ATLAS

UCL

Hacking the ATLAS Detector: Searching for long-lived particles as a proxy for Dark Matter

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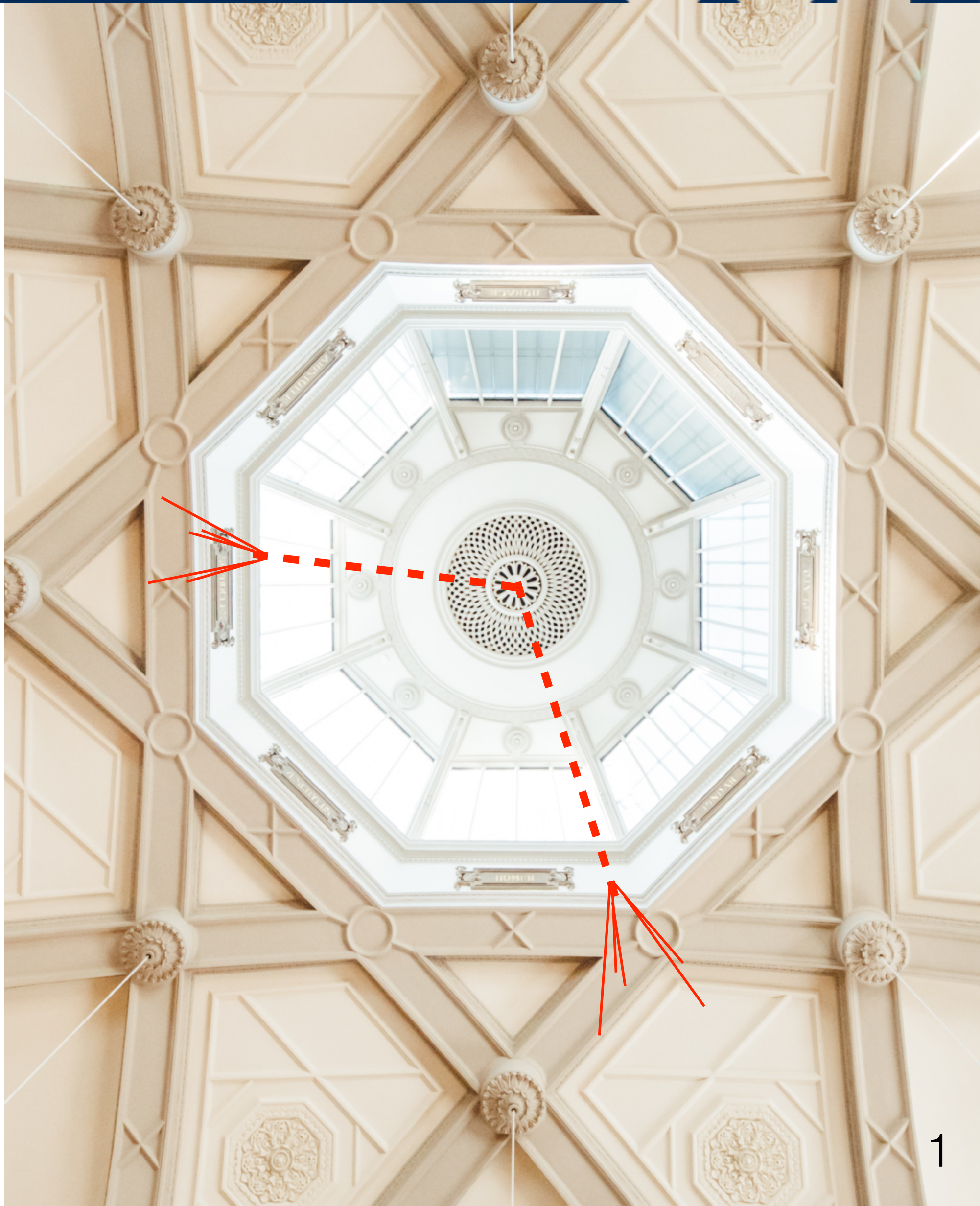
L. Corpe (UCL)

QMUL
HEP Seminar,
31st October 2019



Introduction

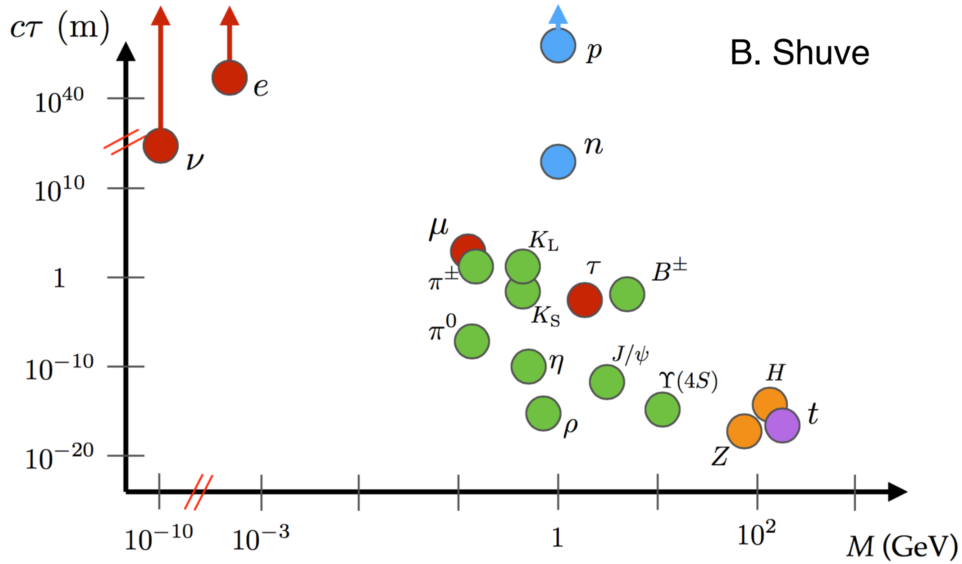
- **Happy ~~Brexit Day~~ Dark Matter Day / Hallowe'en!**
- This talk deals with a novel approach for searching for Dark Matter. The usual approach is look for
  - DM interacting w/ a heavy atom (eg: LZ, ARGO...)
  - DM being produced in high-energy collisions (eg: LHC)

- So far, no sign of DM... time for a new approach?

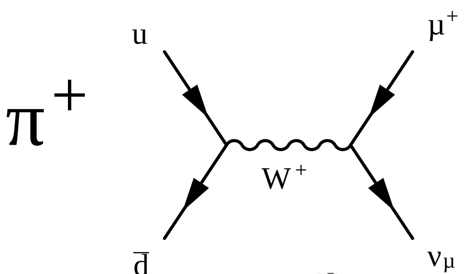
- What if we'd missed DM (or particles in the Dark Sector) because we were looking in the wrong place?
  --> In many DM models, can have other particles with unusual properties...

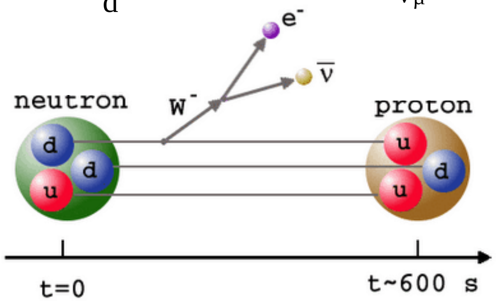
- **What if DM or related particles were "long-lived"** ?

- **Semi-stable particles** everywhere in the SM!
- *Long-lived particles* (LLPs) := **do not decay instantly** (eg Higgs, W/Z, t, etc)

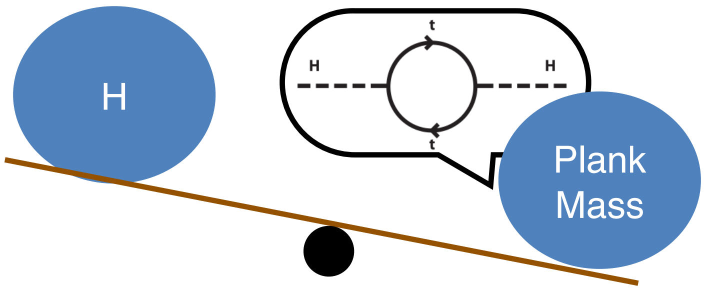


- LLPs occur when **decay suppressed**:
  - Decay interaction **very weak**
    - Mediator particle **very heavy**
  - Density of final states **very low**
    - Particles **very close** in mass



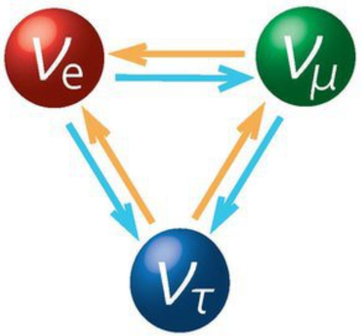


- We all know SM has serious flaws...
  - Why is H so light ? (**Hierarchy Problem**)



Open questions in HEP

- We all know SM has serious flaws...
  - Why is H so light ?
    (Hierarchy Problem)
  - **Neutrino oscillations** + masses



Open questions in HEP

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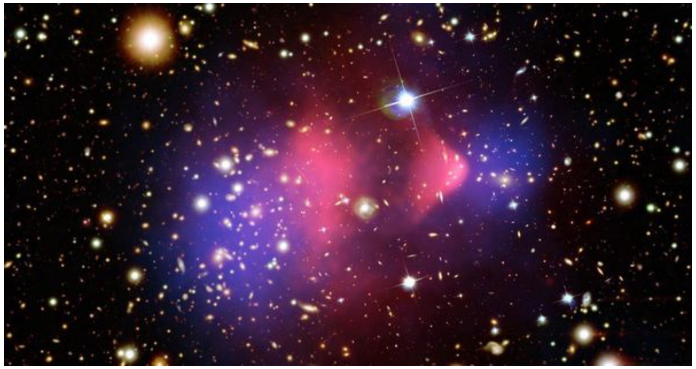
  - Neutrino oscillations + masses
  - What is **Dark Matter**?



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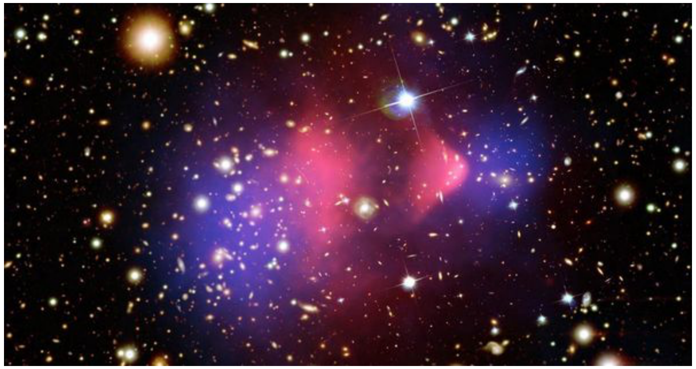
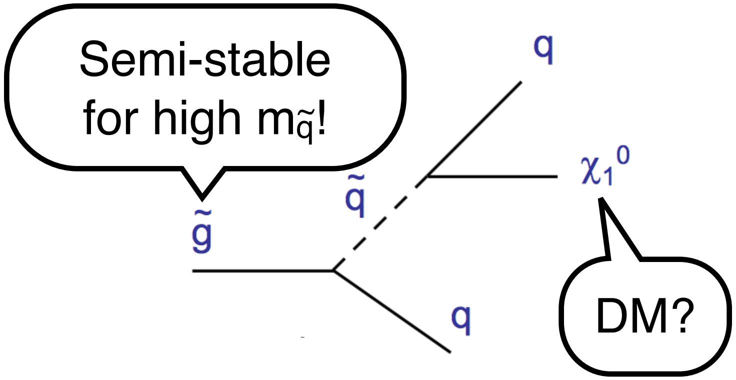


- Proposed DM models often involve LLPs!
  - Why is H so light ? (**Hierarchy Problem**)

→ SUSY



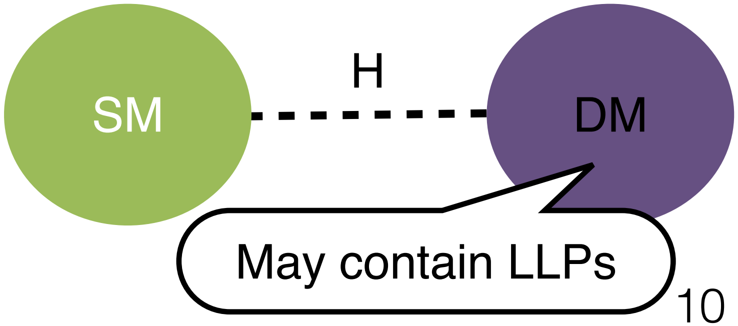
LLPs and DM

- Proposed DM models often involve LLPs!
  - Why is H so light ?
    (Hierarchy Problem)
    → SUSY
  - **Neutrino oscillations** + masses
    → Heavy Neutral Leptons

Semi-stable? DM?

LLPs and DM

- Proposed DM models often involve LLPs!
  - Why is H so light ?
    (Hierarchy Problem)
    → SUSY
  - Neutrino oscillations + masses
    → Heavy Neutral Leptons
  - What is **Dark Matter?**
    → Hidden Sector

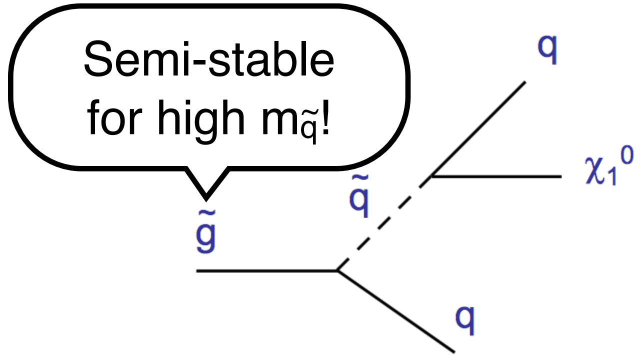


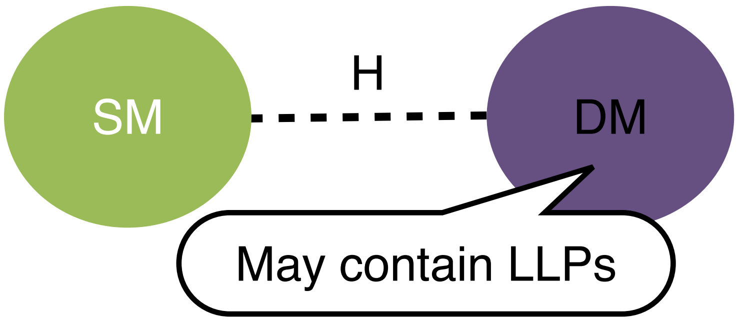
LLPs and DM

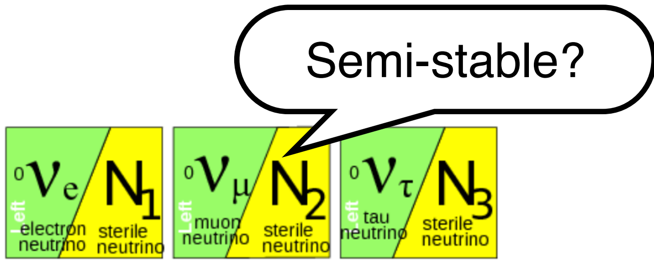
LLP lifetimes typically unconstrained...

could decay **within ATLAS detector volume**?

Could be used as a **proxy to discover Dark Matter**?

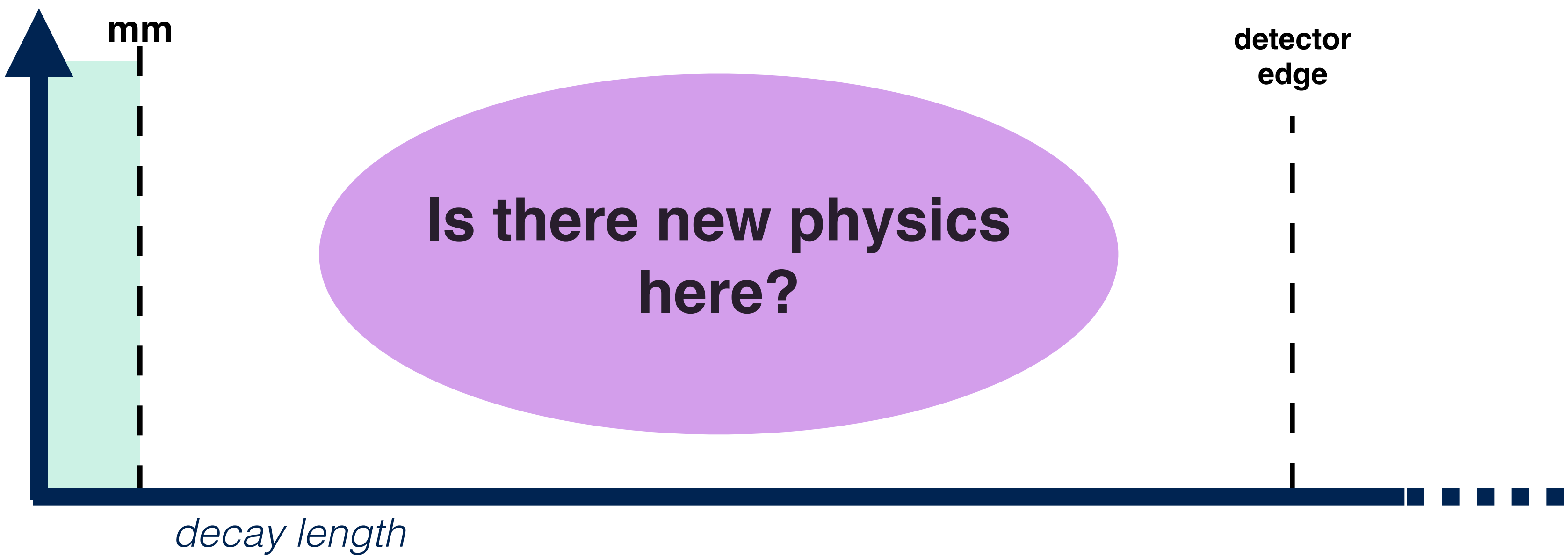






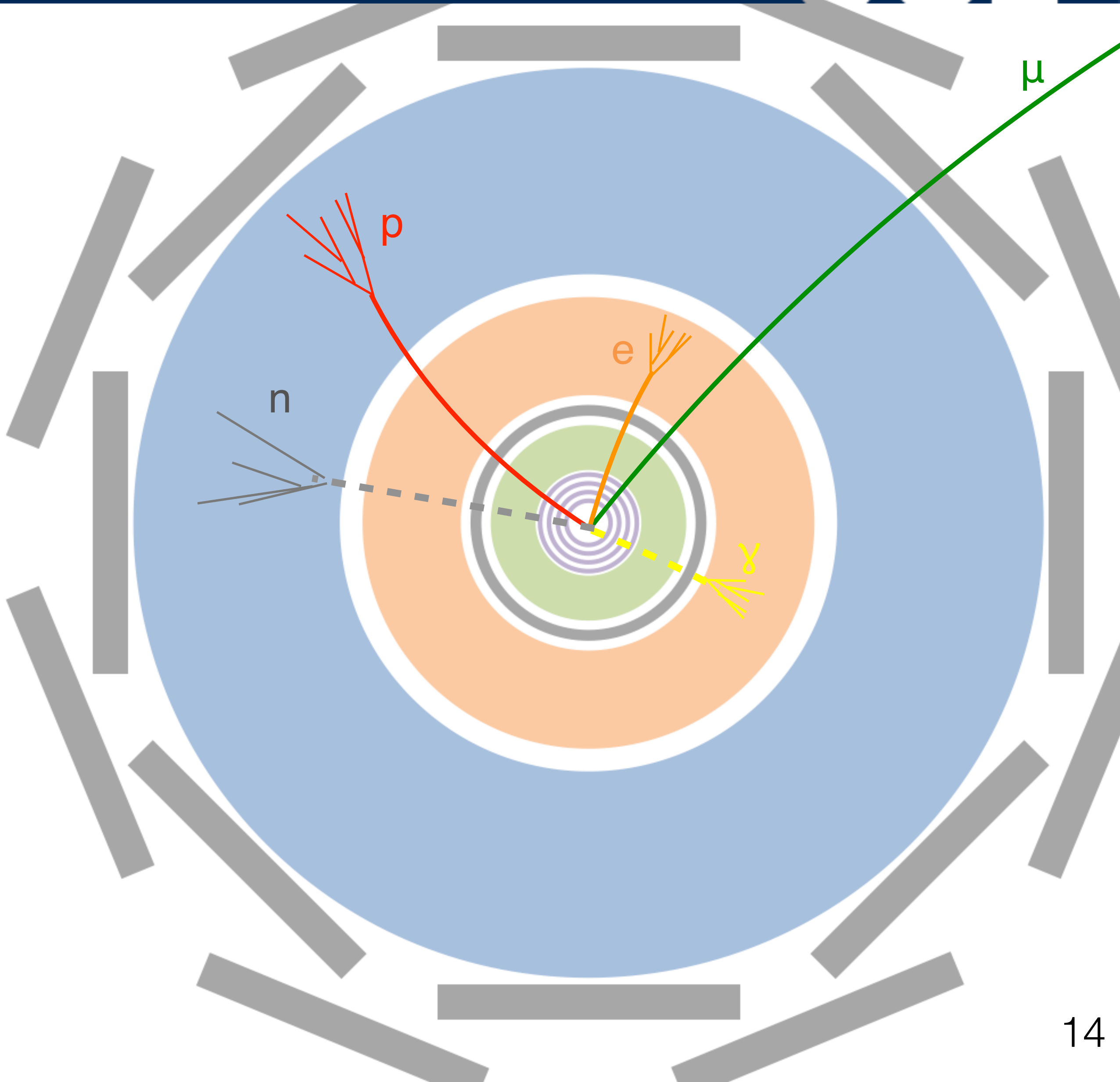
Check your blind spot

- ...but ATLAS not designed for highly displaced activity!
- Usually assume new particles are unstable... LHC detectors designed for particles decaying near beam crossing.
- **LLP signals look like detector noise**
- ***This is ATLAS and CMS's blind spot!***



The ATLAS detector
and neutral LLP signatures

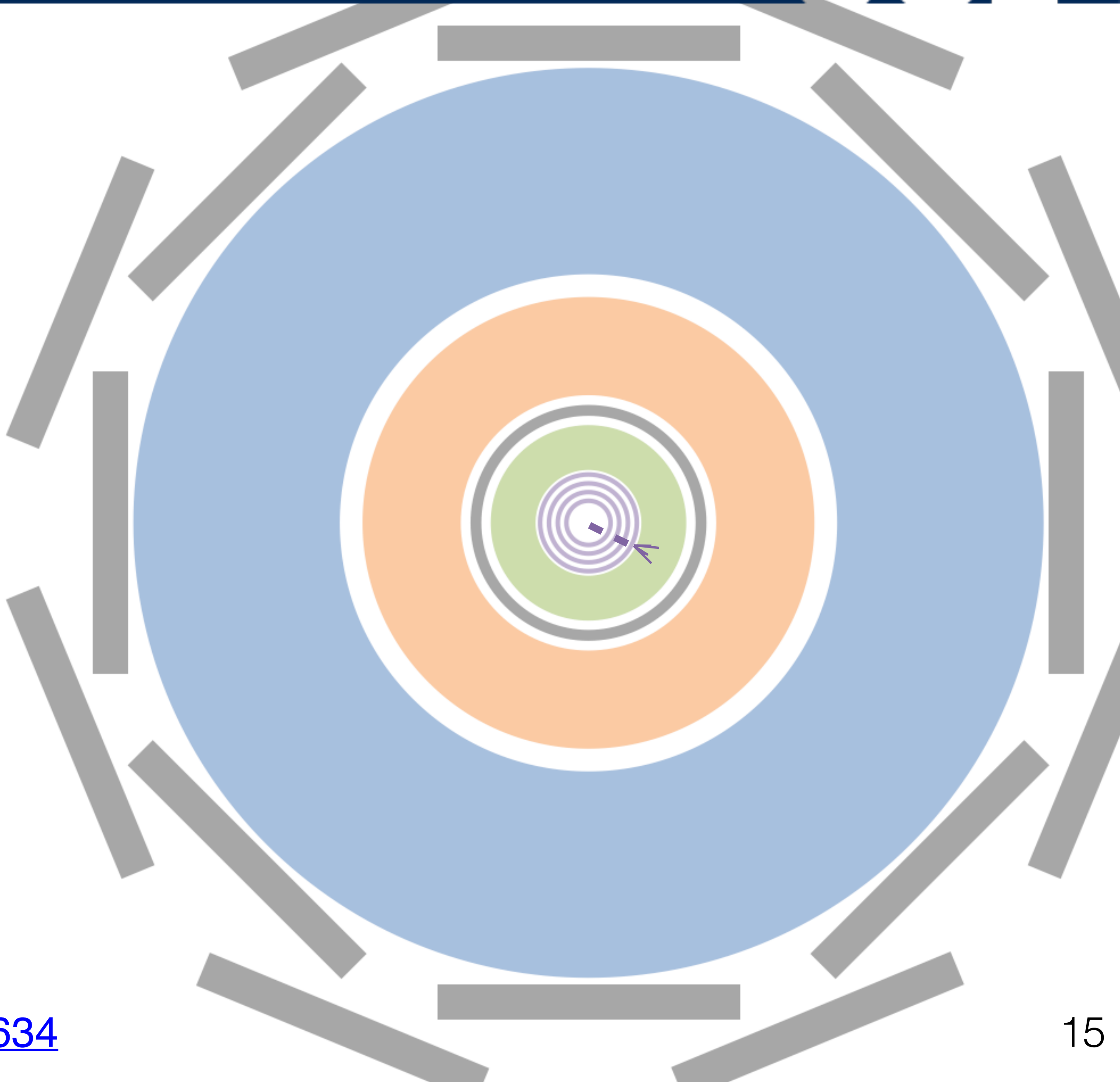
A cross section of ATLAS



What would a neutral LLP signature look like?

Neutral LLP decaying in **tracker**:

Displaced vertex appearing in tracker

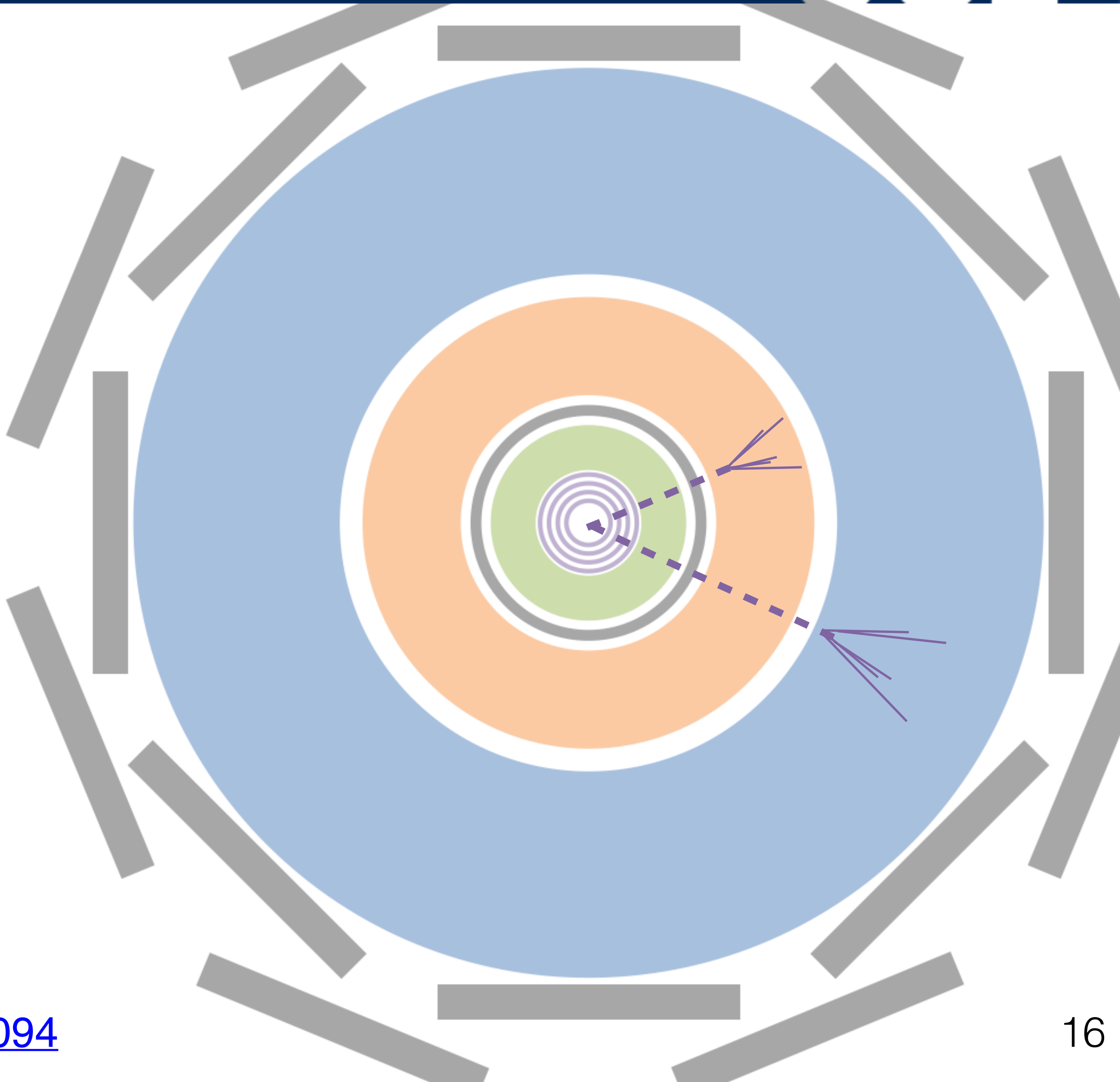


https://arxiv.org/abs/1504.03634

What would a neutral LLP signature look like?

