What lies beyond the LHC:
The Future Collider Landscape

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Fermilab Wine & Cheese
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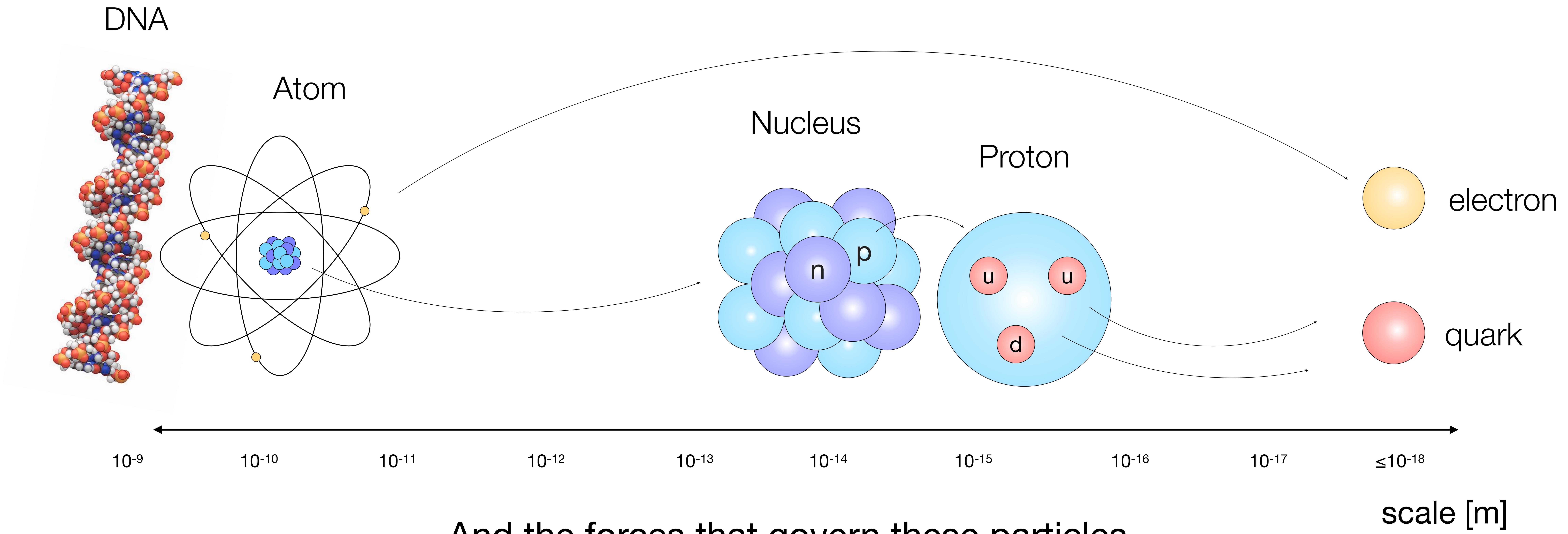
Why High Energy Colliders?

What are we made of?

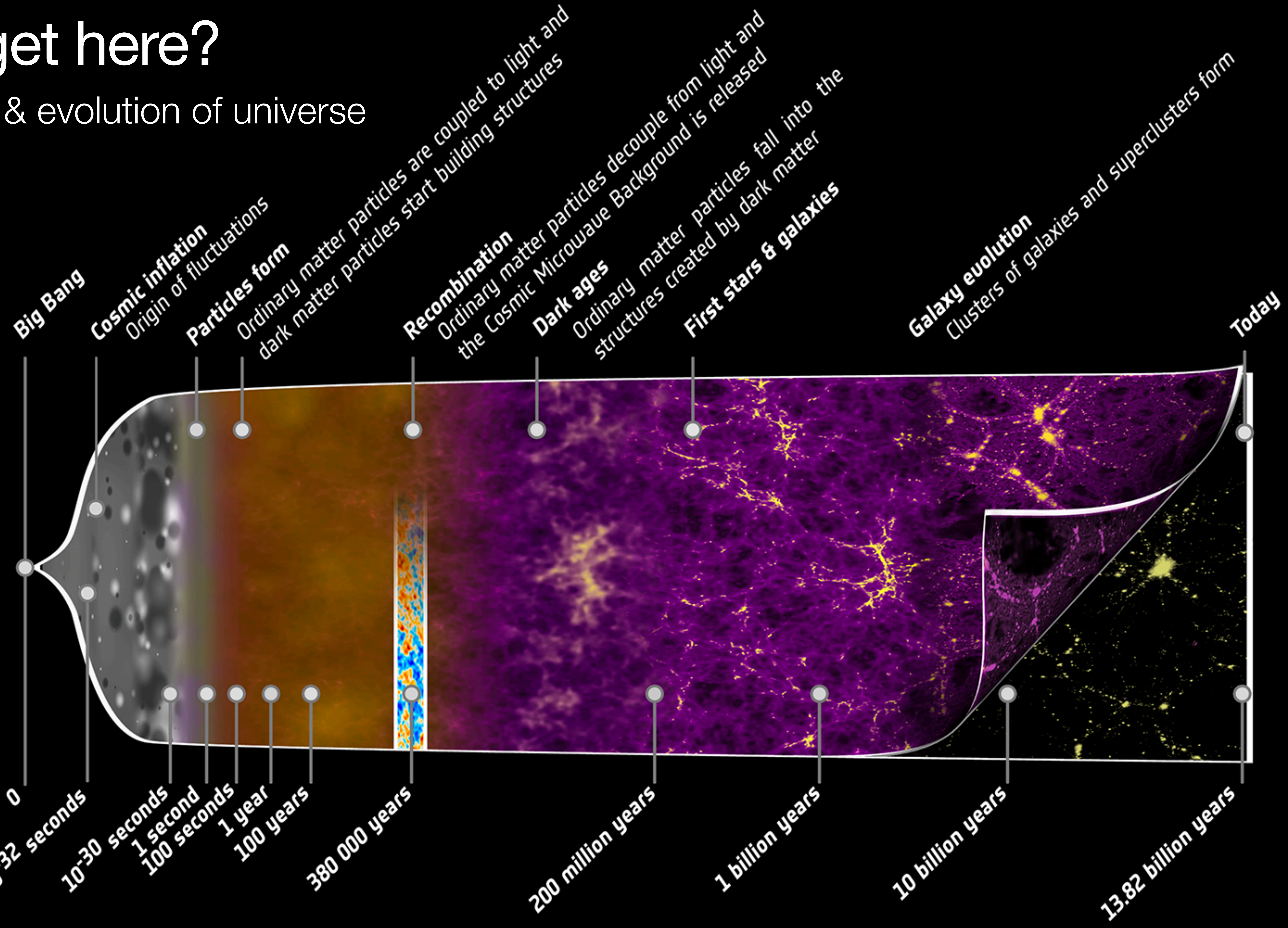
Understand the smallest, irreducible, pieces of matter…
fundamental particles



And the forces that govern these particles

How did we get here?

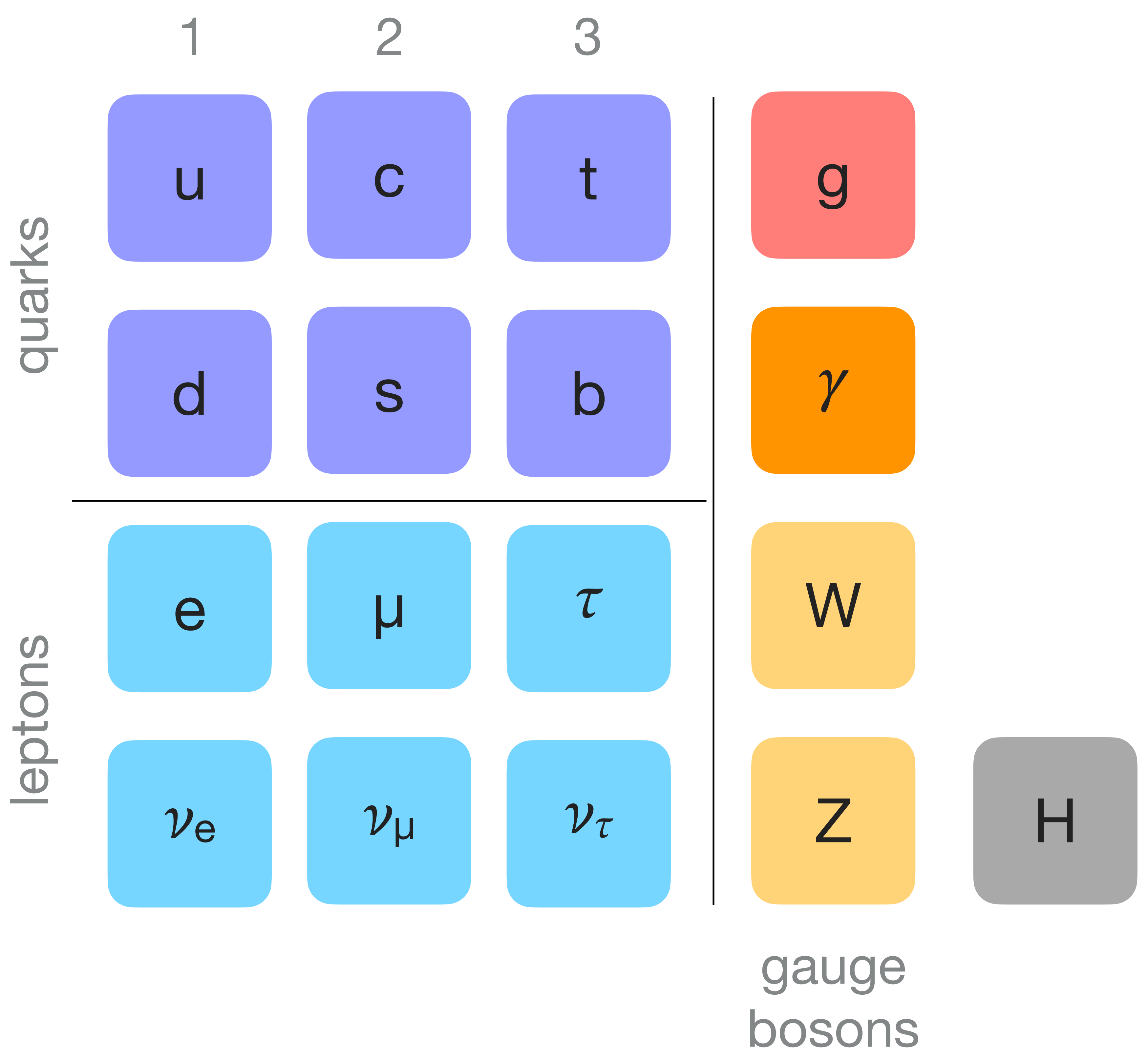
Connections to origin & evolution of universe



Where we stand

The Standard Model

Best known description of fundamental particle content of universe



Several pieces we don’t understand

- Nature of the Higgs Boson
- Origin of neutrino mass
- Deeper underlying pattern?

We also know it’s incomplete

- Dark Matter
- Matter anti-matter asymmetry
- Gravity

The power of colliders

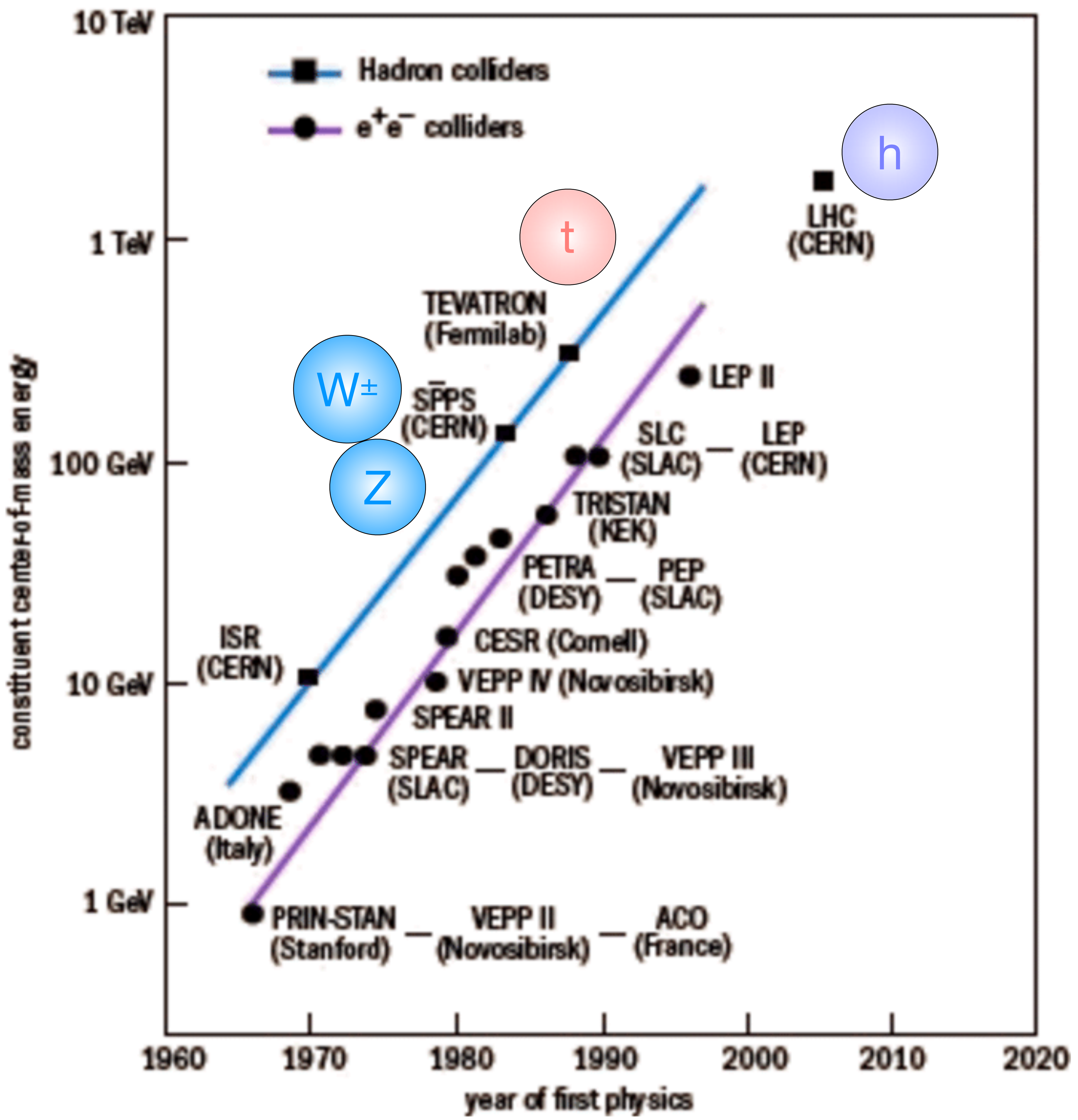
Controlled experiments directly probing

smaller scales: E=hc/λ

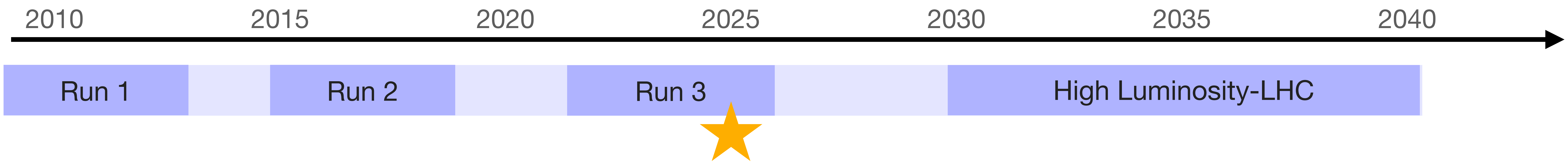
early universe: $E \sim t^{-1/2}$

Highly successful!

Enabled us to establish & test the Standard Model

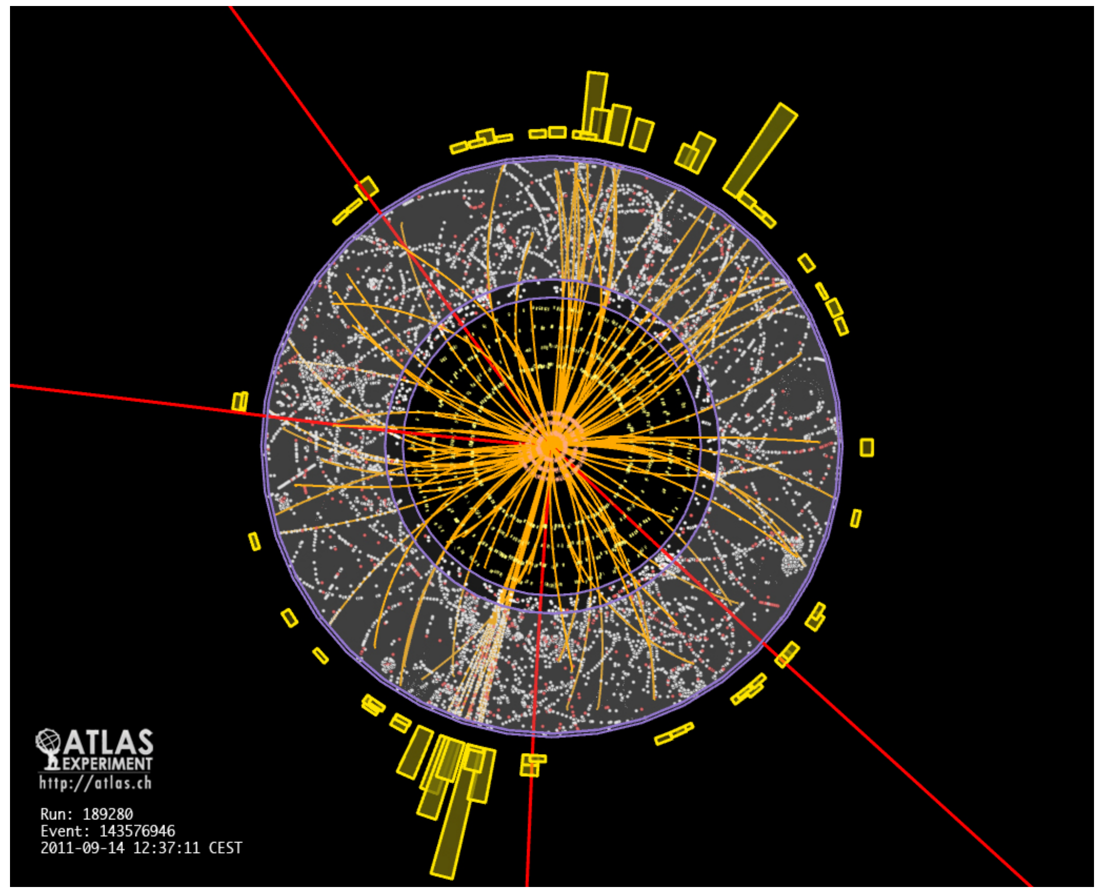


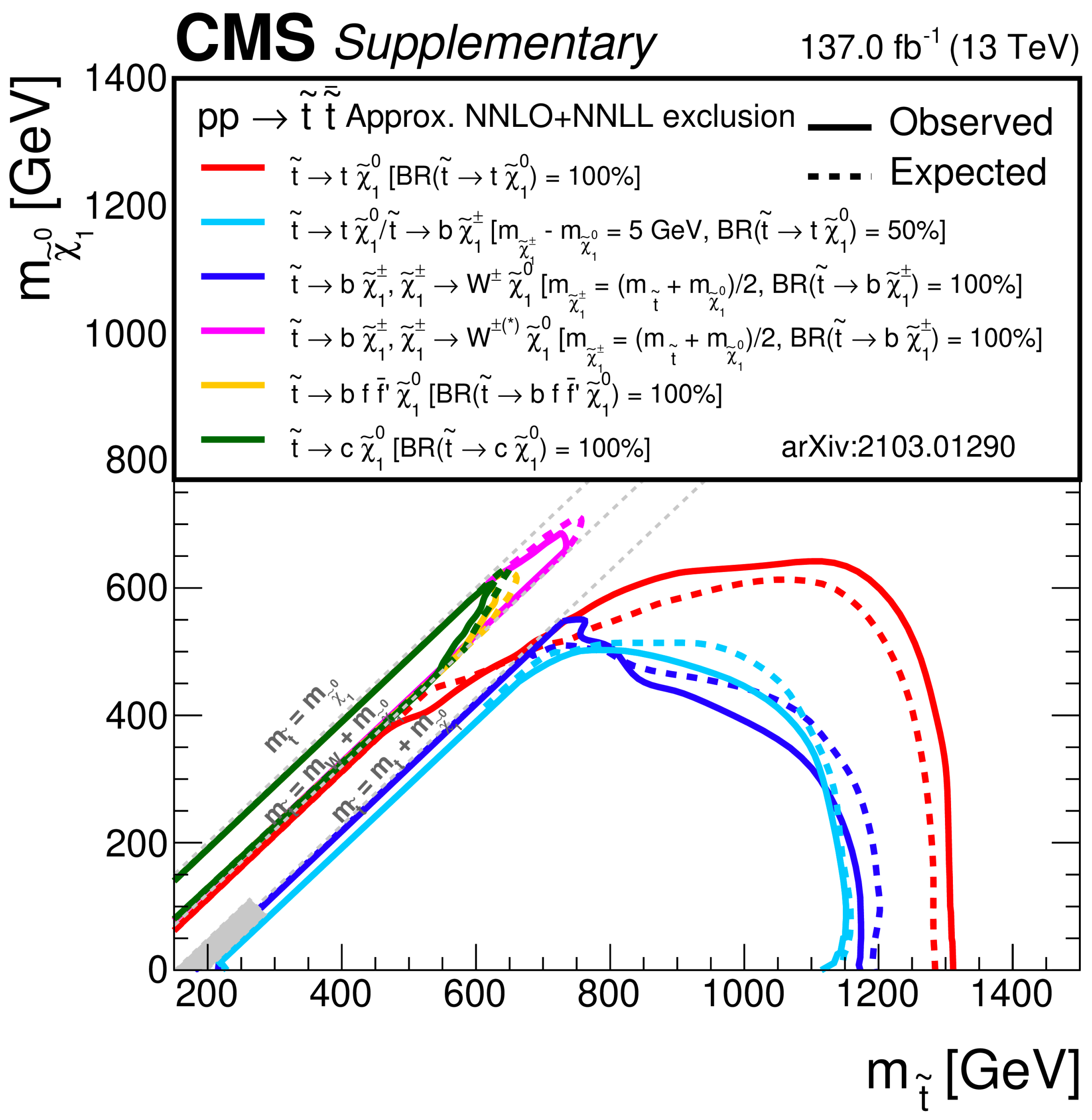
High Energy Physics Landscape



No sign of BSM Particles
at LHC or elsewhere

Discovered the Higgs

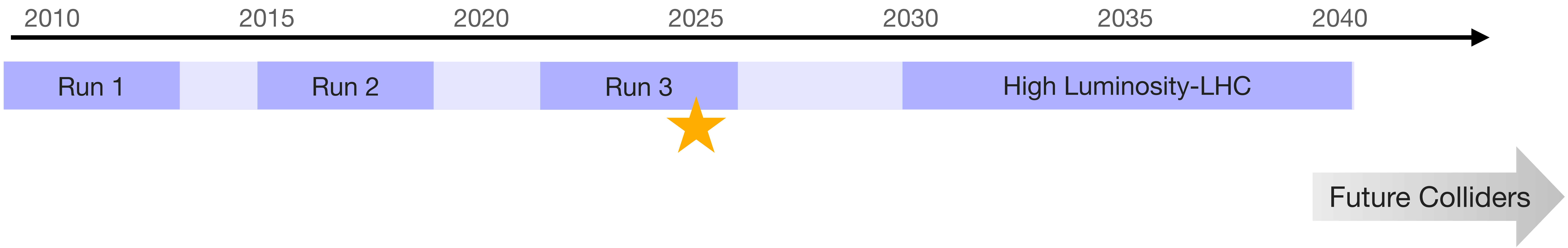




Increase dataset by 10x

Upgrade detectors & trigger

High Energy Physics Landscape



What we know

- Nature is more complex than we expected
- We must leverage HL-LHC data and upgrades to fully explore the TeV scale
- <u>We need to plan for what comes next</u>

This talk

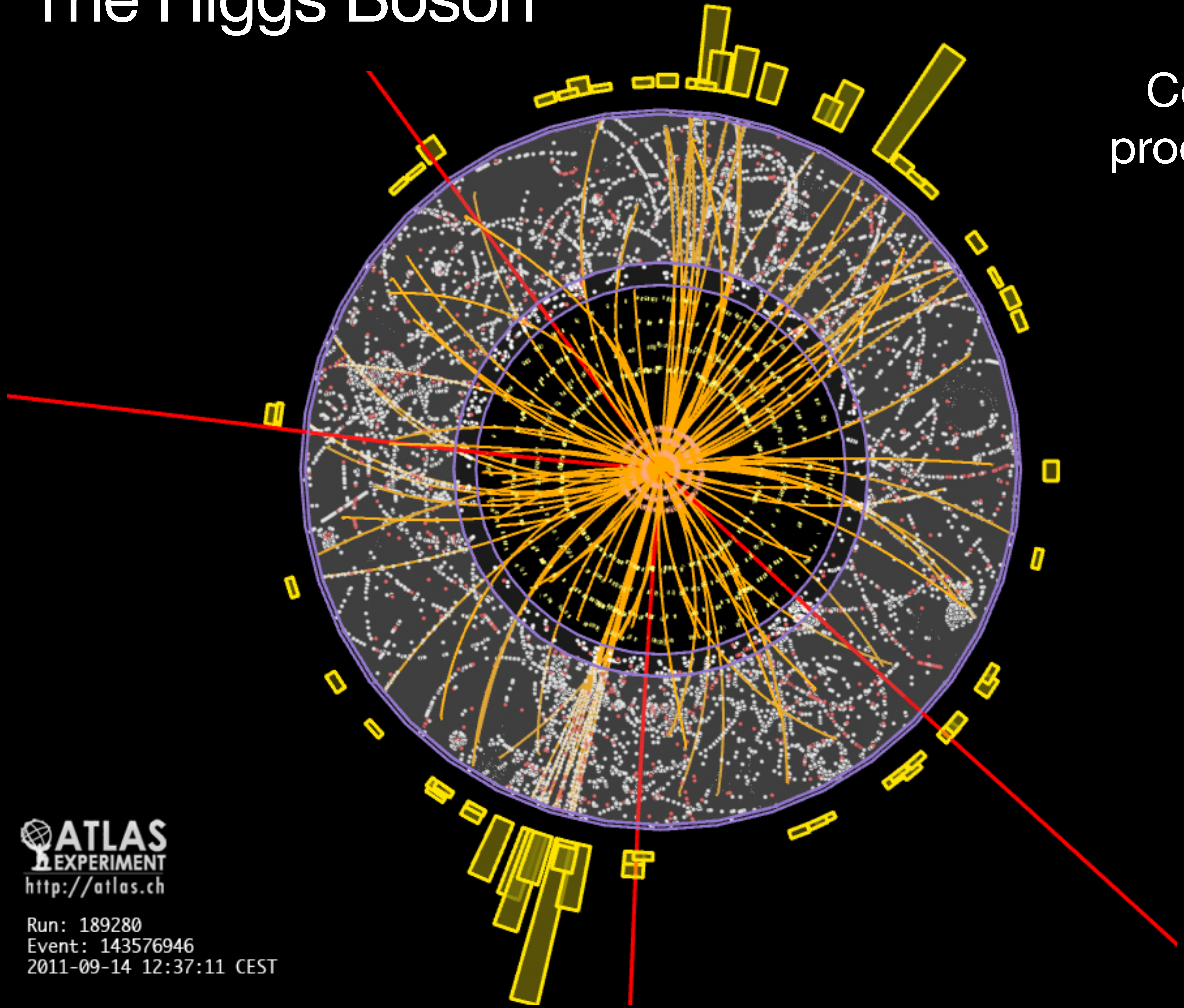
- Questions that require future colliders
- Pedagogical comparison of collider proposals
- Lay out a vision for the energy frontier

Why future colliders?

The Higgs Boson

Dark Matter

The Higgs Boson



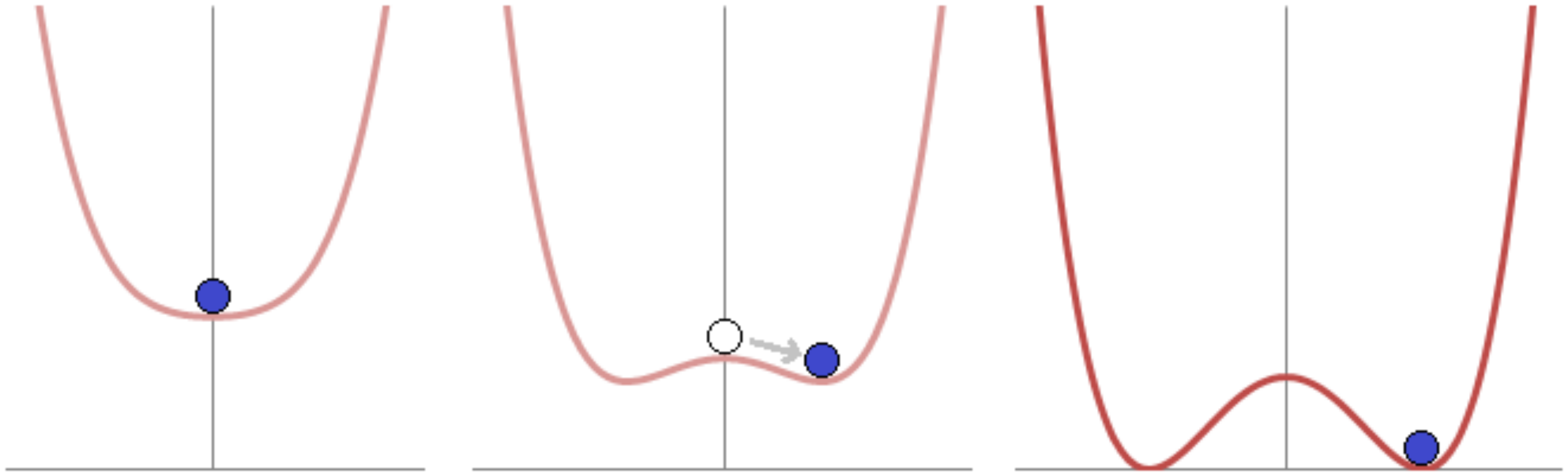
Colliders are the only place we can produce & characterize Higgs Bosons

There is still a lot we don't understand about the Higgs

Questions surrounding the Higgs are central to all of particle physics

Why we care about the Higgs

We exist because of electroweak symmetry breaking



What we're made of

Non-zero minimum is why we have massive fundamental particles

How we got here

Shape of this potential to origin and stability of the universe

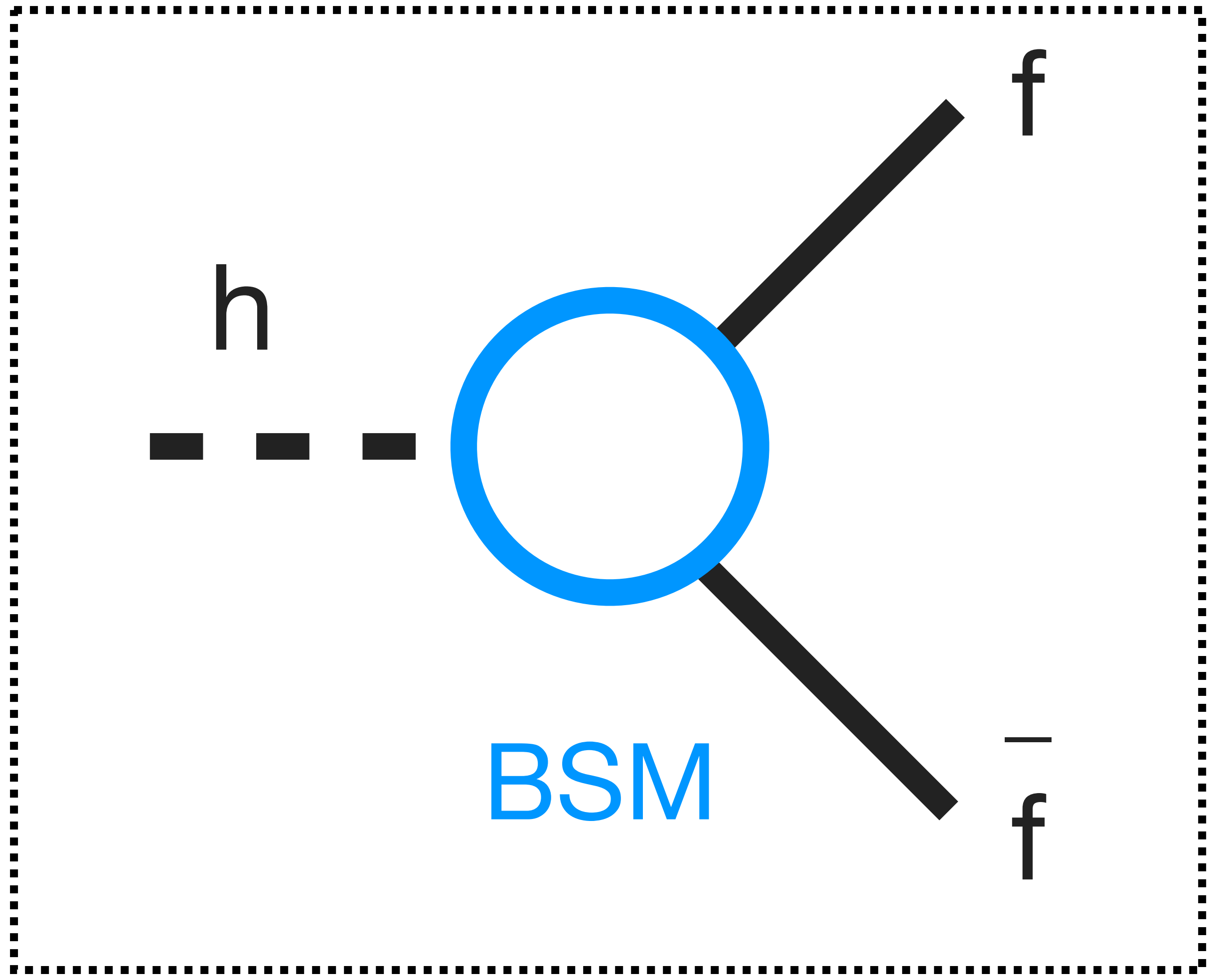
Origin of EWSB?

Baryogenesis?

