Physics Opportunities at Future Colliders

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The University of Chicago
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Why High Energy Colliders

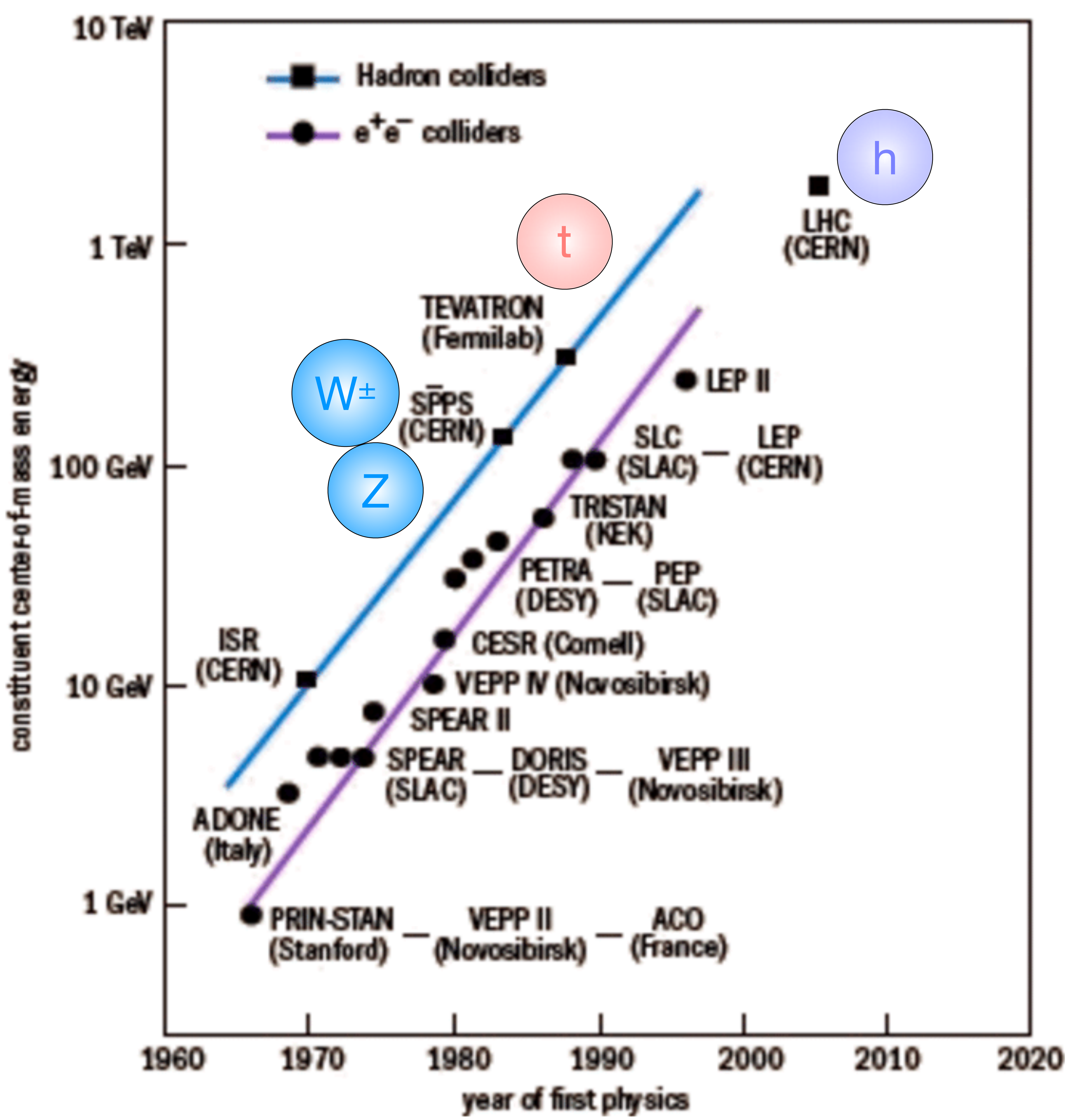
Controlled experiments directly probing

smaller scales: E=hc/λ

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

Highly successful!