Neutral LLP decaying in **calorimeter**:

Trackless jet

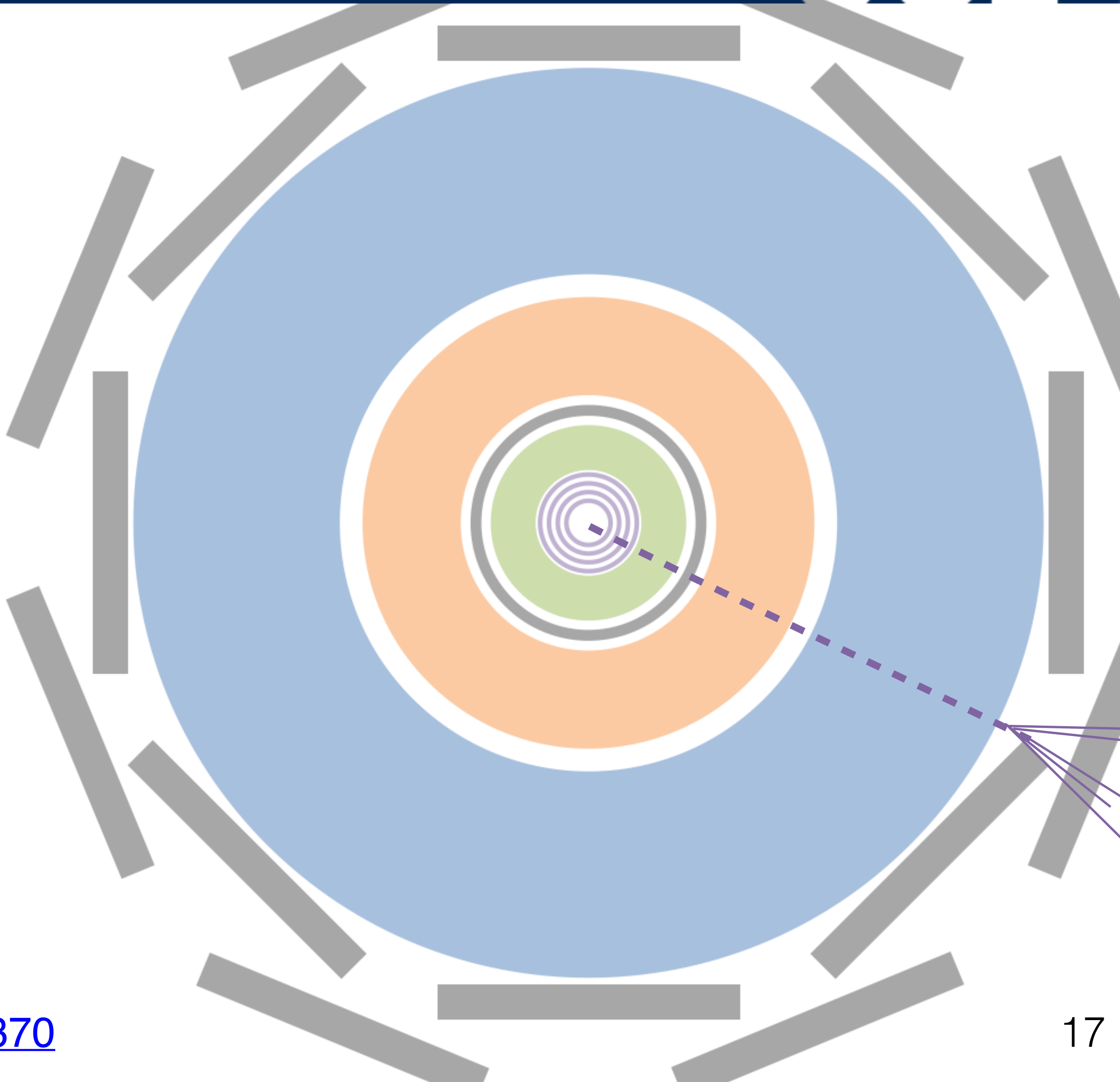


https://arxiv.org/abs/1902.03094

What would a neutral LLP signature look like?

Neutral LLP decaying in **Muons System**:

lepton-jet or vertex in the MS

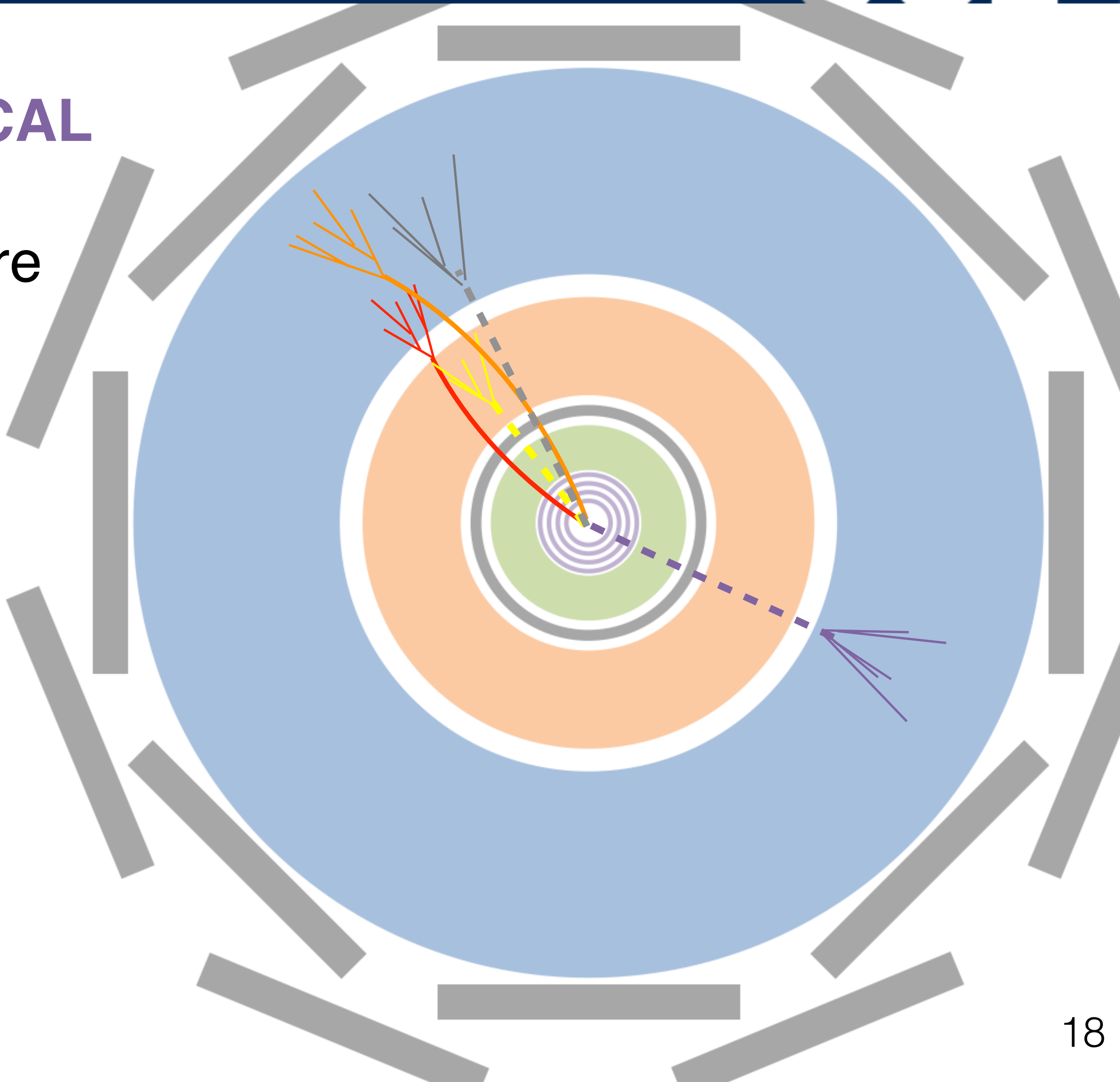


https://arxiv.org/abs/1811.07370

What would a neutral LLP signature look like?

Focus on
LLP decaying in HCAL

How would it compare to a regular SM jet?

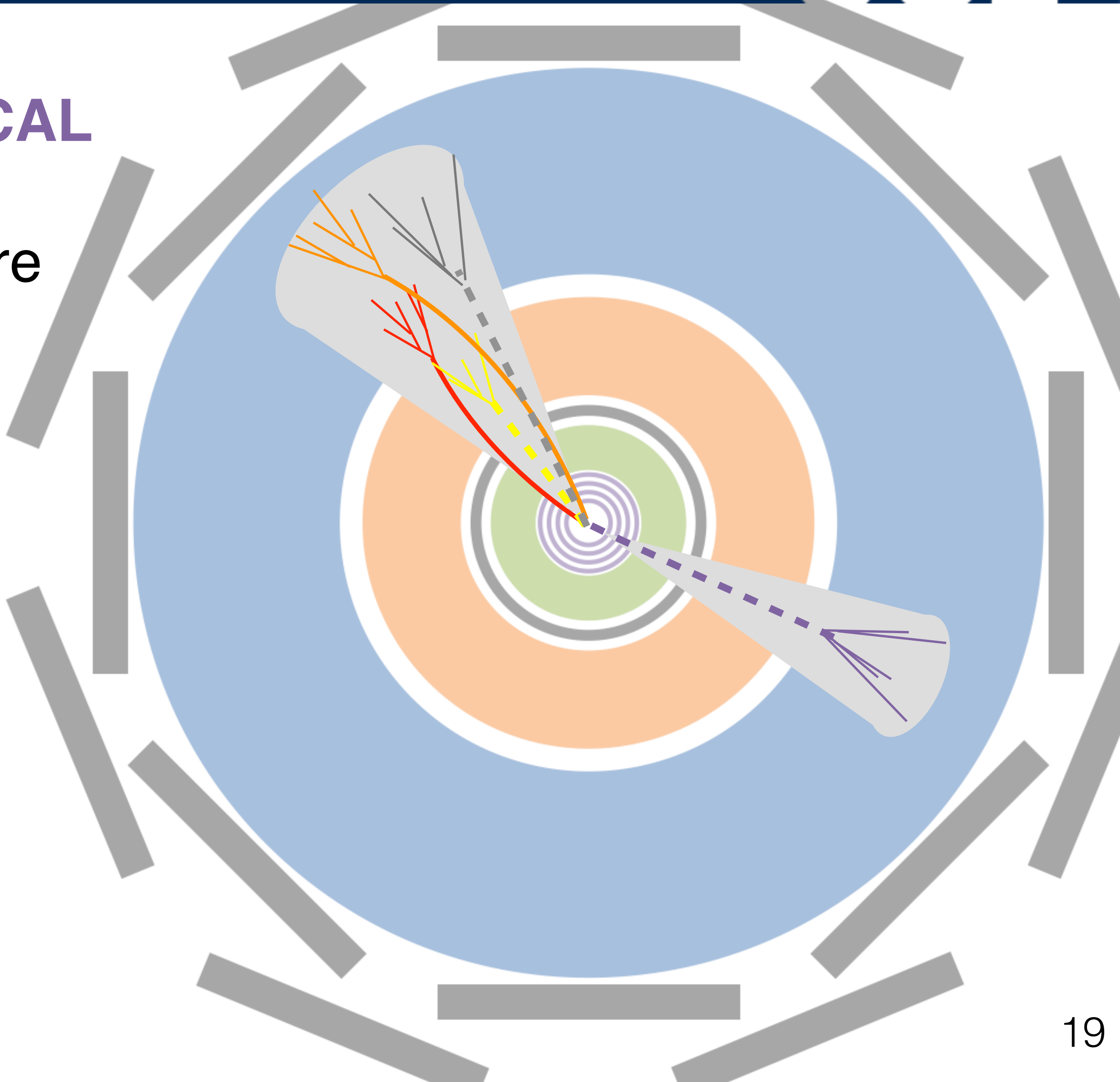


What would a neutral LLP signature look like?

Focus on
LLP decaying in HCAL

How would it compare to a regular SM jet?

- **Narrow :** shower starts much later, has less time to become spatially separated

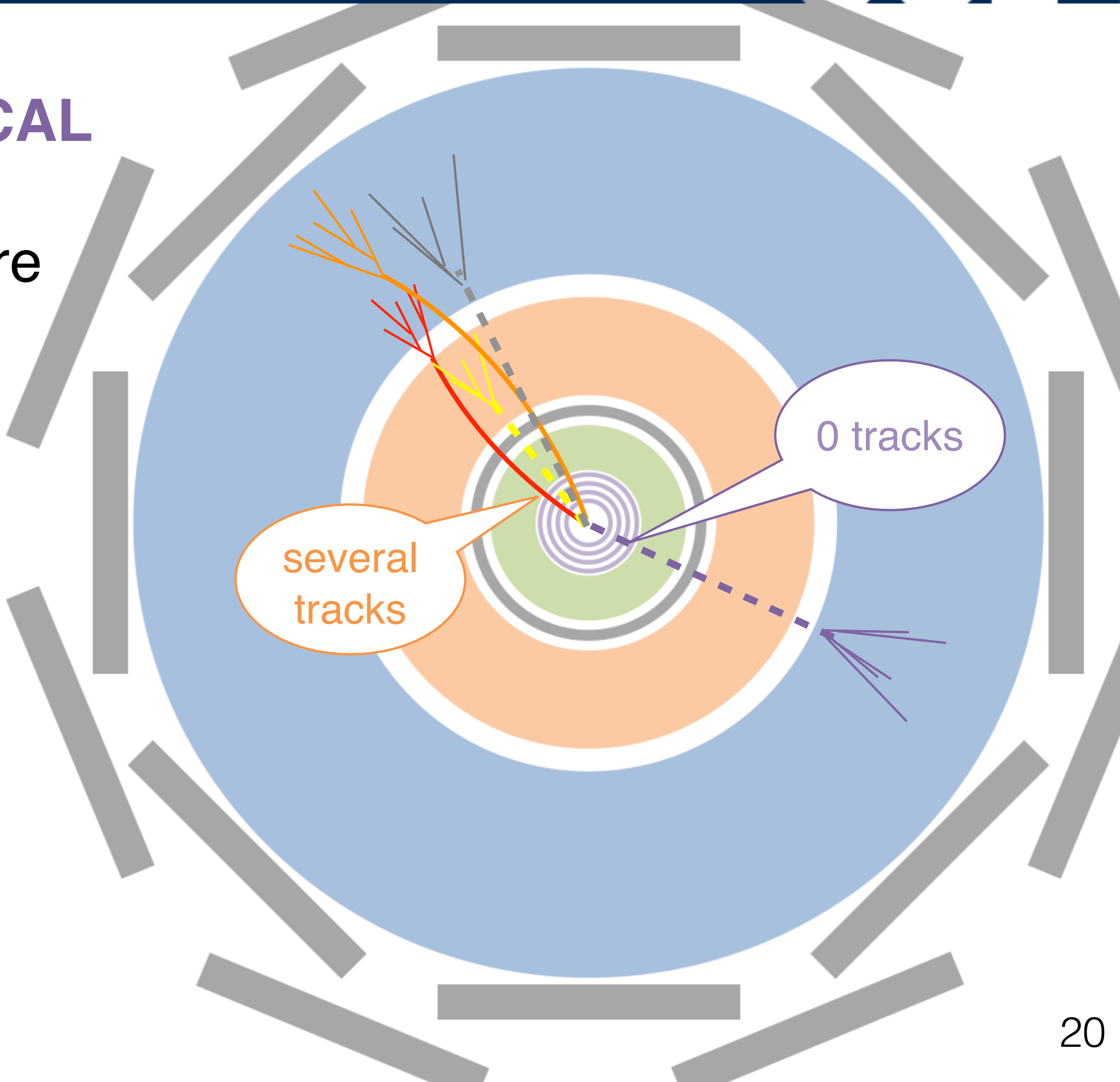


What would a neutral LLP signature look like?

Focus on
LLP decaying in HCAL

How would it compare to a regular SM jet?

- **Narrow**
- **Trackless:** neutral LLPs -> no hits in ID

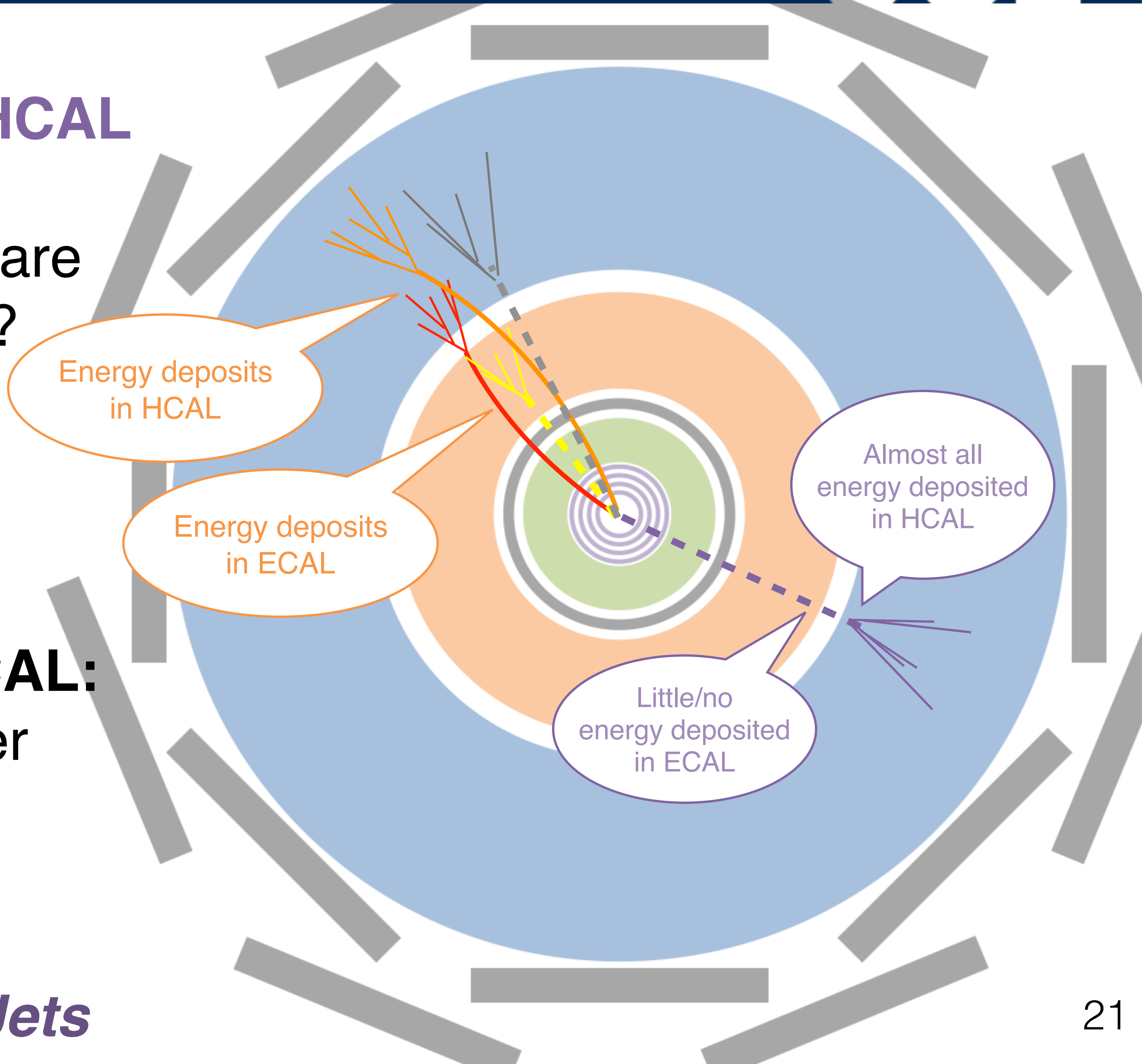


What would a neutral LLP signature look like?

Focus on
LLP decaying in HCAL

How would it compare to a regular SM jet?

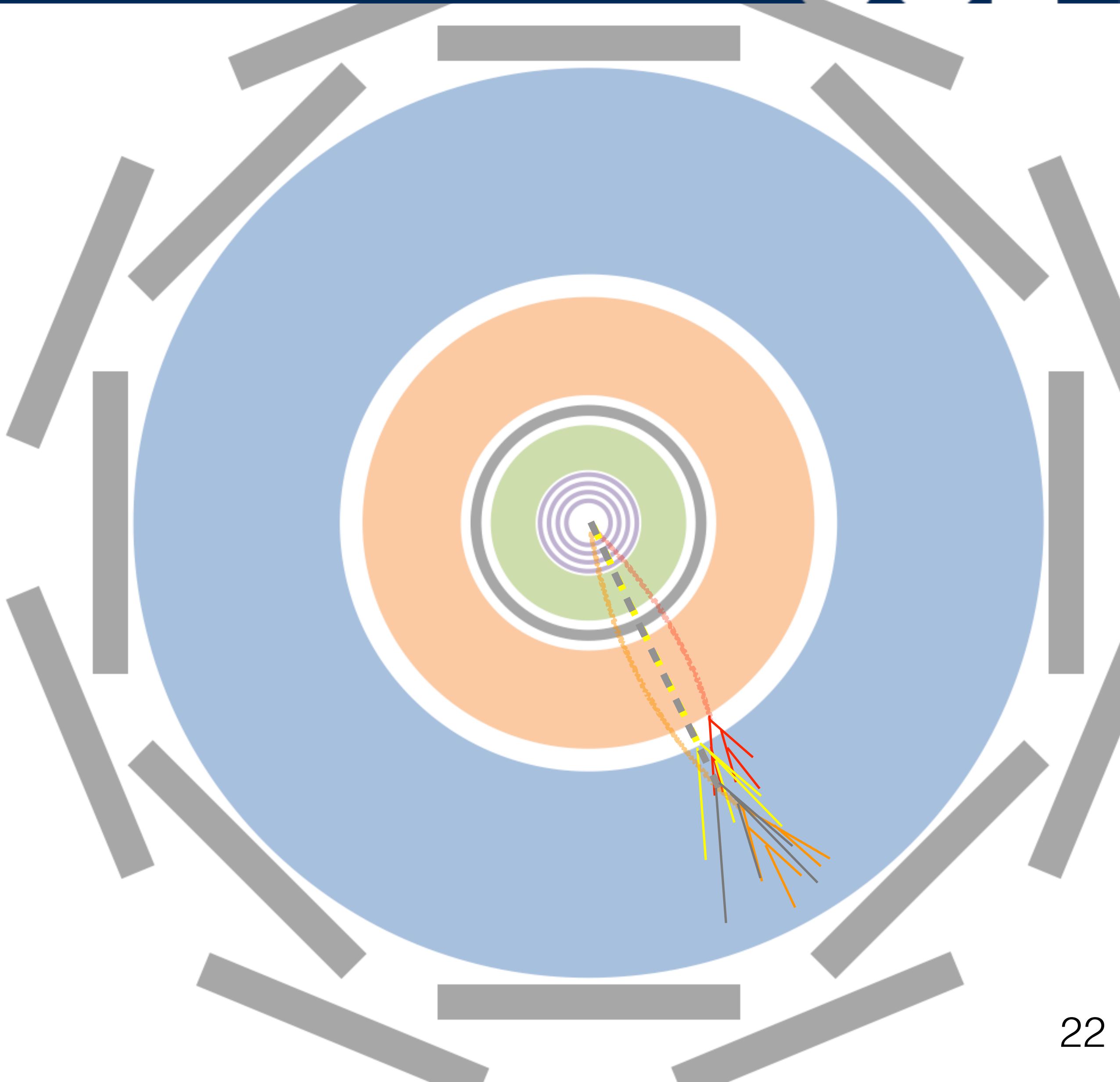
- **Narrow**
- **Trackless**
- **Low fraction of energy in the ECAL:** Define Calorimeter Ratio (CalRatio): E_{HCAL}/E_{ECAL}



Signal: CalRatio Jets

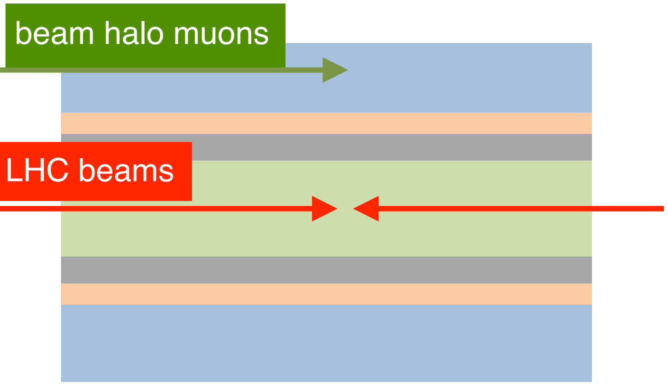
Unusual Backgrounds... QCD from multi-jet events

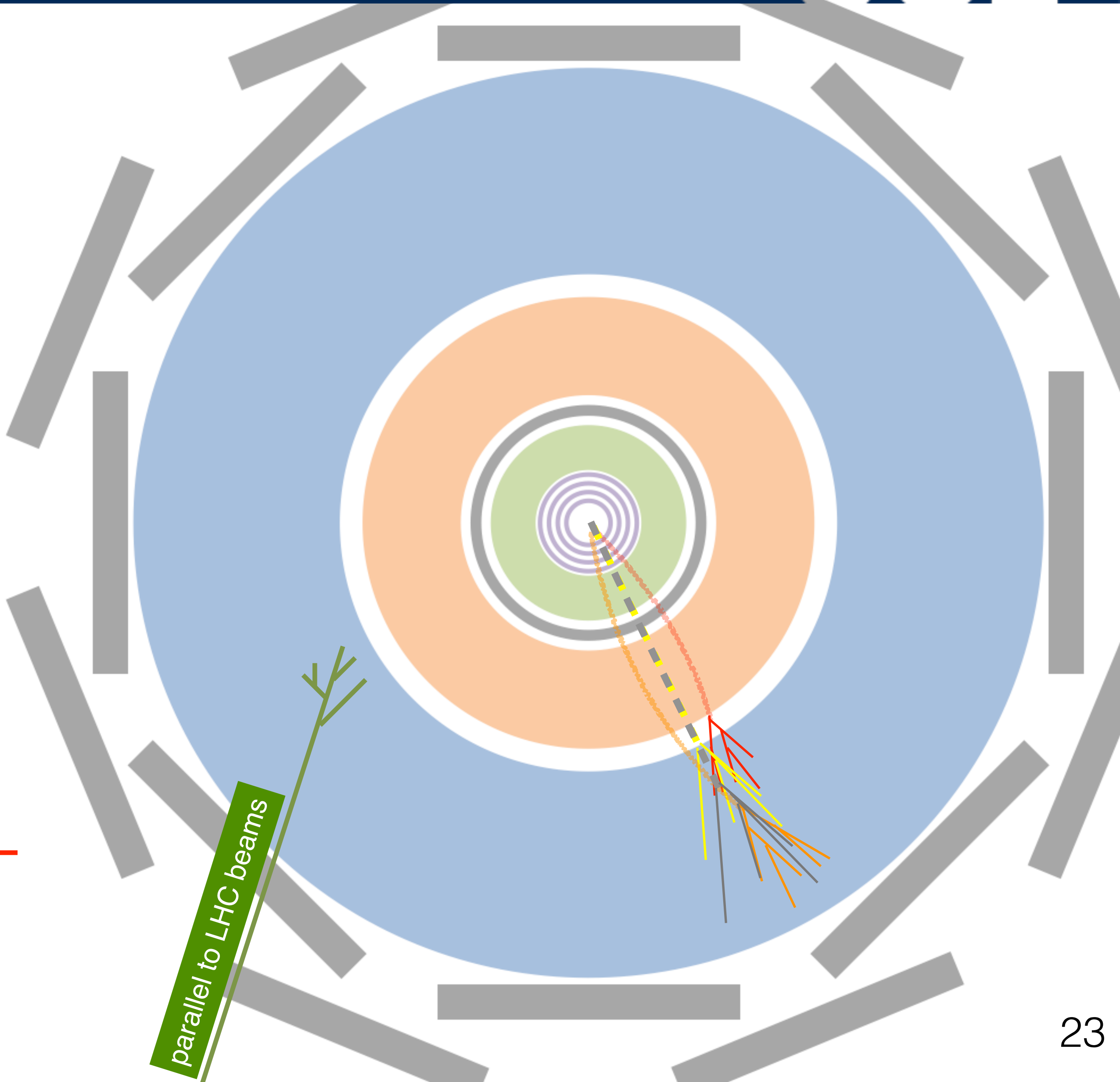
- QCD jets rarely look like CalRatio Jets
- ...but **there are a LOT of QCD jets** (>10^5 x signal!)
- Dominant background!



