Heavy Flavor and Dark Matter Unit Joint Symposium, Nagoya, March 29-30, 2023

Barrel muon trigger upgrade and Long Lived Particle searches at ATLAS

Massimo Corradi (INFN Roma-I)

INFN
Istituto Nazionale
di Fisica Nucleare

Phase-2 ATLAS Upgrade Challenges

- HL-LHC $L=7.5\times10^{34}\ cm^{-2}s^{-1}$: 7.5 times original ATLAS design => harsh conditions with pileup up to 200 inelastic collisions per bunch crossing

- $\int L = 4000\ fb^{-1}$: 4 times original ATLAS design

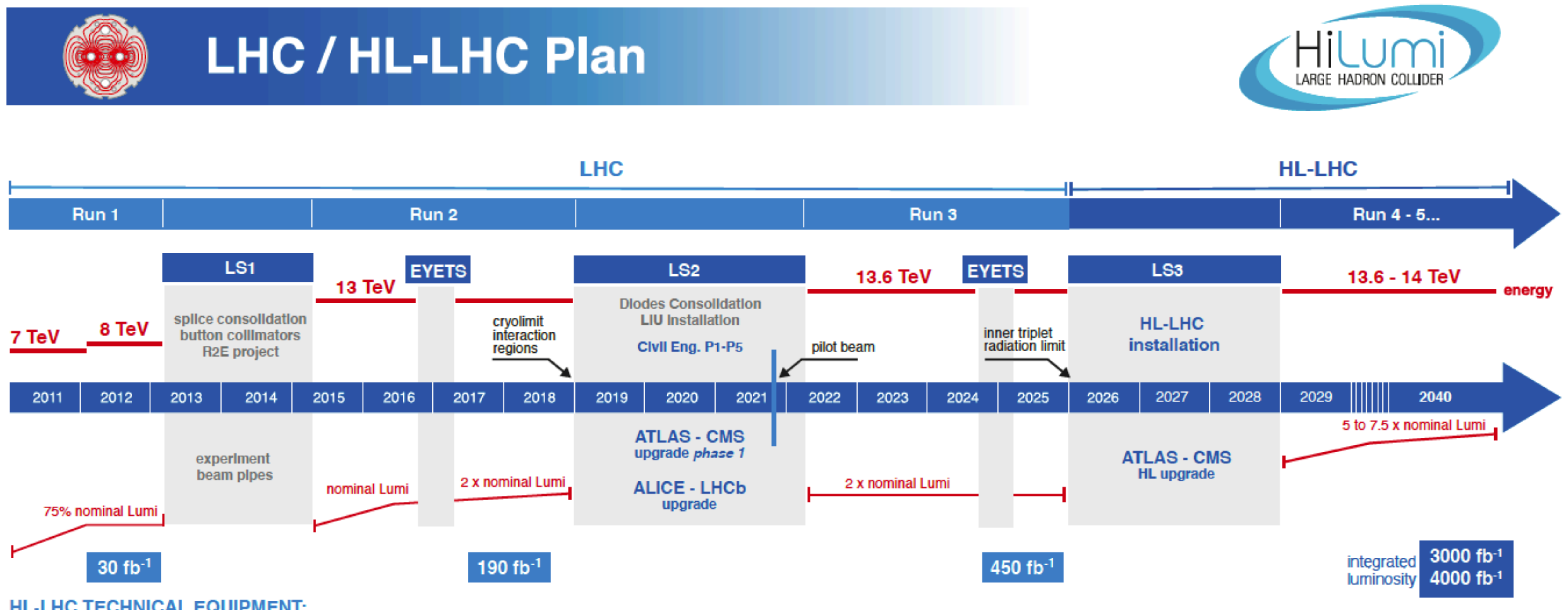
  => Radiation ageing of detectors !

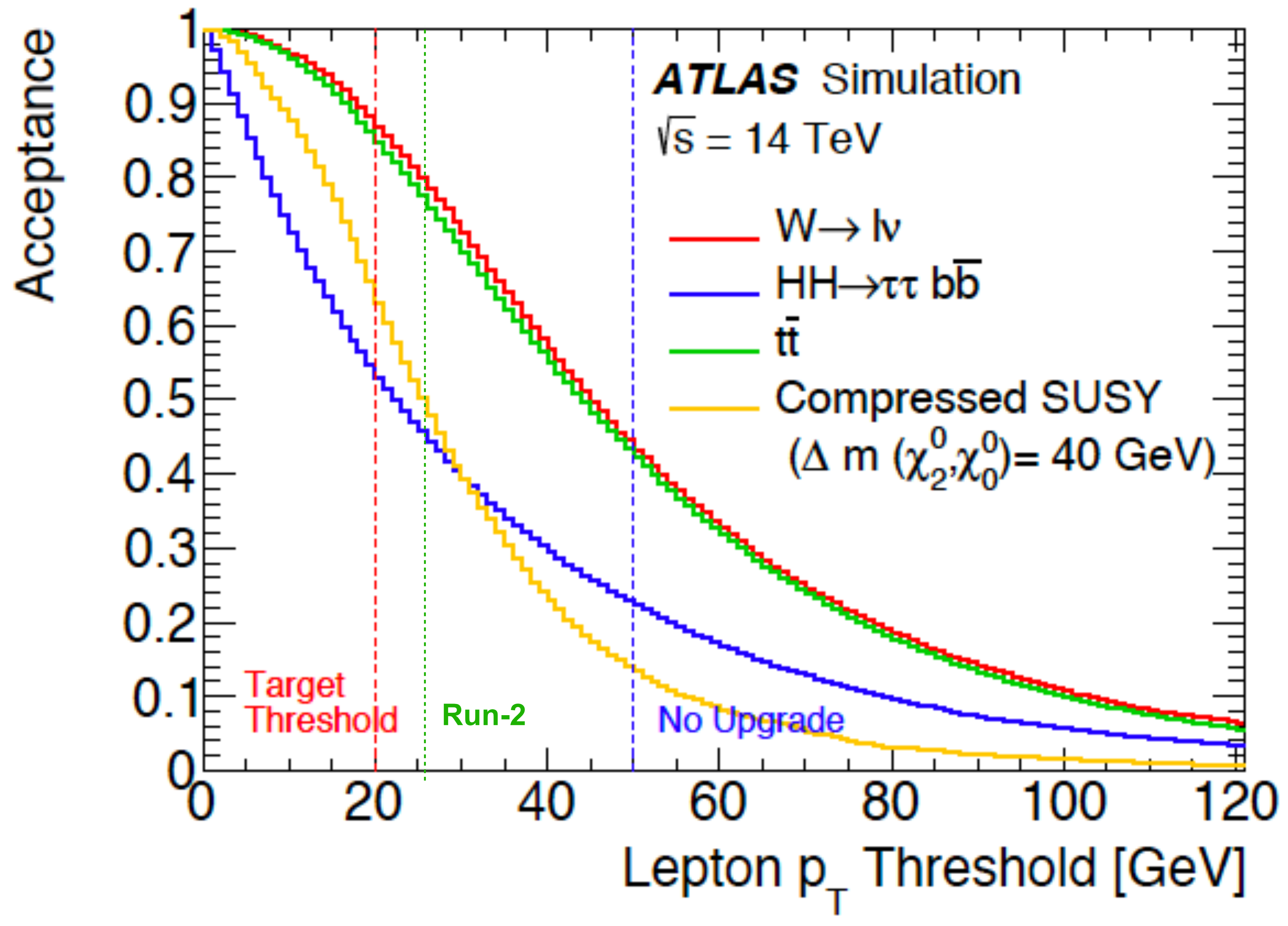
- Experiment lifetime extended from 10 to approximately 30 years:
  => Keep technologies up to date
  => Robustness and maintenance

- Trigger challenges :

  Keep lepton p_T thresholds low without increasing rates too much is crucial to exploit the high luminosity potential

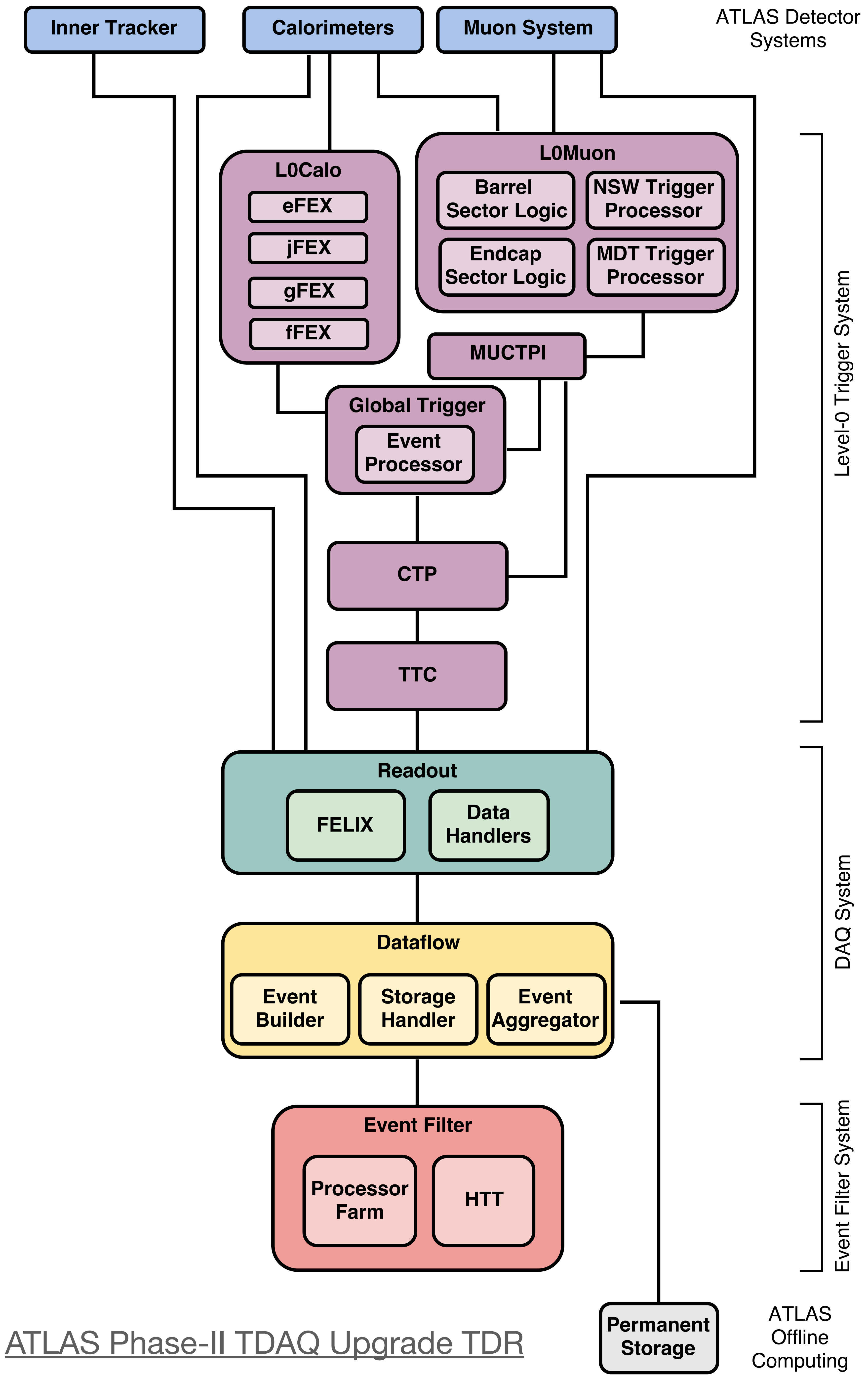
  Add bandwidth for multi-jet at relatively low-E_T for di-Higgs searches and other signatures





The ATLAS Trigger and DAQ schema for HL-LHC

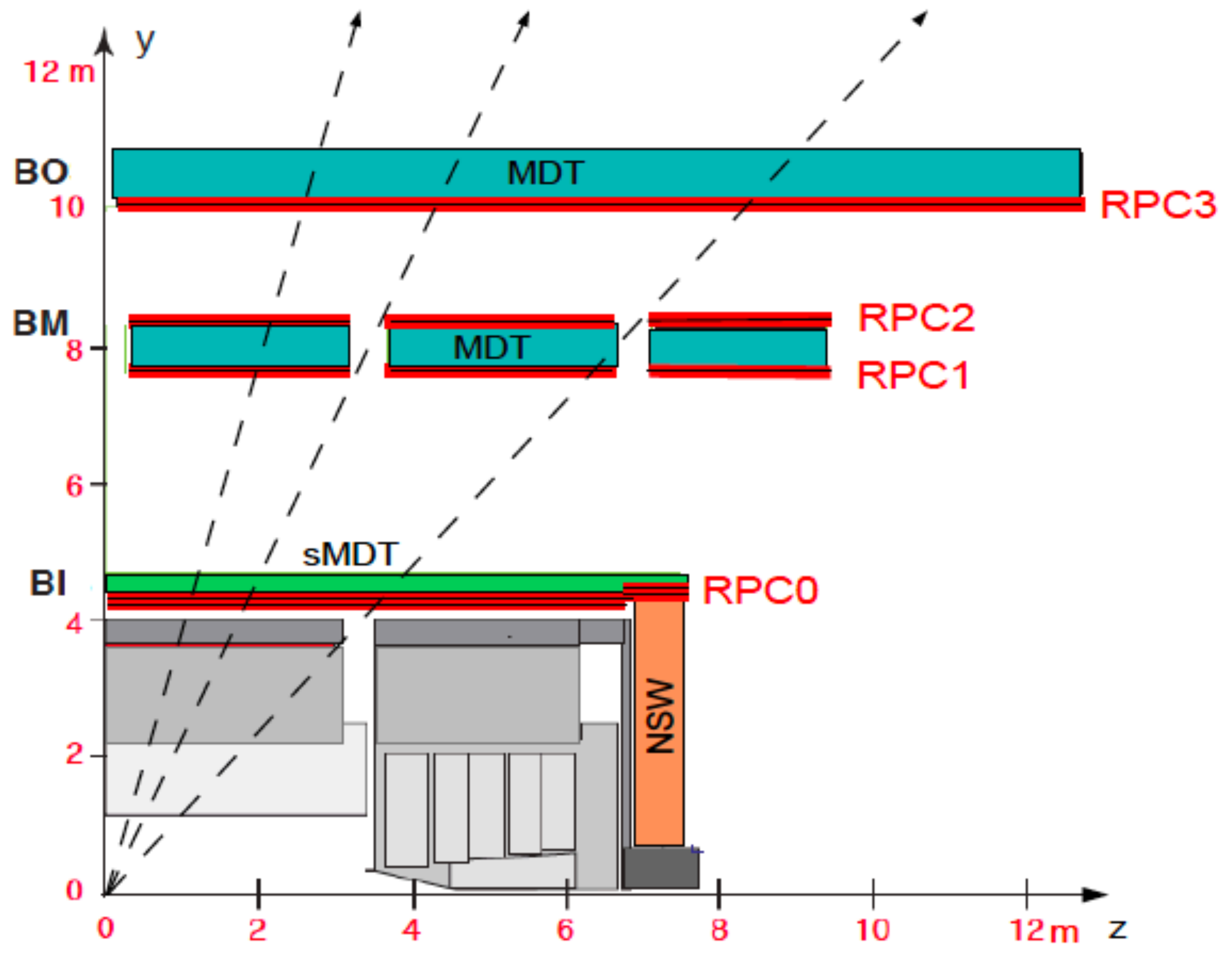
- Single level Level-0 hardware trigger with an output rate of 1 MHz, Level-0 readout latency is 10 μs
- Calorimeters and muons front-end full granularity readout at 40 MHz
- New Global Event processor replaces the current L1Topo and integrates topological functions with additional selection algorithms using information from muons and calorimeters
- Readout based on FELIX system for all detectors
- FPGA-based boards off-detector, on-detector where possible
- Possible hardware accelerator system for tracking at the Event Filter
- Goal of better e, γ, τ, jet identification and measurement, at hardware and software trigger levels and offline
- Event Filter output increases from 1 to 10 kHz

