Detecting long-lived multi-charged particles in neutrino mass models with MoEDAL

https://arxiv.org/abs/2103.05644

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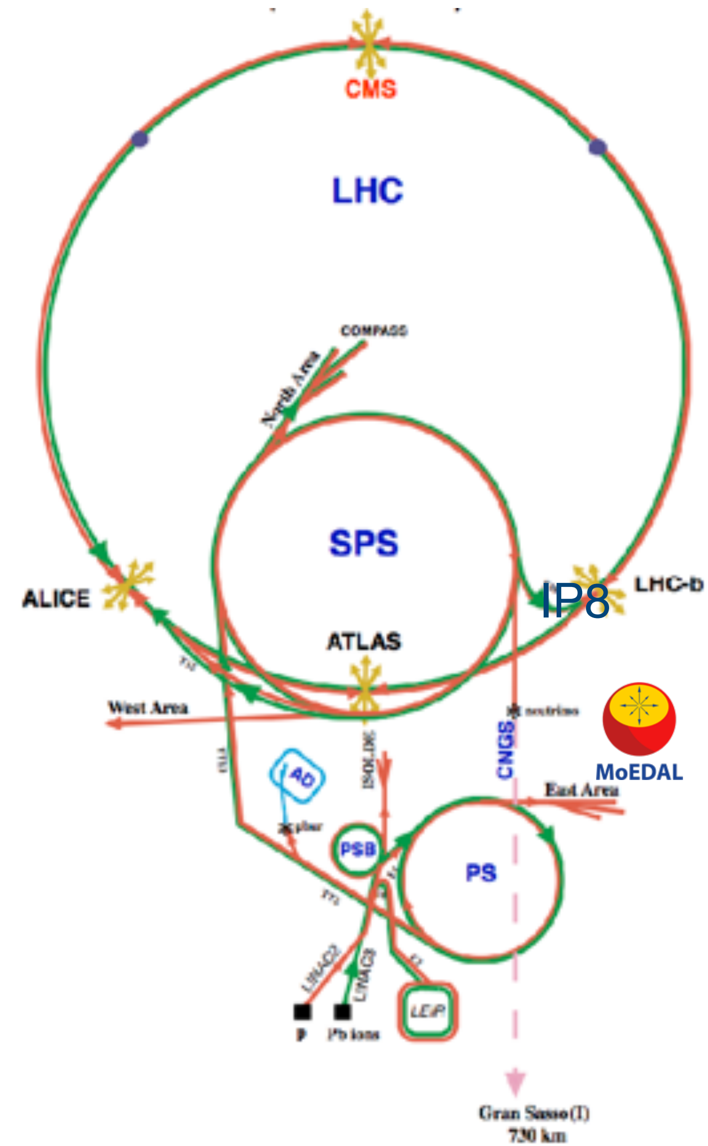
The MoEDAL experiment

- **MoEDAL** is an LHC experiment located in LHCb cavern.
- It's mainly a passive detector.
- It's designed to search for magnetic monopoles.
- It can also detect long-lived charged particles with $c\tau >= 2$m
- MoEDAL detects only slowly moving particles with $\beta < 0.15*|Q|$.
- The higher the charge the more particles it can detect.
- There is practically no background in MoEDAL

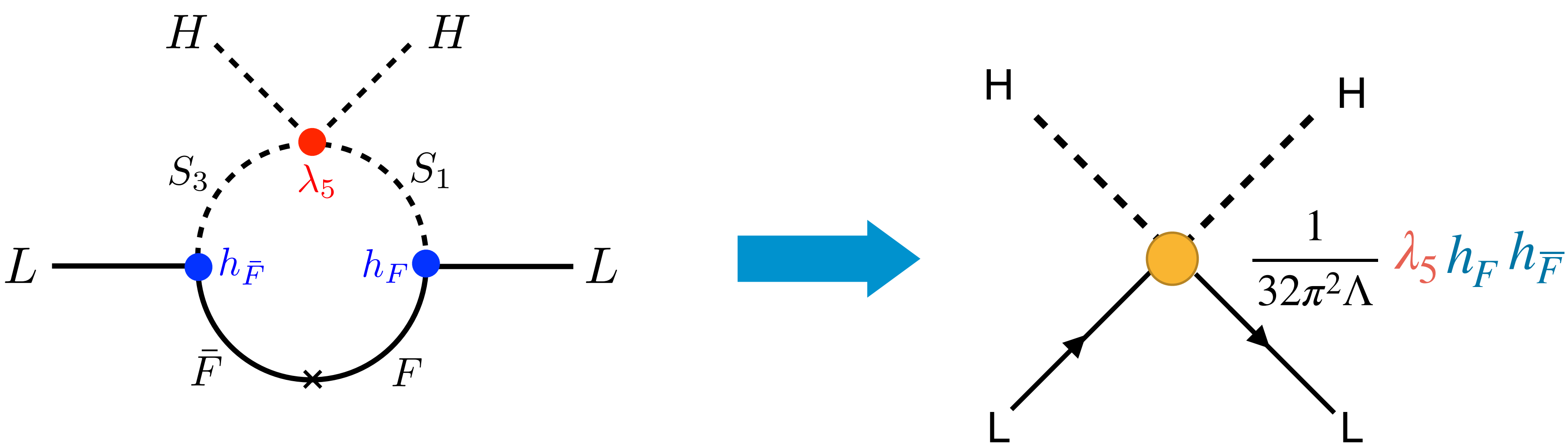


IMG SOURCE: https://www.quantumdiaries.org/2011/10/24/the-25-ns-pumpkin-teeth/

Model selection

[M. Hirsch et al; Phys. Rev. D 101, 095033 (2020)]

	S_1	S_3	F_i	$\bar{F}_i$
Spin	0	0	$\frac{1}{2}$	$\frac{1}{2}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	2	3	$\frac{5}{2}$	$-\frac{5}{2}$
Lepton number	-2	-4	-3	3



$$m_\nu \approx 0.05 \left(\frac{\lambda_5}{10^{-6}}\right)\left(\frac{h_F}{10^{-2}}\right)\left(\frac{h_{\overline{F}}}{10^{-2}}\right)\left(\frac{1\text{TeV}}{\Lambda}\right)\text{eV}$$

Model-1 description

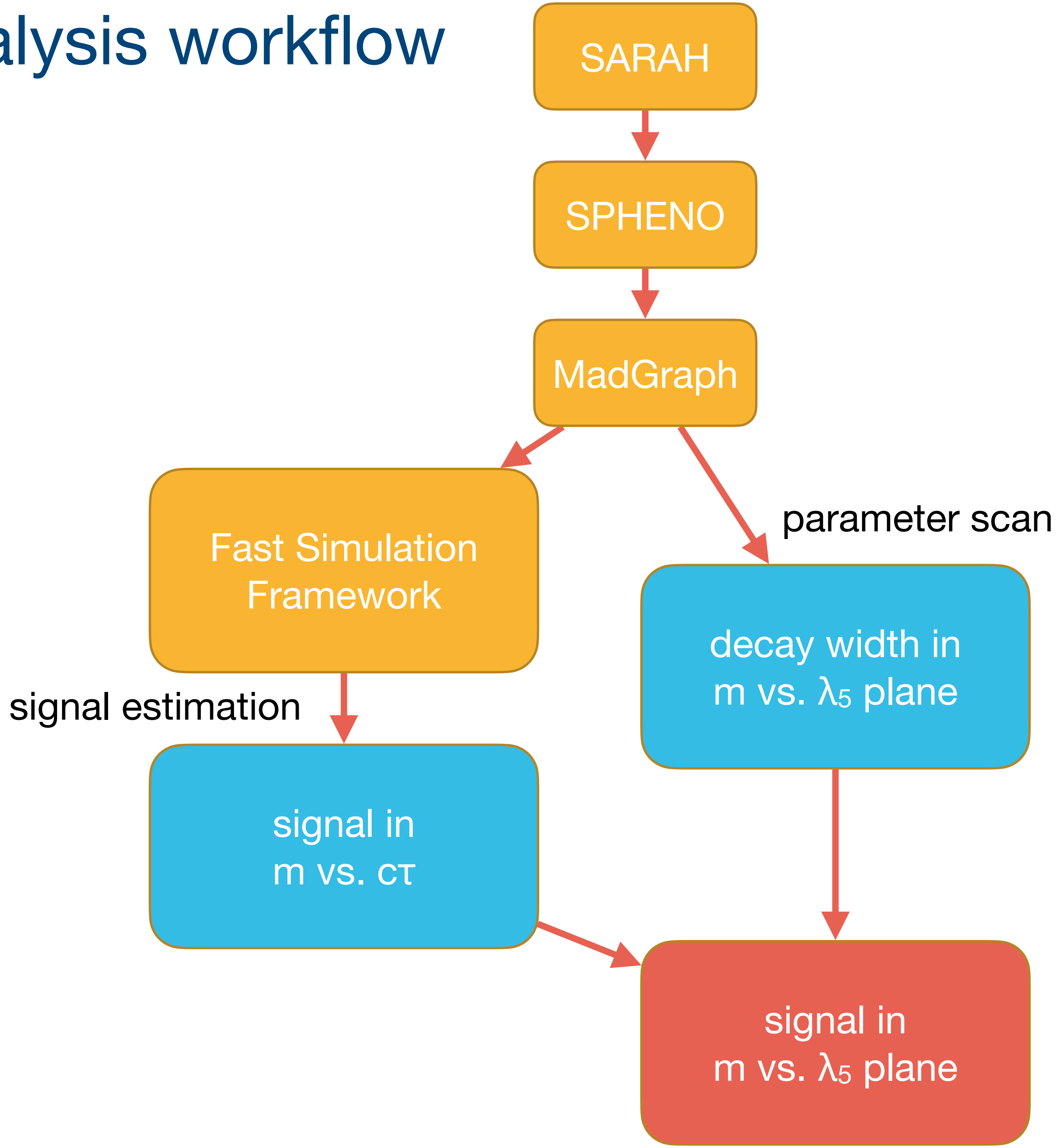
$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{kin}$$
$$-\left[\left(h_{ee}\right)_{ij} e_i^c e_j^c S_1^\dagger + \left(h_F\right)_{ij} L_i F_j S_1^\dagger + \left(h_{\bar{F}}\right)_{ij} L_i \bar{F}_j S_3 + h.c.\right]$$
$$-\left[\lambda_5 HHS_1S_3^\dagger + h.c.\right]$$
$$+\lambda_2 |H|^2|S_1|^2 + \lambda_{3a}|H^2||S_3|^2 + \lambda_{3b}|HS_3|^2 + \lambda_4|S_1|^4$$
$$+\lambda_{6a}|S_3^\dagger S_3|^2 + \lambda_{6a}|S_3S_3|^2 + \lambda_7|S_1|^2|S_3|^2$$

- Lepton number violation and scalar mixing through $\lambda_5 \neq 0$
- h_{ee} breaks BSM parity (for $h_{ee} \to 0$ the lightest BSM particle is stable)
- S_1 and S_3 mix and form $S_{1,3}^{2+}, S_3^{3+}, S_3^{4+}$ mass eigenstates
- For $m_{S_3} < m_{S_1}, m_{F_i}$ there exist long-lived charged scalars
- In the study we vary λ_5 & m_{S_3}, fit $h_F h_{\bar{F}}$ from data, fix m_{S_1} & m_{F_i} fix other couplings to small values —> mass degeneracy

It is possible to modify the model to obtain a coloured version (Model-2):

$$S_1(\mathbf{1},\mathbf{1},2) \to \tilde{S}_1(\bar{\mathbf{3}},\mathbf{1},4/3)$$
$$S_3(\mathbf{1},\mathbf{3},3) \to \tilde{S}_3(\bar{\mathbf{3}},\mathbf{3},7/3)$$
$$F(\mathbf{1},\mathbf{1},5/2) \to \tilde{F}(\bar{\mathbf{3}},\mathbf{2},11/6)$$
$$\overline{F}(\mathbf{1},\mathbf{1},-5/2) \to \tilde{\overline{F}}(\bar{\mathbf{3}},\mathbf{2},-11/6)$$
$$h_{ee}eeS_1^\dagger \to h_{ed}ed\tilde{S}_1^\dagger$$

