Search for exotic long-lived particles using displaced jets in the ATLAS calorimeters

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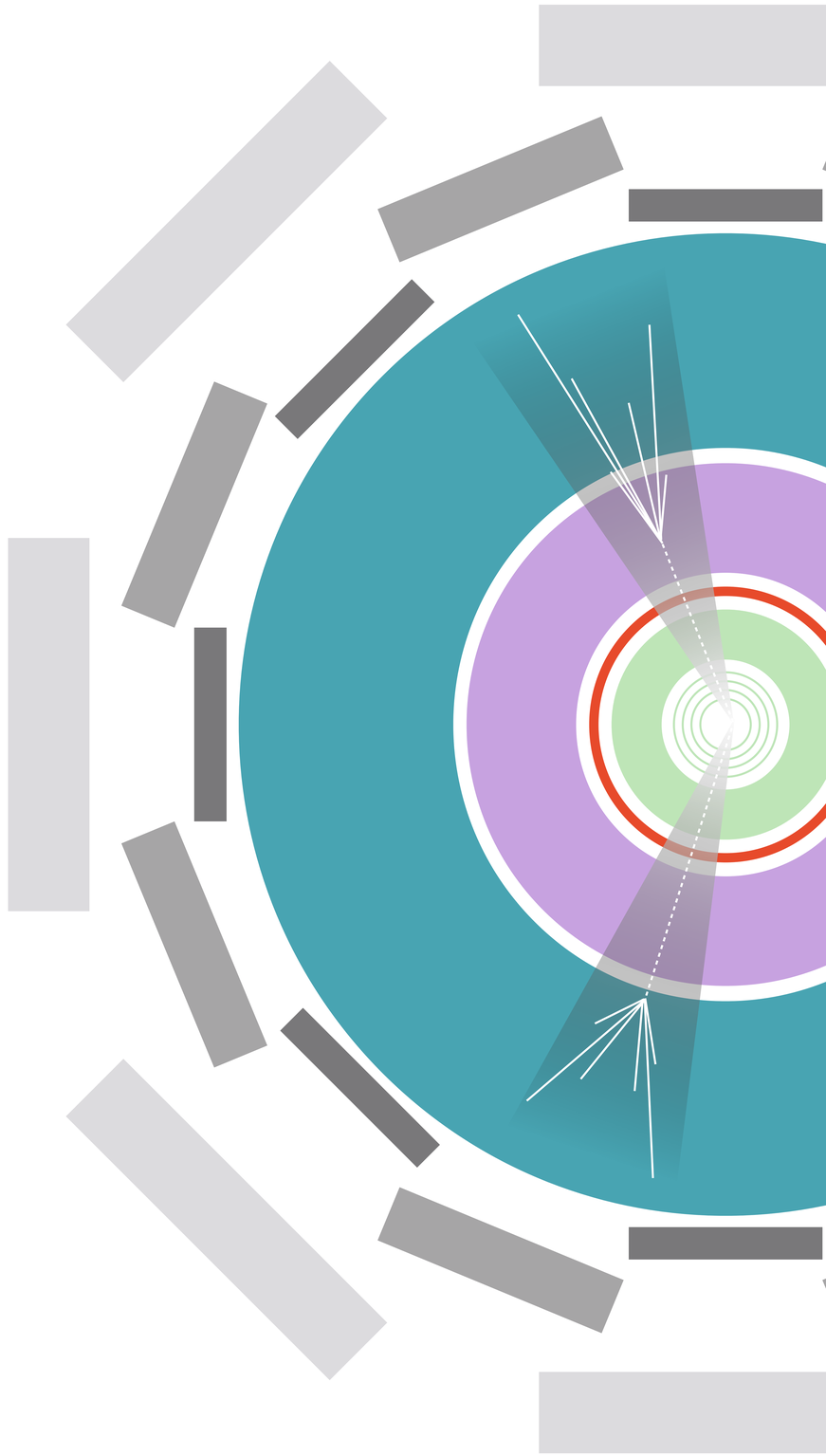
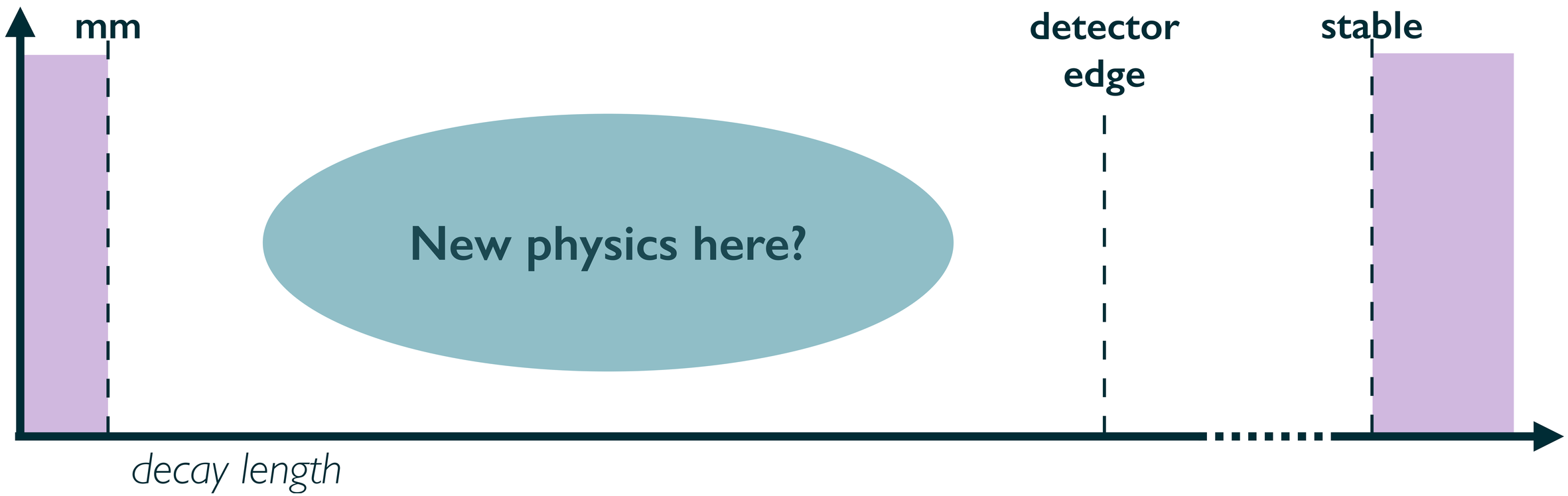
Joint APP and HEPP Annual Conference 2019



arXiv: 1902.03094 (submitted to EPJC)

Introduction to LLPs

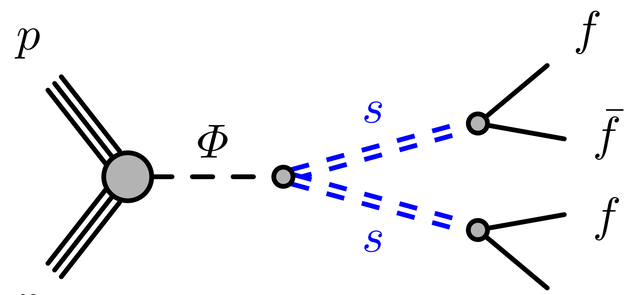
- Long-lived particles (LLPs) abound in the Standard Model
- Many SM extensions predict LLPs
- LLPs could decay within ATLAS detector, however:
  - Highly displaced activity
  - Signals can look like noise
  - Overlooked by other searches?
- Focus on model-independent searches to allow for reinterpretation



Neutral LLPs

- Decays of neutral long-lived particles could result in displaced jets

- **CalRatio displaced jets search**
  - Signature-driven
  - Two displaced jets with high CalRatio (E_{HCal}/E_{ECal})
  - Benchmark simplified Hidden Sector model
    - Φ decays to two long-lived neutral s
    - s decay mainly to b-quarks via coupling to Higgs
  - One of 3 related analyses (others look in ID+MS, MS-only) to cover full detector
  - Use 2016 LHC data (33 fb^{-1})

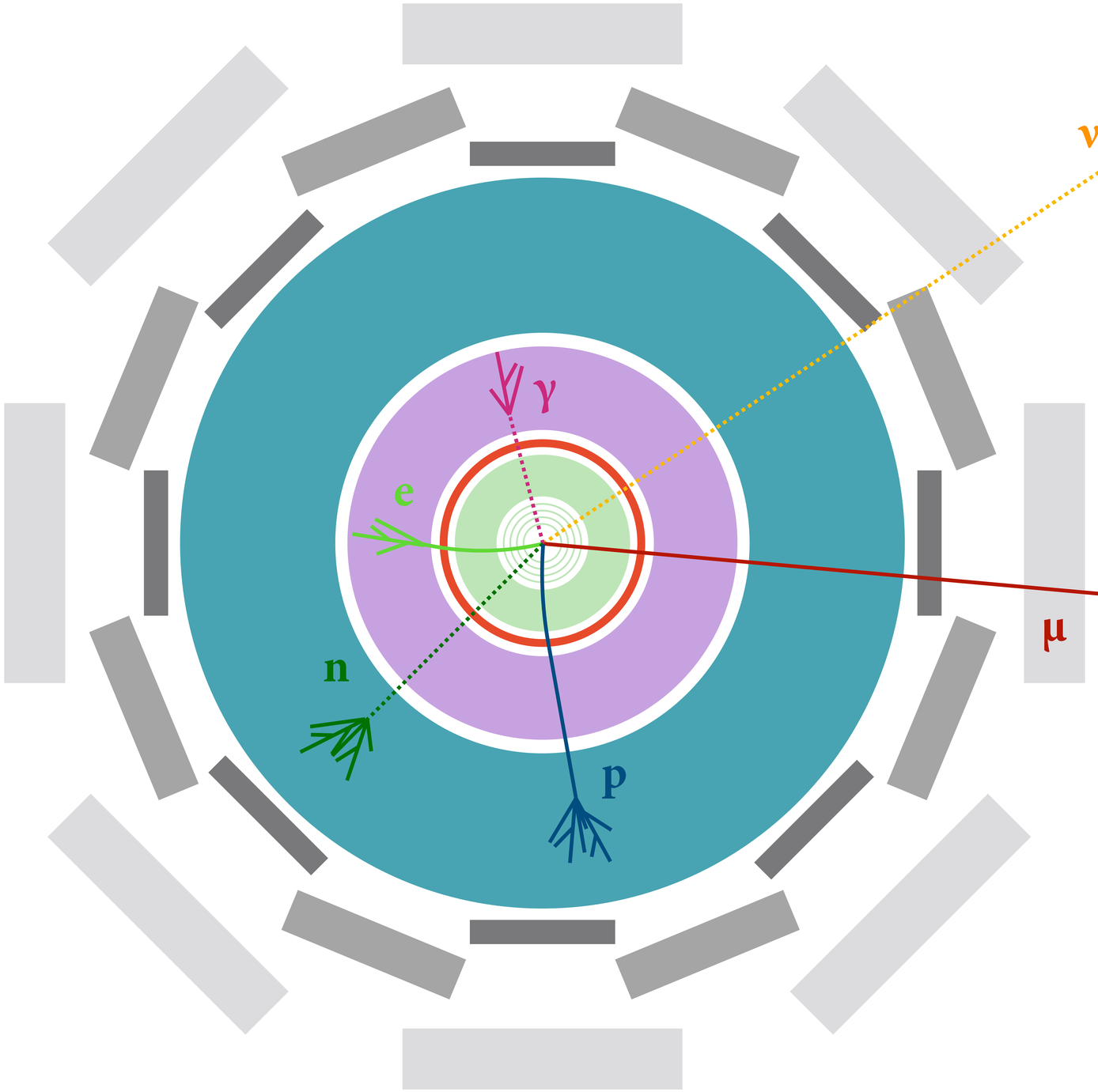


$m_{\Phi} \in [125,1000]$ GeV

$m_{s} \in [5,400]$ GeV

ATLAS detector

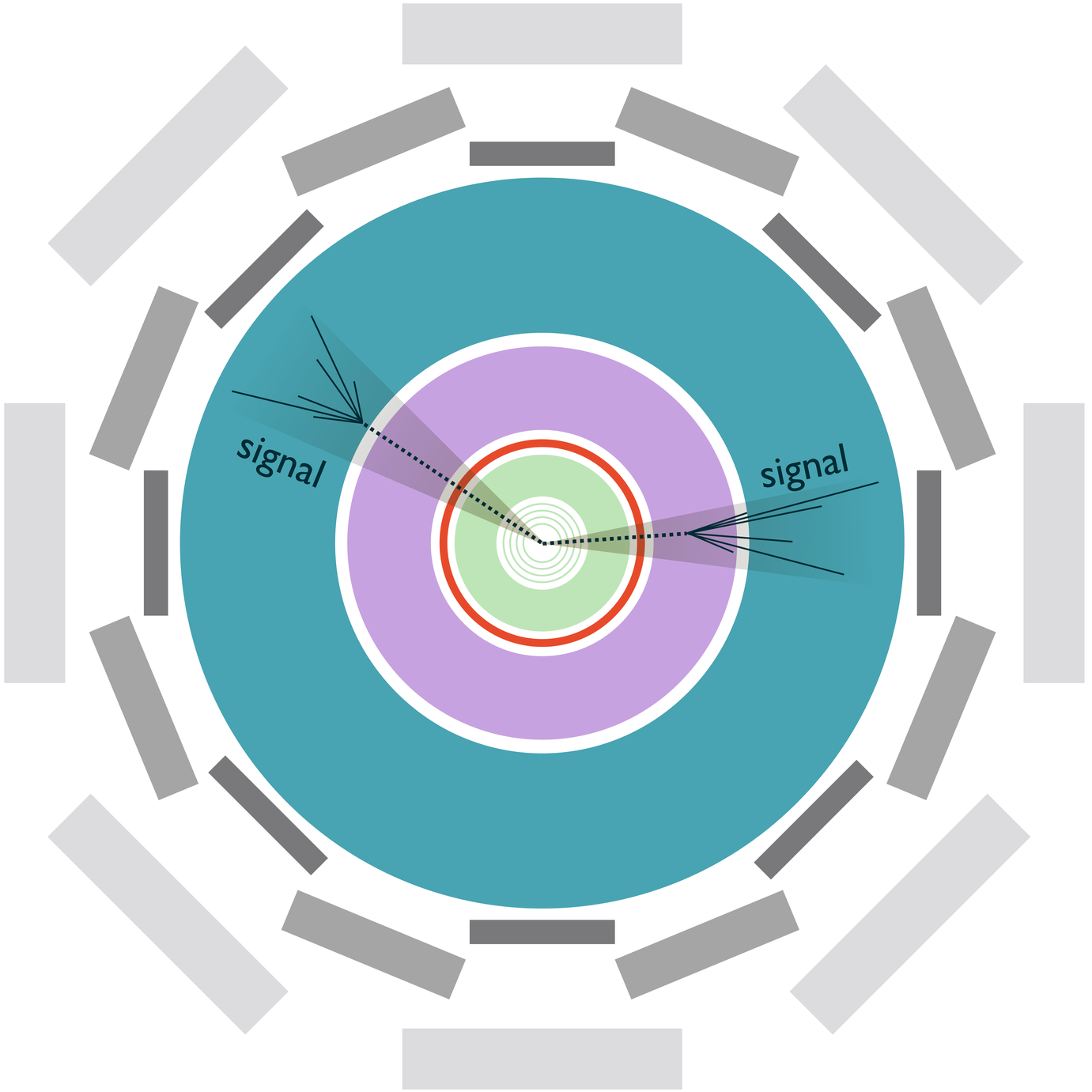
- Inner detector (ID) in solenoid magnetic field
  - Charged particles leave tracks
- Electromagnetic calorimeter (ECal)
  - Electrons and photons deposit energy
- Hadronic calorimeter (HCal)
  - Hadrons deposit energy and are stopped
- **Muon** Spectrometer (MS) in toroidal magnetic field
  - Muons leave tracks but are not stopped



