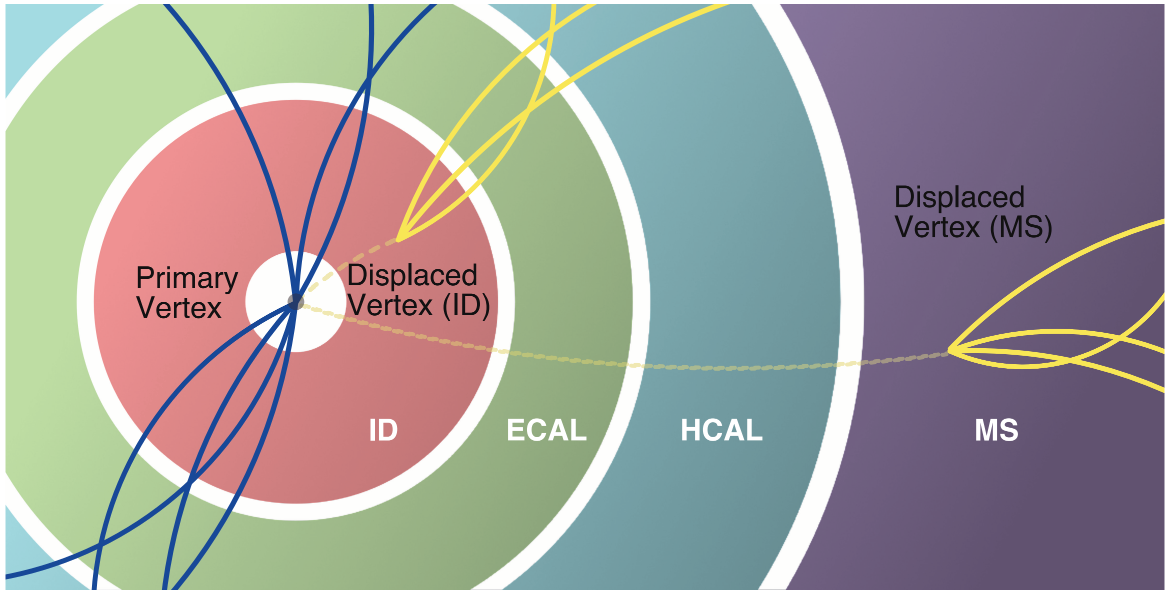
Search for Anomalous Ionization at CMS

Lawrence Lee
On behalf of the CMS Collaboration

[Based on CMS-PAS-EXO-18-002]

The University of Tennessee Knoxville

4 July 2024 - LLP Workshop, Tokyo

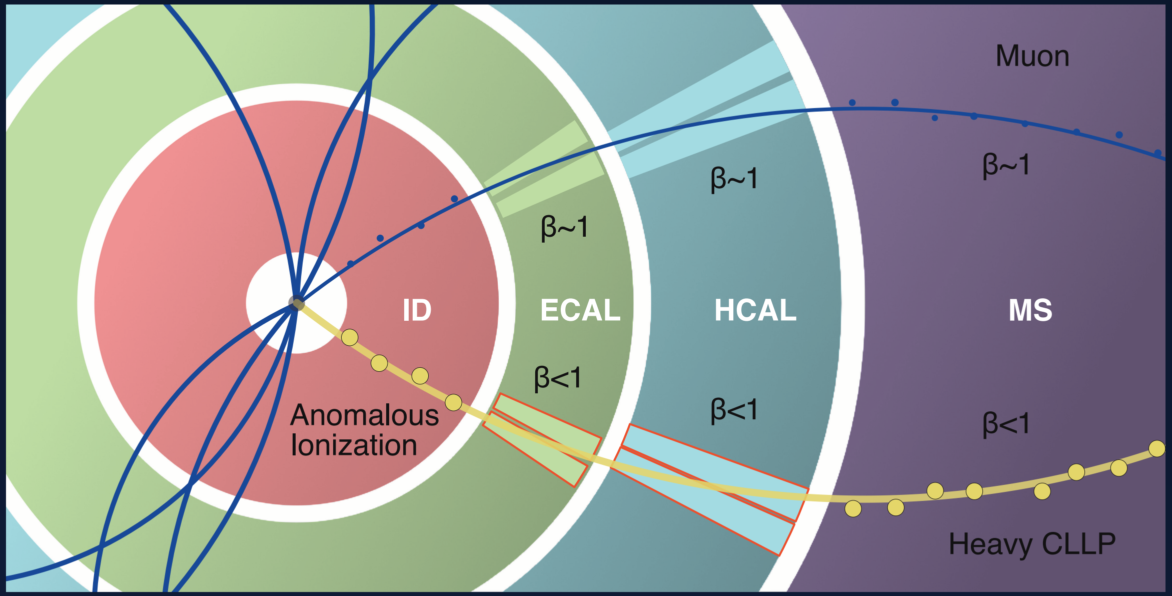


Indirect Detection

Look for SM decay products of LLP

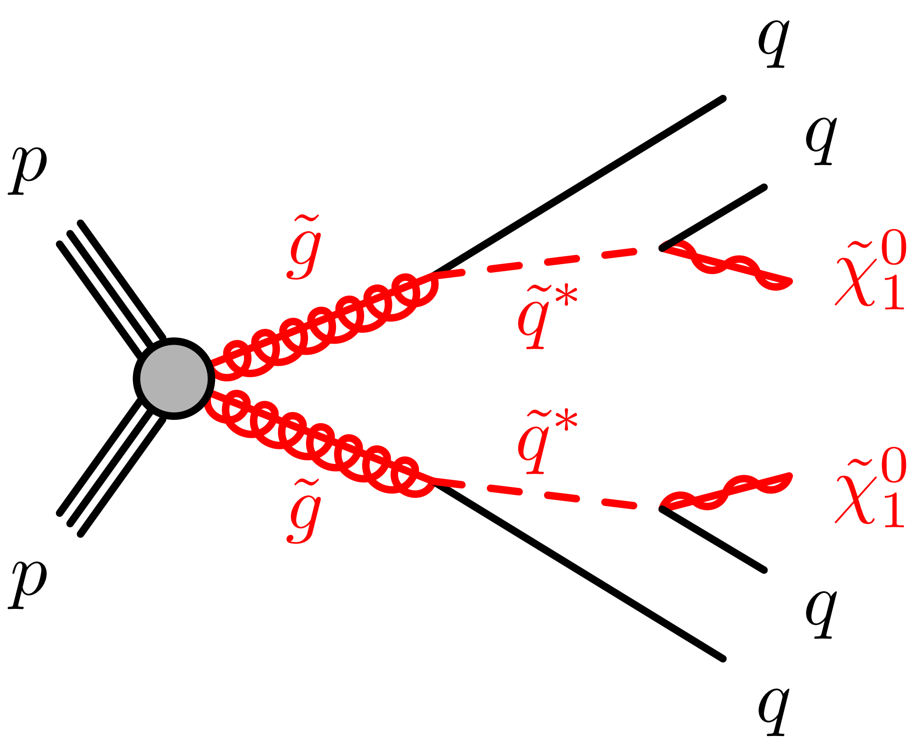
Direct Detection

If LLP carries SM charge, look for its interactions with the detector



[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

E.G. LONG-LIVED GLUINOS



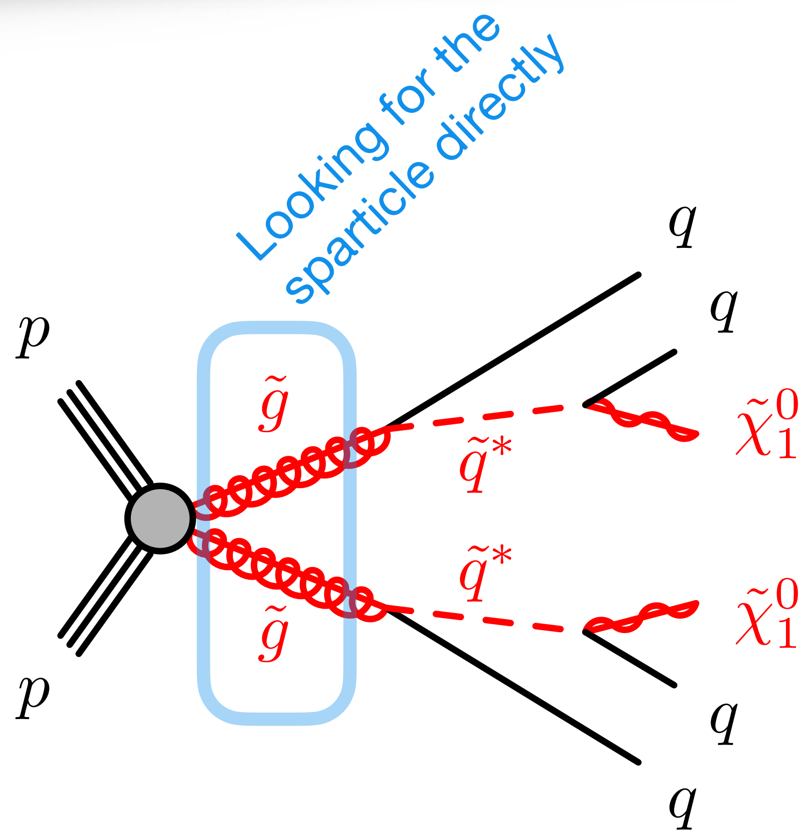
$$m(\tilde{q}) \gg m(\tilde{g})$$

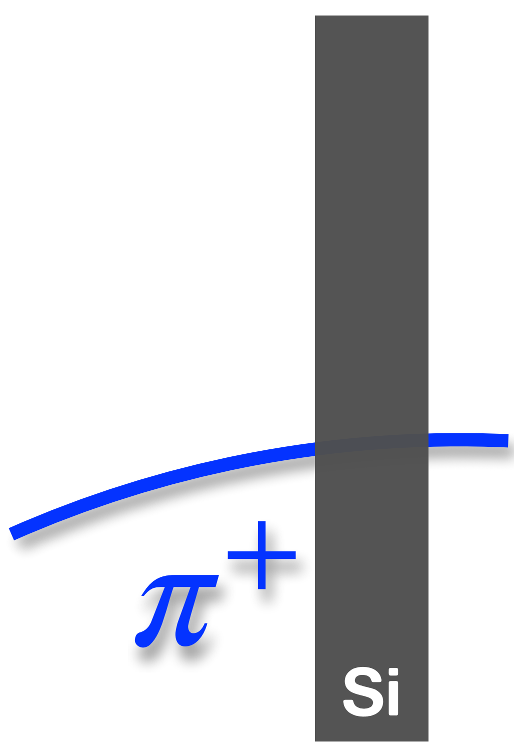
$$\tau(\tilde{g}) \sim 4 \left(\frac{m(\tilde{q})}{1\ \text{PeV}}\right)^4 \left(\frac{1\ \text{TeV}}{m(\tilde{g})}\right)^5 \times 10^{-4}\ \text{ns}$$

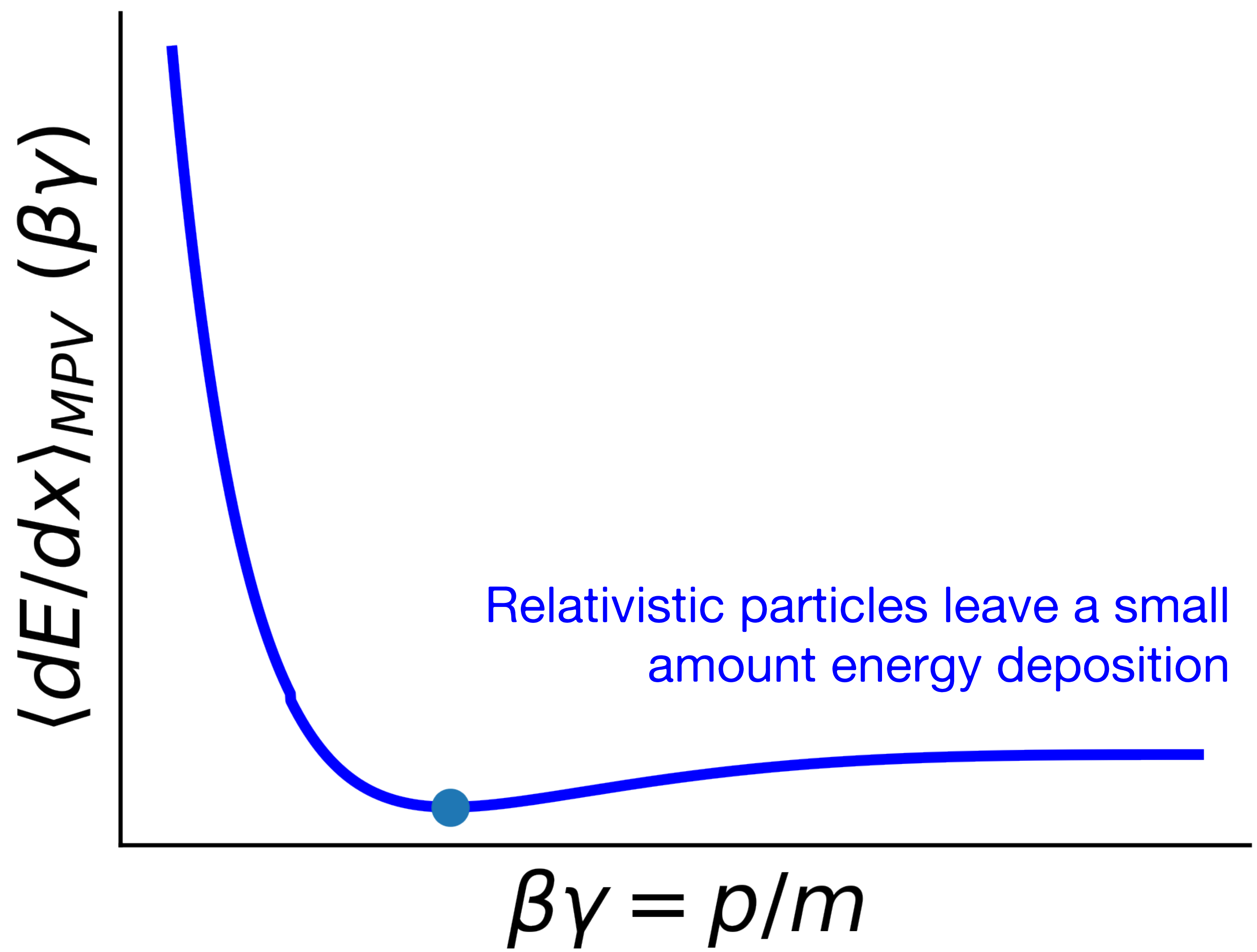
- Maybe we're producing lots of gluinos
  - But because of very high mass squarks, gluinos become meta-stable ("Split-SUSY")
  - Gluinos hadronize to a color singlet ("R-Hadron") that may be charged

Si Tracking Detectors measure ionization energy loss

Modeled by Bethe-Bloch Curve







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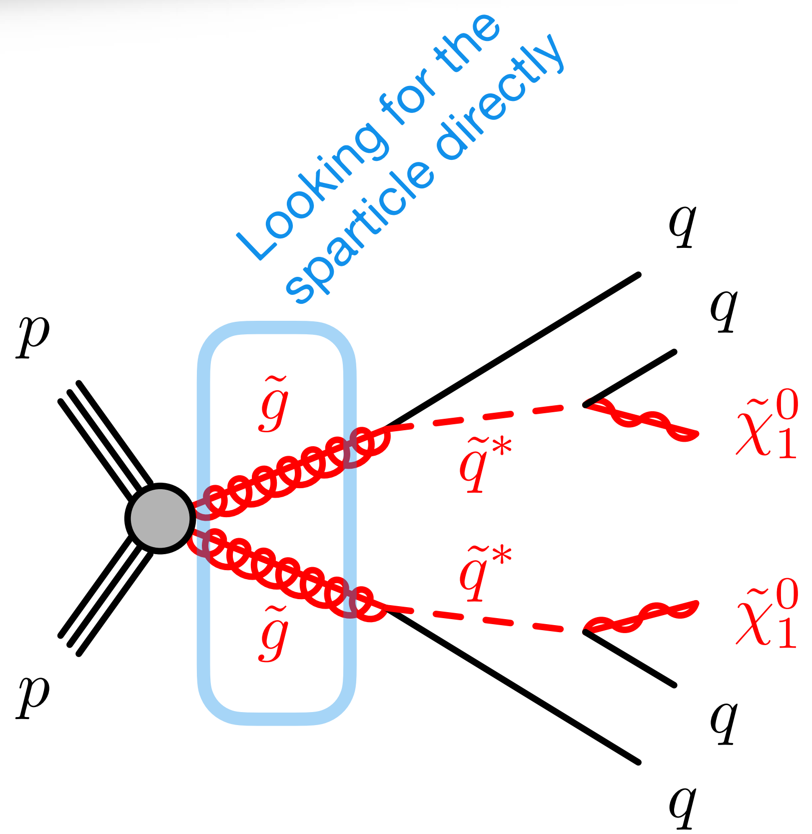
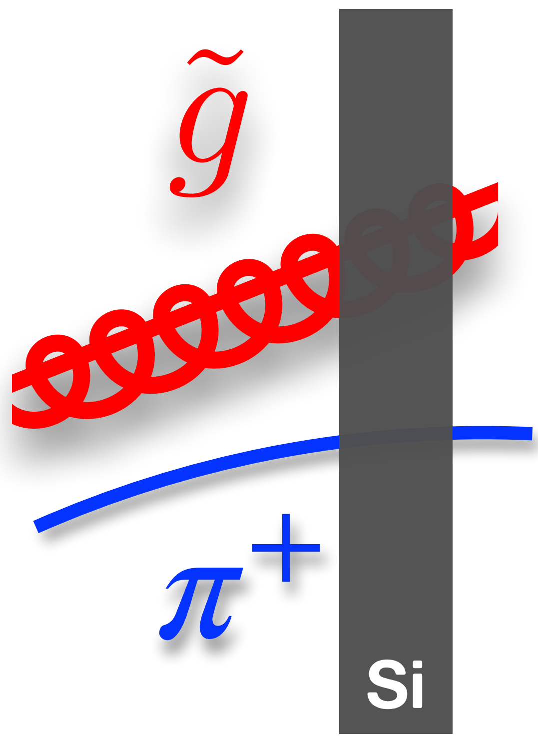
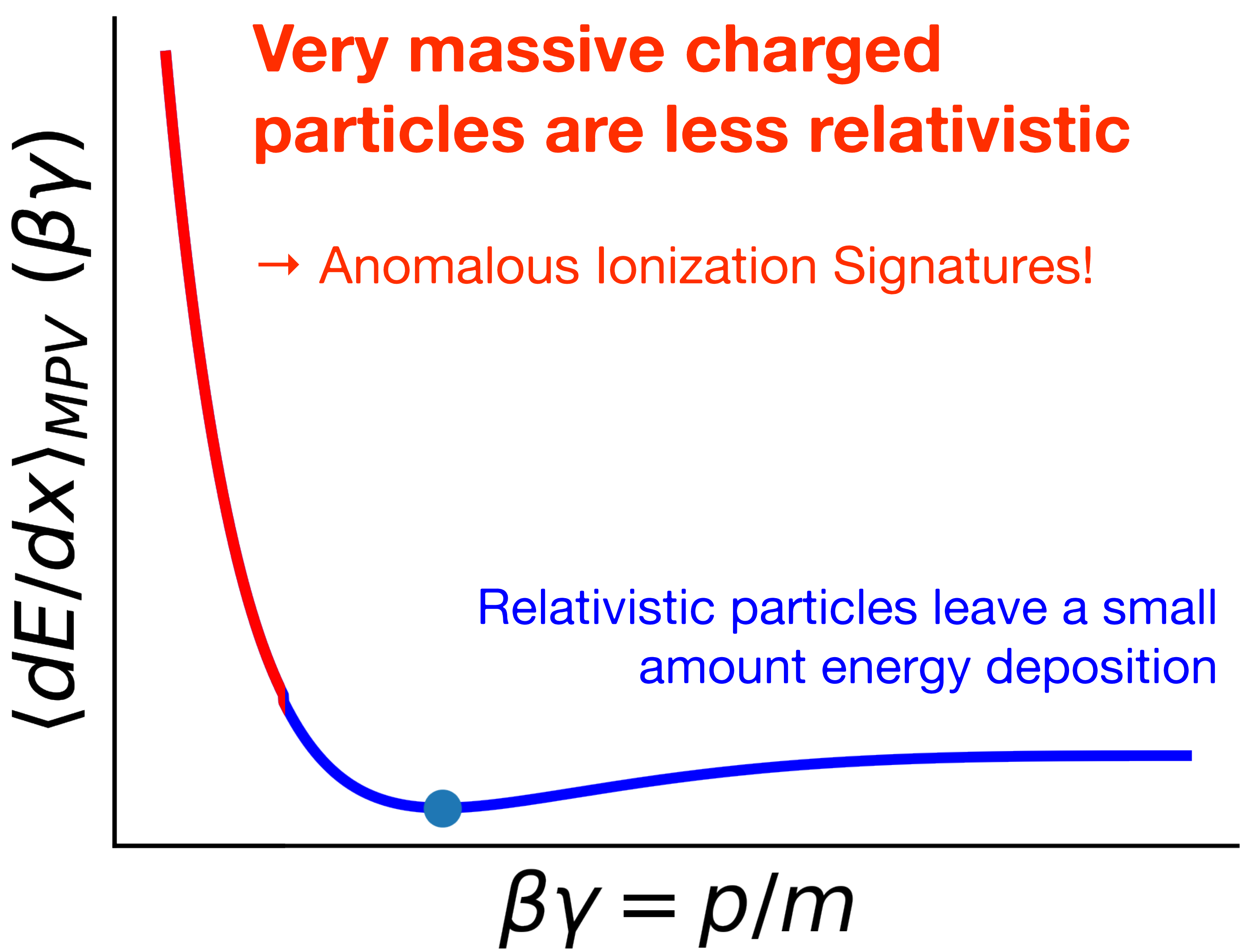
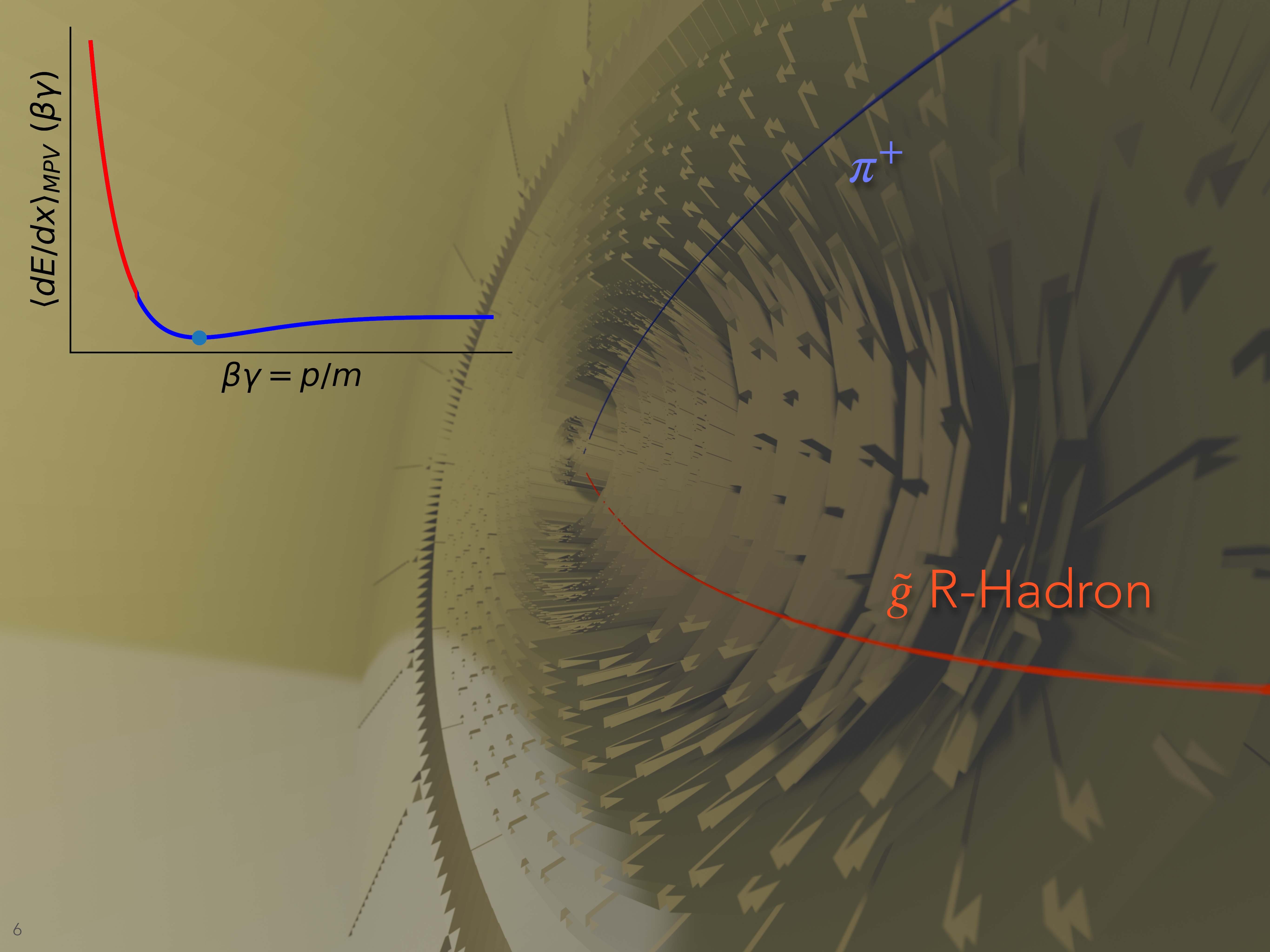