Enabled us to establish & test the Standard Model



Open questions

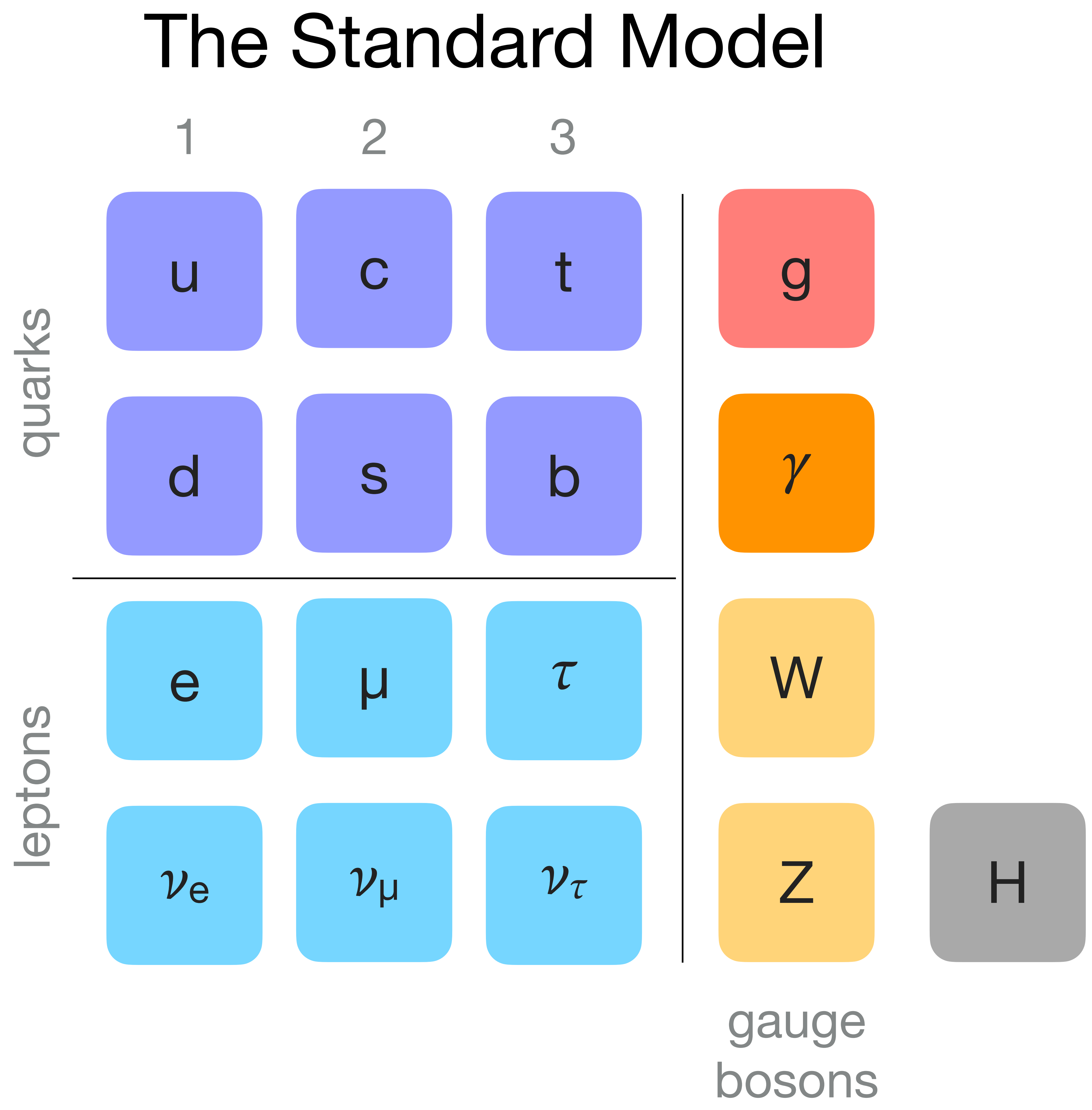
About the Standard Model itself

- Microscopic nature of the Higgs?
- Nature of electroweak symmetry breaking?
- Origin of small neutrino masses?
- Is there a deeper underlying pattern?

We also know it's incomplete

- What is Dark Matter?
- What causes baryogenesis?
- Where does gravity fit in?

Which collider(s) should we build?



