12th Edition of the Large Hadron Collider Physics Conference (LHCP2024)
June3-7, 2024

Recent results on long-lived particles searches with hadronic final states

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7th June 2024

Introduction

- Lots of **Beyond the Standard Model** (BSM) searches are conducted in CMS
  - Many extension to the SM predict the existence of **Long-lived particles** with various experimental signatures

Focus on **long-lived particles** with hadronic final states

- **Displaced jets** (**unique result from CMS !**) : link ★
- **Emerging jets :** link
- **Heavy stable charged particles** ($c\tau$ > 7m) : link

EXO-23-013

Search for displaced jets at 13.6TeV (2022 data)

March 2024

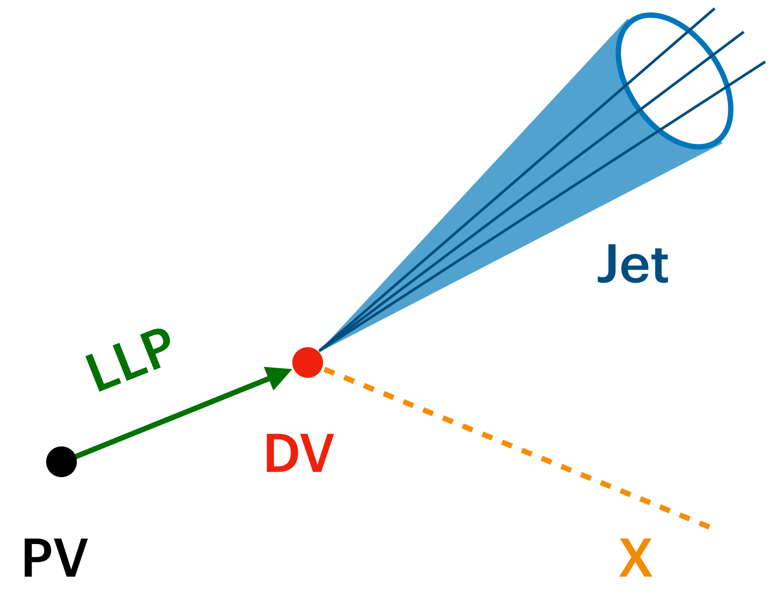
Search for LLP using displaced jets - Overview

Overview : Unique result from CMS

PAS reference

Displaced jet signature

- Look for hadronic decays of long-lived particles **inside the inner tracking** system



- **Focus on low-mass (< 60 GeV)** decaying LLPs : unconstrained phase space

Main physics motivation

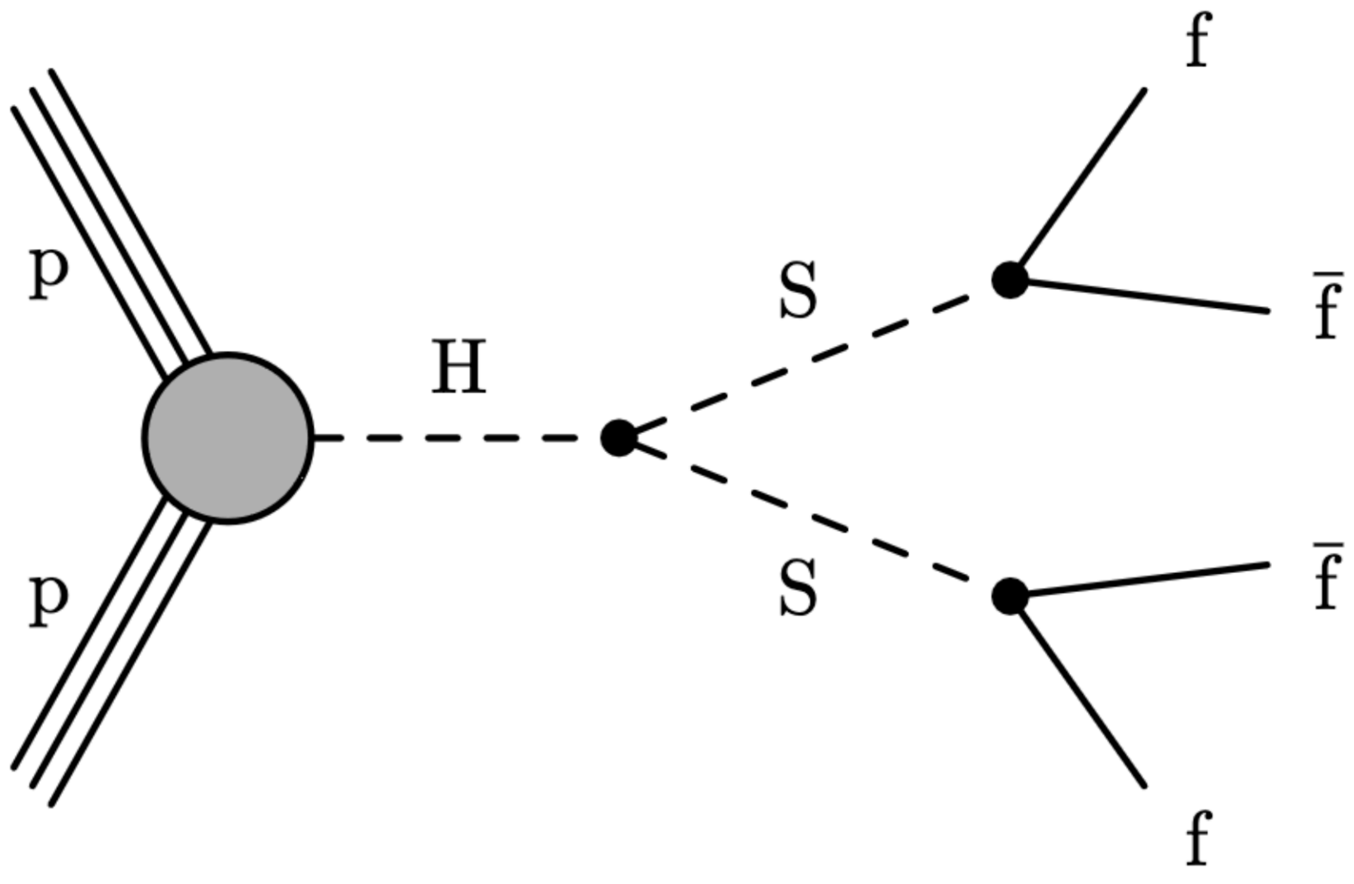
> **Higgs-portal hidden sectors**

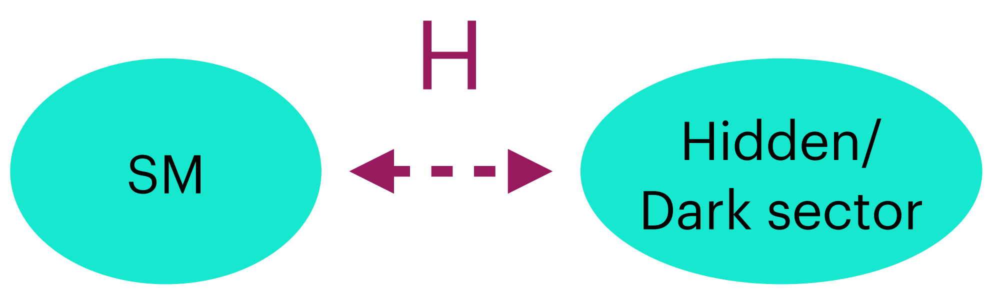
Also sensitive to many other BSM models

>Split SUSY, gauge-mediated SUSY, RPV SUSY, stealth SUSY, HNLs, axions/ALPs,...

Benchmark signature

- Exotic decay of Higgs boson to 2 **long-lived neutral scalars S**, further decaying to 2 SM fermions
  - Focus on **hadronic final states** : $b\bar{b}$, $d\bar{d}$,$\tau\tau$





$H \rightarrow$ **SS, S**$\rightarrow bb/dd/\tau\tau$
(S in an LLP)

Considered signal points
m_S = 15,23,30,40,55 GeV
$c\tau$ = 1 - 1000 mm

Search for LLP using displaced jets - Categories & S/B modelling

New techniques developed for this search

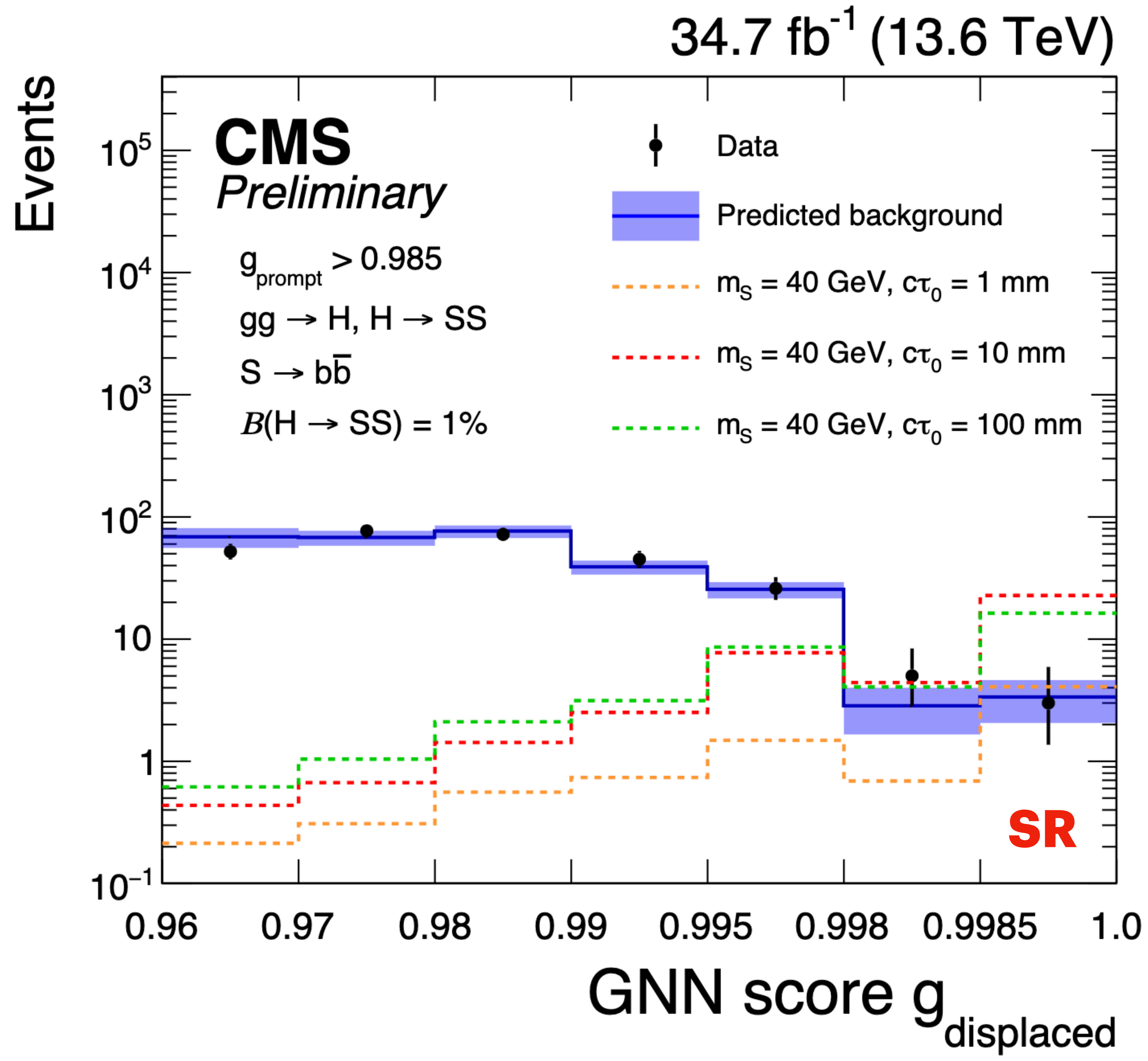
- **New displaced-jet triggers**
- **New displaced vertex reconstruction**
- **New graph-neural-network (GNN) based LLP taggers**
  - **GNN_d** : presence of displaced activities during **LLP decay**
  - **GNN_p** : lack of prompt activities during **LLP production**

Event selection : →

- Dijet with **at least 1 DV**
- Select dijet with **largest g_{prompt}**

Background estimation

- Small correlation between both taggers, allows for **ABCD background estimation with simultaneous fit**
- ABCD regions based on both GNN scores

