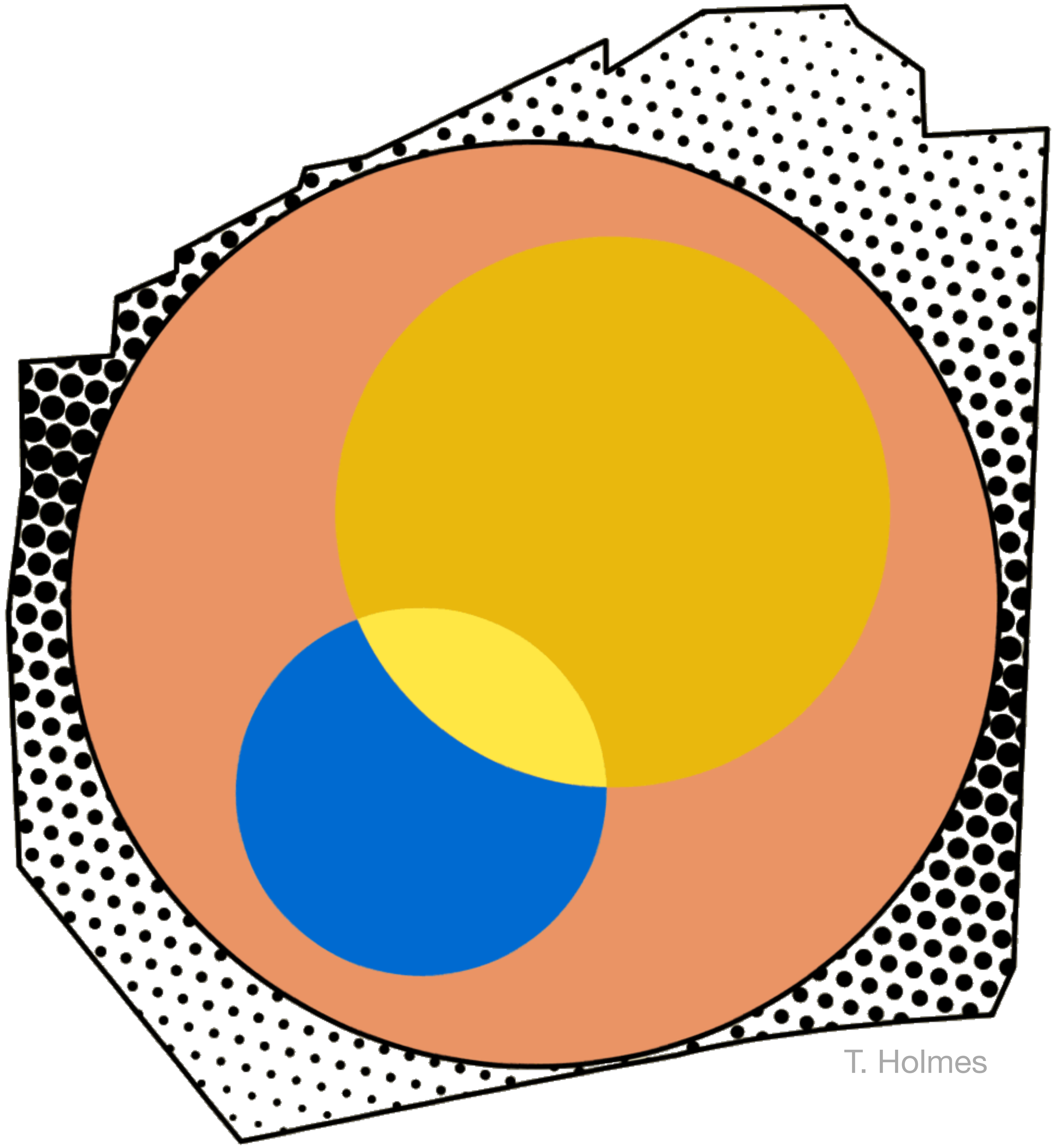
Muon Collider Physics Impact and Detector Needs

Karri Folan DiPetrillo
on behalf of the IMCC
European Lab Directors Workshop
7 June 2024



T. Holmes

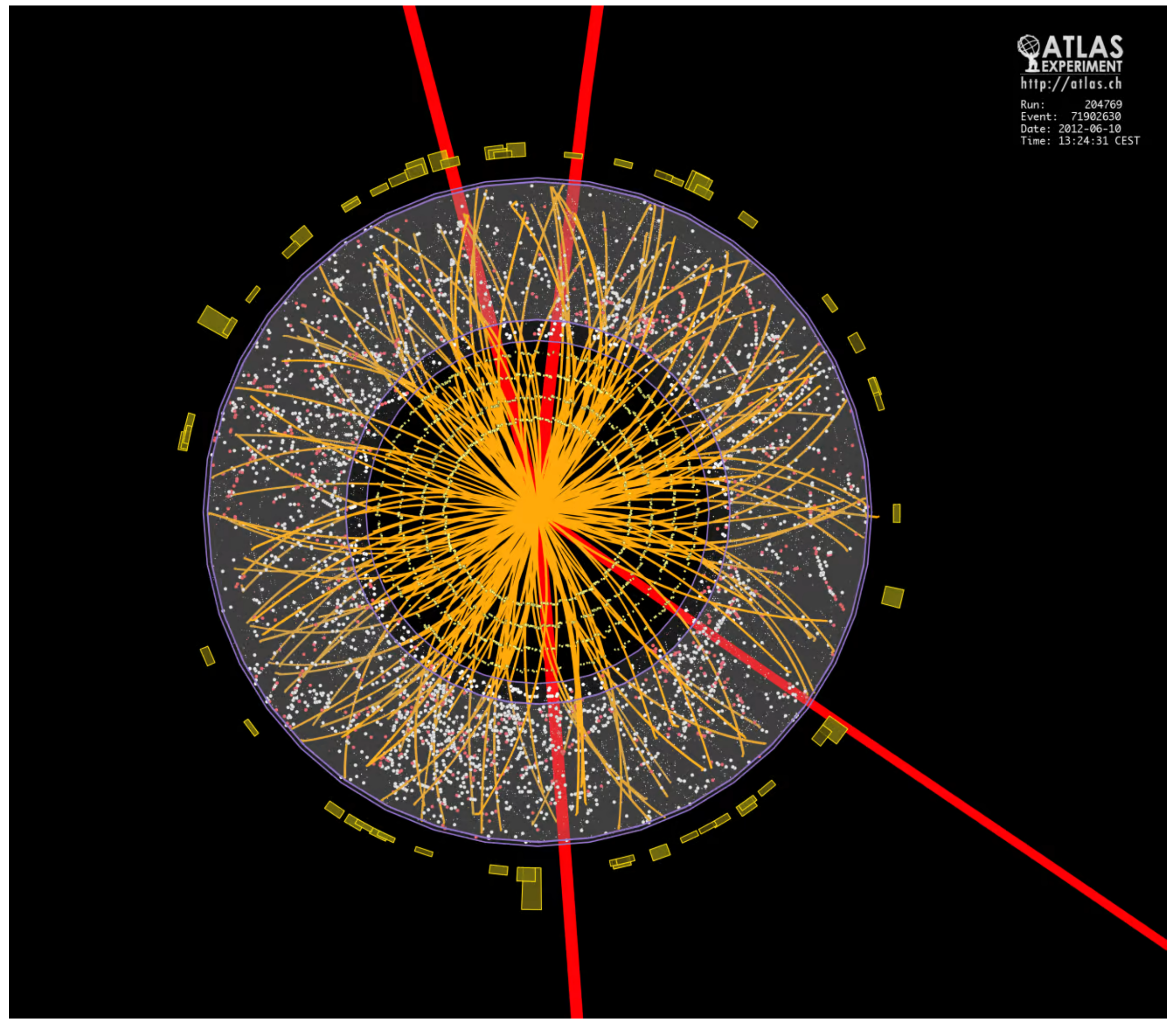
Open questions in particle physics

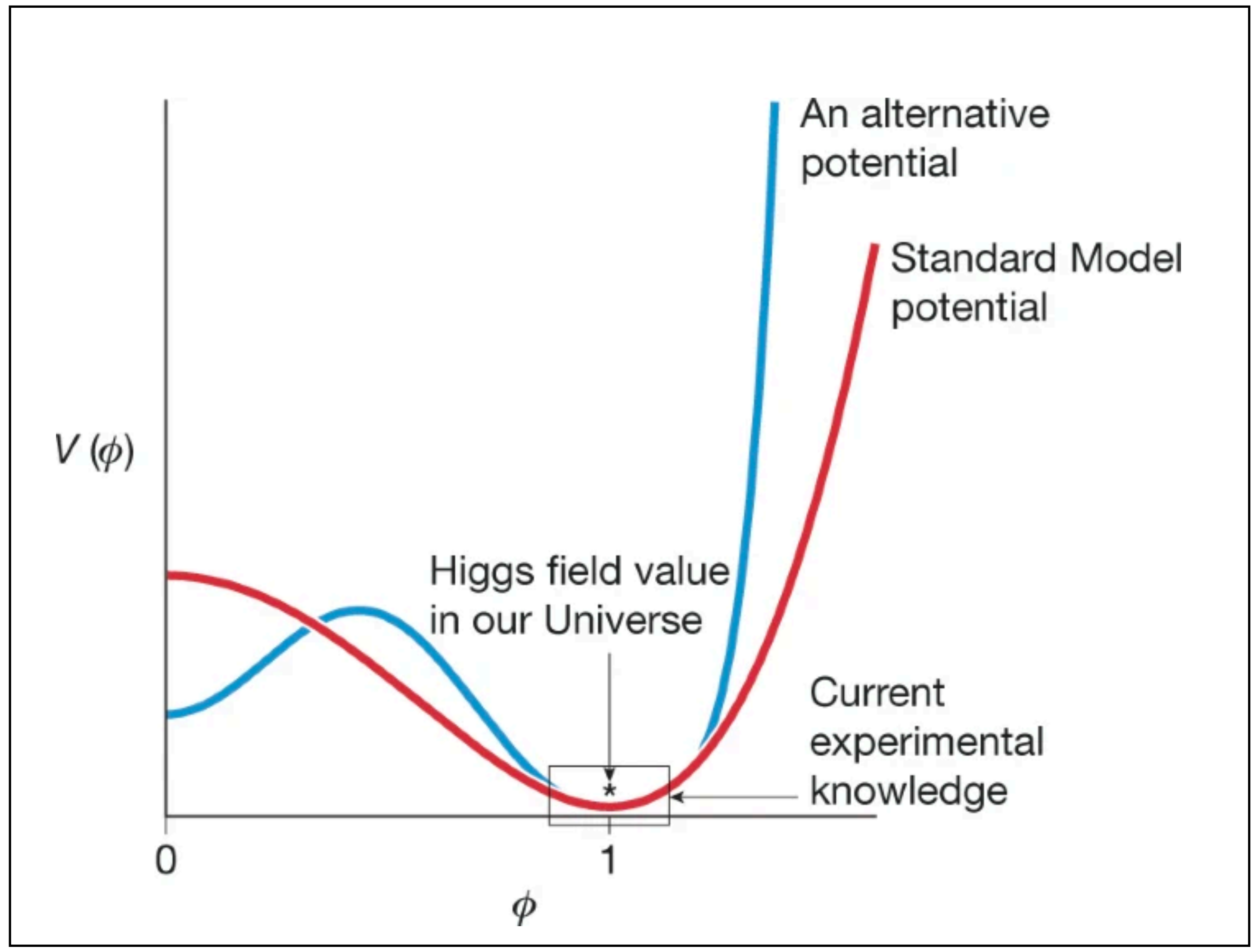
About the Standard Model

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

And the observed universe

What is dark matter?
What causes baryogenesis?



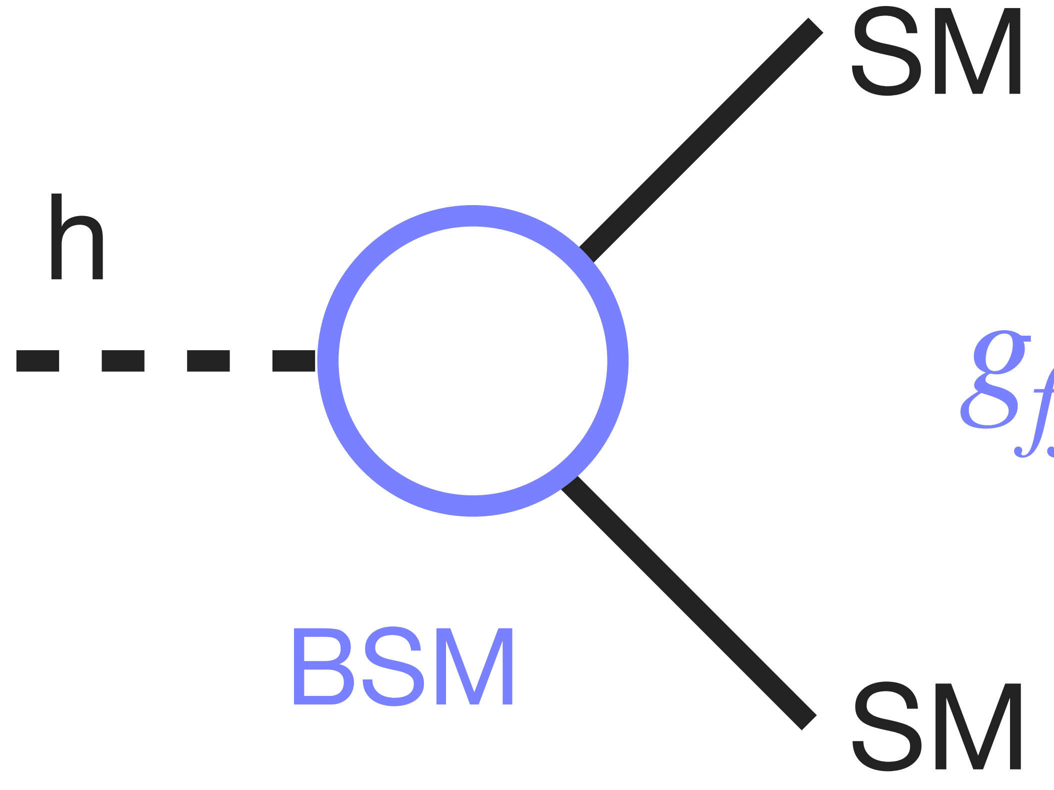


Which collider(s) should we build?

2209.07510

Compare reach from precision (indirect) and energy (direct) w/ realistic models

eg. modified higgs couplings = new particles



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

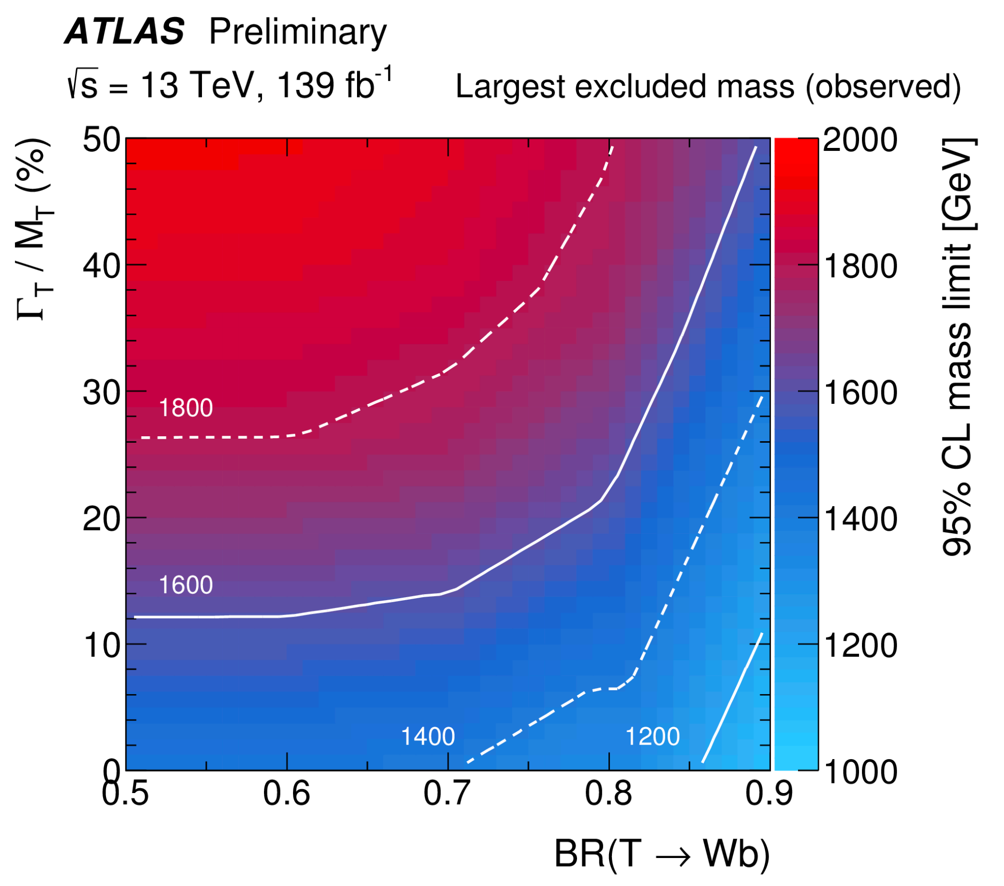
	HL-LHC	Higgs Factory
Higgs Precision	~few%	~0.1%
Indirect Reach	0.1-1 TeV	~few TeV
Direct reach	~1 TeV	-

→ framework for how much energy/precision we need

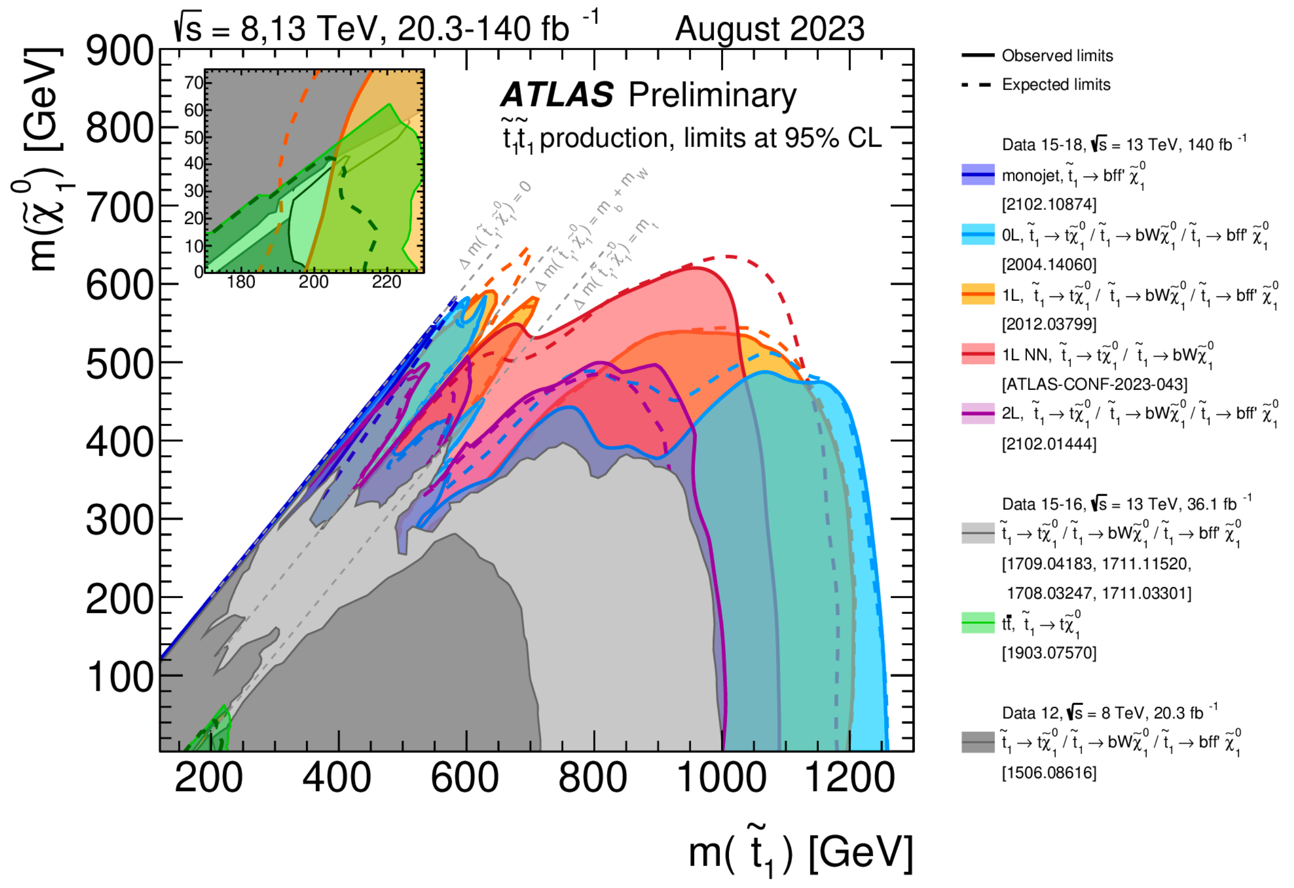
Microscopic nature of the higgs

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

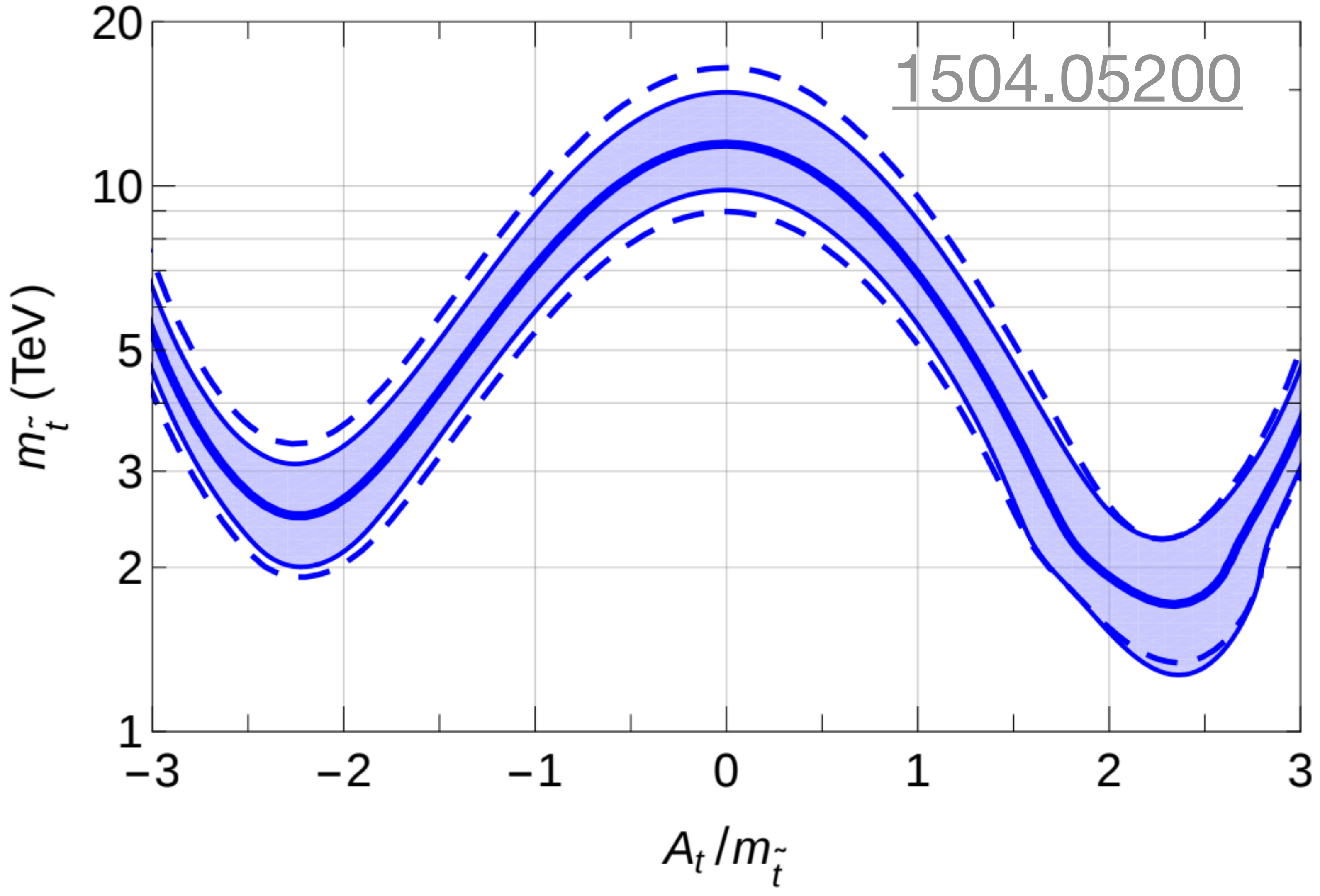
e.g. composite Higgs, like the pion?



e.g. new symmetry & additional particles?



