How not to dig yourself a hole
Long lived particle searches (at LHCb)

Vladimir V Gligorov

CODEX-b

LHCb-UK student meeting, 25-05-2022

European Research Council
Established by the European Commission

Frequently asked questions

Why are we here?

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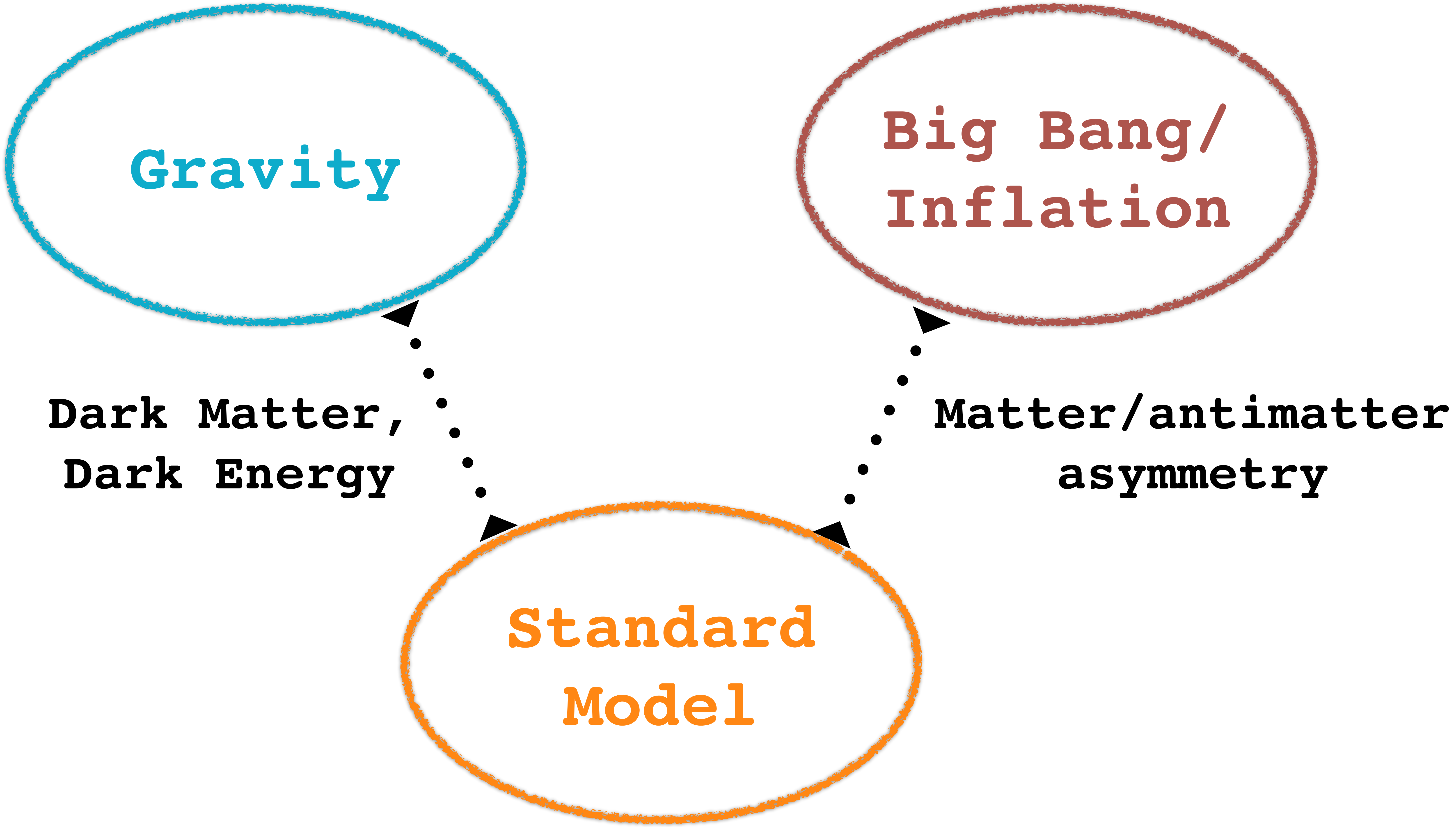


Gravity

Big Bang/
Inflation

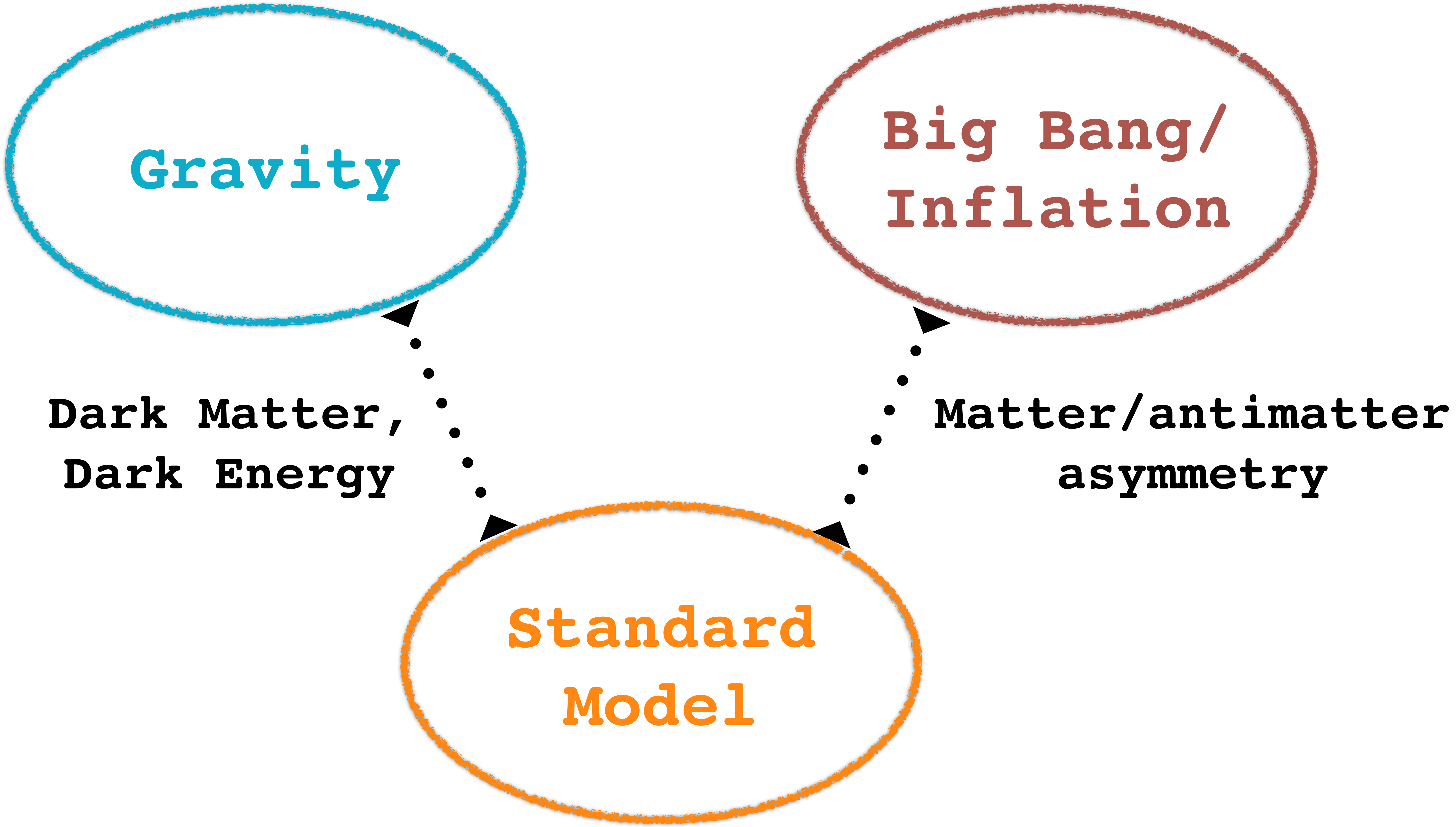
Dark Matter,
Dark Energy

Matter/antimatter
asymmetry

Standard
Model

Why are we here?

And the really big bad ghoul… nonlocality. But let's not go there.



Our theories of nature are inconsistent with each other => new physics!

Possibilities
&
Capabilities

Why long lived particle searches?

Long lifetimes arise from a hierarchy of scales or a small coupling*

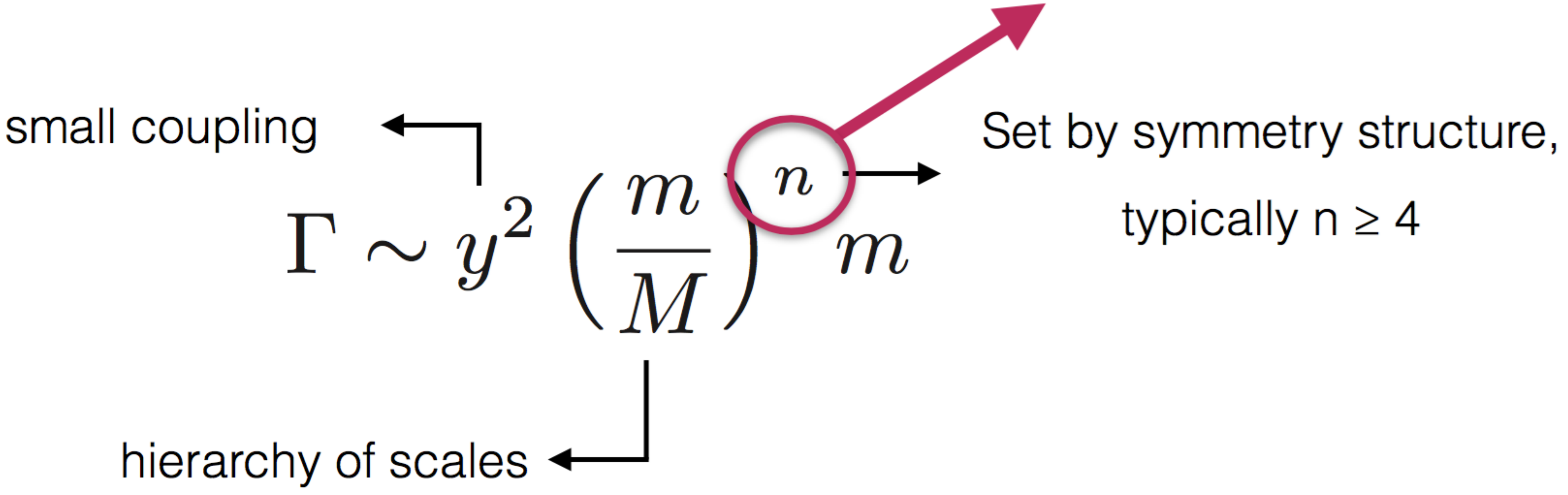
Three mechanisms:

- Off-shell decay
- Small splitting (phase space)
- Small coupling

Lessons from the SM:

- generic if there is more than one scale
- Often 3 body decays
- Weak theory prior on lifetime

(e.g. proton decay!)



small coupling

$$\Gamma \sim y^2 \left(\frac{m}{M}\right)^n m$$

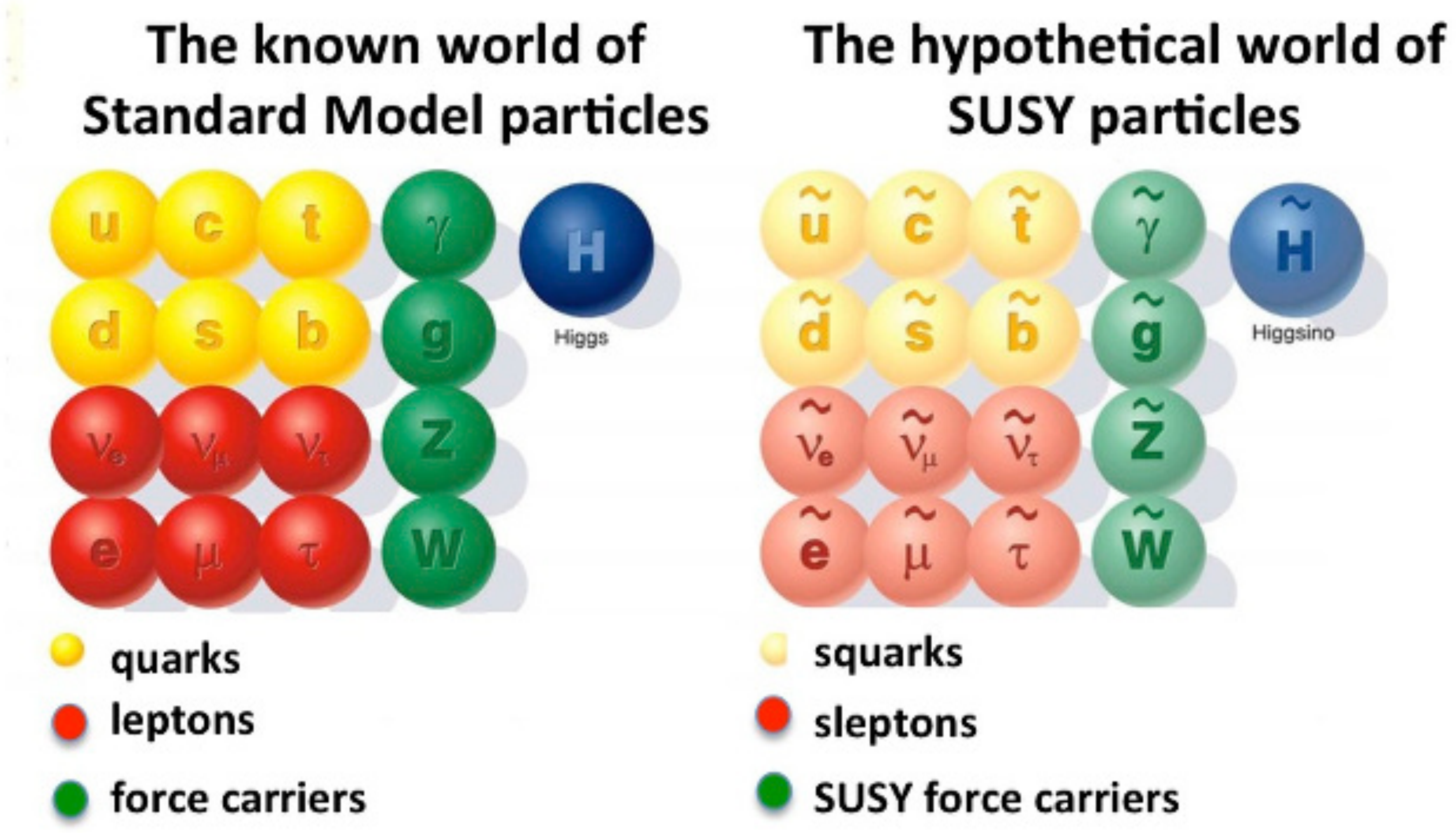
Set by symmetry structure,

typically n ≥ 4

hierarchy of scales

* could either be a hierarchy or loop suppression

Long-lived particles are generic



Other

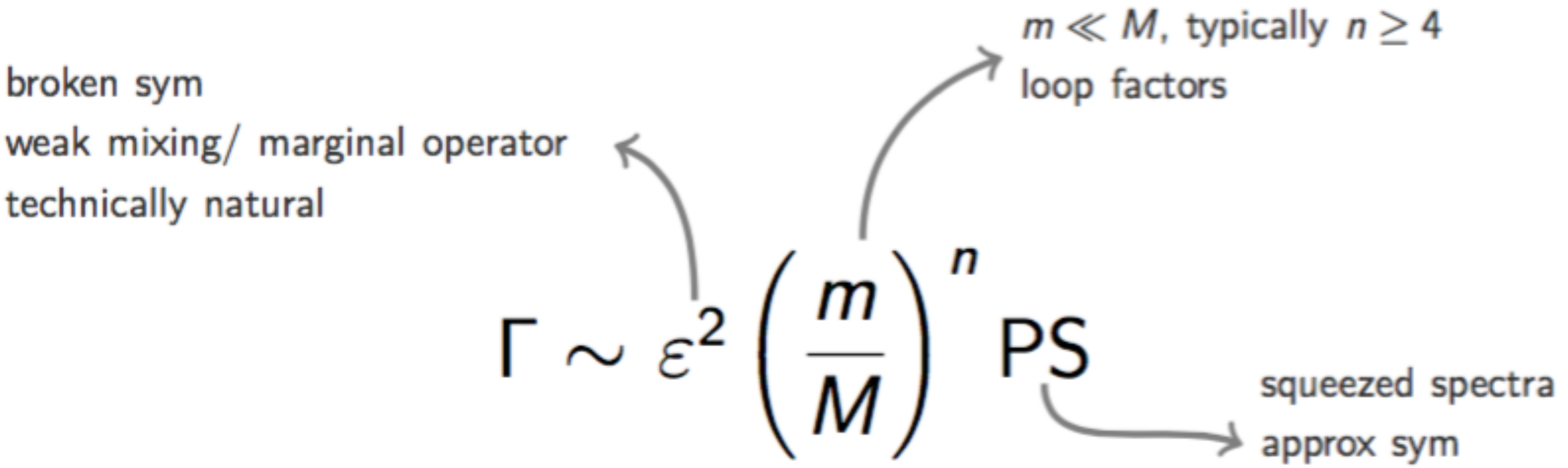
R-parity violation
Gauge mediation
(mini-)split SUSY
stealth SUSY

Asymmetric Dark Matter
Freeze-in
composite Dark Matter
…

Baryogenesis
Neutrino masses
Neutral Naturalness
Hidden Valleys

A very wide range of BSM models introduce long-lived particles

LLP mass vs lifetime vs production



broken sym
weak mixing/ marginal operator
technically natural

$m \ll M$, typically $n \geq 4$
loop factors

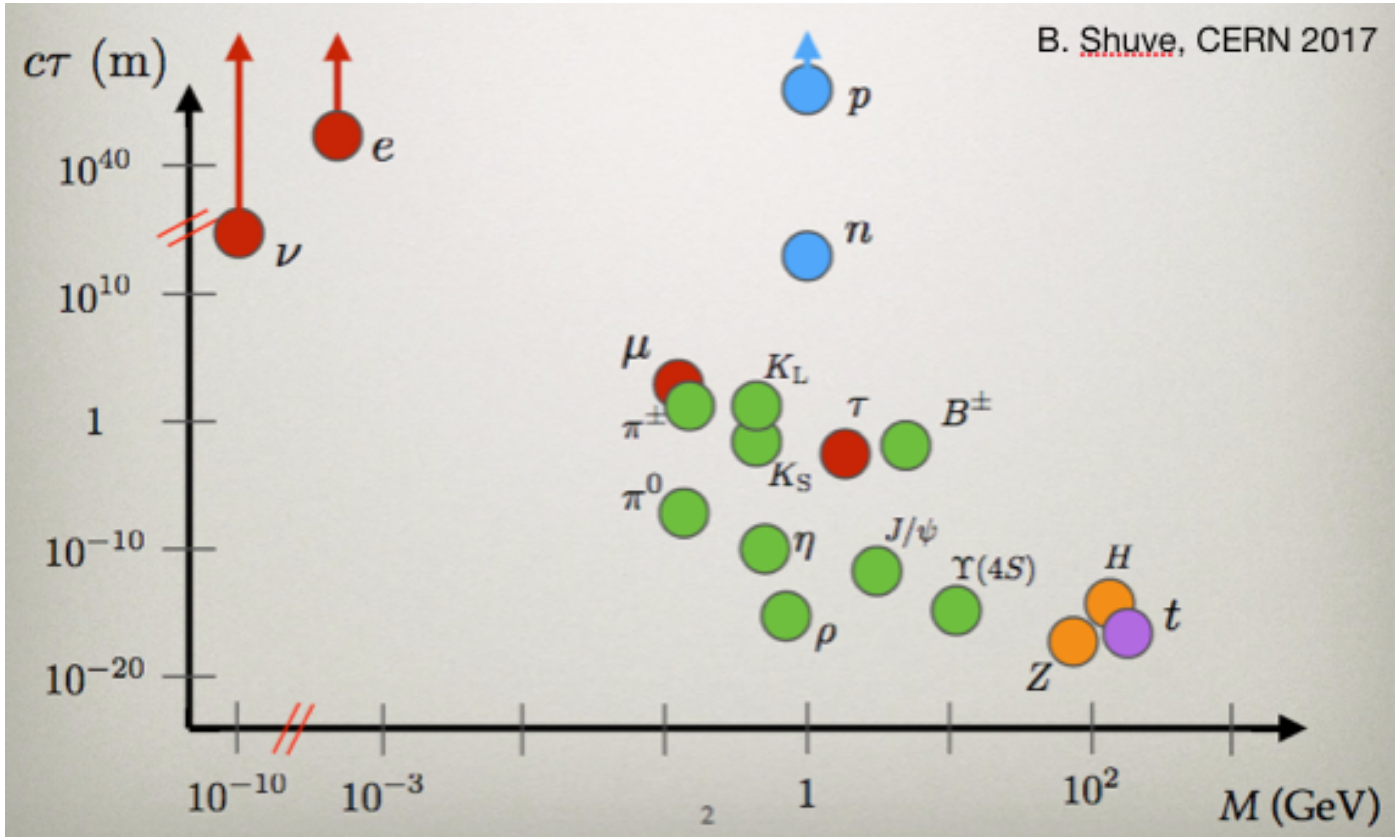
$$\Gamma \sim \varepsilon^2 \left(\frac{m}{M}\right)^n \mathrm{PS}$$

squeezed spectra
approx sym
multibody decays

The bigger the mass, the smaller the required coupling to get a long lifetime

Production & decay heavily depend on the LLP and the portal used to access it.

LLP mass vs lifetime vs production



The bigger the mass, the smaller the required coupling to get a long lifetime

Production & decay heavily depend on the LLP and the portal used to access it.

So how do we search for them?

No theory guidance on lifetime → large detectors

Many possible decay modes → hermeticity, particle ID

Small coupling and production rate → zero background

Small coupling and production rate → huge integrated lumi

Very hard for any single detector to meet all these criteria!

Collider vs. fixed target mode

	Fixed target	Collider
Advantages		
Disadvantages		

Collider vs. fixed target mode

	Fixed target	Collider
Advantages	Production rate Collimated production & decay	
Disadvantages		

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Collider vs. fixed target mode

	Fixed target	Collider
Advantages	Production rate Collimated production & decay	Access to higher mass LLPs via e.g. Higgs portal
Disadvantages	No access to very heavy LLPs Big shielding required for bkg	Uncollimated production Hard to instrument Hard to shield

Collider vs. fixed target mode

To put the production argument in some context, consider the SPS vs. HL-LHC, each over 5 years

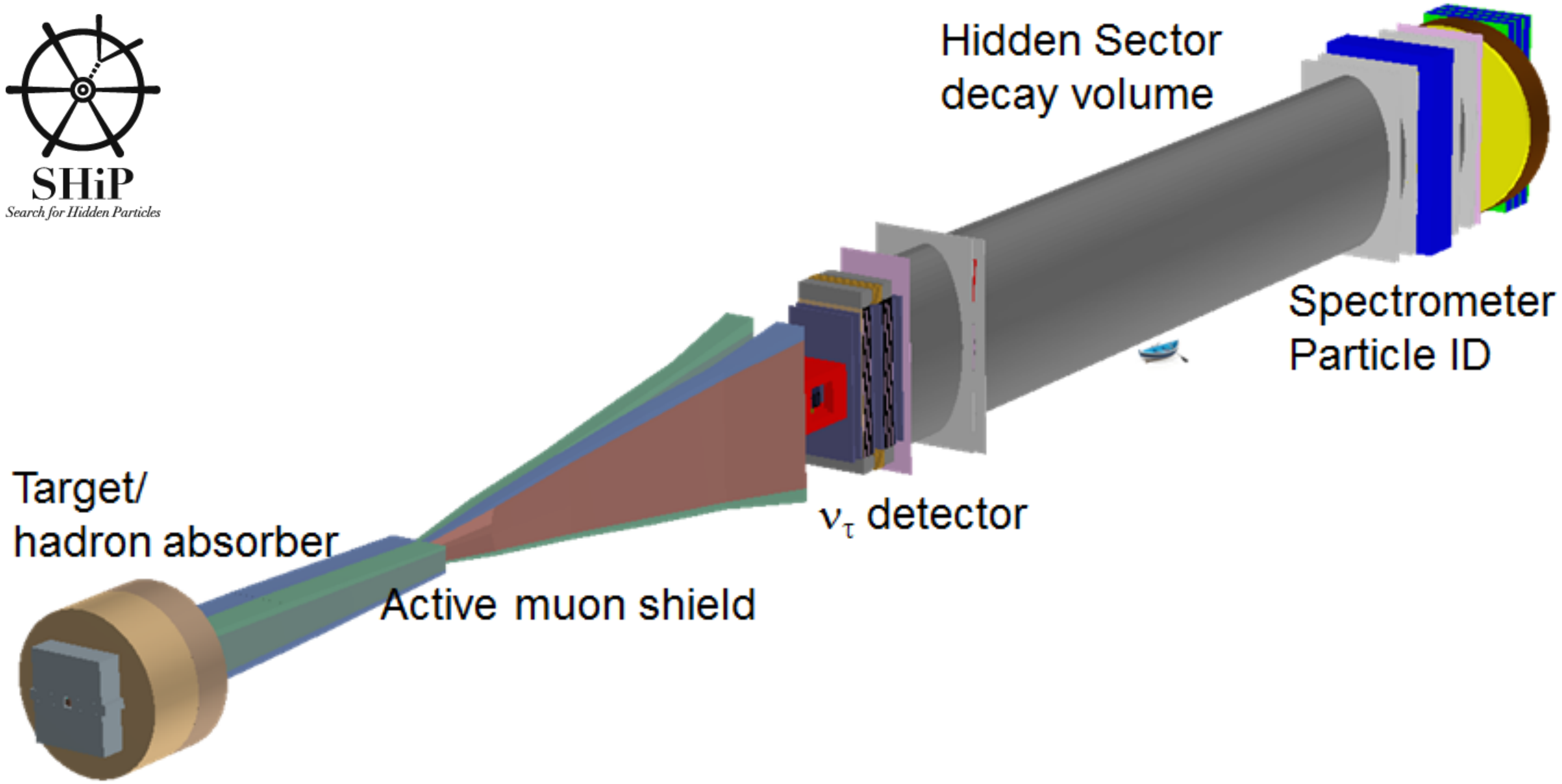
Charm Hadrons @ SPS : $O(10^{18})$
Charm Hadrons @ HL-LHC : $O(10^{16})$

Beauty Hadrons @ SPS : $O(10^{14})$
Beauty Hadrons @ HL-LHC : $O(10^{15})$

This is why SHIP is so great at LLPs produced in charm decays, while HL-LHC can compete for beauty and dominates for anything heavier

Distance versus solid angle coverage

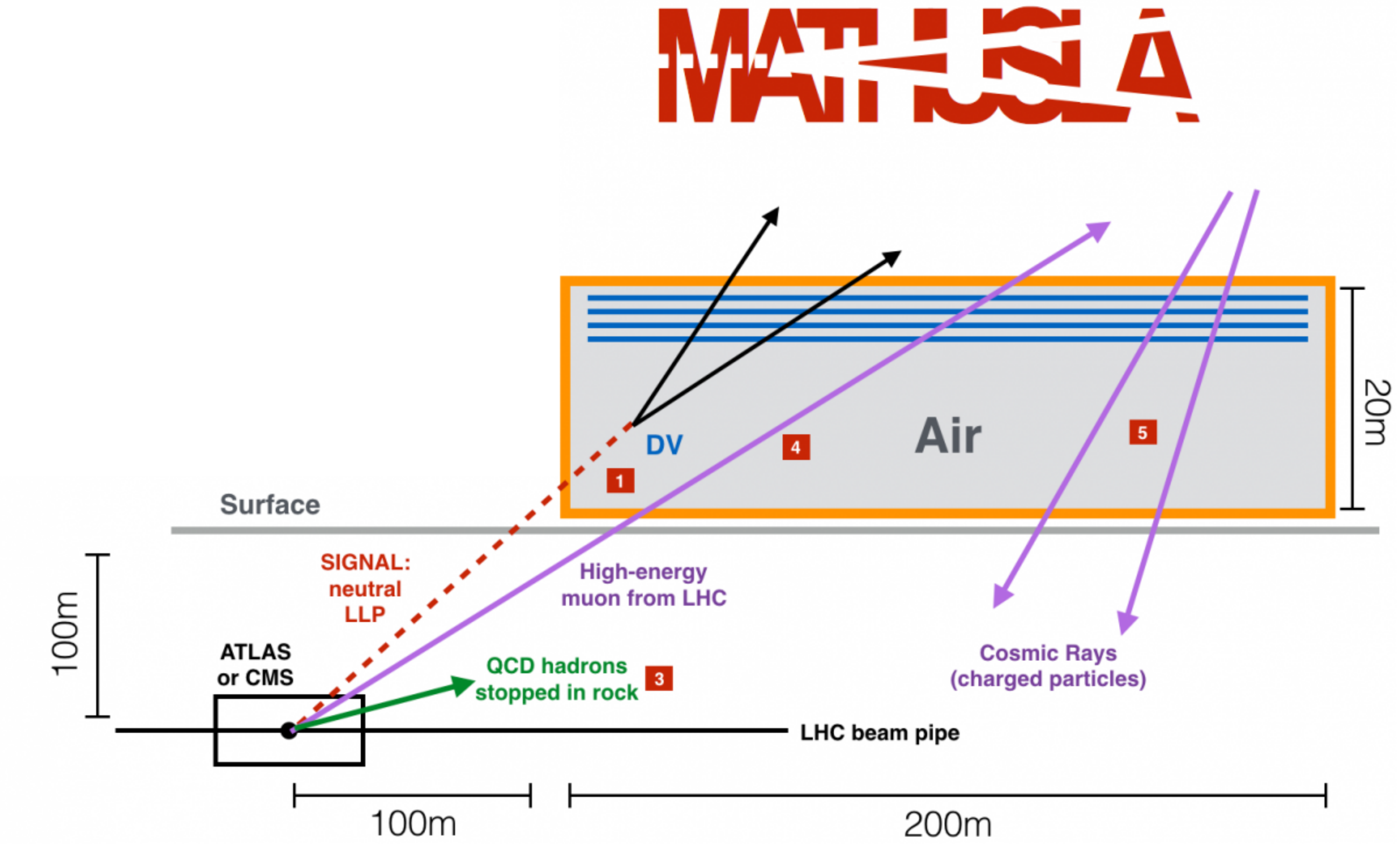
Fixed target : collimated production



Collimated production & decay mean that solid angle coverage is ~independent of optimal decay volume. Geometry is dominated by the required size of shield.