Analysis workflow

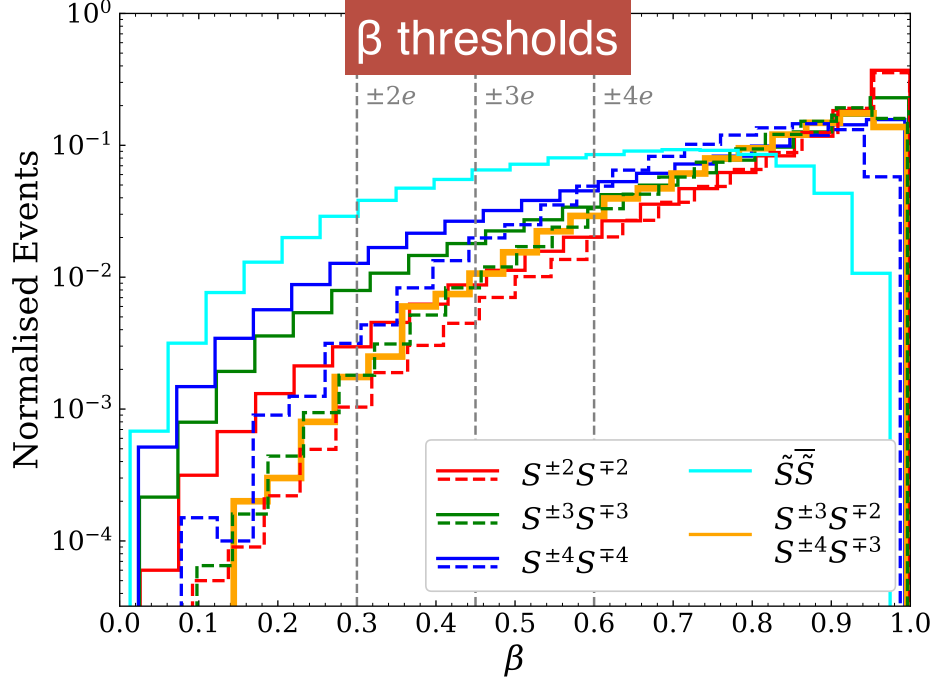


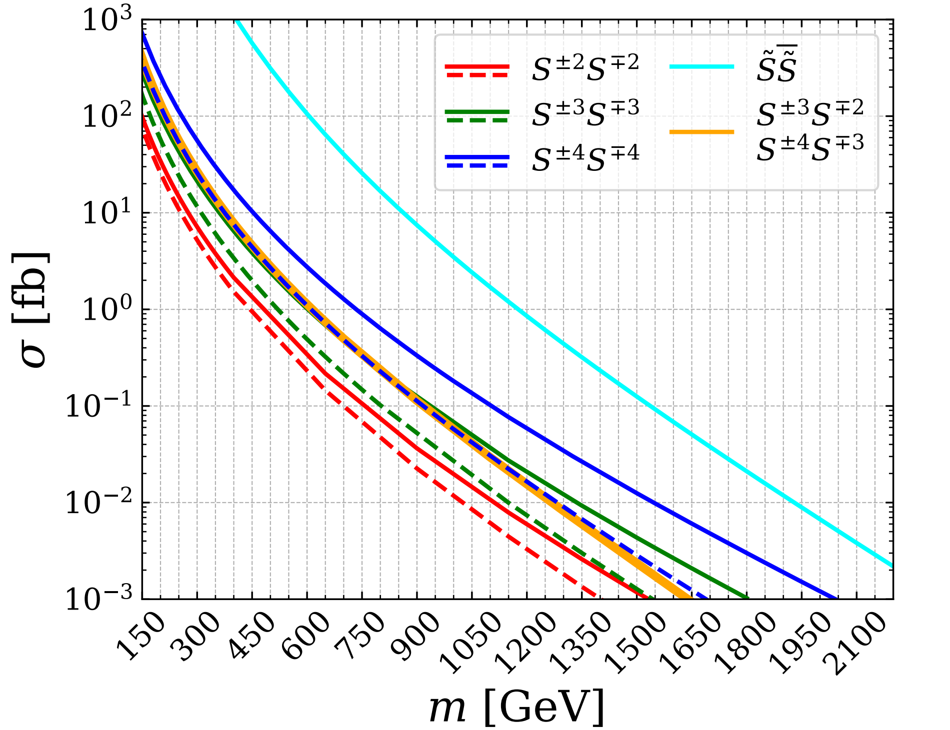
Signal estimation

- **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, $\beta_{th} = 0.15 \times |Q|$ 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.



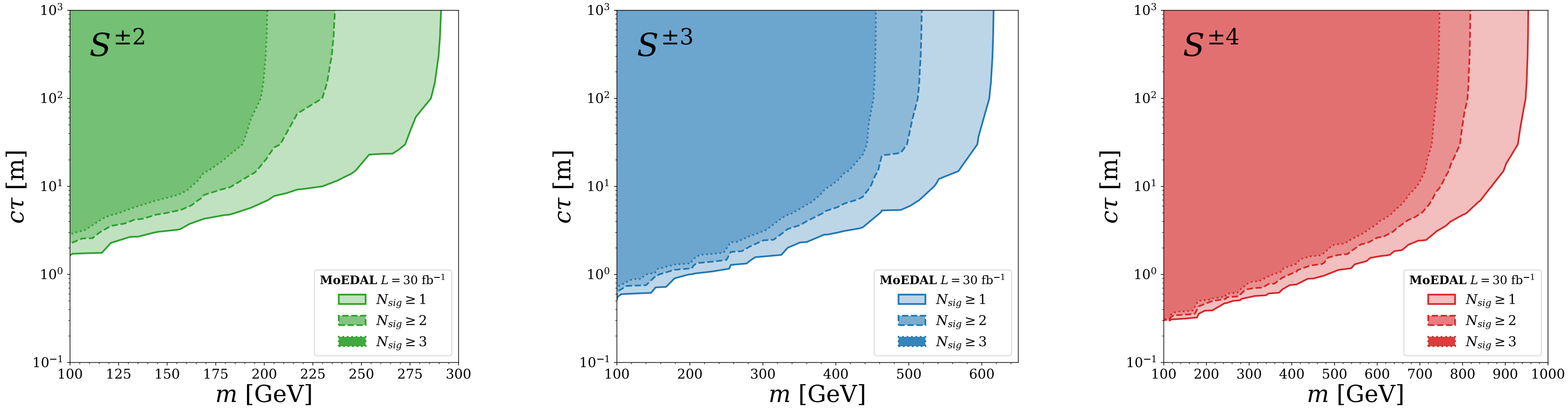


- MoEDAL detects particles with β < 0.15*|Q|
- Drell-Yan s-channel production —> spin conservation disallows small β for scalars
- No suppression for photon-fusion production
- s-channel photon-mediated production ∝ $|Q|^2$

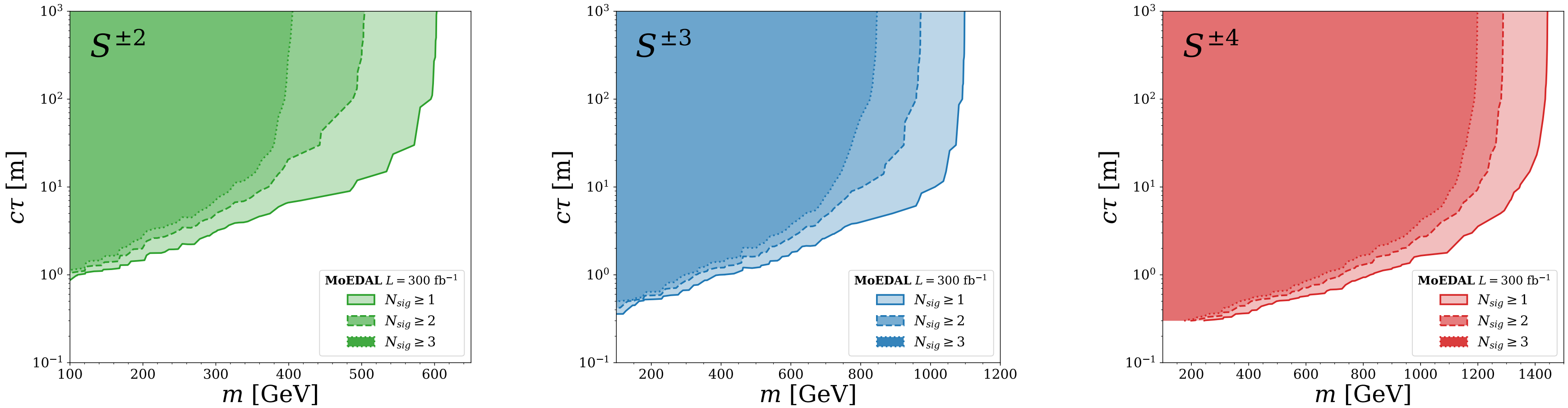
- photon fusion ∝ $|Q|^4$, crucial for highly charged particles
- photon-fusion more significant for heavier particles, because it allows to produce slow particles
- **2-fold advantage: larger cross-section and lower β**

MoEDAL detection reach (model independent)

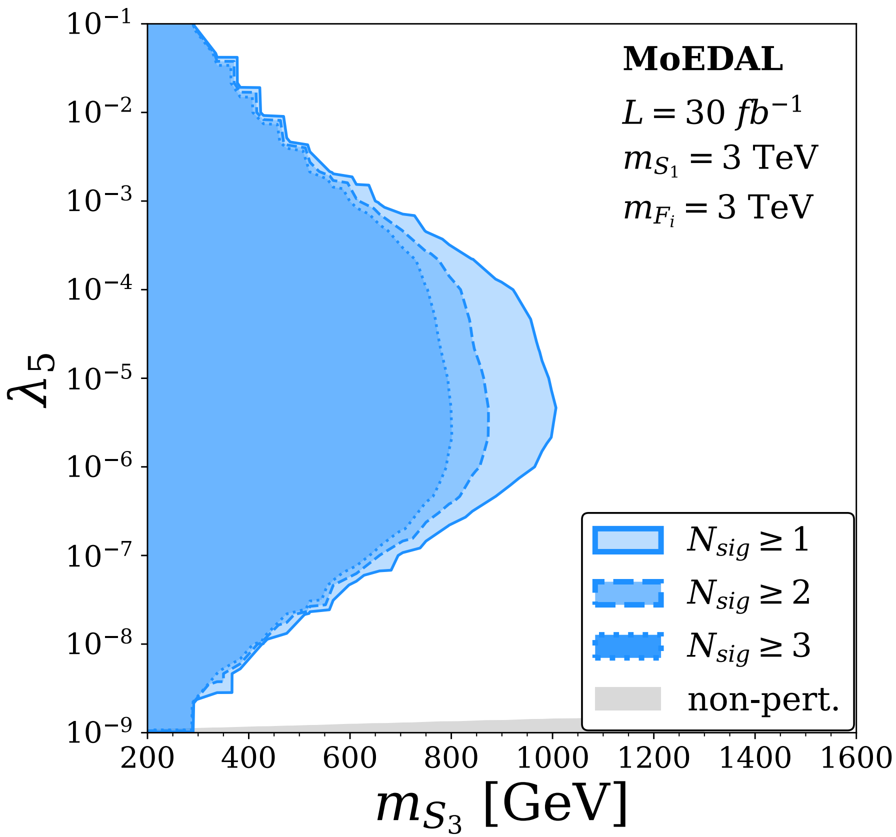
Run-3

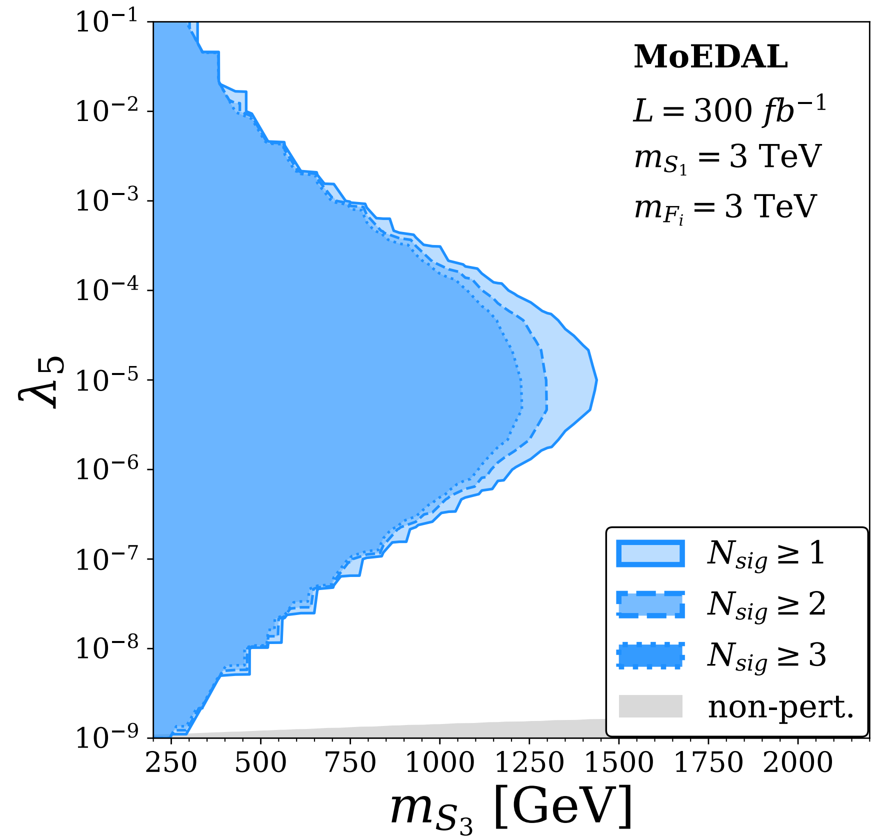


HL-LHC



Model-1 — detection reach





Run-3 **HL-LHC**

colour singlet — experimental constraints

$N_{sig} \geq 3$ ($N_{sig} \geq 1$)

	current HSCP bound 36 fb^{-1} [38]	HSCP (Run-3) 300 fb^{-1} [39]	MoEDAL (Run-3) 30 fb^{-1}	MoEDAL (HL-LHC) 300 fb^{-1}
$S^{\pm 2}$	((650))	–	190 (290)	400 (600)
$S^{\pm 3}$	((780))	–	430 (610)	850 (1100)
$S^{\pm 4}$	((920))	–	700 (960)	1200 (1430)

colour (anti)triplet — experimental constraints

(estimation)

	current HSCP bound 36 fb^{-1} [39]	HSCP (Run-3) 300 fb^{-1} [39]	MoEDAL (Run-3) 30 fb^{-1}	MoEDAL (HL-LHC) 300 fb^{-1}
$\tilde{S}^{\pm 4/3}$	((1450))	1700	880 (1050)	1250 (1400)
$\tilde{S}^{\pm 7/3}$	((1480))	1730	1080 (1250)	1450 (1650)
$\tilde{S}^{\pm 10/3}$	((1510))	1790	1200 (1400)	1600 (1800)