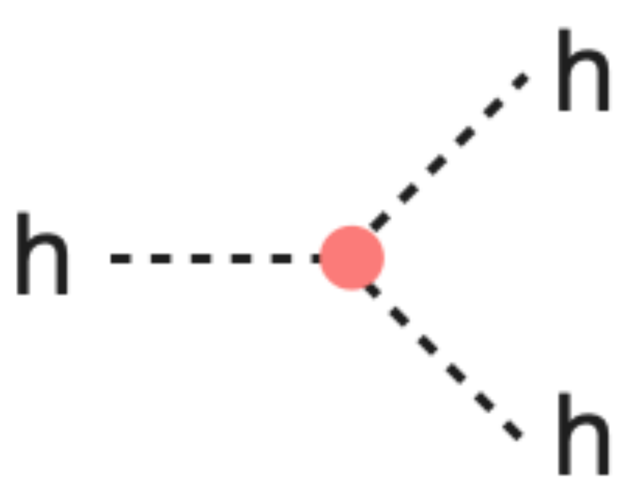
m_h =125 GeV → multi-TeV top-partners

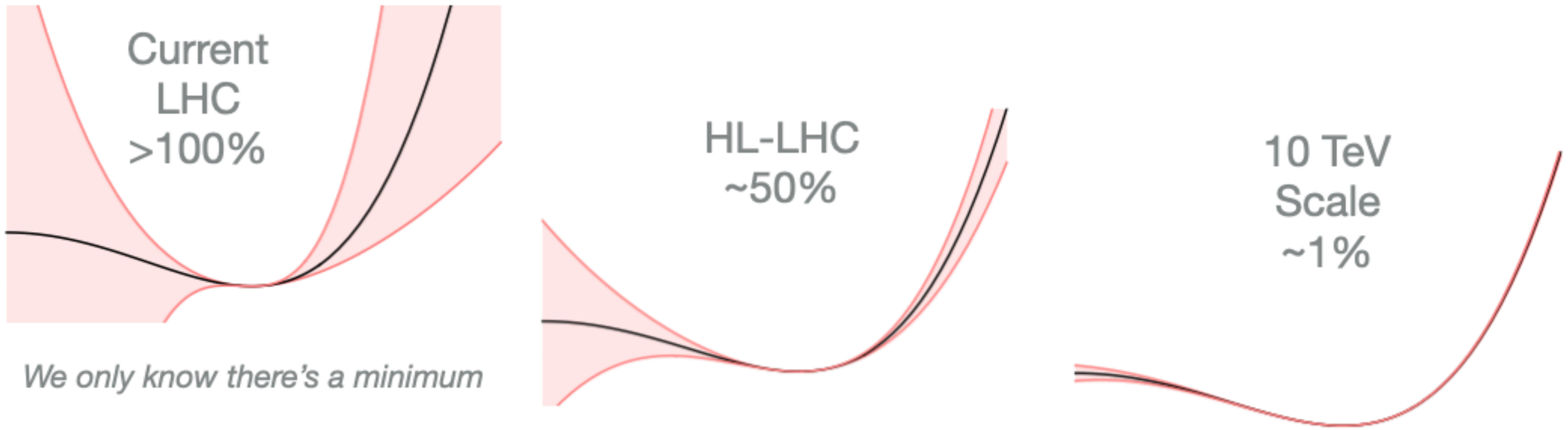


Data & theory suggest strongly coupled particles ≥ 1 TeV

Electroweak symmetry breaking

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





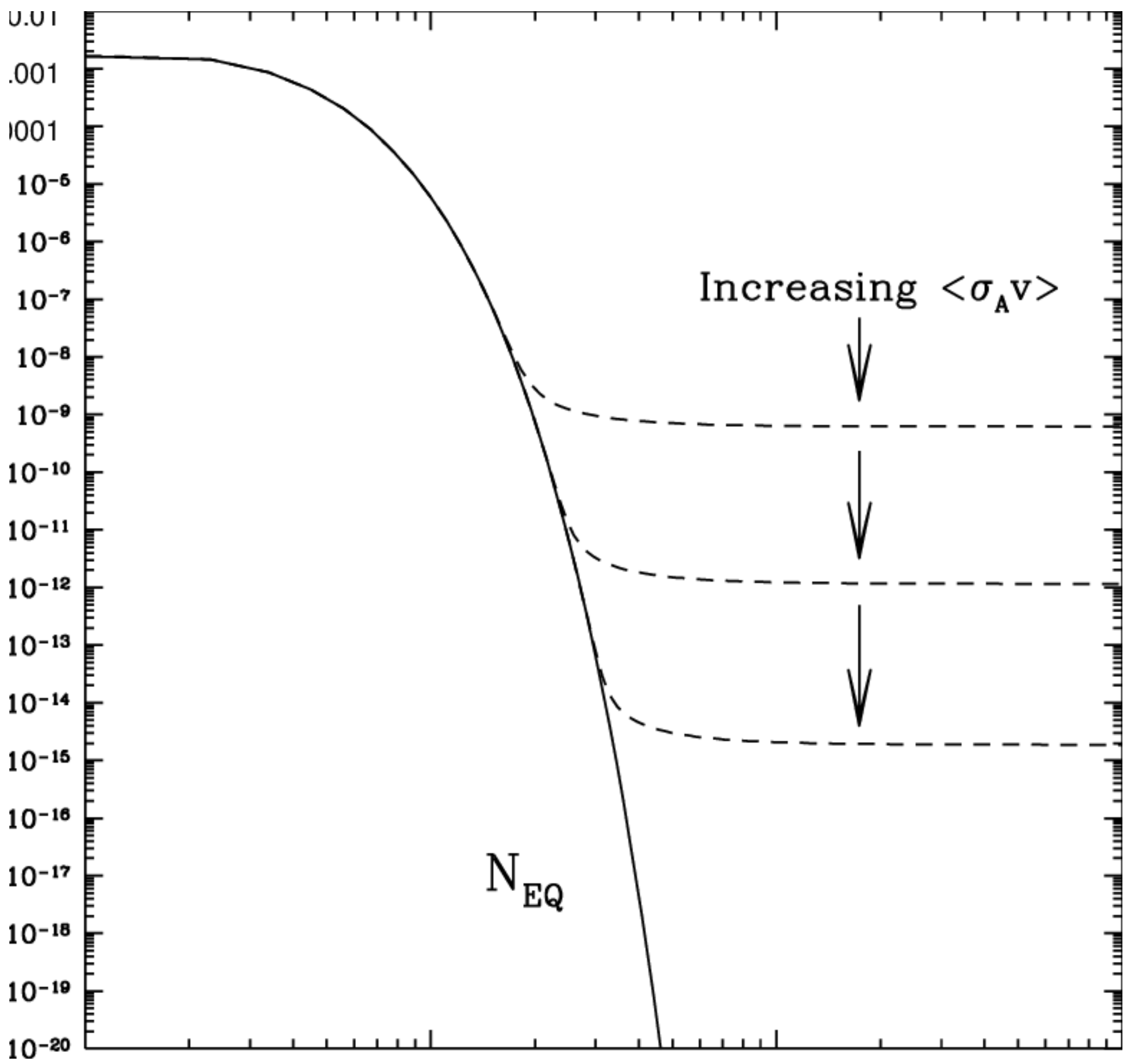
Producing enough multi-Higgs events is only possible at a 10 TeV scale collider

Dark Matter

DM Complementarity Report: 2211.07027

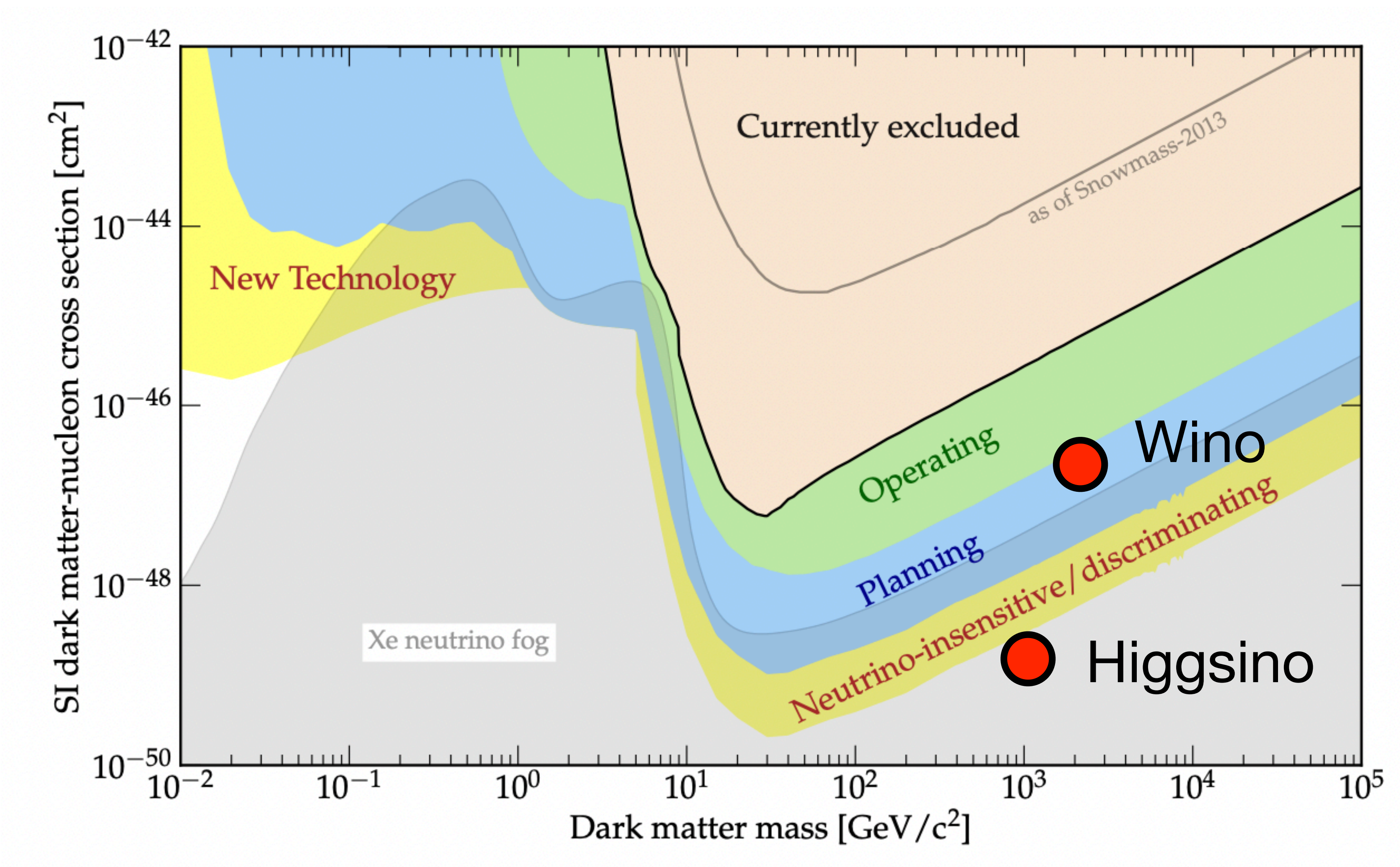
We've yet to probe thermal WIMPs

Number density

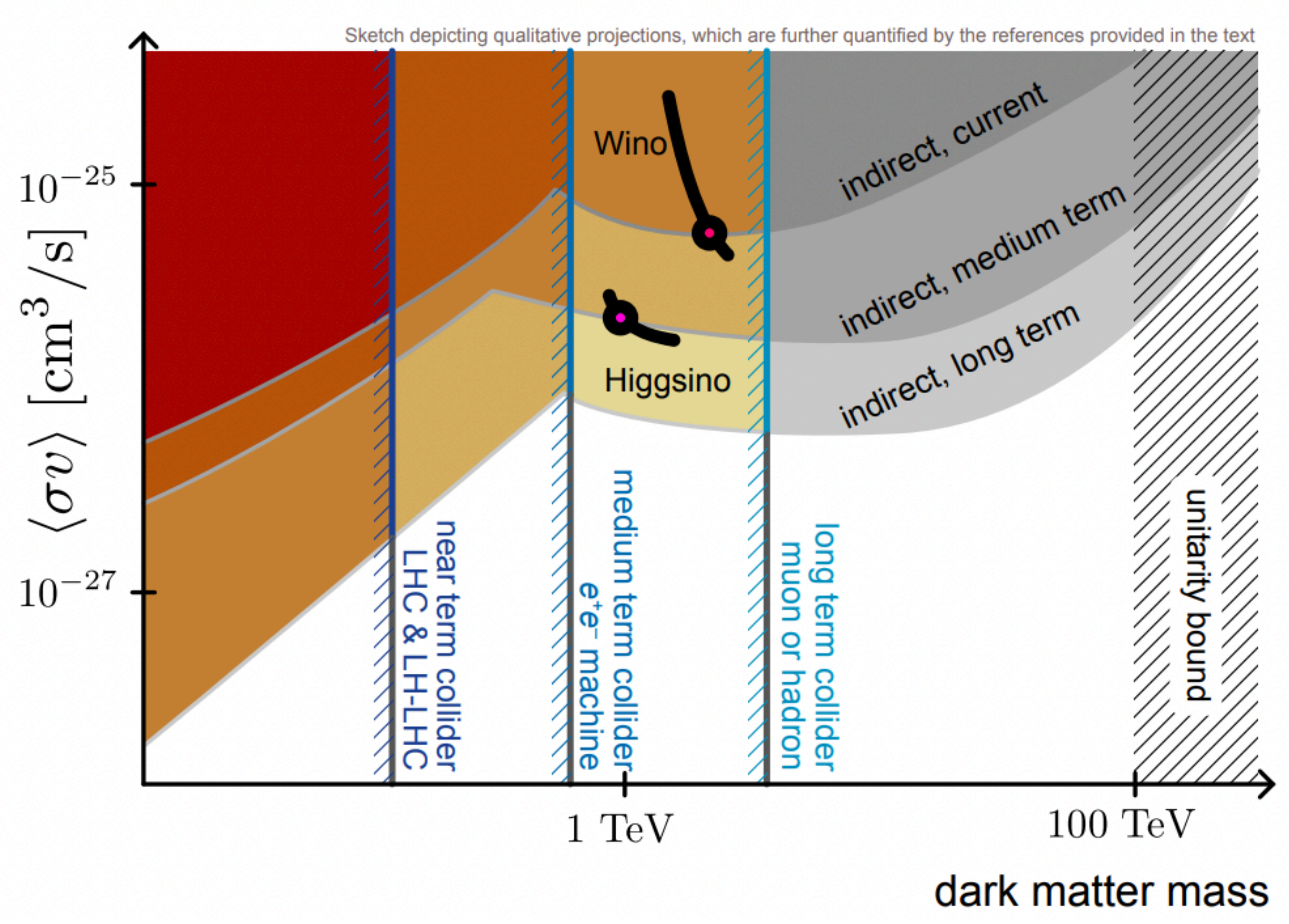


Universe expands & cools

Pure higgsino under neutrino floor!



Out of HL-LHC & e+e- reach



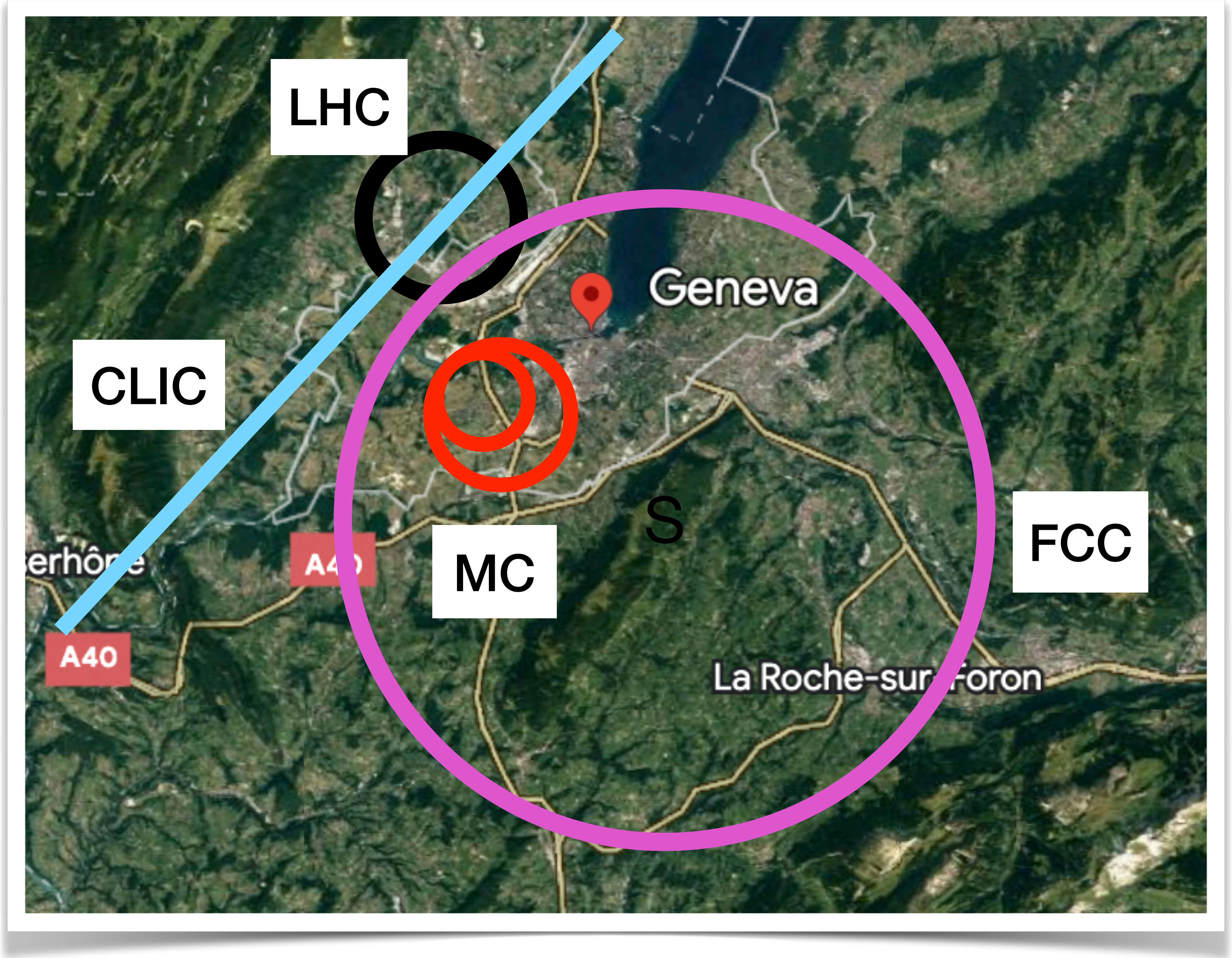
Definitive observation & characterization would require a multi-TeV scale collider

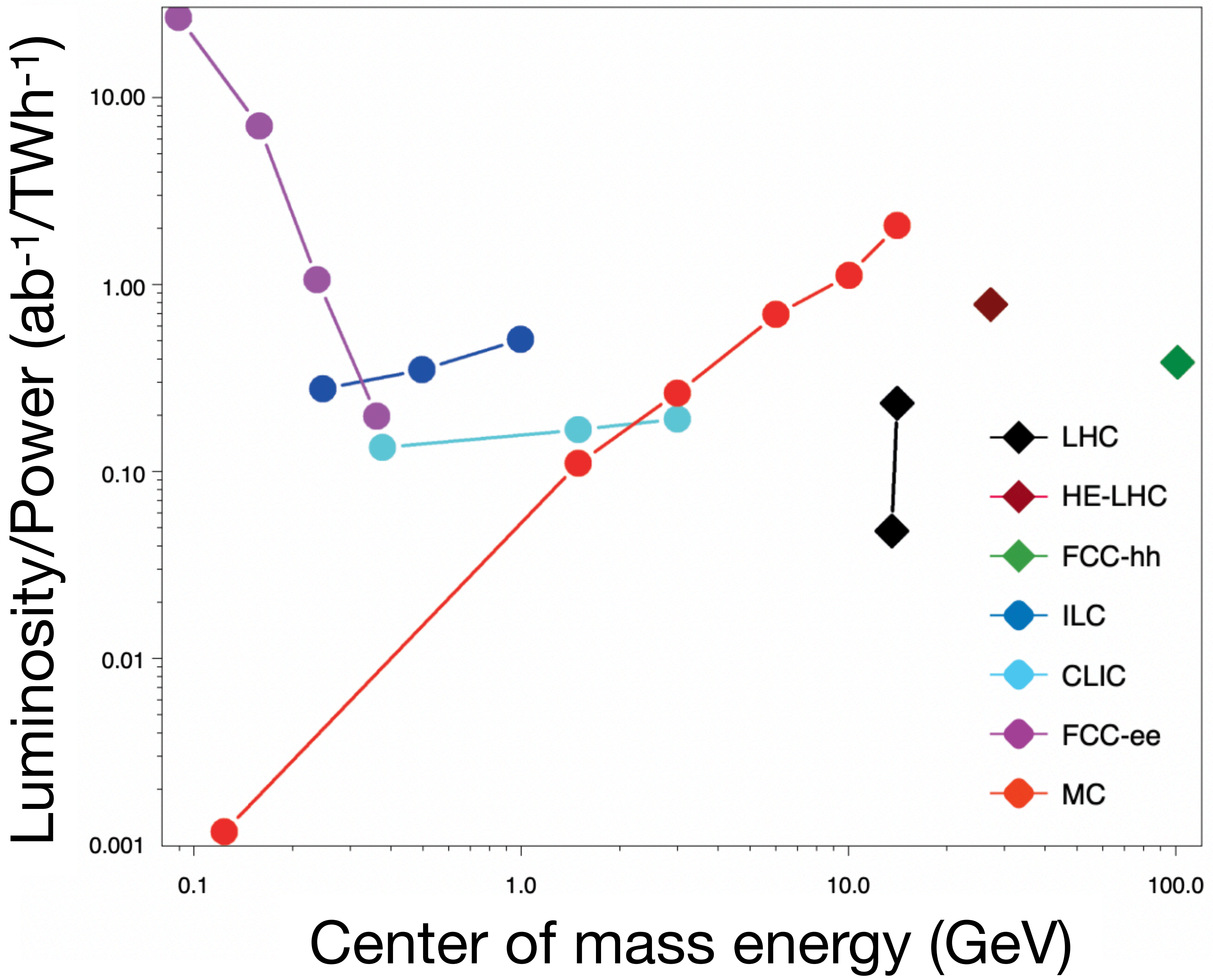
A new way forward?

Input to EPPSU 1901.06150

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

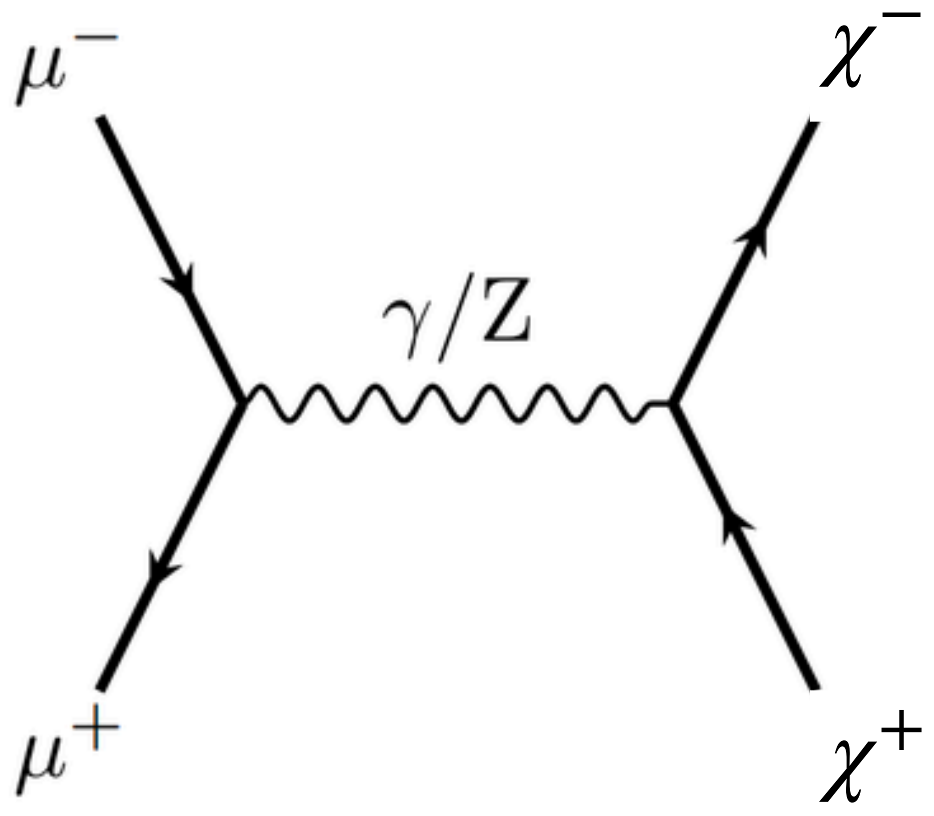
Muons = massive fundamental particles = compact & power-efficient





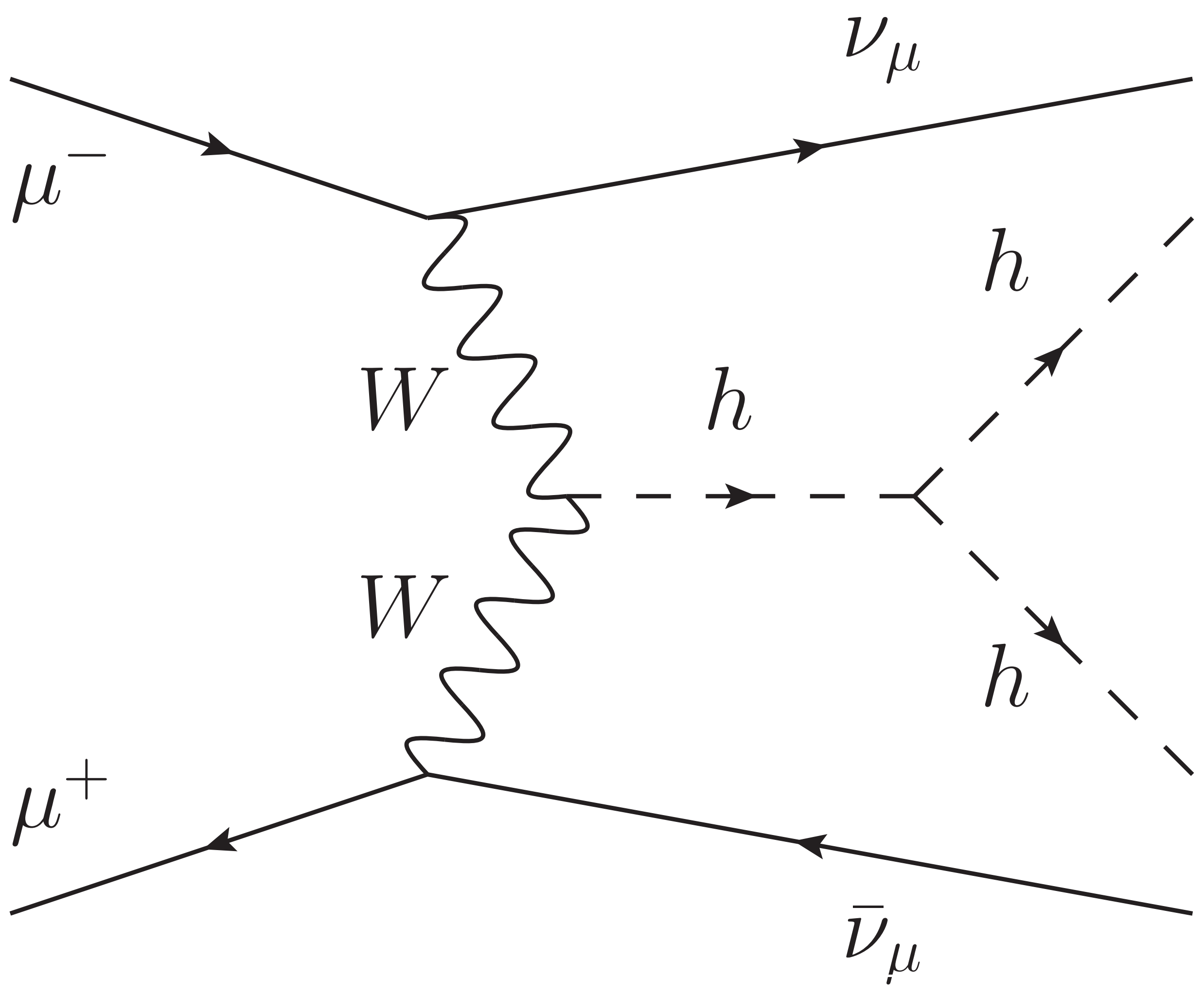
Two colliders in one

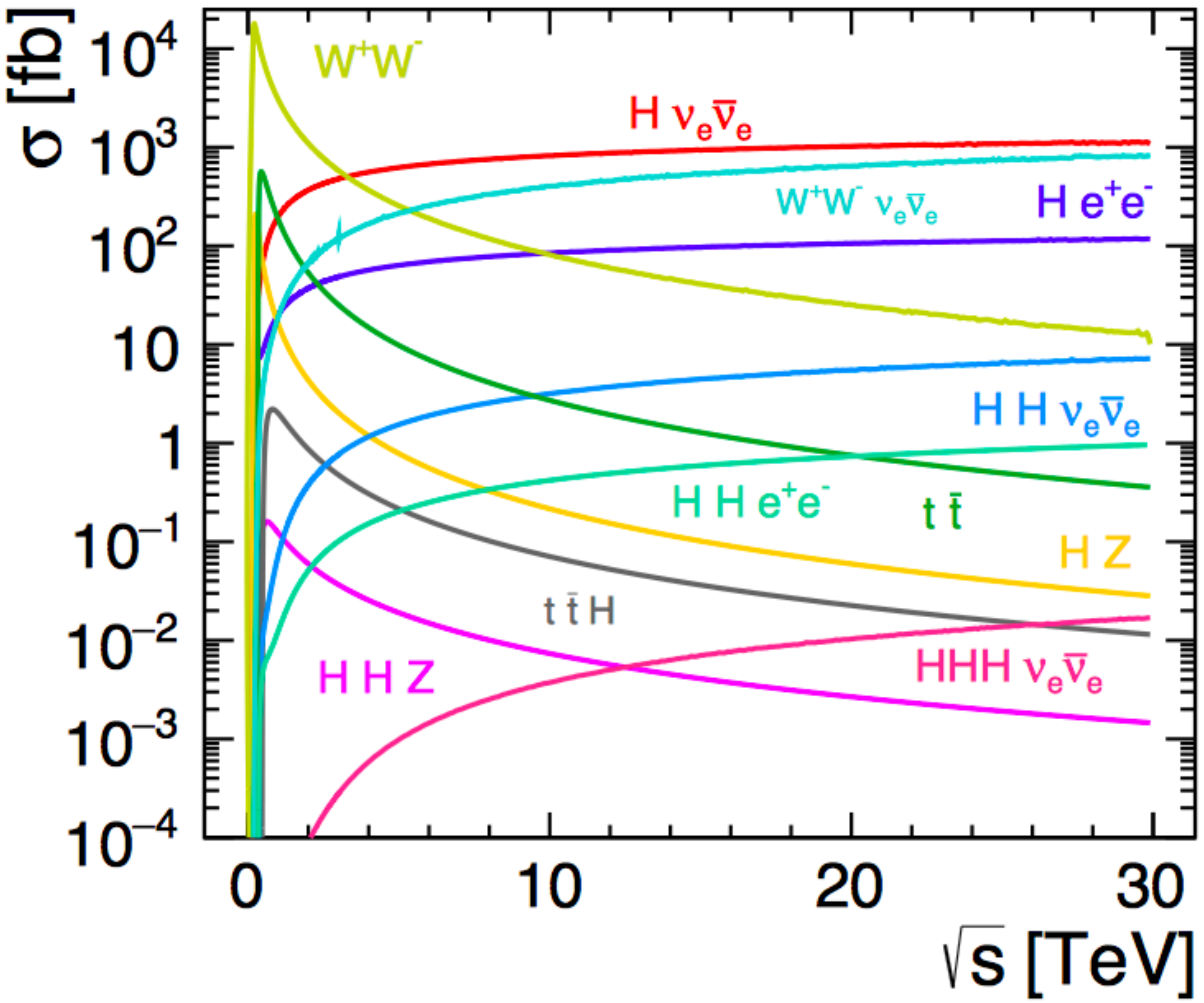
Energy reach & precision electroweak physics in same machine