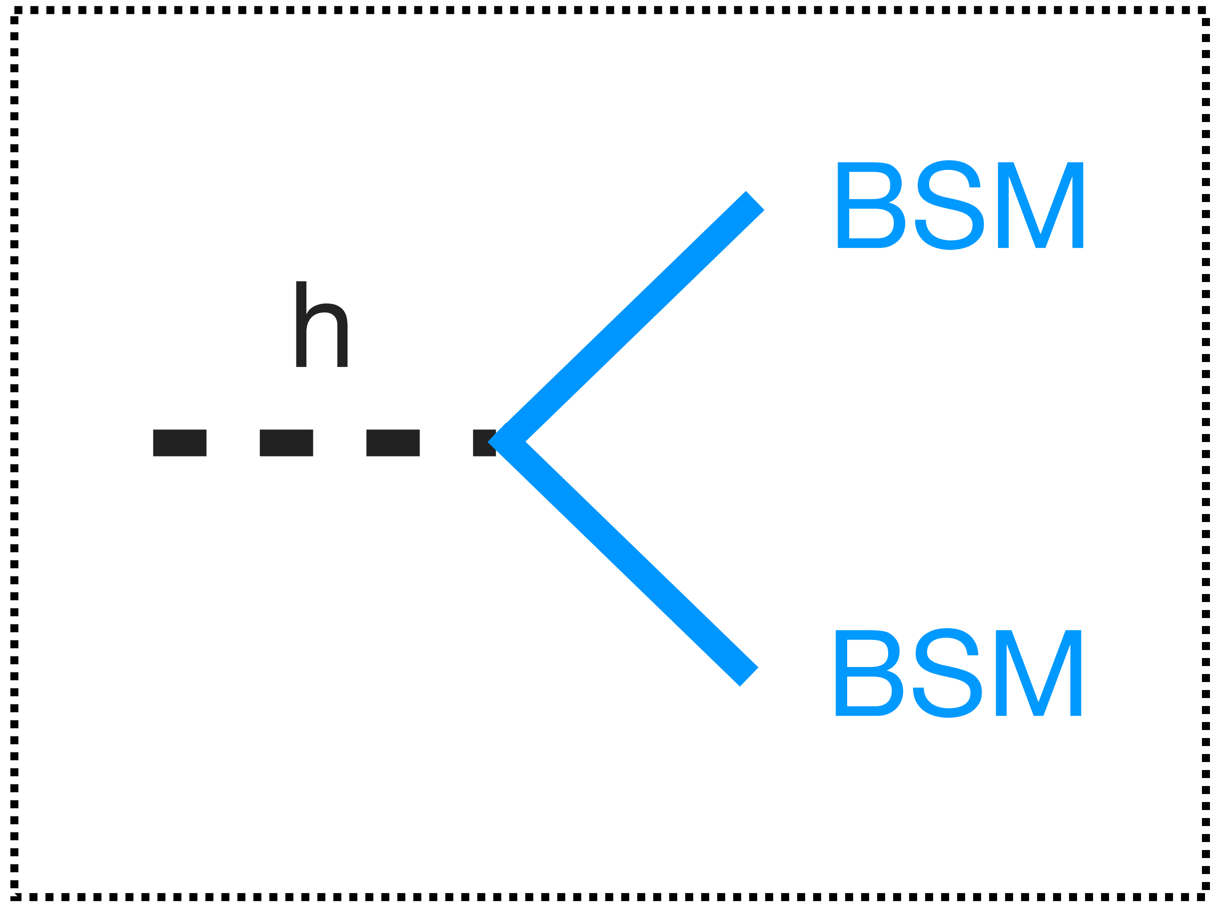
Inflation?

Is it a Standard Model Higgs?

Does it couple to other Standard Model particles as expected?



Are there any implications for origin of flavor, neutrino masses, <u>dark matter</u>?



Is it a Standard Model Higgs?

CMS-HIG-22-001

Matches our expectations so far

At HL-LHC couplings approach precision of few %

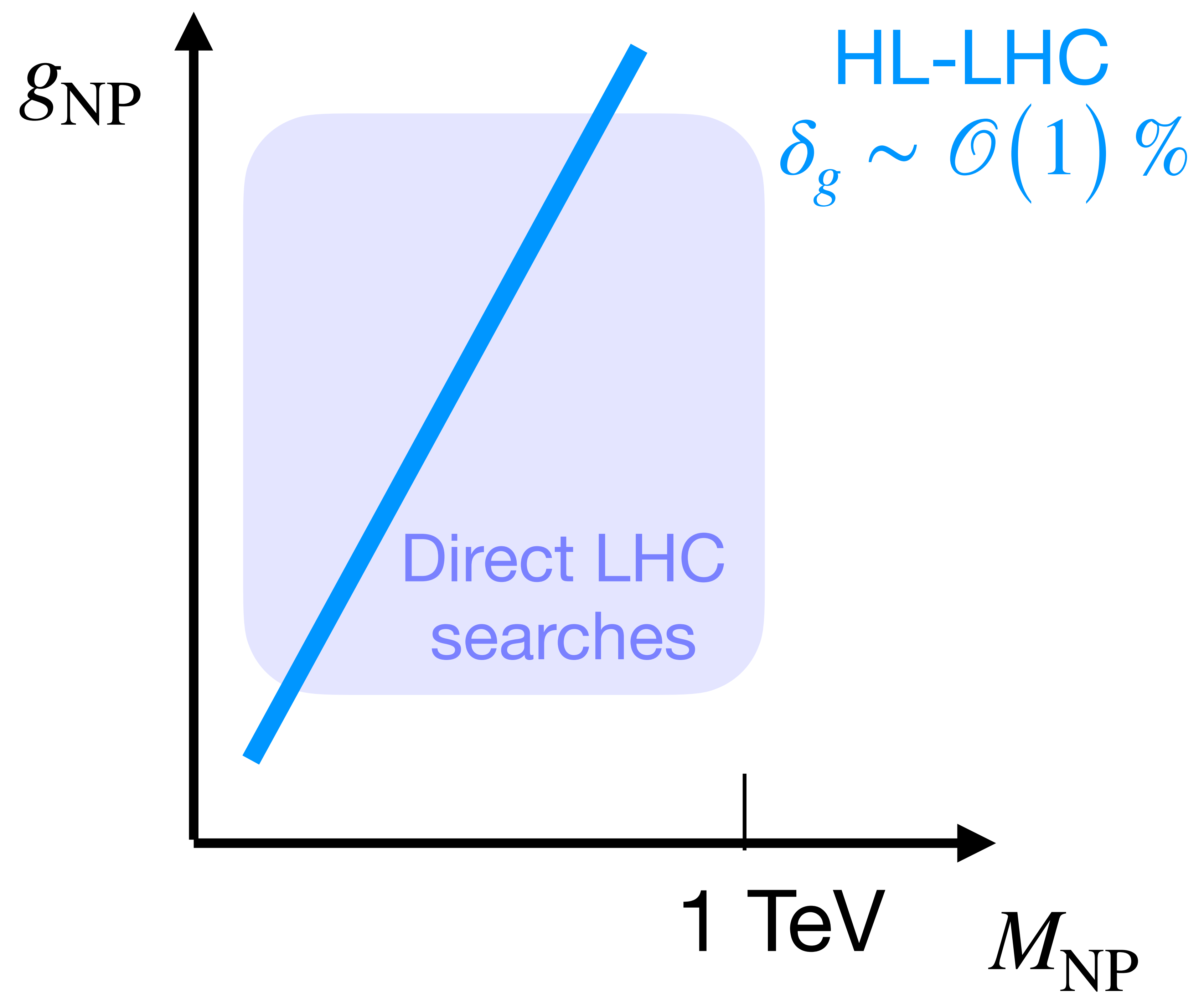
Deviation in coupling from the Standard Model

$$\delta = \frac{g_{\mathrm{SM}} - g_{\mathrm{NP}}}{g_{\mathrm{SM}}}$$

g_{NP} Coupling of new physics to SM

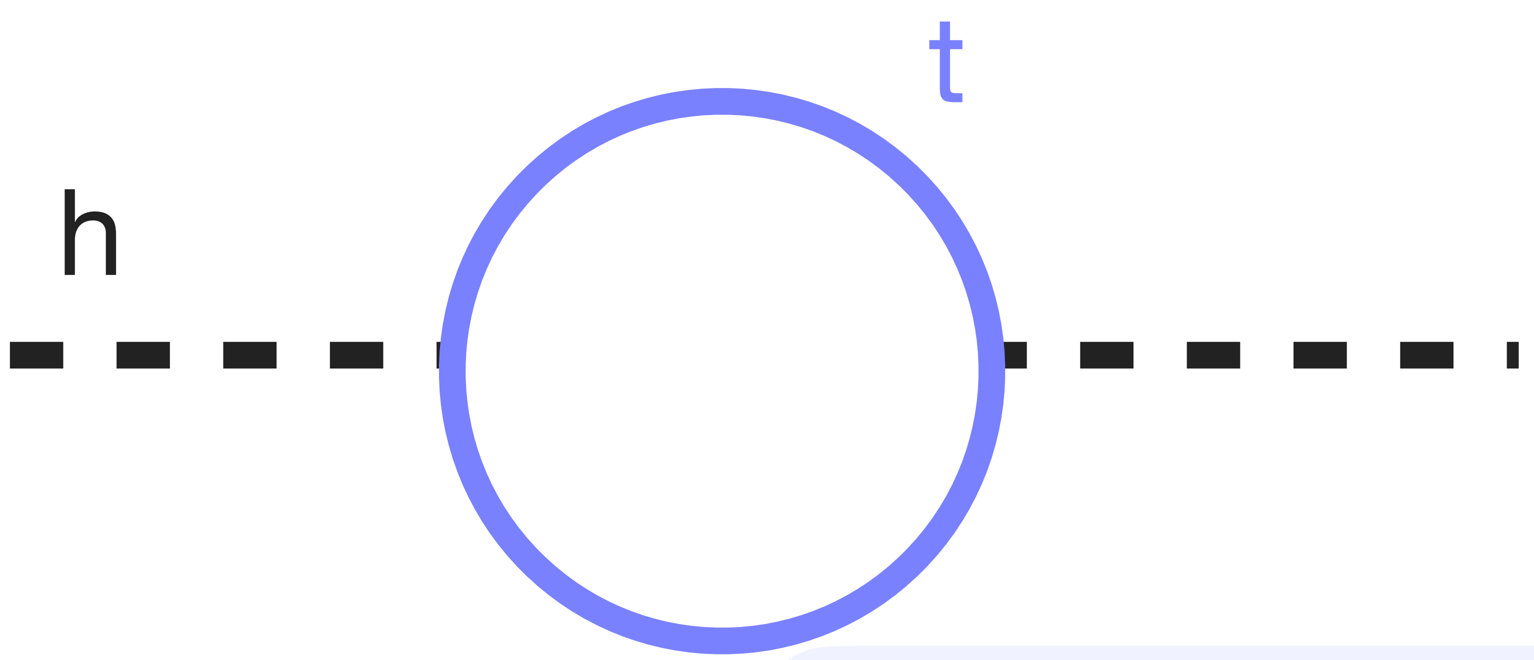
M_{NP} Mass of new physics

$$\delta \sim g_{\mathrm{NP}}^2 \frac{(100\ \mathrm{GeV})^2}{M_{\mathrm{NP}}^2}$$



Microscopic nature of the Higgs?

Seemingly fundamental spin 0 boson



$$\Delta m_h \sim \lambda_t^2 \Lambda_{\mathrm{UV}}^2$$

highly sensitive to quantum fluctuations

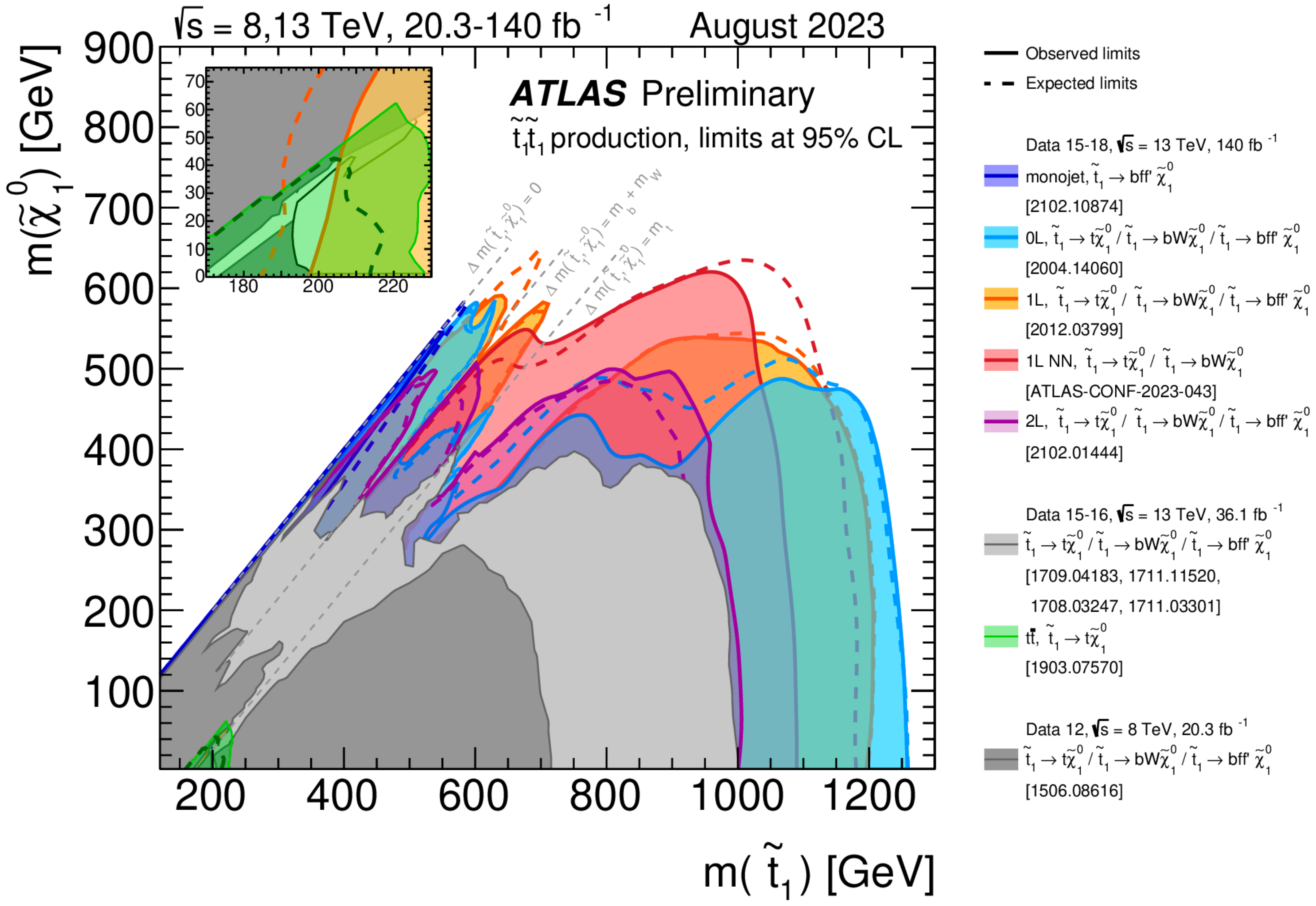
Is there new physics preventing m_h from being pulled up to Plank scale?

e.g. new symmetry & additional particles?

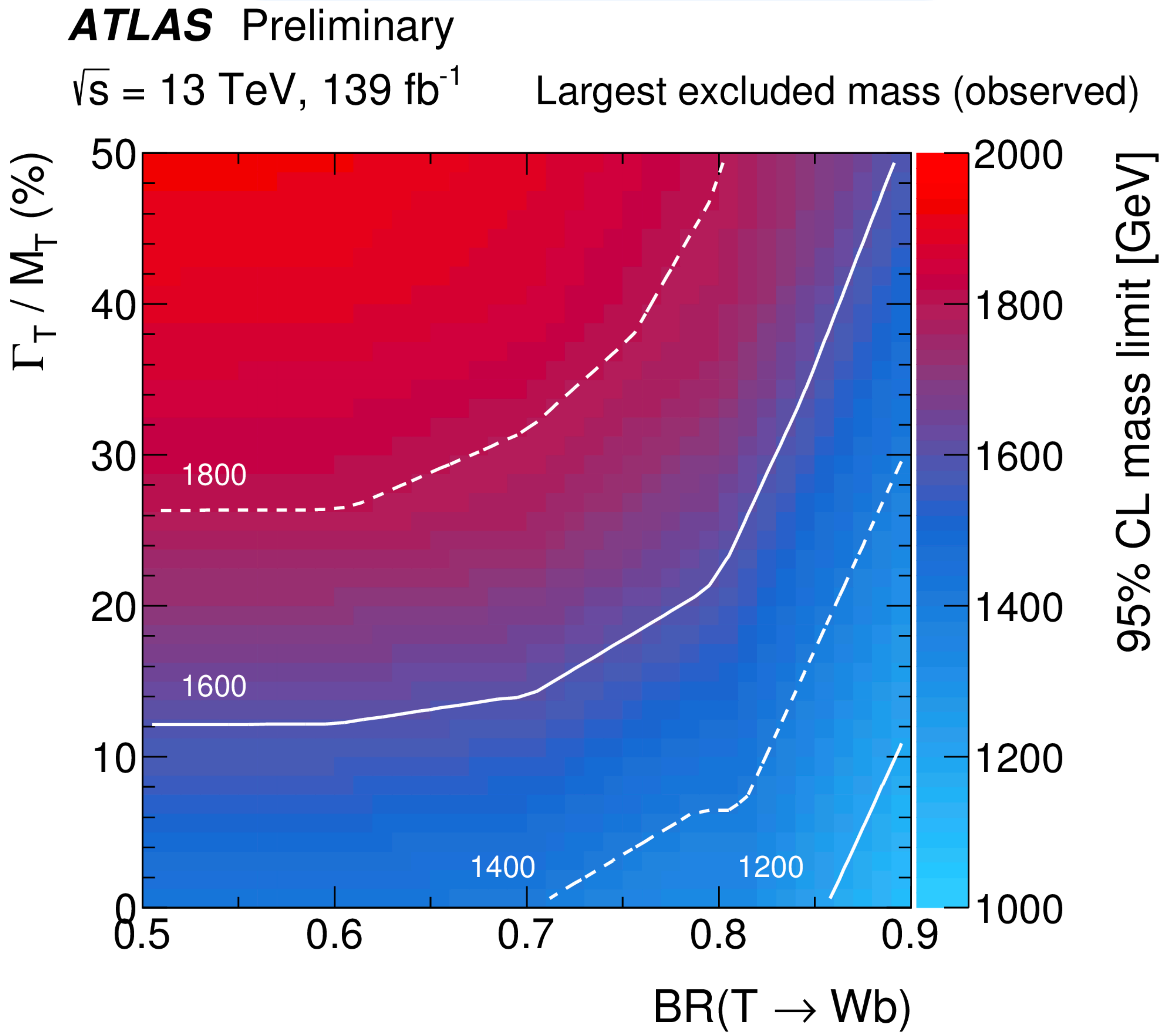
e.g. composite Higgs, like the pion?

Microscopic nature of the Higgs?

e.g. new symmetry & additional particles?



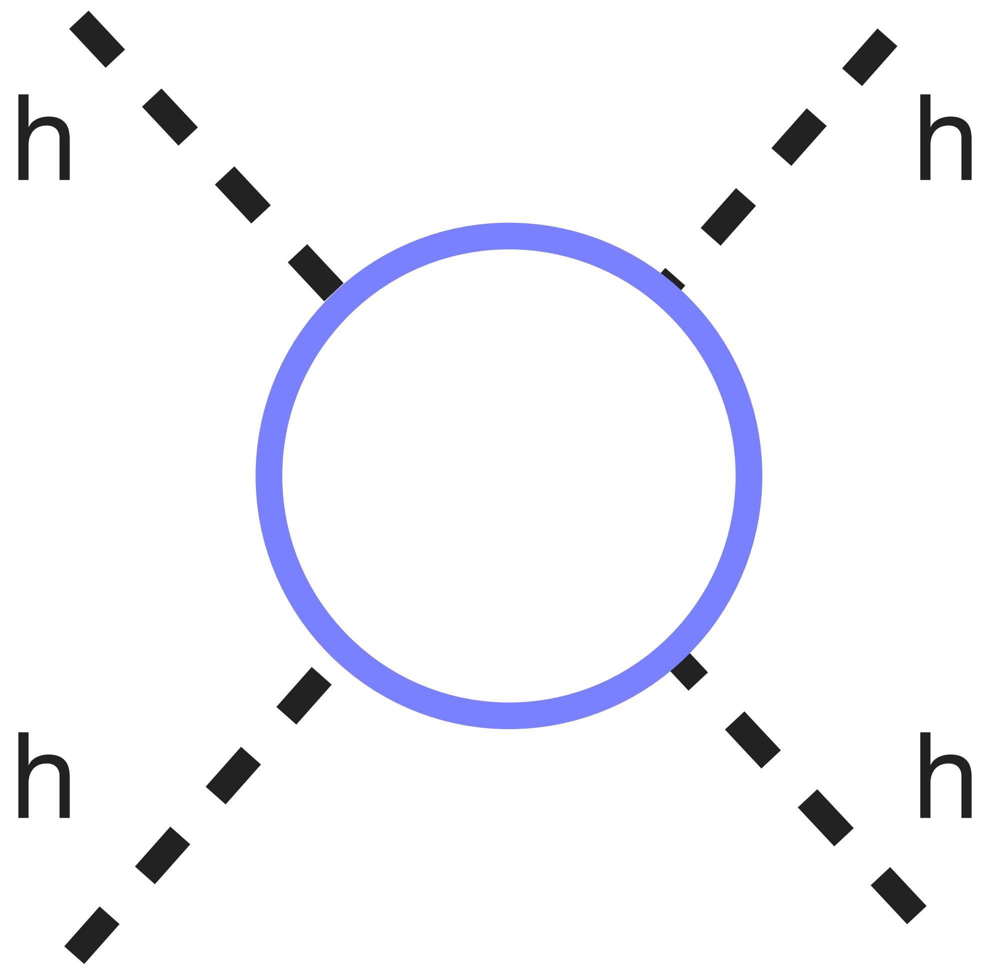
e.g. composite Higgs, like the pion?



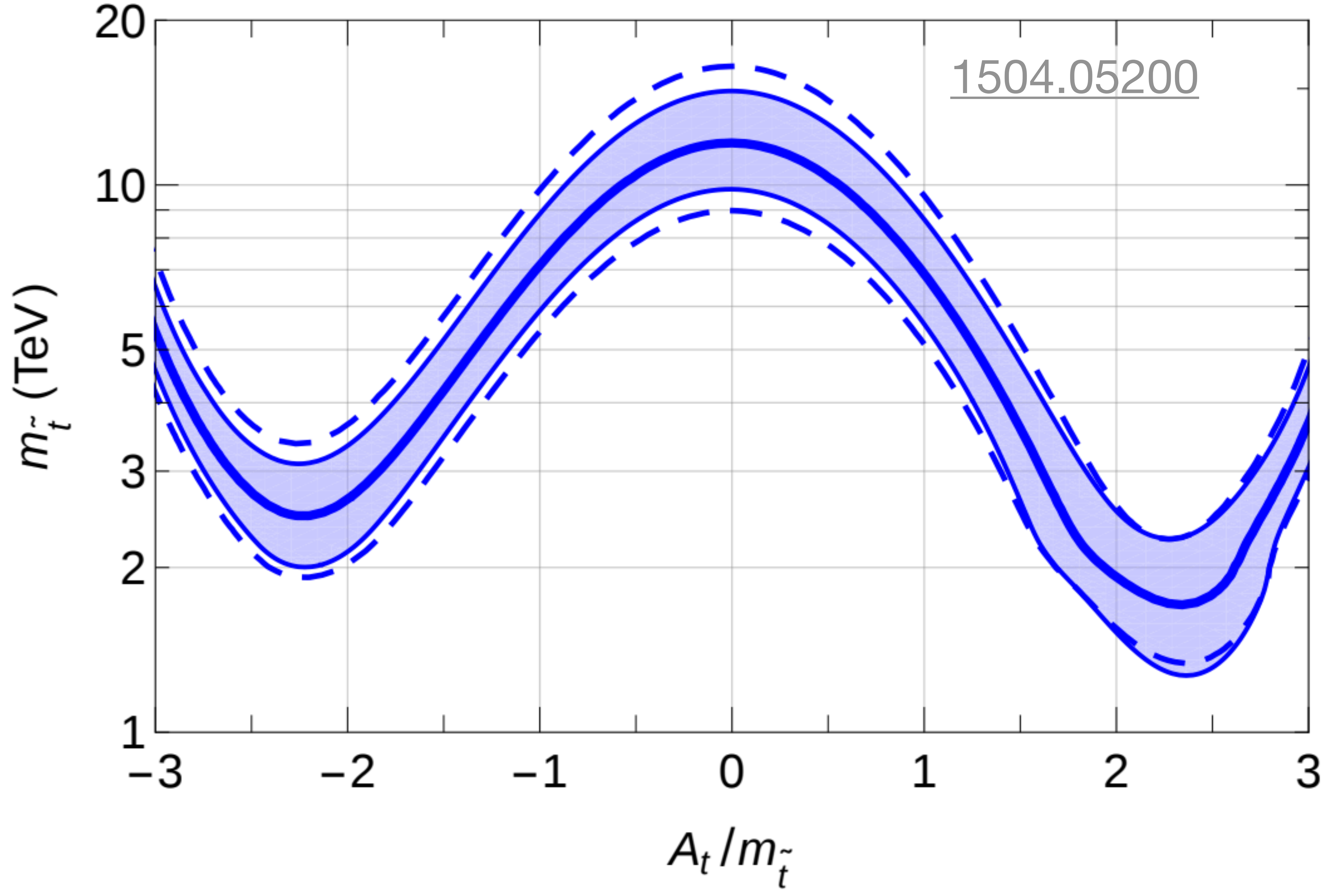
Data so far suggest any new strongly coupled particles > 1 TeV

Microscopic nature of the Higgs?

Observed m_h sets direct targets for supersymmetric particles



m_h =125 GeV → multi-TeV top-partners



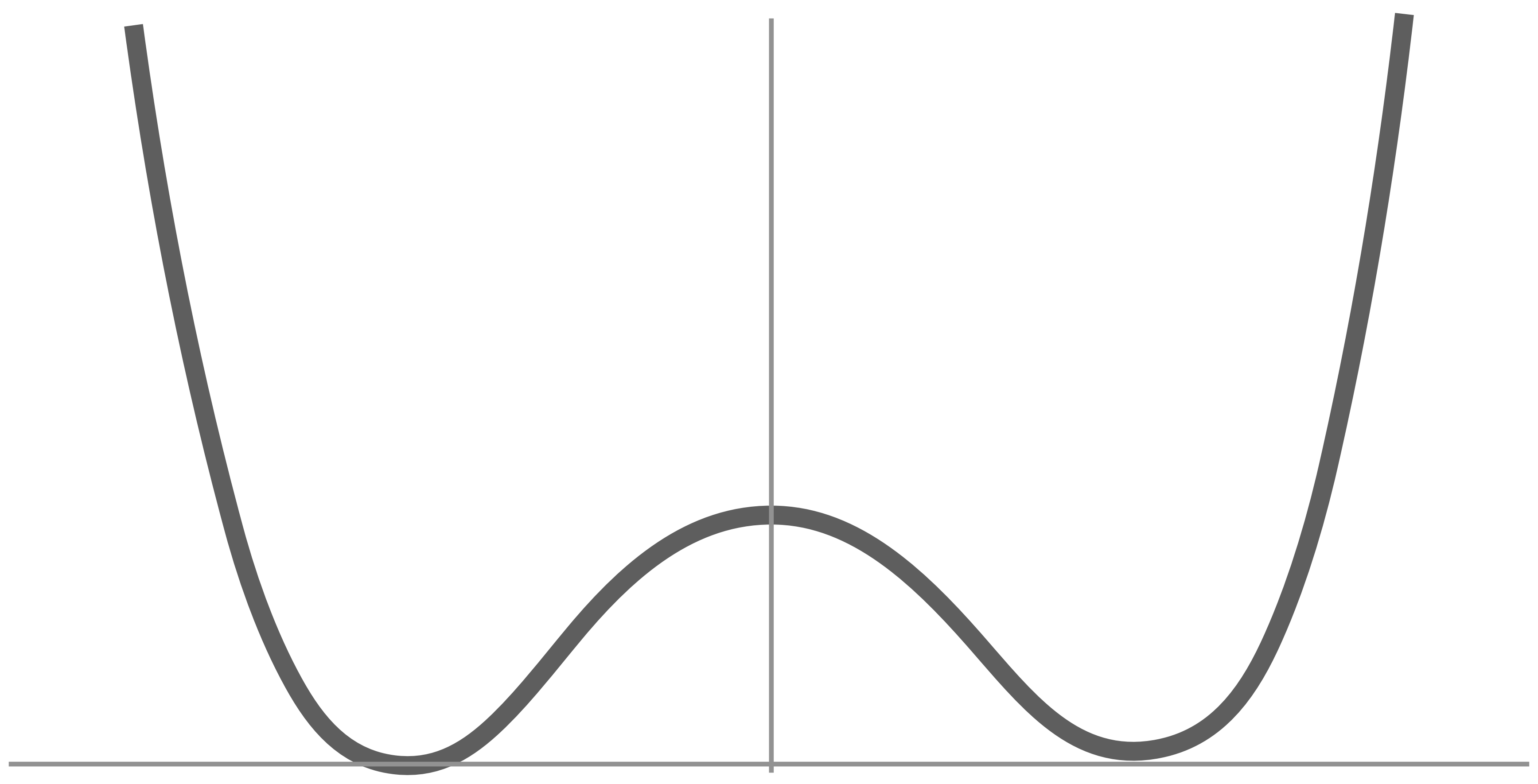
Theory also suggests new strongly coupled particles > 1 TeV

Shape of Higgs potential?

L. Lee

Taylor series expand around the minimum

$$V = \mathcal{O}(H^2) + \mathcal{O}(H^3) + \mathcal{O}(H^4)$$



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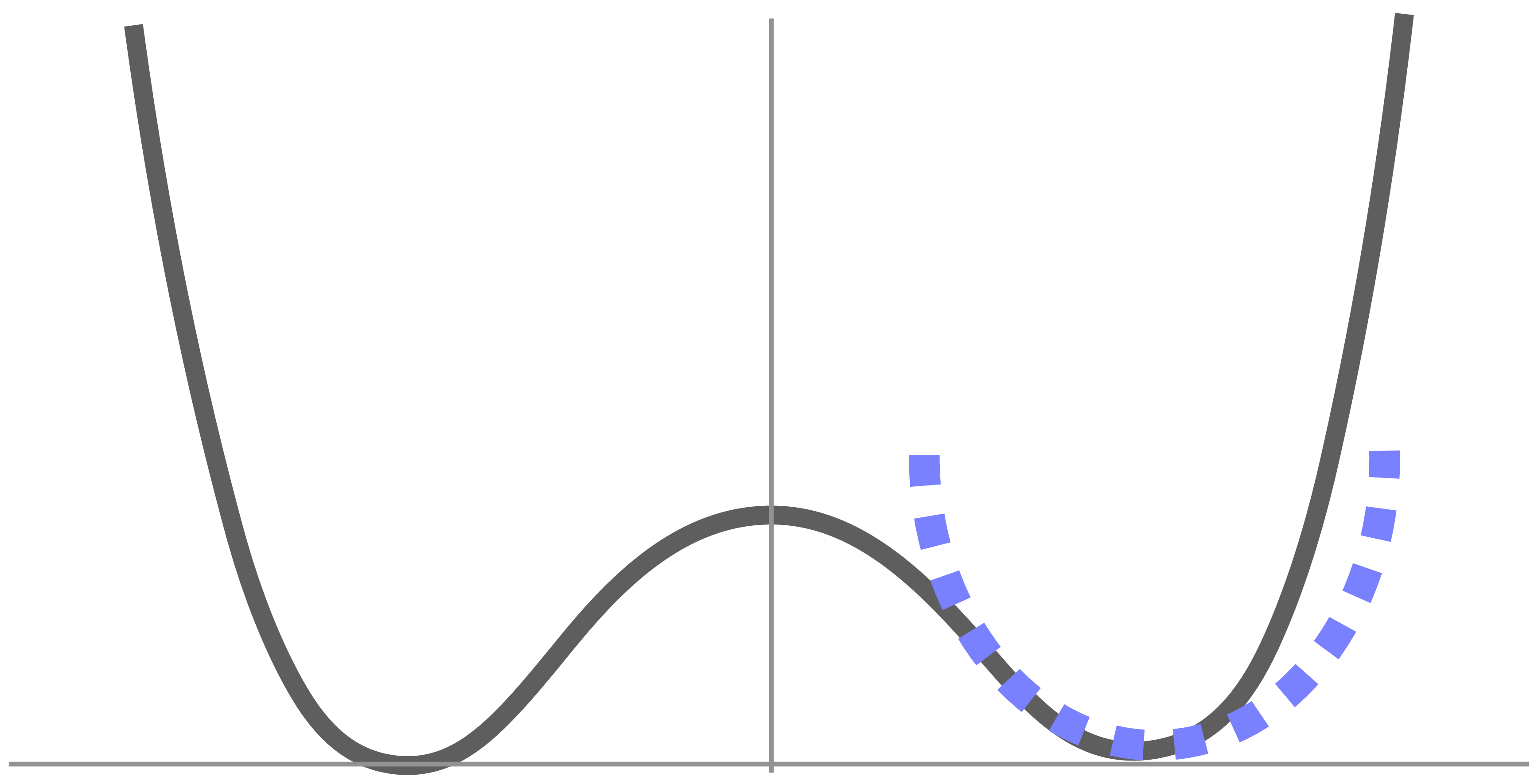

We've only measured the minimum of this potential

$$m_h = \sqrt{2\mu^2} = \sqrt{2\lambda v^2}$$

Gives us harmonic oscillator term

Shape of Higgs potential?

