

Long-lived particle searches at the LHC and FPF

Flavia de Almeida Dias

Theory Meets Experiment 2023 09 June 2023



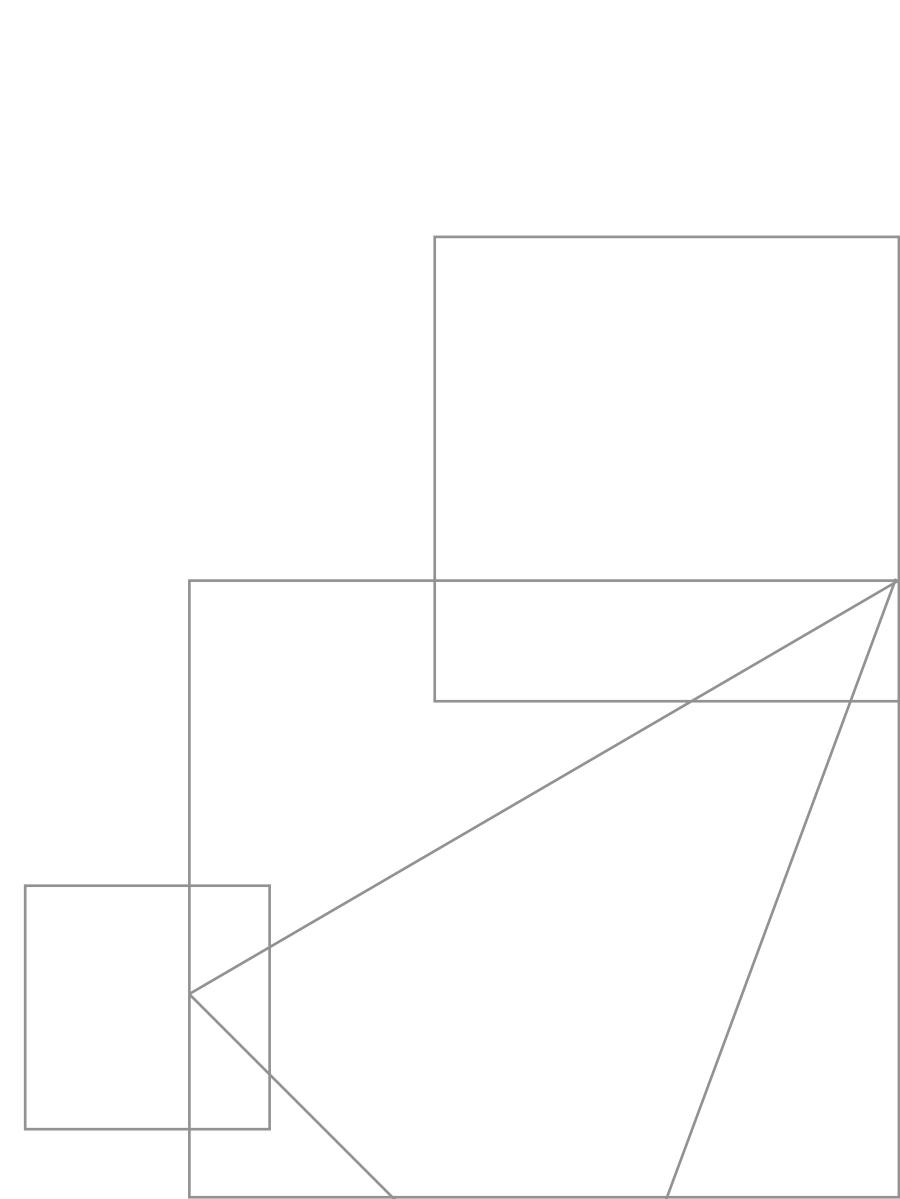
UNIVERSITY OF AMSTERDAM Institute of Physics





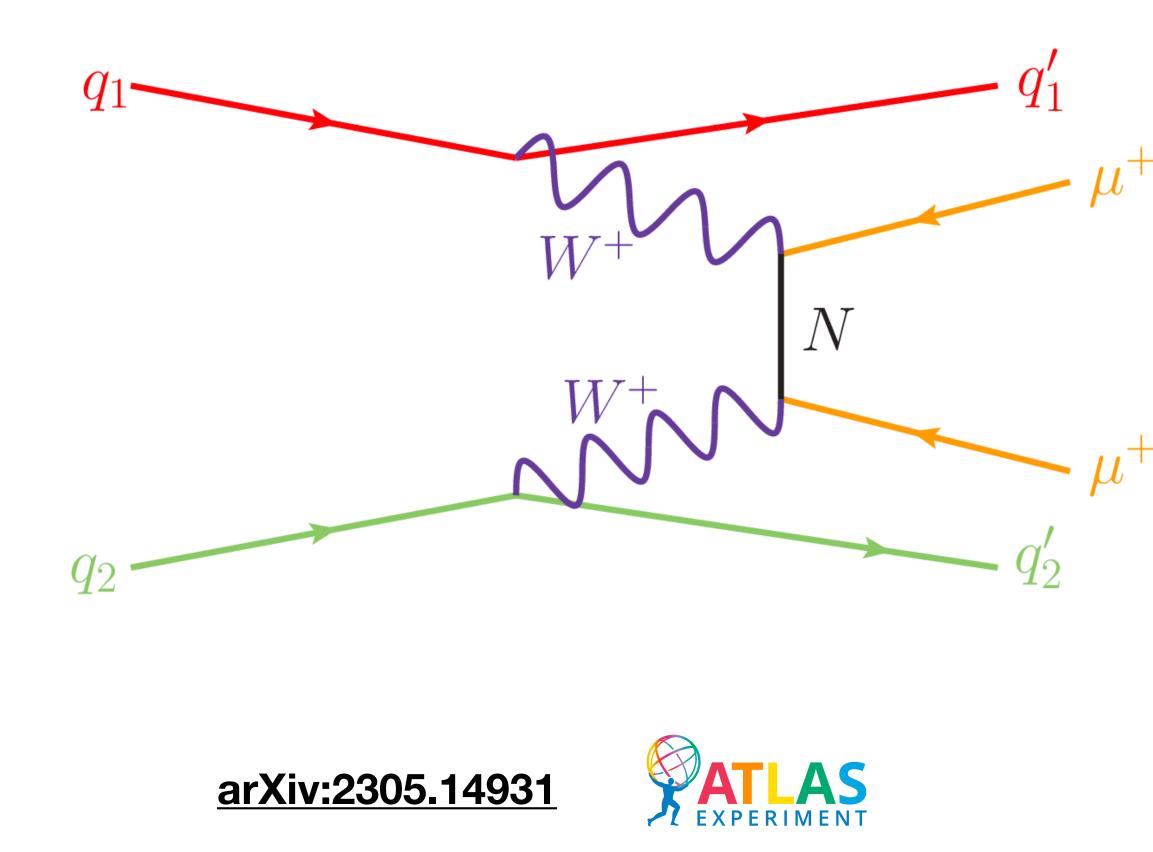


Interlude



Neutrinoless Double Beta Decay at LHC

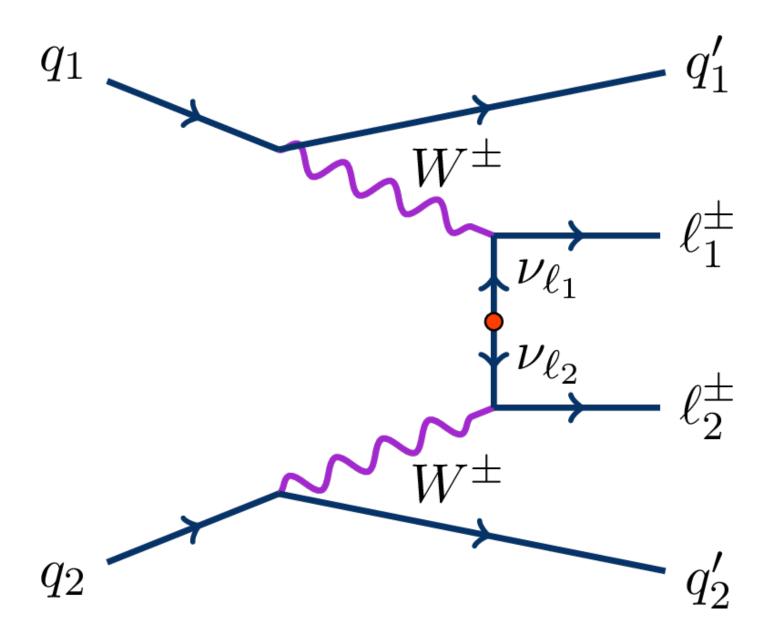
Same-sign µ±µ± production in W±W± scattering mediated by a Majorana neutrino N in proton-proton collisions



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Example Feynman diagram of processes mediated by the Weinberg operator at the LHC









