Long-lived particle searches at MoEDAL

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in collaboration with:

Oscar Vives, Roberto Ruiz De Austri,

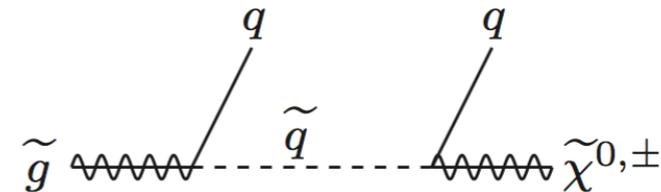Judita Mamuzic, Arka Santra, Vasiliki Mitsou

Long-lived (charged) particles in SUSY models:

- Split SUSY

  $(m_{\tilde{q}} \gg m_{\tilde{g}})$

  long-lived $\widetilde{g}$

  $$c\tau_{\widetilde{g}} = \mathcal{O}(1-10)\ \text{cm} \times \left(\frac{\Delta m}{10\ \text{GeV}}\right)^{-5} \left(\frac{\widetilde{m}}{10\ \text{TeV}}\right)^{4}$$
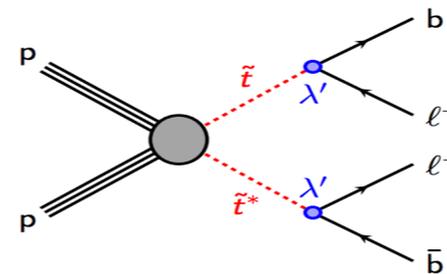
- Gravitino LSP

  Anything: e.g. $\widetilde{\tau}$

  $$\tau_{\widetilde{f}} = 6 \times 10^{-12}\text{sec} \cdot \left(\frac{m_{3/2}}{10\text{eV}}\right)^{2} \left(\frac{m_{\widetilde{f}}}{100\text{GeV}}\right)^{-5}$$
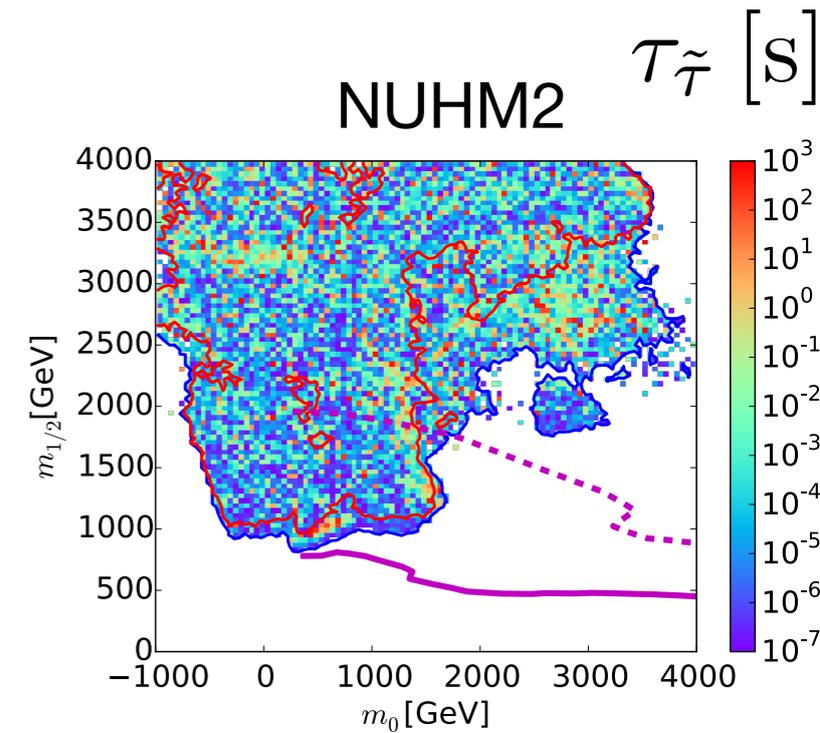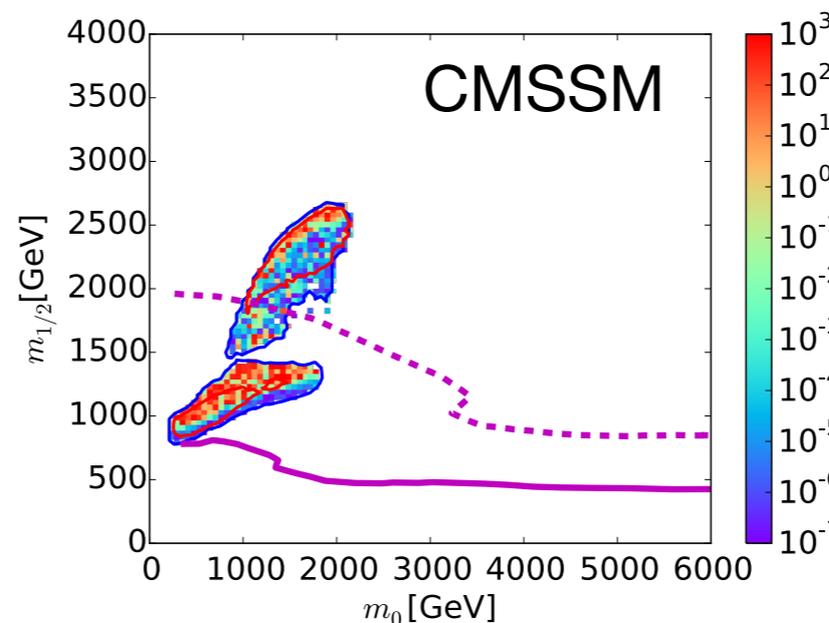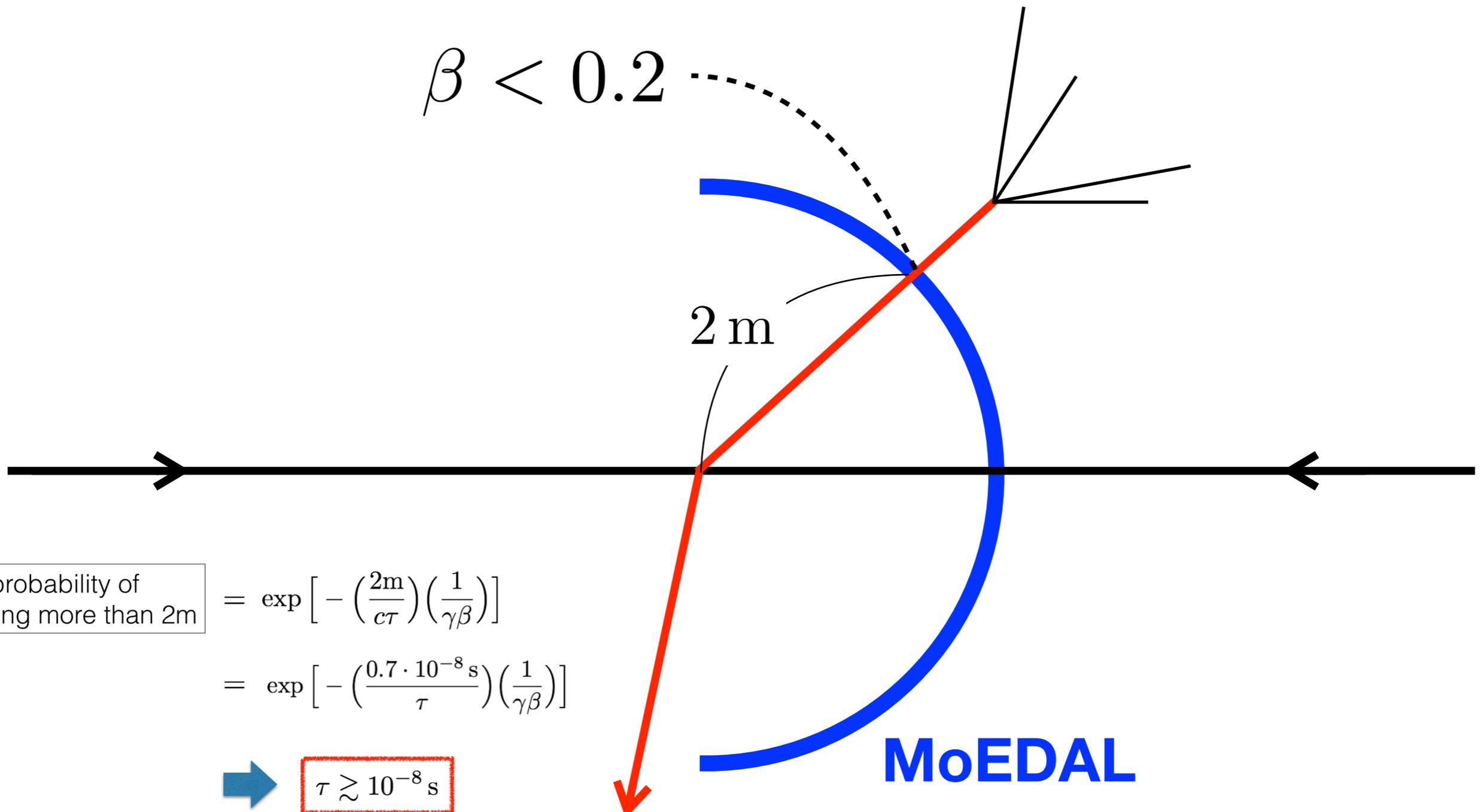
- RPV

  Anything: e.g. $\widetilde{t}$

- Stau-Coannihilaiton

  long-lived $\widetilde{\tau}$

MoEDAL can detect a singly charged particle if its velocity is low: **β < 0.2**.