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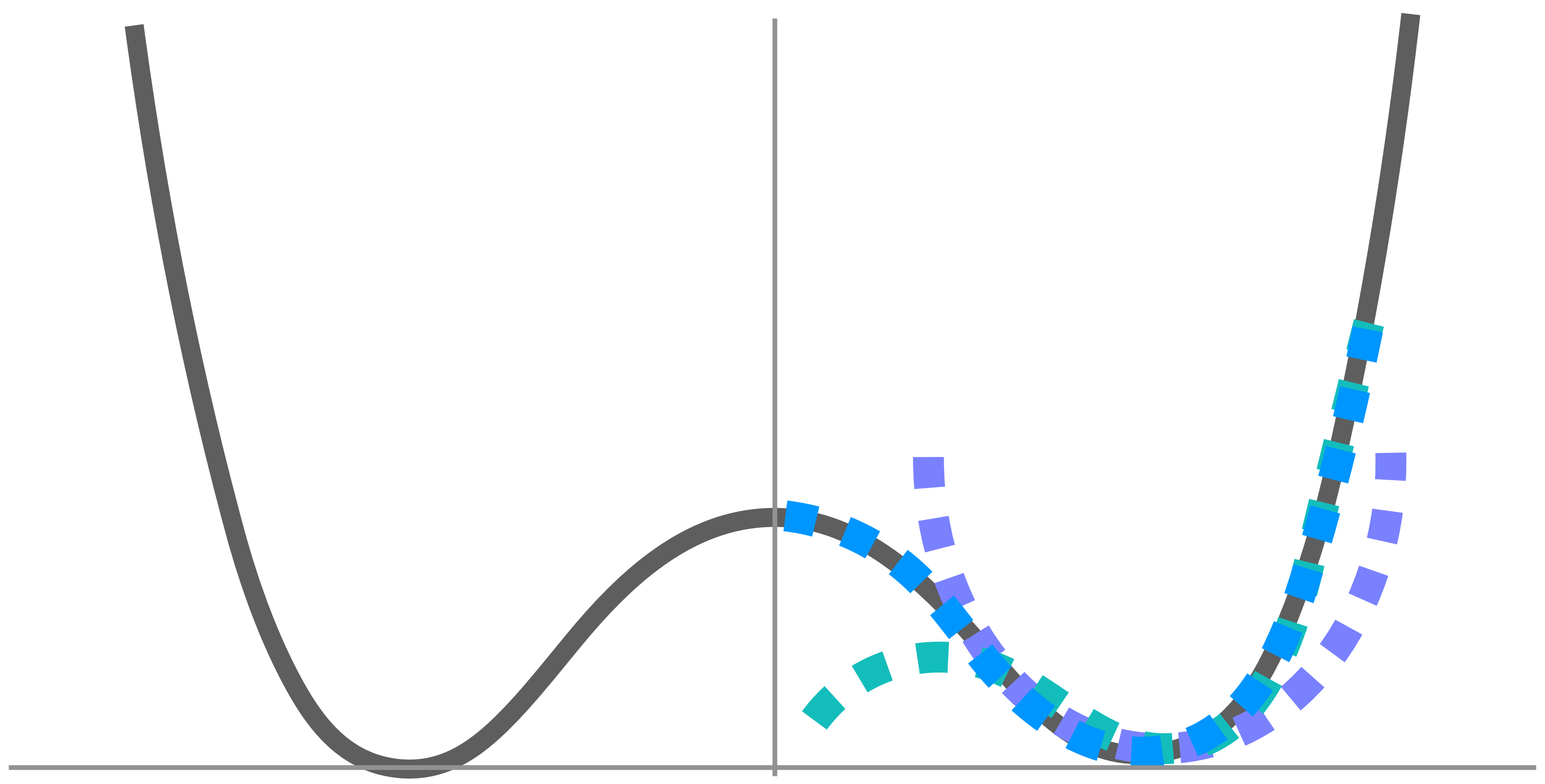
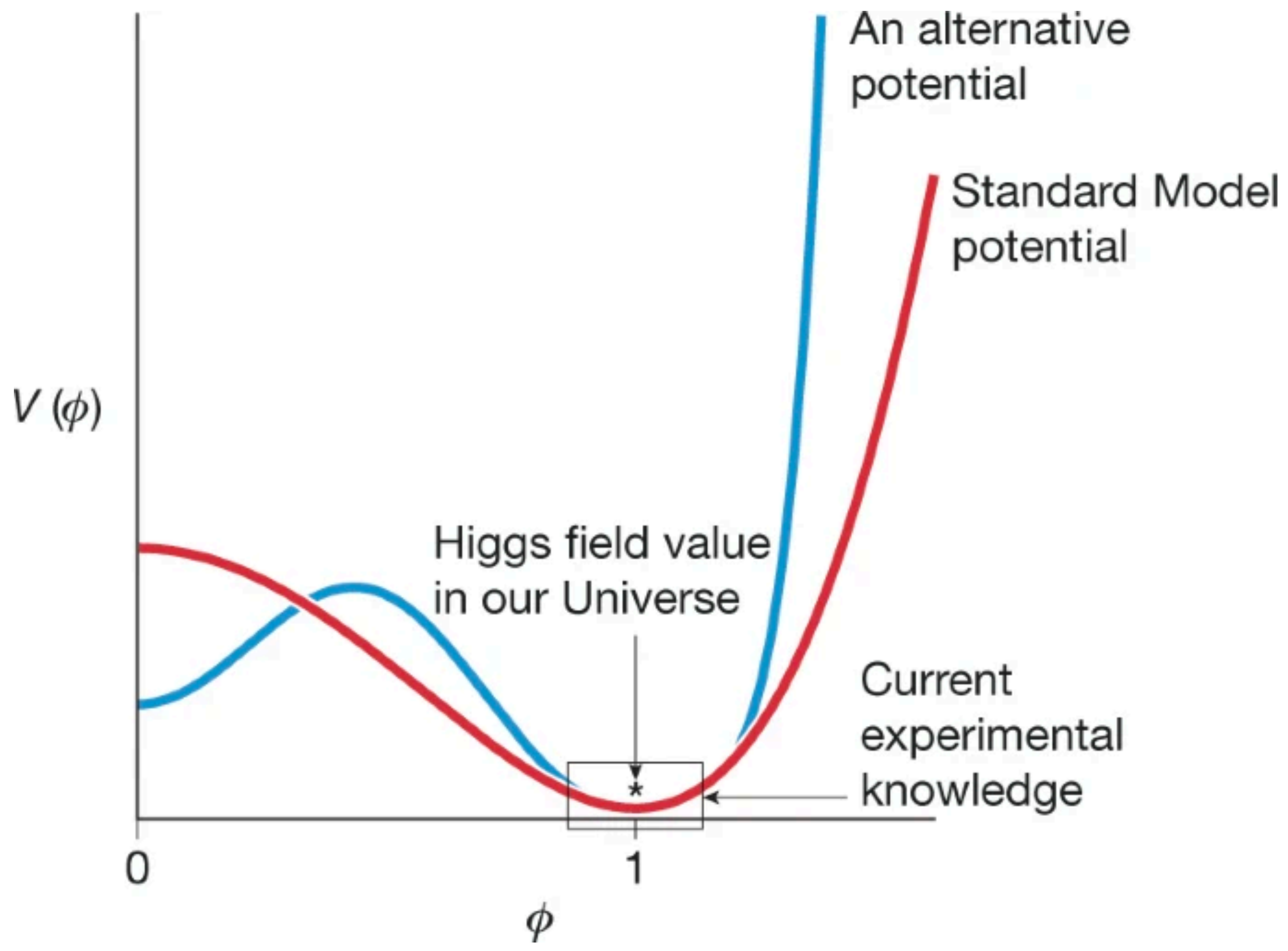


We have no idea if the Higgs potential differes from the Standard Model



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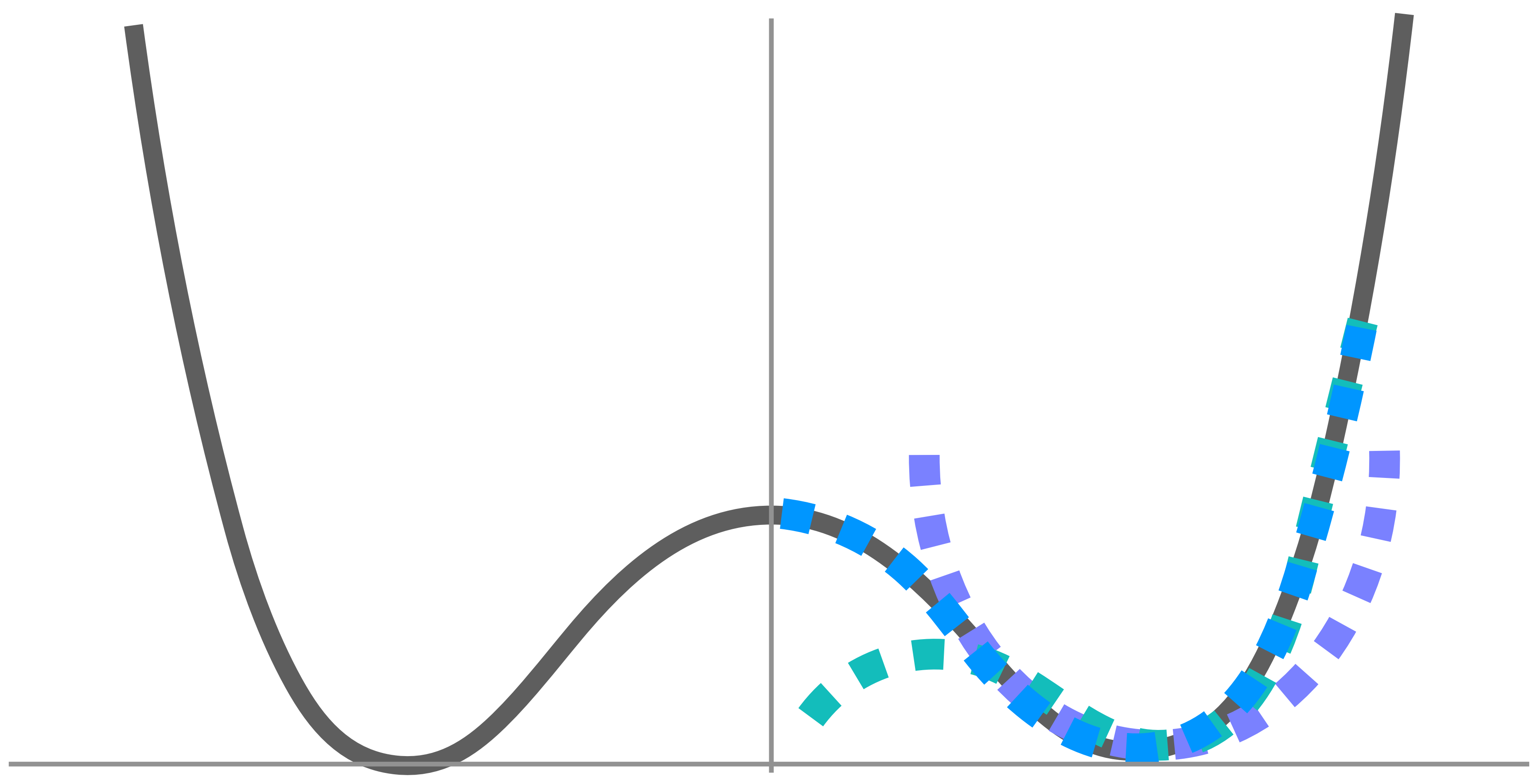
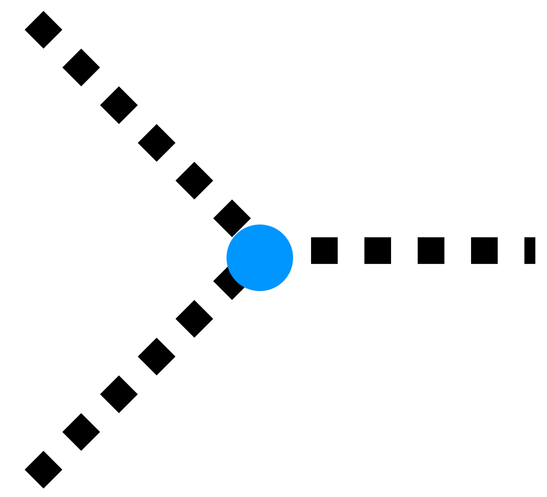
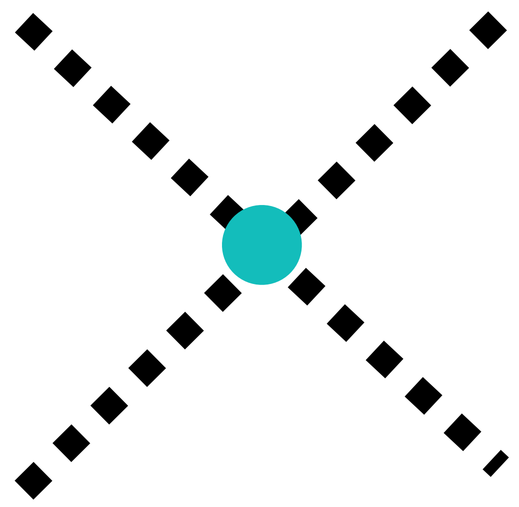


Higgs trilinear-coupling



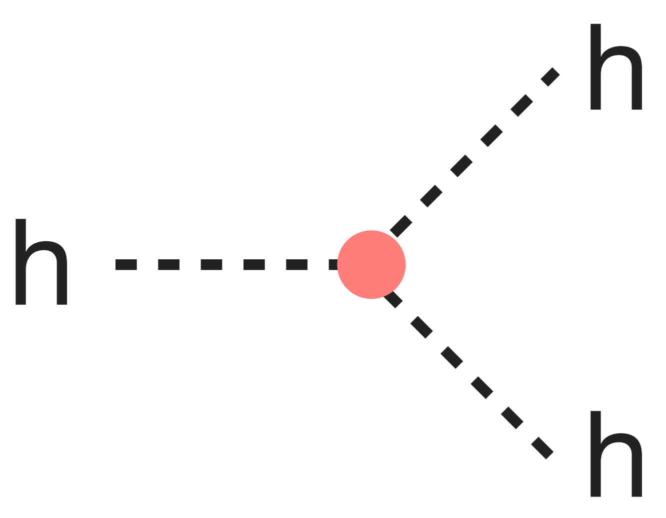
Higgs quartic coupling

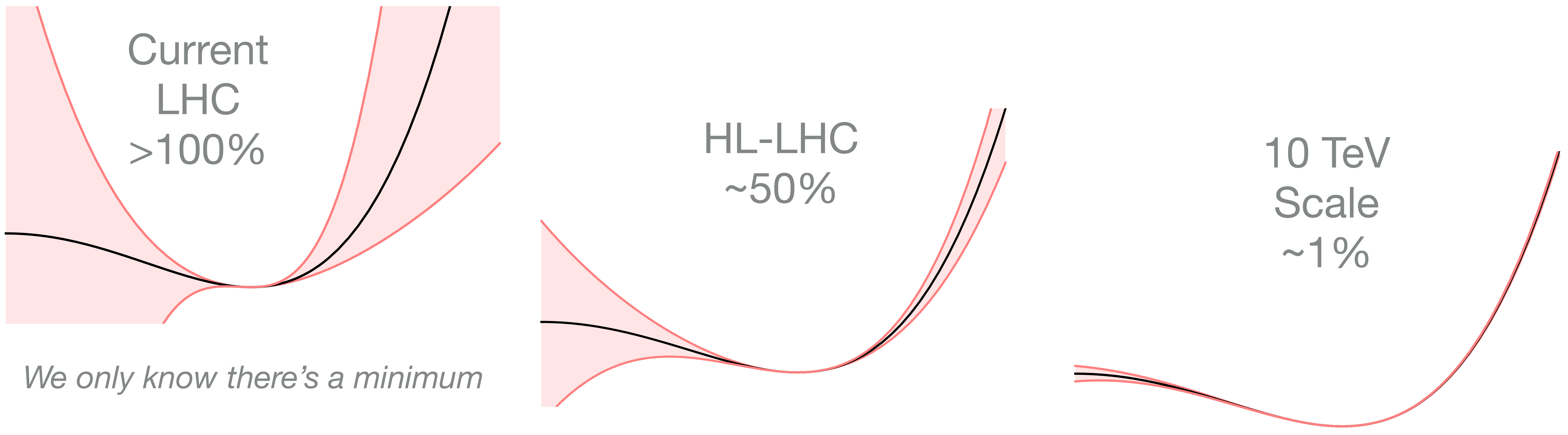


Origin and stability of universe?

R. Petrossian-Byrne & N. Craig

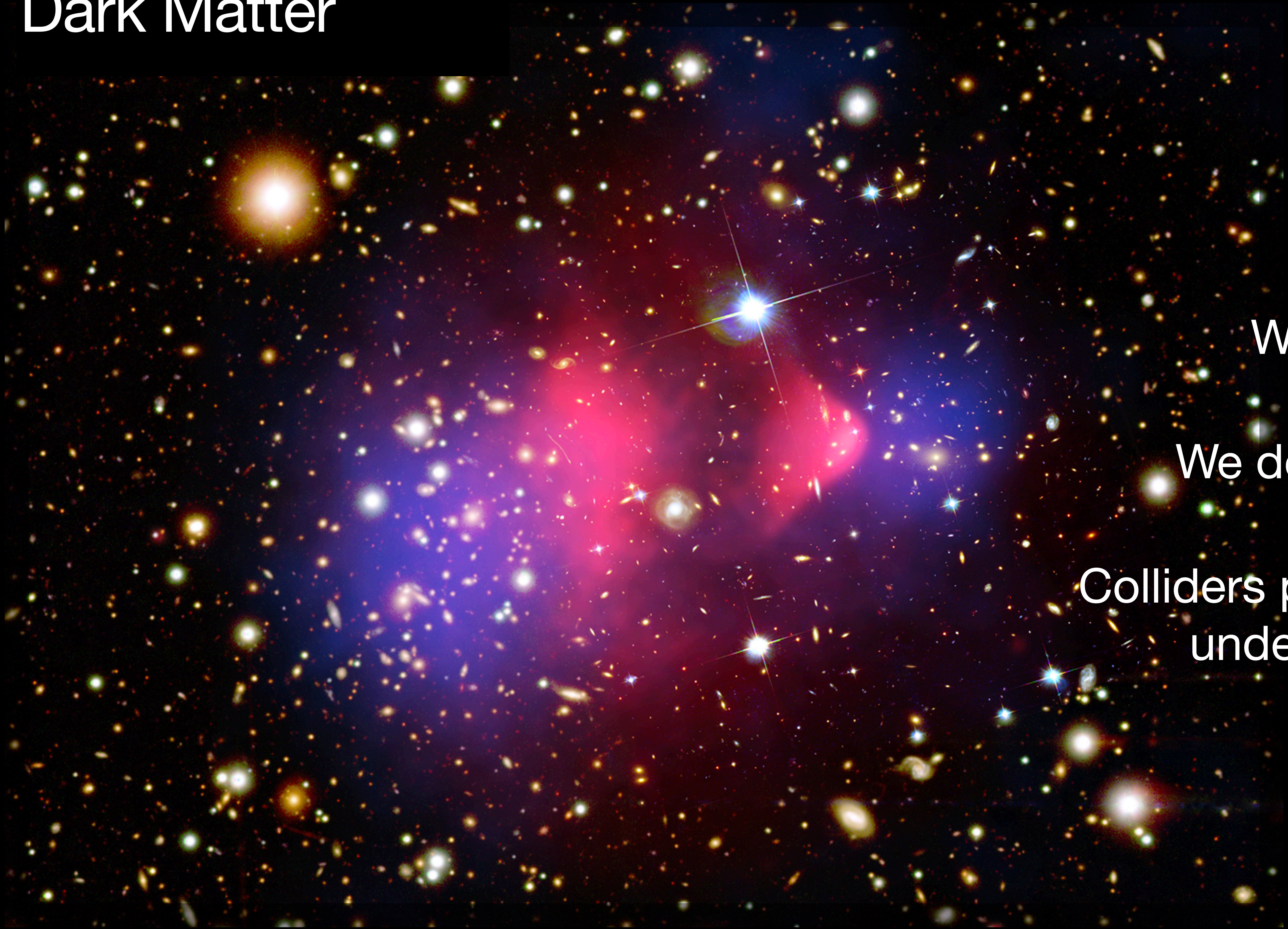
Is electroweak symmetry restored at high energies? Was there a phase transition?
Requires measuring Higgs self-coupling with few % uncertainty





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

Dark Matter



We know it exists

We don’t know what it is

Colliders play an important role in undertanding its nature

Why we care about Dark Matter

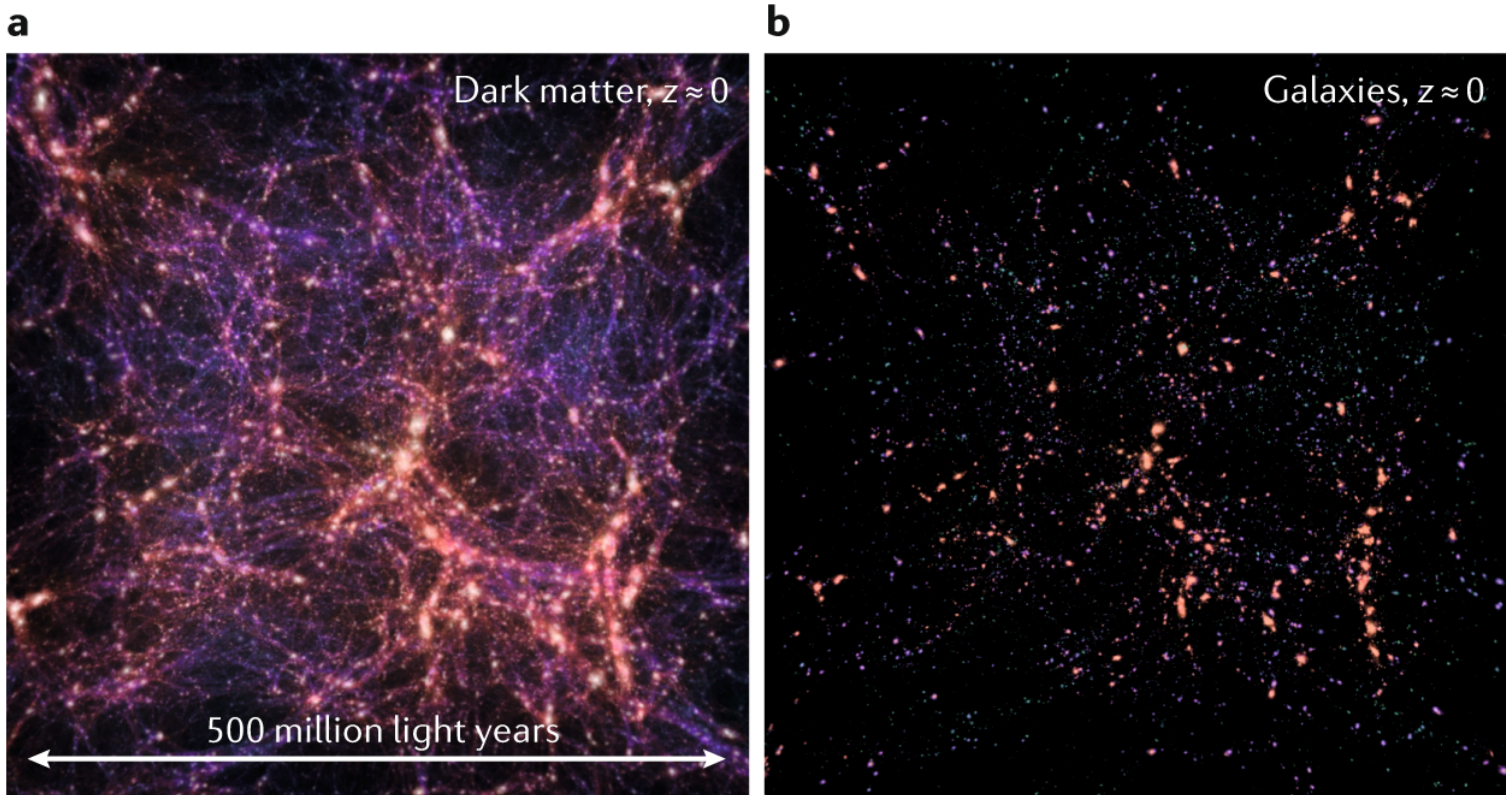
What are we made of:

5x more DM than ordinary matter

How we got here:

-Galaxy formation, clustering, cosmic web

-Without dark matter, early galaxies would be stripped of heavy elements & life as we know it could not exist

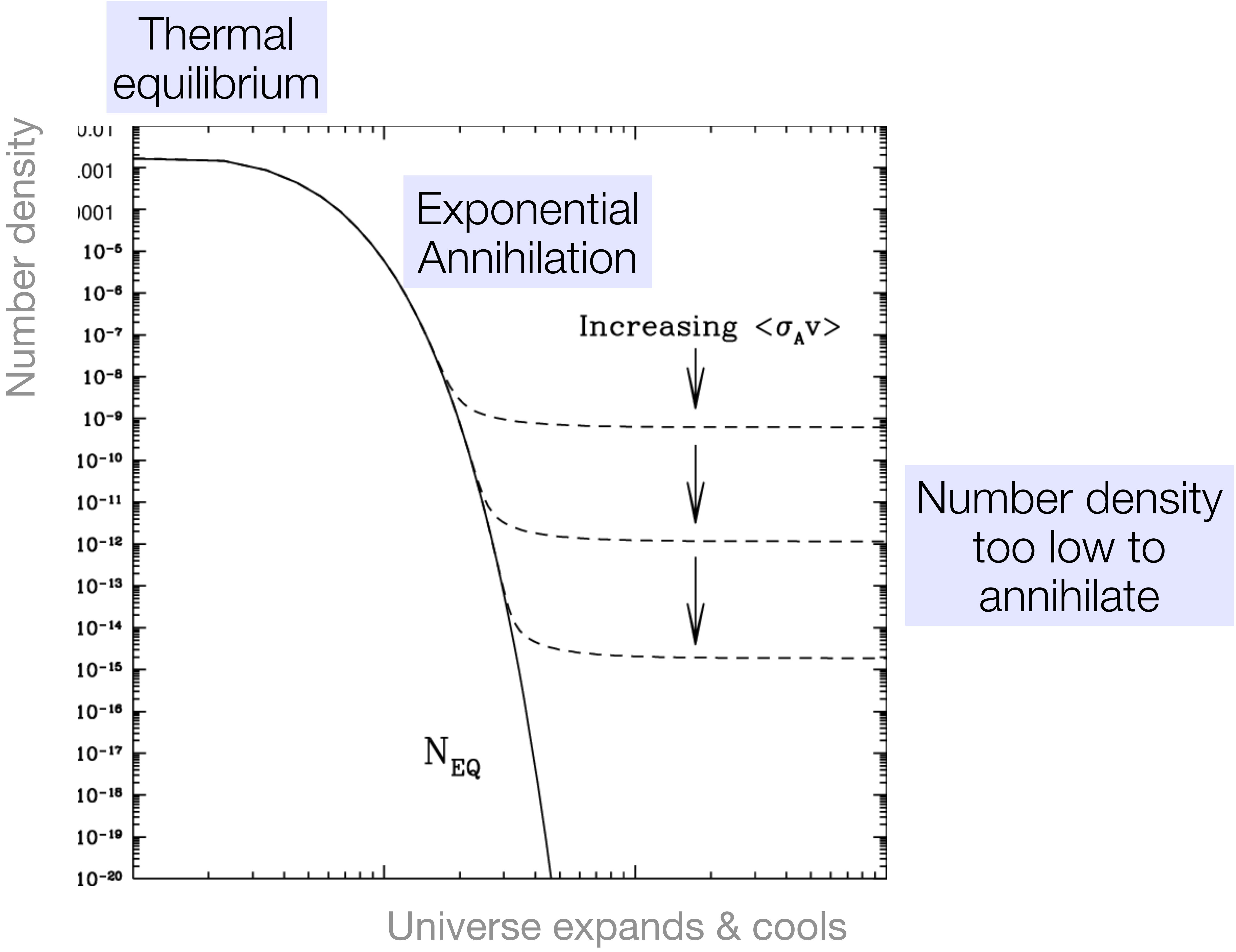


The simplest explanation

Thermal WIMPs are still the simplest explanation for the observed universe

Observed number density suggests DM interacts via weak force (or weaker)

Dirac fermion doublet (Higgsino ~1 TeV)
Majorana fermion triplet (Wino ~3 TeV)

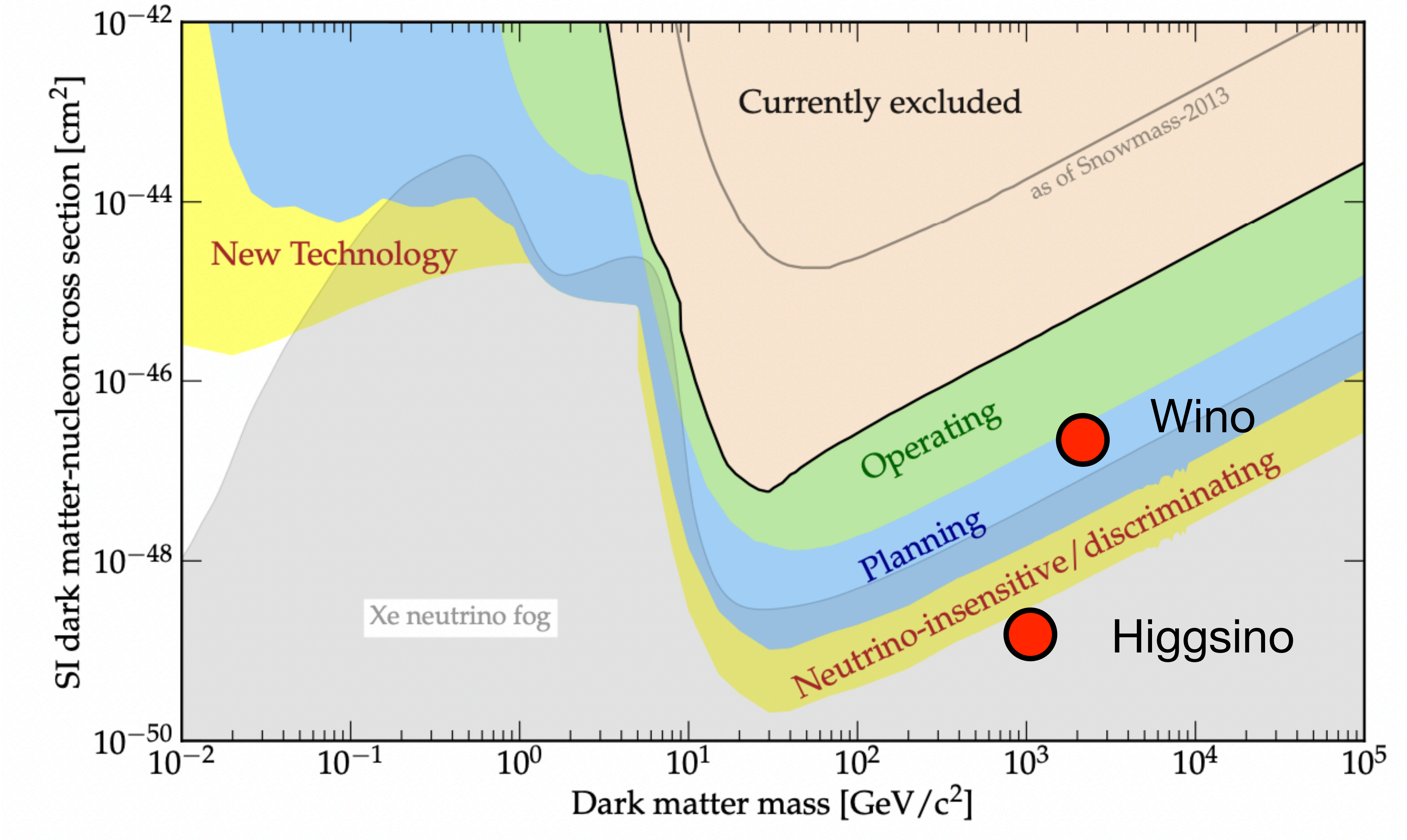


Simplest Dark Matter Candidates

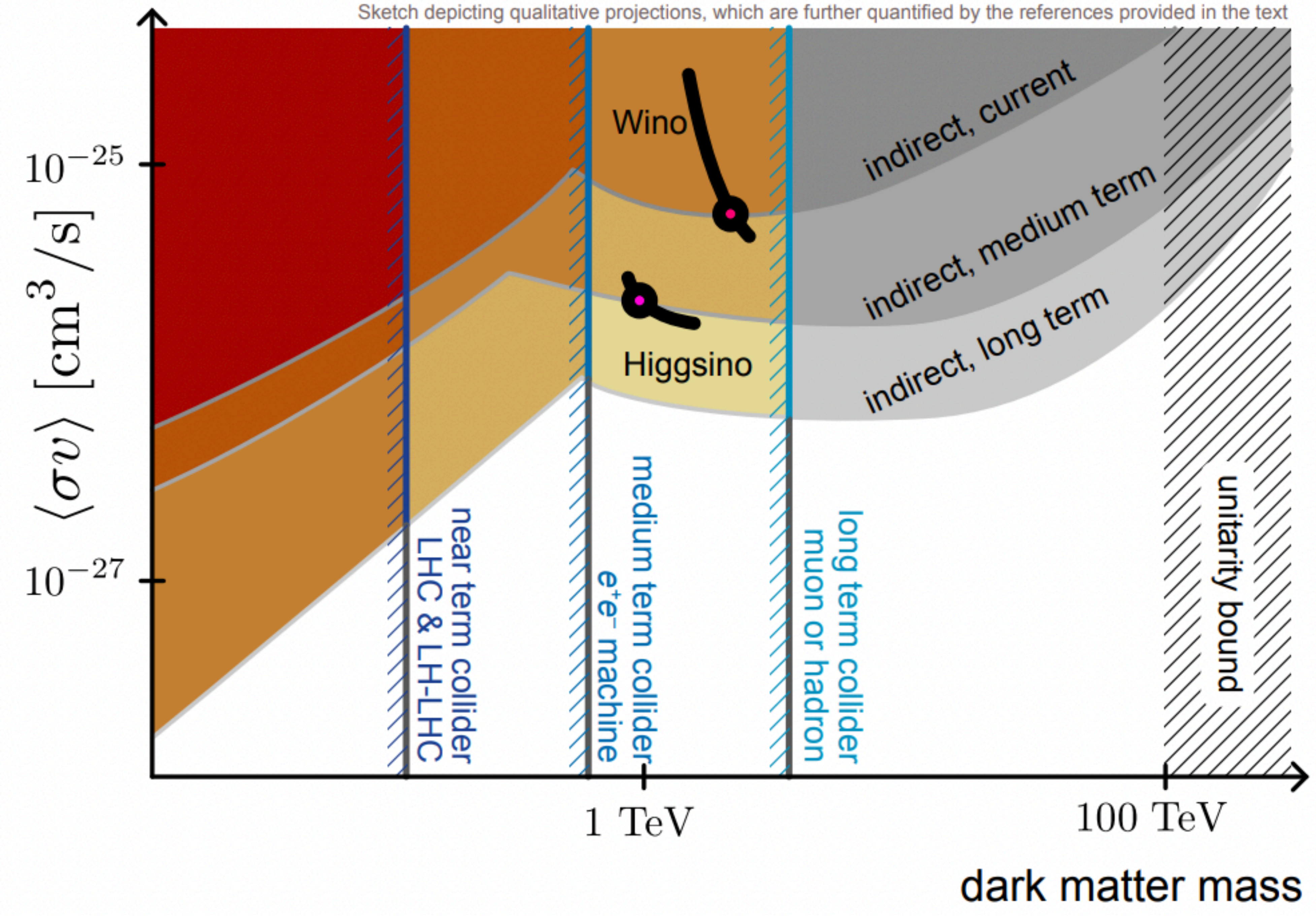
DM Complementarity Report: 2211.07027

We've yet to probe thermal WIMPs

Pure higgsino under neutrino floor



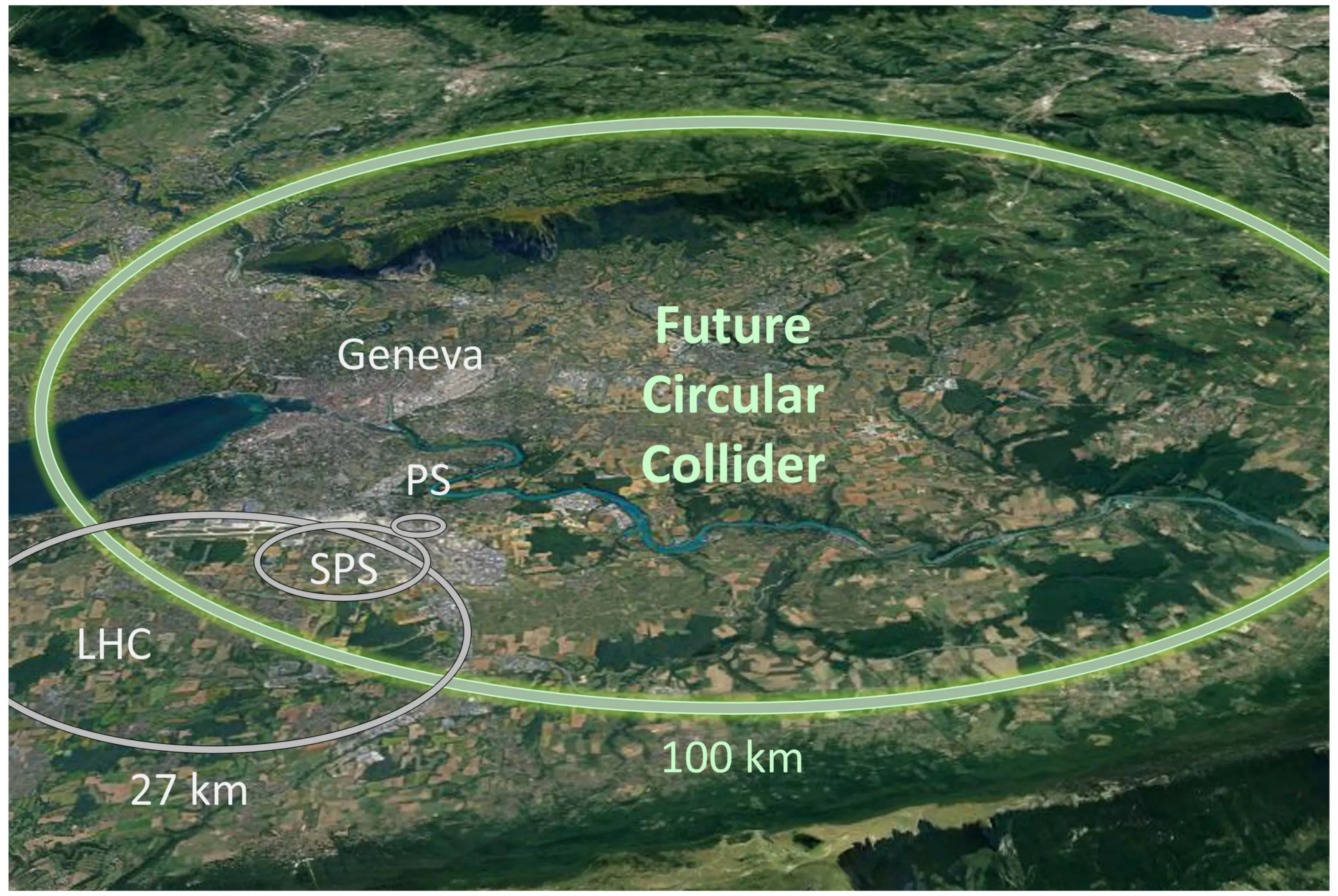
Discovery/characterization requires multi-TeV scale collider



What should we build?

