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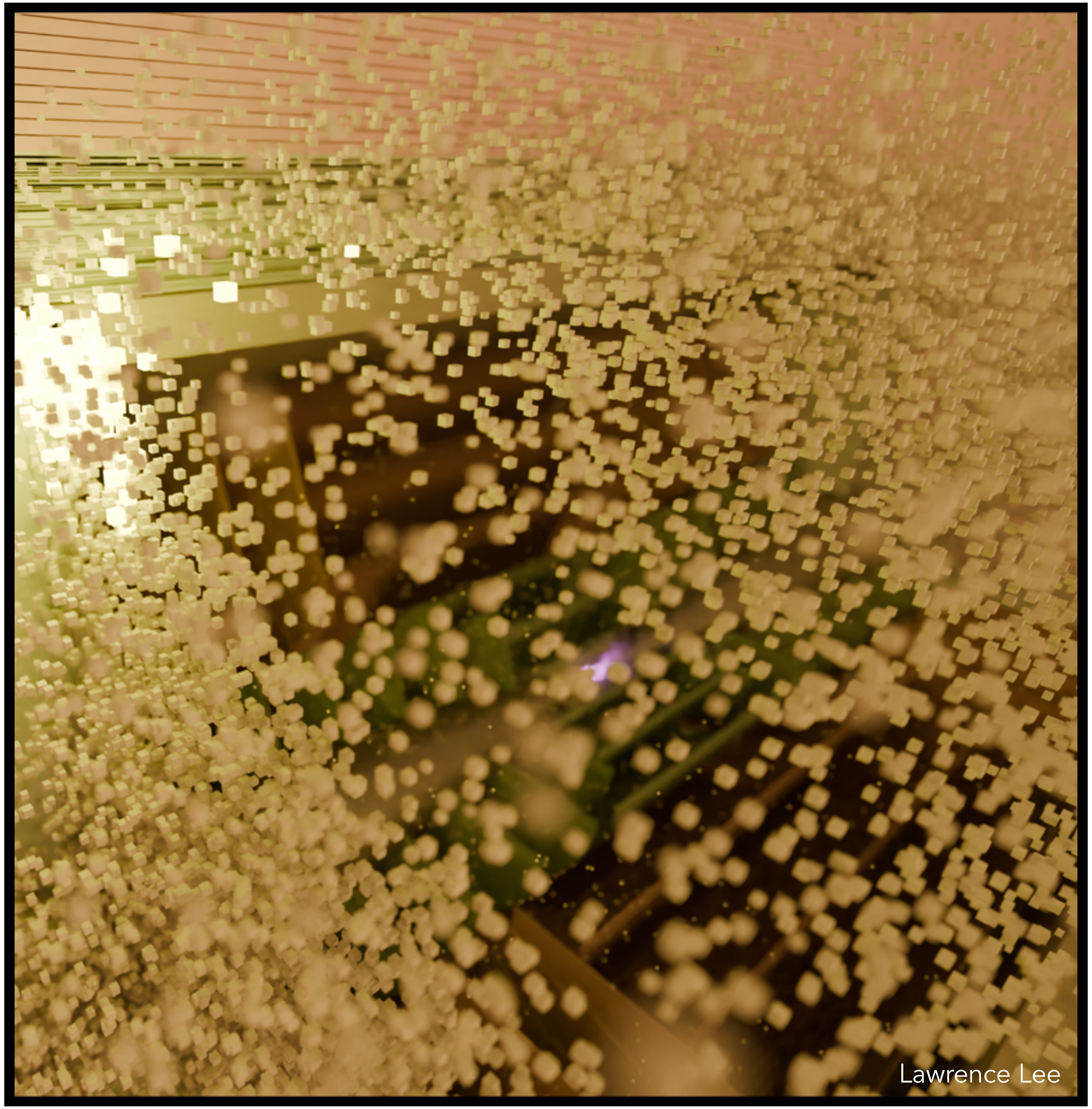


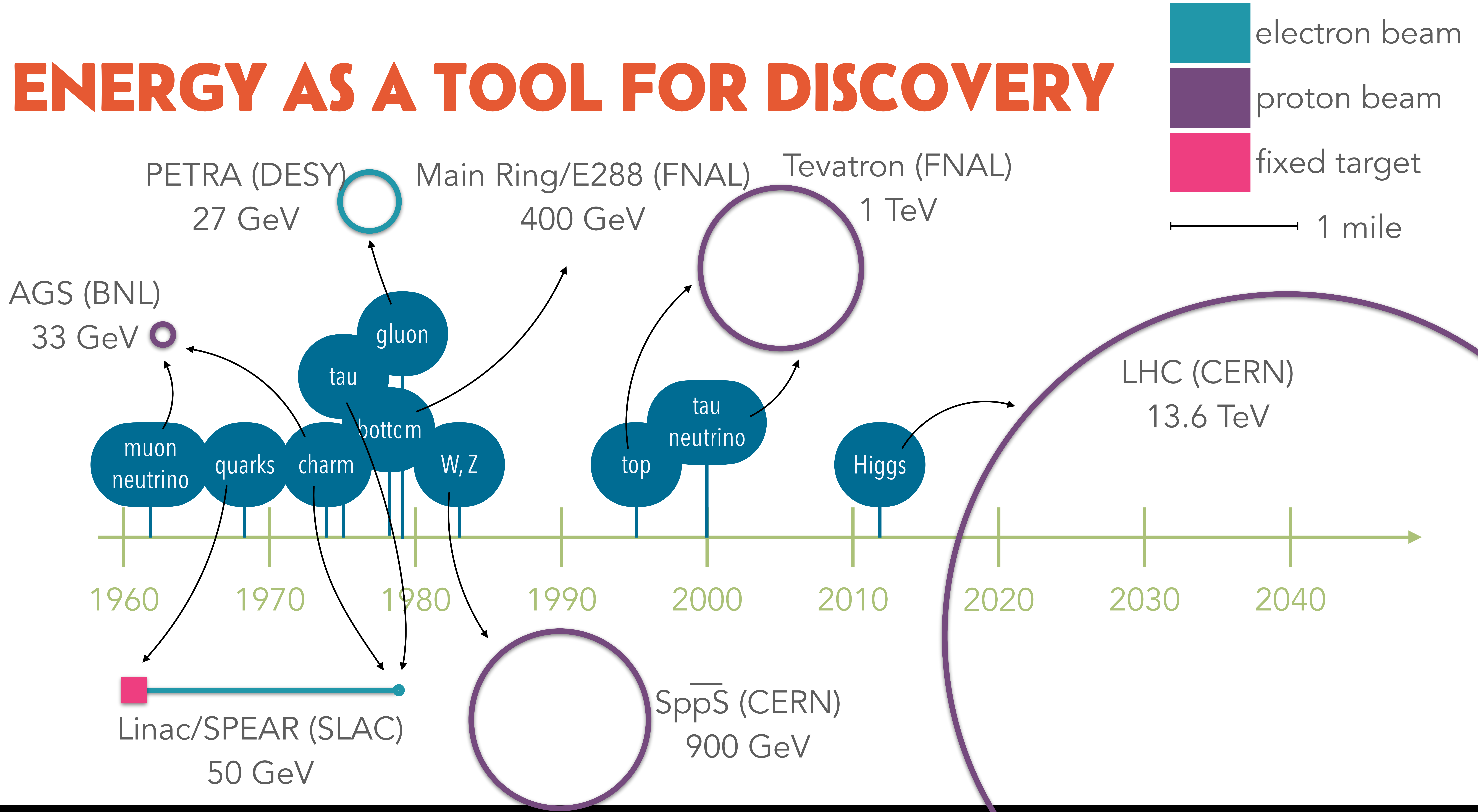
NEEDLES IN A HAYSTACK

Particle Detection at a Muon Collider

Tova Holmes
University of Tennessee, Knoxville
USMCC

SLAC FPD Experimental Seminar
October 7, 2025

ENERGY AS A TOOL FOR DISCOVERY



ENERGY AS A TOOL FOR DISCOVERY

recent history of discovery:
increasingly large *pp* colliders

using *ee* colliders for
precision measurements at
lower energies

ENERGY AS A TOOL FOR DISCOVERY

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precision measurements at
lower energies

synchrotron radiation:

$$P \approx 3 \times 10^{-7} \left(\frac{1\ \mathrm{km}}{R} \right)^2 \left(\frac{E}{m} \right)^4 \ \mathrm{eV/s}$$

charged particles radiate power
when they accelerate

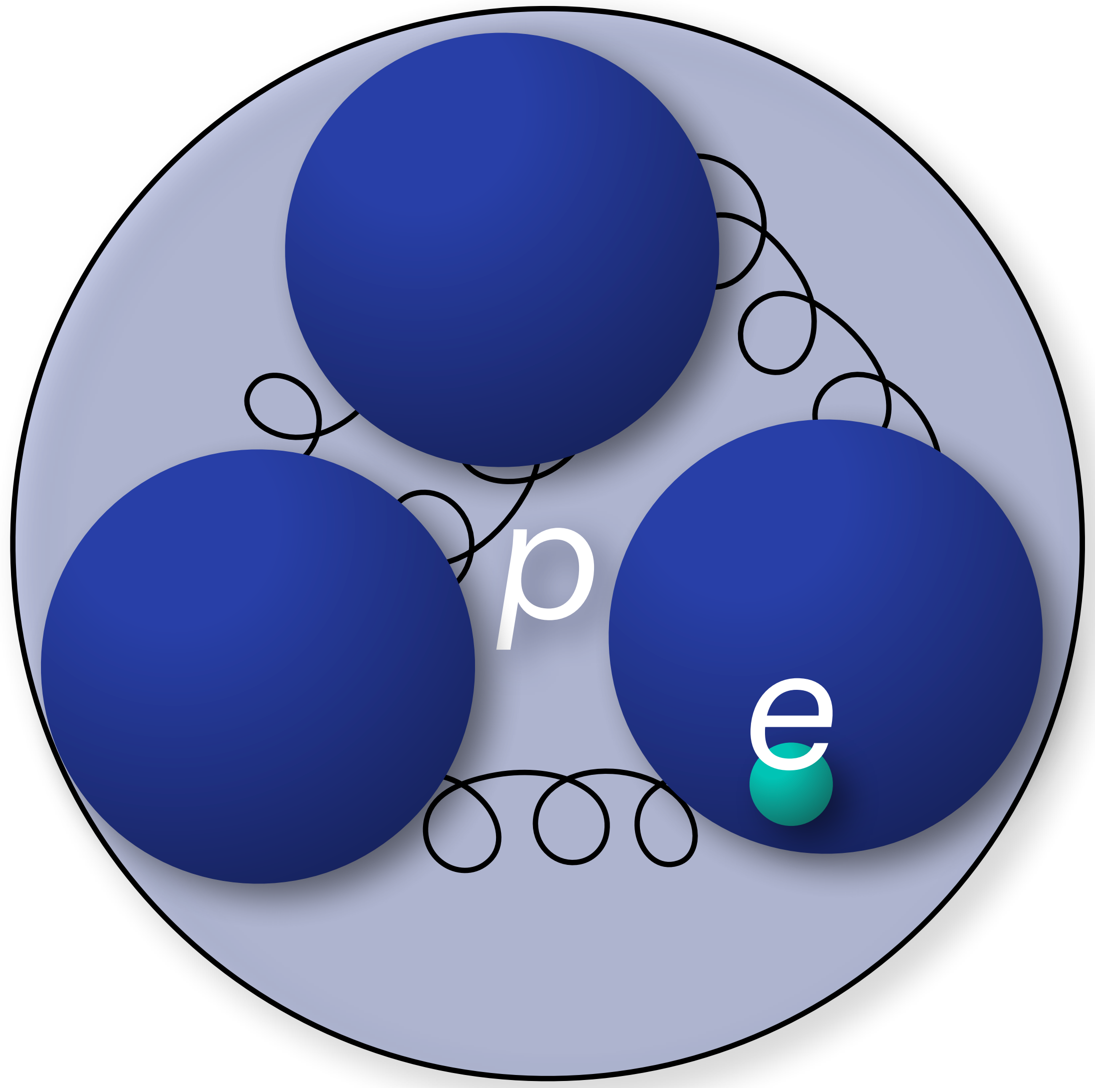
$m_e = 0.51\ \mathrm{MeV}/c^2$
$m_p = 940\ \mathrm{MeV}/c^2$

electrons in a ring radiate
11.5 trillion times more energy

Energy as a tool for discovery

recent history of discovery:
increasingly large *pp* colliders

using *ee* colliders for
precision measurements at
lower energies



protons:
composite particles
→ energy of collided constituents
determines energy of collision

LHC is "13.6 TeV"
but in actual collisions are O(1 TeV)

LOTS of strong production

ENERGY AS A TOOL FOR DISCOVERY

recent history of discovery:
increasingly large *pp* colliders

using *ee* colliders for
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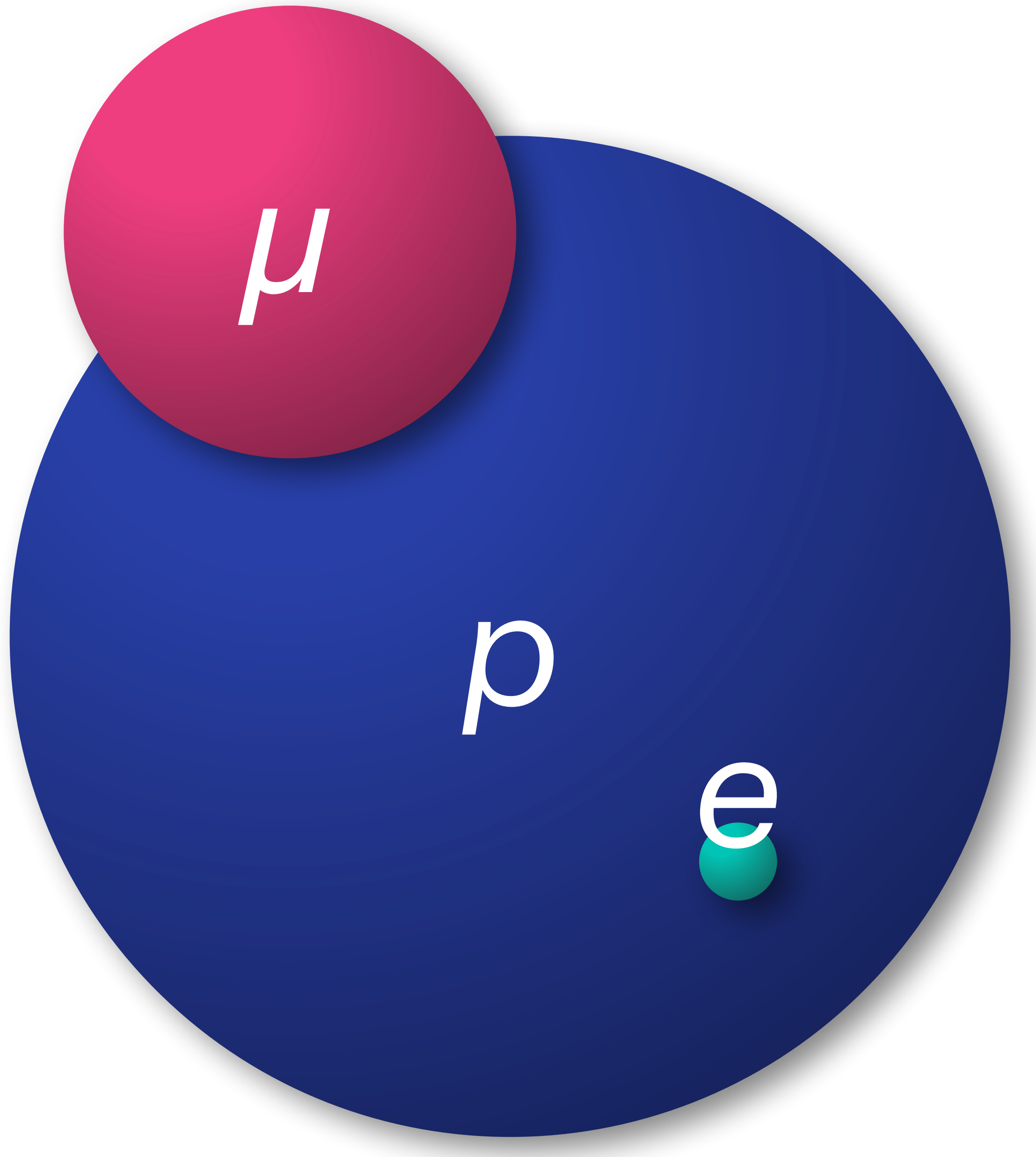
lower energies



looking towards the future:
can we combine their benefits with a
heavier elementary particle?

muons
are the obvious candidate

TO UNDERSTAND IF THIS IS A SANE IDEA, HELPFUL TO FIRST KNOW WHAT WE'RE AFTER IN "THE FUTURE"

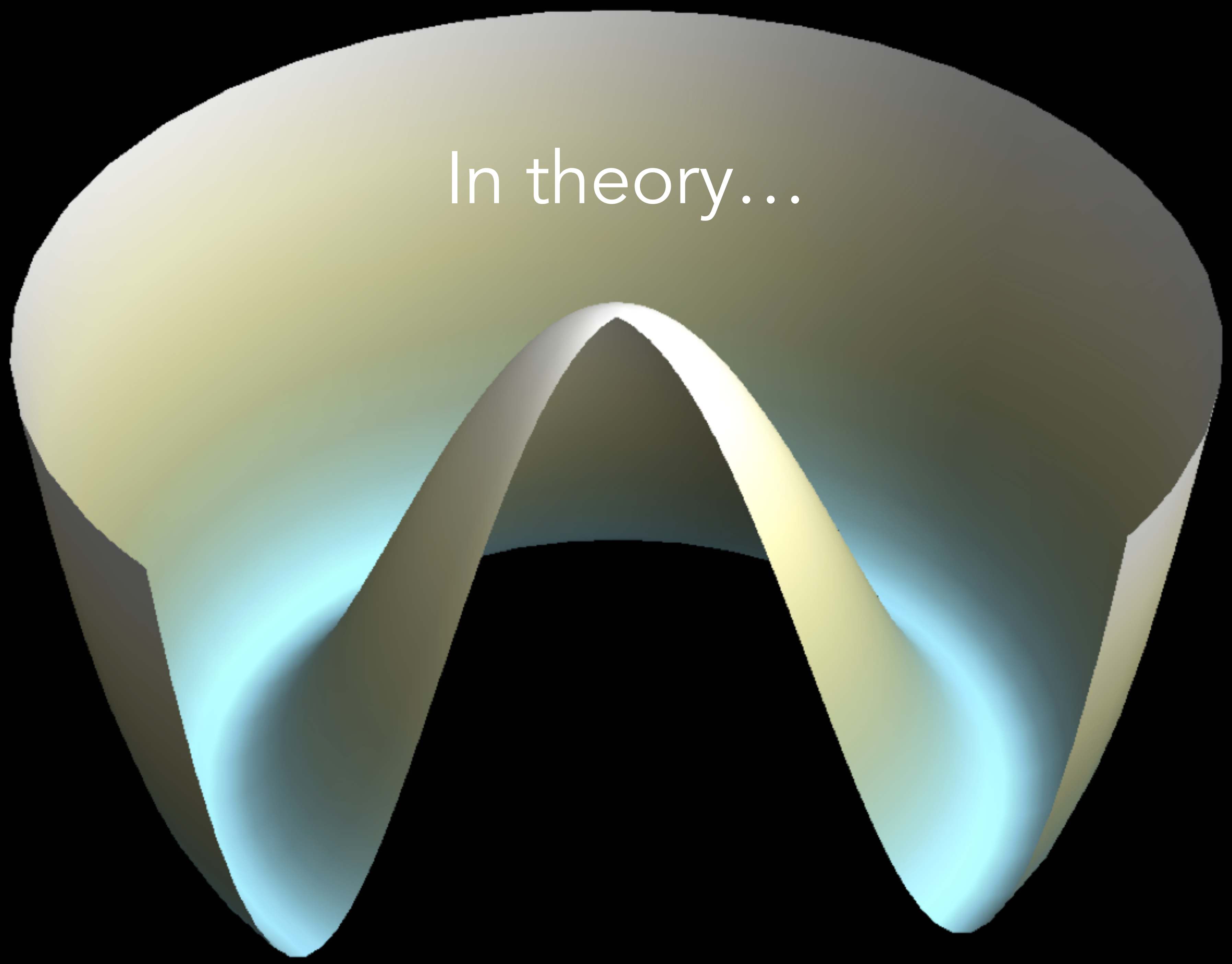
OUR NEXT TARGET: 10 TEV

WHY THE 10 TEV SCALE?

The simplest answer:

to explore the unknown

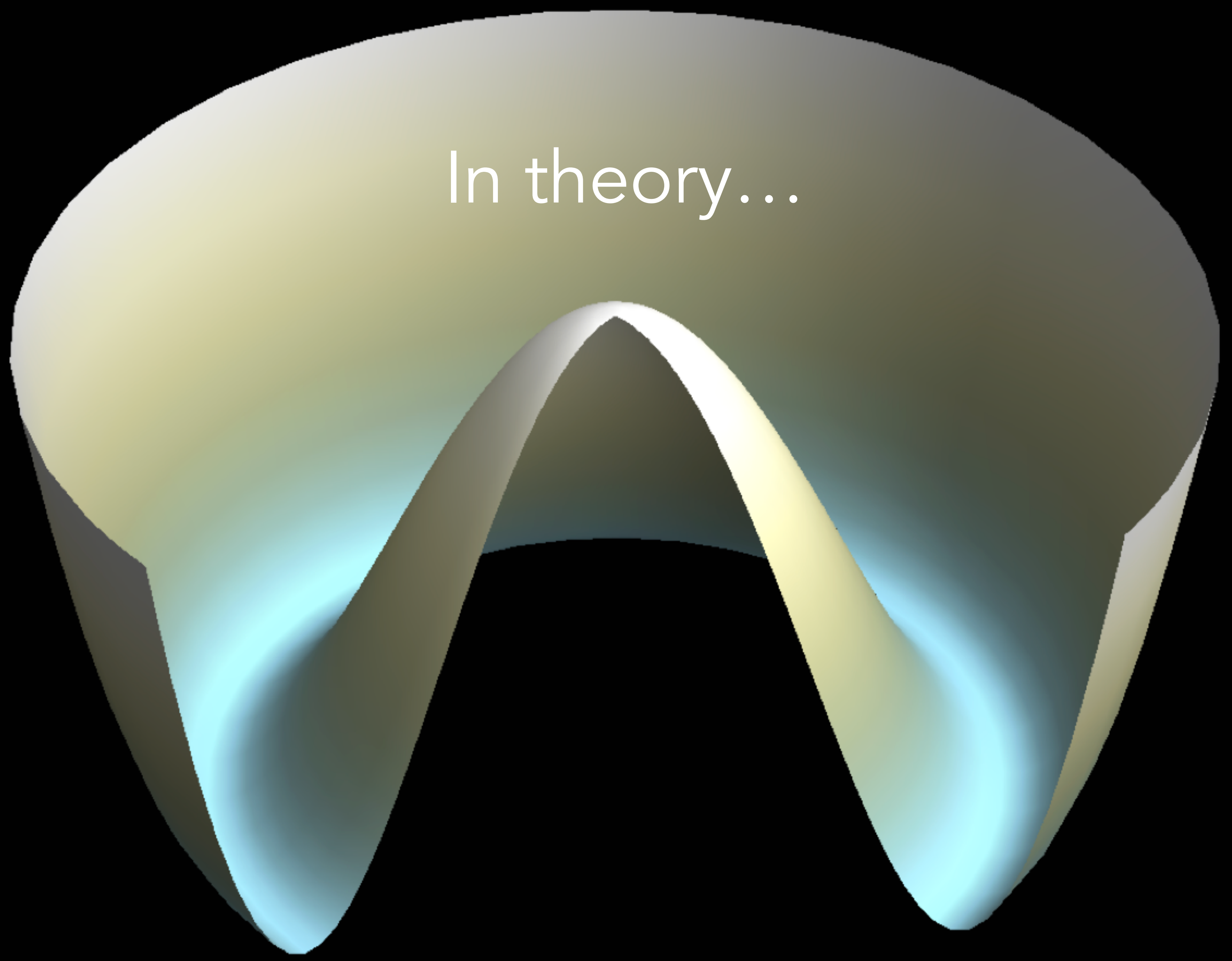
WHY THE 10 TEV SCALE?



$$\mathscr{L} \supset \frac{1}{2}\partial_\mu \phi^* \partial^\mu \phi + \frac{1}{2}\mu^2 \phi^* \phi - \frac{1}{4}\lambda^2 (\phi^* \phi)^2$$

N. Craig, R. Petrossian-Byrne

WHY THE 10 TEV SCALE?



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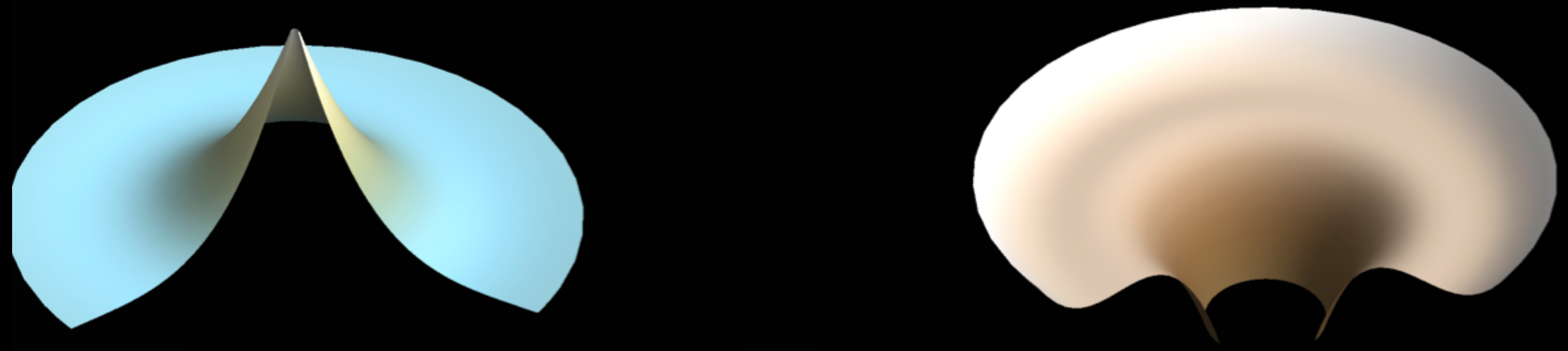
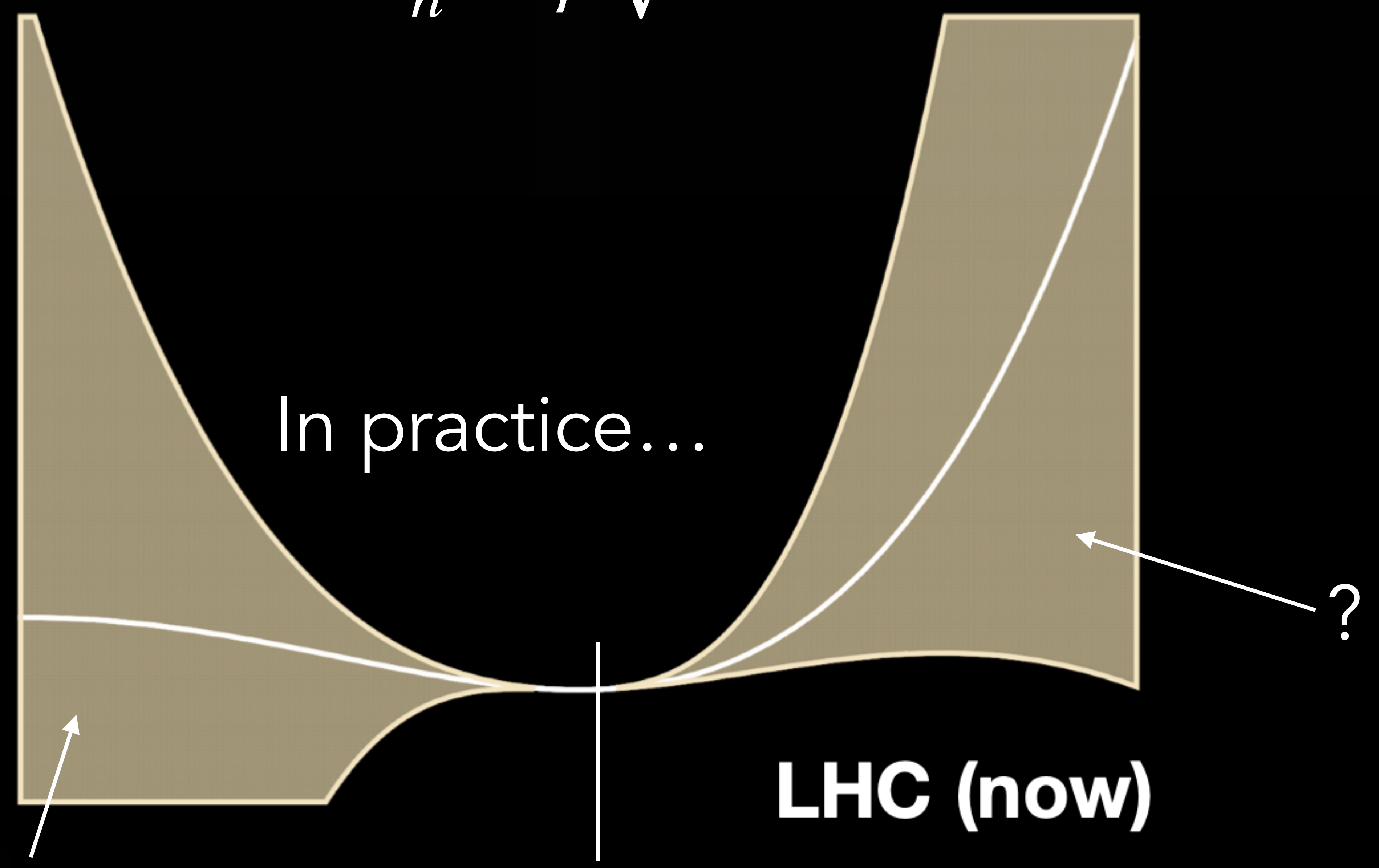


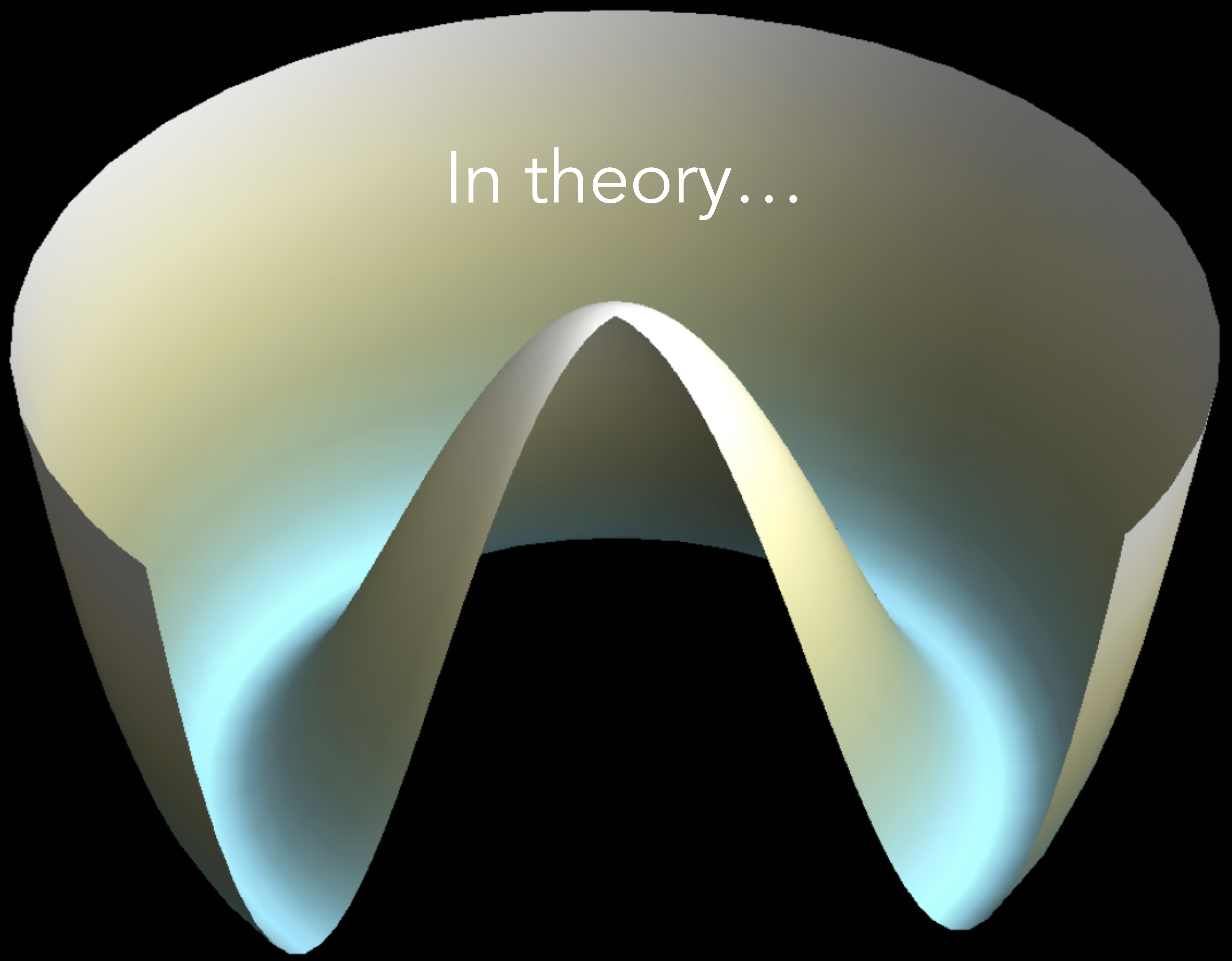
$$m_h = \mu\sqrt{2}$$



$$v = \mu/\lambda$$

N. Craig, R. Petrossian-Byrne

WHY THE 10 TEV SCALE?



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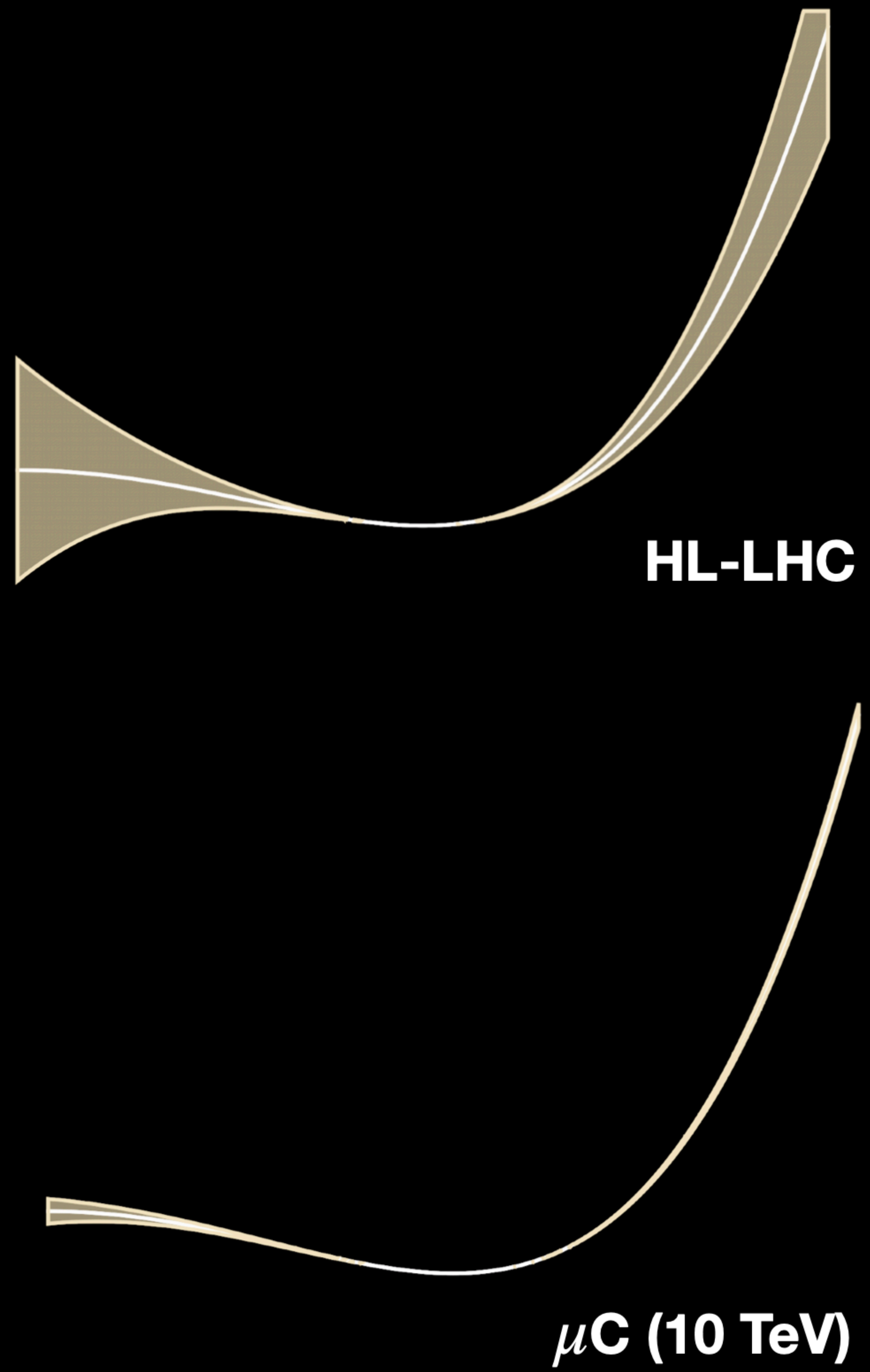


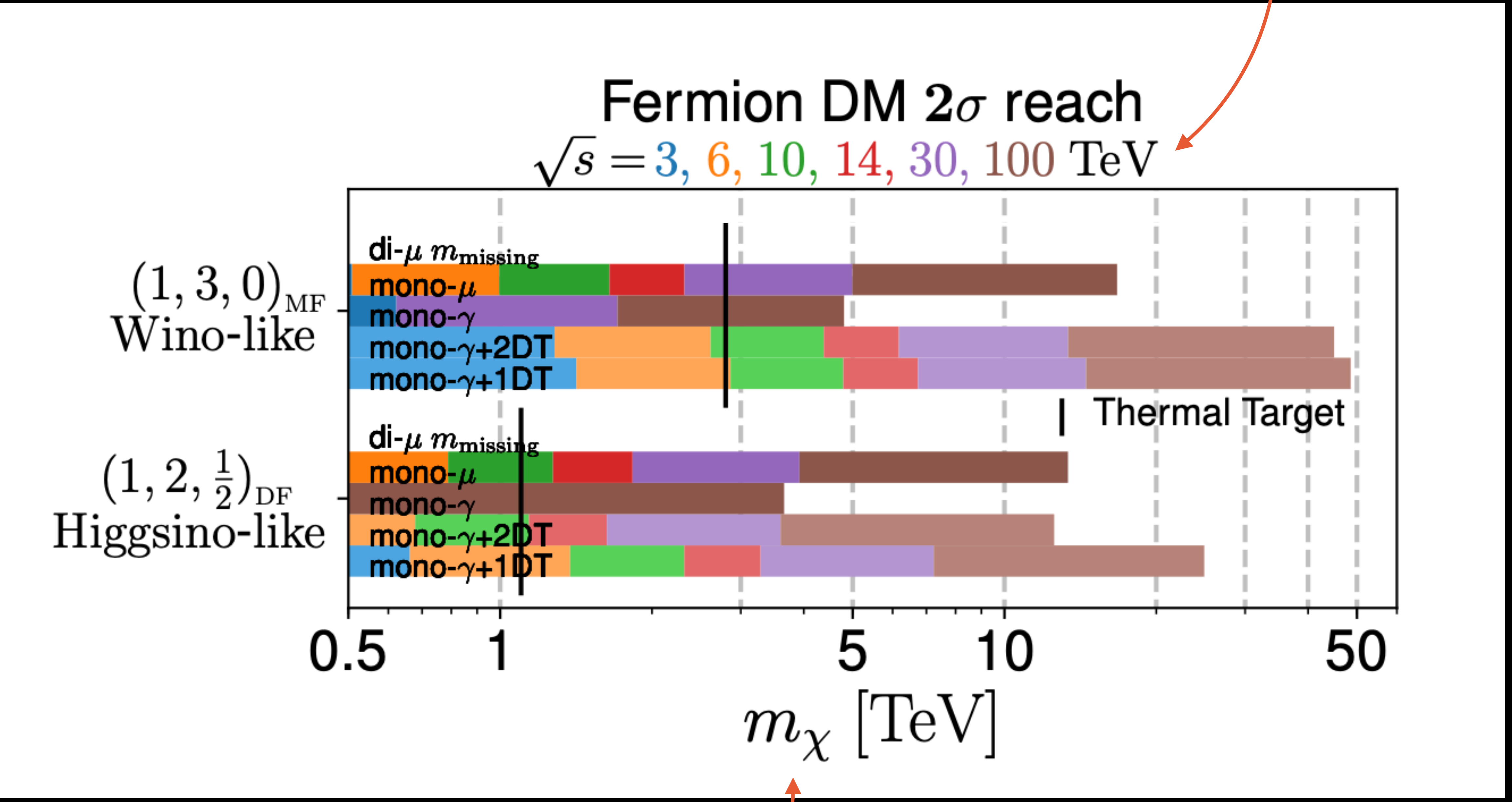
N. Craig, R. Petrossian-Byrne

WHY THE 10 TEV SCALE?

WIMP Dark Matter is alive and well!
we just need higher energies to really look for it

10 TeV collider
would let us explore
all these simple models
in multiple channels

center of mass
needed to reach it

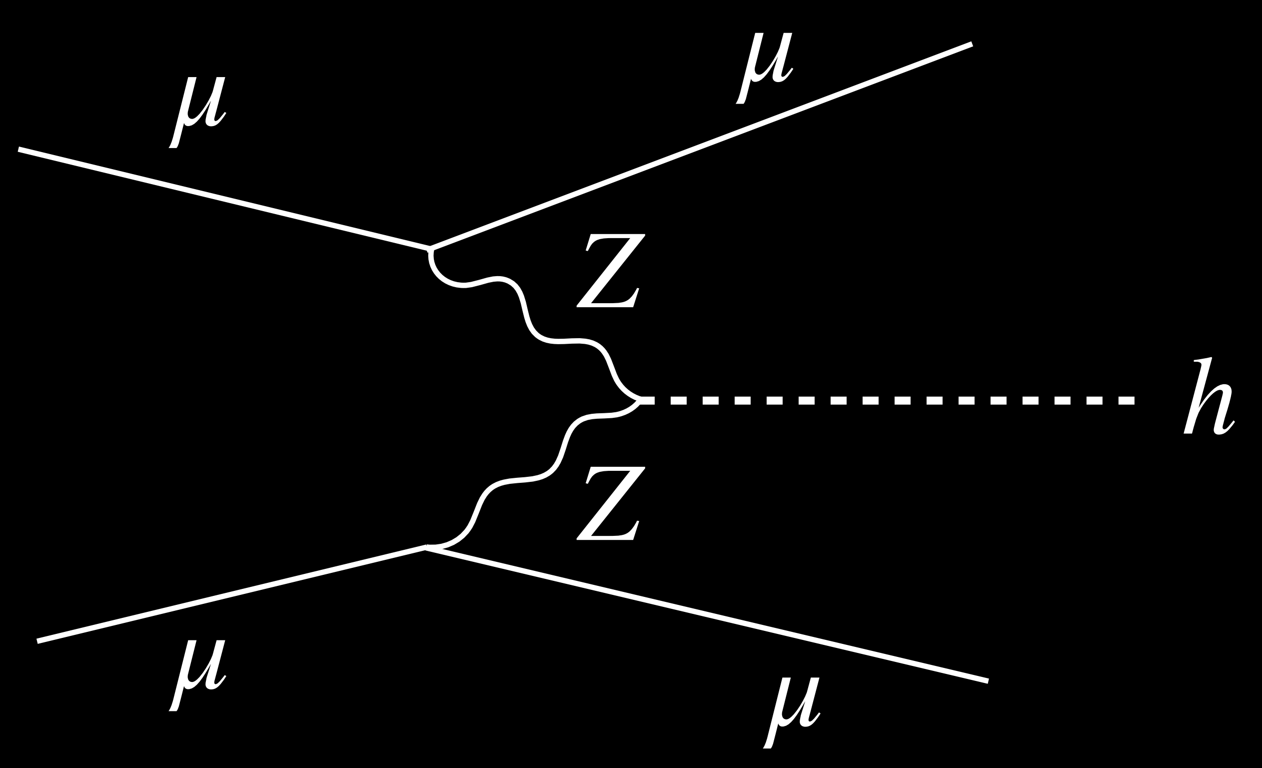


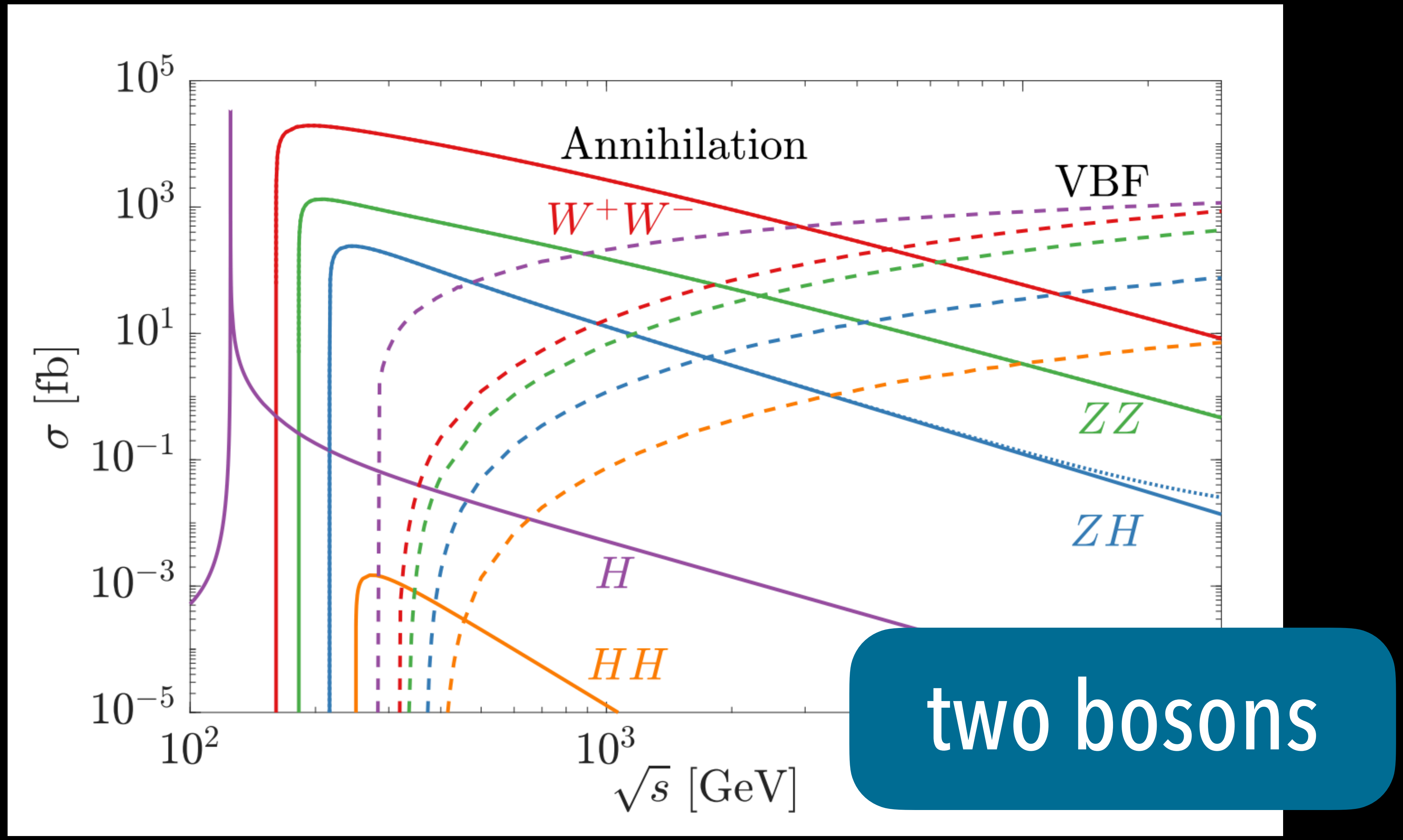
dark matter mass

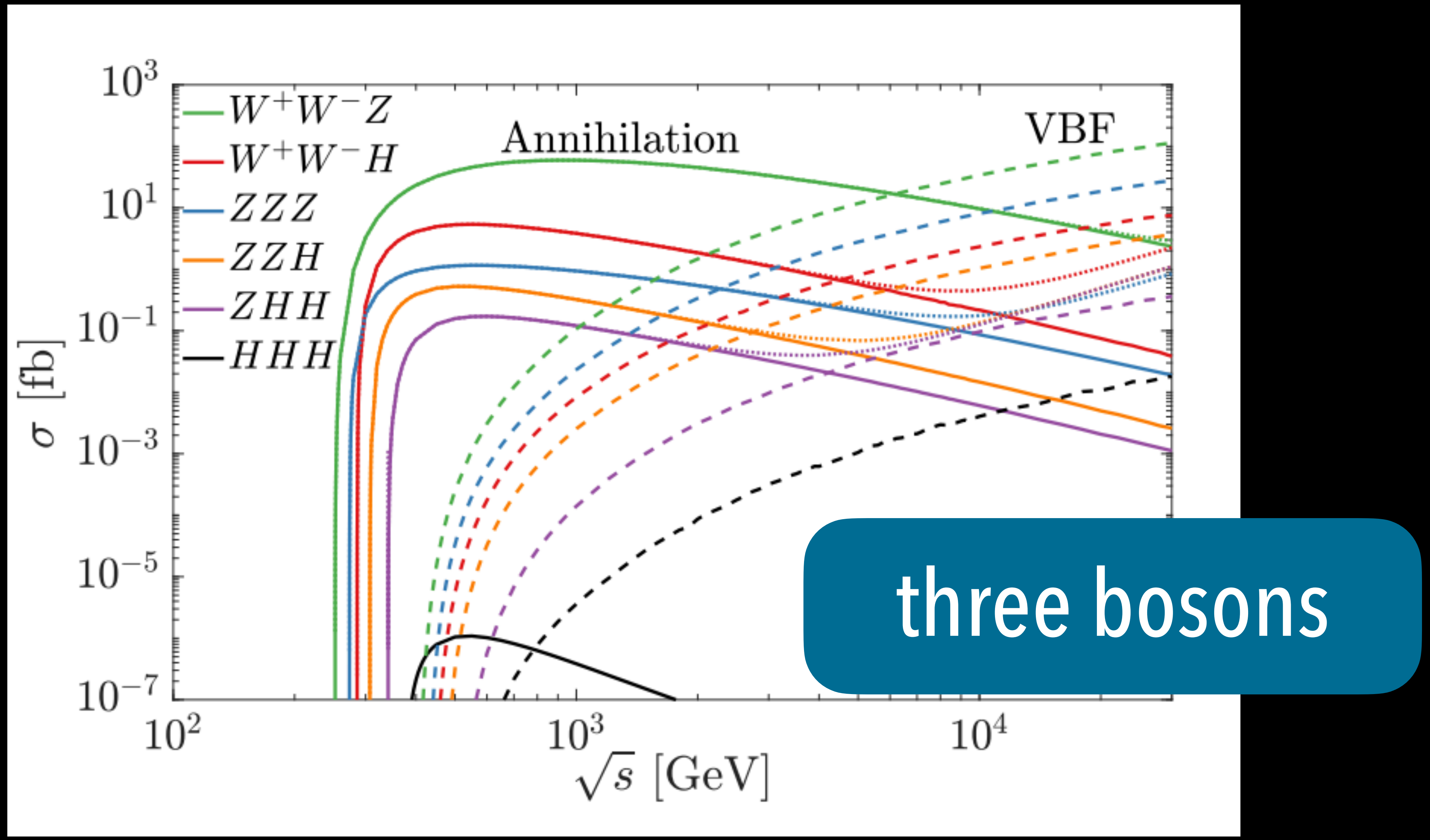
T. Han et al.

Why the 10 TeV scale?

Concrete, direct targets are electroweak
(having an **electroweak collider** would be nice)



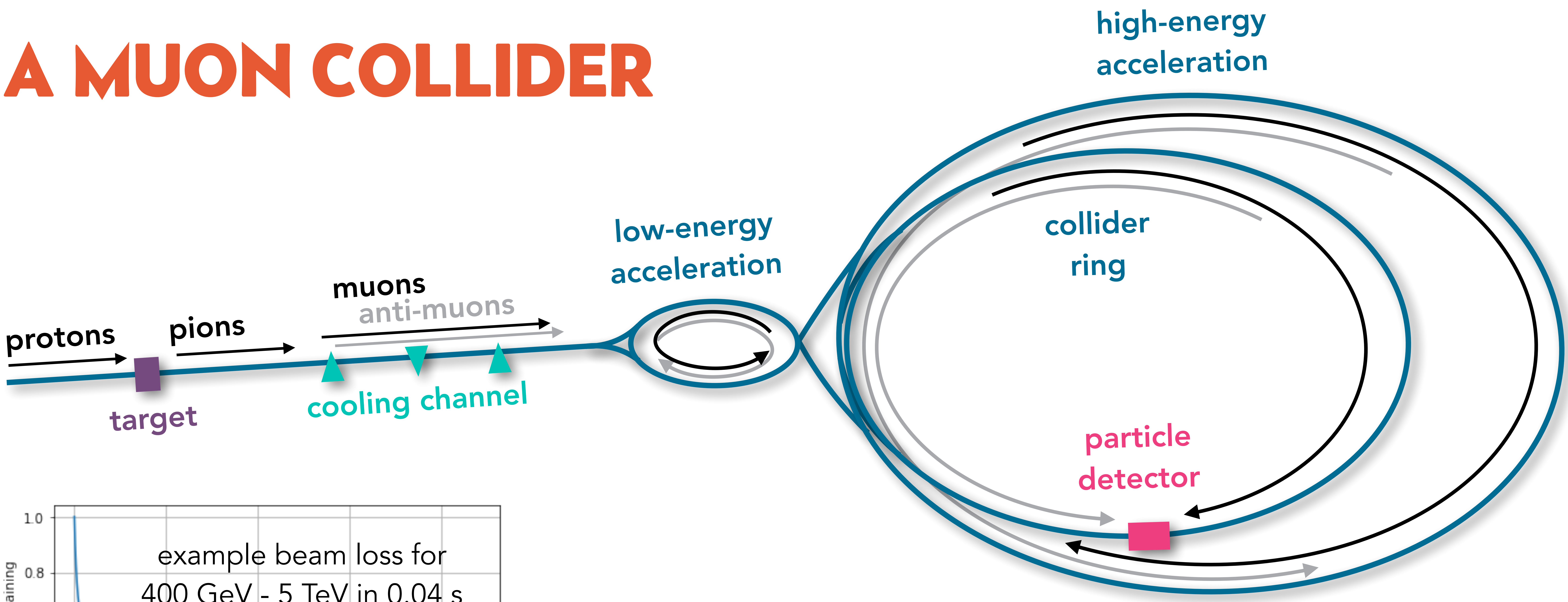


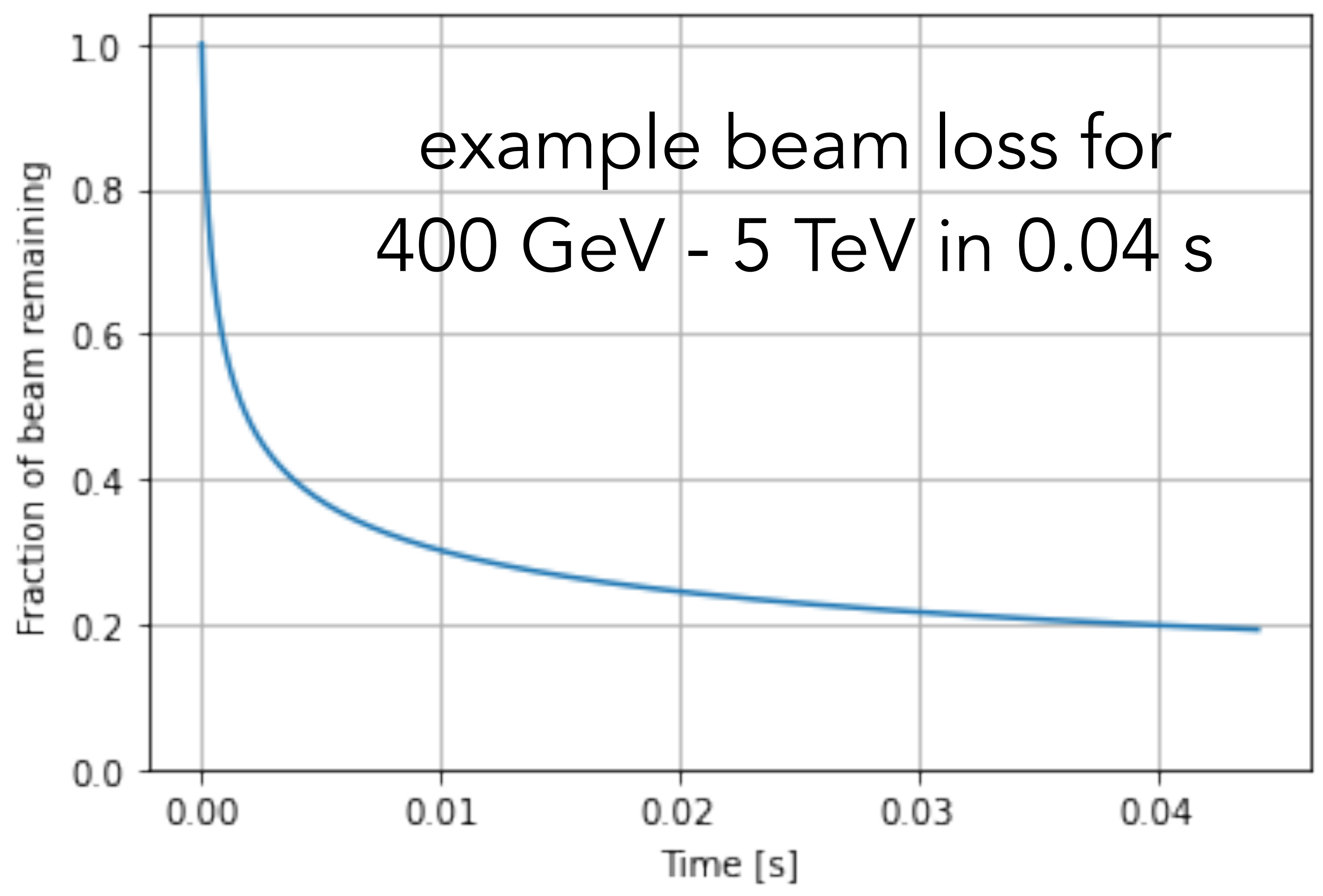


J. Reuter et al, J. Osborne et al

CAN MUONS TAKE US THERE?

A MUON COLLIDER

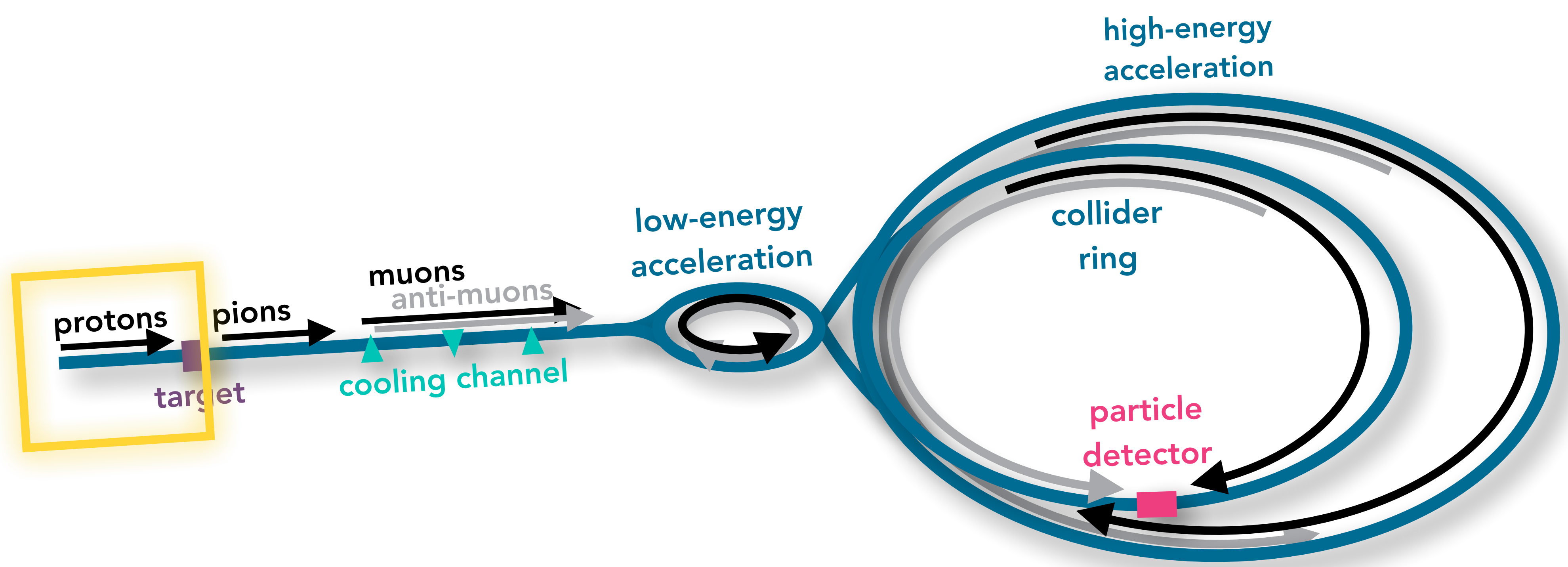


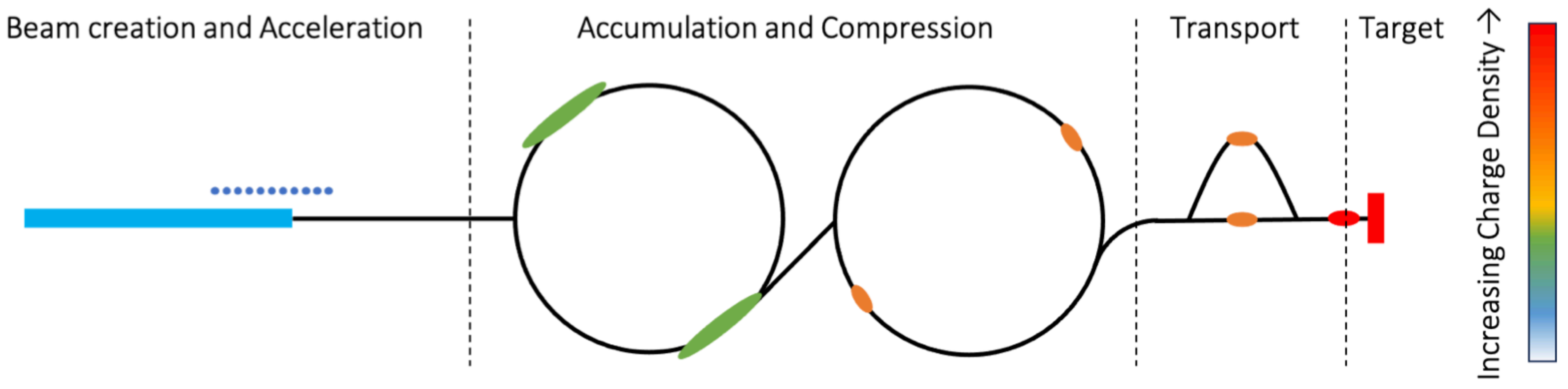


overarching driver is luminosity:

create, cool, and collide muons as fast as possible

A MUON COLLIDER





compare to: spallation sources

proton driver

2-4 MW → starting constraint on number of muons produced

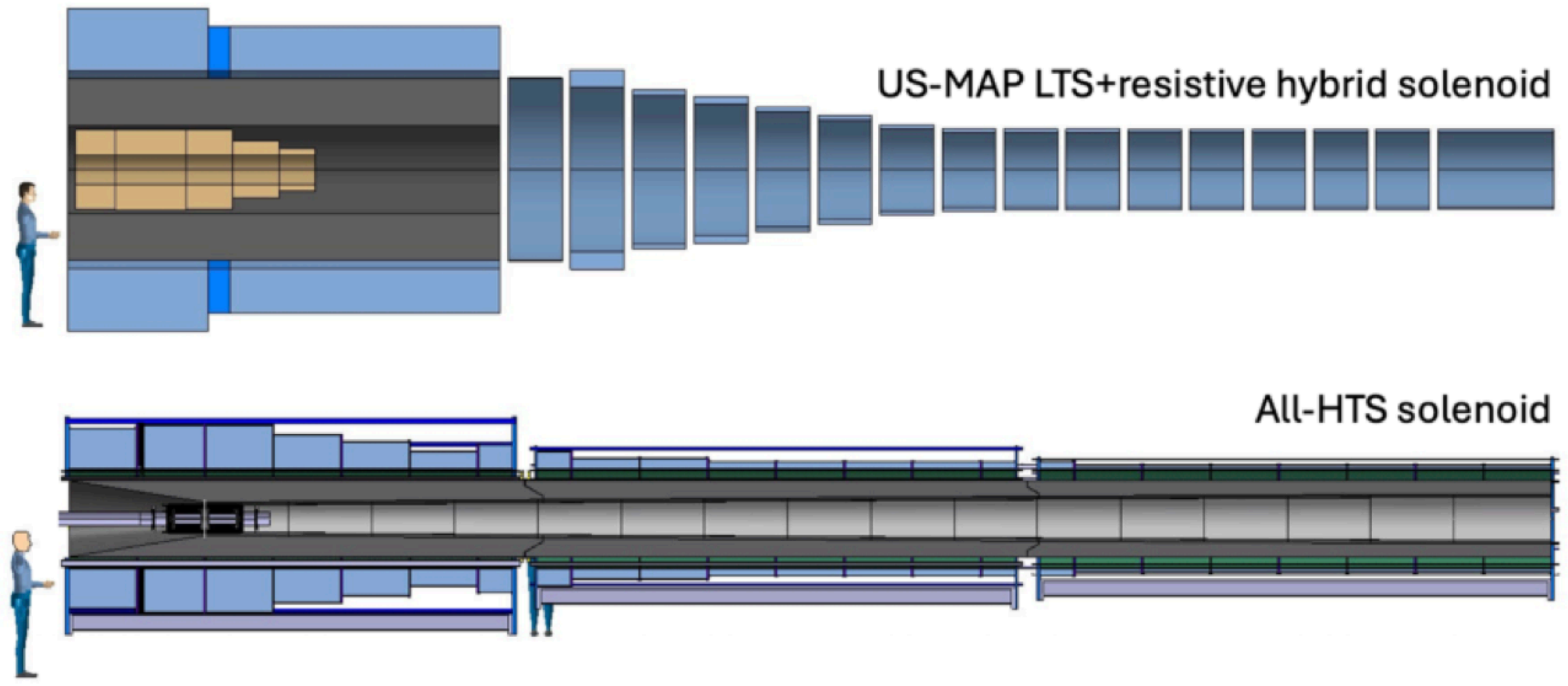
at 5-15 GeV → impacts proton to muon efficiency

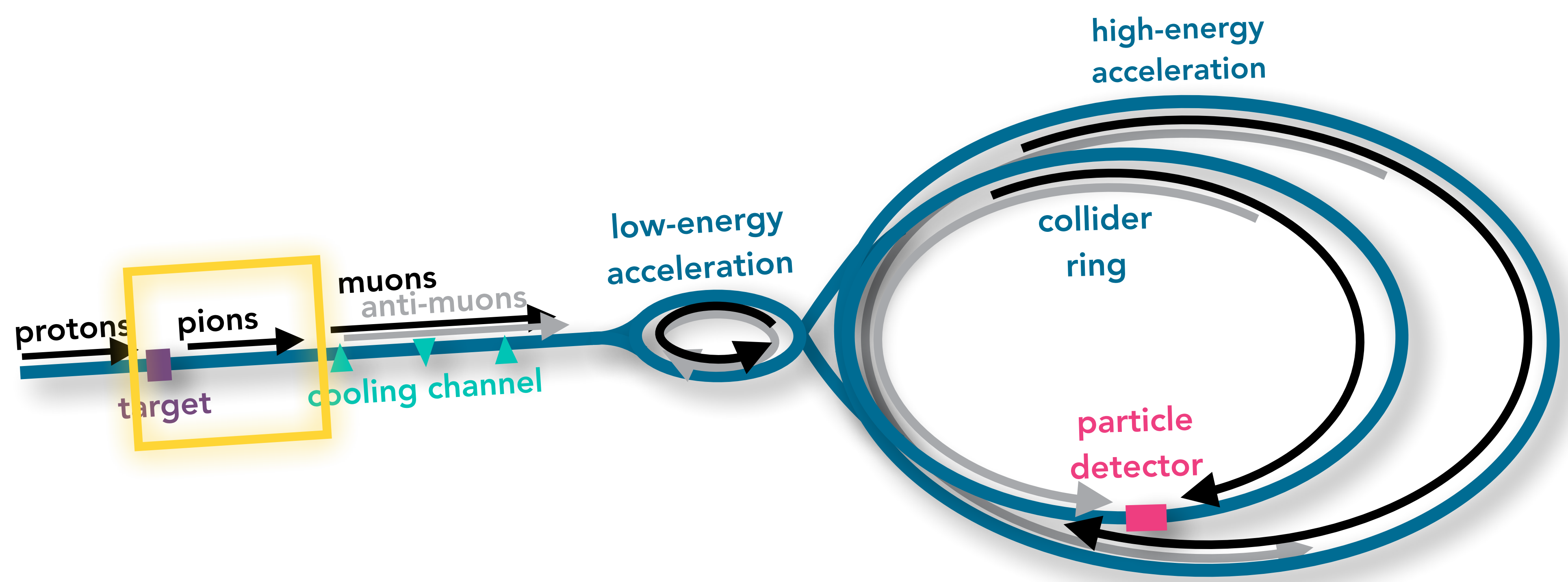
with 2-4 ns bunch size → small bunch size reduces initial muon emittance

space-charge is key constraint: must go to higher energies to increase bunch density

Most recent technical specs from "The Muon Collider" (input to ESPPU)

A MUON COLLIDER





compare to:
spallation sources,
neutrino beams, and
fusion facilities

target and capture

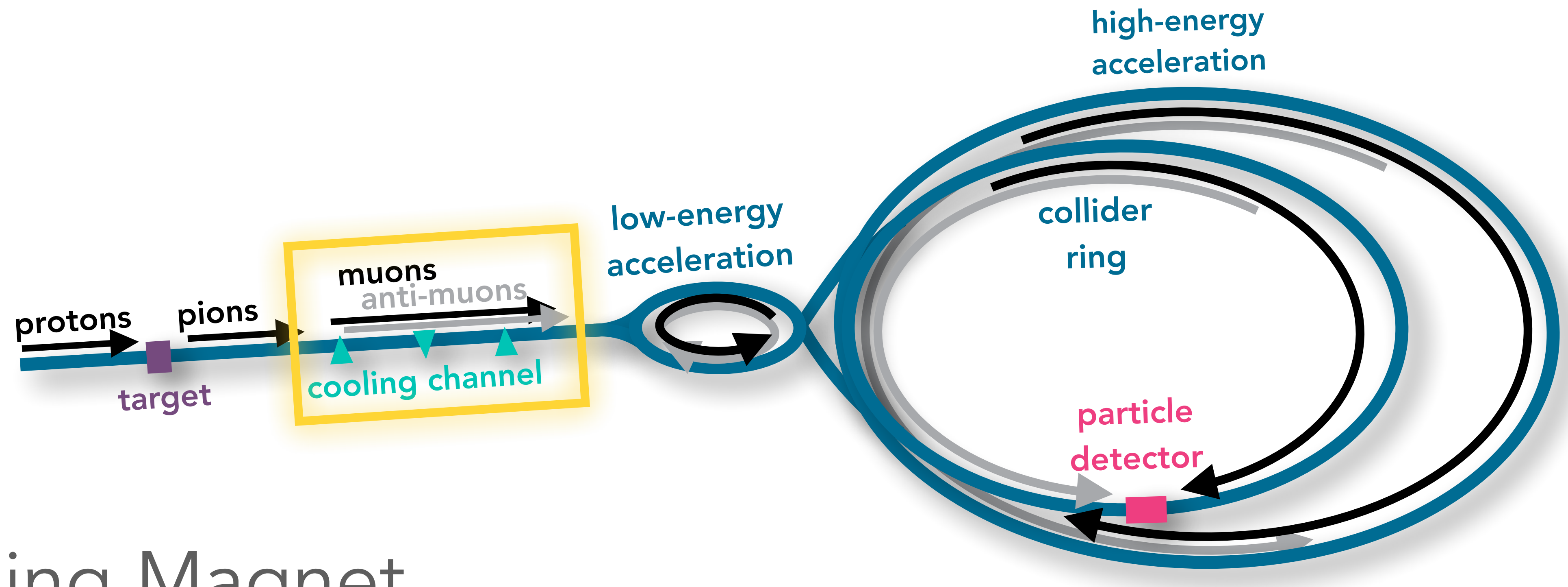
2-4 MW on target → starting constraint on number of muons produced

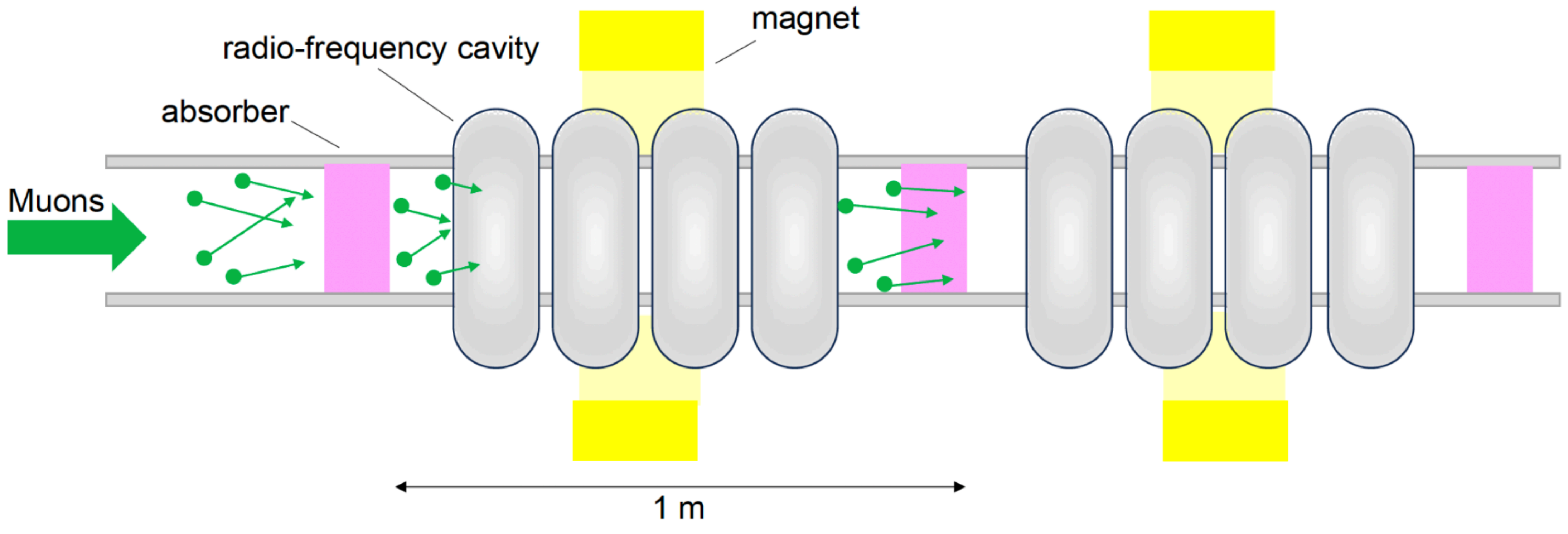
in 20 T solenoid with 0.7 m radius → high field captures more pions and muons; need large bore to accommodate shielding

magnet and **target** materials and design push the limits of what can be done today

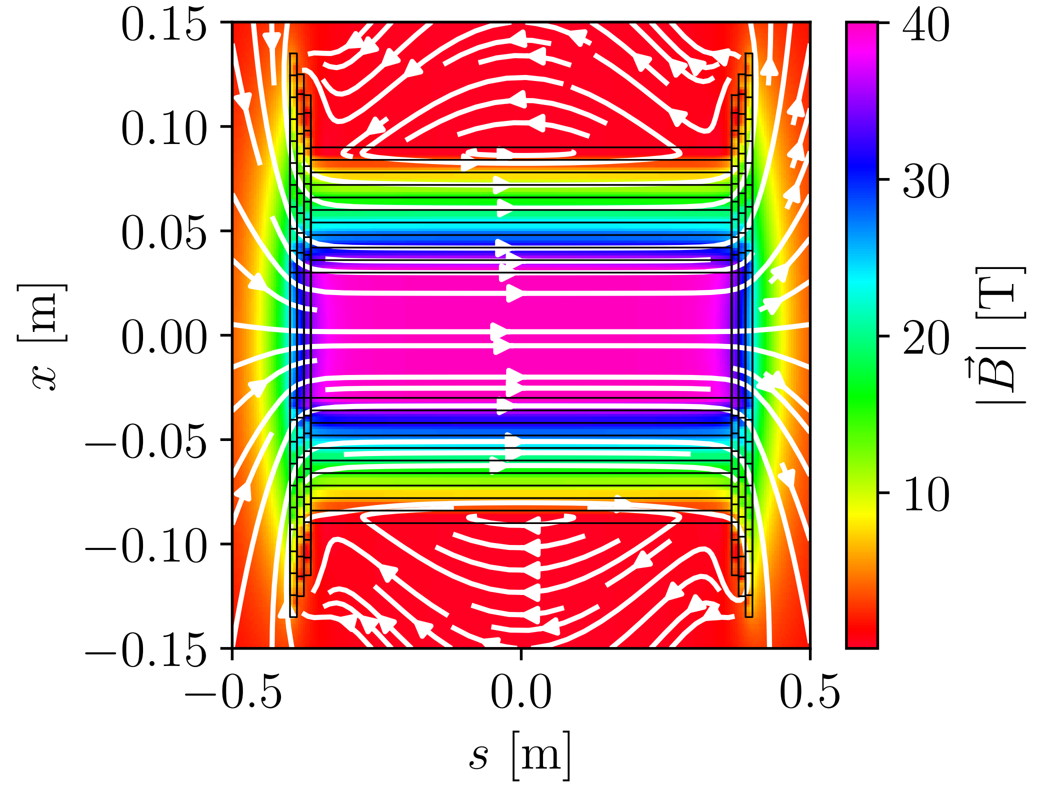
Most recent technical specs from "The Muon Collider" (input to ESPPU)

A MUON COLLIDER





Final Cooling Magnet
B. Stechauner



novel for a muon collider!

cooling channel

6 orders of magnitude of phase space reduction → all parameters (x, y, z, px, py, pz) must shrink to allow collider to provide high luminosity

as compact as possible → reduces loss of muons due to decays

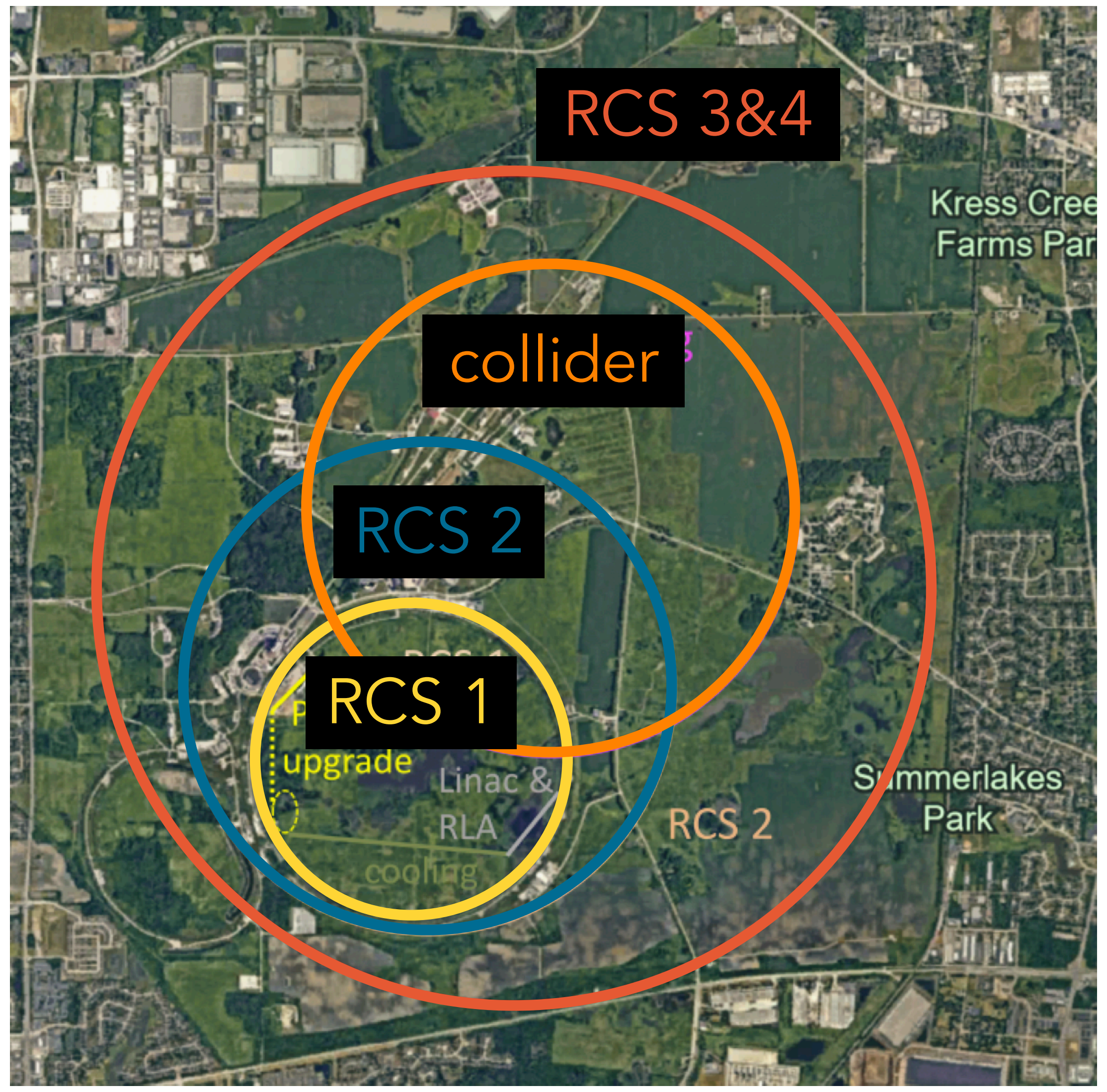
peak B-field of up to 40 T → gives strong focus, improves final cooling rate

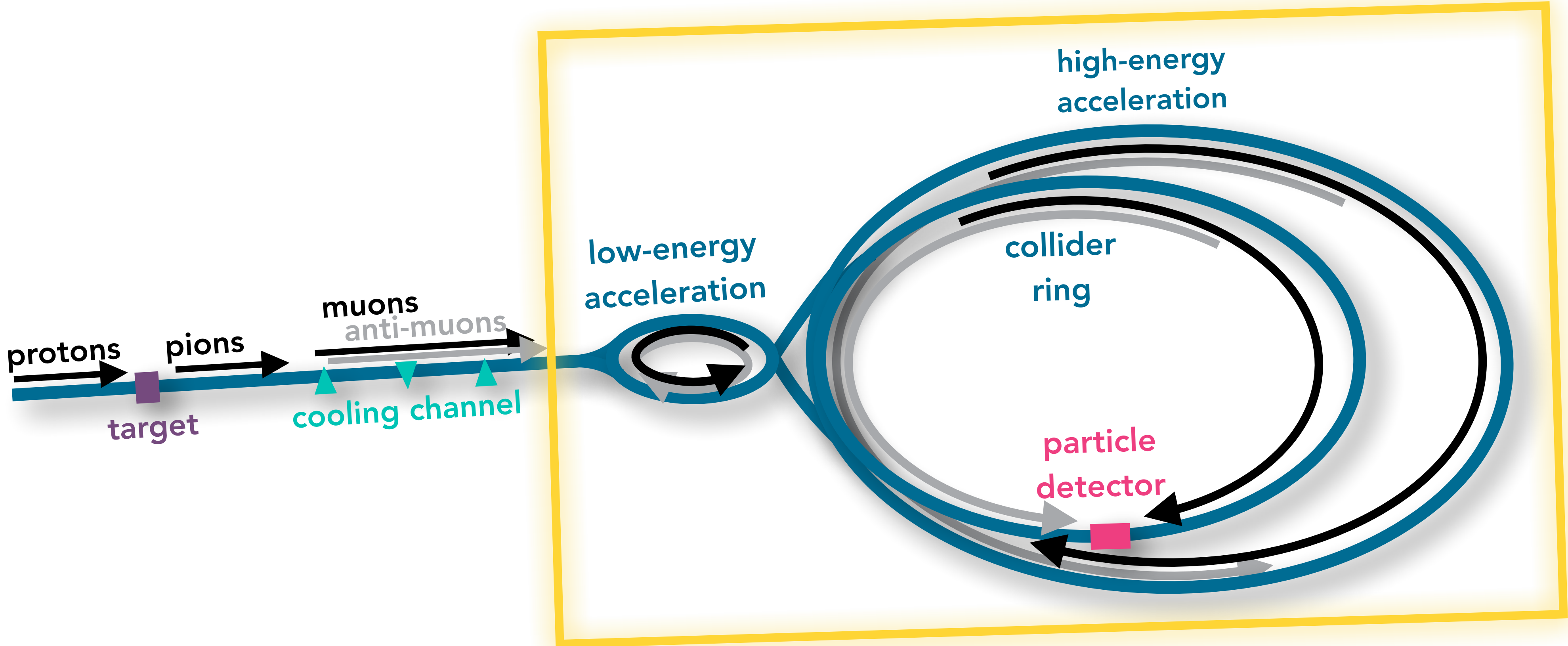
cooling cells involve RF cavities in high fields, challenging solenoid engineering

Most recent technical specs from "The Muon Collider" (input to ESPPU)

A MUON COLLIDER

USMCC





compare to: LCs for gradients, but ramp speed is unique for muC

rapid acceleration

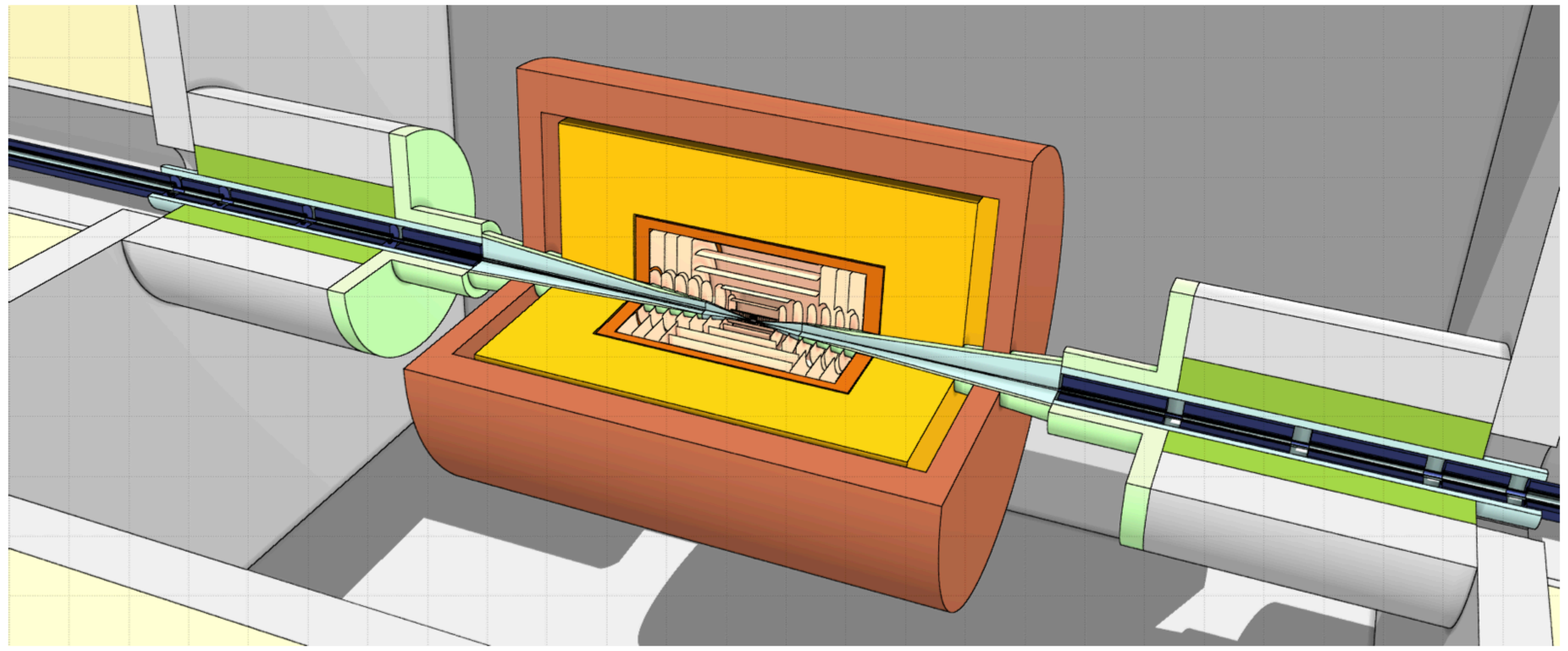
avg. gradients up to 2.4 MV/m
magnet ramp speed O(kT/s)

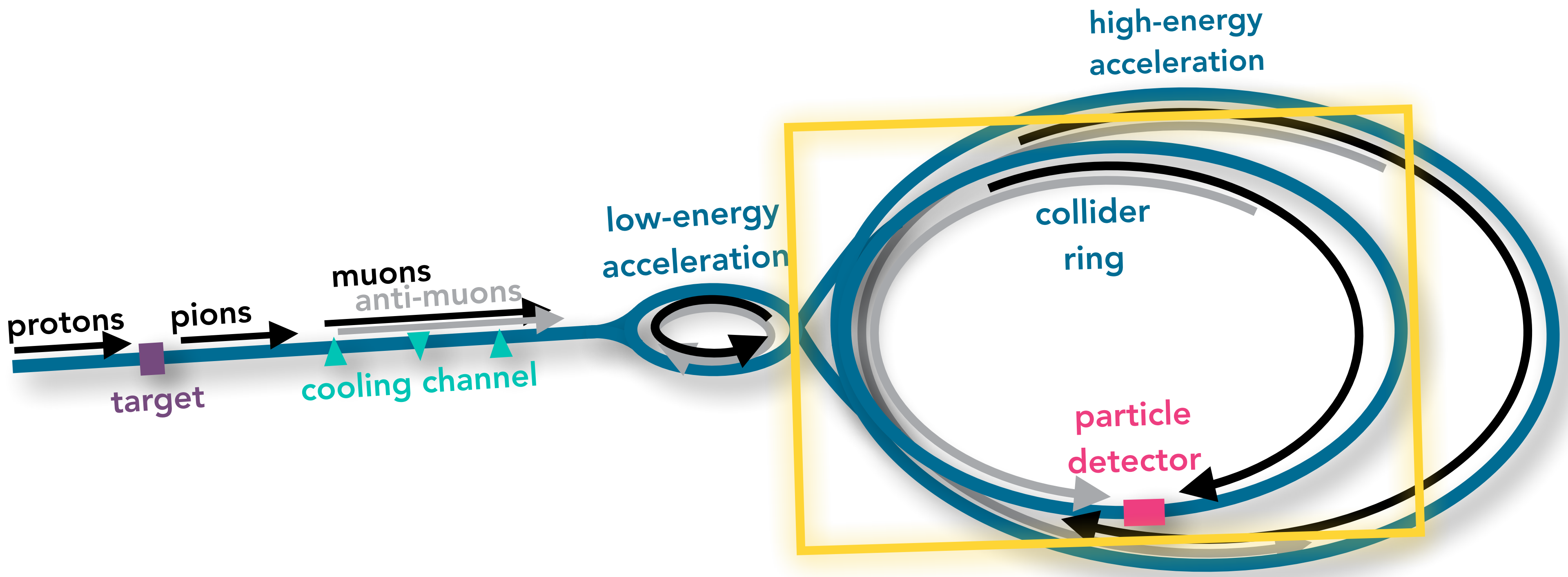
→ fast acceleration required to increase gamma before muons decay

use combination of **fixed-field** and ramping magnets to ease challenge

Most recent technical specs from "The Muon Collider" (input to ESPPU)

A MUON COLLIDER





compare to: dipole needs for FCC-hh, but neutrino mitigation is unique

collider ring

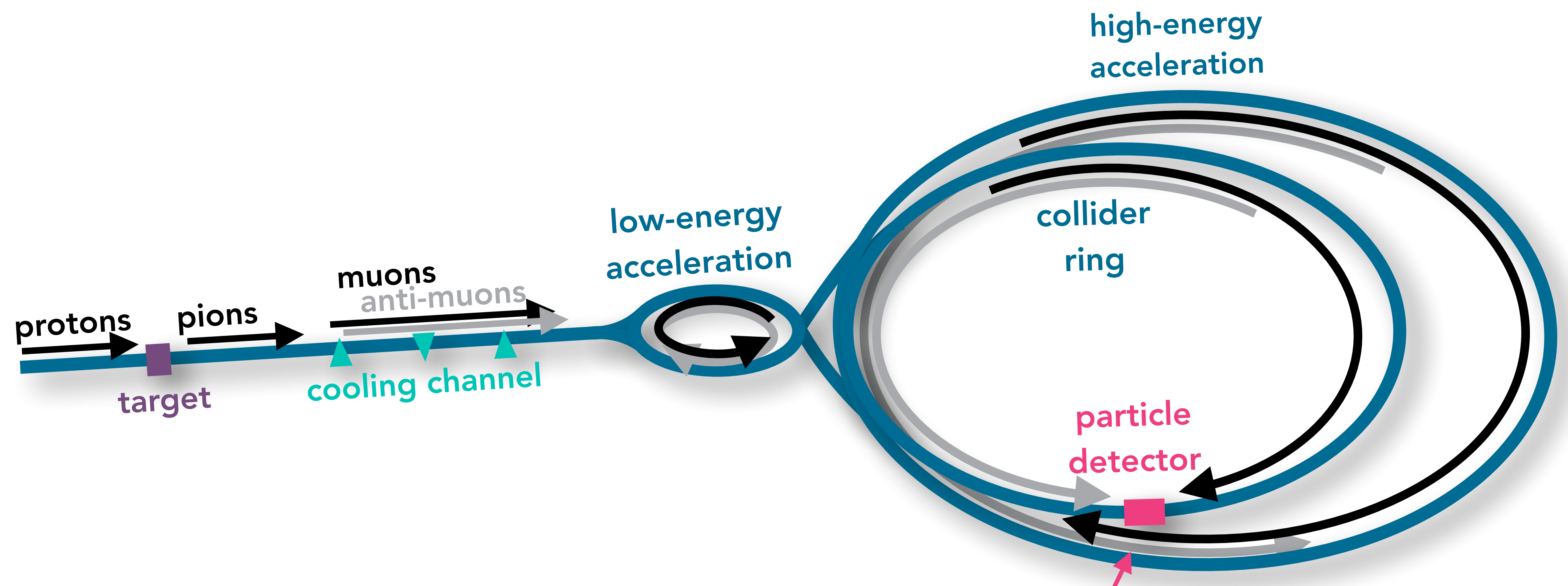
dipoles ideally 16T → smaller ring size means higher luminosity
integrated design of MDI → optimize focus and beam-induced background
beam modulation and/or movers → neutrino mitigation around the ring

engineering and scalability of **HTS magnets** is the biggest constraint

energy staging option uses Nb_3Sn

Most recent technical specs from "The Muon Collider" (input to ESPPU)

A MUON COLLIDER DETECTOR



Exciting challenges across the accelerator complex!

But my focus today is **here**

THE DRIVING DETECTOR CHALLENGE AT A MUON COLLIDER

Larry Lee, Charles Bell

THE DRIVING DETECTOR CHALLENGE AT A MUON COLLIDER

how big is this problem?

HOW MUCH BIB? — FROM FIRST PRINCIPLES

muons have a lifetime of 2.2 μs
(but time dilation can help)

$$\tau'_\mu = 21 \text{ ms} \times \left(\frac{E}{1 \text{ TeV}}\right)$$

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$$\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$$

what fraction decay within 20m
of an interaction point per pass?

$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$

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how much energy do those decay
products have?

$$E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2 \times 10^{12}}\right)$$

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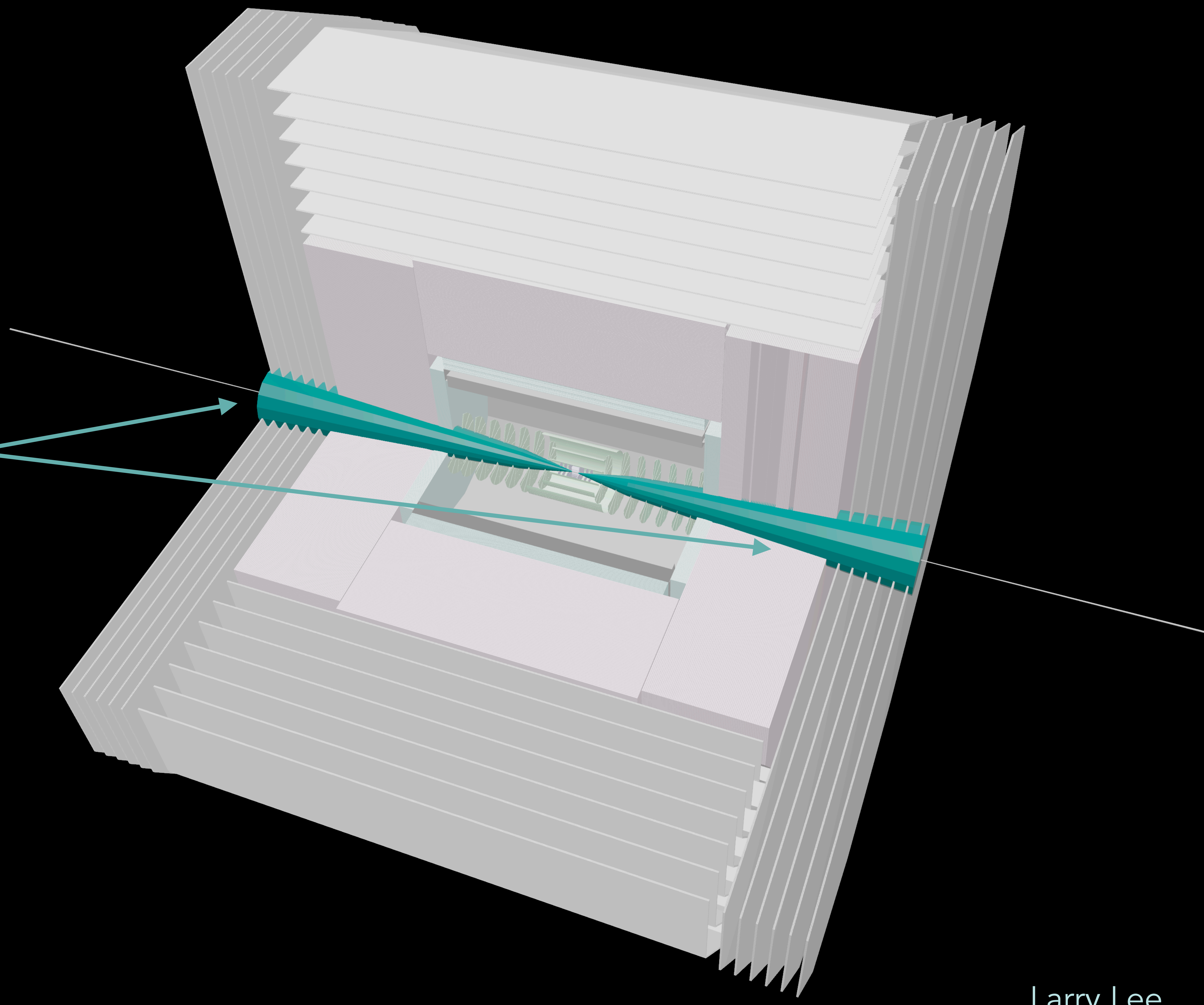
huge backgrounds, huge radiation, huge mess

HOW CAN WE DEAL WITH THIS?

need to block BIB from reaching the detector
without interfering with signal

introduce tungsten nozzles around the beam pipe

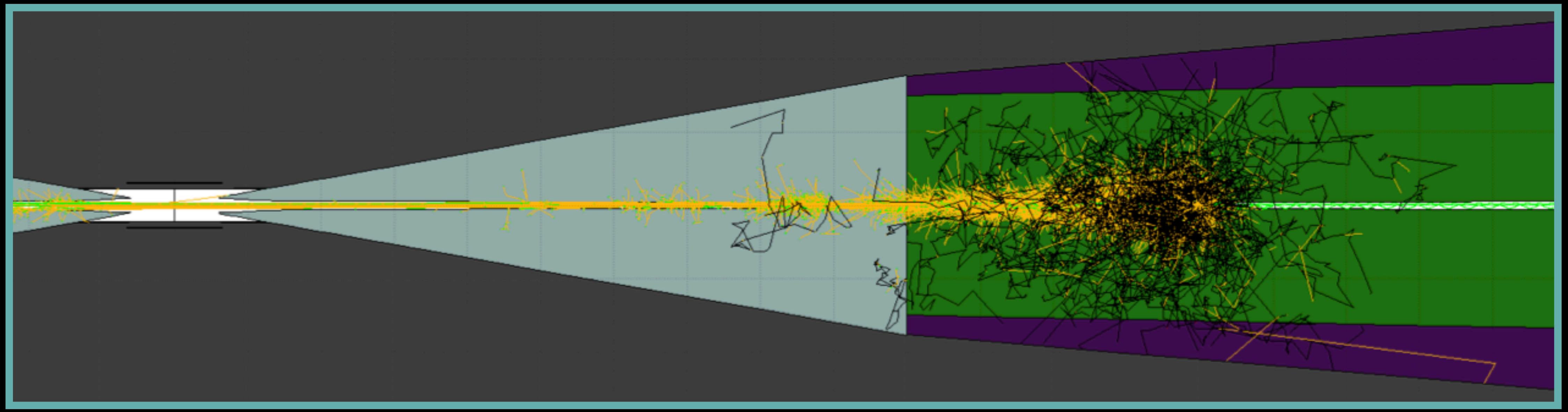


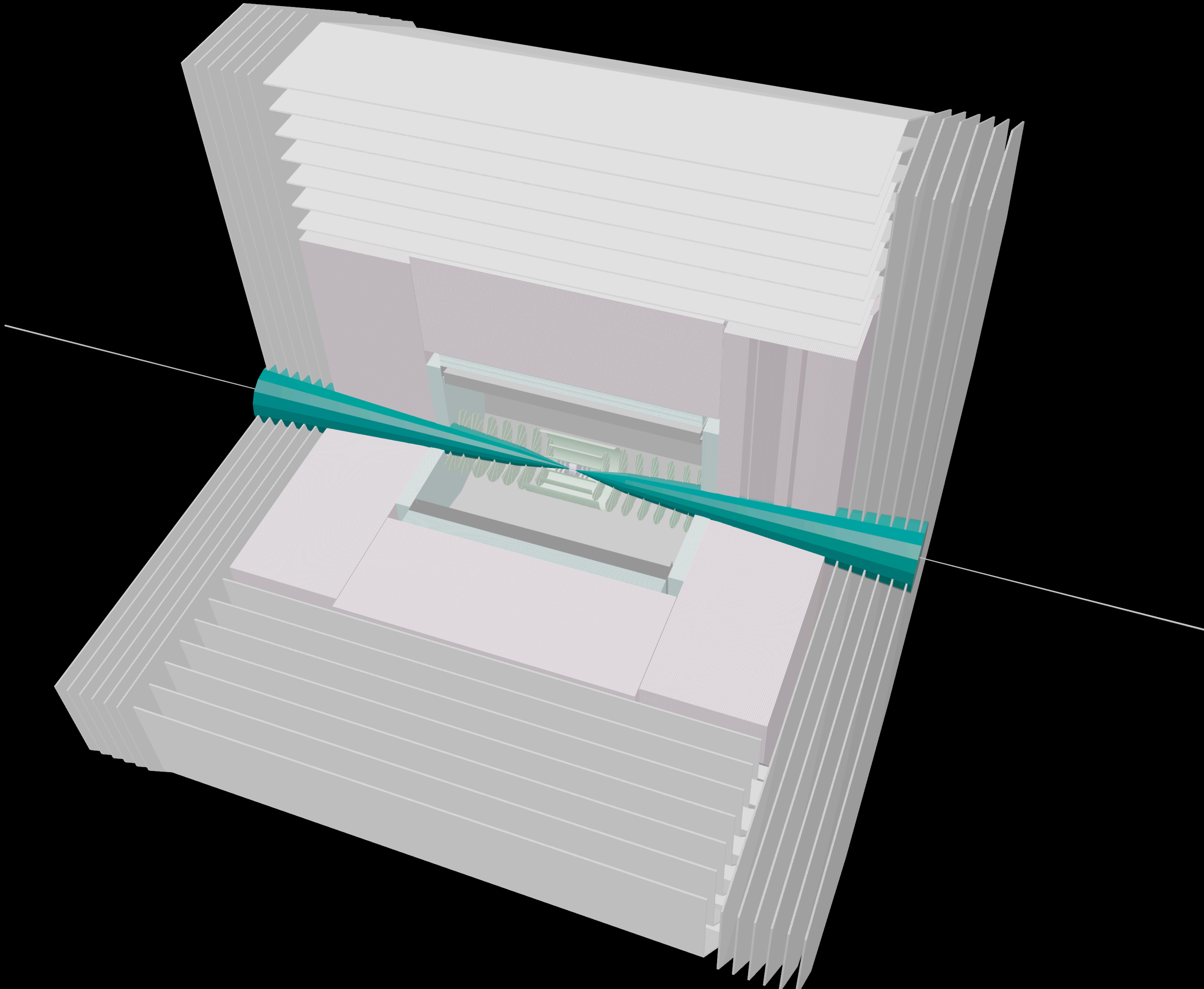
Larry Lee

HOW CAN WE DEAL WITH THIS?

need to block BIB from reaching the detector
without interfering with signal

incoming particles shower in the nozzle;
most energy contained





F. Collamati et al. Larry Lee

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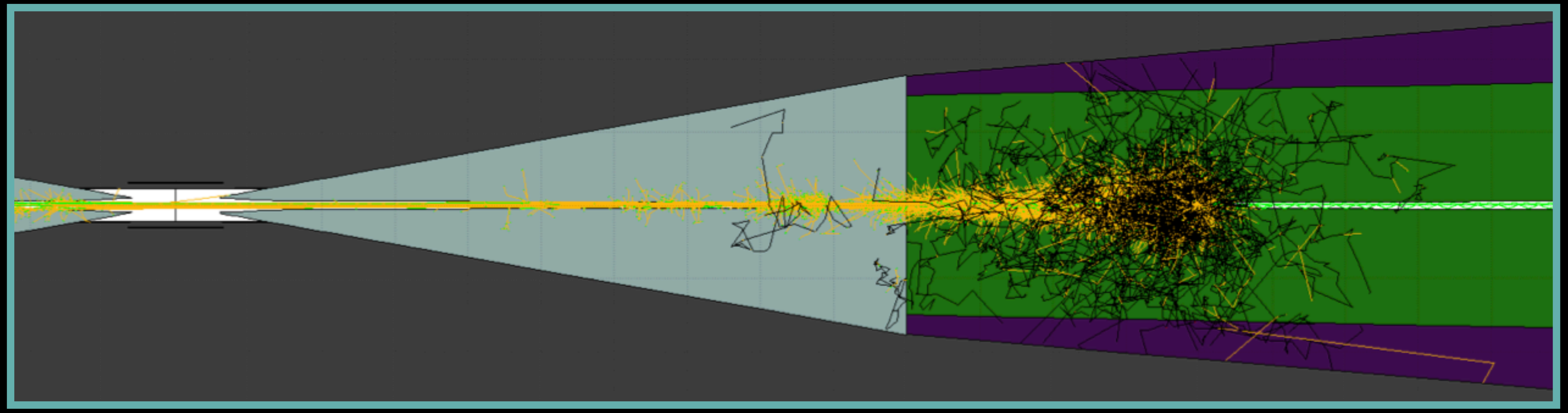
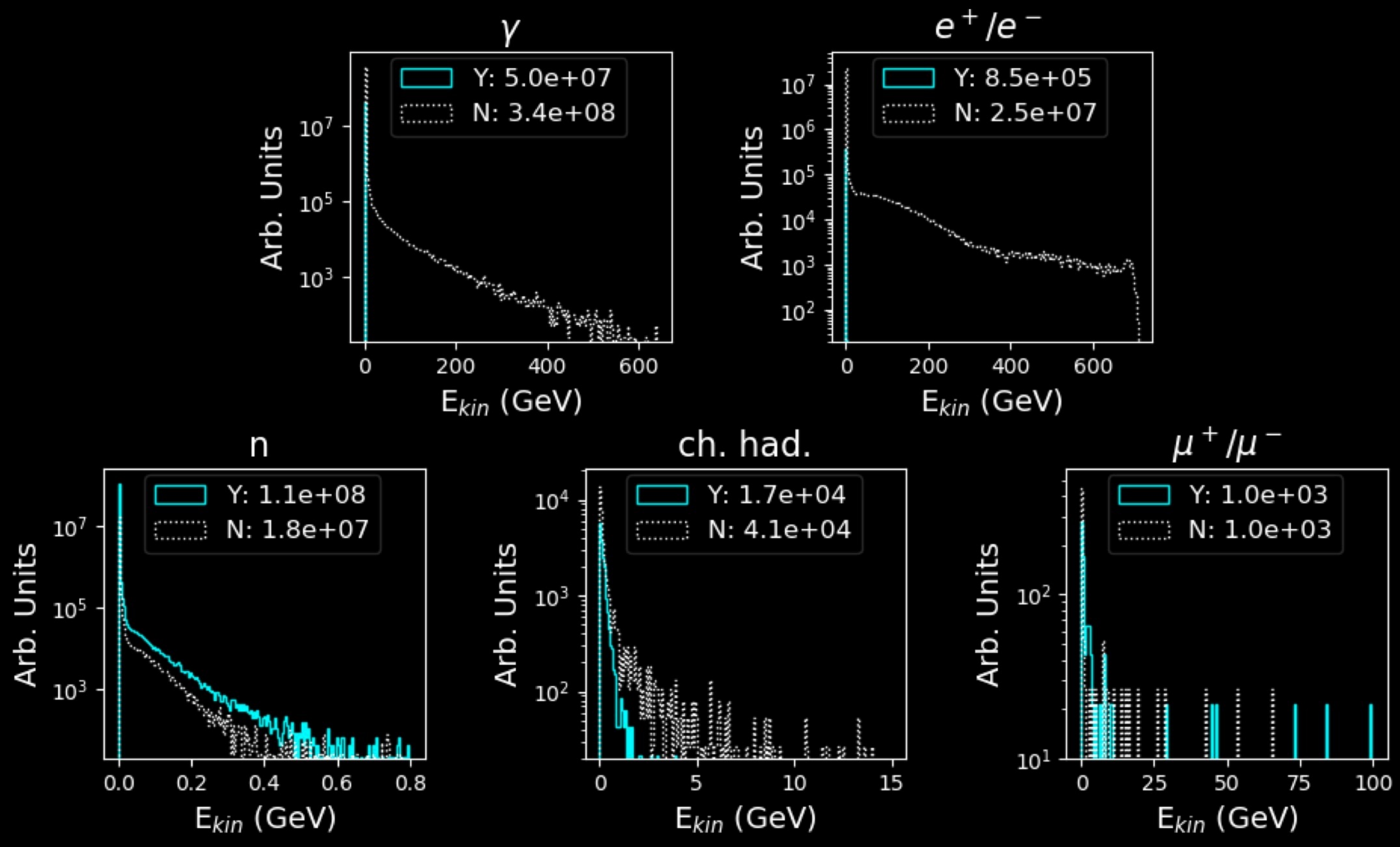
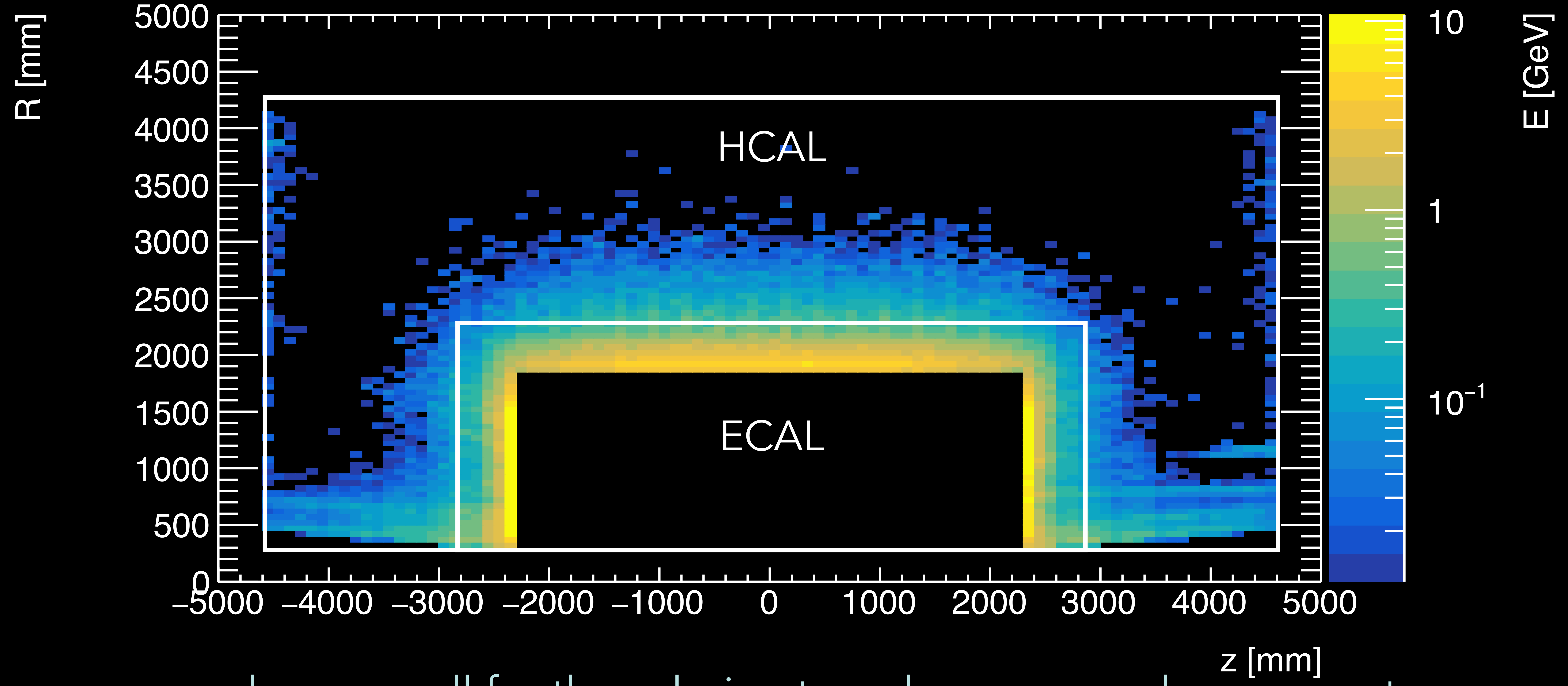


what's left over?



F. Collamati et al.

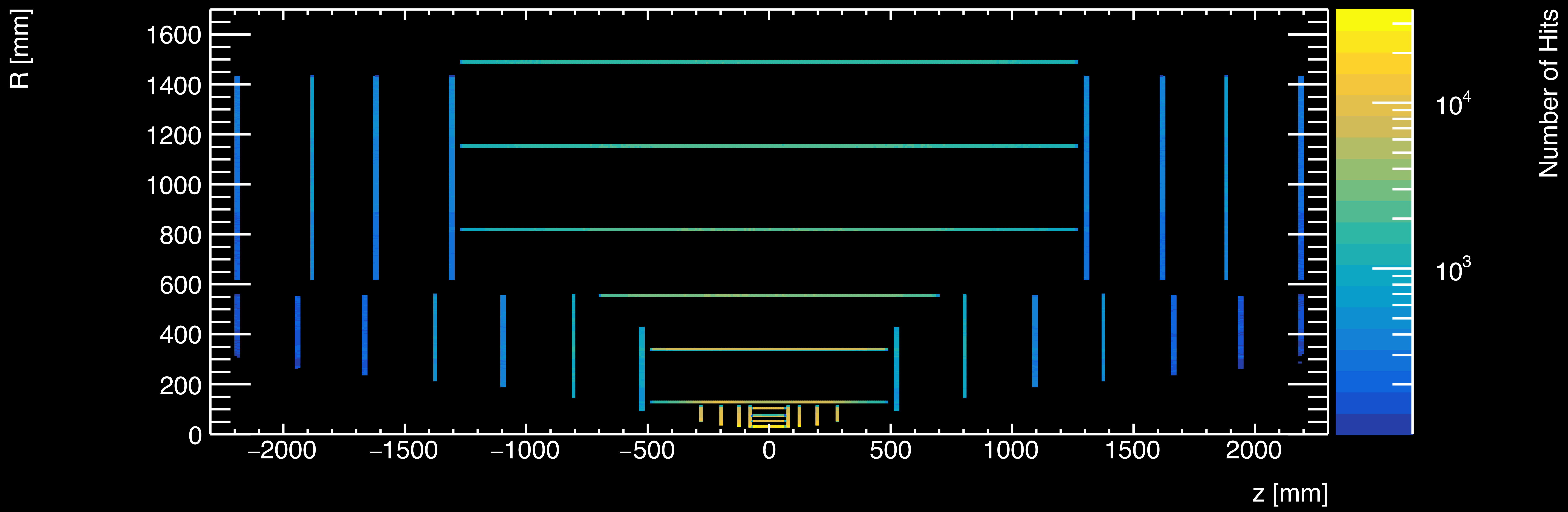
What's left over?



works very well for the calorimetry - decreases and smears out energy

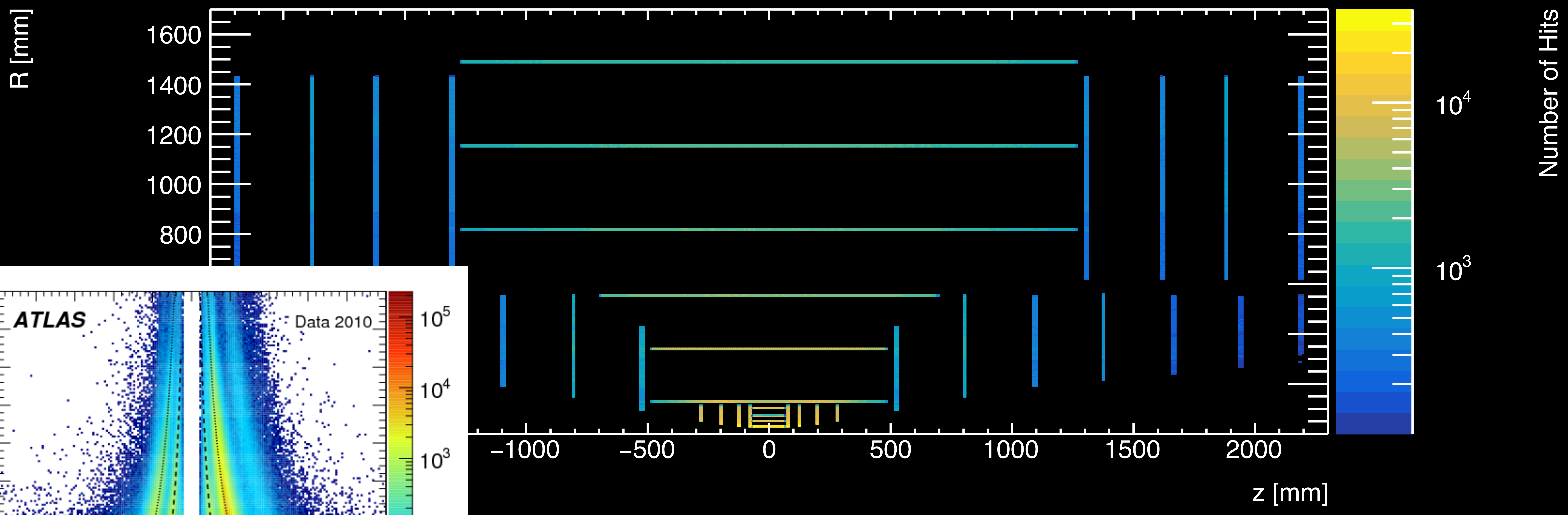
total energy deposited in the calorimeter: ~1.5 TeV

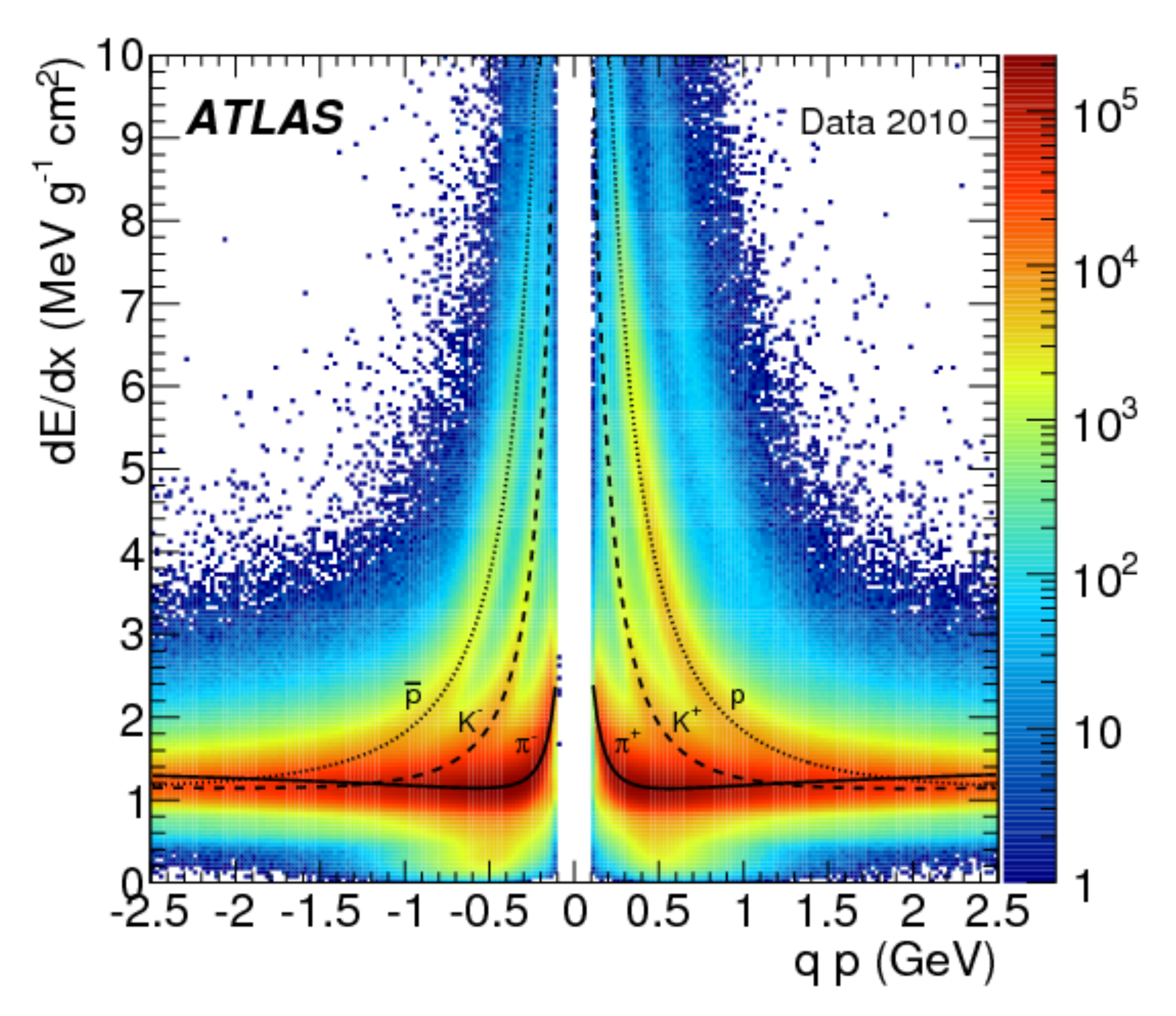
WHAT'S LEFT OVER?



much more challenging in the tracker:
many low energy particles much more challenging
than a few higher energy ones

WHAT'S LEFT OVER?





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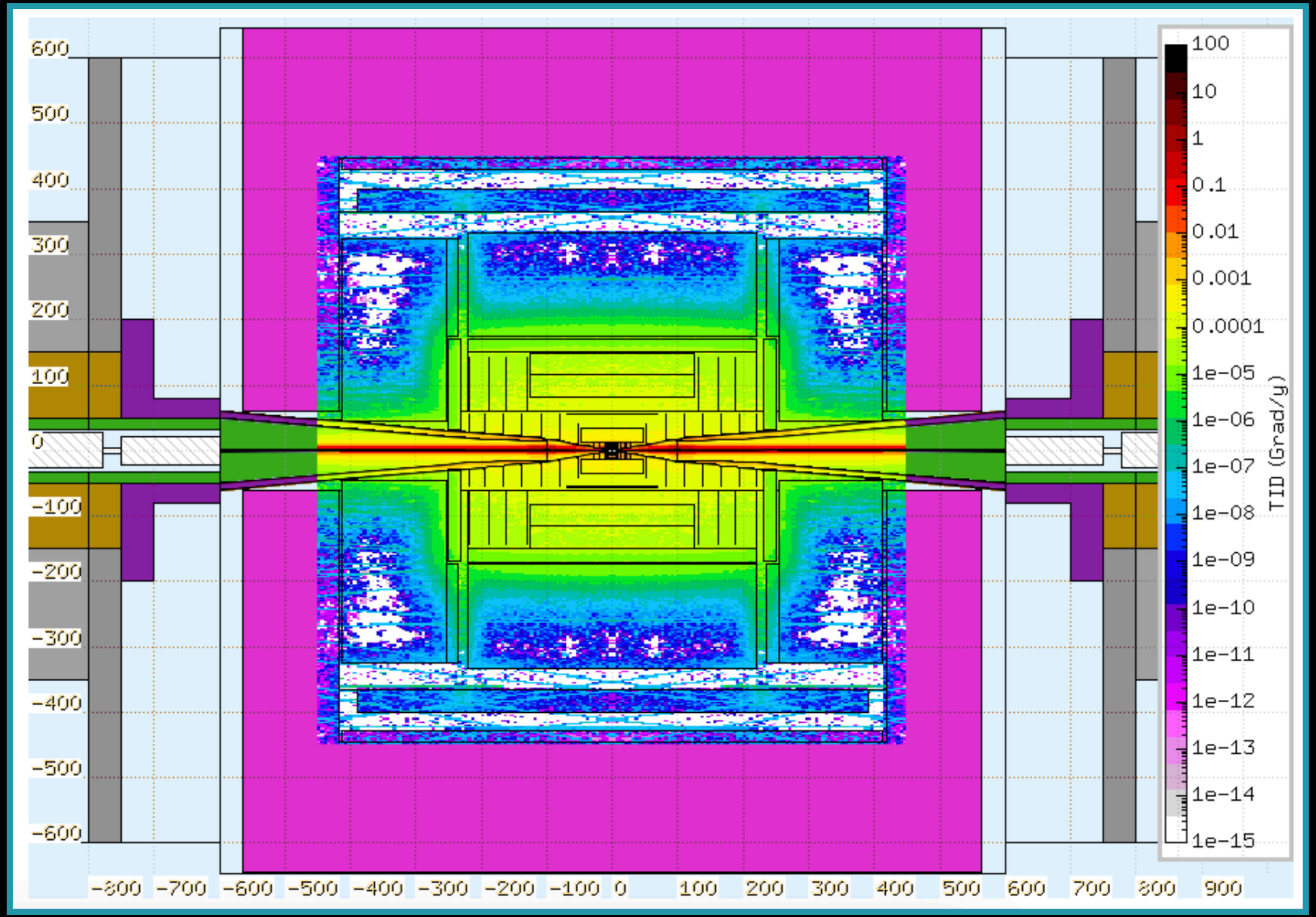
ATLAS

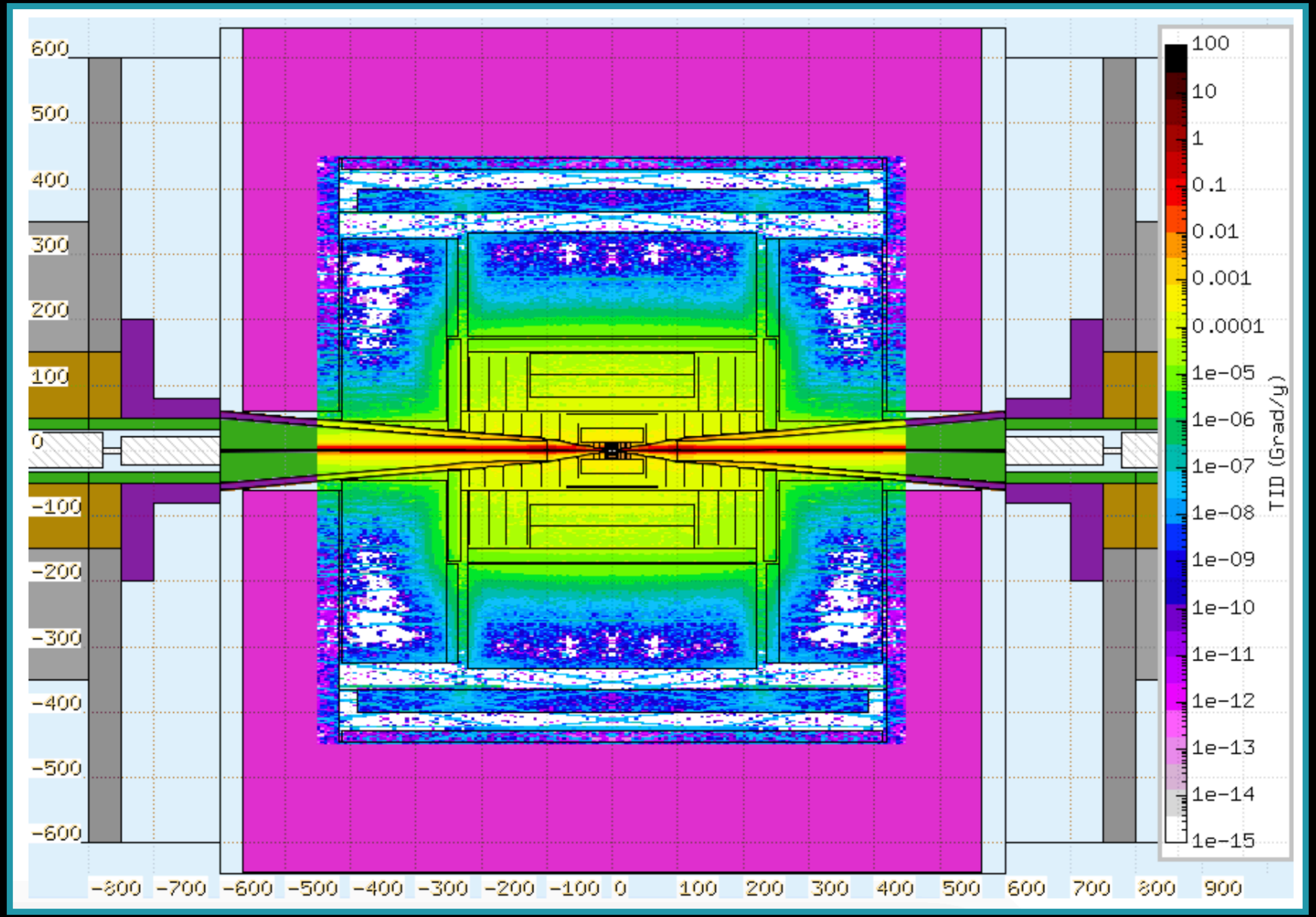
WHAT'S LEFT OVER?



despite large amount of BIB, fluence/doses are comparable to the HL-LHC

	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

WHAT'S LEFT OVER?



despite large amount of BIB, fluence/doses are comparable to the HL-LHC

this is because muon collider circulate only two bunches, so collisions are far less frequent

$$t = 33\ \mu s \times \left(\frac{L}{10\ \mathrm{km}}\right)$$

	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
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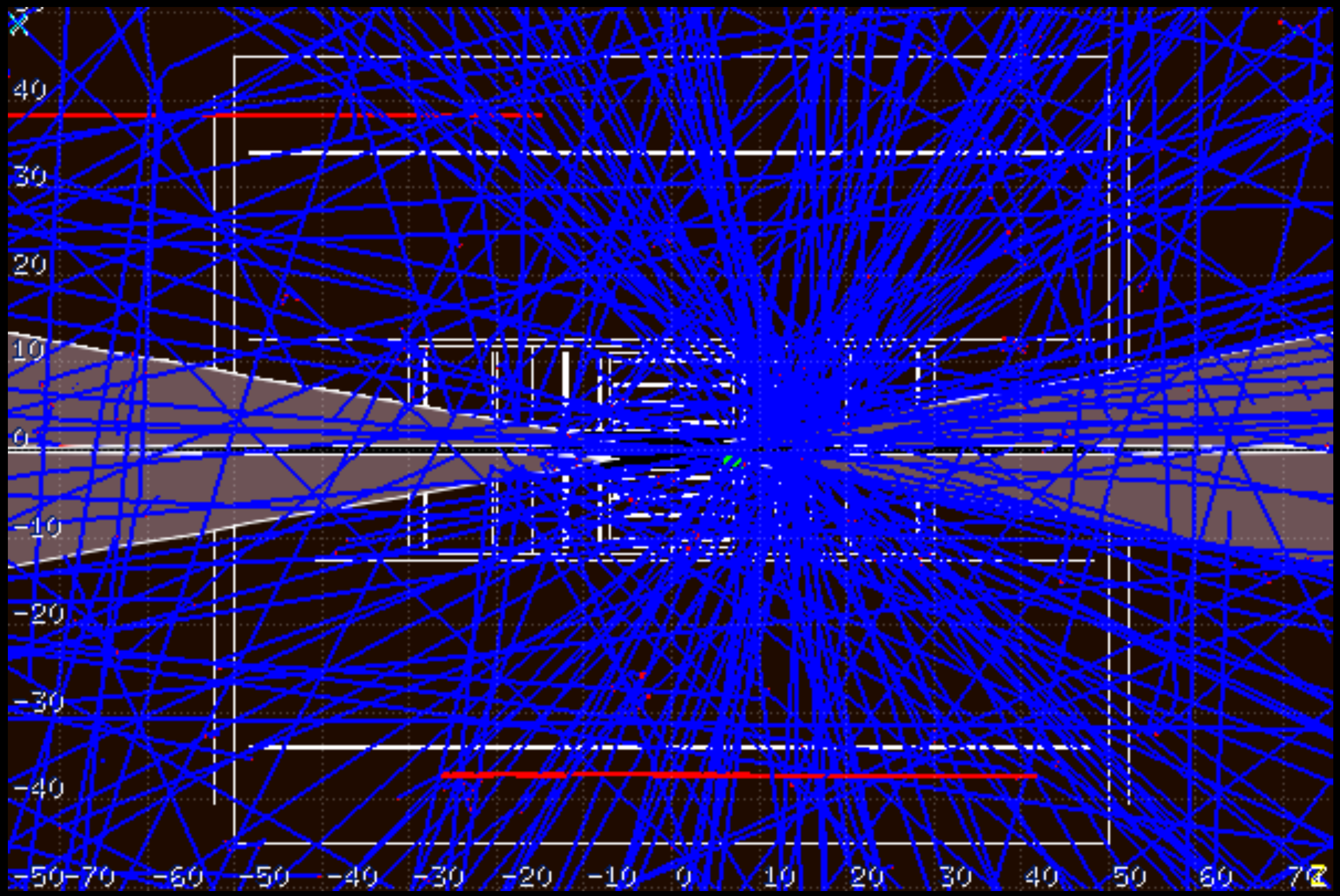
Muon Collider Forum Report

WHAT'S LEFT OVER?

another plus: BIB looks nothing like signal



photons, electrons, positrons

(0.0003% of a BIB event)

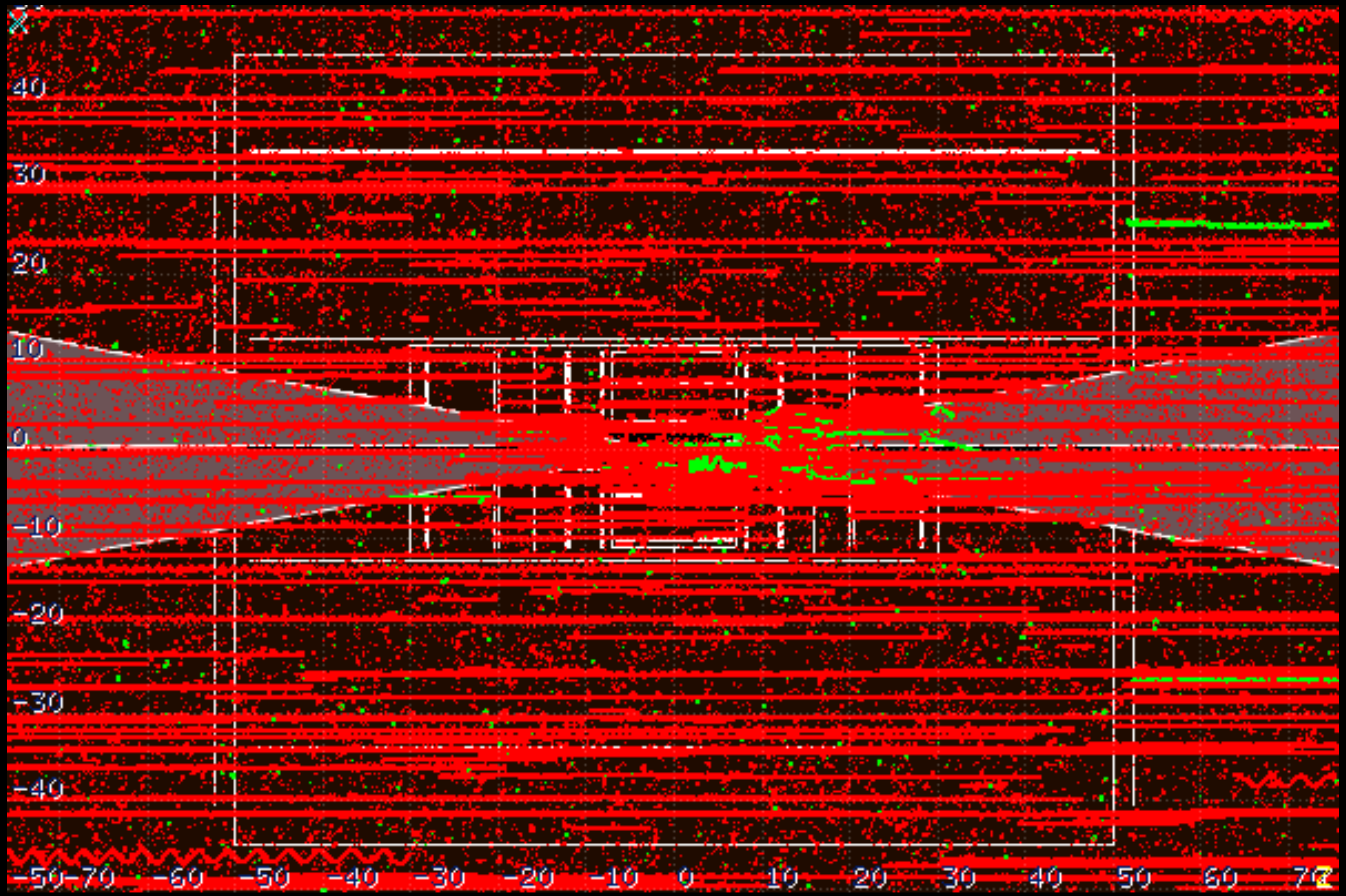
BIB properties:
arrives largely out-of-time
extremely low energy
emerges from nozzles

once reconstruction has been performed,
easy to differentiate from signal

Daniele Calzolari

WHAT'S LEFT OVER?

another plus: BIB looks nothing like signal



(removing photons), electrons, positrons

(0.03% of a BIB event)

BIB properties:
arrives largely out-of-time
extremely low energy
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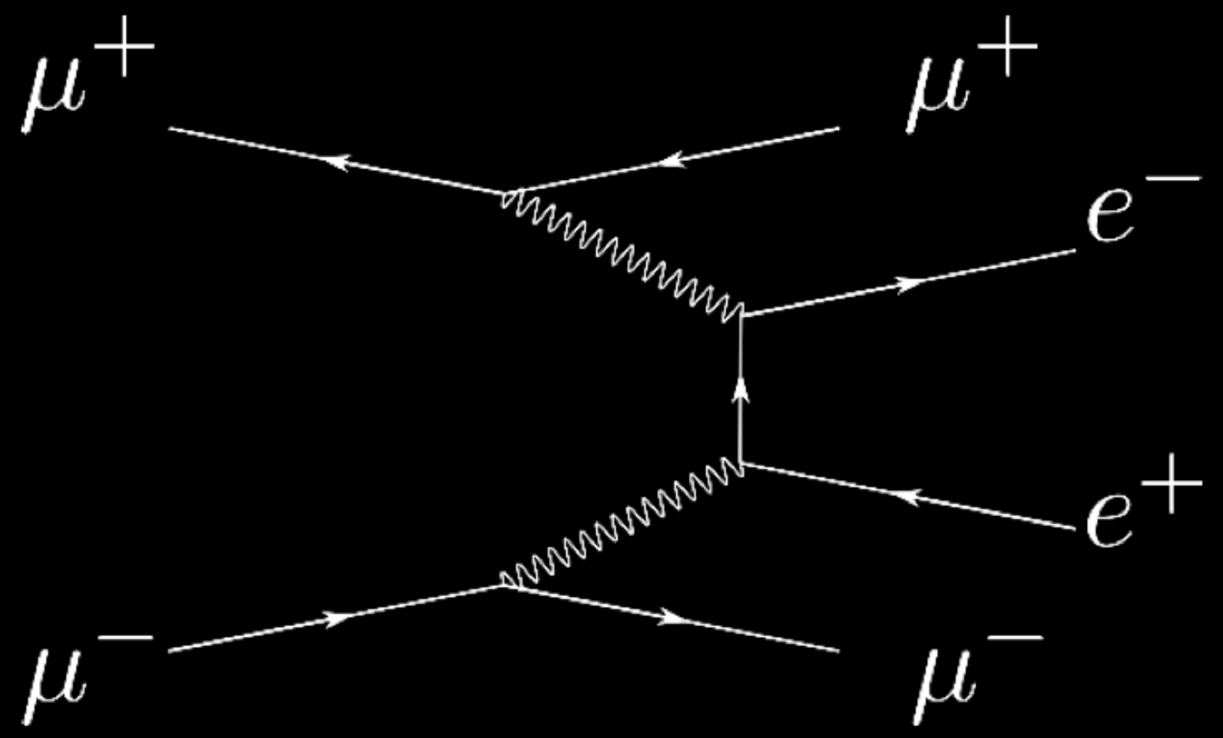
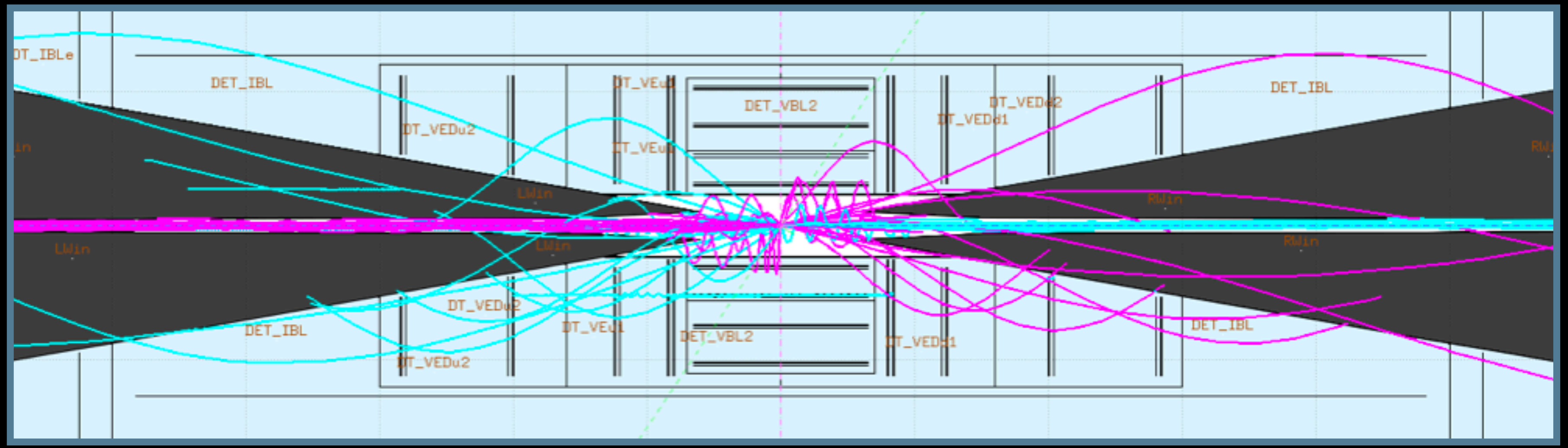
Daniele Calzolari

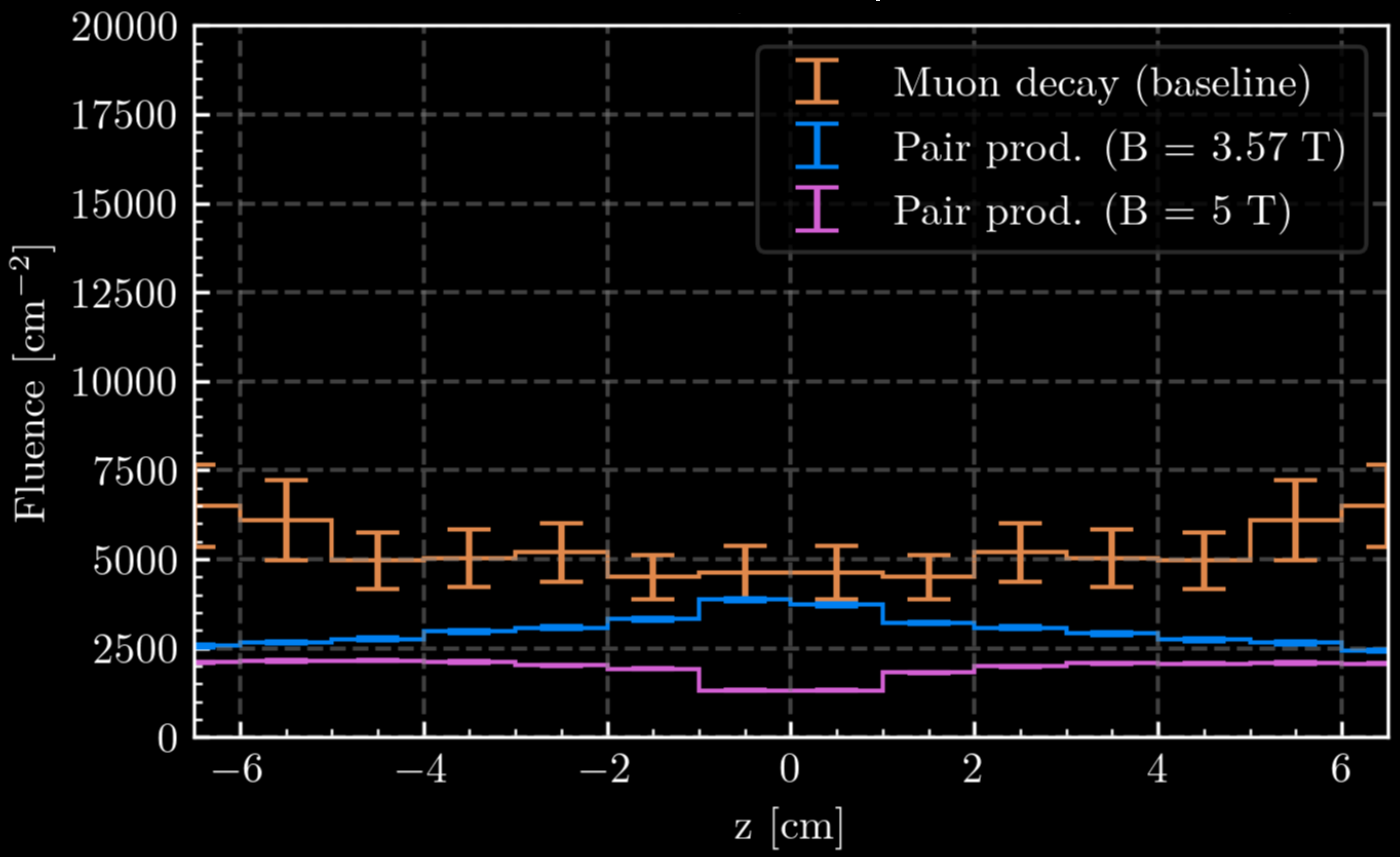
ANOTHER KEY BACKGROUND

incoherent e+e- scattering





fluence in first pixel layer



these particles are low energy and come from the IP

a strong magnetic field can prevent many from interacting with the detector

Daniele Calzolari

CAN WE DO BETTER?

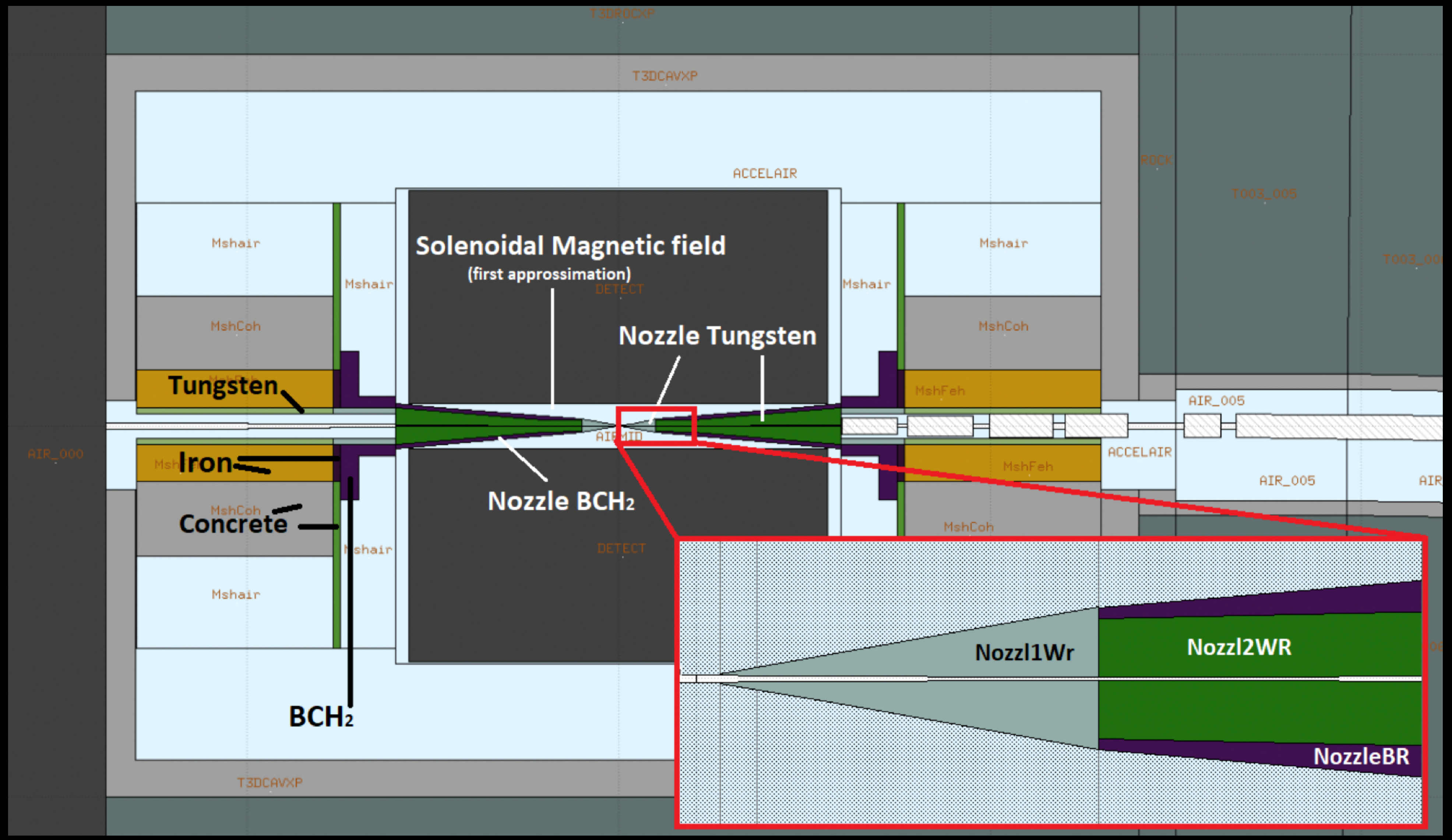
original detector design taken from CLIC (optimized for 3 TeV)

the MAP program optimized nozzles using MARS BIB simulation (at 1.5 TeV)

many efforts to optimize design in recent years, including focus on 10 TeV

tungsten: showers charged particles

borated polyethylene: moderates neutrals



Work in progress: a technical nozzle design
including structural support

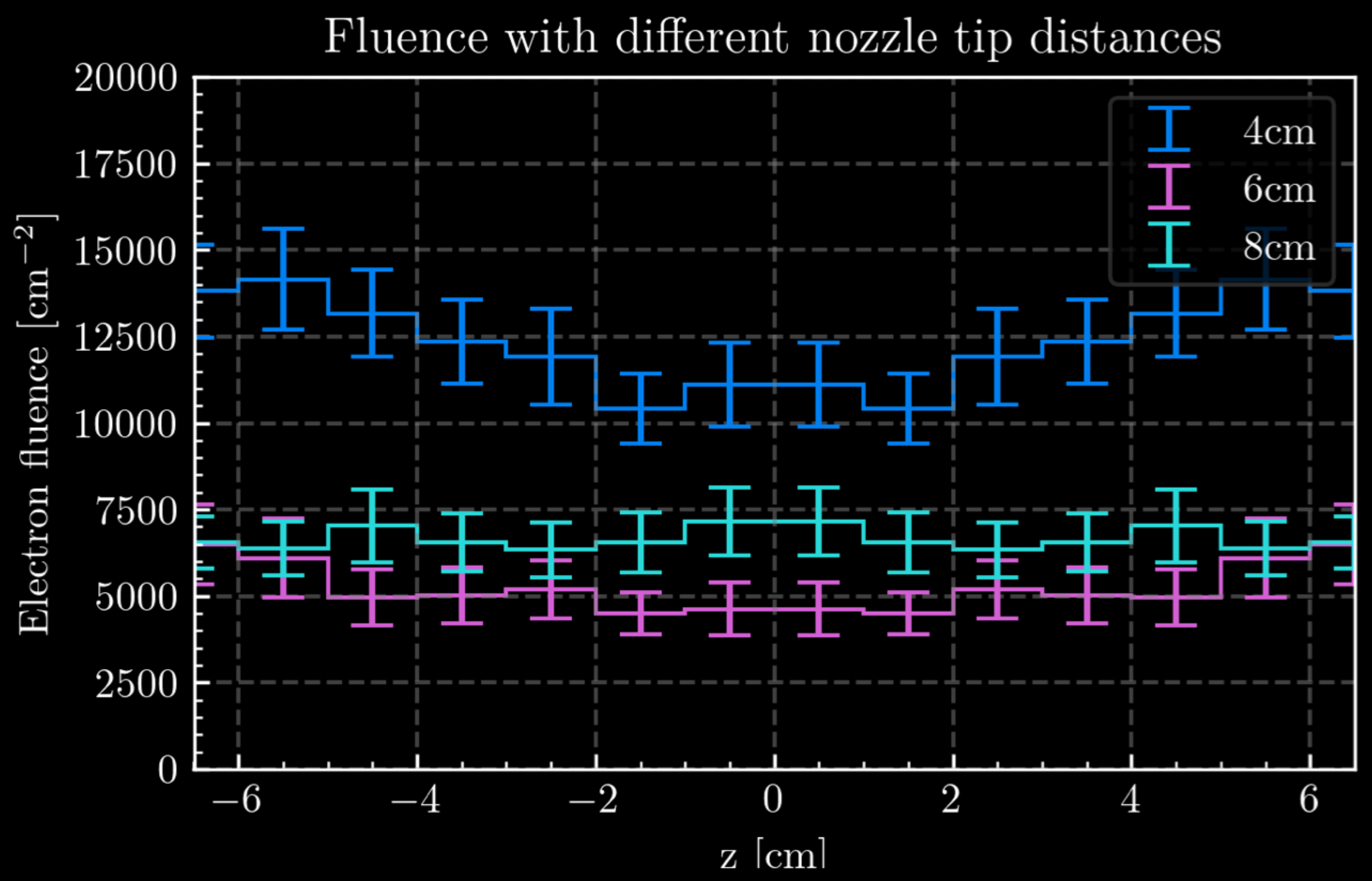
Donatella Lucchesi et al.

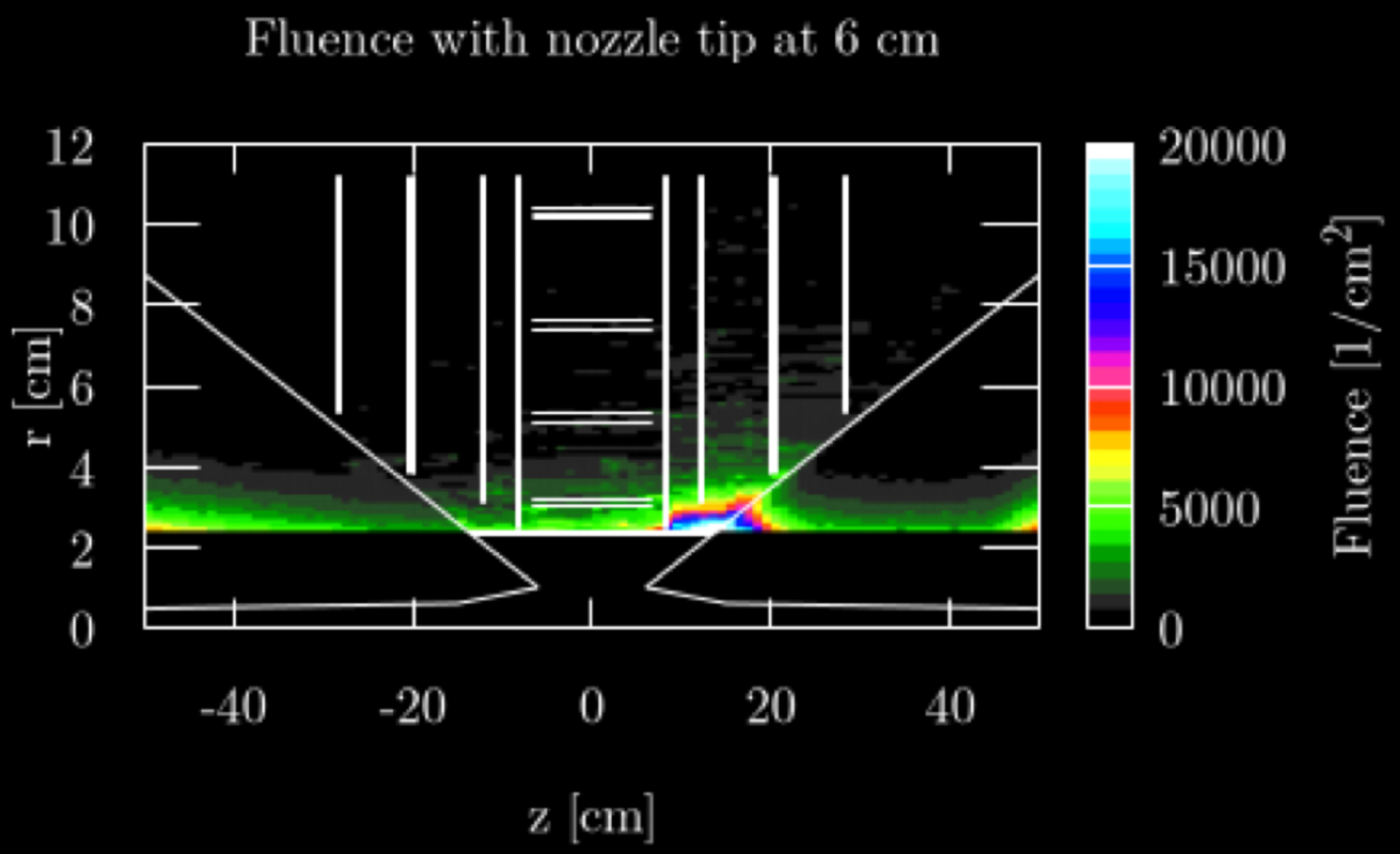
CAN WE DO BETTER?

Studied tweaks to the position of the innermost nozzle tip

Nozzle details have a strong impact on radiation in pixel detectors

Constrained by physics acceptance: currently at $\theta = 10°$ (i.e. $\eta = 2.44$)





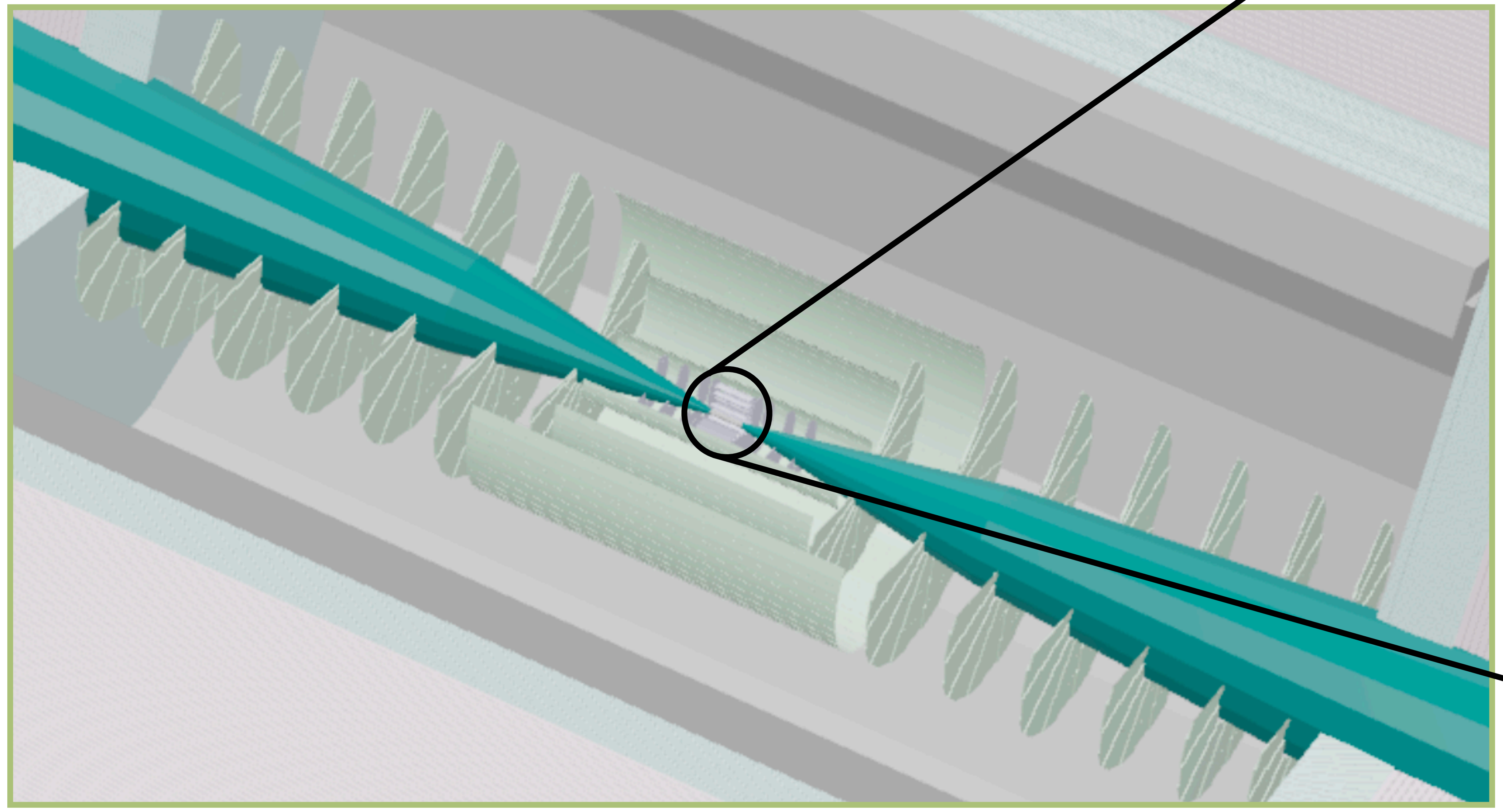
Daniele Calzolari (1, 2)

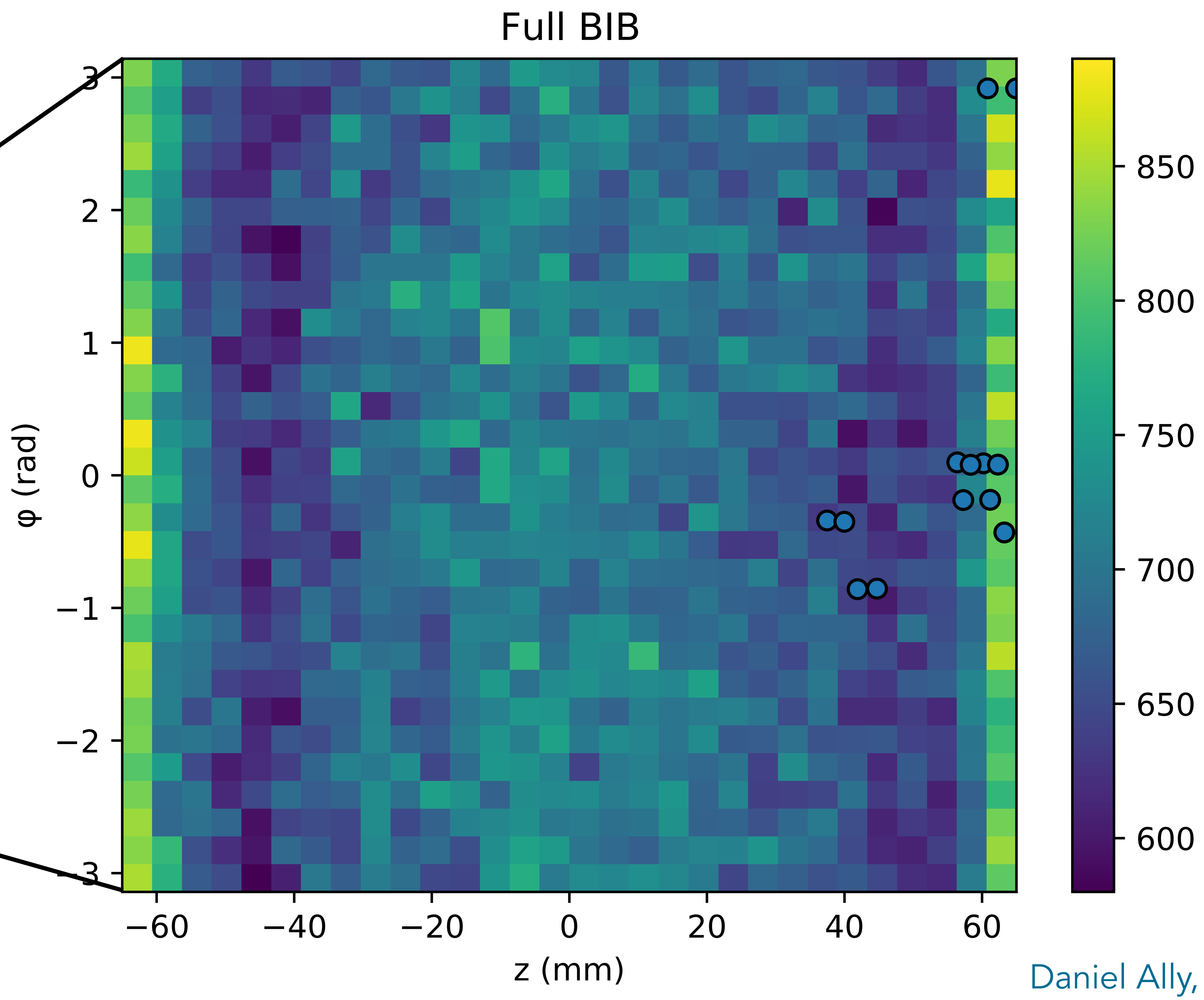
THESE BACKGROUNDS ARE THE DRIVERS FOR DETECTOR DESIGN

HOW CAN WE APPROACH THEM?

IN THE TRACKER…

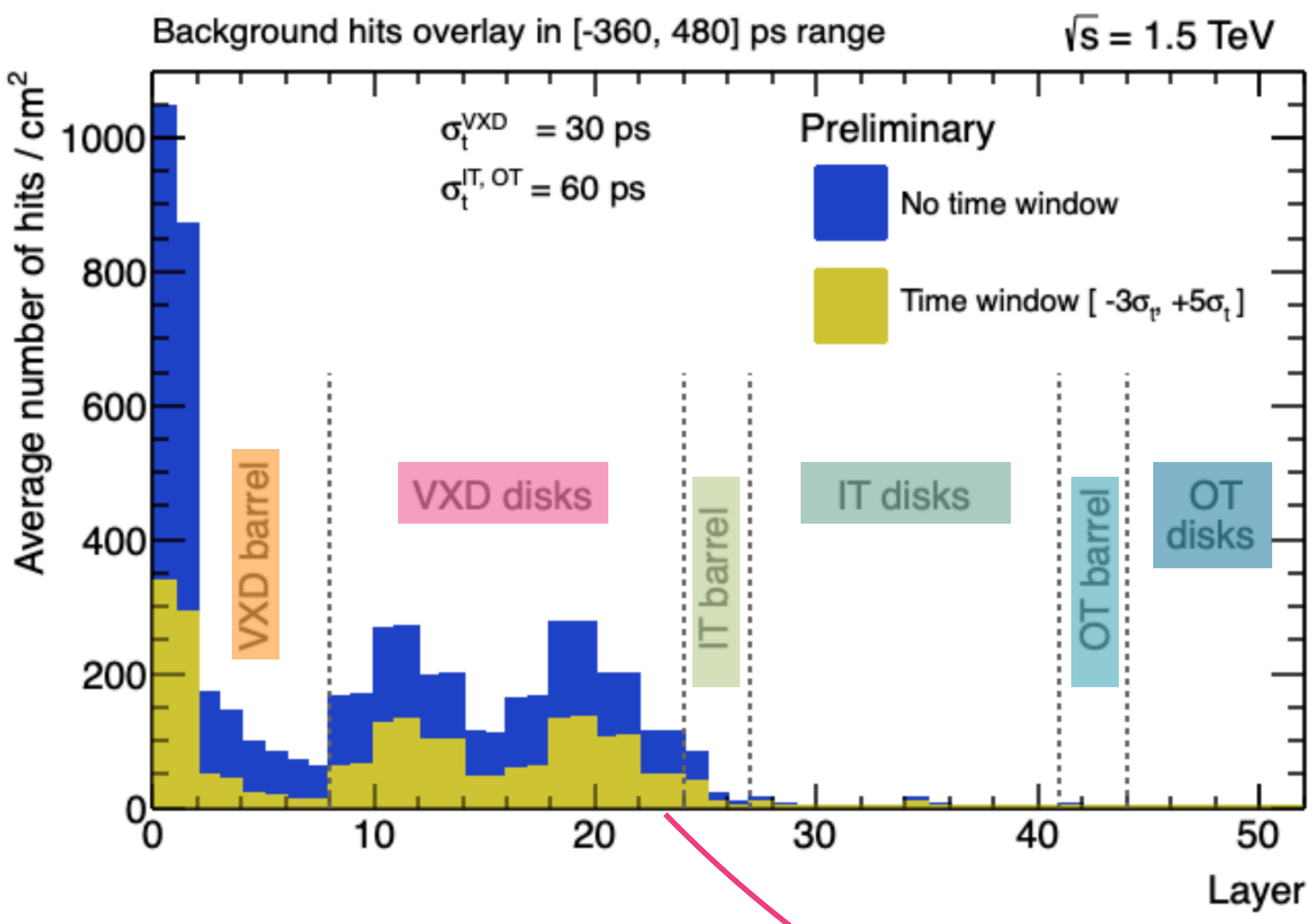
occupancy is the challenge:
in the vertex detector, for a single event see O(100,000) BIB hits compared to O(10-100) signal hits
(within a few nanoseconds)

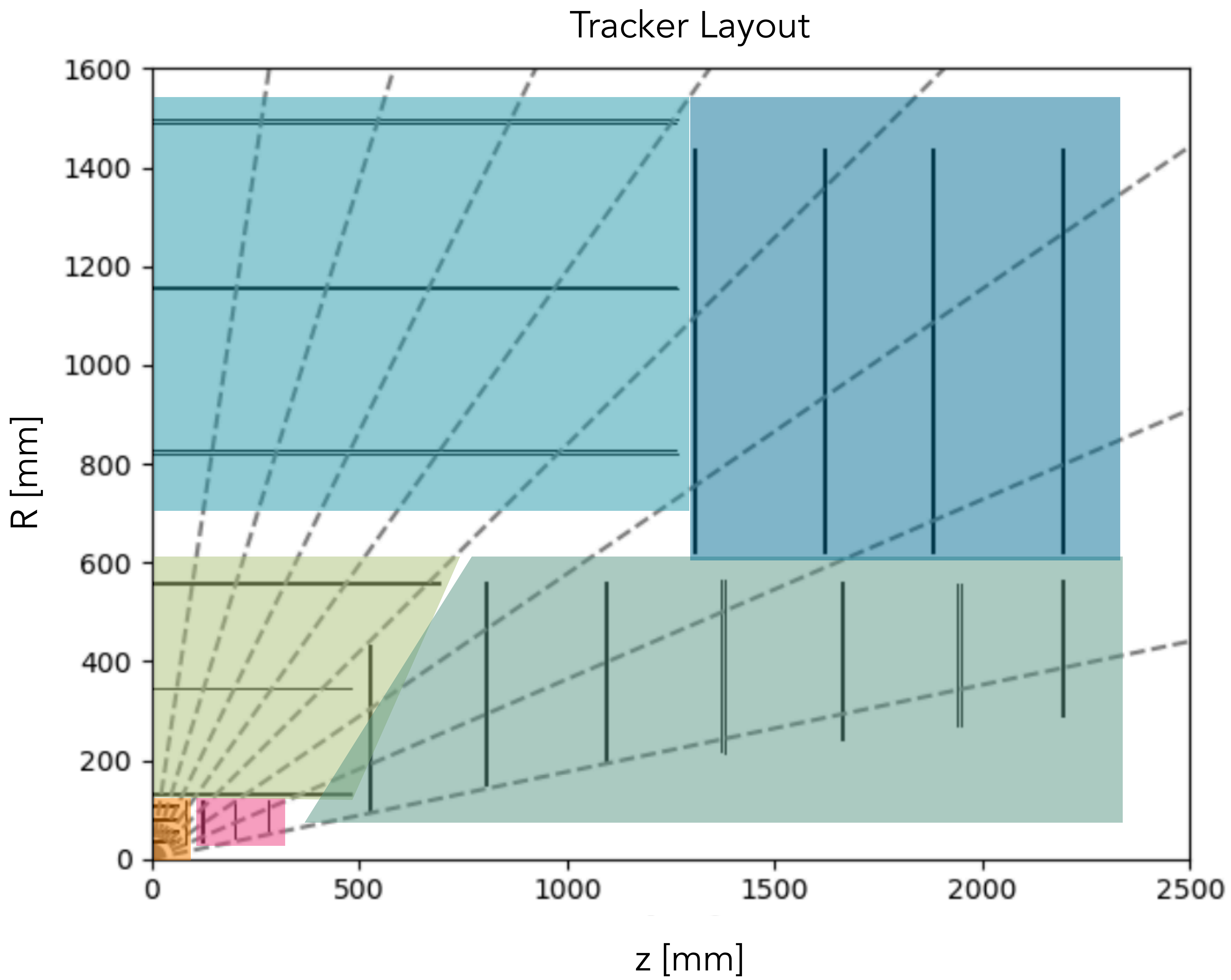




Daniel Ally, Larry Lee

IN THE TRACKER…





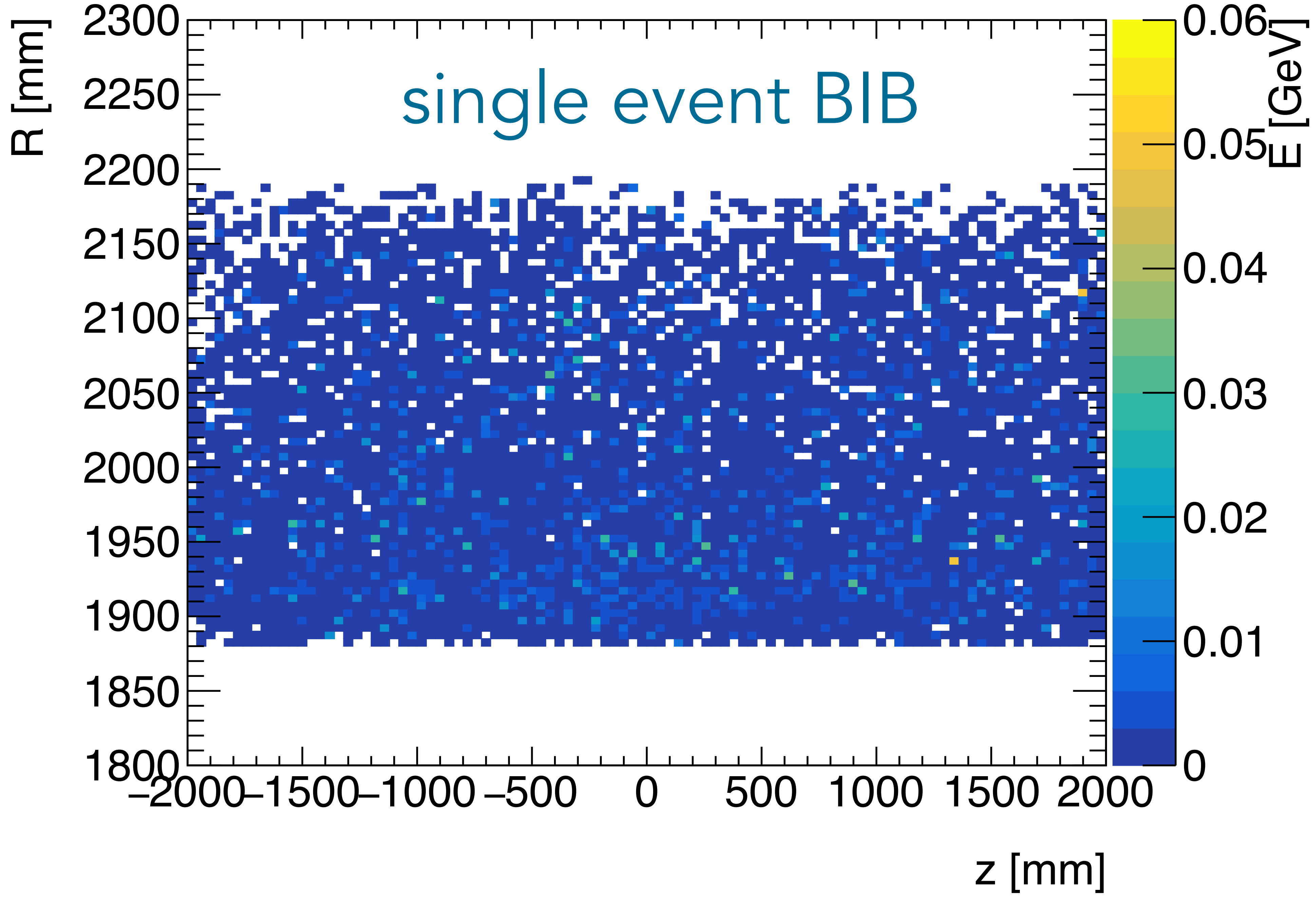
occupancy per layer translates directly into **feature size** and **timing resolution** requirements (targeting ~1%)

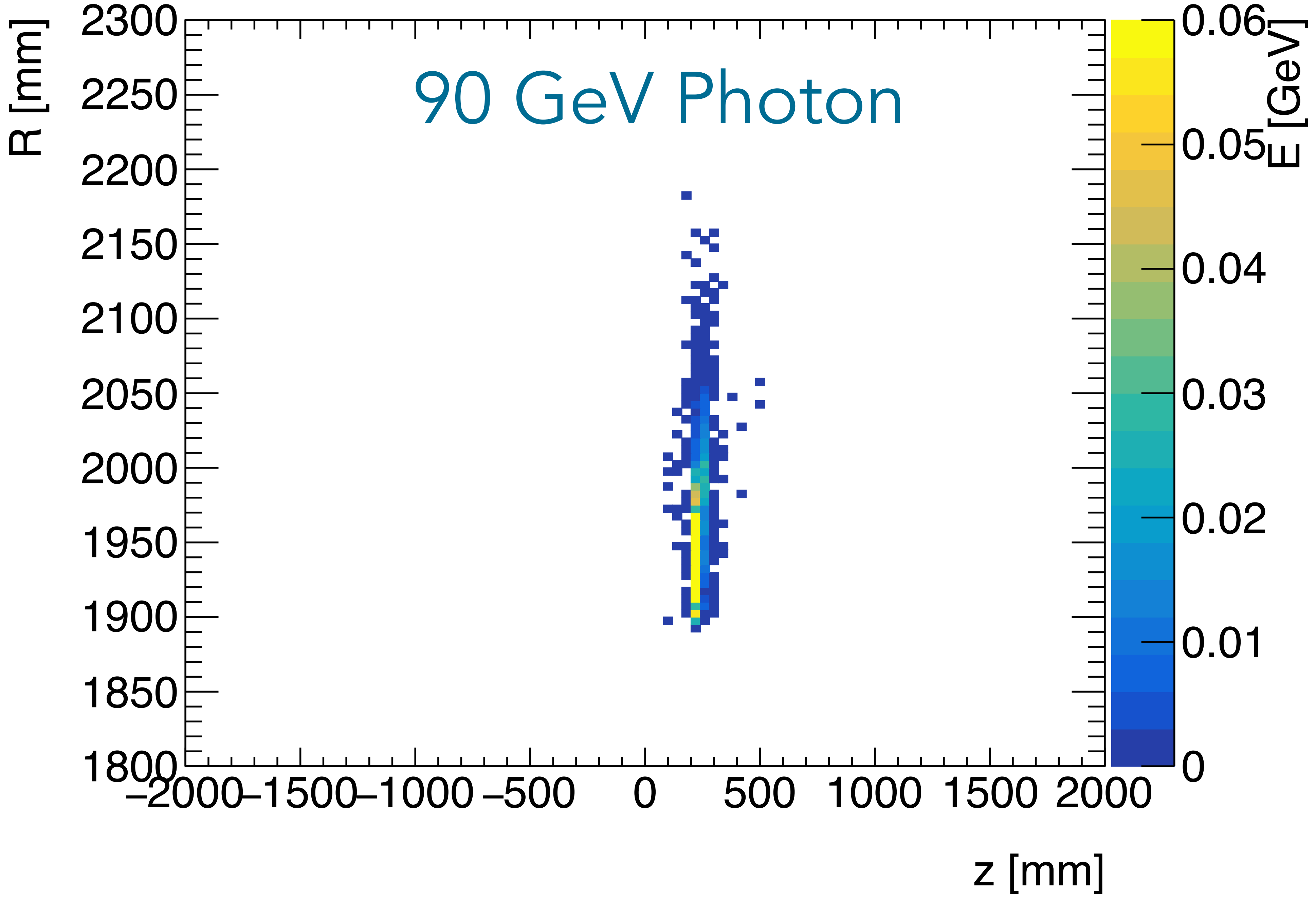
(could play with feature size vs. timing emphasis)

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

Detector Performance Report

IN THE EM CALORIMETER...



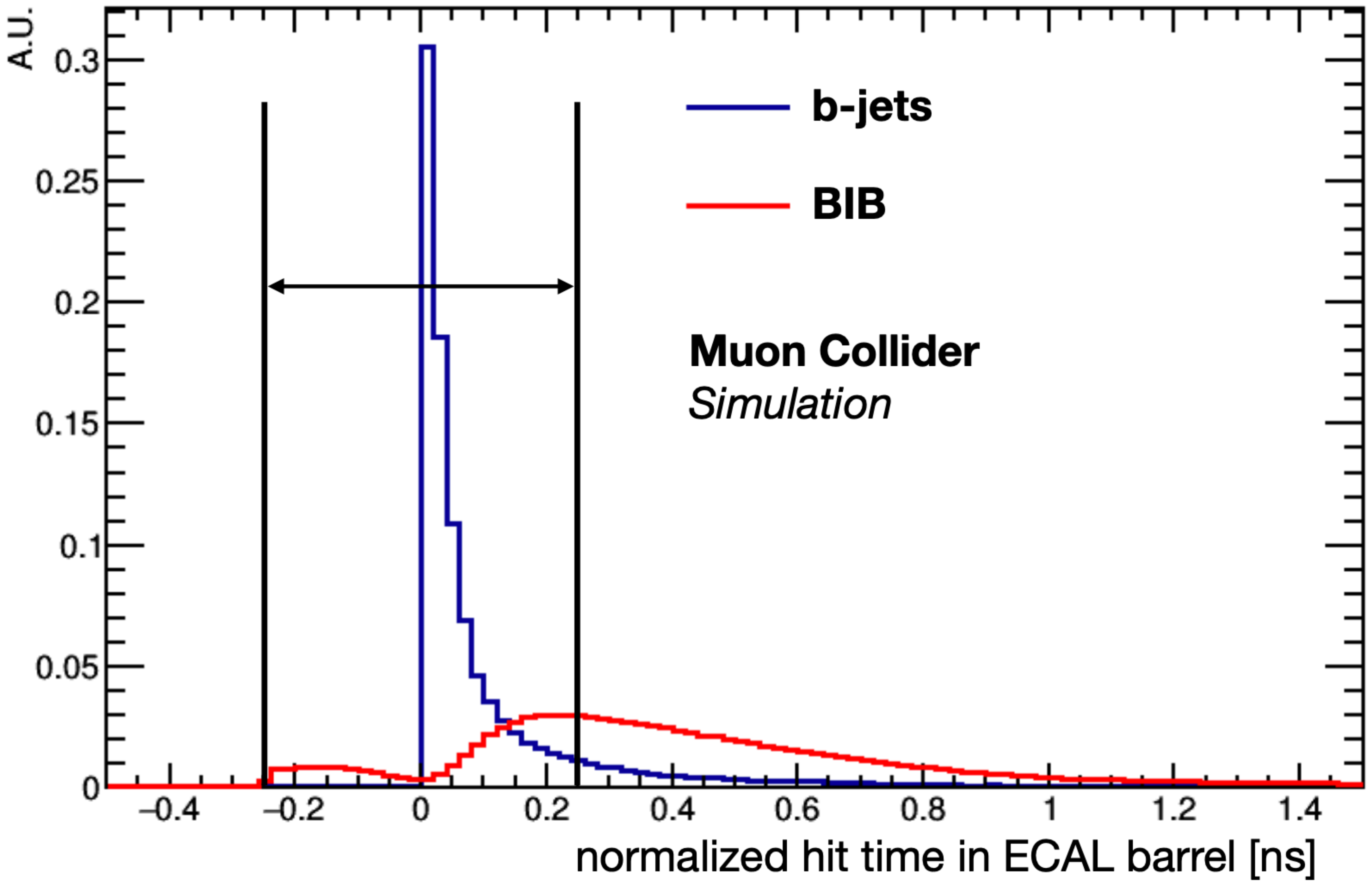


BIB is extremely diffuse, reduced drastically by the end of the ECAL

High-energy signals easy to pick out from BIB

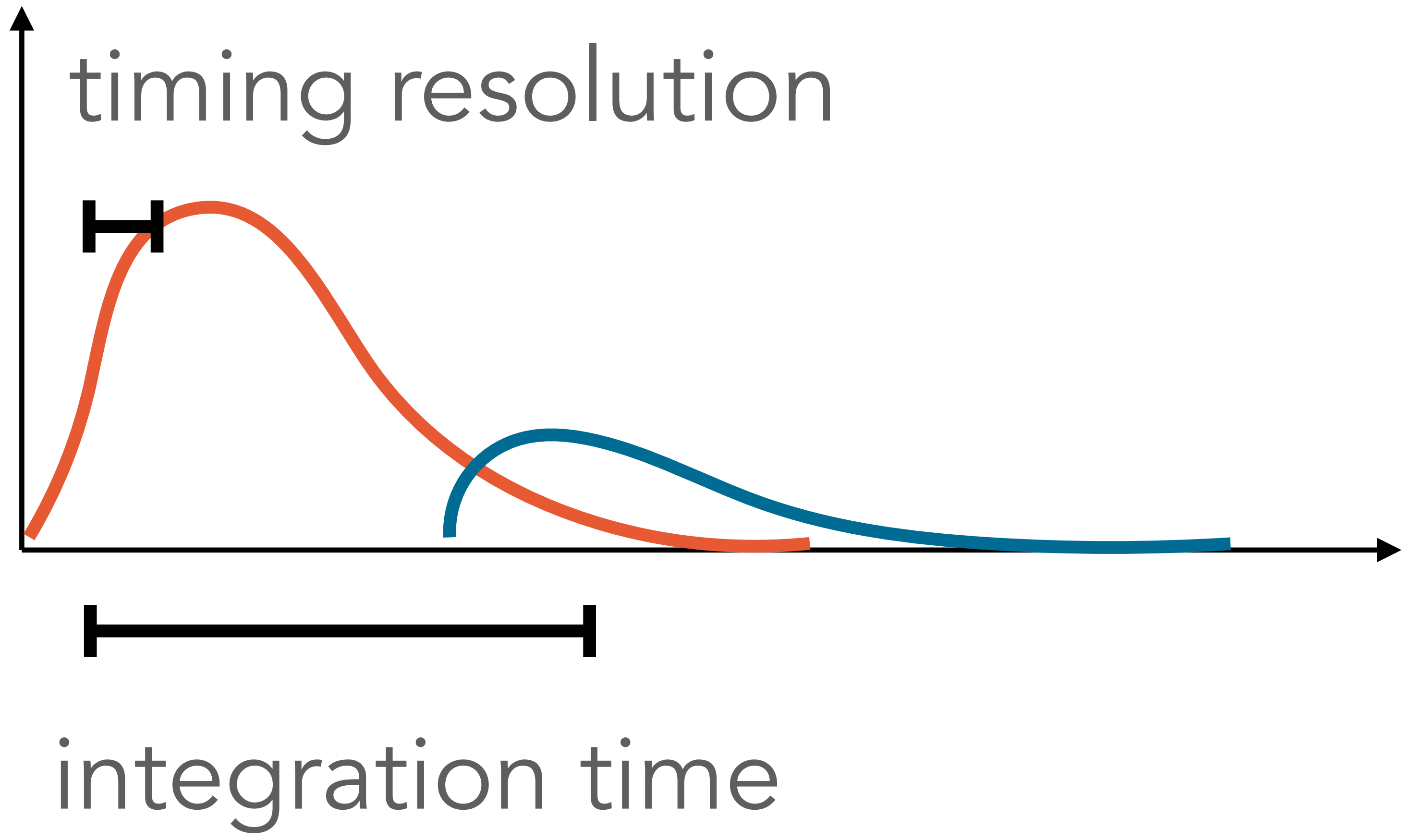
(both made in a phi slice of 0.1, -1 to 10 ns)

IN THE EM CALORIMETER...



Baseline ECAL is W+Si, 5x5 mm cell size but also investigating crystal calorimetry (CRILIN)

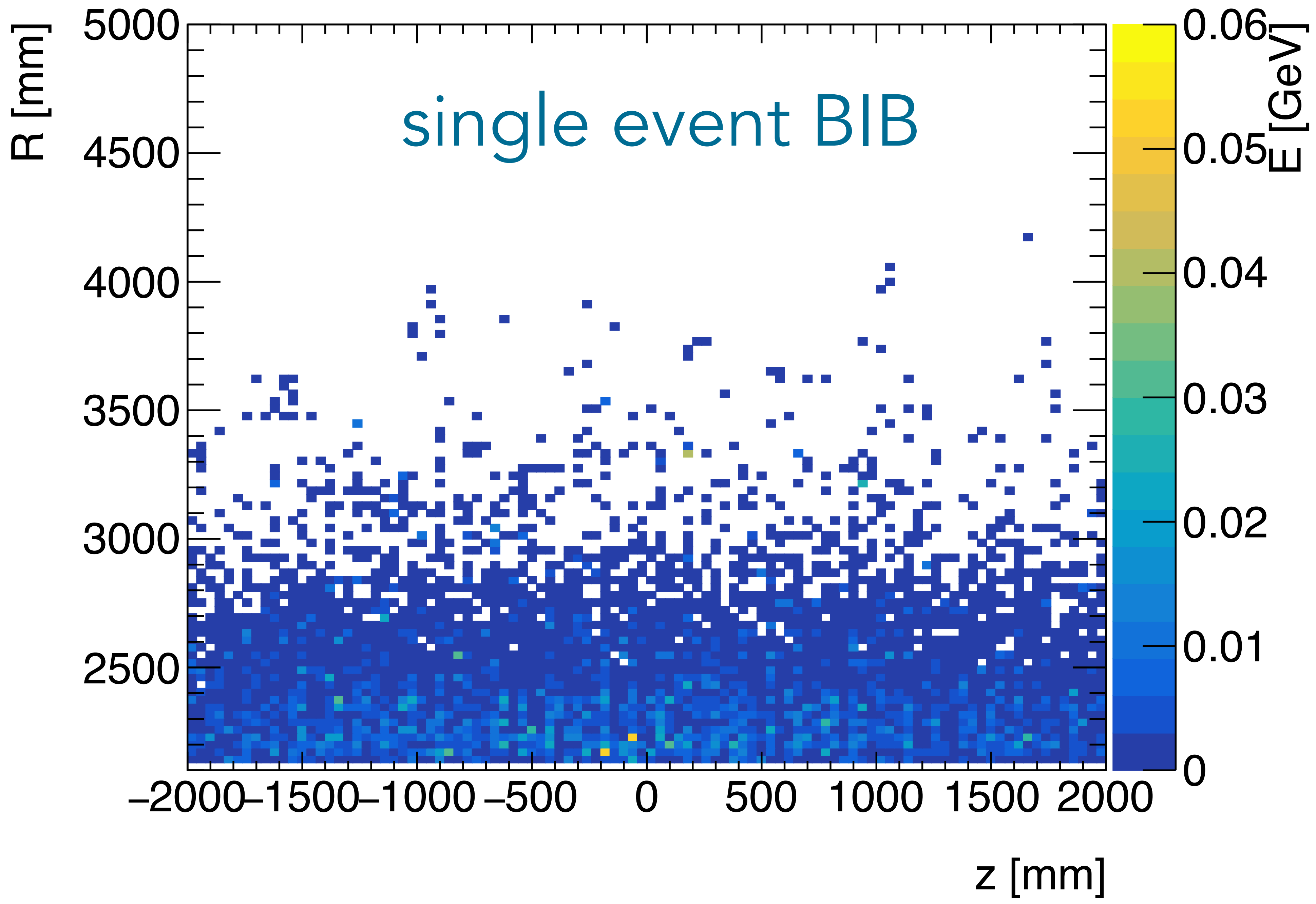
sub-ns timing resolution can further reduce BIB contamination

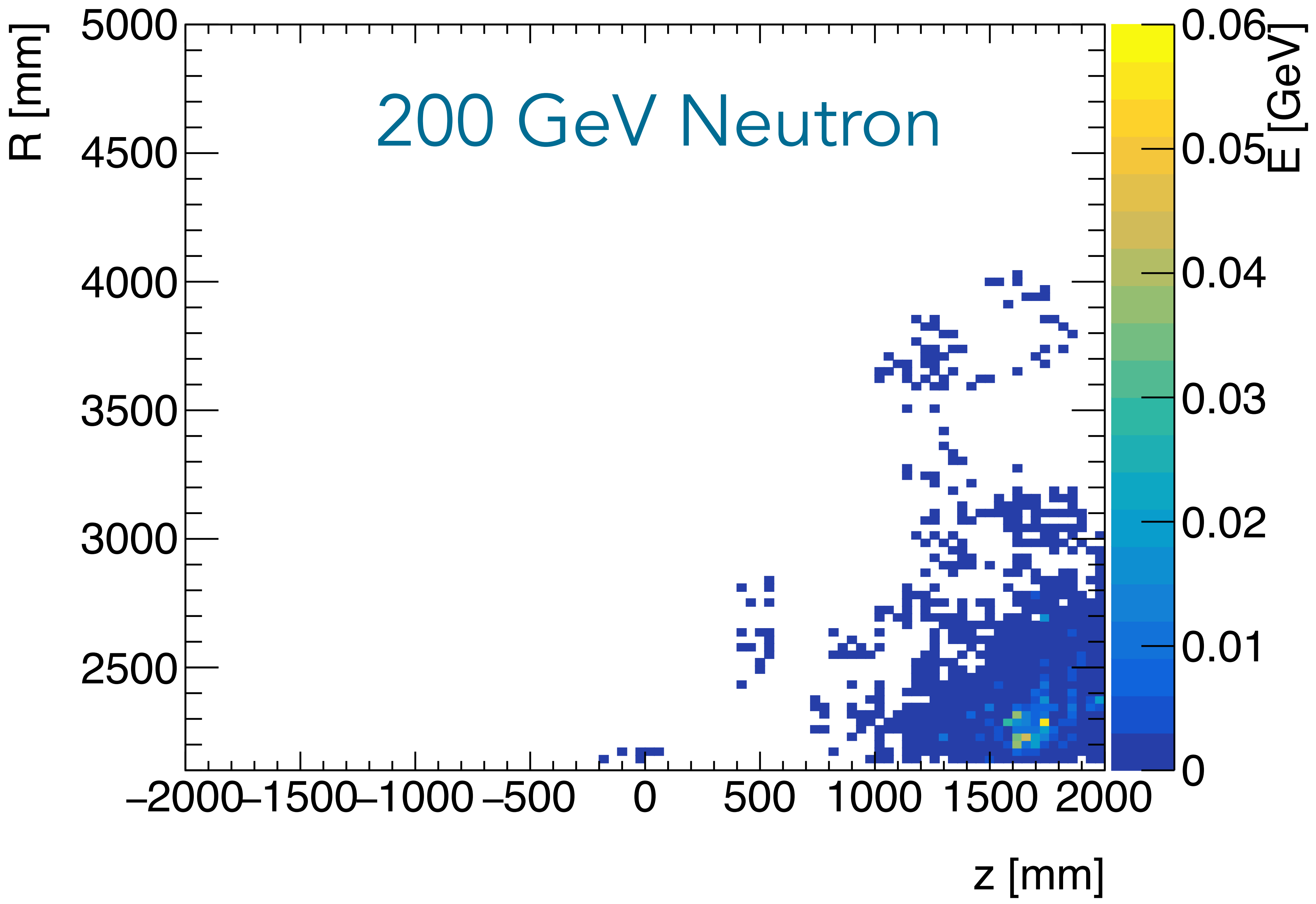


integration time equally important

[Detector Performance Report, S. Ceravolo et al.](#)

IN THE HADRONIC CALORIMETER…





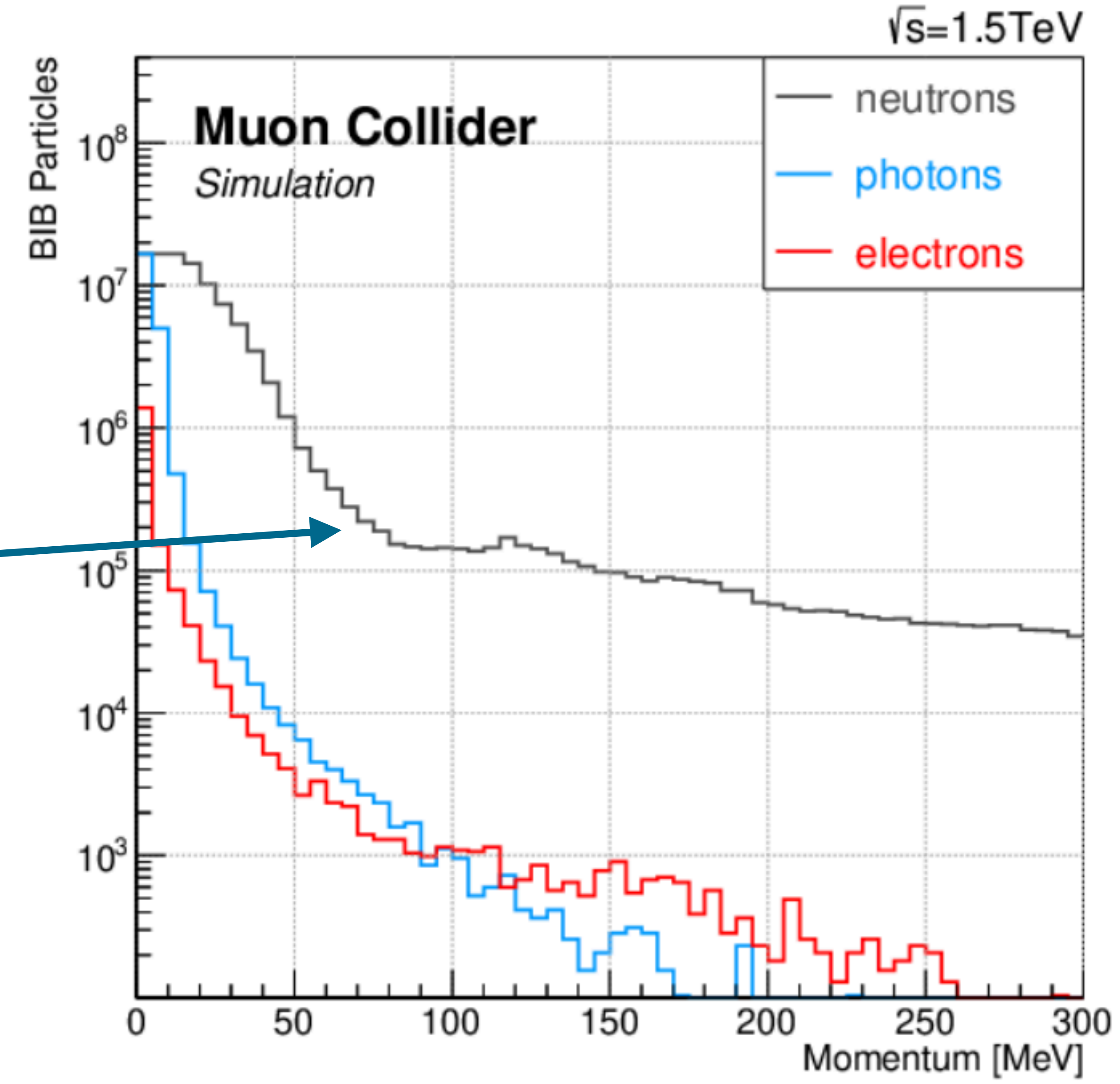
BIB reduced by ECAL, still very diffuse, mostly neutrons remain

Signal still distinct, but stands out less over backgrounds

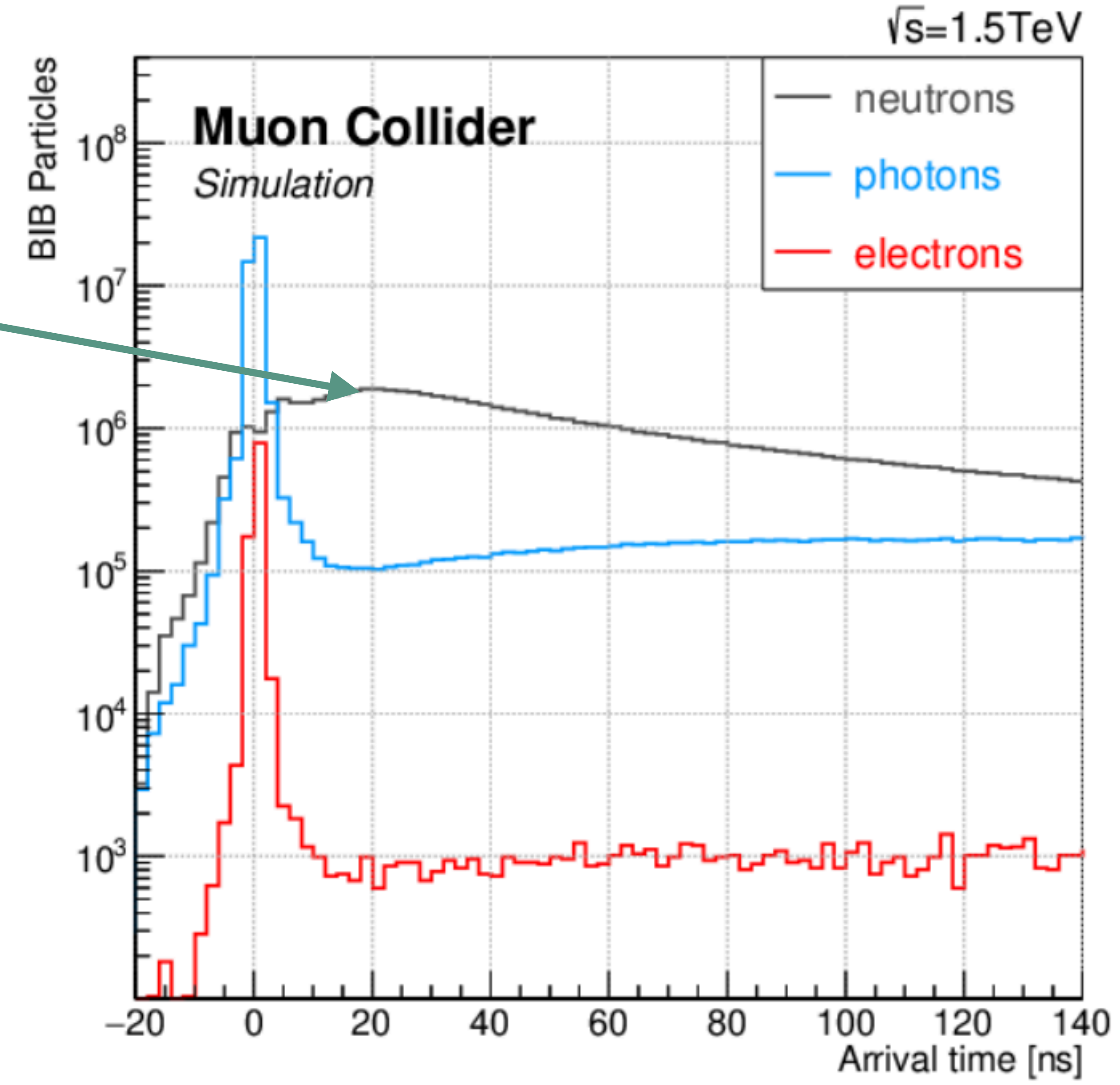
(both made in a phi slice of 0.4, -1 to 10 ns)

In the hadronic calorimeter...

Not surprising:
there are many high-energy neutrons in BIB



These high-energy neutrons are extremely out-of-time — even ns precision can help a lot here



Baseline is 30x30 mm^2 scintillating tiles alternating with steel absorbers

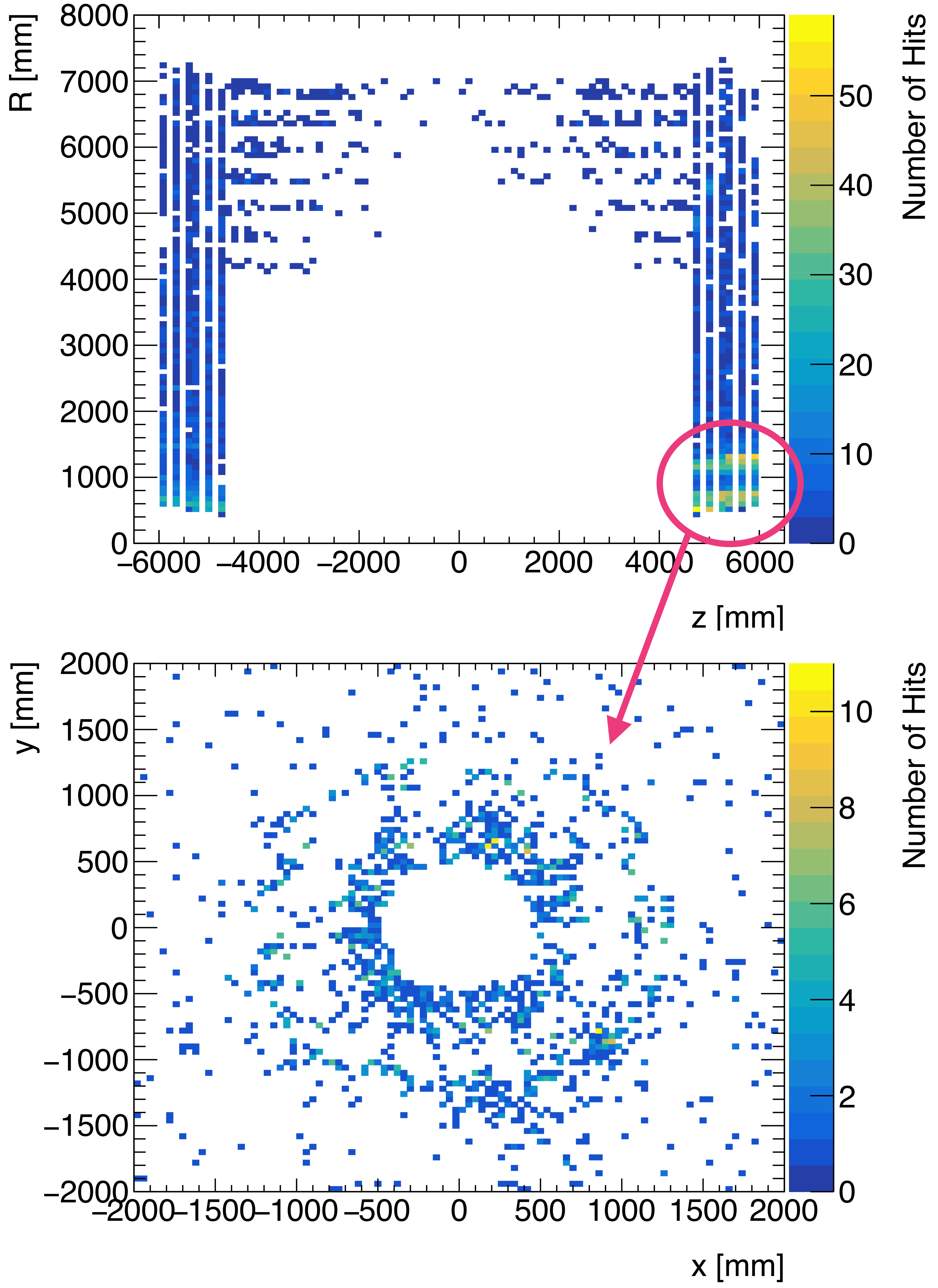
Detector Performance Report

IN THE FORWARD REGION…

very little BIB makes it through the calorimeter
so most of the muon system is straightforward

backgrounds are concentrated in the forward region, near the beam — will need to handle high rate

also impacts forward luminosity monitoring
(BIB not correlated with luminosity)



READING OUT THE DETECTOR...

much slower event rate than what we're accustomed to

$$t = 33\ \mu s \times \left(\frac{L}{10\ \mathrm{km}}\right)$$

plenty of time to process a given event

but reading out all BIB hits requires increased cabling, cooling

pushes the challenge from trigger to on-detector processing

estimates at 3 TeV

	Readout	E Threshold	Hit Size	Total Rate
Tracker	1 ns	n/a	32 bits	~30 Tb/s
ECAL	15 ns	0.2 MeV	20 bits	~30 Tb/s
HCAL	15 ns	0.2 MeV	20 bits	~3 Tb/s
Total				60 Tb/s

60 Tb/s → same as the CMS HL-LHC max HLT input rate

CMS DAQ and HLT TDR Technology and R&D for a Muon Collider Detector

READING OUT THE DETECTOR…

plausible that we could run without triggers… if we reduce enough on detector

estimates at 3 TeV

	Readout	E Threshold	Hit Size	Total Rate
Tracker	1 ns	n/a	32 bits	~30 Tb/s
ECAL	15 ns	0.2 MeV	20 bits	~30 Tb/s
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Total				60 Tb/s

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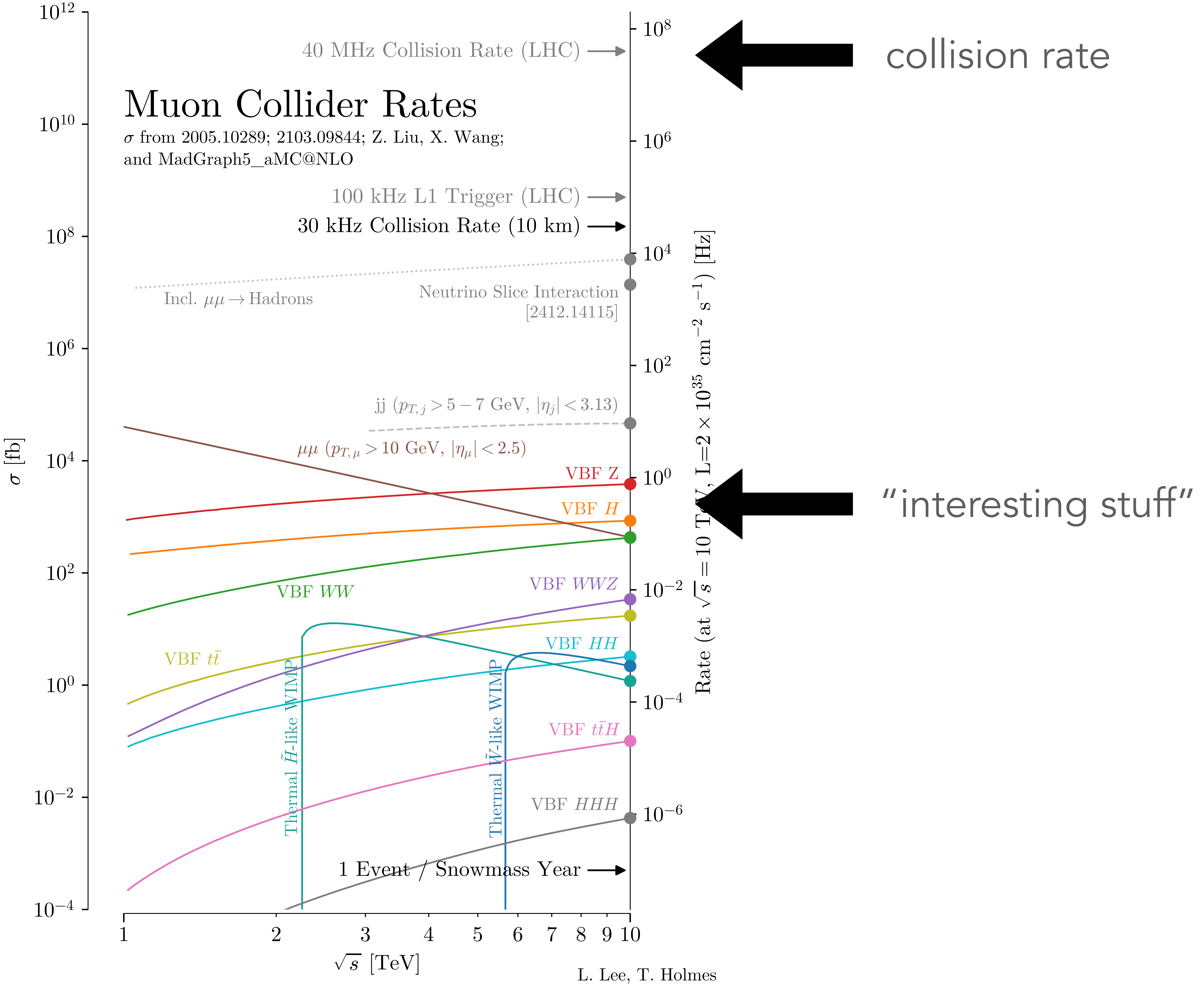
CMS DAQ and HLT TDR Technology and R&D for a Muon Collider Detector

BUT SHOULD WE?

most events are
very boring!



BUT SHOULD WE?

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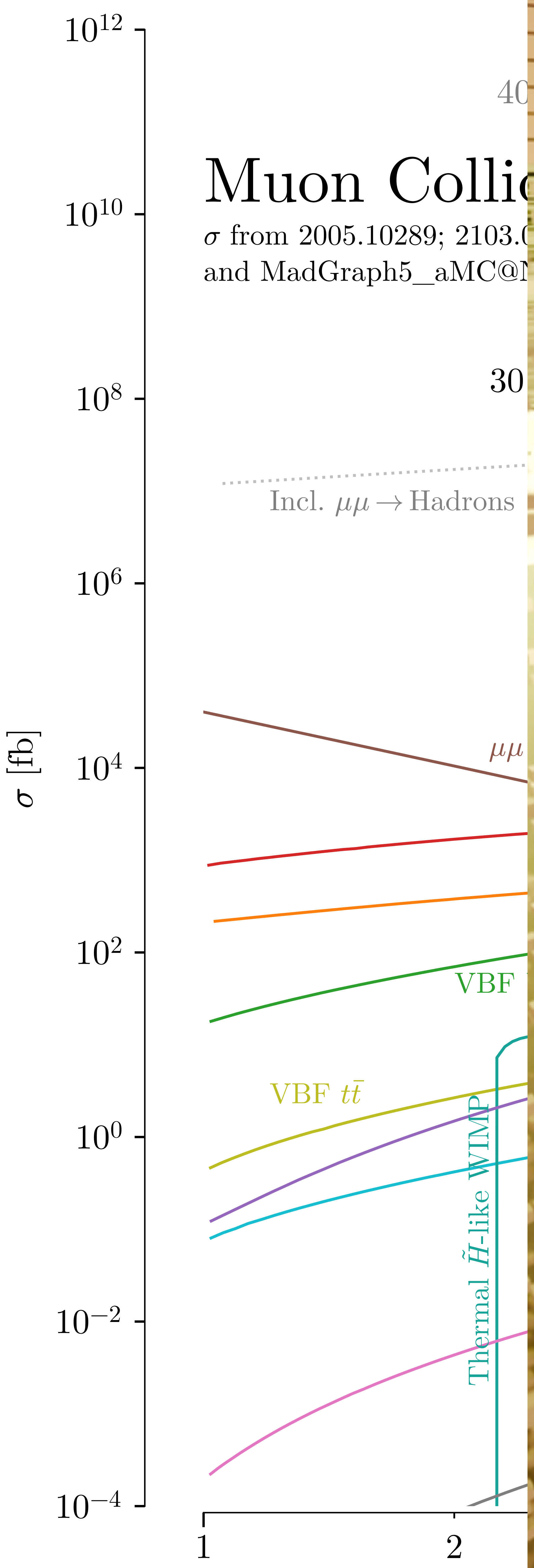
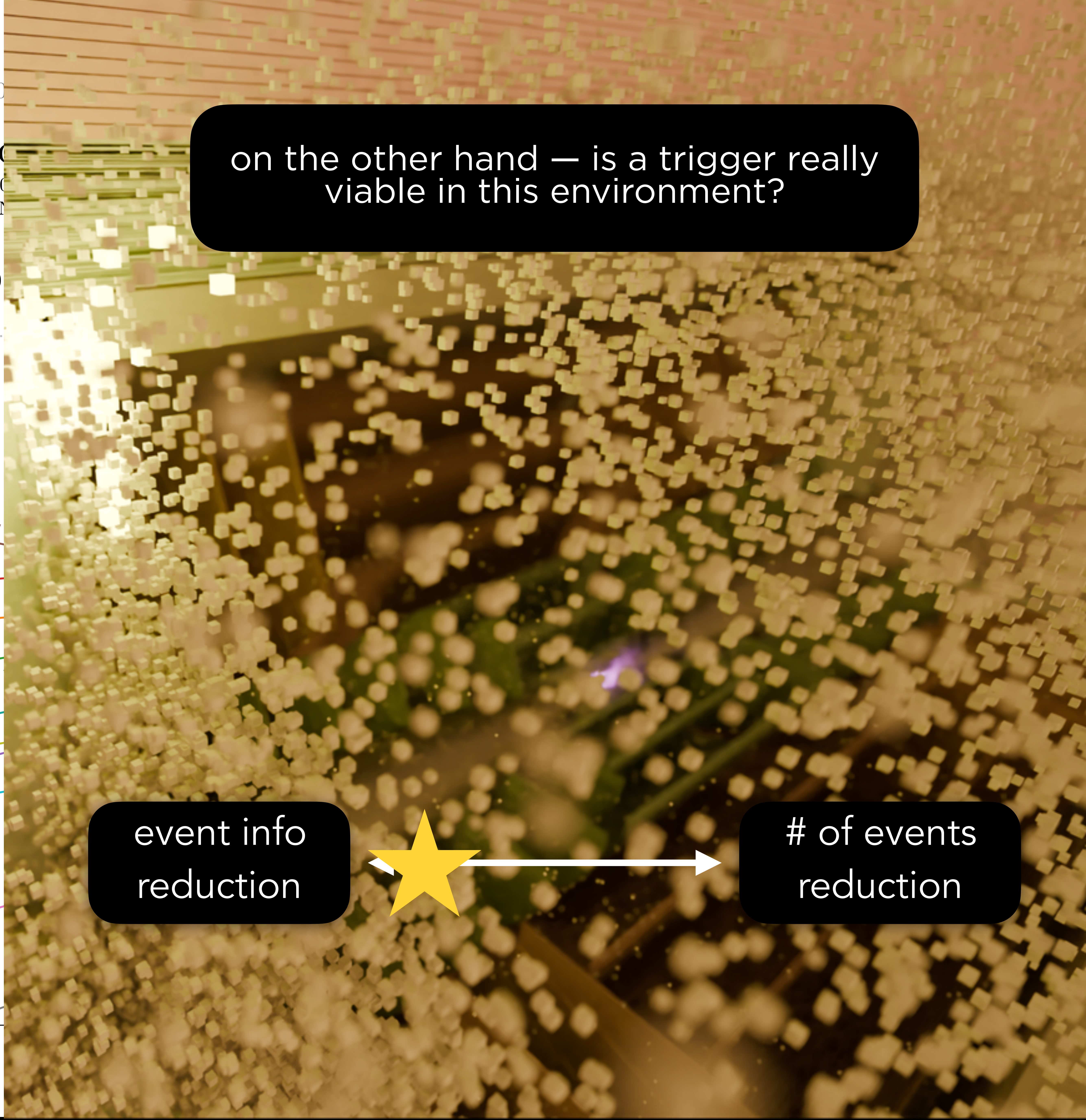




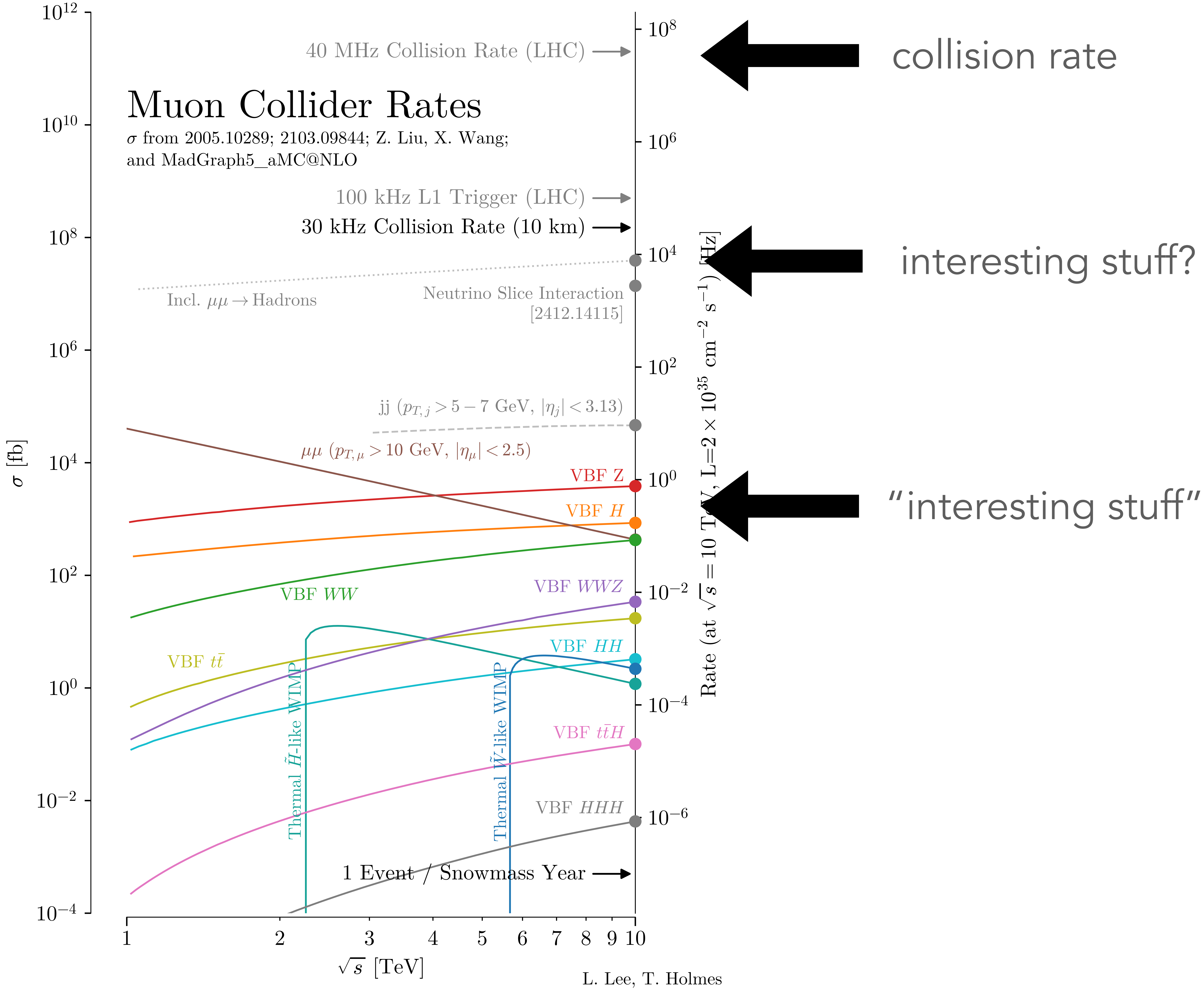
on the other hand — is a trigger really viable in this environment?

event info reduction

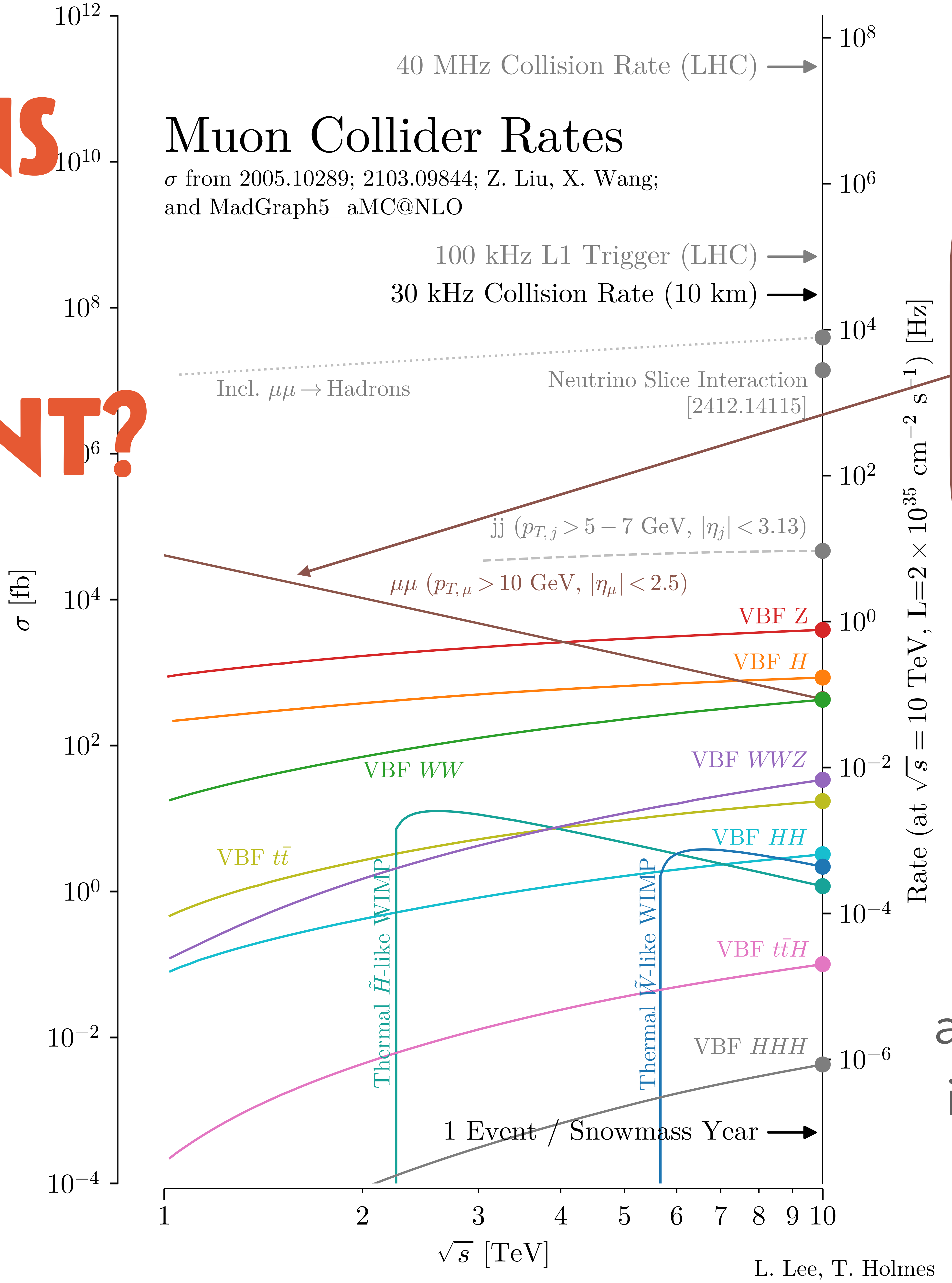
# of events reduction

BUT SHOULD WE?

most events are
very boring!



Implications for Luminosity Measurement?



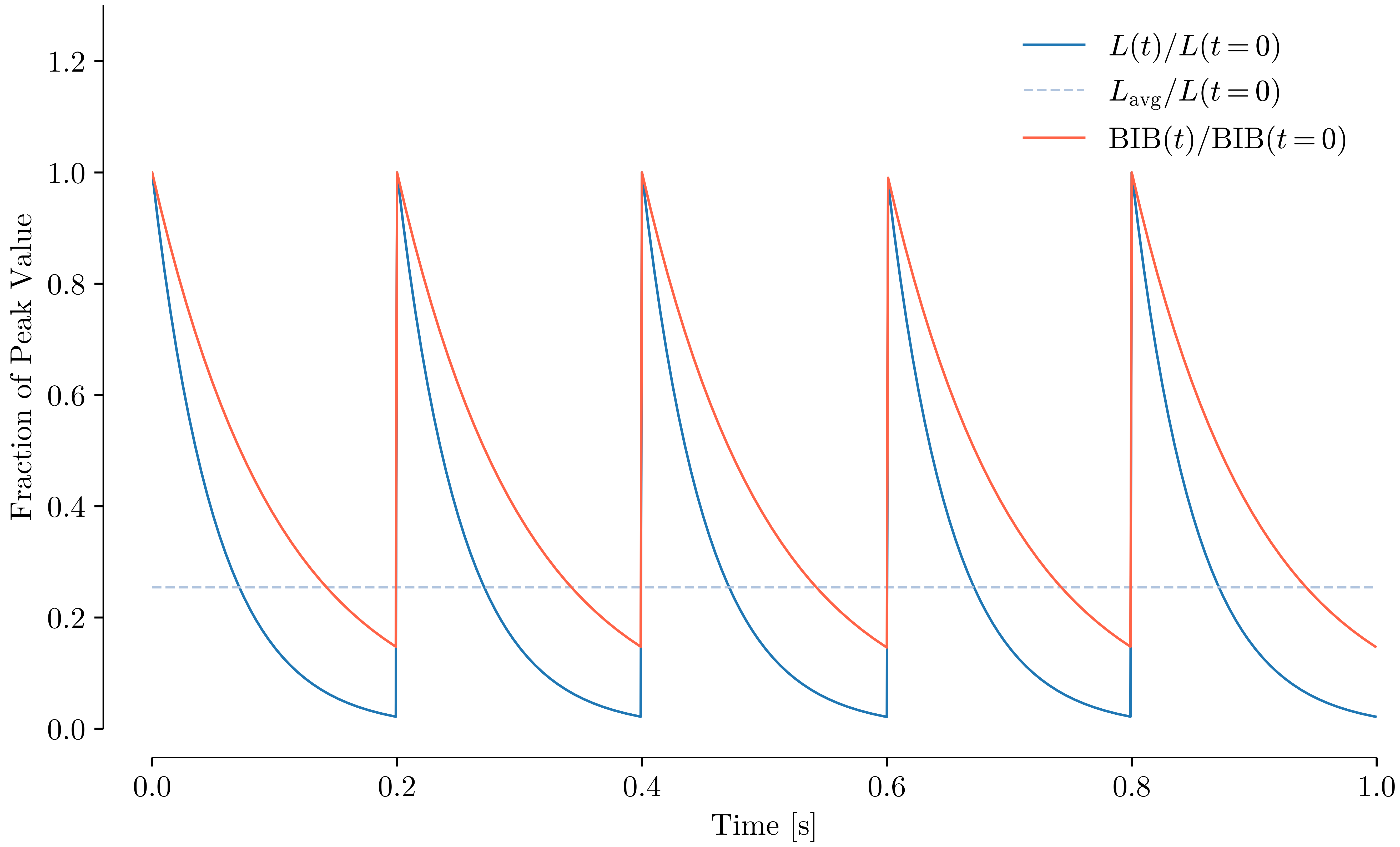
past studies have focused on high-angle μ-Bhabha

estimates at 1.5 TeV predicted 0.2% uncertainty

as energy increases, this process is subdominant to Z production (and H!)

C. Geraldin et al.

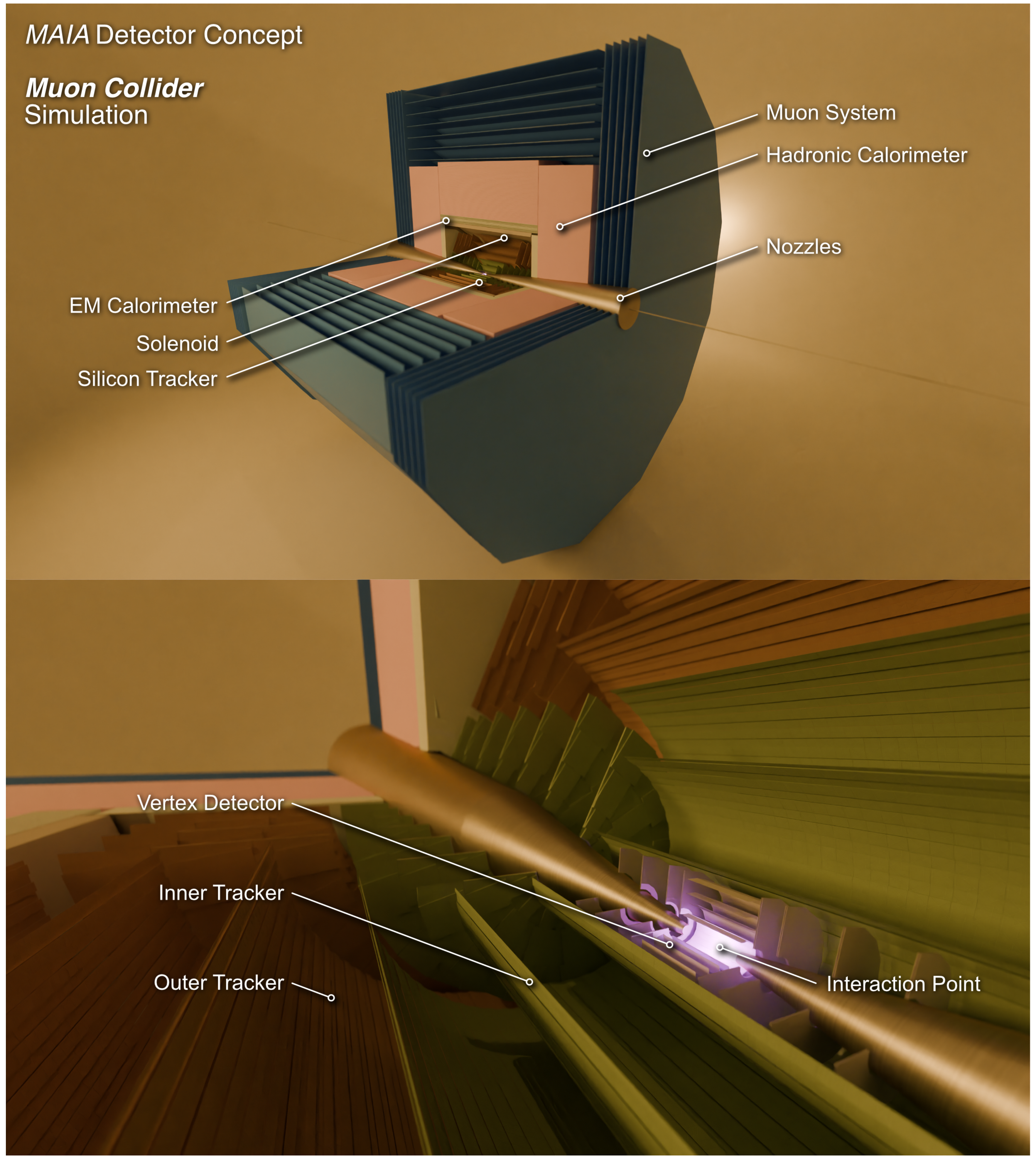
Implications for luminosity measurement?



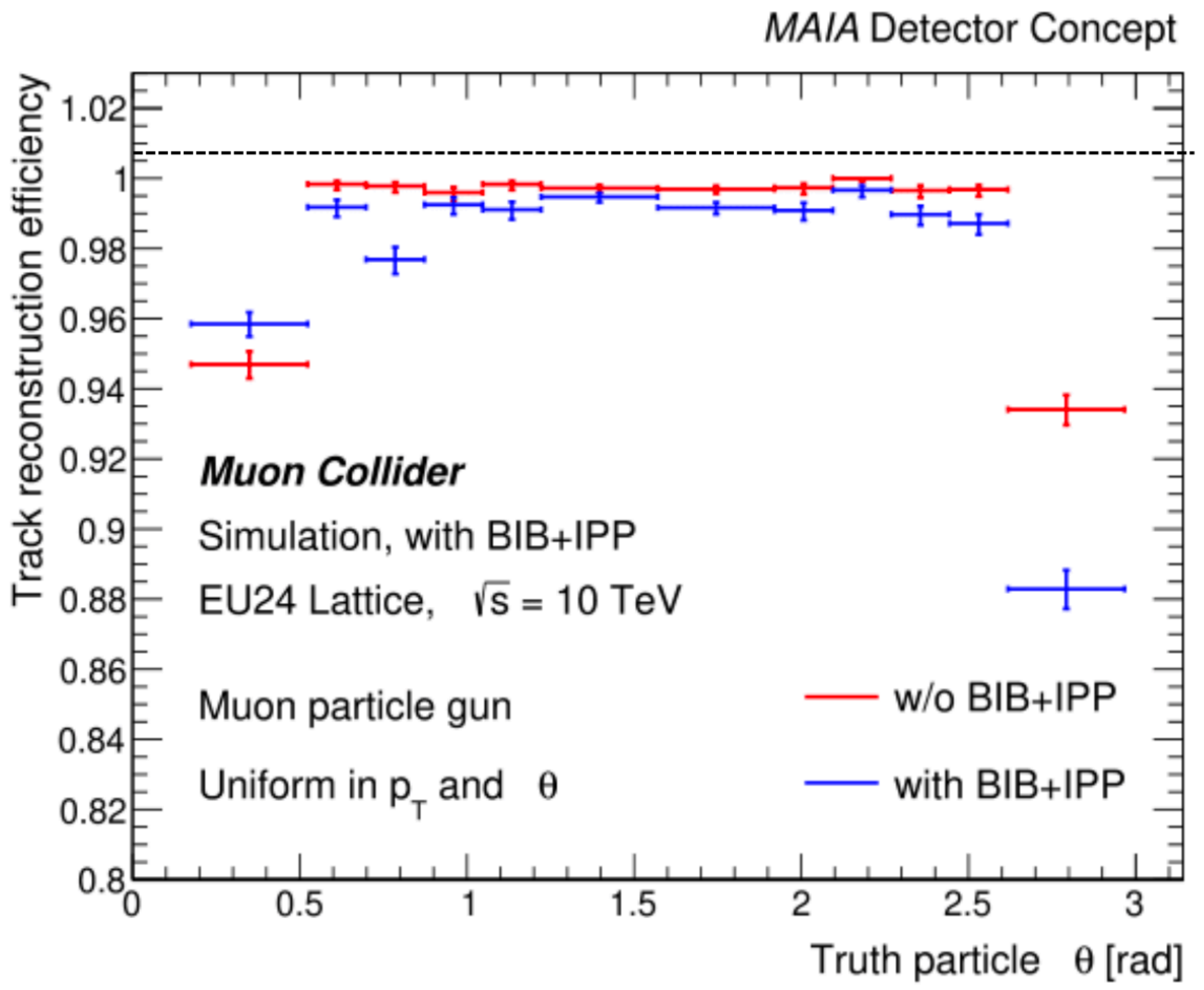
all BIB corrections/subtractions will be highly time dependent and connected to instantaneous luminosity (not dealing with this yet!)

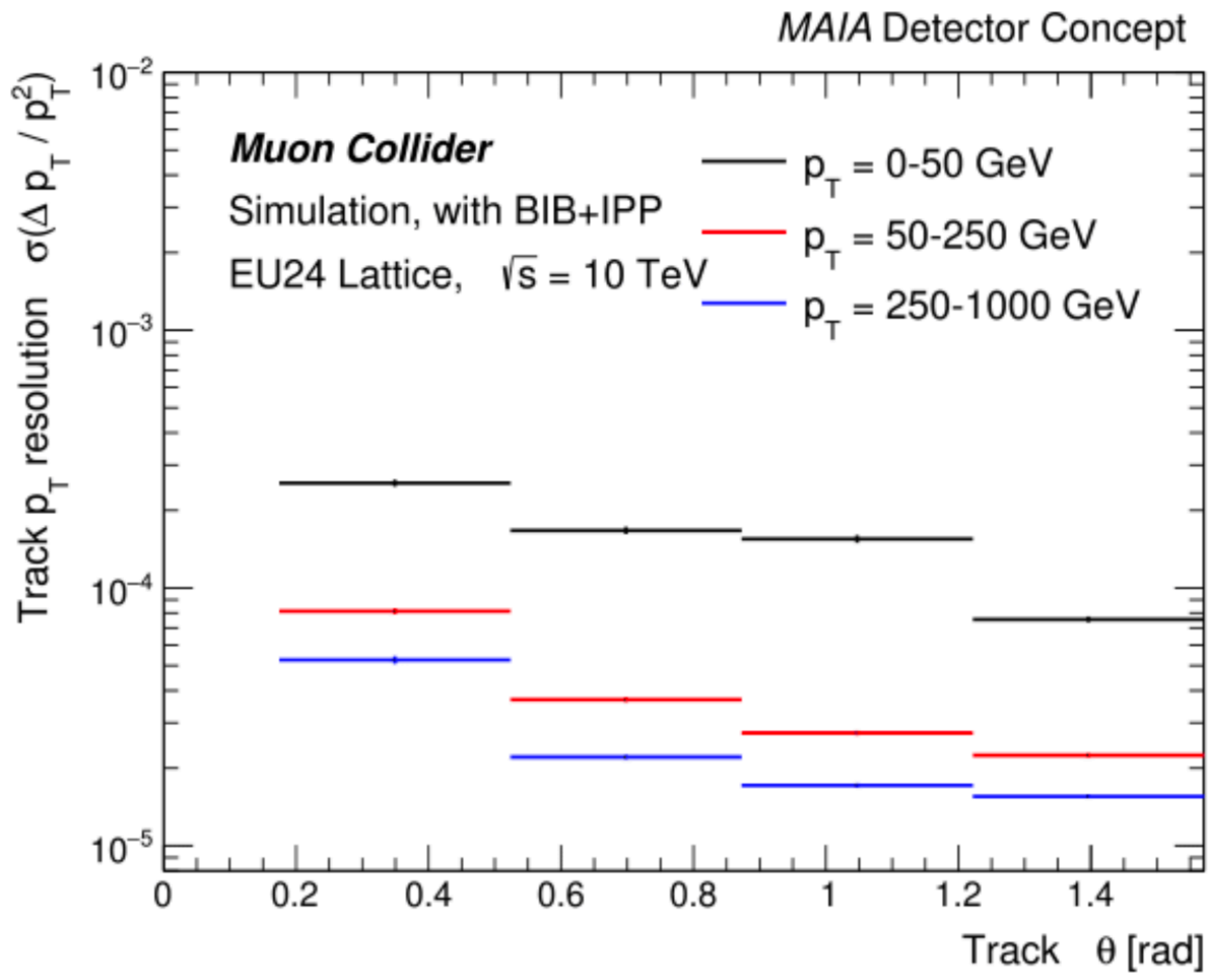
EVOLVING DETECTOR DESIGN

EVOLVING DETECTOR DESIGN



good tracking results using ACTS
(but could use work in end-caps)

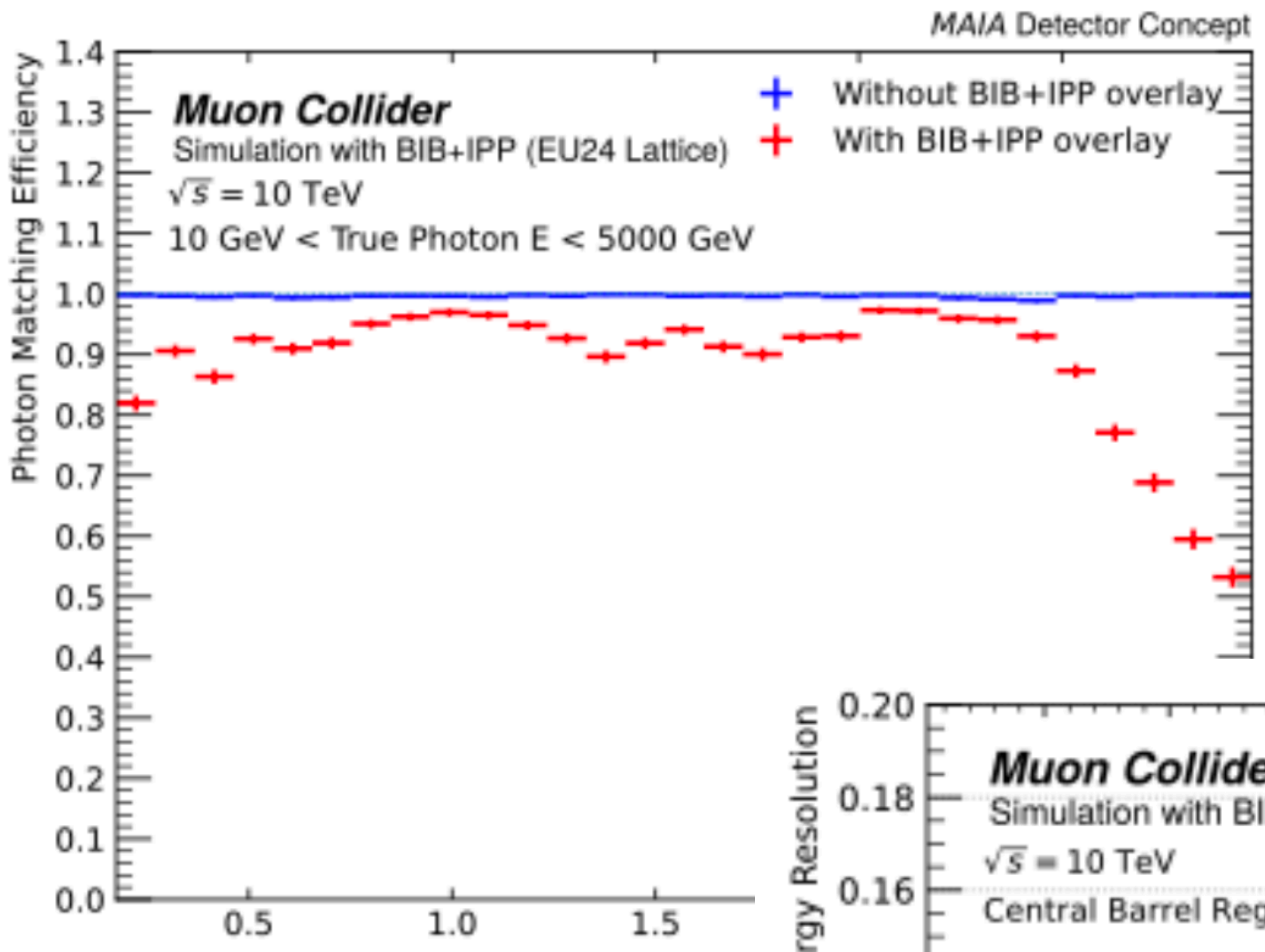




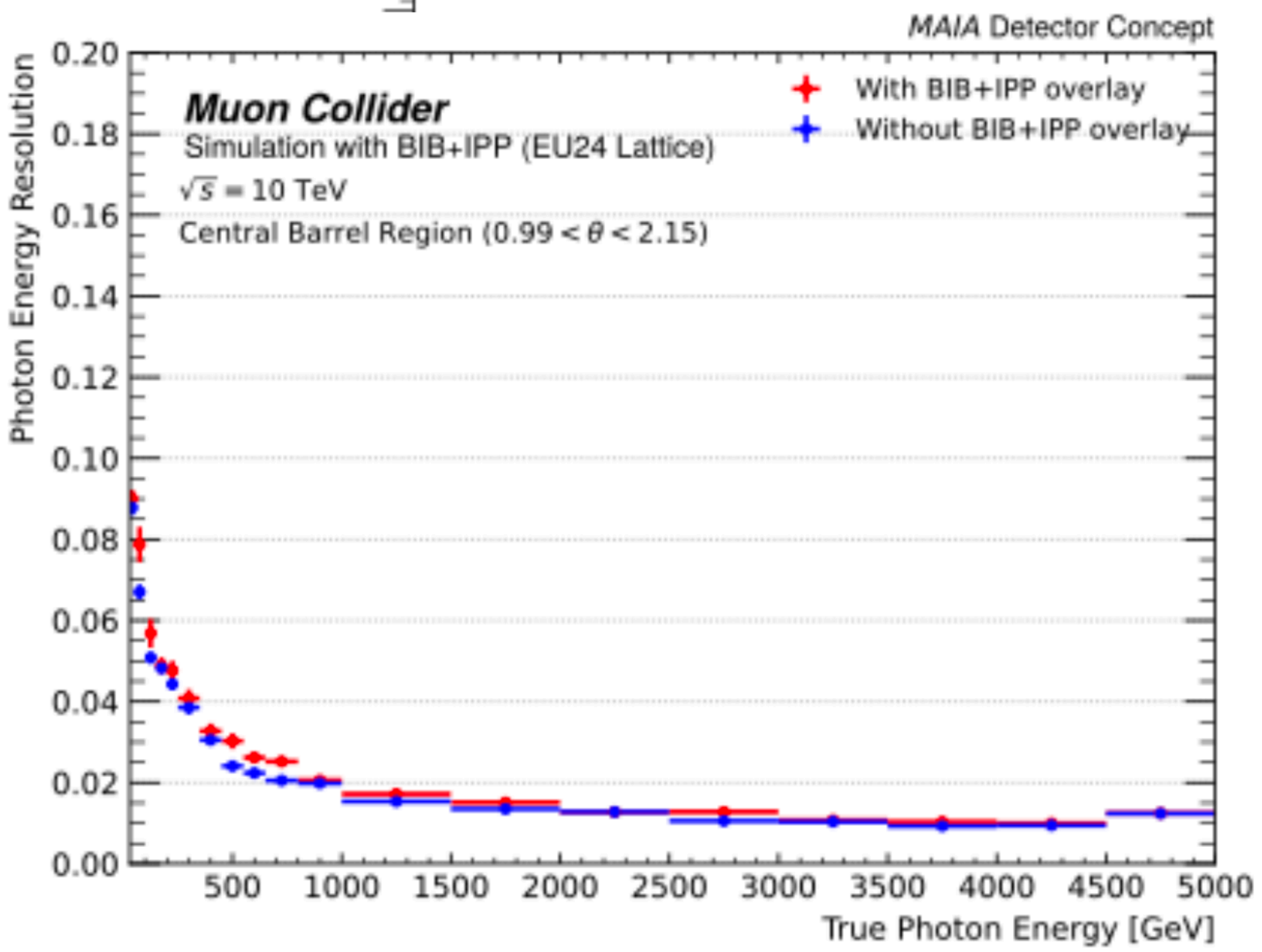
MAIA Detector

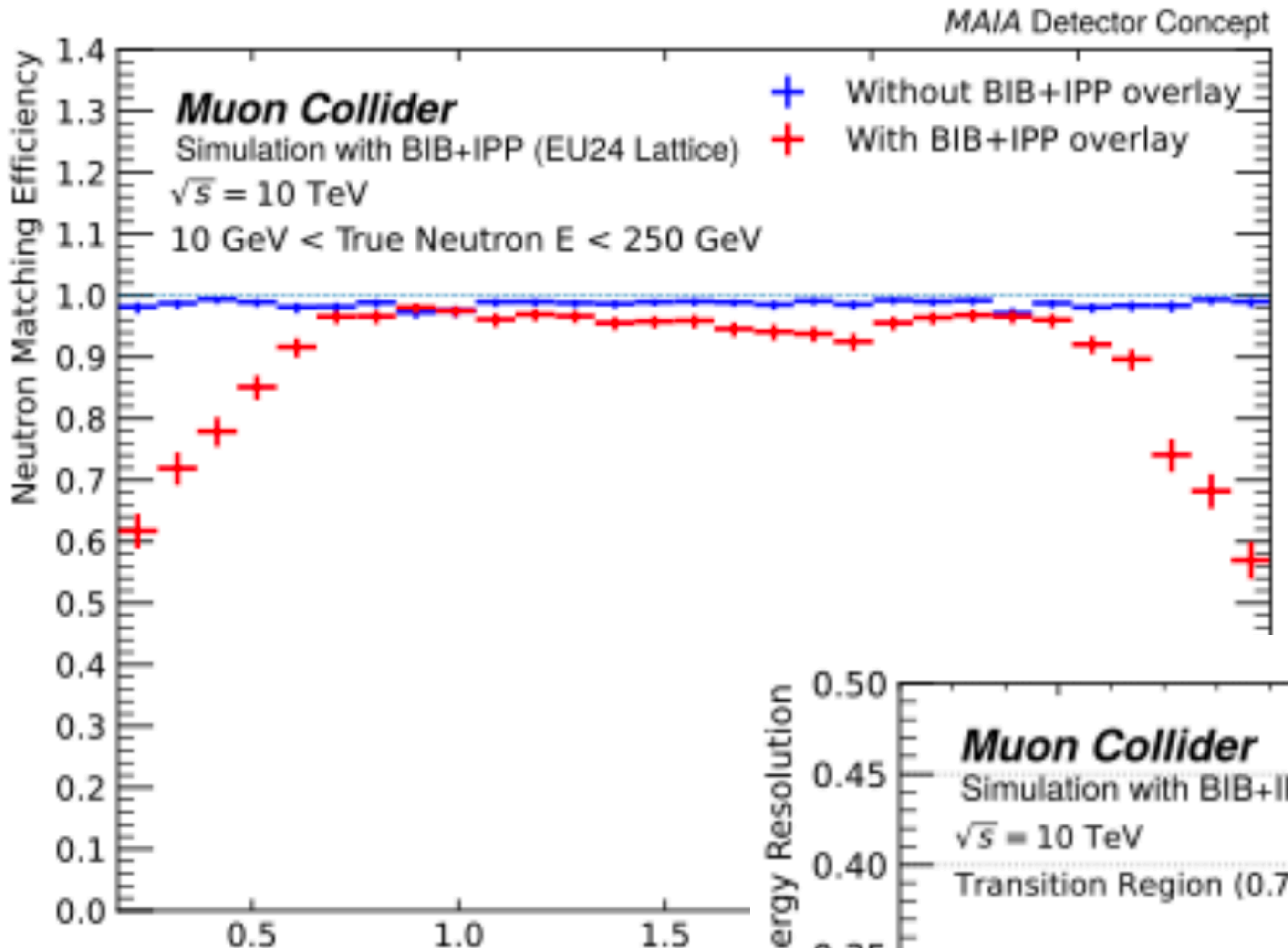
EVOLVING DETECTOR DESIGN

calorimetry results looking promising — but plenty of small mysteries remain

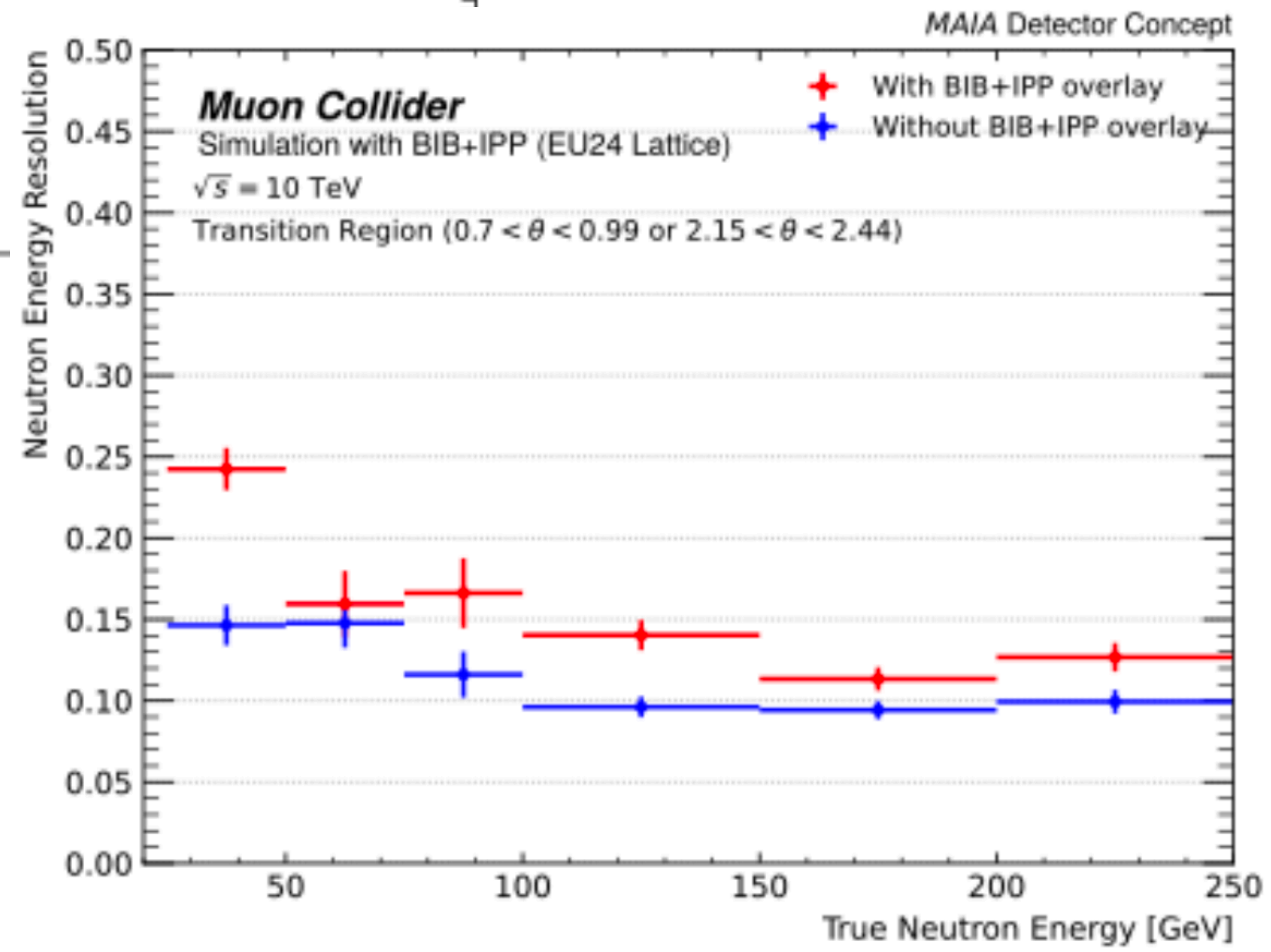


photons





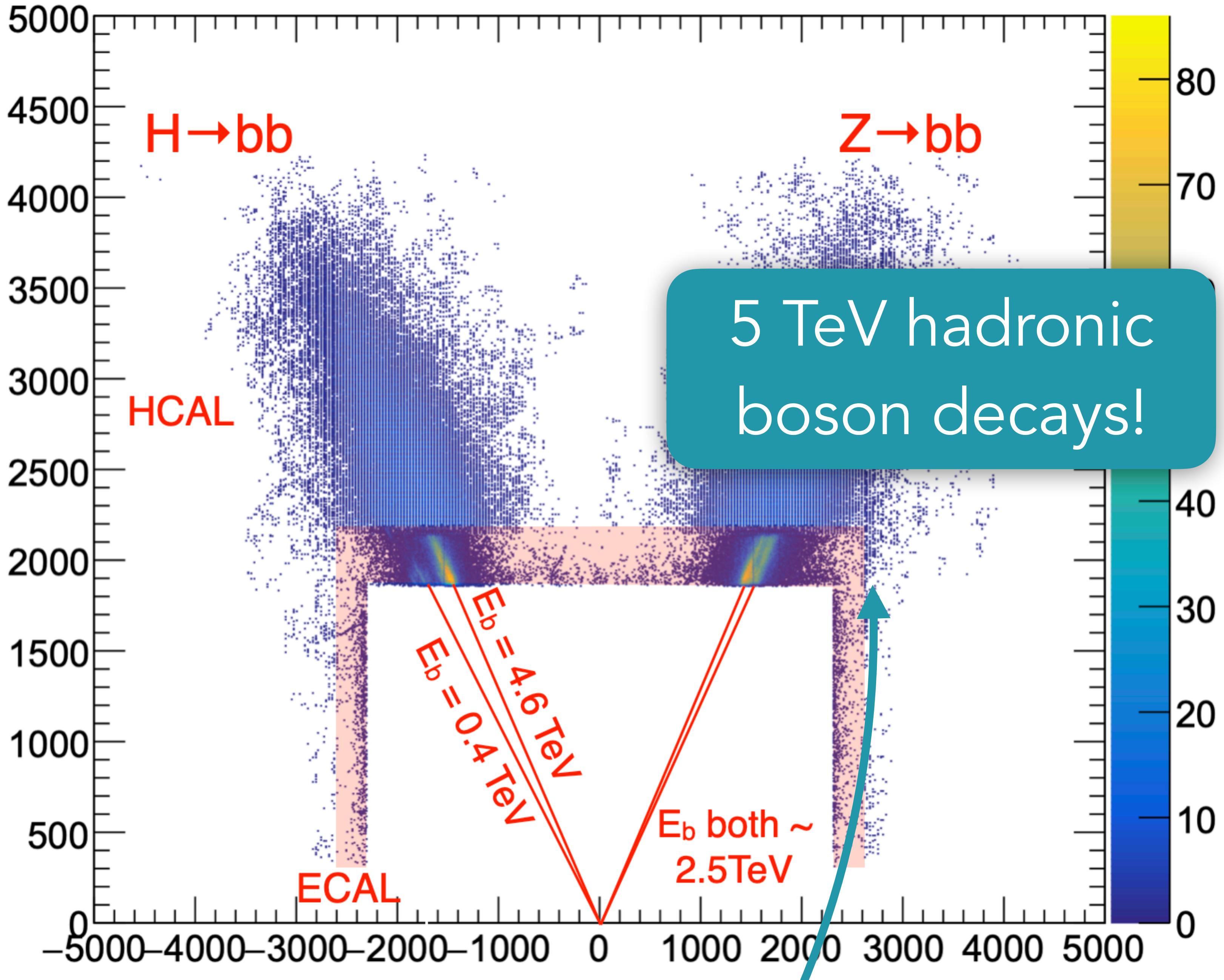
neutrons



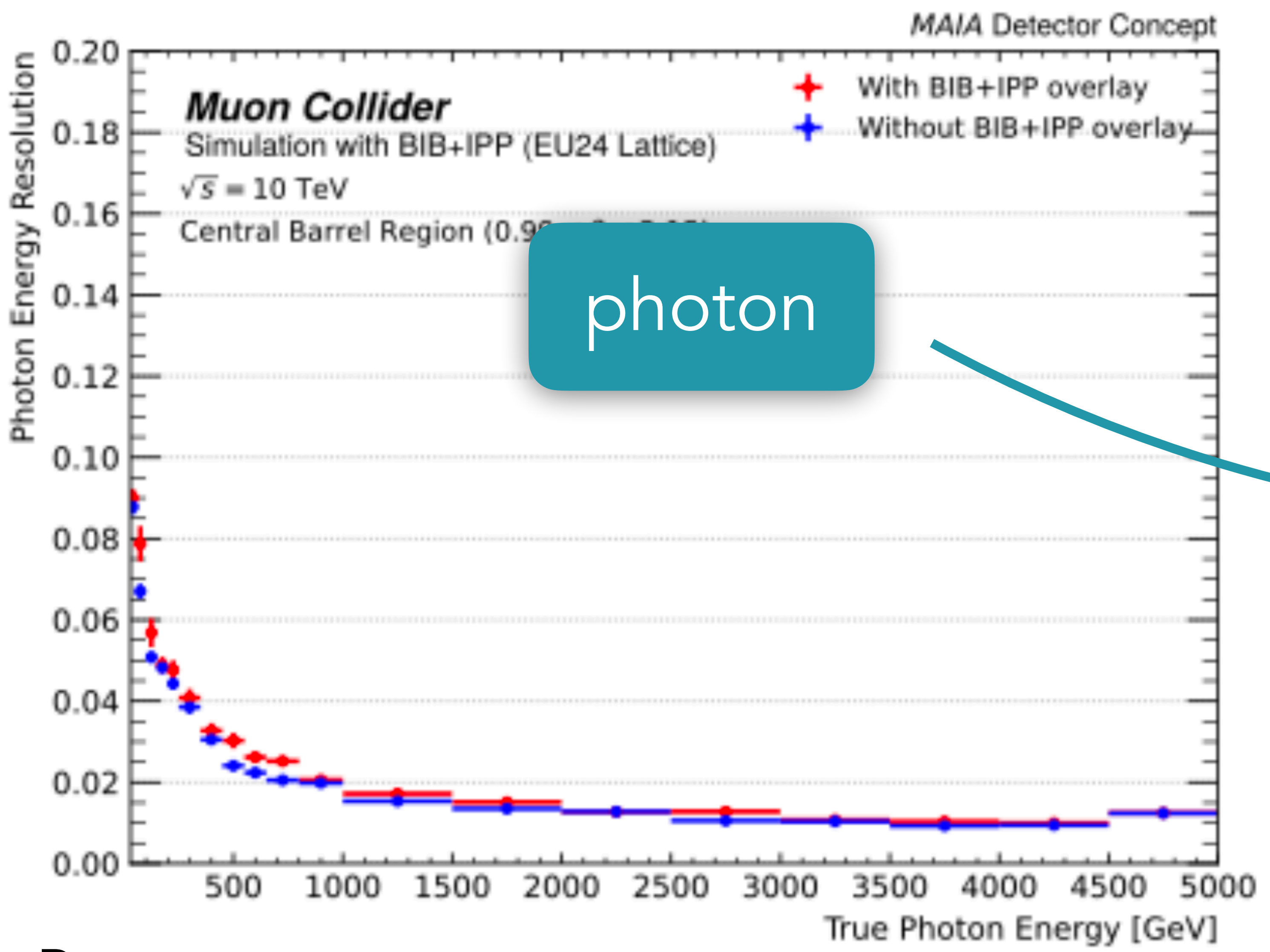
Rose Powers

EVOLVING DETECTOR DESIGN

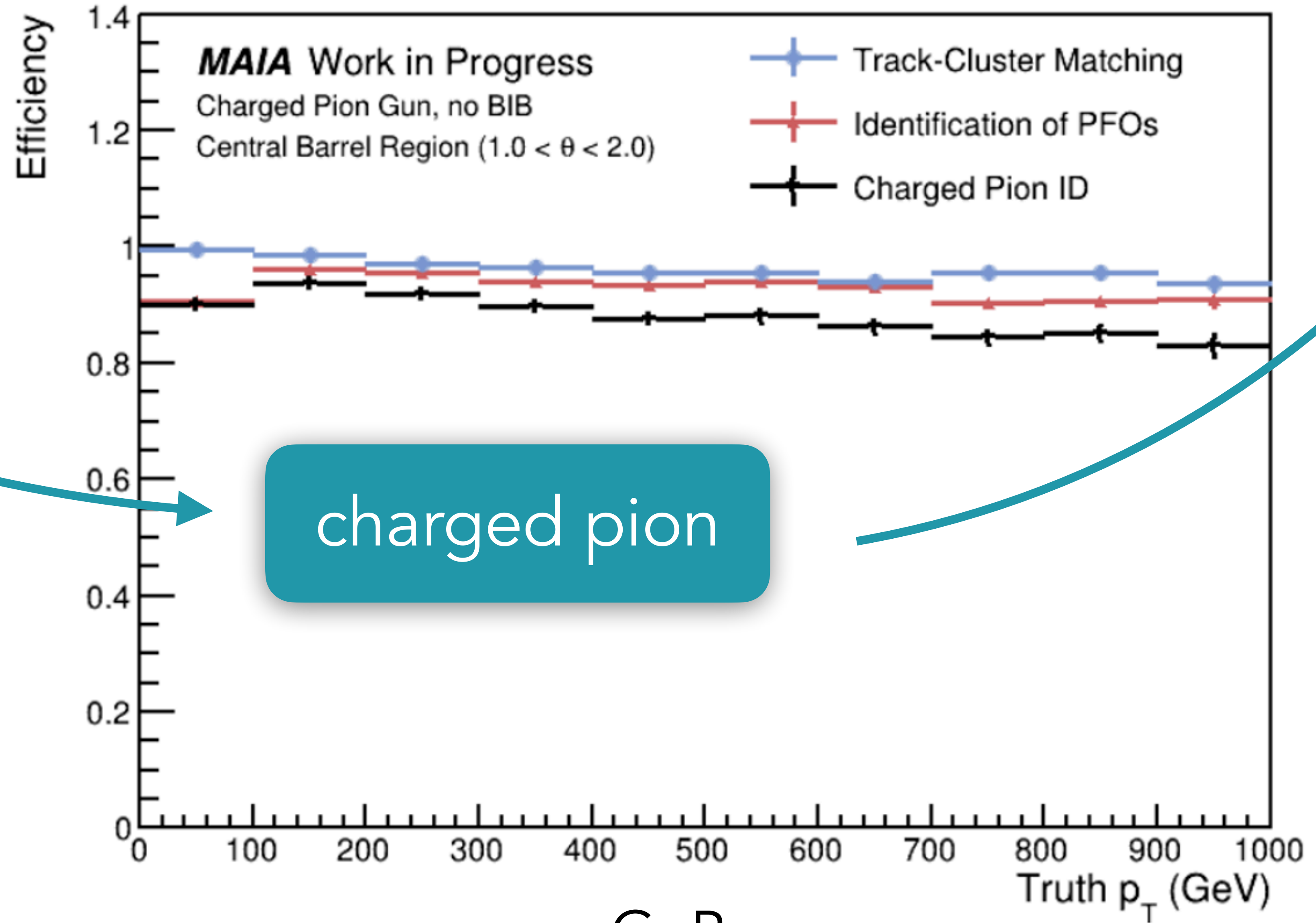
moving from simple to complex object ID and quantifying performance



P. Chang



R. Powers



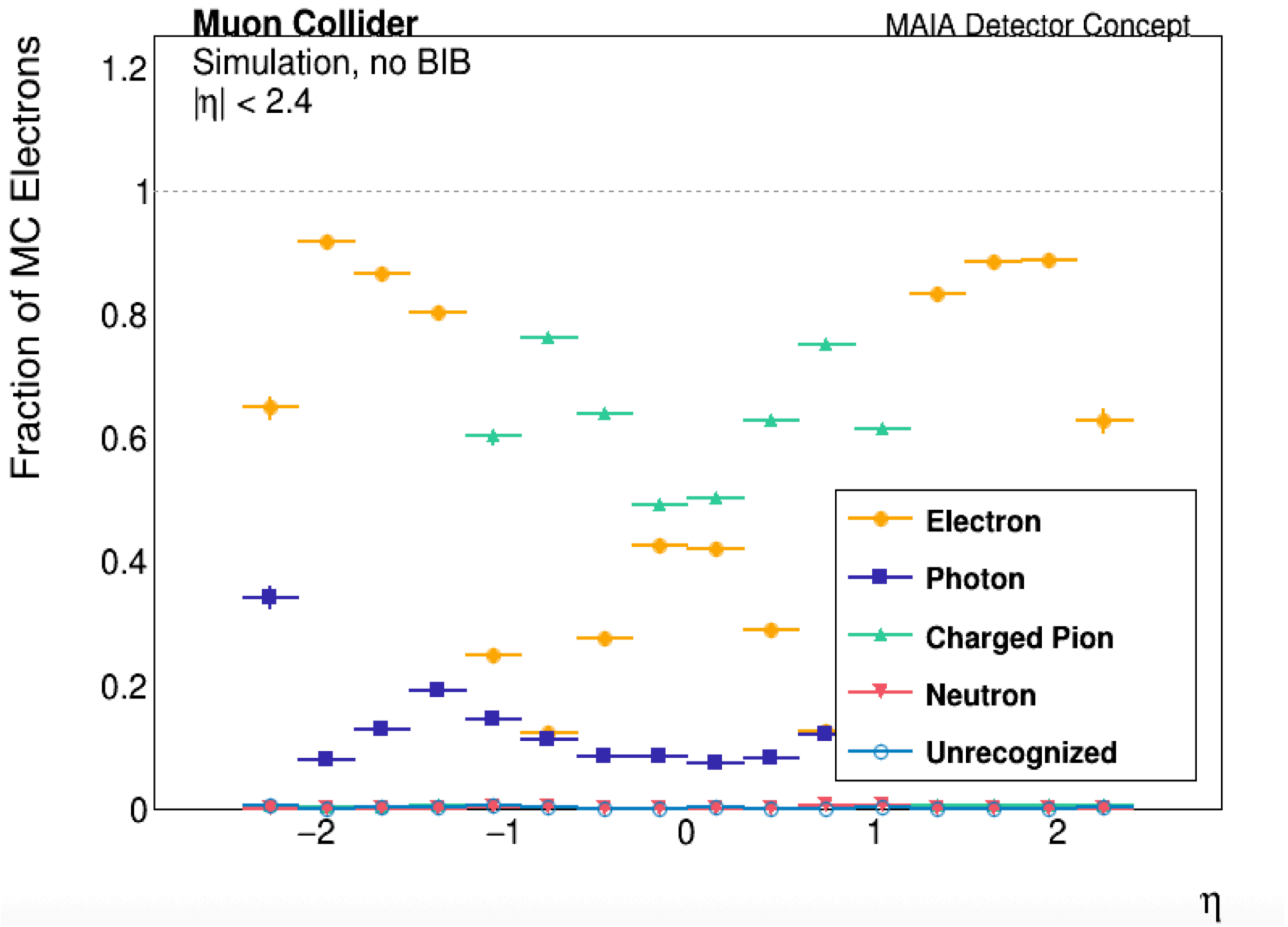
G. Penn

EVOLVING DETECTOR DESIGN

still LOTS of low-hanging fruit

especially for
"compound objects"

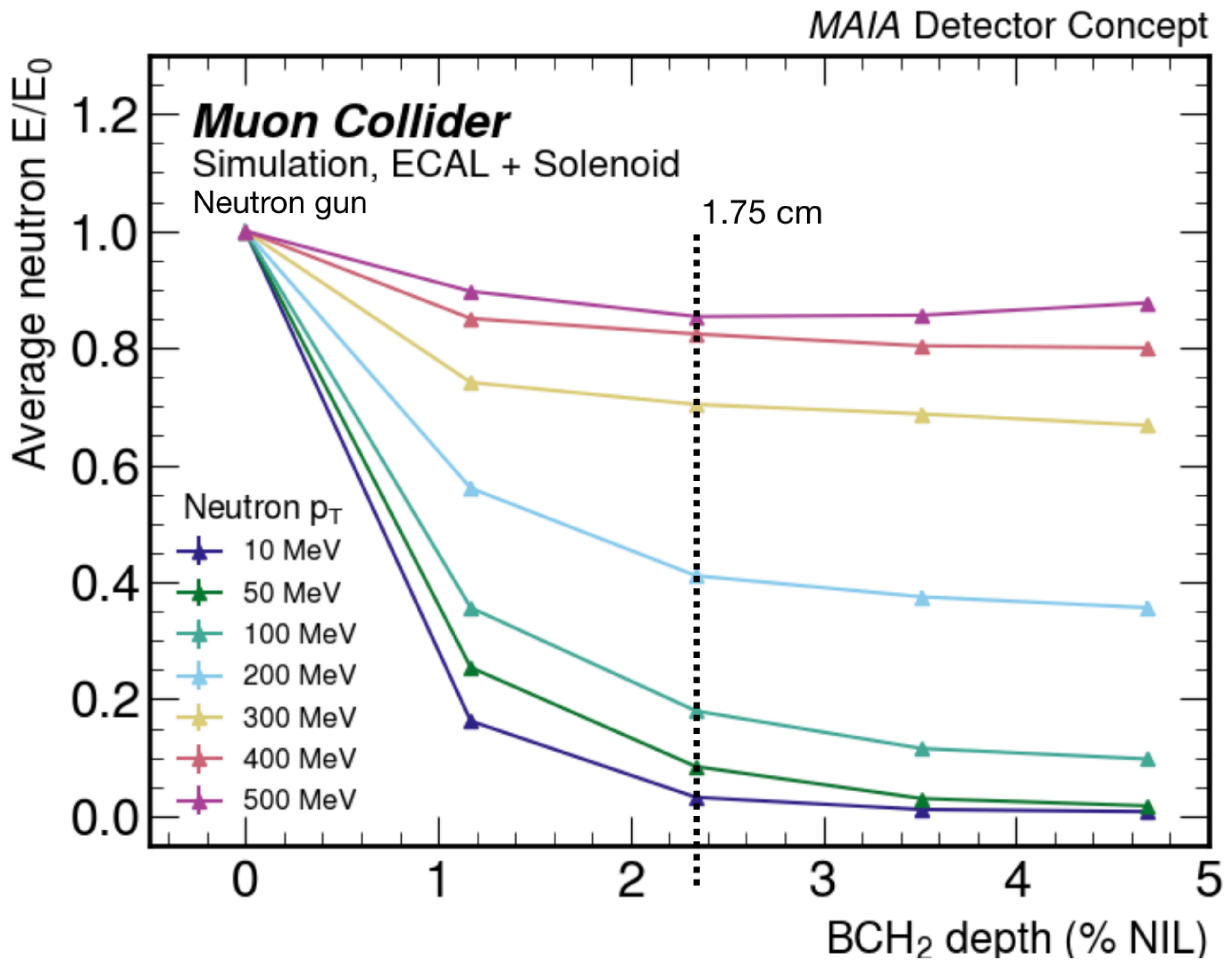
electron mis-identification

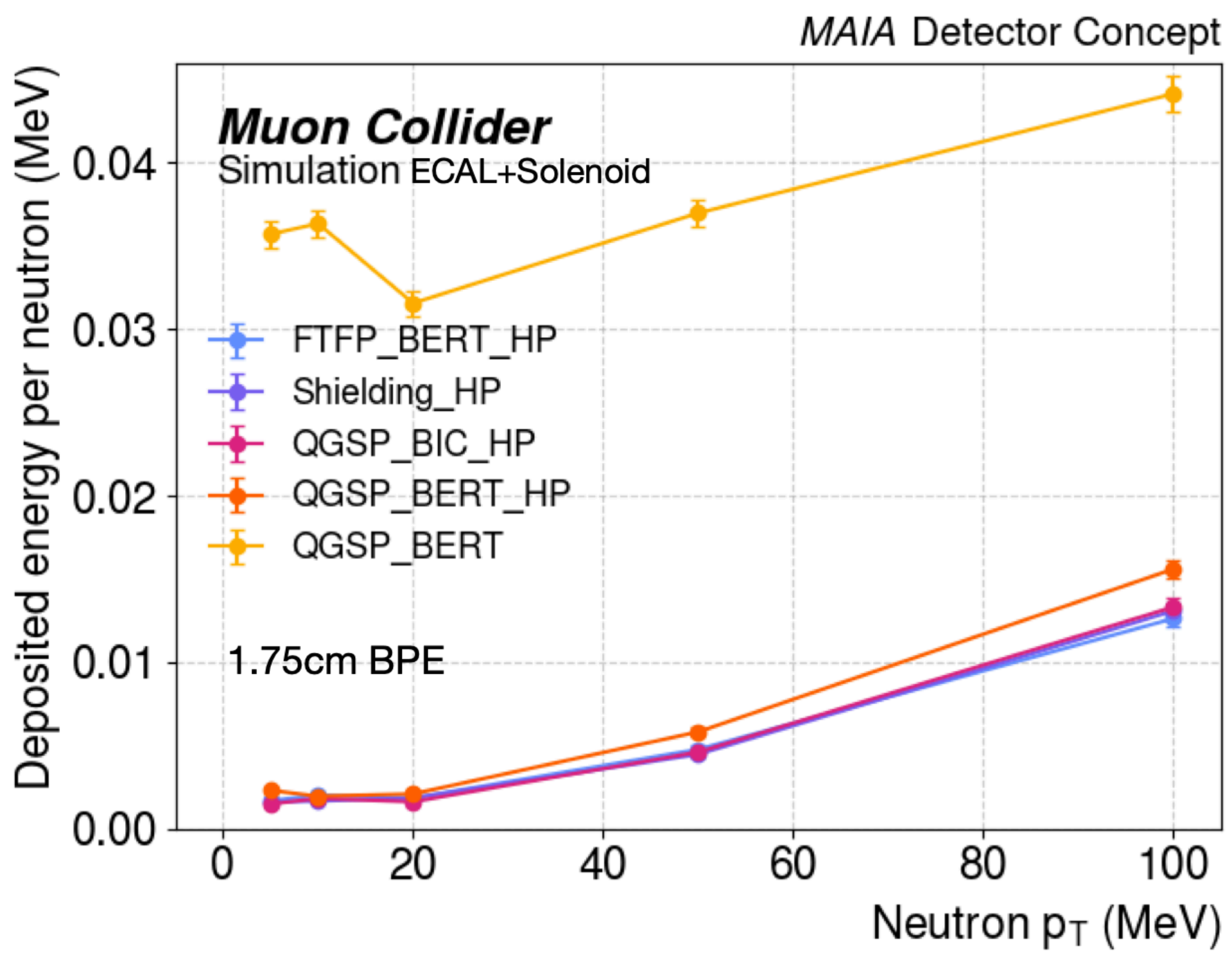


Jullian Watts

Evolving Detector Design

additional shielding could help





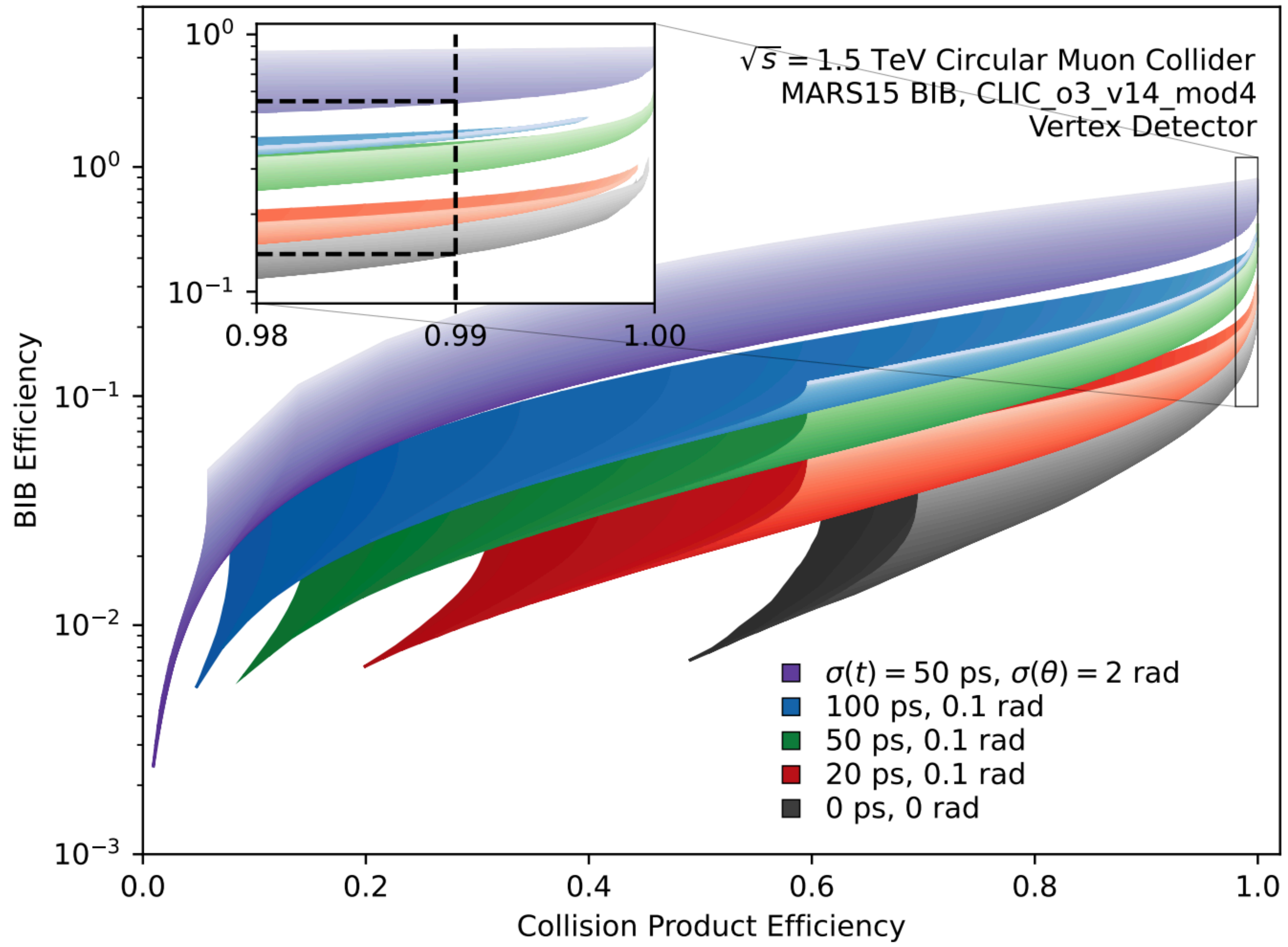
(sidenote: be careful with your physics lists!)

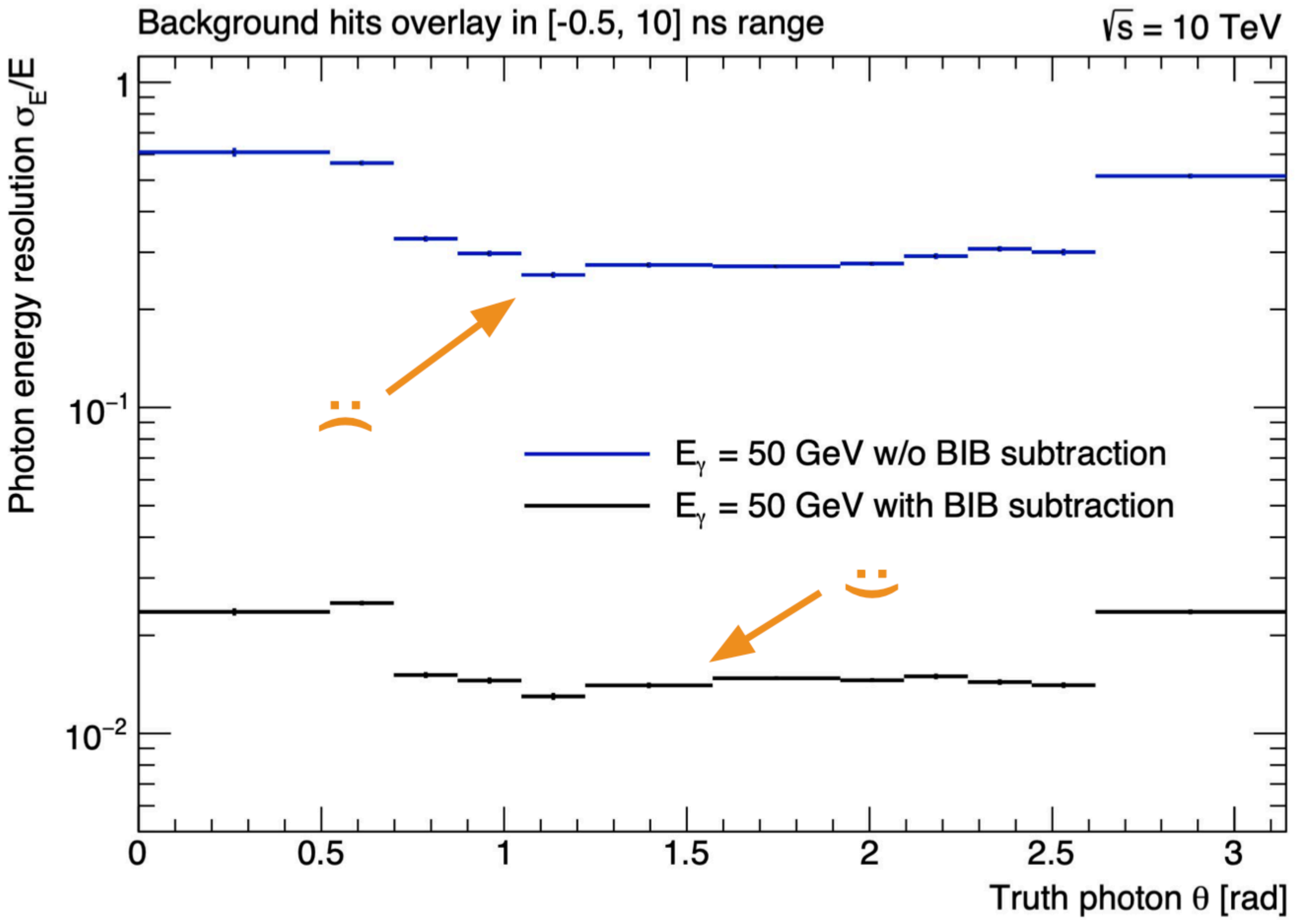
John Dervan

CAN WE DO PHYSICS?

actively exploring strategies for BIB mitigation to keep our resolutions small

and seeing great (early) results

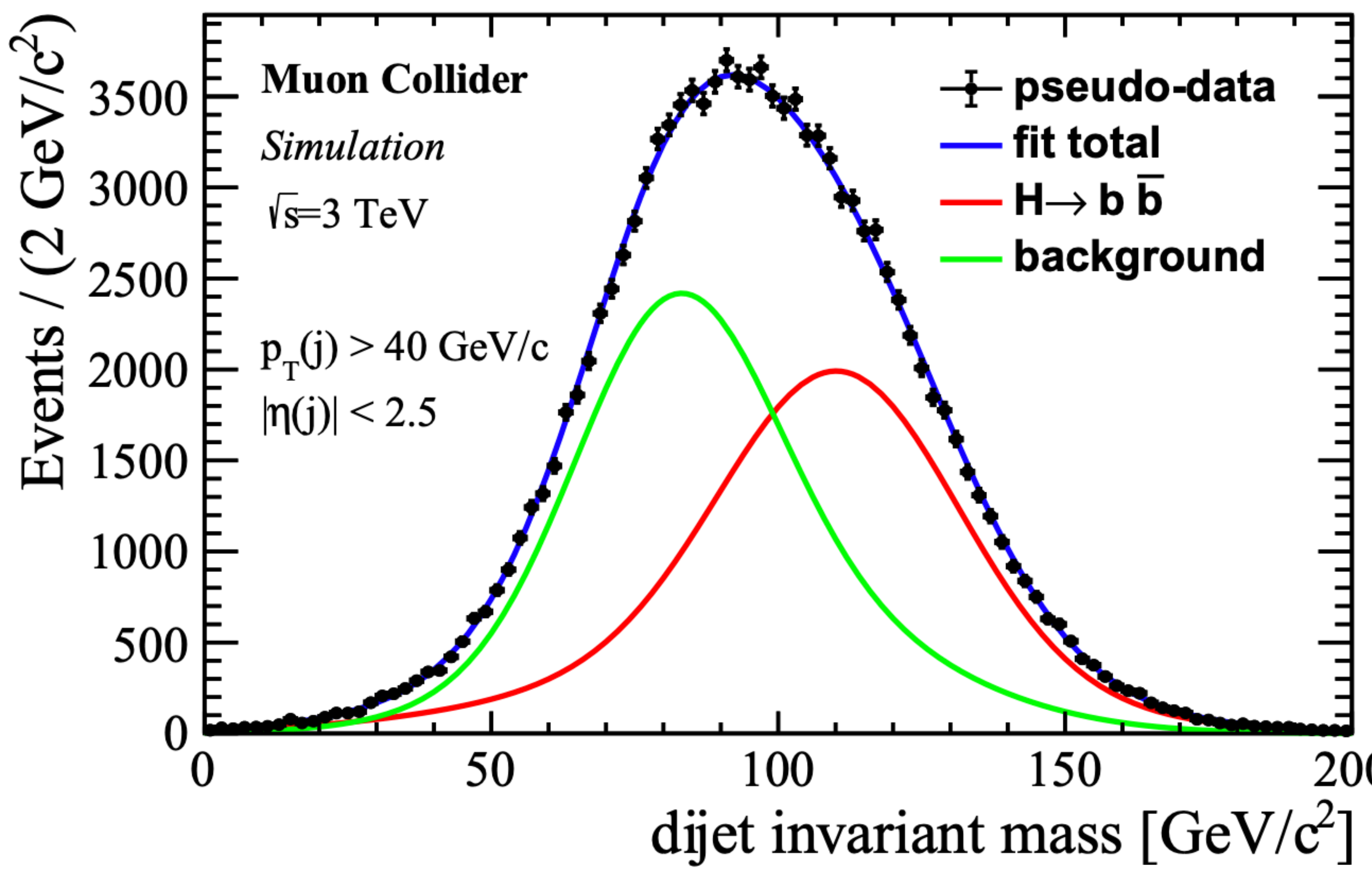




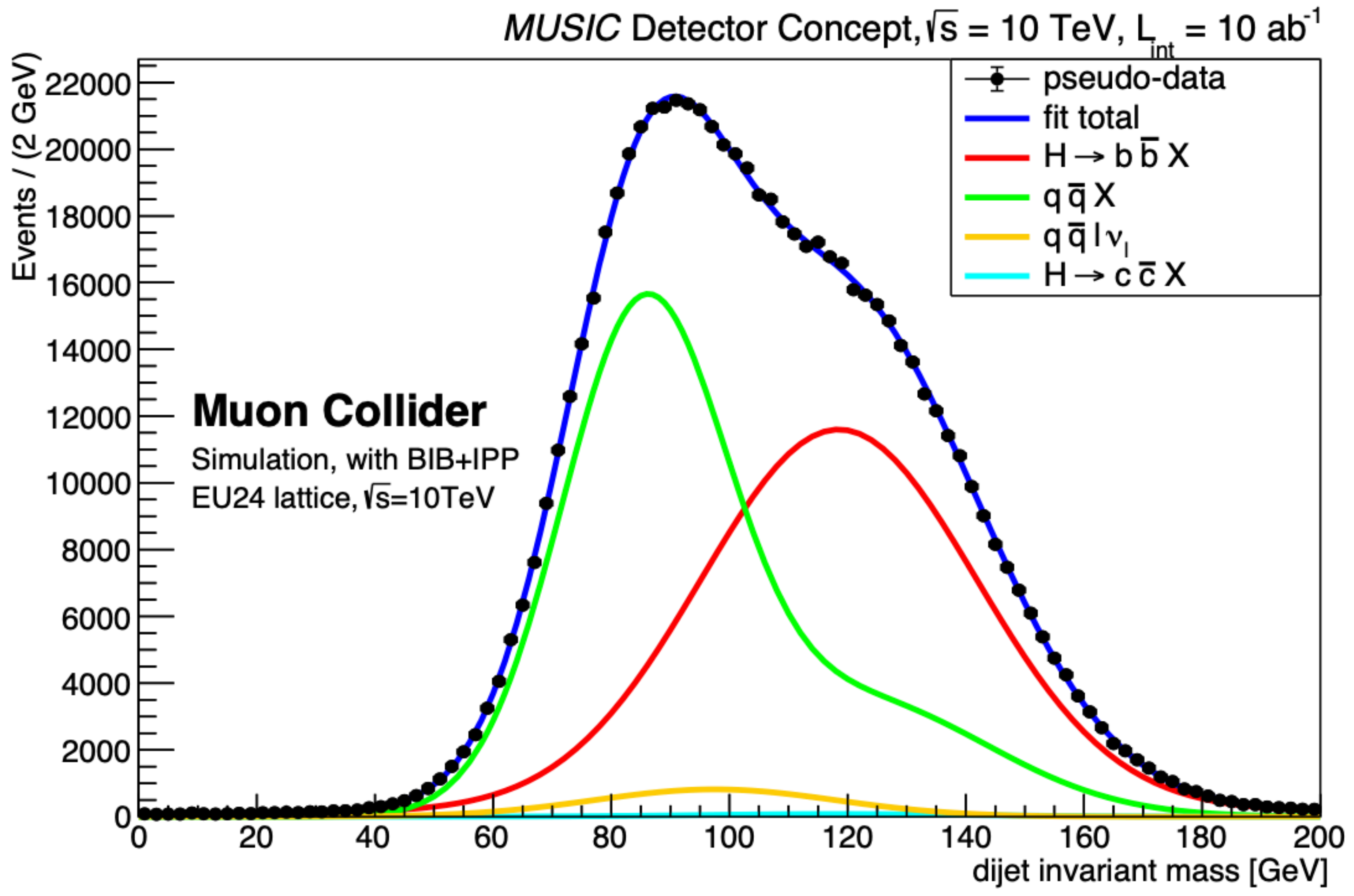
Muon Collider Forum Report, F. Meloni, D. Ally et al.

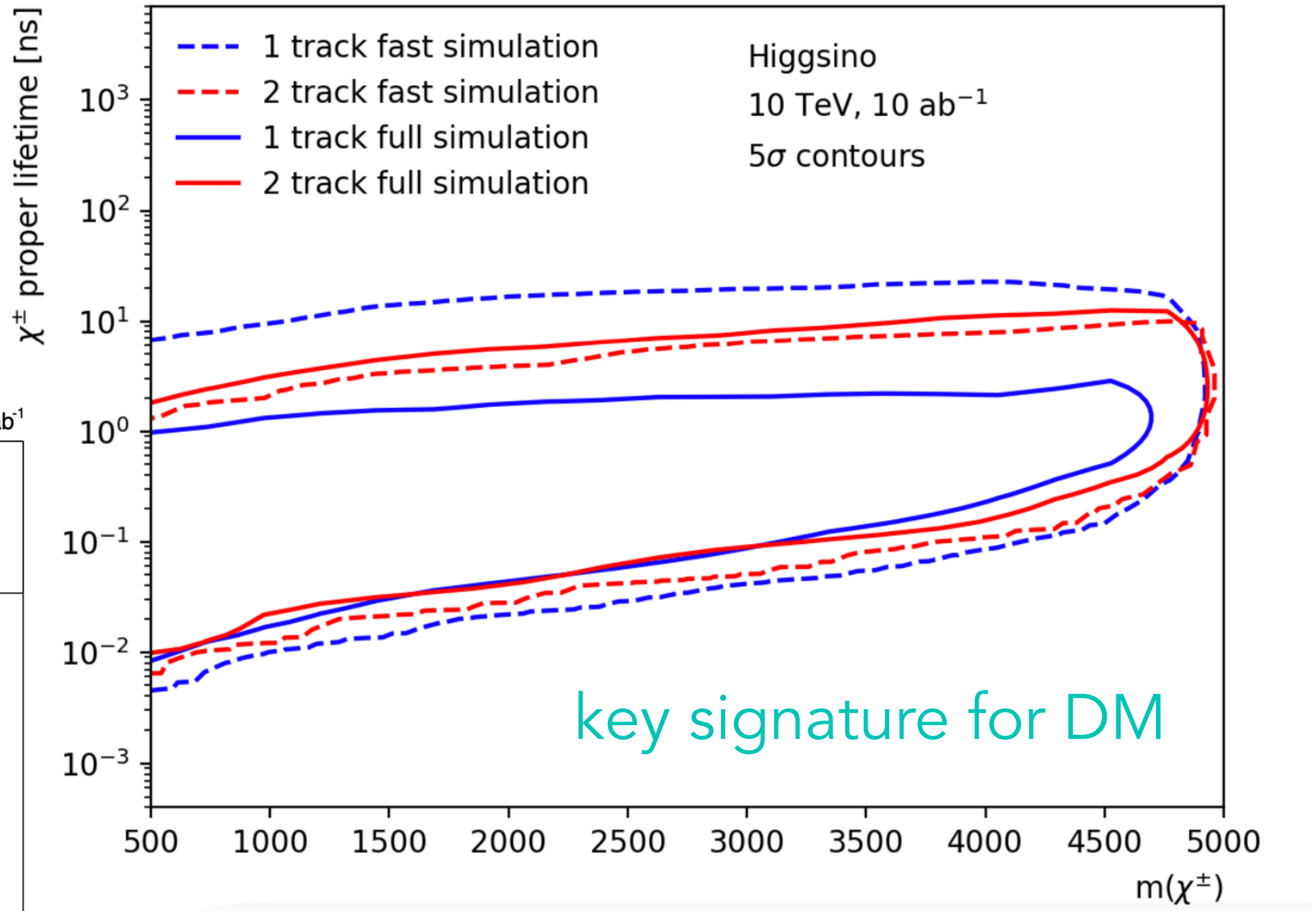
CAN WE DO PHYSICS?

using these to do full-sim studies with our detectors to understand **key physics targets**



more improvement to come!





Muon Collider Forum Report, ESPPU Input

DETECTOR OUTLOOK

big progress in recent years in building a detailed understanding of muon collider detector needs

with the HL-LHC upgrades, we're close to having the technical expertise to build this detector

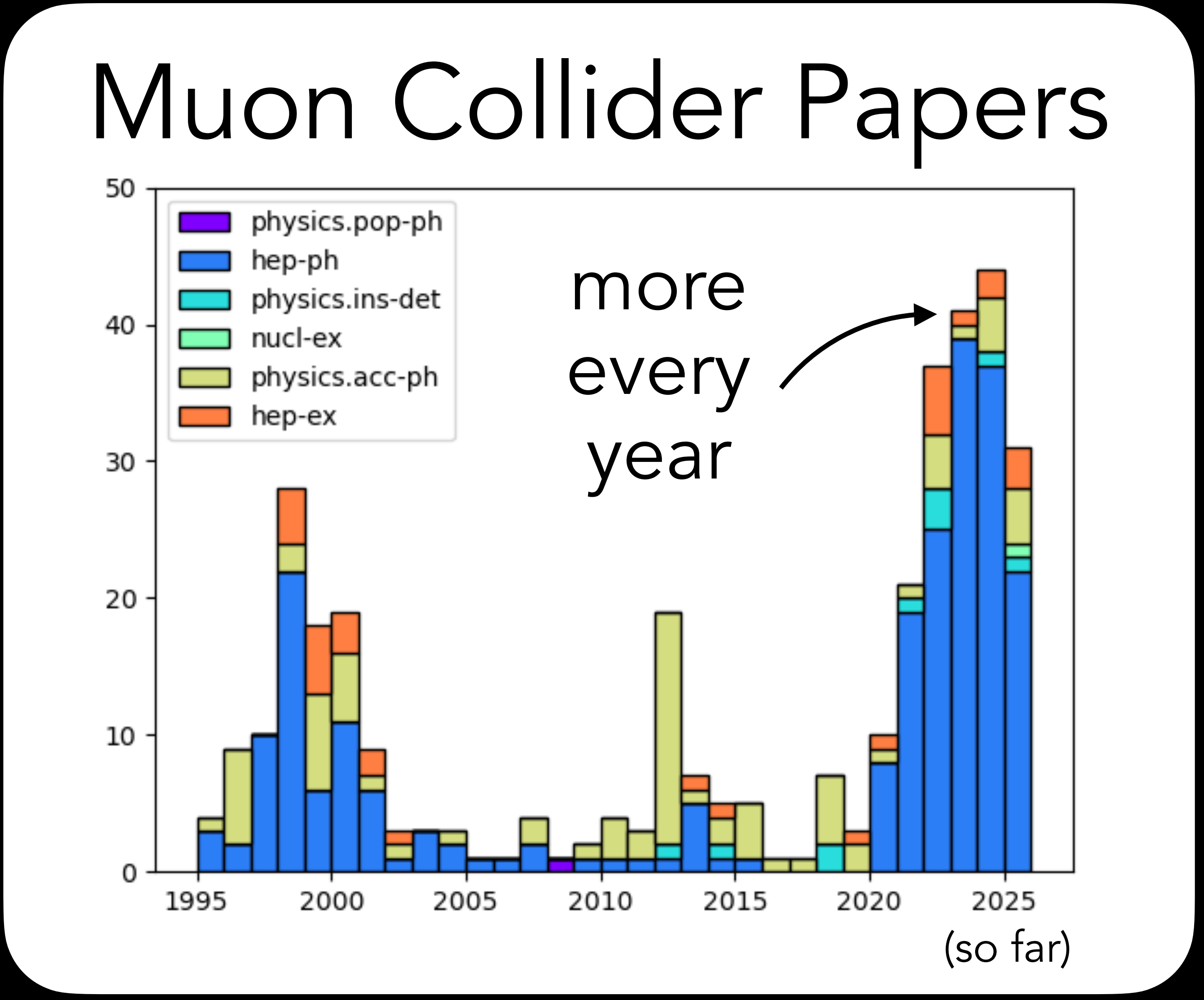
still lots to be done:
further MDI optimization
detector design including support and services
more sophisticated reconstruction and BIB rejection

and of course:
all of the detector R&D to help get us the timing and on-chip intelligence we need

BIGGER PICTURE

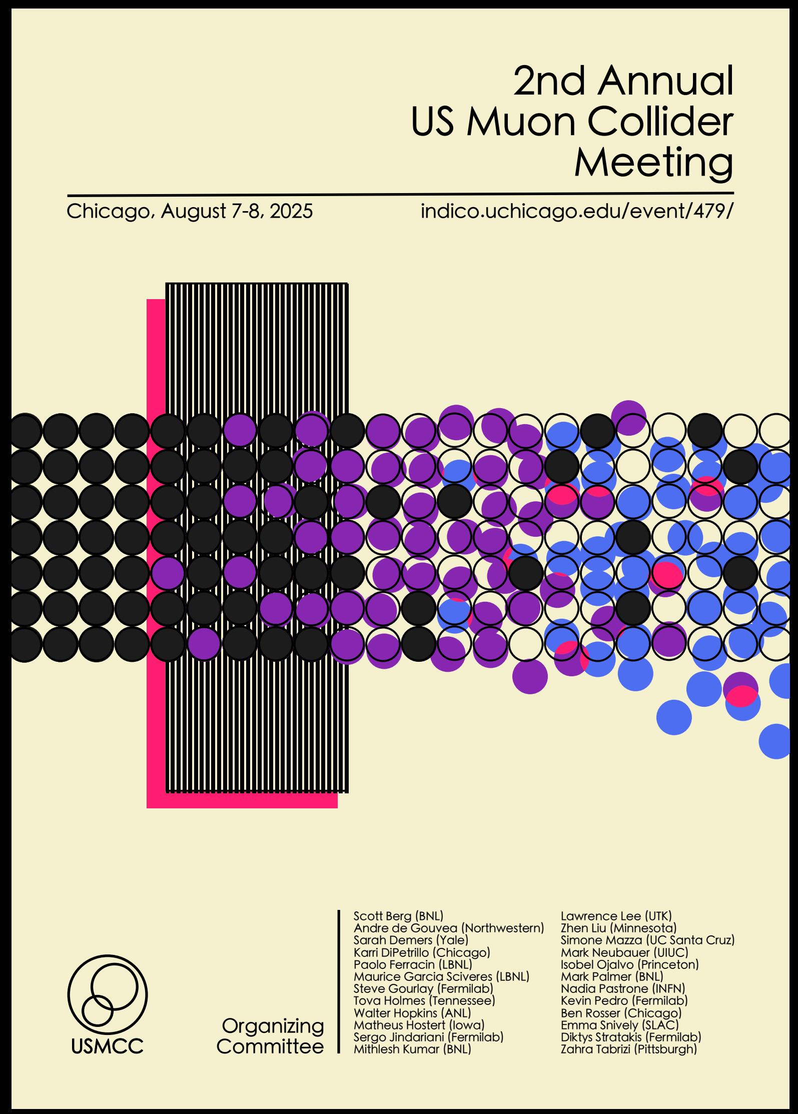
the reports are in: muon colliders hold huge potential for the US and the future of particle physics

the US community is engaging across detector and accelerator efforts



from arxiv

USMCC



big **challenges** still to solve — if you're interested in joining the effort, let us know!


ALFRED P. SLOAN
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THE KAVLI FOUNDATION
U.S. DEPARTMENT OF ENERGY
Office of Science
RESEARCH CORPORATION for SCIENCE ADVANCEMENT
SIMONS FOUNDATION
THANK YOU!