The particle must pass the detector shell located **2m** away from the interaction point.

$$\beta < 0.2$$

$$2\,\mathrm{m}$$

MoEDAL

$$\boxed{\begin{array}{c} \text{probability of} \\ \text{traveling more than 2m} \end{array}} = \exp\left[-\left(\frac{2\mathrm{m}}{c\tau}\right)\left(\frac{1}{\gamma\beta}\right)\right]$$

$$= \exp\left[-\left(\frac{0.7\cdot10^{-8}\,\mathrm{s}}{\tau}\right)\left(\frac{1}{\gamma\beta}\right)\right]$$

$$\boxed{\tau \gtrsim 10^{-8}\,\mathrm{s}}$$
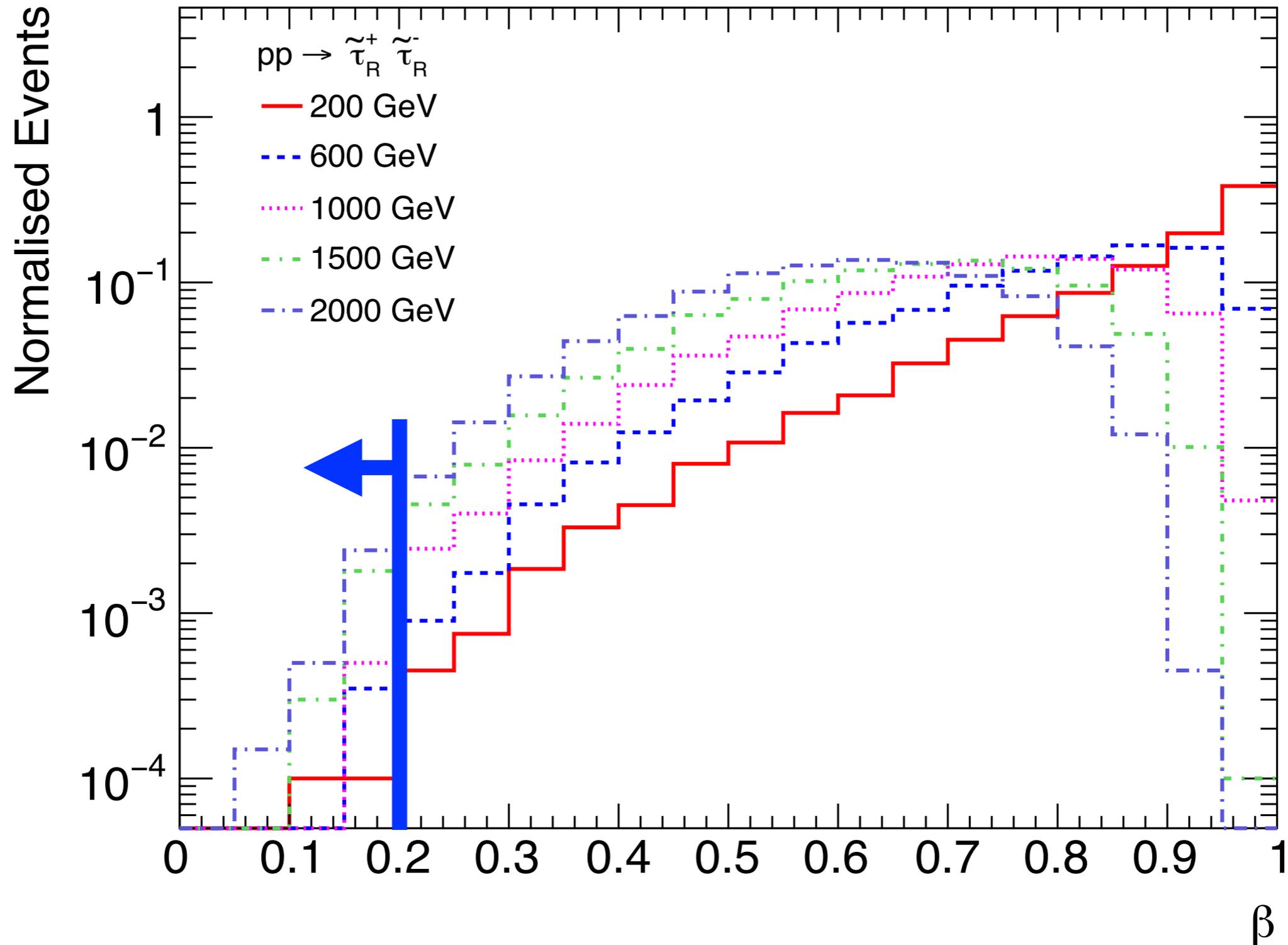
Typically β is not small…

We need a **heavy** particle.

Signal Efficiency ($\beta < 0.2$)

$pp \rightarrow \tilde{\tau}_R^+ \tilde{\tau}_R^-$

x-axis: $m_{\tilde{\tau}_R}$ [GeV]

y-axis: Efficiency($|\beta| < 0.2$)

Signal Cross-Section

x-axis: $m_{\tilde{\tau}_R}$ [GeV]