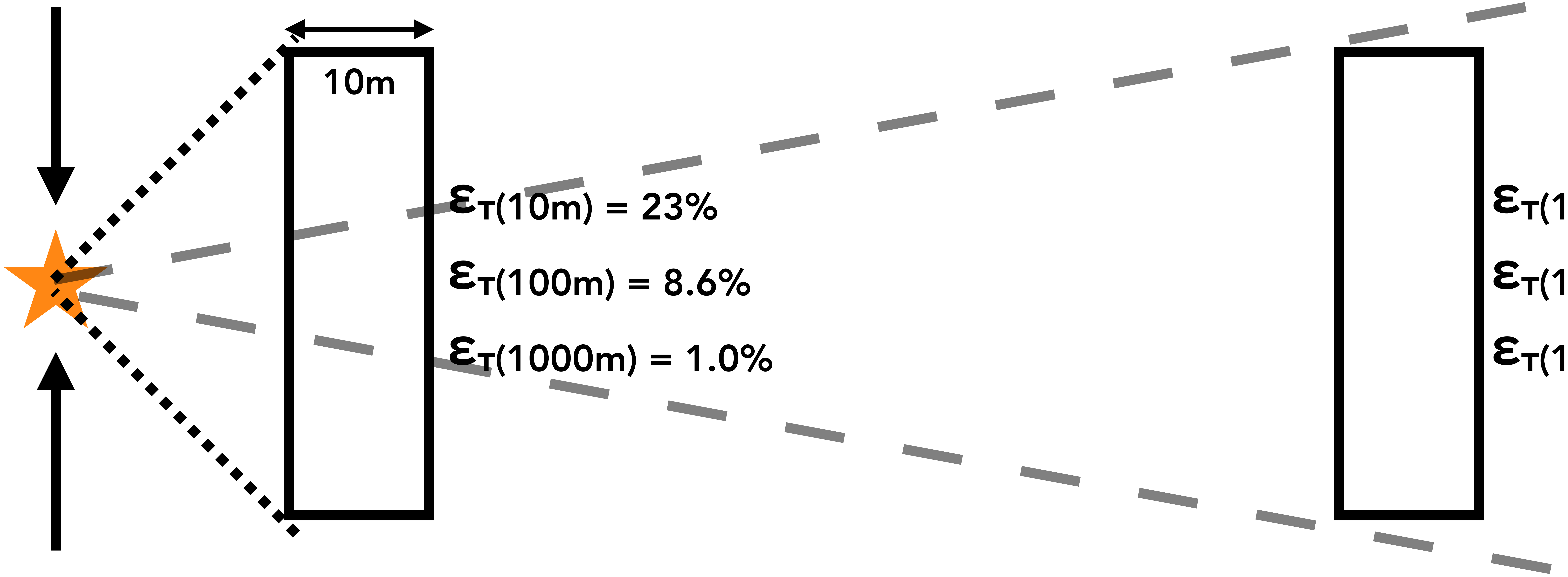
Distance versus solid angle coverage

Collider mode : solid angle is critical!



Uncollimated production means that (unless you go very forward) the size of your detector goes quadratically with distance from collision.

Distance versus lifetime coverage



10 m from IP

$\varepsilon_T(10\text{m}) = 23\%$

$\varepsilon_T(100\text{m}) = 8.6\%$

$\varepsilon_T(1000\text{m}) = 1.0\%$

50 m from IP

$\varepsilon_T(10\text{m}) = 0.4\%$

$\varepsilon_T(100\text{m}) = 5.8\%$

$\varepsilon_T(1000\text{m}) = 1.0\%$

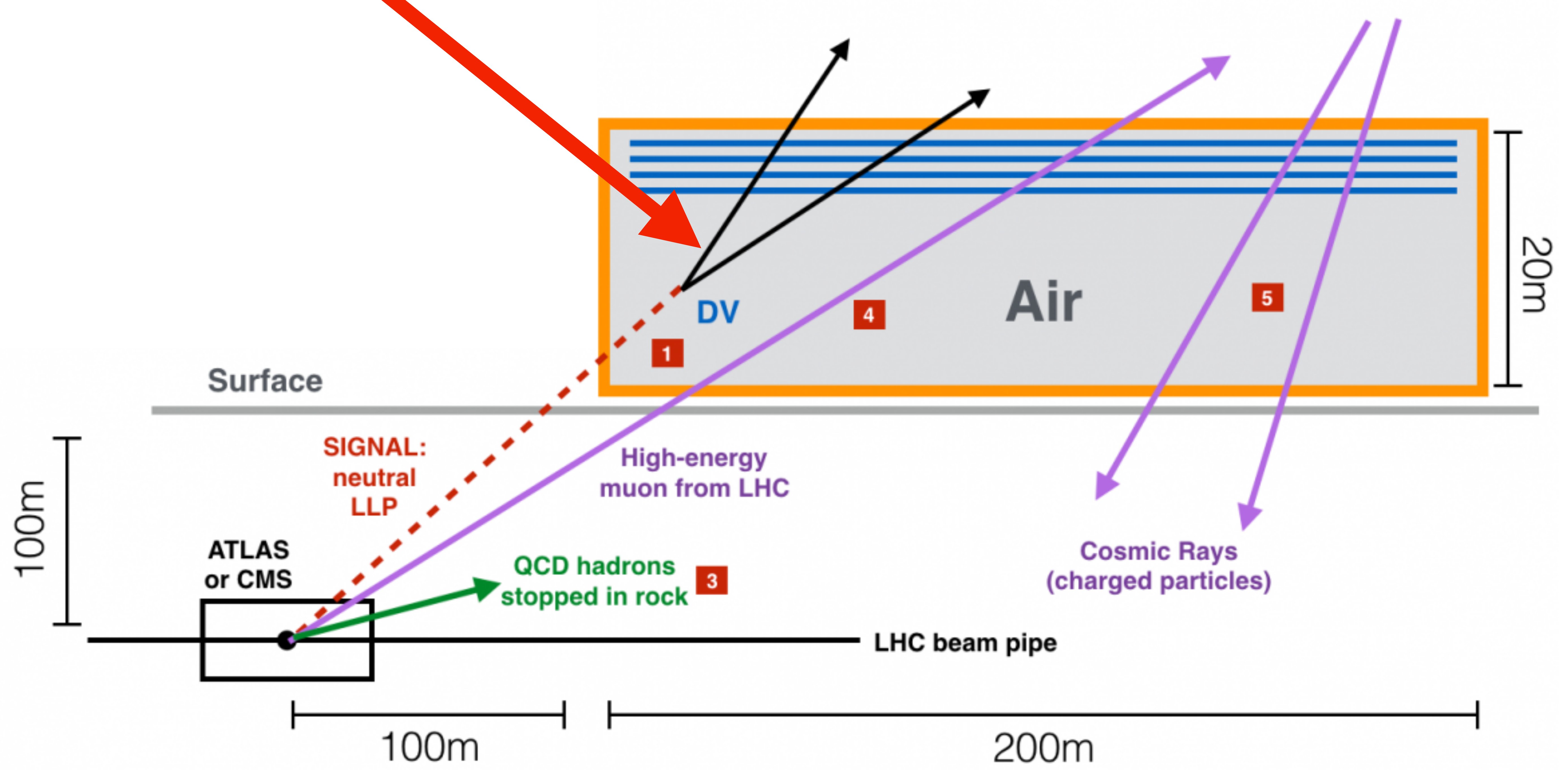
Being far isn’t really helpful for probing longer lifetimes, since for very long lifetimes the exponential is anyway flat.

What really matters is your volume/lumi. If you see a signal, you’ll need a deep detector or precise timing to measure its properties…

Side effects of that kind of size

Huge distance to first measured point inside tracker!

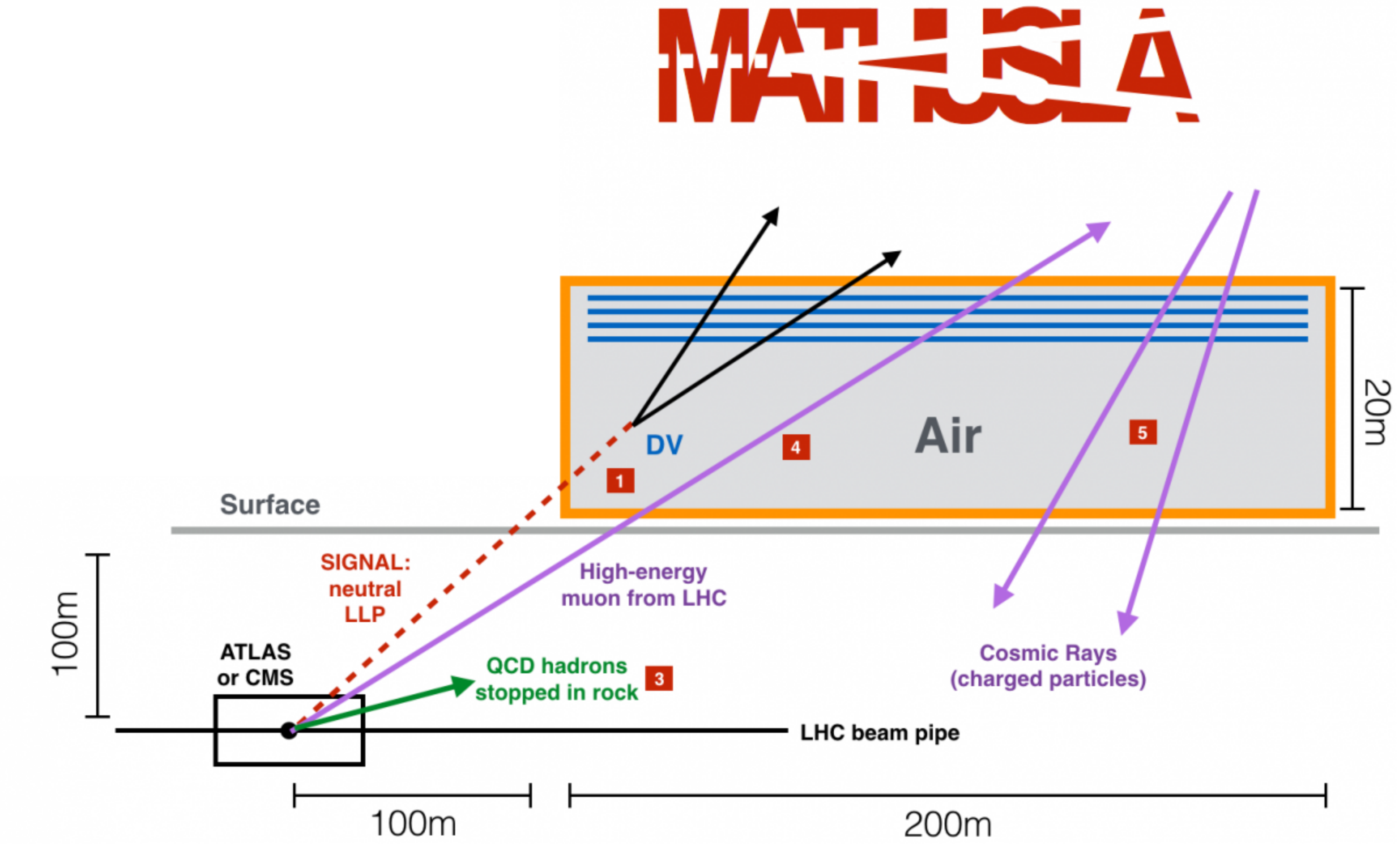
MATHUSLA



This also has an interesting impact on vertex resolution: prepare to have distances of closest approach O(cm) for your signal products…

A kingdom for a magnet

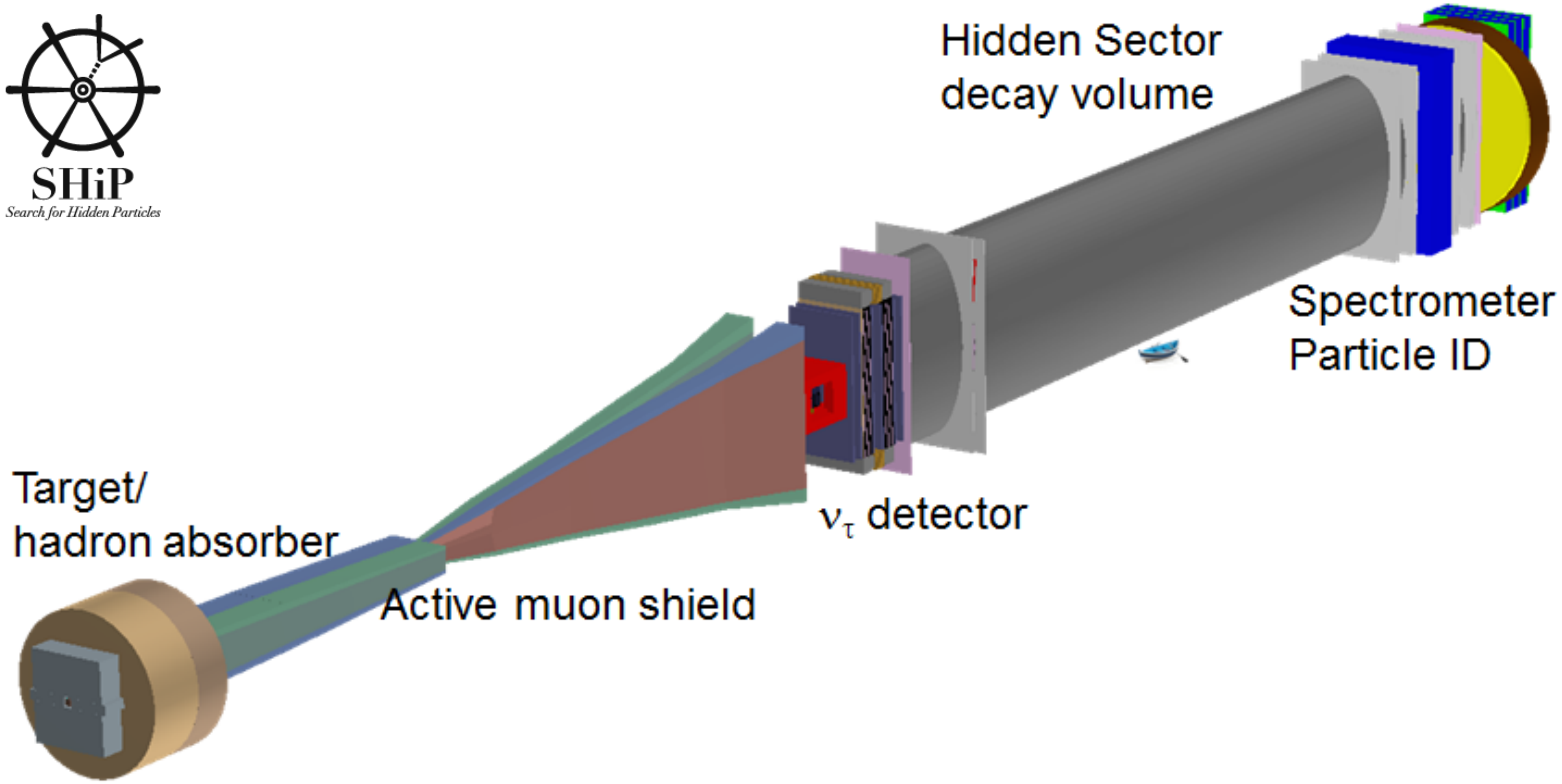
Collider mode : good luck…



The other problem with uncollimated production is that unless you do something wild with permanent magnets, you can't really install one to cover the volume

A kingdom for a magnet

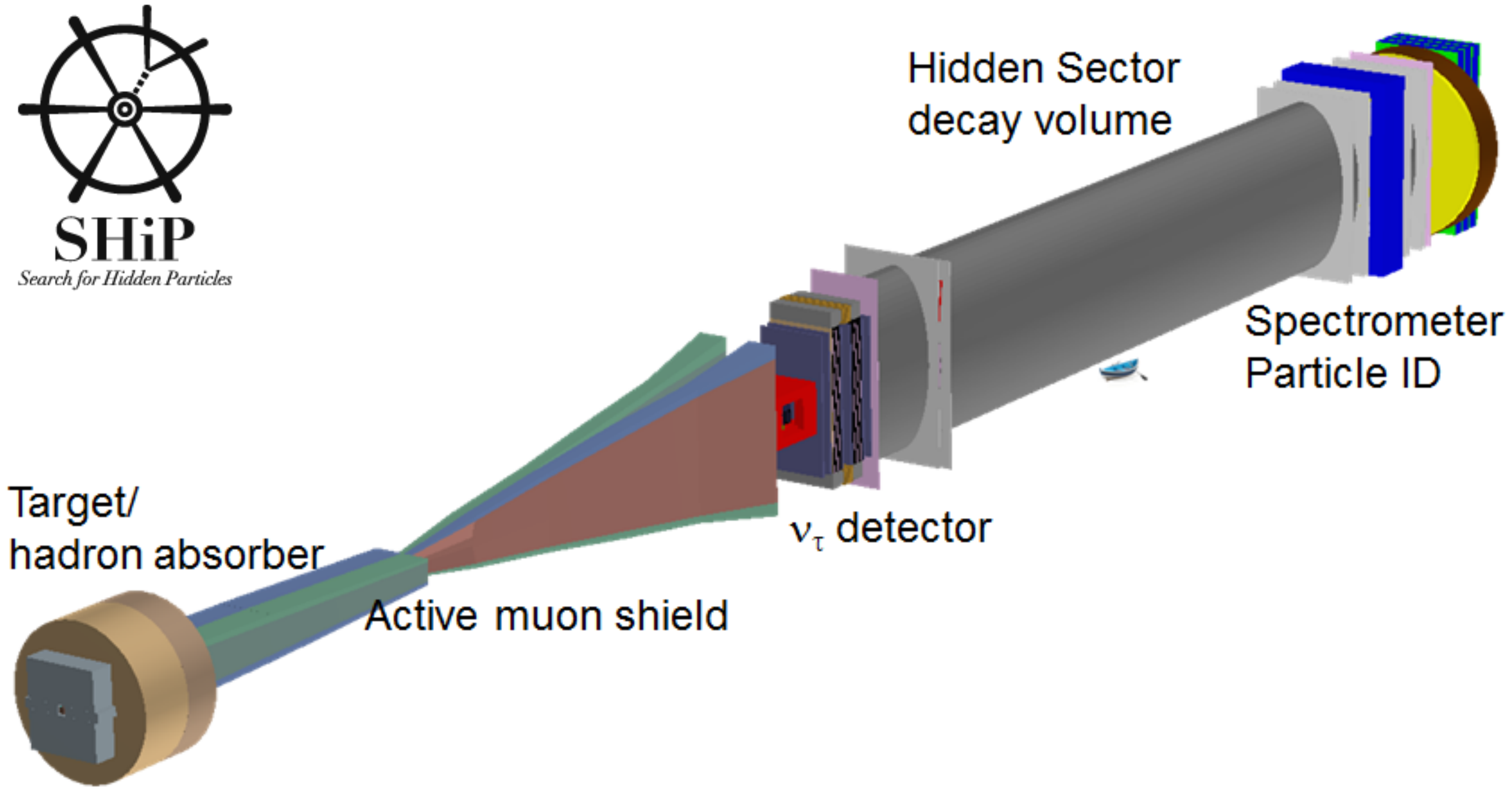
Fixed target : easy!



In fixed target mode, even if distance to the first measured point is large, all decay products go in a small cone, so quite possible to add a magnet

The quest for zero background

SHiP
Search for Hidden Particles



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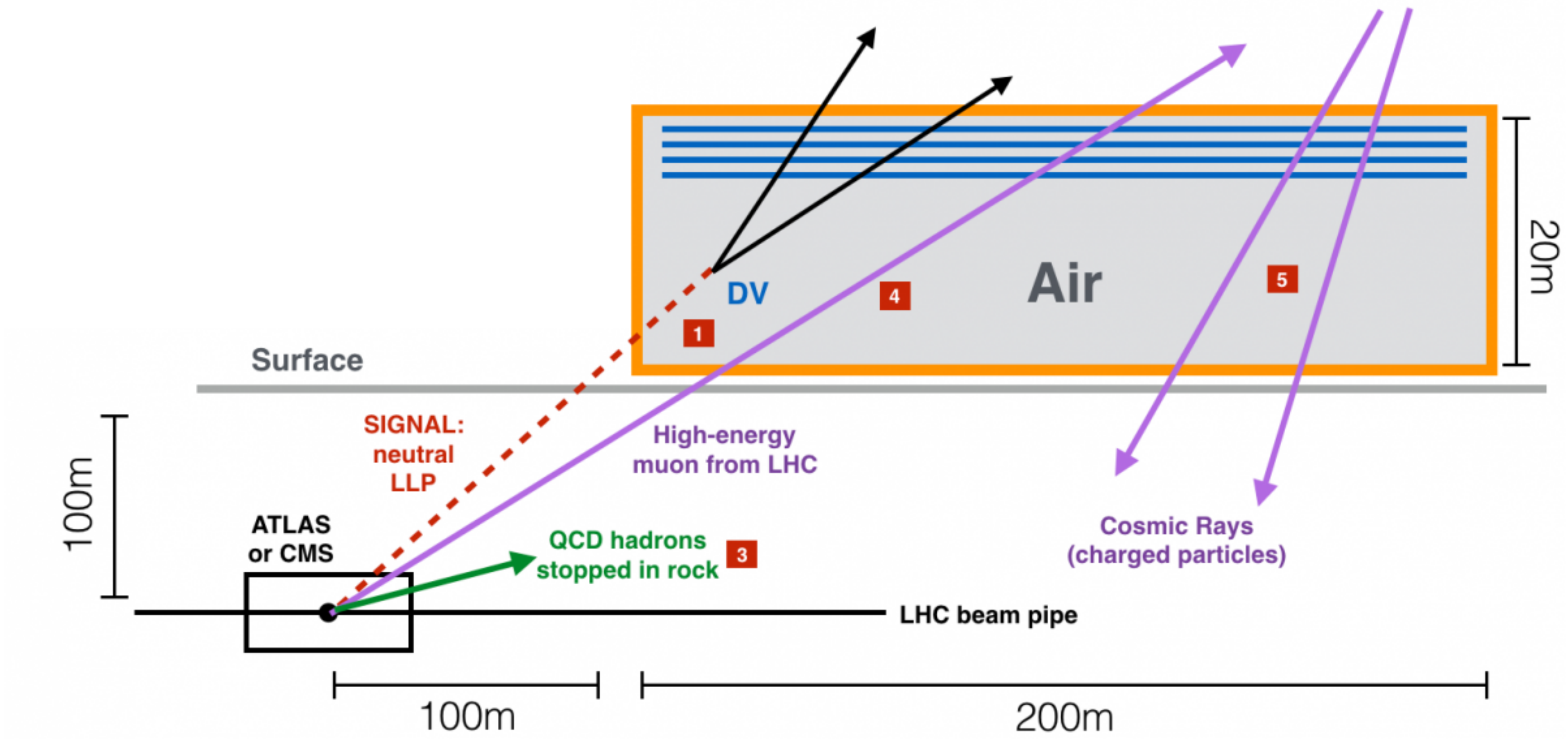
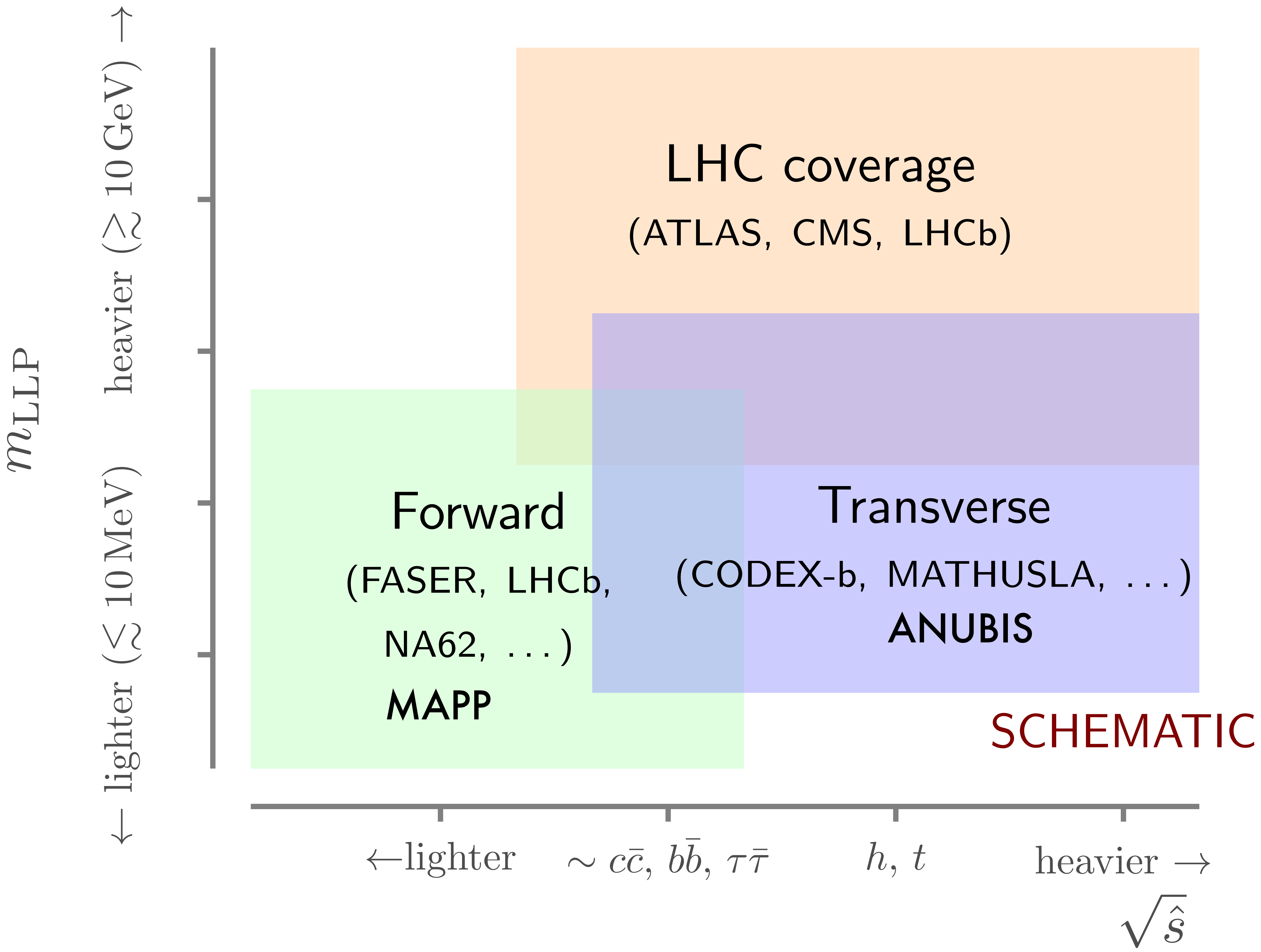


Considerations : size of shield, active layer for in-shield secondary production, vacuum decay vessel or neutrino-like detector, magnet or timing/calorimetry?