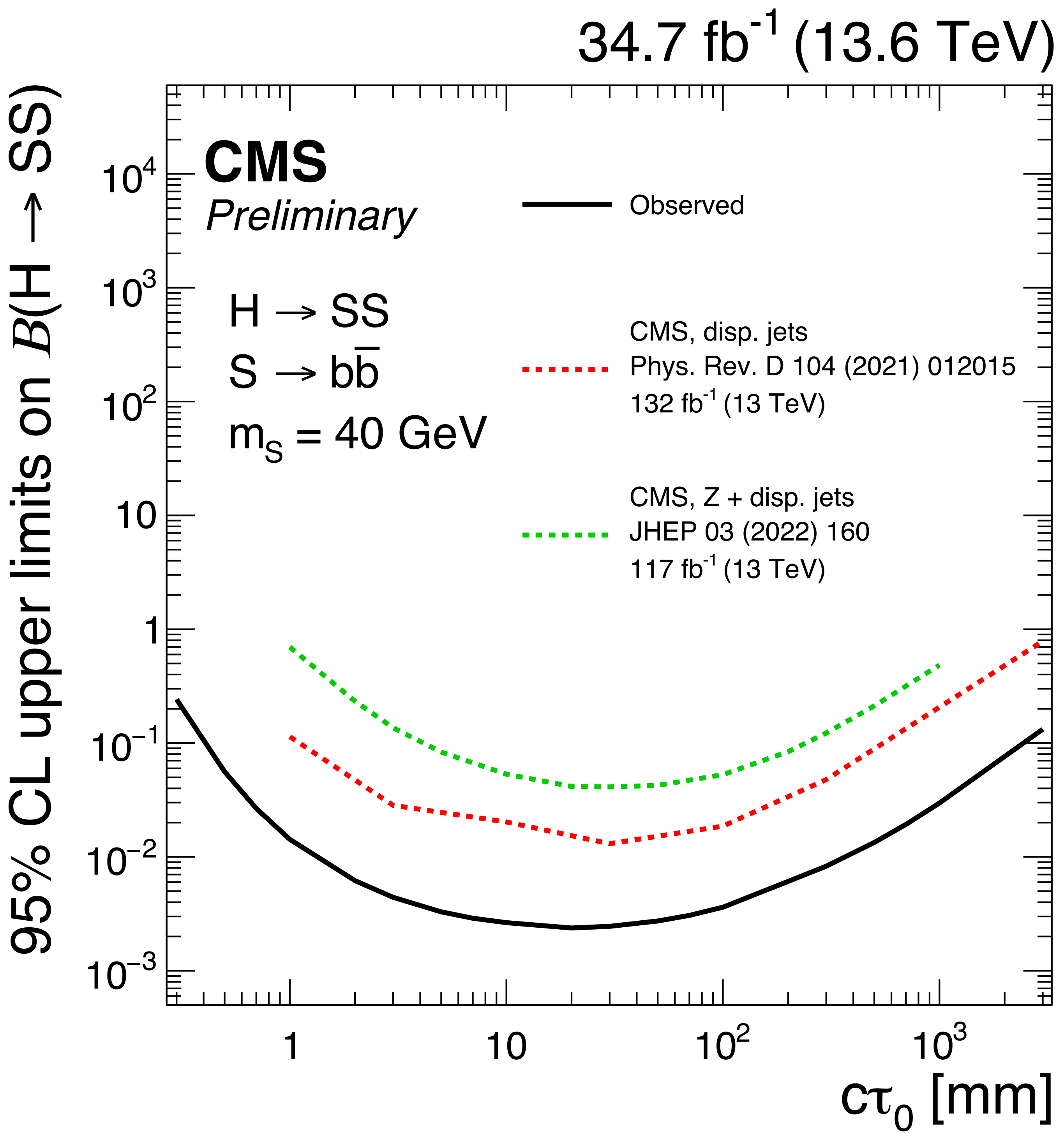


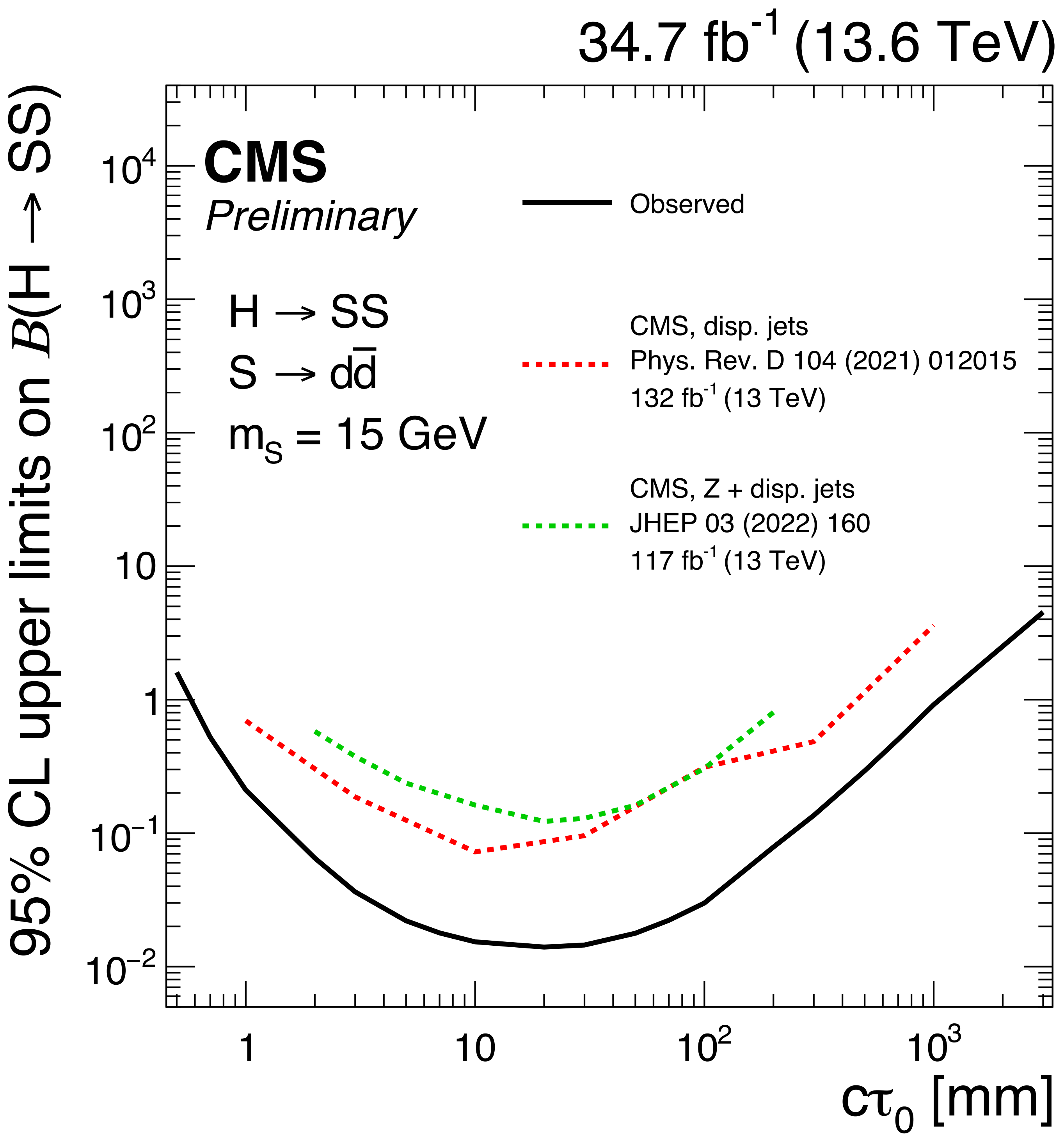
No significant excess observed

Signal region : $g_{displaced} > 0.9985$, $g_{prompt} > 0.985$

Expected bkg : 3.34 ± 1.28 **Observed** : 3

Search for LLP using displaced jets - Results

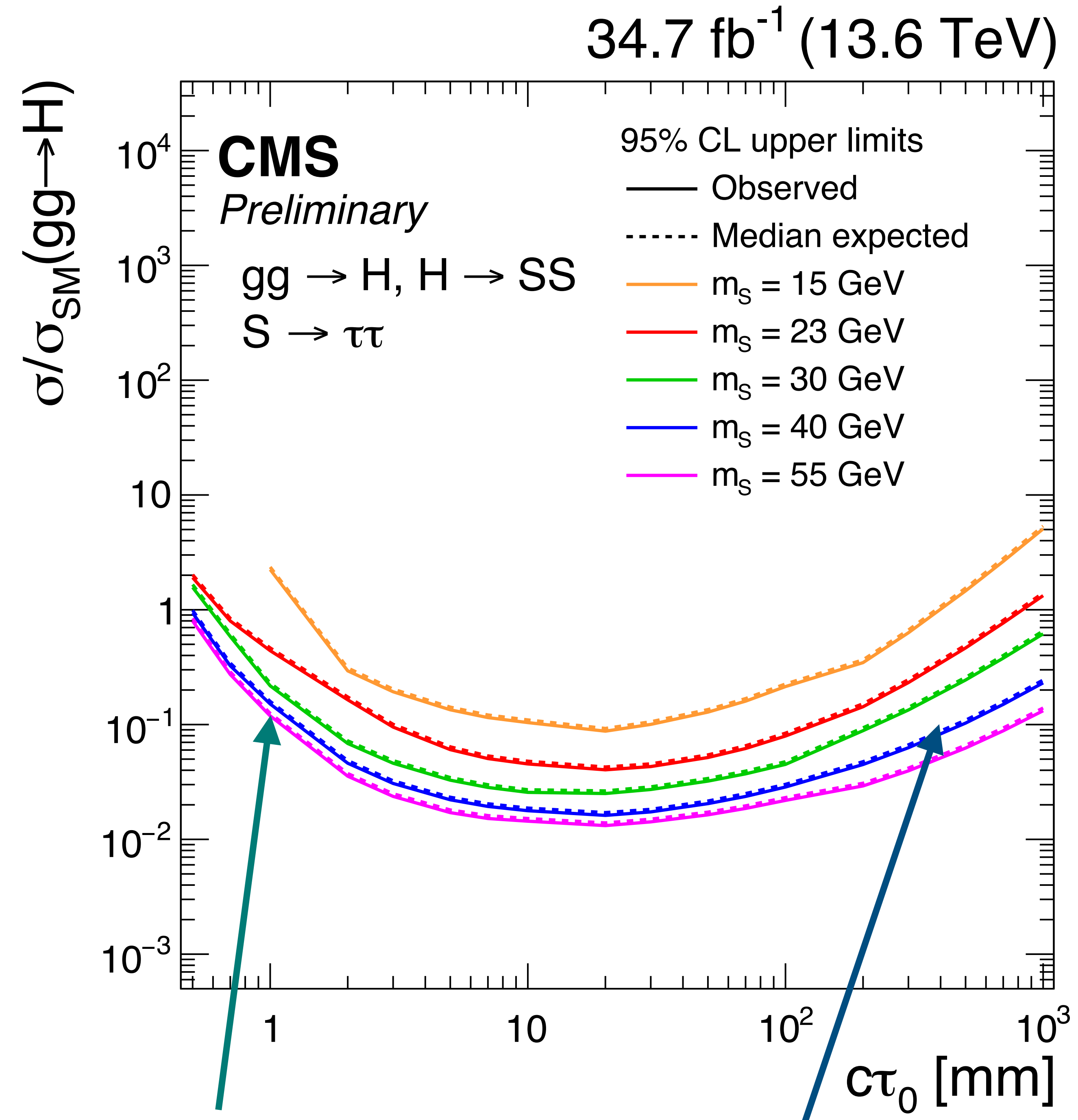




Significant improvement compared to other searches with a **much smaller integrated luminosity** analysed (34.7 fb^{-1})

- S -> $b\bar{b}$ (S -> $d\bar{d}$) **outperforms previous result by factor 10 (8)**

First-ever displaced hadronic tau results with decay lengths smaller than ≈ 1m



Weaker limit at low $c\tau_0$:

- No prompt tracks used to reconstruct DVs

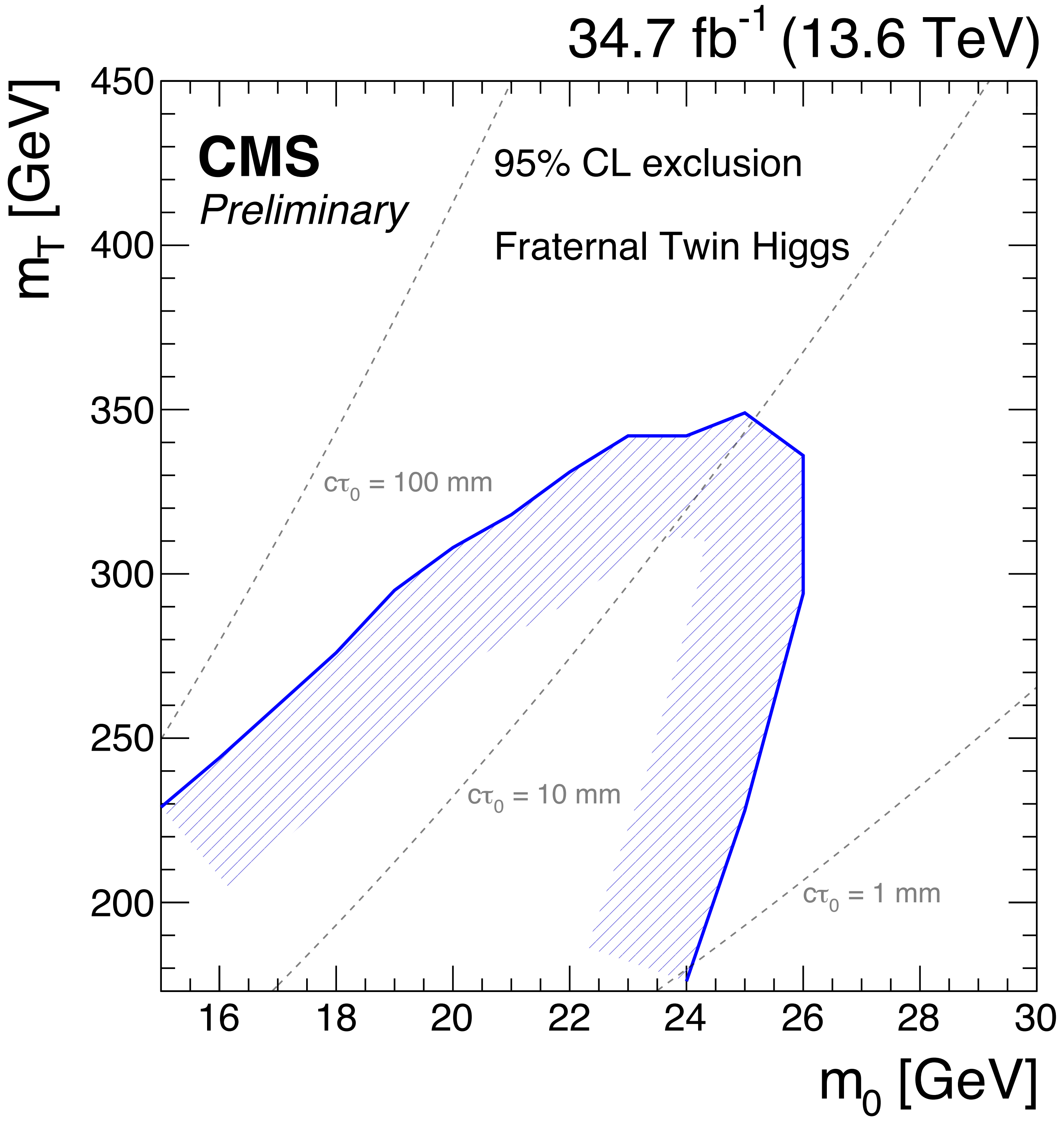
Weaker limit at high $c\tau_0$:

- Tracking efficiency decreases with increased displacement

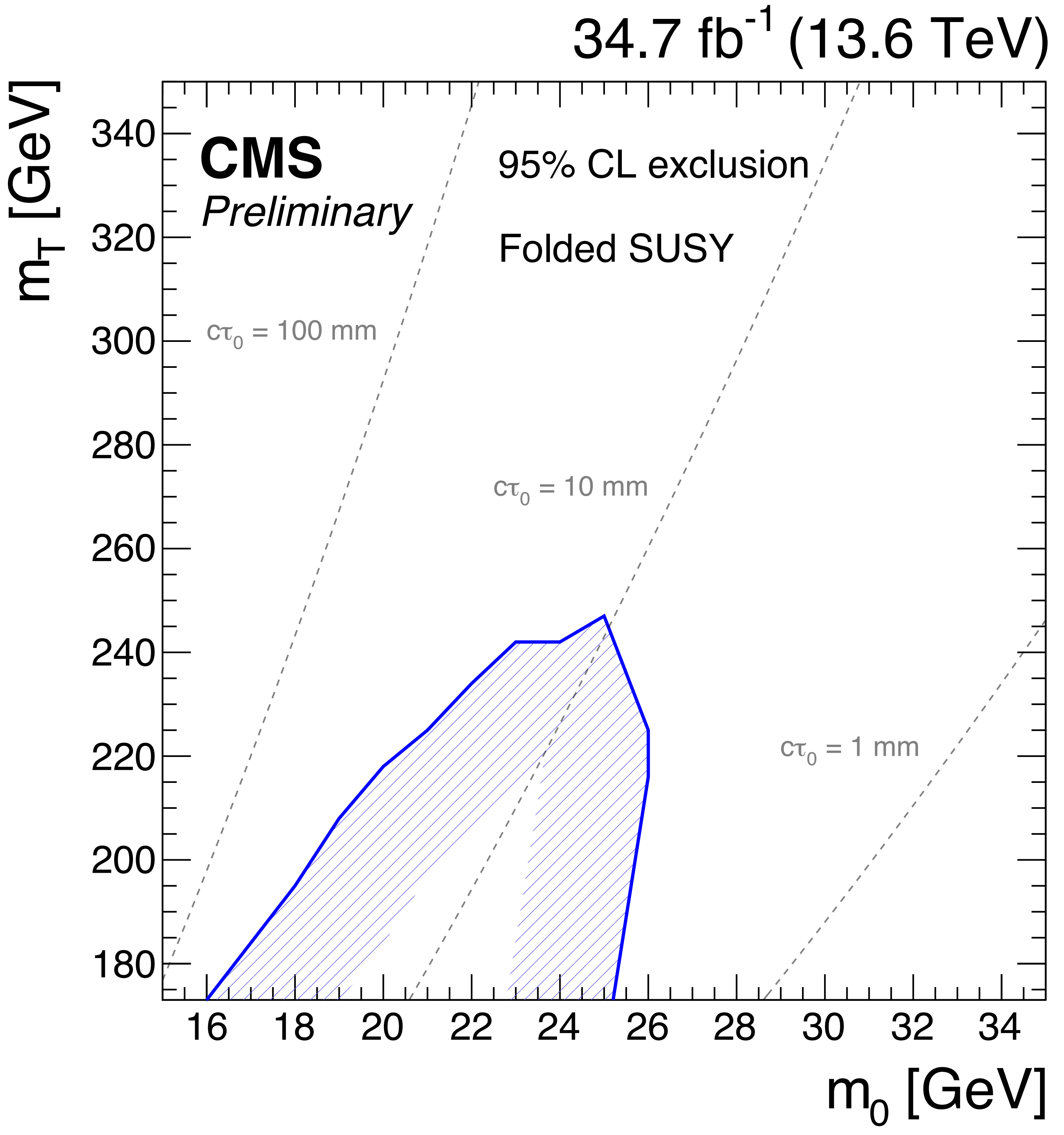
Interpreted with **two models in the neutral naturalness scenario**

Exclusions placed in the theory phase space : **first time from any experiment**

Fraternal Twin Higgs model



Folded SUSY model



- Expect a significant expansion of coverage with full Run-3
  - ➡Factor of 10 better results
- More new techniques will be developed to further improve sensitivity
- New applications to other LLP signatures can be pursued
- Will benefit significantly from the HL-LHC upgrades !

Scalar S interpreted as the lowest-mass glueball in the hidden sector

Exclusion placed in the plane of the glue ball mass and top partner mass of hidden sector

EXO-22-015

Search for emerging jets at 13 TeV *(full Run 2)*

February 2024

Search for emerging jets - Overview

Overview : Dark QCD search **Paper reference**

Emerging jet signature

- Coupling SM - dark sector via dark mediator X_{dark}
- Dark confinement energy at GeV scale
- Unstable dark pions (π_{dark}) decay to SM particles
- m_x, $m_{\pi_{dark}}$, $c\tau_{\pi_{dark}}$ free parameters scanned
  - m_x : [1, 2.5] TeV
  - $m_{\pi_{dark}}$: [6, 20] GeV
  - $c\tau_{\pi_{dark}}$: [1, 1000] mm

X_{dark} -> qQ_{dark} coupling allowed

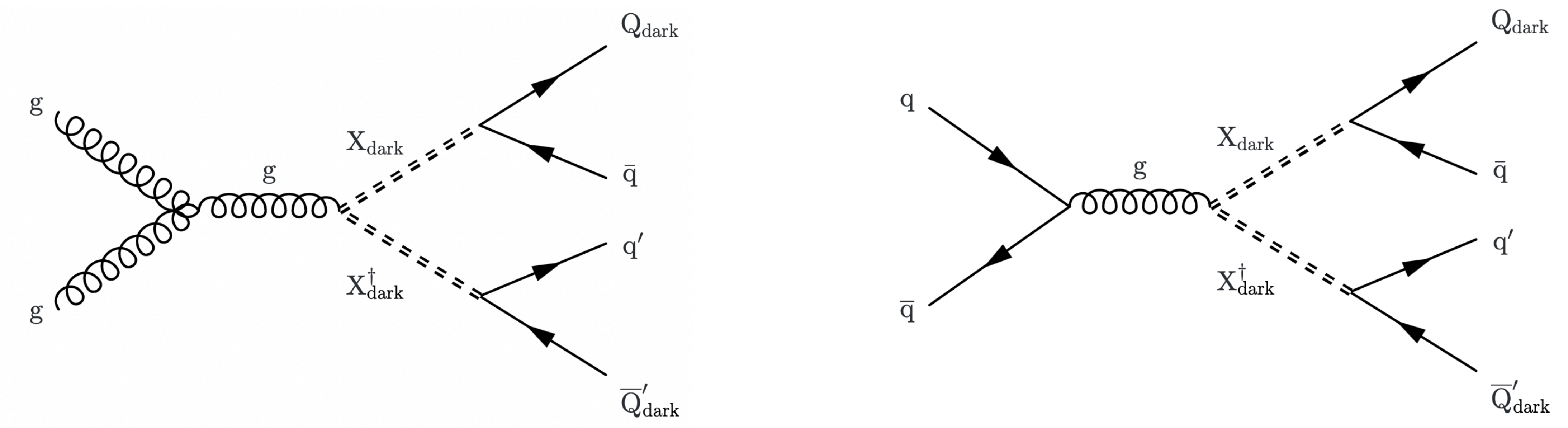
Unflavored scenario : Q_{dark} couples to **down quark ONLY**

Flavor-aligned scenario : Q_{dark} couples to **d/s/b quarks**

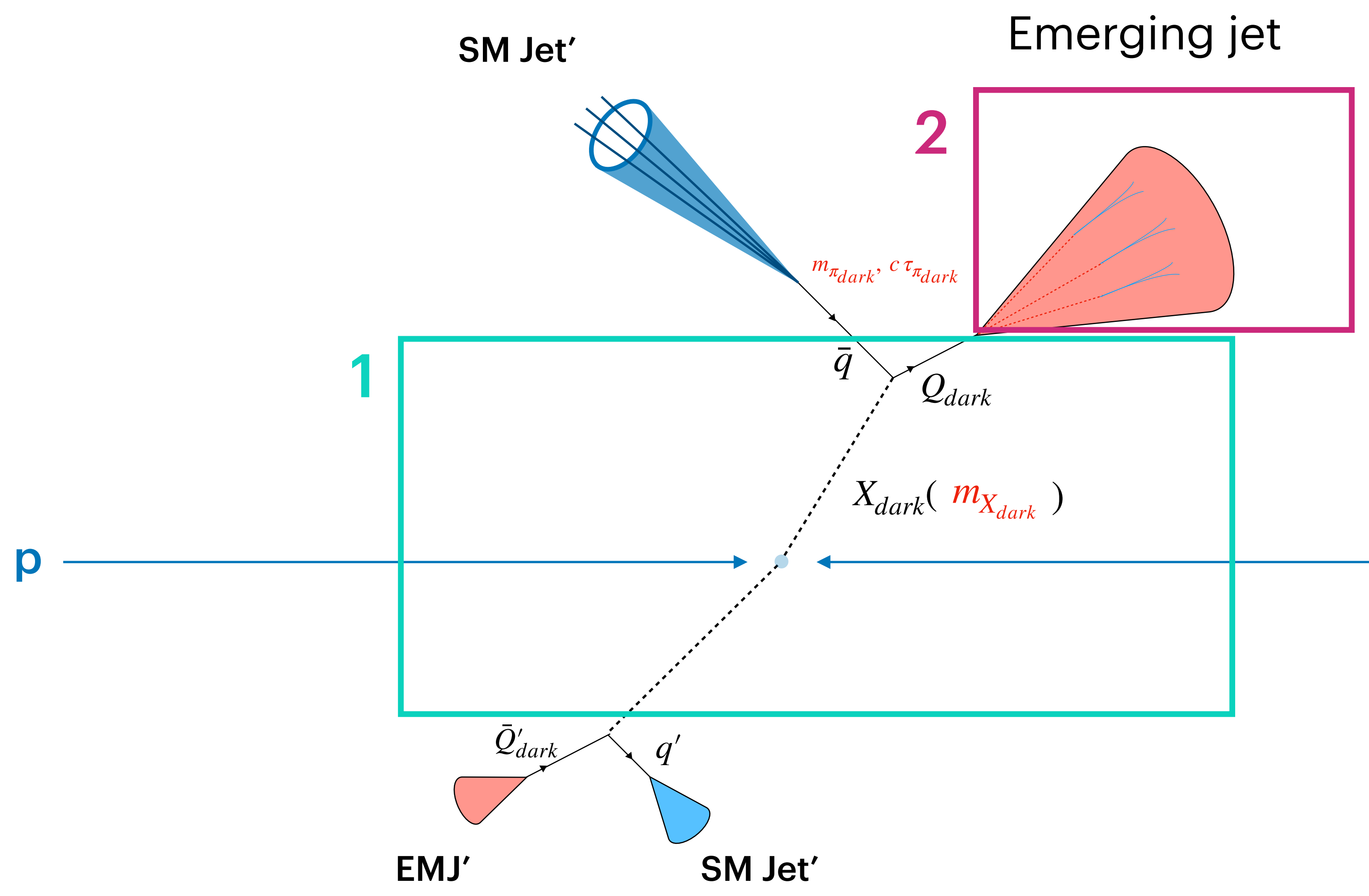
Emerging jet production

1) pp → 2 X_{dark} → 2 (qQ_{dark})