Signature

Two displaced CalRatio jets

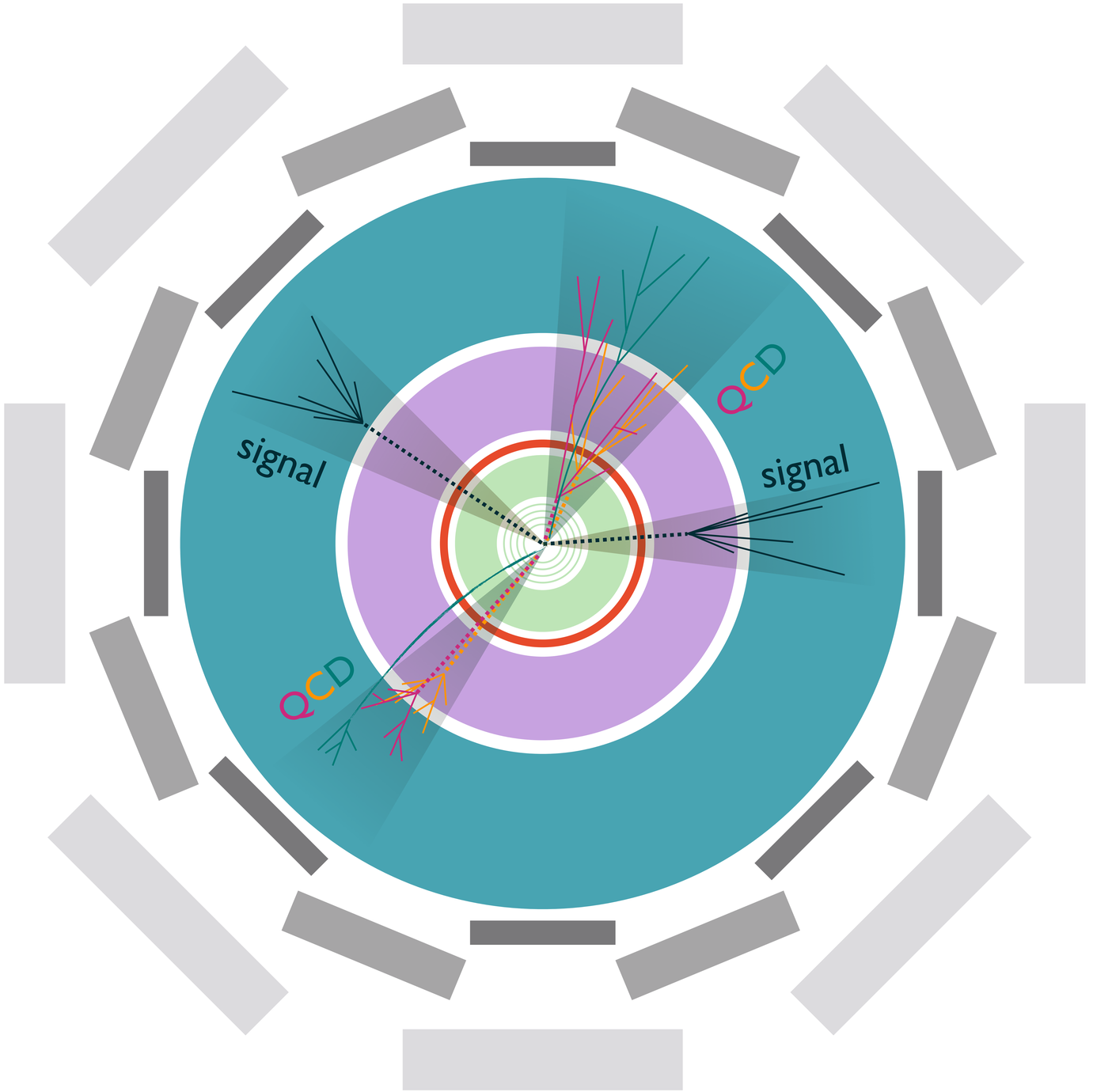
- Narrower than most SM jets
  - Shower starts later, less time to spatially separate
- Trackless
  - Neutral LLPs -> no hits in ID
- Low fraction of energy in the ECal
  - Define CalRatio = E_{HCal}/E_{ECal}



Backgrounds

SM QCD jets

- Low probability to mimic signal
- Very high cross section at LHC
- Dominant background

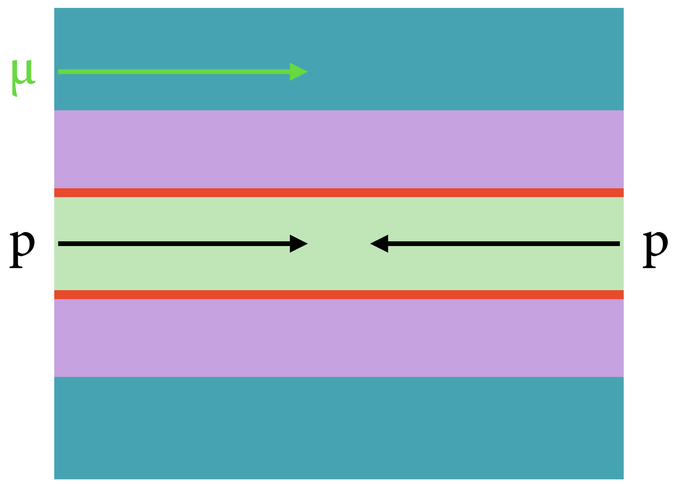


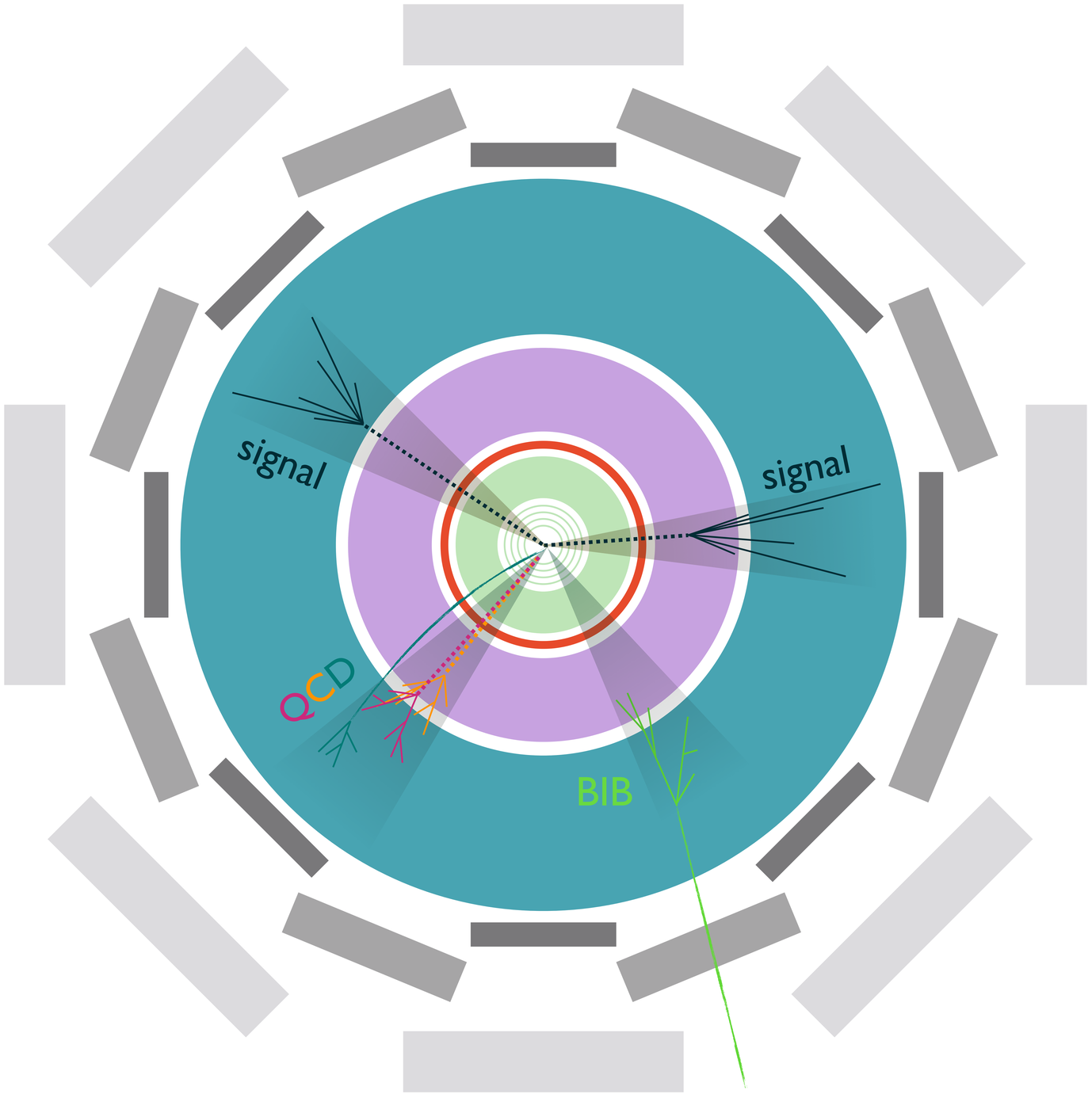
Backgrounds

SM QCD jets

Beam-induced background (BIB)

- Muons from upstream interactions travel parallel to the beam
- Can deposit energy in HCal while missing ID
- Studied in events which fail BIB-removal at trigger level