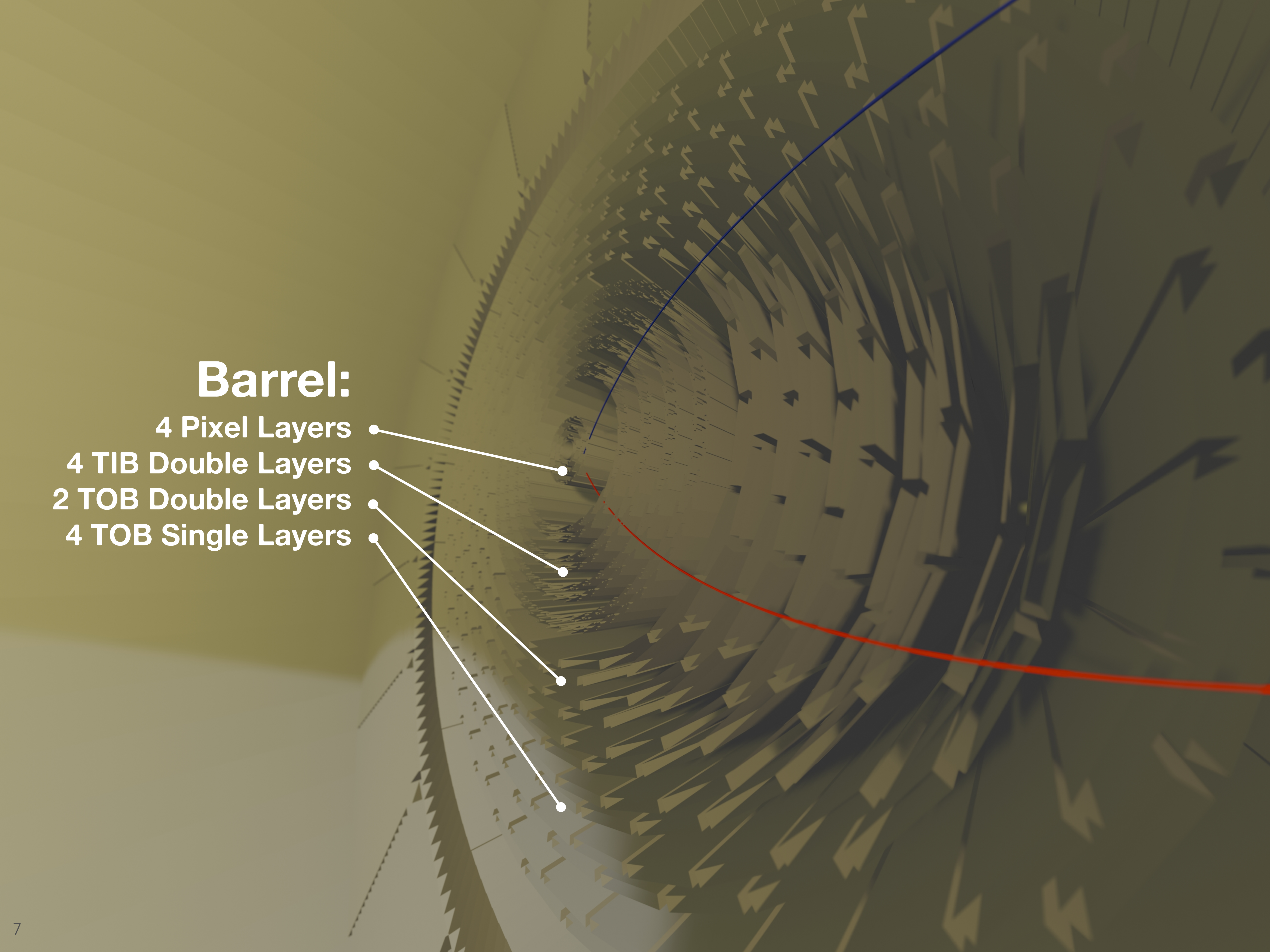


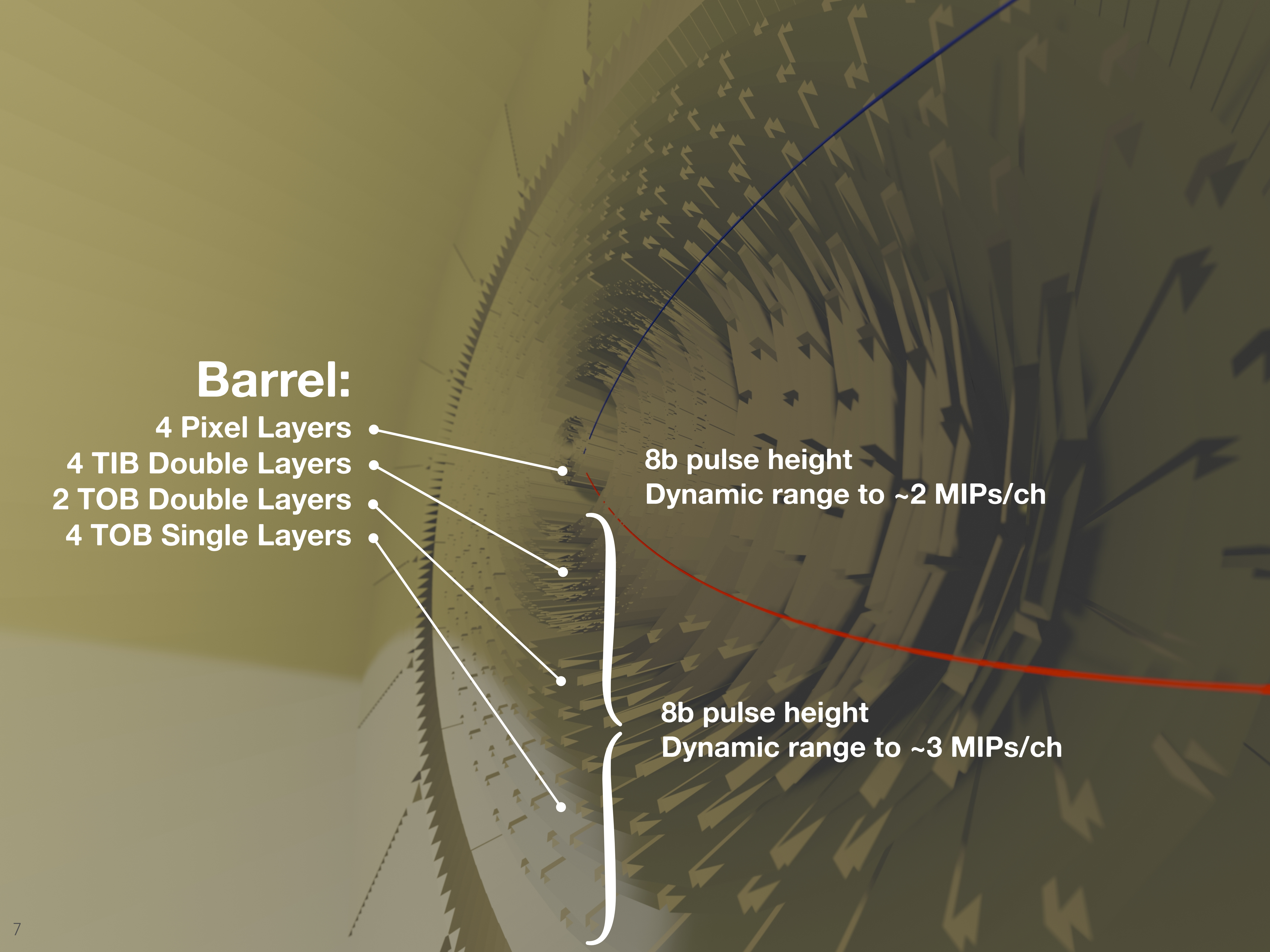


CMS has a lot of silicon!



$\langle dE/dx \rangle_{MPV} (\beta\gamma)$
$\beta\gamma = p/m$
π^+
$\tilde{g}$ R-Hadron


Barrel:
4 Pixel Layers
4 TIB Double Layers
2 TOB Double Layers
4 TOB Single Layers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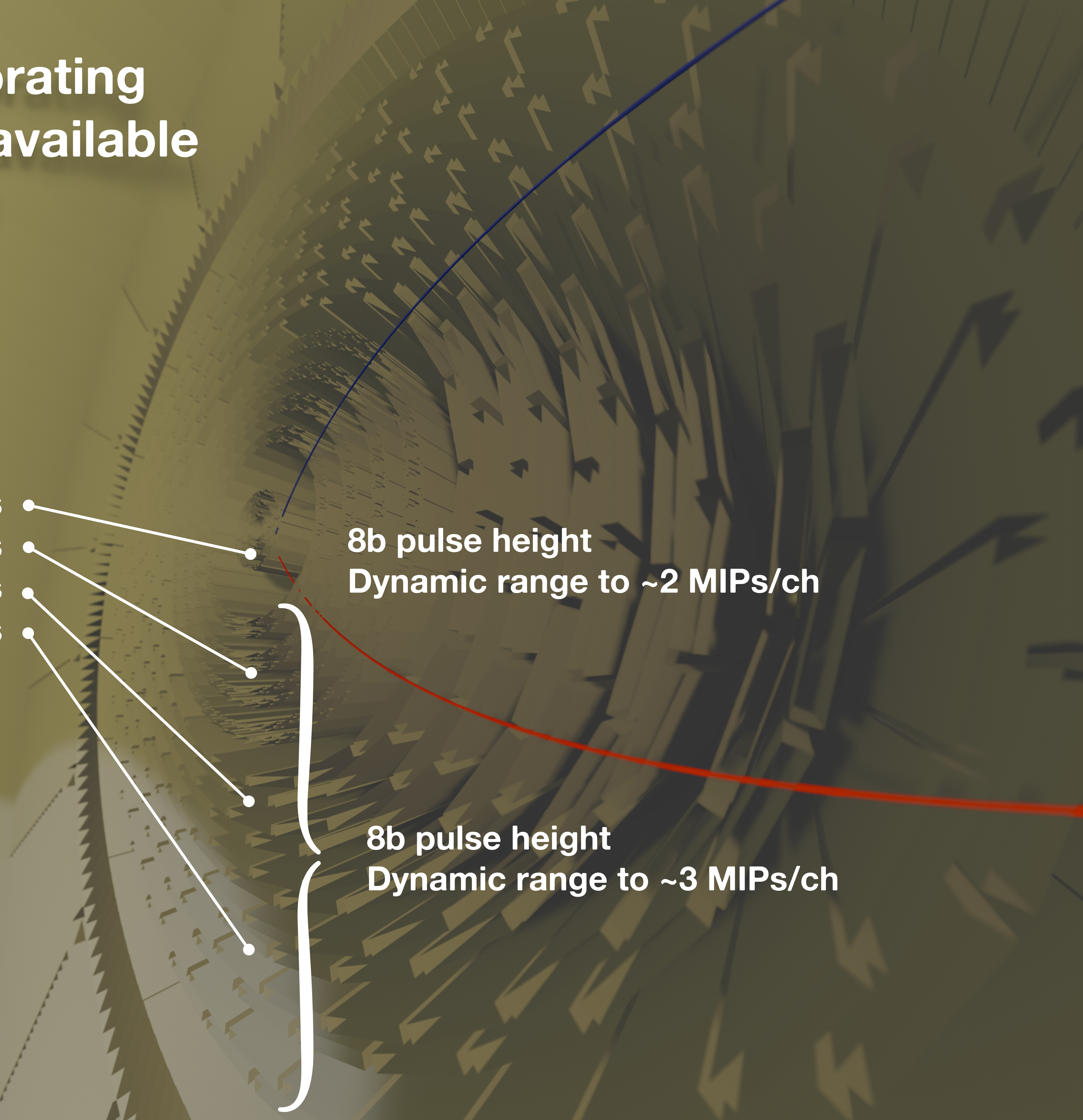
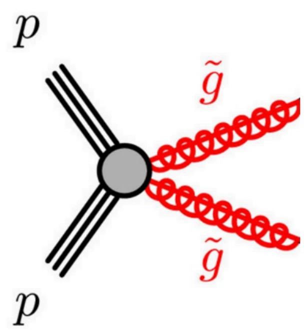
8b pulse height
Dynamic range to ~2 MIPs/ch
8b pulse height
Dynamic range to ~3 MIPs/ch

Lots of corroborating ionization info available for every track!



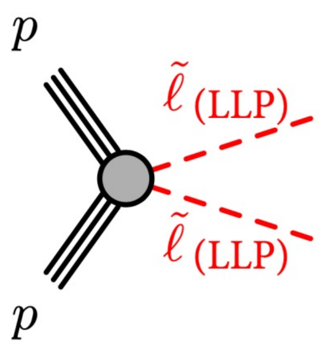
So we'll be looking for inclusive, generic anomalous ionization signatures

We'll optimize and interpret w/ two main classes of models



Long-Lived Gluino R-Hadron

(Strong production, mini-split-SUSY motivated, OOTB Pythia 8 R-Hadron Spectrum)

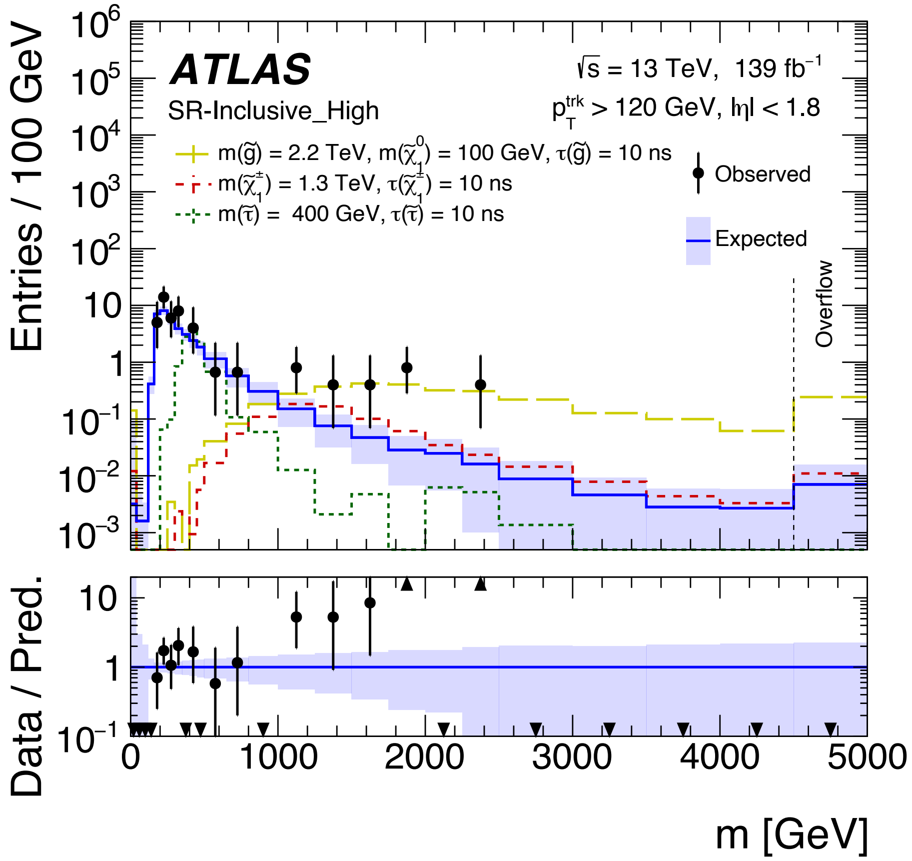


Long-Lived Sleptons/Staus

(Drell-Yan Production, GMSB/GGM Motivated)

[ATLAS Diagrams]

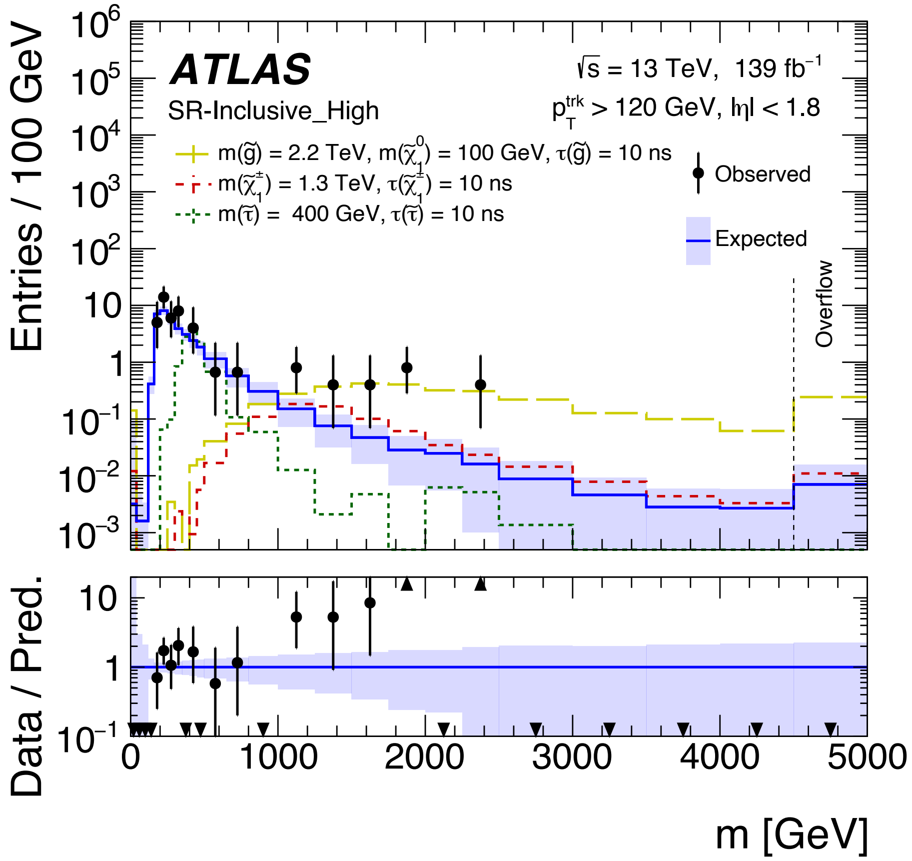
ATLAS Excess



- **With an ionization-based mass measurement, ATLAS sees an excess**
- At high mass, 7 events observed for 0.7±0.4 events expected
  - **3.6σ local, 3.3σ global**

[1606.05129] [2205.06013]

ATLAS Excess



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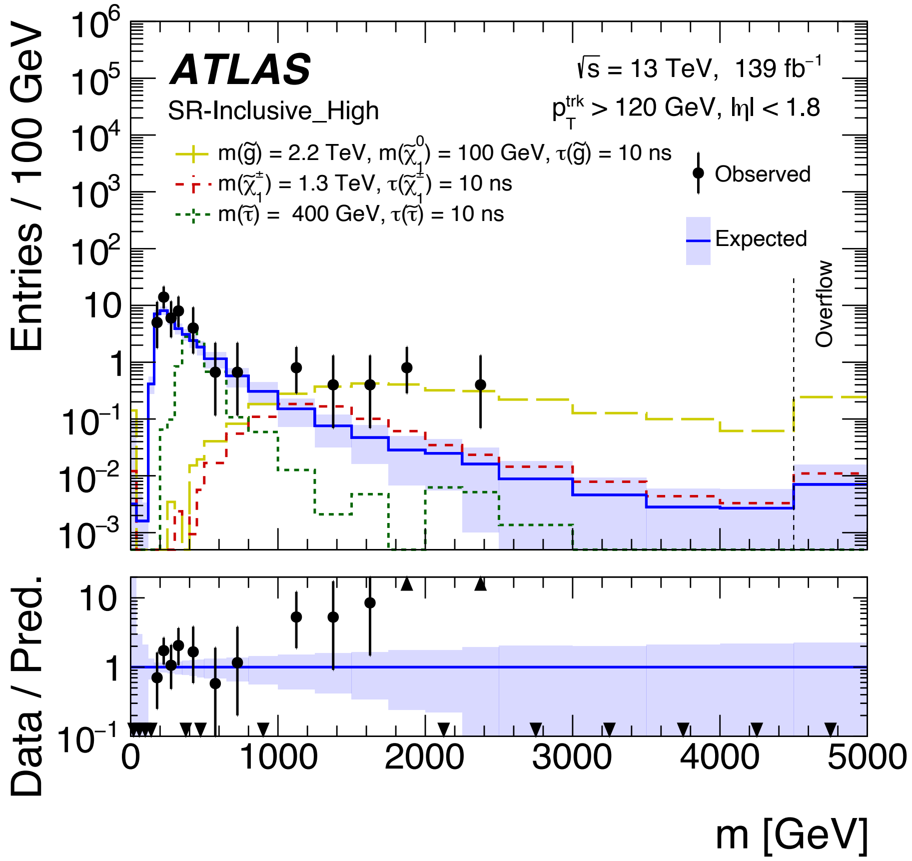
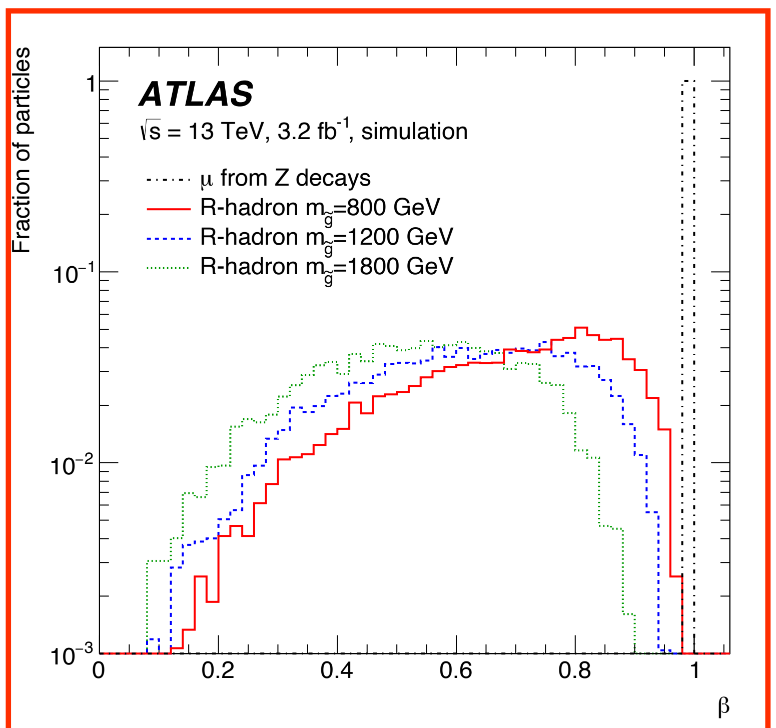
- MET Triggered
- 5 events have reco muons
- 3 of those have 2 reco muons
- All candidates have β consistent with 1 as measured by the Tile Calorimeter and Muon System

[1606.05129] [2205.06013]

ATLAS Excess





β~1 is inconsistent with a heavy pair-produced particle

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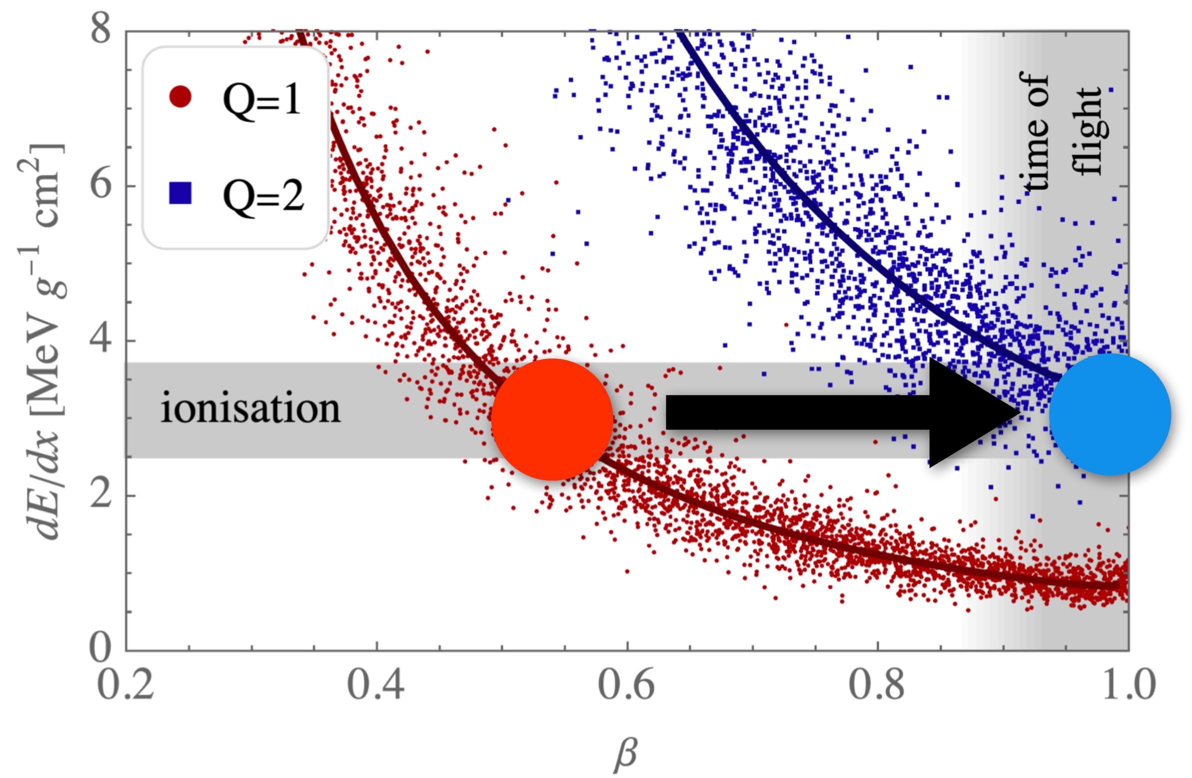
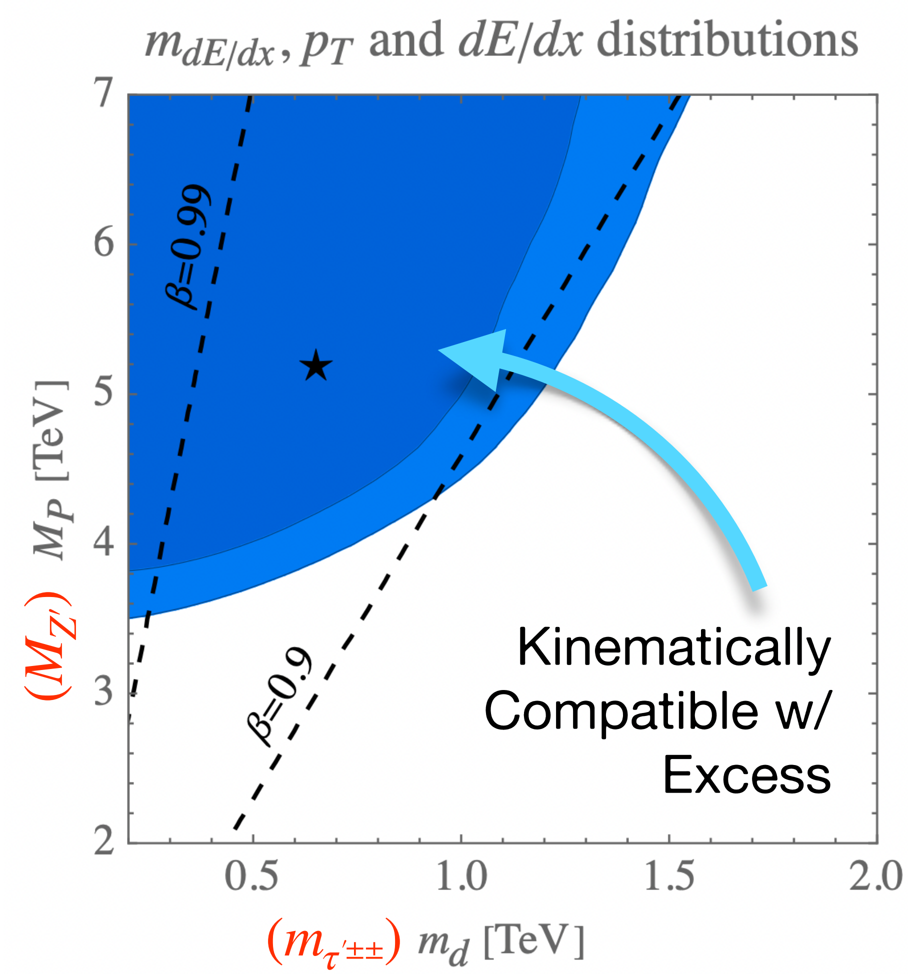
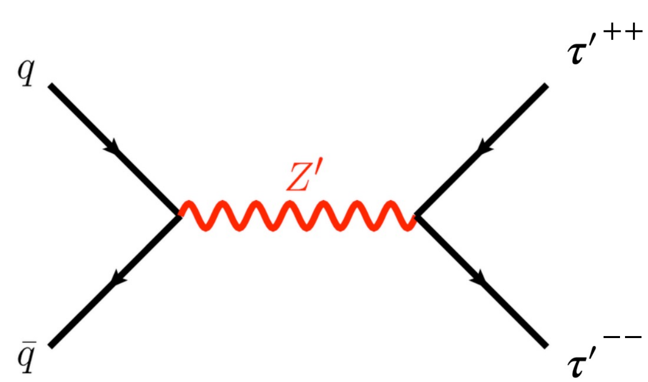
[1606.05129] [2205.06013]

β=1 → Boosted ±2e?

