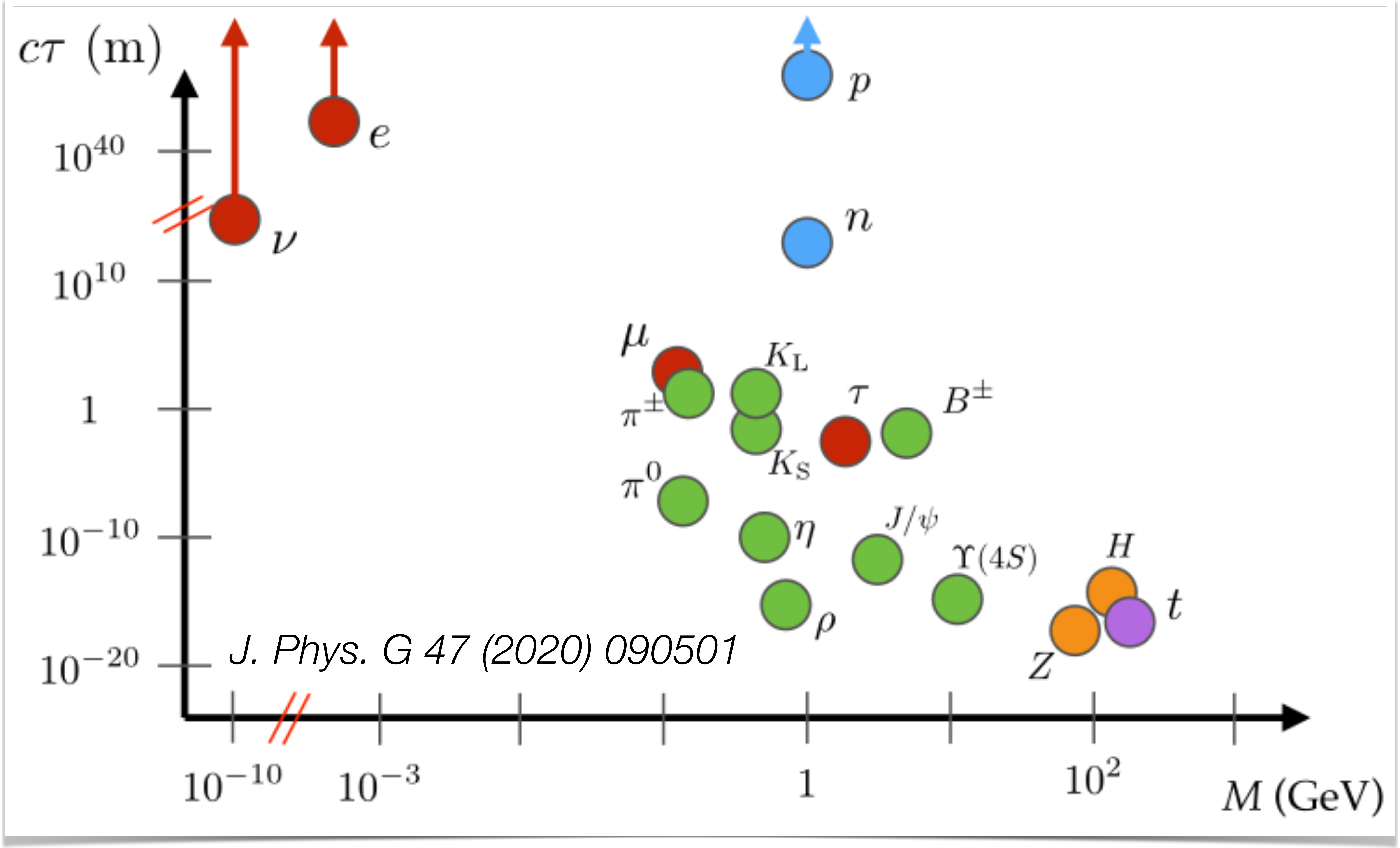
ANUBIS
future large-scale application of RPC detectors

Oleg Brandt for ANUBIS

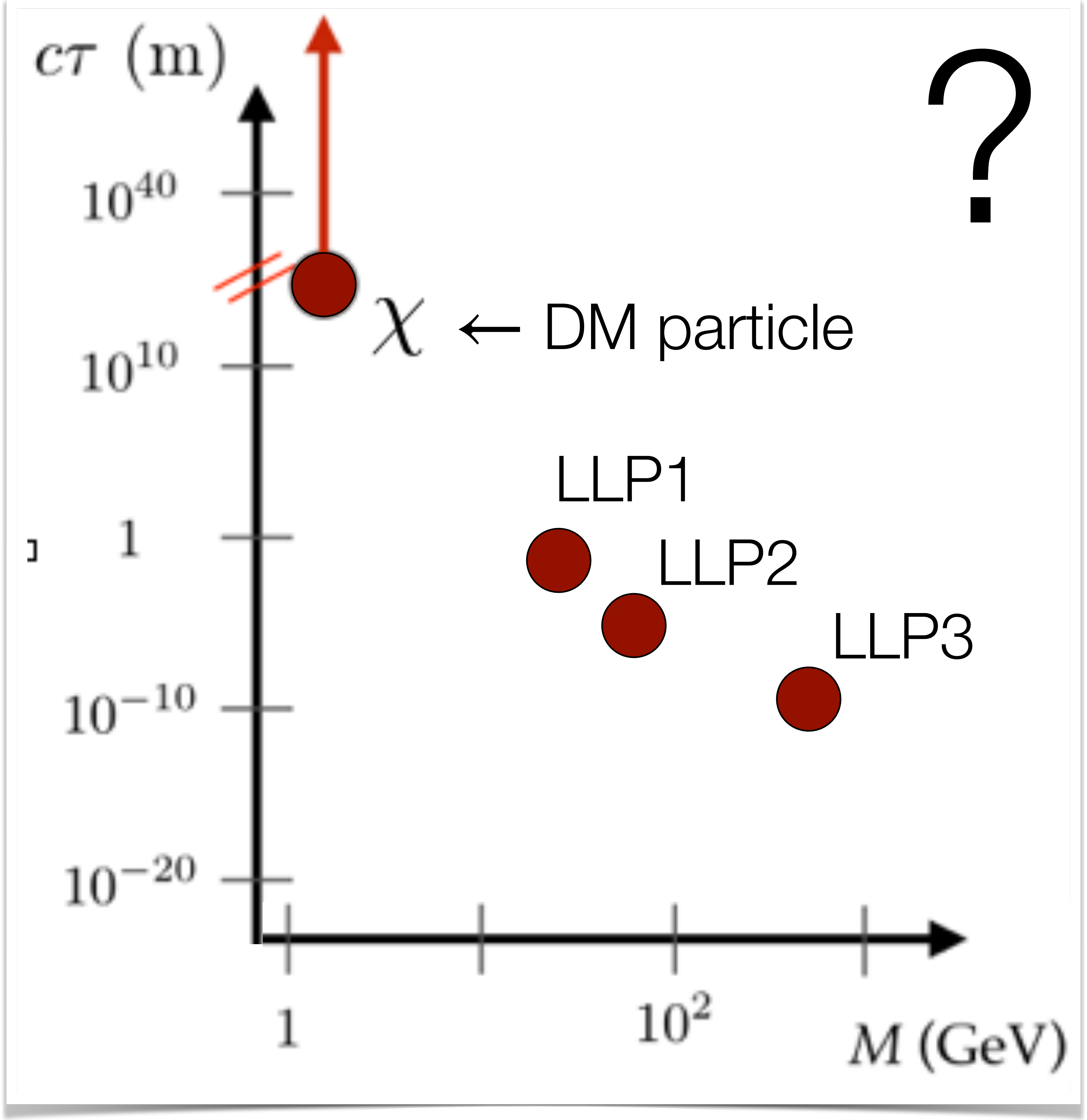
UNIVERSITY OF CAMBRIDGE · UKRI FLF · Isaac Newton Trust · ATLAS EXPERIMENT · ANUBIS EXPERIMENT · CERN

What if the Dark Sector is non-trivial?

SM sector



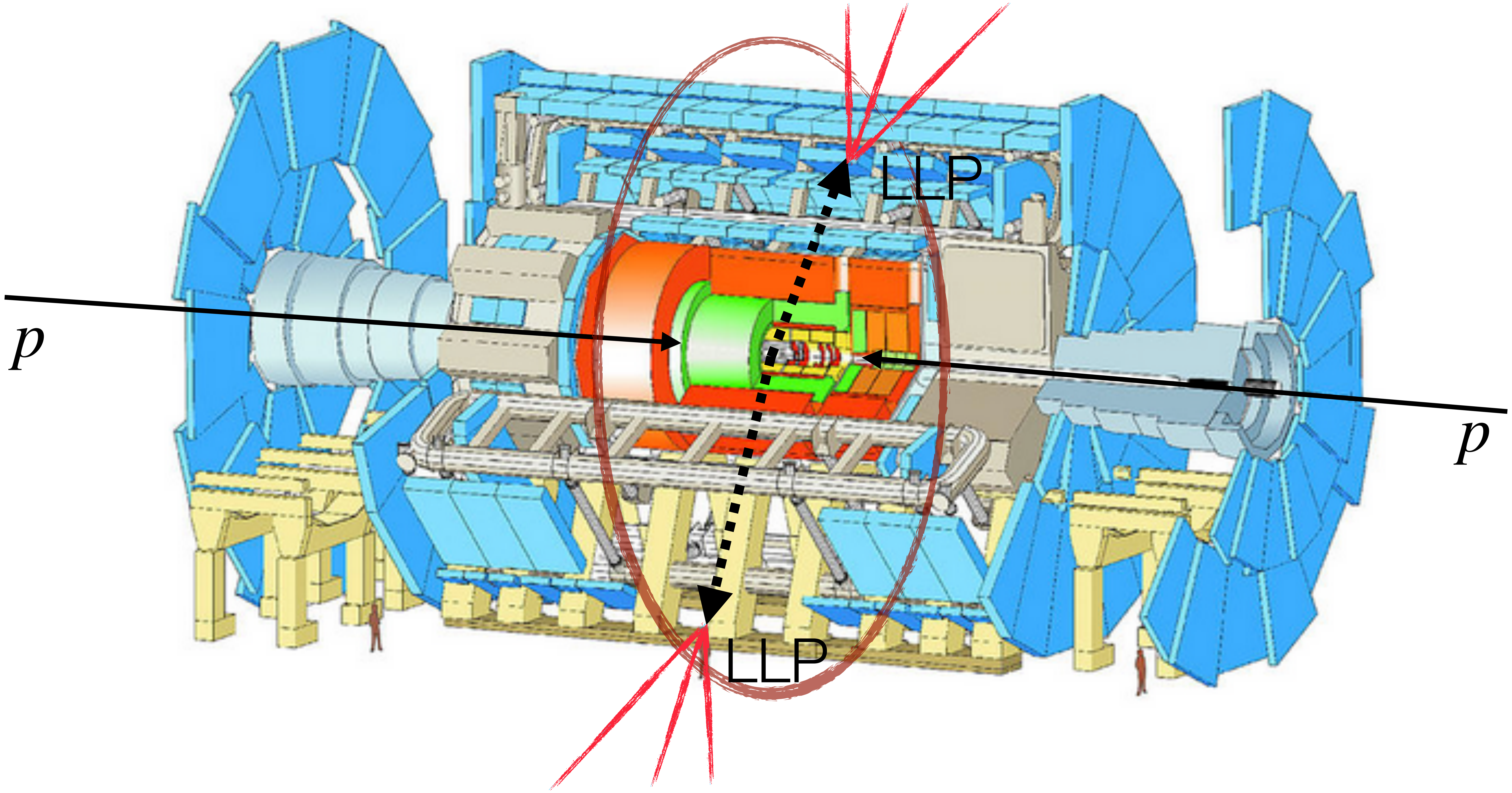
Dark Sector



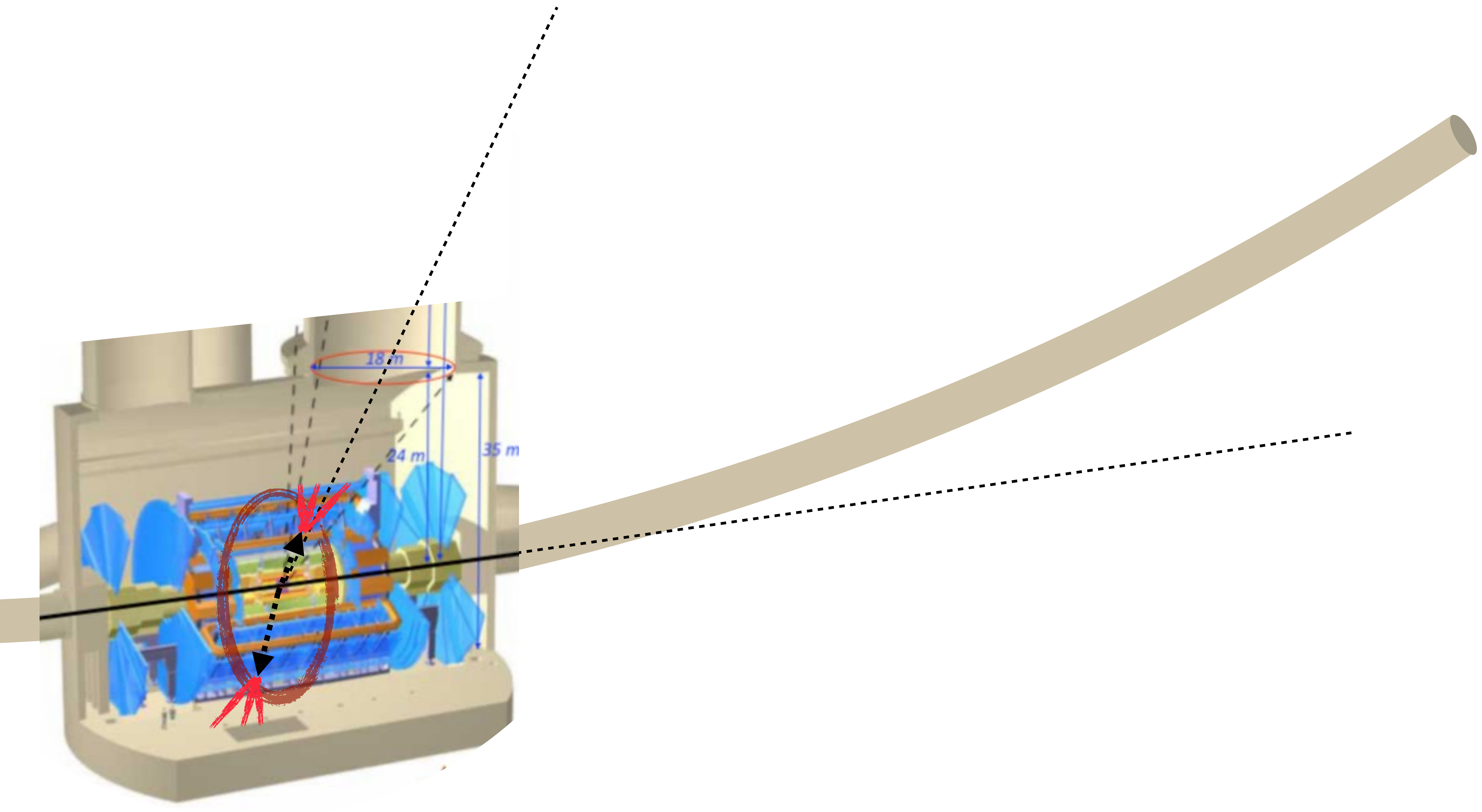
[Long-lived particle (LLP) signatures ubiquitous in many other BSM scenarios like e.g. baryogengesis]

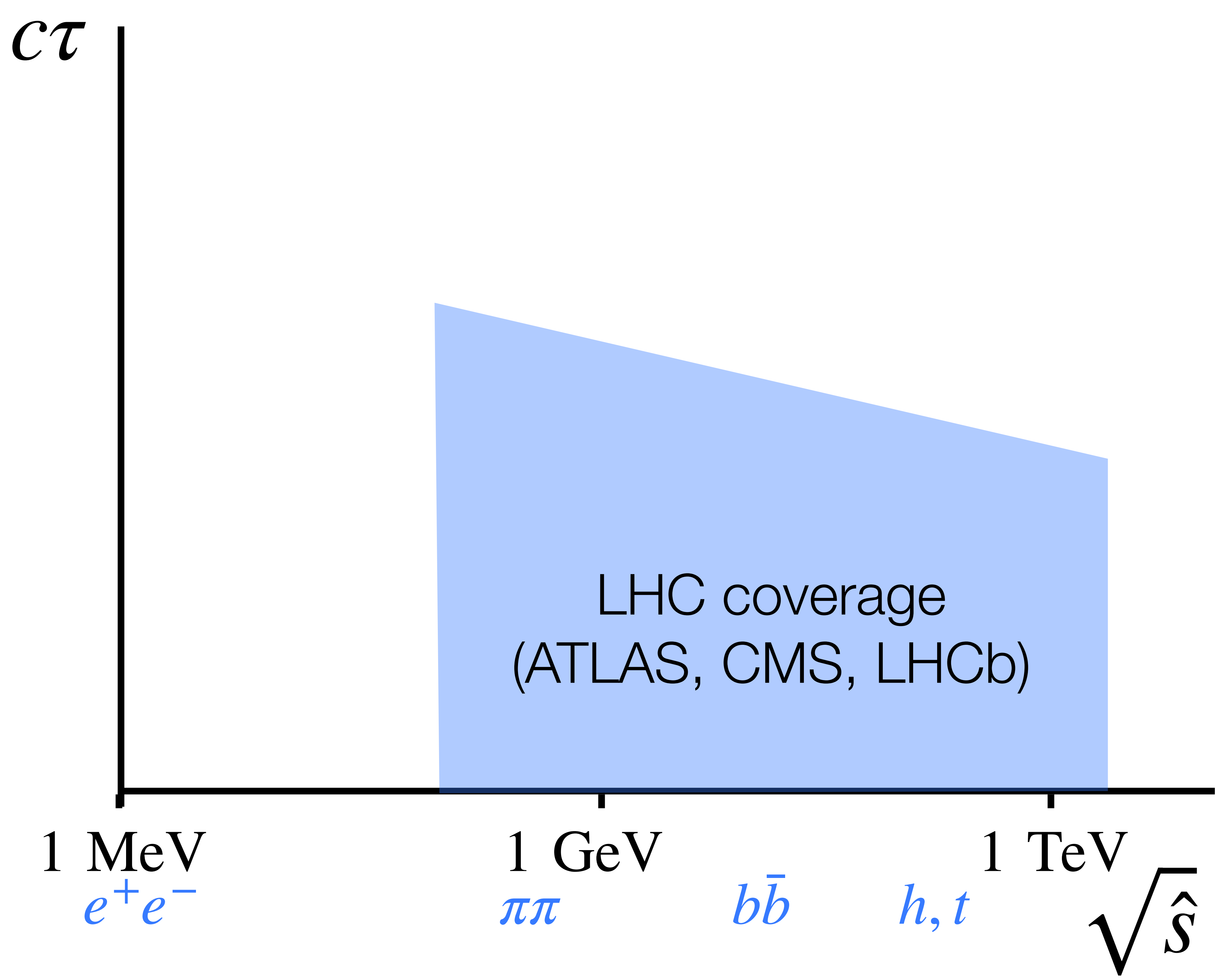
A multitude of smoking gun signatures emerges…

- very small backgrounds
- typically instrumental backgrounds



Where to look for long-lived particles?





WHERE TO LOOK FOR LONG-LIVED PARTICLES?

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+ Other transverse proposals:
MATHUSLA, CODEX, …

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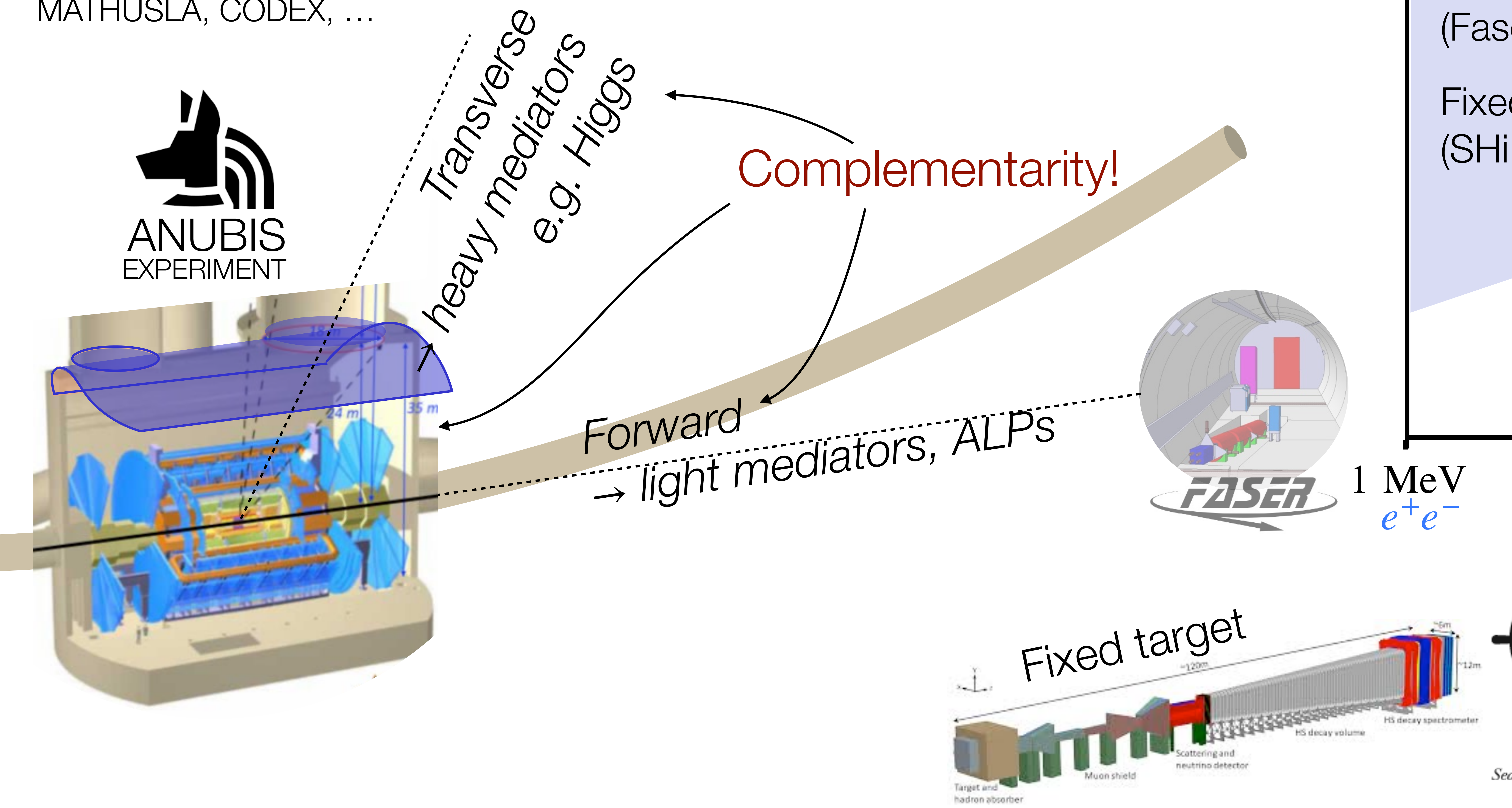
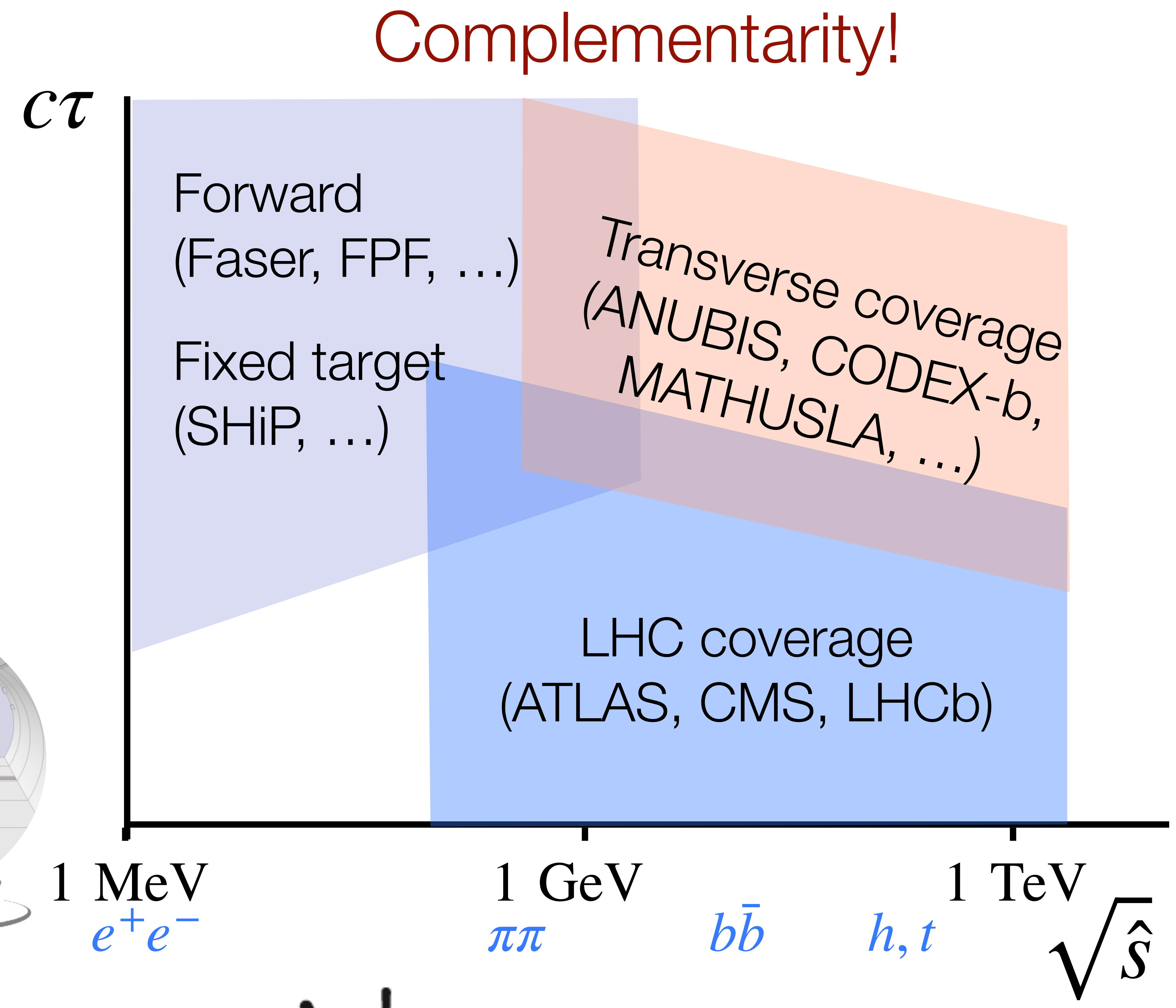


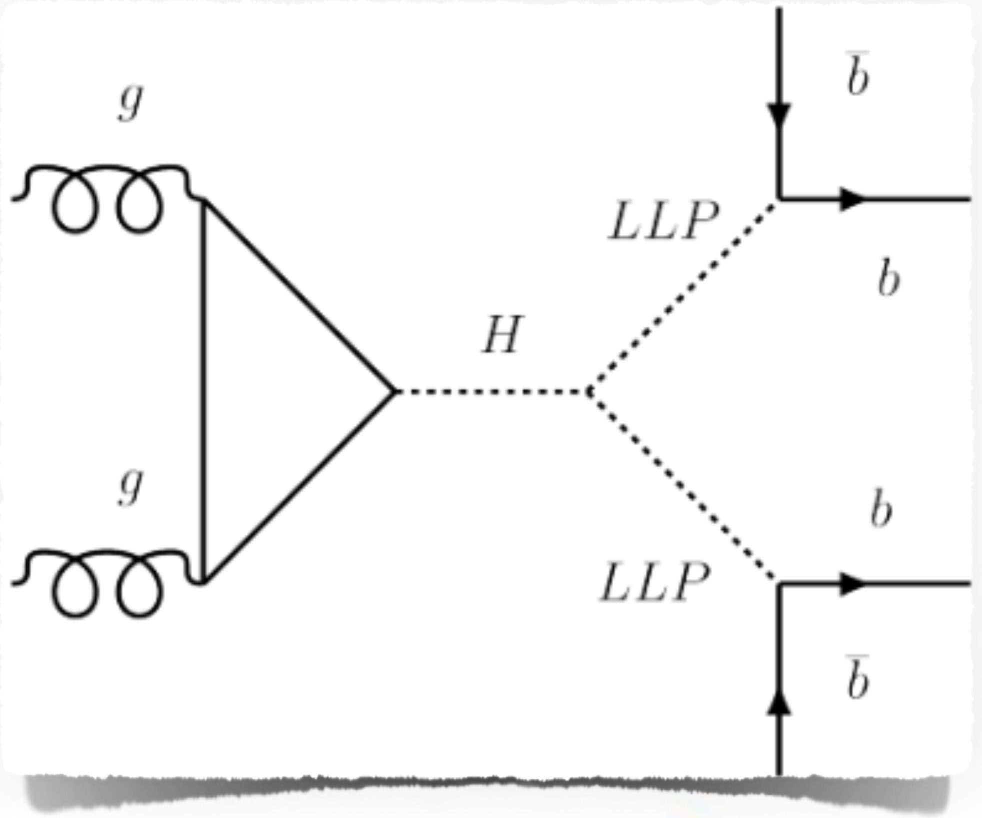


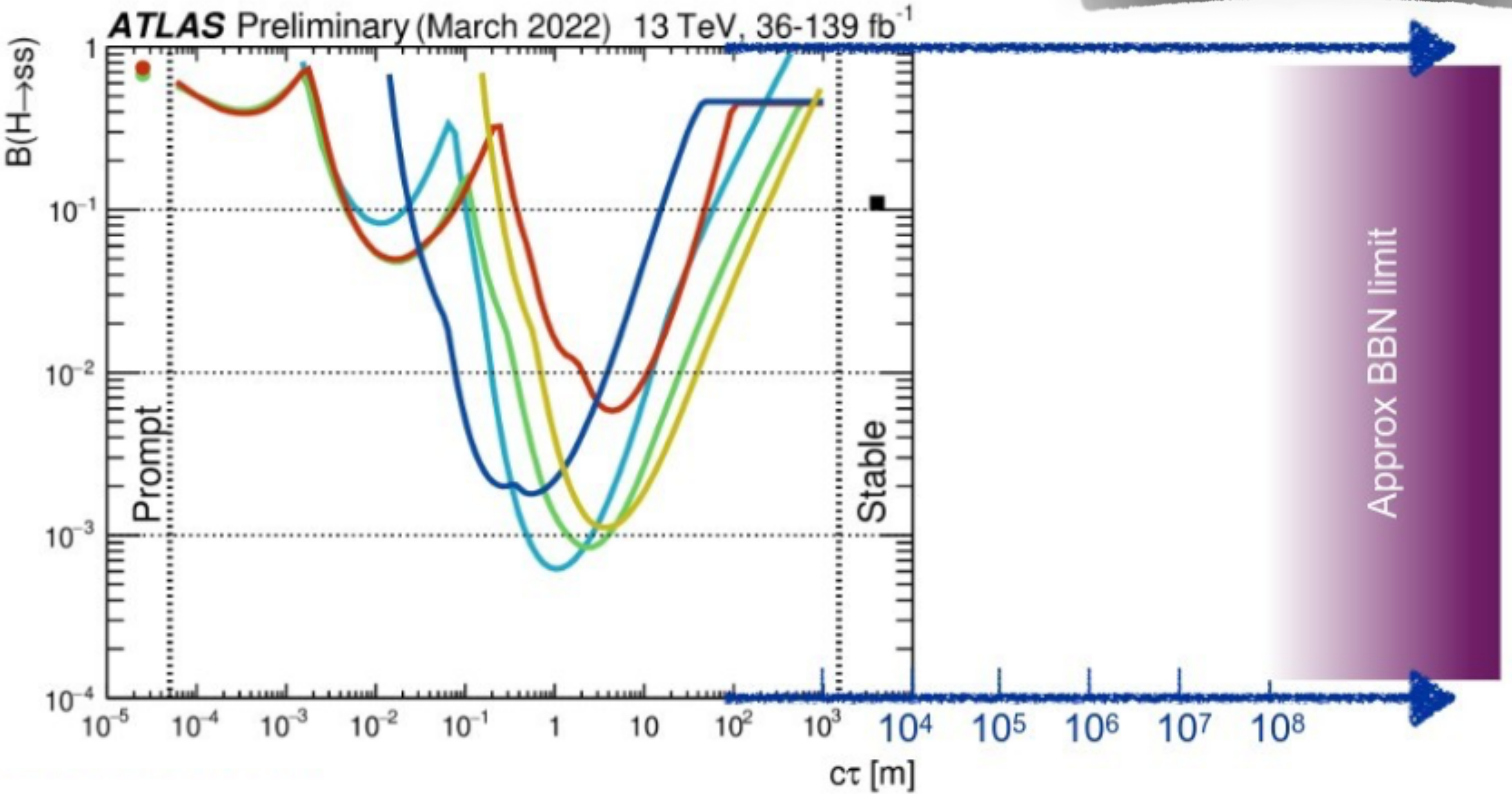
PBC model BC5

ANUBIS proposal:

- Extend fiducial volume
- Use ATLAS as active veto
  → harvest sensitivity!

Physics Beyond Colliders





Adapted from ATL-PHYS-PUB-2022-007

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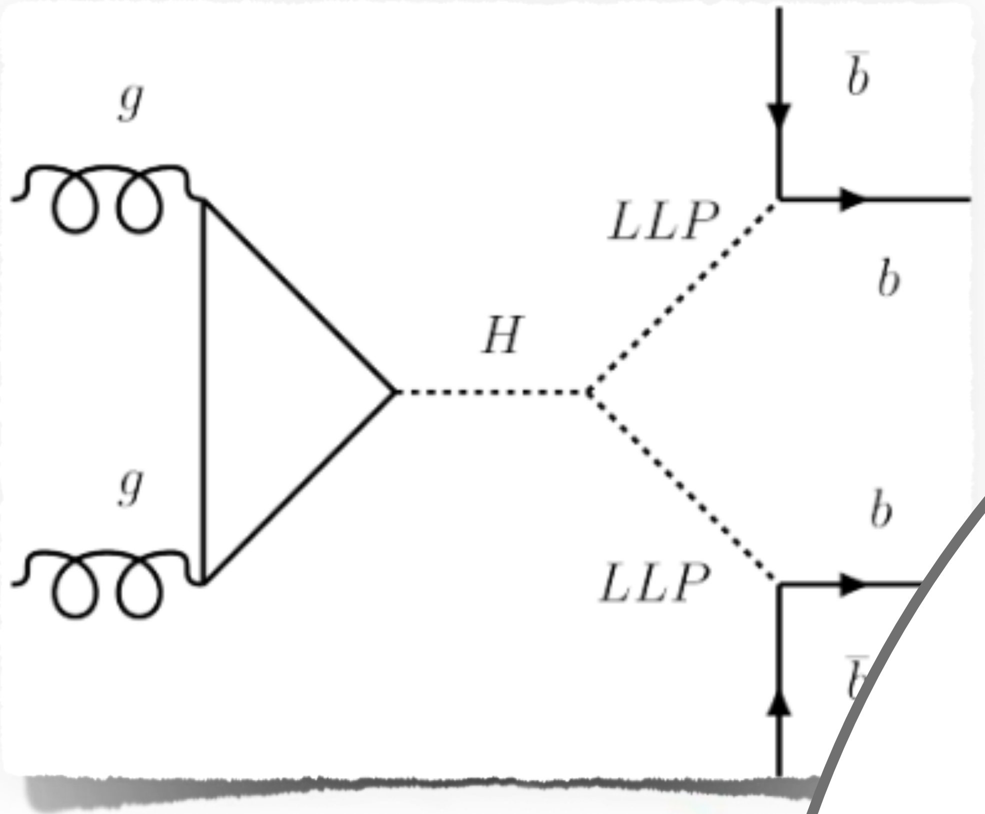

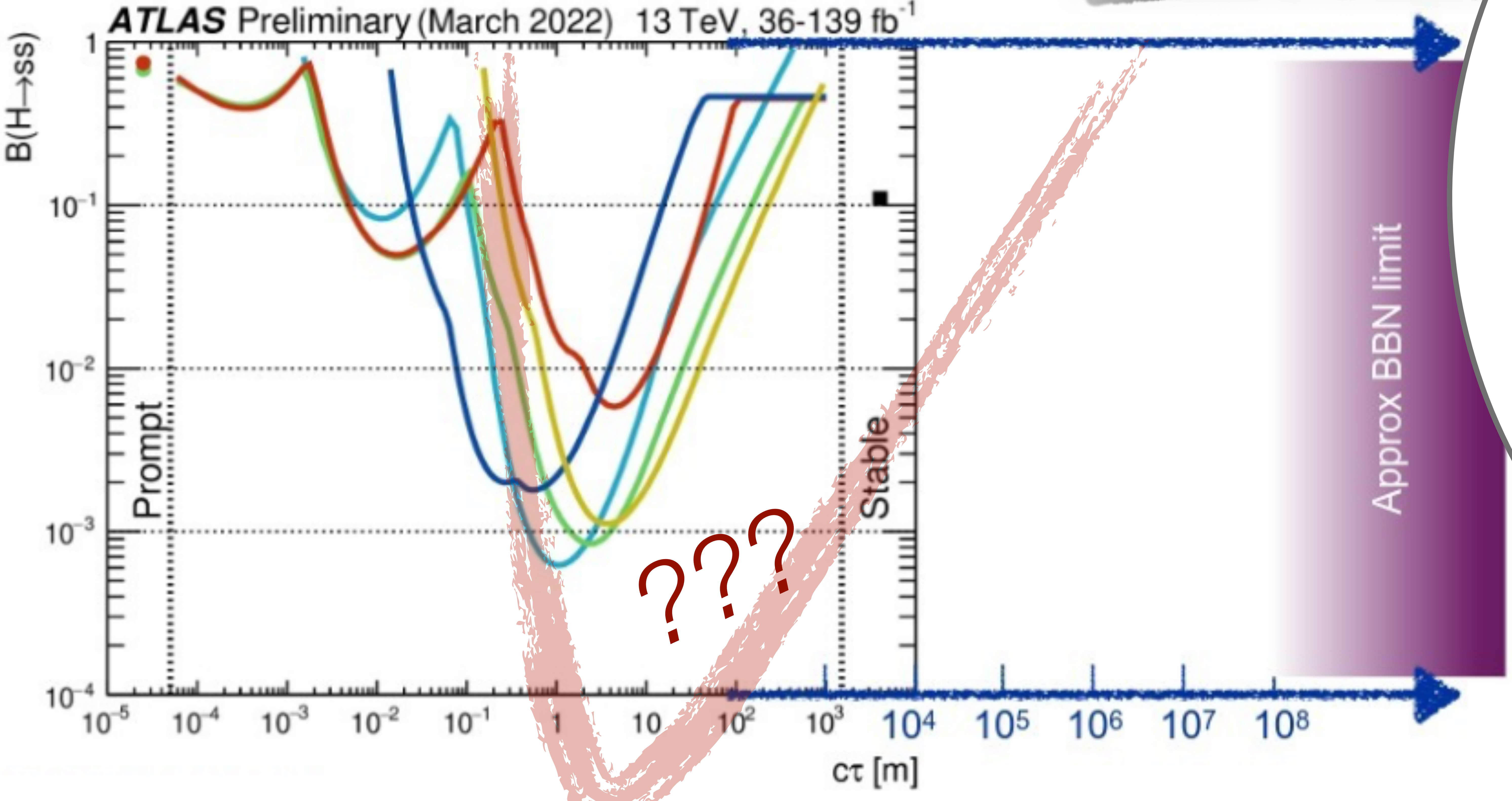

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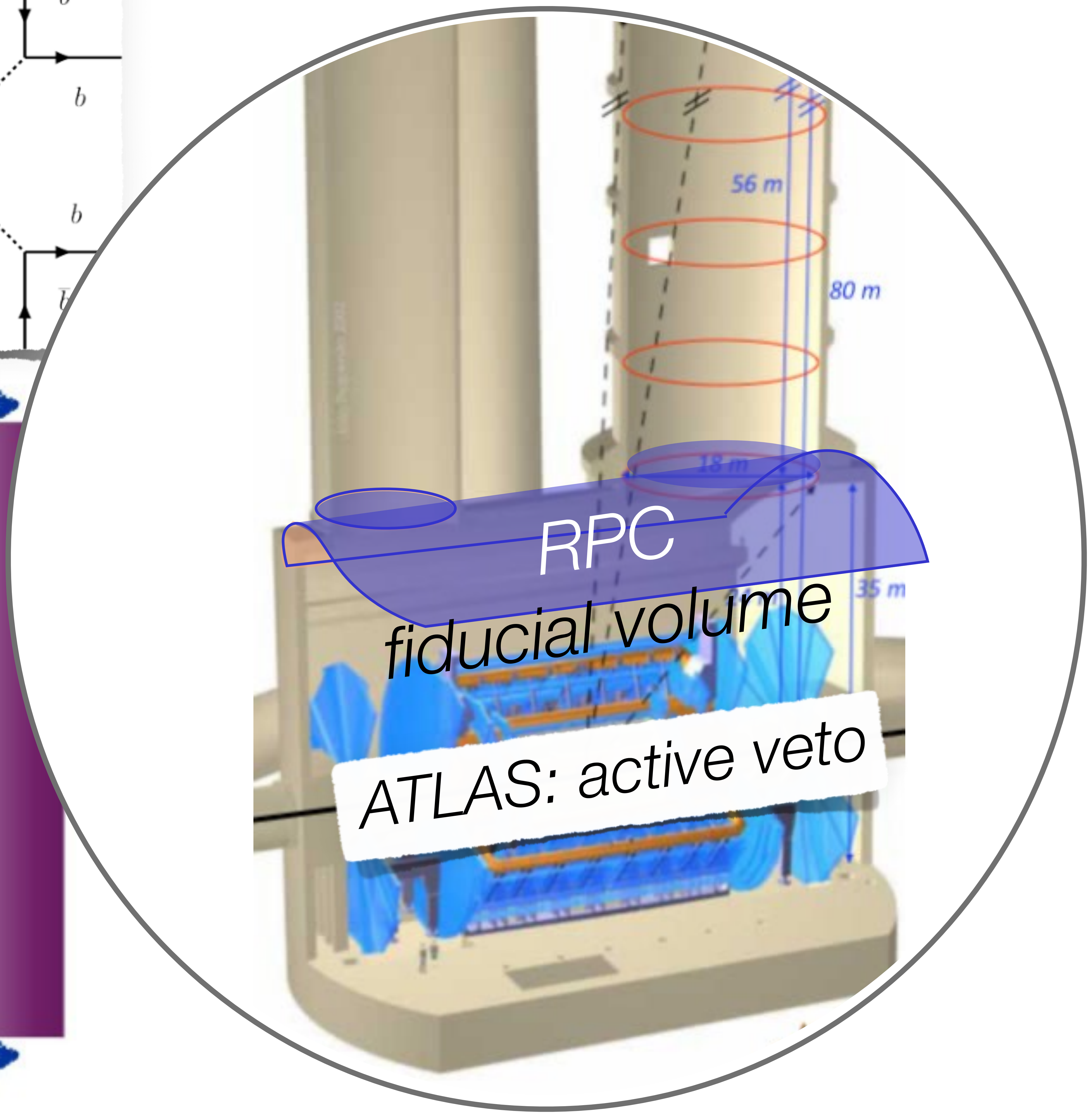

