Search for Massive Metastable Charged Particles with the CMS Detector

Joze Zobec

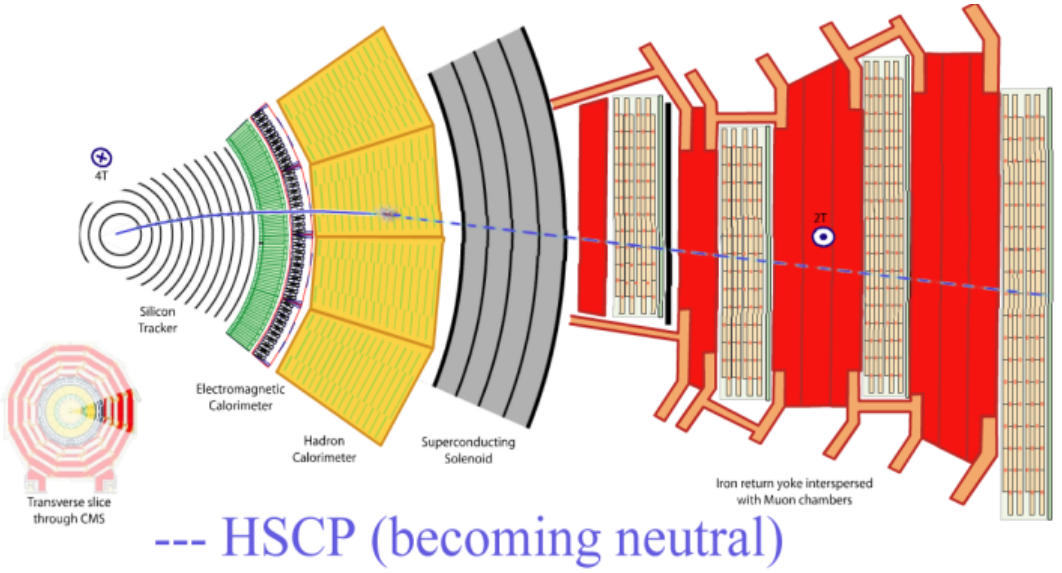
8th of February, 2017

Outline

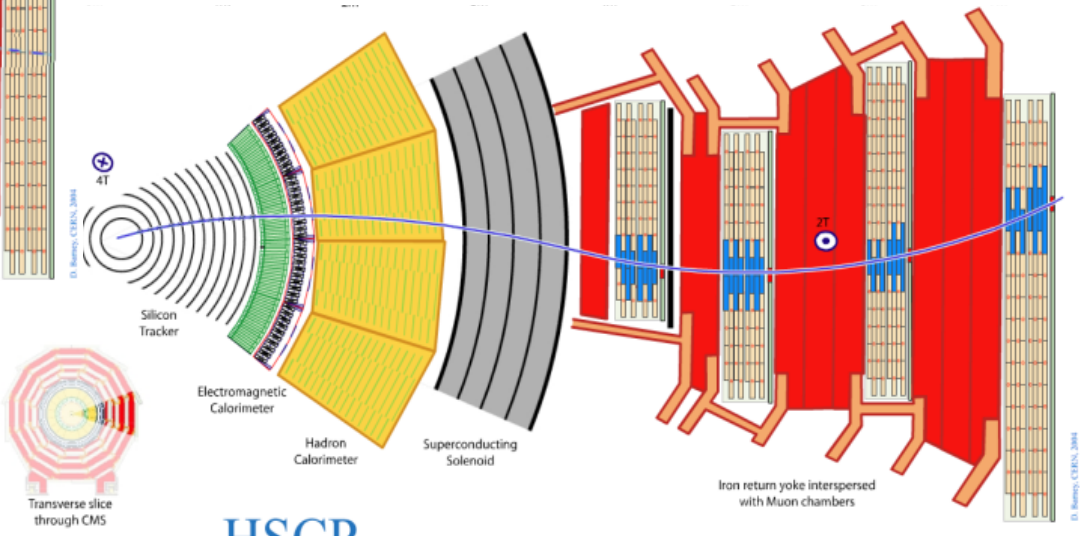
- Introduction
- Search variables measurements, stability and calibration
  - Tracker dE/dx
  - Time-of-flight
  - Transverse momentum stability
- Analysis overview
- Analysis results

Introduction
- Definition -

- HSCP = Heavy Stable Charged Particle



--- HSCP (becoming neutral)

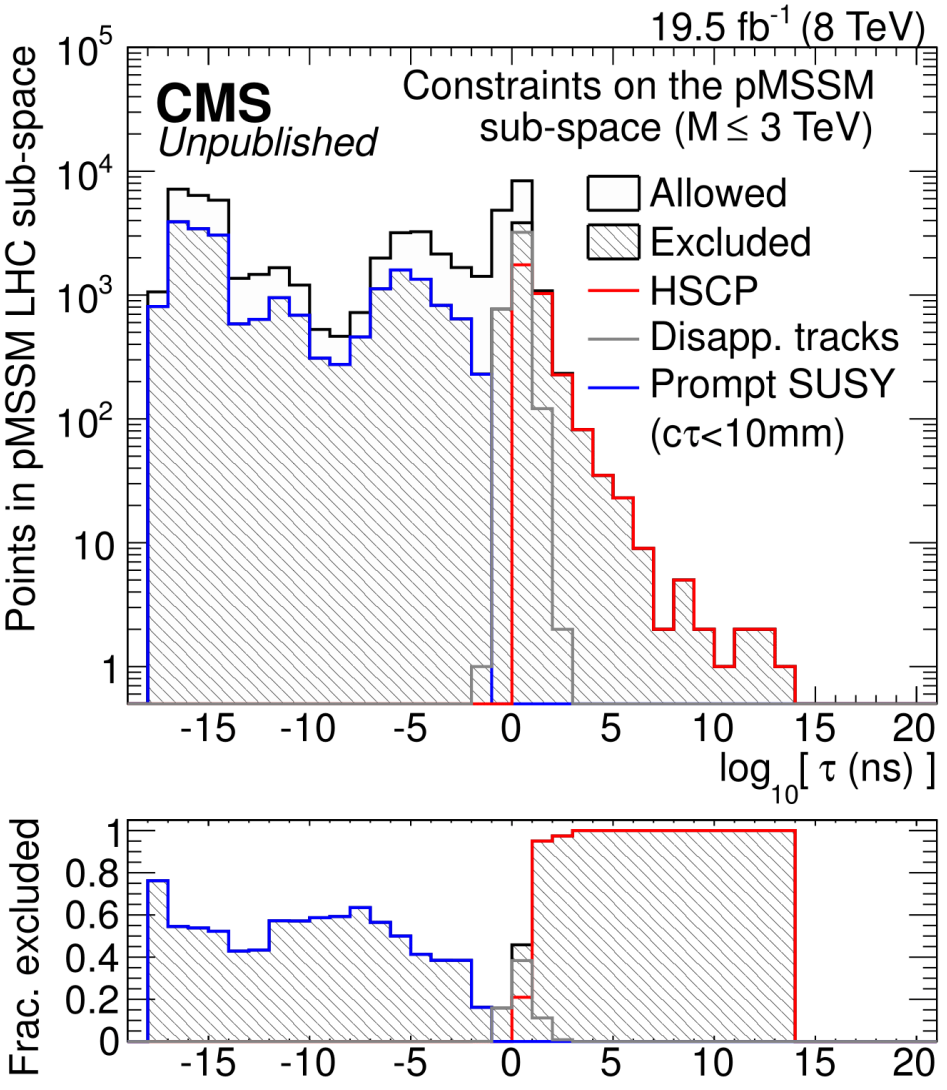


--- HSCP

- Mass ~ O(1 TeV)
- Lifetime > 3 ns
- Curve in magnetic field

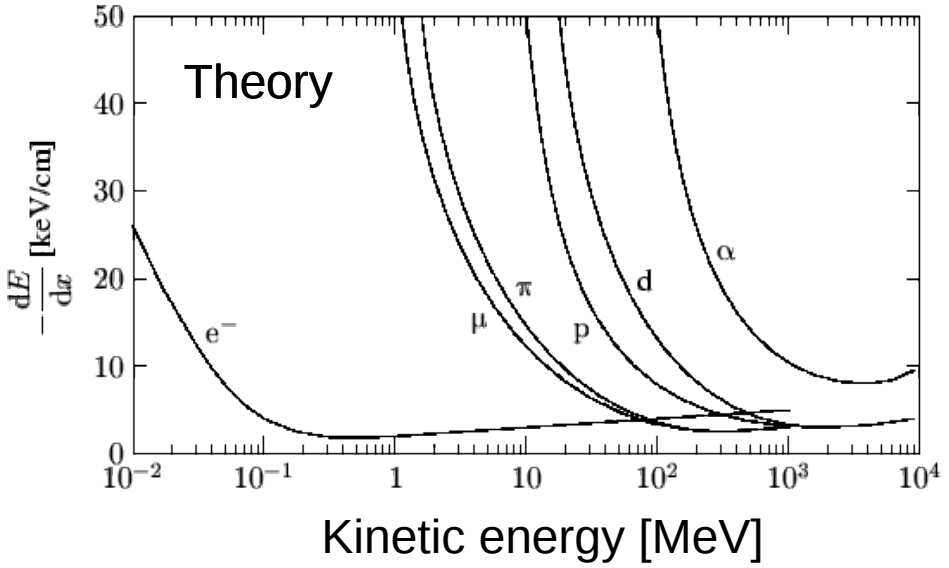
Introduction
- Motivation -

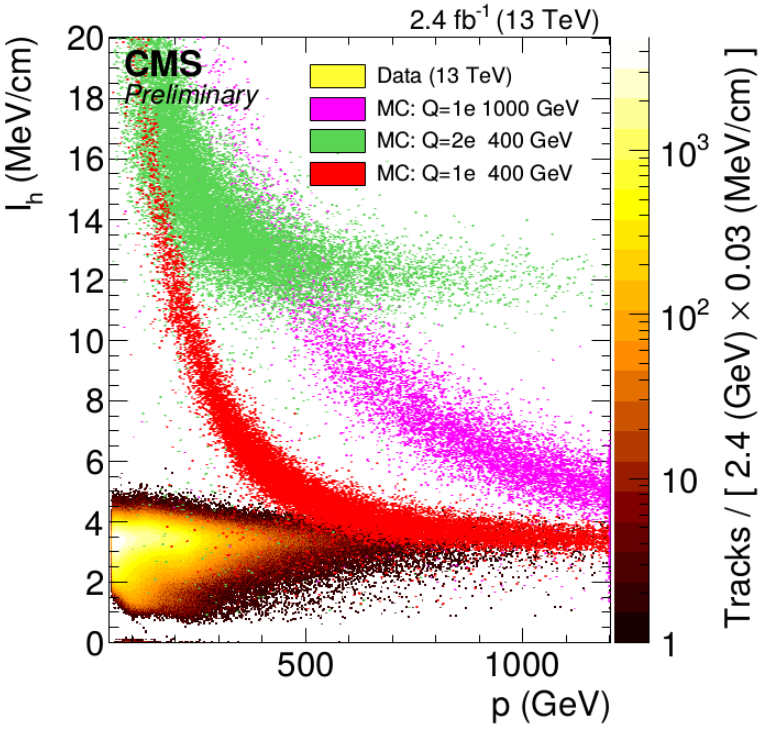
- Predicted by many theories
  - SUSY (pMSSM)
- Inclusive
- Model independent



Introduction
- Method -

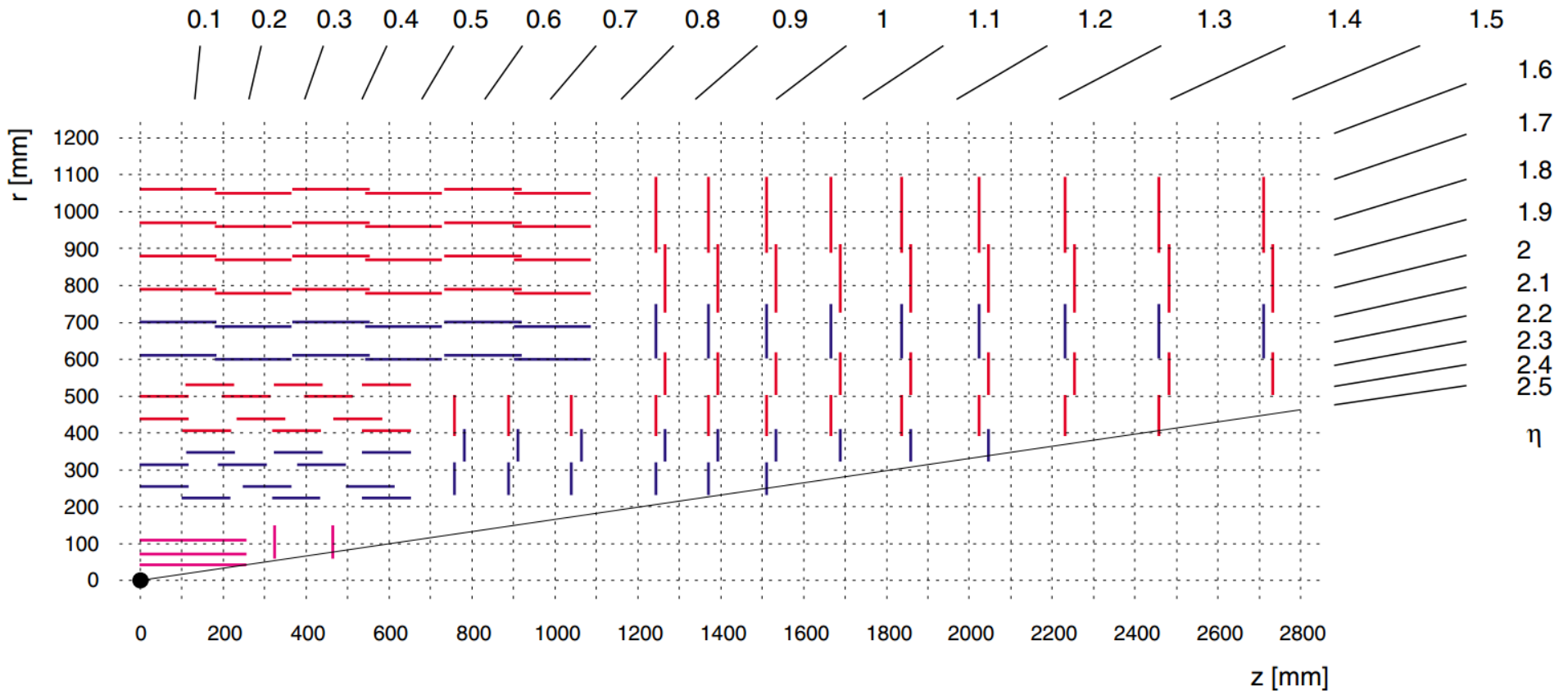
- General tracks
  - Mistaken for a muon
- Discriminate using:
  - Tracker “dE/dx”
  - 1/β
  - p_T





