[CMS] dE/dX measurements for long-lived particle search

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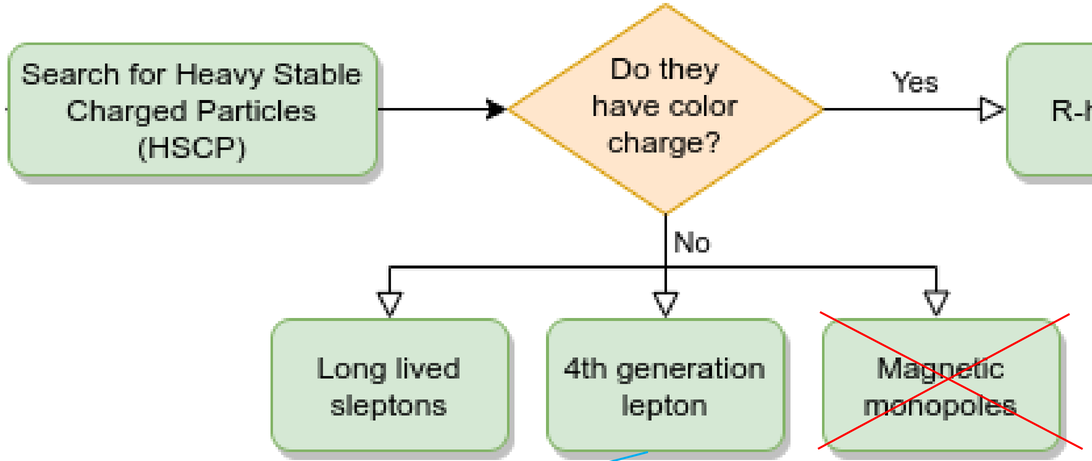
(majority of work done while at)

Johns Hopkins University

Collider Cross Talk

Intro to HSCPs

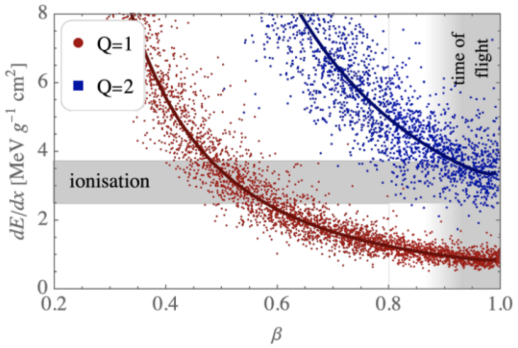


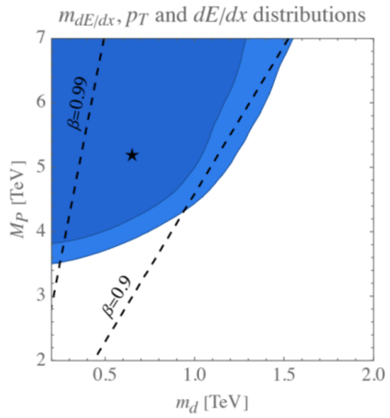
Pheno proposal to explain ATLAS excess

arXiv:2205.04473v3 [hep-ph] 20 Jul 2022

dE/dx from boosted long-lived particles

Gian F. Giudice, Matthew McCullough and Daniele Teresi
CERN, Theoretical Physics Department, Geneva, Switzerland





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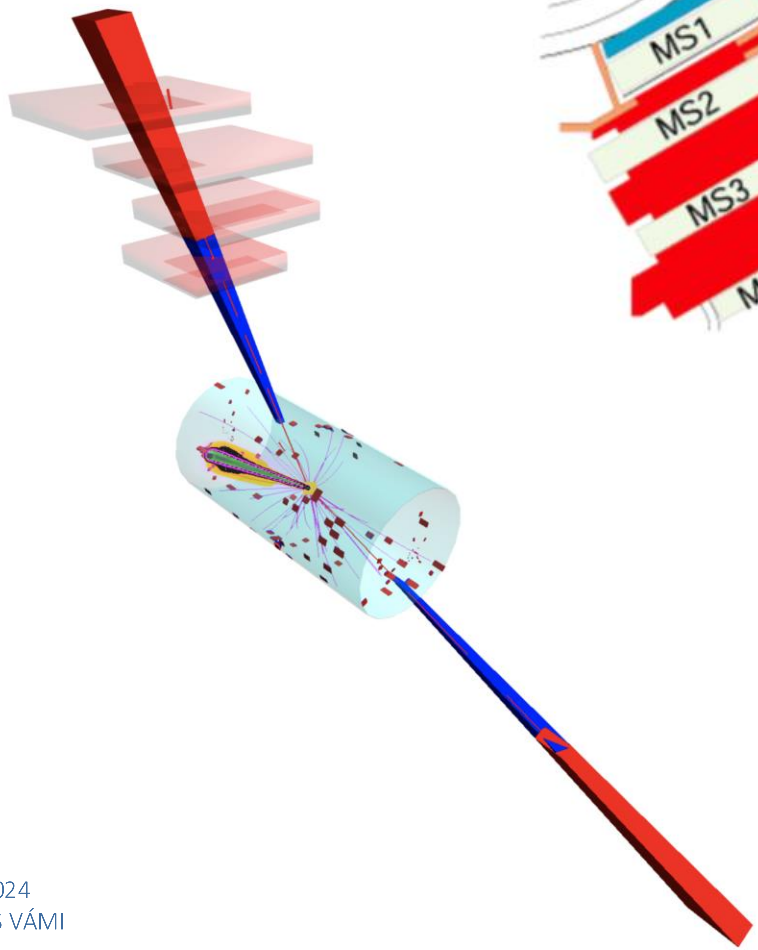
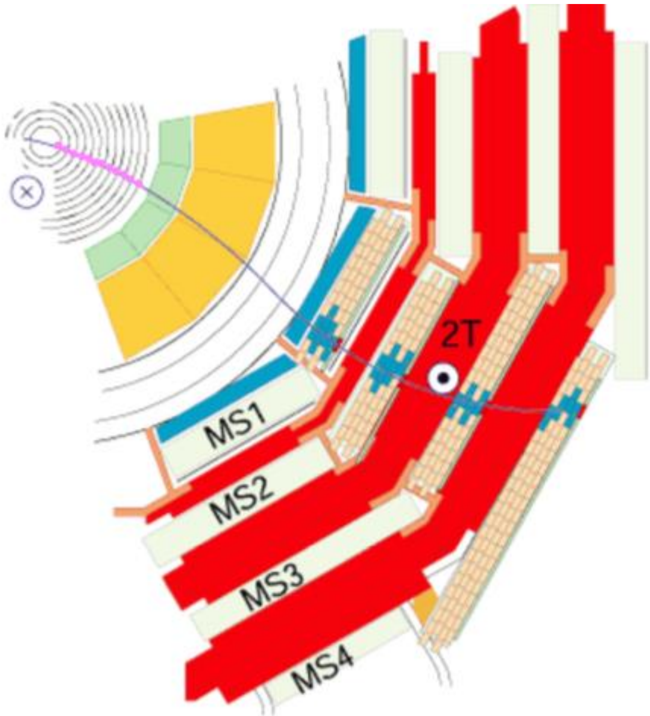
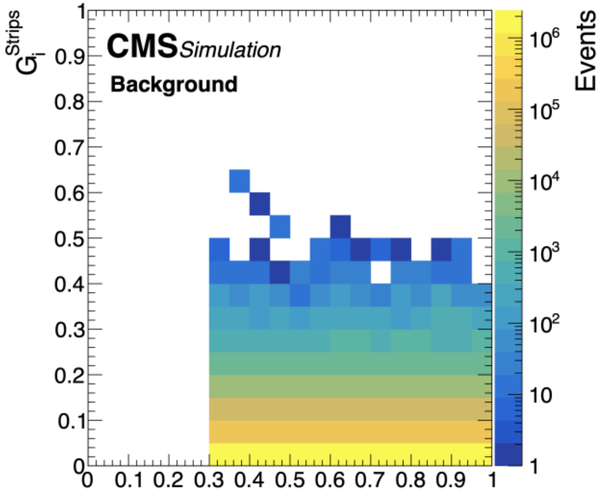
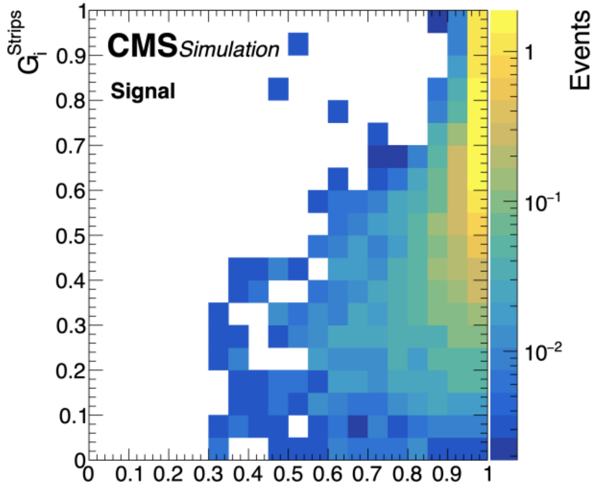




Ionization observables

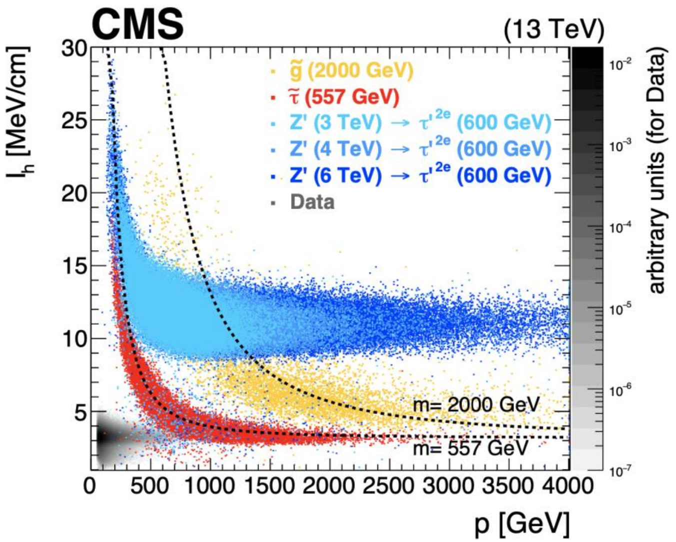
$$G_i^{\text{Strips}} = \frac{3}{N}\left(\frac{1}{12N} + \sum_{j=1}^{N}\left[P_j\left(P_j - \frac{2j-1}{2N}\right)^2\right]\right)$$

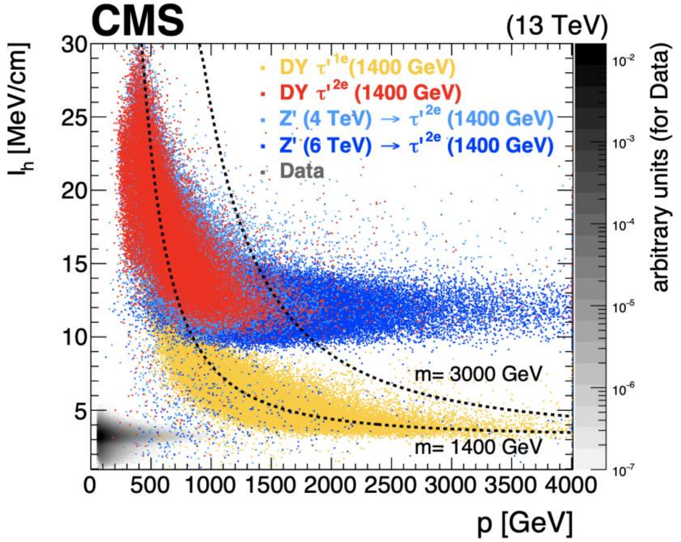




$$F_i^{\text{Pixels}} = 1 - \prod_{j=1}^{n} P'_j \sum_{m=0}^{n-1} \frac{[-\ln(\prod_{j=1}^{n} P'_j)]^m}{m!}$$

$$I_h = \left(\frac{1}{N}\sum_{j}^{N}(\mathrm{d}E/\mathrm{d}x_j)^{-2}\right)^{-1/2},$$