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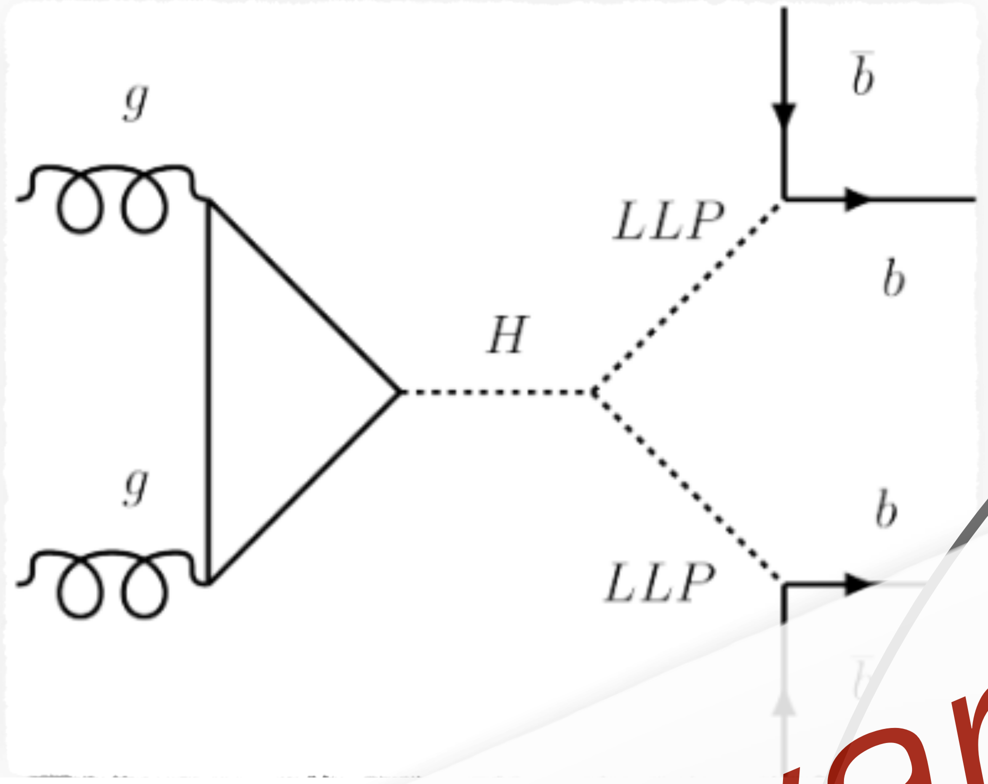
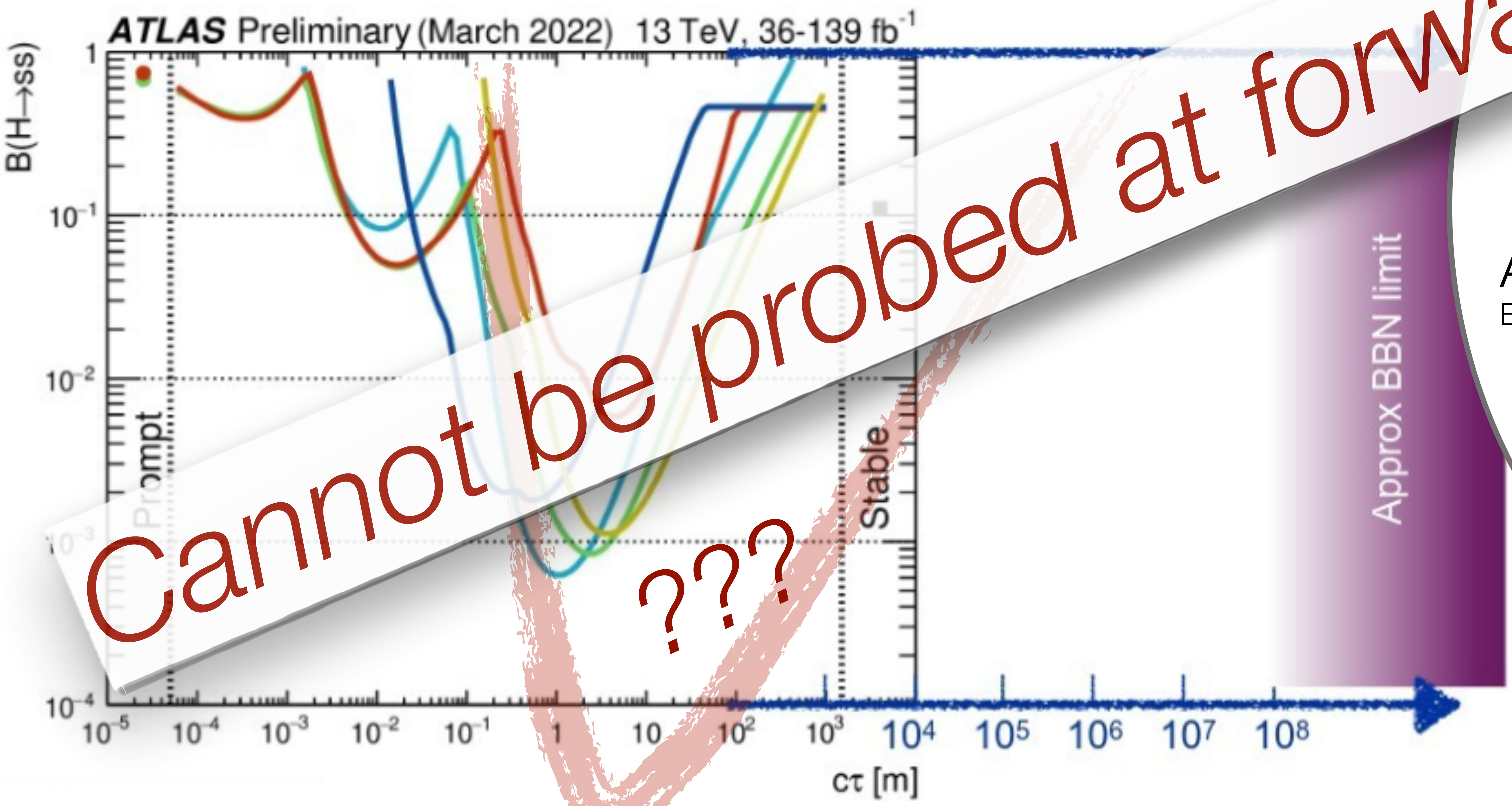
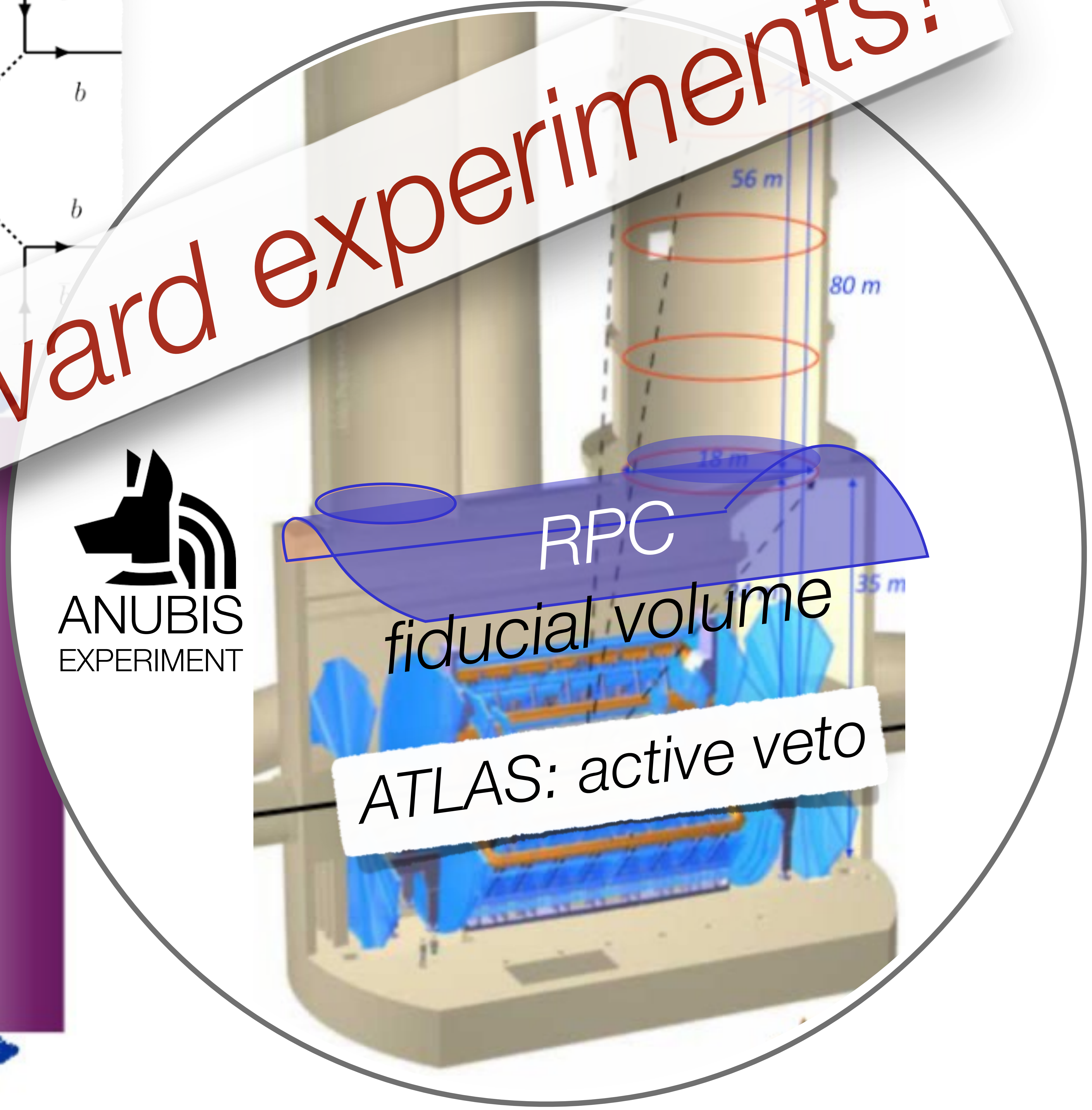




Cannot be probed at forward experiments!



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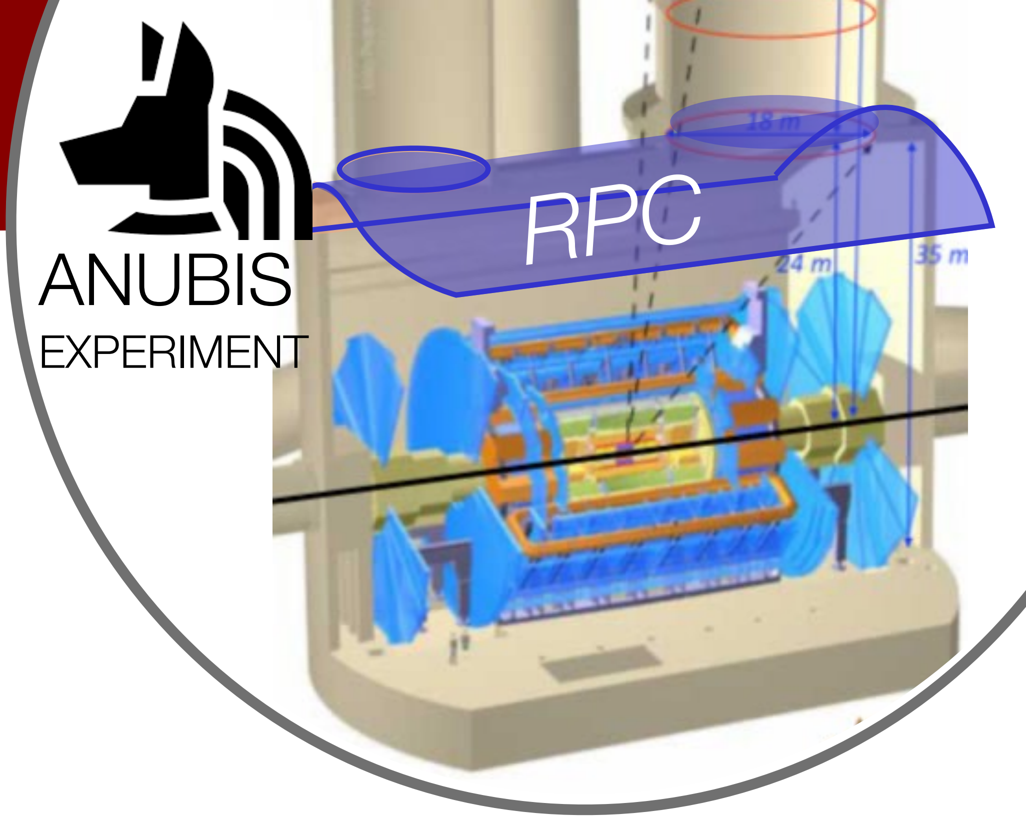
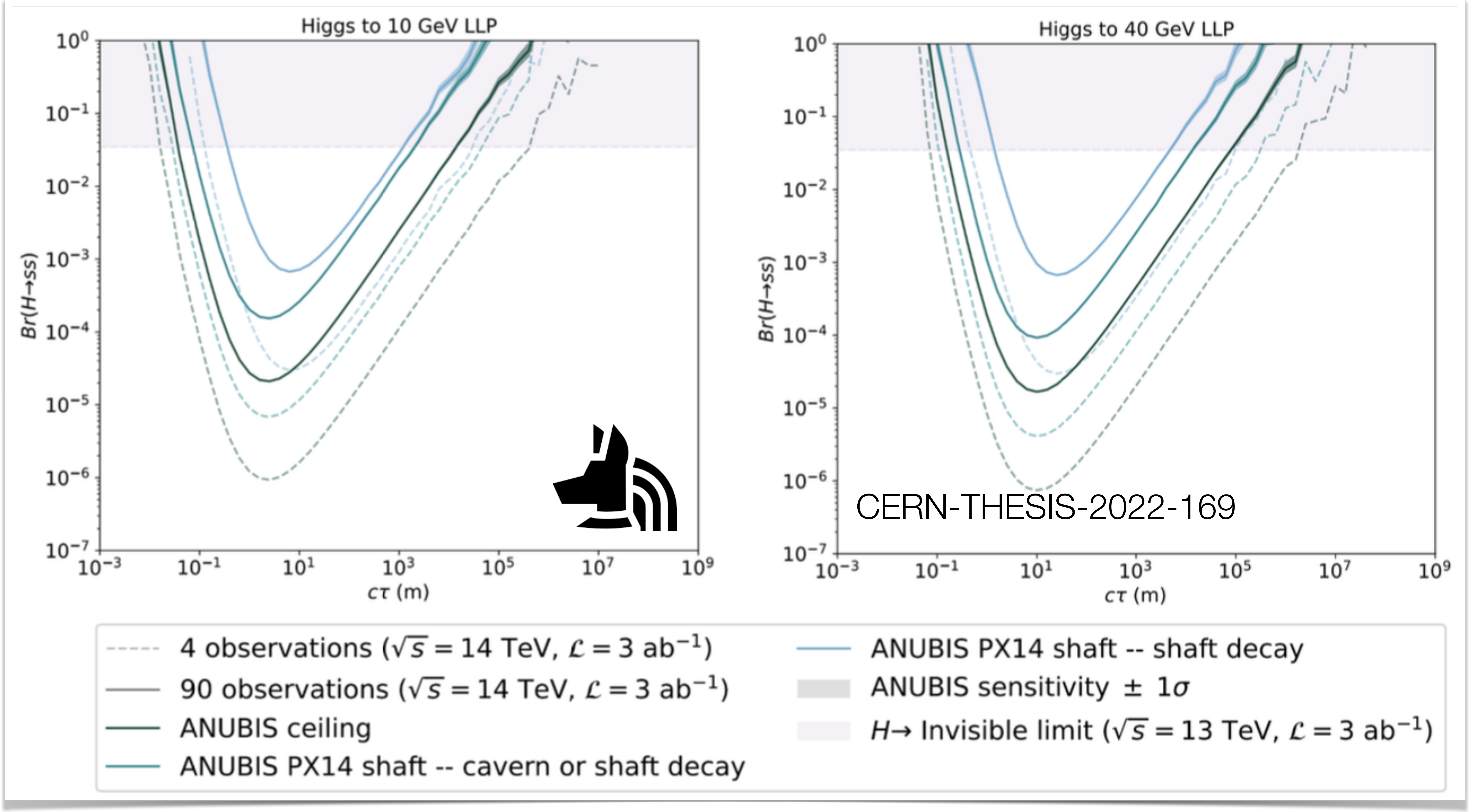
ANUBIS: Sensitivity to Higgs Portal (PBC/FIPS context)

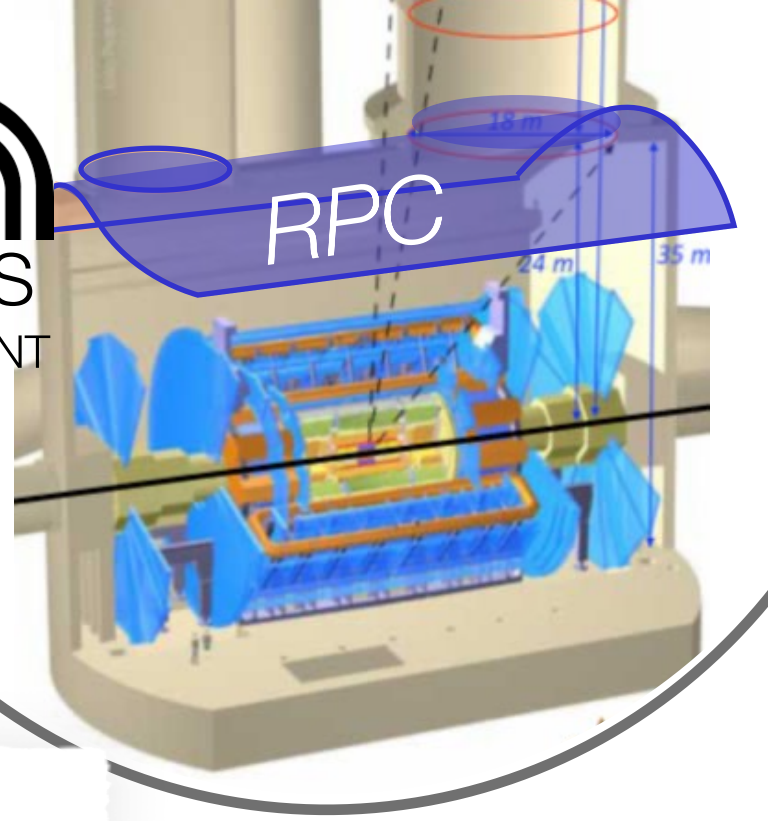


Physics Beyond Colliders

PBC model BC5

Similar sensitivity:
- MATHUSLA (original proposal)
- CODEX-b (bit weaker 1 ab^{-1})





ANUBIS EXPERIMENT

- Preliminary results:
  - 4 production modes x 3 final states
  - Good sensitivity to LLPs at light LLP masses!

PBC model BC6

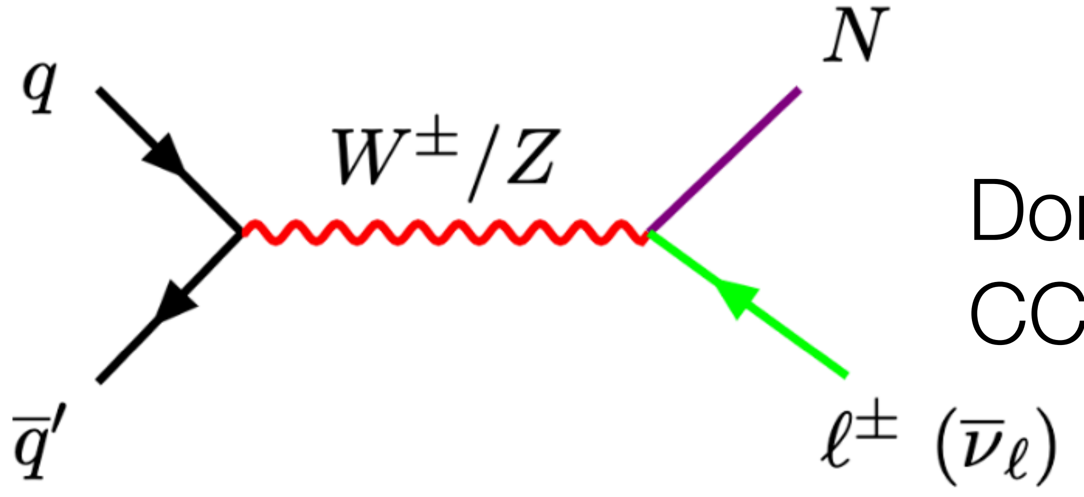
$|U_{\mu N}| = |U_{\tau N}| = 0$

Physics Beyond Colliders

SET-ANUBIS is a perfect theory collaboration platform

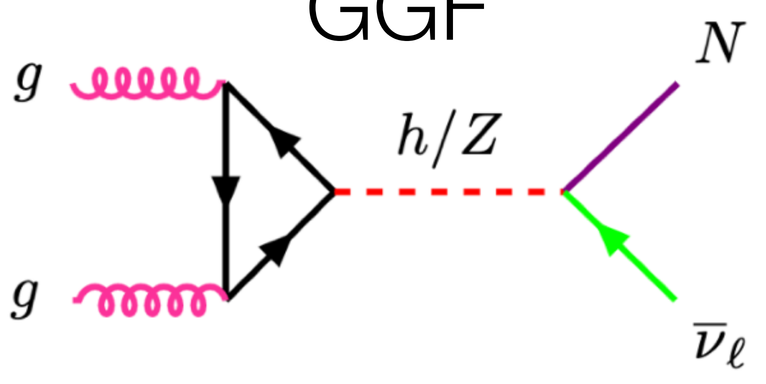
→ Welcoming theory collaborators!

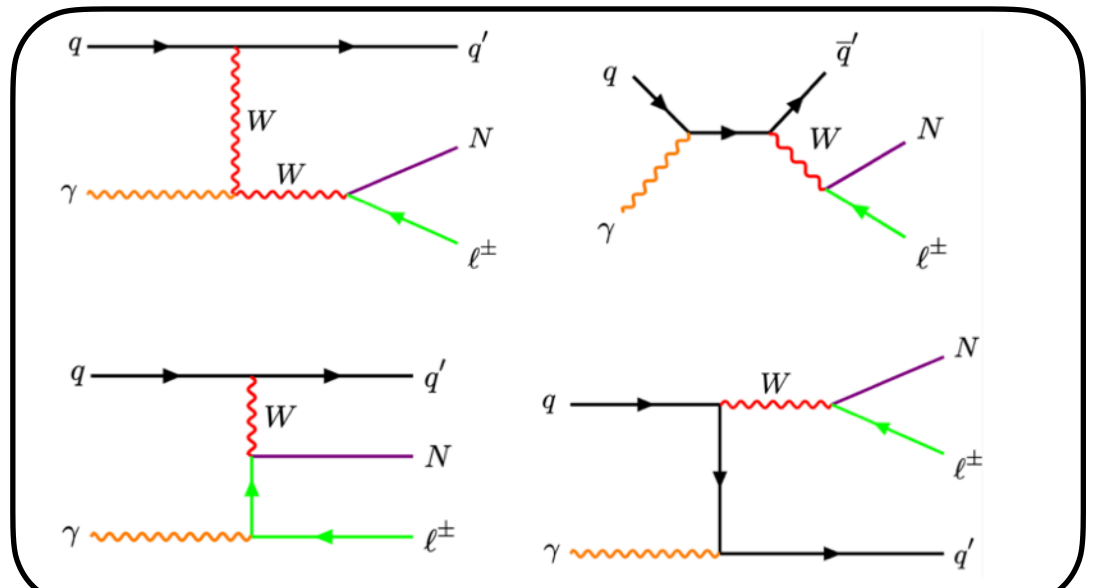
SET-ANUBIS

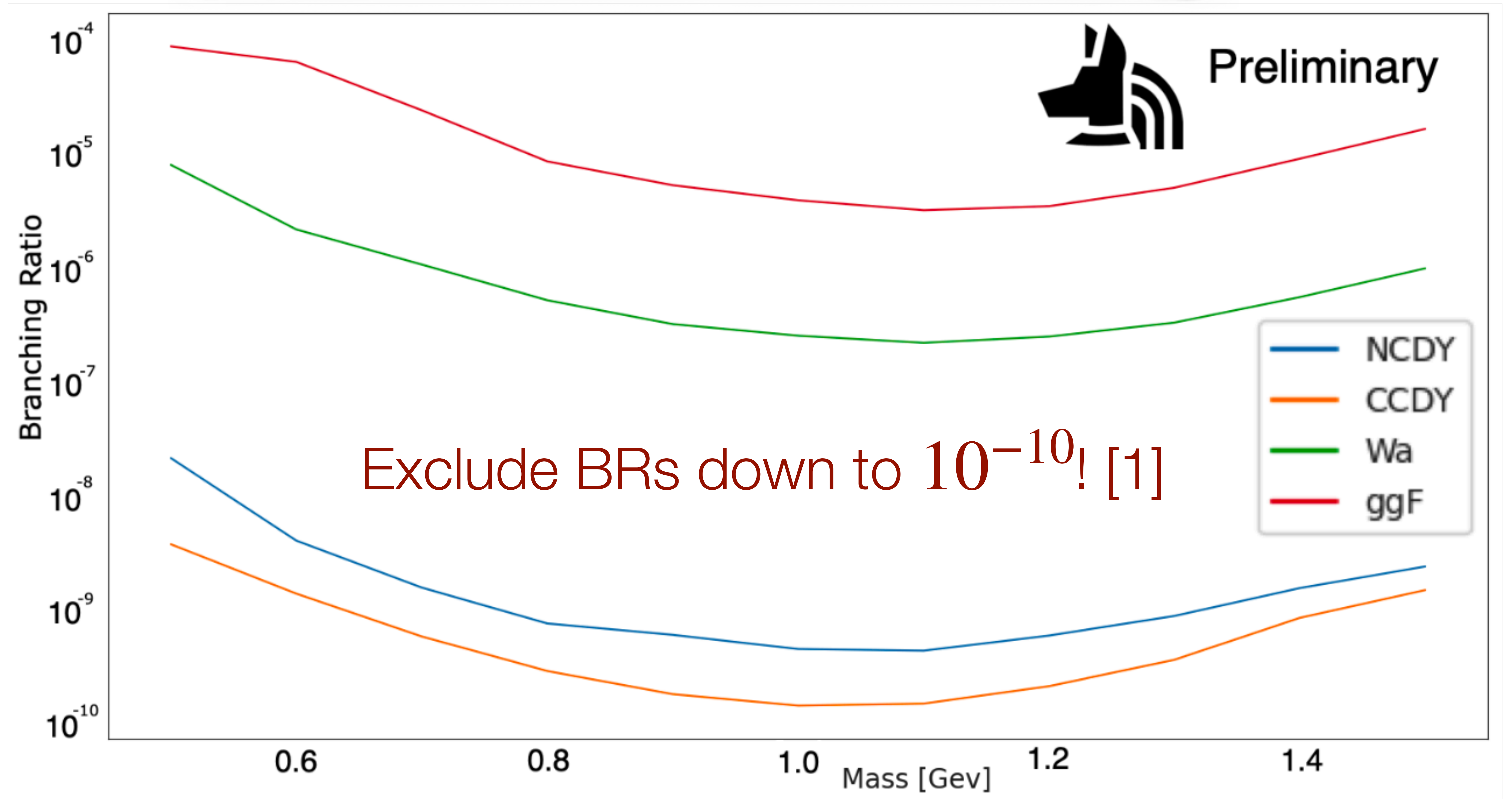


Dominant:
CC and NC Drell-Yan

GGF

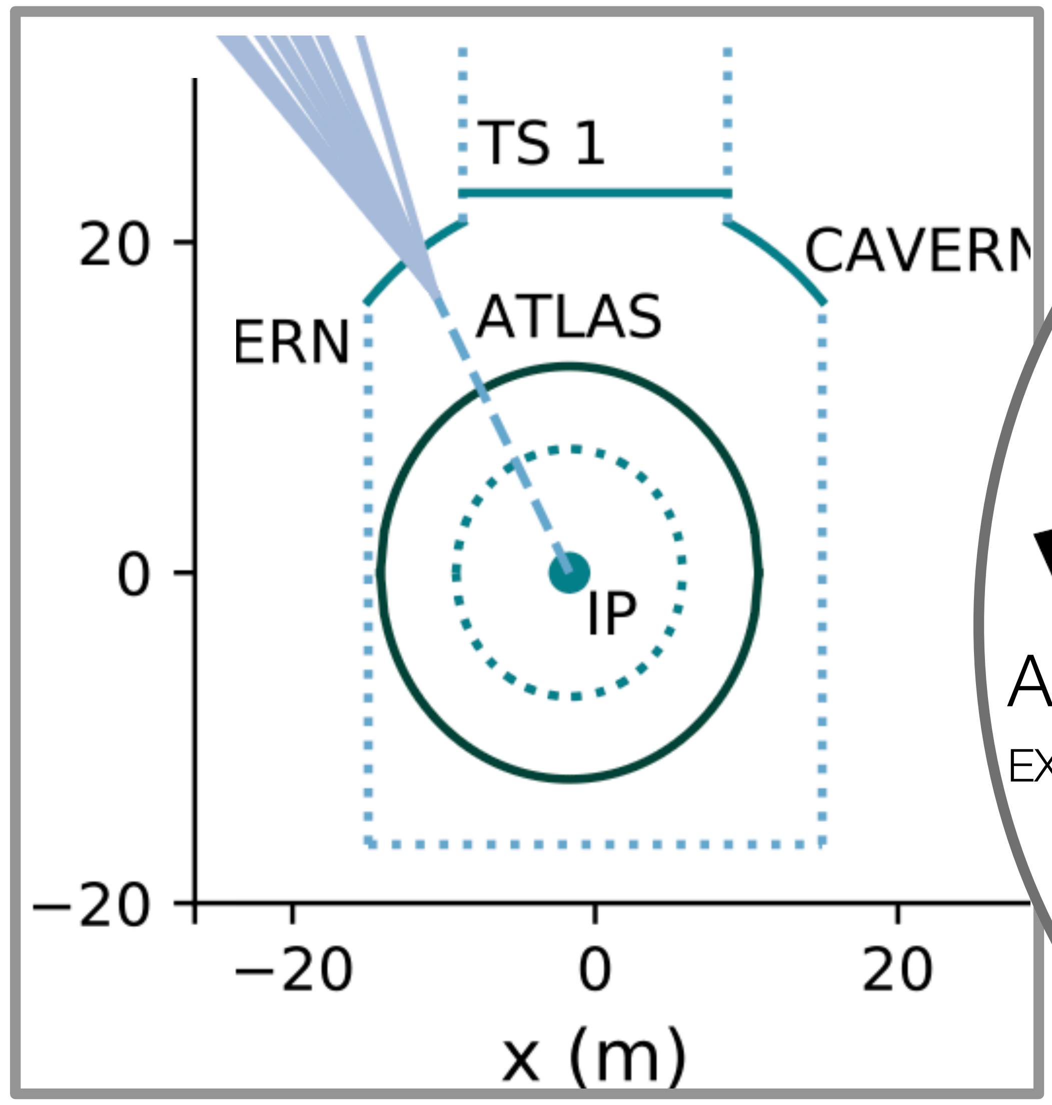


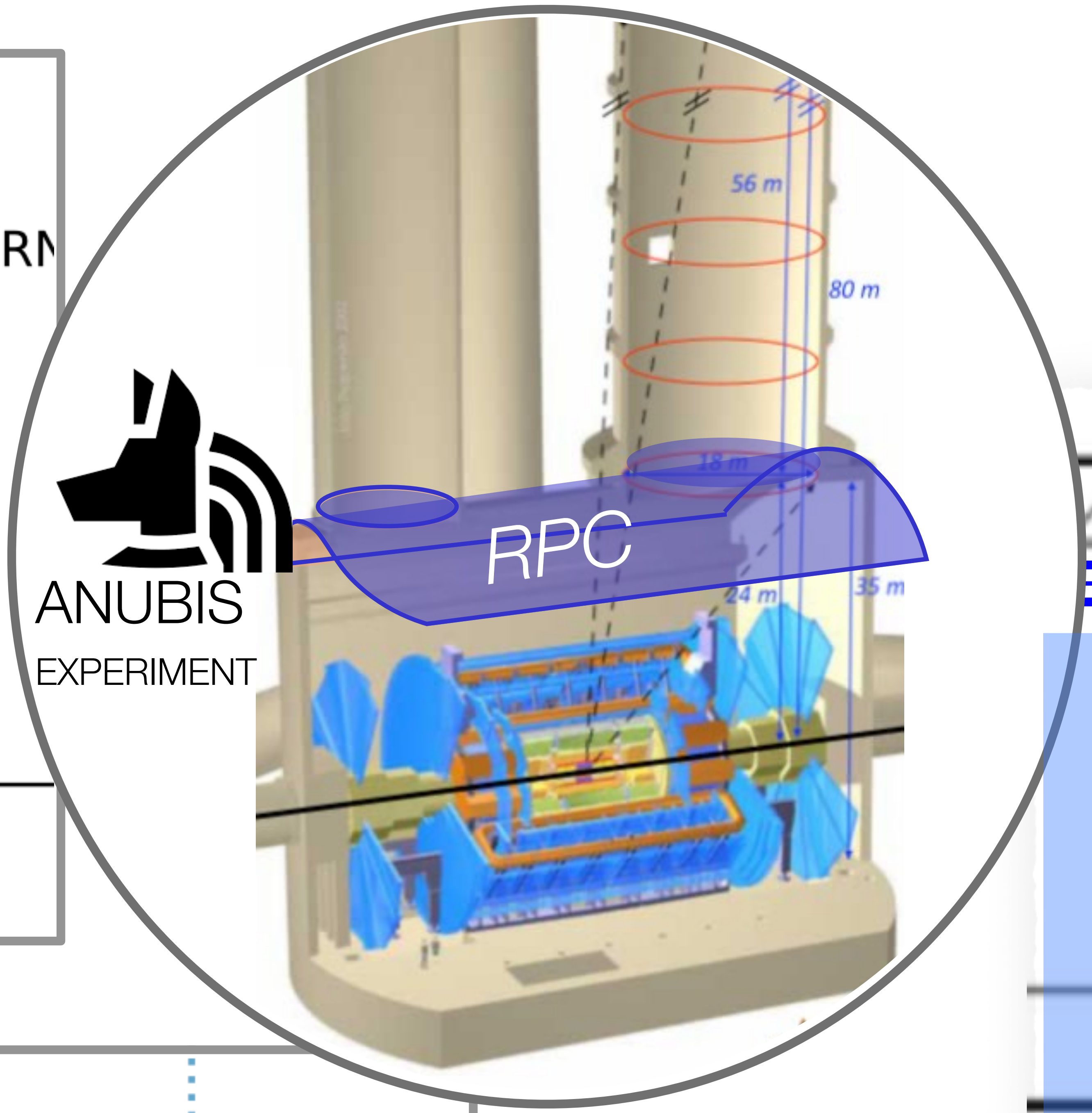


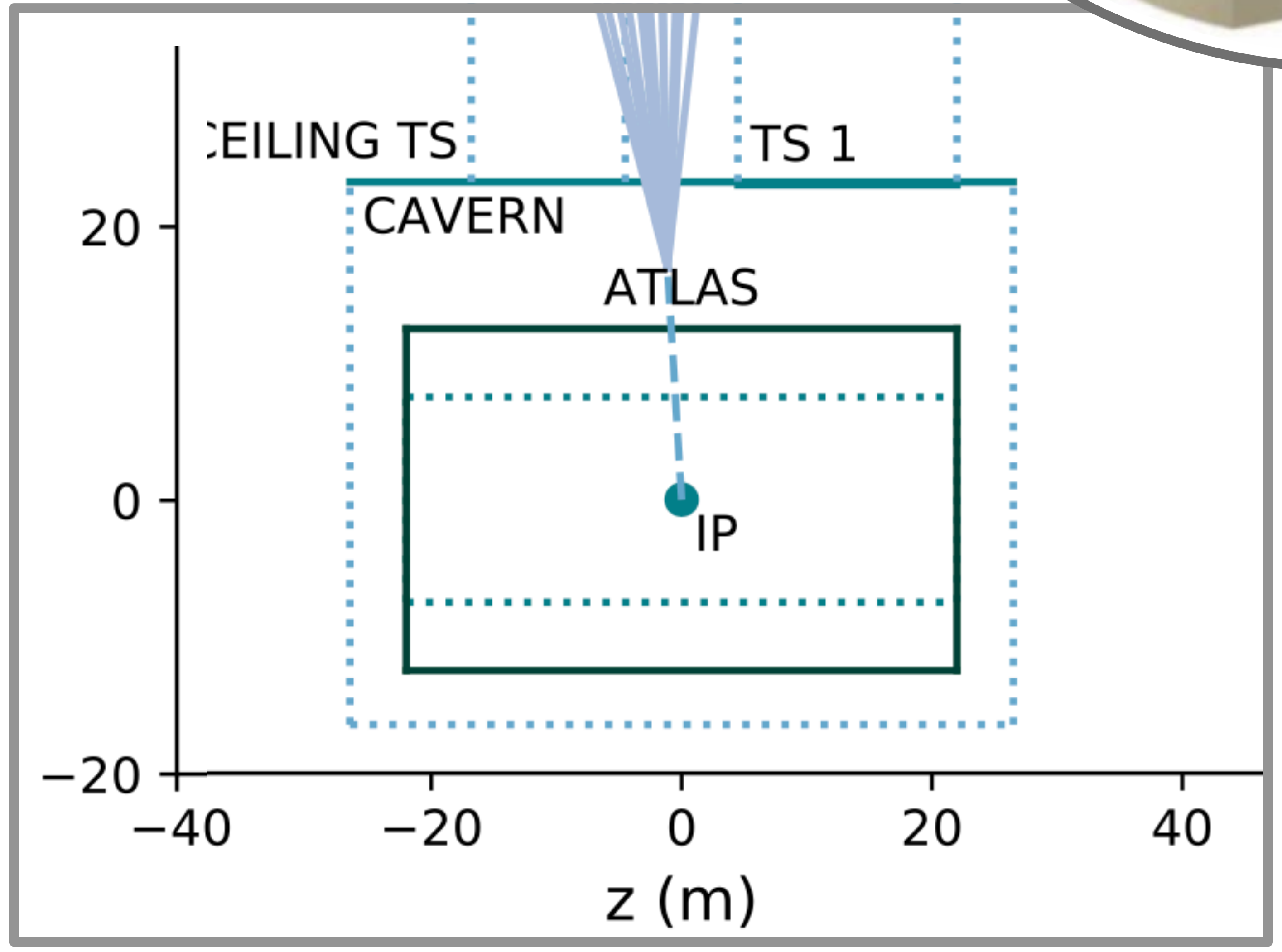


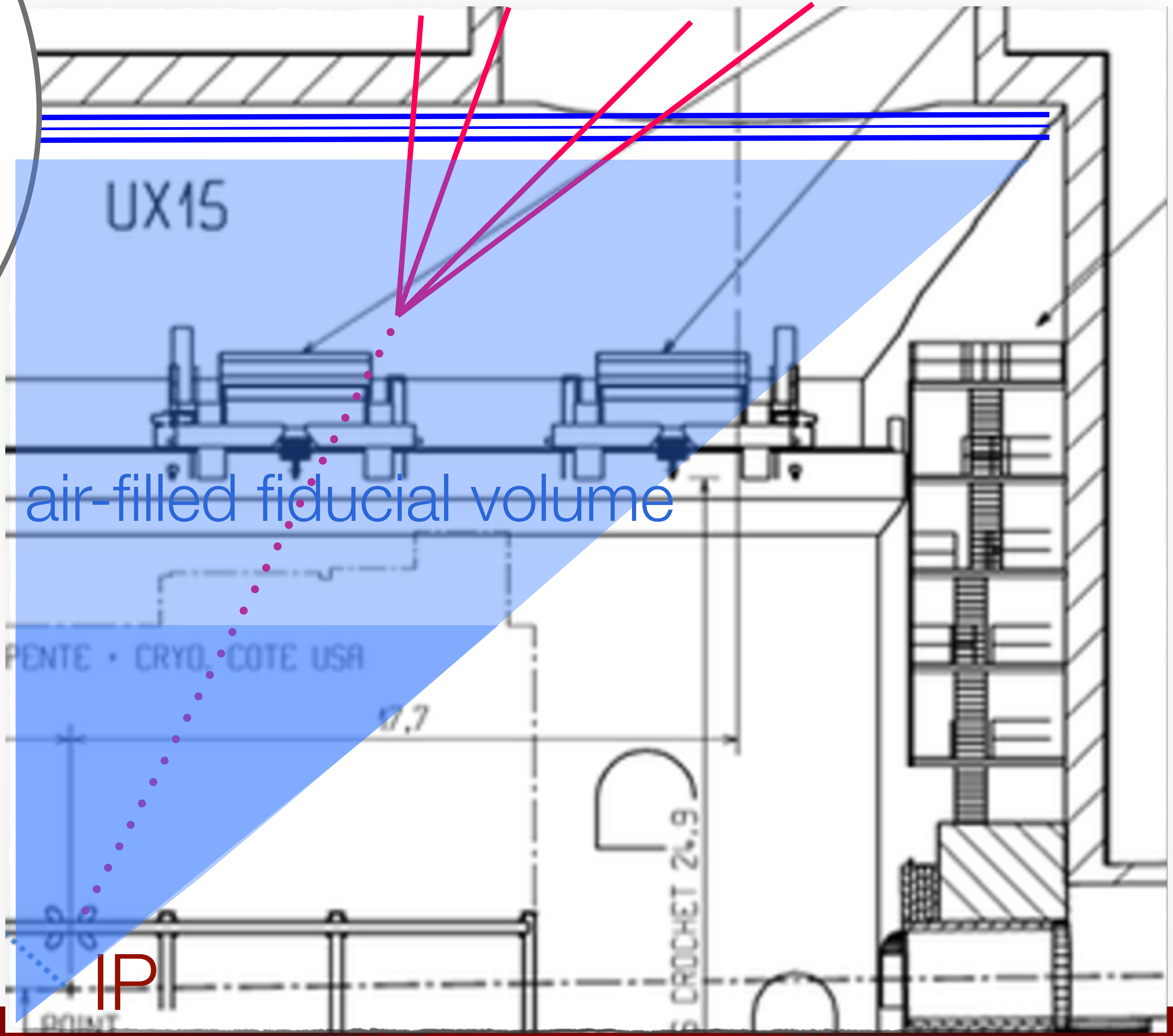
Exclude BRs down to 10^{-10}! [1]