Conclusions

- MoEDAL can study selected neutrino mass generation models, e.g. model by M. Hirsch et al.
- The model predicts long-lived multi-charged particles for intermediate values of λ_5 parameter.
- MoEDAL Run-3 can compete with ATLAS in searches only for $S^{\pm 4}$, however, the window is small (40 GeV).
- MoEDAL HL-LHC can compete with **current** ATLAS constraints for $S^{\pm 3}, S^{\pm 4}, \tilde{S}^{\pm 7/3}, \tilde{S}^{\pm 10/3}$.
- For these particles MoEDAL can scan a wide range of model's parameters

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References

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- B.S. Acharya, A. De Roeck, J. Ellis, D.K. Ghosh, R. Masełek, G. Panizzo, J.L. Pinfold, K. Sakurai, A. Shaa, A. Wall; Eur.Phys.J.C 80 (2020) 5, 572
- C. Abelaez, G. Cottin, J.C. Helo and M. Hirsch; Phys. Rev. D 101, 095033 (2020)
- Current experimental constraints:
  - [38] ATLAS Collaboration, Phys. Rev. D 99 no. 5, (2019) 052003
  - [39] S. Jaeger, S. Kvedarait˙e, G. Perez, and I. Savoray, JHEP 04 (2019) 041
  - [40] CMS Collaboration, S. Chatrchyan et al., JHEP 07 (2013) 122


Thank you for attention

BACKUP SLIDES

Physics program of the MoEDAL experiment

- **Magnetic Monopoles and Dyons**
- Scenarios with extra dimensions
- Highly Ionising Multiparticle Excitations
- Doubly Charged Massive Stable Particles
- Electrically Charged Massive (Meta-)stable Particles in Supersymmetric scenarios
- **Highly Ionising particles in different scenarios**
- …

SUSY

Prospects for discovering supersymmetric long-lived particles with MoEDAL

D. Felea, J. Mamuzic, R. Maselek, N. E. Mavromatos, V. A. Mitsou, J. L. Pinfold, R. Ruiz de Austri, K. Sakurai, A. Santra, O. Vives

PUBLISHED IN EPJC

https://dx.doi.org/10.1140%2Fepjc%2Fs10052-020-7994-7

SUSY

± 2e

Prospects of searches for long-lived charged particles with MoEDAL

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NEUTRINO MASS MODEL

Detecting long-lived multi-charged particles in neutrino mass models with MoEDAL

Martin Hirsch[(a)], Rafał Maselek[(b)] and Kazuki Sakurai[(b)]

SUBMITTED TO EPJC

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Motivation

- "Vanilla" SM does not contain right-handed neutrinos, hence neutrinos are **massless**
- Experiments confirmed that neutrinos are **massive**
- Need to augment SM by a mechanism leading to neutrinos having mass
- Neutrino mass originates from dim-5 operator:

$$\mathscr{L} \ni \frac{1}{\Lambda}(LHLH) + \frac{1}{\Lambda}(LHLH)^* = \frac{<H>^2}{\Lambda}(\nu\nu + \bar{\nu}\bar{\nu})$$

- This operator can be effectively constructed by integrating out heavy mediators from the full theory
- Two popular choices:
  - Seesaw Mechanism with right-handed neutrinos
  - **Radiative neutrino mass generation**

Model selection
[Martin Hirsch et al.'20]

- Radiative neutrino mass generation via effective dimension-5 operator
- Lepton Number Violation
- Predicts multi-charged particles
- **Some of the multi-charged particles can be long-lived and detected by MoEDAL**

	S_1	S_3	F_i	$\bar{F}_i$
Spin	0	0	$\frac{1}{2}$	$\frac{1}{2}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	2	3	$\frac{5}{2}$	$-\frac{5}{2}$
Lepton number	-2	-4	-3	3

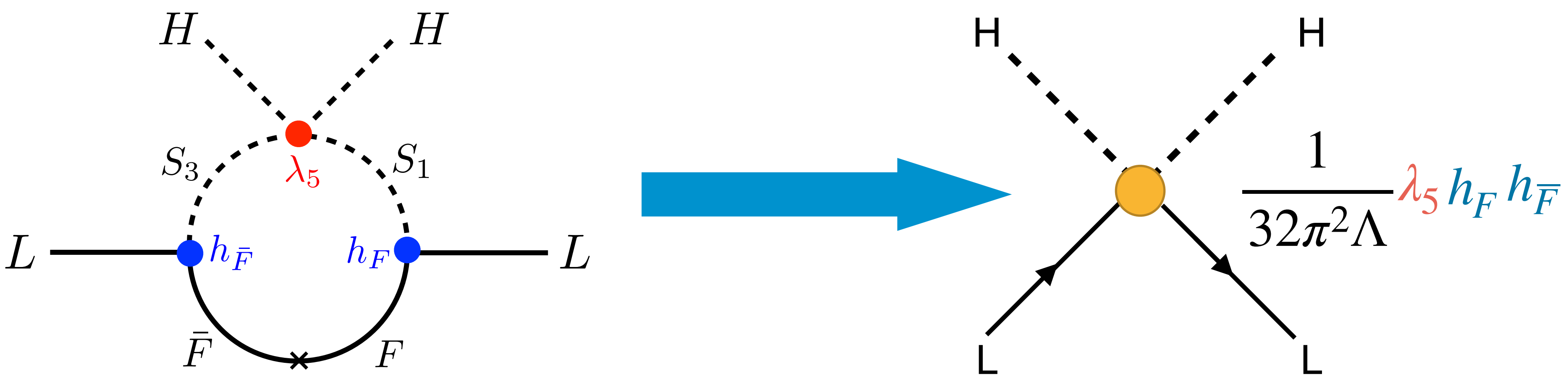
Model-1 description

[Martin Hirsch et al.'20]

$$\mathscr{L}_{\text{BSM}} = \mathscr{L}_{kin}$$
$$-\left[\left(h_{ee}\right)_{ij} e_i^c e_j^c S_1^\dagger + \left(h_F\right)_{ij} L_i F_j S_1^\dagger + \left(h_{\bar{F}}\right)_{ij} L_i \bar{F}_j S_3 + h.c.\right]$$
$$-\left[\lambda_5 H H S_1 S_3^\dagger + h.c.\right]$$
$$+\lambda_2 |H|^2 |S_1|^2 + \lambda_{3a} |H^2| |S_3|^2 + \lambda_{3b} |H S_3|^2 + \lambda_4 |S_1|^4$$
$$+\lambda_{6a} |S_3^\dagger S_3|^2 + \lambda_{6a} |S_3 S_3|^2 + \lambda_7 |S_1|^2 |S_3|^2$$

- Lepton number violation and scalar mixing through $\lambda_5 \neq 0$
- h_{ee} breaks BSM parity (for $h_{ee} \to 0$ the lightest BSM particle is stable)
- S_1 and S_3 mix and form $S_{1,3}^{2+}, S_3^{3+}, S_3^{4+}$ mass eigenstates
- For $m_{S_3} < m_{S_1}, m_{F_i}$ there exist long-lived charged scalars

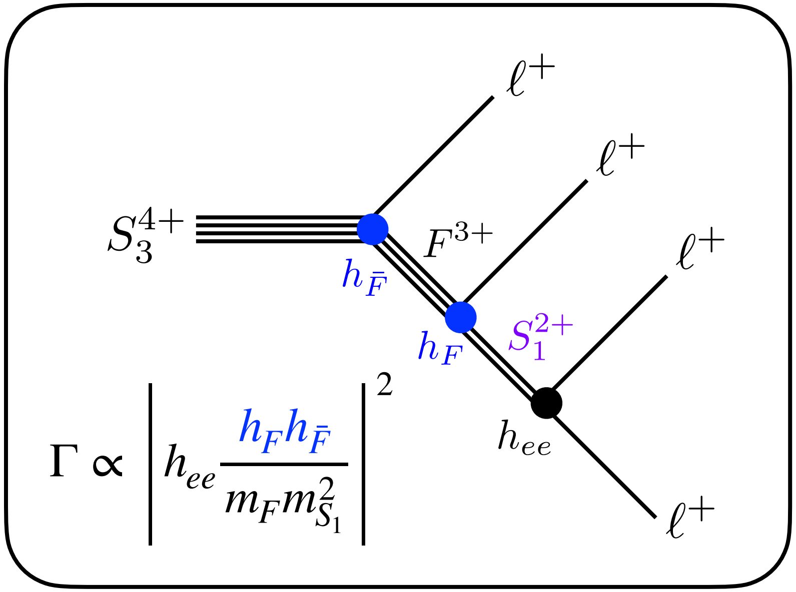
Model-1 description
[Hirsch et al.'20]



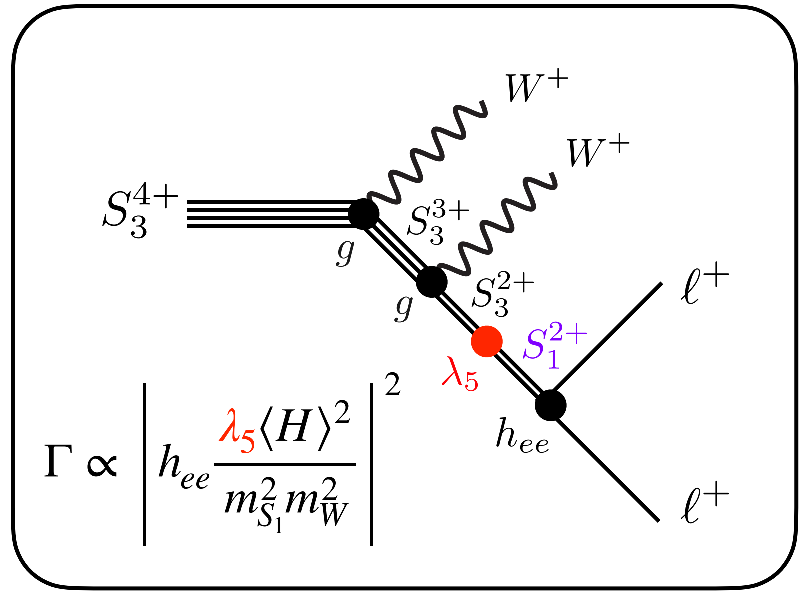
$$m_\nu \approx 0.05 \left(\frac{\lambda_5}{10^{-6}}\right)\left(\frac{h_F}{10^{-2}}\right)\left(\frac{h_{\overline{F}}}{10^{-2}}\right)\left(\frac{1\text{TeV}}{\Lambda}\right)\text{eV}$$

- Λ — mass scale of heavy particles in the model
- $\lambda_5 \ll 1$
- Neutrino masses require $\lambda_5 h_F h_{\overline{F}}$ to be small, but do not fix the ratios of these parameters
- **For what values of $\lambda_5, h_F, h_{\overline{F}}$ there are long-lived particles in the model?**

L-conserving



L-violating

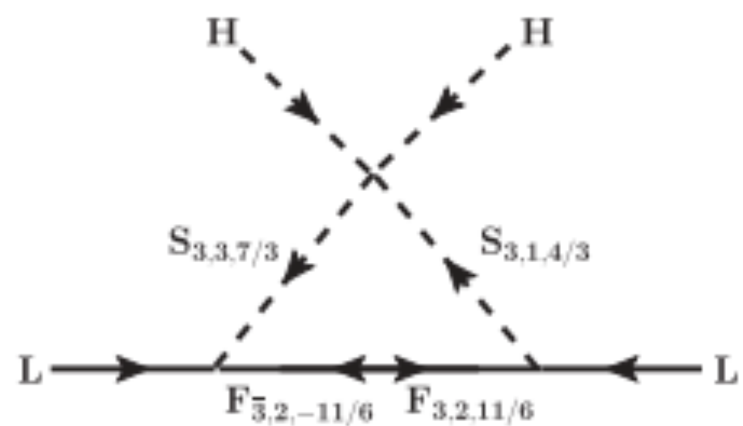


- If $m_{S_3} < m_{S_1}, m_{F_i}$ and $m_{S_3^{4+}} - m_{S_3^{3+}} < m_W$ and $m_{S_3^{4+}} - m_{S_3^{2+}} < m_W$ then S_3^{4+} can be long-lived and will have only 4-body decays
- For $h_F h_{\overline{F}}$ or λ_5 big, one of the S_3^{4+} decay channels will get large decay width and S_3^{4+} will be short-lived
- Because we have an upper constraint on $h_F h_{\overline{F}} \times \lambda_5$ it is enough to have λ_5 with an **intermediate** value when $h_F h_{\overline{F}}$ is fitted from neutrino data
- All diagrams lead to 4-body final states, are therefore phase-space suppressed
- If S1 is heavy, all diagrams are suppressed

