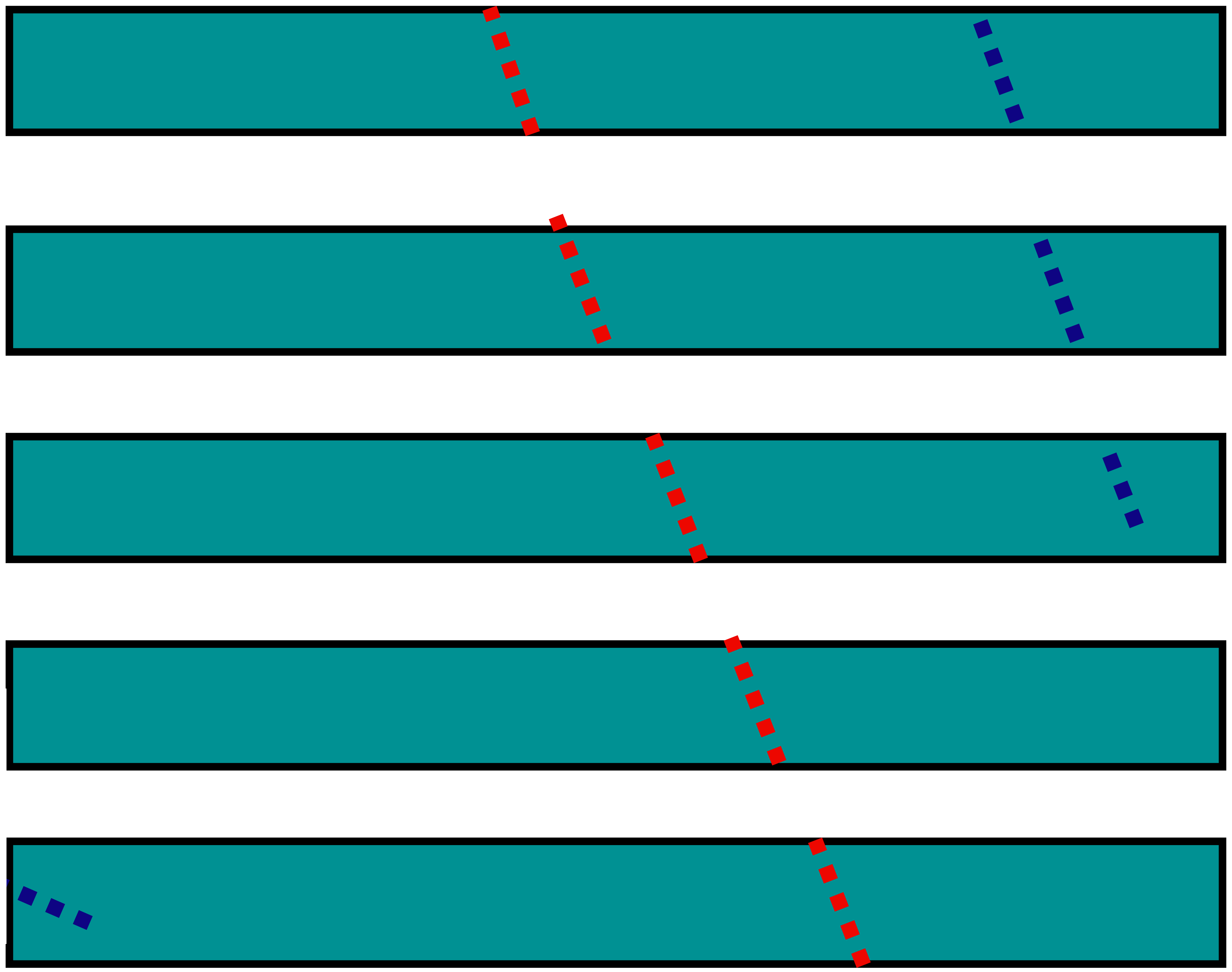
MoEDAL experiment



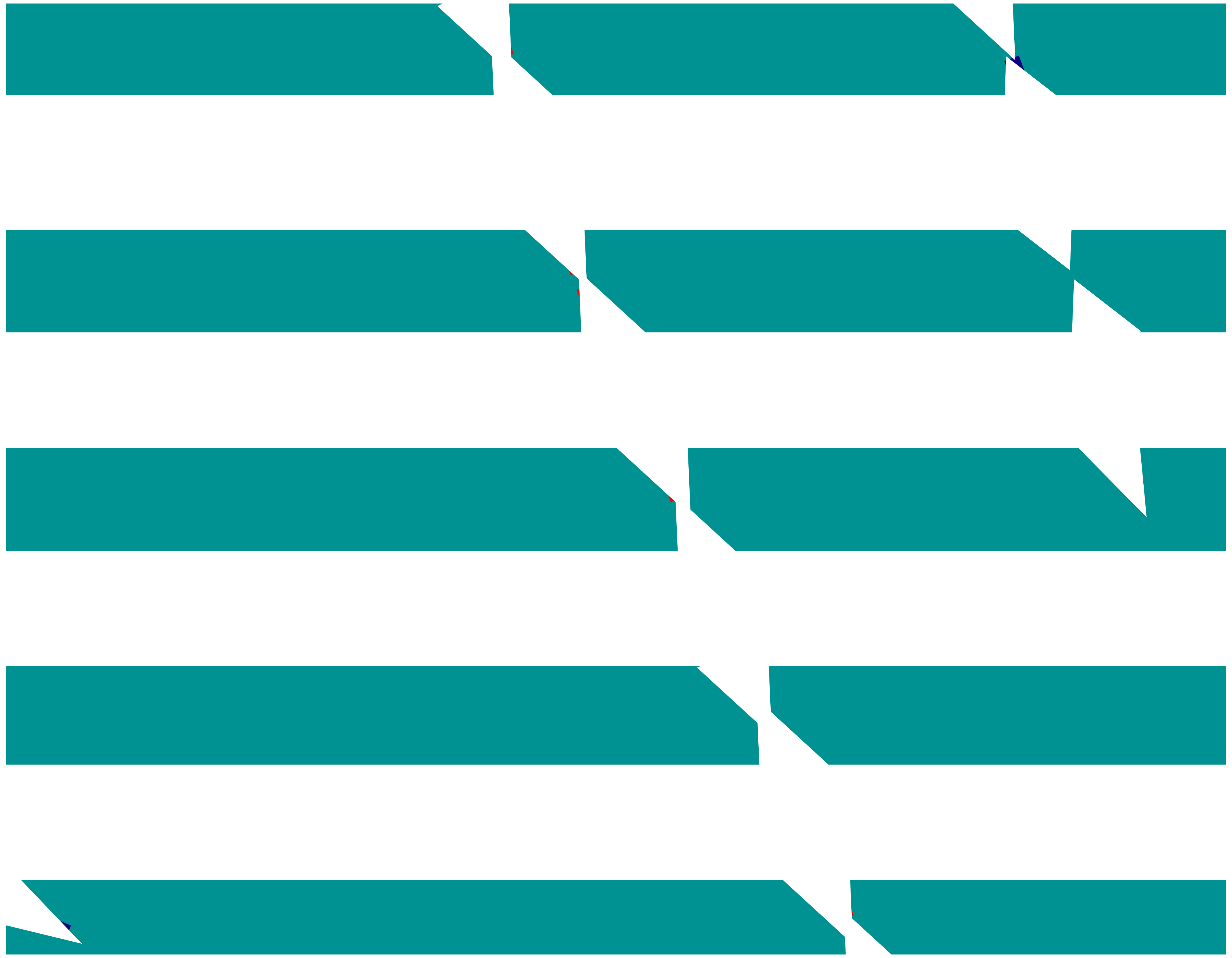
MoEDAL experiment



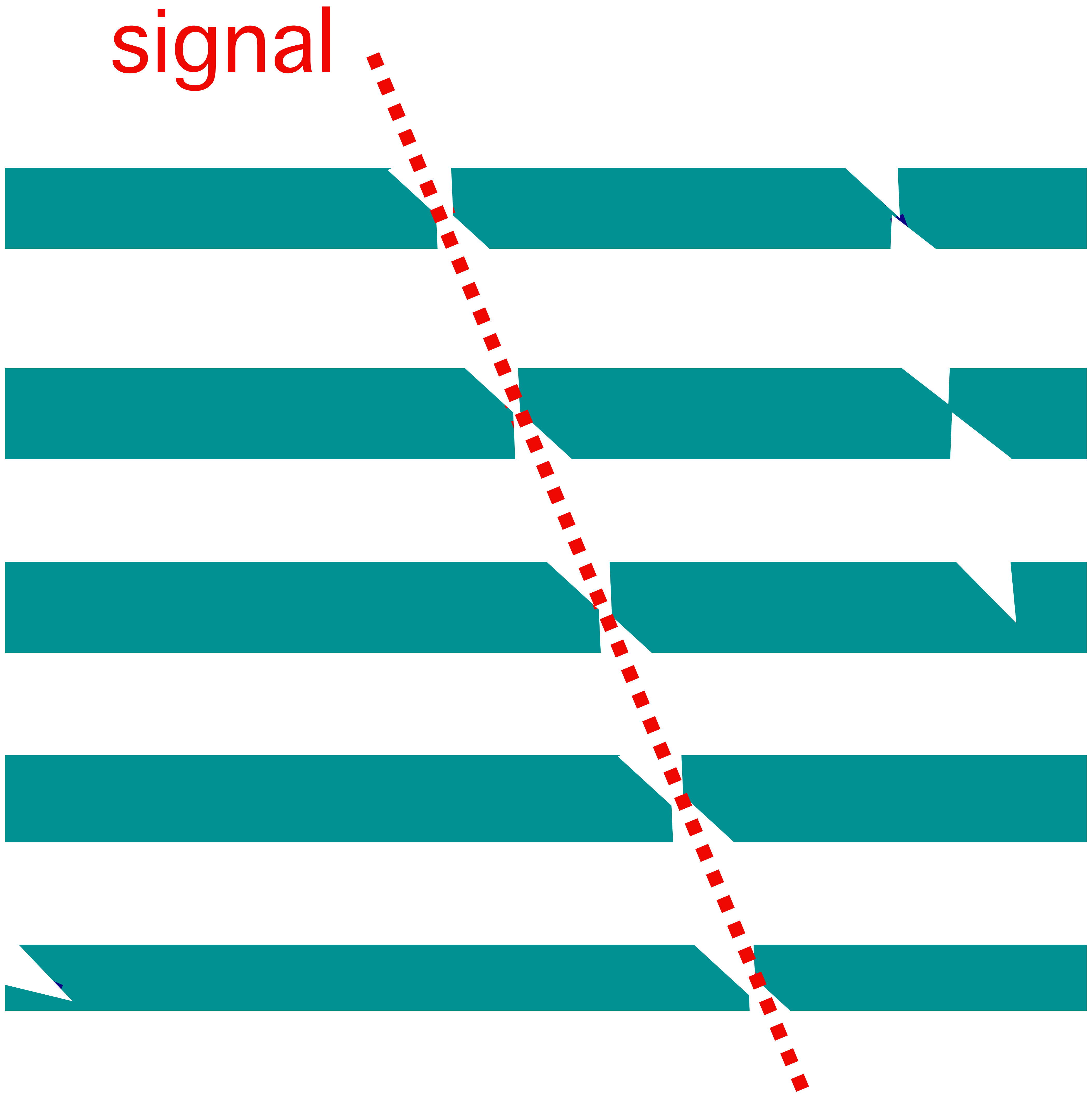
MoEDAL experiment



MoEDAL experiment



MoEDAL experiment



Signal estimation

- Because no background, the signal thresholds considered are low:
  - $N \geq 1, \;\; N \geq 2, \;\; N \geq 3$
- The signal is estimated by

$$N_{sig}(m,\tau) = \sigma(m) \cdot L \cdot \left\langle \sum_i \Theta\left(\beta_{th} - \beta_i\right) P(\overrightarrow{\beta}_i, \tau) \right\rangle_{MC}$$