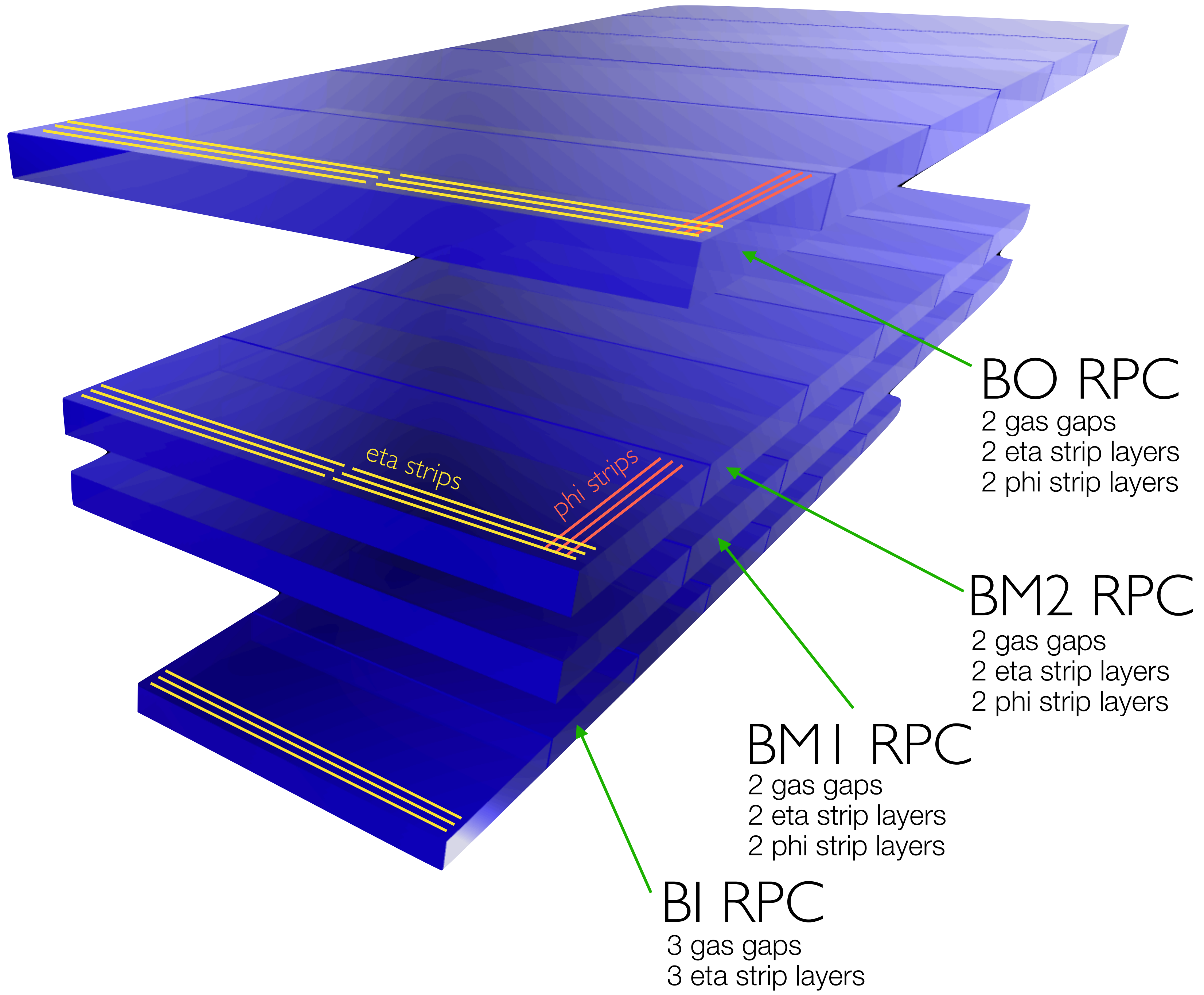


ATLAS Phase-II TDAQ Upgrade TDR

Barrel Muon Trigger Upgrade

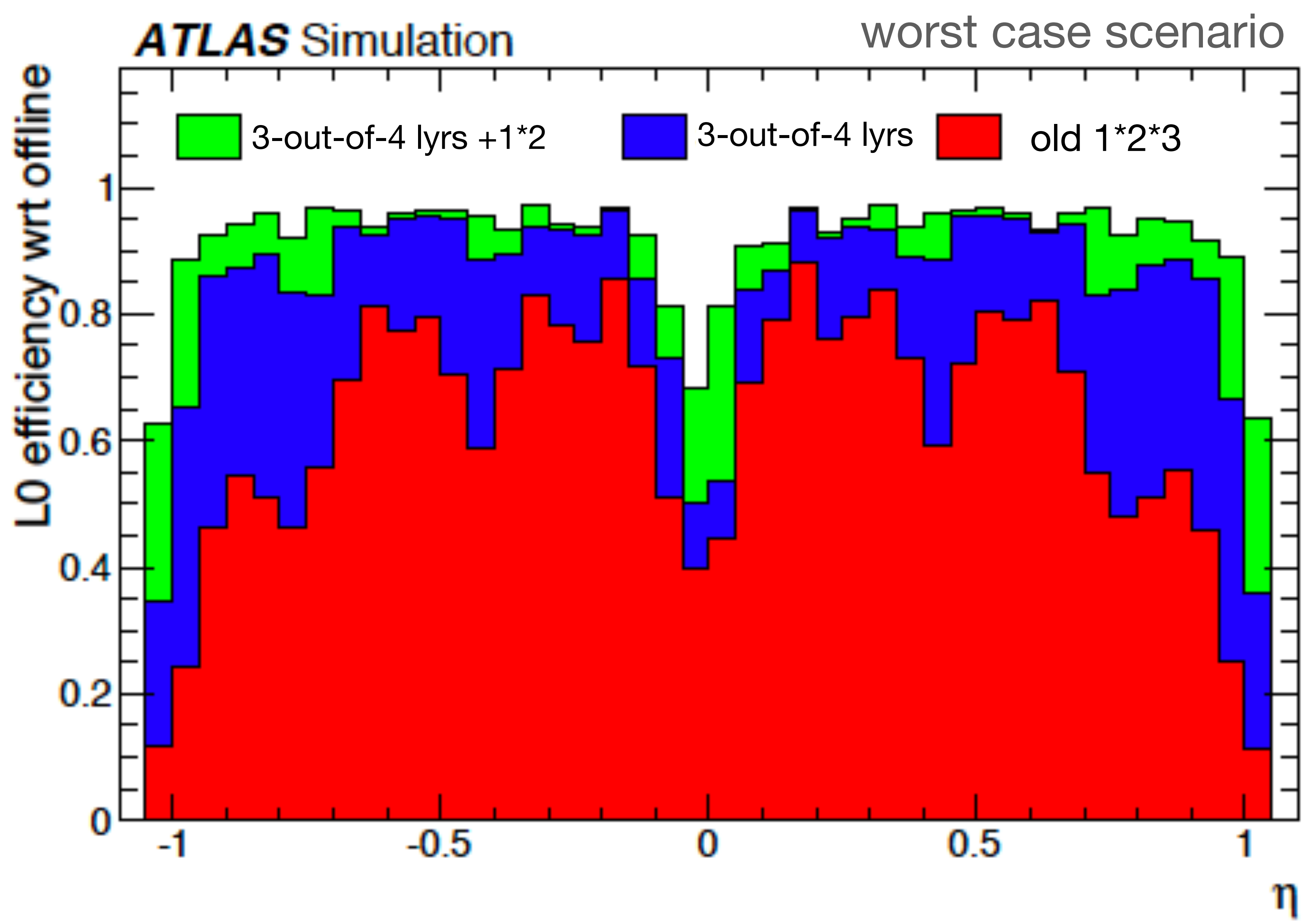
- Current trigger system exploits three doublet RPC detectors layers (RPC1-3)
- Legacy RPCs likely will not be operated at full efficiency at HL-LHC (to limit aging and because of the use of new eco-friendly gas)
- A new Barrel-Inner (BI) triplet layer of new generation RPCs (RPC0) is being added to recover inefficiency and improve geometrical acceptance
- Legacy doublet RPC (middle, BM and outer, BO) have eta-phi strip readout, new BI layer has only eta strips with phi coordinate obtained from time difference of signal readout from both strip ends
- Information from the Hadronic Calorimeter (Tile) cells also made available to L0Muon trigger: (two thresholds given per cell, defining lower and upper m.i.p. range)
- Monitored Drift Tubes (MDTs), not used in current low-level trigger, will be added in L0Muon trigger. L0-MDT processor will be seeded from RPC/TGC trigger candidates, and will provide a refined muon measurement.



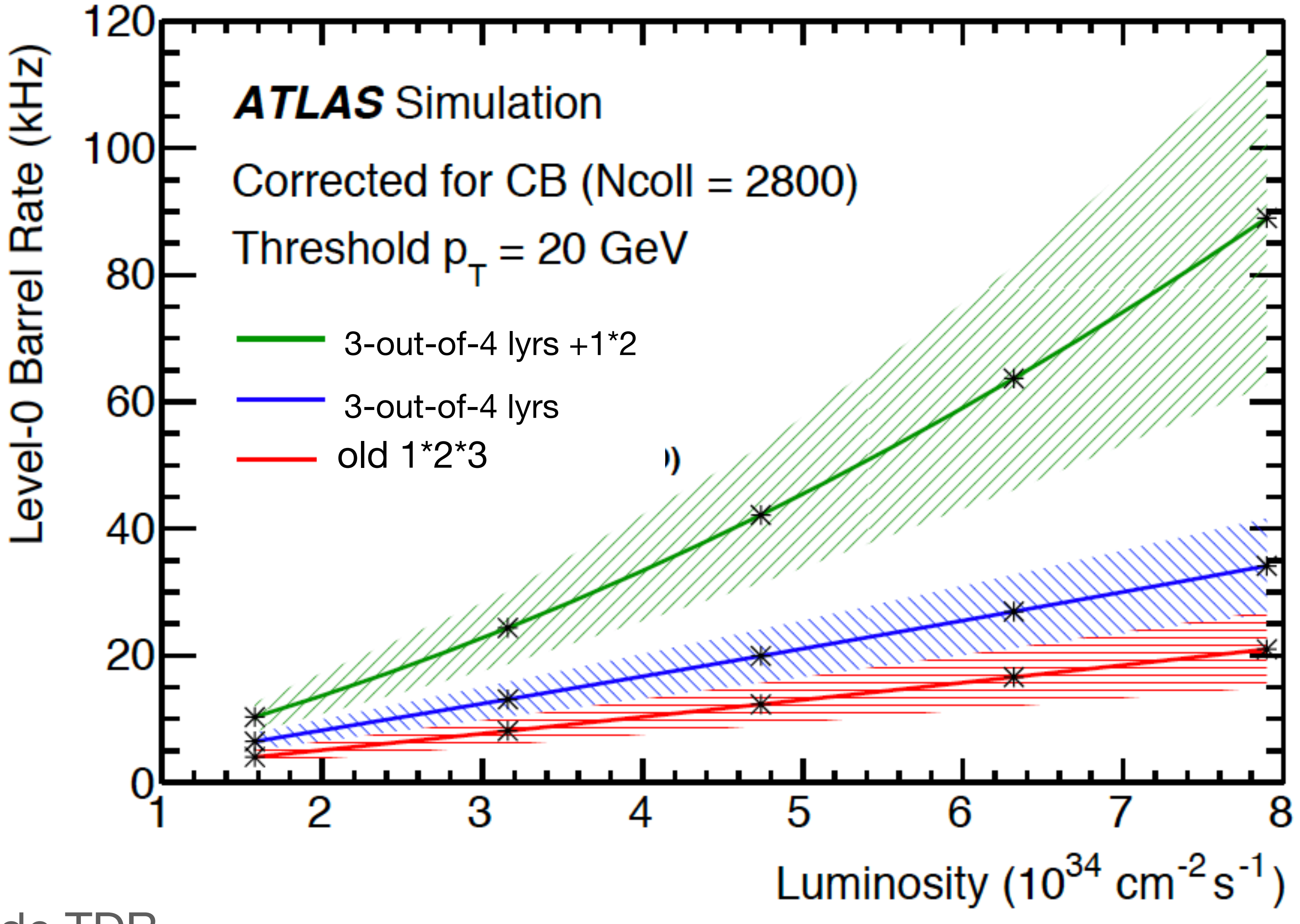


Barrel Trigger expected performance

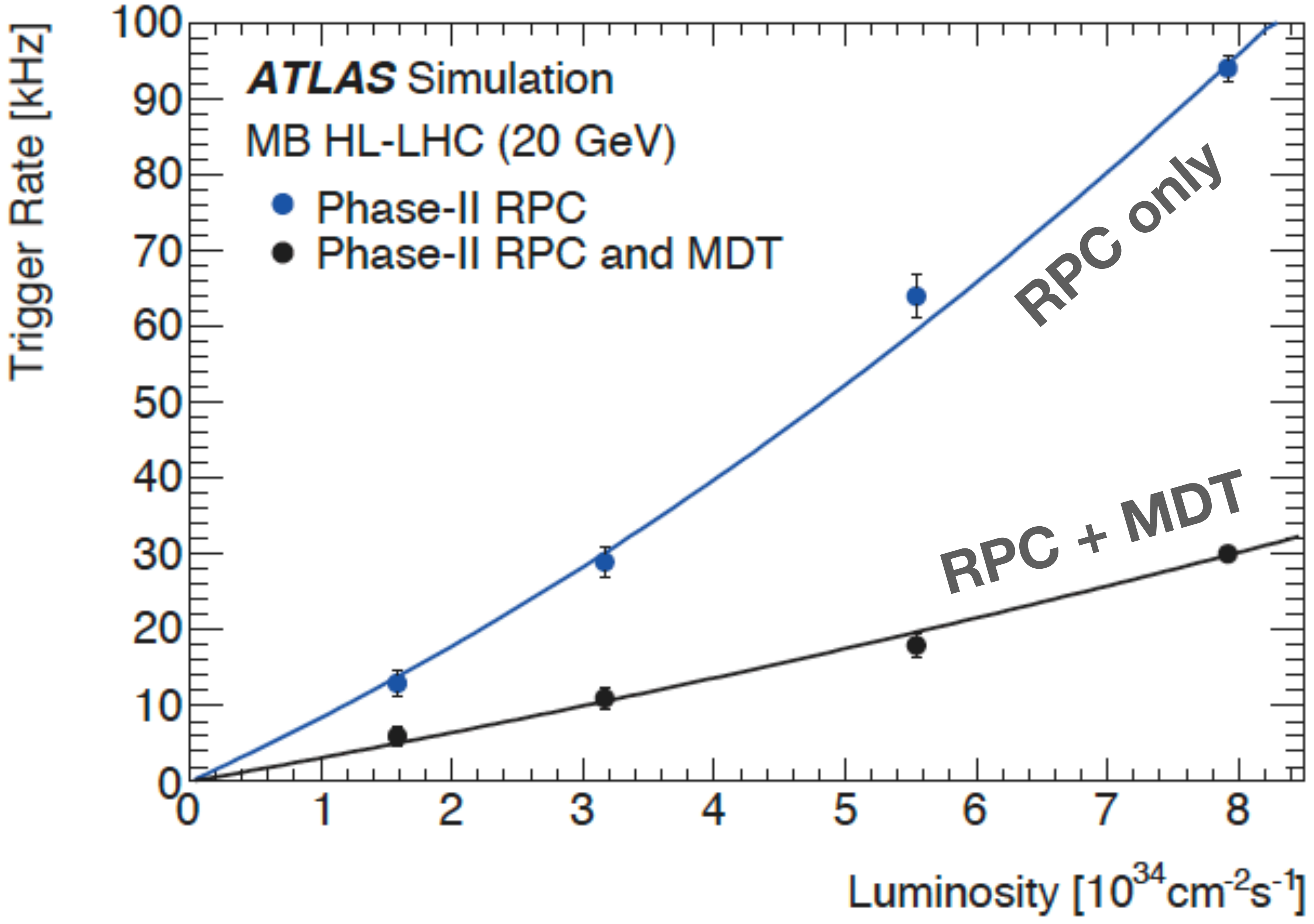
- A requirement of 3-out-of-4 layers would give good efficiency x acceptance (85%) and low rates (~30 kHz) for a single-muon p_T threshold of 20 GeV even in the worst case scenario for legacy RPC efficiency
- Looser coincidences (e.g. RPC1-RPC2) can be added, to further increase the efficiency x acceptance to 92%. Once filtered by the L0-MDT the rate of candidates sent to central trigger is still under control.



Rate (RPC only)



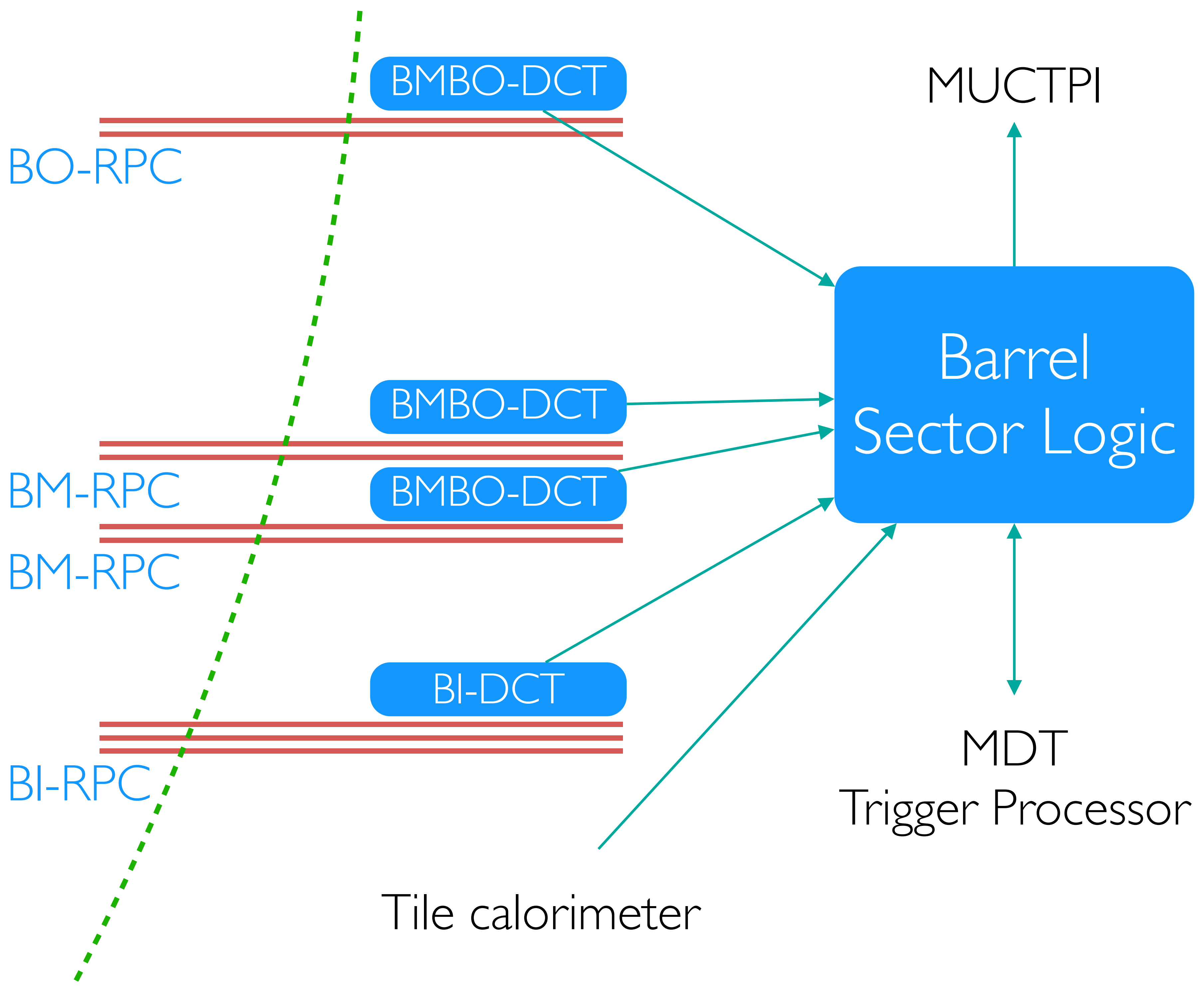
Rate

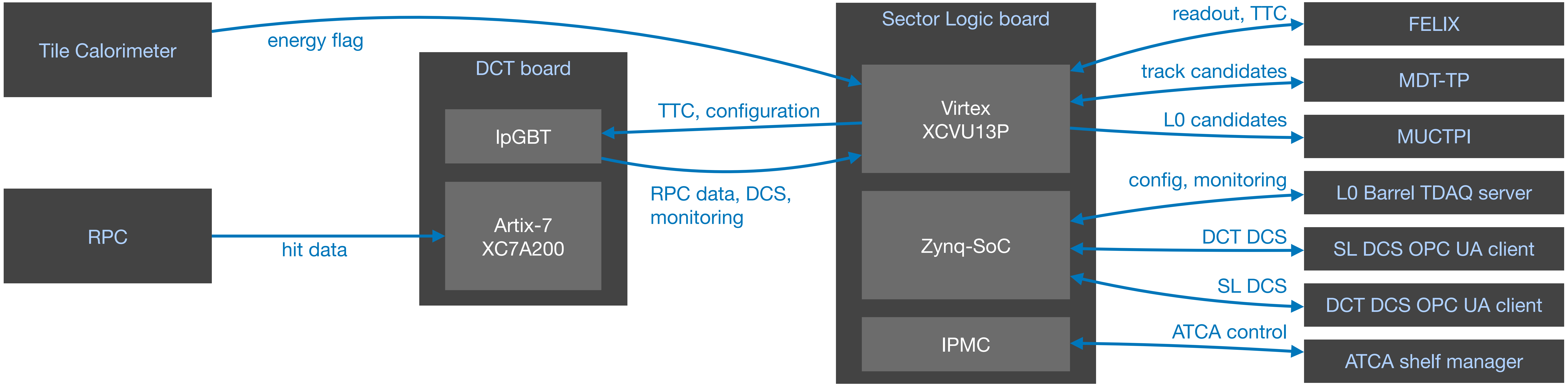


ATLAS Phase-II TDAQ Upgrade TDR

The RPC L0 Barrel Muon Phase-2 System

- ~1500 Data Collector and Transmitter (DCT) on-detector boards send hit data via optical link to 32 Sector Logic (SL) boards in counting room.
- Two DCT flavours to interface with different RPC front-end electronics, BMBO for legacy detectors and BI for new ones
- SL : Same hardware as for Endcaps, different Firmware
- All the trigger logic is implemented in the SL FPGA (XCVU13) for maximum flexibility