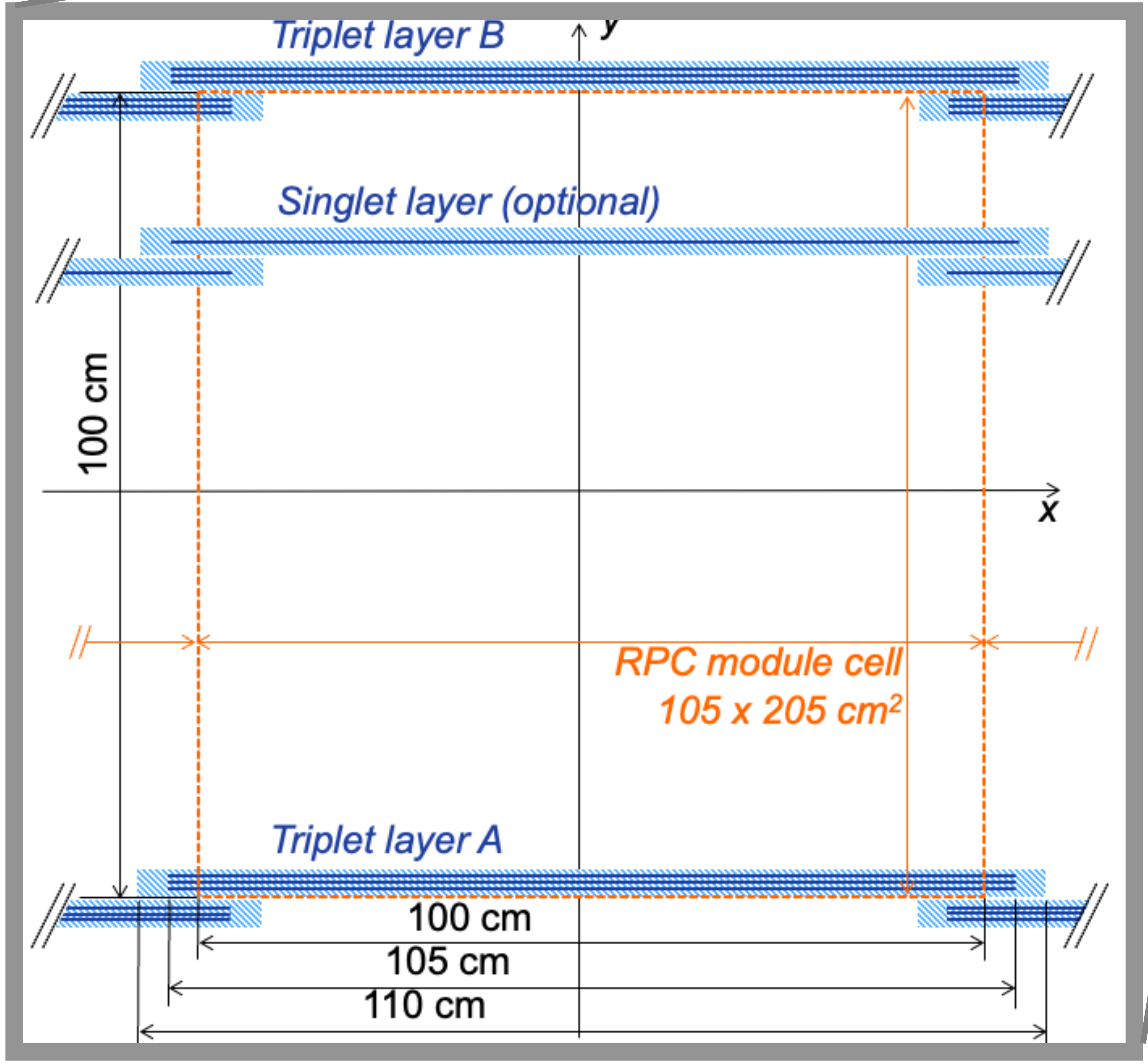
[1] $|U_{eN}| = 1$, background free scenario


TS 1
CAVERN
ERN
ATLAS
IP
20
0
−20
−20
0
20
x (m)

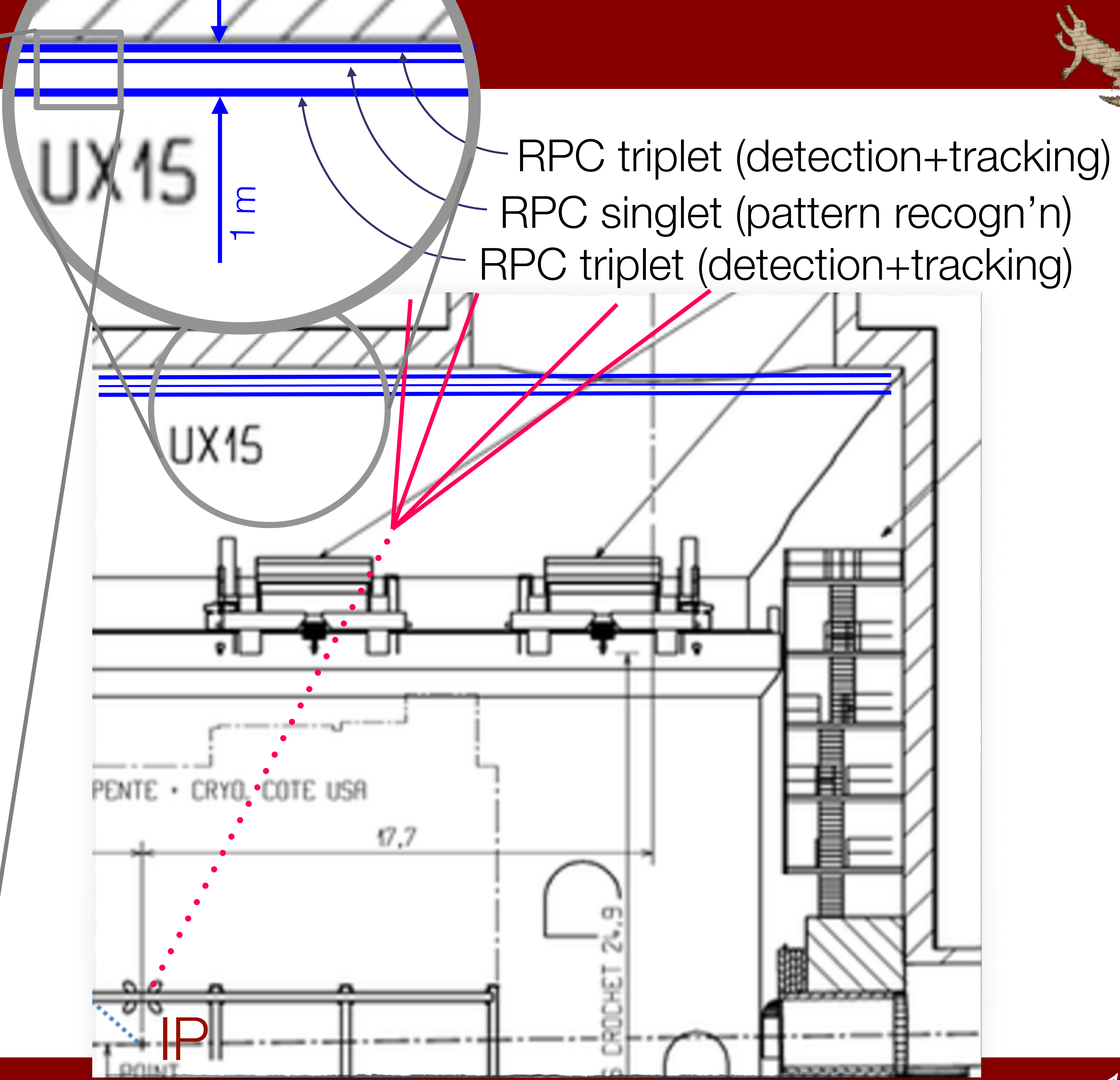

ANUBIS
EXPERIMENT
RPC
56 m
80 m
18 m
24 m
35 m


CEILING TS
TS 1
CAVERN
ATLAS
IP
20
0
−20
−40
−20
0
20
40
z (m)


UX15
air-filled fiducial volume
PENTE · CRYO. COTE USA
IP



Total singlet area: $\approx 9{,}800\ \mathrm{m}^2$

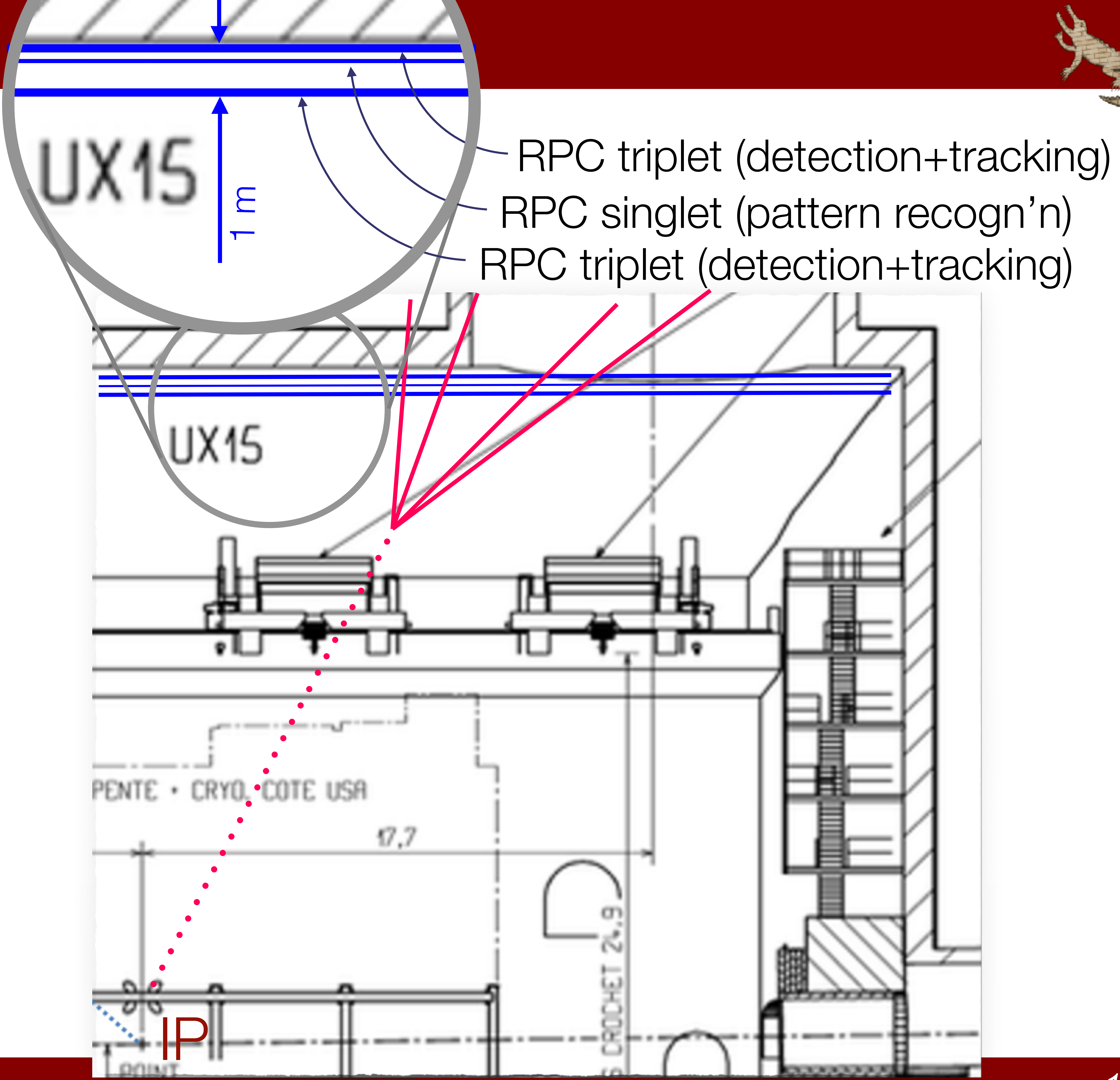


ANUBIS Detector requirements:

Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta \alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

Efficiency:

- Detect signal
- Reject backgrounds



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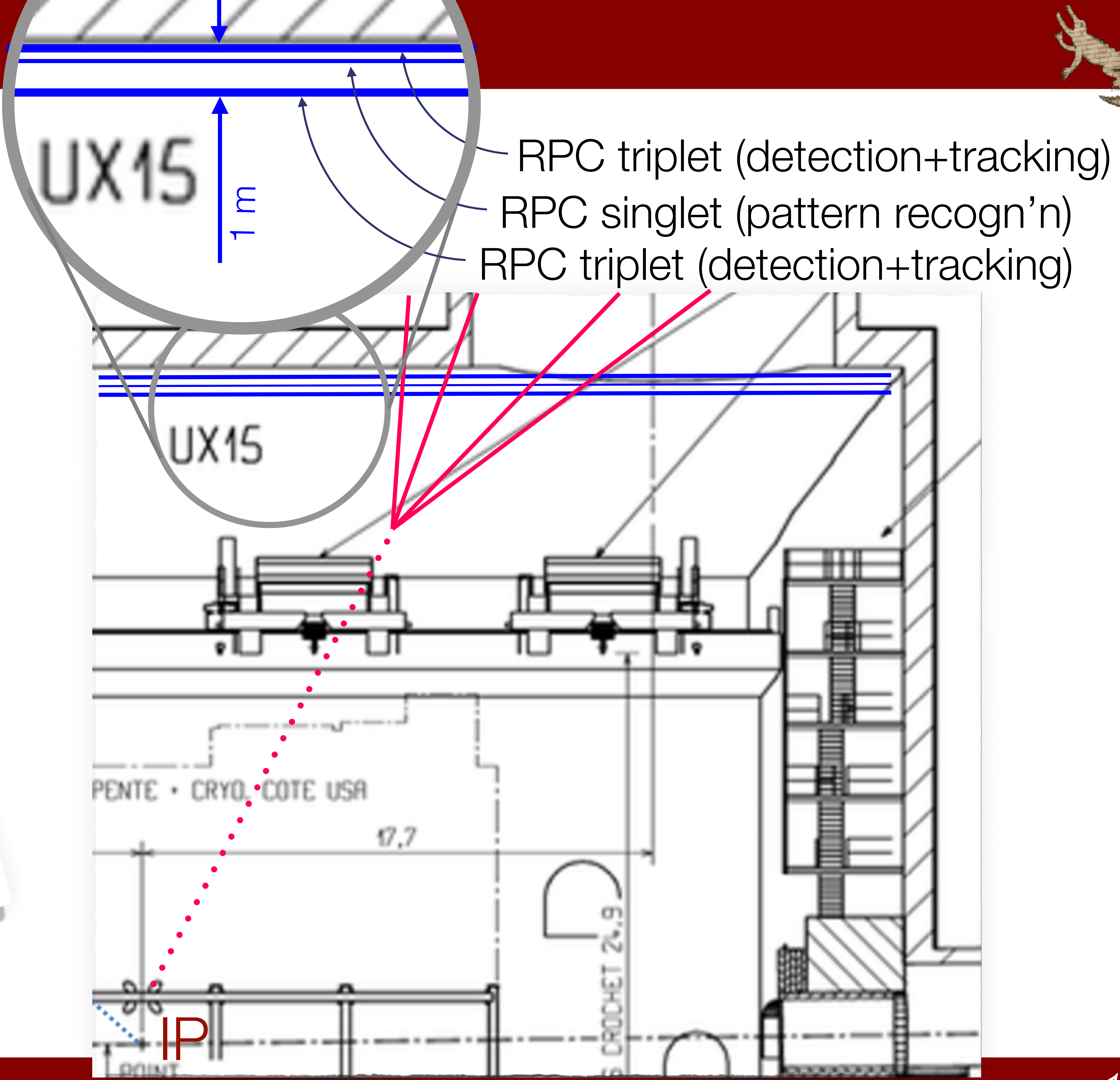
Timing:

- Fiducialise volume: $\delta y_{\mathrm{DV}} \approx 15$ cm
- Eliminate backgrounds e.g. cosmics, non-collision
- measure β

'For free': $\delta\beta \lesssim 0.5\,\%$ (TOF) feasible
→unique sensitivity to slow charged LLP BSM particles (dE/dx excess)



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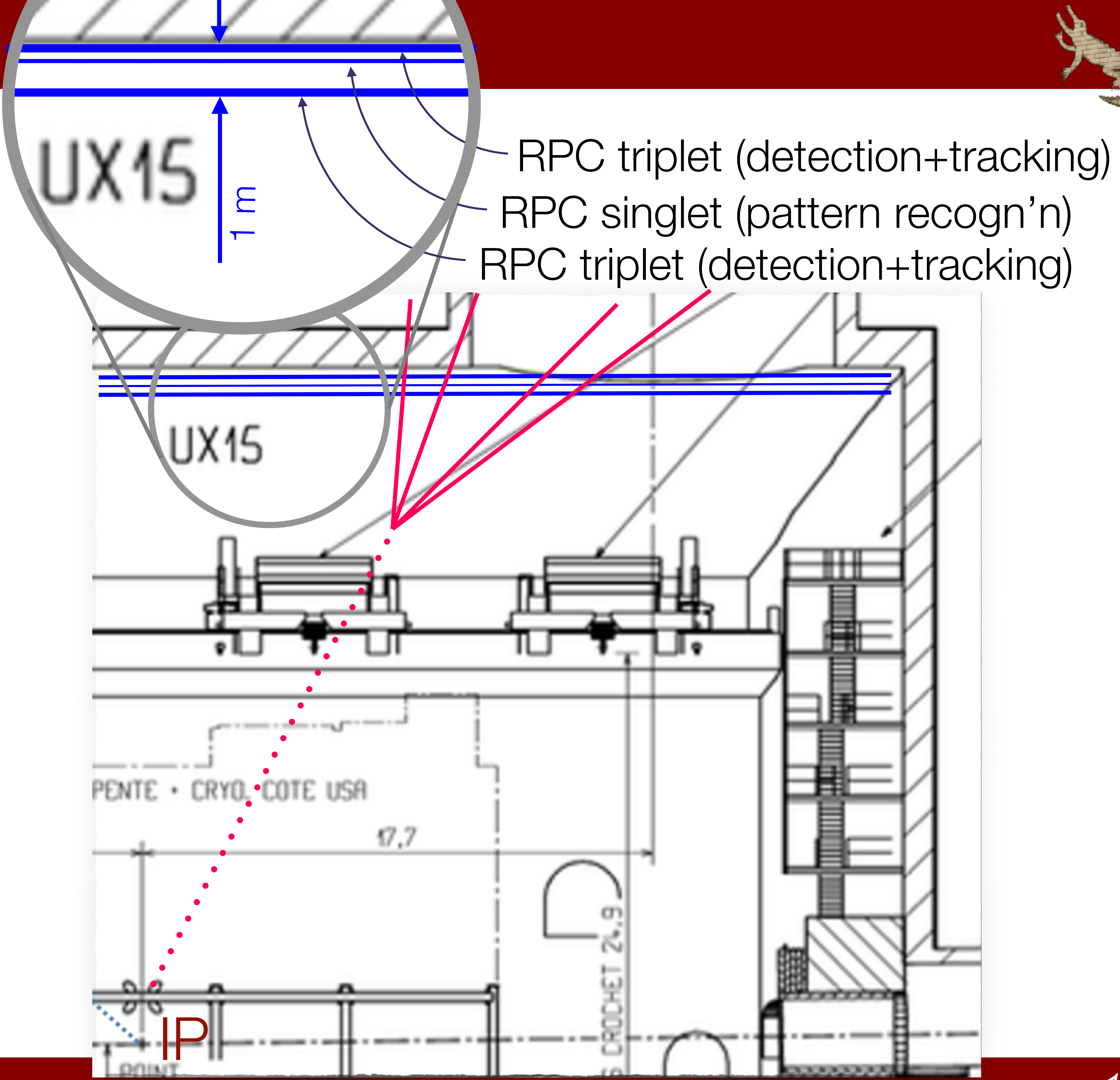
Angular & spatial resolution:

- Reconstruct displaced vertices: reach $m_{\text{LLP}} \approx K_L$ for $m_{\text{mediator}} \approx 100$ GeV
- Fiducialise volume



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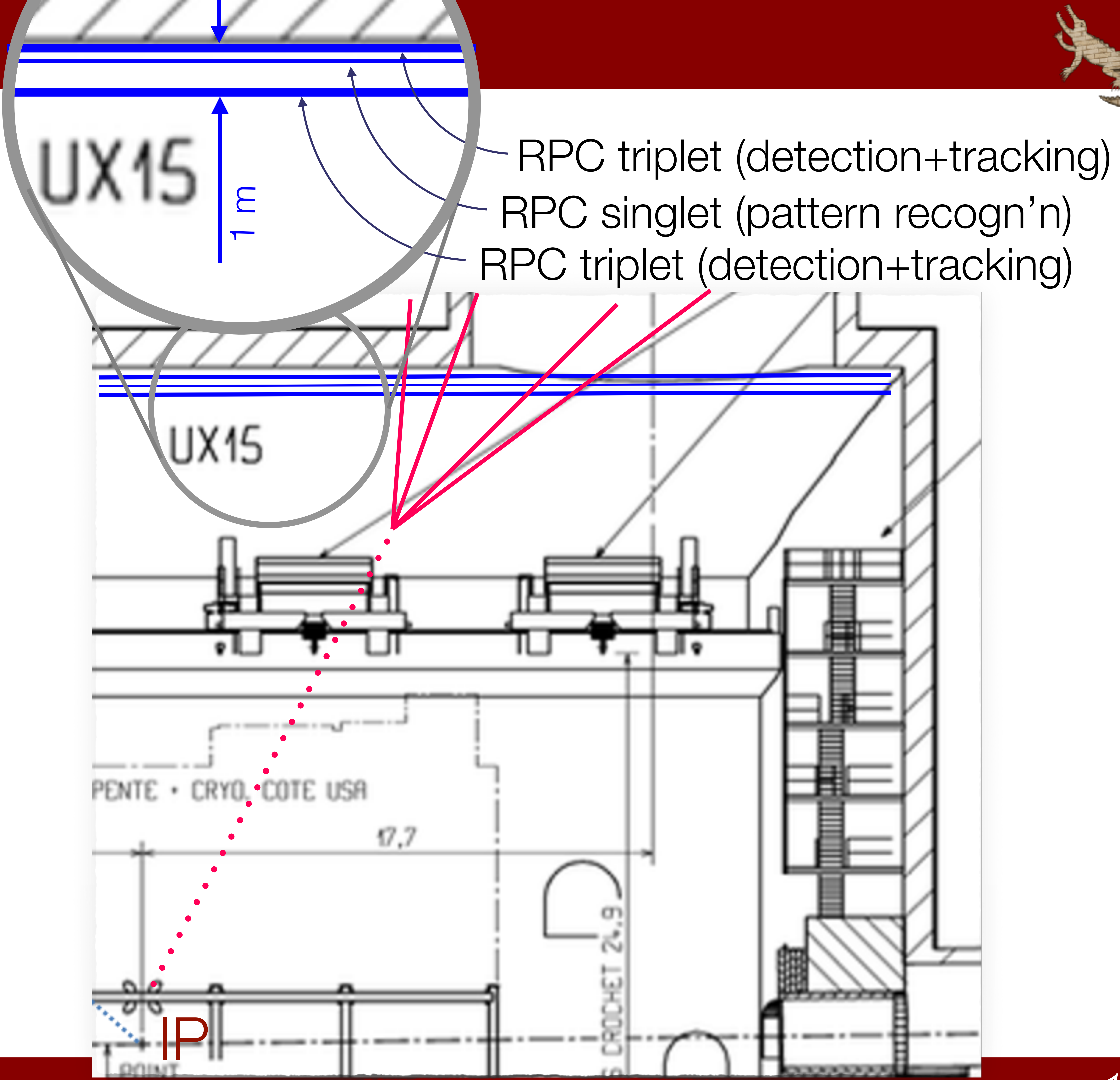
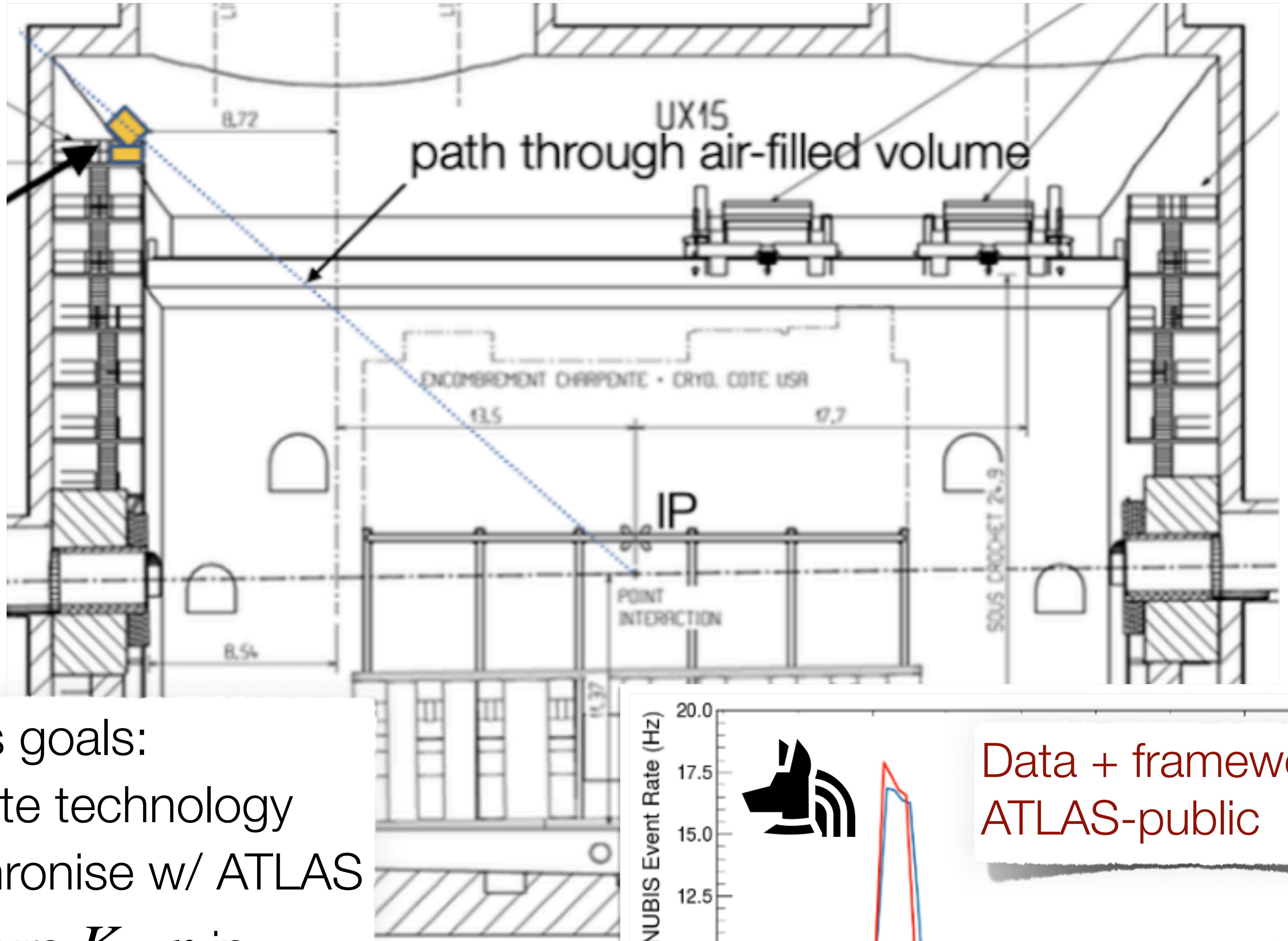
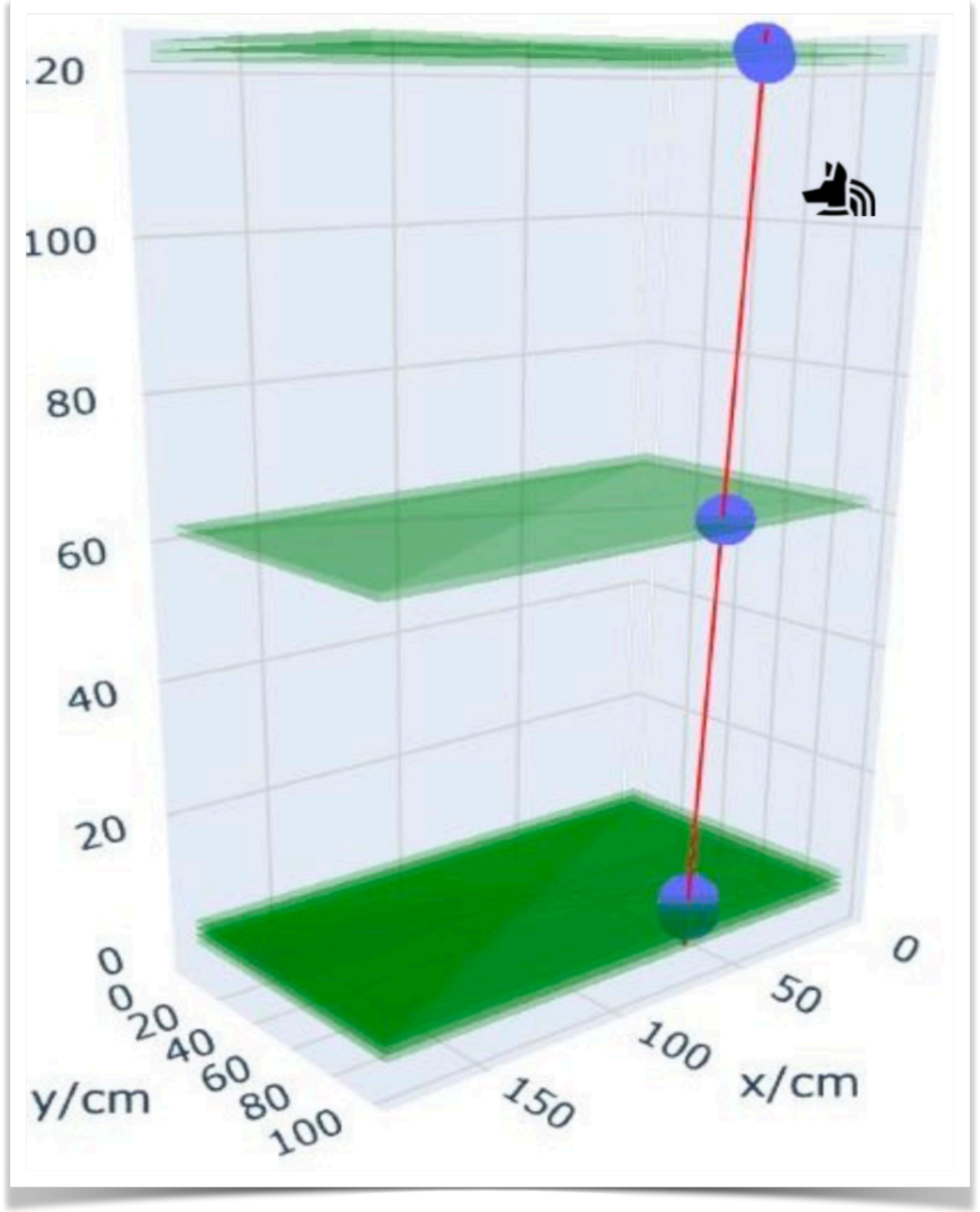
→ ATLAS Phase II RPC technology!



PROANUBIS DEMONSTRATOR

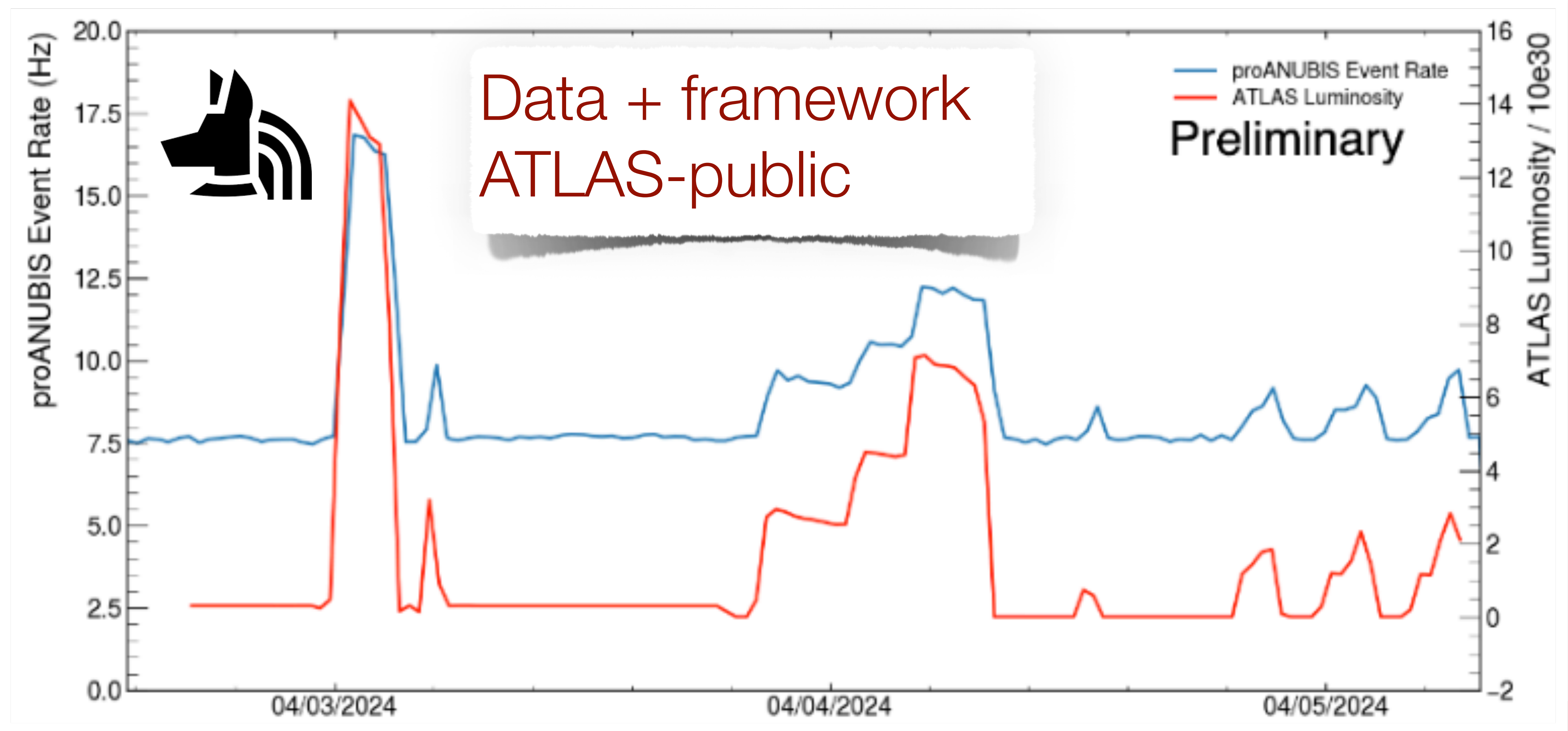
→ *Aashaq's TALK*

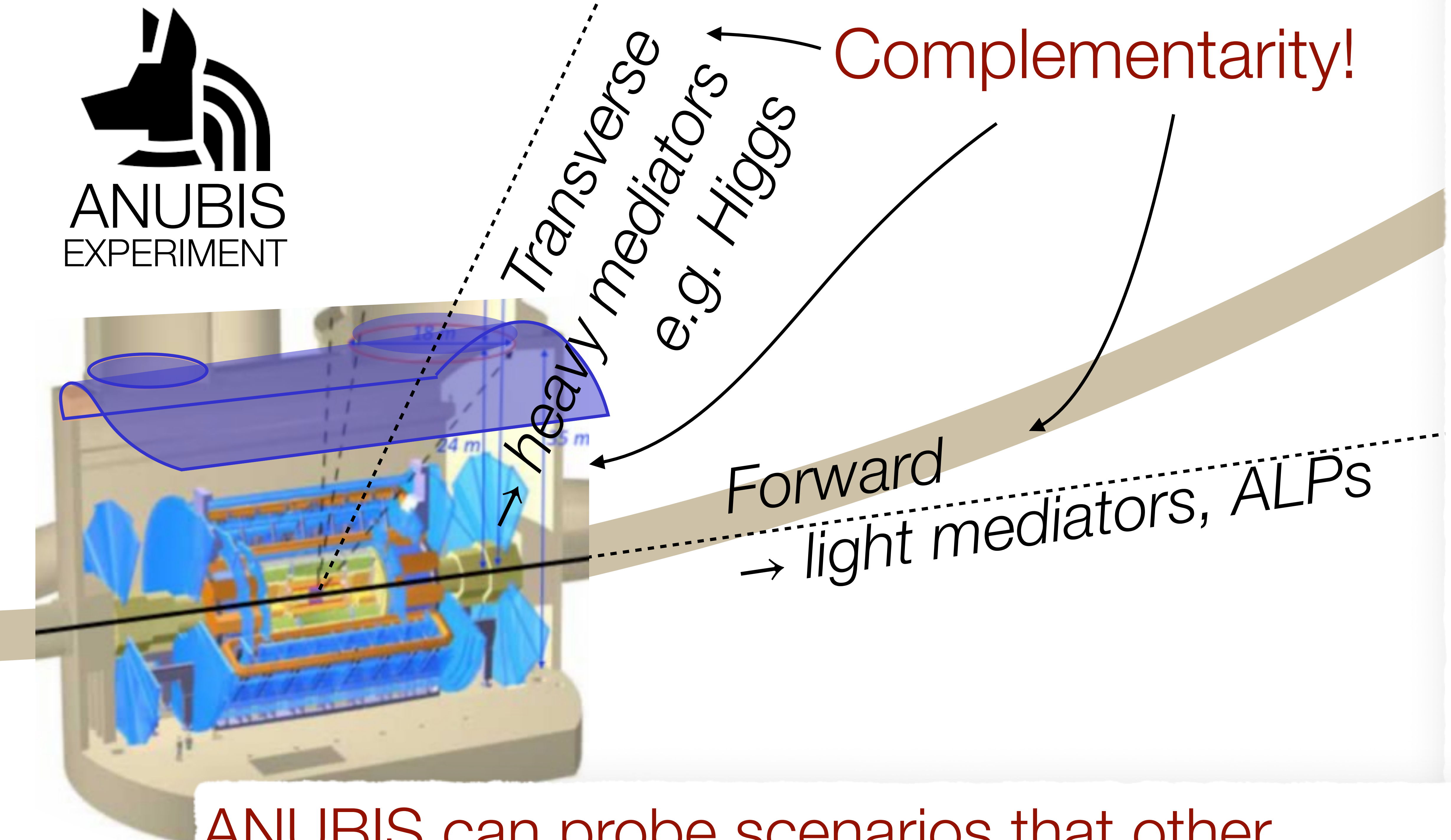




Physics goals:

- validate technology
- synchronise w/ ATLAS
- measure K_L, n in punch-through jets
- measure hadronic interaction rates in air volume (crucial)





ANUBIS can probe scenarios that other experiments are not sensitive to!