Beam-induced Background

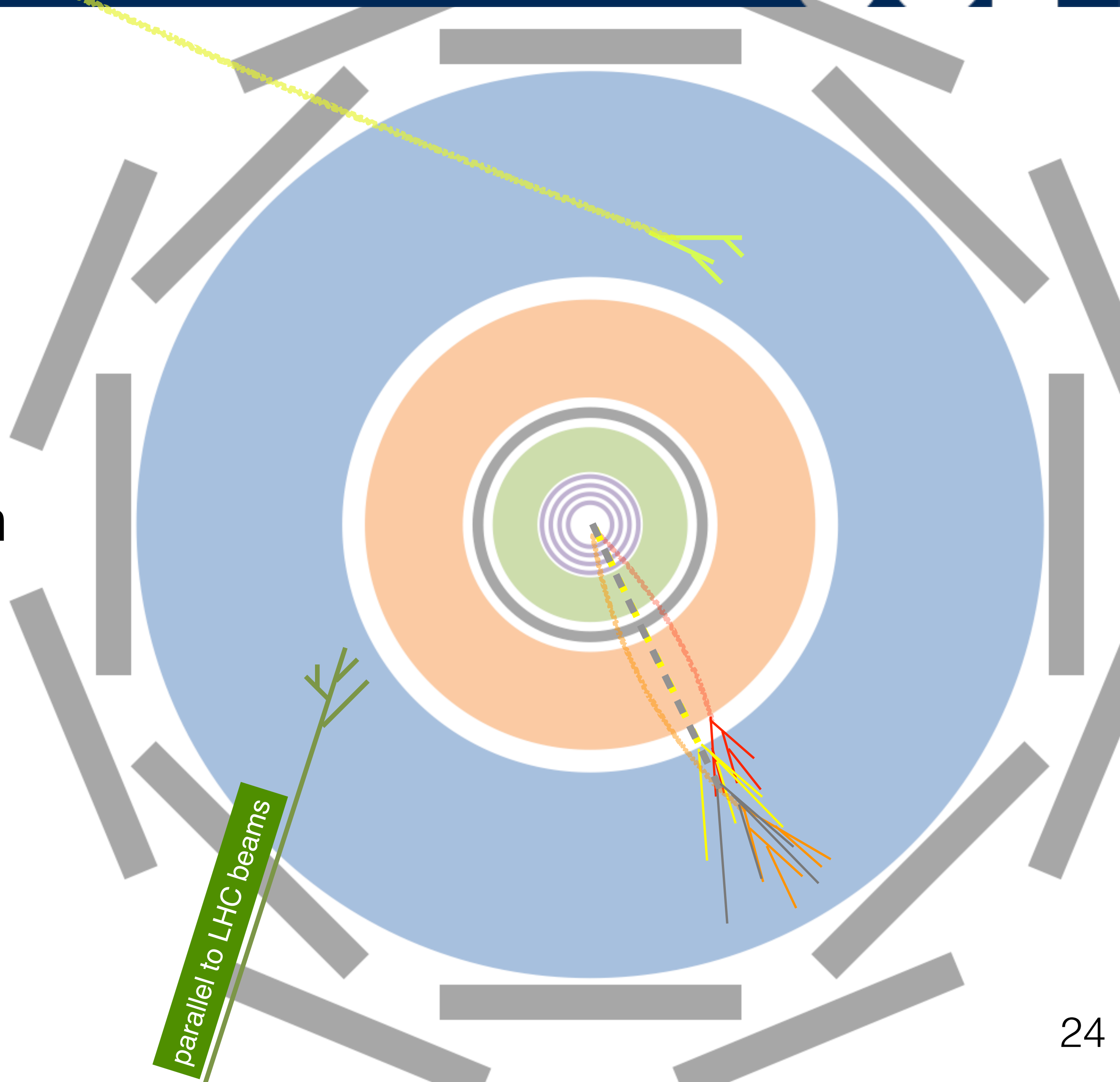
- QCD jets
- Beam-induced background (BIB) from beam halo muons





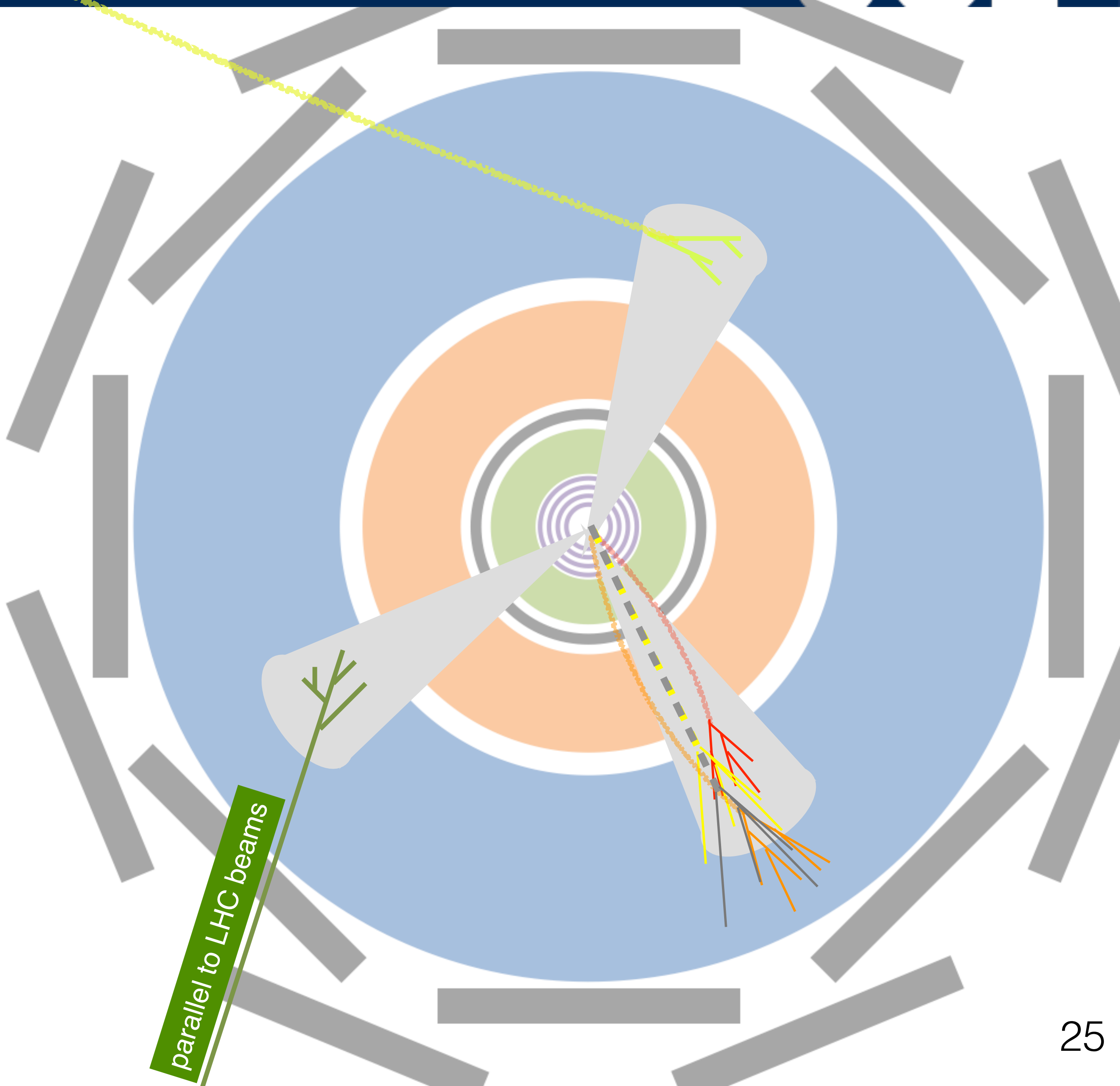
Unusual Backgrounds... Cosmic Rays

- QCD jets
- Beam-induced background (BIB)
- Cosmic Rays can traverse the cavern and leave deposits in the HCAL



Unusual Backgrounds...
Beam-induced Background

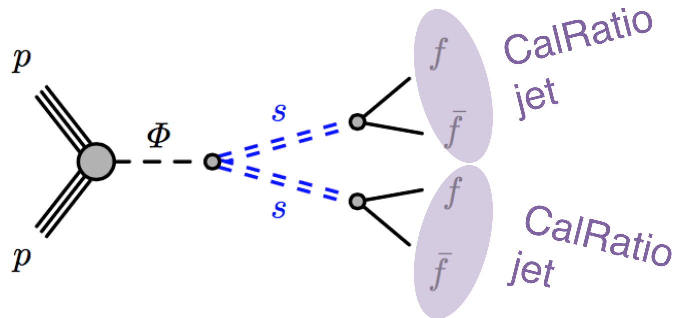
- QCD jets
- Beam-induced background (BIB)
- Cosmic Rays
- **Can all look like narrow, trackless jets with high CalRatio!**



Analysis using CalRatio Jets

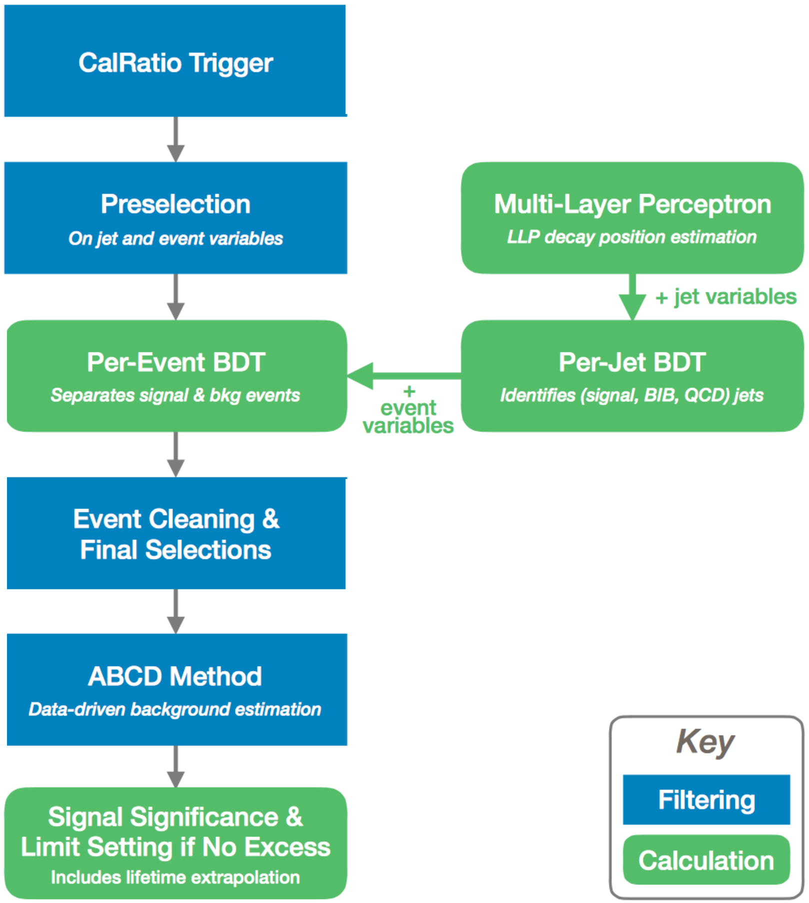
Analysis Strategy

- **Three sister analyses**:
  this one for CalRatio jets
- **Signature-driven** search :
  benchmark model



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

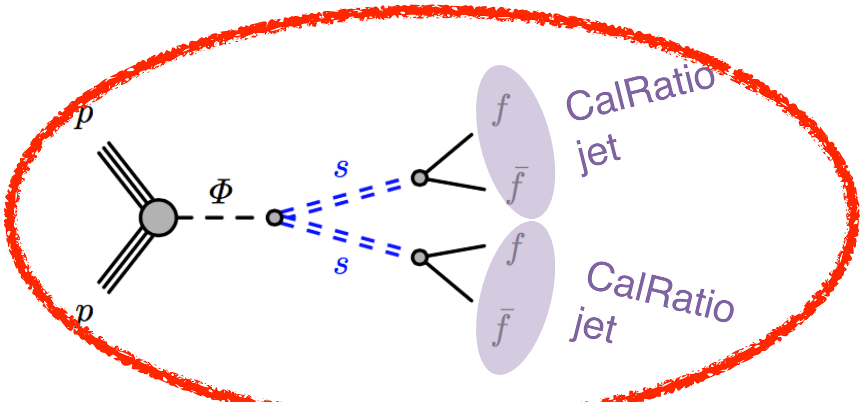
$$m_s \in [5, 400]\ \mathrm{GeV}$$



- 2016 LHC dataset: 33/fb
- **Hack ATLAS** to look for LLPs!

Analysis Strategy

- **Three sister analyses**: this one for CalRatio jets
- **Signature-driven** search : benchmark model



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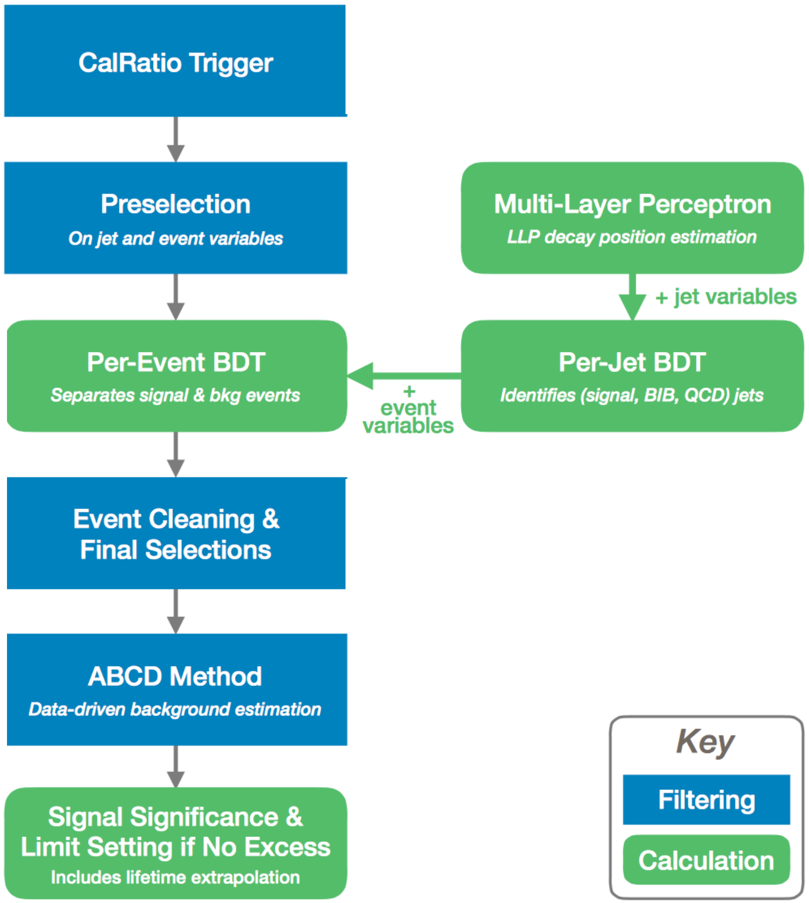
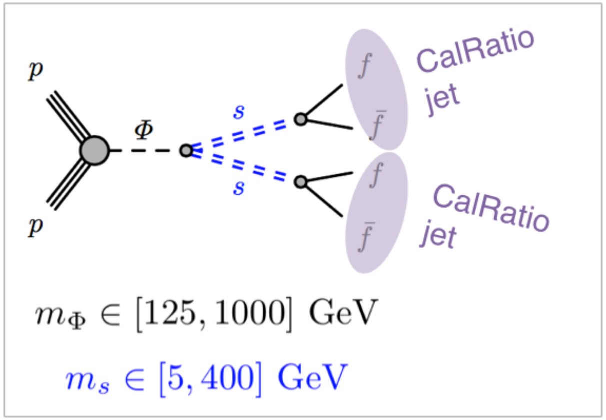


Hallowe'en Interlude



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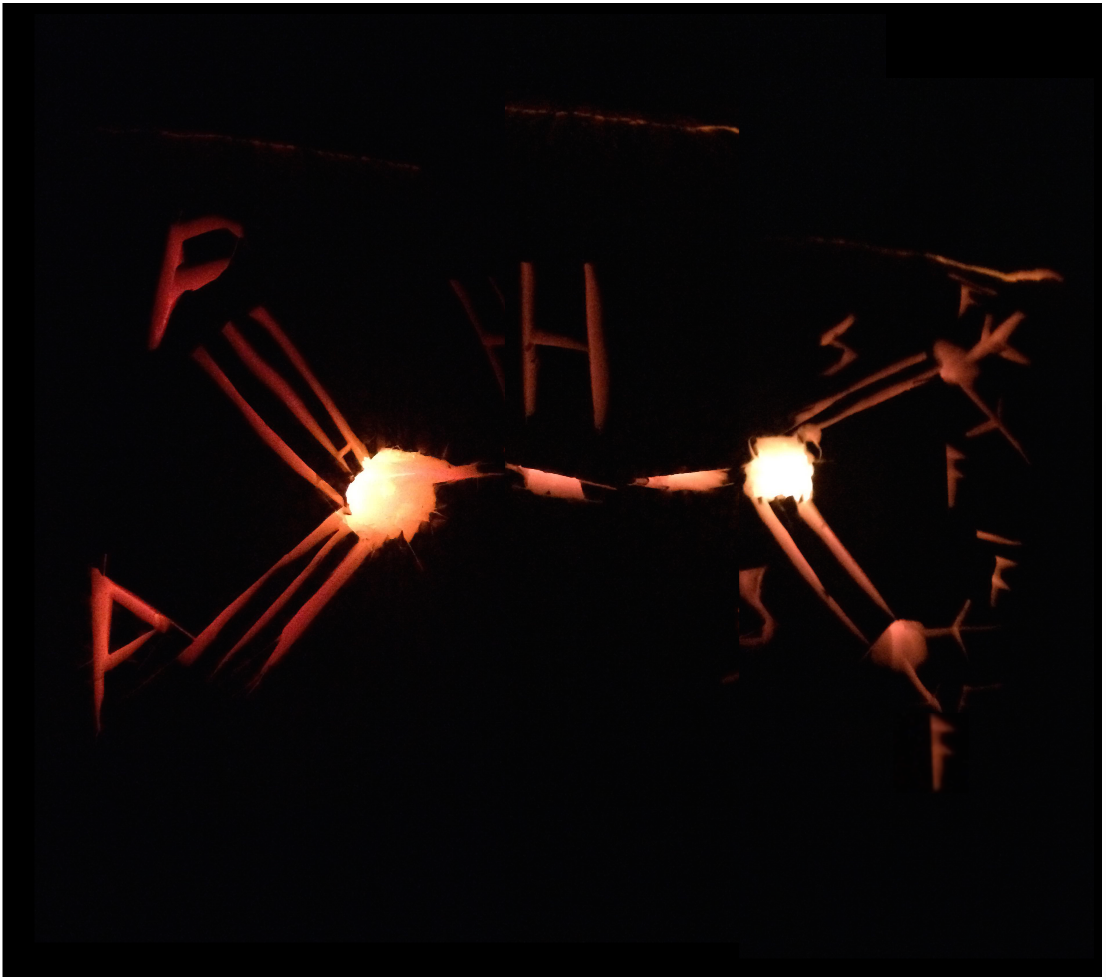

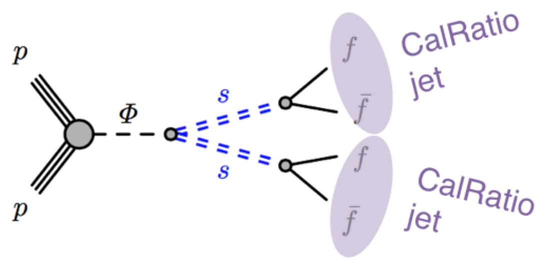

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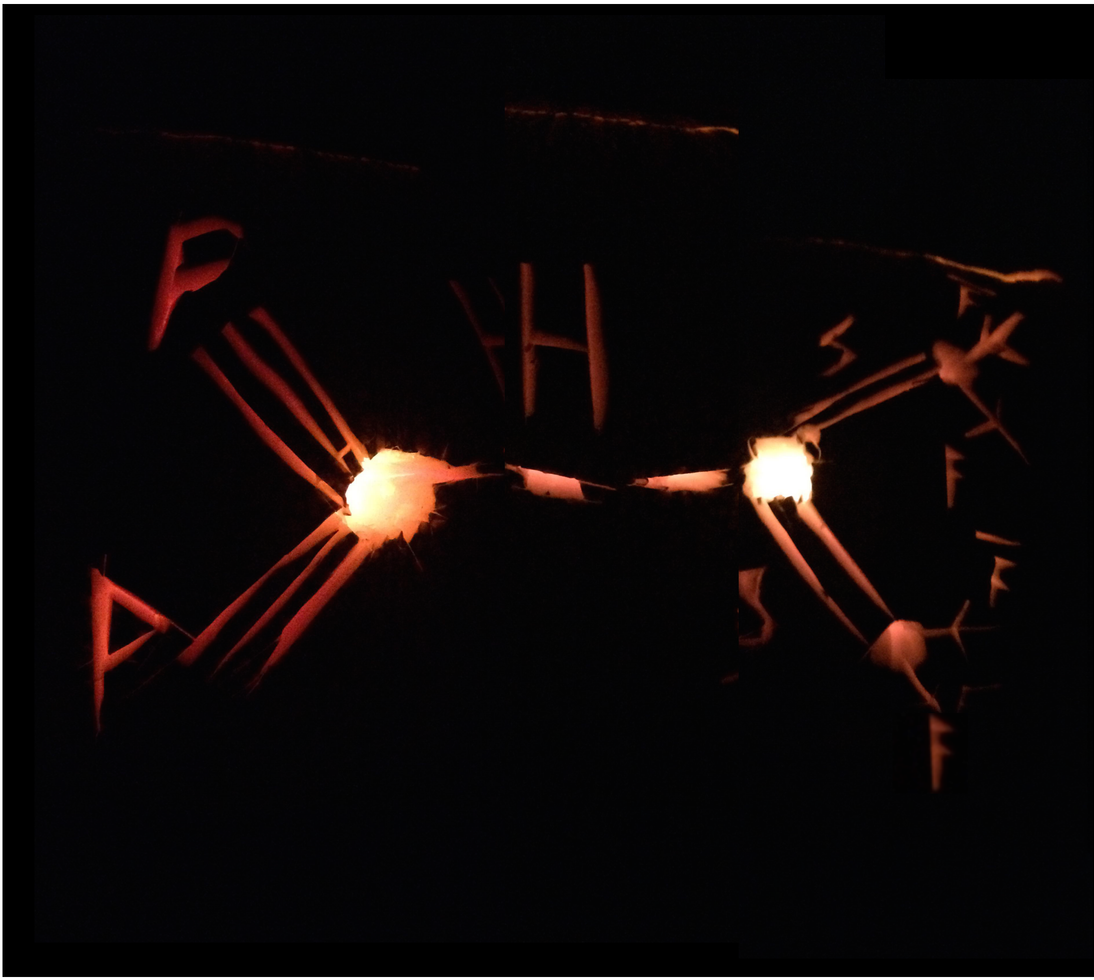
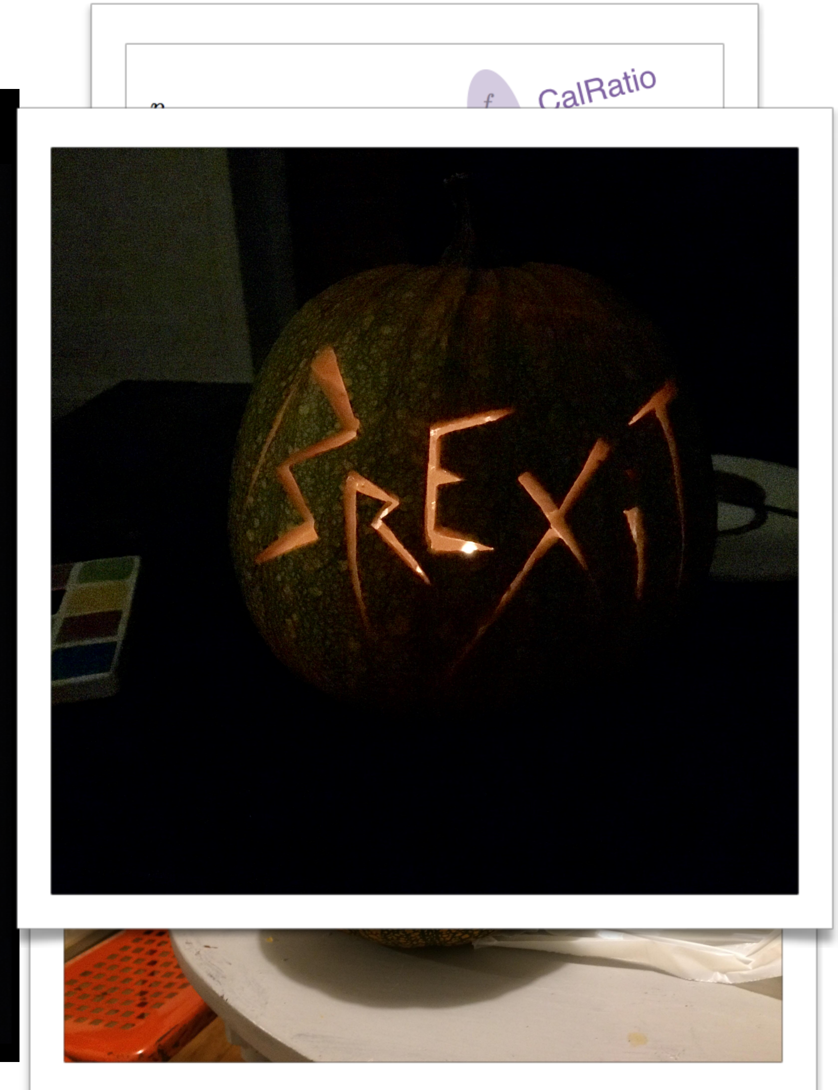
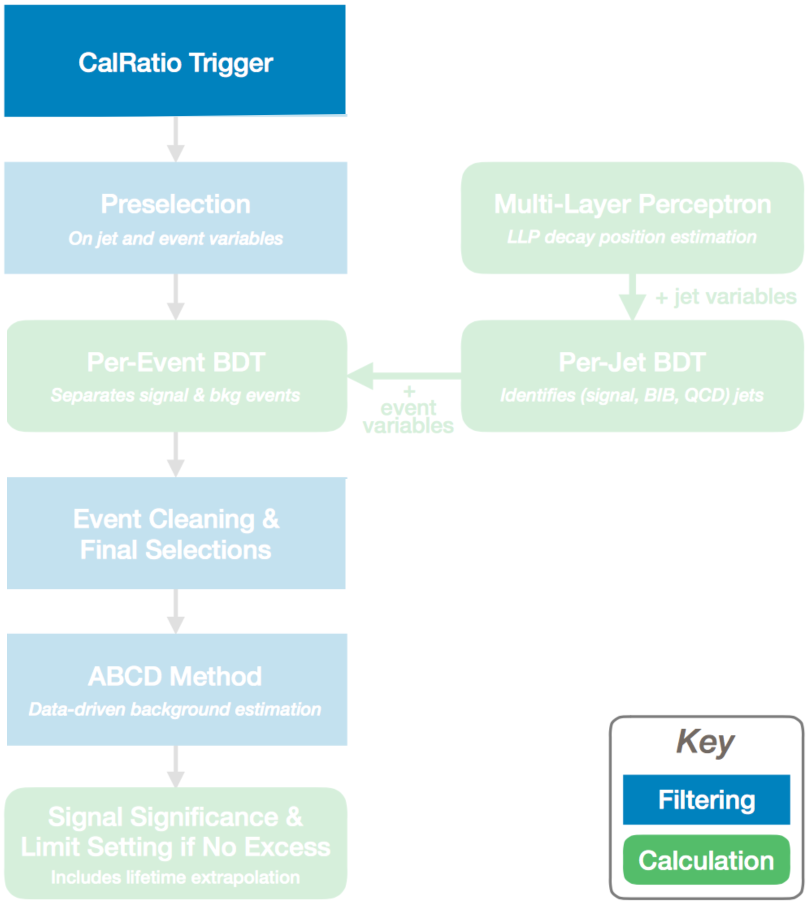