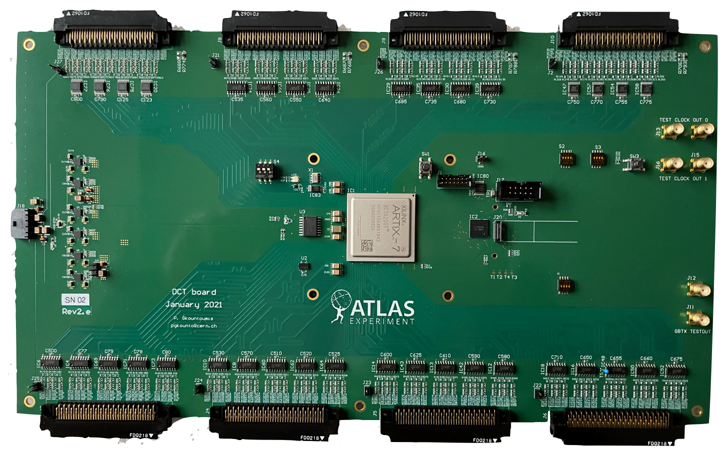




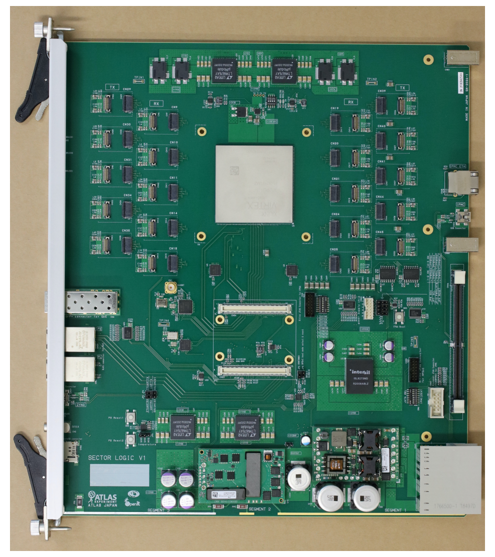
Current Project Status

- DCT prototypes (BMBO version) with firmware implementing full functionalities have been tested in lab and reading out RPC chambers. Communication between DCT and SL also tested.
- First version of SL FW implemented, including most functionalities: DCT data decoding, phi calculation for inner layer, trigger, readout, etc.
- Careful floor planning of XCVU13 FPGA to spread resources on four Super Logic Regions. Free resources still available in the two SLR (1 and 2) used for the trigger algorithm. While SLR0,3 used for BI and for readout are close to the limit.
- Latency is within requirement, 390 ns from last hit arrived to candidates sent (with hit positions) to L0-MDT processor

DCT:
Italy, Greece

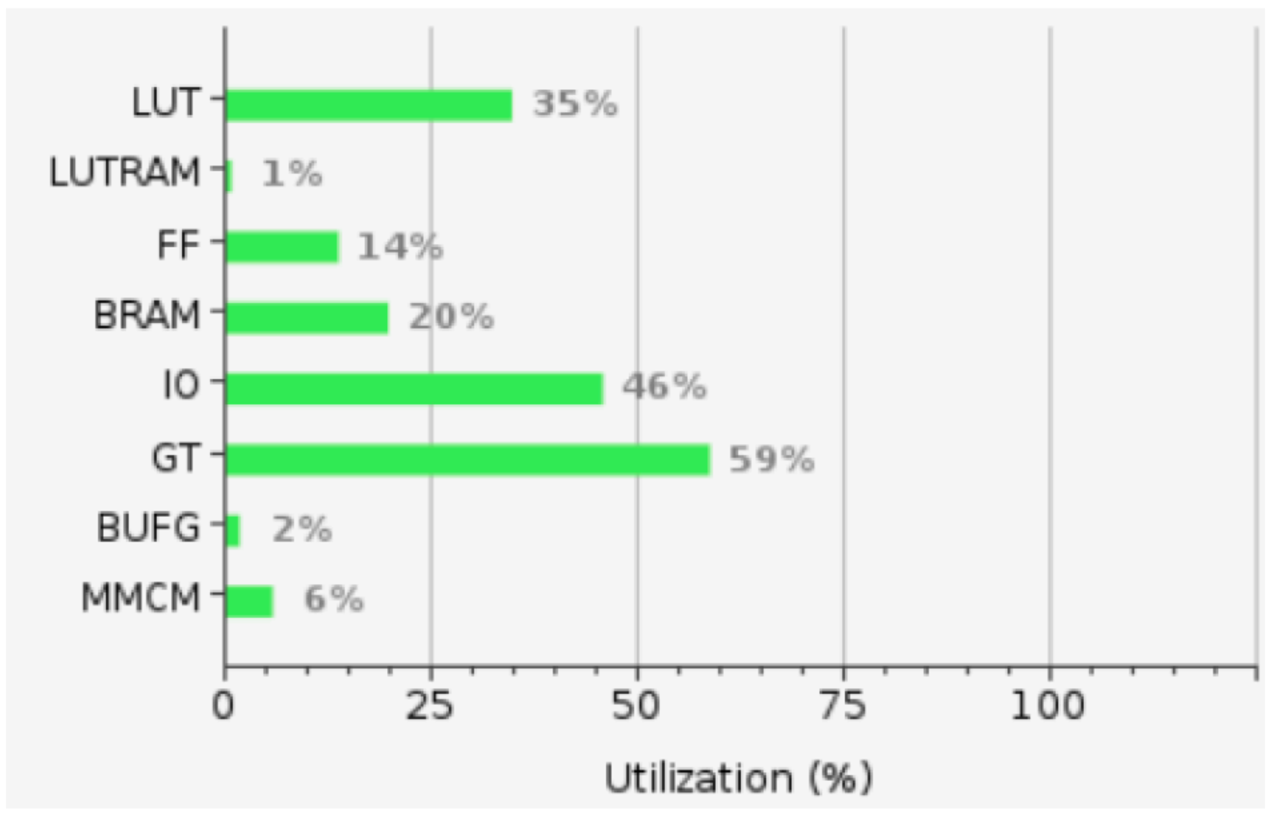


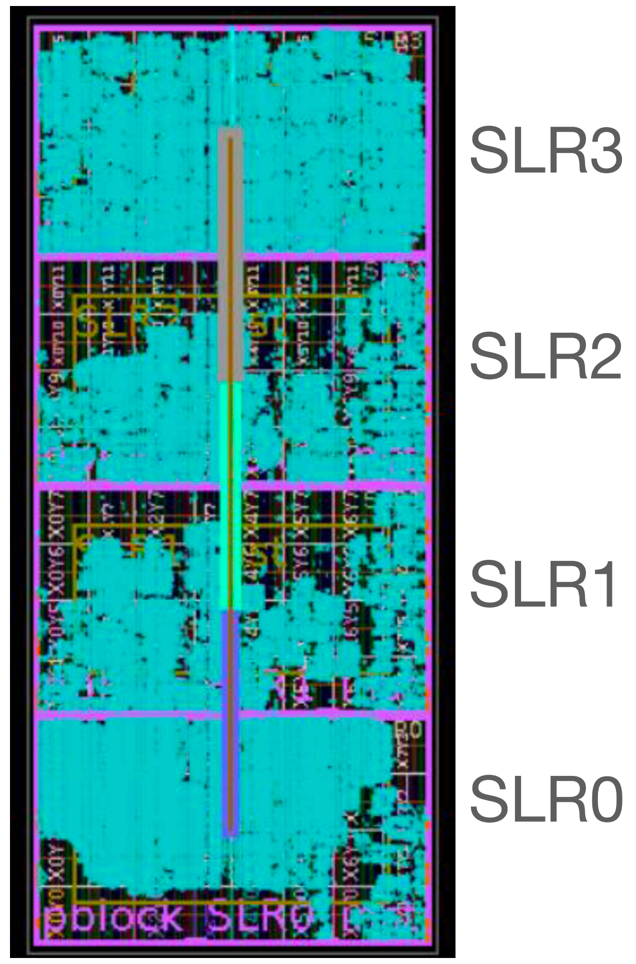
SL
HW: Japan
FW: Italy



XCVU13 floor planning

XCVU13 resource usage

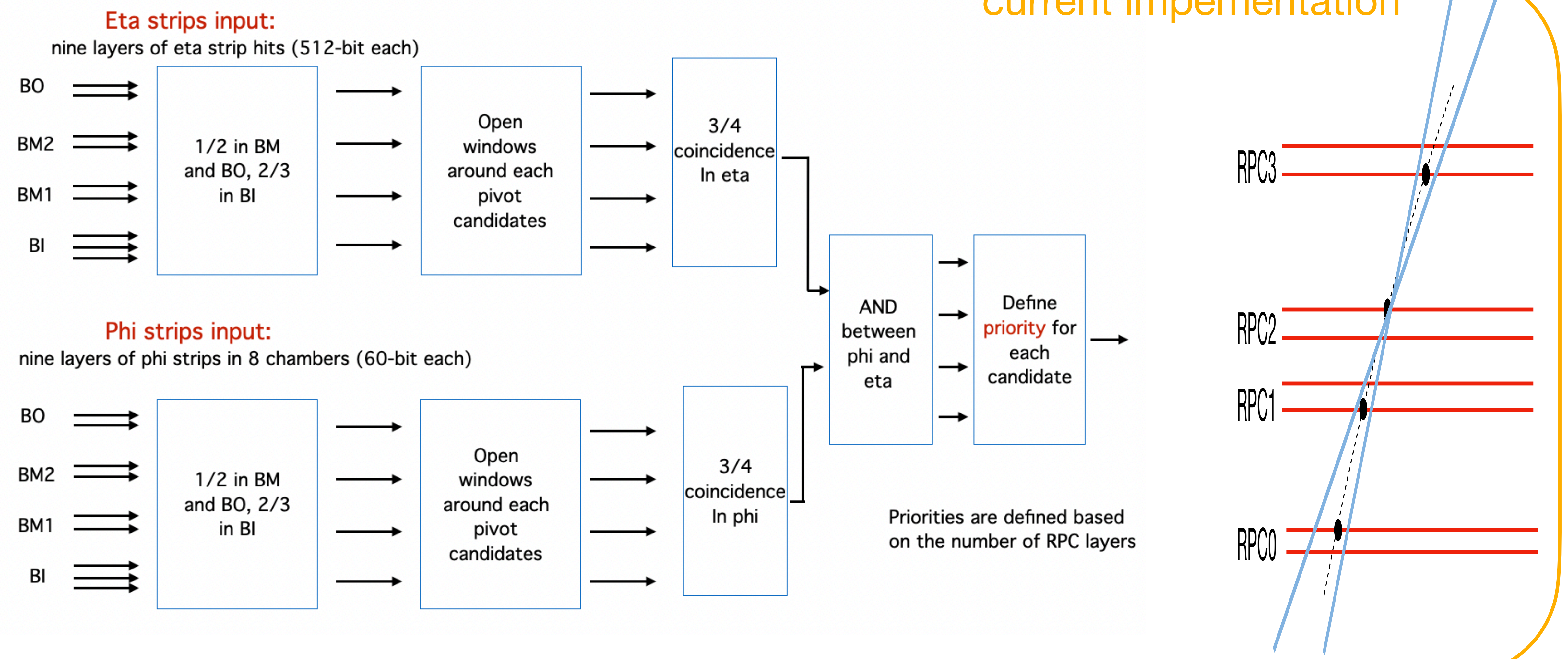




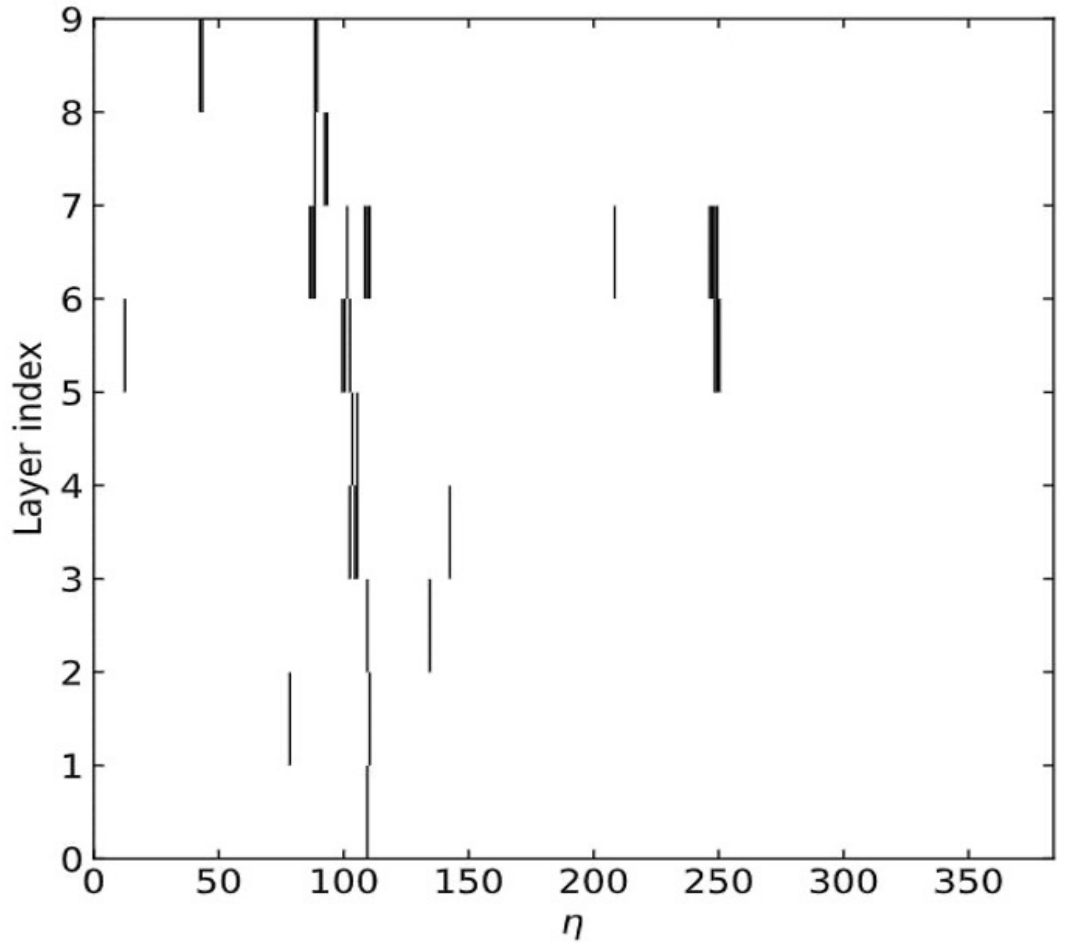
Trigger Algorithm, Machine Learning ?

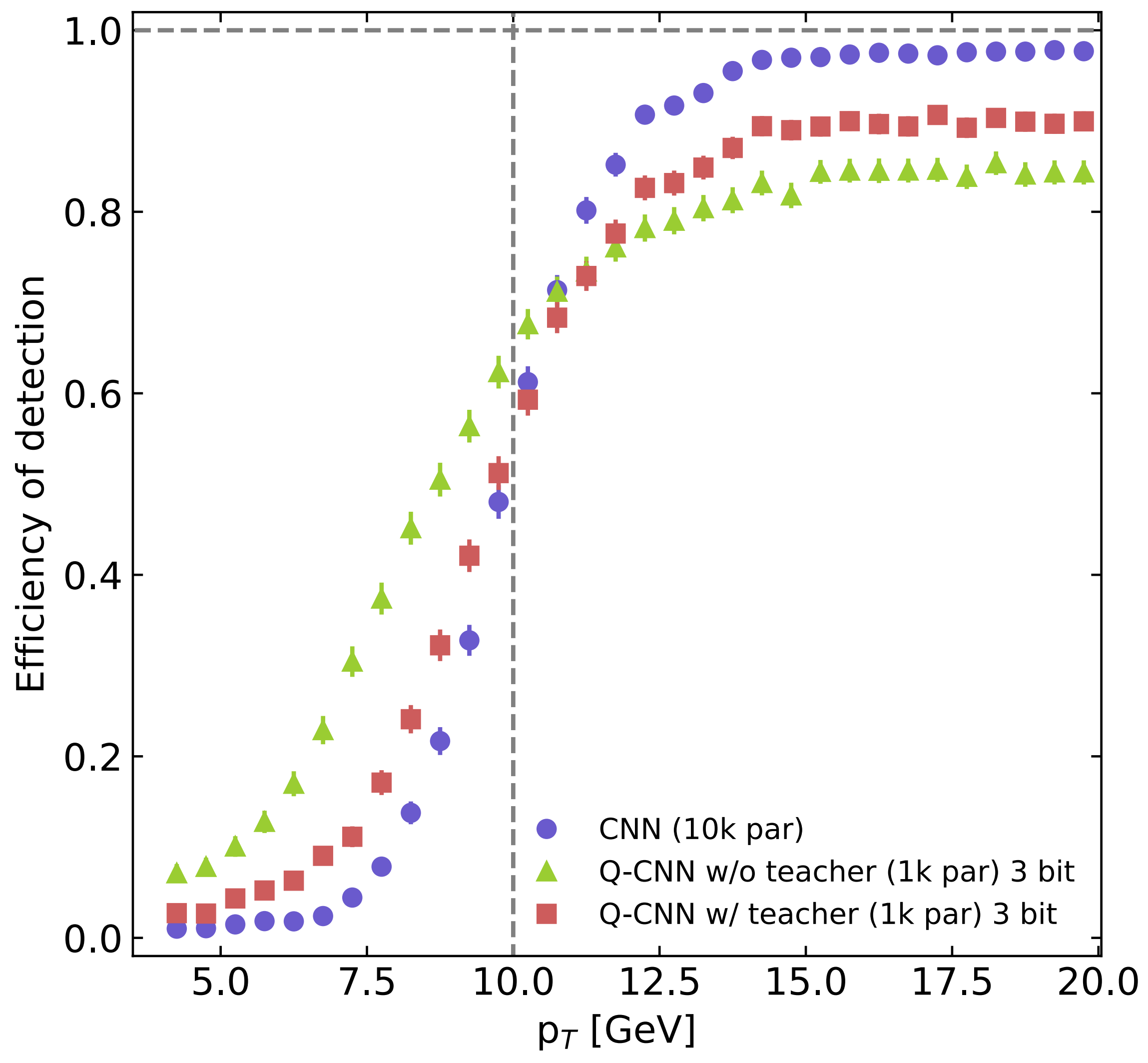
- Standard HL-LHC approach is similar to current one (PatFinder): for each hit in a layer, an hit is looked for in the next layers witin a pre-computed spatial window defined by the p_T threshold
- Currently implemented in SL, optimization and performance studies are in progress
- Alternative approach based on ML technique: use images based on hits in RPC layers to feed a CNN EPJC 81 (2021) 969
- Latency requirements and FPGA resources at Level-0 are challenging for standard ML methods, special techniques are required : Knowledge Distillation, Quantization, code written by hand at low-level in VHDL to optimize latency size etc.
- A similar approach by Ospanov et al. *Eur.Phys.J.C* 82 (2022) 6, 576
- Detailed performance comparison with standard approach will be done to choose the final algorithm