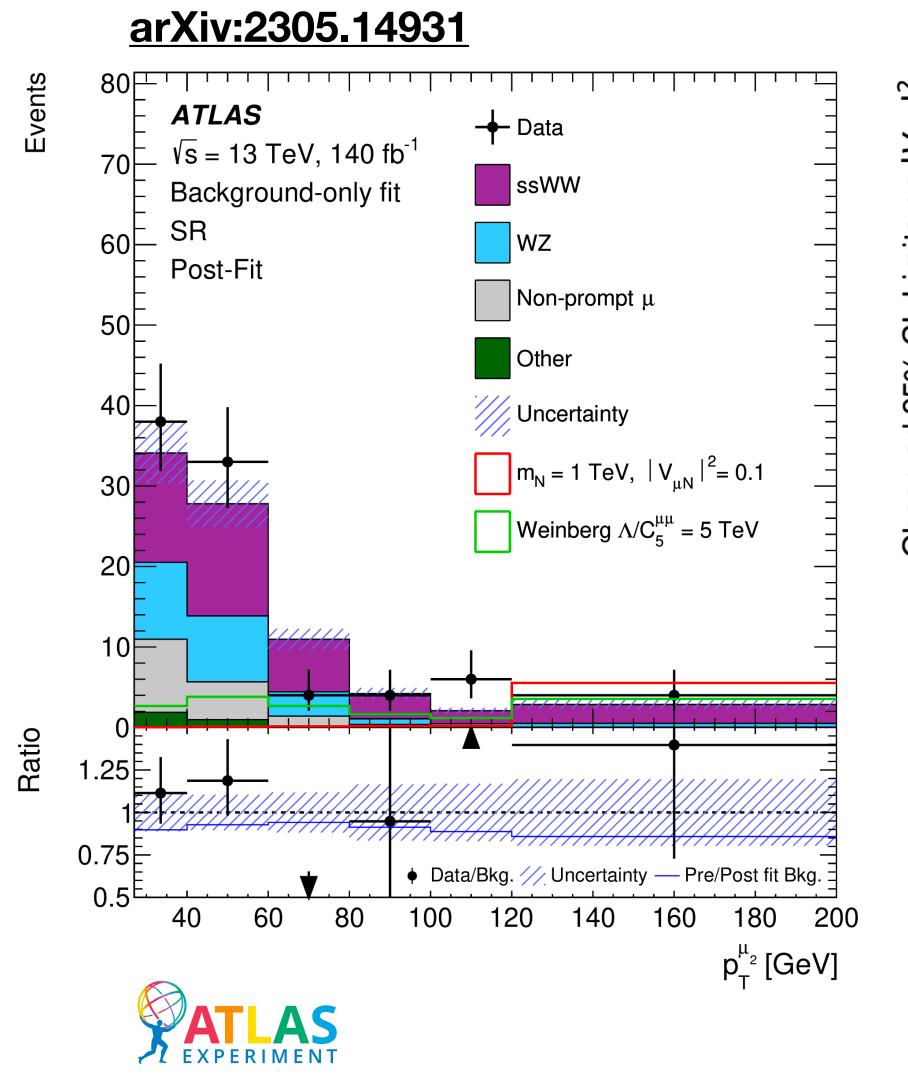
Neutrinoless Double Beta Decay at LHC

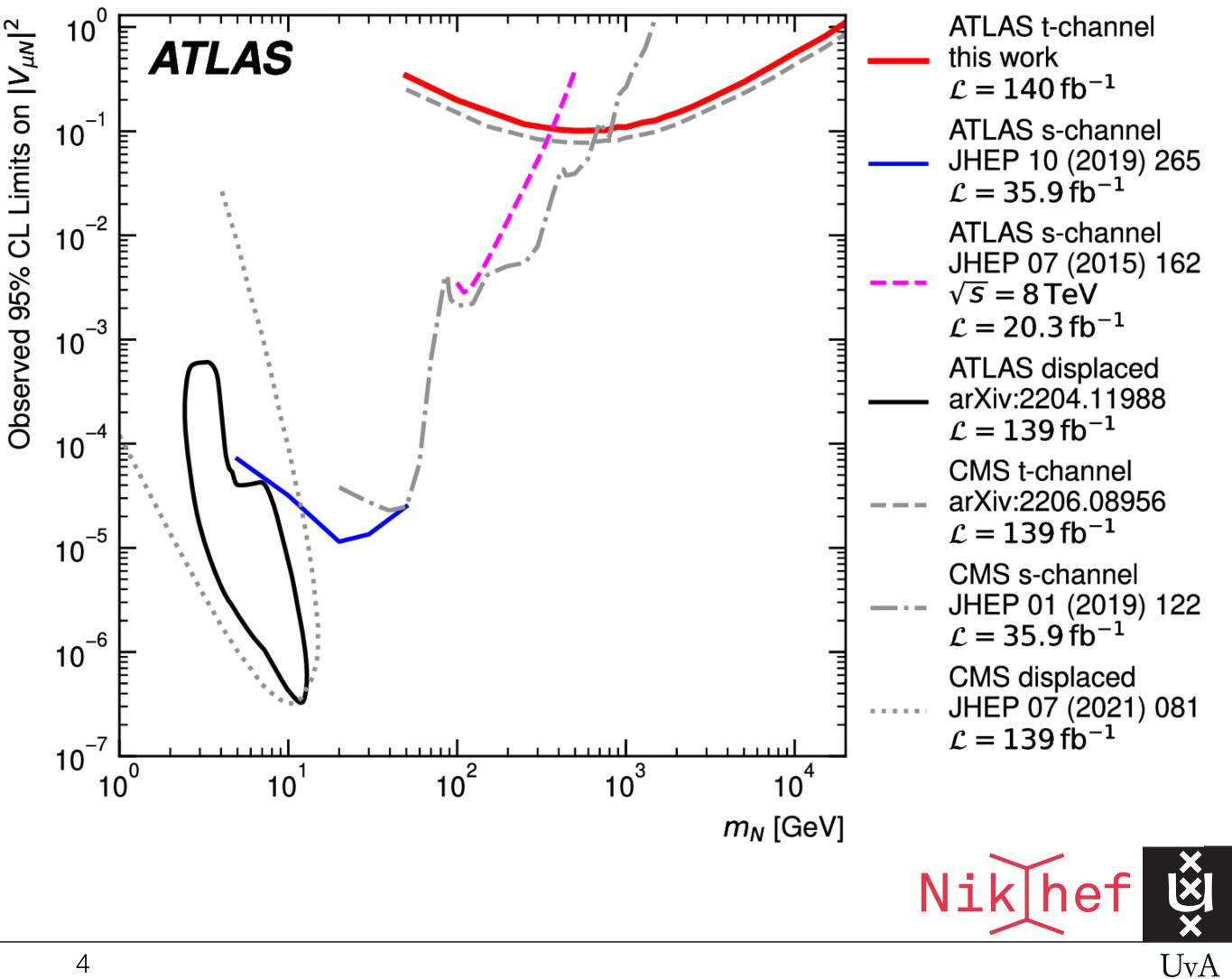


Mengqing Wu



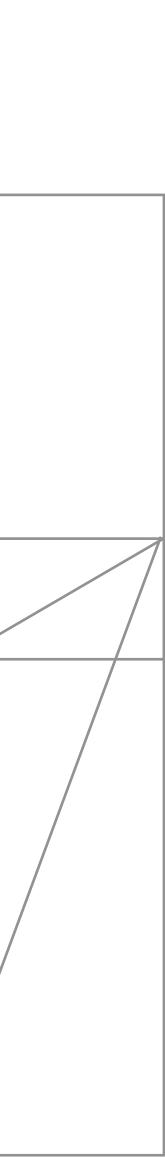
Nicolo de Groot





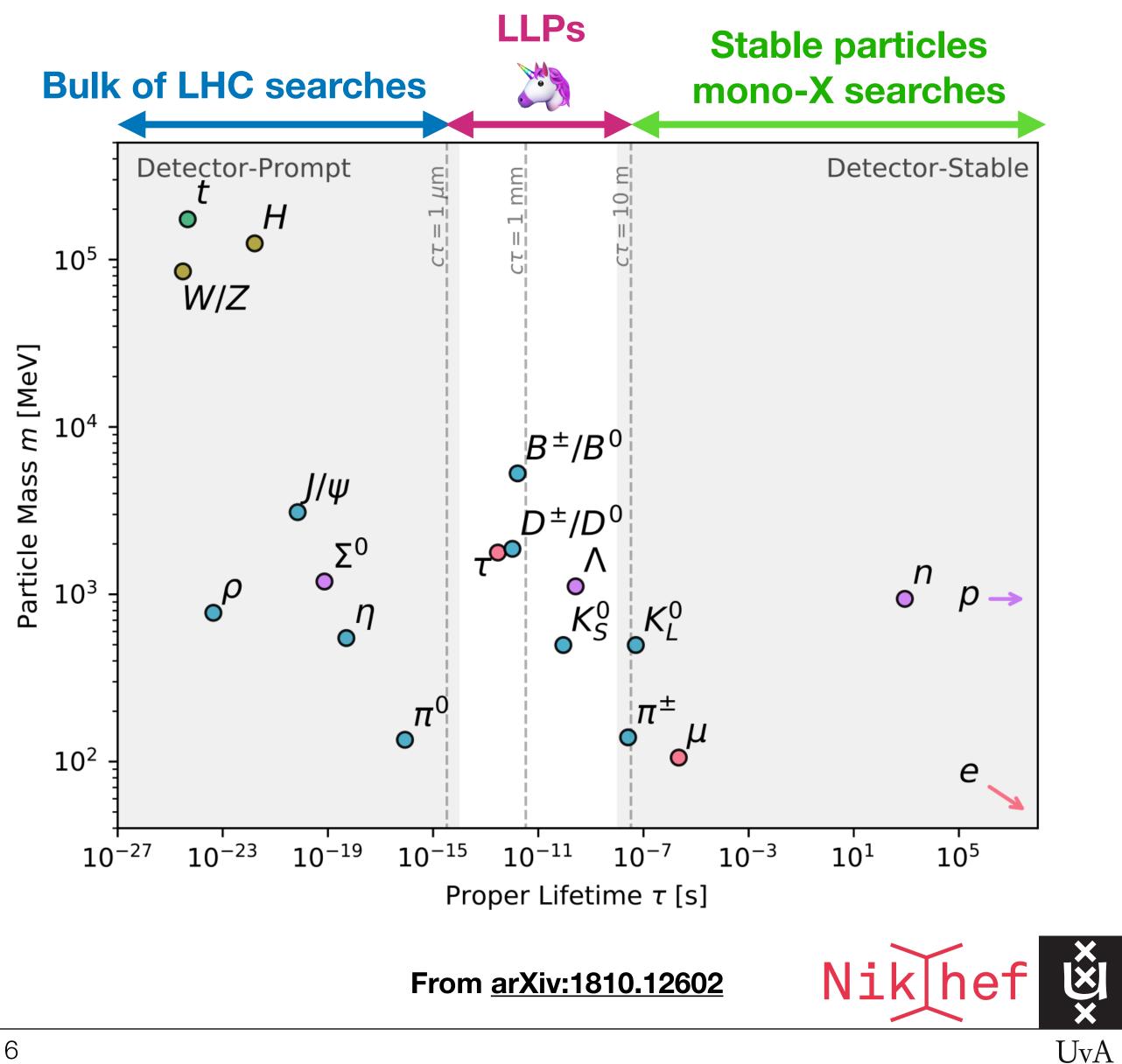


Long-Lived Particles: Experimentalist perspective



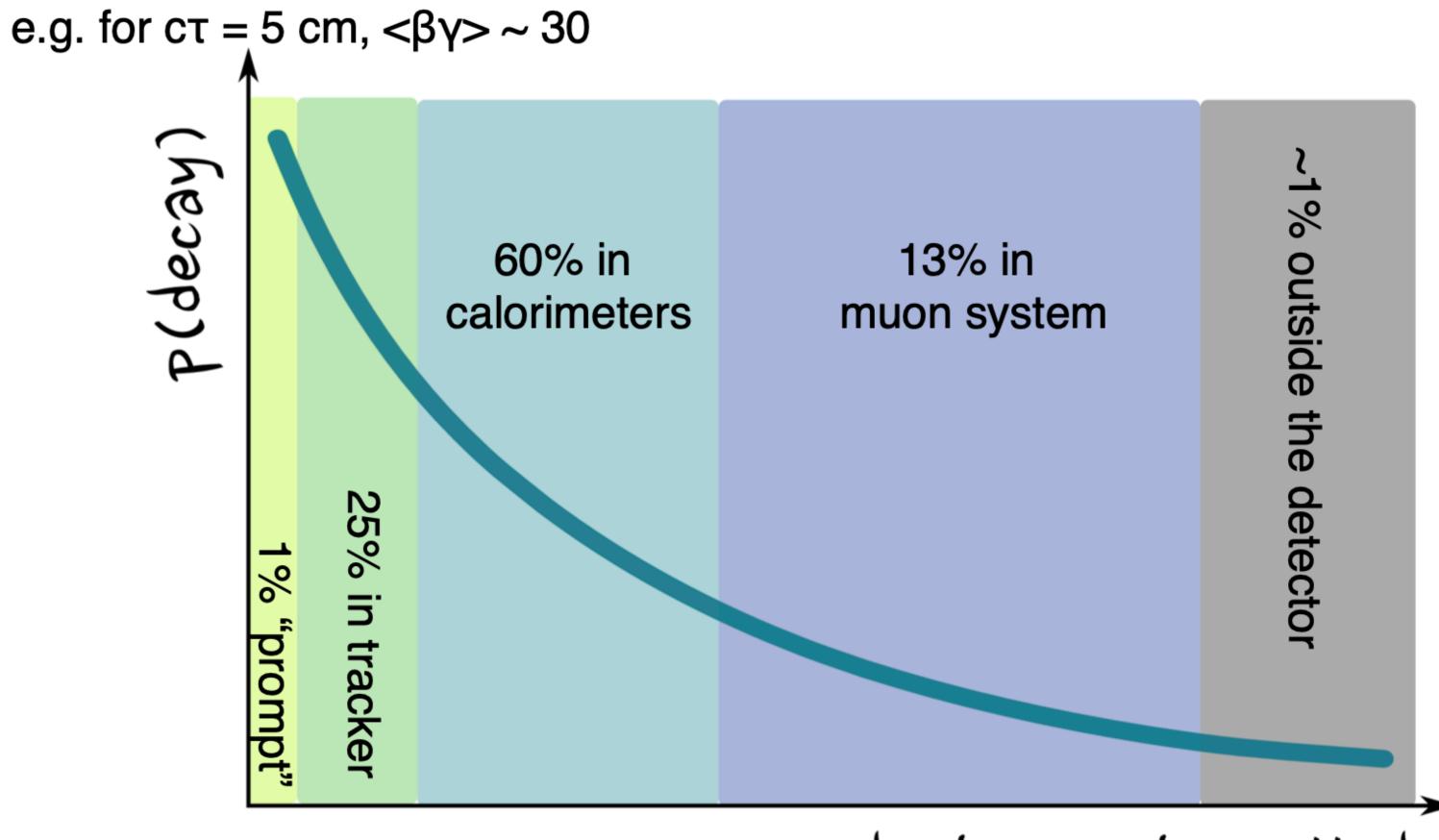
Searching the "lifetime" dimension

- Long-lived particles (LLPs): promising direction to expand searches @ LHC
 - Without dedicated searches, we could be missing new physics!
 - Impressive progress in recent years, but plenty of room for creativity!
 - Theoretically well motivated!
 - Ask the theorists in this room :)



Why do we need so many searches?

• Even particles with a short proper li distance:



From H. Russell

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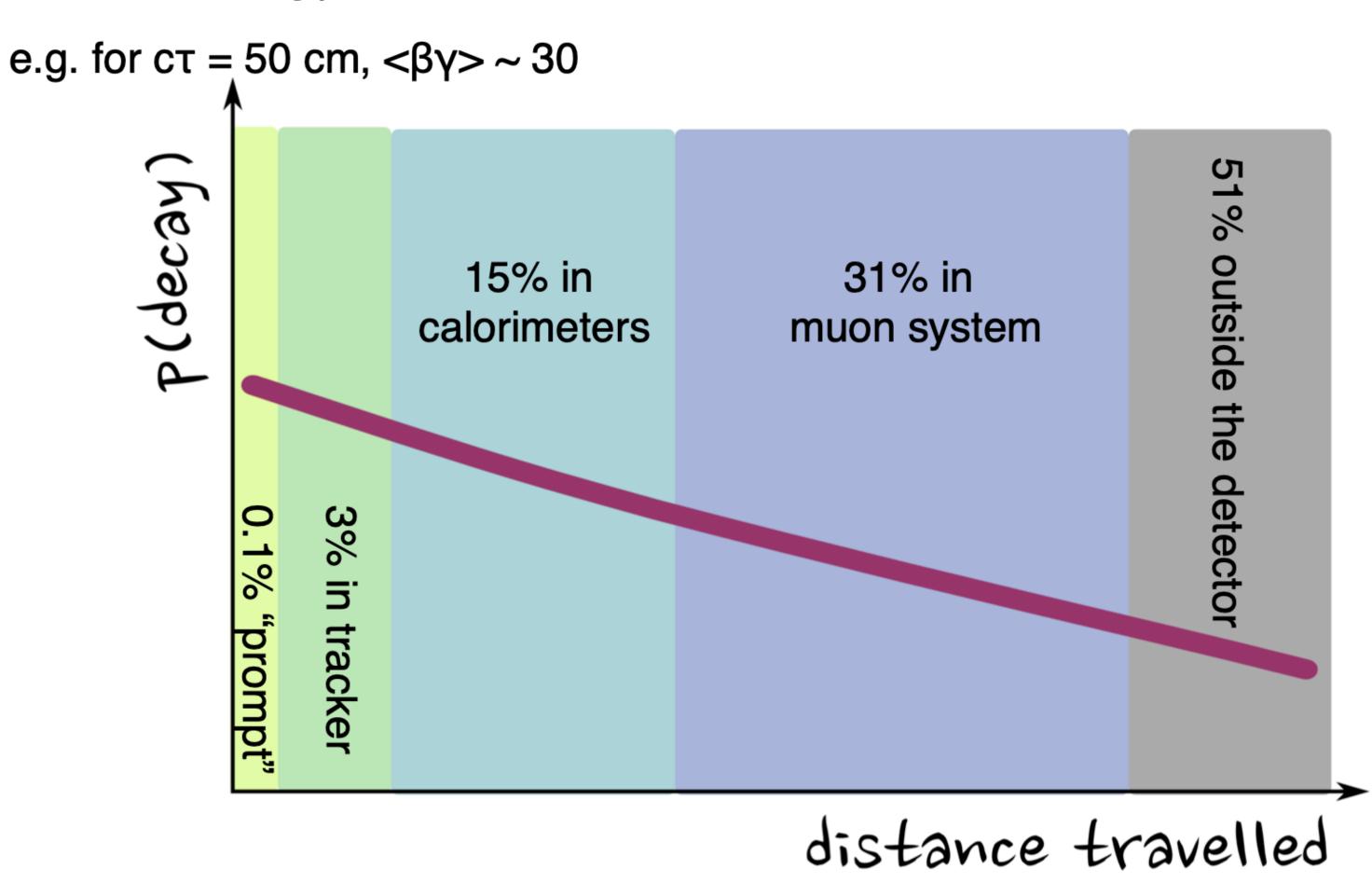
Even particles with a short proper lifetime can decay with a large lab-frame

distance travelled



Why do we need so many searches?

different search strategy!



From H. Russell

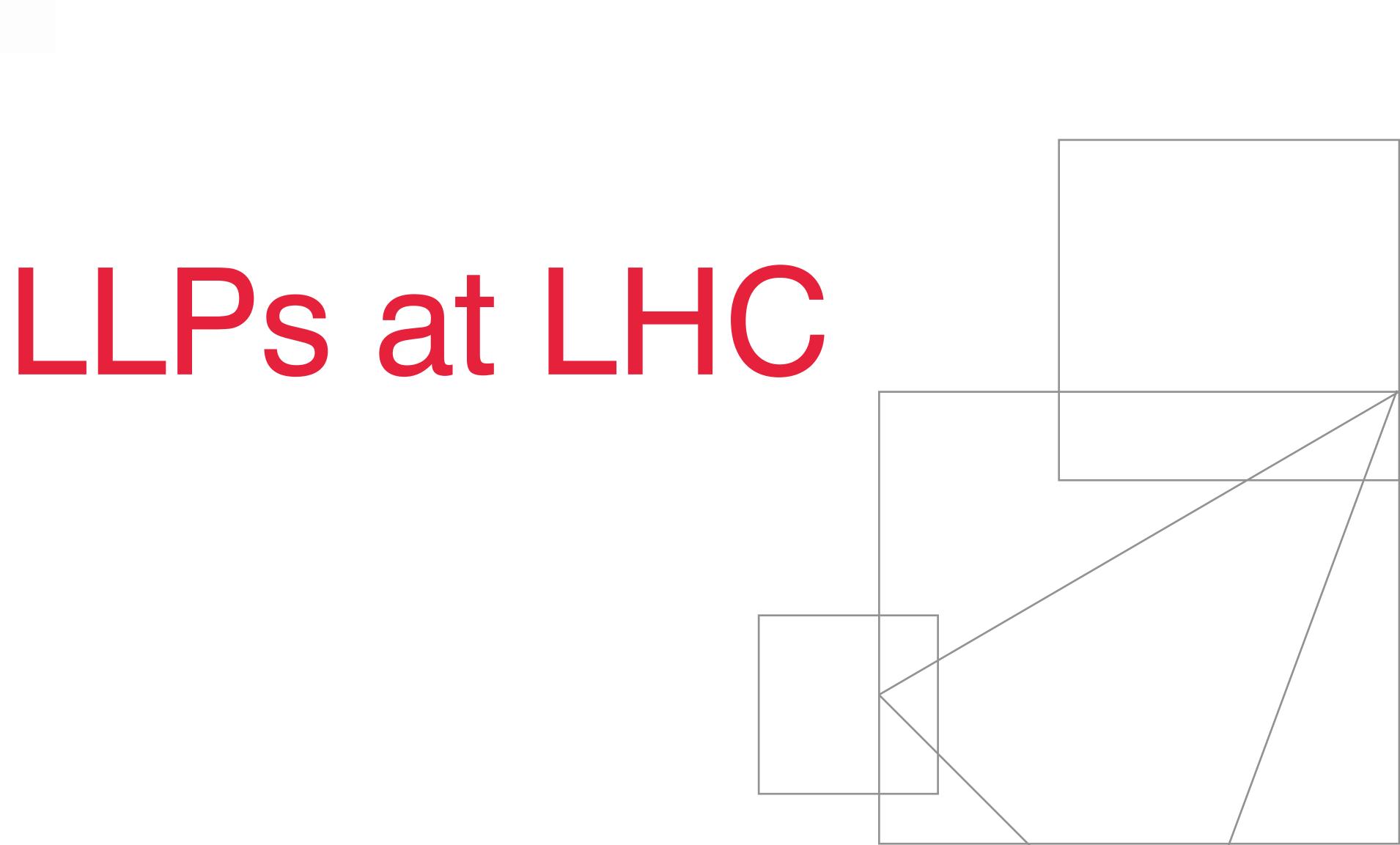
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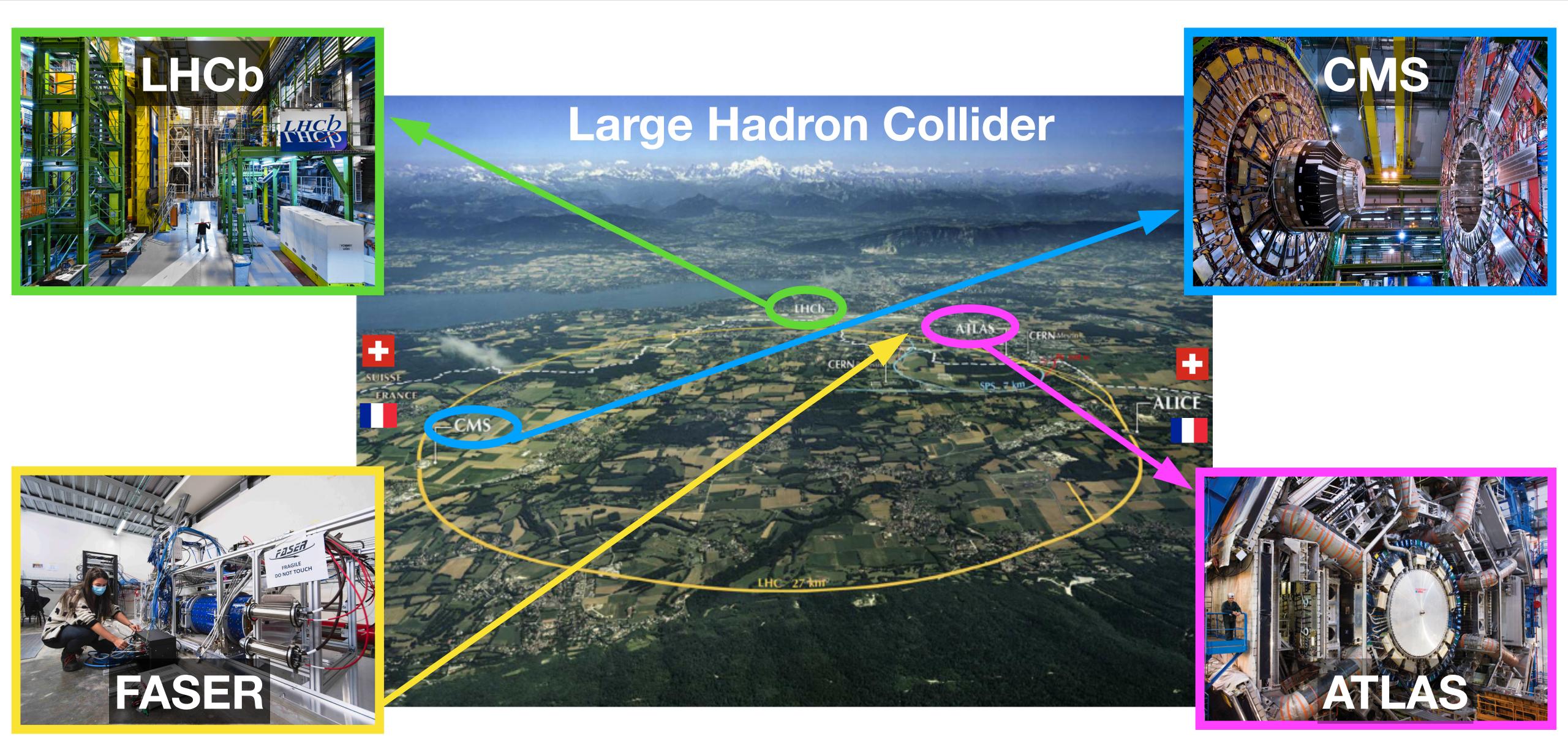
But if we want to consider particles with a longer lifetime, need a dramatically











Credit (all images): <u>cds.cern.ch</u>

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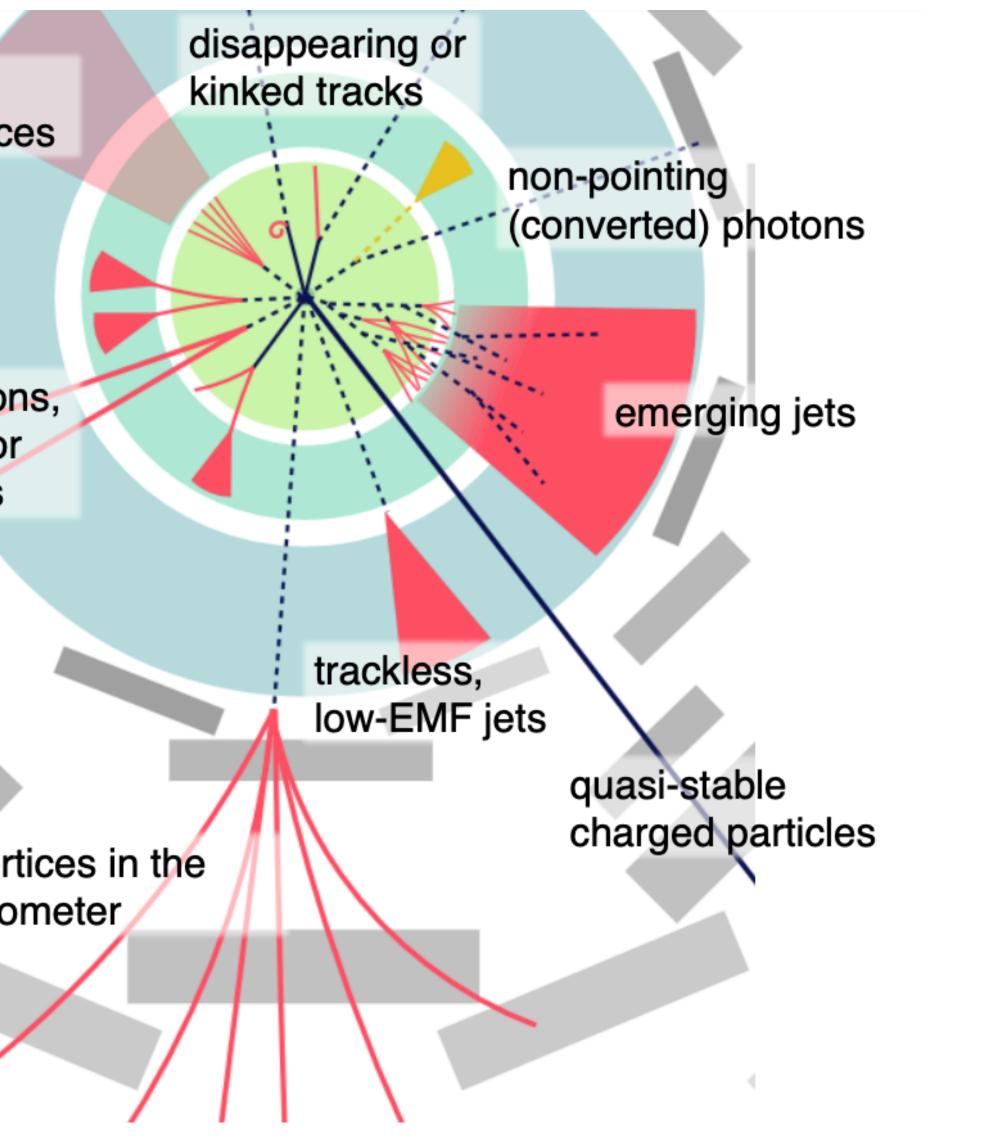
Unconventional Signatures - ATLAS & CMS-Style