- Maybe momentum measurement wrong because of a **q>1 signal**
    - **p_T** off by factor of q
    - dE/dx → $\beta\gamma \rightarrow m_{\beta\gamma}$ **translation** also fails
- Nicely quantified in [2205.04473] by Giudice, McCullough, Teresi
    - Why β~1? **Produced in decay of heavy resonance**
    - If not from low β, why large dE/dx? **q=±2e**







[2205.04473]

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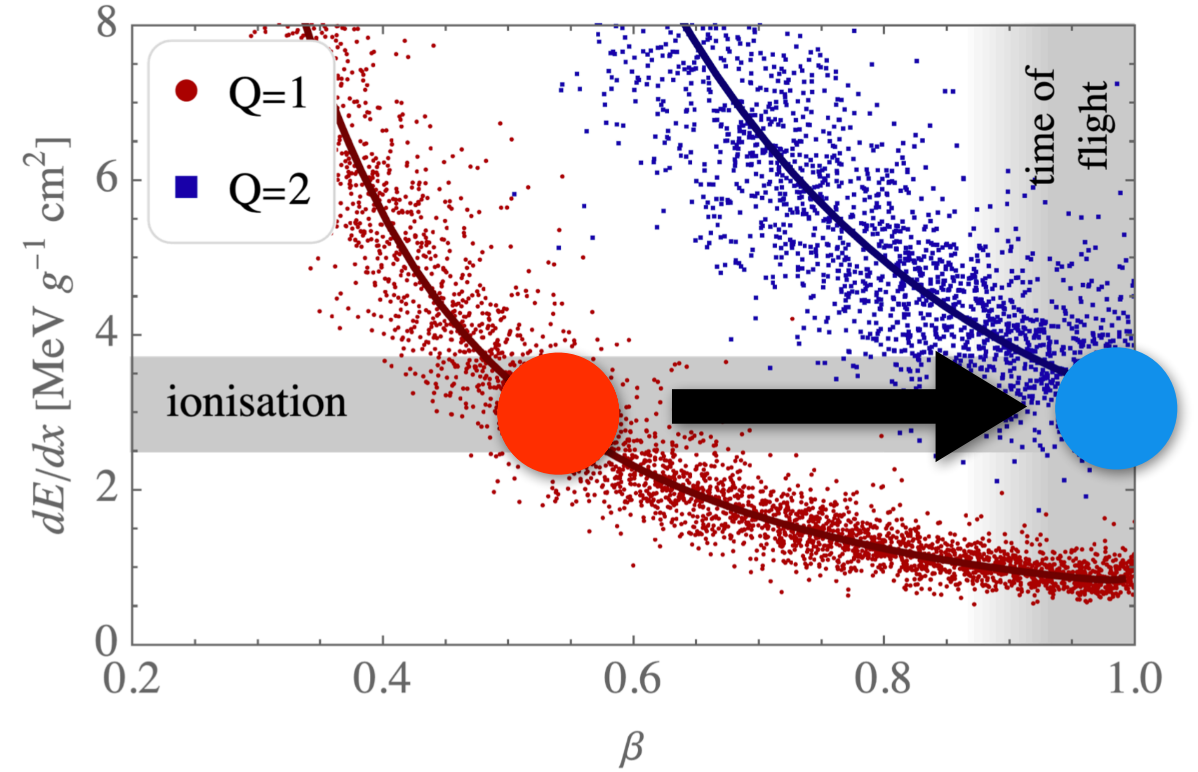

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  - Why β~1? **Produced in decay of heavy resonance**
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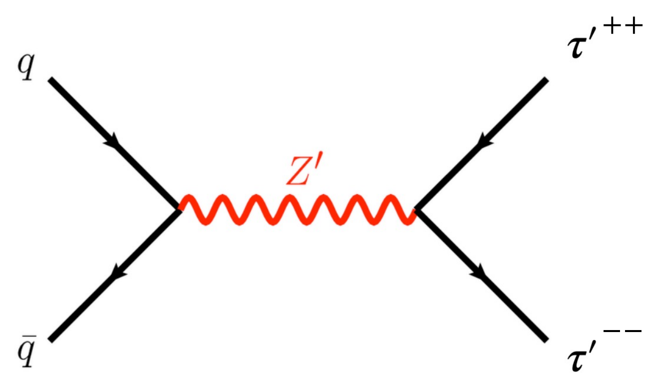
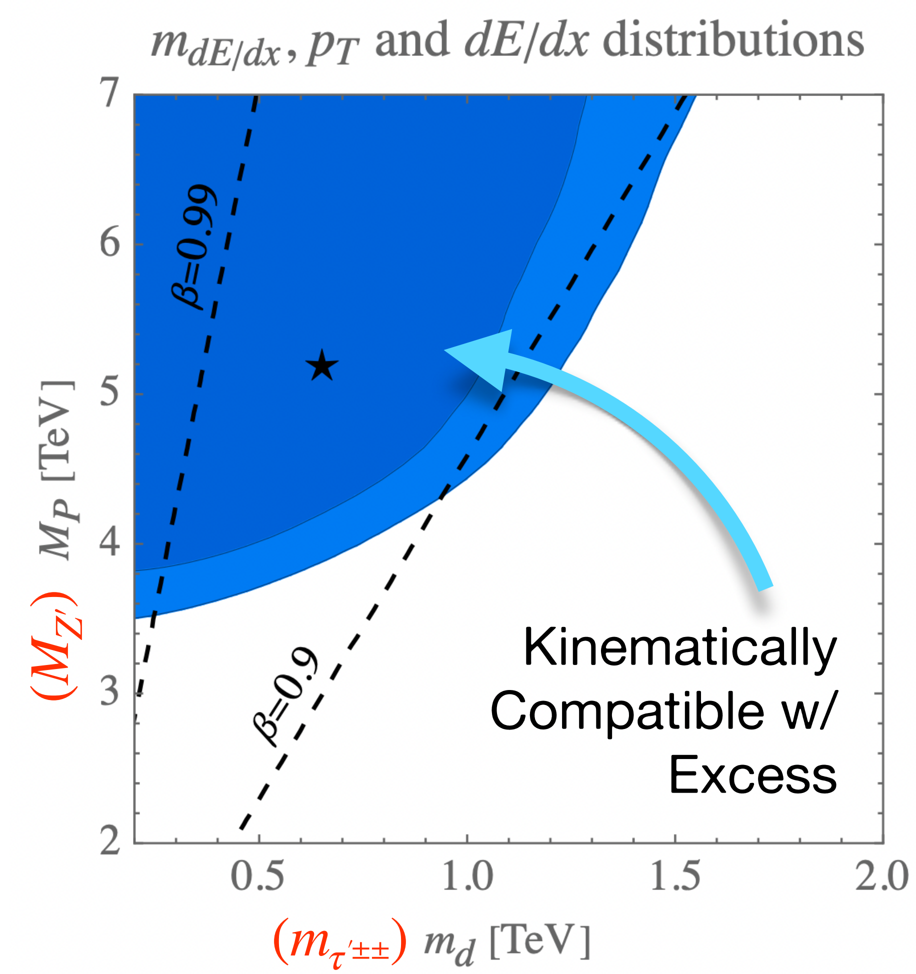
So let's look for this too





[2205.04473]

If there is an excess, we want confidence in result

Two parallel approaches:

1) A simple, very inclusive search.

Minimize look-elsewhere-effect

2) More exclusive channel.

If excess, measure properties
Else, set tighter limits

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Inclusive Ionization Channel

Mass Reconstruction Channel

Both analysis channels share common preselection and object definitions

ATLAS excess had a lot of muons

→ **Focus on muon trigger**

(50 GeV online)

101 fb^{-1}

2017-2018

(Phase-1 Pixels)

Tracker Barrel

for Homogeneous Measurements

High Quality Track w/ Ionization Info

Reduces pileup effects, combinatorial fakes, unlucky landau tails

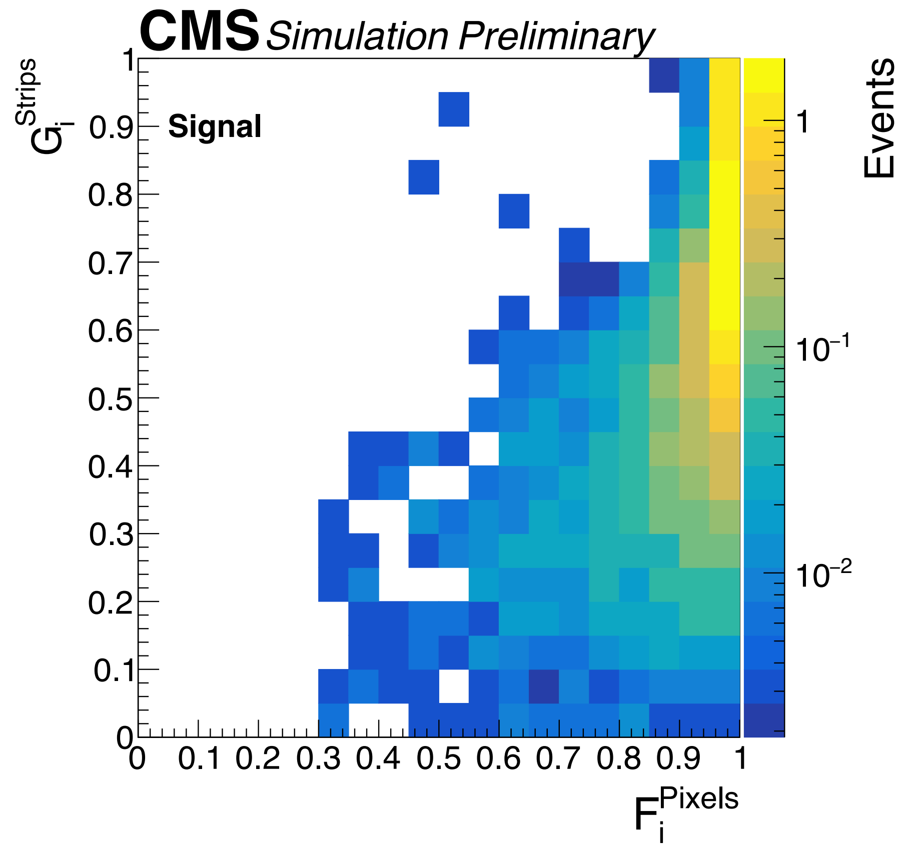
Isolation to ensure clean environment

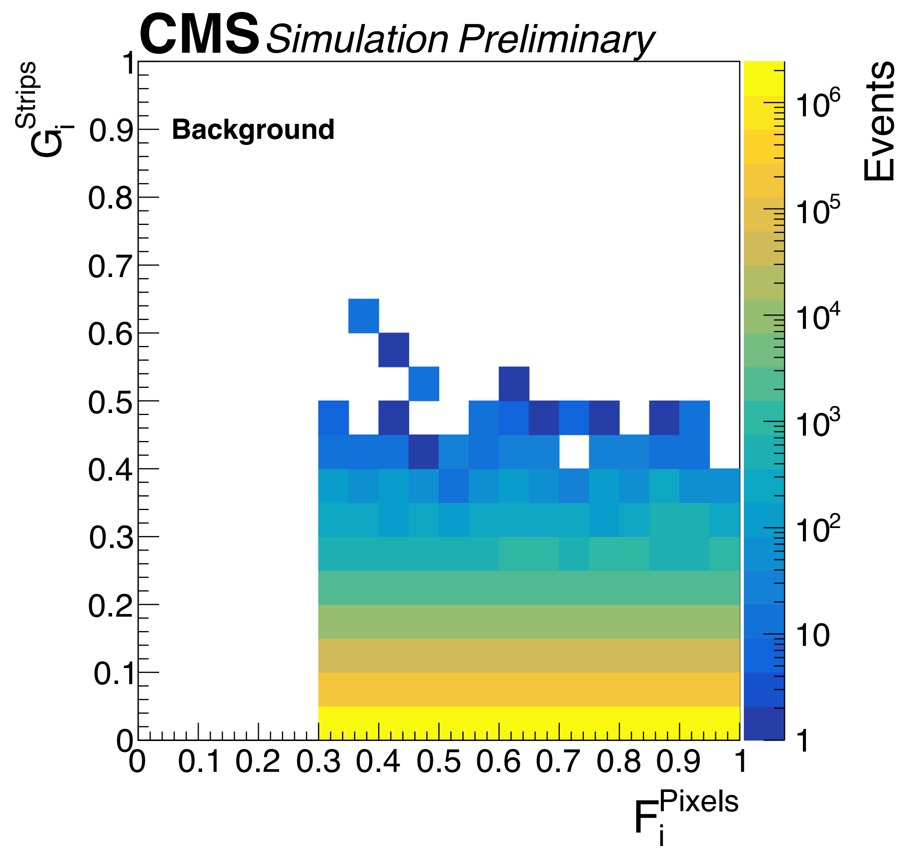
Reduces double-MIP BG (boosted hadrons, ɣ conversions, etc), dense core of jets

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
$\|\eta\| < 1$	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 $\chi^2/\mathrm{dof} < 5$	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

Inclusive Ionization Channel

- Simple, inclusive search channel prioritizing discovery
- Few bins to minimize look-elsewhere effect
- Require p_T>200 GeV
- Final analysis on two **uncorrelated** ionization measurements





Two methods to combine cluster ionization info.
Probability that a track is not a MIP

$$F_I^{Pixels} \qquad G_I^{Strips}$$

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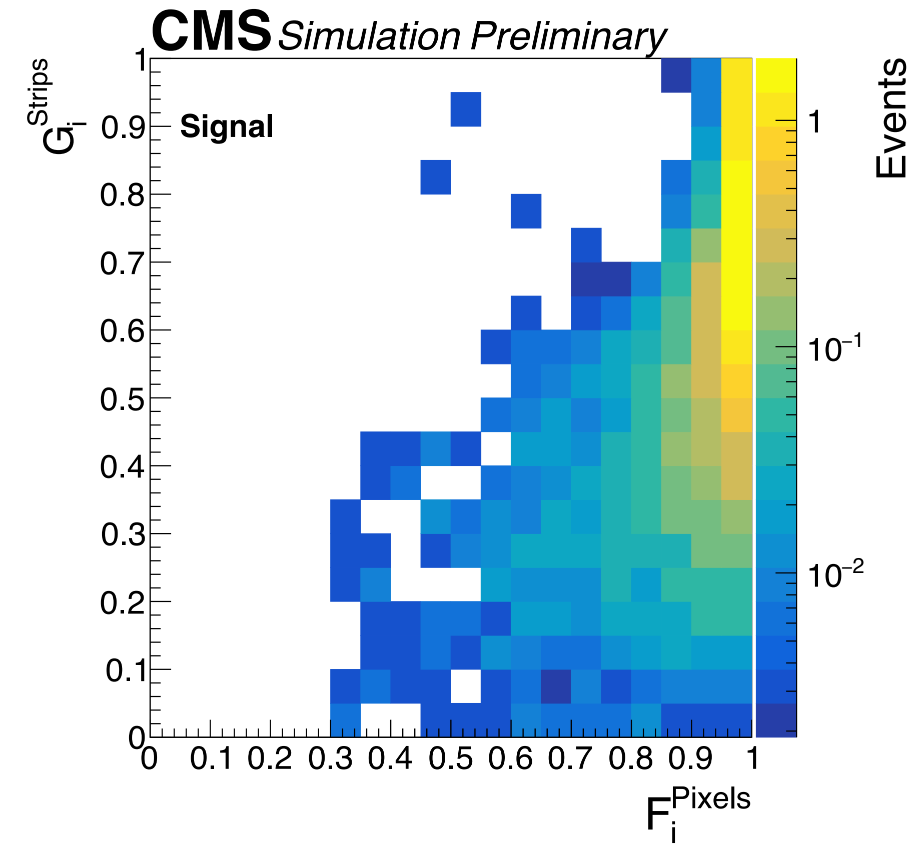

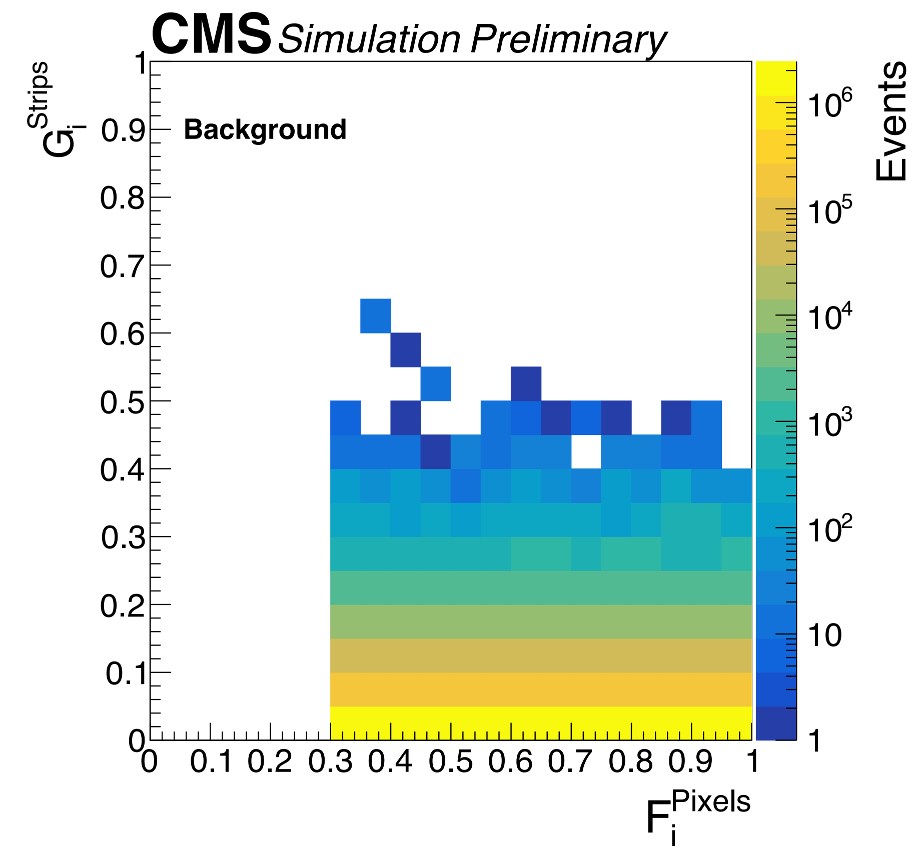

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F_I^{Pixels} G_I^{Strips}

MIP Background: 0-1
Signal →1

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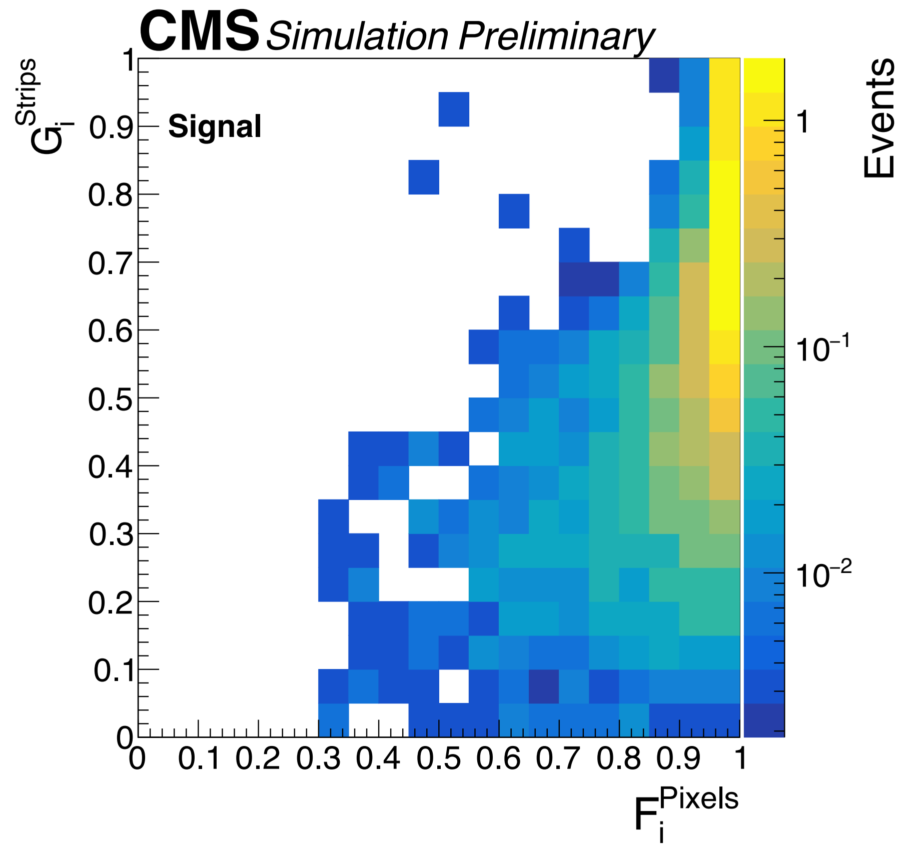

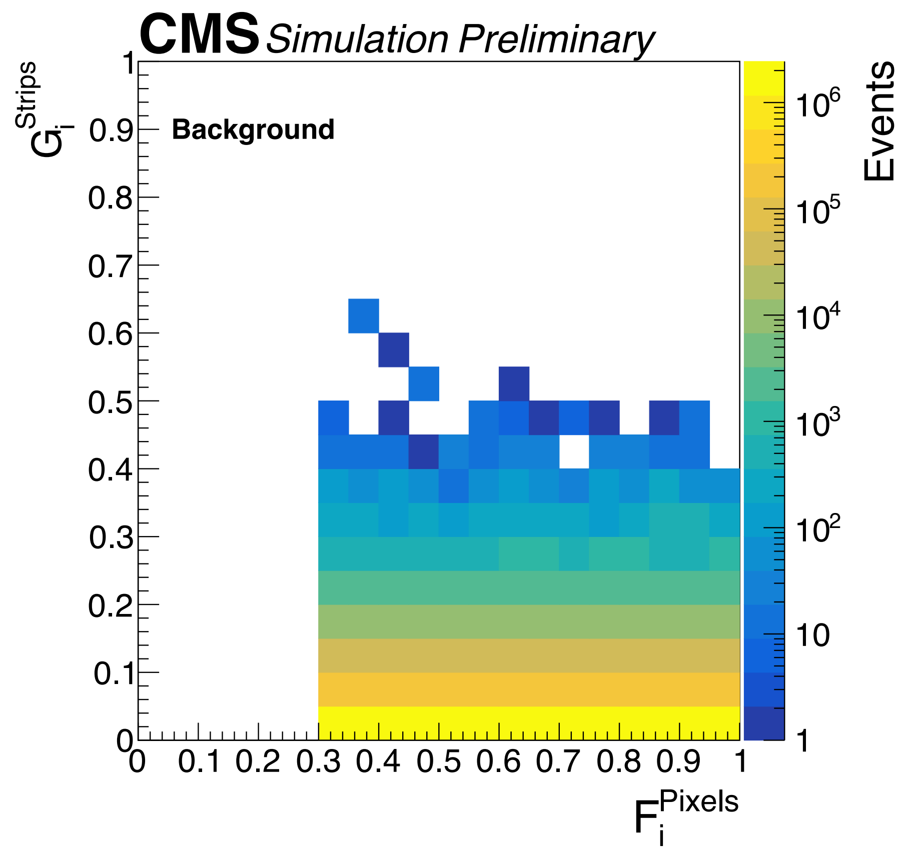

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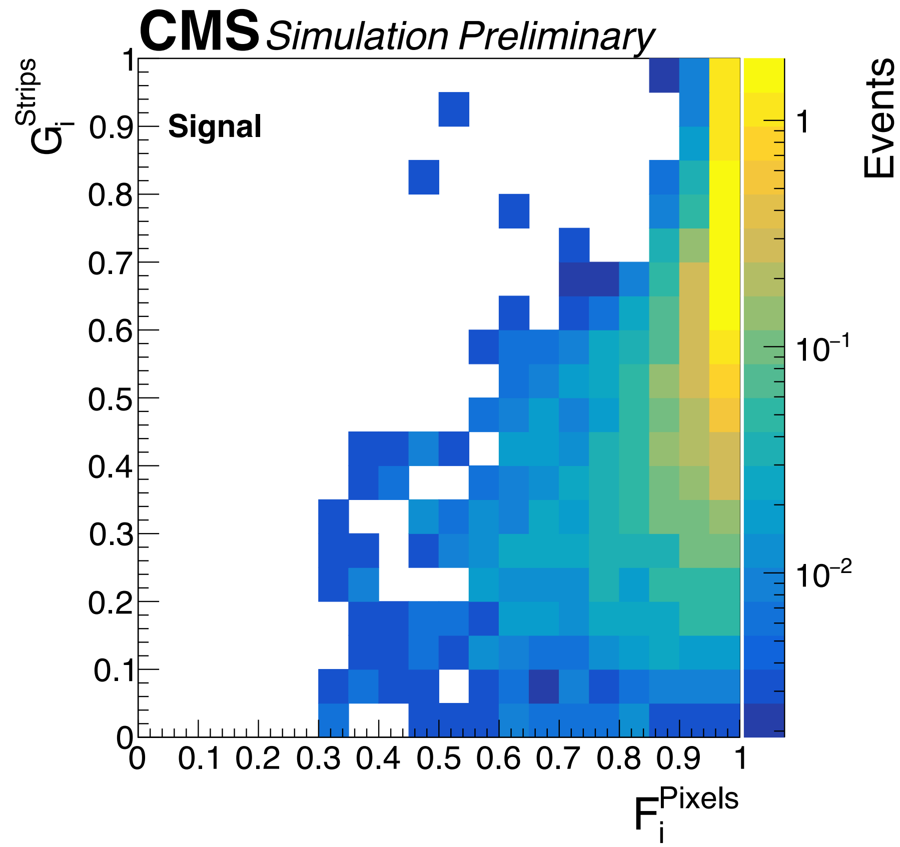