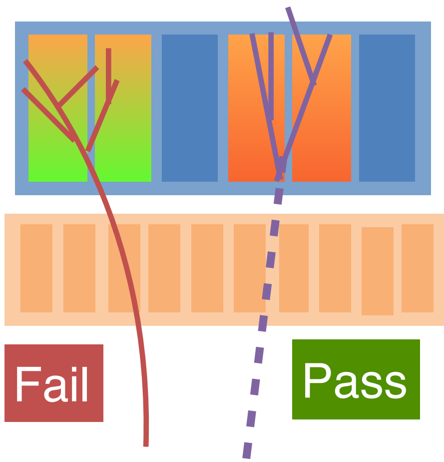
Trigger and Dataset Collection



How to trigger LLP events at Level 1

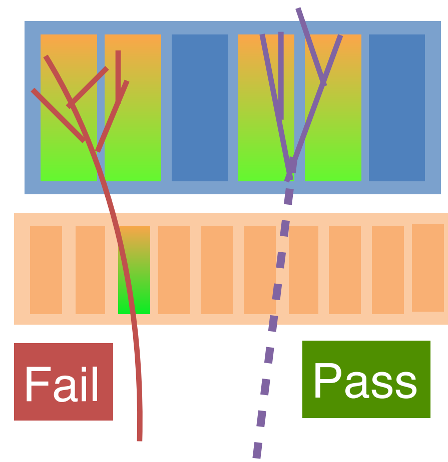
Level 1

High-E_T Trigger
(full 2016 dataset ~33/fb)



E_T > 60 GeV HCAL deposit
in 'narrow' region:
0.2 x 0.2 ($\eta \times \phi$)
(default: 0.8 x 0.8)

Low-E_T Trigger
(1/3 of 2016 dataset ~11/fb)



E_T > 30 GeV HCAL deposit
in 0.2 x 0.2 ($\eta \times \phi$)
veto if matching
E_T > 3 GeV ECAL deposit

Level 1 : Hardware trigger, no track info, only rough calo info

How to trigger LLP events at High Level Trigger

Level 1 — ***High-E_T Trigger*** OR ***Low-E_T Trigger***

HLT

≥1 jet with:

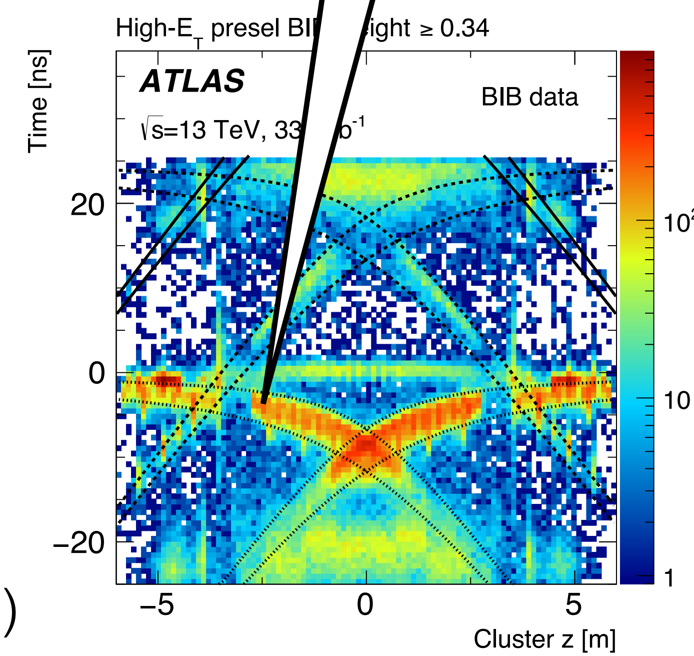
- $E_T > 30$ GeV
- $|\eta| < 2.5$
- $\log(E_H/E_{EM}) > 1.2$
- custom noise suppression

+ BIB-removal algorithm:
cluster timing + alignment

Fail BIB-removal
→ **BIB dataset**

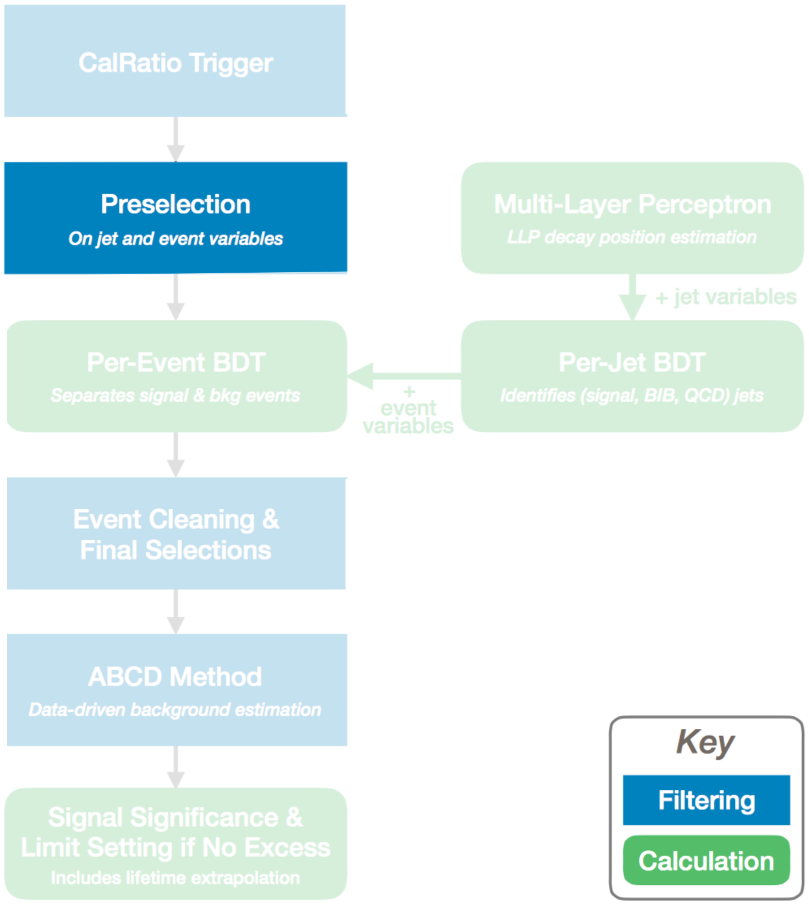
Pass BIB-removal:
→ **Main dataset**
(→or Cosmics dataset)

BIB jets:
'Banana'-shaped
timing-vs-z distribution



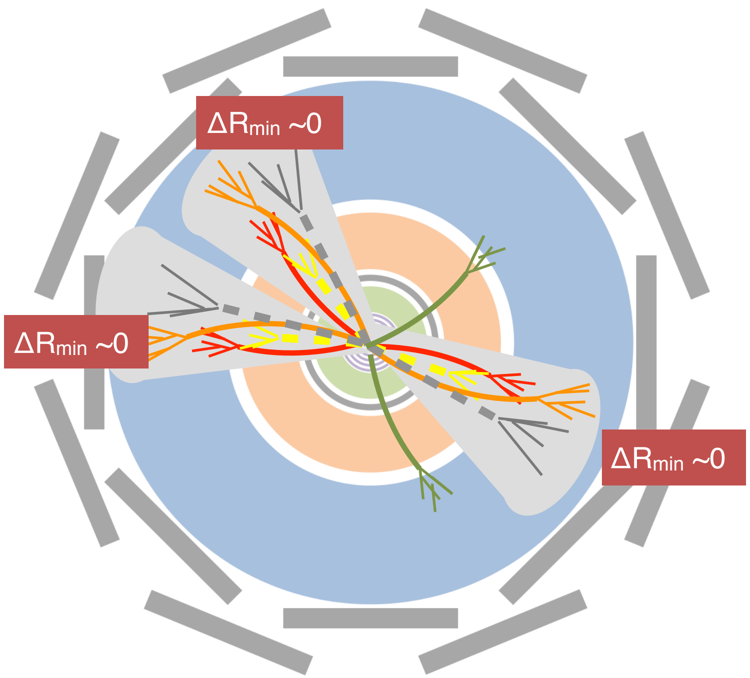
HLT : Computing farm, access to tracking information

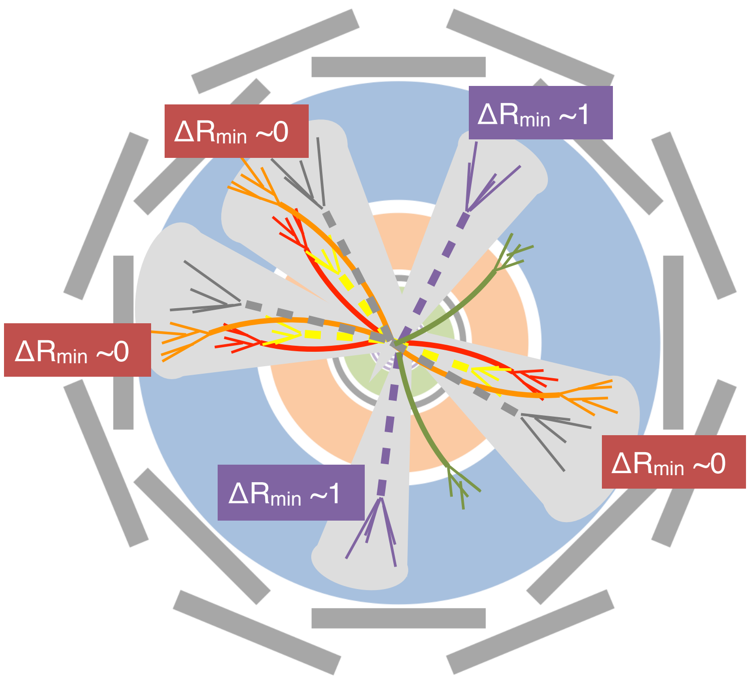
Preselection



Preselection

- Require 2 jets (pT > 40 GeV)
- Pick **events with trackless jets**: $\sum \Delta R_{min}$ (jet, track)





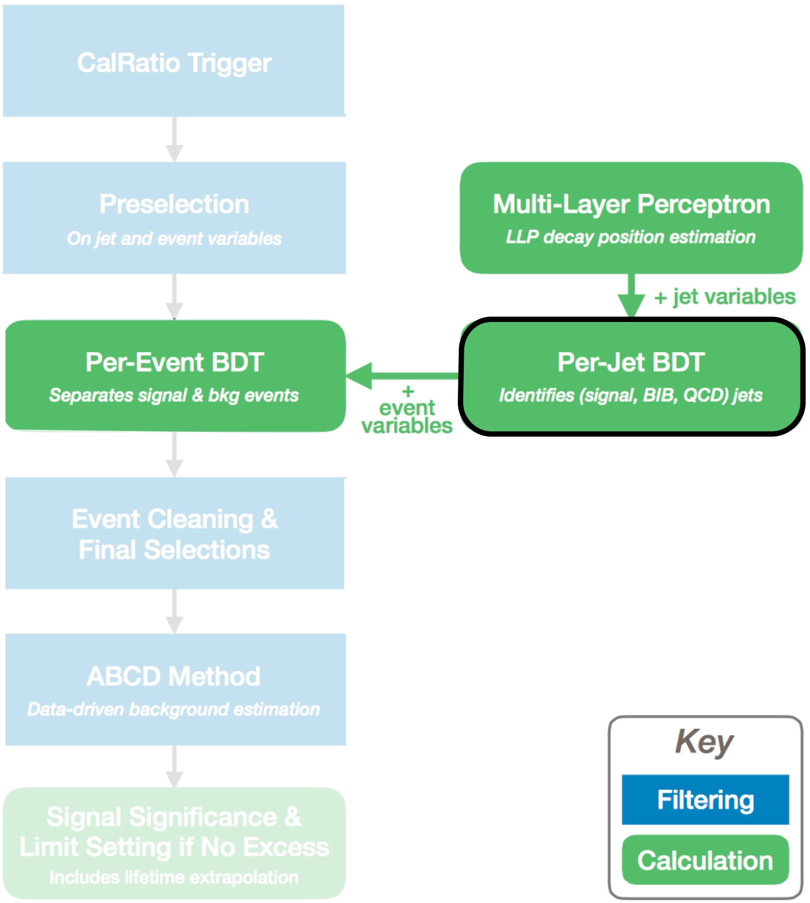
Regular SM events:
$\sum \Delta R_{min} \sim 0$

Event with 2 CalRatio-like jets:
$\sum \Delta R_{min} \sim 2$

Preselection: $\sum \Delta R_{min} > 0.5$

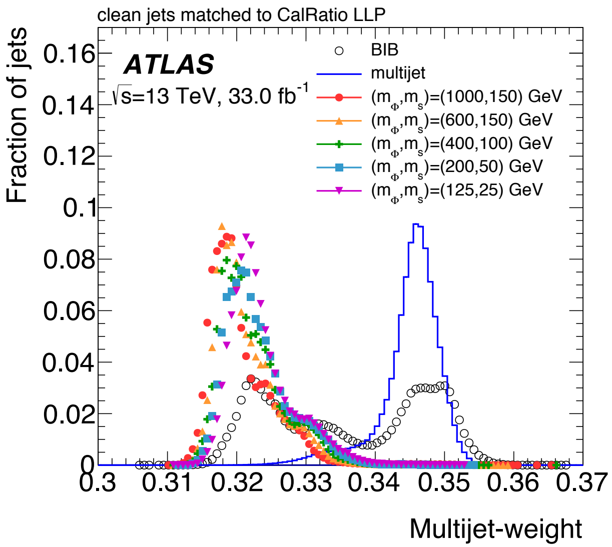
Signal vs Background using Machine Learning

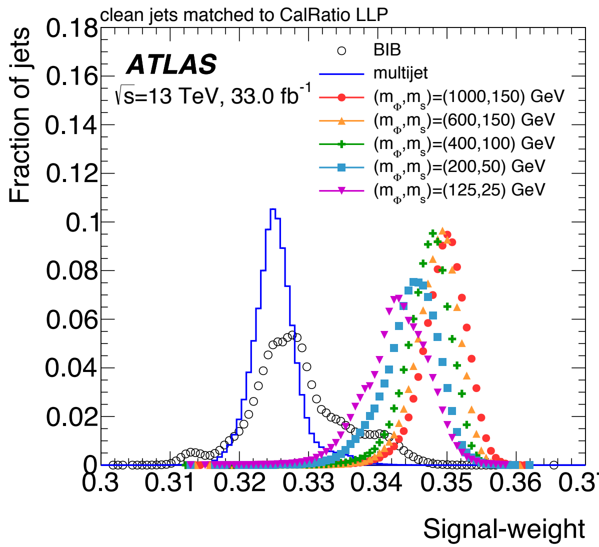
(Focus on Per-Jet BDT)

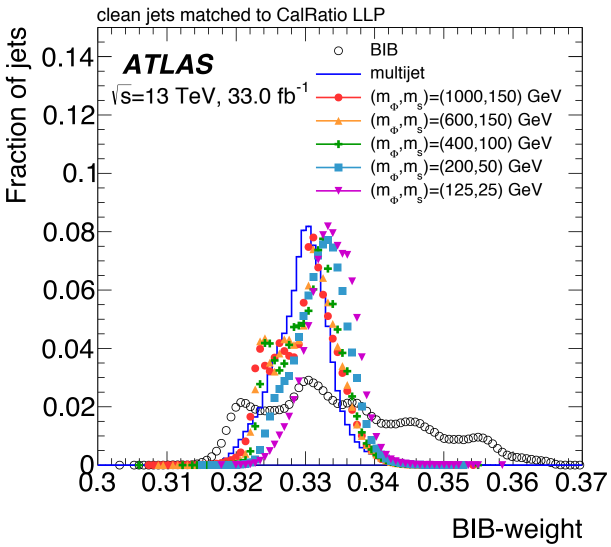


Identify signal jets: Per-jet BDT

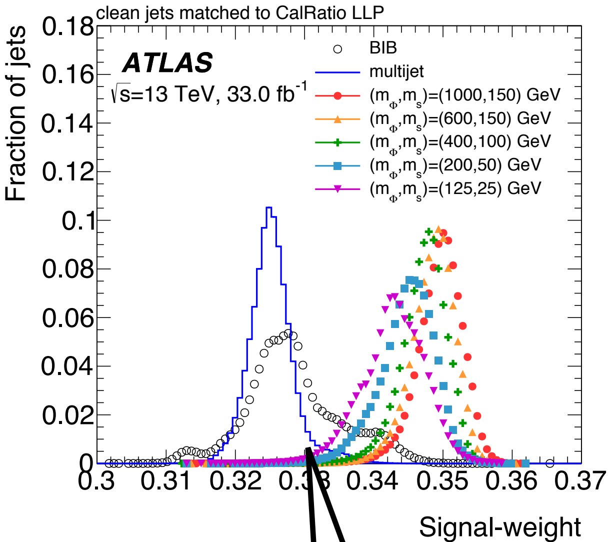
- Multi-class **Boosted Decision Tree** (BDT): separate jets as **signal**-like, **BIB**-like or **multijet**-like
- Inputs: MLP decay position, jet width/energy variables, timing information...
  - Trained on BIB Data, multijet MC, signal samples





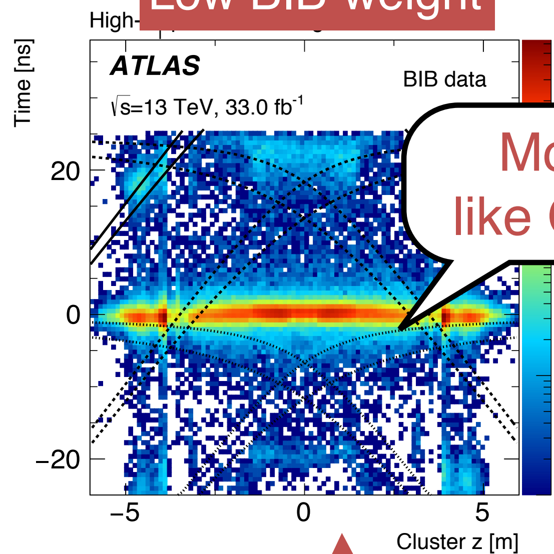


Per-Jet BDT performance



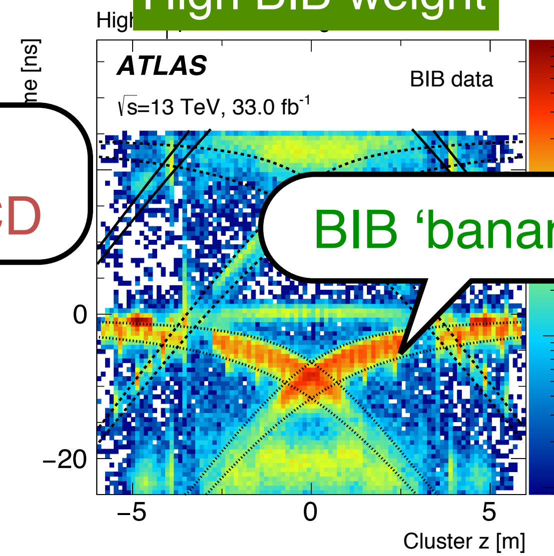
Signal vs bkg(s) discrimination

Low BIB-weight

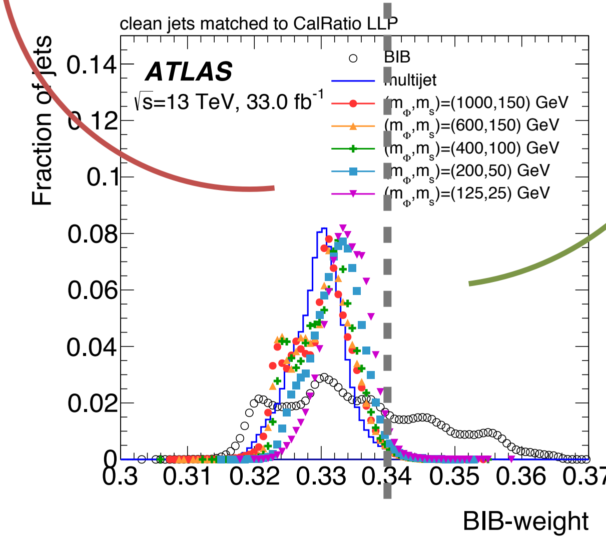


More like QCD

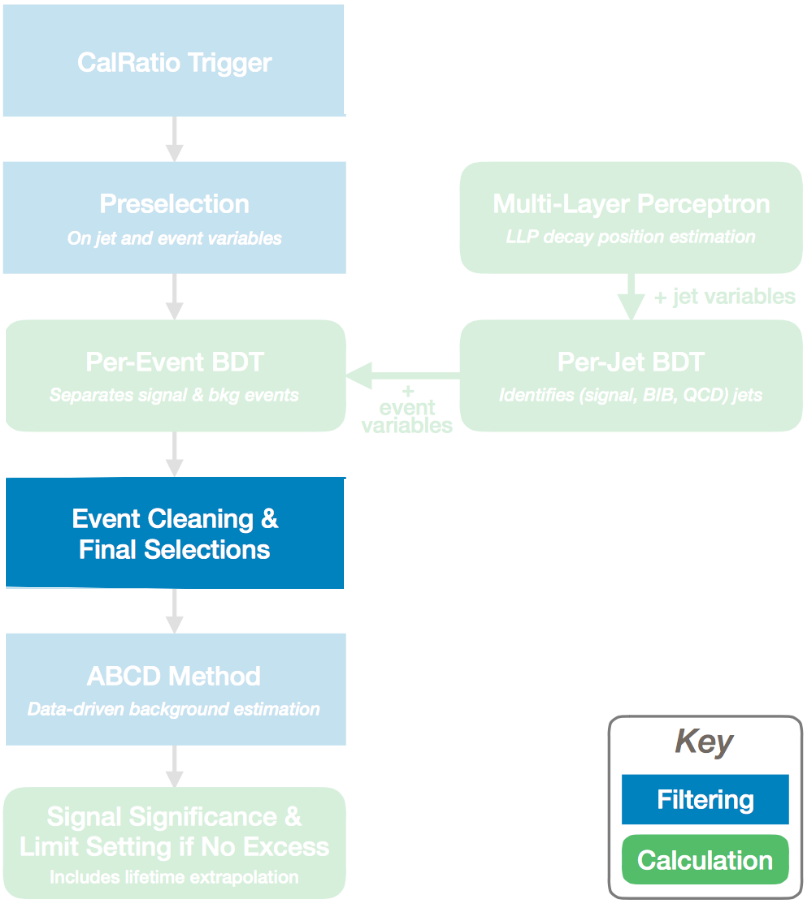
High BIB-weight



BIB 'bananas'



Selection Optimisation



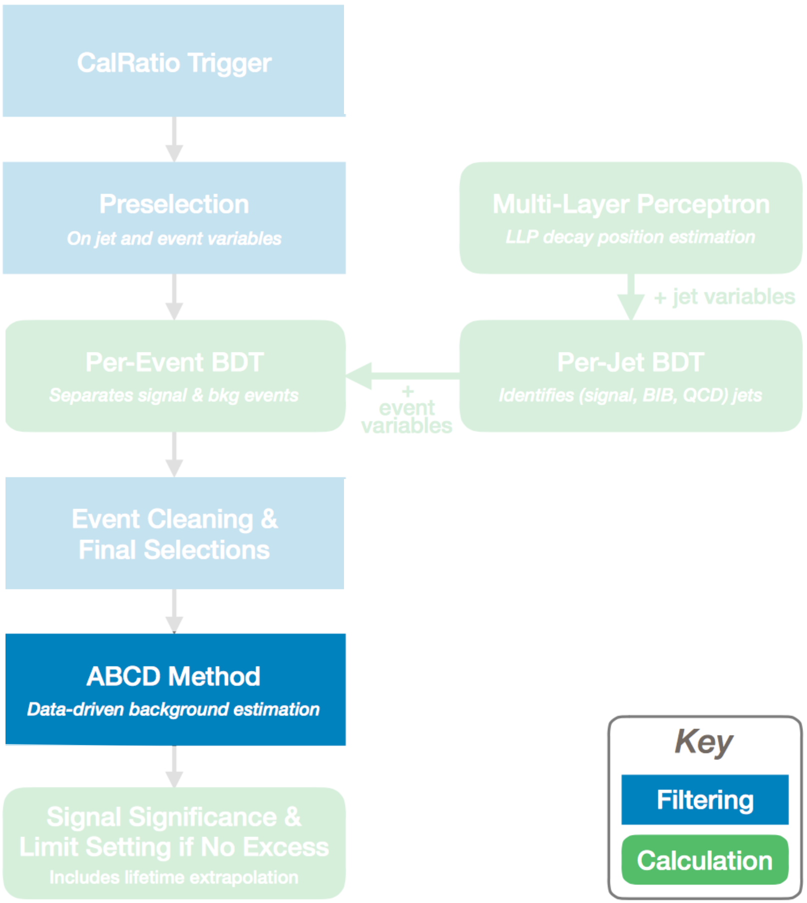
Final Selections

- Final selections **remove any significant BIB or cosmics**
- Optimised for **high S/B in search region** ‘A’

	High-E_T selection:	Main data	BIB	Cosmic rays	Signal (m_Φ, m_s) = (1000, 150) GeV $c\tau$ = 1.17 m	Signal (m_Φ, m_s) = (600, 150) GeV $c\tau$ = 1.72 m	Signal (m_Φ, m_s) = (400, 100) GeV $c\tau$ = 1.46 m
Preselection:	Pass trigger, 2 clean jets & $\sum \Delta R_{min} > 0.5$	1375483	183015	526.0	26.2%	22.4%	17.5%
Event cleaning:	High-E_T per-event BDT > 0.1	4515	192	7.6	25.4%	21.2%	15.3%
	Trigger matching	3627	119	3.8	24.5%	20.4%	15.0%
	$-3 < t < 15$ ns	3388	110	3.2	24.0%	20.0%	14.8%
High-E_T selection:	$\sum_{j_1,j_2} \log_{10}(E_H/E_{EM}) > 1$	1815	61	2.7	21.7%	16.8%	11.5%
	$H_T^{miss}/H_T < 0.6$	1421	41	2.1	18.1%	15.2%	10.9%
	$p_T(j_1) > 160$ GeV	774	26	0	17.5%	13.6%	7.50%
	$p_T(j_2) > 100$ GeV	459	15	0	16.5%	11.8%	5.56%
Region A :		10	1	0	10.7%	7.74%	3.10%

	Low-E_T selection	Main data	BIB	Cosmic rays		Signal (m_Φ, m_s) = (200, 50) GeV $c\tau$ = 1.07 m	Signal (m_Φ, m_s) = (125, 25) GeV $c\tau$ = 0.76 m
Preselection:	Pass trigger, 2 clean jets & $\sum \Delta R_{min} > 0.5$	2180349	95247	319.1		7.58%	4.33%
Event cleaning:	Low-E_T per-event BDT > 0.1	40474	678	65.1		6.26%	2.73%
	Trigger matching	34567	538	42.1		5.97%	2.51%
	$-3 < t < 15$ ns	33680	519	23.4		5.86%	2.46%
Low-E_T selection:	$\sum_{j_1,j_2} \log_{10}(E_H/E_{EM}) > 2.5$	722	13	18.3		0.92%	0.39%
	$p_T(j_1) > 80$ GeV	304	6	7.3		0.69%	0.16%
	$p_T(j_2) > 60$ GeV	136	4	3.5		0.60%	0.10%
Region A:		7	0	0.4		0.43%	0.07%