displaced multitrack vertices

displaced leptons, lepton-jets, or lepton pairs

> multitrack vertices in the muon spectrometer

Figure from H. Russell







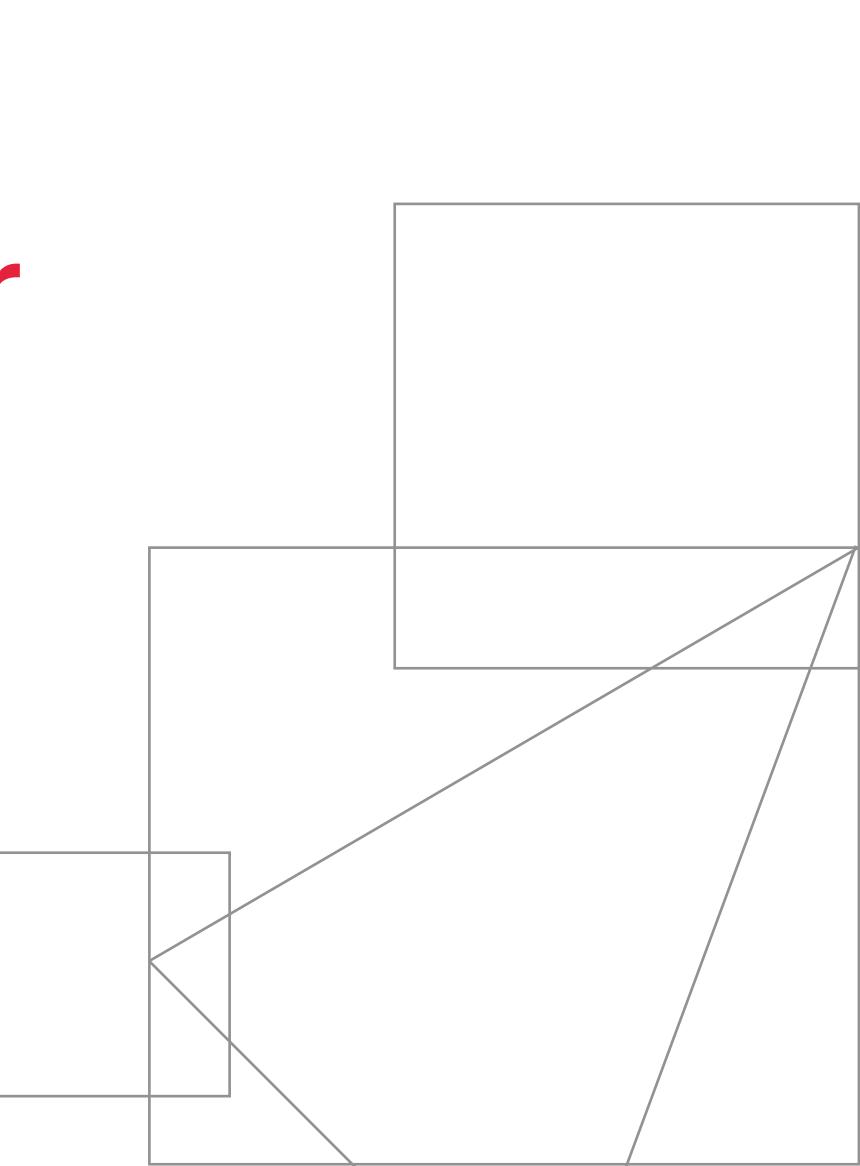




ATLAS Search for Displaced Heavy Neutral Leptons



arXiv:2204.11988, accepted by PRL



Search for Displaced Heavy Neutral Leptons

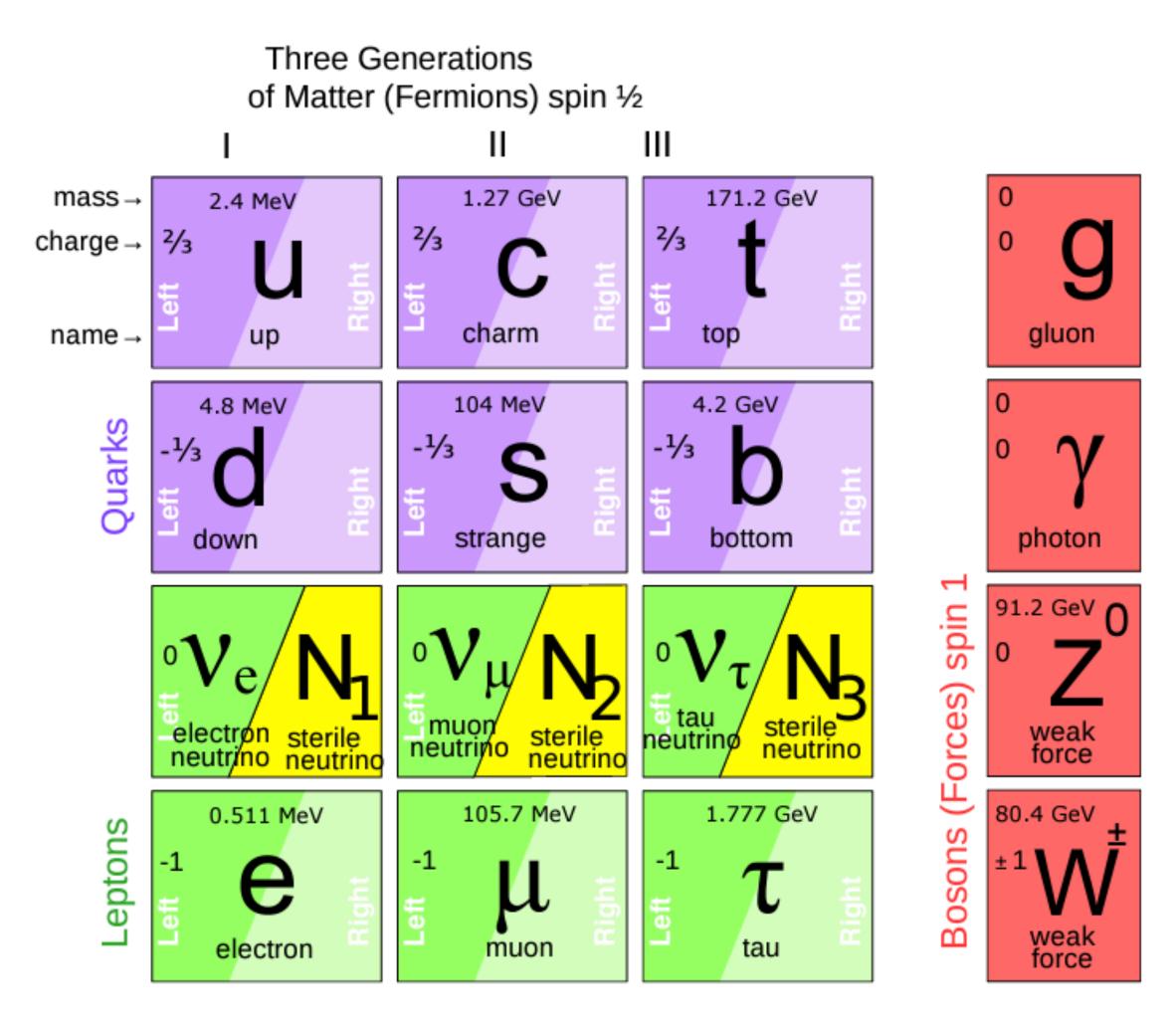
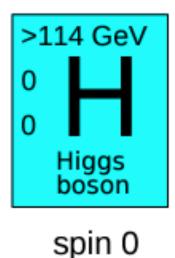




Figure from arXiv:1301.5516

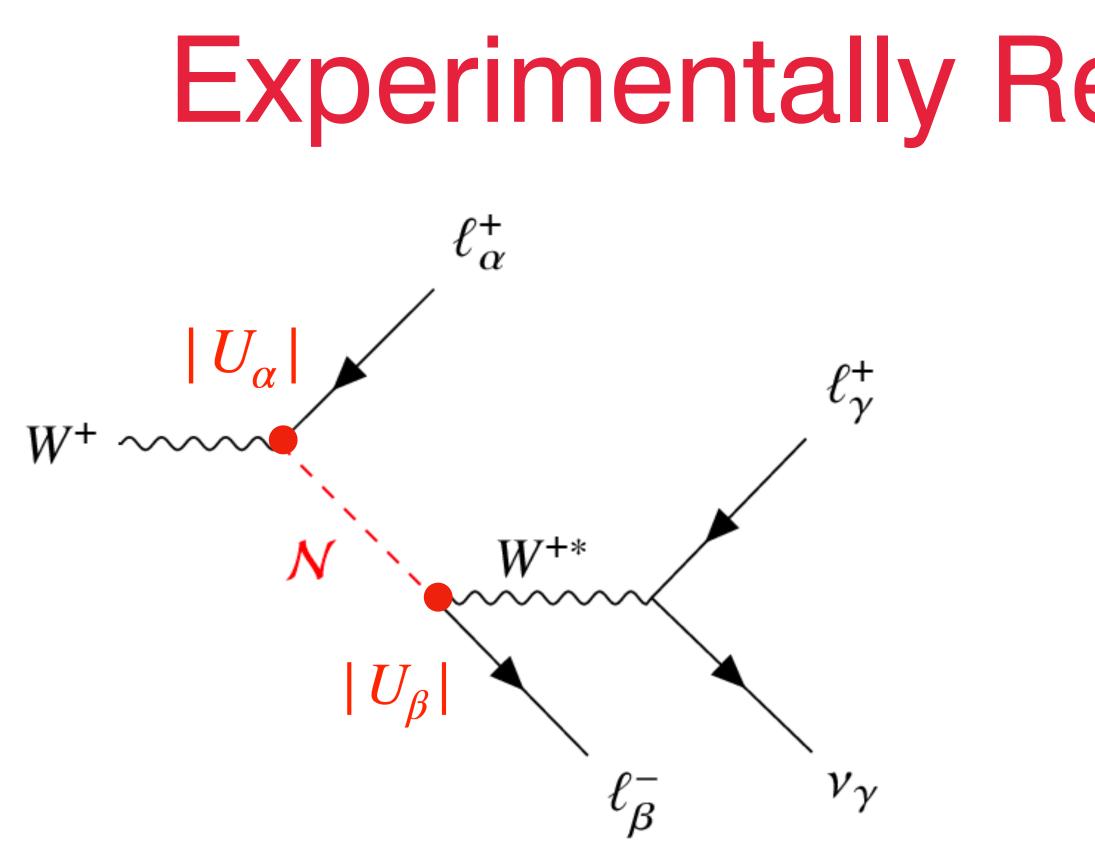
- SM extension with 3 HNLs
 - Introduce right-handed states known as heavy neutral leptons
 - ➡ Type-I seesaw mechanism explains light neutrino masses











- $|U_{\alpha}|^2 \Rightarrow$ mixing angle between SM ν and HNL
- \Rightarrow HNL mass m_N

$\alpha, \beta, \gamma \Rightarrow$ lepton flavour index



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Experimentally Relevant Observables

- HNLs experience "weak-like" interactions controlled by dimensionless mixing angles $(|U_{\alpha}|^2)$
- *m_N* dictates kinematics of decay products HNL lifetime: $\tau_N \propto \frac{1}{m_N^5 |U_{\alpha}|^2}$ Can be LLPs!
- HNL can be Majorana- or Dirac-like particles
 - Dirac \Rightarrow Lepton Number is conserved (LNC)
 - Majorana \Rightarrow Lepton Number is violated (LNV)







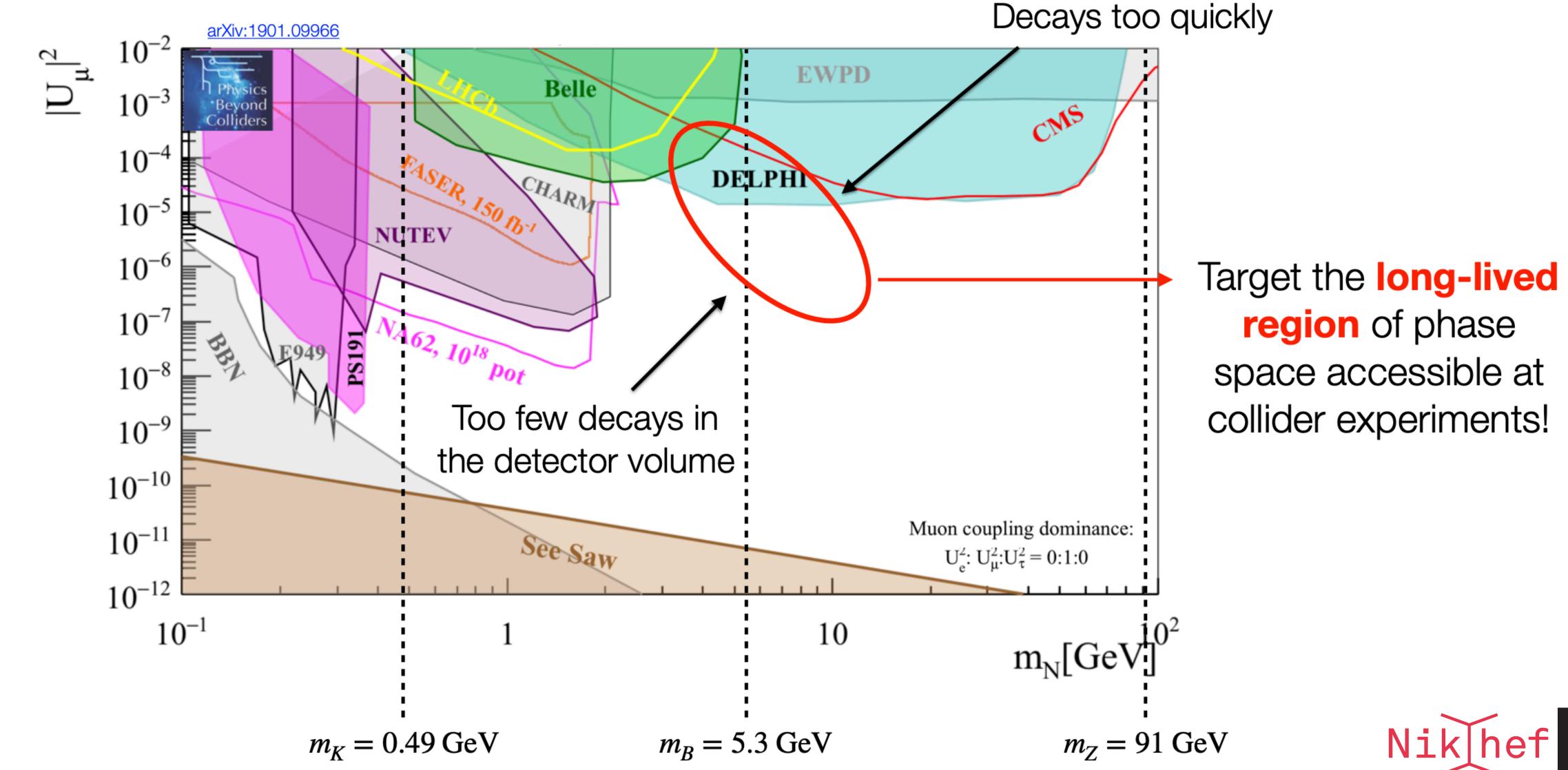








Experimental Picture



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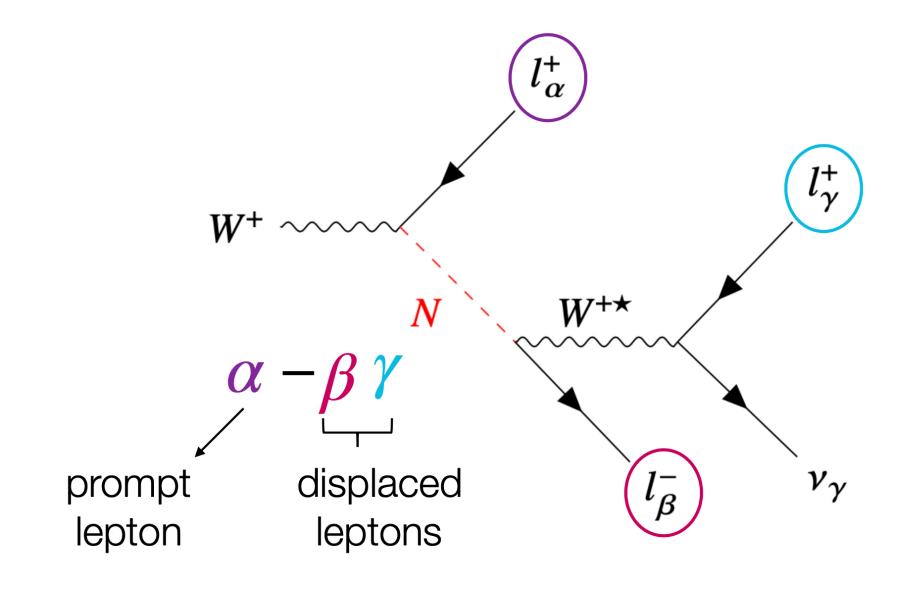






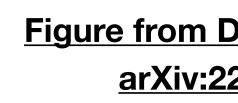
Displaced Heavy Neutral Leptons

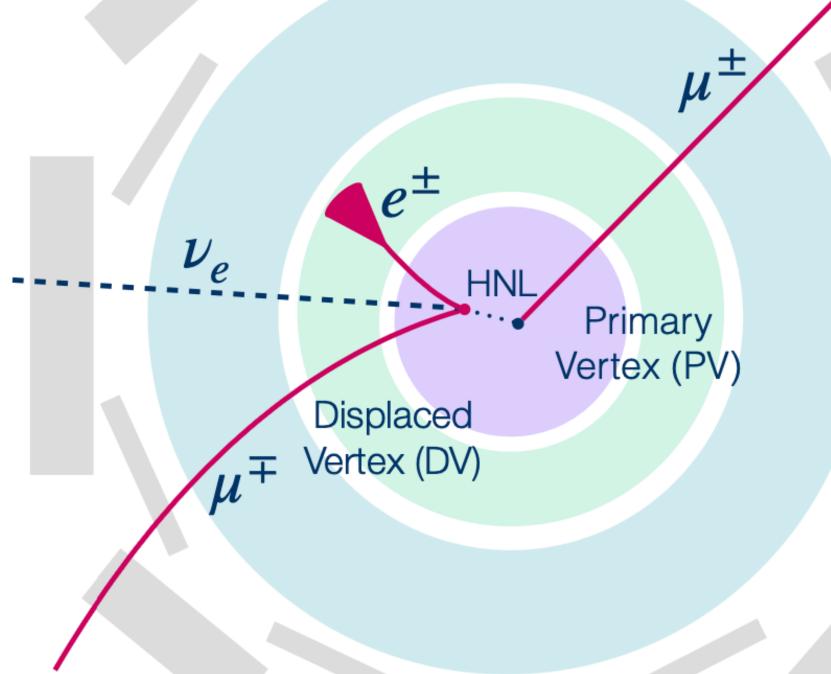
- Experimental dHNL signature:
 - Prompt lepton (trigger)
 - Displaced vertex with two opposite charge leptons