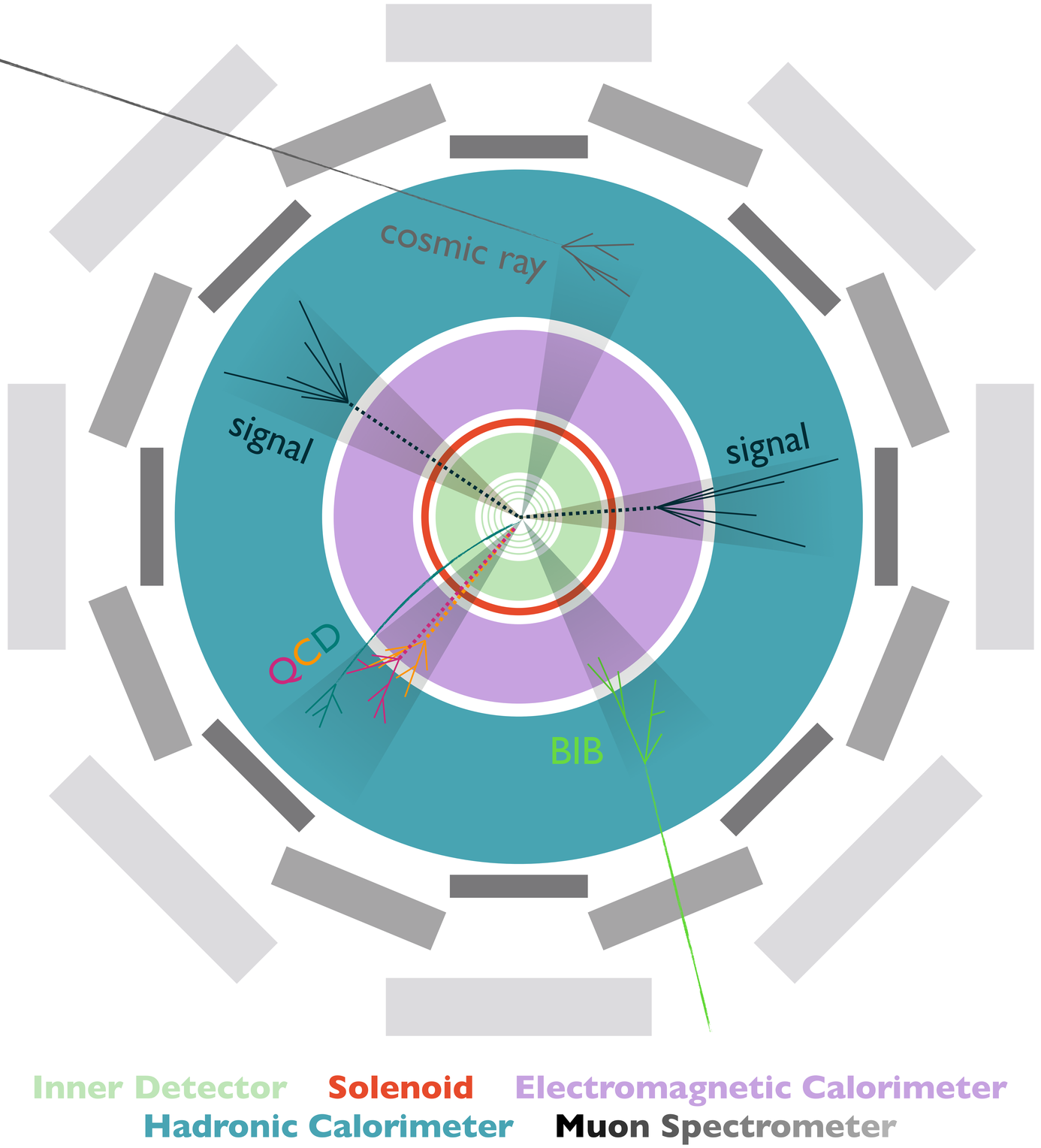
Backgrounds

SM QCD jets

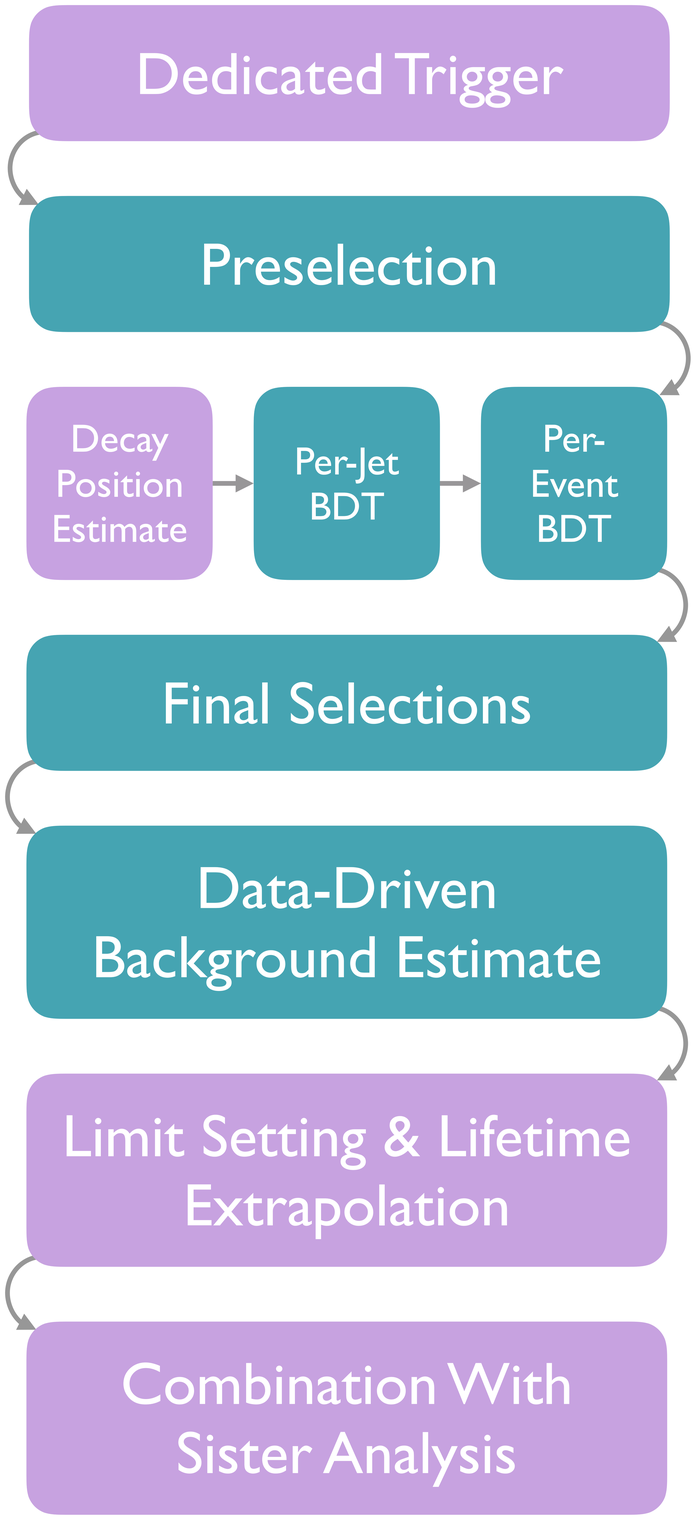
Beam-induced background (BIB)

Cosmic ray muons

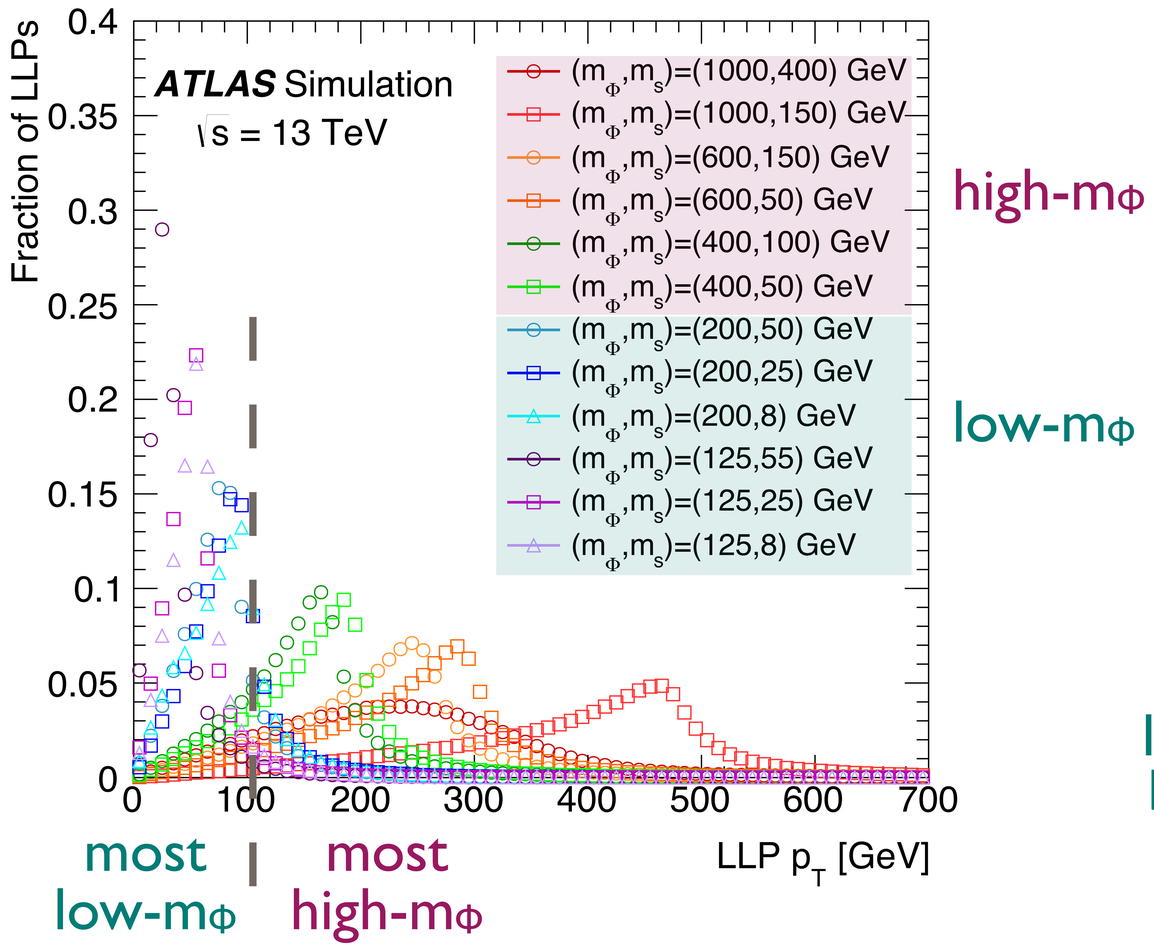
- Enter through cavern access shafts
- Can deposit energy in HCal while missing ID
- Studied in “empty” bunch crossings



CalRatio analysis overview

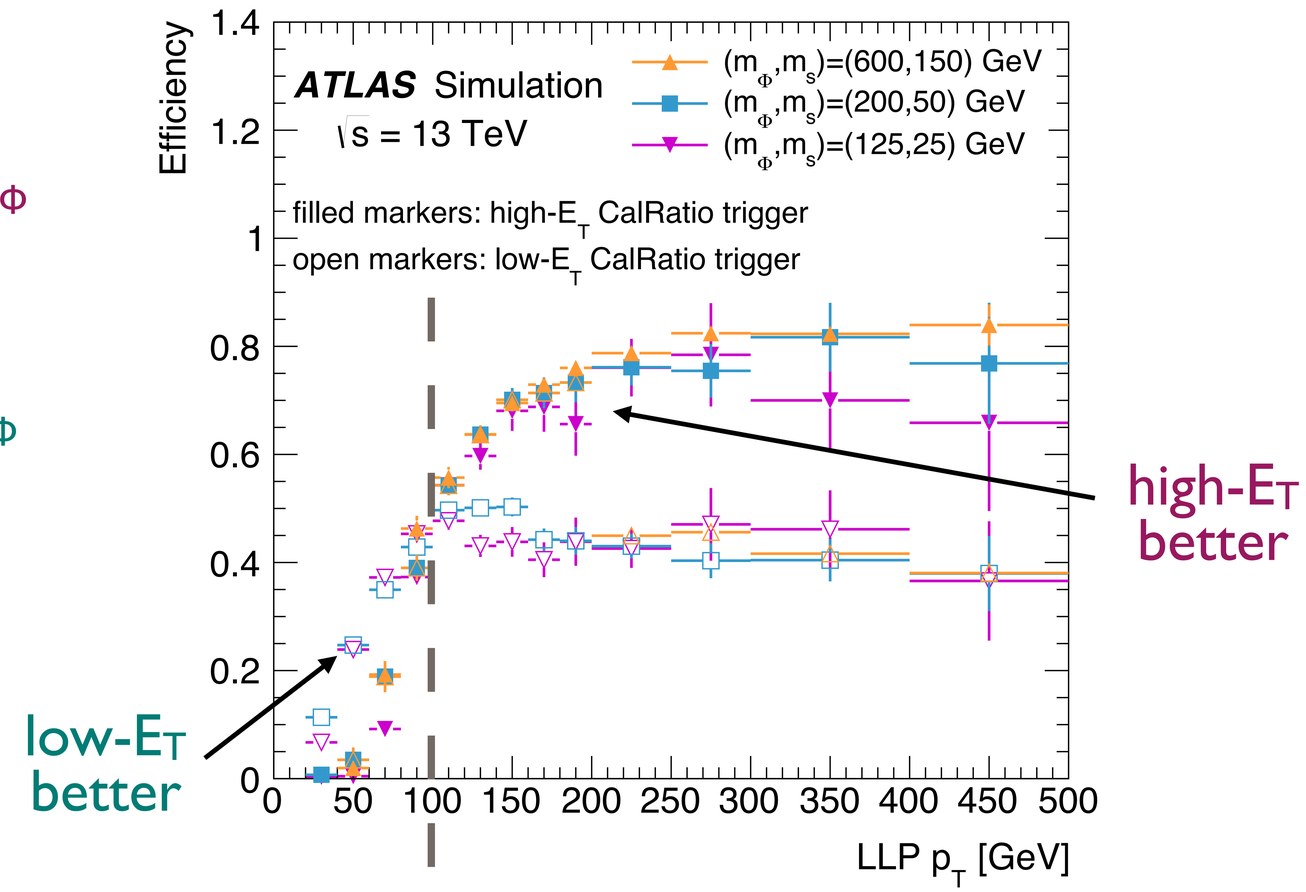


Triggers



high-mΦ

low-mΦ



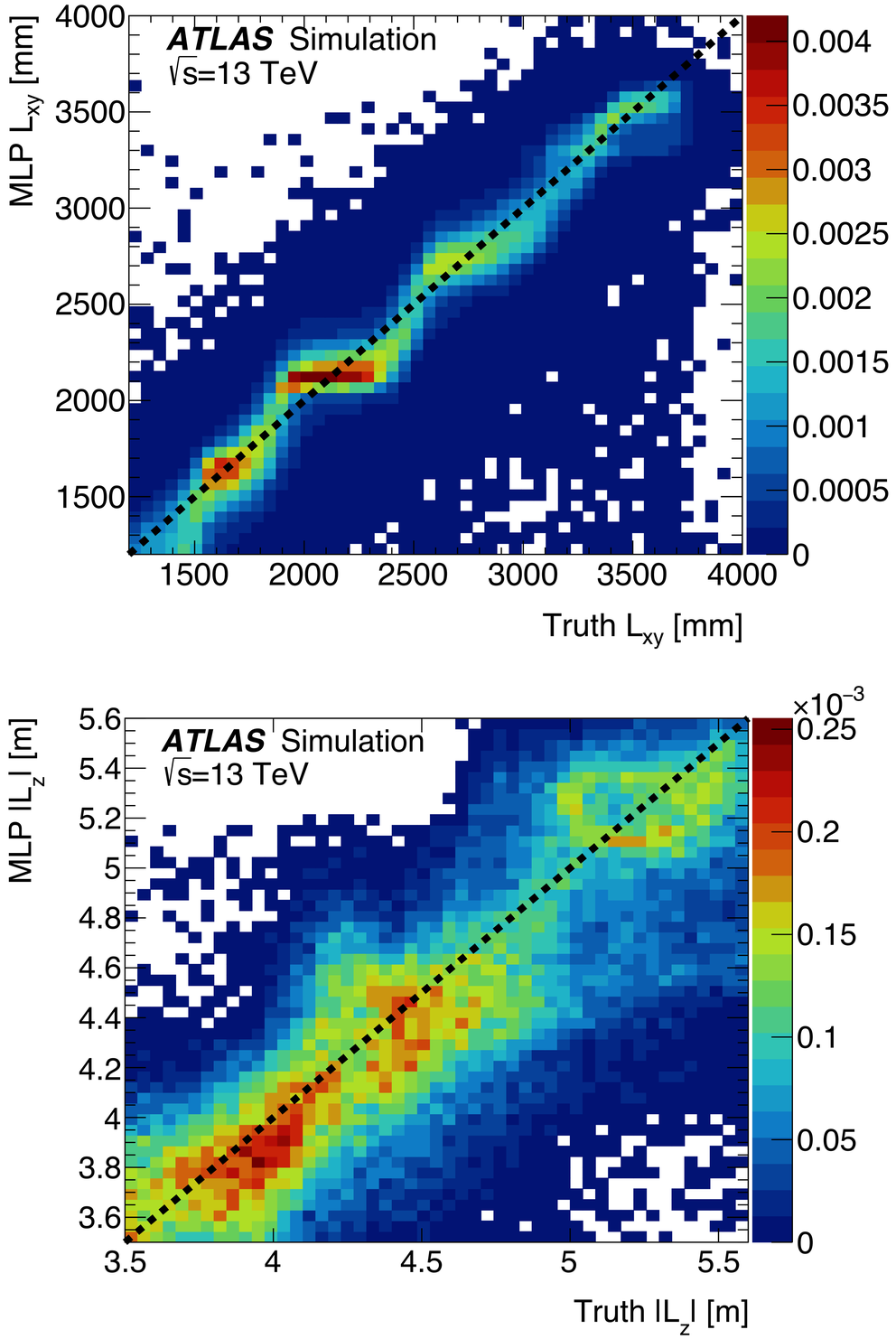
Hardware: narrow HCal deposits

- High-E_T trigger for high-m_Φ models, E_T threshold 60 GeV
- Low-E_T trigger for low-m_Φ models, E_T threshold 30 GeV, uses HCal deposit isolation from ECal deposits

