X17 excess and perspective of its verification

Laura Molina Bueno on behalf of NA64 collaboration
mollaura@phys.ethz.ch

8th Edition of the Large Hadron Collider Physics Conference
25-29th May 2020

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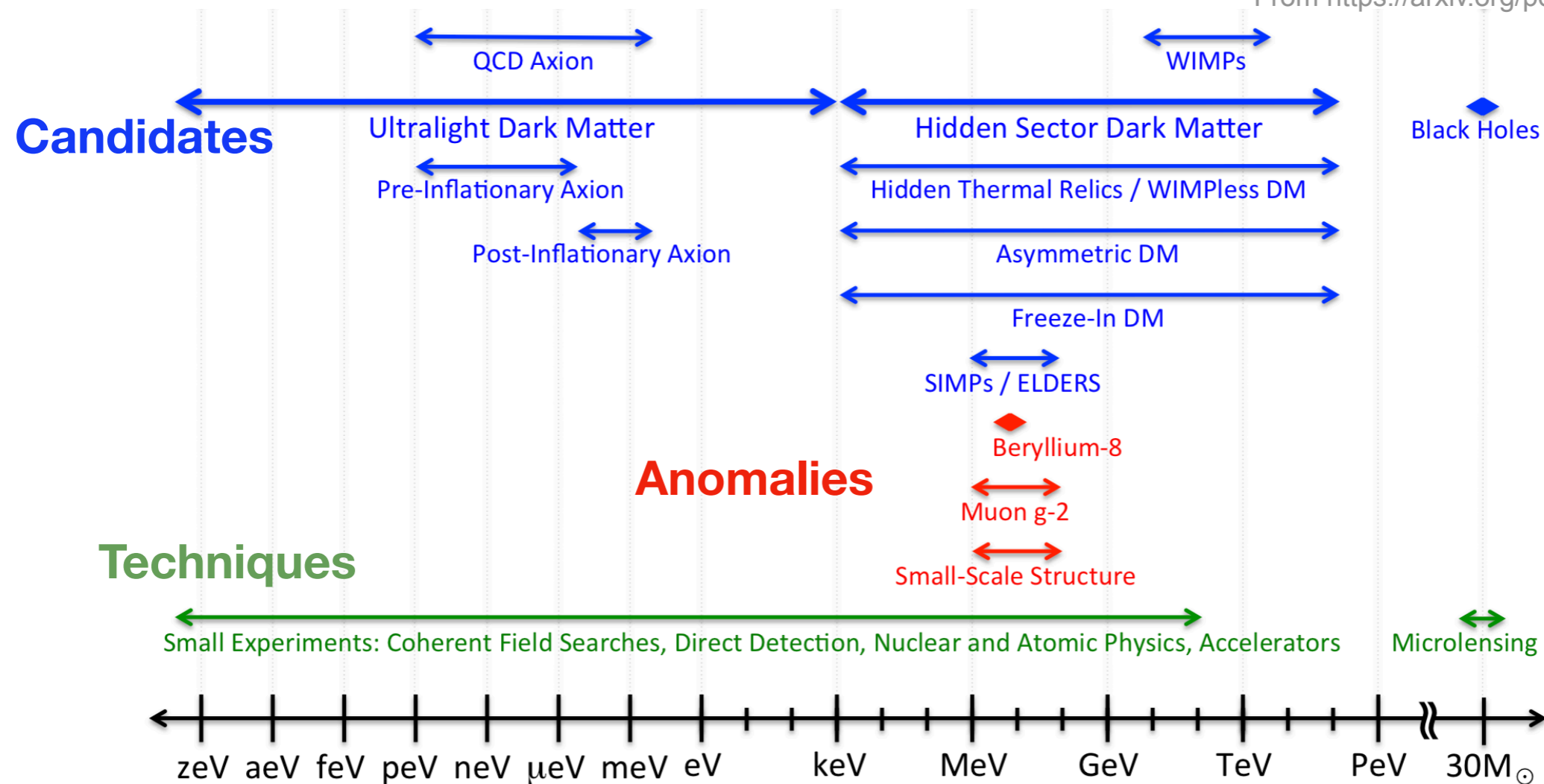Swiss Federal Institute of Technology Zurich

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Dark sectors

An interesting framework to explain the origin of dark matter

Existence of **dark sectors** which couple weakly with standard model particles and can decay into dark matter candidates.

From https://arxiv.org/pdf/1707.04591.pdf

Candidates

QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Black Holes

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion

Asymmetric DM

Freeze-In DM

SIMPs / ELDERS

Beryllium-8

Anomalies

Muon g-2

Small-Scale Structure

Techniques

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

Microlensing

zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M$_\odot$

Broad mass range ➡ **can not be covered by a single experiment**

Complementary searches involving different techniques

Broad mass range ➡ **can not be covered by a single experiment**
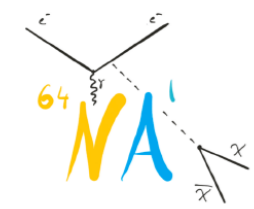
Complementary searches involving different techniques

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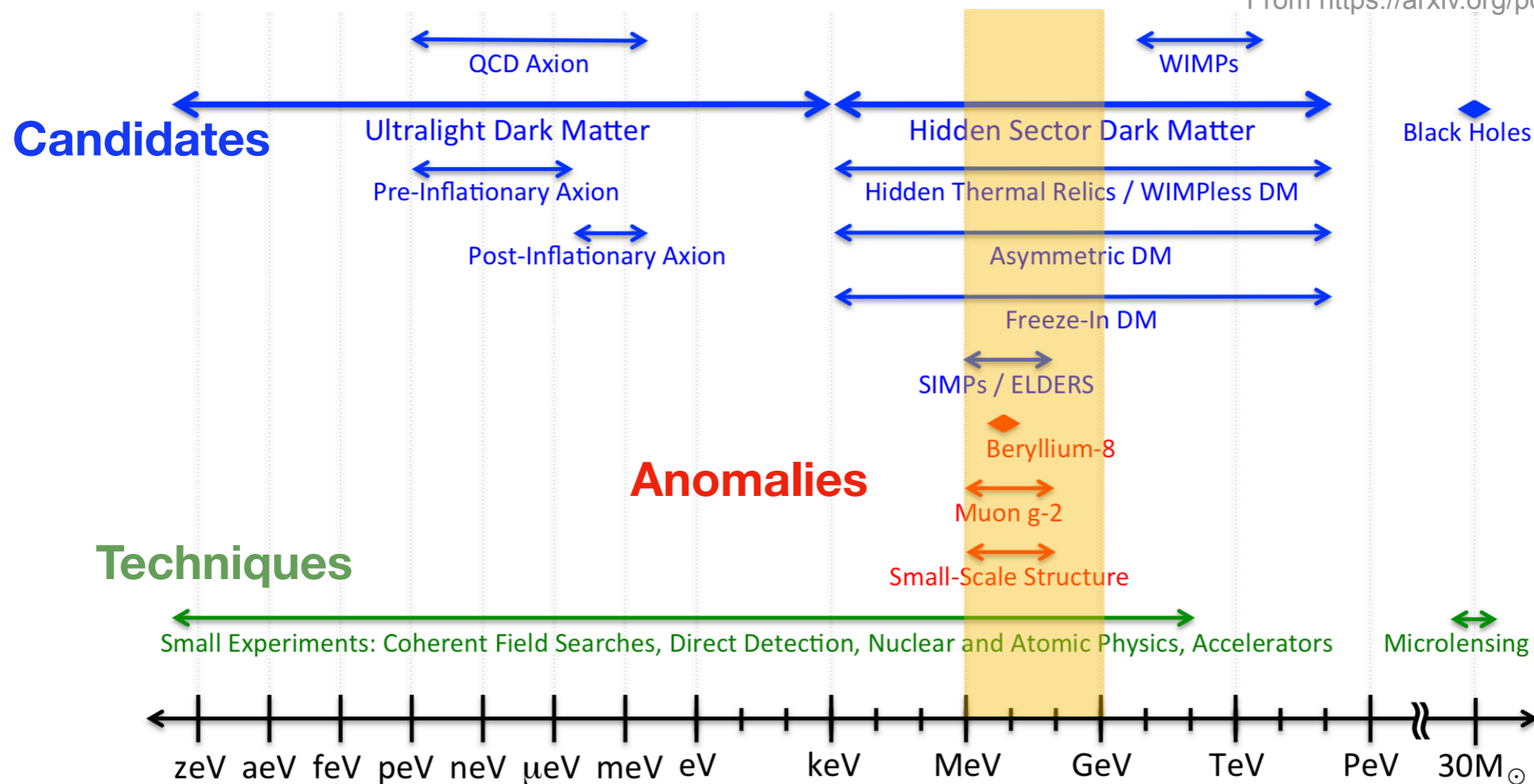
Initial e⁻ beam

Active Dump

A'

Initial e⁻ beam → Active Dump A'

Setup:

Visible mode $m_{A'} < 2m_\chi$

Invisible mode $m_{A'} > 2m_\chi$
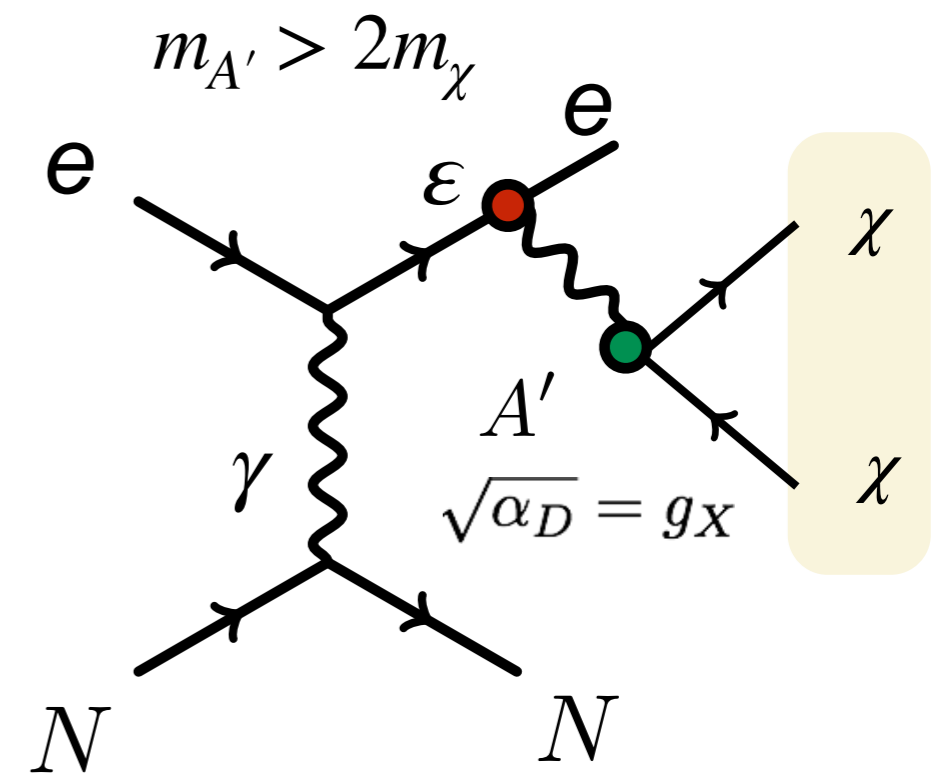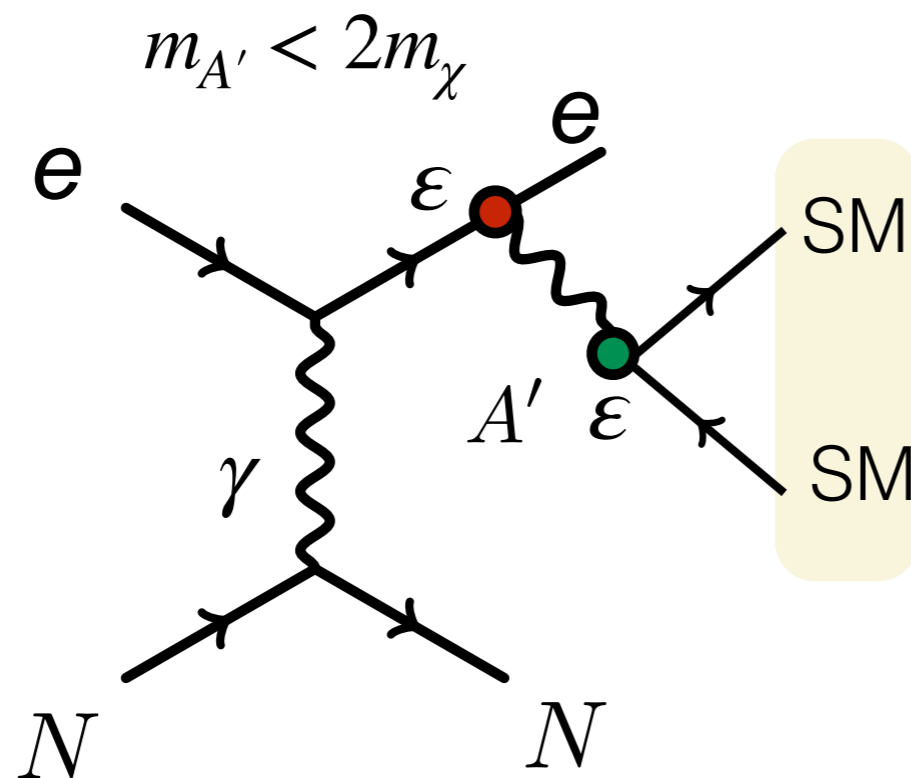
Signature: SM particles pair production