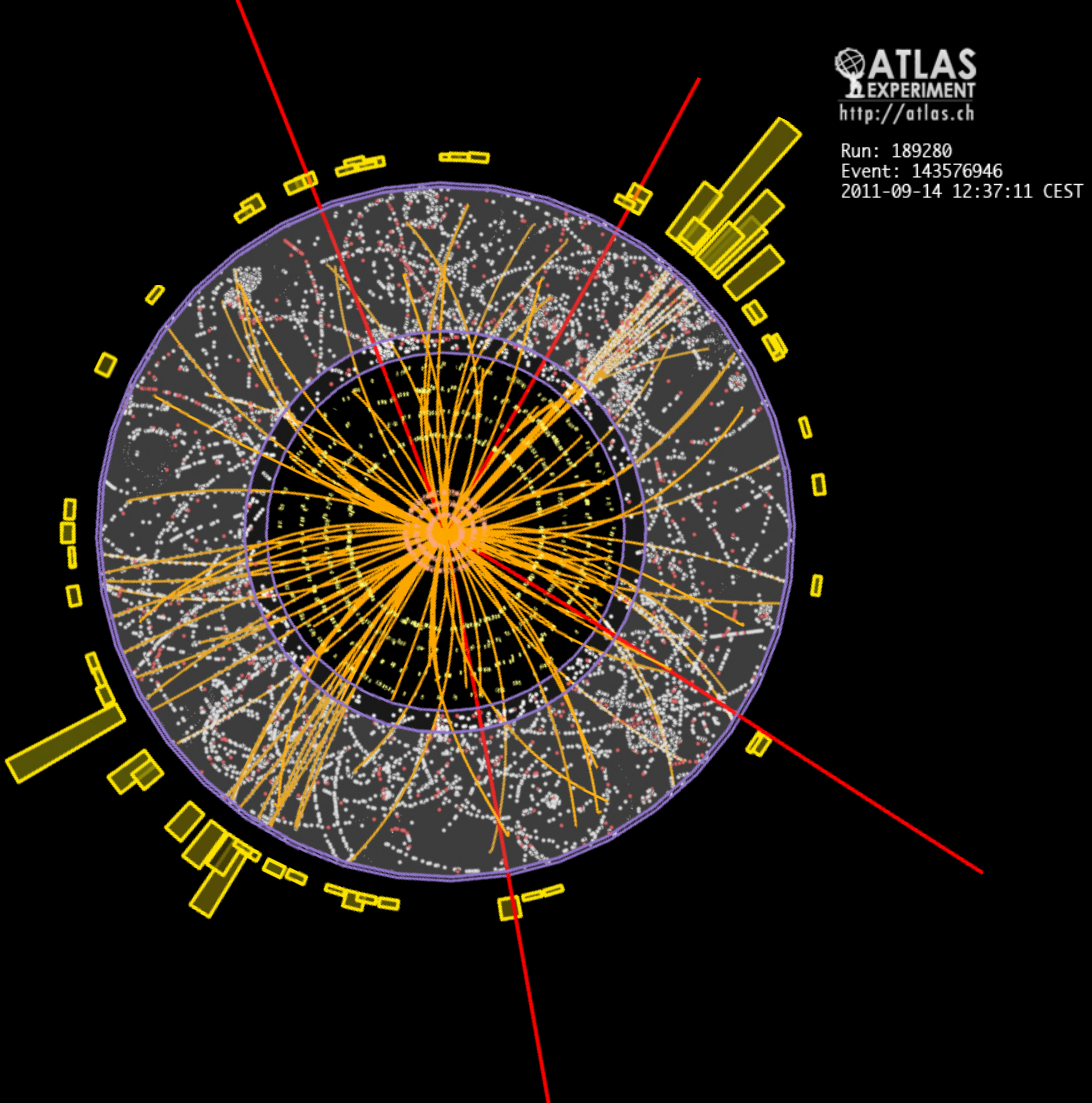
Focus on the Higgs

Questions surrounding the Higgs are central to all of particle physics

Colliders are the <u>only place</u> we can produce & characterize Higgs Bosons

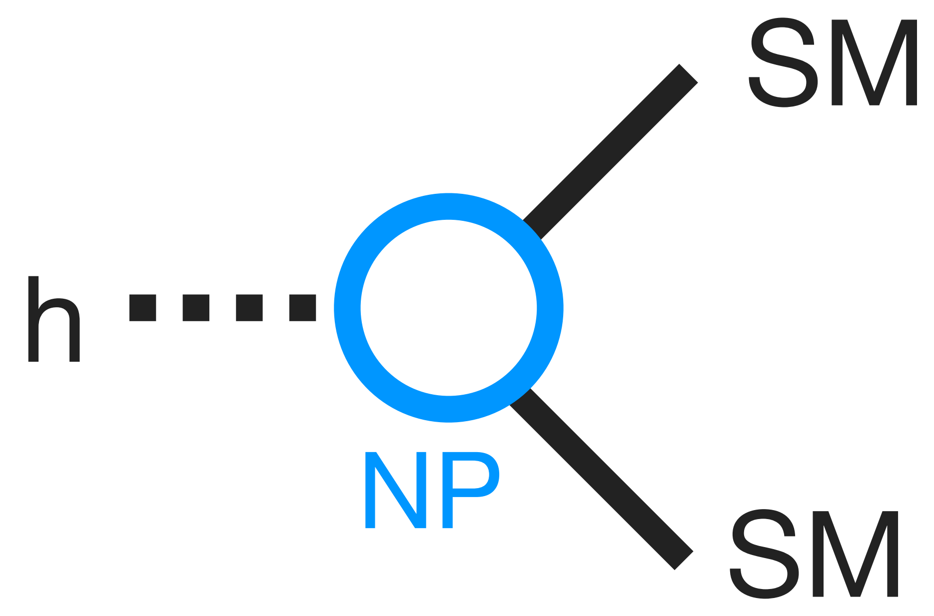
This is our killer app!

Deliverables can inform how to proceed with future colliders



Is it a Standard Model Higgs?

Does the Higgs couple to other particles as expected?



Measure deviation in coupling from the Standard Model $\delta = \frac{g_{\mathrm{SM}} - g_{\mathrm{NP}}}{g_{\mathrm{SM}}}$

Coupling of new physics to SM g_{NP}

Mass of new physics M_{NP}

Map deviation to new physics coupling & scale $\delta \sim g_{\mathrm{NP}}^2 \frac{(100\ \mathrm{GeV})^2}{M_{\mathrm{NP}}^2}$