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

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





Sensitivity to new physics

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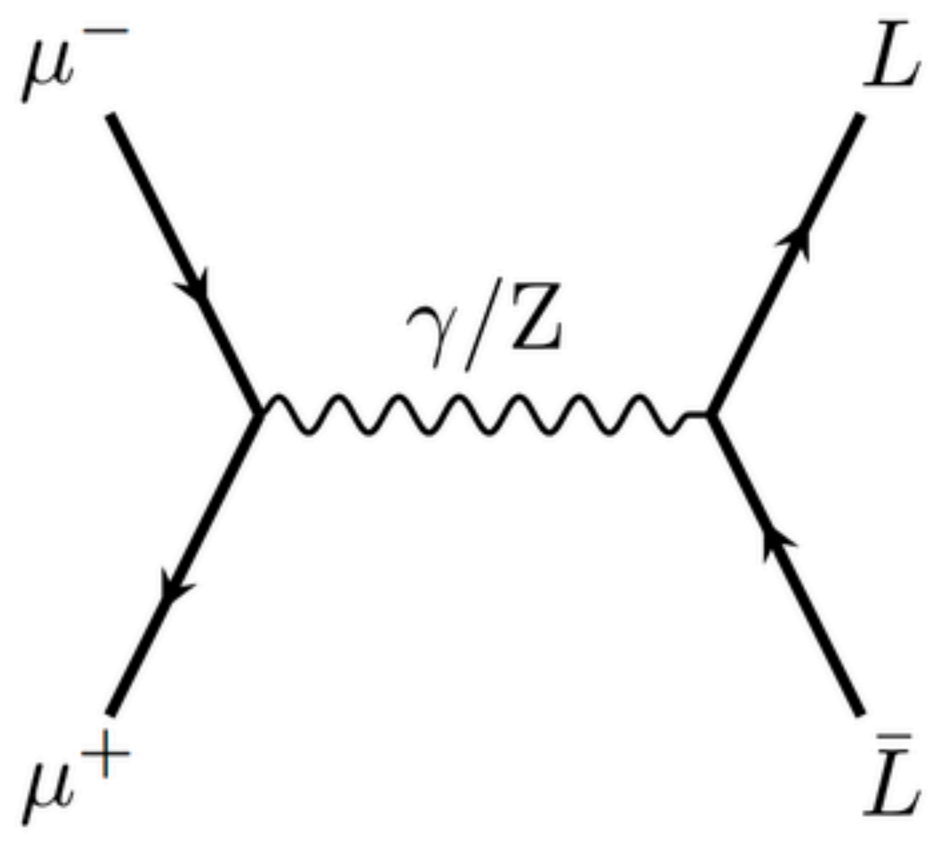
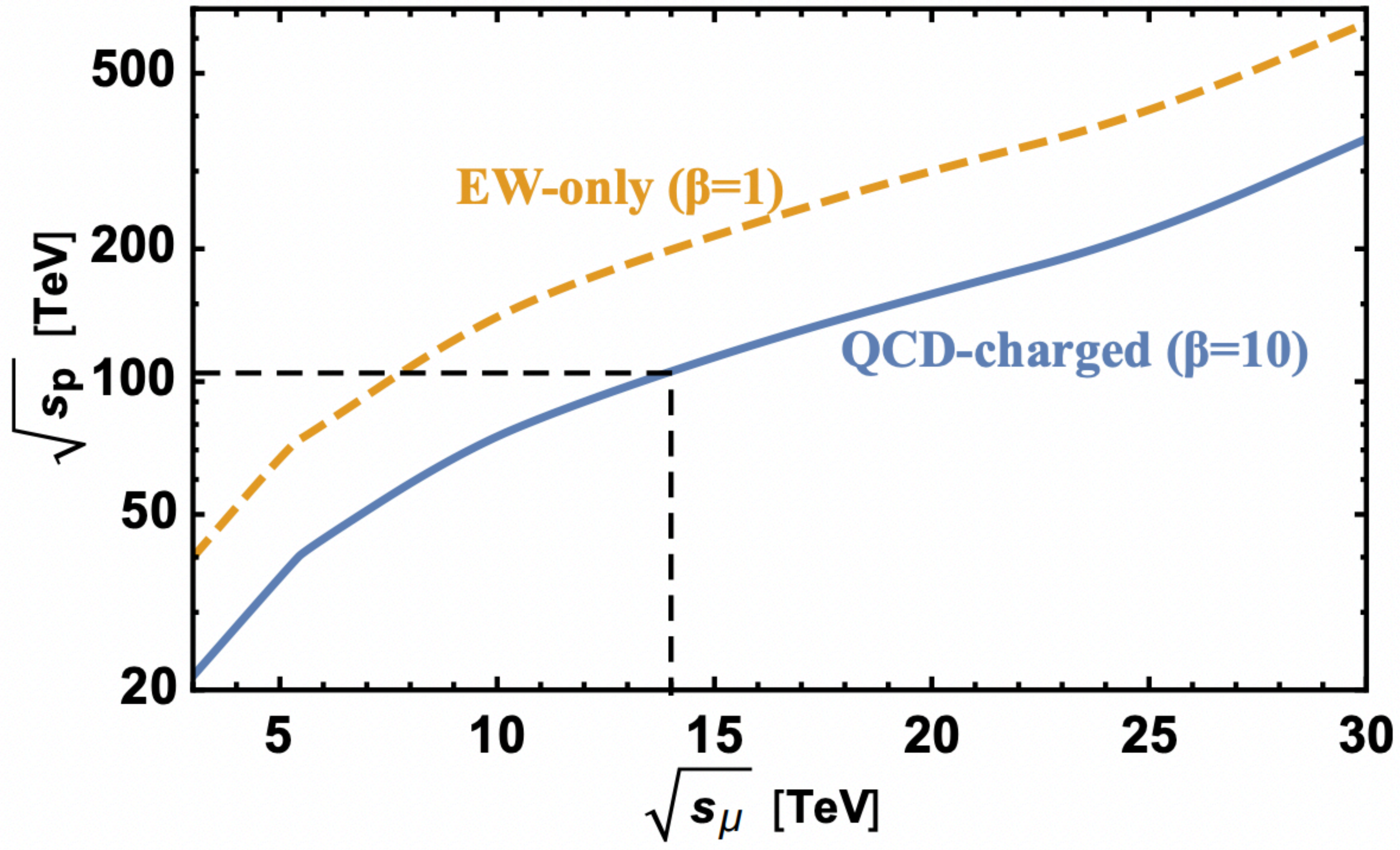
More complicated than 10 TeV μμ ~ 100 TeV pp

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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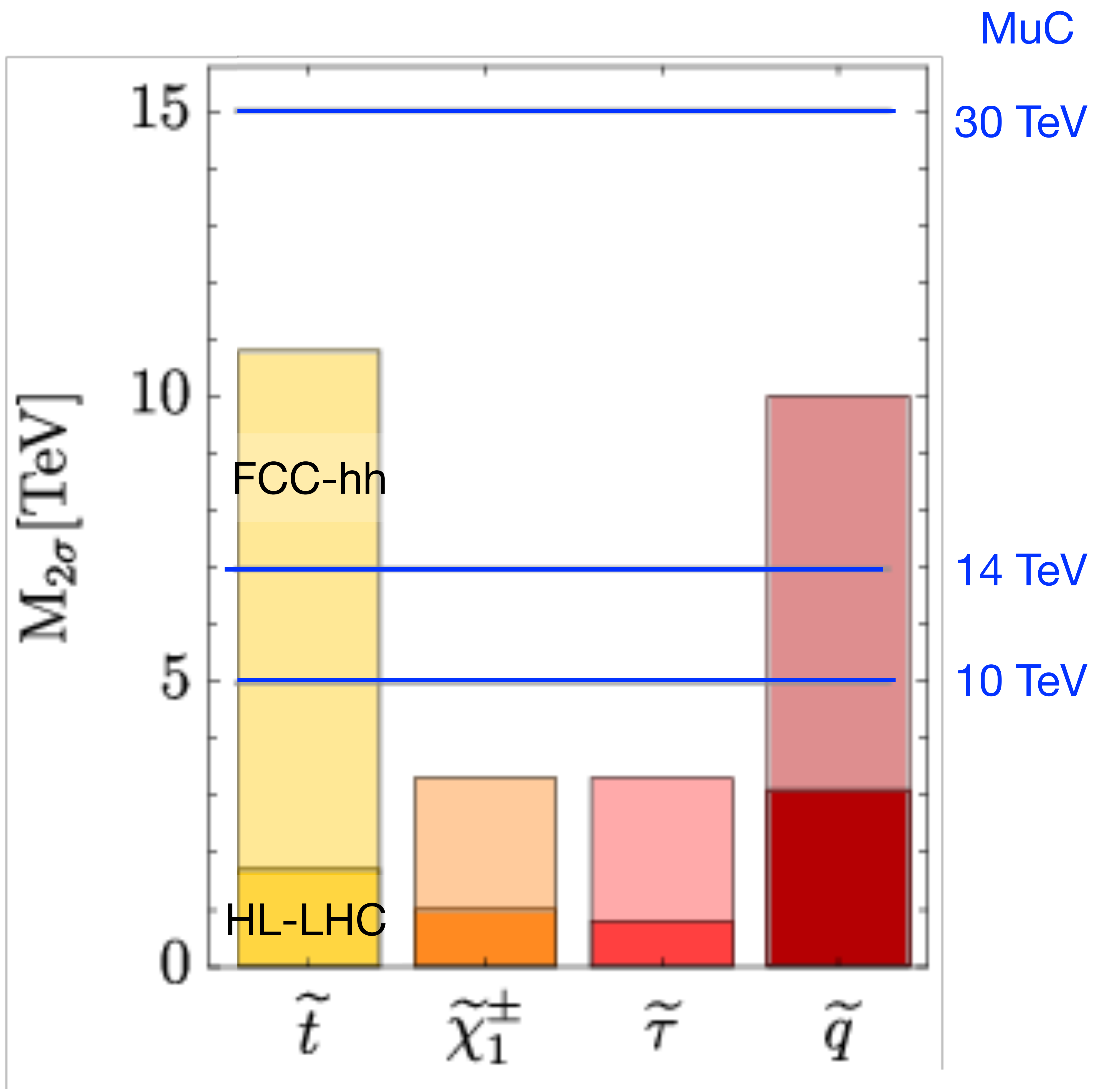
Example of Direct reach
Supersymmetry

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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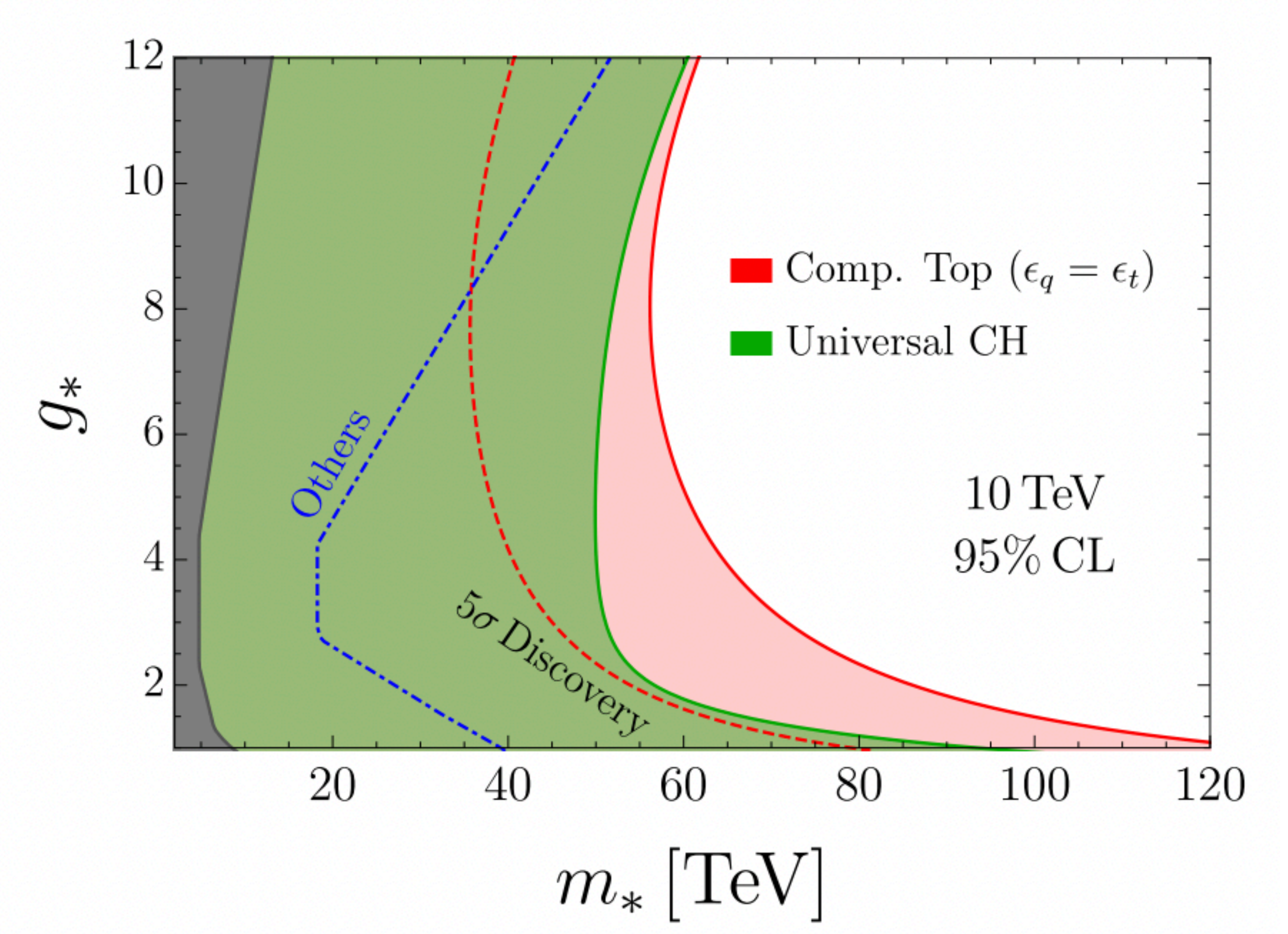
Example of Indirect Reach: Higgs Compositeness

Diboson & di-fermion final states

MuC: sensitivity scales with √s

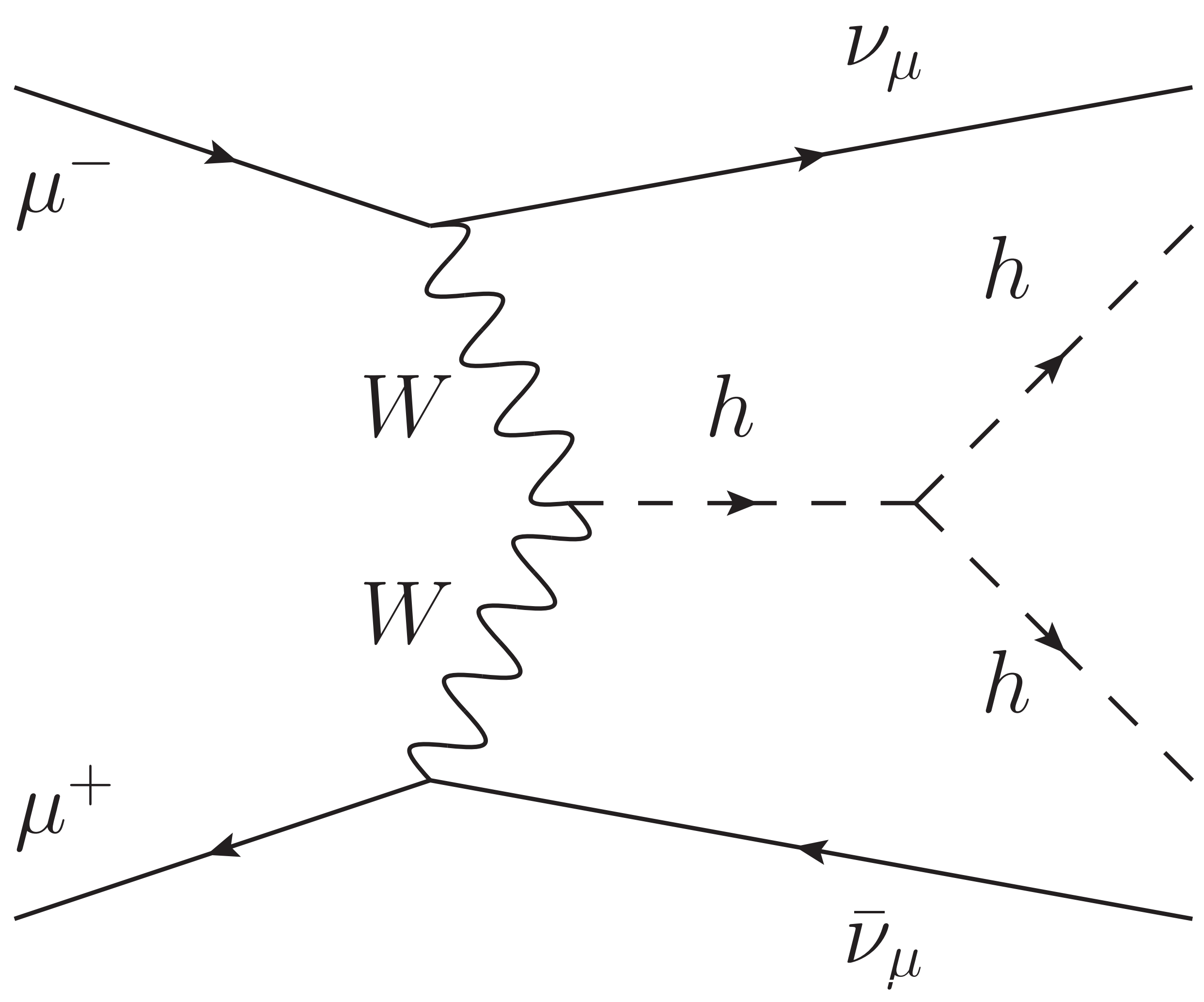
FCC-hh: lower effective parton luminosity



Electroweak precision

1905.03764, 2203.09425, and 2212.11067

≥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

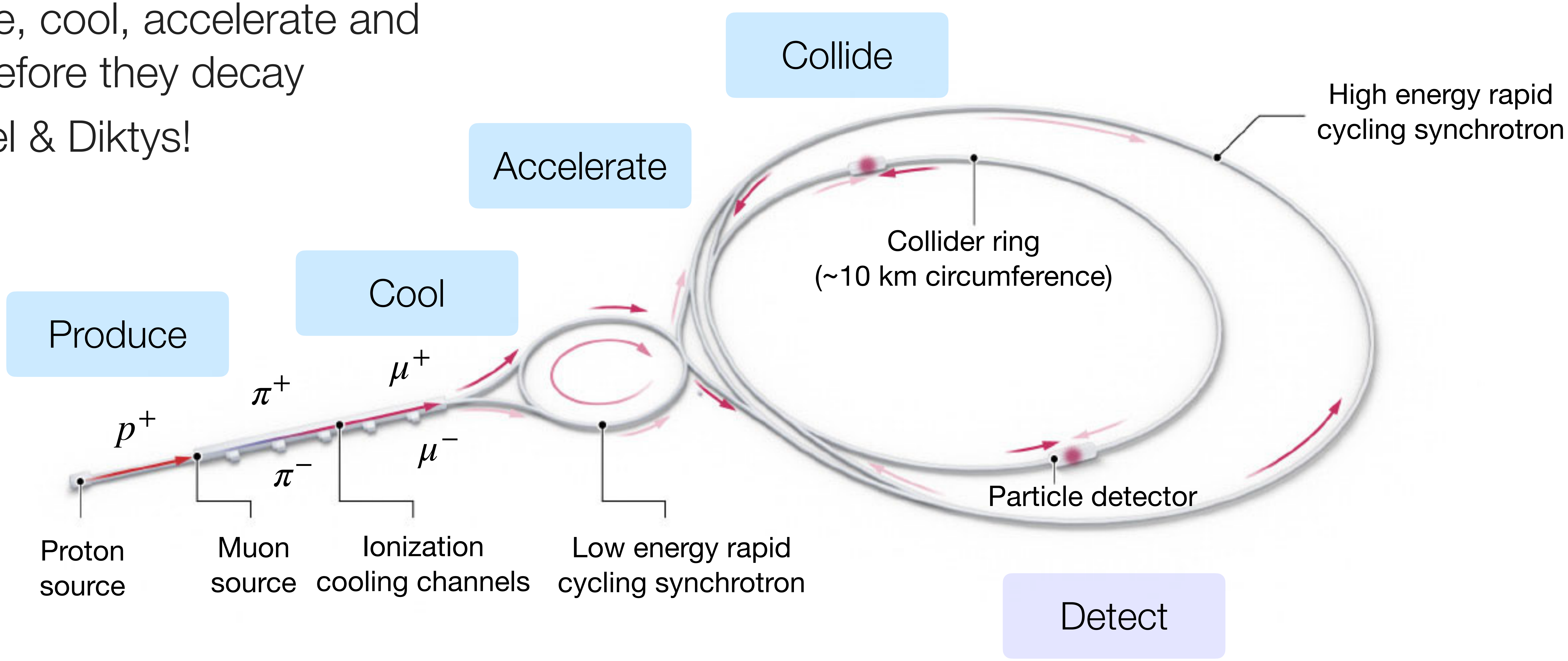
κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 10000
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35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

Muon lifetime τ=2.2 μs

- Need to produce, cool, accelerate and collide muons before they decay
- More from Daniel & Diktys!



Collision environment

Depends on energy, physics goals, and cross-sections

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

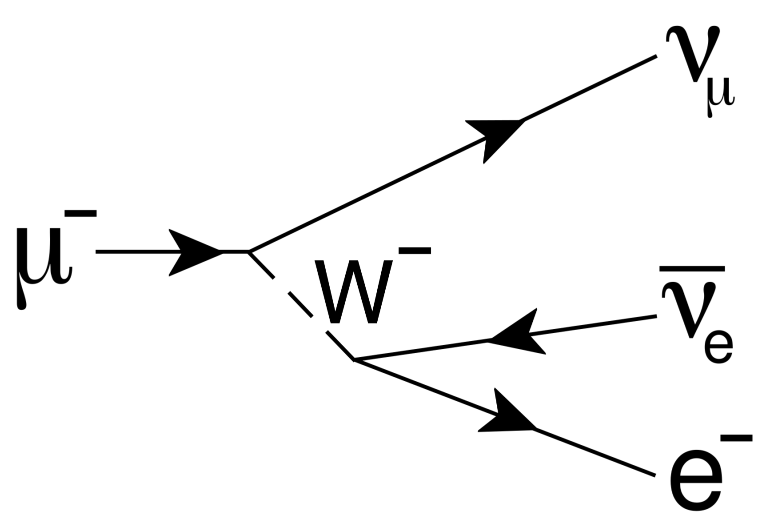
Aim for 10 ab^{-1} in 5 years

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

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 $\beta\gamma\tau$	100 ms
Decays w/in 20 m of detector	10^7