Missing energy

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Fixed target experiment at the CERN SPS designed to probe Dark sector physics

| 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | LS2 → | 2021 | 2021 | LS3 → | 2024 |

2014 — Proposed

2015 — 1st test beam

2016 — Invisible; Approved by SPSC as NA64 experiment

2017 — Invisible / *Visible*

2018 — Invisible / *Visible*

2021 — Already approved to continue running; Invisible / *Visible*

2021 — Muon pilot run

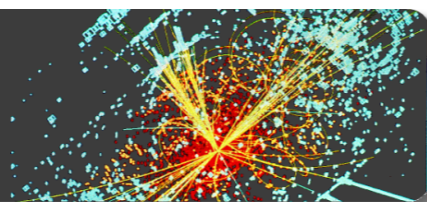**2024** — Proposal to run in muon mode

Beam time

Broad physics program ⟶

International collaboration: 46 researchers from 14 institutions

CERN Council Open Symposium on the Update of
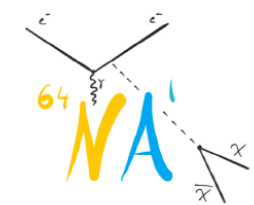**European Strategy for Particle Physics**
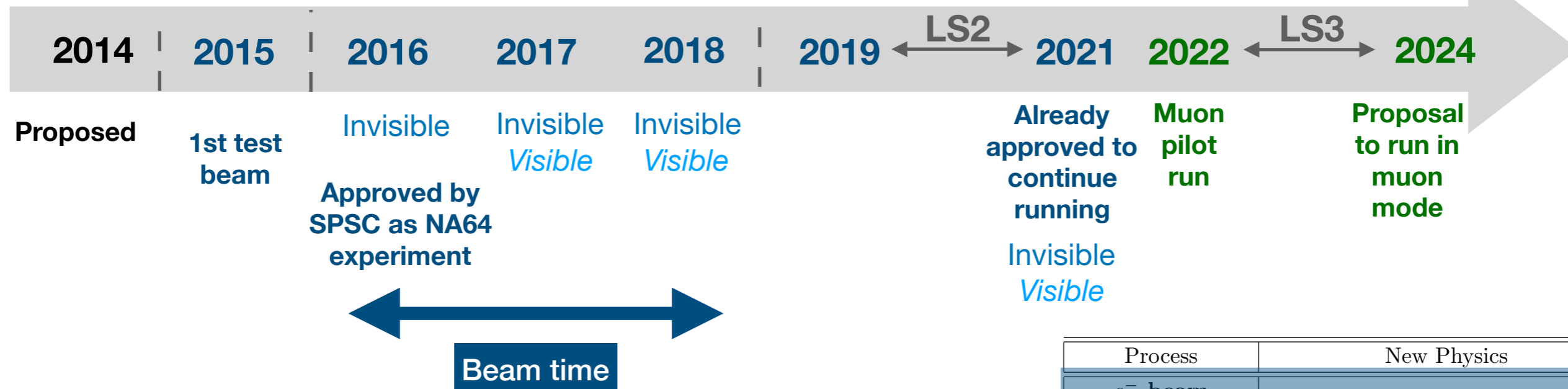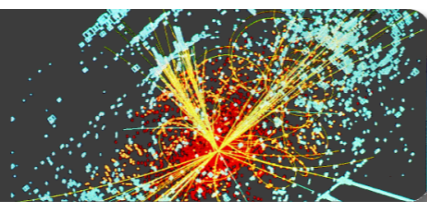13-16 May 2019 - Granada, Spain

CERN-PBC-REPORT-2018-007

CERN — Physics Beyond Colliders

Process	New Physics
e^- beam	
$A' \to e^+e^-$, and $A' \to invisible$	Dark photon
$A' \to \chi\overline{\chi}$	sub-GeV Dark Matter (χ)
$X \to e^+e^-$	new gauge X- boson
milliQ particles	Dark Sector, charge quantisation
$a \to \gamma\gamma, invisible$	Axion-like particles
μ^- beam	
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$
$Z_\mu \to \chi\overline{\chi}$	$L_\mu - L_\tau$ charged Dark Matter (χ)
milliQ	Dark Sector, charge quantisation
$a_\mu \to invisible$	non-universal ALP coupling
$\mu - \tau$ conversion	Lepton Flavour Violation
π^-, K^- beams	Current limits, PDG'2018
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5 \times 10^{-4}$
$K_S^0 \to invisible$	no limits
$K_L^0 \to invisible$	no limits

The NA64 experiment and its physics program

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Fixed target experiment at the CERN SPS designed to probe Dark sector physics

| 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | LS2 | 2021 | 2022 | LS3 | 2024 |

Proposed

1st test beam

Invisible

Invisible
Visible

Invisible
Visible

Approved by SPSC as NA64 experiment

Already approved to continue running

Invisible
Visible

Muon pilot run

Proposal to run in muon mode

Beam time

Broad physics program

International collaboration: 46 researchers from 14 institutions

CERN Council Open Symposium on the Update of
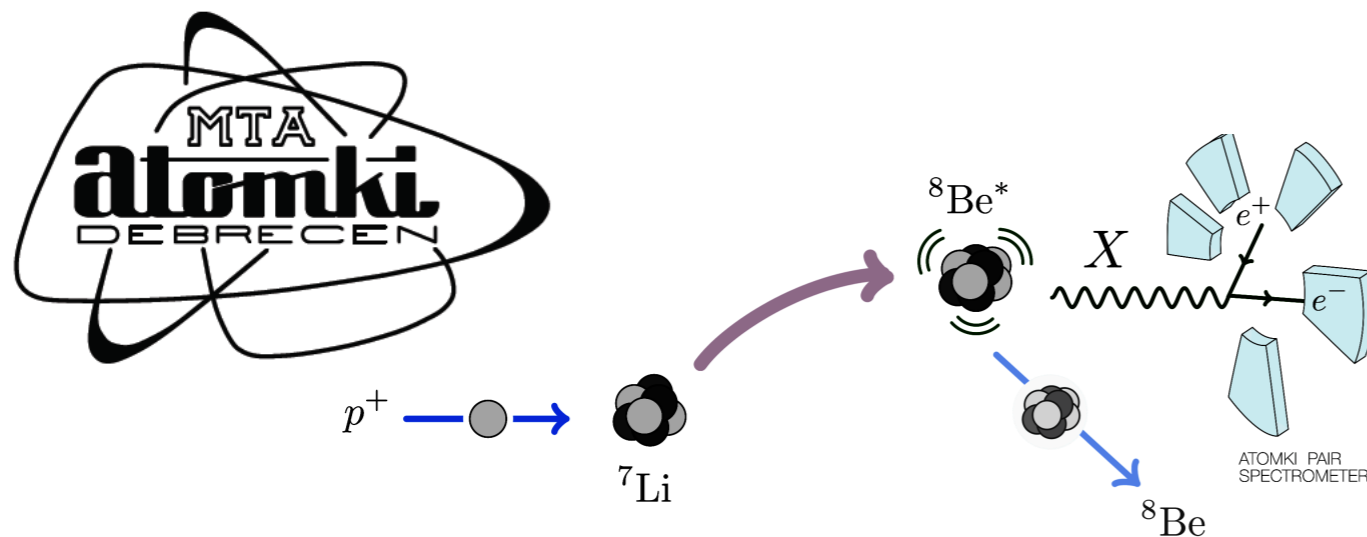**European Strategy for Particle Physics**
13-16 May 2019 - Granada, Spain

CERN-PBC-REPORT-2018-007

CERN — Physics Beyond Colliders

Process	New Physics
e^- **beam**	
$A' \to e^+e^-$, and	Dark photon
$A' \to inv$	
$A' \to$ **Focus of this talk** er (χ)	
$X \to e^+e^-$	new gauge X- boson
milliQ particles	Dark Sector, charge quantisation
$a \to \gamma\gamma, invisible$	Axion-like particles
μ^- **beam**	
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$
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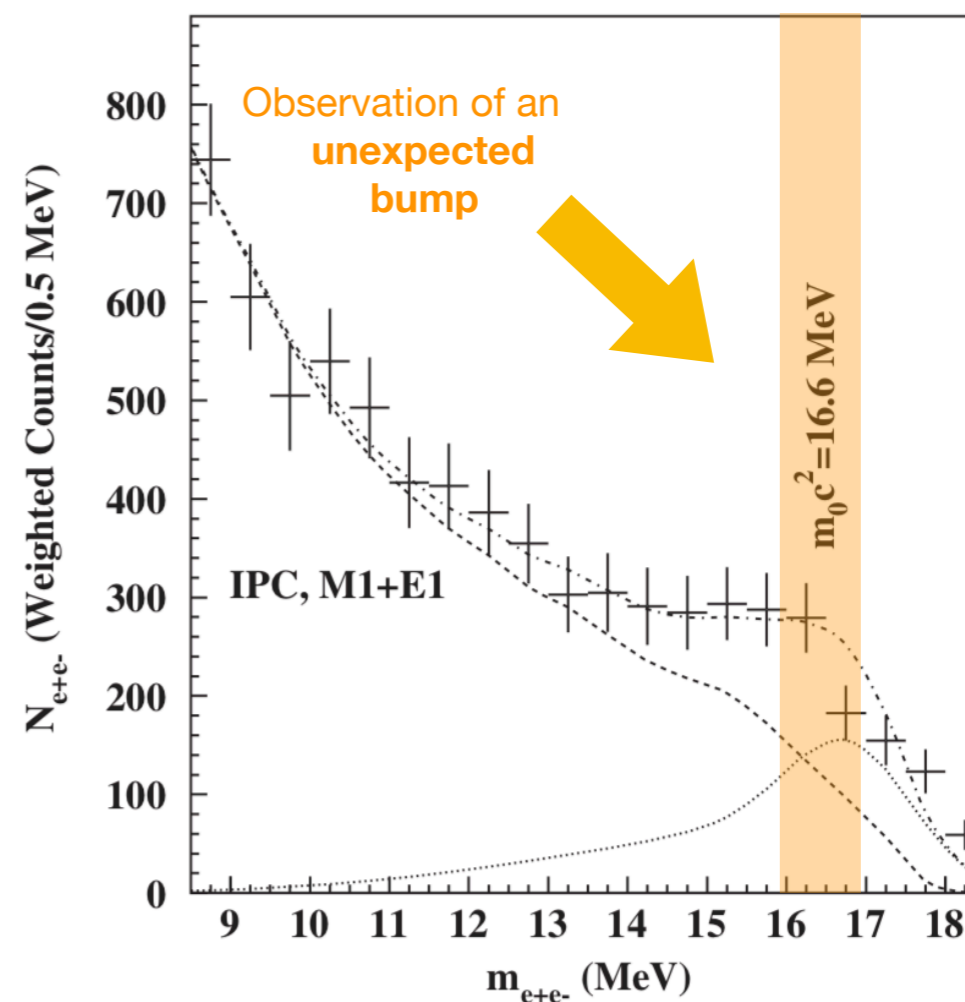
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⁸Be anomaly: **a protophobic gauge boson (X17) with a mass of 17 MeV?**