y-axis: $\sigma(pp \rightarrow \tilde{\tau}_R^+ \tilde{\tau}_R^-)$ [fb]
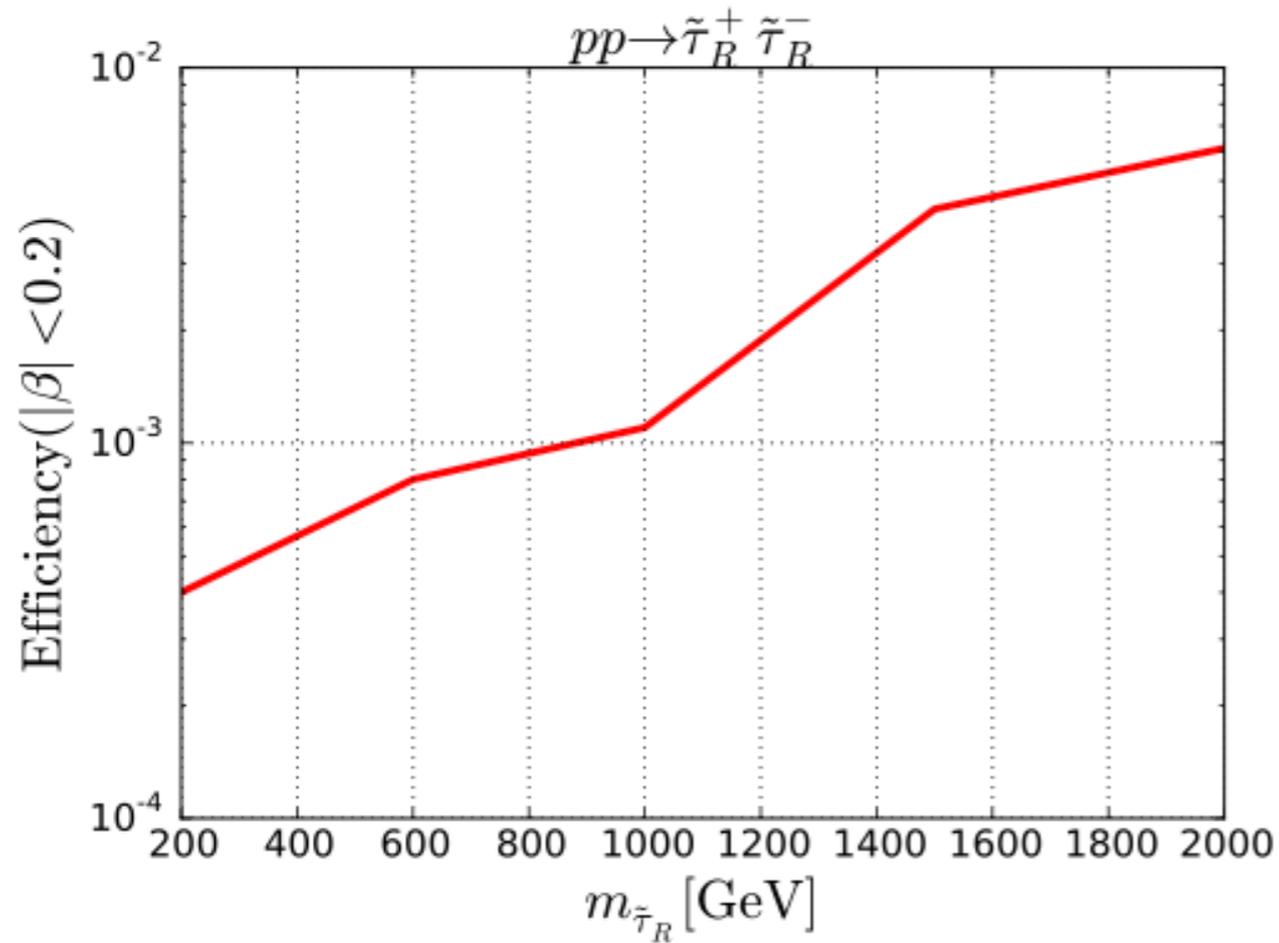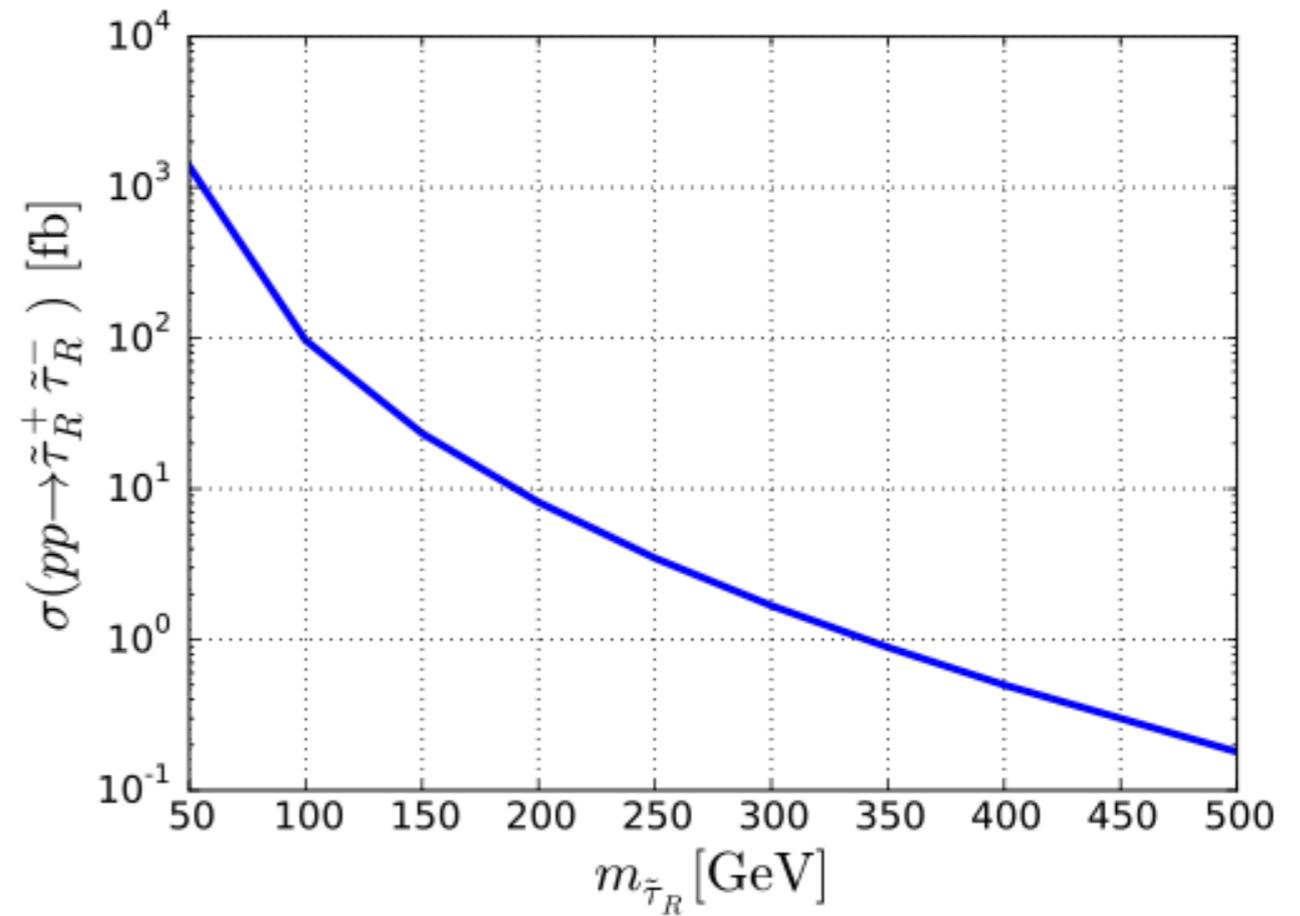
$$\epsilon \cdot \sigma \sim \left(< 10^{-3} \right) \cdot \left(< 100 \, \mathrm{fb}^{-1} \right) \qquad (\text{for } m_{\tilde{\tau}} > 100 \, \mathrm{GeV})$$
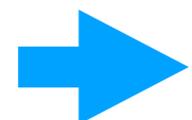
MoEDAL is **insensitive** to **stau direct production.**
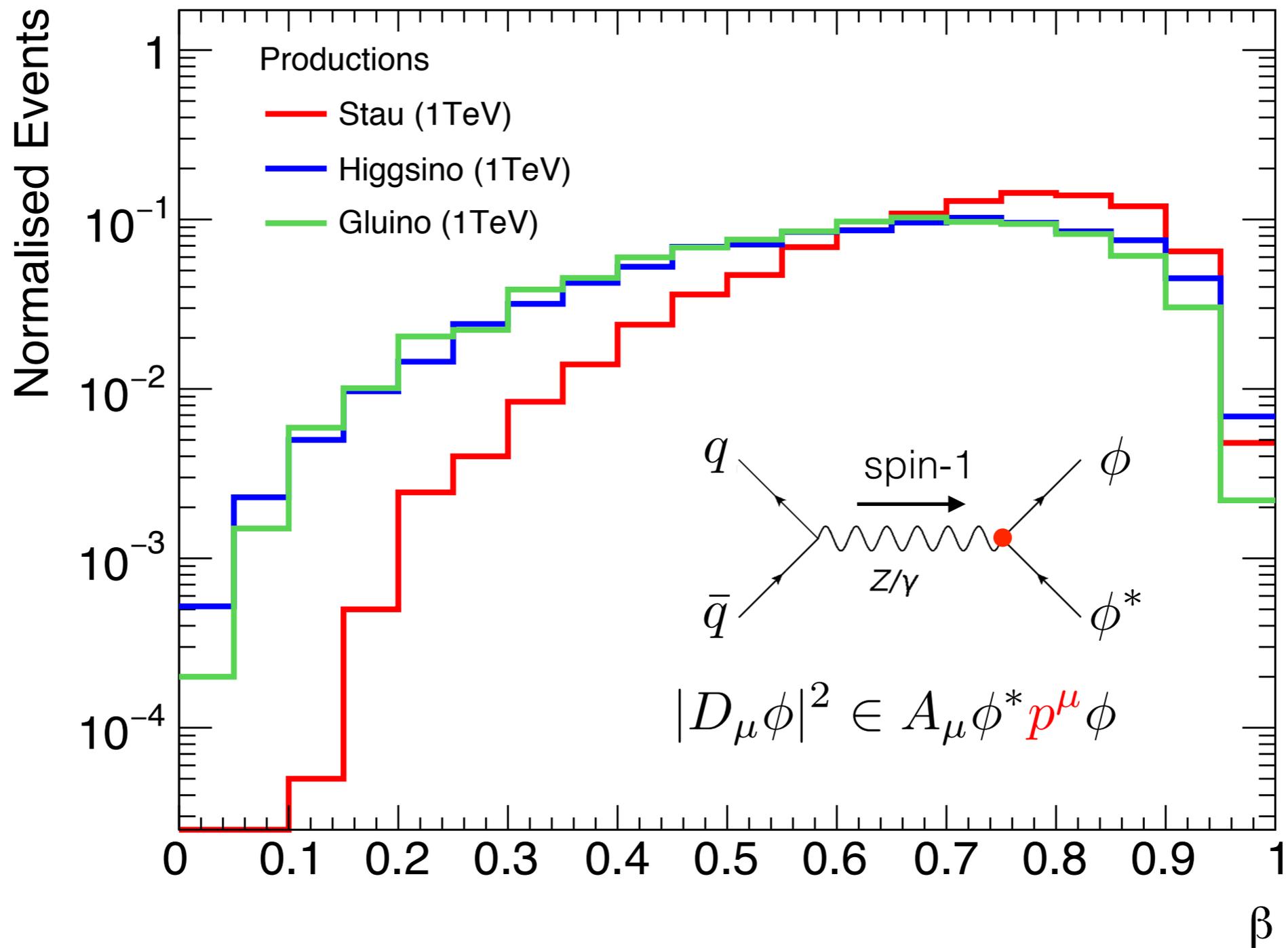
The velocity is smaller for **fermion** pair production.

(s-wave)

MoEDAL is better at:

heavy

fermion

with **large cross-section**
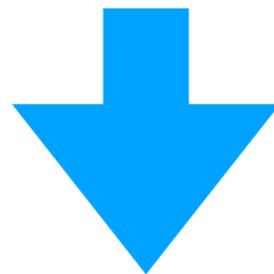
gluino pair production would serve the best scenario.

