Towards a Muon Collider

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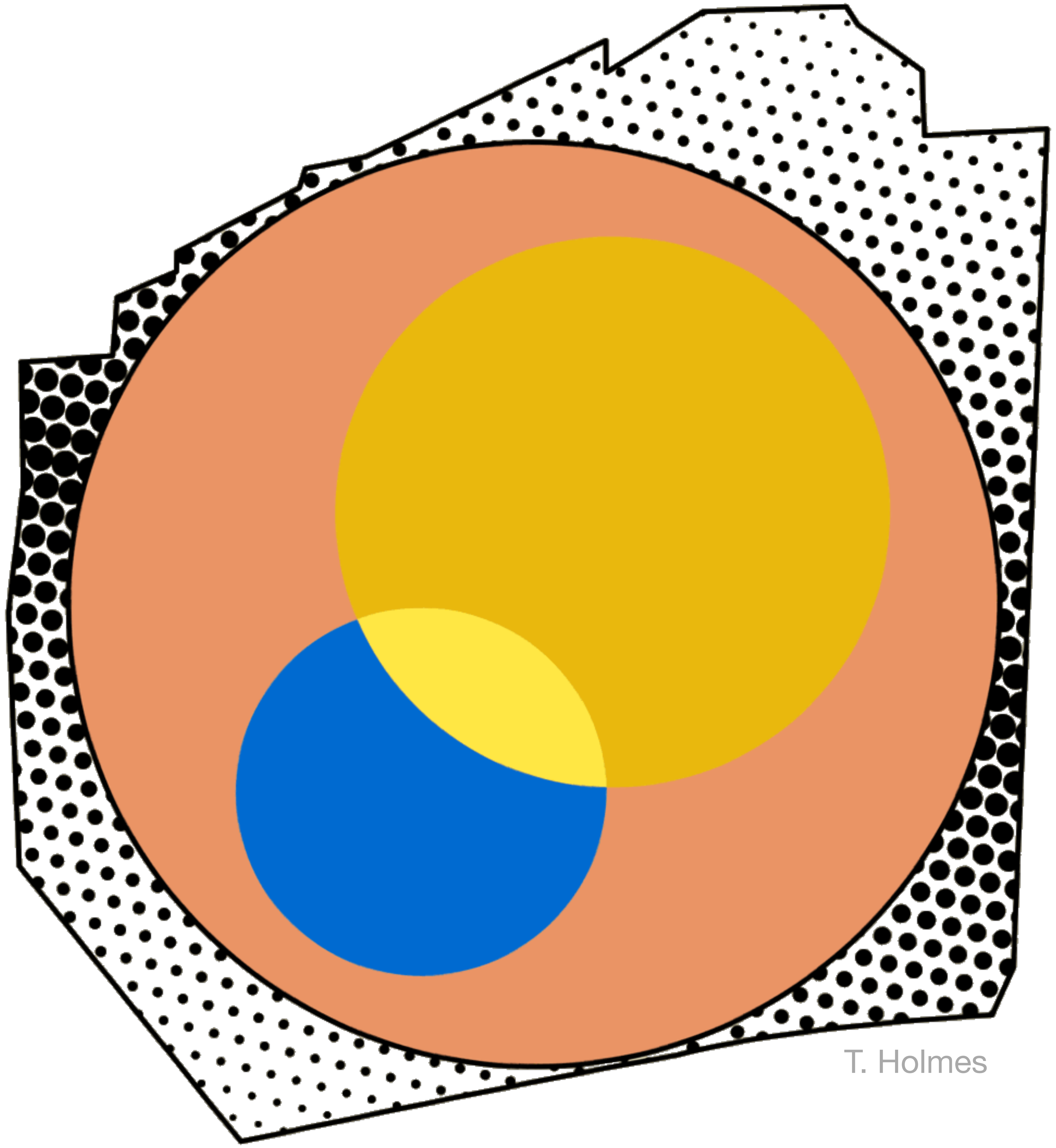


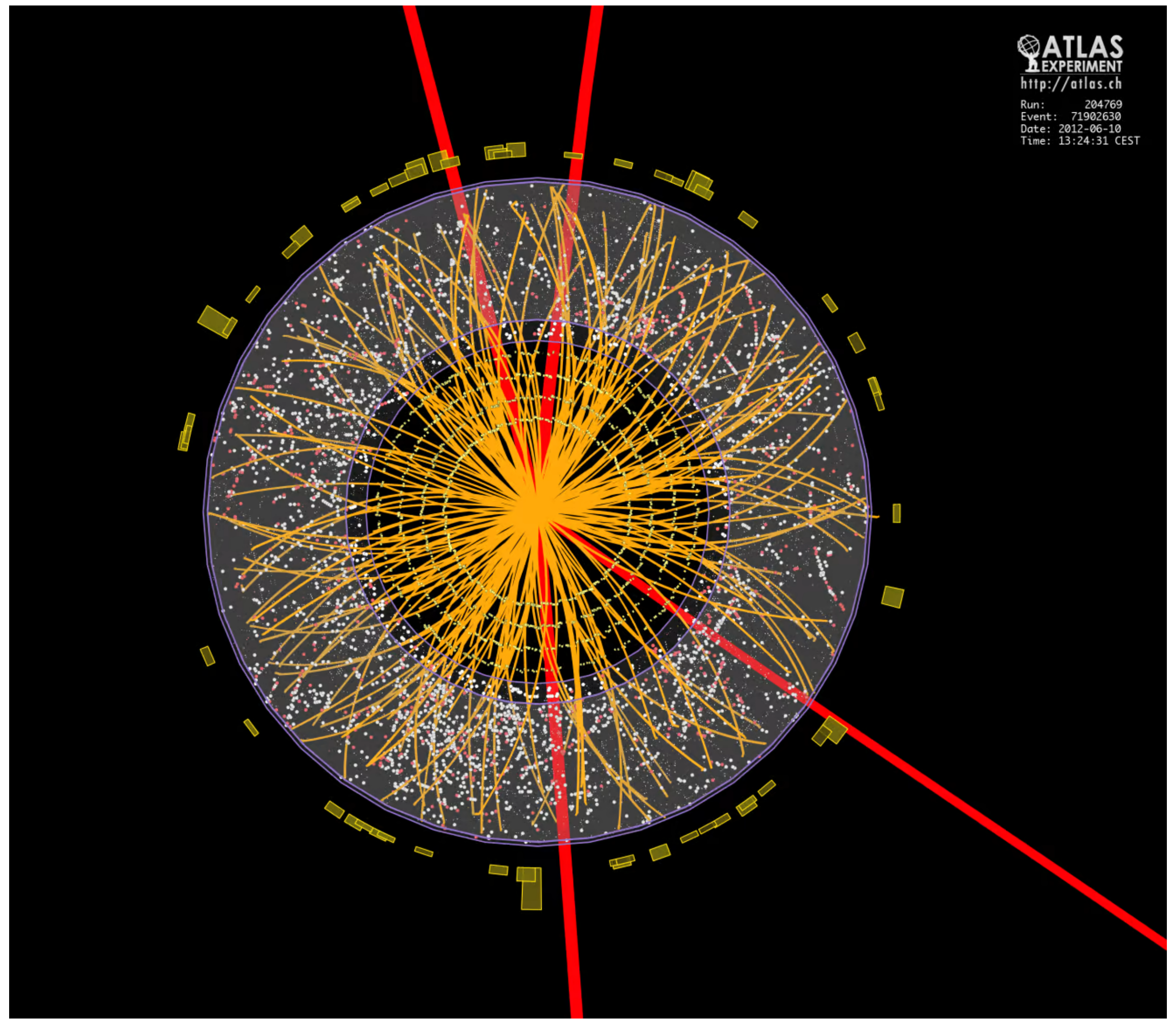
Why we need a new collider

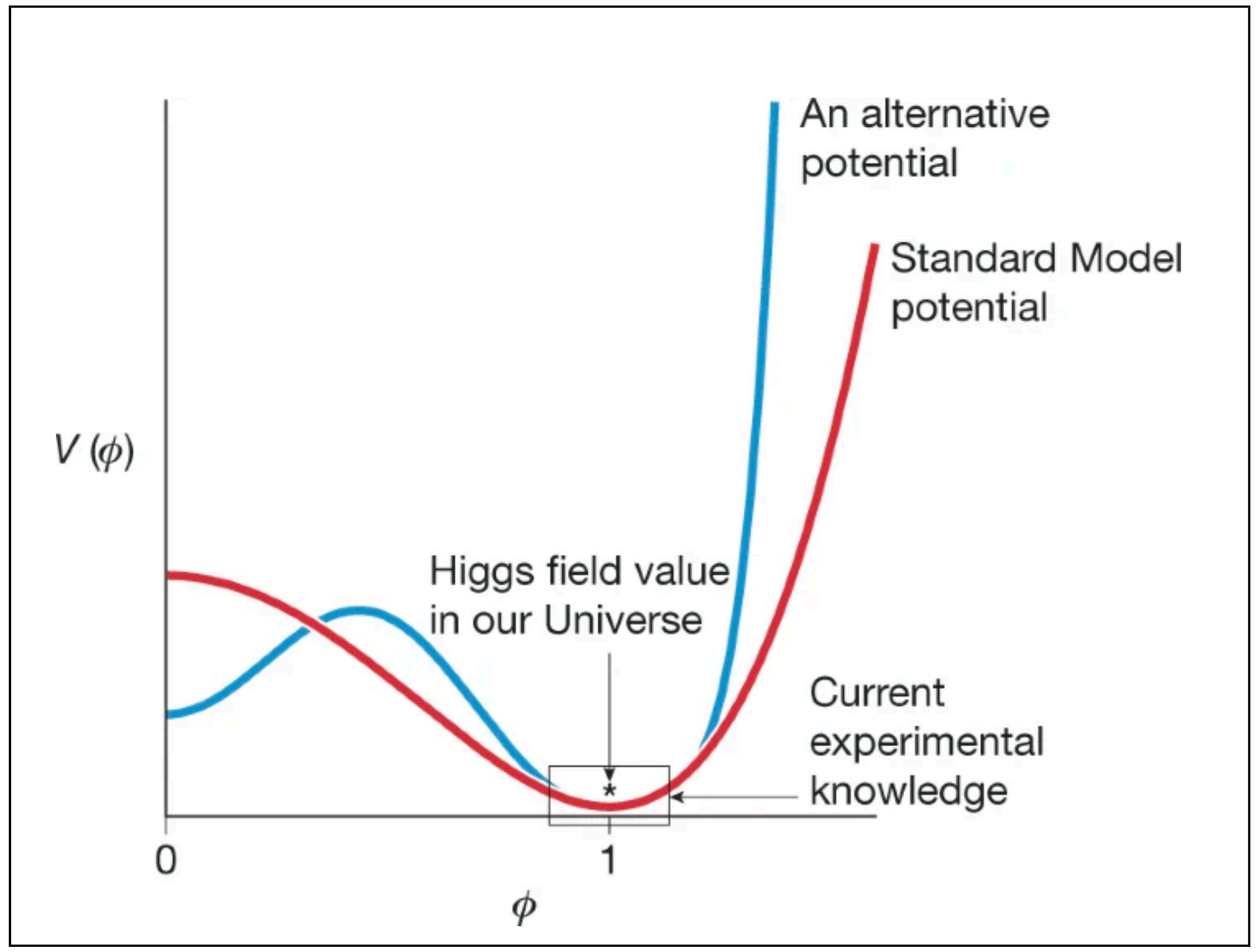
The physics case for 10 TeV

Open questions in particle physics

About the Standard Model
What is the nature of the Higgs Boson & electroweak symmetry breaking?

And the observed universe
What is dark matter?
What causes baryogenesis?

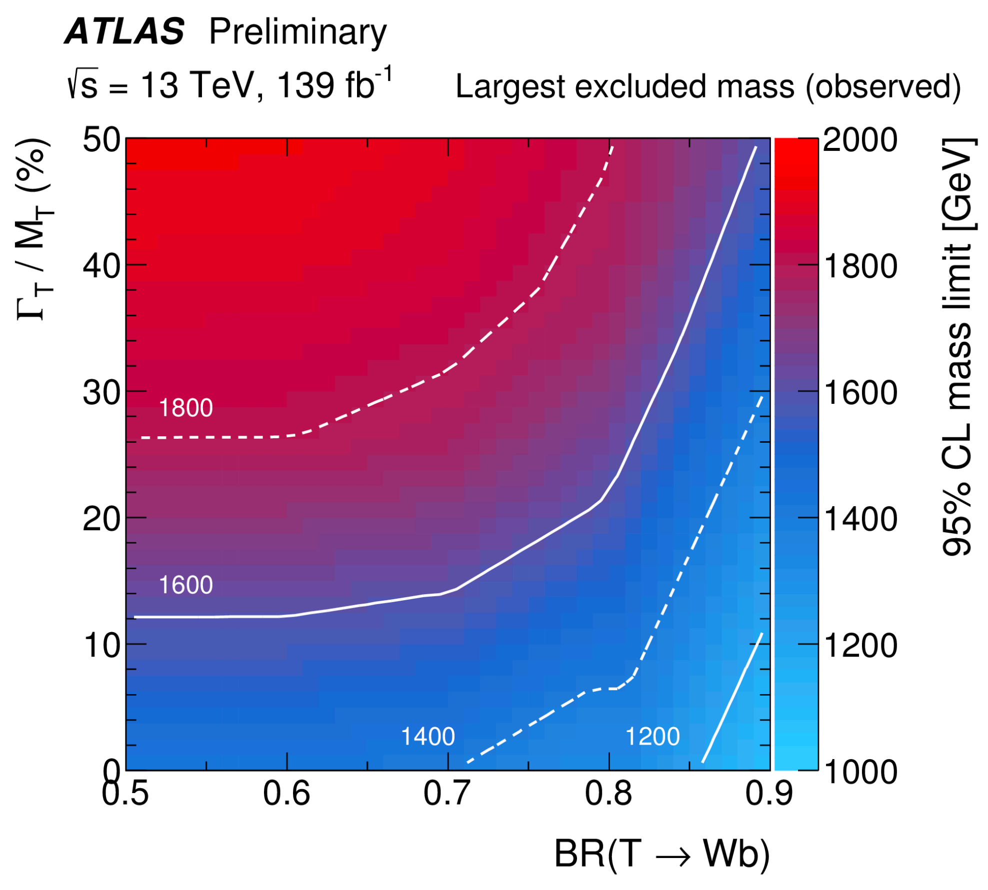




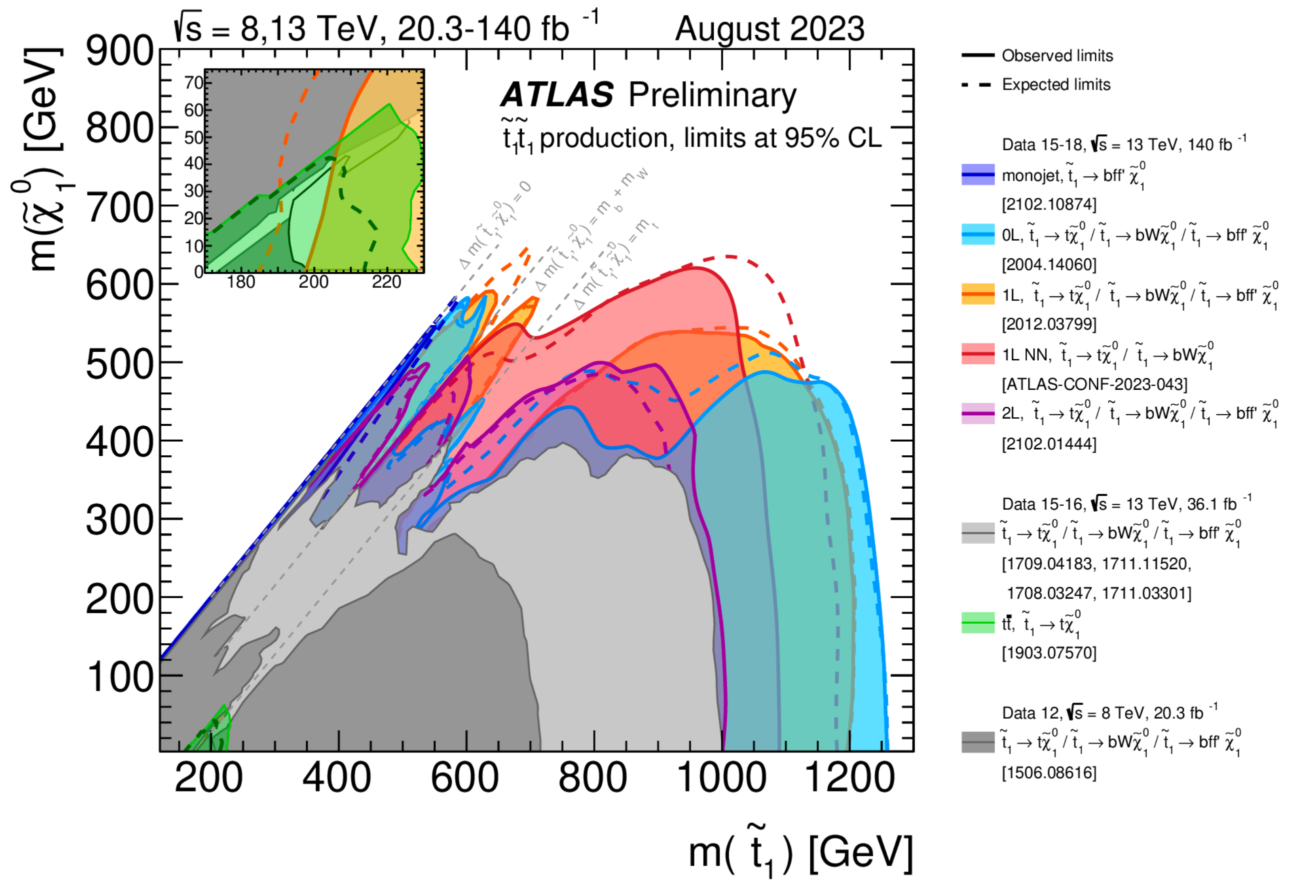
Microscopic nature of the higgs

Is there new physics preventing m_h from being pulled up to Plank scale?

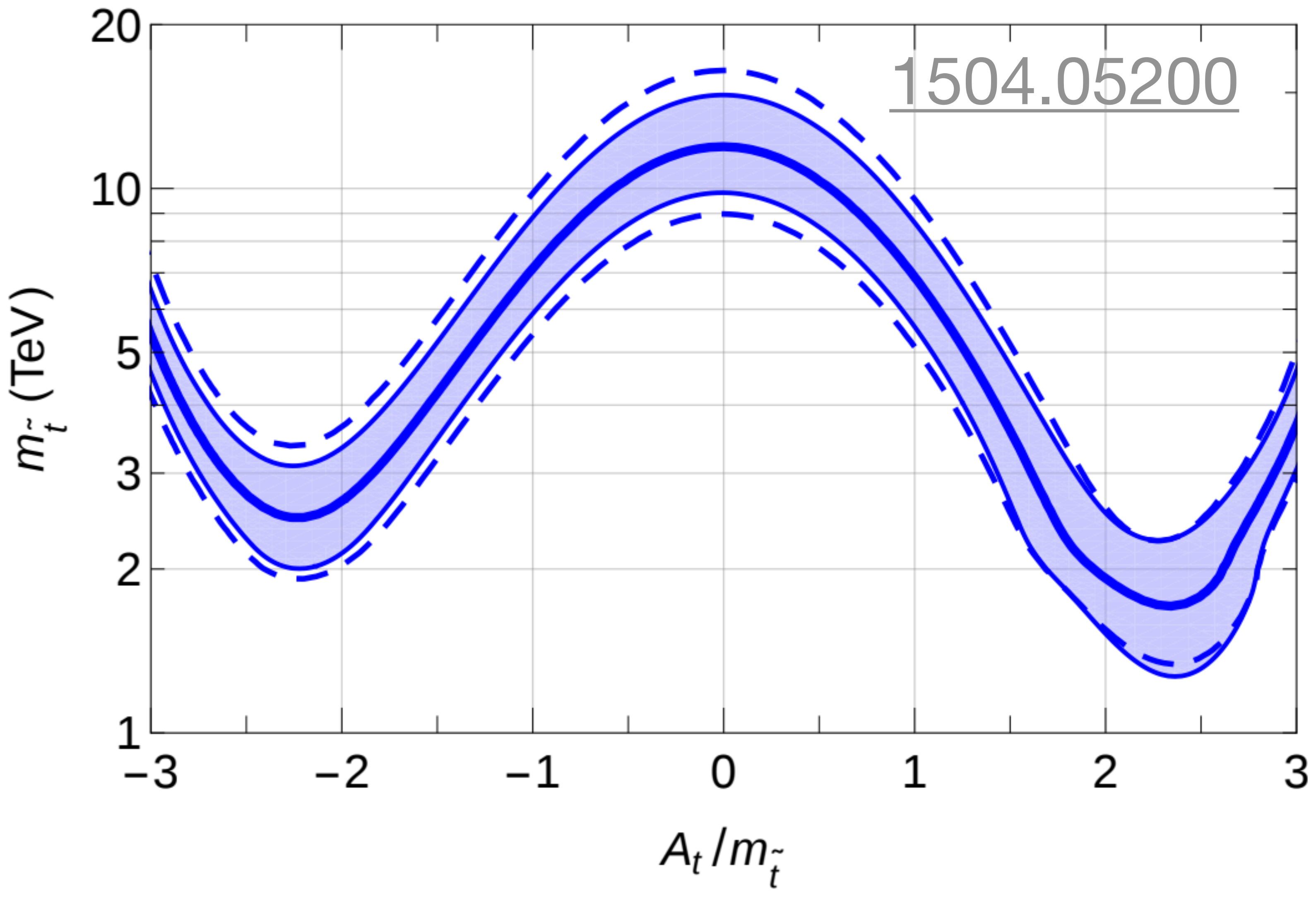
e.g. composite Higgs, like the pion?



e.g. new symmetry & additional particles?



m_h =125 GeV → multi-TeV top-partners

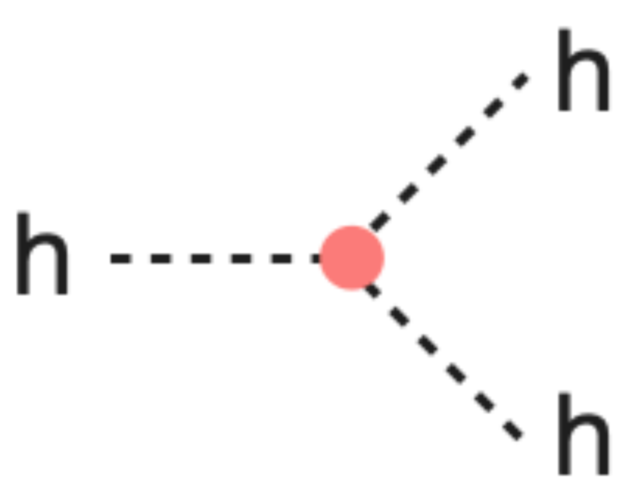


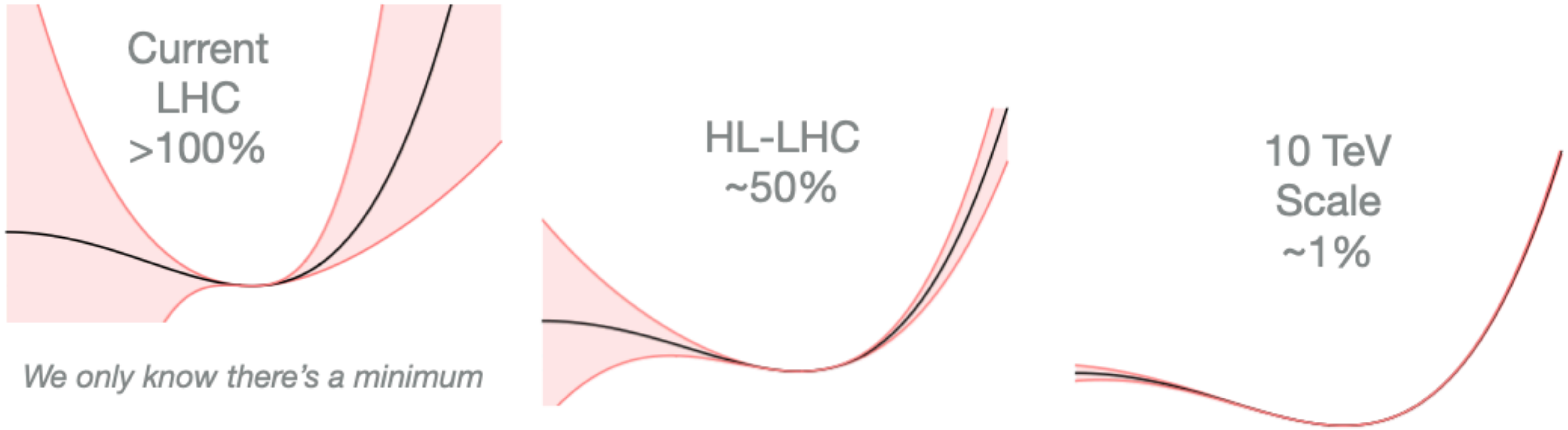
Data & theory suggest strongly coupled particles > 1 TeV

Electroweak symmetry breaking

N. Craig

Was there a first order phase transition? Is electroweak symmetry restored at high temperatures?
Requires measuring Higgs self-coupling with few % uncertainty



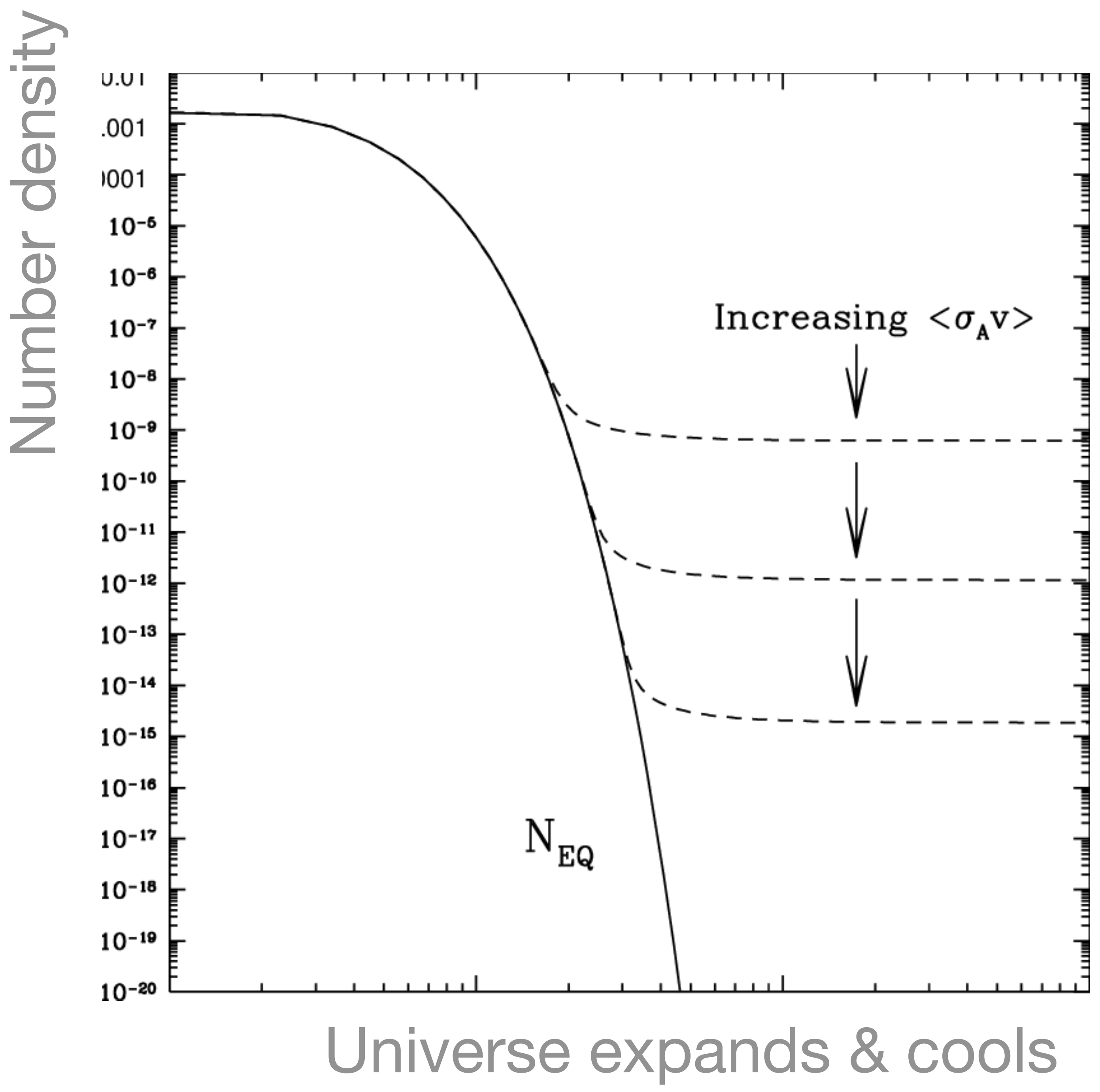


Producing enough multi-Higgs events is <u>only possible at a 10 TeV scale collider</u>

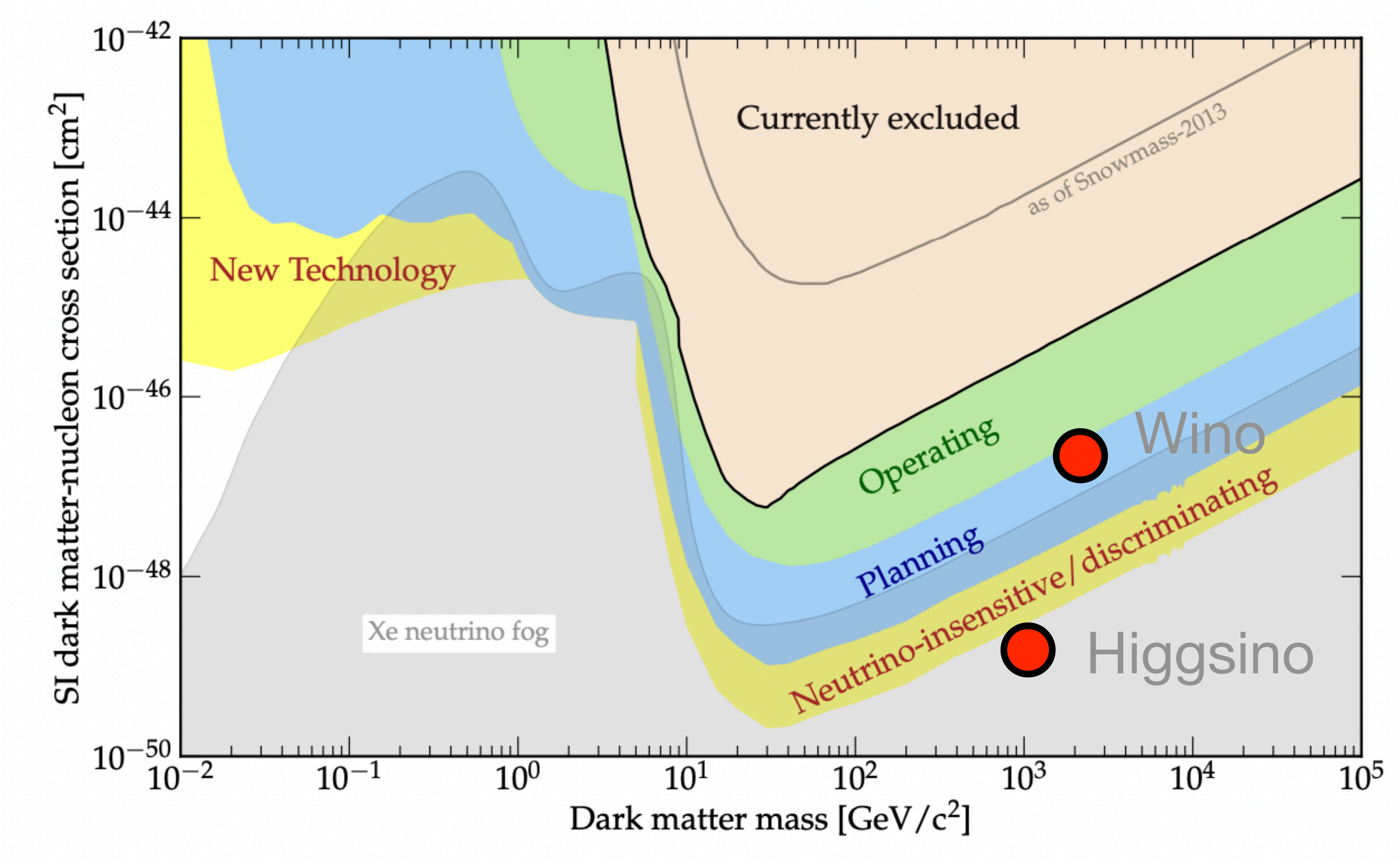
Dark Matter

DM Complementarity Report: 2211.07027

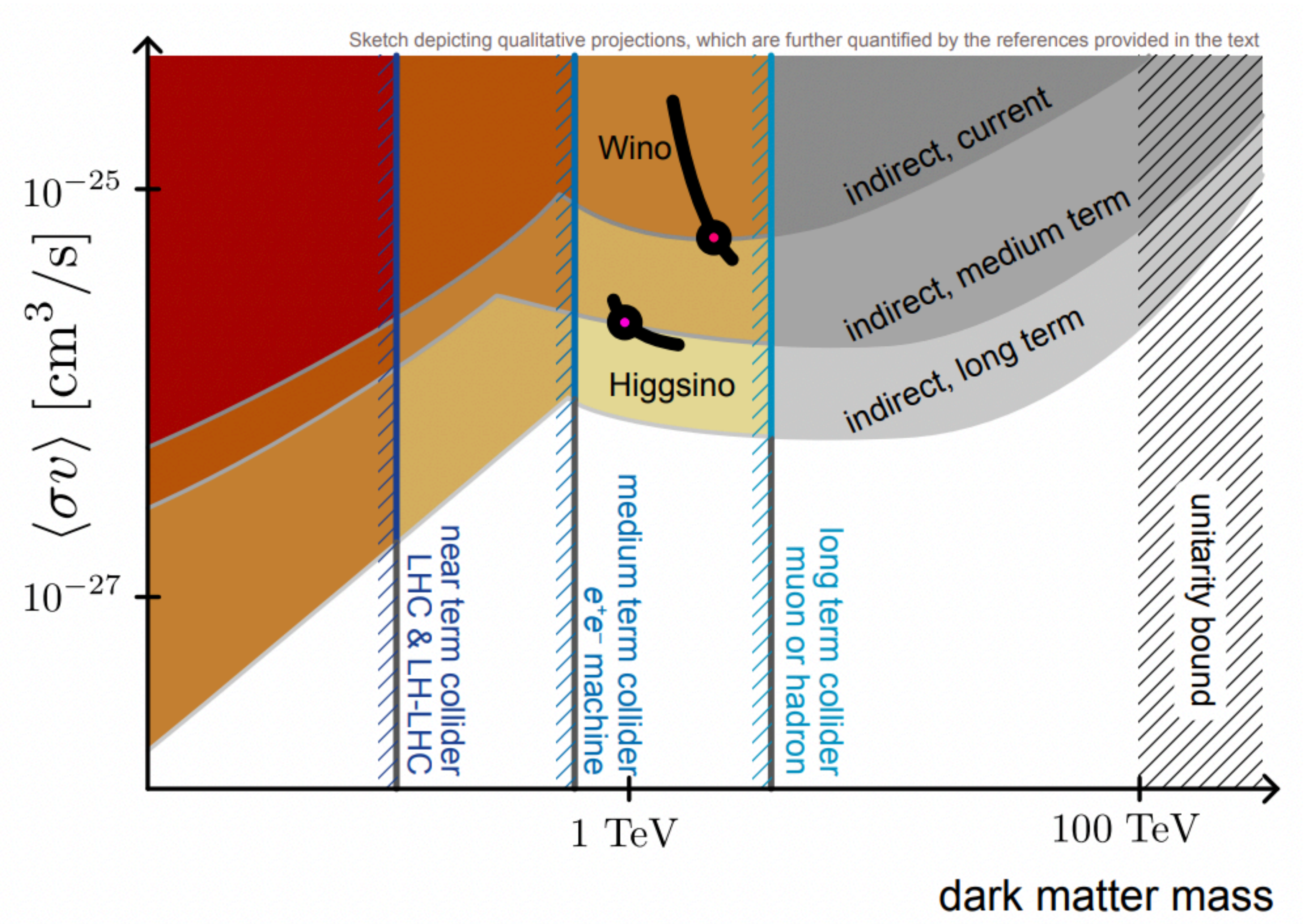
We’ve yet to probe minimal WIMPs up to thermal targets



Pure higgsino under neutrino floor



& out of HL-LHC & e^+e^- reach



Definitive observation & characterization would require a multi-TeV scale collider

What we should build

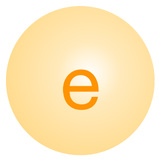
Why muons are a promising path to the 10 TeV scale

& add unique physics opportunities

Traditional Paradigm

Use our favorite, readily available particles

Electrons

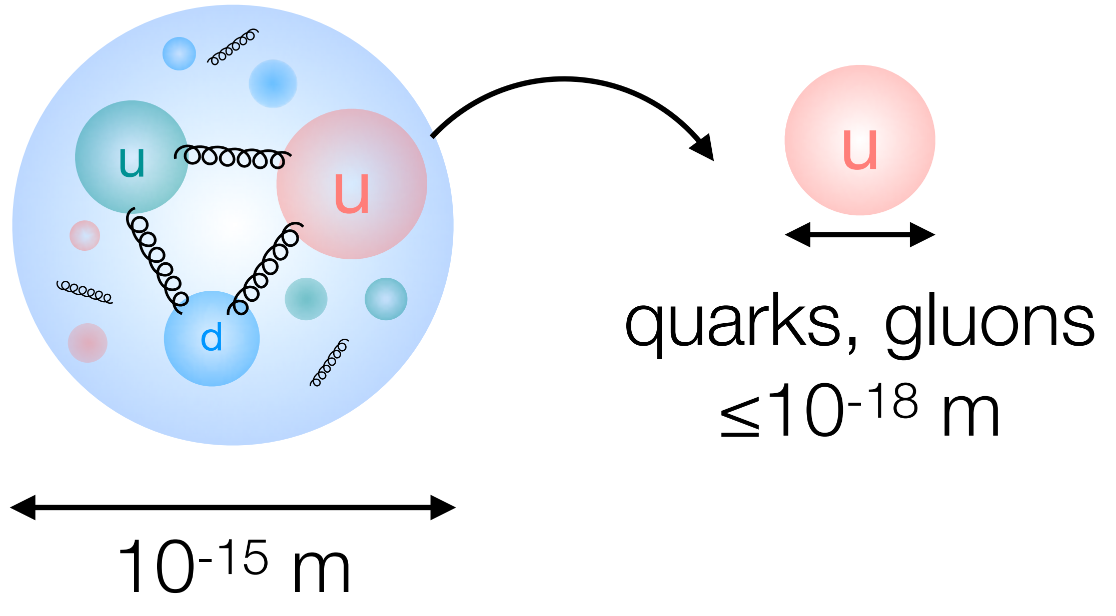


fundamental particles = "clean" collisions

small mass = synchrotron radiation ~ $1/m^4$

Precision

Protons



large mass means higher energies achievable

composite: colliding quarks and gluons.
carry a fraction of proton momentum

high rate of "messy" backgrounds

Energy

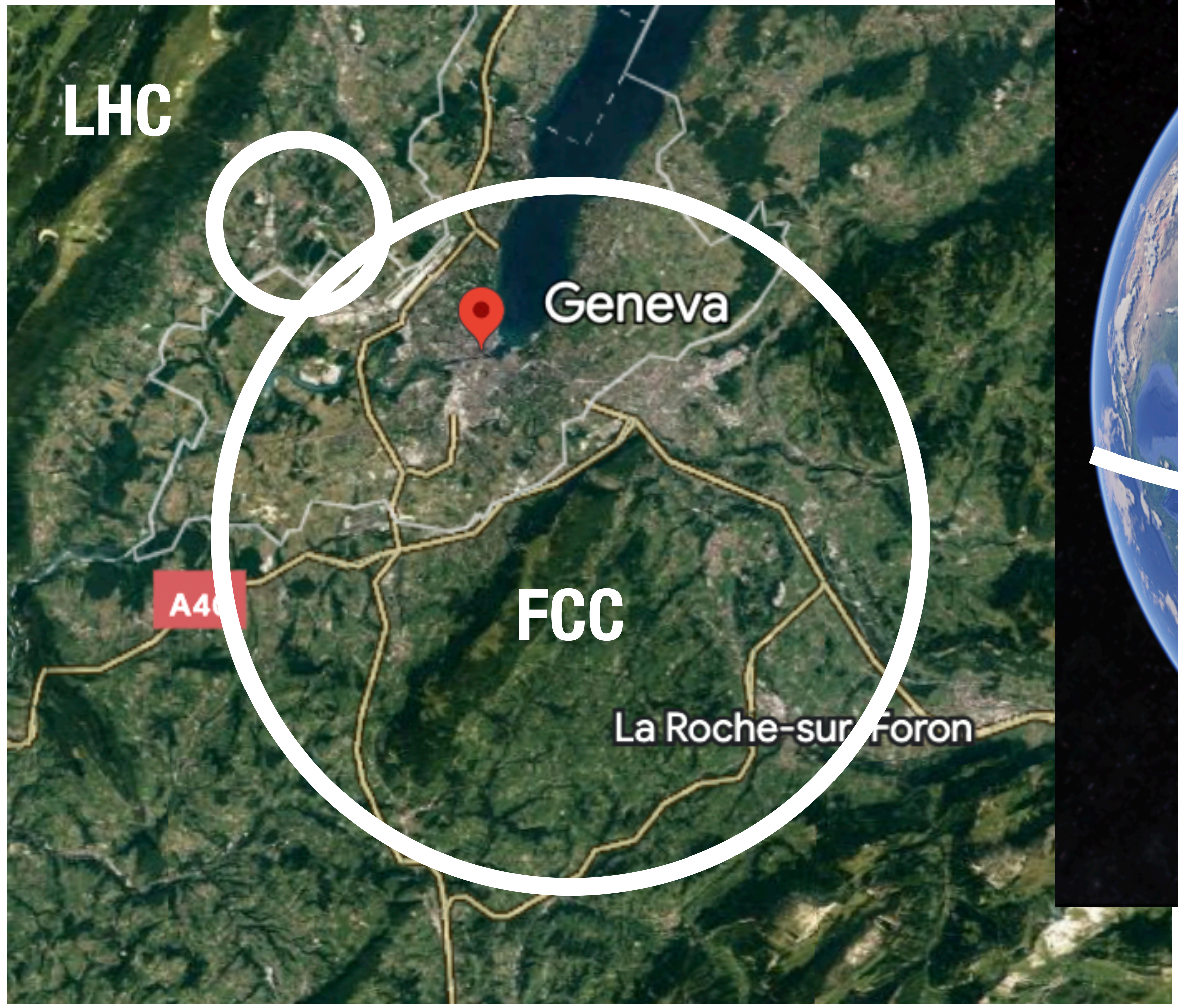
How to get to higher energies

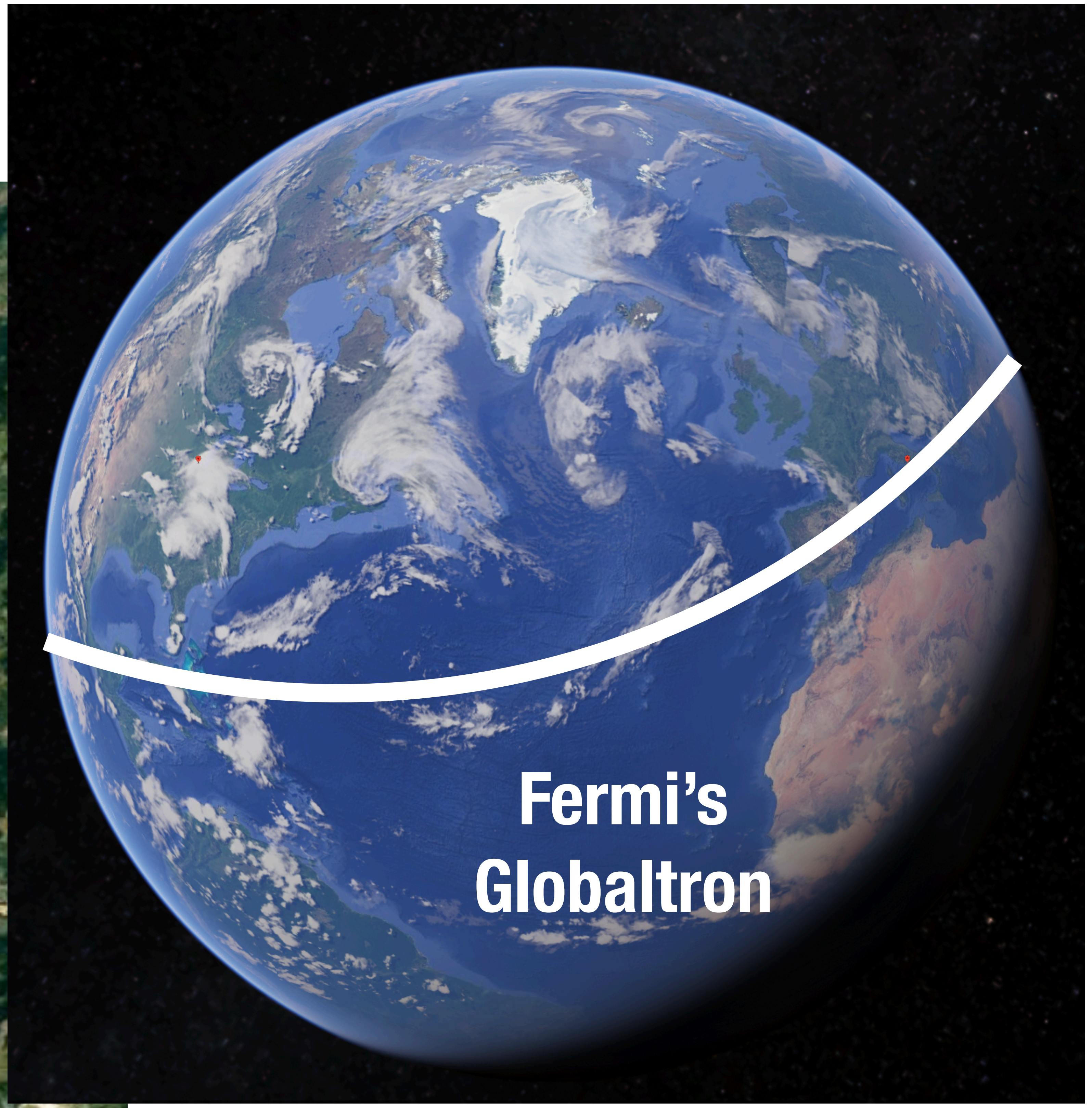
For a fixed technology
→ go bigger

$$E_{\text{beam}} \sim 0.3 \cdot R \cdot B_{\text{dipole}}$$

For 100 TeV pp-collisions

LHC NbTi	8 T	190 km
Record NbSn3	15 T	100 km
Future HTS	20 T	80 km



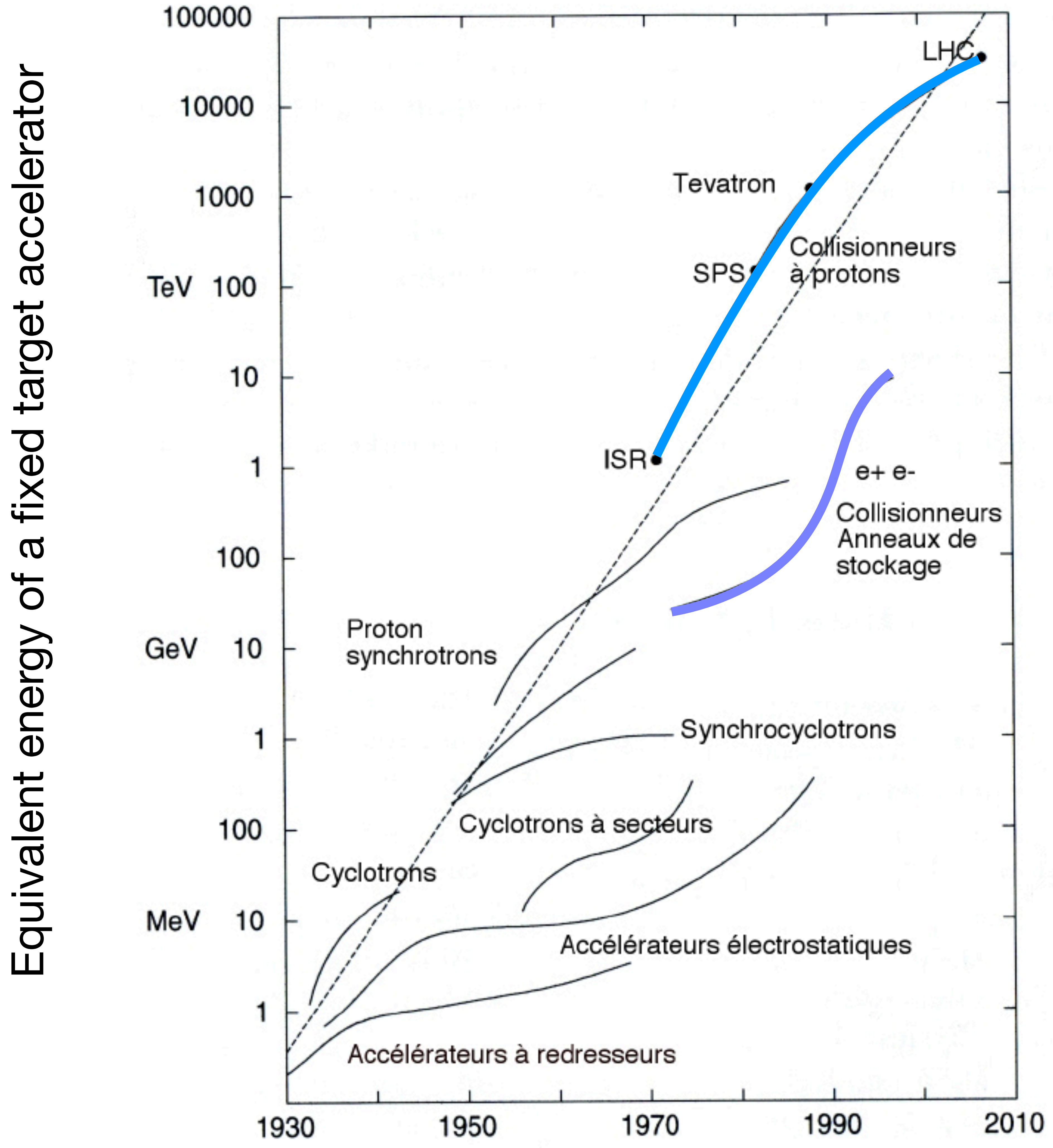


Or take a risk on new technology?

- Energy breakthroughs require leaps in technology & fundamentally new concepts
- Even with next gen magnets we're pushing the limits of what is feasible with protons
  - Tunnel length
  - Power consumption

$$P \sim \frac{(E/m)^4}{R} \cdot I_{\text{beam}}$$

Costs scale with both!



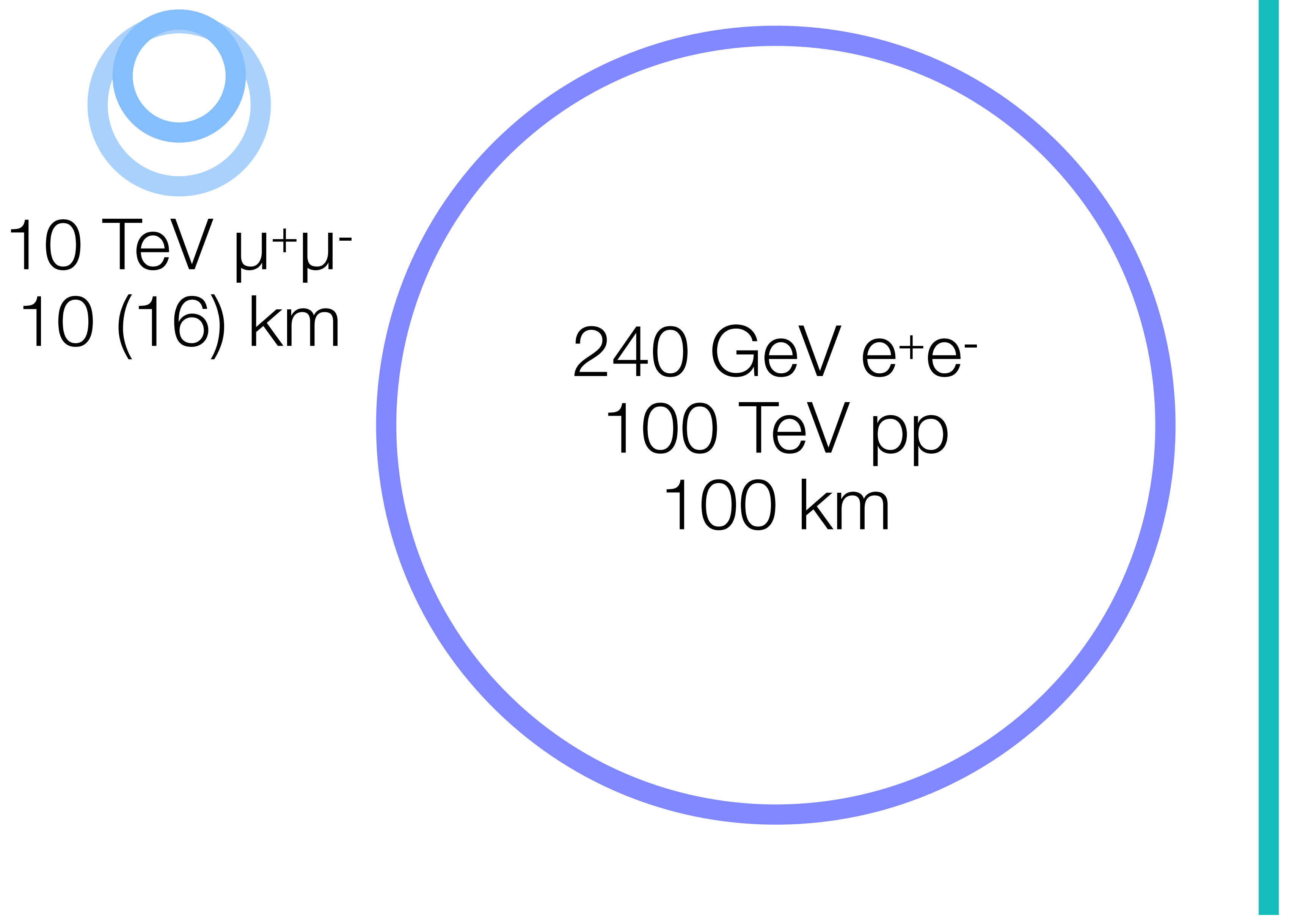
Why collide muons?

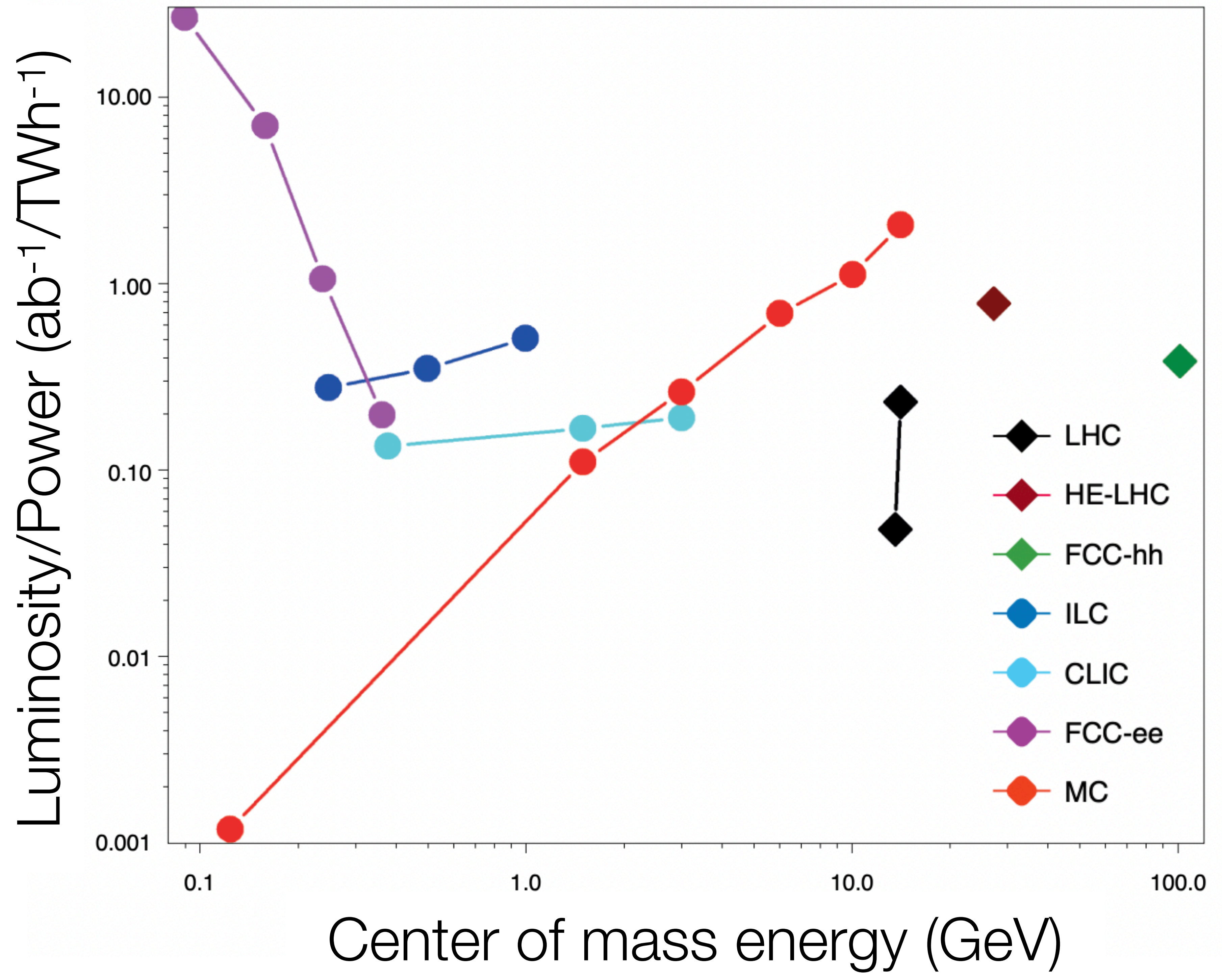
Input to EPPSU 1901.06150

Break the traditional paradigm of larger and larger e^+e^- and hadron colliders

massive fundamental particles = compact, power, and cost-efficient

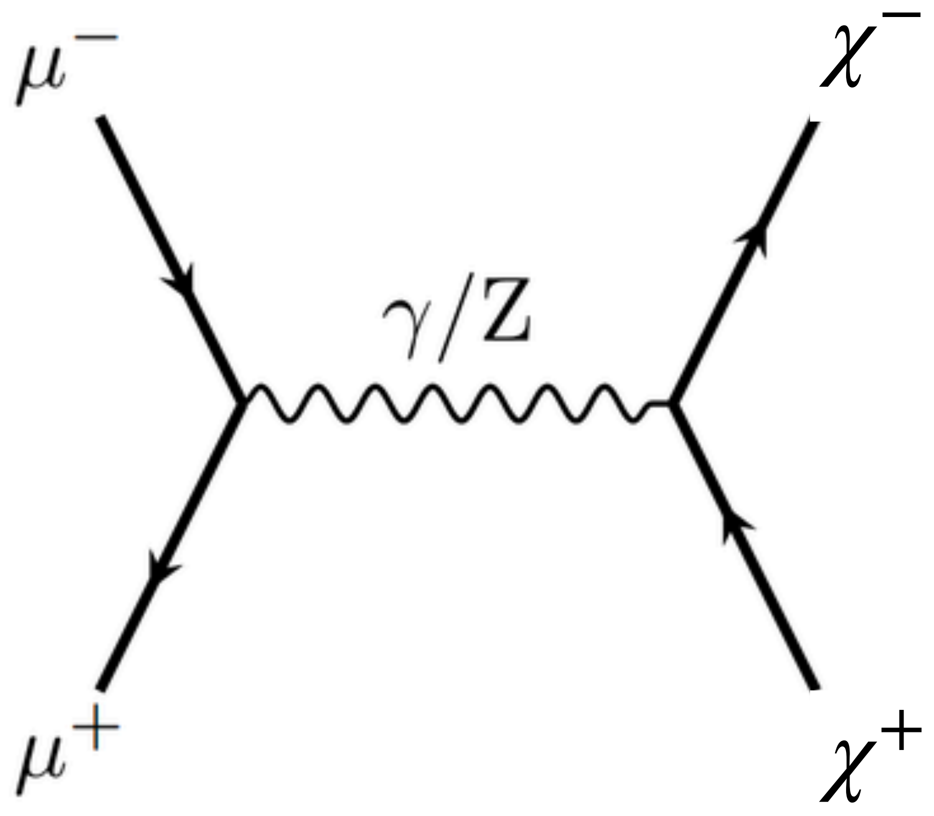
Fits within Fermilab site!





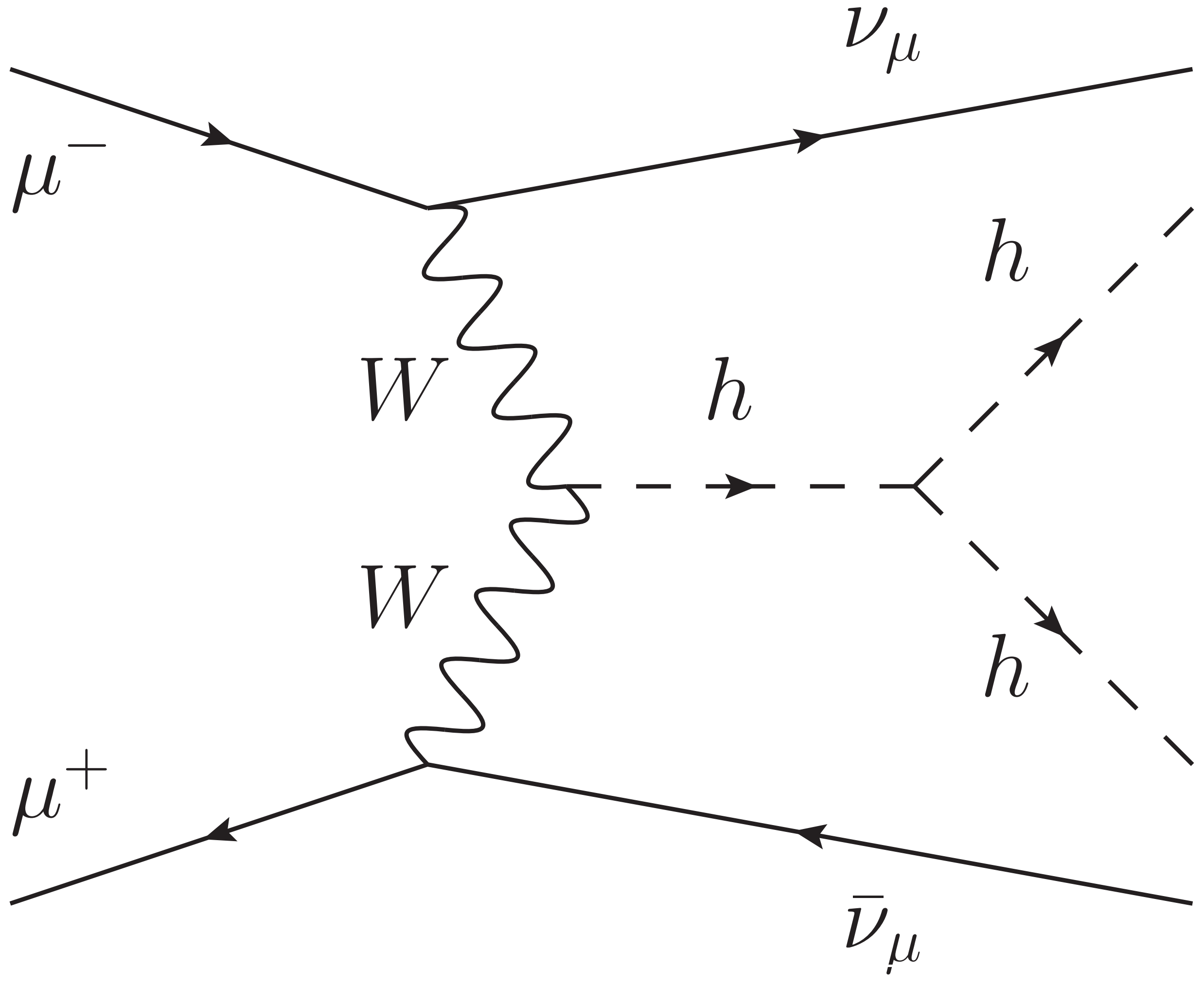
Two colliders in one

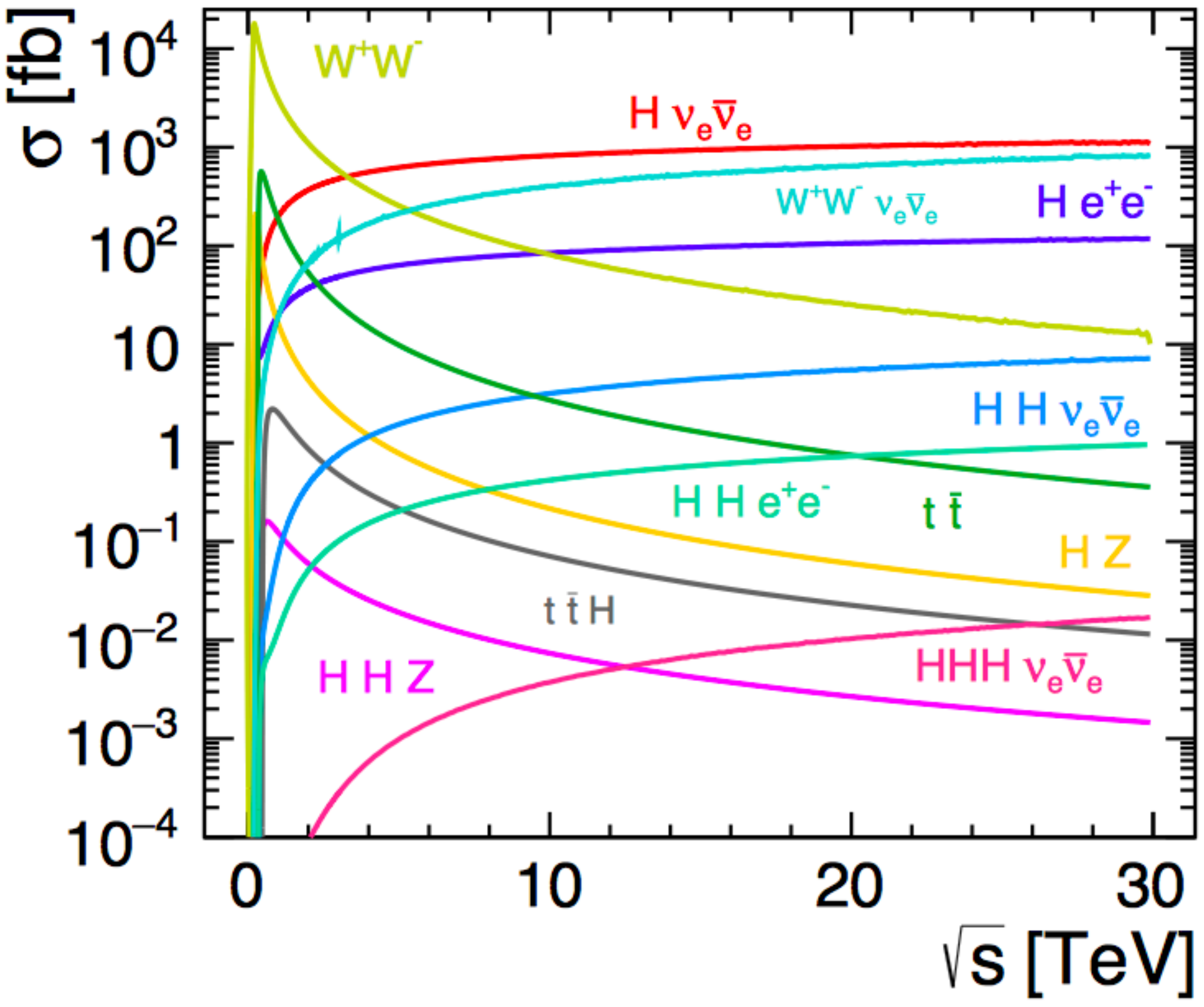
Energy reach & precision electroweak physics in same machine



$$\sigma \sim \frac{1}{E^2}$$

$$\sigma \sim \frac{1}{M^2} \log^2 \frac{E^2}{M}$$



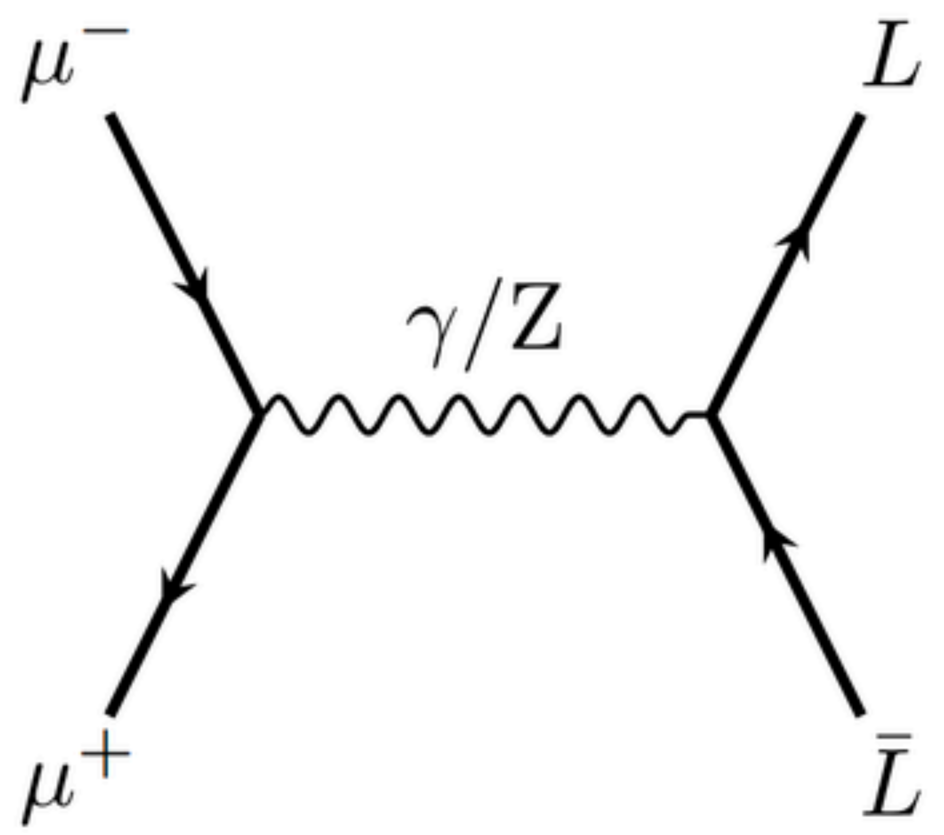


Sensitivity to new physics

2303.08533

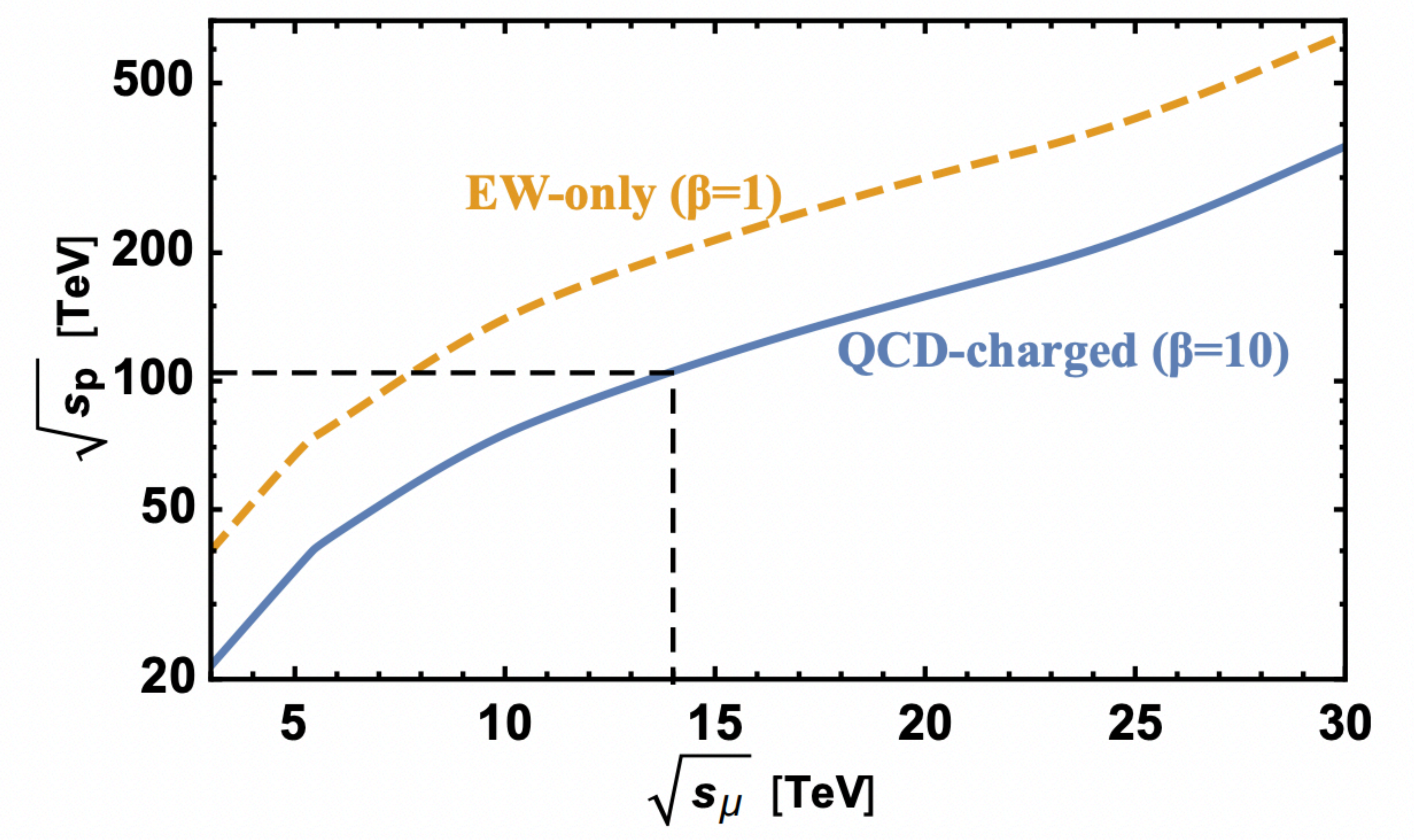
More complicated than 10 TeV μμ ~ 100 TeV pp

For 2x2 processes



$m_L \sim \sqrt{s_{\mu\mu}}/2$

"energy for which cross-sections at the two colliders are equal"



Sensitivity to new physics

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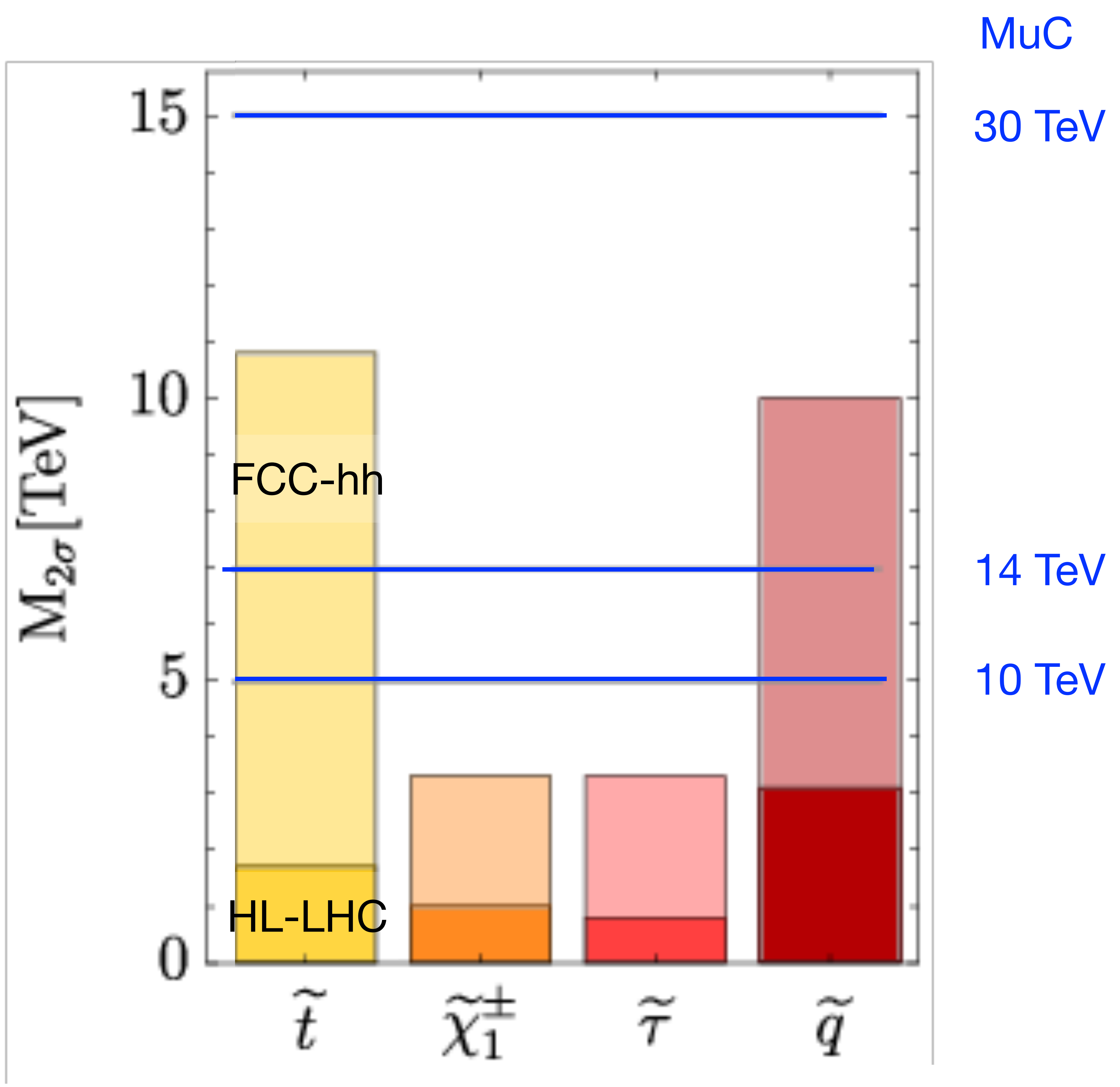
Example of Direct reach
Supersymmetry

MuC: pair-production up to $\sqrt{s}/2$

FCC-hh: better for stops (color charge)

But, most realistic models have TeV scale sleptons/electroweakinos



Sensitivity to new physics

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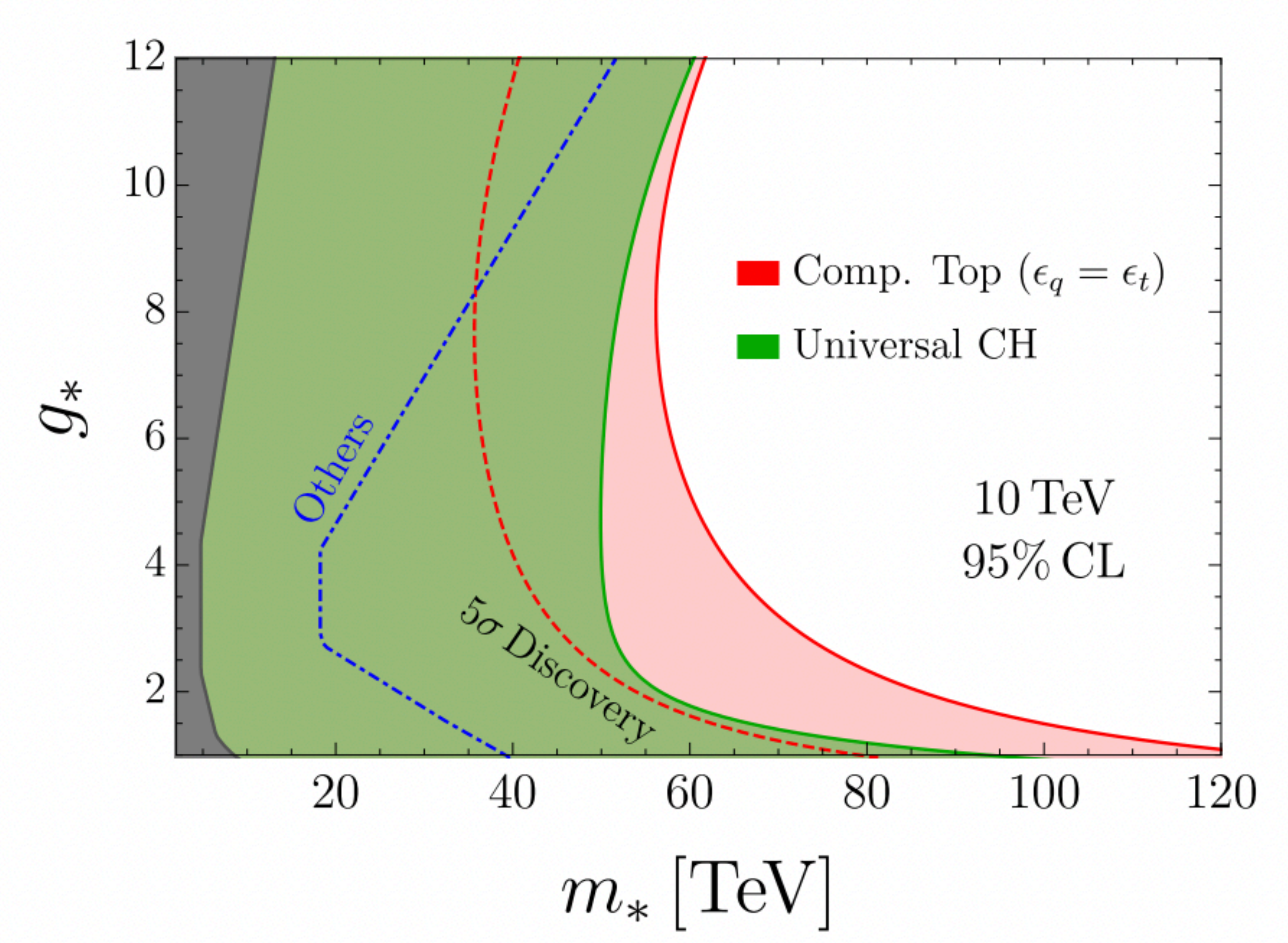
Example of Indirect Reach: Higgs Compositeness

Diboson & di-fermion final states

MuC: sensitivity scales with √s

FCC-hh: lower effective parton luminosity

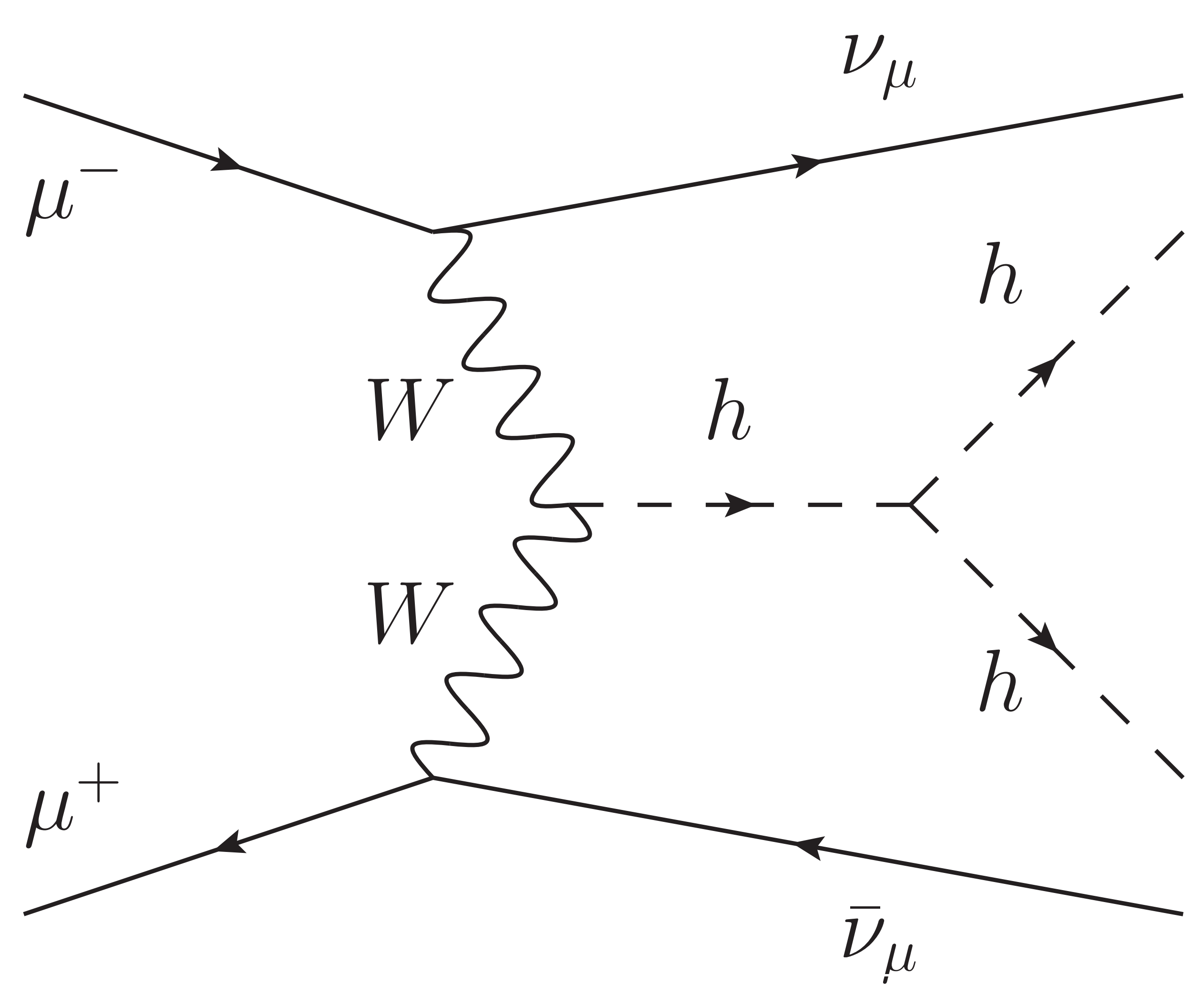
e^+e^-: negligible effects visible



Electroweak precision

1905.03764, 2203.09425, and 2212.11067

$\geq 10^7$ single higgs events → competitive with e+e- Higgs Factories
~10k di-higgs events → self-coupling competitive with 100 TeV pp



O(100) GeV scale SM physics

foward muons/neutrinos

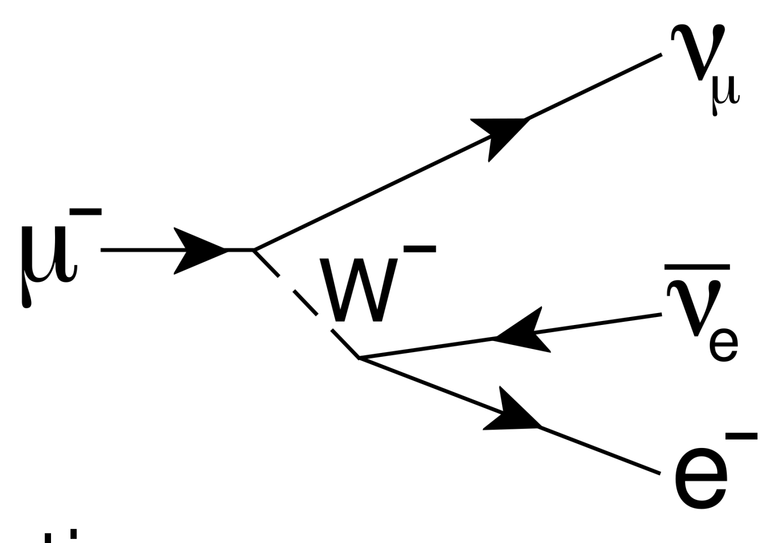
κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	1.4
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

And we can test *origin* of deviations!

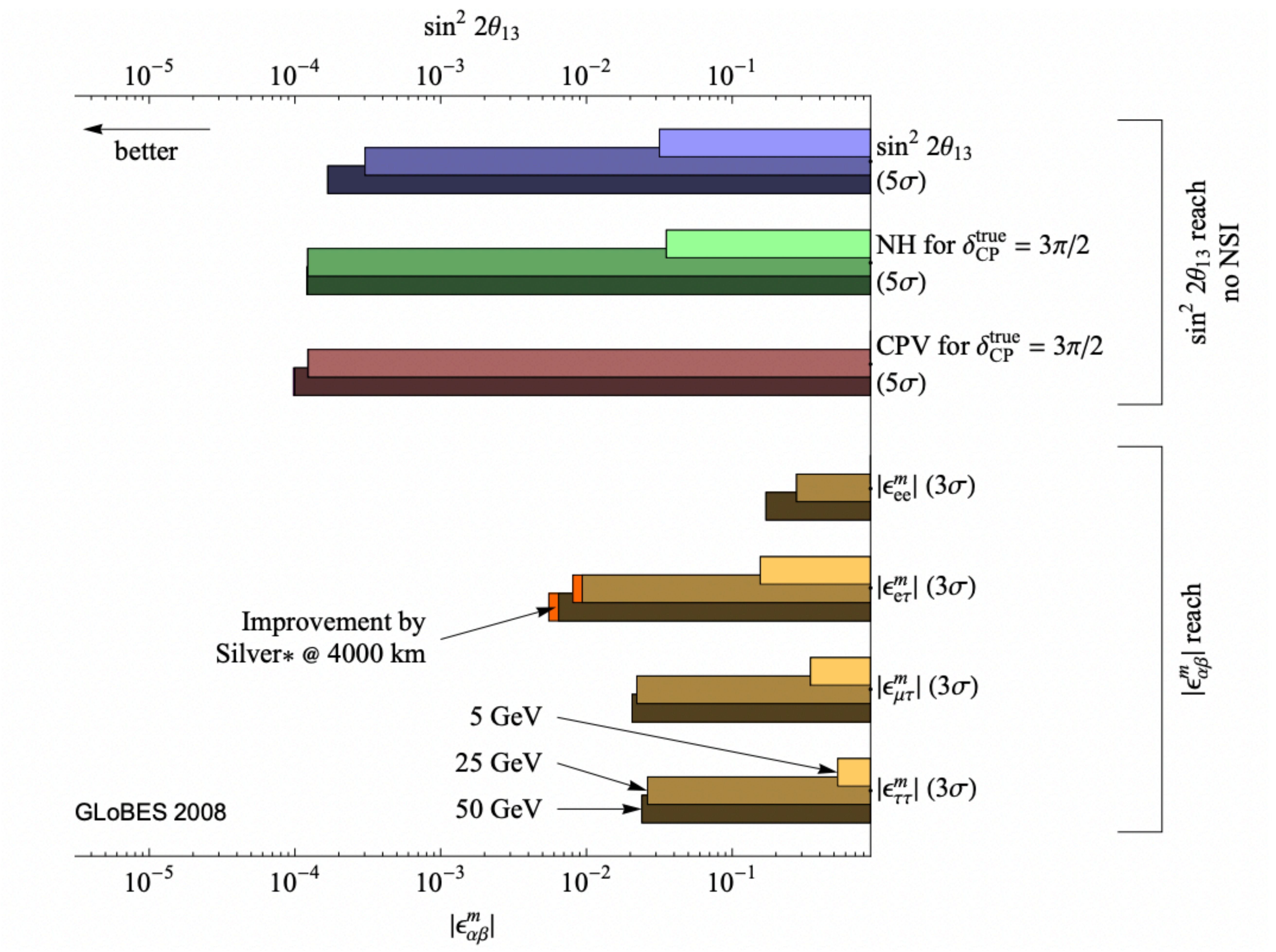
The perfect neutrino beam

2203.08094

Equal numbers of e/μ (anti-)neutrinos
Precisely known energy spectra & intensity



- At low energy:
  - precision cross sections
  - sterile neutrino searches
  - δ_{CP}, Δm^2_{31}, θ_{13}, θ_{23}, ν_τ appearance
  - Over constrain PMNS paradigm
- At high energy: not fully prepared to say
- An appealing future after Dune/Hyper-K?



Realistic Constraints?

2208.06030

Defer to accelerator experts

On the Feasibility of Future Colliders:
Report of the Snowmass'21 Implementation Task Force

Thomas Roser,[1] Reinhard Brinkmann,[2] Sarah Cousineau,[3] Dmitri Denisov,[1] Spencer Gessner,[4] Steve Gourlay,[5,6] Philippe Lebrun,[7] Meenakshi Narain,[8] Katsunobu Oide,[9] Tor Raubenheimer,[4] John Seeman,[4] Vladimir Shiltsev,[6] Jim Strait,[5,6] Marlene Turner,[5] Lian-Tao Wang.[10]

- Energy and Luminosity Reach, and Achievable Science
- Size, Complexity, and Environmental Impact
- Technical Risk and Technical Readiness
- Parametric Cost Estimates and Schedule

The verdict

2208.06030

- e+e- Higgs Factories "(nearly) shovel ready"
- For 10 TeV scale colliders
  - We don't have the technology today & we're not ready to make any decisions
  - We should begin R&D for $\mu^+\mu^-$ AND pp colliders as soon as possible
- "We urge to give high priority to the R&D topics aimed at the reduction of the cost and the energy consumption of future collider projects"

Collider	√s (TeV)	Tunnel (km)	Power (MW)	Cost ($B)	Time to start (yrs)
ILC e+e-	0.24	20	140	7-12	<12
FCC-ee	0.24	100	290	12-18	13-18
μ-3	3	10	230	7-12	19-24
CLIC	3	50	550	18-30	19-24
μ-10	10	16	300	12-18	>25
FCC-hh	100	100	560	30-50	>25

*Cost without contingency/escalation
**Technically limited timelines
***No staging assumed

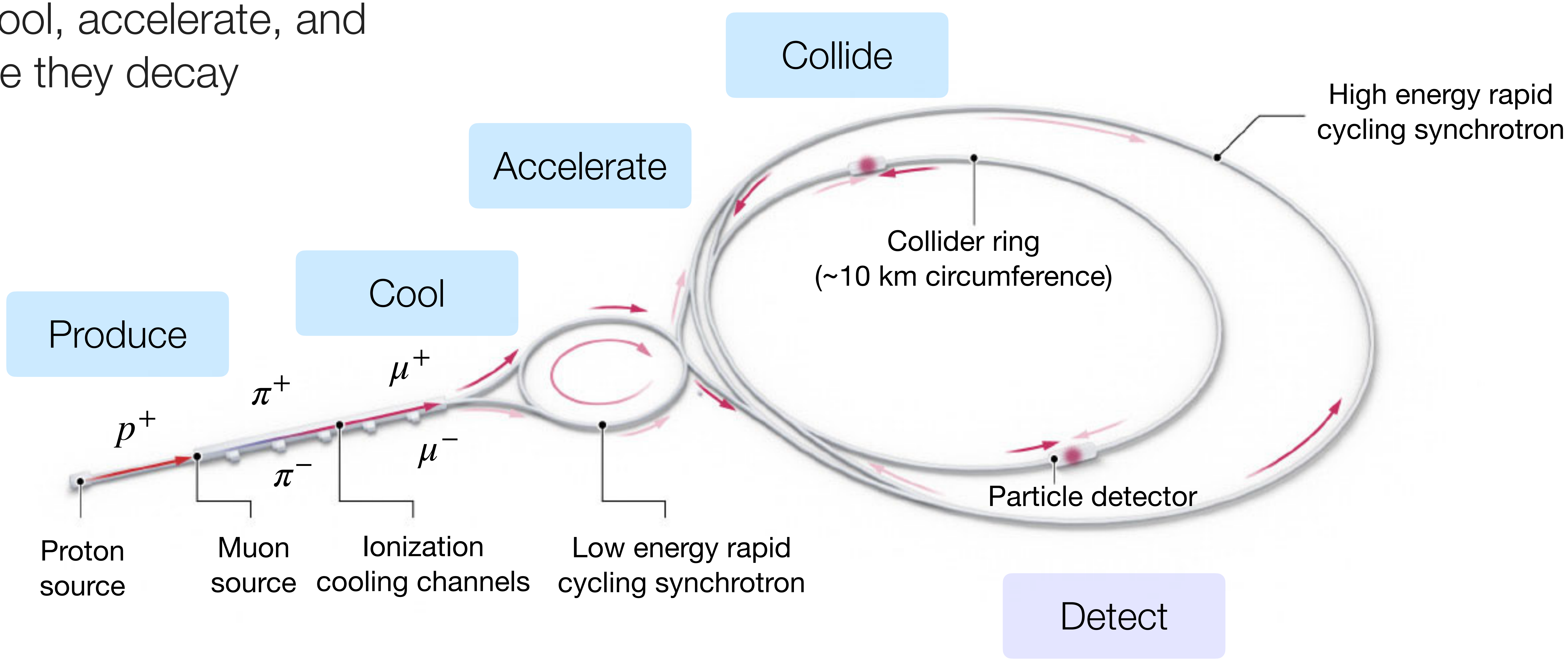
Can we build it

Technical challenges posed by the muon lifetime

The Challenge

Muon lifetime τ=2.2 μs

Need to produce, cool, accelerate, and collide muons before they decay



My focus

Design requirements

Depends on energy, physics goals, and cross-sections

Goal: measure di-higgs cross-section (few fb) with few % uncertainty

Aim for 10 ab^{-1} in 5 years

$$\langle \mathscr{L}_{inst} \rangle = \frac{N_1 N_2 n_b f}{4\pi\sigma_x\sigma_y} = 2 \cdot 10^{35} cm^{-2} s^{-1}$$

Set $n_b = 1$ and maximize N_μ per bunch	$\sim 2 \cdot 10^{12}$ N_μ
Minimize circumference, maximize f	30 kHz
Minimize $\sigma_x\sigma_y$ beam size, aim for	~O(10) μm
Re-inject muons every βγτ	100 ms

Map these needs back on to proton source, cooling, etc

Proton driver

2209.01318

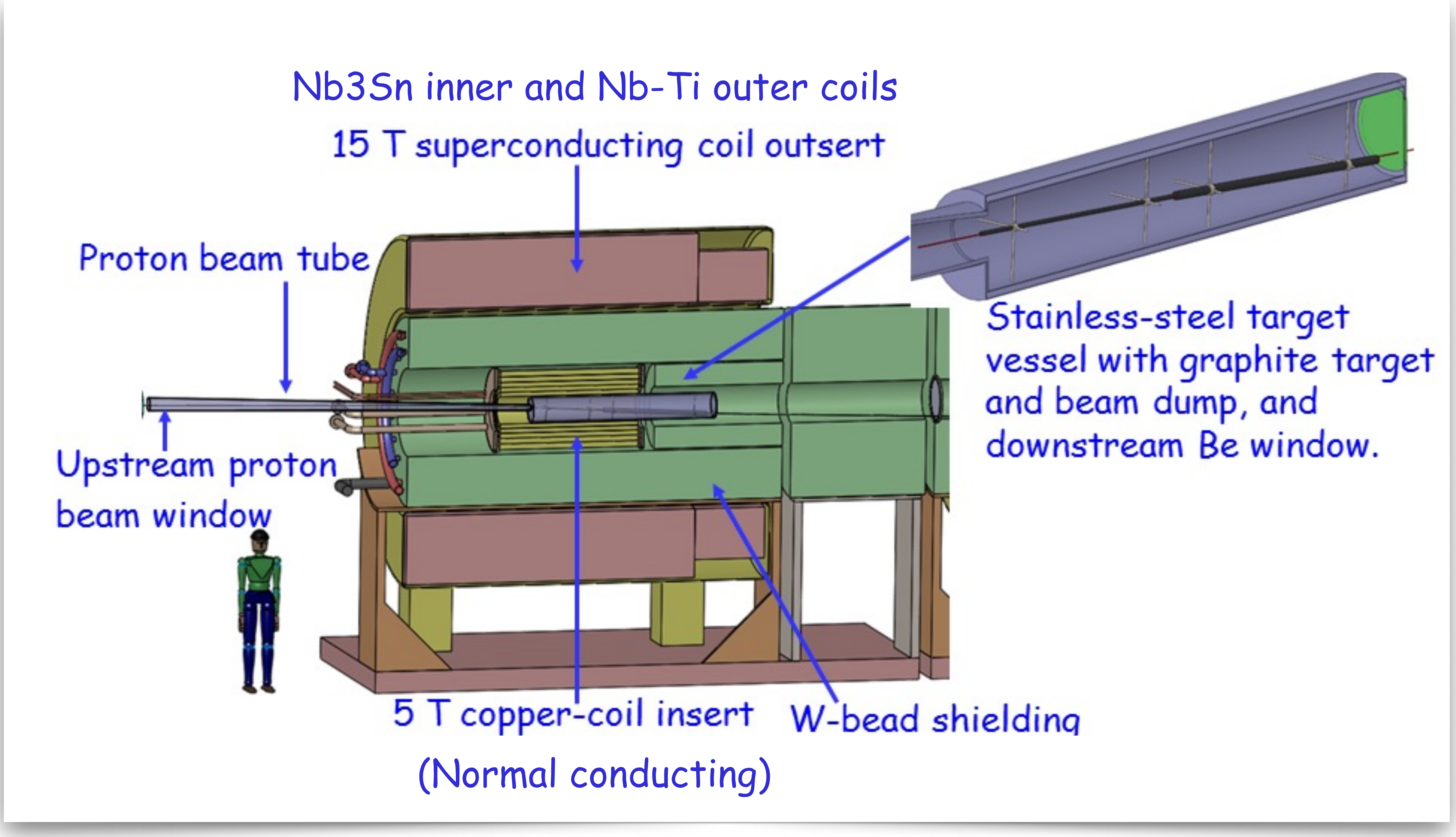
Goal is to deliver ~2e14 protons at 5-8 GeV and rate of ~10 Hz

Requirements:

- Proton source: 1-2 MW
- Accumulator & compressor: ~2ns bunches
- Target: shifted focus from liquid to solid (graphite)
- 20 T capture solenoid

Synergies:

- Spallation neutron and neutrino sources
- Charged lepton flavor violation experiments



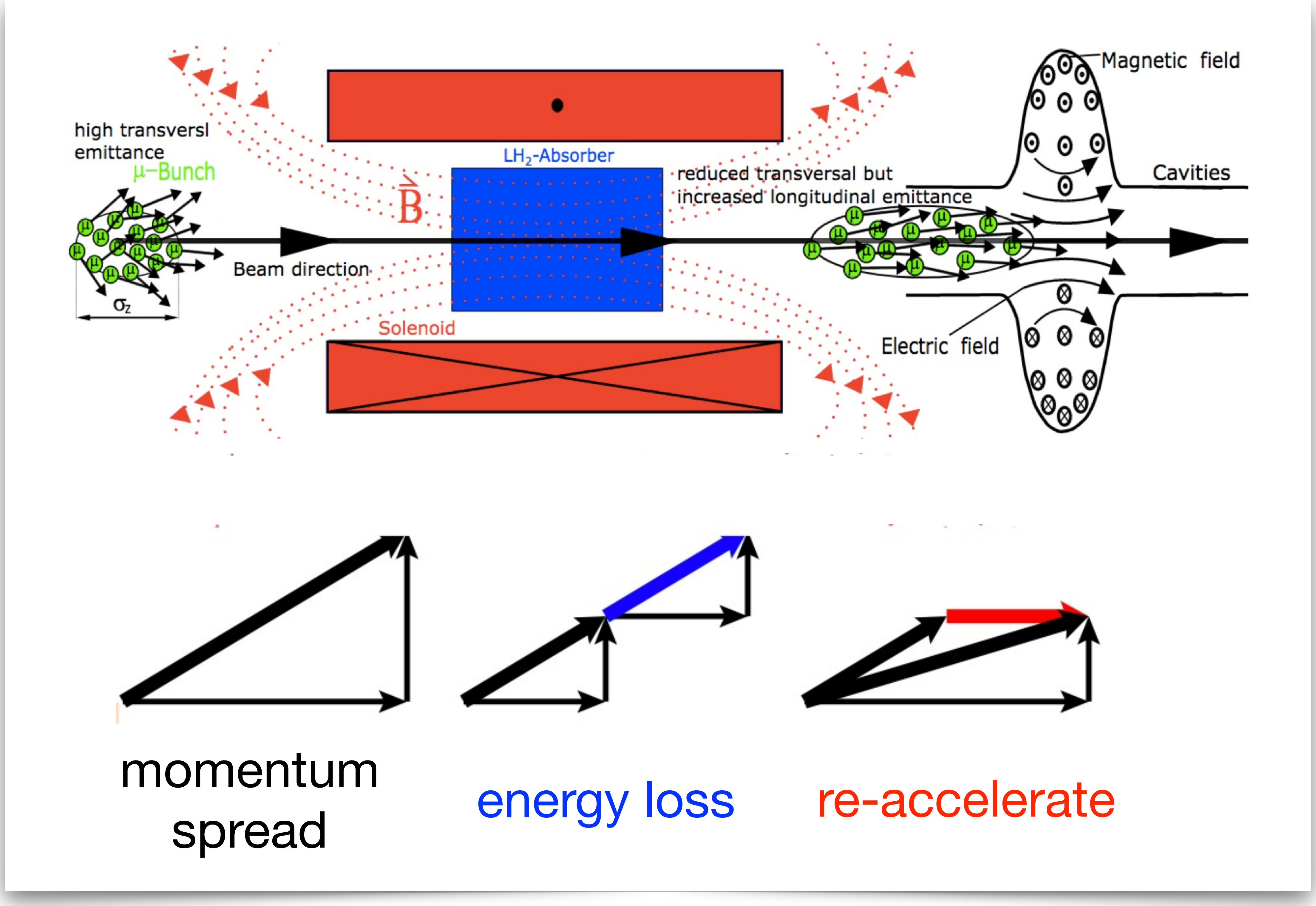
Ionization Cooling

Very rough concept: progressively reduce transverse momentum with low density absorber and restore lost longitudinal momentum with RF cavities

Status

- MAP end-to-end cooling design & simulation with realistic constraints within a factor of 2 of requirements
- MICE: Demonstration of single 4D cooling element
- Muon g-2: Demonstration of longitudinal cooling
- FNAL MuCool Test: RF-cavities in B-fields
- IMCC: improved lattice, test stands, demonstrator designs in progress

6D Cooling demonstrator critical if we want to move forwards with a Muon Collider



Accelerator and Collider Rings

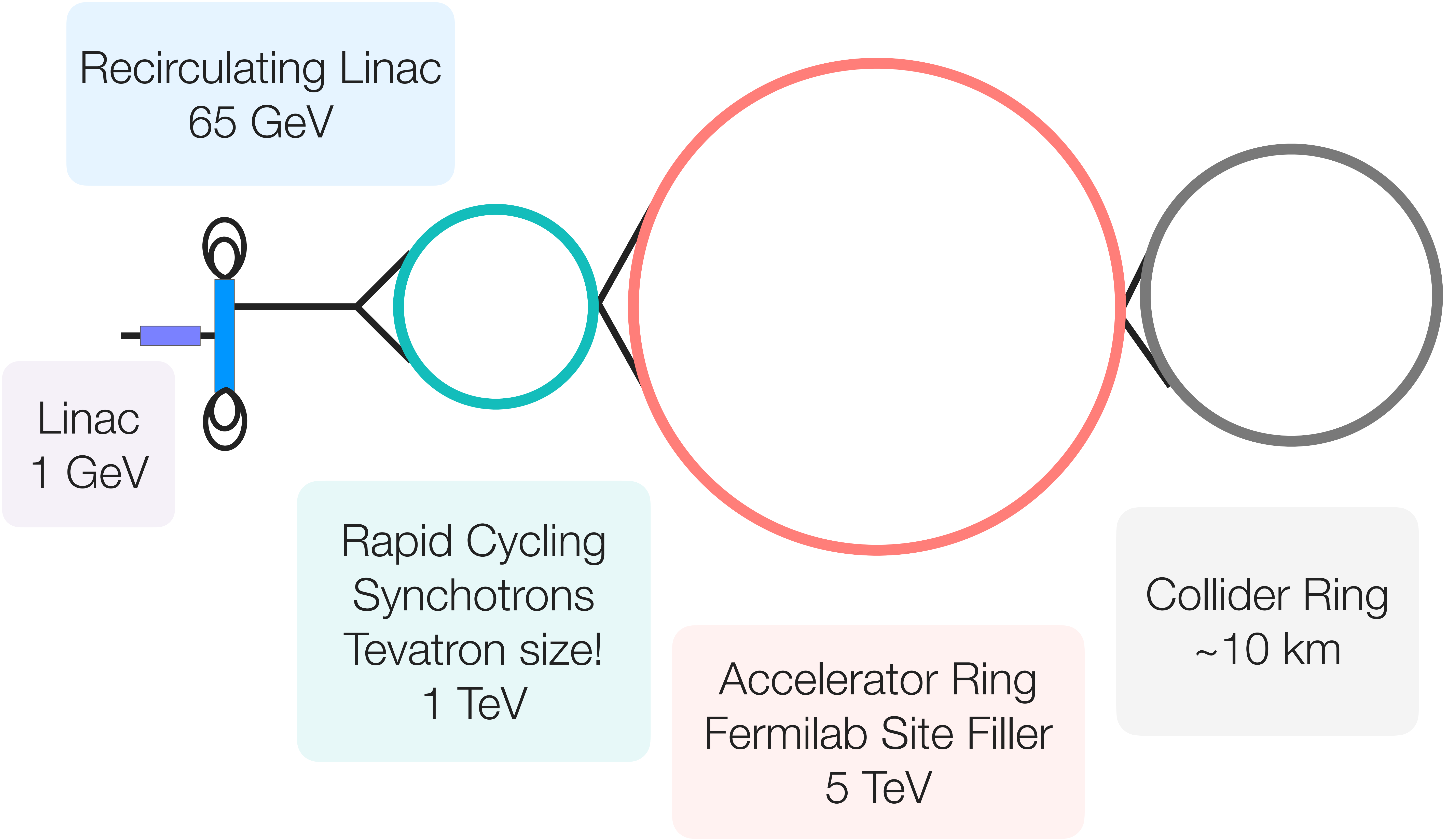
2209.01318

Accelerator

- Normal conducting fast ramping dipoles: ~1.5 T in around 1 ms
- Challenge: max field & power supplies

Collider:

- Circulate two bunches
- Re-fill when depleted
- Minimize size to maximize $N_{collisions}$
- 10 km ring, 16 T dipoles, ~2000 turns
- Large aperture magnets (15-20 cm) to accommodate shielding & prevent quenches



Neutrino Flux

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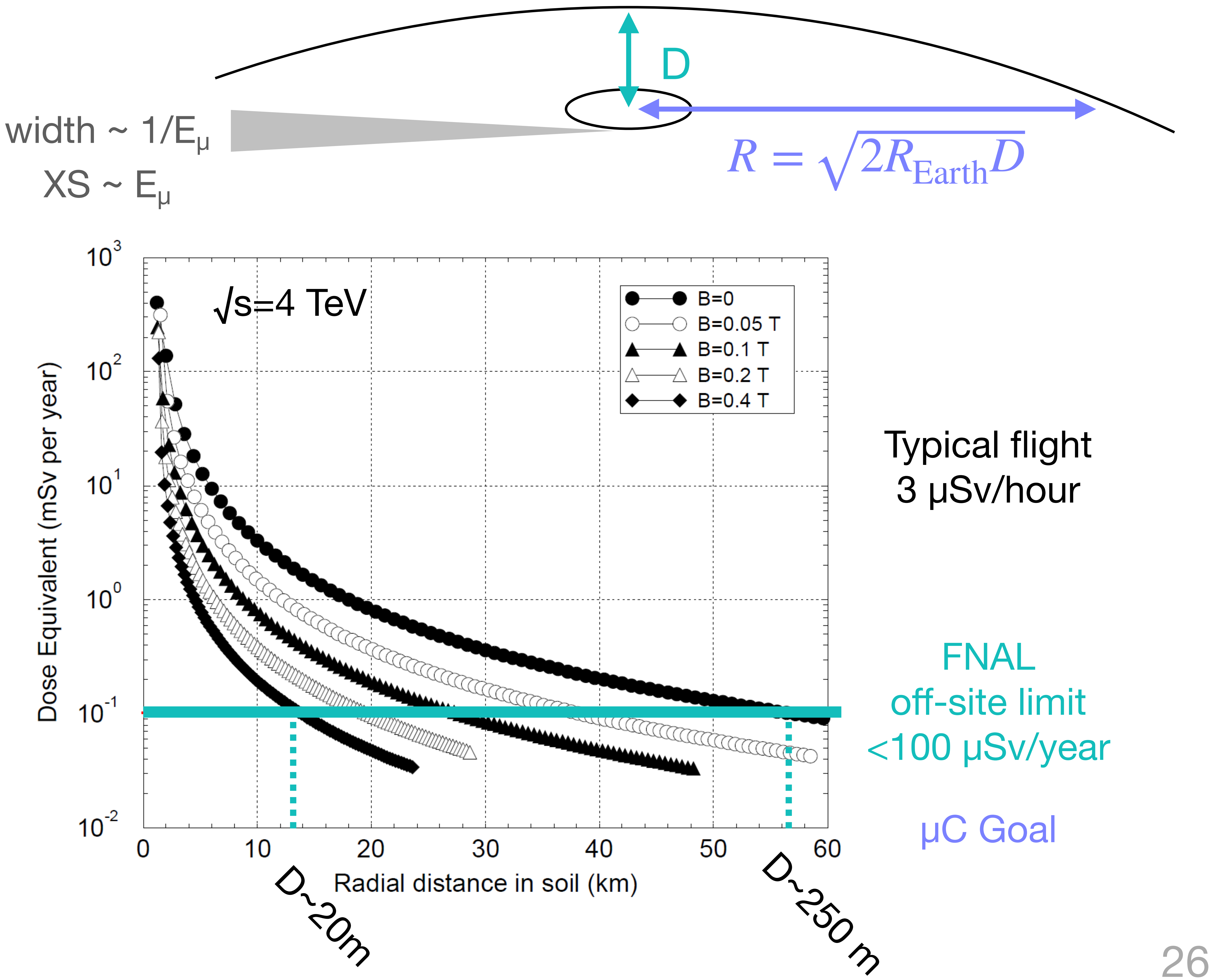
Challenge: TeV neutrinos interacting between the beam and you

Mitigation strategies exist!

- Depth 200 m
- Minimize field free regions
- “Beam wobbling” with B-field and/or high precision movers
  - ~1 cm 10x reduction
  - ~10 cm 100x reduction
- Better cooling/final focusing



Can we build it?

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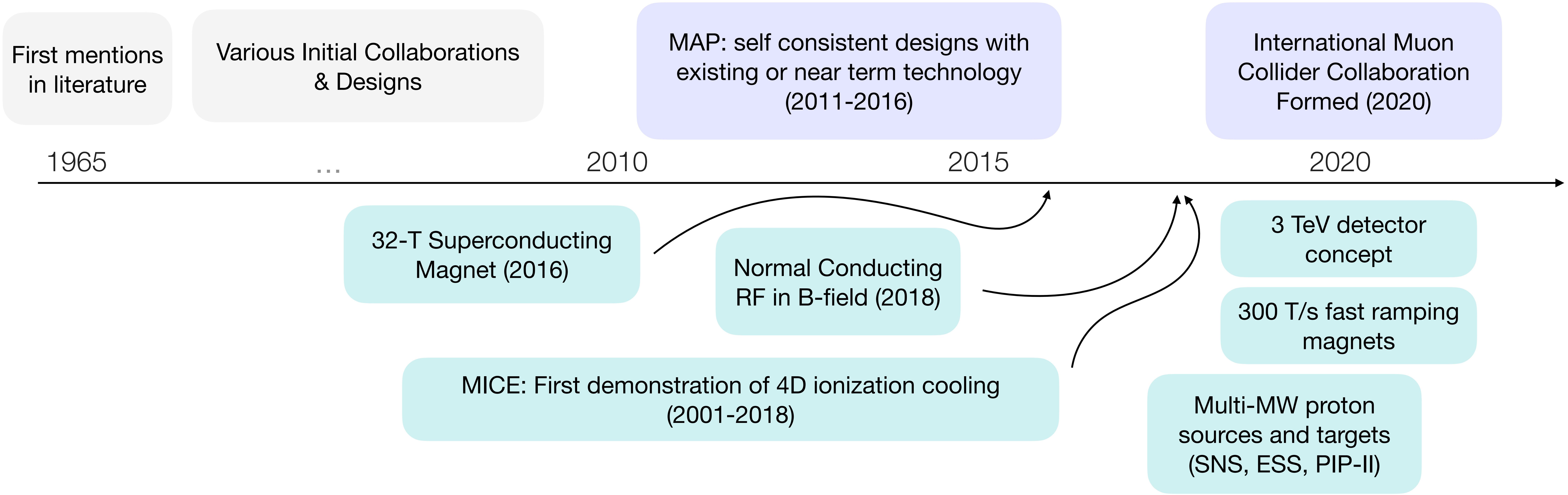
Recent progress in design and technology put a muon collider on a 20 year “*technically limited*” timeline!



Can we do physics

Technical challenges posed by beam induced backgrounds

Collision environment

Circulate two bunches & re-fill when depleted

Time between collisions: t=L/c = 30 kHz

Muons survive ~2000 turns

Beam induced background

Decays w/in 20 m of interaction point: ~10^7

Total energy of decay products: ~ 50 EeV

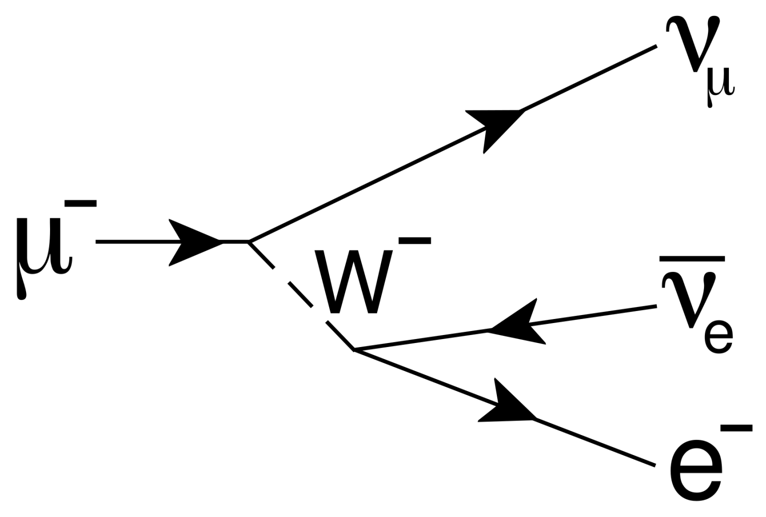
1000 x lower event rate than LHC

N_{decay} decrease with Energy

Total E_{decay} doesn't depend on Energy

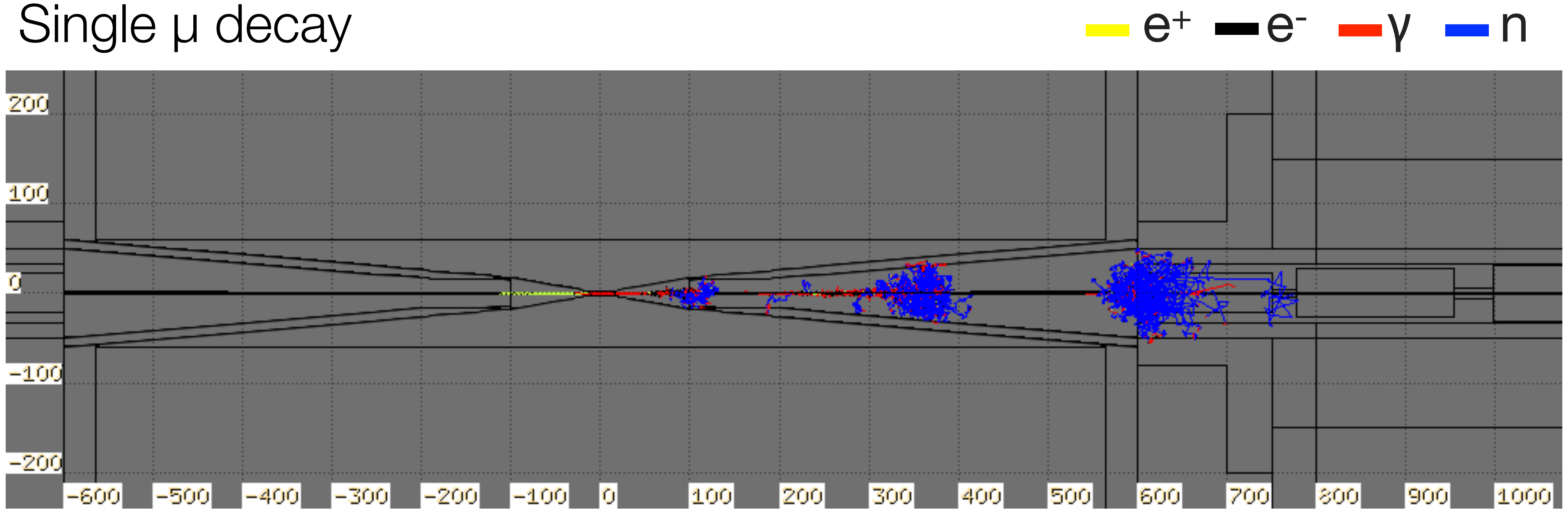
Unique need: Tungsten Nozzles

Suppress high energy component of **beam induced background**

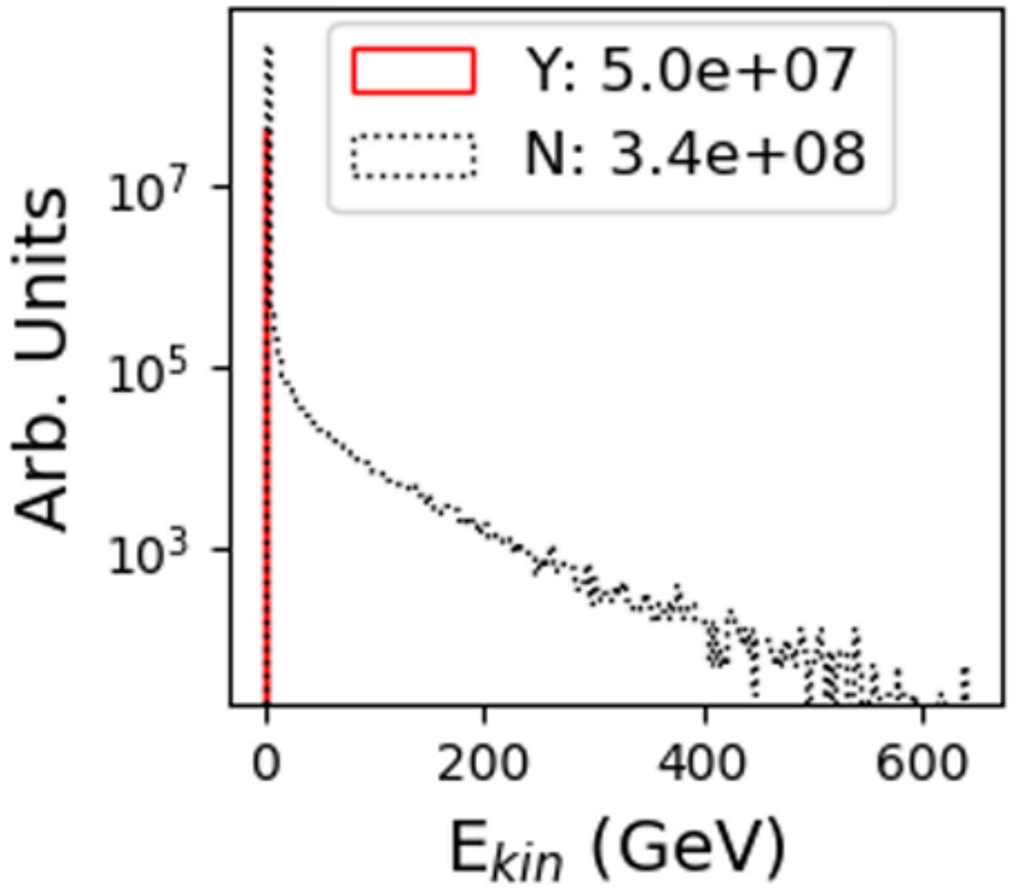


Tradeoff: increase in low energy neutrons

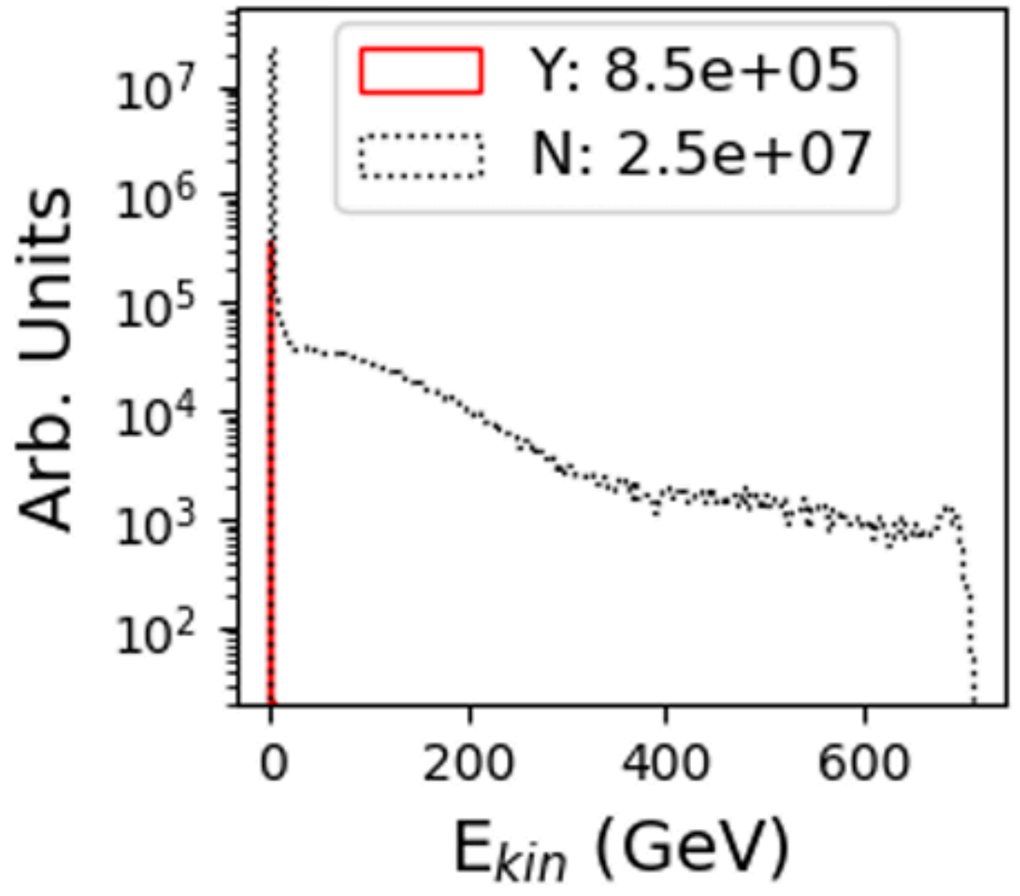
Single μ decay



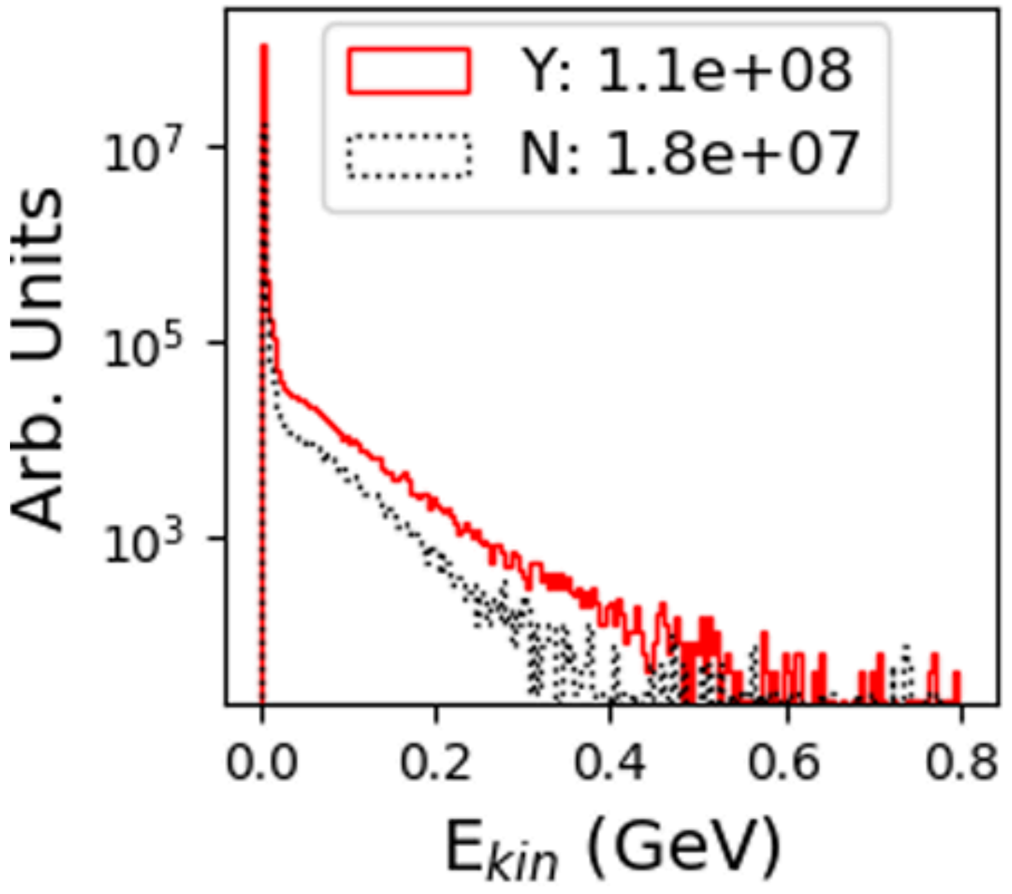
Photons



Electrons



Neutrons



What’s left over

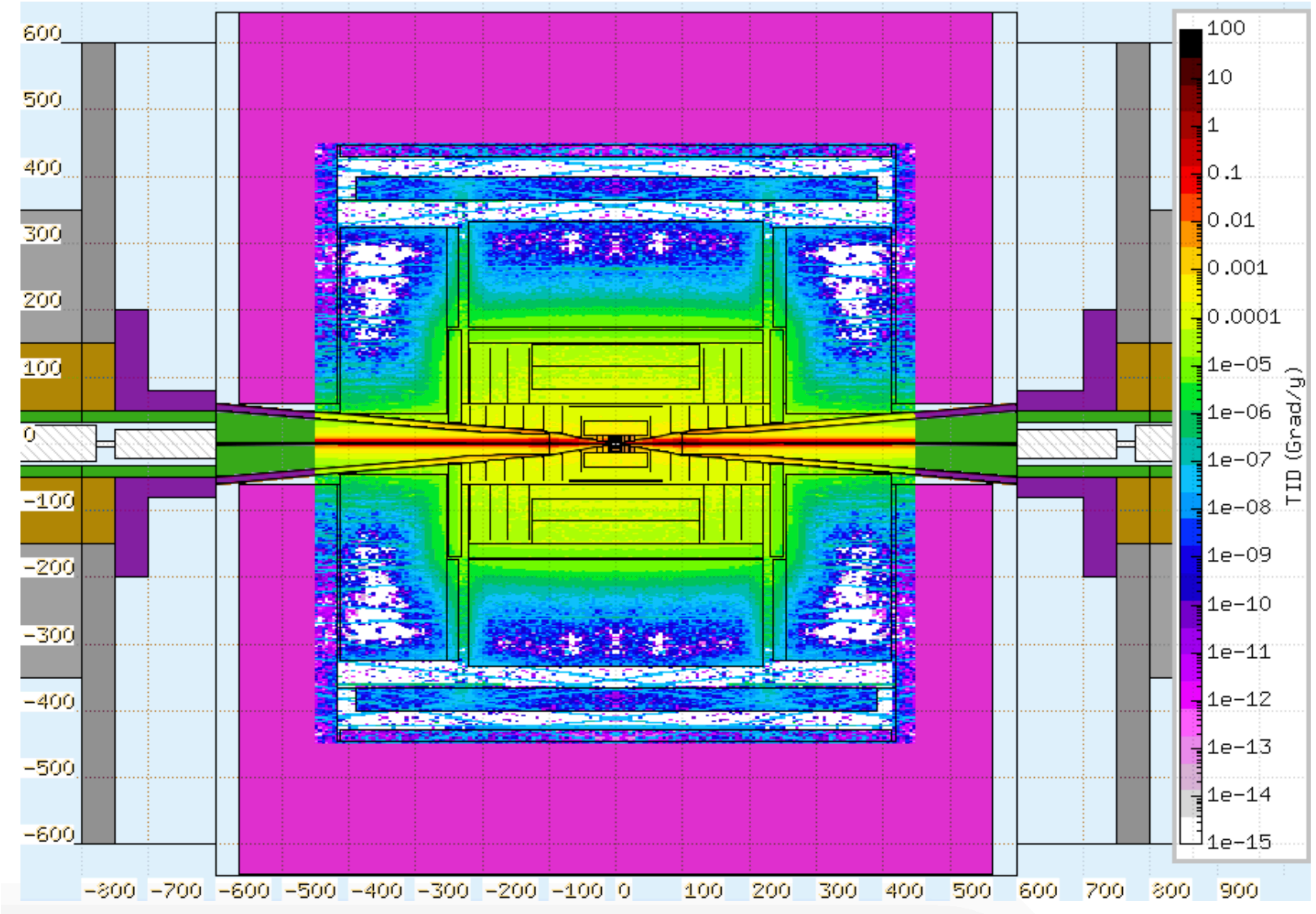
Compared to HL-LHC

Up to ~10 x hit density

~1/1000 event rate

Similar dose & fluence

100 TeV pp ~3 orders of magnitude worse
$\sim 10^{18}$ MeV-neq /cm^2



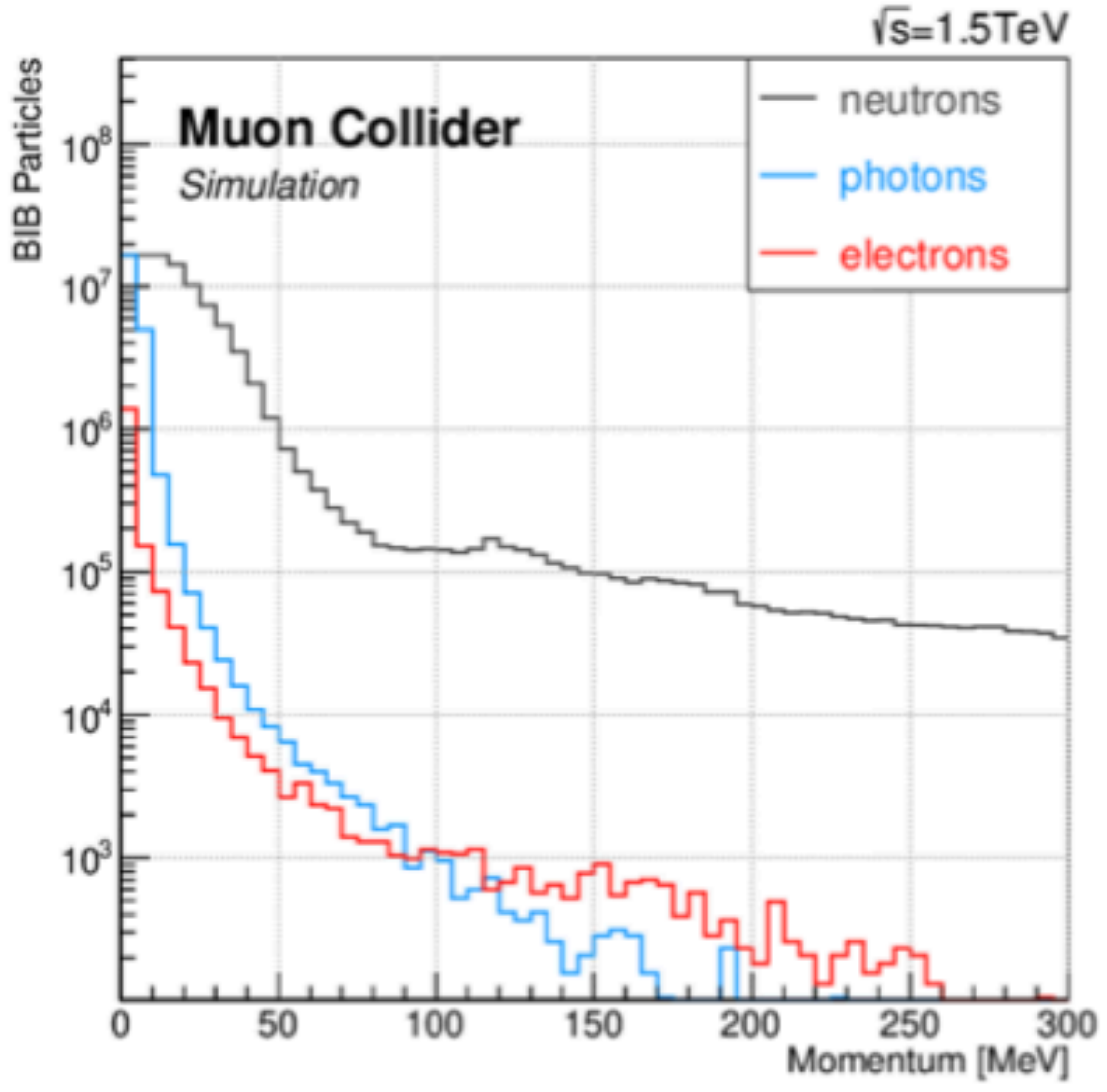
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

Background properties

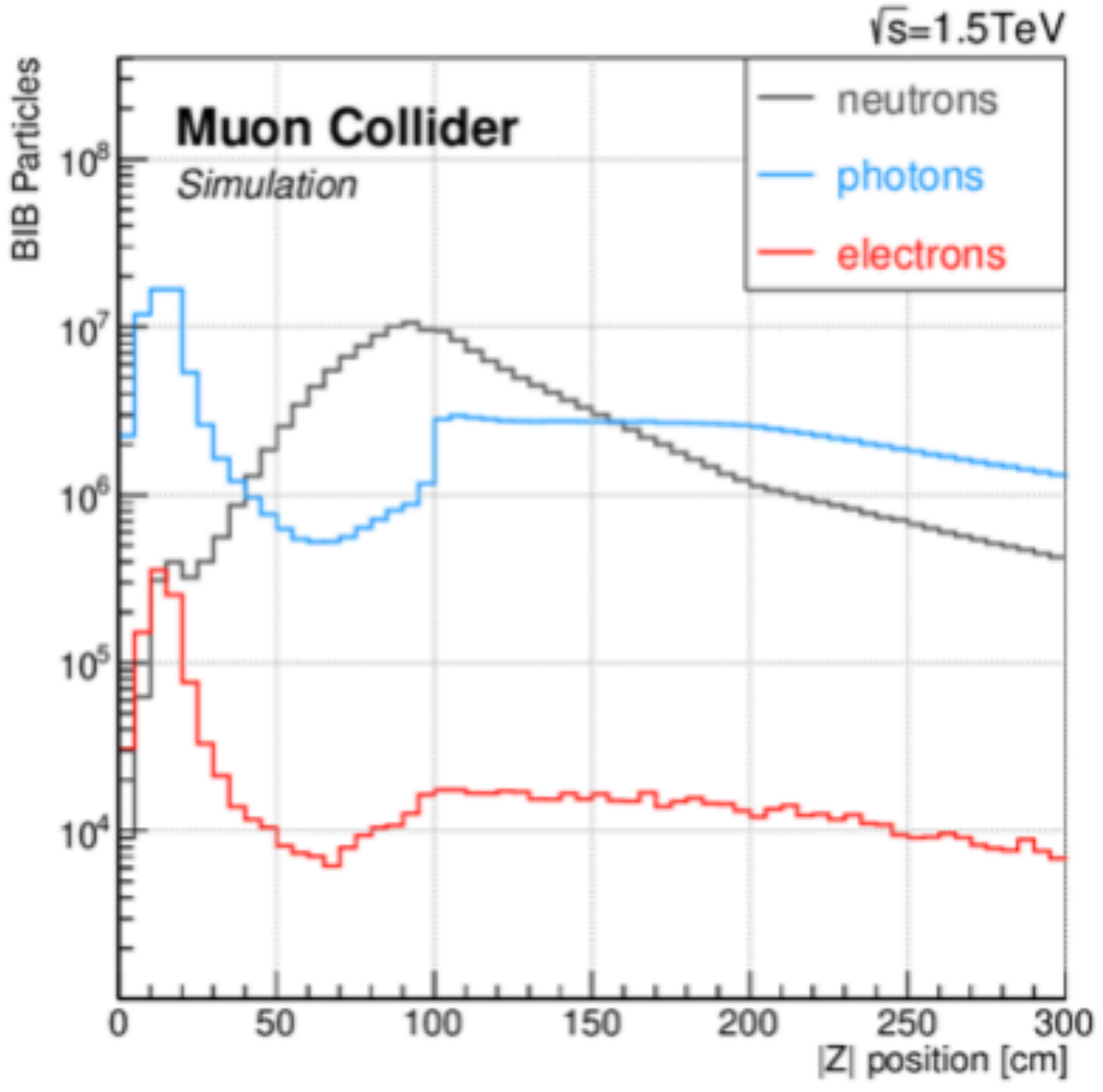
With standard nozzle ~10^8 low momentum particles per event

But this background looks very different from signal!

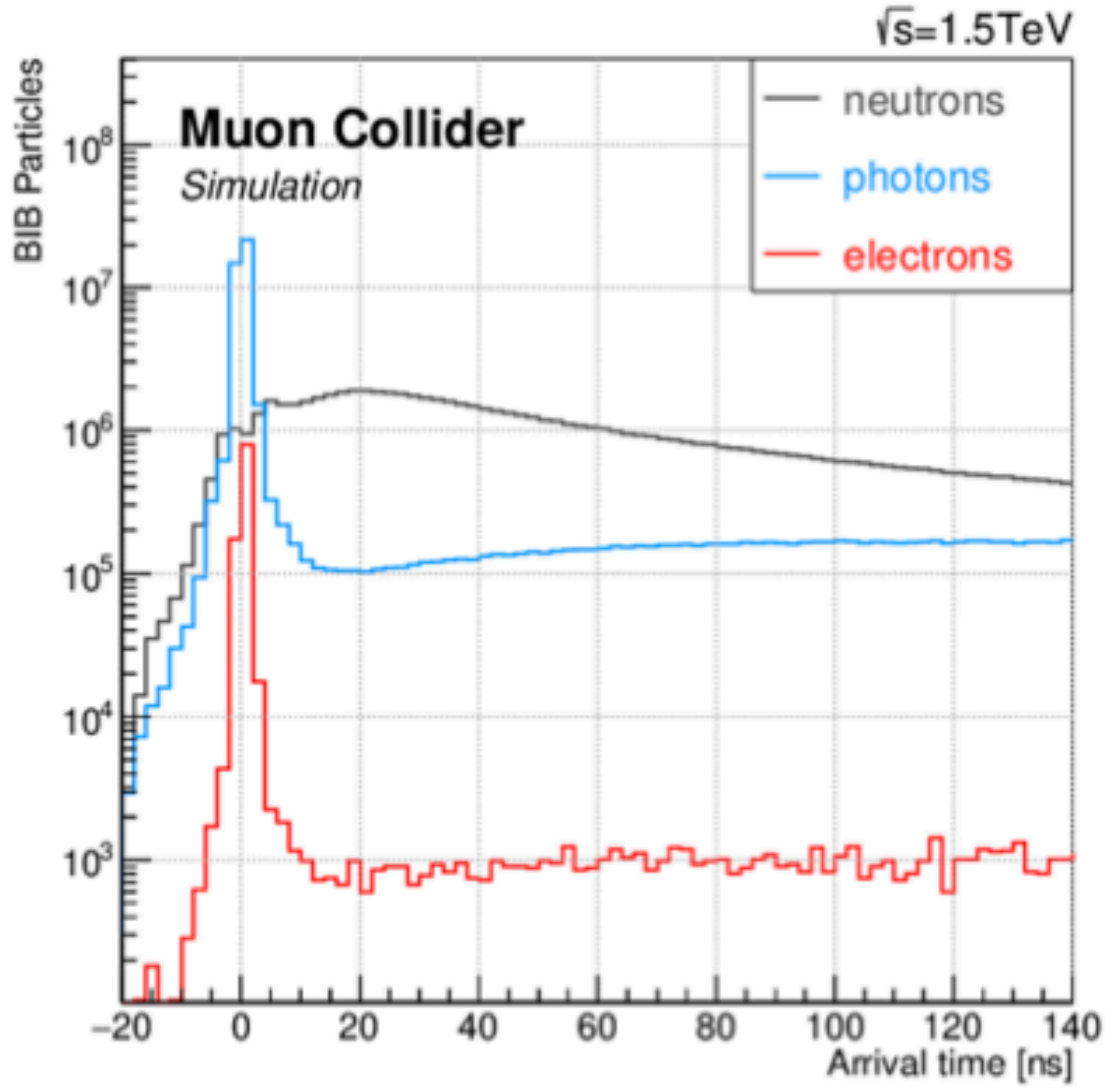
Majority < 200 MeV



Unusual position & direction

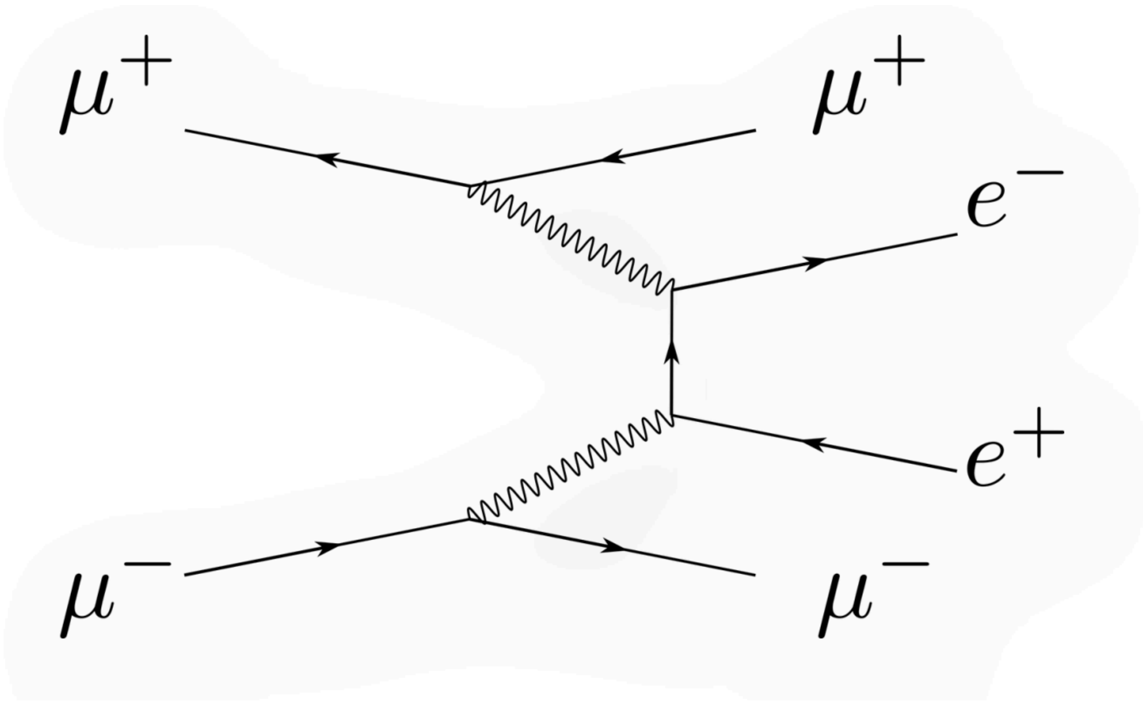


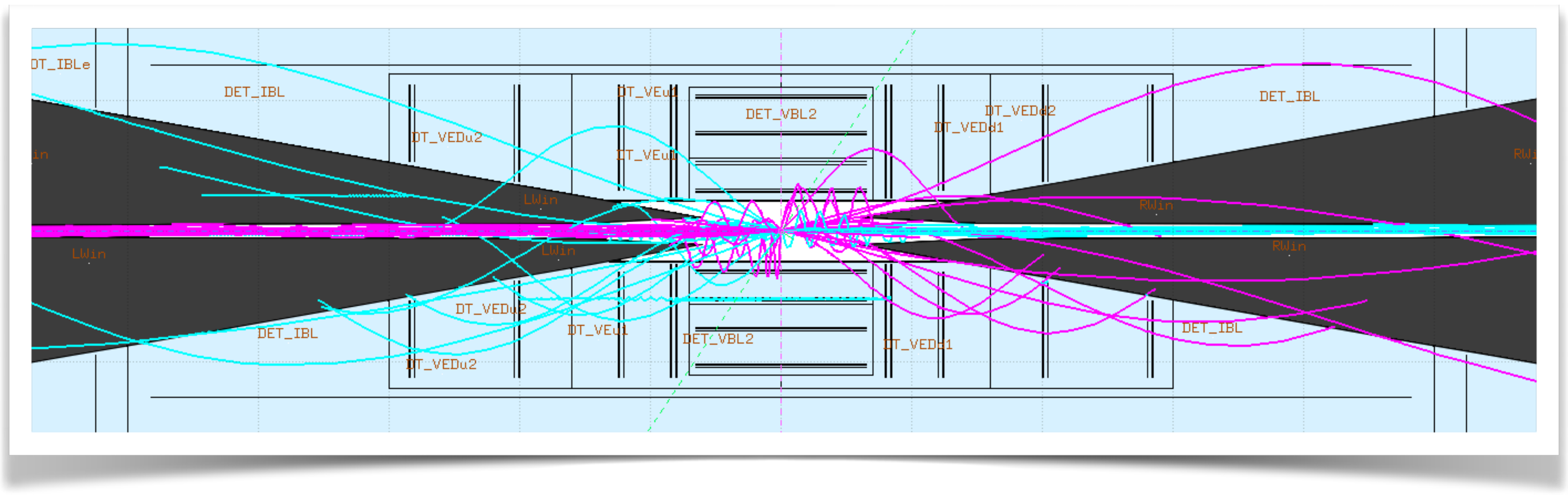
Partially out of time



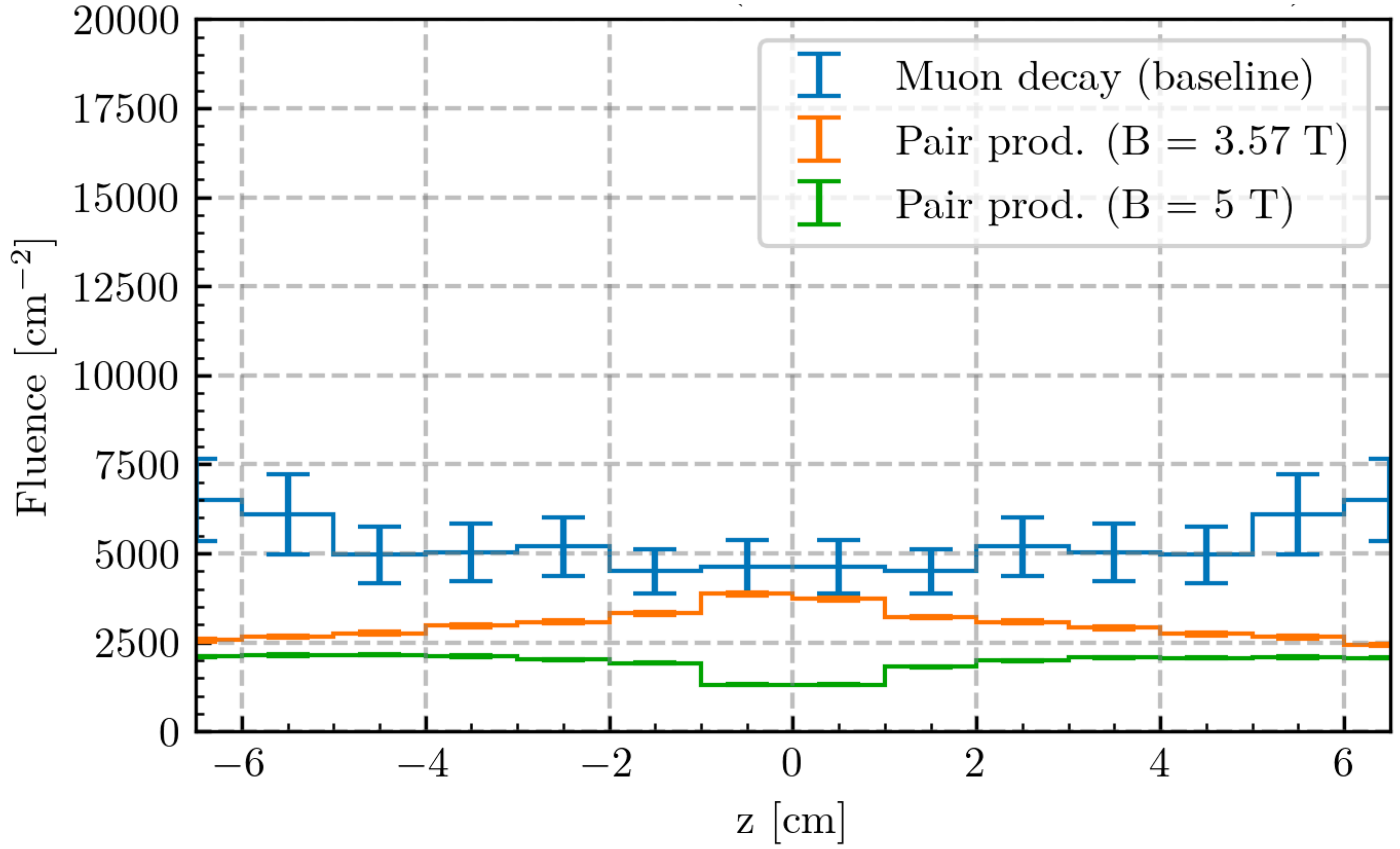
Another key background

Incoherent e+e- production from beamstrahlung





Fluence in the first layer



these particles are low energy and come from the IP

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

The Detector

Baseline design & next steps

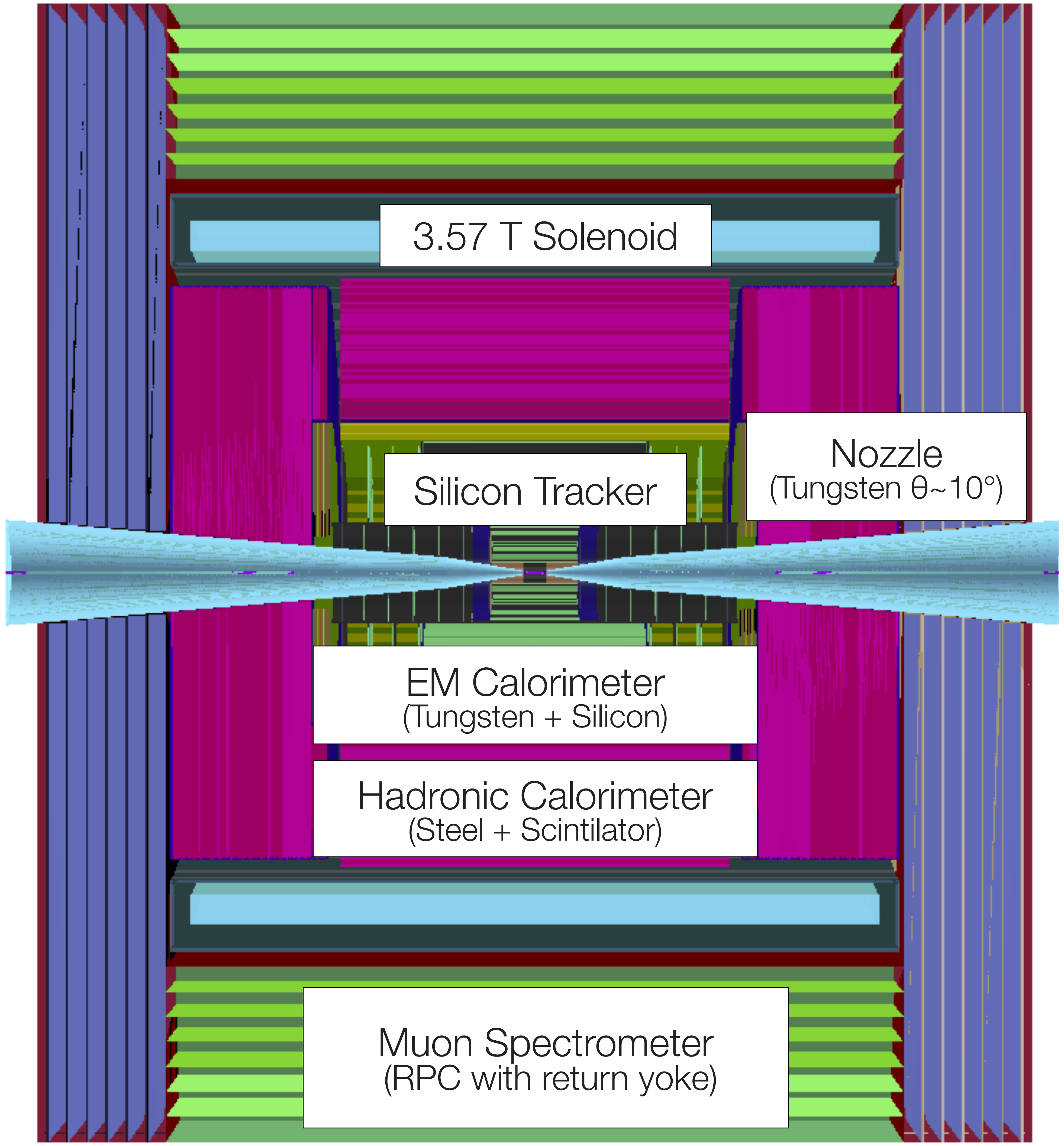
Baseline design for 3 TeV

2303.08533

Major outcome of IMCC/Snowmass

Beam Induced Background with FLUKA
Full simulation physics studies

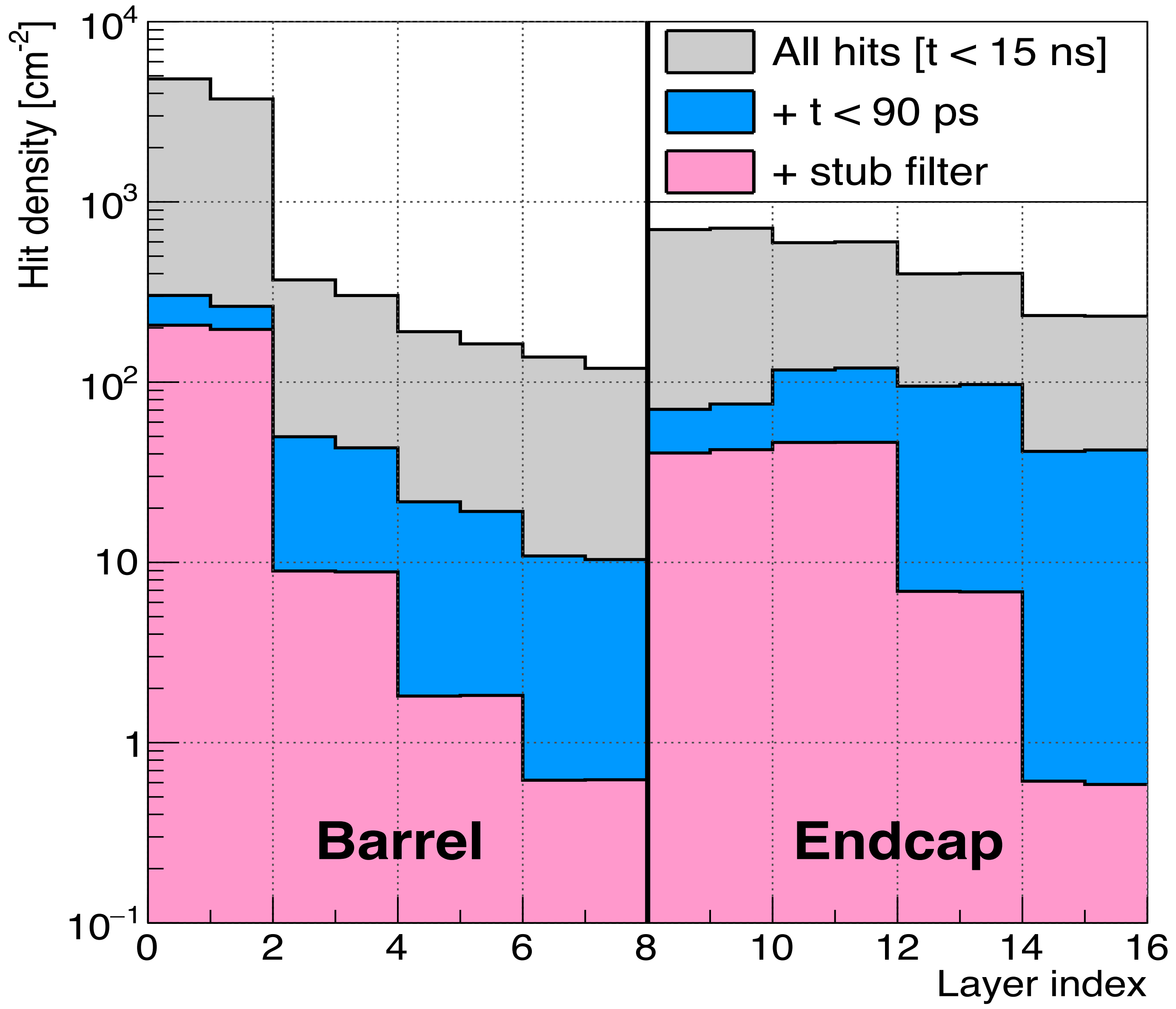
Rest of talk: what we've learned and next steps



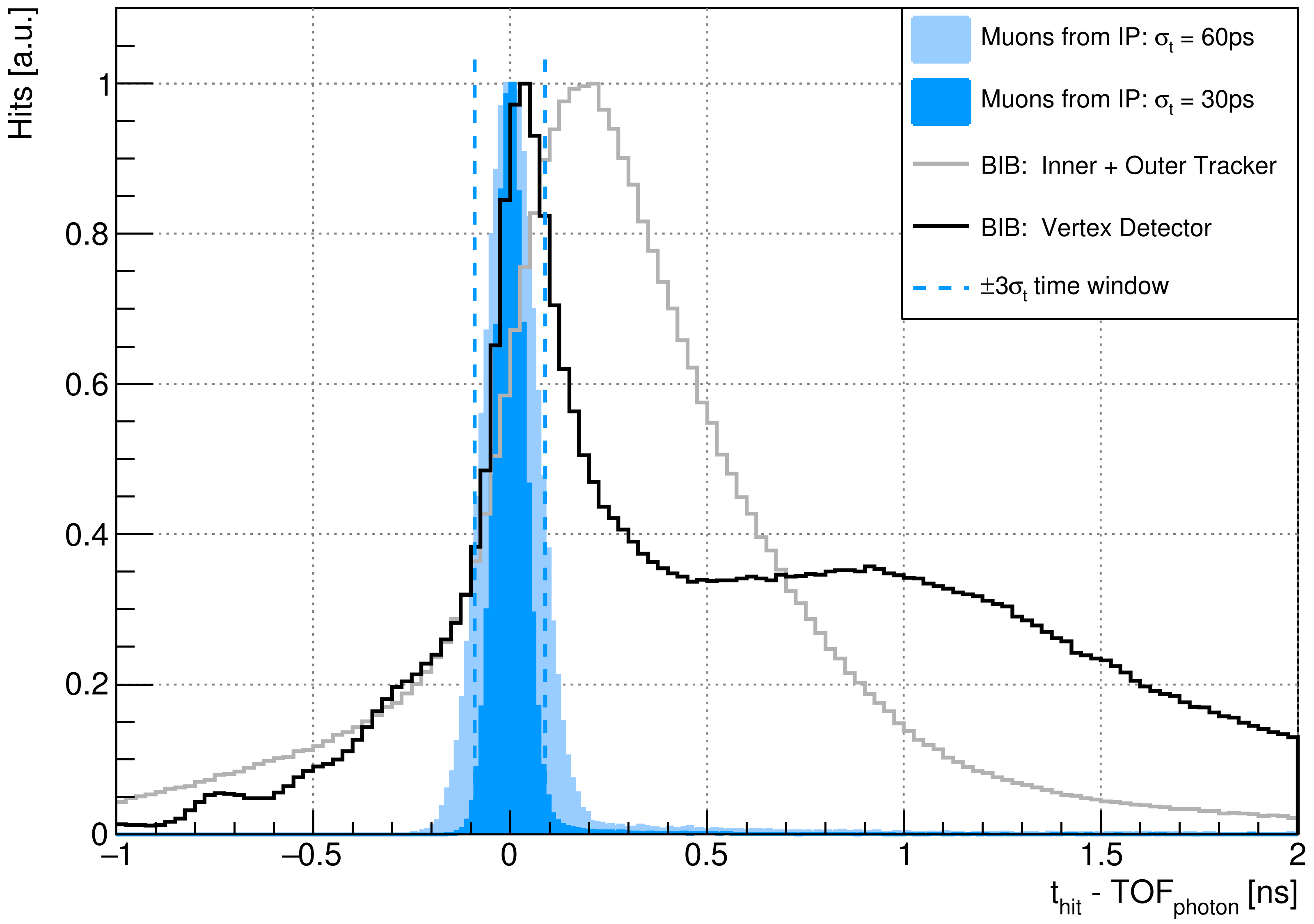
Backgrounds in the tracker

Occupancy most challenging for the innermost layers of the tracker

Optimize for <1% & leverage techniques from HL-LHC upgrades



Pixel sees O(100,000) BIB hits
compared to O(10-100) signal hits



Only readout hits in ~1 ns time window
Only select hits in ±3σ time window

Tracker design & needs

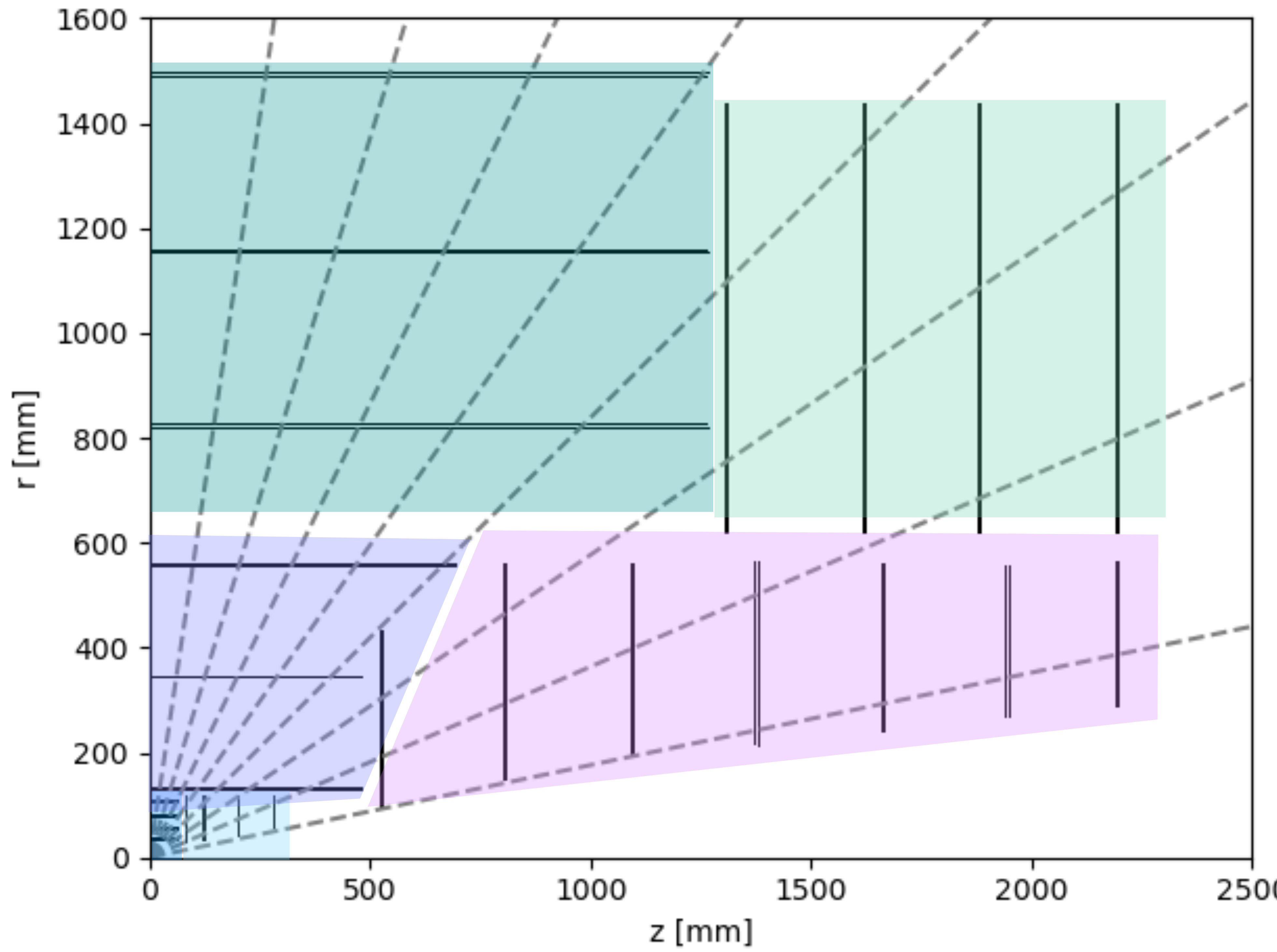
Large area & highly granular

~100 m^2 of silicon sensors
~ 2B channels

Challenges:

Power consumption
Readout

Sub detector	Size	Timing
Vertex Detector	25 x 25 µm^2	30 ps
Inner Tracker	50 µm x 1 mm	60 ps
Outer Tracker	50 µm x 10 mm	60 ps



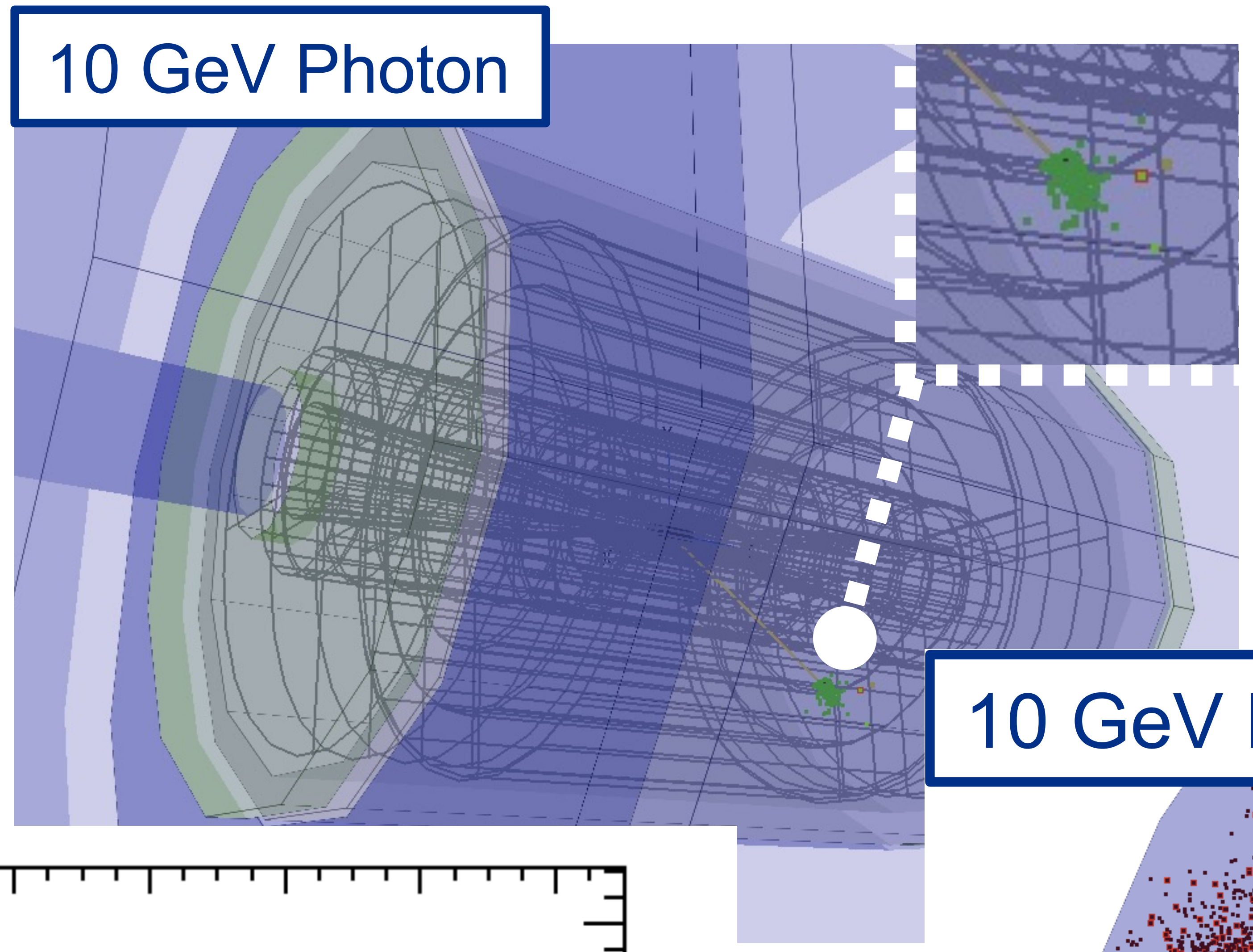
Backgrounds in the Calorimeter

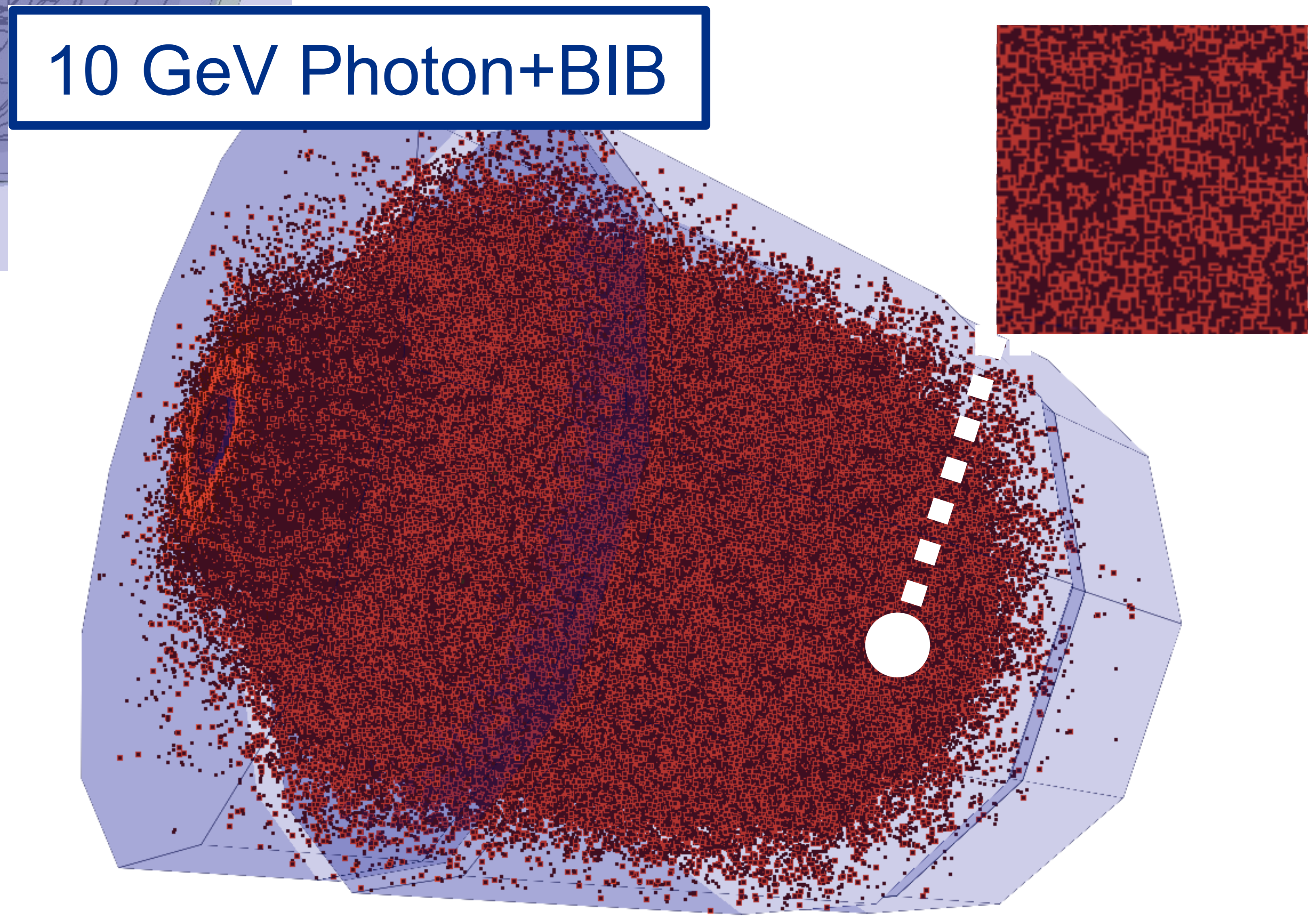
Diffuse, low energy, out of time

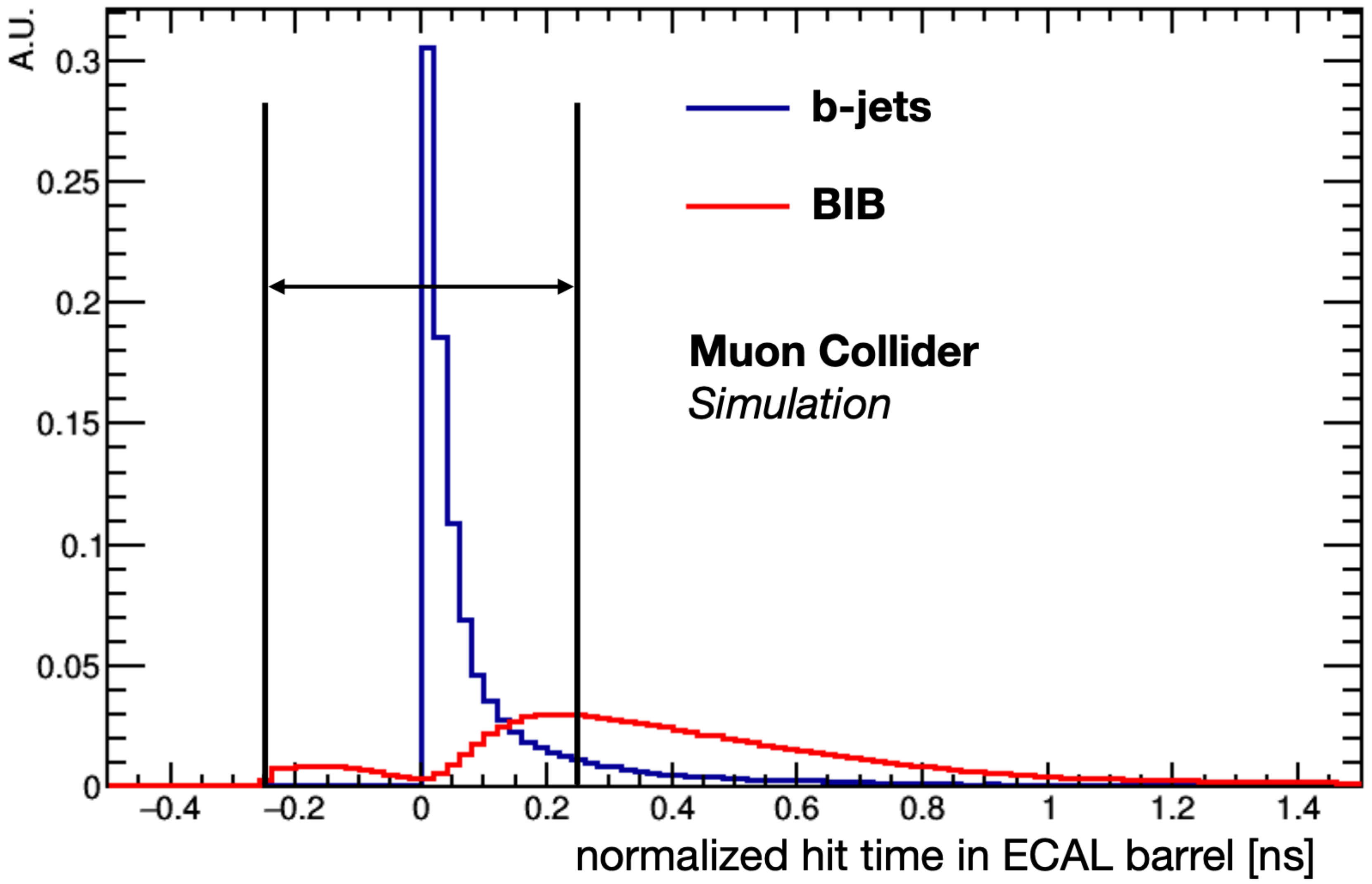
~2 MeV γ (96%) ~500 MeV n (4%)

Ambient E~50 GeV/unit area

Similar to LHC







Calorimeter design & needs

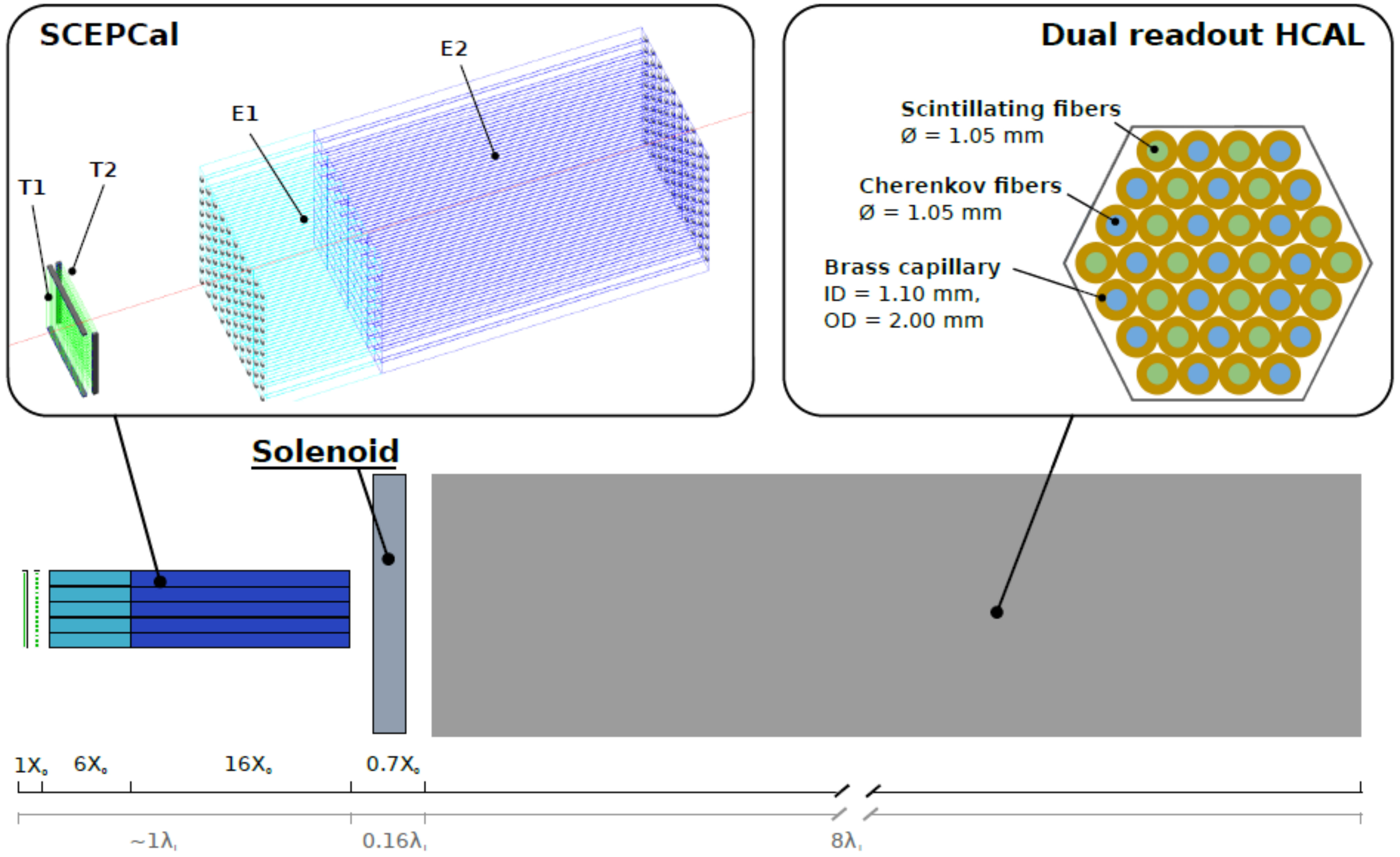
Current design assumes

ECAL: Silicon+Tungsten
5x5 mm^2 cell size

HCAL: Iron+Scintillator
30x30 mm^2 cell size

Timing resolution (~100 ps)
+ Longitudinal segmentation

Room for new ideas



e.g. Crilin, Calvision

Trigger/DAQ

2203.07224

Target “streaming” readout

- Total readout rate = same as the CMS HL-LHC max HLT input rate
- Reading out all BIB hits requires increased cabling, cooling
- Pushes the challenge from trigger to on-detector processing
- Event rate ~30 kHz → plenty of time to process full event off detector

	Readout Window	E Threshold	Hit Size	Total Rate
Tracker	1 ns	n/a	32 bits	~40 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

Work in progress: 10 TeV design

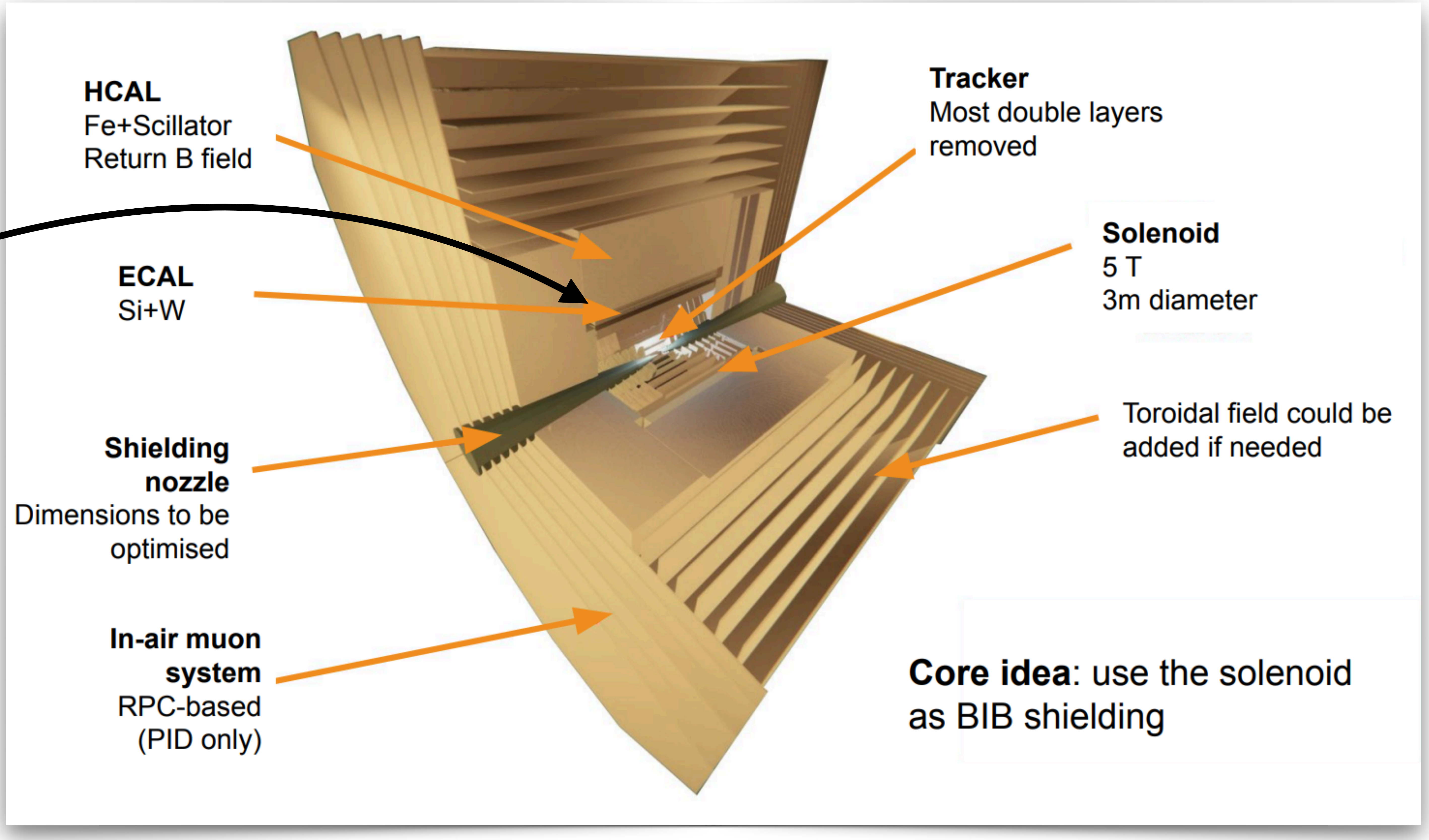
Detector Magnet Workshop
Summary by A. Bersani

Need to grow the detector

Solenoid: Higher B-field & inner radius technically challenging

$$E_{\text{stored}} = \frac{B^2}{2\mu_0}\pi R^2 L$$

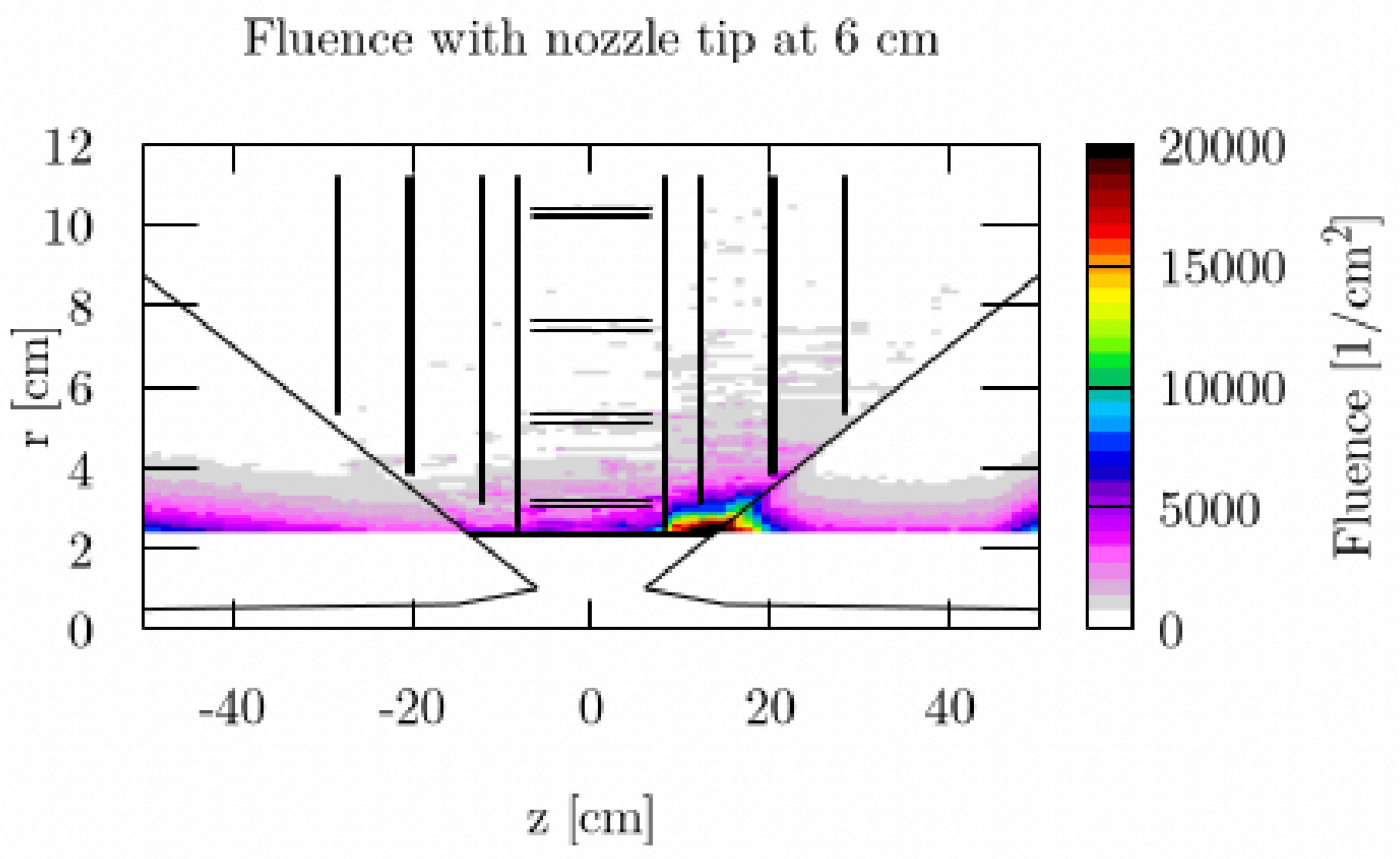
Need to reestablish expertise to build CMS-style magnets!

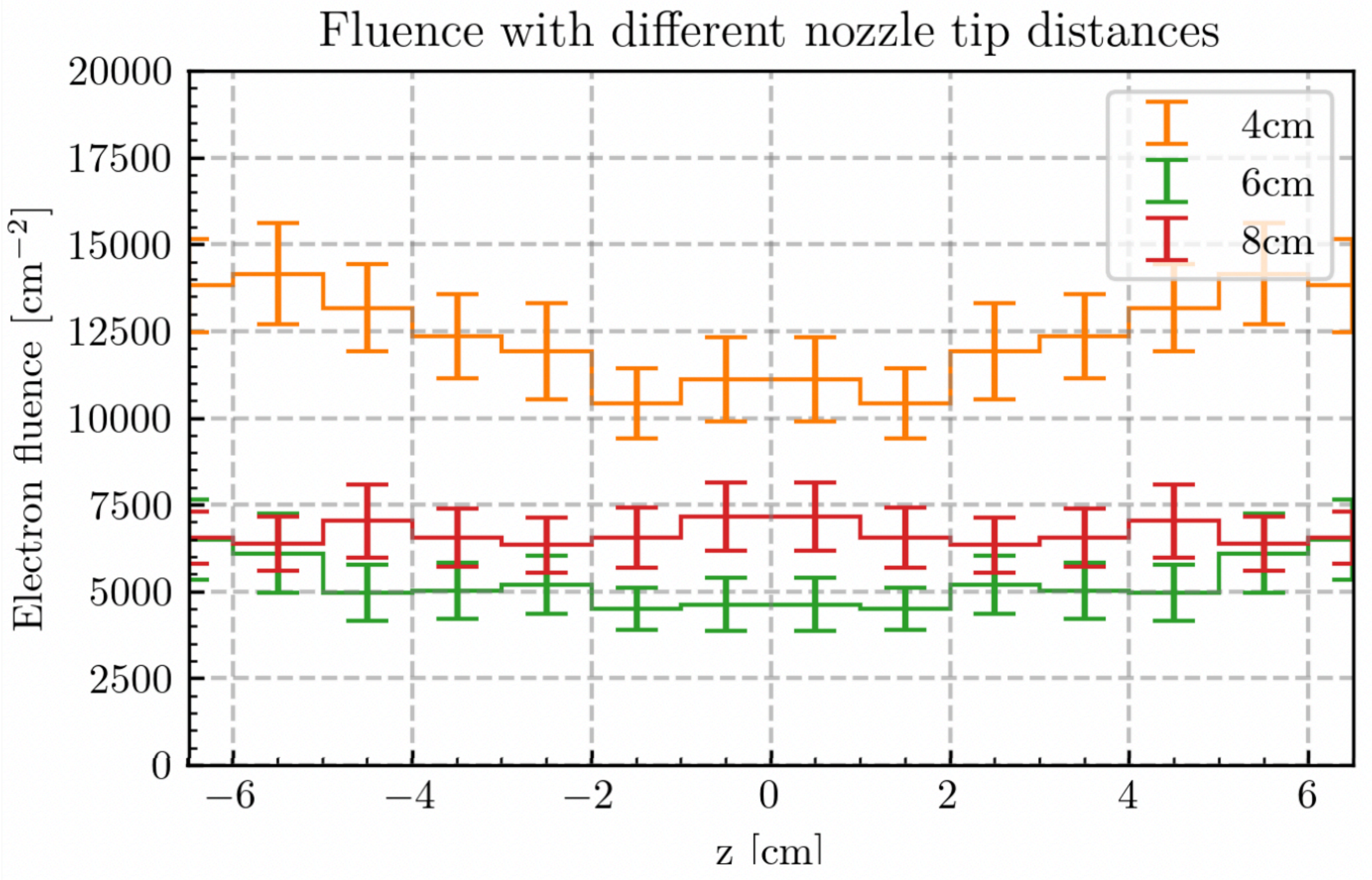


Work in progress: Machine Detector Interface

D. Calzorlari

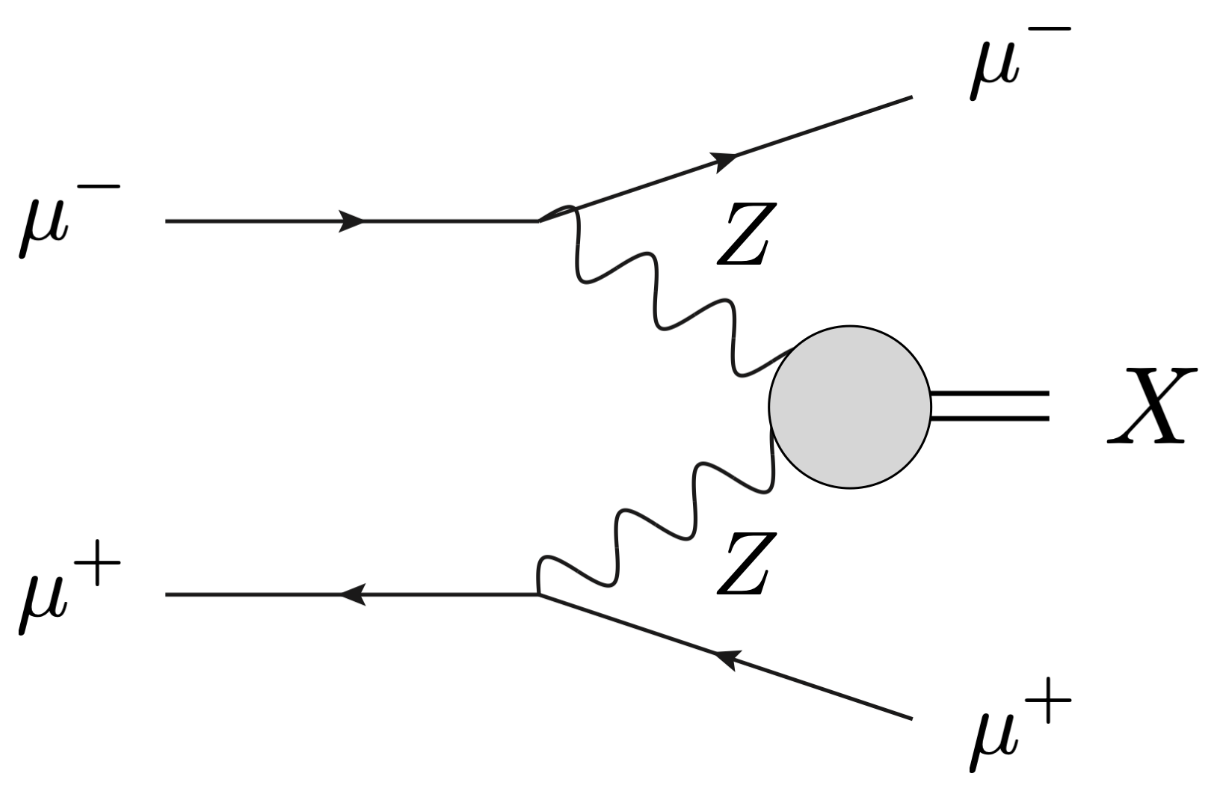
Beam induced background highly dependent on nozzle configuration
Systematic optimization in progress!





Work in progress: Map back to physics

eg. to fully unlock higgs precision, is forward muon tagging possible?



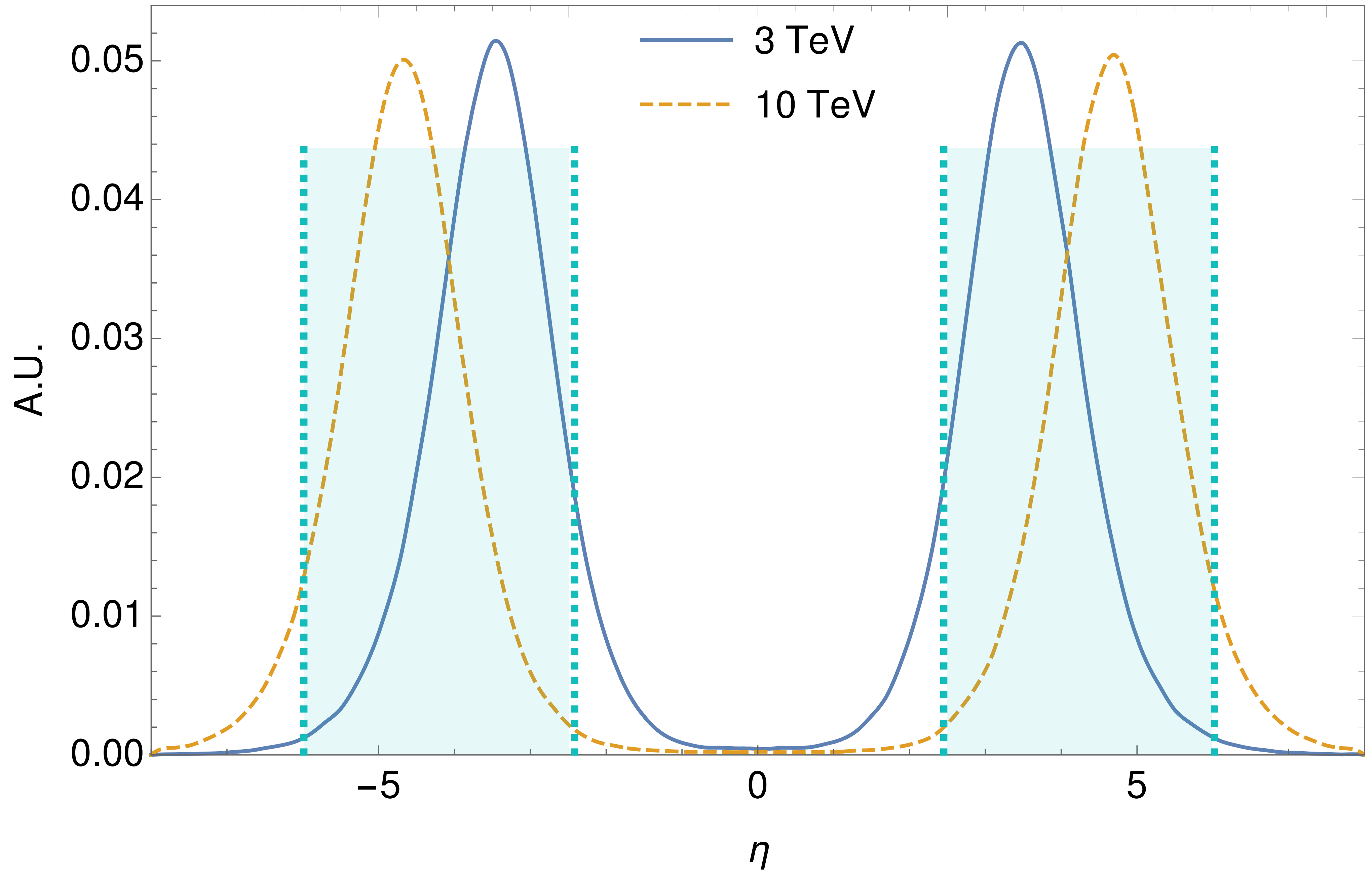
Separate ZZ and WW fusion

Reduce backgrounds

Br(h→invisible) via m_{miss}

Γ_h via inclusive rate

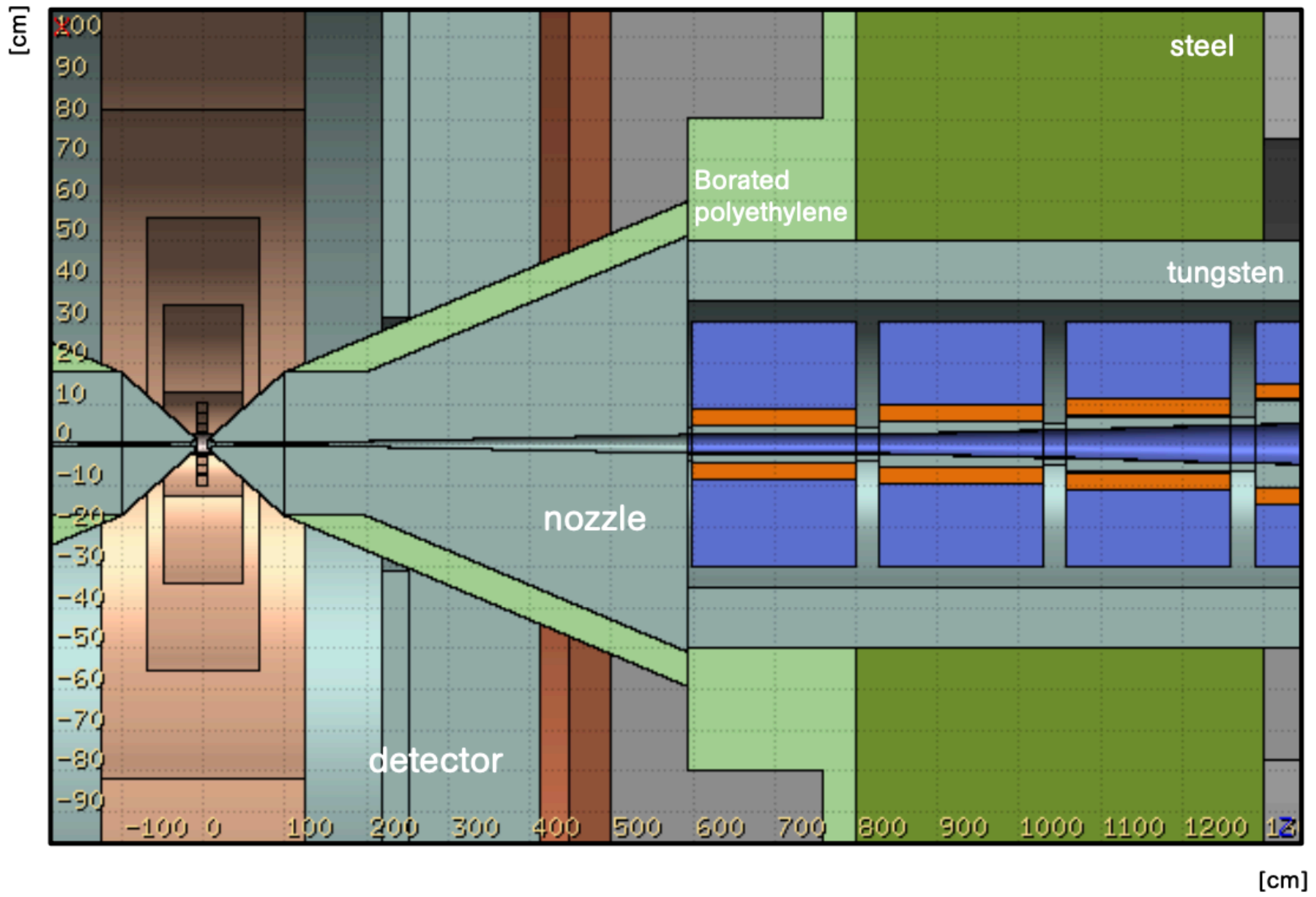
Ideal η coverage



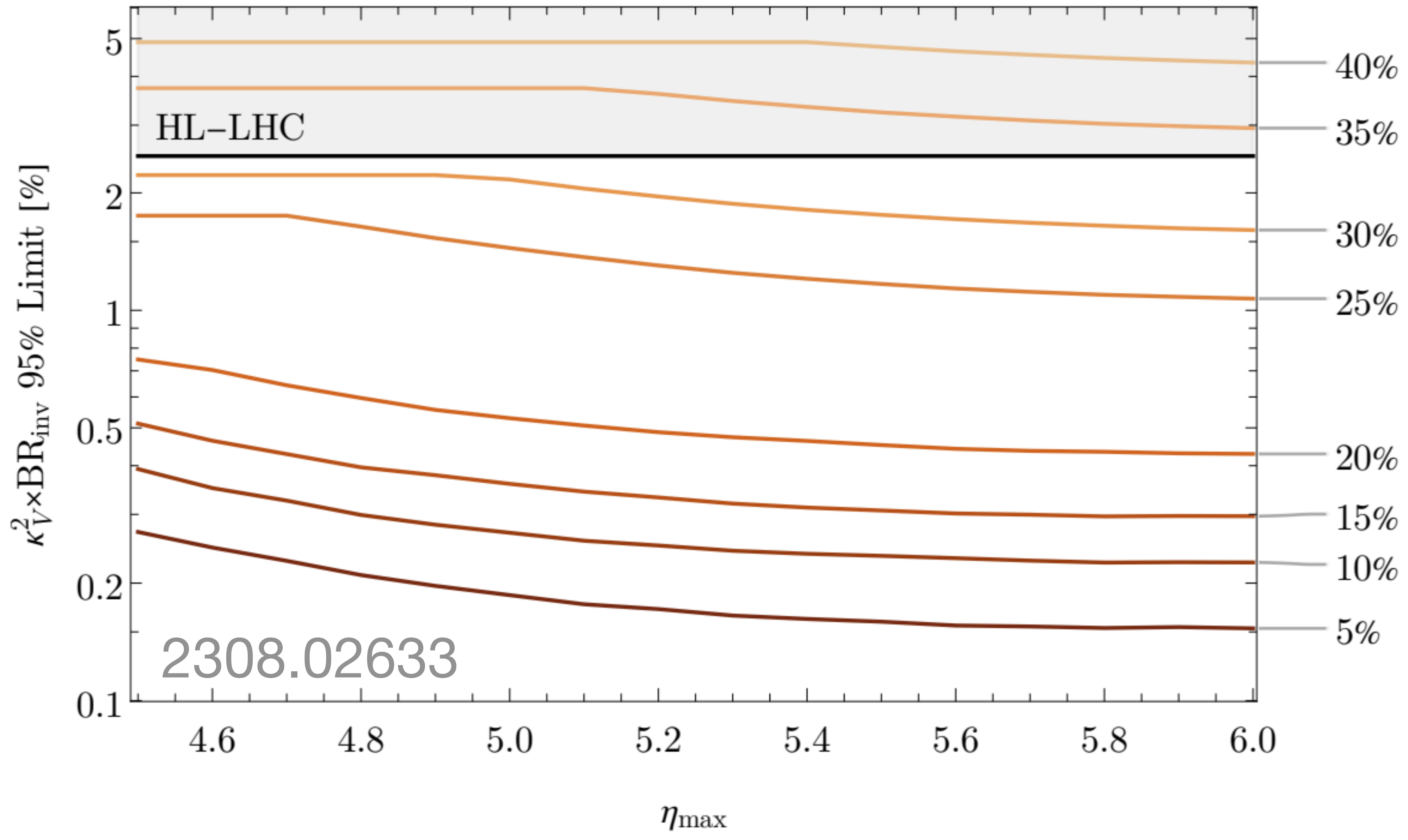
M. Forslund, P Meade
M. Ruhdorfer, E. Salvioni, A. Wulzer
P. Li, Z. Liu, K.F. Lyu

Work in progress: Forward Muon Tagging

Face of the nozzle: covers 3 < |η| < 6



Br(inv) sensitivity with different coverage and σ(E)/E assumptions



B-field & path-length for momentum measurement?

Effects of scattering/energy loss from ~2000 X_0 of Tungsten?

What technology can withstand BIB?

See presentation @MDI workshop by D. Calzolari and M. Casarsa

The takeaway

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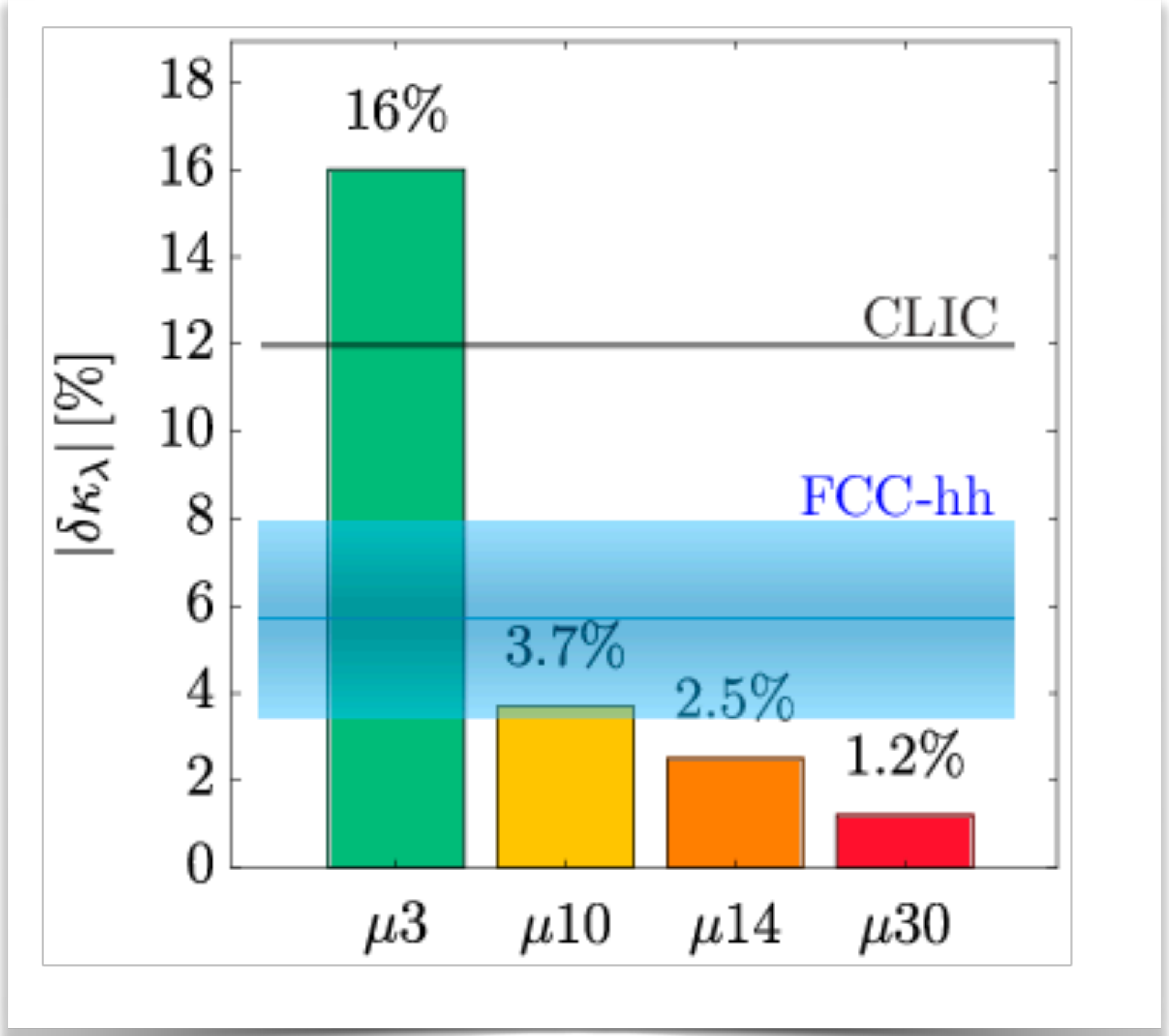
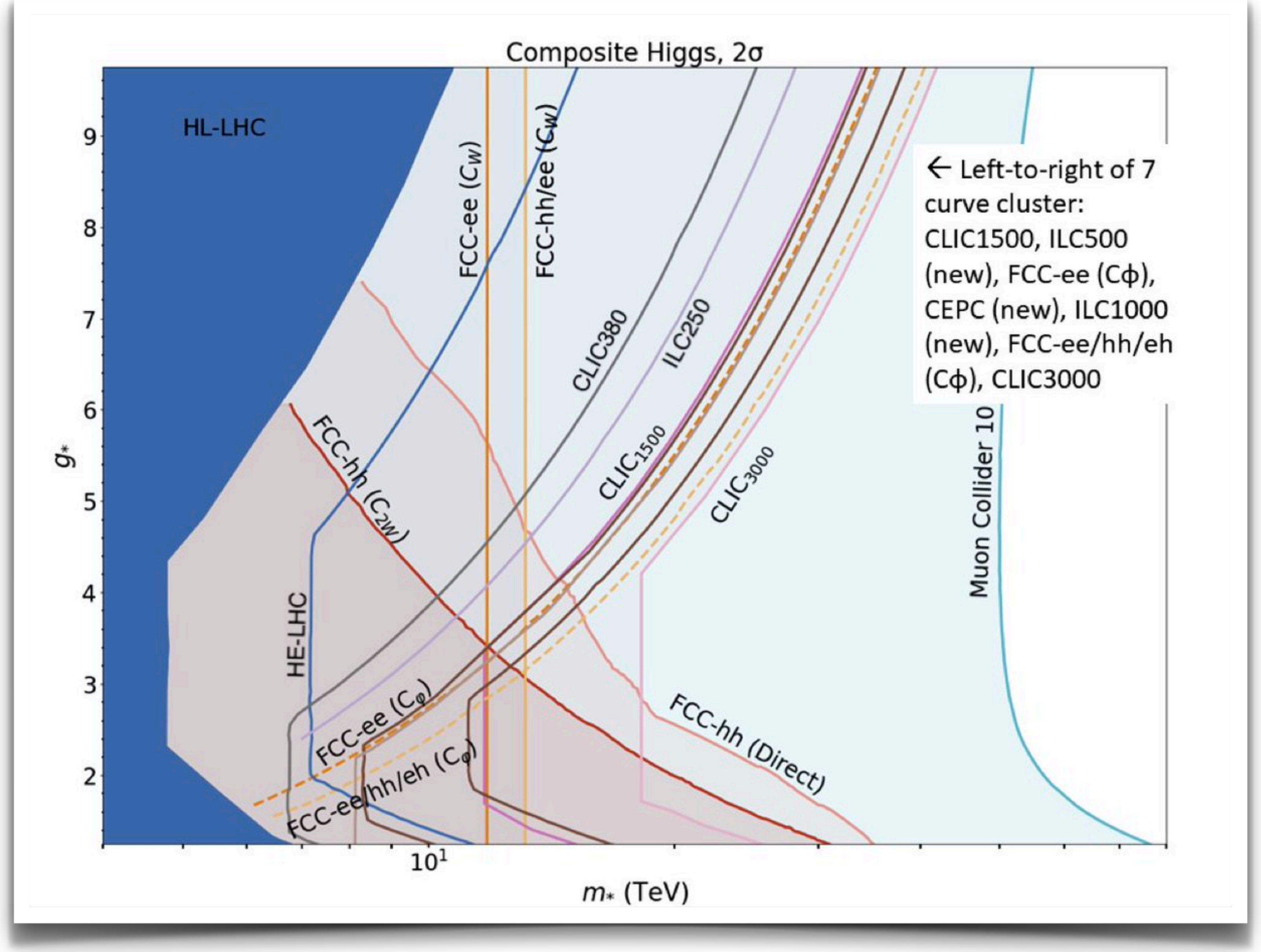
Baseline detector design & full simulation studies demonstrate we can do physics
With work in progress we can likely do even better :)

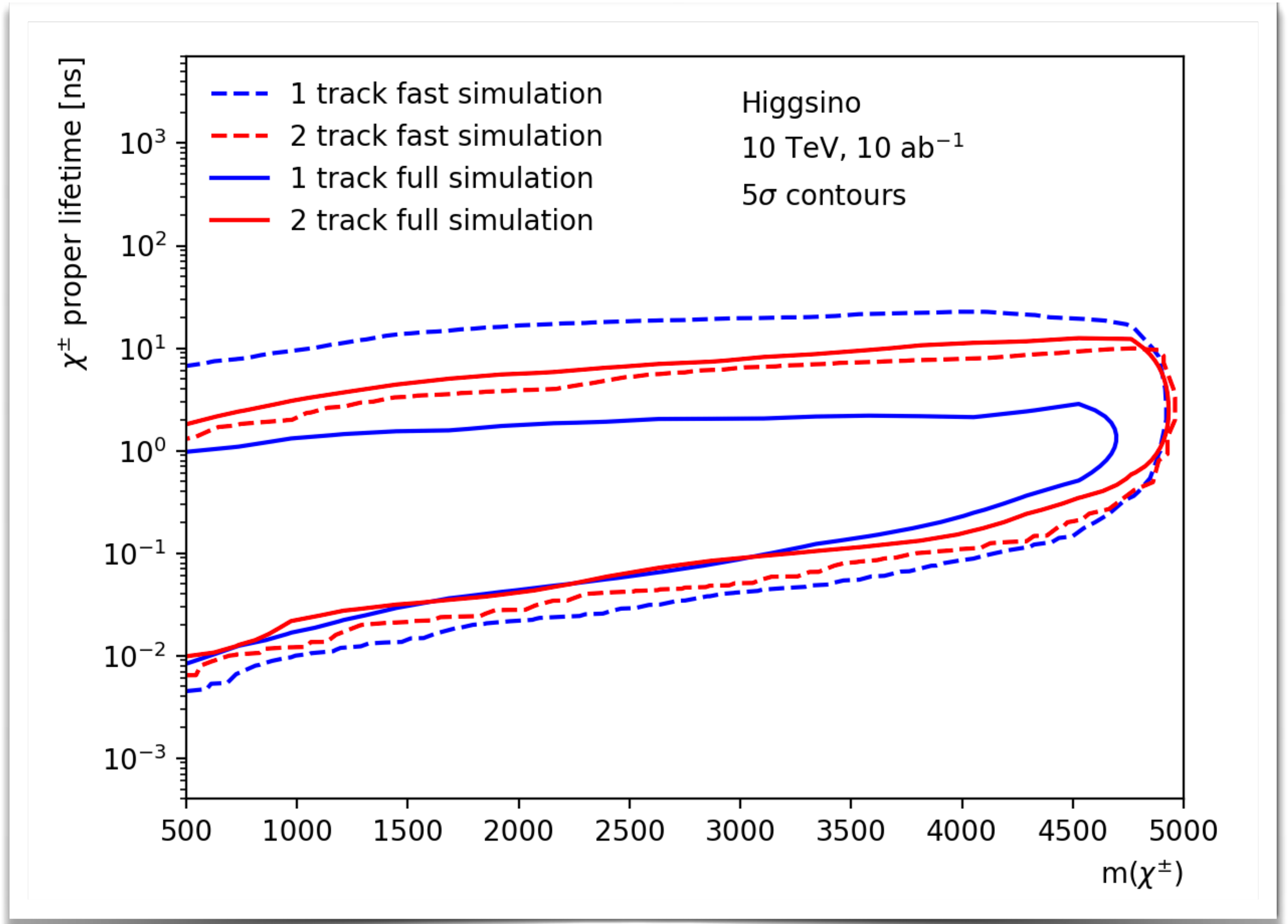
Higgs self-coupling



Composite Higgs Scenarios



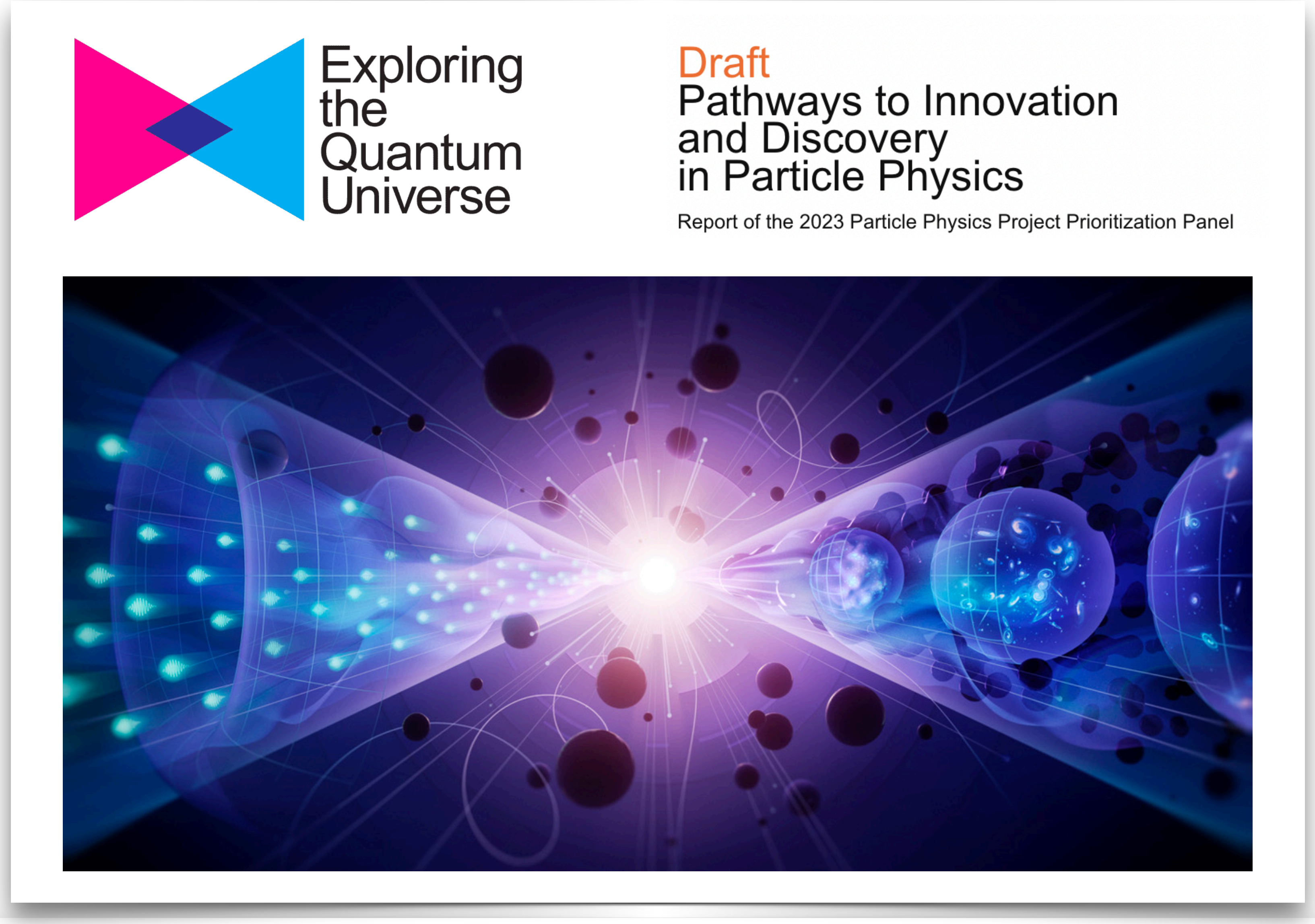
WIMPs/Disappearing track



Cue the excitement!

- Positive outcomes from latest European Strategy & US Planning processes
- Formation of International Muon Collider Collaboration (IMCC)
- “MuCol” Project Funded by EU
- US Muon Collider Collaboration forming soon
- Many dedicated meetings, workshops, and articles

International
MUON Collider
Collaboration



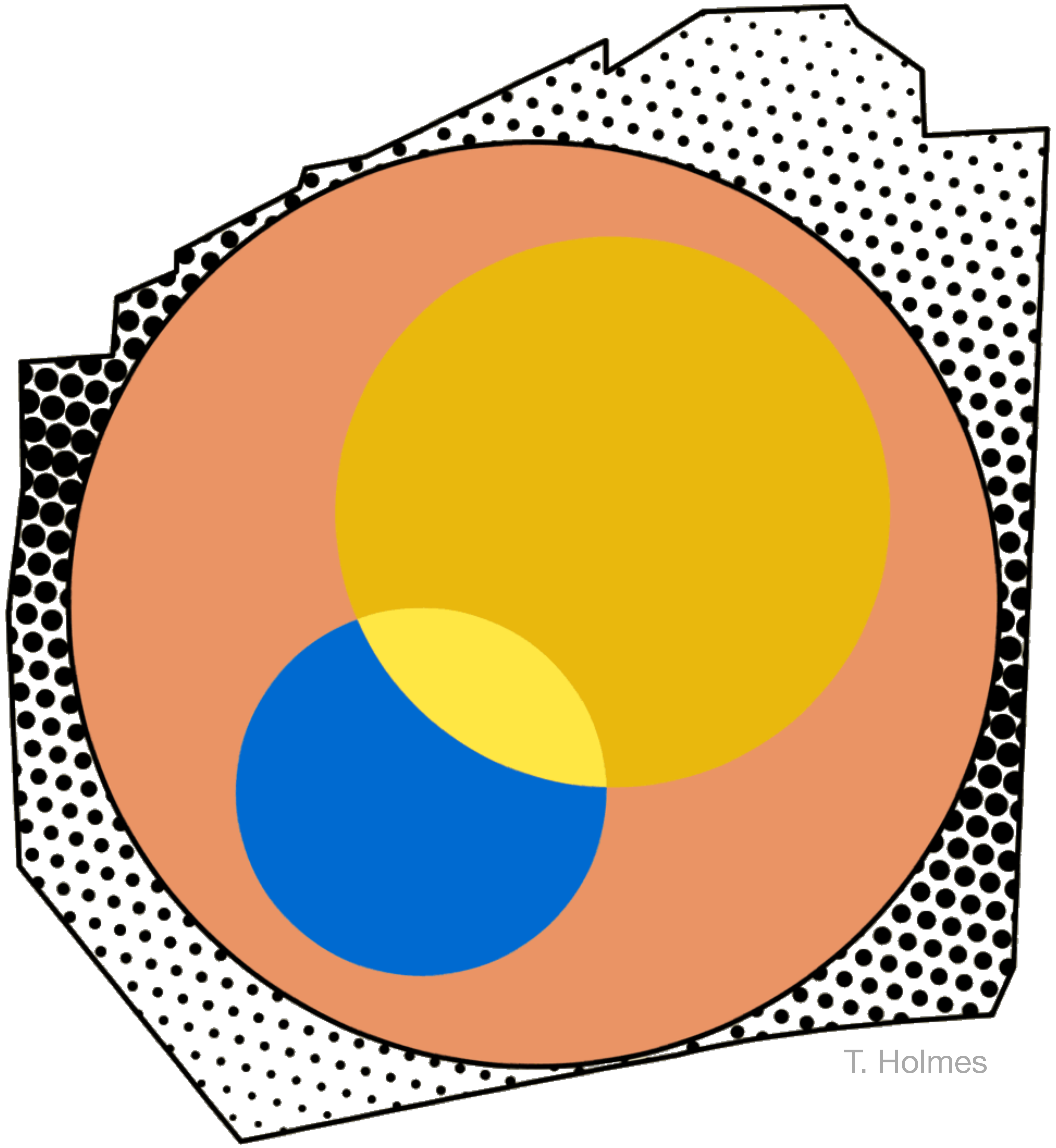
As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.

Conclusions

- Strong Physics Case for a 10 TeV Muon Collider
  - Energy and precision in a single machine
  - Compact, power efficient, and US-hosted option
  - Interesting synergies & staging opportunities
  - No show stoppers identified, R&D should start now!

- Do your homework & decide for yourself!
  - Collider Implementation Task Force
  - International Muon Collider Collaboration
  - Towards a Muon Collider

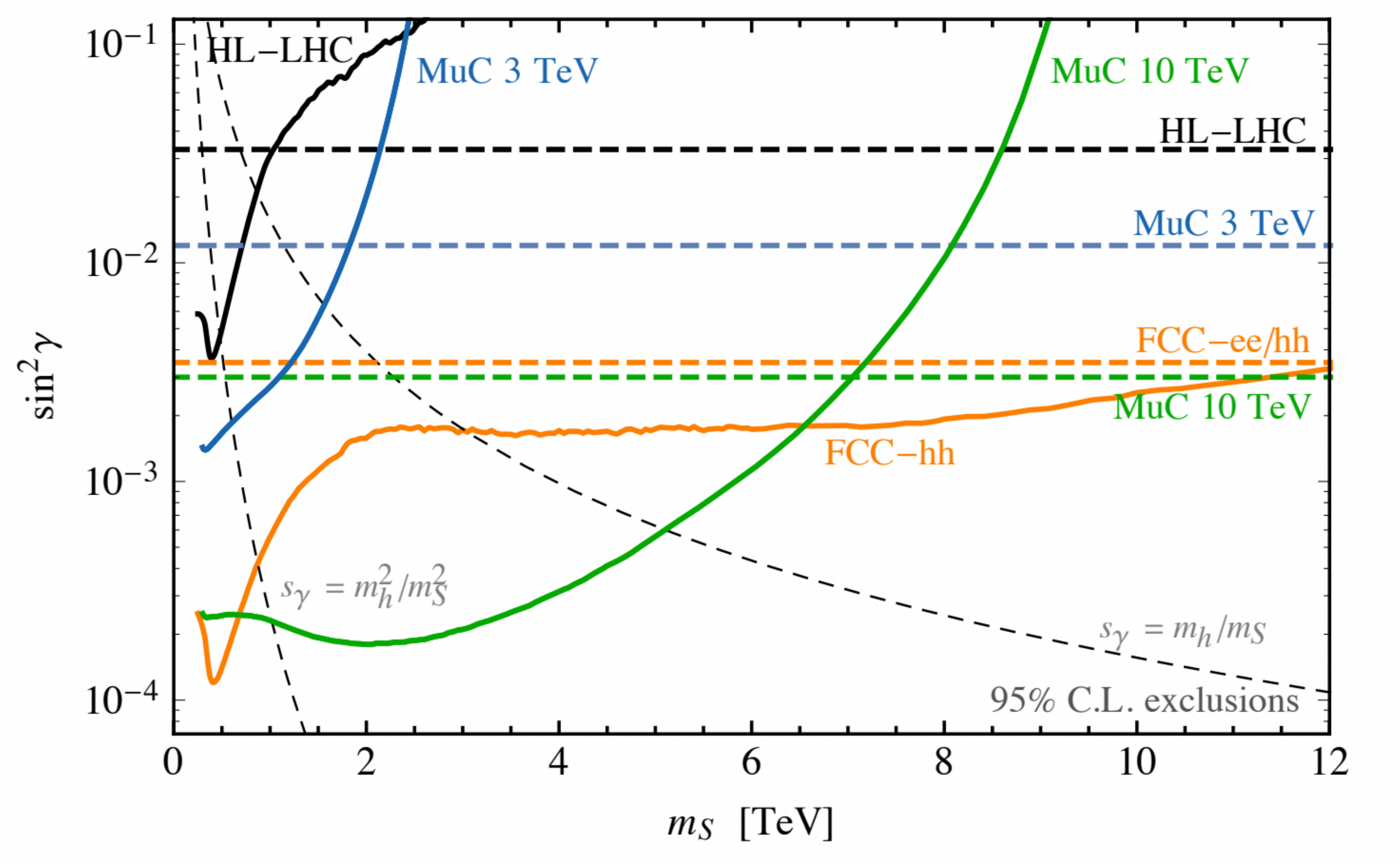
Backup



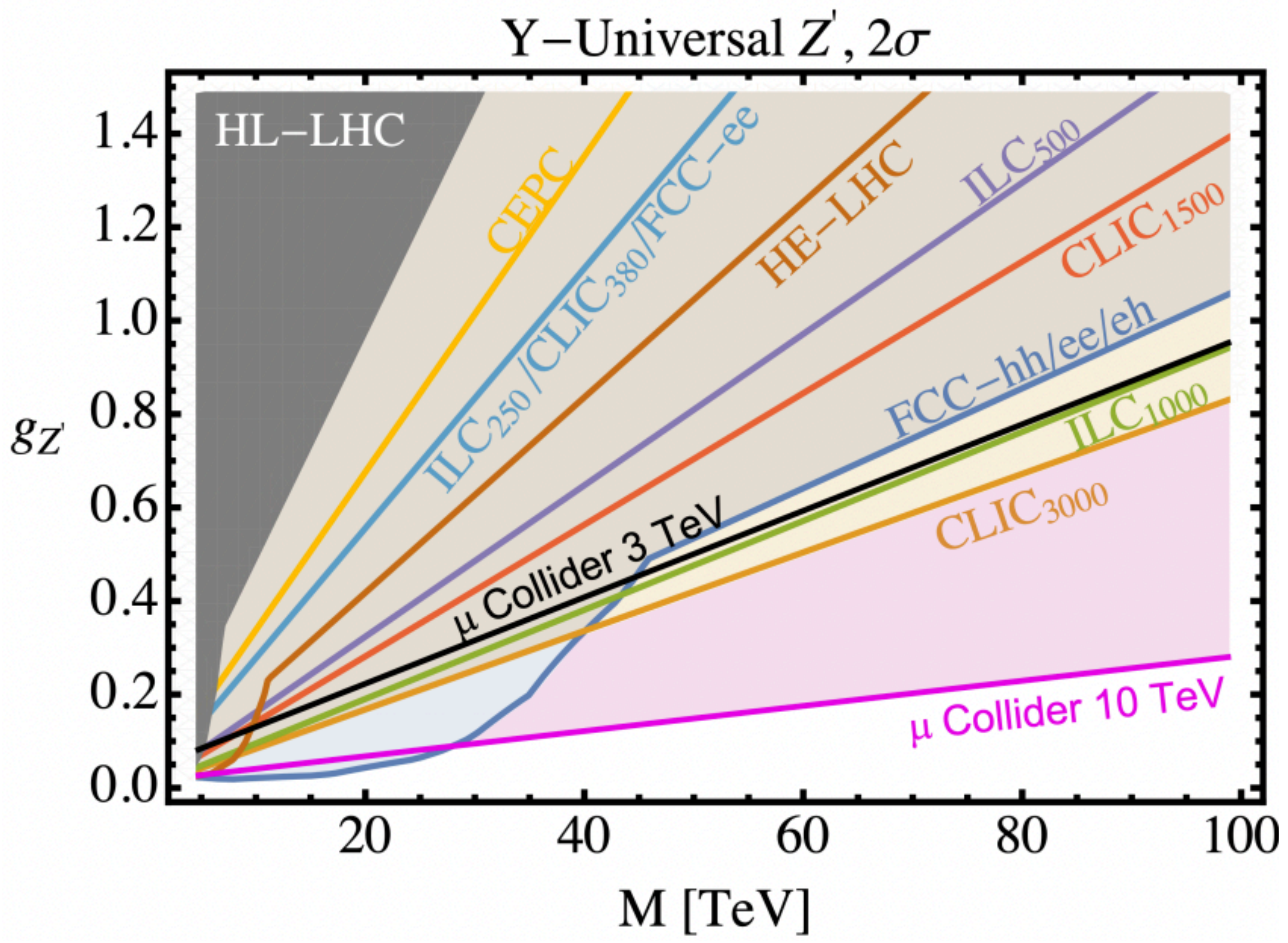
Sensitivity to new physics

2209.13128

New scalar mixes with Higgs
VBF VV → S → hh → 4b
Solid = direct
Dotted = indirect



MuC has an edge in sensitivity when Z' is so heavy that only indirect effects can be measured

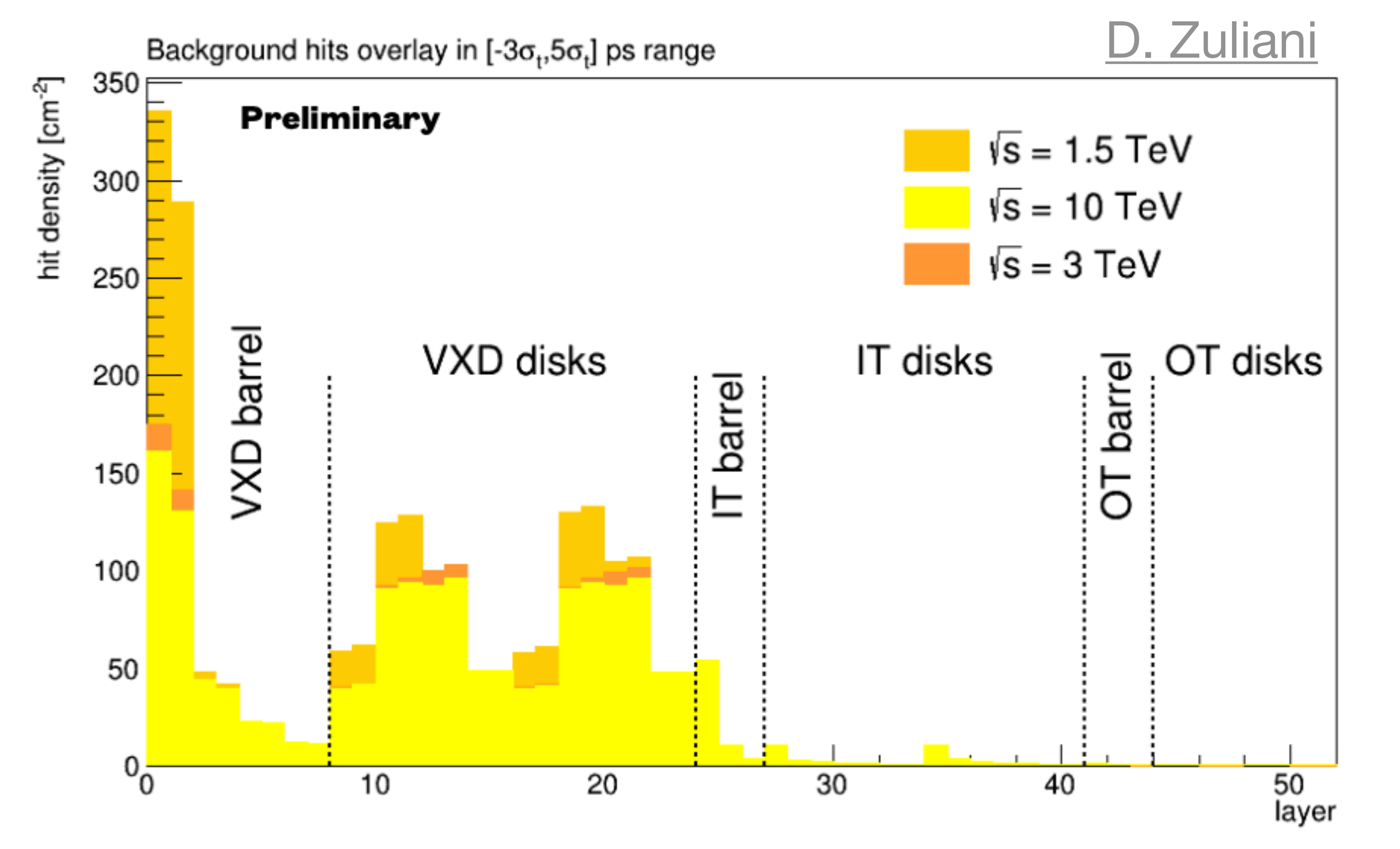


Beam induced background w/ FLUKA

Overview by D. Calzolari

Multiple experts producing and validating BIB at 1.5, 3, and 10 TeV

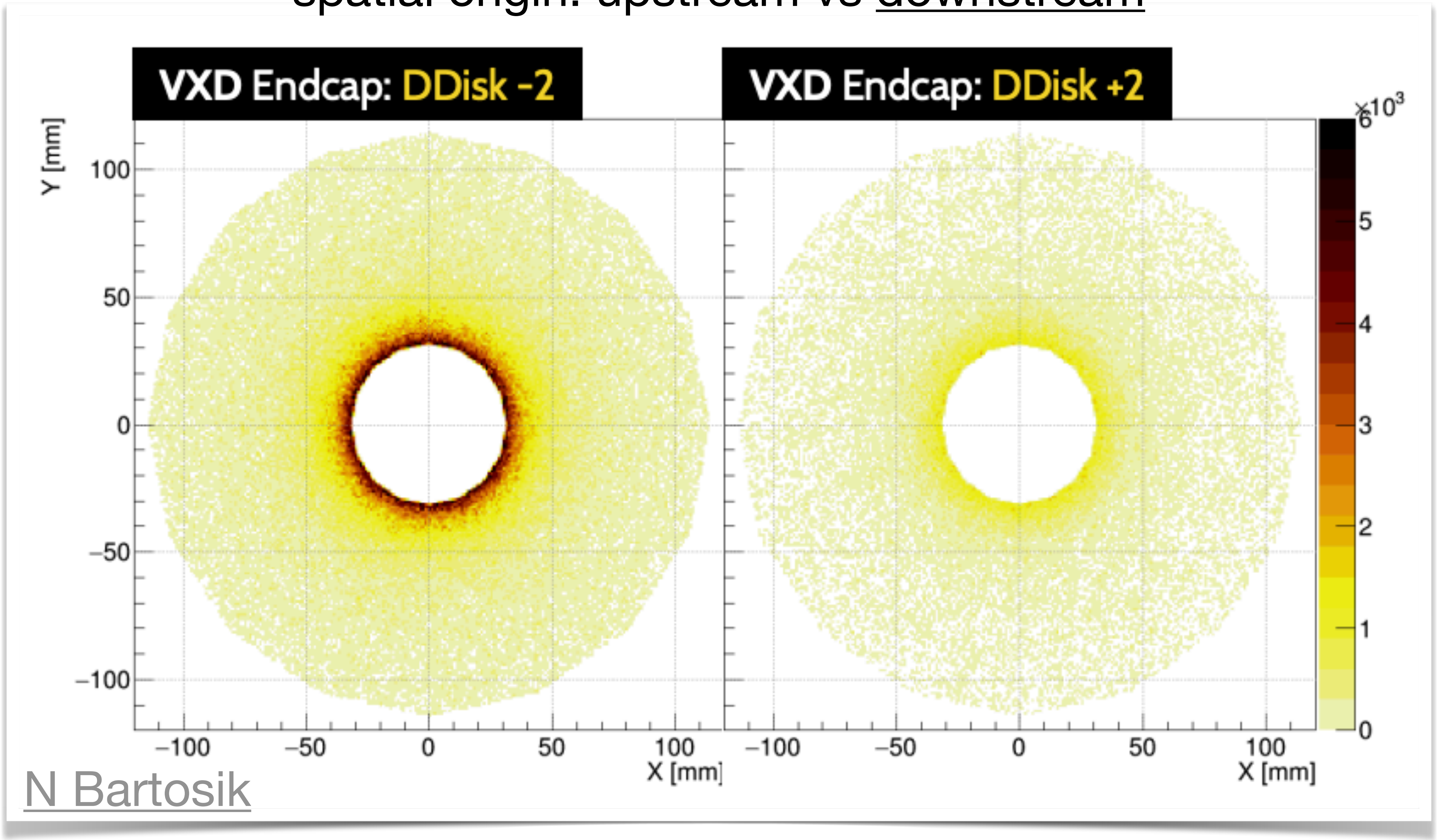
Comparing occupancies at different energies



Characterizing BIB contributions in tracker

eg. particle type: primary vs secondary electrons

spatial origin: upstream vs downstream

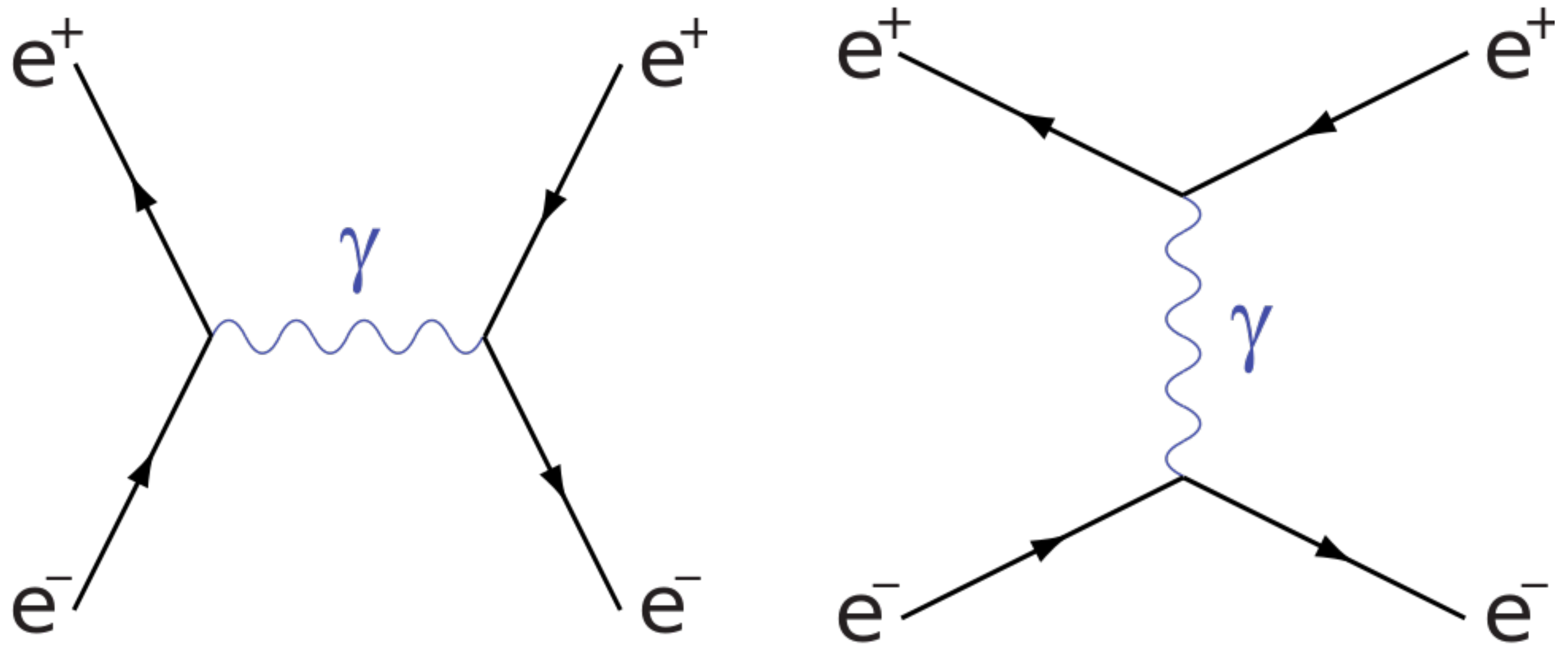


Luminosity

D.Lucchesi - MuC Lumi

Previous lepton colliders:
Forward electrons from Bhabha scattering

$$\mathscr{L} = \frac{N}{\epsilon \sigma_{th}}$$



Proposal to use central muons for μC
Questions: Stats? Theory precision?

$\sqrt{s}$=1.5 TeV, lumi = 1e34
Remaining events

Assuming a Snowmass year = 10^7seconds
$\mathcal{L}=1.25 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
Total events: 213 K

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim \frac{1}{\sqrt{N}} = 0.002$$

We'll need something else to monitor luminosity in real time

Towards a 10 TeV detector

Momentum Resolution

$$\left(\frac{\sigma_{p_T}}{p_T}\right) \sim \frac{p_T}{BL^2}\frac{\sigma_{\text{point}}}{\sqrt{N}}$$

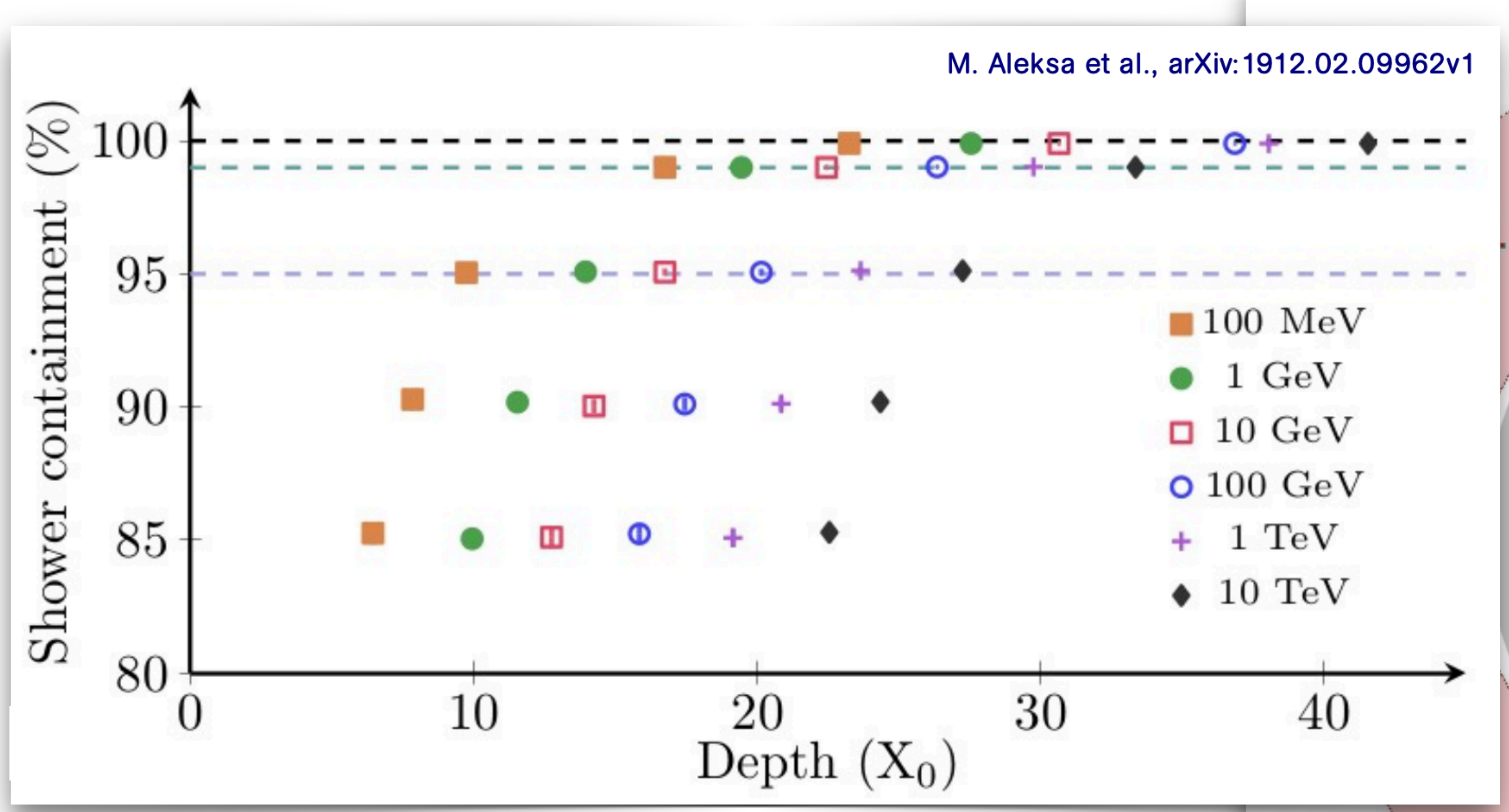
Aim for 5-20% at 5 TeV
→5 T solenoid, R≥1.5 m

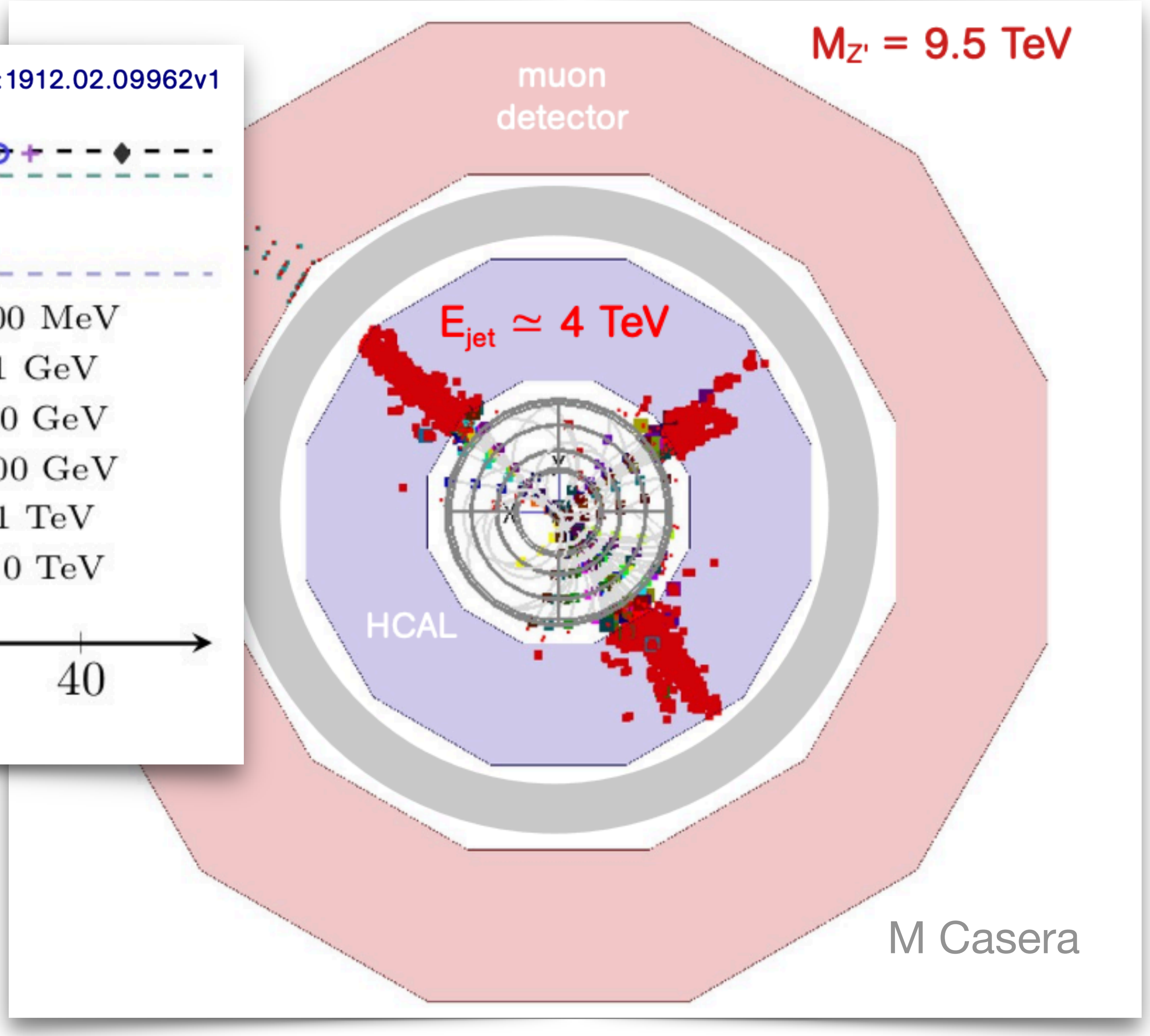
B-meson decay length

$$\langle L \rangle \sim 100\ \text{mm} \times \left(\frac{E}{\text{TeV}}\right)$$

Shower containment

Need to increase Calorimeter λ and X_0





Detector Magnet

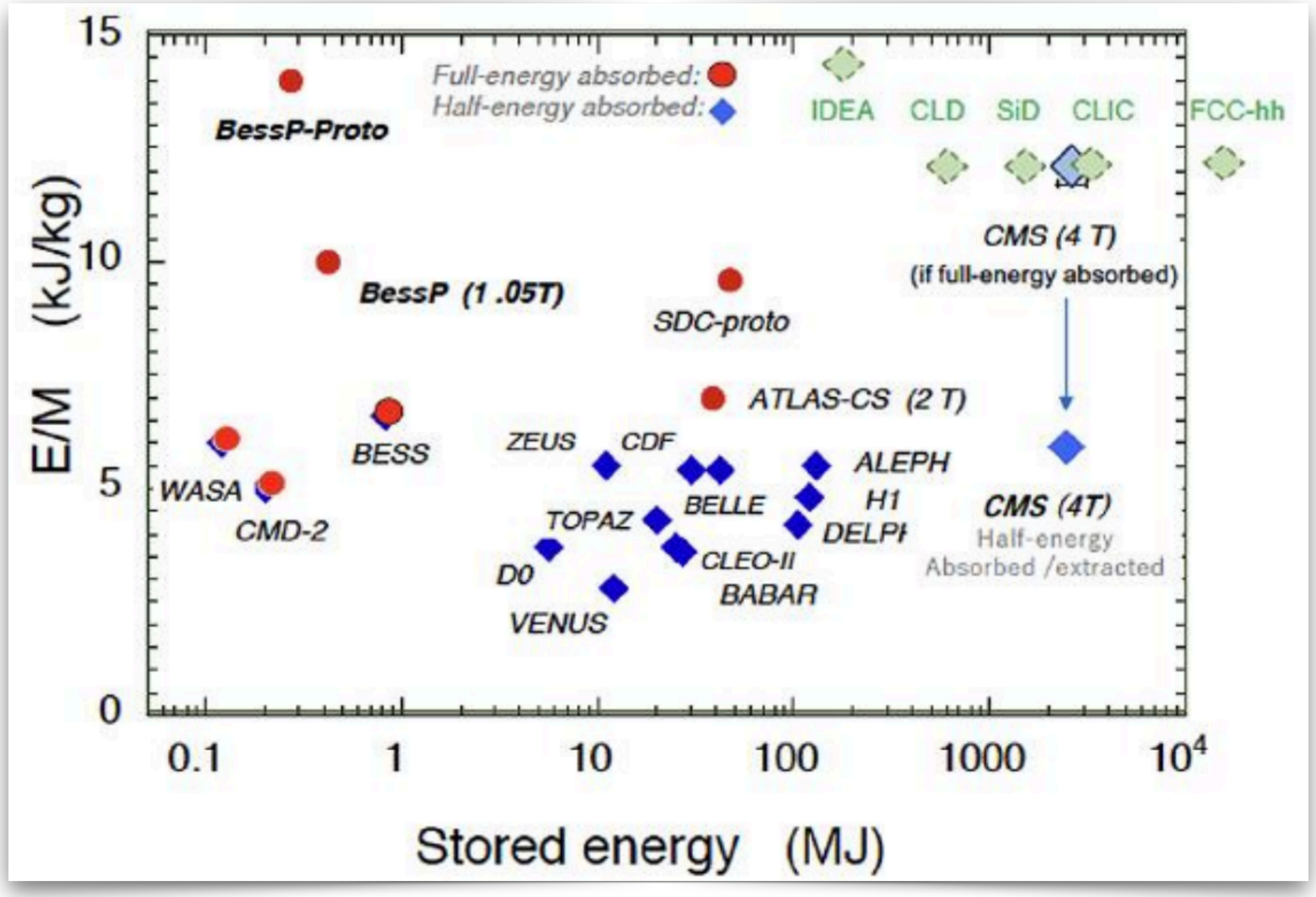
Increasing B-field & inner radius technically challenging

Requires Aluminum-reinforced NbTi/Cu

$$E_{\text{stored}} = \frac{B^2}{2\mu_0}\pi \mathrm{R}^2\mathrm{L}$$

$$t \propto B^2 R$$

Need to reestablish expertise to build CMS style magnets!



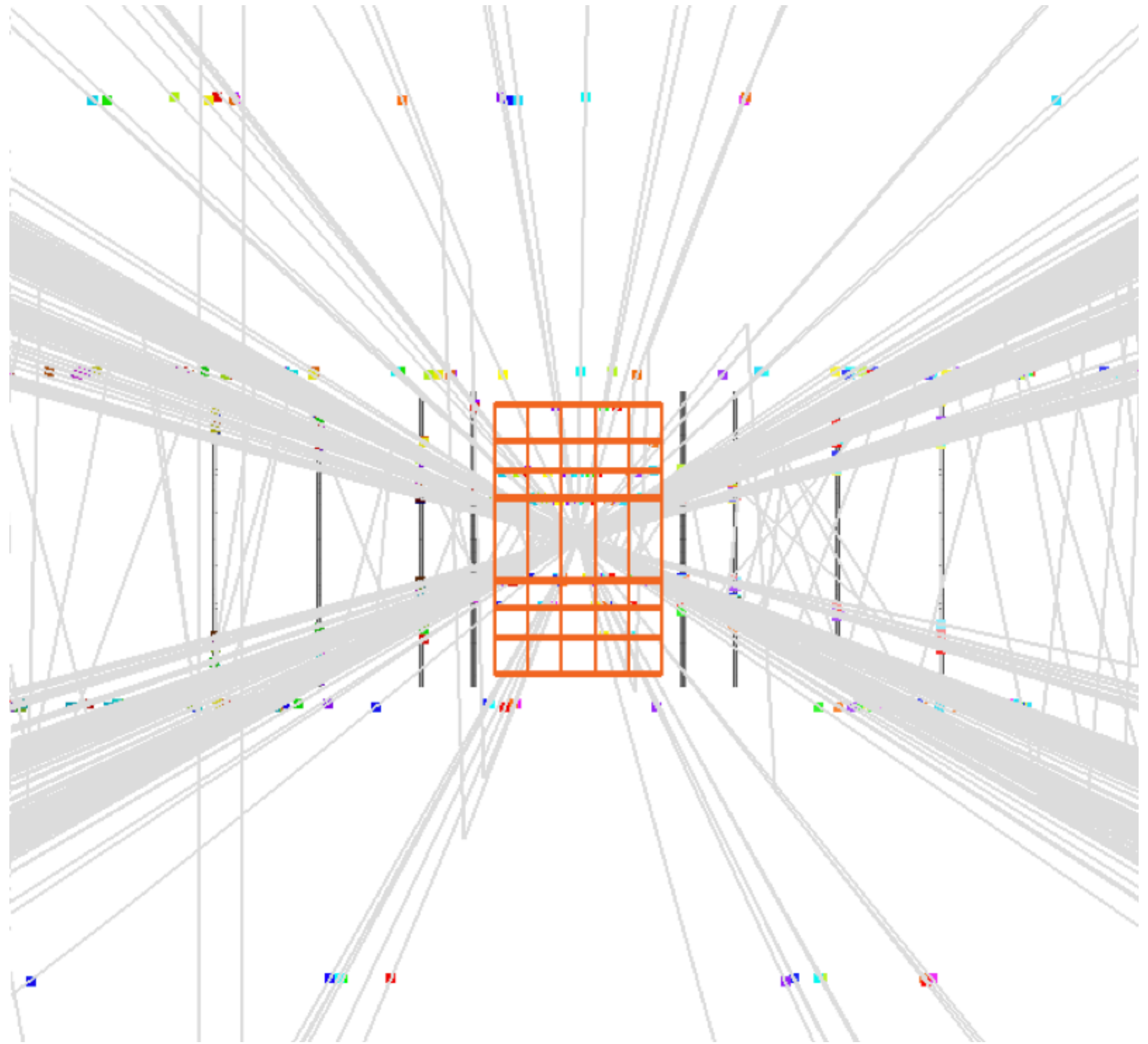
Reconstruction

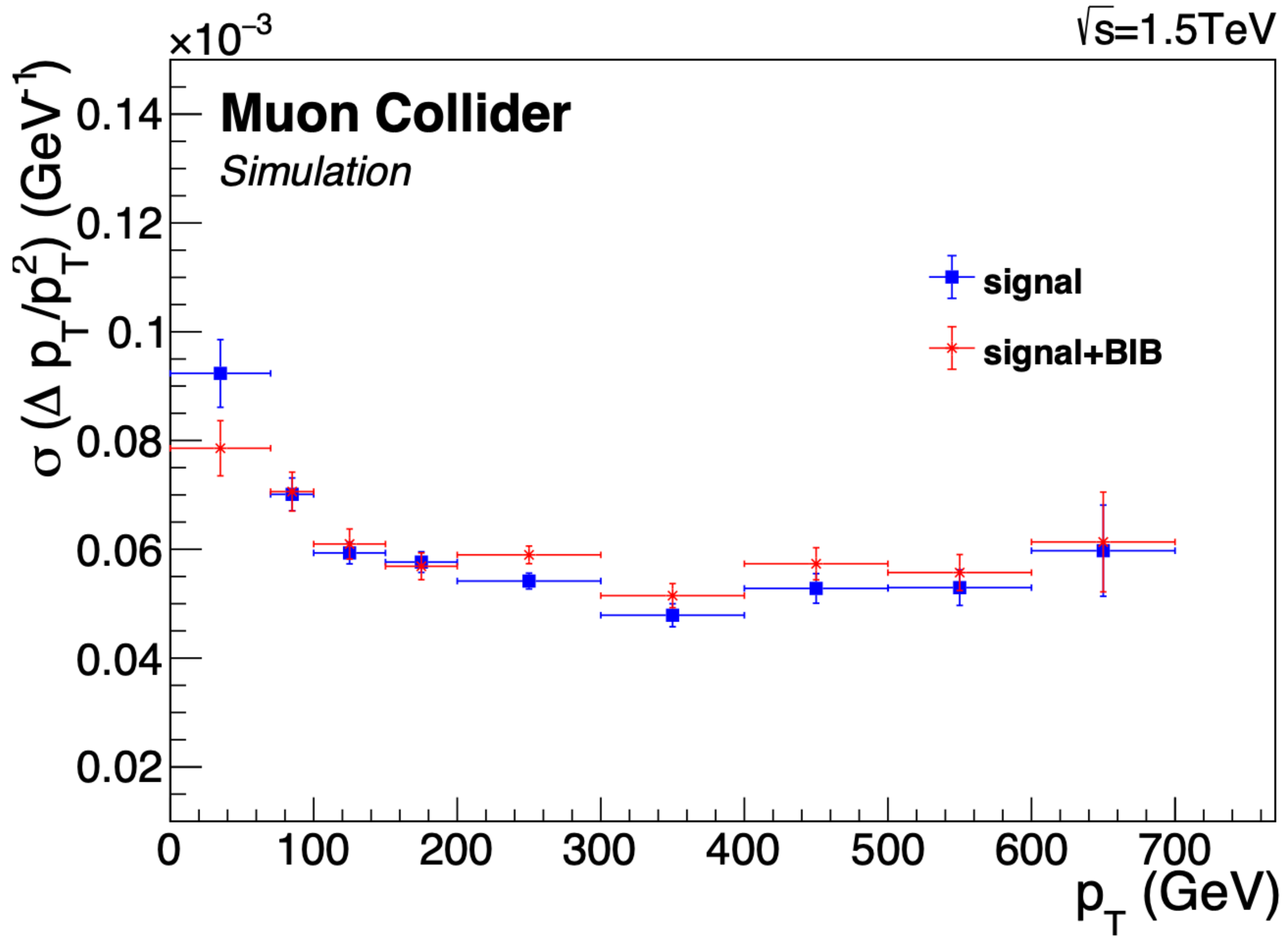
Works well! But is an active area of development

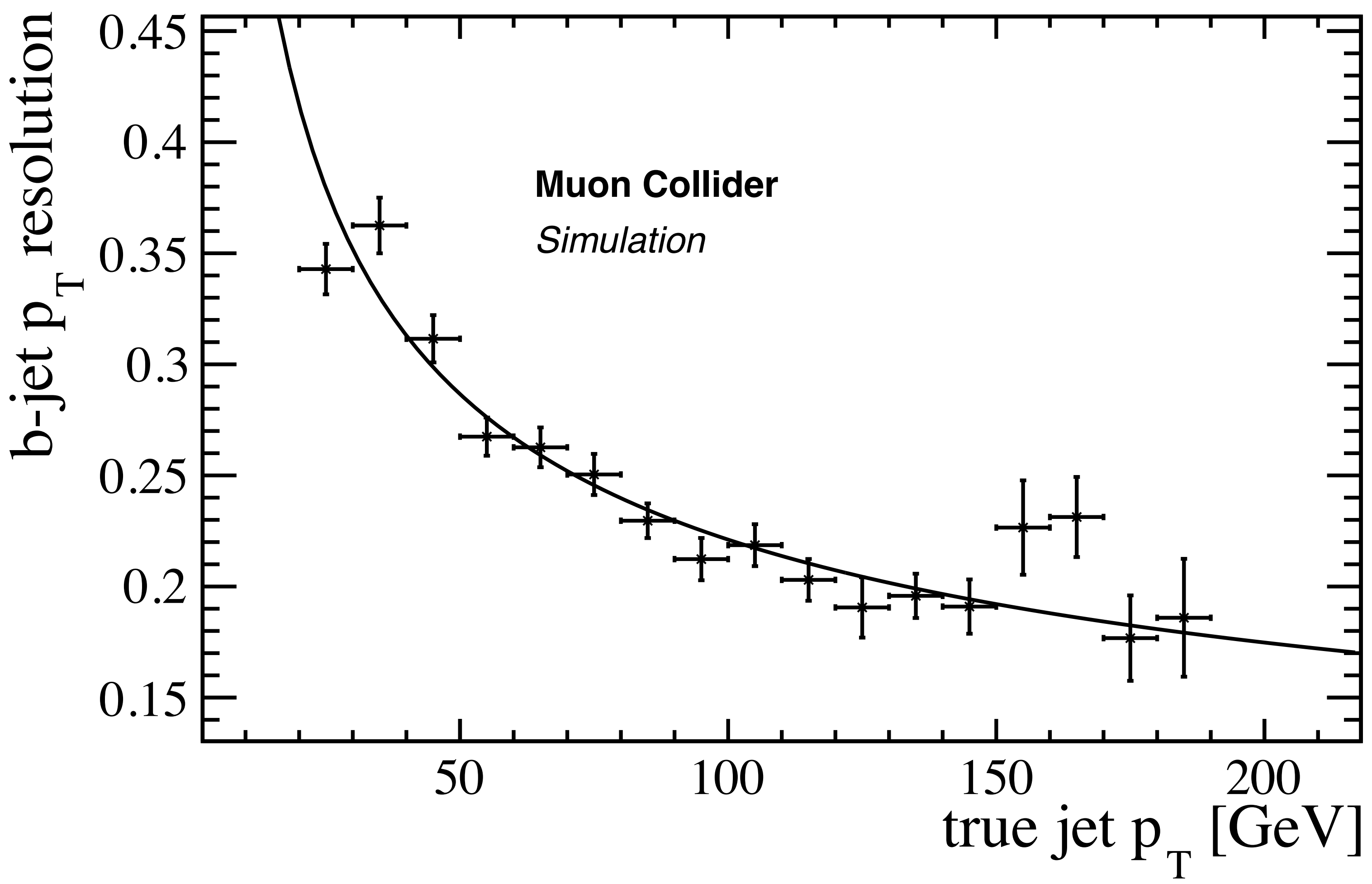
O(100) tracks per event after p_T, n_{hits}, quality of fit requirements

Photon and particle flow jet performance similar to hadron collider

Combinatoric tracks







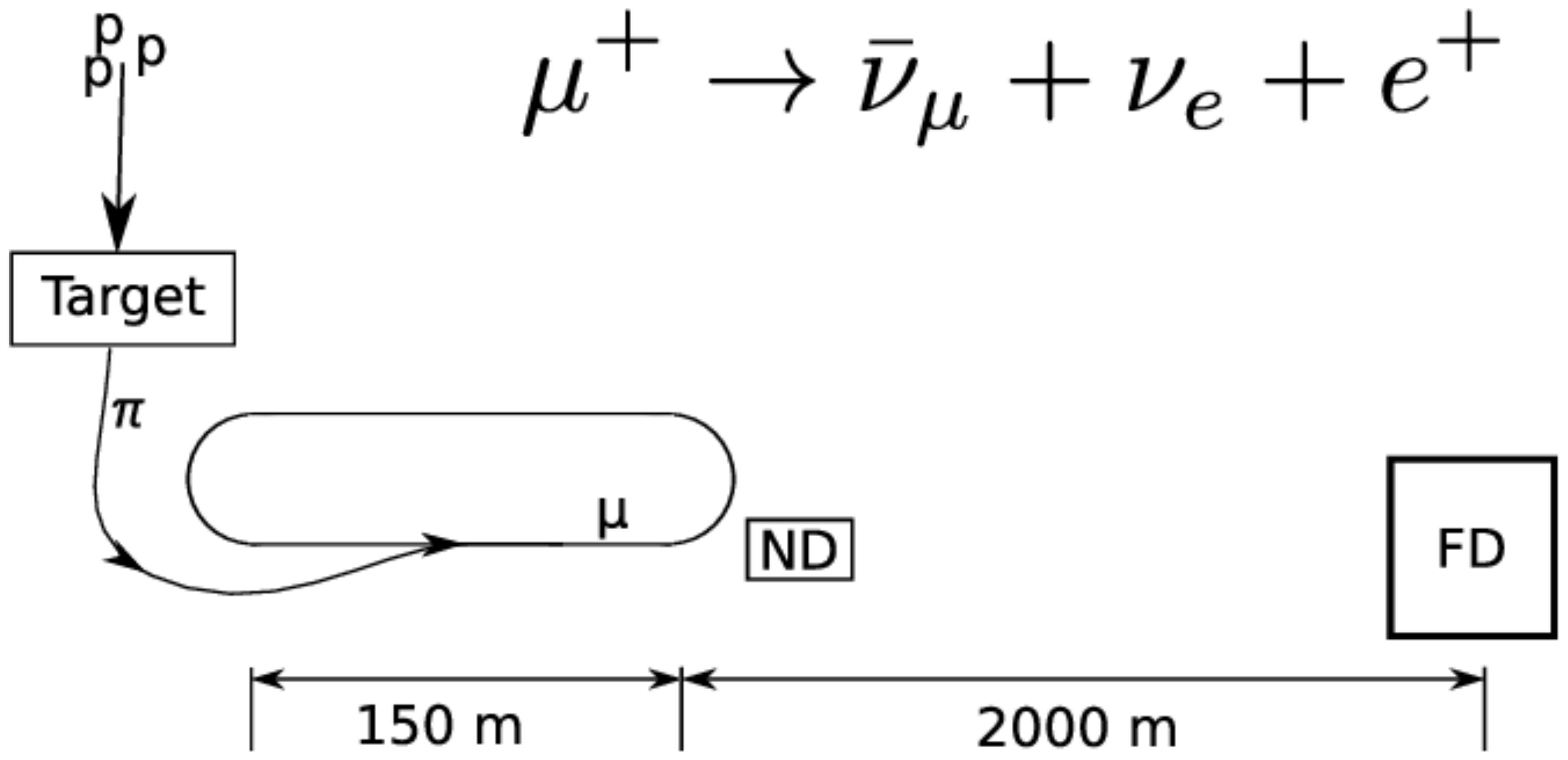
Work in progress: Ideas for physics along the way

2407.02572 - New!

Straight sections = perfect neutrino beam

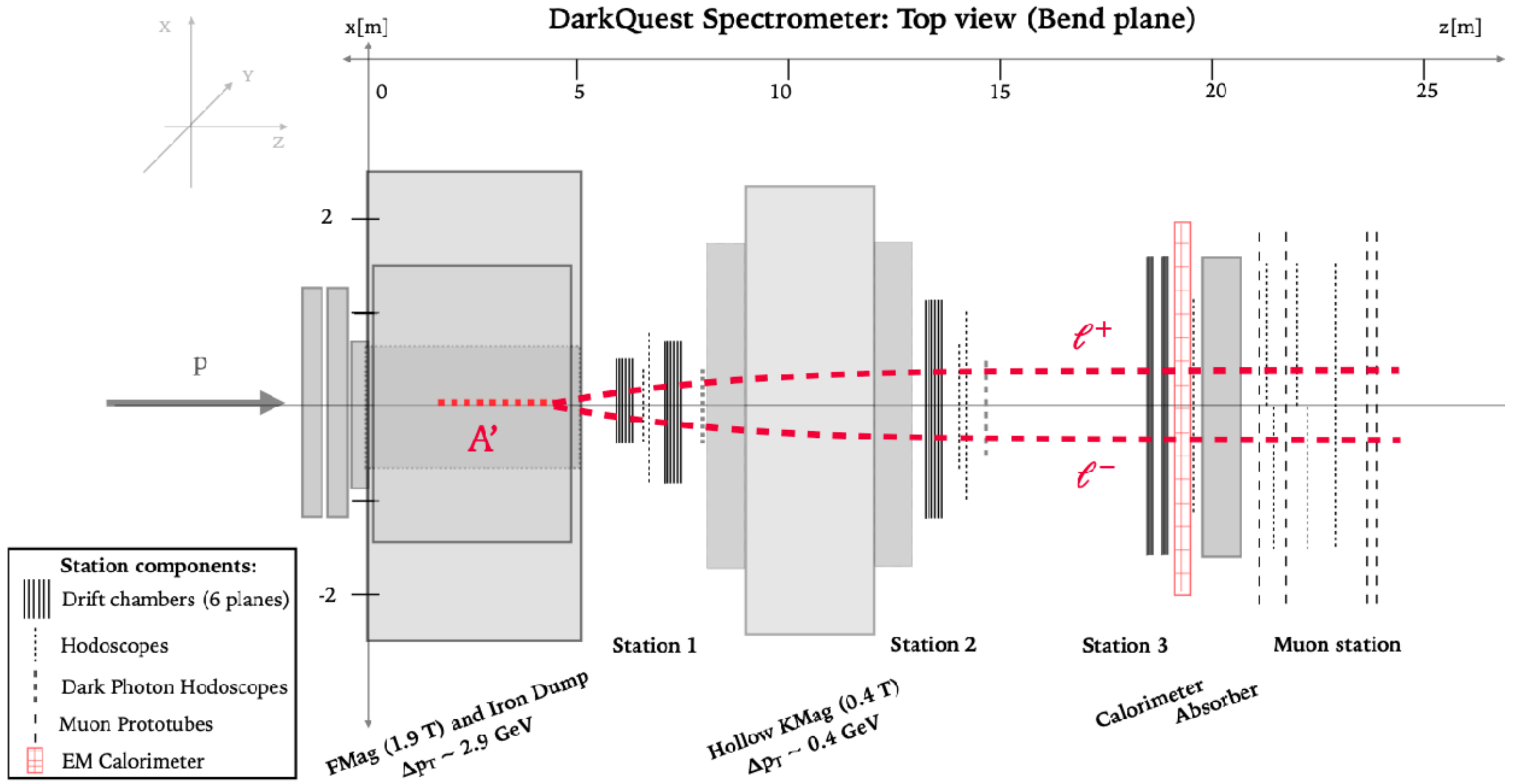
Equal numbers of e/μ (anti-)neutrinos

Precisely known energy spectra & intensity



$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

Low mass dark matter (sector) searches



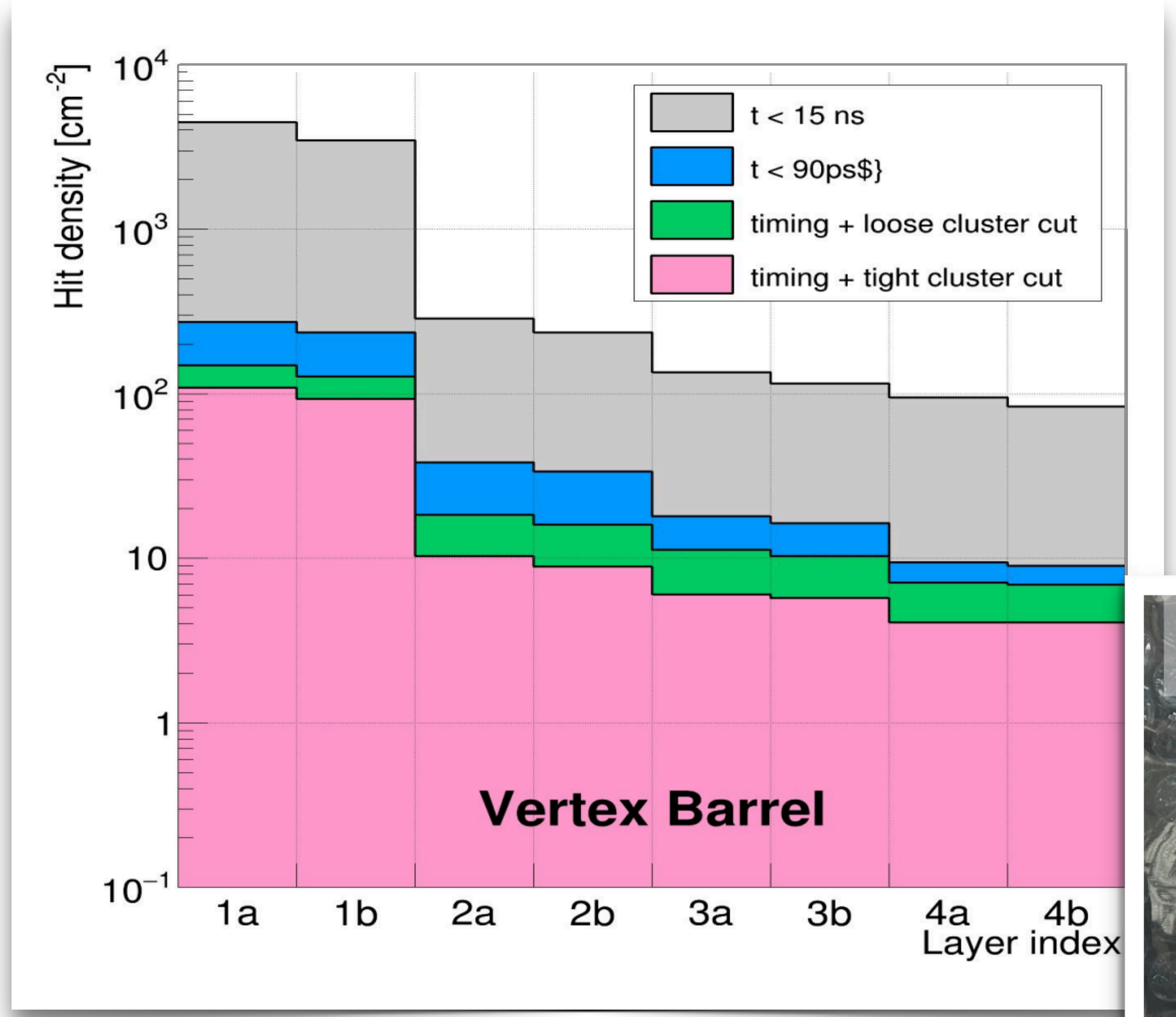
2203.08322

Synergies with charged lepton flavor violation experiments

Subsystem Design ↔ Technology needs

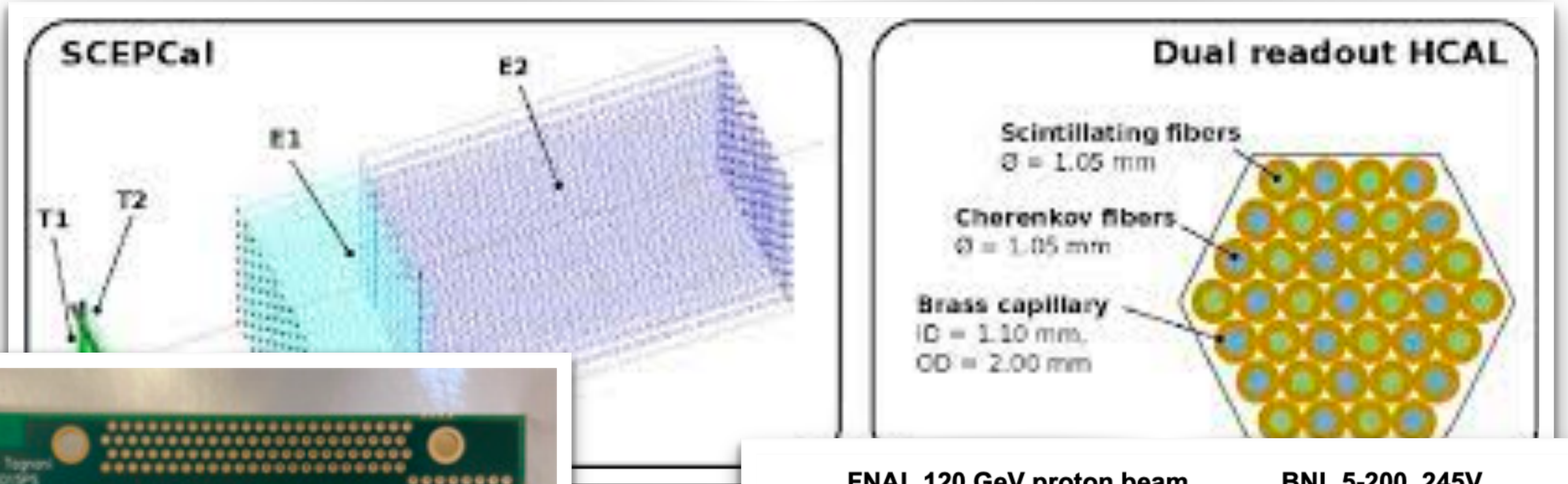
Need to define muon collider specific needs (strict & soft) to ensure technology converges
Also a good way to strengthen community with instrumentation experts

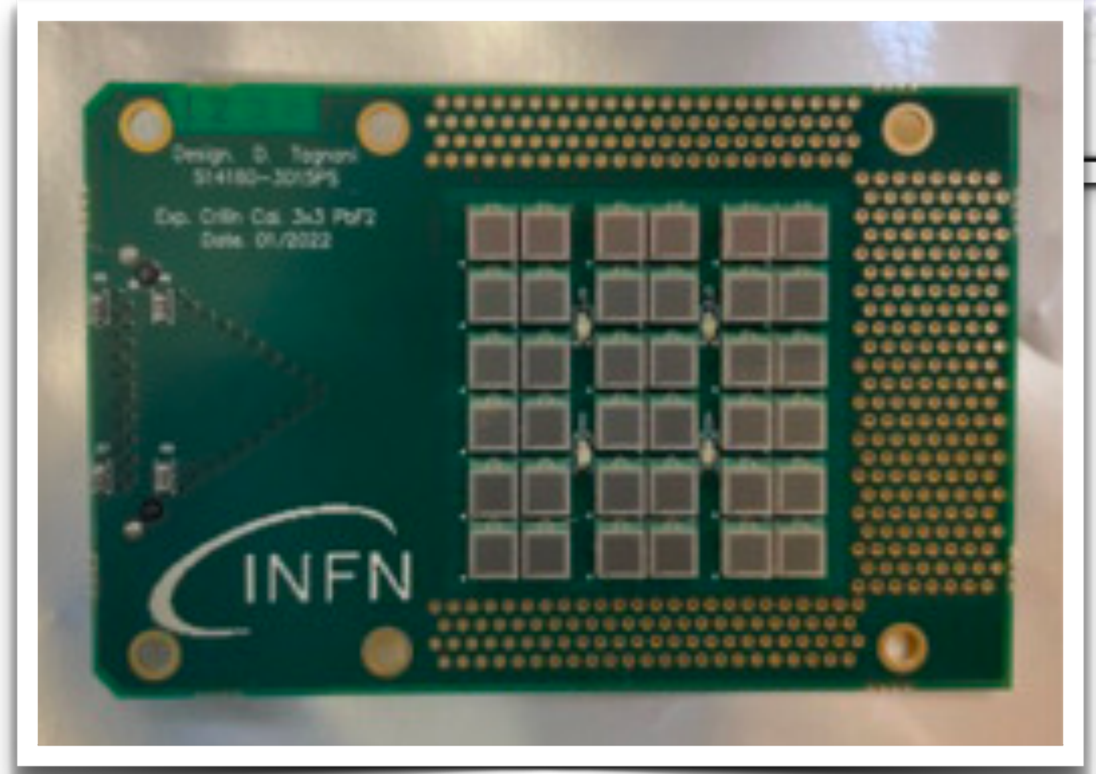
BIB rejection with pixel cluster shapes
C. Sellgren, Simone Pagan Griso



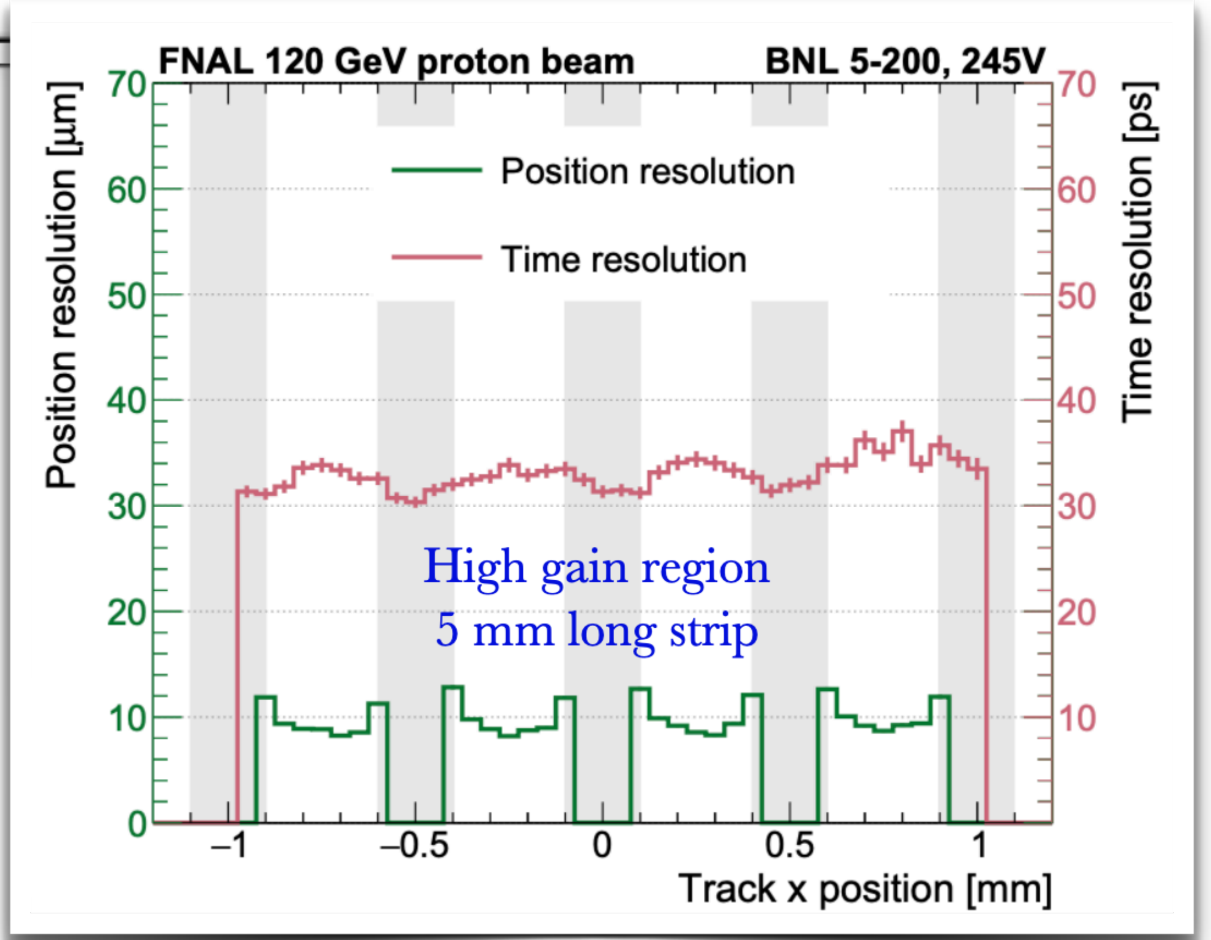
Data reduction with
AI-on chip
Anthony Badea

Dual Readout Crystal Calorimetry - Grace Cummings





CRILIN performance - C. Giraldin



AC-LGADs - Irene Dutta