International MUON Collider Collaboration

What should we build?



Circular e+e- collider

- Electrons
  - Fundamental particles → clean collisions
  - Low mass → synchotron radiation

- Consequences
  - Need to limit E_{Loss} to few % per turn
  - Luminosity/power rapidly drop with energy
  - Poses challenges for energy spread, beam stability, and head load

$$E^{\text{loss}}_{\text{turn}} = \frac{q^2}{2\varepsilon_0} \frac{(E_{\text{beam}}/m)^4}{R}$$

~Sets max beam energy

$$P = E^{\text{loss}}_{\text{turn}} \cdot \frac{N_{\text{particles}}}{T_{\text{turn}}} + \ldots$$

~Sets max beam current

$$\langle \mathcal{L}_{inst} \rangle = \frac{N^2 n_b f_{\text{rev}}}{4\pi\sigma_x\sigma_y}$$

Minizmize bunch size at IP!

Circular e+e- Evolution

From Large Electron Positron Collider (LEP) to a
Future Circular Collider (FCC-ee) or Circular Electron Positron Collider (CEPC)

	LEP-2 27 km	FCC-ee - 90 km			
		Z	W	ZH	Top
CME [GeV]	210	90	160	240	360
E loss/turn [GeV]	3.0	0.039	0.37	1.87	10.0
Beam Current [mA]	3.0	1450	150	30	6.6
Lumi/IP (1e34 $cm^{-2}s^{-1}$)	0.01	200	12	6	1.7

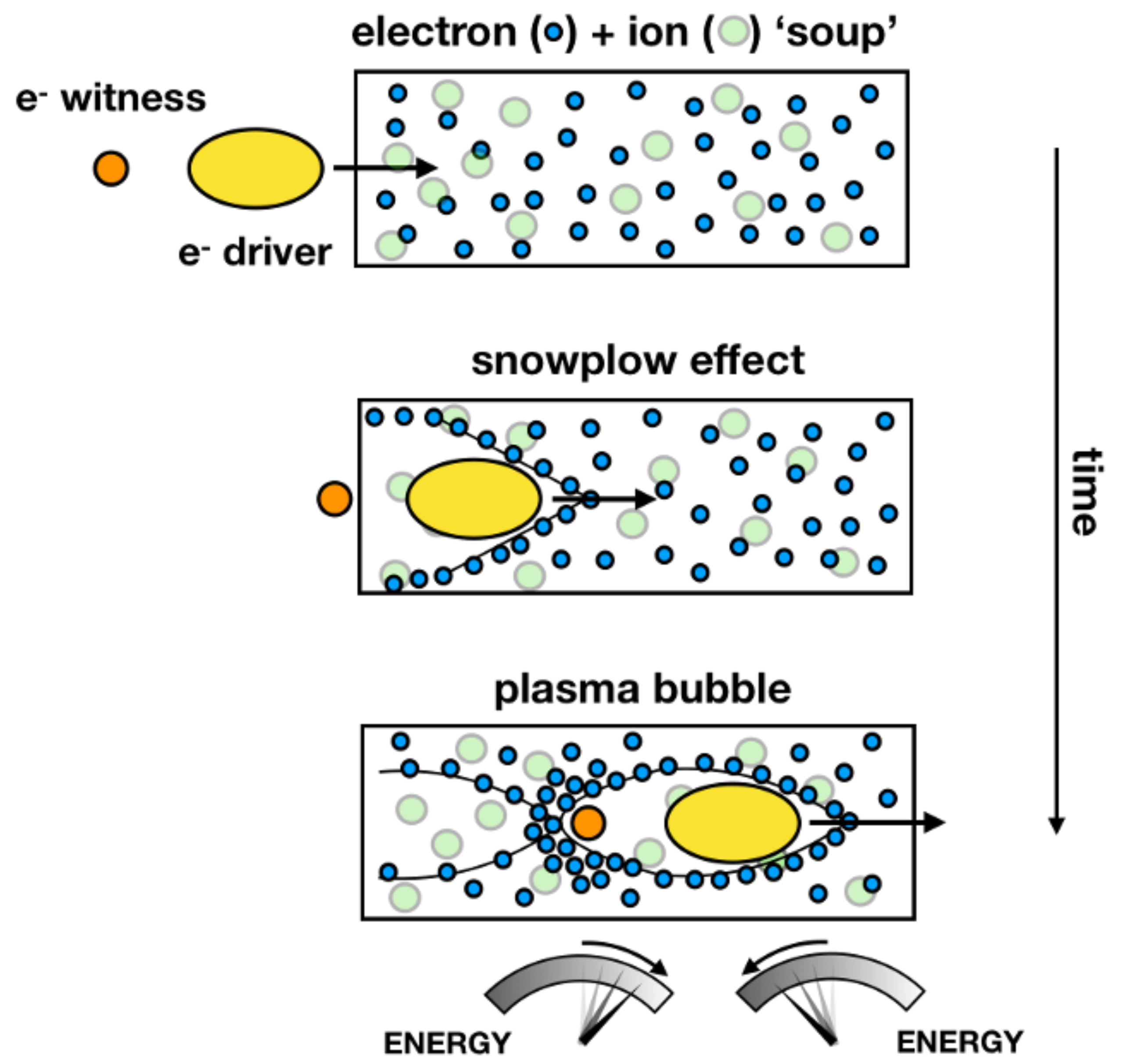
for a fixed energy
3.5x circumference
2x site power
~7x $n_{particles/beam}$

Much smaller bunches
→10^2-10^5 x luminosity

What about linear e+e-?

- Avoids synchotron radiation
- Energy set by accelerating gradient & length
- Luminosity
  - Pro: increases/flat with energy
  - Challenge: positron production & single pass
  - History of not meeting targets
- Bonus: Polarized beams

New alternatives for the further future?



Eg. plasma wakefield ~1 GeV/m

For e- only

I'll focus on bread & butter

Linear Electron Evolution

From Stanford Linear Collider (SLC) to the International Linear Collider (ILC)
or Compact Linear Collider (CLIC)

	SLC	ILC	CLIC
CME (GeV)	90	250-1000	380-3000
Length (km)	3.2	20-40	11-54
Gradient (MV/m)	18	30	100
Positrons/s	$5 \cdot 10^{12}$	$1 \cdot 10^{14}$	$0.5 \cdot 10^{14}$
Lumi (1e34 $cm^{-2}s^{-1}$)	0.0003	3	3

How do linear and circular compare?

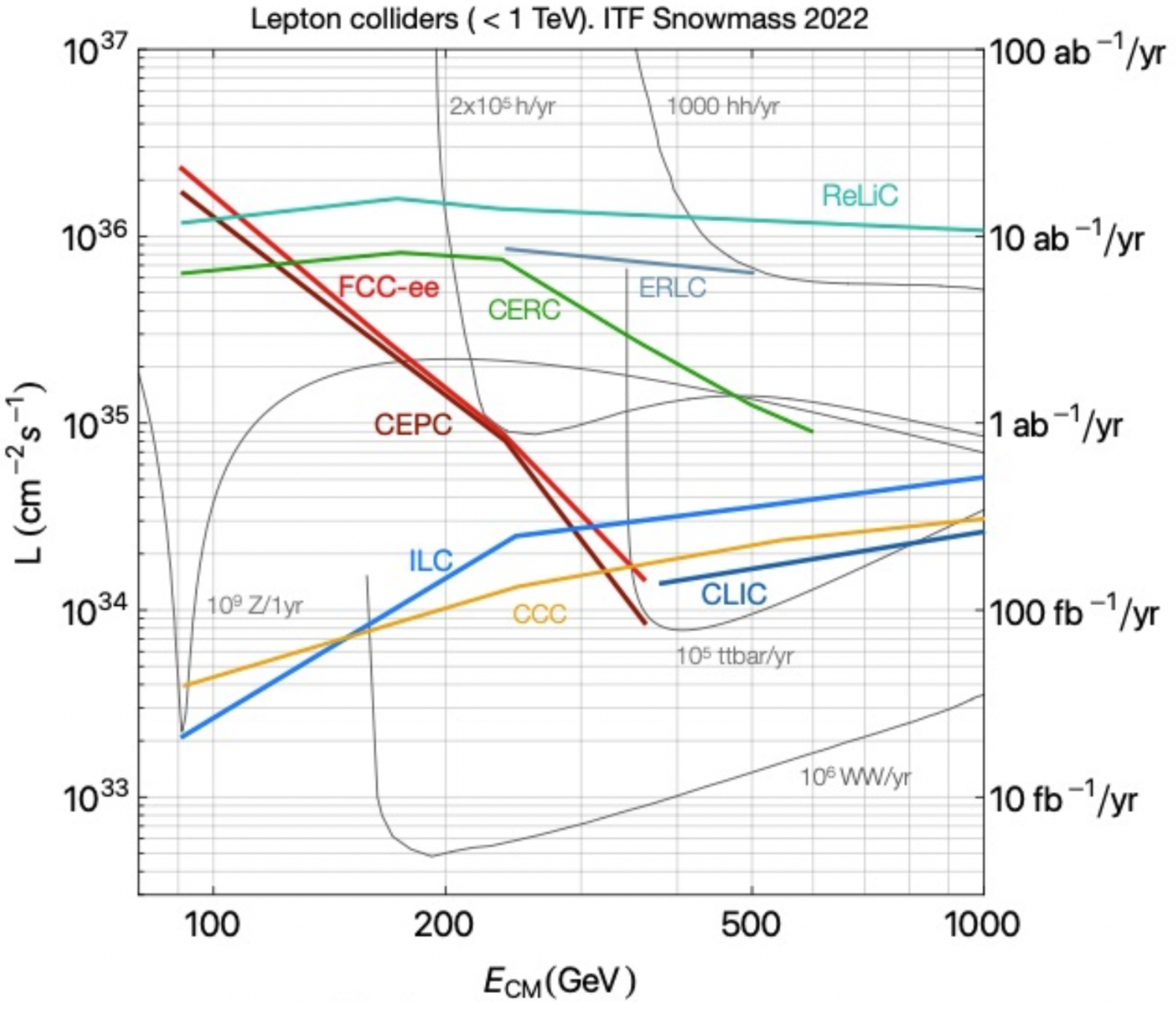
Main output

10^7 Higgses

10^9 - 10^{12} Zs

10^6 WW

10^5 ttbar



Circular Strength

'Tera Z'

Linear Strength

Higher energies

What about for the Higgs?

Liantao Wang @P5

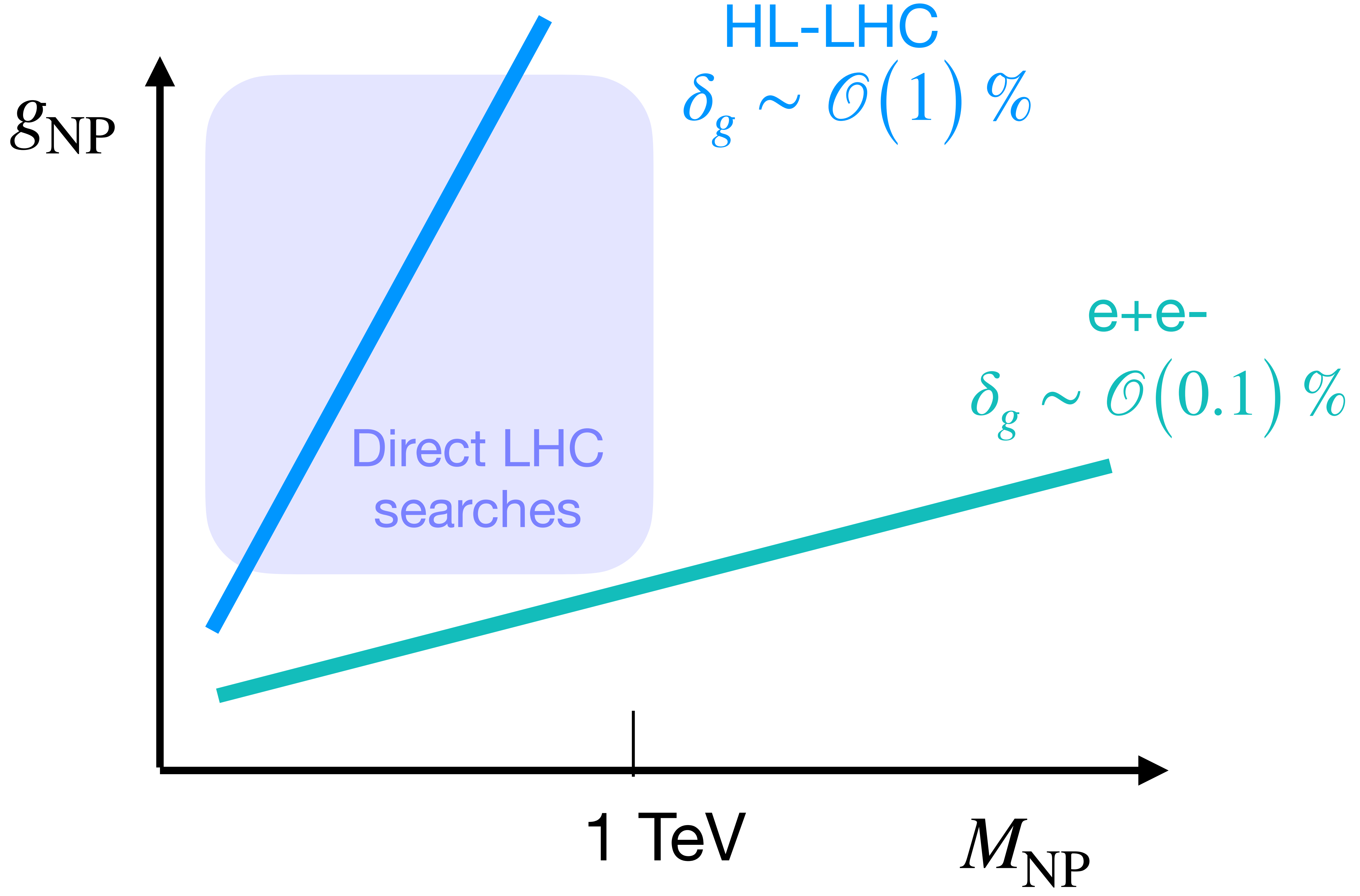
Both aiming for ~10^7 Higgs Bosons

Uncertainty on cross sections & couplings

$$\sigma(g) \sim \frac{\sqrt{N_h}}{N_h} \sim \mathcal{O}(0.1)\ \%$$

Deviations from new physics

$$\delta \sim g_{\mathrm{NP}}^2 \frac{(100\ \mathrm{GeV})^2}{M_{\mathrm{NP}}^2}$$



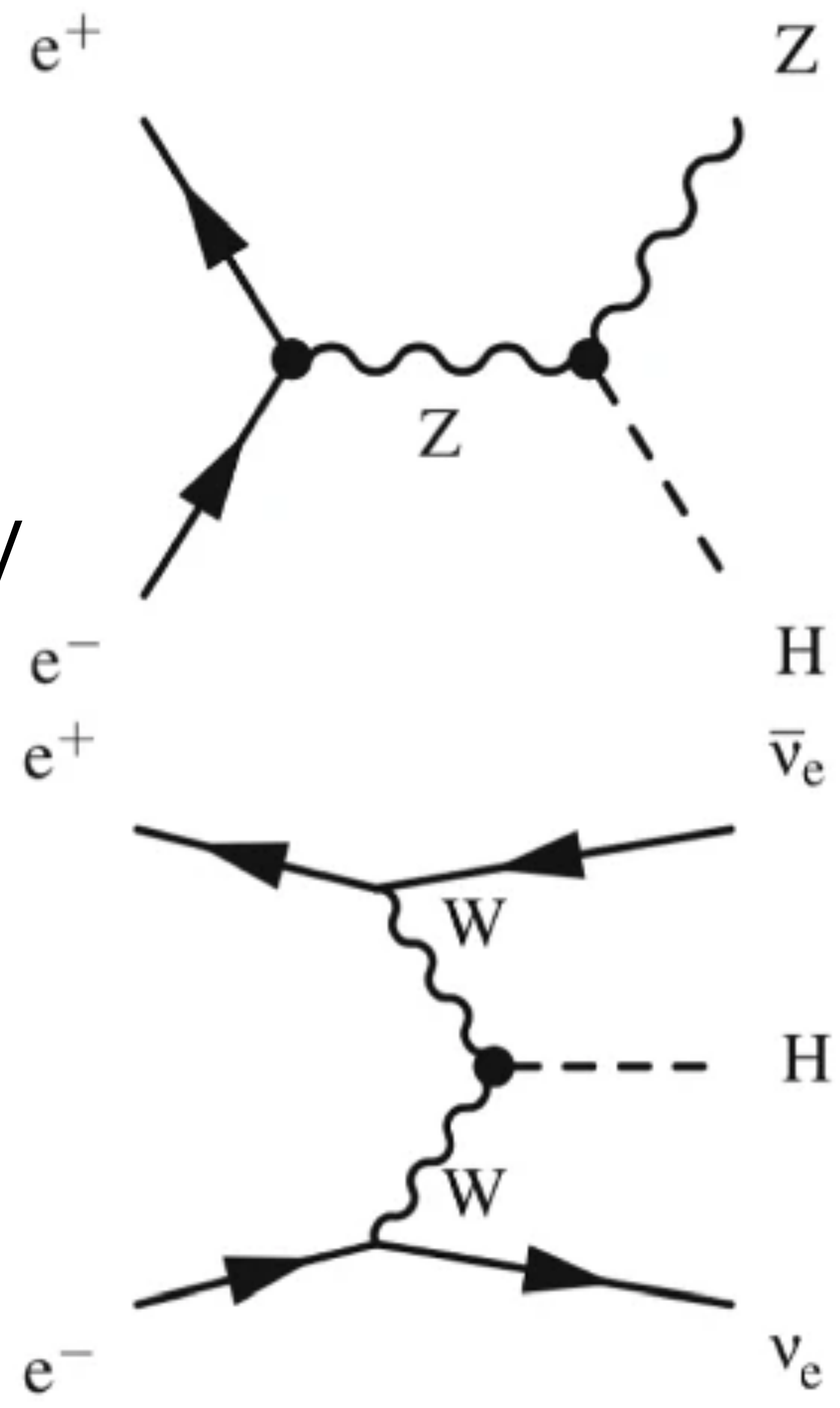
Some differences in production

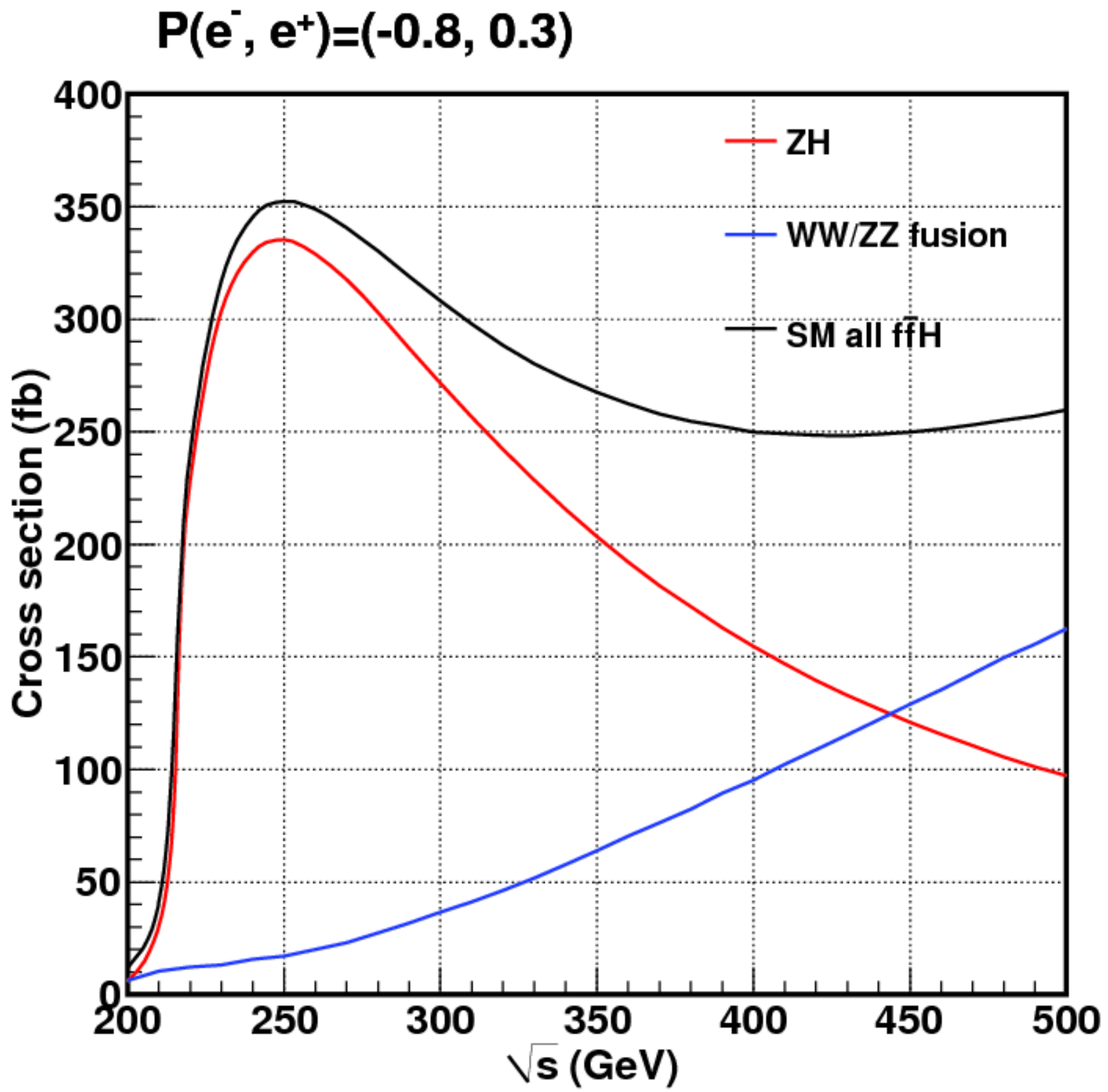
Higgsstrahlung

Peaks at 240 GeV

WW fusion

Takes over at higher E

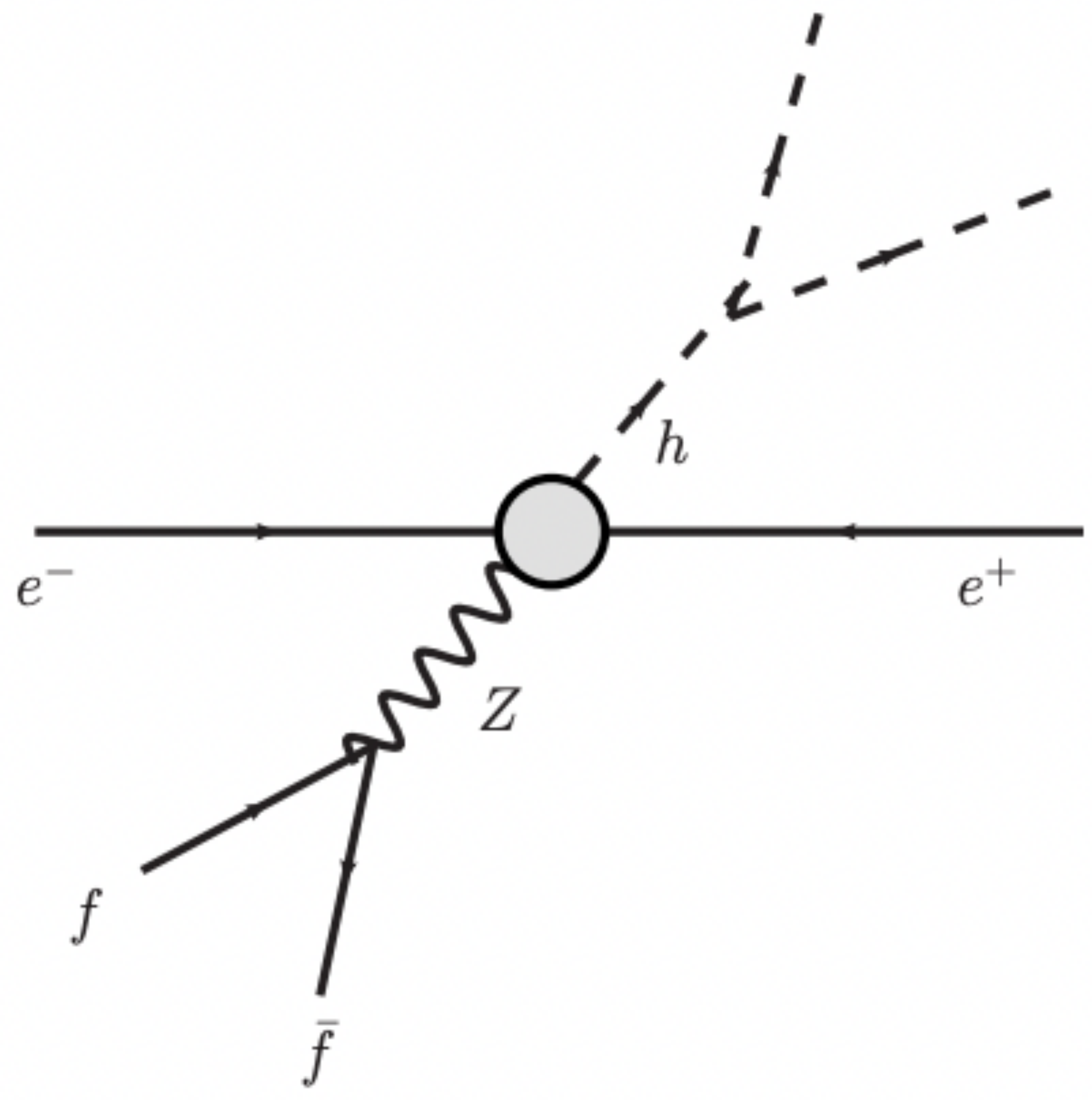


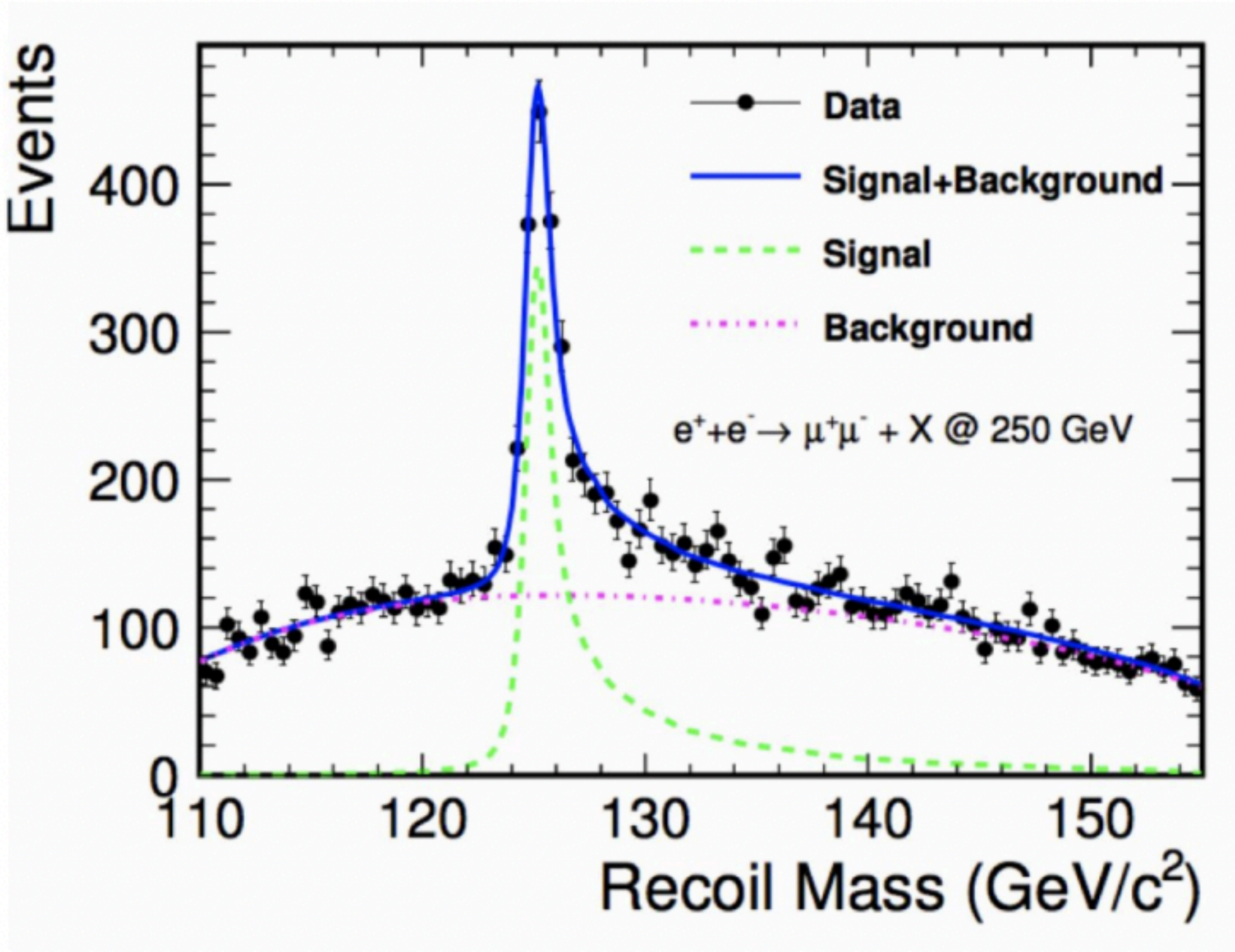


Unique feature: Higgs recoil

Know initial collision energy

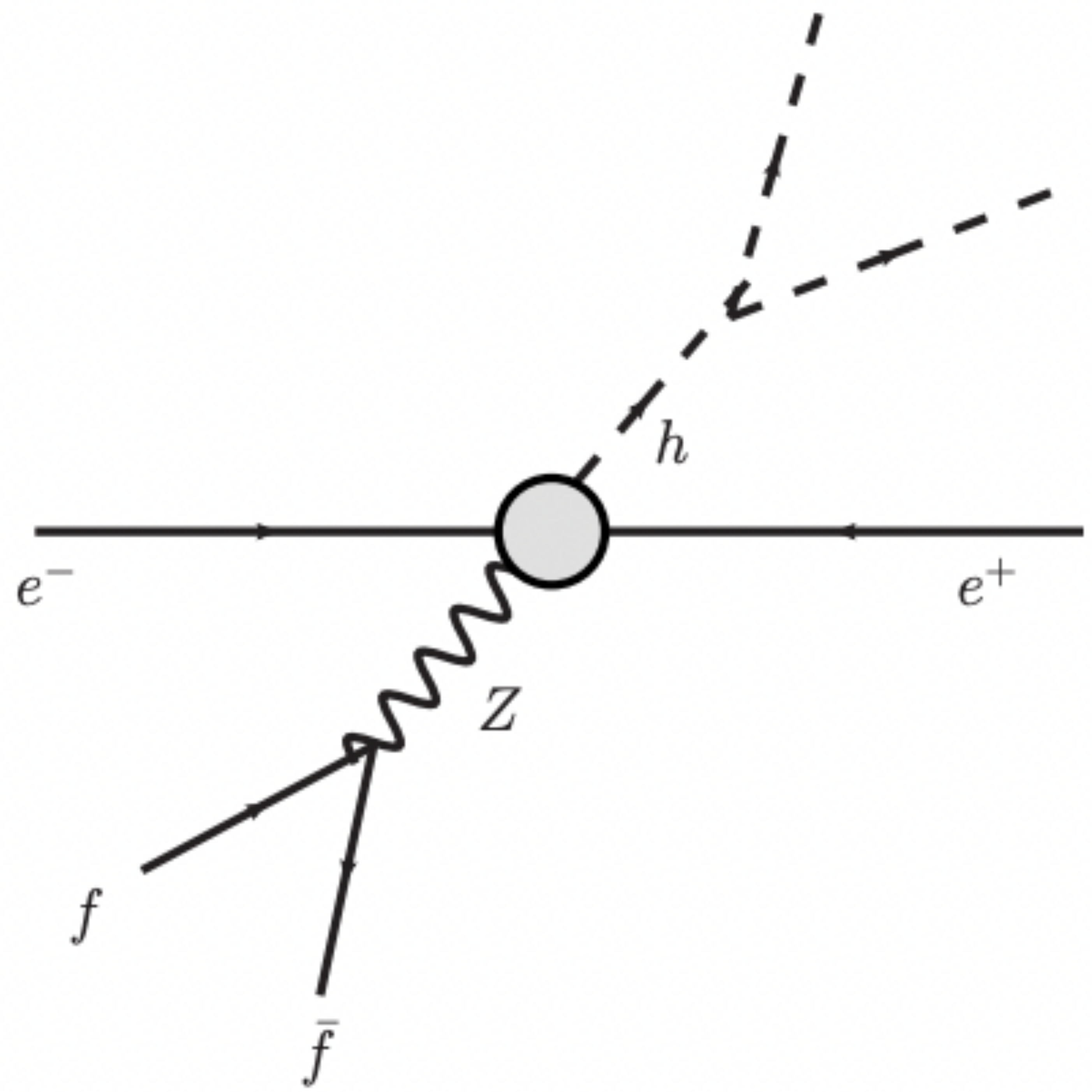
→ reconstruct the Higgs boson without identifying decaying products