2 X_{dark} production modes :
gg fusion / $\bar{q}q$ annihilation



2) Qdark $\xrightarrow{\text{hadronizes}}$ $N\ \pi_{dark}$ $\xrightarrow{\text{Travel } c\tau}$ SM particles



Primary signature :
- High H_T
- 4 high pT jets (2 EMJ, 2 SM jets)

Search for emerging jets - Categories & S/B modelling

Event selection

- **H_T, p_T of 4 leading jets, ≥ 2 EMJ-tagged jets criteria**

  Model-agnostic EMJ tagging :
  - Jet-level variables cuts to select EMJ, less sensitive to parameter space chosen for study

  GNN EMJ tagging :
  - Based on ParticleNet, 2 GNN trained : unflavored / flavor-aligned scenarios

Background estimation

- **Fully data-driven estimation**

  CR : JetHT trigger, $N_{EMJ}^{tagged} = 1$

  SR : JetHT trigger, $N_{EMJ}^{tagged} \geq 2$

  FR : γ-triggered

- Use events in **CR** with mistag rates (ϵ) from **FR** to estimate # of bkg events in **SR**

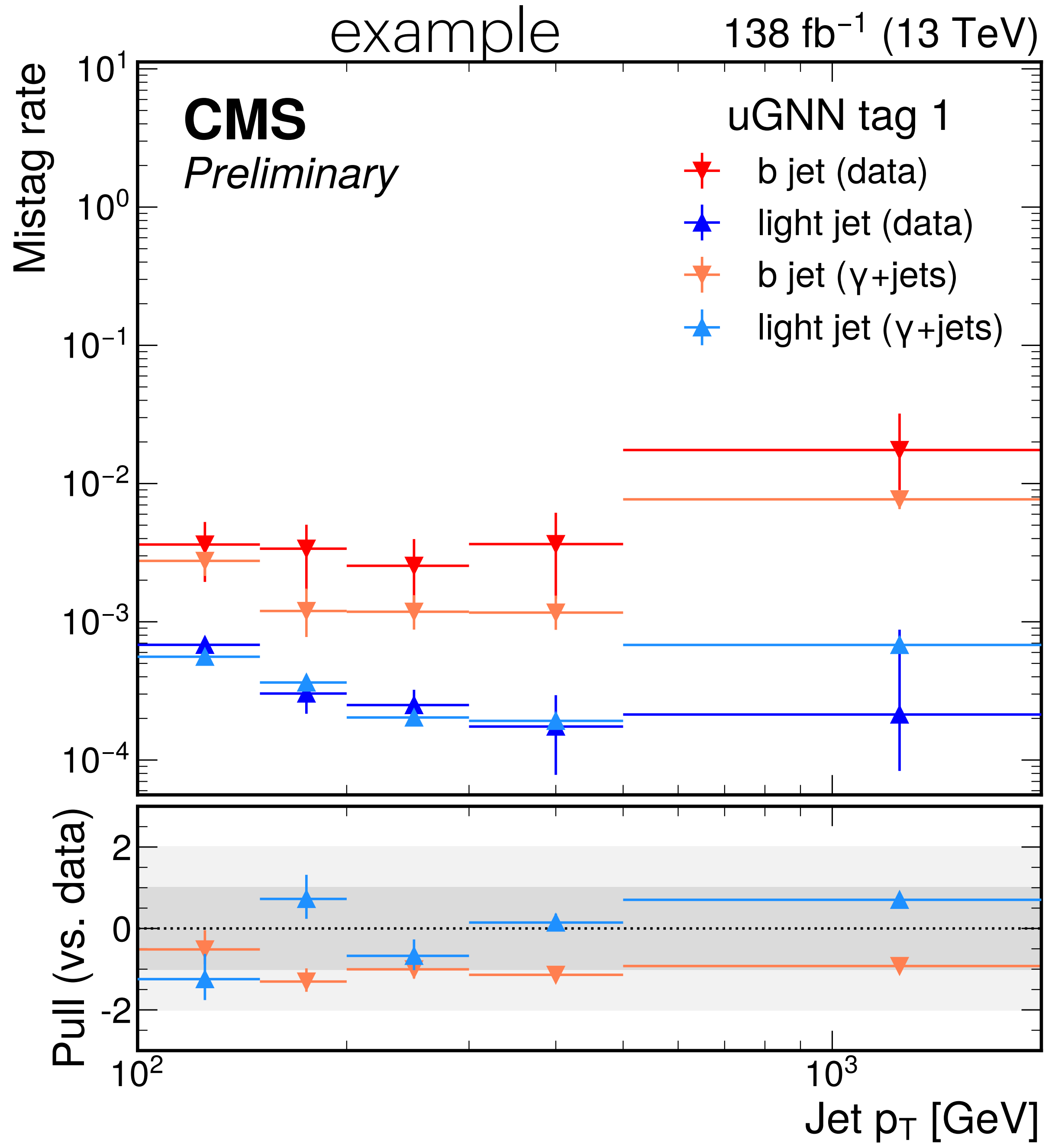
Mistag rate calculations

Use **signal free** γ-triggered data for mistags

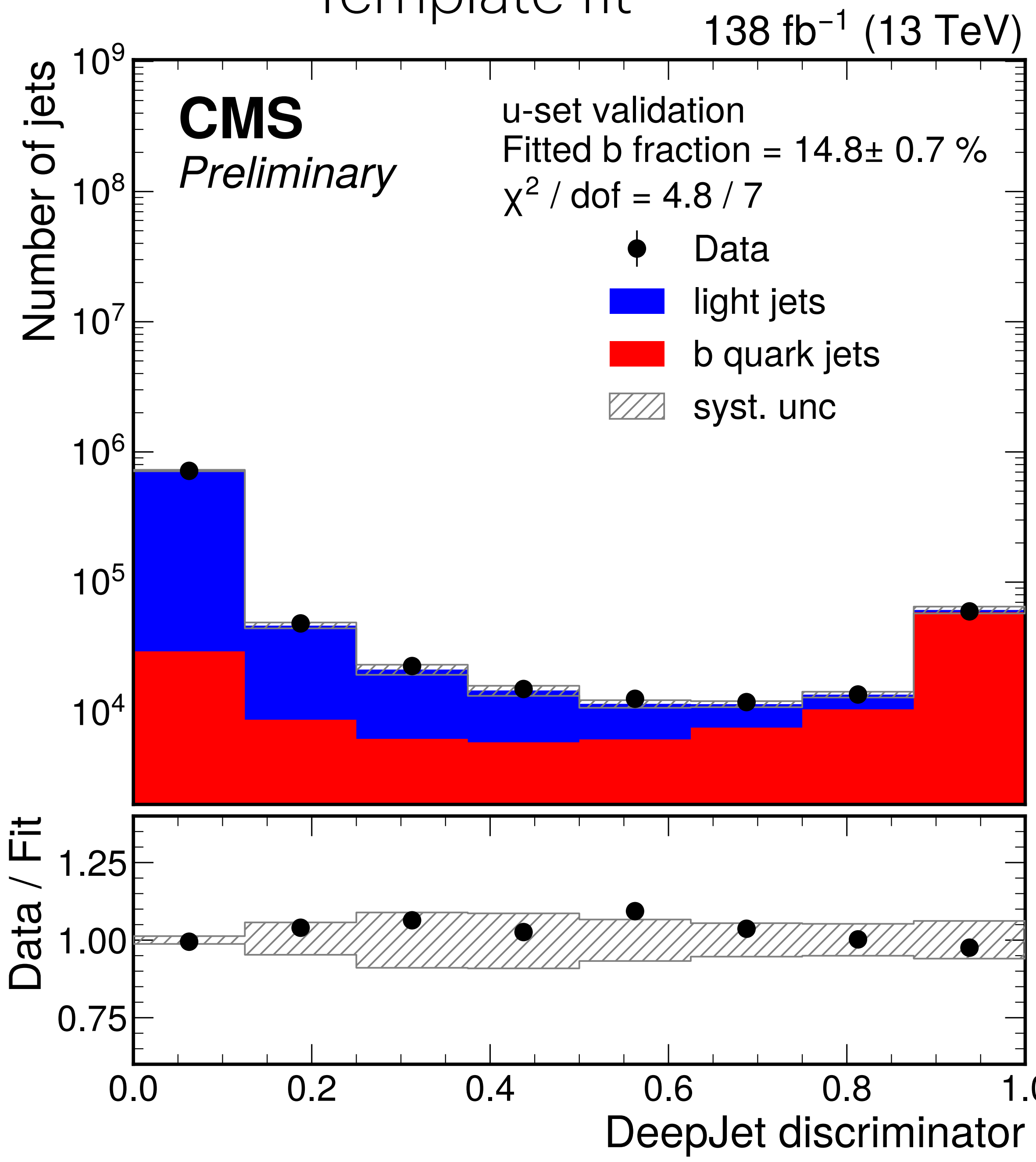
- Same jet kinematics as SR, γ p_T > 200 GeV
- Mistag and b-jet fraction B^{CR} from "b-enhanced/suppressed" (FR_E/FR_S) regions

$$N_{SR} \approx \sum_{evt \in CR} \frac{1}{2} \sum_{j \notin tagged} B^{CR} \epsilon(b, p_{T,j}) + (1 - B^{CR}) \epsilon(l, p_{T,j})$$

GNN tagger mistag example



Template fit



Search for emerging jets - Results

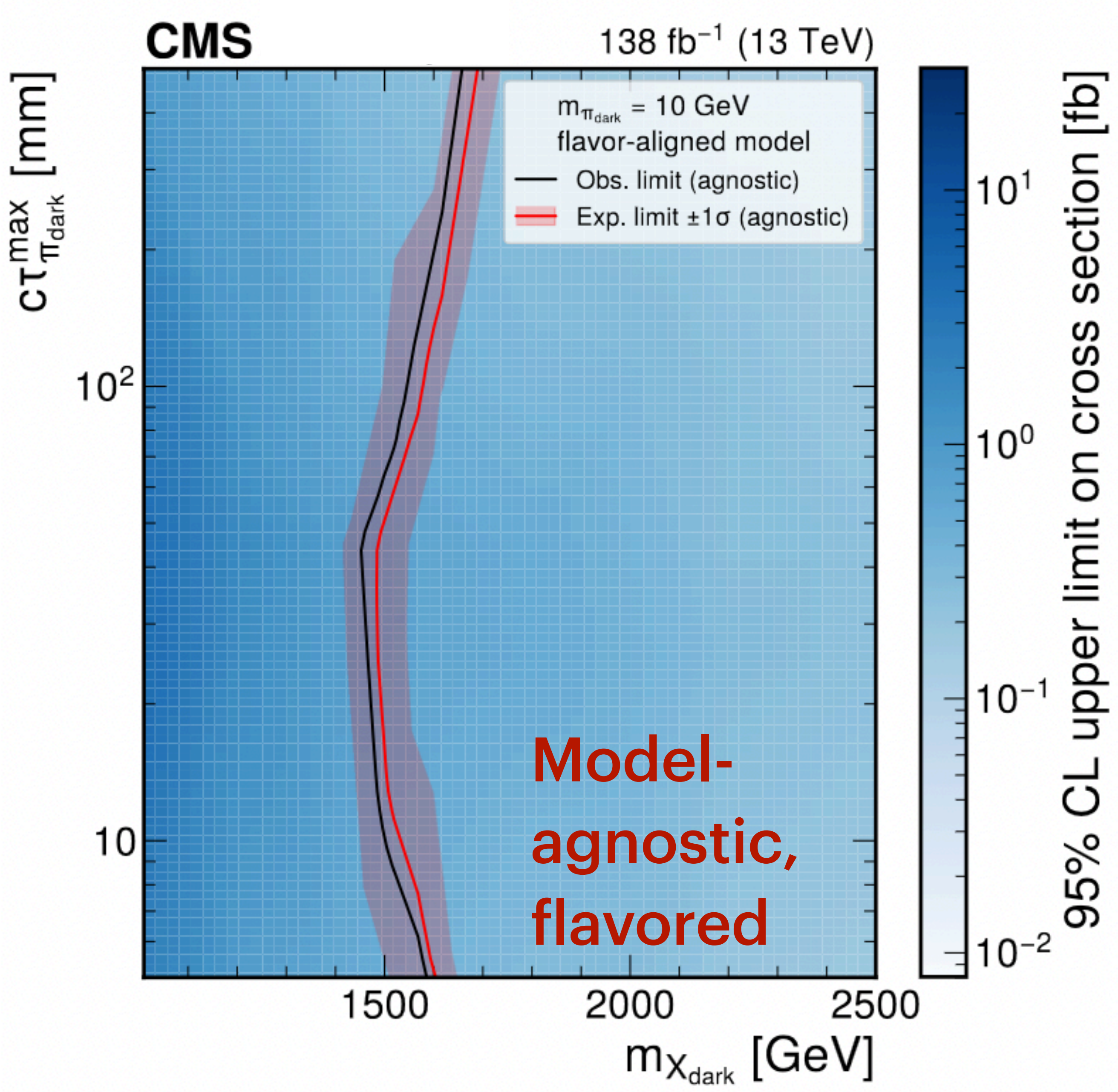
No significant excess observed

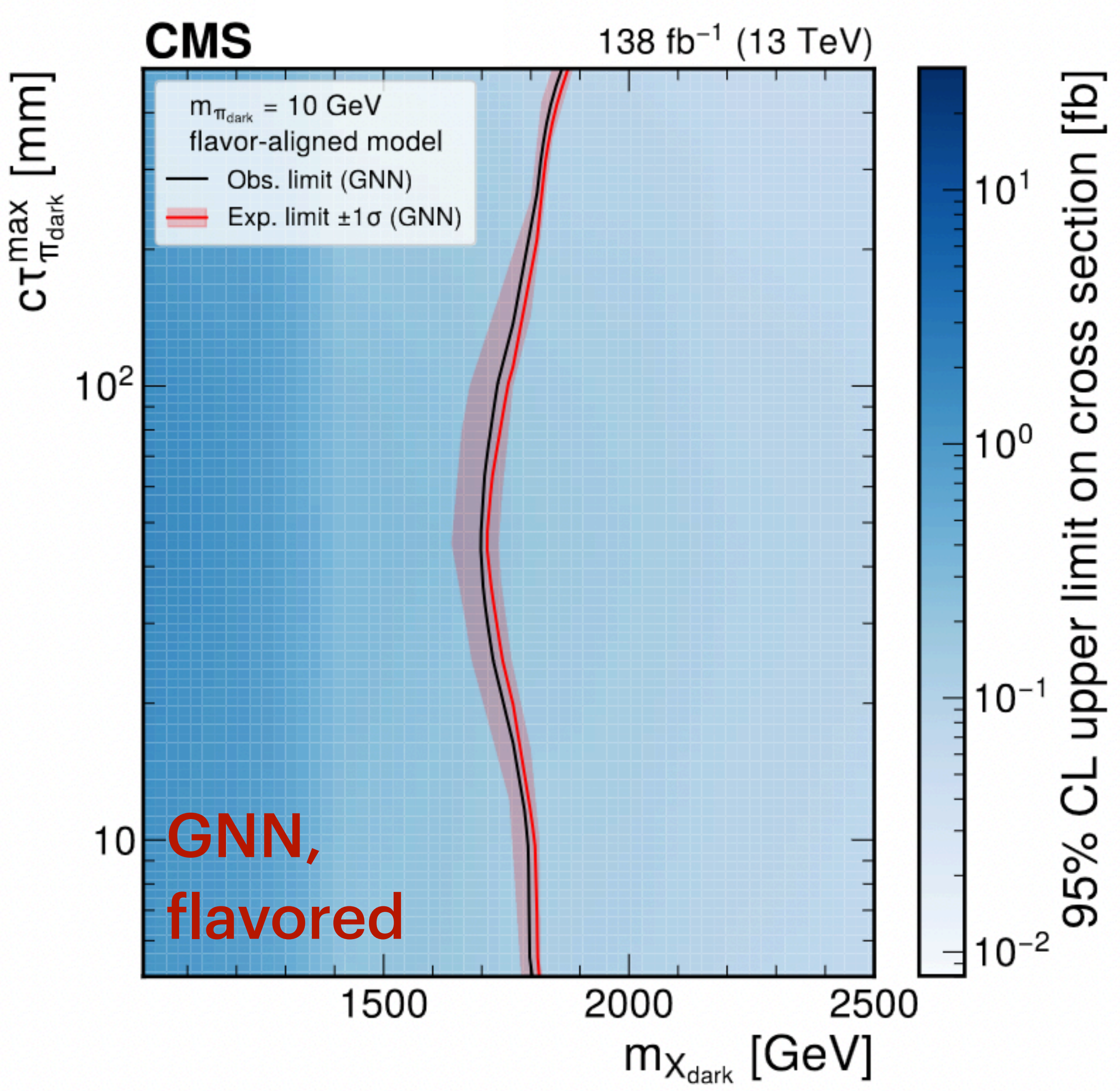
Upper limits set on each EMJ model using the CLs criterion :