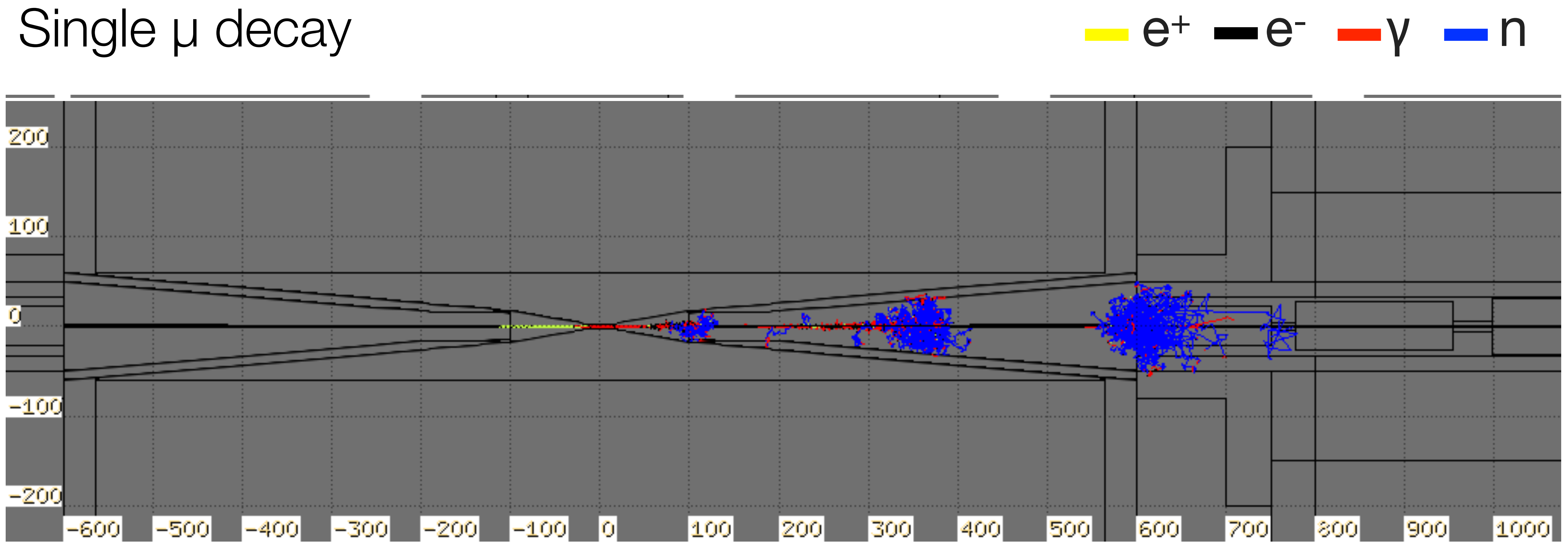
Tungsten Nozzles

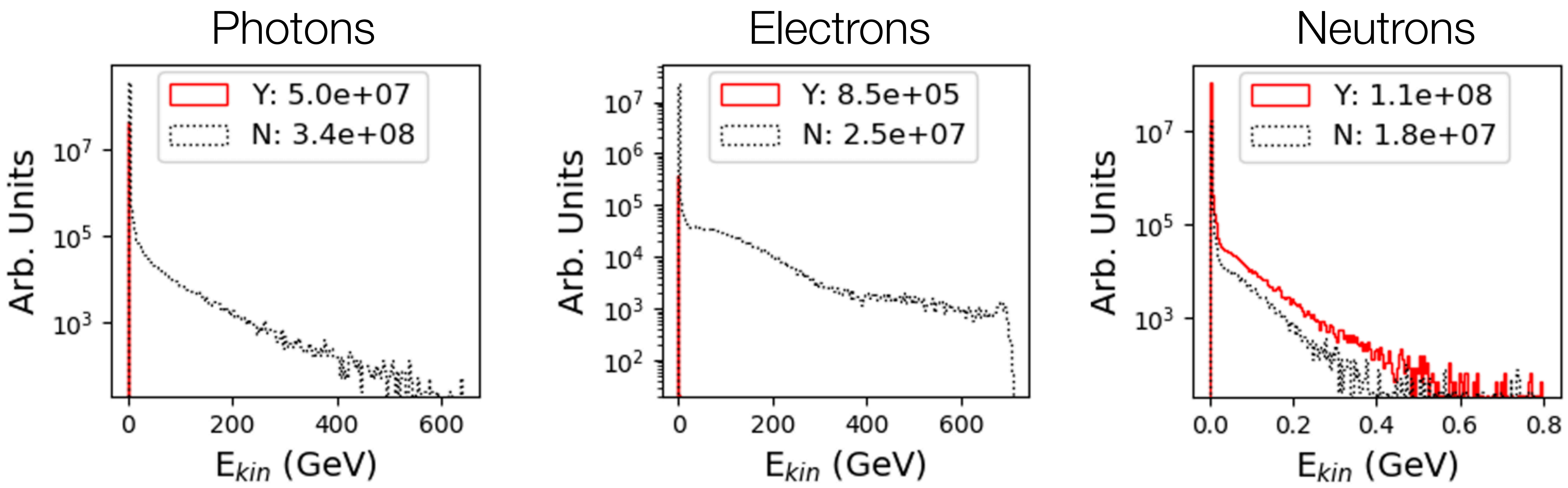
Suppress high energy component



Tradeoff: increase in low energy neutrons

Single μ decay





Inside the detector

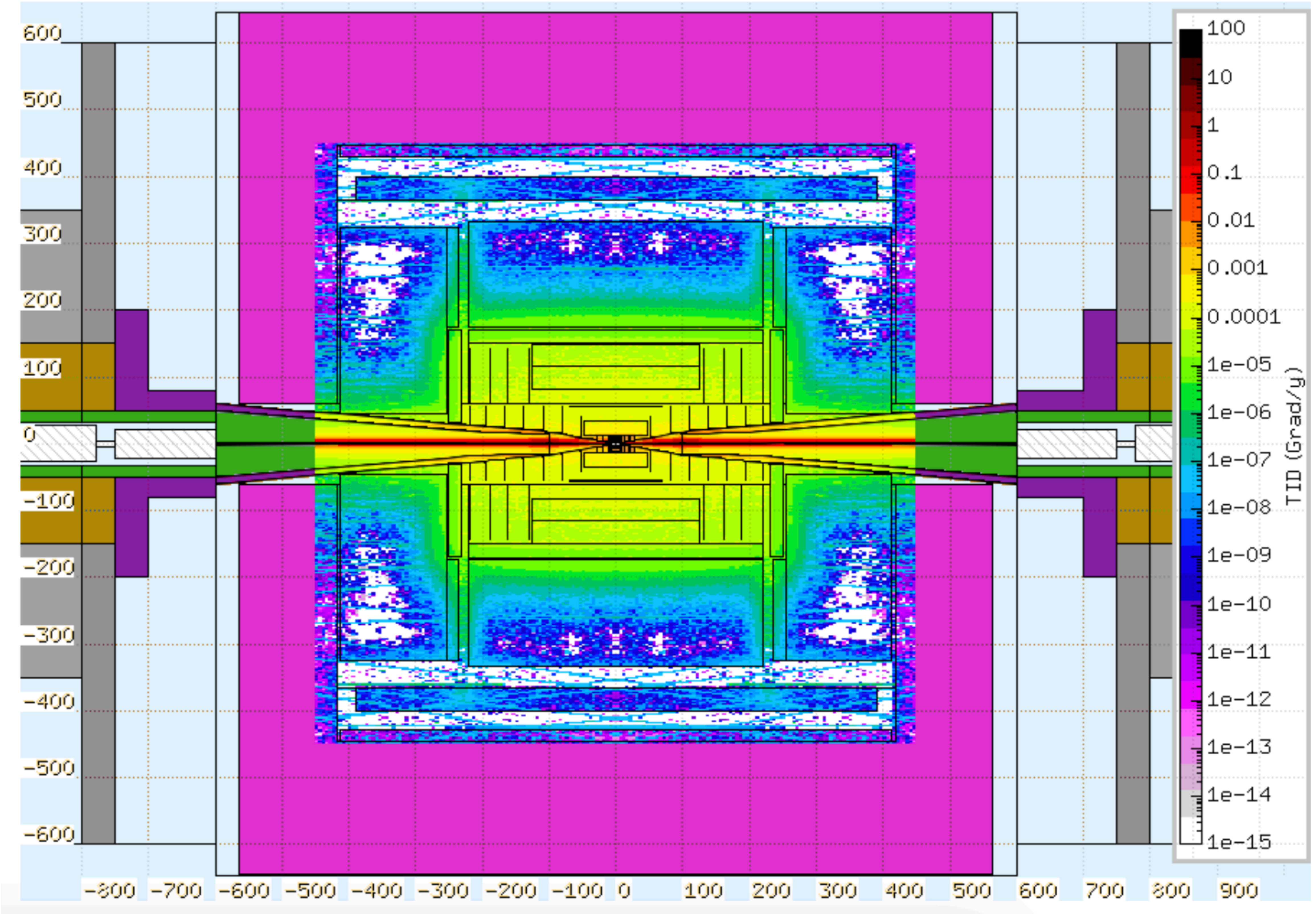
Compared to HL-LHC

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



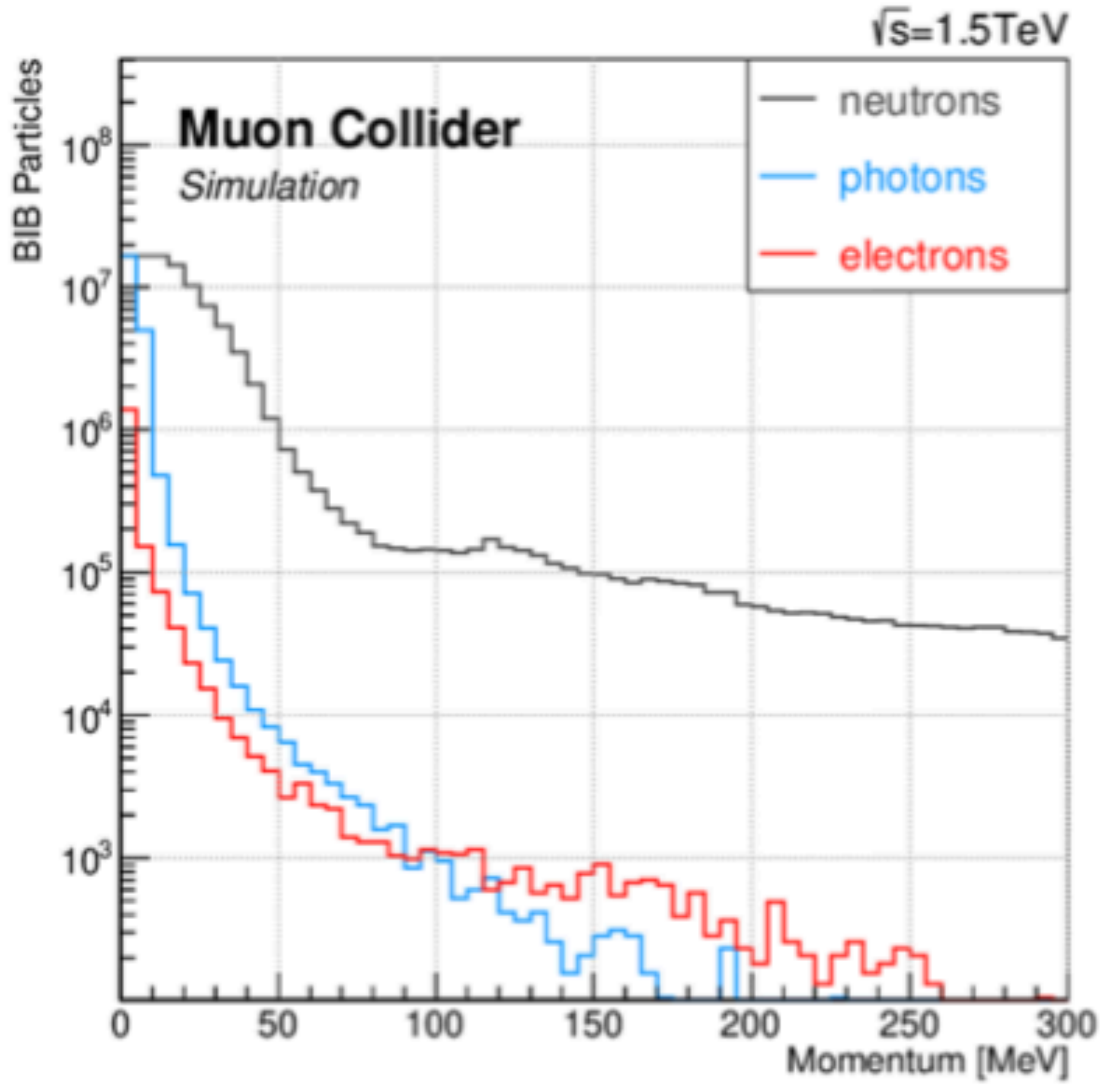
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

Background properties

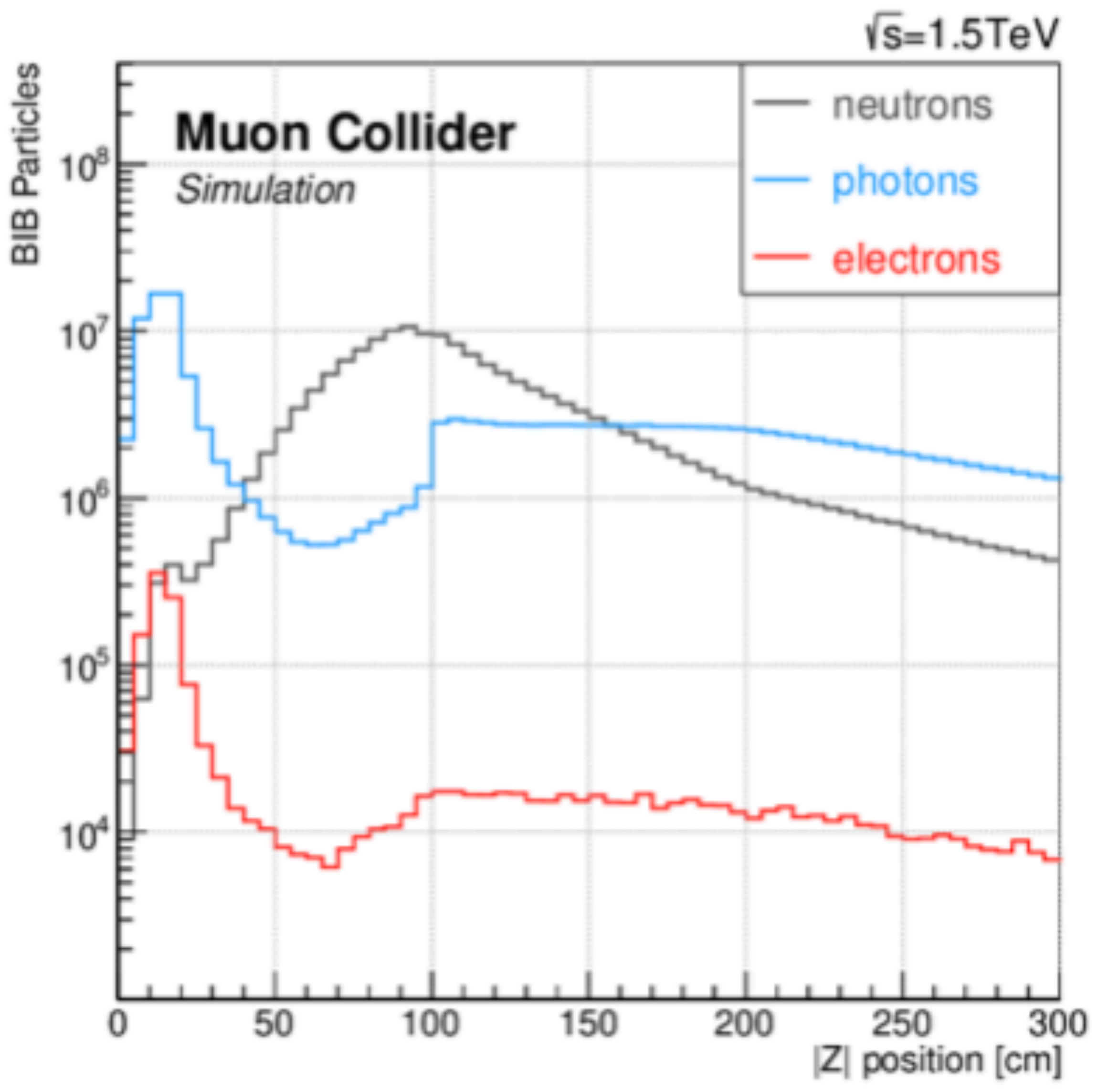
With standard nozzle ~10^8 low momentum particles per event

But this background looks very different from signal!

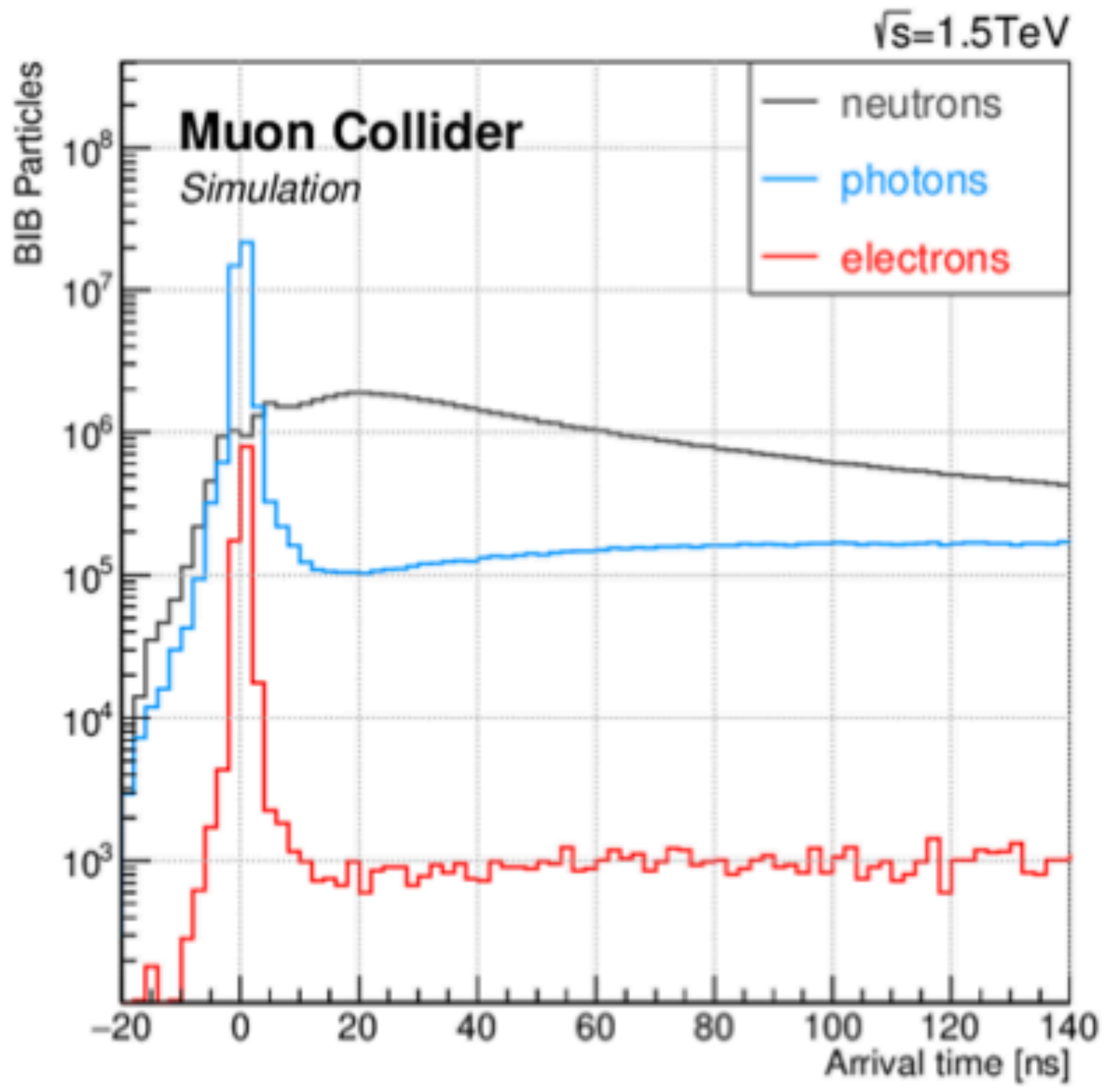
Majority < 200 MeV



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!

Muon Collider Detector

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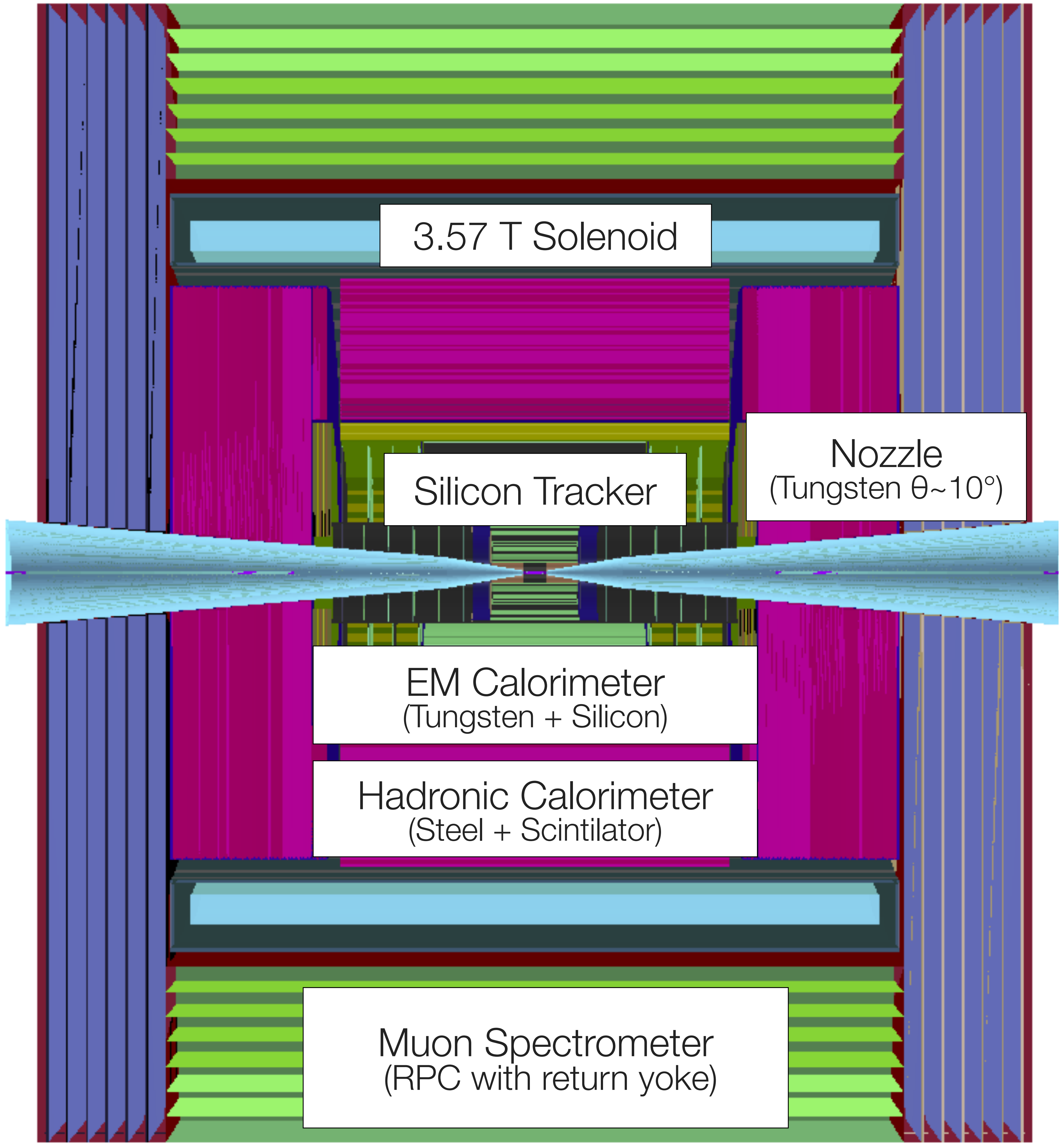
Major outcomes of Snowmass/IMCC

Baseline Detector for 3 TeV

Beam Induced Background with FLUKA

Full simulation physics studies



Now preparing for European Strategy!

Work in progress: 10 TeV design

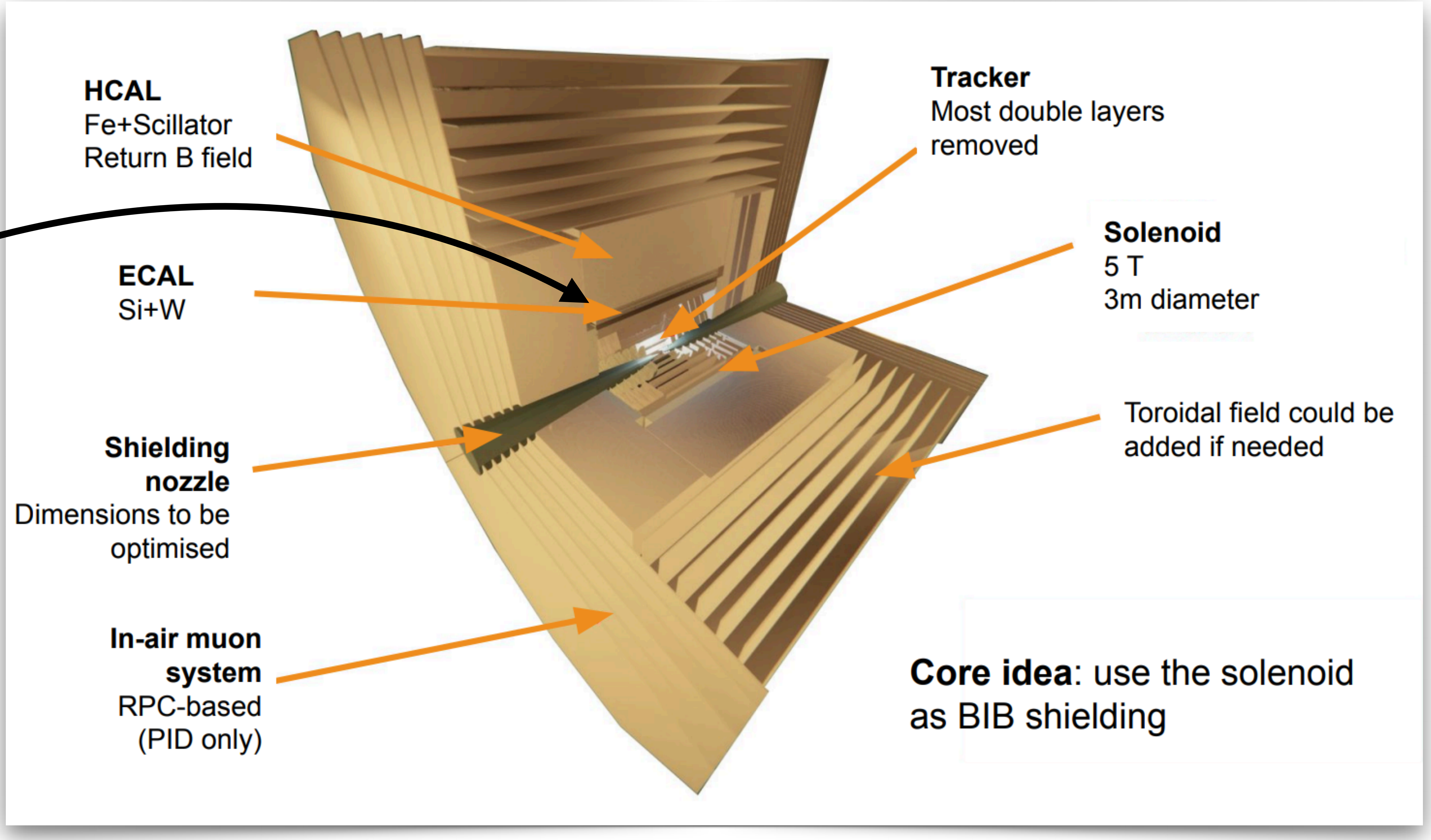
Detector Magnet Workshop
Summary by A. Bersani

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!