$$I_h = K\frac{m^2}{p^2} + C,$$

$$\Rightarrow$$

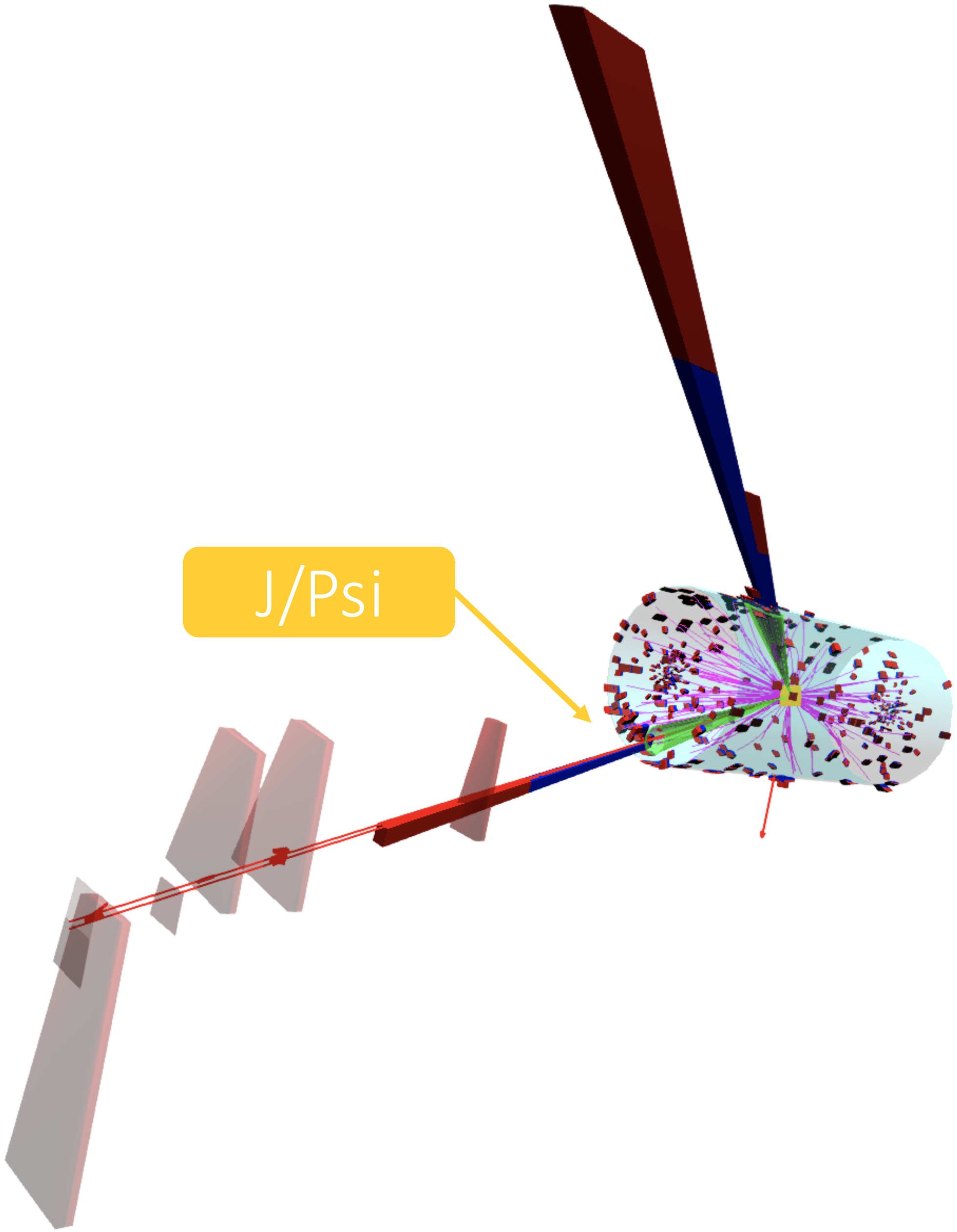
$$m = p\sqrt{\frac{I_h - C}{K}}$$

Event preselection

Selection criteria	Data	$\tilde{g}$ (1.8 TeV)	Pair-prod. $\tilde{\tau}$ (557 GeV)
All events	1	1	1
Trigger	0.15	0.11	0.86
$p_T > 55$ GeV	0.11	0.11	0.86
$\lvert\eta\rvert < 1$	0.059	0.074	0.64
# of valid pixel hits in L2-L4 ≥ 2	0.056	0.071	0.62
Fraction of valid hits > 0.8	0.052	0.069	0.62
# of dE/dx measurements ≥ 10	0.052	0.069	0.62
High purity track	0.052	0.069	0.62
Track $\chi^2/\text{dof} < 5$	0.052	0.069	0.62
$d_z < 0.1$ cm	0.052	0.069	0.62
$d_{xy} < 0.02$ cm	0.048	0.069	0.62
$I_{PF}^{rel} < 0.02$	0.014	0.065	0.61
$I_{trk} < 15$ GeV	0.014	0.065	0.61
PF $E/p < 0.3$	0.014	0.064	0.61
$\sigma_{p_T}/p_T^2 < 0.0008$	0.014	0.064	0.61
$F_i^{Pixels} > 0.3$	0.011	0.064	0.60

$$I_{PF}^{rel} = \frac{\left(\sum_{\Delta R < \Delta R_{\text{mini-iso}}} p_T^{PF}\right) - p_T^{HSCP}}{p_T^{HSCP}}, \qquad I_{trk} = \left(\sum_{\Delta R < \Delta R_{\text{mini-iso}}} p_T^{trk}\right) - p_T^{HSCP},$$

$$\Delta R_{\text{mini-iso}} = \begin{cases} 0.2, & p_T^{HSCP} \leq 50\,\text{GeV} \\ 10\,\text{GeV}/p_T^{HSCP}, & 50\,\text{GeV} < p_T^{HSCP} < 200\,\text{GeV} \\ 0.05, & p_T^{HSCP} \geq 200\,\text{GeV}. \end{cases}$$

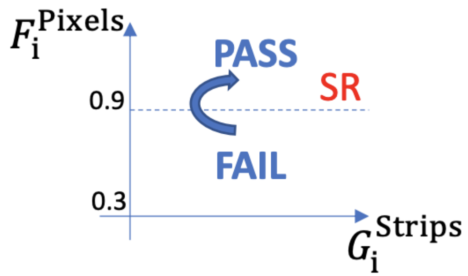


Background prediction – two methods

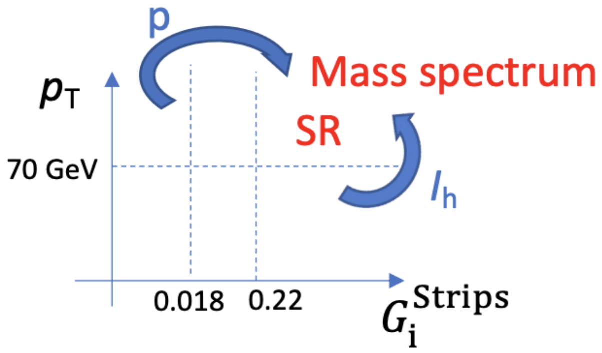
We use two independent methods for the background prediction
* Both of them are data driven
* Reuse the trigger + preselection + signal systematics

Given the ATLAS excess this gives us an extra handle

Ionization method: new approach, relying on independence of the pixels and strips detectors, uses a transfer function and invokes a shape based analysis

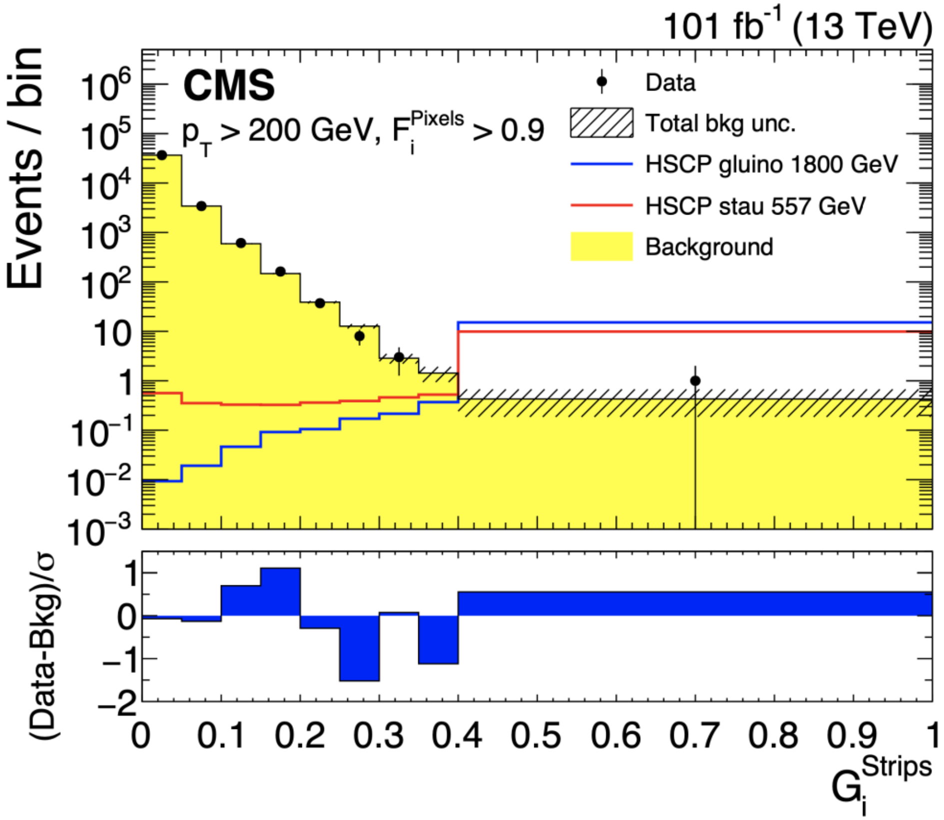


Mass method: improved historical approach, assuming the independence of I_h and p as well as the p_T and G_i^{Strips} as a counting experiment in dedicated mass windows

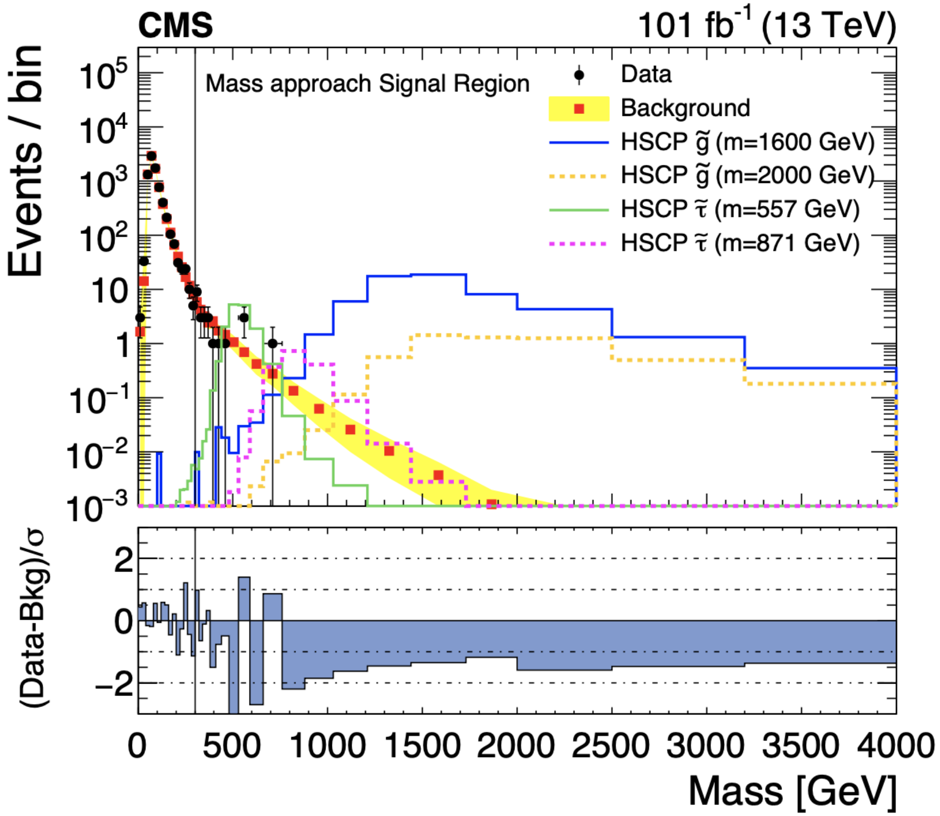


Results

Ionization method: Signal region is defined by $p_T > 200$ GeV, $F_i^{Pixels} > 0.9$ and the full shape of G_i^{Strips} is used