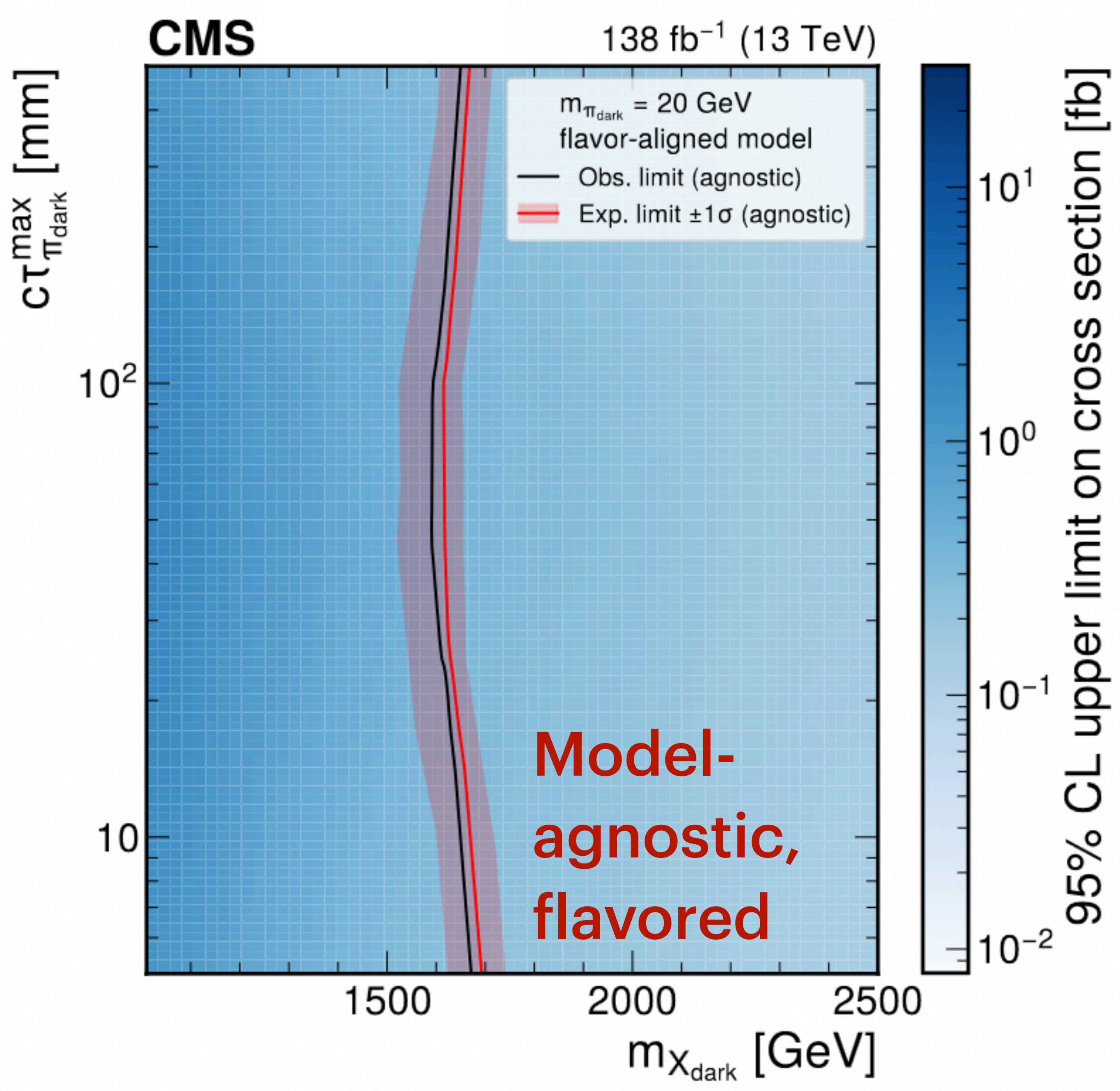
- Exclude $m_{X_{dark}}$ up to **1850 GeV** for **flavored-aligned models** for $m_{\pi_{dark}}$ ~ 10 GeV

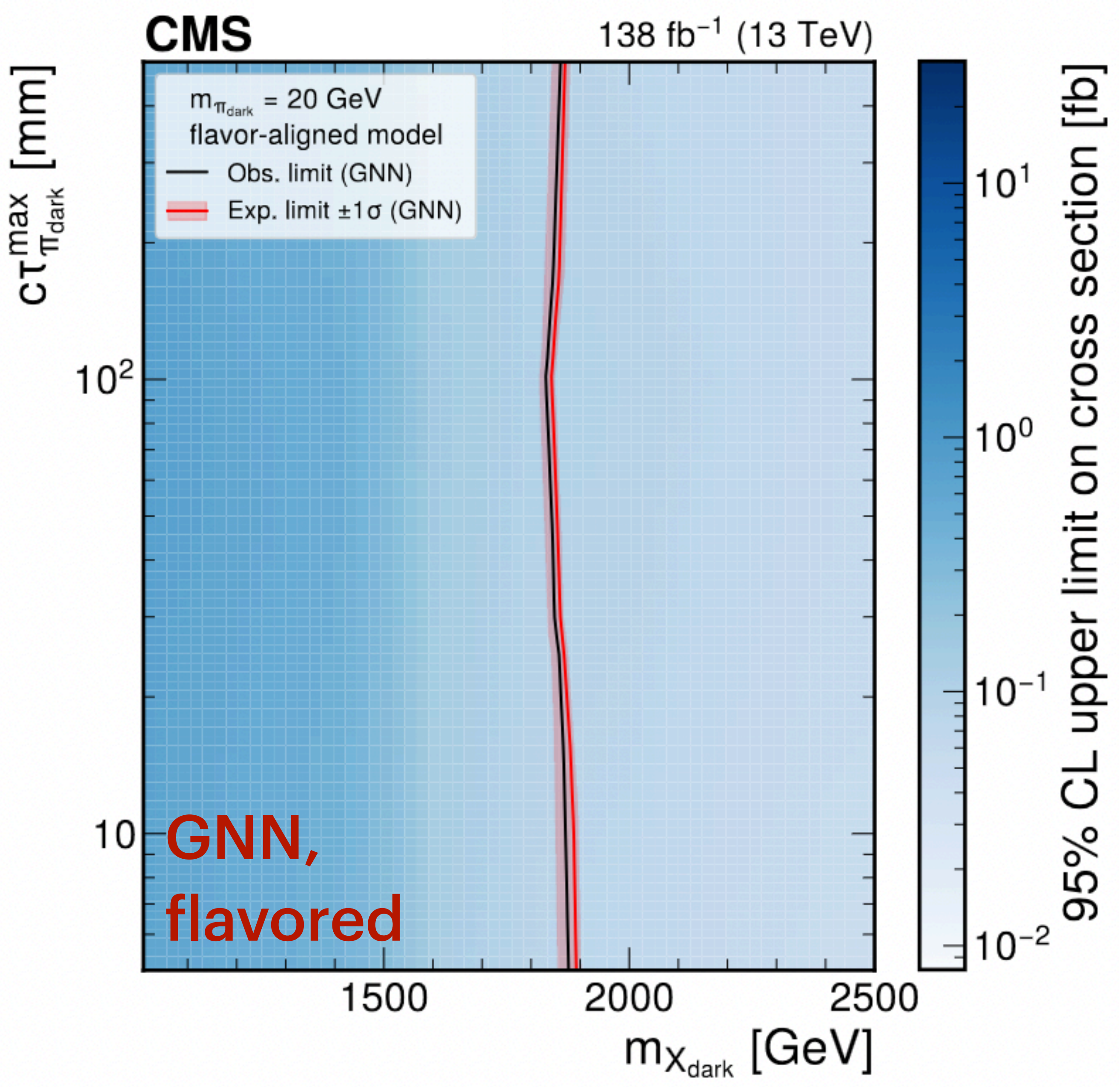
Better limits with GNN than model-generic method, **especially at low lifetimes** :