current impementation



ML implementation

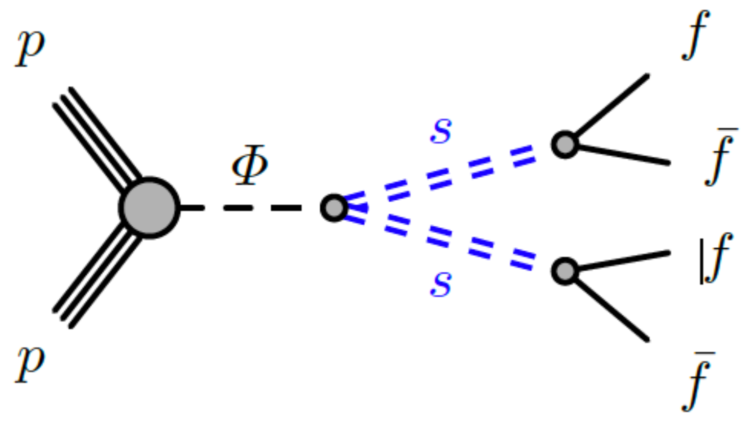




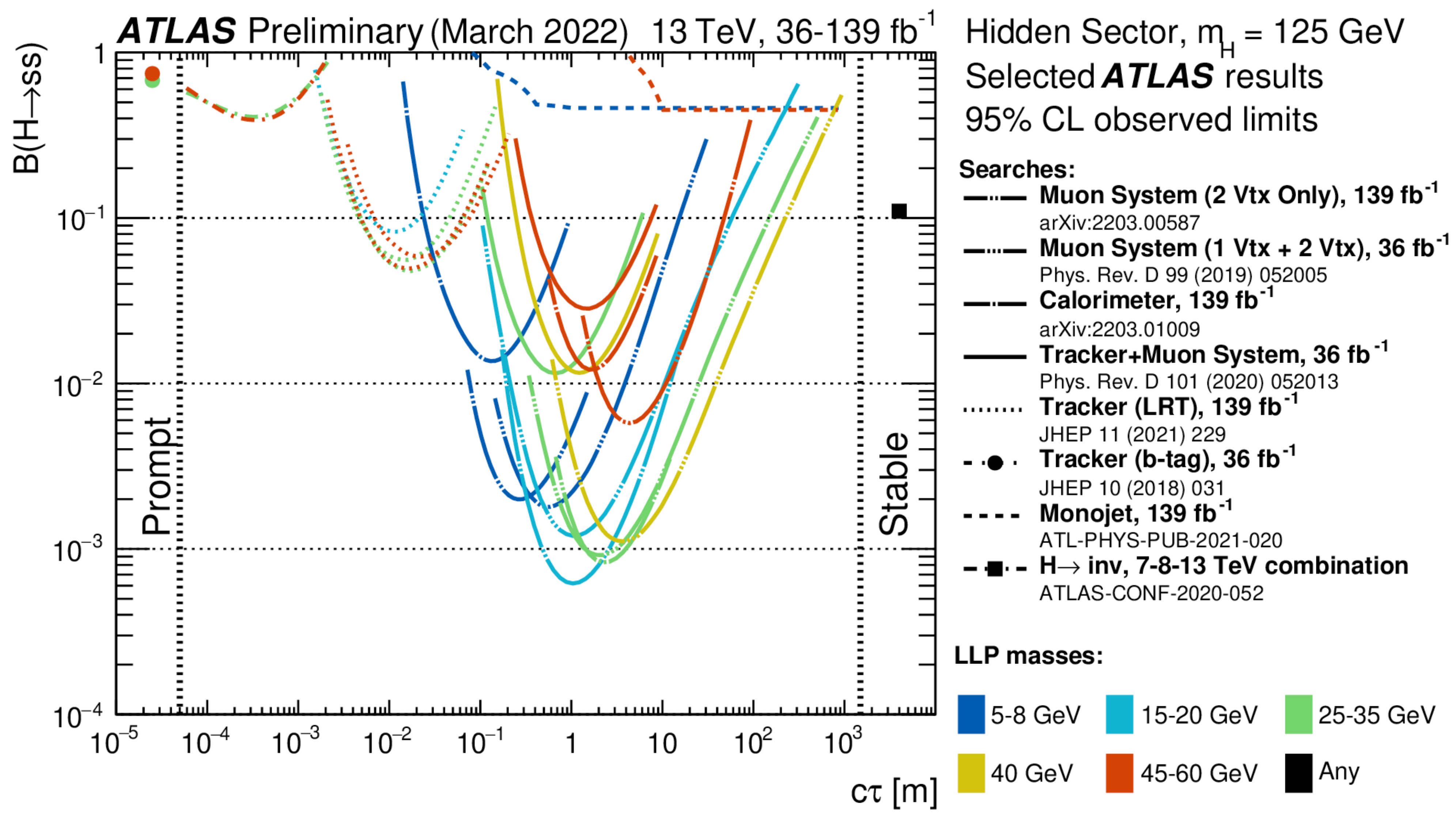
	GPU Tesla V100	FPGA XCV13P with hls4ml	FPGA XCV13P with VHDL implementation
Latency	5 ms	438 ns	84 ns

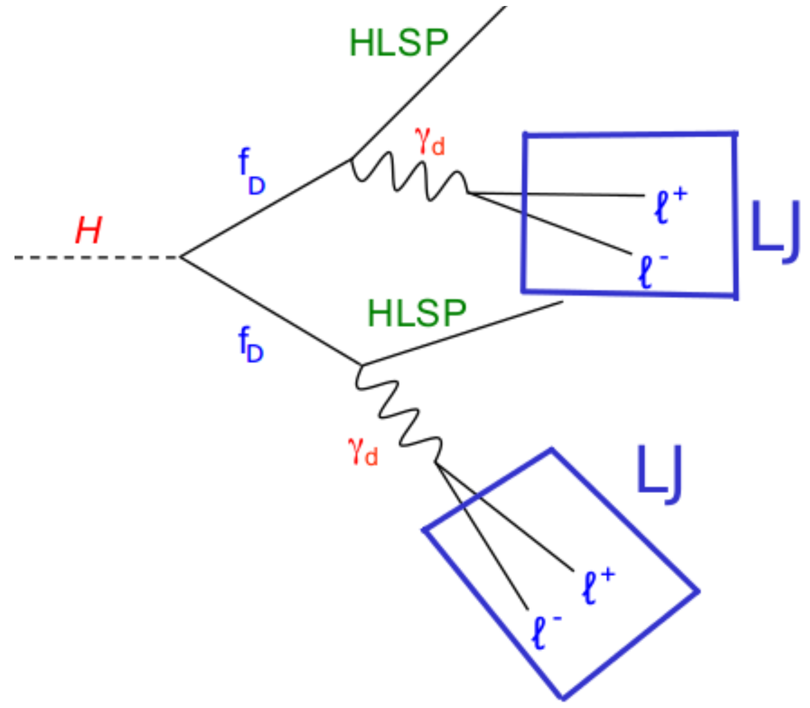
Searches for Long Lived Particles with ATLAS

- Several models beyond SM predict Long Lived Particles (LLPs)
- Using a combination of detectors ATLAS searched displaced decays over a wide range of particle masses and decay lengths in Run2 data
- Example 1 : Scalar Higgs Portal, SM Higgs decays in two long-lived neutral scalars which decay back in two SM fermions. Typical signature are vertices with multiple tracks well displaced from IP
- Example 2 : Dark photons (FRVZ model), produced in Higgs decays, kinematically mix with photon and decay into collimated lepton pairs (lepton jets, LJ)

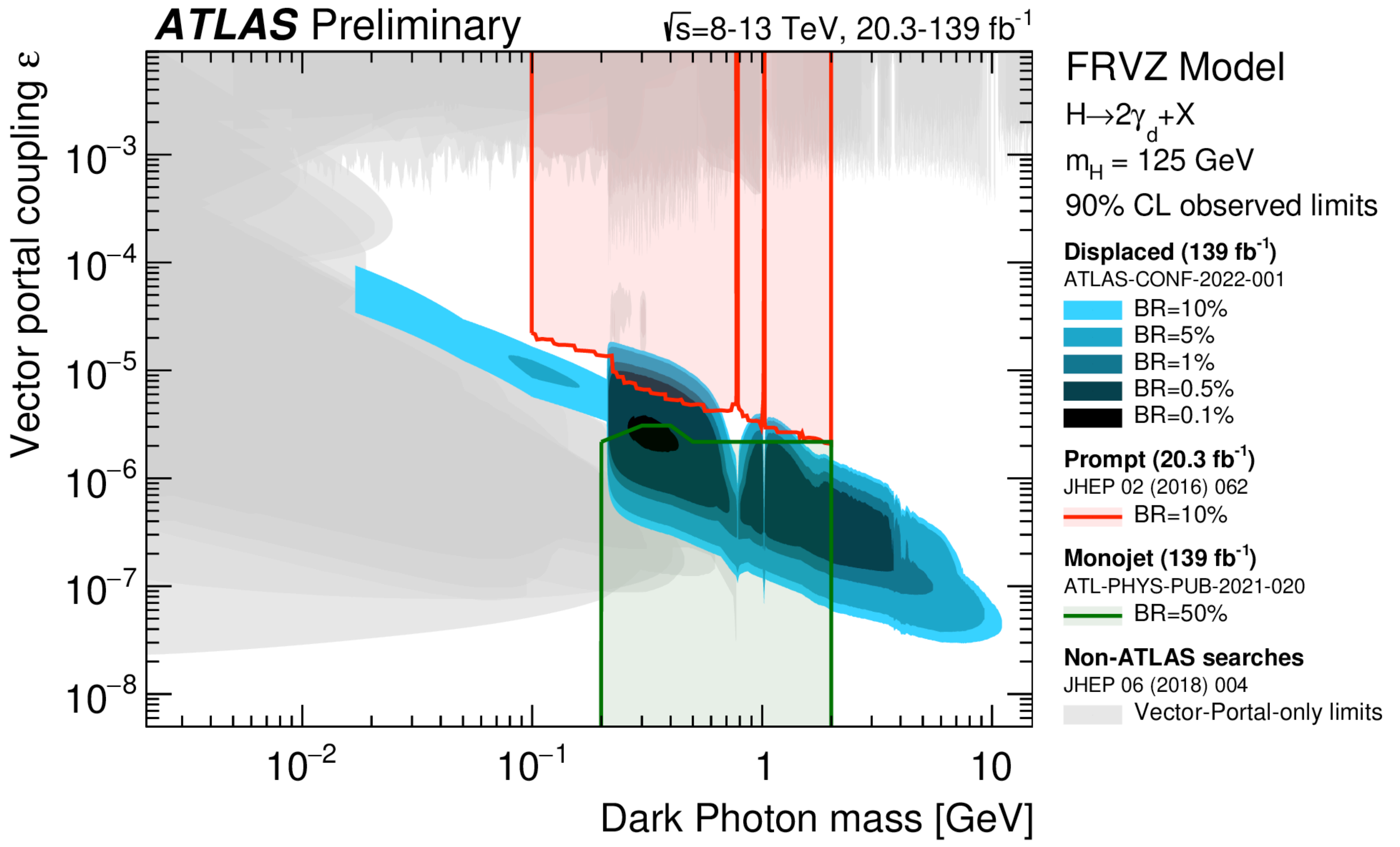


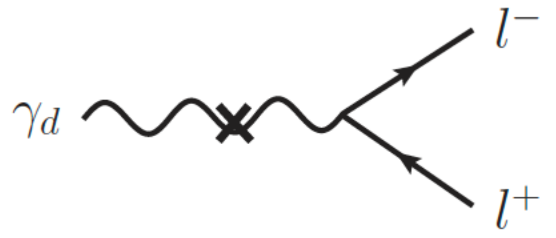
Scalar portal





FRVZ Model



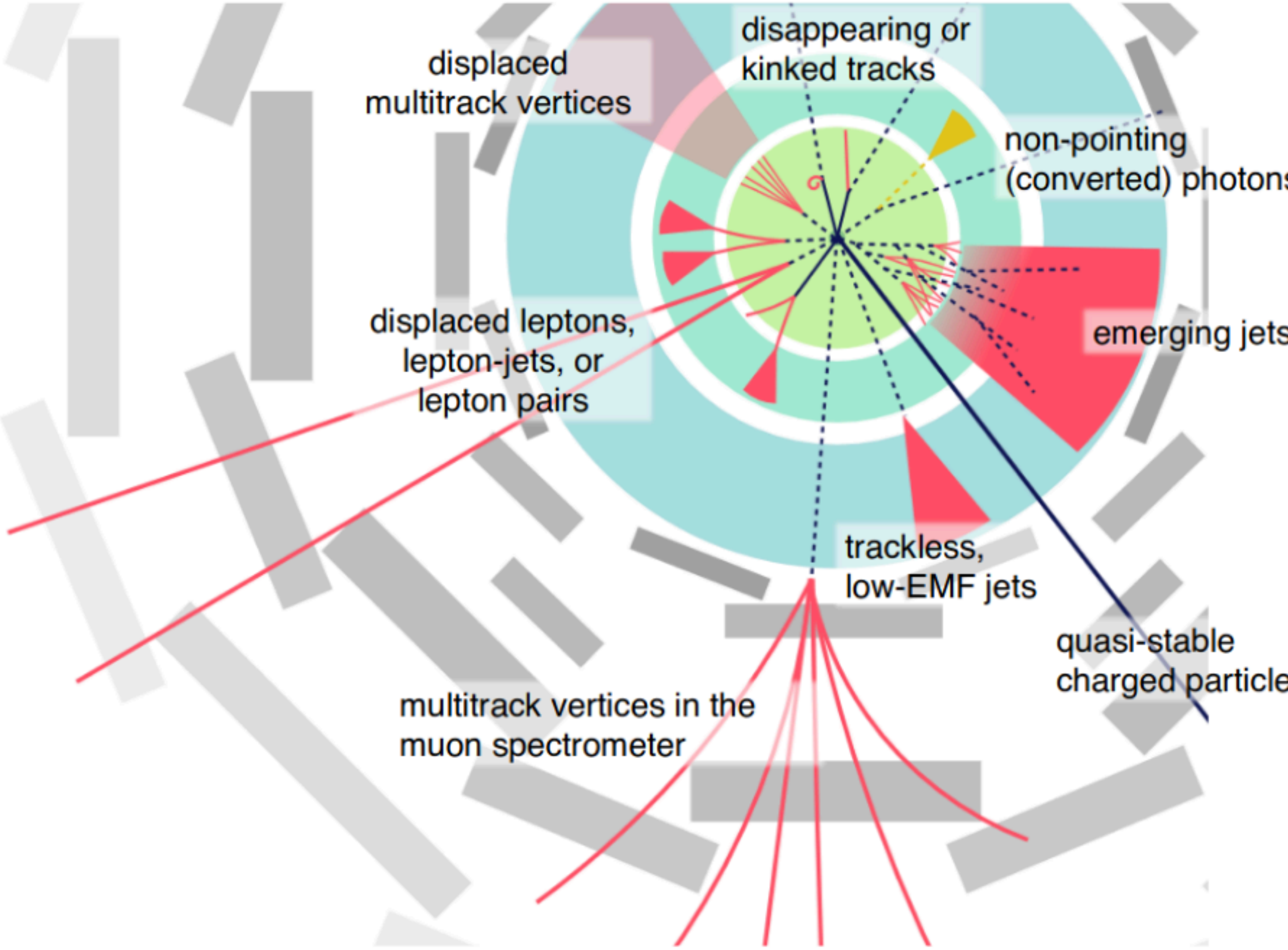
dark photon 

Searches for Long Lived Particles with the ATLAS Muon System

- The ATLAS muon system is a very large "almost" empty volume instrumented with trigger and precision tracking chambers: very good for looking at displaced decays of Long Lived Particles (LLPs)

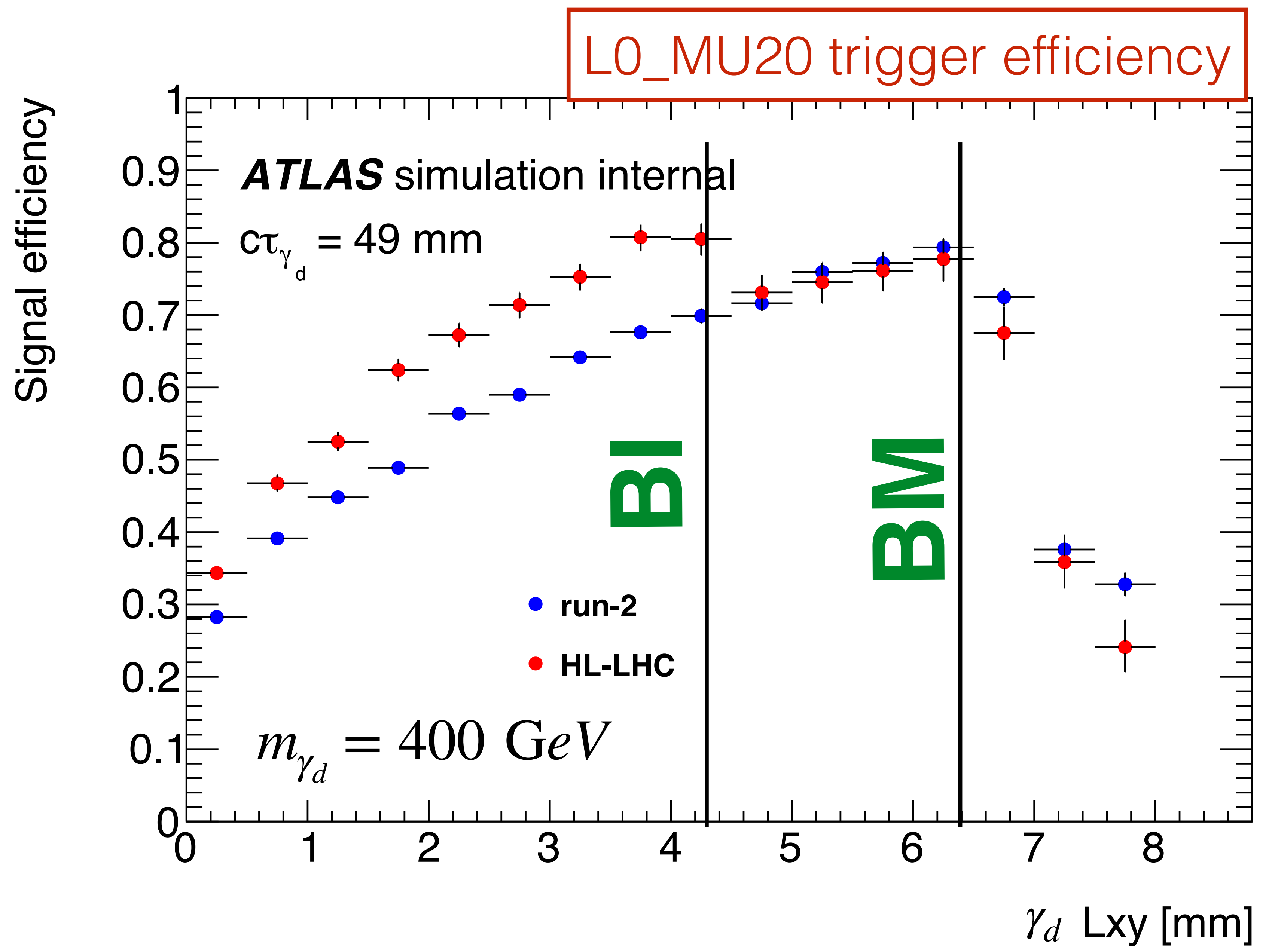
- Several nice results have been published

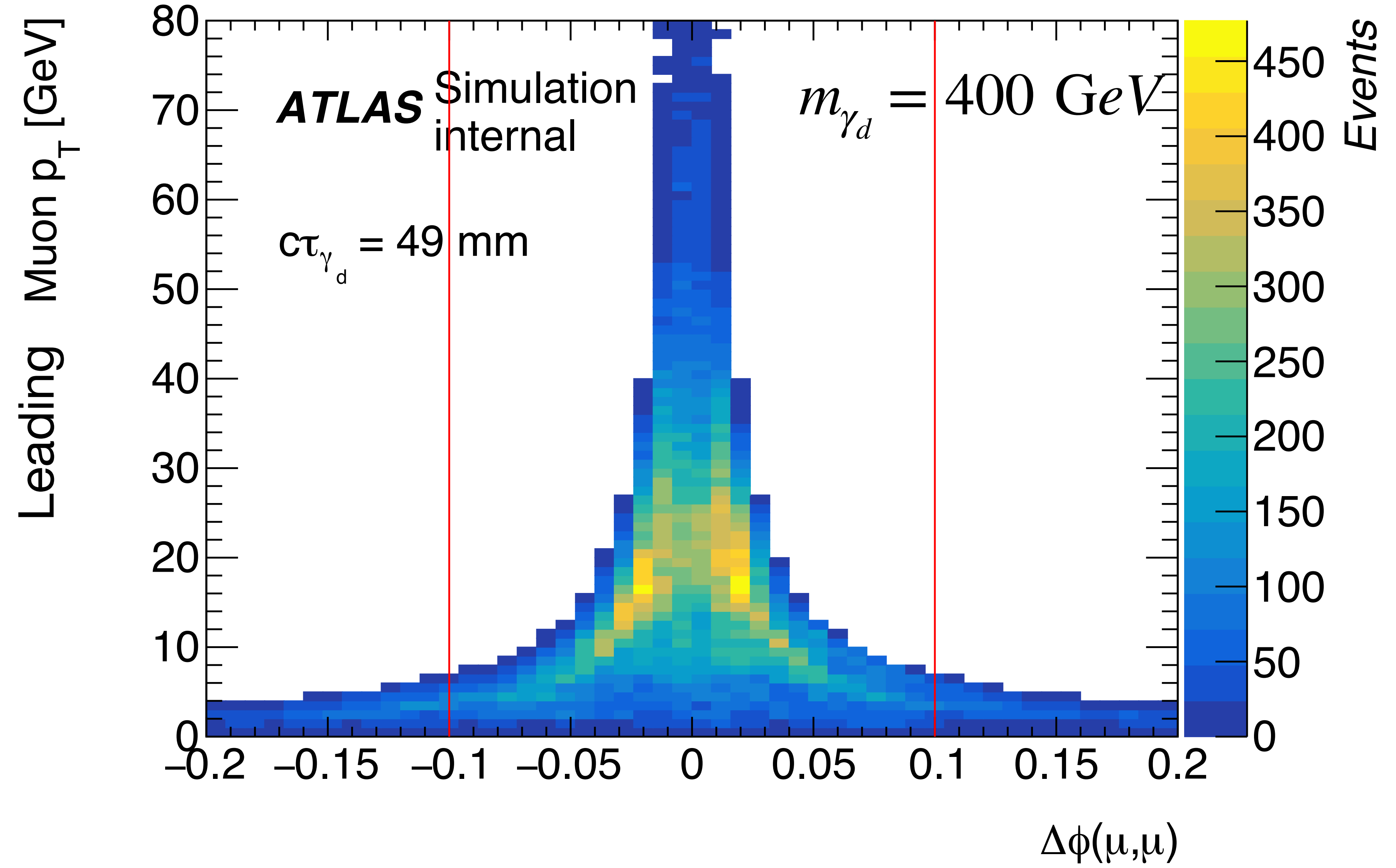
- Will we be able to trigger on these exotic channels at HL-LHC ?