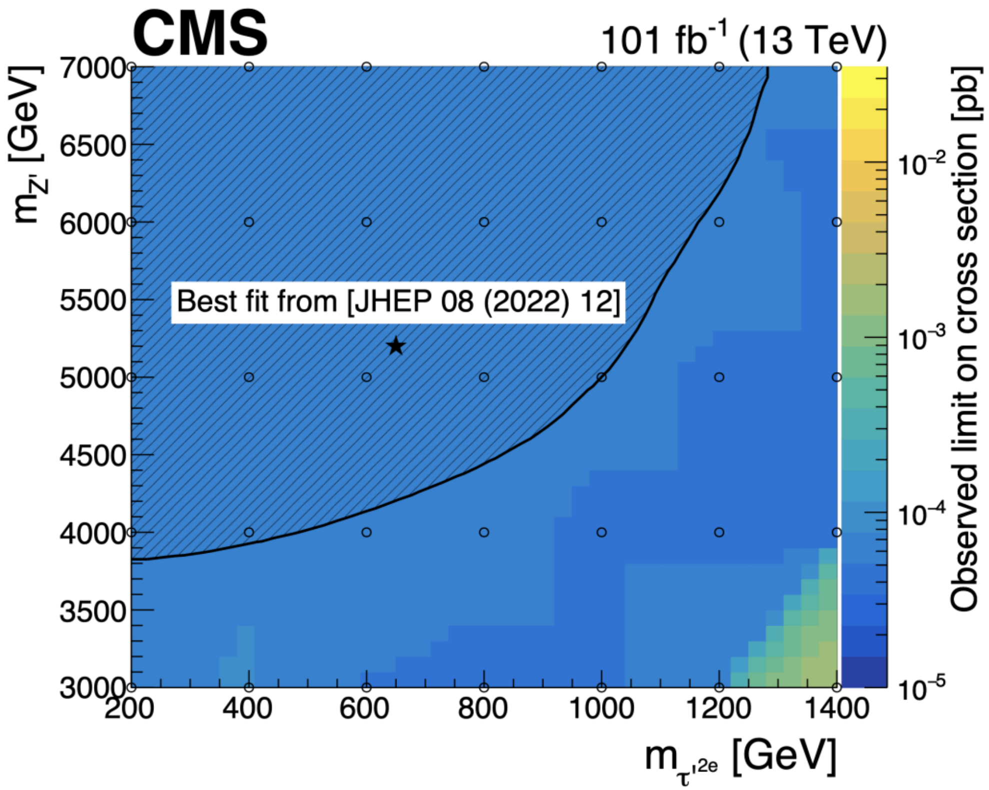


Signal region is defined by $p_T > 70$ GeV and $G_i^{Strips} > 0.22$, counting experiment in mass window



Interpretations summary

This model (2205.04473) was specifically created as an explanation to the ATLAS excess: provides a highly ionizing track with beta ~ 1

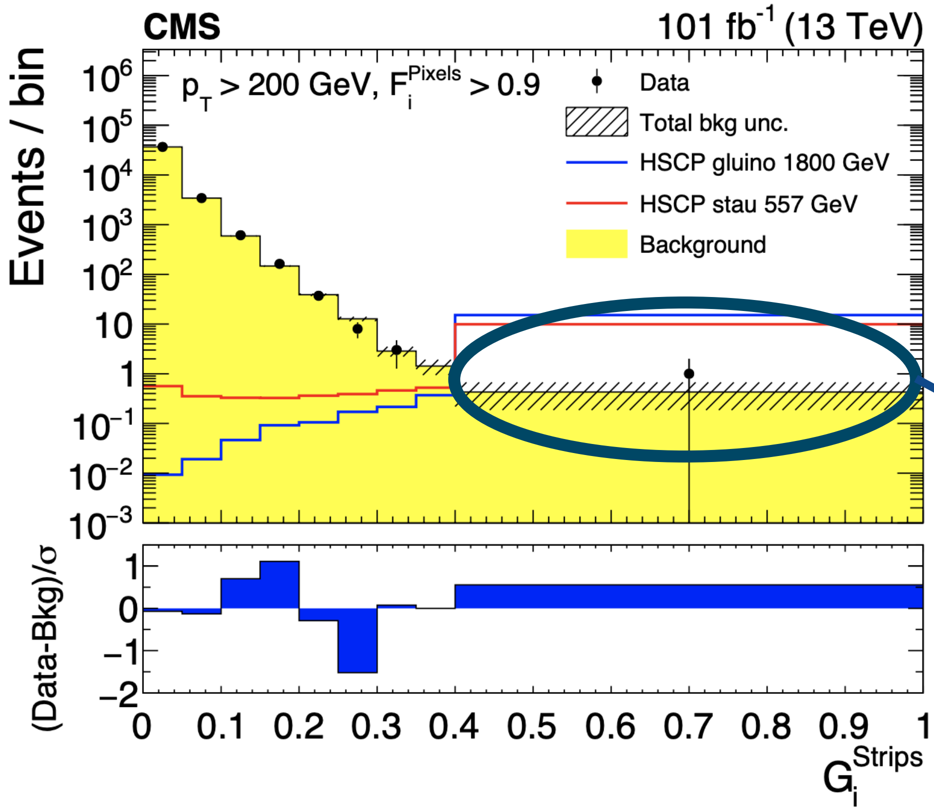


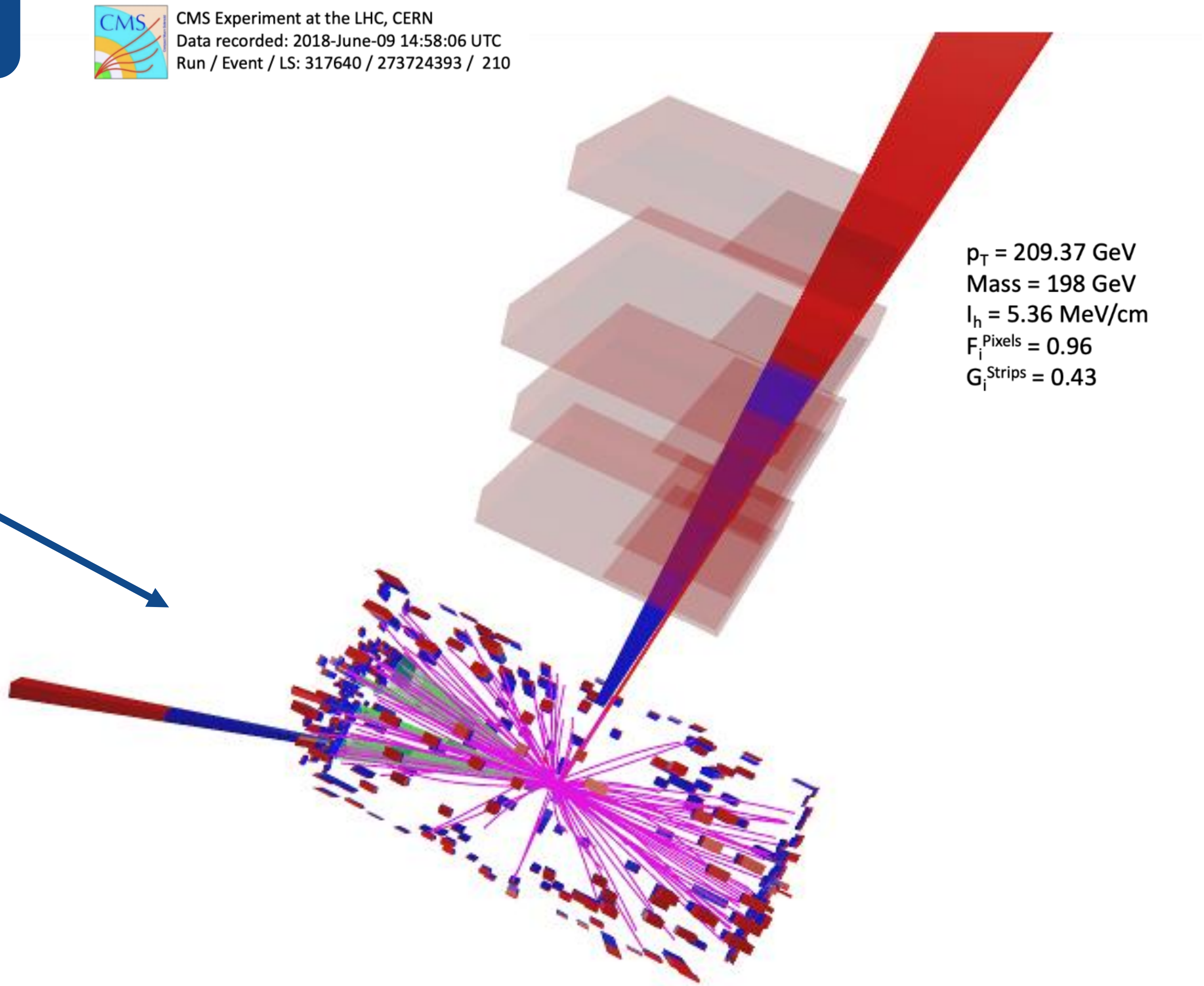
For the cross section limits the ionization method provides better limits at low signal masses while the mass method is more efficient at large masses

Model	Ionization method		Mass method	
	Exp. (TeV)	Obs. (TeV)	Exp. (TeV)	Obs. (TeV)
$\tilde{g}$	2.06 ± 0.06	2.06	2.08 ± 0.02	2.08
$\tilde{t}$	1.43 ± 0.05	1.40	1.47 ± 0.02	1.47
GMSB SPS7 $\tilde{\tau}$	0.86 ± 0.07	0.85	0.87 ± 0.05	0.85
pair-prod. $\tilde{\tau}_R$	0.53 ± 0.03	0.52	0.50 ± 0.07	0.51
pair-prod. $\tilde{\tau}_L$	0.66 ± 0.04	0.64	0.67 ± 0.06	0.61
pair-prod. $\tilde{\tau}_{L/R}$	0.71 ± 0.04	0.69	0.75 ± 0.08	0.64
τ' ($Q = 1e$) from DY prod.	1.05 ± 0.05	1.02	1.14 ± 0.03	1.14
τ' ($Q = 2e$) from DY prod.	1.35 ± 0.05	1.32	1.41 ± 0.02	1.41
$Z'_\psi \to \tau'\tau'$	3.99 ± 0.21	3.95	4.03 ± 0.01	4.03
$Z'_{SSM} \to \tau'\tau'$	4.53 ± 0.23	4.38	4.56 ± 0.01	4.57

Conclusions

Highest ionizing "excess" event in data





Backup

Specific model for ATLAS excess

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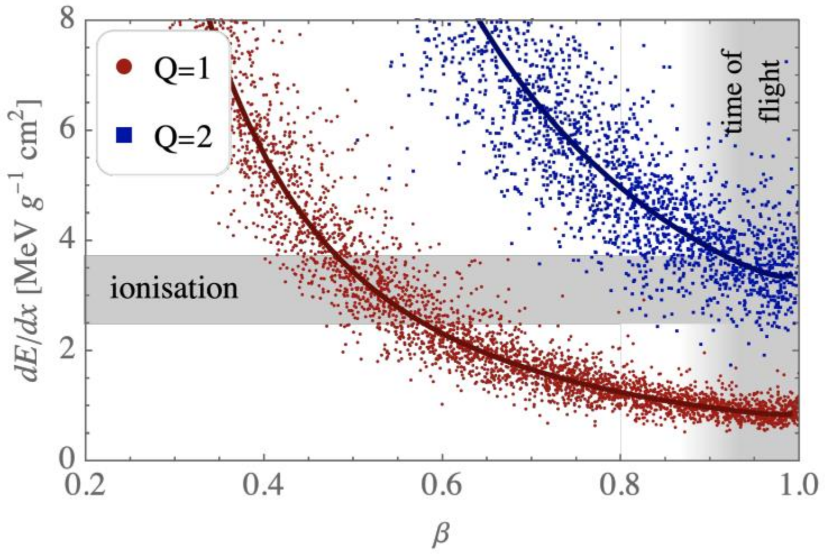
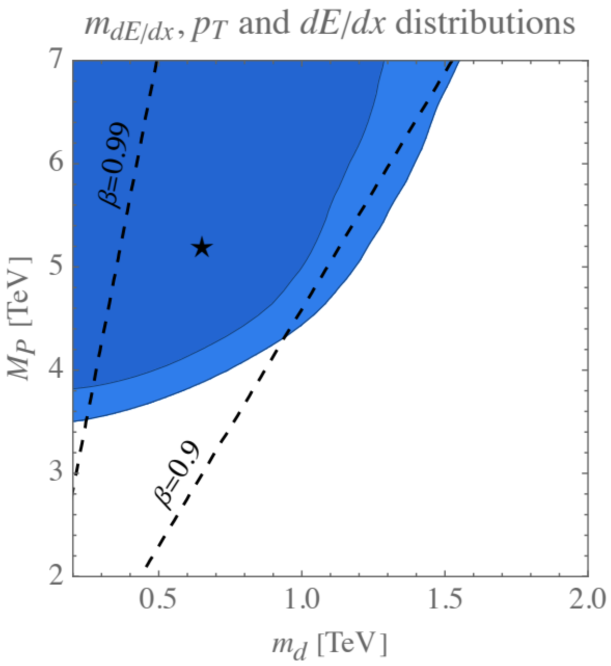
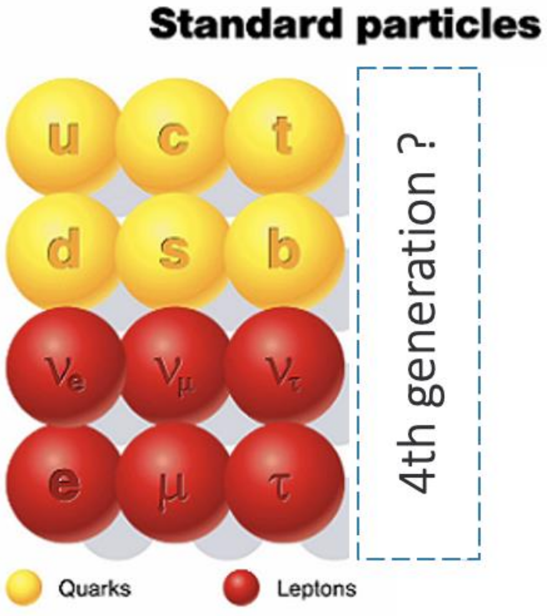