Offline: beam-induced background removal, track isolation, high CalRatio

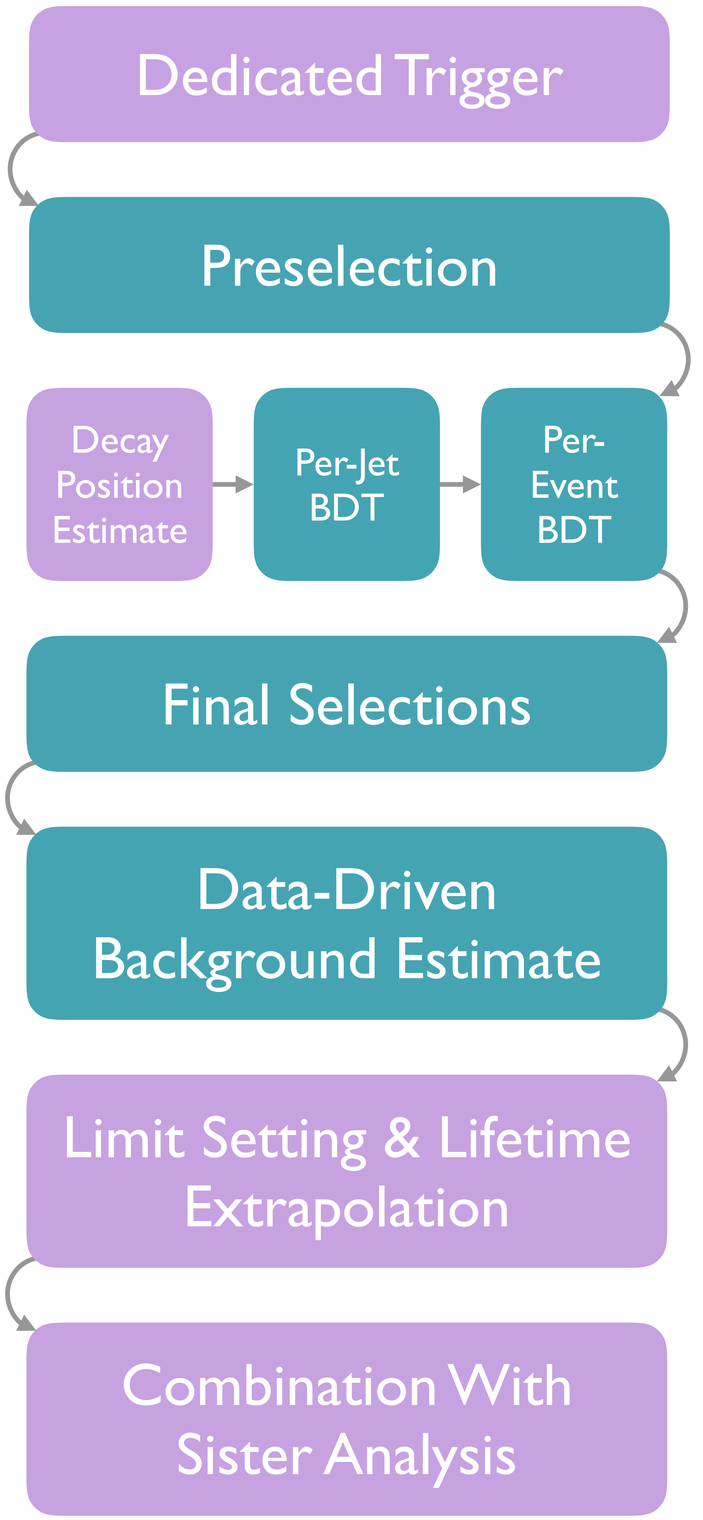
Decay position estimate

- **Multi-layer perceptron** predicts decay position of LLP based on calorimeter layer energy fractions
  - Trained and tested on simulated signal jets with simple selection applied
  - Radial and longitudinal decay positions discriminate between LLP jets and prompt SM jets
  - Decay positions given to per-jet boosted decision tree (BDT) for jet classification



CalRatio analysis overview

- Decay positions and other jet variables used as input for **per-jet BDT**
  - Classifies jets as likely to be signal, BIB or QCD
- **Per-event BDT** uses output of per-jet BDT and other event-level variables to classify events as likely to be signal or background
  - Also used in data-driven background estimate



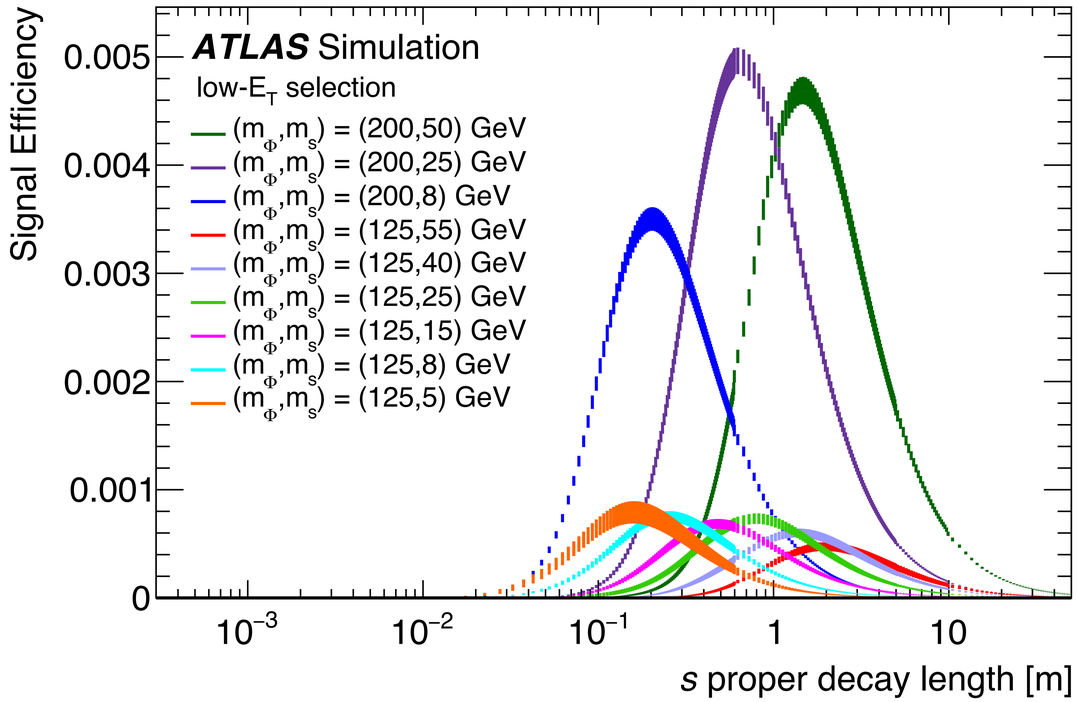
Extrapolation

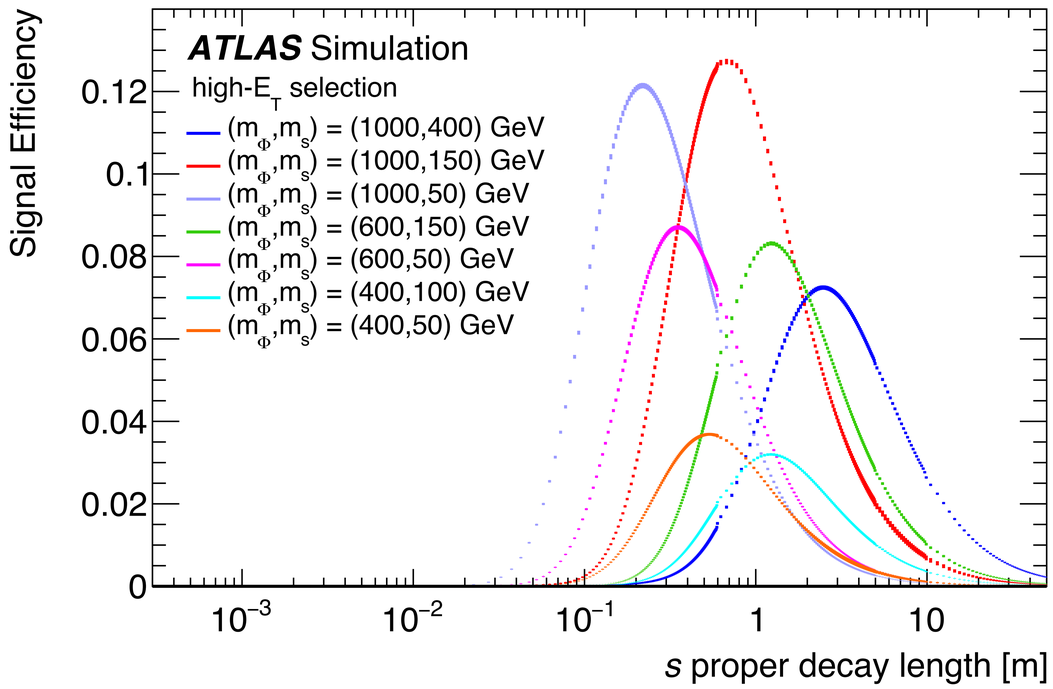
- Simulated signal samples are generated at one LLP proper decay length (cτ)

- Limits set on a range of cτ so signal efficiency extrapolated to other decay lengths

- Simple reweighing procedure based on truth information in signal samples

$$w(t) = \frac{\tau_{gen}}{exp(-t/\tau_{gen})} \times \frac{exp(-t/\tau_{new})}{\tau_{new}}$$



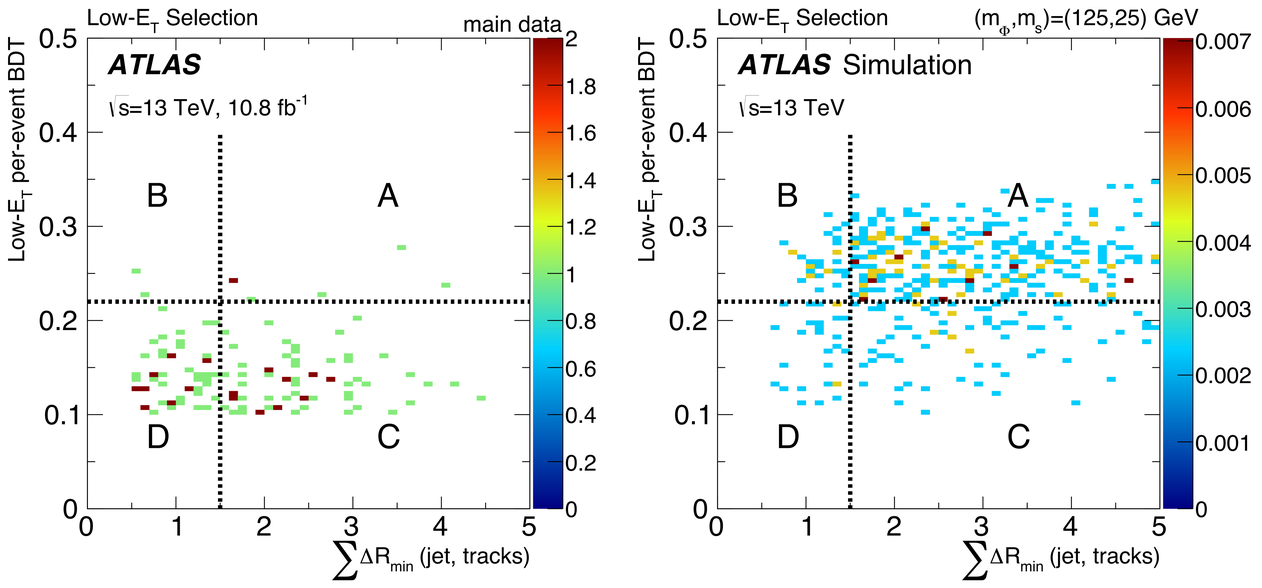


Results

- Data-driven background estimate using ABCD method
- $N_A = N_B \times N_C \,/\, N_D$

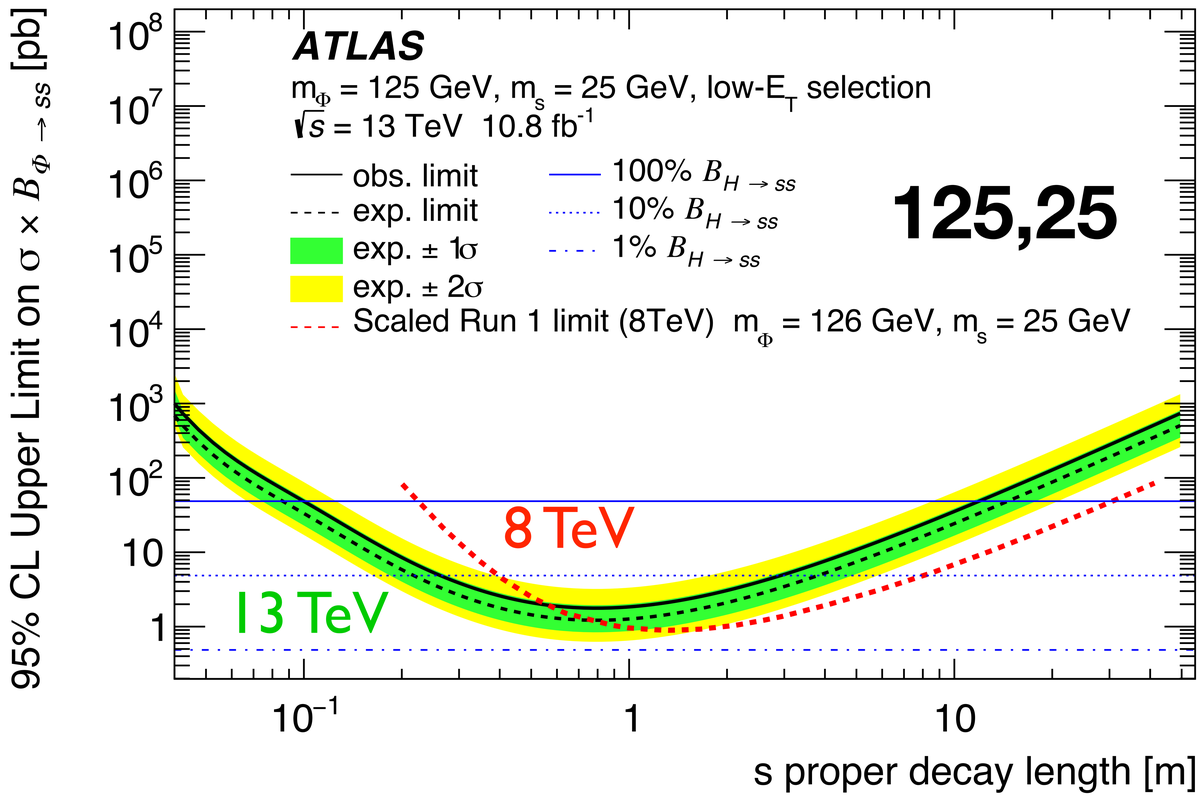
Main selections	Estim. A (*a posteriori*)	A
High-E_T selection	$8.5^{+2.3}_{-2.0}$	10
Low-E_T selection	$5.3^{+2.1}_{-1.6}$	7

no excess



Low-m_Φ models

- Limits extended and improved w.r.t. Run 1 at small decay lengths
- Improvements limited by increased pileup and lower integrated luminosity



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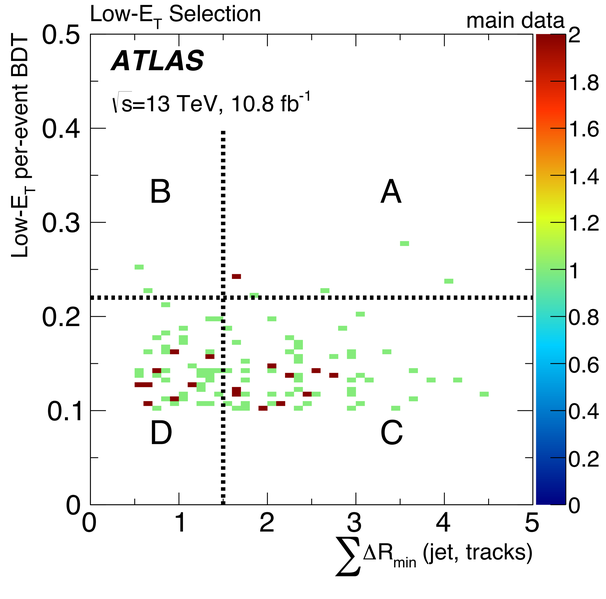