→ Complementarity to:

- general purpose detectors (e.g. CMS)
- forward detectors (e.g. FASER)
- beam dump experiments (SHiP)

→ Full HL-LHC exploitation imperative!

- Great progress towards ANUBIS detector:
  - Coarse geometry concept finalised
    - GeoModel for Geant4 in progress
  - Data-taking with proANUBIS:
    - $79.5\ \mathrm{fb}^{-1}$ collected, $83\ \%$ uptime
    - DAQ system upgrade for 2025
  - Analysis of proANUBIS data:
    - muon ID with proANUBIS & ATLAS
    - hadrons from punch-through jets

  ↗ Aashaq's TALK

  - Hardware R&D for the full detector
    - Daisy-chaining, data concentration, low-GWP gas, pitch optimisation
- → Welcoming new experimental collaborators!

- Progress w/ sensitivity projections for PBC & FIPs
  - SET-ANUBIS is a perfect theory collaboration platform
- → Welcoming theory collaborators!

SET-ANUBIS

Future plans for ANUBIS

ANUBIS collaboration:

→ unique opportunity to join an exciting project with a unique discovery potential (until FCC)

→ interesting hardware project with non-trivial electronics component after Phase II

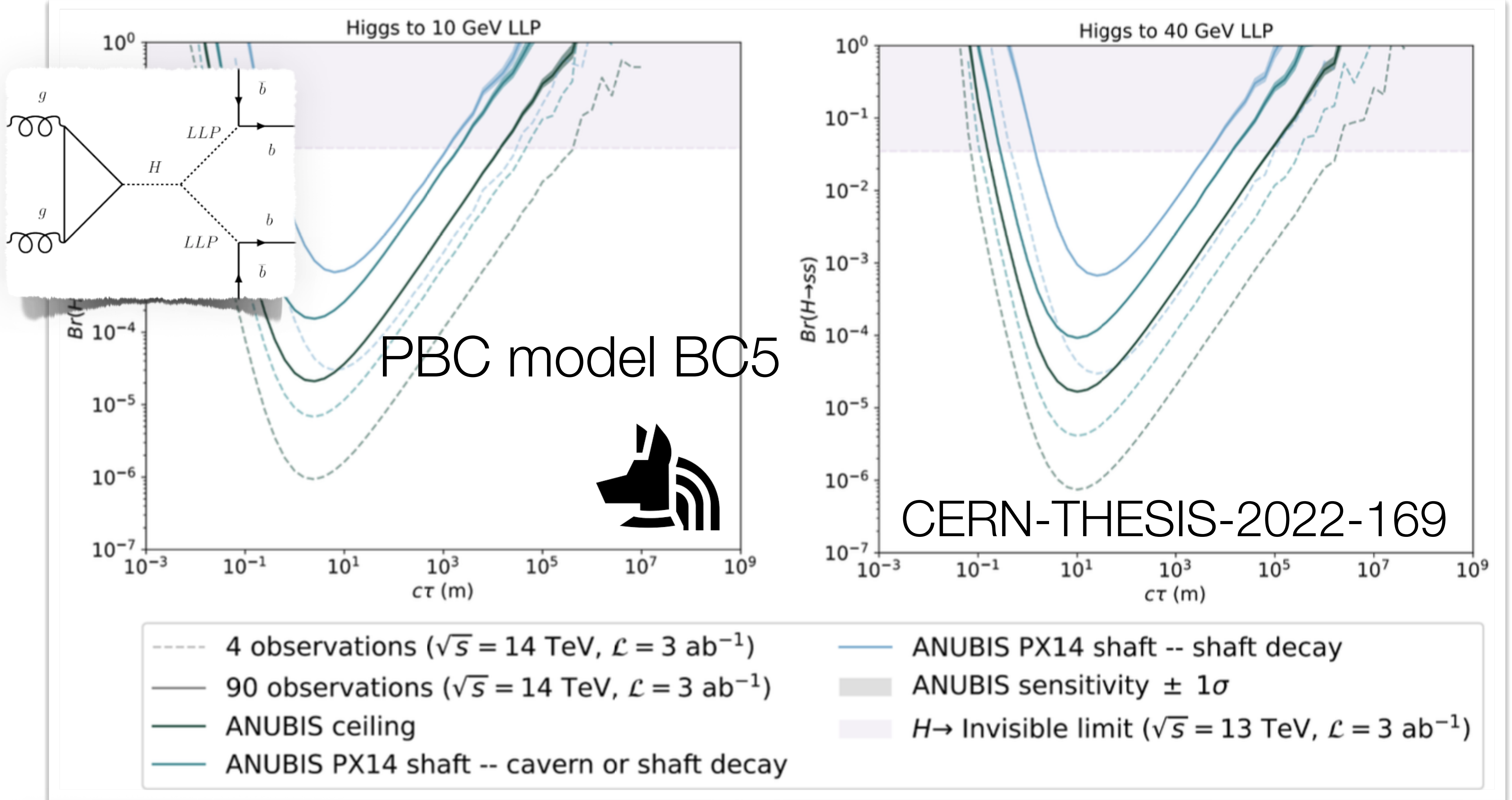
Gaseous detector R&D, DRD1: FCC long-term goal

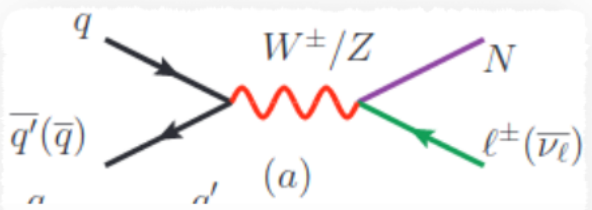
- 2033+: FCC detector construction & exploitation
- 2035+: Run 5 full ANUBIS+ATLAS data taking
- 2033+: bulk ANUBIS deployment in cavern (LS4)
- 2030+: Run 4 partial ANUBIS data taking
- 2028+: partial ANUBIS deployment in cavern (LS3)
- 2026+: ANUBIS detector R&D (electronics, R/O) engineering for cavern deployment
- 2025: proANUBIS data analysis, Letter of Intent
- 2024: PBC model #7 (#8, #9), proANUBIS data taking
- 2023: finalise geometry, PBC model #6, proANUBIS
- 2022: seed funding for proANUBIS
- 2021: ANUBIS location & prototype conception
- 2020: proANUBIS sensitivity studies
- 2019: ANUBIS conception

Thank you!

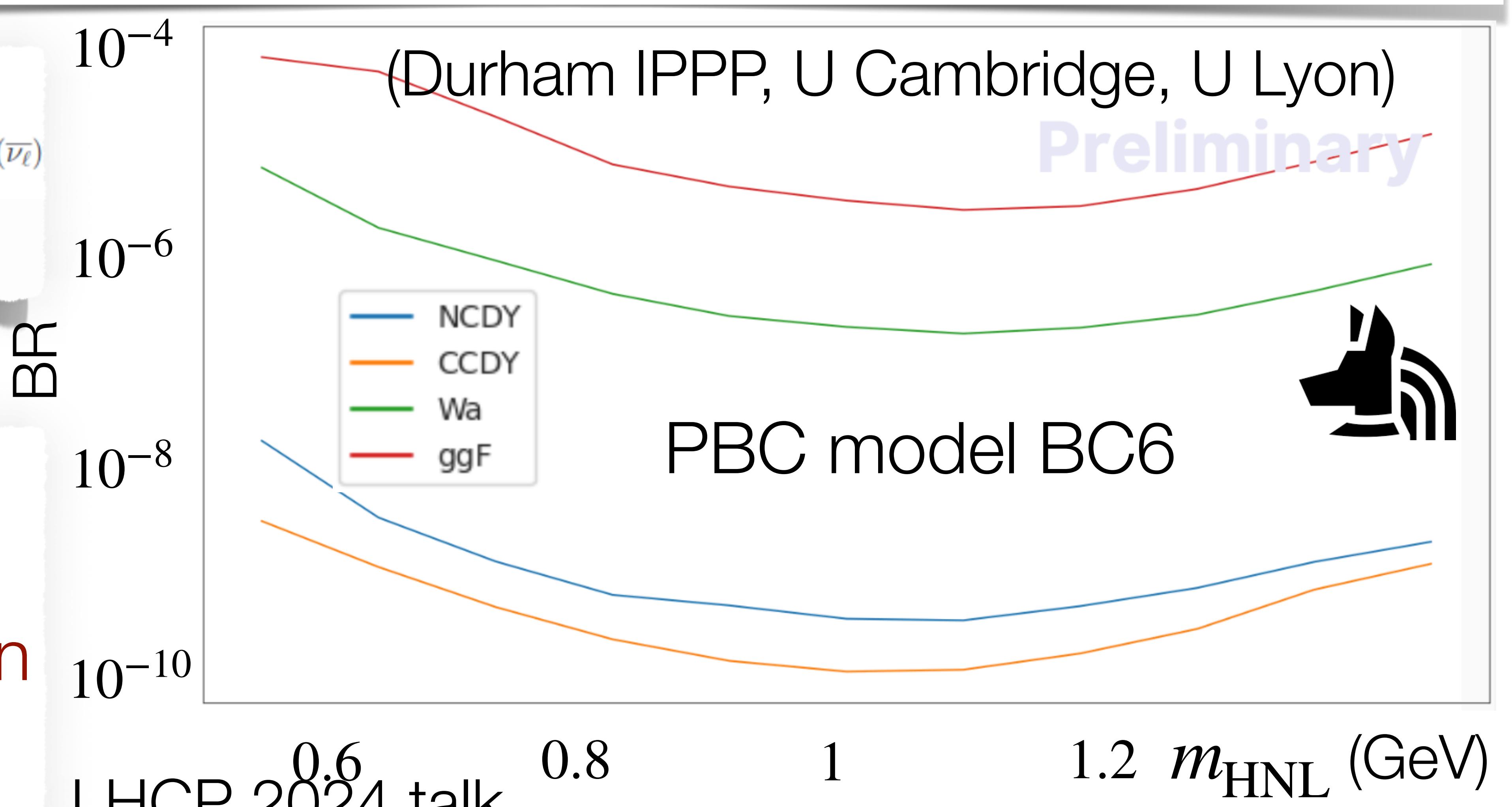
THE WAY TO THE LETTER OF INTENT (EARLY 2025)

SENSITIVITY PROJECTIONS (PBC/FIPS CONTEXT)





(a) Drell-Yan (CCDY, NCDY)

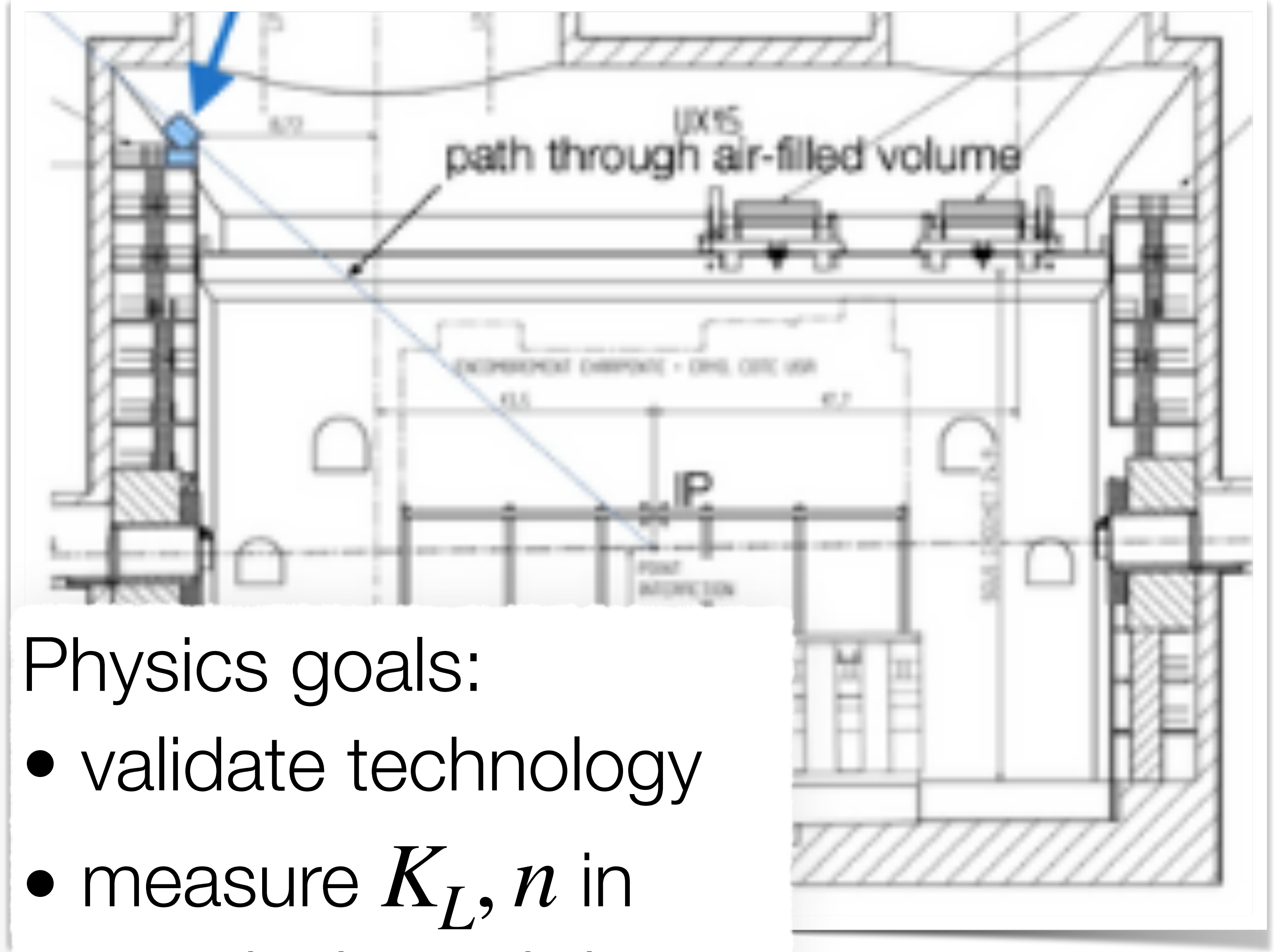


LHCP 2024 talk

Public framework in preparation

→ Happy to collaborate!

PROANUBIS DEMONSTRATOR



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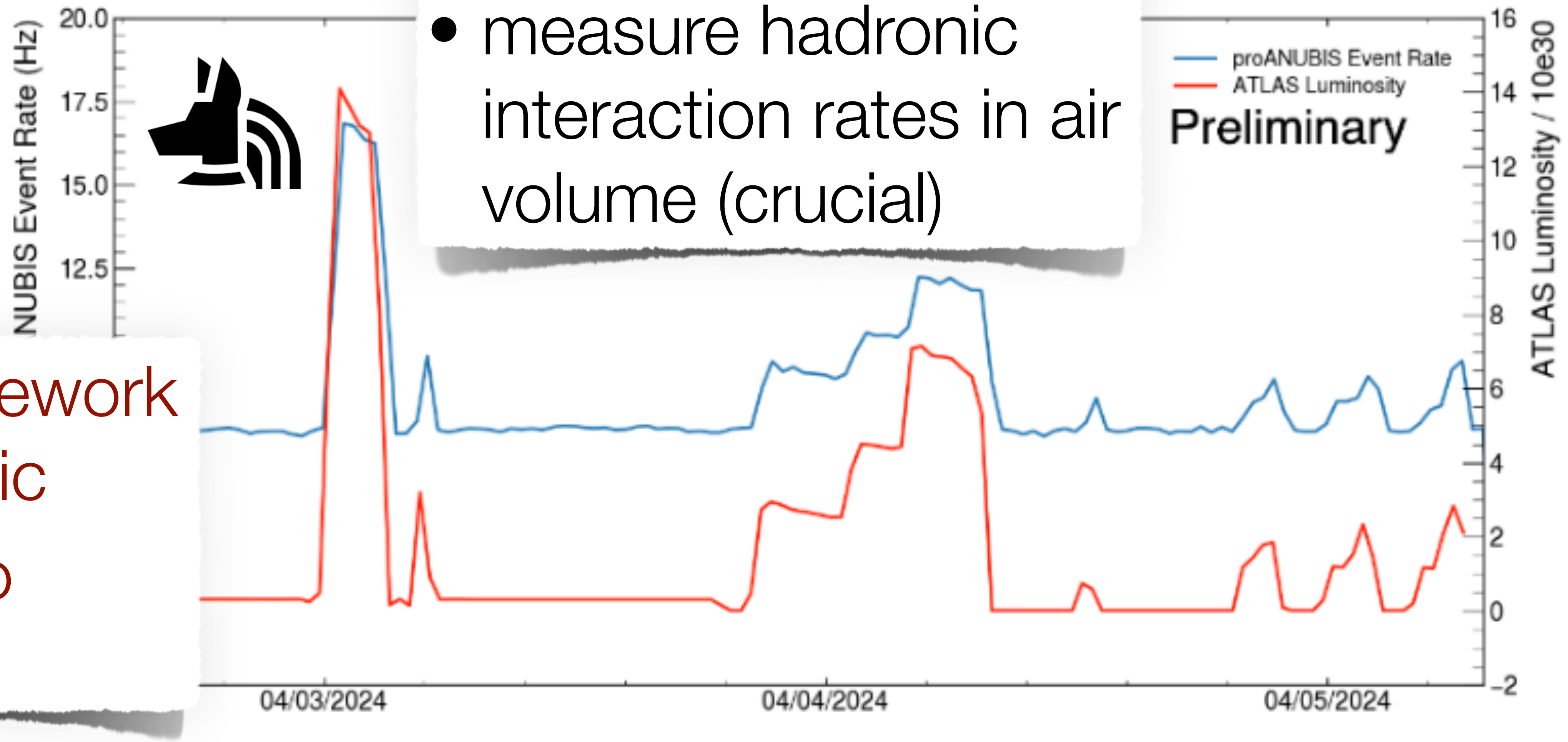

Data + framework ATLAS-public

→ Happy to collaborate!

Università di Roma Tor Vergata

INFN

CERN

IP3

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THE UNIVERSITY OF HONG KONG

UKRI FLF

Isaac Newton Trust

UNIVERSITY OF CAMBRIDGE

LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

Durham University

UNIVERSITÉ DE LYON

Lyon 1

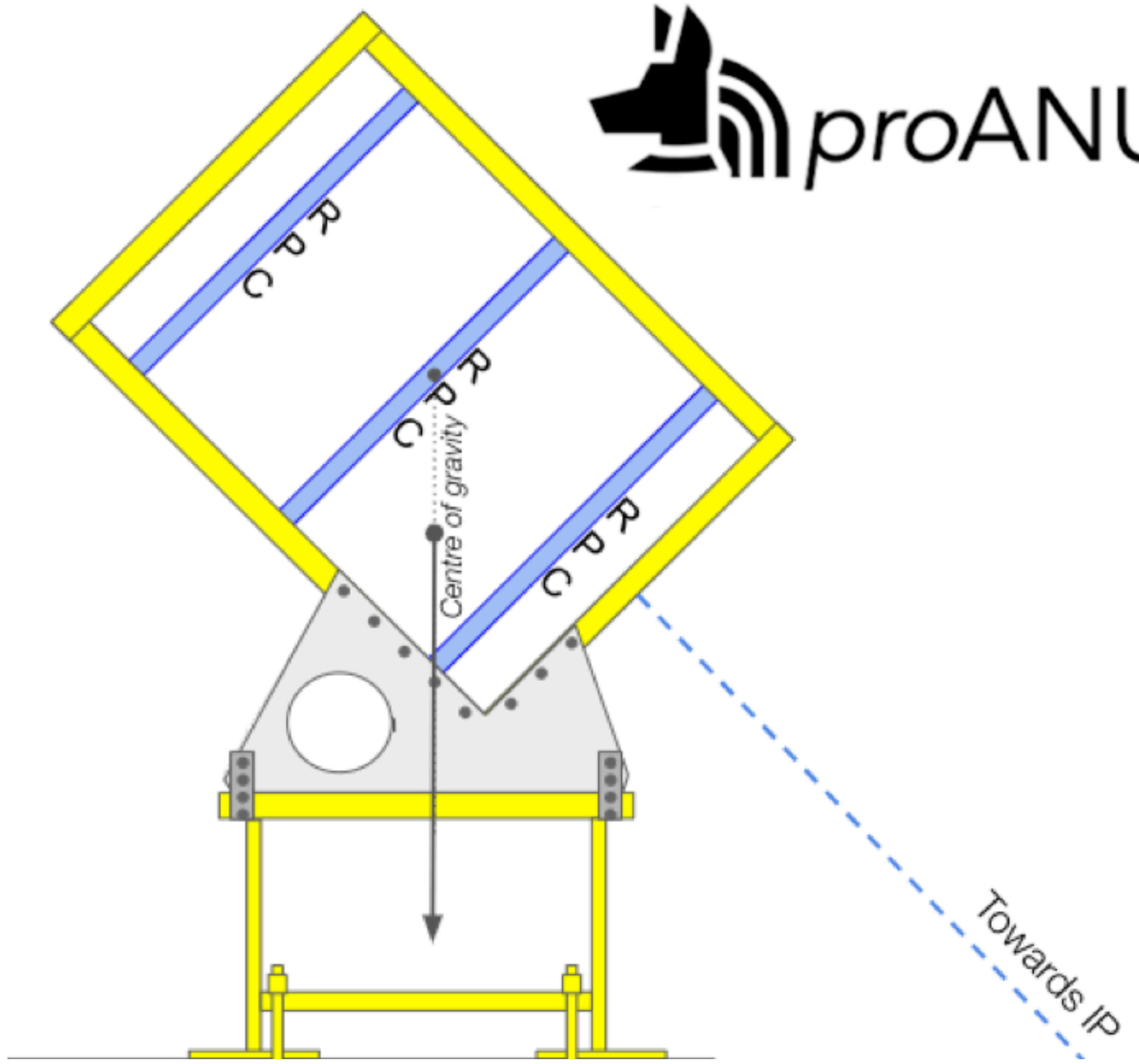
ANUBIS DETECTOR@ ATLAS EXPERIMENT

KTH VETENSKAP OCH KONST

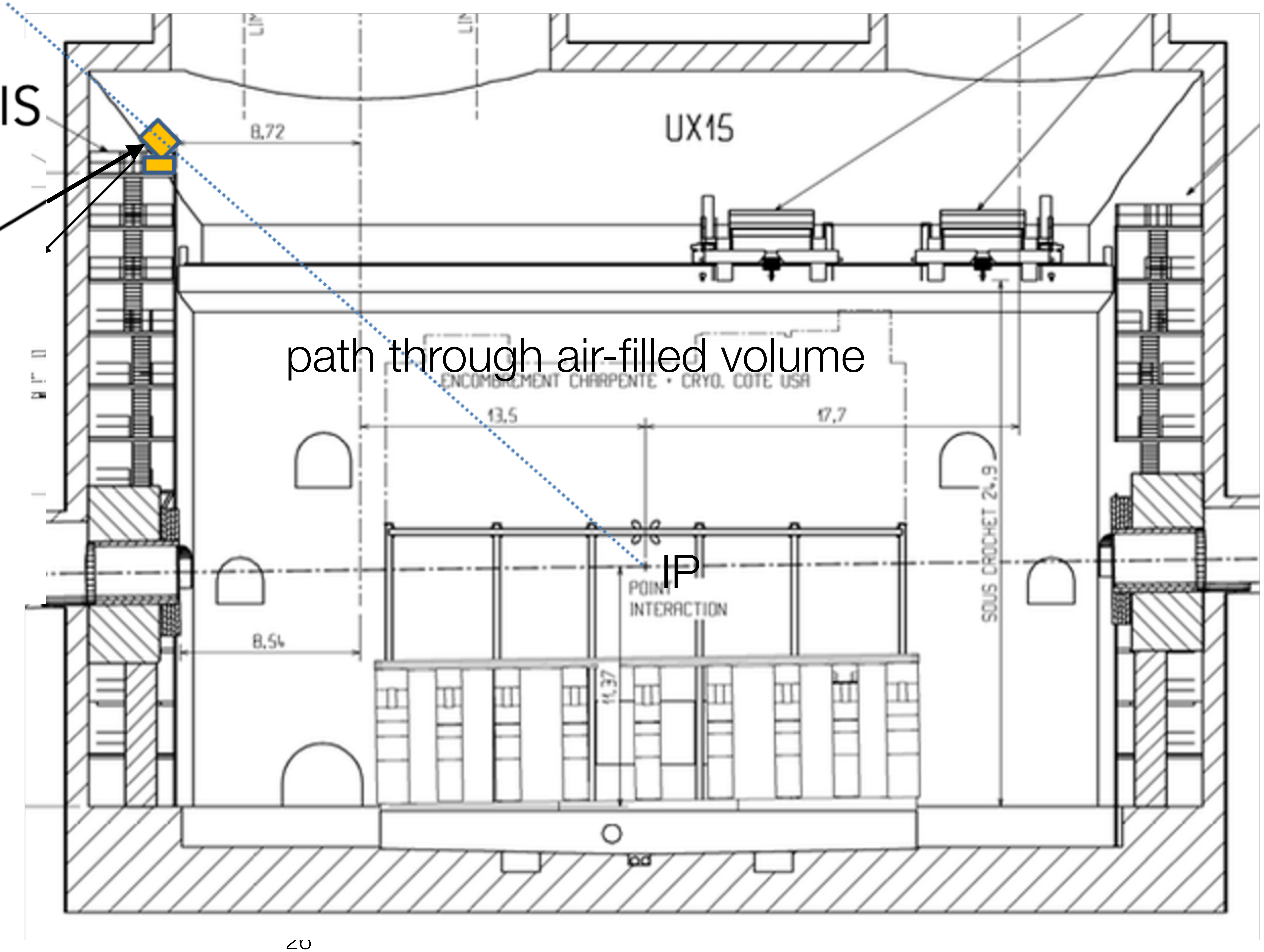
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

proANUBIS physics goals

*pro*ANUBIS location: similar to ANUBIS



proANUBIS

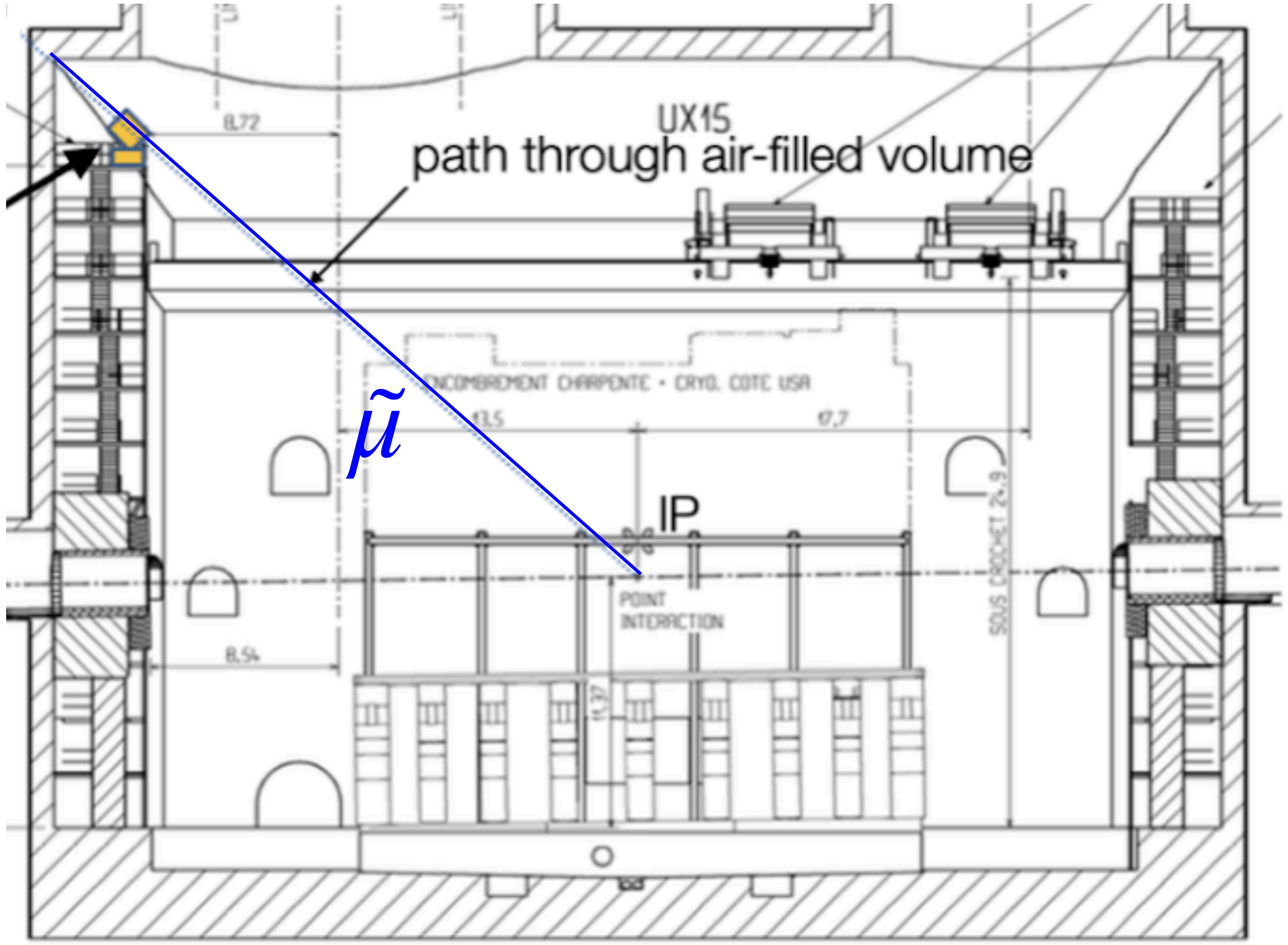


*pro*ANUBIS location: similar to ANUBIS

proANUBIS in Run 3

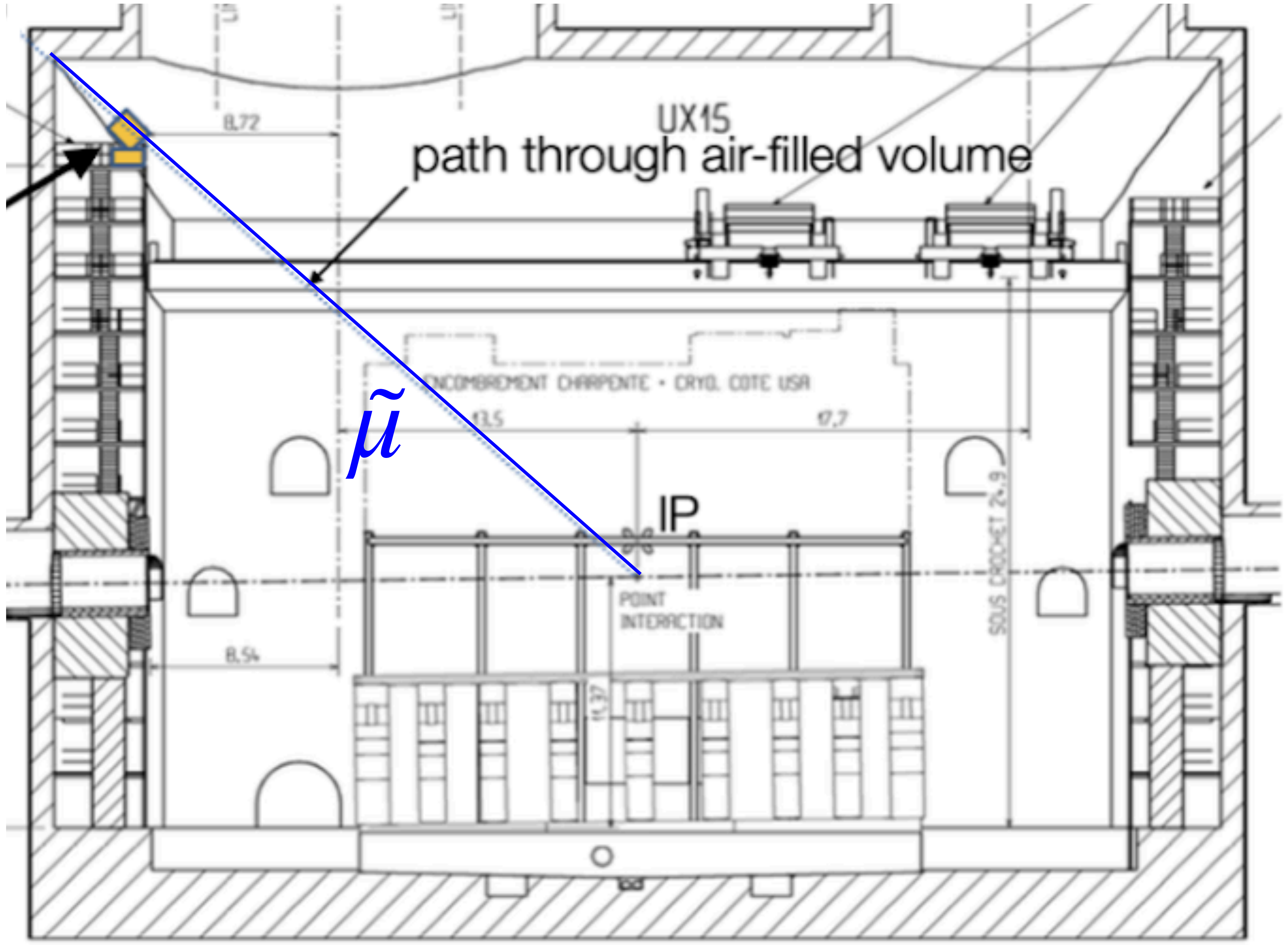
- Performance goals:
  - Commissioning
  - hit+track efficiency
    - Cosmics
    - pp collisions
  - Synchronise ATLAS + proANUBIS
    - Time-stamp events with CTP clock
  - Identify events with muons (triggered by single-μ trigger)
  - Track extrapolation to ATLAS
    - Measure tracking efficiency:

      $\varepsilon = \mu_{\mathrm{ID\ proANUBIS}} / \mu_{\mathrm{ID\ ATLAS}}$



proANUBIS in Run 3

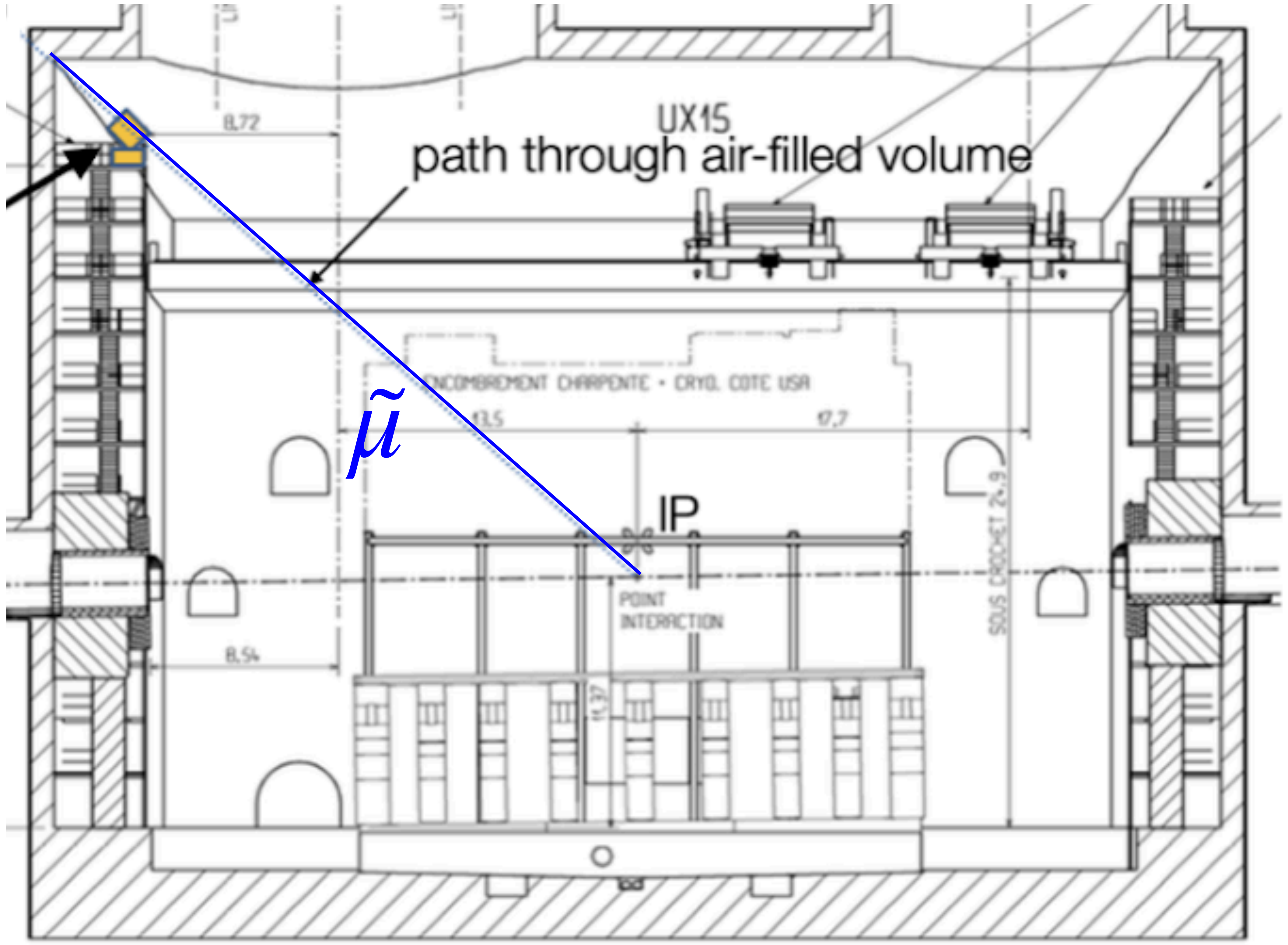
- Physics goals:
  - Measure rate of charged hadrons from punch-through jets
    - → same ϵ_{reco} as for μ?



- Punch-through enriched region:
  - jet pointing towards proANUBIS
- Background-enriched region:
  - jet as above, aligned with E_T^{miss}

proANUBIS in Run 3

- Physics goals
  - Measurements in punch through-enriched region
    - Measure rate of charged hadron interactions with material:
      - material-dense (steel)
      - air
    - Measure rate of K_L, n in background-enriched region
      - material-dense (steel)
      - air
    - Good handle to validate Geant4 simulations!