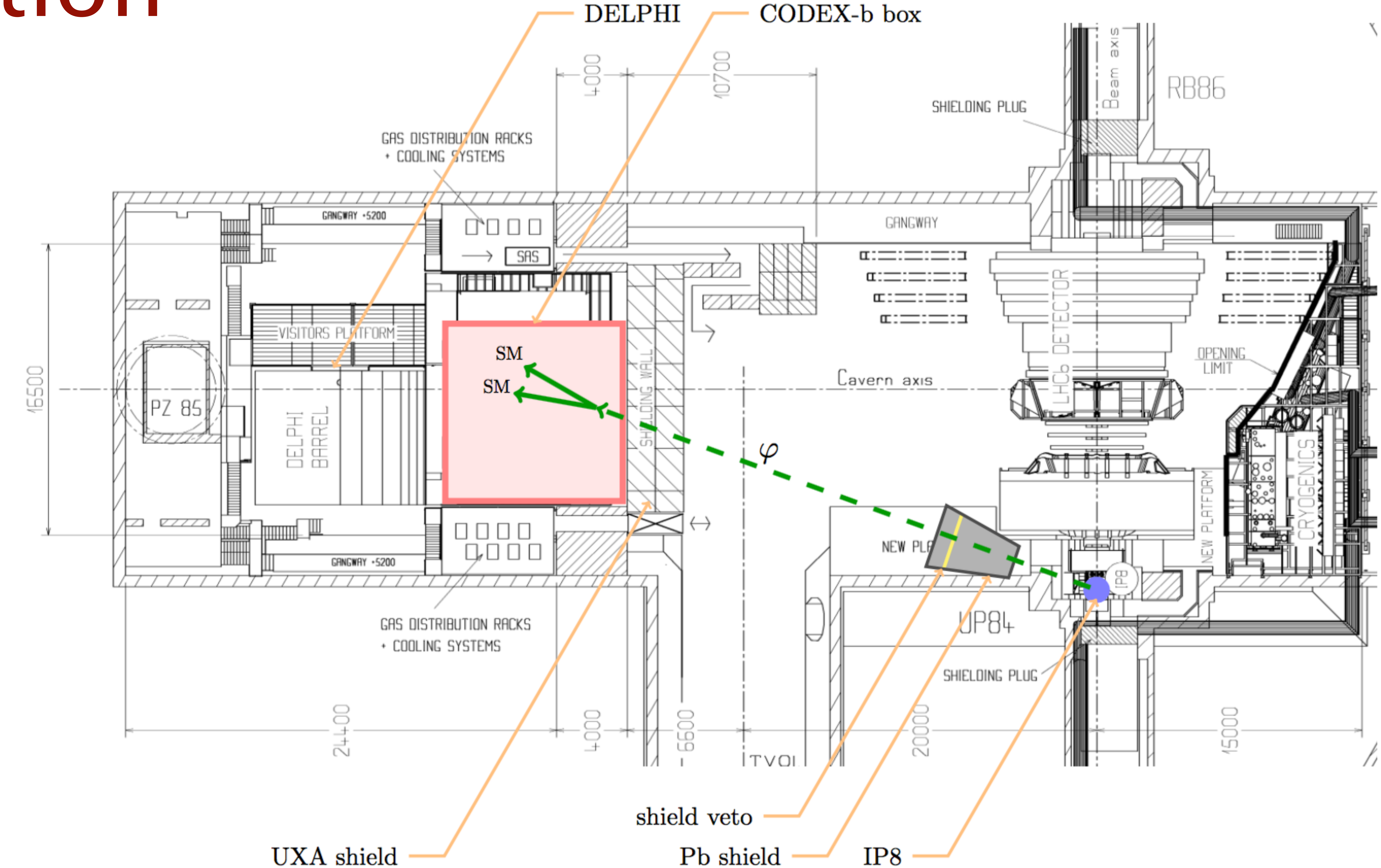
Summary of coverage



No single "golden" experiment — need complementary capabilities!

CODEX-b: a minimal extension to LHCb for LLP searches

Location



DELPHI

CODEX-b box

UXA shield

shield veto

Pb shield

IP8

Why CODEX-b? One slide sales pitch

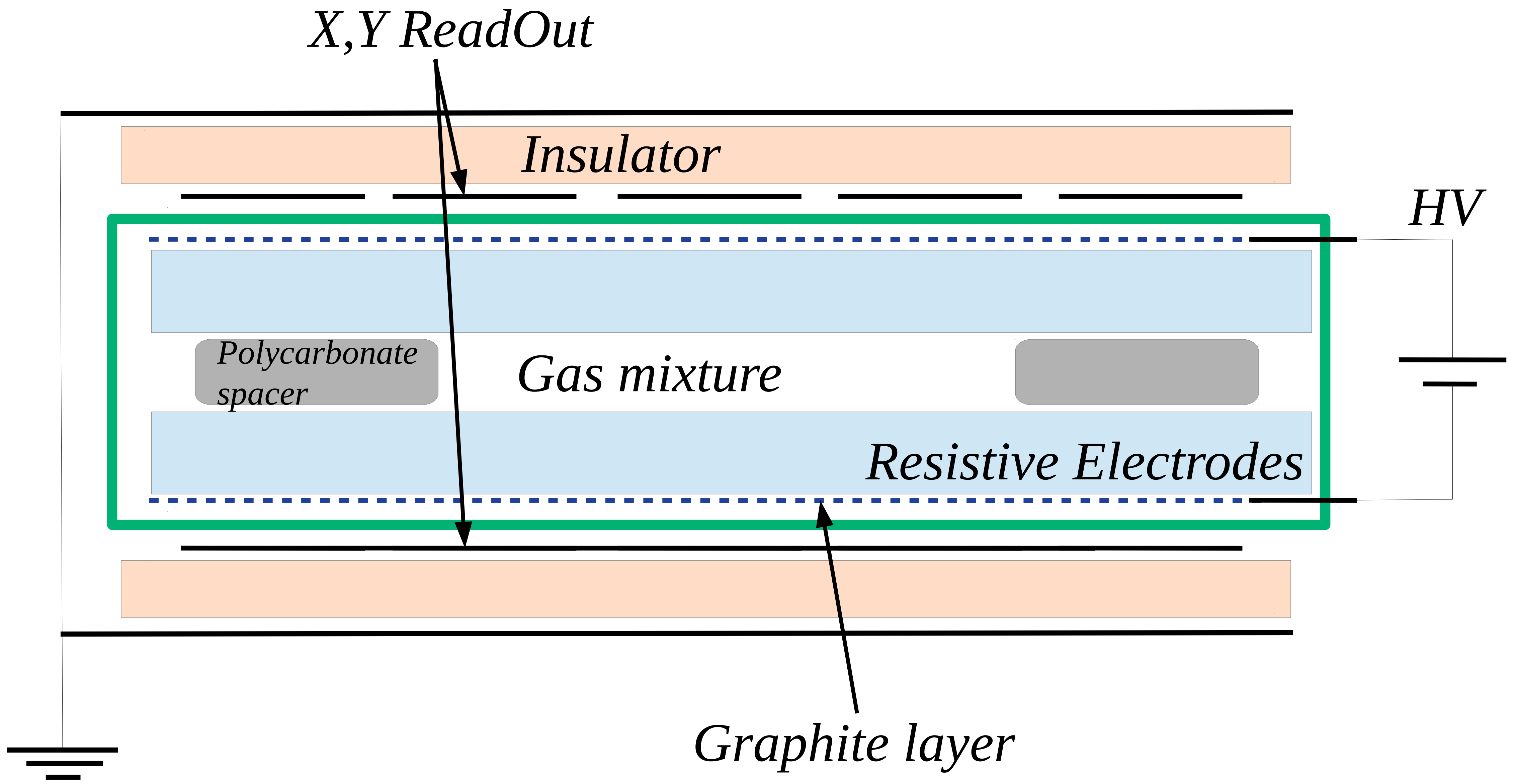
1. Shielded & convenient location “for free”
2. Modest size hence low cost (<10 M$)
3. Trivial integration with LHCb DAQ, no trigger needed
4. Access both forward and transverse physics

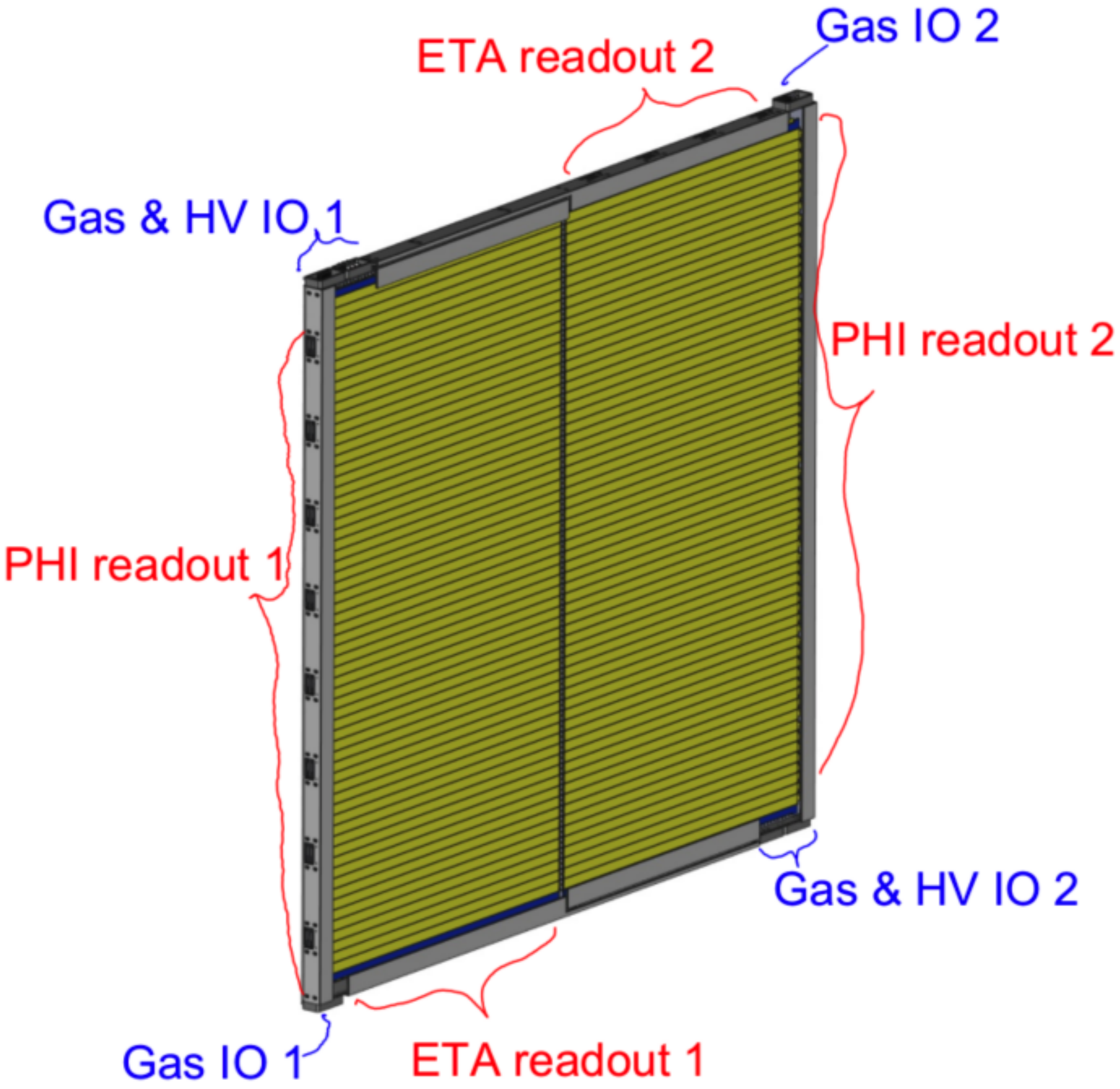
Baseline detector technology

Based on RPCs for the ATLAS upgrade

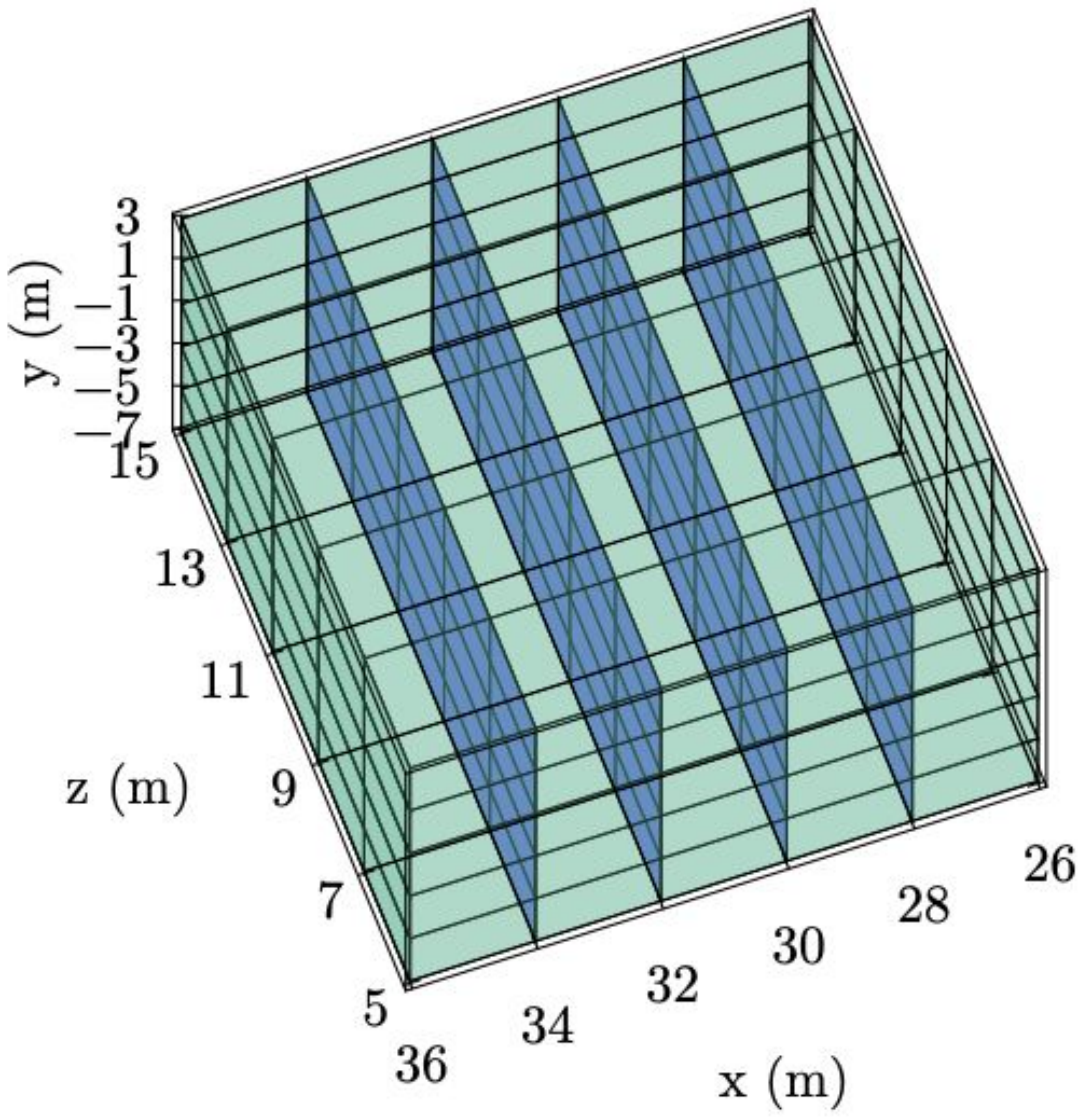
Cheap, fast to read out, with the spatial granularity we need and with the possibility of sufficient timing precision further down the line

Same technology as ANUBIS demonstrator





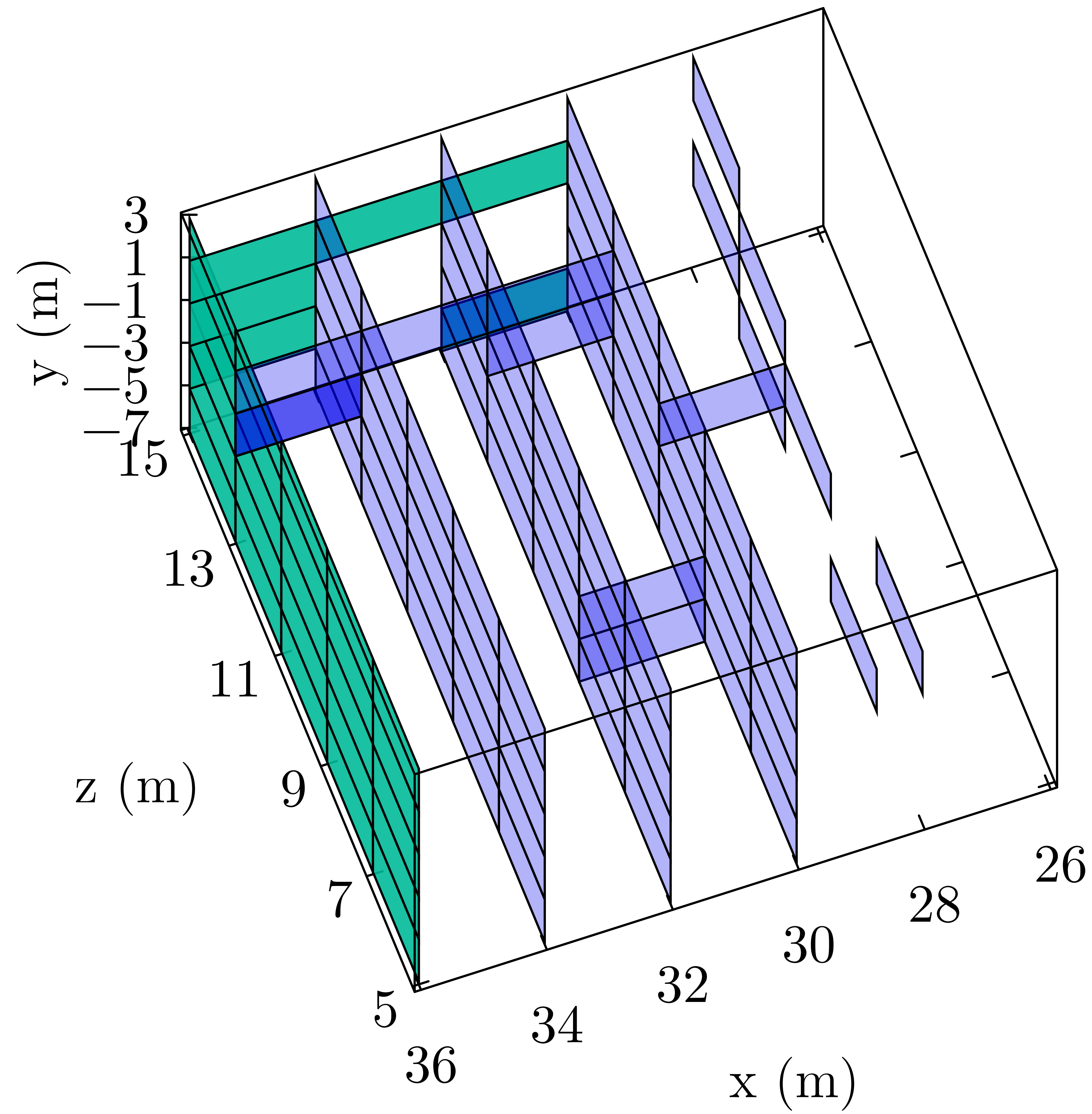
Minimal proof-of-concept geometry

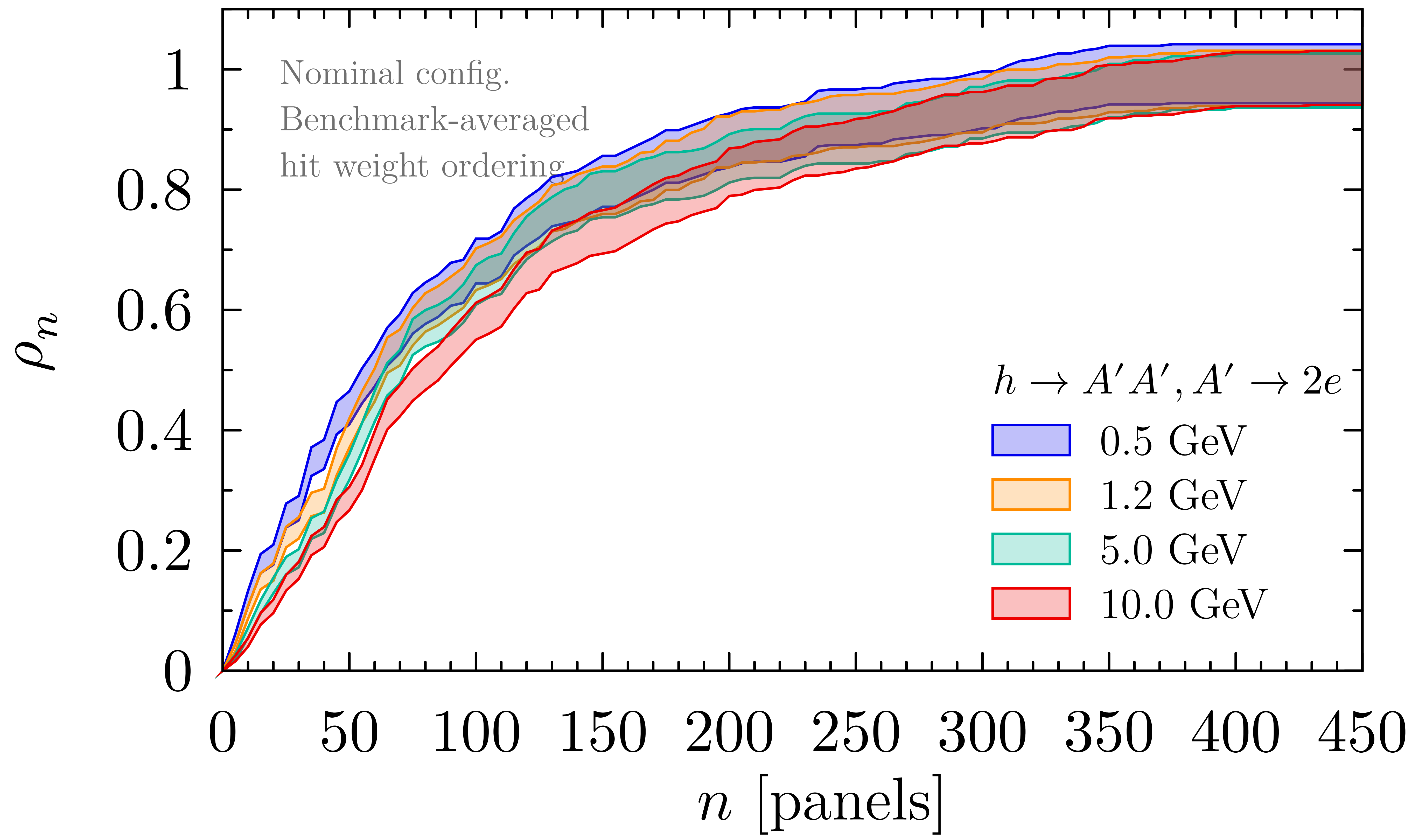


10x10x10 metre box, with 6 RPC layers on each box face. Add 5 other RPC triplet layers equally spaced to minimize the distance to the first measured point for the decay vertex determination.

Optimized geometry

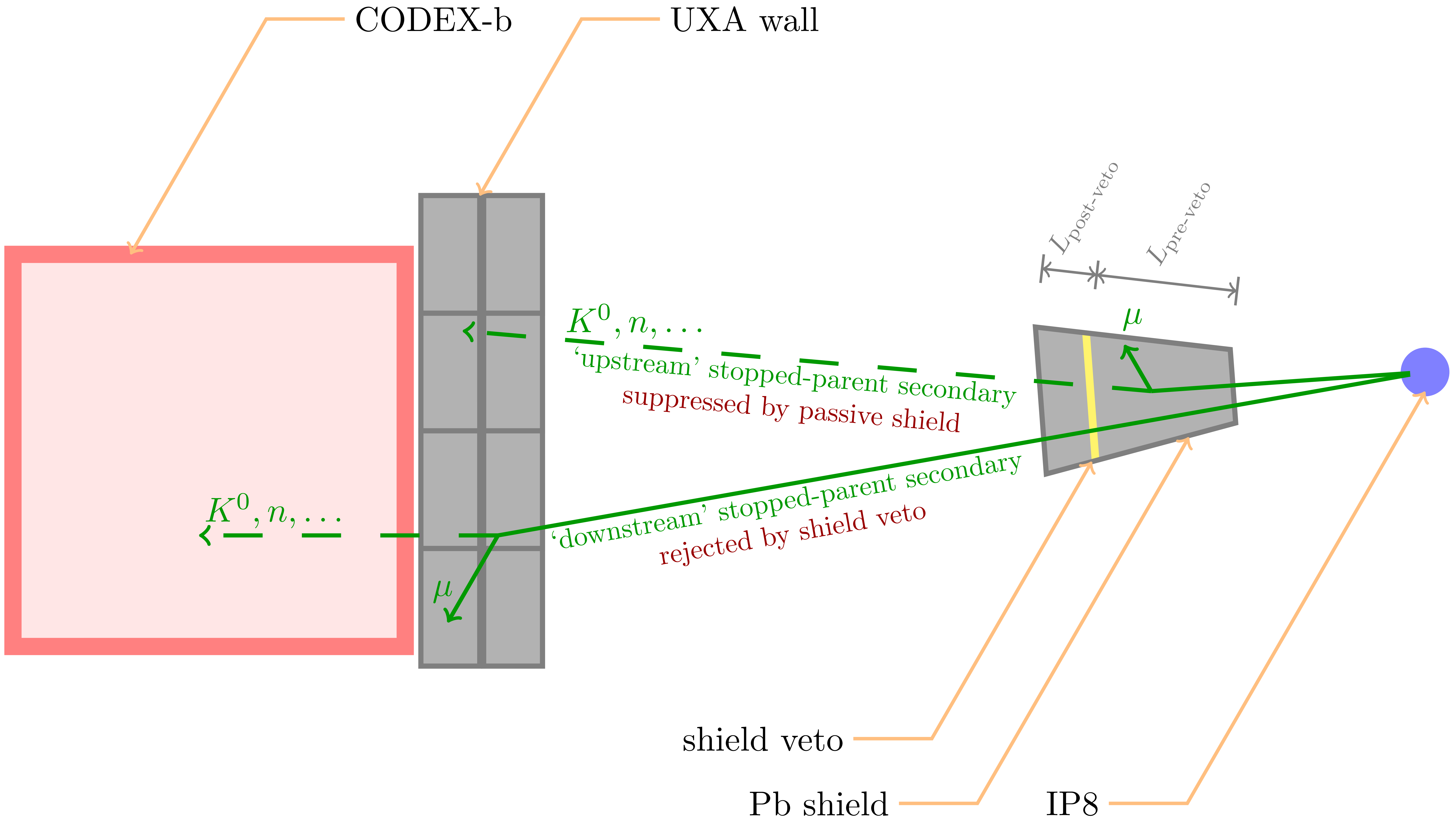
Road ahead for CODEX-b
Snowmass 2021 LOI
https://inspirehep.net/literature/2051244





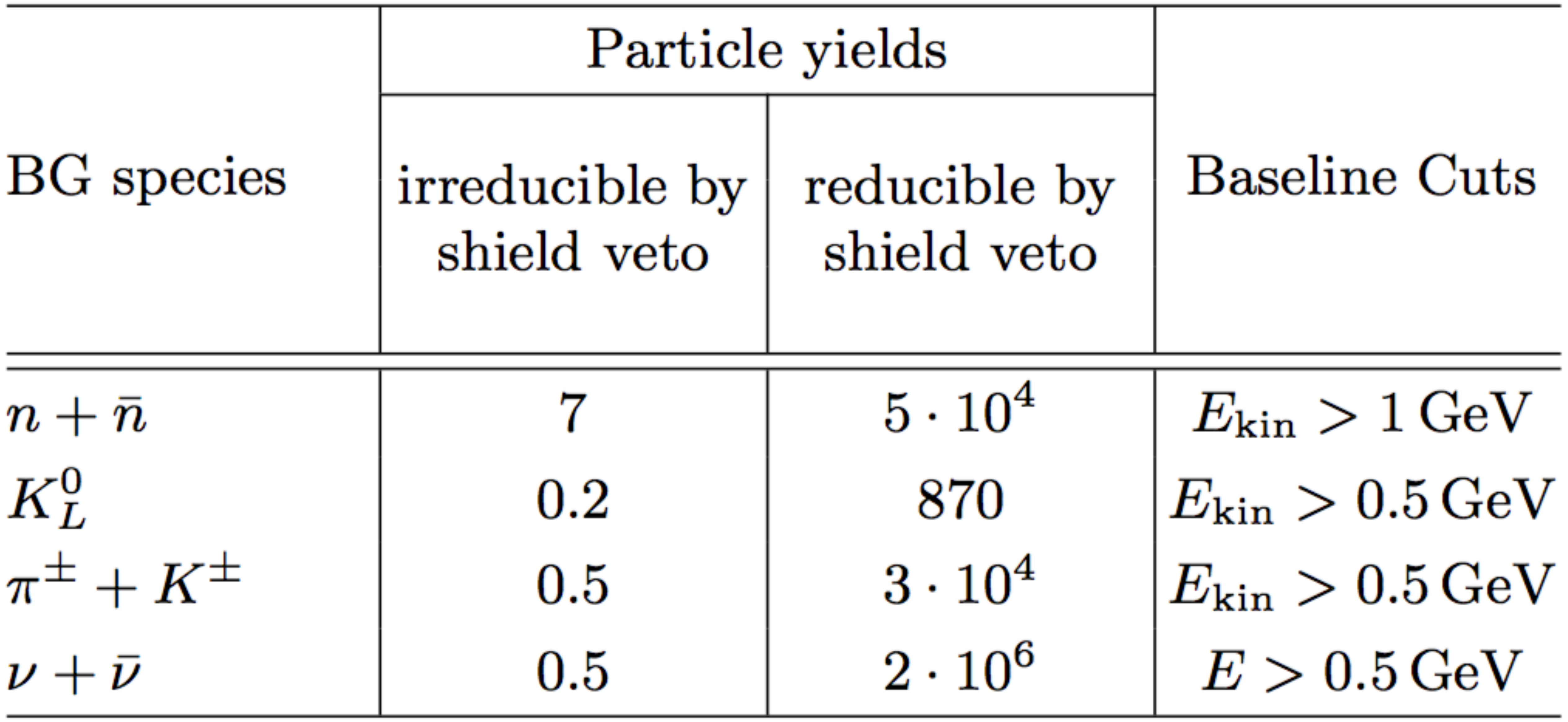
Recent studies show that we can optimize the layout reducing the number of RPC layers but almost a factor two while maintaining most of our sensitivity for many benchmarks — work ongoing

Minimal shield & veto design



First part of the shield attenuates muon & neutral hadron backgrounds which could enter the detector volume and scatter or decay within it. A thin active veto layer eliminates secondary production of backgrounds within the shield itself.