  - $\sigma(m)$ is the production cross-section for pair of particles of mass m
  - $\overrightarrow{\beta}_i$ is particle's three-velocity, β_{th} is its threshold value
  - summation over i includes two particles created in an event
  - $P(\overrightarrow{\beta}_i, \tau) = \epsilon(\overrightarrow{\beta}) \cdot \exp\left(-\frac{L_{NTD}(\overrightarrow{\beta})}{\gamma\beta c\tau}\right)$ is the probability to reach the detector, where

  $\epsilon(\overrightarrow{\beta})$ is 1 if particle's track crosses with and NTD panel, and 0 otherwise.

Bound state calculations

$$V(\vec{r}) = -\frac{C\alpha_s + Q^2\alpha}{r} \qquad C = \frac{C_1 + C_2 - C_{\mathscr{B}}}{2} \qquad C = \begin{cases} 4/3 & \text{SU(3) triplet} \\ 4/3 & \text{SU(3) singlet} \end{cases}$$

$$\Psi_n(0) = \frac{1}{\sqrt{\pi}}(nr_b)^{-3/2}, \qquad r_b^{-1} = (C\overline{\alpha}_s + Q^2\alpha)\mu$$

$$|\Psi_n(0)|^2 = \frac{(C\overline{\alpha}_s + Q^2\alpha)^3 m^3}{8\pi n^3}$$

$$\Gamma_{\mathscr{B}\to\gamma\gamma} = \frac{2\pi Q^4\alpha^2}{m^2} n_c n_f |\Psi(0)|^2, \qquad \Gamma_{\mathscr{B}\to gg} = \frac{\pi C\alpha_s^2}{m^2} n_f |\Psi(0)|^2$$

$$\hat{\sigma}_{ab\to\mathscr{B}}(\hat{s}) = c_{ab} \cdot \frac{2\pi(2J_{\mathscr{B}}+1)D_{\mathscr{B}}}{D_a D_b} \cdot \frac{\Gamma_{\mathscr{B}\to ab}}{M_{\mathscr{B}}} \cdot 2\pi\delta(\hat{s} - M_{\mathscr{B}}^2)$$

$$\sigma_{pp\to\mathscr{B}} = \sum_{ab}^{\gamma\gamma,gg} \int_0^1 d\tau \, \frac{d\mathscr{L}_{ab}(\tau)}{d\tau} \, \hat{\sigma}_{ab\to\mathscr{B}}(s\tau)$$

$$\mathrm{BR}_{\mathscr{B}\to\gamma\gamma} = \frac{\Gamma_{\mathscr{B}\to\gamma\gamma}}{\Gamma_{\mathscr{B}\to\gamma\gamma} + \Gamma_{\mathscr{B}\to Z\gamma} + \Gamma_{\mathscr{B}\to ZZ} + \Gamma_{\mathscr{B}\to gg}} \qquad \sigma_{pp\to\mathscr{B}\to\gamma\gamma} = \sigma_{pp\to\mathscr{B}} \cdot \mathrm{BR}_{\mathscr{B}\to\gamma\gamma}$$

$$\mathrm{BR}_{\mathscr{B}\to\gamma Z} = \Gamma_{\mathscr{B}\to\gamma\gamma} \cdot \tan^2\theta_W \left(1 - \frac{m_Z^2}{M_{\mathscr{B}}^2}\right), \quad \mathrm{BR}_{\mathscr{B}\to ZZ} = \Gamma_{\mathscr{B}\to\gamma\gamma} \cdot \tan^4\theta_W \sqrt{1 - \frac{4m_Z^2}{M_{\mathscr{B}}^2}}$$