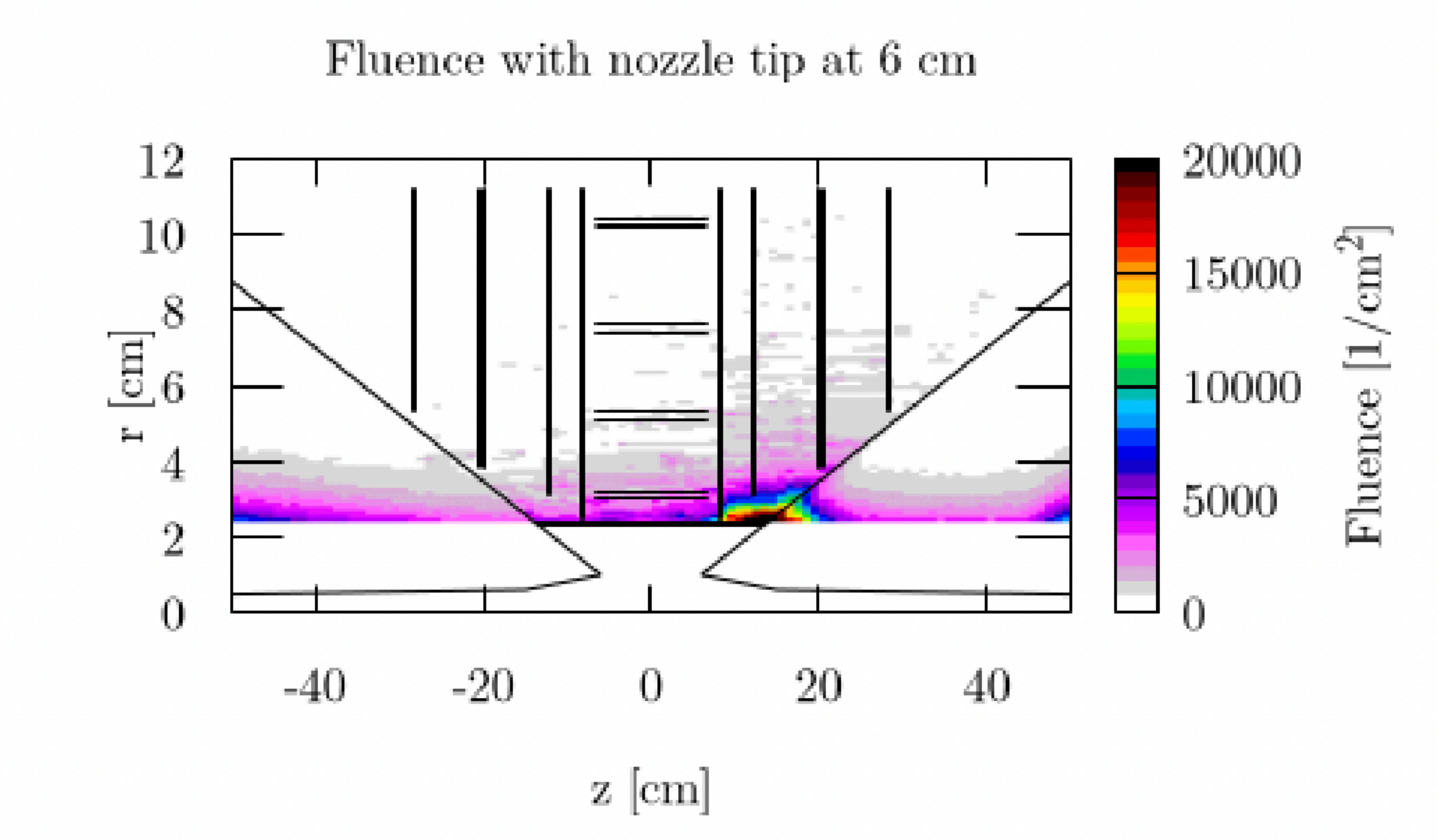


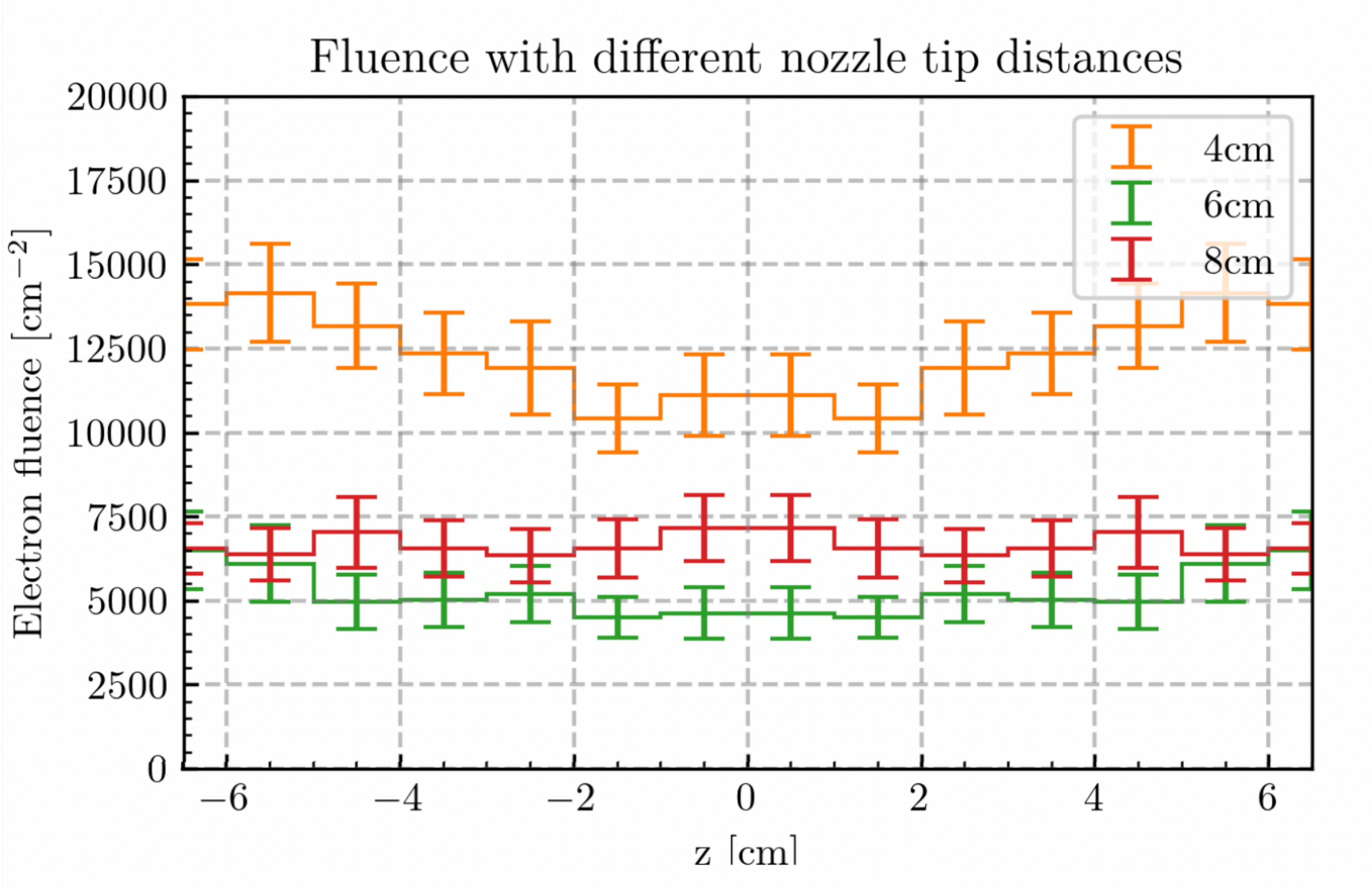
Work in progress: Machine detector interface

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?

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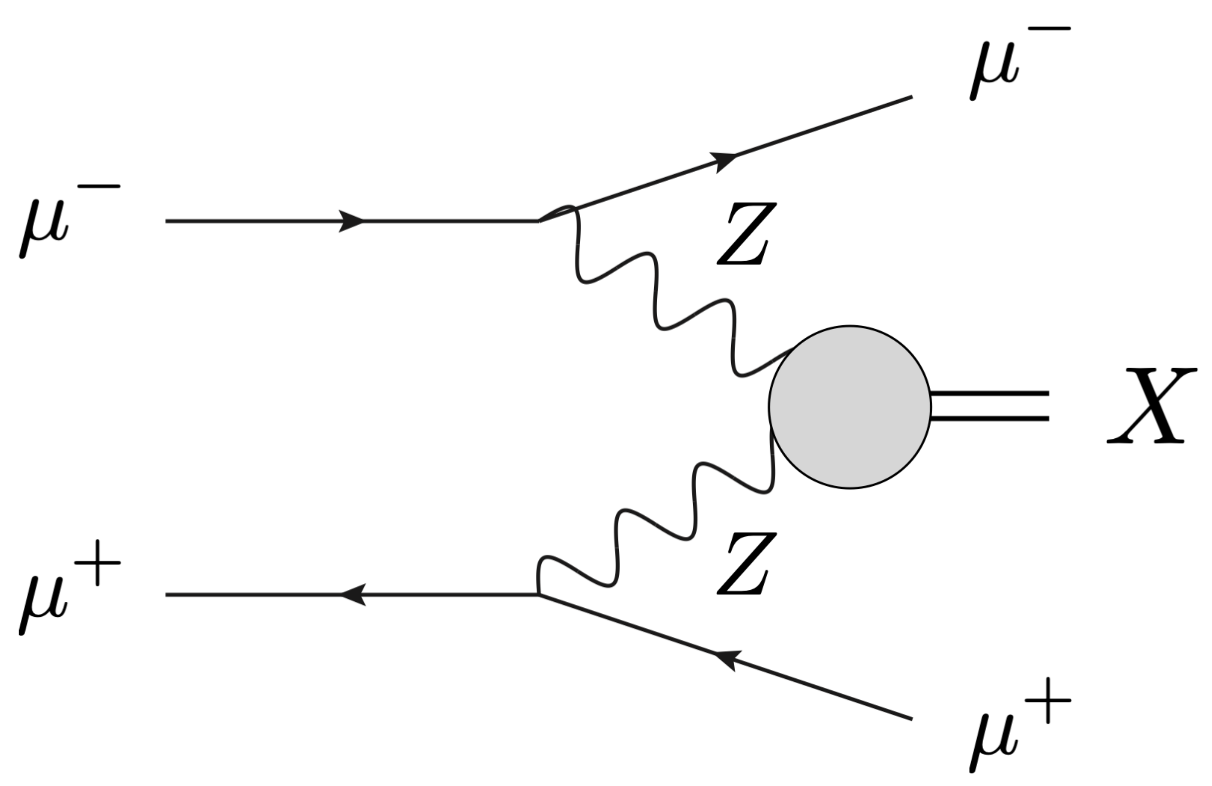


Separate ZZ and WW fusion

Reduce backgrounds

Br(h→invisible) via m_{miss}

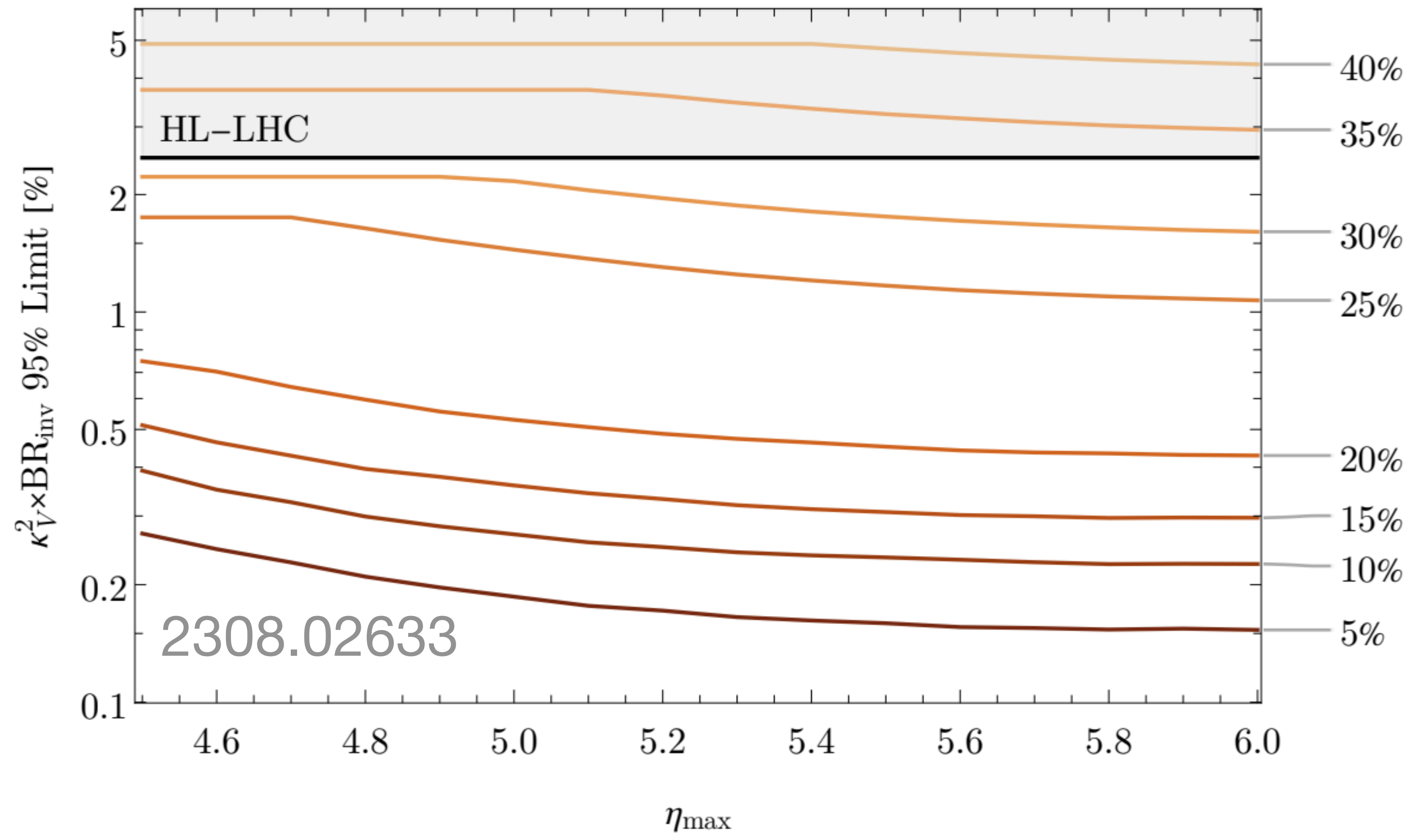
Γ_h via inclusive rate

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



Takeaway: Can we do physics?

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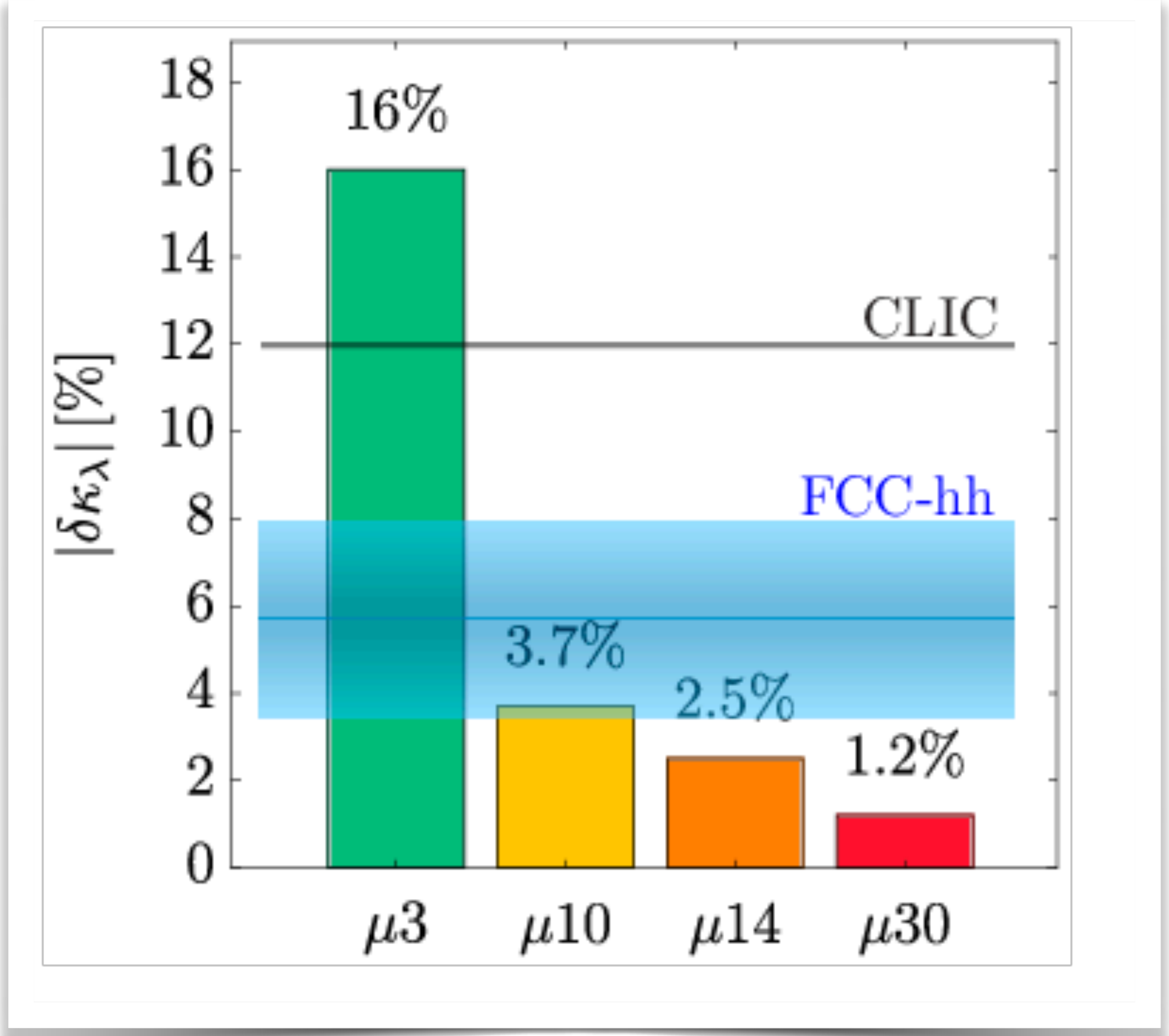
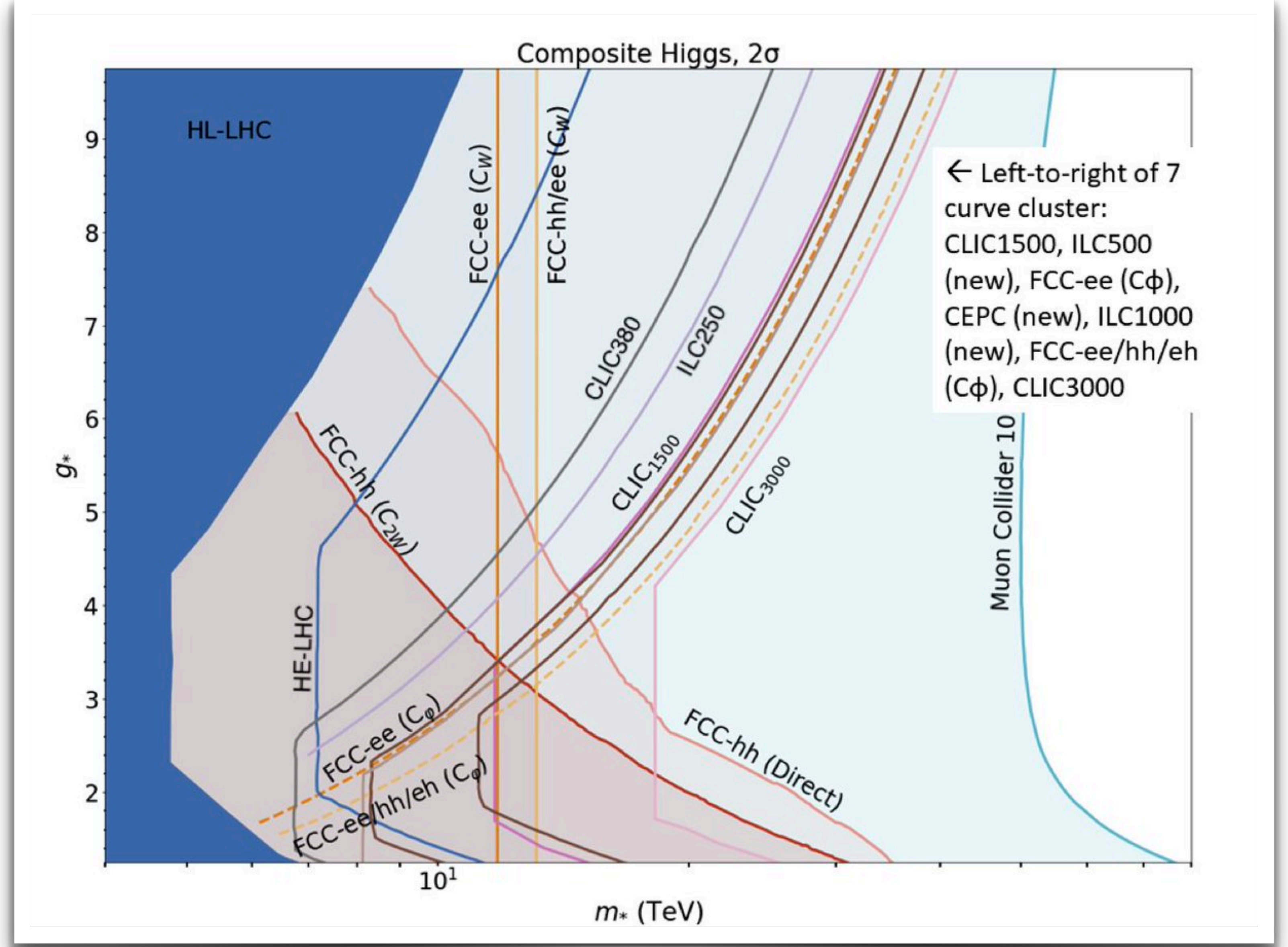
Baseline detector design & full simulation studies indicate yes!

With work in progress we can likely do even better :)

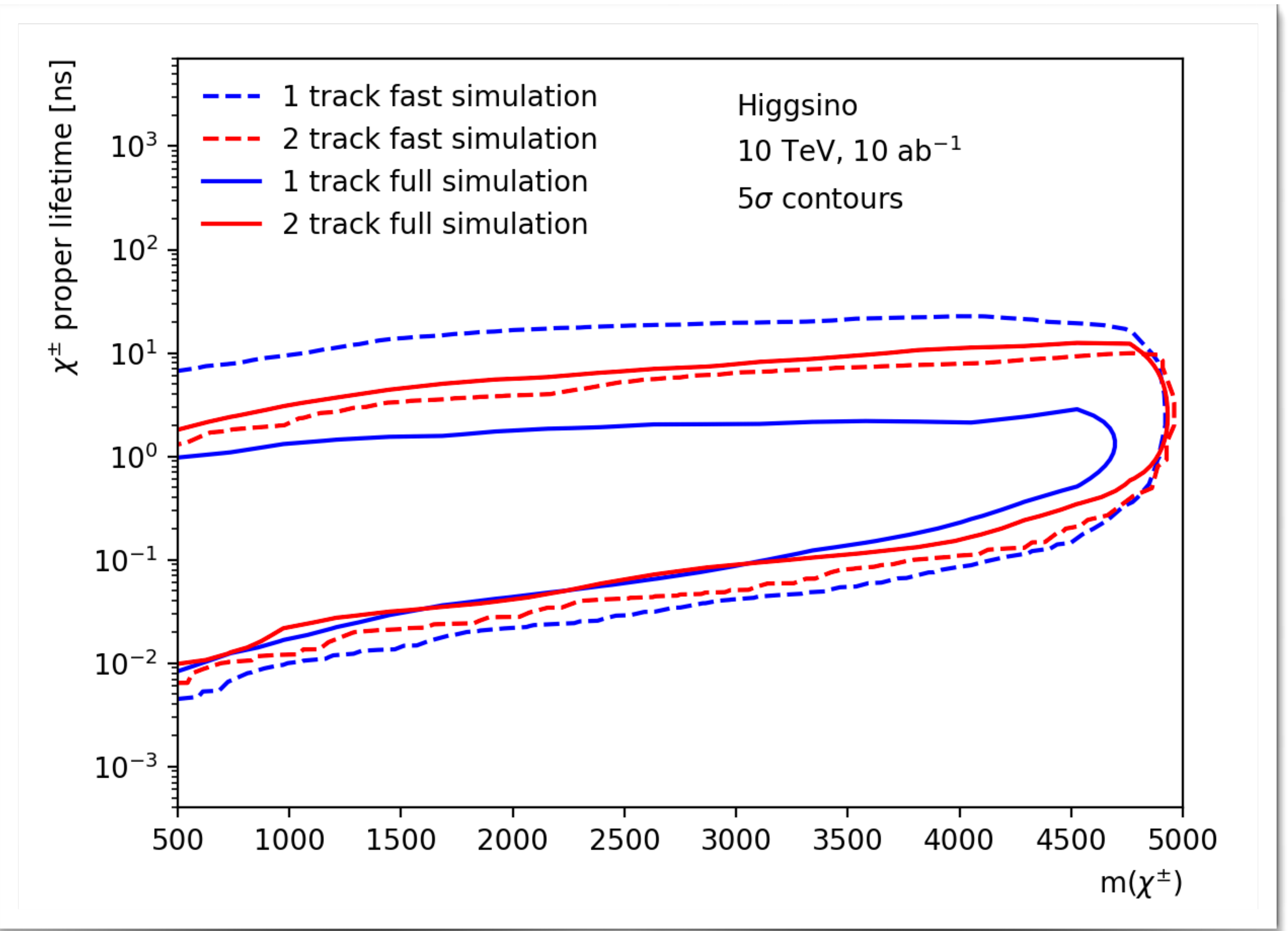
Higgs self-coupling



Composite Higgs Scenarios



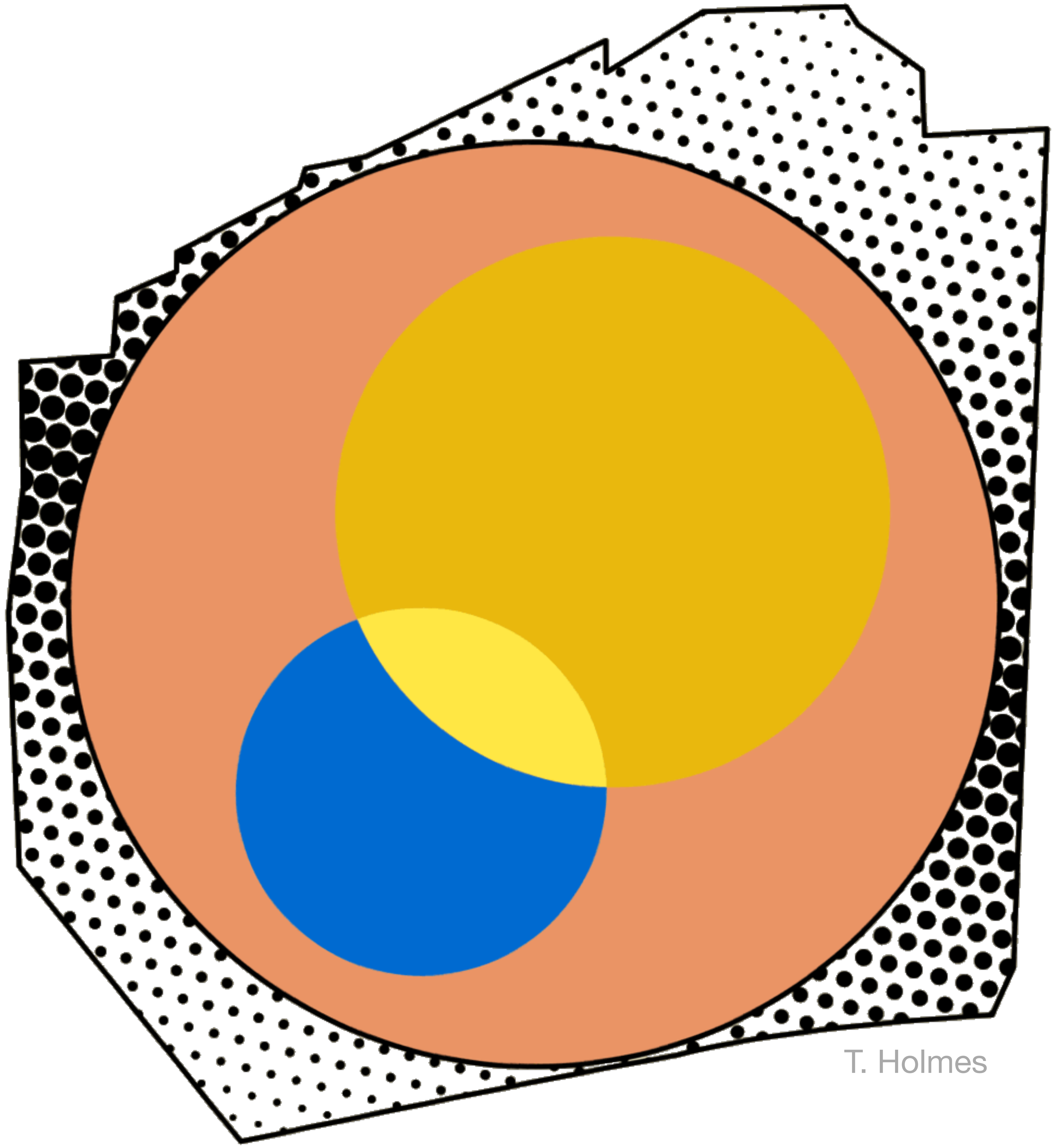
WIMPs/Disappearing track



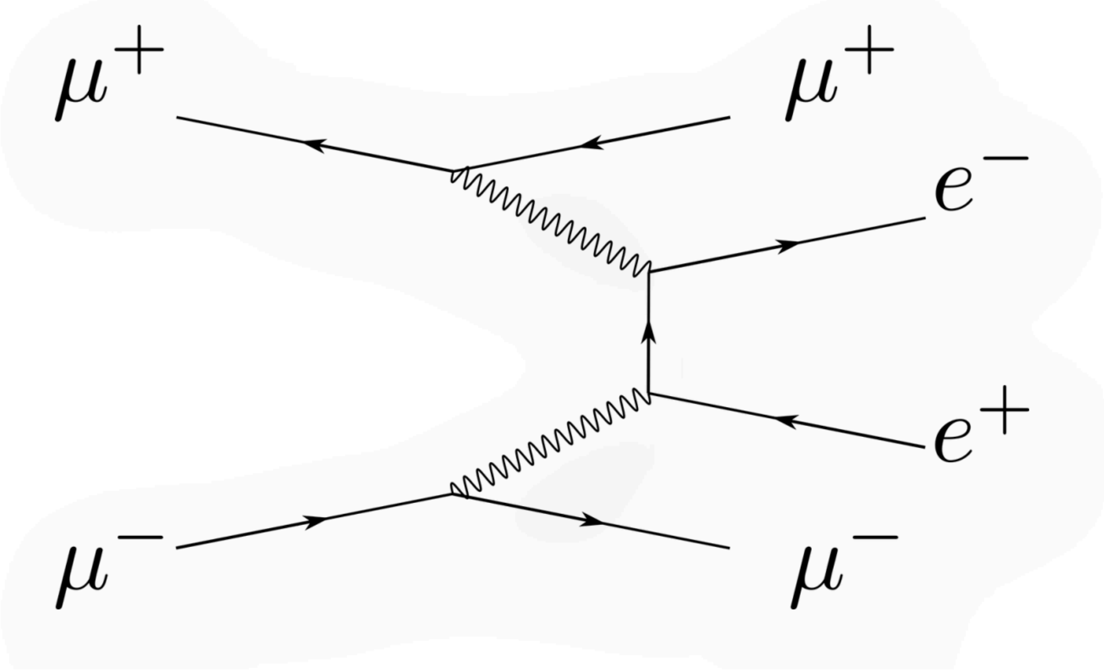
Conclusions

- Strong physics case for 10 TeV Muon Collider
- More work is needed & in progress!
  - Design studies in full simulation (CPU intensive)
  - Map back to physics questions & technology needs
  - Detector R&D: high granularity, precision timing, AI-microelectronics, DAQ