Basic GEANT background estimate



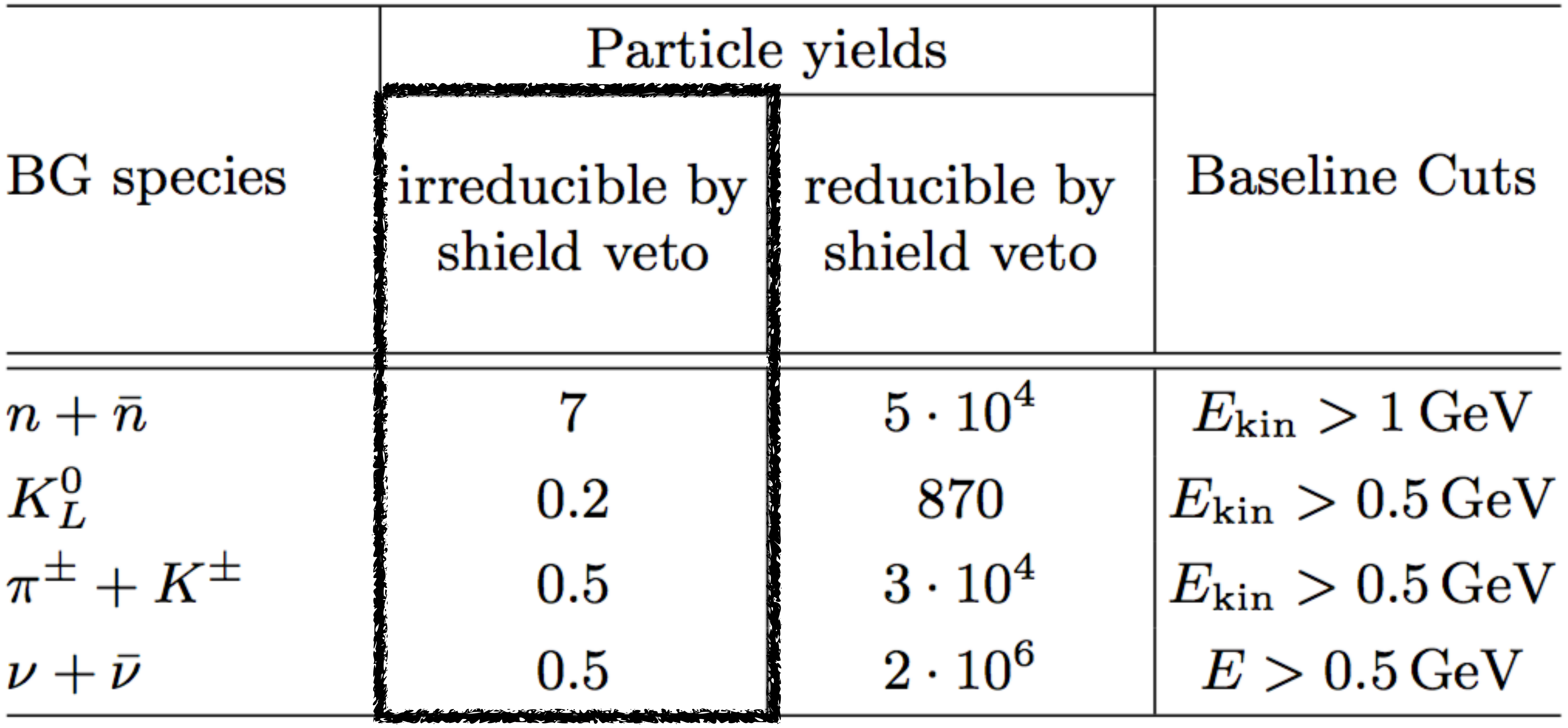
BG species	Particle yields		Baseline Cuts
	irreducible by shield veto	reducible by shield veto	
$n + \bar{n}$	7	$5 \cdot 10^4$	$E_{\text{kin}} > 1\,\text{GeV}$
K_L^0	0.2	870	$E_{\text{kin}} > 0.5\,\text{GeV}$
$\pi^\pm + K^\pm$	0.5	$3 \cdot 10^4$	$E_{\text{kin}} > 0.5\,\text{GeV}$
$\nu + \bar{\nu}$	0.5	$2 \cdot 10^6$	$E > 0.5\,\text{GeV}$

Simulate initial background flux with Pythia 8, propagate through shield, air, and detector using GEANT4. A few things to note :

— Nominally largest background is neutrons entering the box
— Muon-air interactions can be vetoed using front detector faces
— Neutrino backgrounds are entirely negligible.

No attempt yet to use any properties of reconstructed backgrounds to reject them, but timing + spatial information should help there.

Energy spectrum of backgrounds



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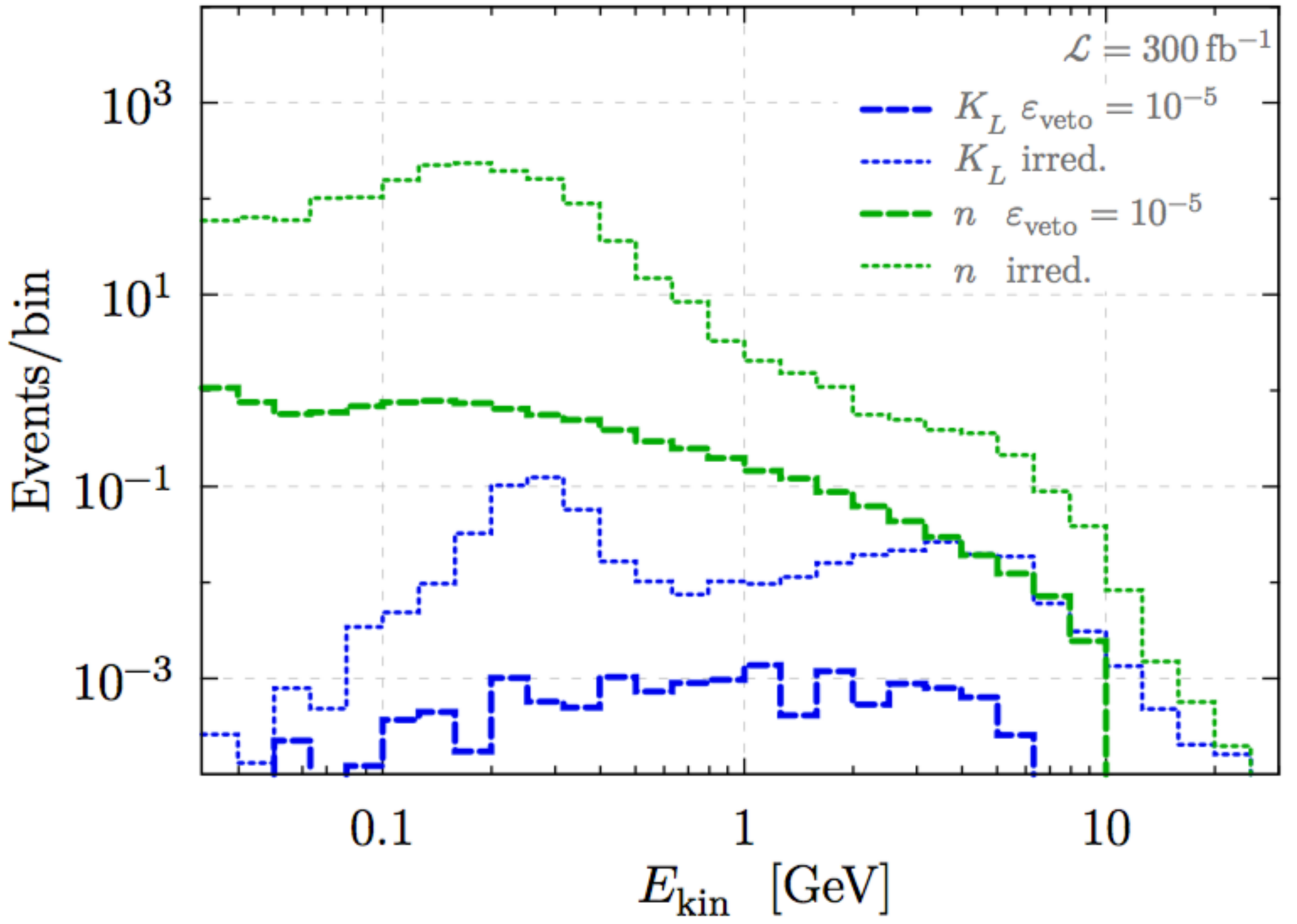
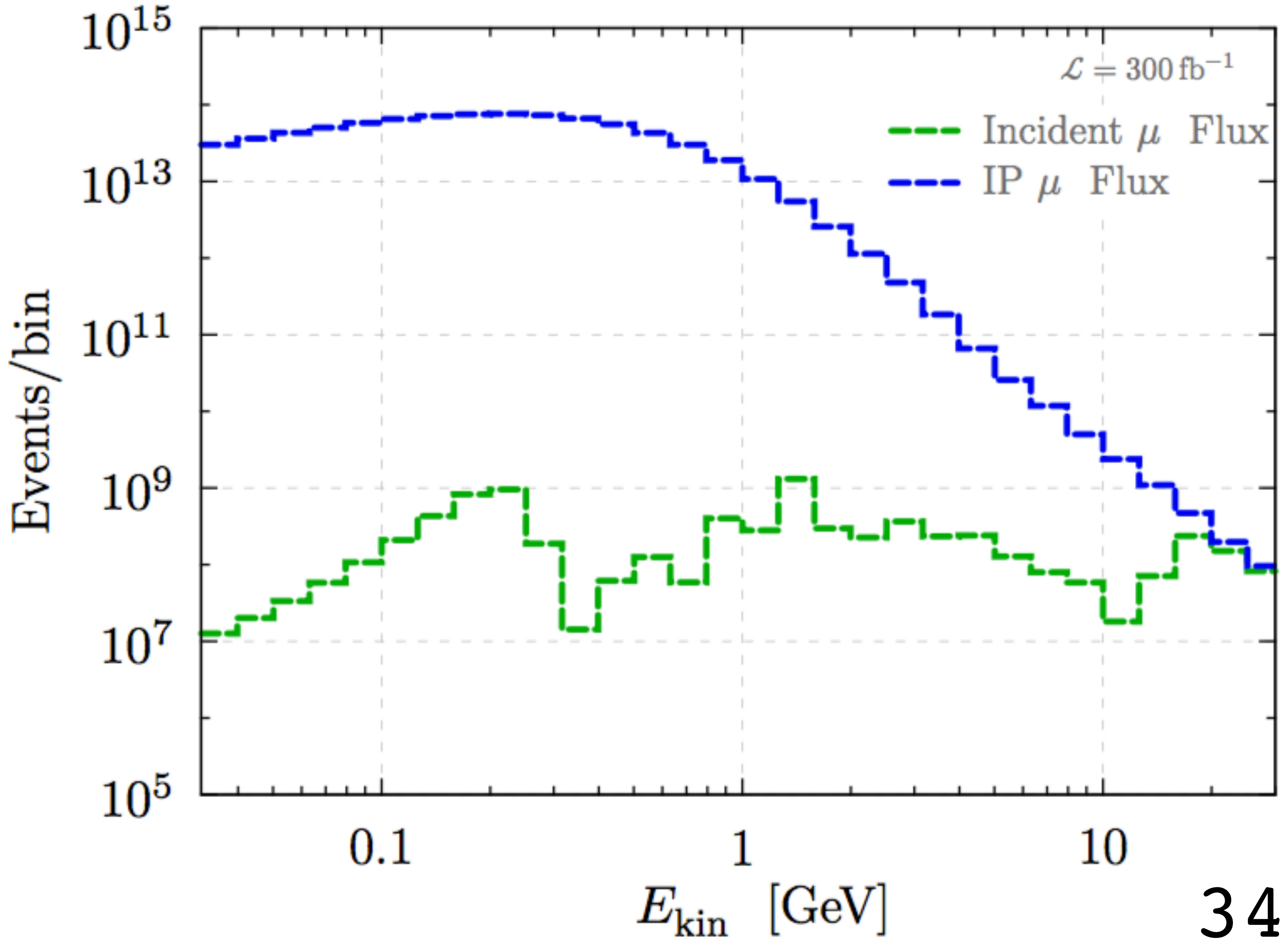


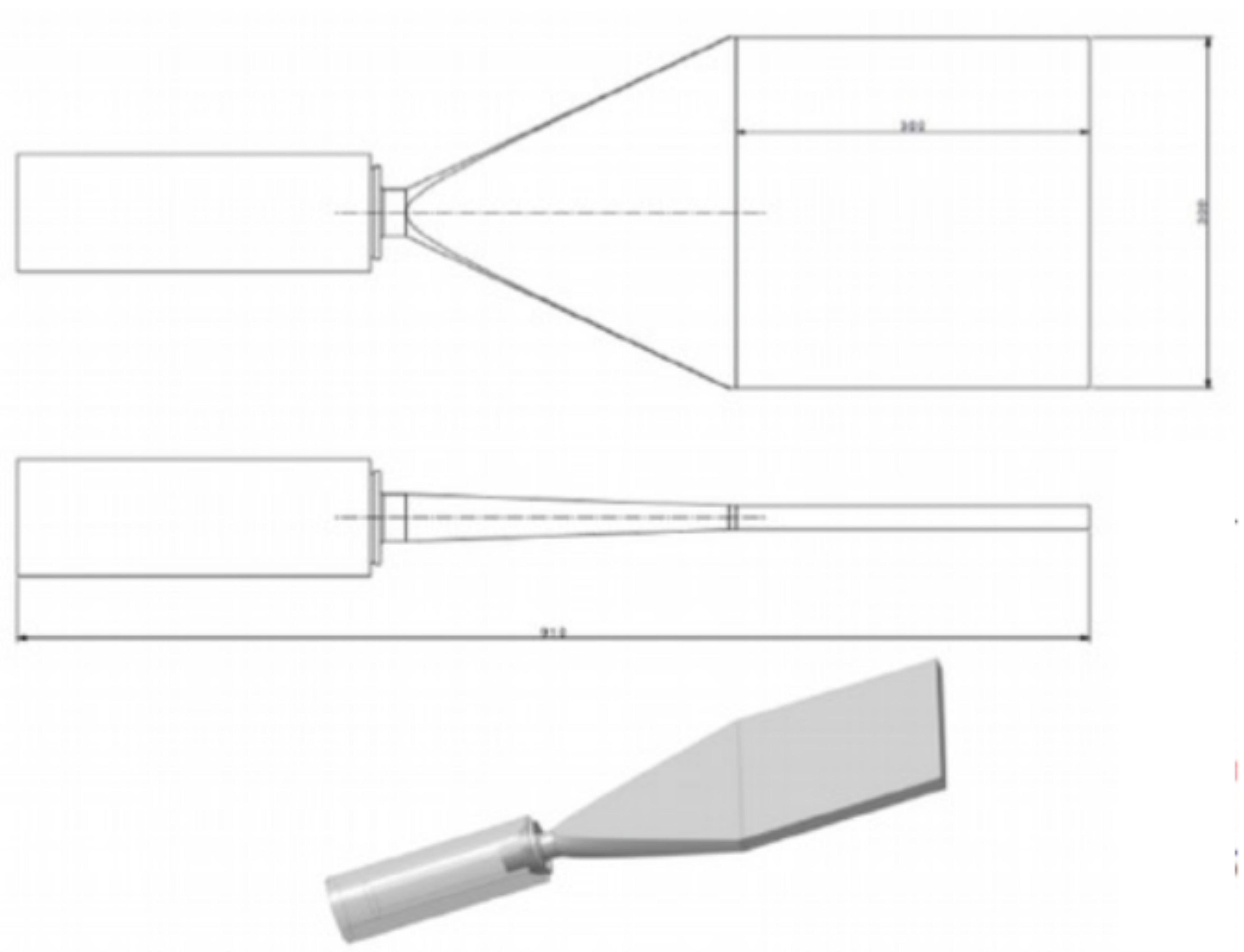


These are the numbers of unvetoable particles entering the box, the estimated number of scatters in box is <1 for all particle species!

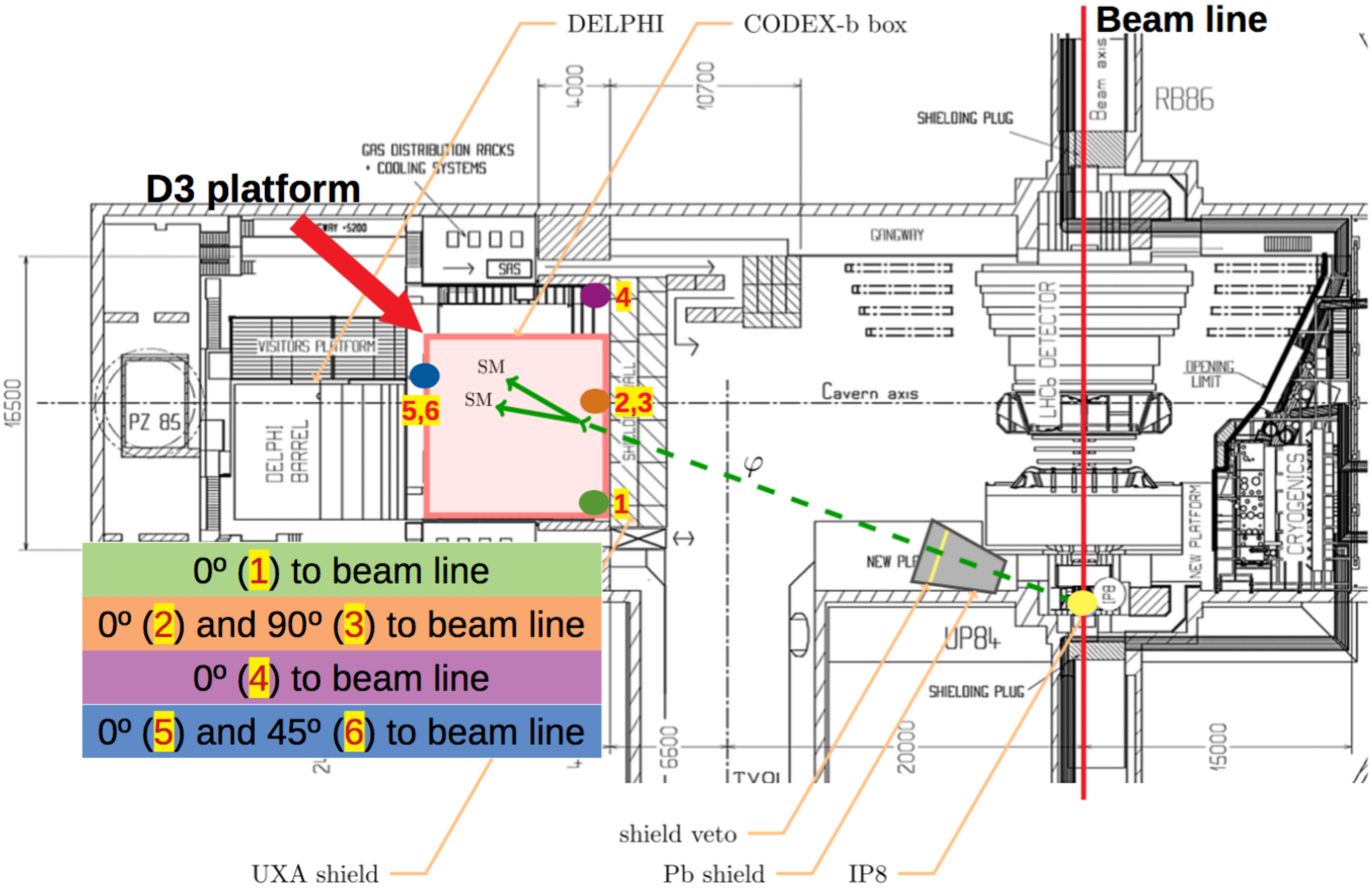
Also notice the energy spectrum of these particles : most of them, especially the neutrons, are very soft!

Backgrounds from data

- Two 30 × 30 × 2 cm wrapped plastic scintillators + PMT + mechanical stand.



Placement of scintillators in cavern



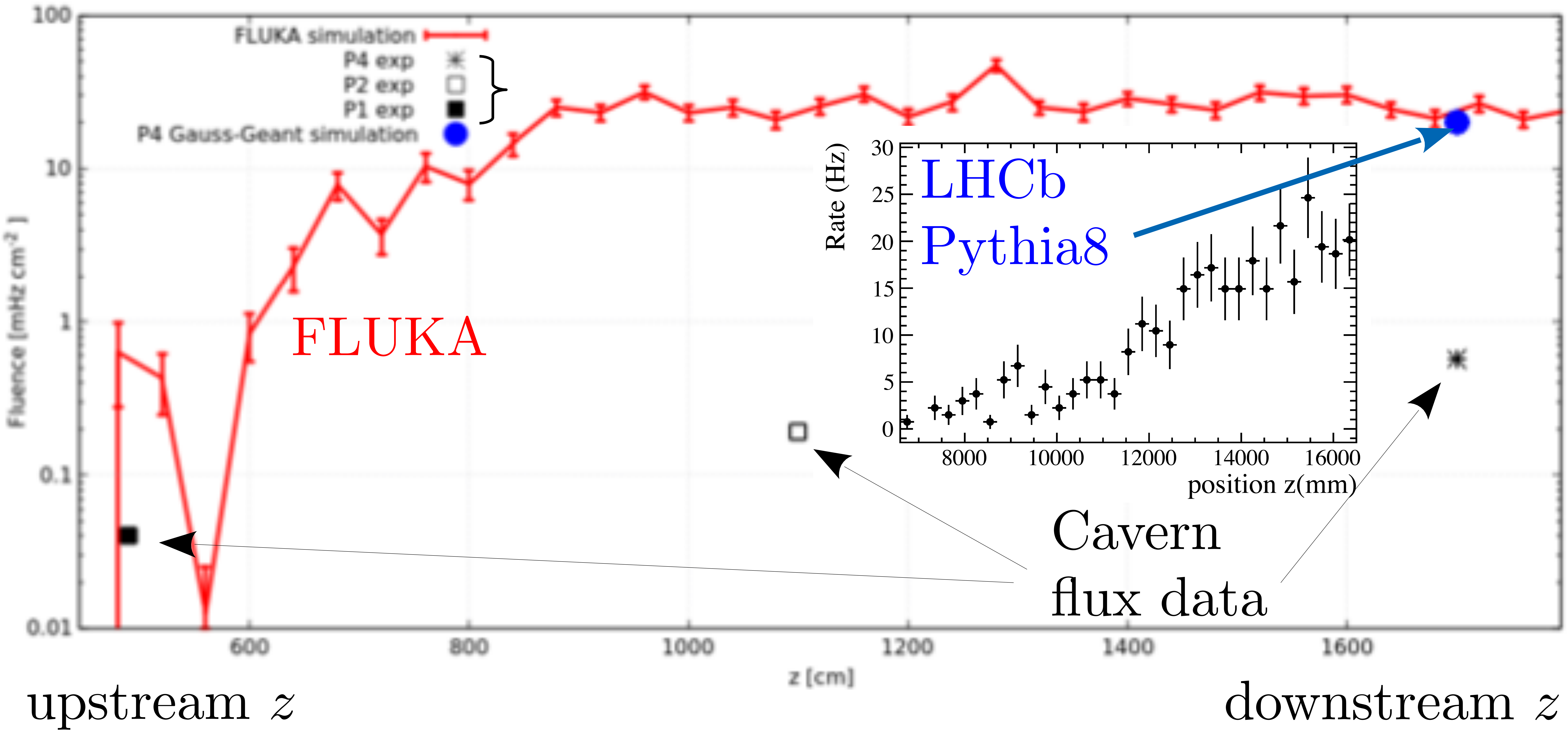
0º (1) to beam line

0º (2) and 90º (3) to beam line

0º (4) to beam line

0º (5) and 45º (6) to beam line

Results

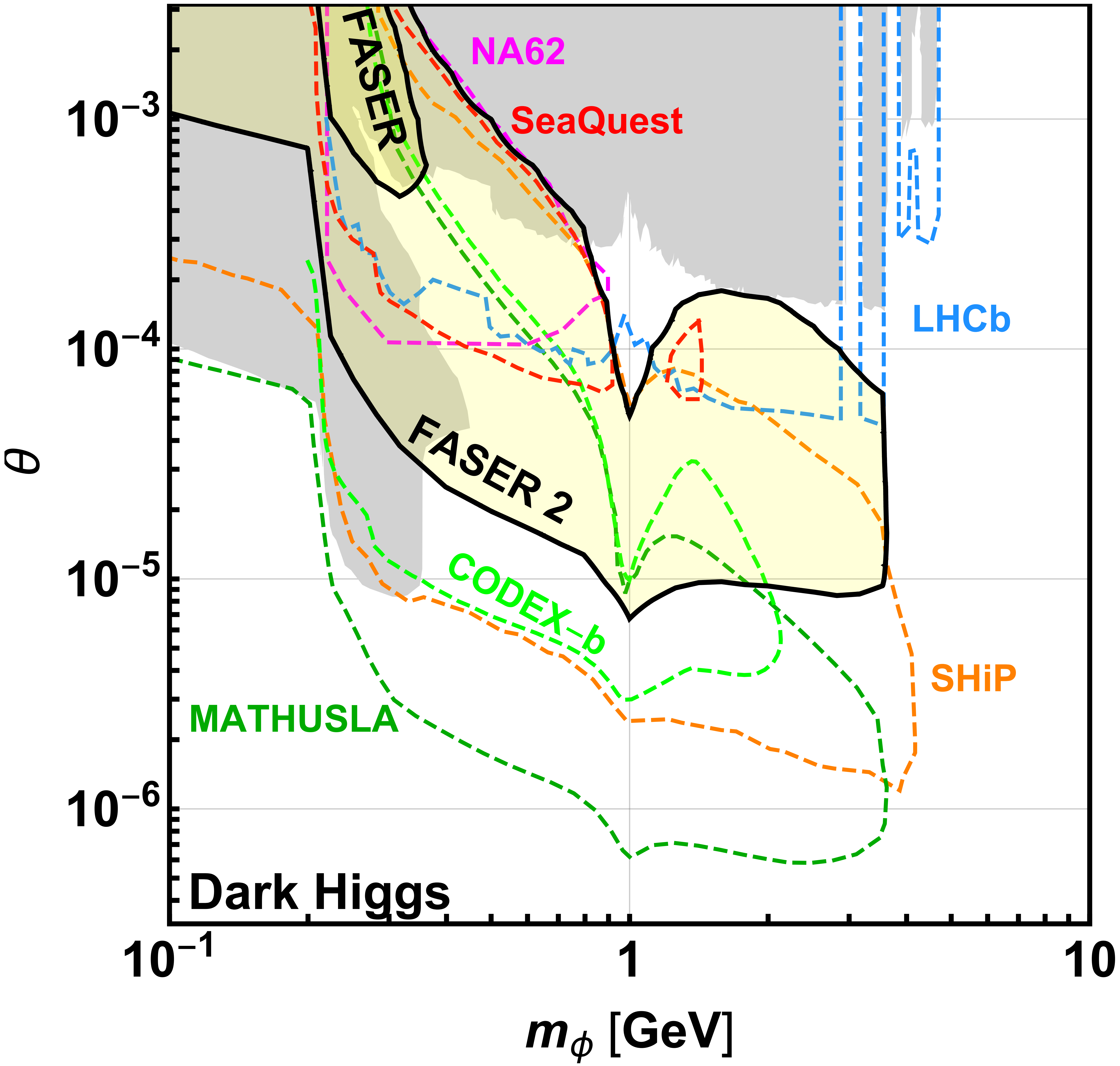


Implies an O(100)Hz hit rate over the whole front face of the detector with only the concrete wall shielding. Better than expected from simulation because of additional structures in cavern!