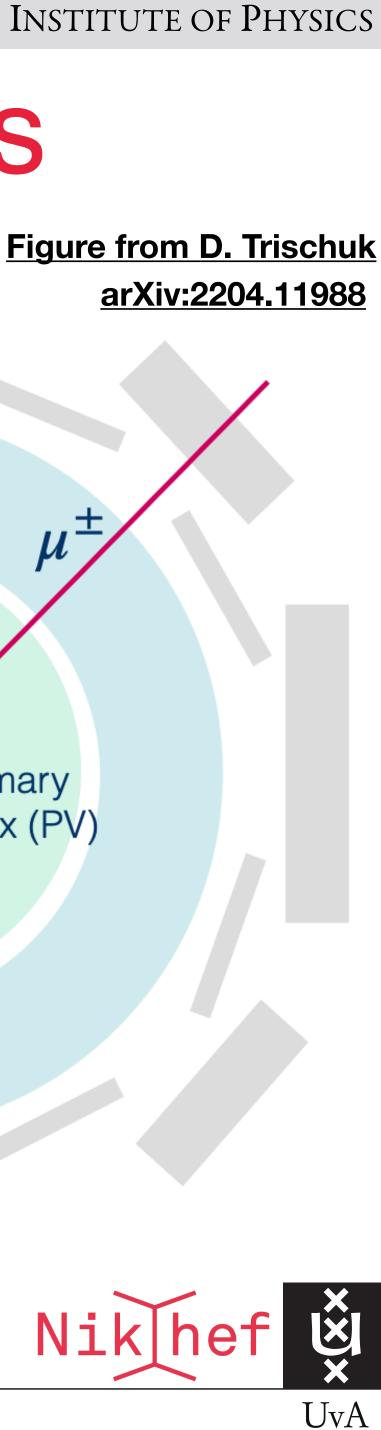


6 signal regions: μ - $\mu\mu$, μ - μ e, μ -ee, e-ee, e-e μ , e- $\mu\mu$

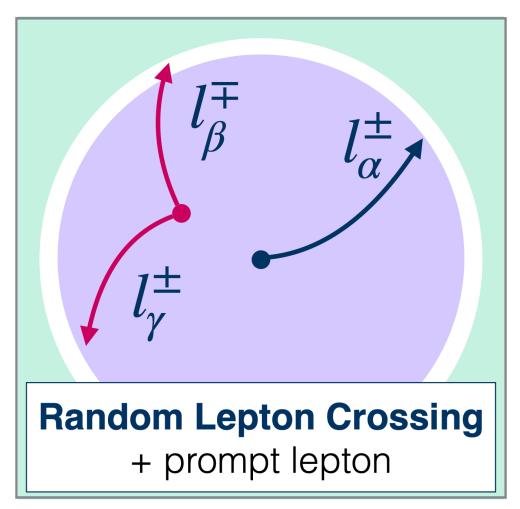








Dominant background

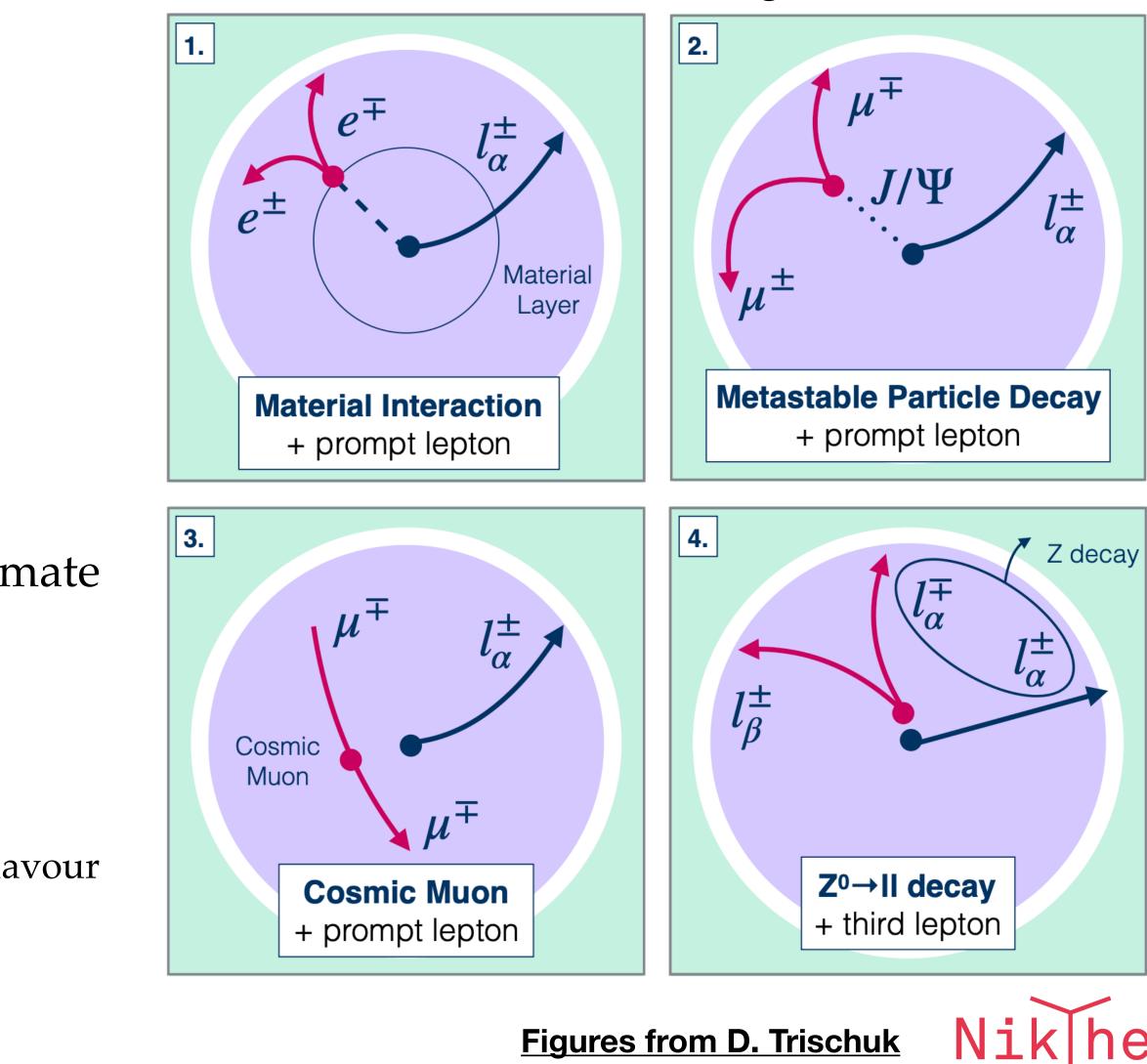


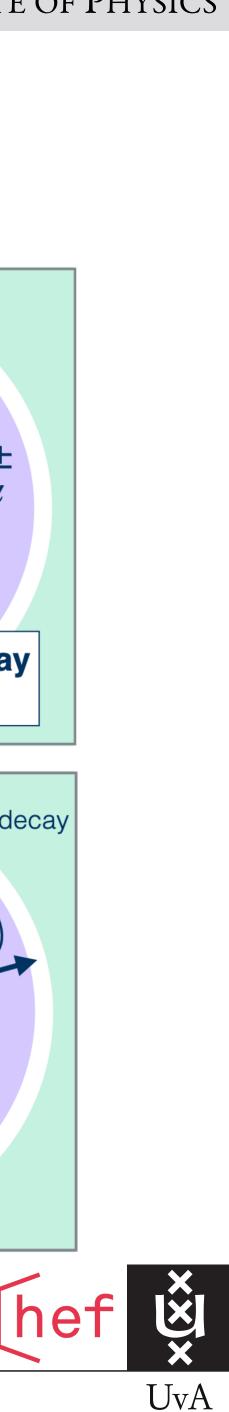
- Data-driven object shuffling method is used to estimate the background from random lepton crossings
- Dedicated selections to remove non-random backgrounds
 - e.g. invariant mass of the displaced vertex to reject heavy-flavour decays



dHNLs: Backgrounds

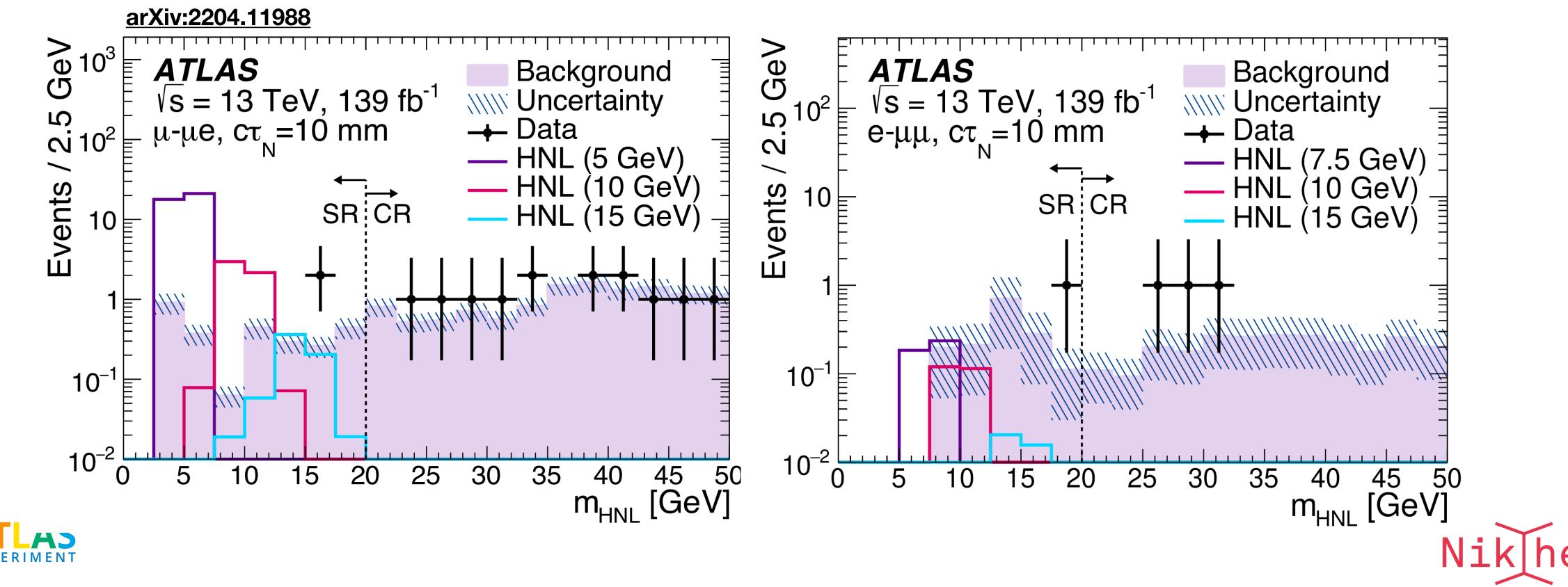
Non-random backgrounds



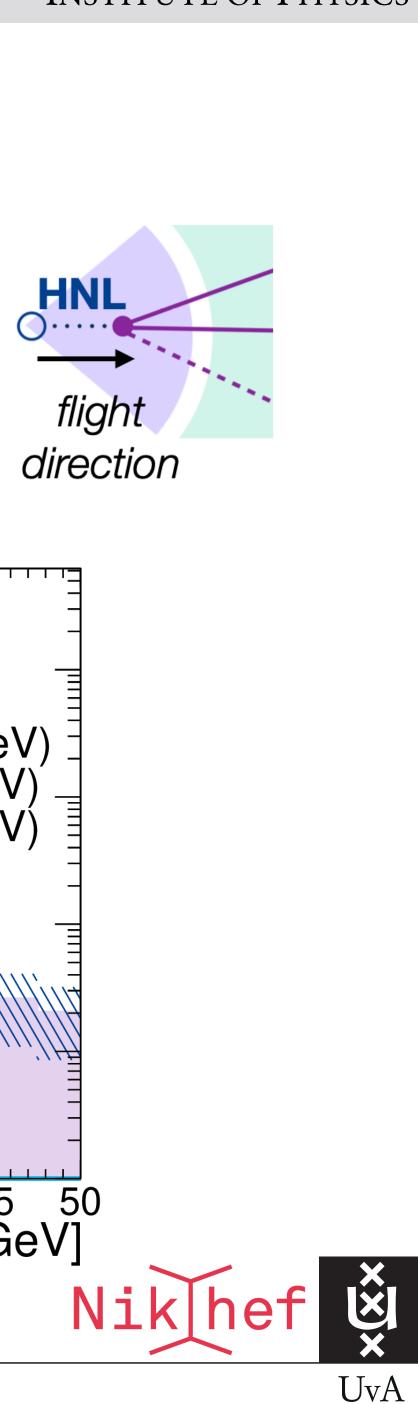


ATLAS Results: dHNL

Energy-momentum conservation is used to reconstruct the HNL mass: $m_{HNL^2} = (P_{1\beta} + P_{1\gamma} + P_{\nu\gamma})^2$

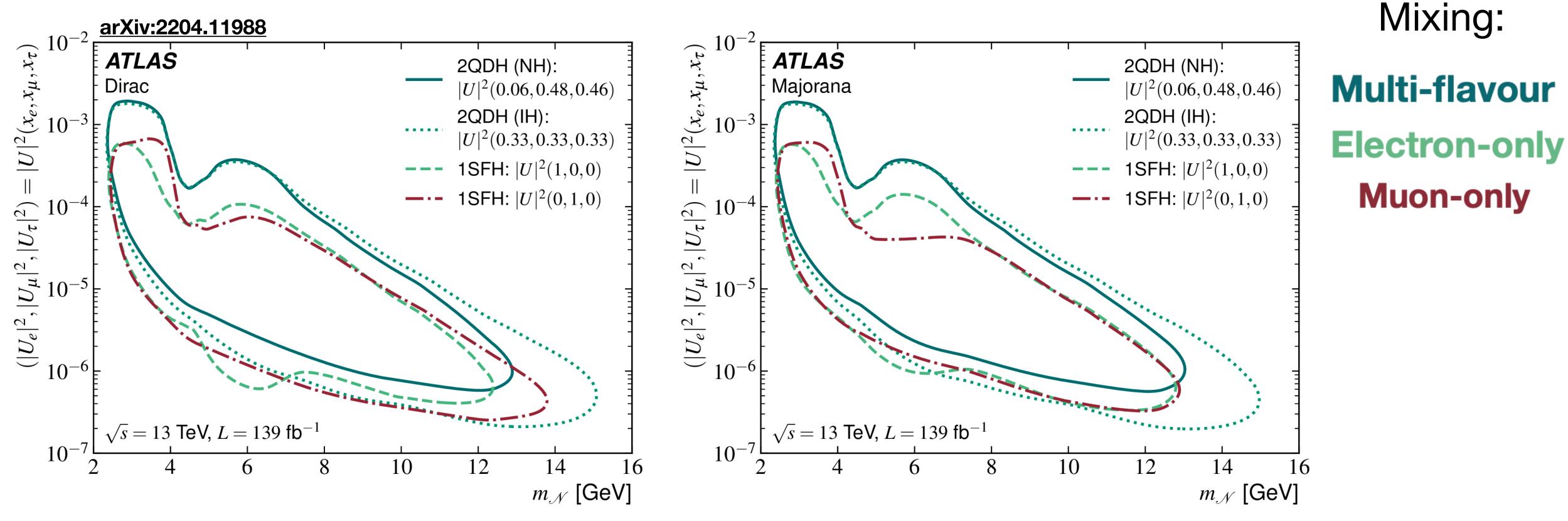


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ATLAS Results: dHNL

No excess observed 😕





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Observed limits in the 2QDH scenario with inverted (IH) and normal (NH) mass hierarchy, and in **1SFH** scenarios where the HNL mixes with only v_{μ} or v_{e} Nik h





Long-Lived Particles at ATLAS - Summary

	Model	Signature	∫£ dt [fb	-1]	Lifeti	me limit		J	\mathcal{L} at $-$ (32.8 – 139) fb ⁻¹	$\sqrt{s} = 13 \text{ Te}^{3}$ Reference
	RPV $\tilde{t} \rightarrow \mu q$	displaced vtx + muon	136	t lifetime				0.003-6.0 m		$m(ilde{t})=$ 1.4 TeV	2003.11956
	$RPV\tilde{\chi}_1^0 \to eev/e\mu v/\mu\mu v$	displaced lepton pair	32.8	$\tilde{\chi}_1^0$ lifetime			0.003-			$m(ilde{q})=$ 1.6 TeV, $m(ilde{\chi}^0_1)=$ 1.3 TeV	1907.10037
	$RPV\tilde{\chi}^0_1 \to qqq$	displaced vtx + jets	139	$\tilde{\chi}_{1}^{0}$ lifetime				0.00135-9.0	m	$m({ ilde \chi}_1^0) = 1.0 { m TeV}$	2301.13866
	$\operatorname{GGM} \tilde{\chi}^0_1 \to Z \tilde{G}$	displaced dimuon	32.9	$\tilde{\chi}_{1}^{0}$ lifetime					9-18.0 m	$m(ilde{g})=$ 1.1 TeV, $m(ilde{\chi}_1^0)=$ 1.0 TeV	1808.03057
	GMSB	non-pointing or delayed y		$\tilde{\chi}_{1}^{0}$ lifetime				0.24-2.4 m	т.	$m(\tilde{\chi}_{1}^{0}, \tilde{G})$ = 60, 20 GeV, $\mathcal{B}_{\mathcal{H}}$ = 2%	2209.01029
	GMSB $\tilde{\ell} \to \ell \tilde{G}$	displaced lepton	139	$\tilde{\ell}$ lifetime			6-750 r			$m(\tilde{\ell}) = 600 \text{ GeV}$	2011.07812
	GMSB $\tilde{\tau} \rightarrow \tau \tilde{G}$	displaced lepton	139	$ ilde{ au}$ lifetime			9-270 mm	_		$m(ilde{\ell}) = 200 ext{ GeV}$	2011.07812
ດ	AMSB $pp \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_1^0, \tilde{\chi}_1^{+} \tilde{\chi}_1^{-}$	disappearing track	136	$\tilde{\chi}_1^{\pm}$ lifetime				0.06-3.06 m		$m(ilde{\chi}_1^{\pm}){=}$ 650 GeV	2201.02472
	AMSB $pp \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_1^0, \tilde{\chi}_1^{+} \tilde{\chi}_1^{-}$	large pixel dE/dx	139	$\tilde{\chi}_1^{\pm}$ lifetime			0	.3-30.0 m		$m(ilde{\chi}_1^{\pm})=$ 600 GeV	2205.06013
	Stealth SUSY	2 MS vertices	36.1	Š lifetime			0.1-519 m			$\mathcal{B}(\tilde{g} \rightarrow \tilde{S}g) = 0.1, \ m(\tilde{g}) = 500 \text{ GeV}$	1811.07370
	Split SUSY	large pixel dE/dx	139	g lifetime				> 0.45 m		$m(ilde{g}){=}$ 1.8 TeV, $m(ilde{\chi}_1^0){=}$ 100 GeV	2205.06013
	Split SUSY	displaced vtx + E_{T}^{miss}	32.8	g lifetime				0.03-1	<mark>3.2 m</mark>	$m(ilde{g}){=}$ 1.8 TeV, $m(ilde{\chi}_1^0){=}$ 100 GeV	1710.04901
	Split SUSY	$0 \ \ell$, 2 – 6 jets + E_{T}^{miss}	36.1	ğ lifetime		-	-	0.0-2.1 m		$m(ilde{g}){=}$ 1.8 TeV, $m(ilde{\chi}_1^0){=}$ 100 GeV	ATLAS-CONF-2018
	$H \rightarrow s s$	2 MS vertices	139	s lifetime			0).31-72.4 m		<i>m</i> (<i>s</i>)= 35 GeV	2203.00587
2 2	$H \rightarrow s s$	2 low-EMF trackless jets	139	s lifetime				0.19-6.94 m		<i>m</i> (<i>s</i>)= 35 GeV	2203.01009
-	VH with $H o ss o bbbb$	2ℓ + 2 displ. vertices	139	s lifetime		4-85 n	Im			<i>m</i> (<i>s</i>)= 35 GeV	2107.06092
5	FRVZ $H ightarrow 2\gamma_d + X$	2 μ –jets	139	γ _d lifetime			0.654-939	9 mm		$m(\gamma_d) = 400 \text{ MeV}$	2206.12181
300	FRVZ $H ightarrow 4 \gamma_d + X$	2 μ –jets	139	γ_{d} lifetime			2.7-534 mm			$m(\gamma_d) = 400 \text{ MeV}$	2206.12181
Higgs	$H \rightarrow Z_d Z_d$	displaced dimuon	32.9	Z _d lifetime		0.009-24.0 m				$m(Z_d) =$ 40 GeV	1808.03057
	$H \rightarrow ZZ_d$ 2	e, μ + low-EMF trackless	jet 36.1	Z _d lifetime				0.21-5.2 m		$m(Z_d) = 10 \text{ GeV}$	1811.02542
	$\Phi(200 \text{ GeV}) \rightarrow ss$ lo	ow-EMF trk-less jets, MS v	/tx 36.1	s lifetime		_		0.41-51.5 m		$\sigma imes \mathcal{B} =$ 1 pb, $m(s) =$ 50 GeV	1902.03094
2	$\Phi(600 \text{ GeV}) \rightarrow ss$ lo	ow-EMF trk-less jets, MS v	/tx 36.1	s lifetime			0.04-21.5 m			$\sigma \times \mathcal{B} =$ 1 pb, $m(s) =$ 50 GeV	1902.03094
Scalar	$\Phi(1 \text{ TeV}) \rightarrow ss$ lo	ow-EMF trk-less jets, MS v	/tx 36.1	s lifetime			0.06-52.4 m		-	$\sigma imes \mathcal{B} =$ 1 pb, $m(s) =$ 150 GeV	1902.03094
	$W \to N\ell, N \to \ell\ell\nu$	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 ($\mu\mu,\mu e,ee$) +	·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 ($\mu\mu,\mu e,ee$) +	e 139	N lifetime		0.49-81 m	m			m(N) = 6 GeV, Dirac	2204.11988
	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu,\mu e,ee$) +	e 139	N life <mark>time</mark>		0.39-51 mm				m(N) = 6 GeV, Majorana	2204.11988
				0.001		0.01	0.1	1	10	¹⁰⁰ cτ [m]	
		$s = 13 \text{ TeV}$ $\sqrt{s} = 13$					<u>.</u>	<u>_</u>			
	p y a selection of the av	artial data full d		0.001	0.01	0.1	<u> </u>	<u> </u>		100	



