A la recherche des secteurs cachées

European Research Council
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Vladimir V Gligorov

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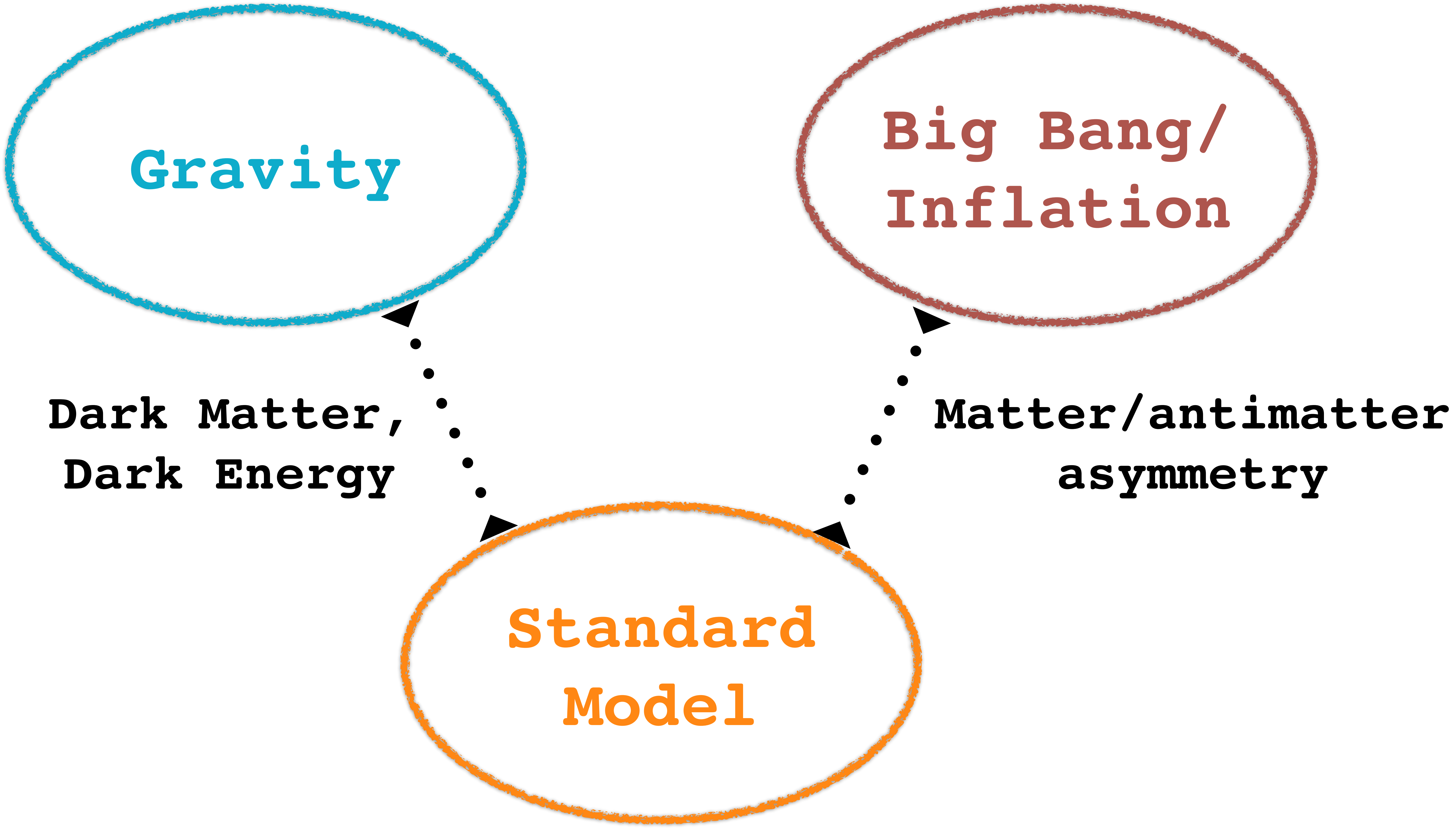
LPNHE PARIS

cnrs

Frequently asked questions

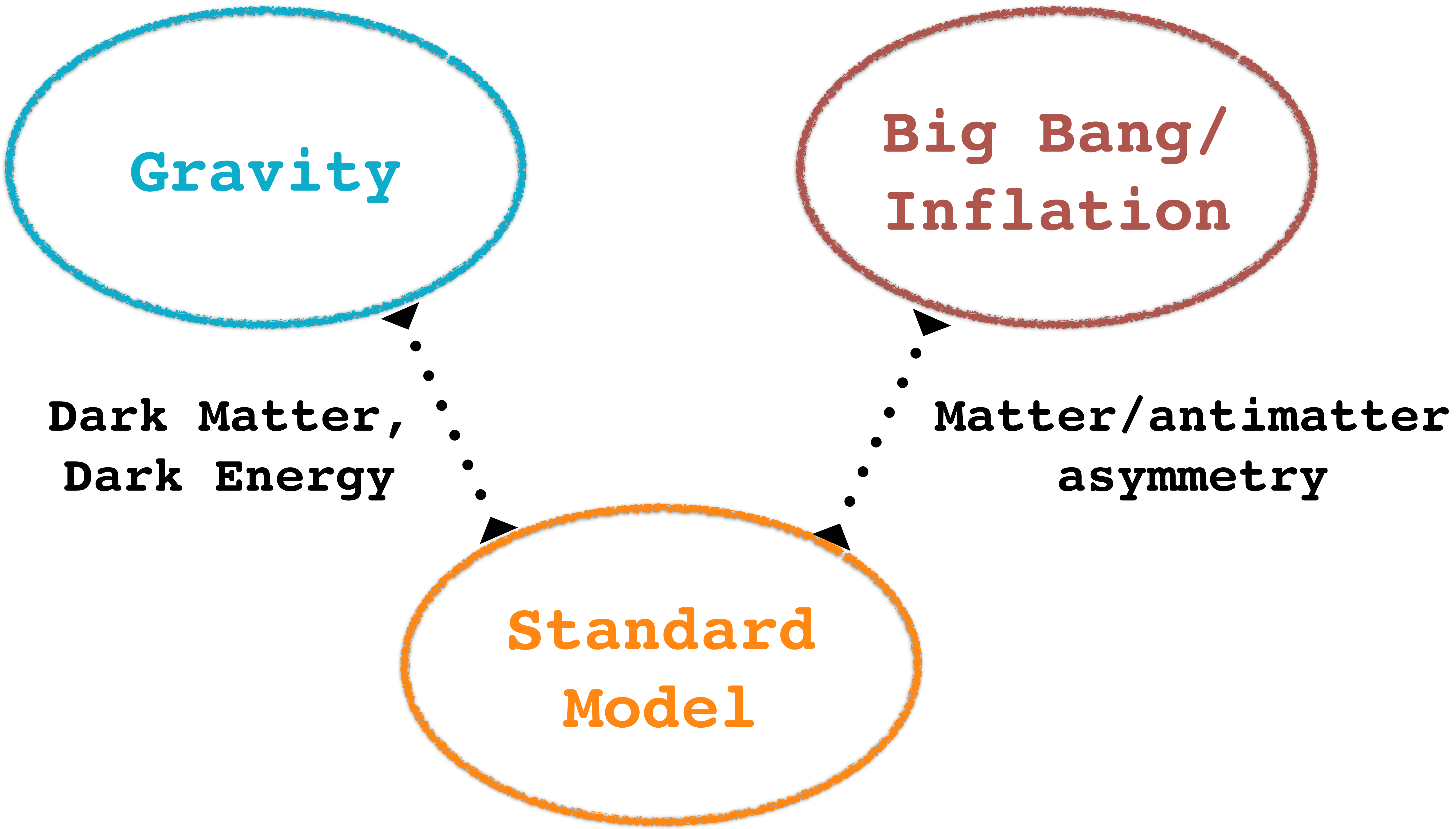
Why are we here?

Why are we here?



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

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

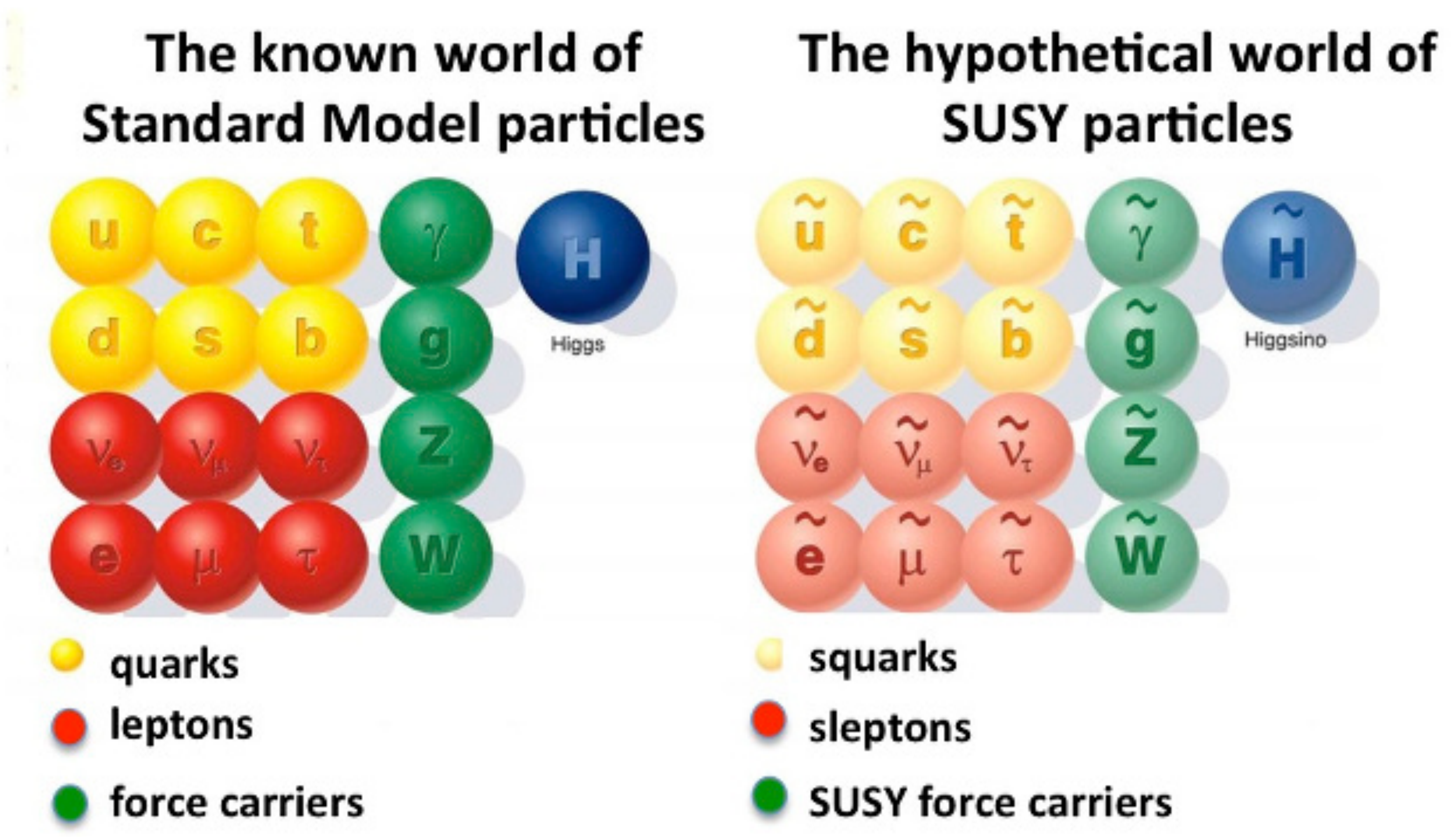
Set by symmetry structure,

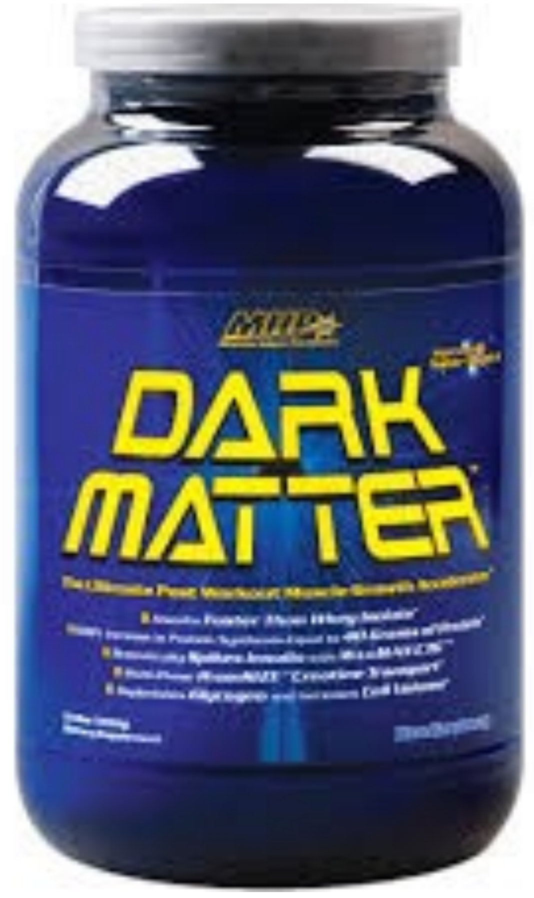
typically n ≥ 4

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

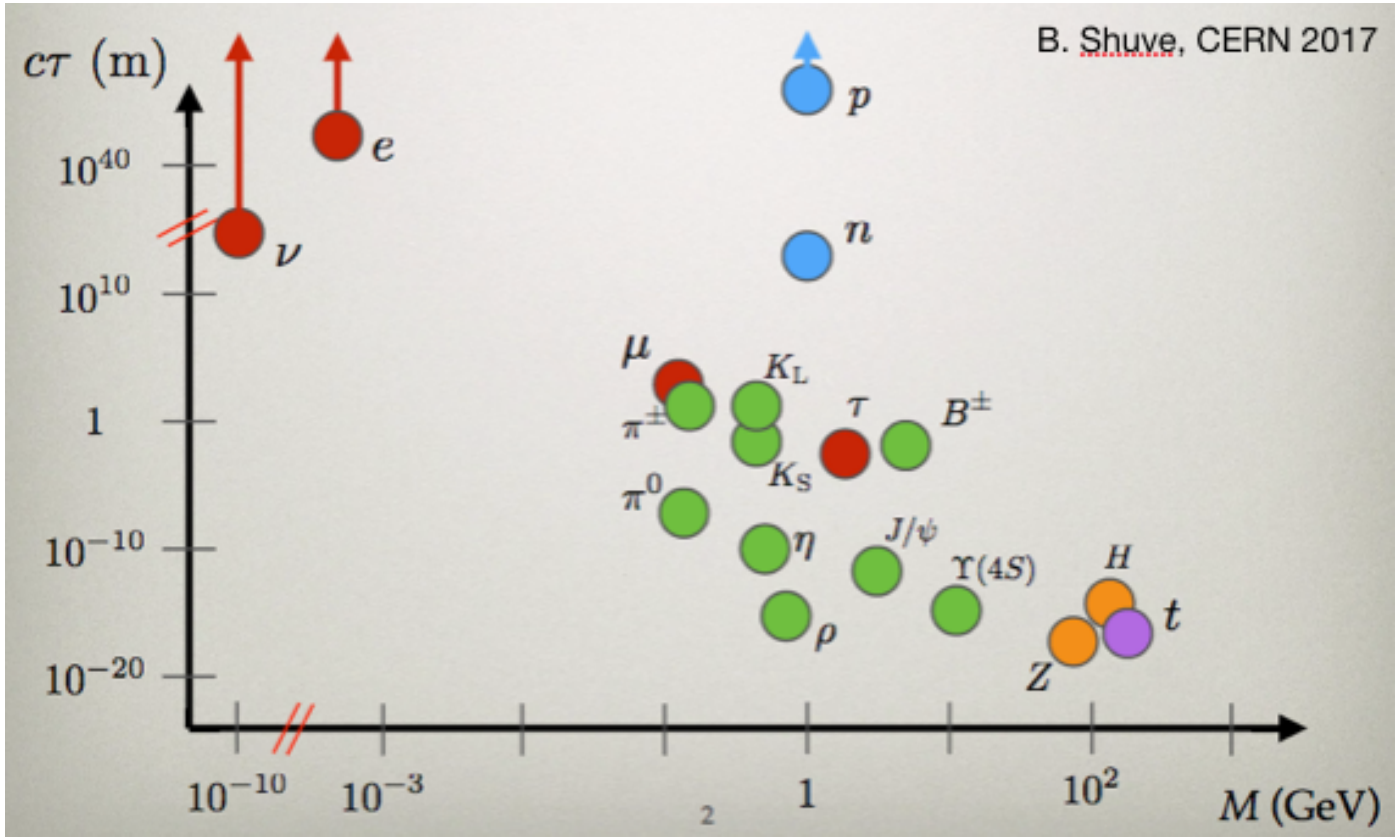
$$\Gamma \sim \varepsilon^2 \left(\frac{m}{M}\right)^n \mathrm{PS}$$

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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Disadvantages	No access to very heavy LLPs Big shielding required for bkg	

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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

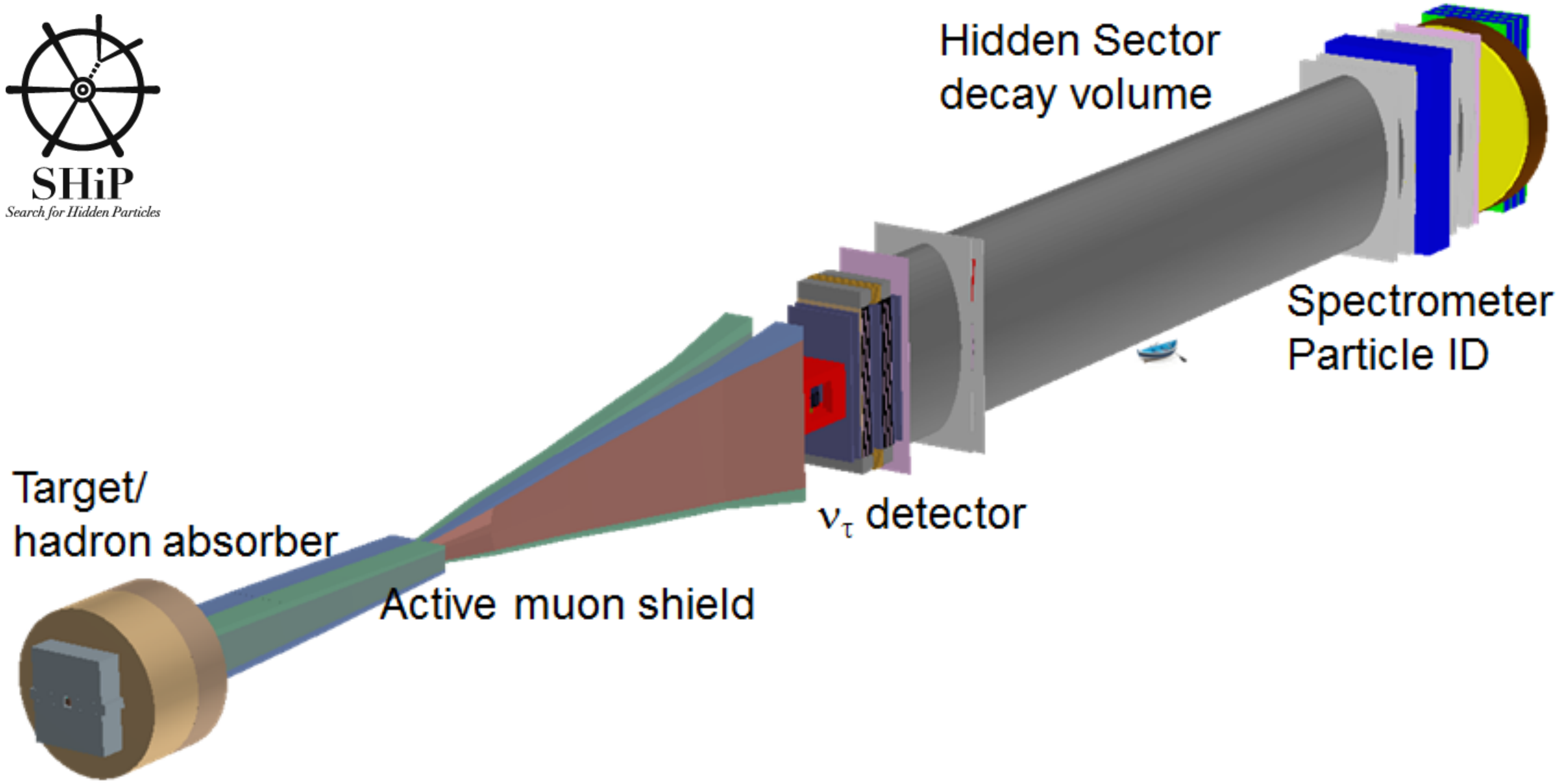
Charm Hadrons @ SPS : $O(10^{18})$
Charm Hadrons @ HL-LHC : $O(10^{16})$