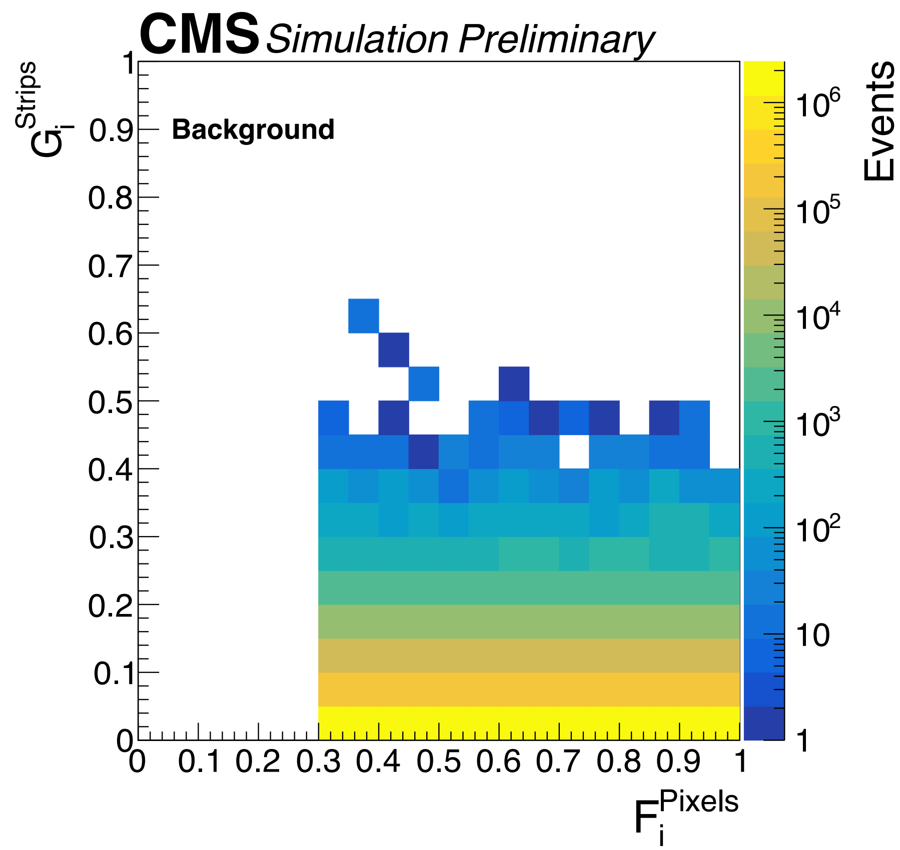

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Probability that a track is not a MIP

F_I^{Pixels}

MIP Background: 0-1
Signal →1

G_I^{Strips}

MIP Background →0
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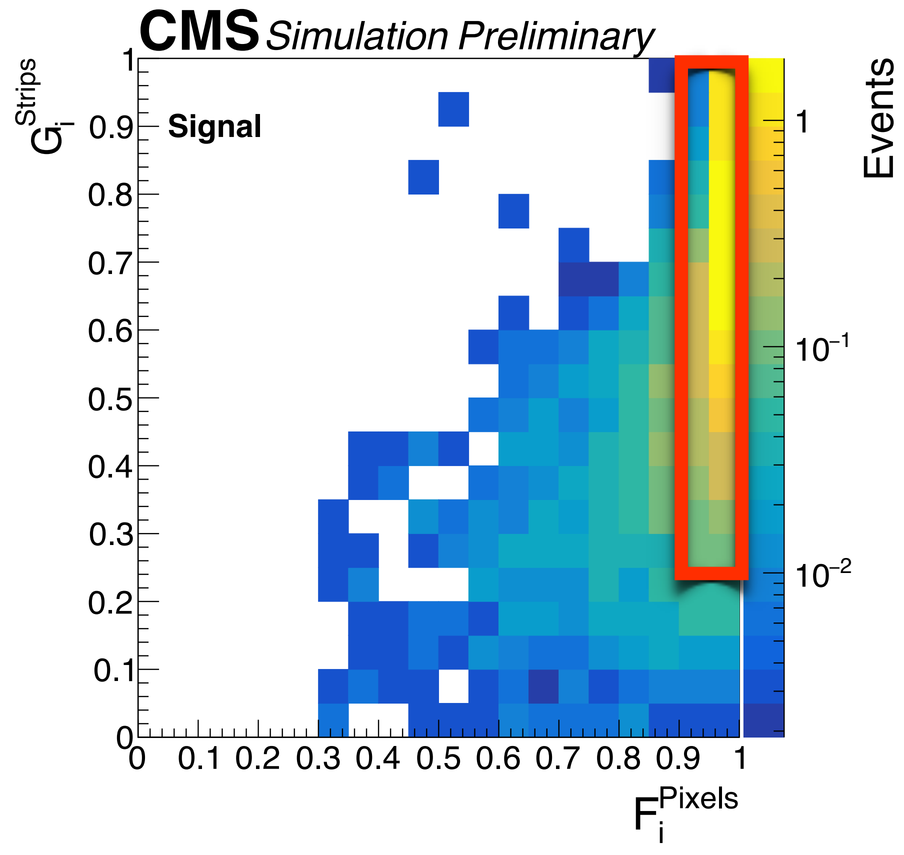

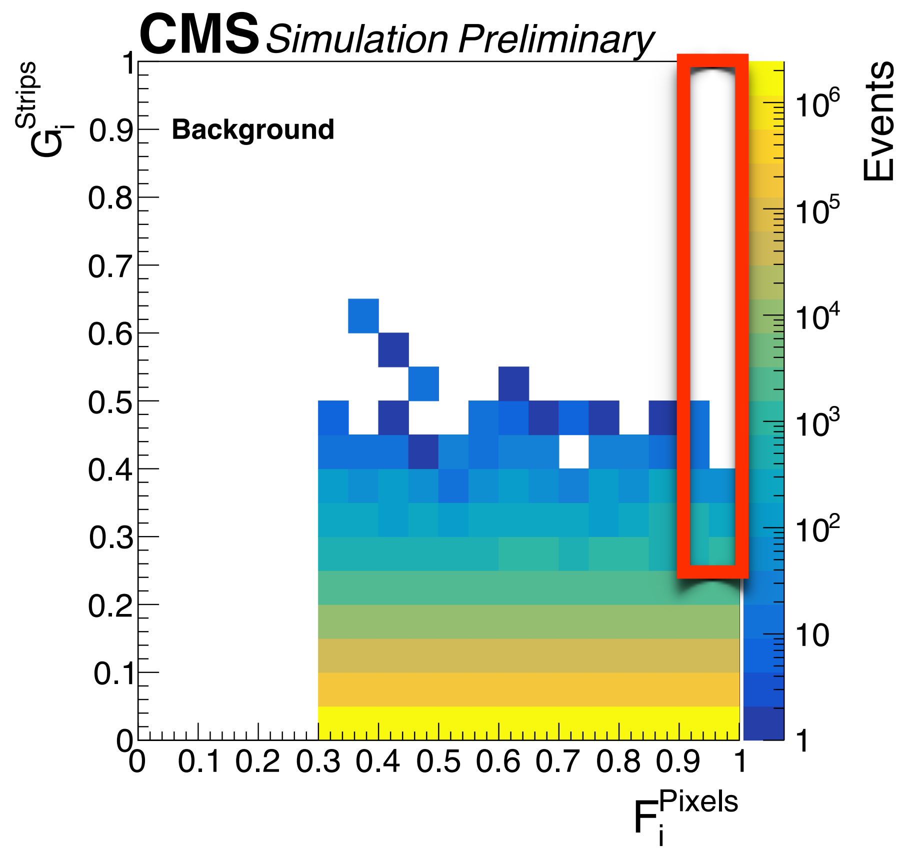

Two methods to combine cluster ionization info.

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F_I^{Pixels}

MIP Background: 0-1

Signal →1

G_I^{Strips}

MIP Background →0

Signal →1

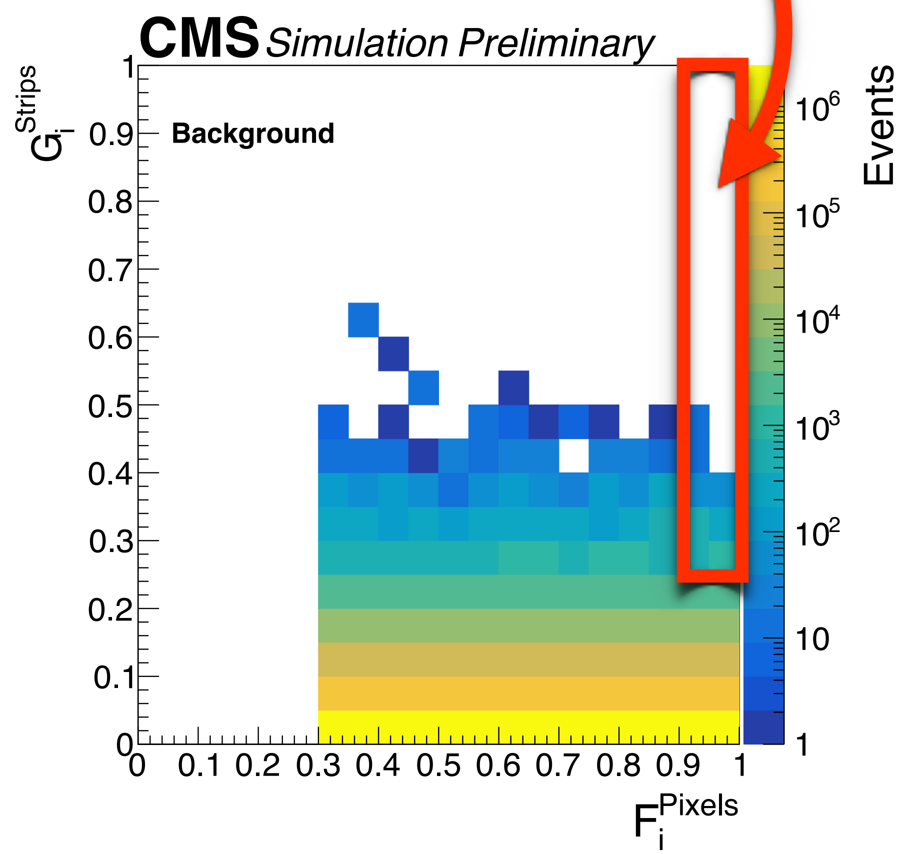
I : **"Ionization"**

Background Estimation

F_I^{Pixels} and G_I^{Strips} are uncorrelated for BG

→ Constrain SR BG assuming CR has the same distribution

Want to estimate BG contribution up here



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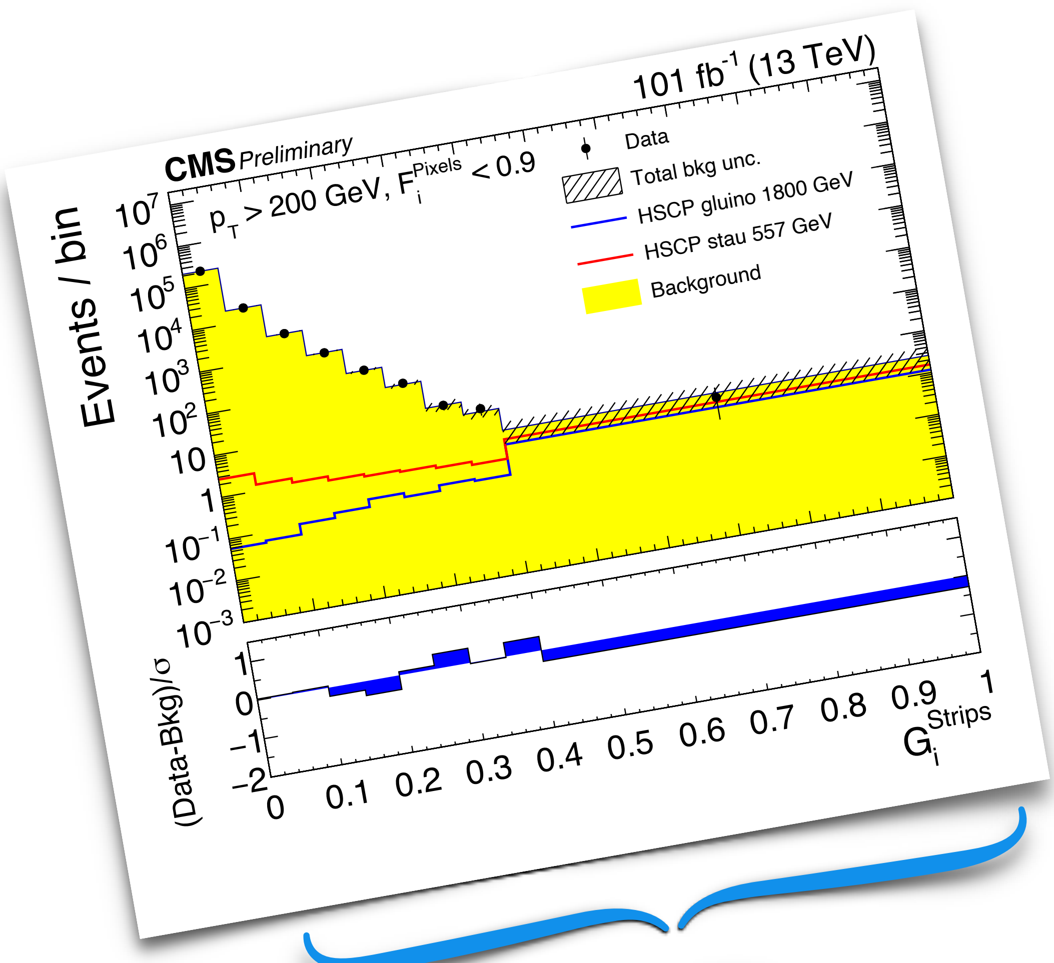
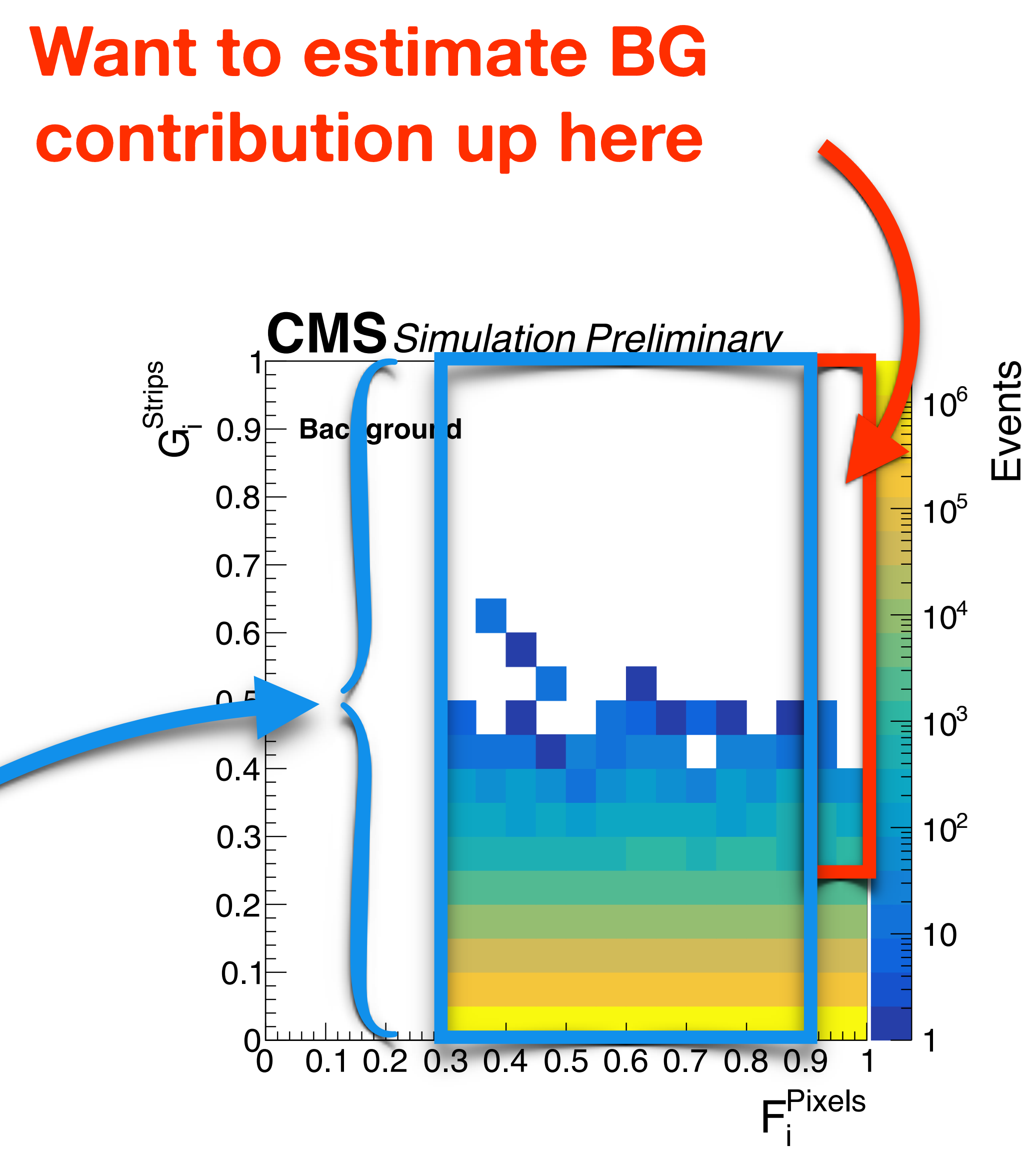


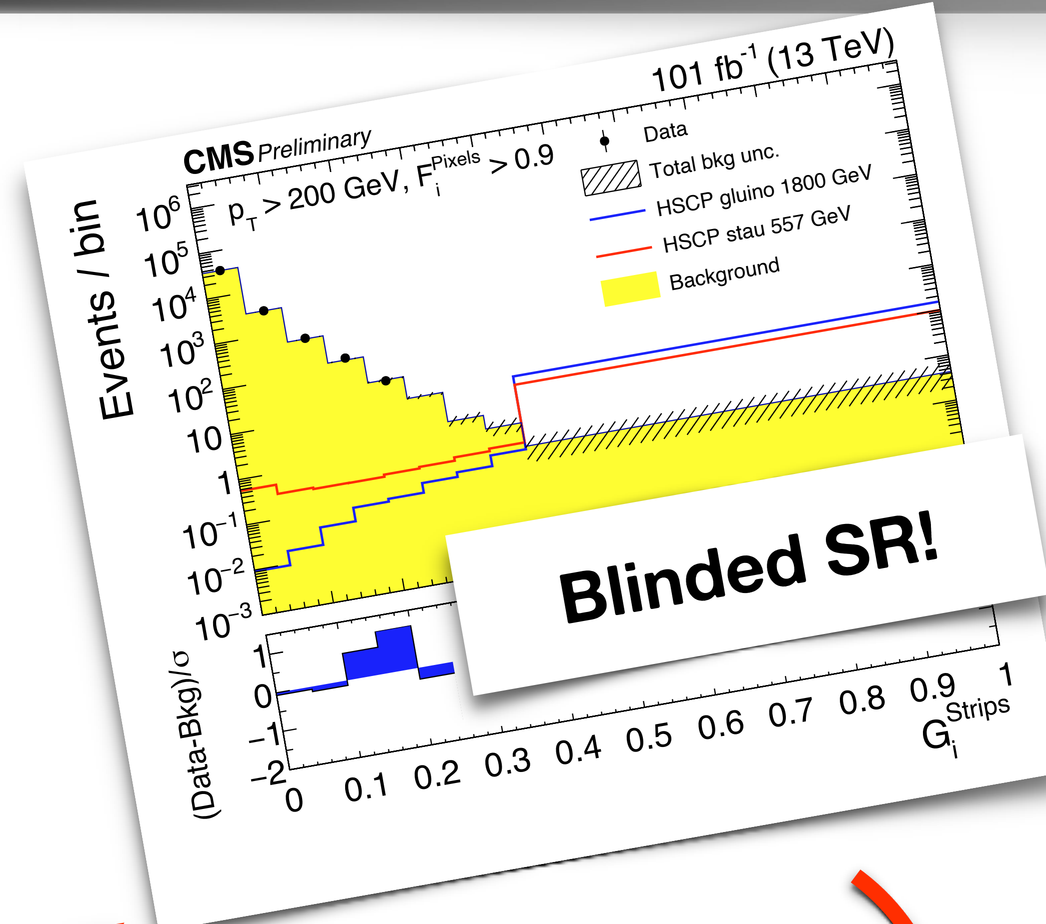


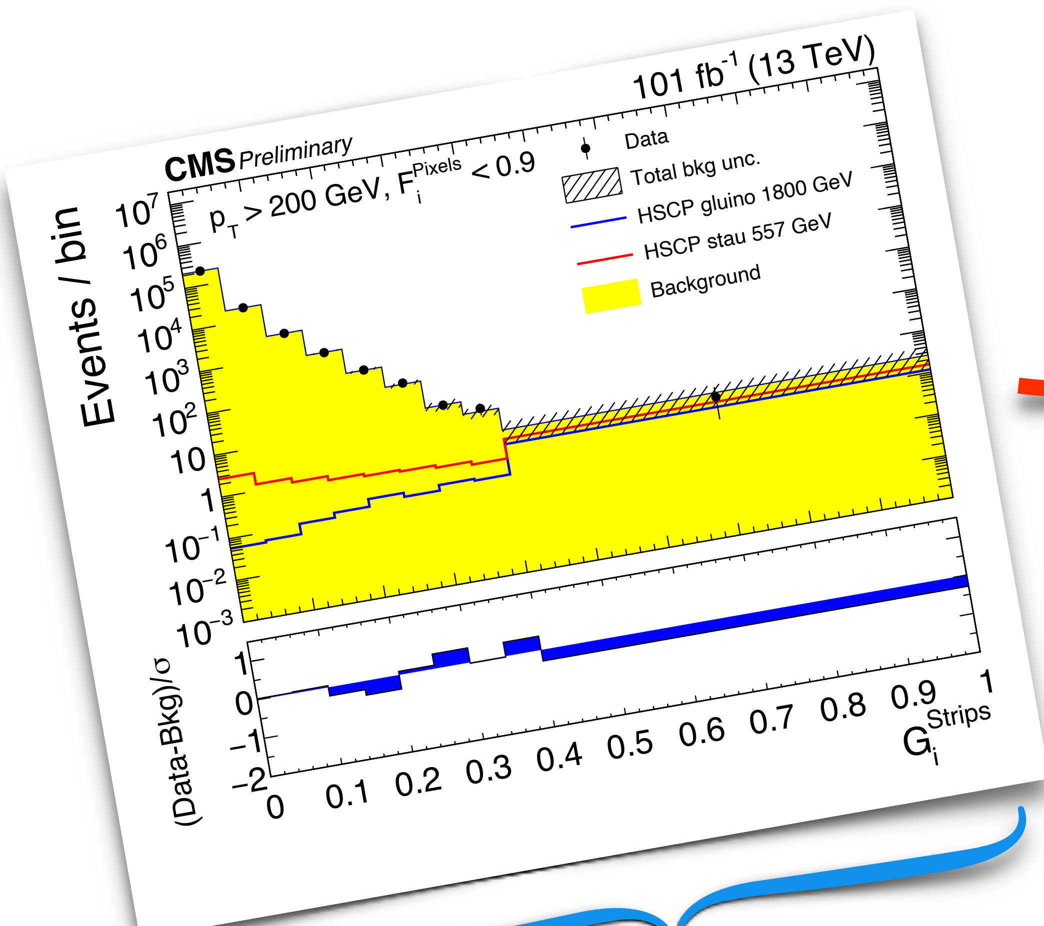
Background Estimation

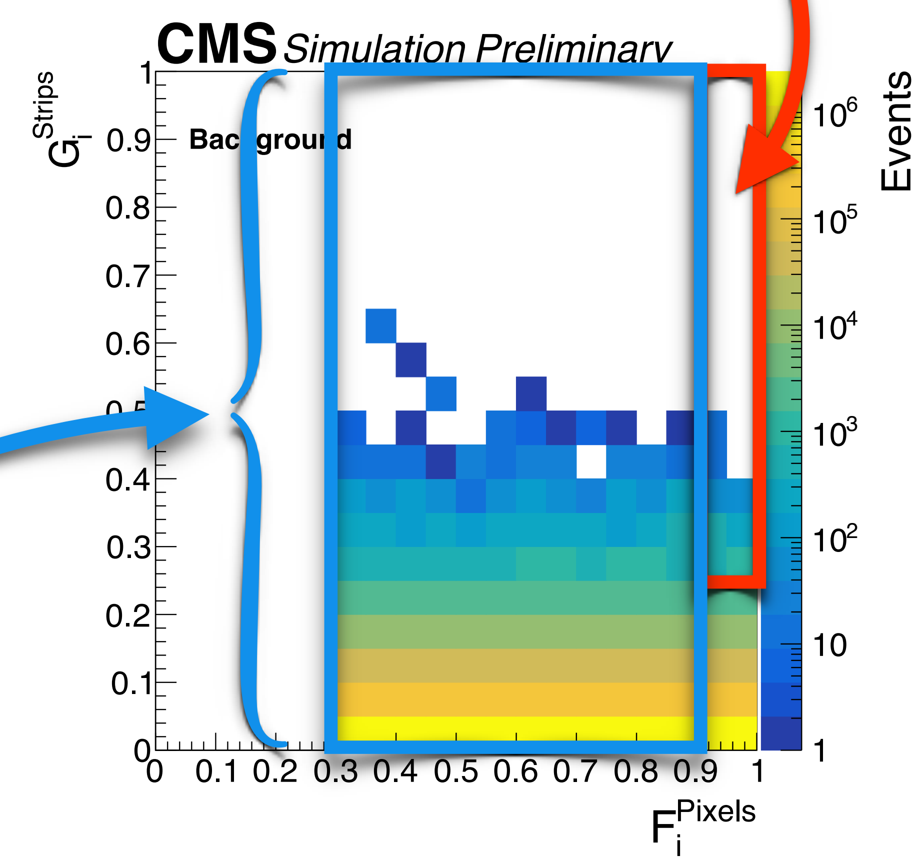
Select p_T>200 GeV, F_I^{Pixels}>0.9

And do shape fit at **G>0.25**

SR sensitivity dominated by last bin in G_I^{Strips}







Mass Reconstruction Method

Suppresses large dE/dx values in Landau tail

Add ≥10 cluster ionization measurements in inverted quadrature. Gives stable ionization measurement.

$$I_h = \left(\frac{1}{N} \sum_j^N \left(\frac{dE}{dx} \right)_j^{-2} \right)^{-\frac{1}{2}}$$