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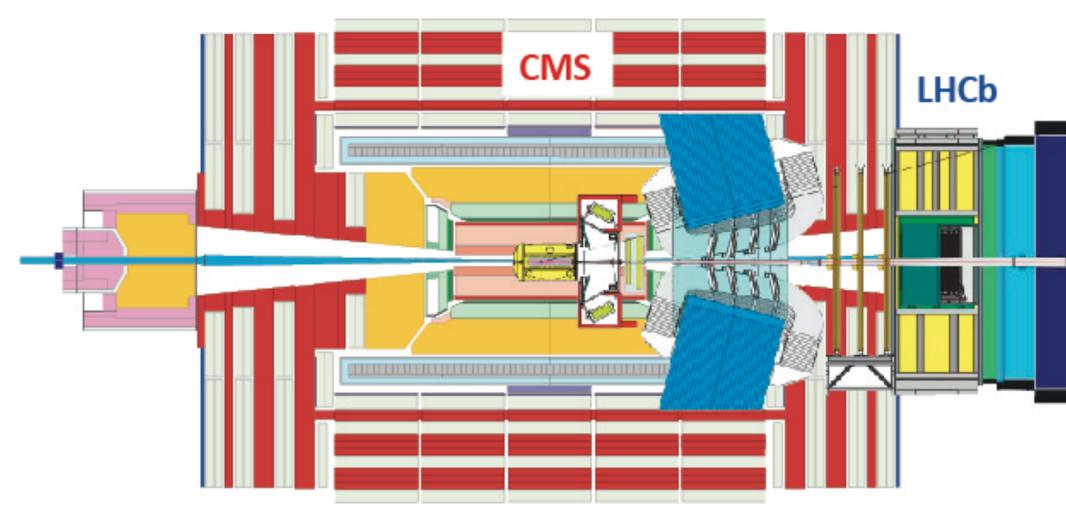
Nikhef

20



LLPs at LHCb

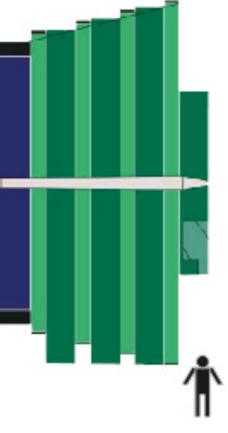
- Unique phase space region ($2 < \eta < 5$) complementary to ATLAS & CMS: low lifetime, low masses
 - Excellent track momentum resolution: 0.4% at 5 GeV to 0.6% at 100 GeV
 - Impact Parameter resolution 20 µm for high-p_T tracks, lifetime resolution of 0.2 ps

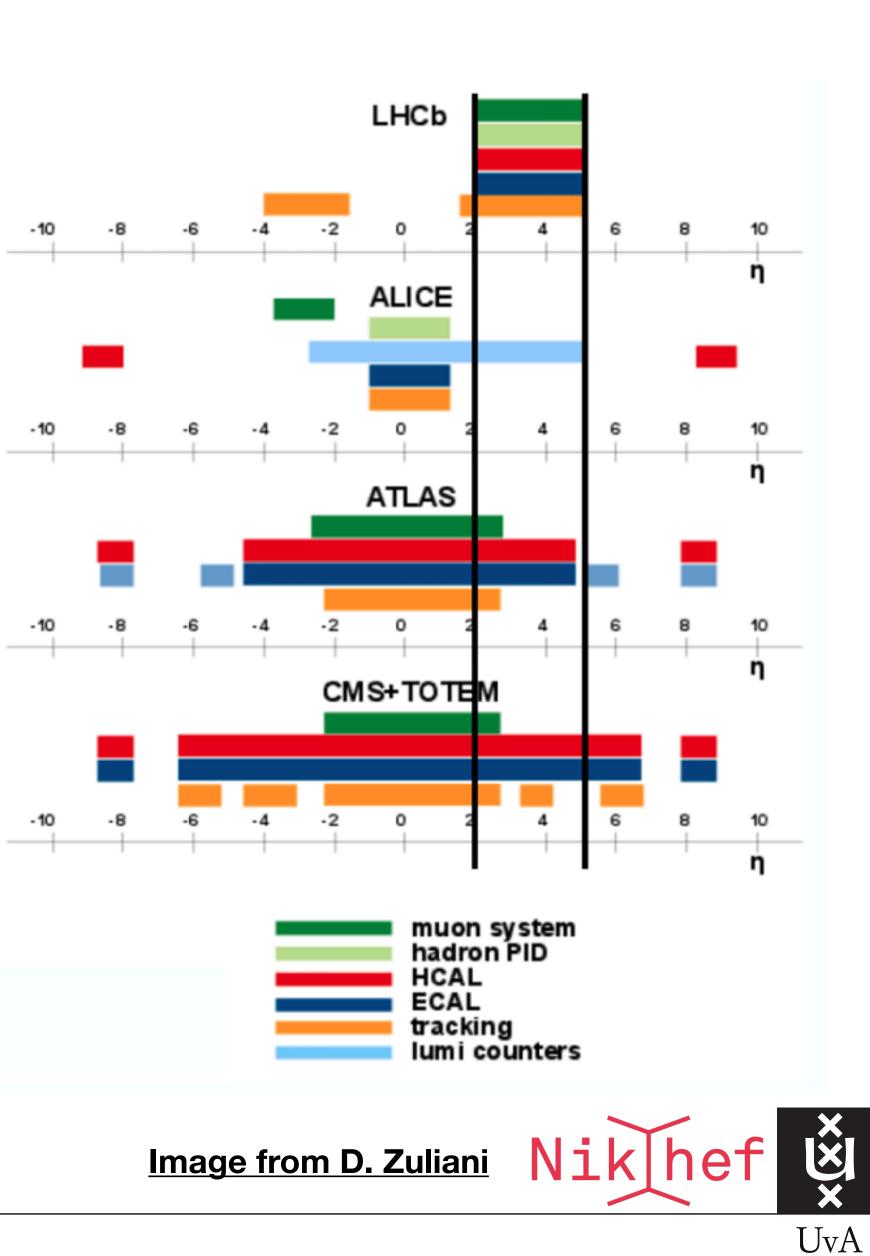




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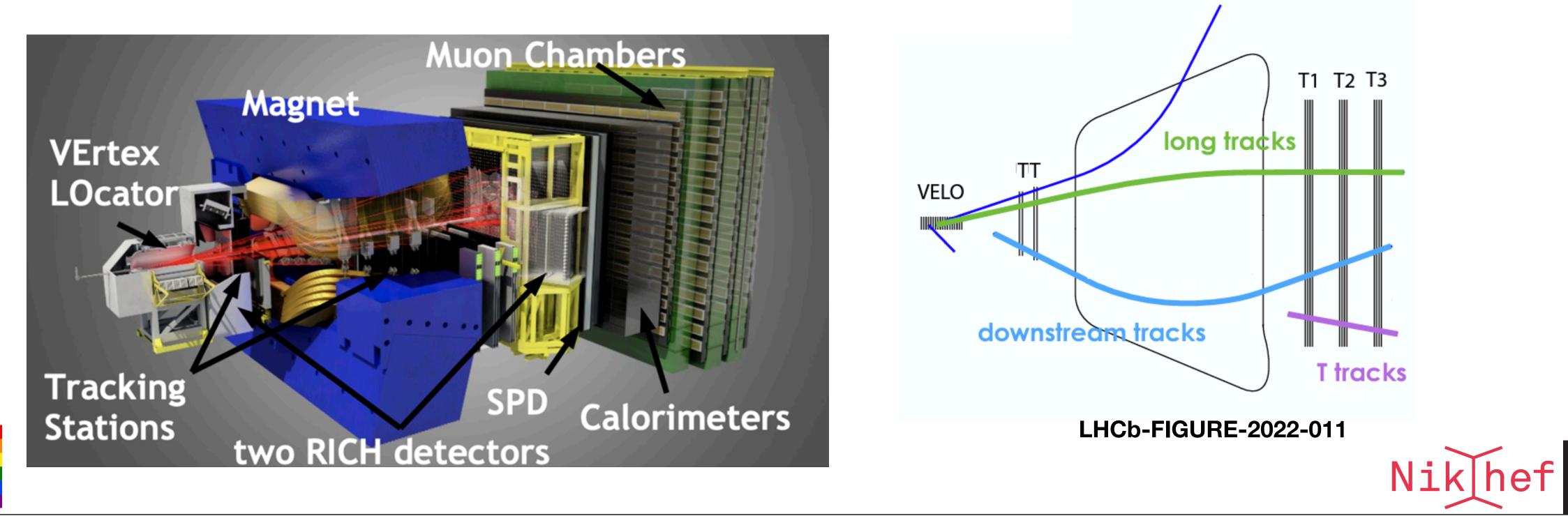
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LLPs at LHCb

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LHCD

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Elena Dall'Occo (Now at TU Dortmund)

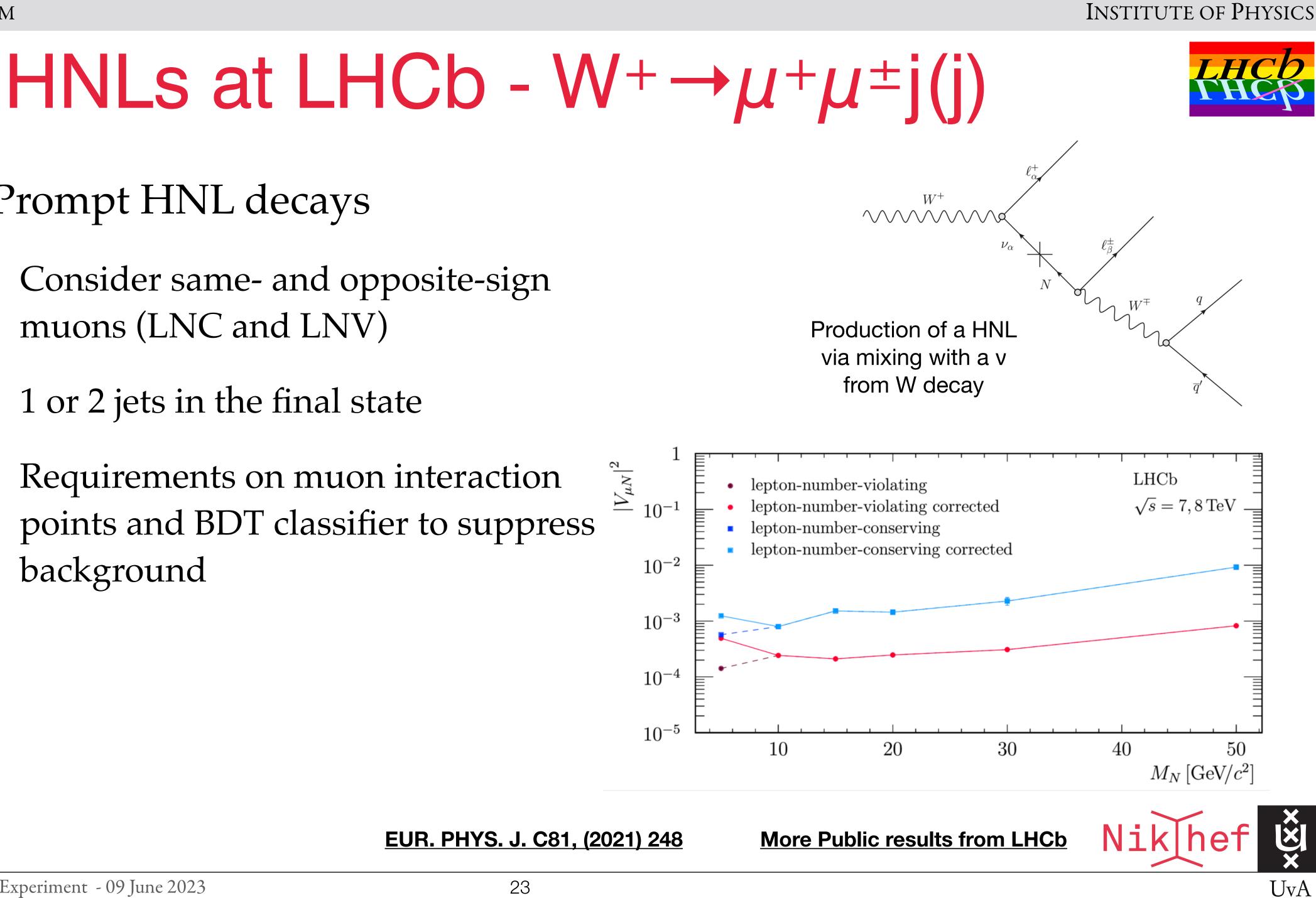


Valeriia Lukashenko (now PhD in B→µeπ)



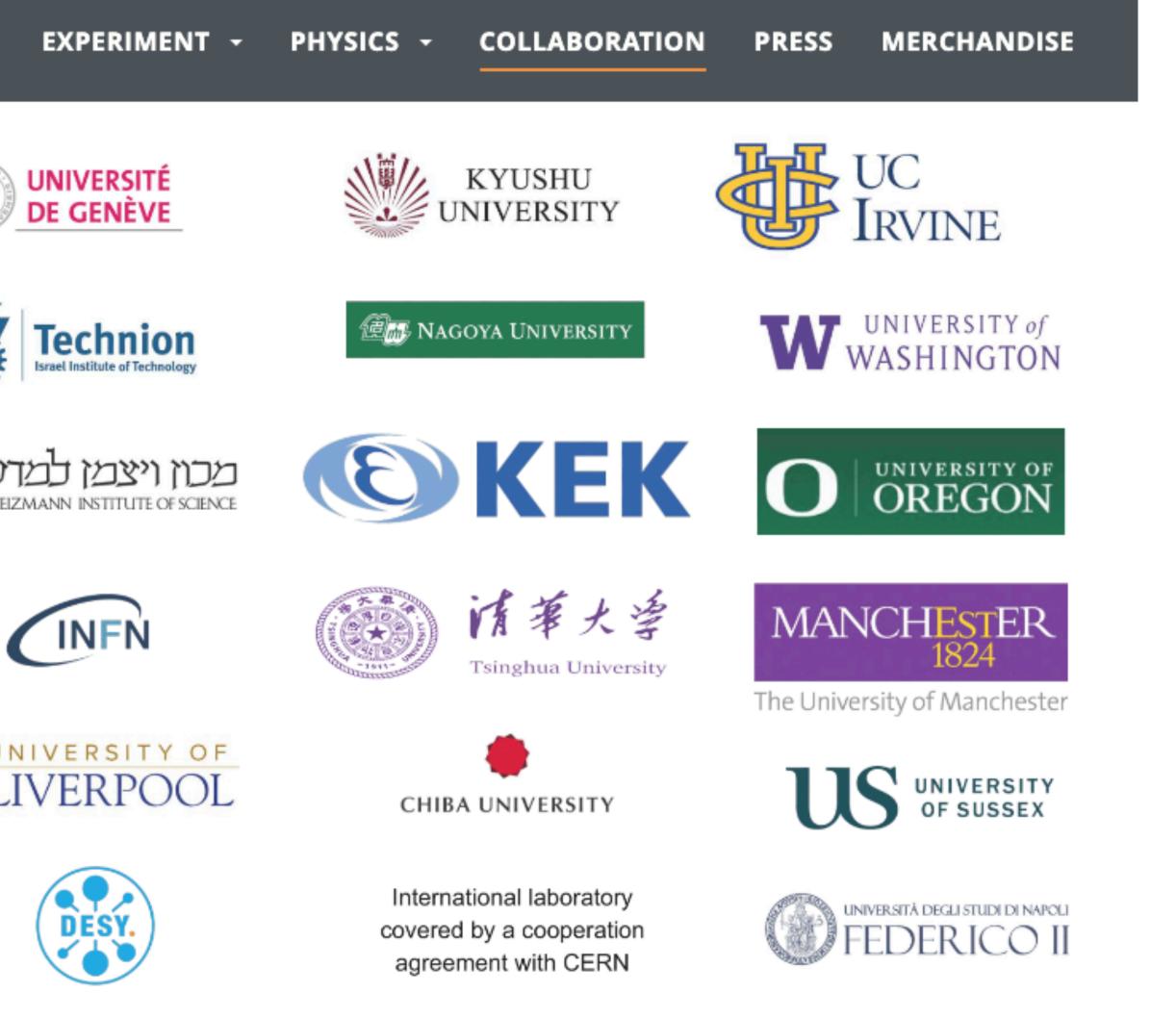
Wouter Hulsbergen

- Prompt HNL decays
 - Consider same- and opposite-sign muons (LNC and LNV)
 - 1 or 2 jets in the final state
 - Requirements on muon interaction points and BDT classifier to suppress background