- GNN better distinguishes more prompt-like EMJ from background





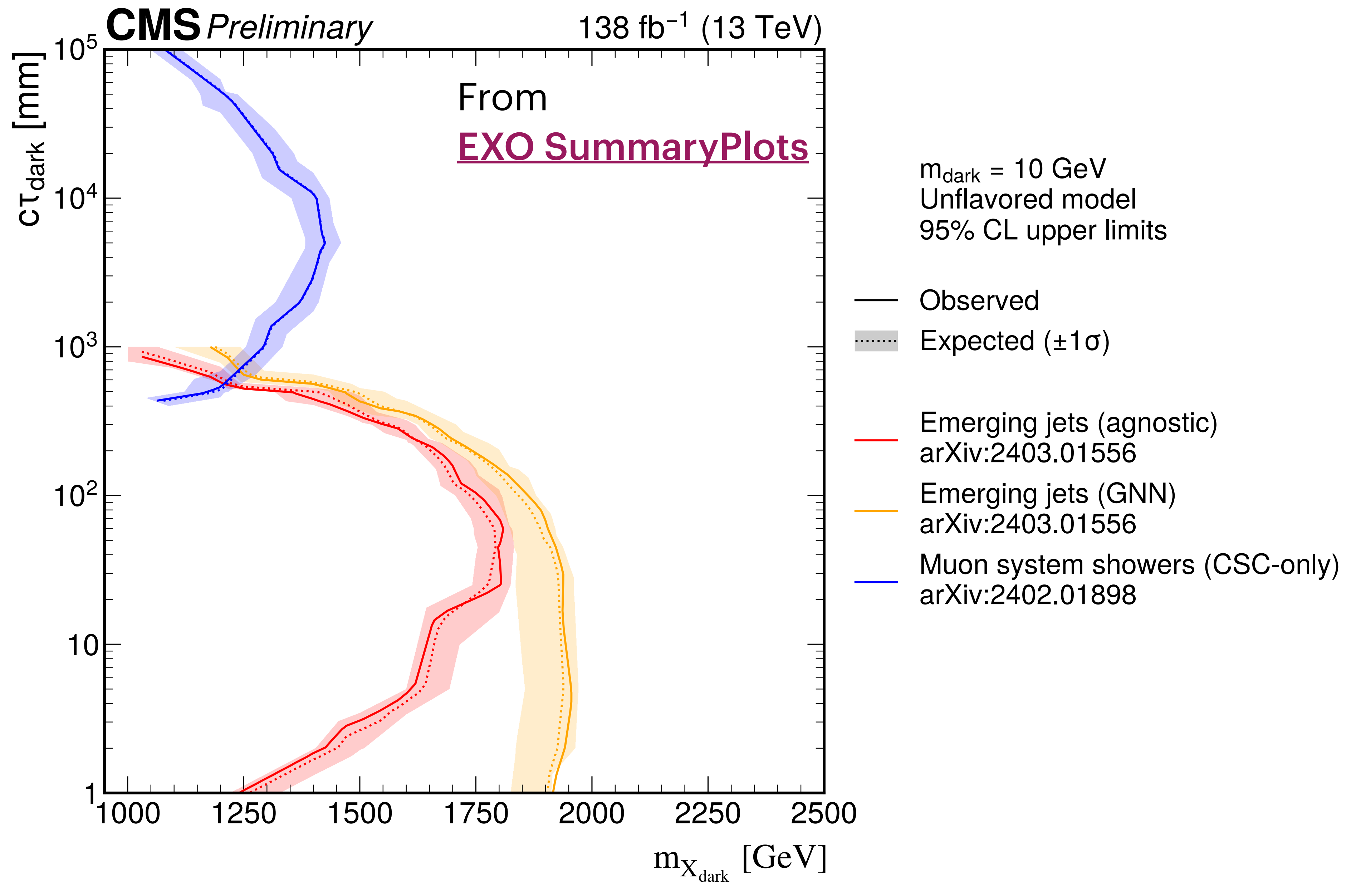


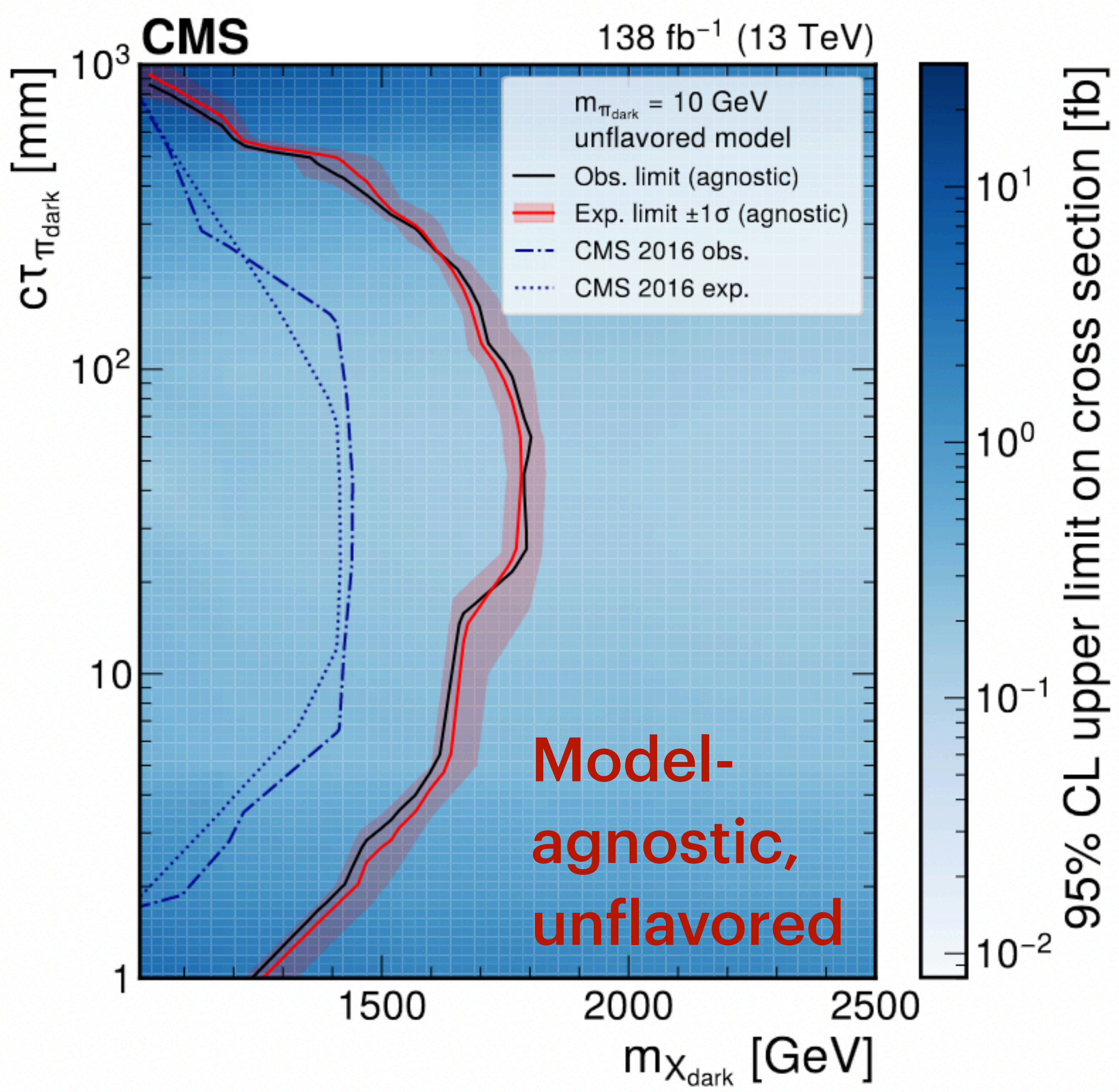


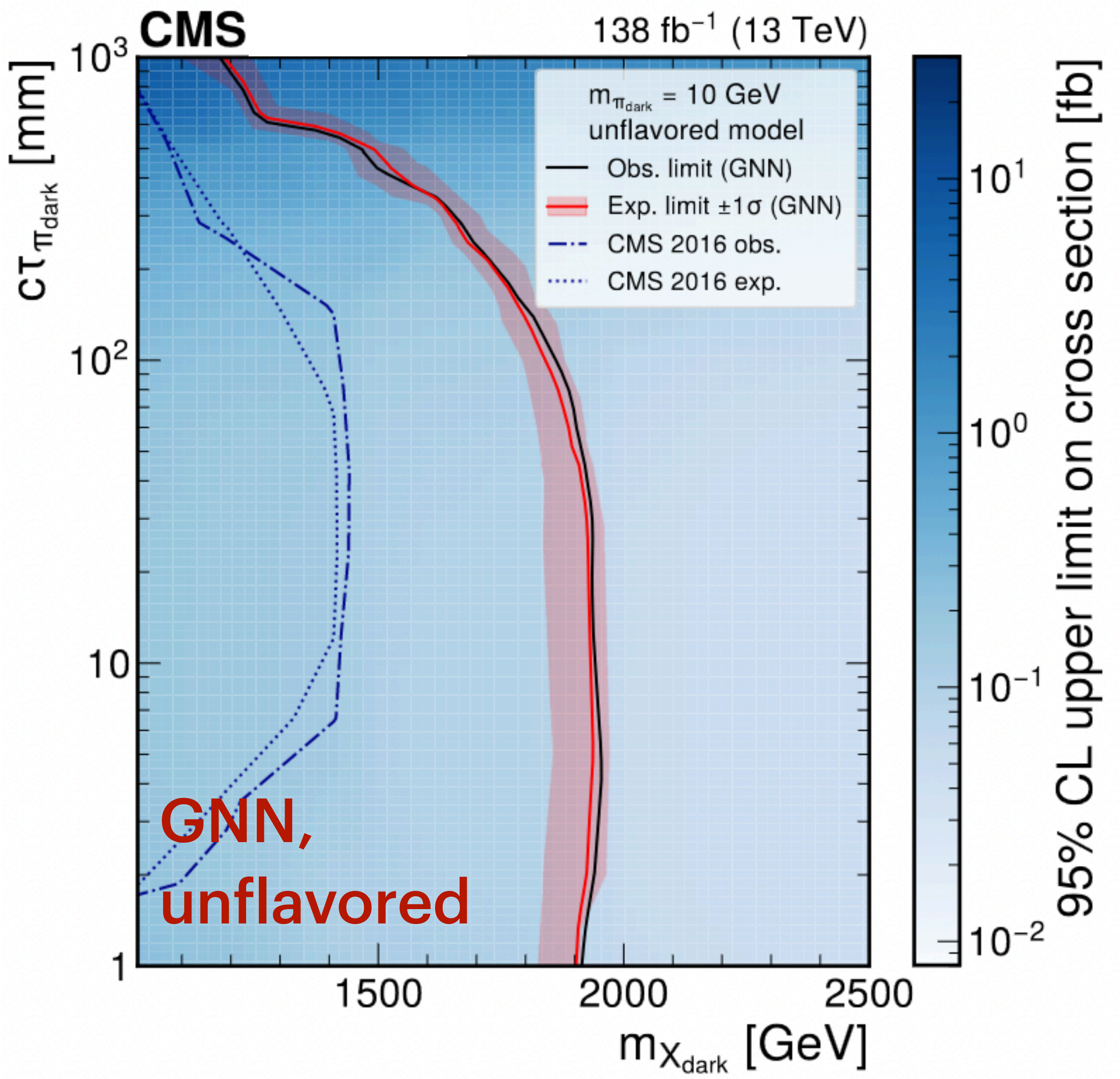
Search for emerging jets - Results

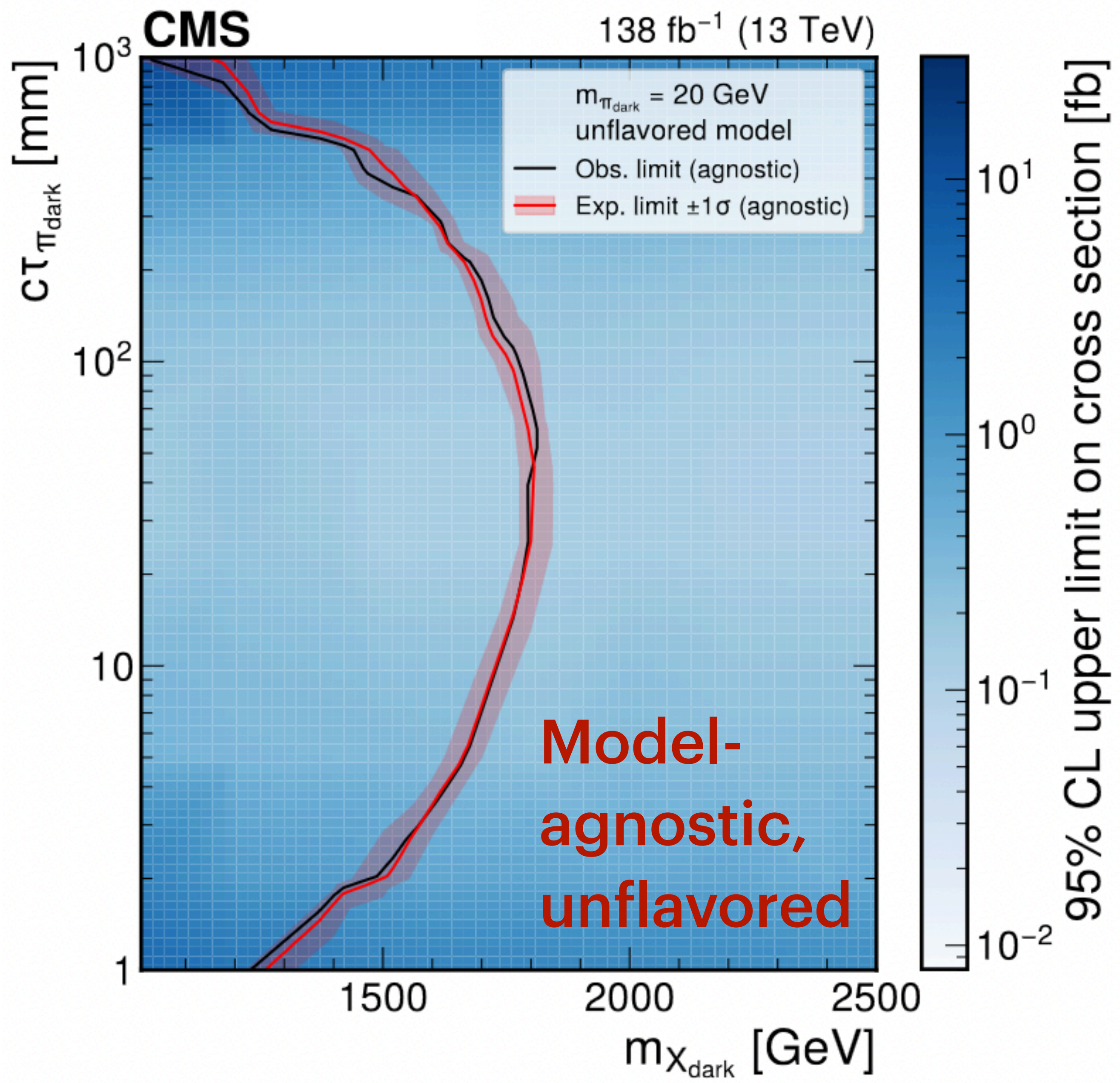
- Exclude $m_{X_{dark}}$ up to **1950 GeV** for **unflavored models** for $m_{\pi_{dark}}$ ~ 10 GeV

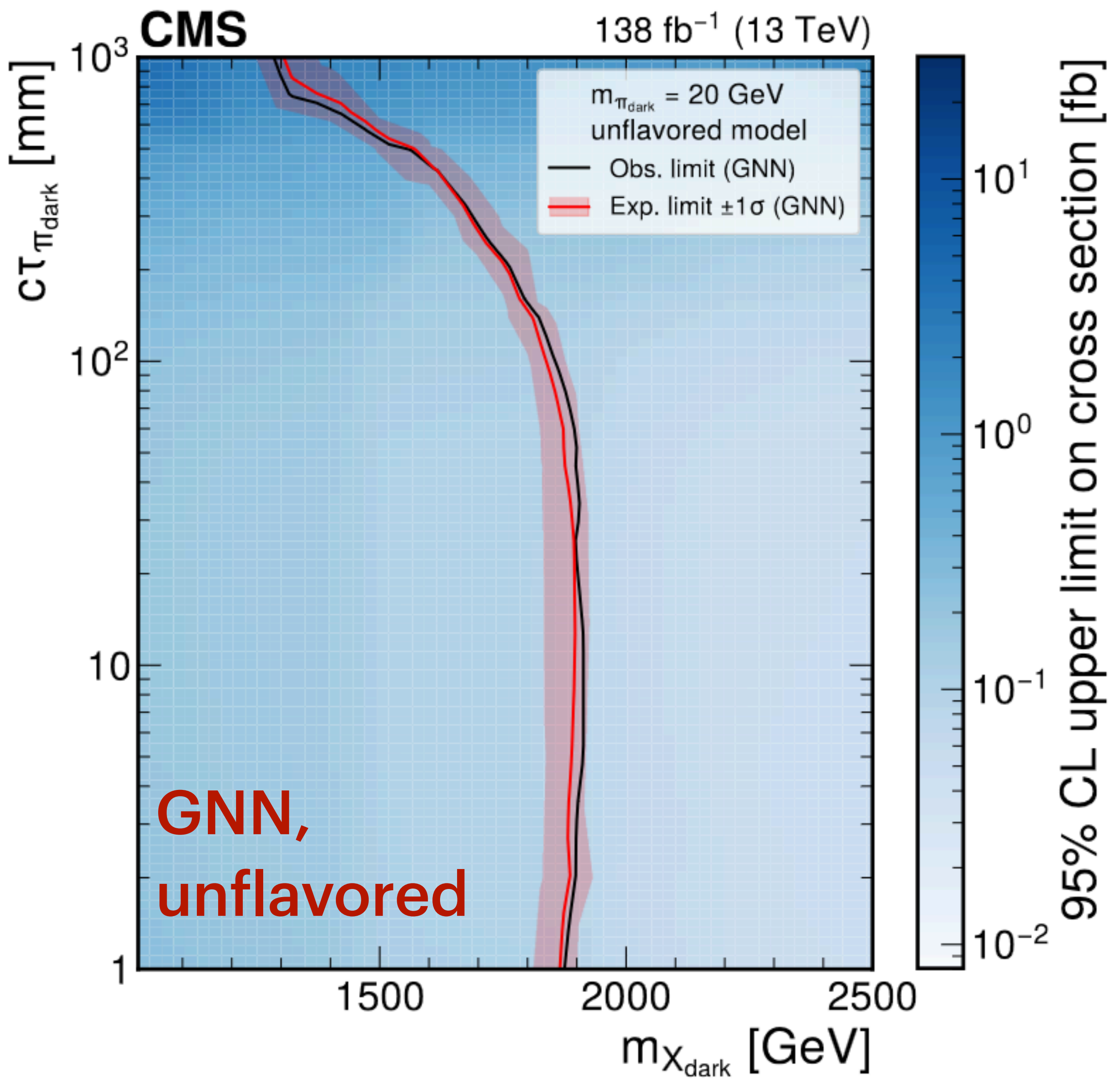
Extended $c\tau_{\pi_{dark}}$ coverage using muon system











EXO-18-002

Search for heavy stable charged particles (HSCP) at 13 TeV *(2017+2018 data from Run 2)*

March 2024

Overview

PAS reference

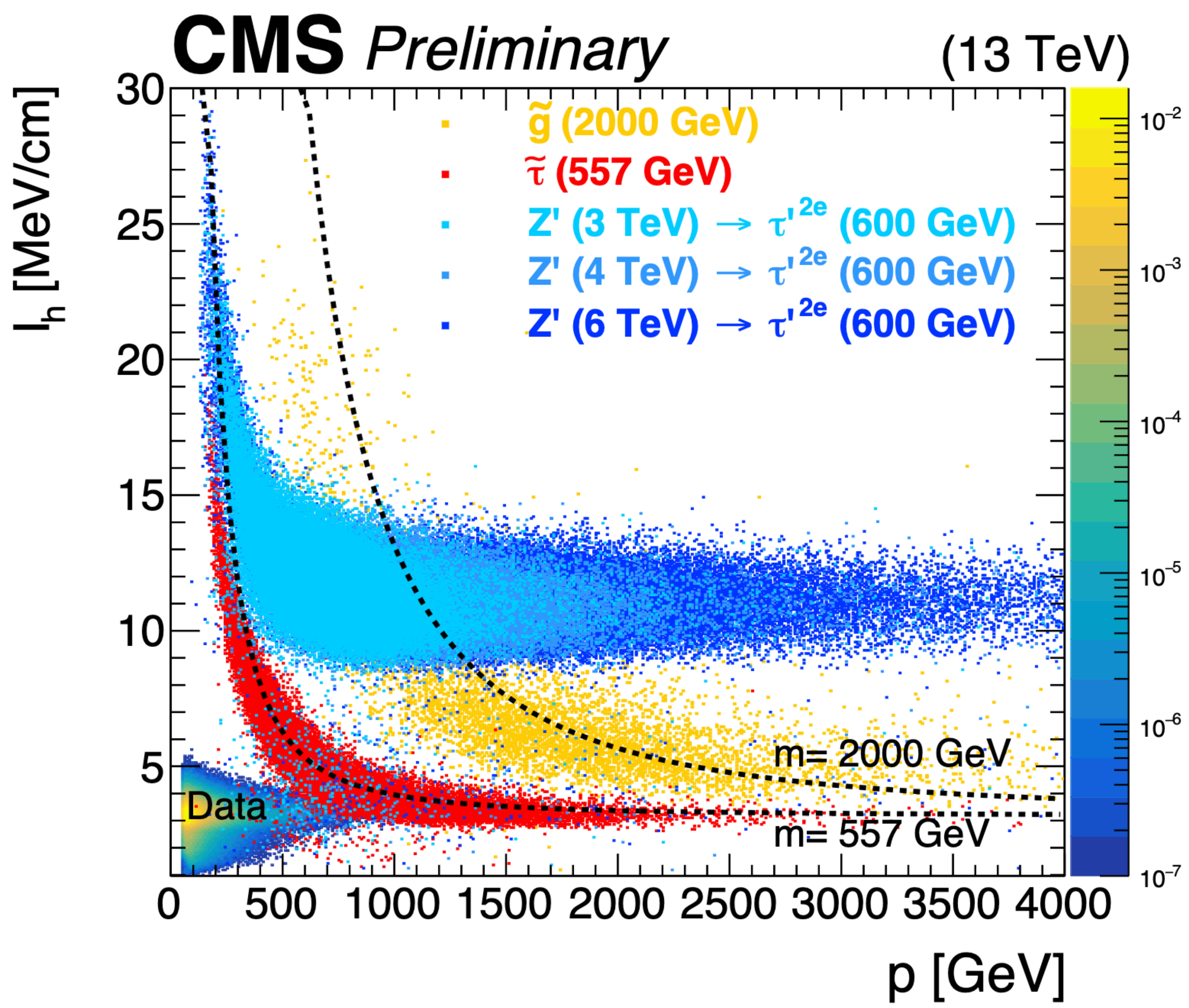
Several BSM models

GMSB, split-SUSY, fourth-generation lepton

- Lepton-like HSCP : $\tilde{\tau}, \tau^{'(1e)}, \tau^{'(2e)}$ [New Z' model !]
- Strongly interacting HSCP : R-hadrons from $\tilde{g}$ or $\tilde{t}$

Experimental signature

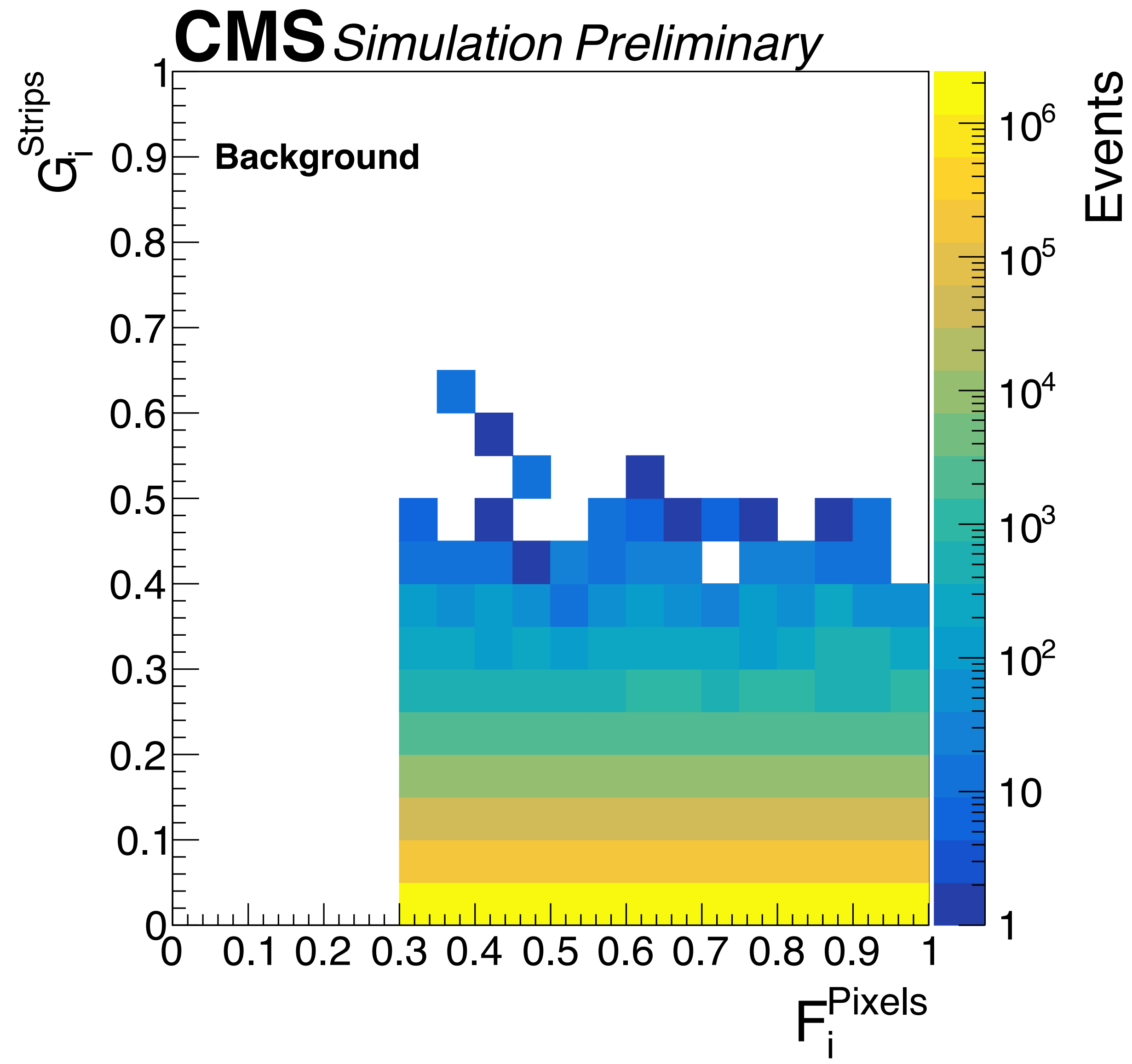
- **Isolated track of high p_T (> 55 GeV)**, with **large dE/dx** in the tracker barrel

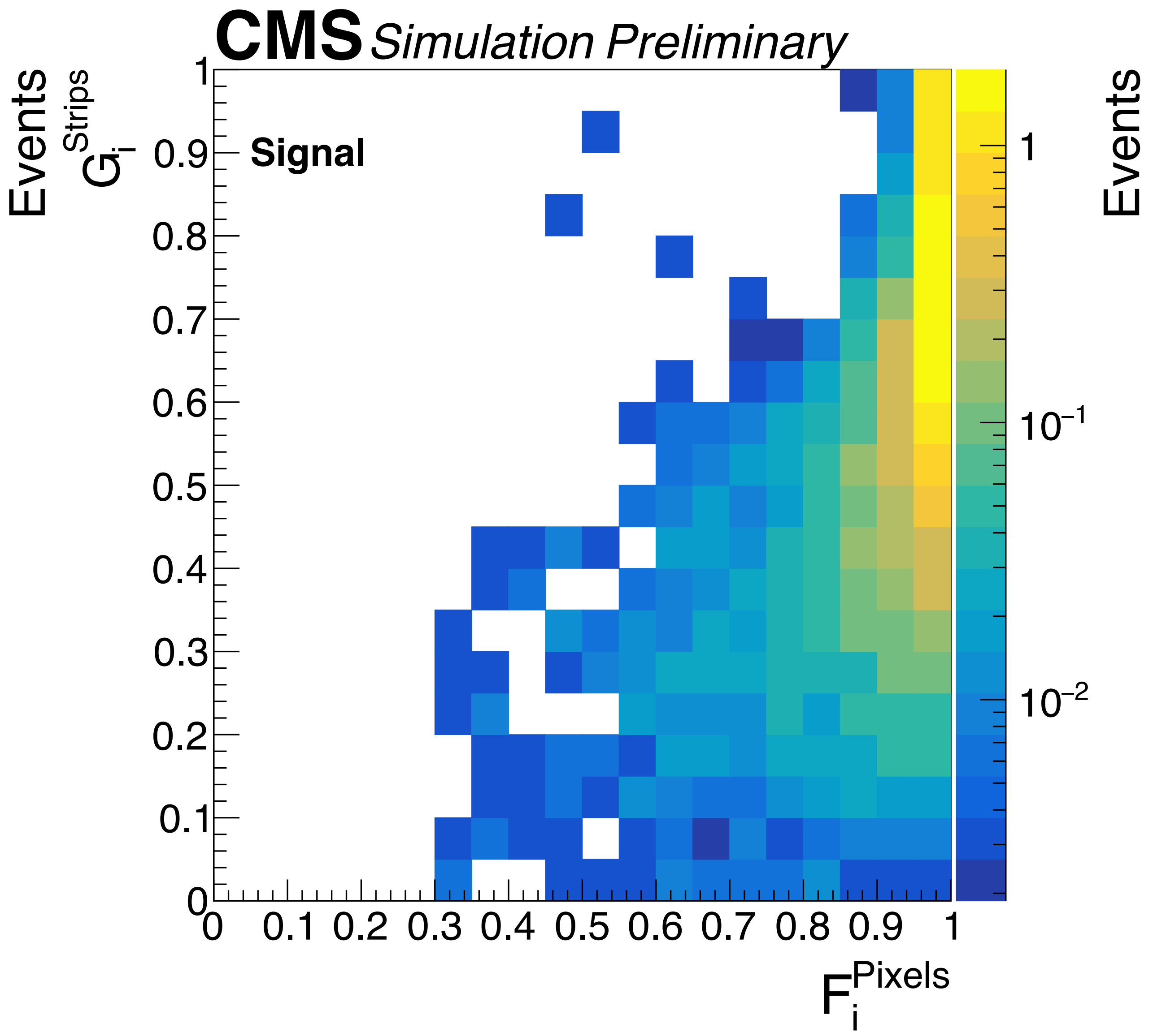


Target **highly ionizing** signals

Three ionisation variables

- dE/dx **estimator** I_h (strips)
  - Parametrise the Bethe-Bloch formula
- dE/dx **discriminator** F_i^{pixels} (pixels)
- dE/dx **discriminator** G_i^{strips} (strips)