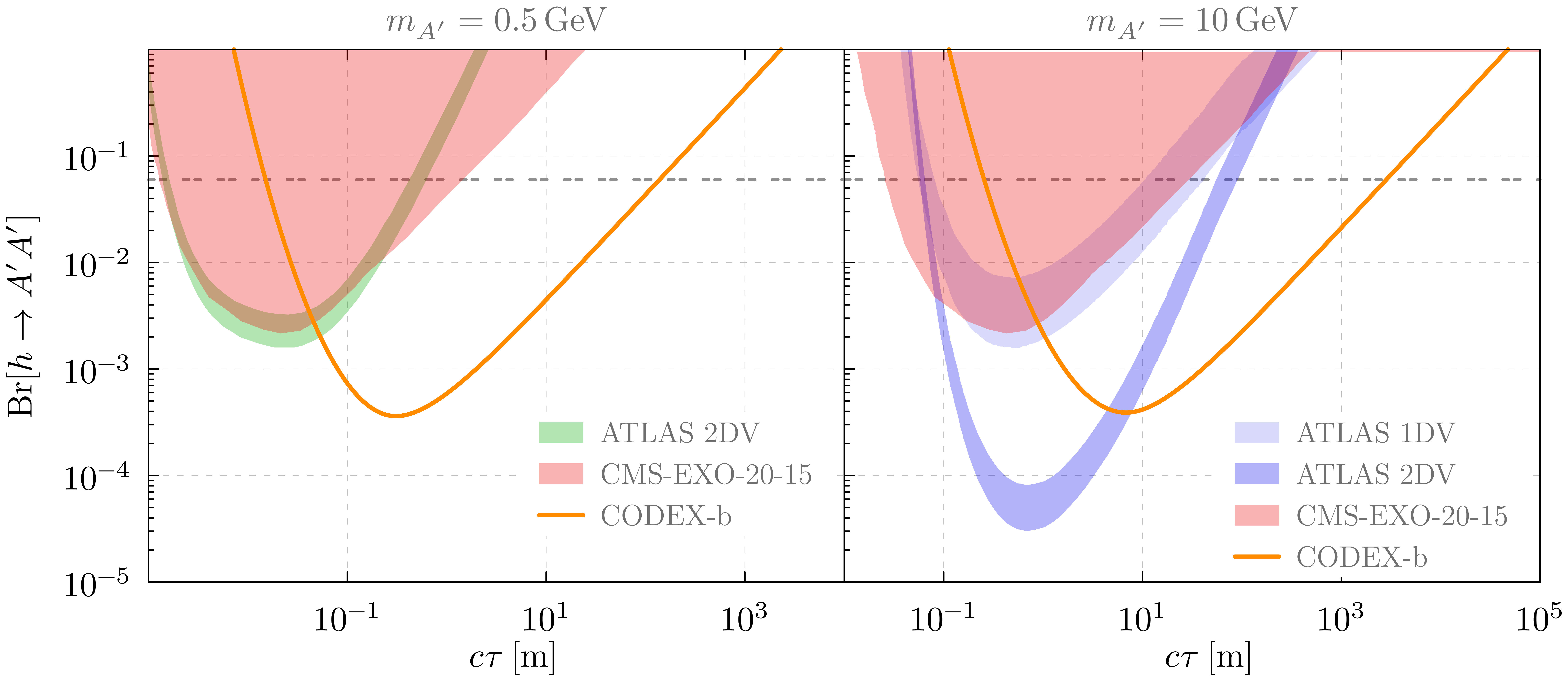
CODEX-b signal reach & ID

Example model 1 — b→sX

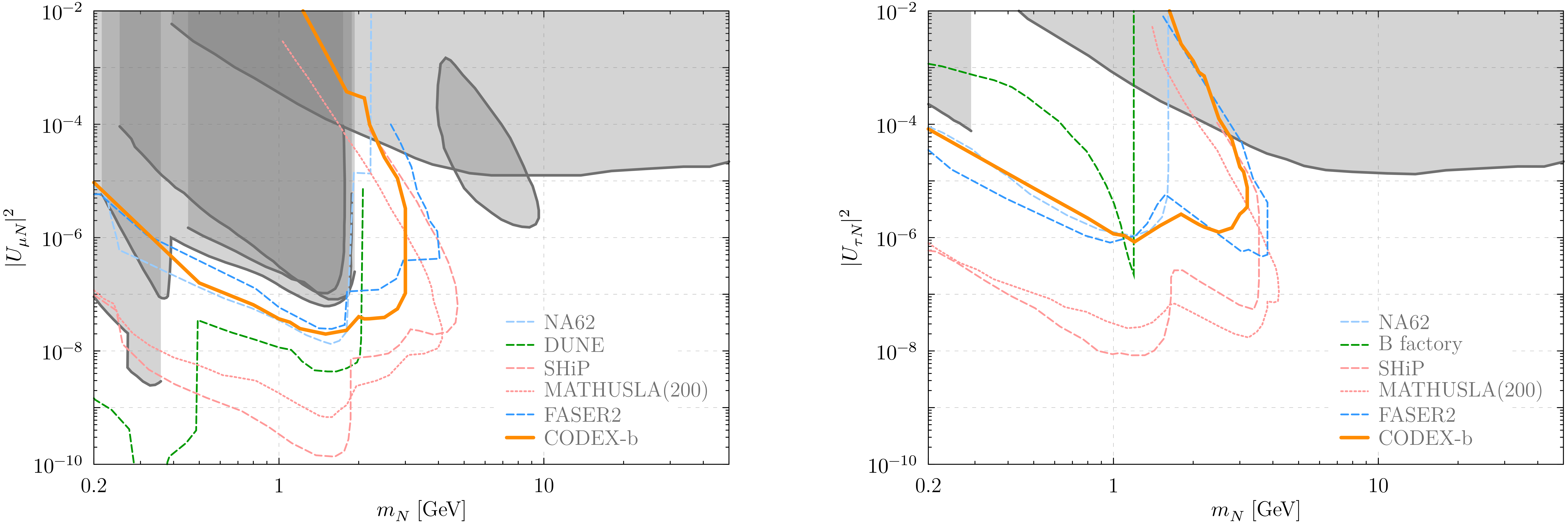
2019 LLP White Paper
https://inspirehep.net/literature/1724682



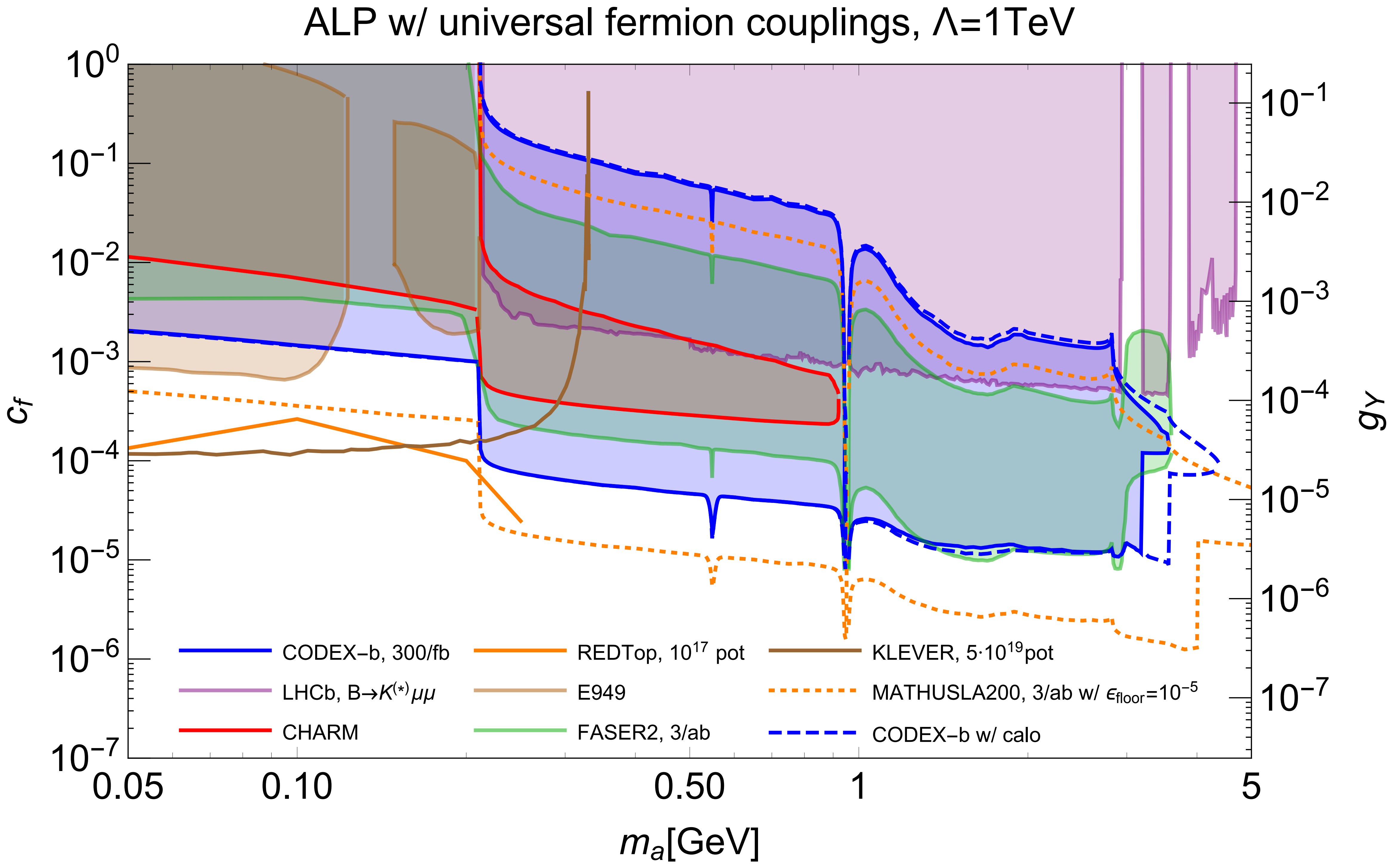
Example model 2 — H→φφ

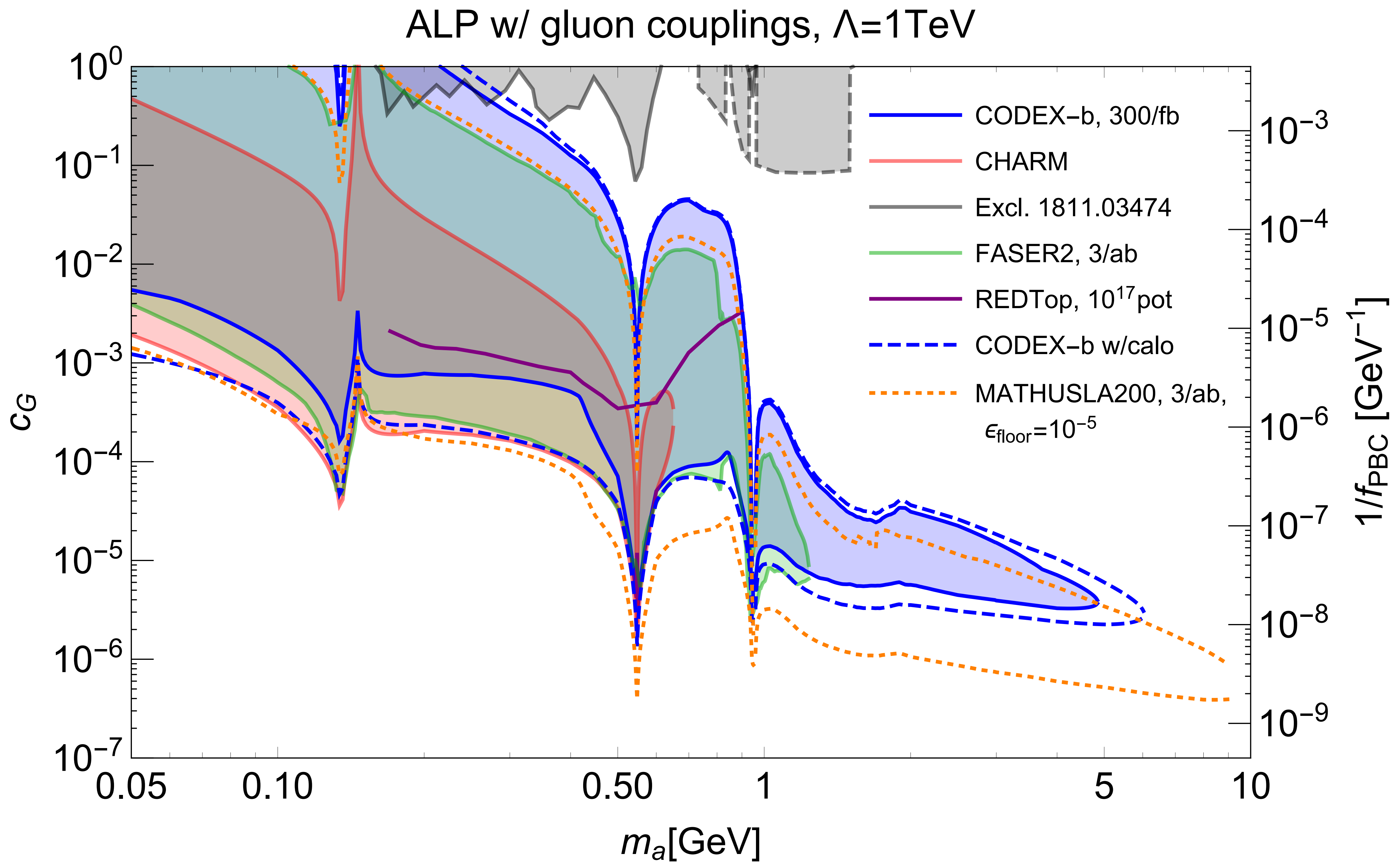


Example model 3 — HNL



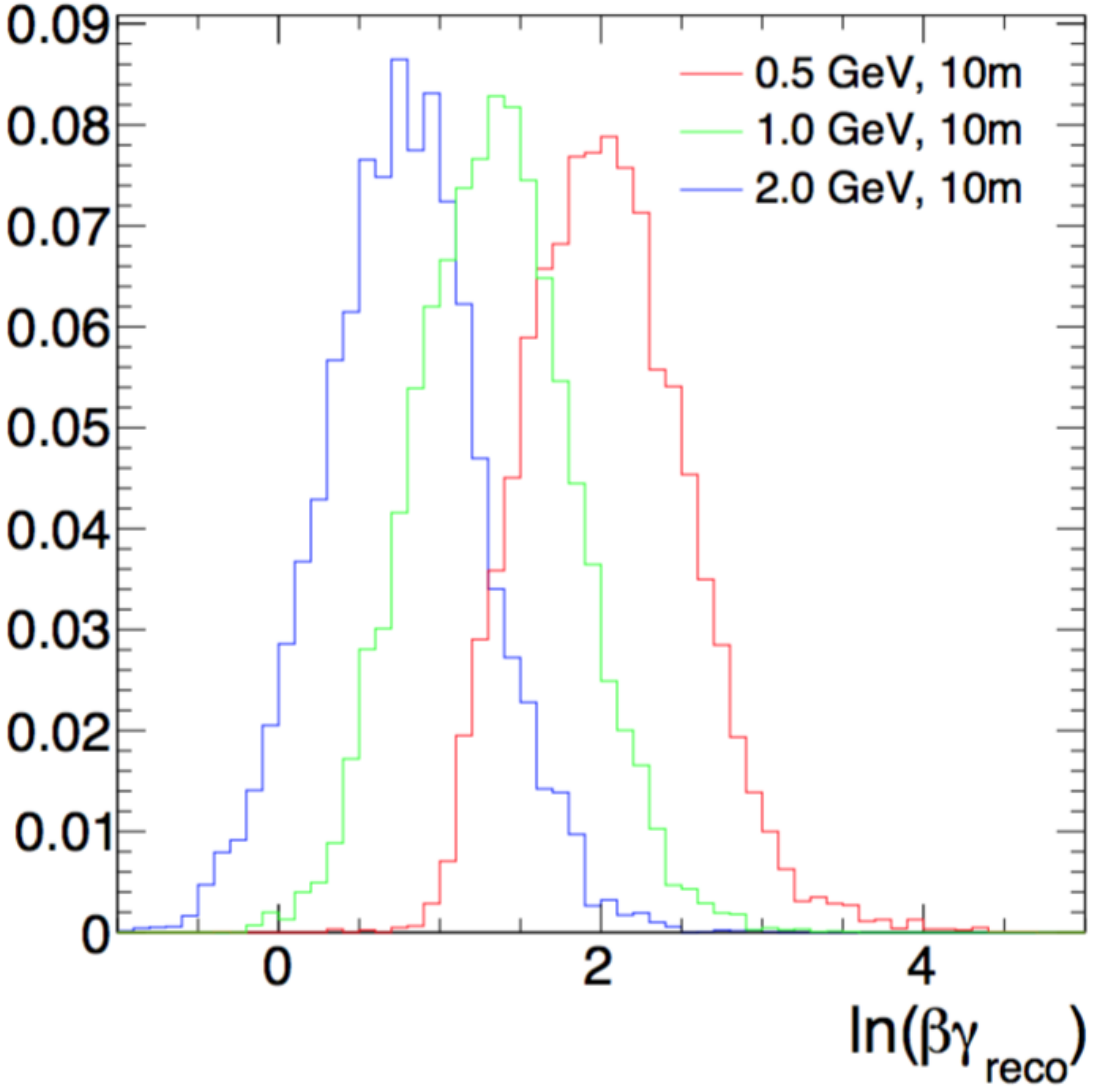
Example model 4 — ALP



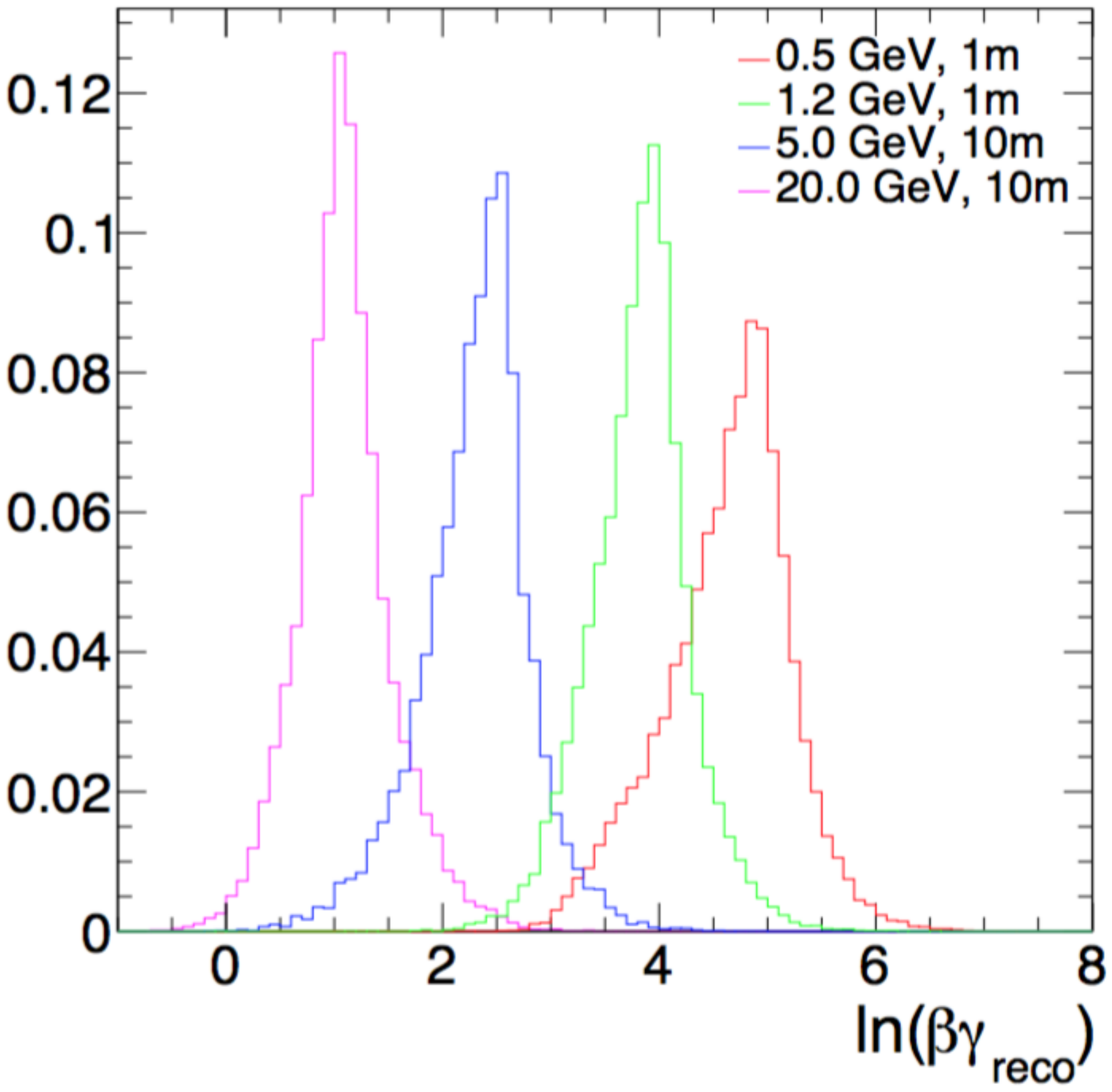


Boost reconstruction

$B \to X_s \varphi$

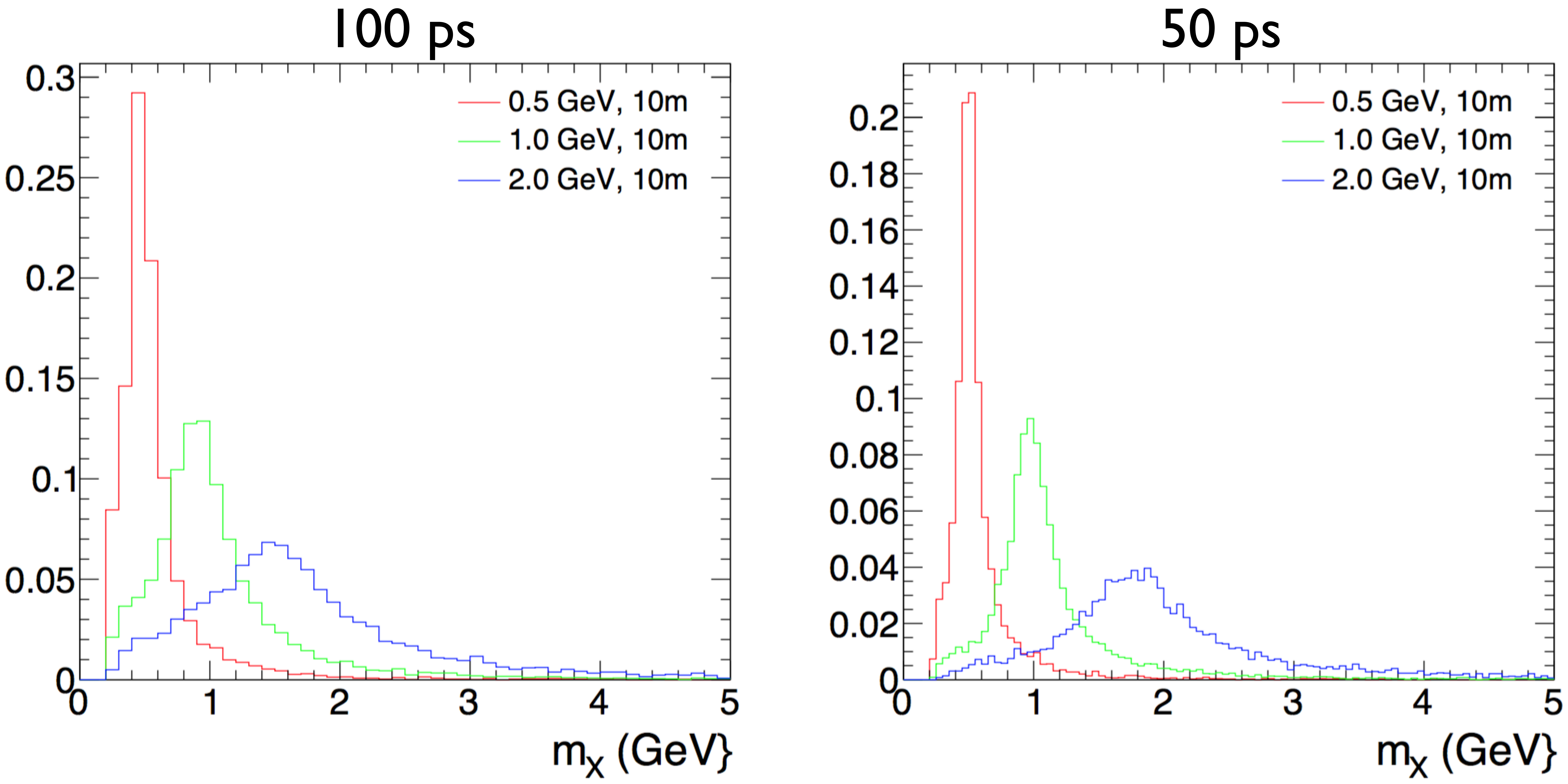


$H \to \varphi\varphi$



Different intial states give different boost distributions; we have some discriminating power between even the B→KX scenarios!