Triggering on lepton jets at HL-LHC

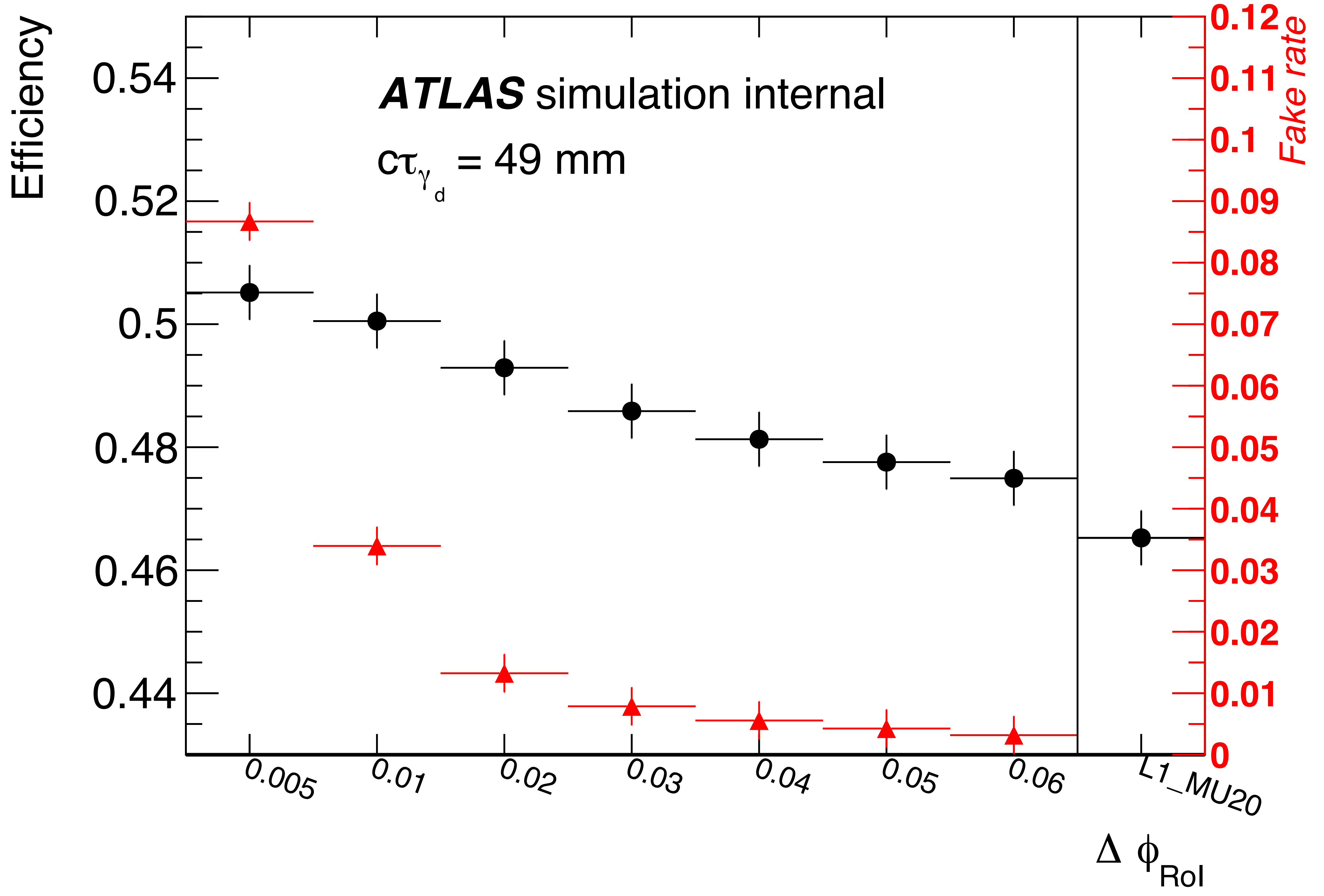
- Study of triggers for lepton-jets at HL-LHC: ATL-PHYS-PUB-2019-002
- Single muon trigger efficient for lepton jets up to L_{xy}=7 m, slightly improved wrt to Run-2
- Muon pairs can be very collimated and/or of moderate p_T
- We studied a triggers for collimated di-muons (similar to B-physics triggers but without invariant mass cuts)

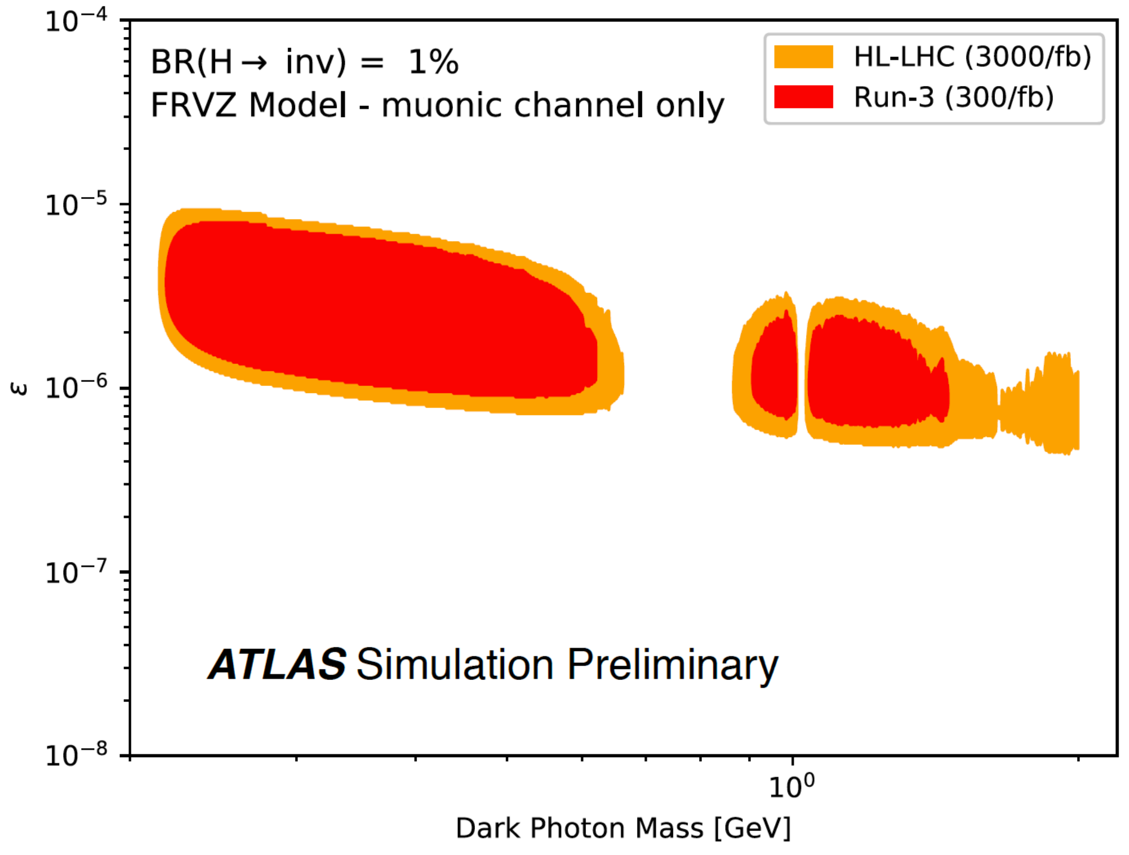




Lepton-jet dimuon trigger

- A simple collimated dimuon trigger
- At very low $\Delta\Phi(\mu,\mu)$ fakes originating from single muon reconstructed as a muon pair
- choosen working point
  $\Delta\Phi(\mu,\mu) > 0.01,\ p_T(\mu_1) > 10\ \mathrm{GeV},\ p_T(\mu_2) > 5\ \mathrm{GeV}$
- Implementation in firmware to be studied
- Study of physics reach at HL-LHC (simple extension of Run-2 analysis, further improvements expected from re-optimization for high-pileup conditions) : the excluded lifetime range is significantly extended

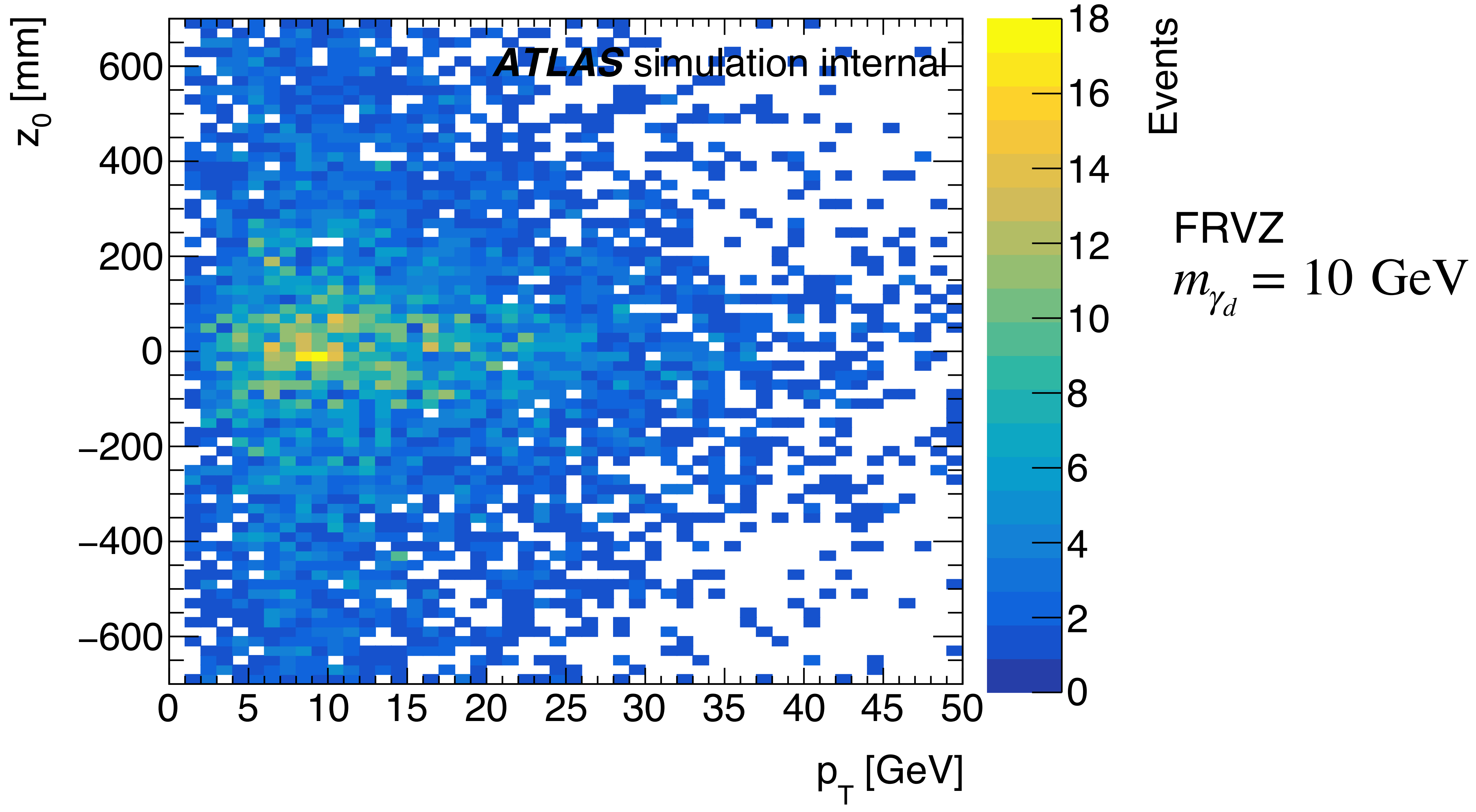


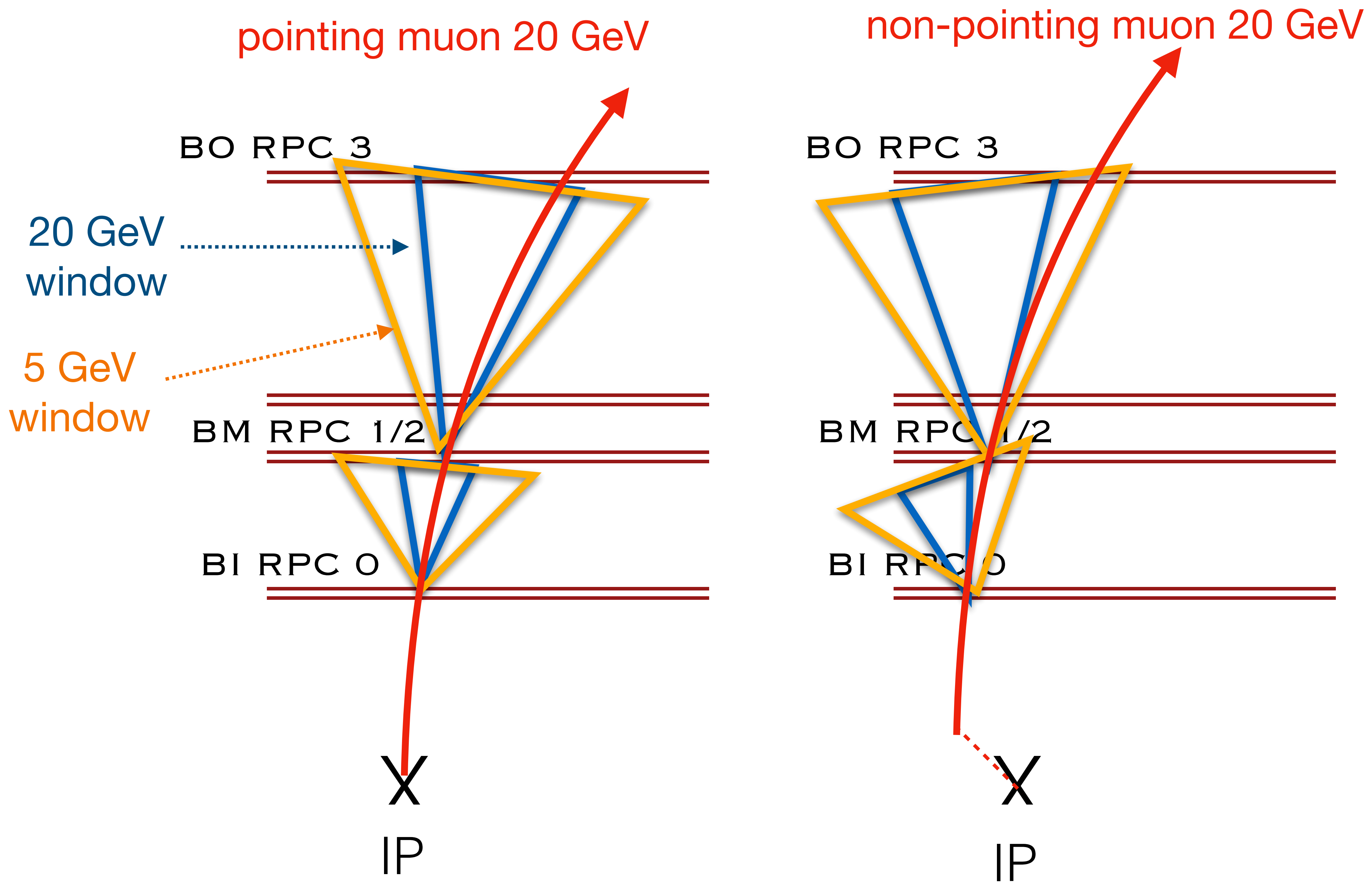


Excluded $c\tau$ [mm] muonic-muonic	Run-2	Run-3	HL-LHC	HL-LHC + Collimated dimuon trigger
BR(H $\to 2\gamma_d + X$)=10 %	$2.2 \le c\tau \le 111$	$1.15 \le c\tau \le 435$	$0.97 \le c\tau \le 553$	$0.97 \le c\tau \le 597$
BR(H $\to 2\gamma_d + X$)=1 %	-	$2.76 \le c\tau \le 102$	$2.18 \le c\tau \le 142$	$2.13 \le c\tau \le 148$