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

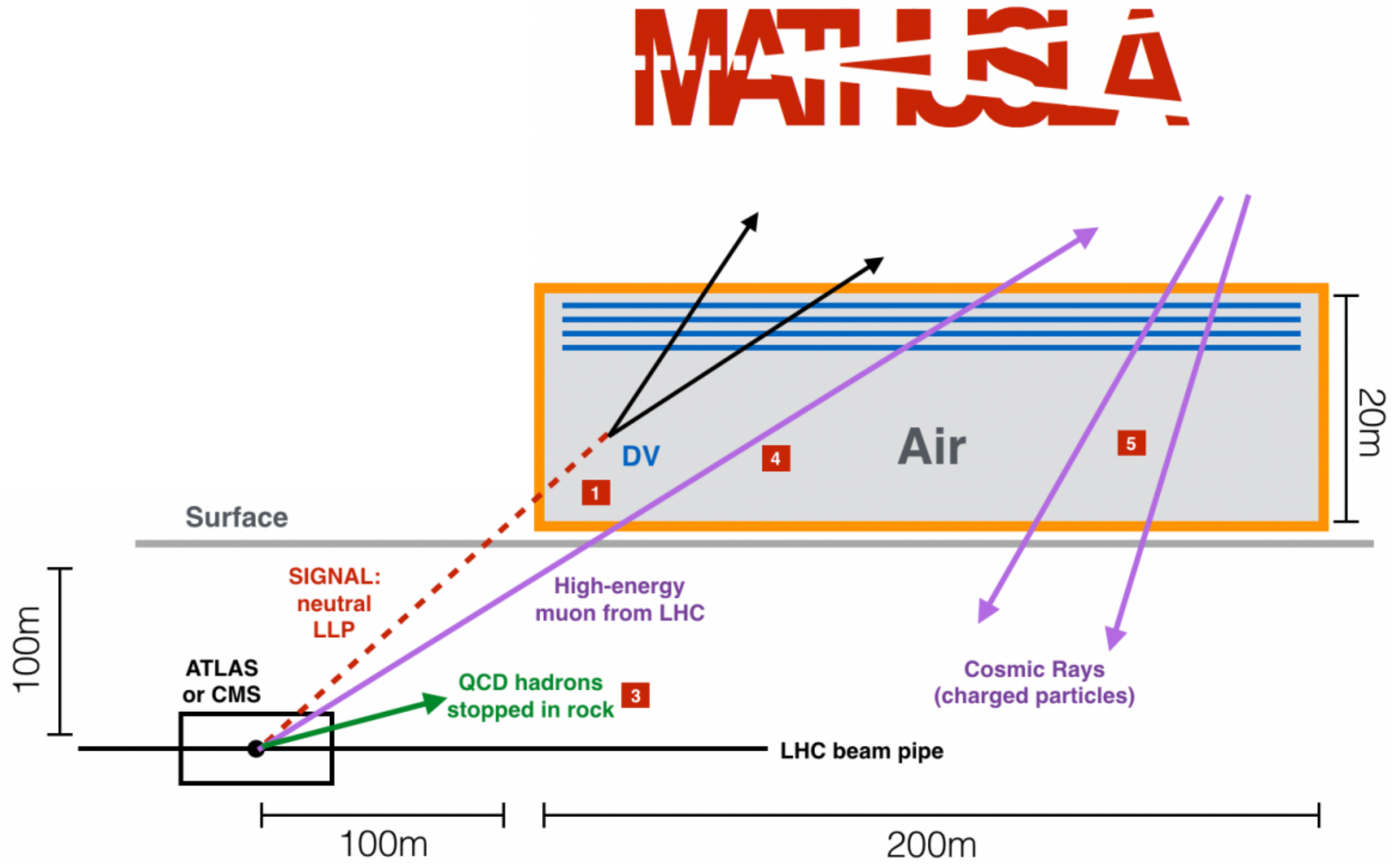
Fixed target : collimated production



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

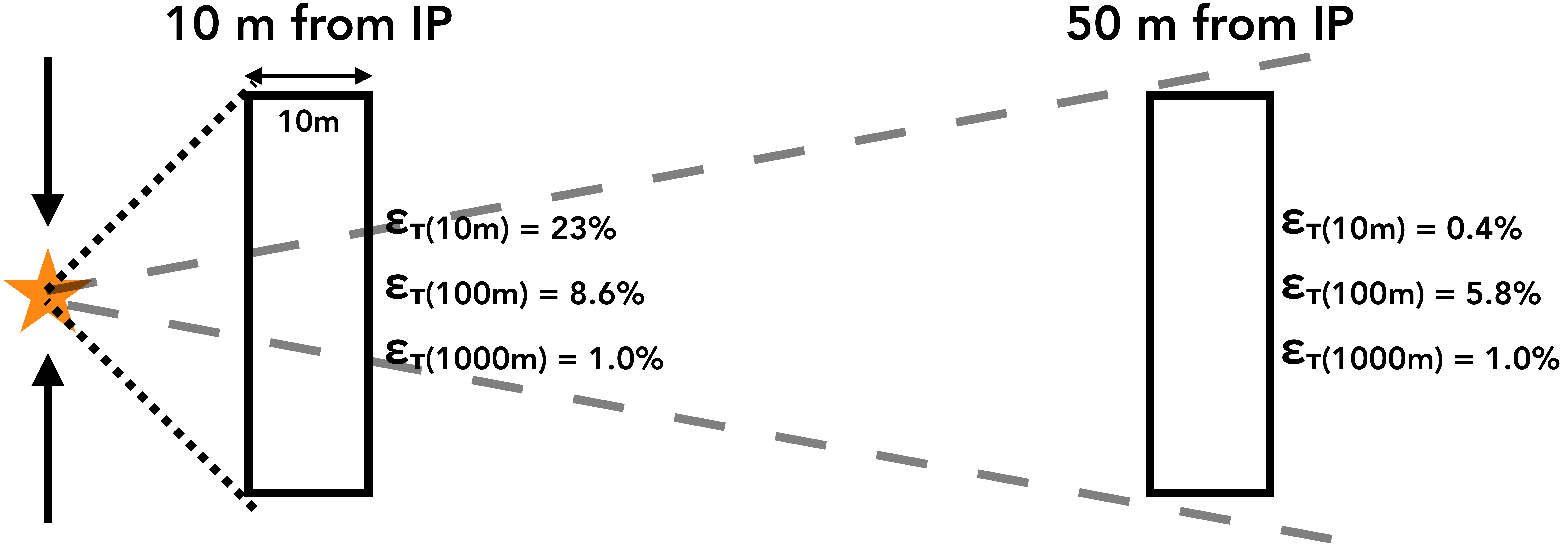
Distance versus solid angle coverage

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

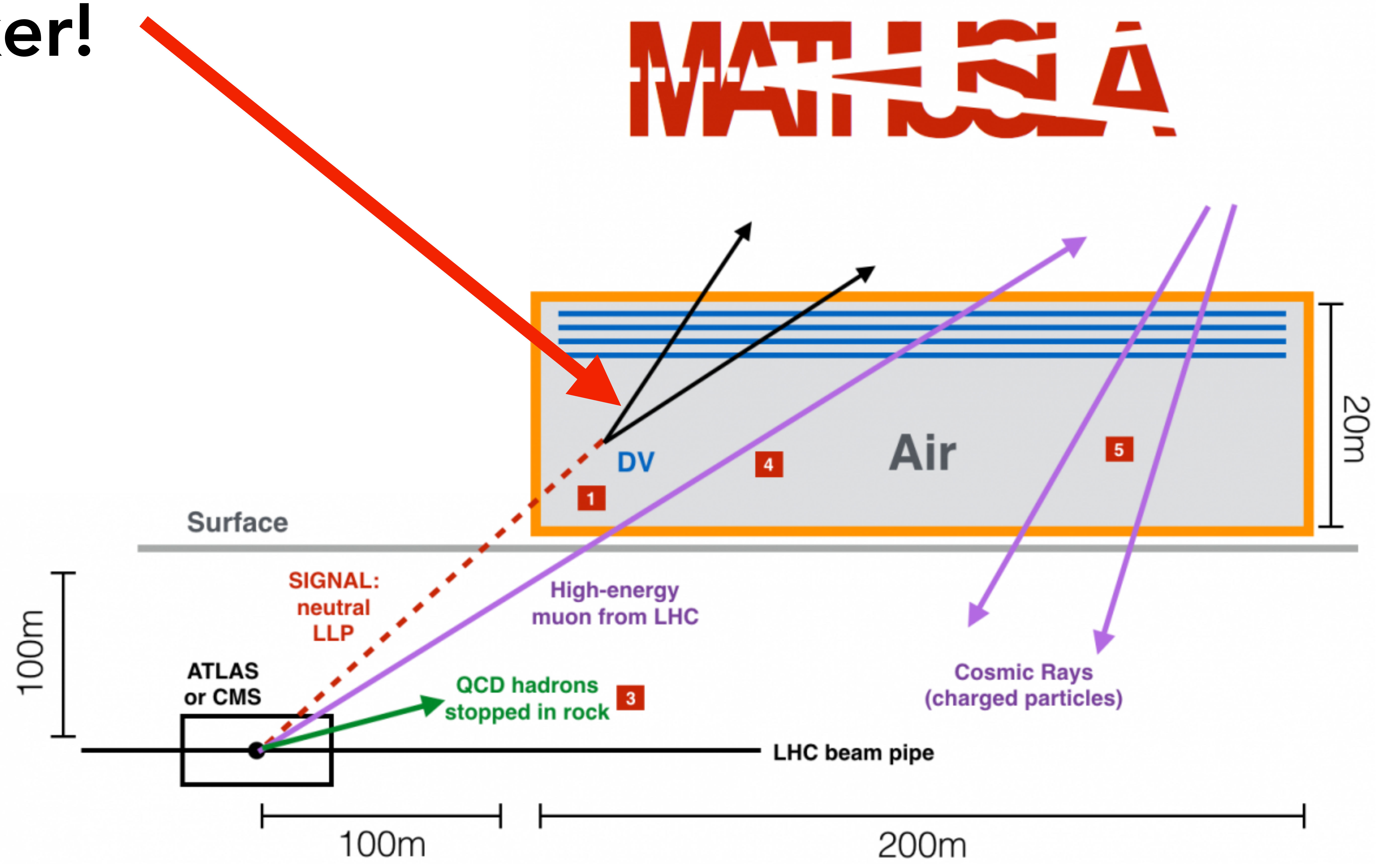


Being far isn't really helpful for probing longer lifetimes, since for very long lifetimes the exponential is anyway flat.

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

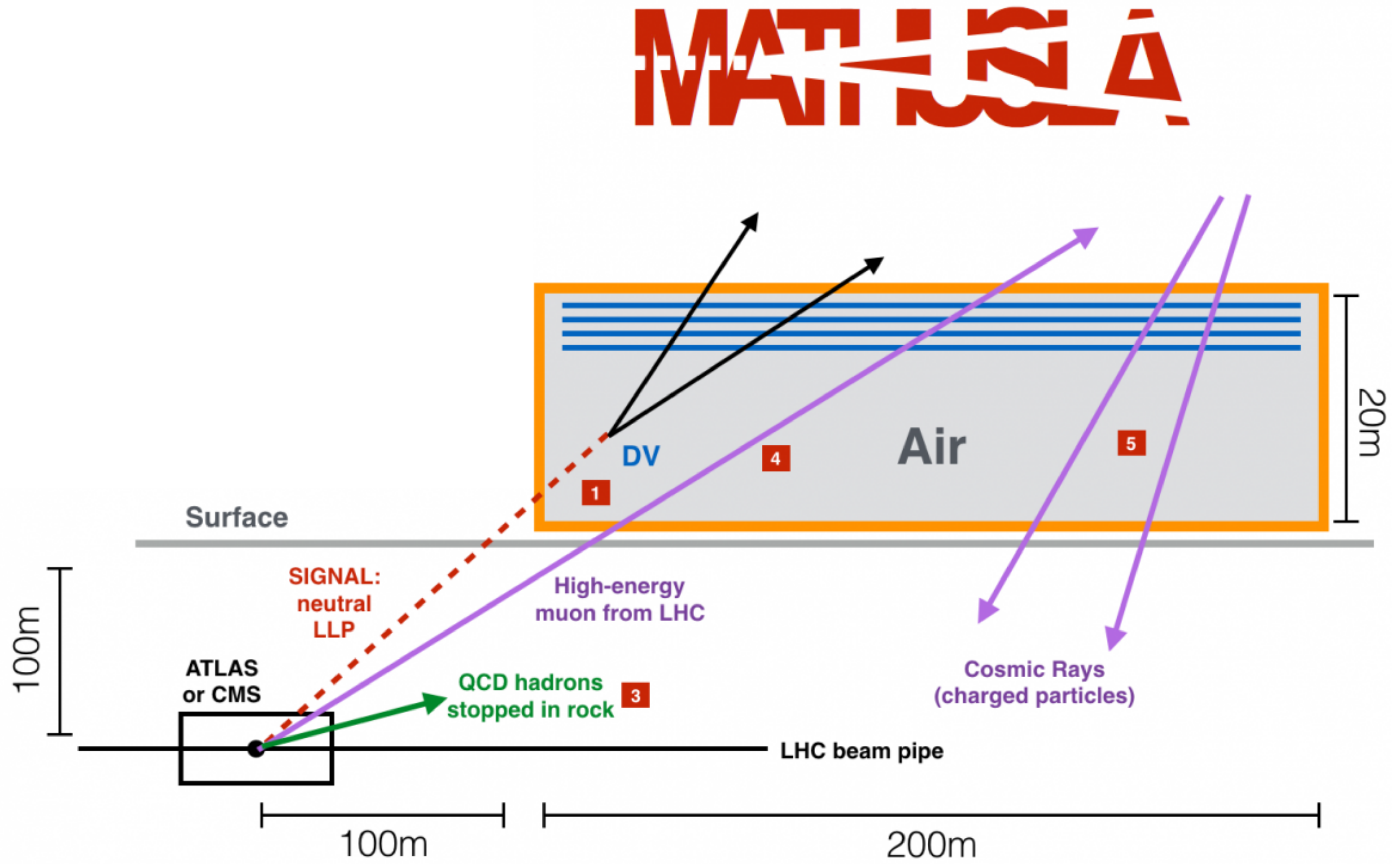
Huge distance to first measured point inside tracker!



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

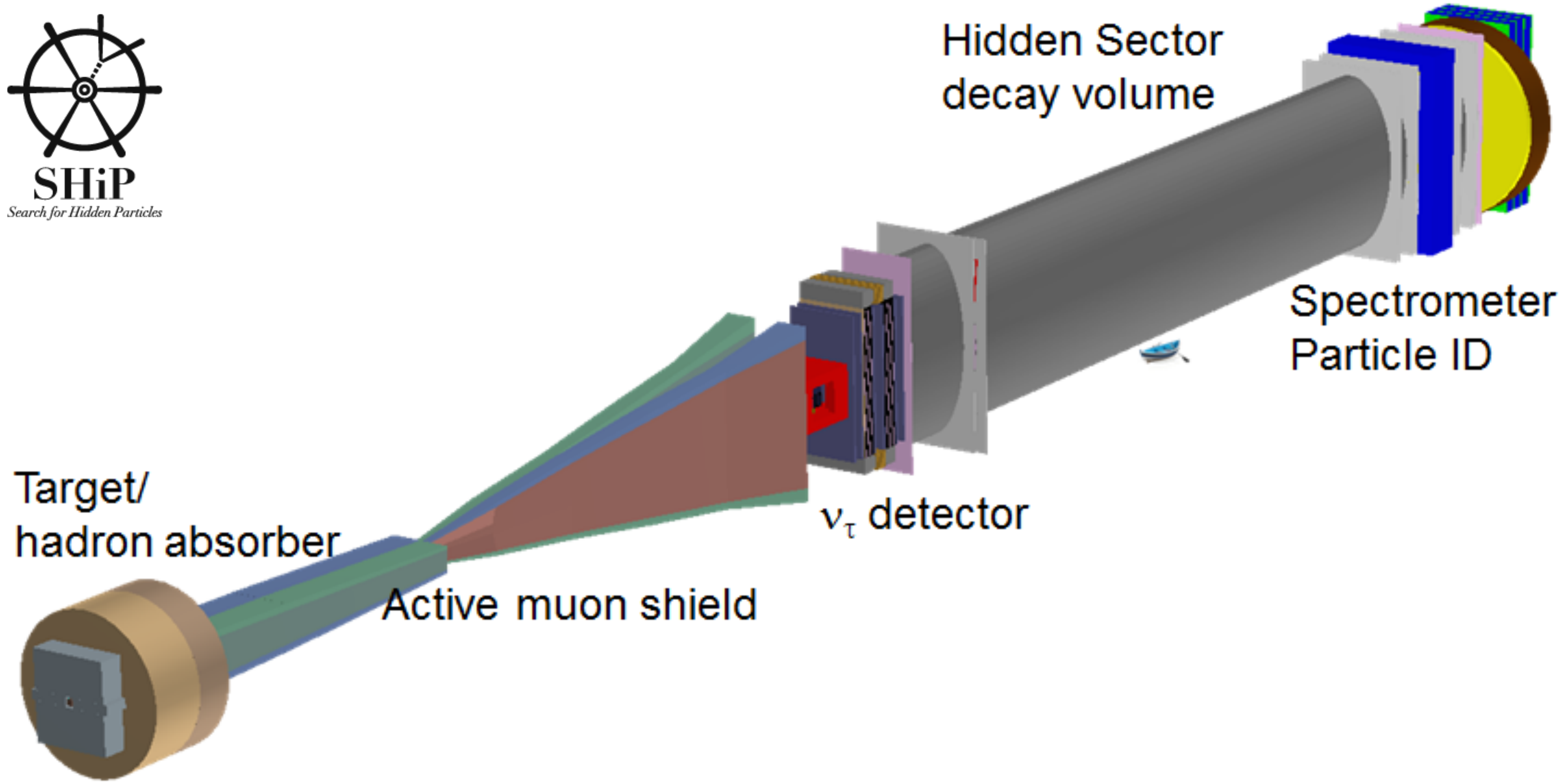
Collider mode : good luck…



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

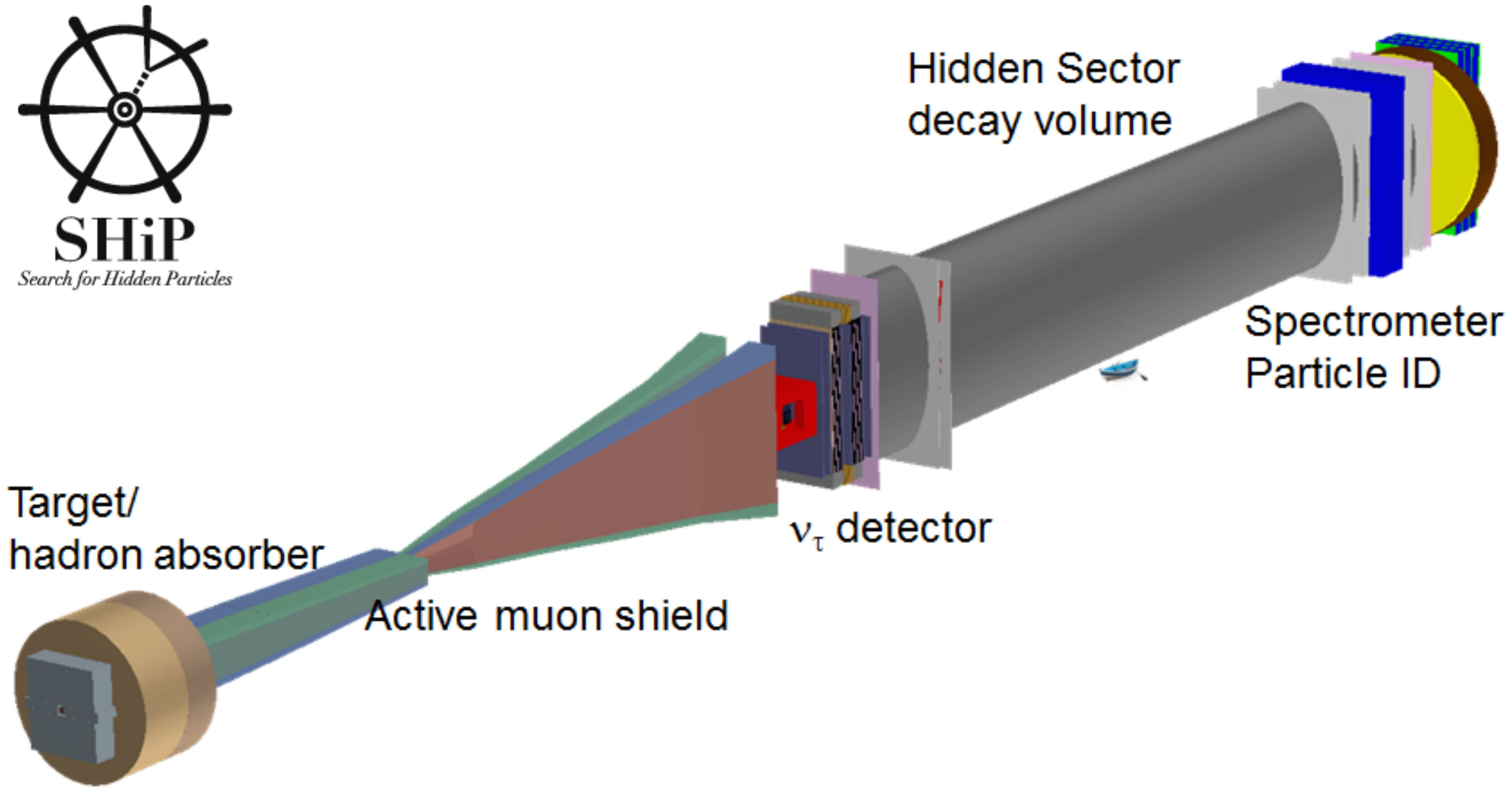
A kingdom for a magnet

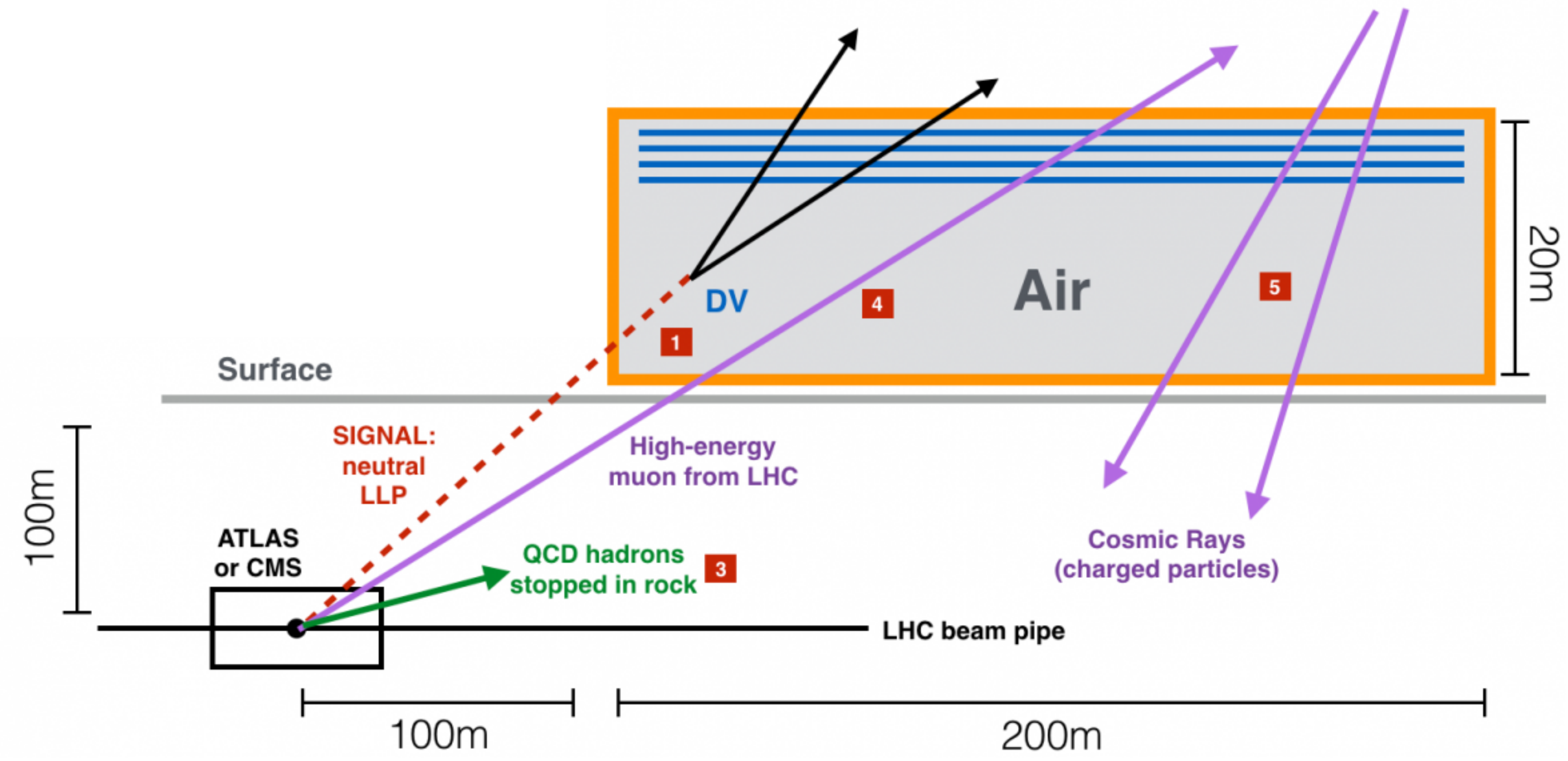
Fixed target : easy!