J. Feng et al. Phys. Rev. Lett. 117, 071803 (2016)

Coupling strength with electrons:
$2 \times 10^{-4} \leq \varepsilon_e \leq 1.4 \times 10^{-3}$ ➡ $10^{-14} \leq \tau_{X17} \leq 10^{-12}$ s
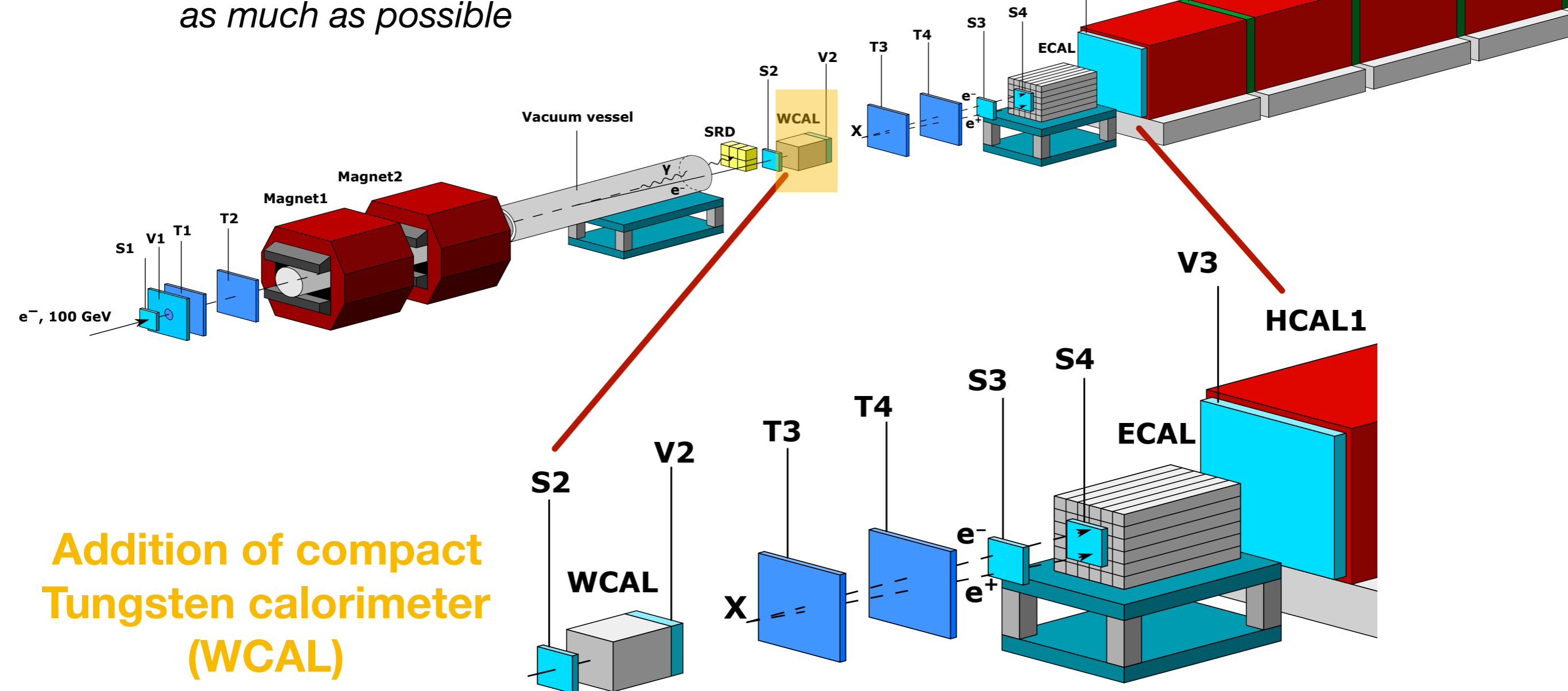

Observation of an **unexpected bump**
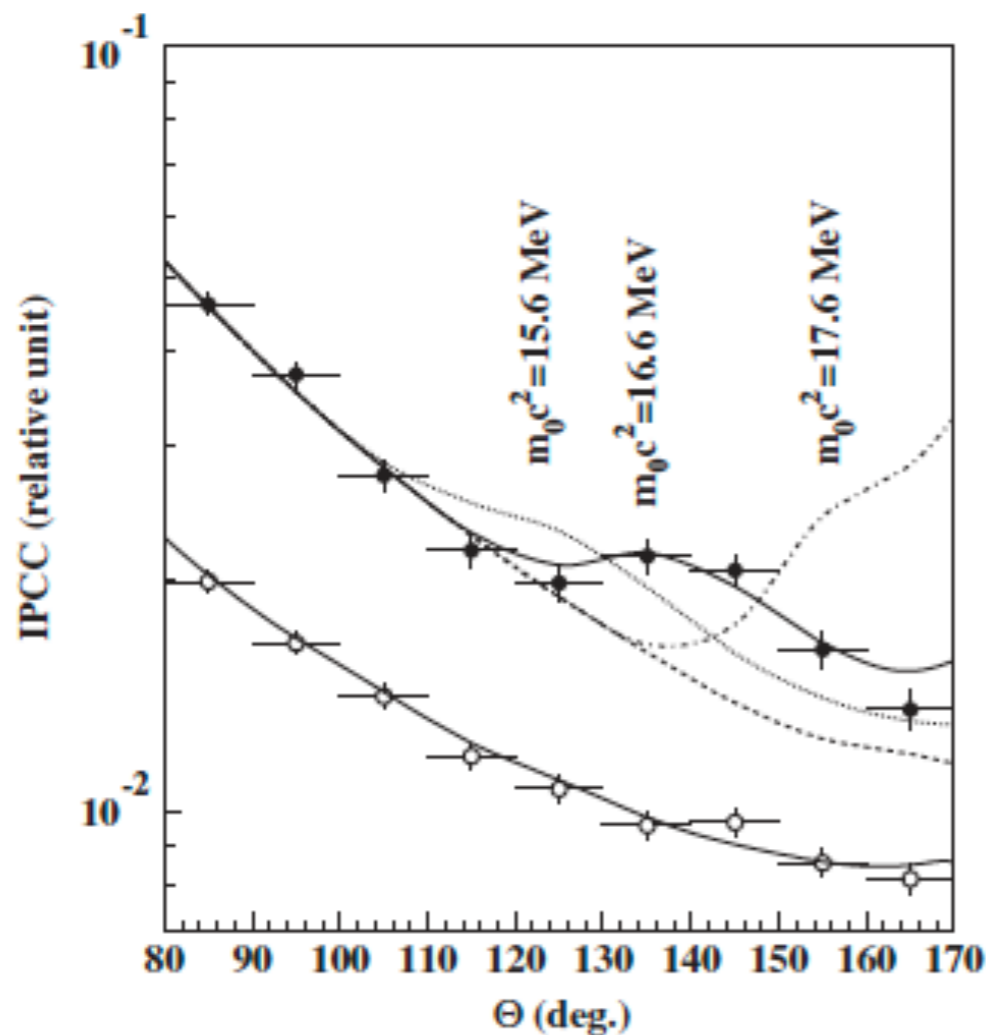
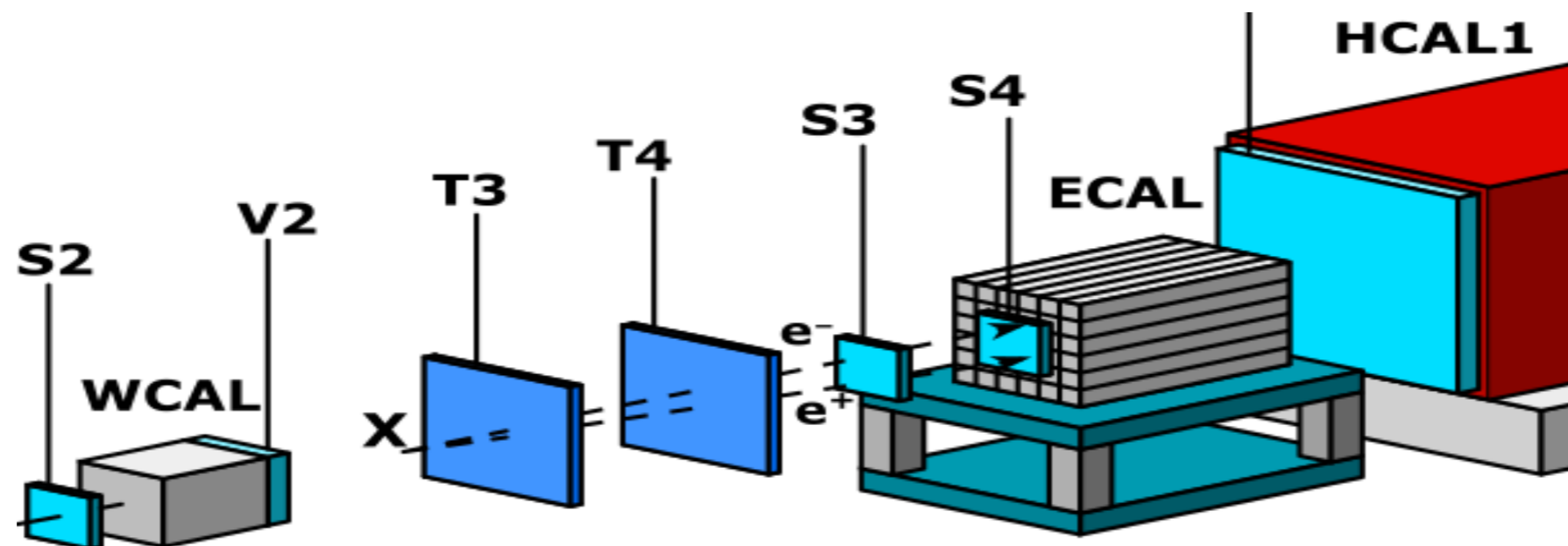A.J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

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2017 setup
*NA64 invisible setup reused
as much as possible*