Long-lived gluino have been constrained by ATLAS/CMS

$\tilde{g}$ (R-hadron) $\to$ qq $\tilde{\chi}_1^0$; m($\tilde{\chi}_1^0$) = 100 GeV

March 2018

- RPC 0L 2-6 jets arXiv:1712.02332 ($\sqrt{s}$=13 TeV, 36 fb^{-1})
- RPC 0L 2-6 jets ATLAS-CONF-2018-003 ($\sqrt{s}$=13 TeV, 36 fb^{-1})
- Displaced vertices arXiv:1710.04901 ($\sqrt{s}$=13 TeV, 33 fb^{-1})
- Pixel dE/dx arXiv:1604.04520 ($\sqrt{s}$=13 TeV, 3.2 fb^{-1})
- Stable charged arXiv:1606.05129 ($\sqrt{s}$=13 TeV, 3.2 fb^{-1})
- Stopped gluino arXiv:1310.6584 ($\sqrt{s}$=7,8 TeV, 5.0,23 fb^{-1})

ATLAS Preliminary
- Expected
- Observed
95% CL limits

Lower limit on m($\tilde{g}$) [GeV]

Prompt

Stable

(r for η=0, $\beta\gamma$=1) Beampipe Inner Detector Calo MS

τ [ns]

$c\tau$ [m]

MoEDAL

Long-lived particle searches

	ATLAS/CMS	MoEDAL	
Analyses	**not simple**, involving several detector components, triggers	**simple**	🙂
Background	**very small** mainly from mismeasurements	**(basically) BG free**	🙂
Signal Efficiency	~ 0.5 - 0.05	**~ 0.01** (β < 0.2)	🤔
Luminosity		**~ 5%** of ATLAS/CMS	🤔

In ordinary scenarios,

ATLAS/CMS expects ~200 times more events than MoEDAL 🤔
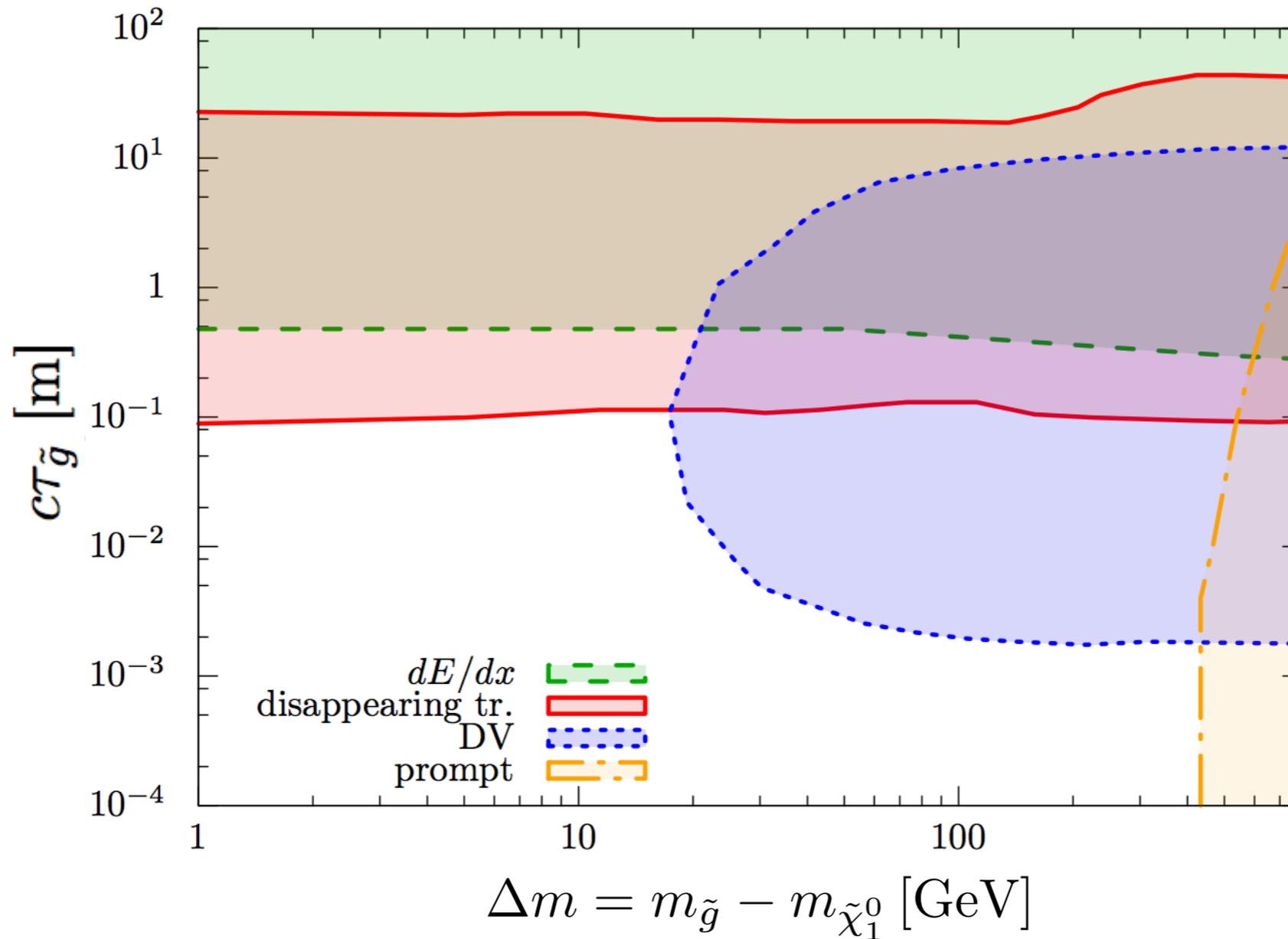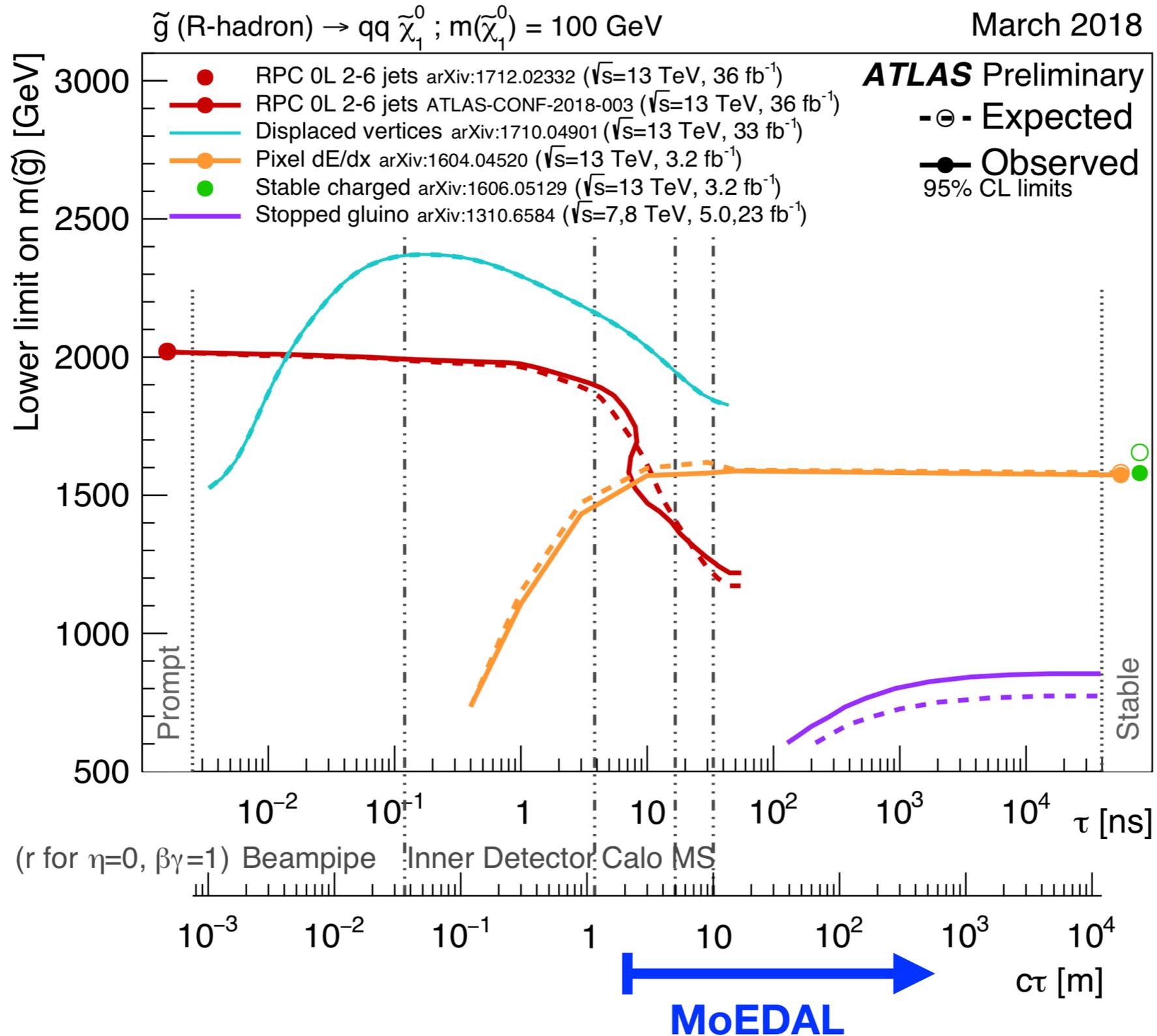
Figure 4: Testable regions of the gluino-LSP mass difference Δm and the gluino decay length $c\tau_{\tilde{g}}$ from the dE/dx, disappearing track, displaced vertex, and prompt inclusive searches at 13 TeV LHC with an integrated luminosity of 40 fb^{-1}. Here we fix the gluino mass to be 1.5 TeV.