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

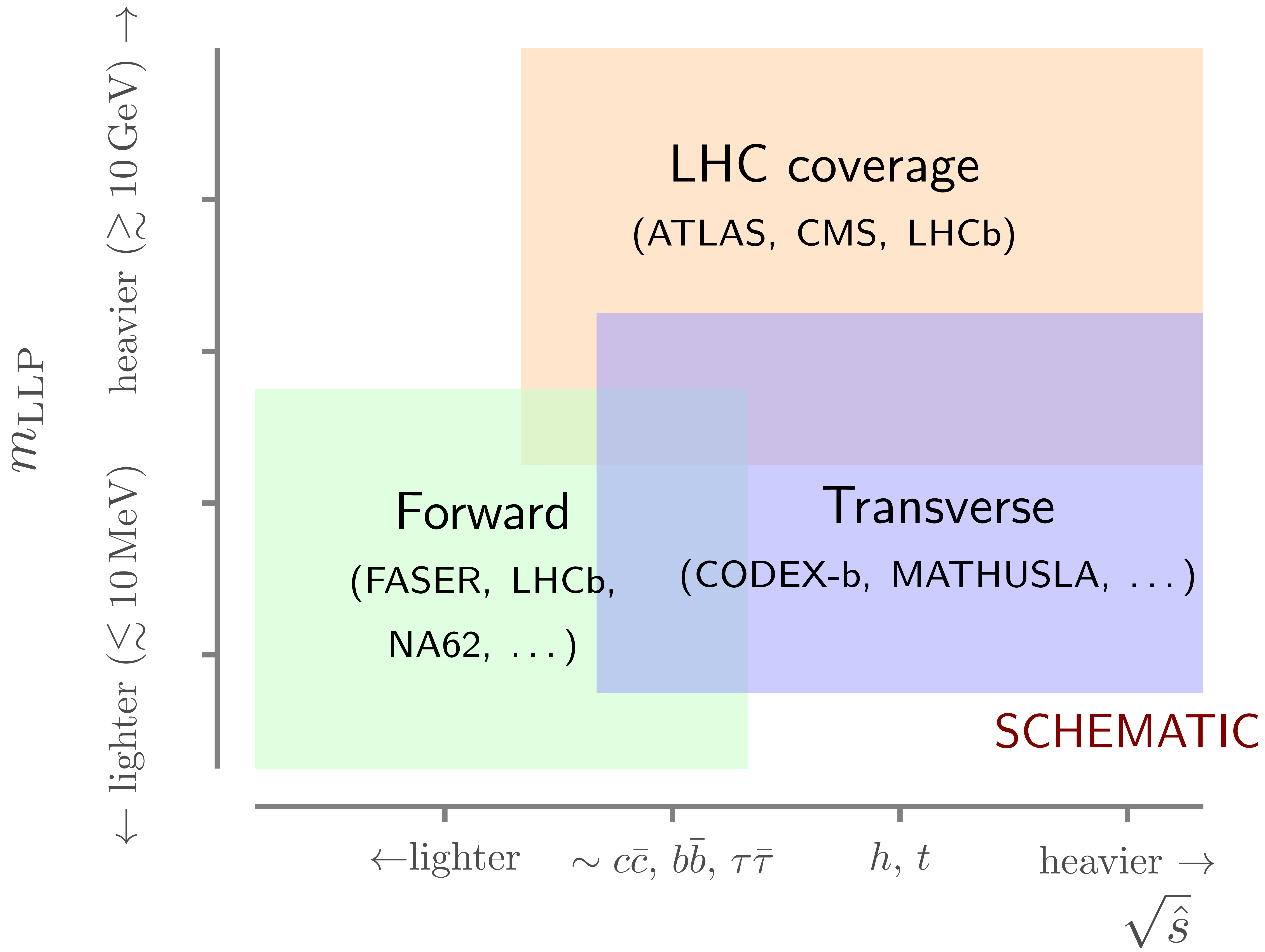
The quest for zero background





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

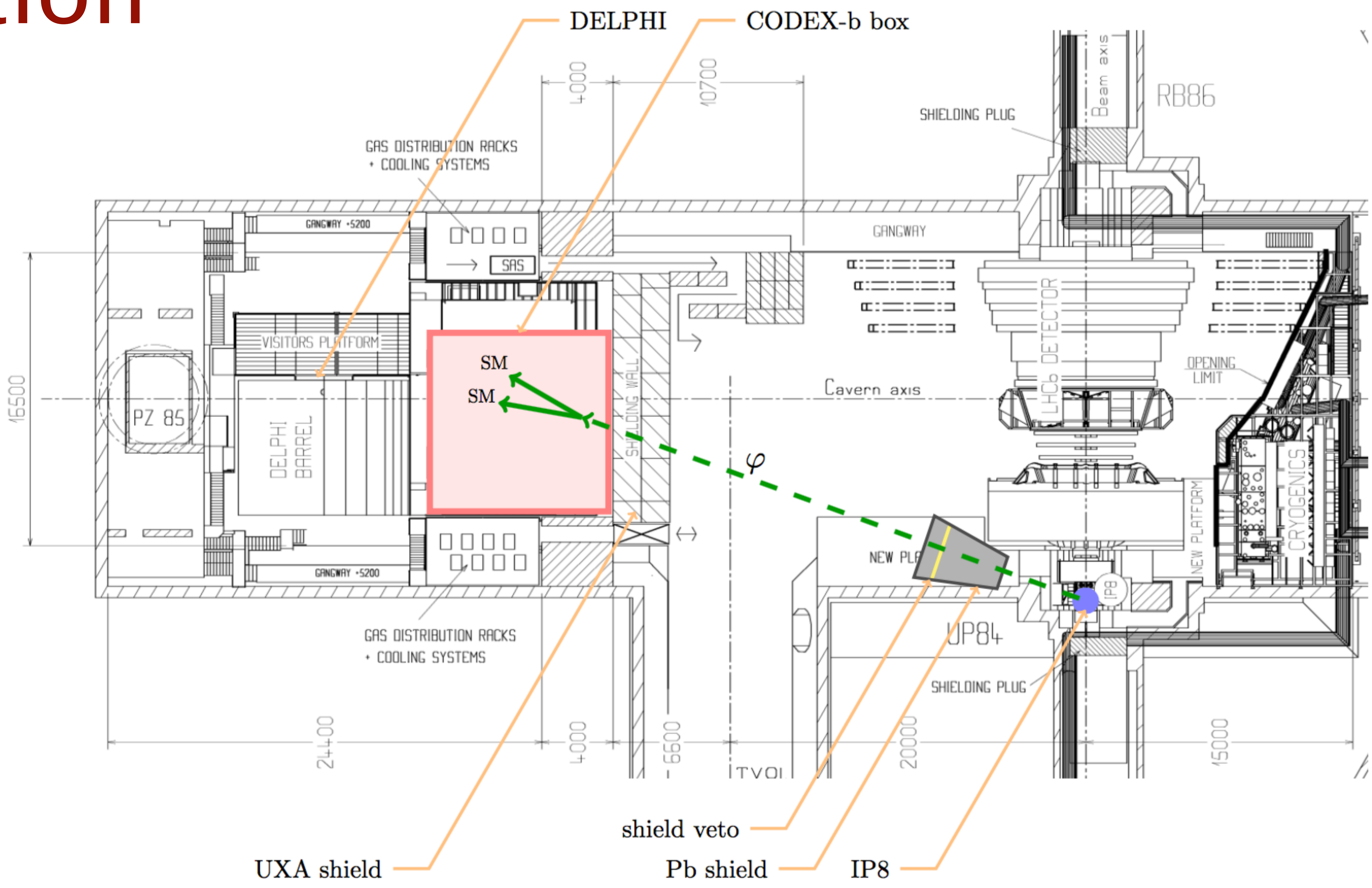
Summary of coverage



No single "golden" experiment — need complementary capabilities!

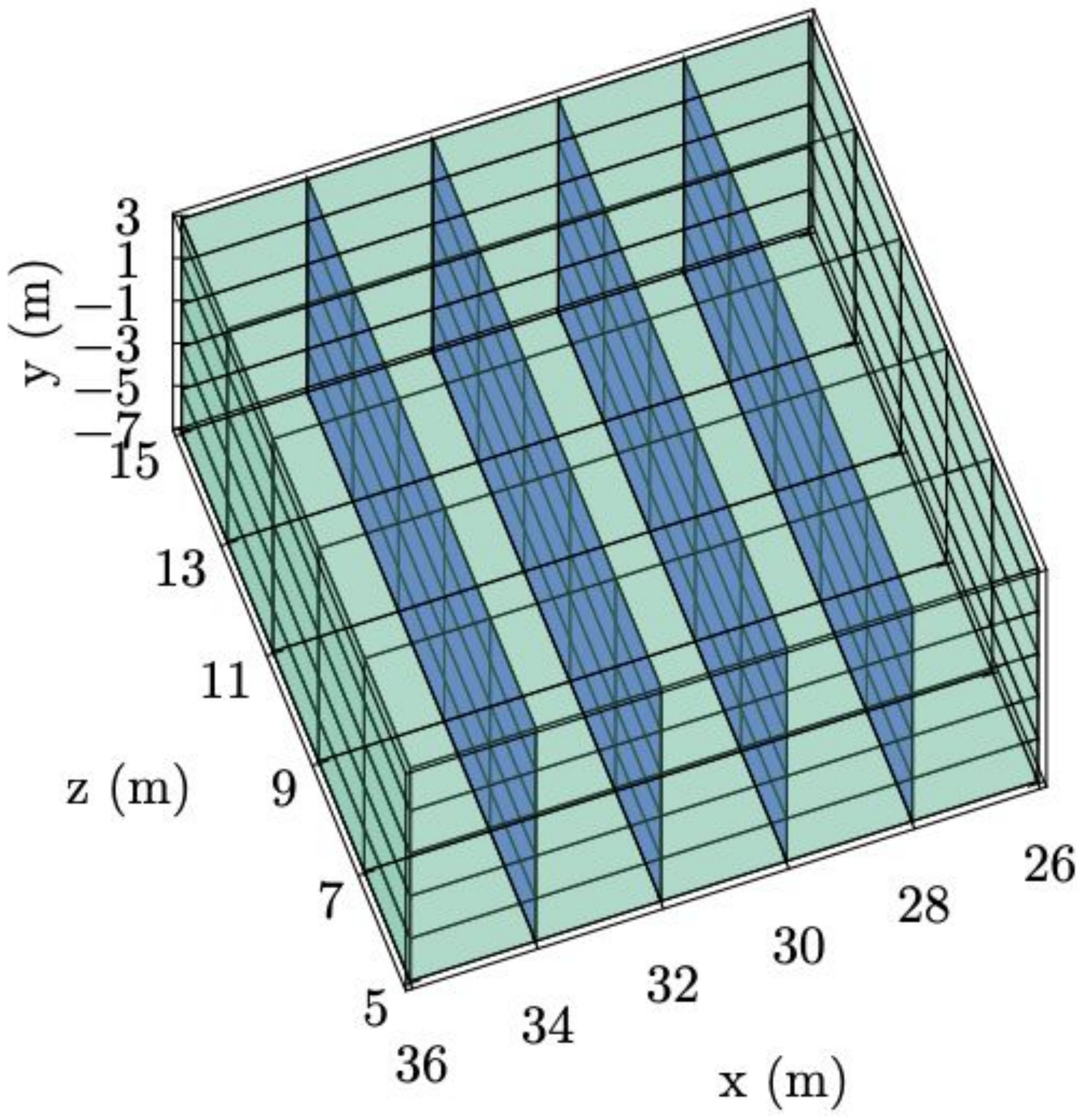
CODEX-b: a minimal extension to LHCb for LLP searches

Location



DELPHI
CODEX-b box
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
GANGWAY +5200
SAS
VISITORS PLATFORM
PZ 85
DELPHI BARREL
SM
SM
SHIELDING WALL
φ
Cavern axis
GANGWAY
SHIELDING PLUG
RB86
Beam axis
LHCb DETECTOR
OPENING LIMIT
NEW PLATFORM
CRYOGENICS
NEW PL
IP8
UP84
SHIELDING PLUG
16500
4000
10700
24400
4000
6600
20000
15000
TVOI
shield veto
UXA shield
Pb shield
IP8

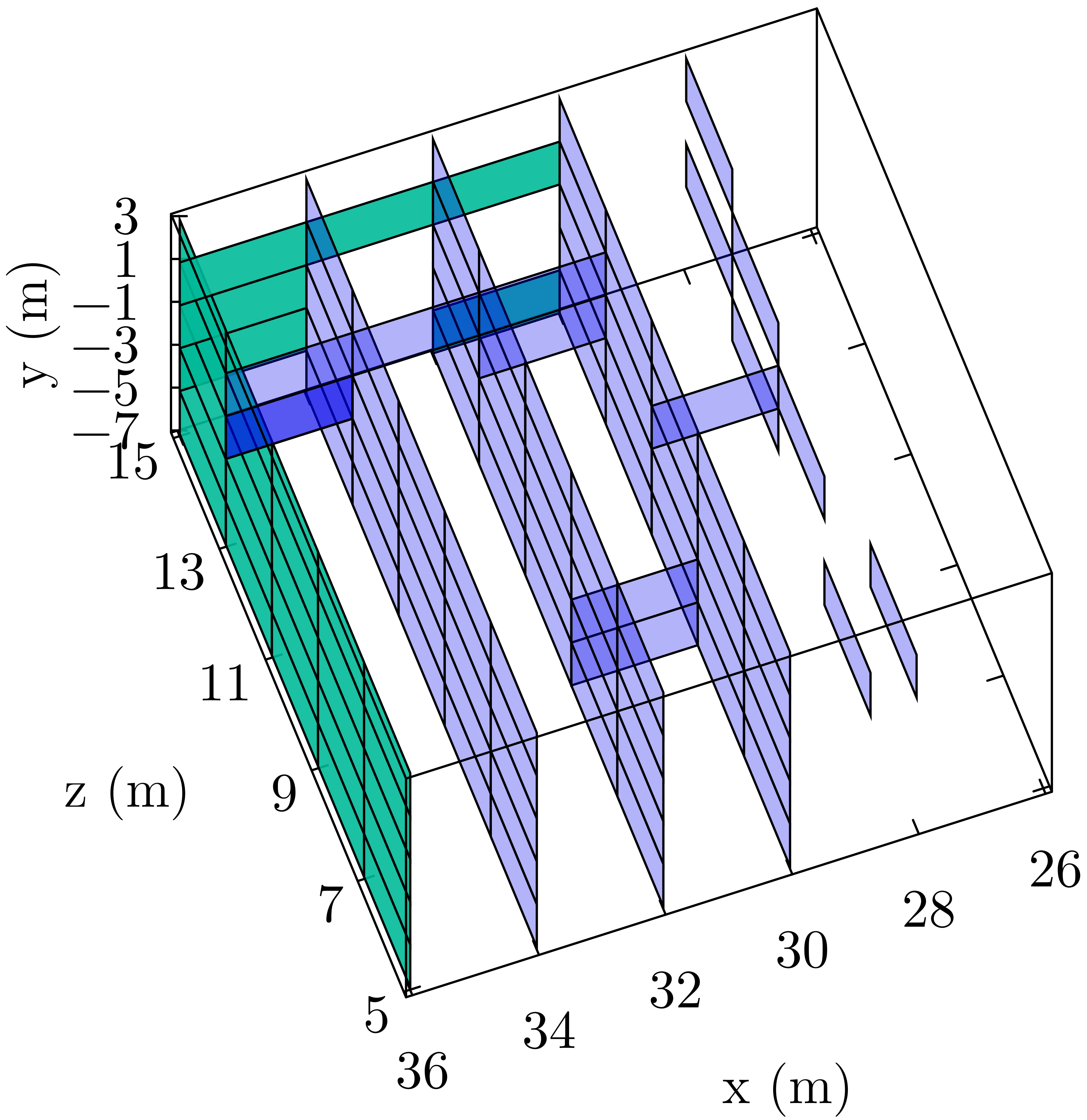
Minimal proof-of-concept geometry

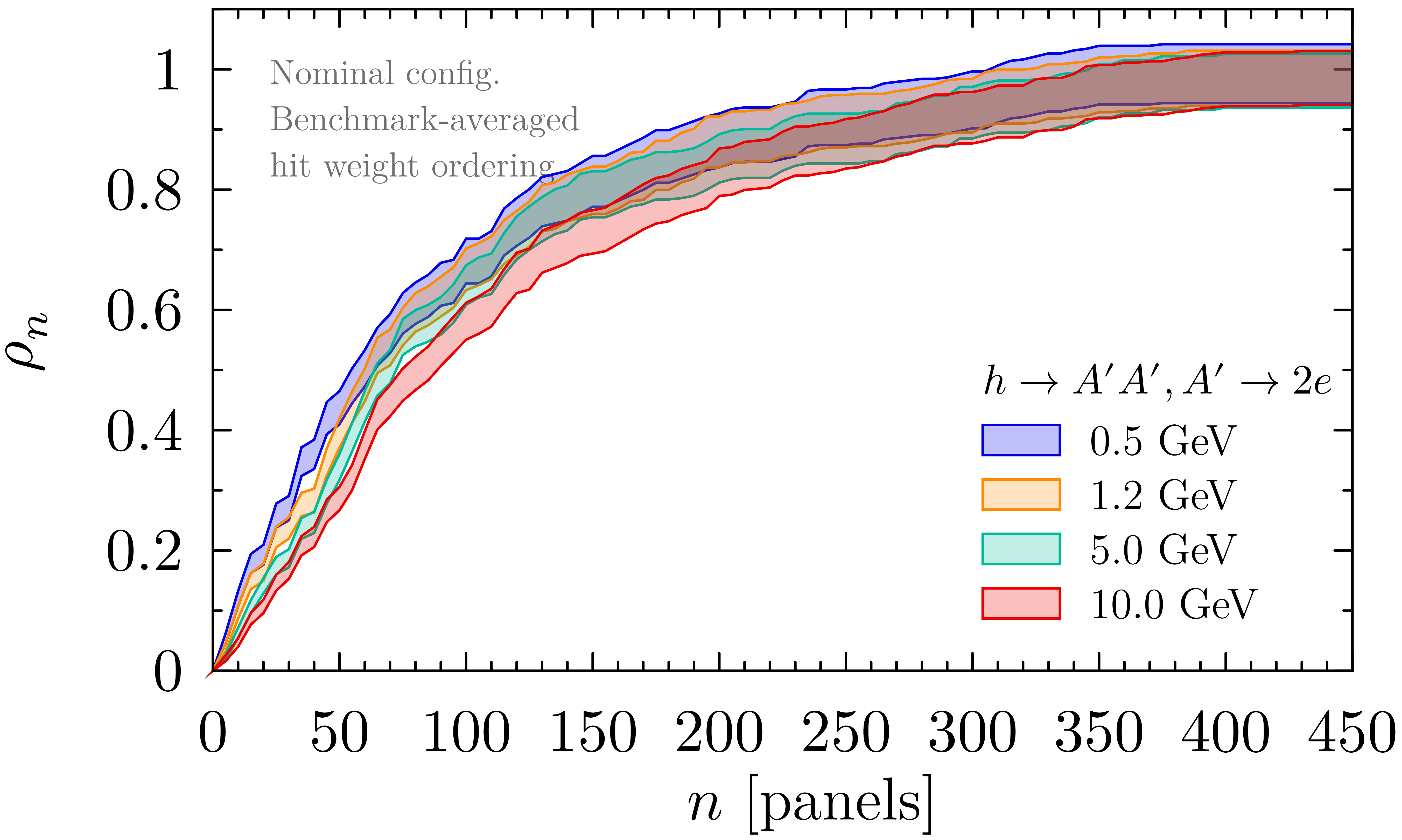


10x10x10 metre box, with 6 RPC layers on each box face. Add 5 other RPC triplet layers equally spaced to minimize the distance to the first measured point for the decay vertex determination.

Optimized geometry

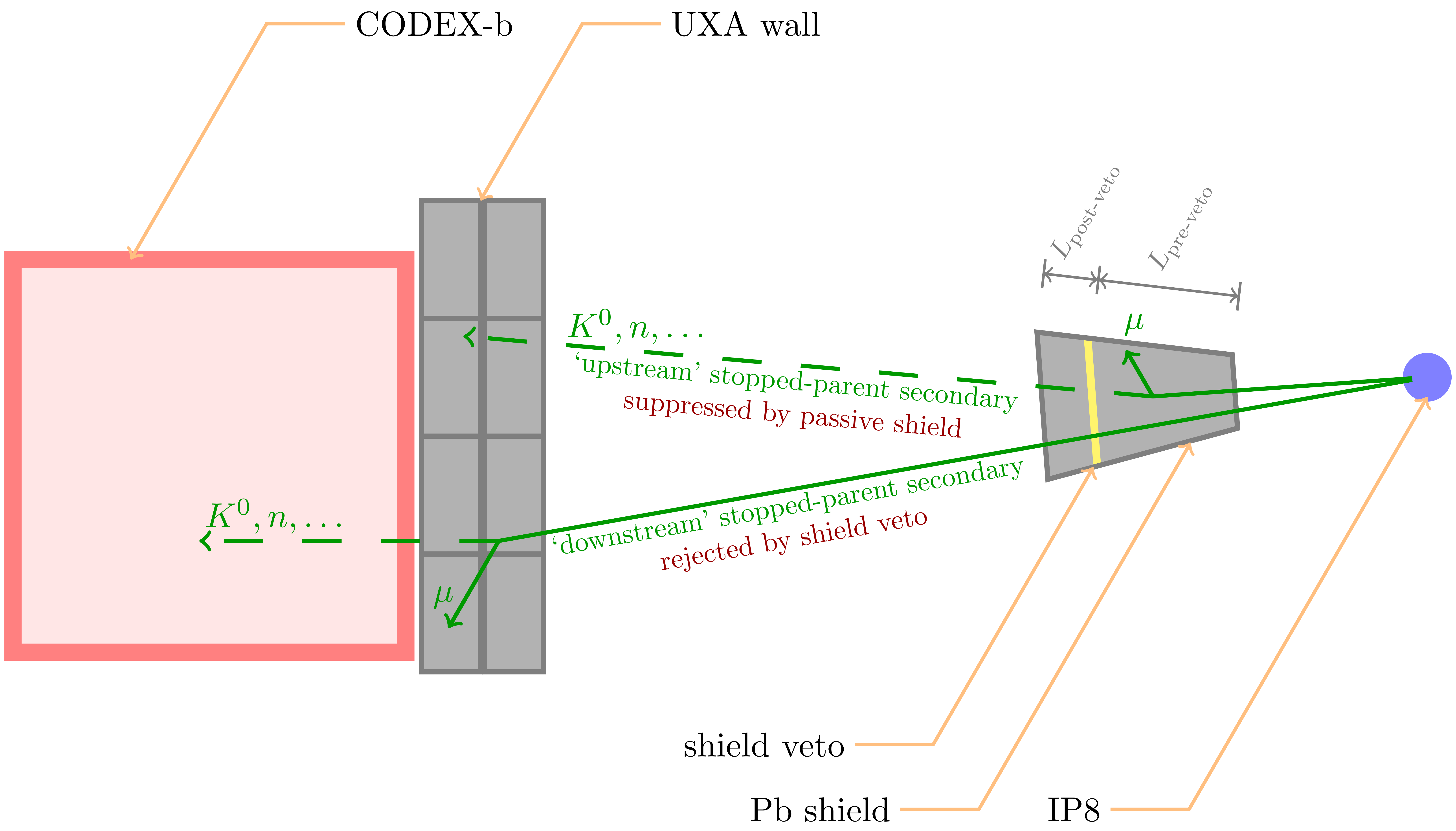
Road ahead for CODEX-b
Snowmass 2021 LOI
https://inspirehep.net/literature/2051244