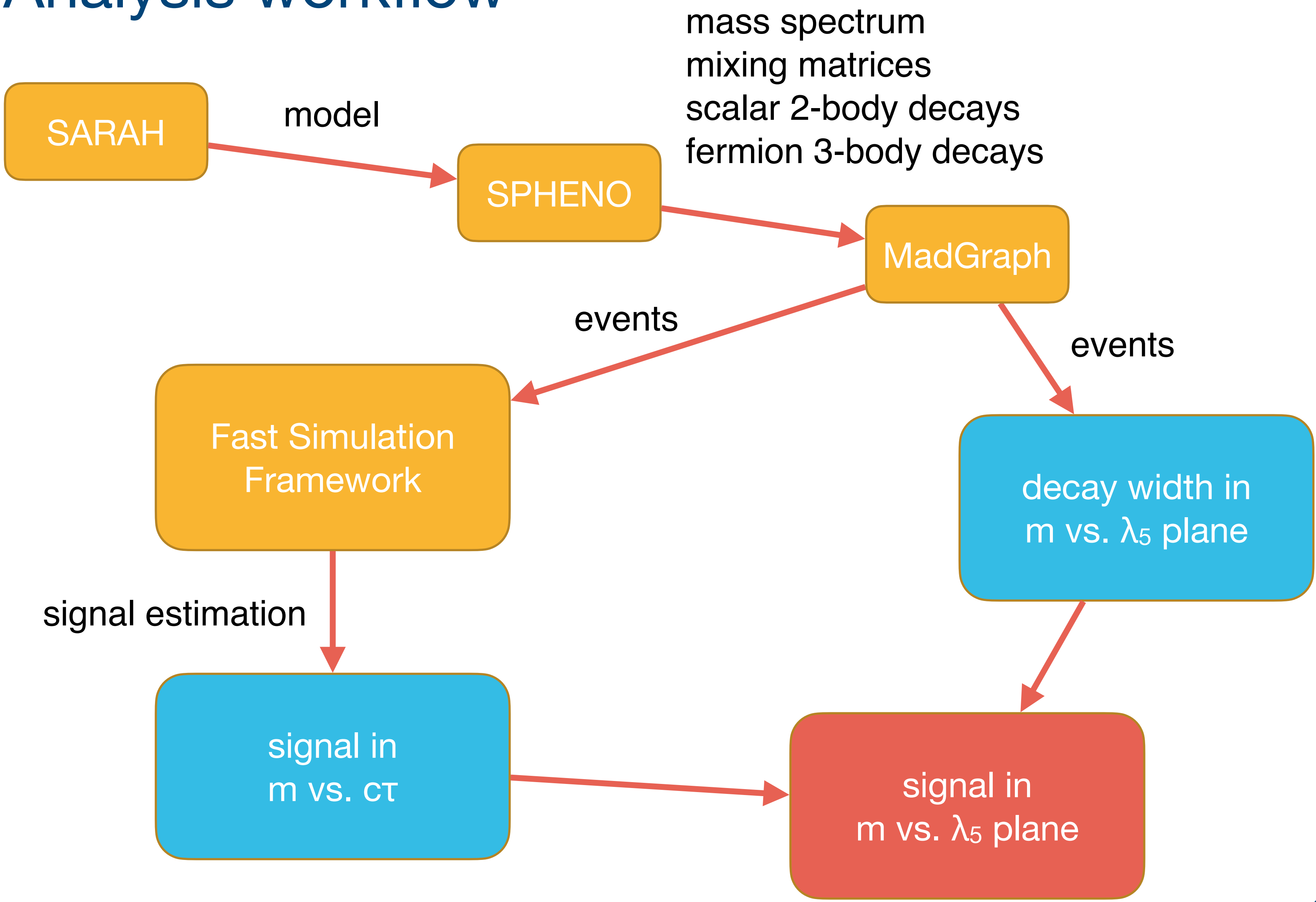
- If $m_{S_3} < m_{S_1}, m_{F_1}$ then S_3^{3+} has two relevant decays:
  - $S_3^{3+} \to ll l\nu, \quad \Gamma \propto \left| h_{ee} \frac{h_F h_{\bar{F}}}{m_F m_{S_1}^2} \right|^2$
  - $S_3^{3+} \to Wll, \quad \Gamma \propto \left| h_{ee} \frac{\lambda_5 \langle H \rangle^2}{m_{S_1}^2 m_W} \right|^2$
- Similar behaviour as for S_3^{4+}.
- For S_3^{2+} there is
  - $S_3^{2+} \to ll\nu\nu, \quad \Gamma \propto \left| h_{ee} \frac{h_F h_{\bar{F}}}{m_F m_{S_1}^2} \right|^2$
  - $S_3^{2+} \to ll, \quad \Gamma \propto \left| h_{ee} \frac{\lambda_5 \langle H \rangle^2}{m_{S_1}^2} \right|^2$

It is possible to modify the model to obtain a coloured version (Model-2):

$$S_1(\mathbf{1},\mathbf{1},2) \to \tilde{S}_1(\bar{\mathbf{3}},\mathbf{1},4/3)$$
$$S_3(\mathbf{1},\mathbf{3},3) \to \tilde{S}_3(\bar{\mathbf{3}},\mathbf{3},7/3)$$
$$F(\mathbf{1},\mathbf{1},5/2) \to \tilde{F}(\bar{\mathbf{3}},\mathbf{2},11/6)$$
$$\overline{F}(\mathbf{1},\mathbf{1},-5/2) \to \overline{\tilde{F}}(\bar{\mathbf{3}},\mathbf{2},-11/6)$$
$$h_{ee} ee S_1^\dagger \to h_{ed} ed \tilde{S}_1^\dagger$$



Analysis workflow

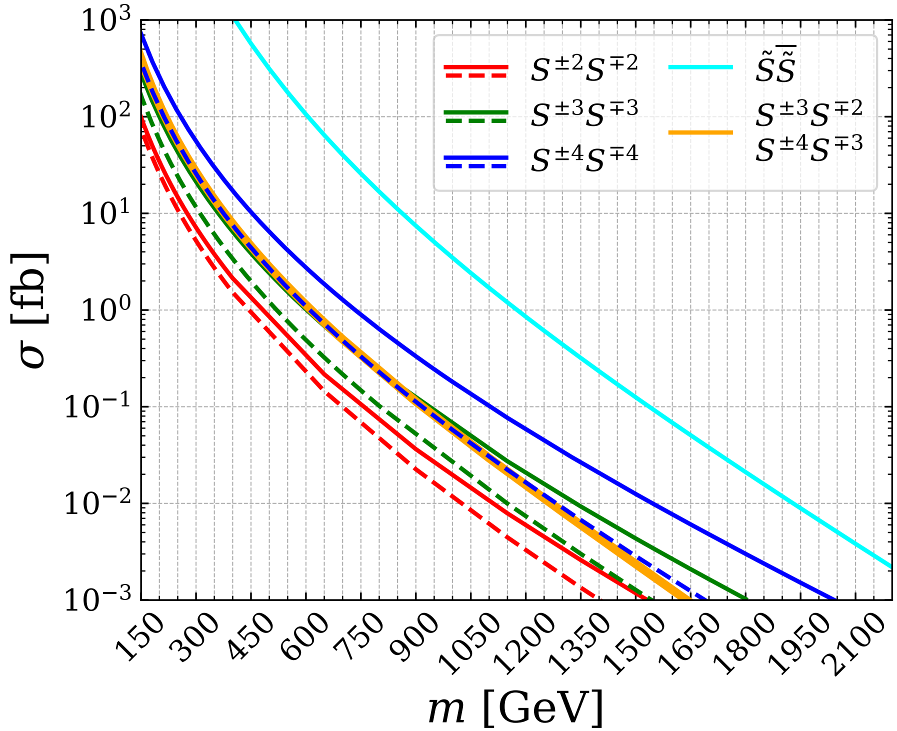


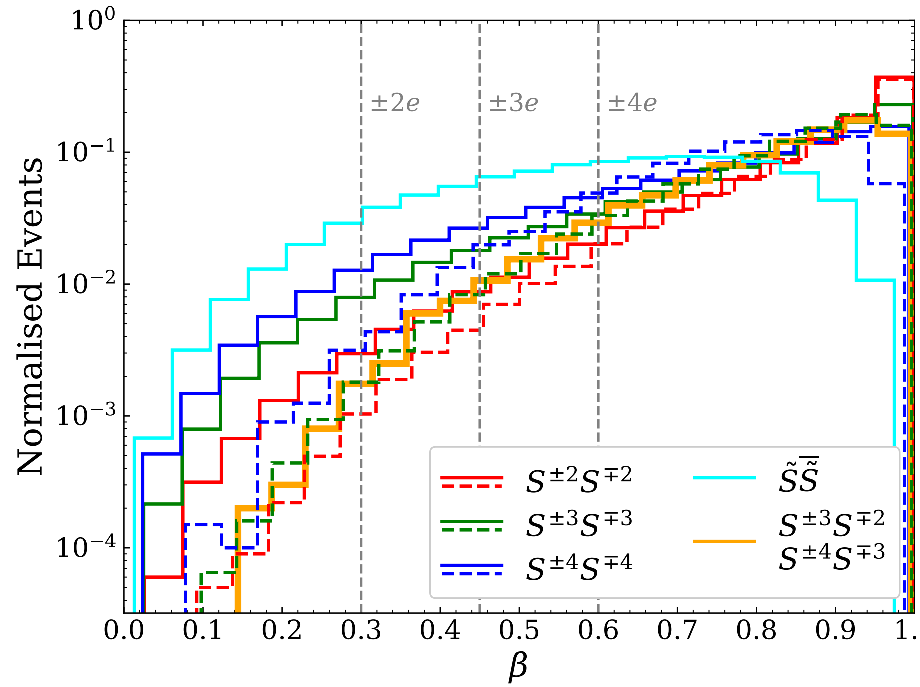
Signal estimation

- **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.





- largest xs for coloured particles
- s-channel photon-mediated production $\propto |Q|^2$
- photon fusion $\propto |Q|^4$, crucial for highly charged particles
- associated production through s-channel

- best β distribution for coloured particles
- Drell-Yan s-channel production —> spin conservation disallows small β for scalars
- large β —> large energy cost —> smaller xs for high masses
- photon fusion enables slowly moving scalars