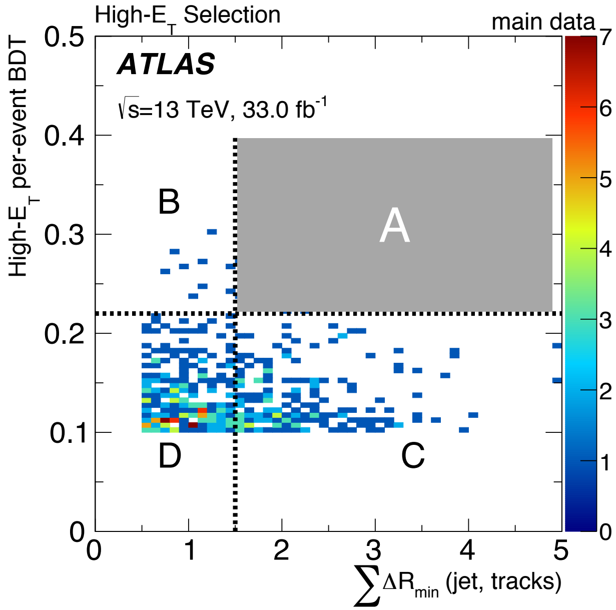
Background Estimate

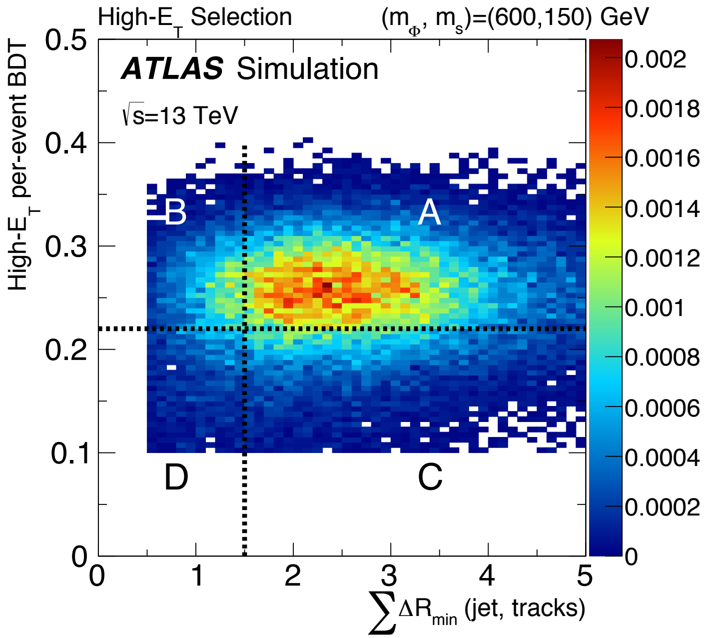


The ABCD method

- 2 ~uncorrelated variables, divide plane into 4 regions

$$N_A^{bkg} = N_B^{bkg} \cdot N_C^{bkg} / N_D^{bkg}$$

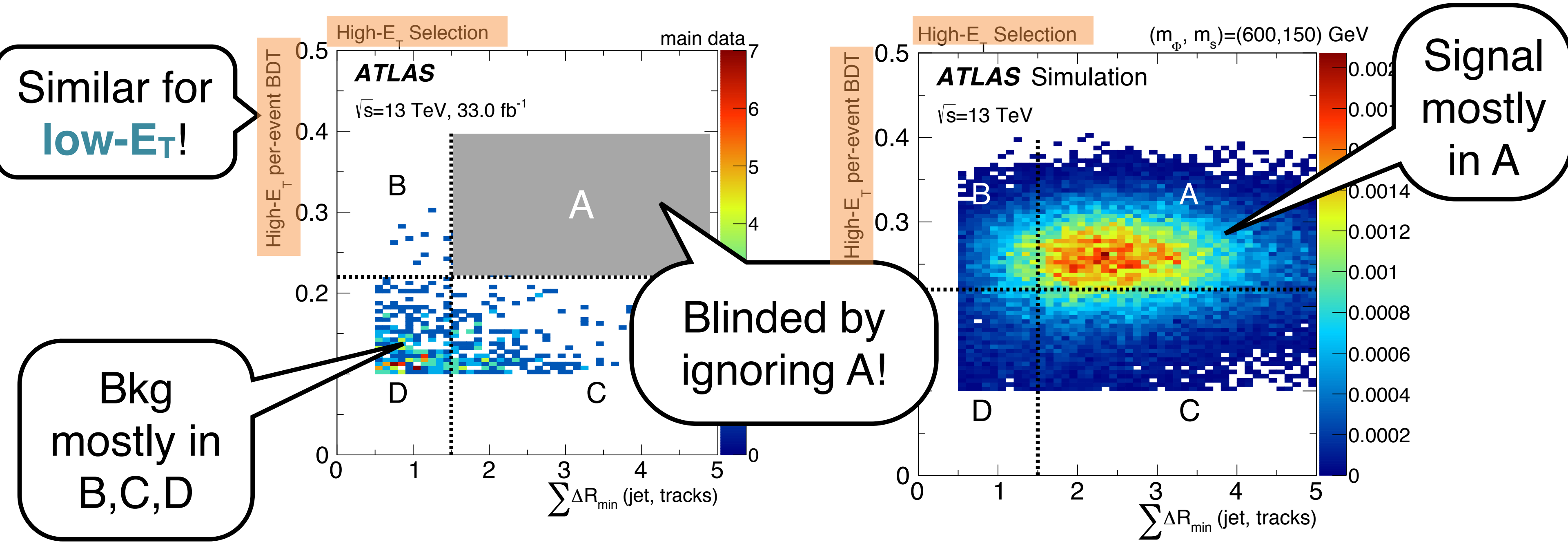




The ABCD method

- 2 ~uncorrelated variables, divide plane into 4 regions

$$N_{\rm A}^{\rm bkg} = N_{\rm B}^{\rm bkg} \cdot N_{\rm C}^{\rm bkg} / N_{\rm D}^{\rm bkg}$$

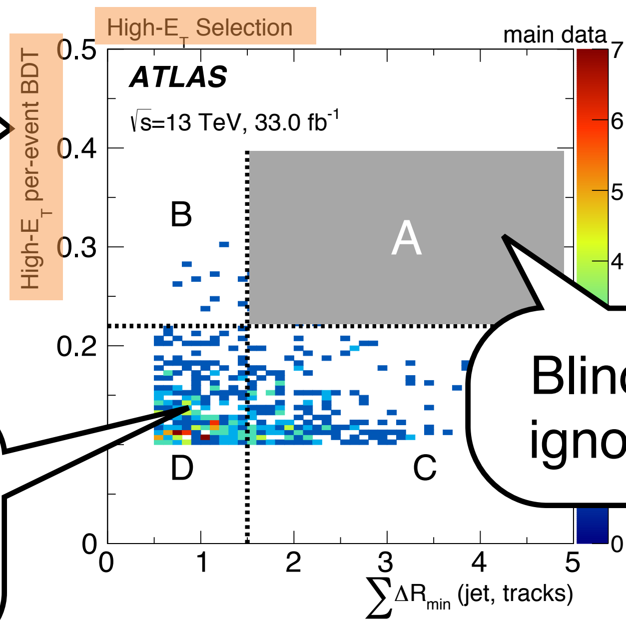


The ABCD method

- 2 ~uncorrelated variables, divide plane into 4 regions

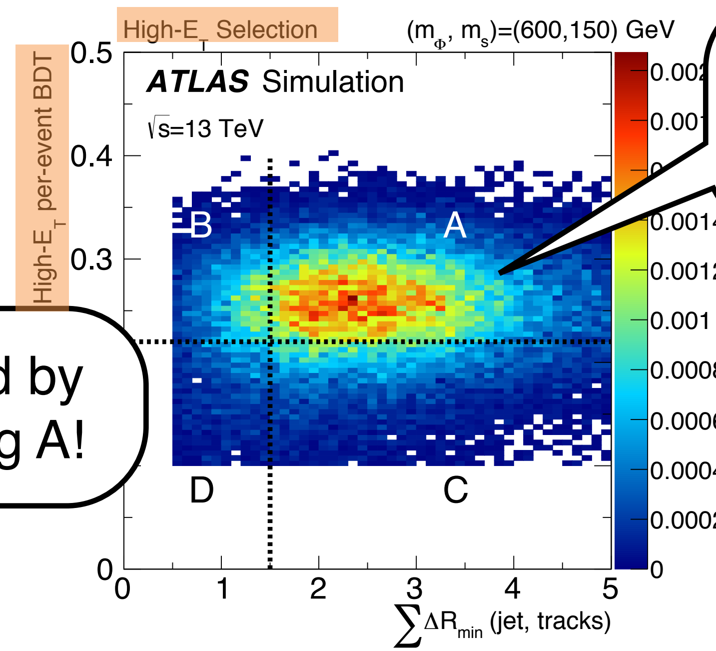
$$N_{\mathrm{A}}^{\mathrm{bkg}} = N_{\mathrm{B}}^{\mathrm{bkg}} \cdot N_{\mathrm{C}}^{\mathrm{bkg}} / N_{\mathrm{D}}^{\mathrm{bkg}}$$

Similar for low-E_T!



Blinded by ignoring A!

Bkg mostly in B,C,D

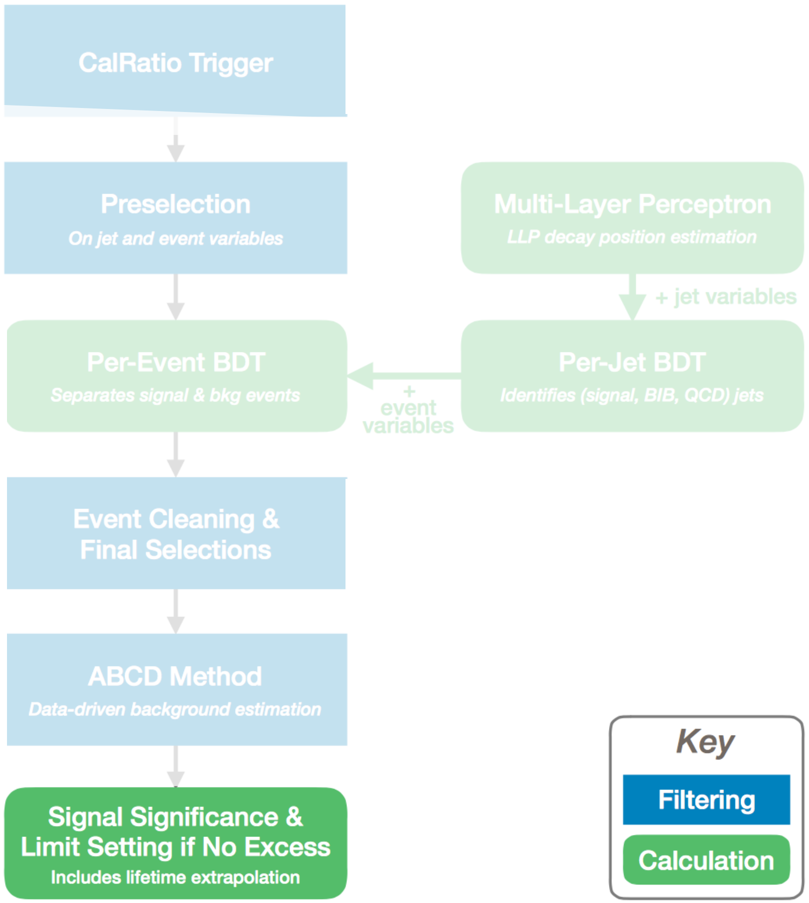


Signal mostly in A

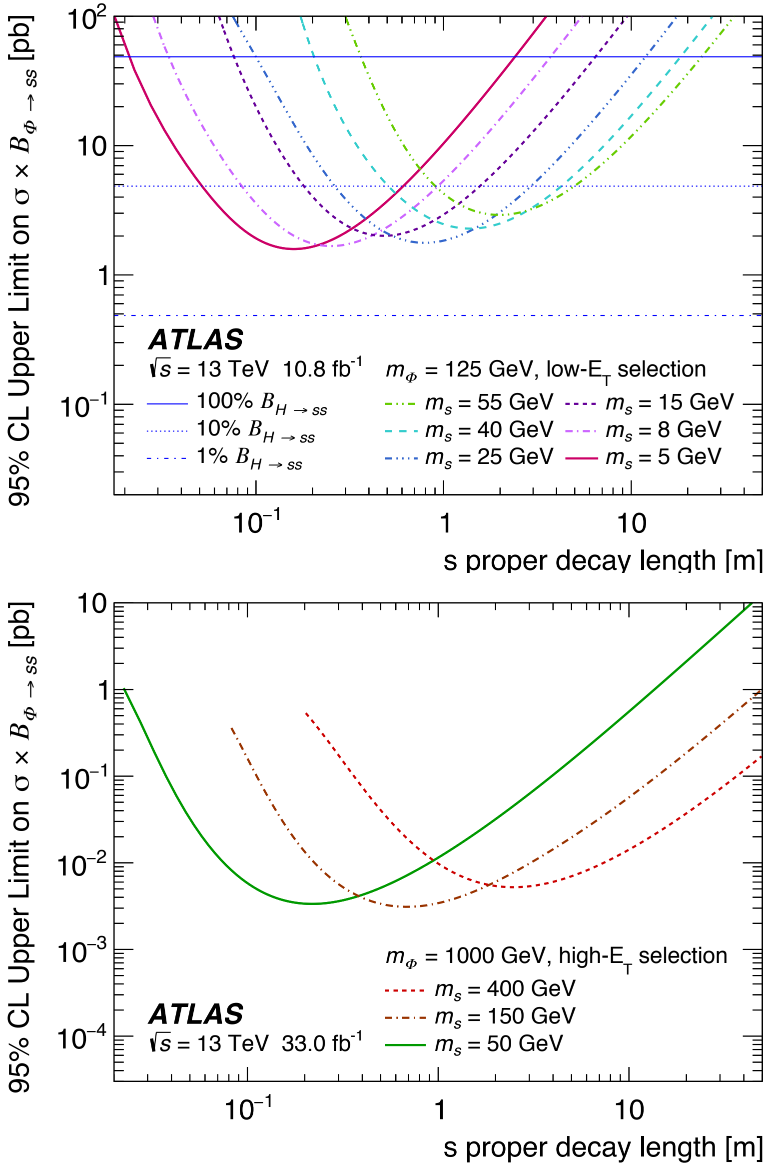
Main selections	Estim. A (*a posteriori*)	A	B	C	D
High-E_{T} selection	$8.5^{+2.3}_{-2.0}$	10	9	187	253
Low-E_{T} selection	$5.3^{+2.1}_{-1.6}$	7	2	70	57

No excess 😞

Statistical Interpretation

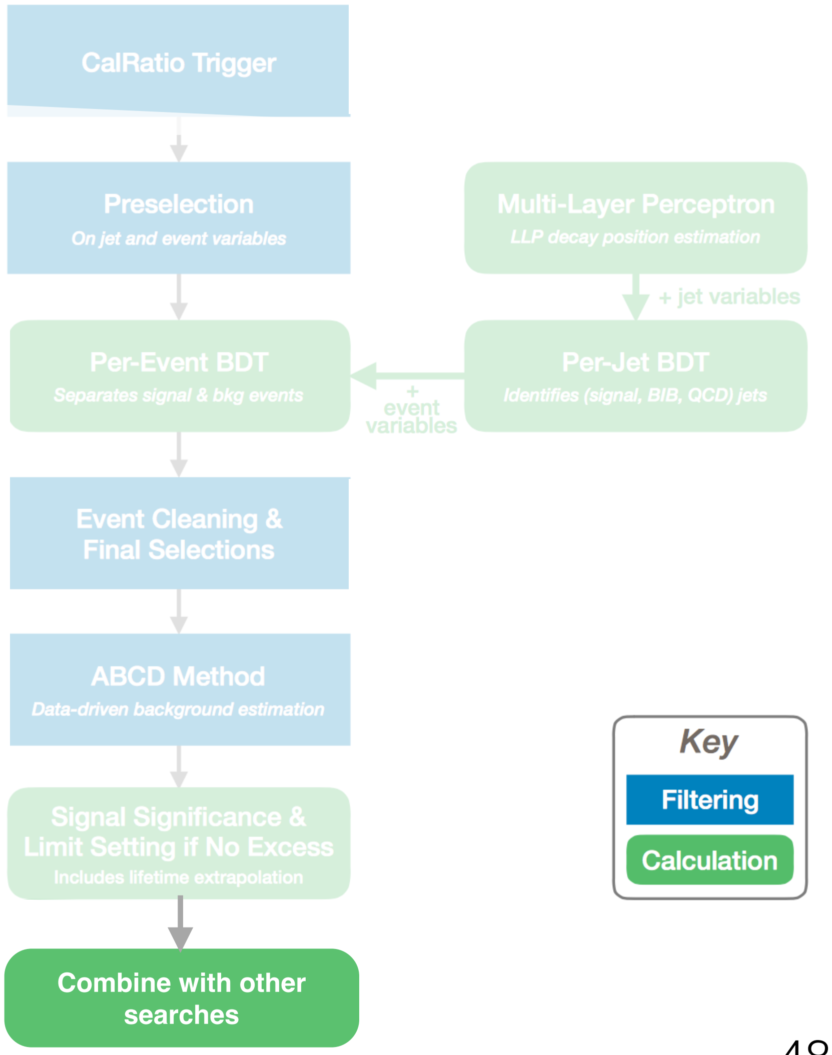


Limit Setting



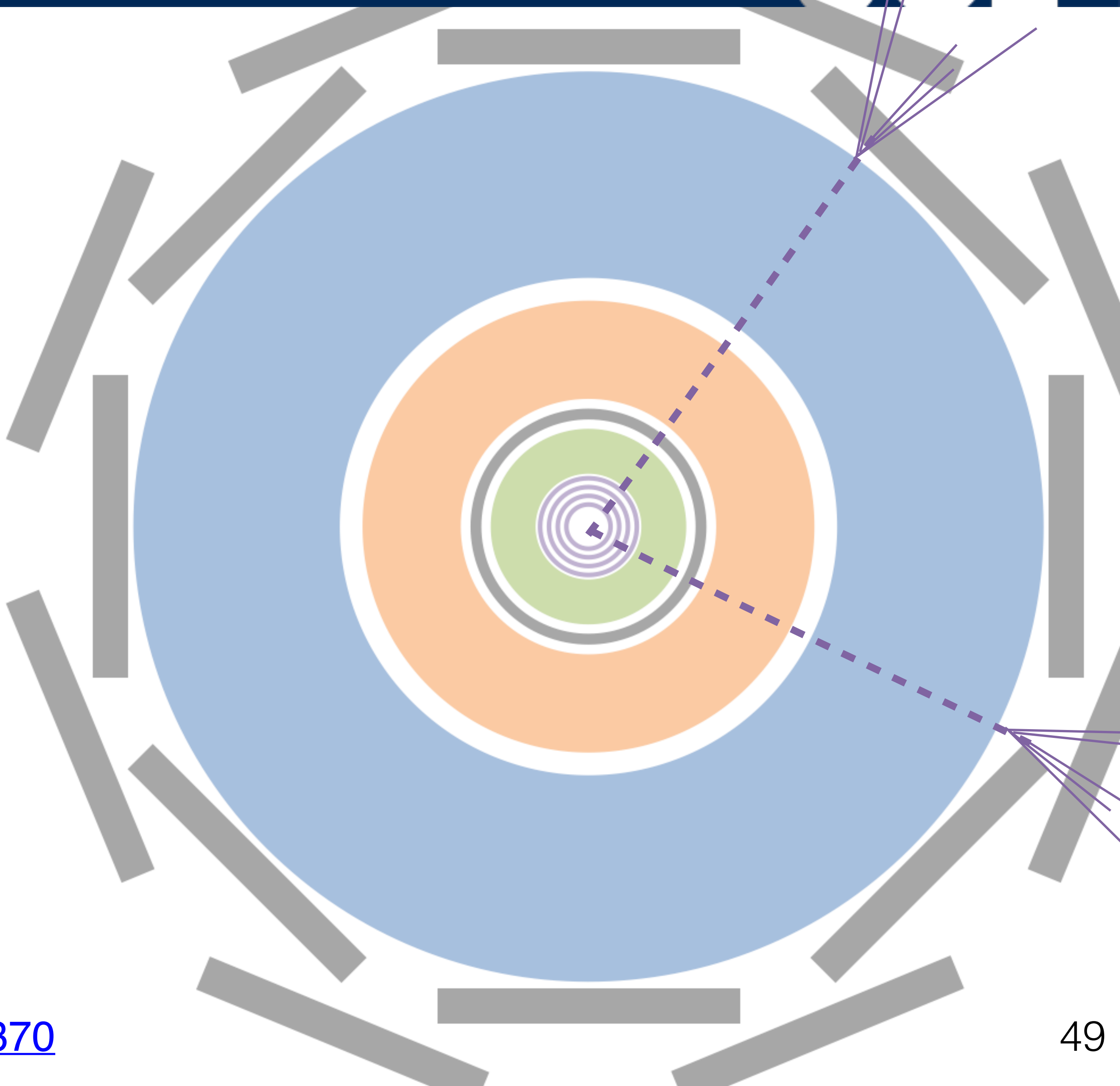
- No excess → **95% CL limits** (CLs method)
- Simultaneous **S+B likelihood fit** to all regions:
- Uncertainties as nuisances with Gaussian constraints.
  - Bkg uncertainty ~25%
  - Main signal uncertainty: Jet Energy (re-derive for CalRatio jets) ~15%
  - Total signal uncertainty: 10-25% depending on model

Combination with MS vertex analysis



MS vertex analysis

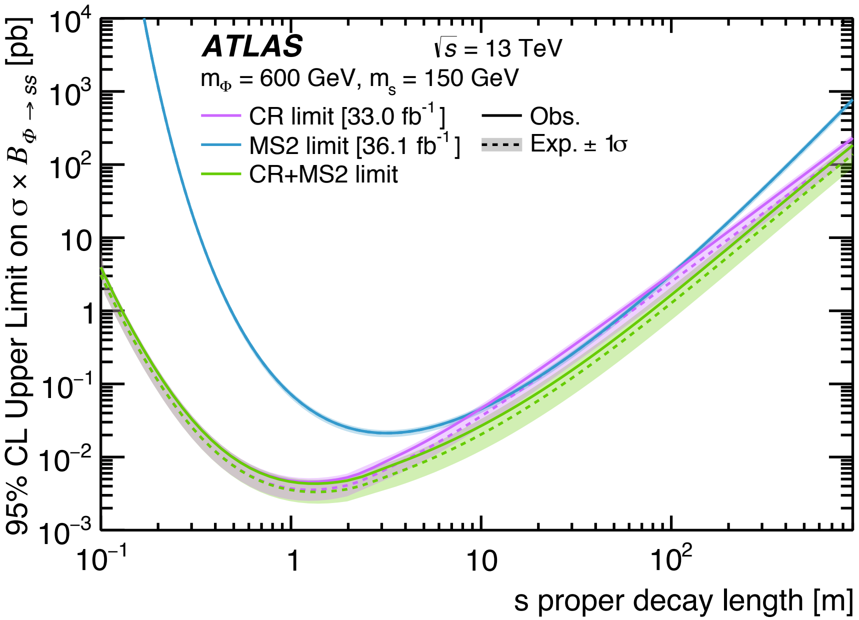
- **Same benchmark models** as CalRatio search
- LLPs decaying in the MS
- Reconstructed as displaced vertices:
    - 1- and 2-vertex channels

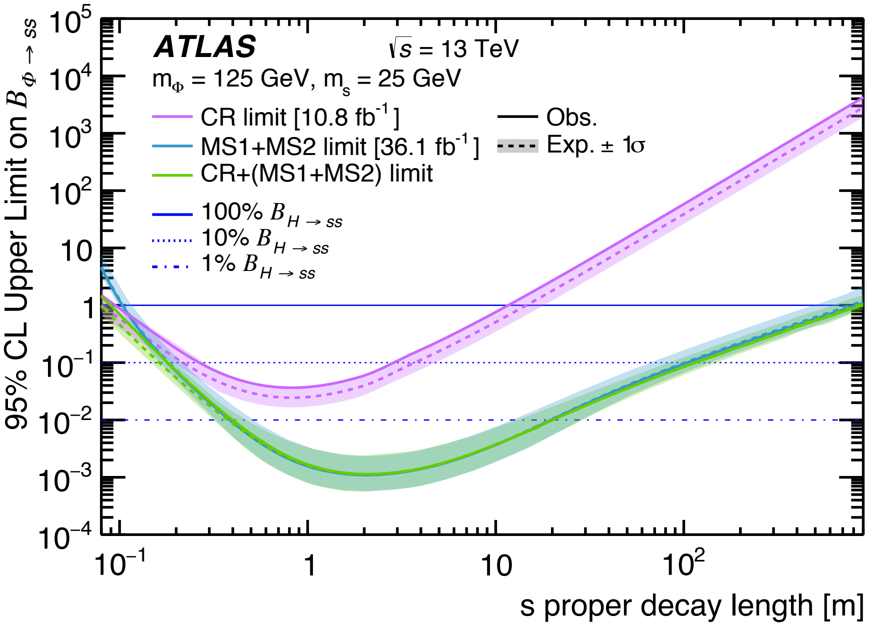


https://arxiv.org/abs/1811.07370

Combination

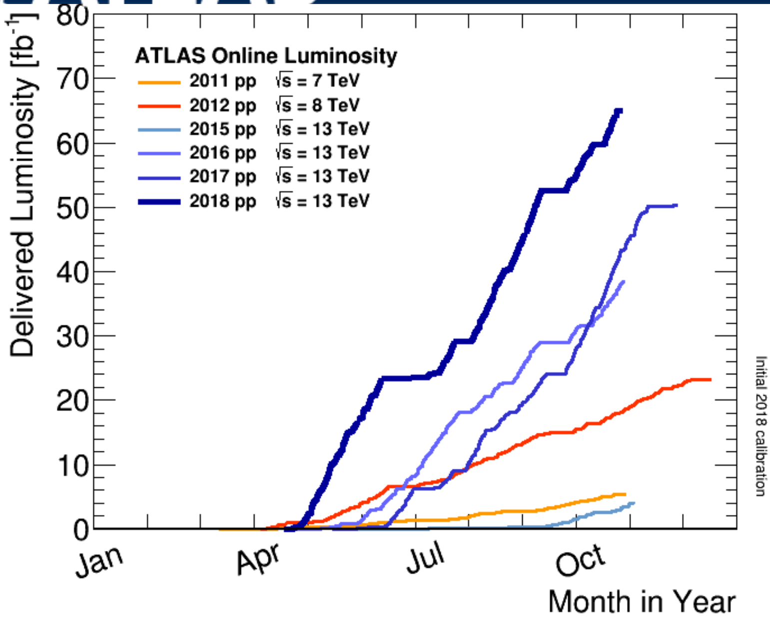
- **Orthogonal** selections
- **Simultaneous fit** of likelihood functions for each search
- Analyses dominated by **different uncertainties**
- **Common resource** for theorists



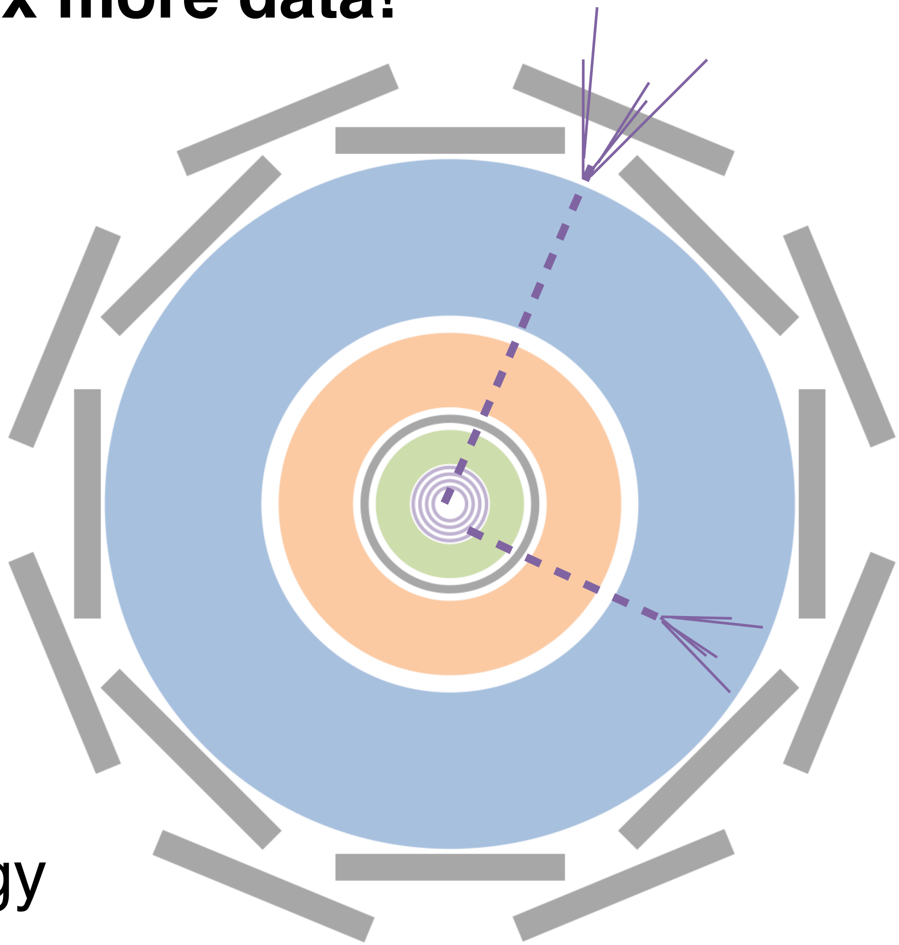


What Next for LLP searches?

What Next ?
Full Run 2 Analysis



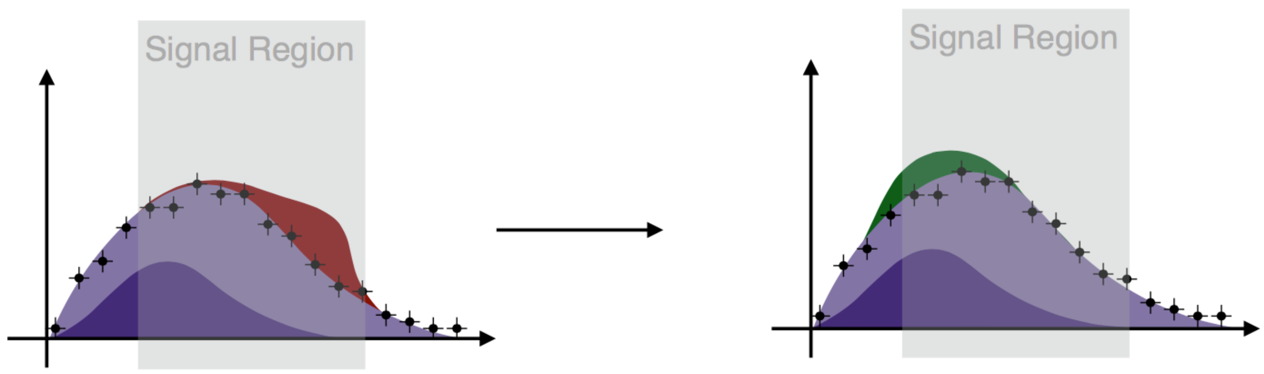
- Full LHC run 2 dataset : **5x more data!**



- Explore **new channels**:
  - ID Vx + CalRatio Jet
  - MS + CalRatio Jet
  - CalRatio Jet + missing energy
- Looking at DNN-based tagger for displaced jets...