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

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

BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n+\bar{n}$	7	$5\cdot10^4$	$E_{\rm kin}>1\,{\rm GeV}$
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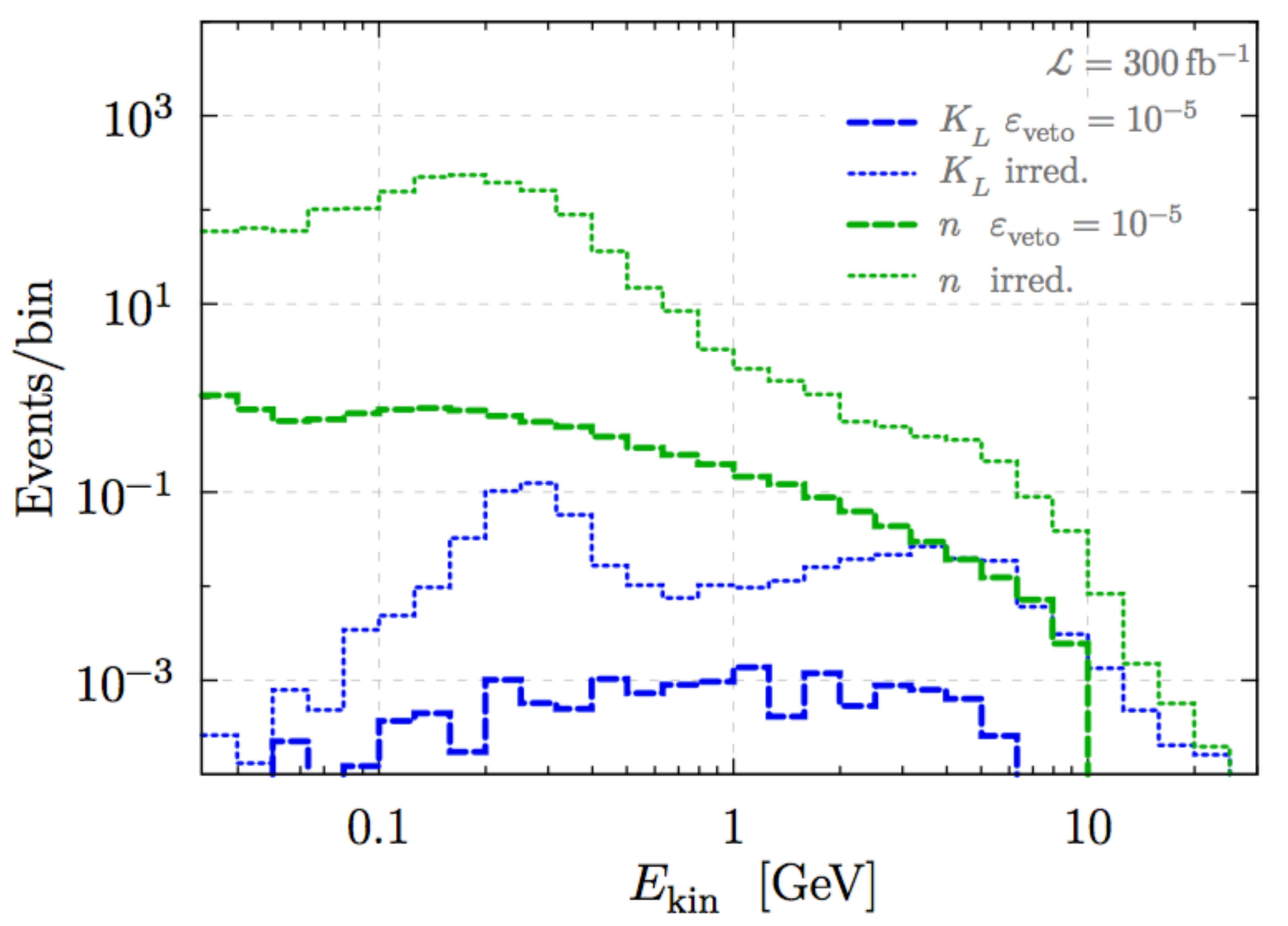
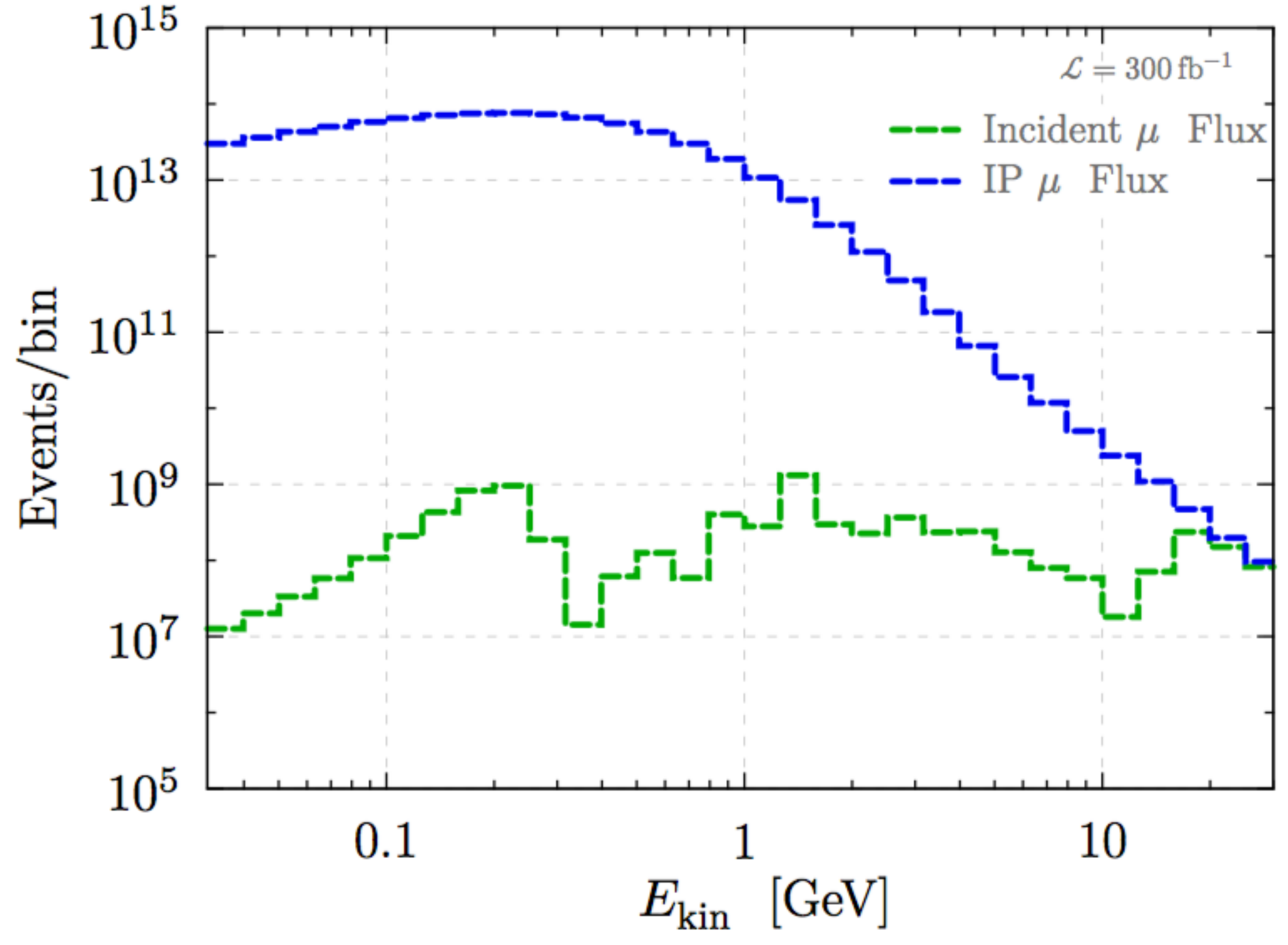


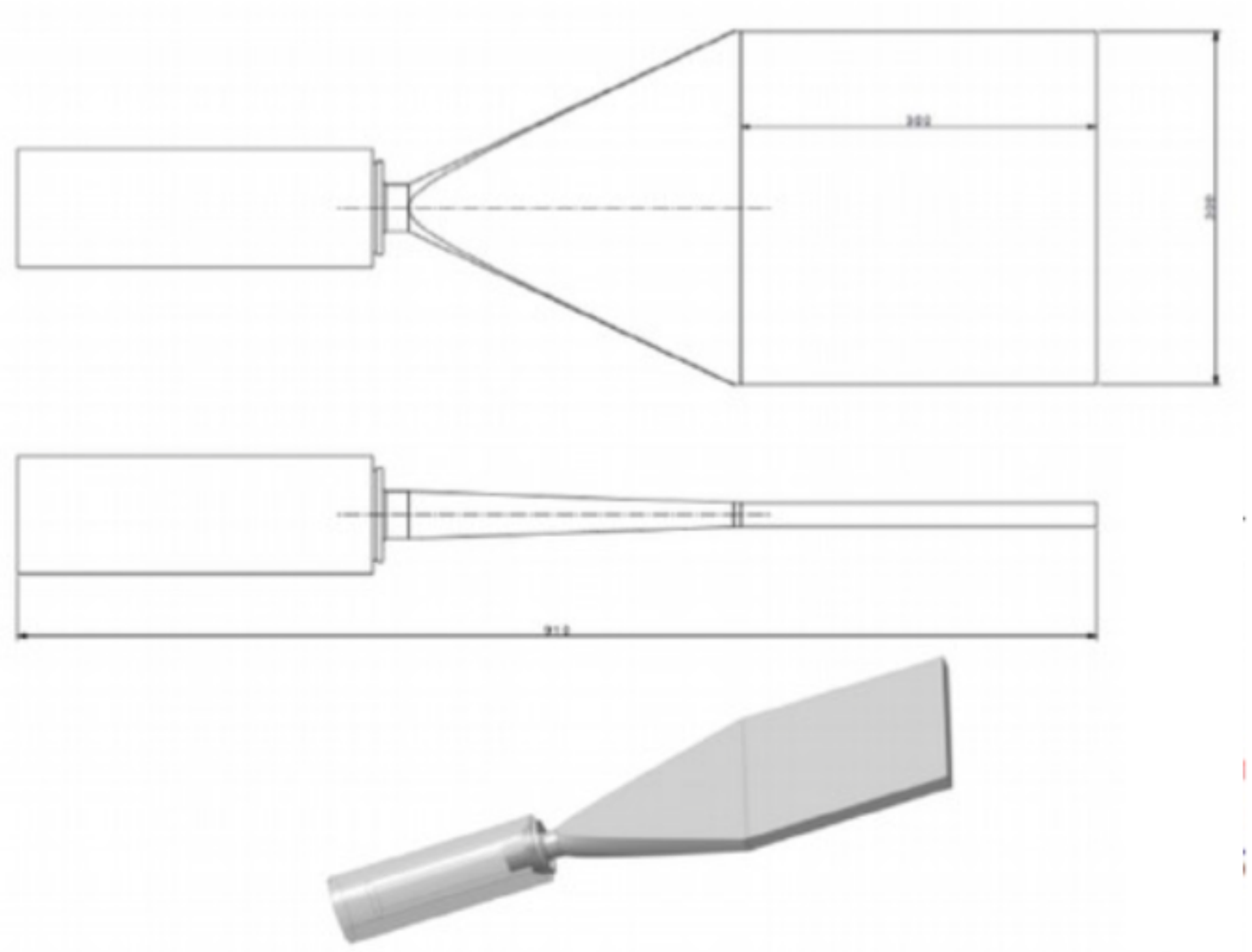
These are the numbers of unvetoable particles entering the box, the estimated number of scatters in box is <1 for all particle species!

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

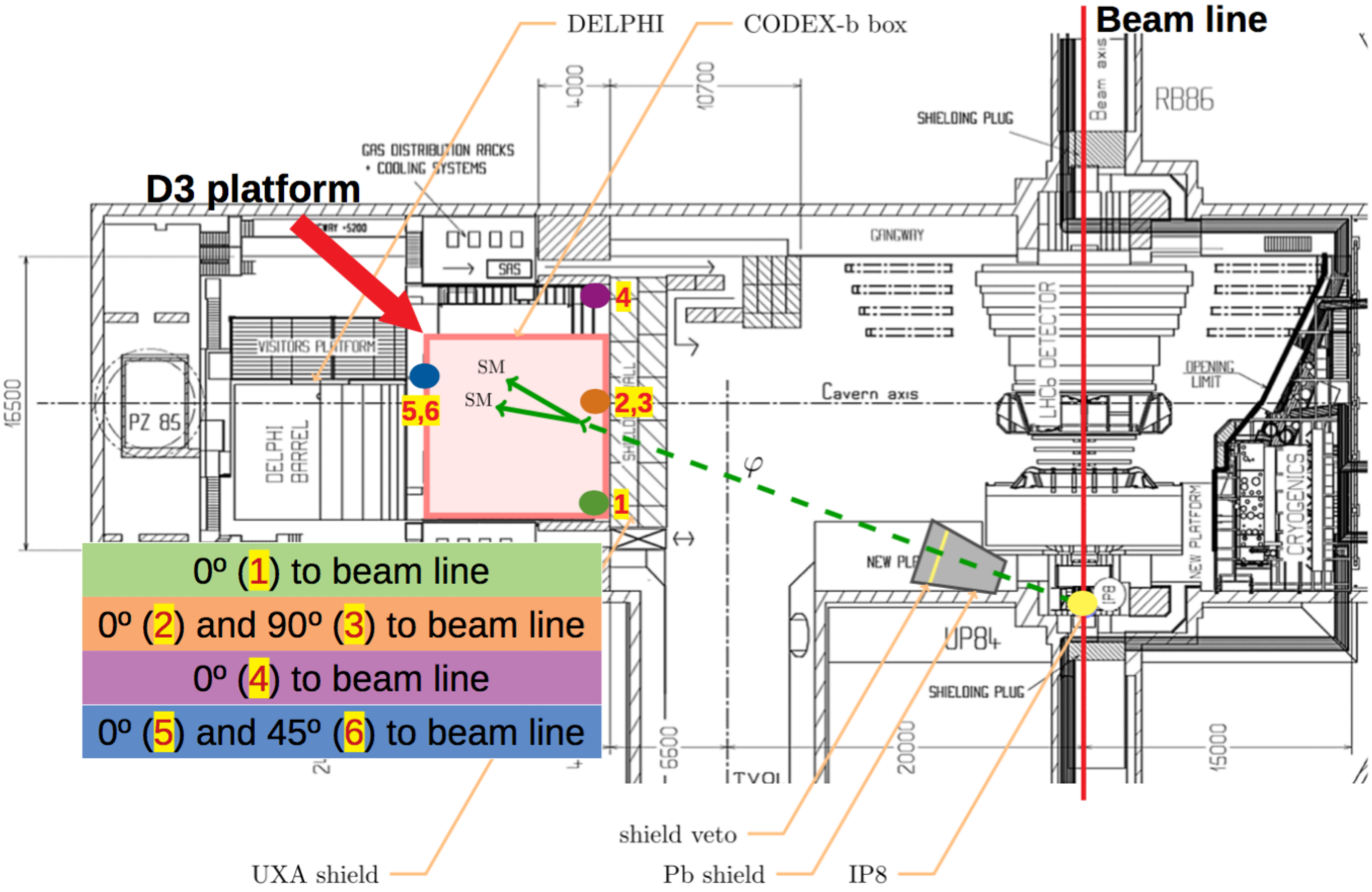


Backgrounds from data

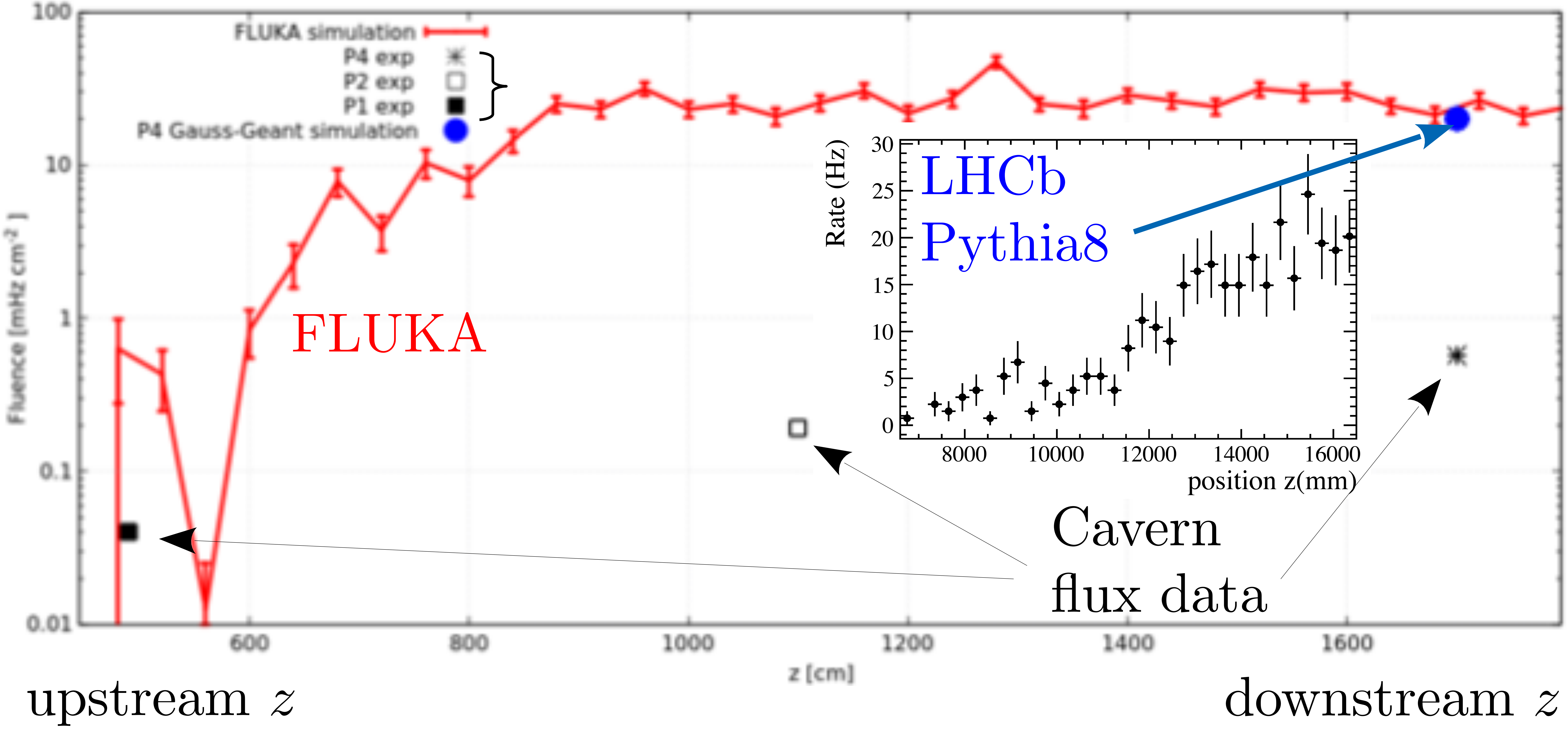
- Two 30 × 30 × 2 cm wrapped plastic scintillators + PMT + mechanical stand.



Placement of scintillators in cavern



Results

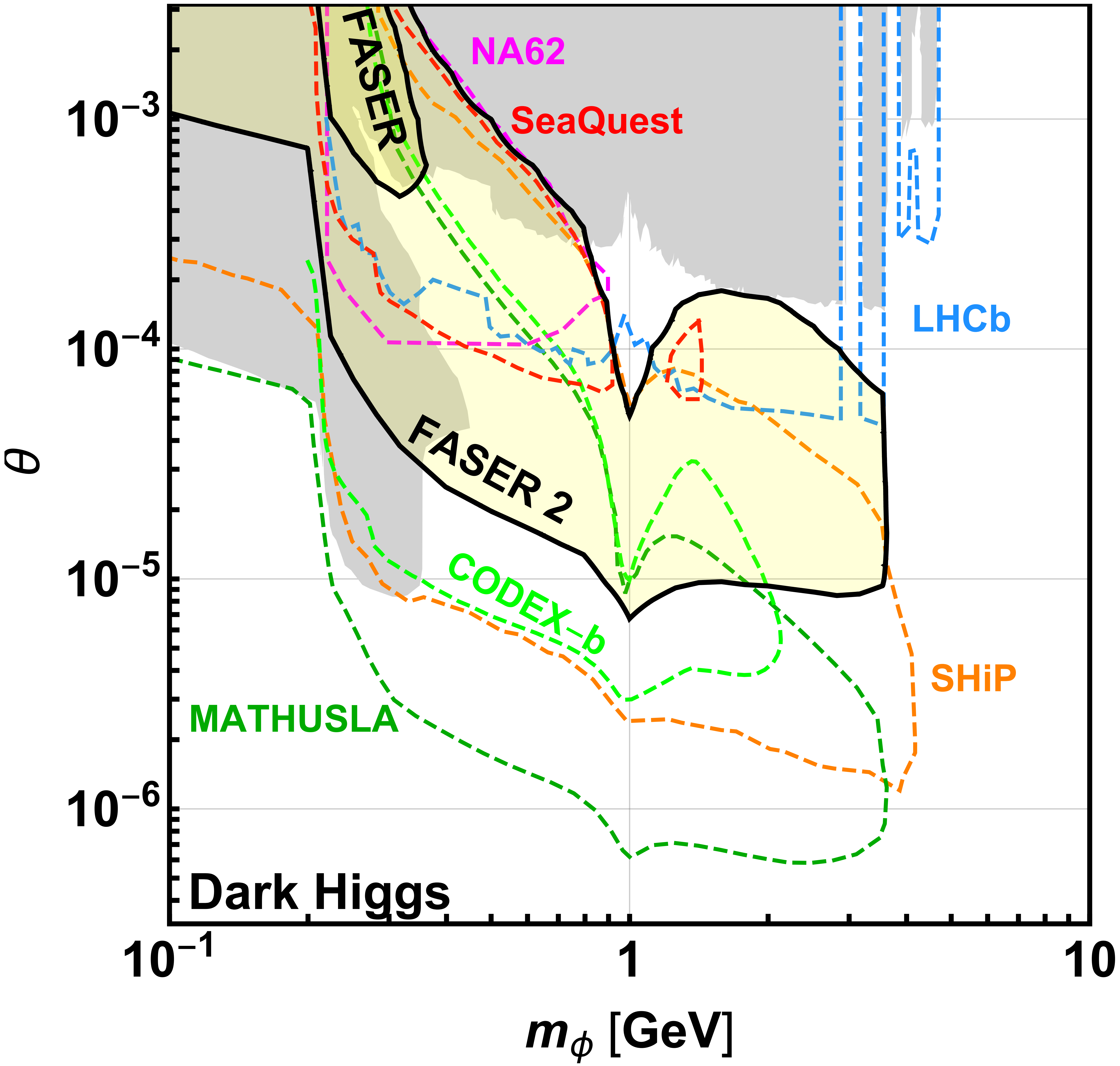


Implies an O(100)Hz hit rate over the whole front face of the detector with only the concrete wall shielding. Better than expected from simulation because of additional structures in cavern!