FASER: ForwArd Search ExpeRiment at the LHC







Lydia Brenner

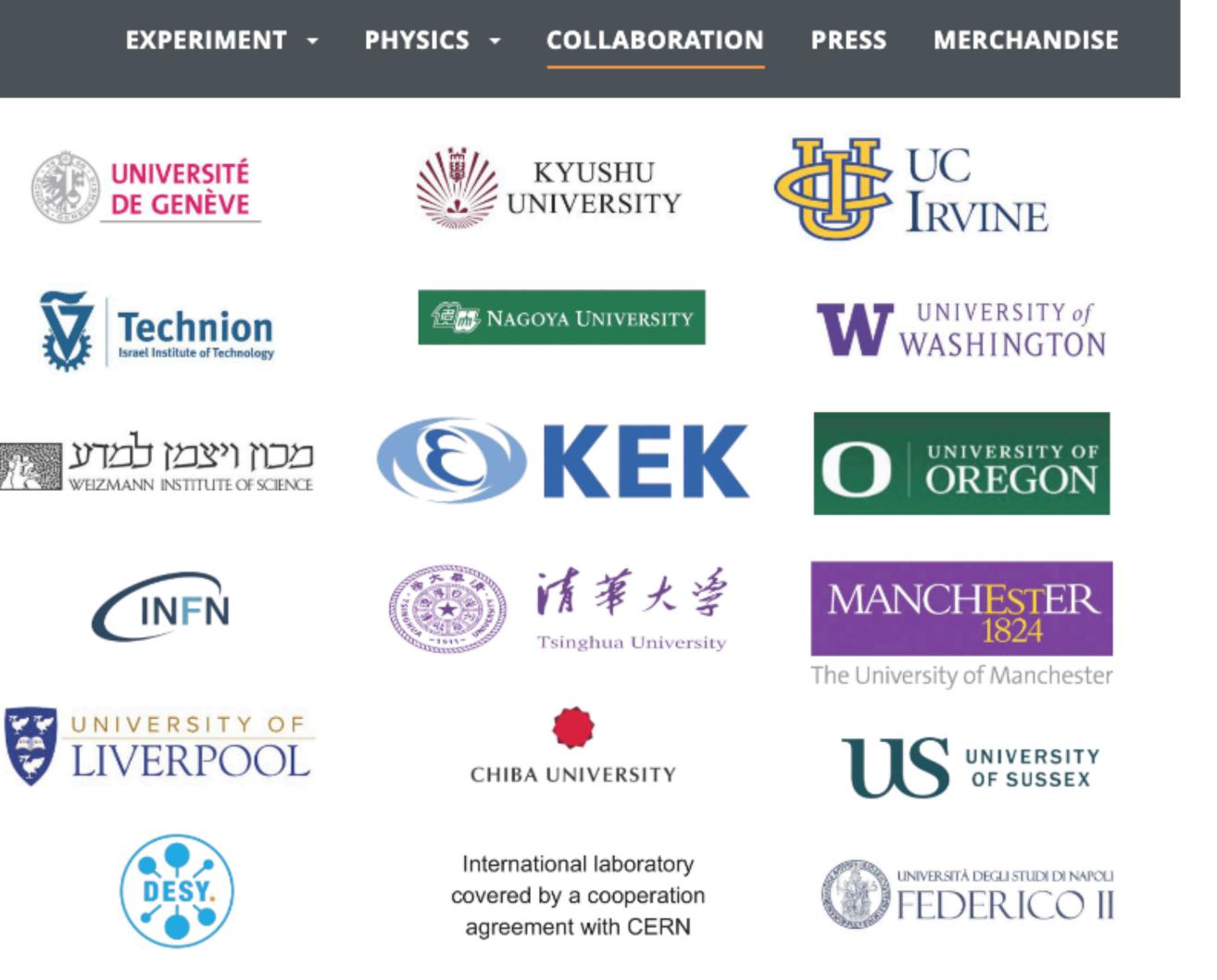










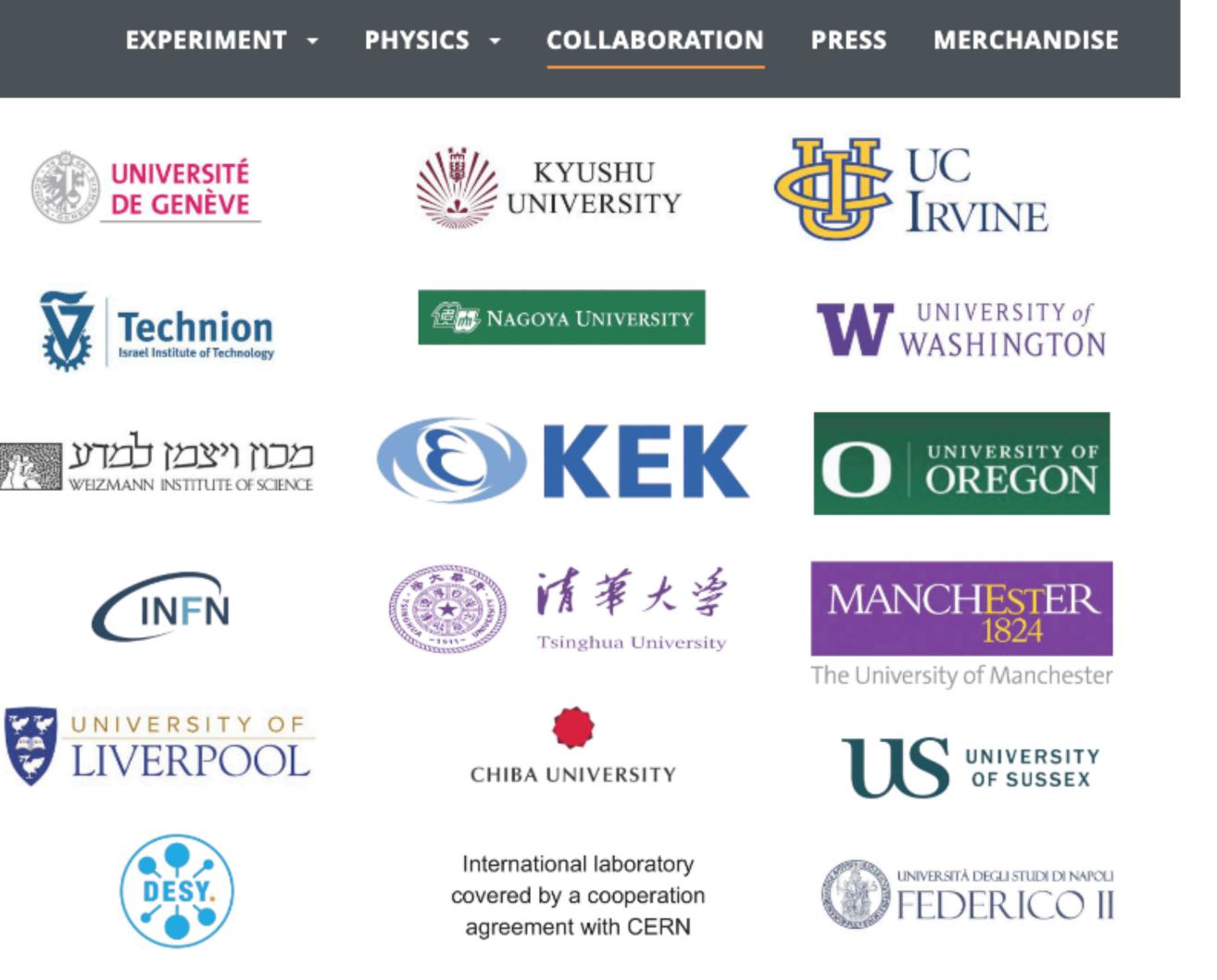
















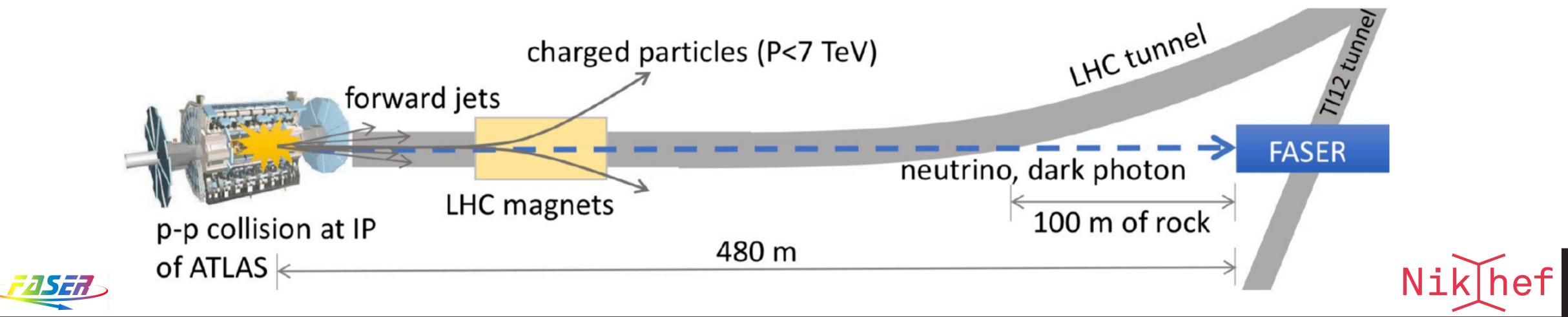






FASER: ForwArd Search ExpeRiment at the LHC

- New, small experiment at the LHC: Constructed and installed in 2019-2021
- Targets light and weakly coupled particles
 - Exploits large LHC collision rate and highly-collimated forward production of light particles, for instance in pion decays (1% of pions with E > 10 GeV produced at $\eta > 9.2$)
 - Designed to detect both new long-lived BSM particles (e.g. dark photons, ALPs) as well as neutrinos
- Located 480m from ATLAS interaction point
 - LHC magnets as well 100m of rock shields most backgrounds

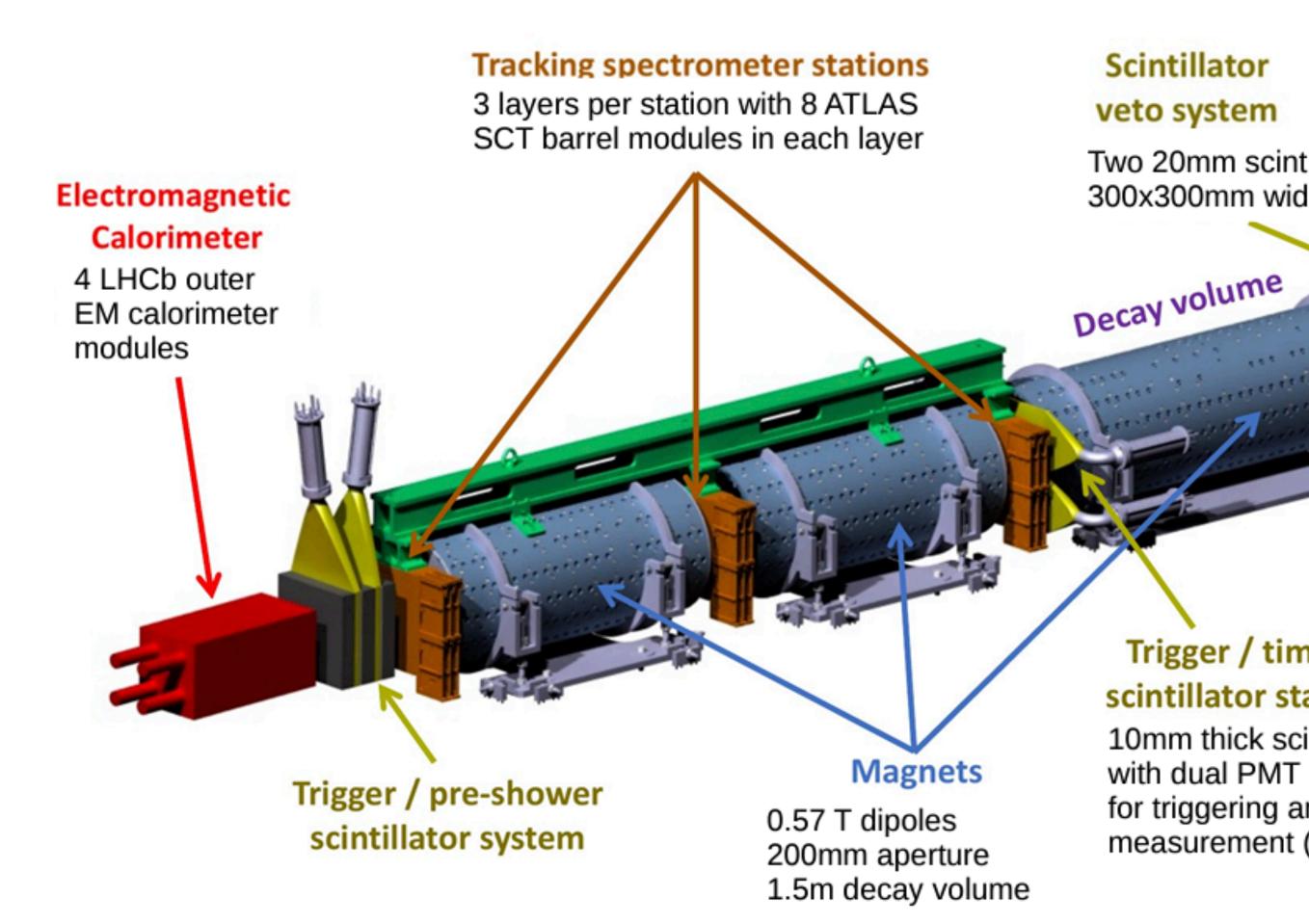








Experiment built from existing spare parts as well as some dedicated new components



arXiv:2207.11427 From B. Petersen

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Scintillator veto system

Two 20mm scint. 300x300mm wide **Front Scintillator** veto system Two 20mm scintillators 350x300mm wide

TO ATLAS IP

10 cm radius

 $\theta \lesssim 1 \,\mathrm{mrad}$

7m long

1.5 m decay volume

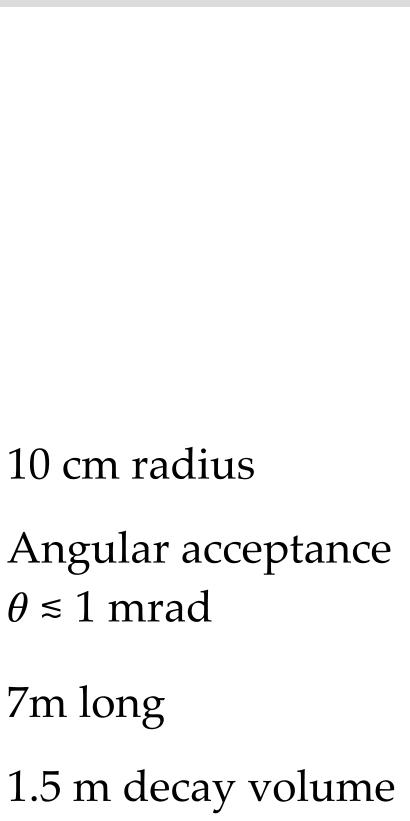
Interface Tracker (IFT)

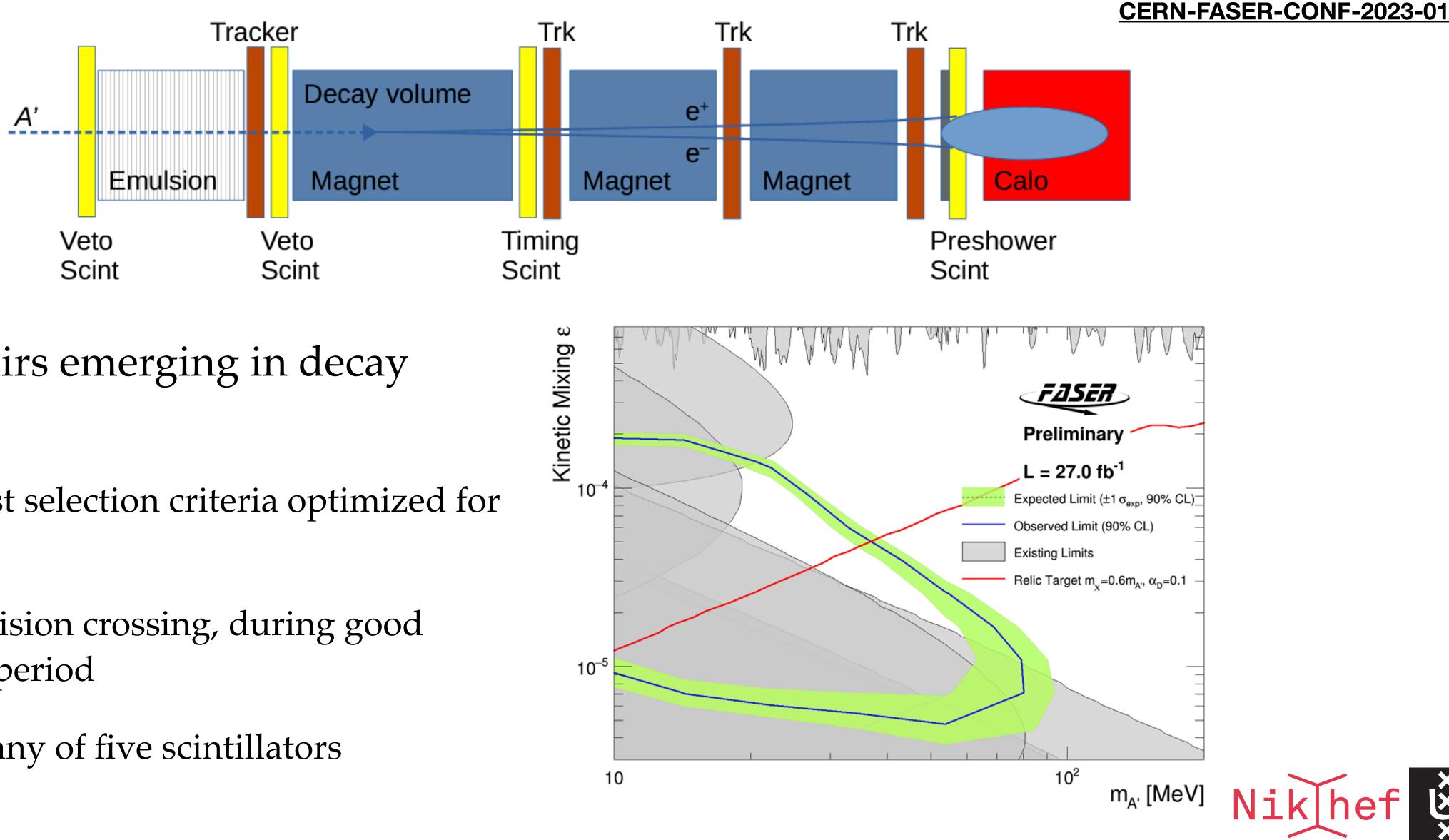
Trigger / timing scintillator station

10mm thick scintillators with dual PMT readout for triggering and timing measurement (σ =400ps) **FASERv** emulsion detector

1.1 ton detector 730 layers of 1.1mm tungsten+emulsion neutrino target and tracking detector Provides 8λ_{int}







- Select e⁺e⁻ pairs emerging in decay volume
 - Simple, robust selection criteria optimized for discovery
 - Events in collision crossing, during good physics data period
 - No signal in any of five scintillators

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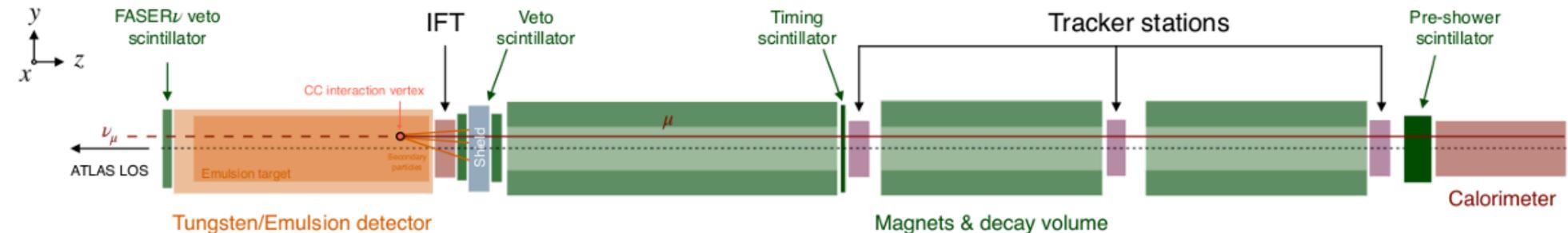
FASER