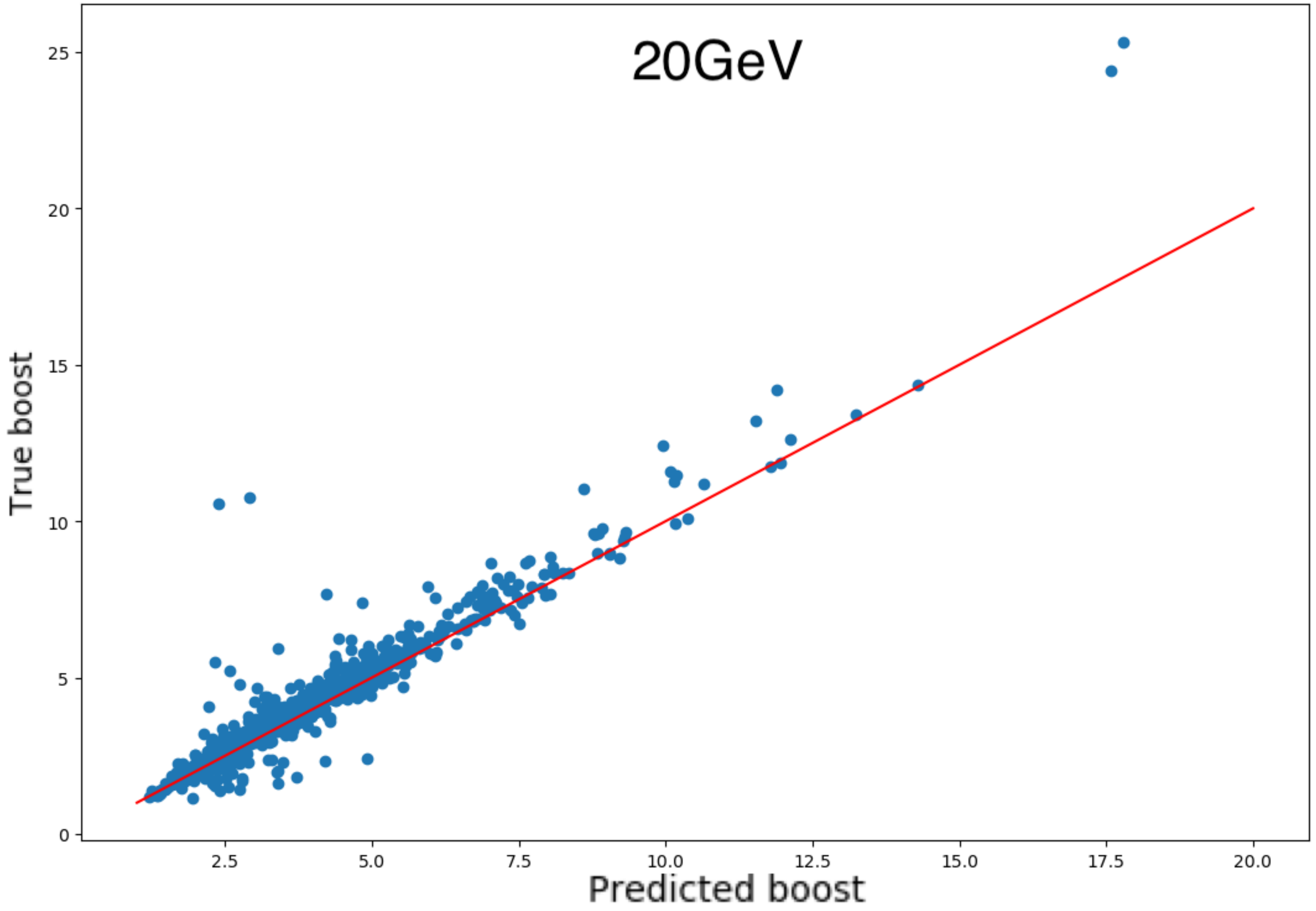
Mass reconstruction using time-of-flight

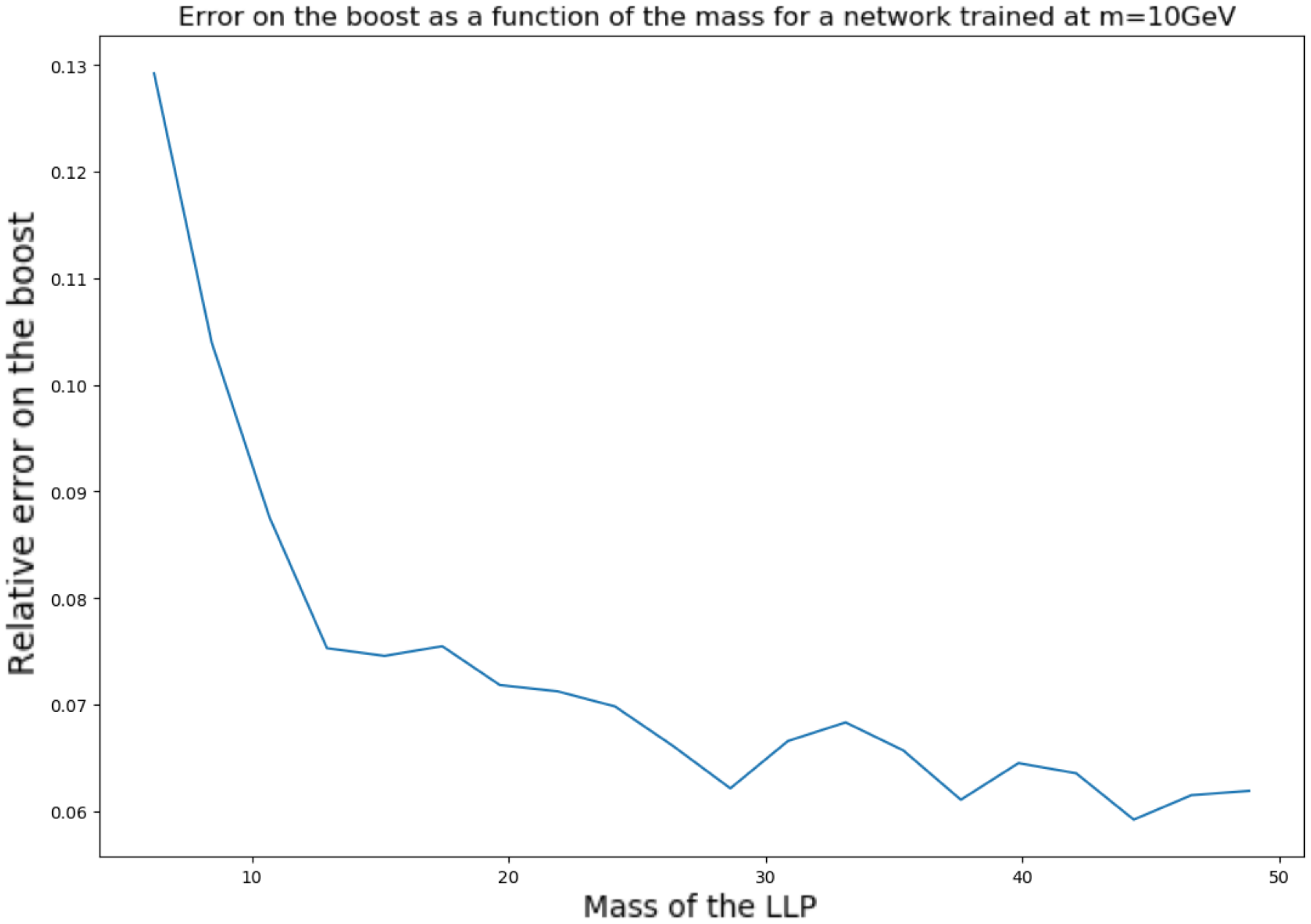


Now assume 100/50 ps time resolution (per hit) in the tracking stations. The B→KX signals are actually slow enough that we can reconstruct the X mass…

Reconstructing X→ττ→6π2ν

Master thesis of Robin Quessard, ENS-LPNHE

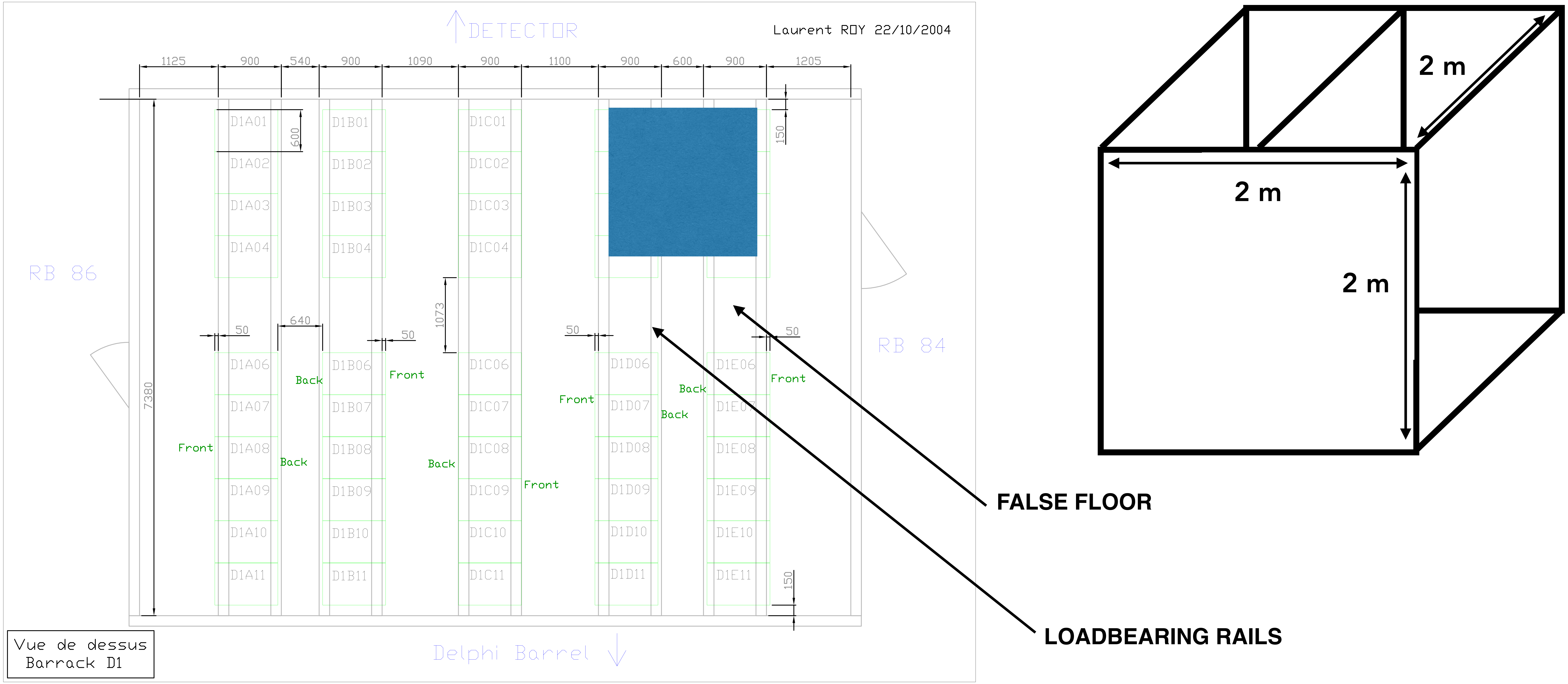




No analytic solution but can train neutral network to reconstruct the boost!
Surprisingly reasonable boost resolutions achievable depending on the mass.

CODEX-b timeline and installation

The CODEX-β demonstrator



FALSE FLOOR

LOADBEARING RAILS

To be installed in the old LHCb HLT server room, 2x2x2 metre cube

Integration with LHCb DAQ

What is better than a smart solution? Not having a problem

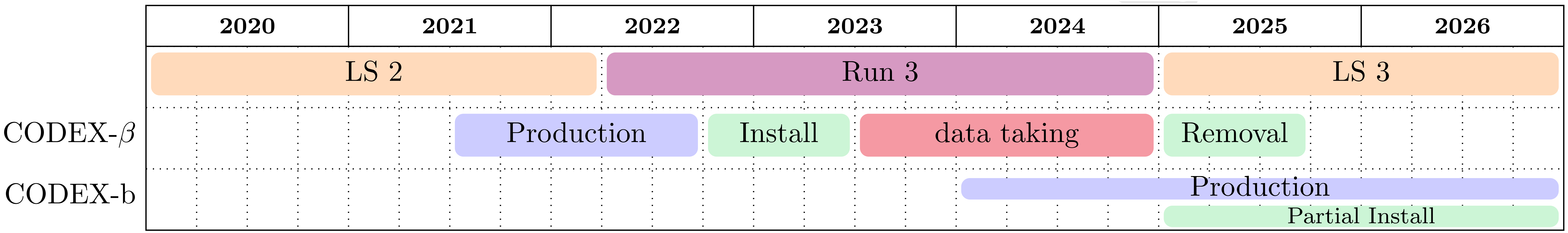
LHCb operates a triggerless DAQ

CODEX-b can plug into this exactly the same way as our muon chambers (it is almost the same distance from the interaction point)

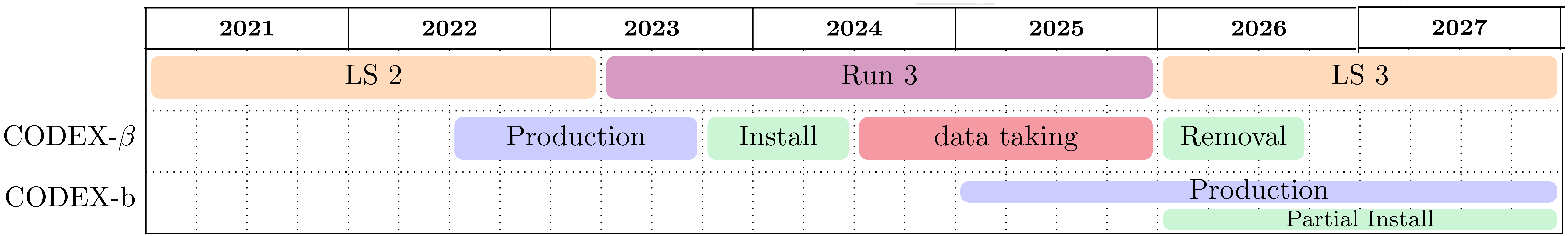
One FPGA readout board can handle the whole demonstrator, scales by construction without extra work for full CODEX-b

Extra data rate is tiny compared to LHCb — total non-issue

The best laid plans…



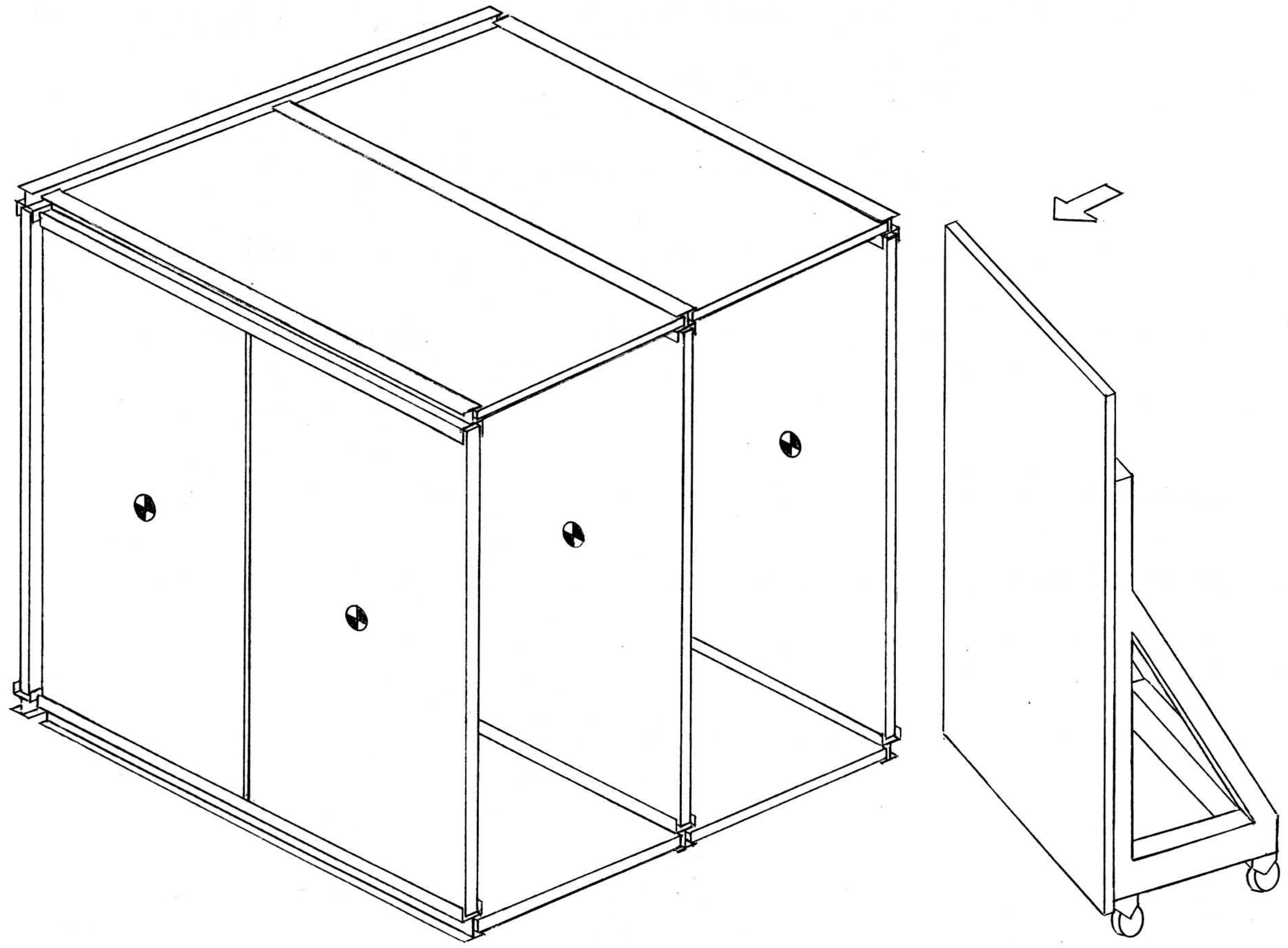
The best laid plans... shifted by a year

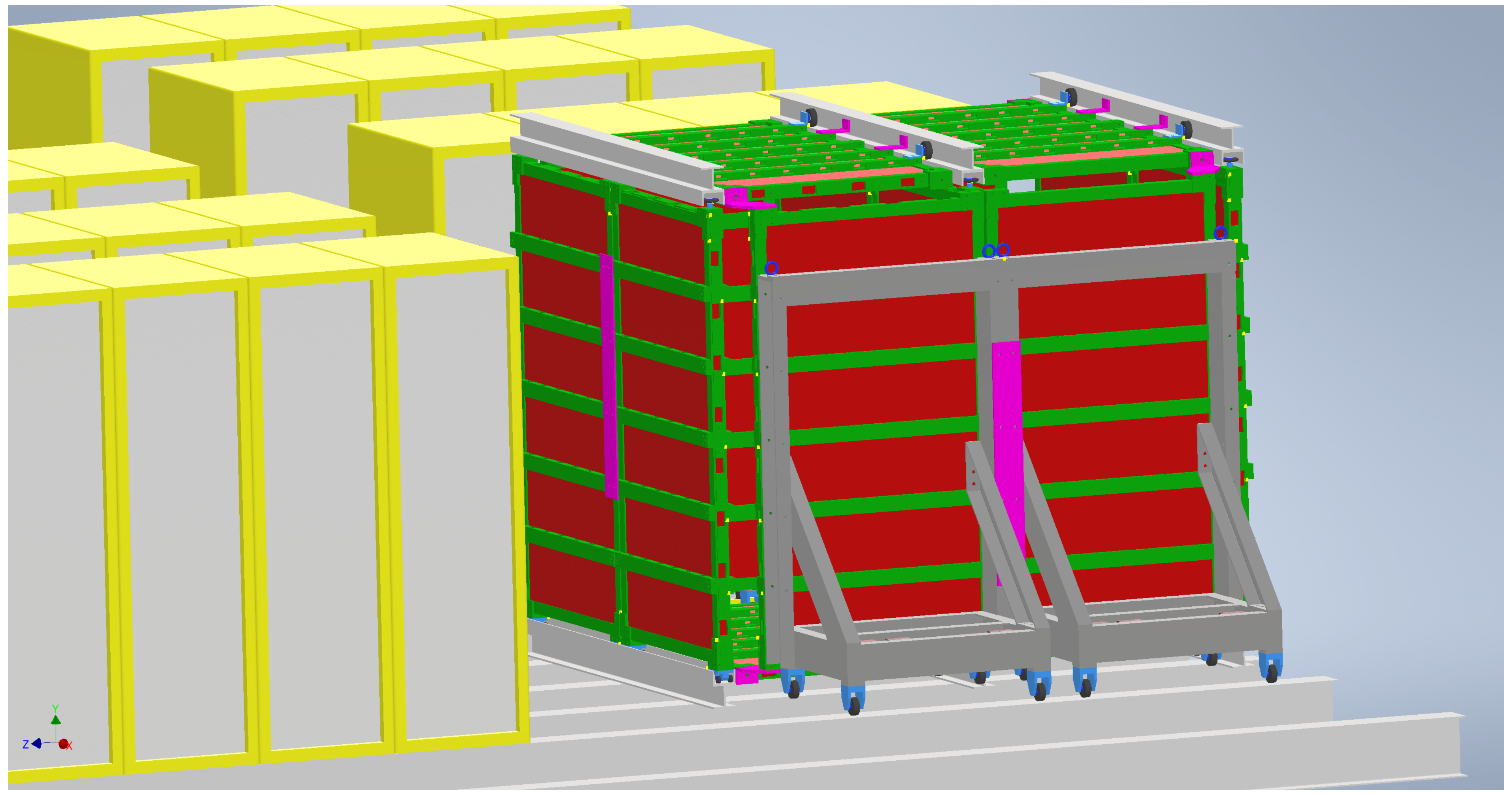


But we keep going

Road ahead for CODEX-b
Snowmass 2021 LOI
https://inspirehep.net/literature/2051244

1. Demonstrator location secured
2. Funding to build RPC chambers secured
3. Mechanical design done
4. Everything in place to integrate with LHCb DAQ
5. Plan to produce modules 2nd half this year, then install
6. CERN-based team secured to commission demonstrator





Conclusion

Conclusion

Interest in direct LLP searches is a natural consequence of

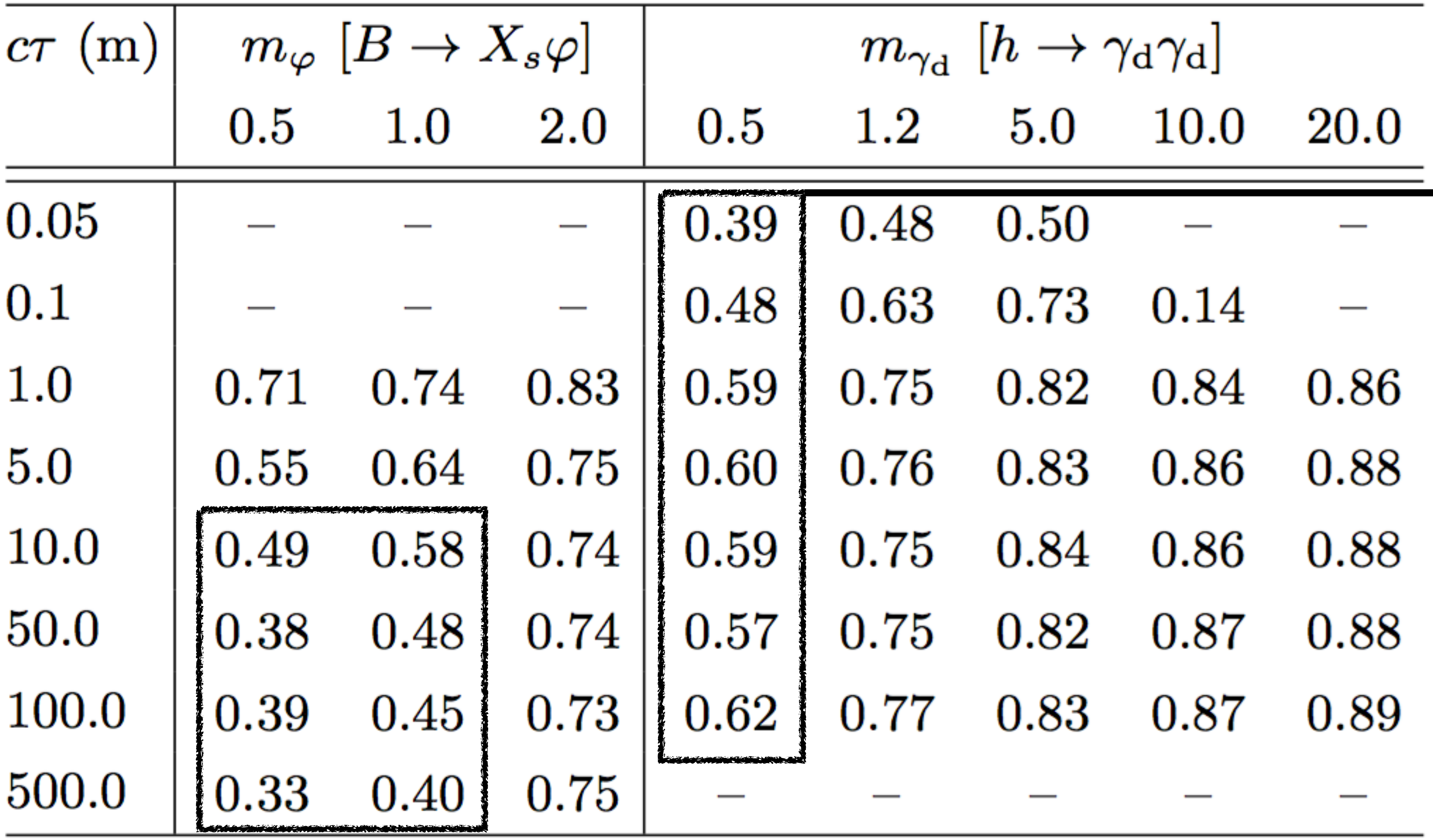
1. Almost any BSM physics generates some such particles
2. No direct signs of short-lived particles beyond the SM
3. Plausible LLPs have been missed in current detectors

A wide range of complementary experiments are being proposed, to see which get built. I've tried to convince you why CODEX-b deserves to be among the built ones.

Thank you to the organisers for the invite!

Backups

Tracker efficiency estimate



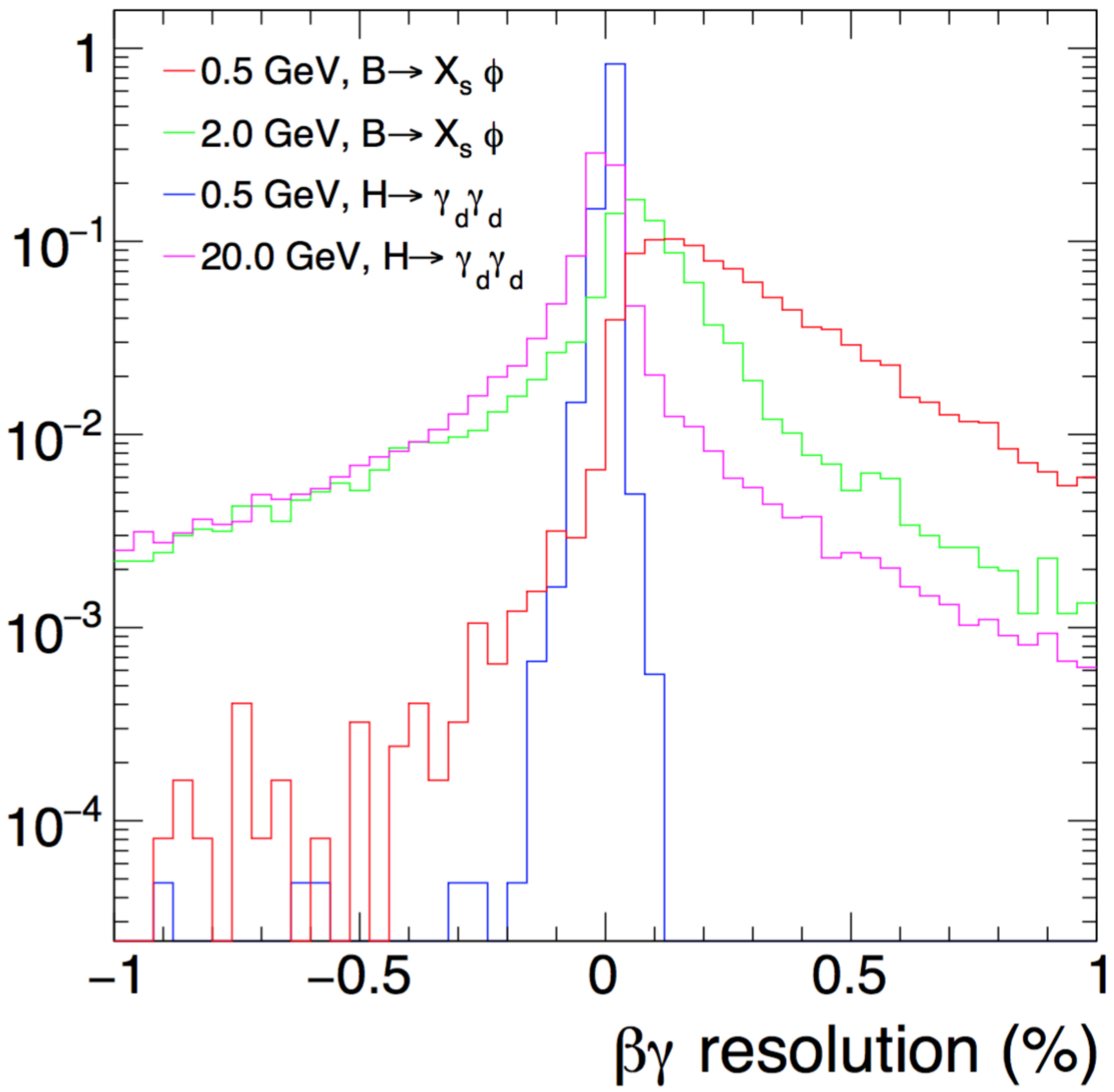
$c\tau$ (m)	m_φ $[B \to X_s\varphi]$			m_{γ_d} $[h \to \gamma_\mathrm{d}\gamma_\mathrm{d}]$				
	0.5	1.0	2.0	0.5	1.2	5.0	10.0	20.0
0.05	–	–	–	0.39	0.48	0.50	–	–
0.1	–	–	–	0.48	0.63	0.73	0.14	–
1.0	0.71	0.74	0.83	0.59	0.75	0.82	0.84	0.86
5.0	0.55	0.64	0.75	0.60	0.76	0.83	0.86	0.88
10.0	0.49	0.58	0.74	0.59	0.75	0.84	0.86	0.88
50.0	0.38	0.48	0.74	0.57	0.75	0.82	0.87	0.88
100.0	0.39	0.45	0.73	0.62	0.77	0.83	0.87	0.89
500.0	0.33	0.40	0.75	–	–	–	–	–

Dominated by partial overlap of decay products due to small opening angle, can be optimized using station spacing and granularity

Dominated by assumption that we don't track below 600 MeV of momentum, conservative since clearly we won't just fall off a cliff, but needs proper simulation

Bottom line : these are O(1) numbers, not O(%), can be optimized further

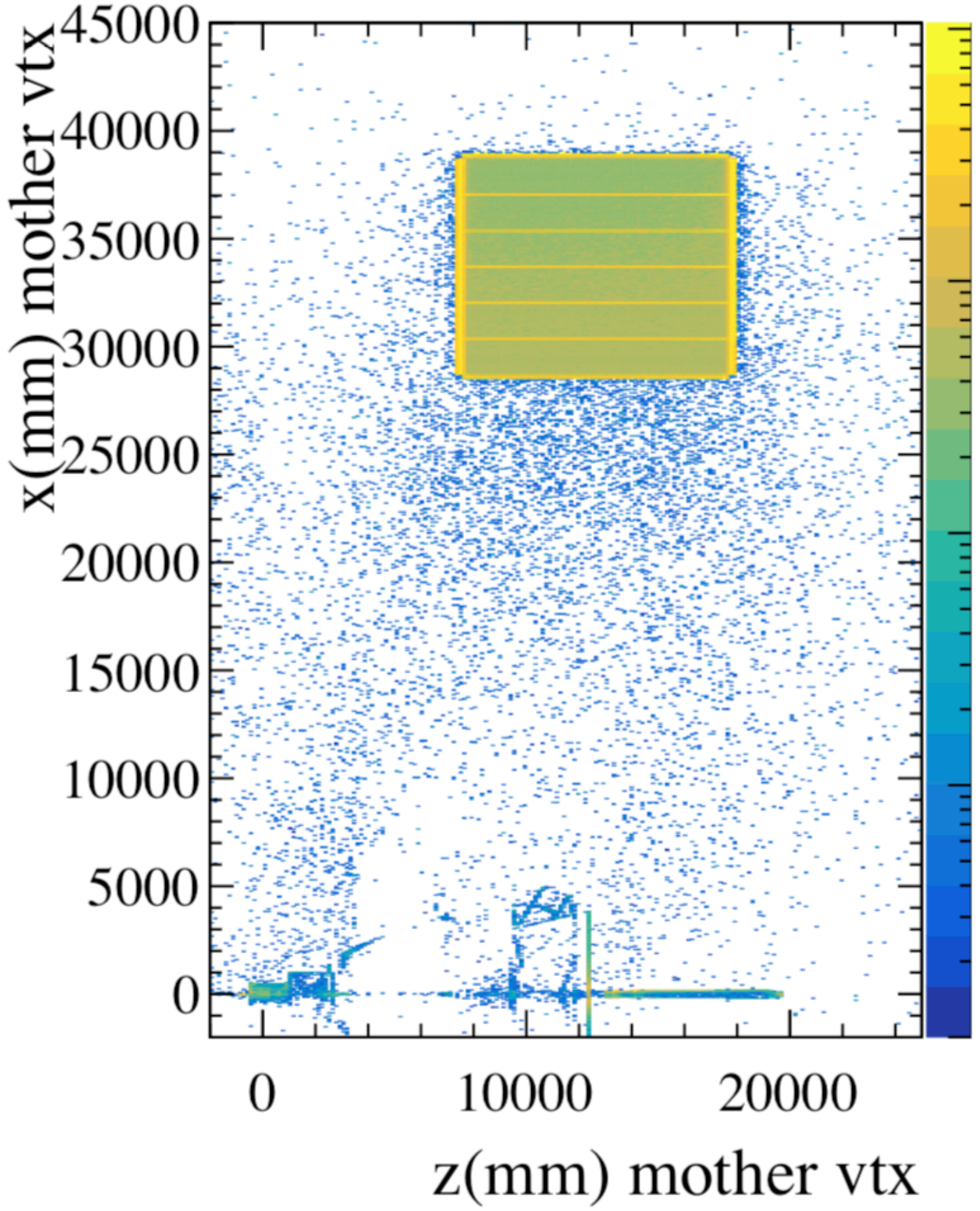
Boost reconstruction



Reconstruct parent boost from the measured decay vertex (no timing!), assuming relativistic decay products. The resolution is < 1% (entirely dominated by distance to first measured point, not detector granularity) so the boost distribution is dominated by the generated spread of boosts, not resolution.