- **HLT Muon trigger** with p_T > 50 GeV

Search for HSCP - Categories & S/B modelling

Two different methods, both background estimation are fully data-driven

- Validations performed in data

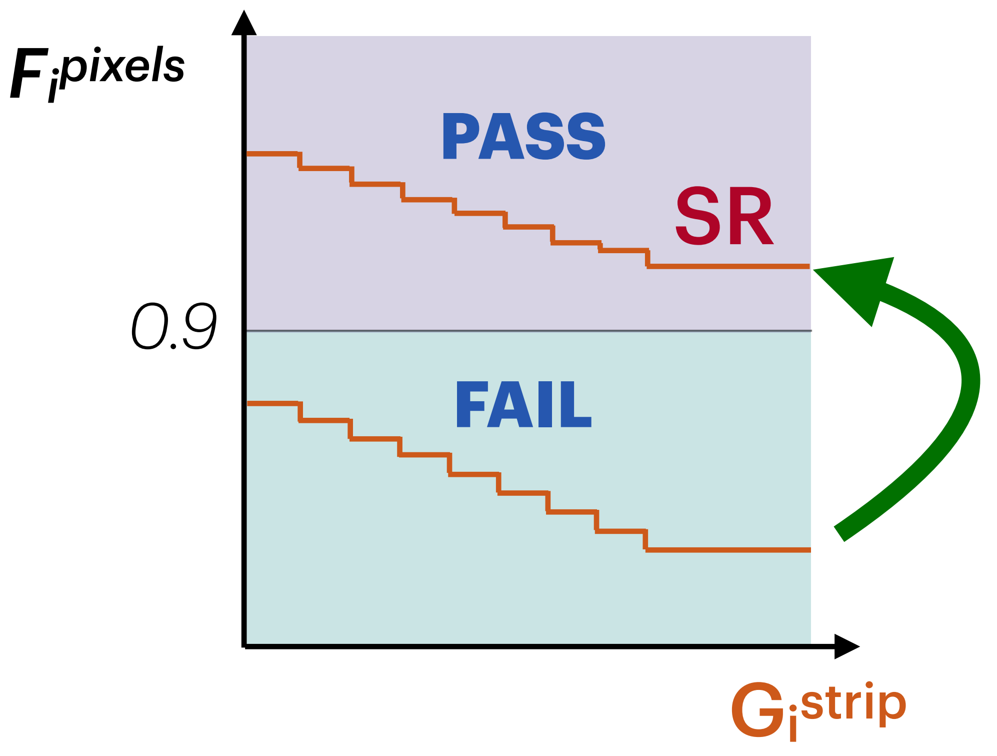
Single search region for all hypothesis in ionisation method :

Expected : 0.4 | Observed : 1

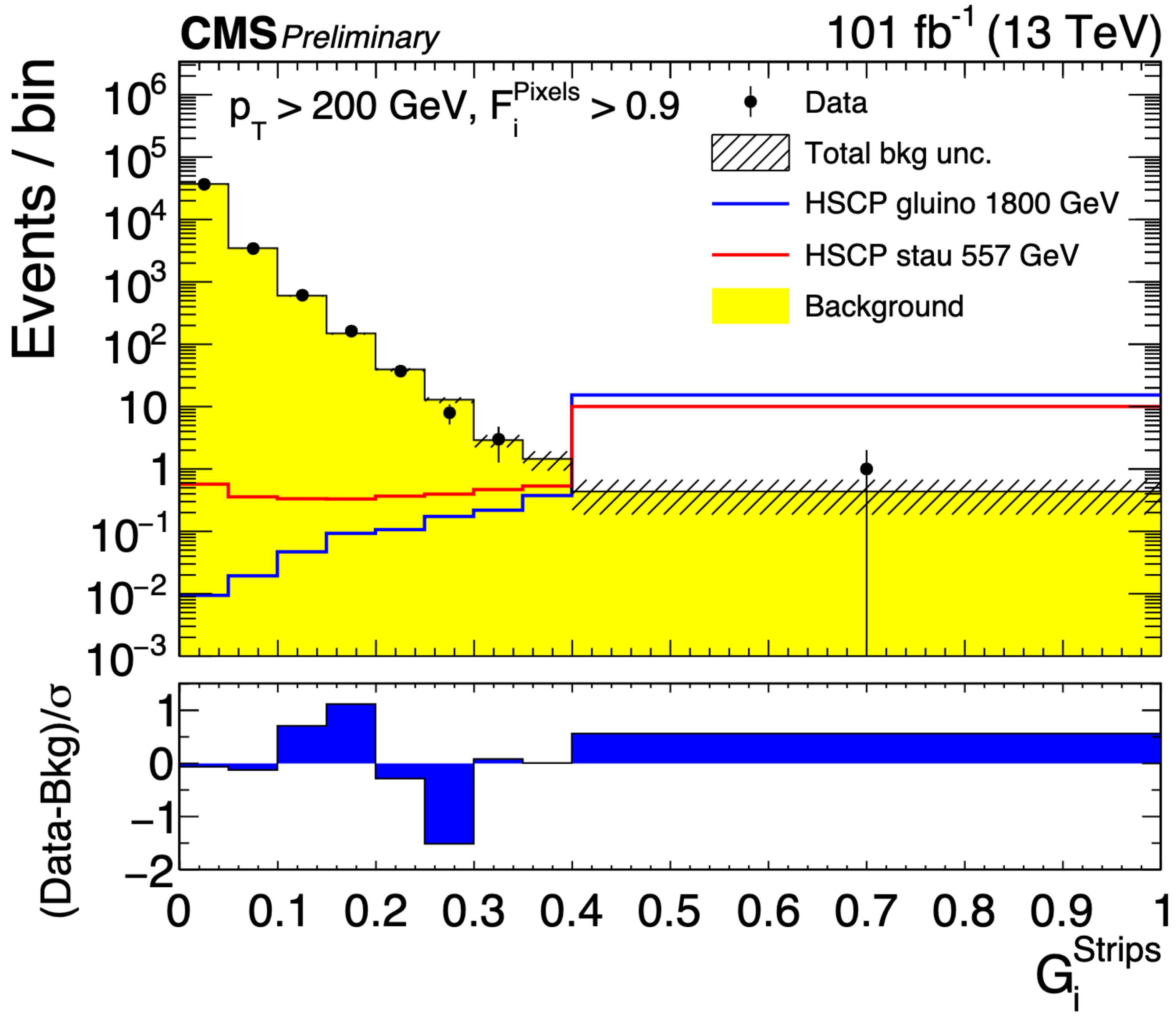
No significant excess observed in data in both methods

Ionisation method : Shape analysis

Predict shape of G_i^{strip} in SR : **transfer function**

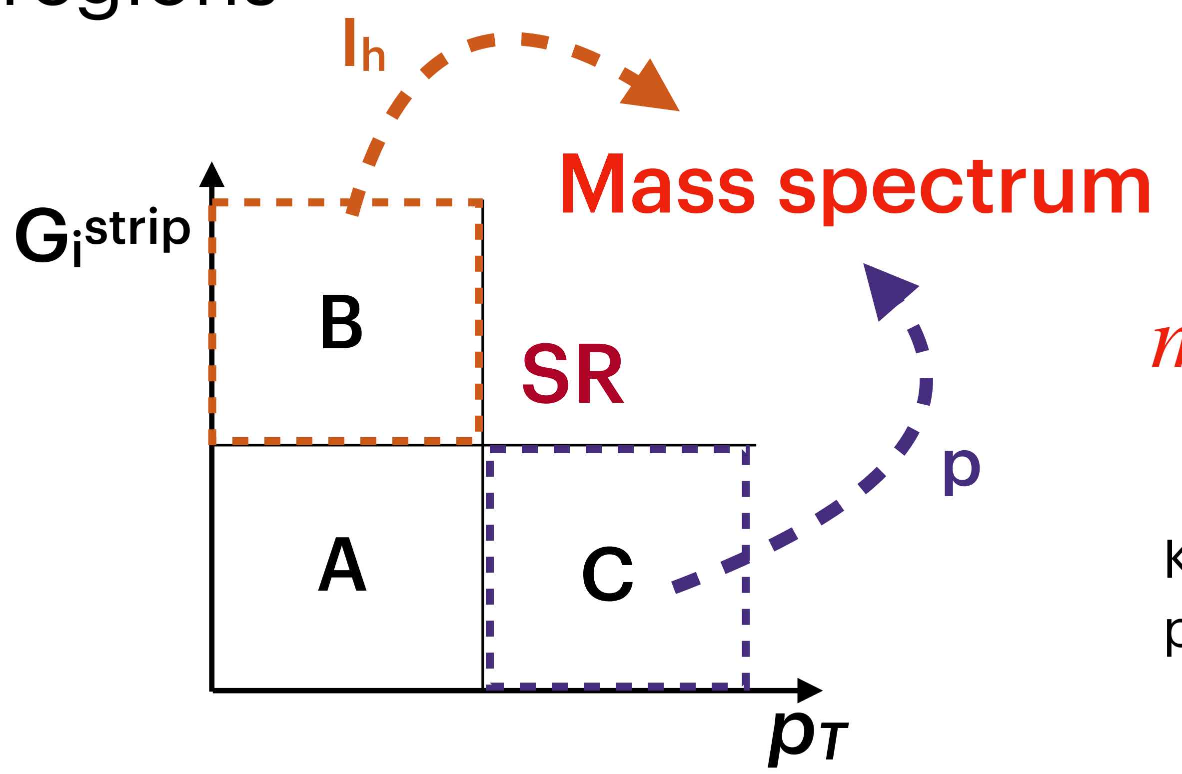


SR : $F_i^{pixels} > 0.9$, $p_T > 200$ GeV



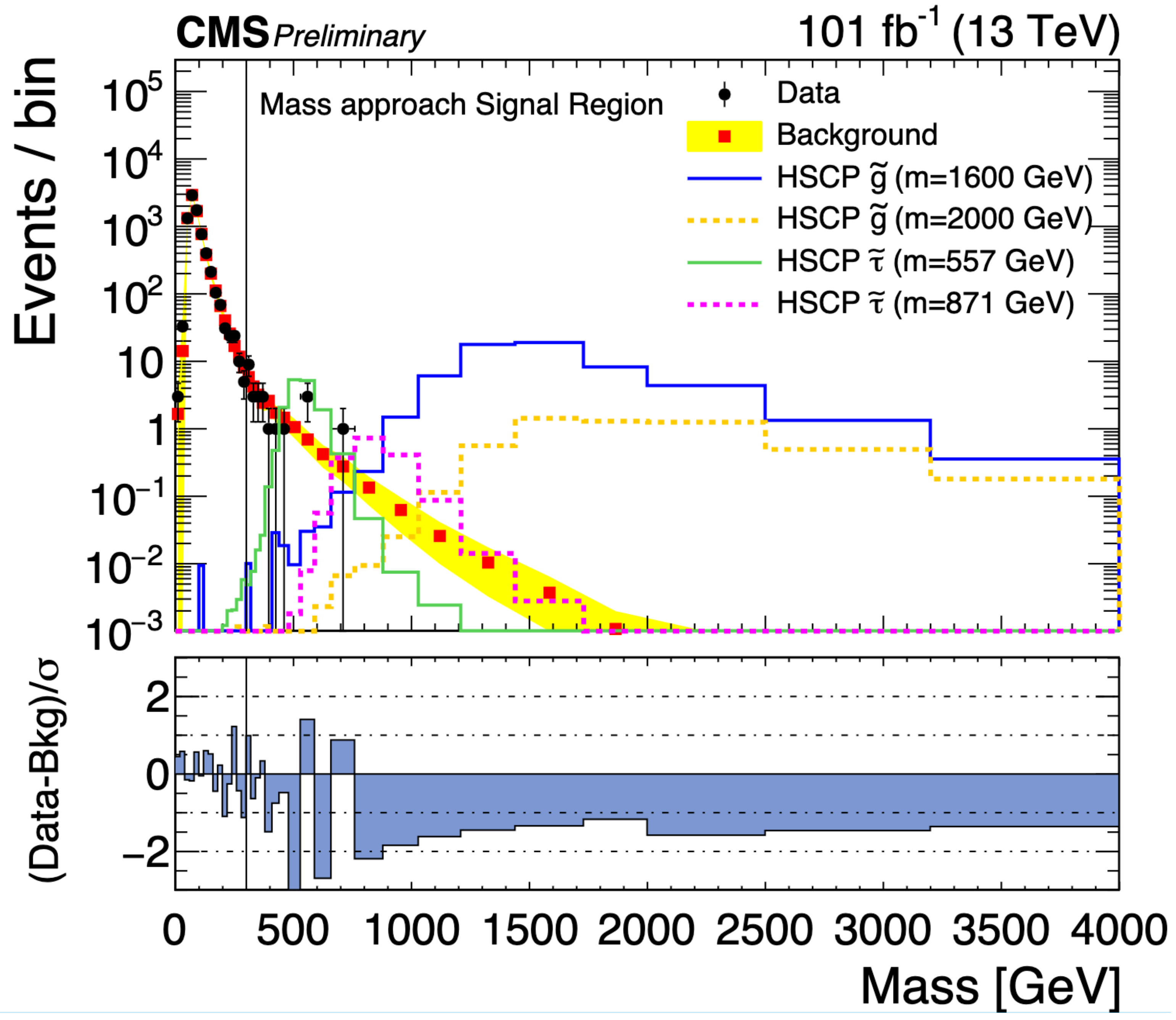
Mass method : cut & count

Predict **mass shape** with templates from control regions



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

K & C from Bethe-Bloch parametrisation on data

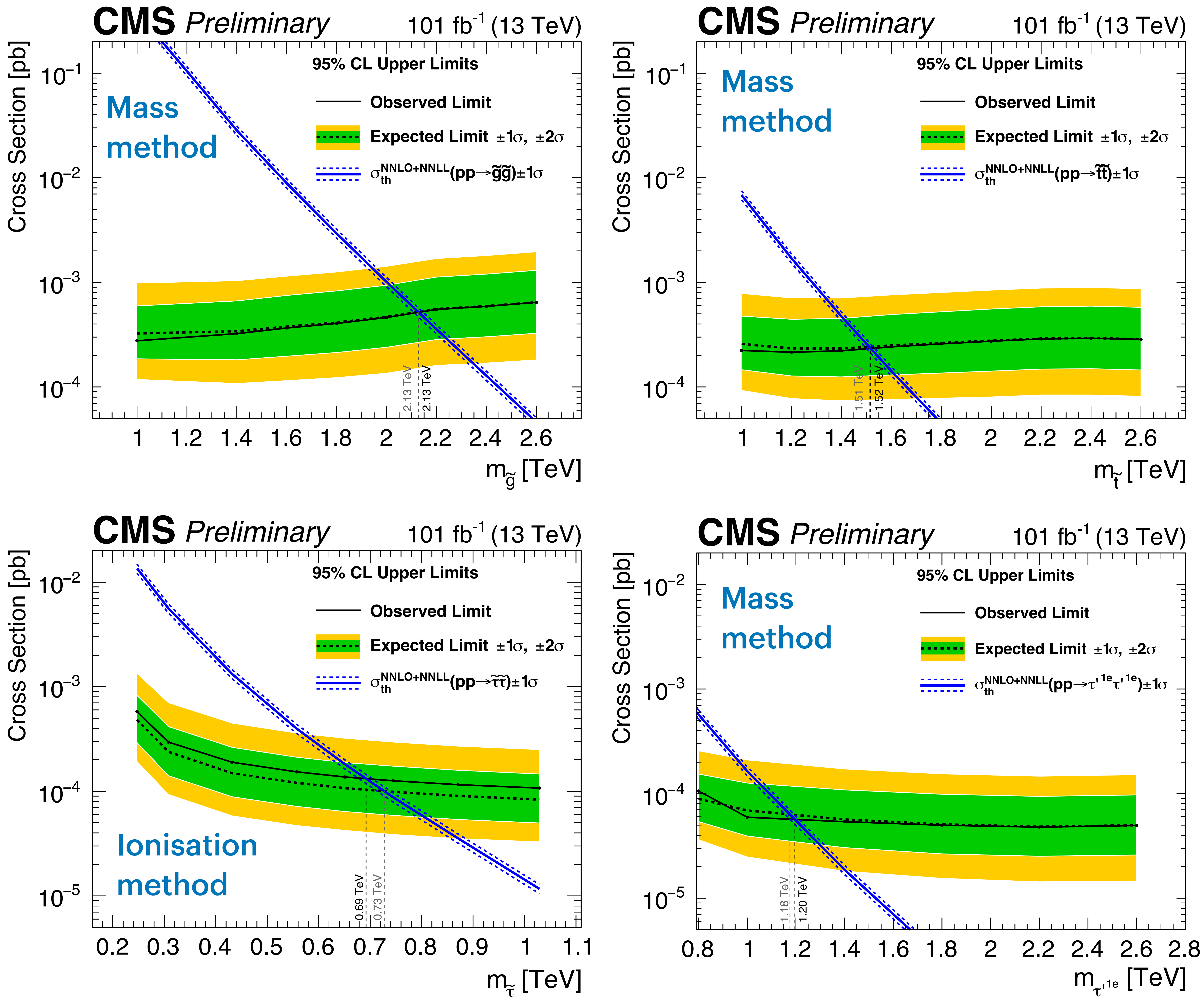


Search for HSCP - Results

Interpretation of the results for various HSCP models using CLs criterion

Model	Obs. limit (TeV)	Previous limit (TeV)
$\tilde{g}$	2.13	1.61
$\tilde{t}$	1.52	1.04
GMSB $\tilde{\tau}$	0.85	0.49
pair − prod. $\tilde{\tau}_R$	0.52	–
pair − prod. $\tilde{\tau}_L$	0.64	–
pair − prod. $\tilde{\tau}_{L/R}$	0.69	0.24
τ' (Q = 1e)	1.20	0.51
τ' (Q = 2e)	1.47	0.68
$Z'_{\psi} \to \tau'\tau'$	4.22	–
$Z'_{SSM} \to \tau'\tau'$	4.76	–