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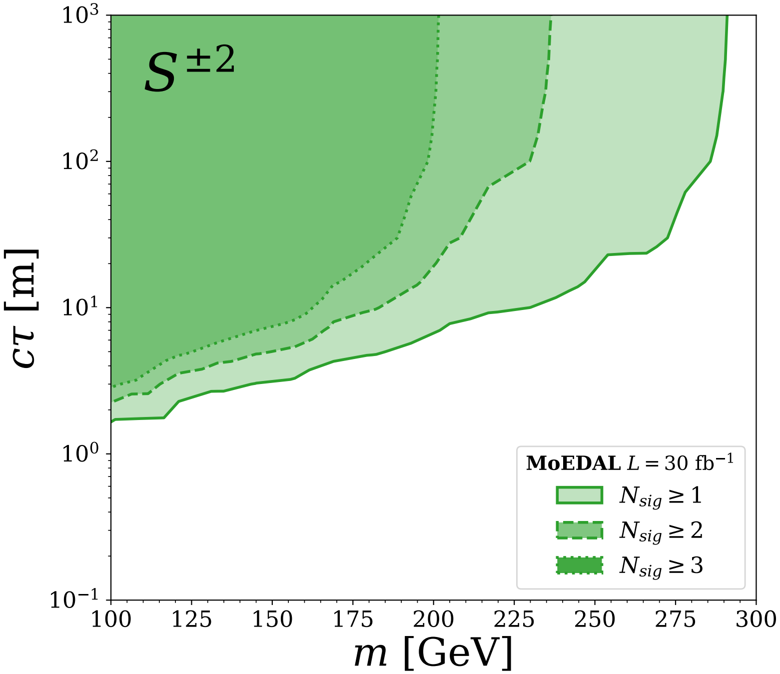
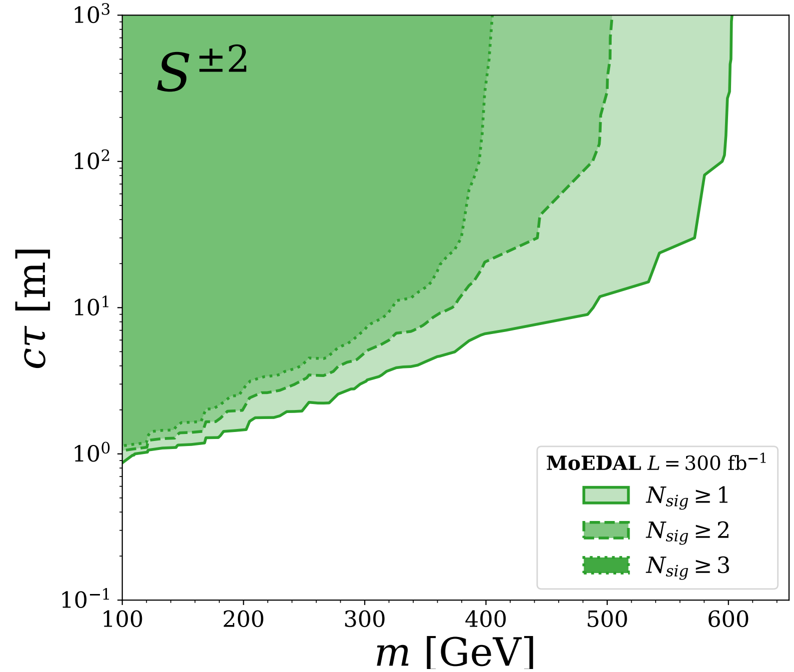
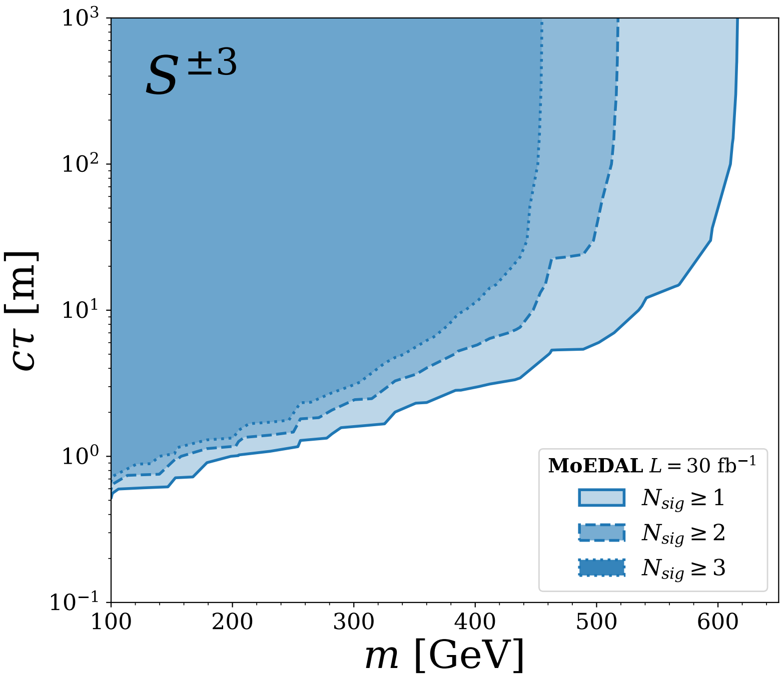


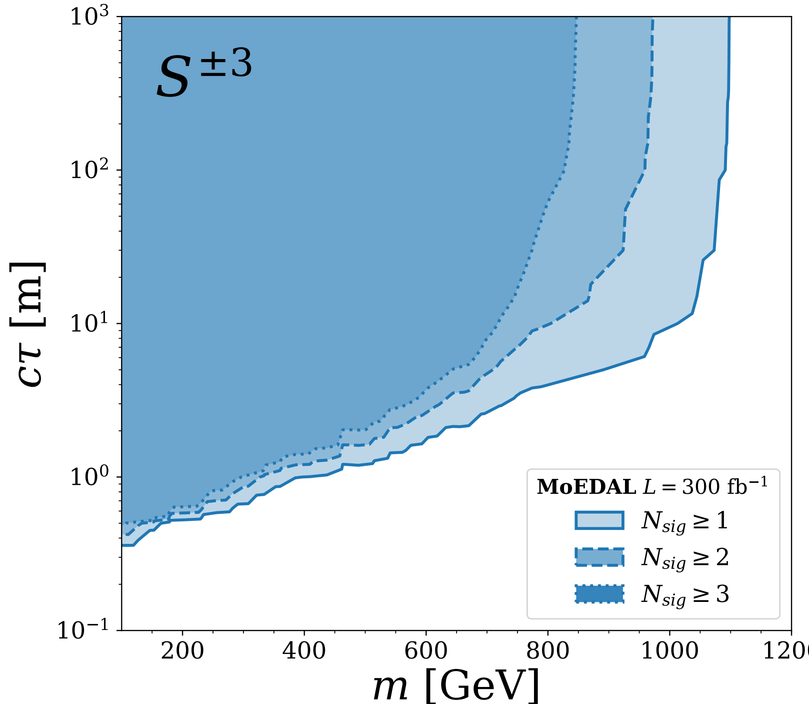
$S^{\pm 2}$
$c\tau$ [m]
m [GeV]
MoEDAL $L = 30$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$



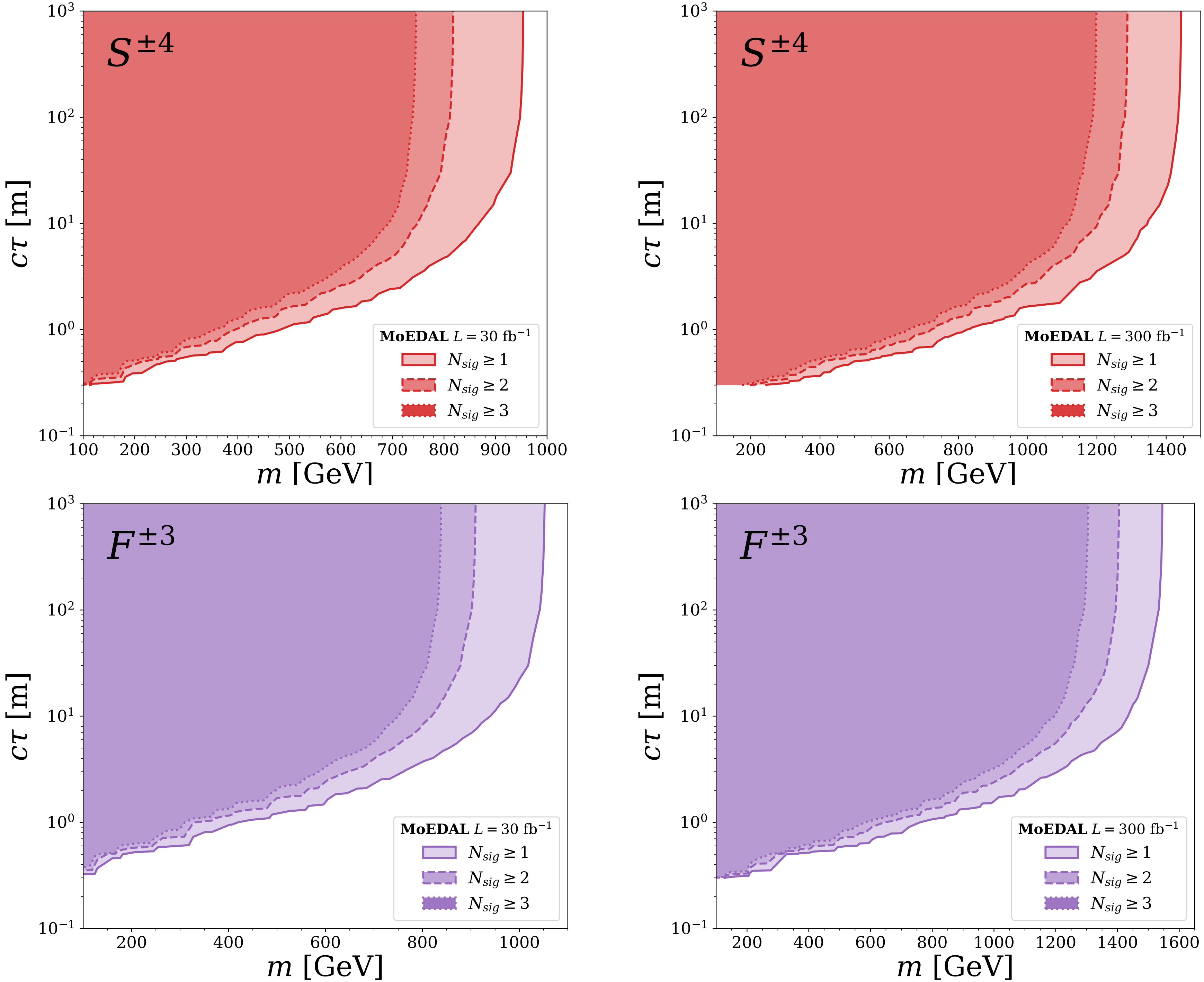
$S^{\pm 2}$
$c\tau$ [m]
m [GeV]
MoEDAL $L = 300$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$



$S^{\pm 3}$
$c\tau$ [m]
m [GeV]
MoEDAL $L = 30$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$



$S^{\pm 3}$
$c\tau$ [m]
m [GeV]
MoEDAL $L = 300$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$



$S^{\pm4}$
MoEDAL $L = 30$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
$c\tau$ [m]
m [GeV]
$S^{\pm4}$
MoEDAL $L = 300$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
$c\tau$ [m]
m [GeV]
$F^{\pm3}$
MoEDAL $L = 30$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
$c\tau$ [m]
m [GeV]
$F^{\pm3}$
MoEDAL $L = 300$ fb^{-1}
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
$c\tau$ [m]
m [GeV]

Current experimental constraints — Model-1

	current HSCP bound 36 fb^{-1} [38]	HSCP (Run-3) 300 fb^{-1} [39]	MoEDAL (Run-3) 30 fb^{-1}	MoEDAL (HL-LHC) 300 fb^{-1}
$S^{\pm2}$	((650))	–	190 (290)	400 (600)
$S^{\pm3}$	((780))	–	430 (610)	850 (1100)
$S^{\pm4}$	((920))	–	700 (960)	1200 (1430)
$F^{\pm3}$	1130	1500	800 (1030)	1300 (1550)

Table 2: Summary for the model-independent mass reaches (in GeV) of the multi-charged particles in Model-1 by MoEDAL (2nd and 3rd columns). The first column shows the current mass bounds from the ATLAS analysis [38] with 36 fb^{-1}. The numbers in the double-brackets correspond to our naive estimate of the mass bounds (see the text). The second column represents the projected mass reach in Run-3 (300 fb^{-1}) obtained in [39]. The numbers outside (inside) the brackets in the third and fourth columns represent MoEDAL's mass reaches with $N_{\rm sig} \geq 3$ (1) assuming $L = 30$ (Run-3) and 300 (HL-LHC) fb^{-1}, respectively.

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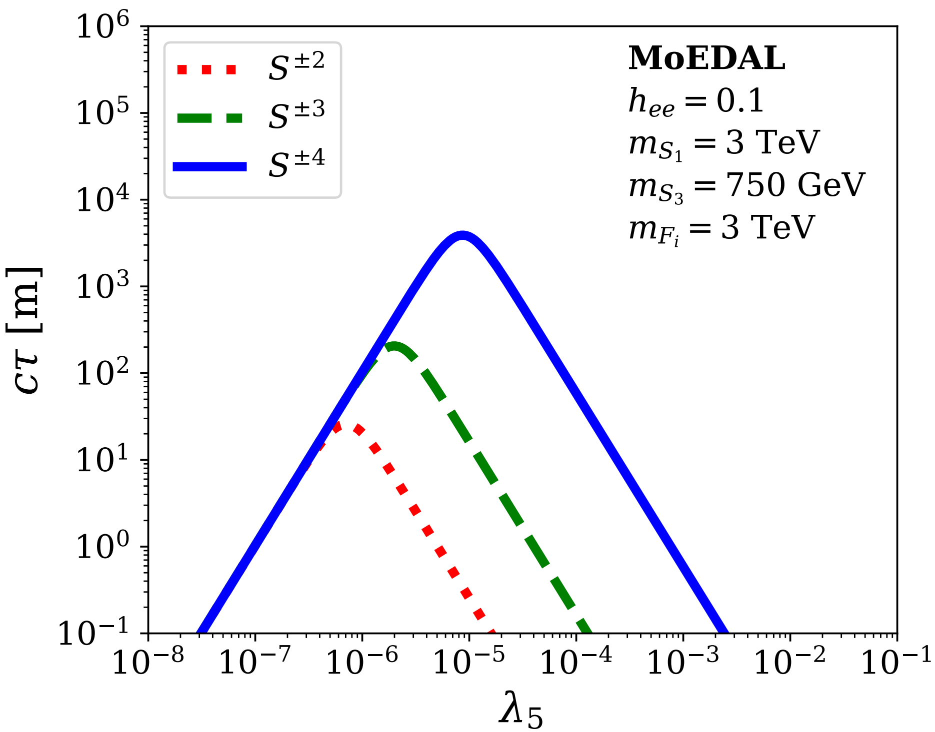
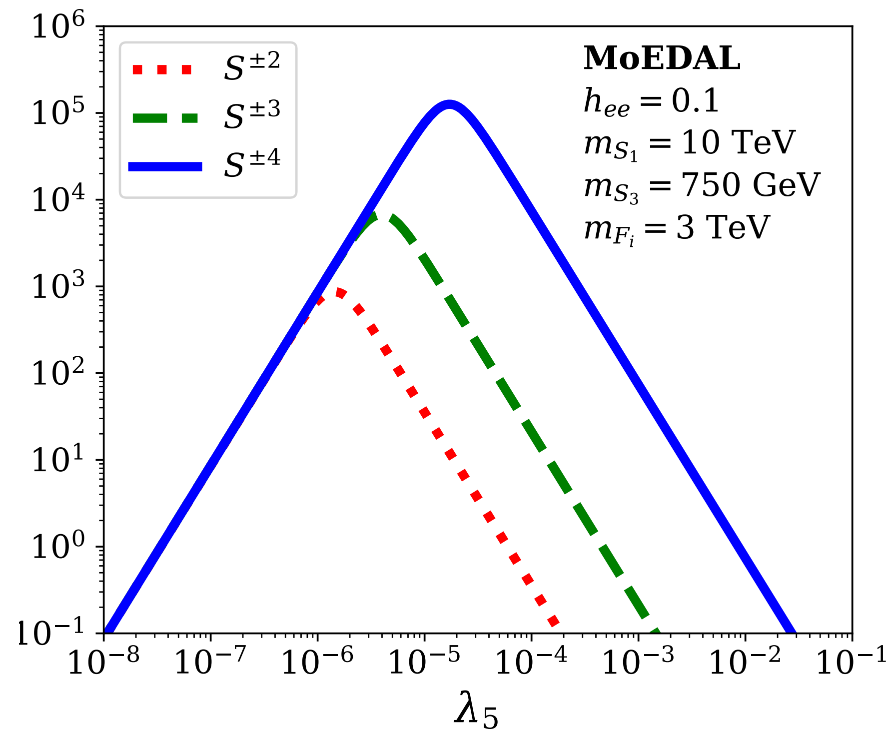
Decay length for Model-1