Heavy Z' decays to 4th generation Q=2 leptons



Tau' could be multi-charged, q=1e and q=2e with two production modes

Ionization observables (3-4)

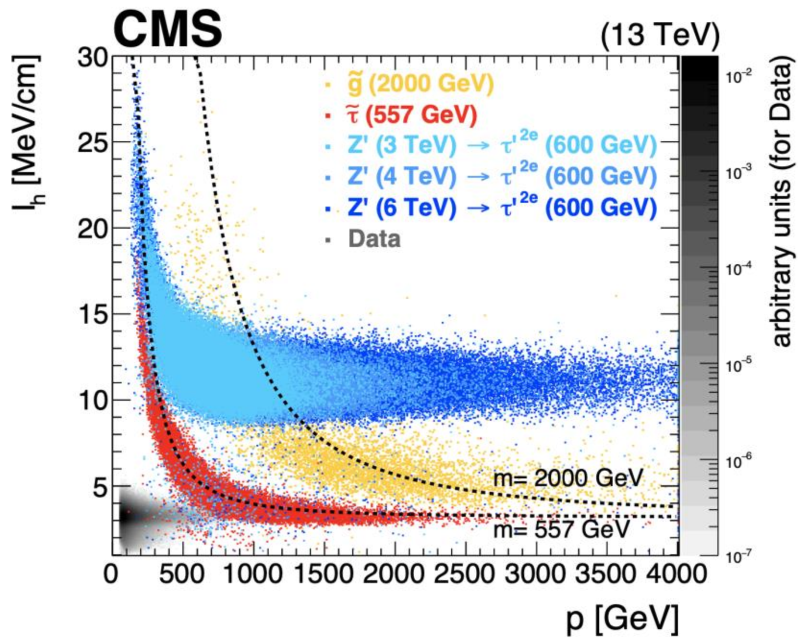
Ionization estimator using the squared harmonic mean in order to suppress the tails of the Landau distribution dE/dx

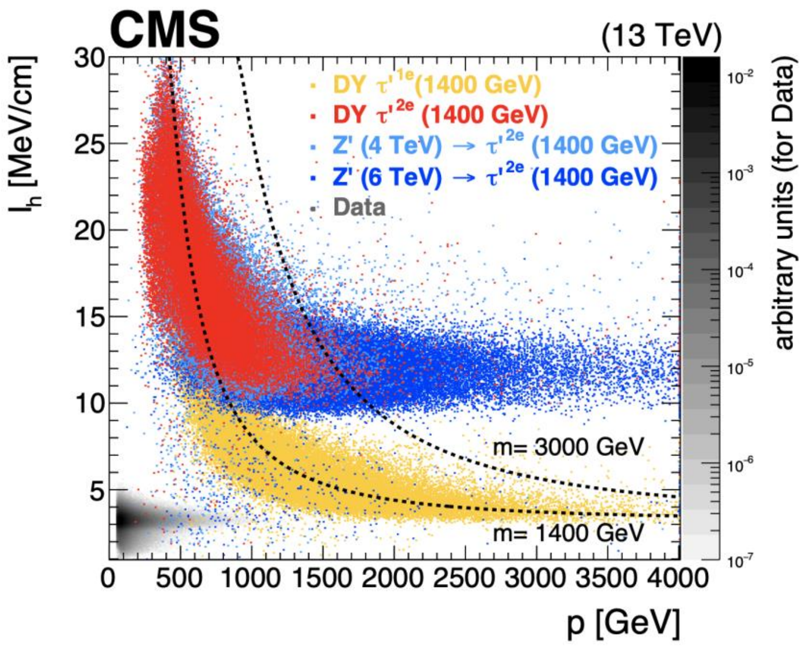
$$I_\mathrm{h} = \left(\frac{1}{N}\sum_j^N (\mathrm{d}E/\mathrm{d}x_j)^{-2}\right)^{-1/2},$$

Mass of the HSCP can be interpreted through approximating the Bethe-Bloch formula with I_h(m,p,K,C), where the empirical parameters K and C are determined using a sample of low-momentum particles composed of protons, kaons and pions.

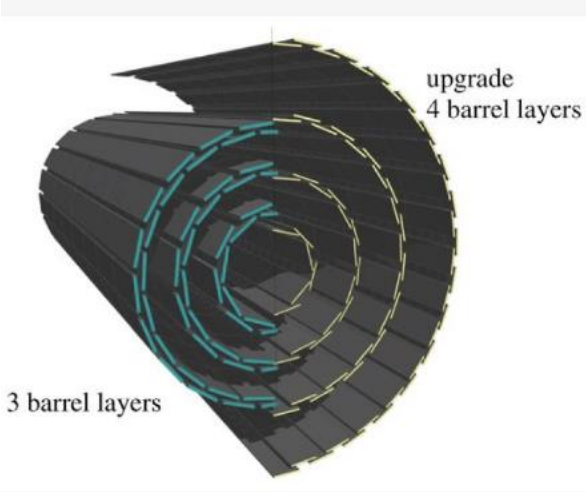
$$I_\mathrm{h} = K\frac{m^2}{p^2} + C,$$

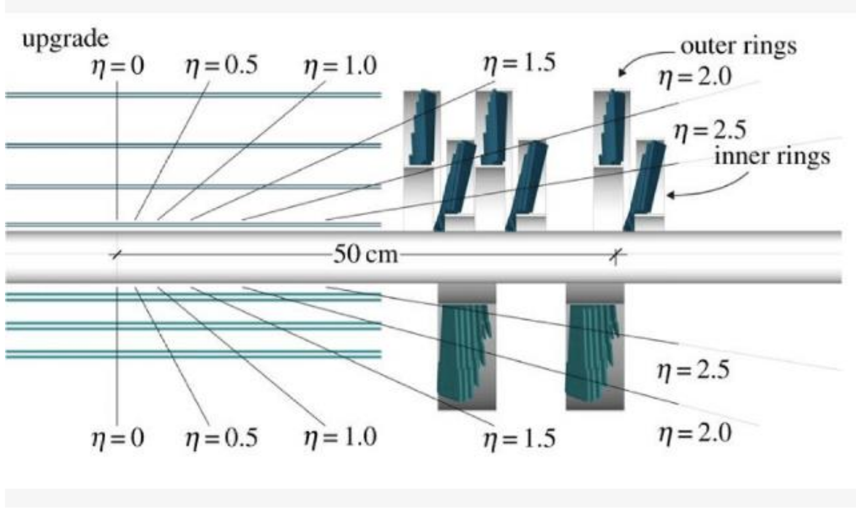
Description	Data 2017	Data 2018	Monte Carlo 2017	Monte Carlo 2018
K (MeV/ cm)	2.54 ± 0.01	2.55 ± 0.01	2.50 ± 0.01	2.49 ± 0.01
C (MeV/ cm)	3.14 ± 0.01	3.14 ± 0.01	3.18 ± 0.01	3.18 ± 0.01





Pixel and strips detectors





Label	Sub-detector	Layer	No. of APV25s	Pitch [μm]
IB1	TIB	1–2	6	80
IB2	TIB	3–4	4	120
OB2	TOB	1–4	4	183
OB1	TOB	5–6	6	122
W1A	TID	1	6	80.5 – 119
W2A	TID	2	6	113 – 143
W2A	TID	3	4	123 – 158
W1B	TEC	1	6	81 – 112
W2B	TEC	2	6	113 – 143
W2B	TEC	3	4	123 – 158
W4	TEC	4	4	113 – 139
W5	TEC	5	6	126 – 156
W6	TEC	6	4	163 – 205
W7	TEC	7	4	140 – 172

Table 2: Summary of number of APV25 chips per module and strip pitch (strip pitch range) for barrel (endcap) sensor geometries in the strips detector, and their labels.

Detailed silicon simulations with PixelAV

The current track reconstruction uses a special reconstruction method (CPE) that was developed to simulate irradiated sensors using an external software called PixelAV.

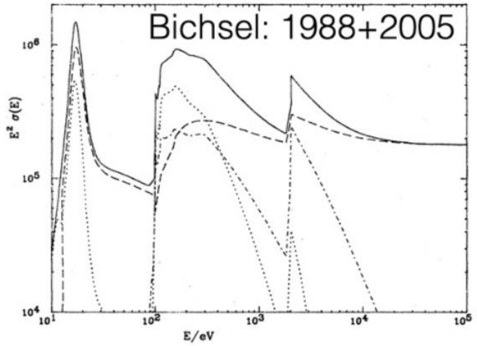
Charge deposition based on Bichsel pion-Si cross-sections

Delta-ray range using continuously slowing-down approach with NIST ESTAR dEdx data

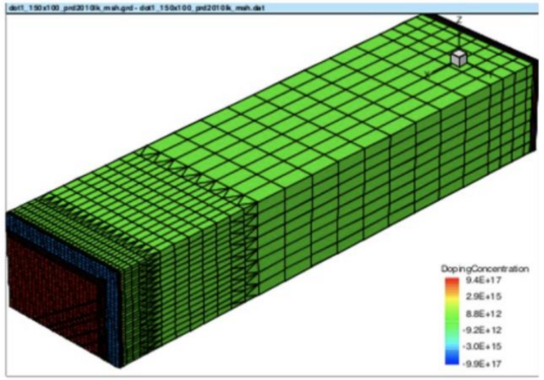
Multiple scattering and magnetic curvature of delta-rays

Carrier transport based on Runge-Kutta integration of saturated drift
- E-field is coming from ISE TCAD simulation of a pixel cell
- Includes charge trapping, diffusion, induction on implants

Electronics simulation: noise, linearity, thresholds, mis-calibration

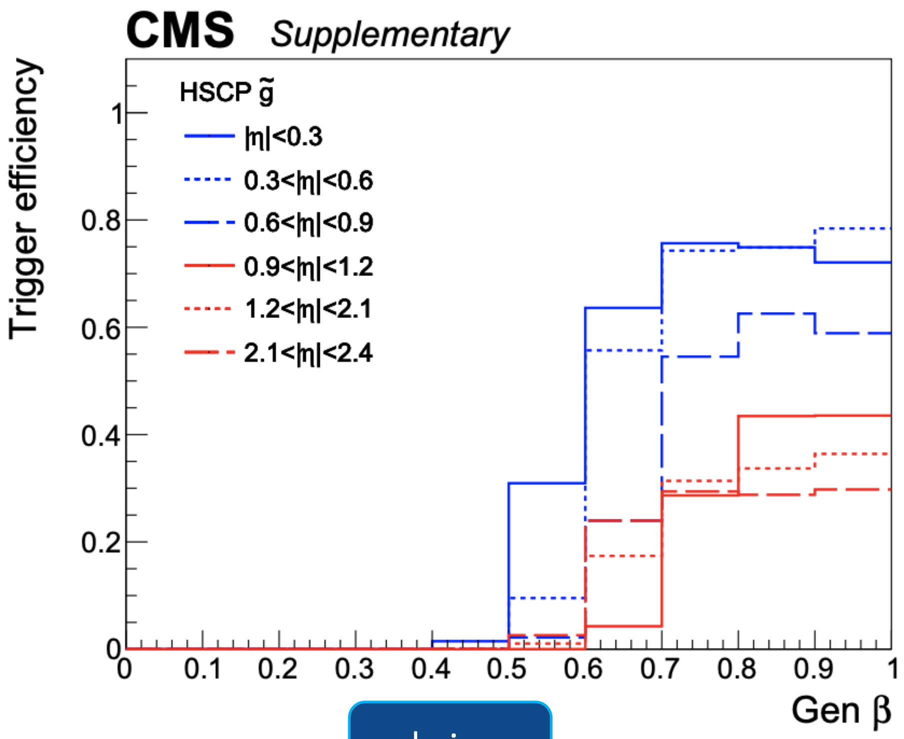


$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\mu\left[q\vec{E} + \mu r_H \vec{E}\times\vec{B} + q\mu^2 r_H^2(\vec{E}\cdot\vec{B})\vec{B}\right]}{1+\mu^2 r_H^2|\vec{B}|^2}$$