Backup



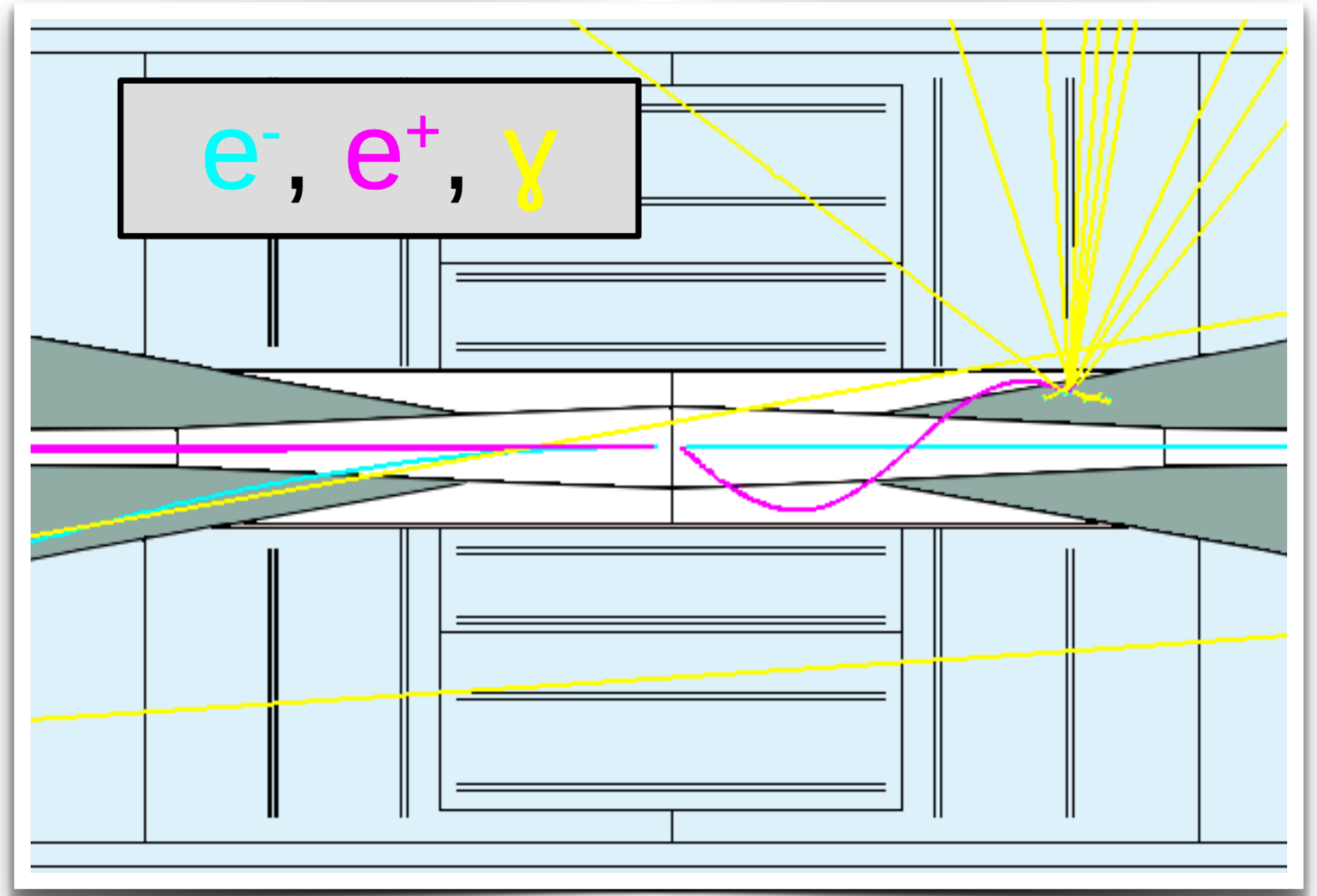
Incoherent e+e- background

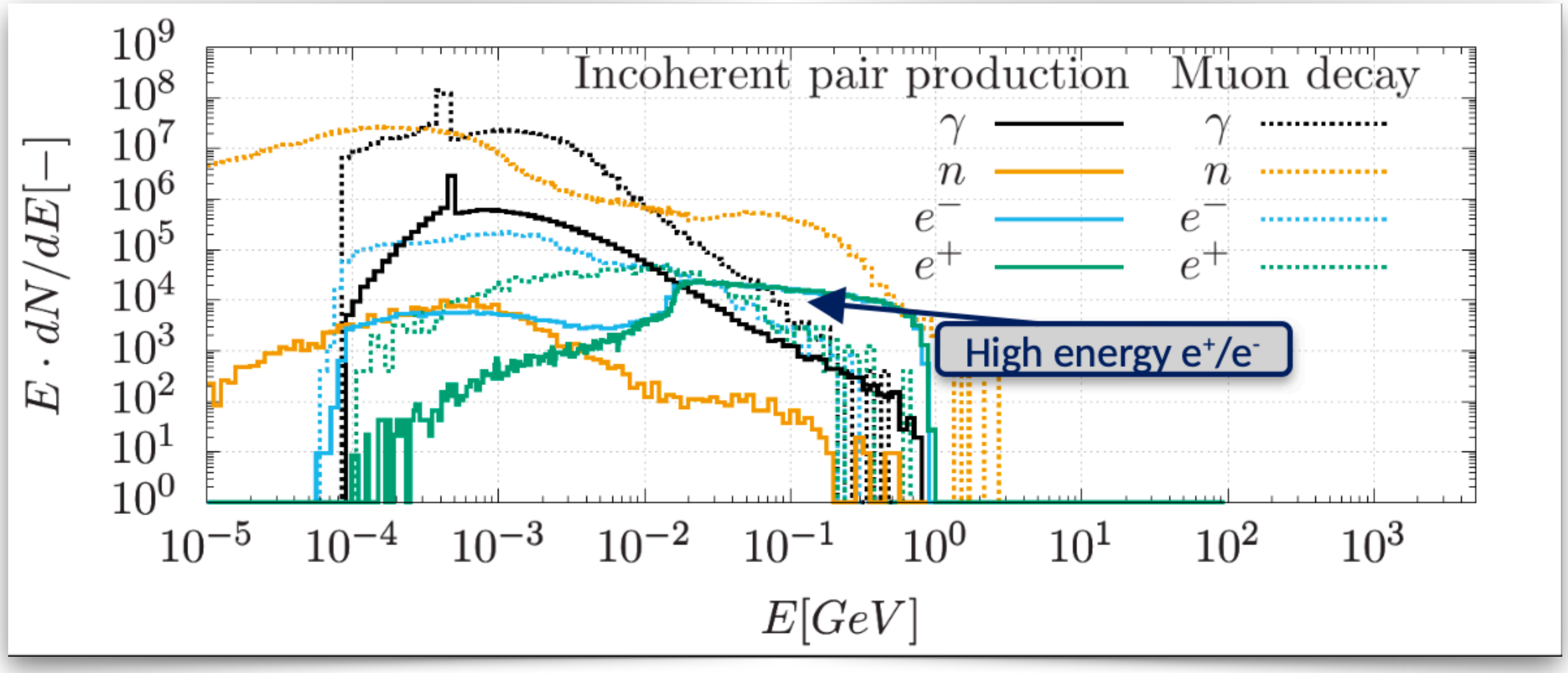


Initial look at e^+e^- pair production from beamstrahlung

lower multiplicity than BIB due to muon decay but higher energy $e^\pm$

→manageable increase in occupancy of innermost layers

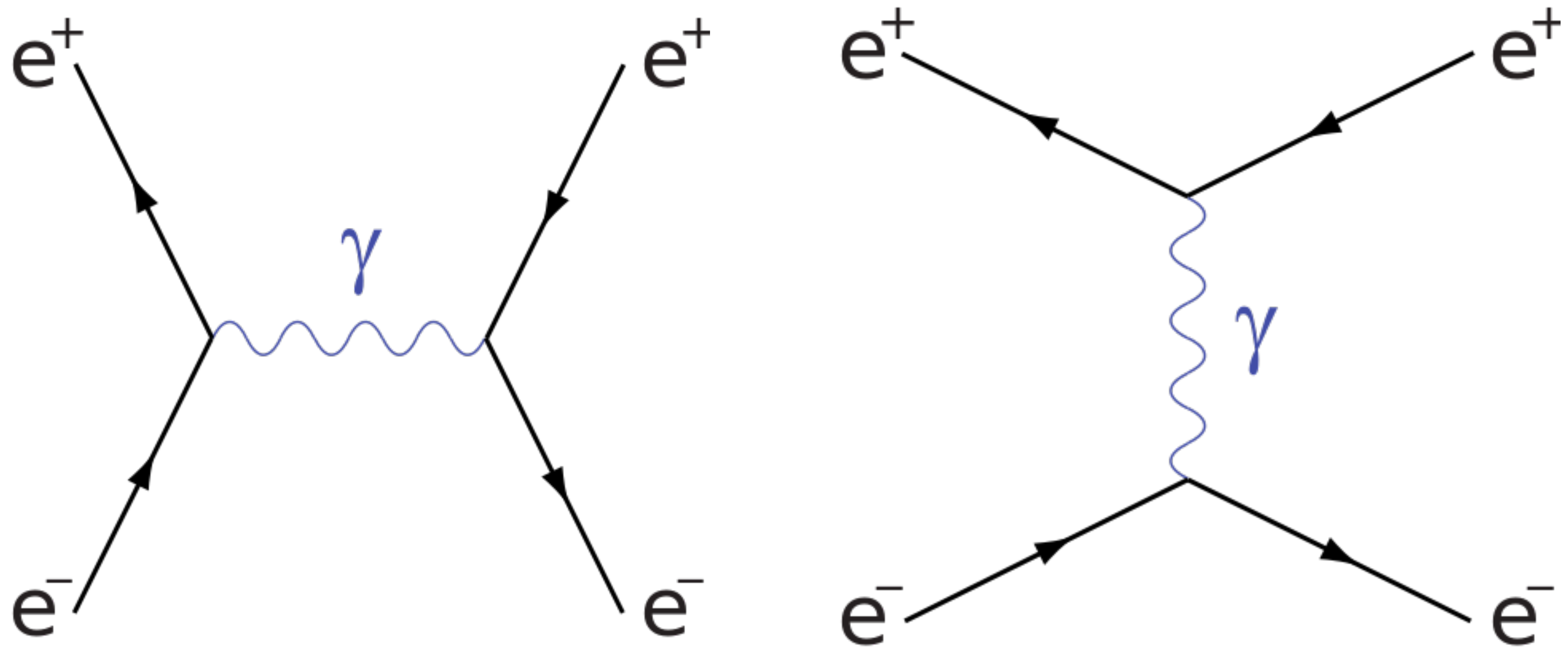




Luminosity

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?

√s=1.5 TeV, lumi = 1e34
Remaining events

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

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

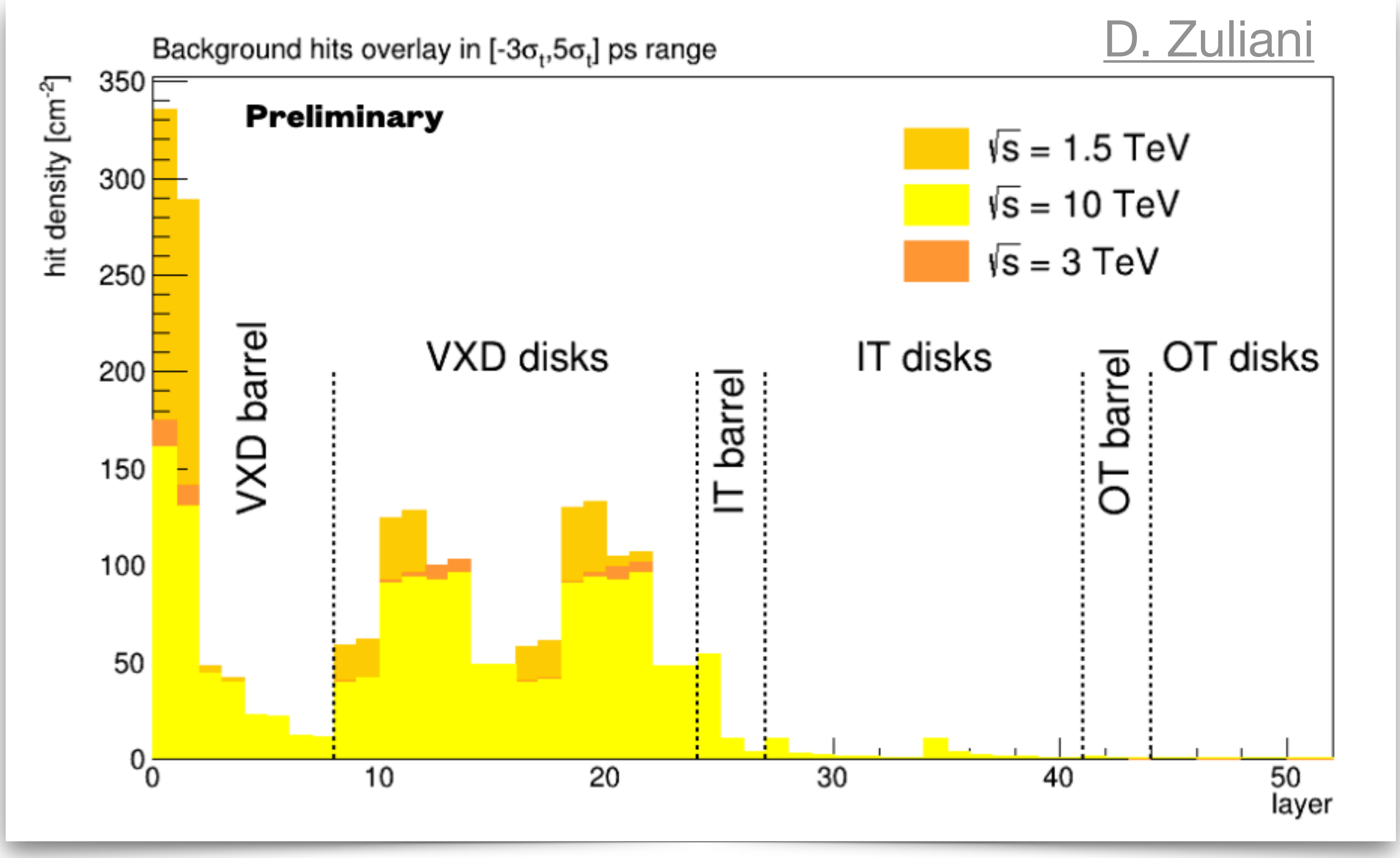
We'll need something else to monitor luminosity in real time

Beam induced background w/ FLUKA

Overview by D. Calzolari

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

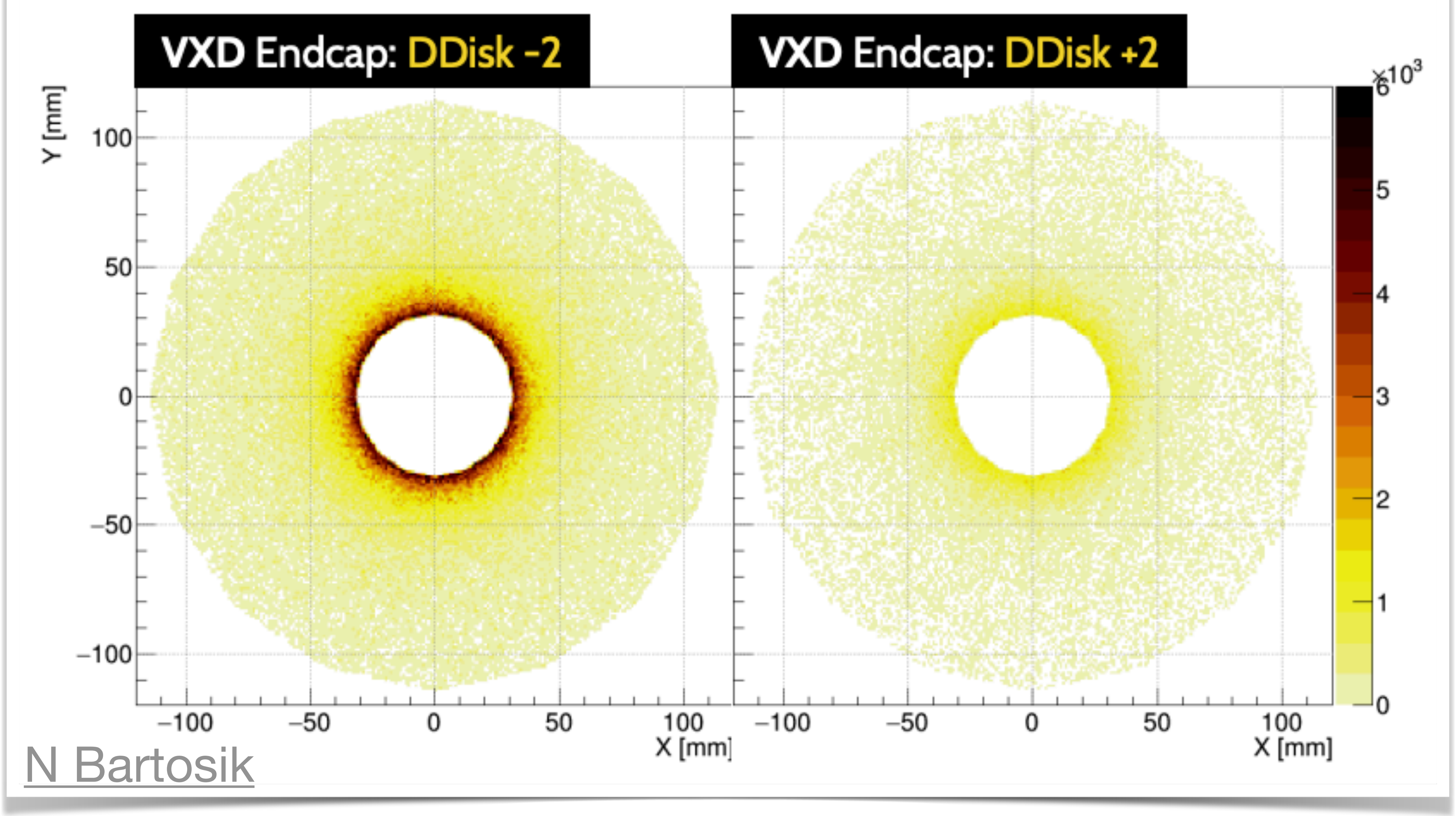
Comparing occupancies at different energies



Characterizing BIB contributions in tracker

eg. particle type: primary vs secondary electrons

spatial origin: upstream vs downstream



Towards a 10 TeV detector

Momentum Resolution

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

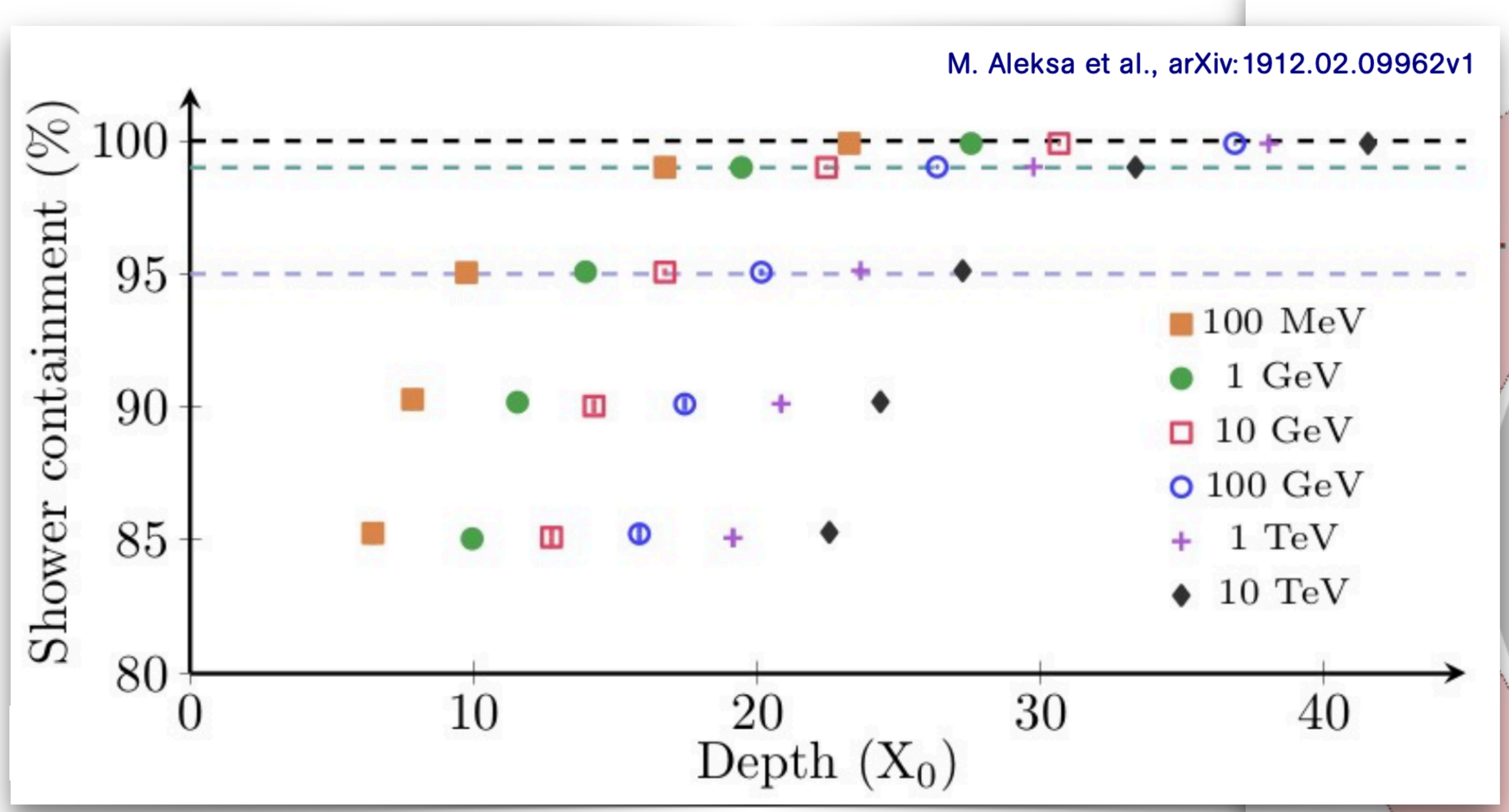
Aim for 5-20% at 5 TeV
→5 T solenoid, R≥1.5 m

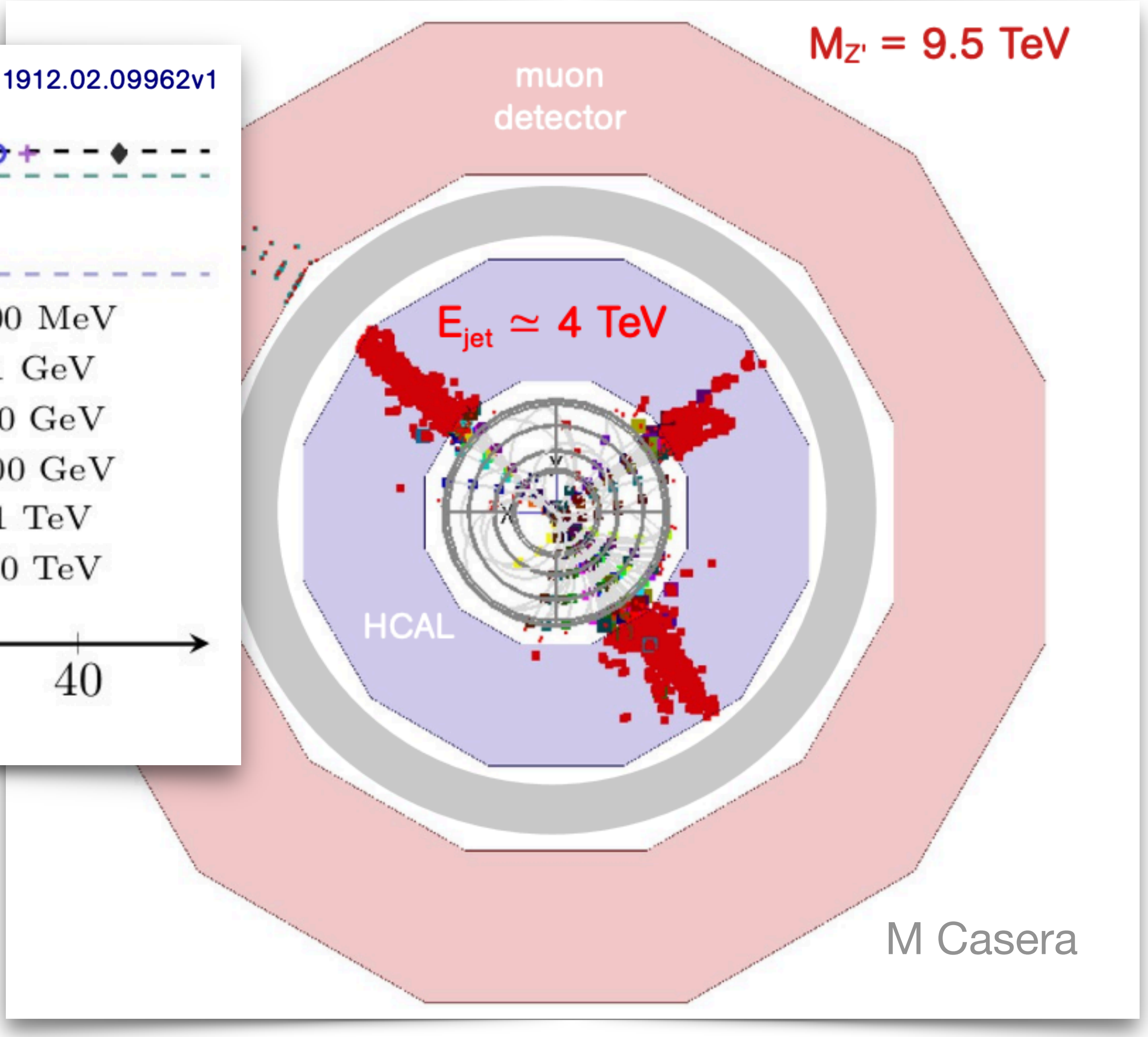
B-meson decay length

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

Shower containment

Need to increase Calorimeter λ and X_0





Detector Magnet

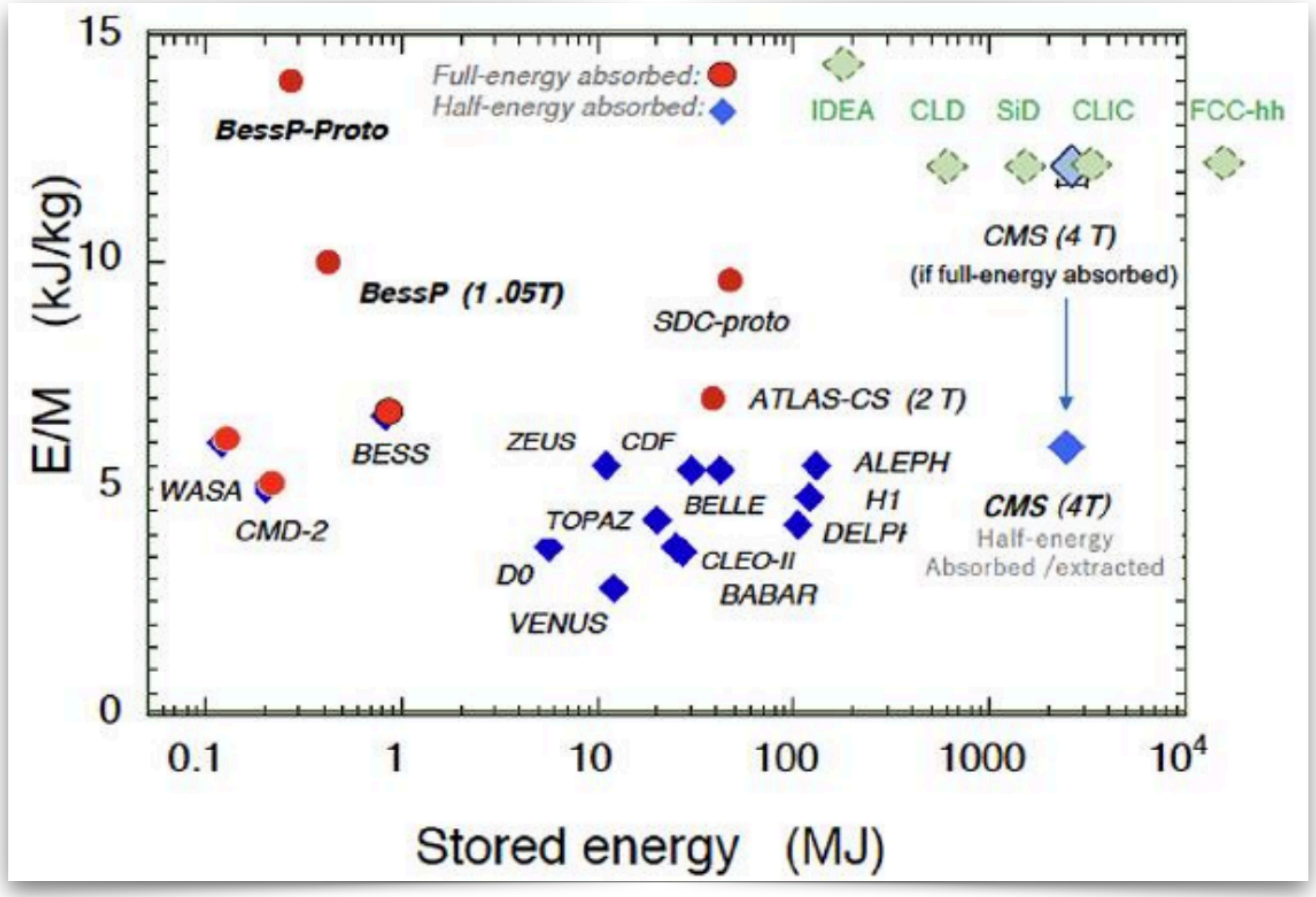
Increasing B-field & inner radius technically challenging