Higgs Couplings

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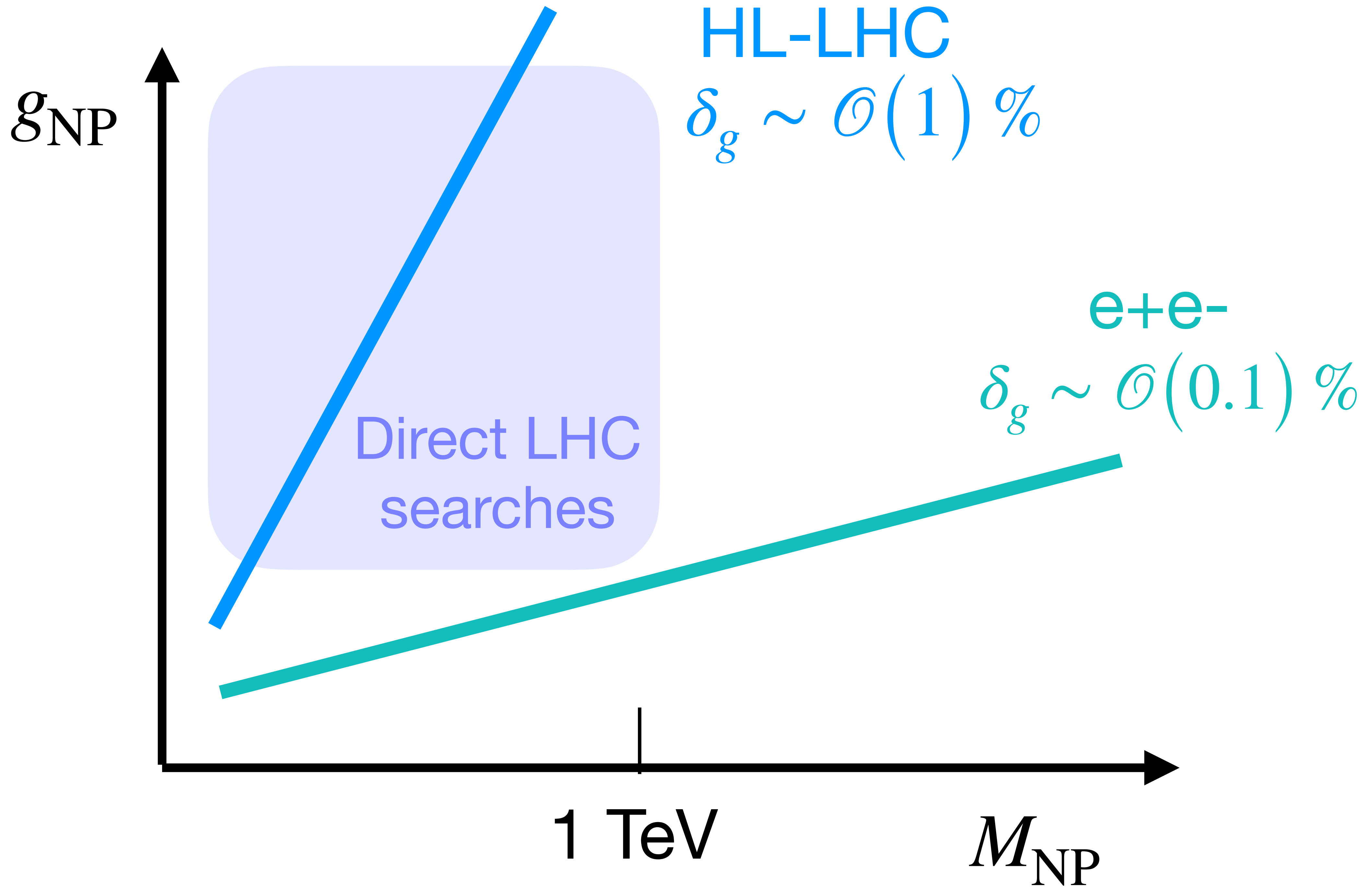
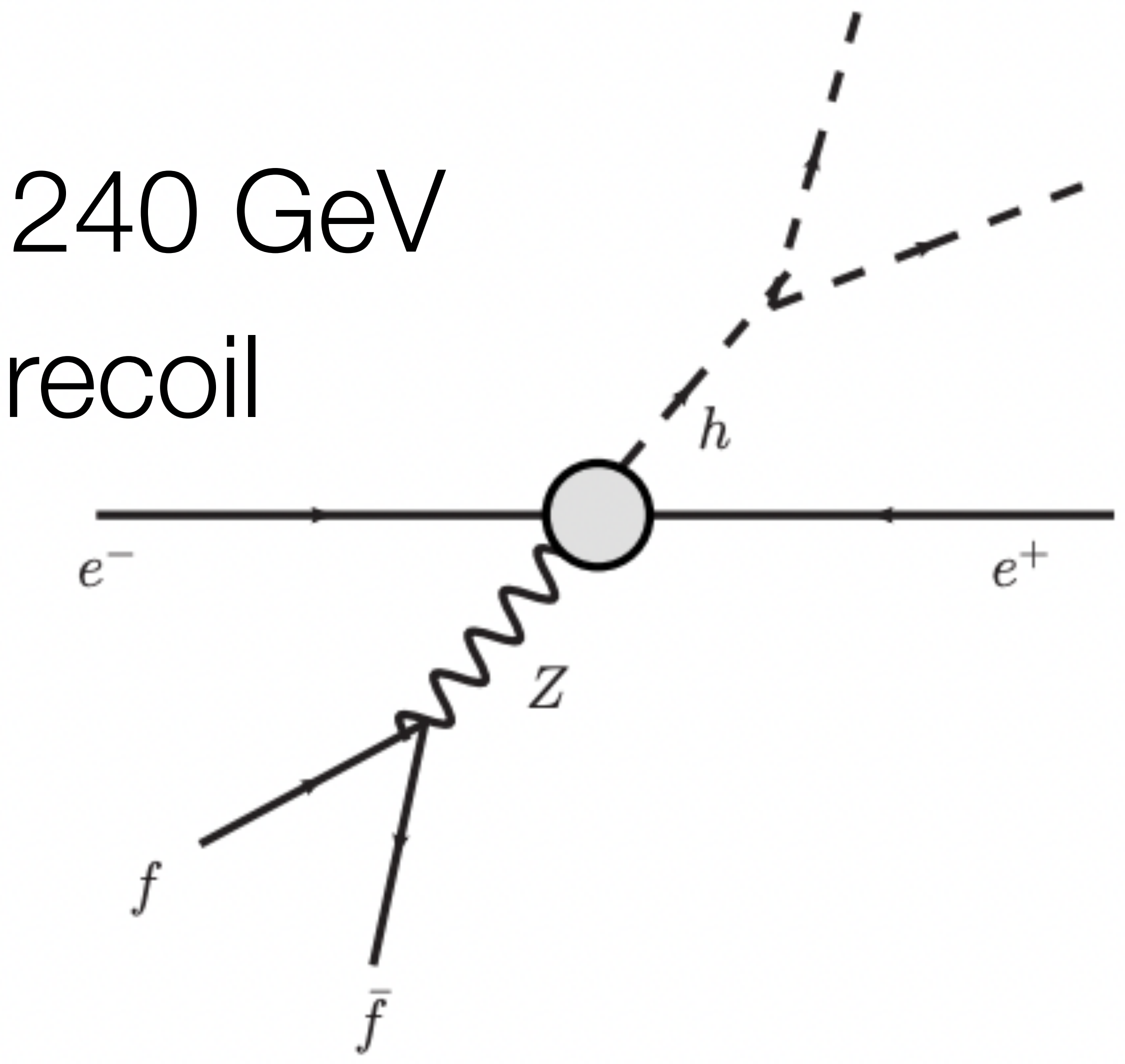
To meaningfully exceed HL-LHC need to measure Higgs couplings to O(0.1)%