Muons from heavy long-lived objects

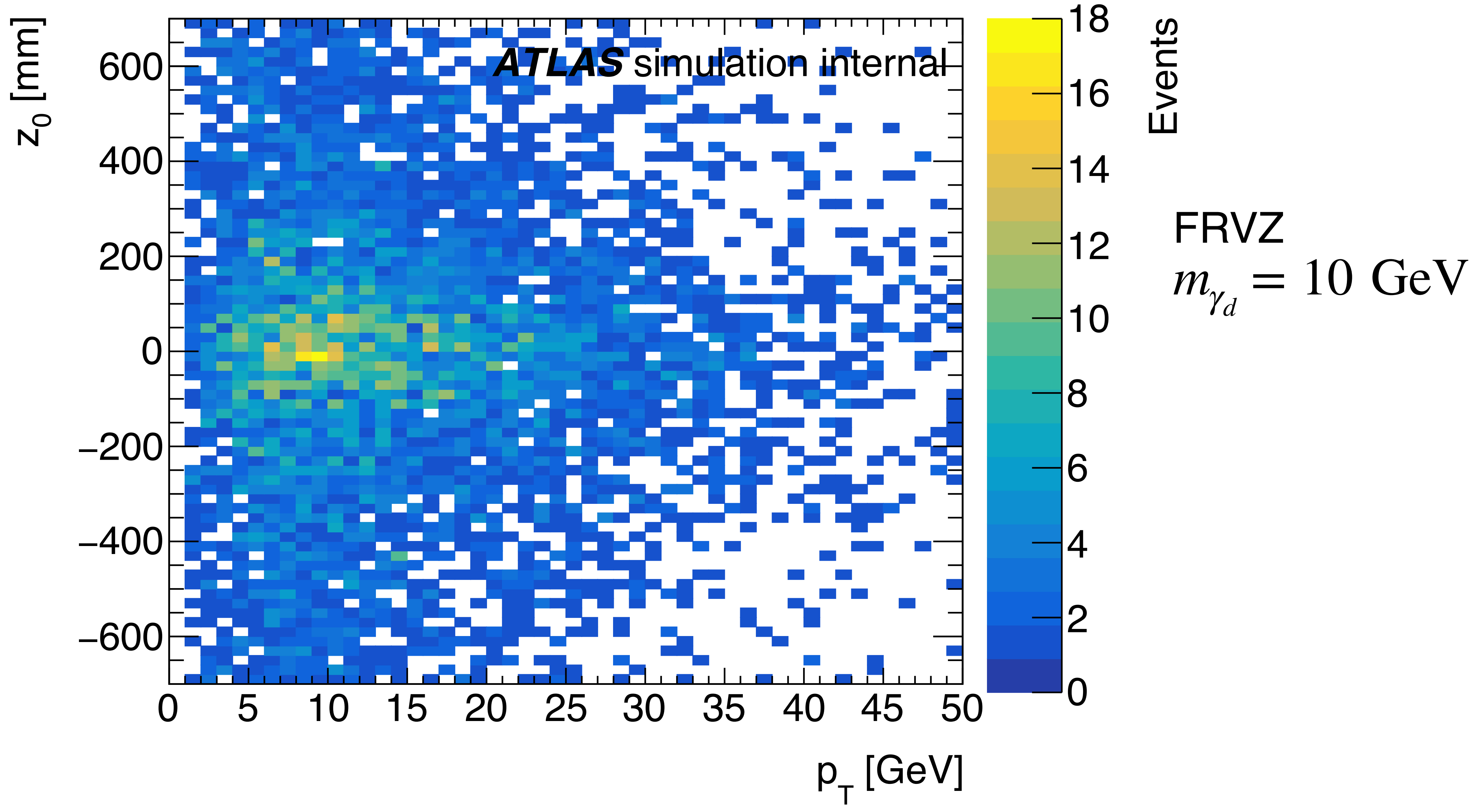
- Long-Lived particles may also be heavy
- E.g. an heavy dark Z can be produced in Drell-Yan via kinematic mixing or in processes or with the FRVZ mechanism
- In this case the muons are not pointing to IP
- standard L0Muon Barrel trigger spatial coincidences assume tracks pointing to IP, will loose these signals !
- Study to use loose spatial coincidences for good candidates with hits in >=3 RPC Layers (including inner and outer ones)
- loose coincidence windows: pointing 5 GeV threshold for eta view and "fully open" coincidence within a trigger phi sector ($2\pi/32$)

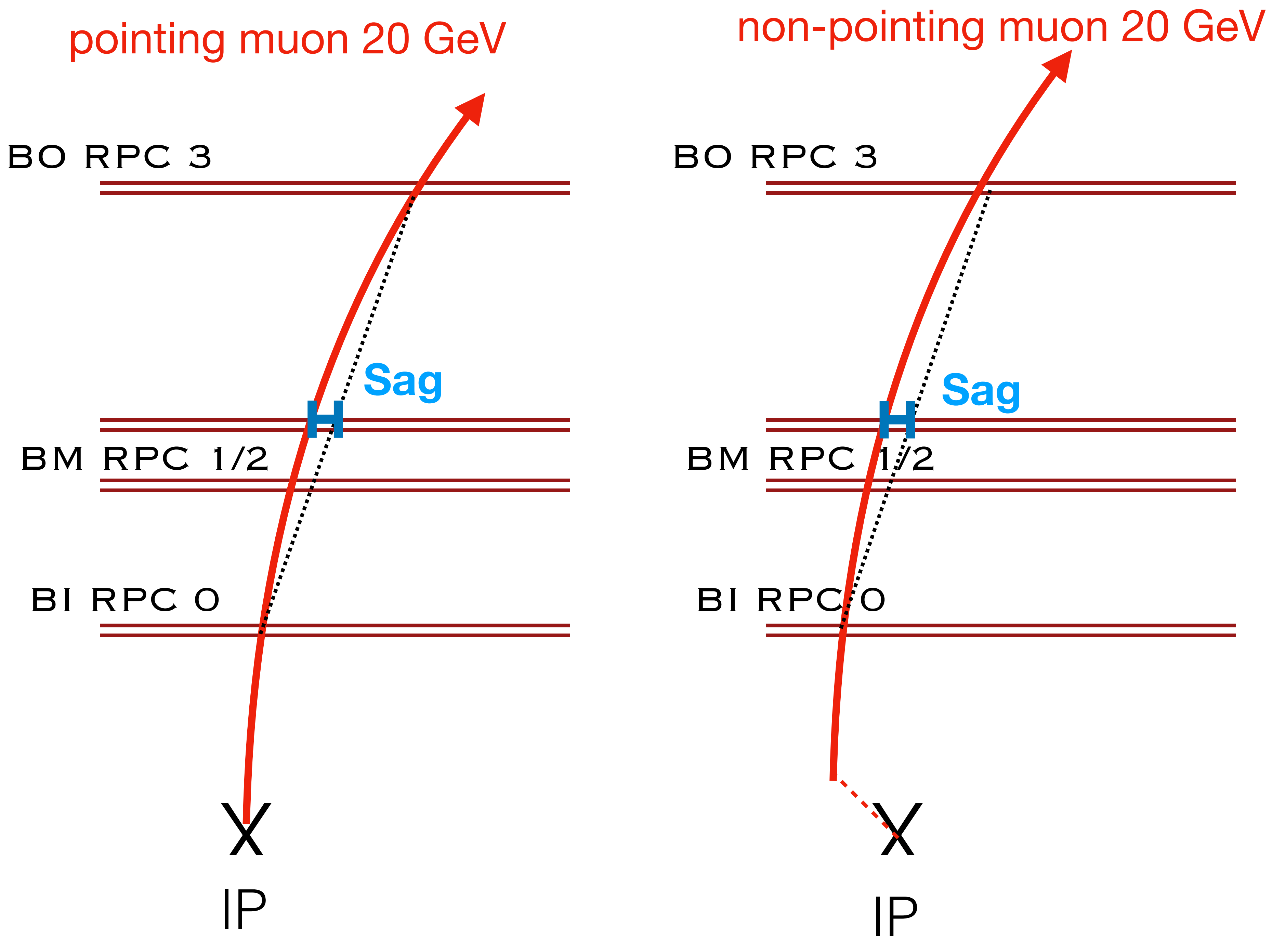




Muons from heavy long-lived objects

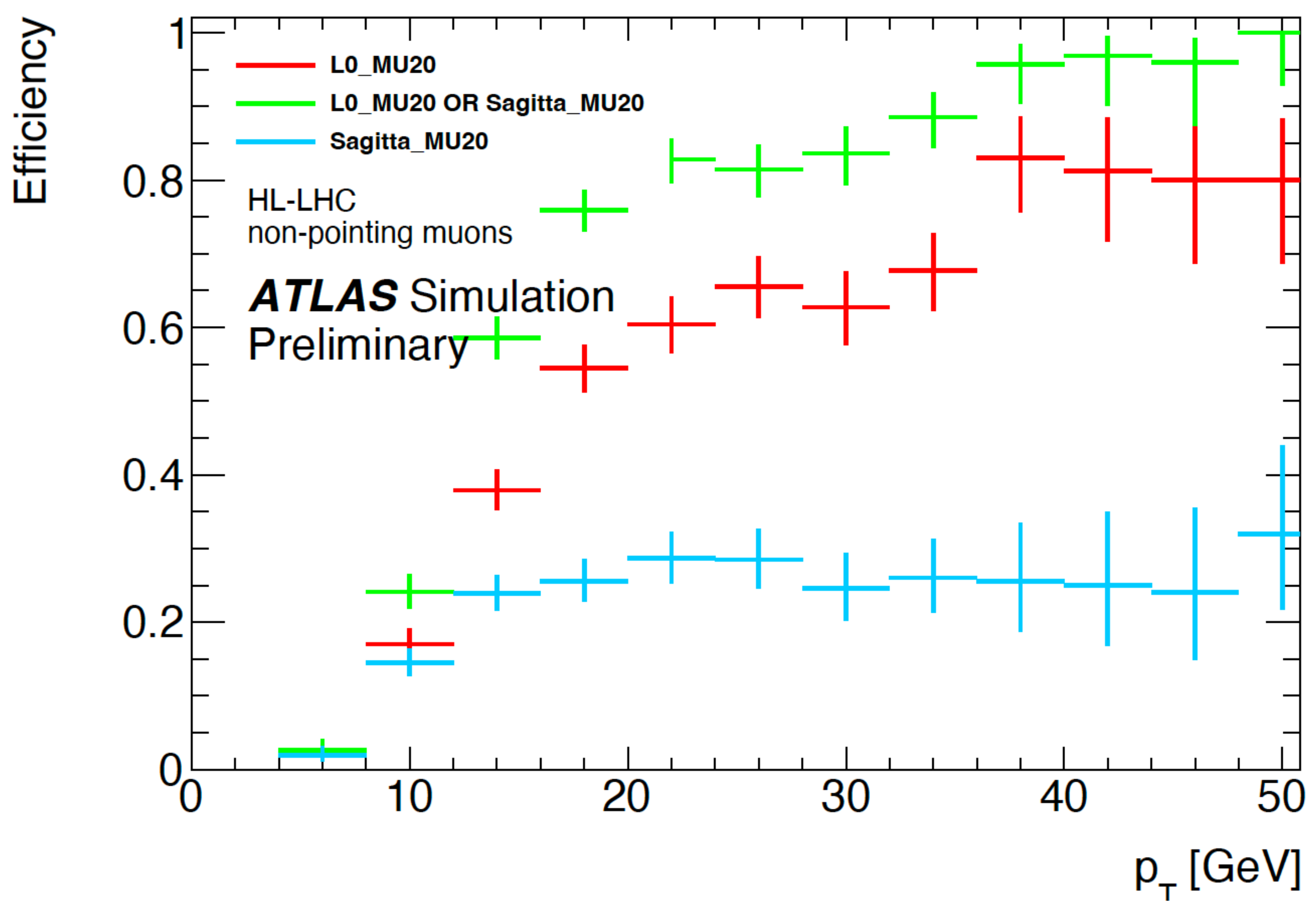
- Long-Lived particles may also be heavy
- E.g. an heavy dark Z can be produced in Drell-Yan via kinematic mixing or in processes or with the FRVZ mechanism
- In this case the muons are not pointing to IP
- standard L0Muon Barrel trigger spatial coincidences assume tracks pointing to IP, will loose these signals !
- Study to use loose spatial coincidences for good candidates with hits in >=3 RPC Layers (including inner and outer ones)
- loose coincidence windows: pointing 5 GeV threshold for eta view and "fully open" coincidence within a trigger phi sector $(2\pi/32)$
- Add a cut on sagitta calculated exploting inner-middle-outer layers

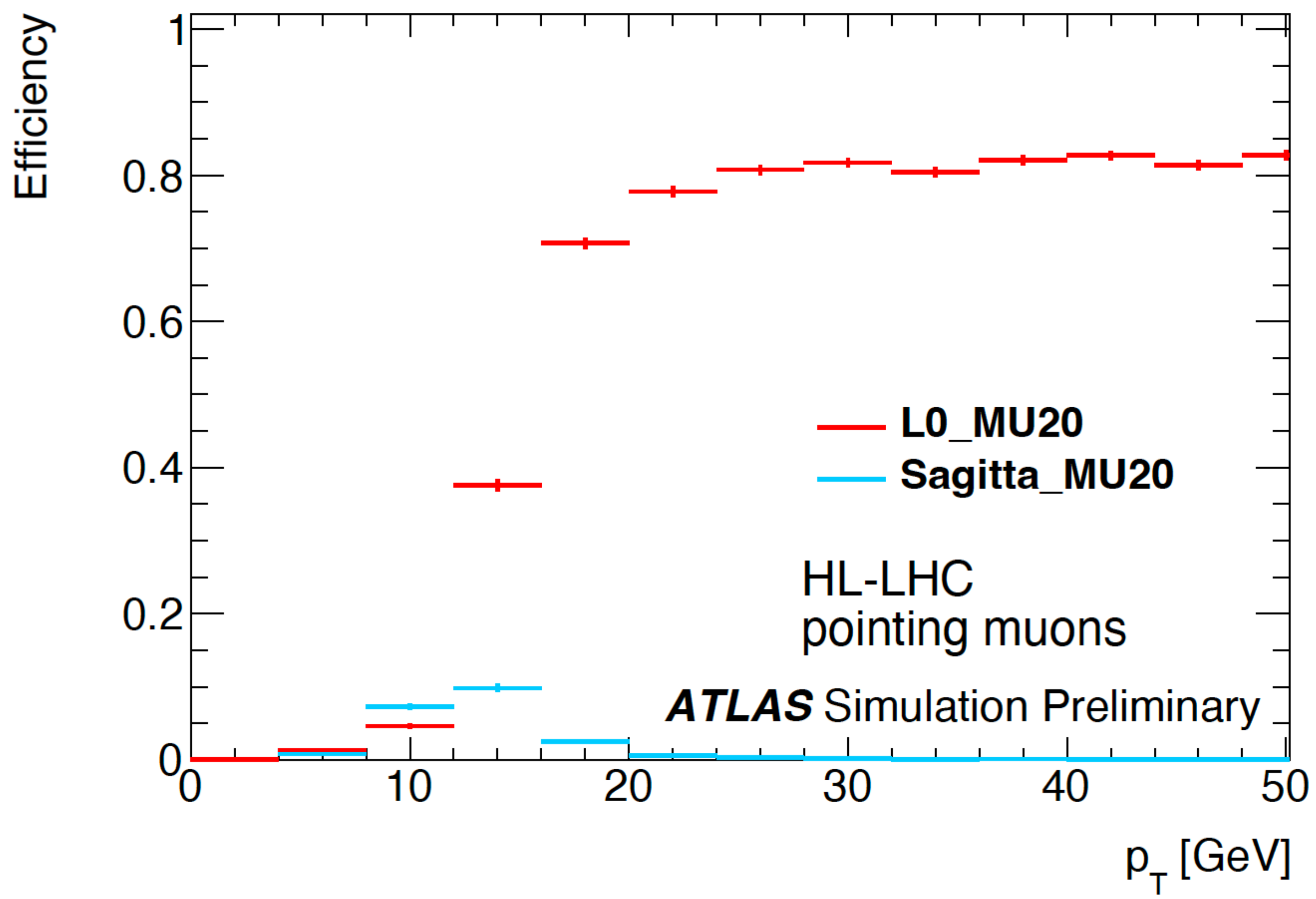




Heavy long-lived objects : performance

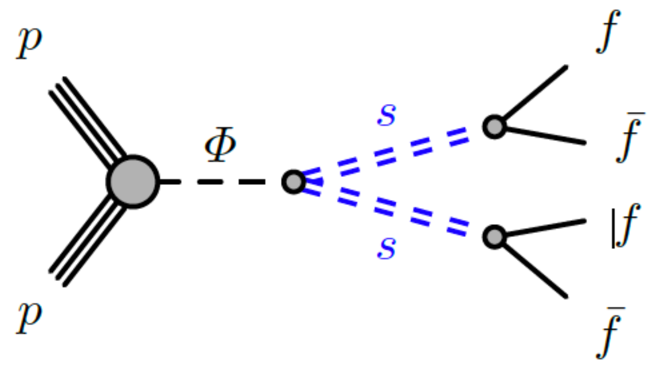
- Significant improvement in efficiency over standard single muon triggers (+20% for FRZV model with 10 GeV dark photon).
- Some residual efficiency on medium-pT pointing muons
- Actual implementation in firmware to be studied.
- Sag calculation could be implemented as a post-processing, in parallel to L0-MDT algorithm as sag=(eta3+eta0)/2-eta2





LLPs with high multiplicity vertices in the Muon Spectrometer

scalar portal



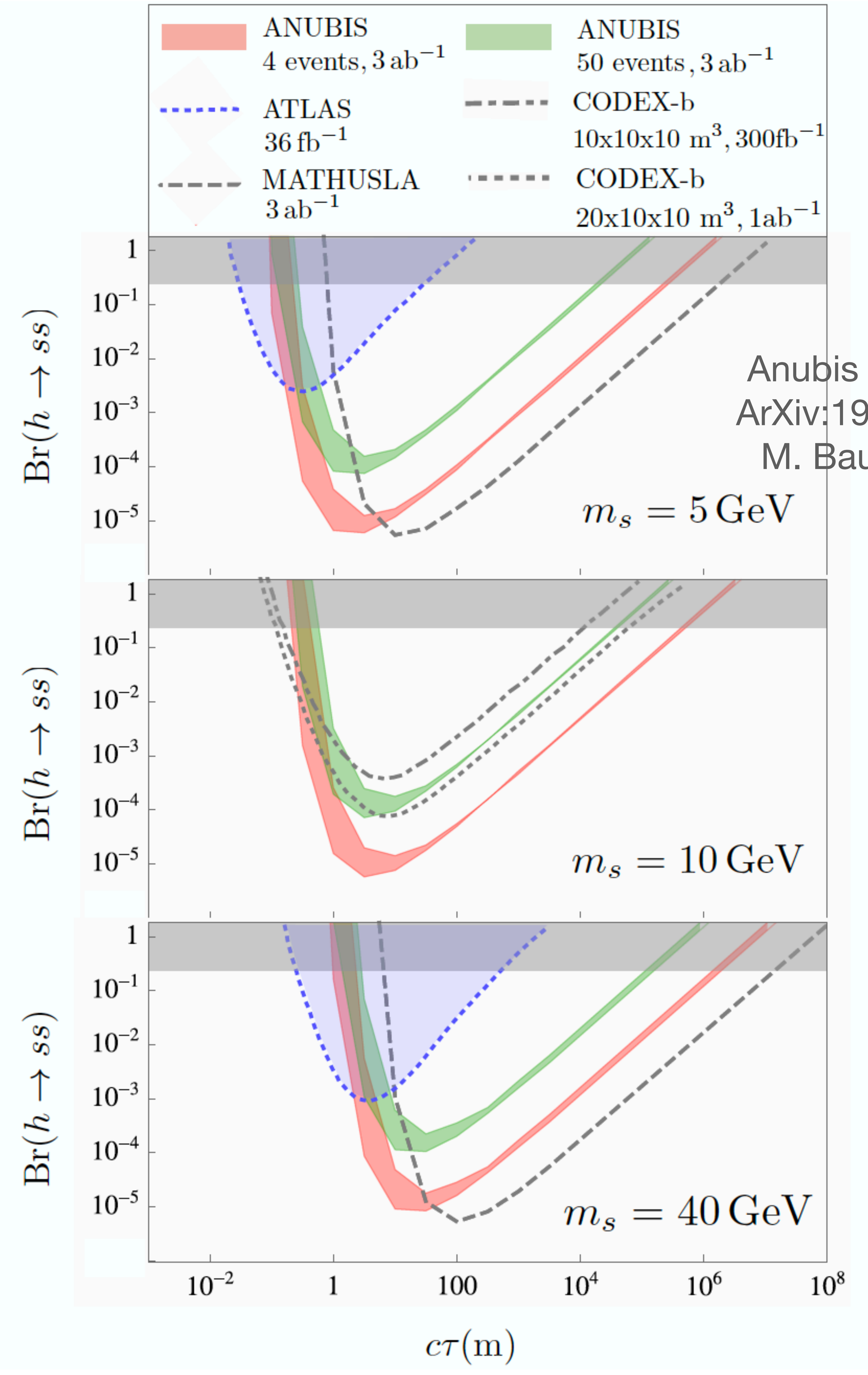
- Dedicated experiment have been proposed at LHC to search for displaced vertices from neutral LLPs

  - MATHUSLA : large tracking system on surface near ATLAS or CMS
  - CODEX : a screened off-axis tracker near LHCb
  - ANUBIS : a tracker in the ATLAS cavern shaft
  - FASER : very forward (in operation !)