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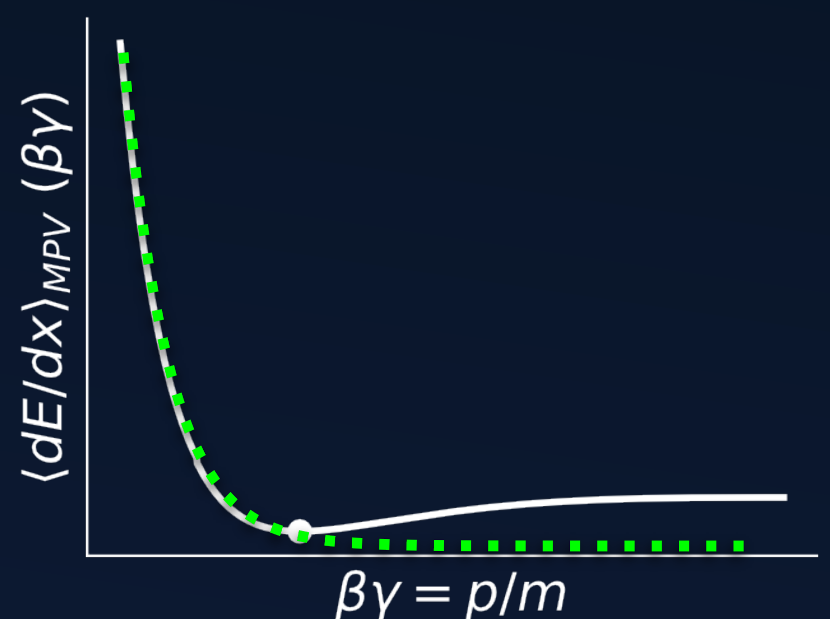
Assume we're in a region where the ionization scales as $1/(\beta\gamma)^2$

$$I_h = \frac{K}{(\beta\gamma)^2} + C = K\left(\frac{m^2}{p^2}\right) + C$$



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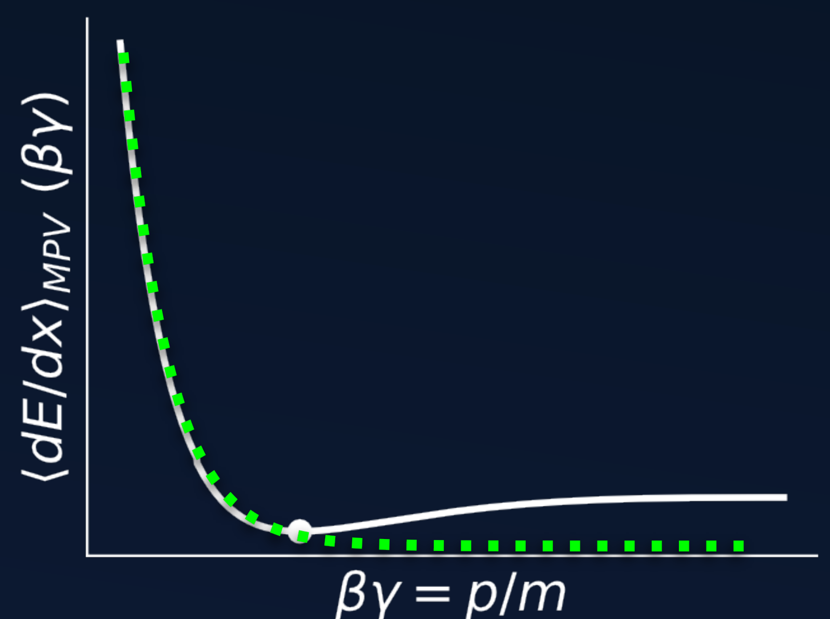

Solve for the mass

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

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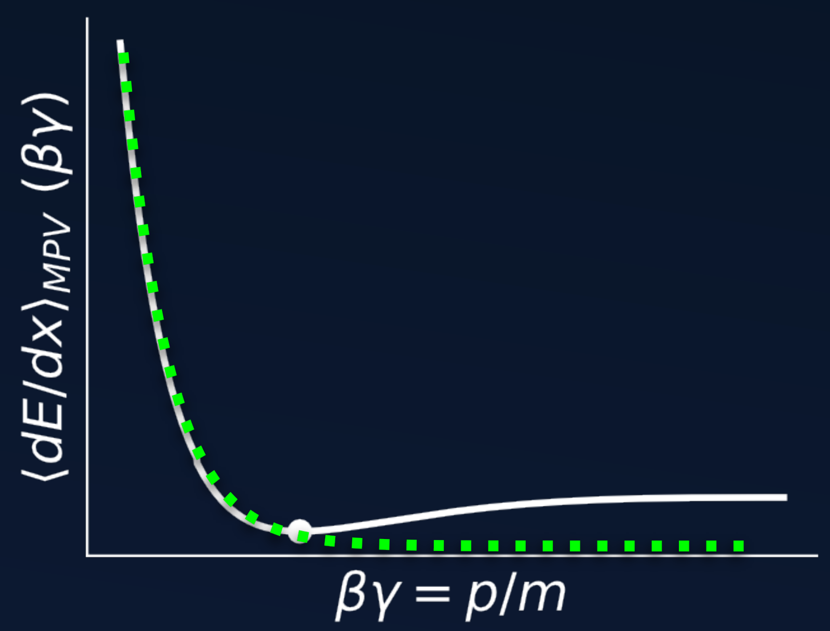

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Use low momentum $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ as standard candles to calibrate

Mass Reconstruction Method

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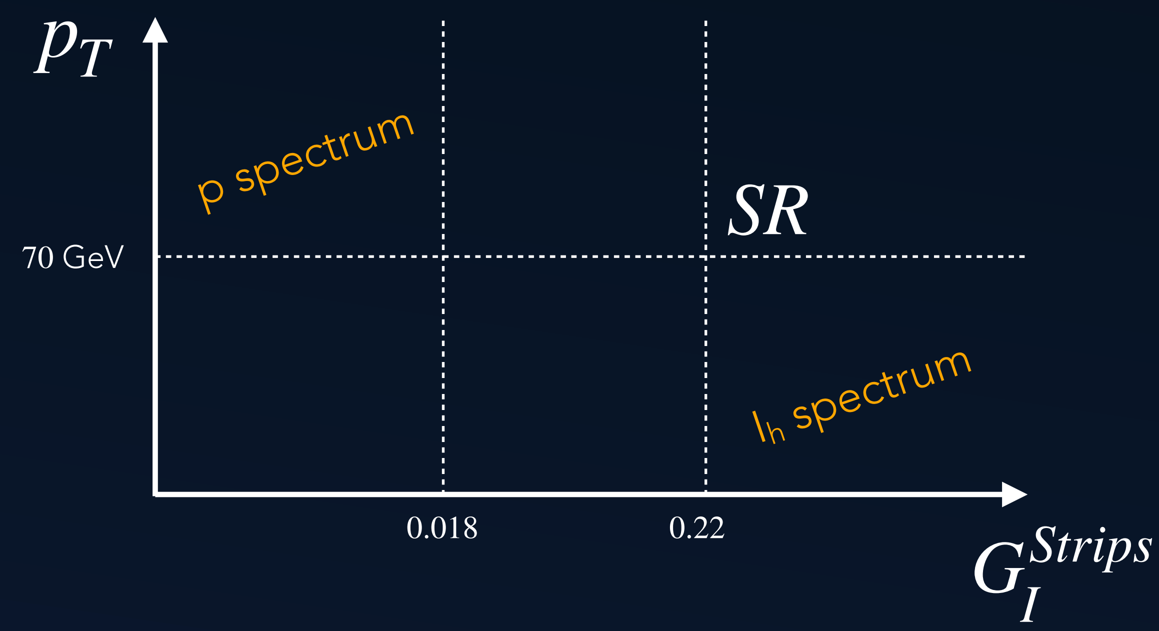
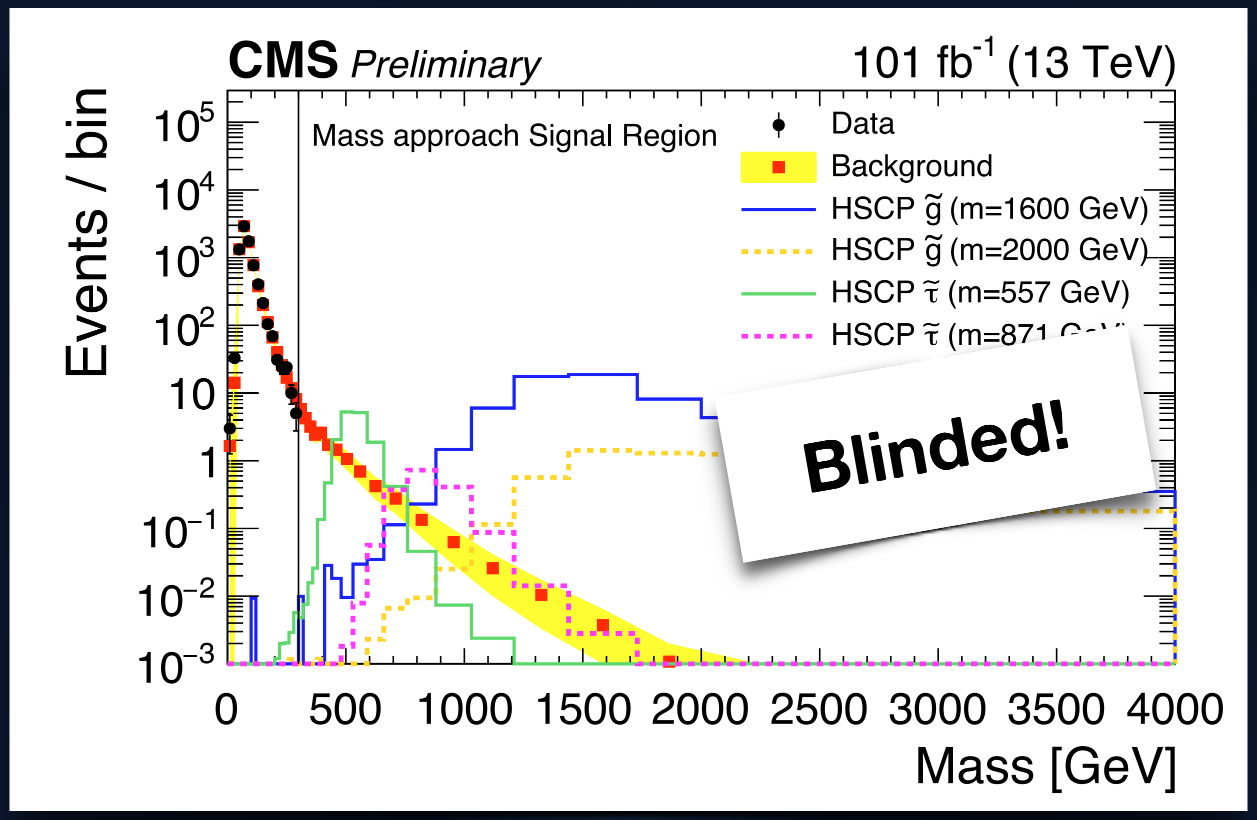


In BG, the momentum and ionization should be uncorrelated

Mix and match momentum and I_h values from different CRs to create a mass template

Validate in intermediate ionization region



Mass Reconstruction Method

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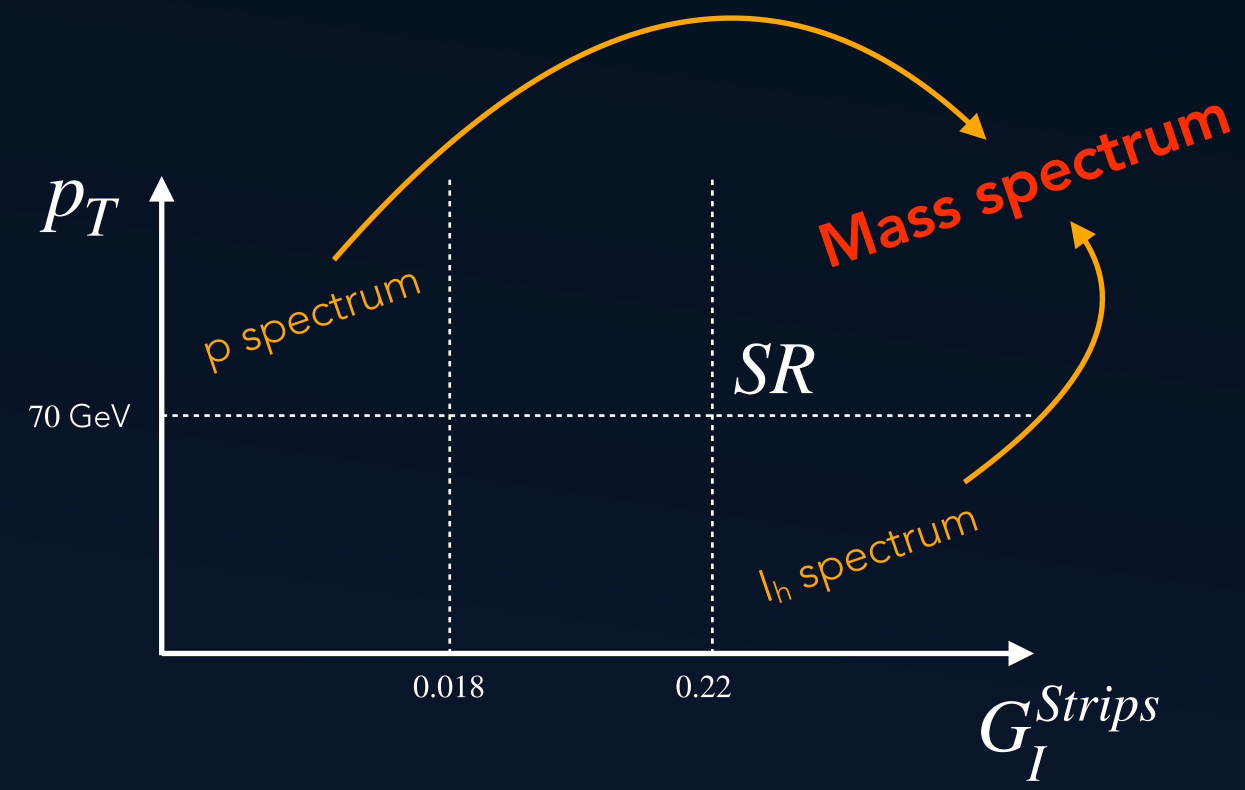
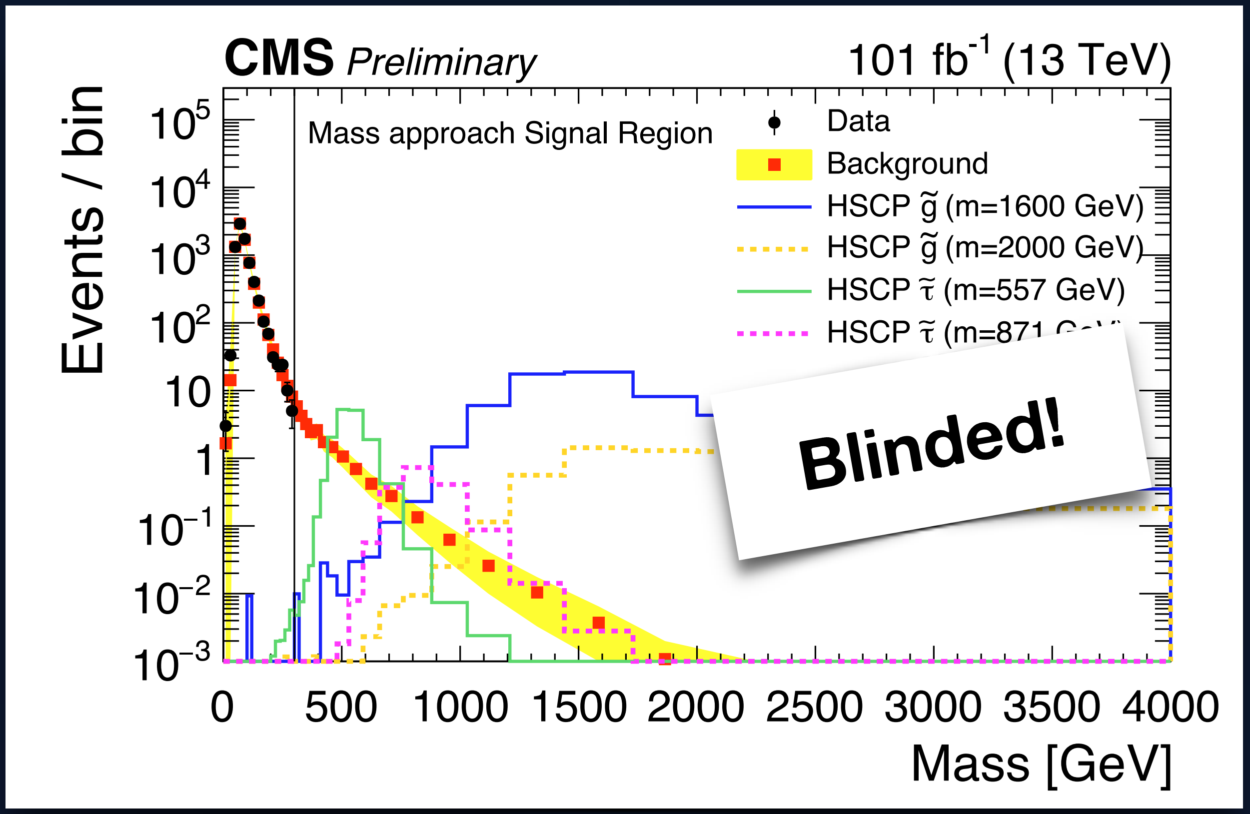


In BG, the momentum and ionization should be uncorrelated

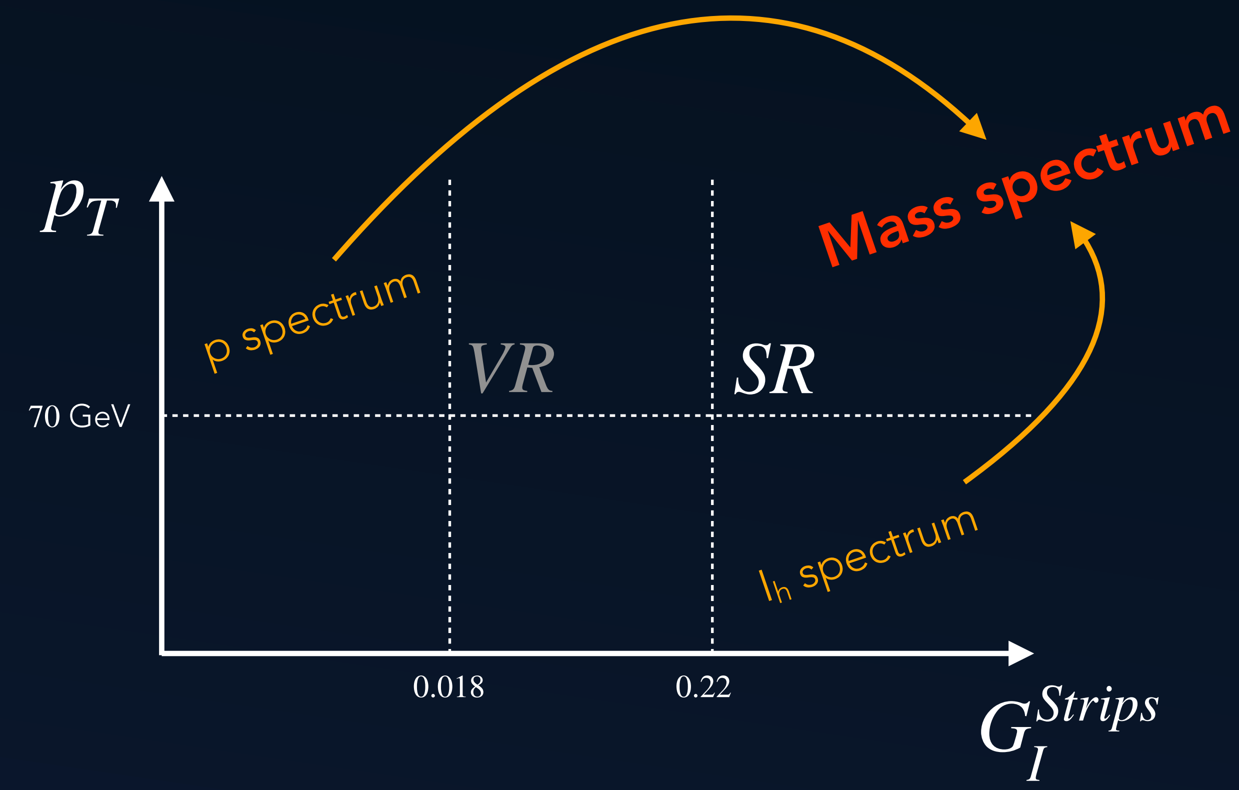
Mix and match momentum and I_h values from different CRs to create a mass template

Validate in intermediate ionization region



Mass Reconstruction Method

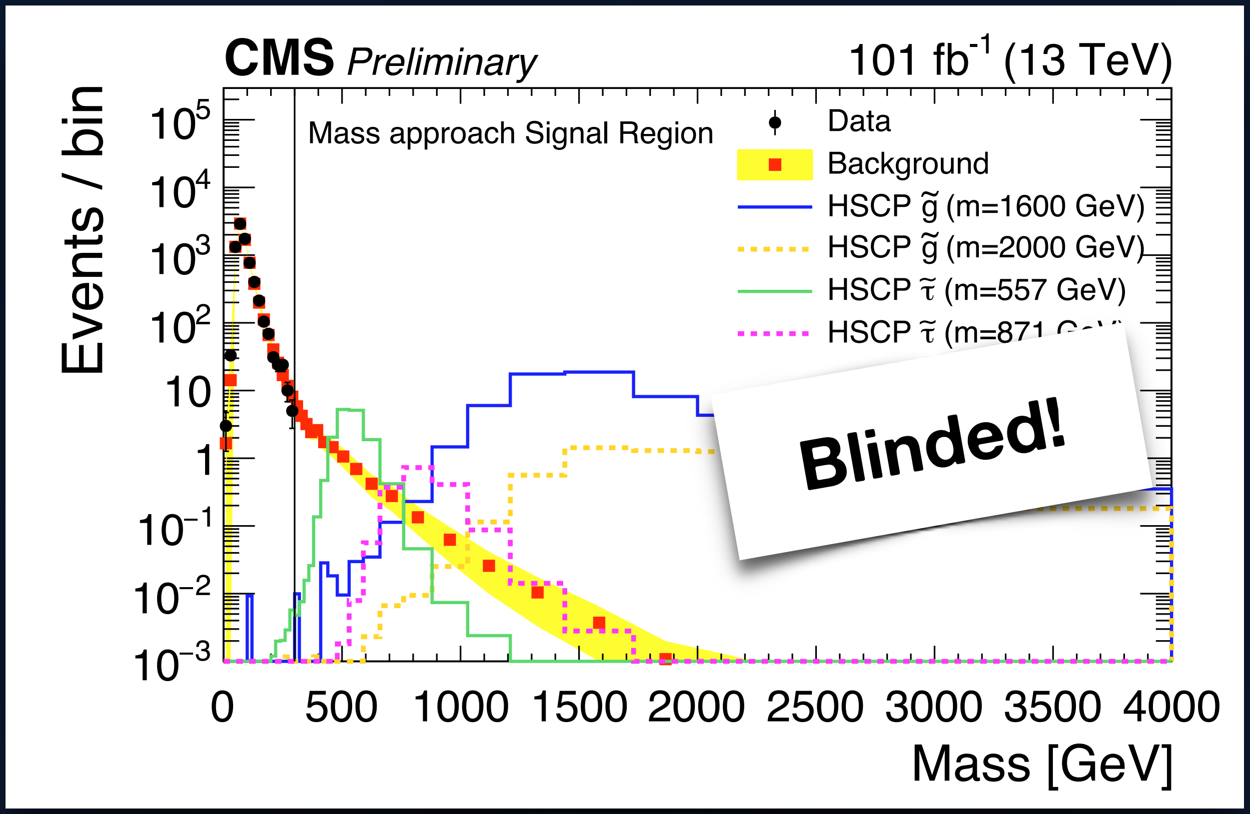
$$m = p\sqrt{\frac{I_h - C}{K}}$$



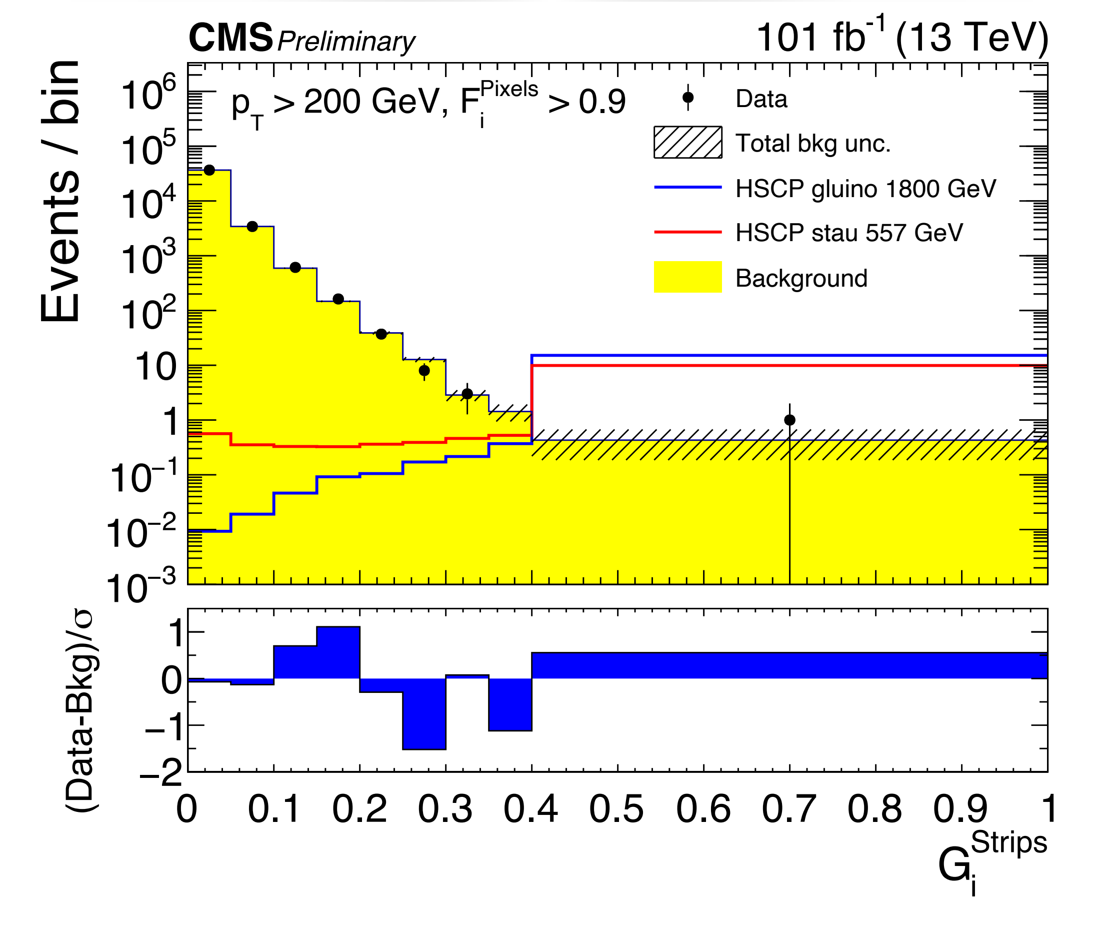
In BG, the momentum and ionization should be **uncorrelated**