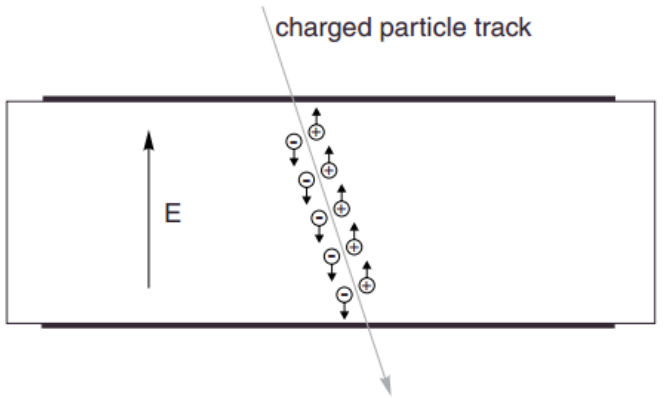
Search variables measurements, stability and calibration

Cross-section of one quarter of the CMS tracker



- Pixel layers
- Single-sided strip layers
- Double-sided strip layers

Measuring dE/dx



Collected charge is read out in units of “ADC”

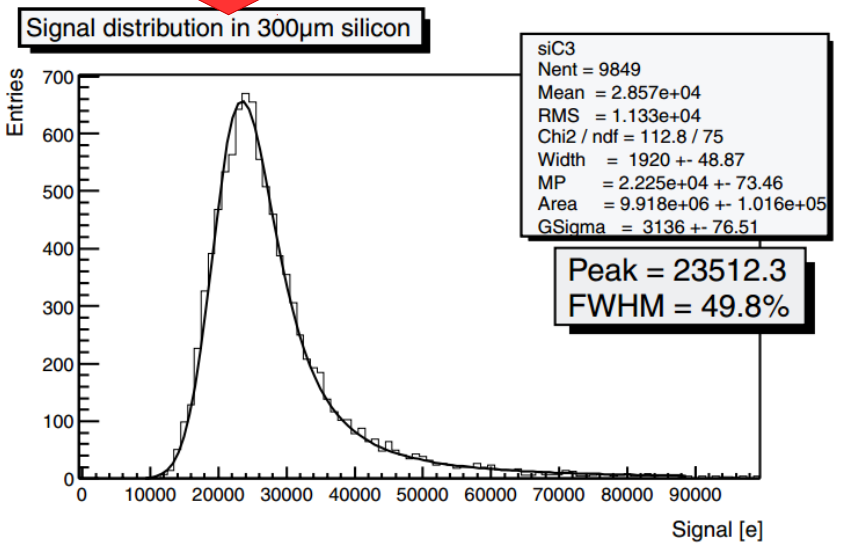
Strips/pixels surrounding point of passage identified as charge clusters

Tracks are fitted and assigned associated hits

Estimate <dE/dx> of the track from its hits

- Strips:
  - 1 ADC → 3.61 eV
- Pixel
  - 1 ADC → 265 * 3.61 eV

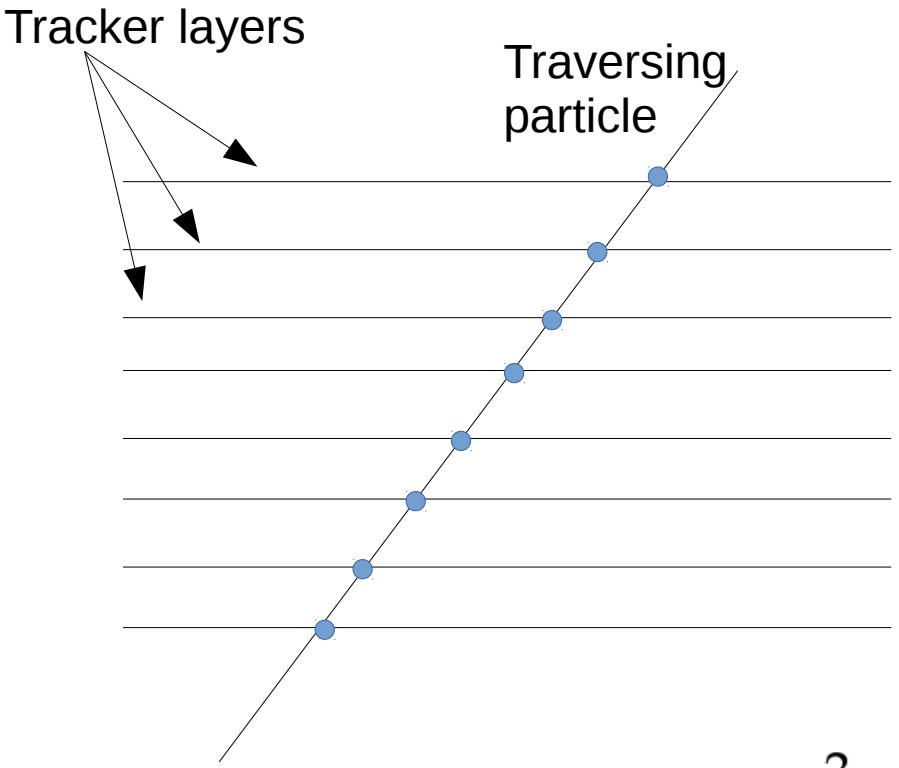
ADC is Landau distributed → biased toward high dE/dx



Assign weights based on cluster charge

$$\left\langle \frac{dE}{dx} \right\rangle_{\text{estim.}} = \frac{1}{N}\left(\sum_{i=1}^{N} c_i^{-2}\right)^{-1/2}$$

Track dE/dx



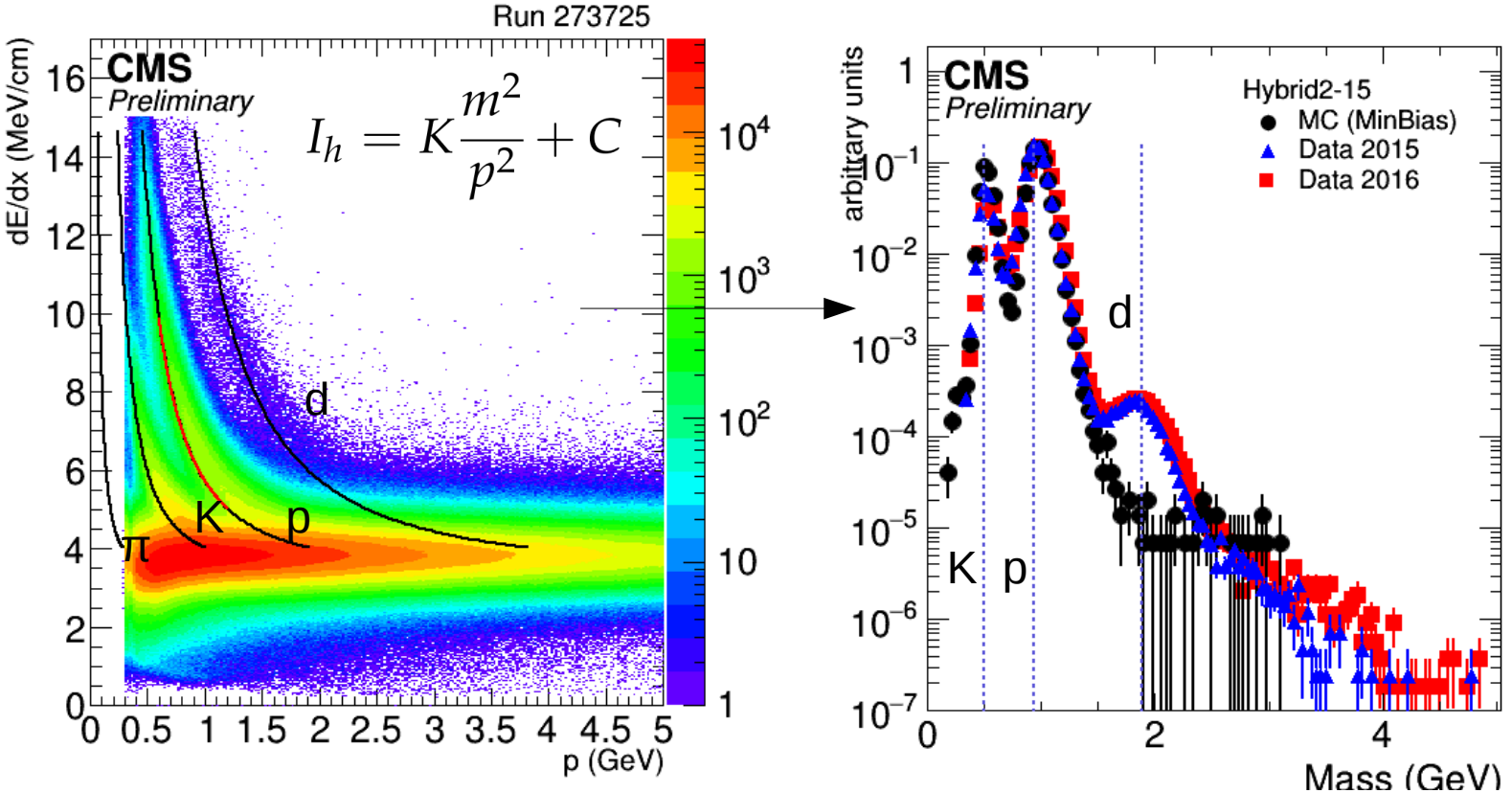
- dE/dx estimator, I_h

$$\left\langle \frac{dE}{dx} \right\rangle_{\text{estim.}} = \frac{1}{N}\left(\sum_{i=1}^{N} c_i^{-2}\right)^{-1/2}$$

- dE/dx discriminator, I_{as}

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N} \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right)$$

dE/dx estimator – mass computation

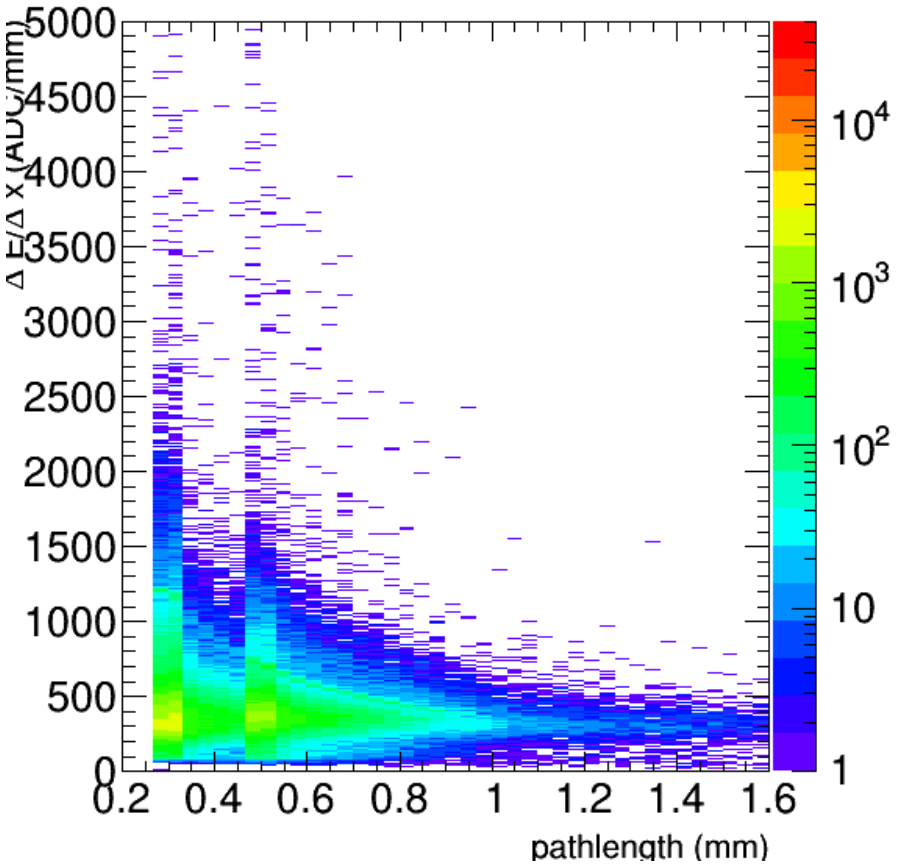


From the red part of the proton line we extract the constants:

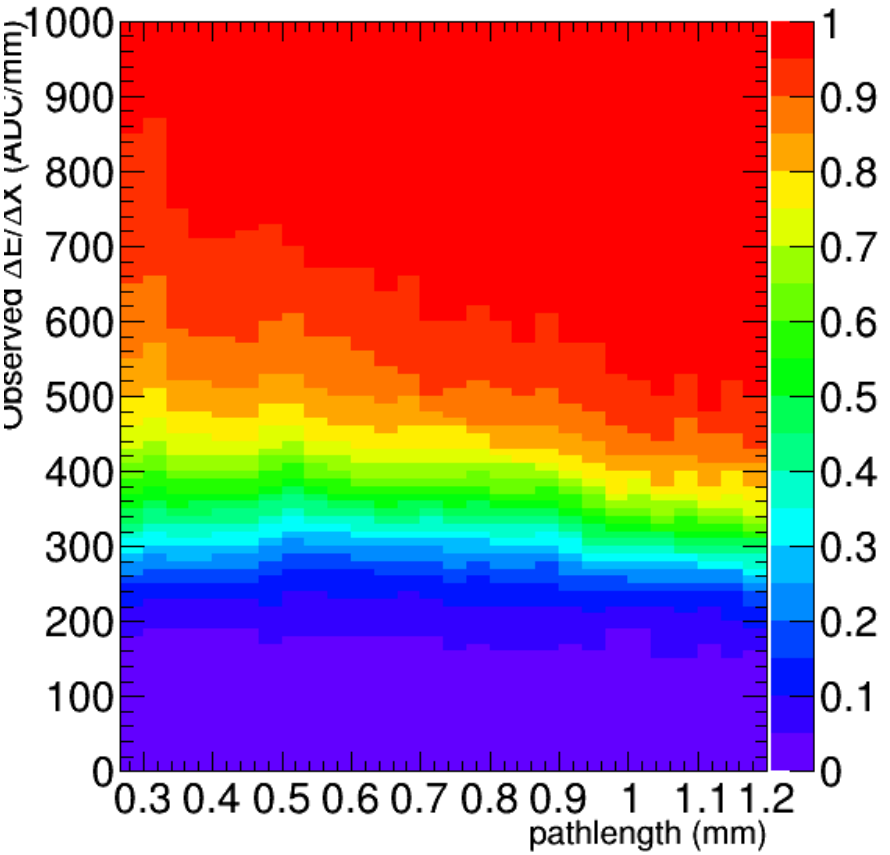
	K (MeV cm^{-1})	C (MeV cm^{-1})
2015	2.68	3.38
2016	2.58	3.92

Error on K ~ ± 0.1 MeV/cm
Error on C ~ ± 0.3 MeV/cm

dE/dx discriminator – distinguish from MIP



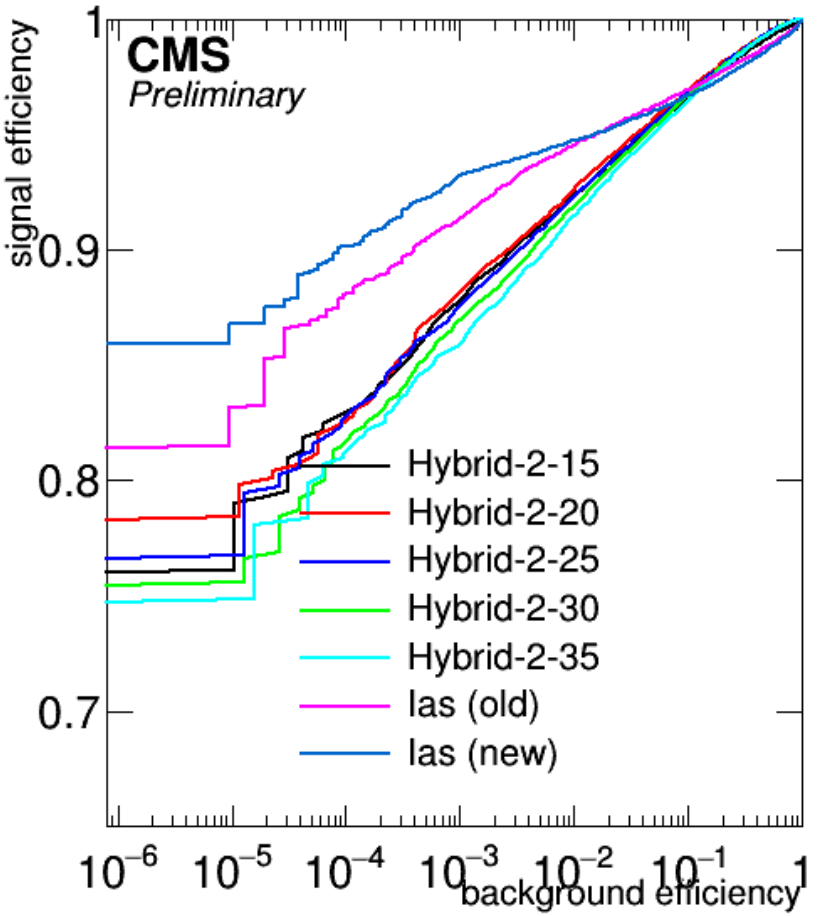
dE/dx (dx) for each geometry of the tracker module.



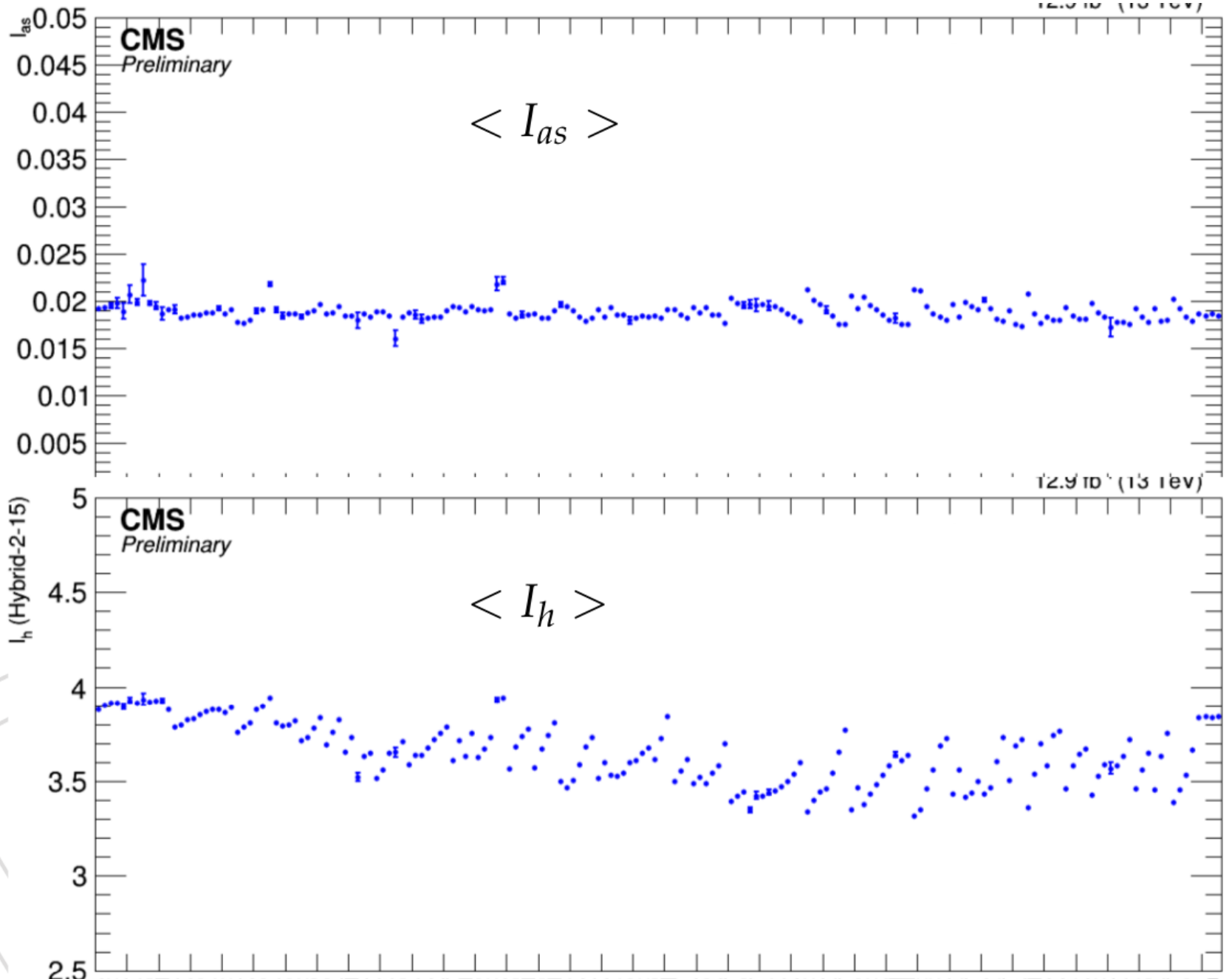
Probability dE/dx (dx) for each is greater to that of a MIP.

dE/dx discriminator properties

- Based on Smirnov-Cramér-von Mises test statistic
  - Robust
  - Normalized
- Gives better separation than dE/dx estimator



dE/dx stability tests



dE/dx summary

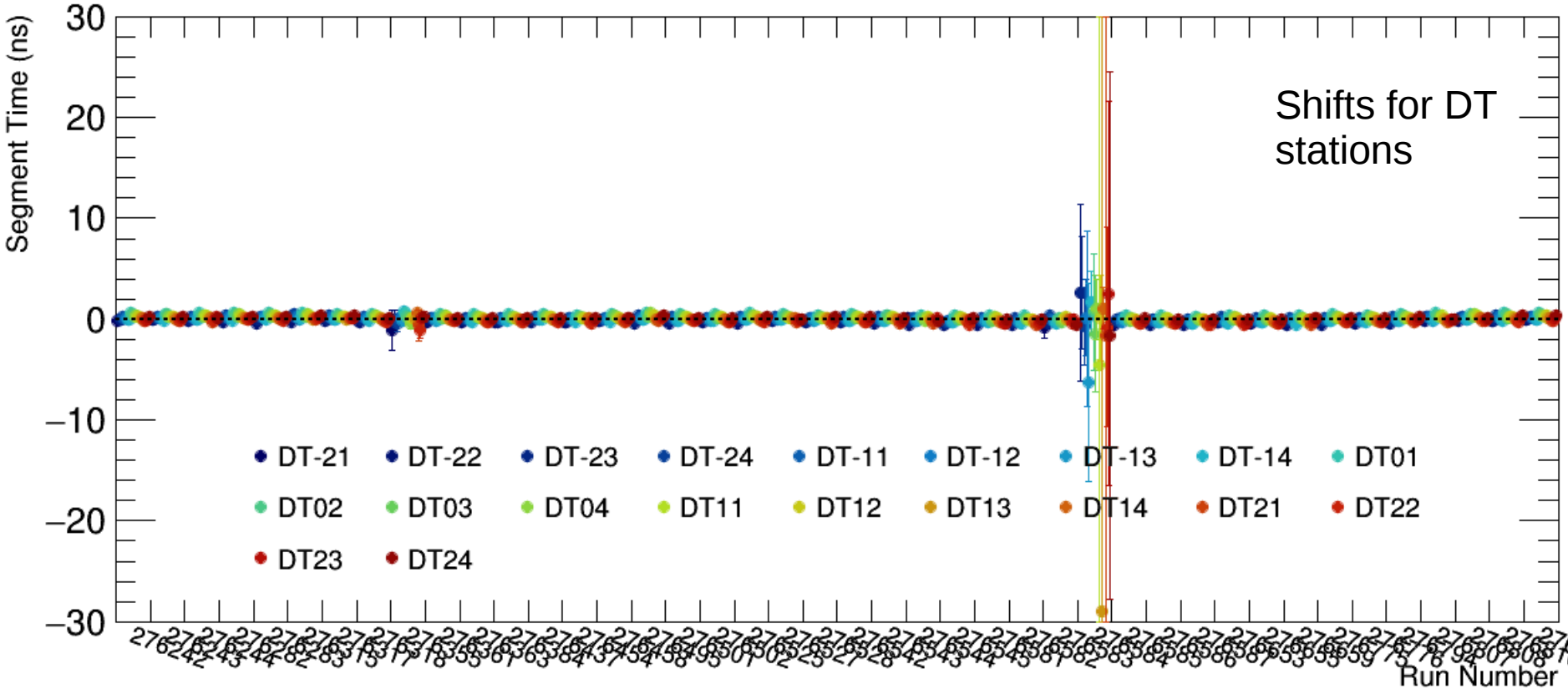
- Hit dE/dx Landau-distributed
- dE/dx estimator
  - Estimate most probable ionisation per unit length
  - Used for mass computation
- dE/dx discriminator
  - Discriminate signal (HSCP) from background (MIP – minimally ionising particle)
  - More stable over time (robust)

Time-of-flight measurements

- Information from muon systems
  - Cathode strips
  - Drift tubes
- Measure 1/β – “inverse velocity”
  - 1/β ~ 1 for muons
  - 1/β > 1 for HSCP
  - 1/β < 1 for tachyons
- Measure mass independently of dE/dx
  - p = mβγ