Compressed spectrum can *kill*

Displaced Vertices and **Prompt searches**

Long-lived gluino have been constrained by ATLAS/CMS

$\tilde{g}$ (R-hadron) → qq $\tilde{\chi}_1^0$; m($\tilde{\chi}_1^0$) = 100 GeV   March 2018

ATLAS Preliminary

- ● RPC 0L 2-6 jets arXiv:1712.02332 ($\sqrt{s}$=13 TeV, 36 fb^{-1})
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- ⊖ - Expected
- ● Observed
95% CL limits

Lower limit on m($\tilde{g}$) [GeV]

Prompt   Beampipe   Inner Detector   Calo   MS   Stable

(r for η=0, βγ=1)

τ [ns]

cτ [m]

MoEDAL

MoEDAL should be compared with **Pixel dE/dx analyses**

An example of dE/dx analyses:

CMS 7/8 TeV [1305.0491]

	tracker+TOF	tracker-only
$\lvert\eta\rvert$	<2.1	
p_{T} (GeV/c)	>45	
d_z and d_{xy} (cm)	<0.5	
$\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}$	<0.25	
Track χ^2/n_d	<5	
# Pixel hits	>1	
# Tracker hits	>7	
Frac. Valid hits	>0.8	
$\Sigma p_{\mathrm{T}}^{\mathrm{trk}}(\Delta R < 0.3)$ (GeV/c)	<50	
# dE/dx measurements	>5	
dE/dx strip shape test	yes	
$E_{\mathrm{cal}}(\Delta R < 0.3)/p$	<0.3	
I_h (MeV/cm)		>3.0
ΔR to another track		−

- A recipe to recast the CMS HSCP search is given by CMS in [1502.02522]

- The key idea is to estimate the total acceptance from the acceptance on each particles:

$$\mathcal{A}_{\text{tot}} = 1 - (1 - \mathcal{A}_1)(1 - \mathcal{A}_2)$$

acceptance for particle i $\longrightarrow$ $\mathcal{A}_i = P_i^{\text{on}}(k_i) P_i^{\text{off}}(k_i)$

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dE/dx strip shape test	yes	
$E_{cal}(\Delta R < 0.3)/p$	<0.3	
I_h (MeV/cm)		>3.0
ΔR to another track		−

charged particle must be present in the pixel detector

Compressed

$$\tilde{g} \rightarrow q\,\bar{q}\,\tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \rightarrow \pi^{\mp}\,\tilde{\tau}_1^{\pm}$$

long-lived   meta-stable

R = 1082 mm

TRT

R = 554 mm
R = 514 mm

R = 443 mm

SCT

R = 371 mm

R = 299 mm

$\tilde{\tau}^{\pm}$

TRT

$\tilde{\chi}_1^0$

SCT

R = 122.5 mm
R = 88.5 mm
R = 50.5 mm

Pixels

Pixels

R = 0 mm

An example of dE/dx analyses:

CMS 7/8 TeV [1305.0491]

	tracker+TOF	tracker-only
$\lvert\eta\rvert$	<2.1	
p_T (GeV/c)	>45	
d_z and d_{xy} (cm)	<0.5	
$\sigma_{p_\mathrm{T}}/p_\mathrm{T}$	<0.25	
Track χ^2/n_d	<5	
# Pixel hits	>1	
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Frac. Valid hits	>0.8	
$\Sigma p_\mathrm{T}^{\mathrm{trk}}(\Delta R < 0.3)$ (GeV/c)	<50	
# dE/dx measurements	>5	
dE/dx strip shape test	yes	
$E_{\mathrm{cal}}(\Delta R < 0.3)/p$	<0.3	
I_h (MeV/cm)		>3.0
ΔR to another track		−

long-lived particle must point to the primary vertex ← (d_z and d_{xy} row)

charged particle must be present in the pixel detector ← (# Pixel hits row)

$$\tilde{g} \to q\,\bar{q}\,\tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \to \tau^{\mp}\,\tilde{\tau}_1^{\pm}$$

Neutralino is long-lived despite a large mass gap.

$$(m_{\tilde{\chi}_1^0} - m_{\tilde{\tau}_1^{\pm}} = 300\,\mathrm{GeV})$$
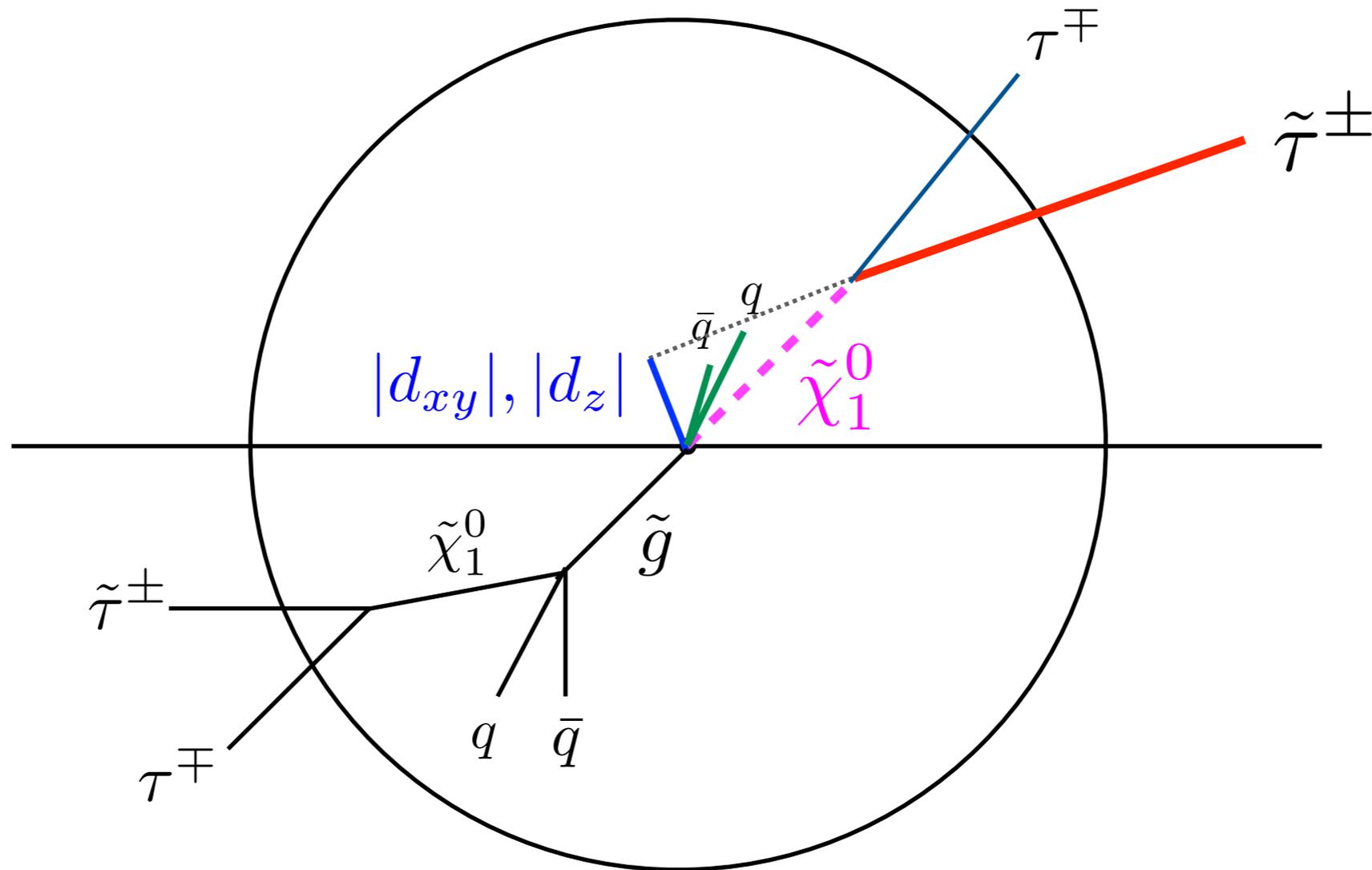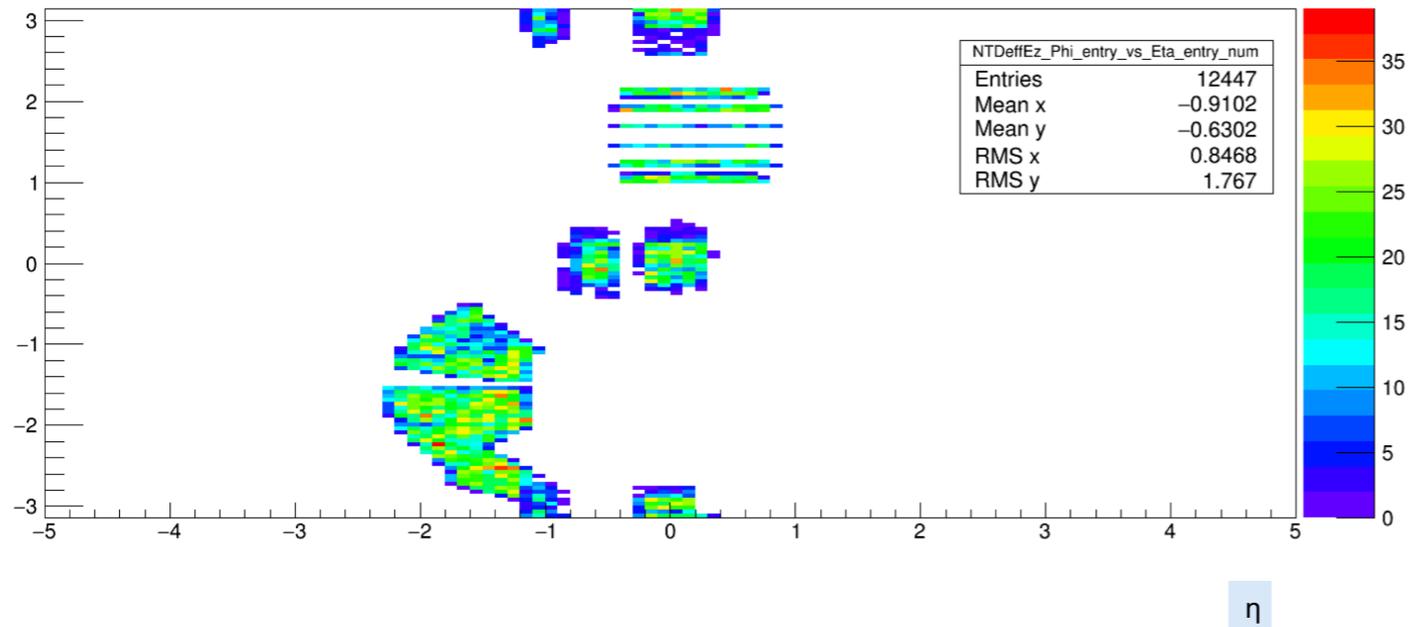