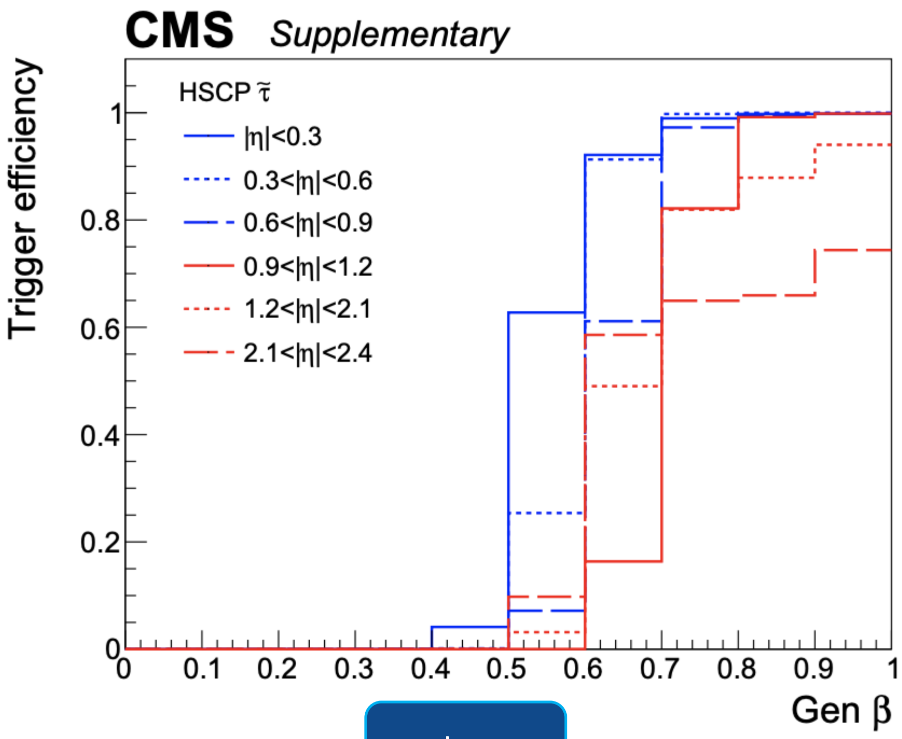


Trigger choice

Trigger choice: Single muon trigger (HLT_Mu50)
* Motivated by the ATLAS excess being compatible with muons.
* Less QCD and more EW processes as background.
* Using MET triggers require a deeper understanding of R-hadrons trigger efficiency, and will be included in a next paper.



gluino



stau

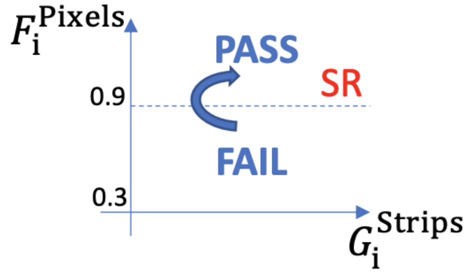
Trigger efficiency binned in eta ranges

More efficient for muon-like signals

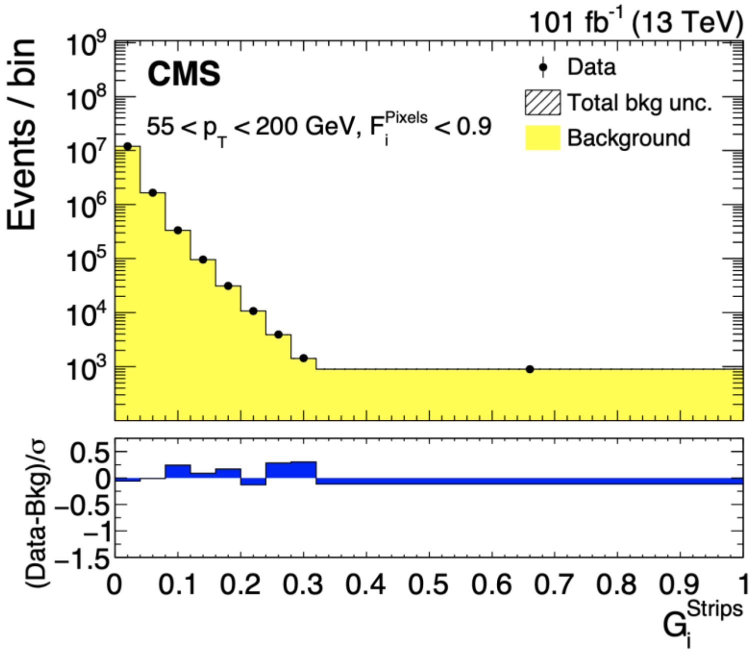
Background prediction – ionization method

Fully data driven method relying in the independence of the pixels and strips detectors

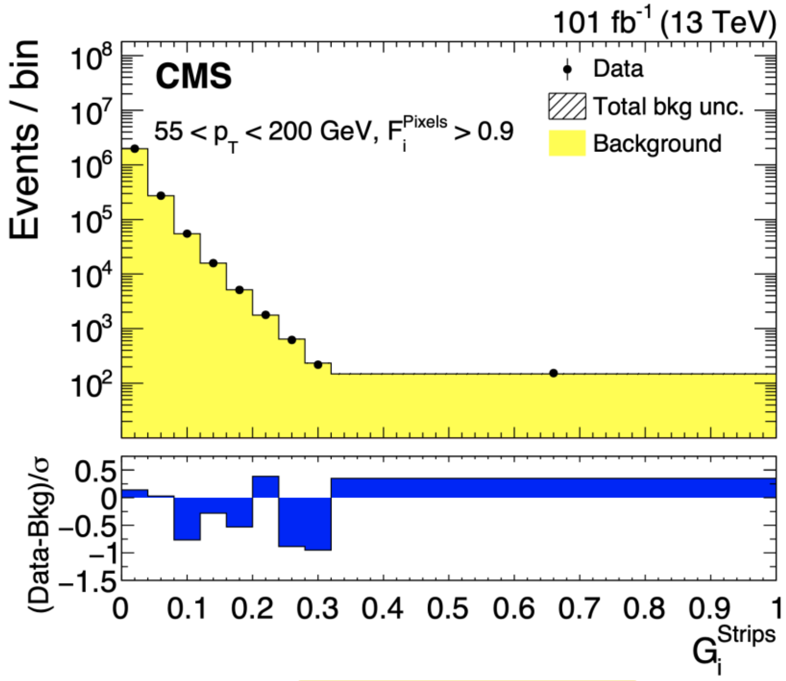
PASS and FAIL regions defined by the F_i^{Pixels} variable, then doing joint fit in bins of the G_i^{Strips} distribution using the full shape



$$N_{\text{PASS}}^{\text{bkg}}(j) = R_{\text{P/F}}(j)\, N_{\text{FAIL}}^{\text{data}}(j)$$



FAIL region



PASS region

A control regions defined by 50 < p_T < 55 GeV and 55 < p_T < 200 GeV show very good performance

No signal curve is shows as there is no signal in this CR

Background prediction – mass method

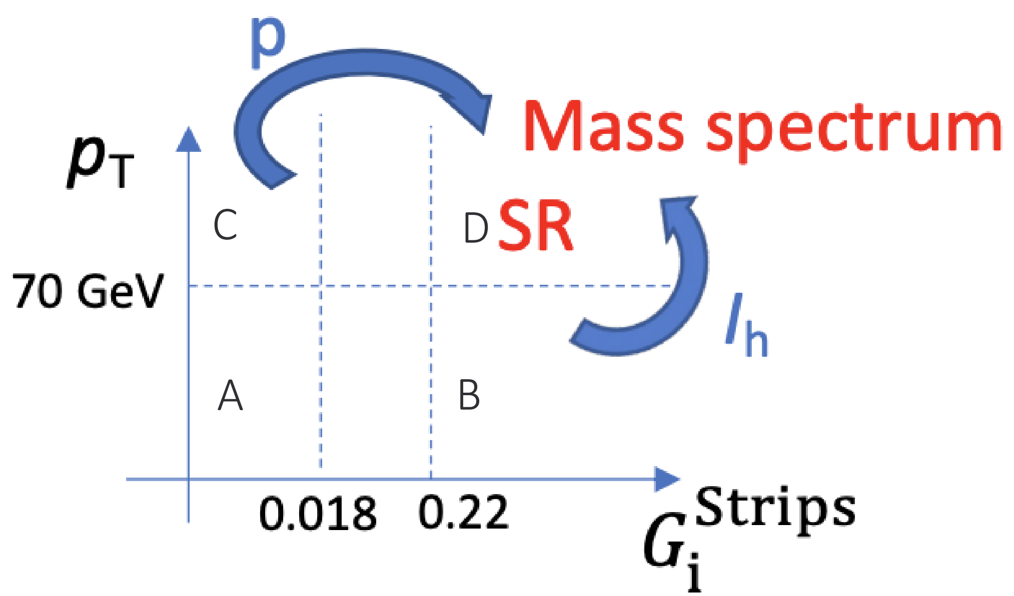
Fully data driven method assuming the independence of I_h and p as well as the p_T and G_i^{Strips} as a counting experiment in dedicated mass windows

The shape of the background mass spectrum in D comes from fitted distributions of I_h in the control region B and p in the control region C

This is done in bins of pseudorapidity to take the correlation between p_T and p into account

$$I_h = K\frac{m^2}{p^2} + C,$$

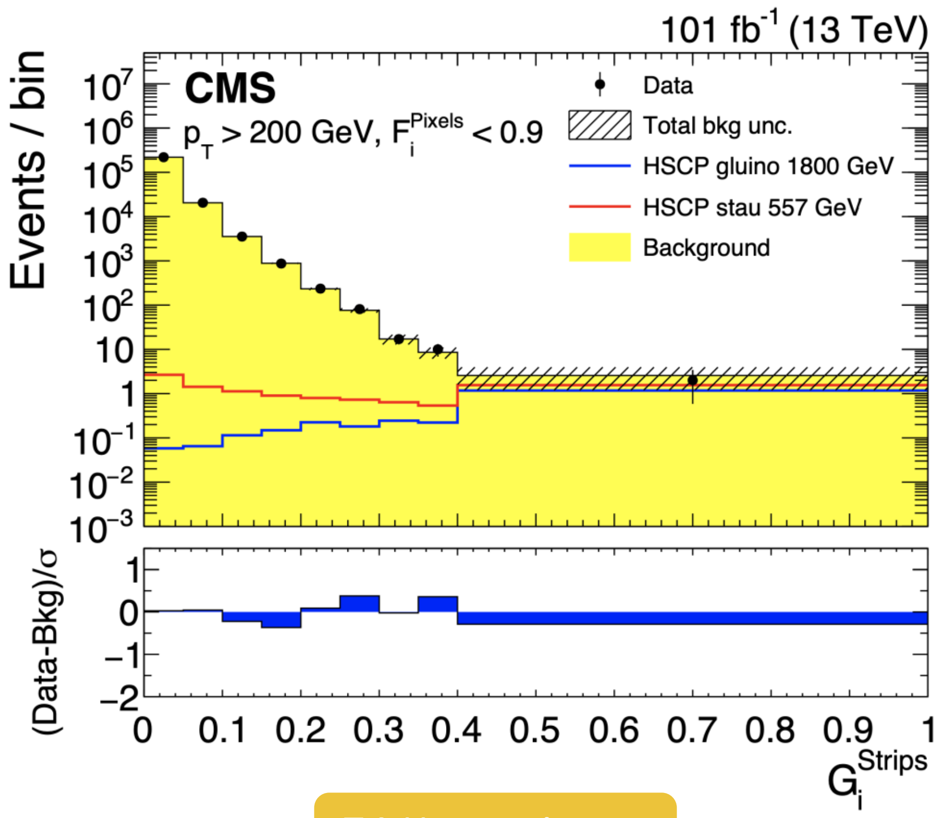
$$\Rightarrow m = p\sqrt{\frac{I_h - C}{K}}$$