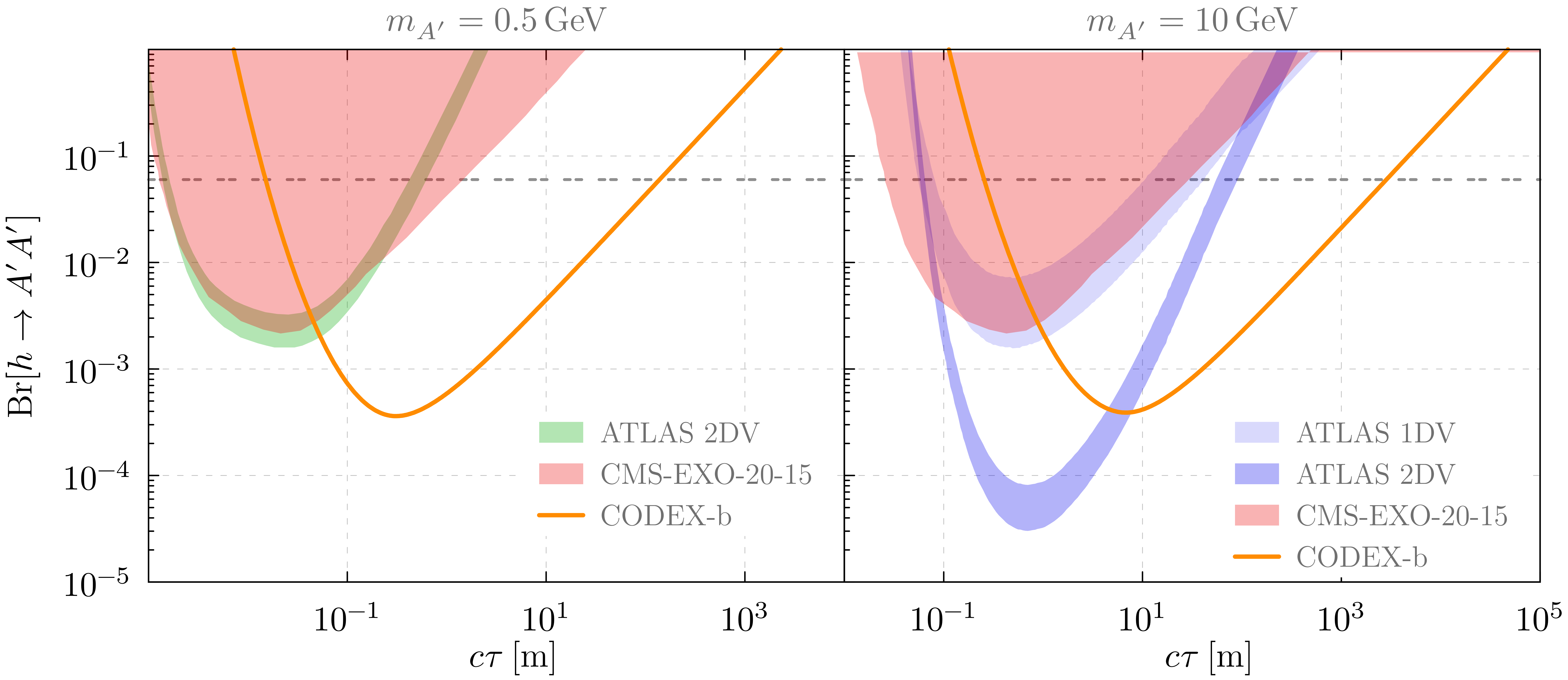
CODEX-b signal reach & ID

Example model 1 — b→sX

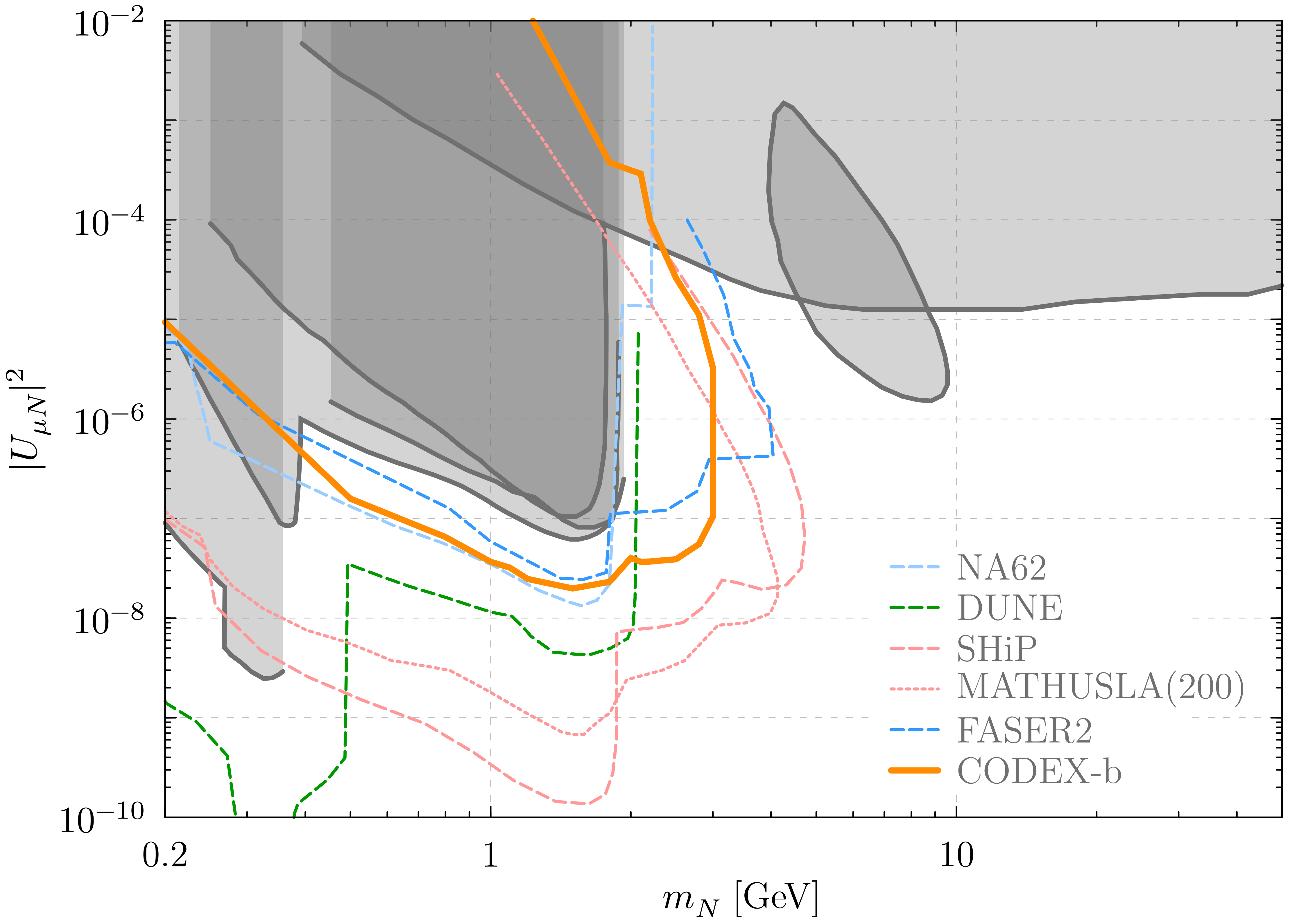
2019 LLP White Paper
https://inspirehep.net/literature/1724682

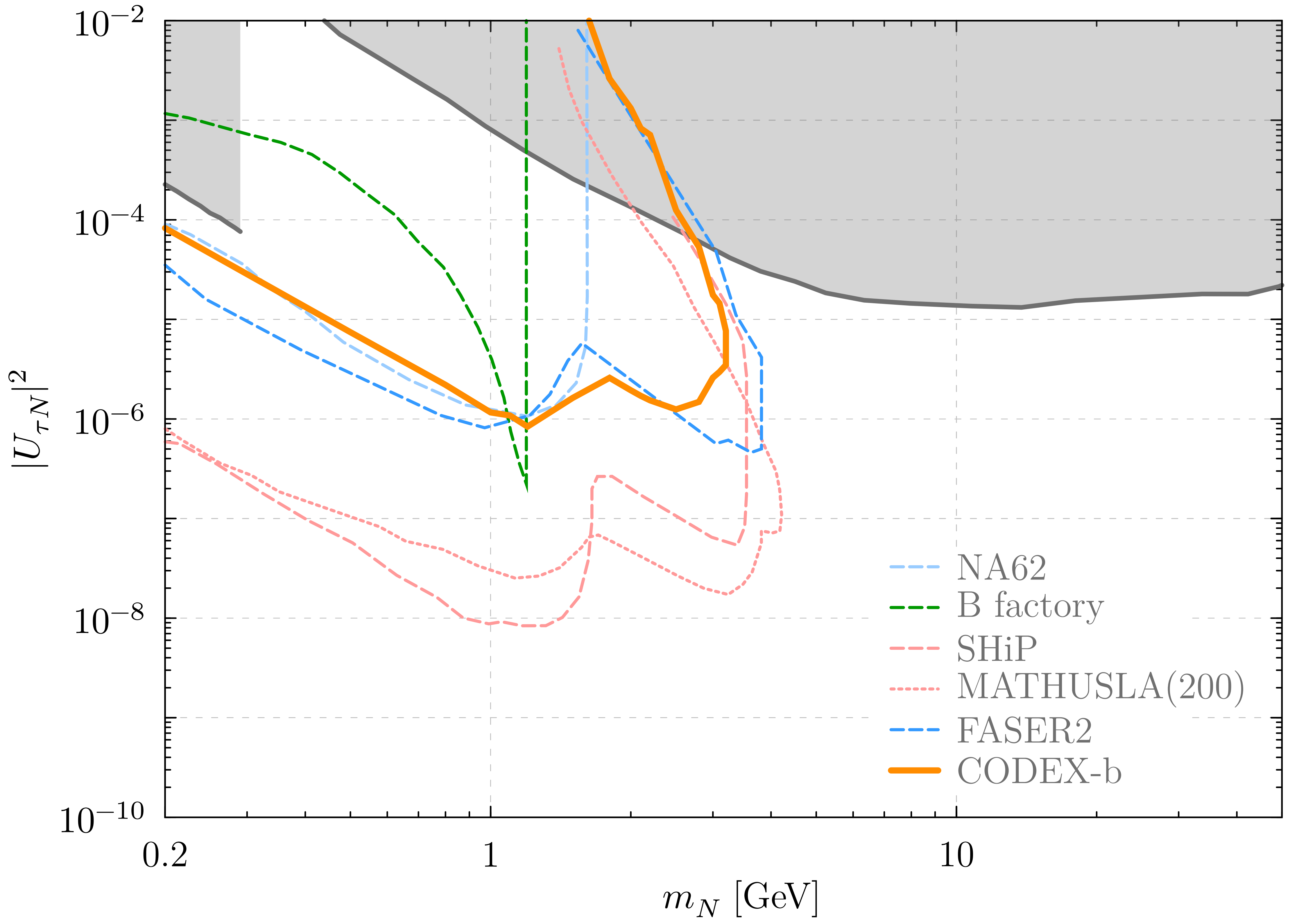


Example model 2 — H→φφ

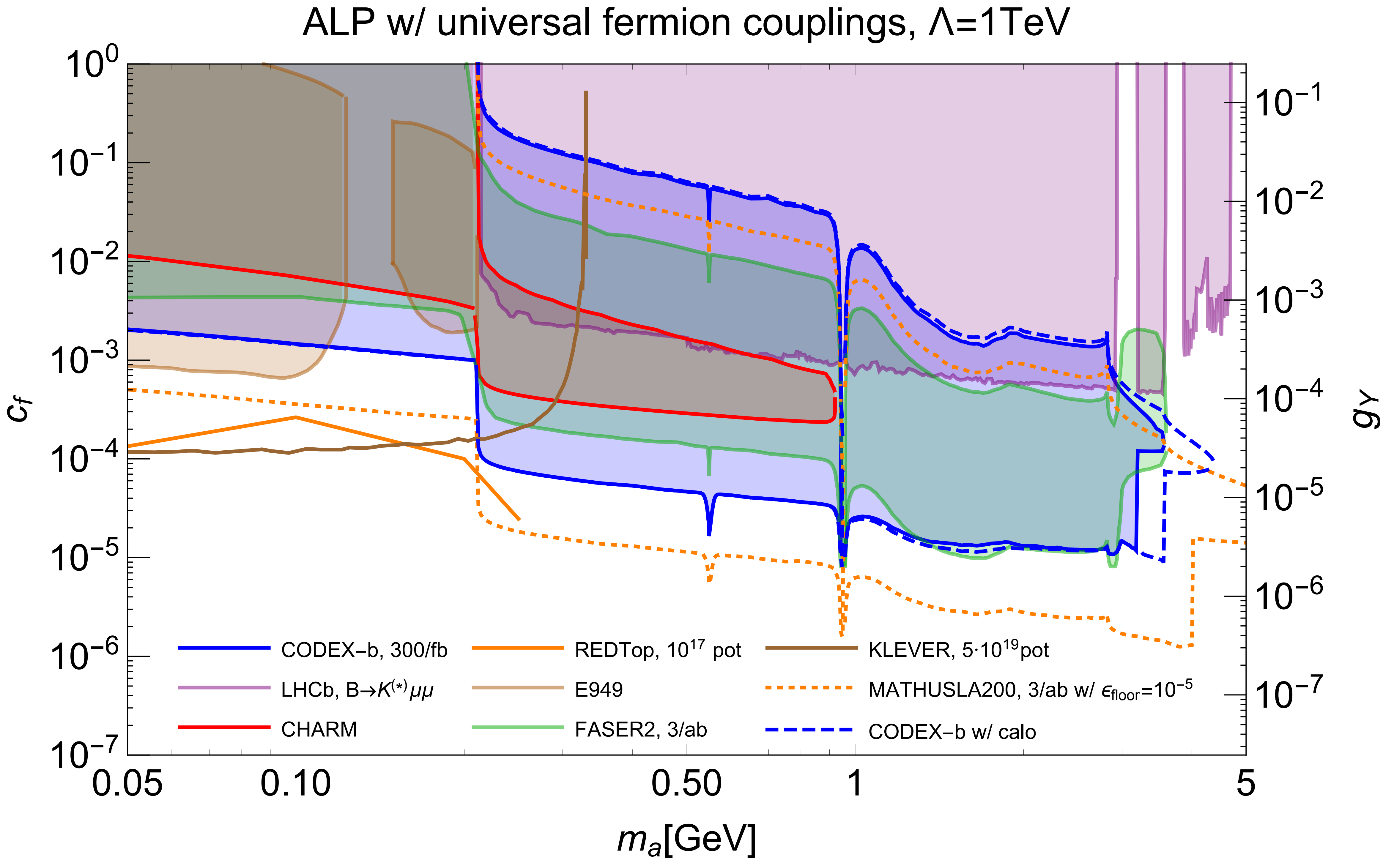


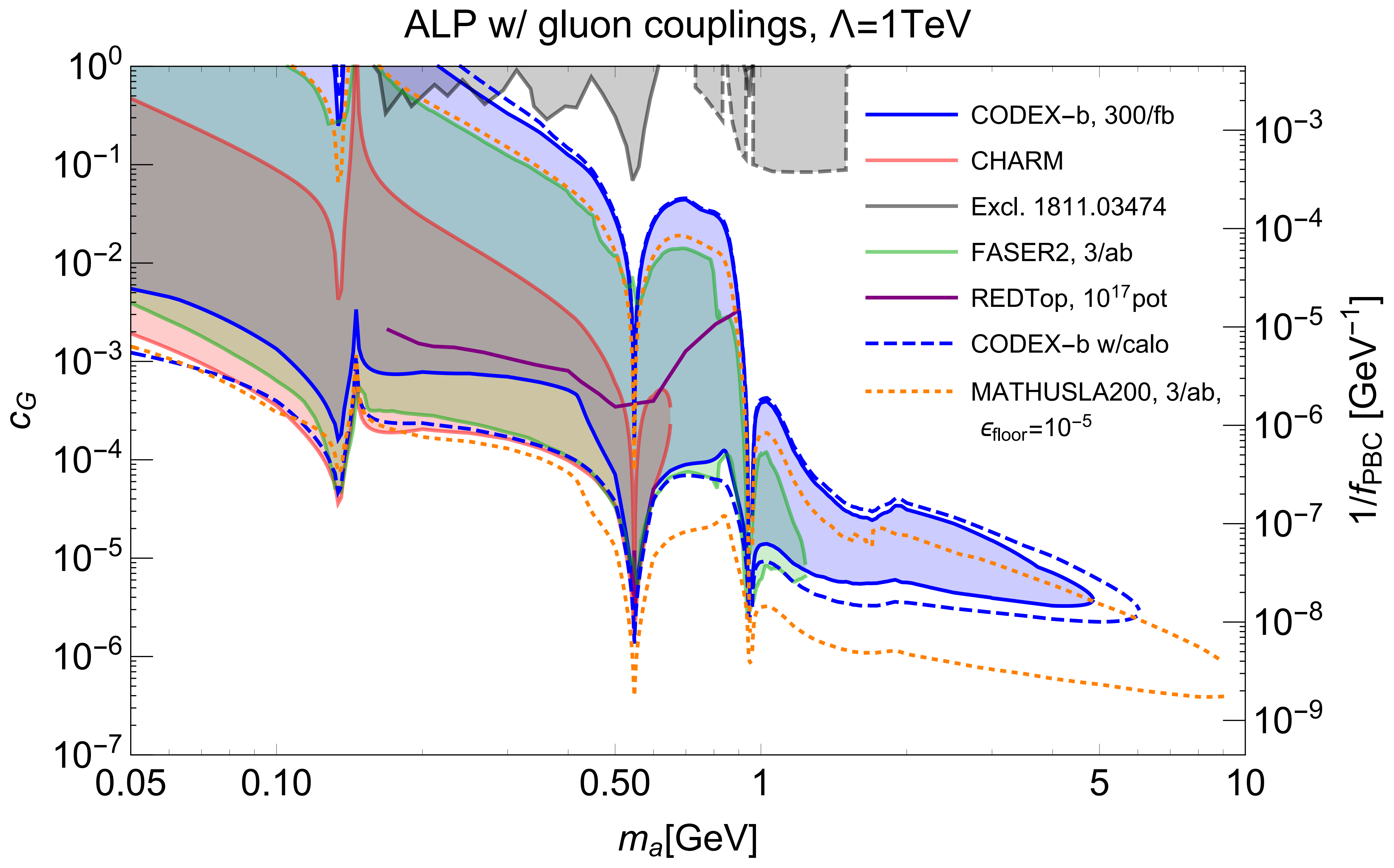
Example model 3 — HNL





Example model 4 — ALP





Conclusion

Conclusion

Increasing interest in direct searches for long-lived particles is a natural consequence of

1. The fact that almost any physics beyond the SM generates at least some such particles
2. As of today we have no direct signs of short-lived particles beyond the SM
3. It's plausible that LLPs have been missed due to existing detector designs

A wide range of complementary experiments are being proposed, to see which if any actually get built.

Backups

Tracker efficiency estimate

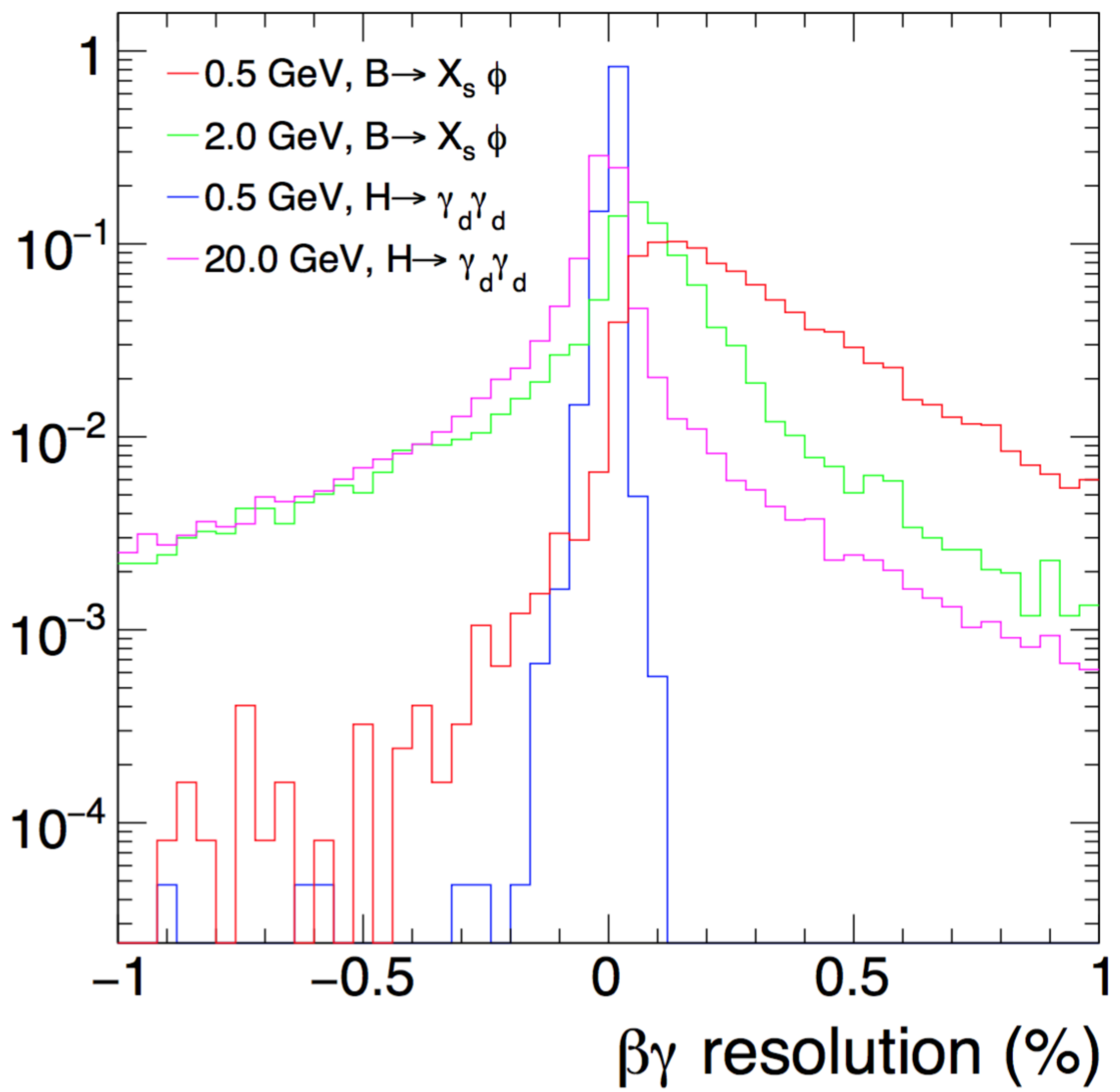
$c\tau$ (m)	m_φ $[B \to X_s \varphi]$			m_{γ_d} $[h \to \gamma_d \gamma_d]$				
	0.5	1.0	2.0	0.5	1.2	5.0	10.0	20.0
0.05	–	–	–	0.39	0.48	0.50	–	–
0.1	–	–	–	0.48	0.63	0.73	0.14	–
1.0	0.71	0.74	0.83	0.59	0.75	0.82	0.84	0.86
5.0	0.55	0.64	0.75	0.60	0.76	0.83	0.86	0.88
10.0	0.49	0.58	0.74	0.59	0.75	0.84	0.86	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