FASER - Dark Photons









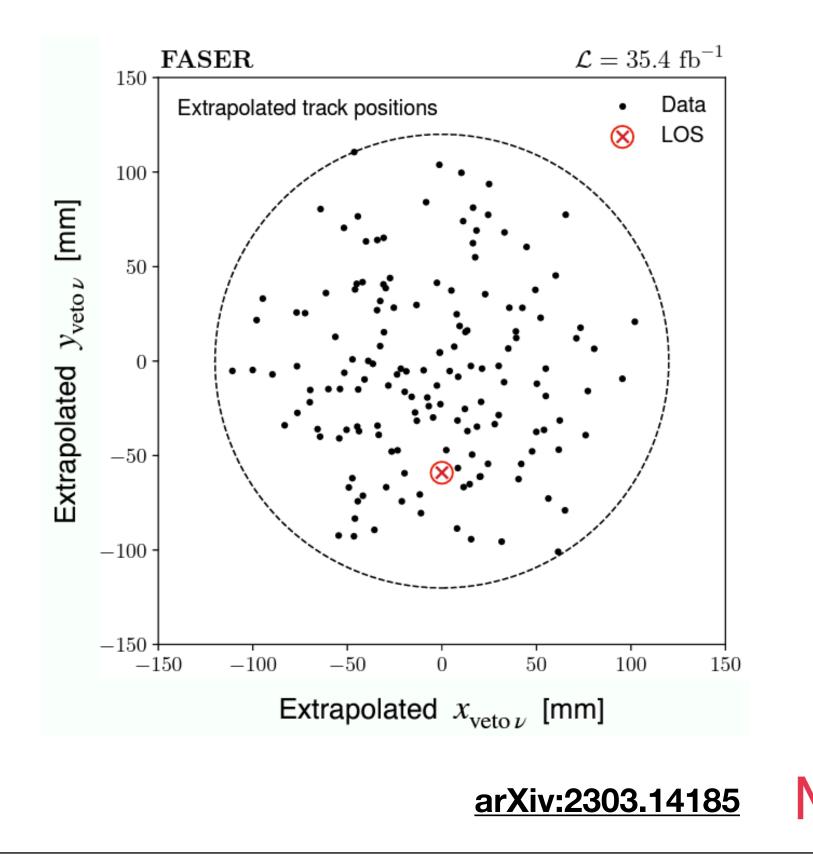
- First observation of collider neutrinos: 153^{+12} -13 events (16 σ)
 - Used active electronic components of FASER
 - Track propagating through the entire length of FASER consistent with a muon neutrino charged-current interaction



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FASER-v

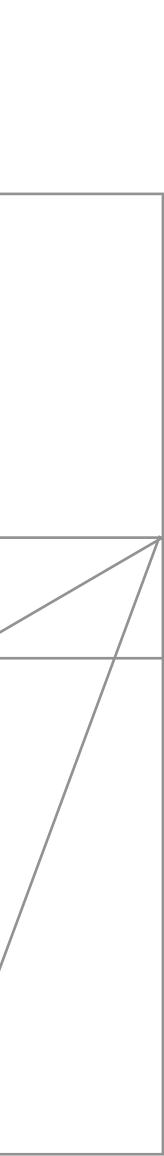
Magnets & decay volume

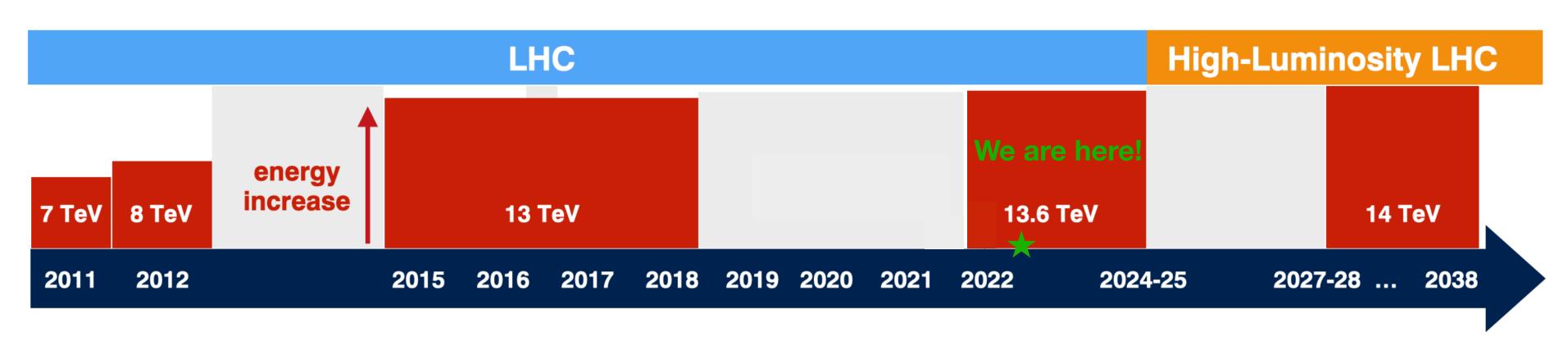




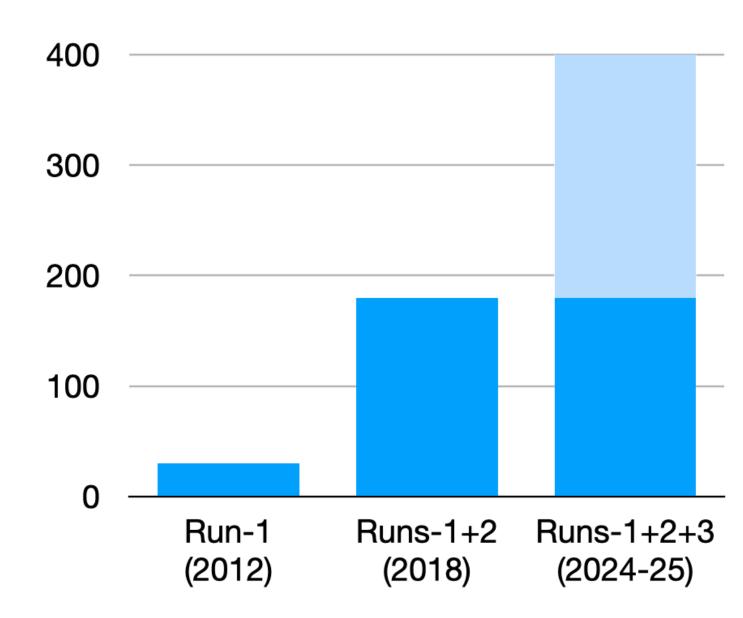


LLPs at LHC: Future Prospects



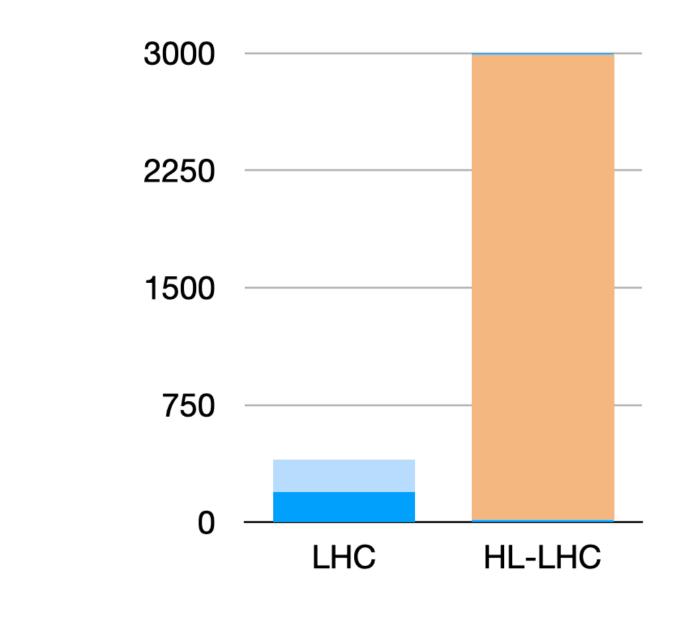


Total LHC data volume (fb⁻¹)



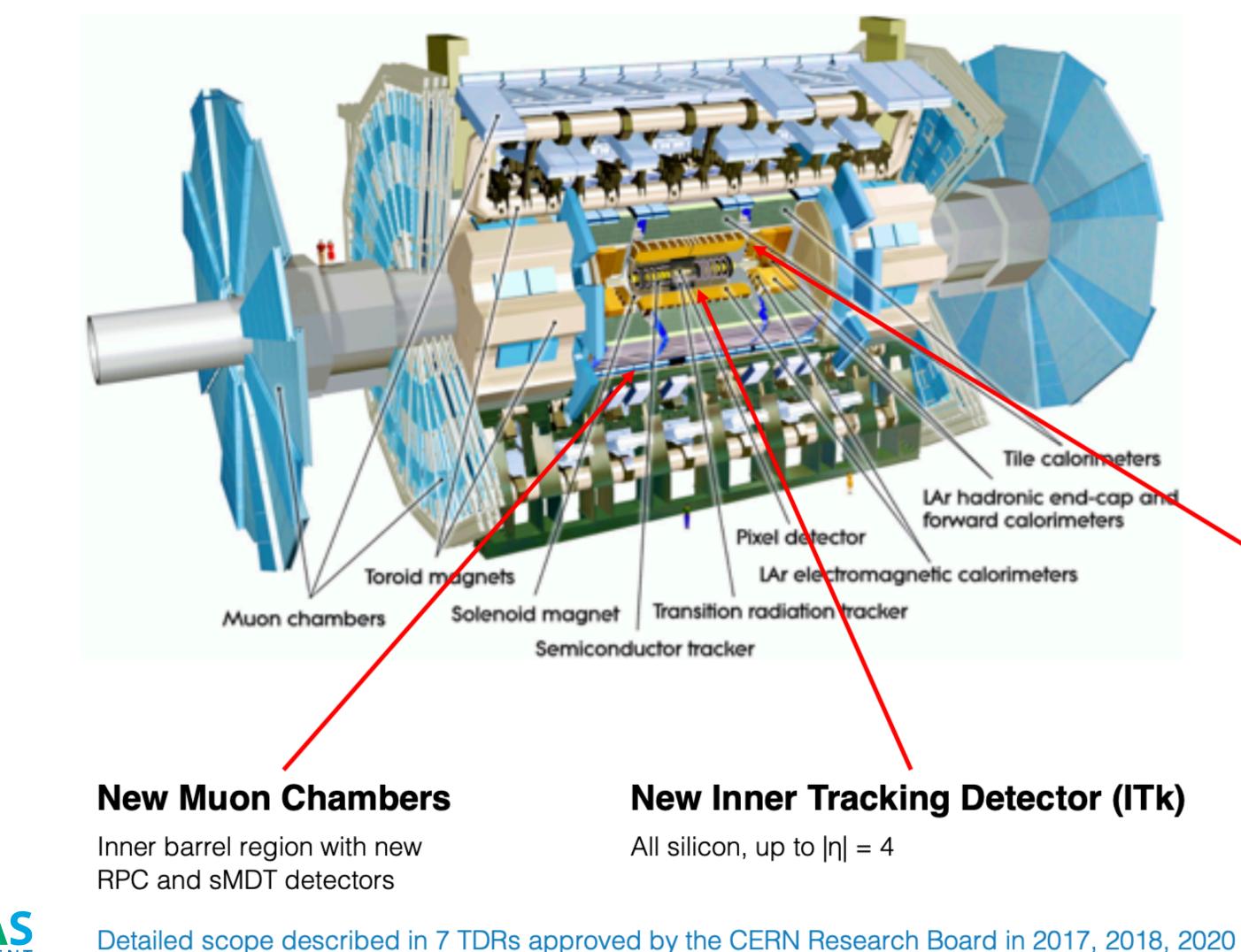
More data = Sharper images







ATLAS Phase-2 Upgrade for HL-LHC



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From G. Unal

Upgraded Trigger and **Data Acquisition system**

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter **Tile Calorimeter** Muon system

High Granularity Timing Detector (HGTD)

Forward region (2.4 < $|\eta|$ < 4.0)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

Additional small upgrades

Luminosity detectors (1% precision goal)

HL-ZDC



Tile calorimeters

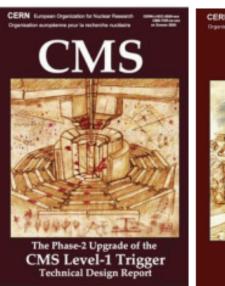
LAr hadronic end-cap and forward calorimeters

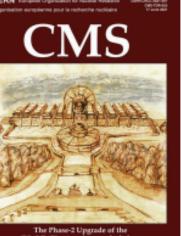
LAr electromagnetic calorimeters

New Inner Tracking Detector (ITk)



CMS Phase-2 Upgrade for HL-LHC



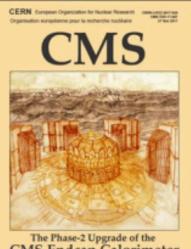


CMS Data Acquisition and High Level Trigger

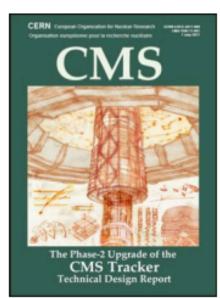
L1-Trigger HLT/DAQ

https://cds.cern.ch/record/2714892 https://cds.cern.ch/record/2759072

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting



The Phase-2 Upgrade of the CMS Endcap Calorimeter Technical Design Report



Calorimeter Endcap https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Tracker https://cds.cern.ch/record/2272264

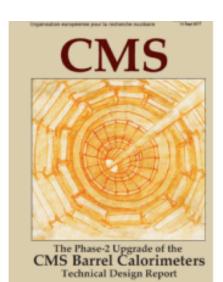
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8



Barrel Calorimeters

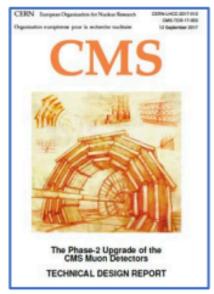
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems

- https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η = 3



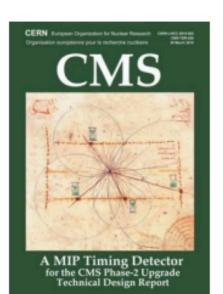
Beam Radiation Instr. and Luminosity http://cds.cern.ch/record/2759074

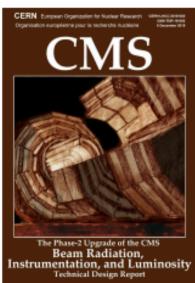
 Bunch-by-bunch luminosity measurement: 1% offline, 2% online

MIP Timing Detector https://cds.cern.ch/record/2667167

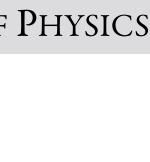
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



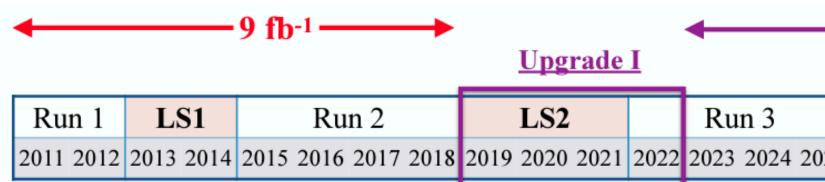




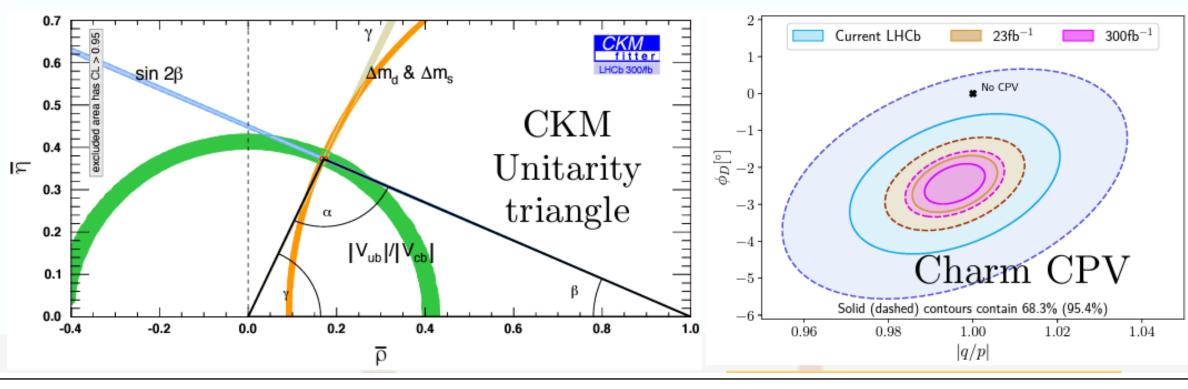




LHCb Phase-2 Upgrade for HL-LHC



- $\mathscr{L}_{peak} = 1.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, $\mathscr{L}_{int} \simeq 300 \text{fb}^{-1}$ (Run 5+6), Pile-up ~ 40
- Starting R&D phase of new technologies
 - precision timing for tracking and PID
 - extreme radiation hardness
 - low-cost monolithic pixels
 - cryogenic cooling (for SiPMs)
- Unprecedented sensitivity expected for flavour physics and beyond





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bridge to future

accelerators

(Goal: 50 fb ⁻	← Goal: 300 fb ⁻¹ →								
	Consolidation	. 1	U <mark>pgrade I</mark>	I						
	LS3	Run 4	LS4	Run 5	LS5	Run 6				
2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2039	2040	2041 2042				

 \rightarrow LHCb welcomes new collaborators!





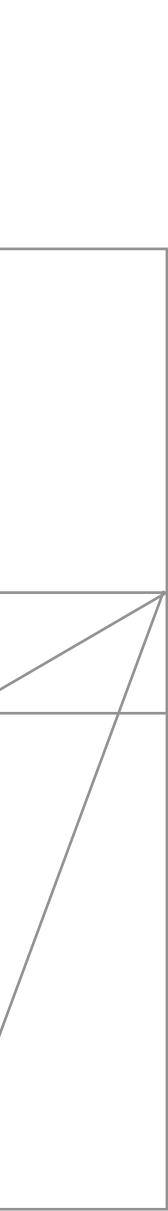




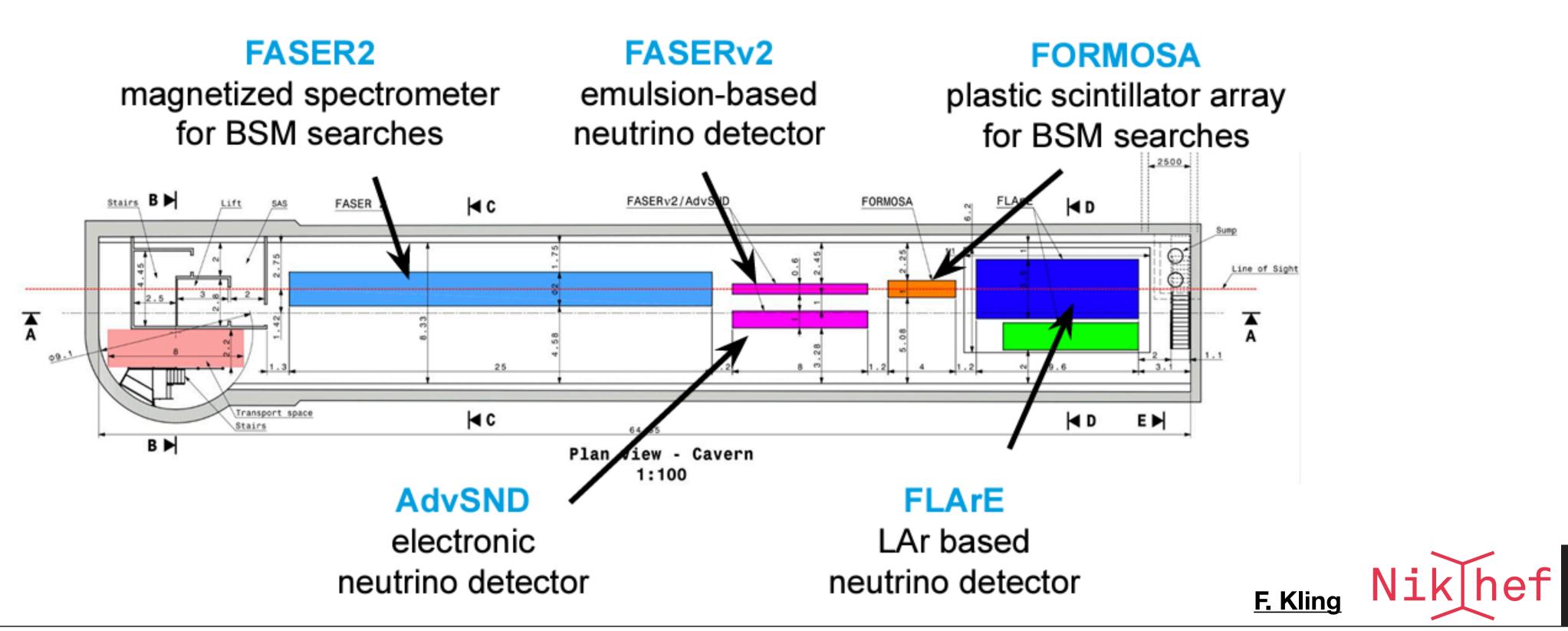


Future Facilities FPF: The Forward Physics Facility





FPF: Experiments



• The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for **BSM physics searches**, neutrino physics and QCD.