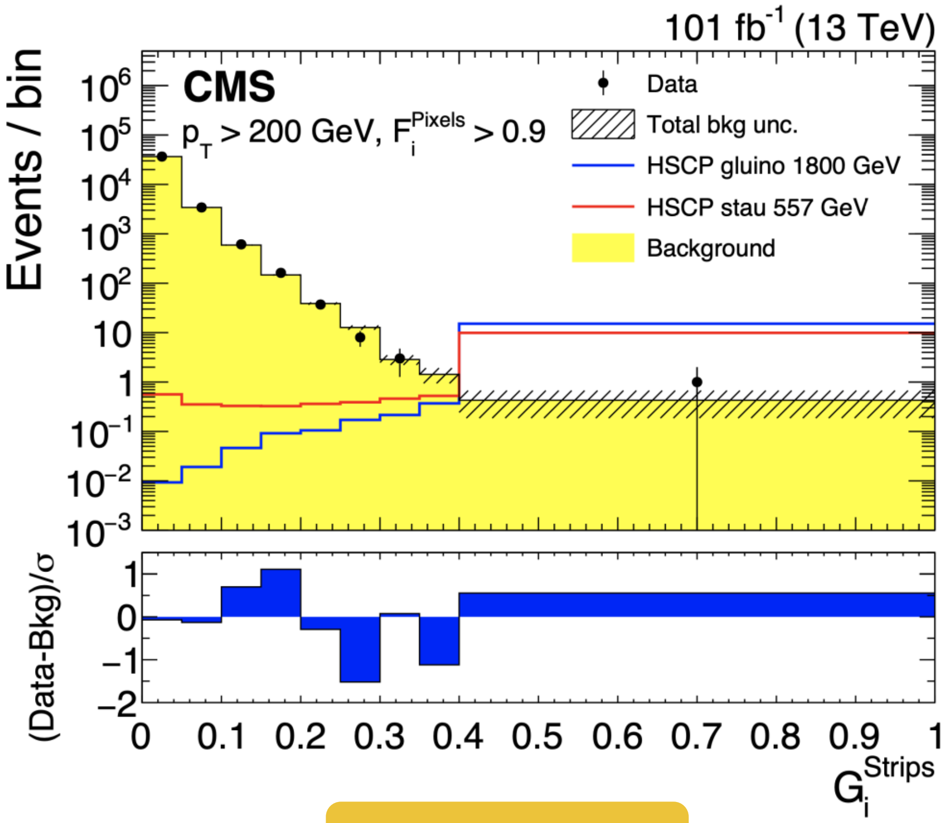
Results – ionization method

Signal region is defined by $p_T > 200$ GeV, $F_i^{Pixels} > 0.9$ and the full shape of G_i^{Strips} is used

No significant excess beyond the SM is observed (expected 0.4, observed 1)



FAIL region



PASS region

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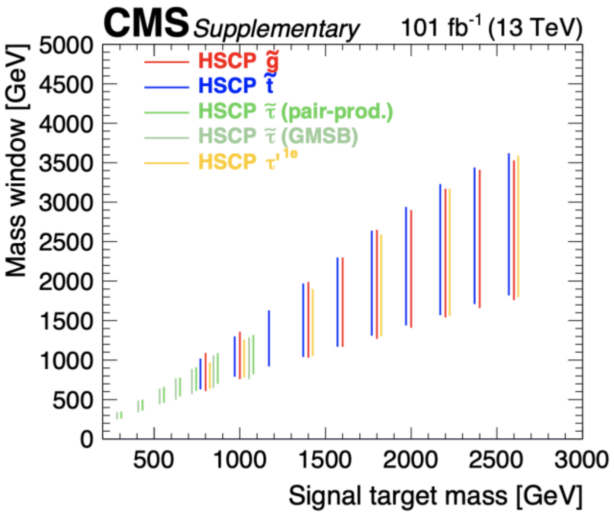
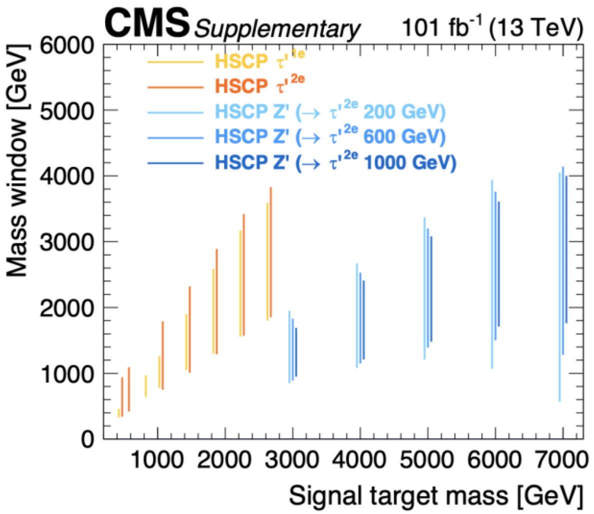
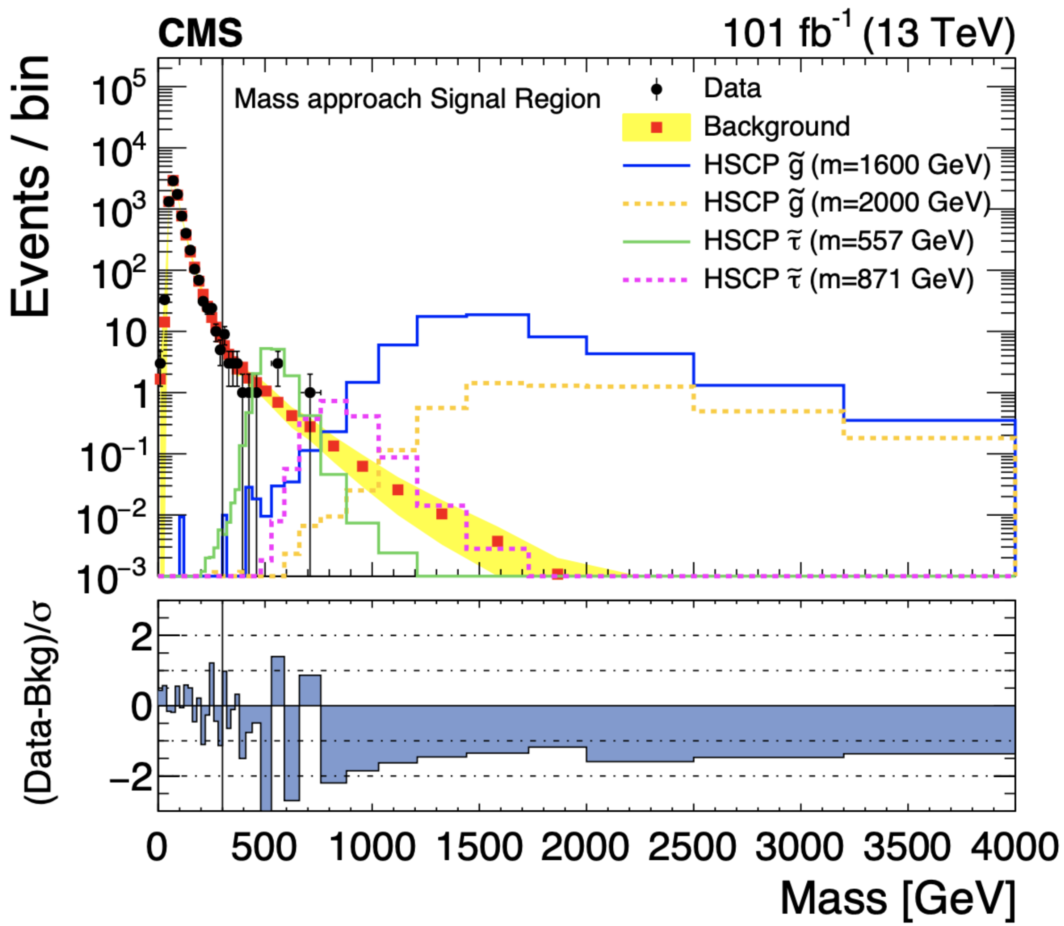




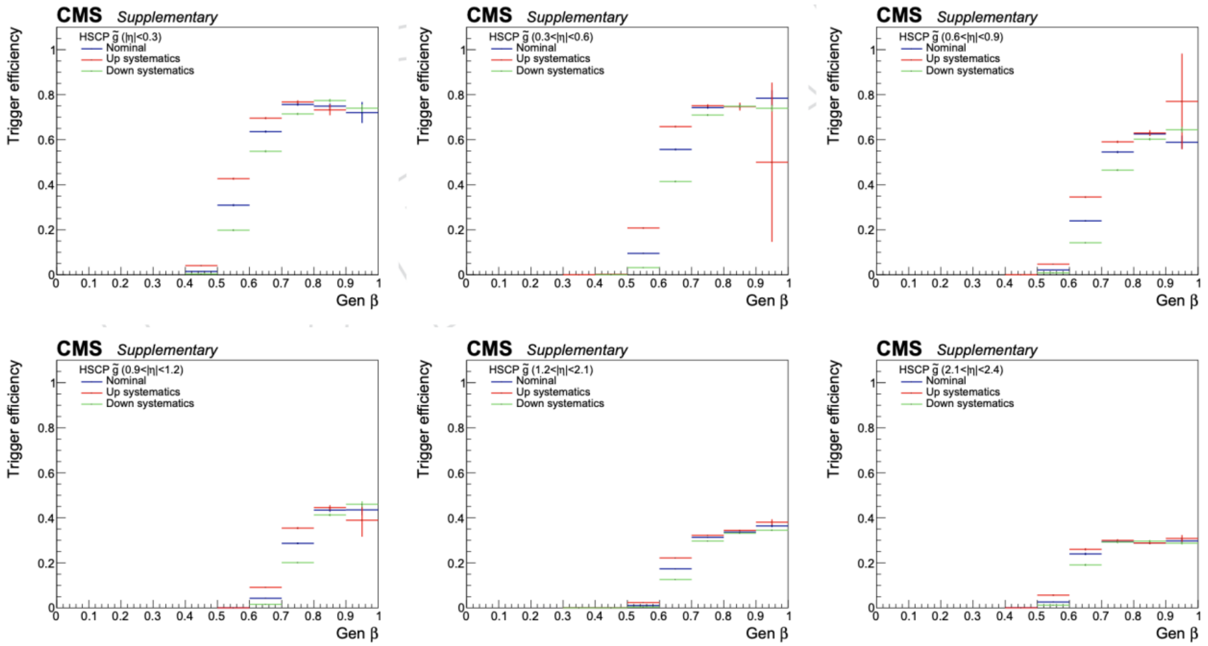


Mass windows for different interpretations

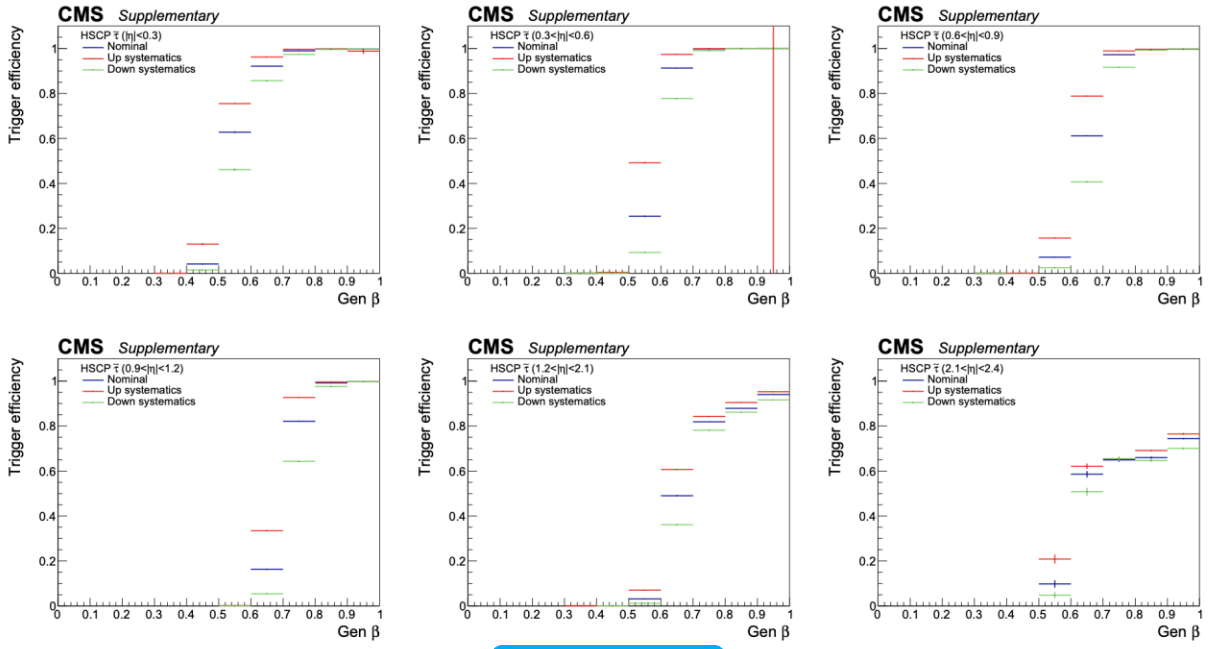
Signal systematic uncertainties (1)