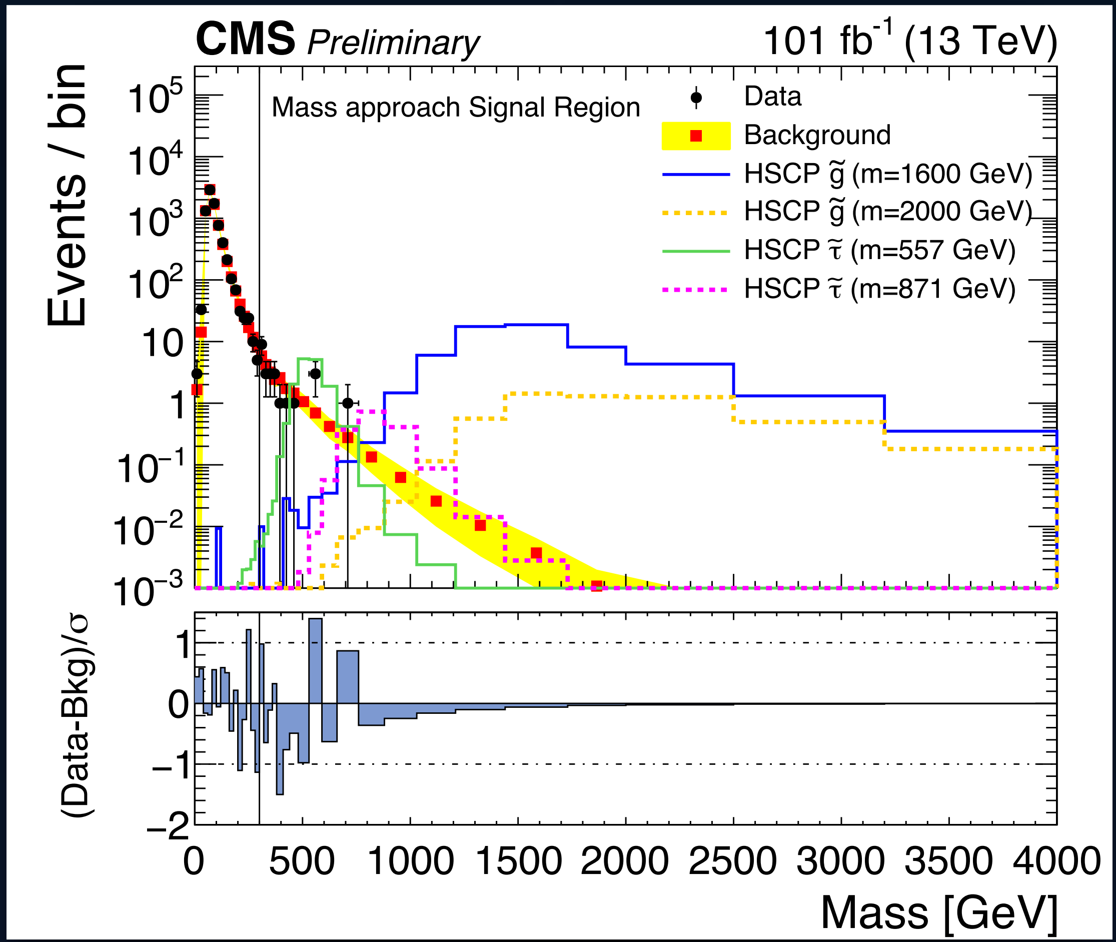
Mix and match momentum and I_h values from different CRs to create a mass template

Validate in intermediate ionization region

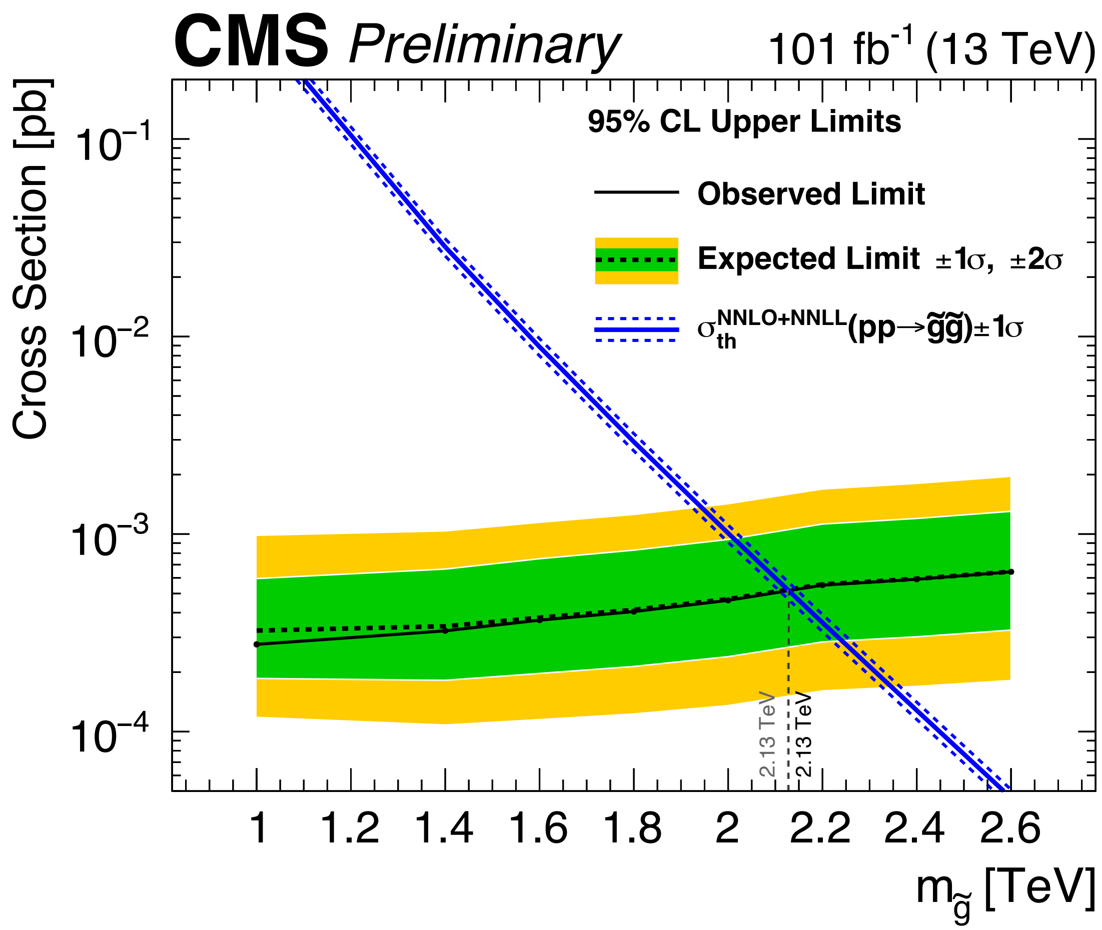


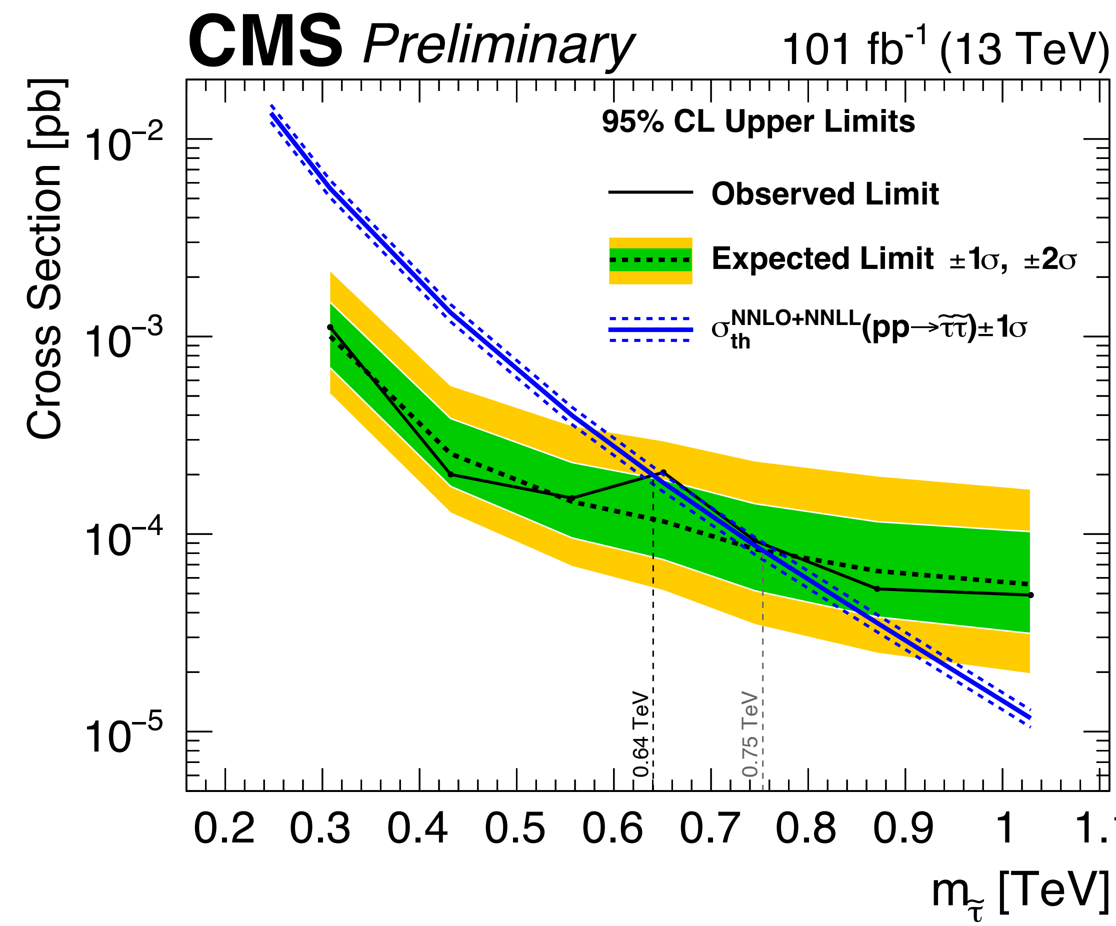
Unblinded Results

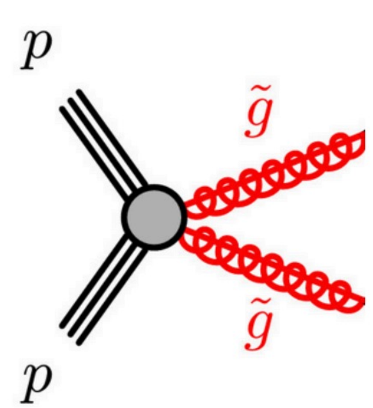


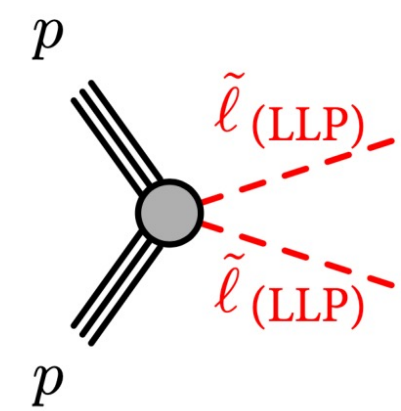


Good agreement with SM expectation









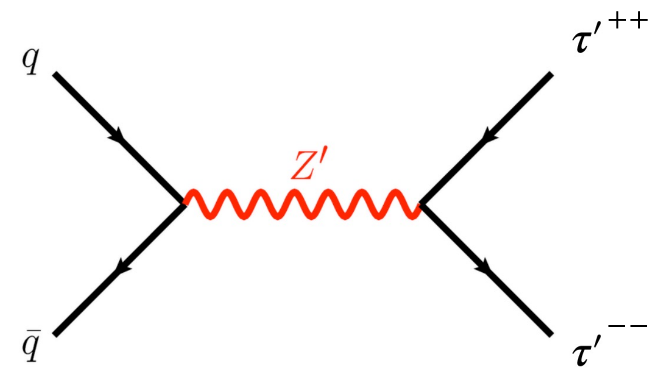
Long-Lived Gluino R-Hadron

(Strong production, mini-split-SUSY motivated, OOTB Pythia 8 R-Hadron Spectrum)

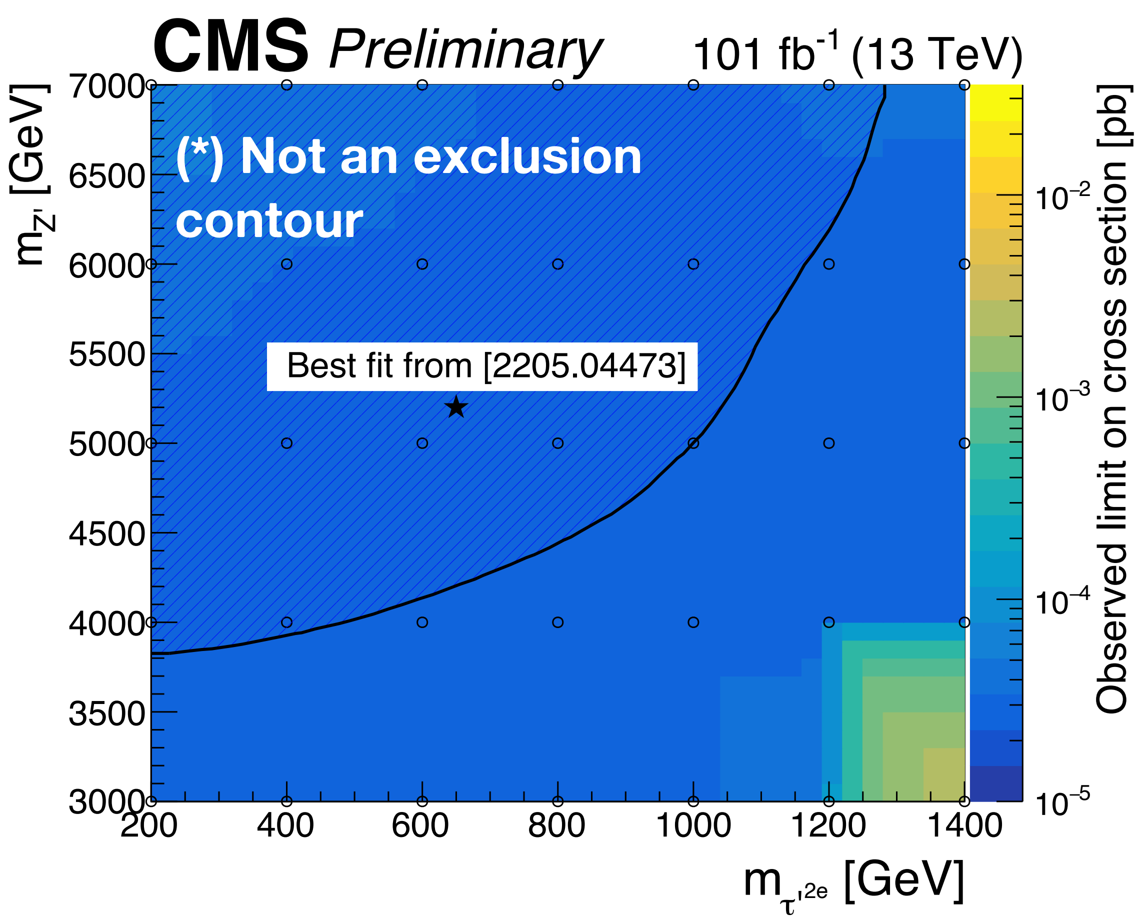
Long-Lived Sleptons/Staus

(Drell-Yan Production, GMSB/GGM Motivated)

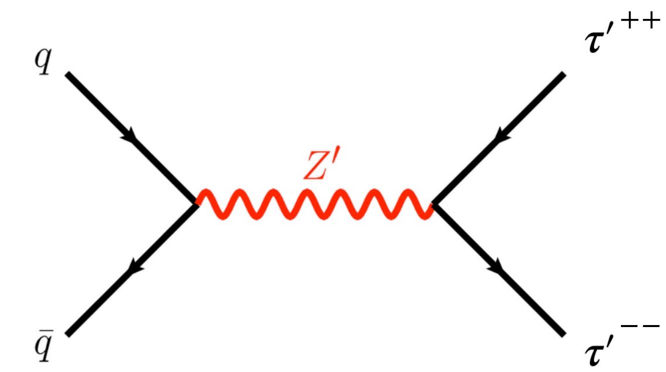
Boosted ±2e Model

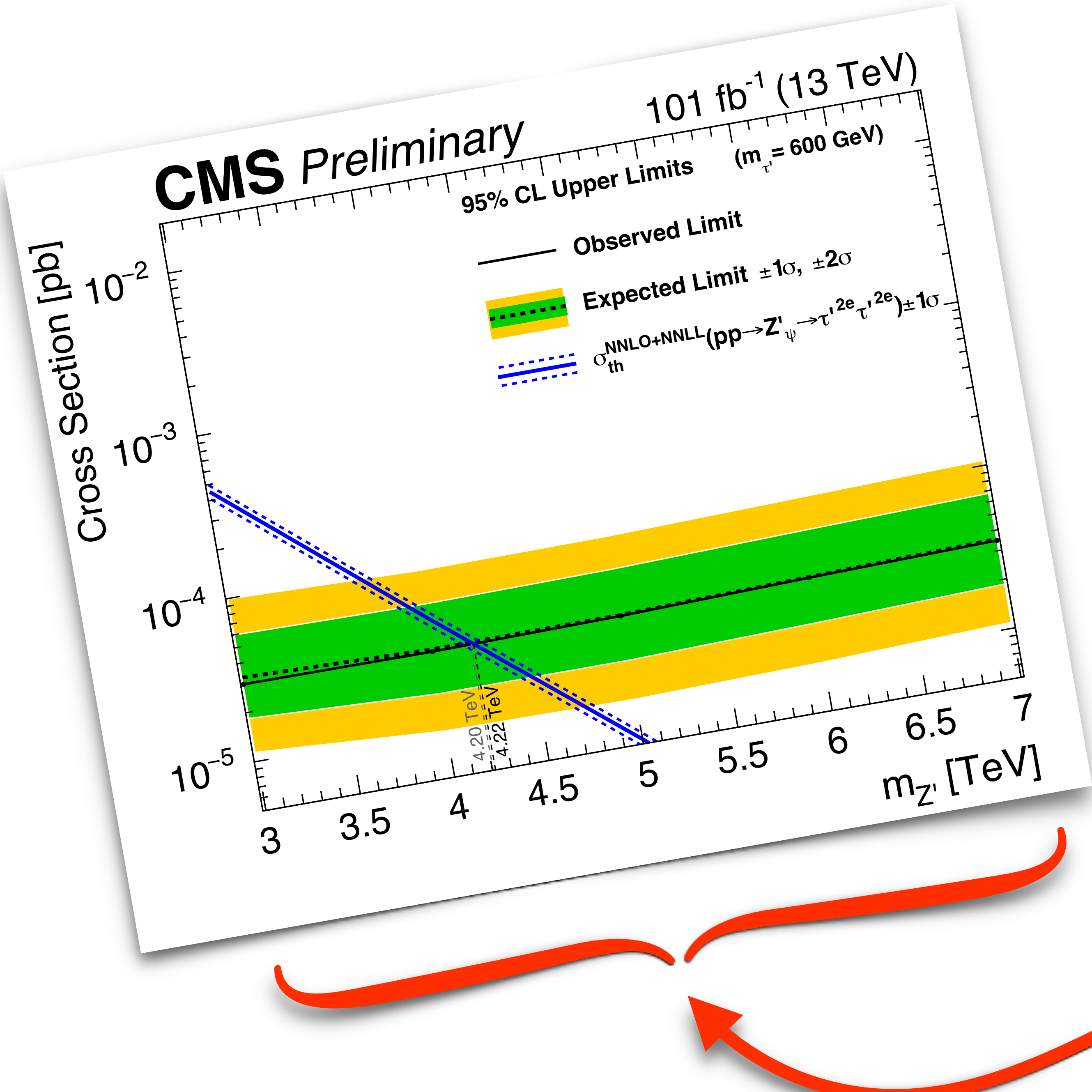


High mass Z' to boosted doubly-charged lepton-like LLPs



Boosted ±2e Model





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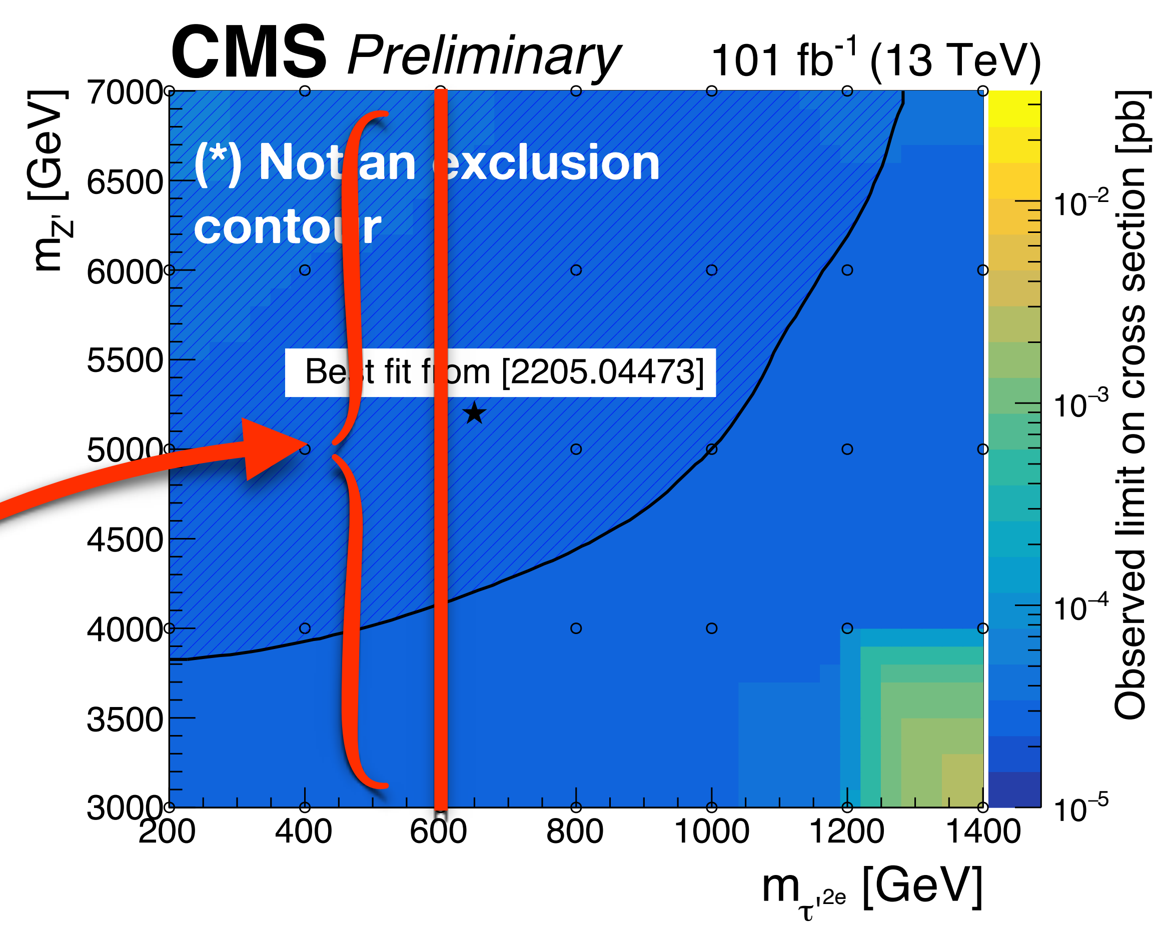
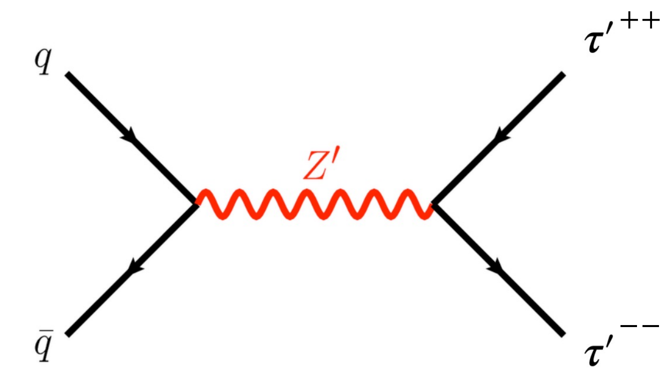
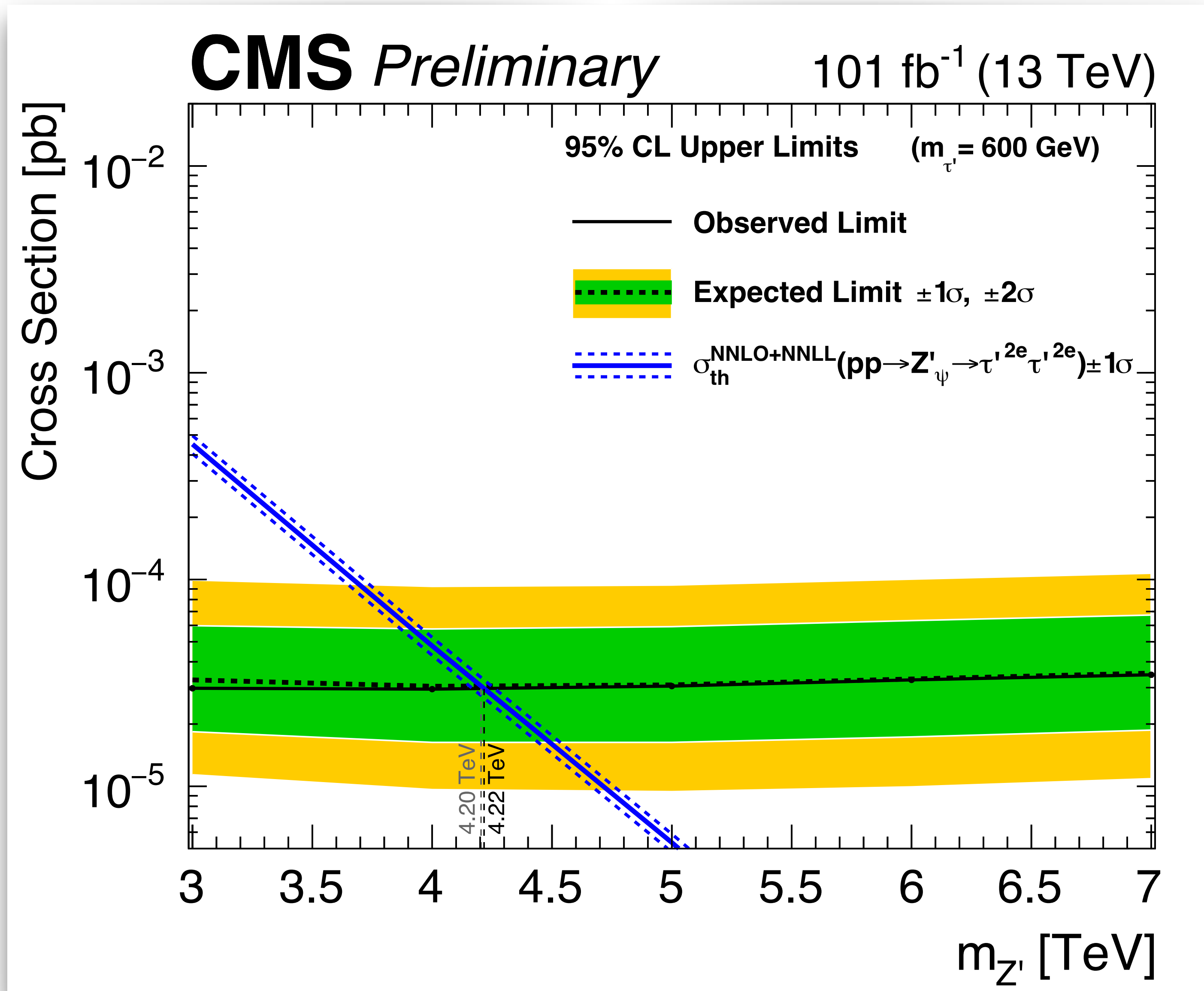