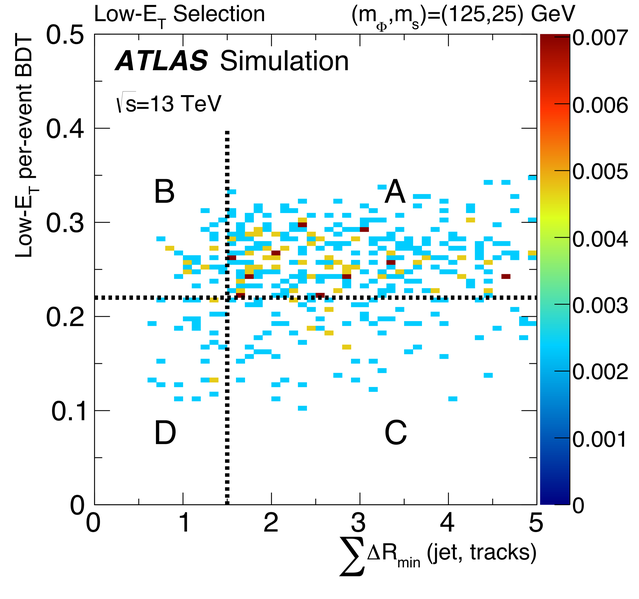

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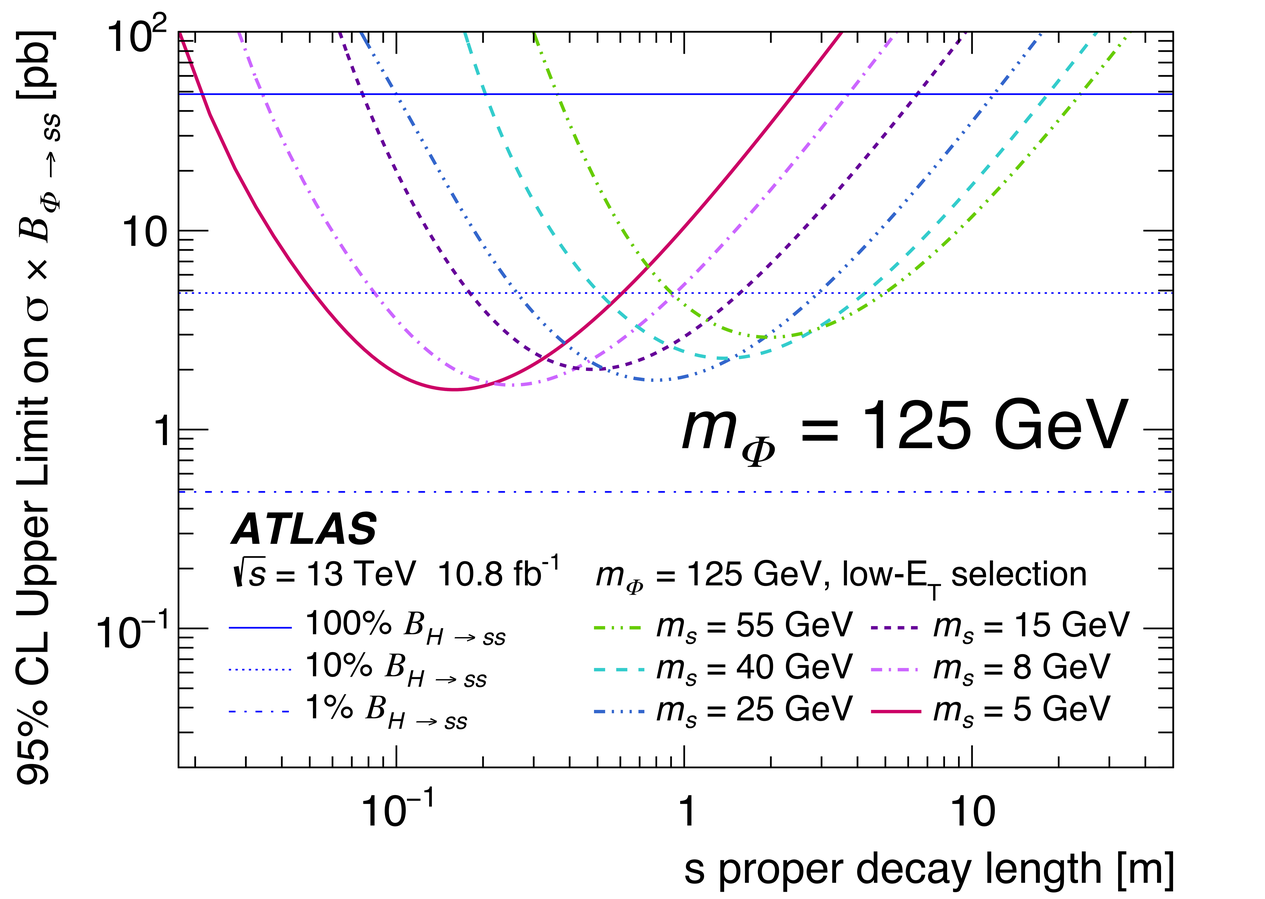
- Lighter scalars have better exclusion at lower decay lengths and vice versa



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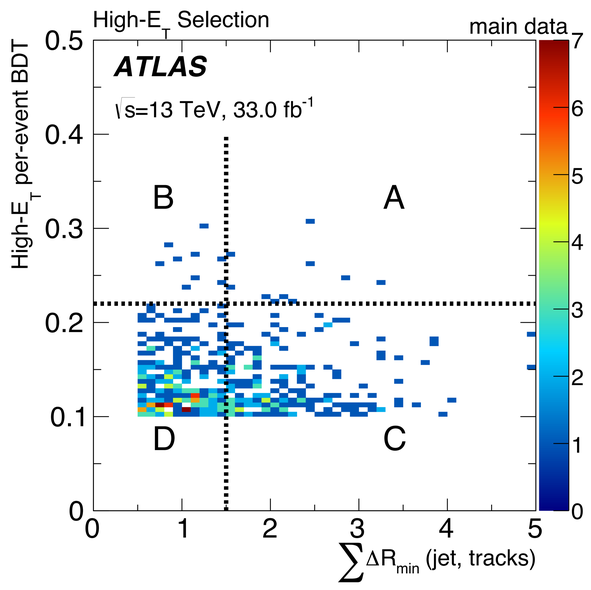
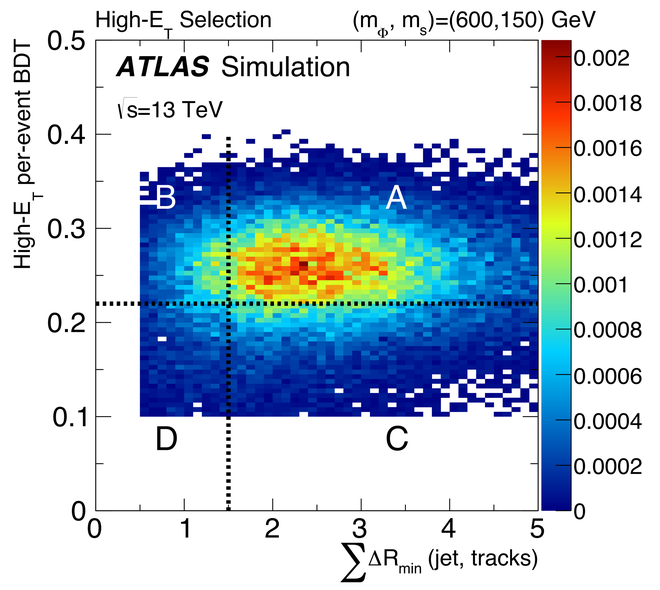
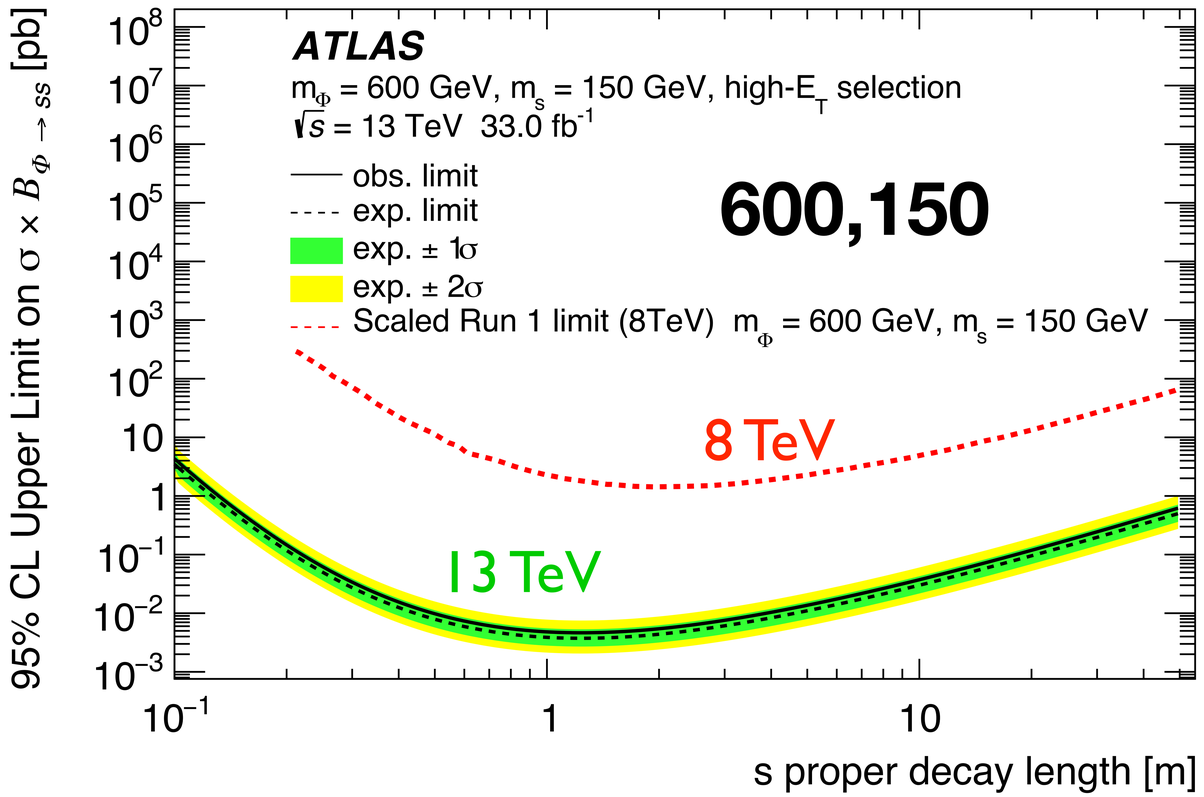




High-mΦ models

- Limits improved across whole decay length range
- Machine learning leads to factor 20 improvement in sensitivity compared to cut-based approach



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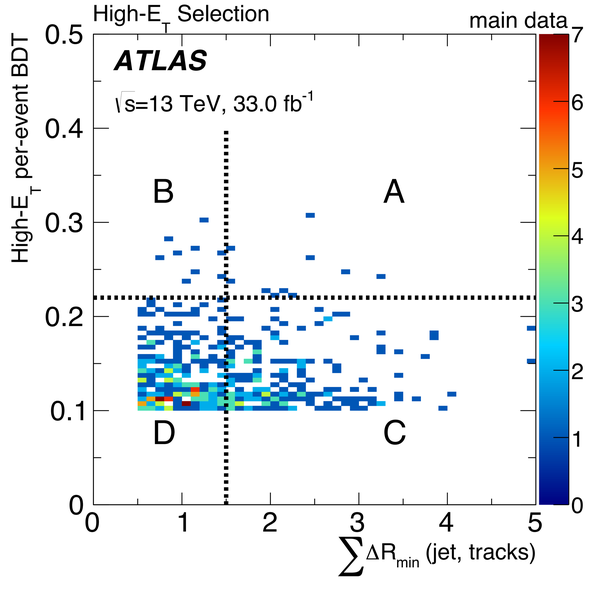