$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

Unique feature: Higgs recoil



Useful for

Higgs→invisible

Higgs→rare/unconventional

And Total Higgs width

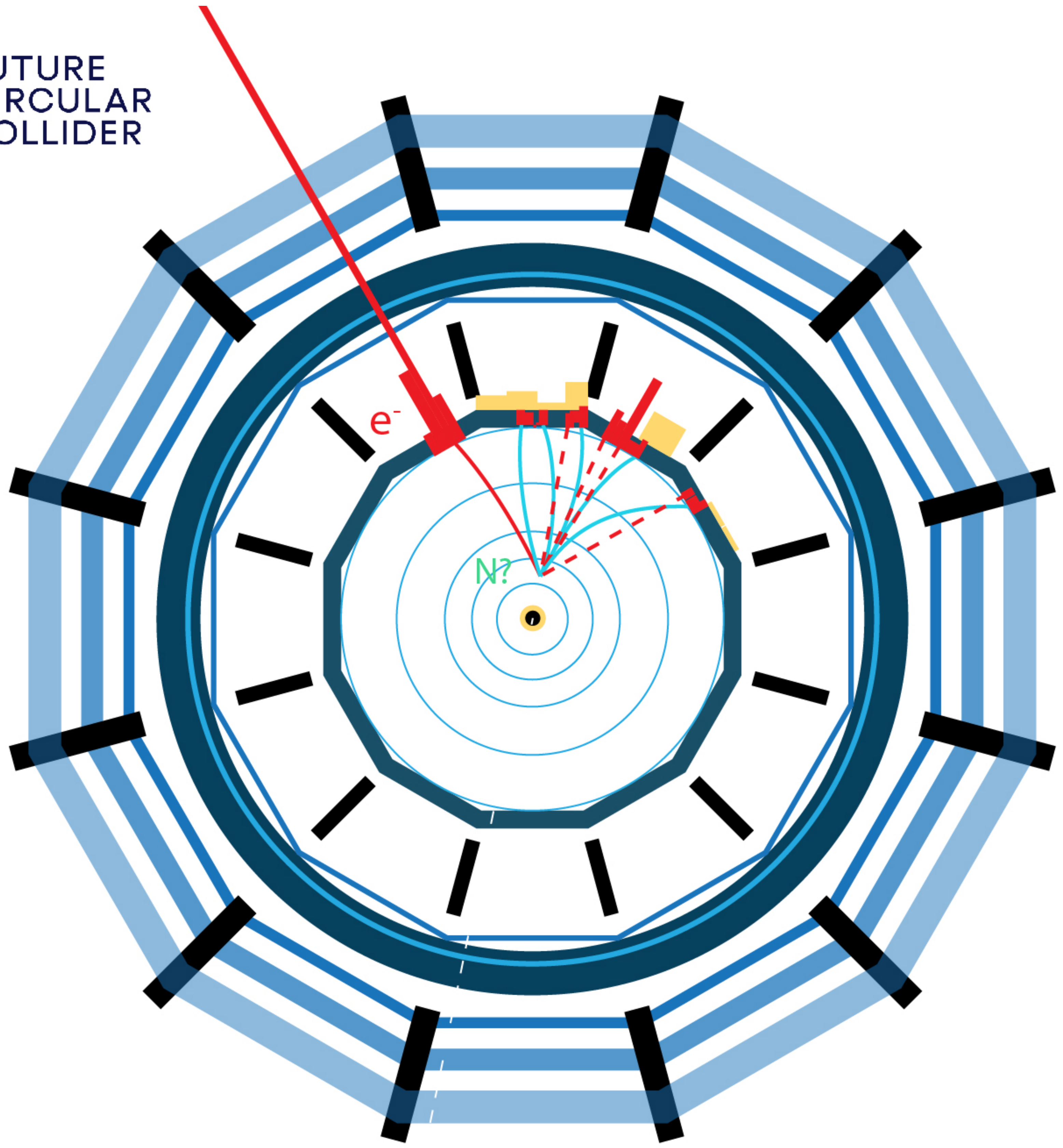
$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

<u>Or with h→WW and WW fusion</u>

What this means for our detectors

- Need to read out all events
- Low occupancy
- Need excellent p & E resolution!
  - Low density precision trackers
  - Hadronic W/Z/h separation

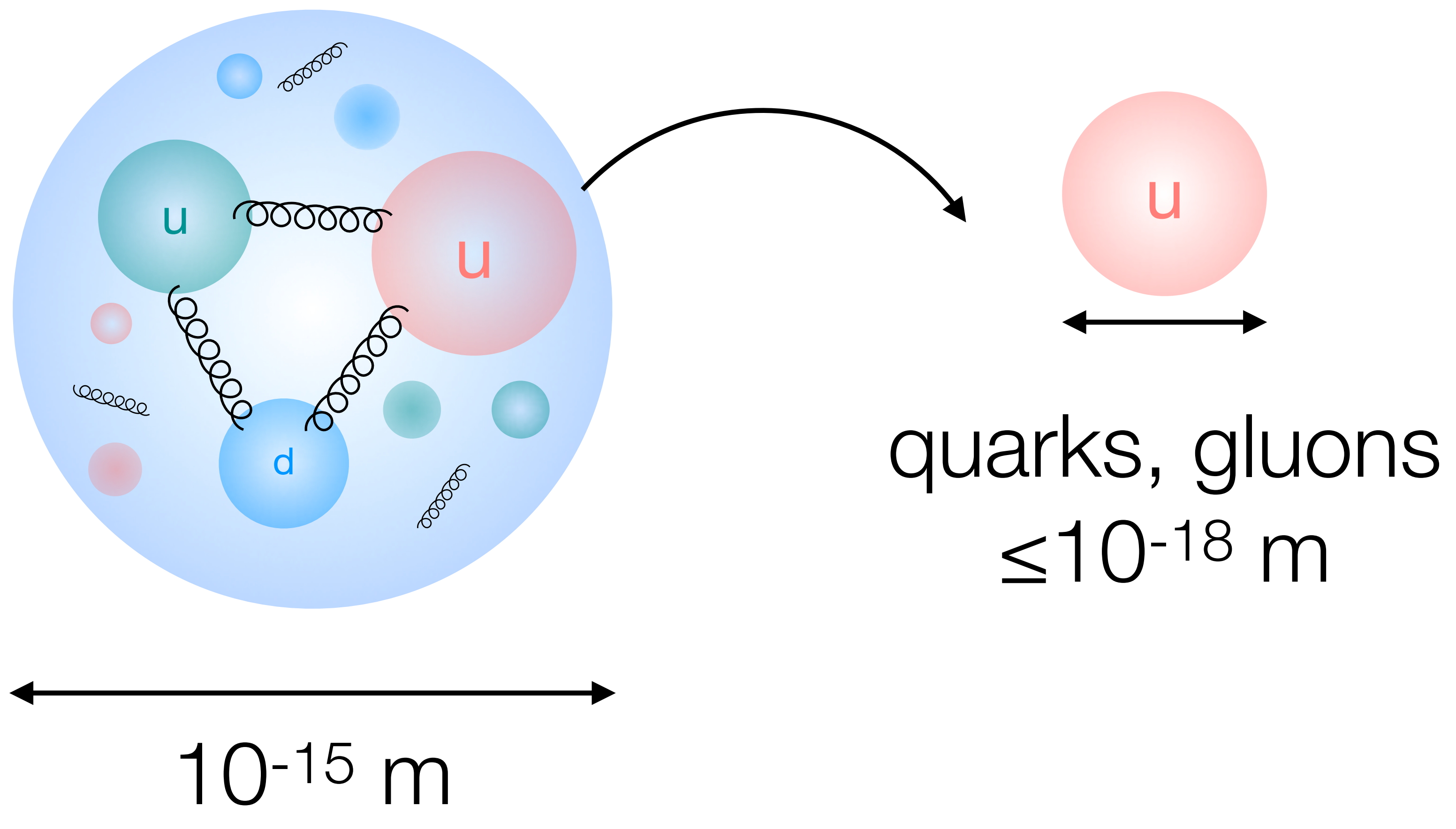
FUTURE CIRCULAR COLLIDER



Circular hadron colliders

- Higher mass
  - Less synchotron radiation
  - Higher energies achievable
- Composite particles
  - Quarks and gluons only carry a fraction of proton momentum
  - Probe a range energies at once
  - High rate of “messy” backgrounds

Protons



Hadron collider constraints

Energy reach given by
Collider size
High field dipoles

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

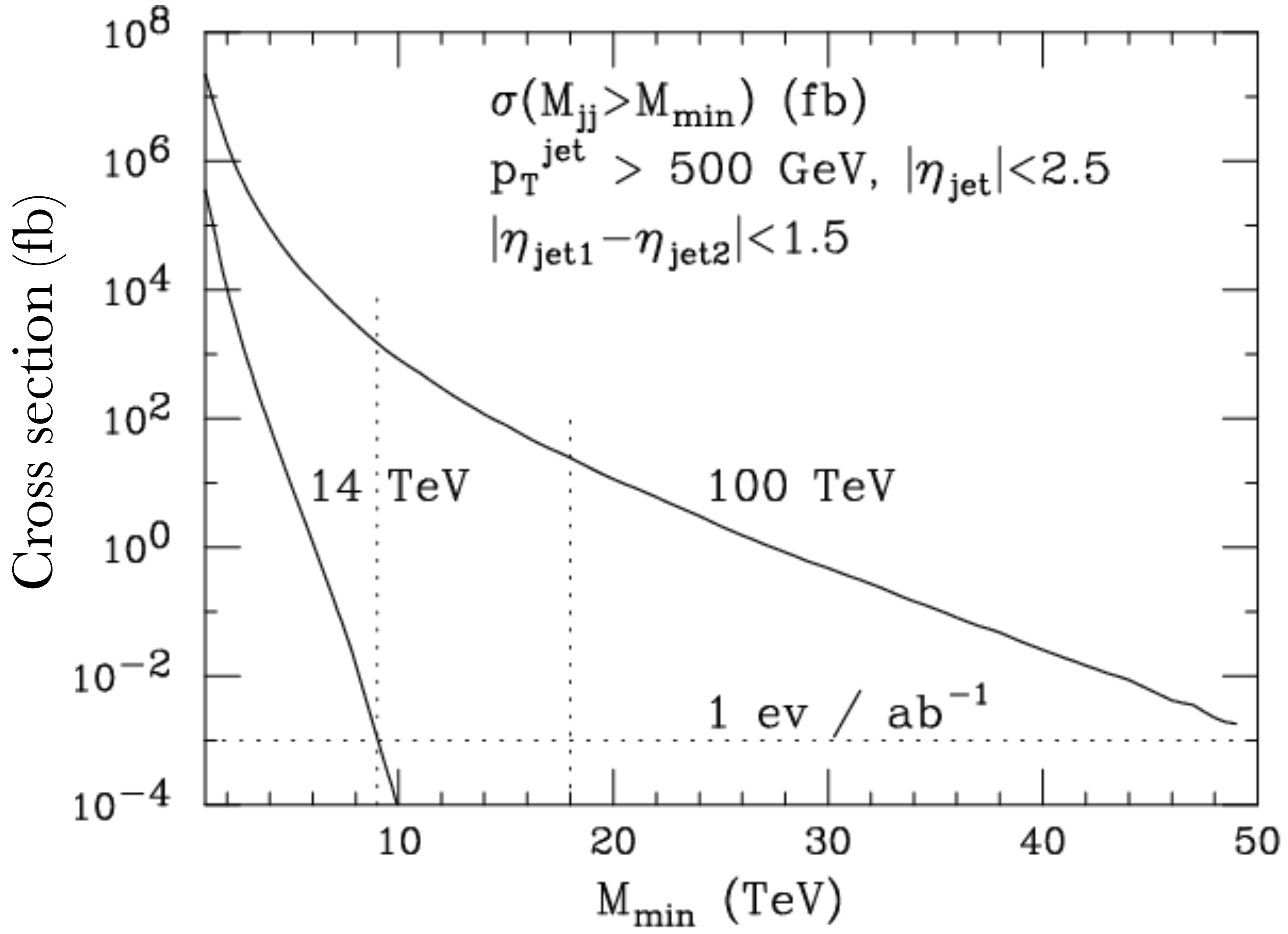
		LHC tunnel	FCC tunnel
Circumference [km]		27.0	90.0
COM [TeV]	LHC NbTi - 8.3 T	14	46
	Record NbSn3 - 14 T	23	78
	Future HTS - 18 T	30	100

Physics reach with 100 TeV hadrons

http://collider-reach.web.cern.ch/collider-reach/

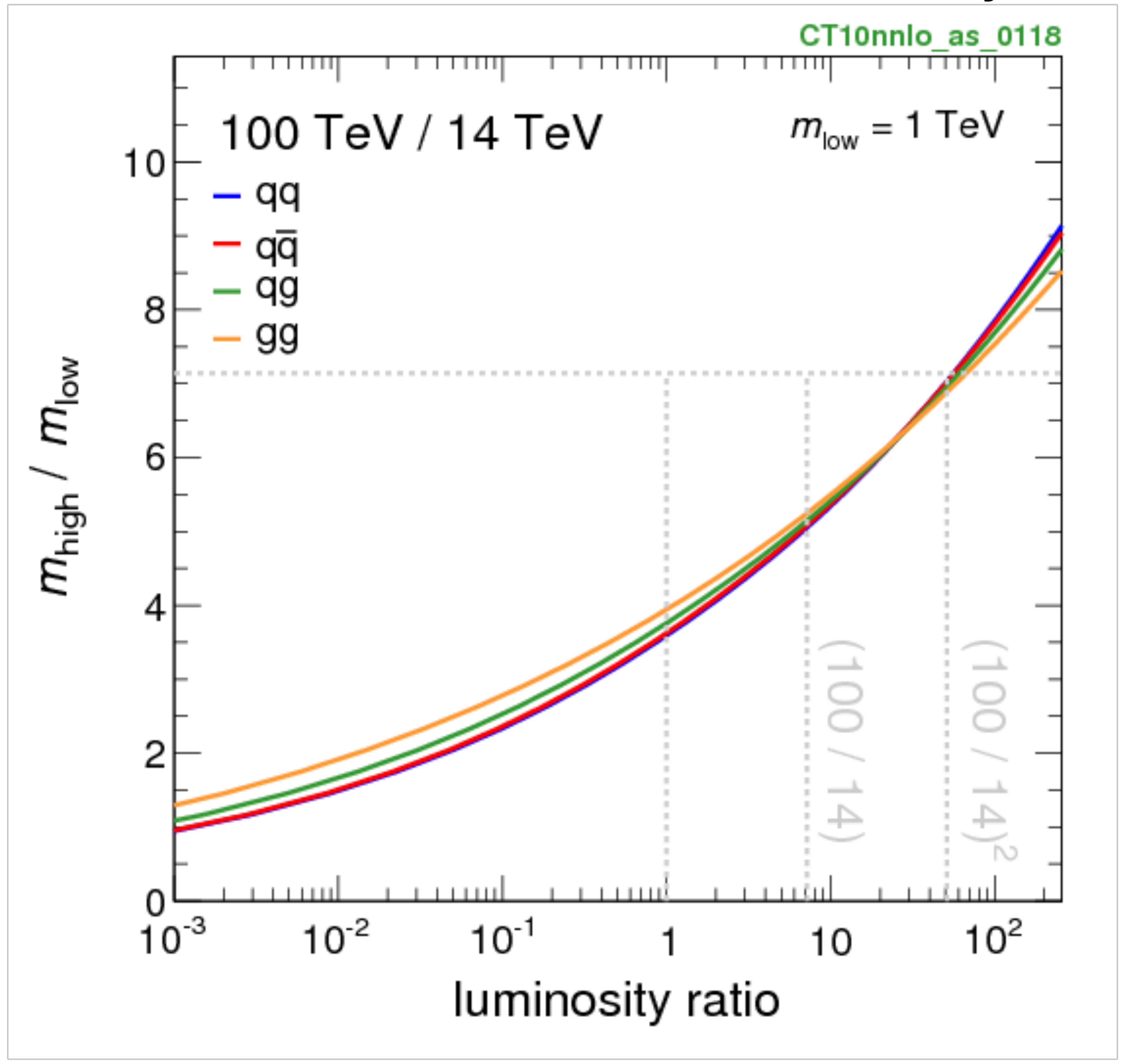
For higher mass ~O(10) TeV

Large increase in XS means new sensitivity almost immediately



Lower mass ~O(1) TeV

Smaller increase in XS means need at least 10x luminosity



Detector challenges at 100 TeV

Driven by increase in luminosity: eg. n_{Tracks} per event ~7x HL-LHC

	LHC	HL-LHC	FCC hh
COM [TeV]	13.6	14	100
Pile-up	60	200	1000
Integrated Lumi (iab)	0.3	3	20
Years of running	~10	~10	~20

- Pixels: 25 x 50 μm & 10 ps res
  - ~2x granularity
  - ~3x timing resolution <u>per track</u>
  - Data rates: 1000 TB/s
  - Radiation: ~10^2 x HL-LHC

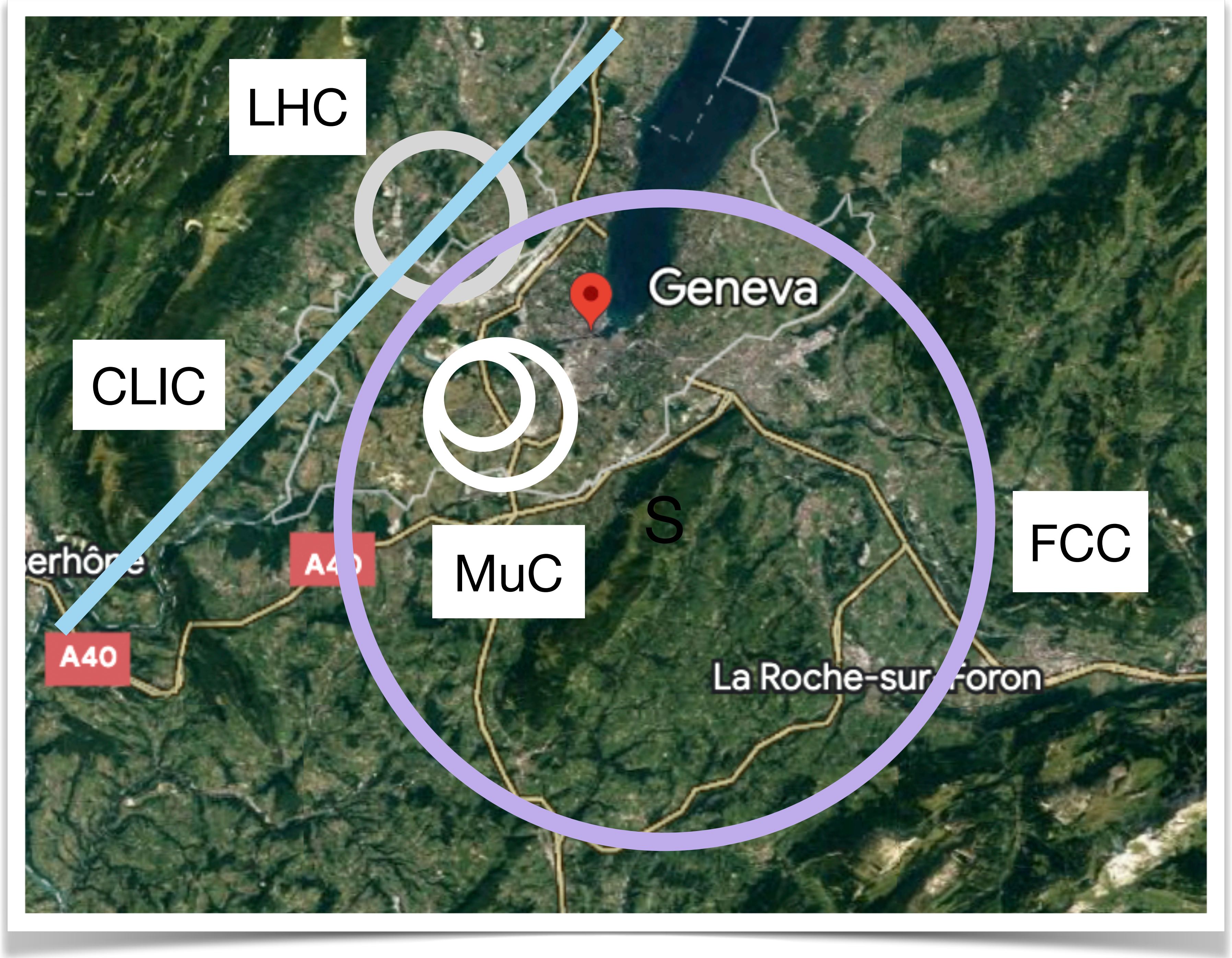
We are many decades away from being able to build these detectors

Also need forward coverage |η|=4-6 and larger detectors/magnets

What about muons?

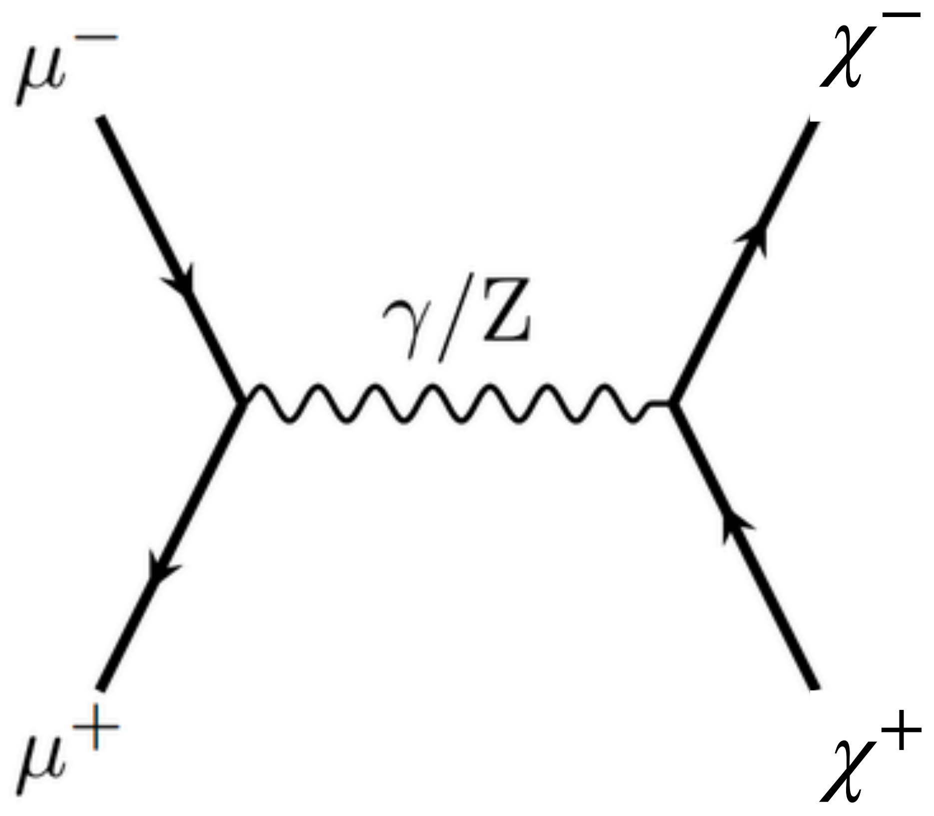
Break the traditional paradigm of larger and larger e^+e^- and hadron colliders

- Compact & power-efficient
  - Massive → no synchotron radiation
  - Leptons → 2 E_{beam}=$E_{collision}$
- Mulit-TeV Muon Collider conveniently fits within the Fermilab site!



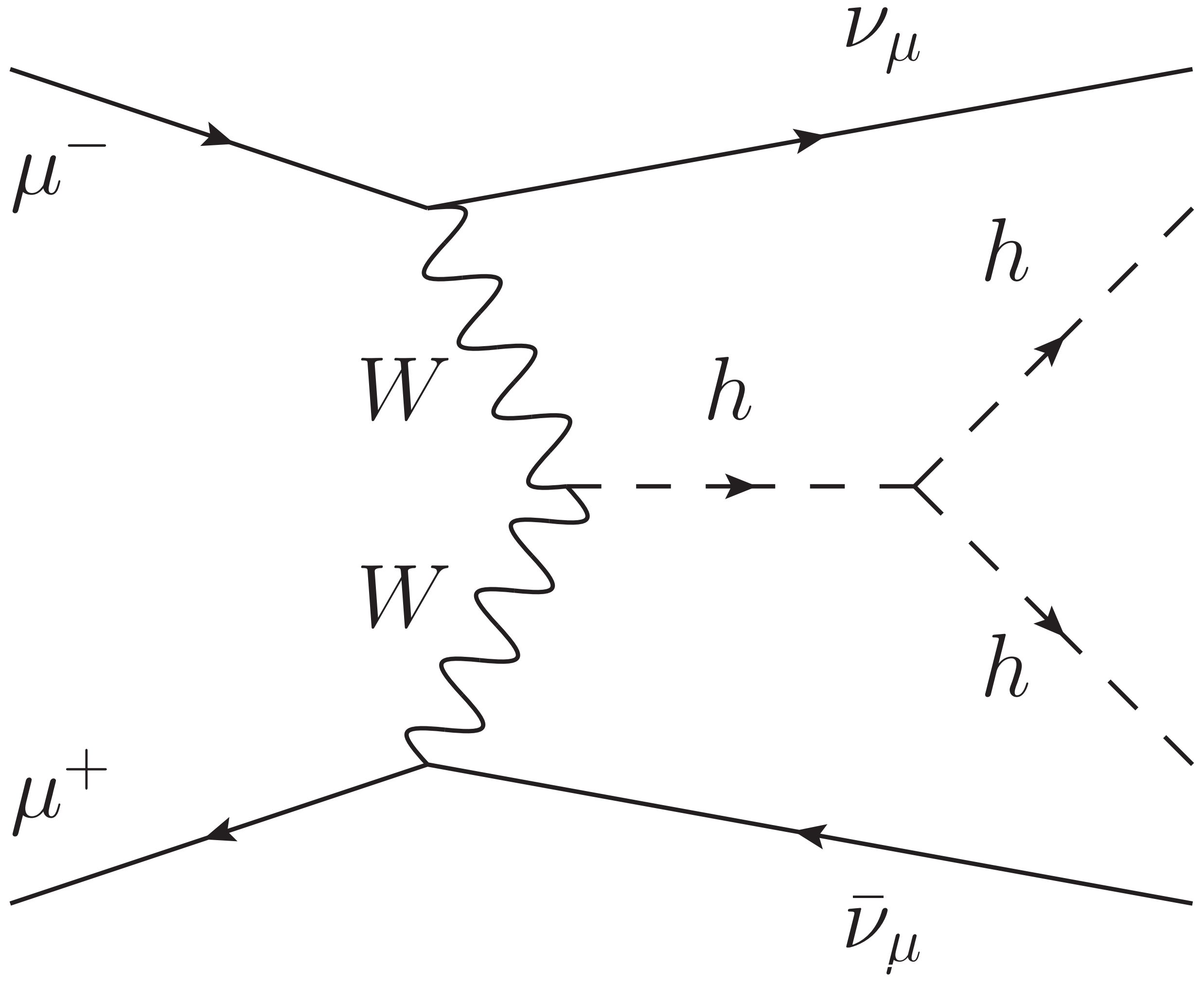
Muon Collider Physics

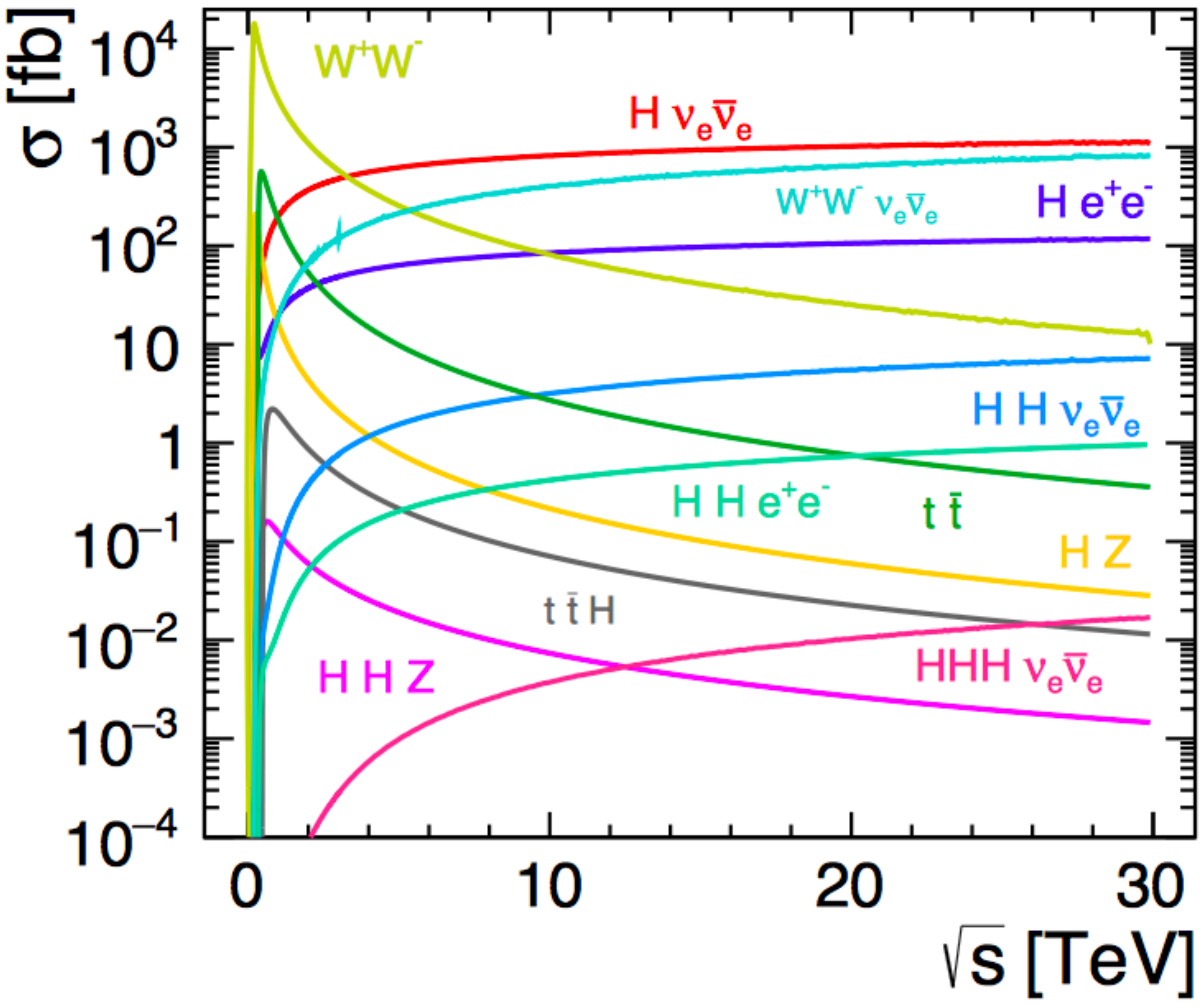
Energy reach & precision electroweak physics in same machine



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

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

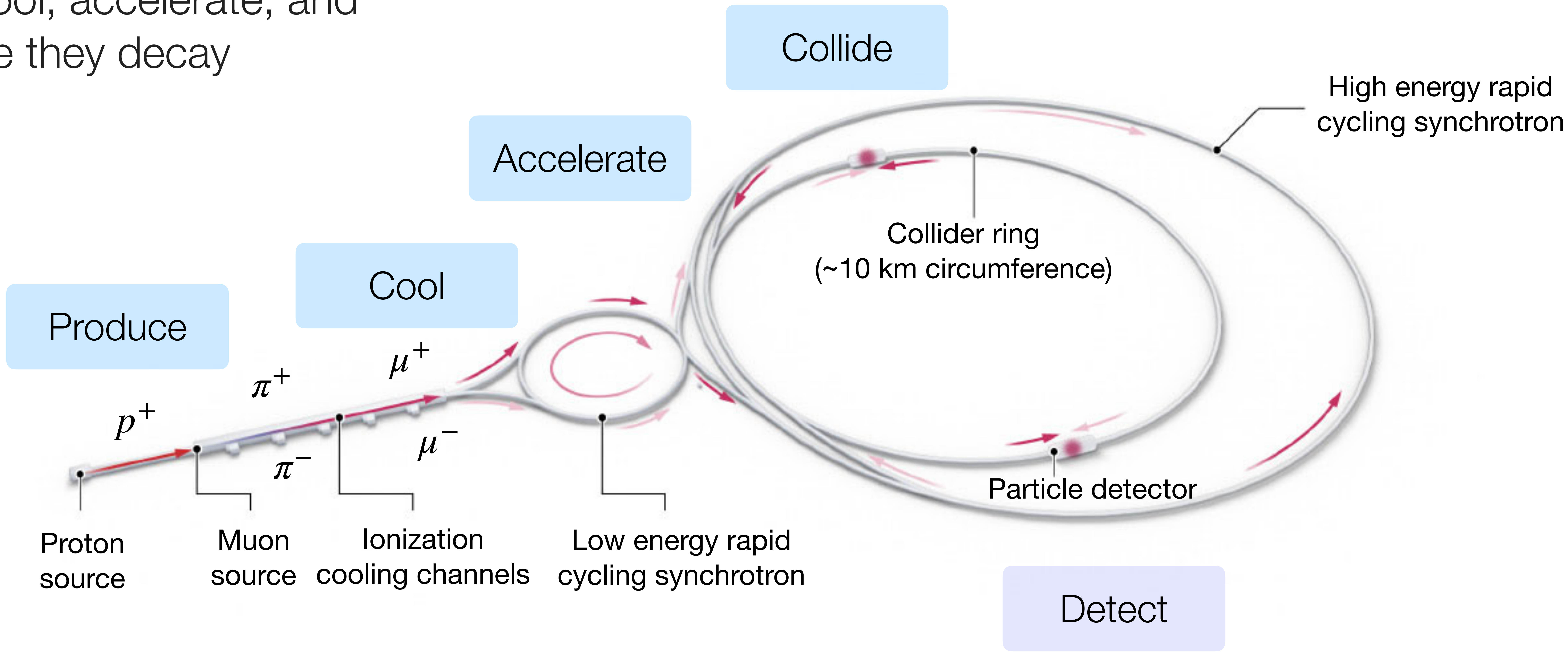




The Challenge

Muon lifetime τ=2.2 μs

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

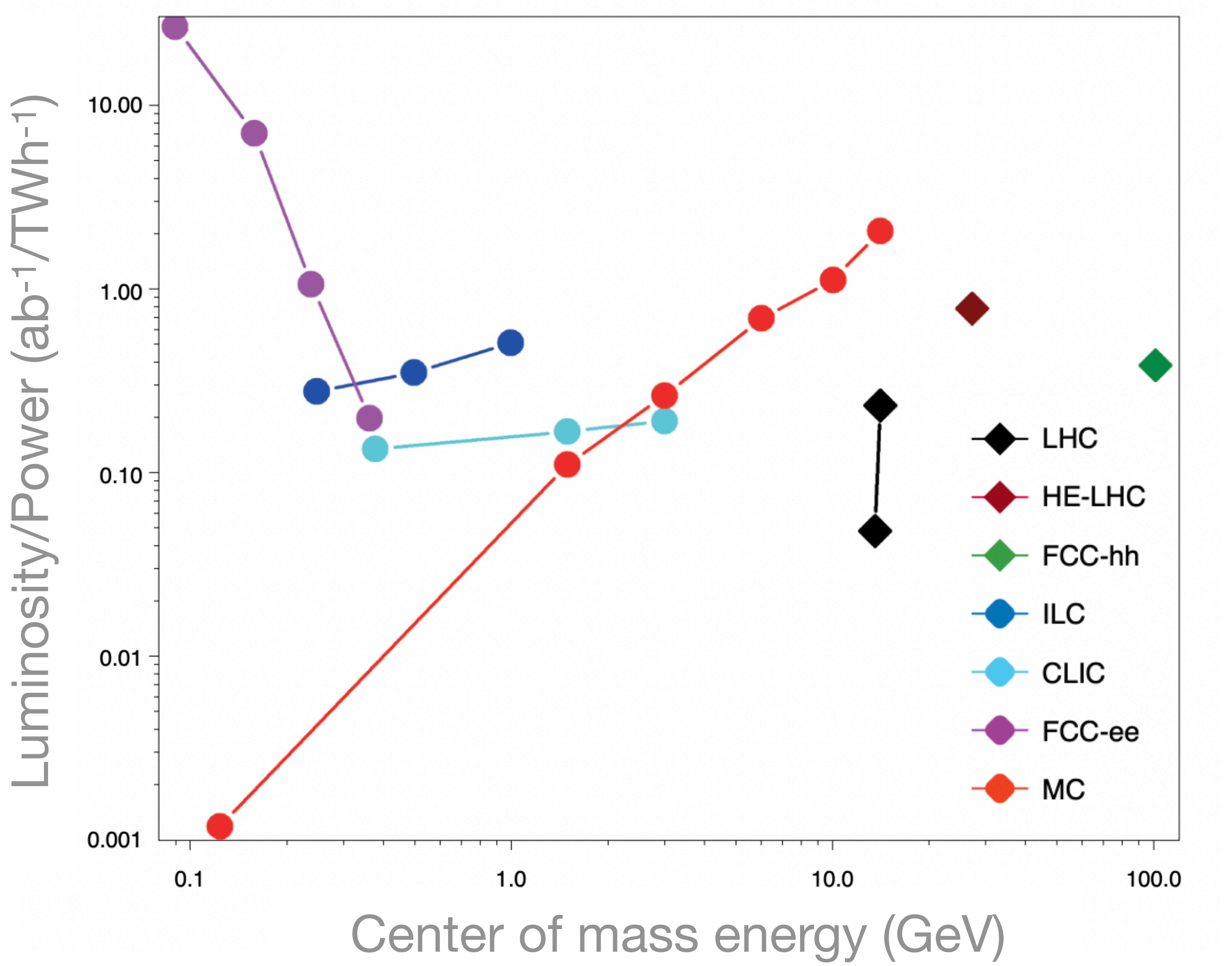


The Challenge

Muon lifetime τ=2.2 μs

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

- Also an opportunity
  - Well suited to higher energies
  - Builds on existing/planned proton infrastructure
  - Synergies with neutrinos/flavor physics
  - Lots of progress in the last decade!