Machine backgrounds

- Around 0.6 M hits produced, almost all e^+, with mom as $\gamma/e/\mu$.
- Hit energy deposit < 0.3 MeV. Source of the track hits, mostly scattering in the volume.

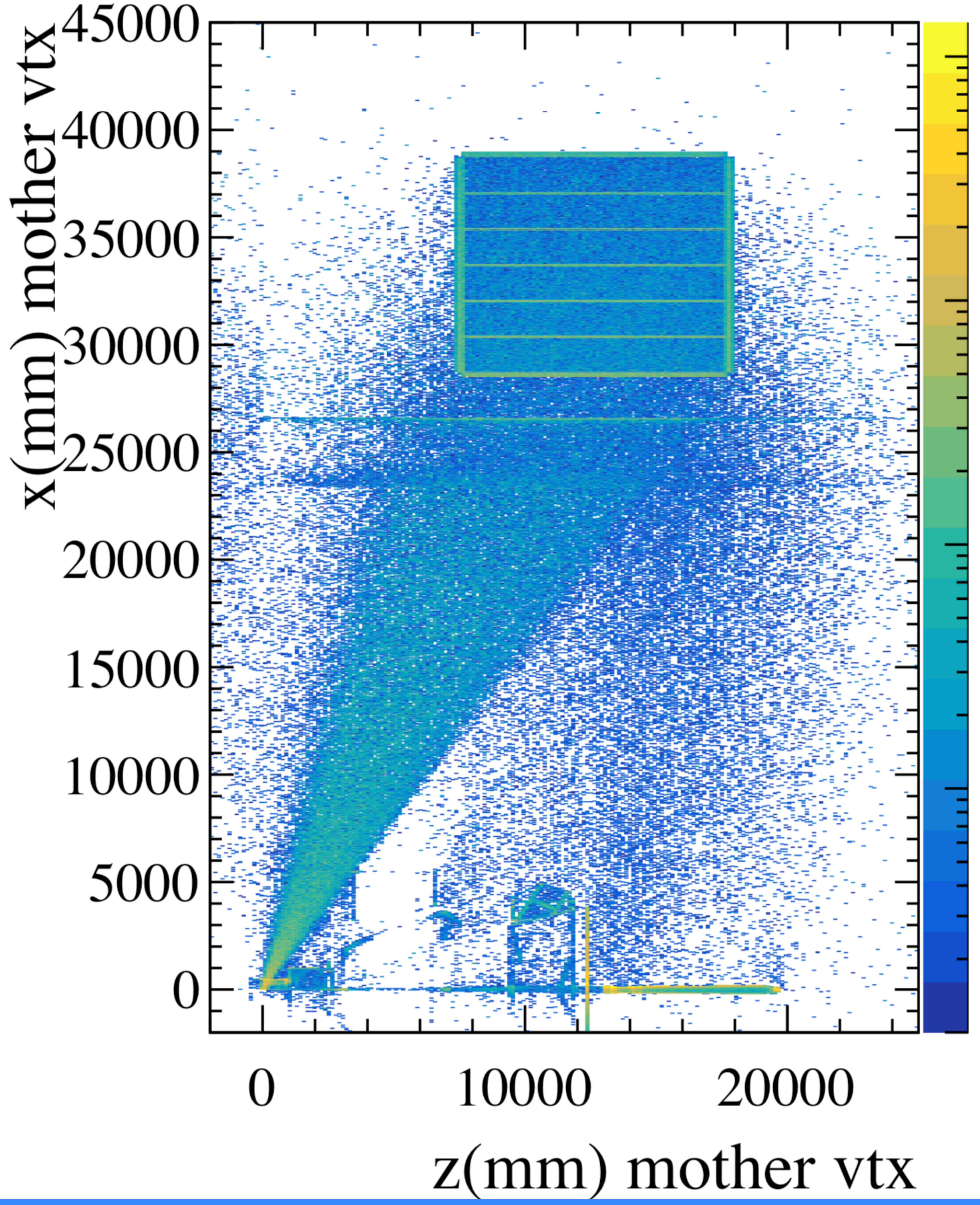


Note that current geometry is actually a silicon detector for simplicity, we are working to implement a realistic RPC based geometry and simulate signal.

Minbias

Work ongoing to understand agreement with data measurements

Next: generate signal with realistic RPC geometry, measure resolutions and hit efficiencies, validate tracking efficiency estimates

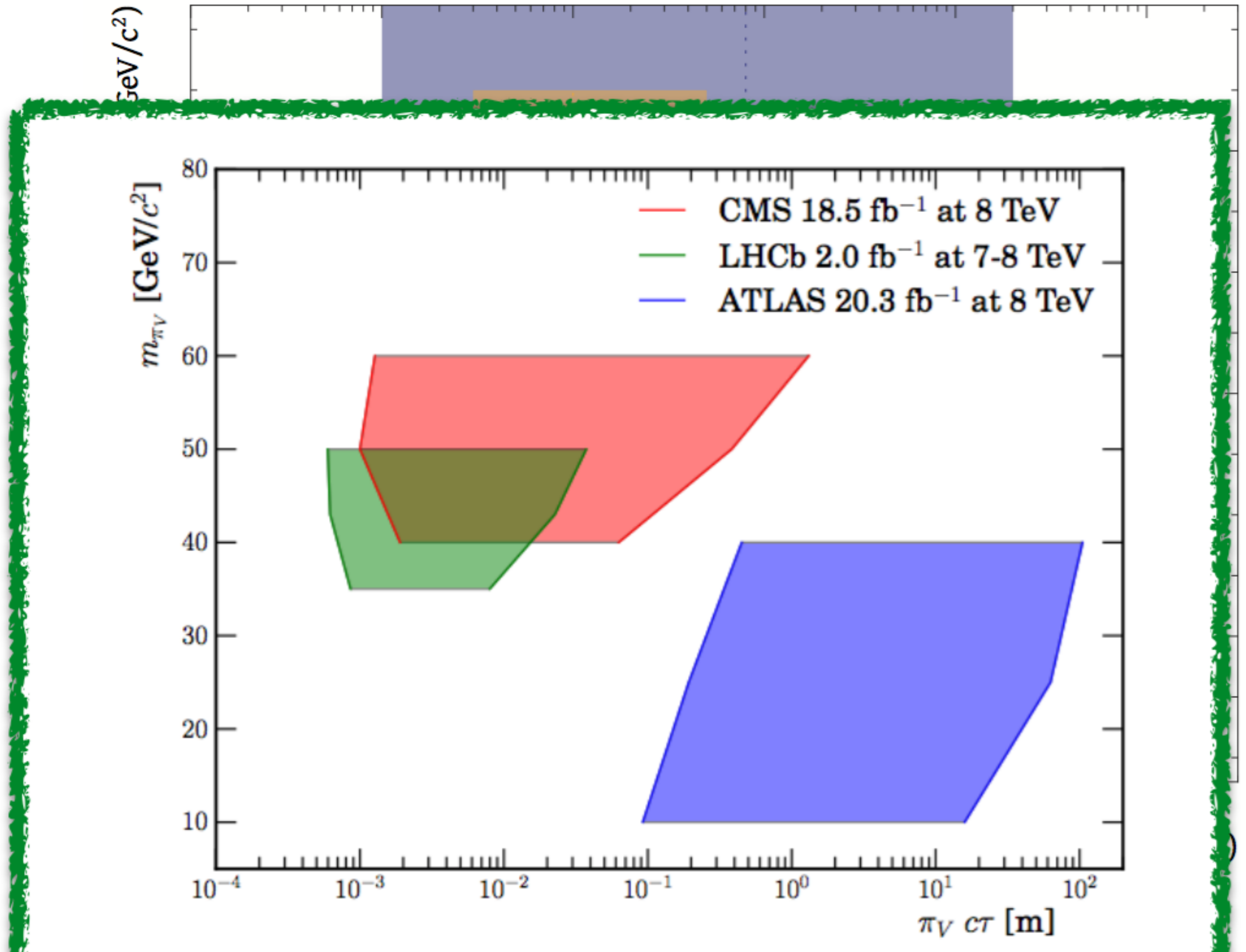


Note that current geometry is actually a silicon detector for simplicity, we are working to implement a realistic RPC based geometry and simulate signal.

Minbias with only the concrete wall gives an occupancy of around 6 hits in the whole of CODEX-b per LHC bunch crossing — very low, as expected.

LHCb already complements ATLAS/CMS

- Obvious disadvantage: LHCb collects less data than ATLAS/CMS and has worse acceptance for several searches
- But softer triggers (for instance, can trigger detached di-muons with p_T~1 GeV/c), other advantages already mentioned
- In practice that means we can look into **complementary** phase space regions



excluded areas where the limit set for $H \to \pi_V \pi_V$ is smaller than 50% the SM Higgs (plot by M. Borsato)

Many thanks to Xabier for the slide from our recent HL-LHC discussions!

Fixed target case study : SHIP

Detector design

Key points :

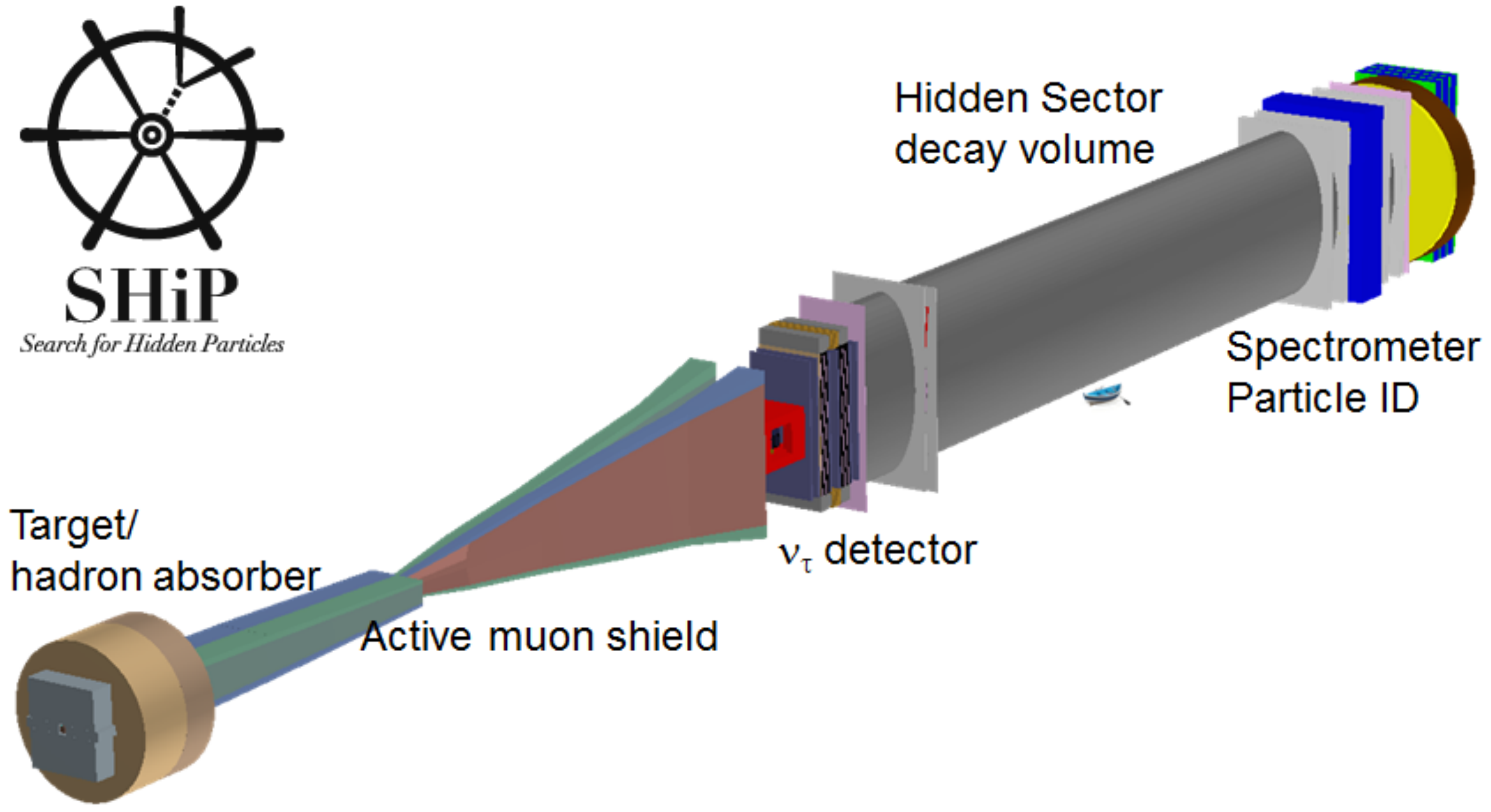
Active shield and vacuum decay volume to minimize backgrounds

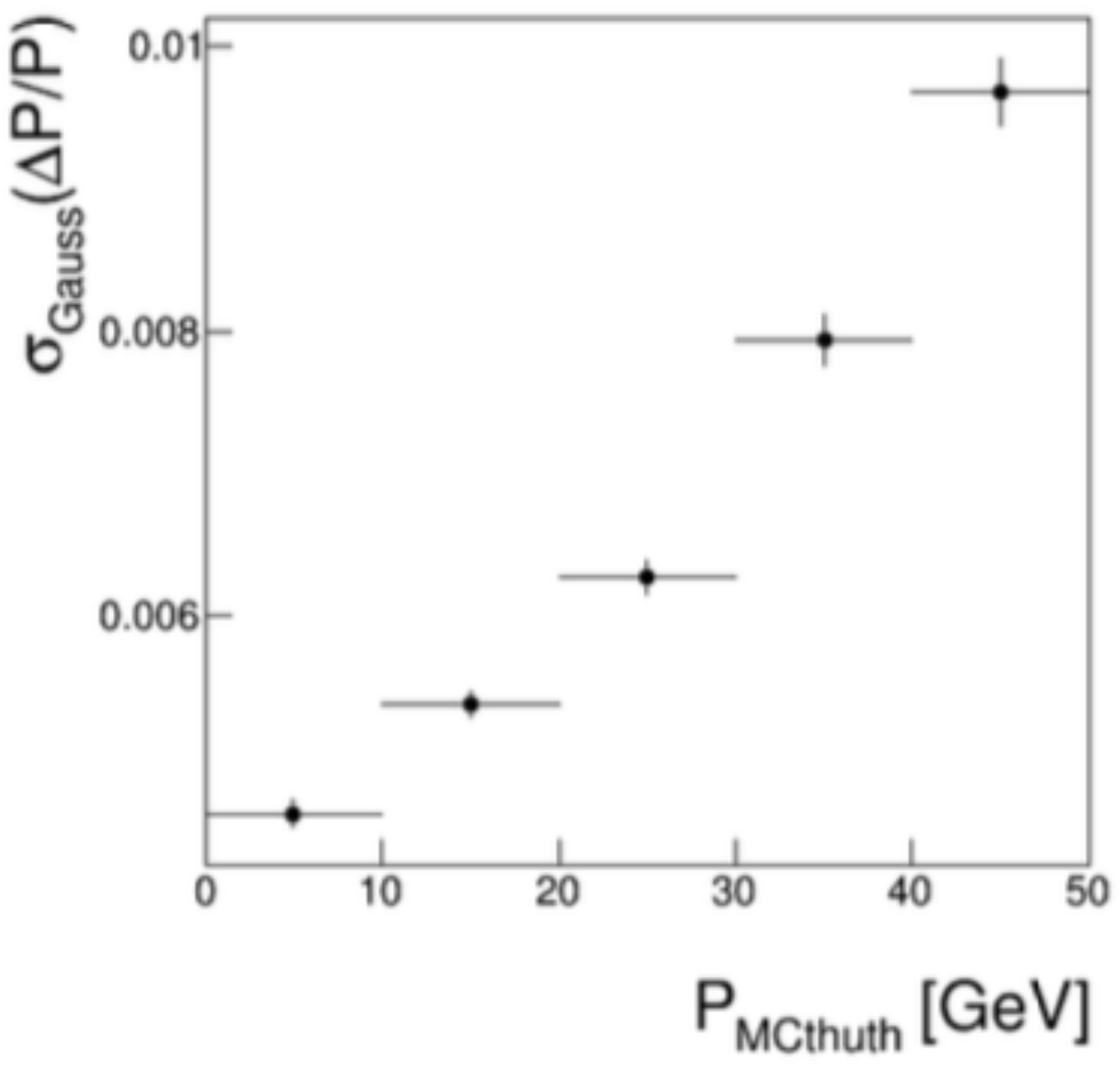
Sub percent momentum resolution, particle ID, mm vertex resolution in the transverse plane

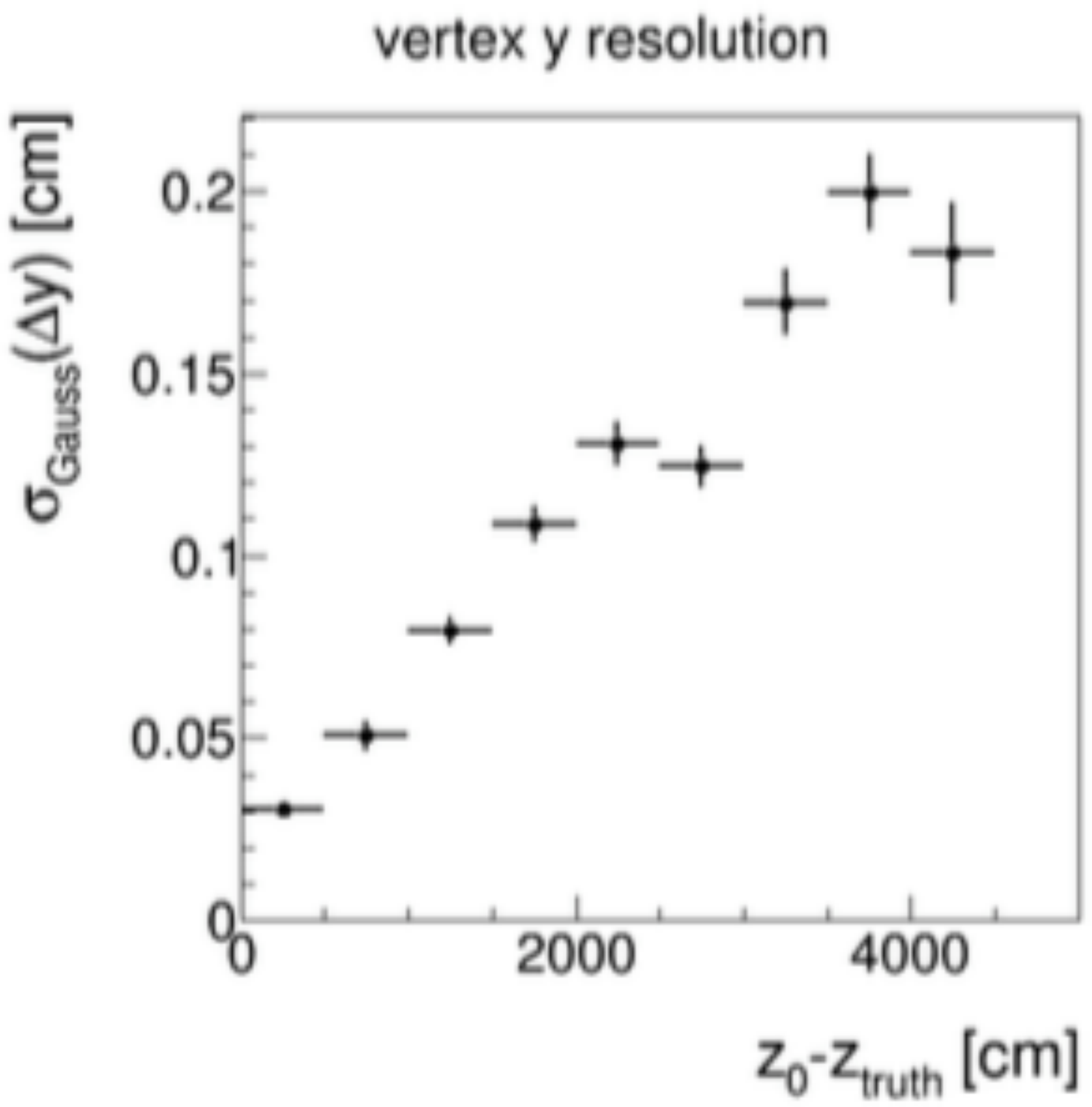
Timing coincidence (a la NA62) used to suppress backgrounds

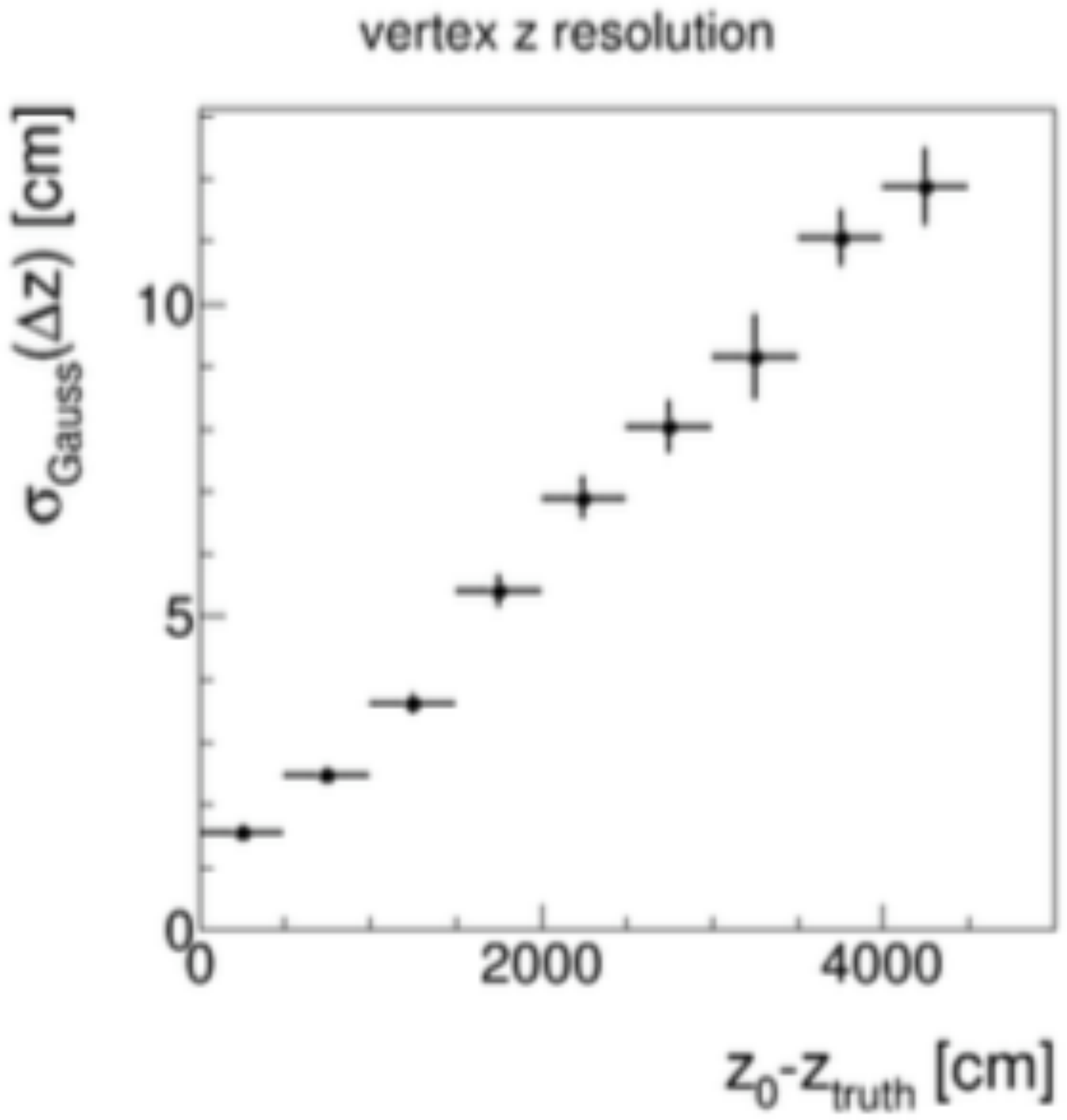
Exploits boost of produced heavy flavour to improve acceptance for LLPs, particularly shorter lived ones