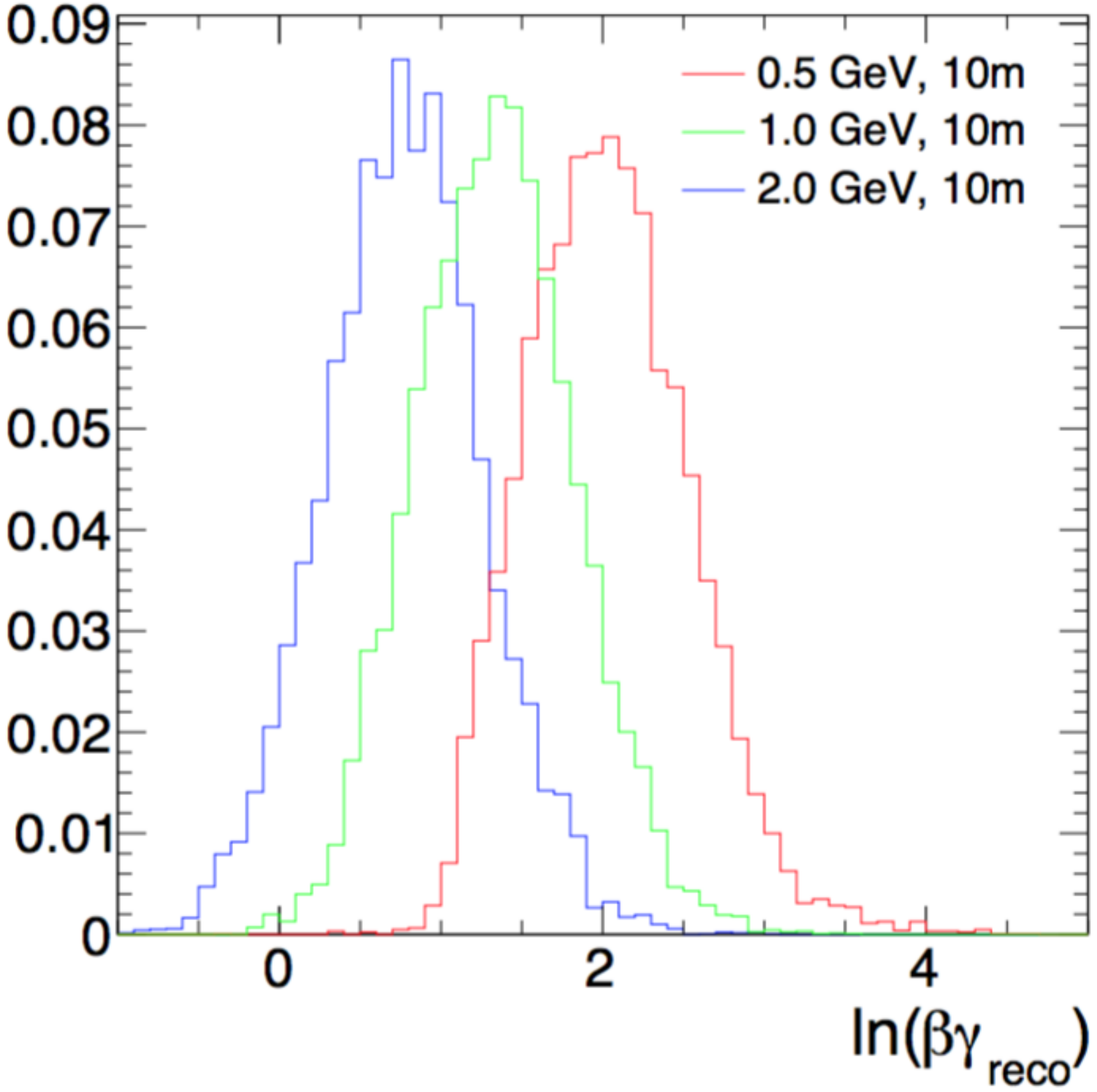
Boost reconstruction



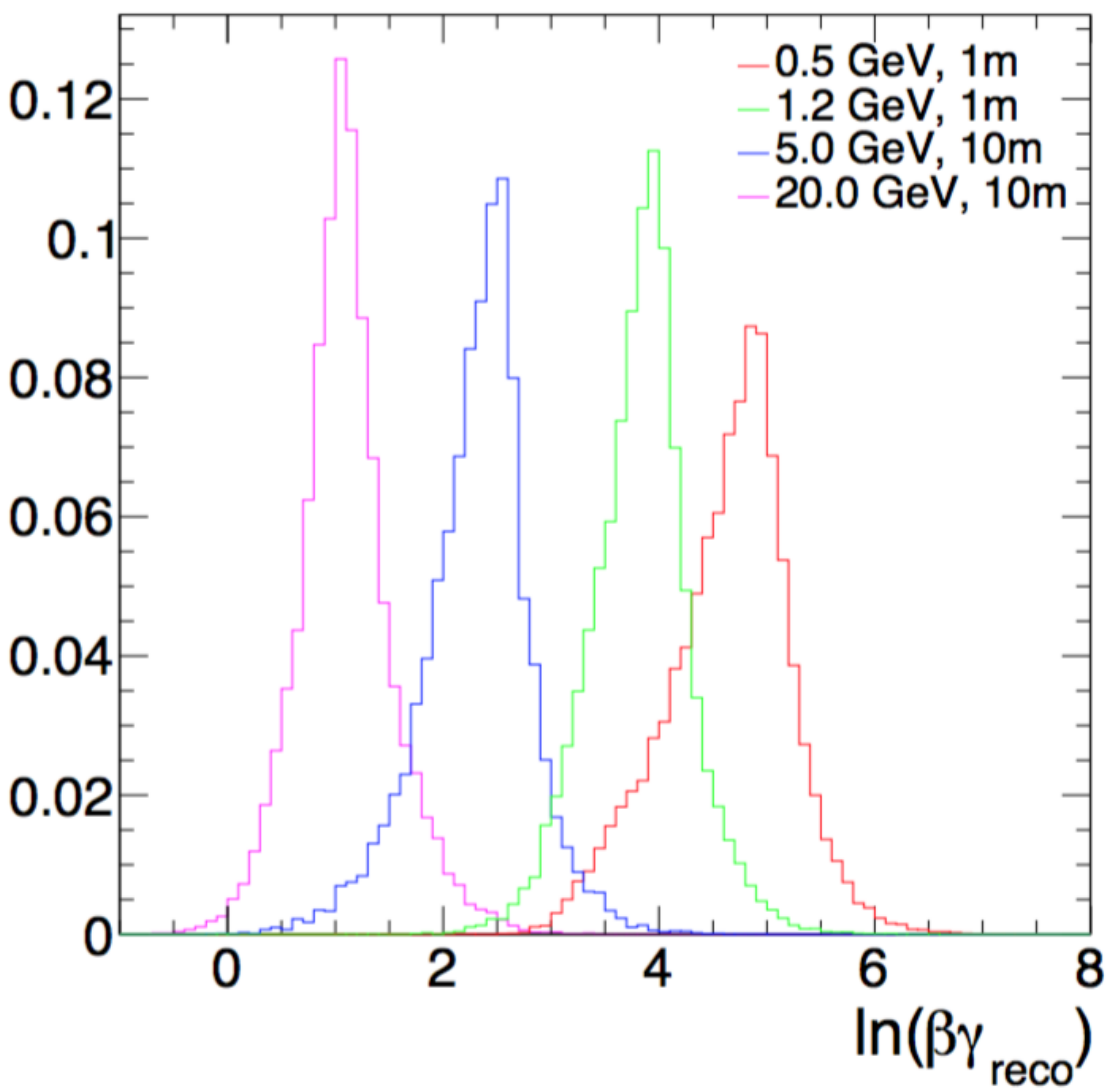
Reconstruct parent boost from the measured decay vertex (no timing!), assuming relativistic decay products. The resolution is < 1% (entirely dominated by distance to first measured point, not detector granularity) so the boost distribution is dominated by the generated spread of boosts, not resolution.

Boost reconstruction

$B \to X_s \varphi$

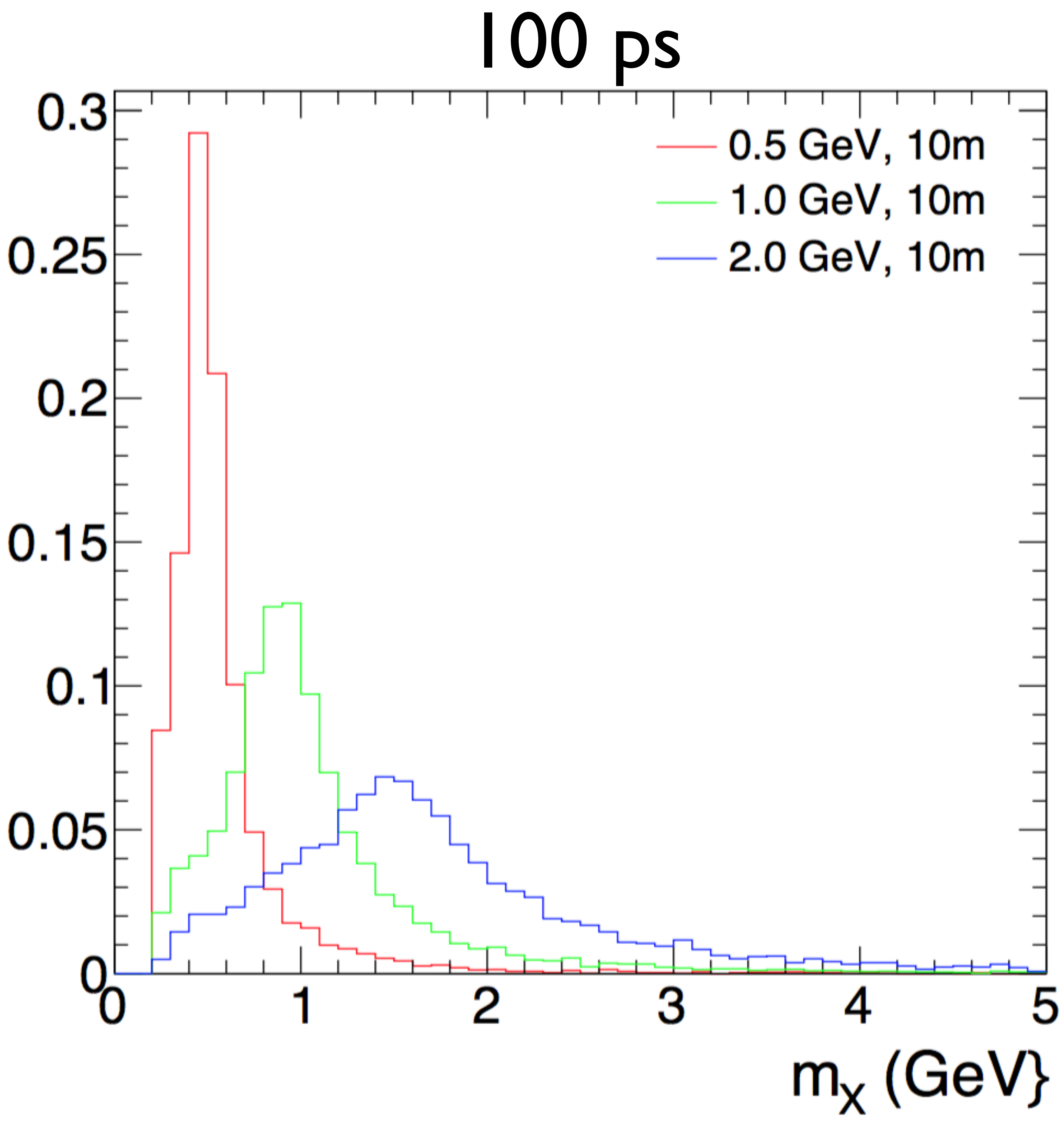


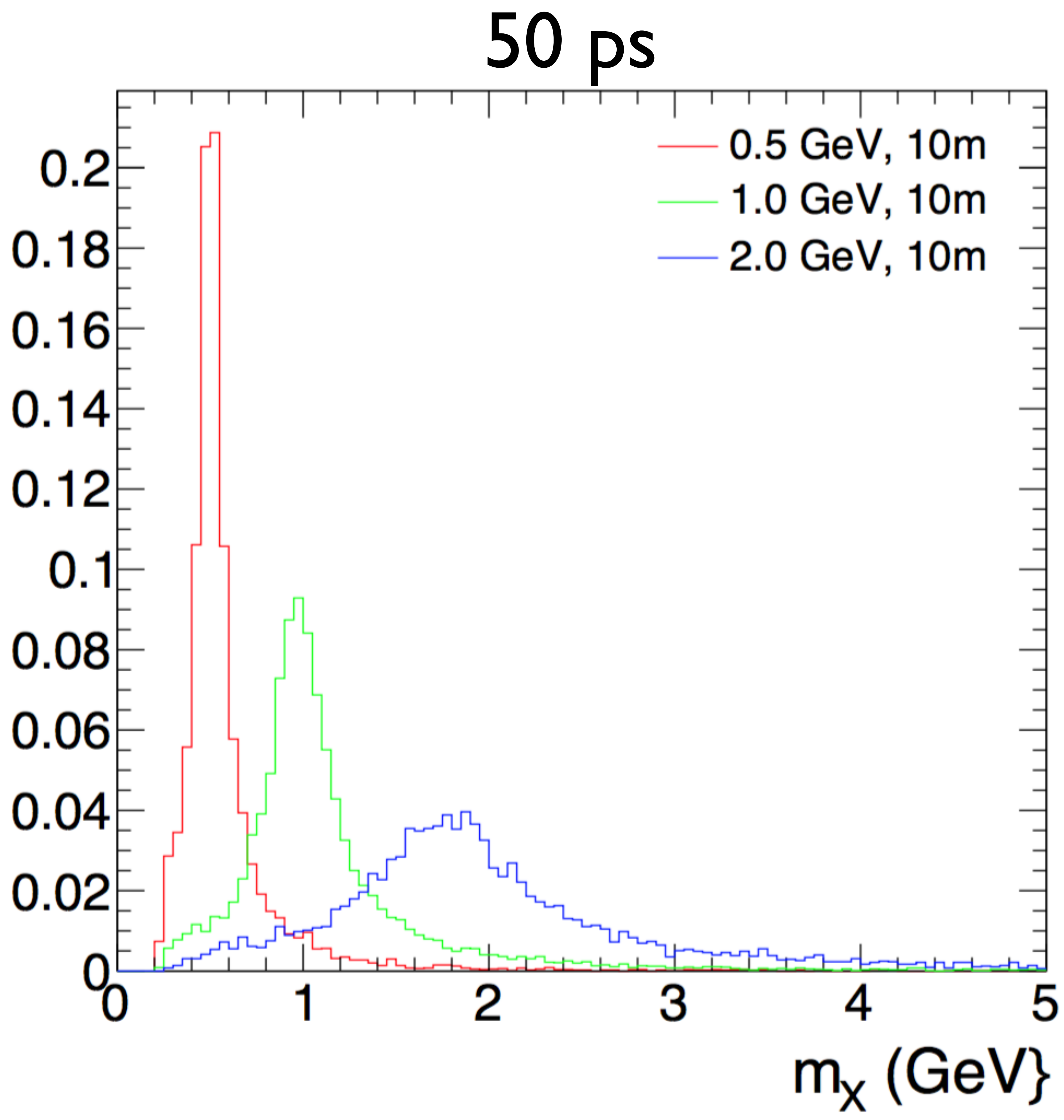
$H \to \varphi\varphi$



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

Mass reconstruction using time-of-flight

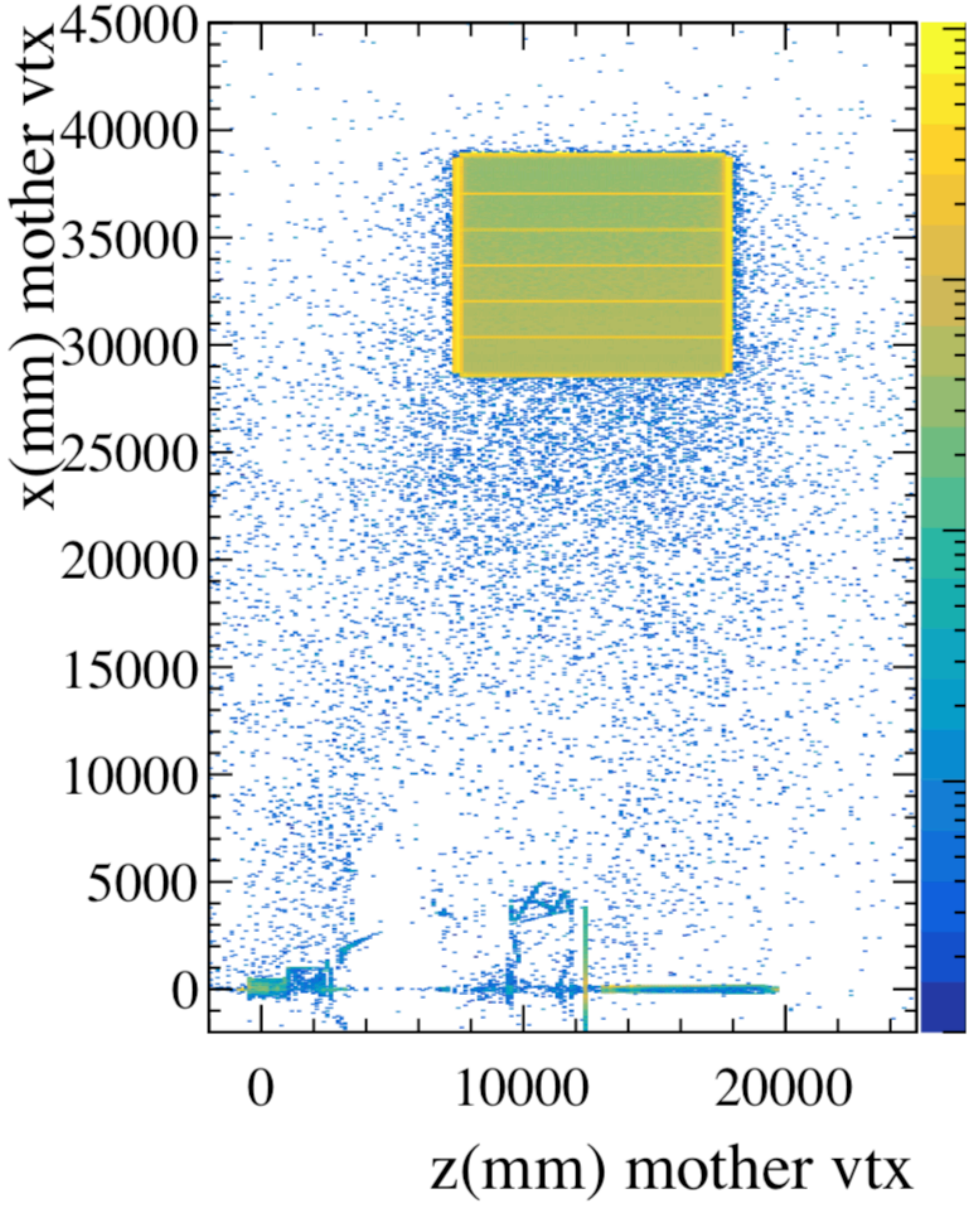




Now assume 100/50 ps time resolution (per hit) in the tracking stations. The B→KX signals are actually slow enough that we can reconstruct the X mass…

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.

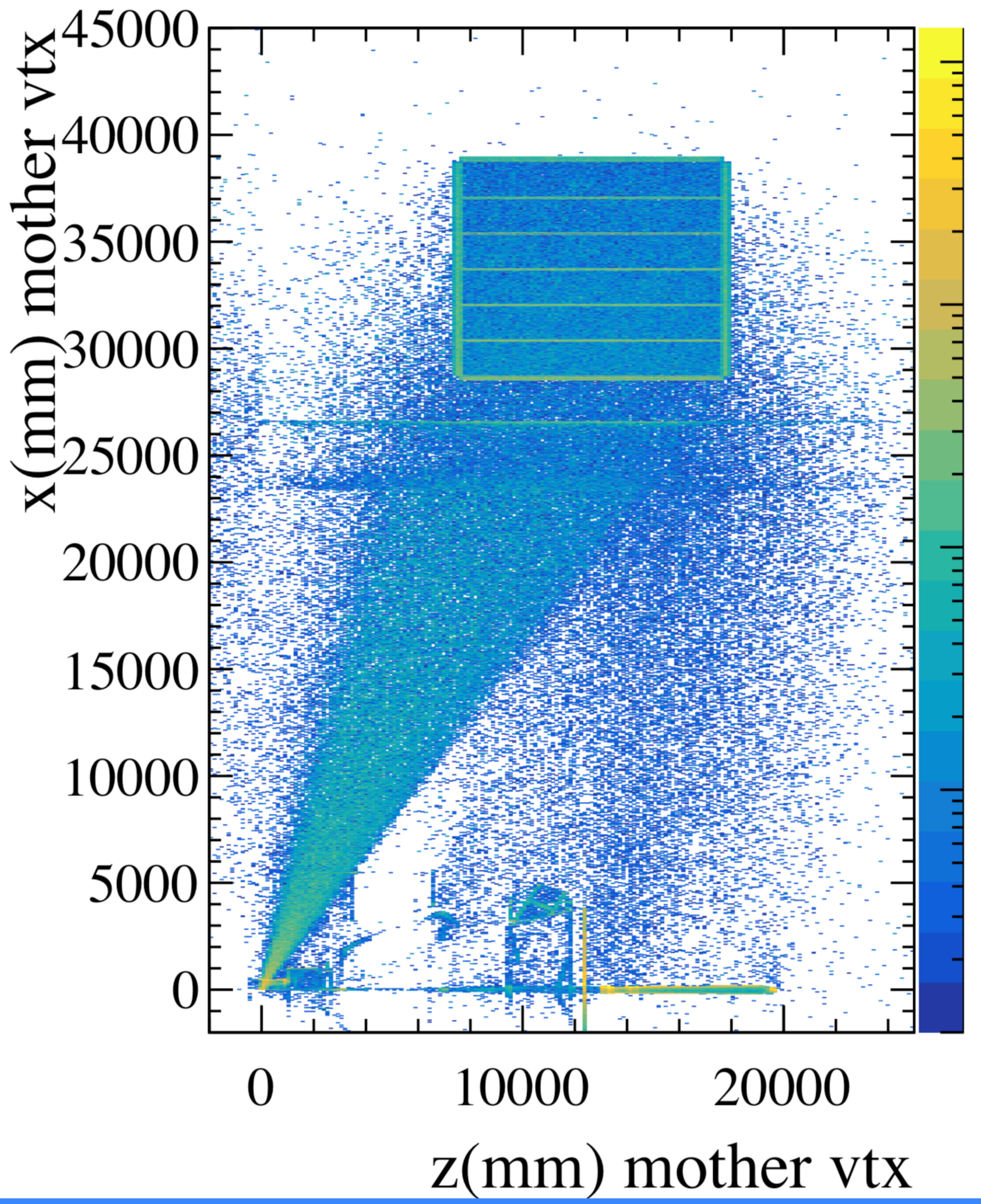


Note that current geometry is actually a silicon detector for simplicity, we are working to implement a realistic RPC based geometry and simulate signal.

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

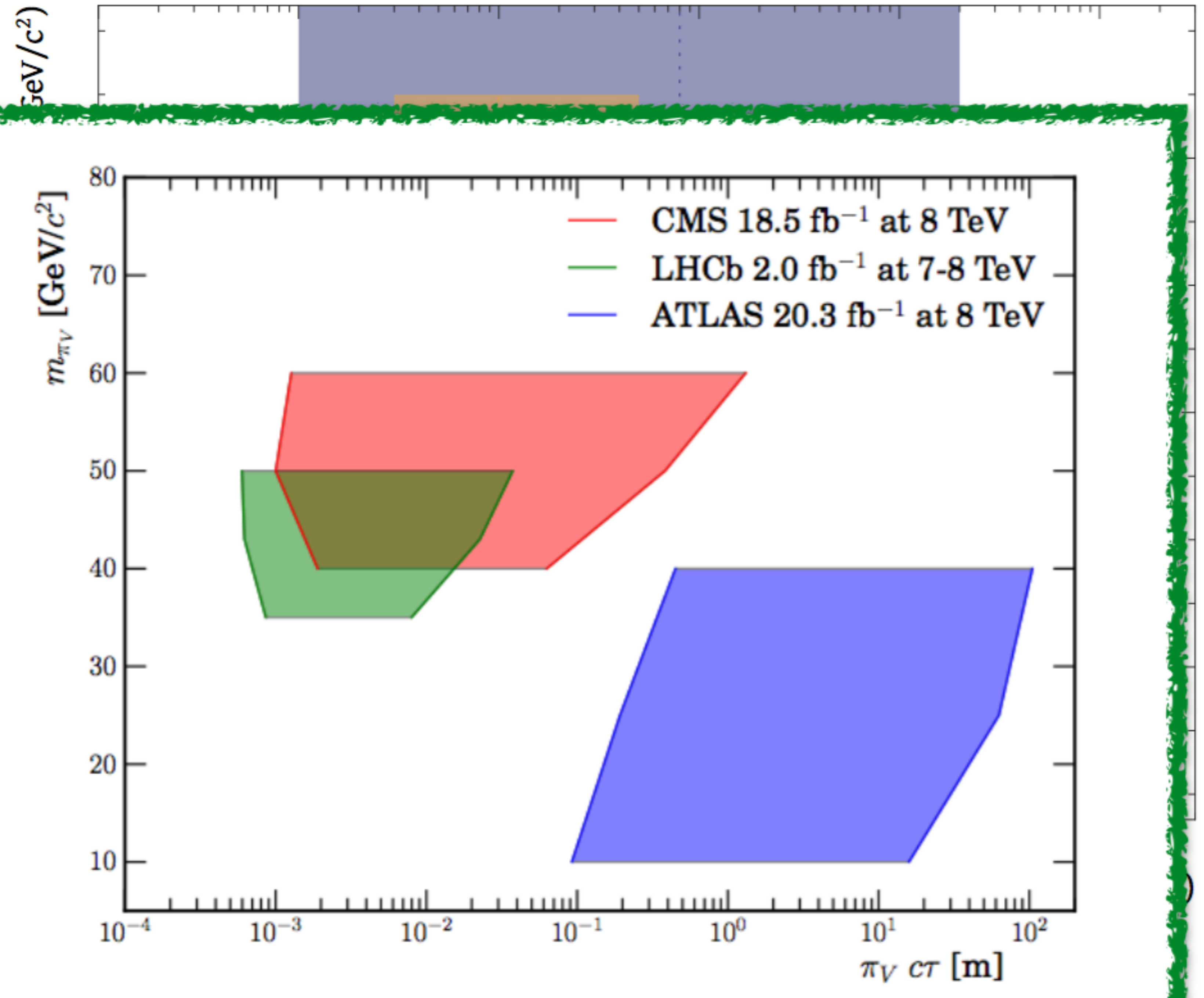


Note that current geometry is actually a silicon detector for simplicity, we are working to implement a realistic RPC based geometry and simulate signal.