Collect 1M Higgs Bosons in a clean e+e- environment *'shovel ready'*



Unique at 240 GeV

Higgs recoil



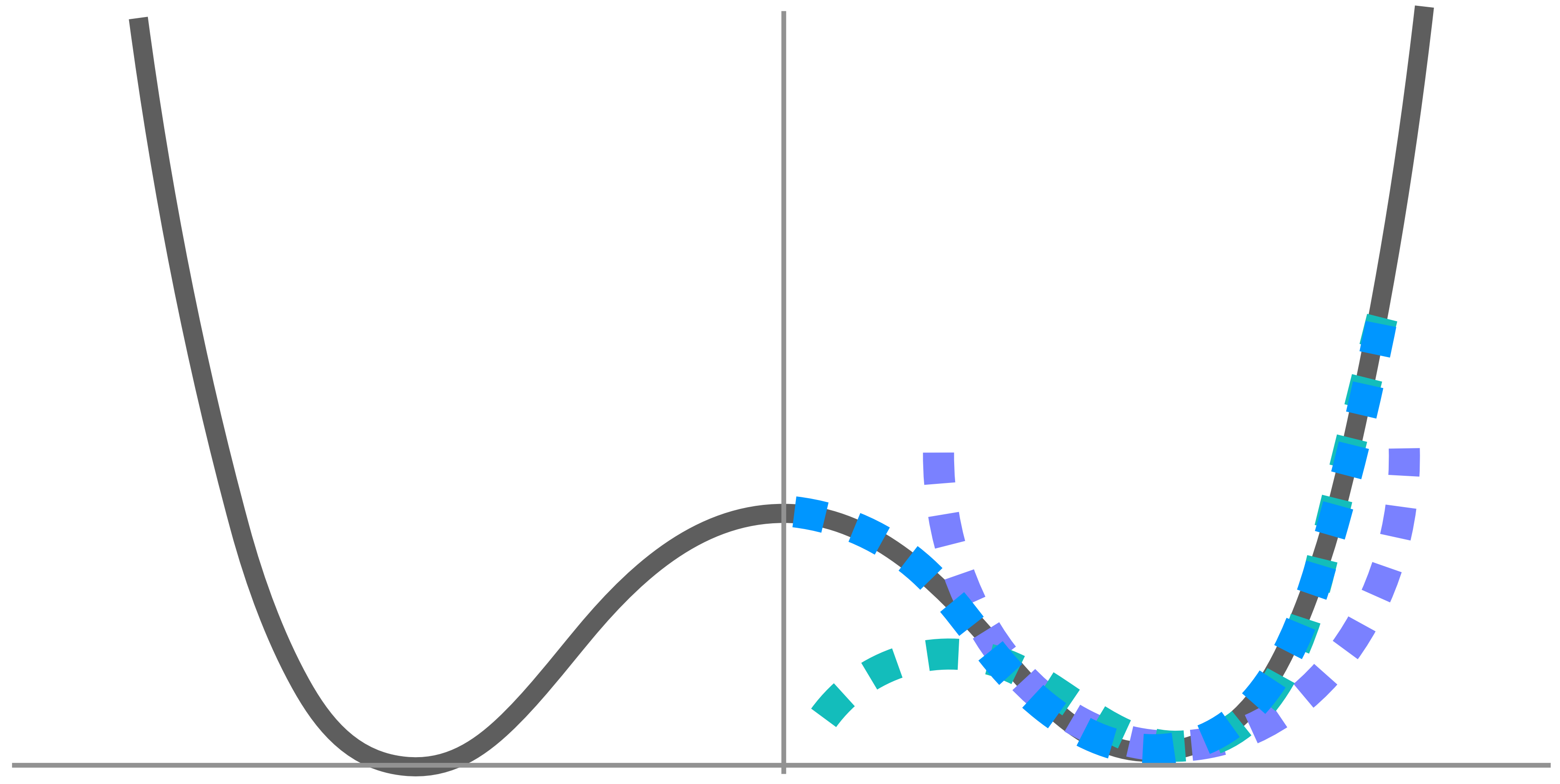
Model independent total width, h→inv, rare decays

What is the shape of Higgs potential?

L. Lee

Taylor series expand around the minimum

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

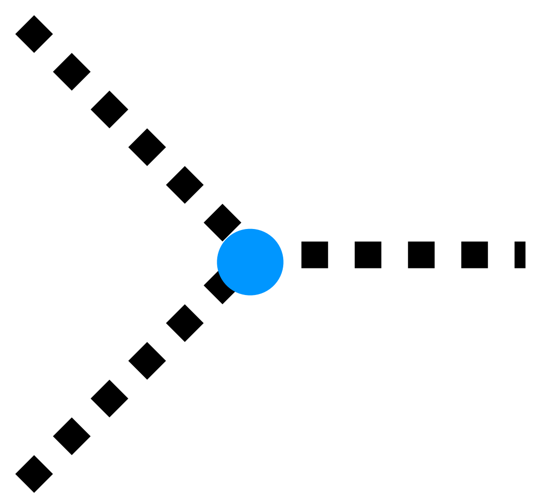


We've only measured the minimum of this potential

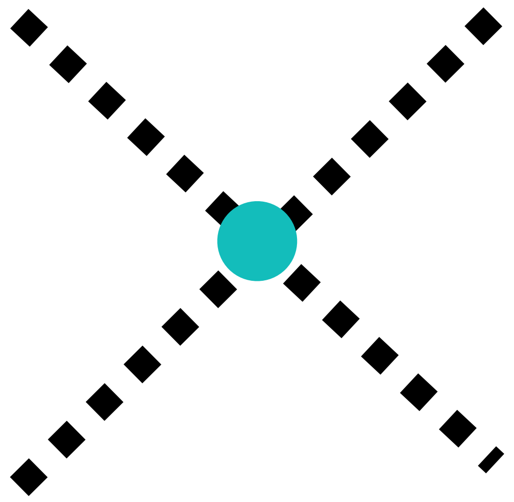
$$m_h = \sqrt{2\mu^2} = \sqrt{2\lambda v^2}$$