- All share a (more or less) large decay volume with tracking stations

- Why not using the ATLAS Muon system itself ?, it has a large decay volume all around the IP

- In fact it has been used in Run-2…



Anubis proposal
ArXiv:1909.13022
M. Bauer et al.

$$P_{decay} = e^{-\frac{L_{min}}{bc\tau}} - e^{-\frac{L_{max}}{bc\tau}}$$

Vertices in the Muon Spectrometer

	ATLAS (barrel)	MATHUSLA
$\epsilon \times A$	0.20	0.05
L_{min} [m]	5.5	200
L_{max} [m]	9.5	230

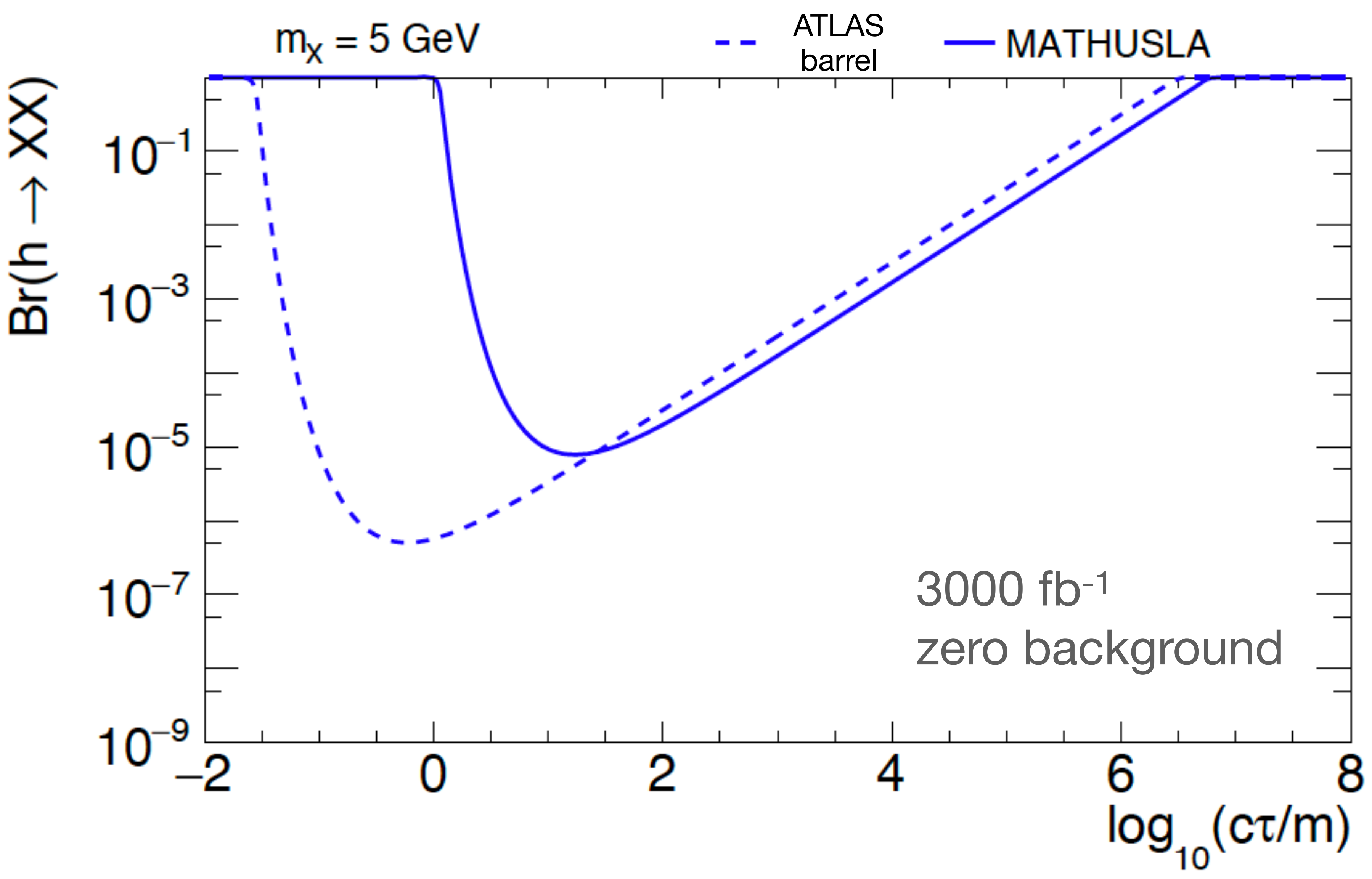
- Thanks to the very large angular acceptance and the depth of the ATLAS spectrometer, ATLAS is very competitive in terms of acceptance, as can be seen with a simple calculation

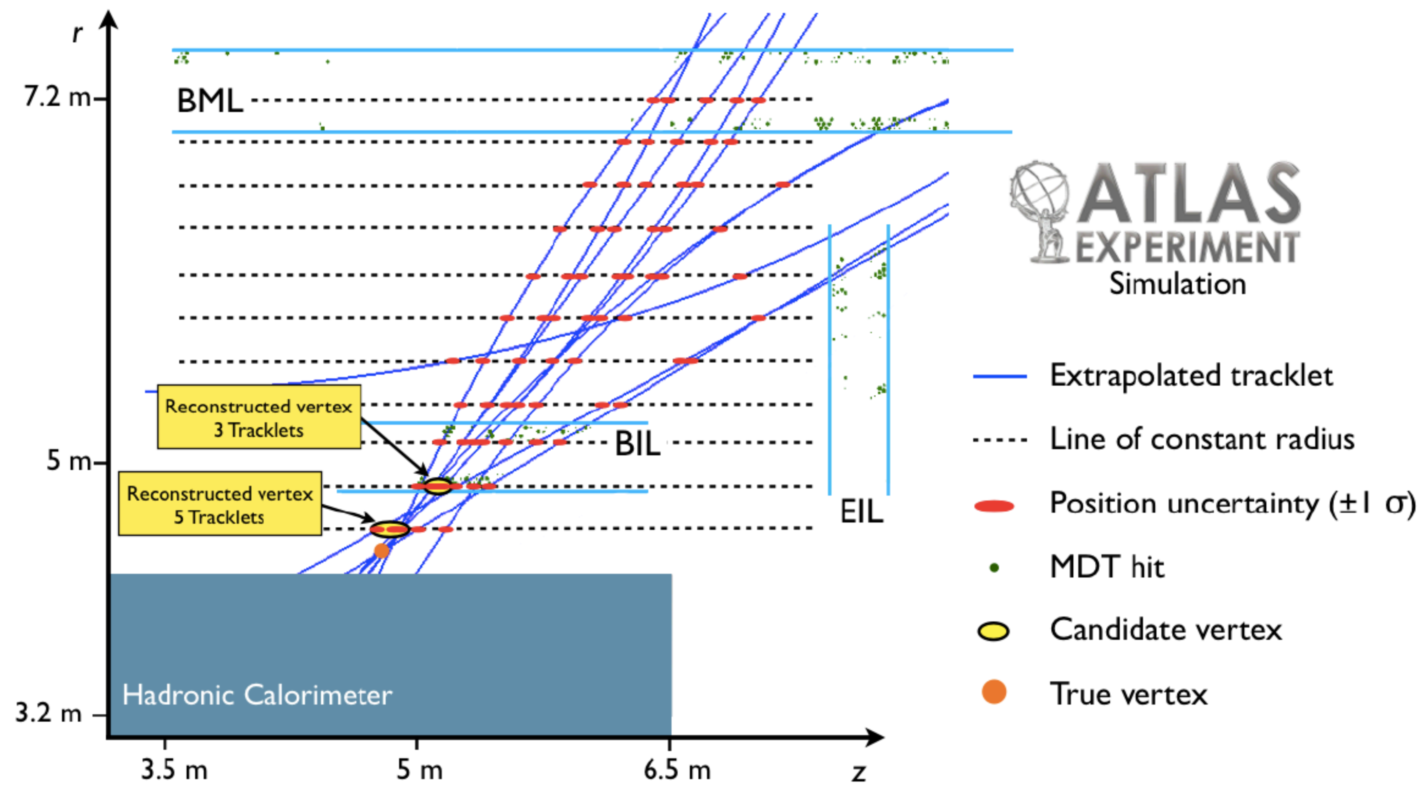
- The main limitation of Run-2 analyses was background.

- To remain close to zero background, two vertices had to be required, at the cost of hugely reduced acceptance at high ctau (both objects need to decay in the fiducial volume)

- The most difficult backgrounds are jets leaking from calorimeters, either mis-reconstructed as displaced or producing showers inside the Muon System. There room to improve: vetoing on calorimeter deposits before the Muon Spectrometer, excluding vertices originating from regions with with materials, improving precision of sec. vertices reconstruction. All this would require the development of some new technology

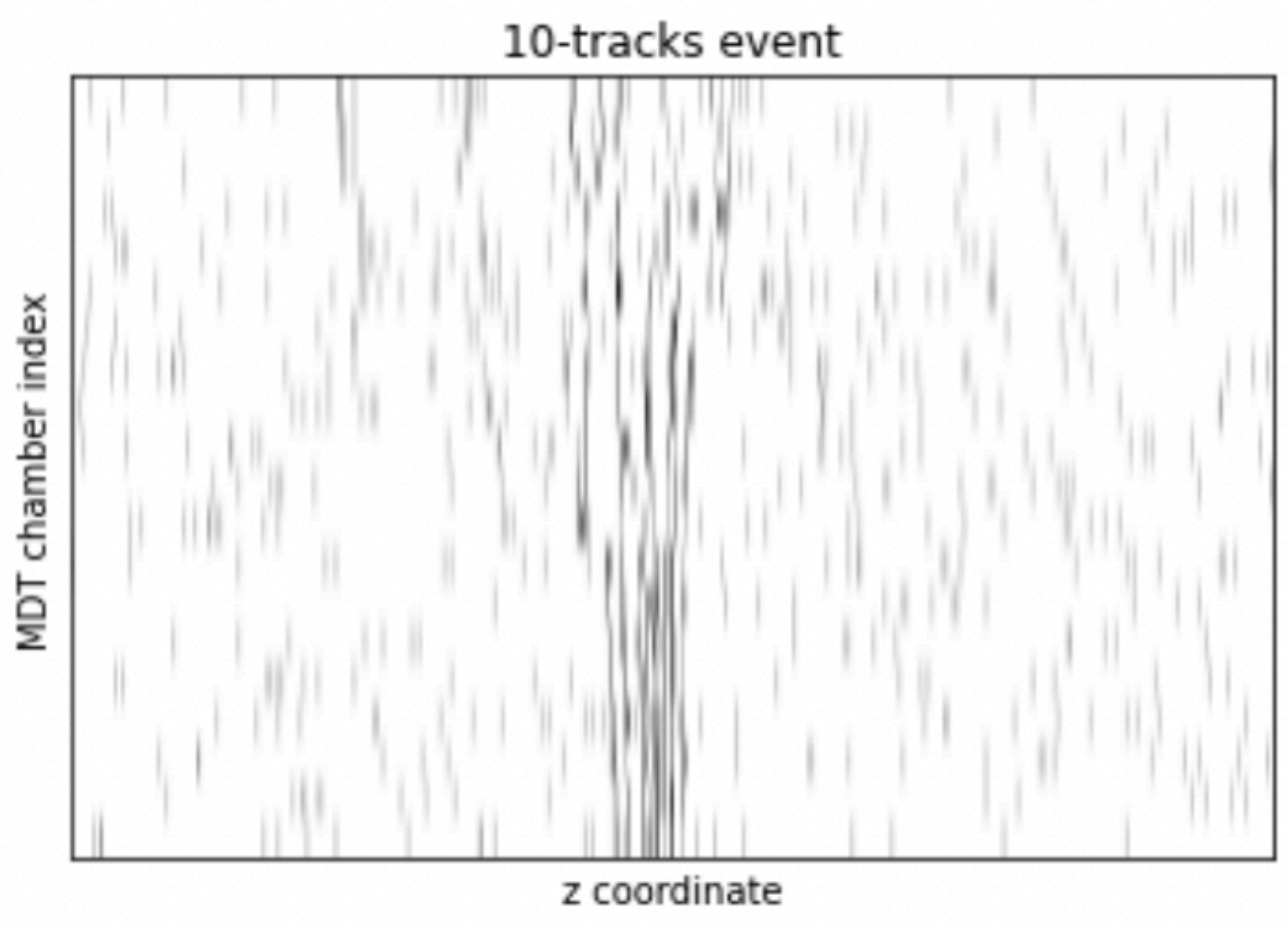
- Whether ATLAS could be competitive with proposed experiments will be clear only after a careful estimate of backgrounds (from all experiments) and ATLAS is the only one approved => it's worth trying

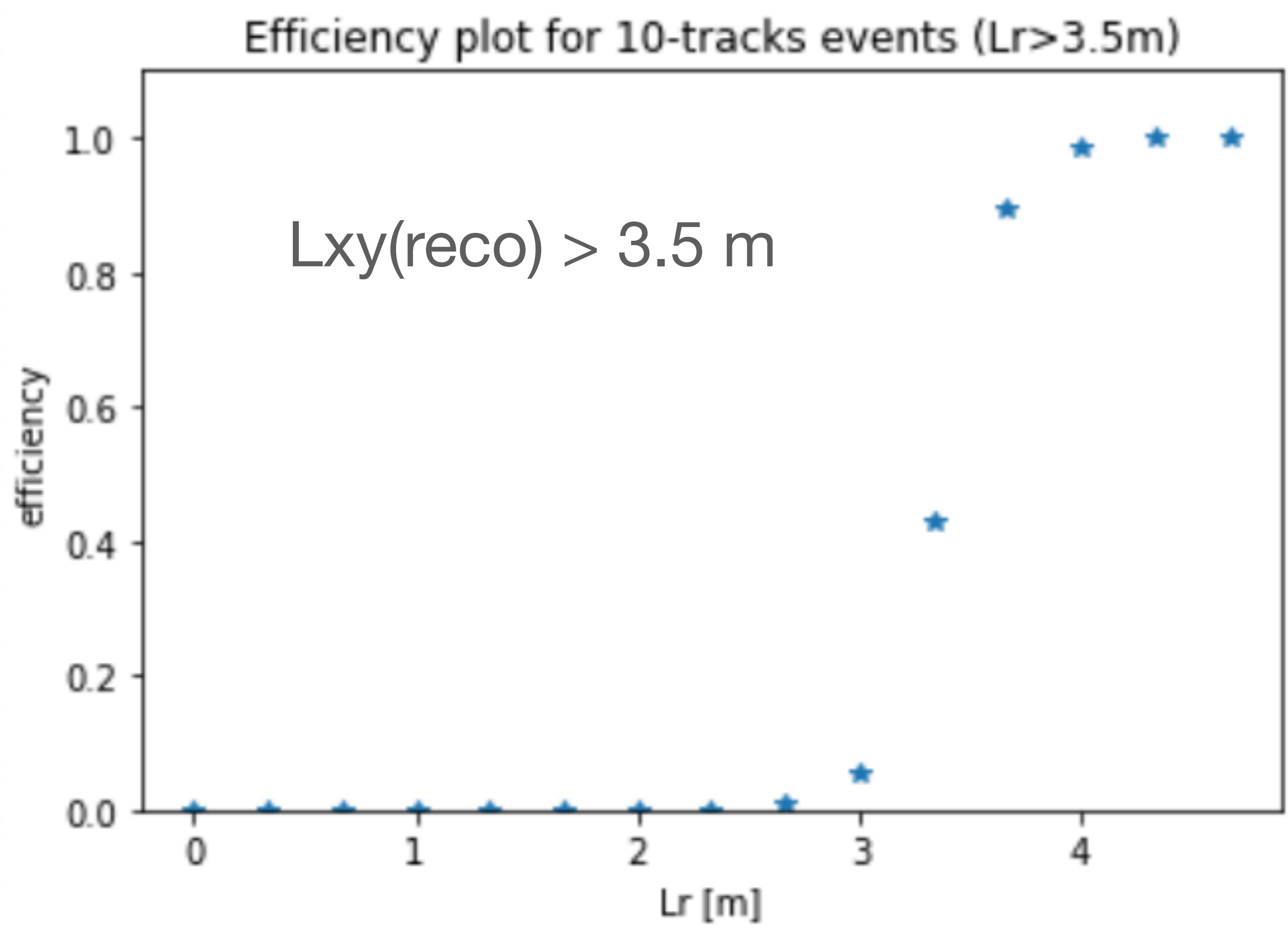




HL-LHC: high multiplicity vertices in the Muon Spectrometer

- At level-0 a trigger on hit multiplicity (possibly with a veto on energy in the Tile Calorimeter) should provide good efficiency and acceptable rate.
- Something more fancy is required in the High-Level Trigger (HLT): we are studying a ML approach to reconstruct multiple track vertices
- CNN using as input images made with hits in RPC and MDT layers from simulated $\gamma_d \rightarrow \pi^+\pi^-$ and $\pi_V \rightarrow b\bar{b}$ decays with pileup and cavern background
- Good reconstruction of decay distance
- Resources available at HLT may be an issue, we tried an implementation on Xilinx Alveo U50 FPGA accelerator with *Vitis AI,* promising results !