Unique collision environment

Depends on energy, physics goals, and cross-sections

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

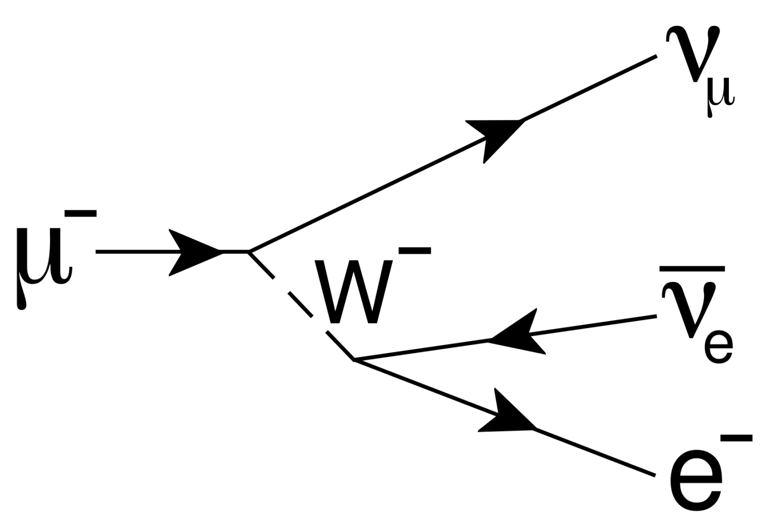
Aim for 10 ab^{-1} in 5 years

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

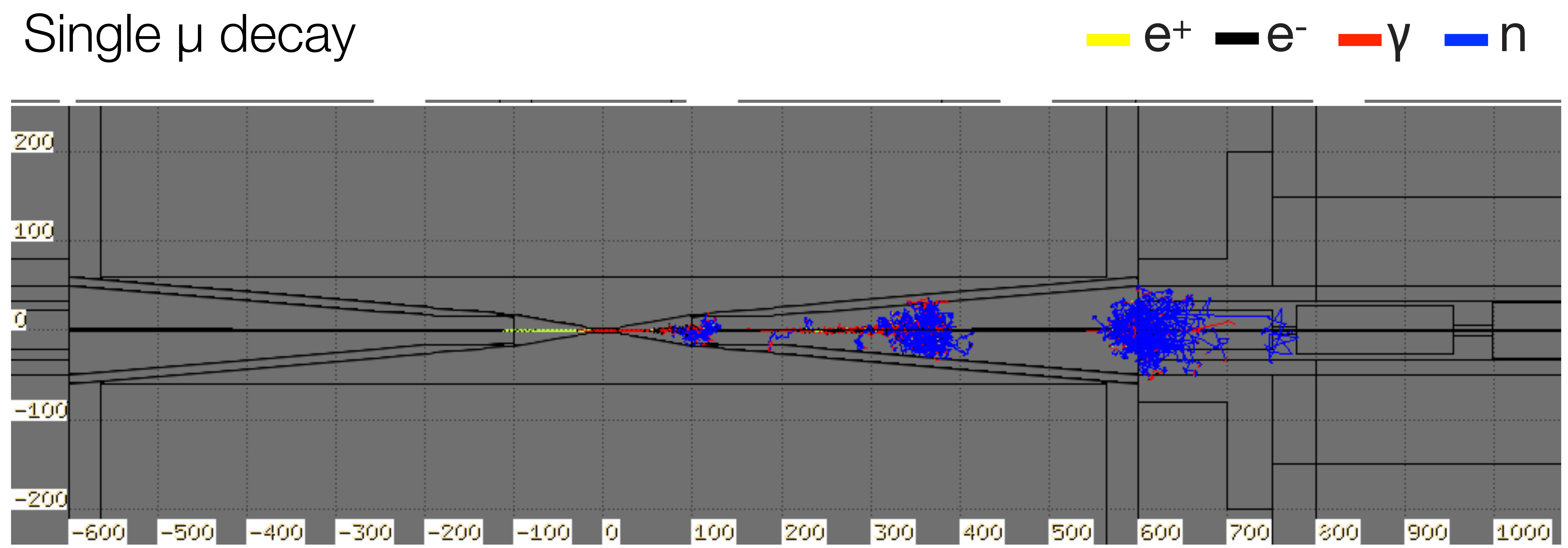
Set $n_b = 1$ and maximize N_μ per bunch	~$2 \cdot 10^{12}$ N_μ
Minimize circumference, maximize f	30 kHz
Minimize $\sigma_x \sigma_y$ beam size, aim for	~O(10) μm
Re-inject muons every βγτ	100 ms
Decays w/in 20 m of detector	10^7

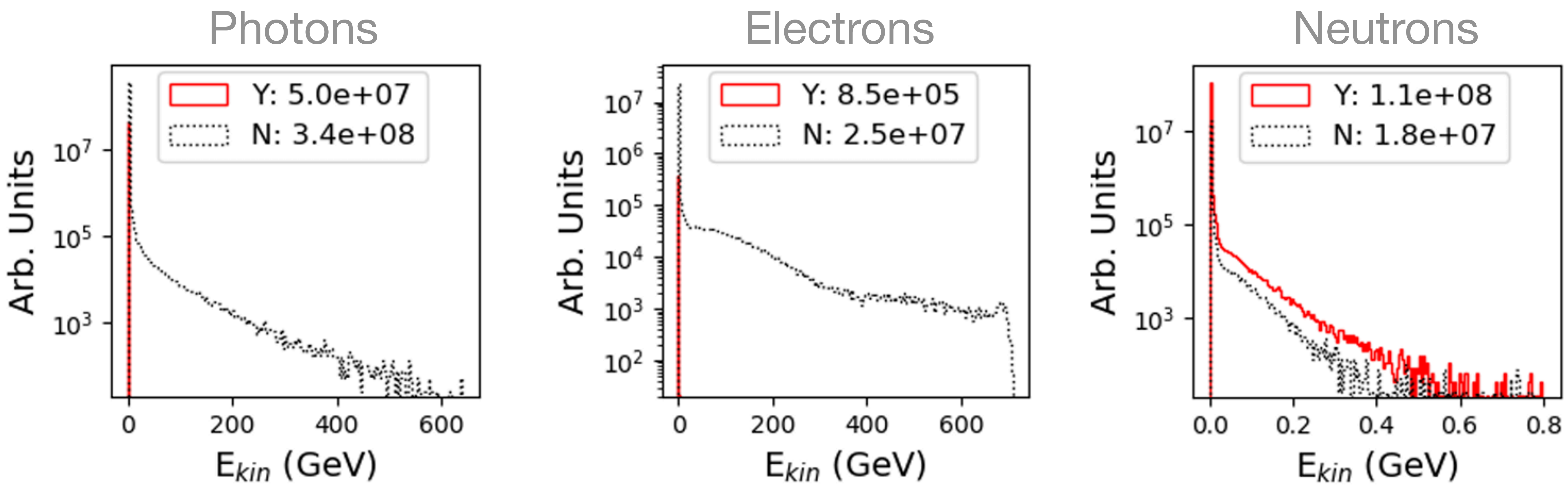
Tungsten Nozzles

Suppress high energy component



Tradeoff: increase in low energy neutrons





Inside the detector

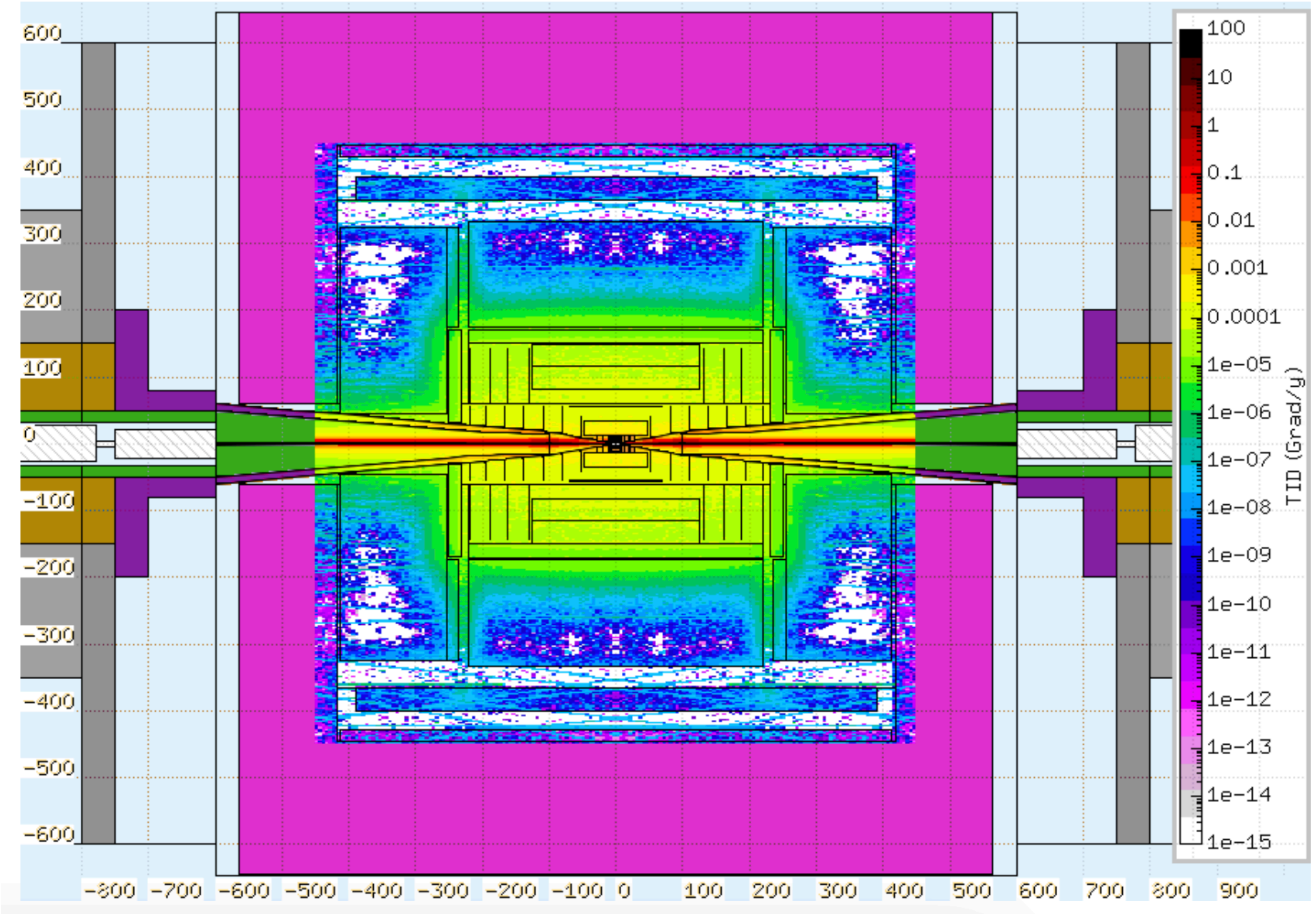
Compared to HL-LHC

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



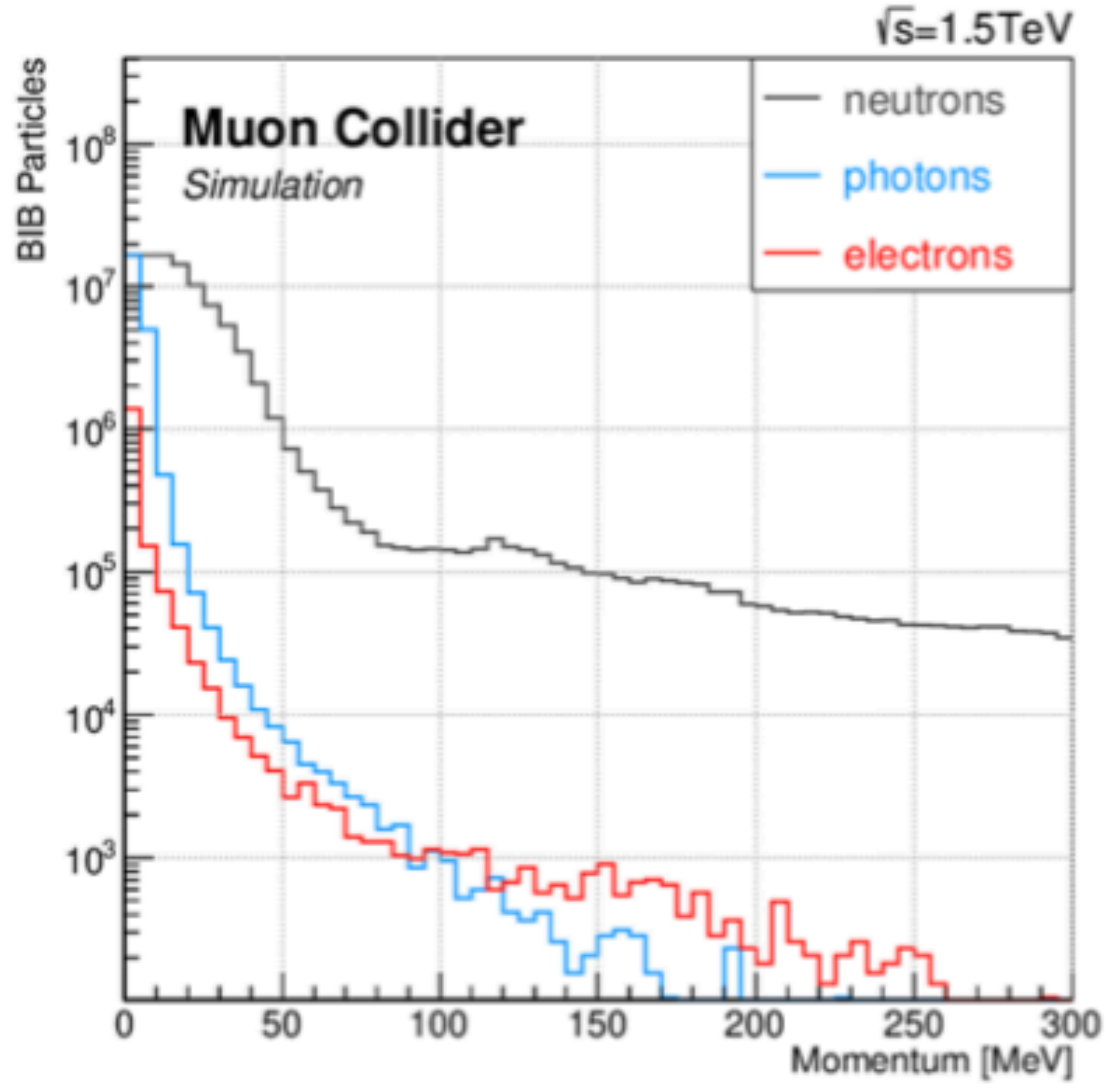
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

Background properties

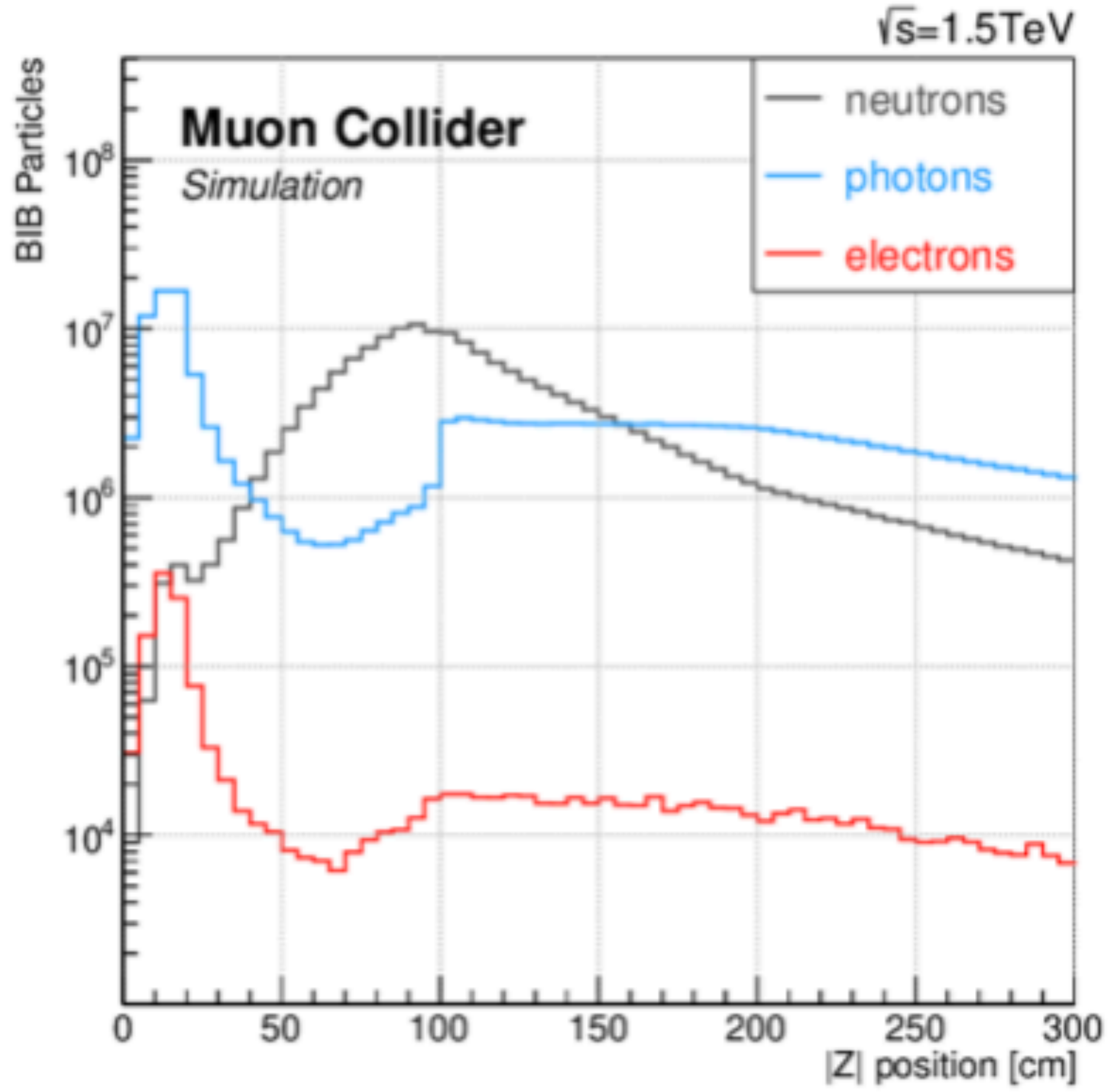
With standard nozzle ~10^8 low momentum particles per event

But this background looks very different from signal!

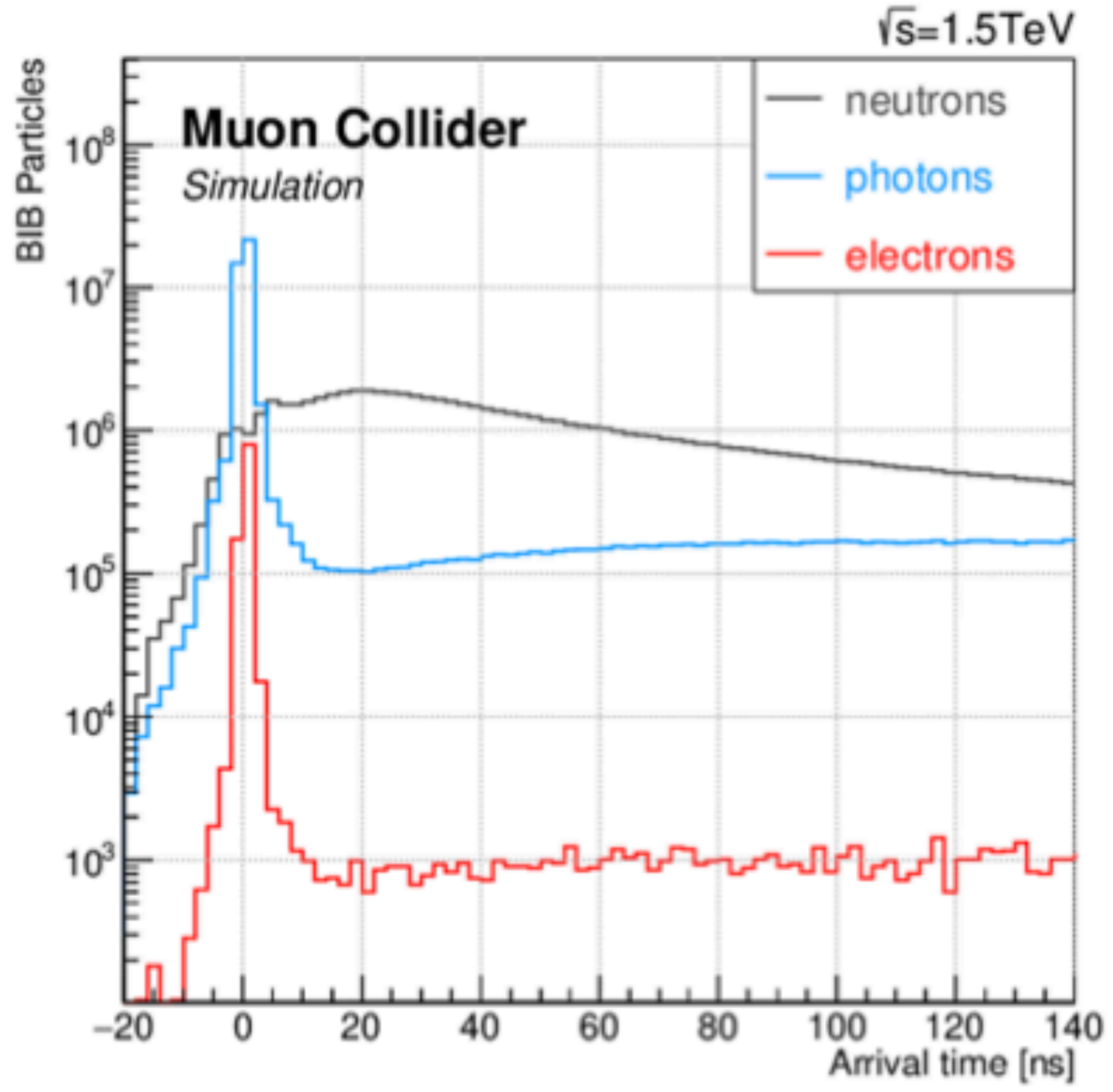
Majority < 200 MeV



Unusual position & direction



Partially out of time



Comparing muons & hadrons

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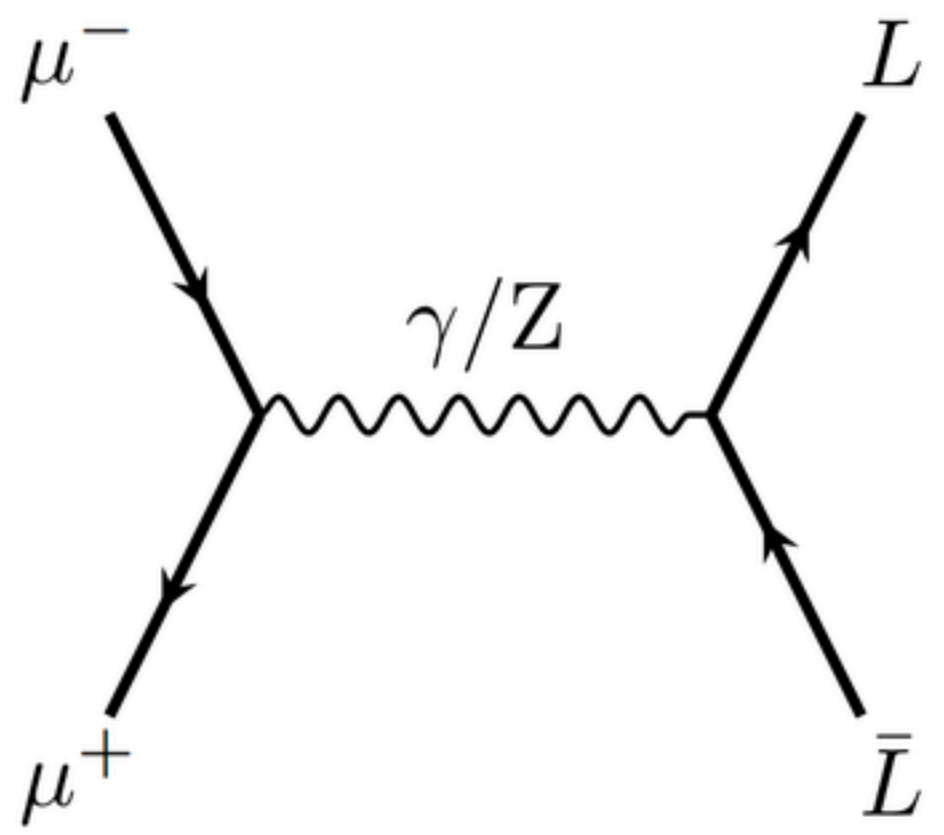
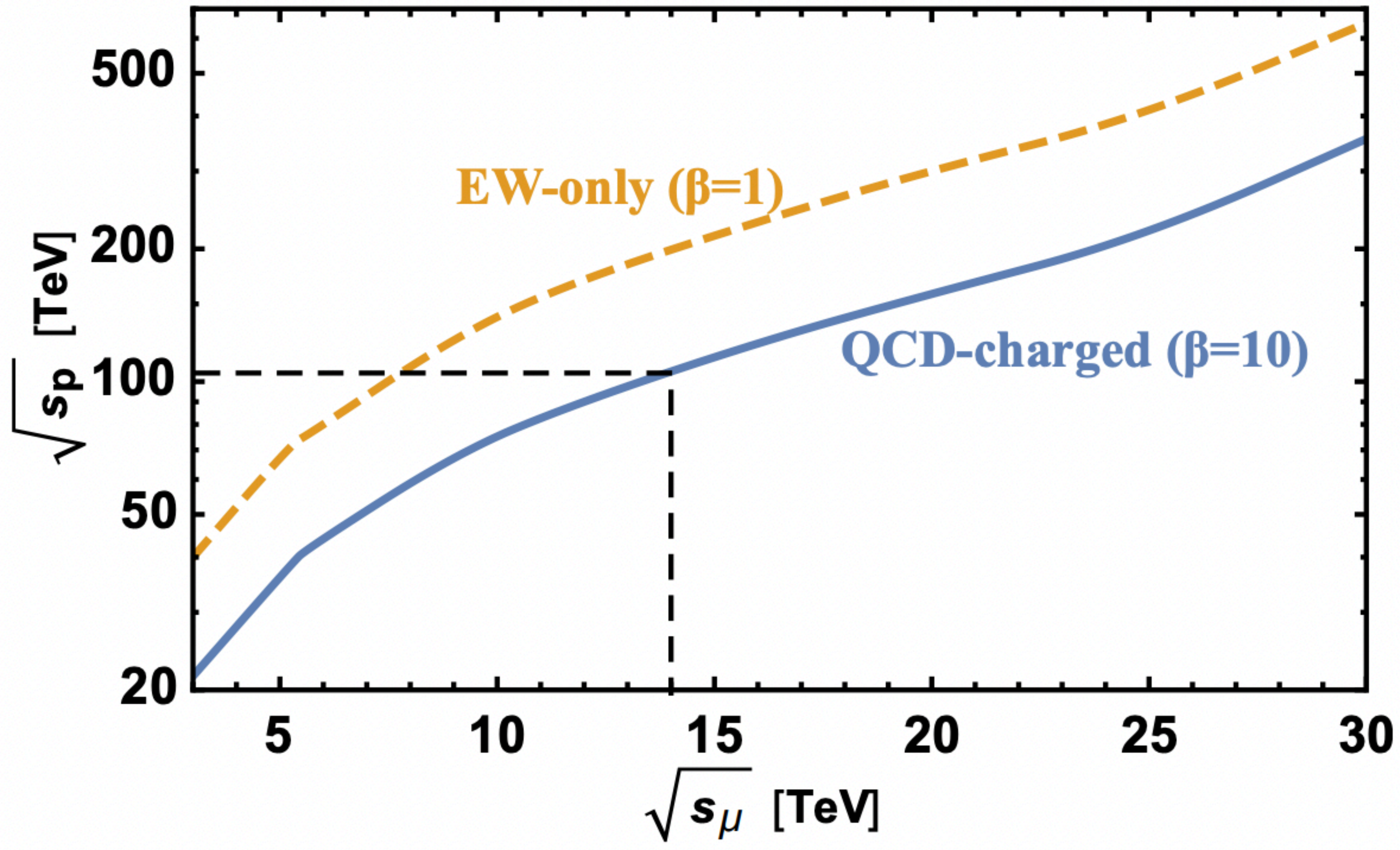
More complicated than 10 TeV μμ ~ 100 TeV pp

For 2x2 processes



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

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



Comparing direct reach

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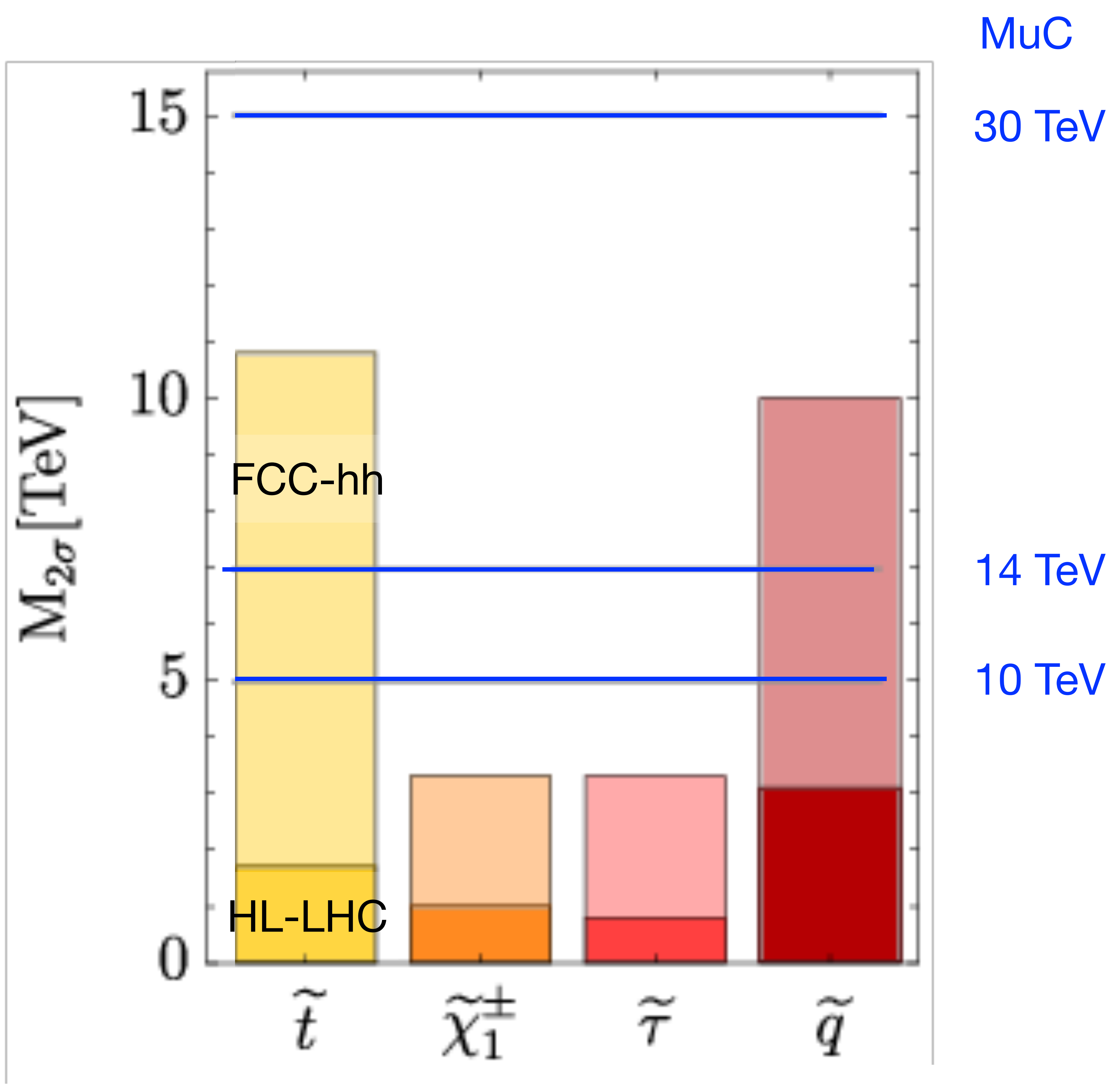
Example: Supersymmetry

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

FCC-hh: better for stops (color charge)

But, most realistic models have TeV scale sleptons/electroweakinos



Comparing indirect reach

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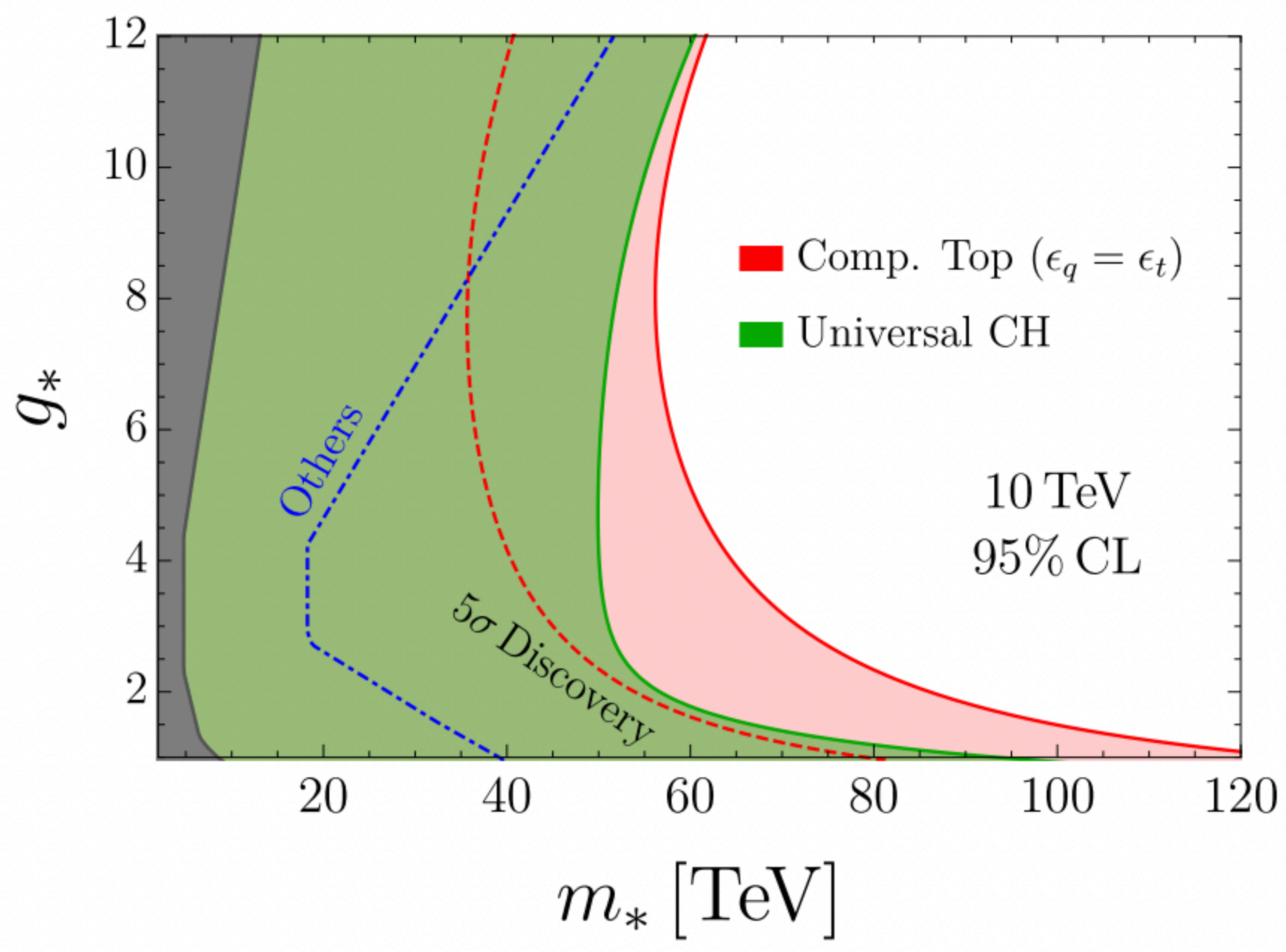
Example: Higgs Compositeness