$m_{S_1} = 3$ TeV

$m_{S_1} = 10$ TeV

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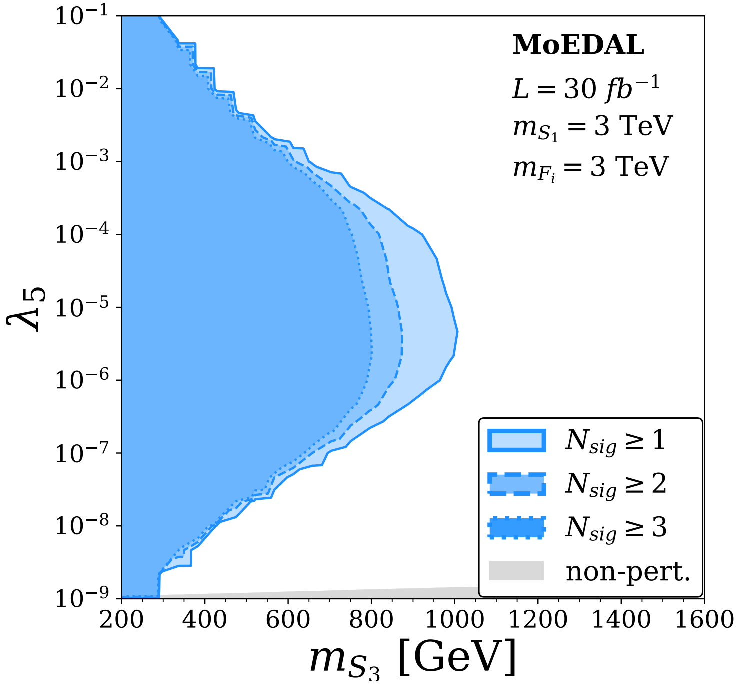
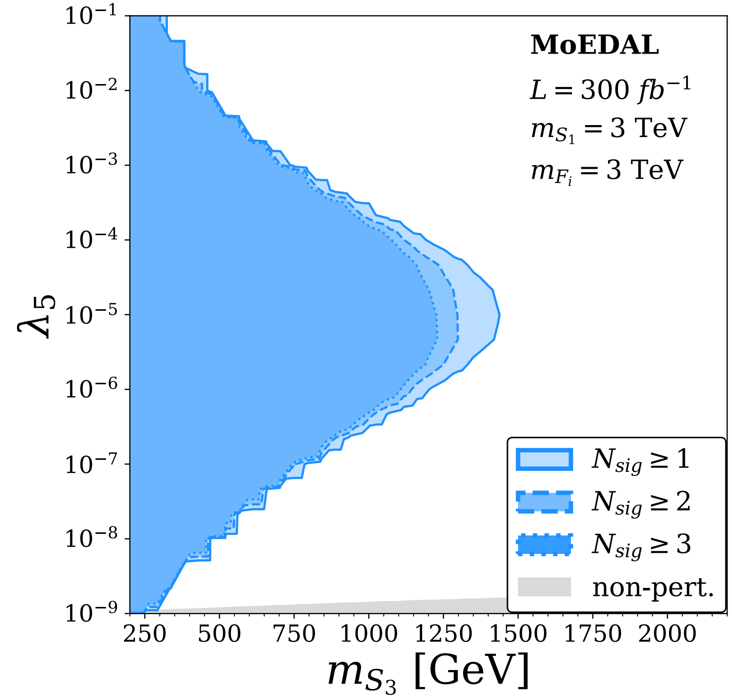
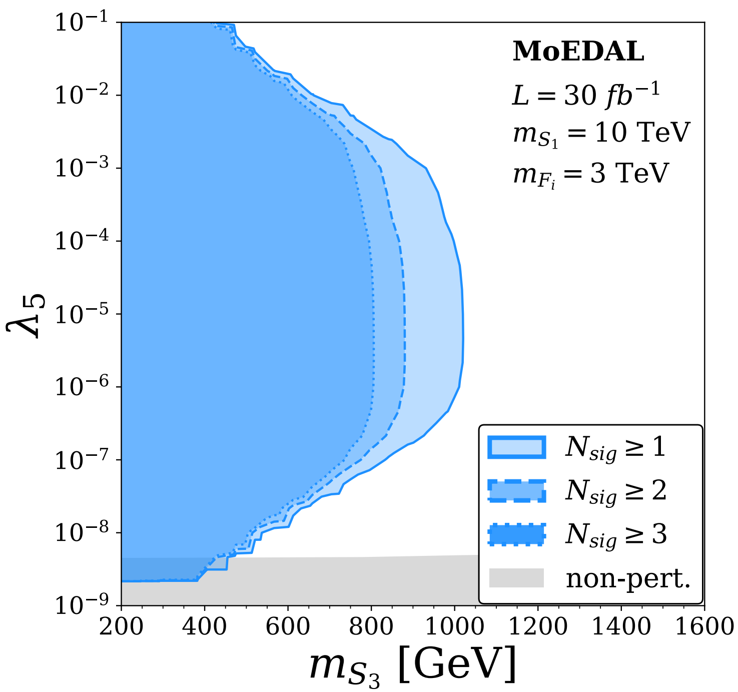
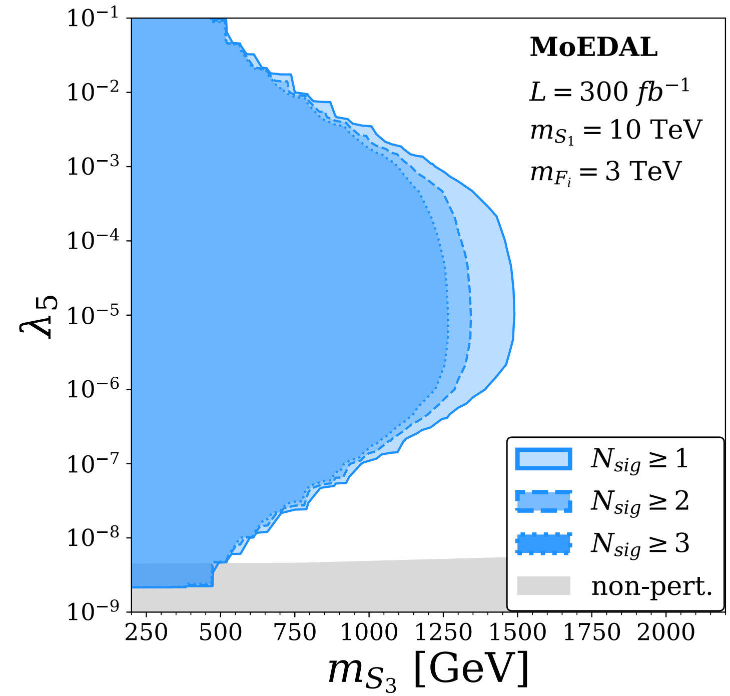
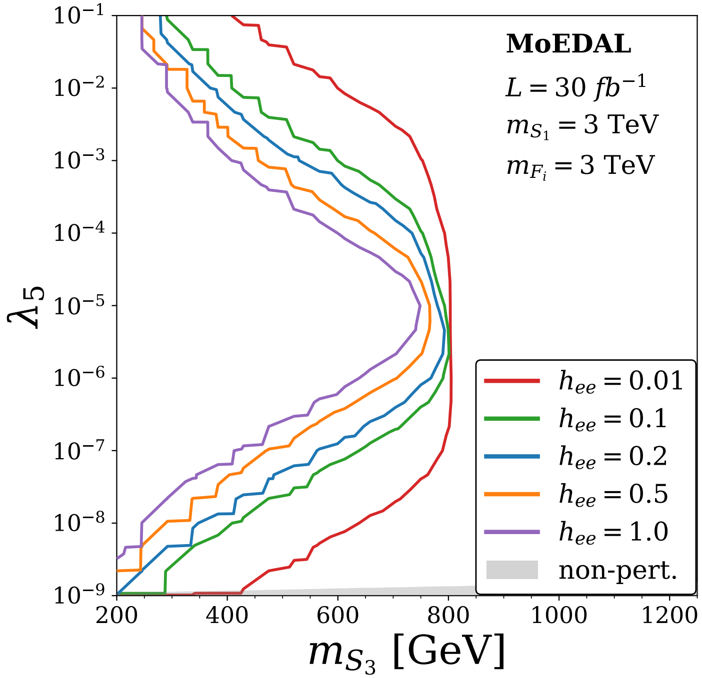
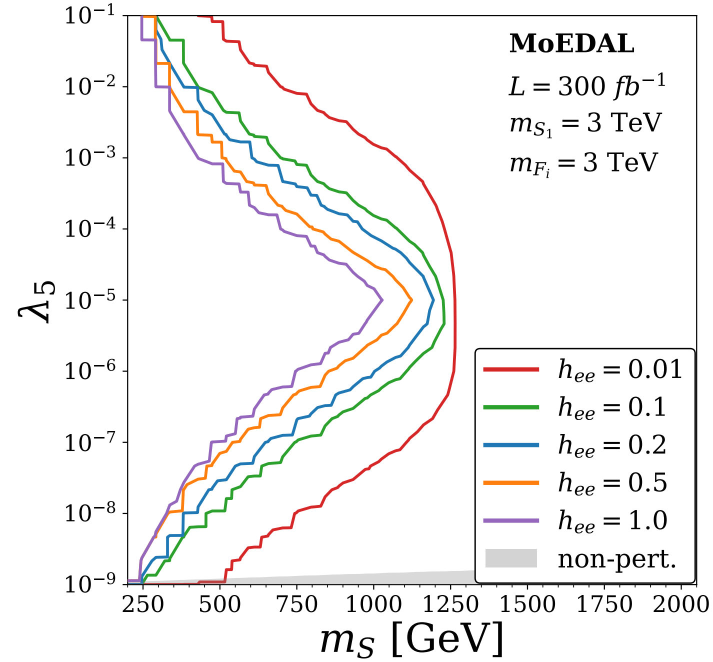

MoEDAL
$L = 30\ fb^{-1}$
$m_{S_1} = 3$ TeV
$m_{F_i} = 3$ TeV
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
non-pert.
λ_5
m_{S_3} [GeV]

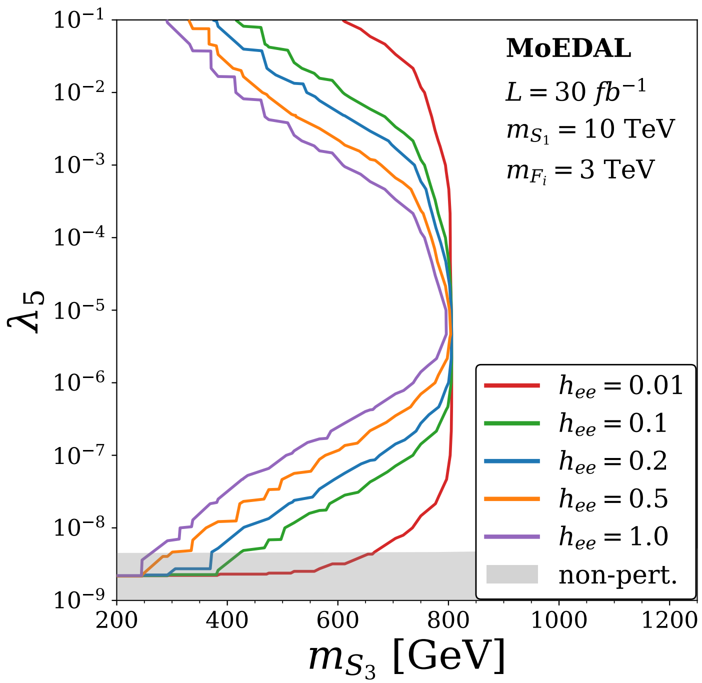

MoEDAL
$L = 300\ fb^{-1}$
$m_{S_1} = 3$ TeV
$m_{F_i} = 3$ TeV
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
non-pert.
λ_5
m_{S_3} [GeV]