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 $p_T \sim 1$ 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 → $\pi_V\pi_V$ 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

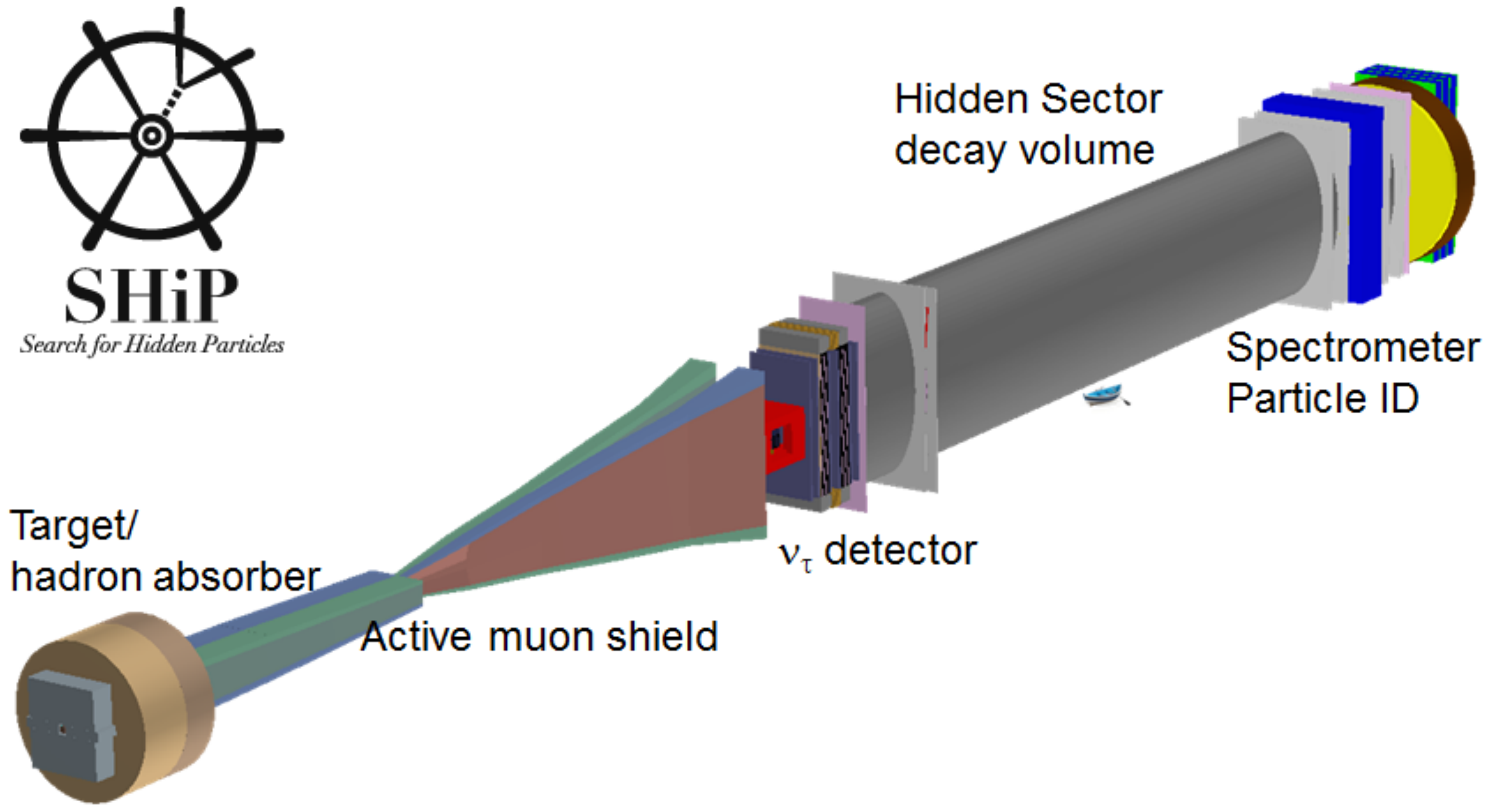
Key points :

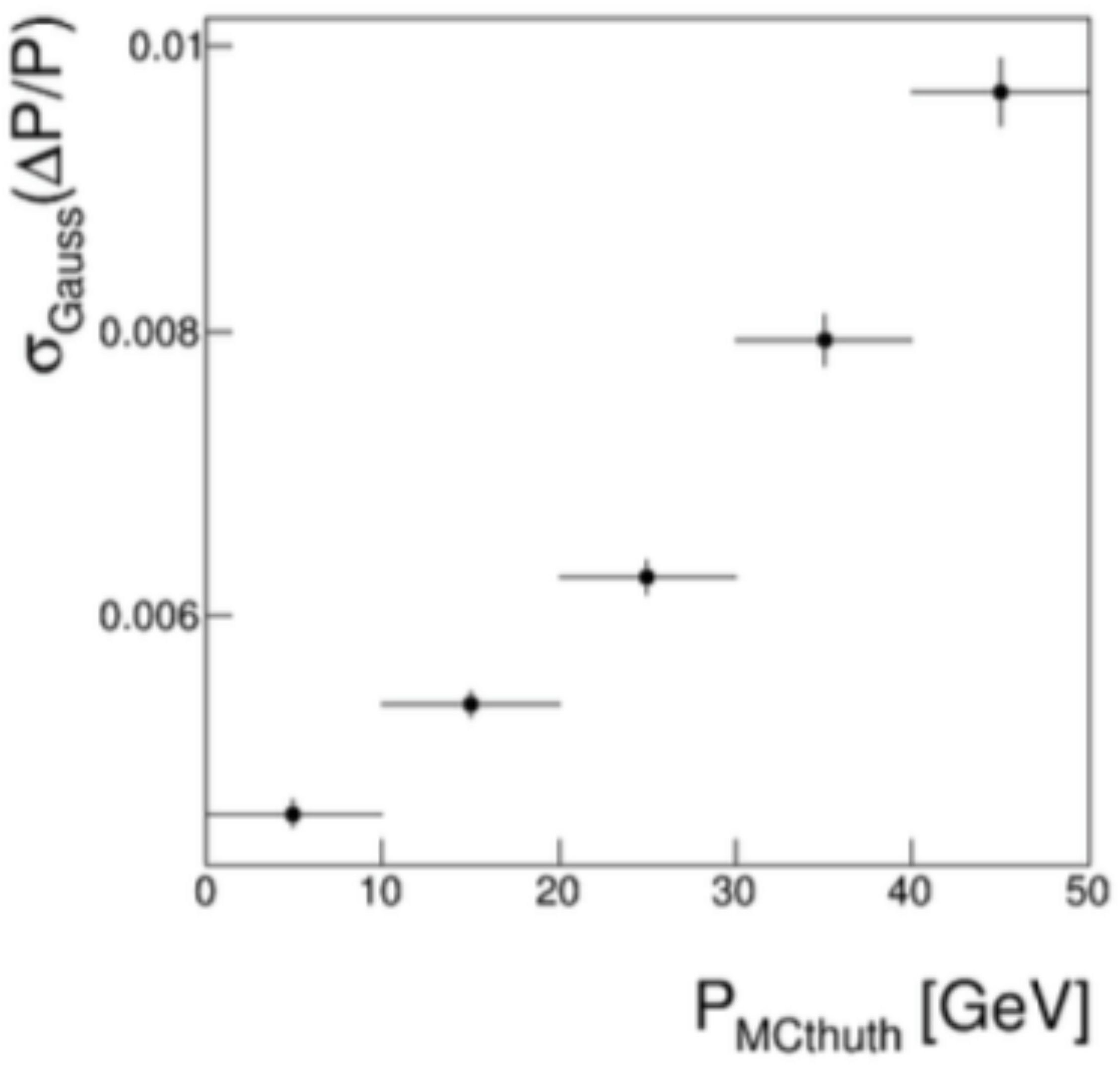
Active shield and vacuum decay volume to minimize backgrounds

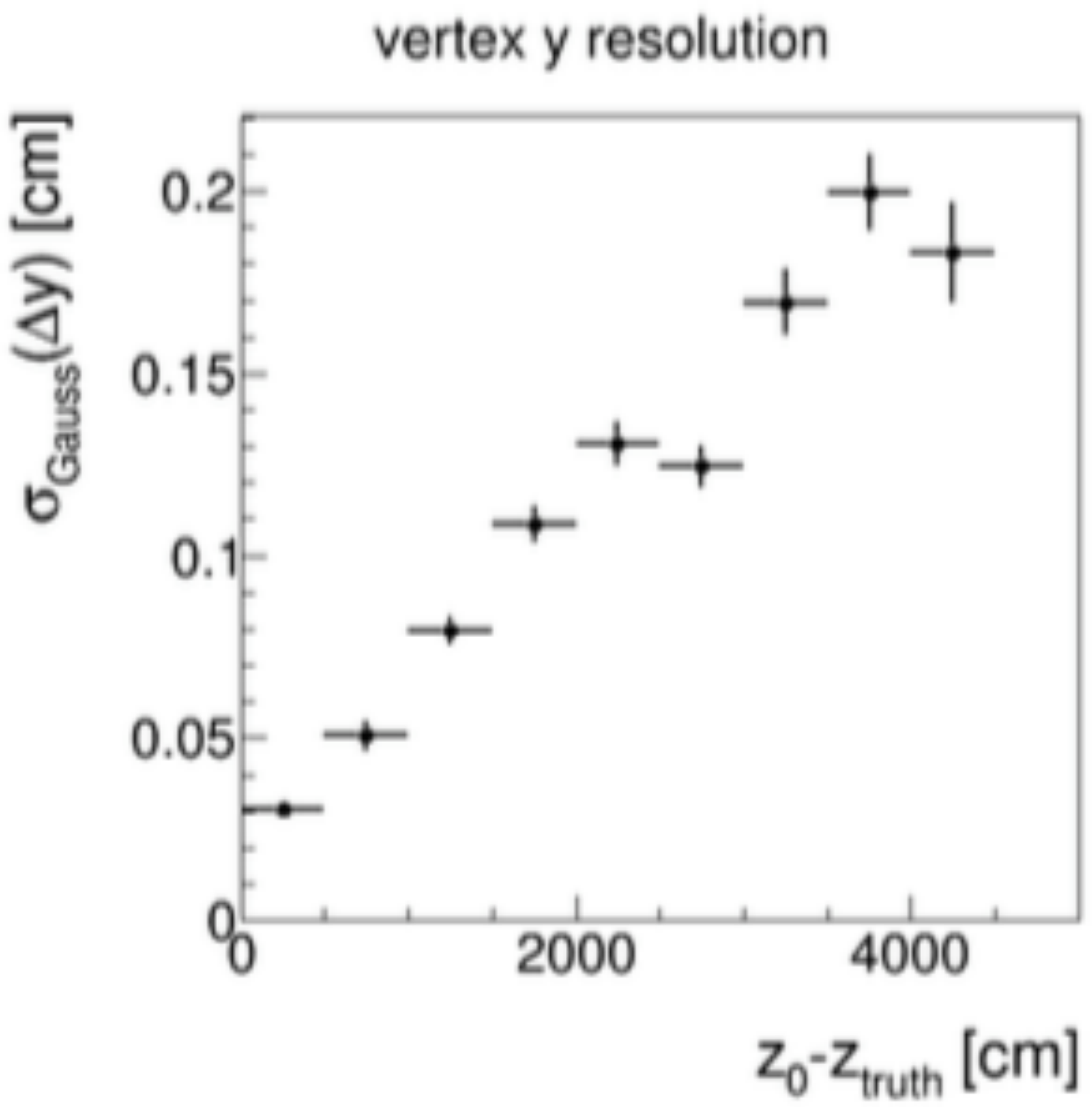
Sub percent momentum resolution, particle ID, mm vertex resolution in the transverse plane

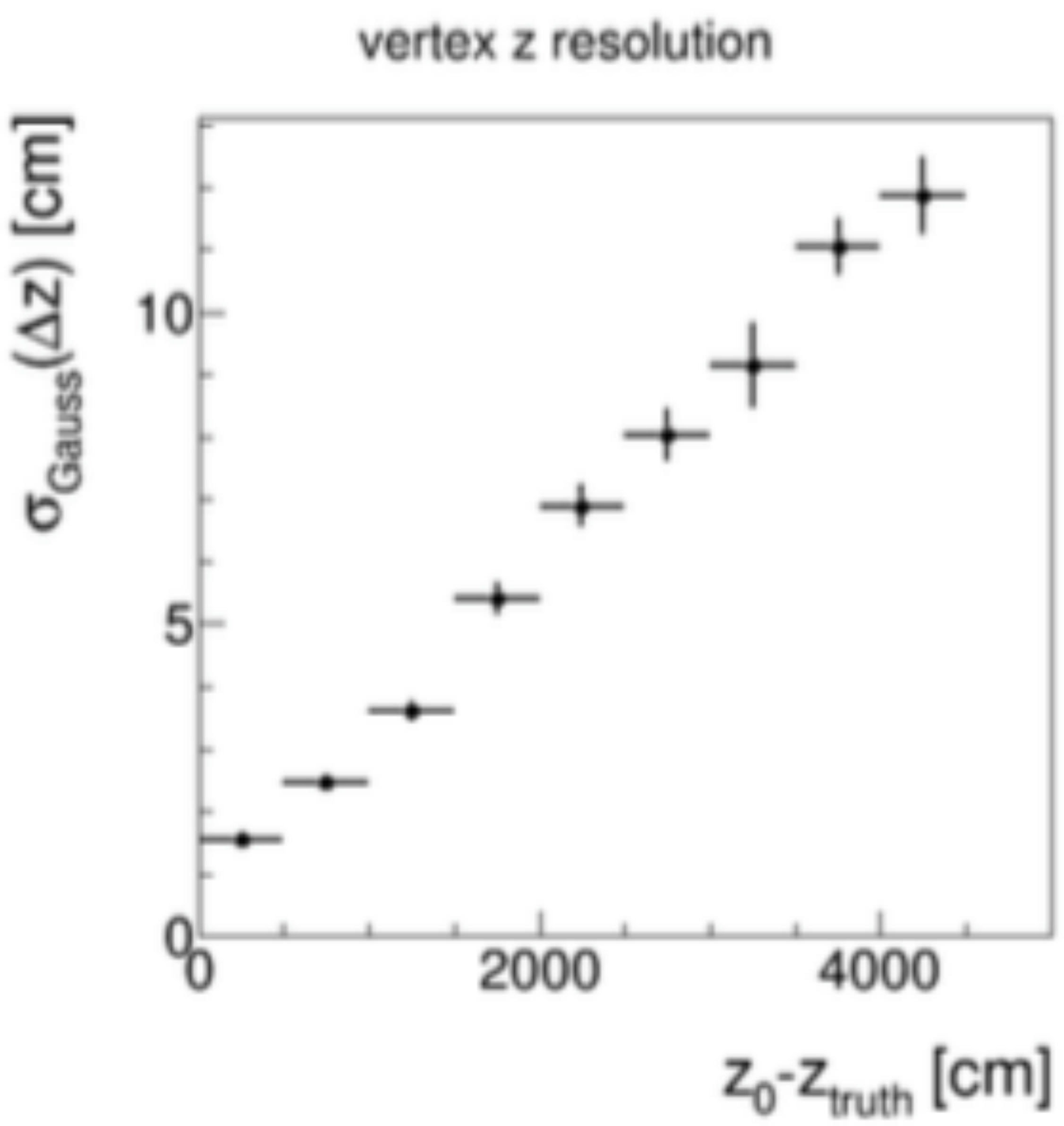
Timing coincidence (a la NA62) used to suppress backgrounds