Calibrating 1/β measurements

- Postulate 1/β = 1 for muons
- Shift responses of all components



Estimating track 1/β

- Each hit gives us a measurement – delay:

$$\beta^{-1} = 1 + \frac{c\delta_t}{L}$$

- Weighted mean for tracks
  - Based on resolution

CSC;

$$w_i = \frac{d_i^2}{\sigma_i^2}$$

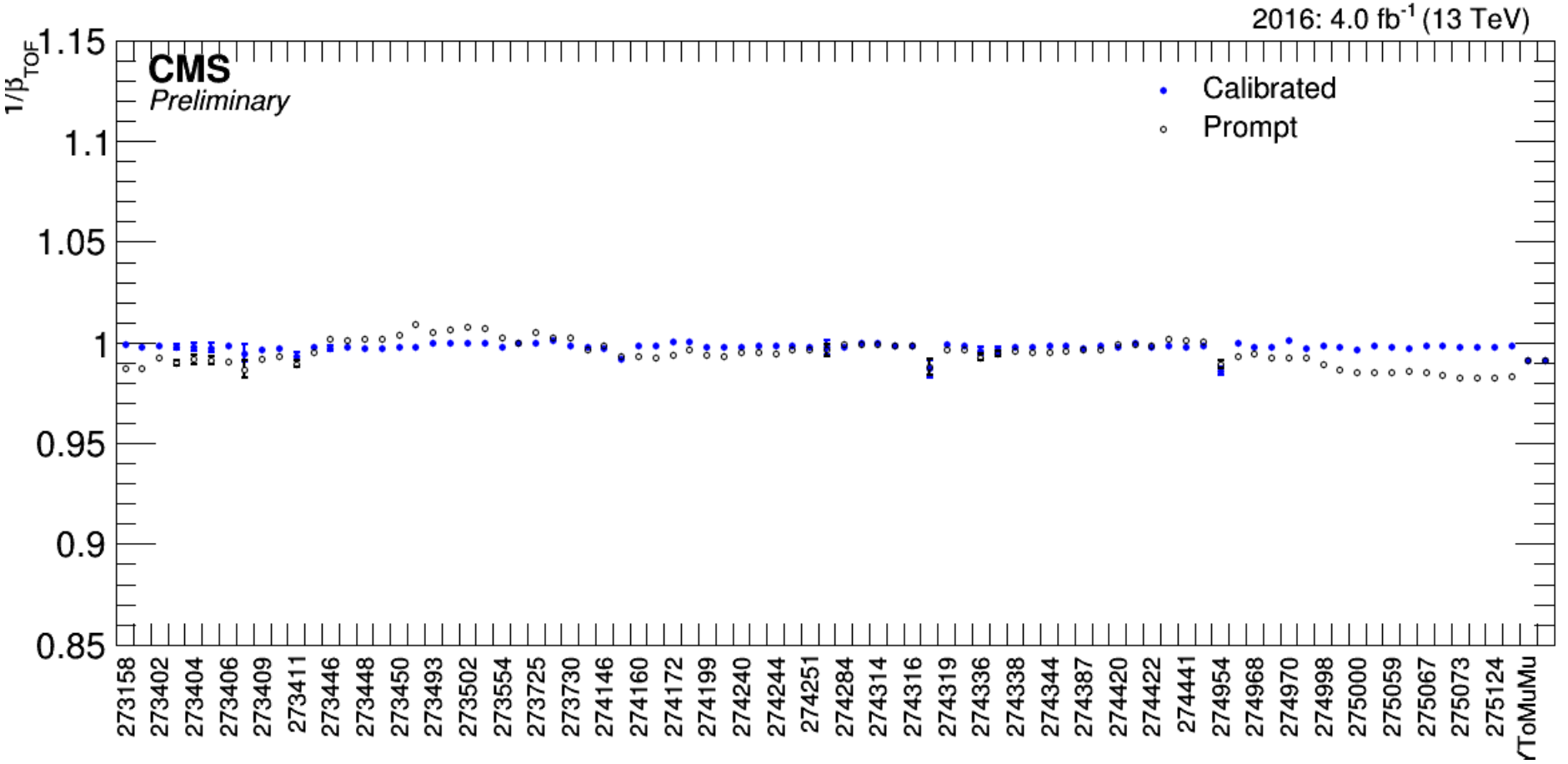
DT; σ_{DT} = 3.0 ns

$$w_i = \frac{(n-2)}{n}\frac{d_i^2}{\sigma_{DT}^2}$$

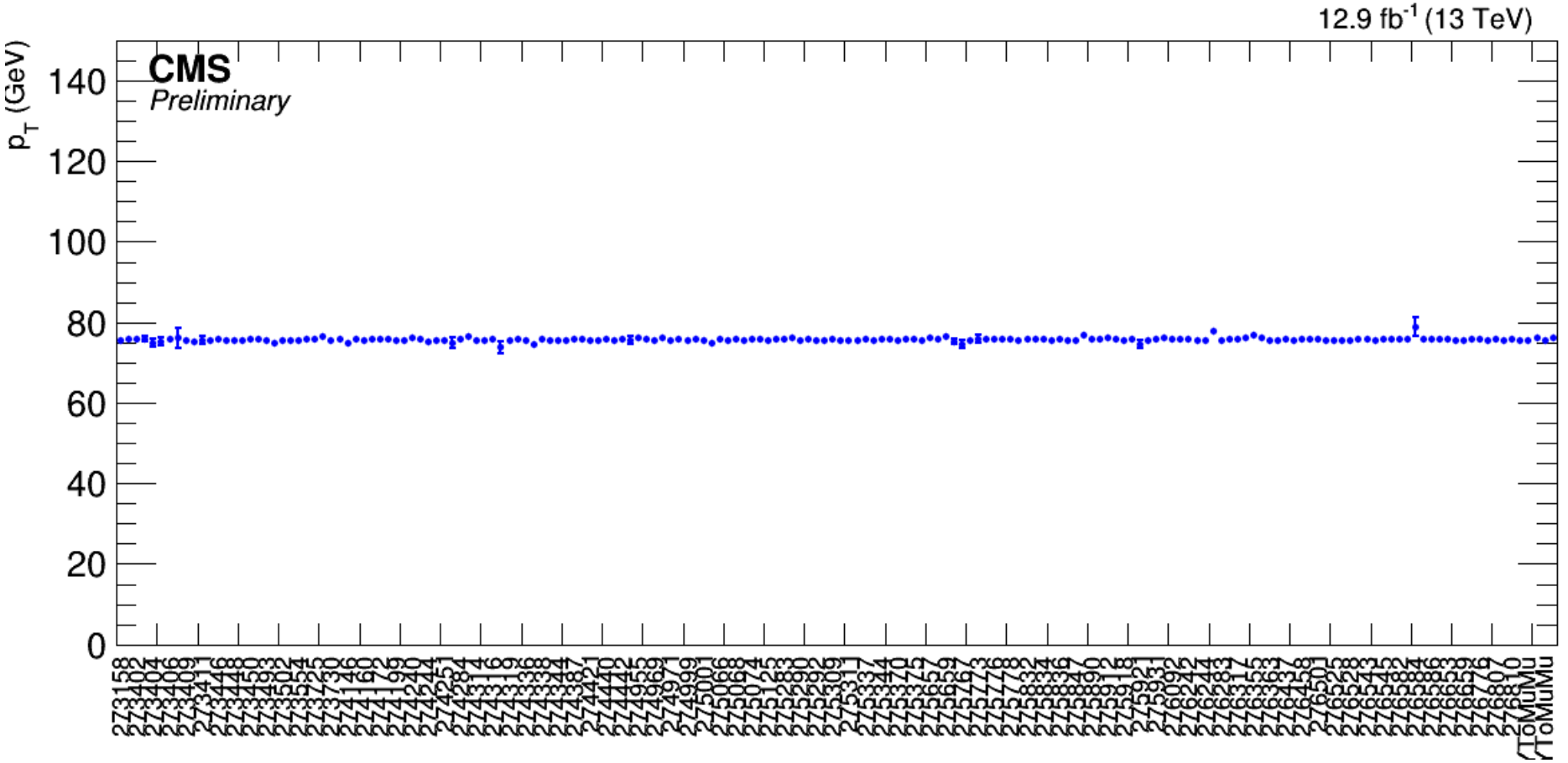
σ_i = 7.0 ns (strip), 8.6 ns (wire)

Stability over time

- By construction this variable is stable



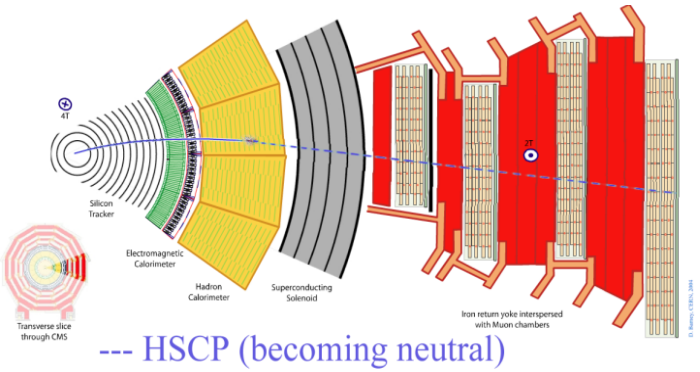
Transverse momentum stability



Analysis overview

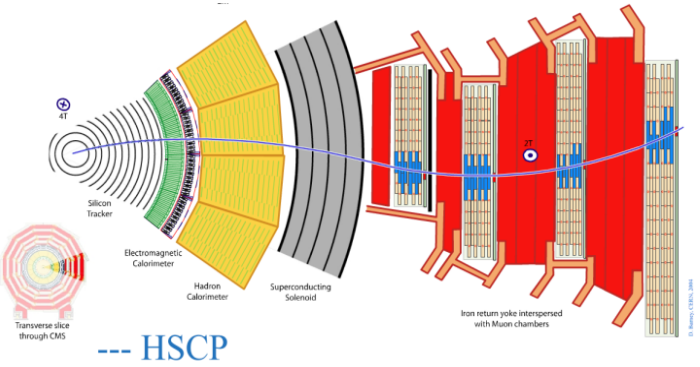
Analysis strategy

- Tracker-Only



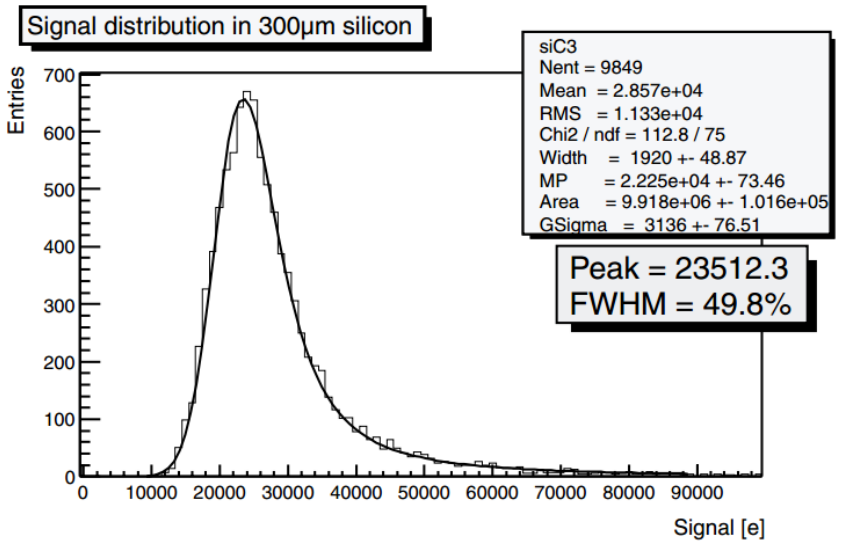
  - Only use dE/dx and p_T
  - Hadron-like signal
    - Charge flipping
    - Gluinos/scalar top quarks

- Tracker+TOF



  - Use all three variables (dE/dx, p_T and 1/β)
  - Lepton-like signal
    - Scalar tau

Background sources



- SM tracks with extreme energy deposits
- Overlapping tracks
- Instrumental sources

Benchmark signal models

- R-hadrons
  - Split SUSY
  - High squark mass assumption (10 TeV) for gluino scenarios
- Lepton-like
  - Staus next-to-lightest SUSY particle
  - Minimal Gauge Mediated SUSY Breaking (mGMSB)
  - mGMSB parameters:
    - Λ in [31, 510] TeV (high mass staus)
    - $N_{mes} = 3$
    - $\tan \beta = 10$
    - $\mu > 1$
    - $C_{grav} = 10000$ (produces long-lived staus)
    - $M_{mes}/\Lambda = 2$
- Drell-Yan produced exotic spin ½ fermions
  - Neutral under $SU(3)_C \times SU(2)_L$
  - Arbitrary electric charge
    - Two models: |Q| = 1e and |Q| = 2e
  - Couple only to Z bosons and photons

Signal Samples

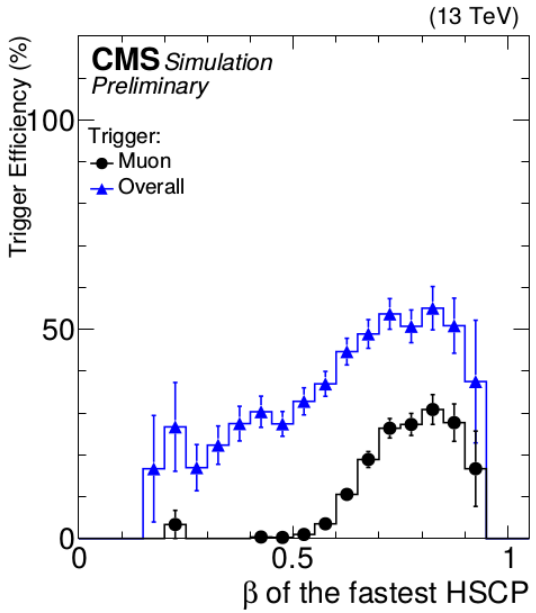
- *R-hadrons*
  - Two interaction models:
    - Cloud interaction
    - Charge-suppressed model
  - Gluino: 100 GeV ≤ M ≤ 2600 GeV
    - Scenarios with 10% and 50% form gluino balls
  - Stop: 100 GeV ≤ M ≤ 2600 GeV
- *Lepton-like HSCP – stau*
  - Two production channels:
    - Pair-produced
    - Cascade decays (GMSB)
  - 156 GeV ≤ M ≤ 1599 GeV
- *Drell-Yan production of exotic fermions*
  - Electric charge |Q| = 1 and |Q| = 2
  - Hypercharge Y = 0
  - 100 GeV ≤ M ≤ 2600 GeV

Benchmark background models

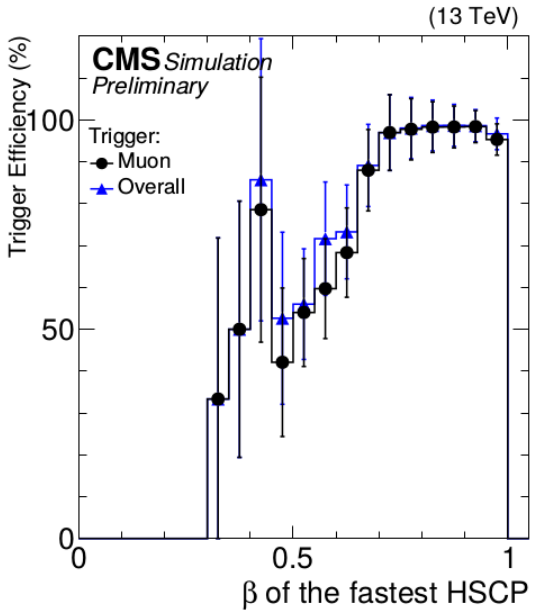
- Muons
  - Drell-Yan → μμ
  - W → lν
- QCD background not included:
  - Resource intensive
  - Unlikely to enter the final selection