**Addition of compact
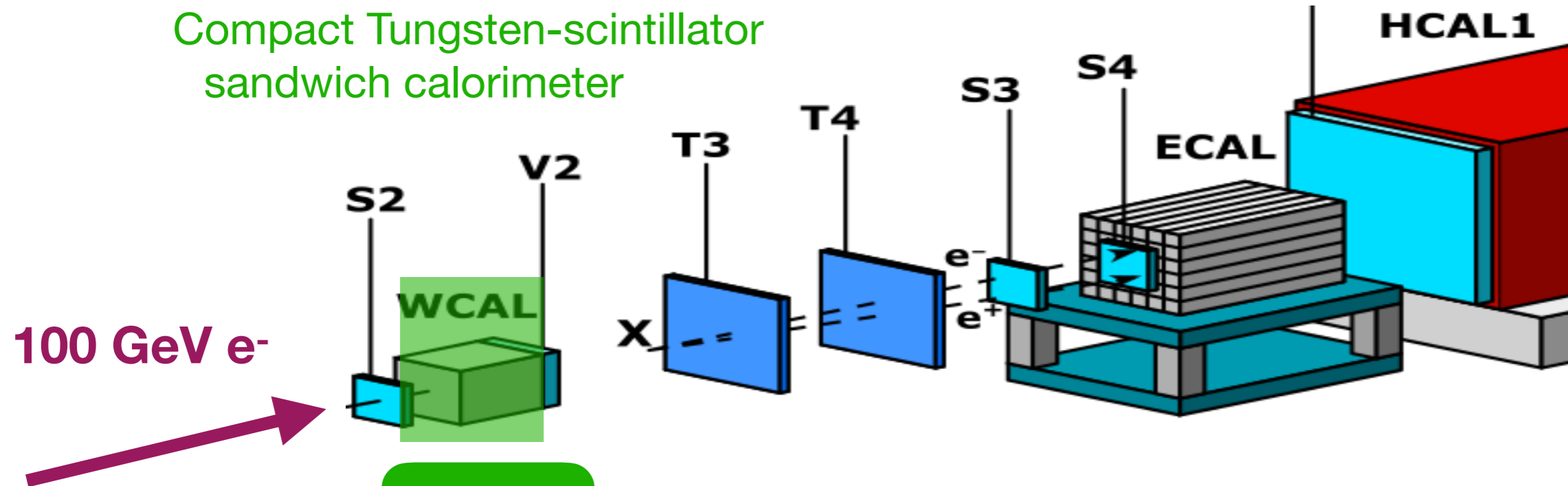Tungsten calorimeter
(WCAL)**

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HCAL1
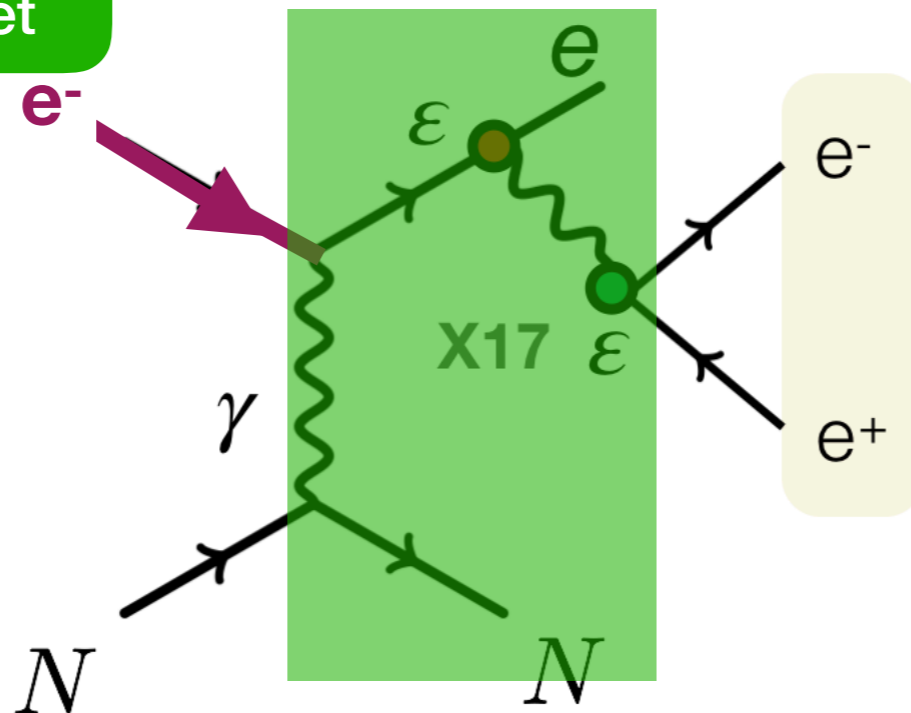
S3 S4

T4 ECAL

T3

S2 V2

WCAL

e^-

X

e^+

100 GeV e^- from
the H2 SPS
beam line

e^-

e

ε

e^-

X17 ε

γ

e^+

N N

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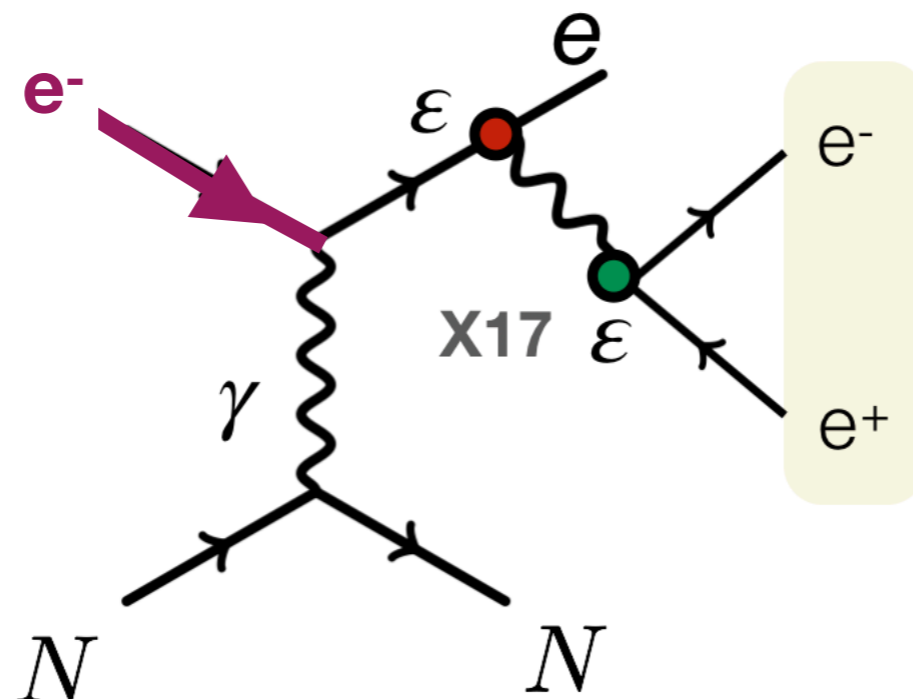
Compact Tungsten-scintillator sandwich calorimeter

HCAL1

S4

S3

ECAL

T4

T3

S2

V2

WCAL

100 GeV e⁻

e^-

e^+

Active target

e⁻

e

ε

X17 ε

e^-

e^+

γ

N

N

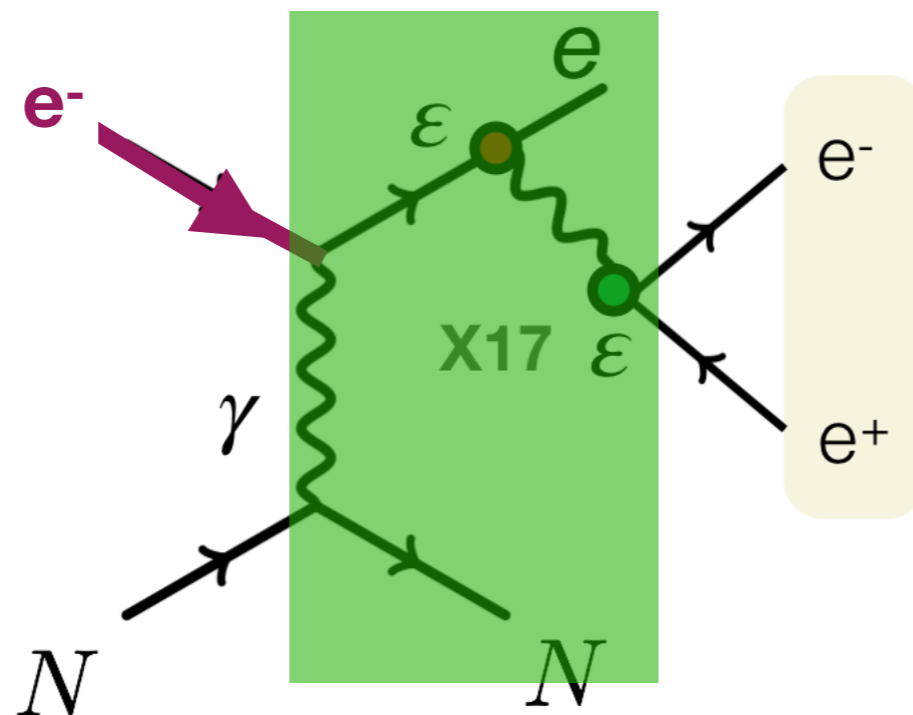**X17 boson** Bremsstrahlung

Energy loss of the initial electromagnetic shower measured in the WCAL

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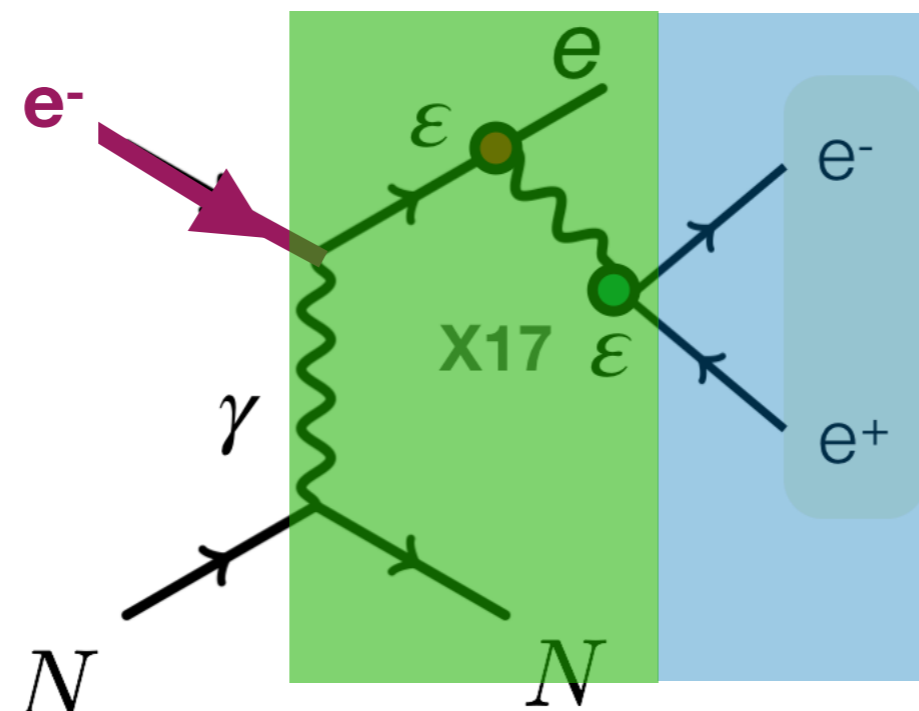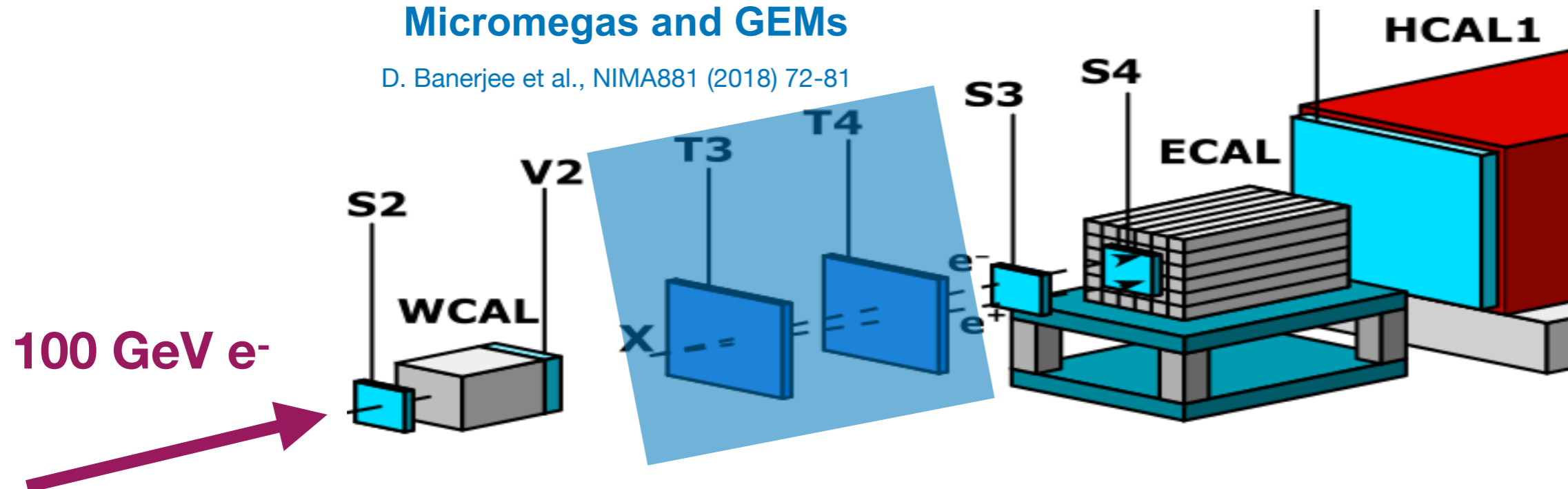L.Molina Bueno