Requires Aluminum-reinforced NbTi/Cu

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

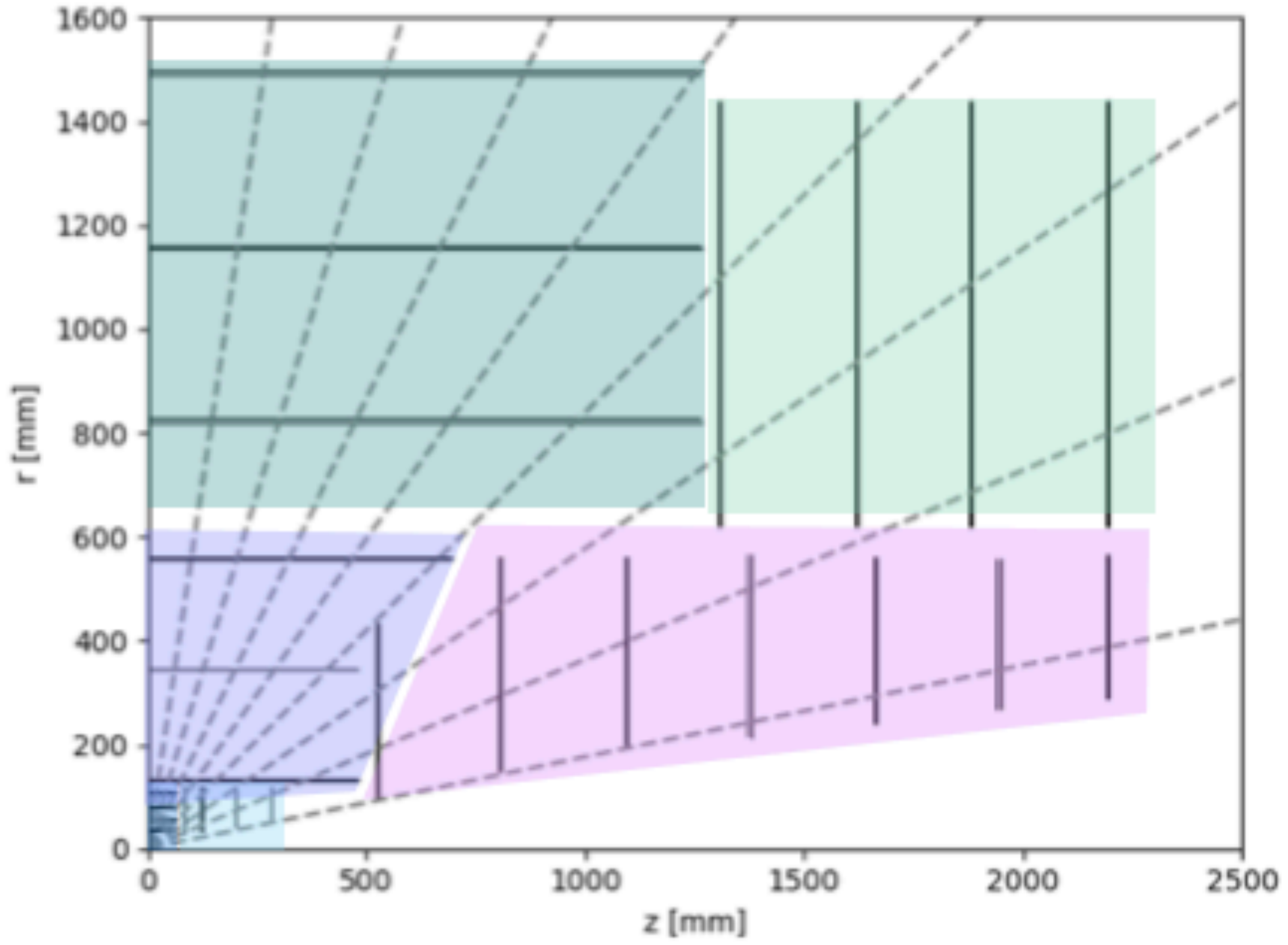
$$t \propto B^2 R$$

Need to reestablish expertise to build CMS style magnets!



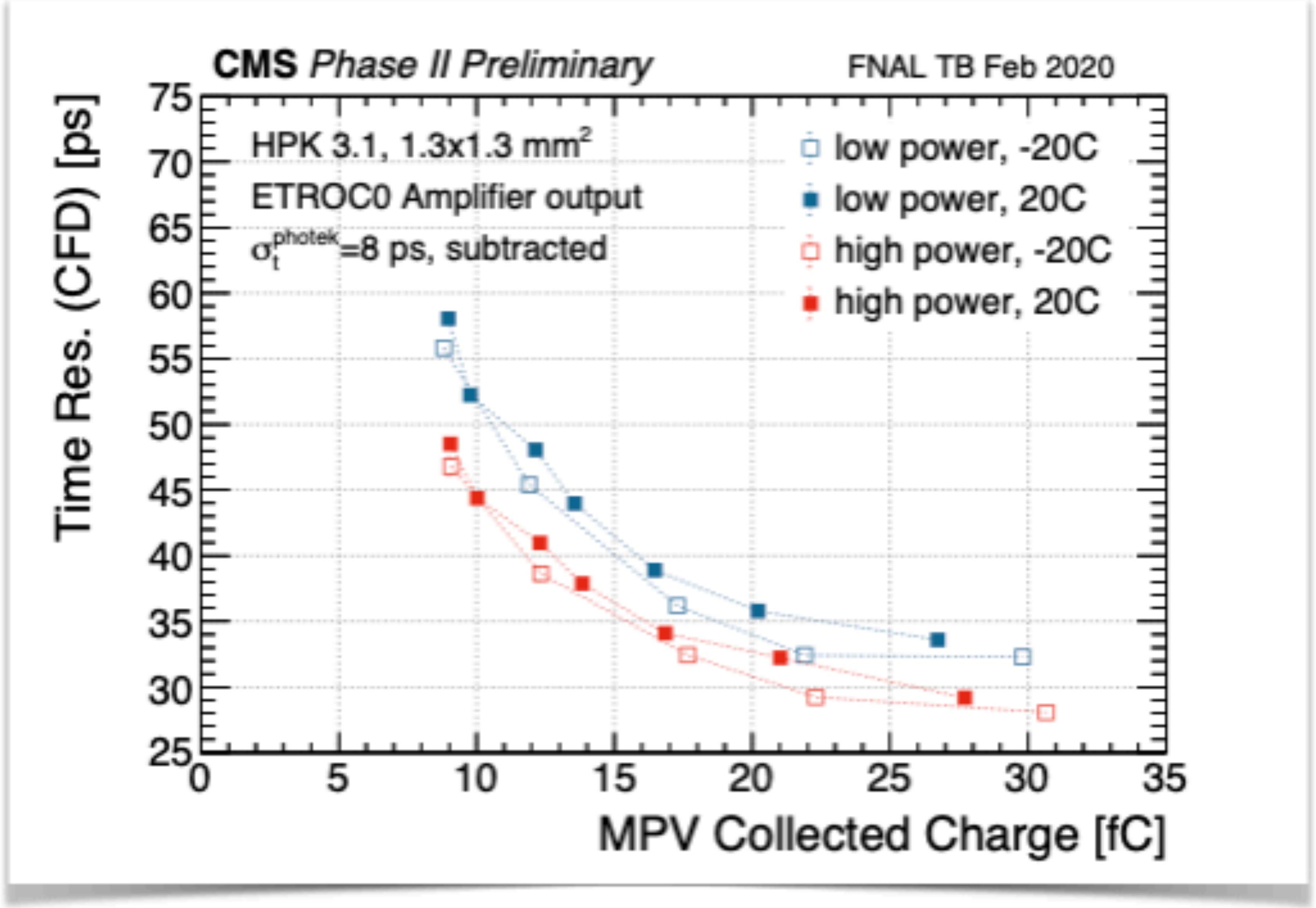
Tracker

- Large area & highly granular
  - ~100 m^2 of silicon sensors
  - ~ 2B channels
- Promising R&D directions
  - Monolithic sensors
  - Devices with intrinsic gain
  - Intelligent sensors
- Challenges:
  - Power consumption
  - DAQ/trigger: O(100) TB/s
  - "Streaming" readout looks feasible



Sub detector	Size	Timing
Vertex Detector	25 x 25 μm²	30 ps
Inner Tracker	50 μm x 1 mm	60 ps
Outer Tracker	50 μm x 10 mm	60 ps

ATLAS & CMS building timing layers with ~30 ps timing resolution for HL-LHC



Calorimeter

Background = large, out of time low energy cloud of neutrals

~2 MeV γ (96%)

~500 MeV n (4%)

Current design assumes

ECAL: Silicon+Tungsten 5x5 mm² cells

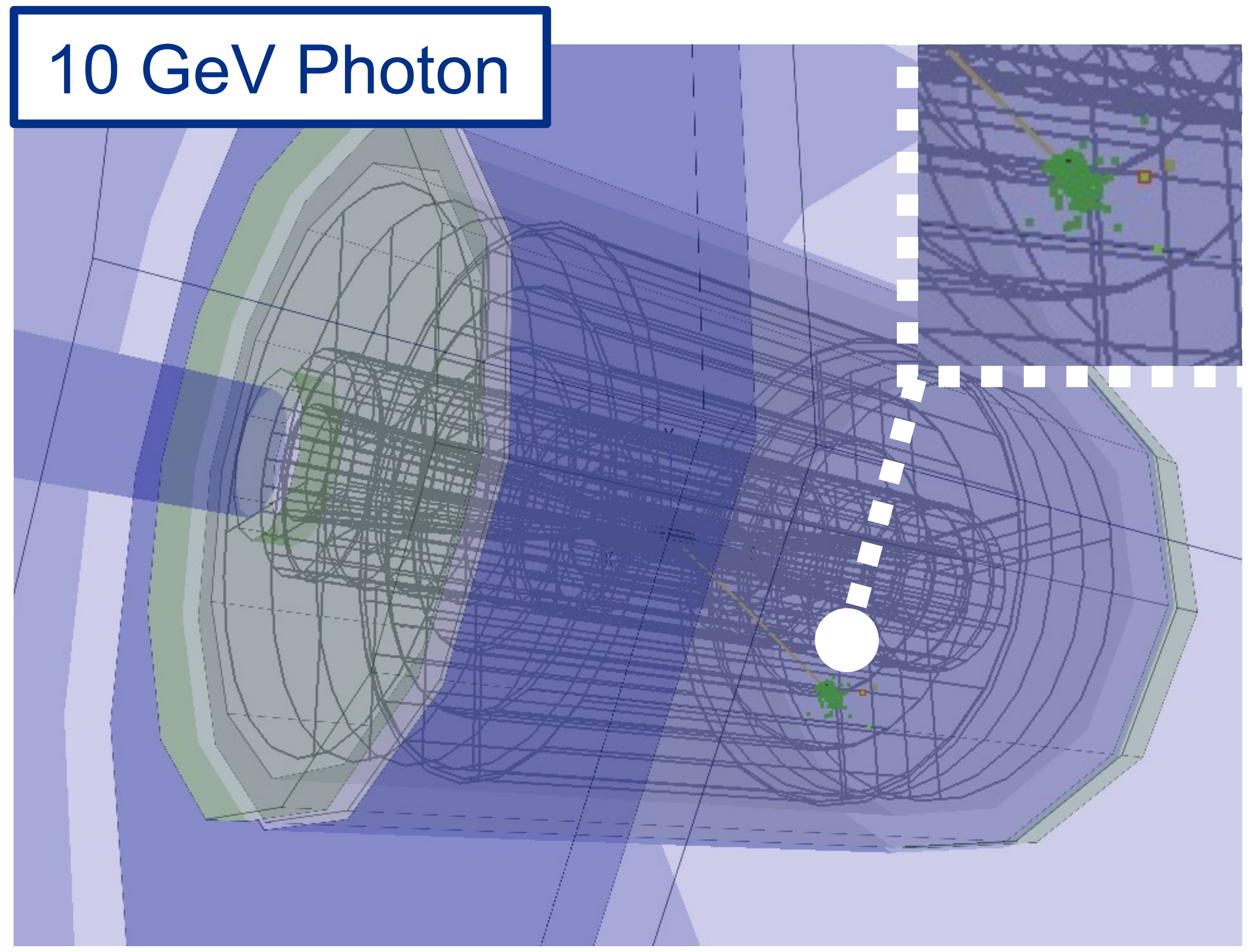
HCAL: Steel+Scintillator 30x30 mm² cells

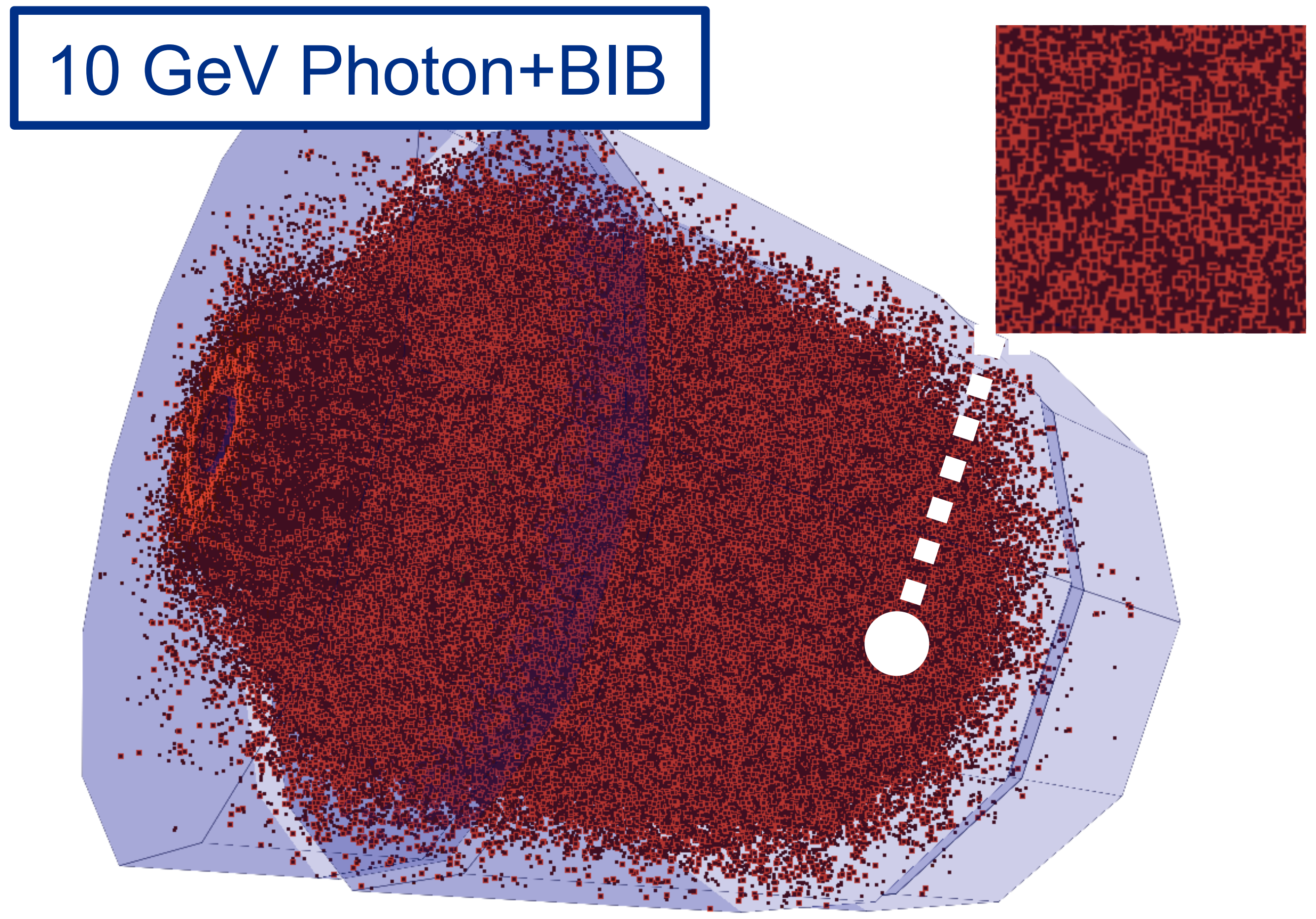
Timing resolution (~100 ps)

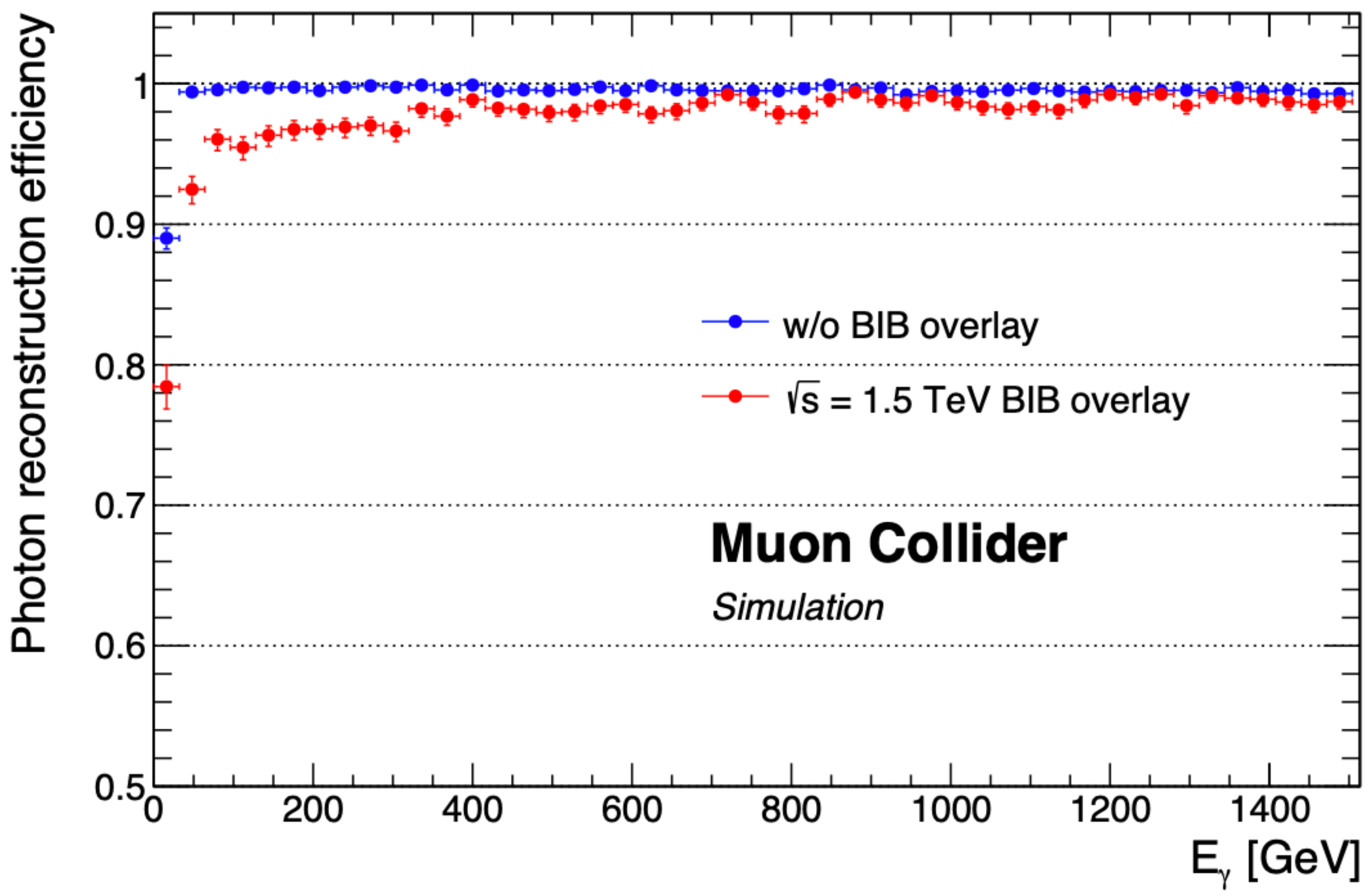
\+ Longitudinal segmentation

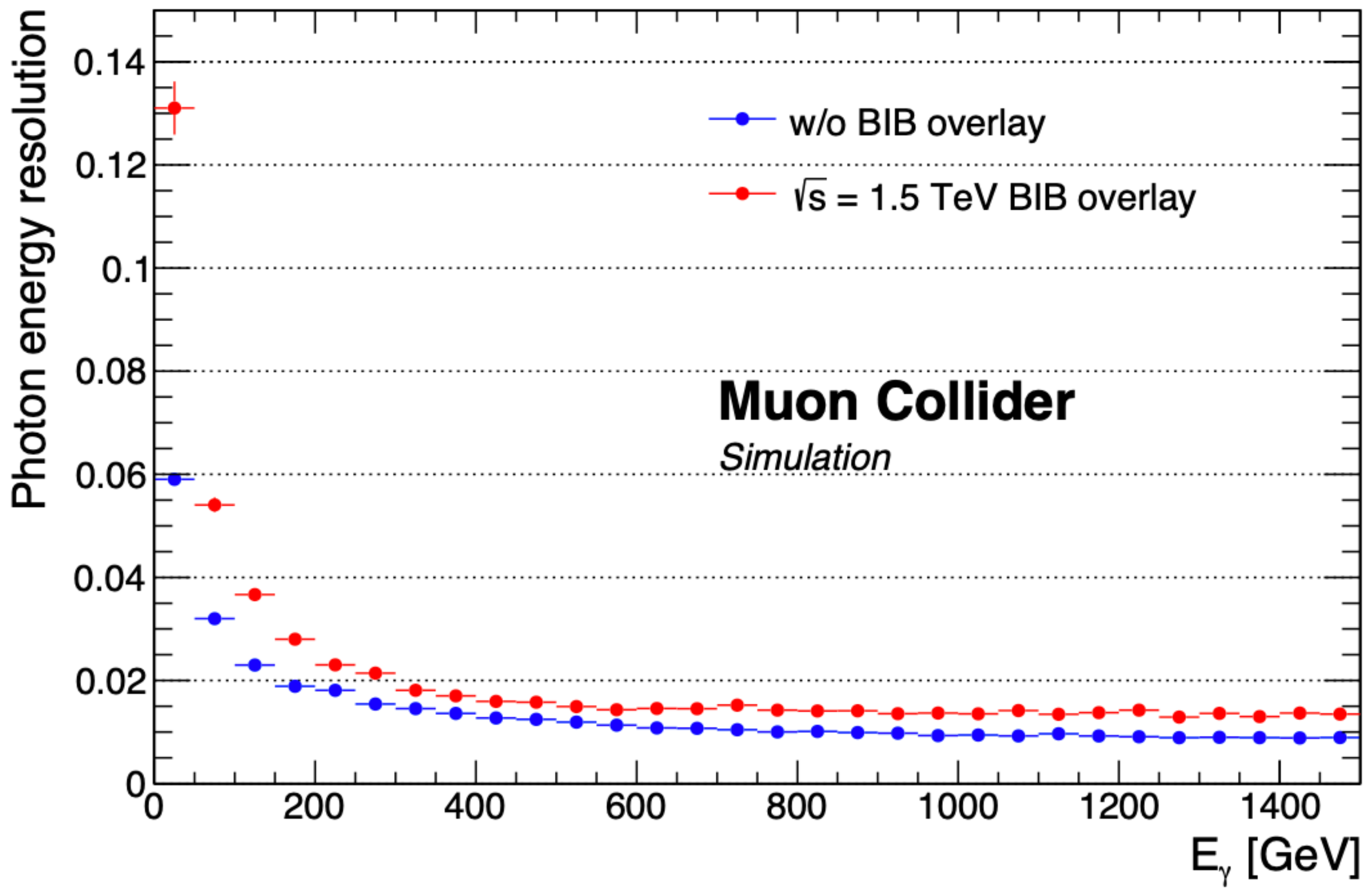
Room for new ideas

(e.g. Crilin, Calvision?)