Data samples

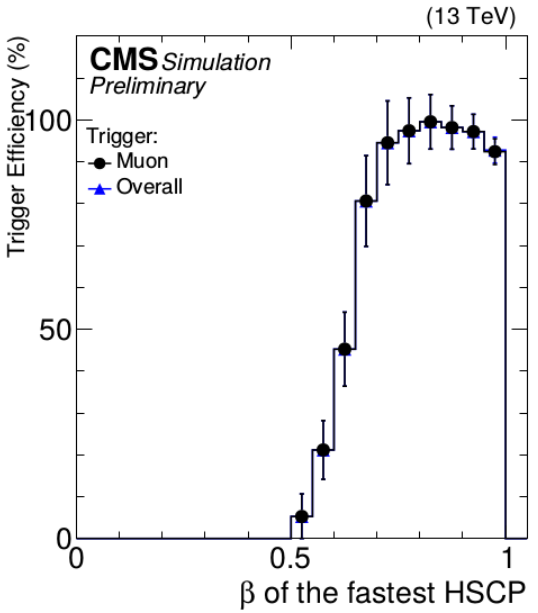
- Dataset from ICHEP 2016
- Tracks come from events with muon/missing E_T
  - OR of single muon and missing E_T triggers



Gluino



Cascade-prod. stau



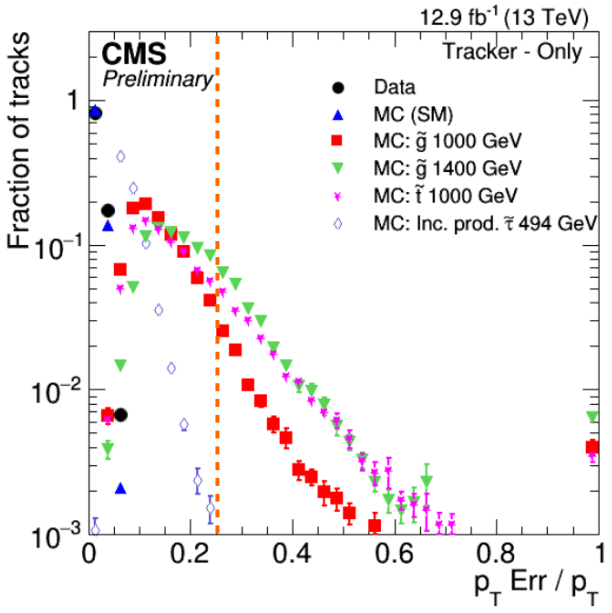
Pair-prod. stau

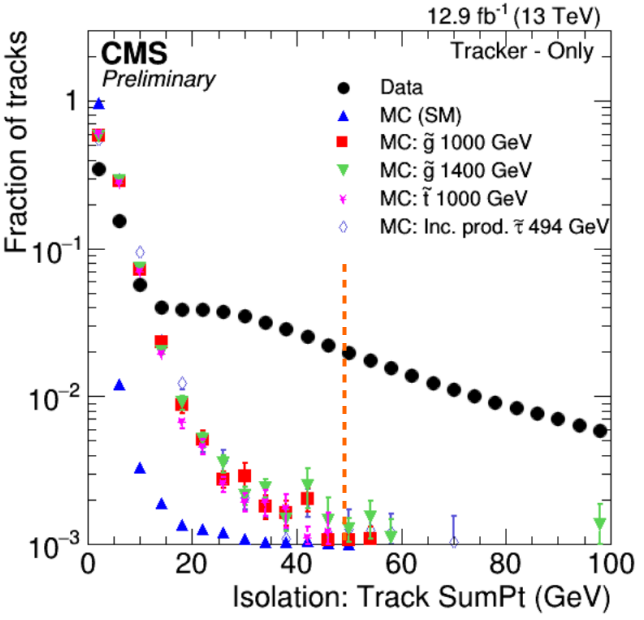
Track quality

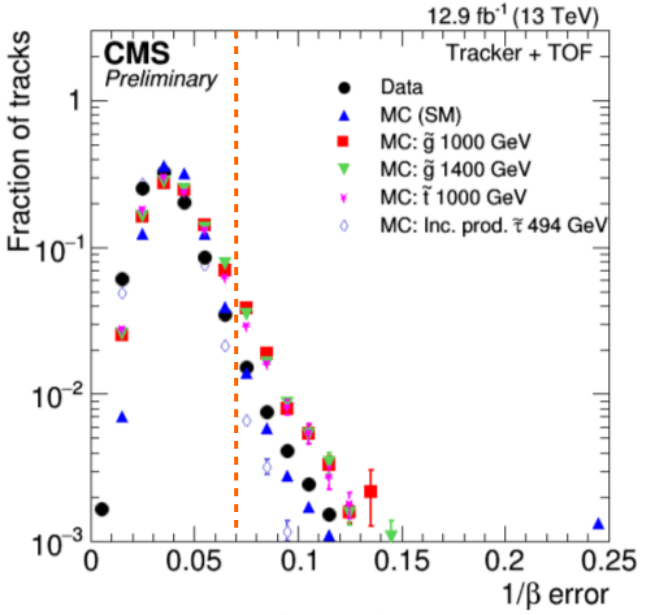
- Preselection
  - Ensure track quality!
- Quality tracks are candidates
  - Signal
  - Background prediction

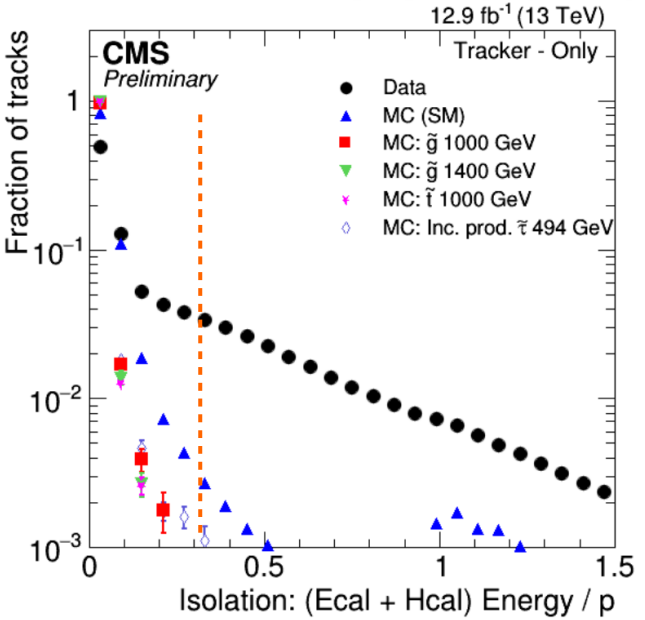
	Trk-only	Trk+TOF
Track Type	Inner Track	Global Muon
$\|\eta\|$	< 2.1	
p_T (GeV)	> 55	
d_z and d_{xy} (cm)	< 0.5	
σ_{p_T}/p_T	< 0.25	
Track $\chi^2/d.o.f$	< 5	
# Pixel Hits	> 1	
# Tracker Hits	> 7	
Frac. Valid Hits	> 0.8	
# dE/dx Measurements	> 5	
dE/dx Strip Shape Test	yes	
$\Sigma p_T^{trk}(\Delta R < 0.3)$ (GeV)	< 50	
$E_{cal}(\Delta R < 0.3)/p$	< 0.3	
I_h (MeV/cm)	> 3.0	
# TOF Measurements	/	> 7
$\sigma_{1/\beta}$	/	< 0.07
$1/\beta$	/	> 1

Some preselection control plots

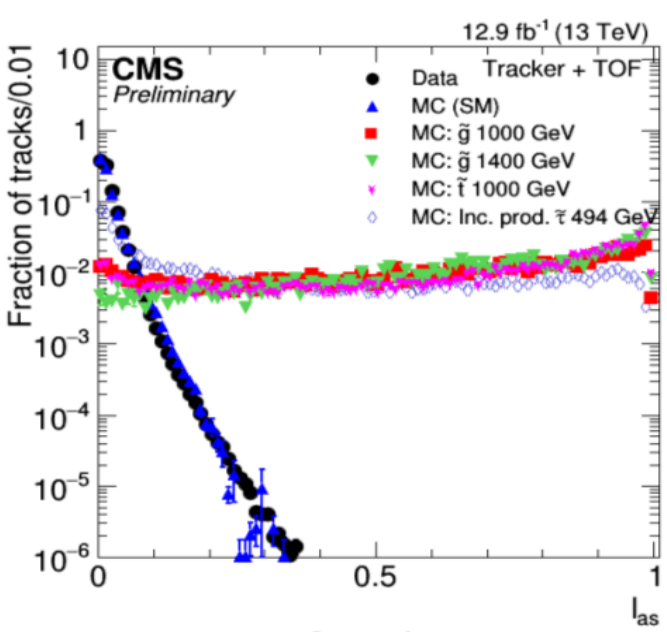


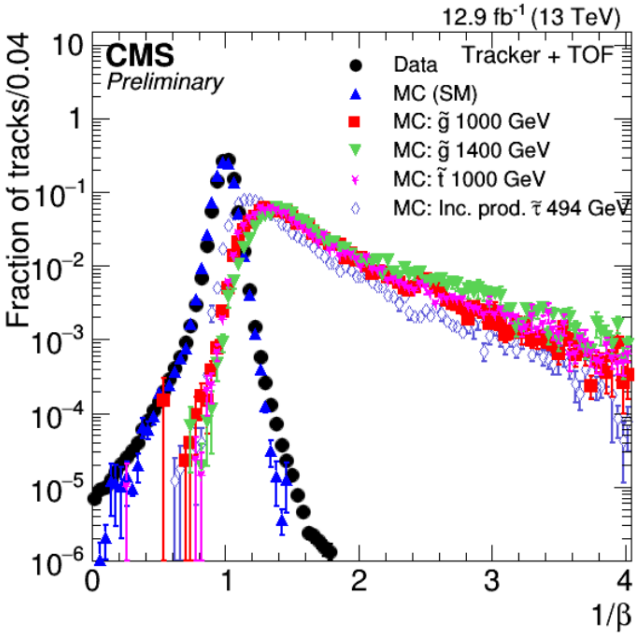


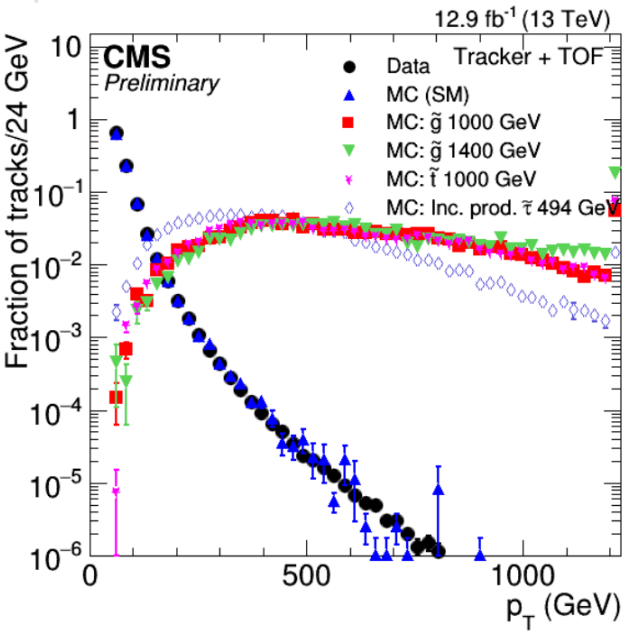


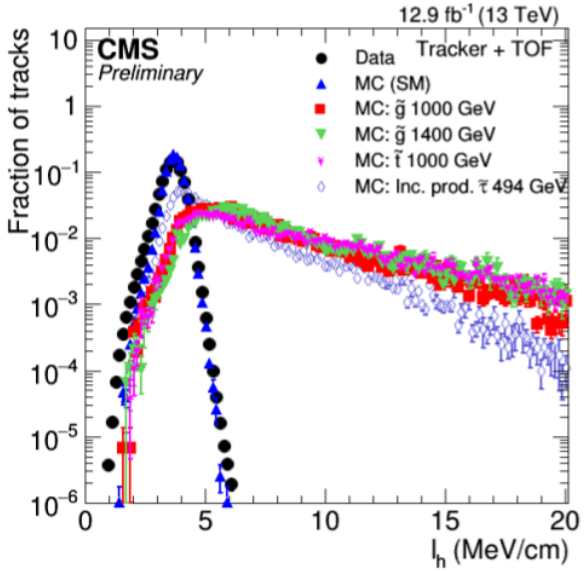


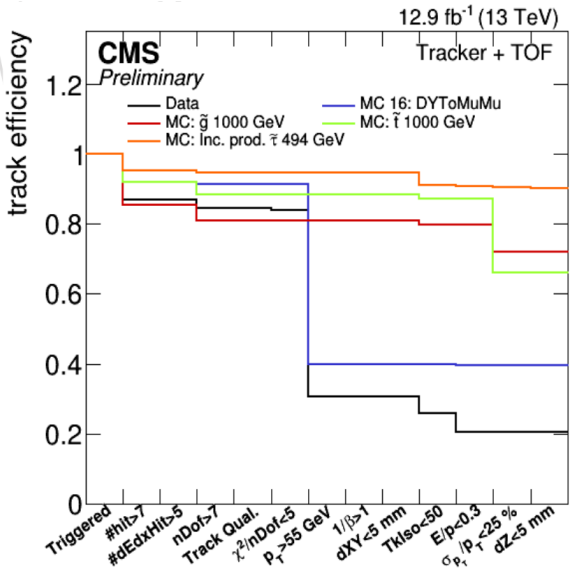
Distributions before the final selection