100 GeV e⁻

Veto
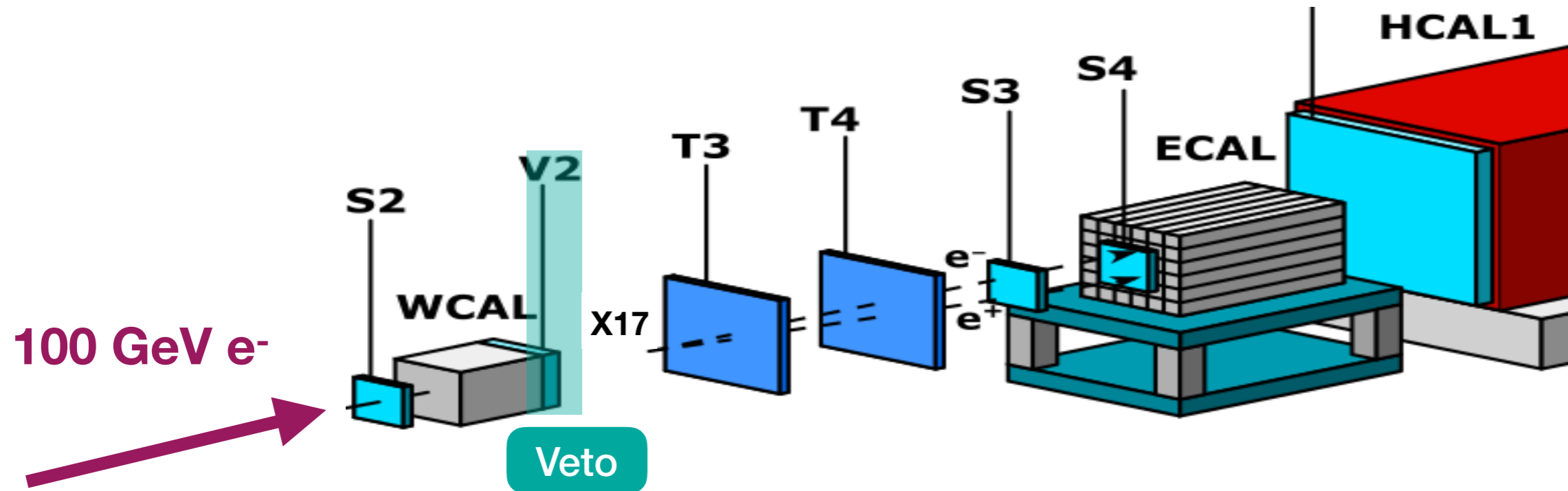
To reject particle leak

Large Energy (>50 GeV)
transported outside the WCAL

To be accepted as candidate
the particle need to be
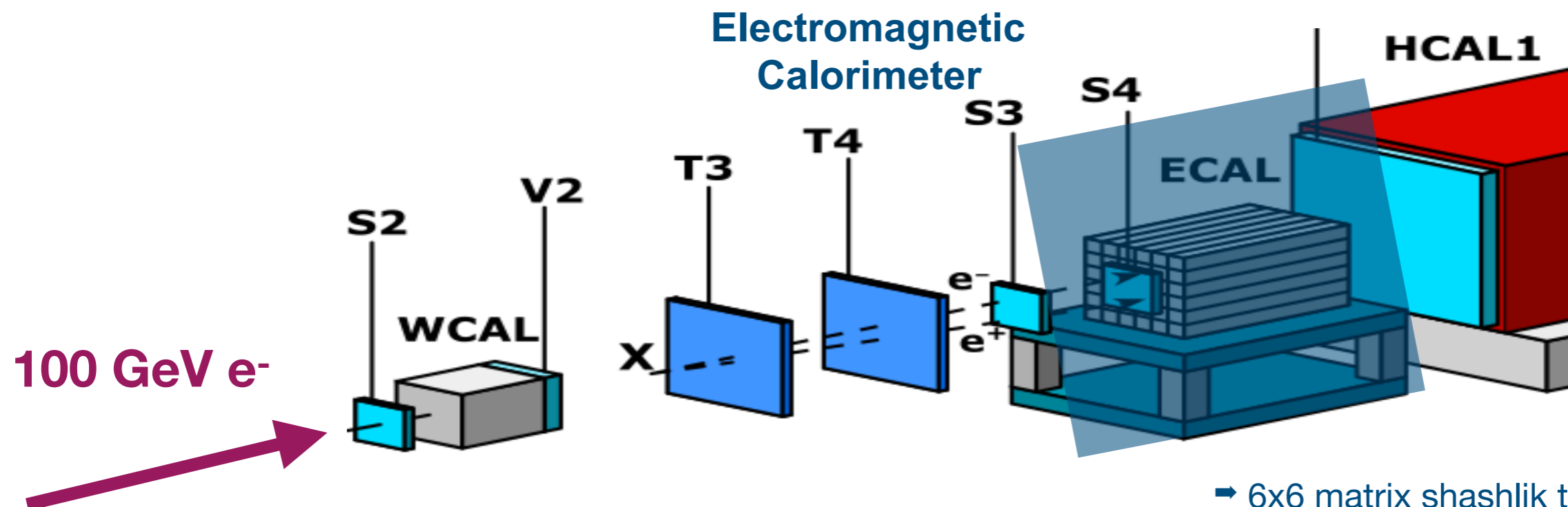neutral (no activity on V2)

Micromegas and GEMs

D. Banerjee et al., NIMA881 (2018) 72-81

100 GeV e⁻

e⁻

used to track the particle in the decay volume

X17 would decay after the WCAL to e⁺e⁻ pair

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100 GeV e⁻

Electromagnetic Calorimeter
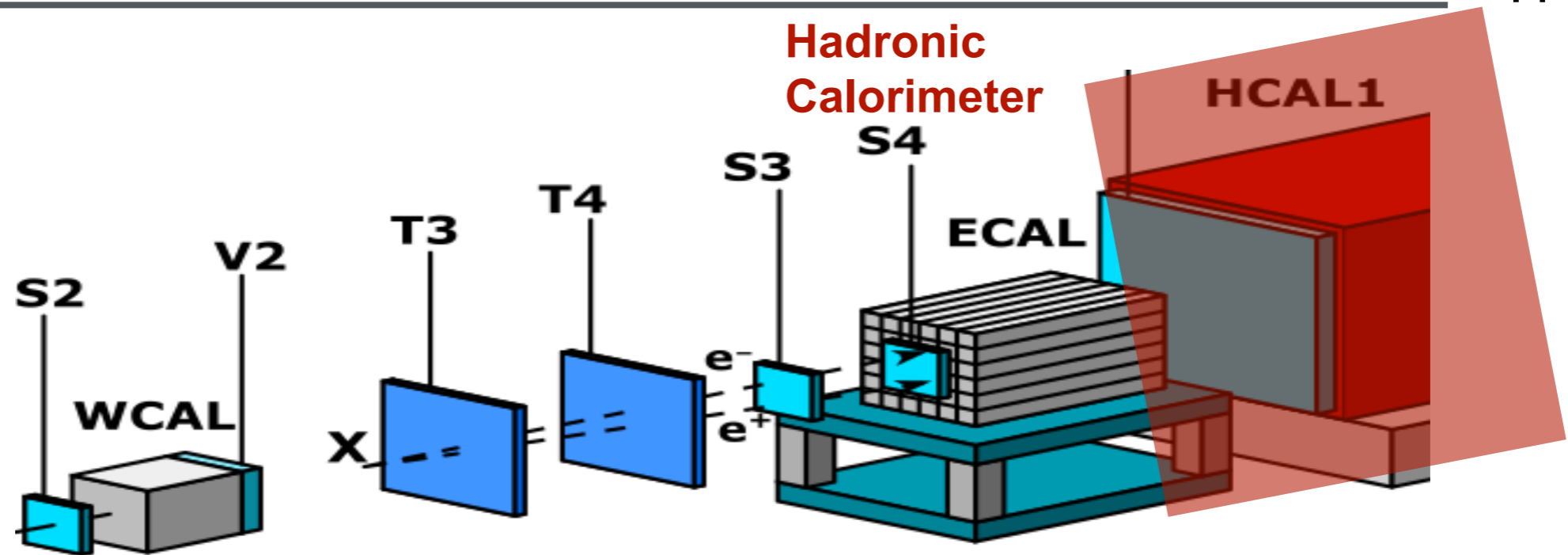
S2 V2 WCAL T3 T4 X S3 e⁻ e⁺ S4 ECAL HCAL1