Previous publication : here

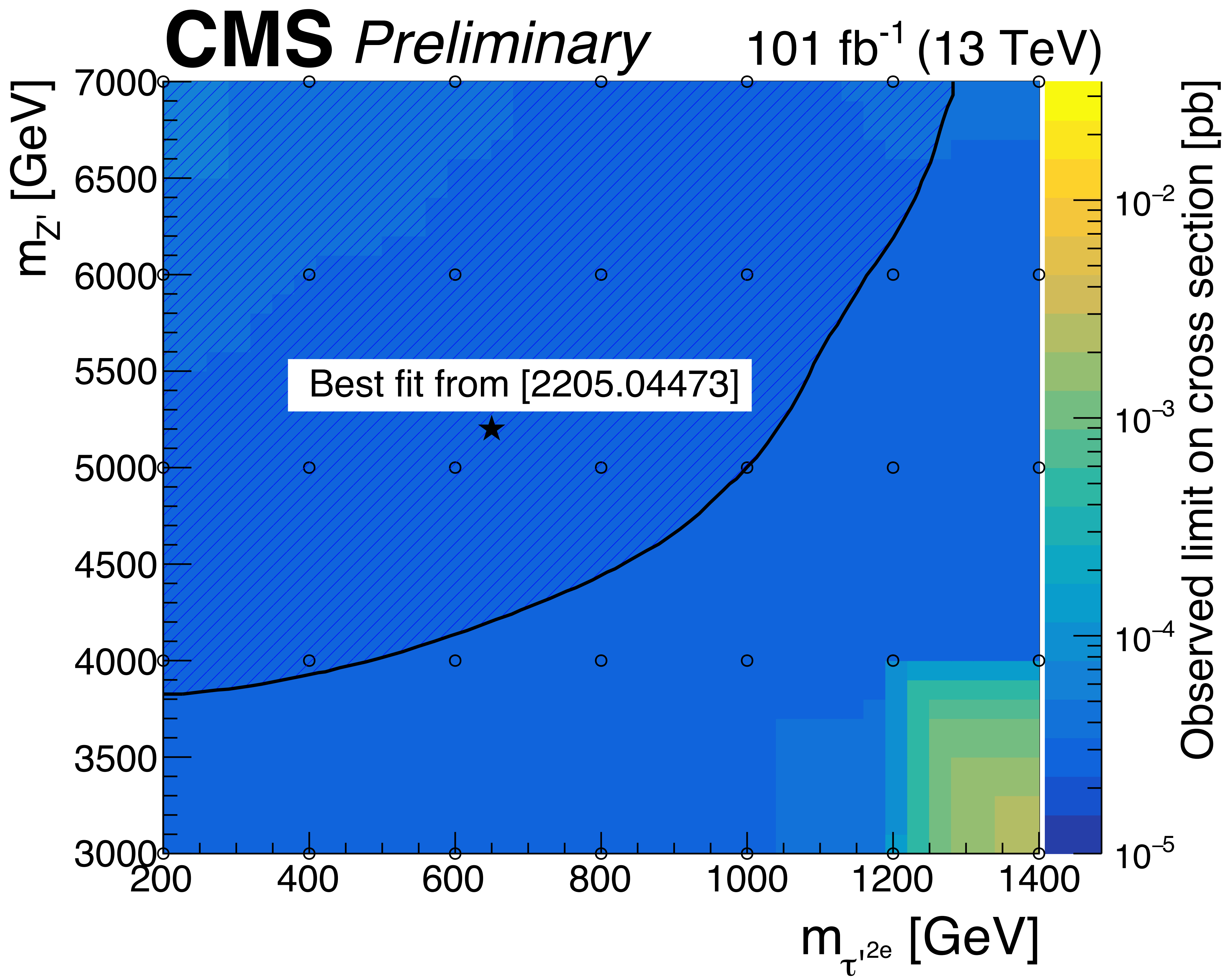


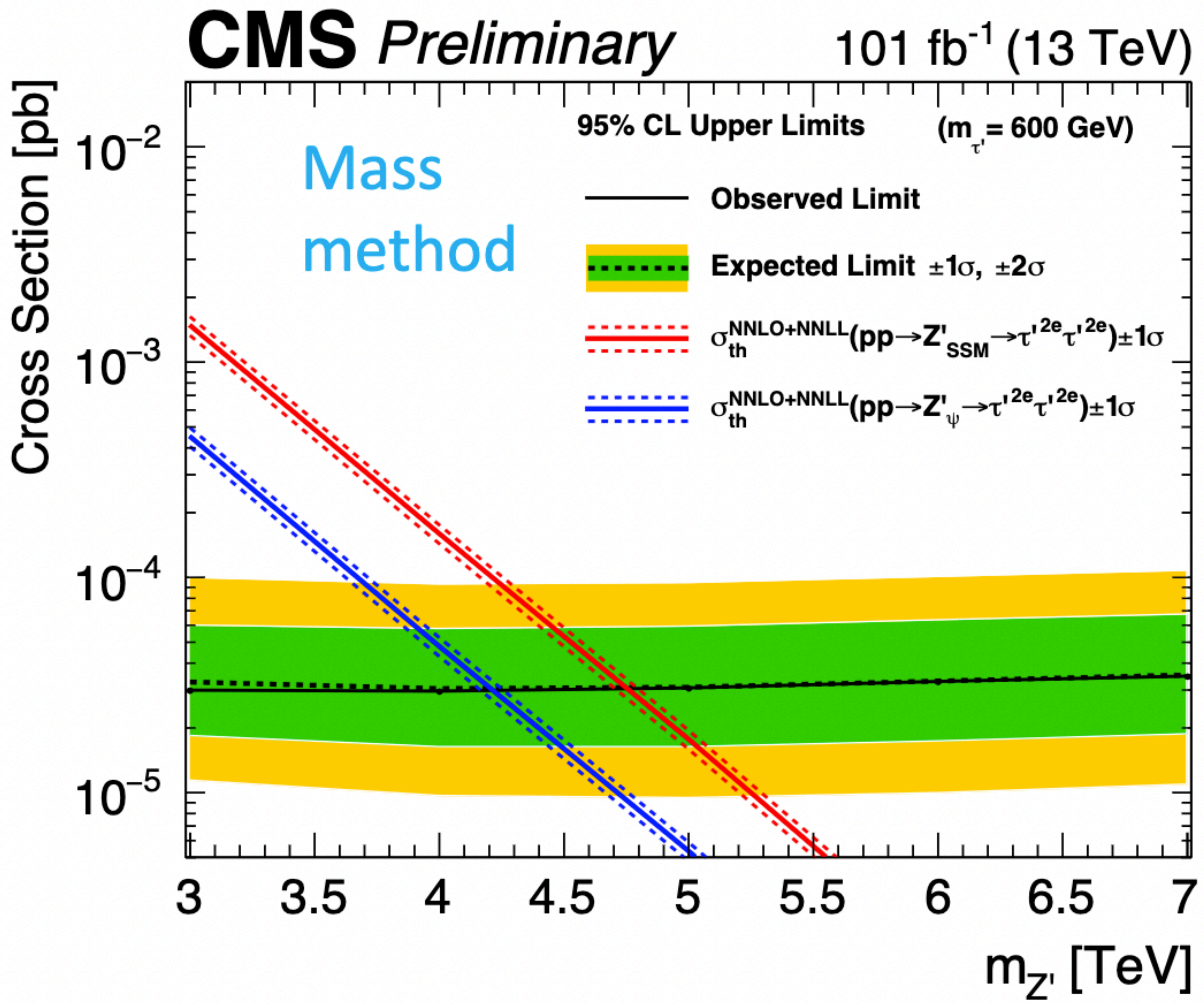
Search for HSCP - Results

Motivated by ATLAS excess (JHEP 06 (2023) 158) go

- ATLAS excess -> compatible with hypothesis of 1.4 TeV pair-produced gluino : **excluded by this result**

- **New interpretation :** production of **Z′ ->** $\tau'^{(2e)}\,\tau'^{(2e)}$ could explain the excess
  - Set limits on the Z′ model by Giudice, McCullough and Teresa [JHEP 08 (2022) 012], **claim of excess not confirmed !**





Conclusion

- If **no significant excess observed**, limits are given for several BSM models

Low-mass LLP using displaced jets

With only 2022 data analysed :

- Surpass the full Run-2 ATLAS results by up to an order of magnitude and the HL-LHC projection of LHCb
- First ever displaced hadronic tau results

Search for emerging jets

UL Run 2 data analysed :

- Push back previous limits for unflavored $m_{\pi_{dark}}$ = 10 GeV (EXO-18-001)
- Set limits for **new EMJ models** :
  - Exclude $m_{X_{dark}}$ up to 1950 (1800) for aligned (unflavored) models

Search for heavy stable charged particles

- Interpretation on a wide range of models and answer to ATLAS excess
- Significant improvements w.r.t previous CMS publication (ref)

- These results are a small fraction of the long-lived searches conducted by **CMS**
  - **The full Run-3 data will bring exciting new results, we are all looking forward to it !**

Thank you all !

BACKUP

EXO-23-013

Search for displaced jets at 13.6TeV (2022 data)

BACKUP

EXO-23-013 - New techniques developed

- New displaced-jet triggers

L1HTT (main) :

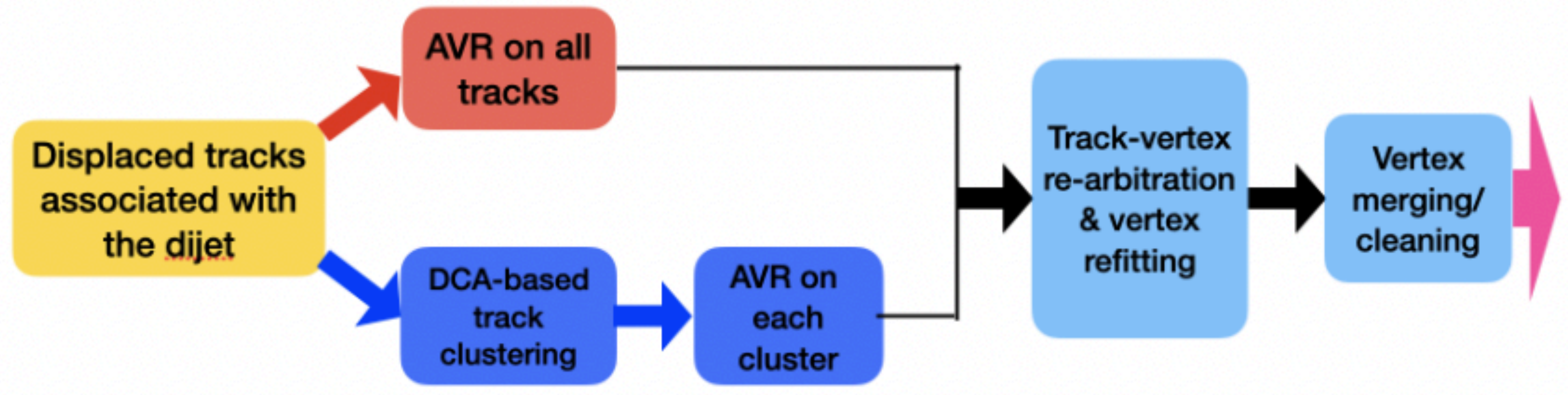
- HLT H_T > 430 GeV matched with offline H_T > 450 GeV
- ≥ 2 online CALO jets

L1Mu6HTT240 (auxiliary):

- HLT H_T > 250 GeV matched with offline H_T > 240 GeV
- Muon (p_T > 6 GeV)
- ≥ 2 online CALO jets (p_T > 40 GeV, $|\eta|$ < 2.0)

- New displaced vertex reconstruction

Starting with the displaced tracks ($IP_{2D} > 0.5$ mm, $Sig[IP_{2D}] > 5.0$) associated with two jets



Compared to the Run-2 algorithm, the main difference is the reconstruction of the additional DVs within the dijet, which is crucial for the improvements of sensitivities to S -> bb decays

EXO-23-013 - Future prospectives

Expectations for full Run-3 data :

- **Expect to achieve a factor of 10 better results**

Direction of new developments

Low m_0 (~<30 GeV) and high m_T (~>600 GeV)

- Boosted (merged) displaced jet tagging
- Complementarities provided by other sub detectors (CALO and muon detector)

High m_0 (~>40 GeV) and low m_T (~<550 GeV)

- New track classification, clustering and DV reconstruction algorithms
- Search for a pair of LLPS

Many projections for future collider experiments

- **We are getting close to these projections even with only the first year of Run-3 data**

Example :
LHCb HL-LHC projection
[arXiv:2105.12668]

Example :
Recent studies for CLIC
[JHEP 03(2023)131]

EXO-23-013 - Comparison with previous searches

Orders-of-magnitude improvements compared to previous results, significant expansion of the probed phase space

1. Full Run-2 displaced-jets search (EXO-19-021)
2. Run-2 Z+displaced-jets search (EXO-20-003)
3. ATLAS full Run-2 DV search