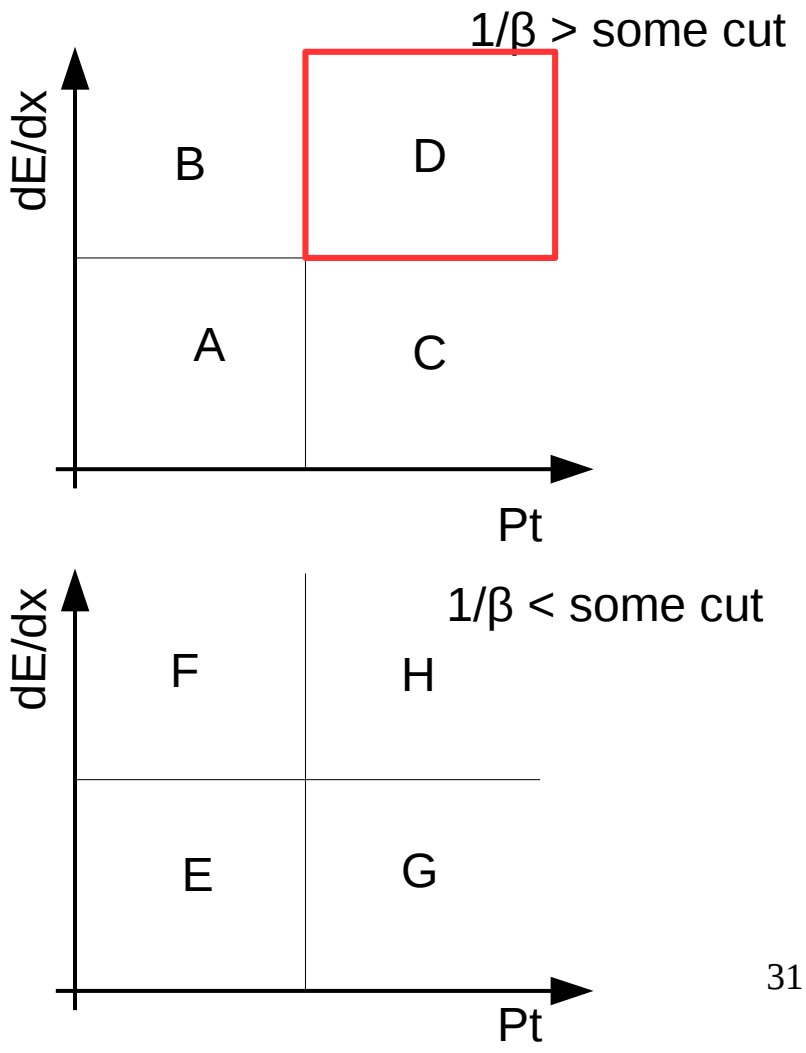
Final selection

- Tracker-Only
  - p_T > 65 GeV
  - dE/dx “discriminator” (I_{as}) > 0.3
- Tracker+TOF
  - p_T > 65 GeV
  - dE/dx “discriminator” (I_{as}) > 0.175
  - $1/\beta > 1.25$
- Tracks that pass these cuts are signal candidates
- Tracks that fail either of the selection cuts fall into the control regions
  - Used for background prediction

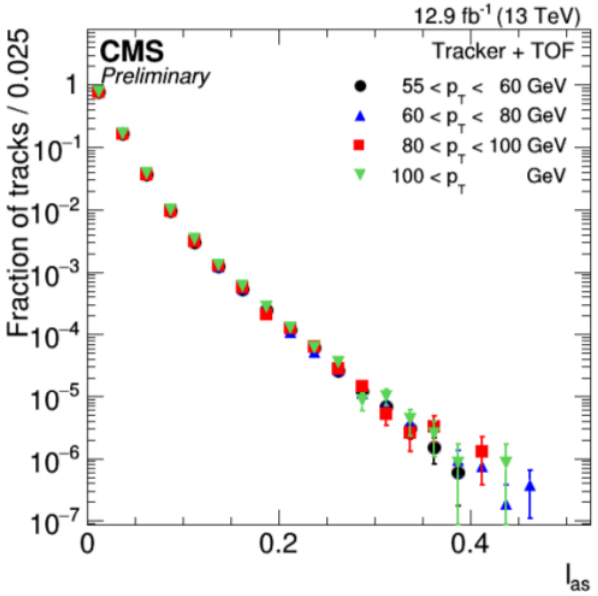
Background prediction method

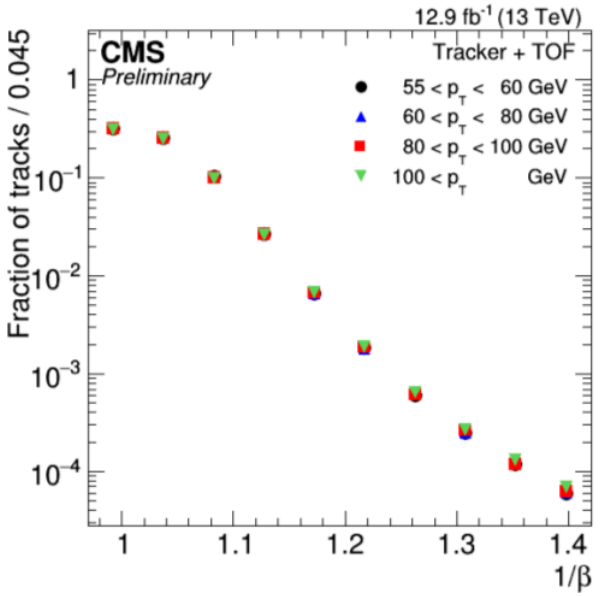
- Robust and data-driven
- “ABCD” method requires
  - Uncorrelated variables for background
  - Signal “confined” to D region
- Tracker-Only
  - B/A = D/C
  - D = BC/A
- Tracker+TOF
  - A/E = C/G → C = AG/E
  - D/F = C/E → D = CF/E
  - D = AFG/E^2

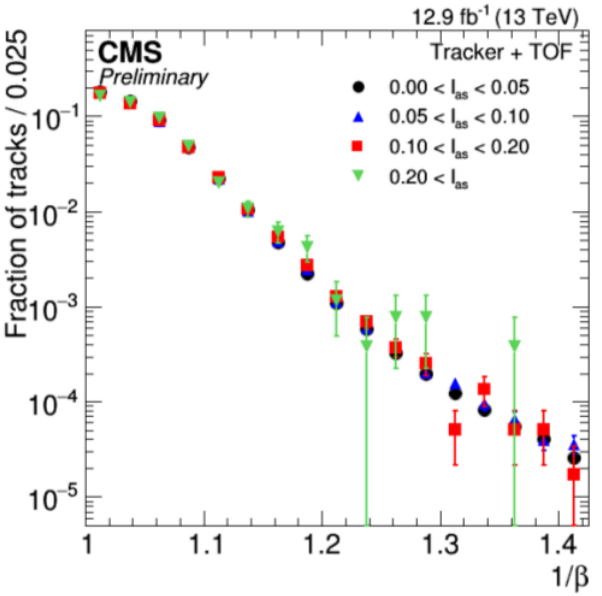
1/β > 1

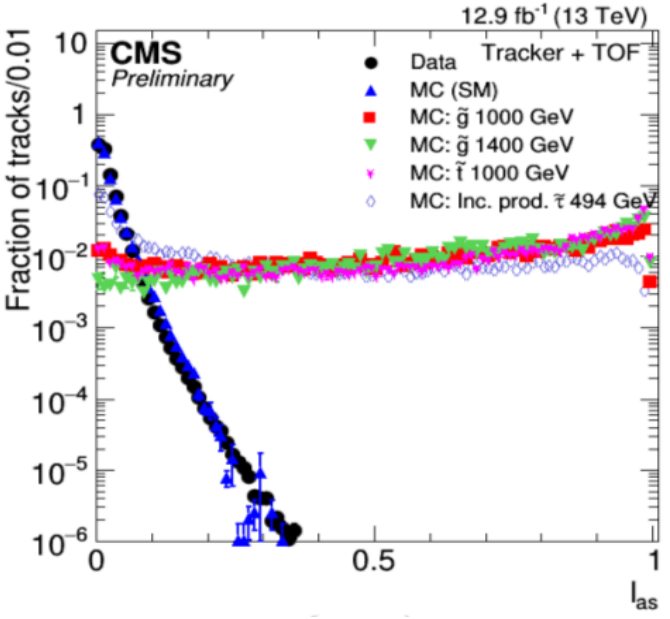


Justification of the “ABCD” method

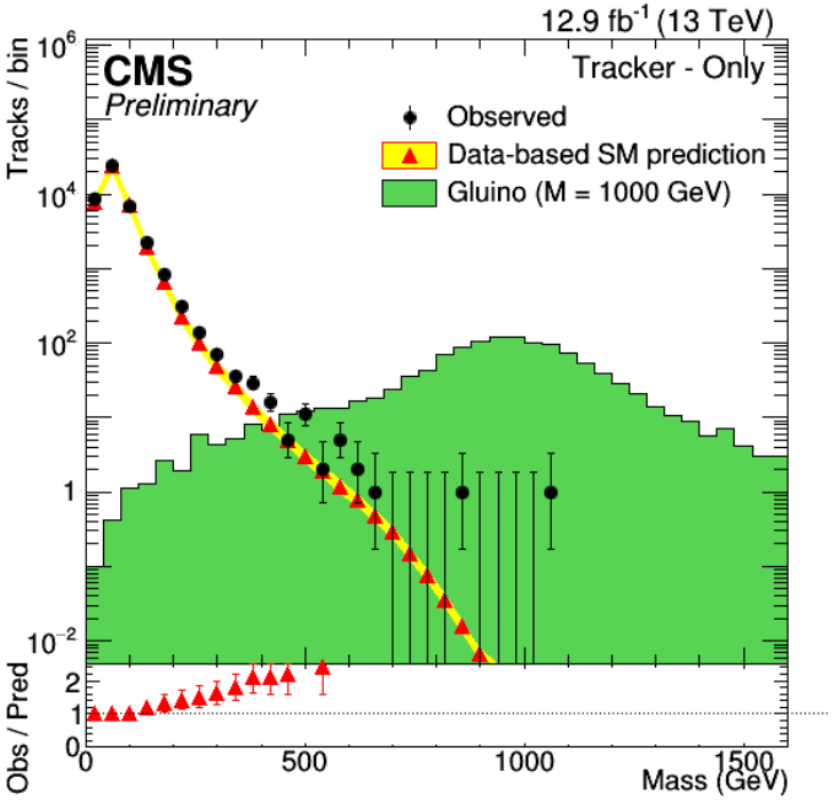


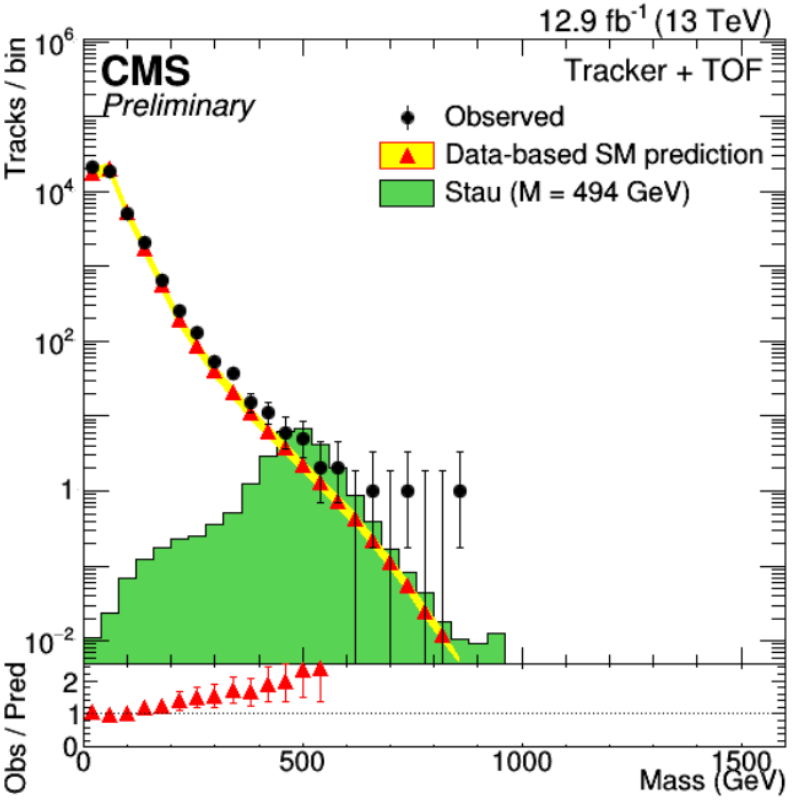






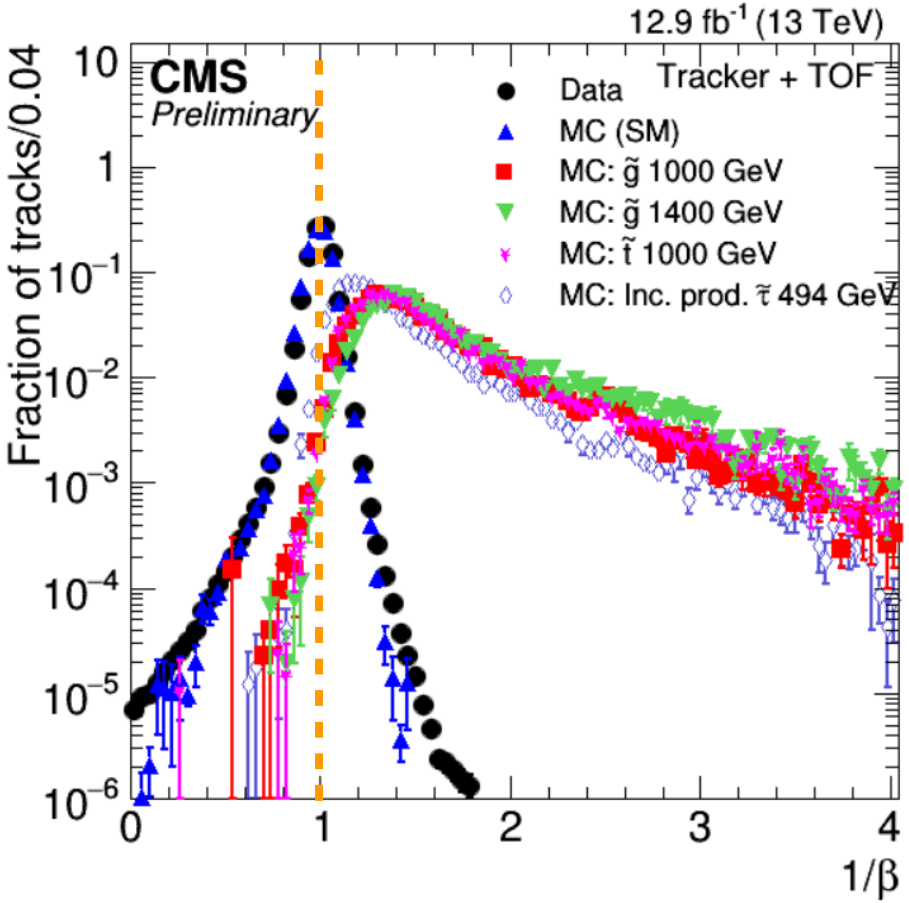
Testing prediction on loose selection cuts