CMS suffers twice: (1) no pixel hit, (2) too large impact parameters

Simulation for MoEDAL

Daniel Felea

position of Nuclear Track Detector (NTD)

NTDeffEz_Phi_entry_vs_Eta_entry_num	
Entries	12447
Mean x	−0.9102
Mean y	−0.6302
RMS x	0.8468
RMS y	1.767

φ

η

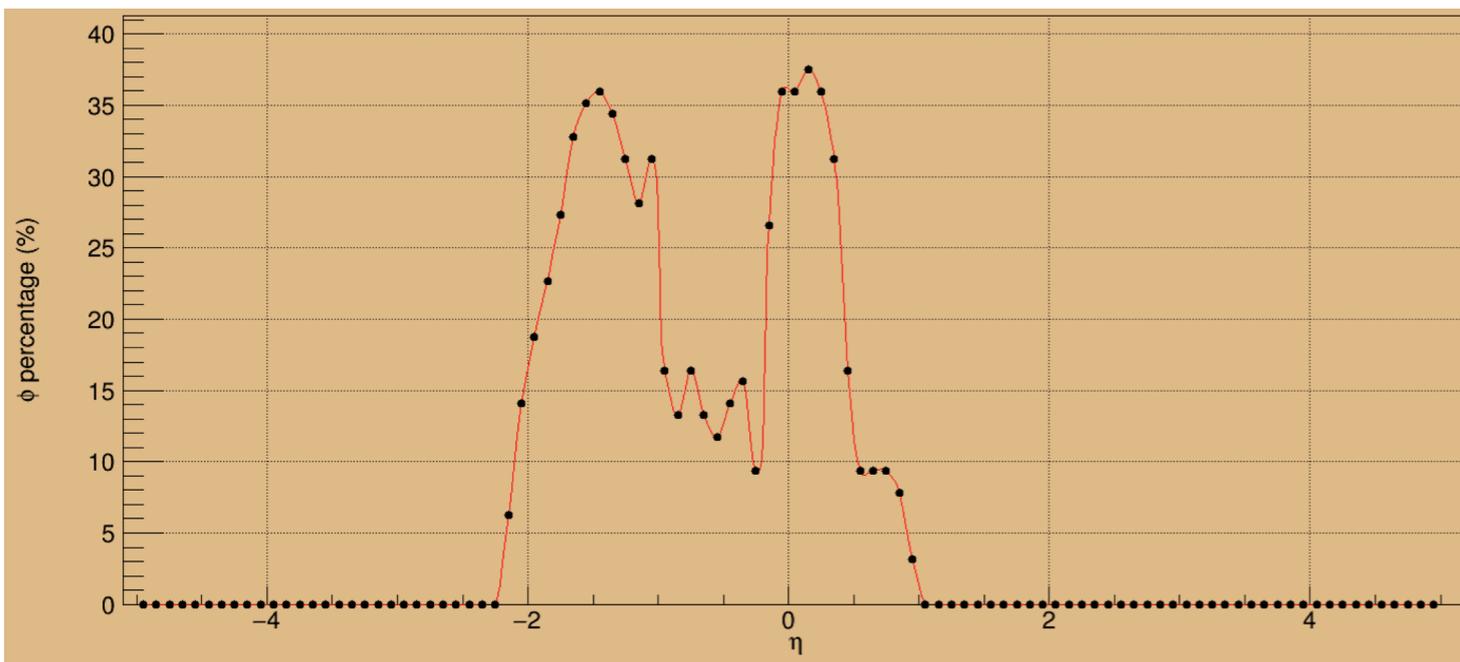- taking into account the geometrical coverage of NTD

$$\int A(\eta)d\eta \simeq 18.7\%$$

- efficiency is modelled by

$$\epsilon = \begin{cases} 1 & \beta < \beta_{\mathrm{thr}} \\ 0 & \beta \geq \beta_{\mathrm{thr}} \end{cases}$$