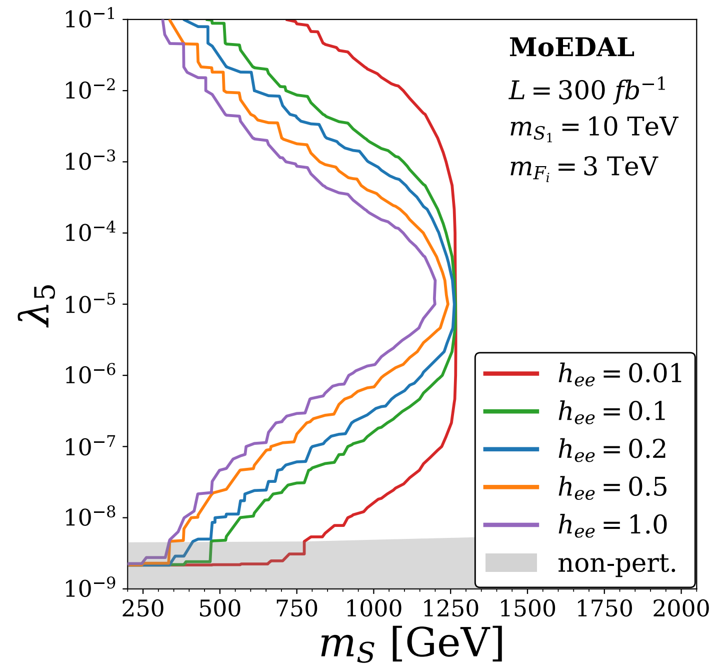

MoEDAL
$L = 30\ fb^{-1}$
$m_{S_1} = 10$ TeV
$m_{F_i} = 3$ TeV
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
non-pert.
λ_5
m_{S_3} [GeV]


MoEDAL
$L = 300\ fb^{-1}$
$m_{S_1} = 10$ TeV
$m_{F_i} = 3$ TeV
$N_{sig} \geq 1$
$N_{sig} \geq 2$
$N_{sig} \geq 3$
non-pert.
λ_5
m_{S_3} [GeV]


MoEDAL
L = 30 fb^-1
m_S1 = 3 TeV
m_Fi = 3 TeV
h_ee = 0.01
h_ee = 0.1
h_ee = 0.2
h_ee = 0.5
h_ee = 1.0
non-pert.
λ5
m_S3 [GeV]


MoEDAL
L = 300 fb^-1
m_S1 = 3 TeV
m_Fi = 3 TeV
h_ee = 0.01
h_ee = 0.1
h_ee = 0.2
h_ee = 0.5
h_ee = 1.0
non-pert.
λ5
m_S [GeV]

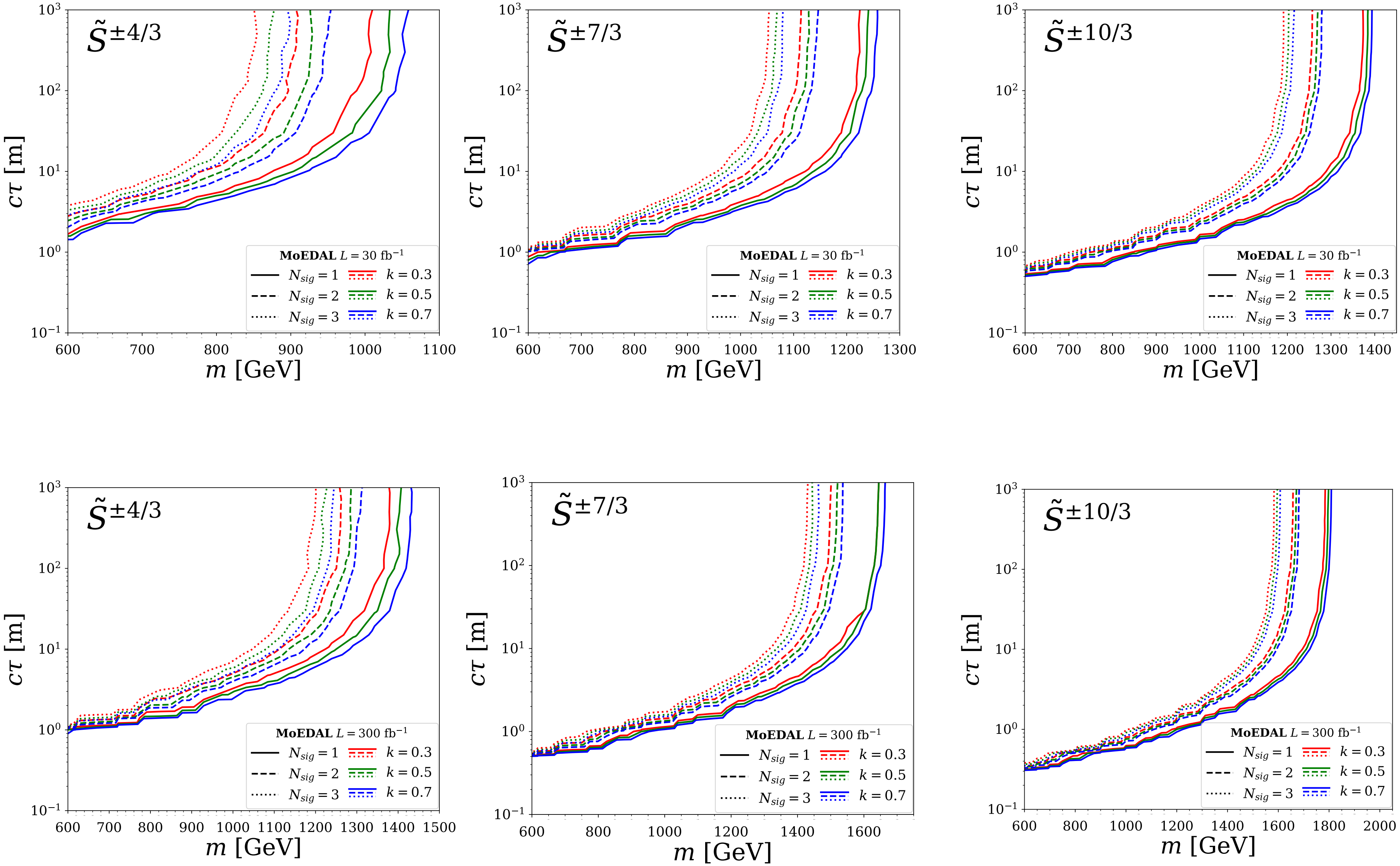

MoEDAL
L = 30 fb^-1
m_S1 = 10 TeV
m_Fi = 3 TeV
h_ee = 0.01
h_ee = 0.1
h_ee = 0.2
h_ee = 0.5
h_ee = 1.0
non-pert.
λ5
m_S3 [GeV]


MoEDAL
L = 300 fb^-1
m_S1 = 10 TeV
m_Fi = 3 TeV
h_ee = 0.01
h_ee = 0.1
h_ee = 0.2
h_ee = 0.5
h_ee = 1.0
non-pert.
λ5
m_S [GeV]

Coloured model — hadronisation

- **Free parameter k**
- Spin-1/2 mesons: Prob=k
  - $\tilde{S} + u_{L/R} \quad (+2/3)$
  - $\tilde{S} + d_{L/R} \quad (-1/3)$
- Spin-0 baryons: Prob=2/3(1-k)
  - $\tilde{S} + \bar{u}_L \bar{u}_R \quad (-4/3)$
  - $\tilde{S} + \bar{d}_L \bar{d}_R \quad (+2/3)$
  - $\tilde{S} + \bar{u}_L \bar{d}_R \quad (-1/3)$
  - $\tilde{S} + \bar{d}_L \bar{u}_R \quad (-1/3)$
- Spin-1 baryons: Prob=1/3(1-k)
  - $\tilde{S} + \bar{u}_L \bar{d}_L \quad (-1/3)$
  - $\tilde{S} + \bar{u}_R \bar{d}_R \quad (-1/3)$

MoEDAL read for hadrons in Model-2



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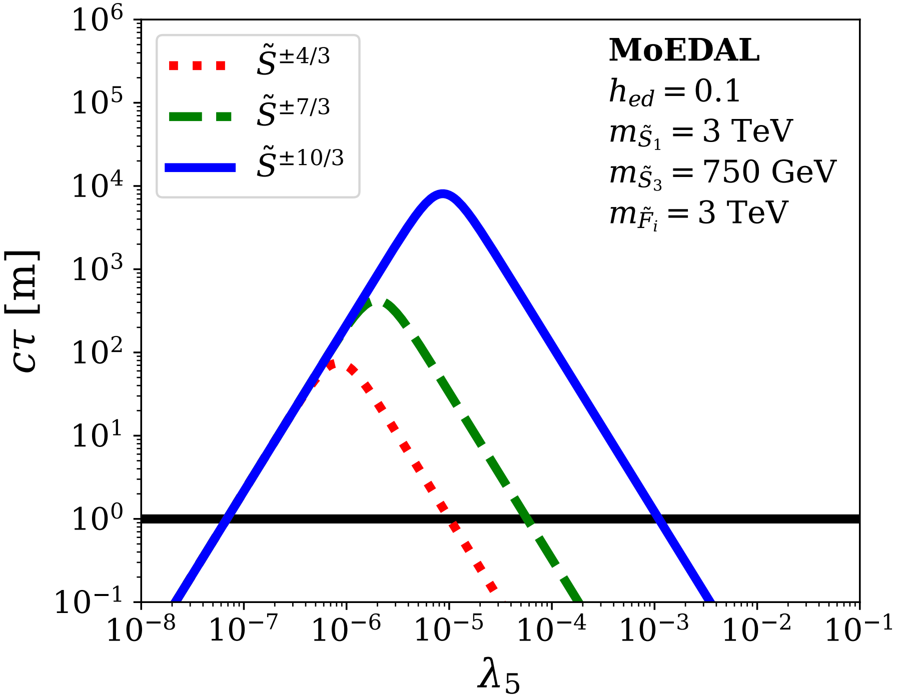
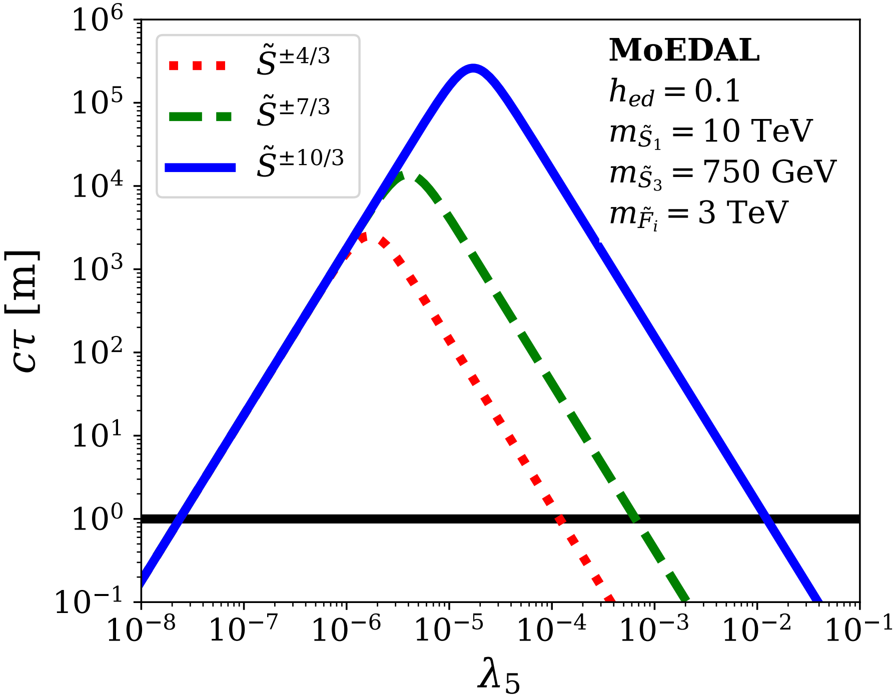
Decay length for Model-2



$$m_{S_1} = 3 \text{ TeV}$$



$$m_{S_1} = 10 \text{ TeV}$$

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Current experimental constraints— Model-2

	current HSCP bound 36 fb^{-1} [39]	HSCP (Run-3) 300 fb^{-1} [39]	MoEDAL (Run-3) 30 fb^{-1}	MoEDAL (HL-LHC) 300 fb^{-1}
$\tilde{S}^{\pm 4/3}$	((1450))	1700	880 (1050)	1250 (1400)
$\tilde{S}^{\pm 7/3}$	((1480))	1730	1080 (1250)	1450 (1650)
$\tilde{S}^{\pm 10/3}$	((1510))	1790	1200 (1400)	1600 (1800)

Table 3: Summary for the model-independent mass reaches (in GeV) of the multi-charged particles in Model-2 by MoEDAL (2nd and 3rd columns). In the first column, the numbers in the double-brackets show the estimated mass bounds obtained in [39] by rescaling the 8 TeV CMS result [40] to the 13 TeV LHC with $L = 36$ fb^{-1}. The second column represents the projected mass reach for Run-3 (300 fb^{-1}) obtained in [39]. The numbers outside (inside) the brackets in the third and fourth columns represent MoEDAL's mass reaches with $N_{\rm sig} \geq 3$ (1) assuming $L = 30$ (Run-3) and 300 (HL-LHC) fb^{-1}, respectively.