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

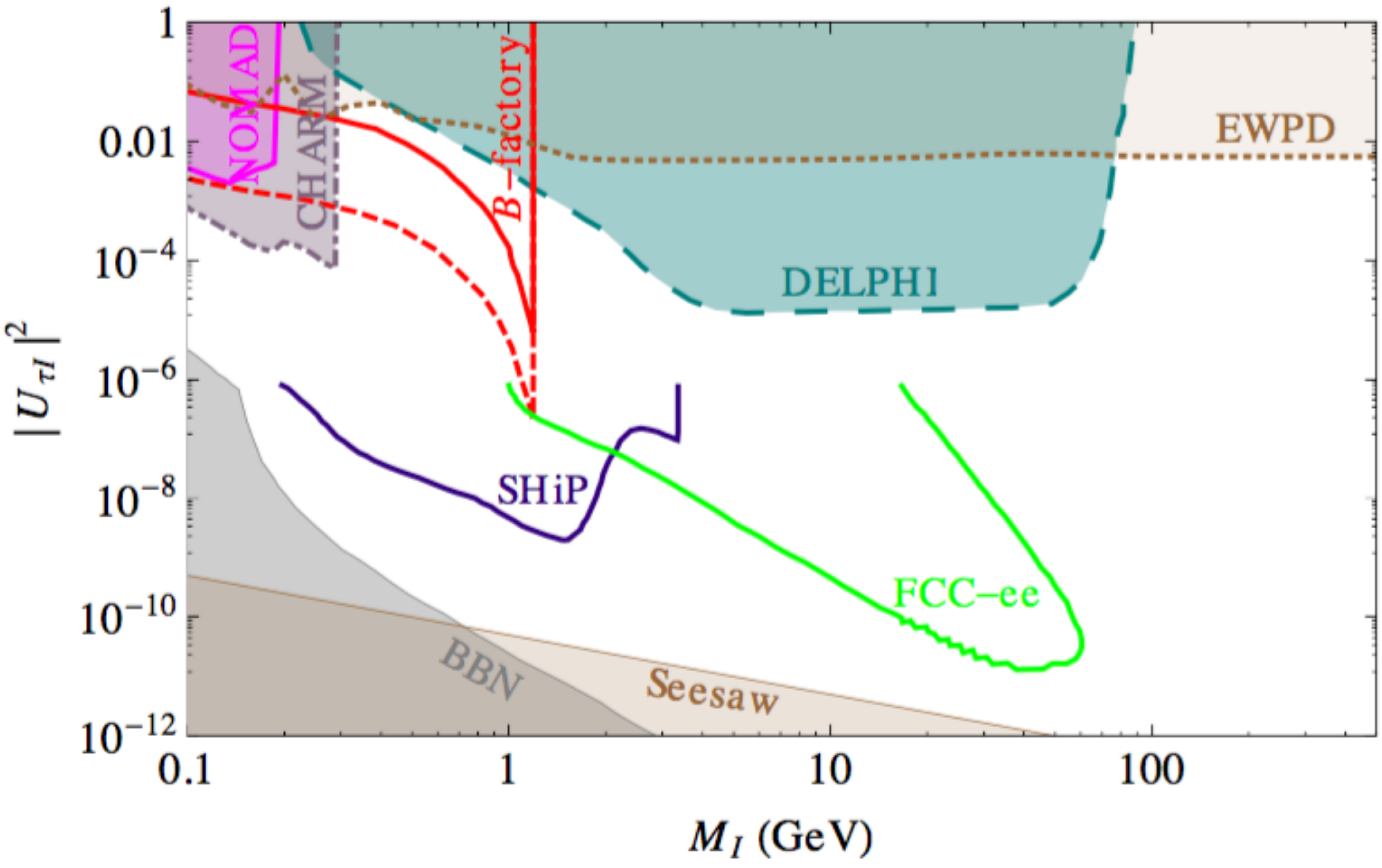




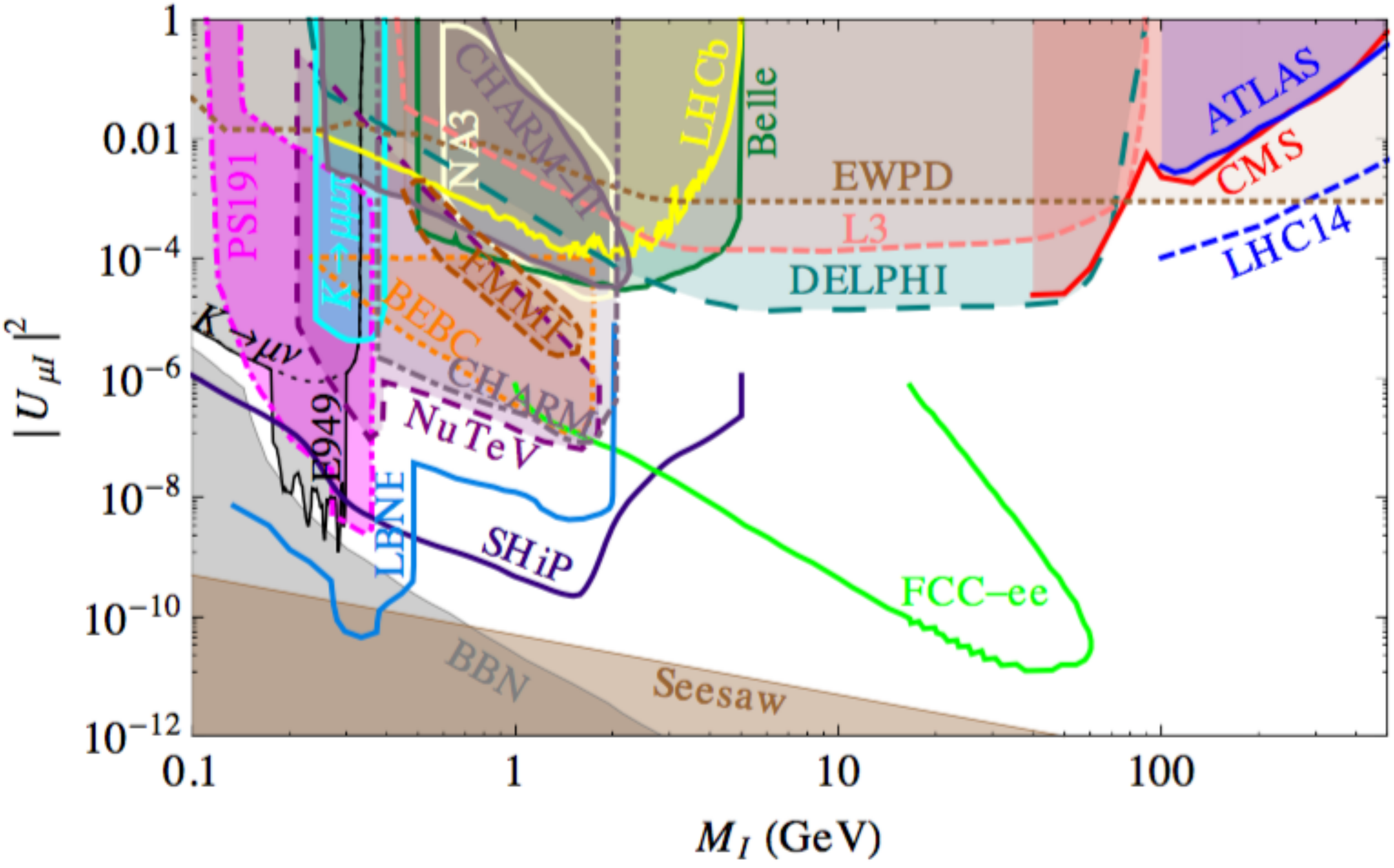




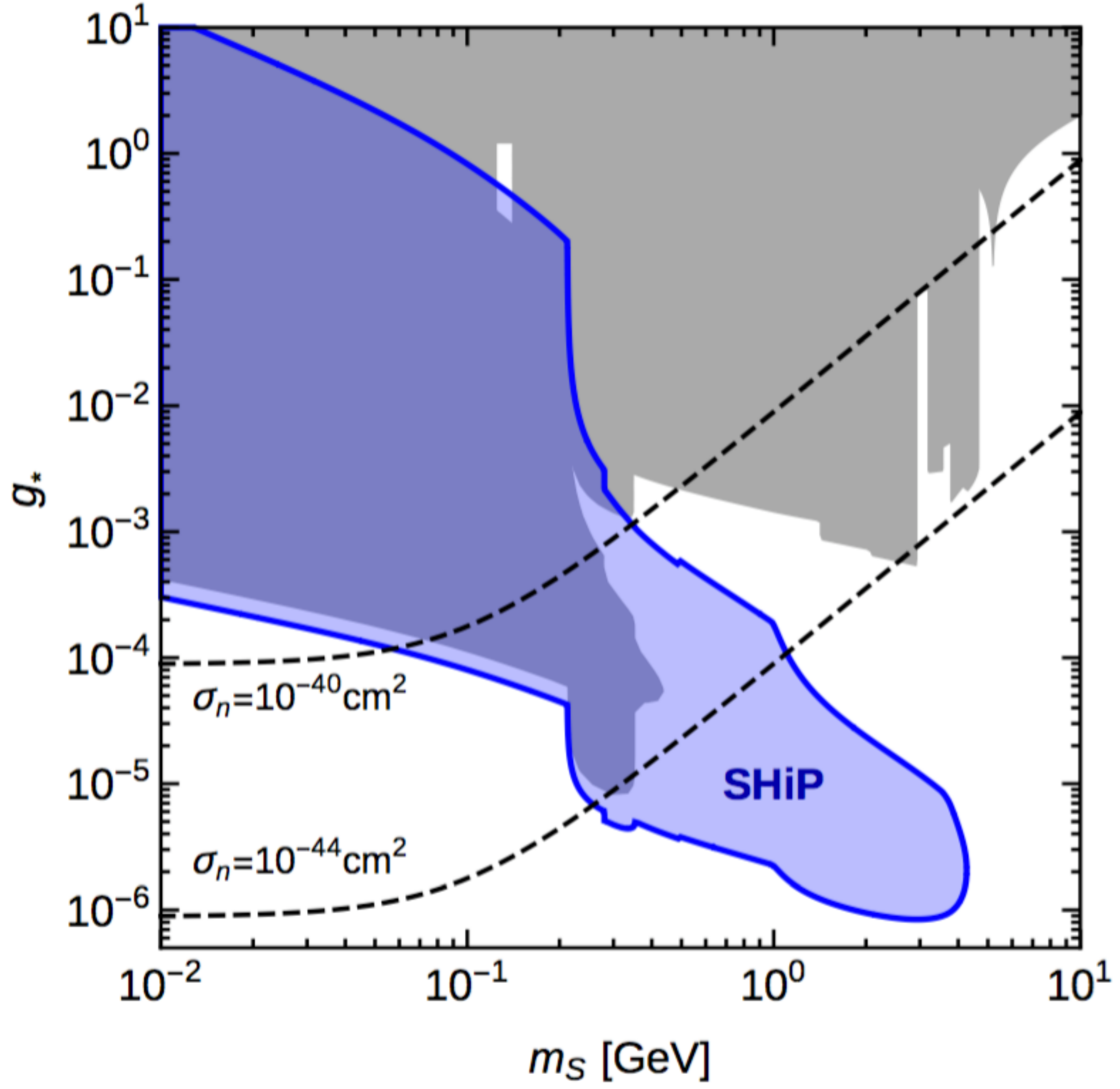
Reach estimates for HNLs



Reach estimates for HNLs



Reach estimates for b→sX



Collider case study : MATHUSLA

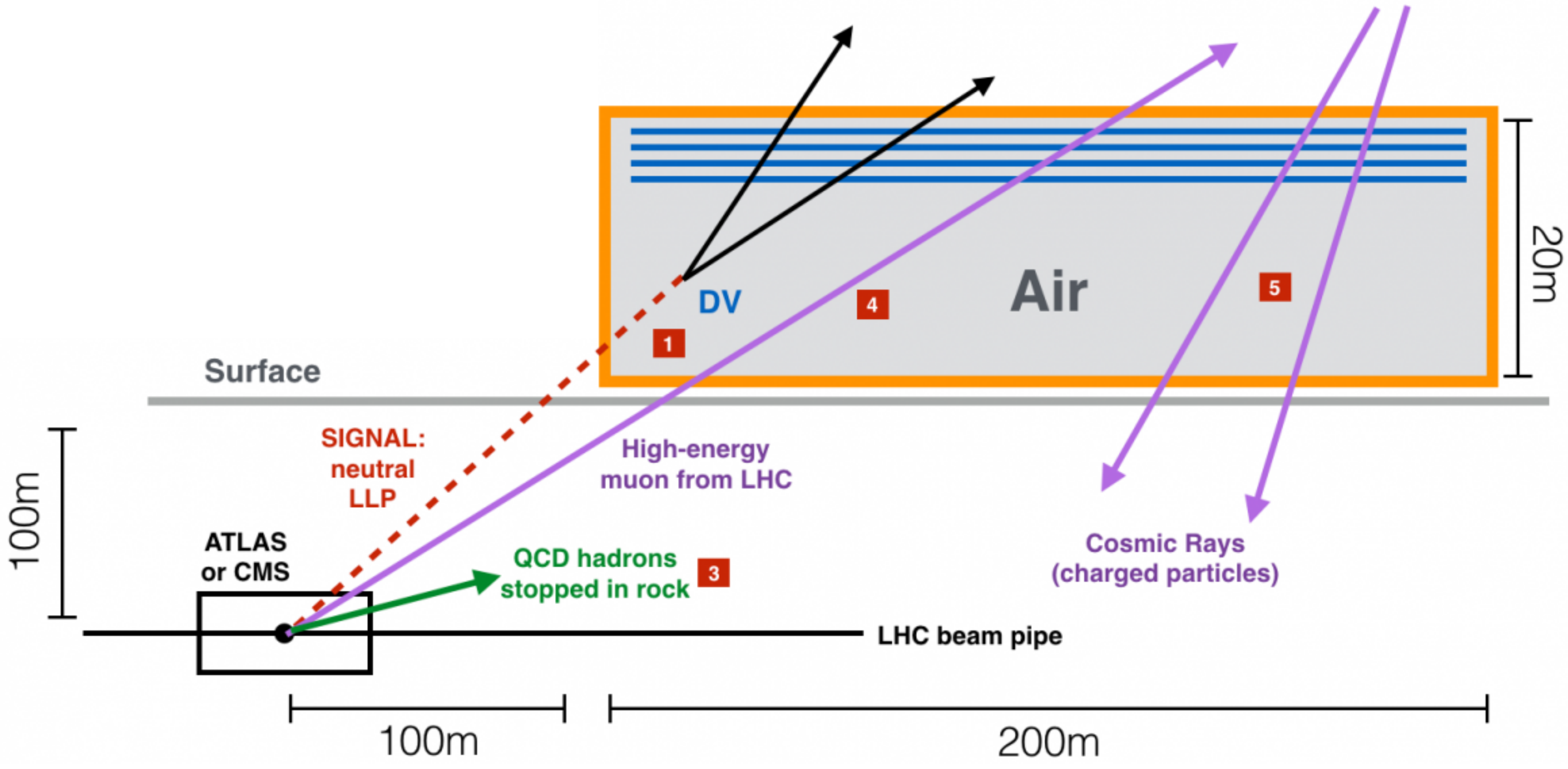
Detector design

Key points :

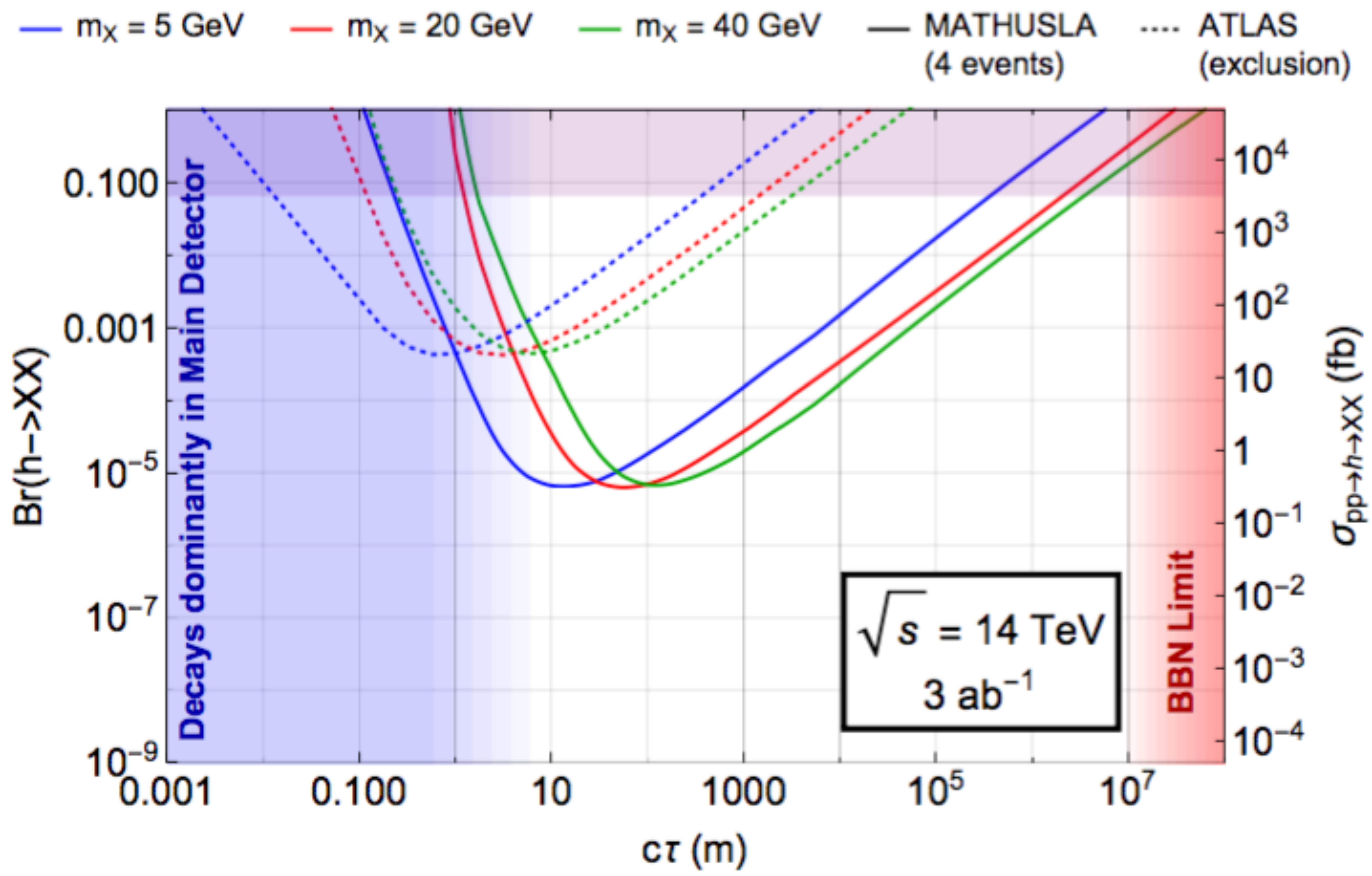
Access full HL-LHC luminosity

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

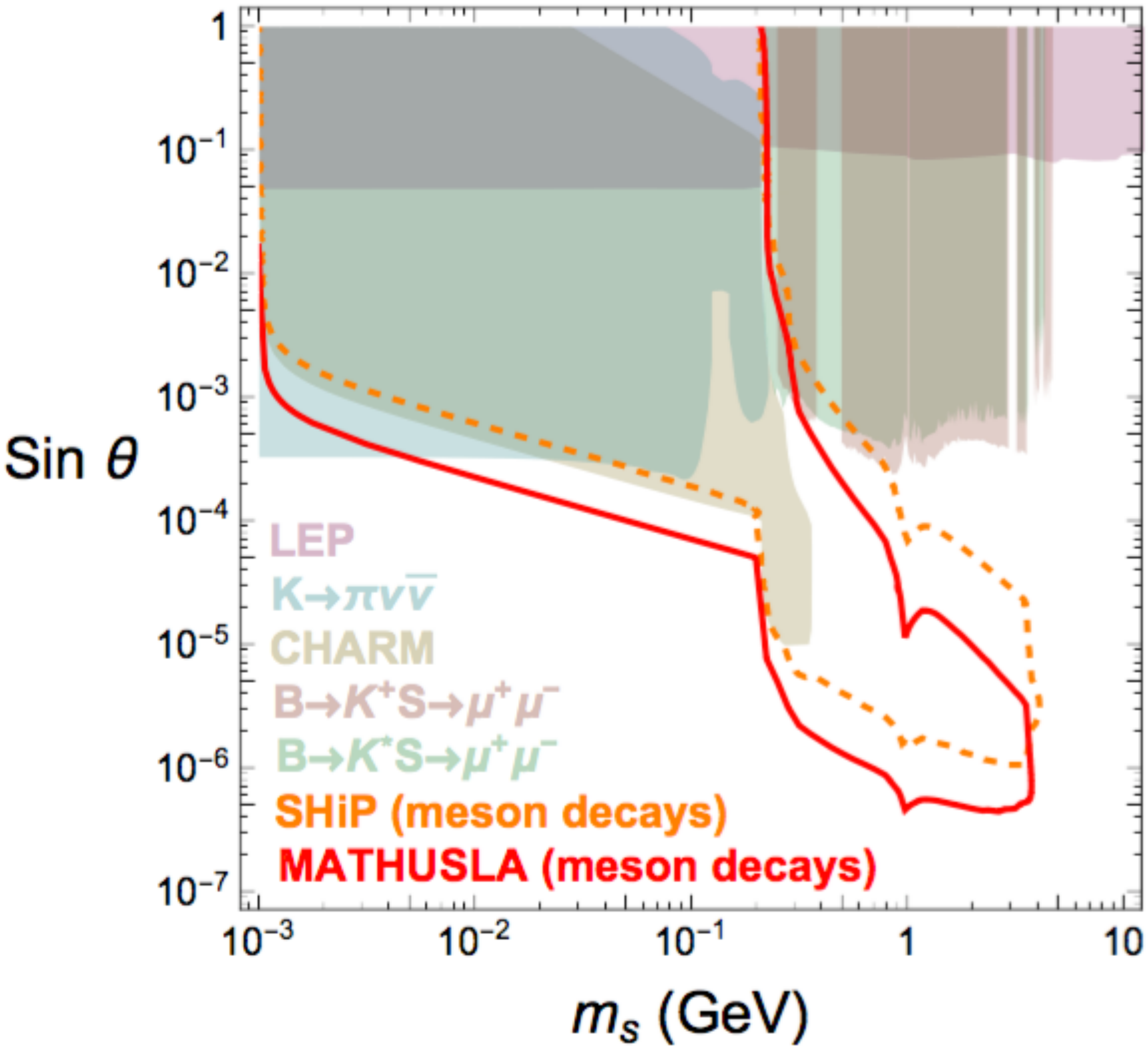
Enormous size : several tracking layers of 200x200 m² each



Reach estimates for Higgs portal

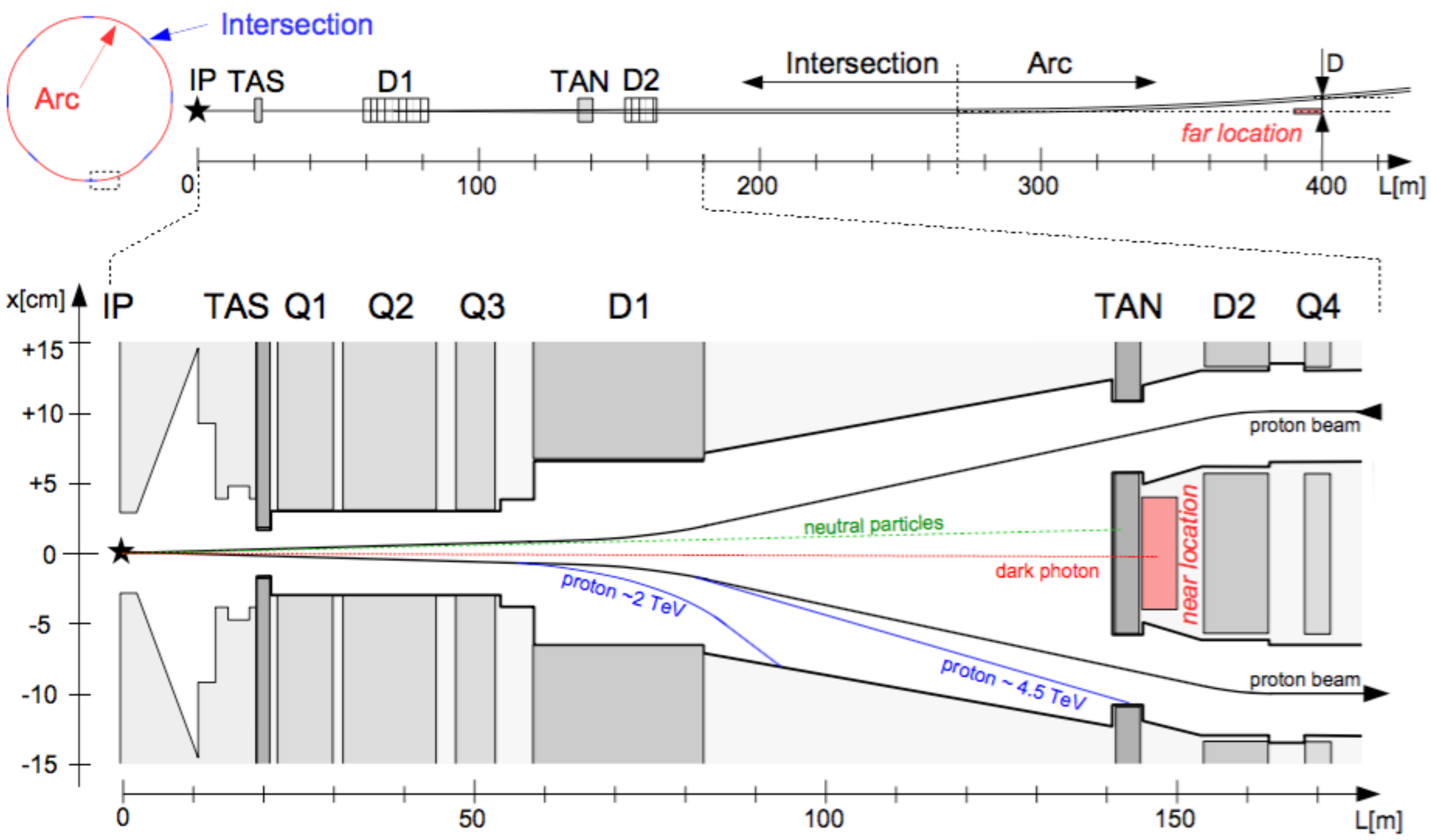


Reach estimates for b→sX



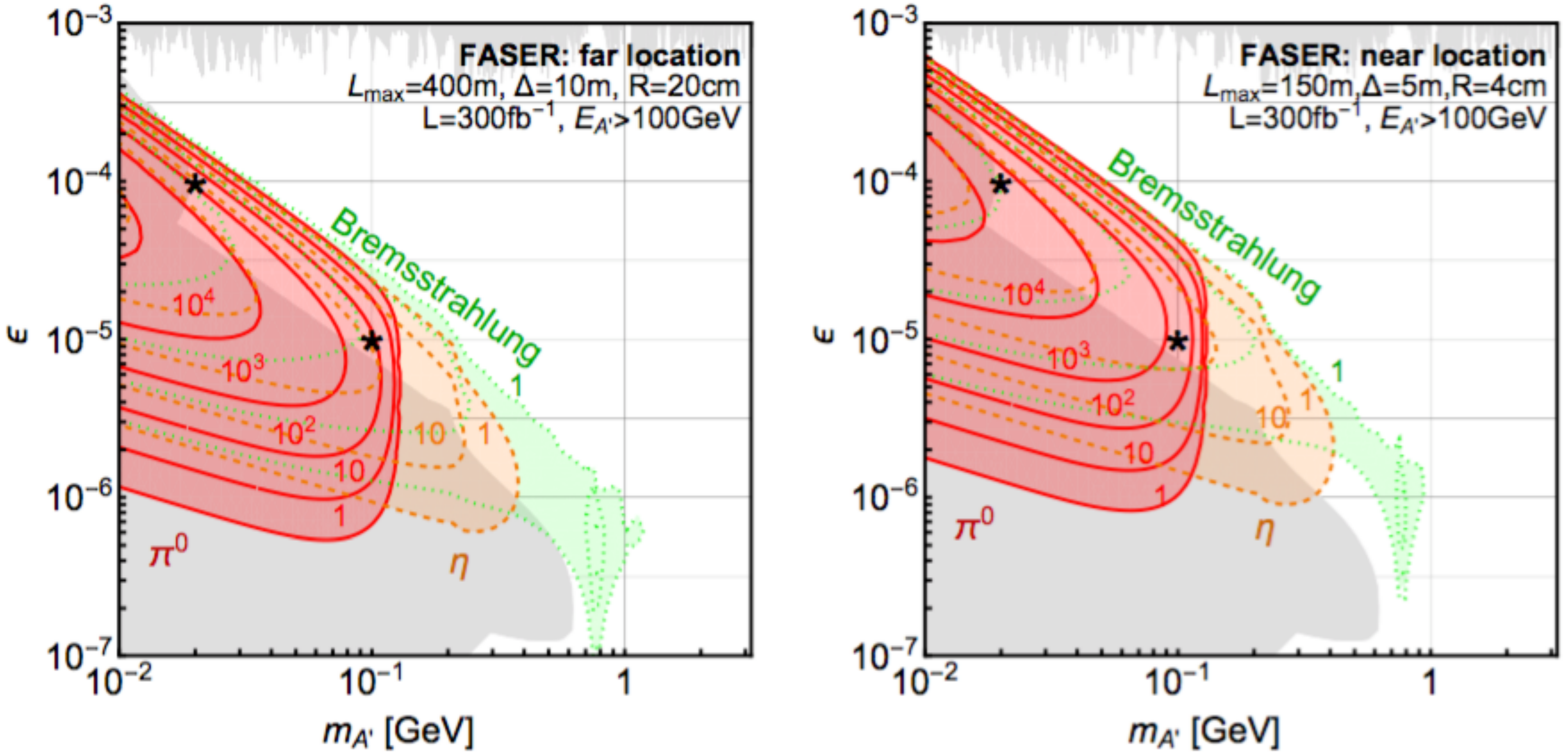
Collider case study : FASER

Detector design



Very forward, exploits tail of the boost distribution

Reach estimates for dark photons



Production of proton brems (!) highlights unique forward regime