Trigger/DAQ

2203.07224

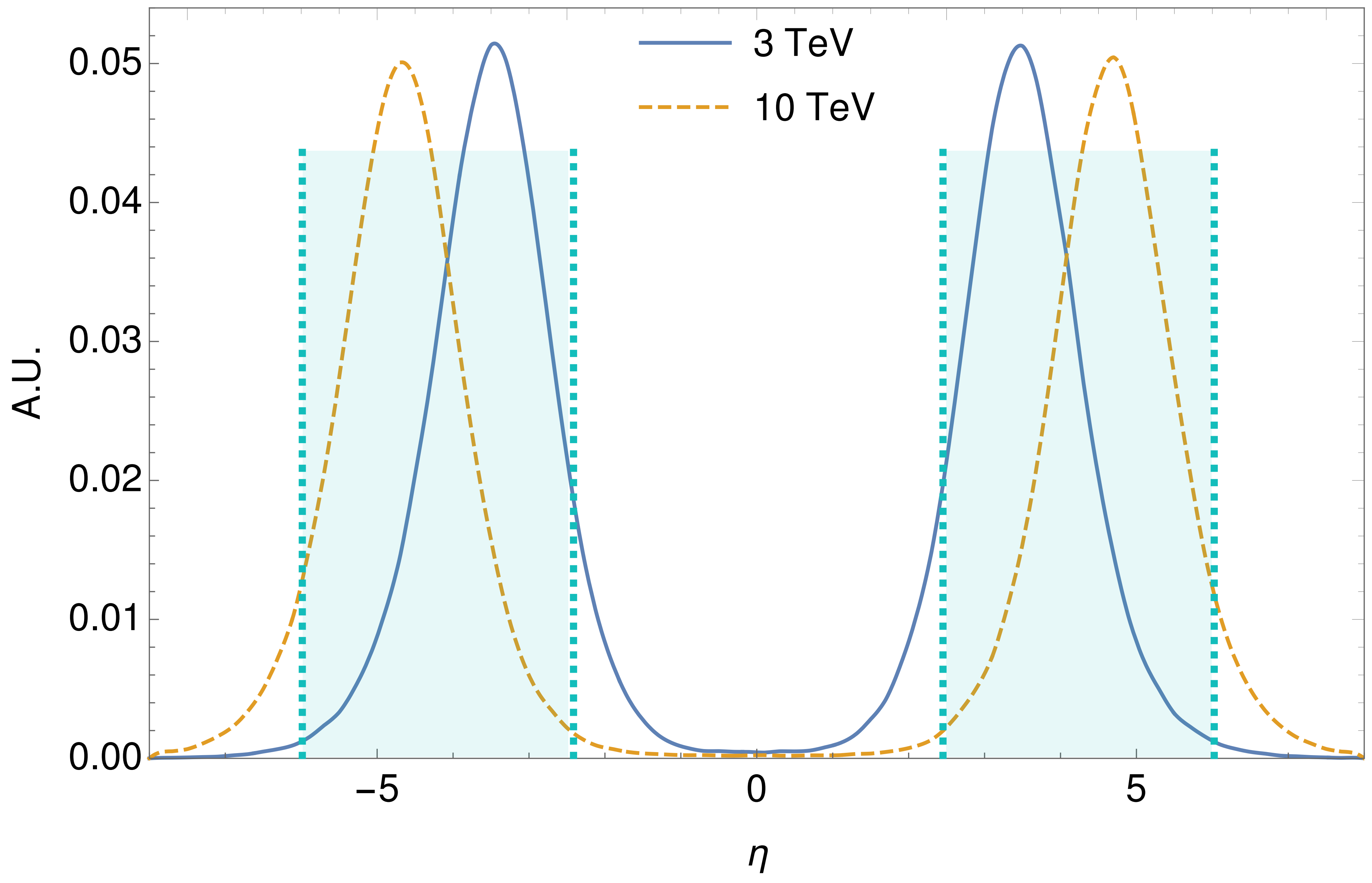
Target “streaming” readout

- 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 <u>on-detector processing</u>
- Event rate ~30 kHz ➝ plenty of time to process full event off detector

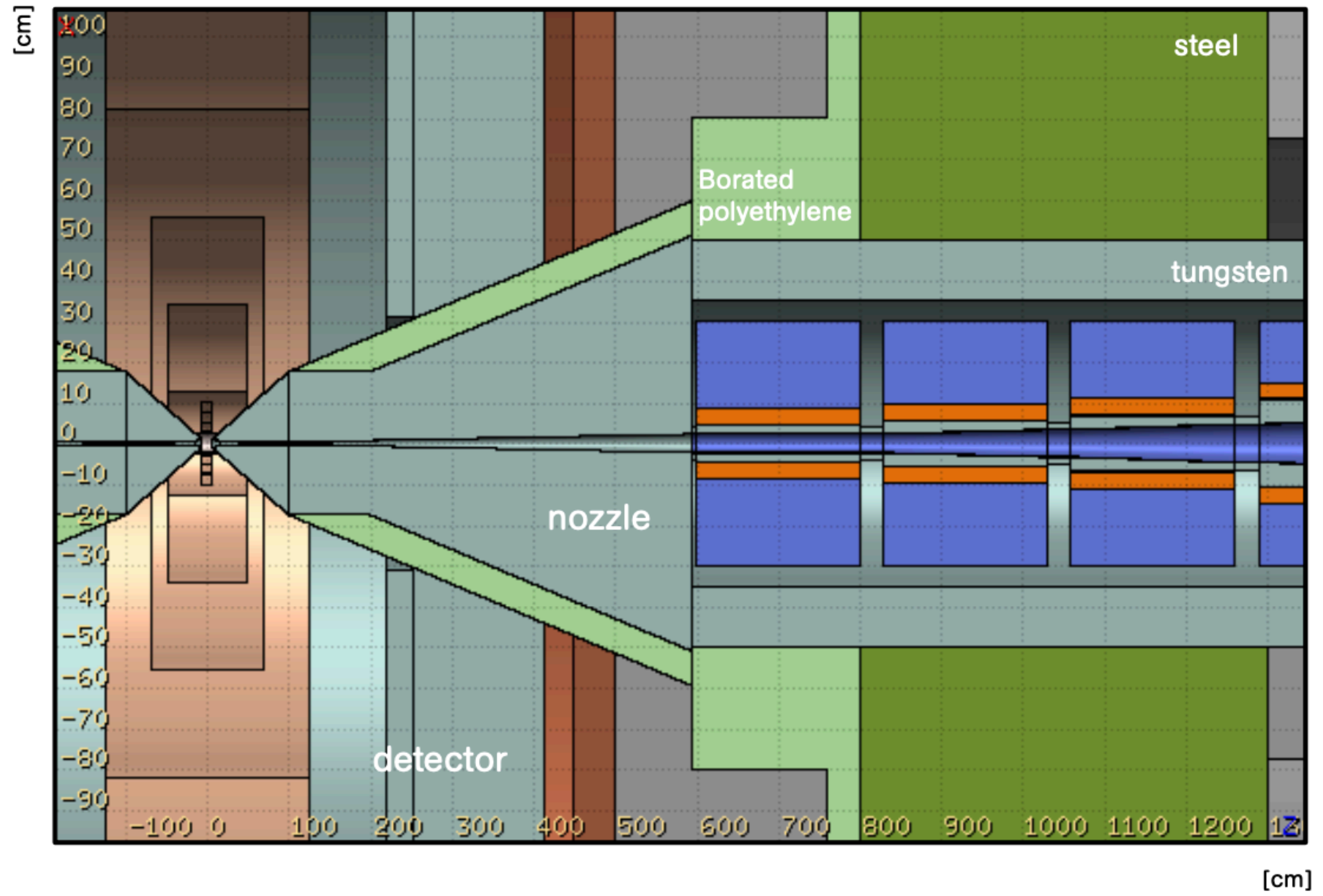
	Readout Window	E Threshold	Hit Size	Total Rate
Tracker	1 ns	n/a	32 bits	~40 Tb/s
ECAL	15 ns	0.2 MeV	20 bits	~30 Tb/s
HCAL	15 ns	0.2 MeV	20 bits	~3 Tb/s
Total				60 Tb/s

Forward Muon Tagging

Ideal η coverage



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



B-field & path-length for momentum measurement?

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

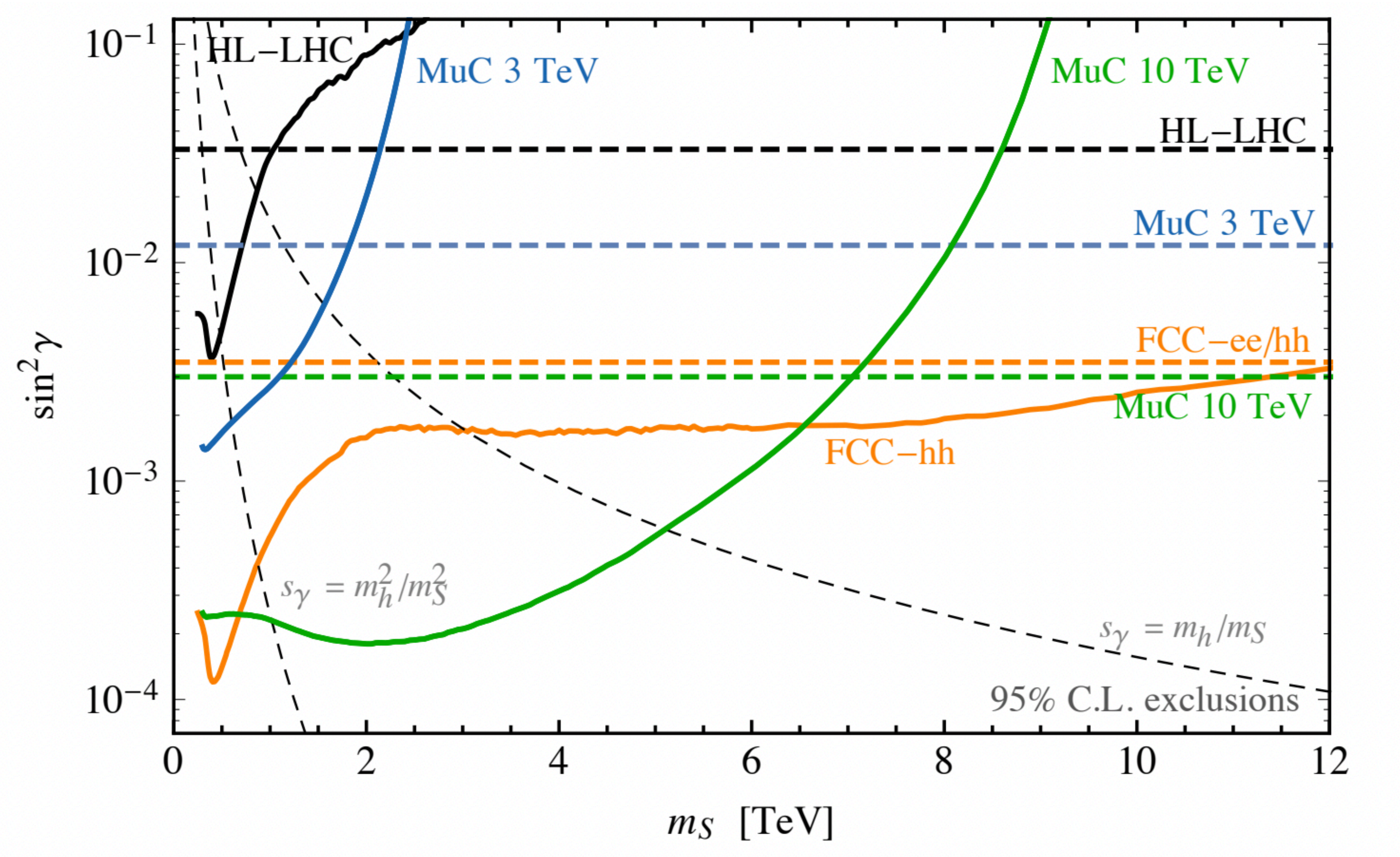
What technology can withstand BIB?

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

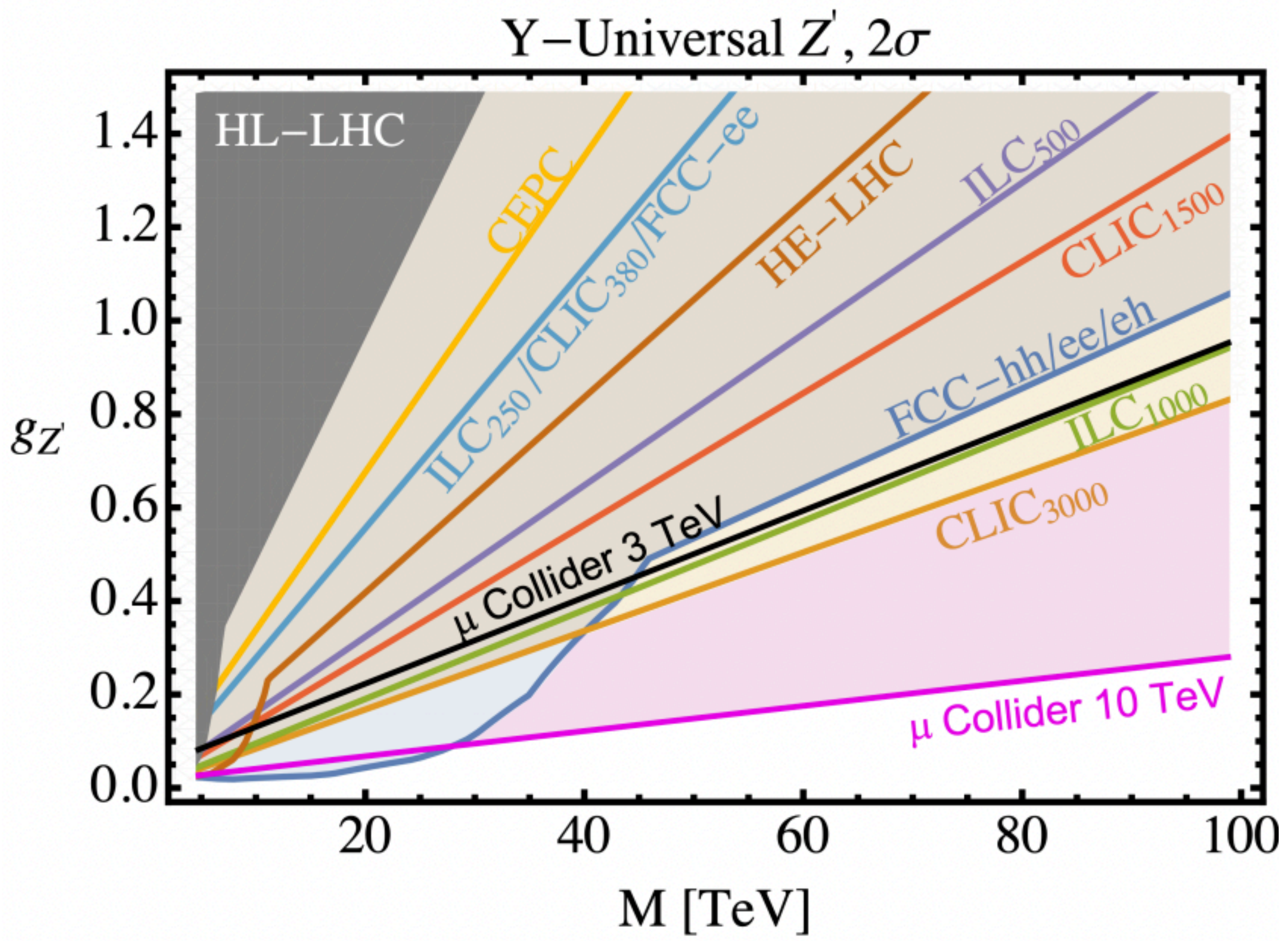
Sensitivity to new physics

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

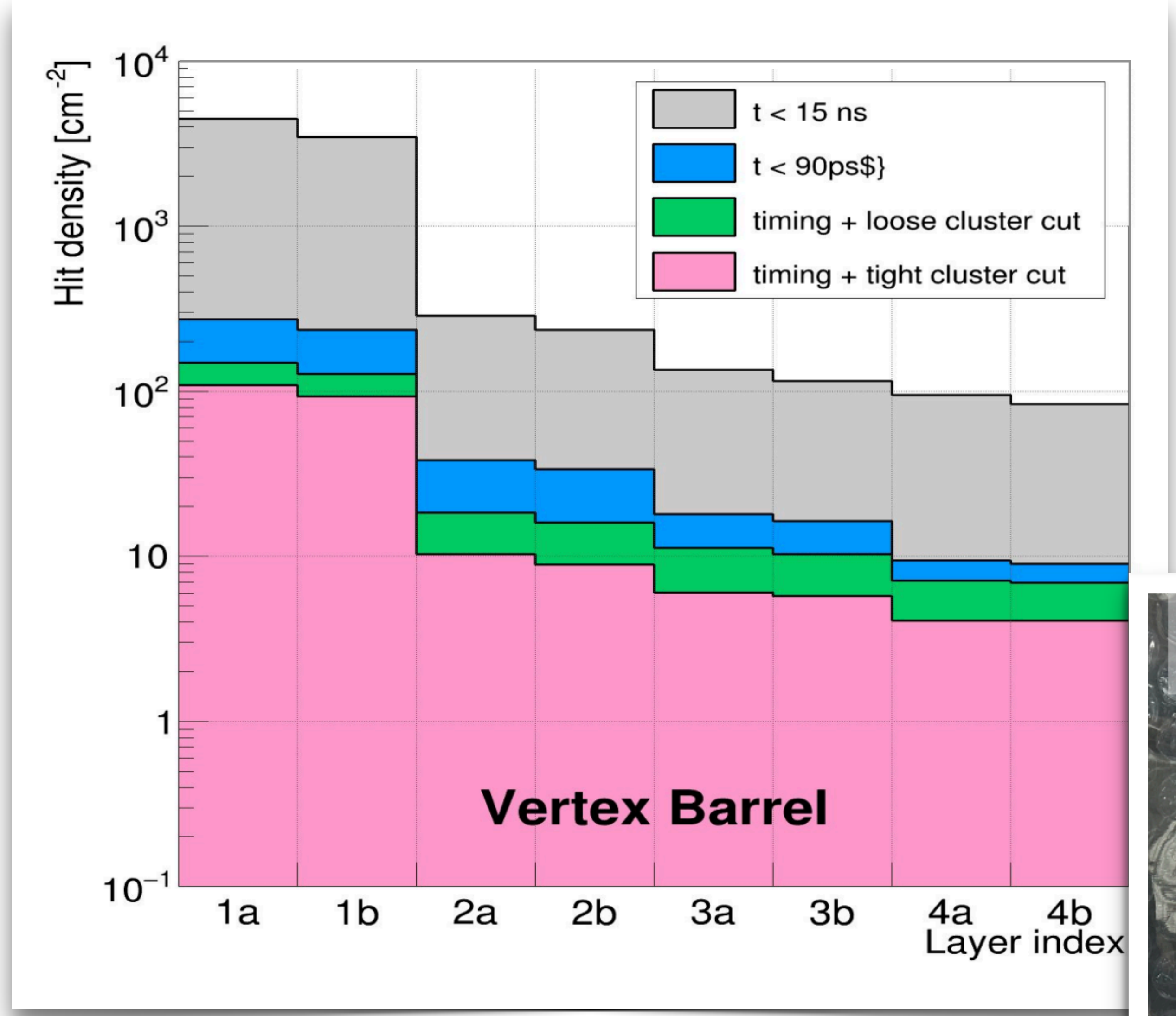


Subsystem Design ↔ Technology needs

Need to define muon collider specific needs (strict & soft) to ensure technology converges

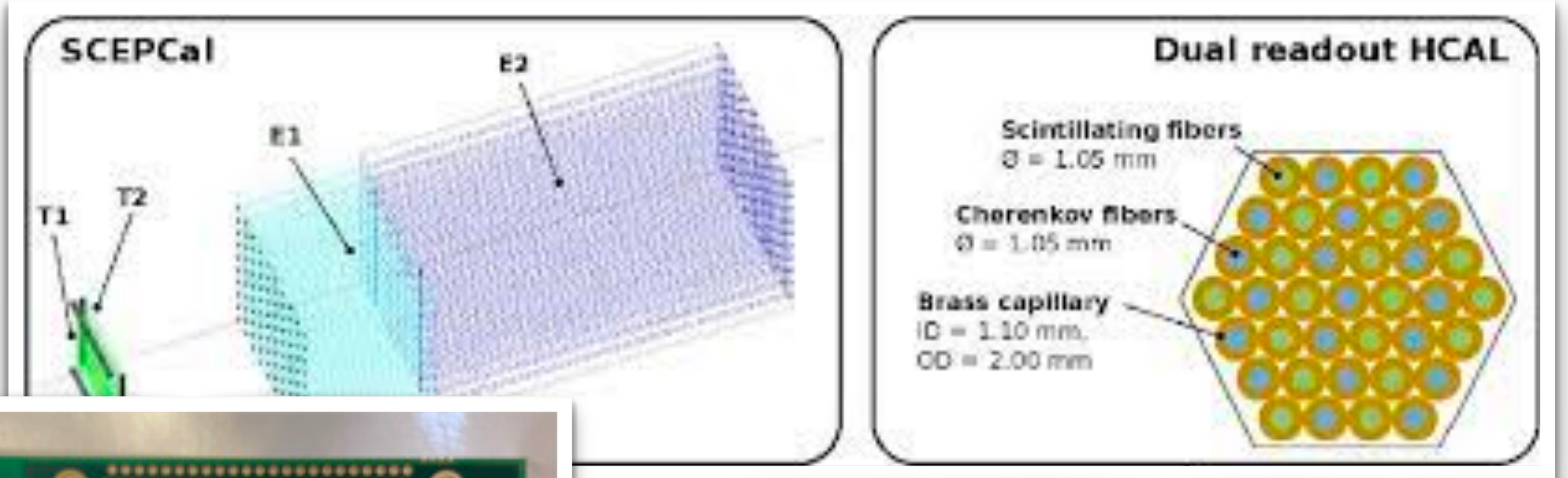
Also a good way to strengthen community with instrumentation experts

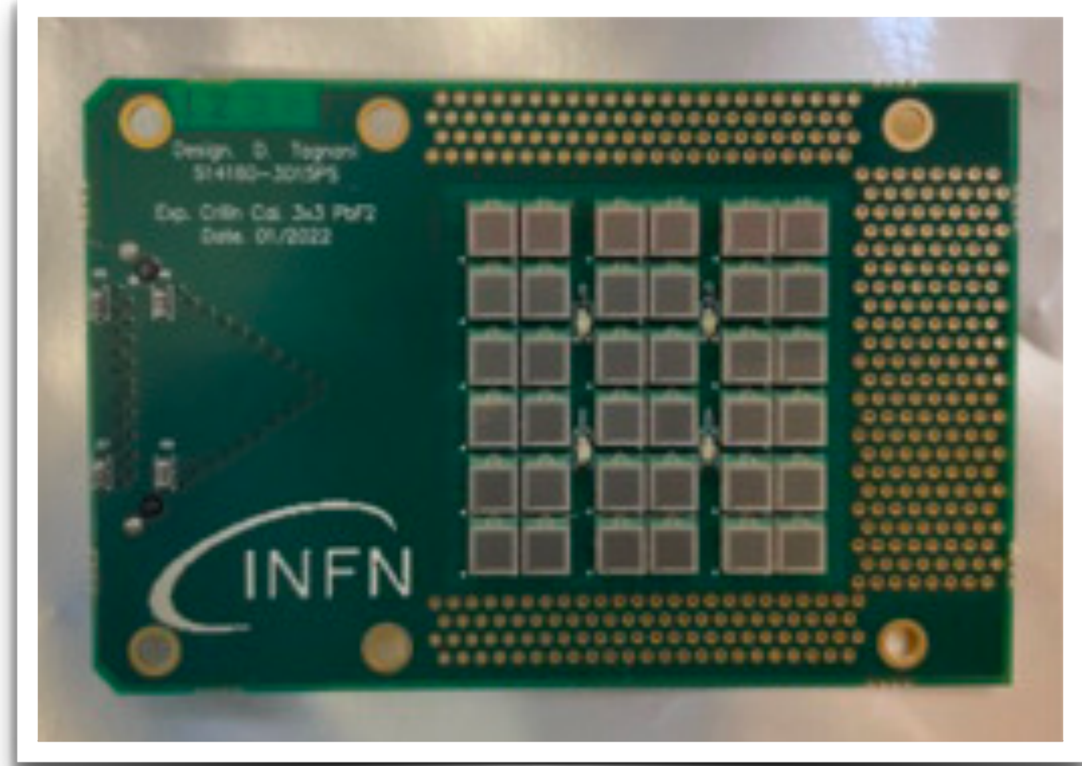
BIB rejection with pixel cluster shapes
C. Sellgren, Simone Pagan Griso



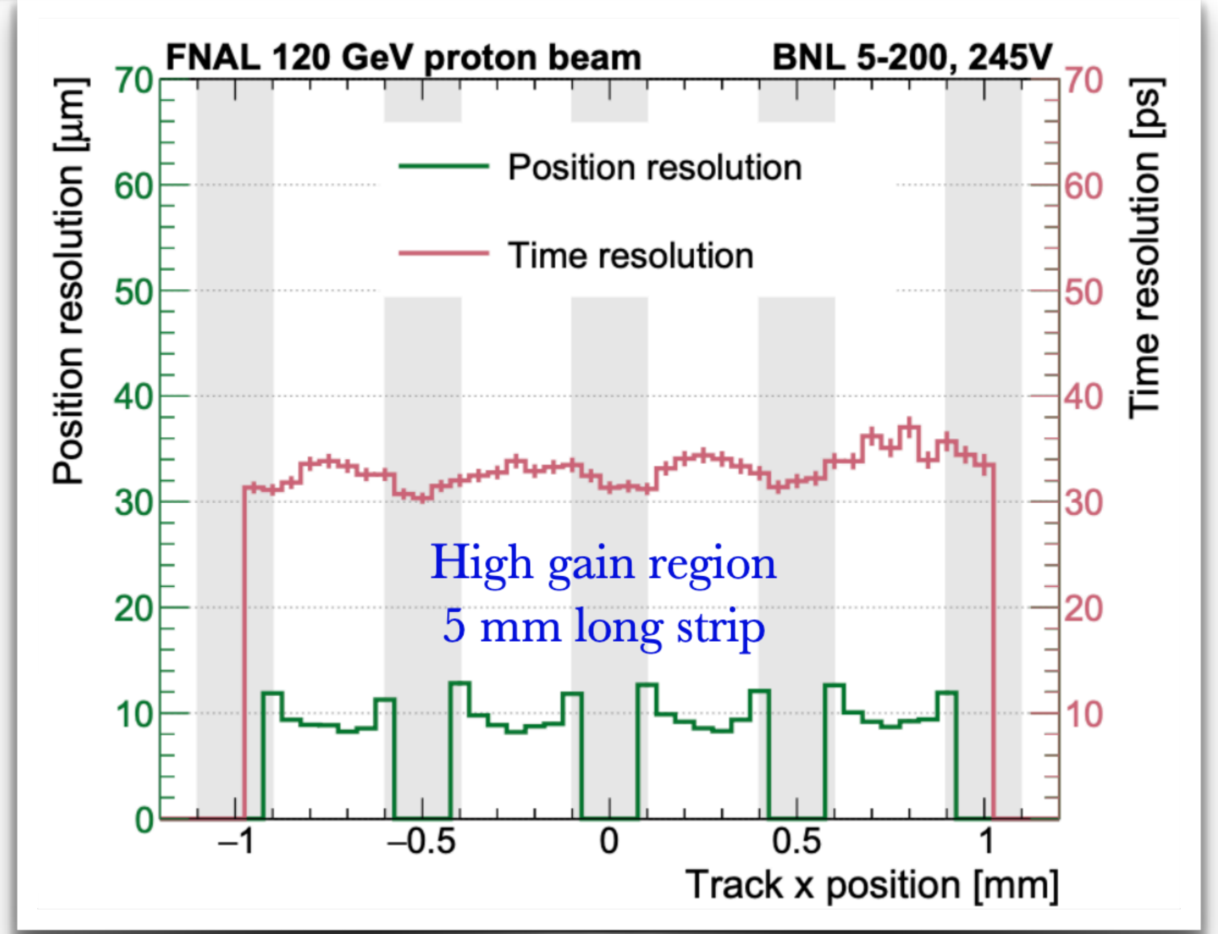
Data reduction with AI-on chip
Anthony Badea

Dual Readout Crystal Calorimetry - Grace Cummings





CRILIN performance - C. Giraldin



AC-LGADs - Irene Dutta