$$\beta_{\mathrm{thr}} = 0.1, \, 0.15, \, 0.2$$

- 2 signal events (N=2) is used as the discovery criterion

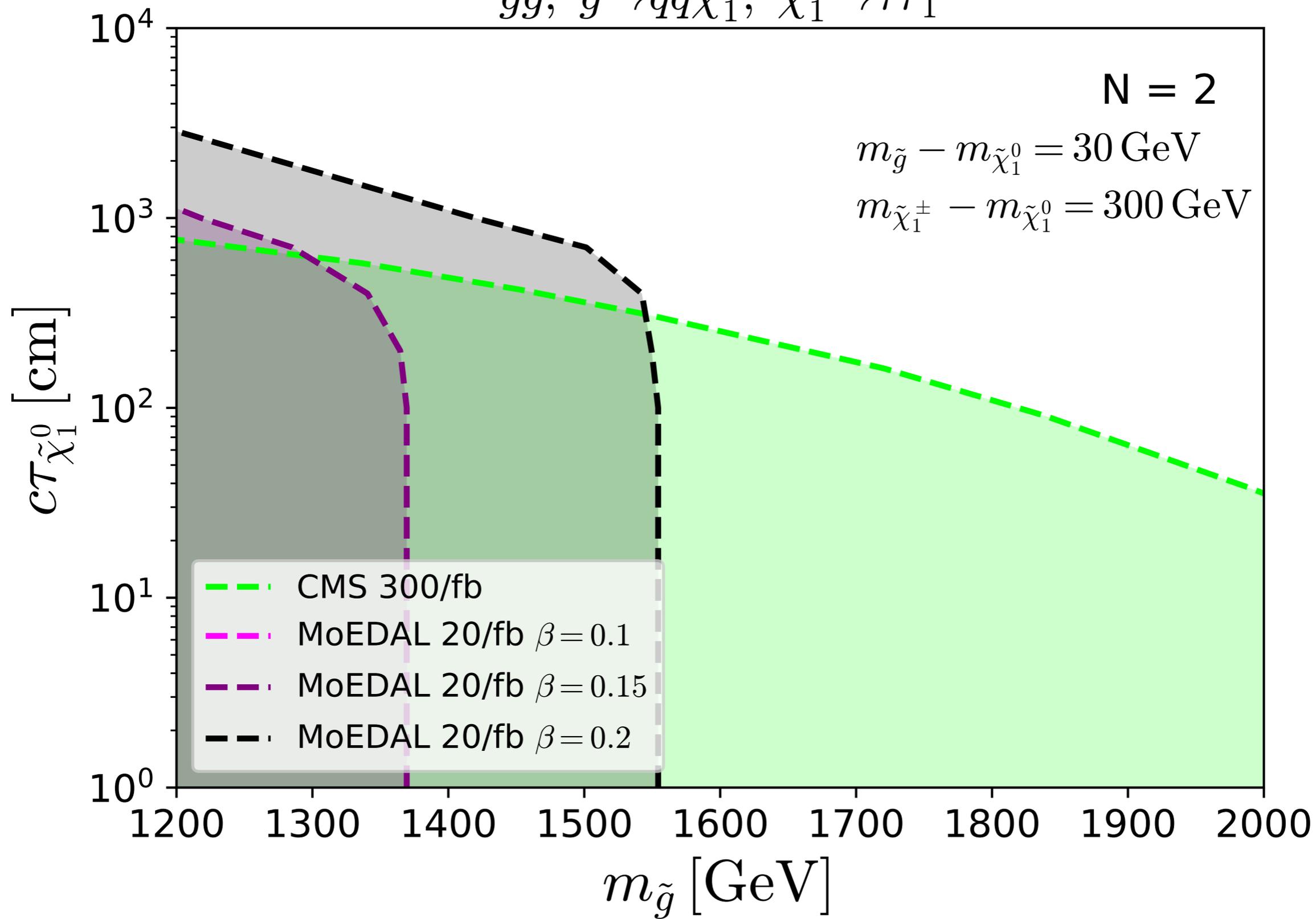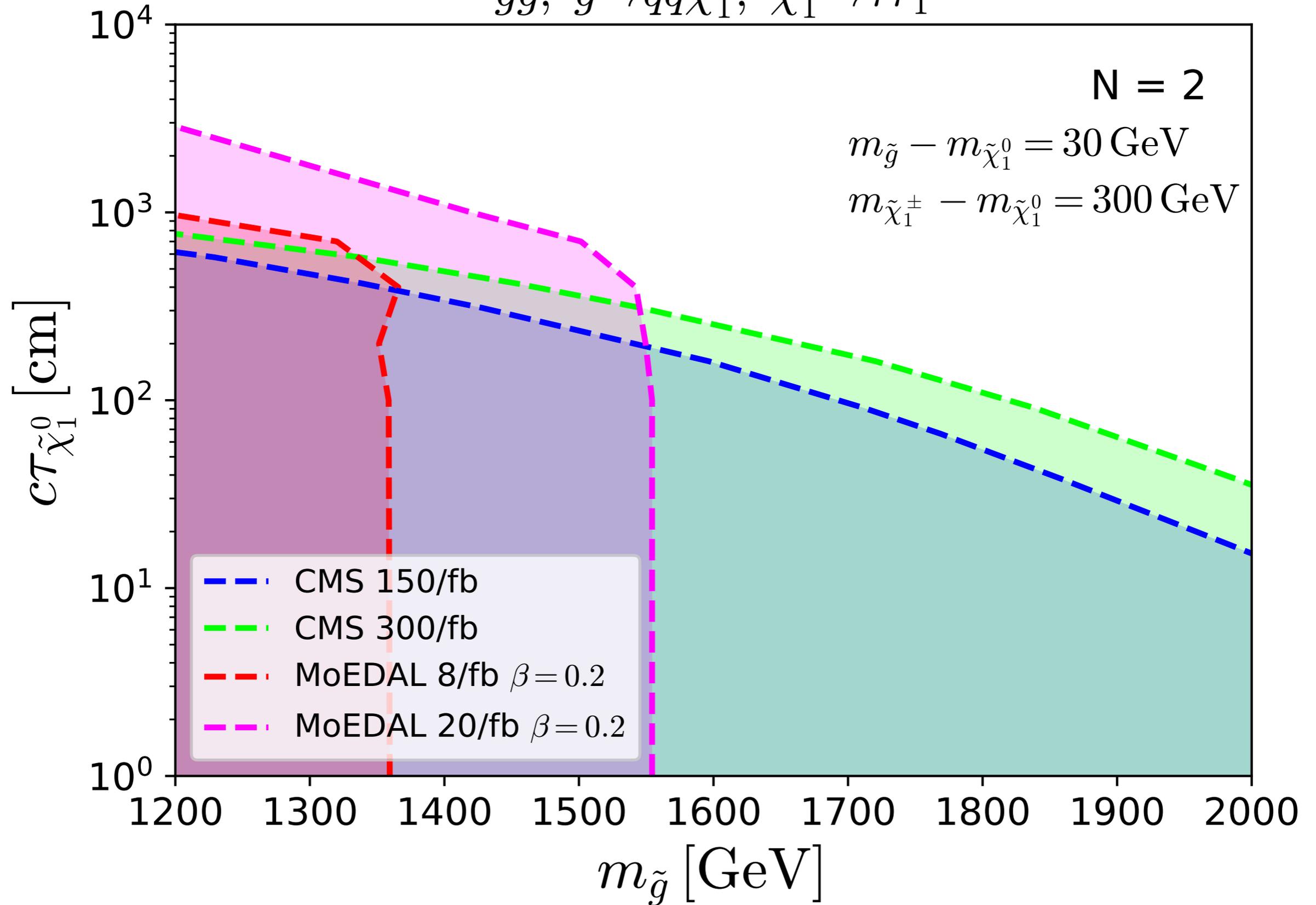Figure showing exclusion limits in the plane of $c\tau_{\tilde{\chi}_1^0}$ [cm] versus $m_{\tilde{g}}$ [GeV] for the process $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tilde{\tau}_1$ with $N=2$, $m_{\tilde{g}}-m_{\tilde{\chi}_1^0}=30\,\mathrm{GeV}$ and $m_{\tilde{\chi}_1^\pm}-m_{\tilde{\chi}_1^0}=300\,\mathrm{GeV}$.

Legend:
- CMS 300/fb
- MoEDAL 20/fb $\beta=0.1$
- MoEDAL 20/fb $\beta=0.15$
- MoEDAL 20/fb $\beta=0.2$

Conclusions

- MoEDAL requires ($\beta < 0.2$), implying it is sensitive to a production of heavy fermions with a large cross-section: 👉 **Gluinos!**

- MoEDAL efficiency is about an order of magnitude smaller than ATLAS/CMS dE/dx analyses, and the luminosity is ~5% of ATLAS/CMS: 👉 Need to look for holes in the ATLAS/CMS analyses.

- dE/dx analyses require (1) the charged particle to point the primary vertex, (2) a hit in the Pixel detector.

- If we have a long-lived neutralino produced from a gluino and decays into a meta-stable stau, MoEDAL can explore the region where ATLAS/CMS are not sensitive.

- We may need more consideration: understanding ATLAS/CMS analyses, find motivating models, etc..

Backup

Figure: $\tilde{g}\tilde{g}, \ \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \ \tilde{\chi}_1^0 \rightarrow \tau\tilde{\tau}_1$

N = 2

$m_{\tilde{g}} - m_{\tilde{\chi}_1^0} = 30\,\mathrm{GeV}$

$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 5\,\mathrm{GeV}$

Legend:
- CMS 300/fb
- MoEDAL 20/fb $\beta = 0.1$
- MoEDAL 20/fb $\beta = 0.15$
- MoEDAL 20/fb $\beta = 0.2$