Gives us harmonic oscillator term

Higgs trilinear-coupling



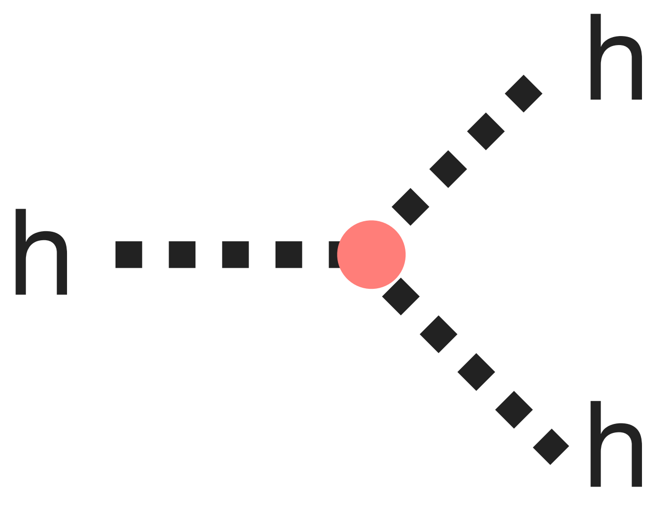
Higgs quartic coupling

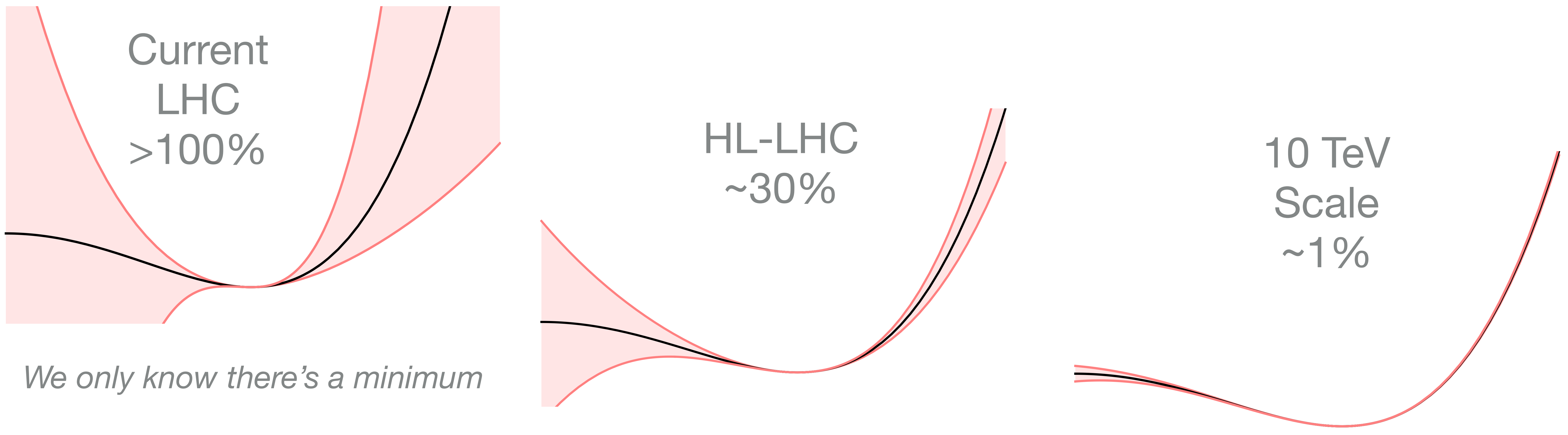


Higgs self-coupling

R. Petrossian-Byrne & N. Craig

Measuring higgs self coupling to a few% is the ultimate test of electroweak phase transition and vacuum stability





Requires a ~10 TeV scale collider to produce enough multi-Higgs events

We don't have the technology in hand yet

Electroweak symmetry breaking

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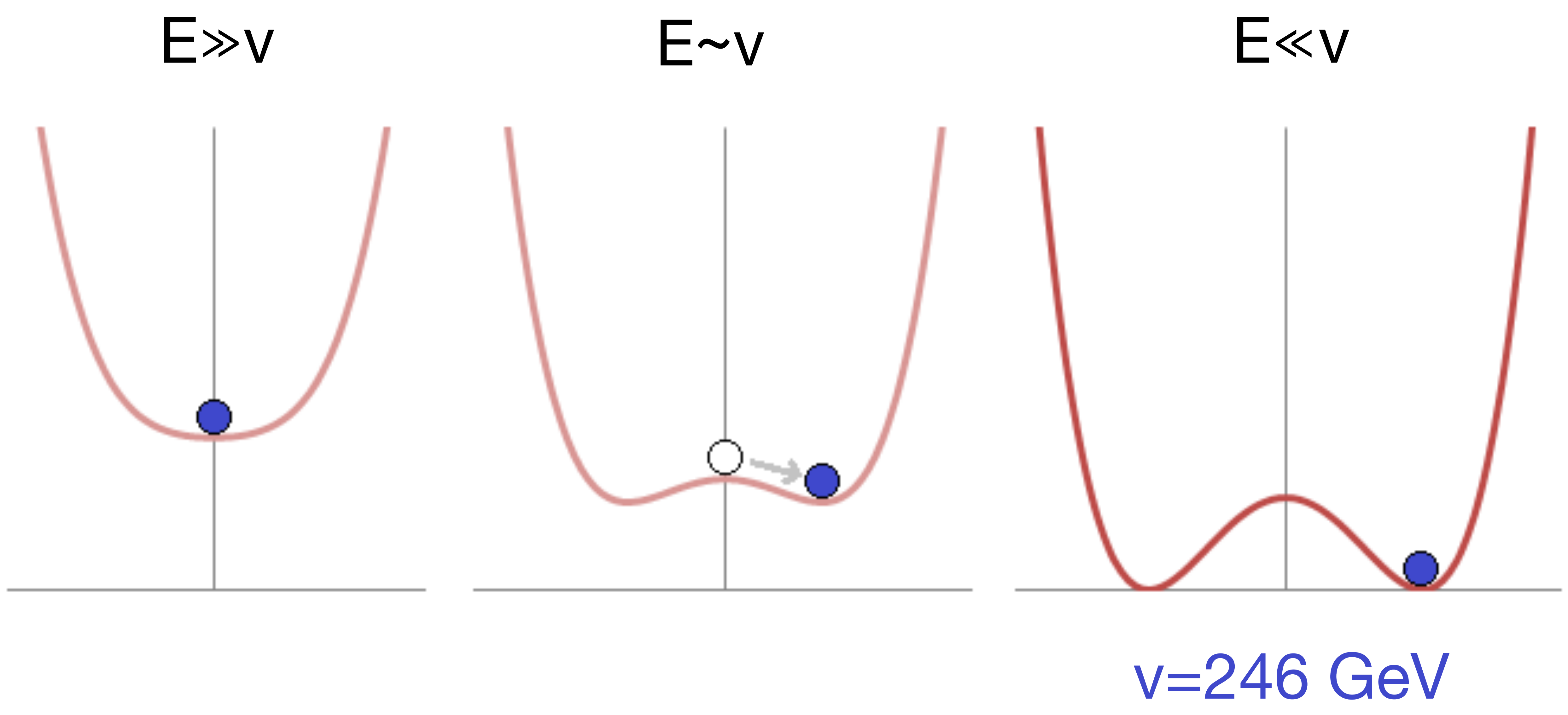
We should also enter a new regime 'Electroweak Restoration'