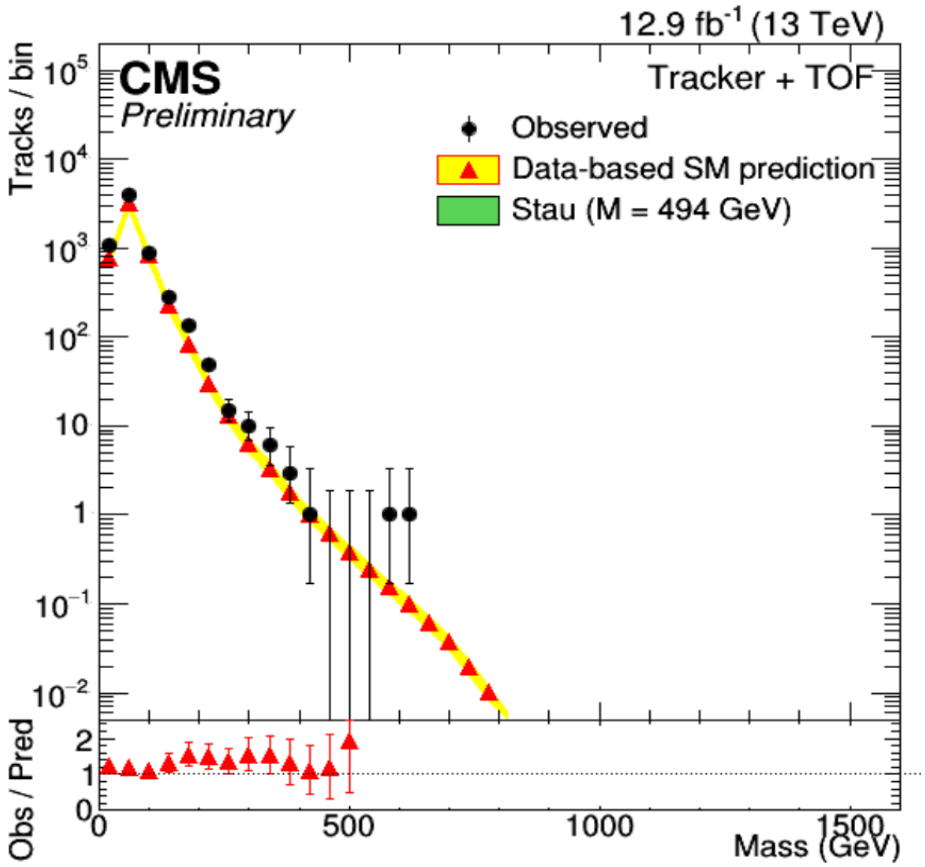




Some match, however, observed signal region could contain signal events.

Tachyon test – 1/β < 1



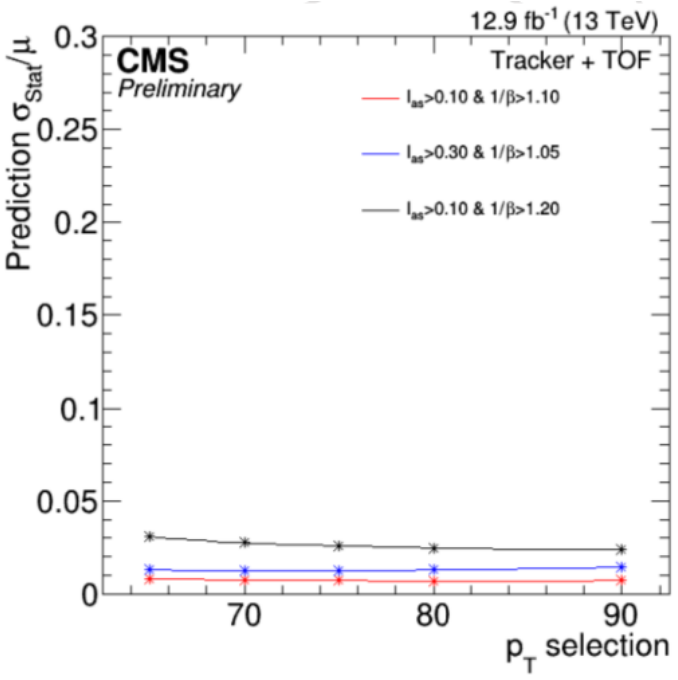


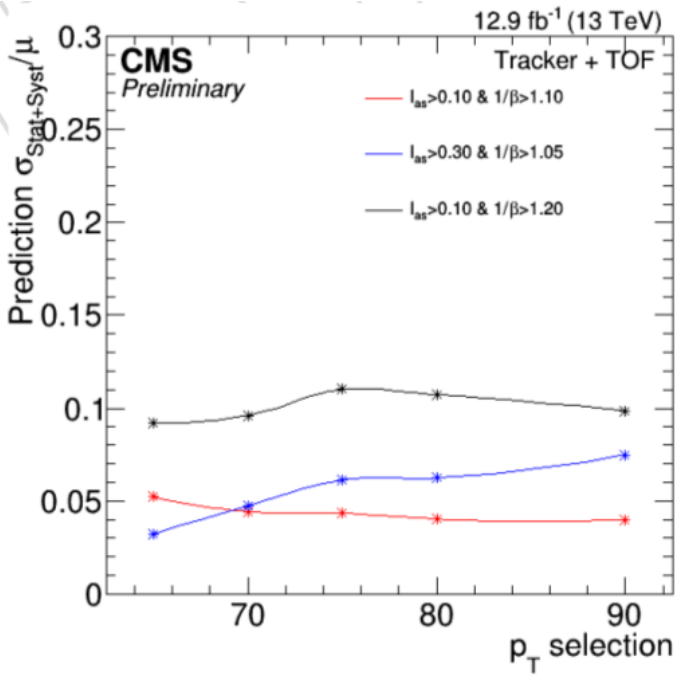
1/β < 1 has no signal → expect good match in background distributions → check!

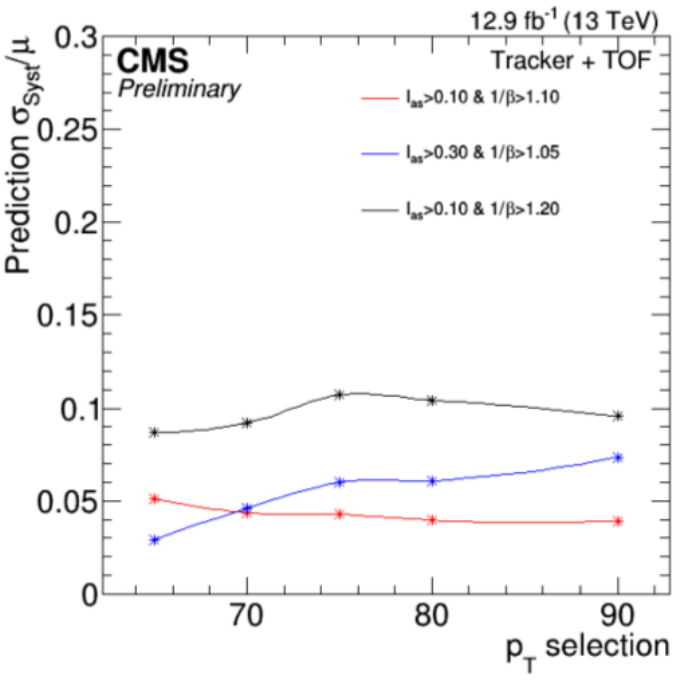
Systematic uncertainties on the background prediction

$$V_N^{stat} = \sqrt{\sum_i (\sigma_i)^2 / N} \qquad V^{syst} = \sqrt{V_{syst+stat}^2 - V_{stat}^2}$$

$$V_N^{syst+stat} = \sqrt{\sum_i (x_i - < x >)^2 / (N-1)}$$





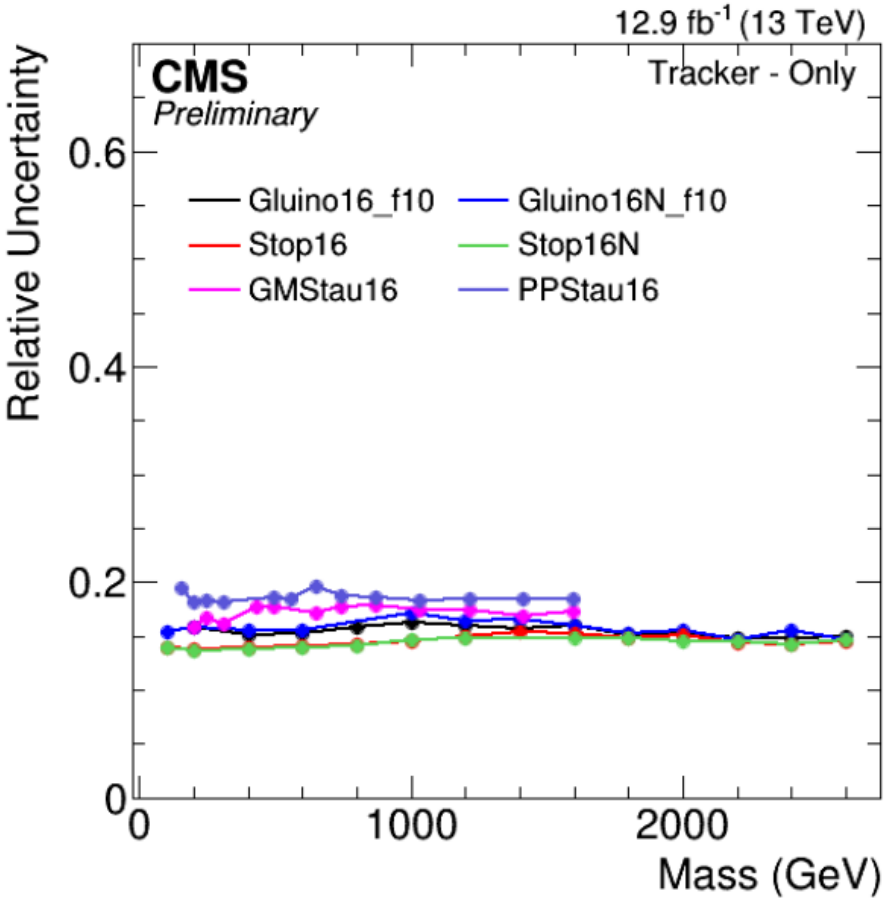


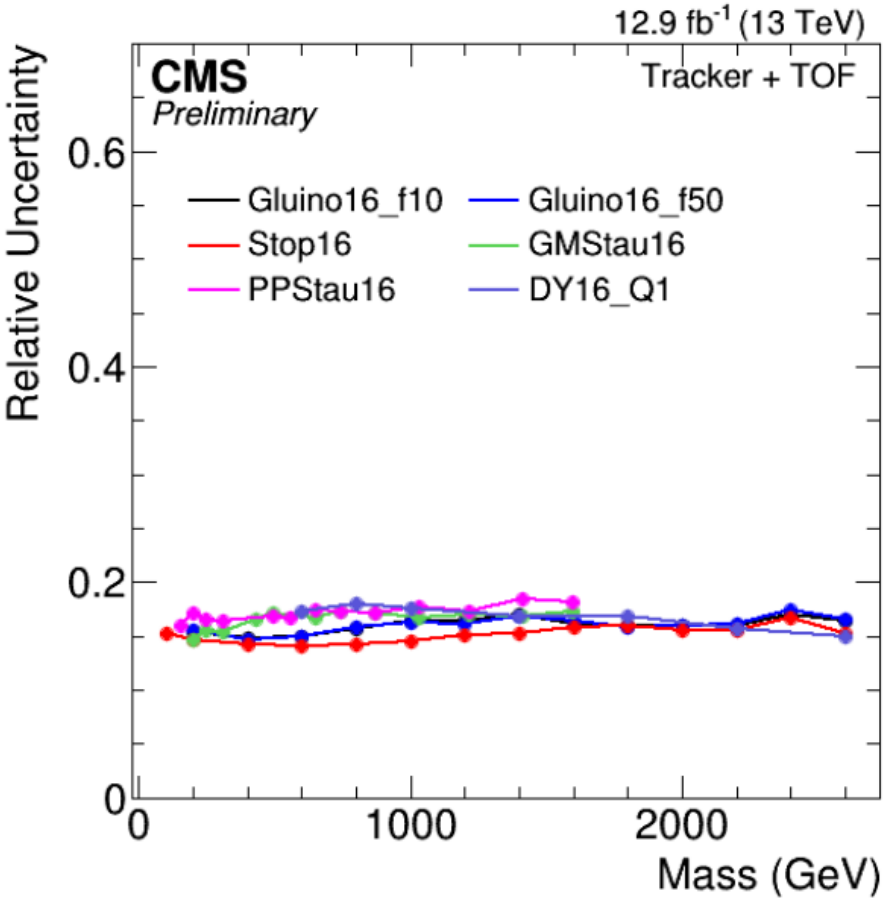
Sources of systematic uncertainties

Source of Systematic Uncertainties	Relative Uncertainty (%)	
Signal acceptance	Trk-only	Trk+TOF
- Trigger efficiency	13	13
- Track momentum scale	< 5	< 14
- Track reconstruction	< 2	< 2
- Ionization energy loss	< 13	< 7
- HIP background effect	< 10	< 10
- Time-of-flight	-	< 6
- Muon reconstruction	-	2
- Pile-up	< 2	< 2
Total uncertainty on signal acceptance	< 20	< 20
Collision background uncertainty	20	20
Luminosity uncertainty	6.2	