Diboson & di-fermion final states

MuC: sensitivity scales with √s

FCC-hh: lower effective parton luminosity

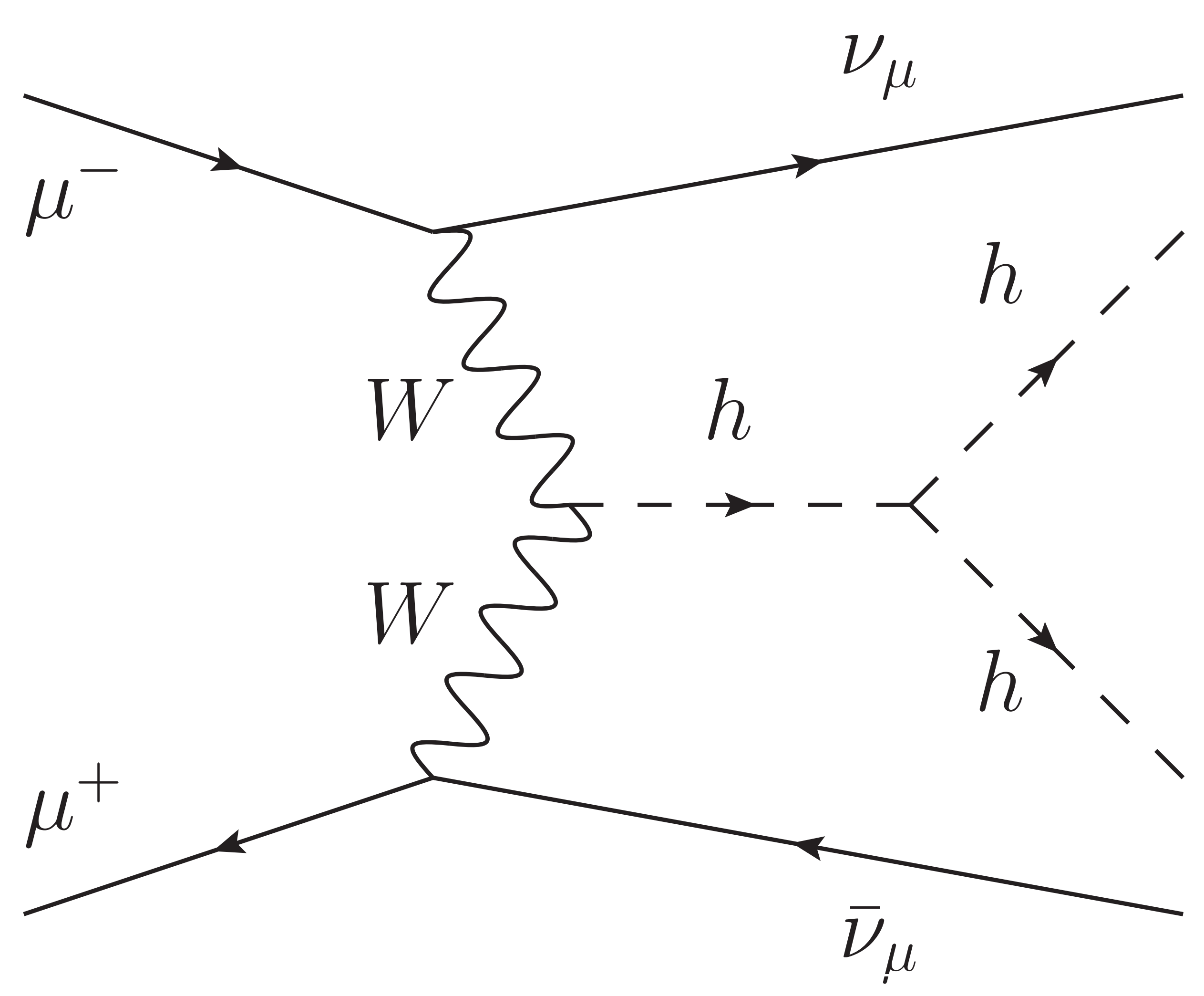
Doesn't compare



Comparing 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!

How realistic are these machines

Total projected cost

$$\text{TPC} \sim a \cdot \left(\frac{L}{10\ \text{km}}\right)^{0.55} + b\left(\frac{E}{\text{TeV}}\right)^{0.46} + c\frac{P}{100\ \text{MW}}$$

a = 1.1B “civil construction”
b = 1.2B “accelerator components”
c = 1.7B “site power infrastructure”

*correlated with *environmental impact**

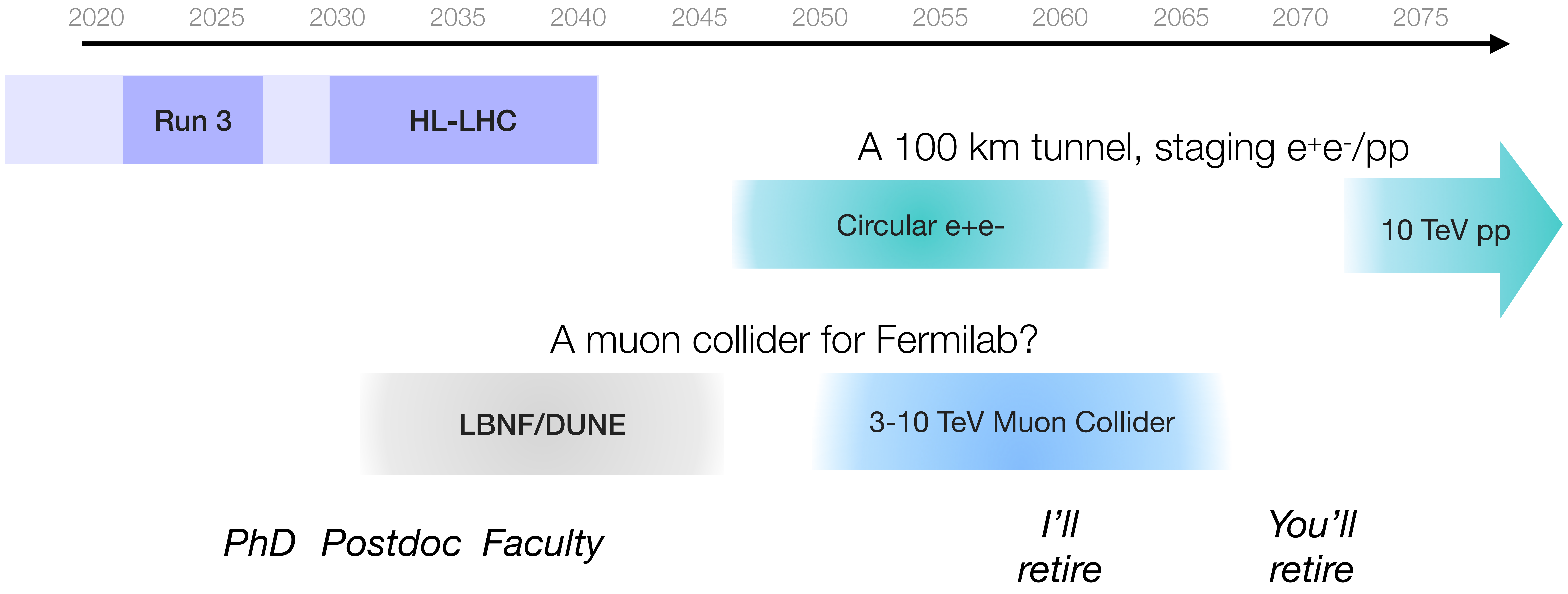
Cost & time to physics correlated with energy reach

Translates to roughly three categories

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
MuC-3	3	10	230	7-12	19-24
CLIC	3	50	550	18-30	19-24
MuC-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

And a possible future collider landscape



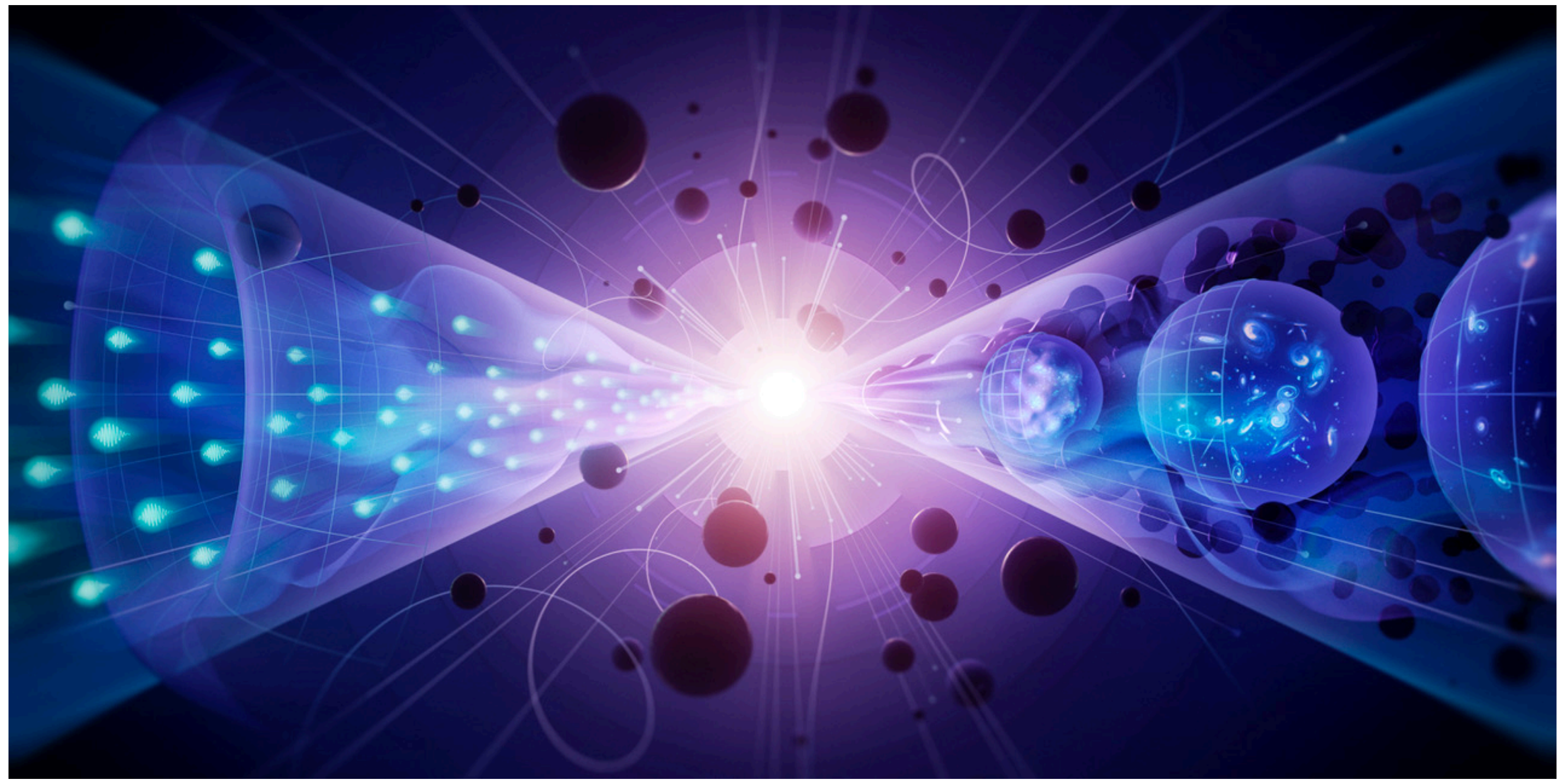
Reflecting on the past few years

- Especially exciting for Muon Colider
  - 2020: ESPPU recommends MuC Design Study
  - 2021: International Muon Collider Collaboration
  - 2022: Surge in interest at Snowmass
  - 2023: “MuCol” project funded by EU
  - <u>2023: Very positive outcome from P5!</u>
  - 2023: Inaugural US Muon Collider Meeting
  - 2024: US funding starting to come in

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.

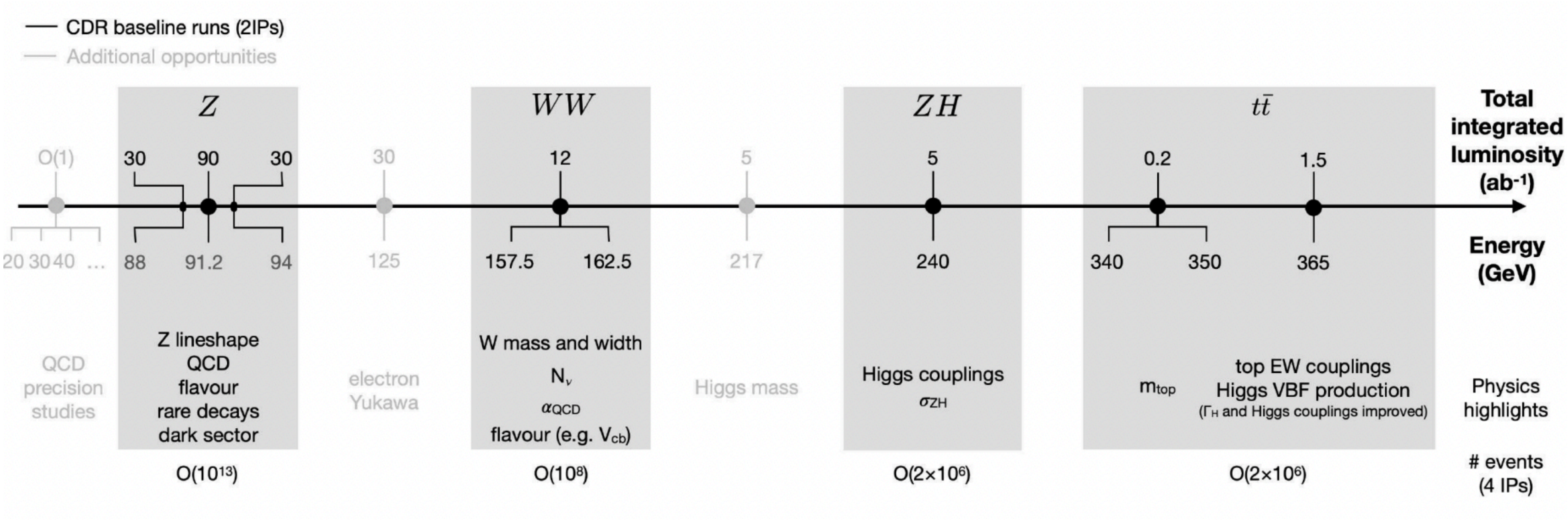
Takeaways for CMS DAS students

- Future Colliders are YOUR future
- Form your own opinions
  - Read the Snowmass Implementation Task Force report
  - Learn from your senior colleagues
- Prepare for an exciting career
  - Learn how to build & operate experiments at the LHC & HL-LHC
  - Get involved in Future Collider R&D
- Make your vision a reality

Backup

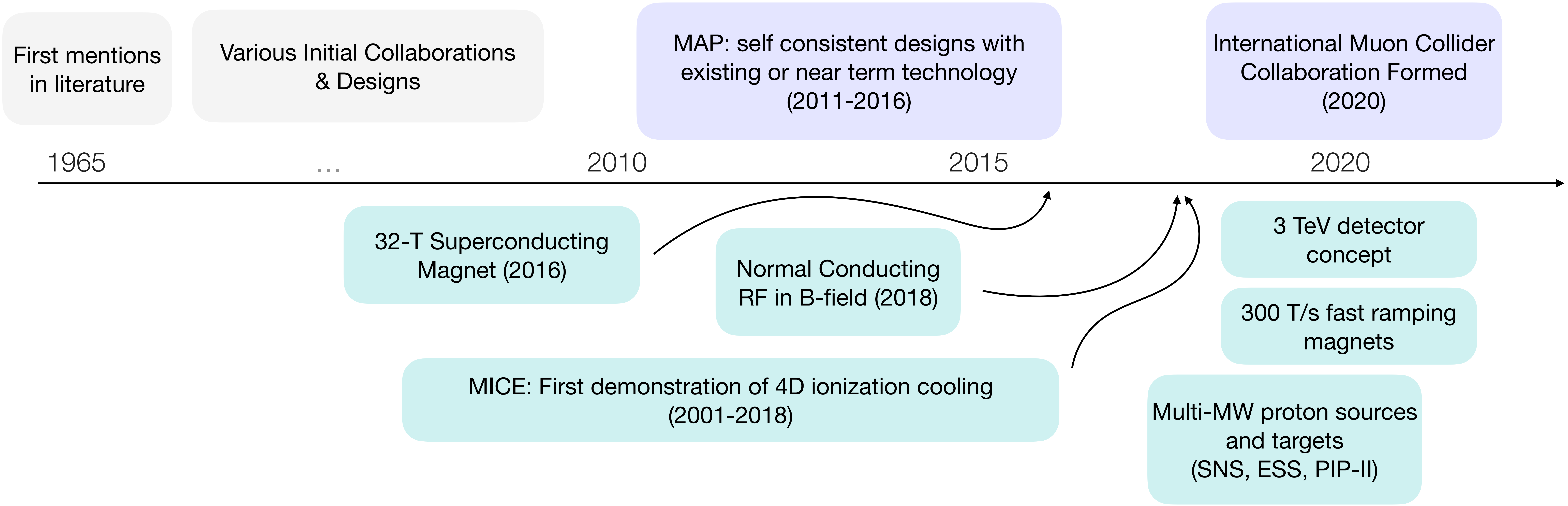
Karri Folan DiPetrillo
University of Chicago
Fermilab Wine & Cheese
17 January 2025

A potential FCC-ee run program



Muon Collider: Progress so far

Perception: “no progress in past 50 years”



Reality: recent design progress and advances in technology

Muon Collider Detector

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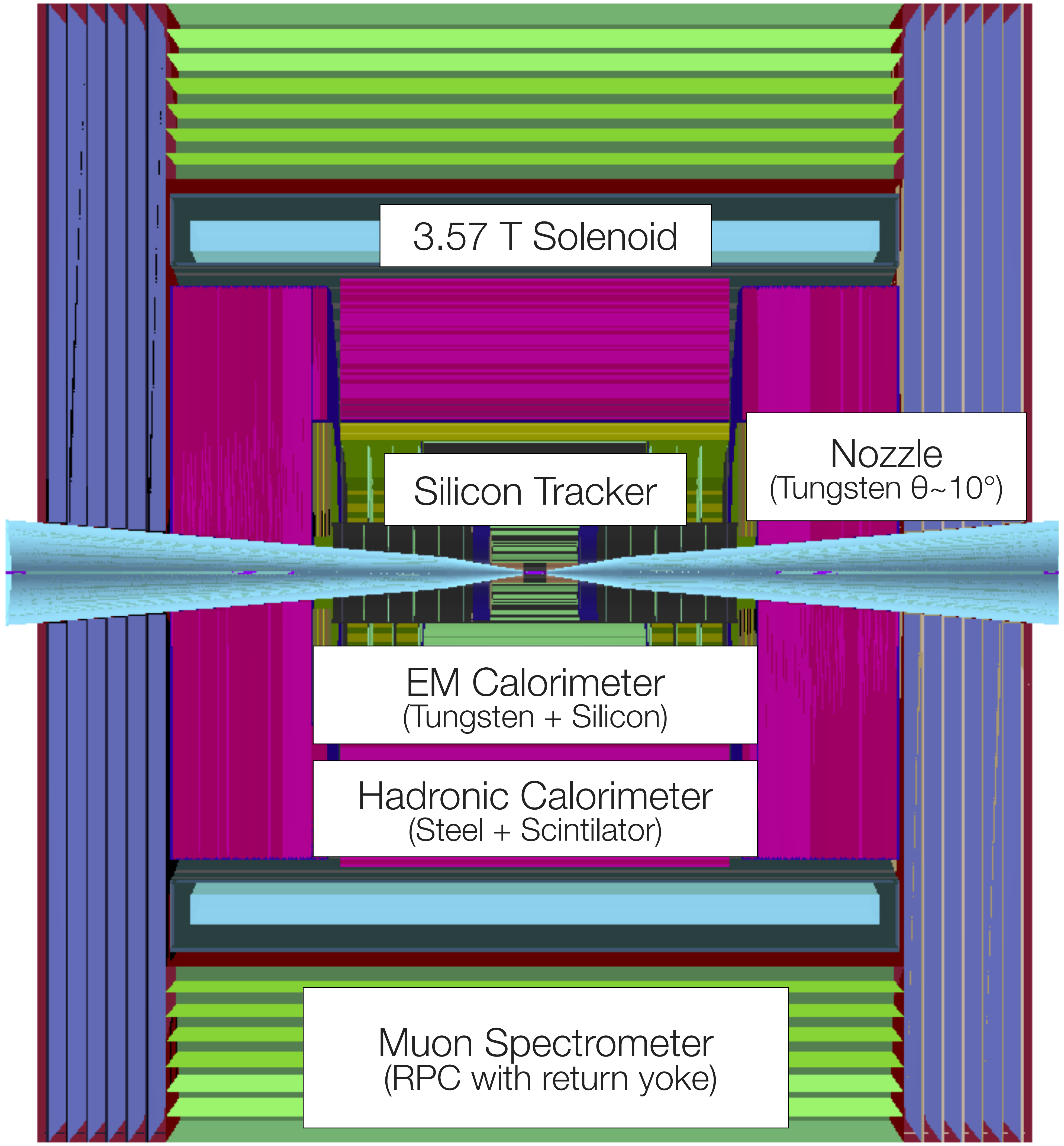
Major outcomes of Snowmass/IMCC

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

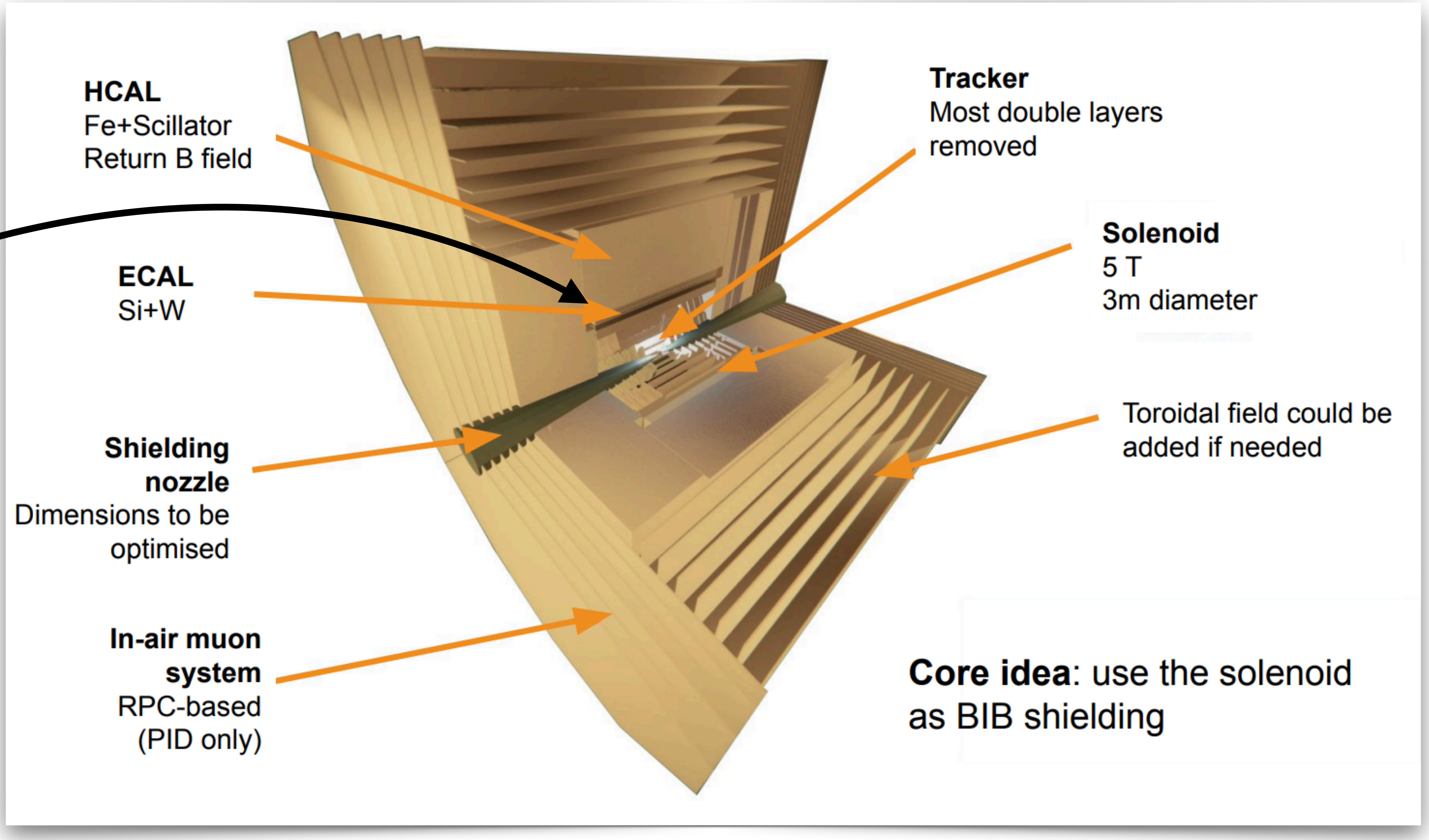
Detector Magnet Workshop
Summary by A. Bersani

Need to grow the detector

Solenoid: Higher B-field & inner radius technically challenging

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

Need to reestablish expertise to build CMS-style magnets!



Muon Collider Detector: 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

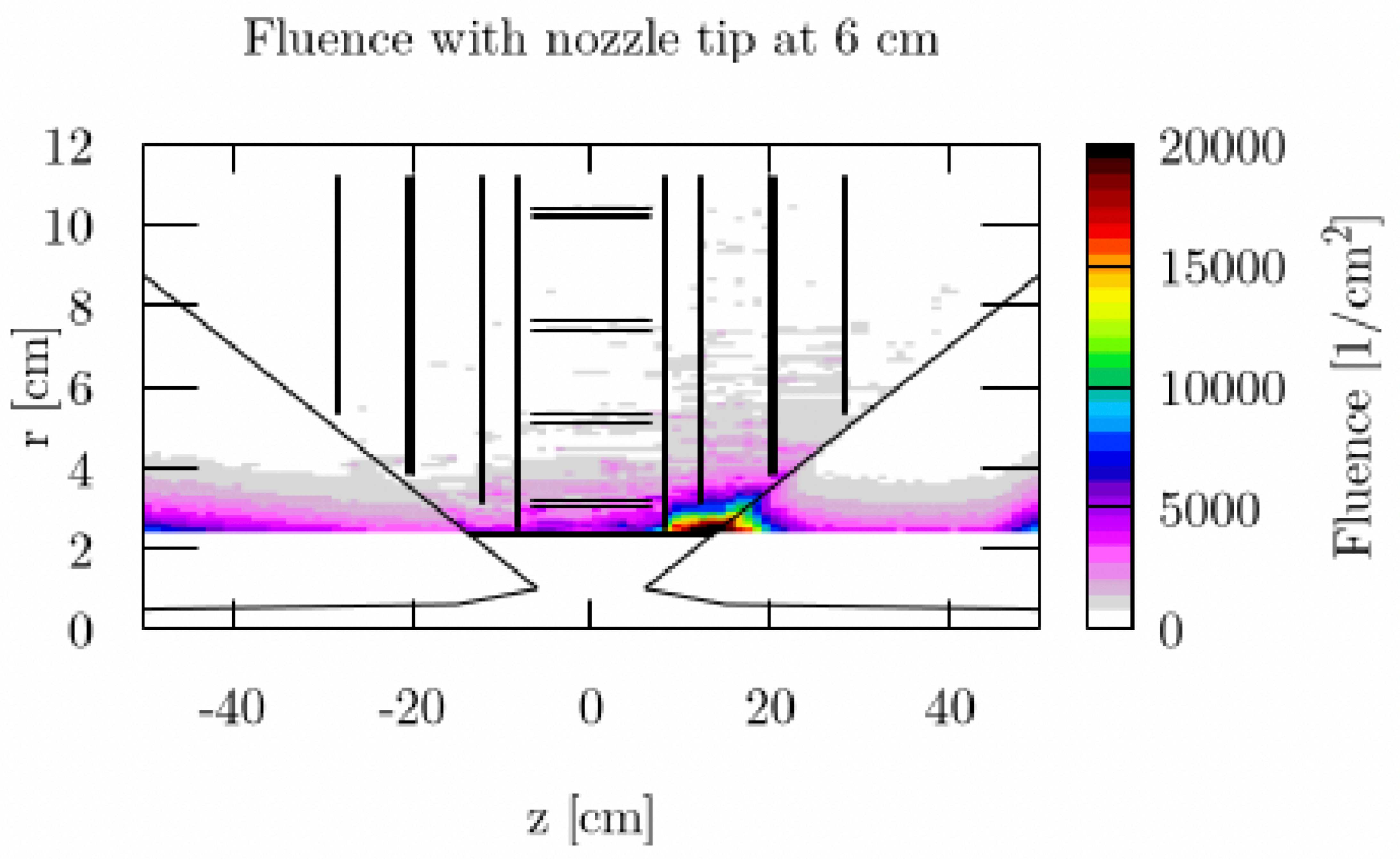
→ Silicon+Tungsten 5x5 mm^2 cells
Timing resolution (~100 ps)
Longitudinal segmentation

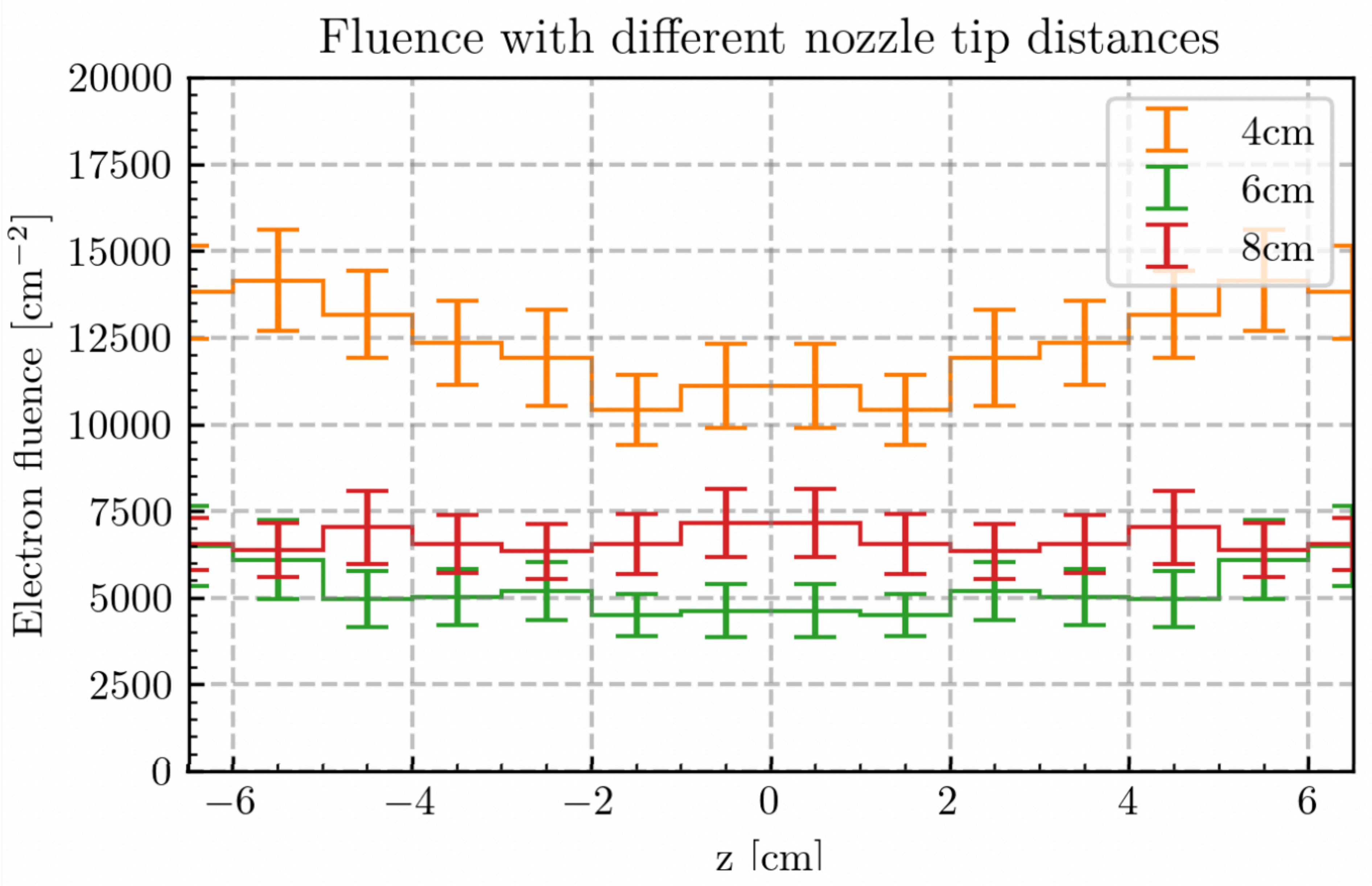
Room for new ideas!