analogous to studying QCD at higher energies



At 10 GeV: $\Lambda_{QCD}/E \sim 10^{-2}$

massless quarks (u, d, s) and gluons

rather than hadrons in the broken phase

At 10 TeV: $v/E \sim 10^{-2}$

Massless $W^{\pm}_T, Z_T, \gamma$ & fermions

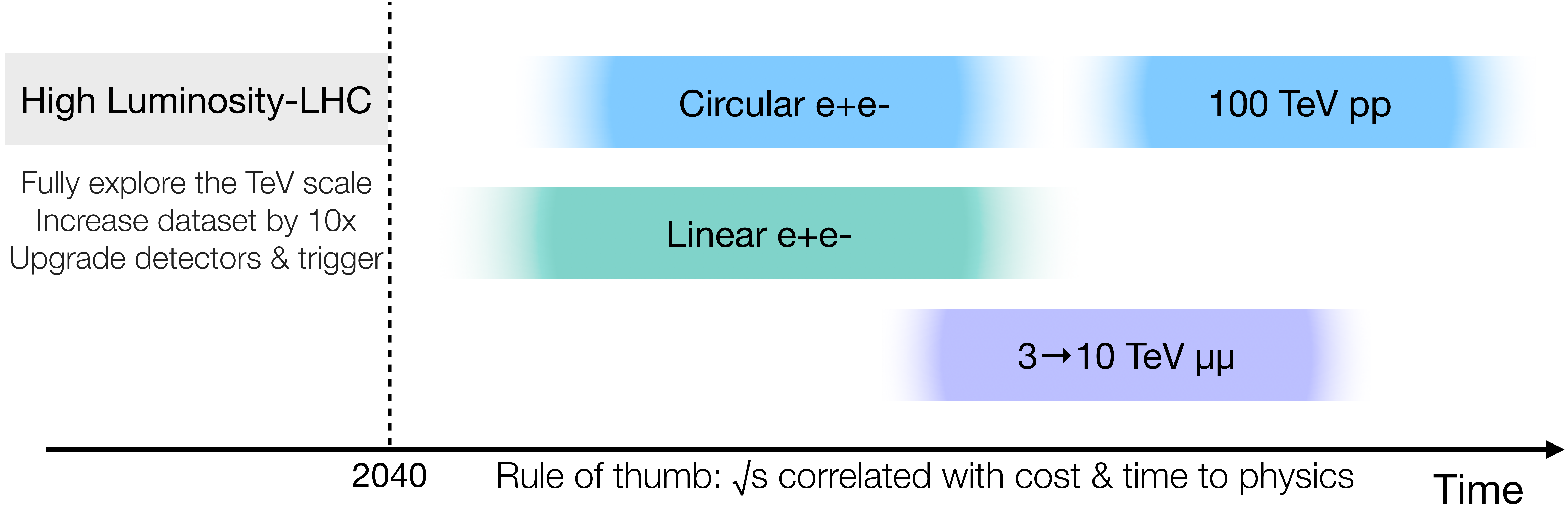
$W^{\pm}_L, Z_L$ behave like goldstone bosons

Restore unbroken O(4) symmetry

Which collider(s) we should we build

Consensus: e+e- higgs factory & R&D towards 10 TeV scale

Decisions need to be made ~now



We should also look beyond Higgs precision narrative

Hearing X% versus Y% versus Z% a thousand times can lose all meaning

We can't forget any deviation would be caused by new particles or interactions

Surprises have happened in particle physics before - may happen again

The Higgs may be the most important thing but it can't be the only thing

A broad program strengthens our physics case

Opens up possibilities for intellectual contributions

For rest of this talk - two topics with BSM focus

We know from LHC data, new physics is either weakly coupled or above TeV scale

How can Tera-Z at an e+e-collider help us tease out a specific scale or mechanism?

How do muon and hadron colliders compare in terms of BSM discovery potential?

These topics are actively developing & a great place for a new person to make an impact