What Next ? Re-interpretation

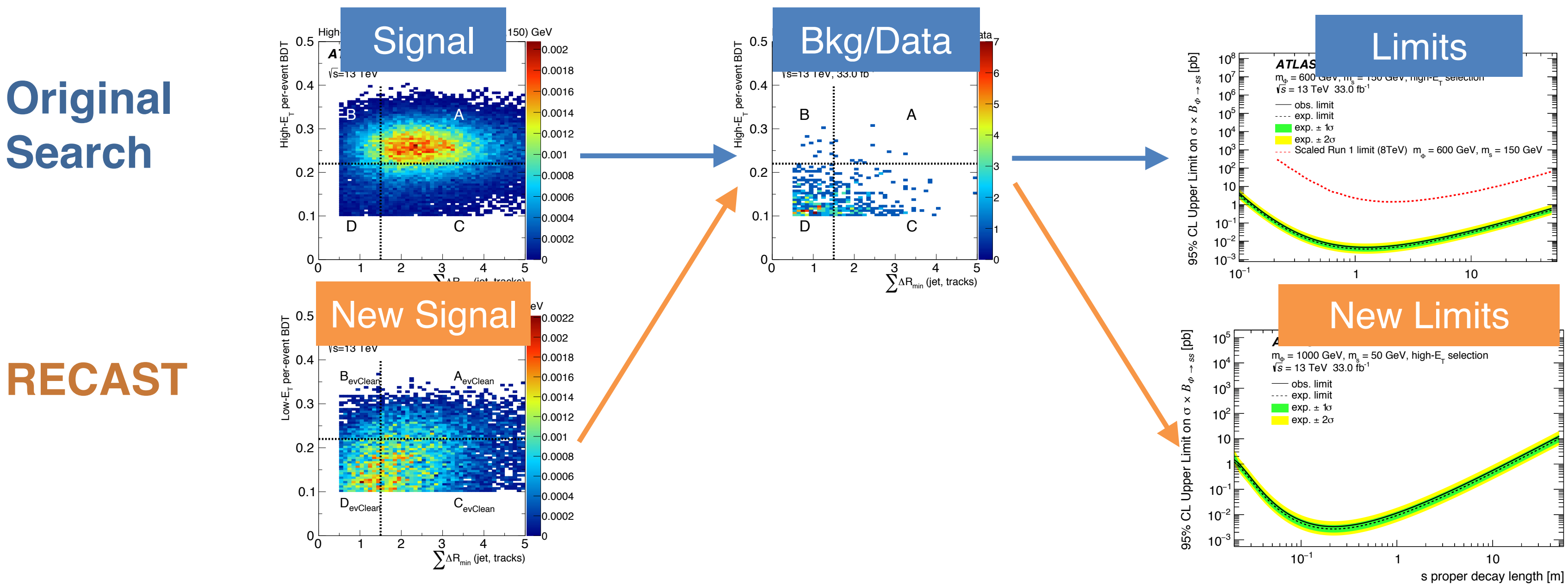
- LHC is a billion-dollar machine :
  → How can we **preserve analyses for the future?**



- **Why**?
  - Duty to the taxpayer 😉
  - Test new models without repeating search
  - Faster feedback to theory community
- **Challenges...** How to get around BDTs, etc?

What Next ? Re-interpretation

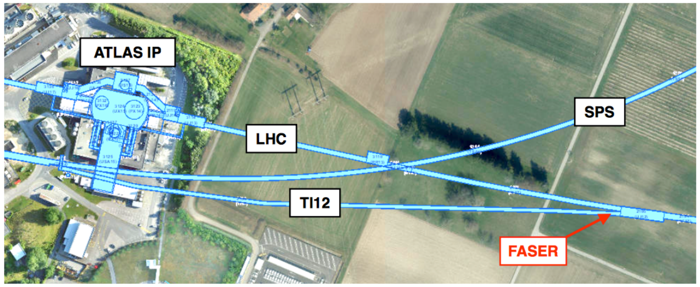
- **How**? Searches with Non-SM bkg (eg CalRatio jets): use eg RECAST https://arxiv.org/abs/1010.2506

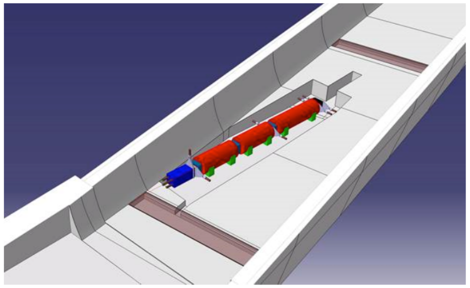


- Preserve + automate entire workflow in Docker
- Theorists may request new signals to be propagated
- Upcoming note: CalRatio search as proof of concept

Longer-term Searches for LLPs

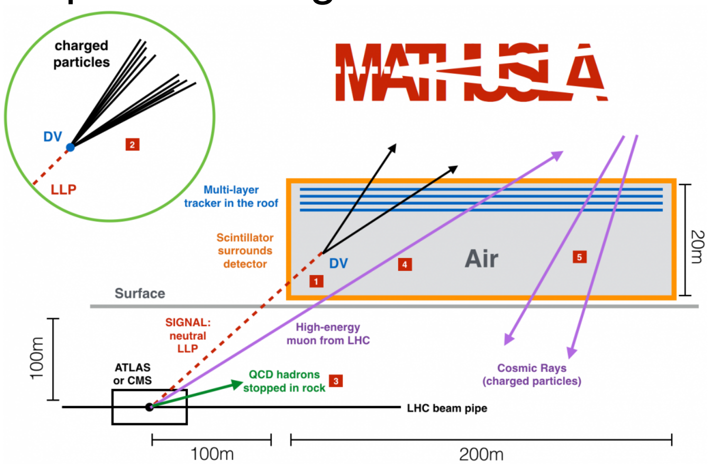
https://arxiv.org/abs/1901.04040



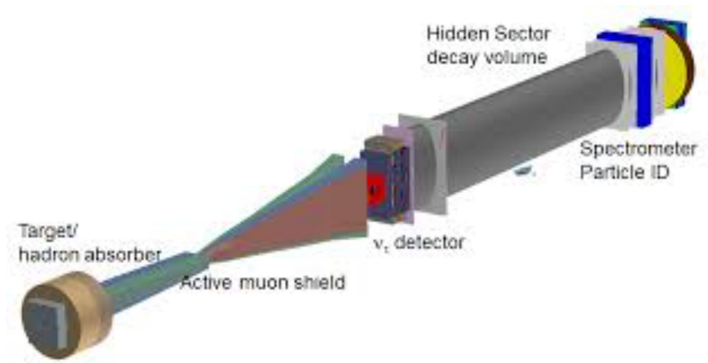


https://arxiv.org/abs/1810.06733

https://arxiv.org/abs/1901.04468



SHiP
Search for Hidden Particles

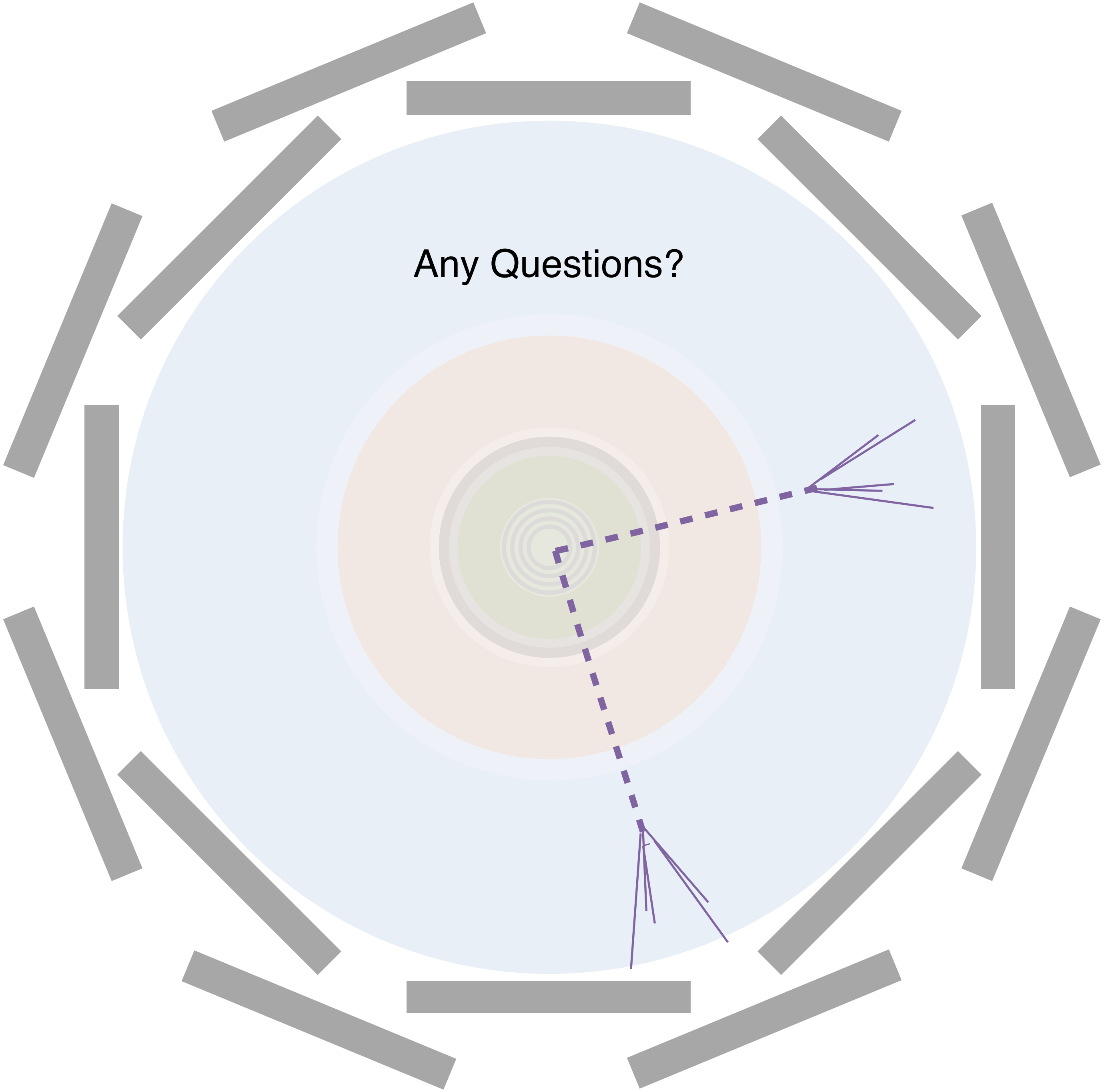


https://arxiv.org/abs/1710.03277

Summary

- Long-lived particles and DM occur in many BSM models...
- ... but could be in the blind spot for LHC experiments!
- LLP community: plug gap with signature-driven searches
  → Showed CalRatio jets example
- No sign of LLPs yet... but programme very active
  - Recently-published LLP community white paper details current efforts and promising avenues https://arxiv.org/abs/1903.04497
  - → stay tuned!
- In meantime, focus on demonstrating re-interpretation of signature-driven searches for DM and LLPs

Any Questions?



Backup

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CMS vs ATLAS sensitivity

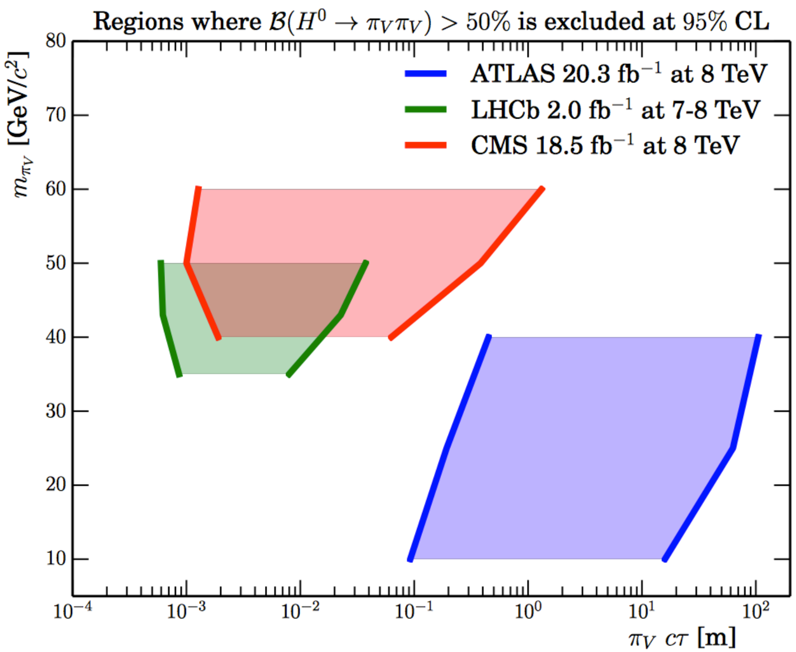
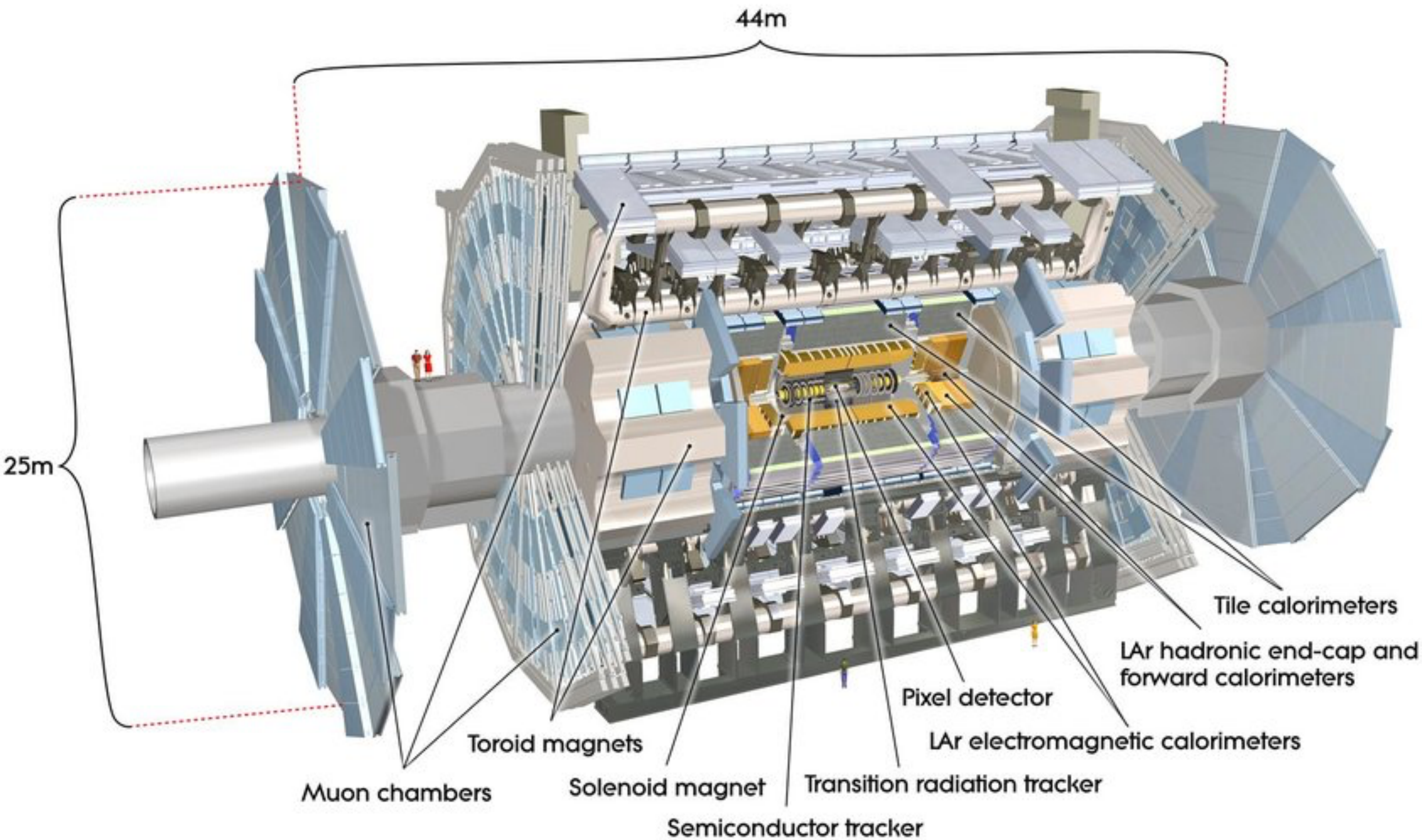


Figure 3.1: Comparison of the ATLAS [189], CMS [244] and LHCb [246] reaches for dark pions π_V decaying into jets. The CMS result is taken from the recast done in reference [253] of the 8 TeV analysis [244]. In the shaded regions $B(H \to \pi_v \pi_v)$ is constrained to be below 50%. Note that the ATLAS reach extends to higher masses as well; the plot was produced using the benchmark scenarios presented in [189], hence the meaningful bound is on the lifetimes. Taken from Ref. [246].

https://arxiv.org/abs/1903.04497

ATLAS Overview



Signal Samples

- We consider a range of different options for the mass of the mediator
    - From Higgs-like...
    - ... to 1 TeV!
- And masses of the LLPs
- For each hypothesis, we have two samples with different lifetimes:
    - One for training BDTs, systematic and cross-checks
    - the other for evaluating analysis efficiency

Statistically independent!

m_Φ [GeV]	m_s [GeV]	LF=5 m $c\tau$ [m]	LF=5 m Events	LF=9 m $c\tau$ [m]	LF=9 m Events
low mass samples					
125	5	0.127	400k	0.229	200k
	8	0.200	400k	0.375	200k
	15	0.580	400k	0.715	200k
	25	0.760	400k	1.210	200k
	40	1.180	400k	1.900	200k
	55	1.540	400k	2.730	200k
200	8	0.170	400k	0.290	200k
	25	0.540	400k	0.950	200k
	50	1.070	400k	1.900	200k
high mass samples					
400	50	0.700	400k	1.260	200k
	100	1.460	400k	2.640	200k
600	50	0.520	400k	0.960	200k
	150	1.720	400k	3.140	200k
1000	50	0.380	400k	0.670	200k
	150	1.170	400k	2.110	200k
	400	3.960	400k	7.200	200k

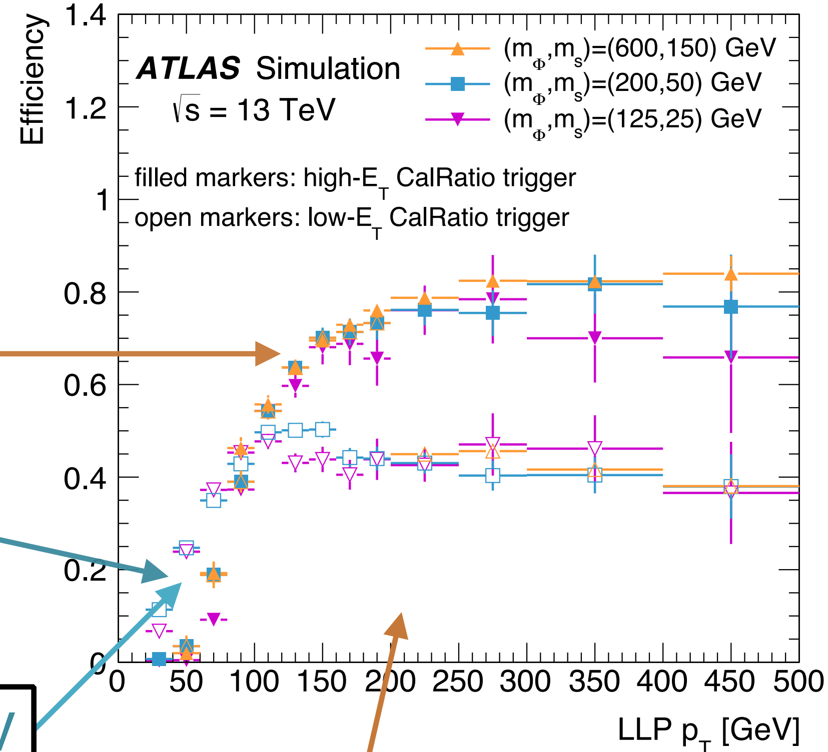
Used analysis efficiency/limits, and for BDT testing

Used mainly for BDT training and systematics

Two analysis streams

High-E_T Trigger
turns on much later than
Low-E_T Trigger

too complicated?



- Low-m_Φ models peak ~ 60-100 GeV
  high-ET trigger would kill signal!

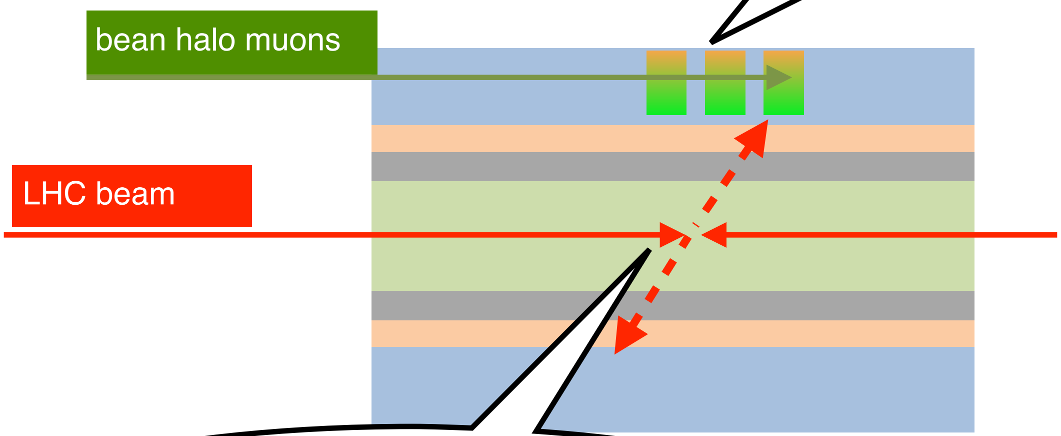
- High-m_Φ models peak > 150 GeV

- **Low-ET Trigger** **for** **$m_\Phi \leq$ 200 GeV**: more sensitive, even with 1/3 data
- Better off with **High-ET Trigger** **for** **$m_\Phi >$ 200 GeV**

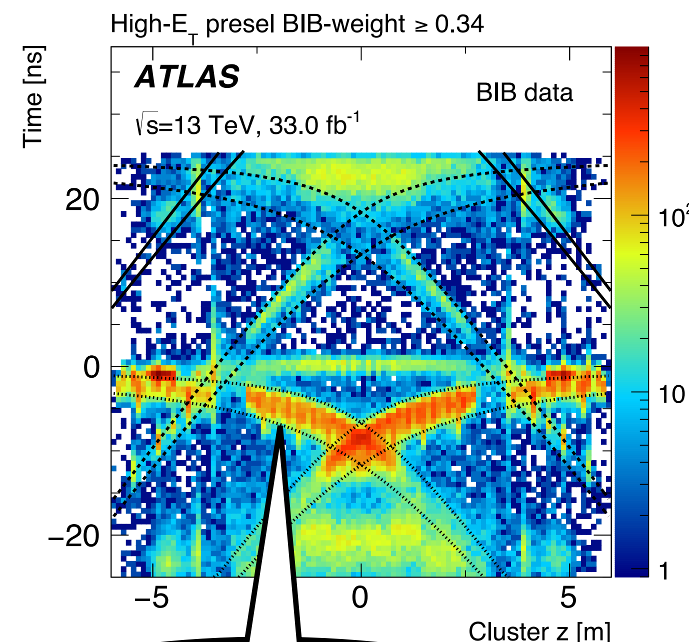
How to trigger LLP events

- Combatting QCD / Pileup at Trigger level:
  - Requiring a high ET threshold or lack of activity in before the HCAL
- Combatting BIB at Trigger level:

BIB deposits tend to be aligned horizontally

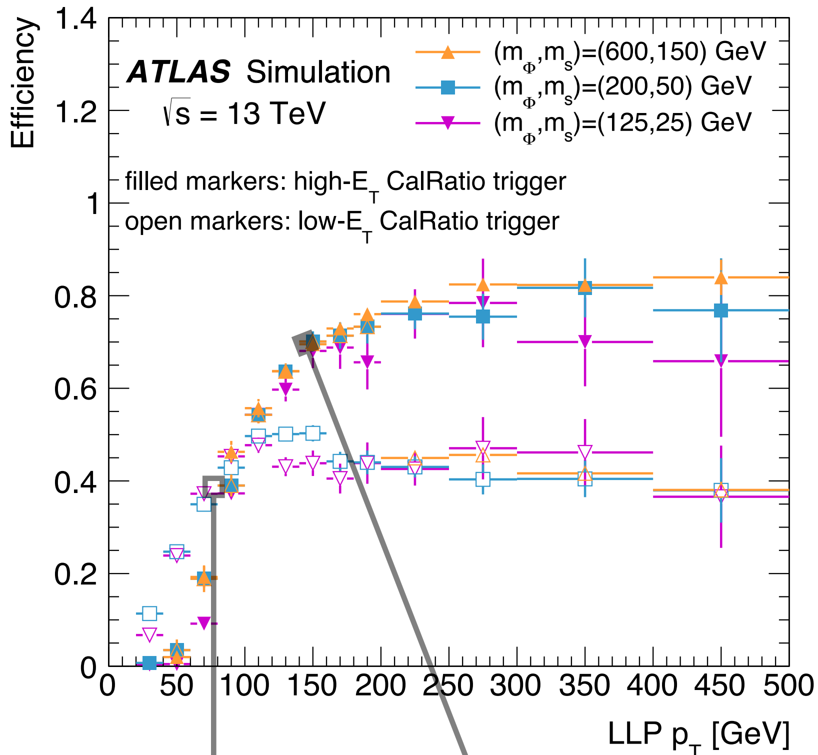


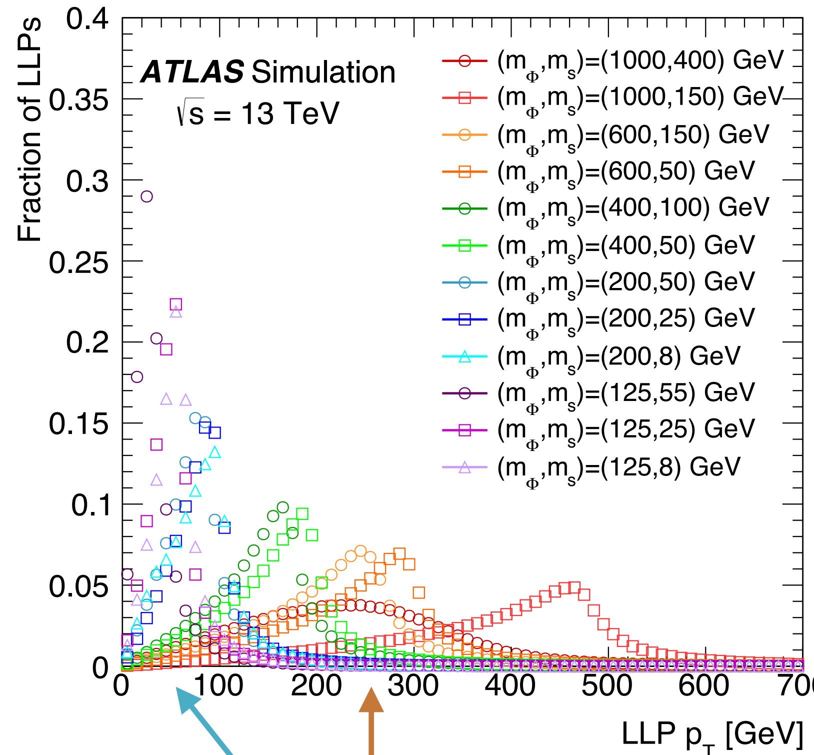
BIB does not need to travel via collision point, so appears 'early' with respect to particles from IP



BIB events have a characteristic distribution in timing vs z.
We call them 'banana plots'