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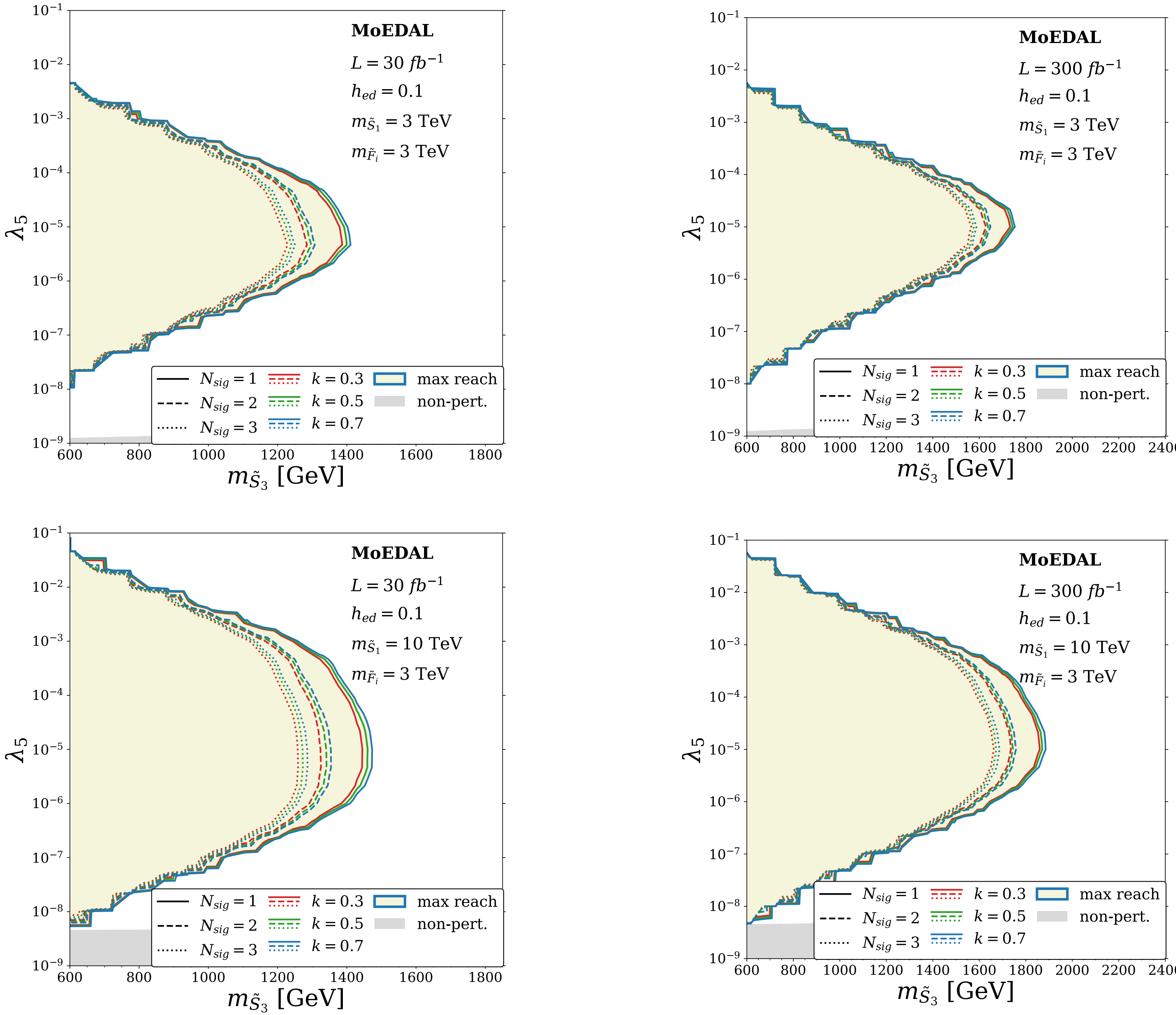
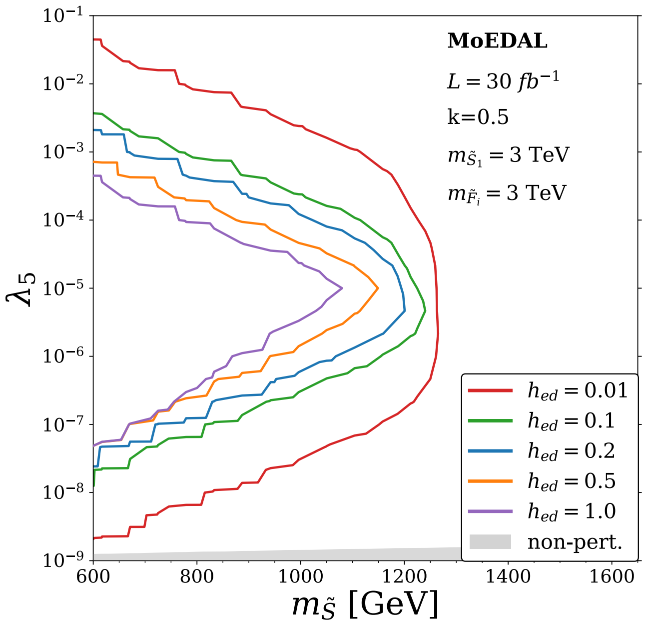
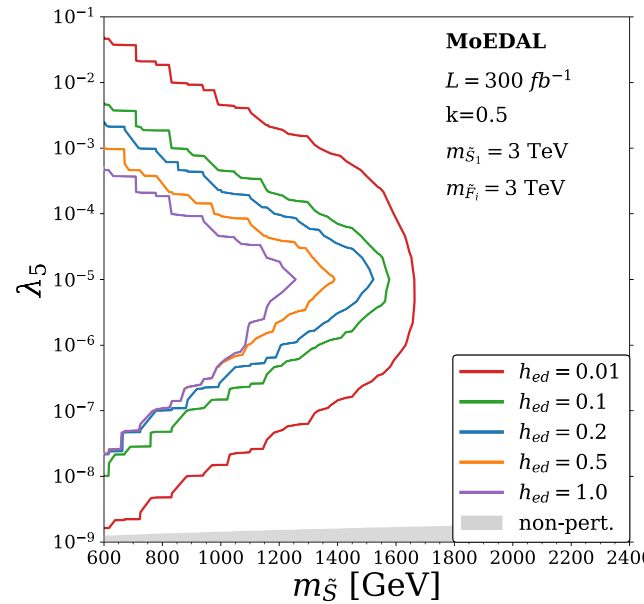
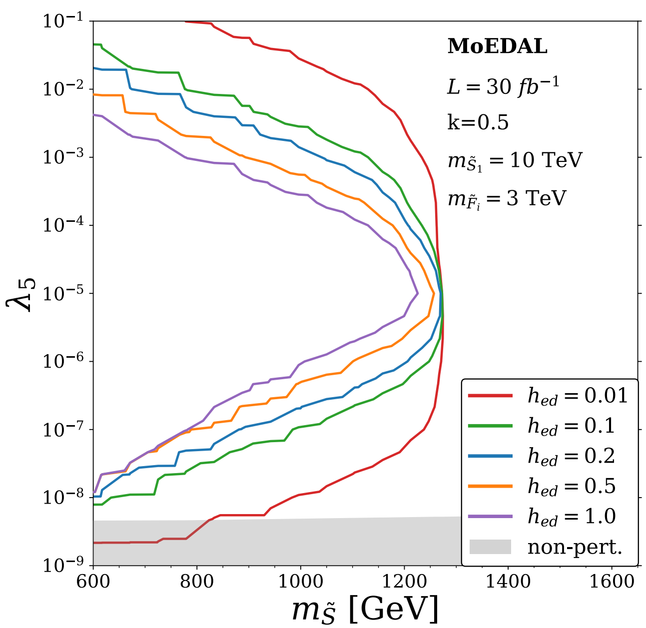

MoEDAL
$L = 30\ fb^{-1}$
$h_{ed} = 0.1$
$m_{\tilde{S}_1} = 3$ TeV
$m_{\tilde{F}_i} = 3$ TeV
MoEDAL
$L = 300\ fb^{-1}$
$h_{ed} = 0.1$
$m_{\tilde{S}_1} = 3$ TeV
$m_{\tilde{F}_i} = 3$ TeV
MoEDAL
$L = 30\ fb^{-1}$
$h_{ed} = 0.1$
$m_{\tilde{S}_1} = 10$ TeV
$m_{\tilde{F}_i} = 3$ TeV
MoEDAL
$L = 300\ fb^{-1}$
$h_{ed} = 0.1$
$m_{\tilde{S}_1} = 10$ TeV
$m_{\tilde{F}_i} = 3$ TeV
$N_{sig} = 1$
$N_{sig} = 2$
$N_{sig} = 3$
$k = 0.3$
$k = 0.5$
$k = 0.7$
max reach
non-pert.
λ_5
$m_{\tilde{S}_3}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
600
800
1000
1200
1400
1600
1800
2000
2200
2400


MoEDAL
$L = 30\ fb^{-1}$
k=0.5
$m_{\tilde{S}_1} = 3$ TeV
$m_{\tilde{F}_i} = 3$ TeV
$h_{ed} = 0.01$
$h_{ed} = 0.1$
$h_{ed} = 0.2$
$h_{ed} = 0.5$
$h_{ed} = 1.0$
non-pert.
λ_5
$m_{\tilde{S}}$ [GeV]


MoEDAL
$L = 300\ fb^{-1}$
k=0.5
$m_{\tilde{S}_1} = 3$ TeV
$m_{\tilde{F}_i} = 3$ TeV
$h_{ed} = 0.01$
$h_{ed} = 0.1$
$h_{ed} = 0.2$
$h_{ed} = 0.5$
$h_{ed} = 1.0$
non-pert.
λ_5
$m_{\tilde{S}}$ [GeV]


MoEDAL
$L = 30\ fb^{-1}$
k=0.5
$m_{\tilde{S}_1} = 10$ TeV
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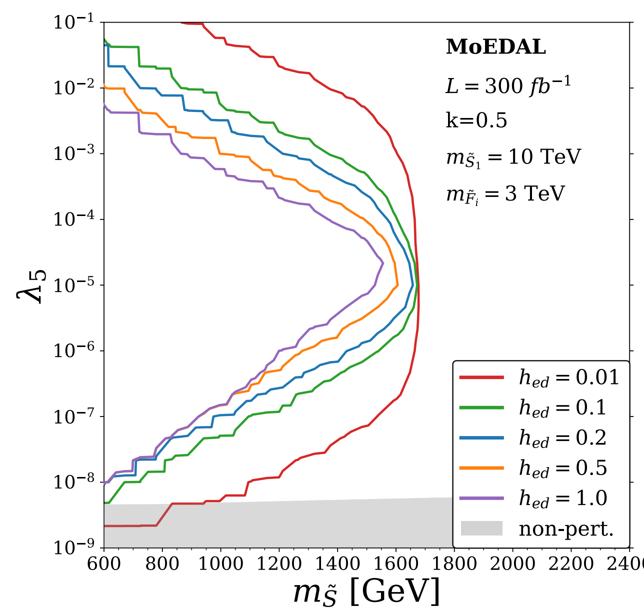
$h_{ed} = 0.01$
$h_{ed} = 0.1$
$h_{ed} = 0.2$
$h_{ed} = 0.5$
$h_{ed} = 1.0$
non-pert.
λ_5
$m_{\tilde{S}}$ [GeV]


MoEDAL
$L = 300\ fb^{-1}$
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$m_{\tilde{S}_1} = 10$ TeV
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$h_{ed} = 0.01$
$h_{ed} = 0.1$
$h_{ed} = 0.2$
$h_{ed} = 0.5$
$h_{ed} = 1.0$
non-pert.
λ_5
$m_{\tilde{S}}$ [GeV]

Conclusions

- MoEDAL can study selected neutrino mass generation models, e.g. model by M. Hirsch et al.
- The model predicts long-lived multi-charged particles for intermediate values of λ_5 parameter.
- MoEDAL Run-3 can compete with ATLAS in searches only for $S^{\pm 4}$, however, the window is small (40 GeV).
- MoEDAL HL-LHC can compete with **current** ATLAS constraints for $S^{\pm 3}, S^{\pm 4}, F^{\pm 3}, \tilde{S}^{\pm 7/3}, \tilde{S}^{\pm 10/3}$.
- For these particles MoEDAL can scan a wide range of h_{ee} and λ_5 parameters

Outlook