Background studies
for ANUBIS

Aside: angular resolution

- Consider decay into two particles — this is the most challenging case!
  - Higher multiplicity → easier reconstruction & (even) lower backgrounds
- Assume mediator at EW scale (e.g. 125 GeV Higgs):

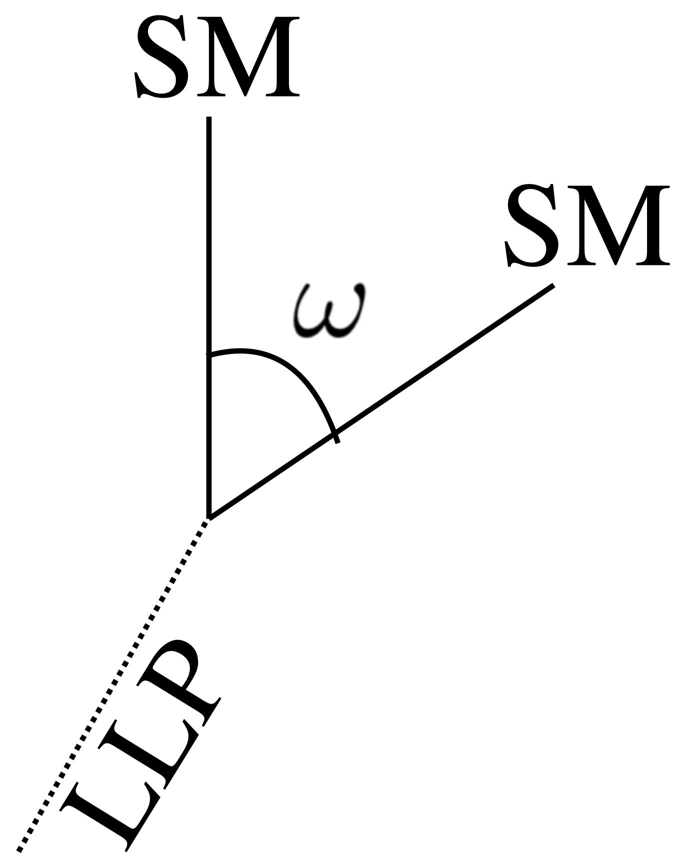
$$m_{\rm med} \approx 100 \text{ GeV}$$

- Average boost from pure kinematics:

$$\frac{m_{\rm med}}{2m_{\rm LLP}} \quad \Rightarrow \quad m_{\rm LLP} \approx \frac{1}{2} m_{\rm med} \cdot \omega$$

- Assume symmetric LLP decay

$$\delta\omega \approx \sqrt{2} \cdot \delta\alpha$$



ANUBIS: backgrounds

ATLAS detector for background reduction:

- passive shield:
  calorimeter depth ~10 nuclear interaction lengths λ_I
- *active veto*:
  high-p_T neutral SM LLPs (n, K_L) typically come from energetic jets and give no large E_T^{miss}

Almost background-free by requiring $E_T^{\text{miss}} > 30$ GeV

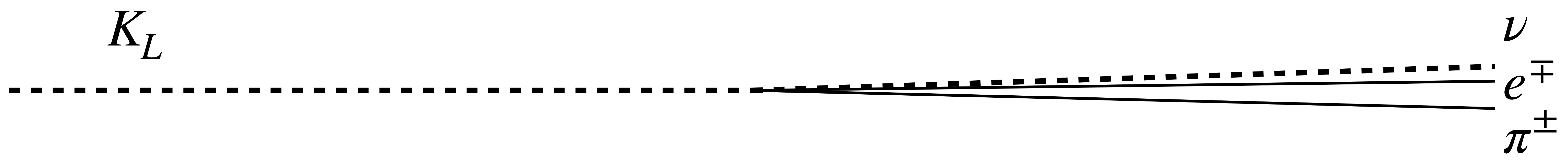
Require isolation in $\Delta R(\text{DV}, x)$ from inner detector tracks, calorimeter jets, muon spectrometer tracks

→ Active veto by *ANUBIS triggering the readout of ATLAS*

ANUBIS: backgrounds

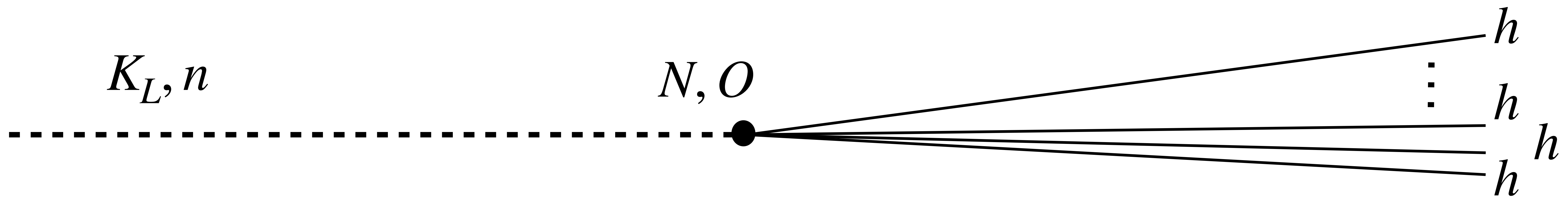
Two main background mechanisms to enter the signal region:

- Decay (K_L only, $c\tau \approx 14$ m):



  - easy to discriminate:
    2 charged, collimated tracks

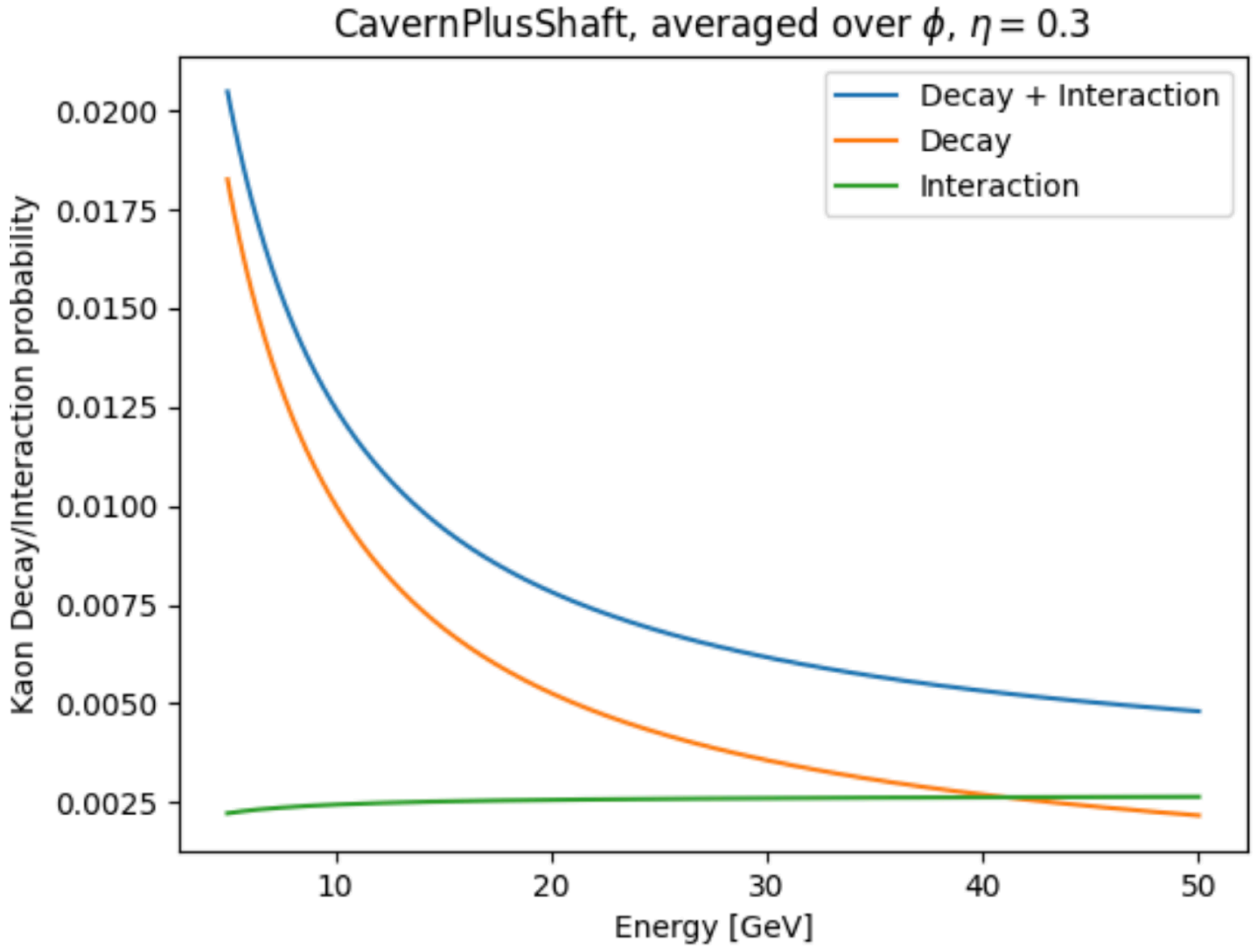
- Hadronic interactions of n, K_L:



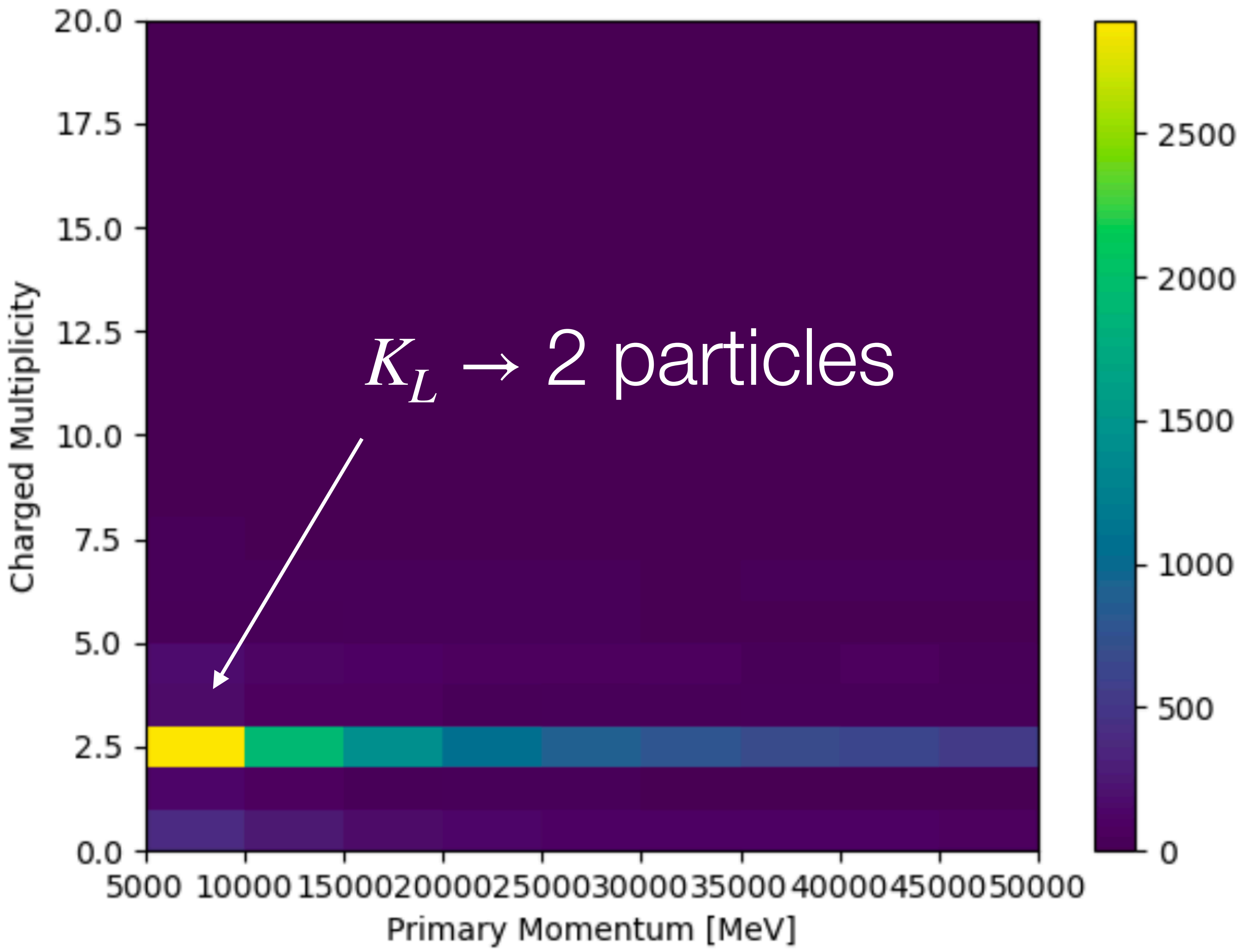
  - Decimate by fiducialising the signal region for LLP decays:
    - accept vertices from air-filled region only ($\Lambda_{\text{free}} \approx 800$ m)

ANUBIS: backgrounds: K_L

Decays typically dominate:

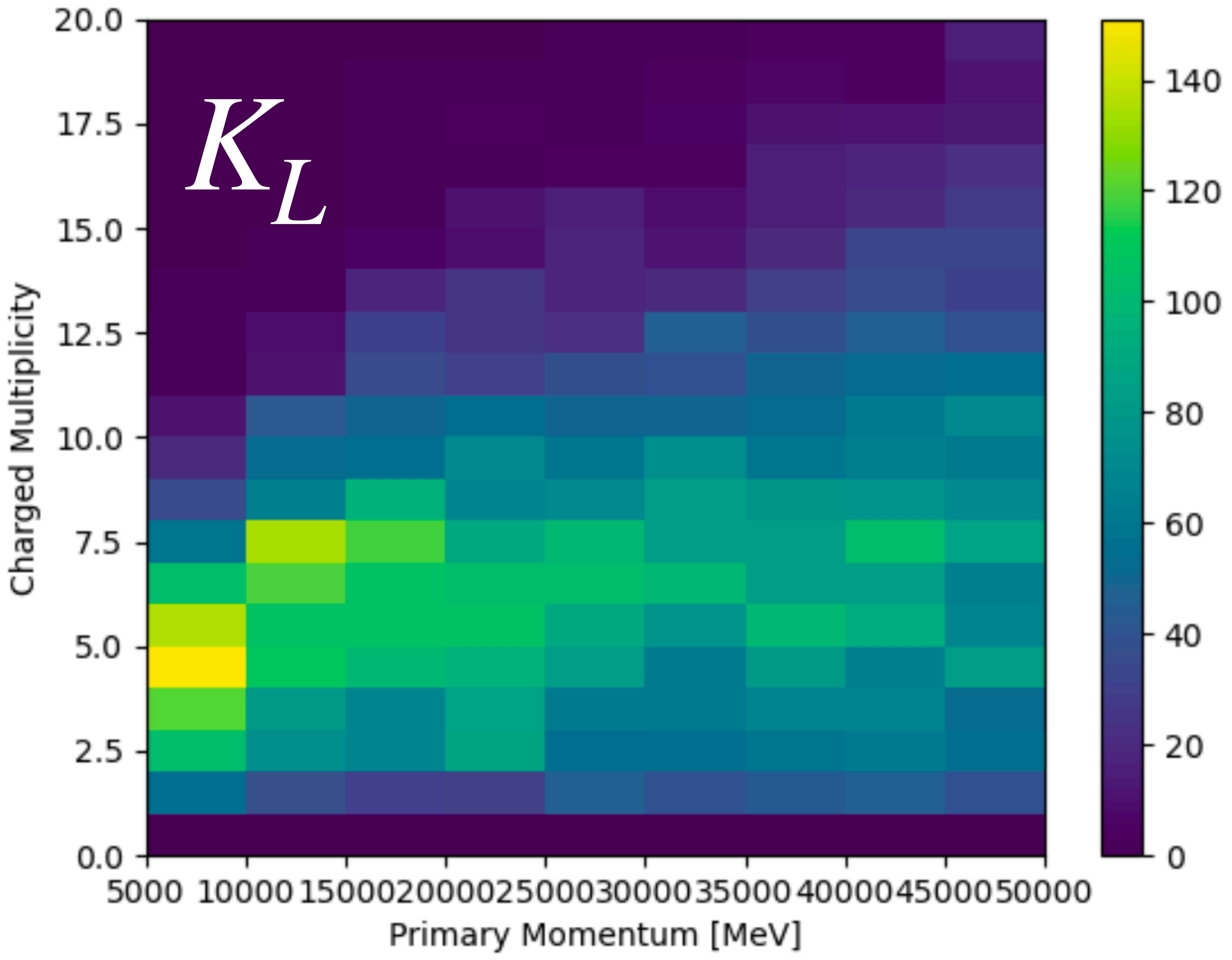


Detailed Geant4 studies:
K_L, n with $E = 5,10,...50$ GeV
on cylinder of air of 100 m depth

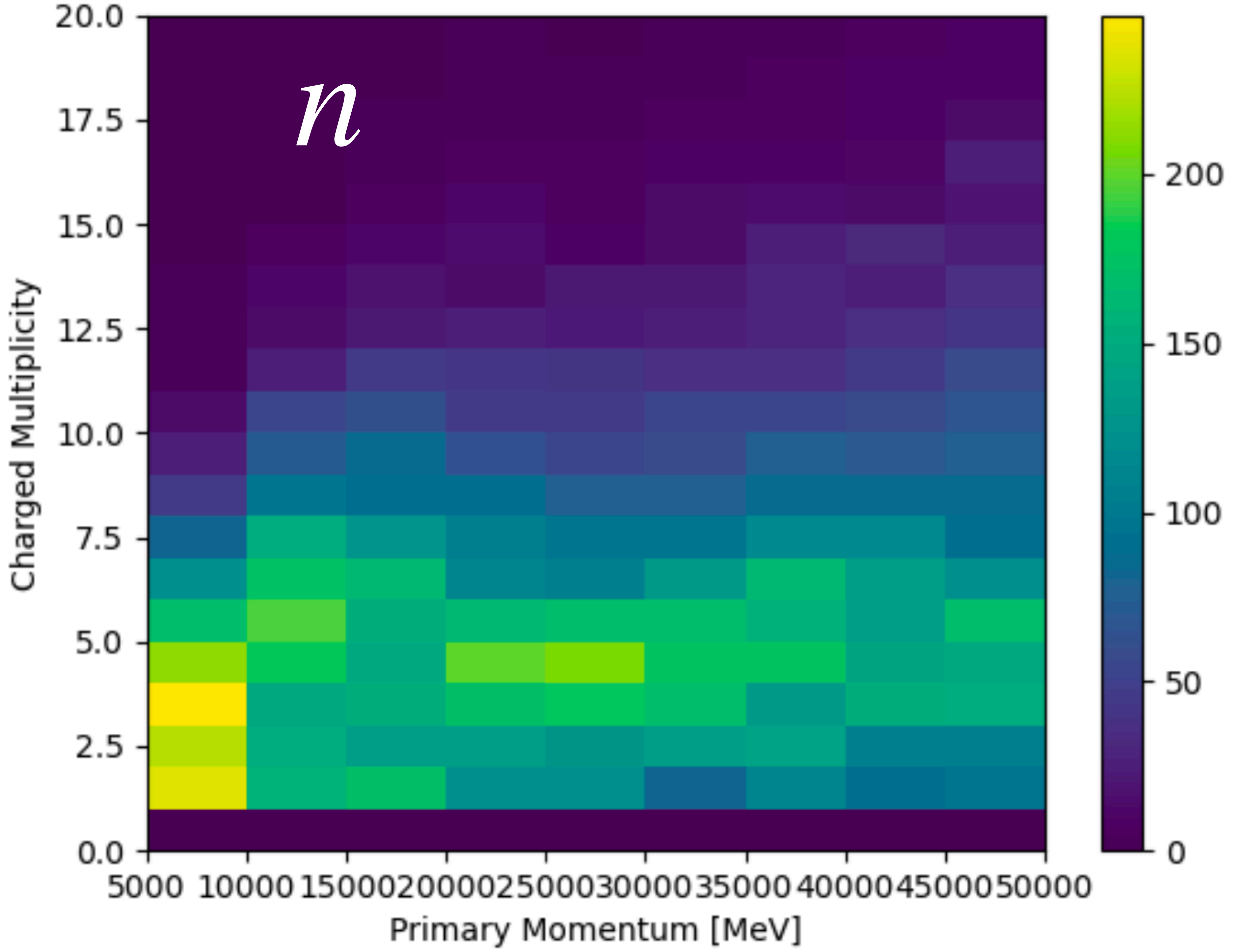


ANUBIS: backgrounds

Hadronic interactions as background from Geant4 studies

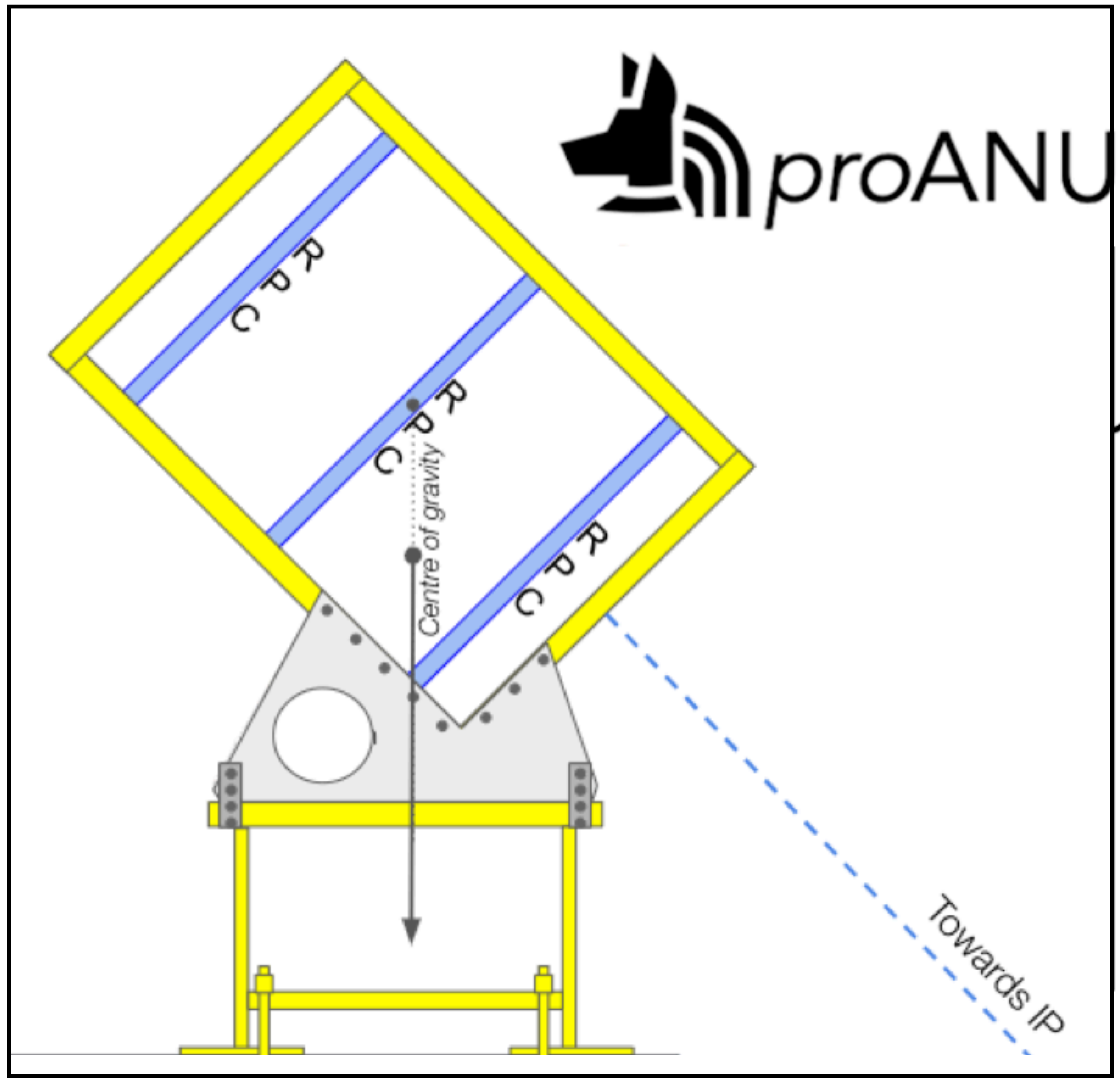


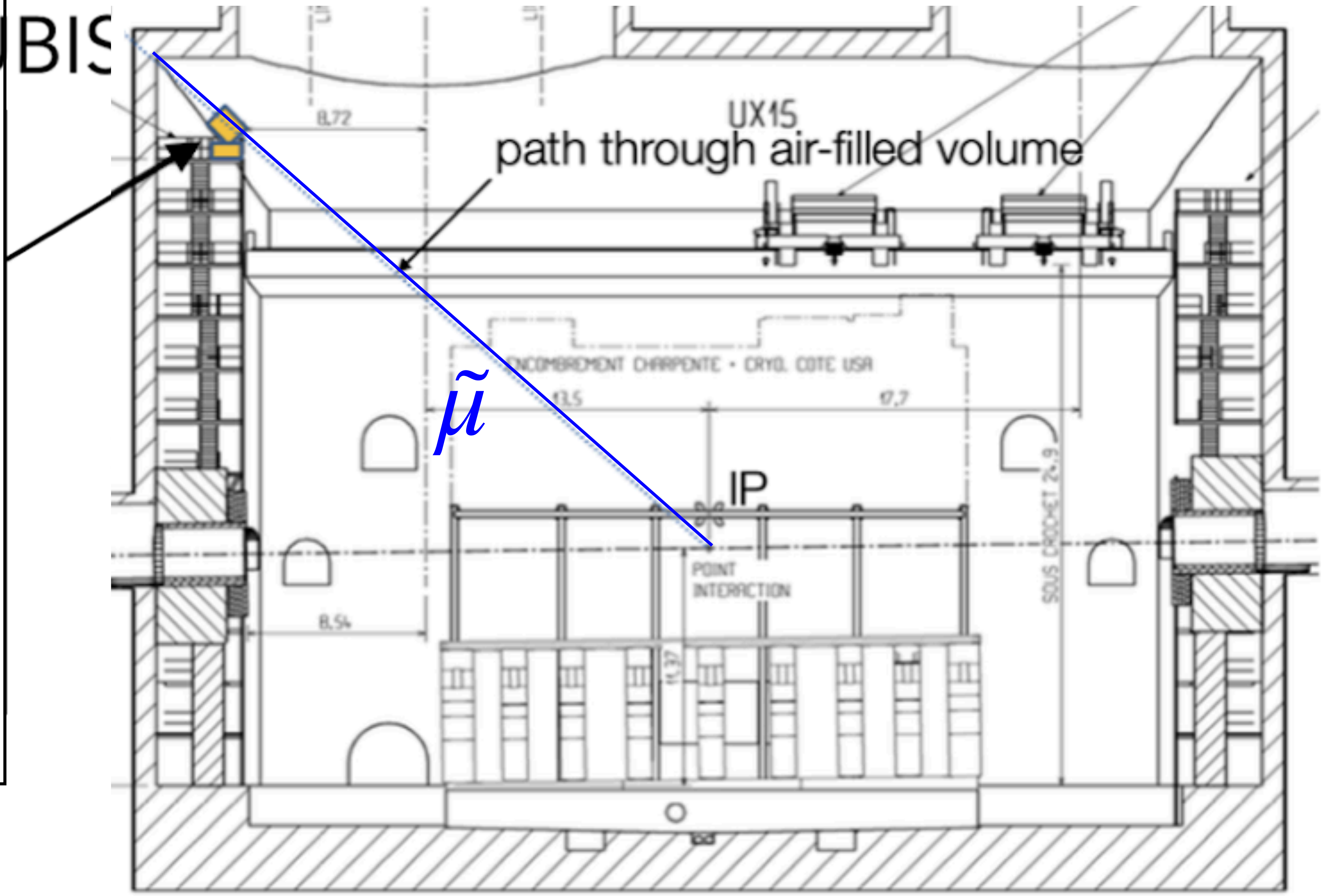
Detailed Geant4 studies:
K_L, n with $E = 5,10,...50$ GeV
on cylinder of air of 100 m depth



Unique sensitivity of proANUBIS to whacky new BSM models?

- Tracking station element — two RPC triplets of ~1 x 2 m, 1 m apart
  - **Measure fluxes** in PX14 shaft & **correlate** to ATLAS (Run 3)
  - Is there any unique BSM sensitivity for proANUBIS?

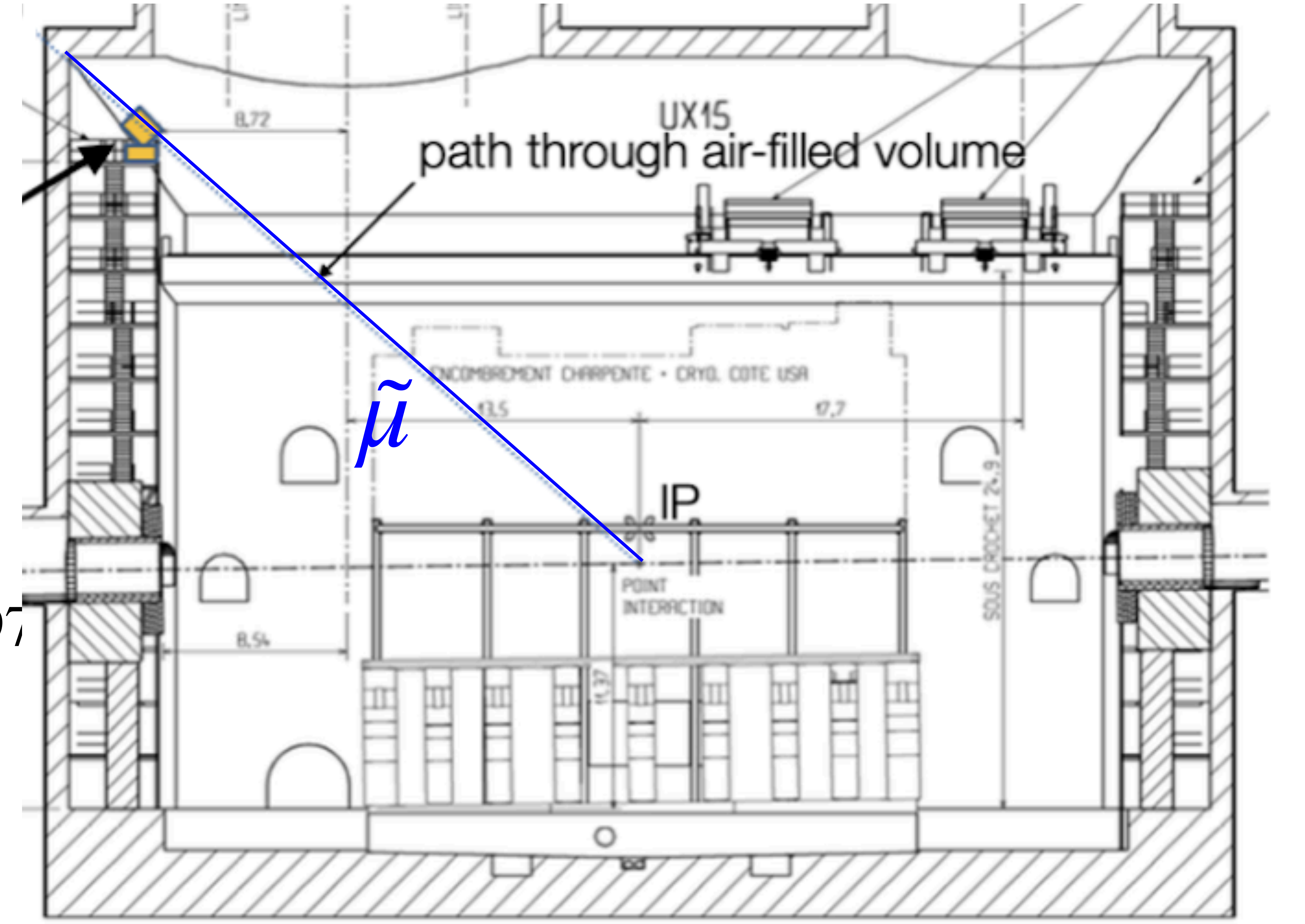


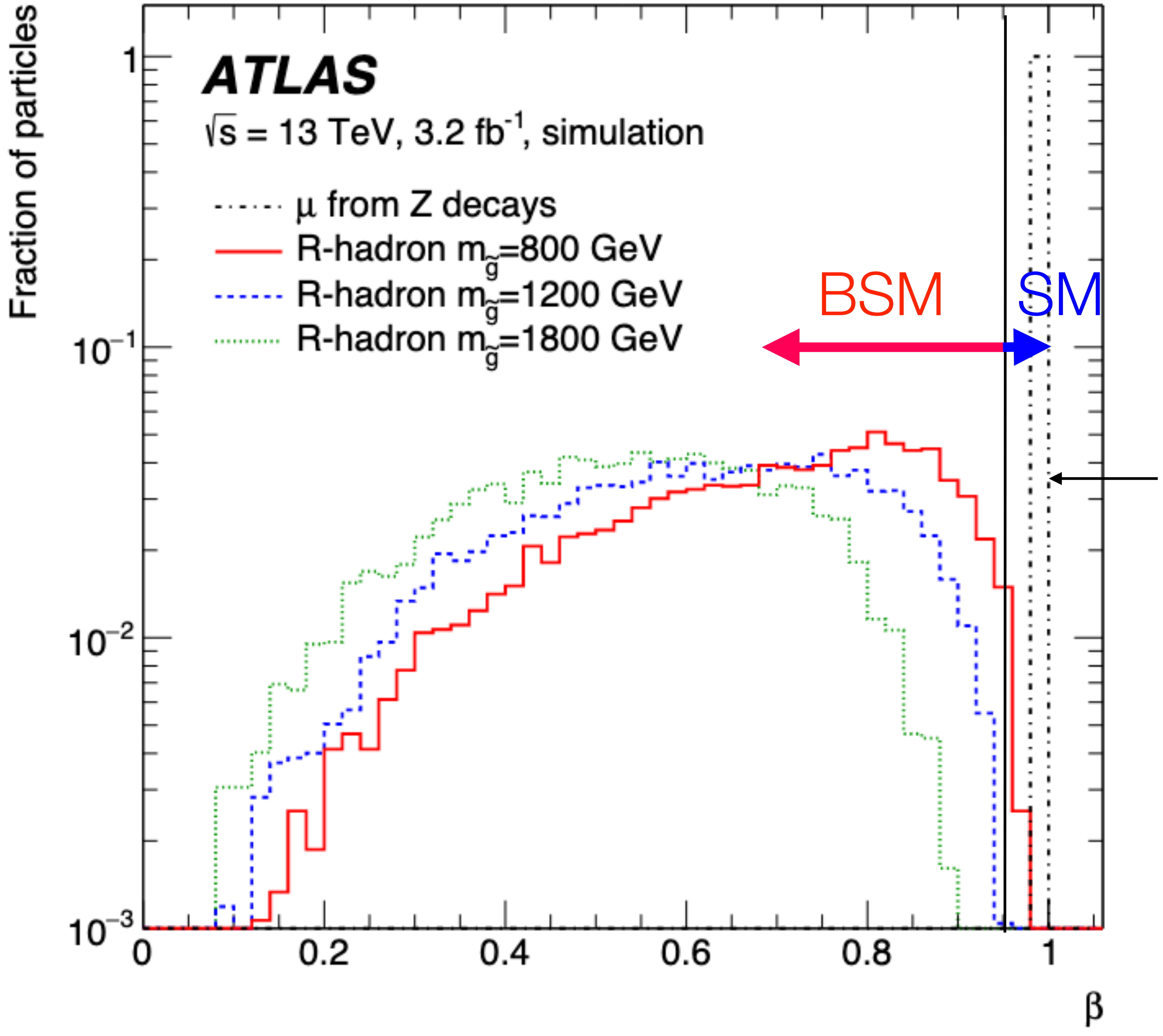


Credit: mechanics design by Chris

proANUBIS BSM

- Can we explore some uniquely accessible phase space?
- Example signature:
  - massive “muons” $\tilde{\mu}$: look like SM μ in the detector, but smaller β due to much larger mass (e.g. $m_{\tilde{\mu}} > 100$ GeV)
  - ATLAS: difficult to probe if $\beta \simeq 1$ (β resolution 2%)
  - proANUBIS has better chances:
    - larger distance from interaction point (ToF)
    - better timing precision (<300 ps)
      - $\rightarrow$ Resolution on velocity β of $\delta\beta \approx$ 0.3%!
        - $\Rightarrow$ measurable difference between $\beta = 1$ and $\beta = 0.997$
- **Models where precision in β can be leveraged???**





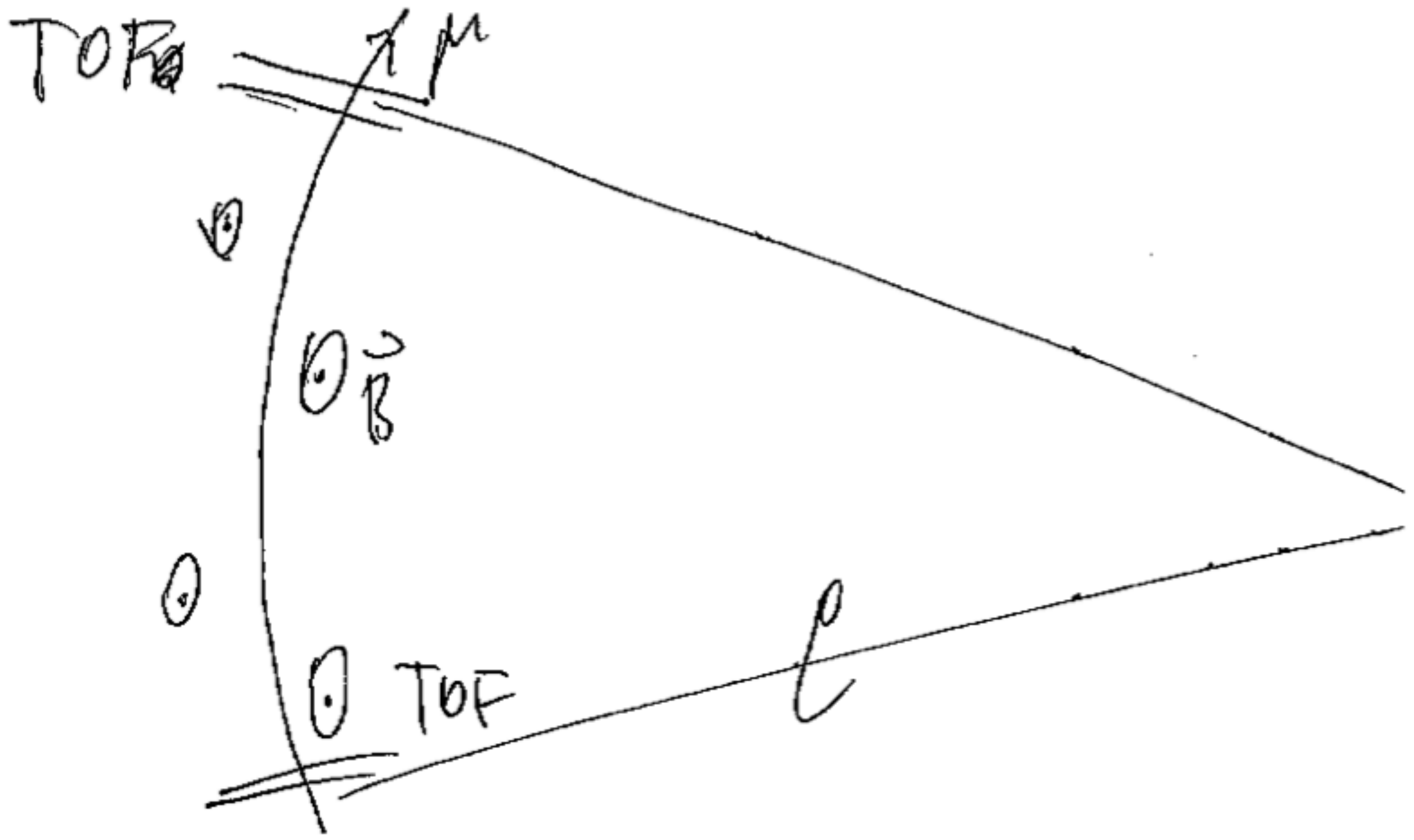
Note:
Plot is truth-level!
After reconstruction, this peak would be smeared with the detector resolution:

- $\delta_\beta \approx 0.02$ for ATLAS
- $\delta_\beta \approx 0.003$ for proANUBIS

proANUBIS BSM

- massive “muons” $\tilde{\mu}$: look like normal SM μ in the detector, but smaller β due to much larger mass (e.g. $m_{\tilde{\mu}} > 100$ GeV)

Testing for massive "muons" with ANUBIS



TOF: determine β
[and γ]

Get momentum $|\vec{p}| =: p$ from magnetic field $\vec{B}$:

$$\frac{1}{\ell} = q \frac{B}{p_T}$$

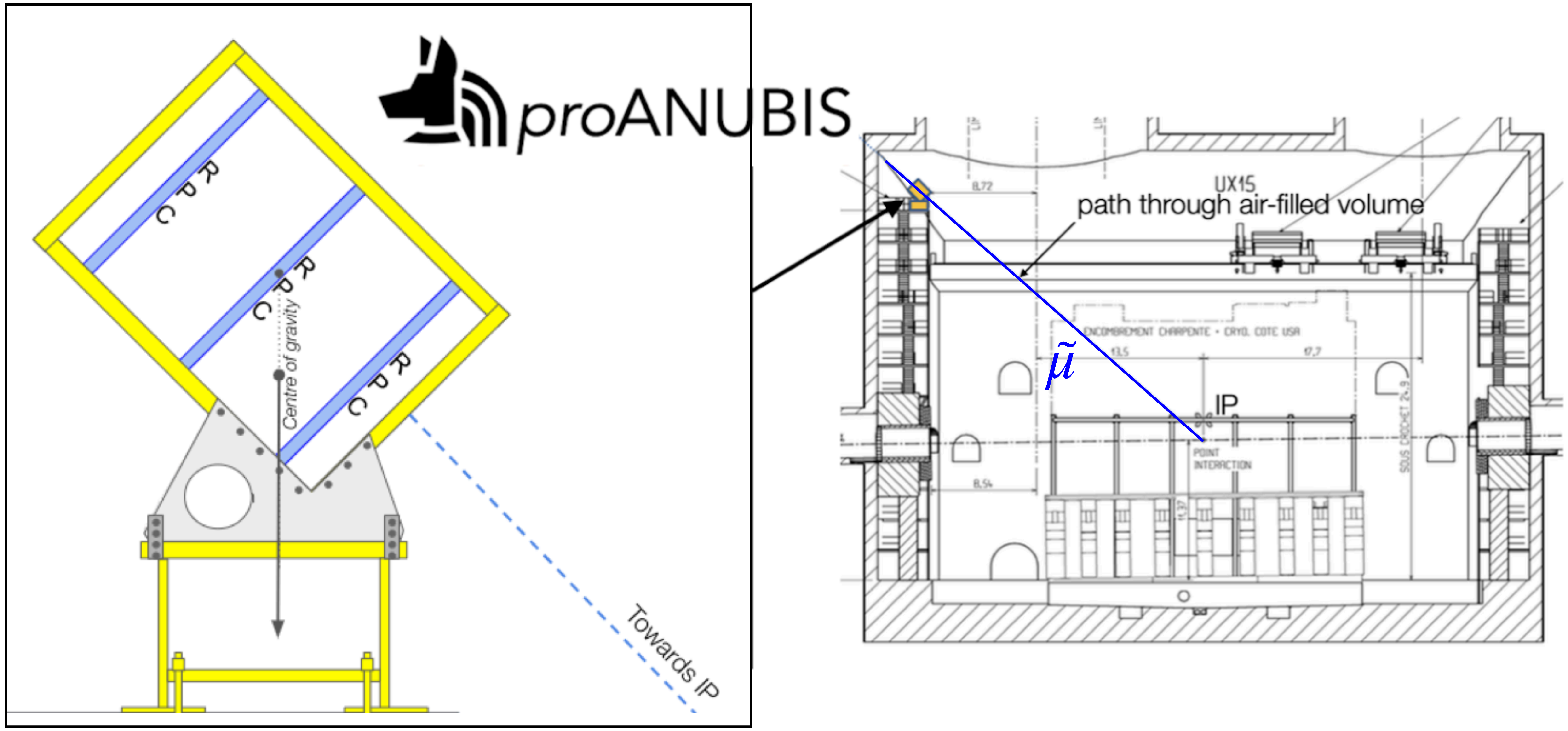
B ← known

ℓ ← measure

p_T — $\beta\gamma m$ ($\beta\gamma$ ↑ get from TOF)