EXO-22-015

Search for emerging jets at 13 TeV *(full Run 2)*

BACKUP

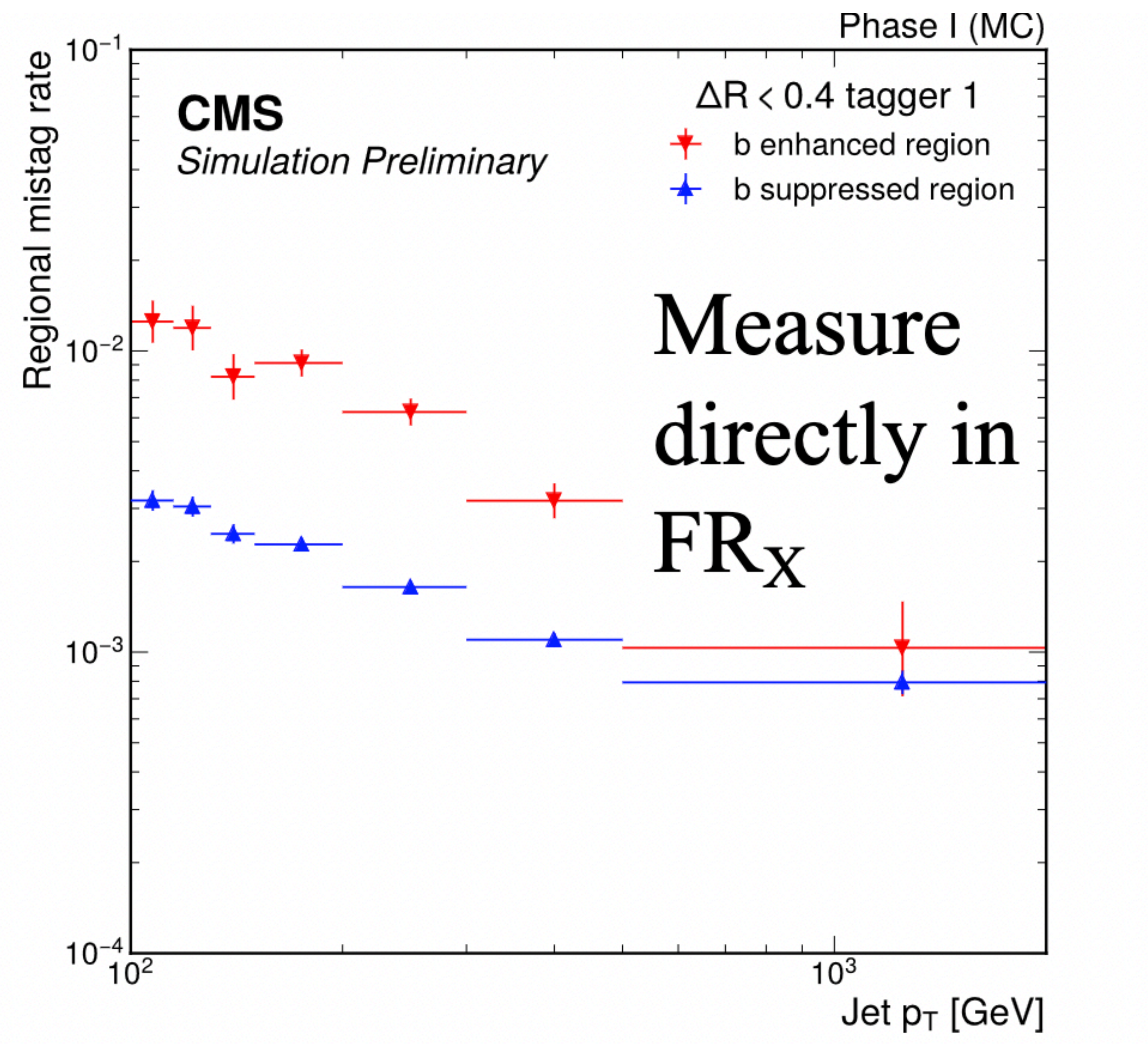
GNN : Mistag rate calculations

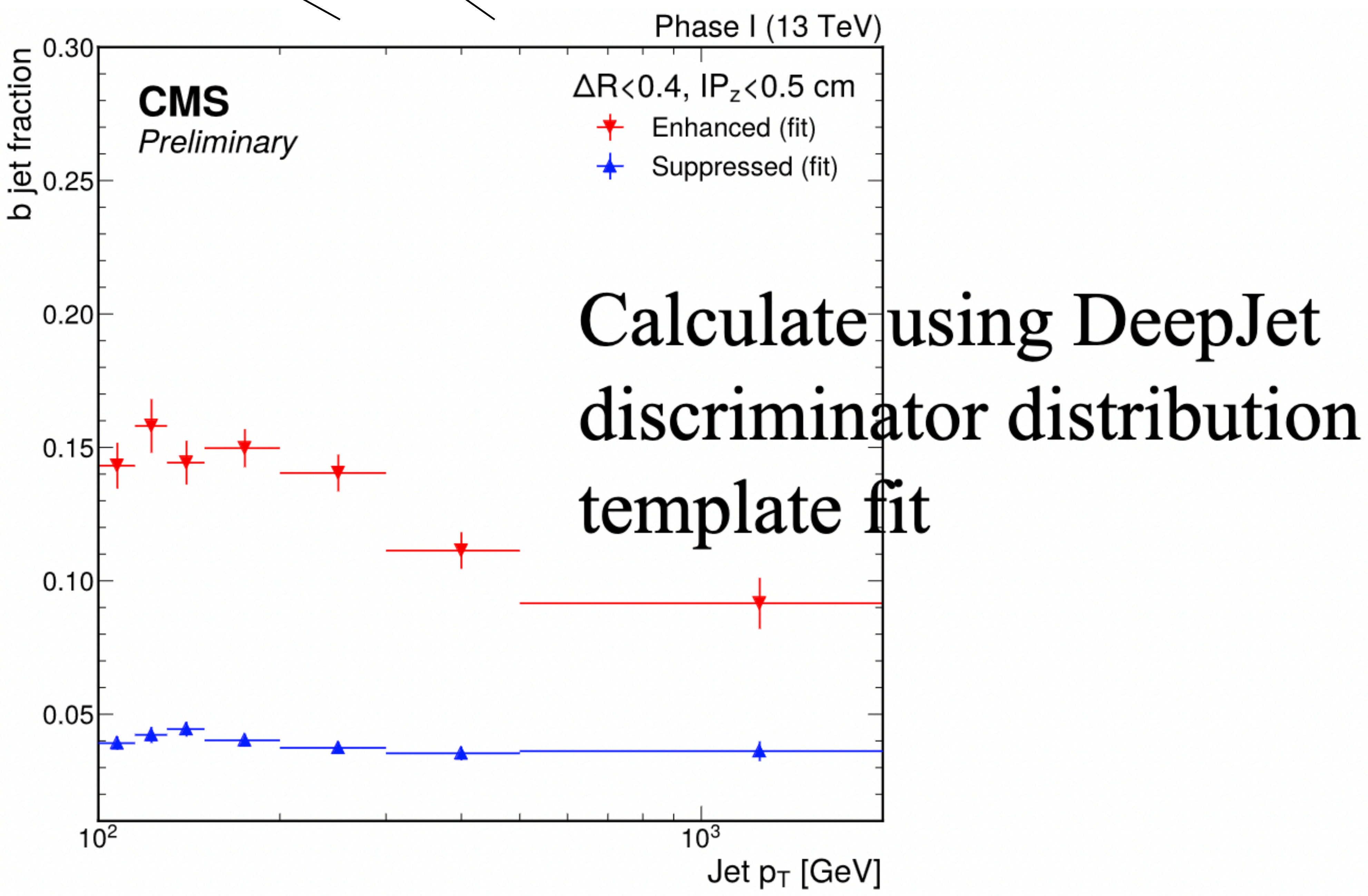
- Mistag and b-jet fraction B^{CR} from "b-enhanced/suppressed" (FR_E/FR_S) regions

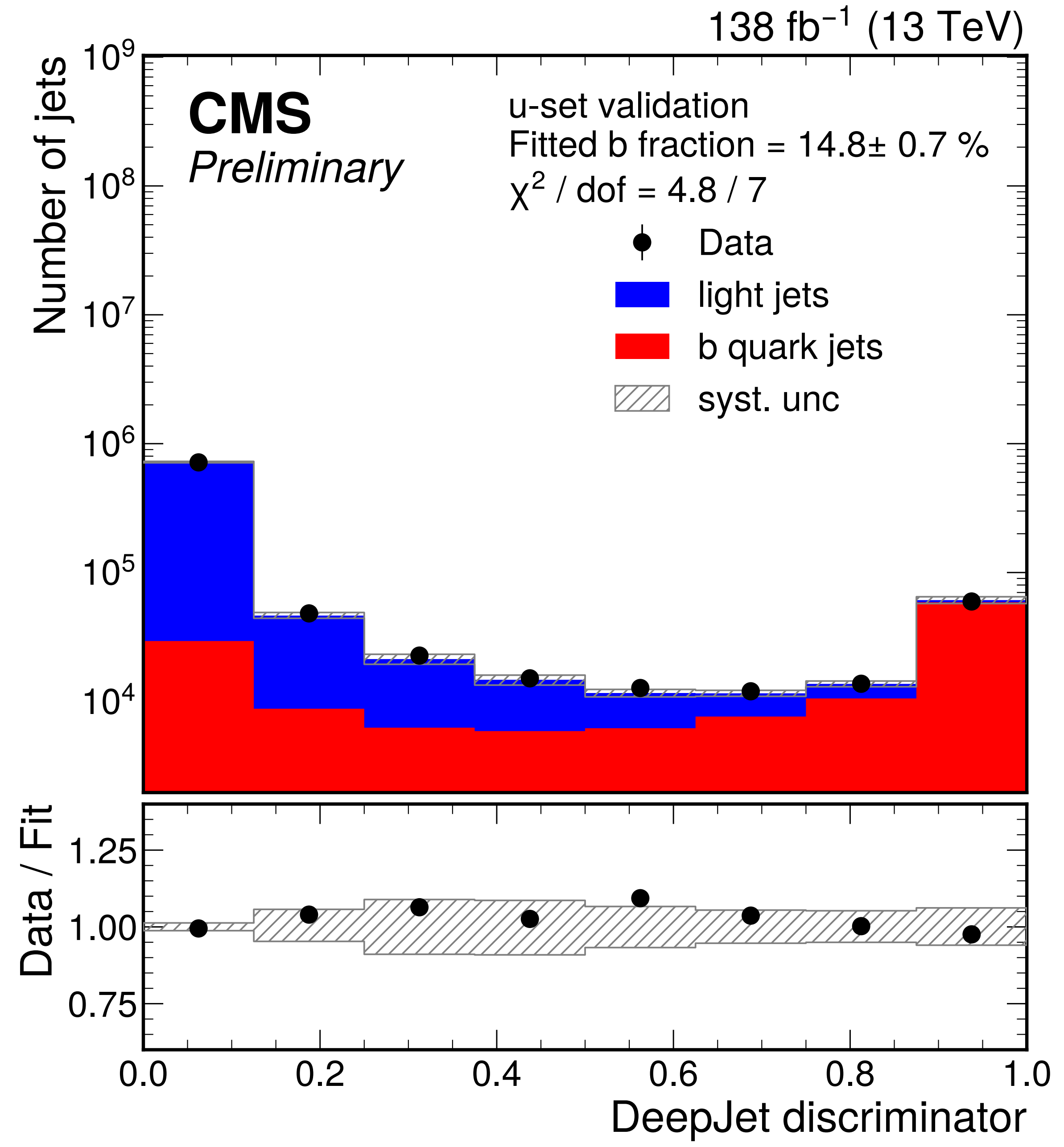
2 equations, 2 unknowns : solve for $\epsilon(b/l, p_T)$

$$FR_E: \quad \epsilon^E(p_T) = B^E(p_T)\epsilon(b, p_T) + (1 - B^E)\epsilon(l, p_T)$$

$$FR_S: \quad \epsilon^S(p_T) = B^S(p_T)\epsilon(b, p_T) + (1 - B^S)\epsilon(l, p_T)$$







Results in each model set

- Optimisation for each signal model : best threshold H_T, jet p_T and EJ tagging by maximising σ_{opt}

$$\sigma_{opt} = \frac{S}{\sqrt{S + B + \beta^2 B^2}}$$

β : estimated background uncertainty taken as 10%

Signal selection efficiency

π_{dark} lifetime	Model-agnostic tagger	ML-based tagger
40 mm	40%	60%
~ 1000 mm **~1mm**	few %	few %

	Selection set	Estimation$^{+stat}_{-stat}$ ± syst.	Obs
Model-agnostic unflavored	u-set 1	$56^{+9}_{-5} \pm 20$	67
	u-set 2	$20^{+4.3}_{-2.5} \pm 7.0$	21
	u-set 3	$22.9^{+7.3}_{-2.1} \pm 4.9$	24
	u-set 4	$7.9^{+2.0}_{-1.6} \pm 2.2$	10
	u-set 5	$11.3^{+2.7}_{-1.9} \pm 2.0$	13
Model-agnostic flavored	a-set 1	$8.8^{+2.4}_{-2.0} \pm 2.0$	16
	a-set 2	$1.67^{+0.49}_{-0.23} \pm 0.38$	3
	a-set 3	$1.97^{+0.47}_{-0.22} \pm 0.37$	2
	a-set 4	$2.30^{+0.81}_{-0.30} \pm 0.39$	3
	a-set 5	$10.2^{+2.3}_{-1.1} \pm 3.4$	16
GNN unflavored	uGNN set 1	$15.6^{+5.4}_{-1.9} \pm 3.8$	18
	uGNN set 2	$0.73^{+0.44}_{-0.16} \pm 0.27$	0
	uGNN set 3	$7.6^{+3.5}_{-1.3} \pm 2.3$	9
GNN flavored	aGNN set 1	$45^{+18}_{-8} \pm 16$	59
	aGNN set 2	$0.30^{+0.23}_{-0.07} \pm 0.18$	1
	aGNN set 3	$3.8^{+2.2}_{-0.7} \pm 2.0$	5

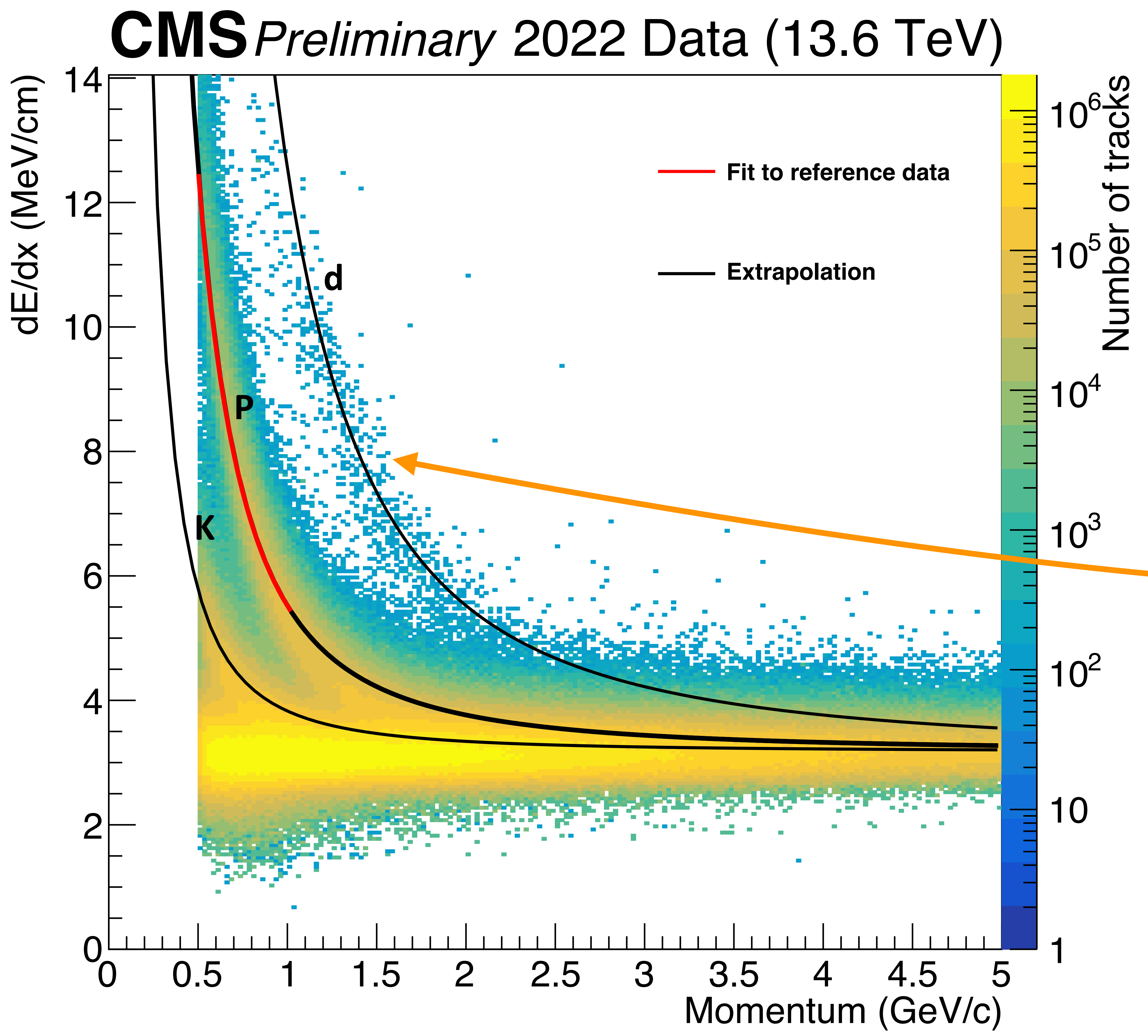
EXO-18-002

Search for heavy stable charged particles (HSCP) at 13 TeV *(2017+2018 data from Run 2)*

BACKUP

- Target massive particles

Link to plot



$$\beta\gamma = \frac{p}{m}$$

- Increase **m** for a fixed **p** leads to lower $\beta\gamma$, in turn leading to higher dE/dx

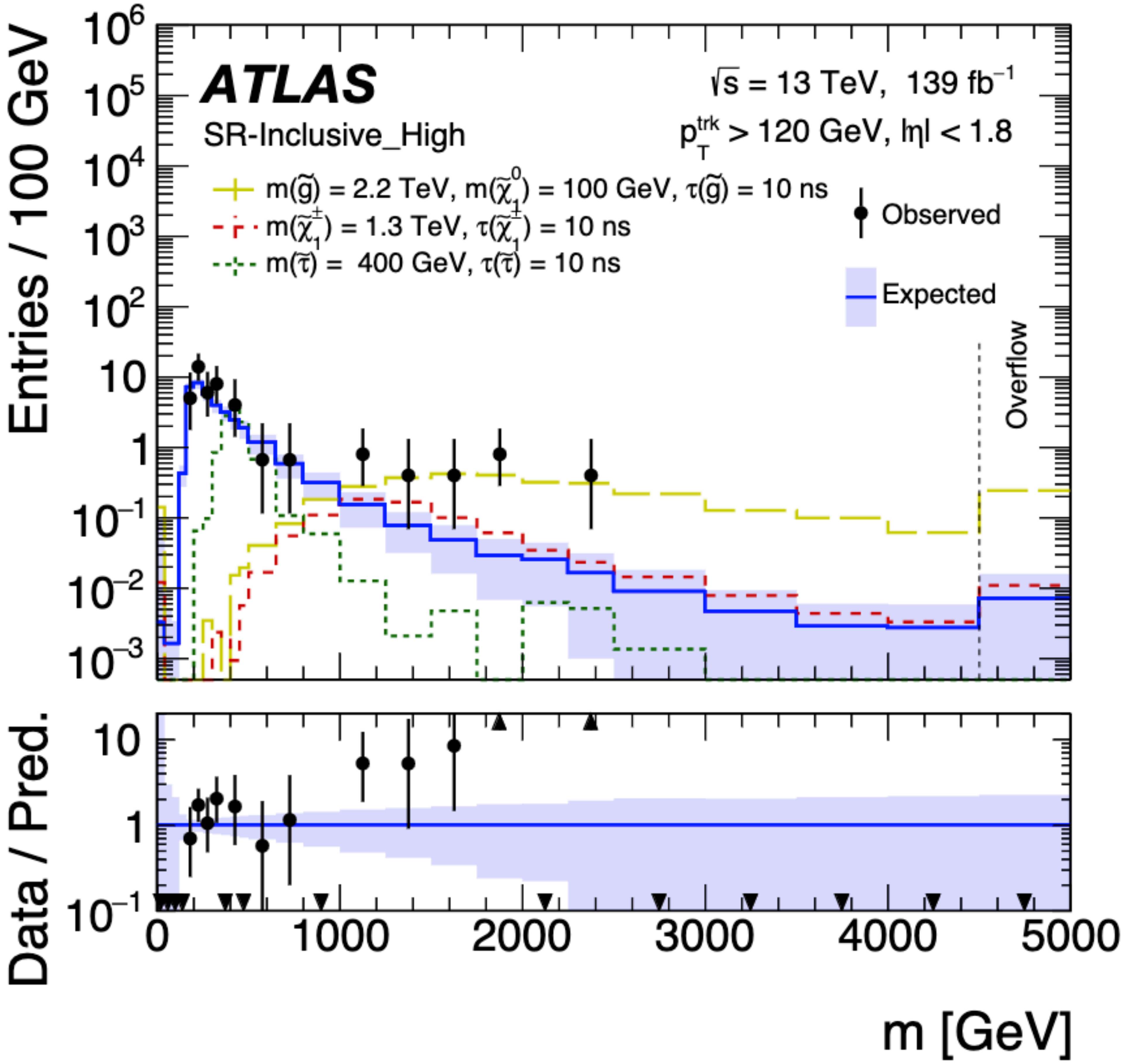
- We are looking for massive particles with **m ~ 2 TeV** and **$\beta\gamma$ ~ 0.5**
  - Find them below MIP, with higher ionization

EXO-18-002 - ATLAS excess

[arXiv:2205.06013]

3σ excess reported (expected 0.7, observed 7), with SM compatible v/c :

- Majority of them compatible with muons
- We at CMS are able to provide an answer for this observation



Excess compatible with 1.4 TeV pair-produced gluino hypothesis

EXO-18-002 - Comparison with previous publication

- Both methods results comparison with previous CMS publication

Model	Ionization method		Mass method		Last CMS result
	Exp. (TeV)	Obs. (TeV)	Exp. (TeV)	Obs. (TeV)	Obs. (TeV)
gluino	2.08 ± 0.09	2.03	2.13 ± 0.11	2.13	1.61
stop	1.45 ± 0.08	1.40	1.51 ± 0.10	1.52	1.04
GMSB tau slepton	0.88 ± 0.07	0.84	0.87 ± 0.09	0.85	0.49
Pair-prod. RR tau slepton	0.55 ± 0.07	0.52	0.52 ± 0.07	0.51	-
Pair-prod. LL tau slepton	0.68 ± 0.08	0.64	0.68 ± 0.10	0.61	-
Pair-prod. L/R tau slepton	0.73 ± 0.08	0.69	0.75 ± 0.10	0.64	0.24
τ' $(Q = 1e)$ from DY prod.	1.06 ± 0.10	1.02	1.18 ± 0.12	1.20	0.51
τ' $(Q = 2e)$ from DY prod.	1.68 ± 0.11	1.62	1.46 ± 0.13	1.47	0.68
$Z'_{\psi} \to \tau'\tau'$	4.01 ± 0.27	3.88	4.20 ± 0.29	4.22	-
$Z'_{SSM} \to \tau'\tau'$	4.56 ± 0.28	4.41	4.75 ± 0.28	4.76	-

Previous CMS publication here