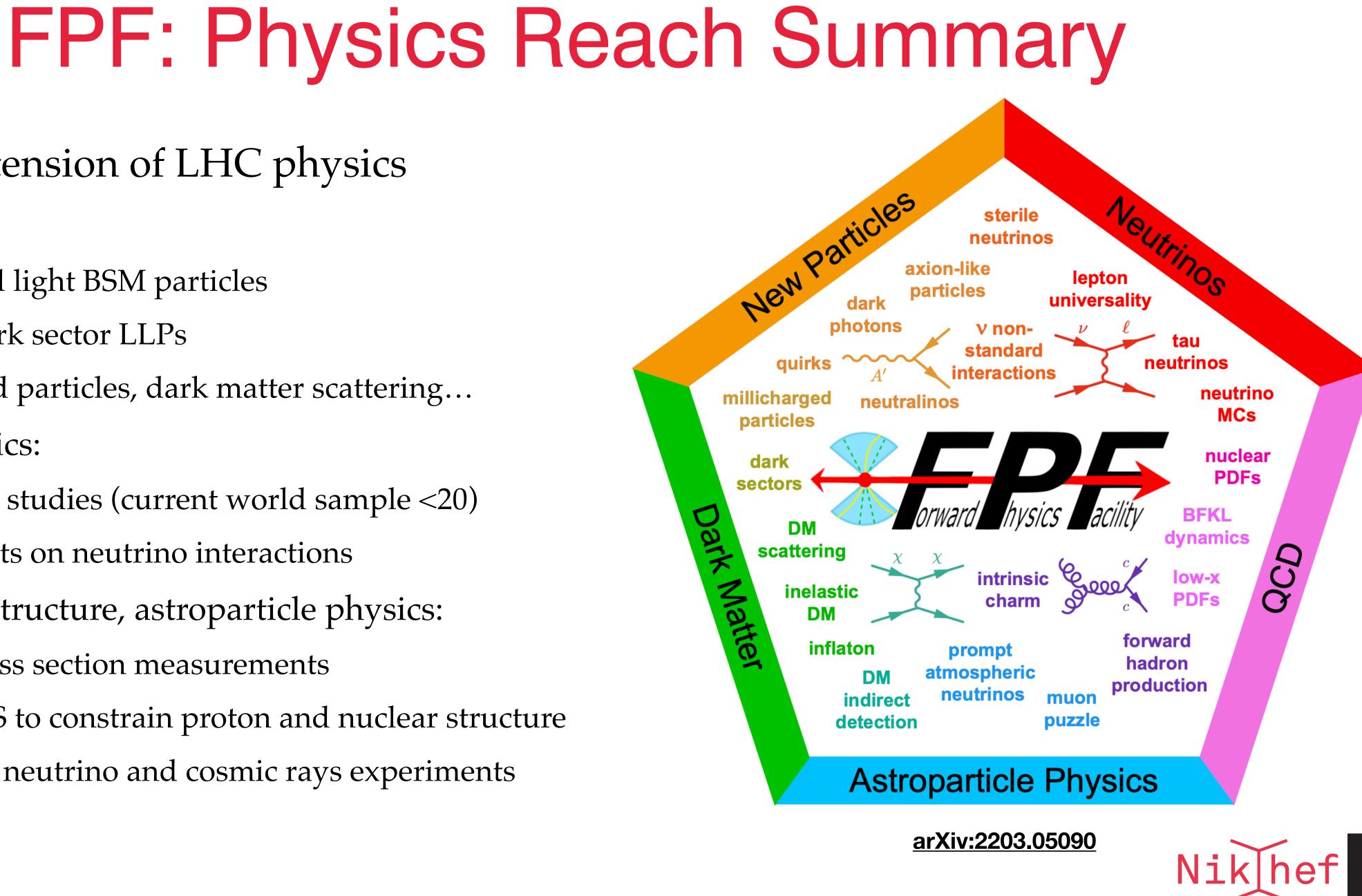






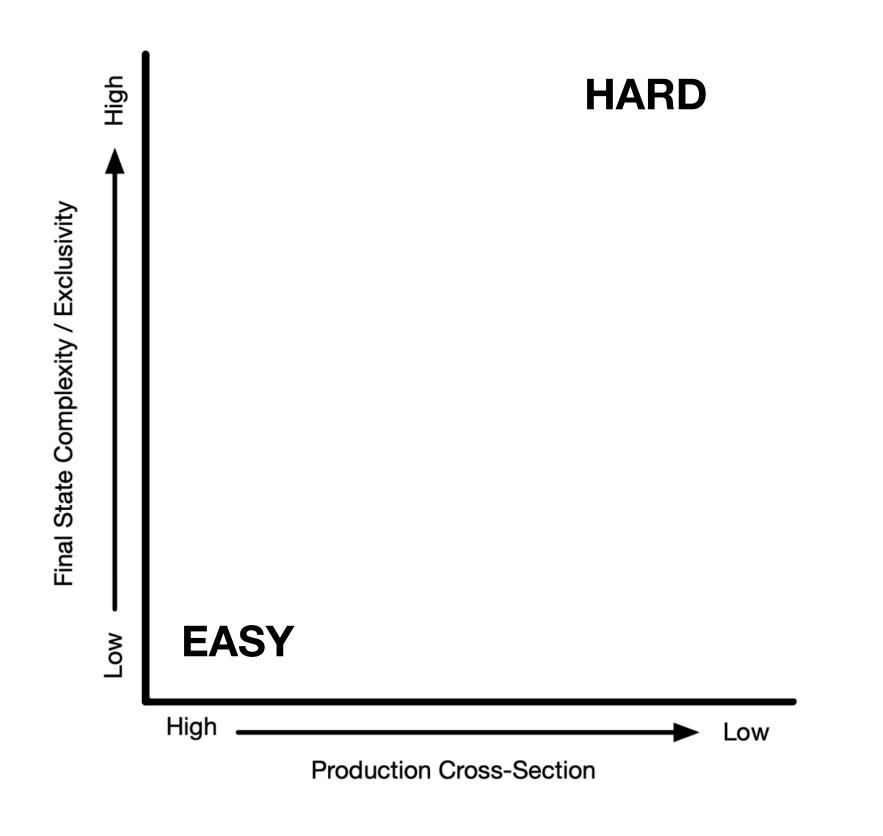
- Significant extension of LHC physics
 - BSM searches:
 - Very forward light BSM particles
 - Decaying dark sector LLPs
 - Milli-charged particles, dark matter scattering...
 - Neutrino physics:
 - Tau neutrino studies (current world sample <20)
 - EFT contraints on neutrino interactions
 - QCD, hadron structure, astroparticle physics:
 - Neutrino cross section measurements
 - Neutrino DIS to constrain proton and nuclear structure
 - Kay input to neutrino and cosmic rays experiments

J. Rojo, L. Brenner





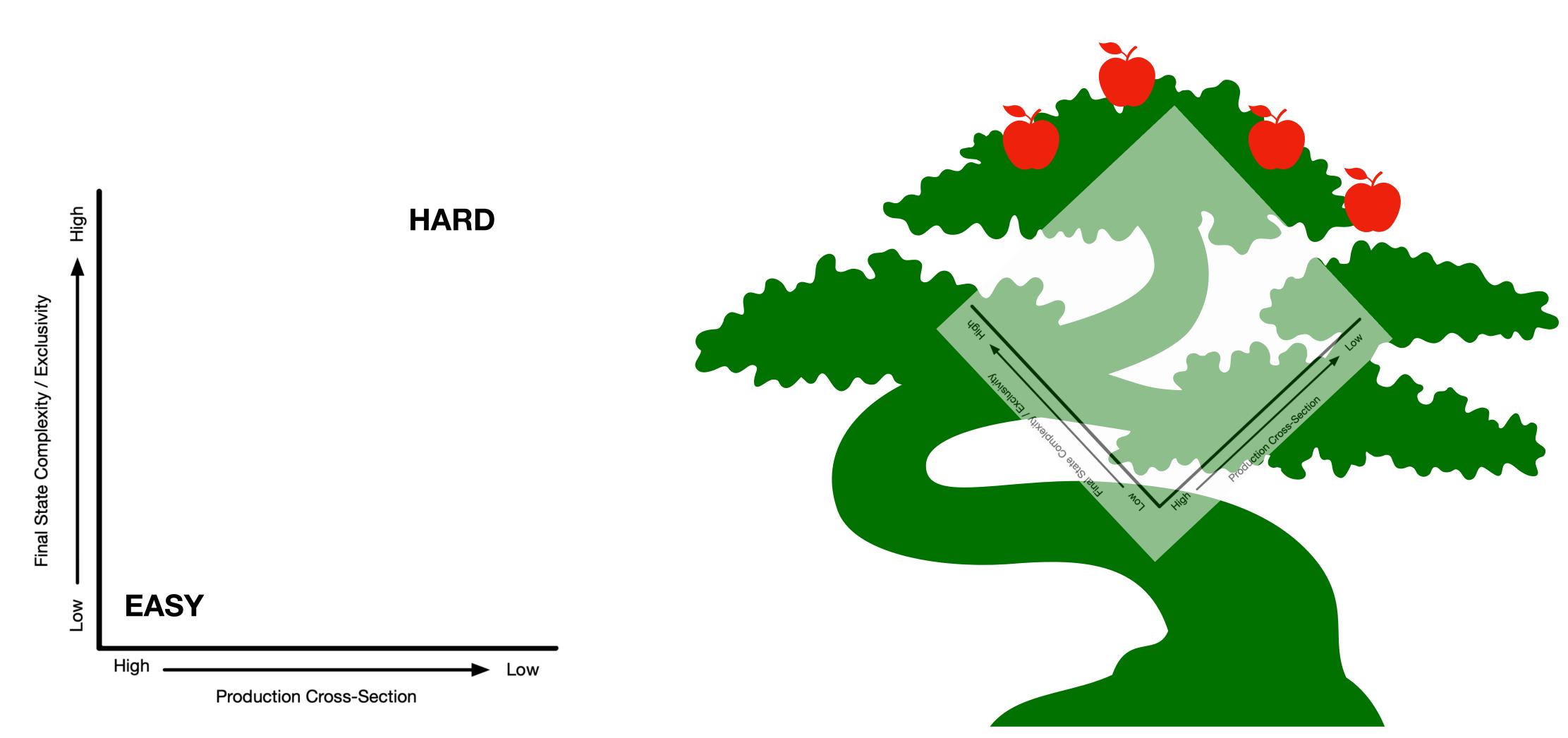
BSM Searches



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INSTITUTE OF PHYSICS

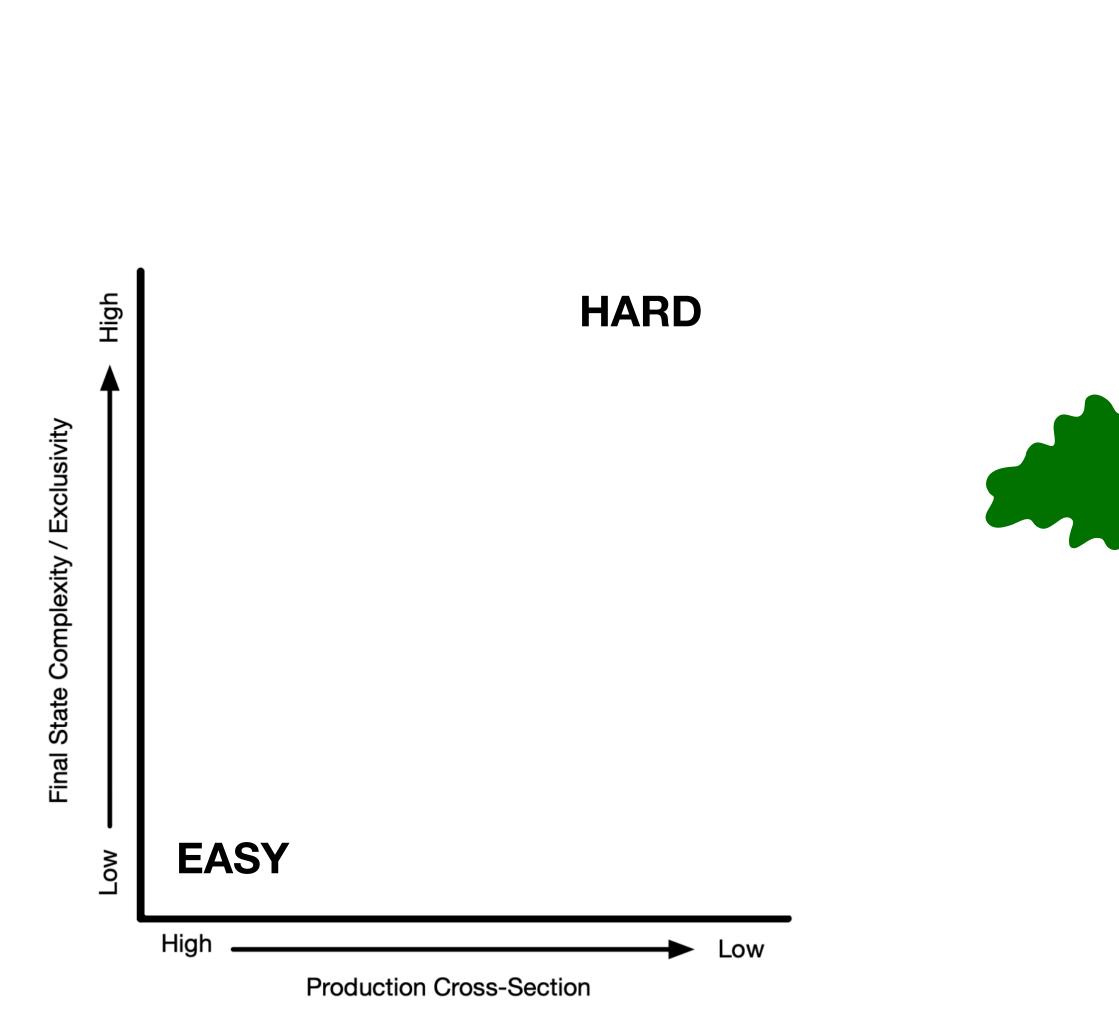




INSTITUTE OF PHYSICS

BSM Searches



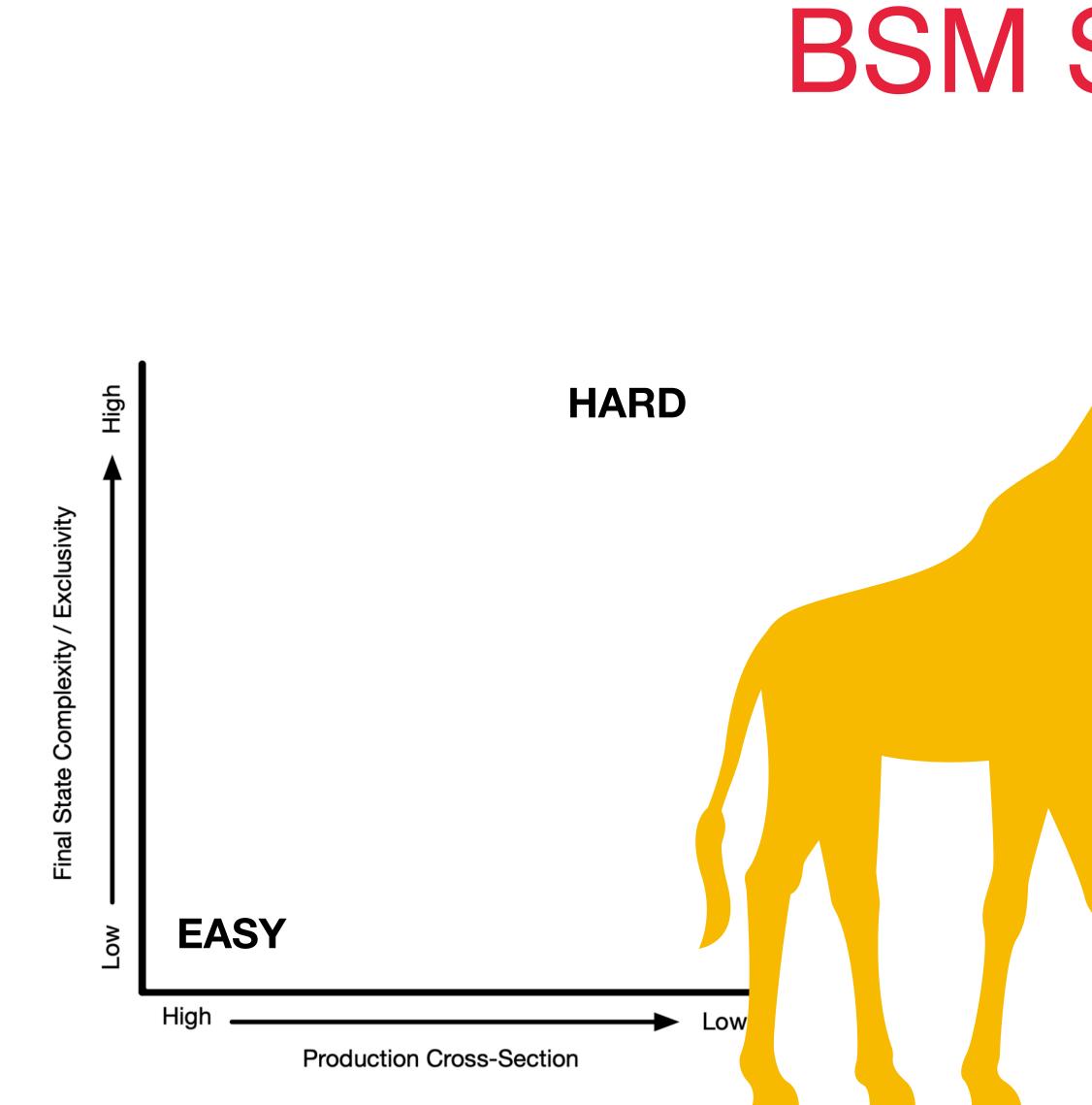


INSTITUTE OF PHYSICS

BSM Searches



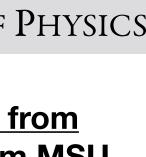
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BSM Searches

<u>Analogy adapted from</u> <u>Dr. Dan Hayden from MSU</u>

Disclaimer: biology not scientifically sound!





- Long-lived particles expand the scope of searches at the LHC
- Many innovative searches ongoing in ATLAS, CMS, LHCb, FASER (but also SND@LHC, NA 62)
- Crucial to plan ahead: look towards experiment upgrades and the Forward Physics Facility
- Stay tuned for many new exciting things ahead!
 - 13th LLP Community Workshop: 19-23 June, CERN

Summary and Outlook



UvA