Axes: $m_{\tilde{g}}\,[\mathrm{GeV}]$ (horizontal), $c\tau_{\tilde{\chi}_1^0}\,[\mathrm{cm}]$ (vertical)
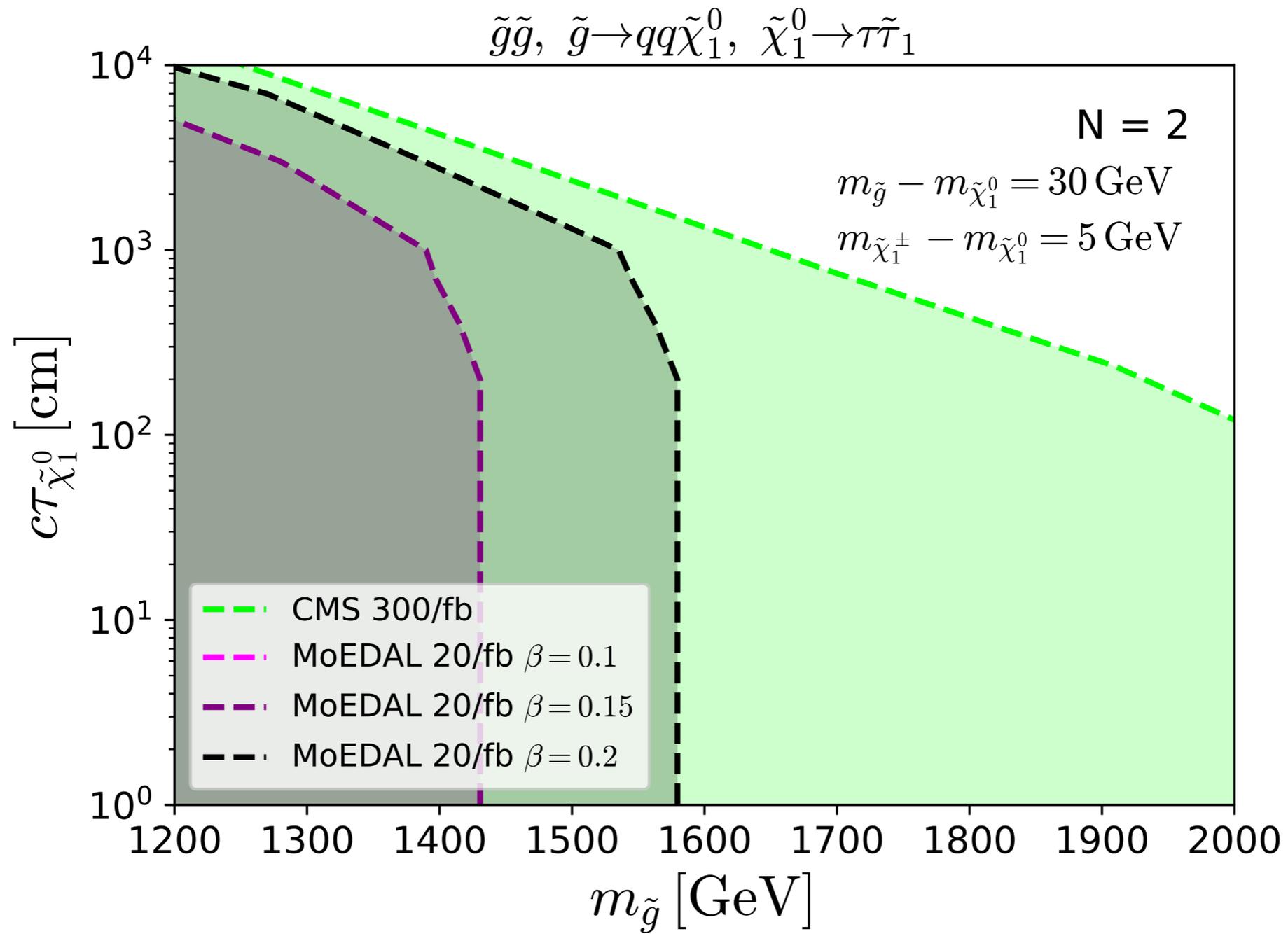
$$\tilde{g} \to q \, \bar{q} \, \tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \to \tau^{\mp} \, \tilde{\tau}_1^{\pm}$$

- How can one realise this simplified model?

- How can one make neutralino long-lived keeping a large mass gap?

An example: introduce a doublet D (and $\overline{D}$): $\quad D = (\tilde{\chi}_1^0, \tilde{\chi}^-)$
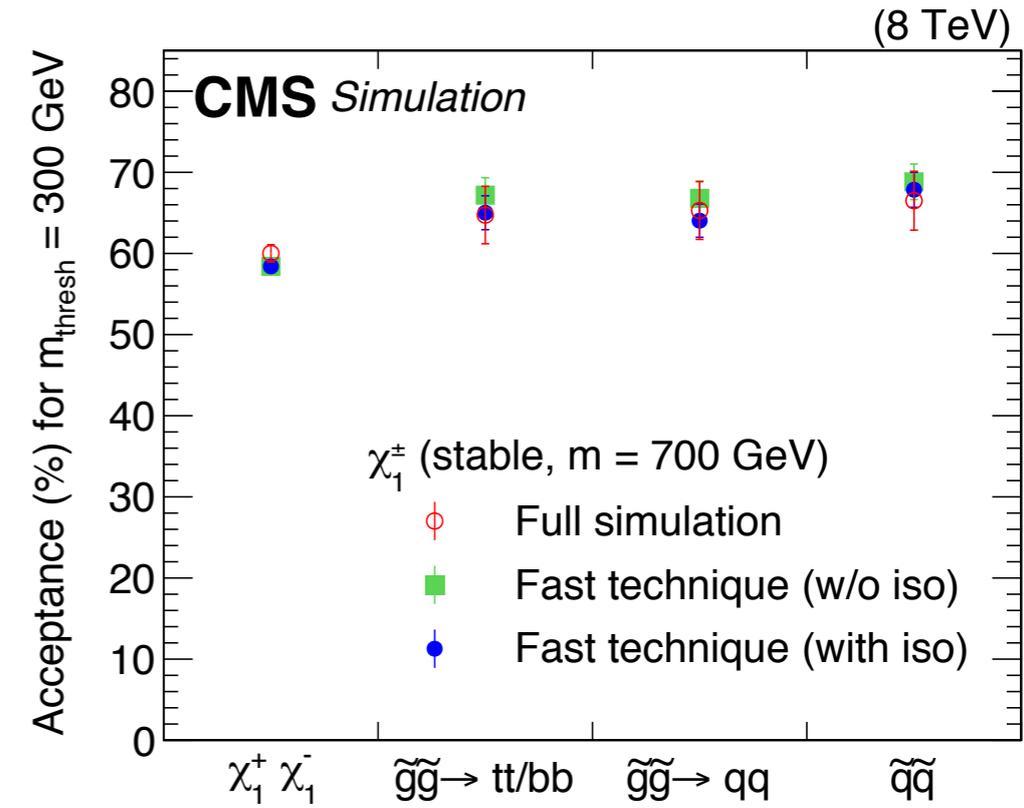
$$W \ni \lambda_q Q d_R^c D + \lambda_\tau L \tau_R^c D$$
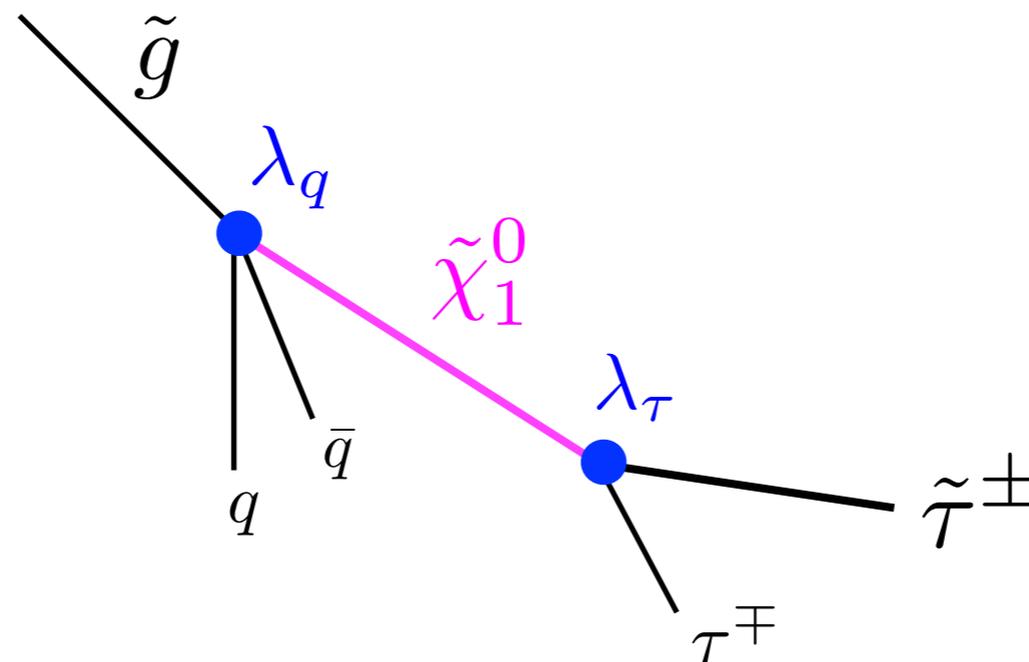
(1502.02522)

Table 2: Signal acceptance estimated from the fast technique and with the full simulation of the detector, as well as the corresponding expected and observed cross section limits. Results are provided for both the pair production and the inclusive production of staus as predicted by the GMSB model. The mass threshold, the corresponding expected background and the observed numbers of events is also shown.

Mass (GeV)	m_{thresh} (GeV)	Predicted backg...	Data	Full simulation			Fast technique		
126	0	44							
156	0	44							
200	100	5.6							
247	100	5.6							
308	100	5.6							
370	200	0.56							
494	200	0.56							
745	300	0.09							
1029	300	0.09							
126	0	44							
156	0	44							
200	100	5.6							
247	100	5.6							
308	100	5.6							
370	200	0.56							
494	200	0.56							
745	300	0.09							
1029	300	0.09							

Because the online selection in Ref. [12] uses a missing transverse energy ($E_\mathrm{T}^\mathrm{miss}$) trigger in combination with a single-muon trigger, there is one caveat to the proposed factorization method: the efficiency of the $E_\mathrm{T}^\mathrm{miss}$ trigger cannot be modeled accurately in terms of single long-lived particle kinematic properties. Accounting for the presence of other undetectable particles using a Monte Carlo method would not help because $E_\mathrm{T}^\mathrm{miss}$ often depends significantly on detector effects due to the other particles. The assumption that the $E_\mathrm{T}^\mathrm{miss}$ trigger adds negligibly to the event selection performed by the muon trigger must therefore be satisfied in order to apply the method to a given signal. Deviations from this assumption would result in an underestimation of the signal acceptance. The assumption is satisfied by models with lepton-like long-lived particles. Models with long-lived colored particles, such as top squarks or gluinos, do not satisfy this condition and thus cannot currently be tested with the technique presented in this paper.