Dominant uncertainty coming from trigger efficiency: HSCPs that are moving too slowly could be associated with the next bunch crossing collision

Efficiency curves are derived as a function of the generator-level beta for different bins in eta, and variations on these curves have been conservatively estimated assuming a delay of 1.5 ns in the muon chambers, that is equivalent to the time resolution of the chambers.



gluinos



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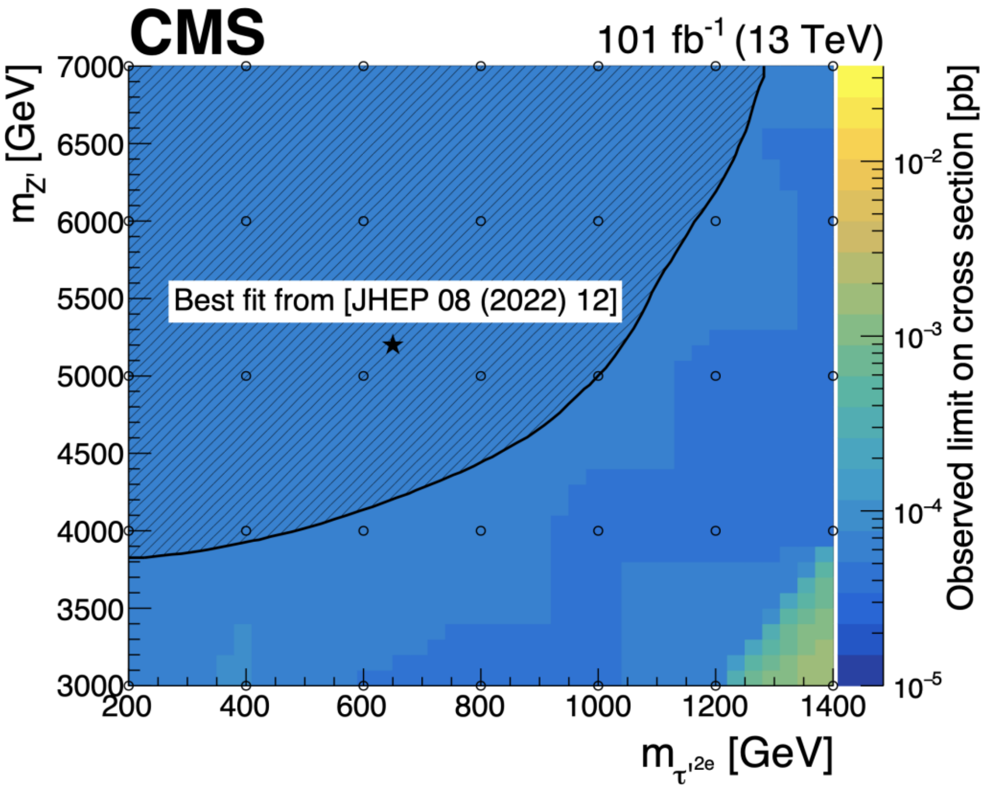
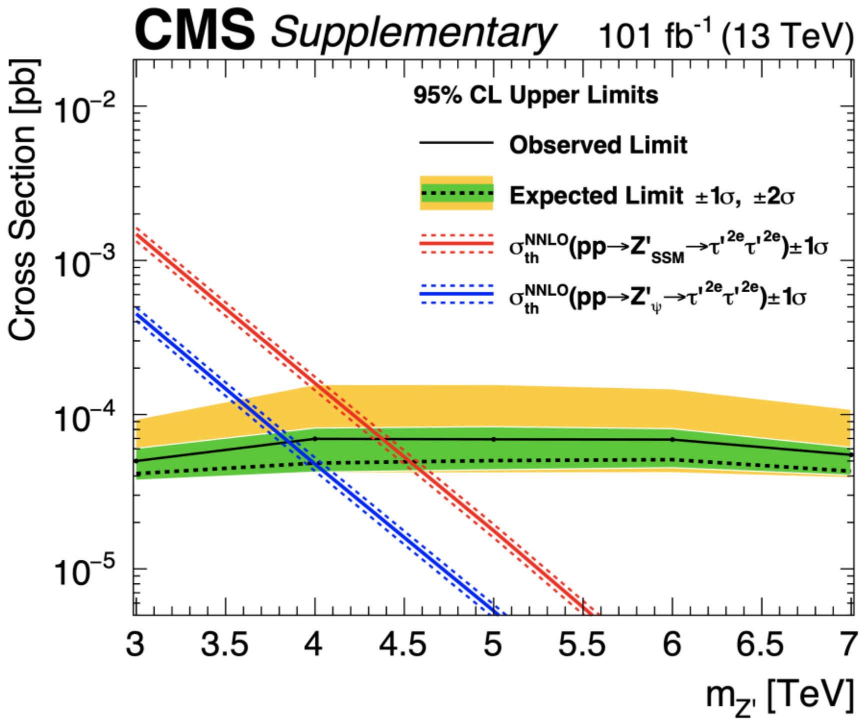
Interpretations

This model (2205.04473) was specifically created as an explanation to the ATLAS excess: it provides a highly ionizing track with beta ~ 1

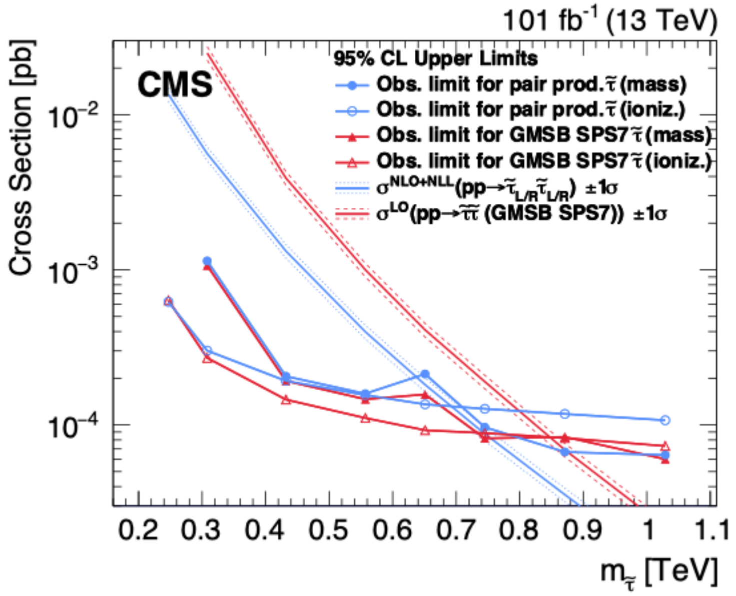


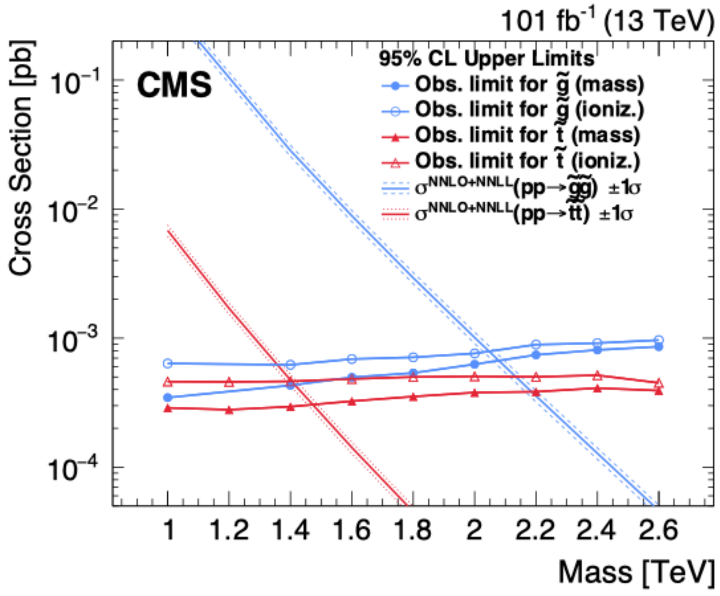
Make a slice at M(tau') = 600 GeV and set limits on the Z' mass

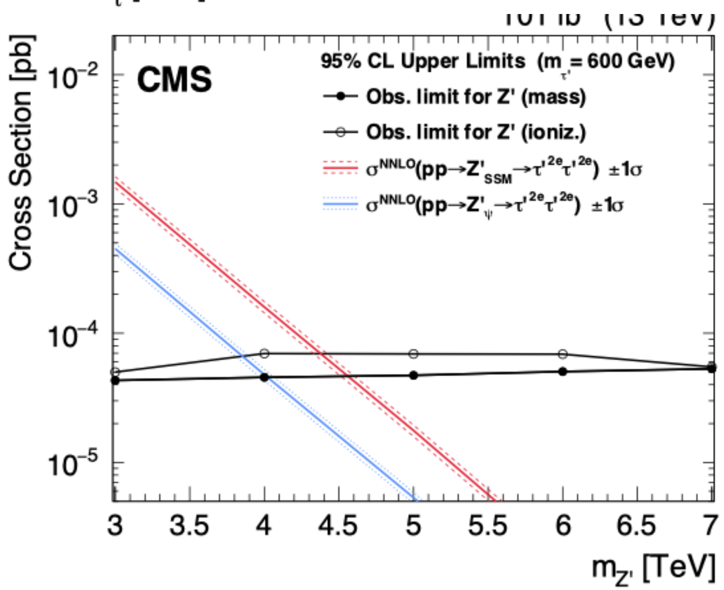


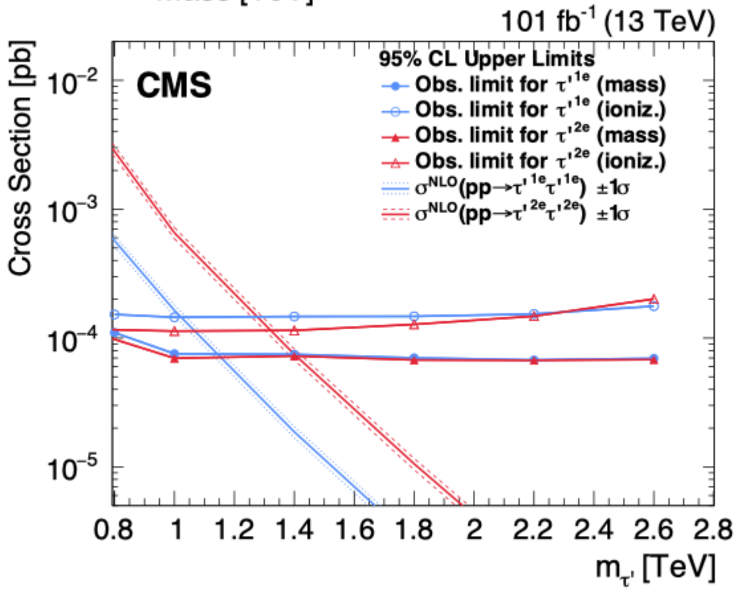
Z' obs (exp) mass limits for ion method: 3.95-4.38 (3.99-4.53) TeV

Interpretations summary (1)