Boosted ±2e Model



ATLAS didn't release A×ϵ numbers for this kind of model



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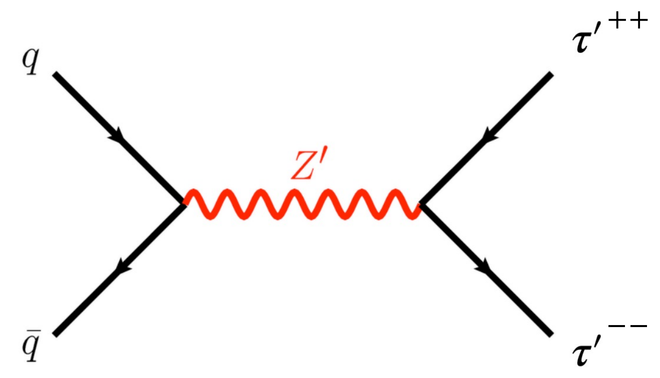

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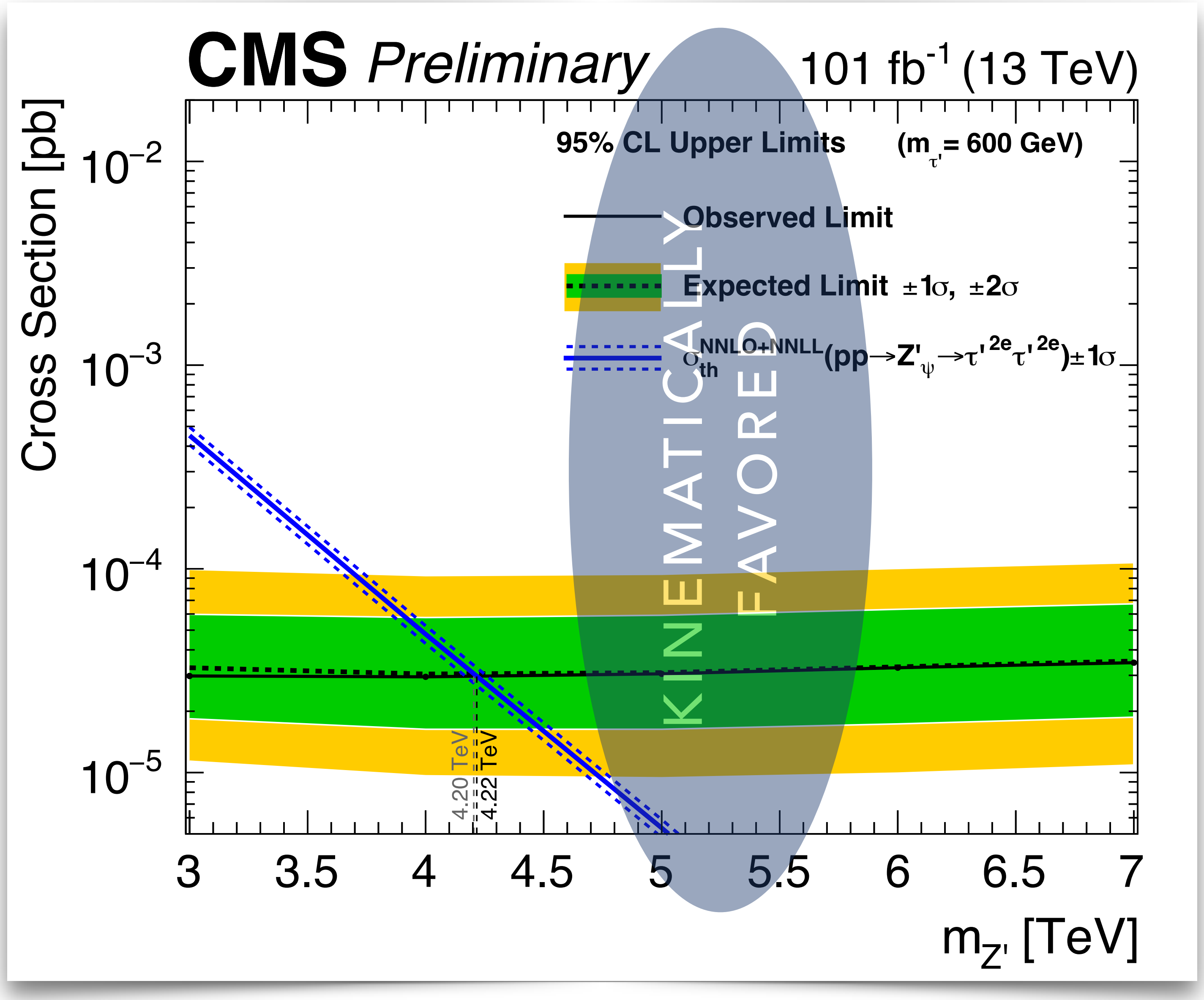
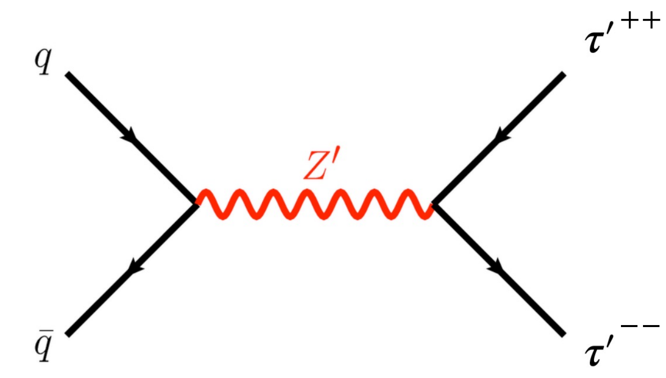
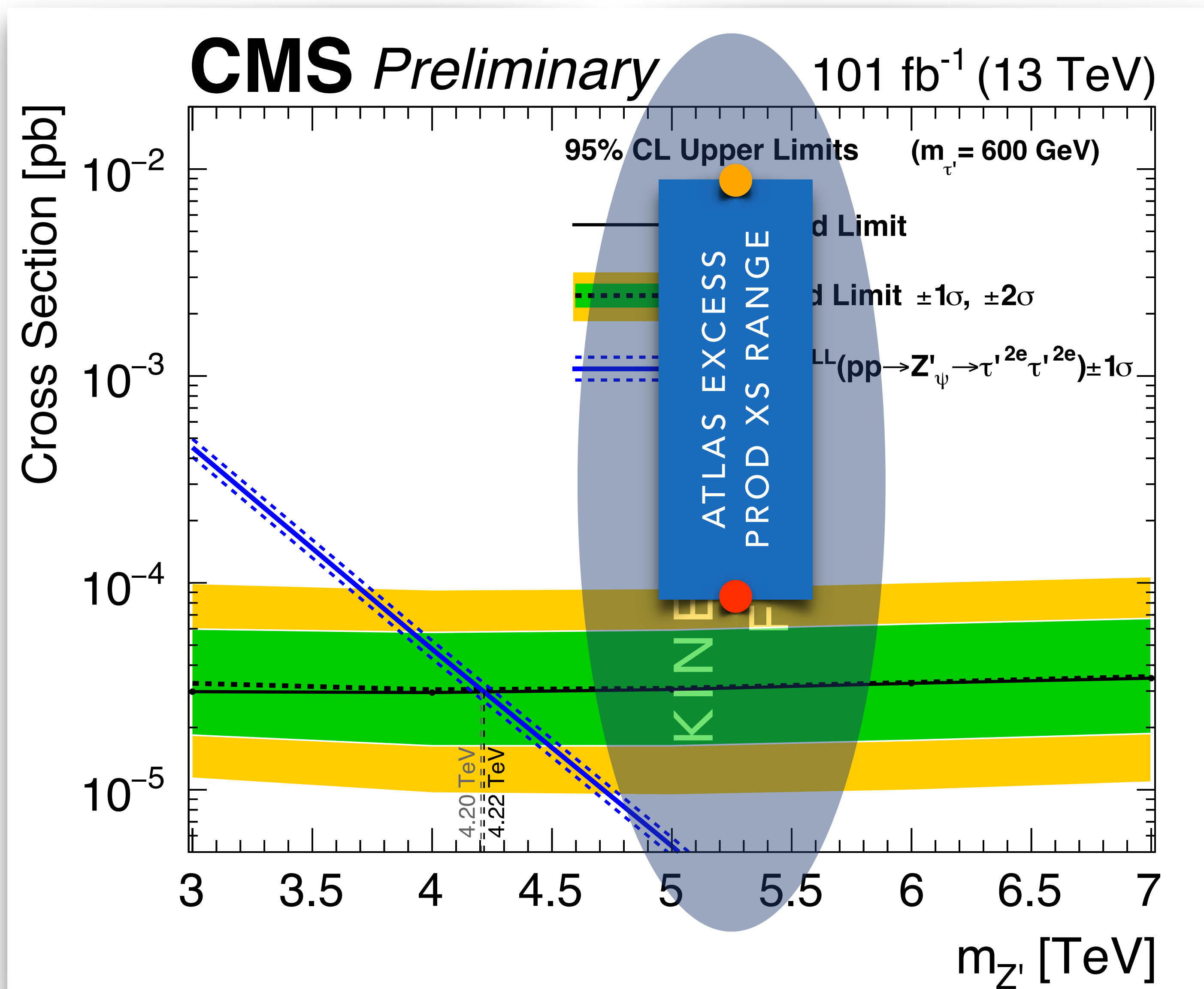


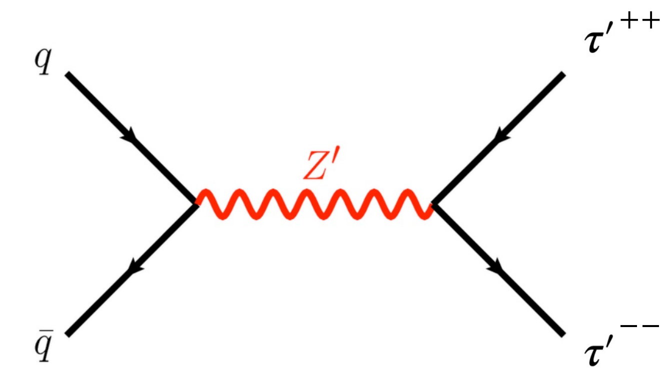
Boosted ±2e Model



ATLAS didn't release A×ϵ numbers for this kind of model



Boosted ±2e Model



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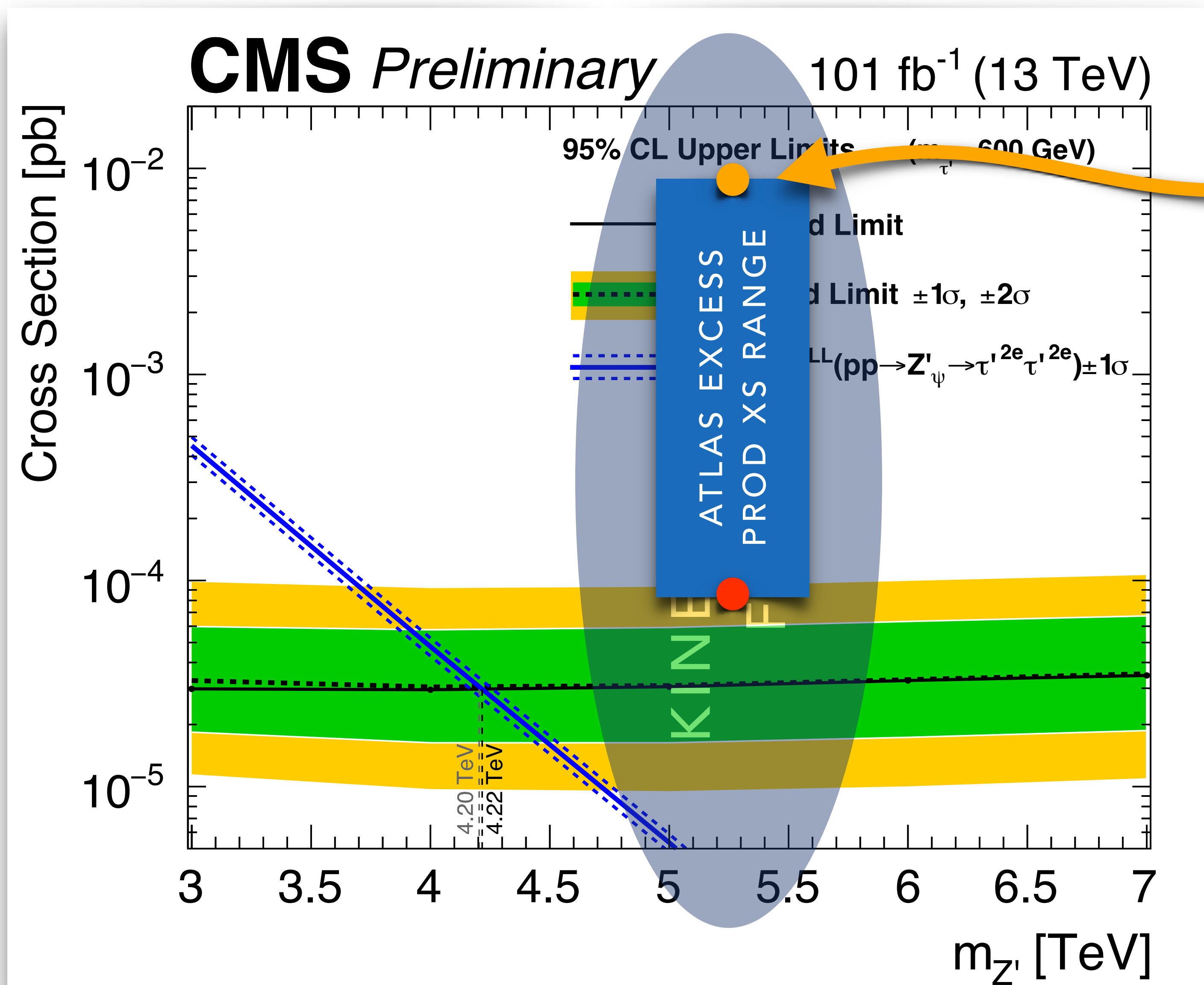
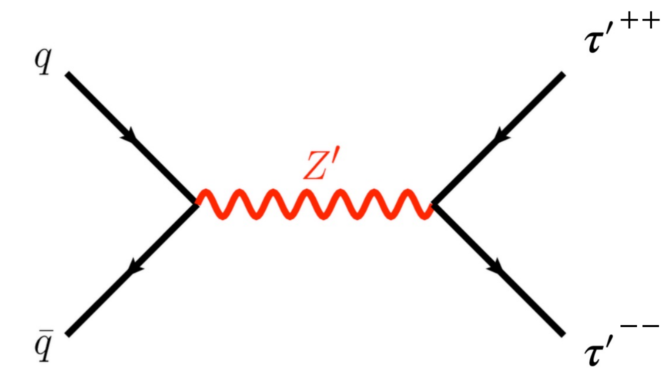


Using ATLAS Aux Material: If A×ϵ~1%, this explanation is ruled out

Boosted ±2e Model



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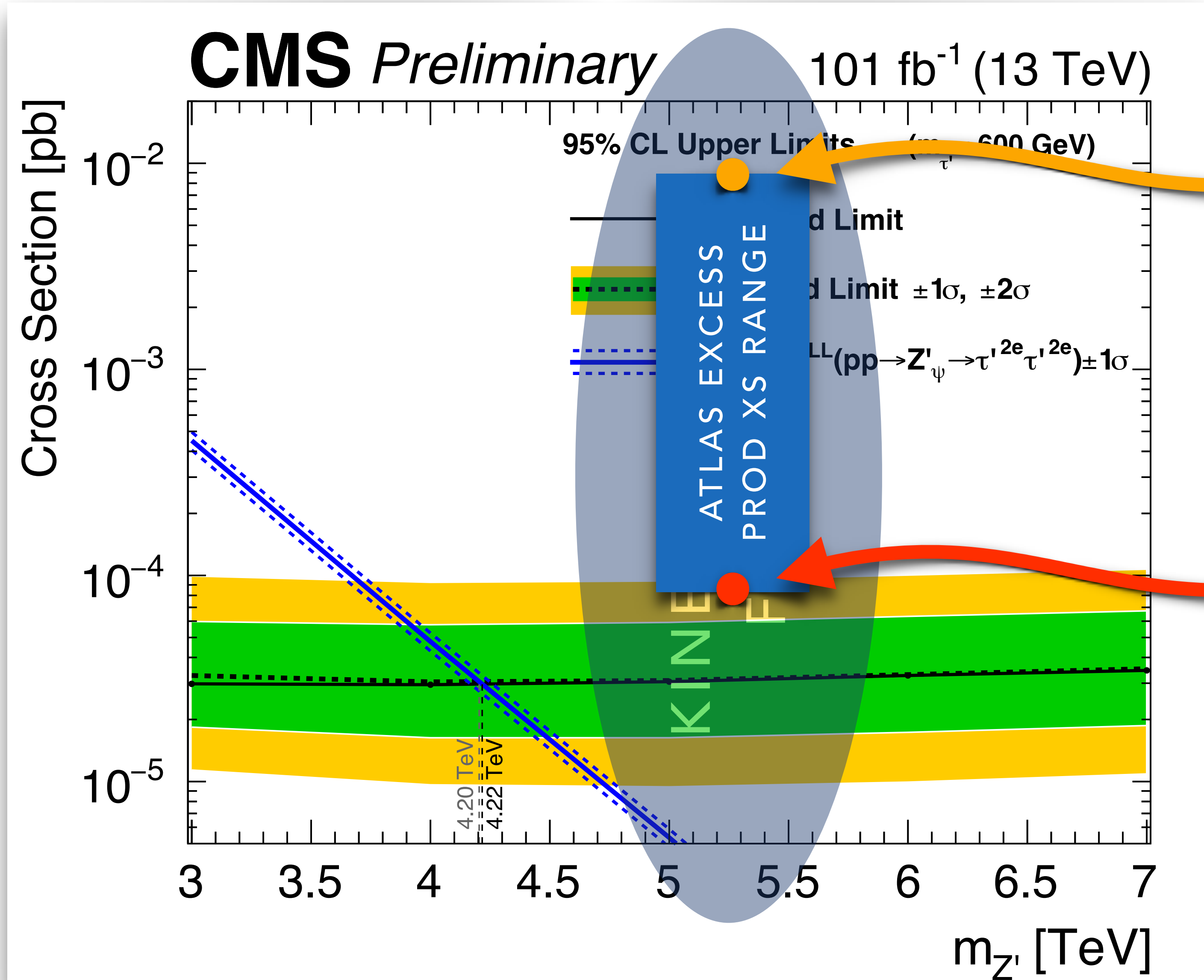

Using ATLAS Aux Material: If A×ϵ~1%, this explanation is ruled out

But even with most conservative A×ϵ~100%, this explanation is ruled out

Searching for **anomalously ionizing tracks**, two complementary approaches show good agreement with BG expectation

Limits set on a variety of BSM models

U.S. DEPARTMENT OF ENERGY | Office of Science

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Searching for **anomalously ionizing tracks**, two complementary approaches show good agreement with BG expectation

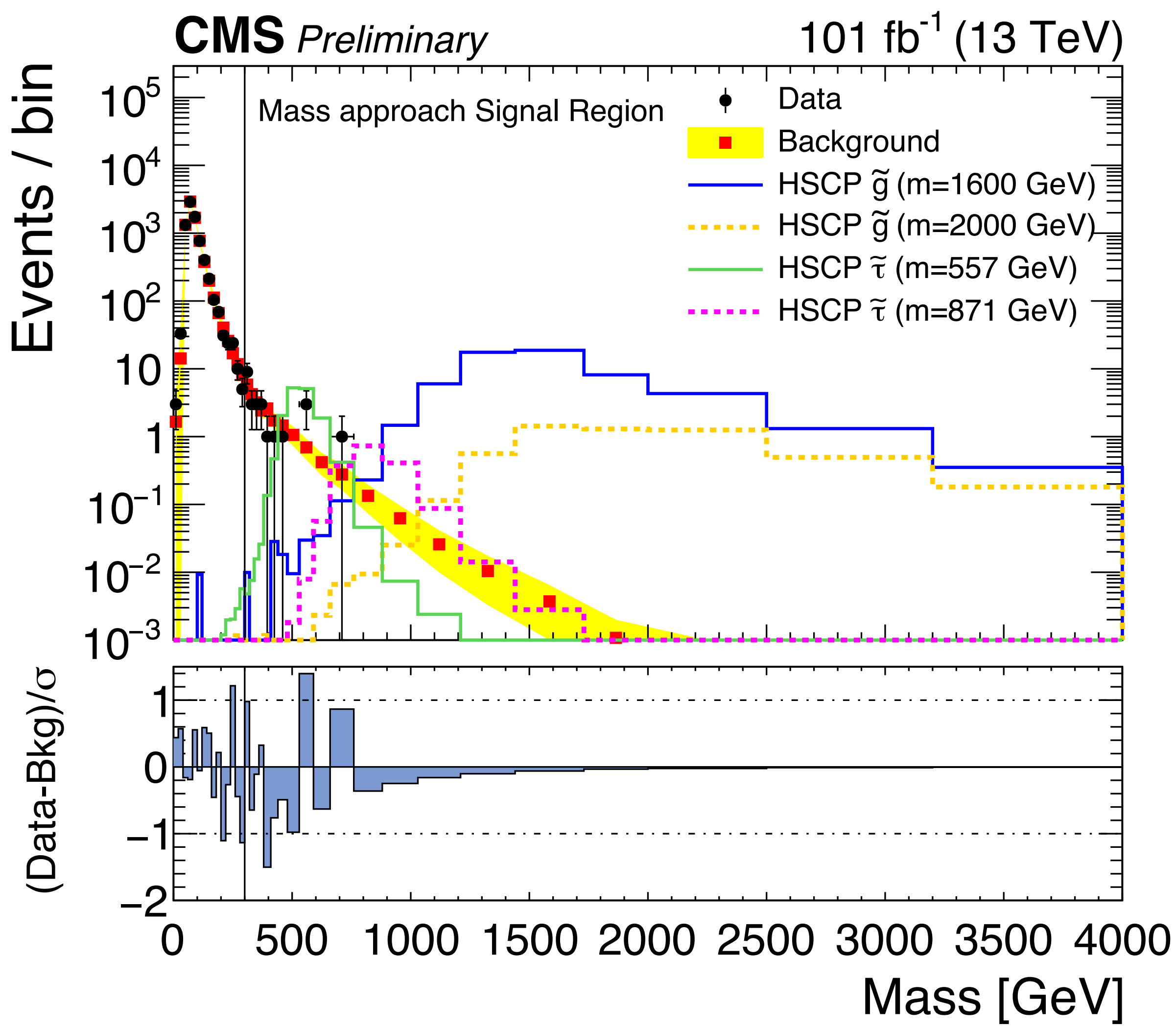
Limits set on a variety of BSM models

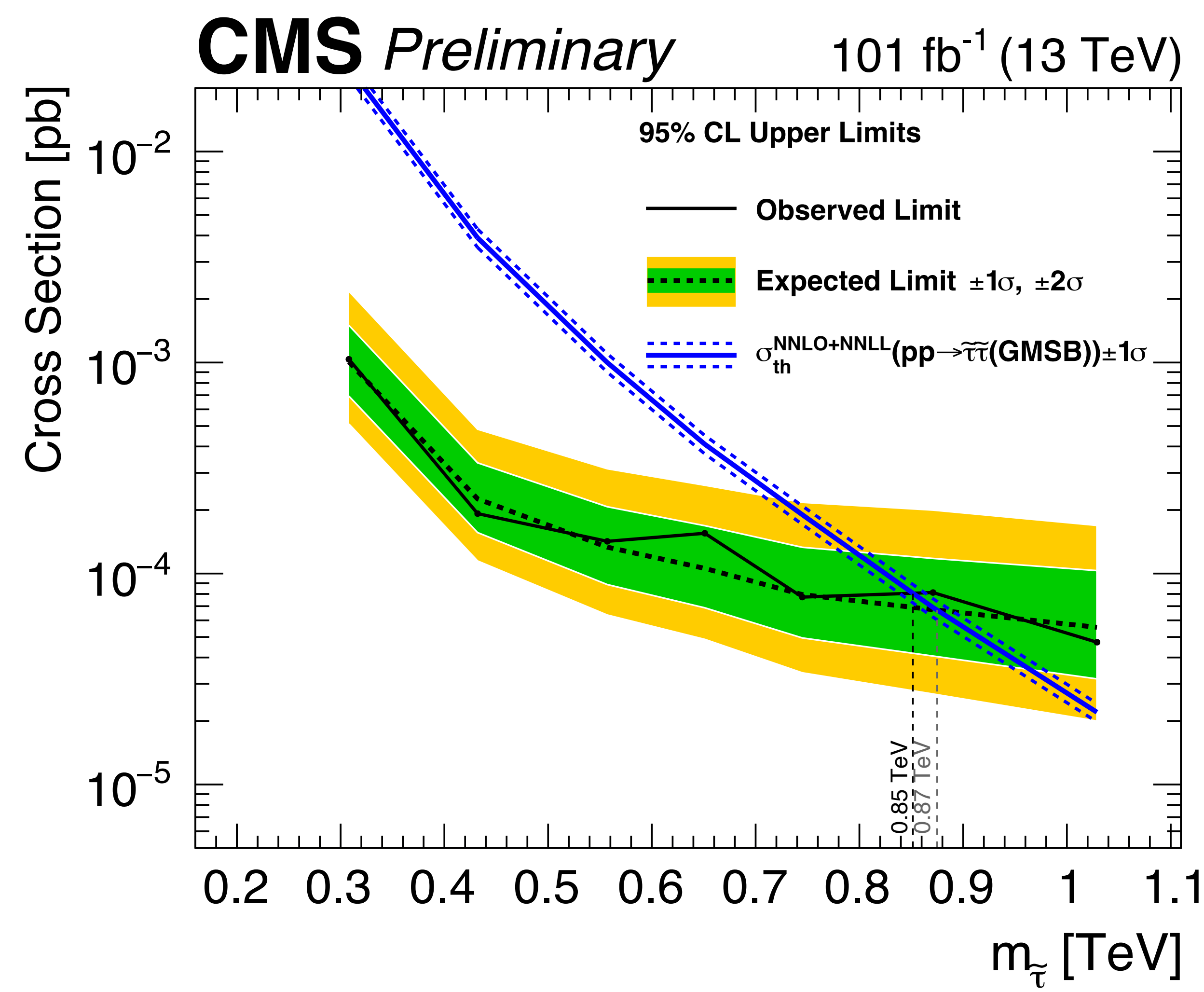
Exciting time for direct detection of LLPs, but we exclude the simplest explanations for the ATLAS excess

But ∃ some key differences, so there's more to do and more to dig for.