Two analysis streams





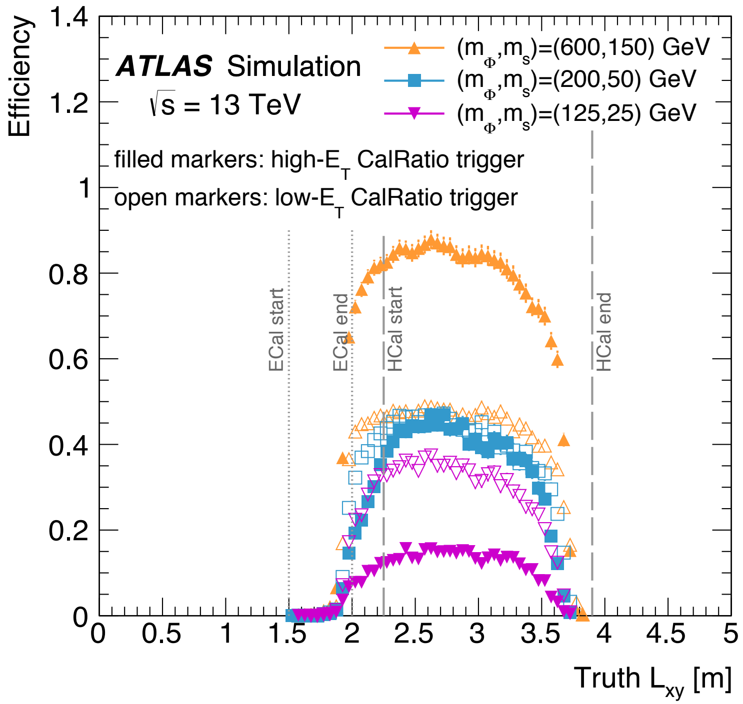
Low-E_T Trigger plateau ~60 GeV

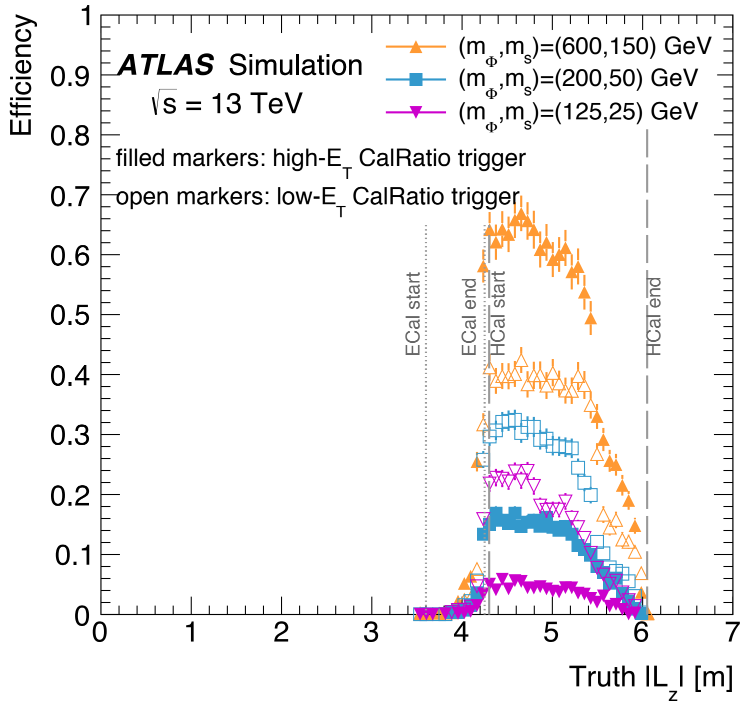
High-E_T Trigger plateau >150 GeV

- Low-m_ϕ models peak ~ 60-100 GeV
- High-$m\phi$ models peak > 150 GeV

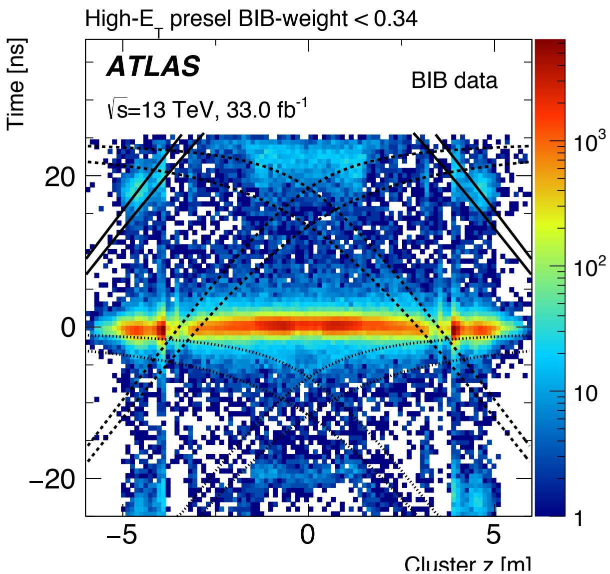
- **Low-ET Trigger for $m_\phi \leq$ 200 GeV**: more sensitive, even with 1/3 data
- **Better off with High-ET Trigger for $m_\phi >$ 200 GeV**

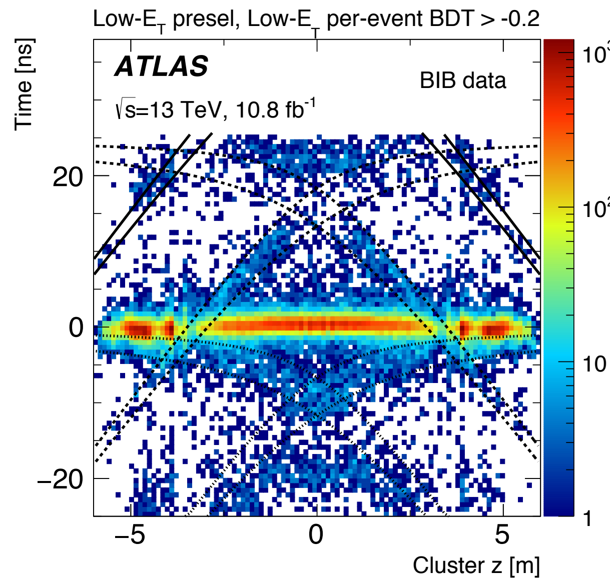
Trigger Plots

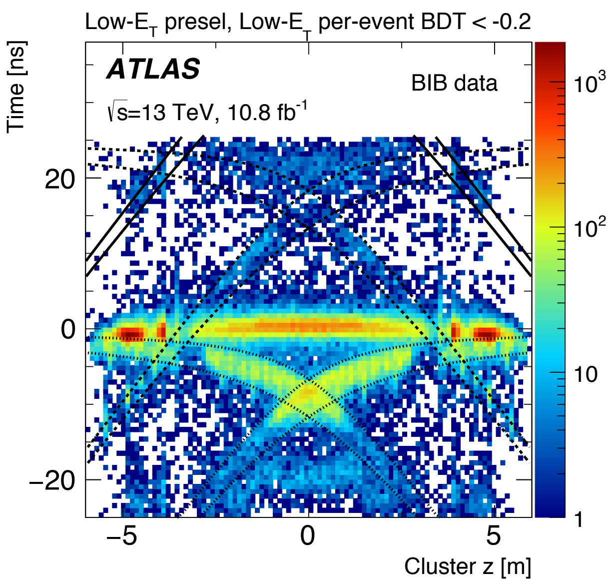


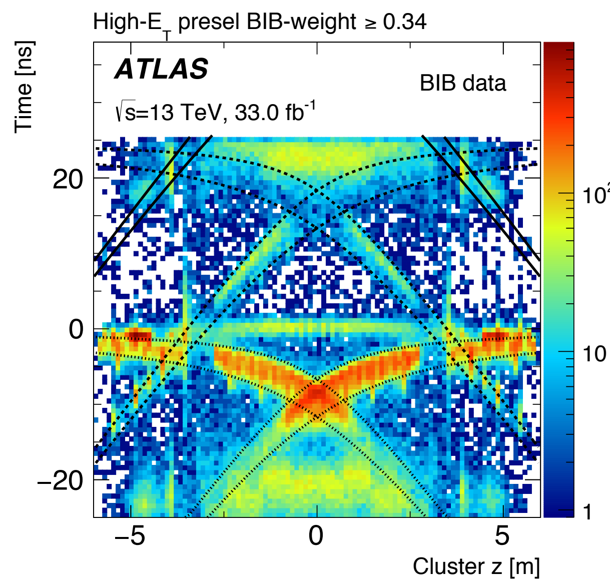


BIB timing plots

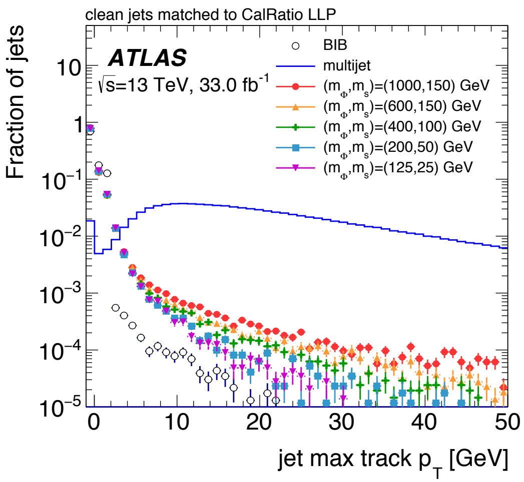


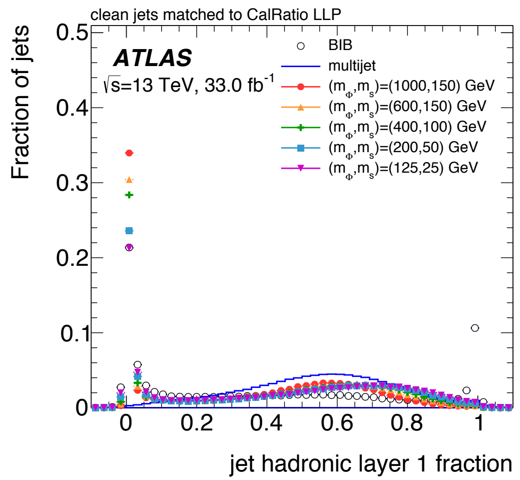


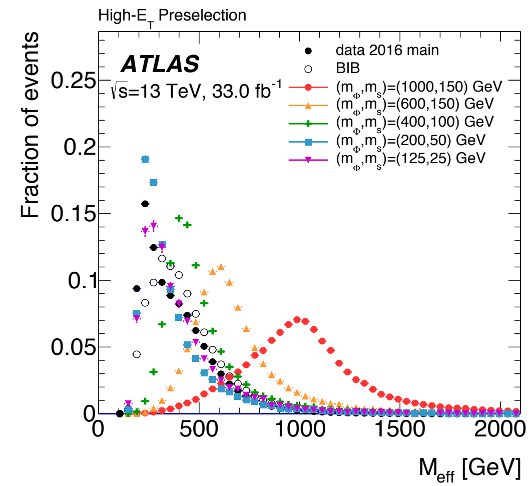


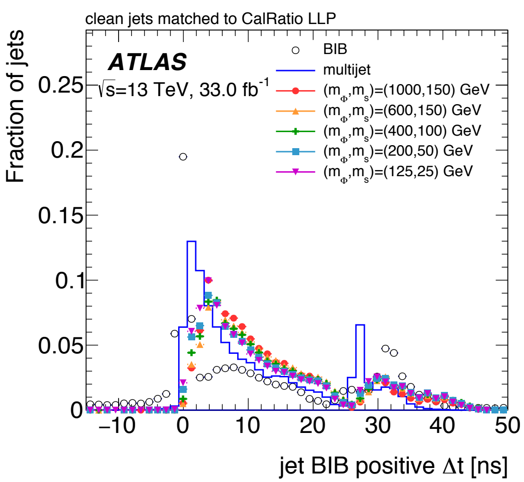


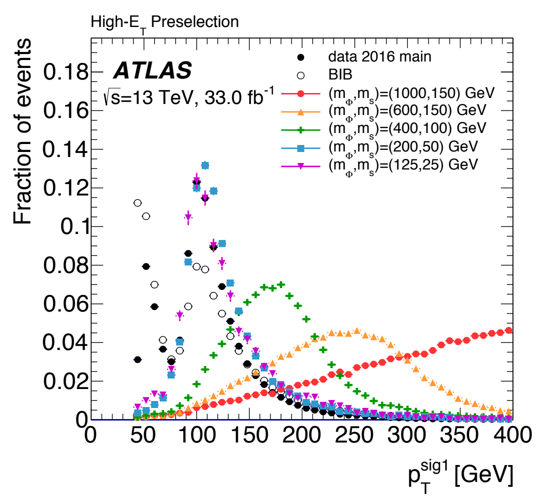
BDT feature examples

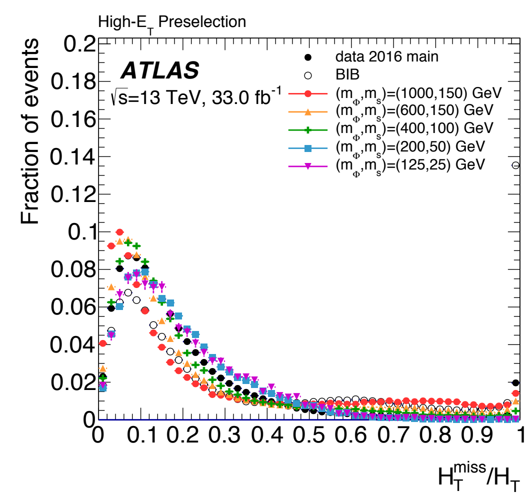








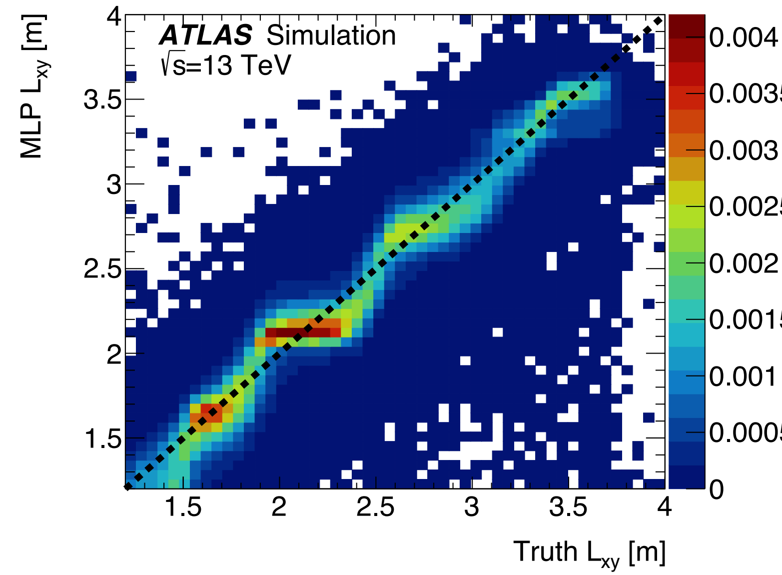




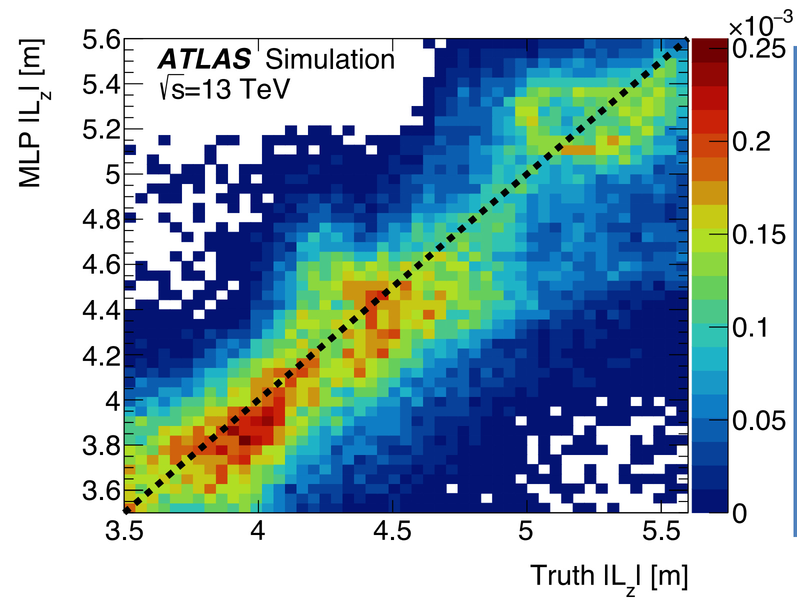
Decay position estimate using machine learning

- Multi-layer Perceptron (MLP) regression
- Objective: estimate LLP decay positions

- Inputs:
  - jet energy in each ECAL+HCAL layer
  - jet η
  - truth LLP decay positions
- Trained on range of signal models to reduce model dependence



Radial Decay Position (Transverse to beam)



Longitudinal Decay Position (// to beam)

MLP inputs

- Signal jets used to train have:
  - ΔR(jet, truthLLP) < 0.2
  - pT > 50 GeV
  - Standard jet cleaning
- ~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 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

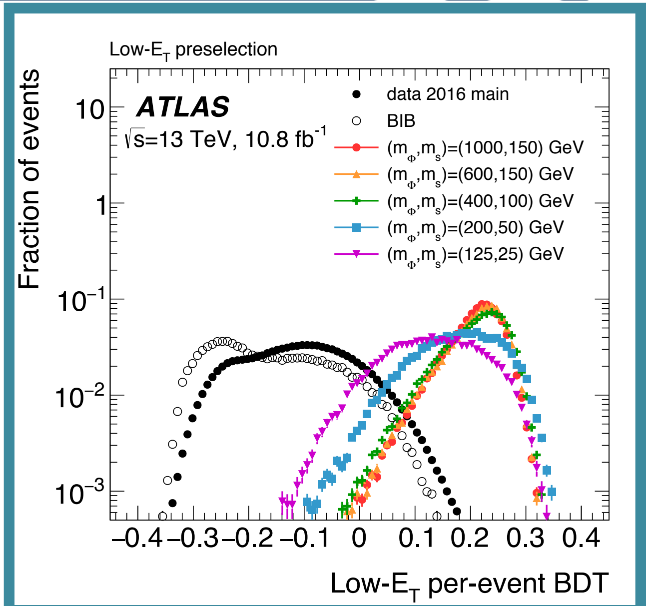
BIB: 2016 noiso data

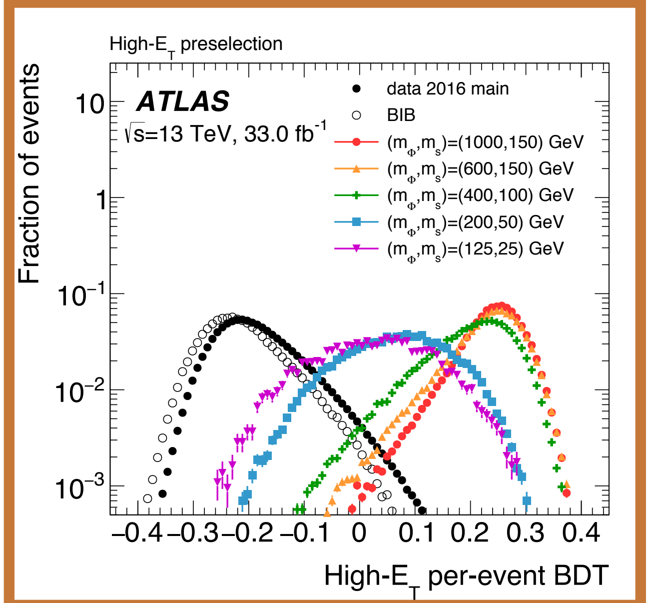
Input variables:

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

- Separate events as: signal-like vs BIB/QCD-like
- Inputs:
  - jet signal- & BIB-weights, pT, timing, cluster info
  - event-level variables eg: H_T/H_T^{miss}, M_{eff}
- Trained on signal vs BIB data
- Separately for High-E_T and low-E_T analyses





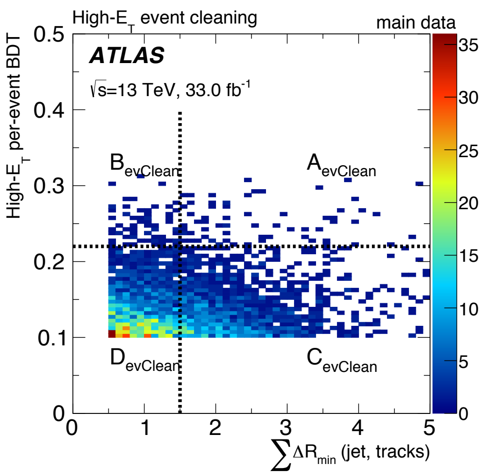
Per-Event BDT inputs

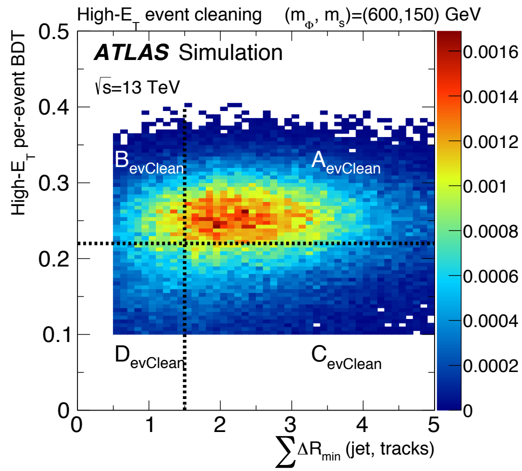
High E_T low, intermediate & high mass signal vs. BIB data

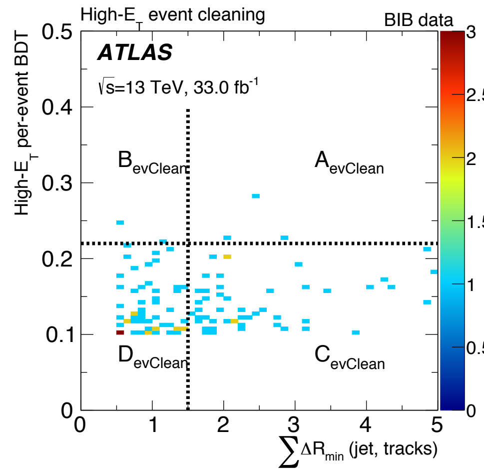
Low E_T: low mass signal passing trigger vs. BIB data

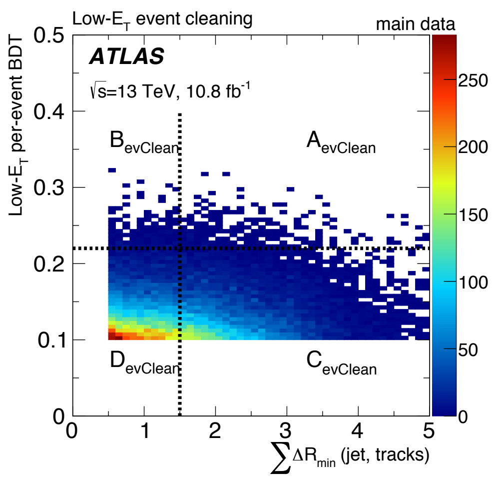
- Input variables:
  - the per-jet BDT signal-weights of the CalRatio jet candidates and of the BIB jet candidates;
  - the per-jet BDT BIB-weights of the CalRatio jet candidates and of the BIB jet candidates;
  - p_T, time and number of clusters of the CalRatio jet candidates;
  - H_T^{miss}/H_T, where H_T is the scalar sum of jet p_T for jets with $p_T > 30$ GeV and $|\eta| < 3.2$ and H_T^{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_T^{miss};
  - $\Delta\phi(\text{jet}^{\text{sig}_1}, \text{jet}^{\text{sig}_2})$ and $\Delta R(\text{jet}^{\text{sig}_1}, \text{jet}^{\text{sig}_2})$, 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

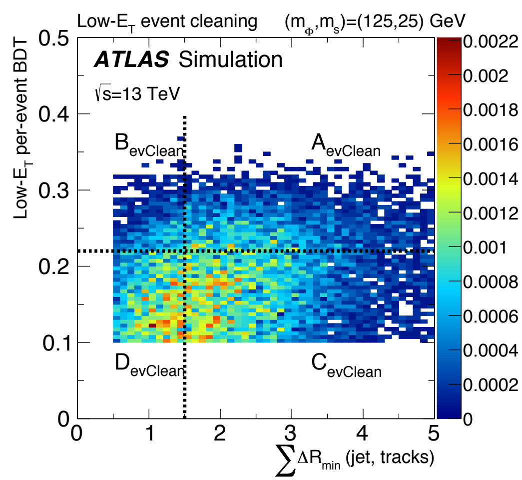
ABCD plots after even cleaning

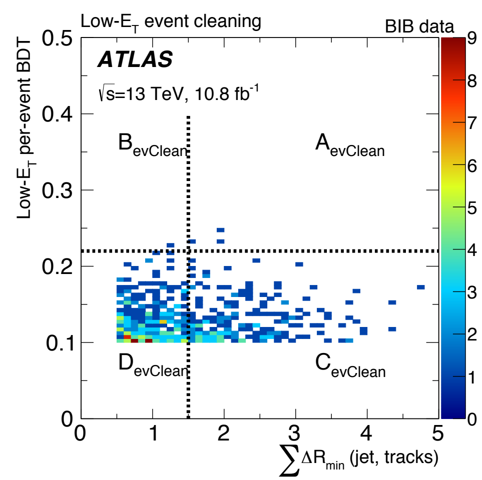












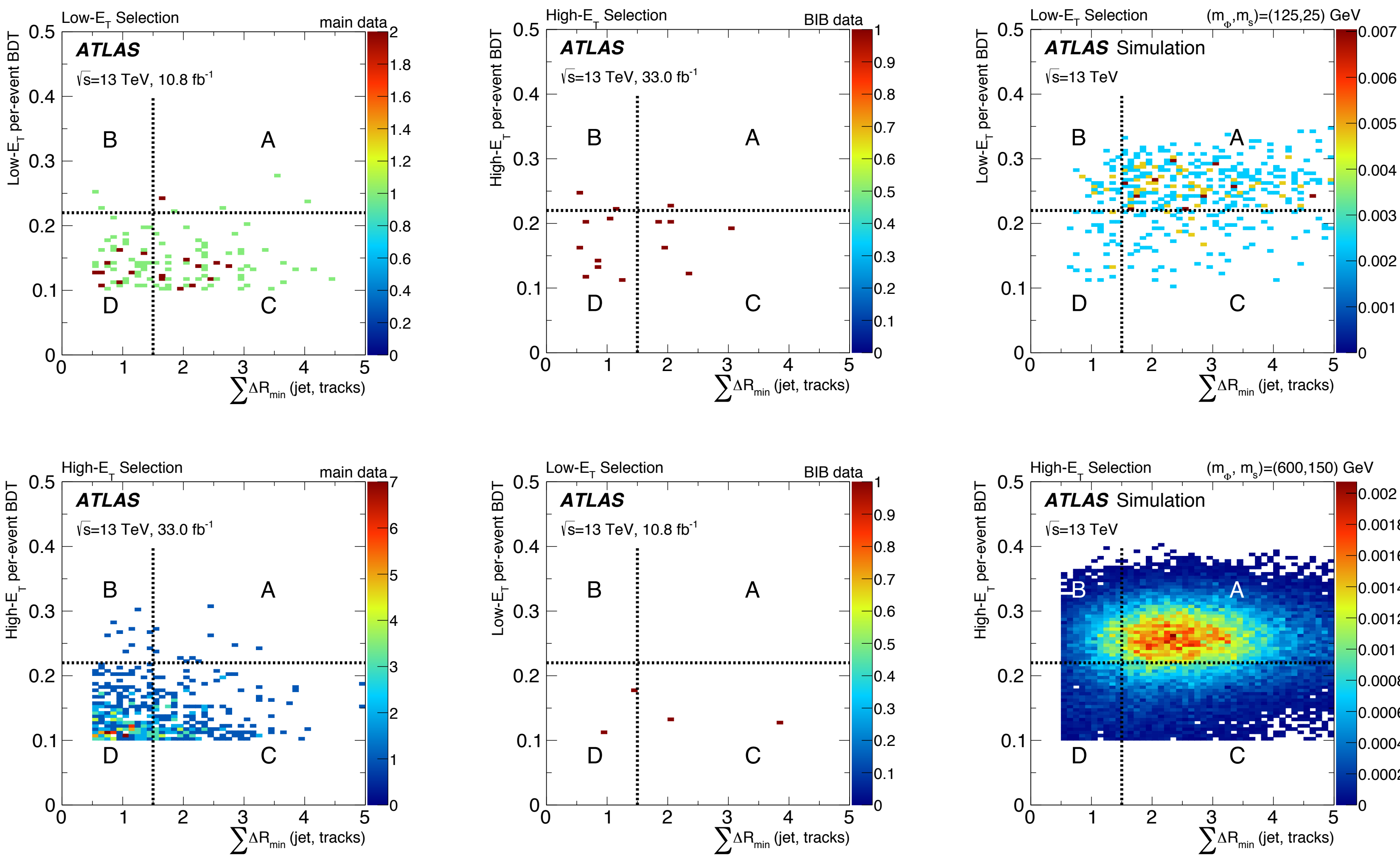
Validation of ABCD Method

Validation selections	Estim. A	A	B	C	D
$\mathrm{VR}_{\text{high-}E_\mathrm{T}}$	66 ± 15	70	64	57	55
$\mathrm{VR}_{\text{low-}E_\mathrm{T}}$	54 ± 17	36	35	34	22

The validity of the ABCD method is tested by applying it to two validation regions (VRs). These are similar to the main selections, but have modified requirements and boundaries for the ABCD plane variables, to ensure orthogonality to the high-E_T and low-E_T selections. The VR for the high-E_T selection ($\mathrm{VR}_{\text{high-}E_\mathrm{T}}$) is defined as the nominal selection except for requiring $100 < p_\mathrm{T}(\mathrm{j}_1) < 160$ GeV and it is evaluated in the ABCD plane defined within 0.1 < high-E_T per-event BDT < 0.22. The VR for the low-E_T selection ($\mathrm{VR}_{\text{low-}E_\mathrm{T}}$) is defined as the nominal selection and it is evaluated in the ABCD plane defined within 0.1 < low-E_T per-event BDT < 0.22.