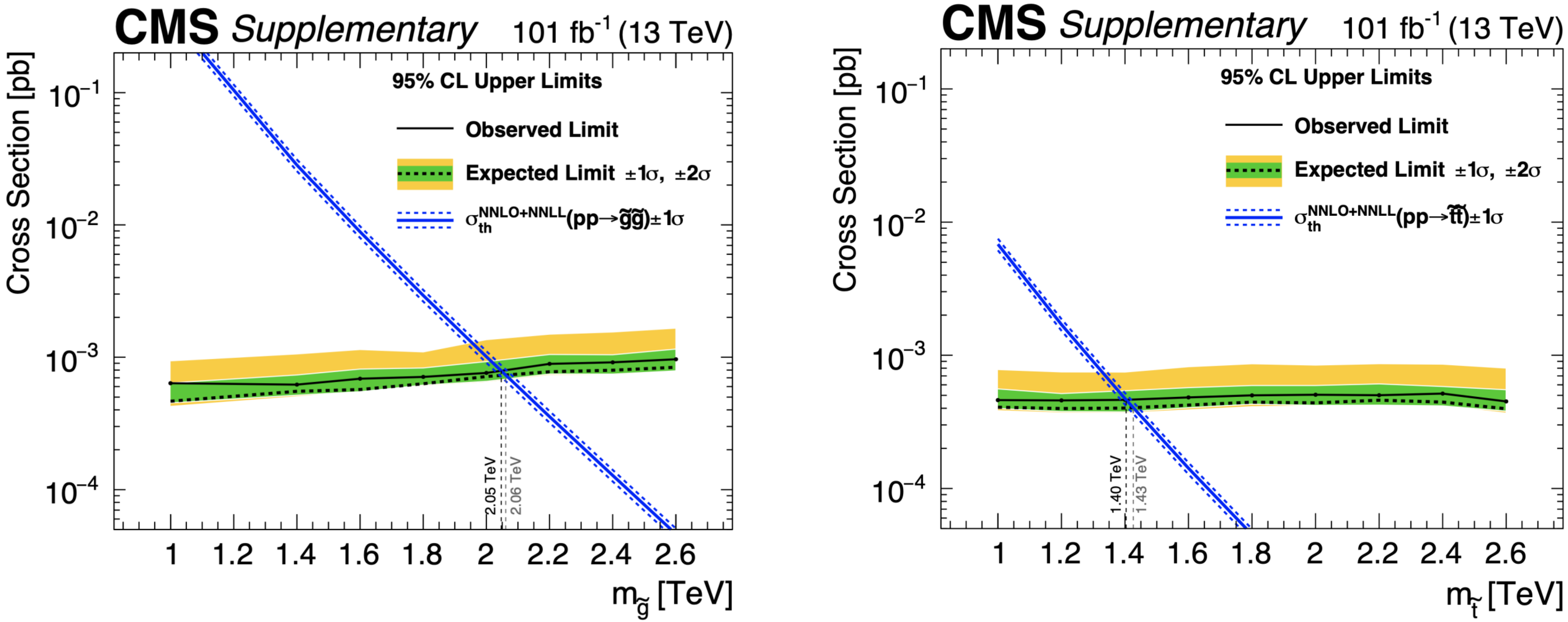






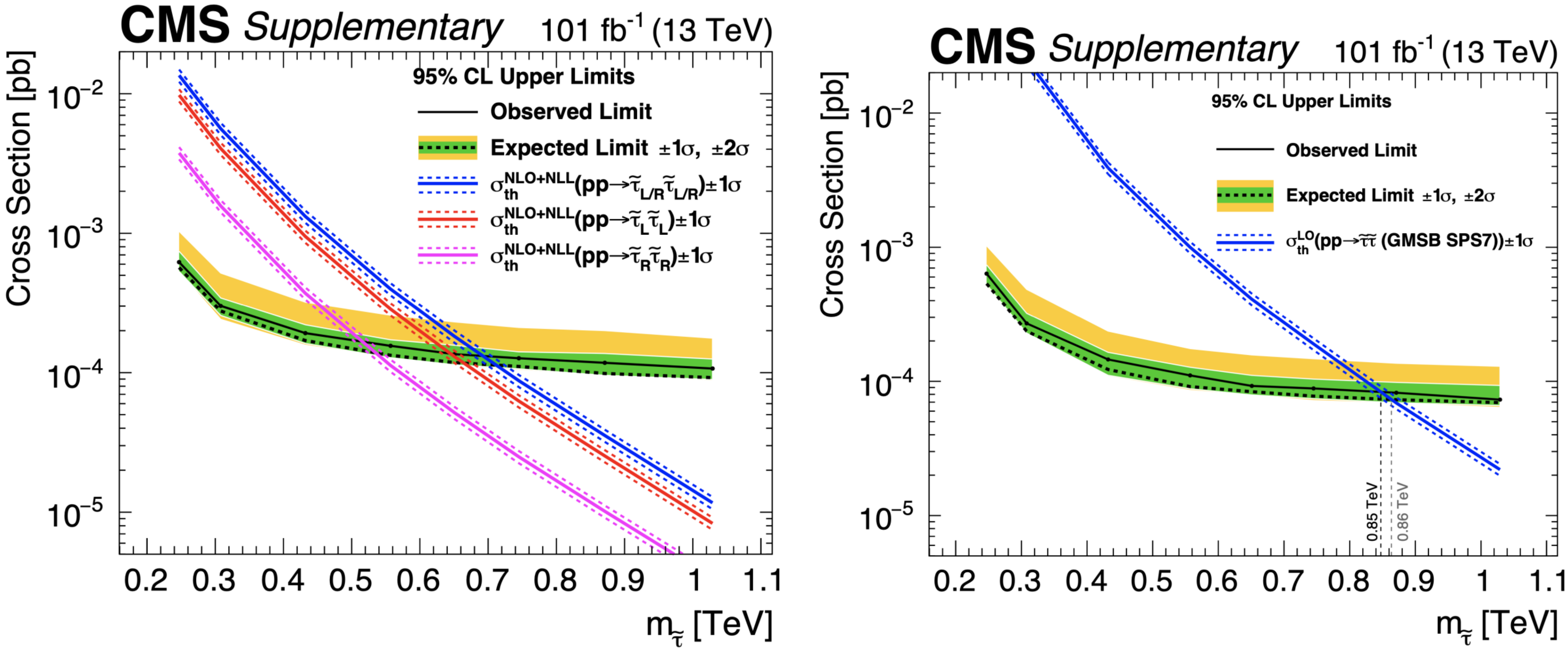


Interpretations (1-2)



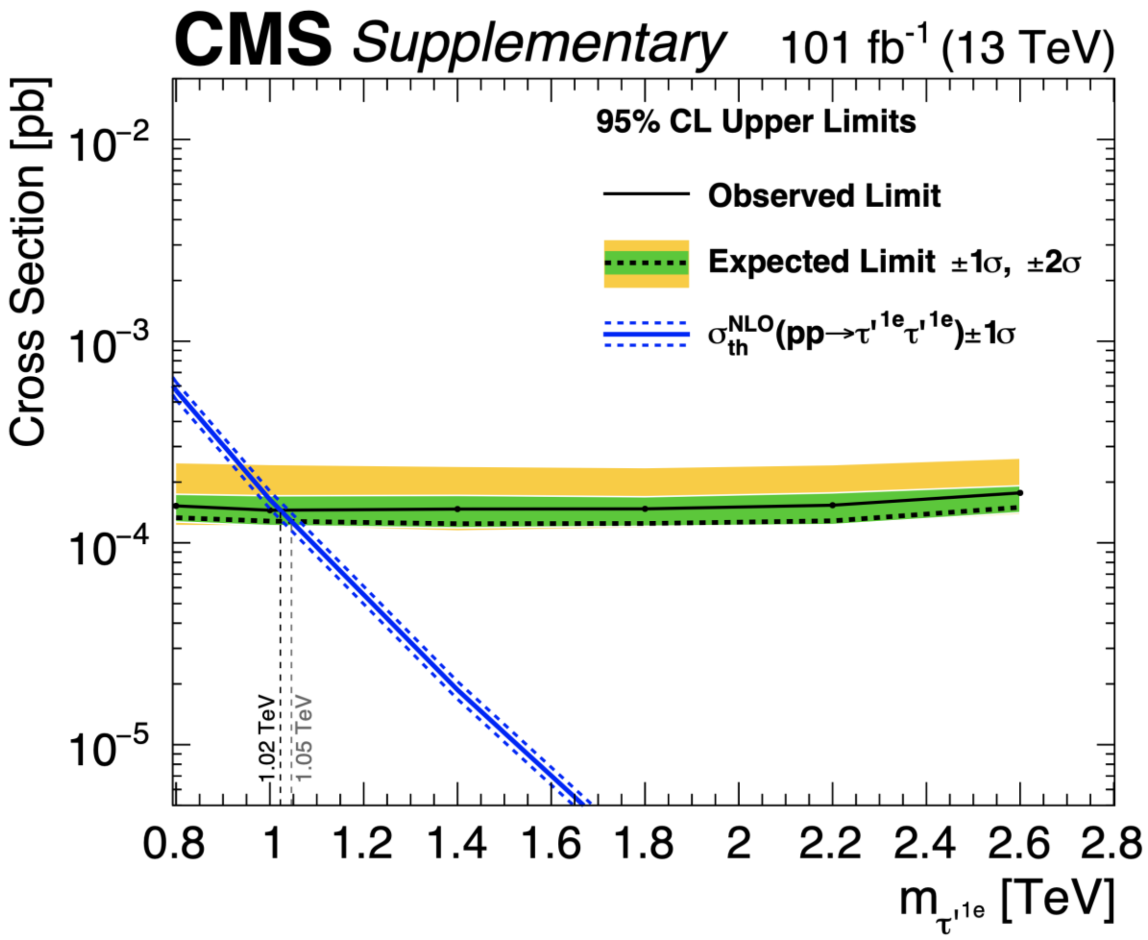
Gluino obs (exp) mass limits for ion method: 2.06 (2.06) TeV
Stop obs (exp) mass limits for ion method: 1.40 (1.43) TeV

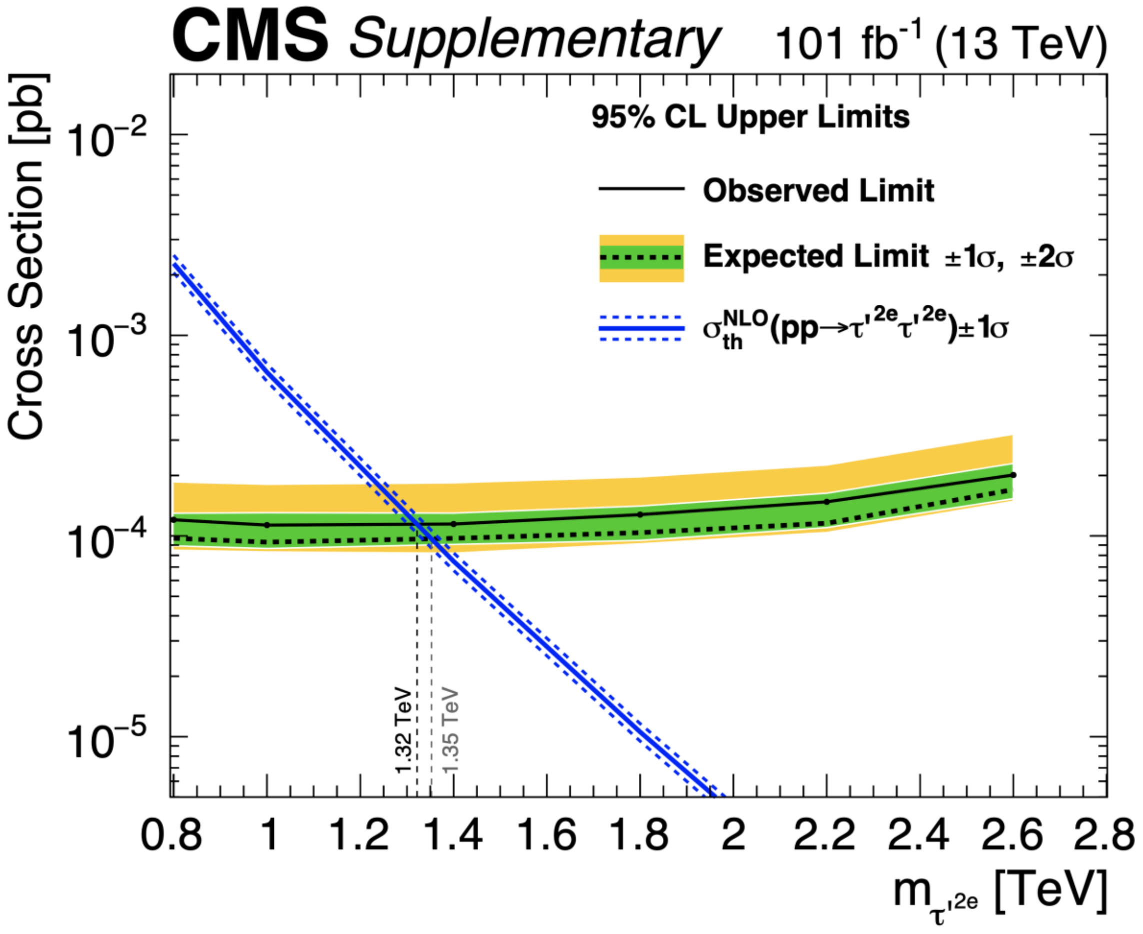
Interpretations (3abc-4)



Pair produced stau obs (exp) mass limits for ion method: 0.52-0.69 (0.53-0.71) TeV
GMSB produced stau obs (exp) mass limits for ion method: 0.85 (0.86) TeV

Interpretations (5-6)





Pair produced tau'-1e obs (exp) mass limits for ion method: 1.02 (1.05) TeV
Pair produced tau'-2e obs (exp) mass limits for ion method: 1.32 (1.35) TeV

Conclusions

A signature based, model independent search for HSCPs has been presented

The background was studied with MC samples, and the preselection was optimized

Two methods of data-driven background predictions were developed:
* a novel approach relying on the independence of the ionization in the tracking detectors
* an improved version of the historical mass method

No significant excess over the SM expectation was found

The results were interpreted in 10 different models,
one of them is a direct response to an excess seen by ATLAS

All figures are part of the results submitted to JHEP!
ArXiv:2410.09164, SUPP material EXO-18-002.
HEPData record containing the (re)interpretation material: doi:10.17182/hepdata.153850