Thanks for your attention

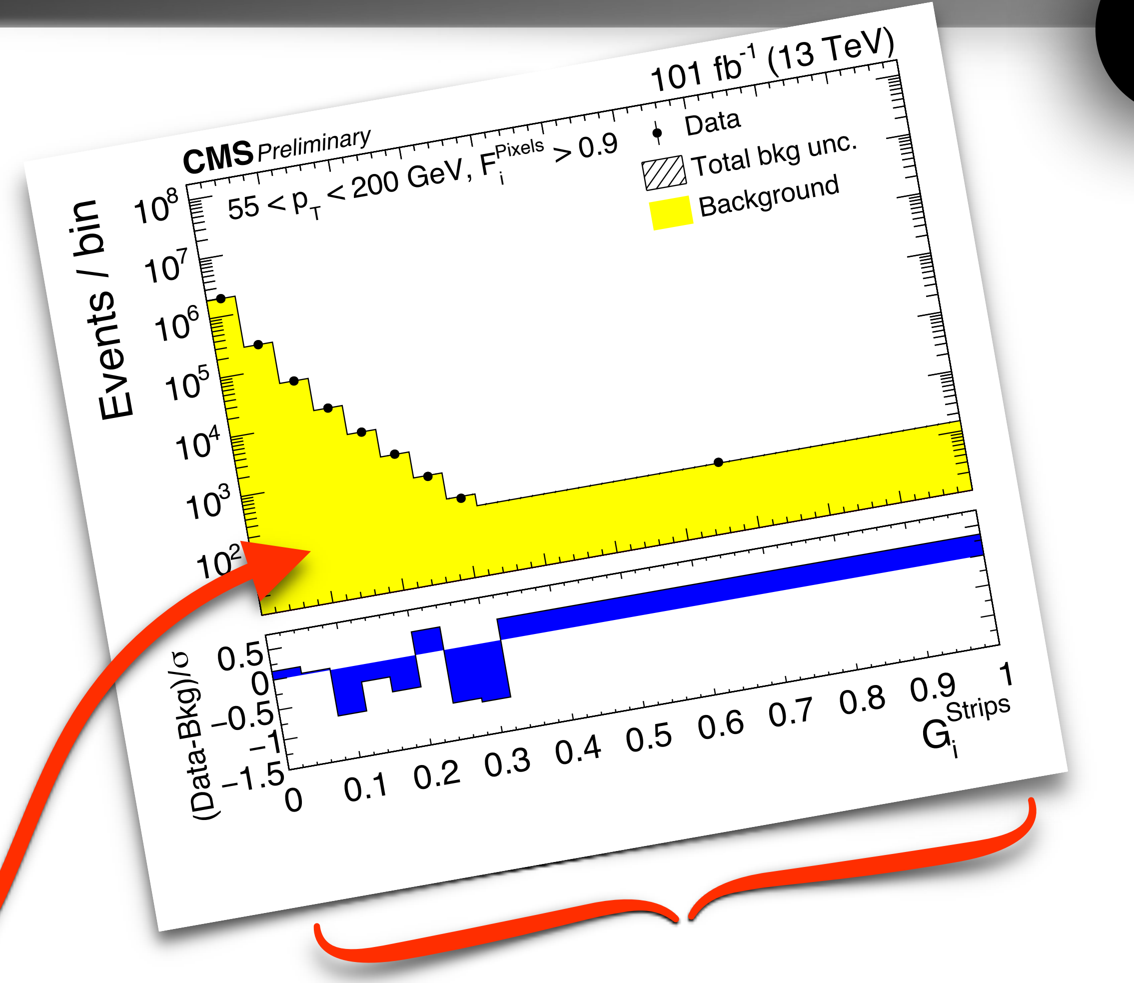
Backup

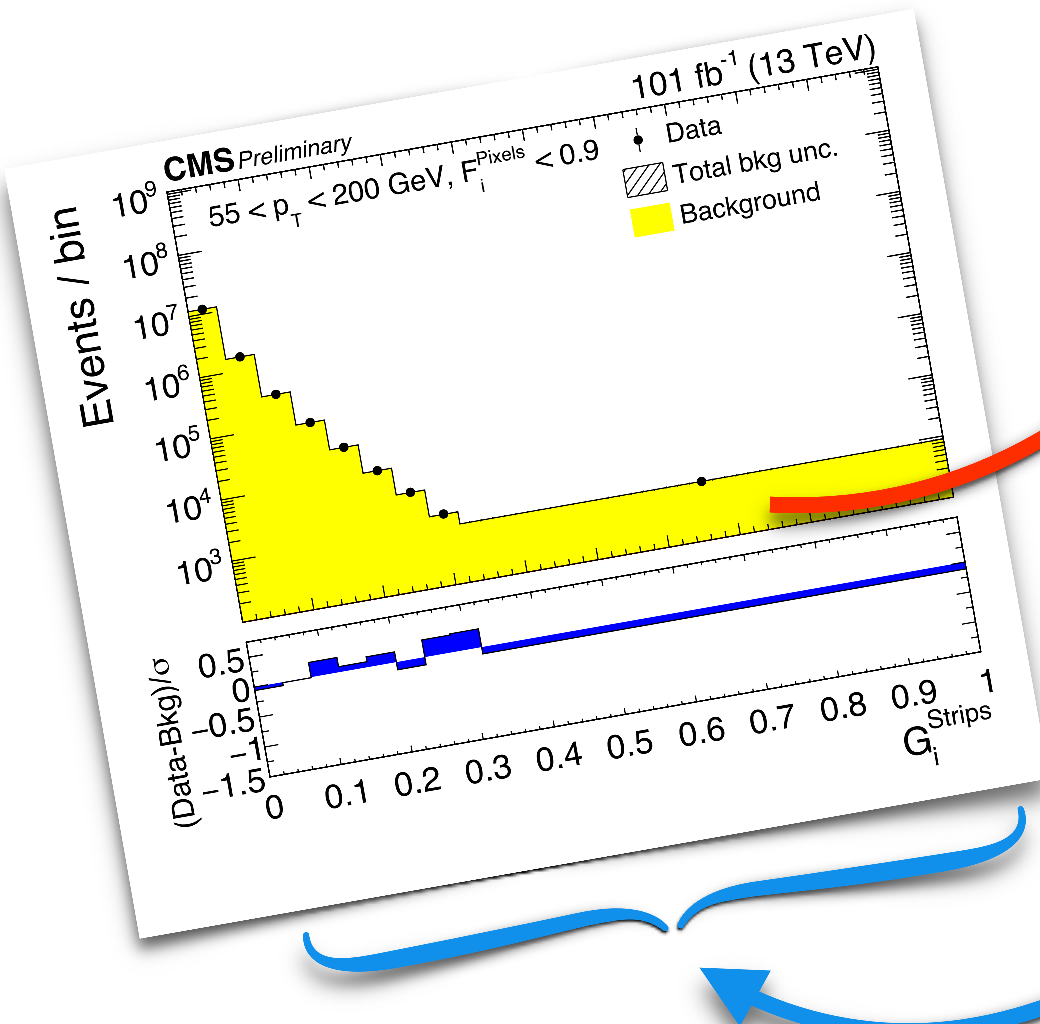

CMS Preliminary
101 fb-1 (13 TeV)
Mass approach Signal Region
Data
Background
HSCP g̃ (m=1600 GeV)
HSCP g̃ (m=2000 GeV)
HSCP τ̃ (m=557 GeV)
HSCP τ̃ (m=871 GeV)
Events / bin
(Data-Bkg)/σ
Mass [GeV]

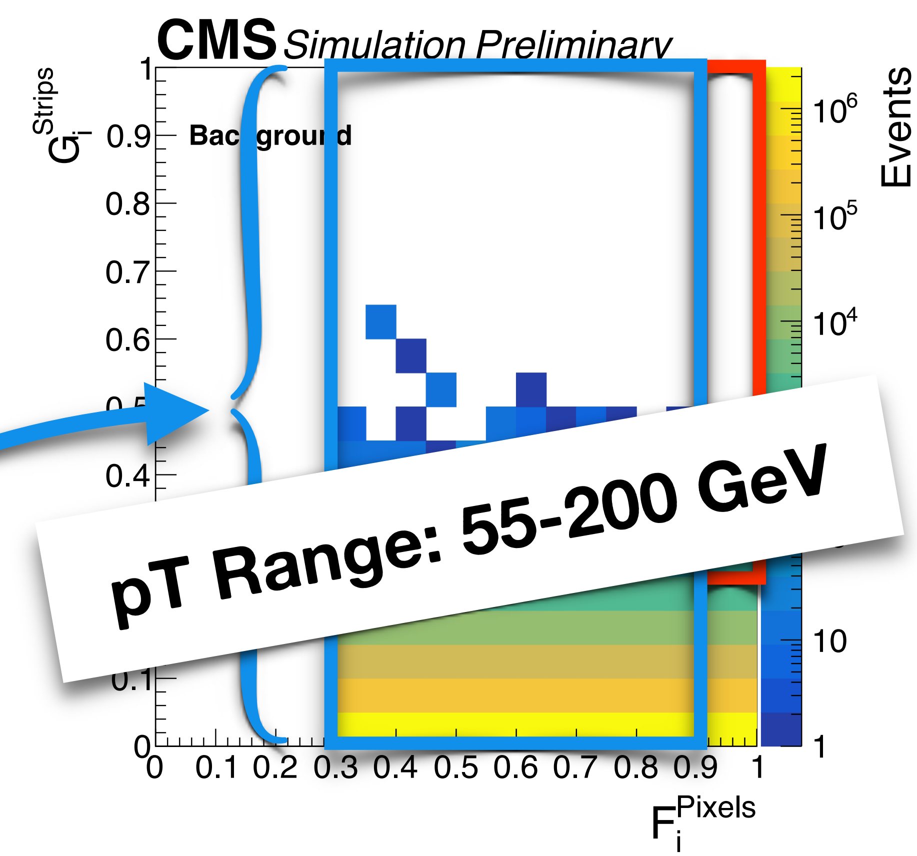

CMS Preliminary
101 fb-1 (13 TeV)
95% CL Upper Limits
Observed Limit
Expected Limit ±1σ, ±2σ
σth NNLO+NNLL(pp→τ̃τ̃(GMSB))±1σ
Cross Section [pb]
0.85 TeV
0.87 TeV
mτ̃ [TeV]

Technique validated in lower pT regions (50-55 GeV; 55-200 GeV)

Shapes agree well at low and high F_I^{Pixels}







Ionization observables (1)

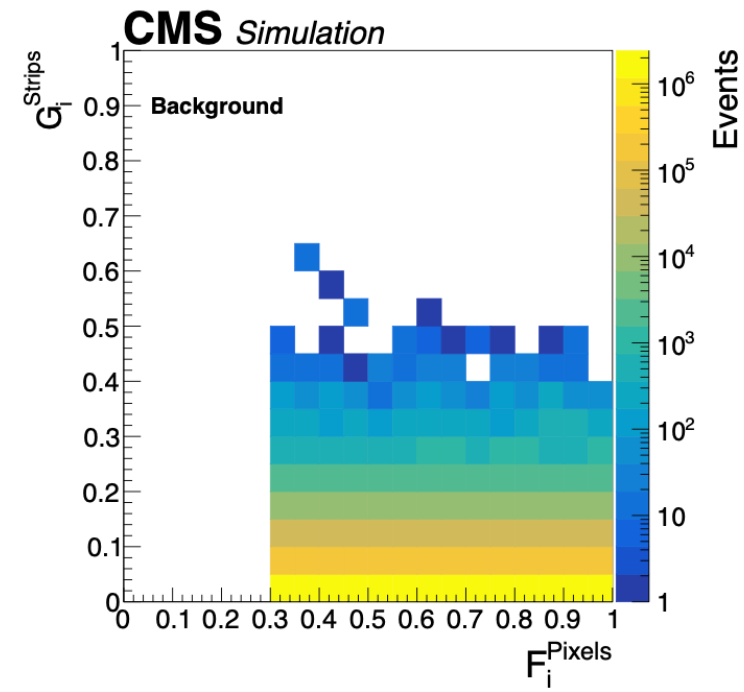
Discriminator in the pixel detector F_i^{Pixels}
where P_j is a hit level MIP compatibility based on the Tracker DPG's detailed calibrations,
n is the number of pixel hits (excluding layer 1)

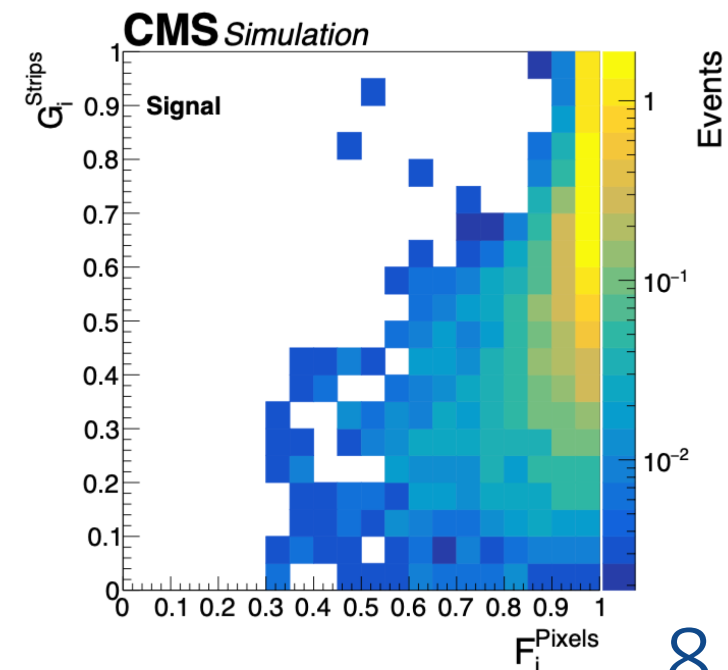
$$F_{\mathrm{i}}^{\mathrm{Pixels}} = 1 - \prod_{j=1}^{n} P_j' \sum_{m=0}^{n-1} \frac{[-\ln(\prod_{j=1}^{n} P_j')]^m}{m!}$$

Discriminator in the strips detector G_i^{Strips}
where P_j is a hit level MIP probability for a charge to be smaller/equal to the measured charged based on our templates calibrated at low momentum (20-48 GeV) data,
N is the number of (cleaned) hits in the strips detector

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

Uncorrelated by construction!





Selection criteria	Data	$\widetilde{g}$ (1.8 TeV)	Pair-prod. $\widetilde{\tau}$ (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

Description	Data		Monte Carlo	
	2017	2018	2017	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

ToF Measurements

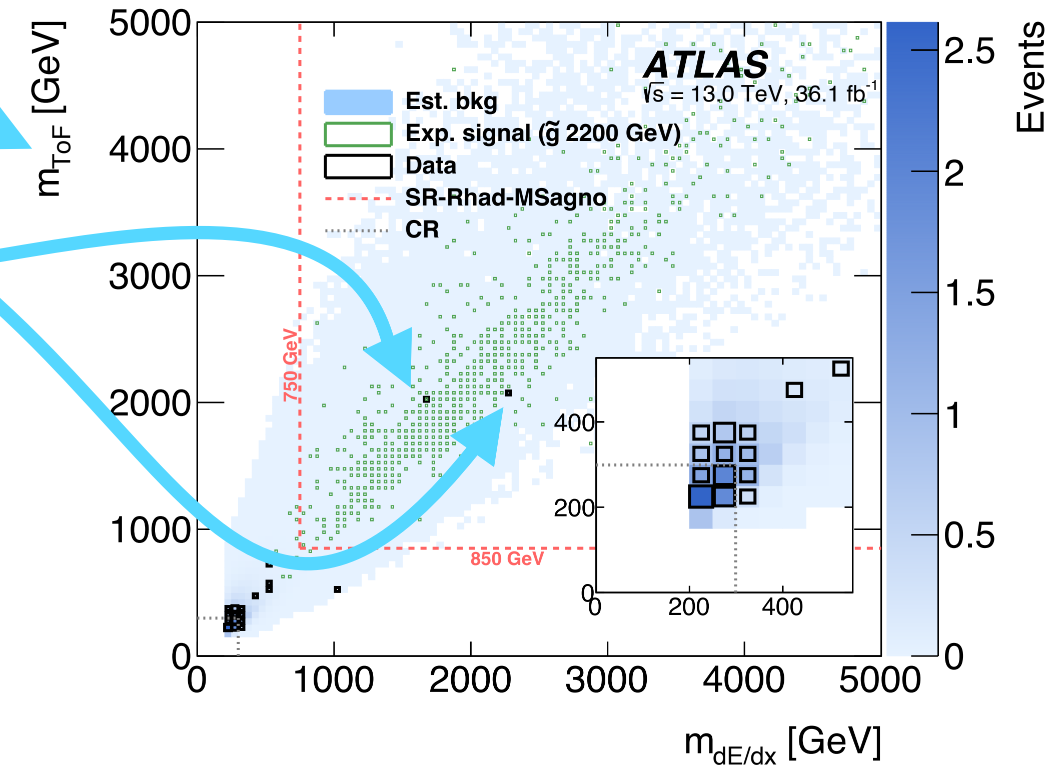
(Strange) description of β resolution

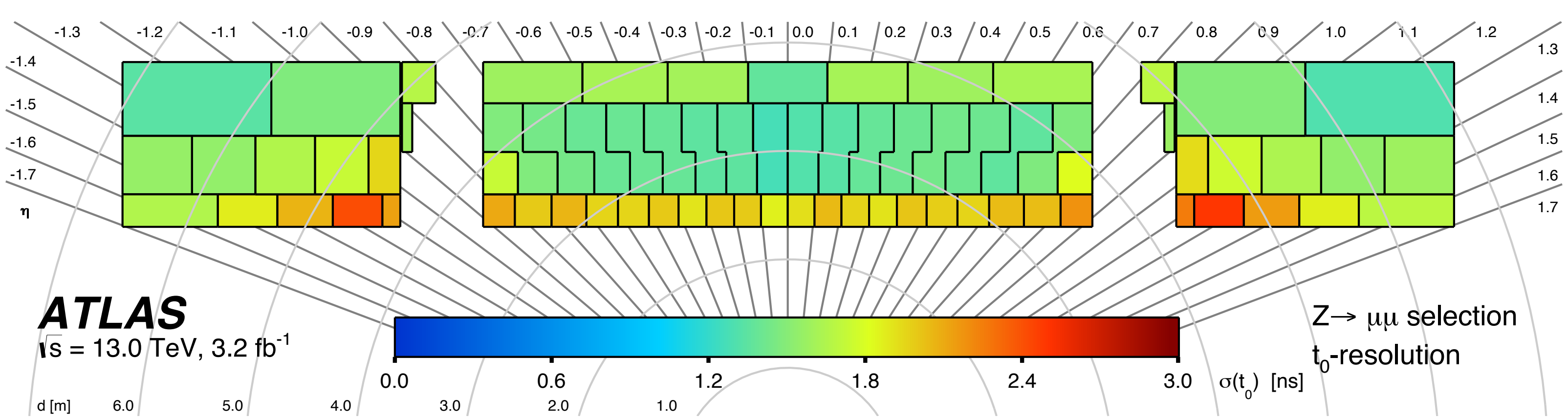
approximately symmetric side-lobes. The FWHM of the peak divided by 2.35 for β_{MS} is 0.045, while it is 0.075 and 0.050 for β_{calo} in the CR-kin-Mu and CR-kin-Trk samples, respectively. The efficiency of obtaining a β_{MS} value from the CR-kin-Mu sample is 95%, while that of obtaining a β_{calo} value is 85% from the CR-kin-Mu sample and 95% for the CR-kin-Trk sample. Using MC signal samples, where particles have low β, it was found that the β values from the ToF observables and the β value deduced from the pixel dE/dx measurement agree within 6%.

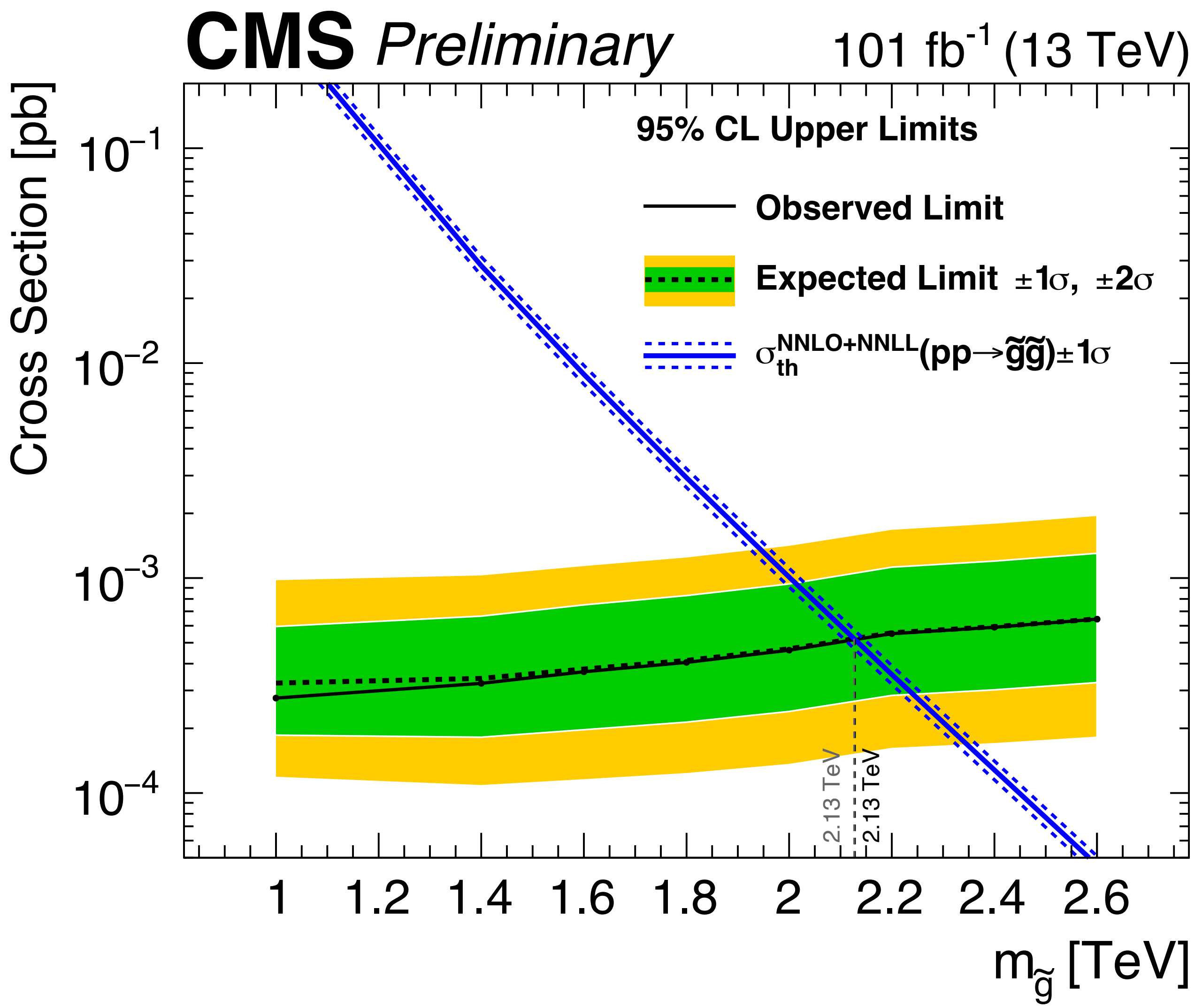
The β values measured by ToF of the seven candidate tracks were all found to be compatible with $\beta = 1$, with all the β_{MS} and β_{calo} values being well within the 95% confidence interval of the distribution. Therefore, the low particle speed suggested by the pixel dE/dx measurement for the seven candidate tracks in the excess was not confirmed by these ToF observables.

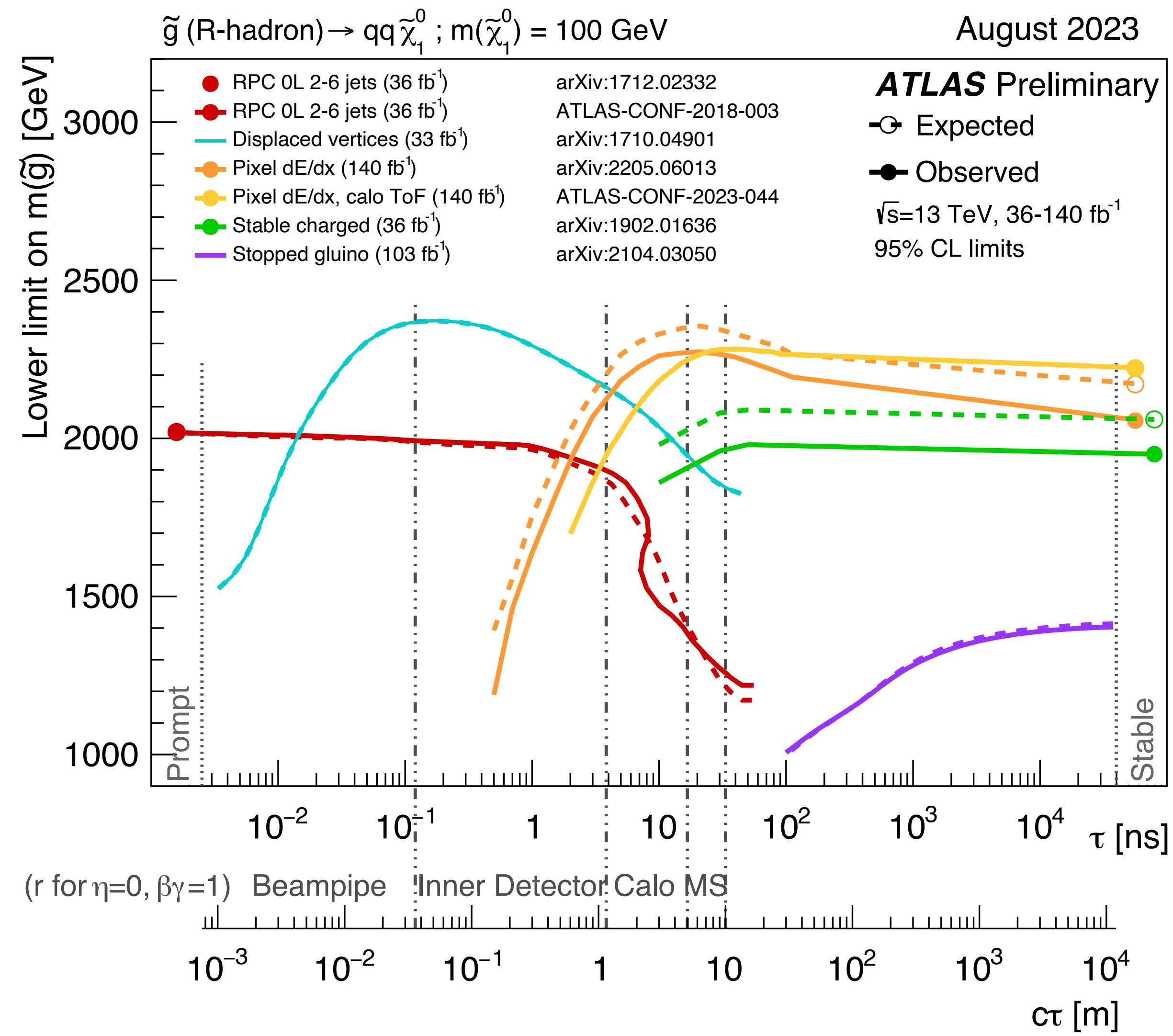
Candidates well within bulk of resolution

- Time of flight (β) measurements requested after unblinding. They do not agree with expected β~[0.52,0.62]
  - Using SMP tools (TileCal + Muon System measurements)
  - Candidates have β consistent with 1
- Previously ATLAS SMP showed high mass events w/ corroborated β values!









Expected to exclude gluino masses < 2.13 TeV

Expectation: ~2.2 TeV

Driven by lumi differences (101 ifb vs 140 ifb)

ATLAS Pixels