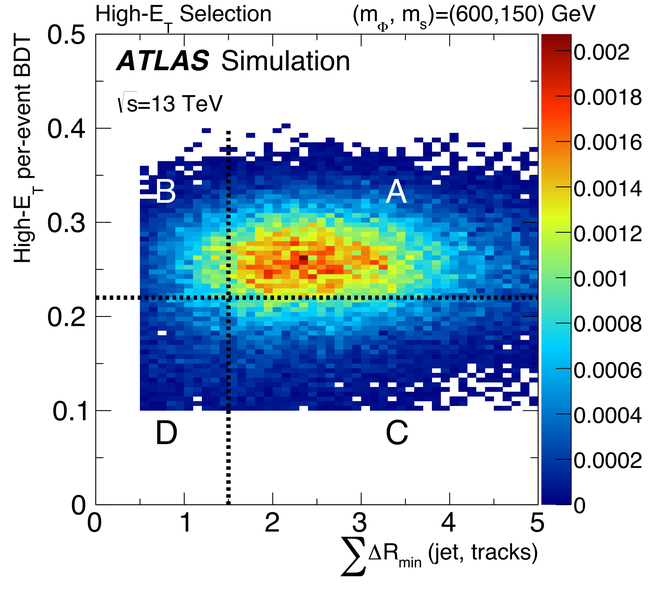

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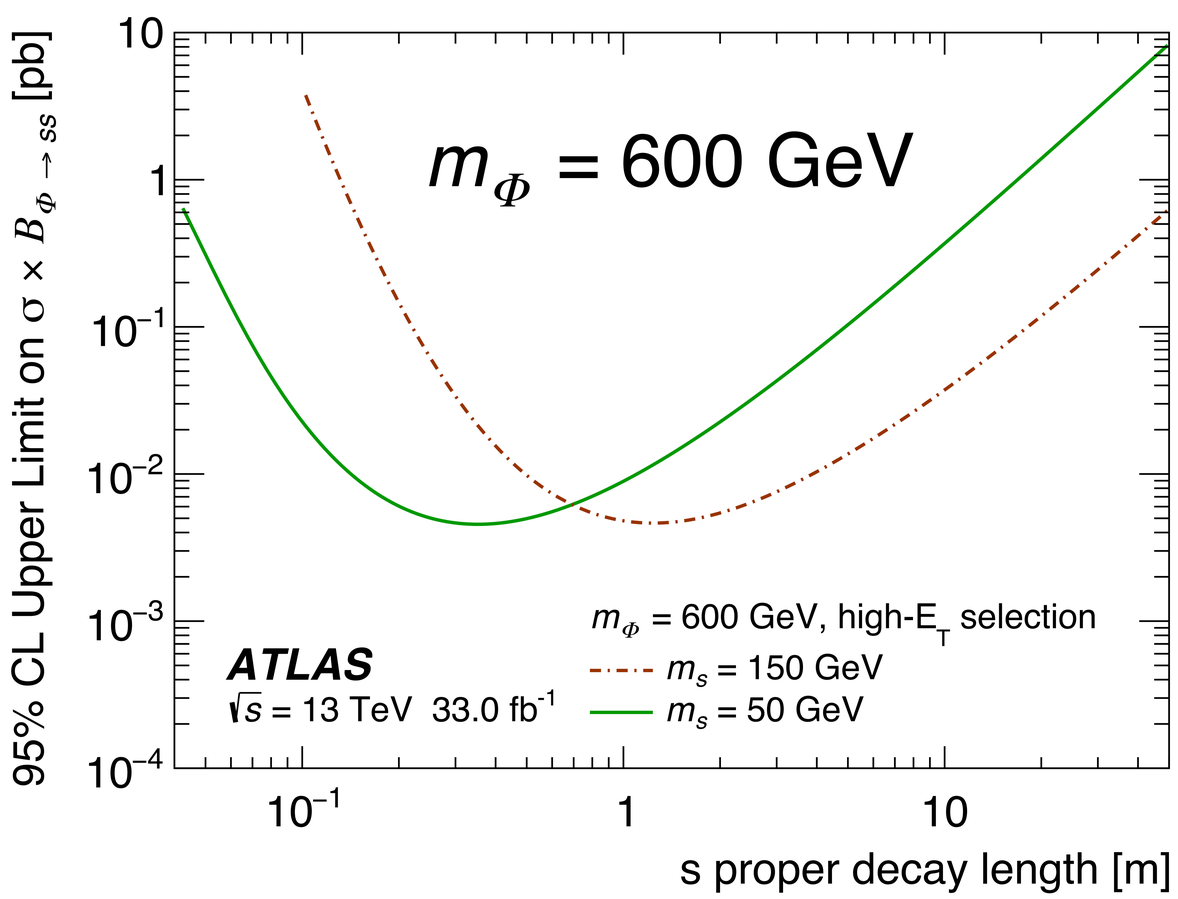
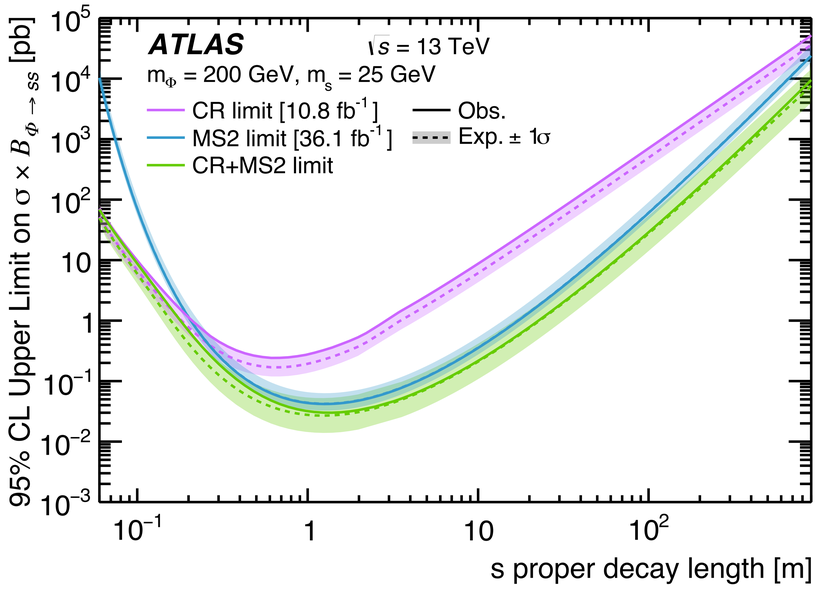
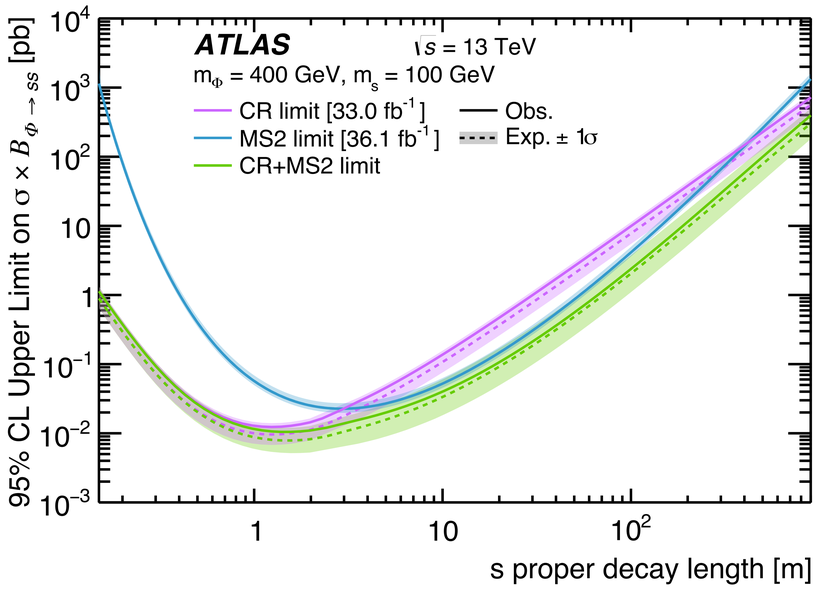


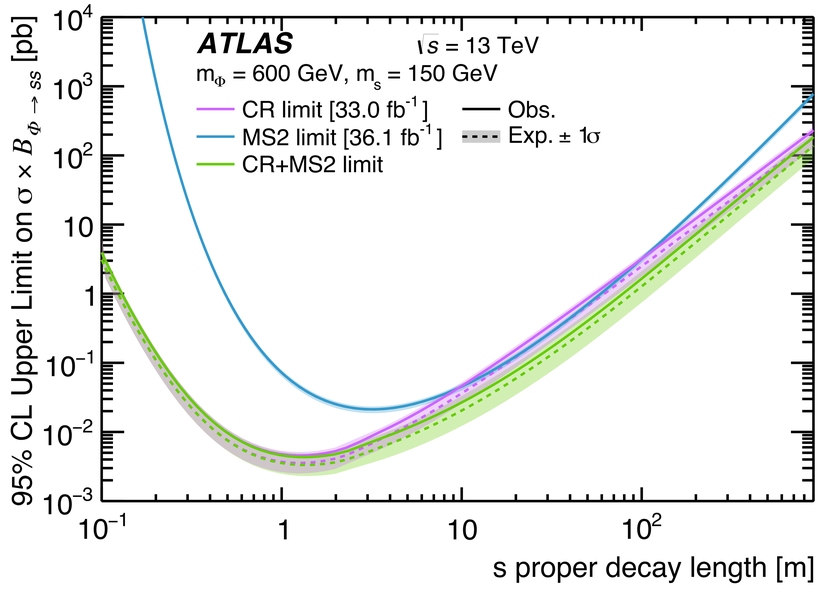
Combination with MS search



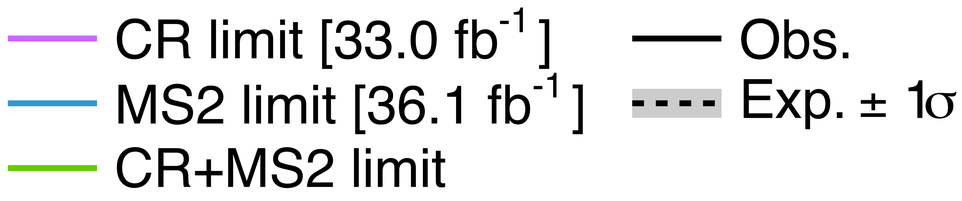
m_Φ = 200 GeV, m_s = 25 GeV



m_Φ = 400 GeV, m_s = 100 GeV



m_Φ = 600 GeV, m_s = 150 GeV



- Limits combined with analysis looking for displaced jets in the muon spectrometer (MS) *
  - Same benchmark Hidden Sector model considered
  - Orthogonal selections and analyses dominated by different uncertainties
  - Simultaneous fit to the likelihood functions of each analysis performed
  - Provides a common resource for theorists

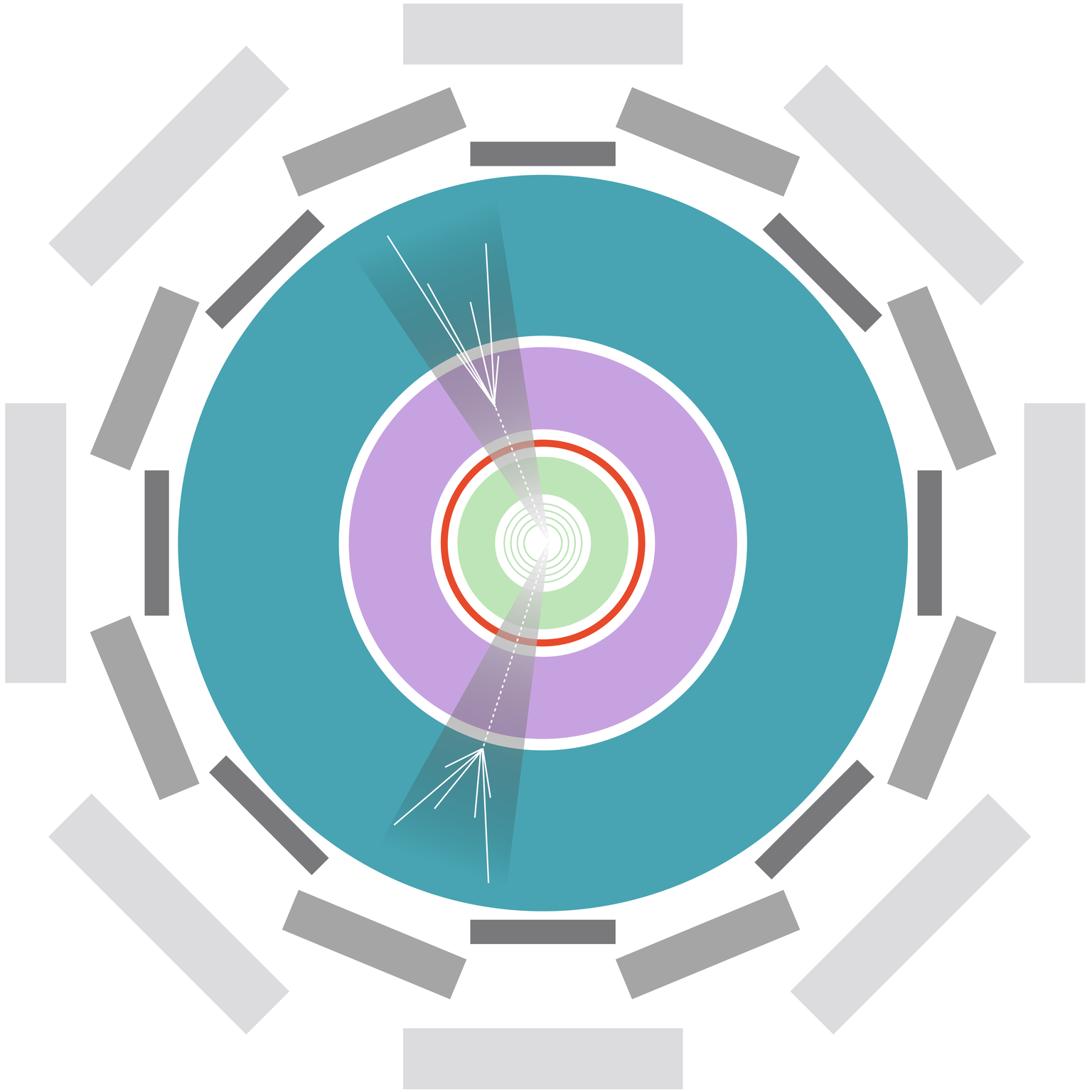
* ATLAS Collaboration, arXiv: 1811.07370

Summary

- Search for exotic long-lived particles using displaced jets in 33 fb^{-1}, using machine learning techniques and data-driven background estimation
  - Proper decay lengths between a few cm and 10's of m excluded
  - Combination with MS search provides a summary of ATLAS results for pair-produced neutral LLPs
  - More information in our paper: arXiv: 1902.03094 (submitted to EPJC)
- Future plans taking shape
  - Analysis will be preserved in RECAST* for future reinterpretations
  - Full Run-2 effort beginning (~150 fb^{-1}), with possibility to include new jet identification techniques and look for new signatures e.g. 1 CalRatio jet + X
- Information on wider LLP effort in LHC LLP community white paper: arXiv: 1903.04497

* Cranmer, K., & Yavin, I. (2011). RECAST—extending the impact of existing analyses. *Journal of High Energy Physics*, *2011*(4), 38.

Backup



Trigger

Level 1

Running on filled BCs

L1_TAU60

- low efficiency for low E_T jets
- high rate ~3kHz

L1_LLP-NOMATCH

- TAU30 object NOT MATCHED to EM3 object
- better efficiency for low E_T jets
- rate of ~400Hz

Running on empty/unpaired BCs

L1_TAU30_EMPTY

- study of cosmics

L1_TAU30_UNPAIRED_ISO

- study of BIB

HLT

Jet reconstruction

Jet selection:

$E_T > 30$ GeV

$|\eta| < 2.5$

cleanLLP

$\log(E_H/E_{EM}) > 1.2$

track isolation

`HLT_j30_jes_cleanLLP_PS_llp_noiso_L1XXX`

BIB removal

`HLT_j30_jes_cleanLLP_PS_llp_L1XXX`

study of BIB in collisions

main data

low-E_T high-E_T

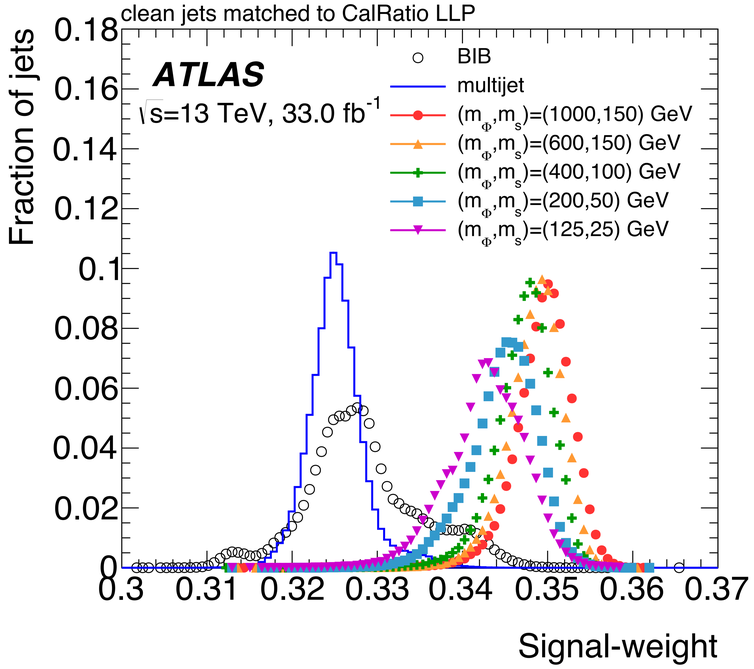
MLP inputs

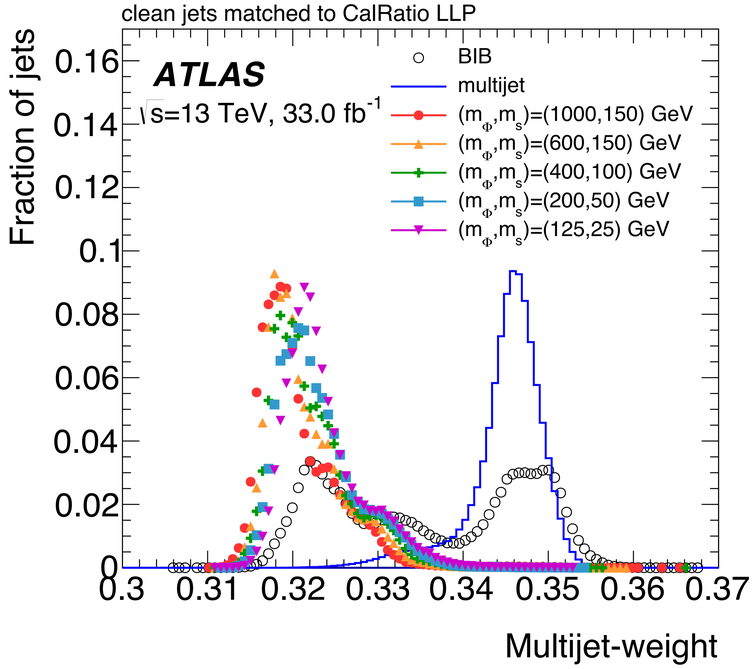
- Signal jets used to train have:
  - ΔR(jet, truthLLP) < 0.2
  - pT > 50 GeV
  - Standard jet cleaning (except CalRatio cut)
- ~1M signal jets used for training, from 9m samples
- Input variables:

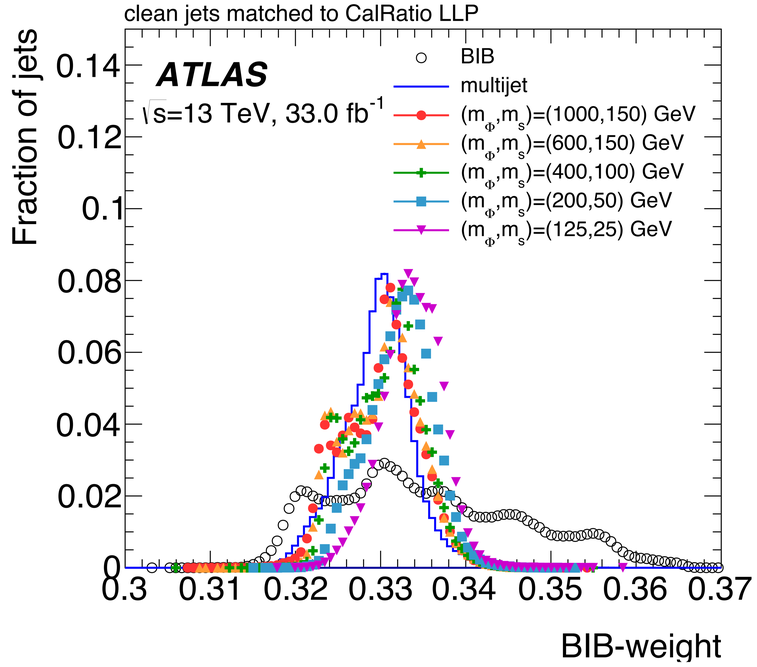
- Hadronic Energy Fraction, Central Barrel: Divided into three layers in the xy-direction, these three variables show the energy fraction for the central barrel section of the hadronic calorimeter;
- Hadronic Energy Fraction, Extended Barrel: Divided into three layers in the xy-direction, these three variables show the energy fraction for the exterior barrel section of the hadronic calorimeter;
- Hadronic Energy Fraction, Endcap: Divided into four layers in the z-direction, these four variables show jet energy fraction for the forward endcap hadronic calorimeter;
- Electromagnetic Energy Fraction, Barrel: Divided into four sections in xy-direction, these four variables show the energy fraction for the barrel section of the EM Calorimeter;
- Electromagnetic Energy Fraction, Endcap: Divided into four sections in the z-direction, these four variables show the energy fraction for the endcap section of the EM Calorimeter;
- Jet η: The jet pseudorapidity is included in the training so that the MLP learns at which specific set of layers it should look for when prediciting decays.

Per-jet BDT

- Separates signal jets from BIB jets and QCD multijets
- Takes MLP result and other jet shape variables as input
- Assigns each jet 3 weights (signal, multijet, BIB)







Per-jet BDT inputs

Jet selections:

The selection for jets in the training samples are:

- jet $p_{\mathrm{T}} > 40$ GeV
- jet $p_{\mathrm{T}} < 550$ GeV: There are not many signal jets above 550 GeV and since events are flattened as a function of jet p_{T}, this gives these events an artificially large weight. To avoid this they are eliminated from the training sample. They are not eliminated from any other part of the analysis.
- jet $|\eta| < 2.5$
- Clean LLP jet

Further, for signal jets - those produced by the decay of an LLP, the following additional requirements are made:

- $\Delta R < 0.2$ between the jet axis an the closest LLP
- truth $L_{xy} > 1250$ mm if jet $|\eta| \leq 1.4$: This cuts was determined by examining the sensitivity of the MLP results.
- truth $L_z > 3500$ mm if jet $|\eta| > 1.4$: This cuts was determined by examining the sensitivity of the MLP results.

As a result of these cuts, the per-jet BDT is sensitive to LLP's that decay in front of the ECAL.

Signal: 9m samples

QCD: JZ2-JZ12

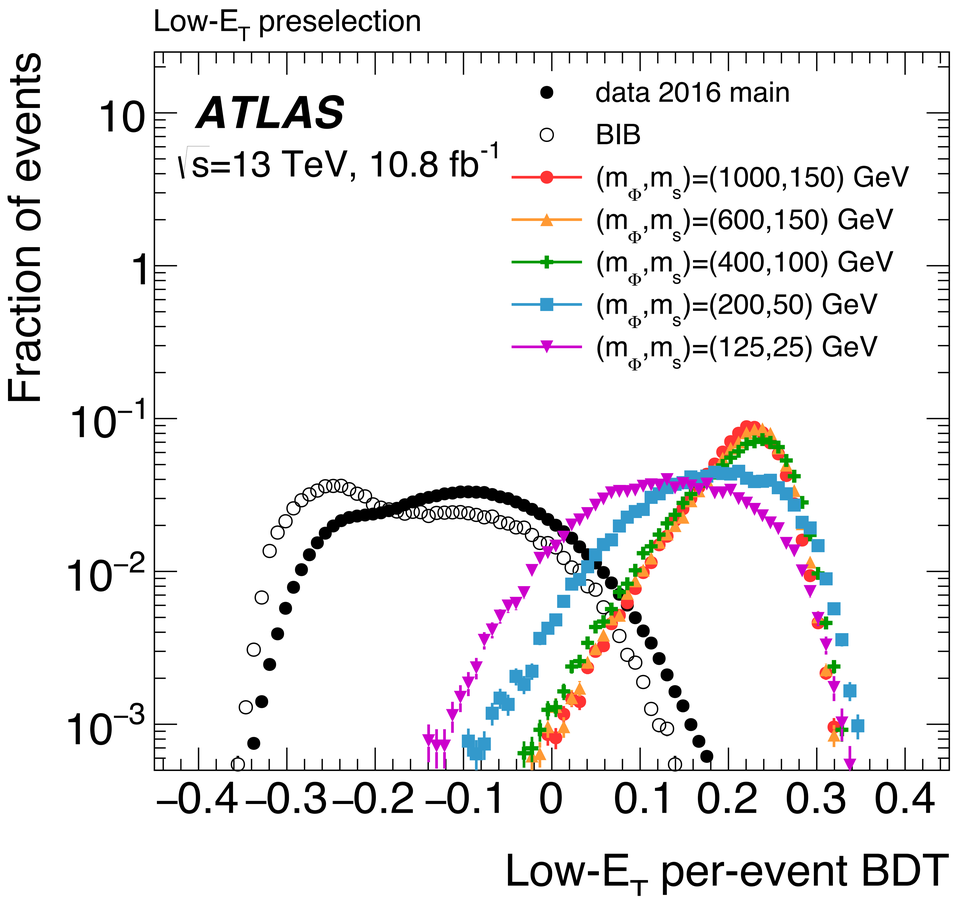
BIB: 2016 noiso data

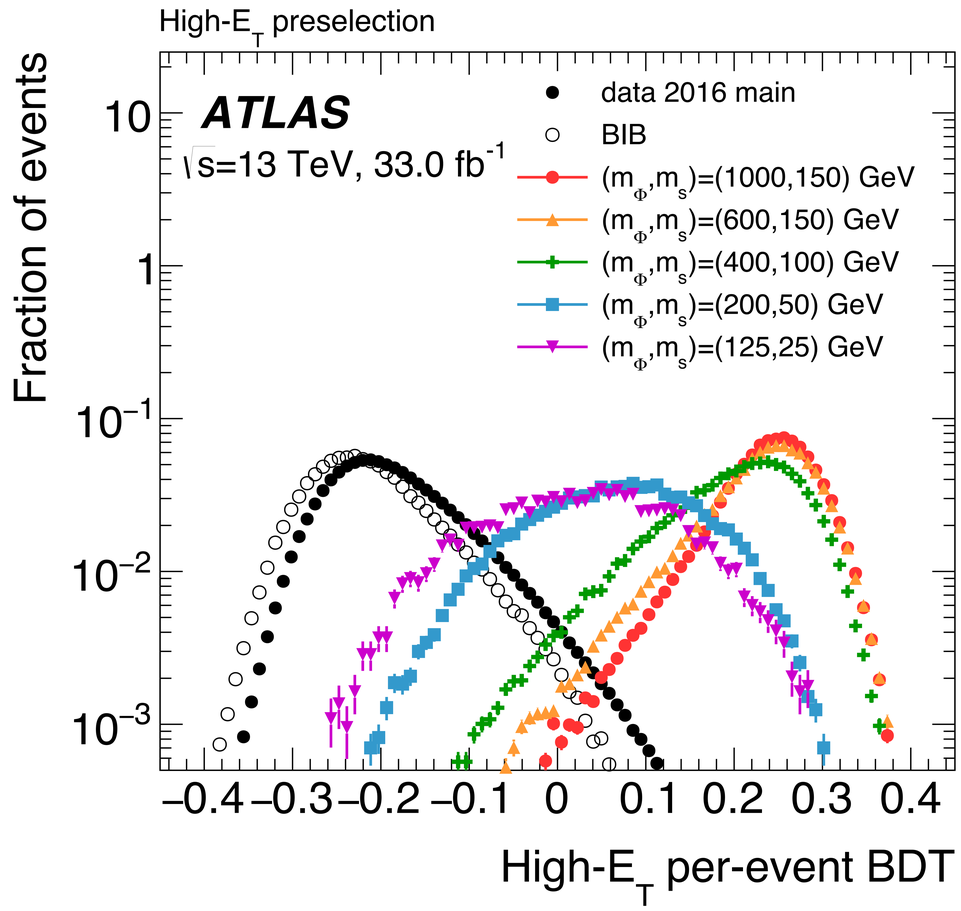
Input variables:

Jet p_{T}
First Cluster Radius
Shower Center
BIB ΔT - Positive
Hadronic Layer 1 Fraction
Predicted L_{xy}
Jet Latitude
Jet Longitude
Energy Density
BIB ΔT - Negative
Max Track p_{T}
Sum p_{T} of all Tracks
Predicted L_z

Per-event BDT

- Separates signal events from background events
- Takes per-jet BDT output and other event-level variables as input
- Two BDTs trained for low-E_T and high-E_T models & selections
- Output BDT score used in ABCD background estimation





Per-event BDT inputs

- L1Tau: low, intermediate & high mass signal vs. BIB data
- L1Topo: low mass signal passing trigger vs. BIB data
- Input variables:
  - the per-jet BDT signal-weights of the CalRatio jet candidates and of the BIB jet candidates;
  - the per-jet BDT BIB-weights of the CalRatio jet candidates and of the BIB jet candidates;
  - p_{T} of the CalRatio jet candidates;
  - $H_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}$, where H_{T} is the scalar sum of jet p_{T} for jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 3.2$ and $H_{\mathrm{T}}^{\mathrm{miss}}$ is the magnitude of the negative vectorial sum of the same jets;
  - M_{eff}, which is defined as the scalar sum of H_{T} and $H_{\mathrm{T}}^{\mathrm{miss}}$;
  - $\Delta\phi(\mathrm{jet}^{\mathrm{sig}_1}, \mathrm{jet}^{\mathrm{sig}_2})$ and $\Delta R(\mathrm{jet}^{\mathrm{sig}_1}, \mathrm{jet}^{\mathrm{sig}_2})$, the opening angle and distance between the two most signal-like jets in the event;
  - the mean signal-weight value of all the clean jets in the event
  - the mean BIB-weight value of all the clean jets in the event

Modified ABCD method

- Likelihood function is the product of four likelihoods, one for each region

- n_A, n_B, n_C, n_D:

$$L(n_A, n_B, n_C, n_D | \mu, \theta_\mu) = \prod_{i=A,B,C,D} \frac{e^{-N_i} N_i^{n_i}}{n_i!}$$

- μ: signal strength

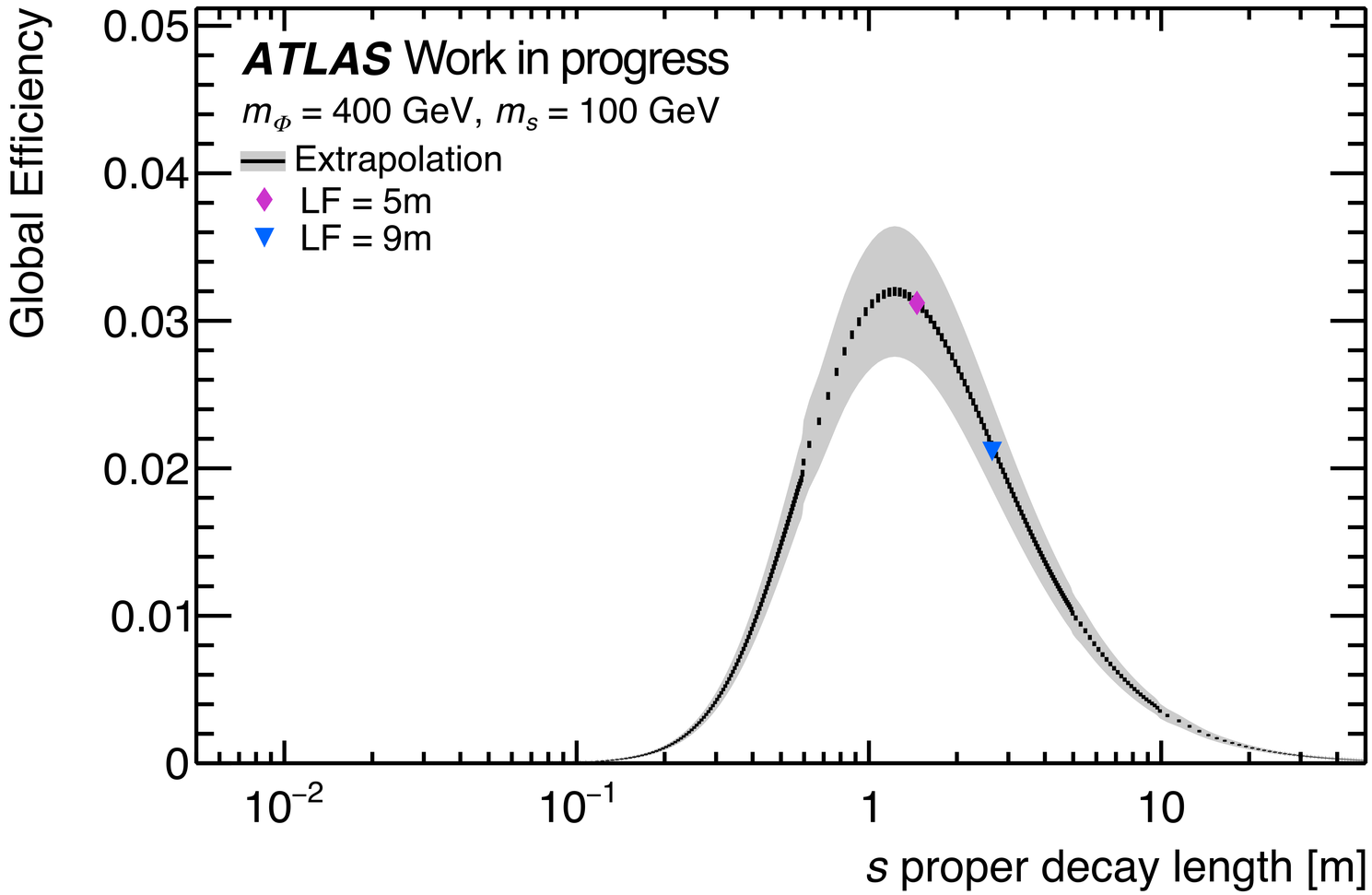
- θ_μ: nuisance parameters (describe systematic uncertainties)