Work in progress: Machine detector interface

D. Calzorlari

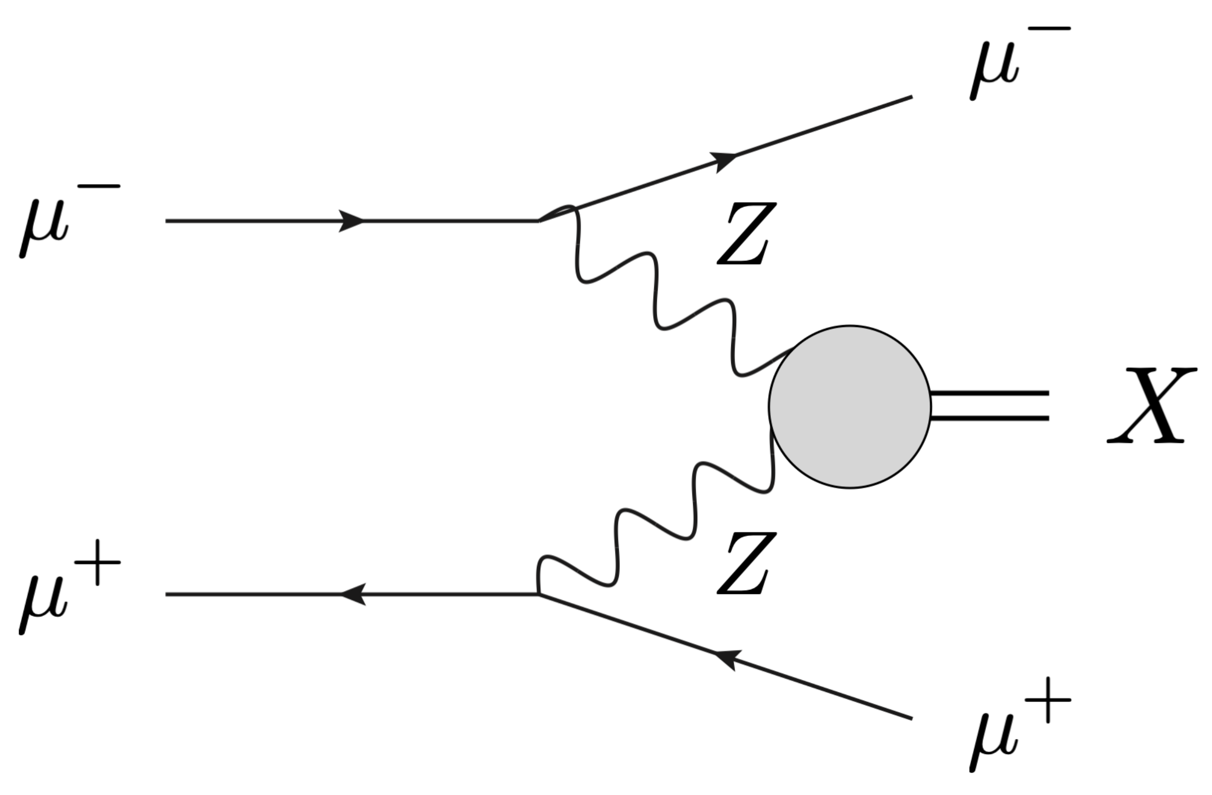
Beam induced background highly dependent on nozzle configuration
Systematic optimization in progress!





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}

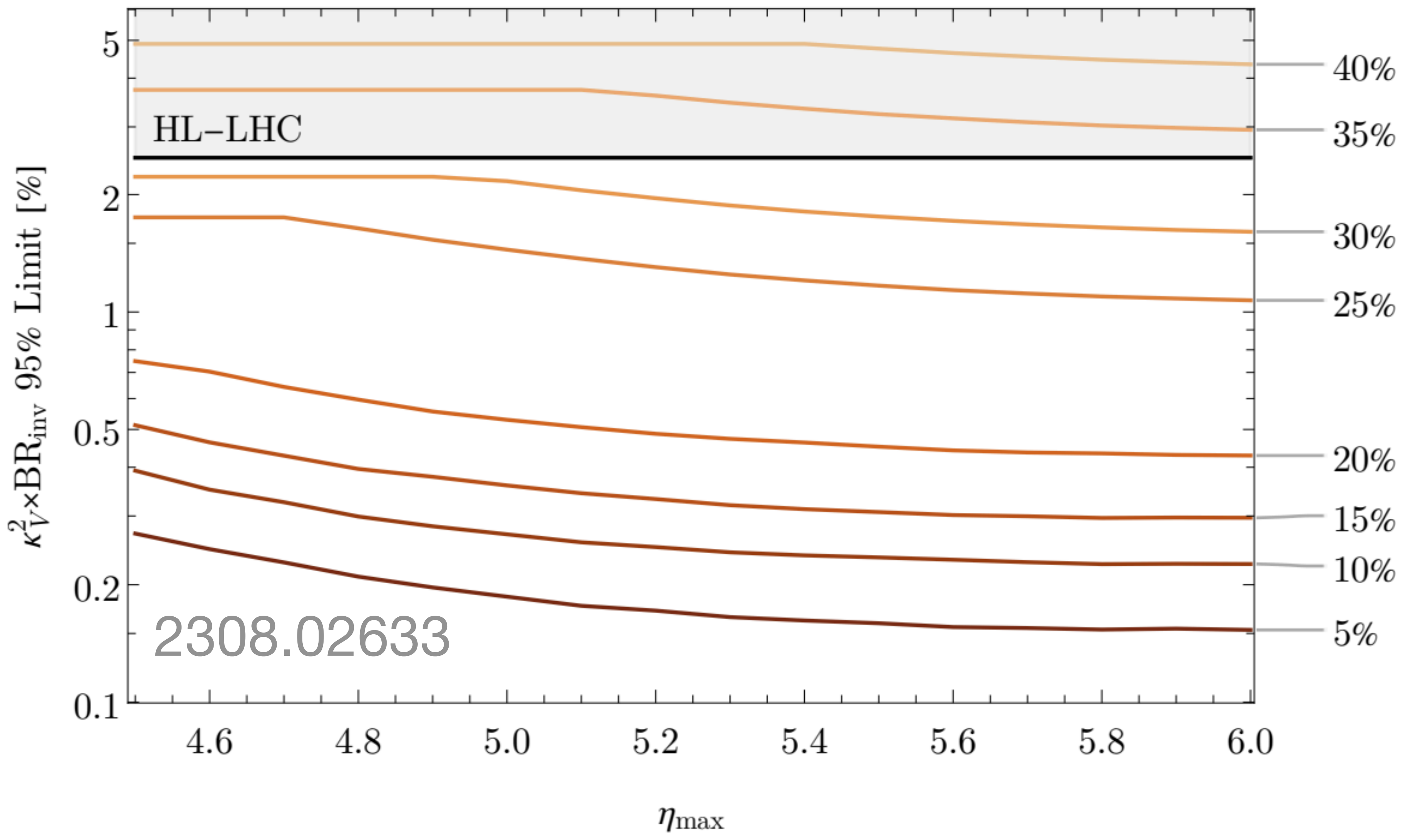
Γ_h via inclusive rate

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



Takeaway: Can we do physics?

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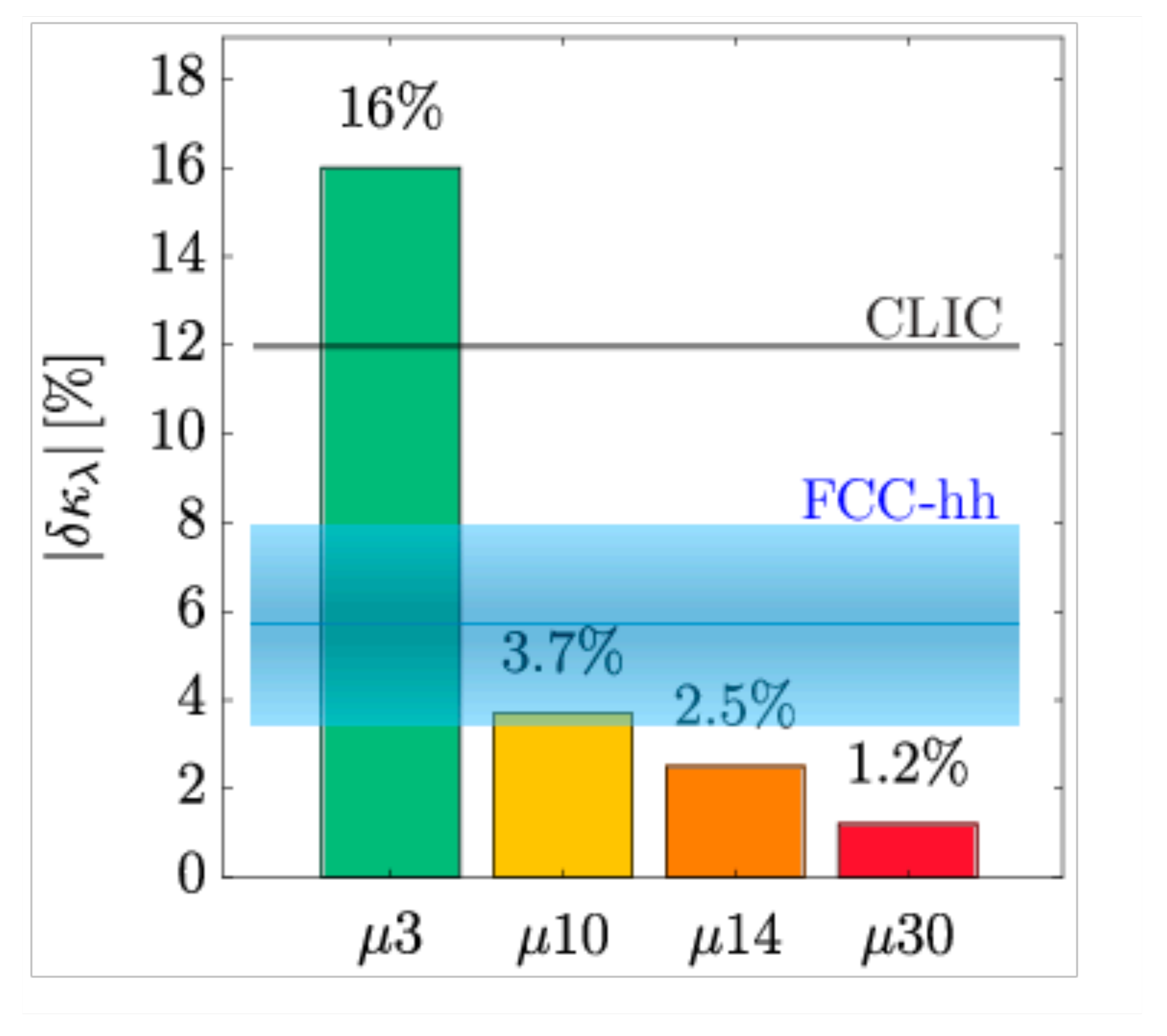
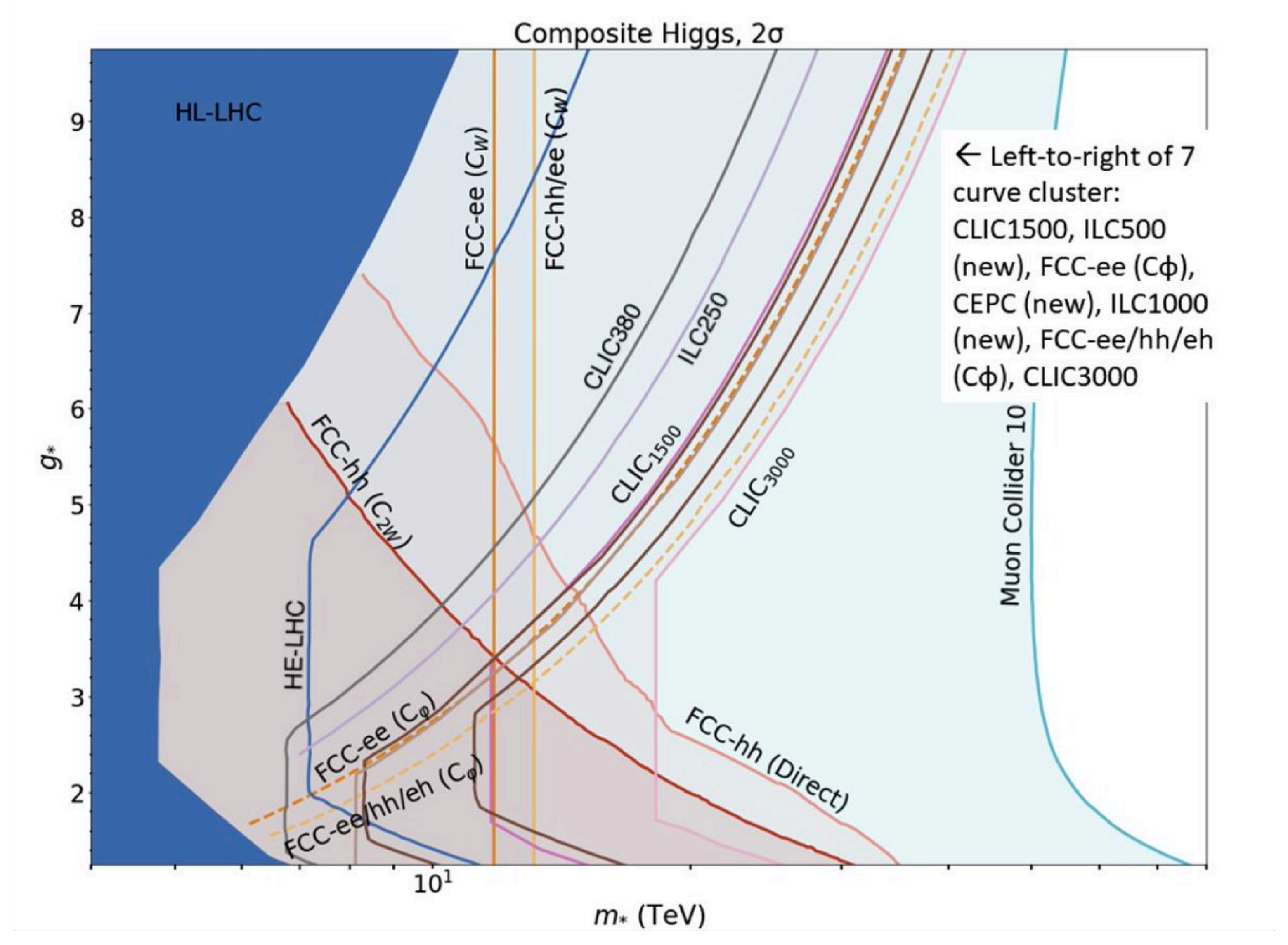
Baseline detector design & full simulation studies indicate yes!
With work in progress we can likely do even better :)

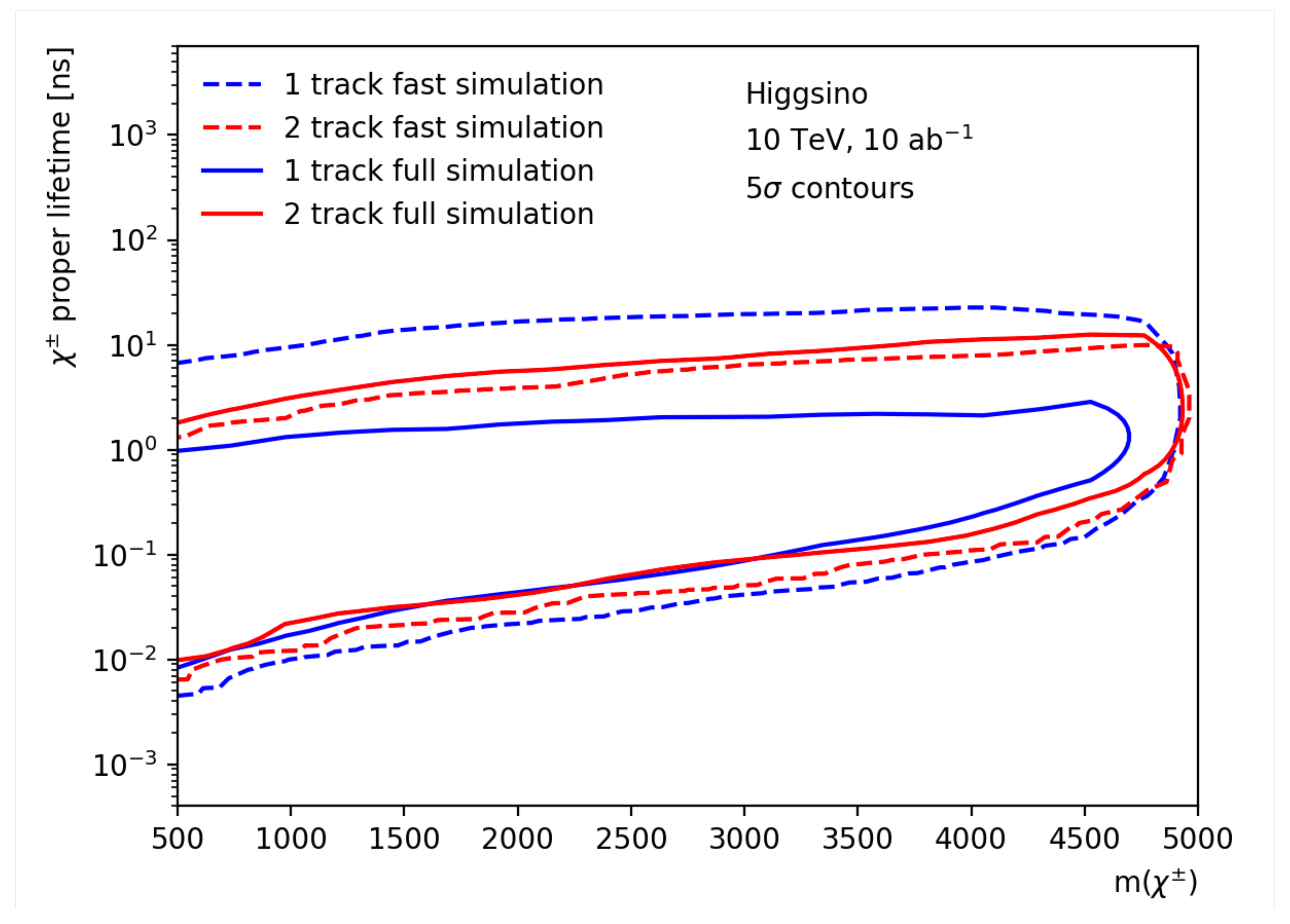
Higgs self-coupling



Composite Higgs Scenarios



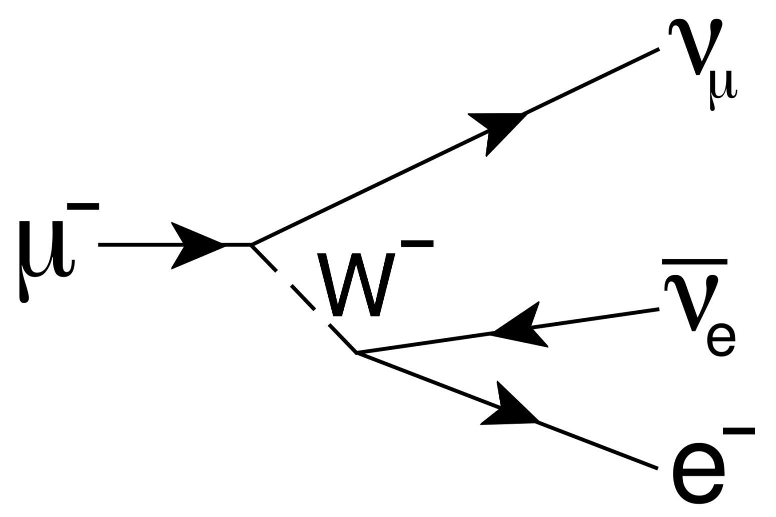
WIMPs/Disappearing track



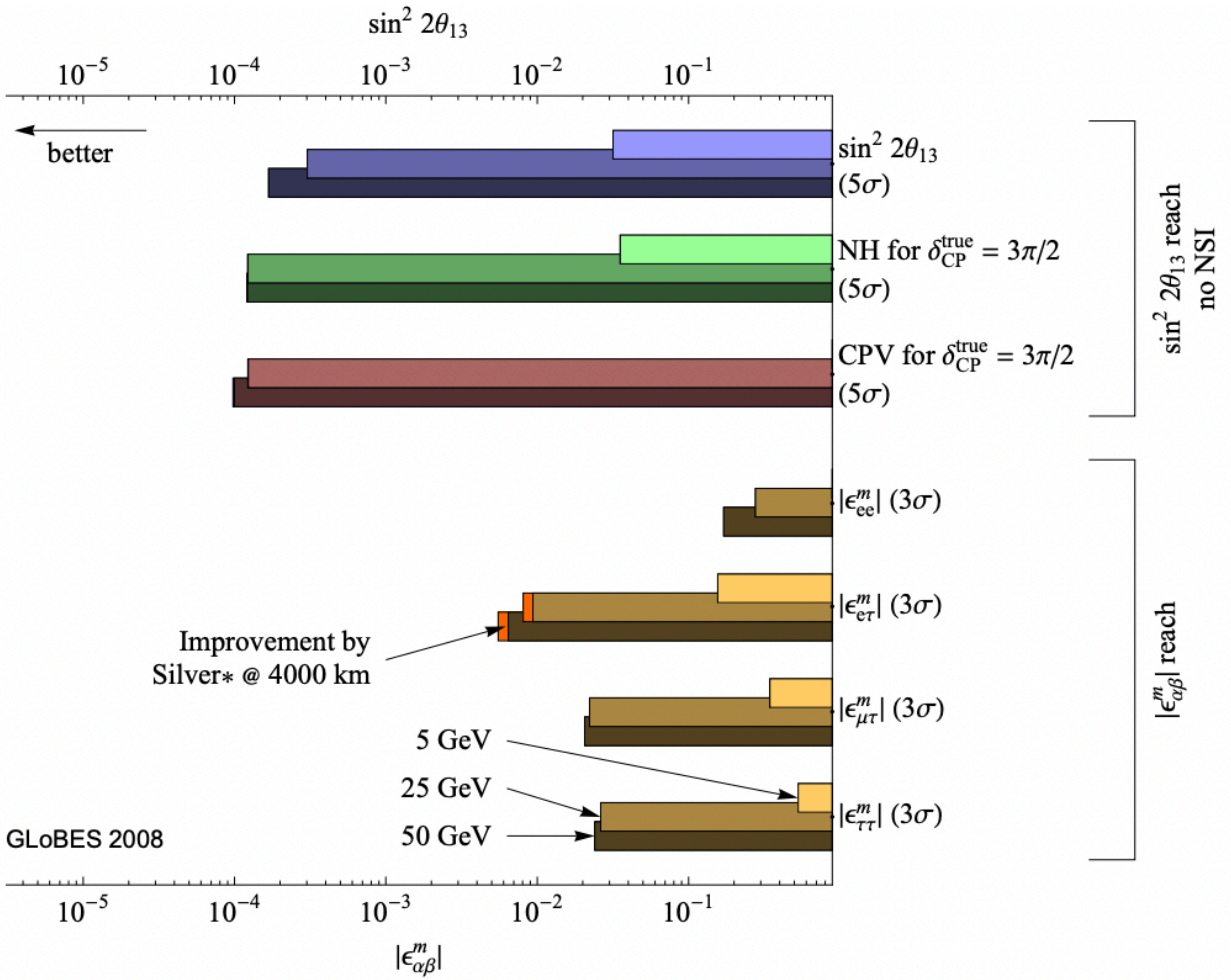
The perfect neutrino beam

2203.08094

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



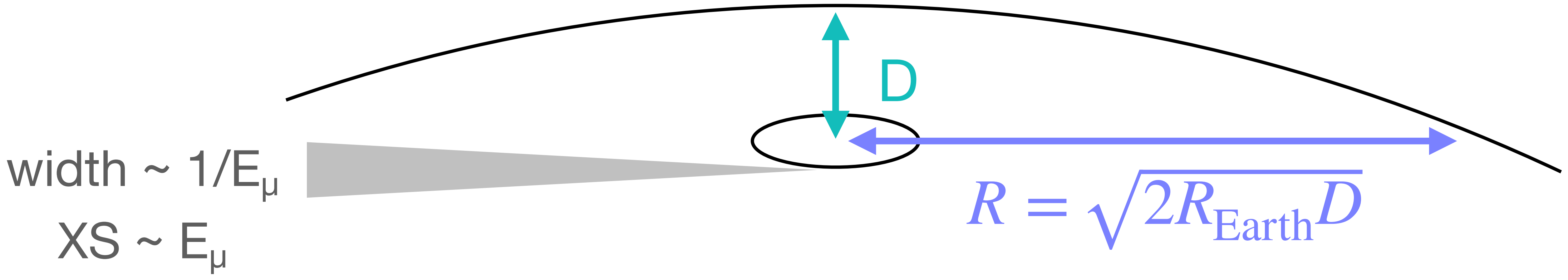
- At low energy:
  - precision cross sections
  - sterile neutrino searches
  - δ_{CP}, Δm^2_{31}, θ_{13}, θ_{23}, ν_τ appearance
  - Over constrain PMNS paradigm
- At high energy: not fully prepared to say
- An appealing future after Dune/Hyper-K?



Neutrino Flux

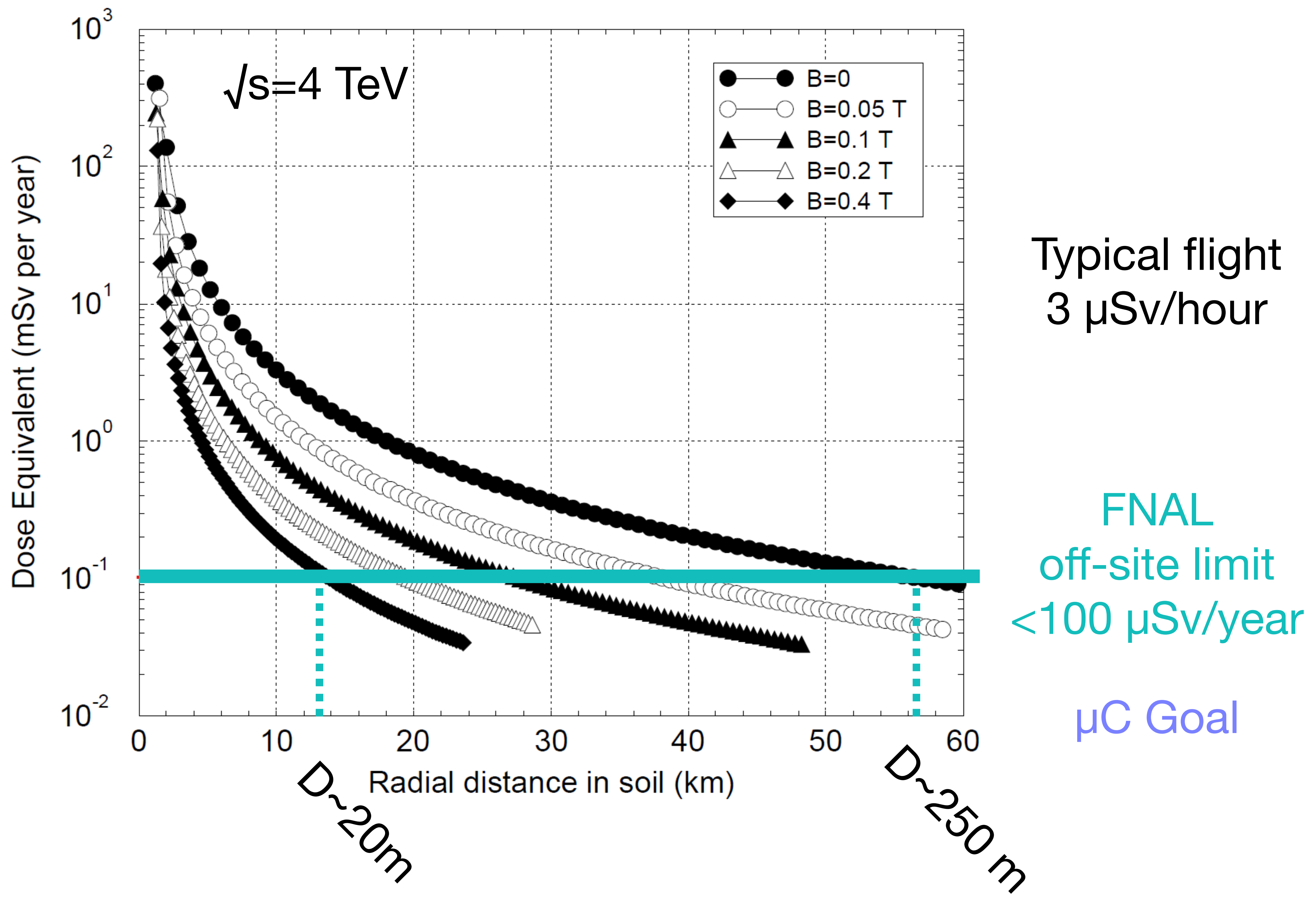
2209.01318

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



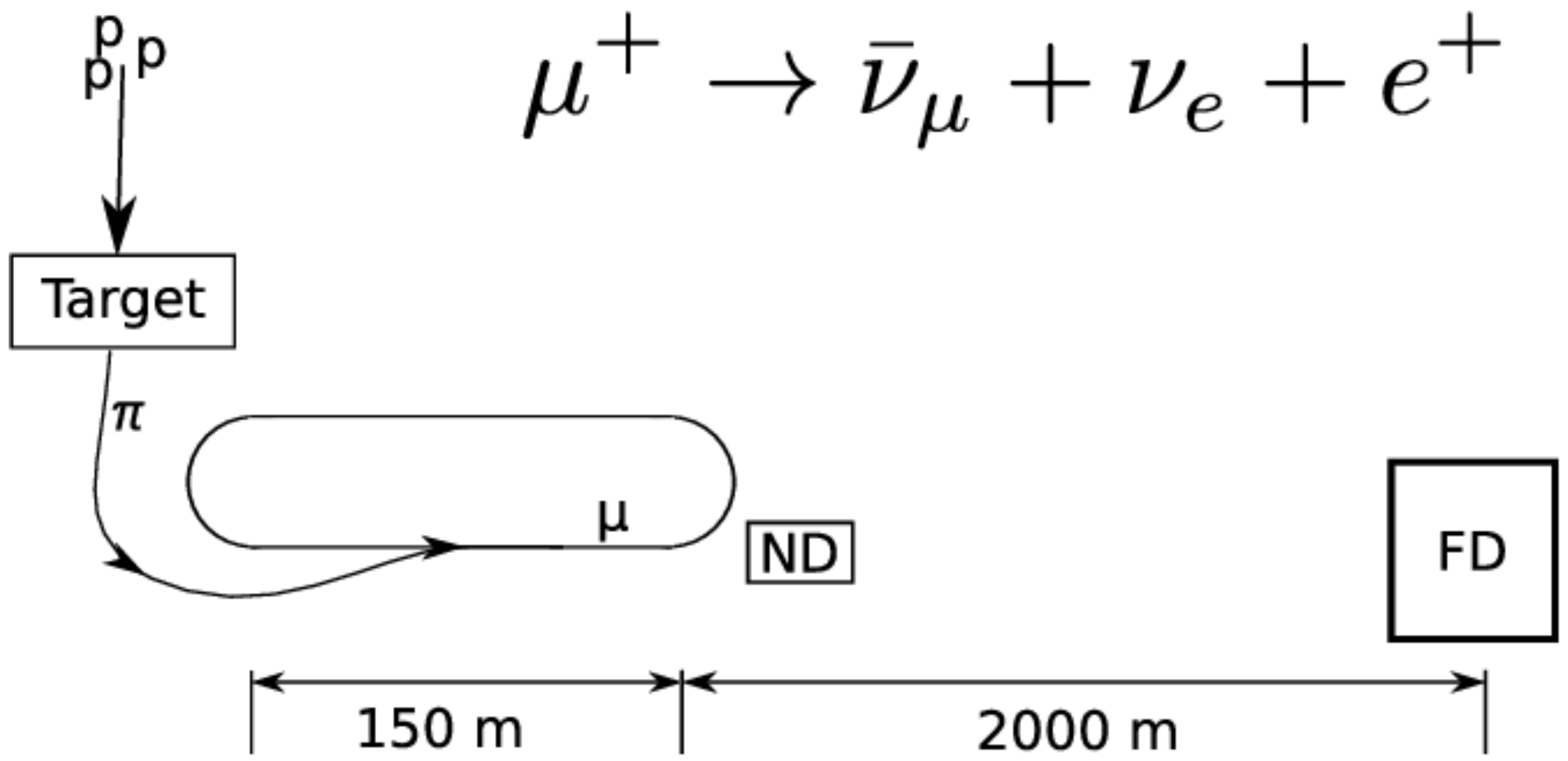
Ideas for physics along the way?

Straight sections = perfect neutrino beam

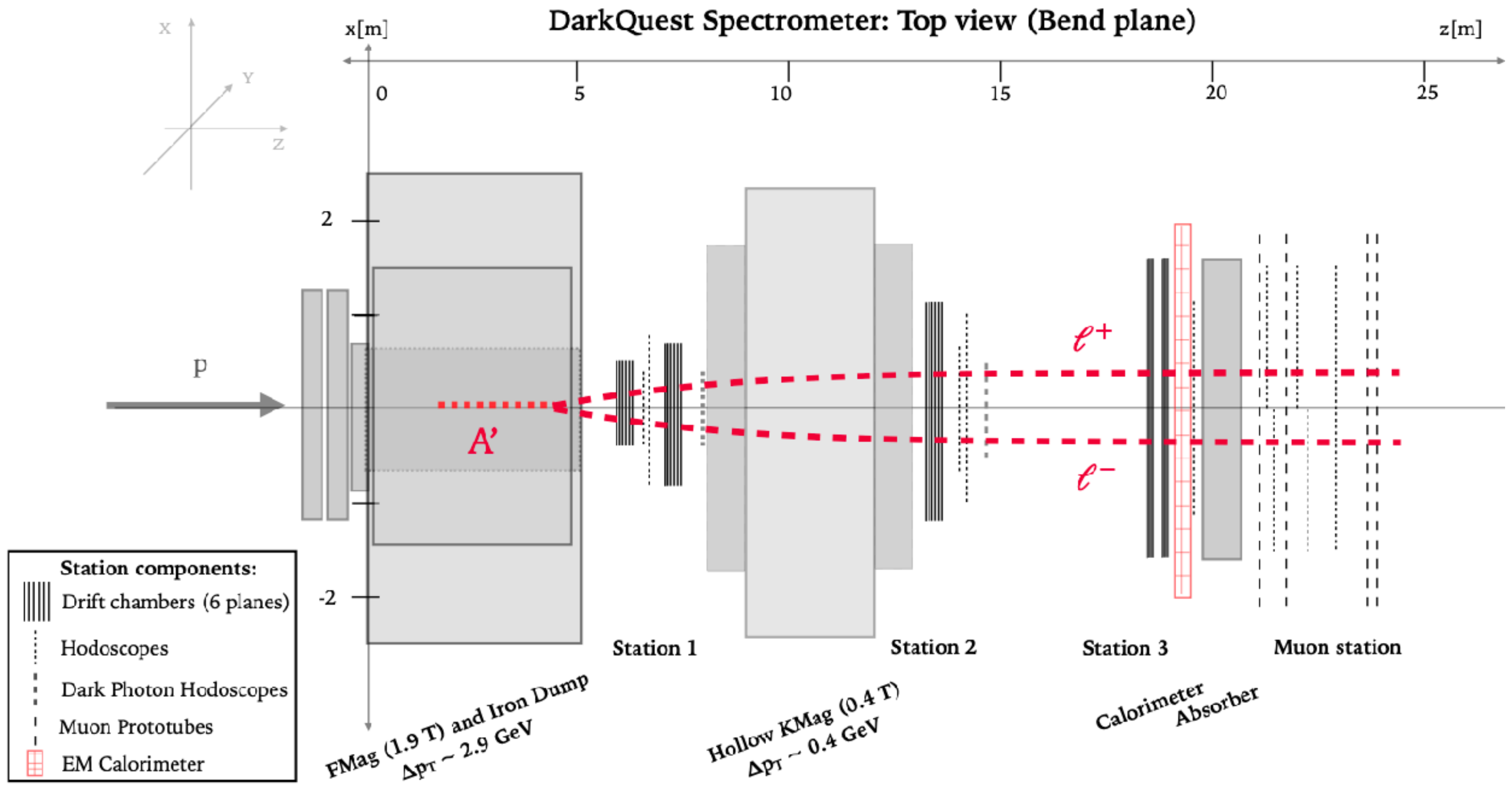
Equal numbers of e/μ (anti-)neutrinos

Precisely known energy spectra & intensity

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



Low mass dark matter (sector) searches



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Synergies with charged lepton flavor violation experiments