➡ 6x6 matrix shashlik type
➡ Lead Scintillator sandwich
➡ High hermeticity ($\sim$40 X_0)
➡ Energy resolution ~ 9%/$\sqrt{(E[GeV])}$
➡ Readout through WLS fibers in spiral to avoid energy leaks
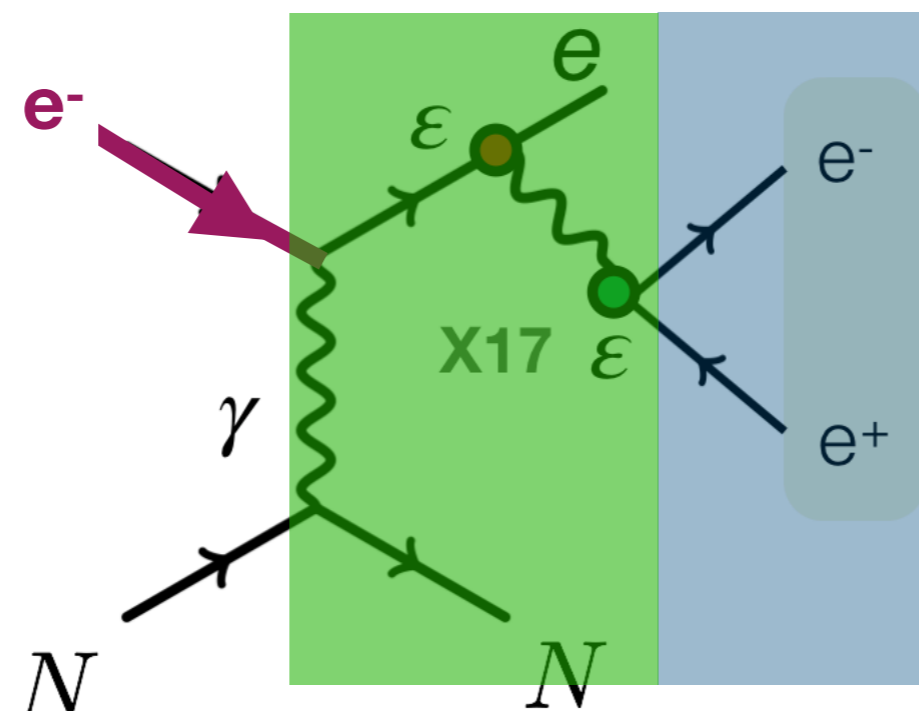
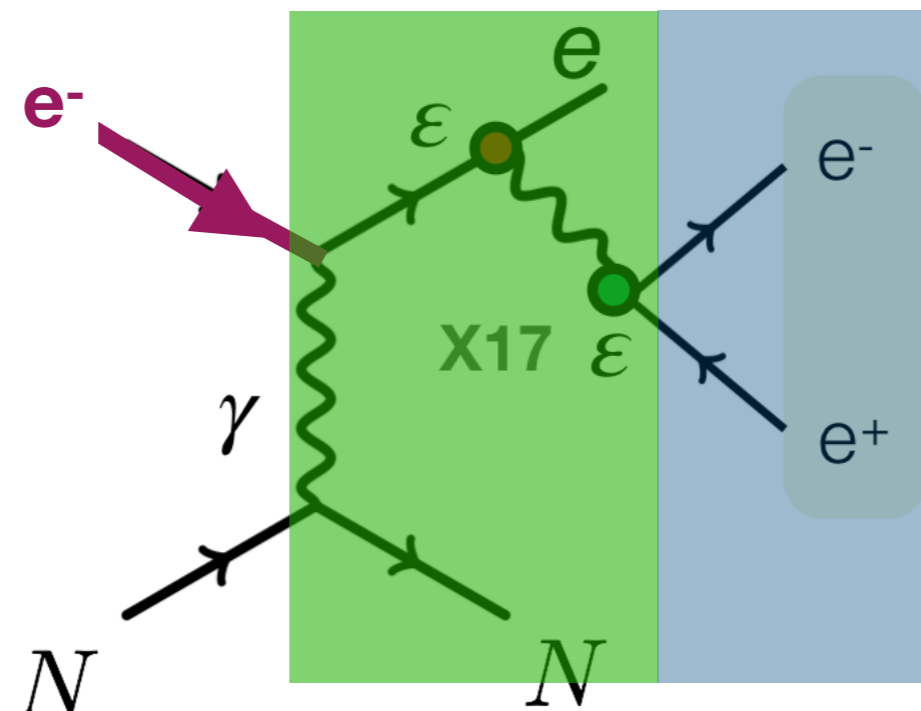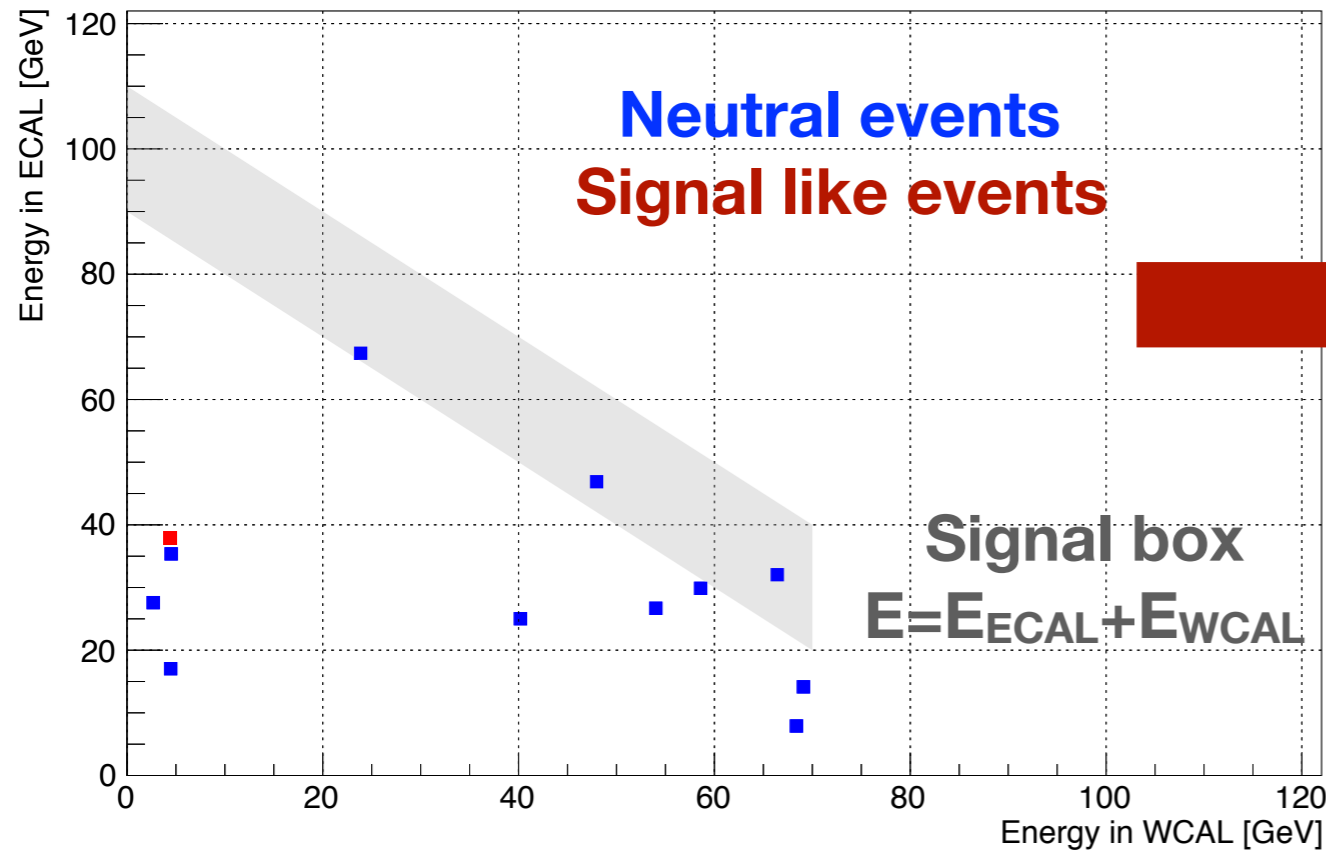**All the missing energy measured in the WCAL should be detected in the ECAL.**

Hadronic Calorimeter

HCAL1

S4

S3

ECAL

T3

T4

V2

S2

WCAL

100 GeV e⁻

X

e⁻

e⁺

➡ Iron Scintillator sandwich
➡ High hermeticity (~28λ)
➡ Energy resolution ~ 60%/$\sqrt{(E[GeV])}$
➡ Readout through WLS fibers in spiral to avoid energy leaks

e⁻

e

ε

X17 ε

e⁻

e⁺

γ

N

N

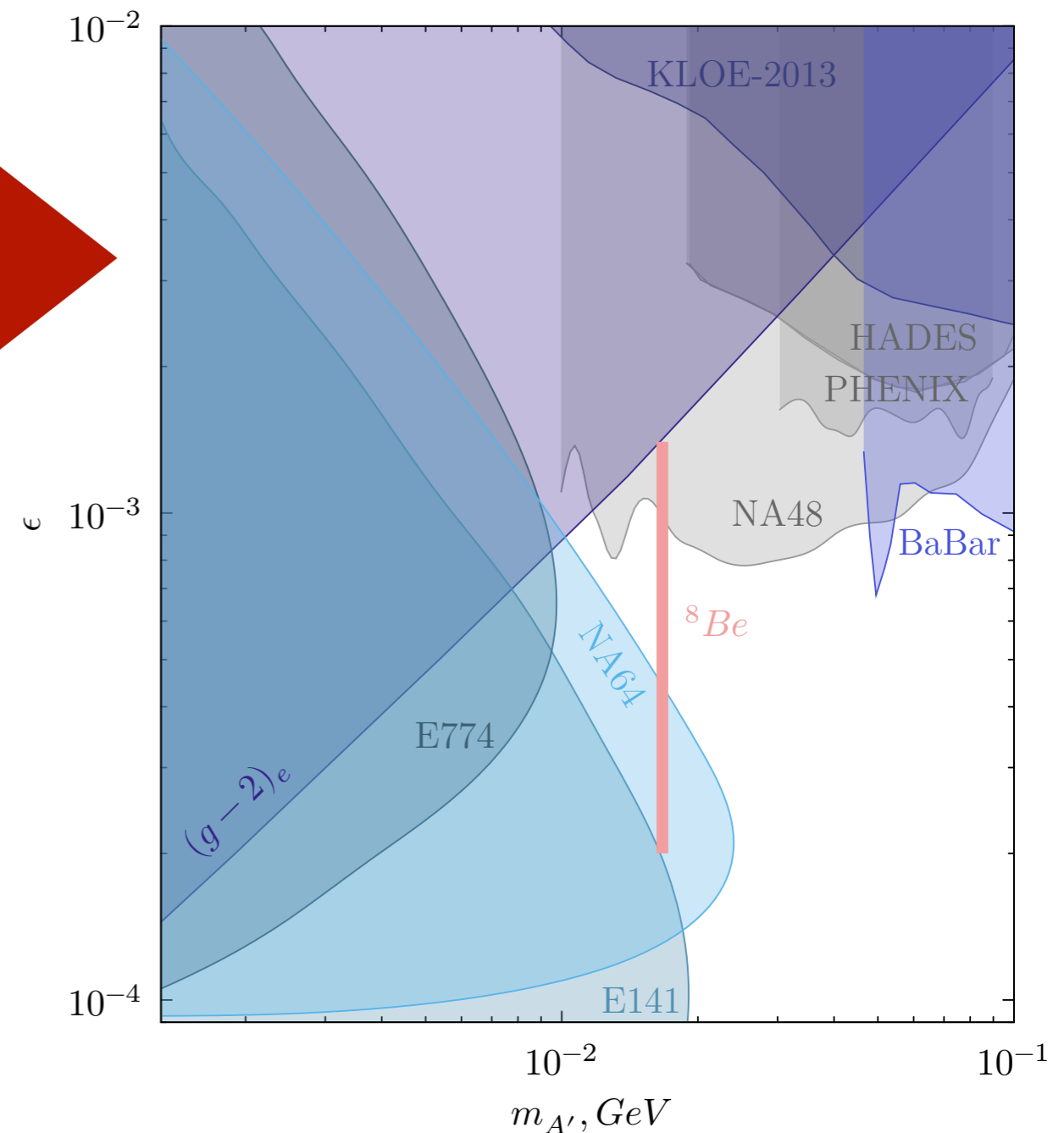**No energy deposited!**

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Event selection
- Neutral exiting WCAL: no activity in V2
- Charged particle in decay volume: single track in T3-T4, double MIP signal in S3,S4
- No hadron large scattering: no activity in HCAL/Veto

Signature
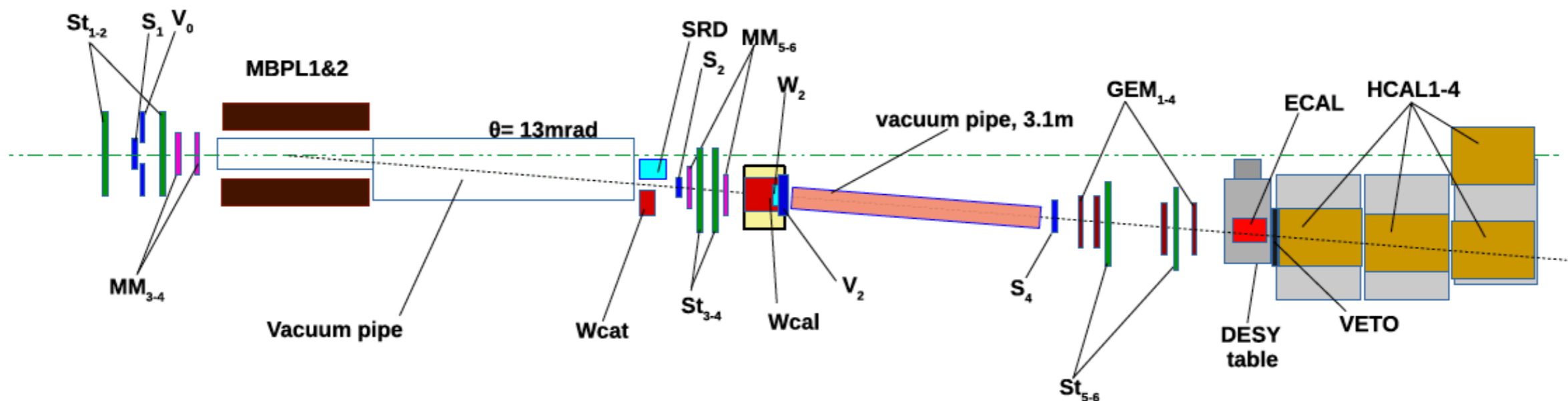- Two electromagnetic showers (1 ECAL and 1 WCAL)
- $E_{Beam}=E_{ECAL}+E_{WCAL}$