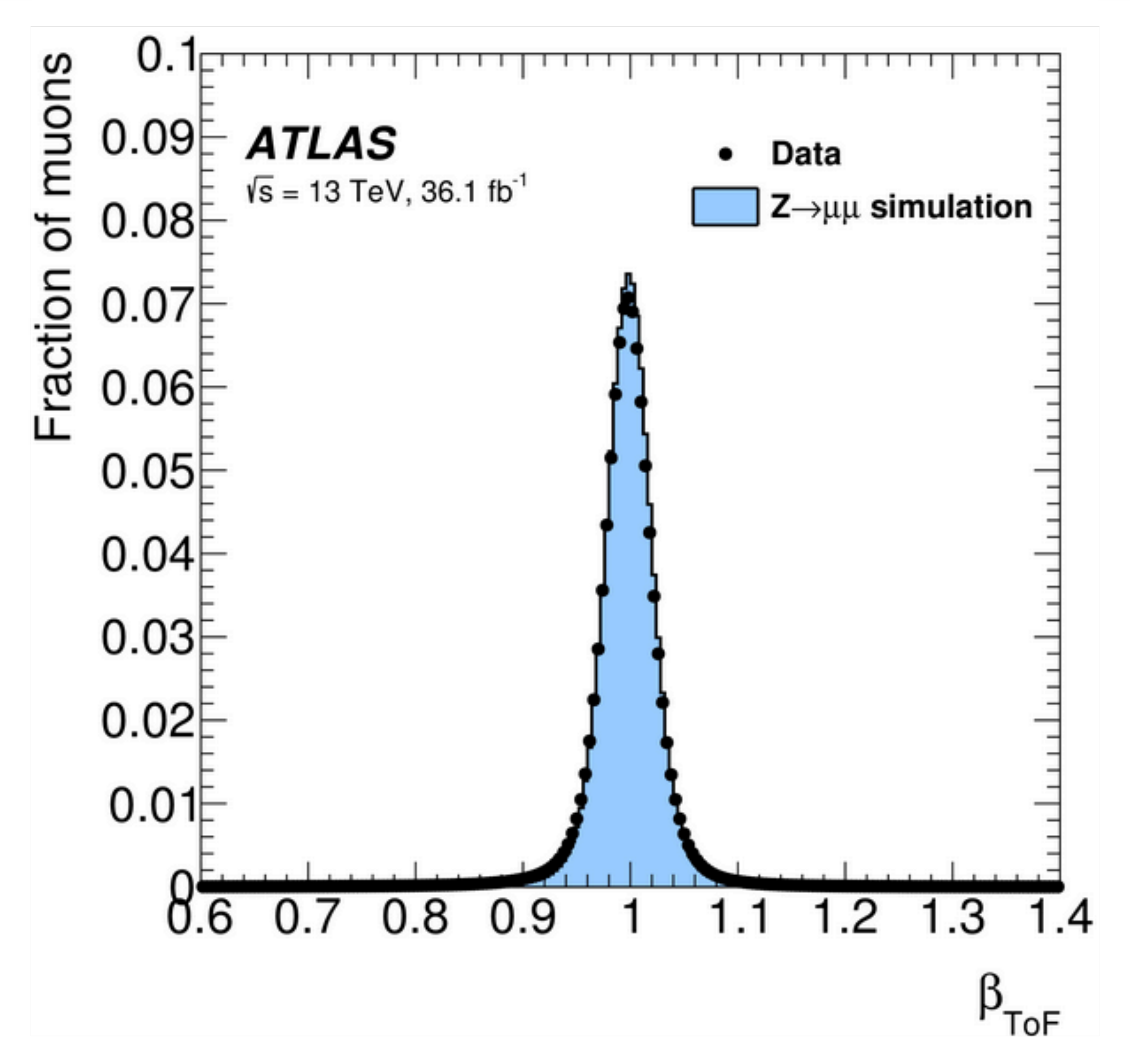
⇒ can determine $\frac{q}{m}$

or m when assuming $q = q_e$

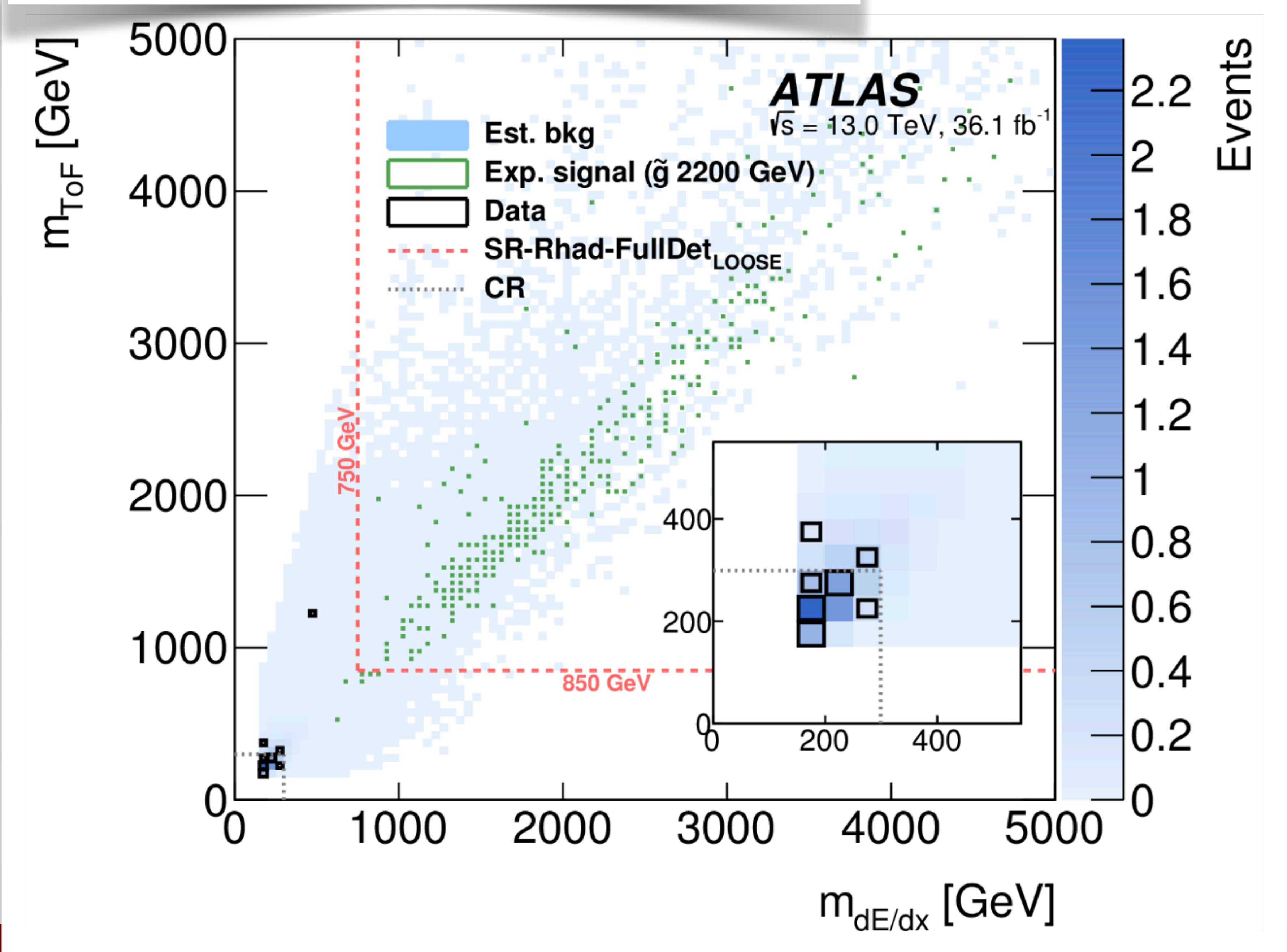


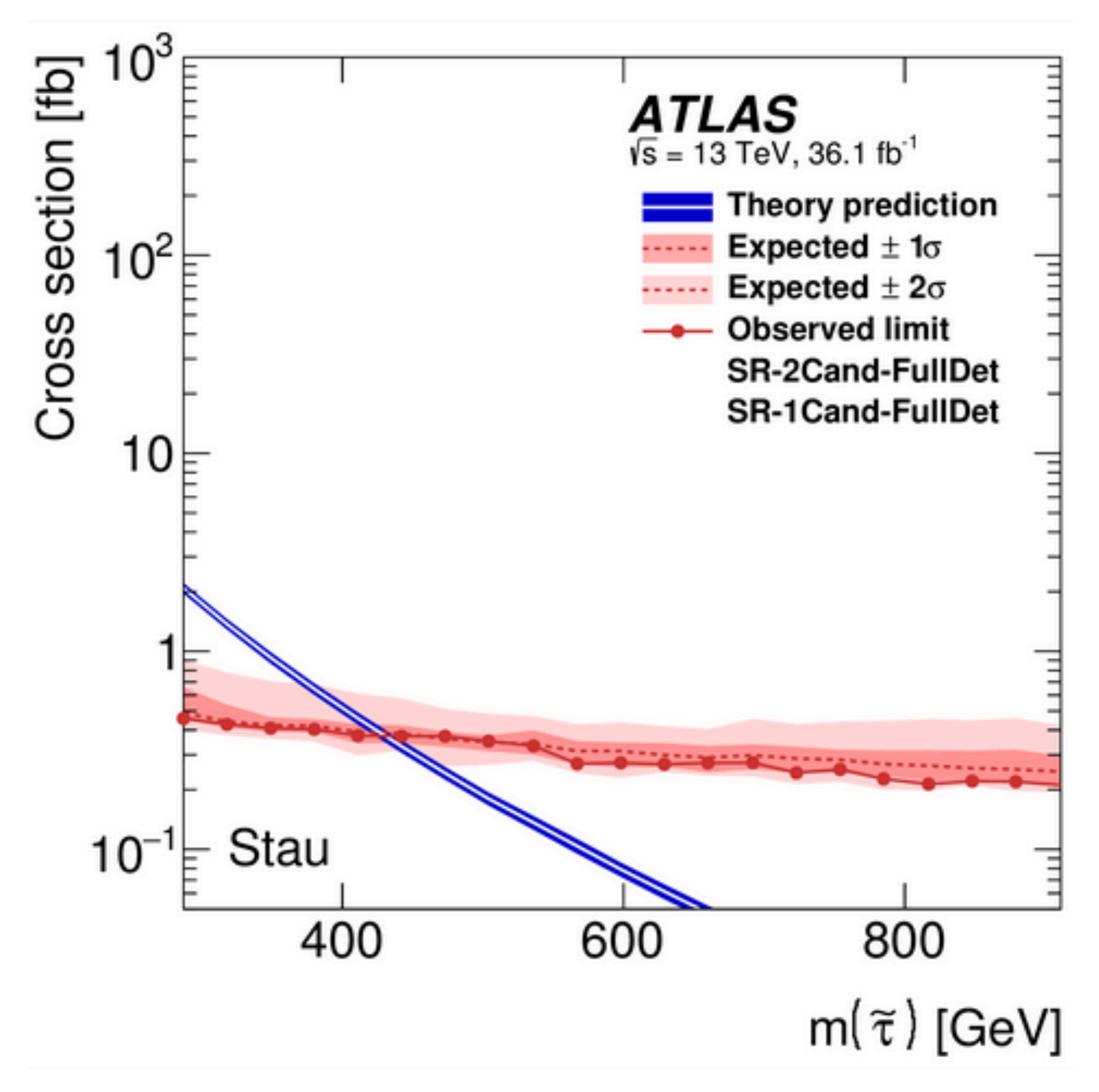
- Solid angle coverage: $2\ \mathrm{m}^2/25\ \mathrm{m}^2 \approx 0.08$
- Large integrated luminosity: $\approx 100\ \mathrm{fb}^{-1}$ in Run 3
- Superb velocity / ToF meas't: $\delta_\beta = 0.003$

Search for heavy charged long-lived particles in the ATLAS detector in 36.1 fb^{-1} of proton–proton collision data at $\sqrt{s}$ = 13 TeV



A search for heavy charged long-lived particles is performed using a data sample of 36.1 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV collected by the ATLAS experiment at the Large Hadron Collider. The search is based on observables related to ionization energy loss and time of flight, which are sensitive to the velocity of heavy charged particles traveling significantly slower than the speed of light. Multiple search strategies for a wide range of lifetimes, corresponding to path lengths of a few meters, are defined as model-independently as possible, by referencing several representative physics cases that yield long-lived particles within supersymmetric models, such as gluinos/squarks (*R*-hadrons), charginos and staus. No significant deviations from the expected Standard Model background are observed. Upper limits at 95% confidence level are provided on the production cross sections of long-lived *R*-hadrons as well as directly pair-produced staus and charginos. These results translate into lower limits on the masses of long-lived gluino, sbottom and stop *R*-hadrons, as well as staus and charginos of 2000 GeV, 1250 GeV, 1340 GeV, 430 GeV and 1090 GeV, respectively.

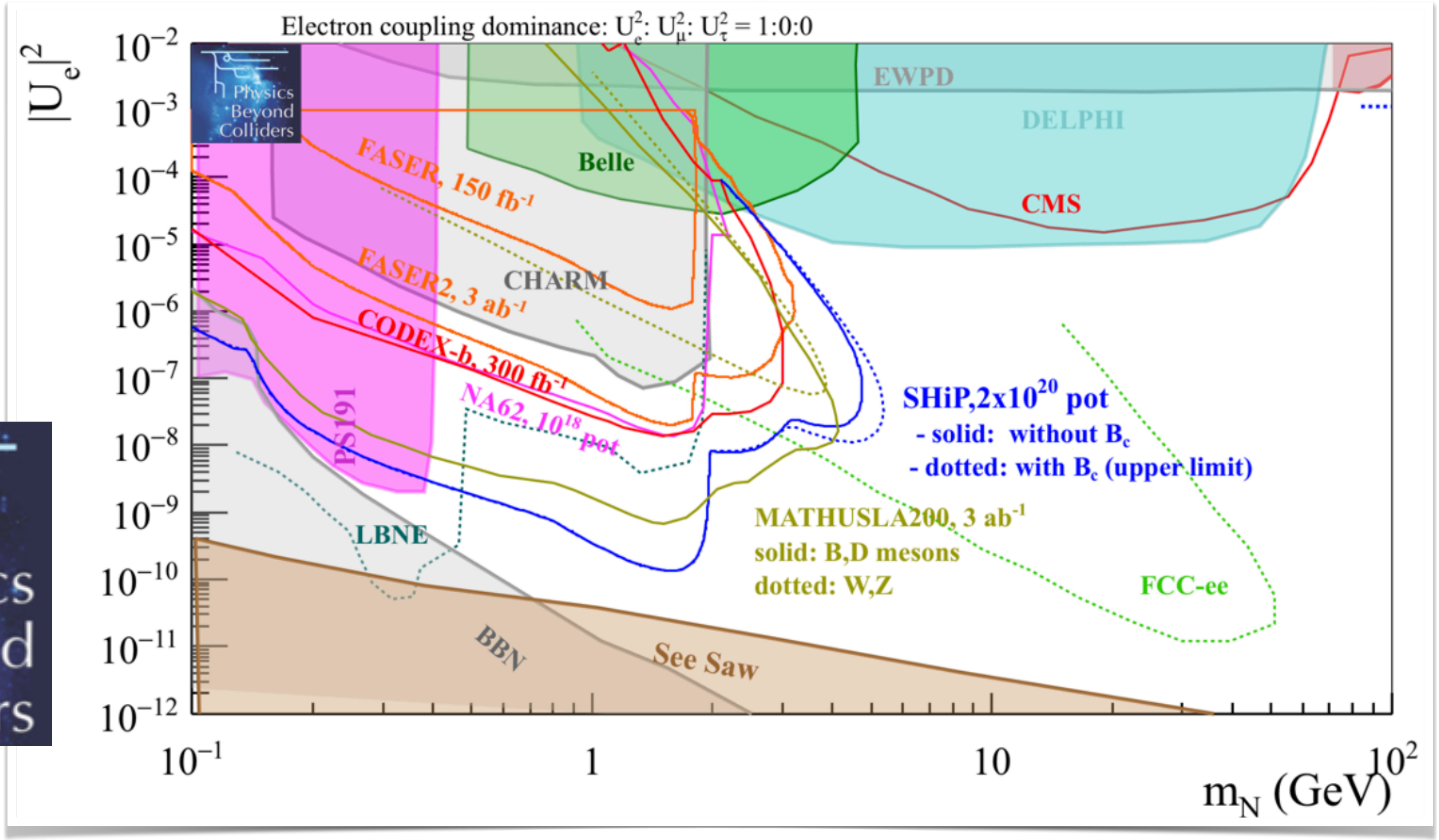




Overview of sensitivity to HNLs

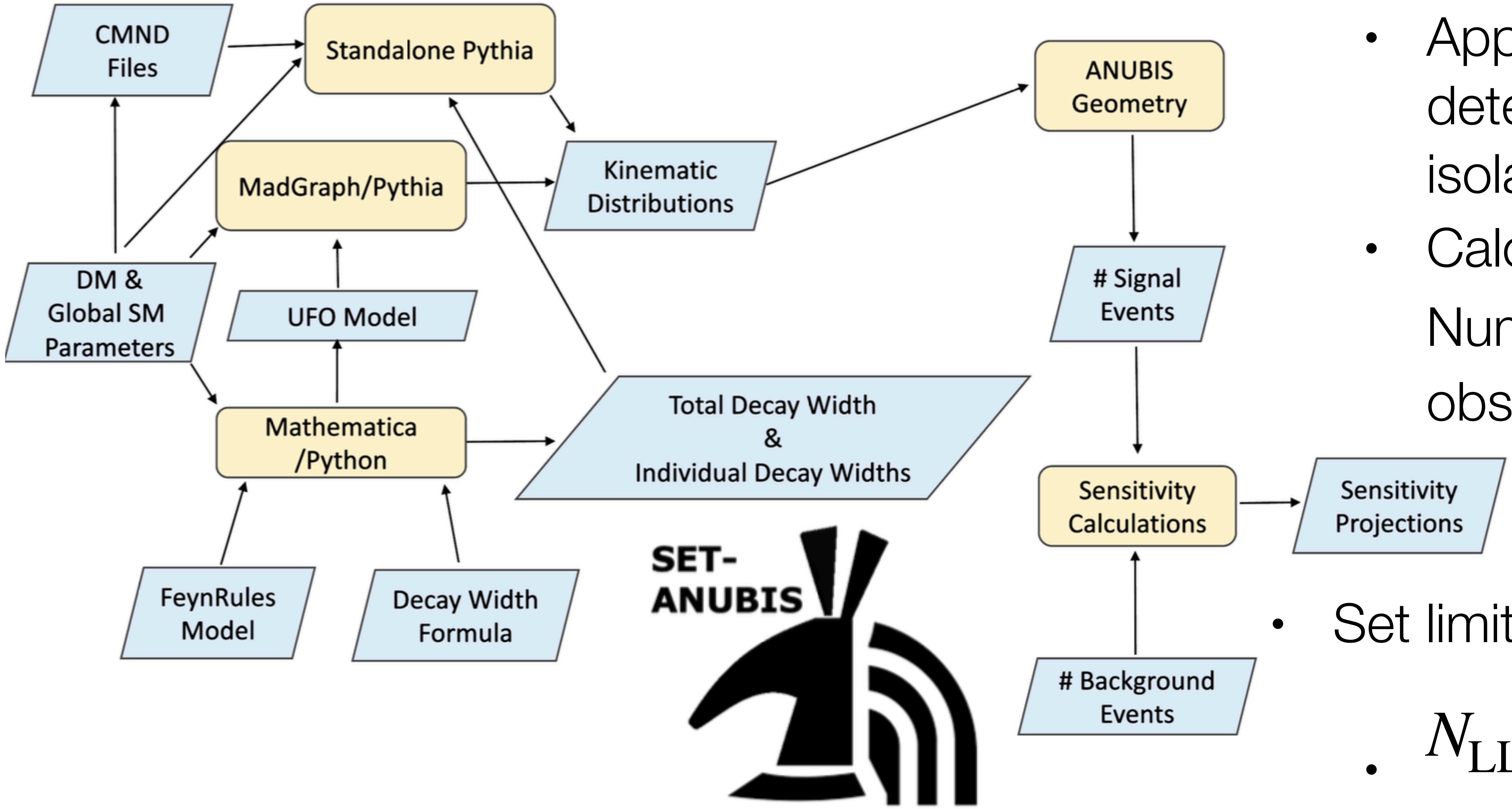
- Heavy Neutral Leptons (HNL) / RH neutrinos: natural feature in models relating to small ν mass
  - e.g. Type-I Seesaw [2,3].
  - → HNLs mix with SM neutrinos:
    $\nu_\alpha \to \sum_I U_{\alpha I} N_I$
  - small HNL-$\nu_{\rm SM}$ mixing → LLP
- HNLs excellent LLP benchmark target
  - Well-defined theoretical framework.
  - Strong physics motivation
- Physics Beyond Coliders (PBC):
  - HNLs feature in 3 / 11 benchmarks suggested by PBC in 2019
- "HNLs ... are one of the simplest extensions of the SM accounting for neutrino masses and mixings, baryogenesis and potentially also dark matter. BC6, BC7 and BC8 correspond to an HNL interacting exclusively with the e, μ and τ neutrinos, respectively."

$$\mathcal{L}_N^{\rm M} = \frac{\rm i}{2}\,\overline{N_I^{\rm R}}\,\partial\!\!\!/\,N_I^{\rm R} - y_{I\alpha}\,\overline{N_I^{\rm R}}\,\tilde{\phi}^\dagger L_\alpha - \frac{1}{2}\,\overline{N_I^{\rm R}}\,M_{IJ}\,(N_J^{\rm R})^{\rm C} + {\rm h.c.}$$



(SEE ANNA MULLIN'S LHCP 2024 TALK AND PAUL SWALLOW'S LLP2024 TALK)

SET-ANUBIS:
Generic sensitivity study framework



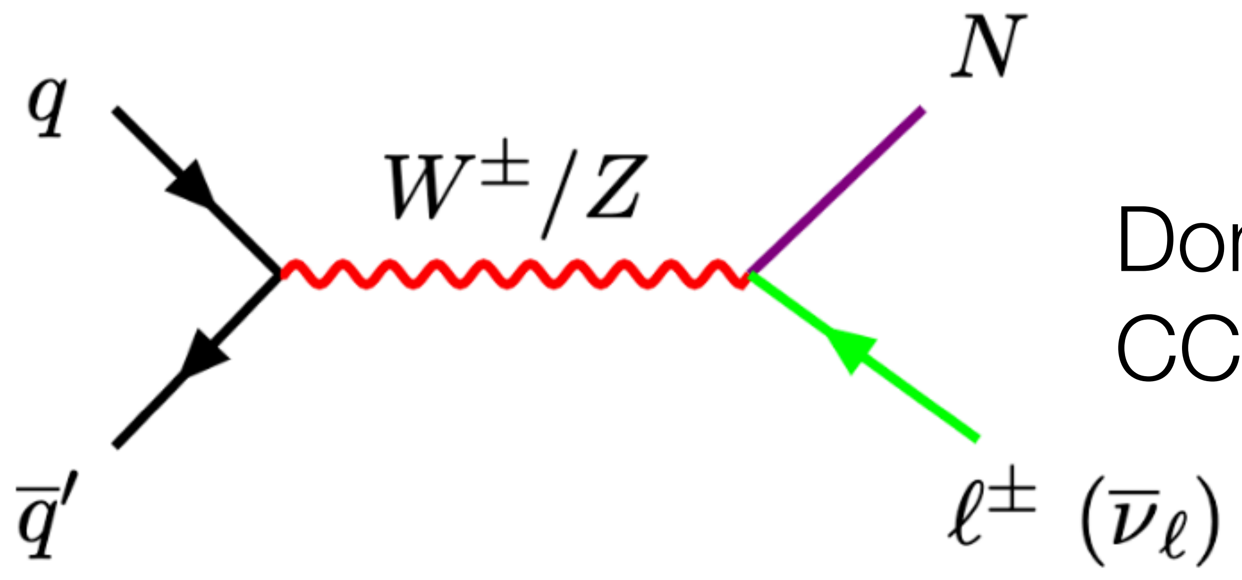
- Methodology:
  - Simulate LLP model (MadGraph, Pythia etc.):
  - Apply Selection: detector acceptance, background removal e.g. isolation requirements
  - Calculate sensitivity: Number of LLP candidates (N_{LLP}) required for observation
- Set limits from:
  - $$N_{\mathrm{LLP}} = \mathscr{L}_{\mathrm{HL-LHC}} \cdot \sigma_{\mathrm{HNL}} \cdot \mathscr{B}_{\mathrm{HNL}} \cdot \frac{N_{\mathrm{obs}}}{N_{\mathrm{gen}}}$$
  - Background-free: $N_{\mathrm{LLP}} \approx 4$ for observation
  - Data-driven background estimate [1,3]: $N_{\mathrm{LLP}} \approx 90$ for observation

- Targeted benchmark models:
  - HNLs (this talk), Dark Scalar [1], Dark Photon, …
  - Primary focus on PBC [2] and FIPs models

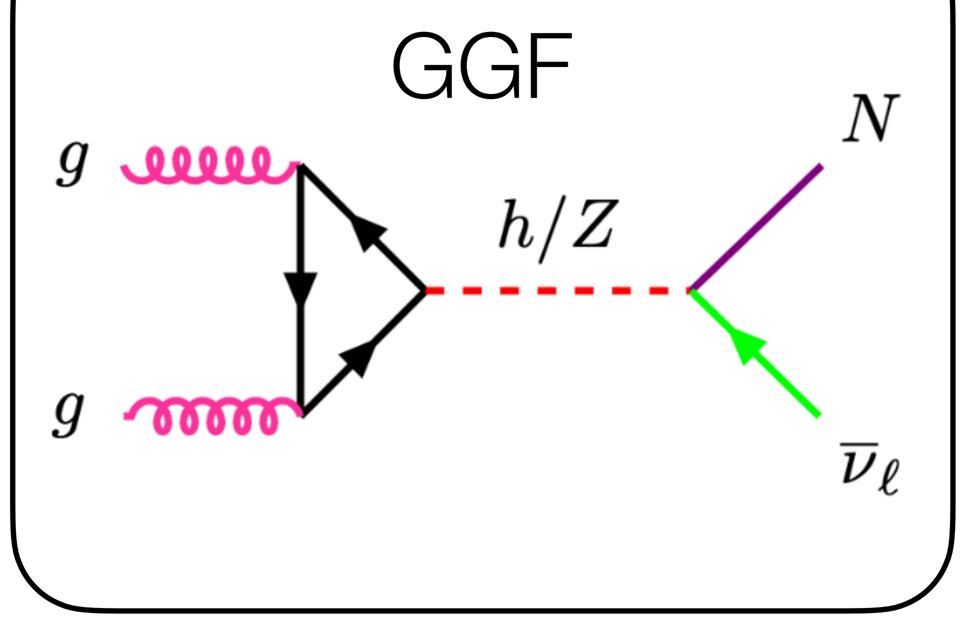
(SEE ANNA MULLIN'S LHCP 2024 TALK AND PAUL SWALLOW'S LLP2024 TALK)

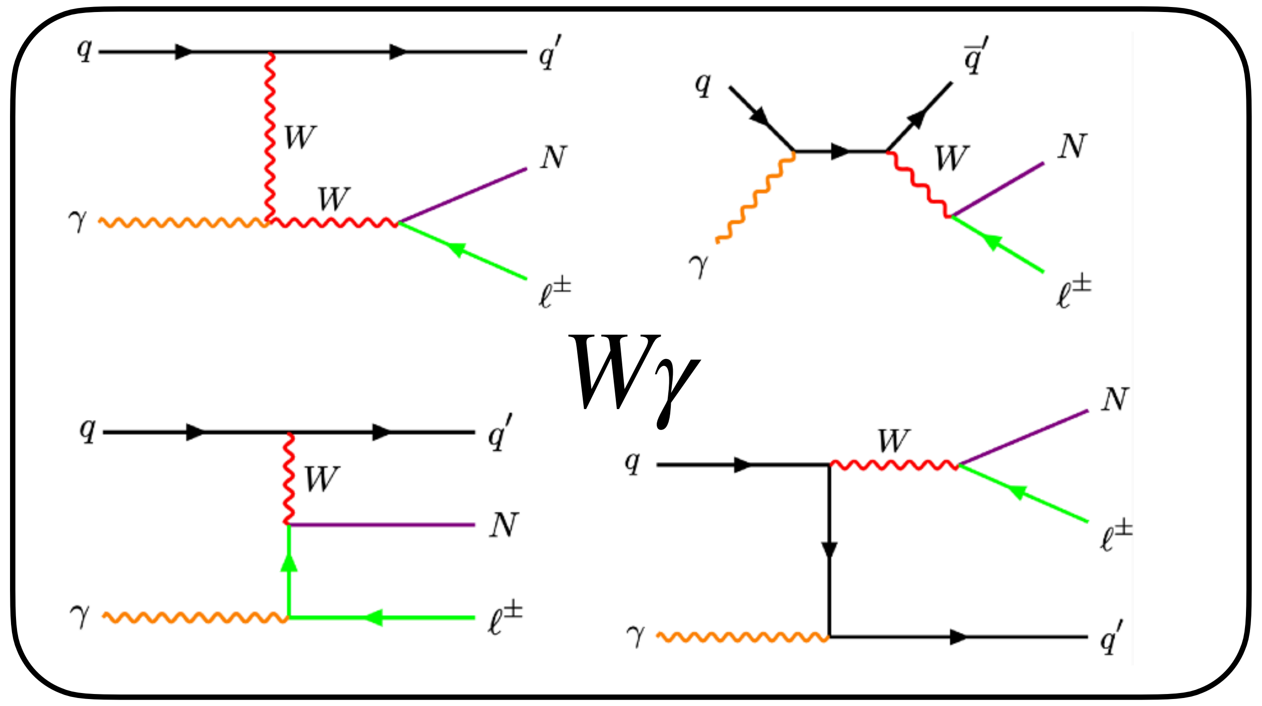
Production

- Focus on electroweak production (MG+Pythia)):



Dominant:
CC and NC Drell-Yan

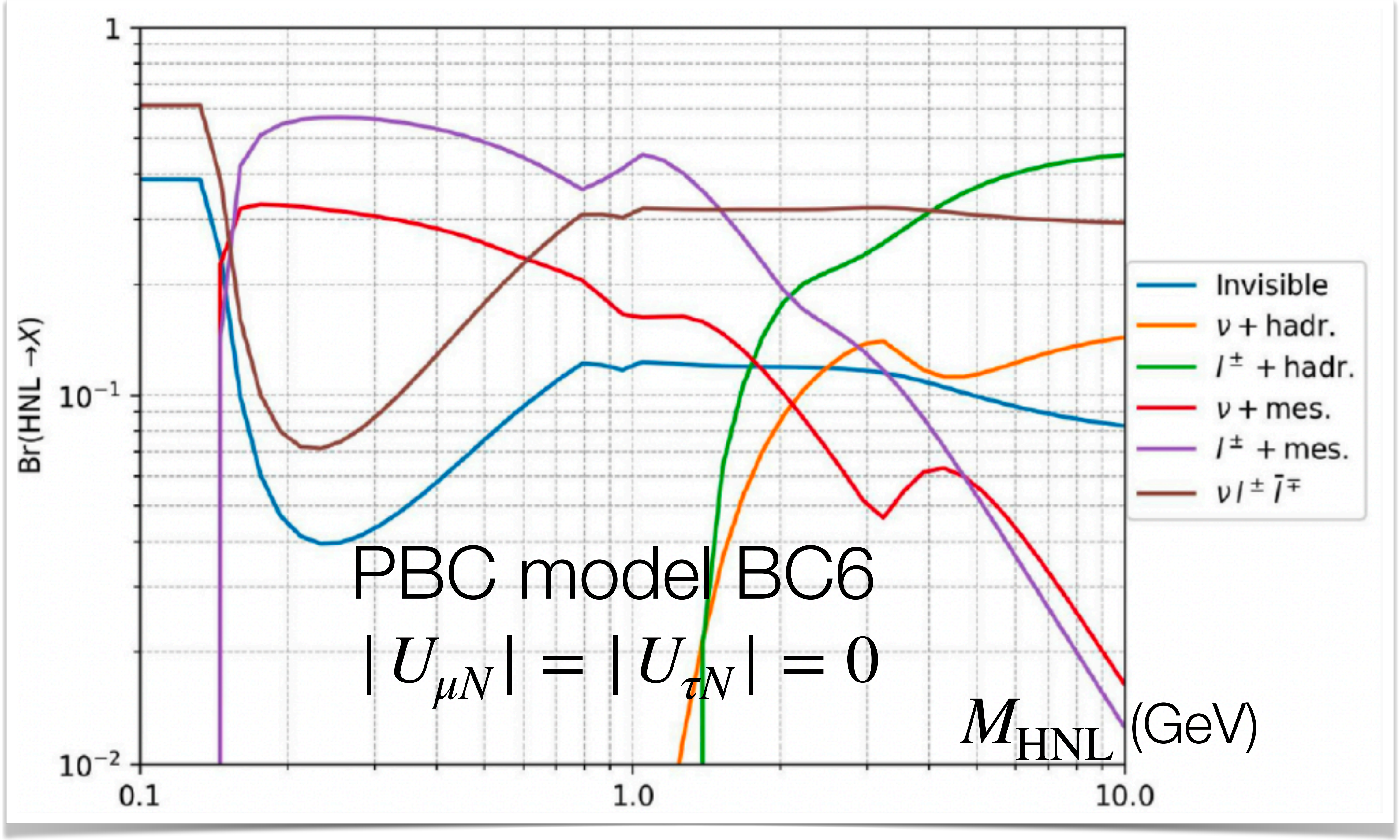




- Production from meson decays not as relevant
  - Meson production in/with jets → subject to isolation requirement (being studied w/ Pythia)
- Expect best sensitivity:
  - boosted, high mass HNL from $W^\pm/Z/H$

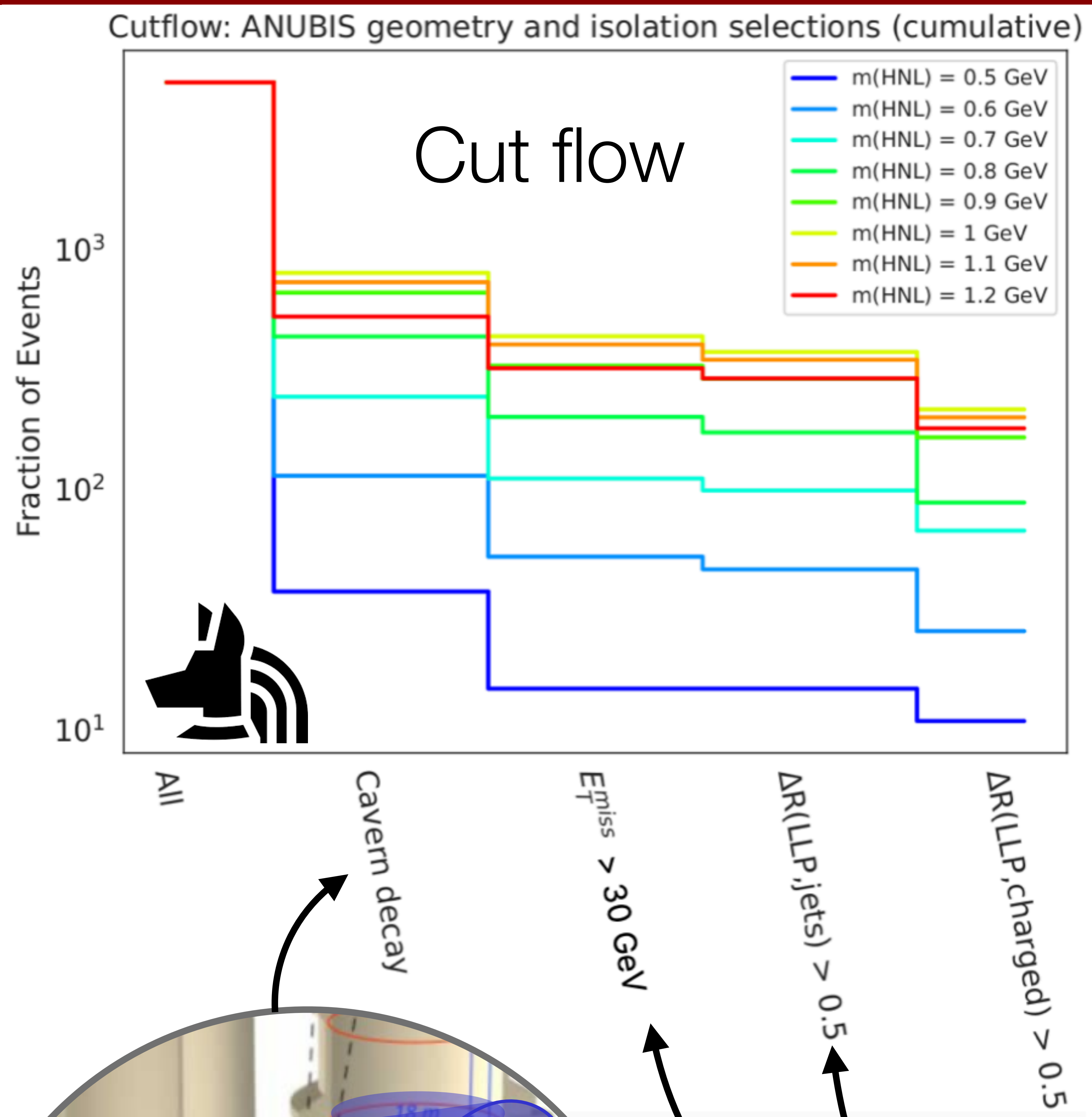
Decay

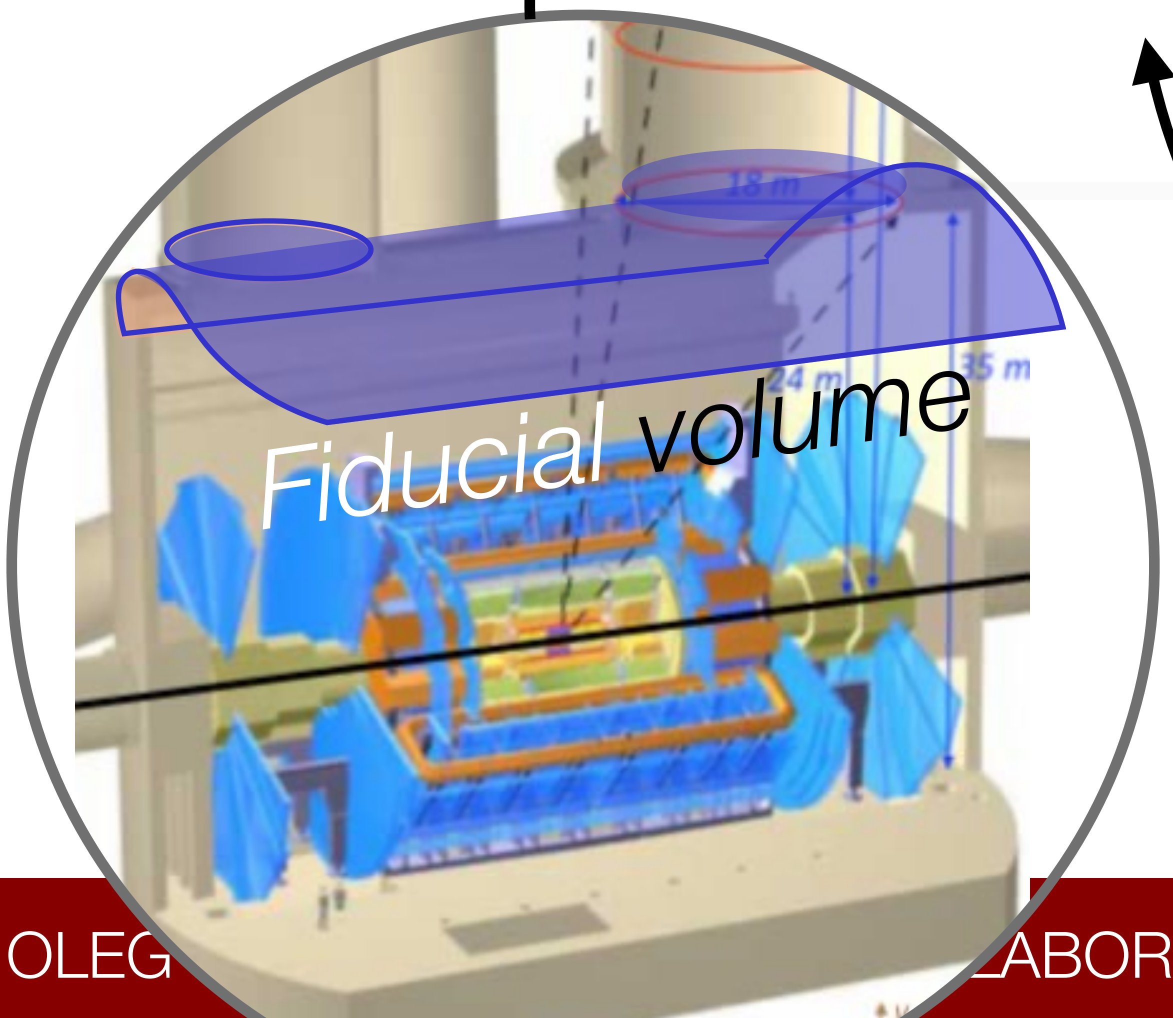
- Type-I SeeSaw [1,2] for simplicity
- This talk: PBC model BC6
  - only $|U_{eN}| \neq 0$
- Possible final states (visible to ANUBIS):
  - $N \to e^\pm q\bar{q}'; N \to \nu_e q\bar{q}'; N \to e^\pm e^\mp \nu_e \ldots$