	CPU*	FPGA	Improvement
Memory occupancy (MB)	10.96	2.77	4x
Processing time (fps)	348	694.2 (1 thread) 1909.9 (8 threads)	2x (1thread) 5.5x (8 threads)
Energy consumption (Watt)	135	75	1.8x

*CPU Intel Xeon E5-2698 @2.2

Conclusion and outlook

- New ATLAS L0-Muon Barrel trigger for HL-LHC: project progressing well, first prototypes tested

- Some resources may be available for new triggers dedicated to exotic signals, in particular for LLPs

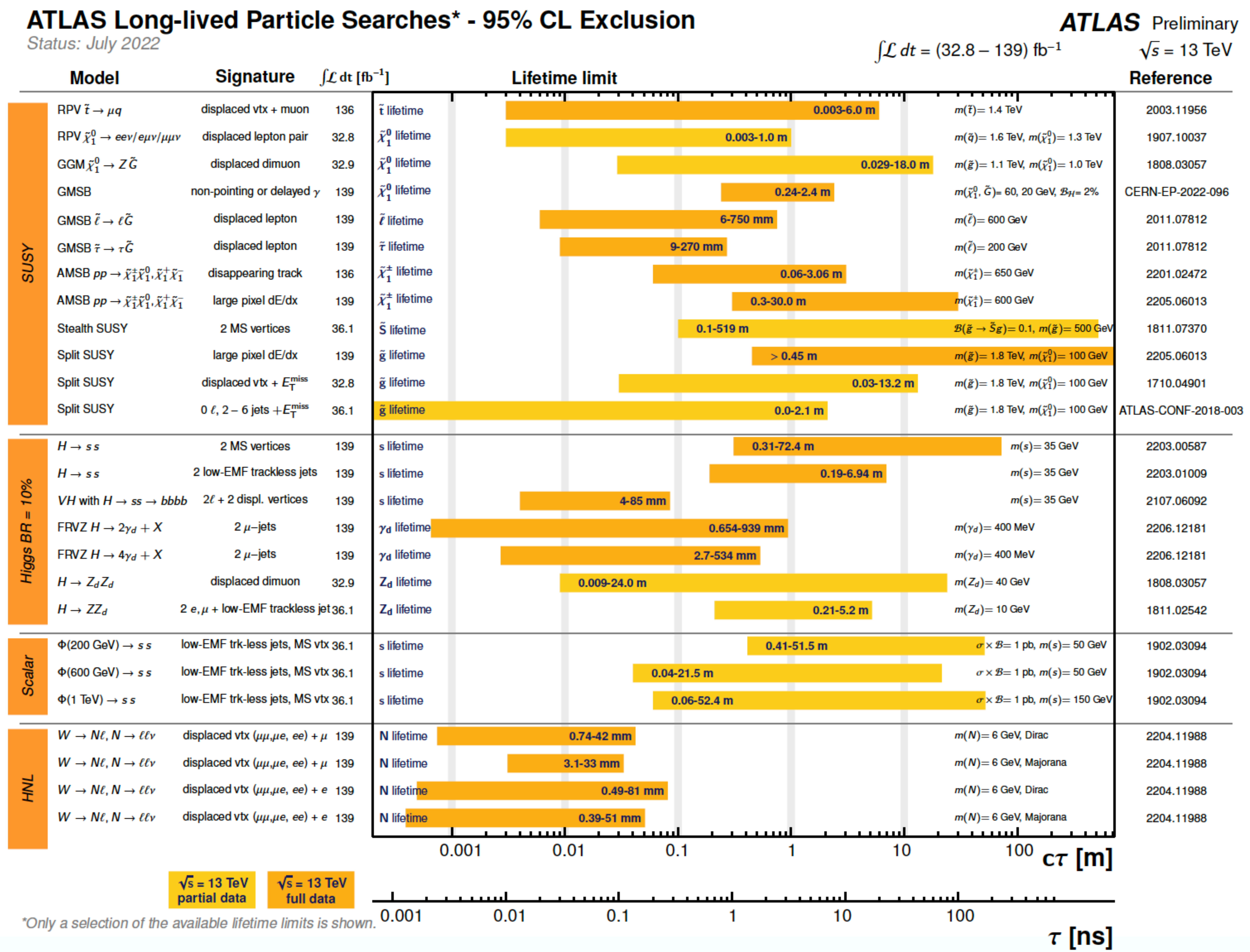
- Some possibilities have been studied:
  - collimated dimuon lepton-jet trigger
  - "sagitta" trigger for muons from displaced vertices

  all very interesting, detailed firmware-based study to be done next

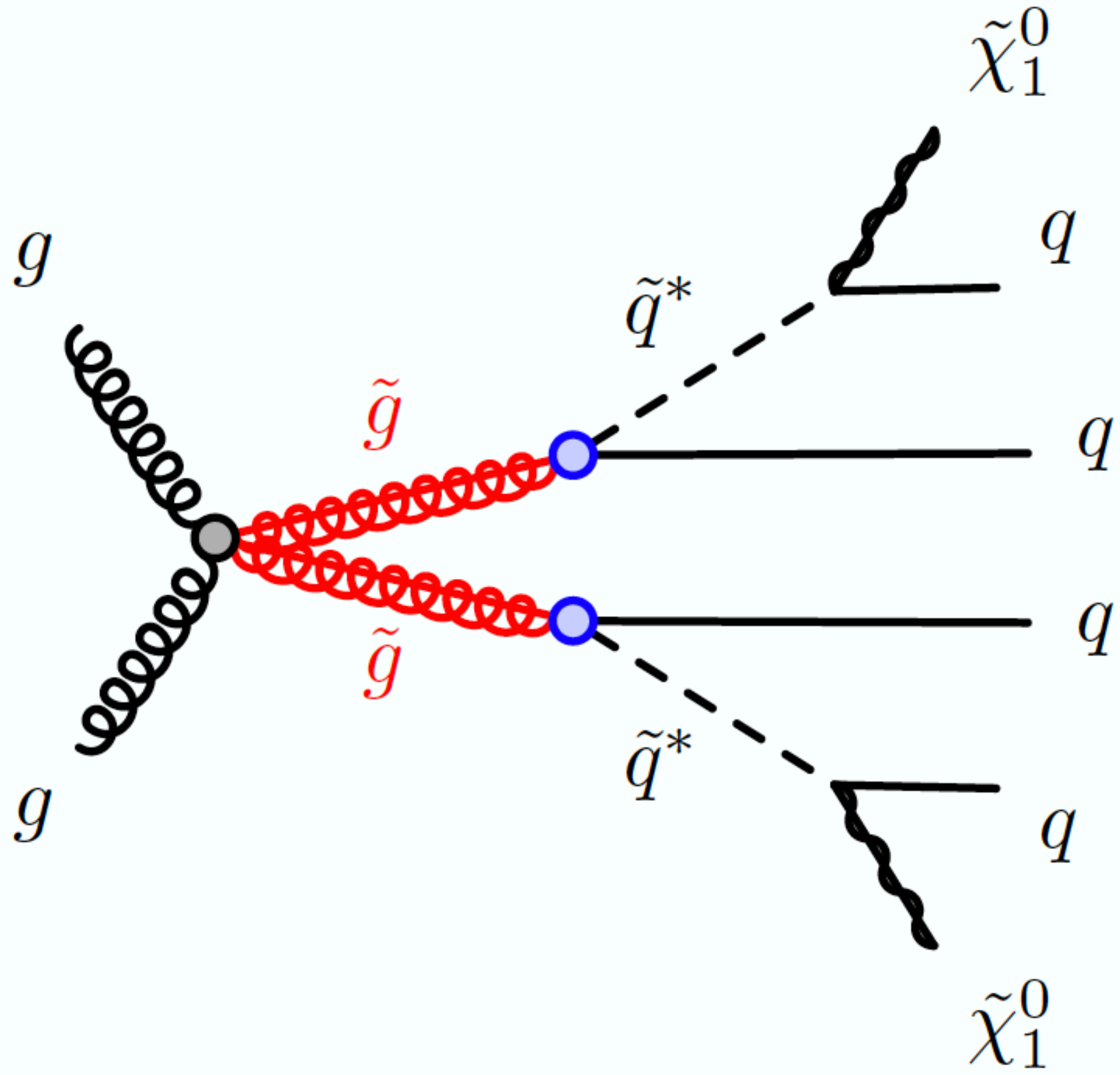
- Machine Learning techniques tried for L0-Muon single-muon trigger and for higher-level trigger displaced vertices searches, look promising but further studies needed

- Next steps: implement the new exotic triggers in actual hardware

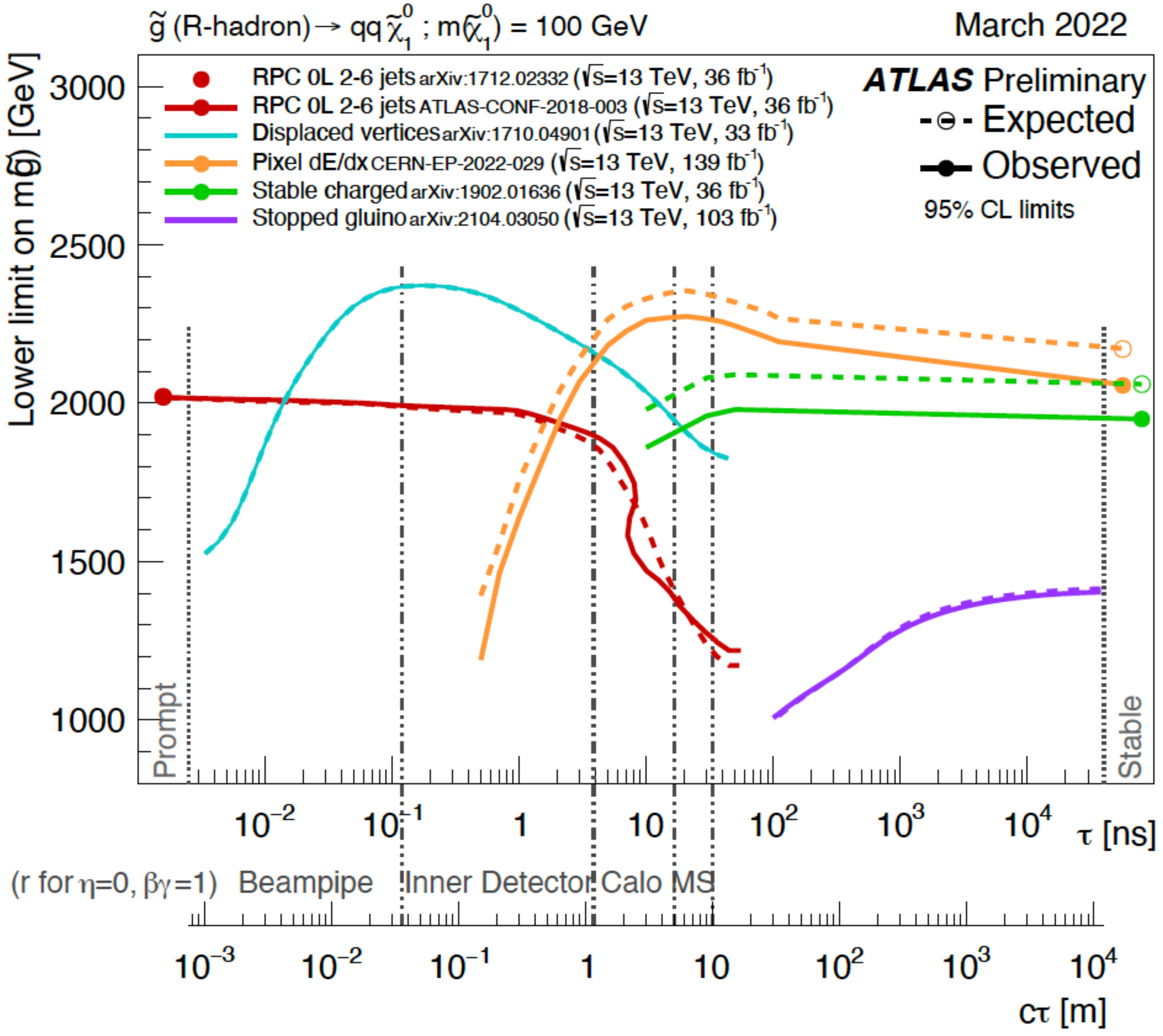
BACKUP



ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2022
ATLAS Preliminary
$\int \mathcal{L}\, dt = (32.8 - 139)$ fb^{-1}
$\sqrt{s} = 13$ TeV
Model
Signature
$\int \mathcal{L}\, dt$ [fb^{-1}]
Lifetime limit
Reference
SUSY
RPV $\tilde{t} \to \mu q$ | displaced vtx + muon | 136 | $\tilde{t}$ lifetime | 0.003-6.0 m | $m(\tilde{t})$= 1.4 TeV | 2003.11956
RPV $\tilde{\chi}^0_1 \to ee\nu/e\mu\nu/\mu\mu\nu$ | displaced lepton pair | 32.8 | $\tilde{\chi}^0_1$ lifetime | 0.003-1.0 m | $m(\tilde{q})$= 1.6 TeV, $m(\tilde{\chi}^0_1)$= 1.3 TeV | 1907.10037
GGM $\tilde{\chi}^0_1 \to Z\tilde{G}$ | displaced dimuon | 32.9 | $\tilde{\chi}^0_1$ lifetime | 0.029-18.0 m | $m(\tilde{g})$= 1.1 TeV, $m(\tilde{\chi}^0_1)$= 1.0 TeV | 1808.03057
GMSB | non-pointing or delayed γ | 139 | $\tilde{\chi}^0_1$ lifetime | 0.24-2.4 m | $m(\tilde{\chi}^0_1, \tilde{G})$= 60, 20 GeV, $\mathcal{B}_H$= 2% | CERN-EP-2022-096
GMSB $\tilde{\ell} \to \ell\tilde{G}$ | displaced lepton | 139 | $\tilde{\ell}$ lifetime | 6-750 mm | $m(\tilde{\ell})$= 600 GeV | 2011.07812
GMSB $\tilde{\tau} \to \tau\tilde{G}$ | displaced lepton | 139 | $\tilde{\tau}$ lifetime | 9-270 mm | $m(\tilde{\ell})$= 200 GeV | 2011.07812
AMSB $pp \to \tilde{\chi}^\pm_1\tilde{\chi}^0_1, \tilde{\chi}^+_1\tilde{\chi}^-_1$ | disappearing track | 136 | $\tilde{\chi}^\pm_1$ lifetime | 0.06-3.06 m | $m(\tilde{\chi}^\pm_1)$= 650 GeV | 2201.02472
AMSB $pp \to \tilde{\chi}^\pm_1\tilde{\chi}^0_1, \tilde{\chi}^+_1\tilde{\chi}^-_1$ | large pixel dE/dx | 139 | $\tilde{\chi}^\pm_1$ lifetime | 0.3-30.0 m | $m(\tilde{\chi}^\pm_1)$= 600 GeV | 2205.06013
Stealth SUSY | 2 MS vertices | 36.1 | $\tilde{S}$ lifetime | 0.1-519 m | $\mathcal{B}(\tilde{g} \to \tilde{S}g)$= 0.1, $m(\tilde{g})$= 500 GeV | 1811.07370
Split SUSY | large pixel dE/dx | 139 | $\tilde{g}$ lifetime | > 0.45 m | $m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}^0_1)$= 100 GeV | 2205.06013
Split SUSY | displaced vtx + E_T^{miss} | 32.8 | $\tilde{g}$ lifetime | 0.03-13.2 m | $m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}^0_1)$= 100 GeV | 1710.04901
Split SUSY | $0\ \ell$, $2-6$ jets $+E_T^{miss}$ | 36.1 | $\tilde{g}$ lifetime | 0.0-2.1 m | $m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}^0_1)$= 100 GeV | ATLAS-CONF-2018-003
Higgs BR = 10%
$H \to ss$ | 2 MS vertices | 139 | s lifetime | 0.31-72.4 m | $m(s)$= 35 GeV | 2203.00587
$H \to ss$ | 2 low-EMF trackless jets | 139 | s lifetime | 0.19-6.94 m | $m(s)$= 35 GeV | 2203.01009
VH with $H \to ss \to bbbb$ | 2ℓ + 2 displ. vertices | 139 | s lifetime | 4-85 mm | $m(s)$= 35 GeV | 2107.06092
FRVZ $H \to 2\gamma_d + X$ | 2 μ–jets | 139 | γ_d lifetime | 0.654-939 mm | $m(\gamma_d)$= 400 MeV | 2206.12181
FRVZ $H \to 4\gamma_d + X$ | 2 μ–jets | 139 | γ_d lifetime | 2.7-534 mm | $m(\gamma_d)$= 400 MeV | 2206.12181
$H \to Z_d Z_d$ | displaced dimuon | 32.9 | Z_d lifetime | 0.009-24.0 m | $m(Z_d)$= 40 GeV | 1808.03057
$H \to ZZ_d$ | 2 e,μ + low-EMF trackless jet | 36.1 | Z_d lifetime | 0.21-5.2 m | $m(Z_d)$= 10 GeV | 1811.02542
Scalar
Φ(200 GeV) $\to ss$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.41-51.5 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV | 1902.03094
Φ(600 GeV) $\to ss$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.04-21.5 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV | 1902.03094
Φ(1 TeV) $\to ss$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.06-52.4 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV | 1902.03094
HNL
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + μ | 139 | N lifetime | 0.74-42 mm | $m(N)$= 6 GeV, Dirac | 2204.11988
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + μ | 139 | N lifetime | 3.1-33 mm | $m(N)$= 6 GeV, Majorana | 2204.11988
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + e | 139 | N lifetime | 0.49-81 mm | $m(N)$= 6 GeV, Dirac | 2204.11988
$W \to N\ell, N \to \ell\ell\nu$ | displaced vtx ($\mu\mu$,μe, ee) + e | 139 | N lifetime | 0.39-51 mm | $m(N)$= 6 GeV, Majorana | 2204.11988
0.001
0.01
0.1
1
10
100
$c\tau$ [m]
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
0.001
0.01
0.1
1
10
100
τ [ns]
*Only a selection of the available lifetime limits is shown.

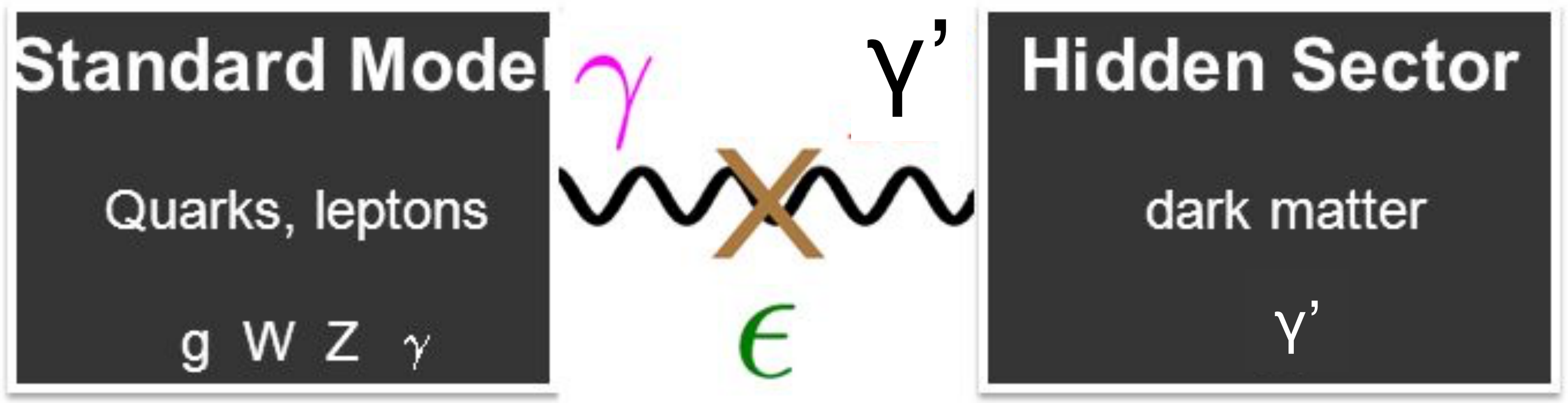


g
g
g̃
g̃
q̃*
q̃*
q
q
q
q
χ̃⁰₁
χ̃⁰₁



g̃ (R-hadron) → qq χ̃⁰₁ ; m(χ̃⁰₁) = 100 GeV
March 2022
RPC 0L 2-6 jets arXiv:1712.02332 (√s=13 TeV, 36 fb⁻¹)
RPC 0L 2-6 jets ATLAS-CONF-2018-003 (√s=13 TeV, 36 fb⁻¹)
Displaced vertices arXiv:1710.04901 (√s=13 TeV, 33 fb⁻¹)
Pixel dE/dx CERN-EP-2022-029 (√s=13 TeV, 139 fb⁻¹)
Stable charged arXiv:1902.01636 (√s=13 TeV, 36 fb⁻¹)
Stopped gluino arXiv:2104.03050 (√s=13 TeV, 103 fb⁻¹)
ATLAS Preliminary
Expected
Observed
95% CL limits
Lower limit on m(g̃) [GeV]
3000
2500
2000
1500
1000
Prompt
Stable
10⁻²
10⁻¹
1
10
10²
10³
10⁴
τ [ns]
(r for η=0, βγ=1)
Beampipe
Inner Detector
Calo
MS
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
10⁴
cτ [m]

Lepton jets : models



- Many models of new physics weakly coupled to SM
- A typical example is a "hidden" sector with its U(1) symmetry, including a dark photon γ_d which can mix kinematically with normal photon
- Production can occur through specific "portals", e.g. Higgs portal, or directly via kinematic mixing in Drell-Yan process
- We consider here as a benchmark light γ_d produced via Higgs portal (FRVZ model)
- If mass is low they can only decay in lepton pairs giving rise to collimated, non-prompt lepton jet signatures: lepton jets
- Current limits from ATLAS: