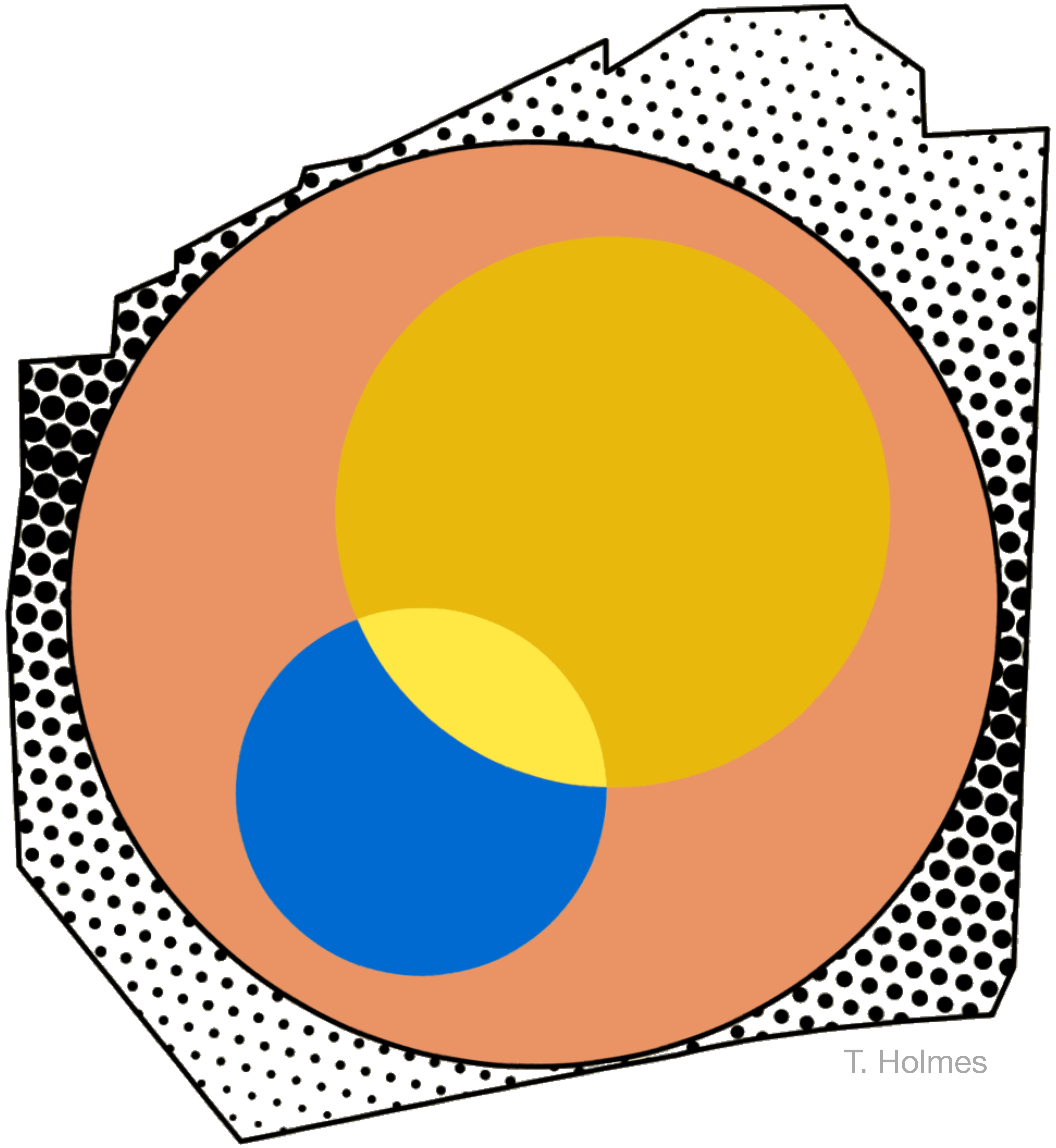
Towards a Muon Collider

Karri Folan DiPetrillo
University of Chicago
PASCOS 2024


T. Holmes

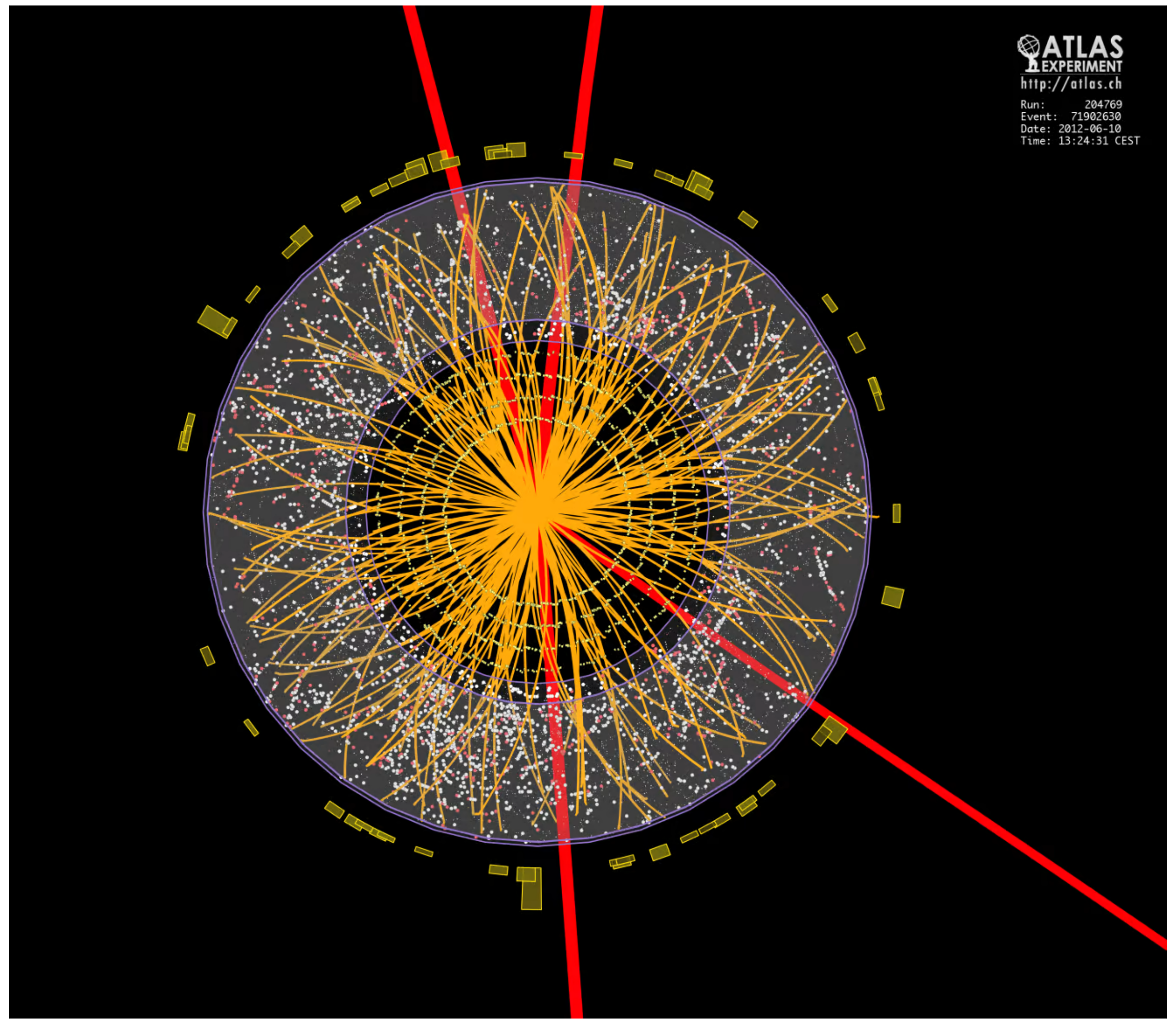
Open questions in particle physics

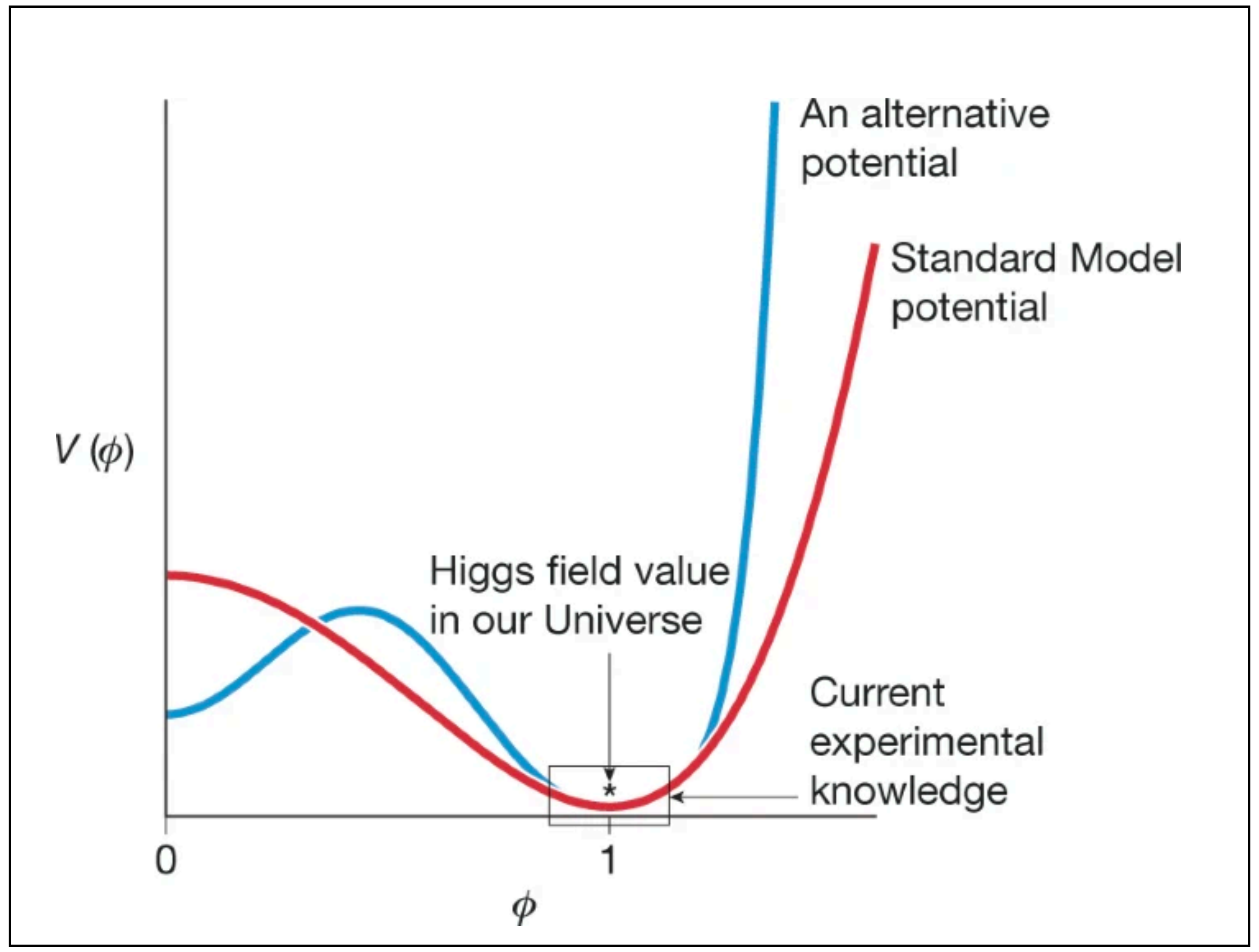
About the Standard Model

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

And the observed universe

What is dark matter?
What causes baryogenesis?



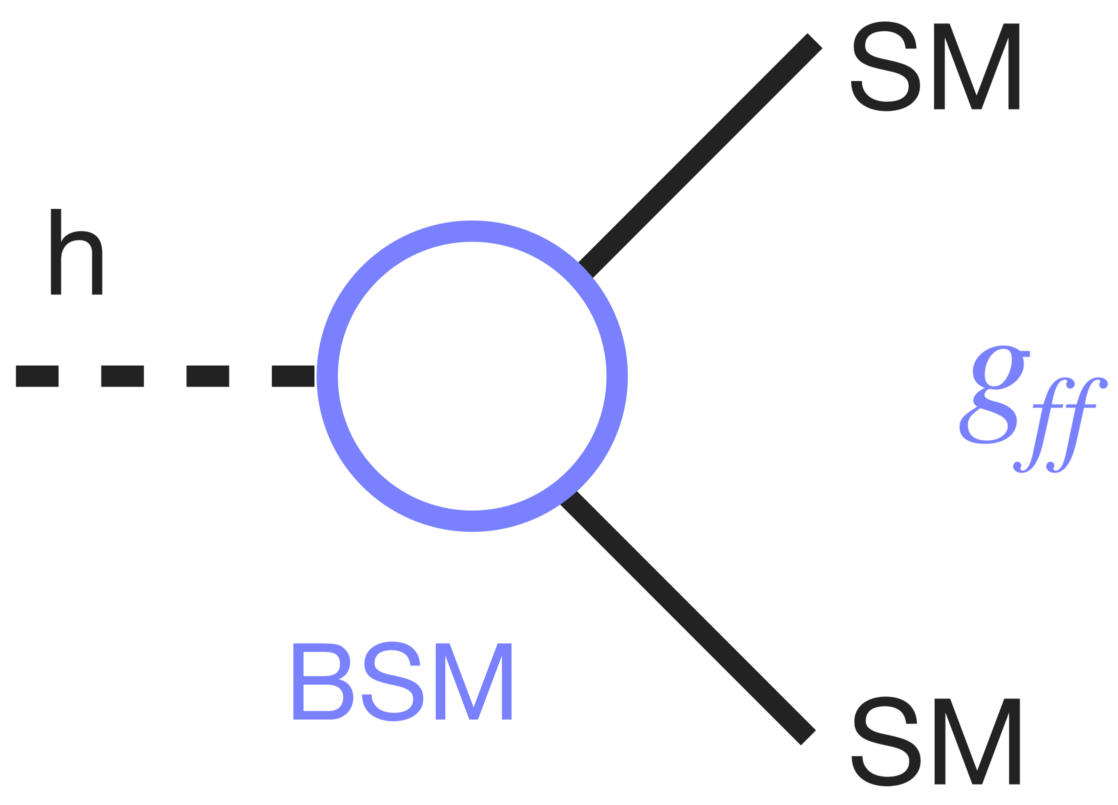


Why 10 TeV?

2209.07510

Need to compare reach from precision (indirect) and energy (direct)

eg. modified higgs couplings implies new particles
→ need to consider realistic models not just EFT



$$g_{ff} \sim \frac{\nu^2}{M^2}$$

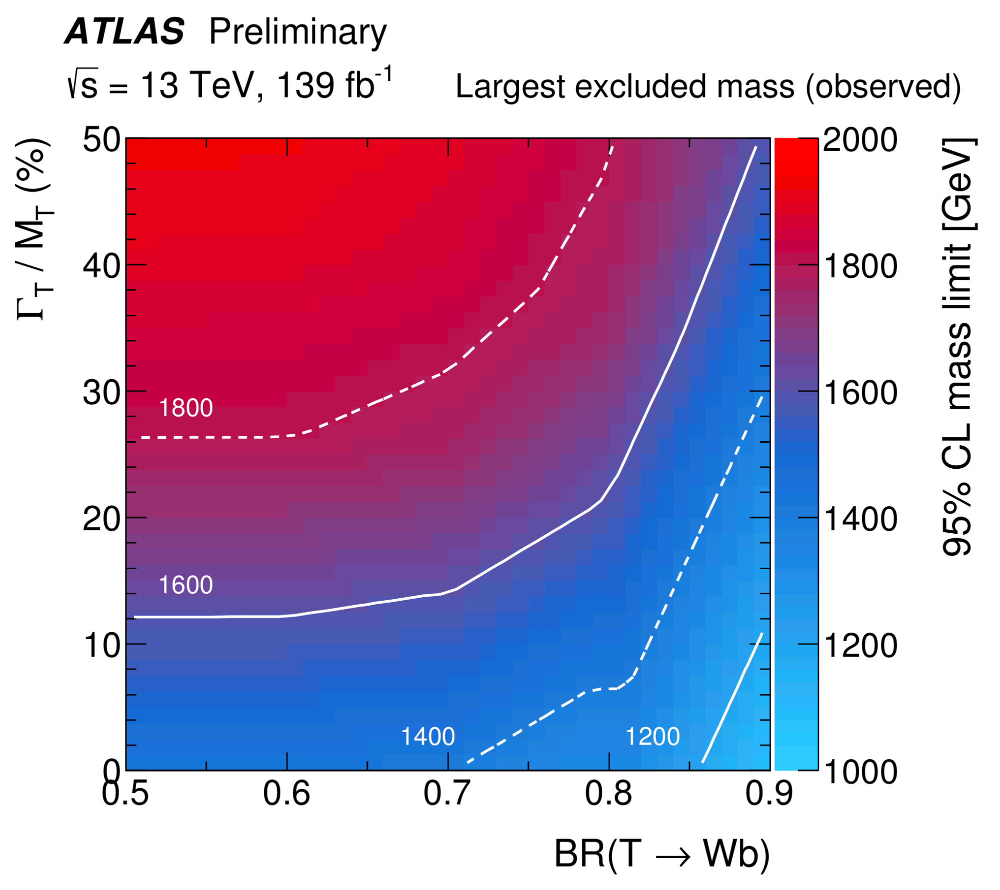
	HL-LHC	Higgs Factory
Higgs Precision	~few%	~0.1%
Indirect Reach	0.1-1 TeV	~few TeV
Direct reach	~1 TeV	-

Will discuss a few key examples

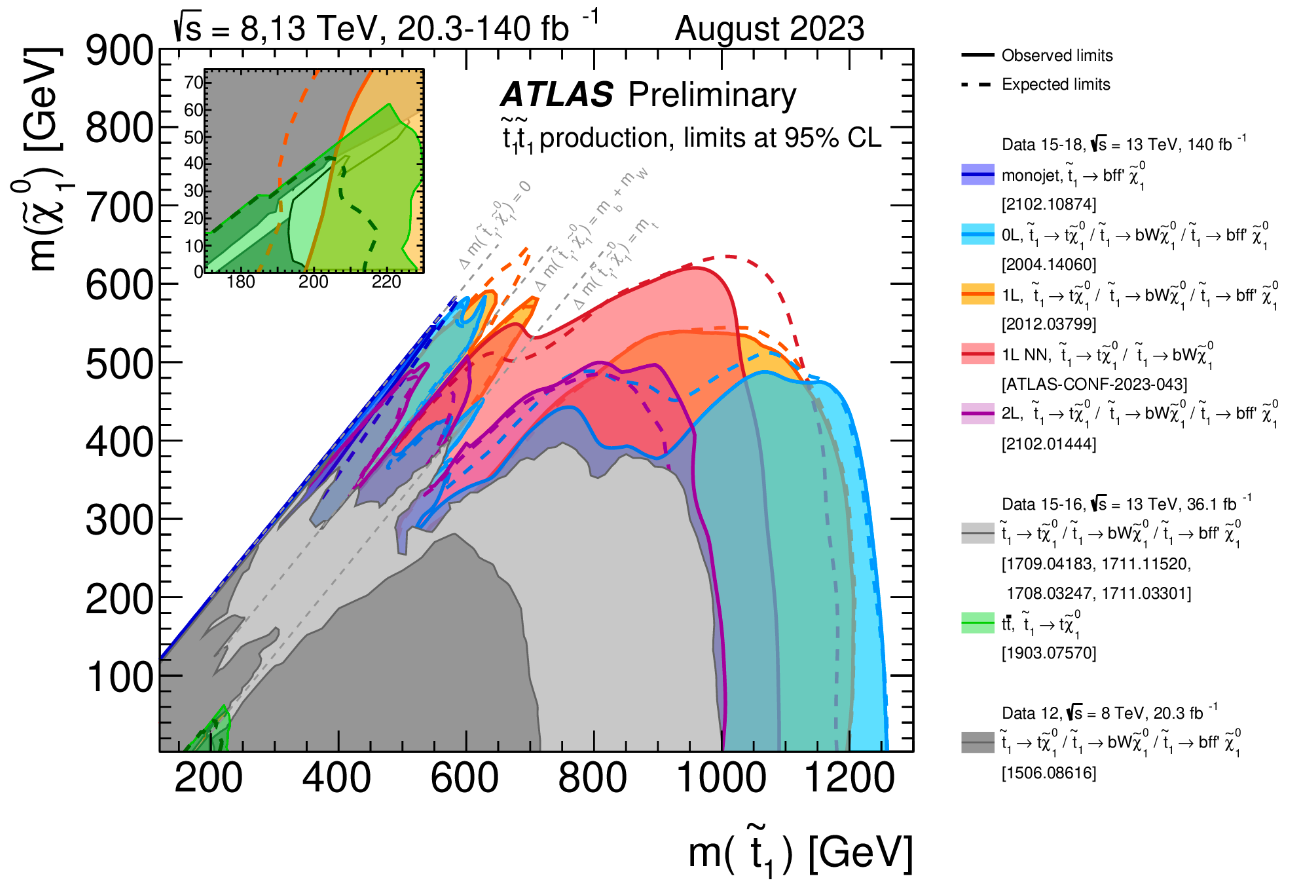
Microscopic nature of the higgs

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

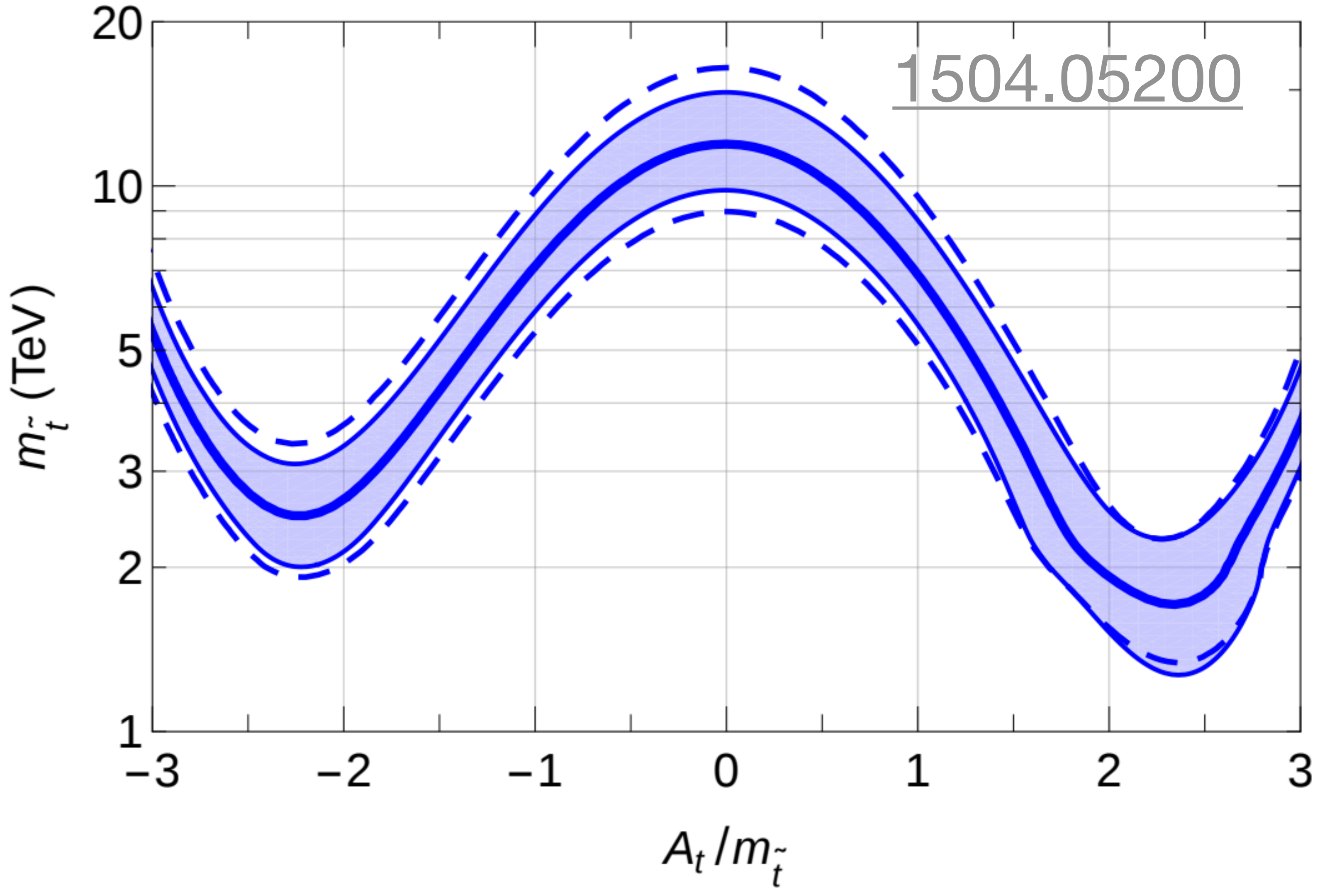
e.g. composite Higgs, like the pion?



e.g. new symmetry & additional particles?



m_h =125 GeV → multi-TeV top-partners

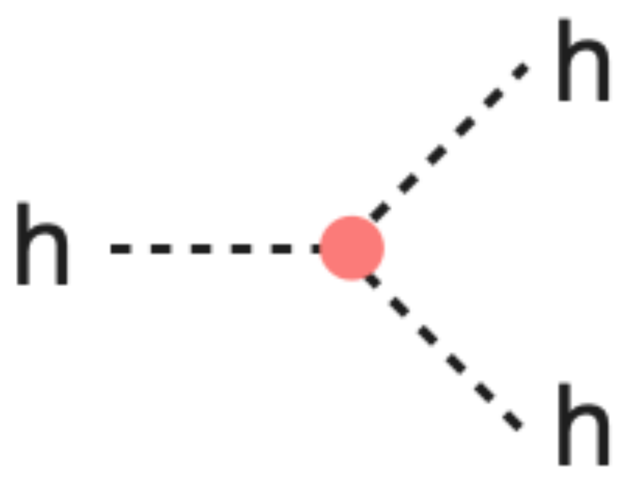


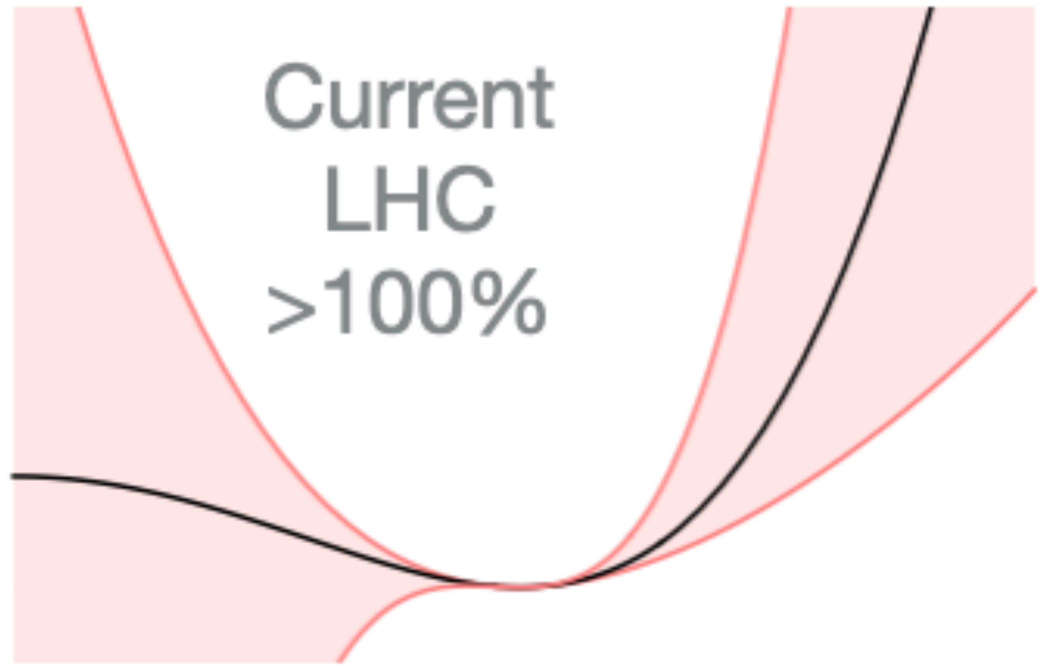
Data & theory suggest strongly coupled particles <u>> 1 TeV</u>

Electroweak symmetry breaking

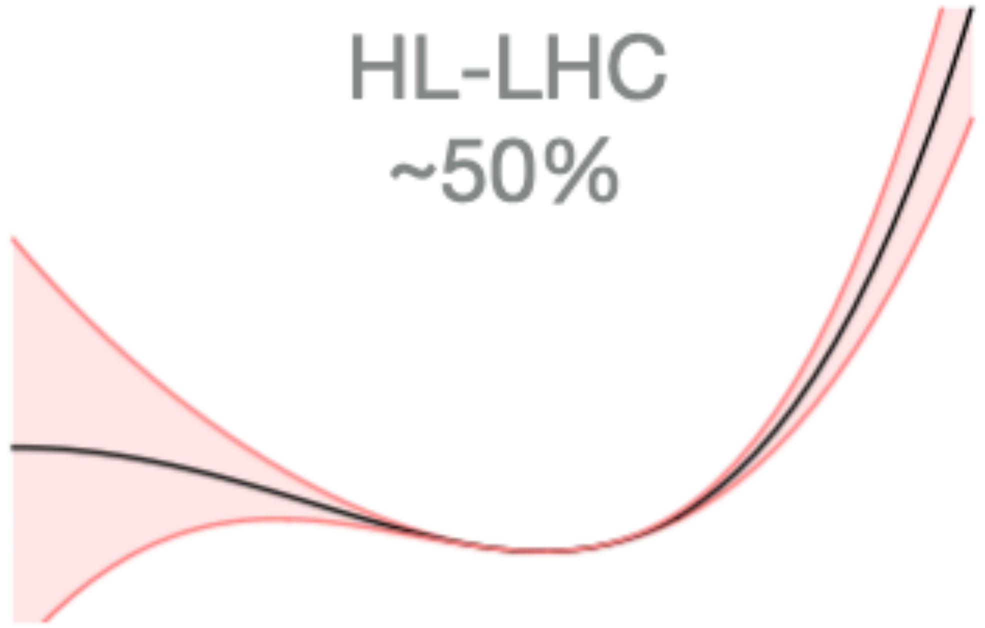
N. Craig

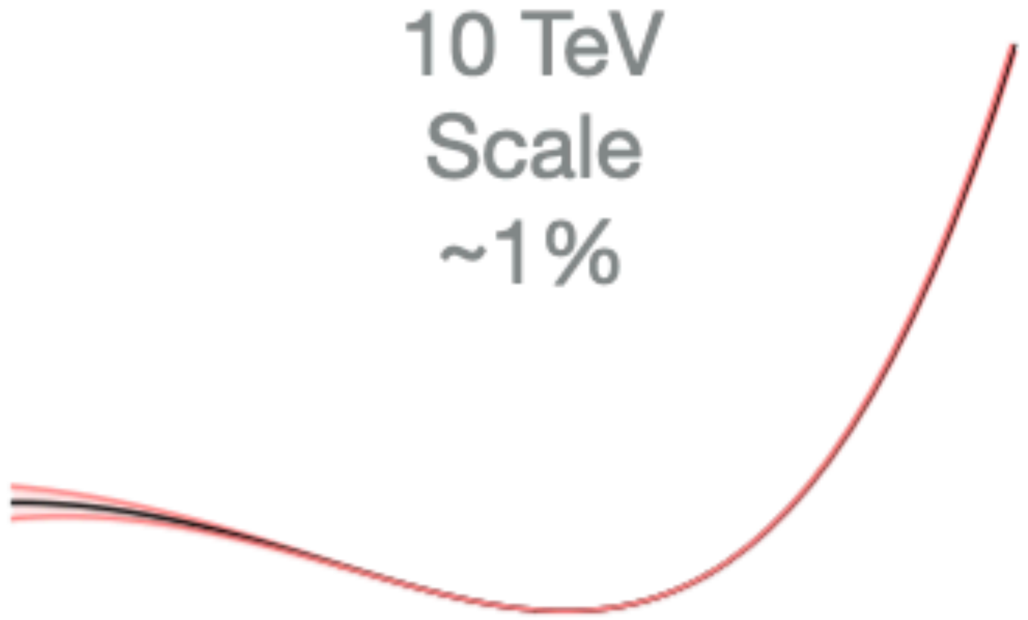
Was there a first order phase transition? Is electroweak symmetry restored at high temperatures?
Requires measuring Higgs self-coupling with few % uncertainty





We only know there's a minimum



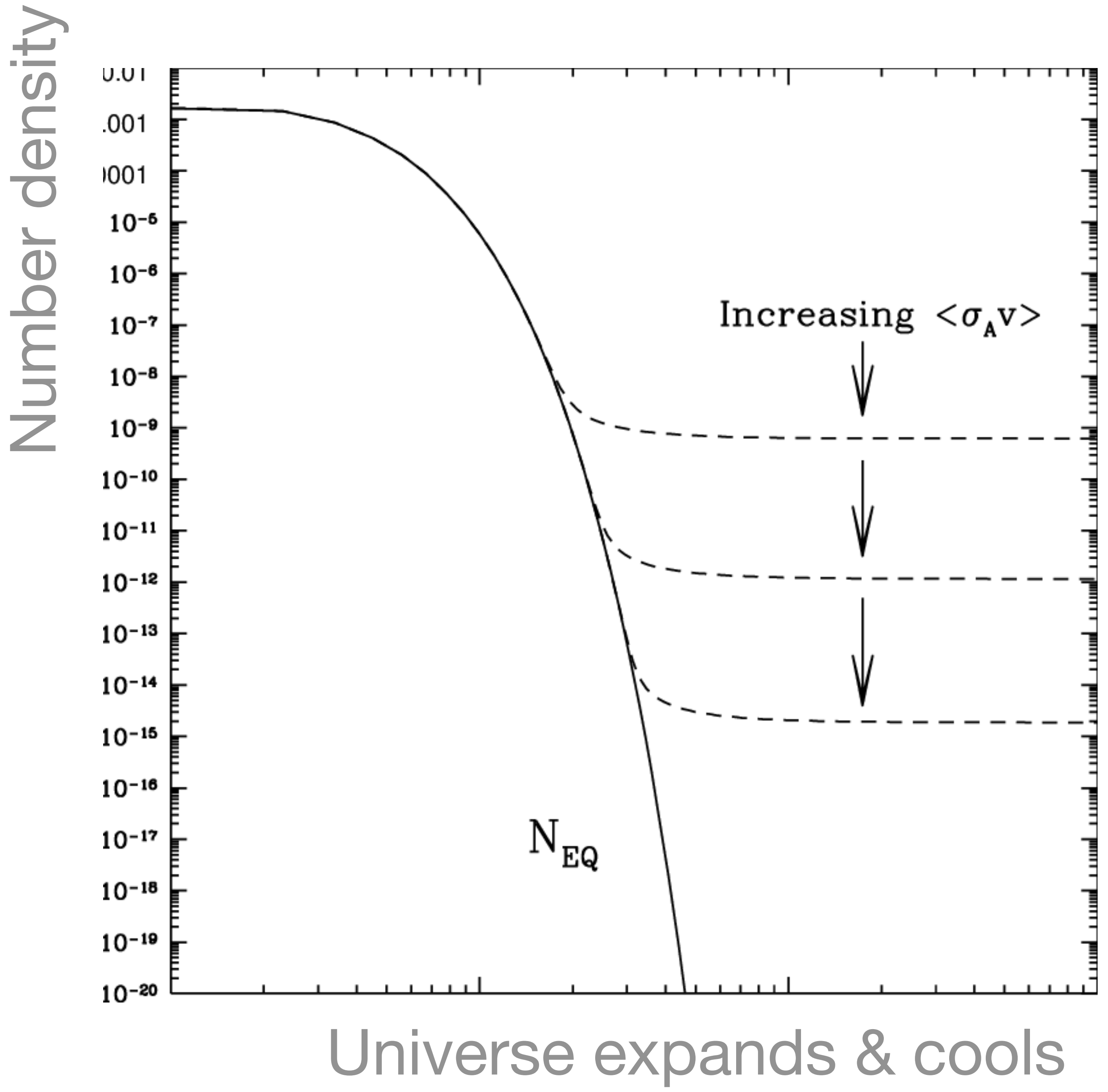


Producing enough multi-Higgs events is only possible at a 10 TeV scale collider

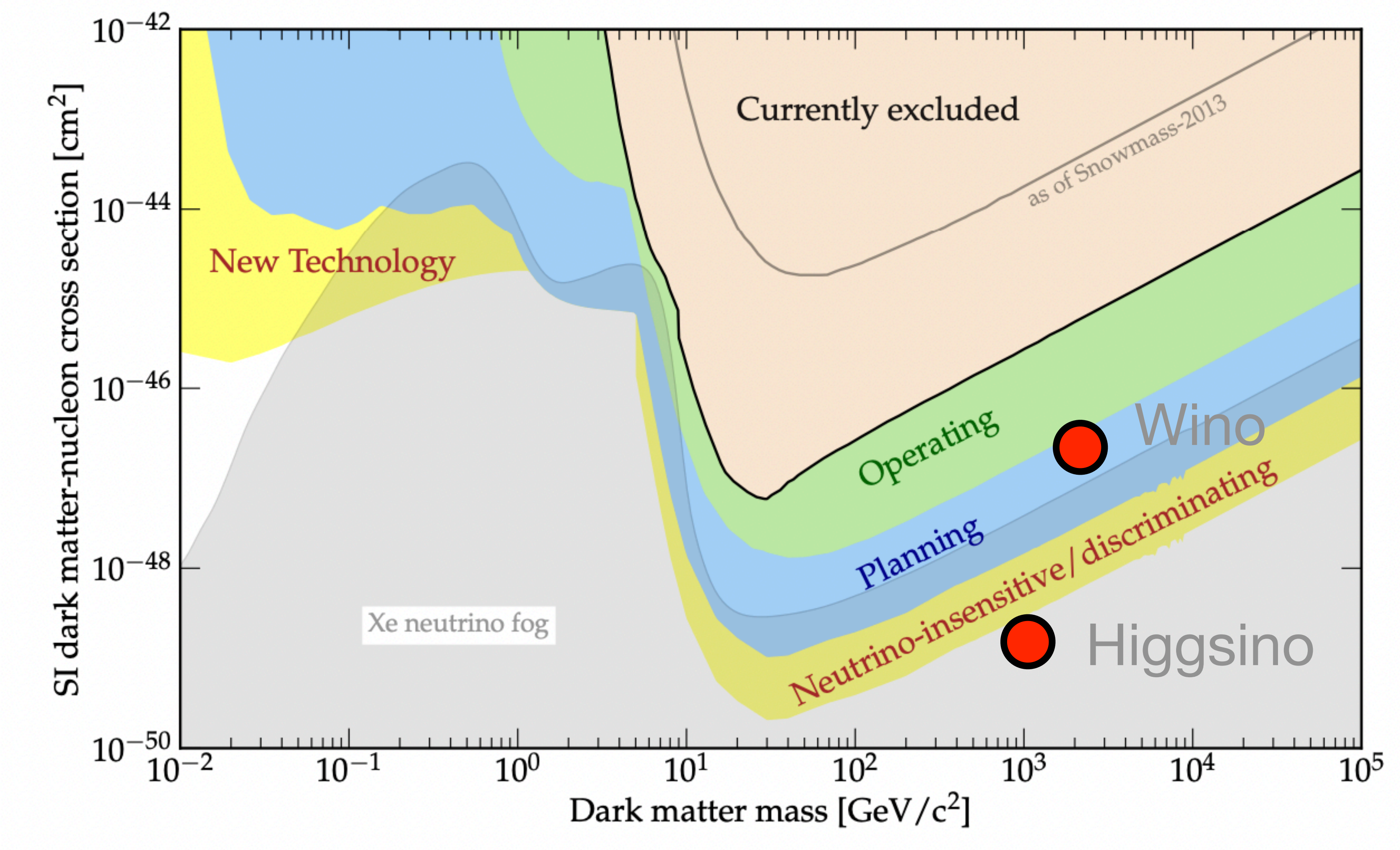
Dark Matter

DM Complementarity Report: 2211.07027

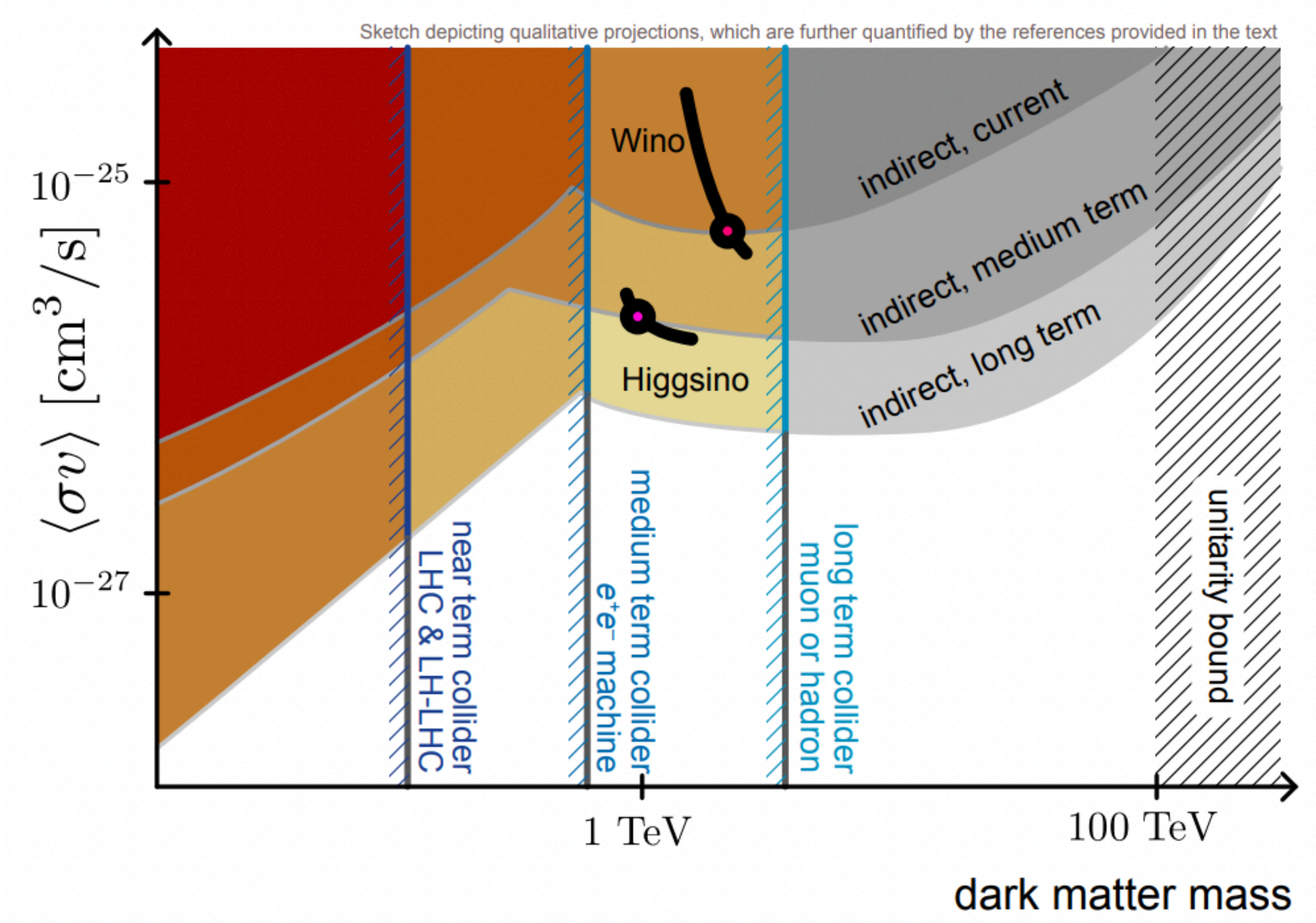
We’ve yet to probe minimal WIMPs up to thermal targets



Pure higgsino under neutrino floor



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



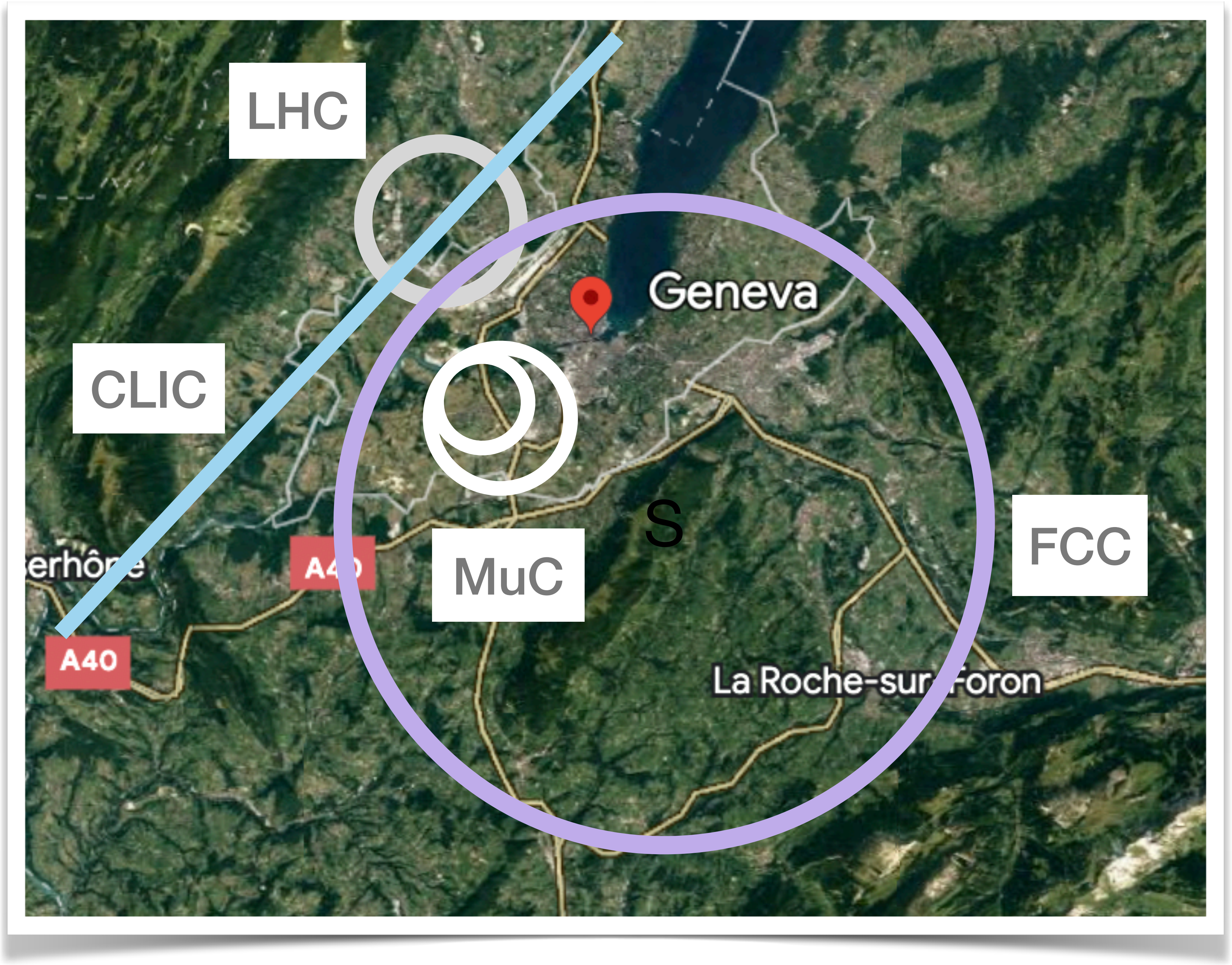
Definitive observation & characterization would require a multi-TeV scale collider

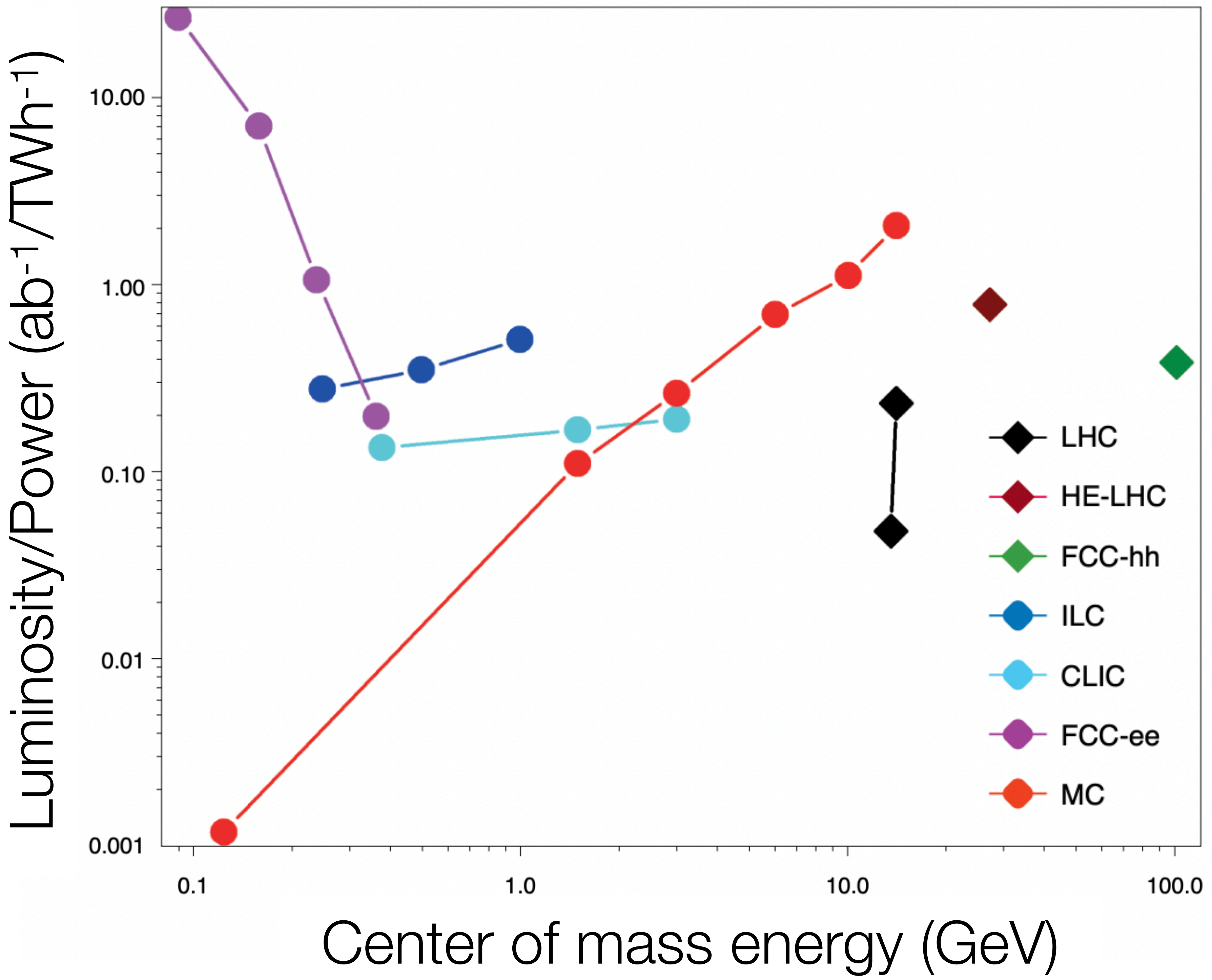
Why collide muons?

Input to EPPSU 1901.06150

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

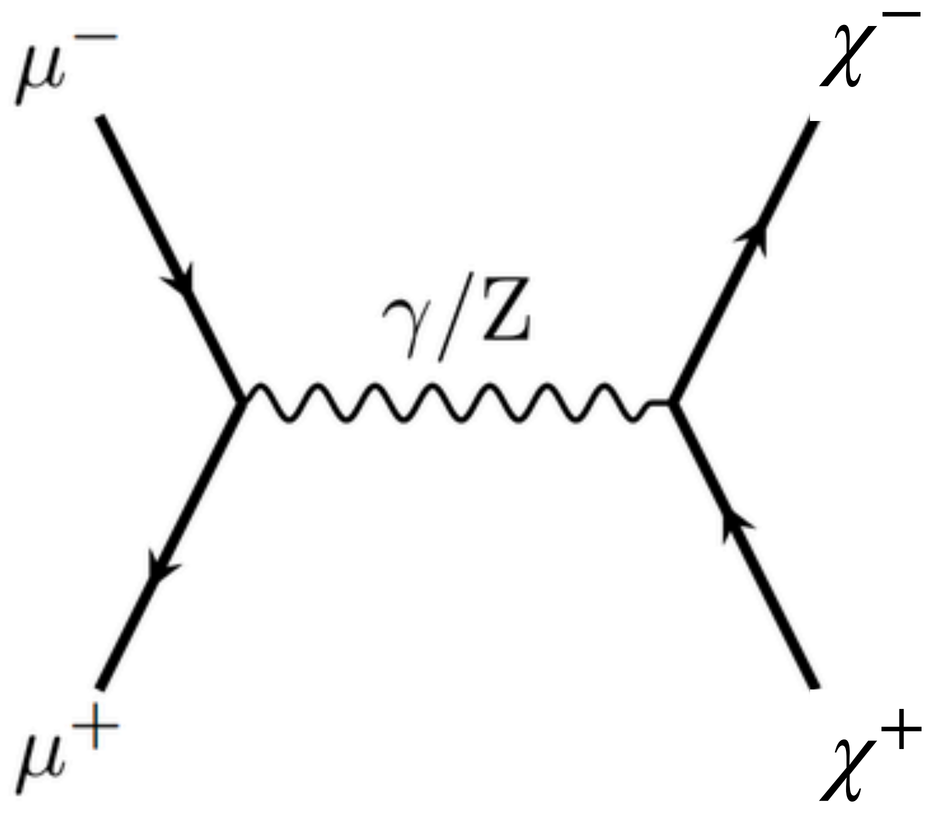
massive fundamental particles = compact, power, and cost-efficient





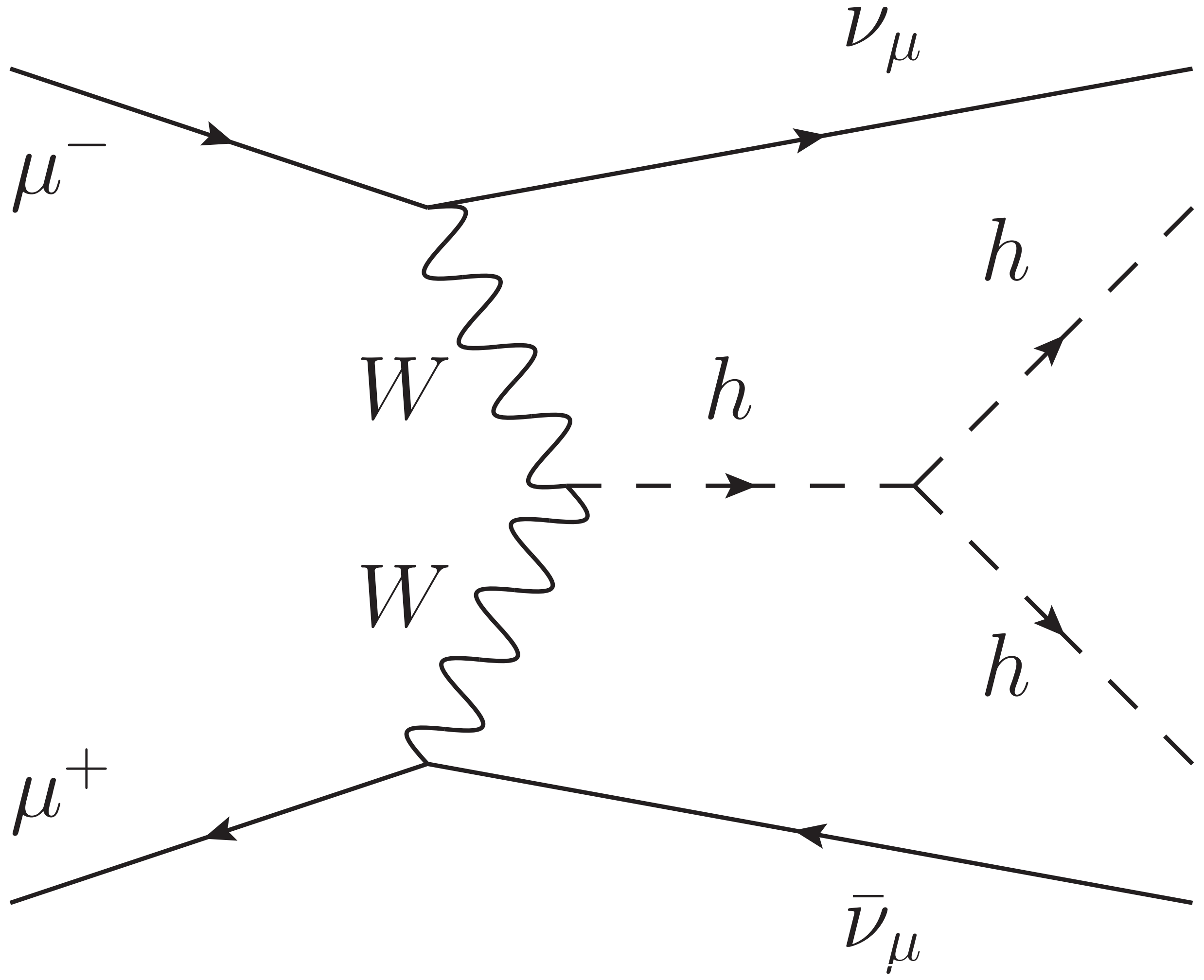
Two colliders in one

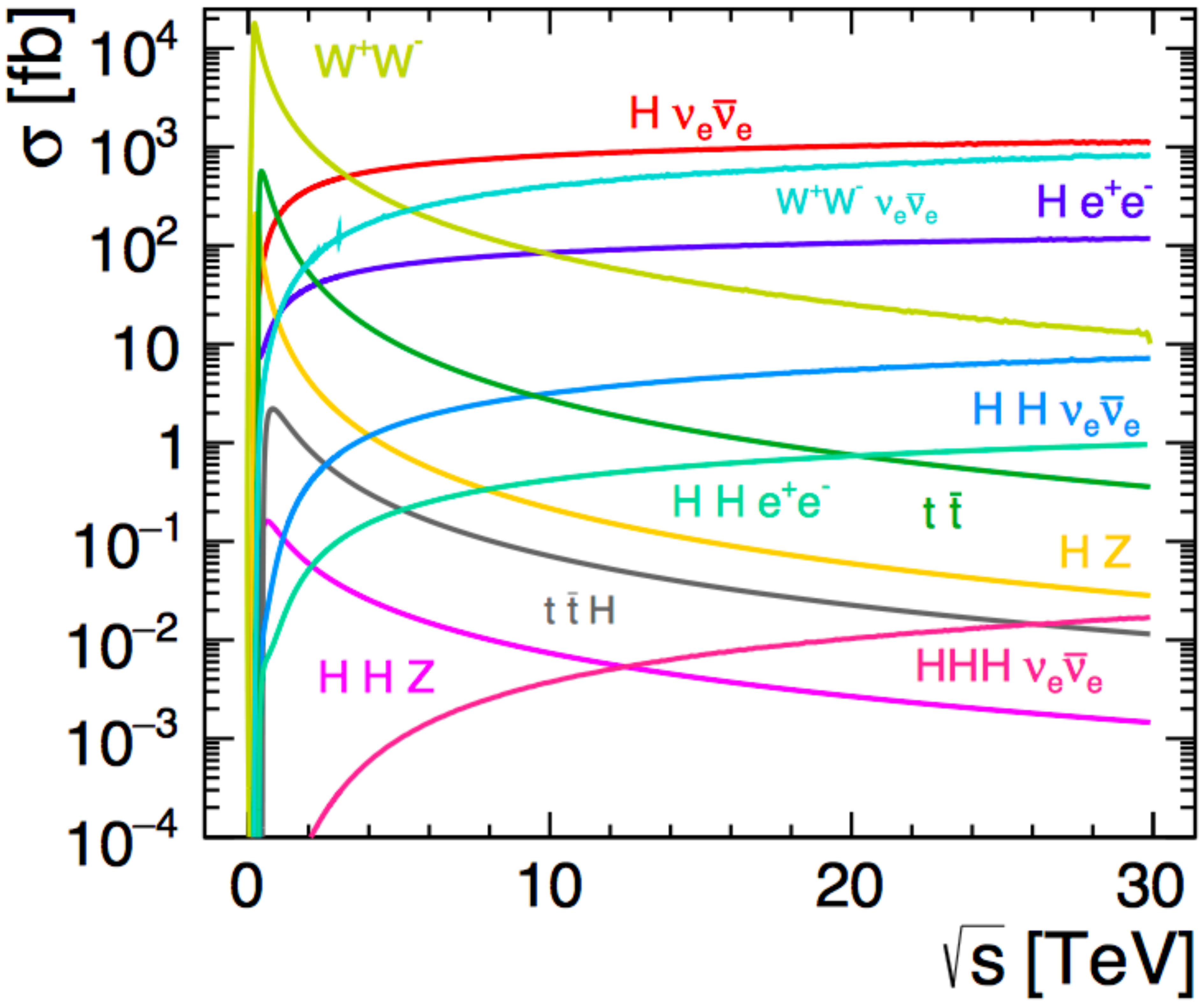
Energy reach & precision electroweak physics in same machine



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

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



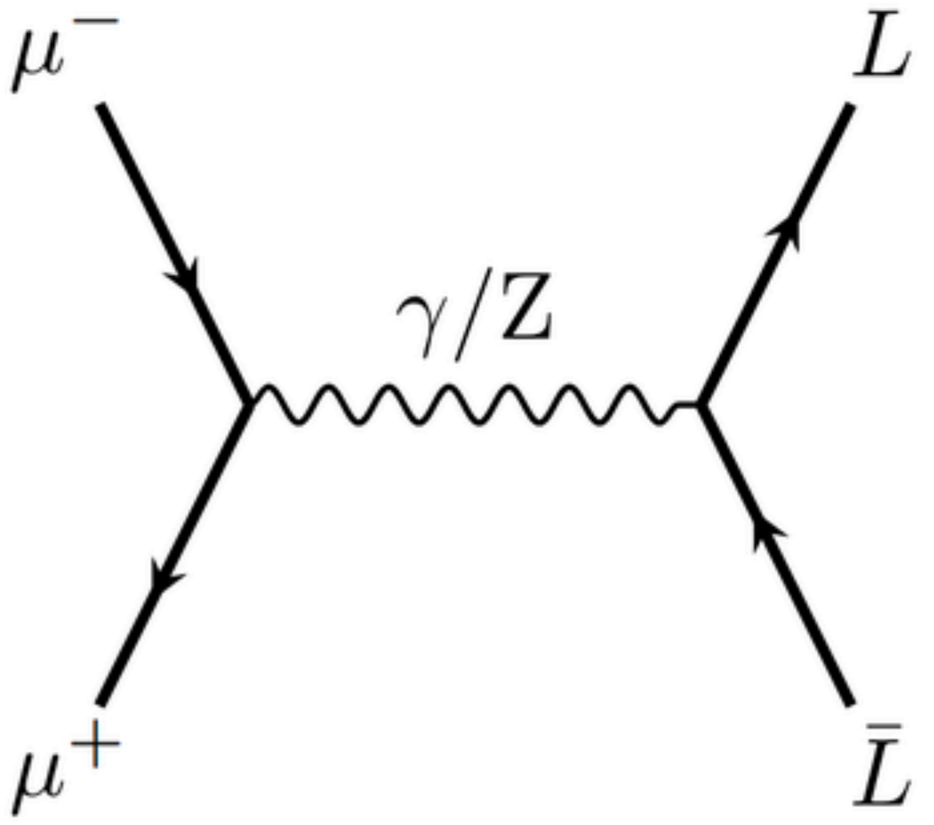


Sensitivity to new physics

2303.08533

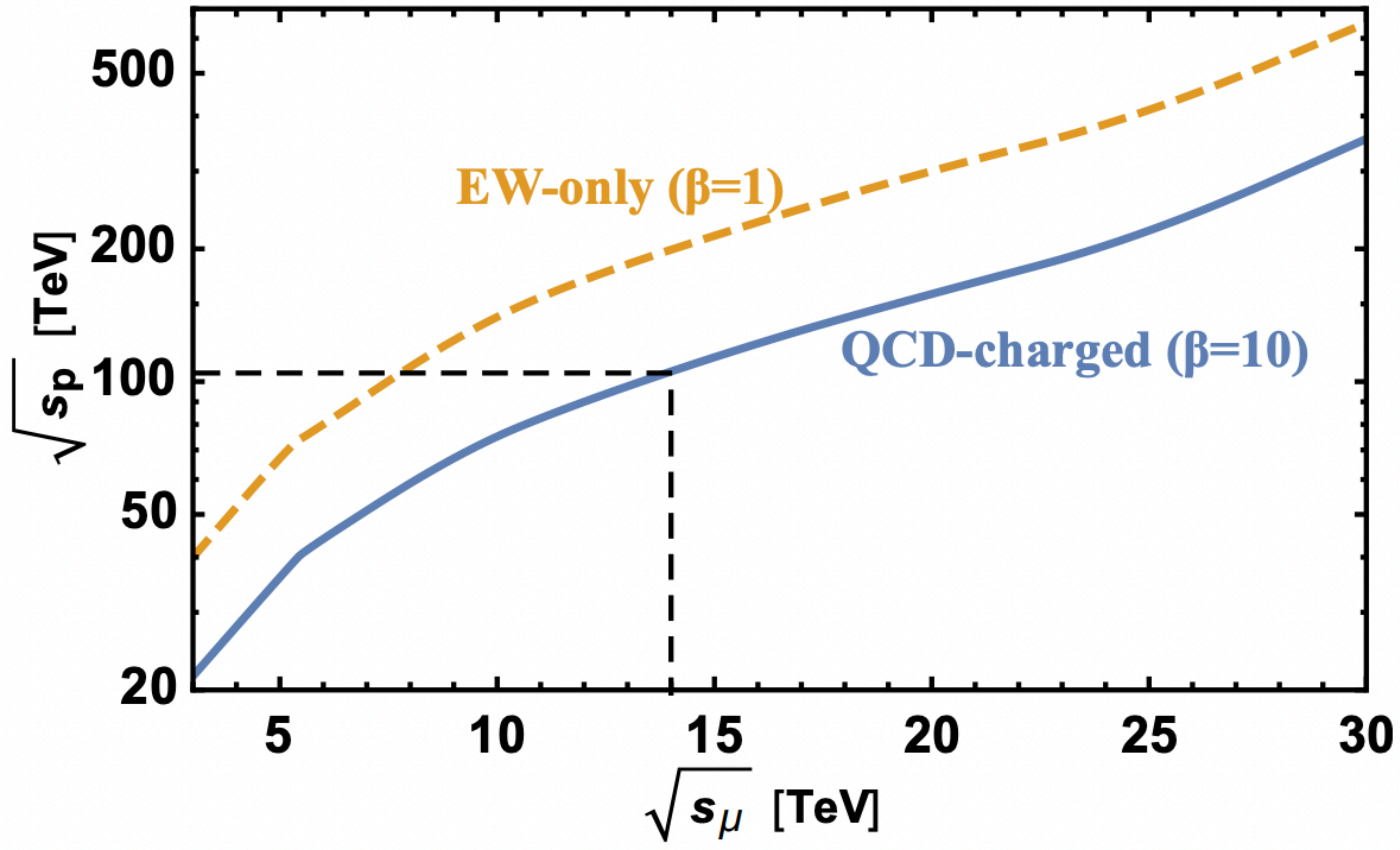
More complicated than 10 TeV μμ ~ 100 TeV pp

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

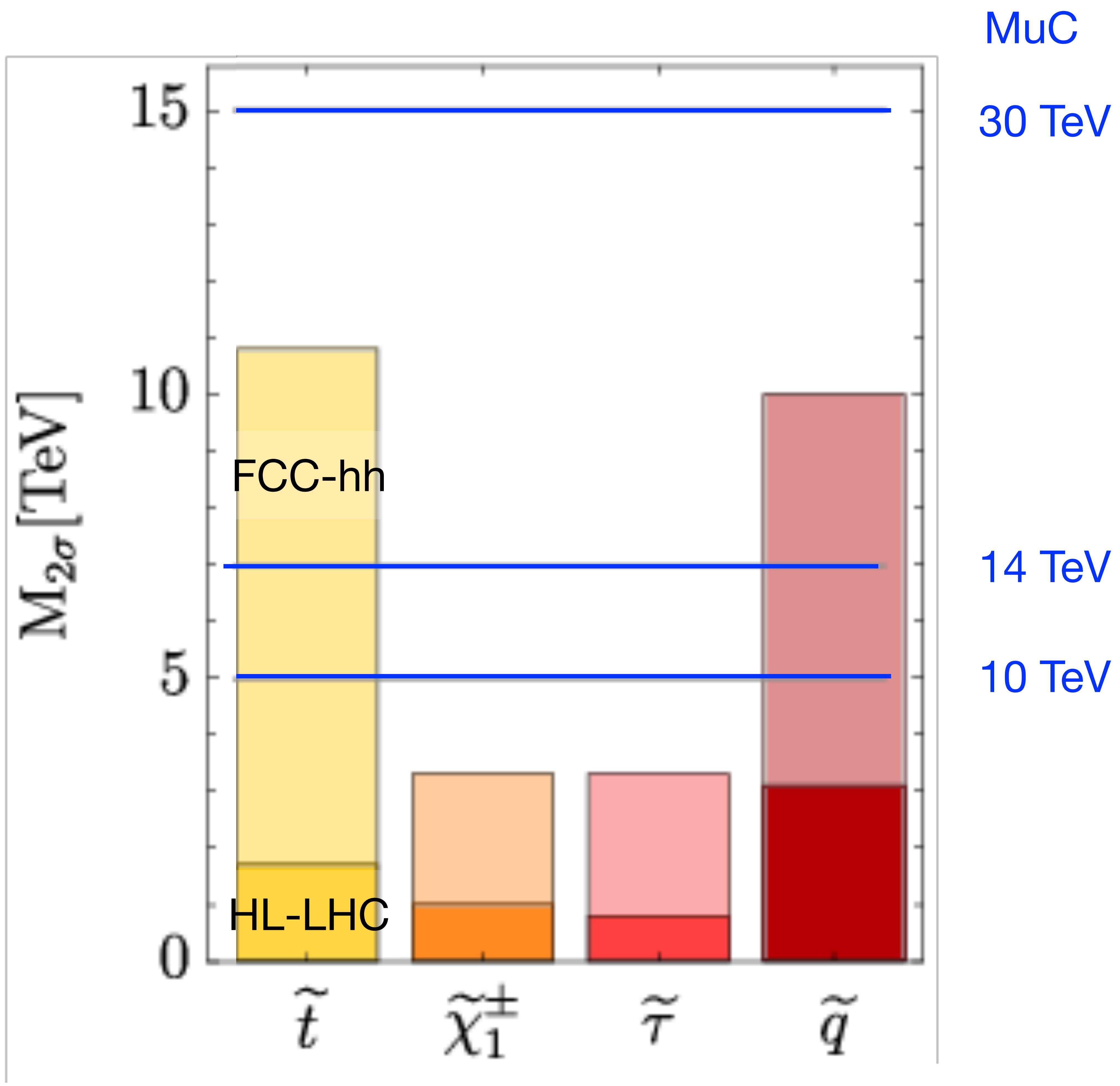
2303.08533

Example of Direct reach
Supersymmetry

MuC: pair-production up to √s/2

FCC-hh: better for stops (color charge)

But, most realistic models have TeV scale sleptons/electroweakinos



Sensitivity to new physics

2303.08533

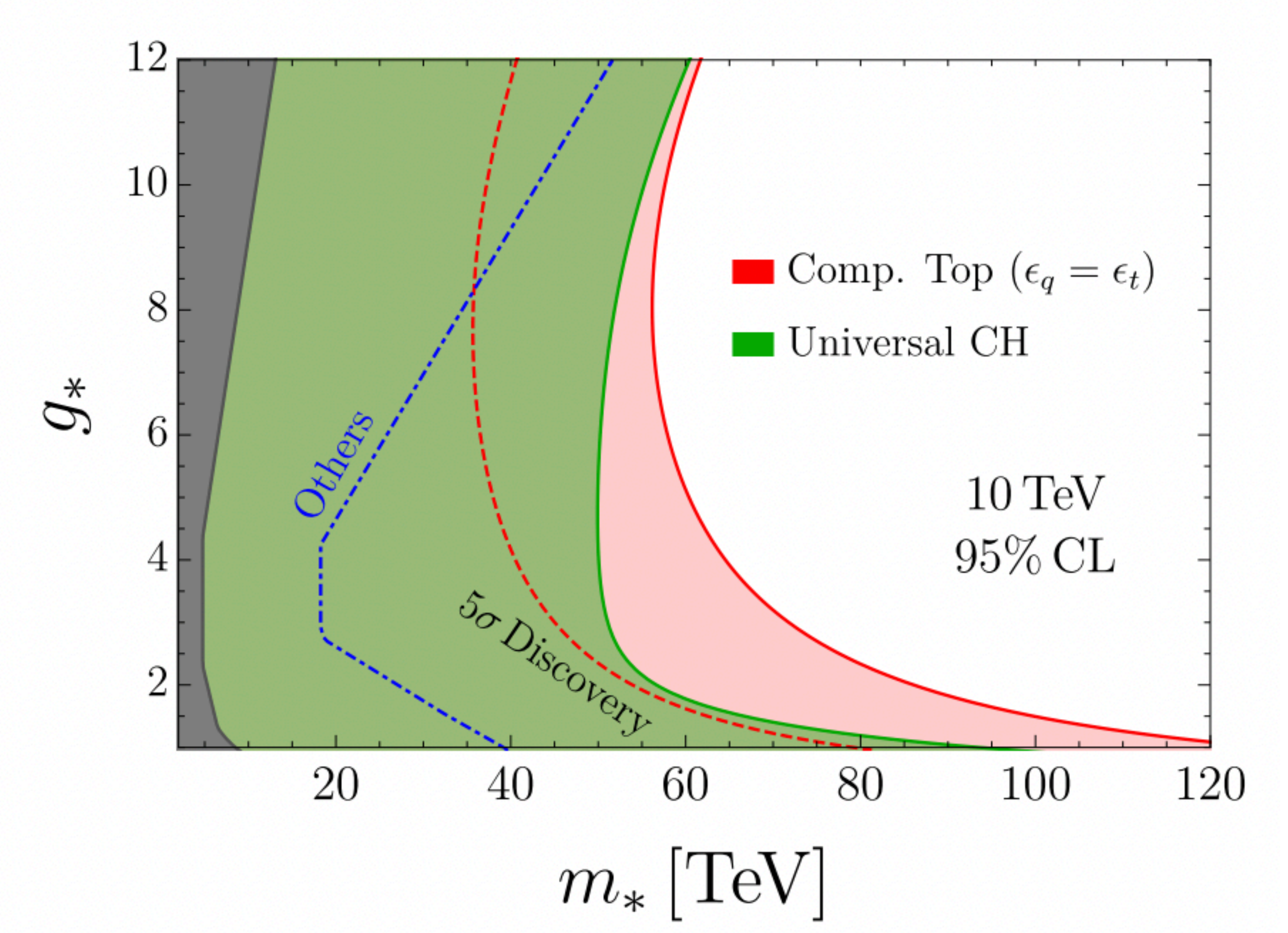
Example of Indirect Reach:
Higgs Compositeness

Diboson & di-fermion final states

MuC: sensitivity scales with √s

FCC-hh: lower effective parton luminosity

e^+e^-: negligible effects visible

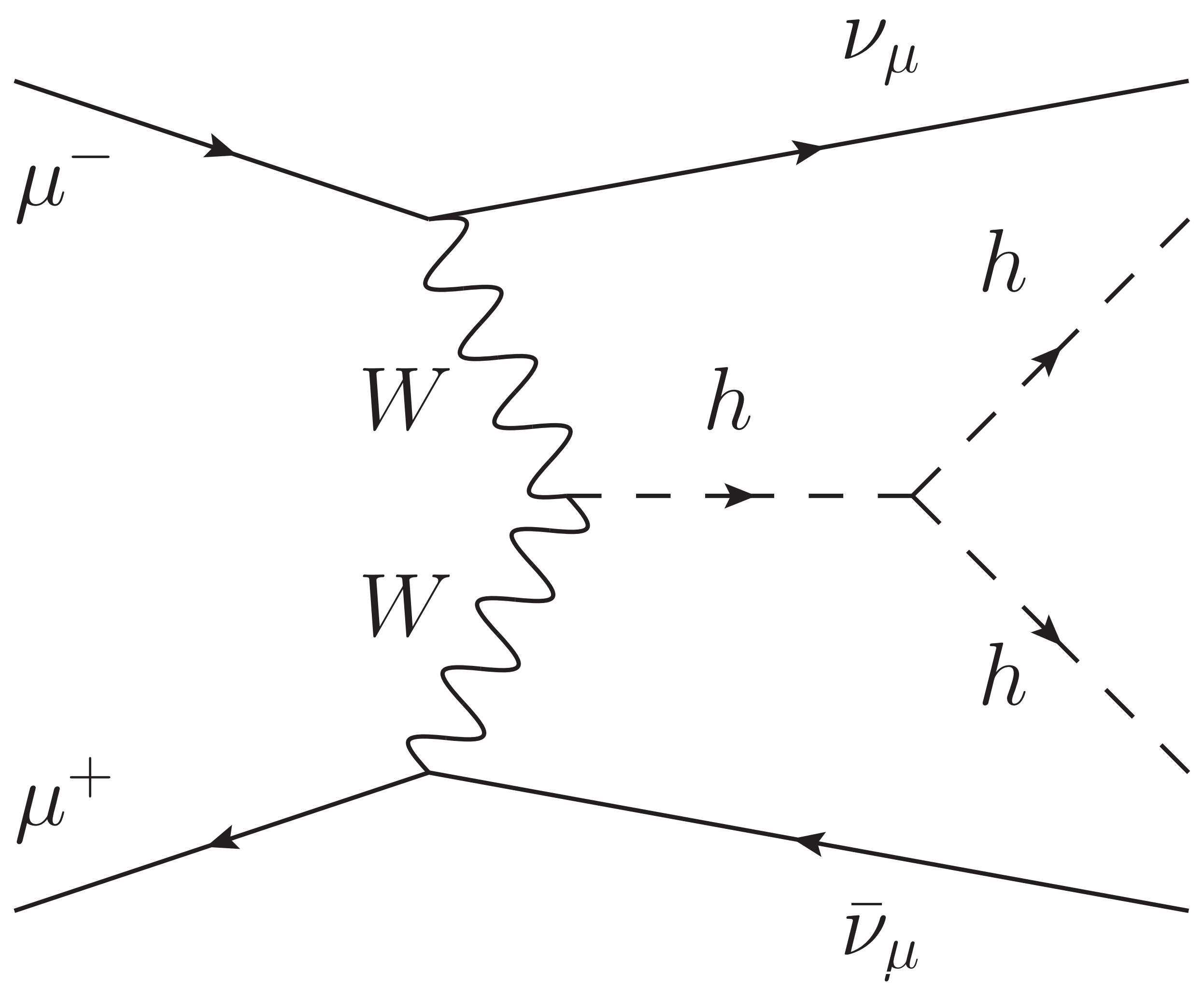


Electroweak precision

1905.03764, 2203.09425, and 2212.11067

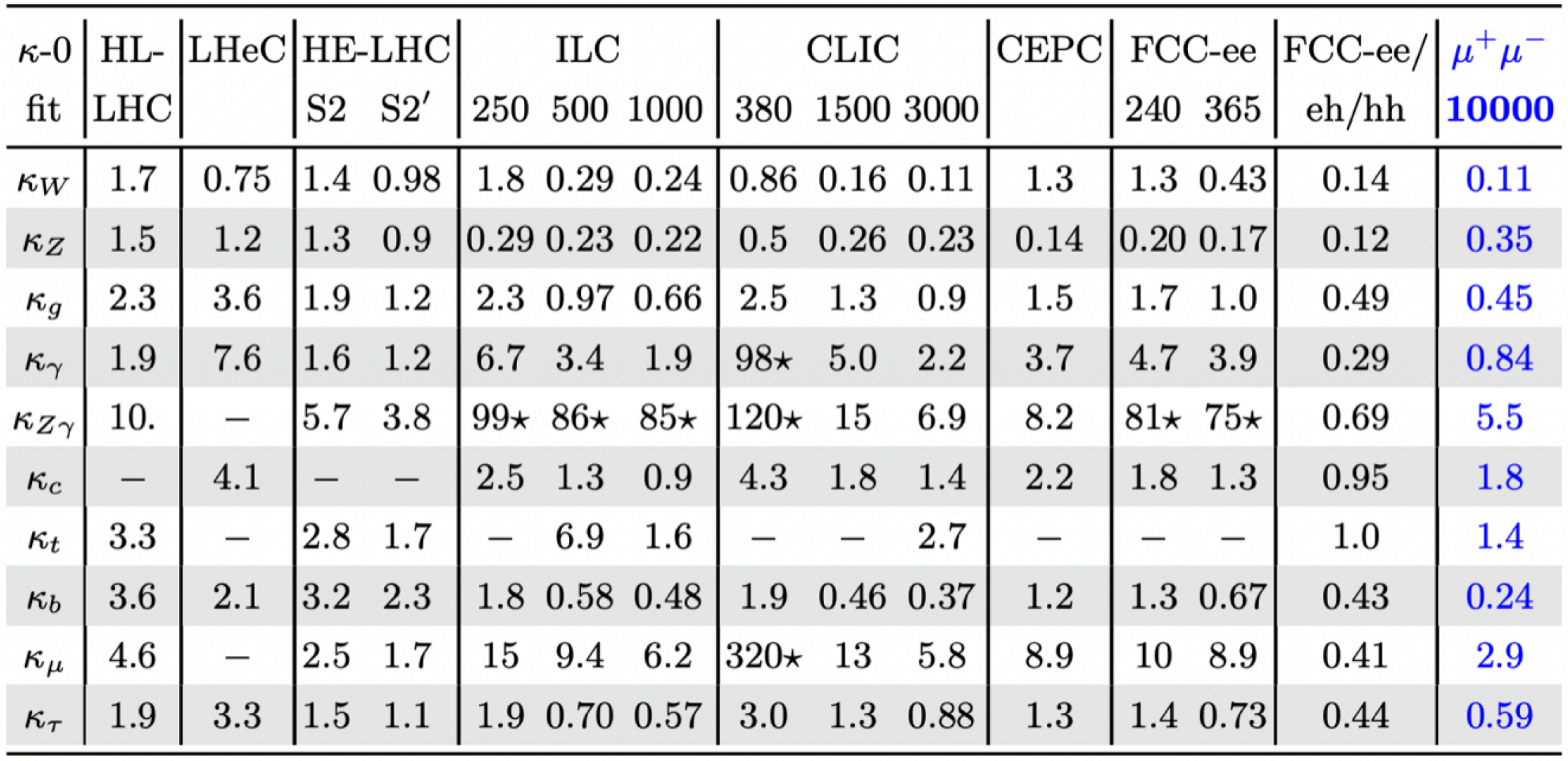
$\geq 10^7$ single higgs events → competitive with e+e- Higgs Factories

~10k di-higgs events → self-coupling competitive with 100 TeV pp



O(100) GeV scale SM physics

foward muons/neutrinos



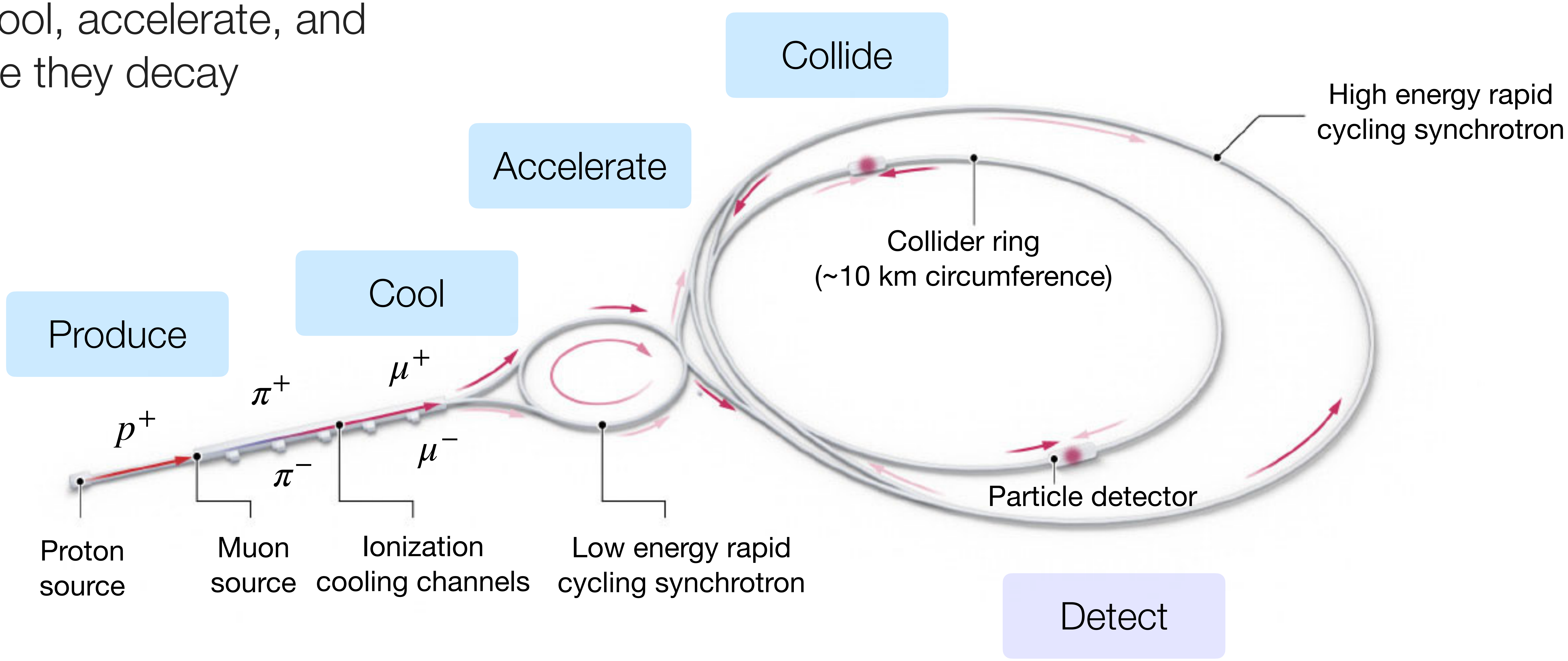
κ-0	HL-	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/	$\mu^+\mu^-$
fit	LHC		S2	S2′	250	500	1000	380	1500	3000		240	365	eh/hh	**10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	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 Challenge

Muon lifetime τ=2.2 μs

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

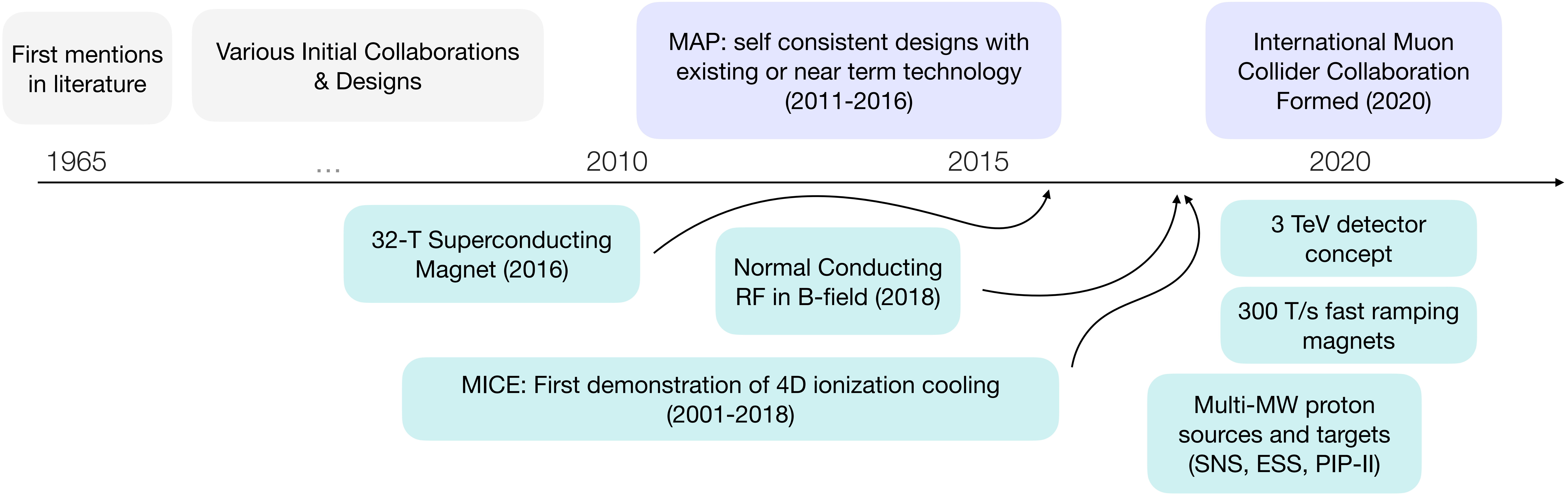


My focus

Can we build it?

2209.01318

Perception: “no progress in past 50 years”



First mentions in literature

Various Initial Collaborations & Designs

MAP: self consistent designs with existing or near term technology (2011-2016)

International Muon Collider Collaboration Formed (2020)

32-T Superconducting Magnet (2016)

Normal Conducting RF in B-field (2018)

MICE: First demonstration of 4D ionization cooling (2001-2018)

3 TeV detector concept

300 T/s fast ramping magnets

Multi-MW proton sources and targets (SNS, ESS, PIP-II)

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

Can we do physics?

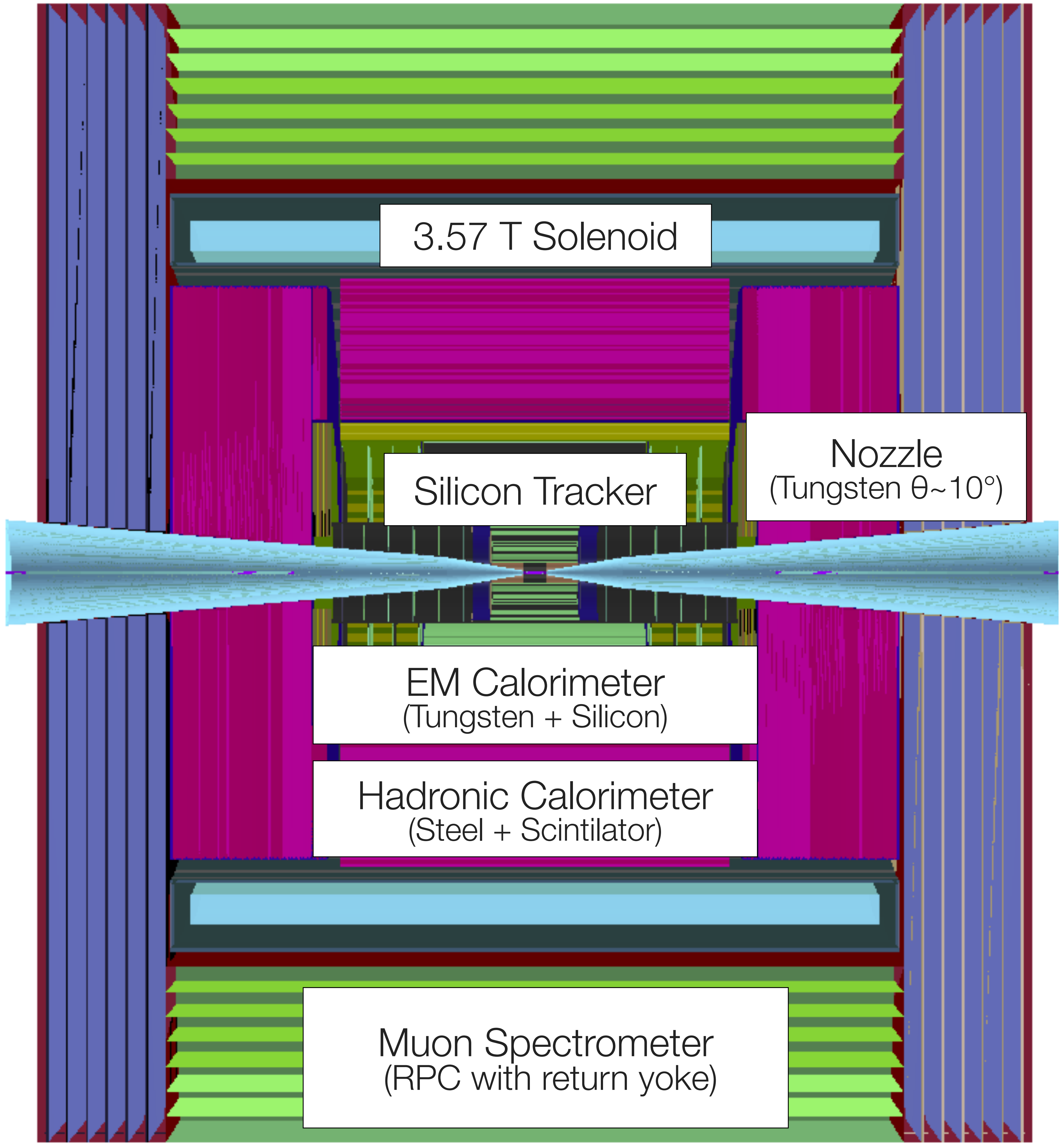
2303.08533

Baseline Detector for 3 TeV was a major outcome of IMCC/Snowmass

Beam Induced Background with FLUKA

Full simulation physics studies

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



Collision environment

Depends on energy, physics goals, and cross-sections

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

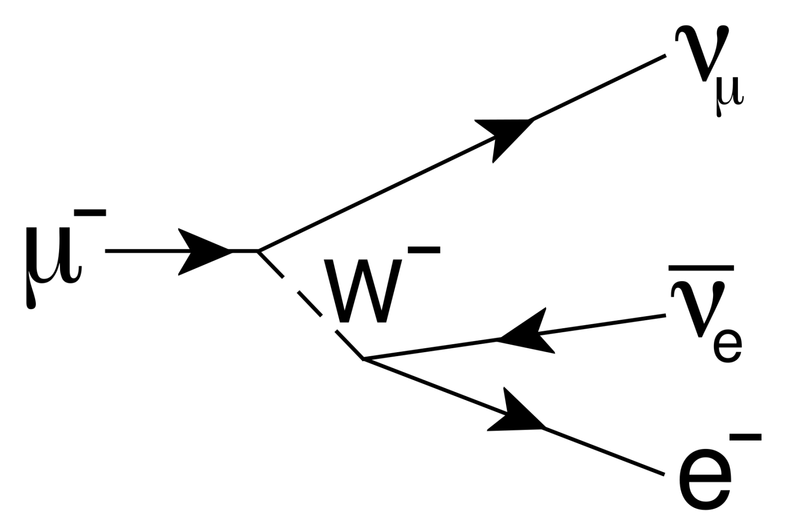
Aim for 10 ab^{-1} in 5 years

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

Set $n_b = 1$ and maximize N_μ per bunch	~$2 \cdot 10^{12}$ 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
Decays w/in 20 m of detector	10^7

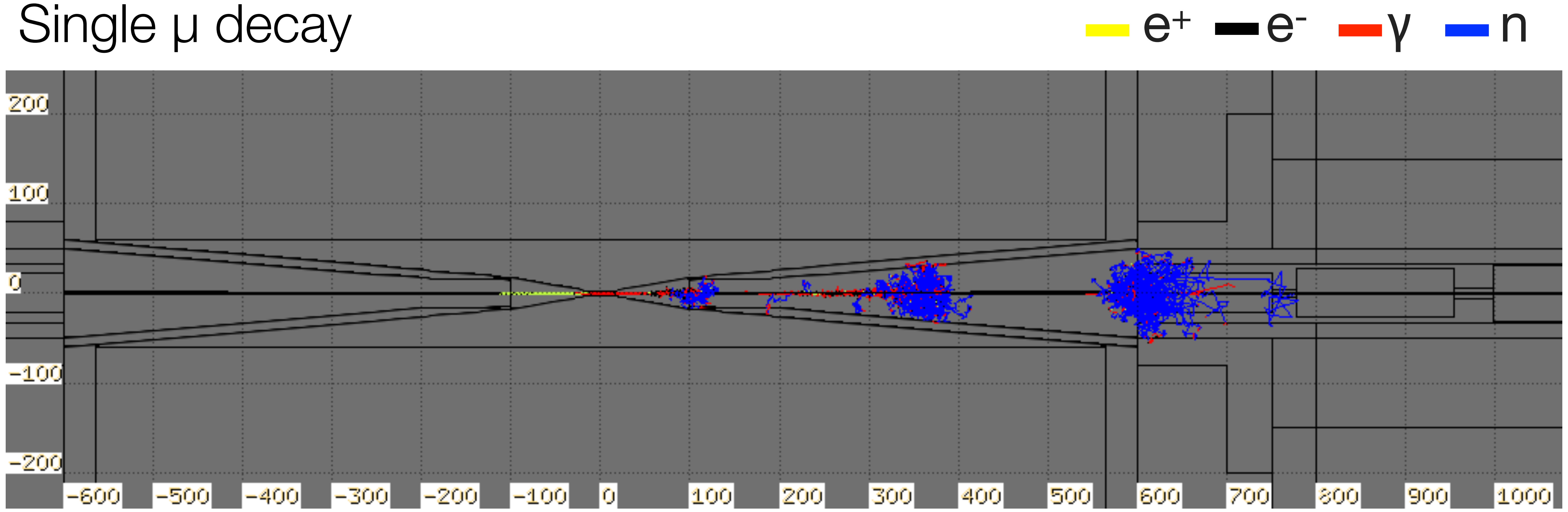
Unique need: Tungsten Nozzles

Suppress high energy component of **<u>beam induced background</u>**

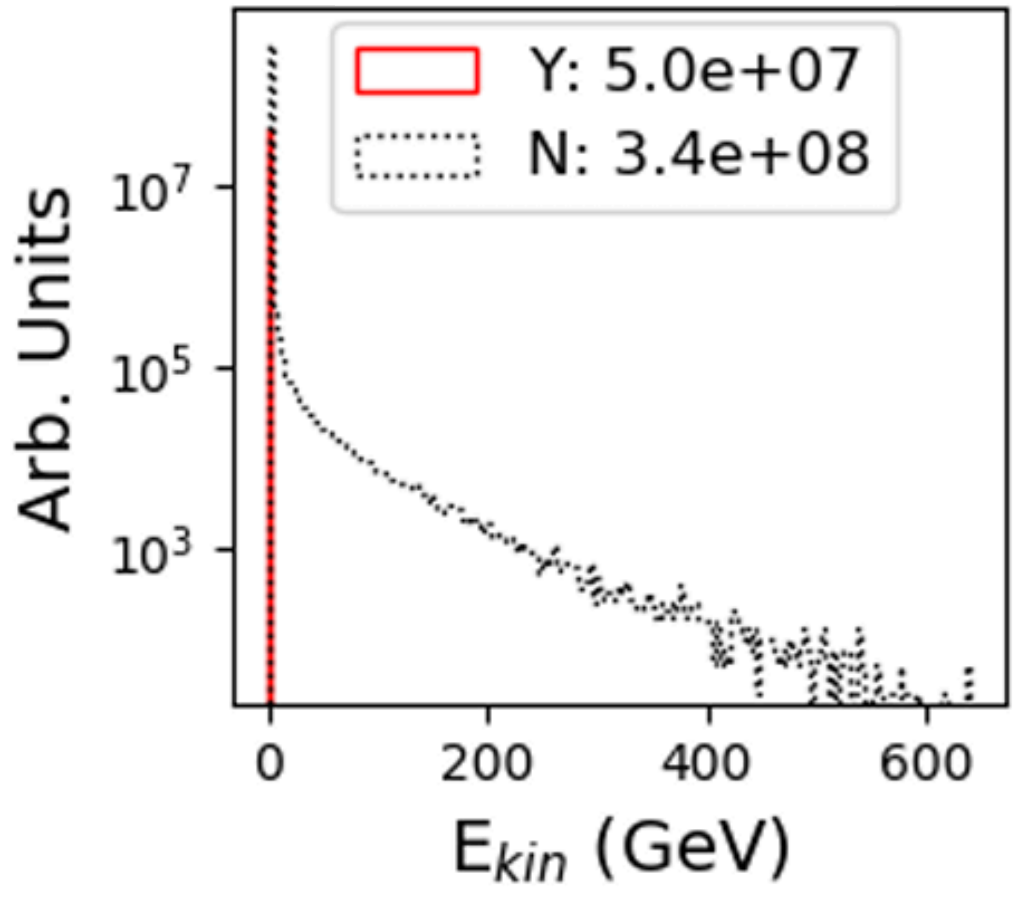


Tradeoff: increase in low energy neutrons

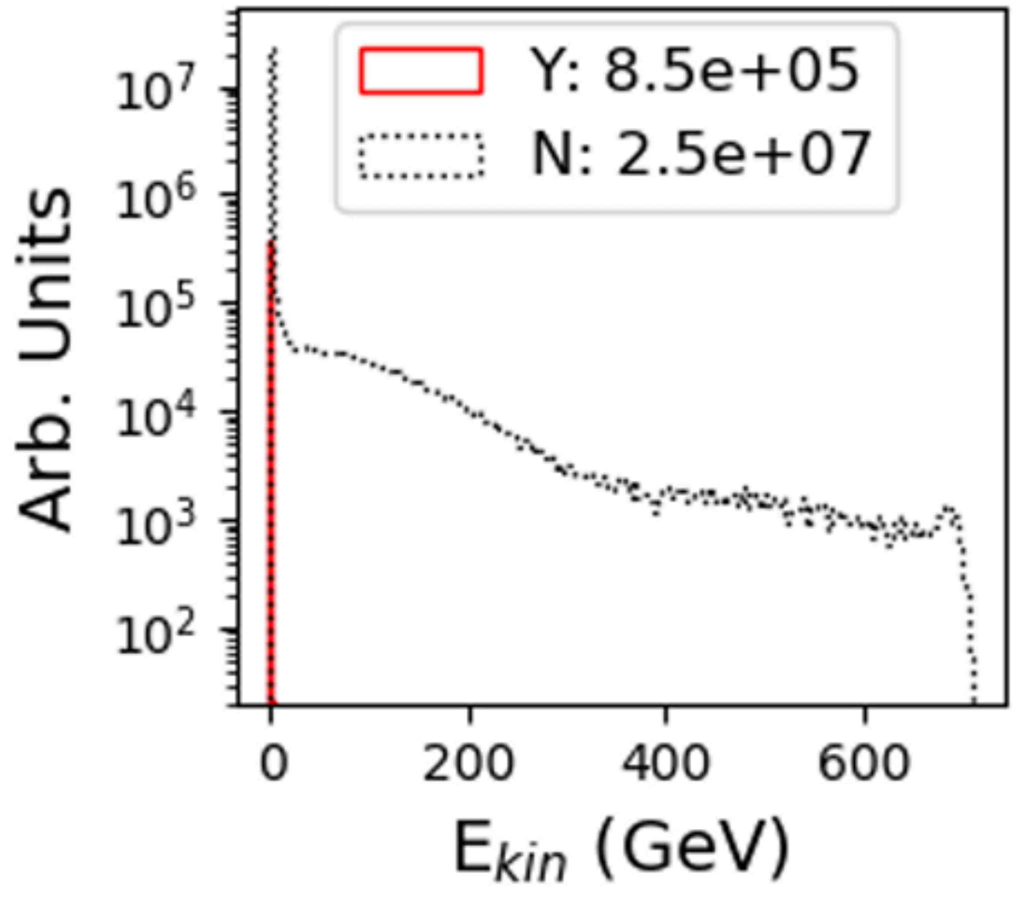
Single μ decay



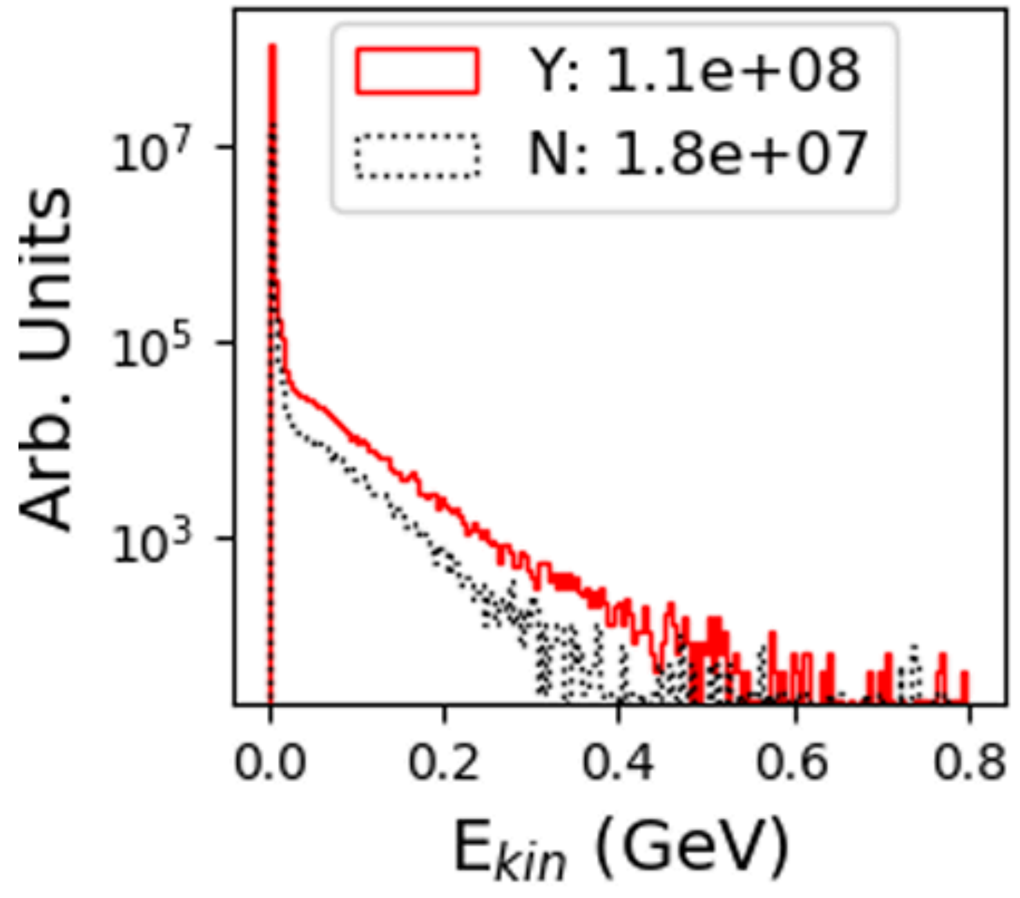
Photons



Electrons



Neutrons



Inside the detector

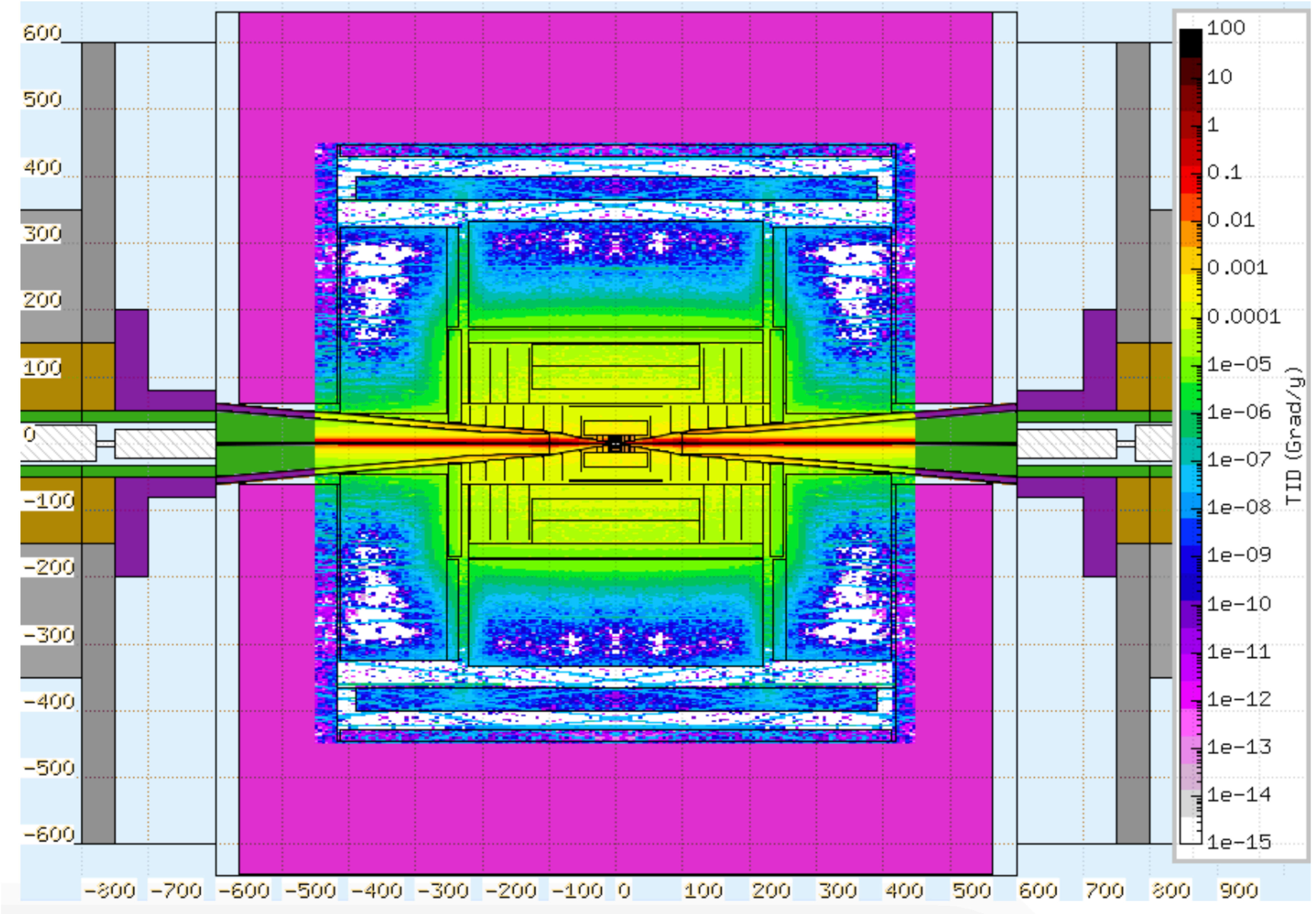
Compared to HL-LHC

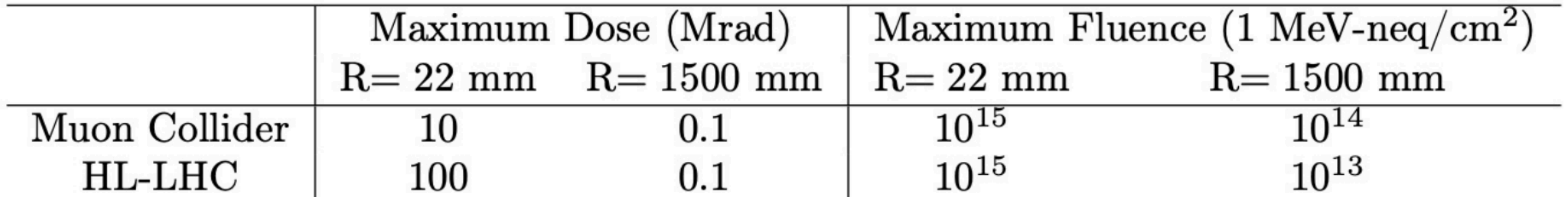
Up to ~10 x hit density

~1/1000 event rate

Similar dose & fluence

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





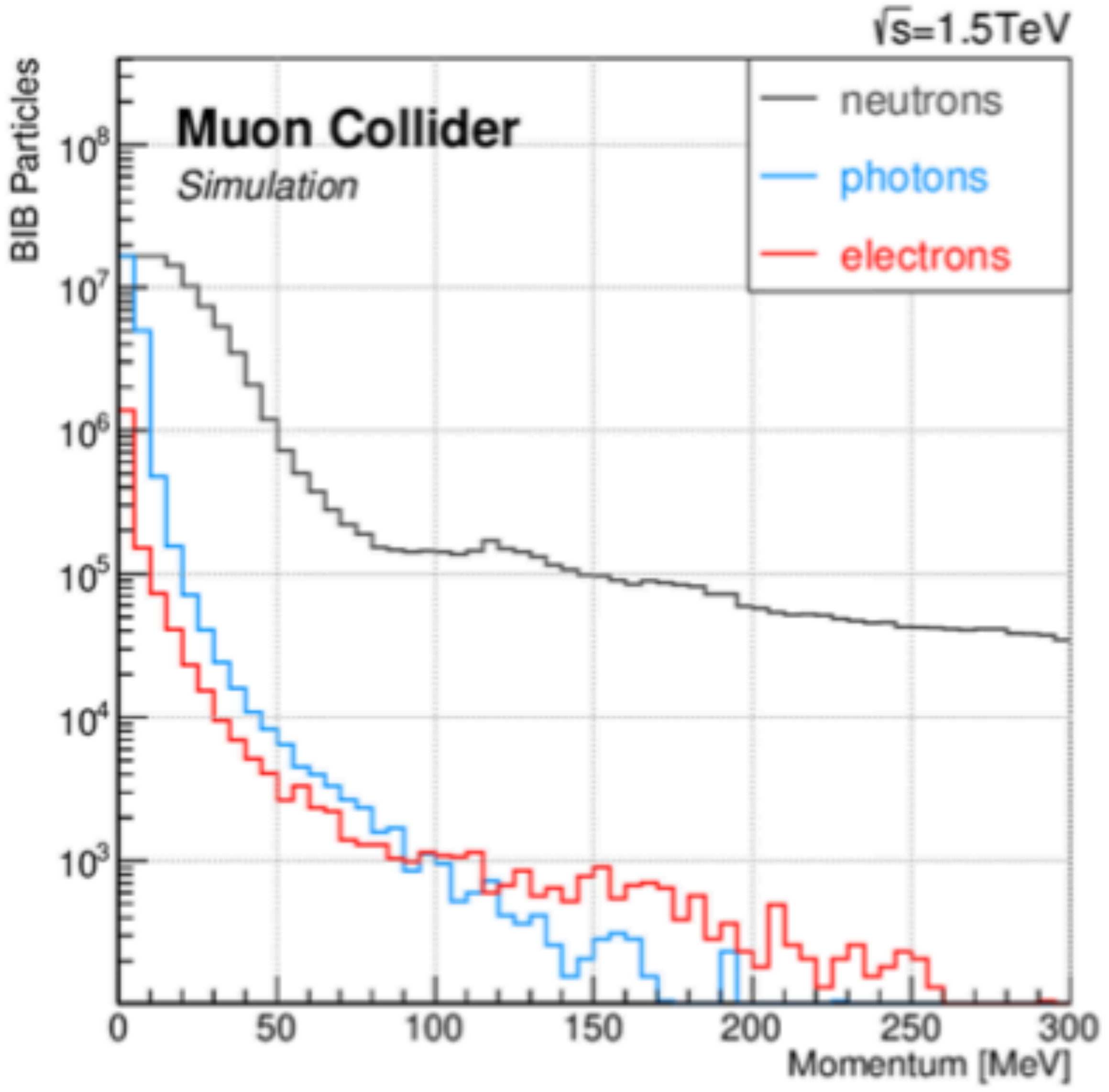
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

Background properties

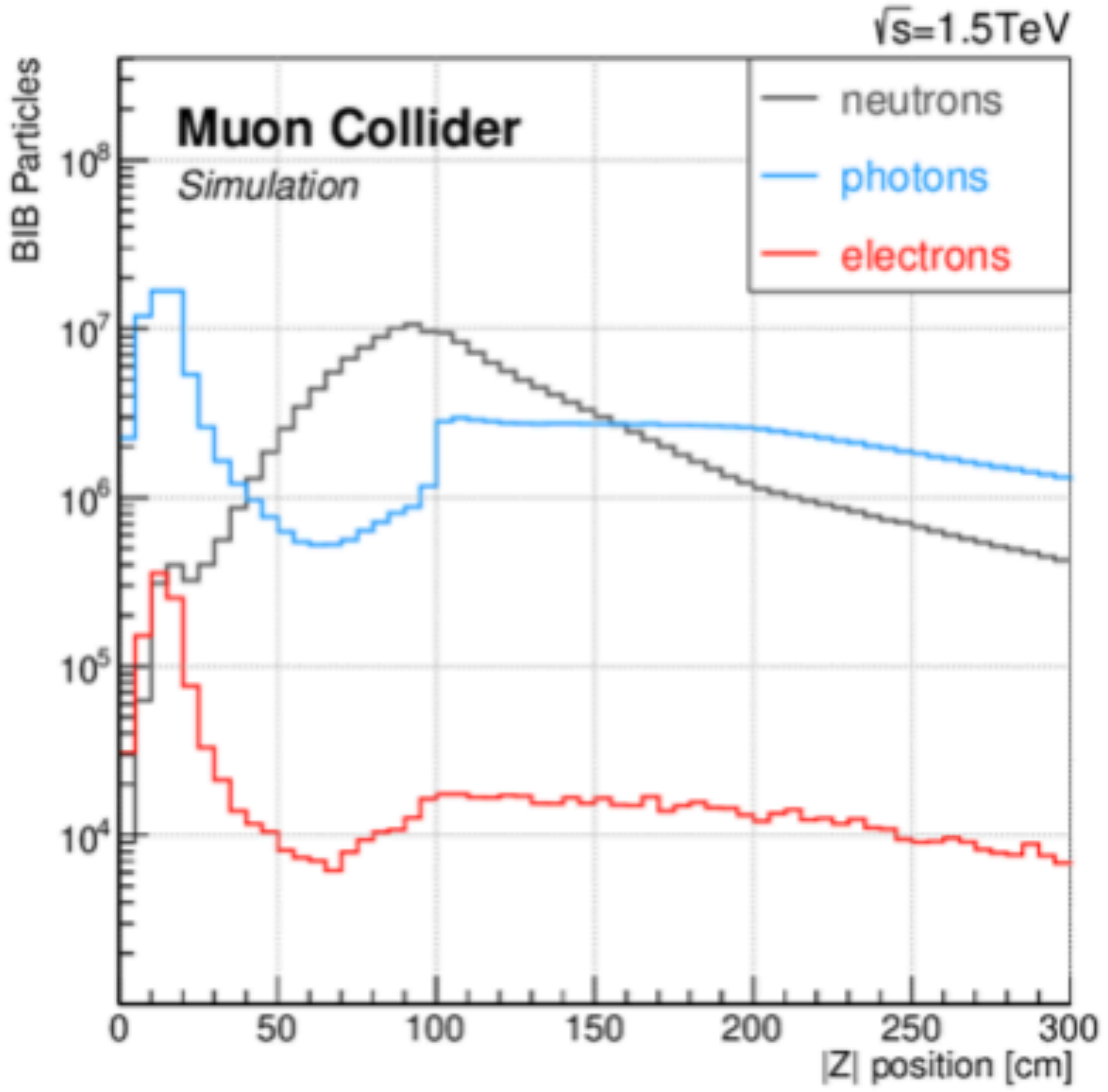
With standard nozzle ~10^8 low momentum particles per event

But this background looks very different from signal!

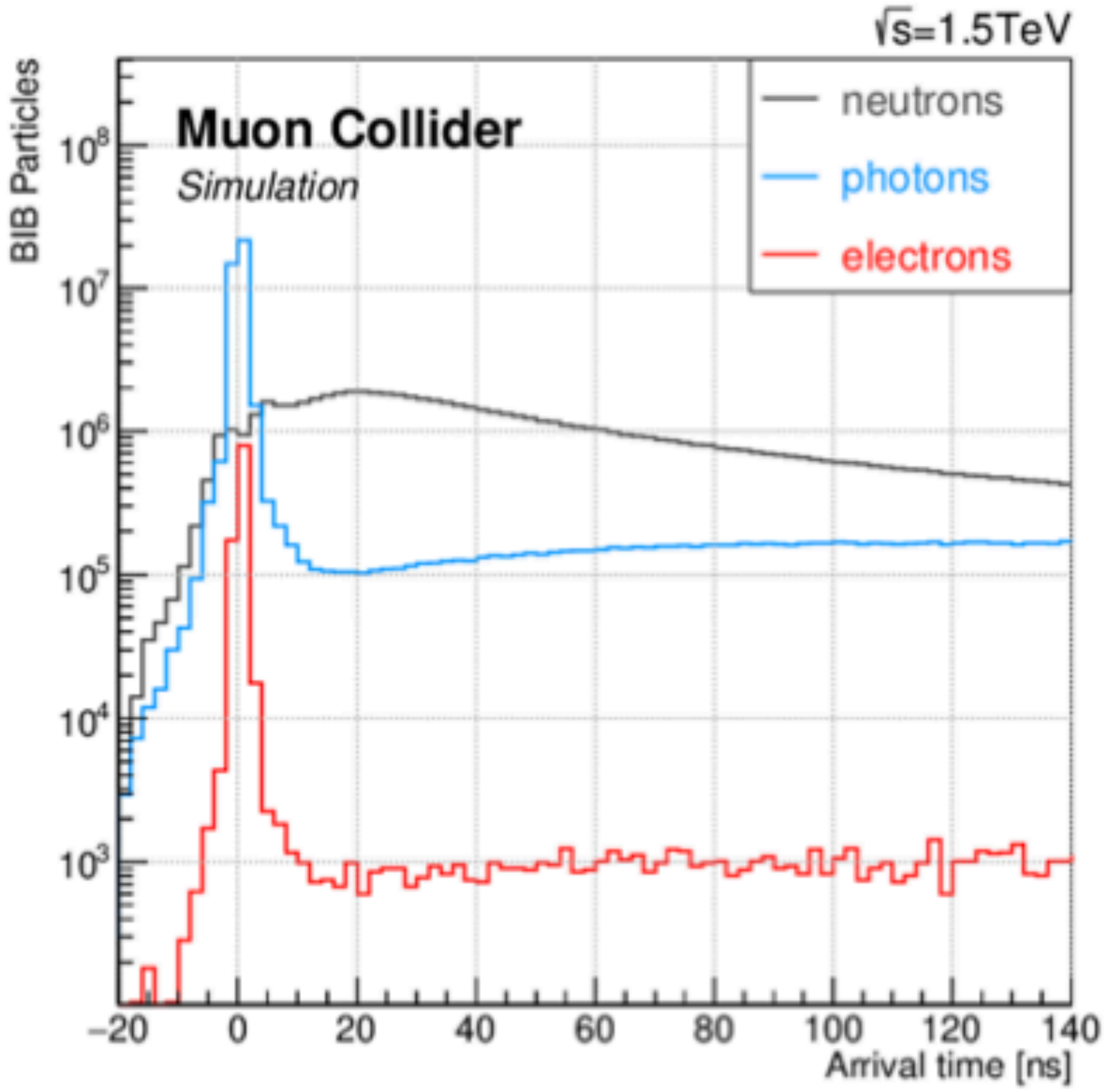
Majority < 200 MeV



Unusual position & direction

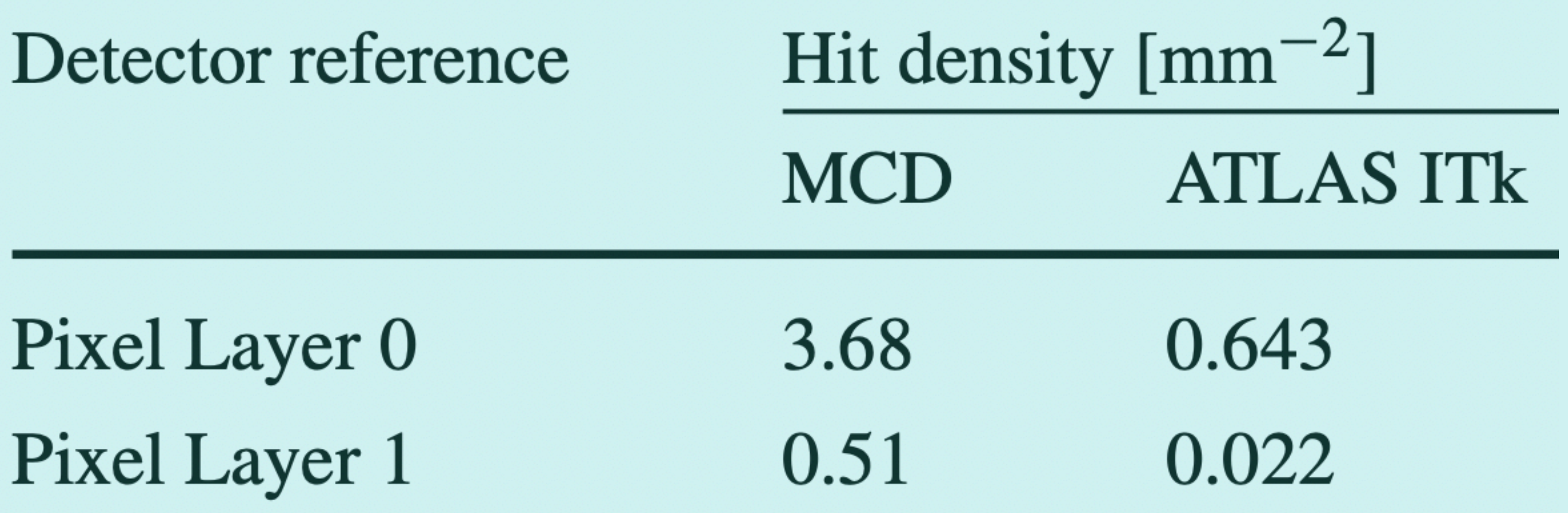


Partially out of time



Technology needs

Beam background primarily a challenge for the pixels & electromagnetic calorimeter



Detector reference	Hit density [mm^{-2}]	
	MCD	ATLAS ITk
Pixel Layer 0	3.68	0.643
Pixel Layer 1	0.51	0.022

→25 x 25 μm^2 with 30 ps timing

Challenges: front-end power consumption & readout

Similar to HL-LHC

Ambient energy 50 GeV/unit area

→ Silicon+Tungsten 5x5 mm^2 cells
Timing resolution (~100 ps)
Longitudinal segmentation

Room for new ideas!

Work in progress: 10 TeV design

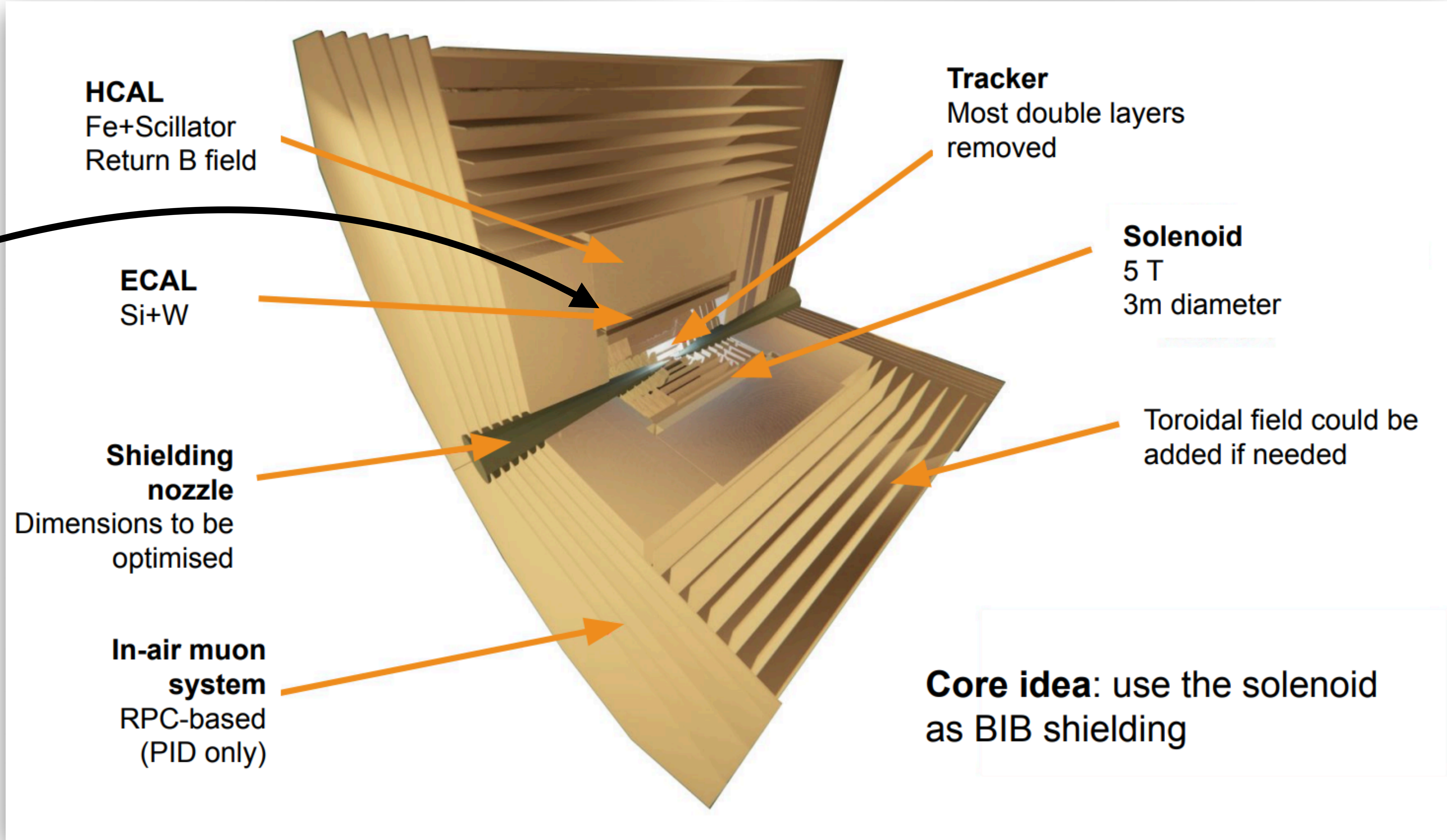
Detector Magnet Workshop
Summary by A. Bersani

Need to grow the detector

Solenoid: Higher B-field & inner radius technically challenging

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

Need to reestablish expertise to build CMS-style magnets!



HCAL
Fe+Scillator
Return B field

ECAL
Si+W

Shielding nozzle
Dimensions to be optimised

In-air muon system
RPC-based
(PID only)

Tracker
Most double layers removed

Solenoid
5 T
3m diameter

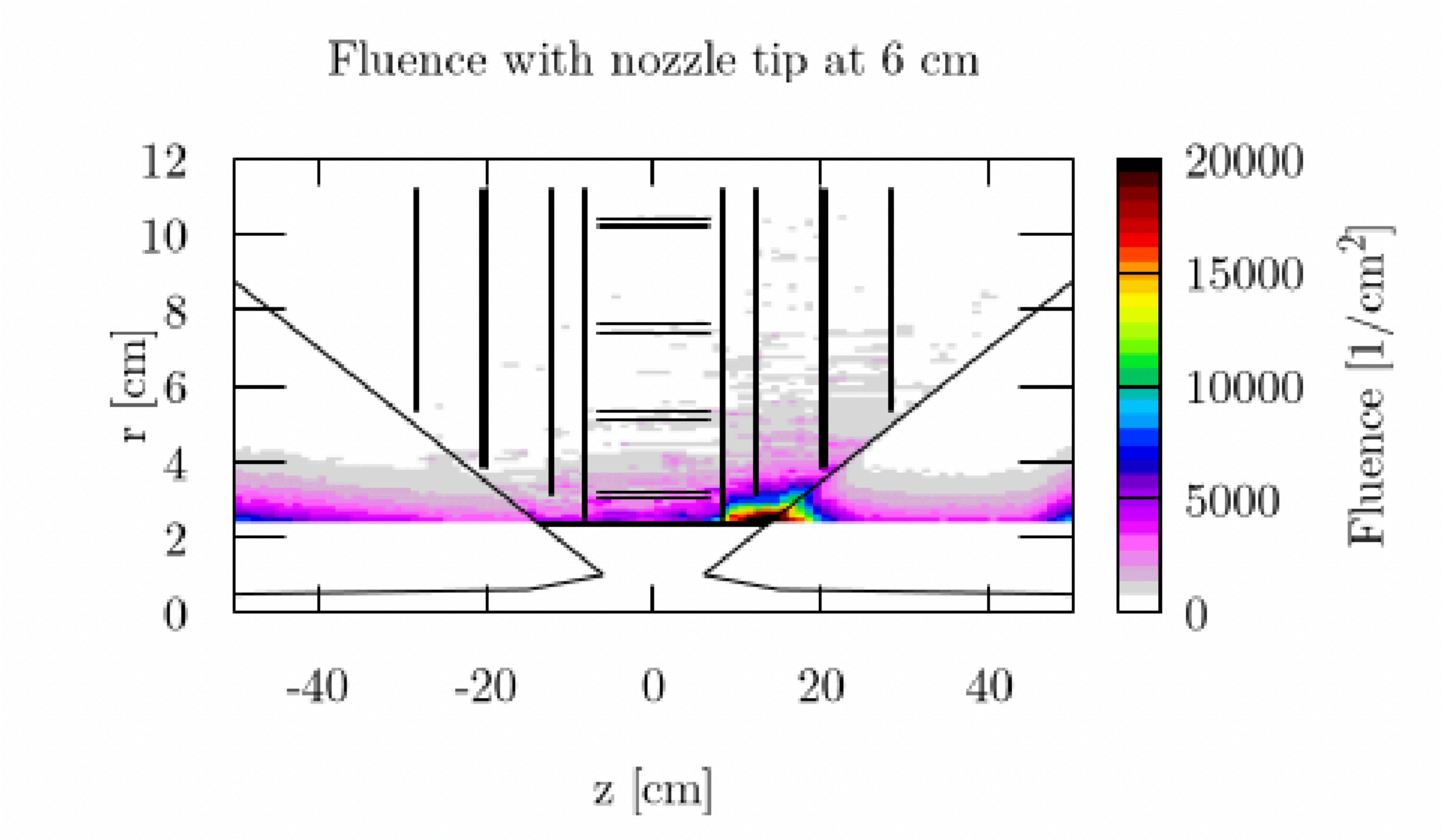
Toroidal field could be added if needed

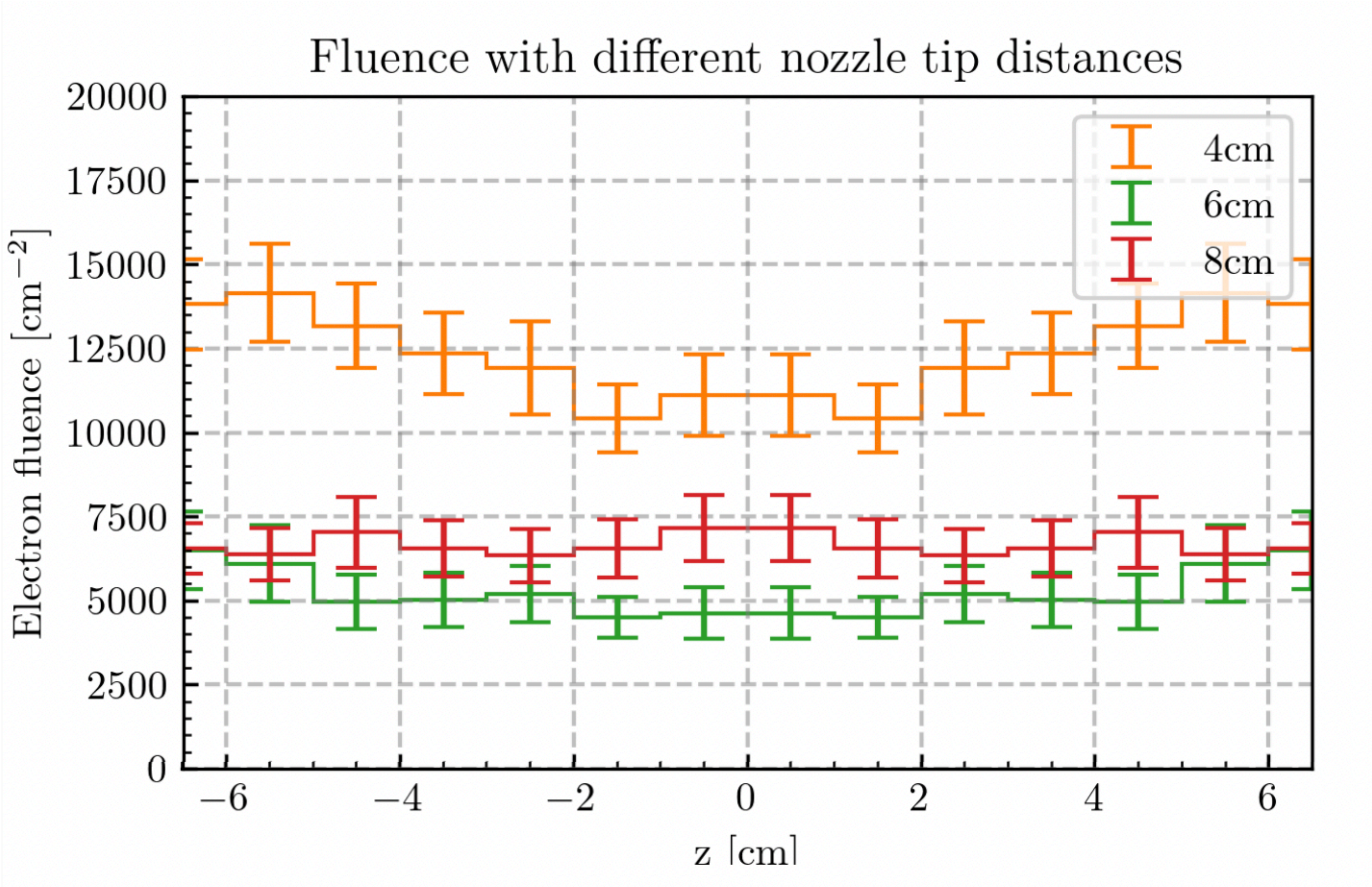
Core idea: use the solenoid as BIB shielding

Work in progress: Machine detector interface

D. Calzorlari

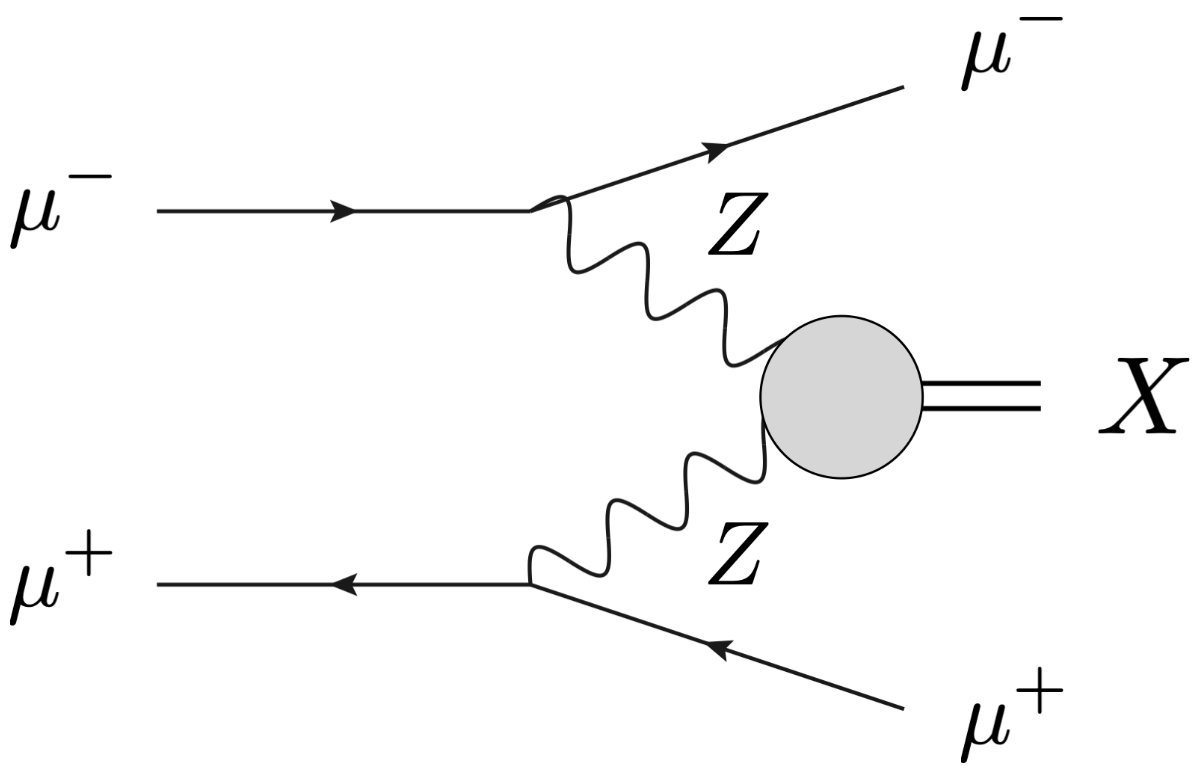
Beam induced background highly dependent on nozzle configuration
Systematic optimization in progress!





Work in progress: Map back to physics

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



Separate ZZ and WW fusion

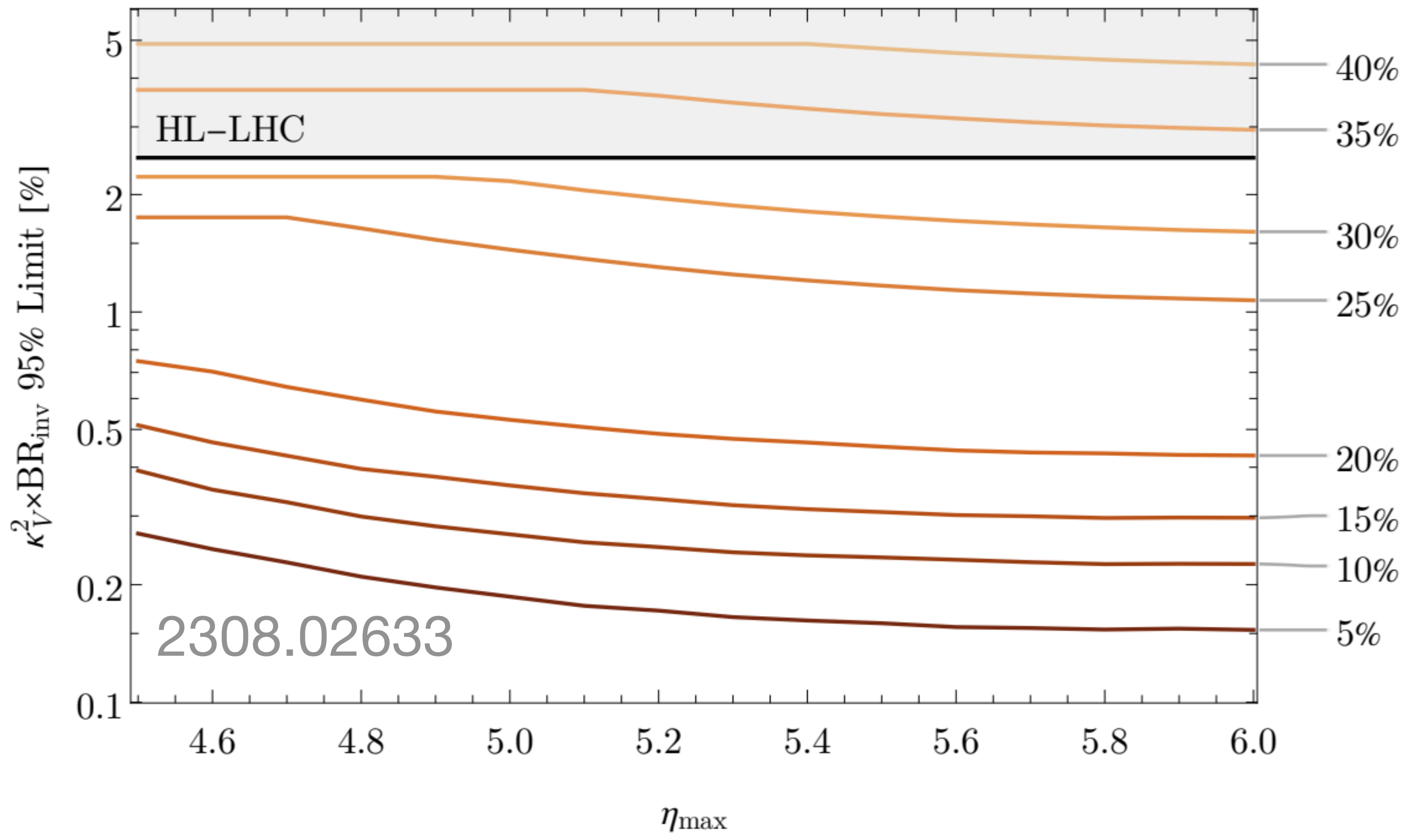
Reduce backgrounds

Br(h→invisible) via m_{miss}

Γ_h via inclusive rate

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

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



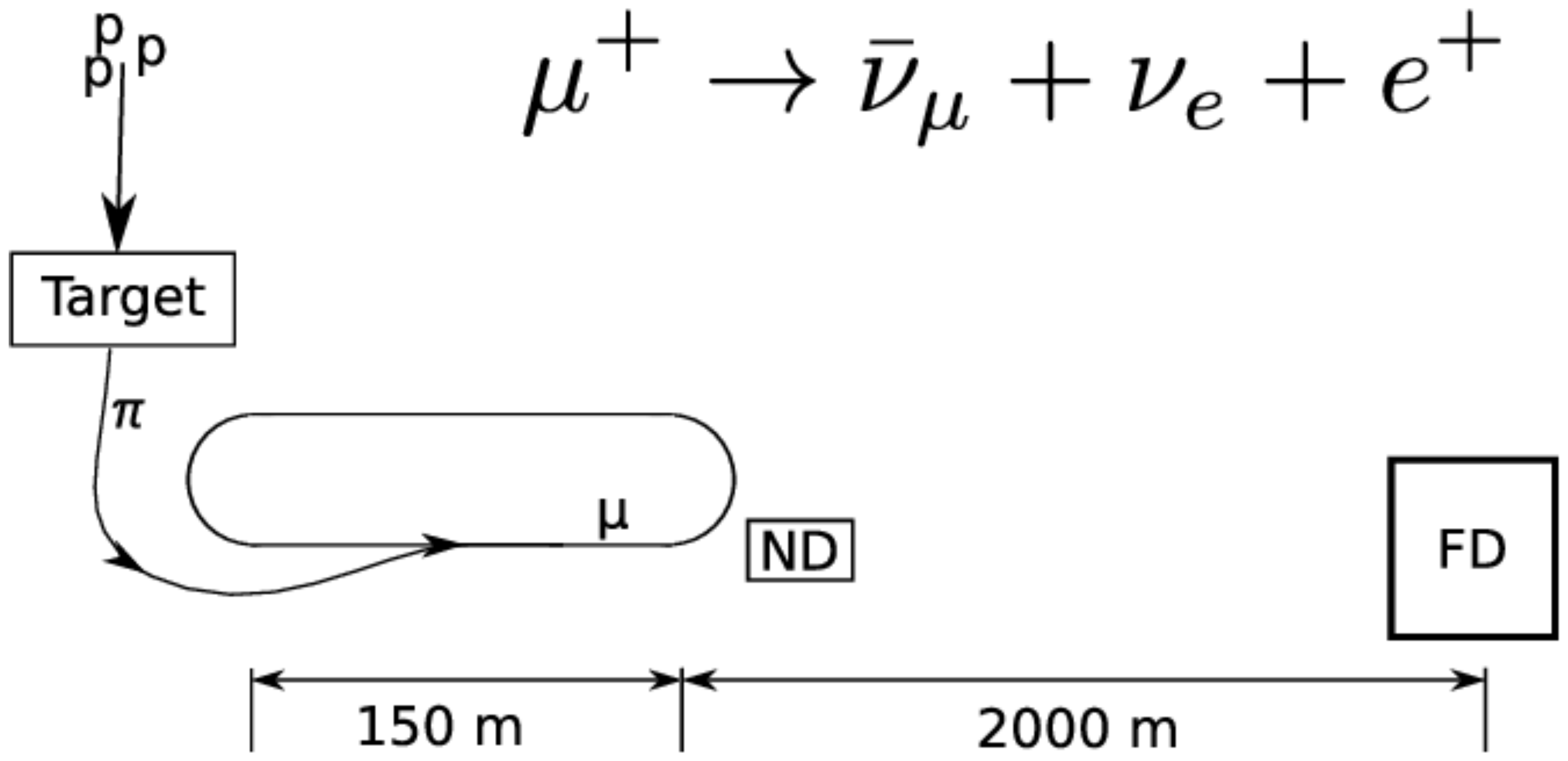
Work in progress: Ideas for physics along the way

2407.02572 - New!

Straight sections = perfect neutrino beam

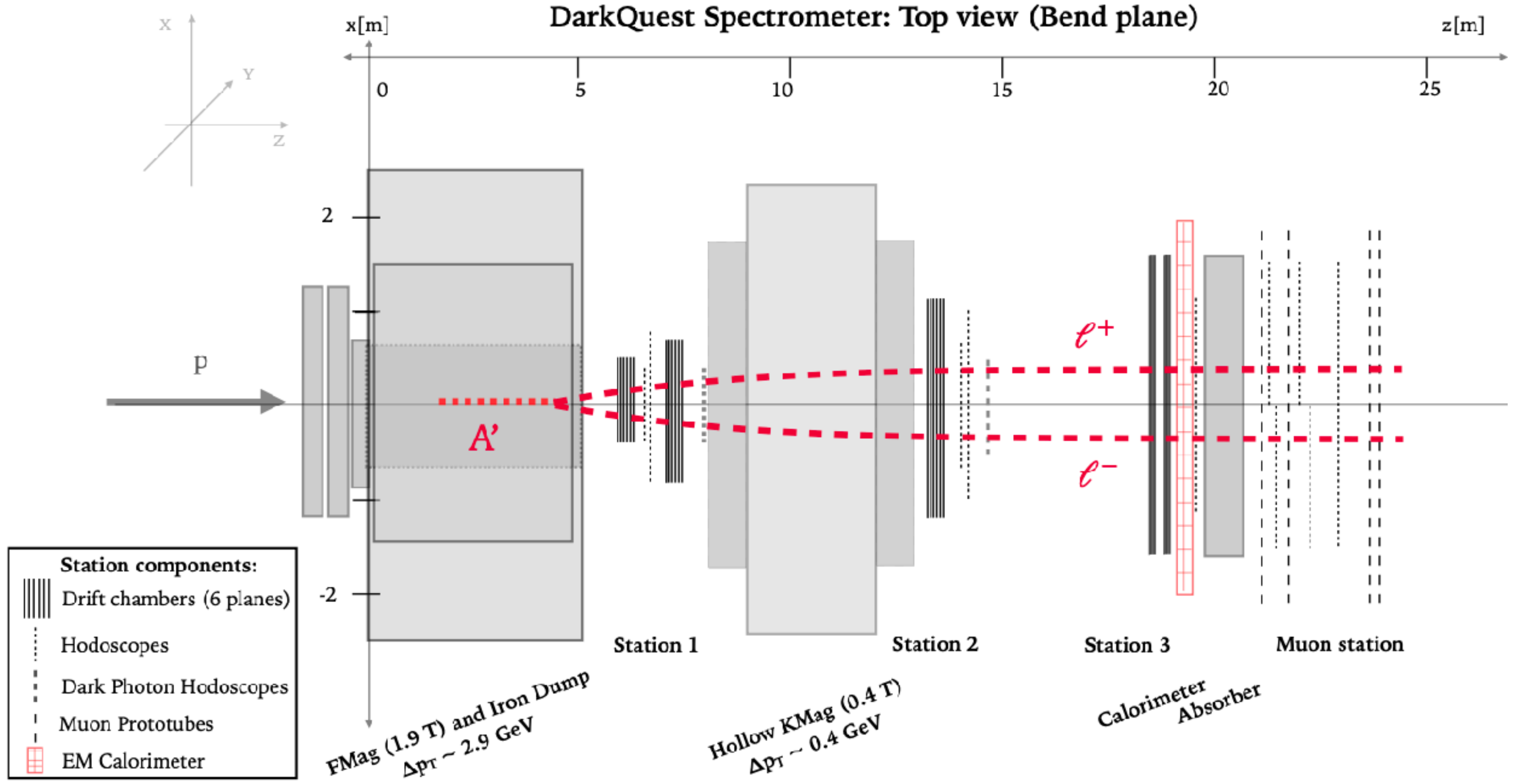
Equal numbers of e/μ (anti-)neutrinos

Precisely known energy spectra & intensity



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

Low mass dark matter (sector) searches



2203.08322

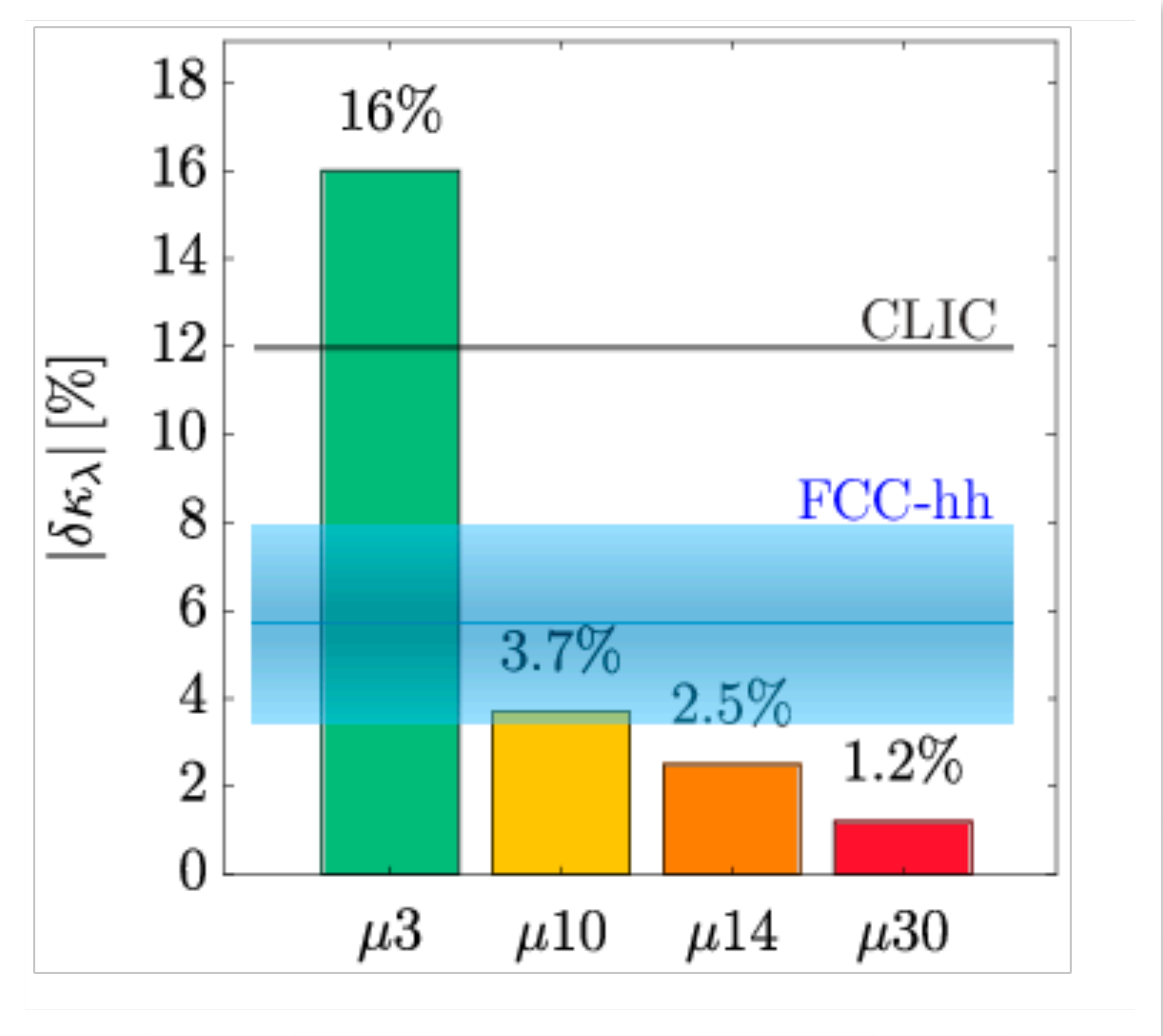
Synergies with charged lepton flavor violation experiments

The takeaway

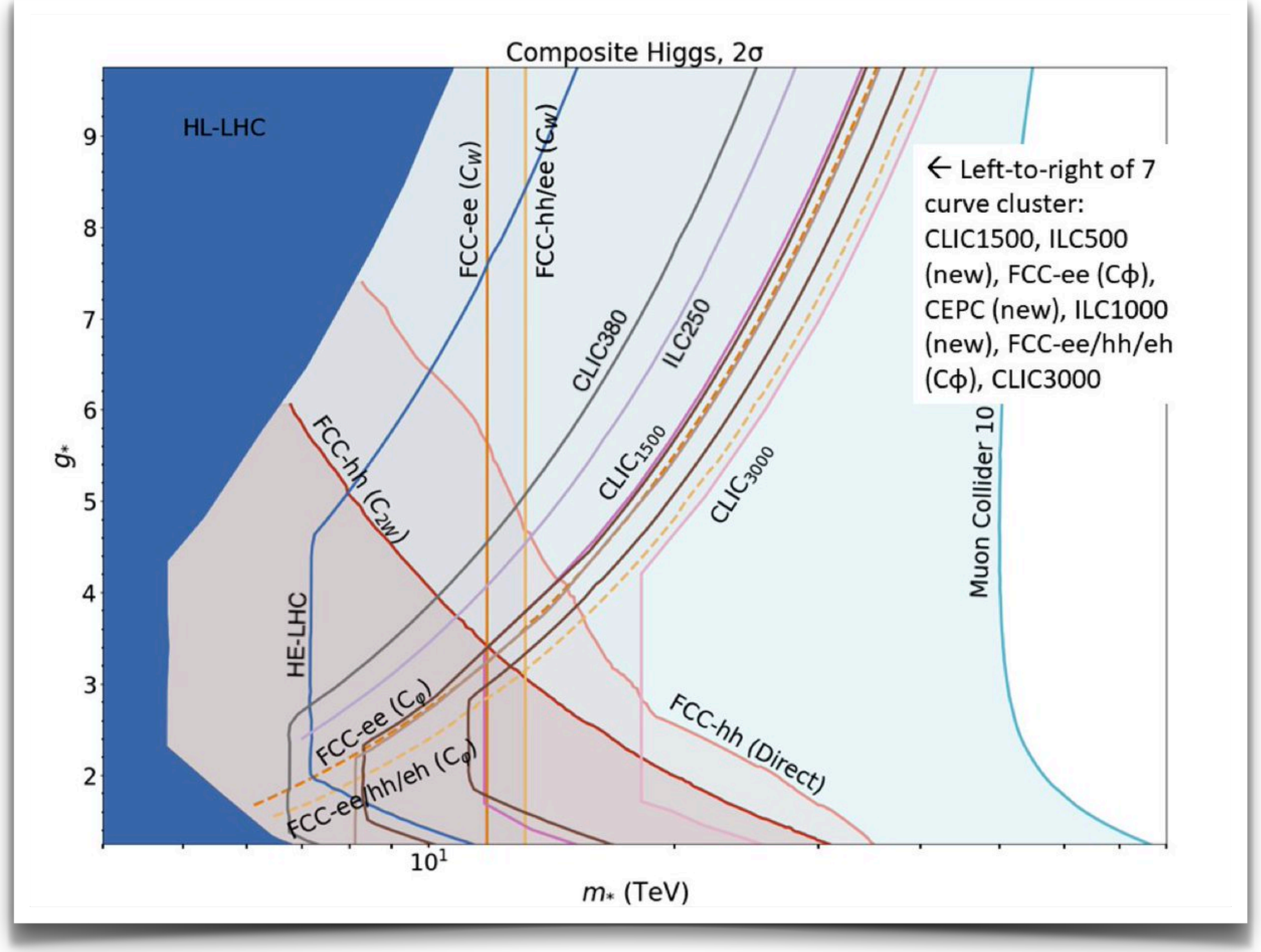
2303.08533

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

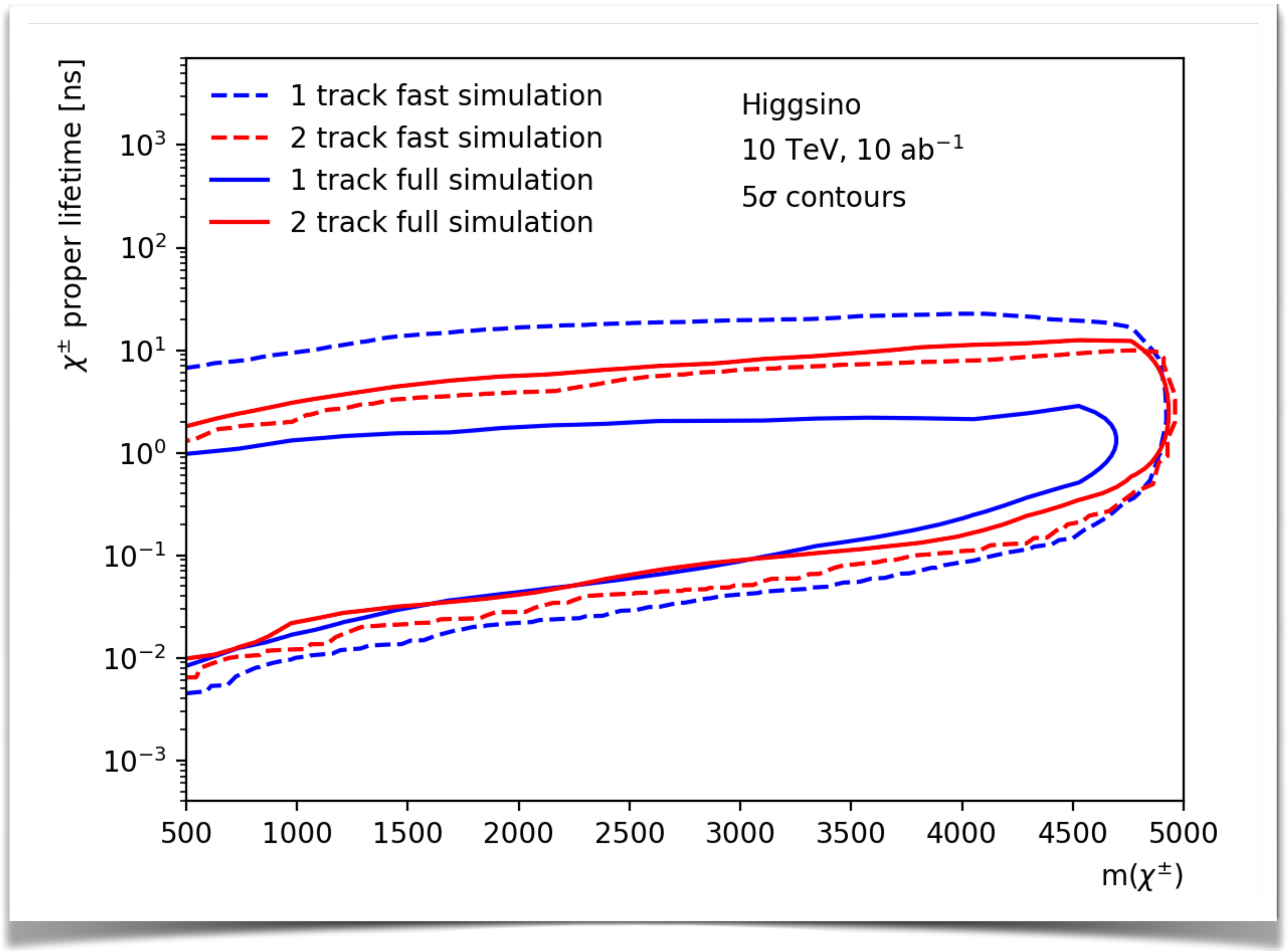
Higgs self-coupling



Composite Higgs Scenarios



WIMPs/Disappearing track



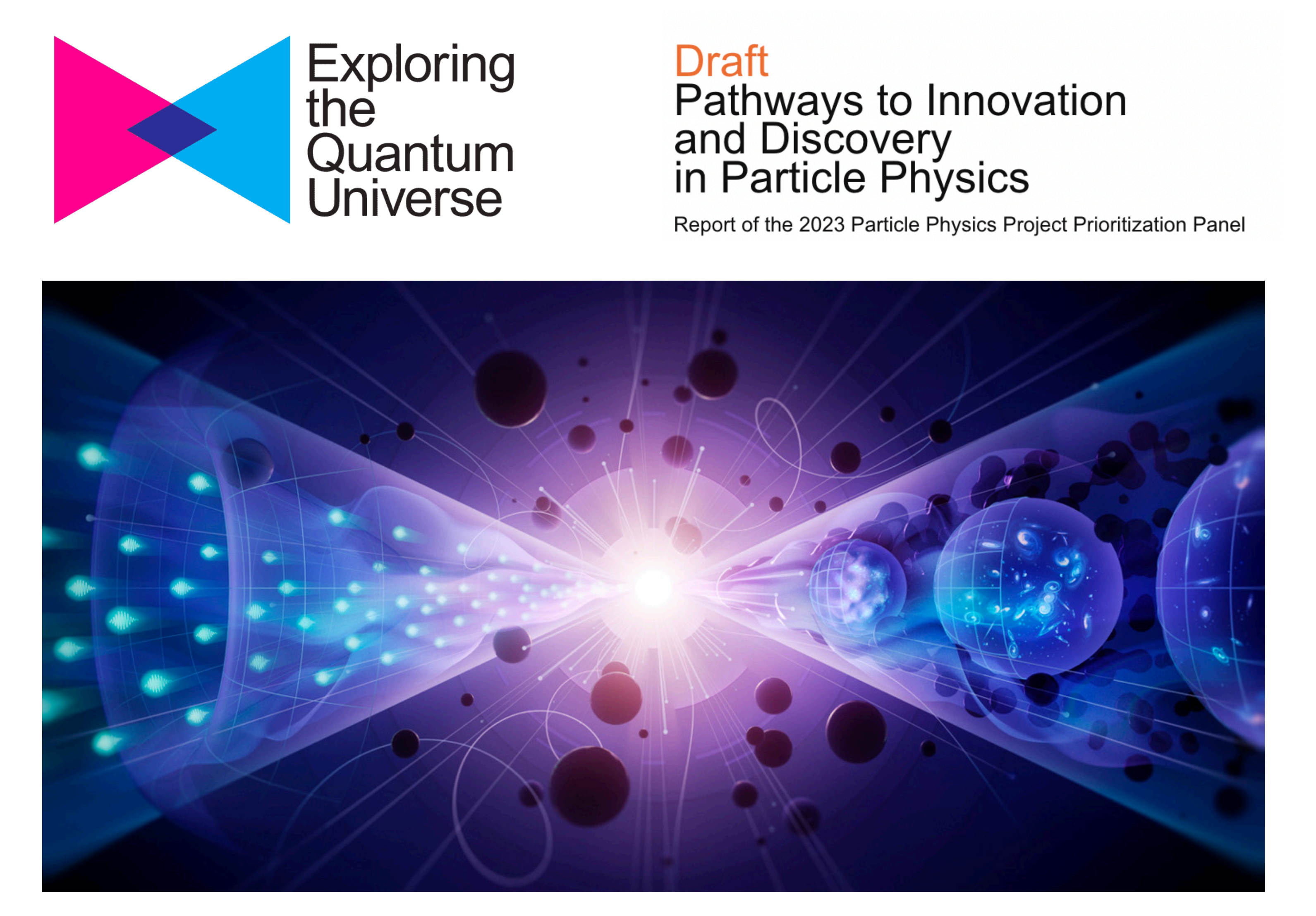
Cue the excitement!

- 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

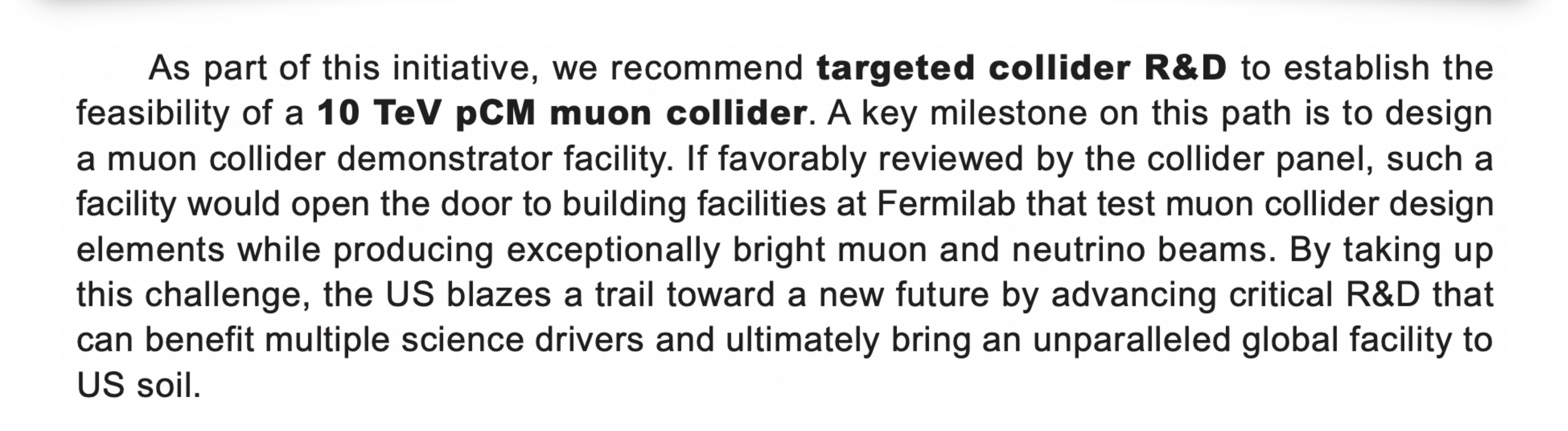
International
MUON Collider
Collaboration


Science
$15
29 MARCH 2024
science.org
AAAS

A radical new particle accelerator concept emerges. Call it physicists'
MUON SHOT
p. 1405


Exploring the Quantum Universe

Draft
Pathways to Innovation and Discovery in Particle Physics
Report of the 2023 Particle Physics Project Prioritization Panel


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 10 TeV scale
- Strong case for colliding muons
- “No show stoppers identified”
- More work is needed & in progress

Do the homework & decide for yourself!
Collider Implementation Task Force
Towards a Muon Collider