Mathematica for Γ_N calculations [3]

[1]: PRD 25 (1982) 2951 [2] 1905.12634 [3] 0901.3589

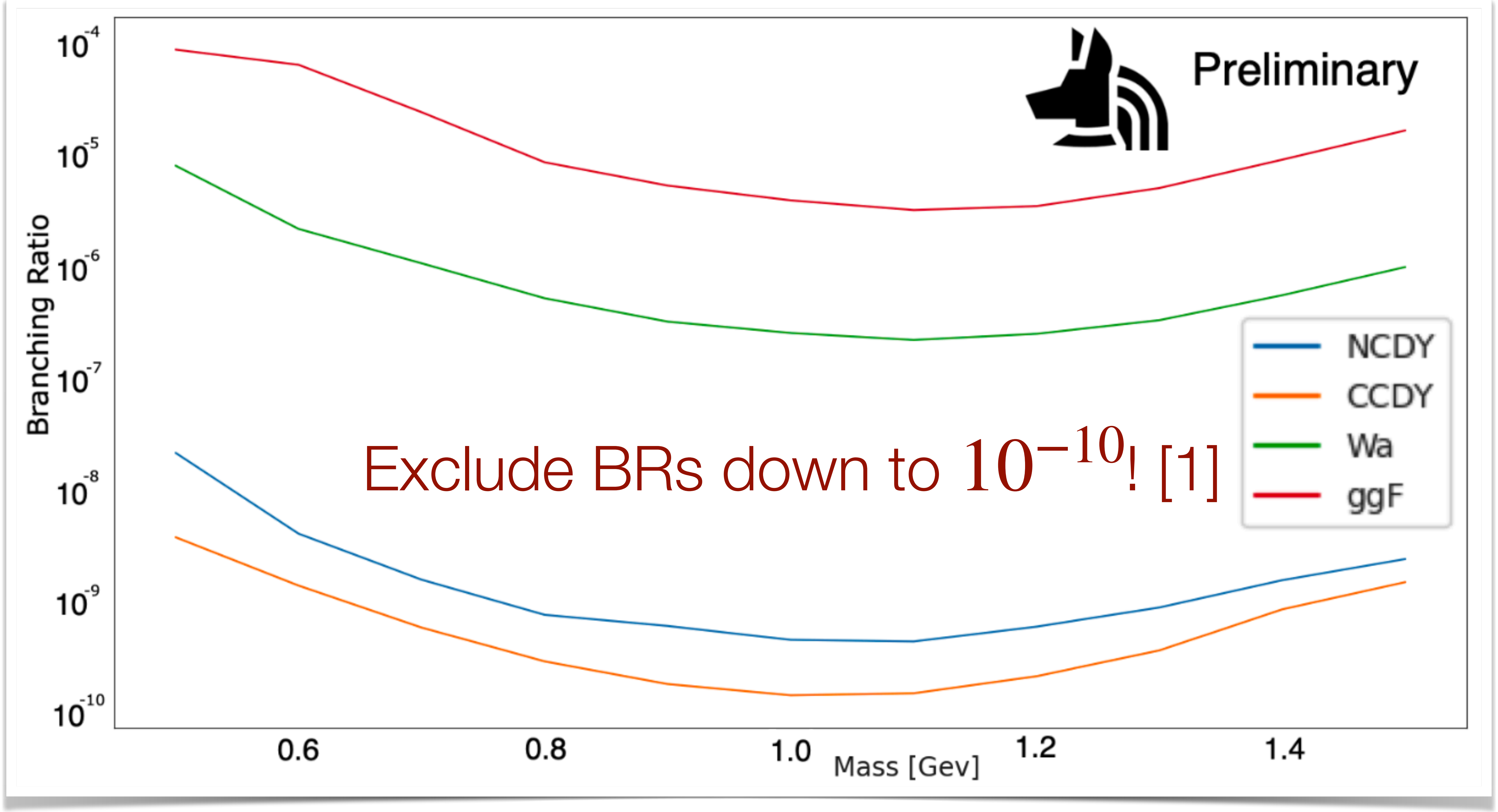




Active veto through ATLAS:

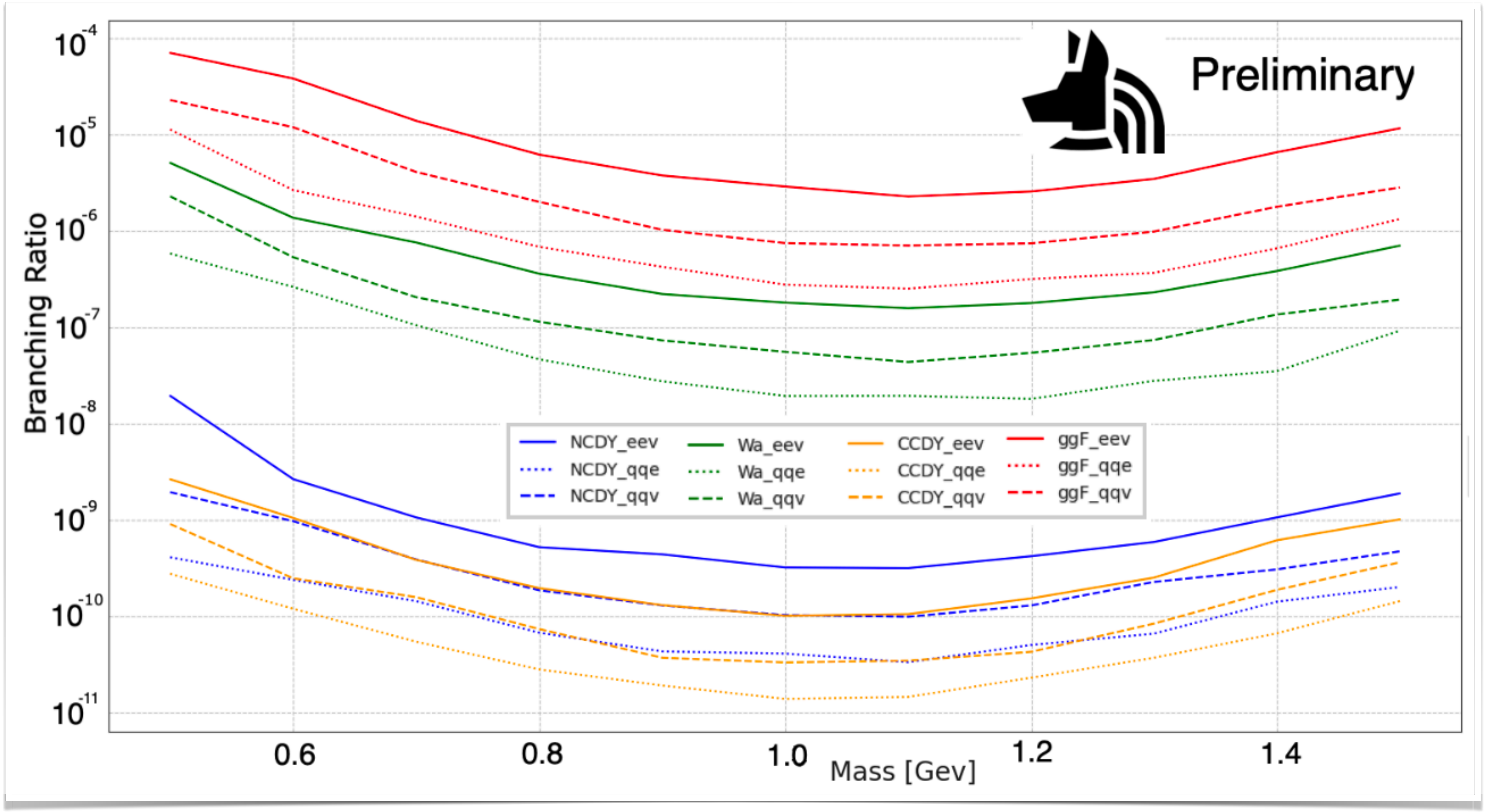
- K_L, n typically produced in/with jets
- isolated LLP candidates!

- Preliminary results:
  - 4 production modes x 3 final states
  - Good sensitivity to LLPs at light LLP masses!



- Next steps:
  - extend M_{HNL} to [0.1,10] GeV
  - Recast into (BR,$c\tau$) and ($|U_{eN}|^2, M_{\mathrm{HNL}}$)
  - 2nd and 3rd generation couplings (BC7+8)

[1] $|U_{eN}| = 1$, background free scenario

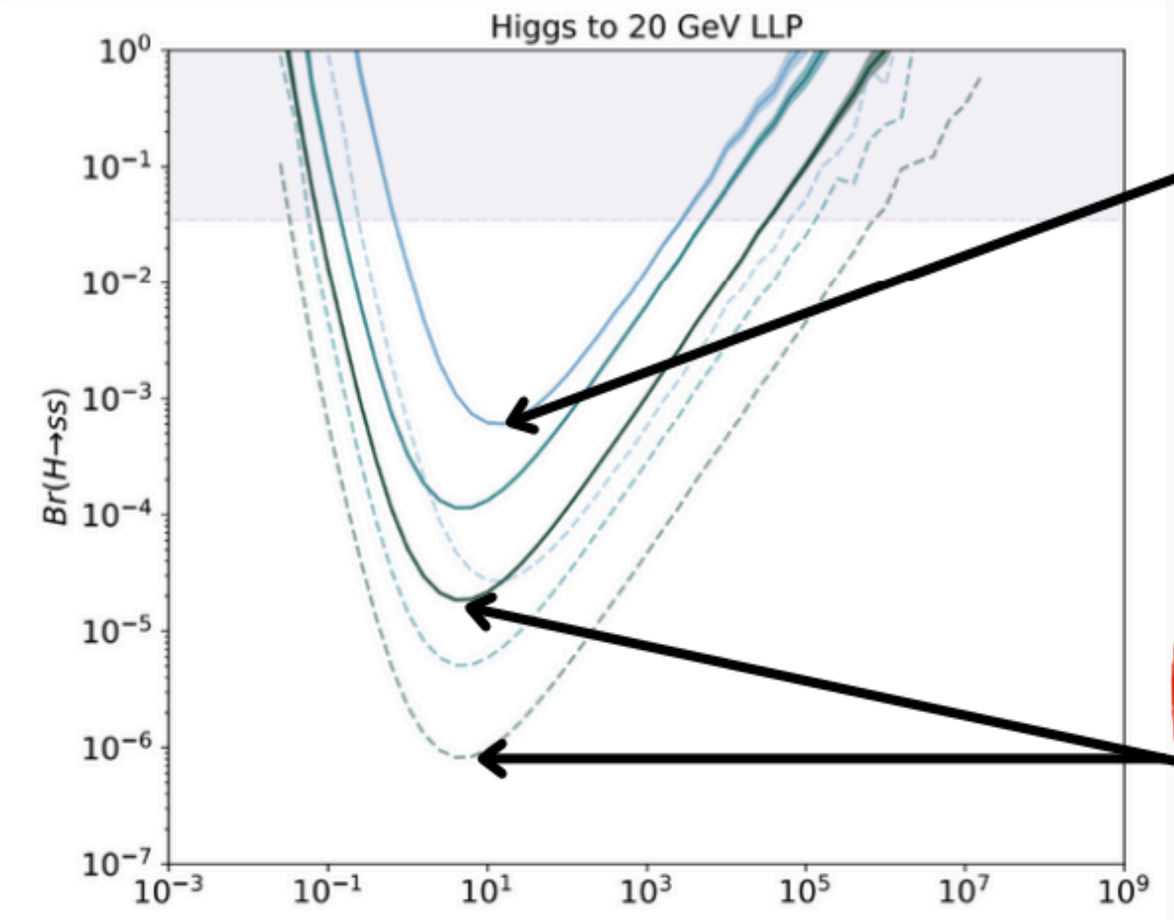


Preliminary
Branching Ratio
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
NCDY_eev
NCDY_qqe
NCDY_qqv
Wa_eev
Wa_qqe
Wa_qqv
CCDY_eev
CCDY_qqe
CCDY_qqv
ggF_eev
ggF_qqe
ggF_qqv
0.6
0.8
1.0
1.2
1.4
Mass [Gev]

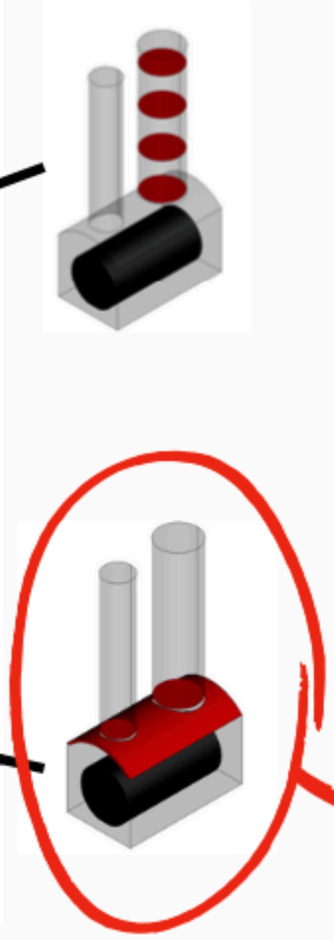
LHCP talk (Anna Mullin, LINK)

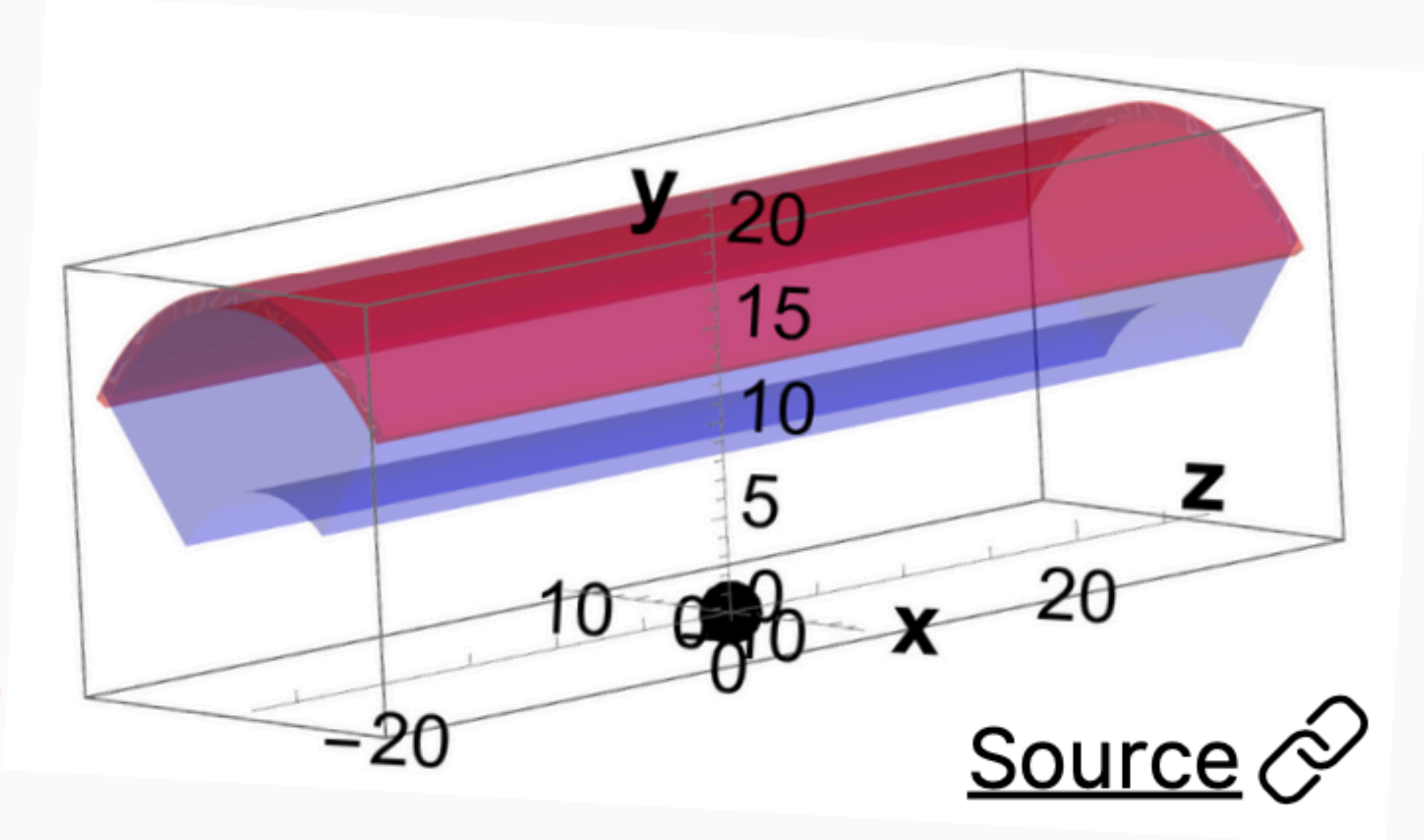
Detector design

Recent update to geometry:



sensitivity to scalar (SM + S)



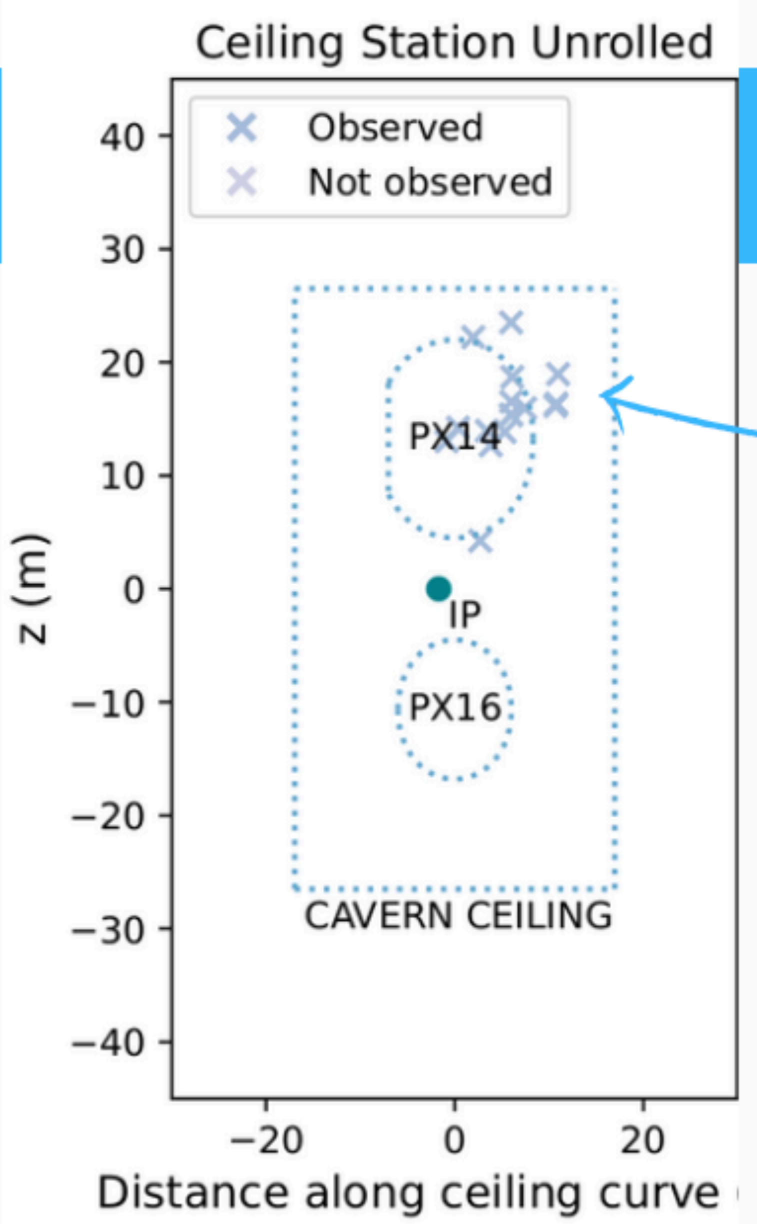


Background removal

- **Most backgrounds:** exploit an active veto from ATLAS detector
- **Cosmics:** rock shielding
- n^0 and K_L^0 : isolate our signal from nearby jets and charged tracks
  - Neutral long-lived kaon mean decay length is ~15.3 m

Data-driven background estimate from ATLAS muon spectrometer search

1. Background-free assumption (**4 events** -> discovery)
2. Conservative assumption (**90 events** -> discovery))



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Target modes

At LHC:

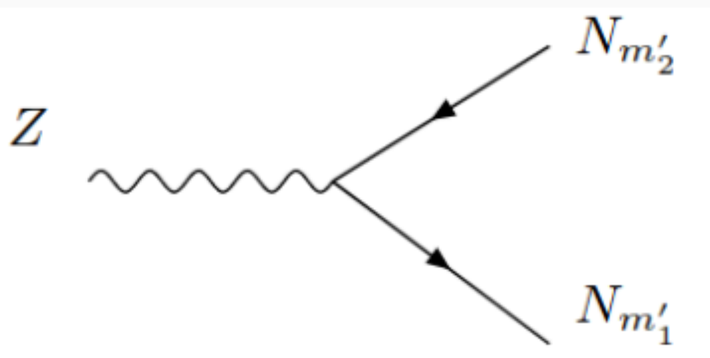
- Kinematically accessible production+decay ->final states
- Mesons produced dominantly (esp. abundant lighter mesons, e.g. Ds)

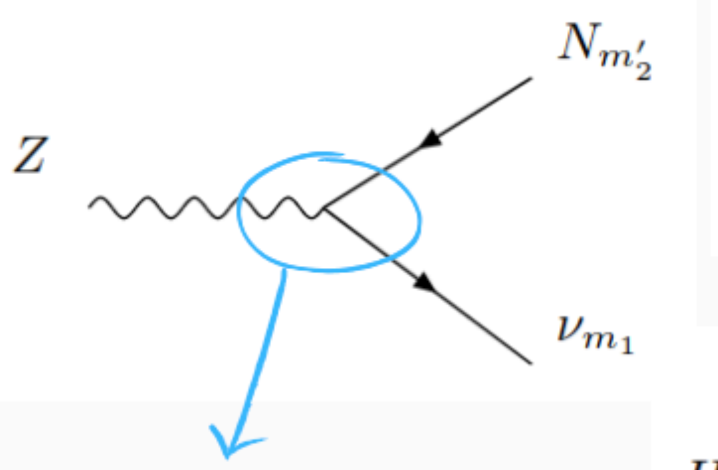
$$pp \to \ell^{\pm}_{\alpha} N \quad \to \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta} + nj$$

$$pp \to \ell^{\pm}_{\alpha} N \quad \to \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta}\ell^{\mp}_{\gamma}\nu$$

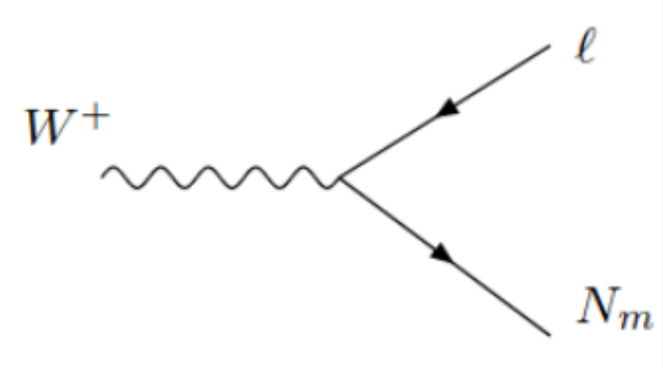
Production

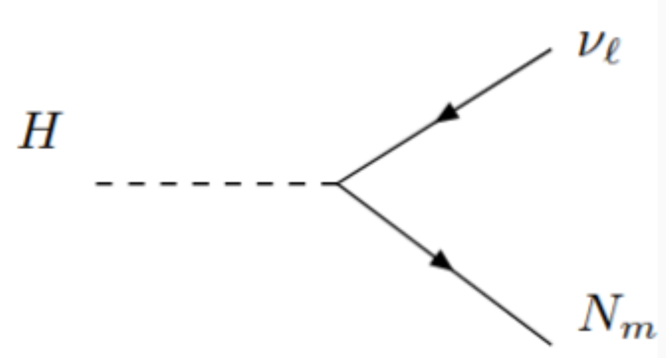
Boson decays





$$-i\frac{g}{2\cos_W}U^{\nu N}_{m_1 m'_2}\gamma^{\mu}P_L$$

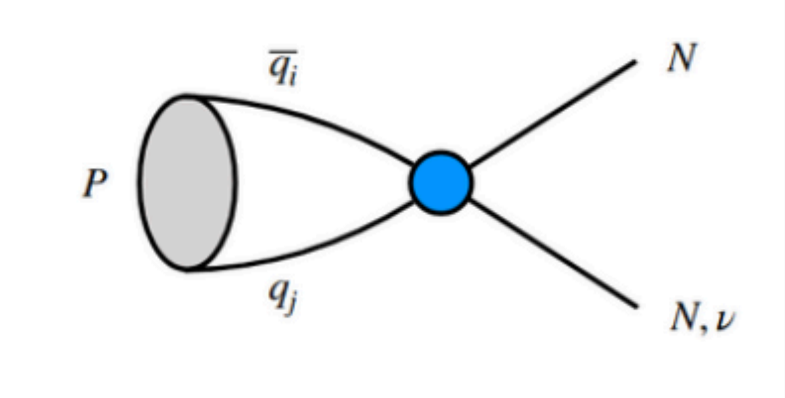


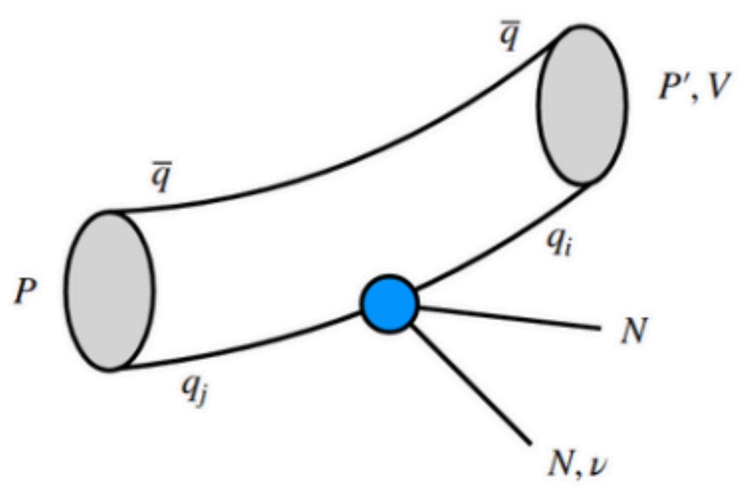


arXiv:0901.3589

2- and 3-body pseudoscalar meson decays

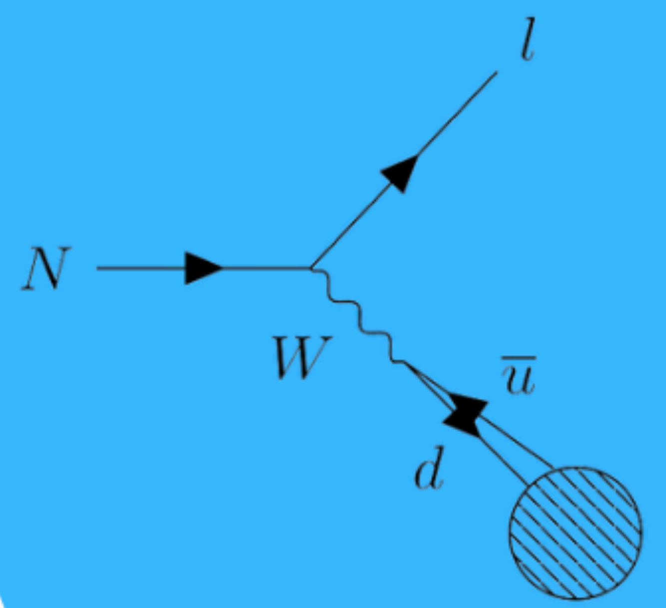
E.g. $B^0_s \to \nu N$





arXiv:2210.02461

Decay



Decay mode of heavy neutrino
$N_4 \to \nu_{\ell_1}\nu_{\ell_2}\overline{\nu_{\ell_2}}$
$N_4 \to \nu_\ell e^- e^+$
$N_4 \to e^-\mu^+\nu_m + c.c$ $N_4 \to \mu^- e^+\nu_e + c.c$
$N_4 \to \nu_\ell\pi^0$
$N_4 \to e^-\pi^+ + c.c$
$N_4 \to \nu_\ell\mu^-\mu^+$
$N_4 \to \mu^-\pi^+ + c.c$
$N_4 \to e^-K^+ + c.c$
$N_4 \to \nu_\ell\eta$
$N_4 \to \mu^-K^+ + c.c$
$N_4 \to \nu_\ell\rho^0$
$N_4 \to e^-\rho^+ + c.c$
$N_4 \to \nu_\ell\omega$
$N_4 \to \mu^-\rho^+ + c.c$
$N_4 \to e^-K^{*+} + c.c$
$N_4 \to \nu_\ell K^{*0}$
$N_4 \to \nu_\ell\overline{K}^{*0}$
$N_4 \to \nu_\ell\eta'$
$N_4 \to \mu^-K^{*+} + c.c$
$N_4 \to \nu_\ell\phi$
$N_4 \to e^-\tau^+\nu_\tau + c.c$ $N_4 \to \tau^- e^+\nu_e + c.c$
$N_4 \to e^-D^+ + c.c$

PAGE 6

Complementary mass + lifetime ranges

If the HNLs are too light then forward detectors benefit from a high flux of mesons in forward region

1. Boost from W / Z modes >> boost from B / D meson modes

HNLs produced by mesons (B+D) vs bosons (W,Z,h) are complementary in ANUBIS

Overall: expect best sensitivity for W/Z production modes with boosted, ~heavier mass HNLs

2. Effect of isolating from backgrounds containing jets is stronger for mesons

B / D mesons are typically part of jets, produced in association with collimated hadronic radiation e.g. pions.

Drell-Yann modes have less hadronic radiation reaching ANUBIS as their jets are produced in any angular direction

PAGE 7

Sensitivity

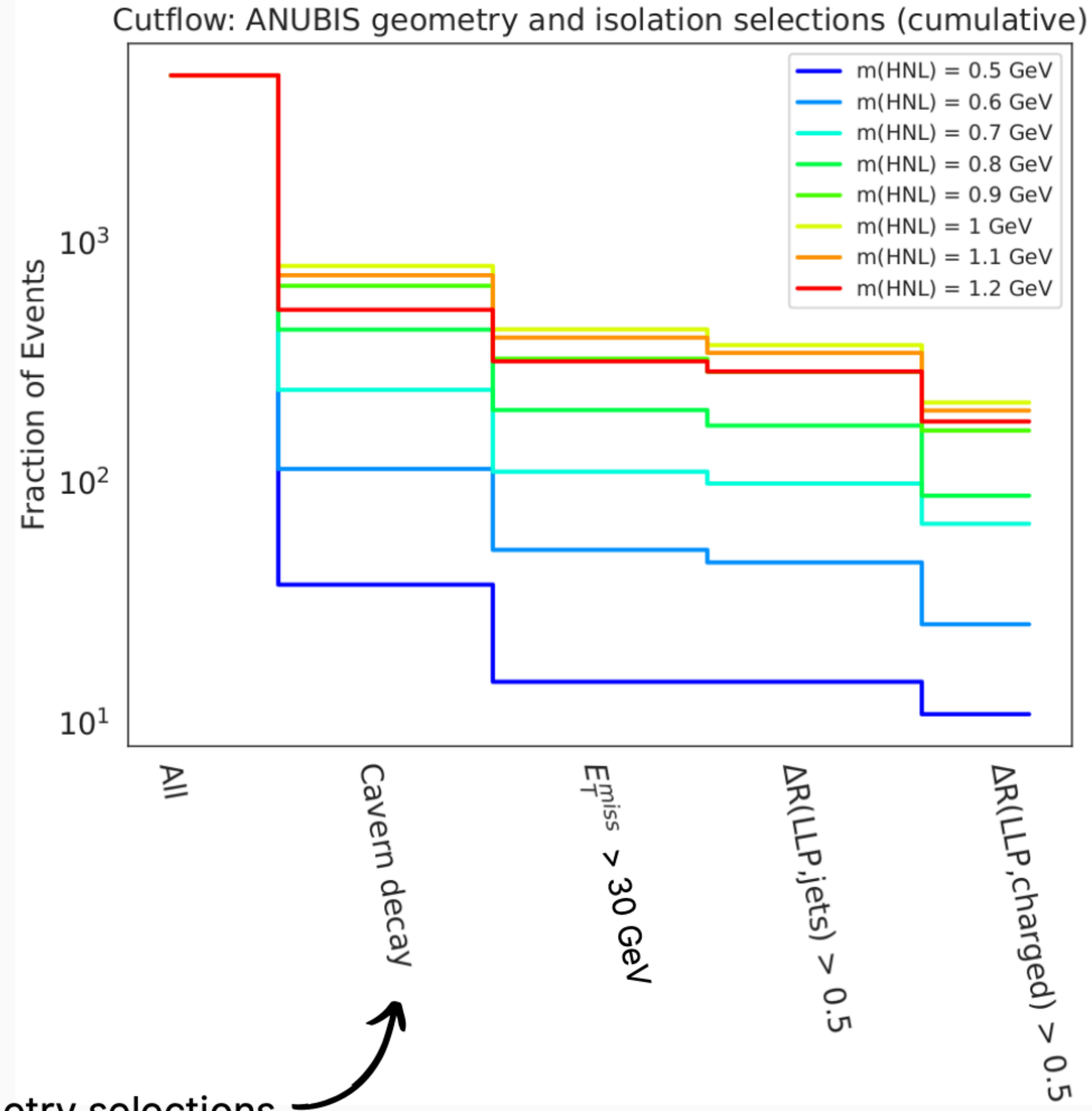
Branching ratio vs mass

- First look at sensitivity:
  - 4 production modes + 3 final states
    - (N -> e(+/-) q q', v q q', e+ e- v)
  - HNL mass range 0.5 - 1.5 GeV

- **Work in progress!**

Example of calculating Nobs

$$N_{\text{LLP}} = \mathcal{L}_{\text{HL-LHC}} \cdot \sigma_{\text{HNL}} \cdot \text{Br}(\ \text{HNL}\ ) \cdot \frac{N_{\text{obs}}}{N_{\text{tot}}}$$



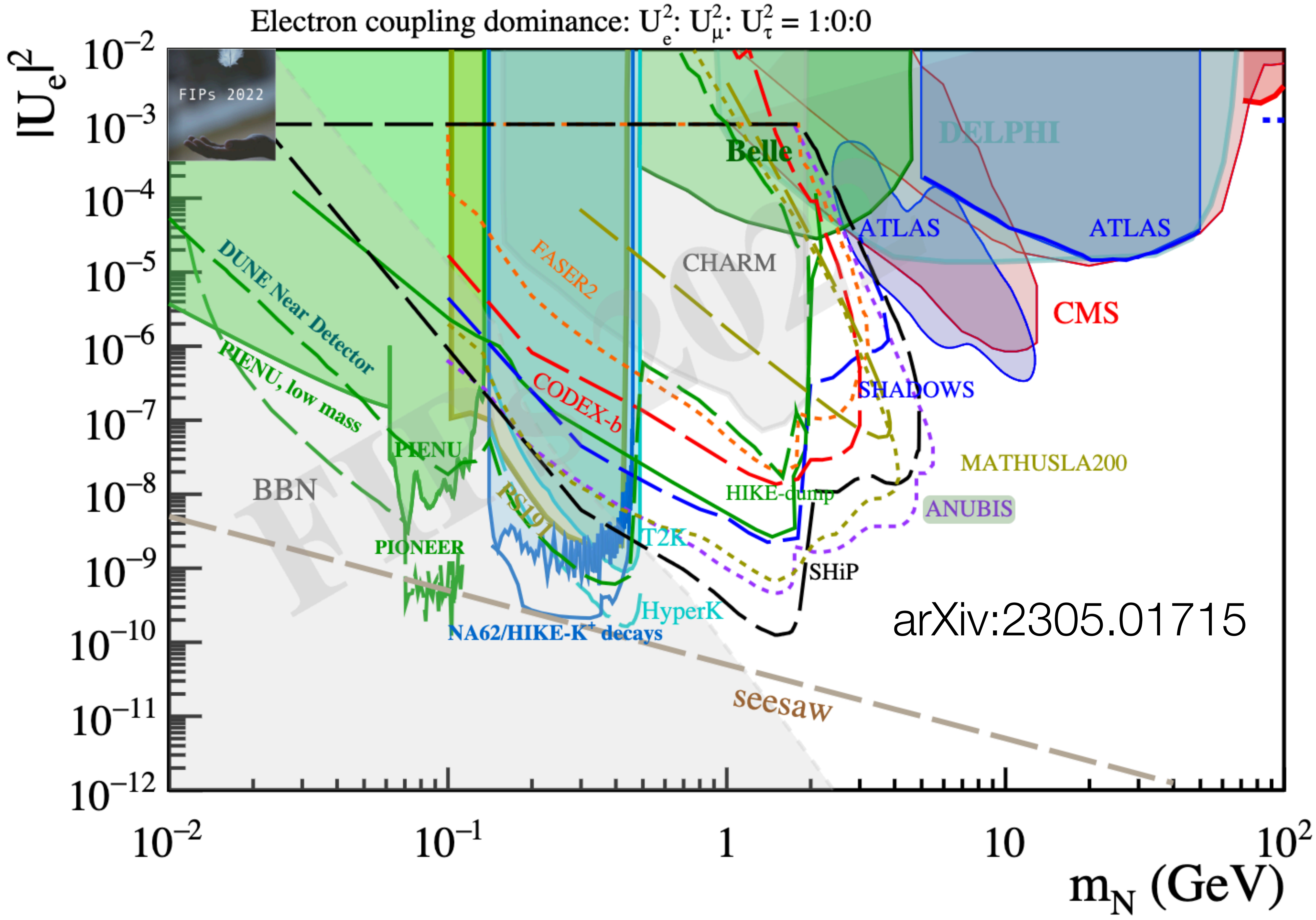
Nobs for the ~higher masses

ANUBIS geometry selections

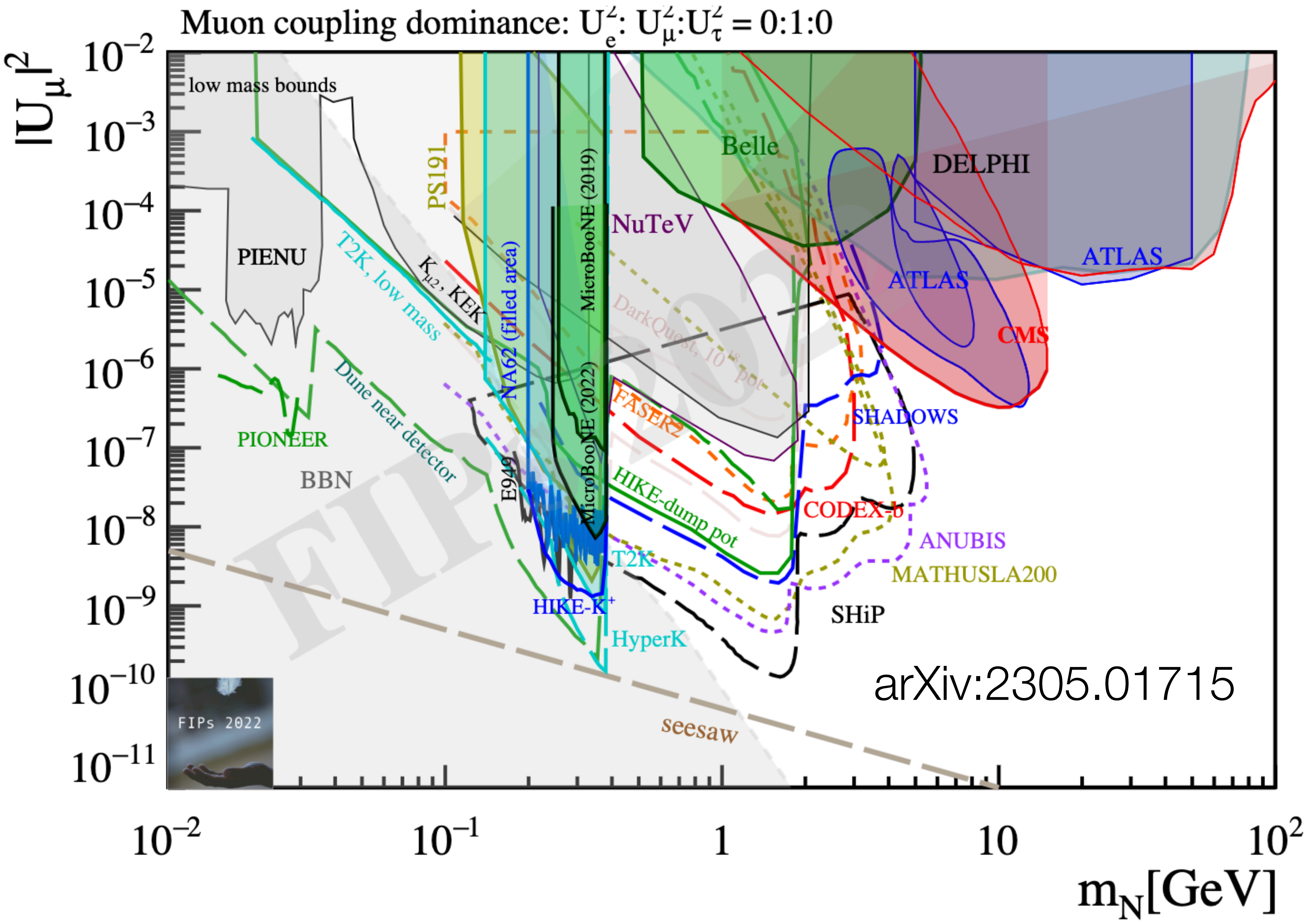
Background removal, e.g. isolating from hadronic radiation