NA64 Collaboration,
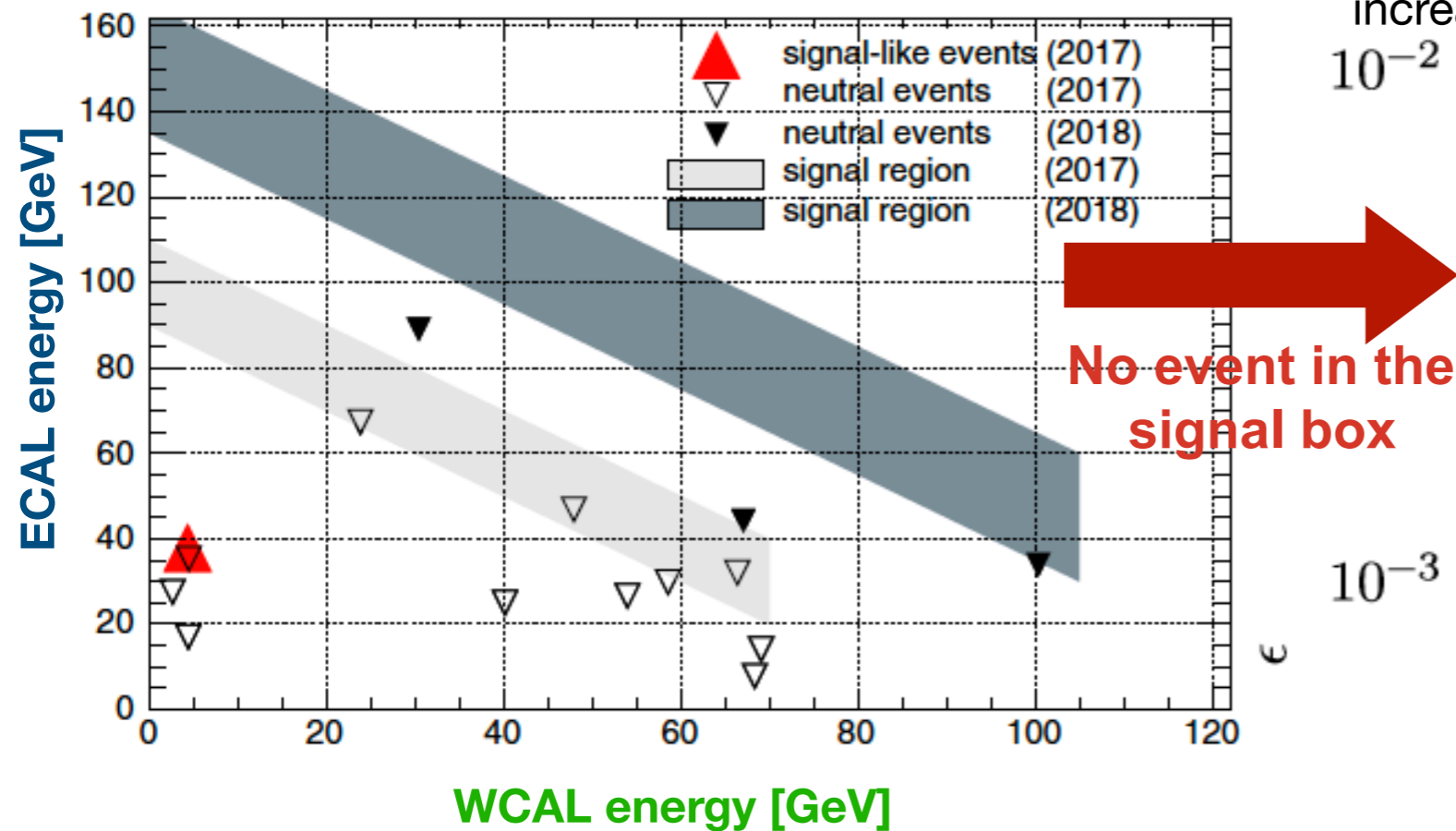Phys.Rev.Lett. 120, 231802 (2018)

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Improvements in the 2018 setup **to probe the remaining region for short-lived X17 (larger ε)**

- Beam energy from 100 to **150 GeV** to boost X17 outside WCAL.
- Shorter WCAL to probe large epsilon
- Thinner veto (W2) after WCAL to minimise the probability that X17 decays in it.
- For Background suppression: vacuum pipe installed+increased WCAL-ECAL distance
- Additional trackers

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Without the 2018 setup optimisation ε would have only increased logarithmically with the number of EOTs.

No event in the signal box

Source of background	2017 data	2018 data
$K_S^0 \rightarrow 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
$\pi N \rightarrow (\geq 1)\pi^0 + n + \cdots$	0.01 ± 0.004	0.001 ± 0.0004
Punchthrough π^-	0.0015 ± 0.0008	0.0007 ± 0.0004
Punchthrough γ	<0.001	<0.0005
$\pi, K \rightarrow e\nu, K_{e4}$ decays		<0.001
$eZ \rightarrow eZ\mu^+\mu^-; \mu^\pm \rightarrow e^\pm \nu\bar{\nu}$		<0.001
Total	0.07 ± 0.035	0.006 ± 0.003
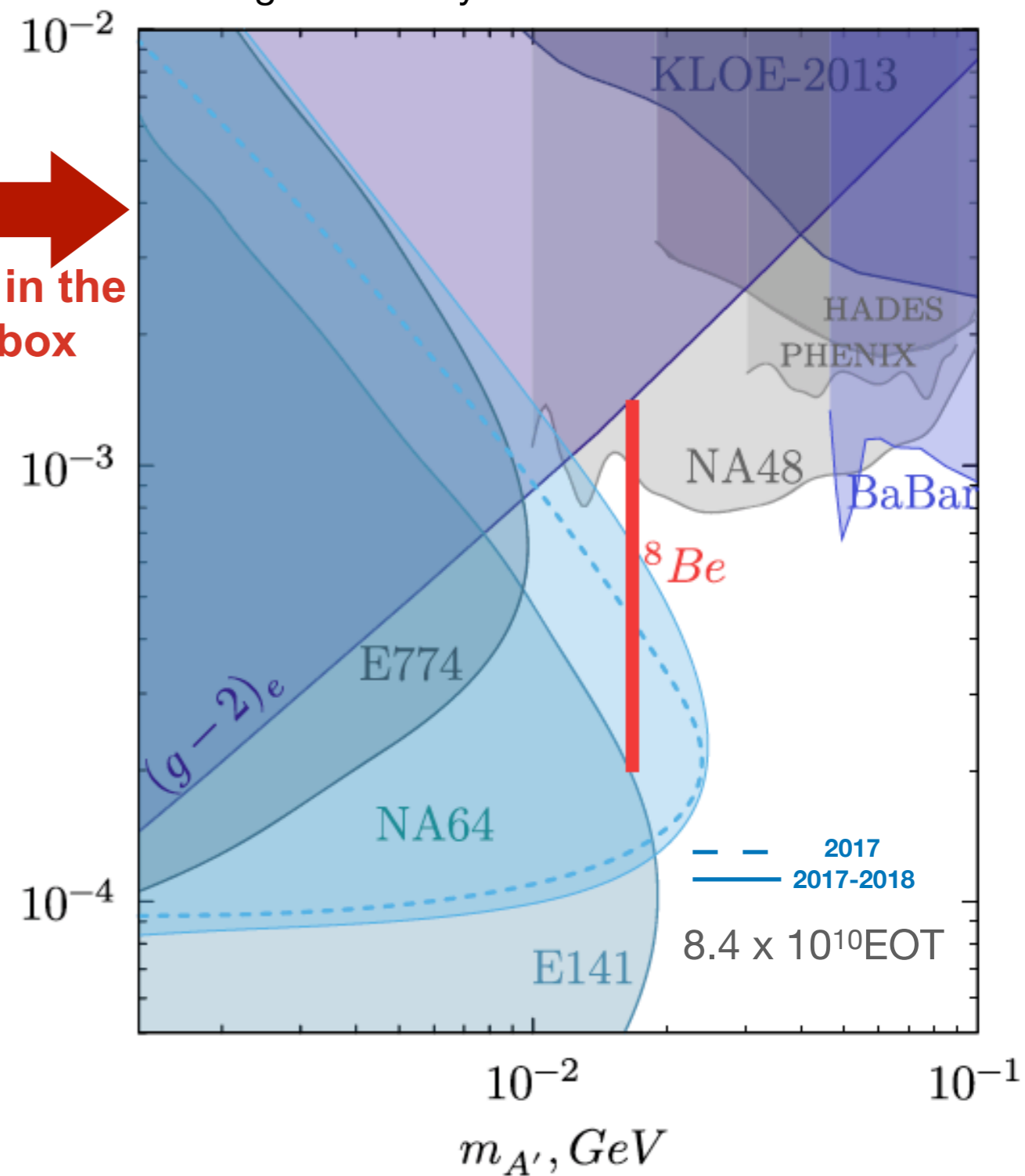
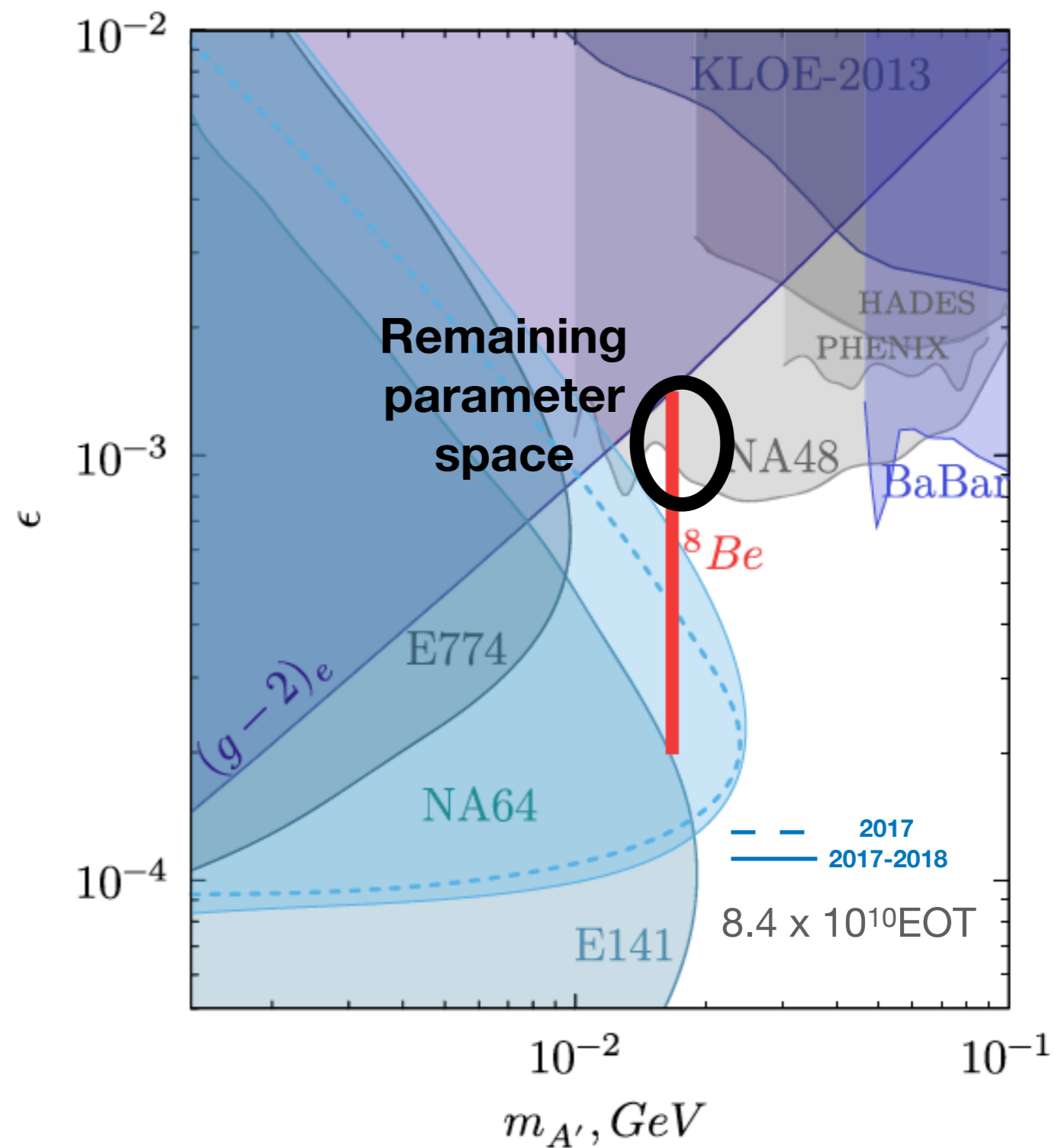NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