SHiP
Search for Hidden Particles

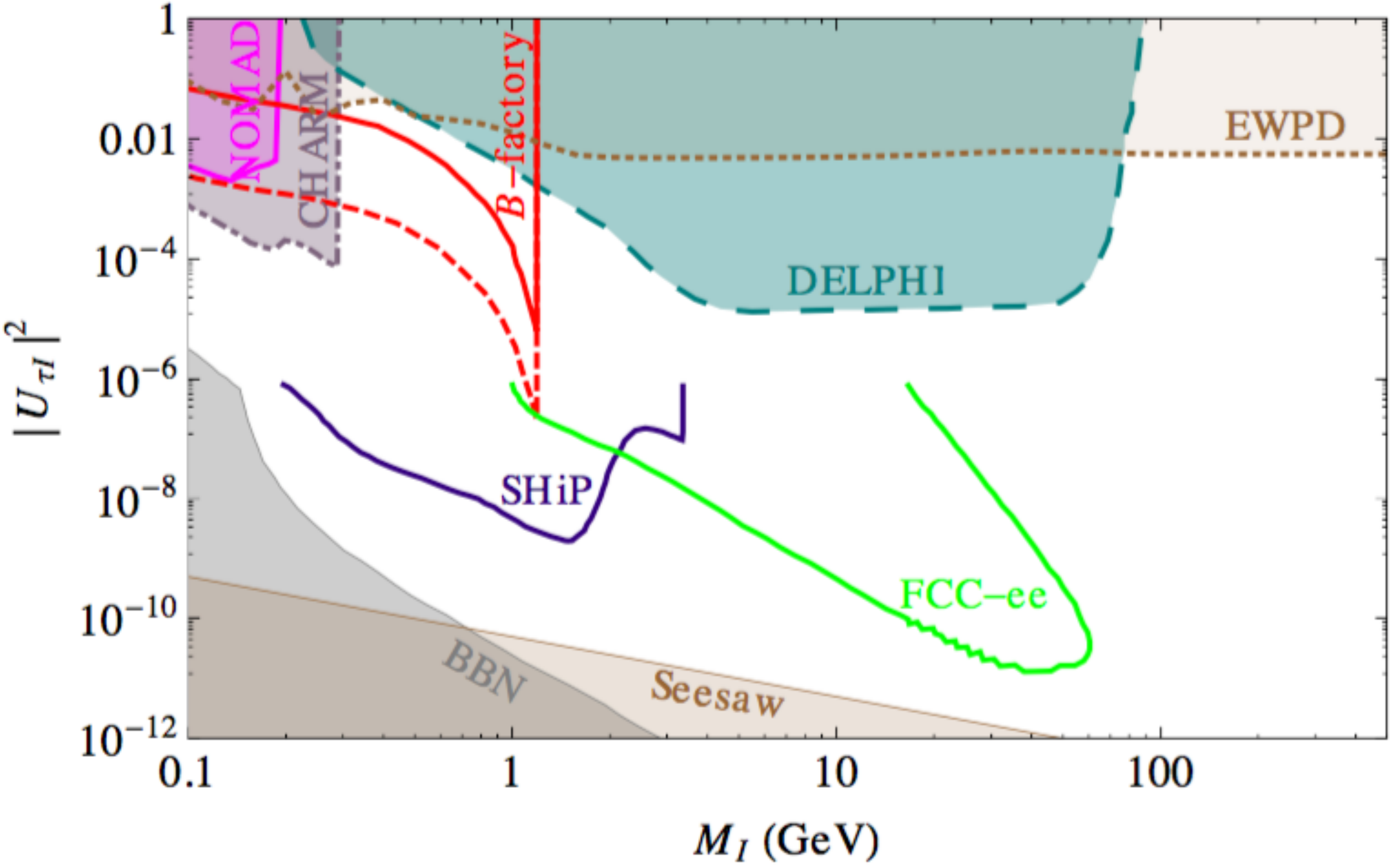




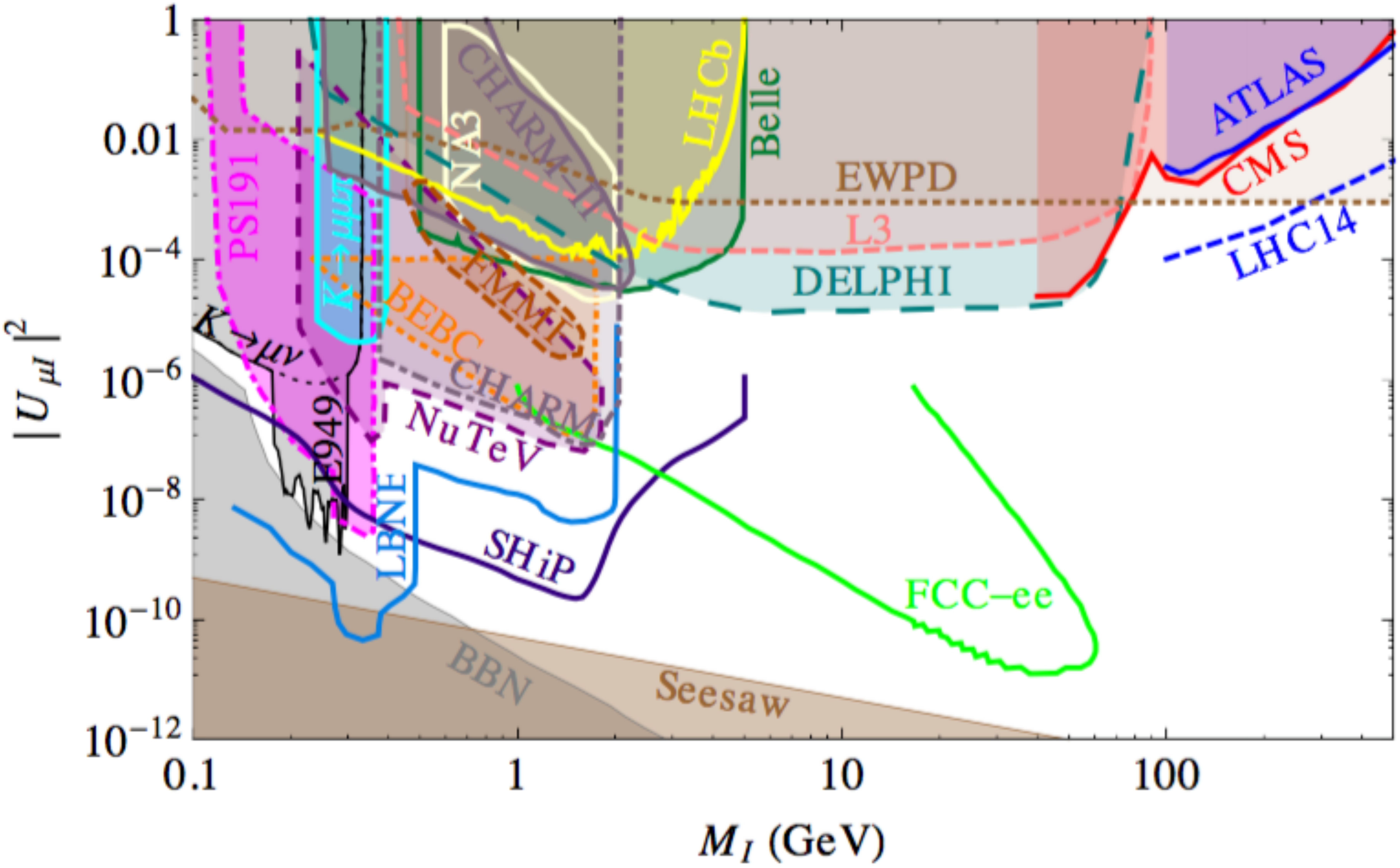




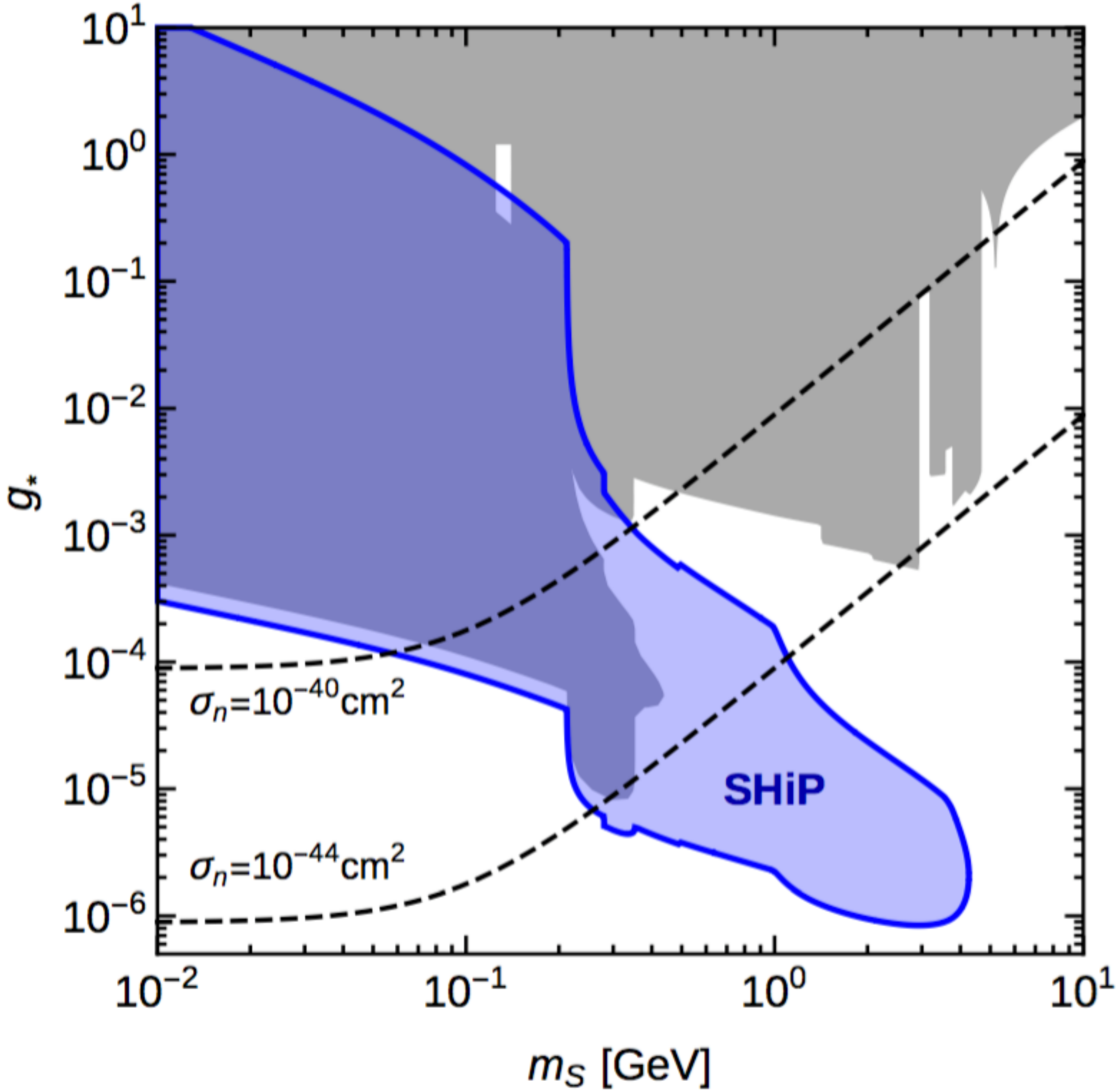
Reach estimates for HNLs



Reach estimates for HNLs



Reach estimates for b→sX



Collider case study : MATHUSLA

Detector design

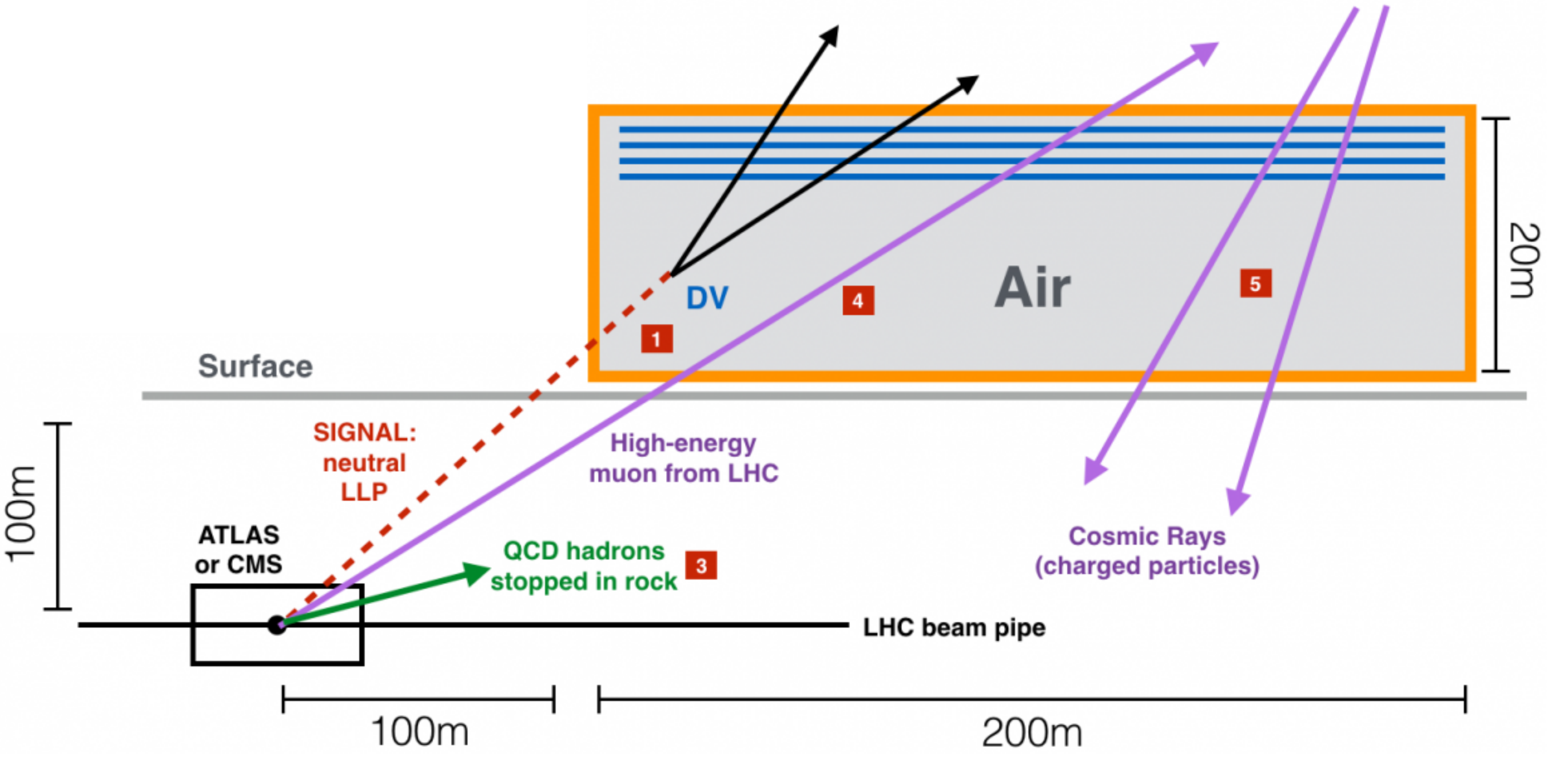
MATHUSLA

Key points :

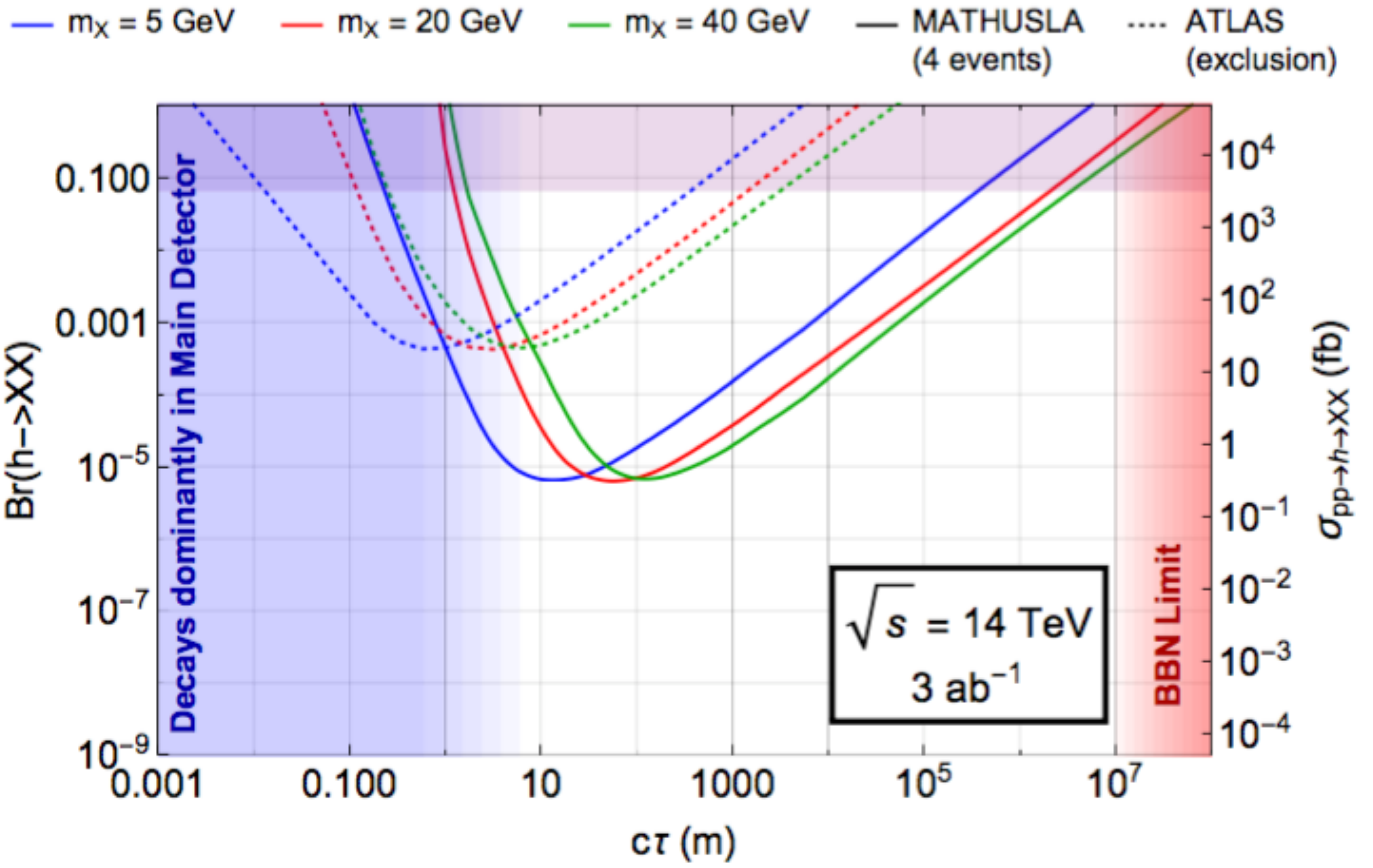
Access full HL-LHC luminosity

"Natural" shielding from LHC backgrounds, active vetoes on sides for cosmics and similar

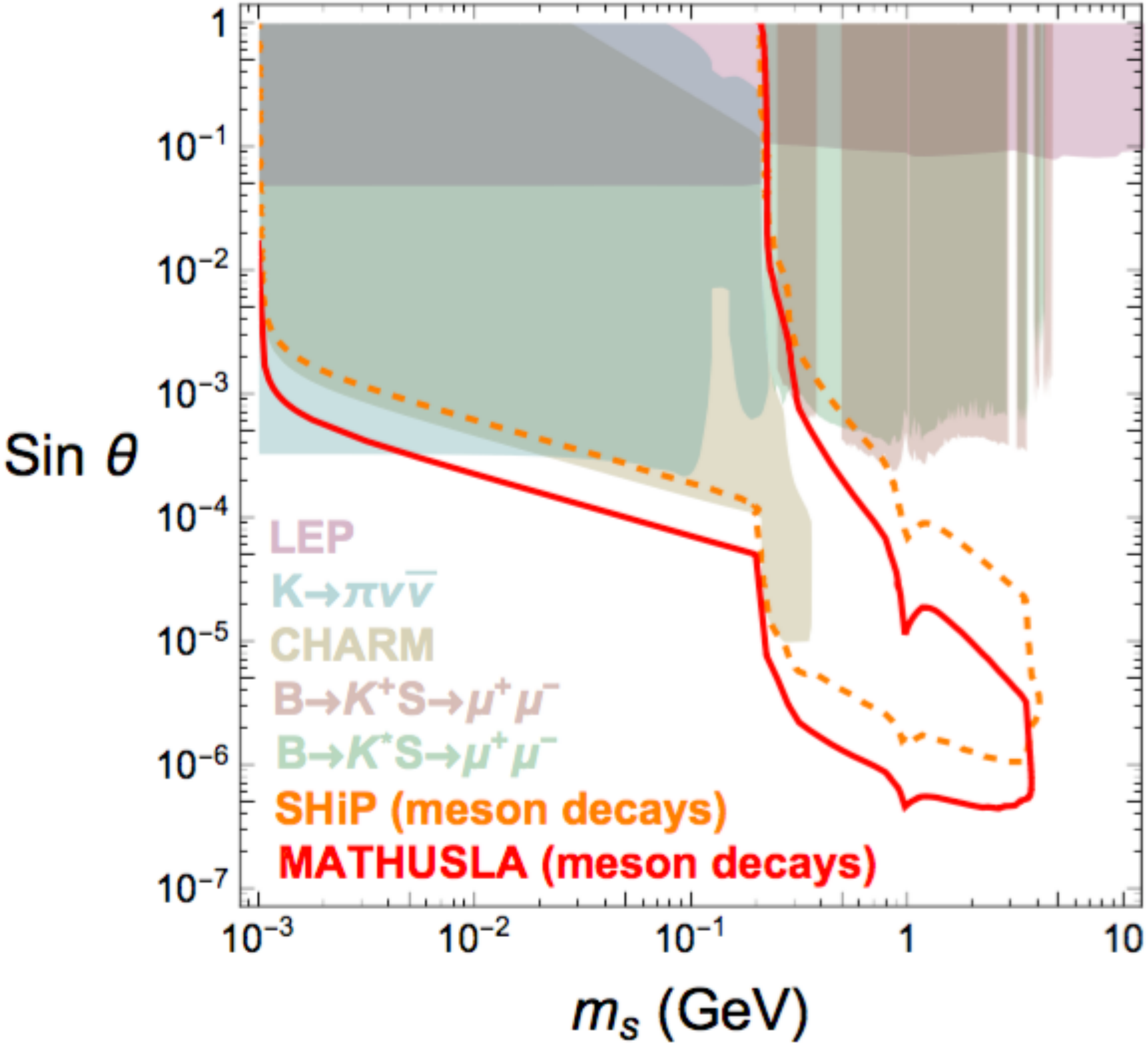
Enormous size : several tracking layers of 200x200 m² each



Reach estimates for Higgs portal

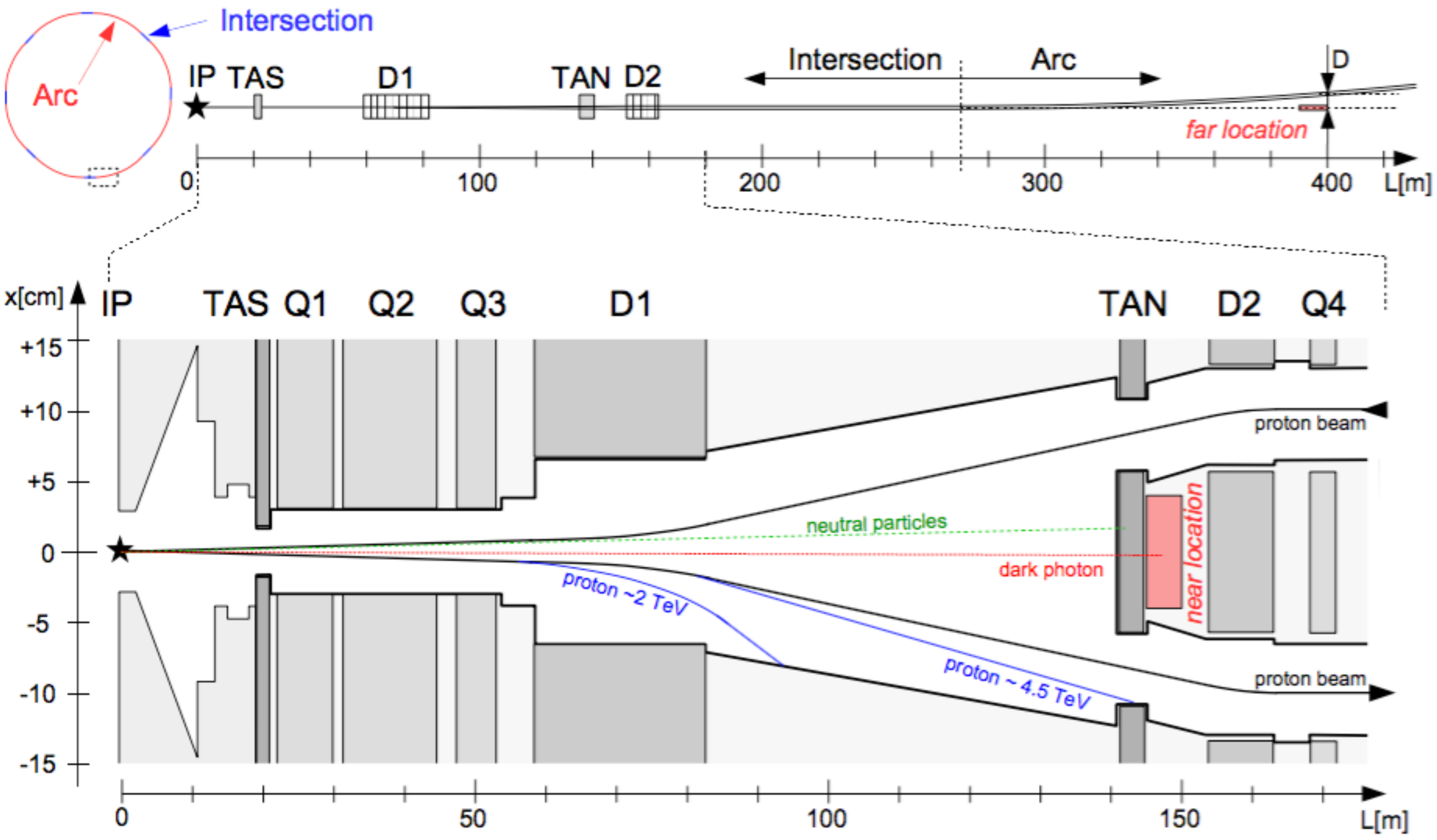


Reach estimates for b→sX



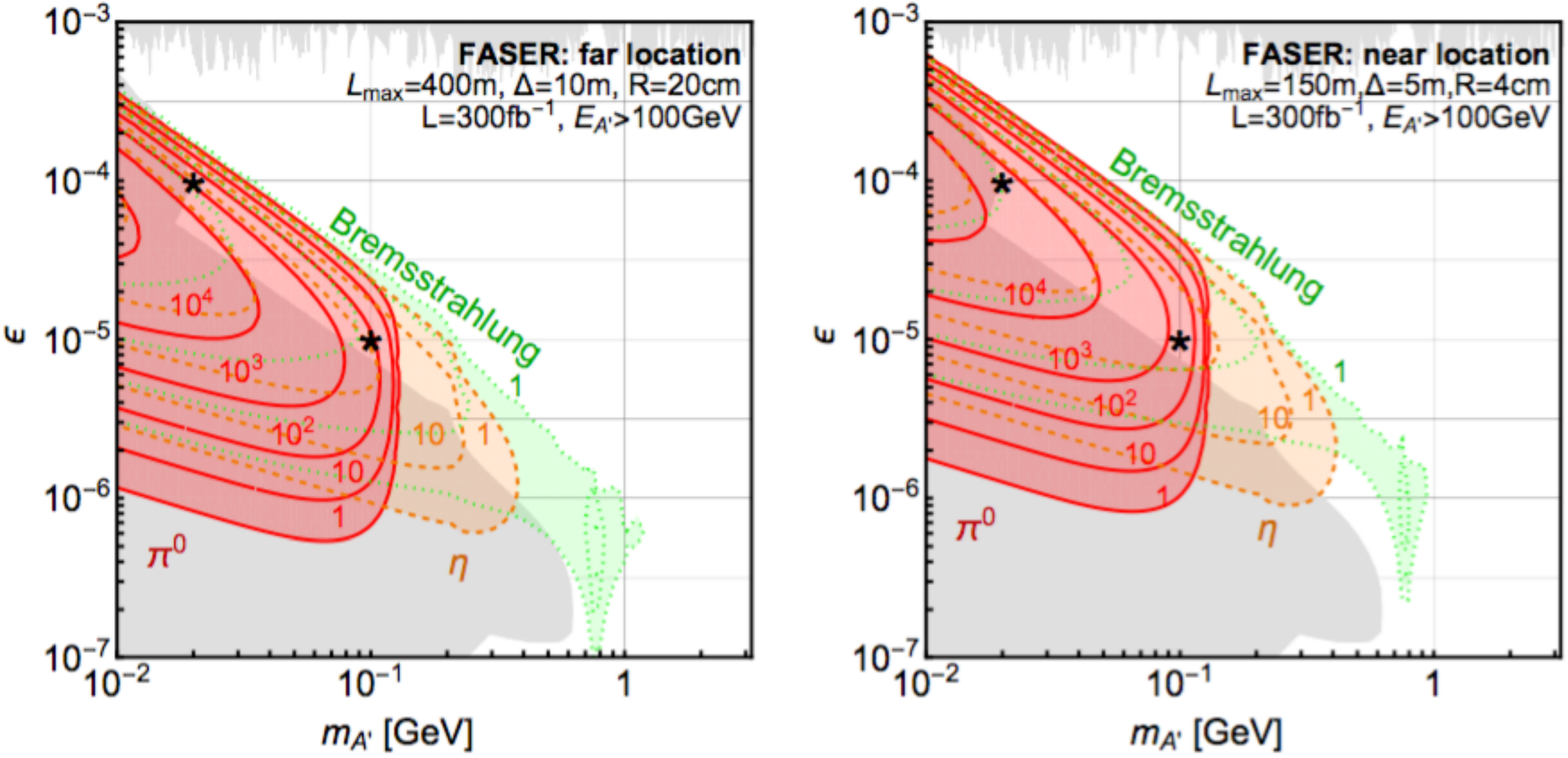
Collider case study : FASER

Detector design



Very forward, exploits tail of the boost distribution

Reach estimates for dark photons



Production of proton brems (!) highlights unique forward regime