Main selections	Estim. A (*a priori*)	Estim. A (*a posteriori*)	A	B	C	D
High-E_T selection	$6.7^{+3.2}_{-2.3}$	$8.5^{+2.3}_{-2.0}$	10	9	187	253
Low-E_T selection	$2.5^{+2.5}_{-1.4}$	$5.3^{+2.1}_{-1.6}$	7	2	70	57

The ABCD method



Overview of uncertainties

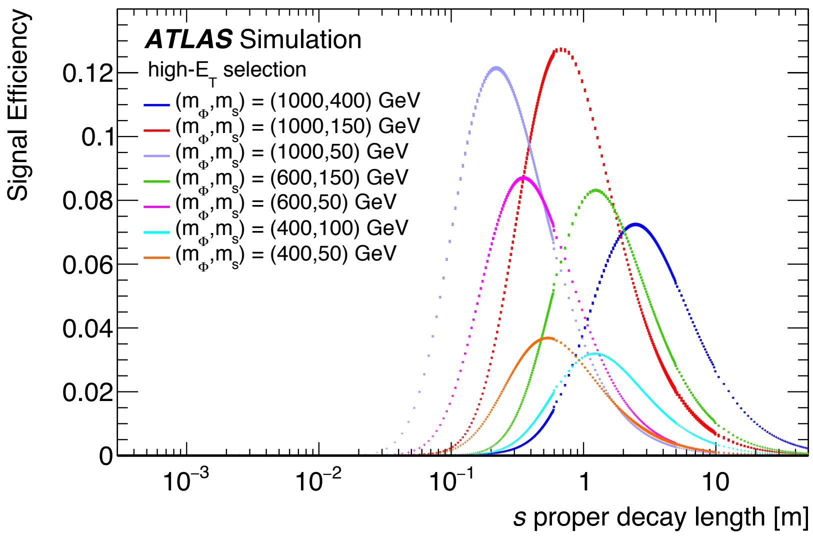
- ABCD method 22% hight-ET plane, 25% low-ET plane
- Jet energy scale and resolution 1 -10 %
    - Since we use non-standrad jets, estimate additional resolution, which is parametrised as a function of EMF in addition to eta. 1 -17 %
- Trigger efficiency estimated from tag-and-probe method using b-triggers. Small, around 2% for all models
- Pileup RW 1-12 %
- PDF uncertainties 8% to 3%
- BDT mis-modelling, around 2%
- Lumi 2%

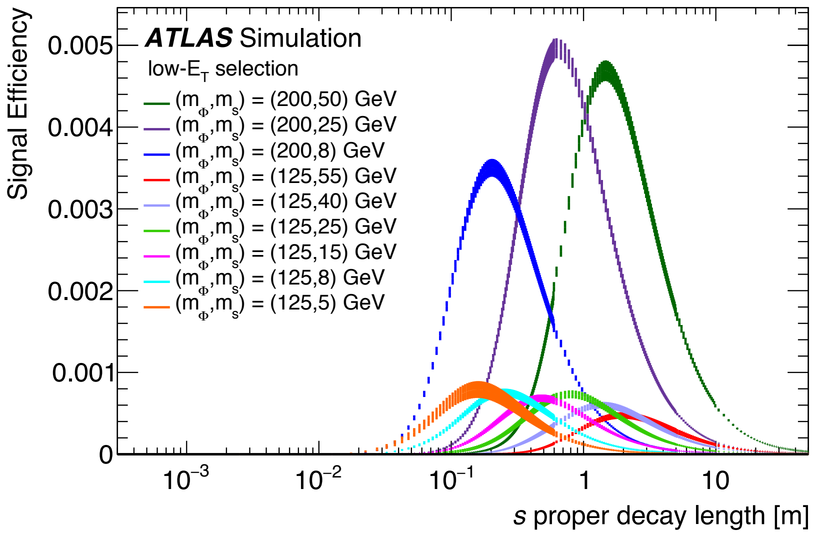
Lifetime Extrapolation

- Signal generated for specific LLP lifetimes τ_{gen}
- Signal efficiency for other lifetimes by reweighing:

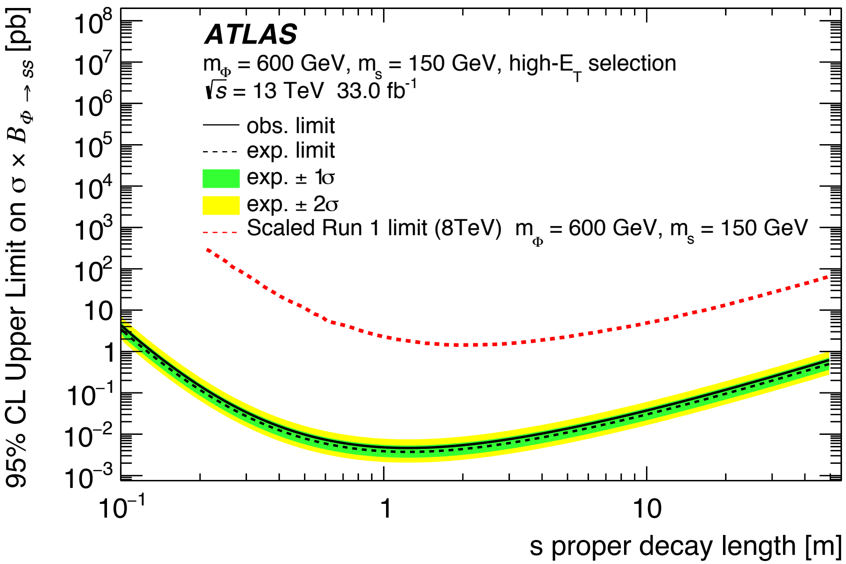
$$w(t) = \frac{\tau_{gen}}{\exp(-t/\tau_{gen})} \cdot \frac{\exp(-t/\tau_{new})}{\tau_{new}}.$$

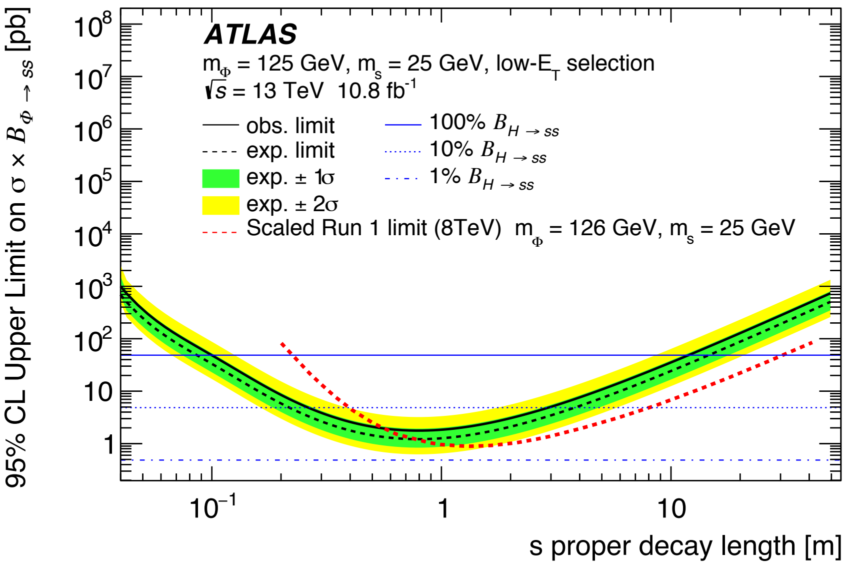
- *w(t)* for each LLP weight per-event to τ_{new}
- Method validated in test samples with alternate lifetimes



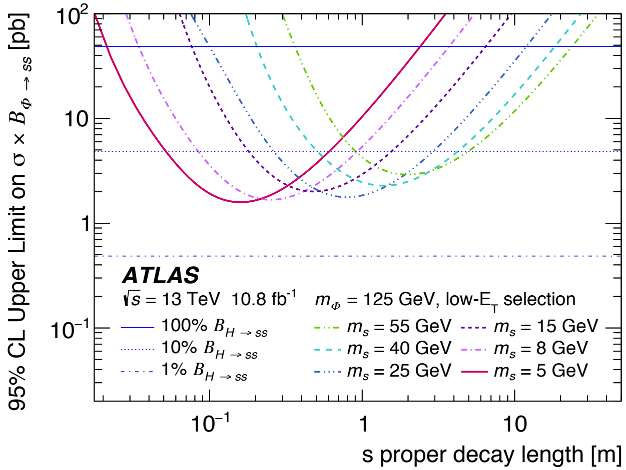


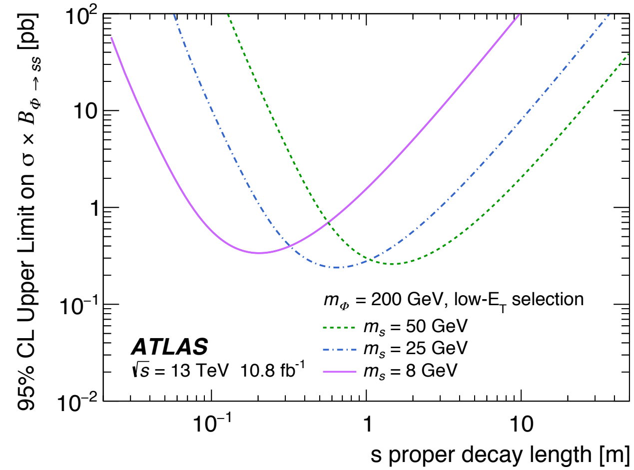
Comparison to Run 1

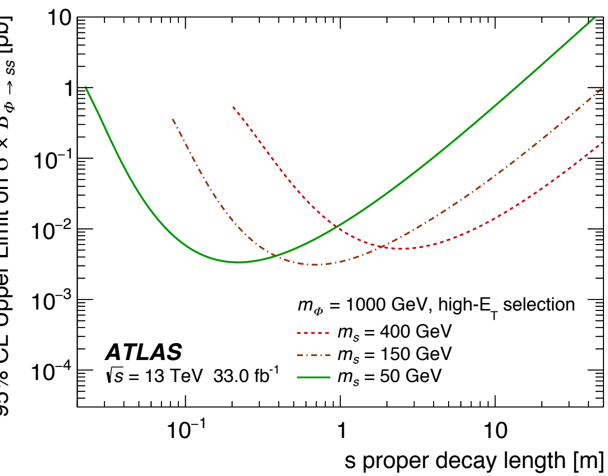


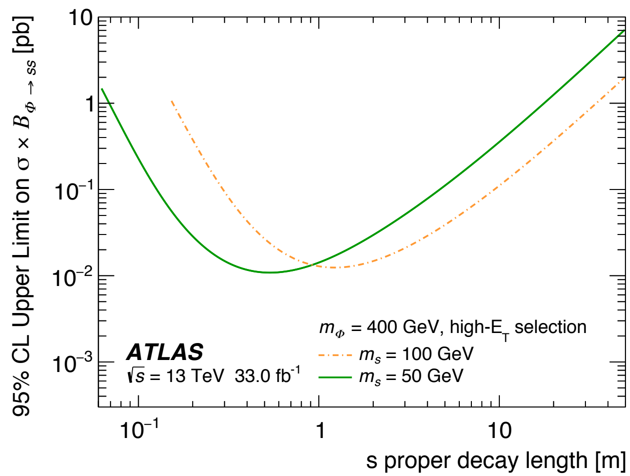


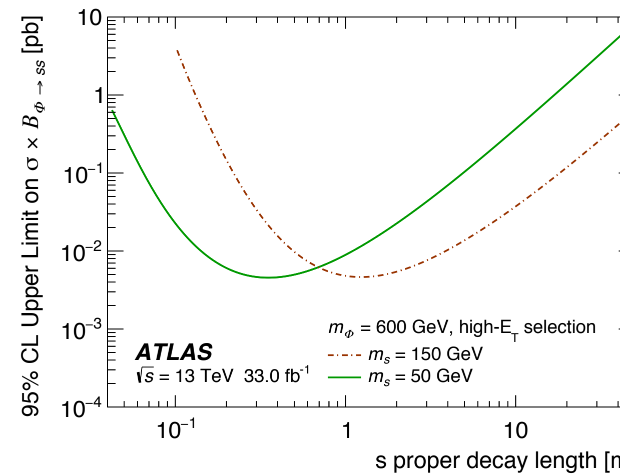
Limit Setting



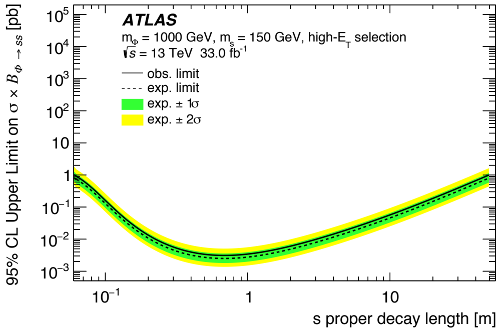


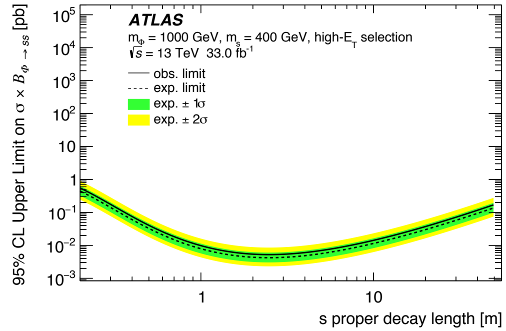


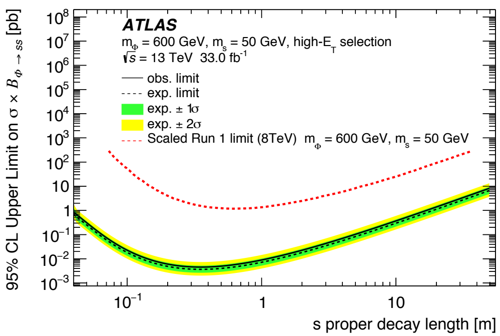


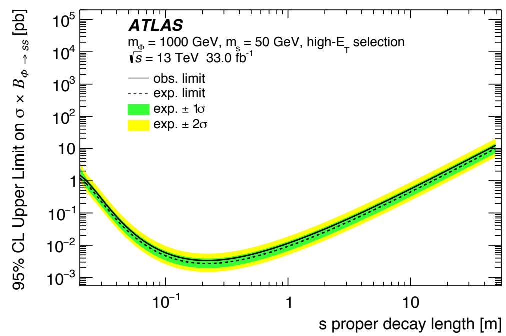


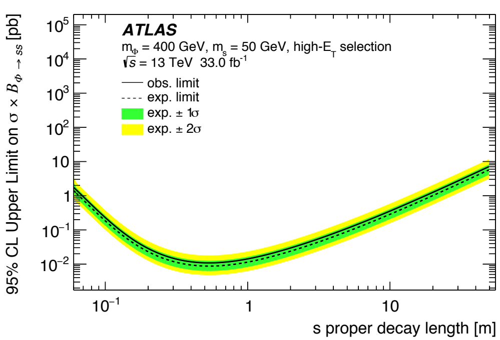
Extra Limit Plots

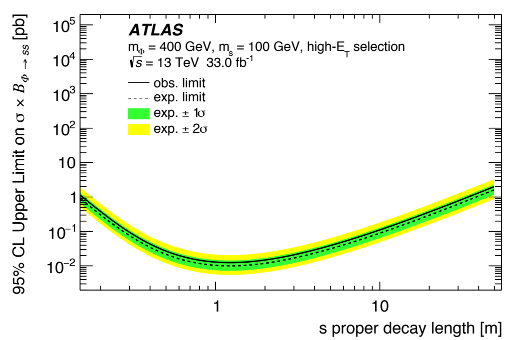




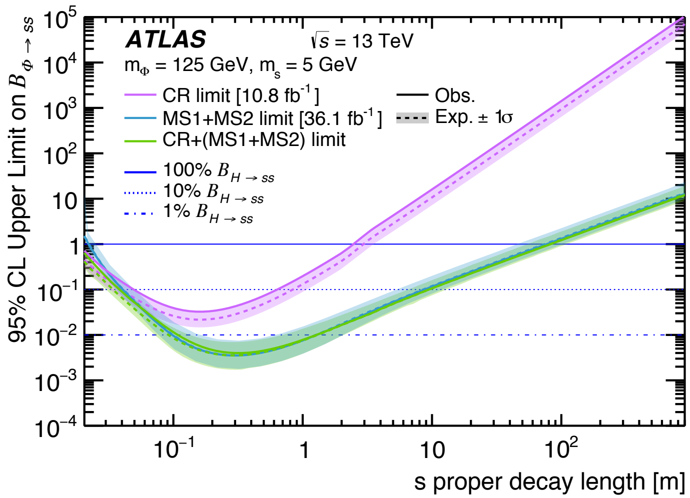


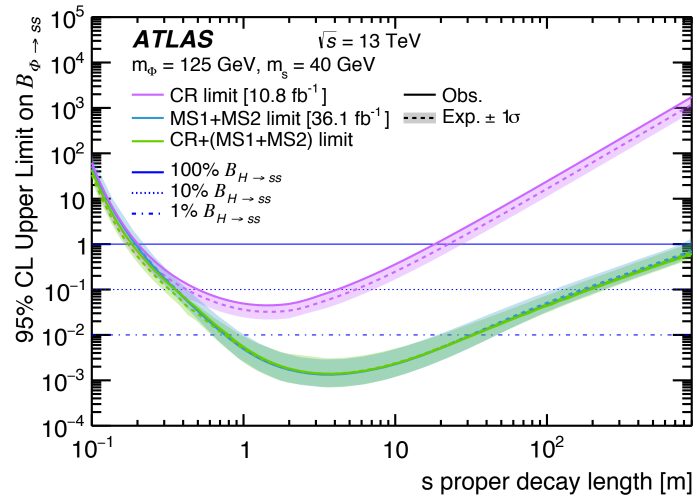


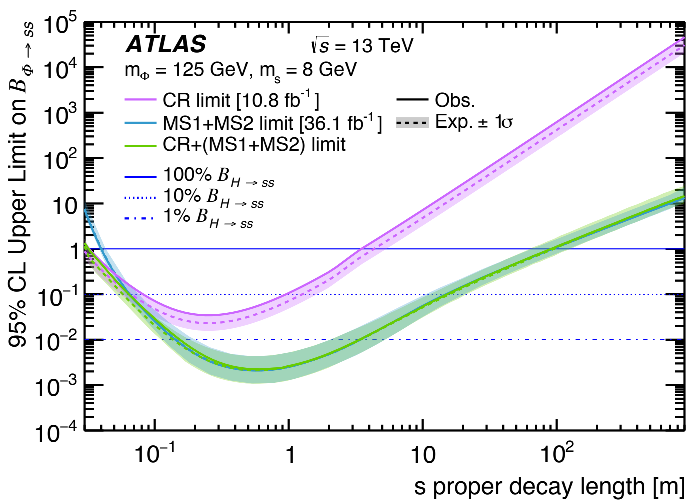


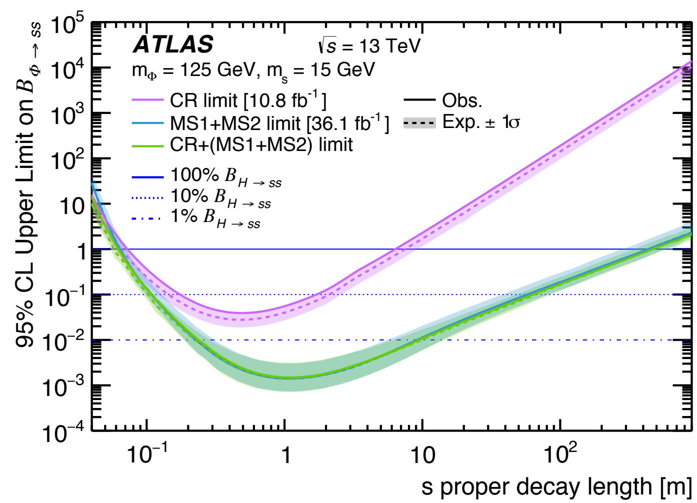


Extra Combination Plots









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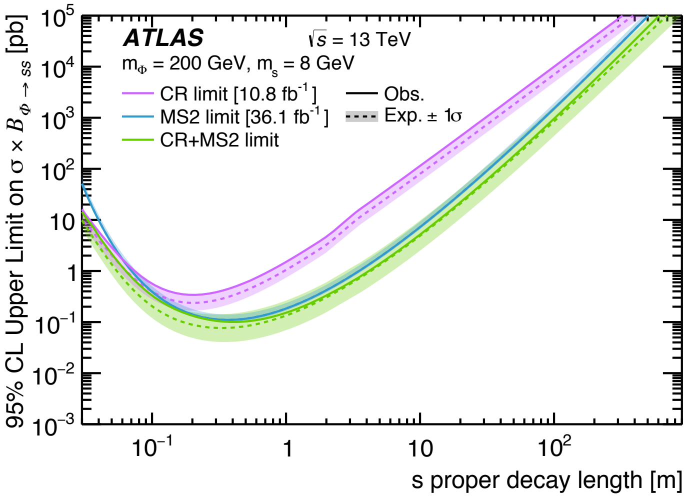

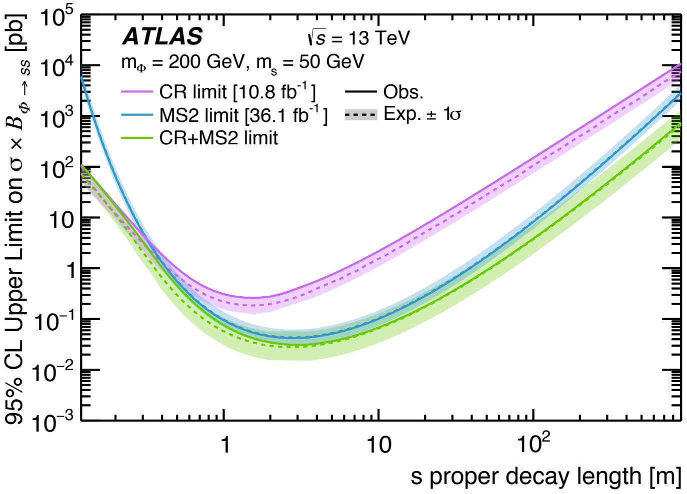

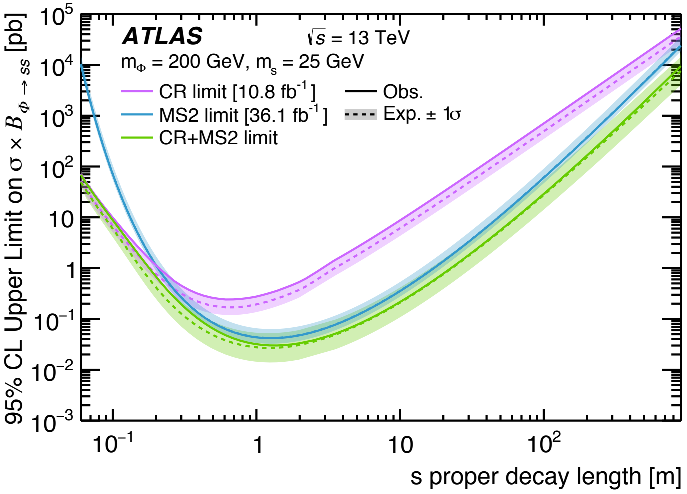

Tracks per Jet in SM jets

https://arxiv.org/pdf/1704.07983.pdf

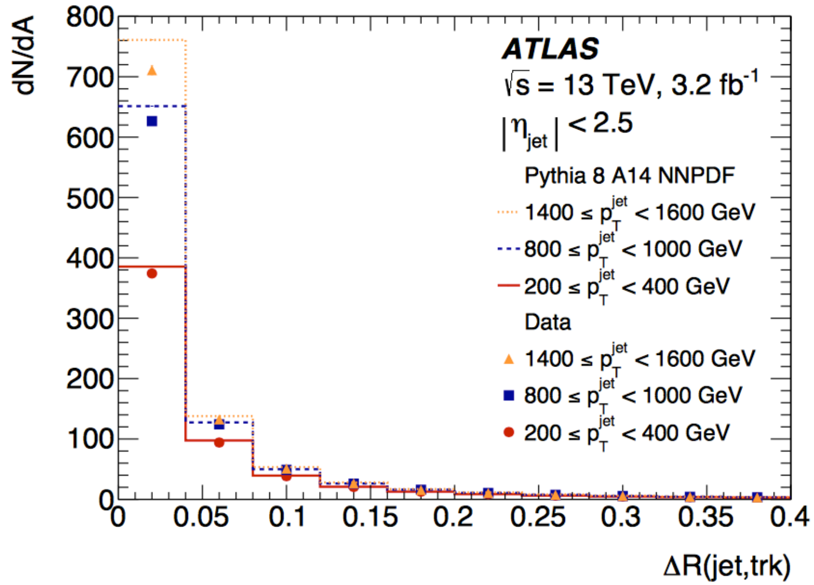

Figure 4: The average number of primary tracks per unit of angular area as a function of the angular distance from the jet axis. Data (markers) and dijet MC (lines) samples are compared in bins of jet p_T showing the high density in the cores of energetic jets.

SM Jet rate

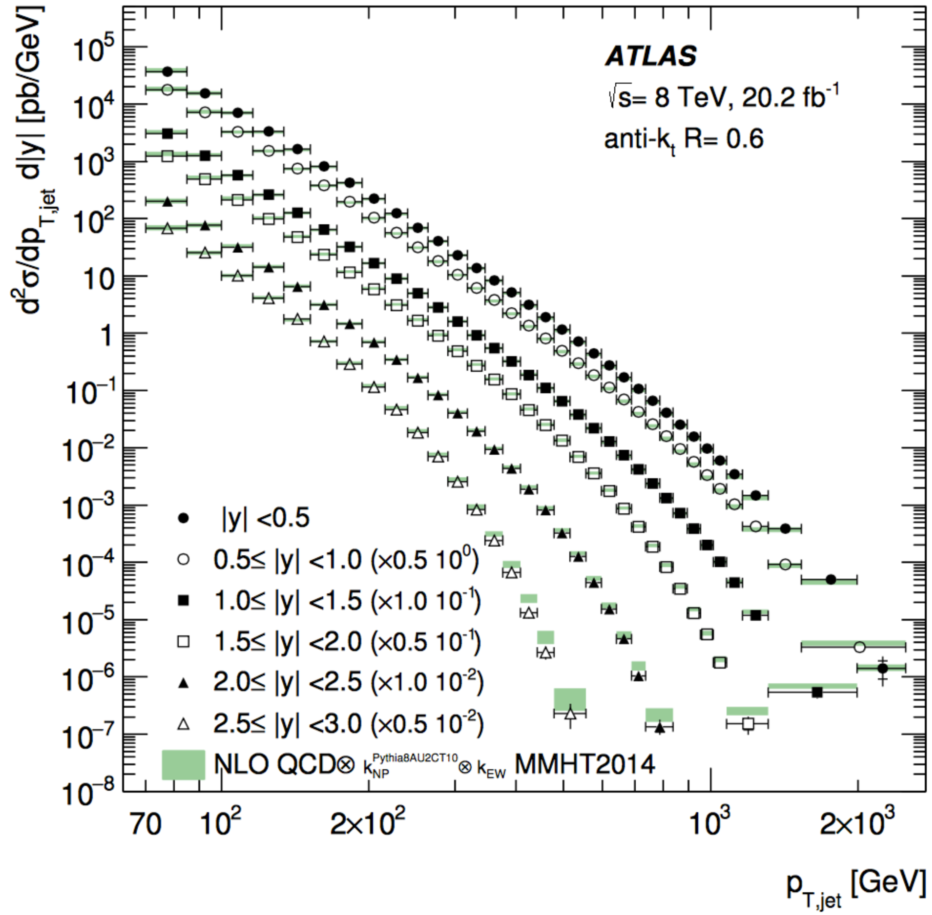

Figure 6: Inclusive jet cross-section as a function of jet p_T in bins of jet rapidity. The results are shown for jets identified using the anti-k_t algorithm with $R = 0.6$. For better visibility the cross-sections are multiplied by the factors indicated in the legend. The data are compared to the NLO QCD prediction with the MMHT2014 PDF set corrected for non-perturbative and electroweak effects. The error bars indicate the statistical uncertainty and the systematic uncertainty in the measurement added in quadrature. The statistical uncertainty is shown separately by the inner vertical line.