DRAFT

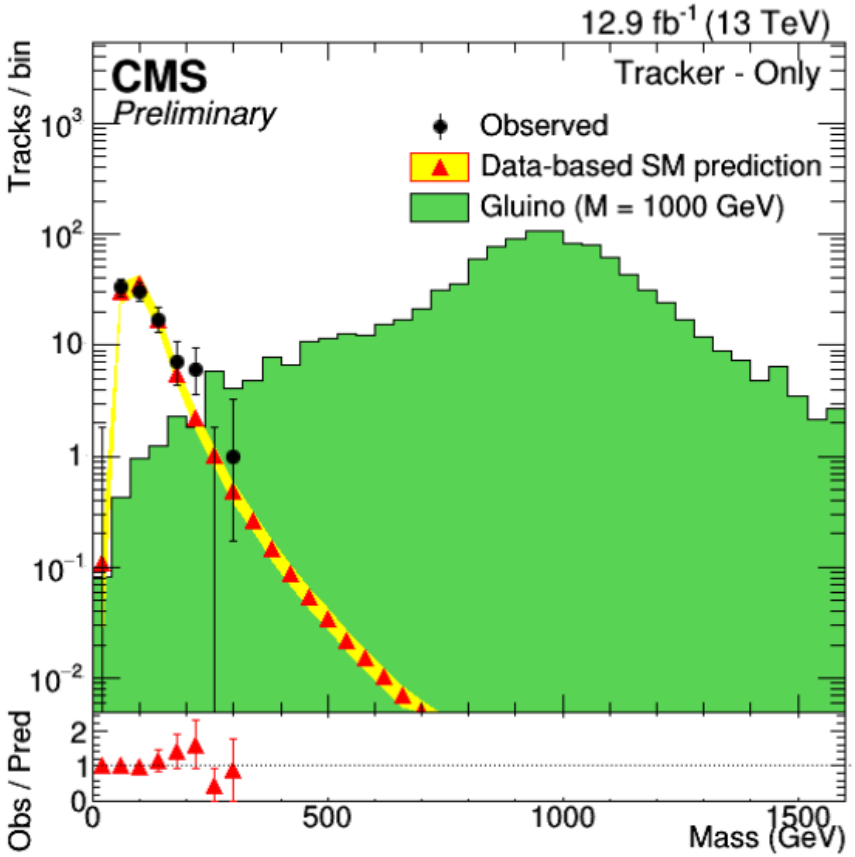
Relative total uncertainty for various samples

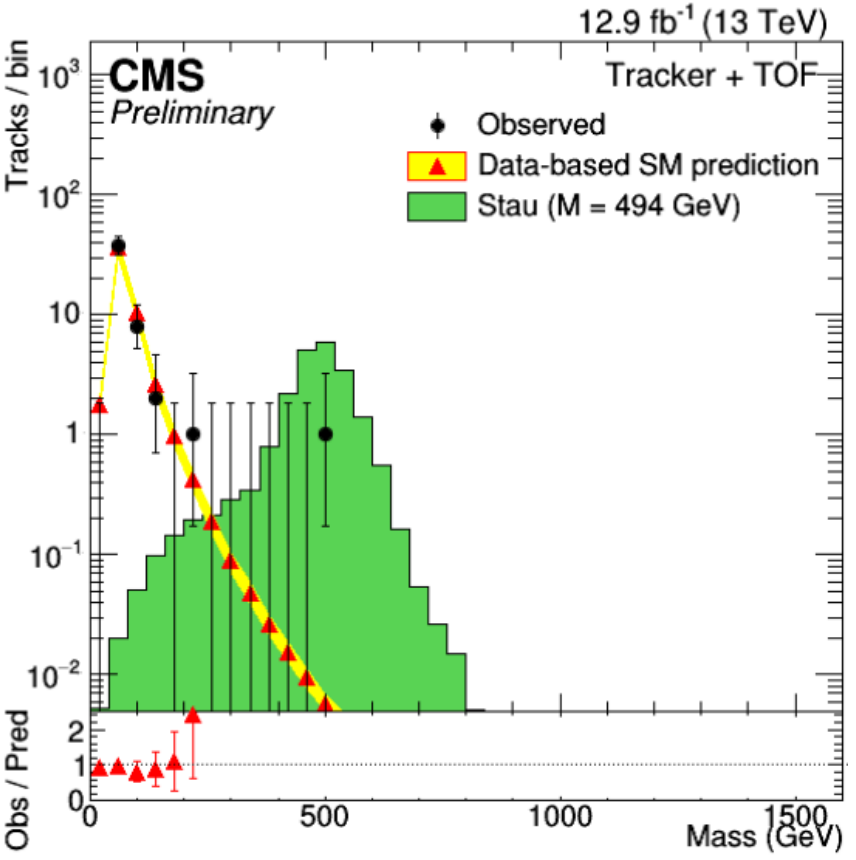




Analysis results

Results: reconstructed mass

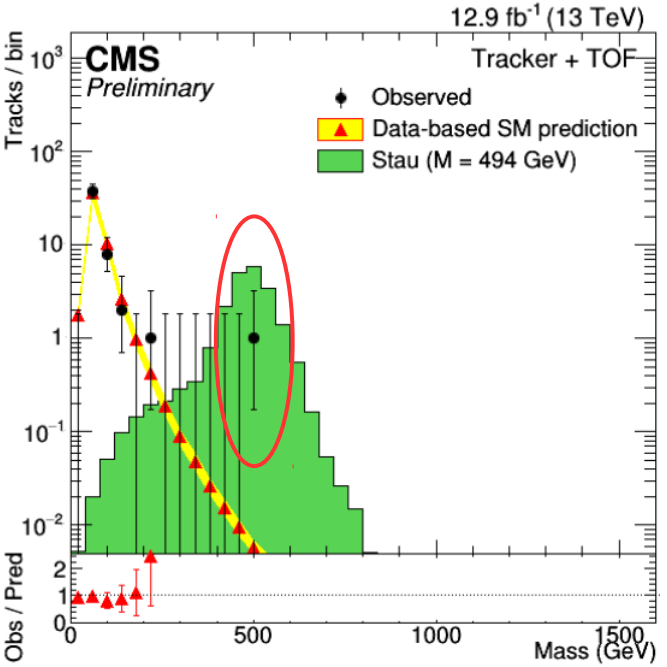




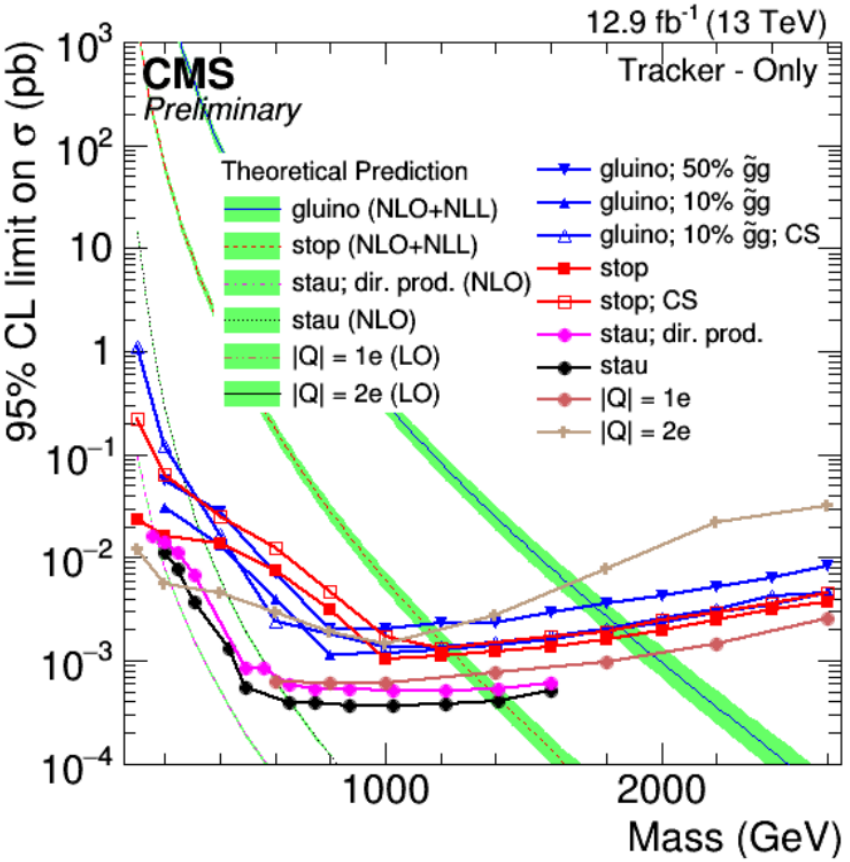
Plots show observed vs. predicted number of events for each mass bin in the signal region, overlain with a benchmark model. No significant excess has been found.

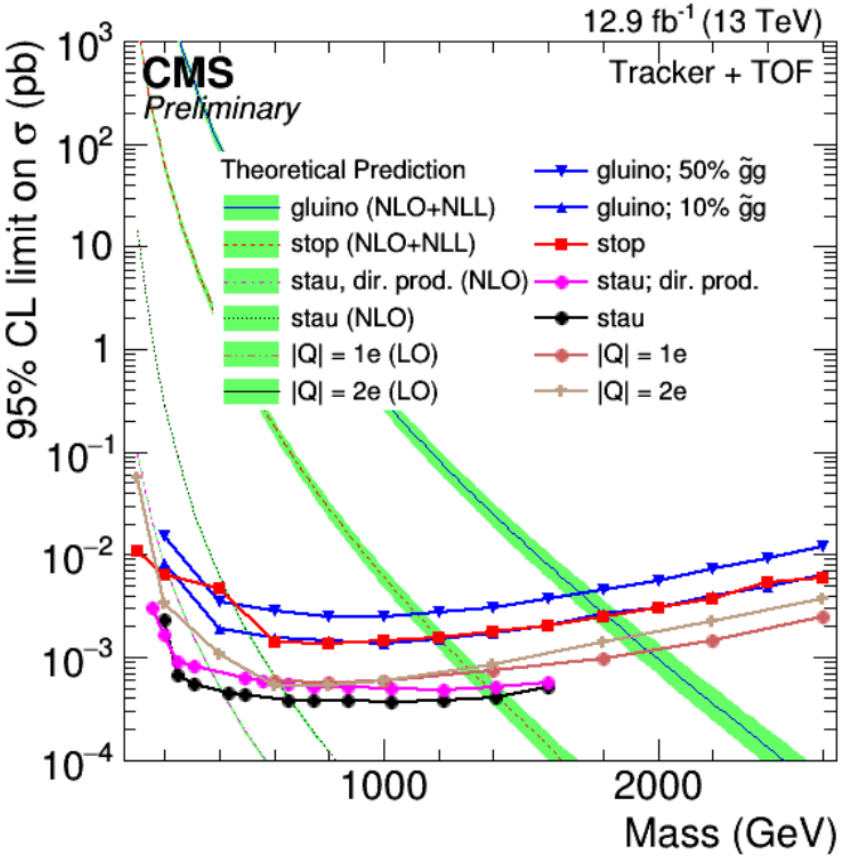
High-mass track in Tracker+TOF

- Event passed muon triggers
- Quality = 15
- χ^2/nDof = 0.96
- Dz = 0, Dxy = 0
- p = 730 GeV
- p_T = (340 ± 50) GeV
- η = 1.38
- φ = -0.70
- 1/β = 1.14 ± 0.07
- E/p = 0.10
- Number of hits = 15; 3 Pixel hits, 12 Strip hits, 3 were rejected (superimposed tracks)
- dE/dx “discriminator” value = 0.23
- dE/dx “estimator” value = 4.56 MeV/cm
- Mass = 509 GeV
  - 290 GeV if 1 sigma lower in momentum
  - 310 GeV if 1 sigma lower in dE/dx



Results: Limit Plots





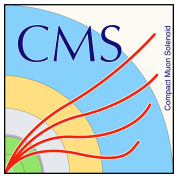
Limits on the observed cross-section were put on the benchmark models.

Results: Mass Limits

Model	analysis	2015 analysis	2016 analysis
Gluino $f = 0.1$	*tracker-only*	$M > 1610$ GeV	$M > 1850$ GeV
	tracker+TOF	$M > 1580$ GeV	$M > 1810$ GeV
Gluino $f = 0.1$ CS	*tracker-only*	$M > 1580$ GeV	$M > 1850$ GeV
Gluino $f = 0.5$	*tracker-only*	$M > 1520$ GeV	$M > 1750$ GeV
	tracker+TOF	$M > 1490$ GeV	$M > 1720$ GeV
Gluino $f = 0.5$ CS	*tracker-only*	$M > 1540$ GeV	$M > 1800$ GeV
Stop	*tracker-only*	$M > 1040$ GeV	$M > 1250$ GeV
	tracker+TOF	$M > 990$ GeV	$M > 1200$ GeV
Stop CS	*tracker-only*	$M > 1000$ GeV	$M > 1220$ GeV
GMSB Stau	*tracker-only*	$M > 480$ GeV	$M > 660$ GeV
	tracker+TOF	$M > 490$ GeV	$M > 660$ GeV
Pair Prod. Stau	*tracker-only*		$M > 170$ GeV
	tracker+TOF	$M > 240$ GeV	$M > 370$ GeV
DY $Q = 1e$	*tracker-only*	$M > 510$ GeV	$M > 720$ GeV
	tracker+TOF	$M > 550$ GeV	$M > 730$ GeV
DY $Q = 2e$	*tracker-only*	$M > 680$ GeV	$M > 670$ (720) GeV
	tracker+TOF	$M > 660$ GeV	$M > 890$ GeV

All the numbers are derived from the observed cross-section. Expected cross-section in the brackets where it differs by more than ±10 GeV.





Thank you for your attention!

Predicting the signal region mass spectrum

- Pseudo experiments

$$B_i C_i / A_i \times (k_{il} / C_i) \times (n_{ij} / B_i) = (k_{il} n_{ij} / A_i)$$

  - i = pseudo experiment index
- k – dE/dx drawn from the “B” region (low p, high dE/dx)
  - l = dE/dx estimator bin index
  - η distribution weights applied!
- n – p, drawn from the “C” region (high p, low dE/dx)
  - j = p bin index