- $$N_A = \mu N^S_{A,expected} + N^B_A$$
  $$N_B = \mu \epsilon_B N^S_{A,expected} + N^B_A \tau_B$$
  $$N_C = \mu \epsilon_C N^S_{A,expected} + N^B_A \tau_B \tau_D$$
  $$N_D = \mu \epsilon_D N^S_{A,expected} + N^B_A \tau_D$$

Fit number of events in each region

- $$N^S_{B,expected} = \epsilon_B N^S_{A,expected}$$

Extrapolation checks



- Extrapolation result at a different decay length to the generated decay length is checked using a second sample
- Further studies ongoing to investigate whether this extrapolation breaks down at very small/very large decay lengths
  - Joint effort between CalRatio and MS displaced jets analyses

Final selections

- Determined with an optimization procedure
- Several variables used, different combinations tested
- Selection with best S/sqrtB chosen (with low signal contamination in BCD and low statistical uncertainty on background estimate)

- L1Topo selection:
  - L1Topo per-event BDT > 0.1,
  - $(\sum_{\text{jet}^{\text{sig}_1},\text{jet}^{\text{sig}_2}} \log_{10}(E_{\text{H}}/E_{\text{EM}})) > 2.5$,
  - $p_{\text{T}}(\text{jet}^{\text{sig}_1}) > 80$ GeV and $p_{\text{T}}(\text{jet}^{\text{sig}_2}) > 60$ GeV

- L1Tau selection:
  - L1Tau per-event BDT > 0.1,
  - $H_{\text{T}}^{\text{miss}}/H_{\text{T}} < 0.6$,
  - $(\sum_{\text{jet}^{\text{sig}_1},\text{jet}^{\text{sig}_2}} \log_{10}(E_{\text{H}}/E_{\text{EM}})) > 1$,
  - $p_{\text{T}}(\text{jet}^{\text{sig}_1}) > 160$ GeV and $p_{\text{T}}(\text{jet}^{\text{sig}_2}) > 100$ GeV

Final cutflows

	L1Tau selection:	main data	BIB	1000,150	600,150	400,100
Preselection:	2 clean jets and $\sum \Delta R_{min} > 0.5$	1375483	183015	26.2%	22.4%	17.5%
Event cleaning:	L1Tau per-event BDT > 0.1	4515	192	25.4%	21.2%	15.3%
	Trigger matching	3627	119	24.5%	20.4%	15.0%
	$-3 <$ time(sig; bib) < 15 ns	3388	110	24.0%	20.0%	14.8%
L1Tau selection:	$\sum_{jet^{sig_1}, jet^{sig_2}} \log_{10}(E_H/E_{EM}) > 1$	1815	61	21.7%	16.8%	11.5%
	$H_T^{miss}/H_T < 0.6$	1421	41	18.1%	15.2%	10.9%
	$p_T(jet^{sig_1}) > 160$ GeV	774	26	17.5%	13.6%	7.50%
	$p_T(jet^{sig_2}) > 100$ GeV	459	15	16.5%	11.8%	5.56%
Region A :		10 (Obs.)	1	10.7%	7.74%	3.10%
		6.65 ± 2.31 (Estim.)				

	L1Topo selection	main data	BIB	200,50	125,25
Preselection:	2 clean jets and $\sum \Delta R_{min} > 0.5$	2180349	95247	7.58%	4.33%
Event cleaning:	L1Topo per-event BDT > 0.1	40474	678	6.26%	2.73%
	Trigger matching	34567	538	5.97%	2.51%
	$-3 <$ time(sig; bib) < 15 ns	33680	519	5.86%	2.46%
L1Topo selection:	$\sum_{jet^{sig_1}, jet^{sig_2}} \log_{10}(E_H/E_{EM}) > 2.5$	722	13	0.92%	0.39%
	$p_T(jet^{sig_1}) > 80$ GeV	304	6	0.69%	0.16%
	$p_T(jet^{sig_2}) > 60$ GeV	136	4	0.60%	0.10%
Region A:		7 (Obs.)	0	0.43%	0.07%
		2.46±1.79 (Estim.)			

- Only statistical uncertainties on background estimate shown here

Systematics

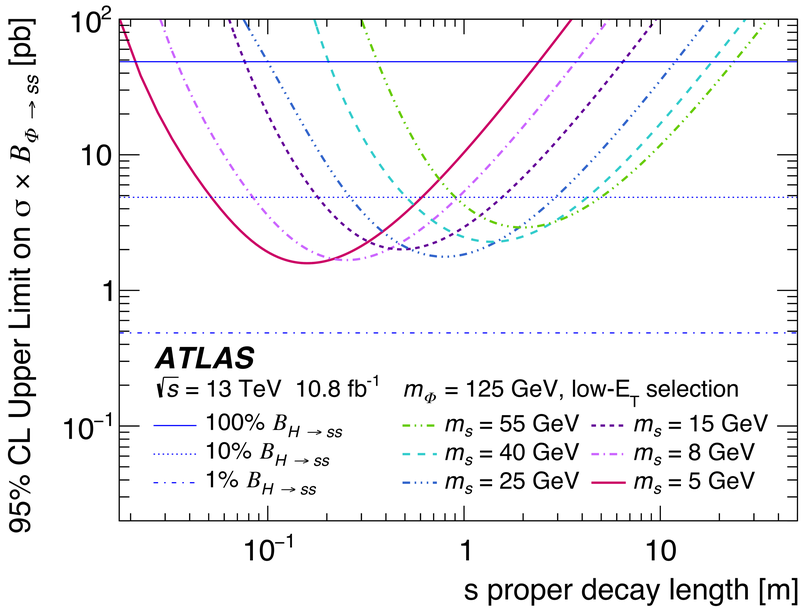
- **ABCD uncertainty** derived using multijet-enriched sample with event cleaning applied (except trigger matching) and same ABCD plane definition
  - Discrepancy between predicted and expected no. in A taken as systematic uncertainty associated with method (21.5% for high-E_T and 23.9% for low-E_T)
- Other systematics:
  - Standard JER/JES, also calculated for low EMF jets
    - Low-EMF JES checked with 2016 data and found to be consistent with 2015, and low-EMF JER found to be negligible
  - BDT input variable modelling systematic derived
  - Pileup, trigger, PDF and luminosity uncertainties

m_Φ Point (GeV)	JES	JES$_{E_{EM}/(E_{EM}+E_H)}$	JER	Trigger	Pileup	PDFs	BDT
125	9%	18%	5%	1%	12%	3%	2%
200	3%	6%	2%	1%	10%	3%	1.5%
400	3.0%	9.9%	1.3%	2.1%	4.0%	4.2%	1%
600	0.6%	2.5%	1.0%	1.2%	2.8%	5.4%	0.5%
1000	0.3%	0.5%	1.0%	0.5%	1.4%	8.2%	0.3%

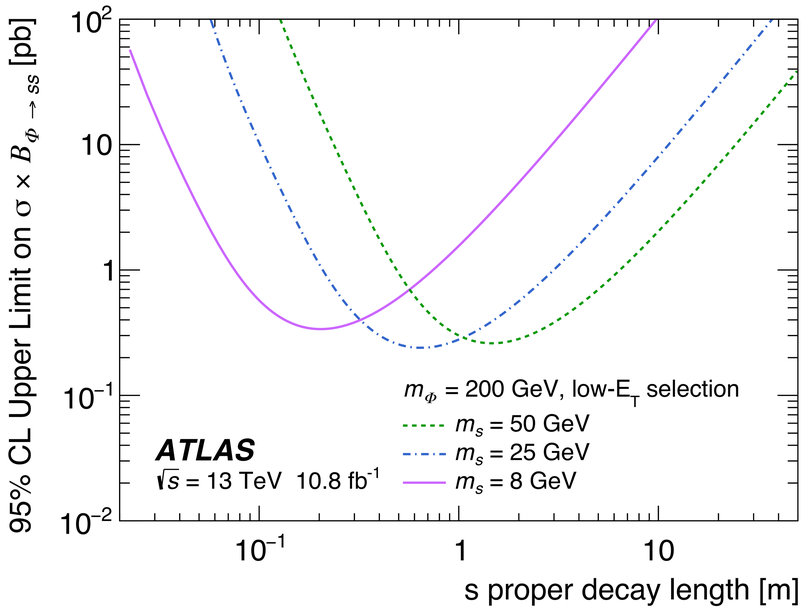
Systematic Error	Value
Luminosity	±2.2%

- See other backup slides for study of limits' sensitivity to systematics

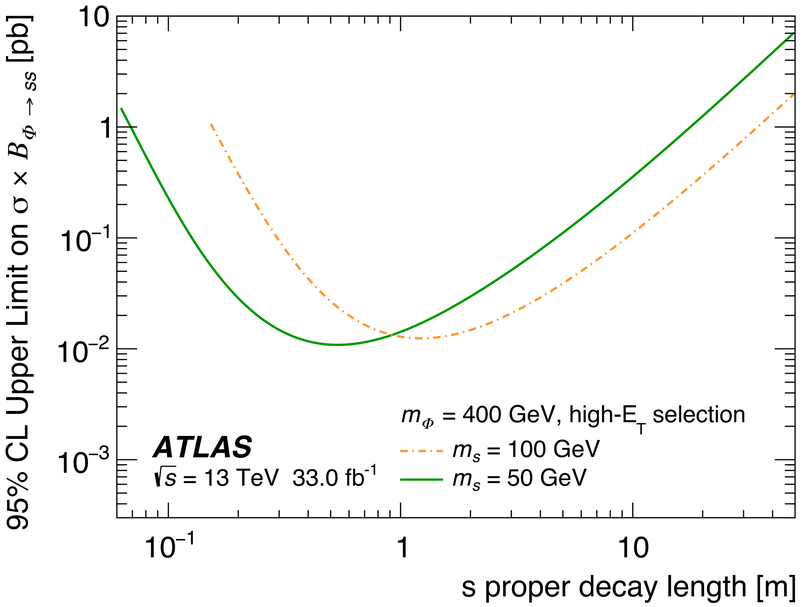
Limits



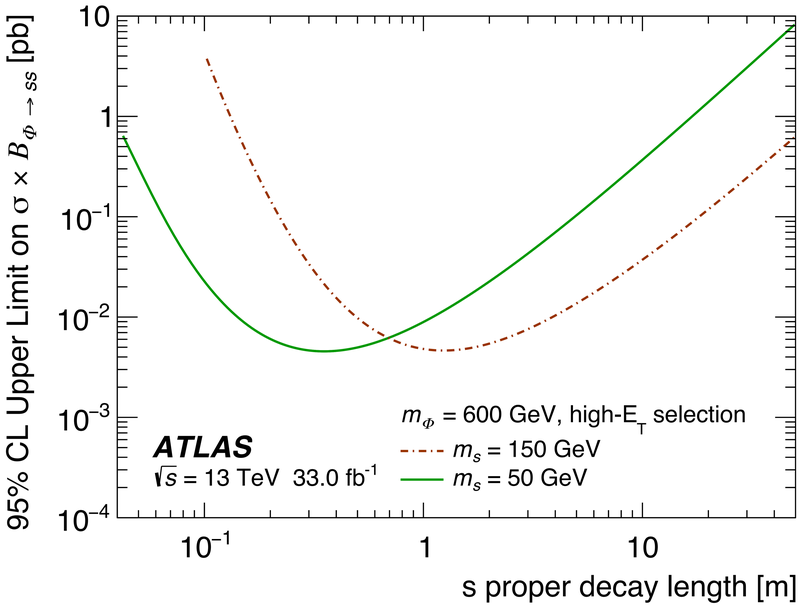
mΦ = 125 GeV



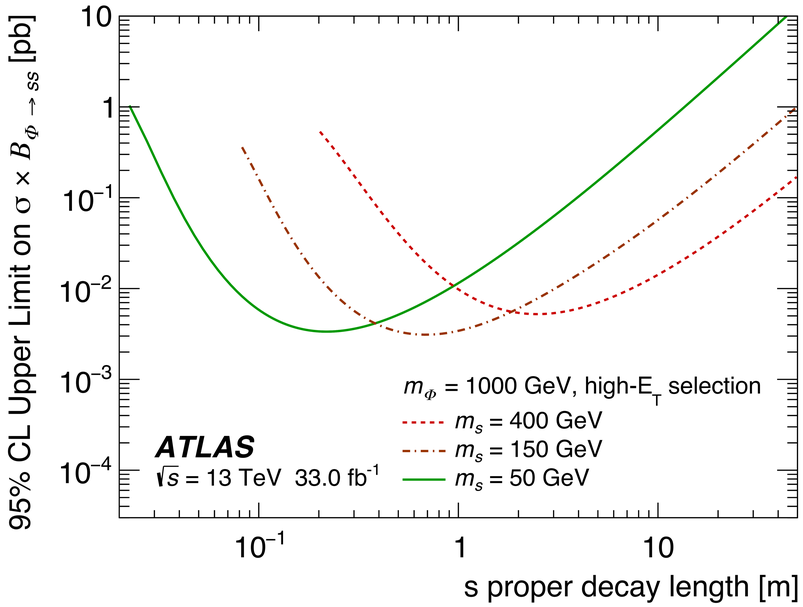
mΦ = 200 GeV



mΦ = 400 GeV



mΦ = 600 GeV



mΦ = 1000 GeV