New recent results on other nuclei, ^{4}He, show a similar excess

^{3}H(p,e$^+$e$^-$)^{4}He

$E_p = 900$ keV
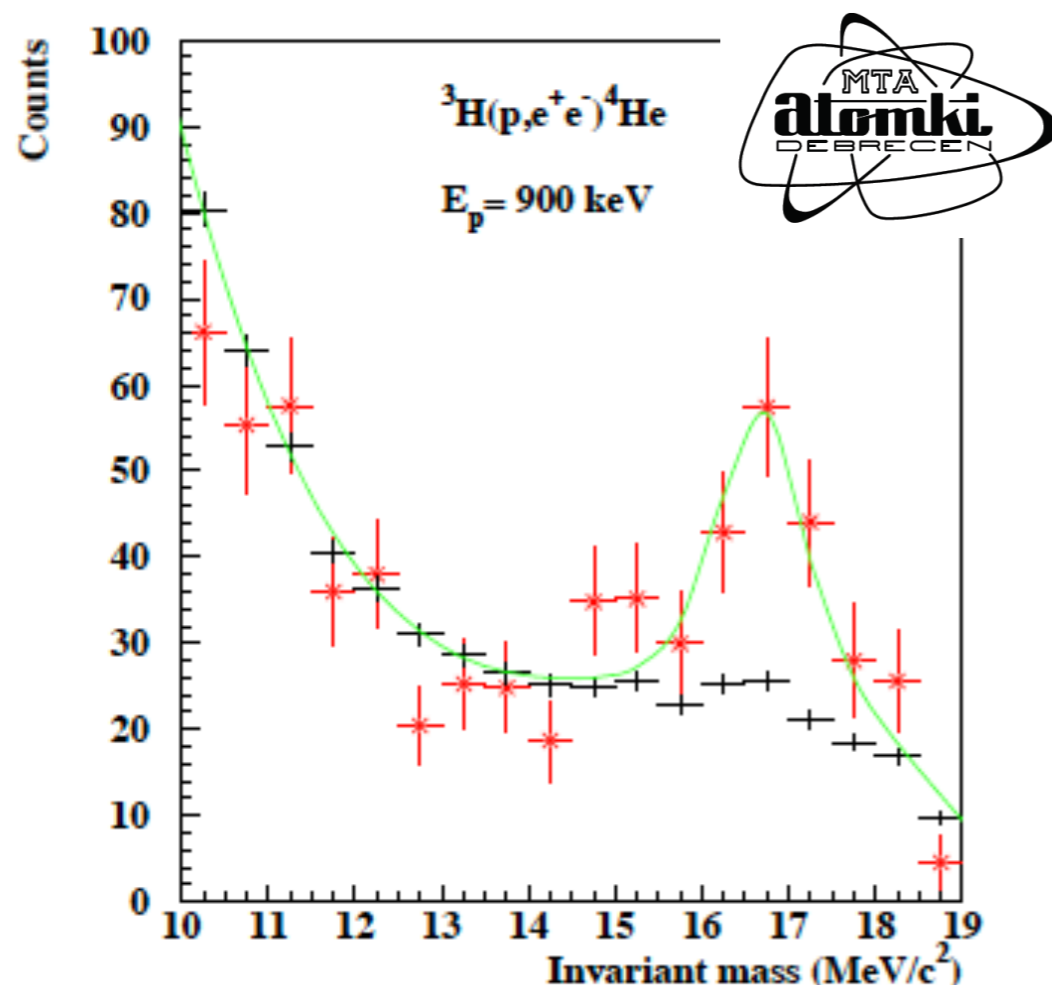
A. J. Krasznahaorkay et. Al Arxiv:1910.10459 (2019)

Additional motivation for an independent measurement

Remaining parameter space

^{8}Be

8.4×10^{10}EOT

NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020

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Explore the **full X17 allowed parameter space** to explain the ^{8}Be anomaly
Invariant mass reconstruction in case signal-like events are founded

New setup under study
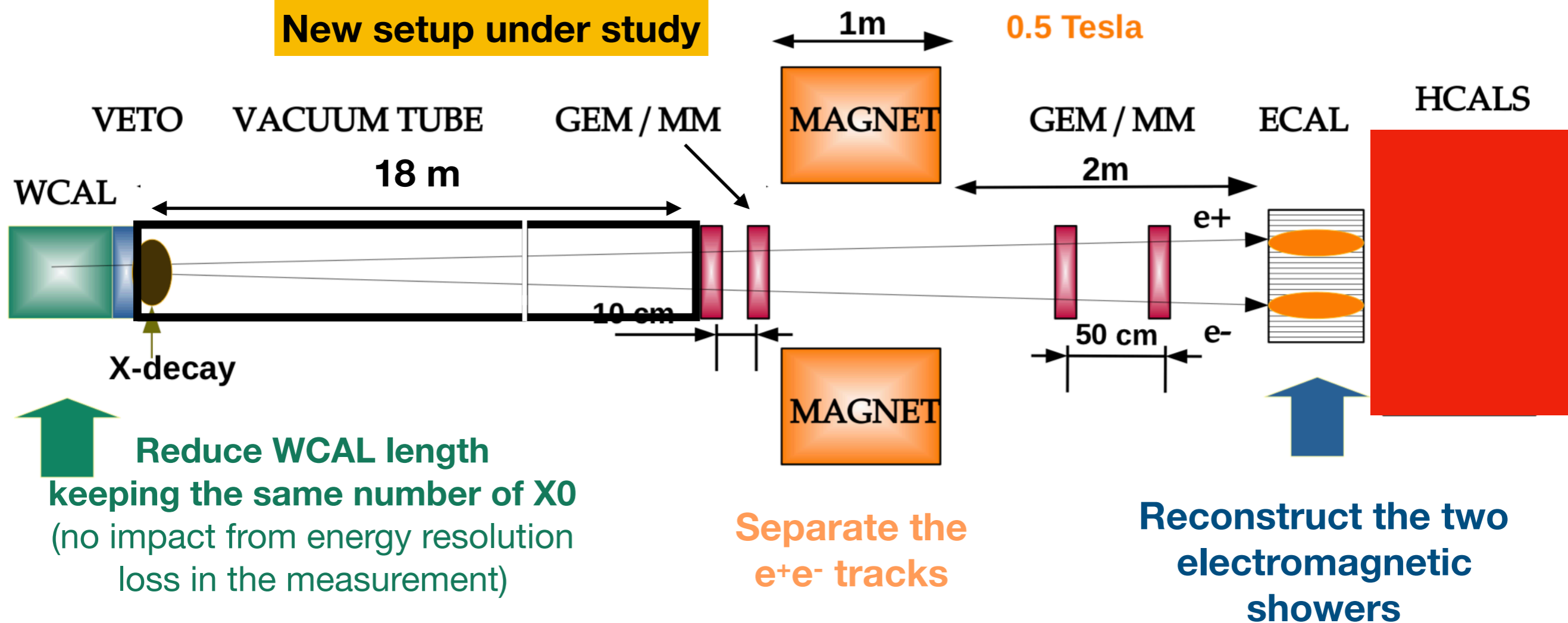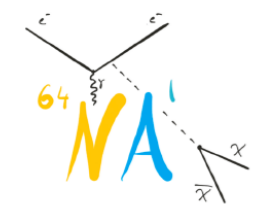
1m   0.5 Tesla

VETO   VACUUM TUBE   GEM / MM   MAGNET   GEM / MM   ECAL   HCALS

WCAL   18 m

10 cm   2m   e+

X-decay   MAGNET   50 cm   e-

**Reduce WCAL length
keeping the same number of X0**
(no impact from energy resolution
loss in the measurement)

**Separate the
e⁺e⁻ tracks**

**Reconstruct the two
electromagnetic
showers**

Explore the **full X17 allowed parameter space** to explain the ^{8}Be anomaly
Invariant mass reconstruction in case signal-like events are founded

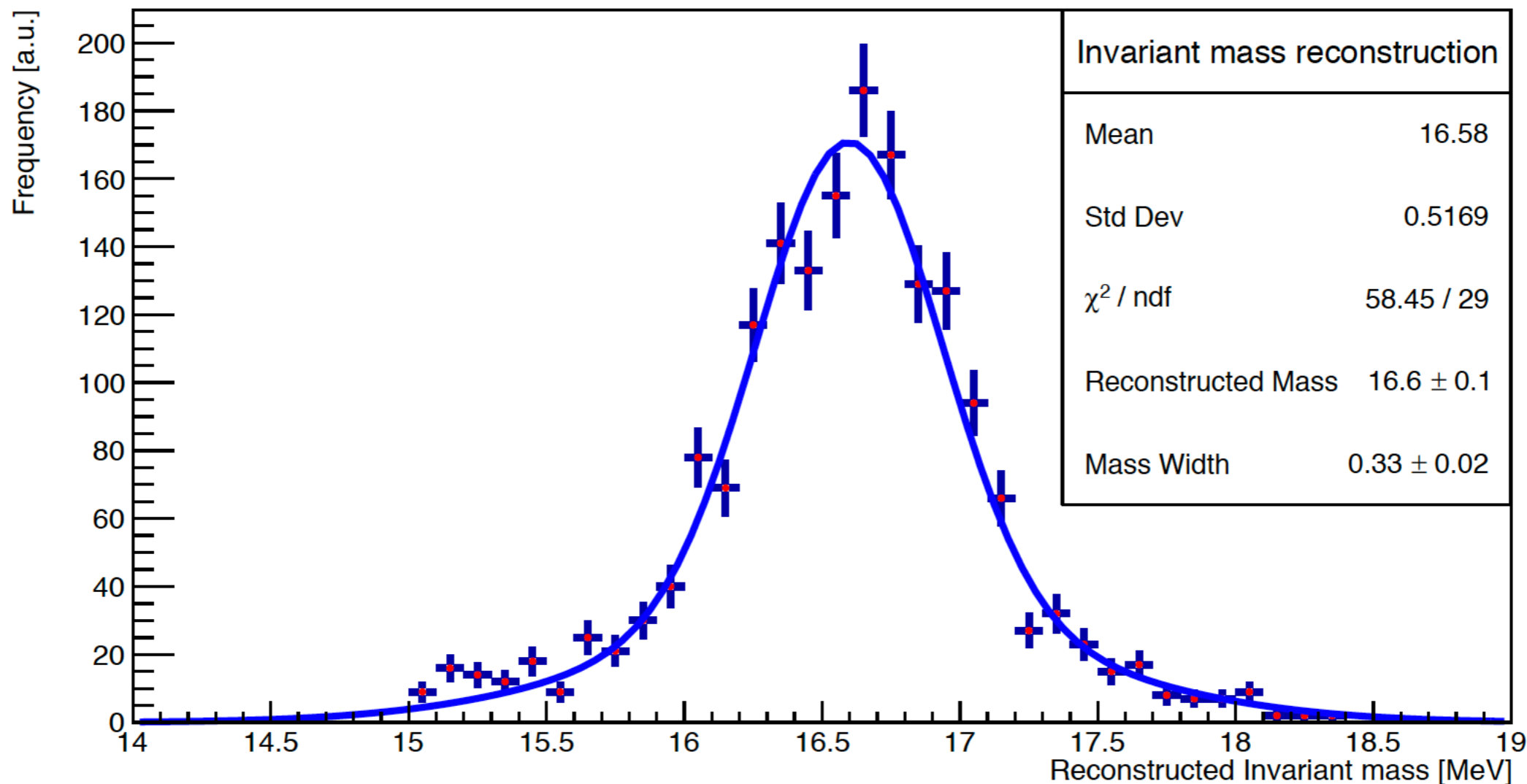| Invariant mass reconstruction	
Mean	16.58
Std Dev	0.5169
χ^2 / ndf	58.45 / 29
Reconstructed Mass	16.6 ± 0.1
Mass Width	0.33 ± 0.02

WCAL

HCALS

V

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s

Invariant mass reconstruction precision at the level of 2%

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Summary

Dark sector physics **interesting framework to explain dark matter**

NA64 **ideal experiment to probe or rule out many candidates**

Combined data 2017-2018 with 8.4 x 10^{10} EOT

X17 →e^+e^-: Coupling with electrons at $\varepsilon < 6.8 \times 10^{-4}$ and a mass of 16.7 excluded

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Future prospects after the long shutdown 2 in 2021

- Optimisation of the setup to probe the remaining parameter space of *X17*→ e^+e^-
- In case of signal-like events reconstruct the invariant mass with a precision of the percent level.
- 7×10^{11} EOTs required at 150 GeV corresponding to 3 months of data taking.
- Search expected to be background free up to 5×10^{12} EOTs.

THANKS!

Acknowledgements

NA64 collaboration in particular *P.Crivelli* and *S.Gninenko*
ETH Zürich group: A.Rubbia, P. Crivelli, B.Radics, E. Depero and *H.Sieber*