PAGE 12

Sensitivity studies by other groups



Electron coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 1:0:0$
$|U_e|^2$
FIPs 2022
DELPHI
Belle
ATLAS
ATLAS
CHARM
FASER2
CMS
DUNE Near Detector
PIENU, low mass
CODEX-b
SHADOWS
MATHUSLA200
PIENU
HIKE-dump
ANUBIS
BBN
PS191
T2K
SHiP
PIONEER
HyperK
NA62/HIKE-K$^+$ decays
seesaw
arXiv:2305.01715
m_N (GeV)


Muon coupling dominance: $U_e^2:U_\mu^2:U_\tau^2 = 0:1:0$
$|U_\mu|^2$
m_N[GeV]
low mass bounds
PIENU
T2K, low mass
$K_{\mu 2}$, KEK
PS191
NA62 (filled area)
MicroBooNE (2019)
MicroBooNE (2022)
NuTeV
Belle
DELPHI
ATLAS
ATLAS
CMS
DarkQuest
FASER2
SHADOWS
HIKE-dump pot
CODEX-b
ANUBIS
MATHUSLA200
SHiP
T2K
HIKE-K+
HyperK
E949
PIONEER
BBN
Dune near detector
seesaw
FIPs 2022
arXiv:2305.01715

ANUBIS: sensitivity

Hirsch, Wang 2001.04750

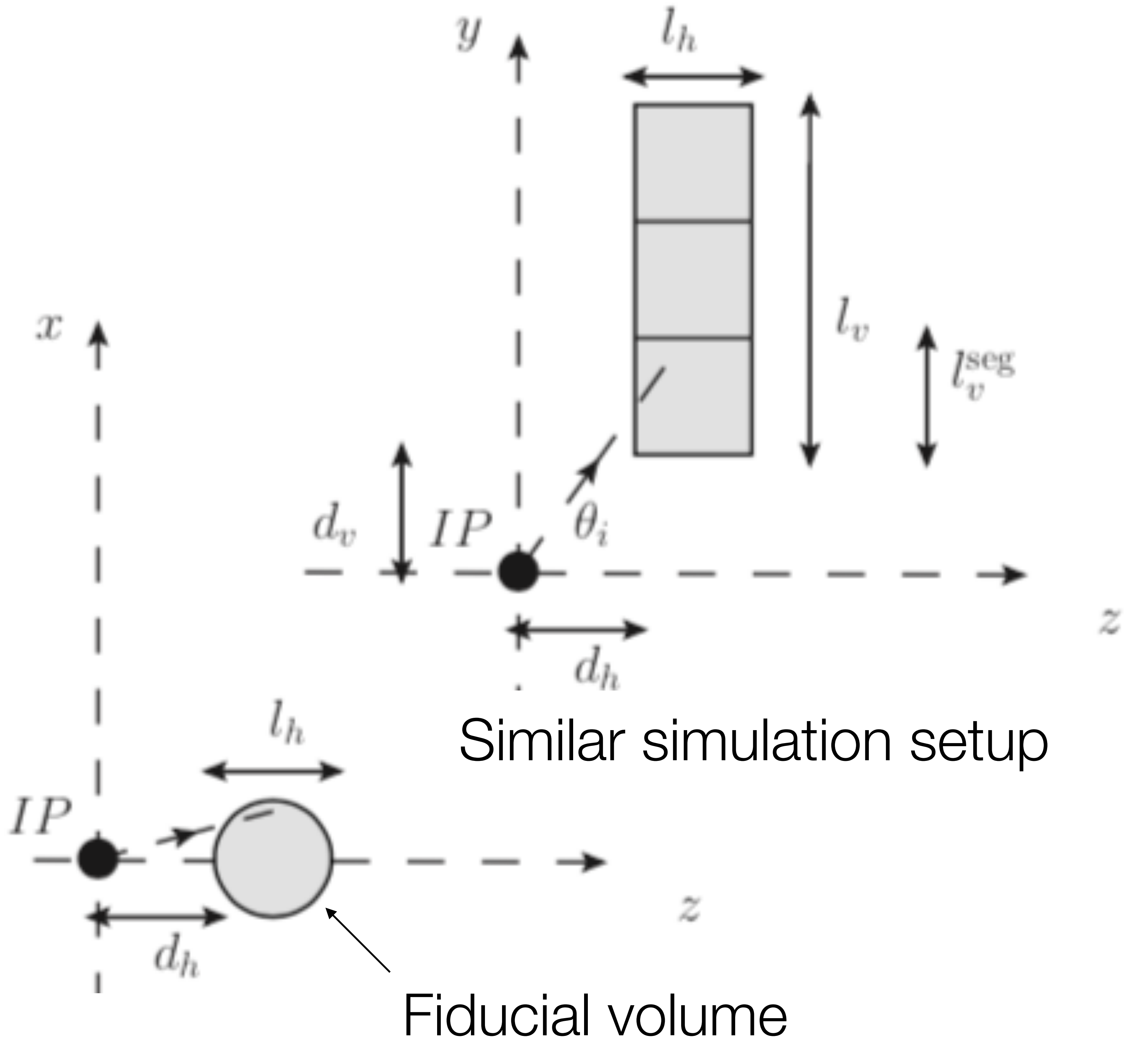
Sensitivity study for Heavy Neutral Leptons ("sterile neutrinos")
a) minimal scenario, Seesaw Type-I:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \underline{V_{\alpha N_j}} \, \bar{\ell}_\alpha \gamma^\mu P_L \underline{N_j} W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} \underline{V^L_{\alpha i}} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$

mixing with active ν — heavy neutrinos — mixing in active ν sector

Similar simulation setup:

- Require the LLP to decay within fiducial volume
- 3 ab^{-1} at 14 TeV
- Optimistic scenario considered
- Assume one additional heavy lepton, light enough for LHC



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Hirsch, Wang 2001.04750

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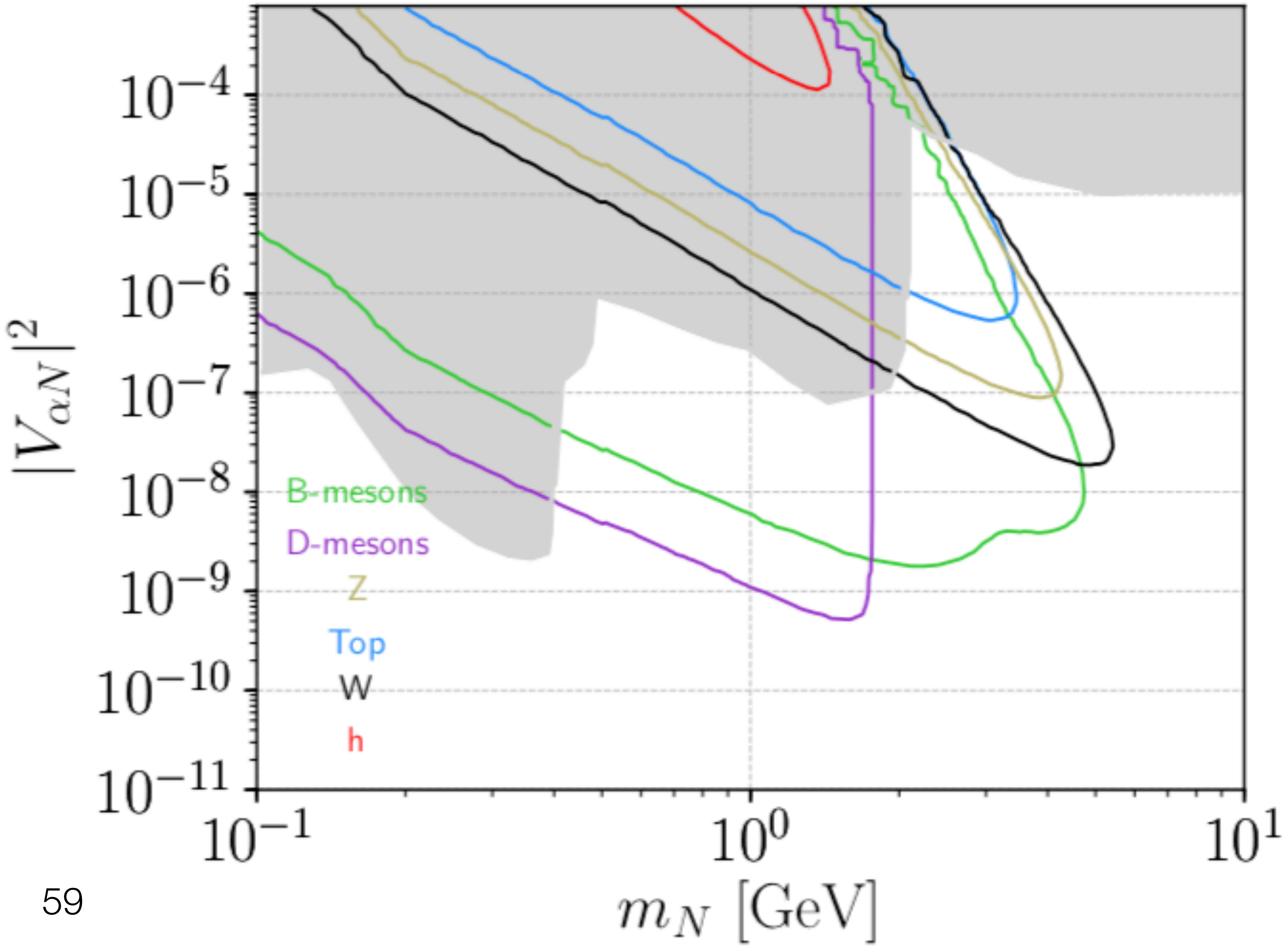
a) minimal scenario, Seesaw Type-I:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \underline{V_{\alpha N_j}} \, \bar{\ell}_\alpha \gamma^\mu P_L \underline{N_j} W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} \underline{V^L_{\alpha i}} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$

mixing with active ν — heavy neutrinos — mixing in active ν sector

Similar simulation setup:

- Require the LLP to decay within fiducial volume
- 3 ab^{-1} at 14 TeV
- Optimistic scenario considered
- Assume one additional heavy lepton, light enough for LHC



ANUBIS: sensitivity

Hirsch, Wang 2001.04750

Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)
a) minimal scenario, Seesaw Type-I:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \underline{V_{\alpha N_j}}\, \bar{\ell}_\alpha \gamma^\mu P_L \underline{N_j} W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} \underline{V^L_{\alpha i}} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$

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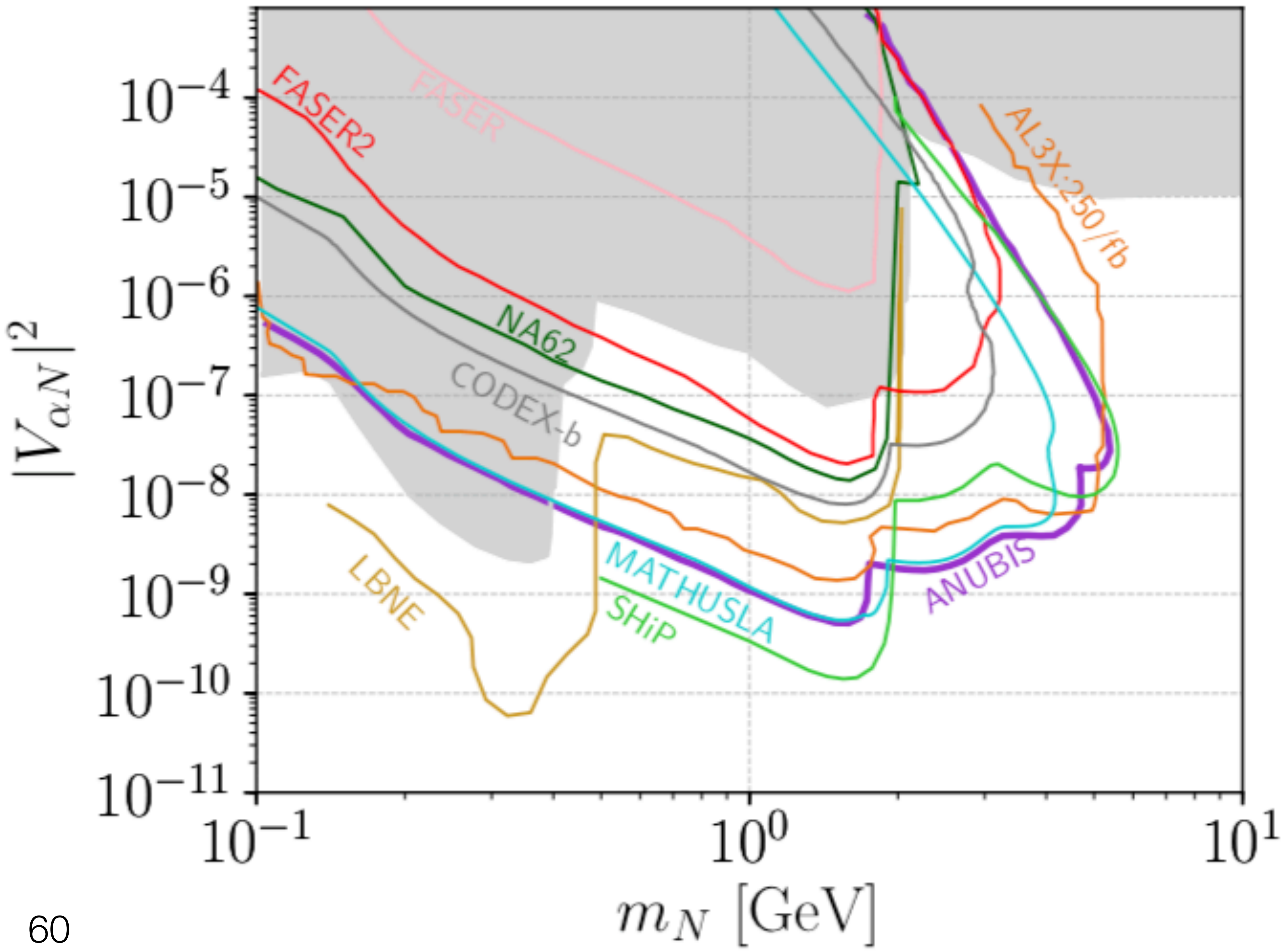


Br$(h \to ss)$
Br$(h \to ss)$
Br$(h \to ss)$

ANUBIS: sensitivity

Hirsch, Wang 2001.04750

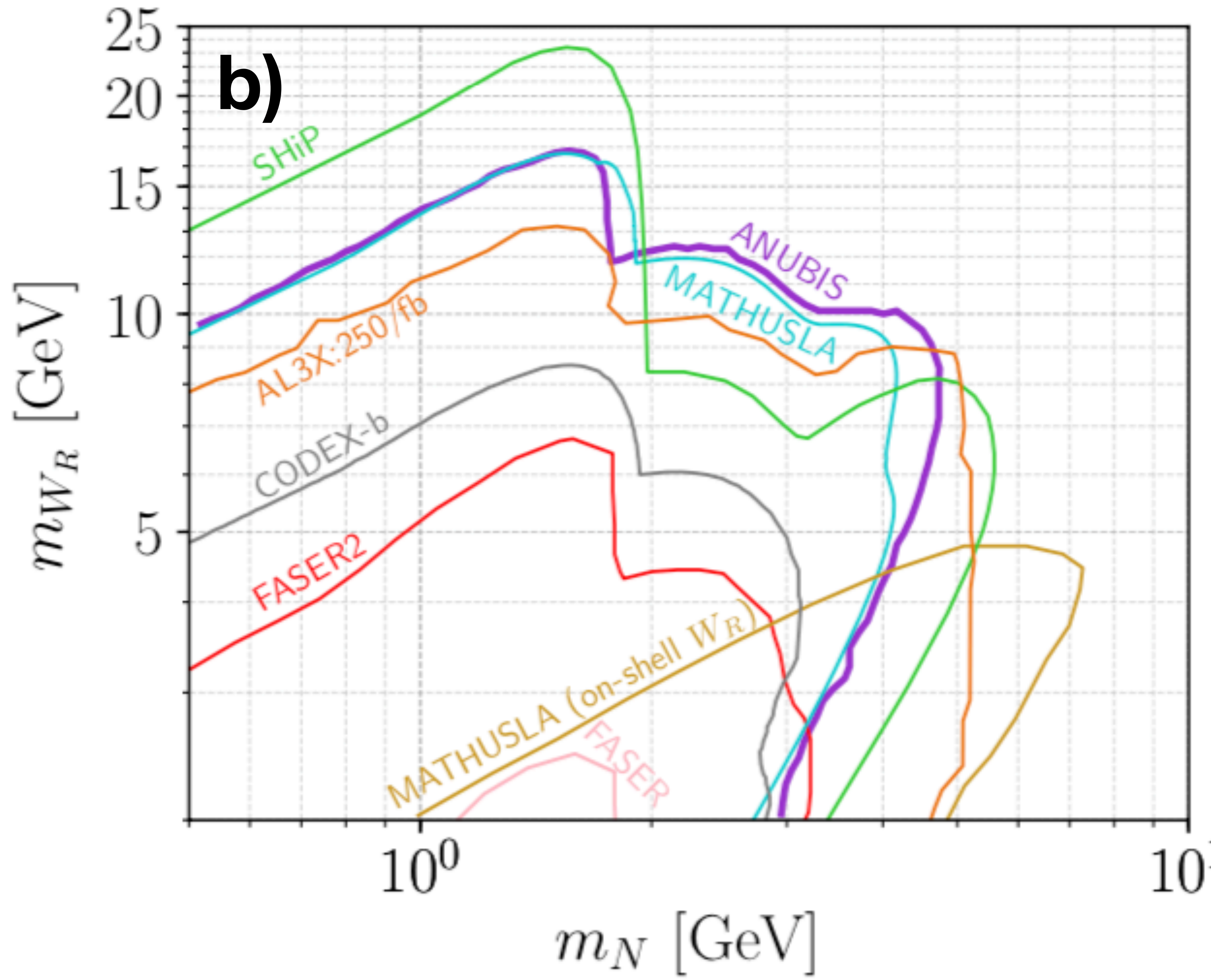
Sensitivity study for Heavy Neutral Leptons ("sterile neutrinos")

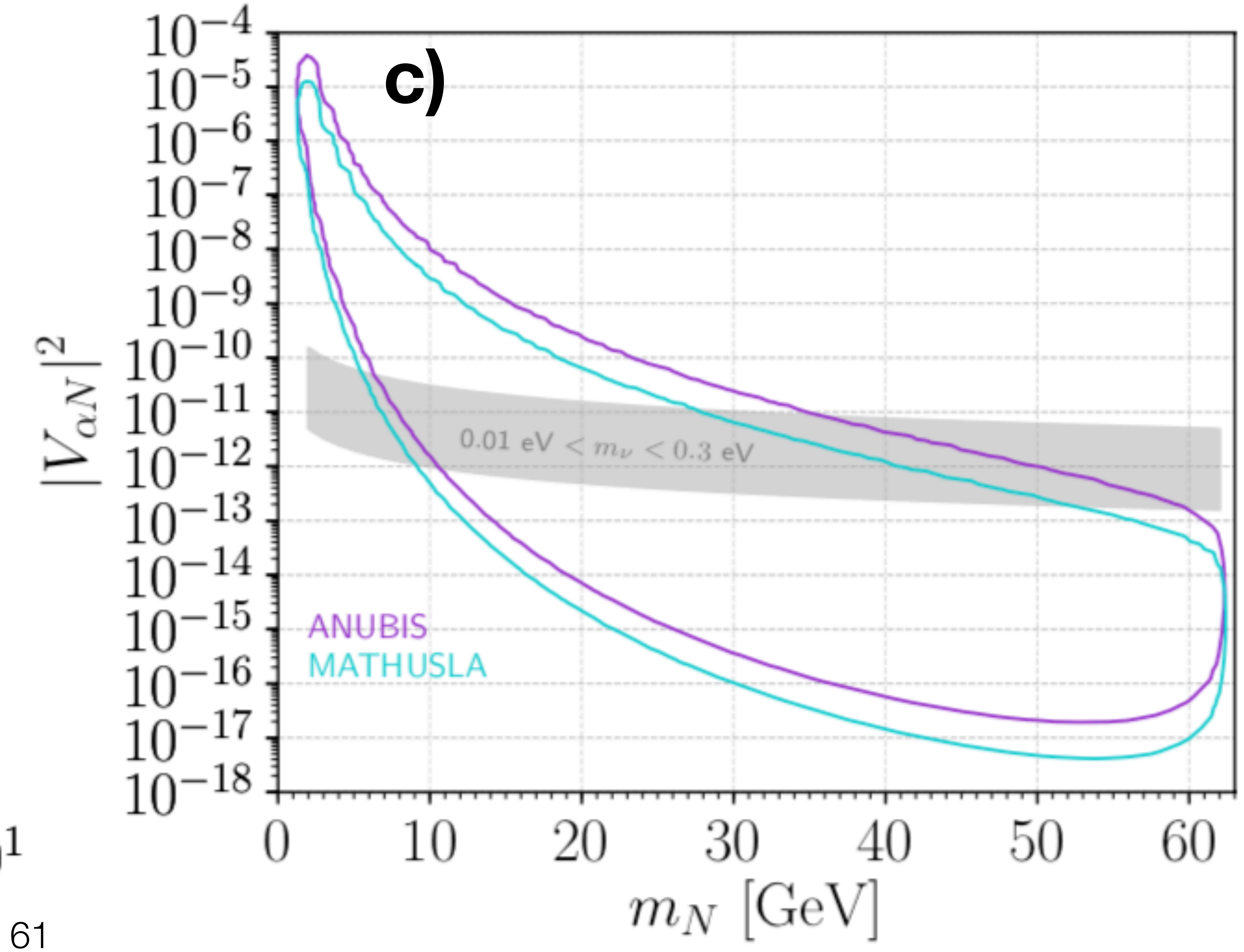
b) minimal left-right symmetric model:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

c) gauged $U(1)_{B\text{-}L}$ model:

$$U(1)_{B-L}$$ + extra Higgs boson breaking it





ANUBIS: sensitivity

Hirsch, Wang 2001.04750

Heavy neutral leptons at ANUBIS

Martin Hirsch[1,*] and Zeren Simon Wang[2,†]

[1] *AHEP Group, Instituto de Física Corpuscular – CSIC/Universitat de València Calle Catedrático José Beltrán, 2 E-46980 Paterna, Spain*

[2] *Asia Pacific Center for Theoretical Physics (APCTP) - Headquarters San 31, Hyoja-dong, Nam-gu, Pohang 790-784, Korea*

Recently Bauer *et al.* [1] proposed ANUBIS, an auxiliary detector to be installed in one of the shafts above the ATLAS or CMS interaction point, as a tool to search for long-lived particles. Here, we study the sensitivity of this proposal for long-lived heavy neutral leptons (HNLs) in both minimal and extended scenarios. We start with the minimal HNL model where both production and decay of the HNLs are mediated by active-sterile neutrino mixing, before studying the case of right-handed neutrinos in a left-right symmetric model. We then consider a $U(1)_{B-L}$ extension of the SM. In this model HNLs are produced from the decays of the mostly SM-like Higgs boson, via mixing in the scalar sector of the theory. In all cases, we find that ANUBIS has sensitivity reach comparable to the proposed MATHUSLA detector. For the minimal HNL scenario, the contributions from W's decaying to HNLs are more important at ANUBIS than at MATHUSLA, extending the sensitivity to slightly larger HNL masses at ANUBIS.

$\mathrm{Br}(h \to ss)$

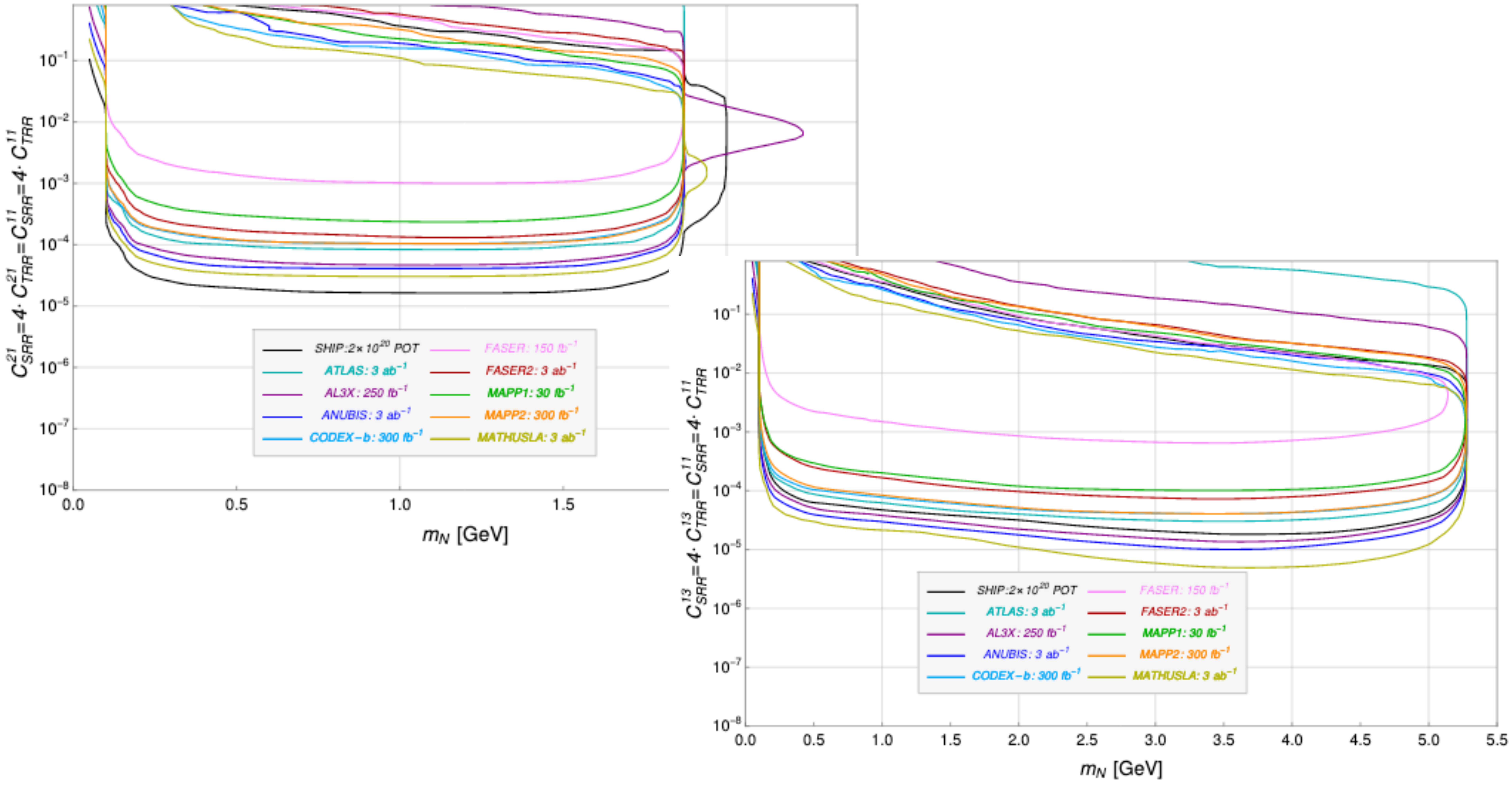
$\mathrm{Br}(h \to ss)$

$\mathrm{Br}(h \to ss)$

ANUBIS: sensitivity

de Vries, Reiner, Günther, Wang, Zhou 2010.07035

Long-lived Sterile Neutrinos at the LHC in Effective Field Theory

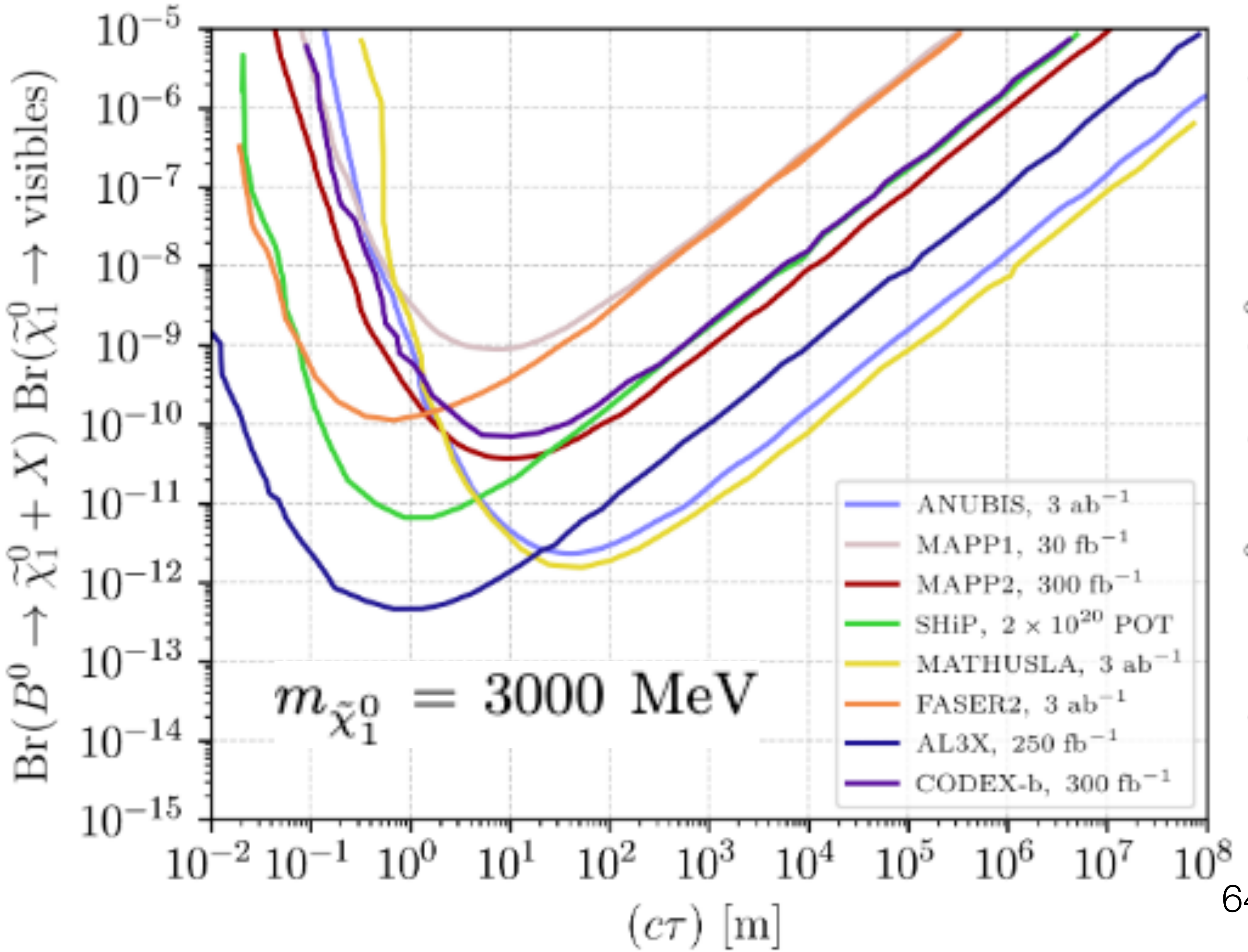


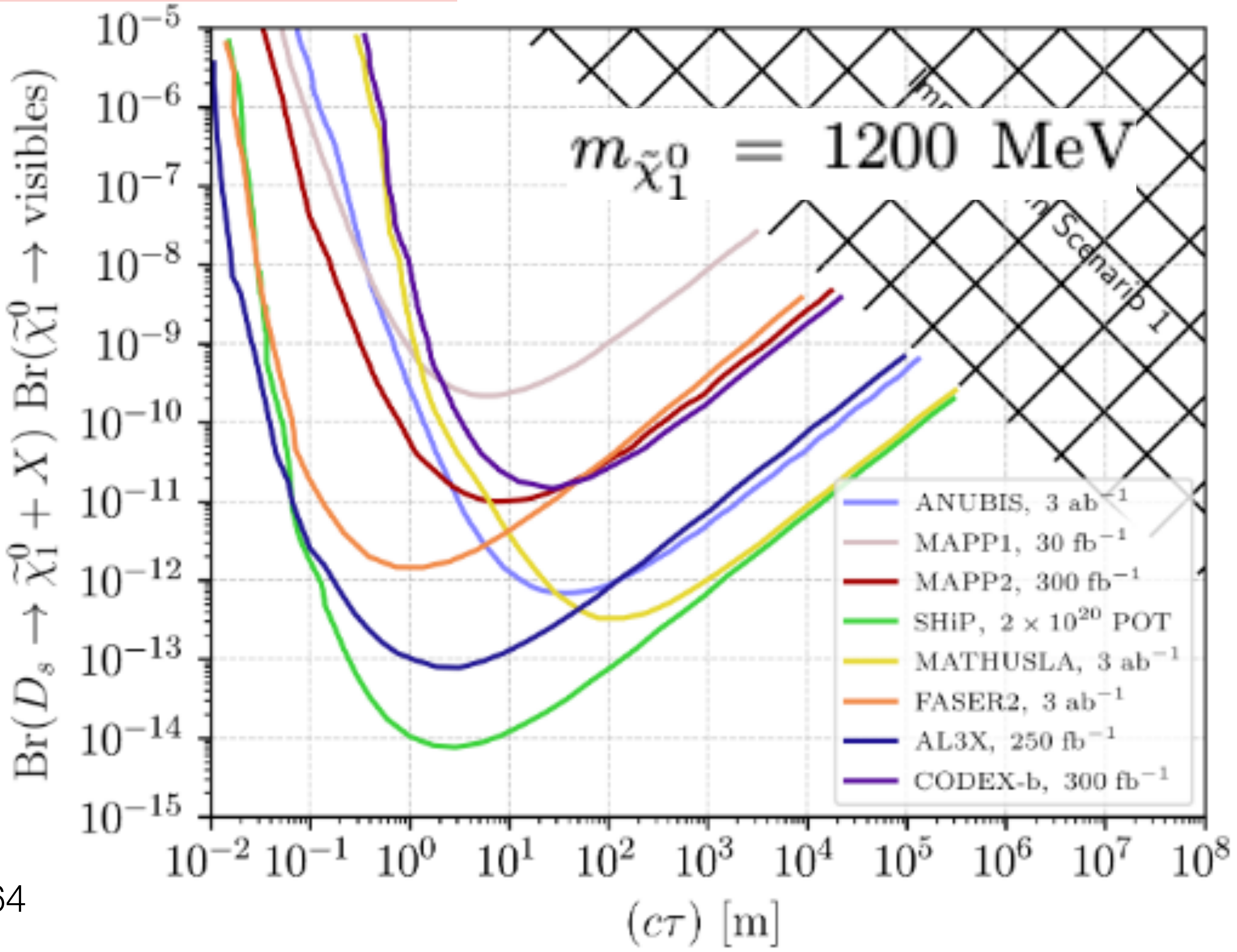
ANUBIS: sensitivity

Dreiner, Günther, Wang 2008.07539

R-parity Violation and Light Neutralinos at ANUBIS and MAPP

In R-parity-violating supersymmetry the lightest neutralino can be very light, even massless. For masses in the range 500 MeV $\lesssim m_{\tilde{\chi}_1^0} \lesssim$ 4.5 GeV the neutralino can be produced in hadron collisions from rare meson decays via an R-parity violating coupling, and subsequently decay to a lighter meson and a charged lepton. Due to the small neutralino mass and for small R-parity violating coupling the lightest neutralino is long-lived, leading to displaced vertices at fixed-target and collider experiments. In this work, we study such signatures at the proposed experiments ANUBIS and MAPP at the LHC. We also compare their sensitivity reach in these scenarios with that of other present and proposed experiments at the LHC such as ATLAS, CODEX-b, and MATHUSLA. We find that ANUBIS and MAPP can show complementary or superior sensitivity.



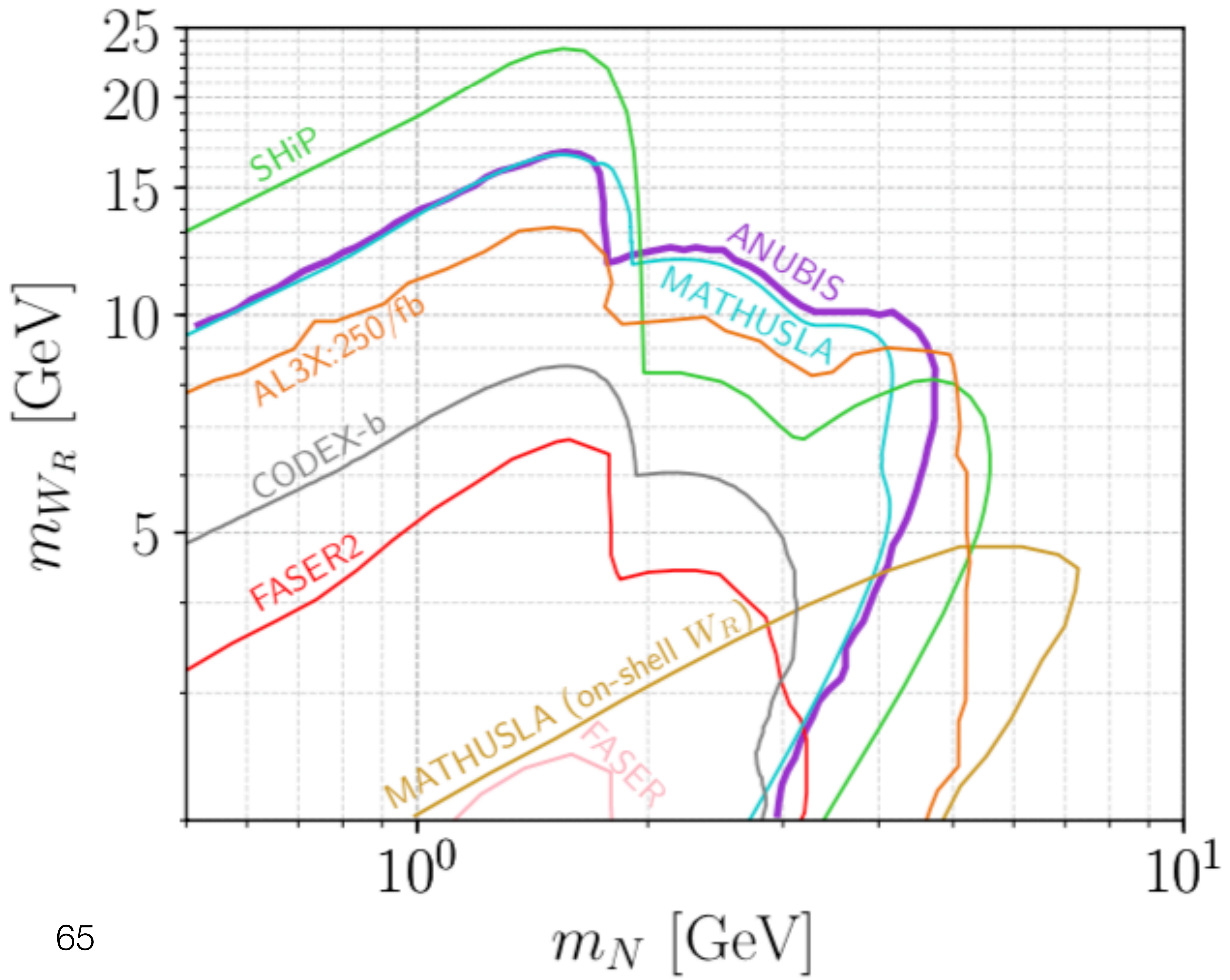


ANUBIS: sensitivity

Hirsch, Wang 2001.04750

Sensitivity study for Heavy Neutral Leptons ("sterile neutrinos")
b) minimal left-right symmetric model:

$$\mathcal{L} = \frac{g_R}{\sqrt{2}} \left(\bar{d}\gamma^\mu P_R u + \underline{V^R_{\alpha N}} \cdot \bar{l}_\alpha \gamma^\mu P_R \underline{N} \right) W^-_{R\mu} + $$
$$+ \frac{g_R}{\sqrt{1 - \tan^2\theta_W (g_L/g_R)^2}} Z^\mu_{LR} \bar{f} \gamma_\mu \left[T_{3R} + \tan^2\theta_W (g_L/g_R)^2 (T_{3L} - Q) \right] f$$



$\mathrm{Br}(h \to ss)$
$\mathrm{Br}(h \to ss)$
$\mathrm{Br}(h \to ss)$