LHC
SWITZERLAND
Tera Z
FRANCE
FCC

Circular e+e- reminder

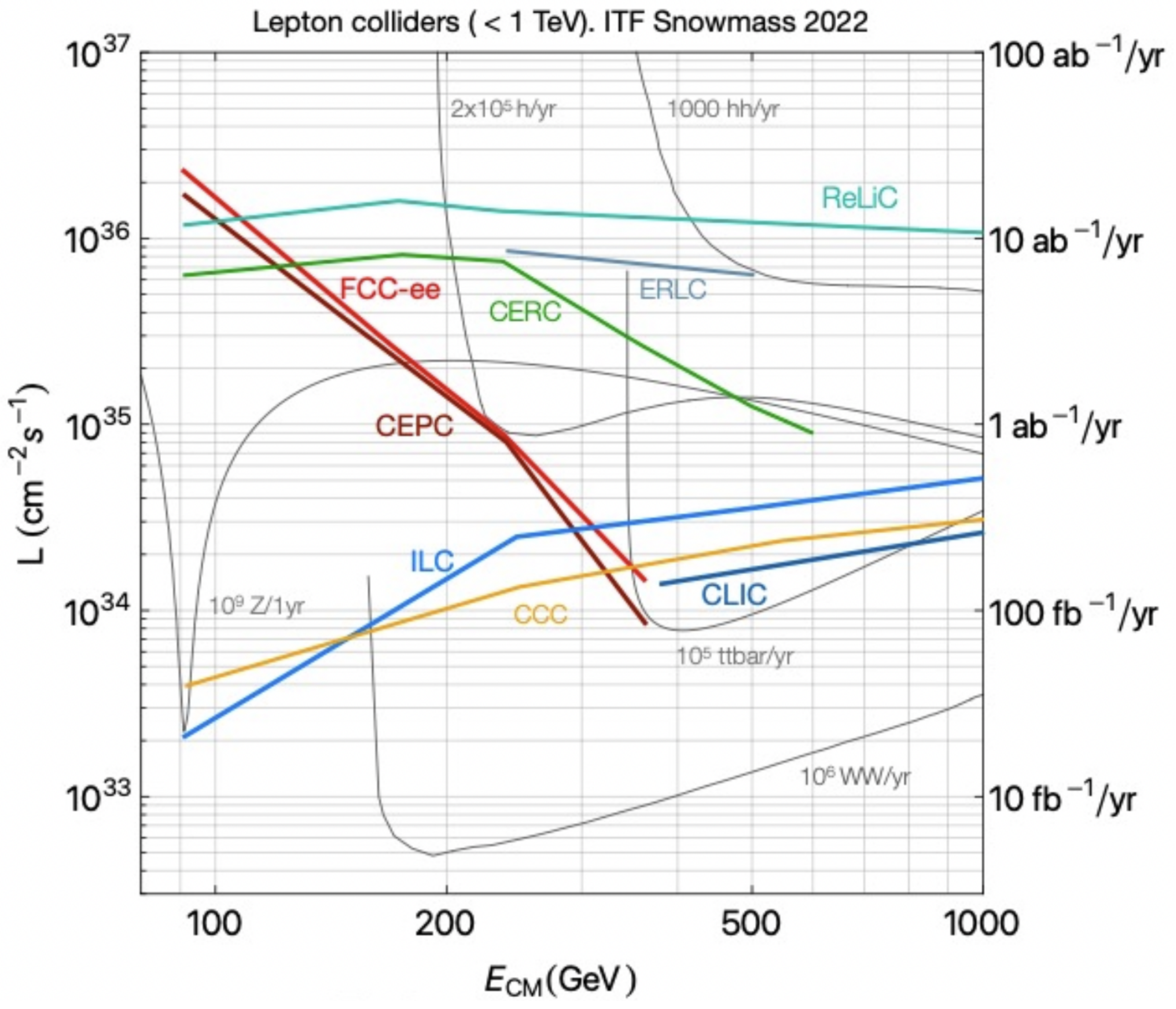
Constrained by synchrotron radiation

Circular Strength

'Tera Z'

Linear Strength

Energies above ~300 GeV



Tera Z compared to LEP

At $\sqrt{s}$=90 GeV		LEP 27 km	FCC-ee 90 km
E loss/turn [MeV]		120	40
Beam Current [mA]		3	1450
Beam size at IP	σx (μm)	100	81
	σy (nm)	1000	30
Lumi/IP ($cm^{-2}s^{-1}$)		10^{31}	10^{36}

10^5x Increase in Luminosity

~500x beam current (more bunches)

~400x smaller bunches at IP

Improvements

Double rings

Top-up injection booster

Crab waist collisions

Superconducting final focus

Ultra Low Emittance Lattice

Electroweak precision

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Rich program under development

Key observables:

1-2 orders of magnitude beyond present day uncertainties

Opportunities for new approaches to measurements & controlling systematics

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge

Electroweak precision

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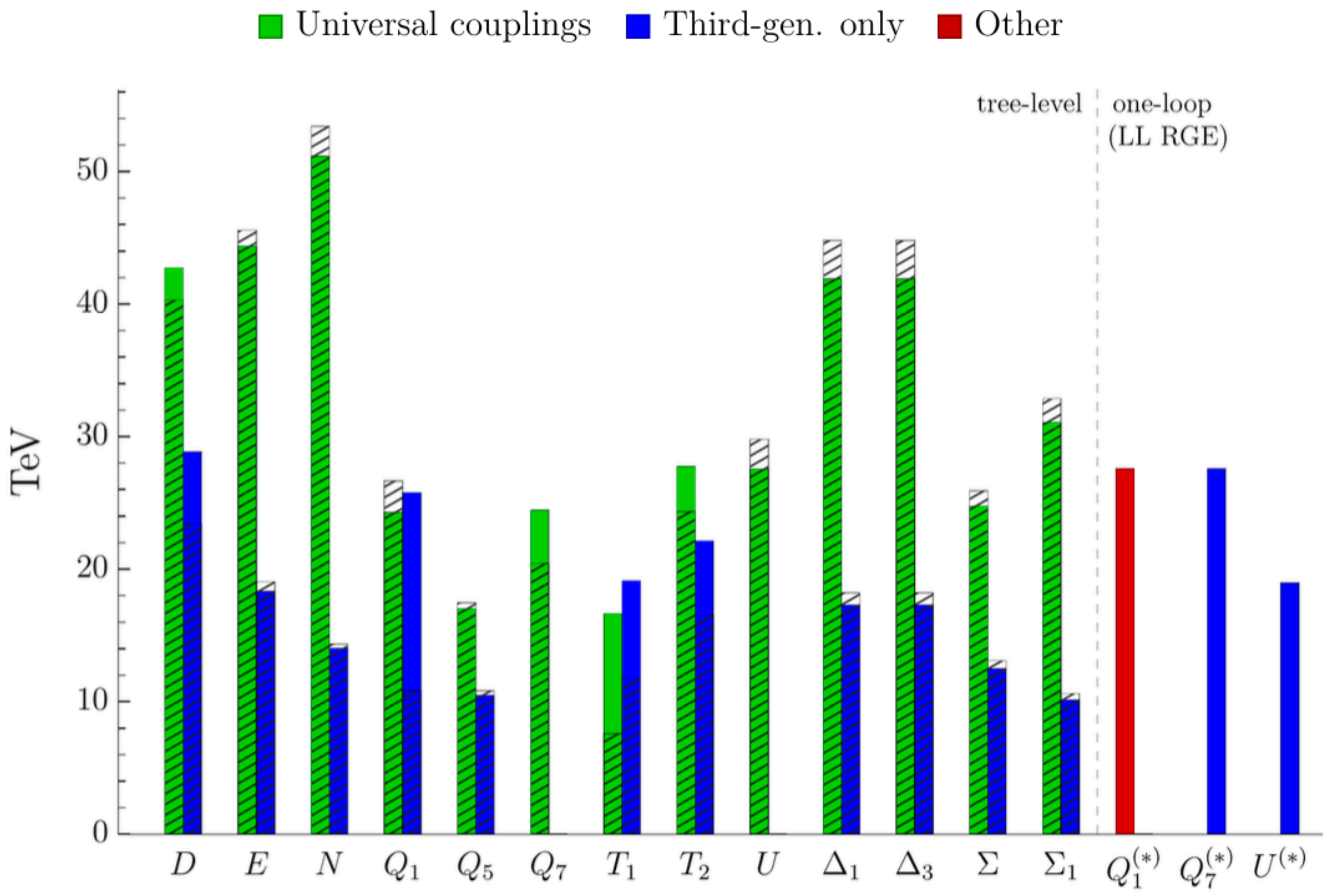
Translates to BSM sensitivity up to ~10s of TeV

✓Well beyond HL-LHC

✓In the range probed by a 10 TeV scale machine



Projected bounds on the masses of new vector fields

Questions related to flavor

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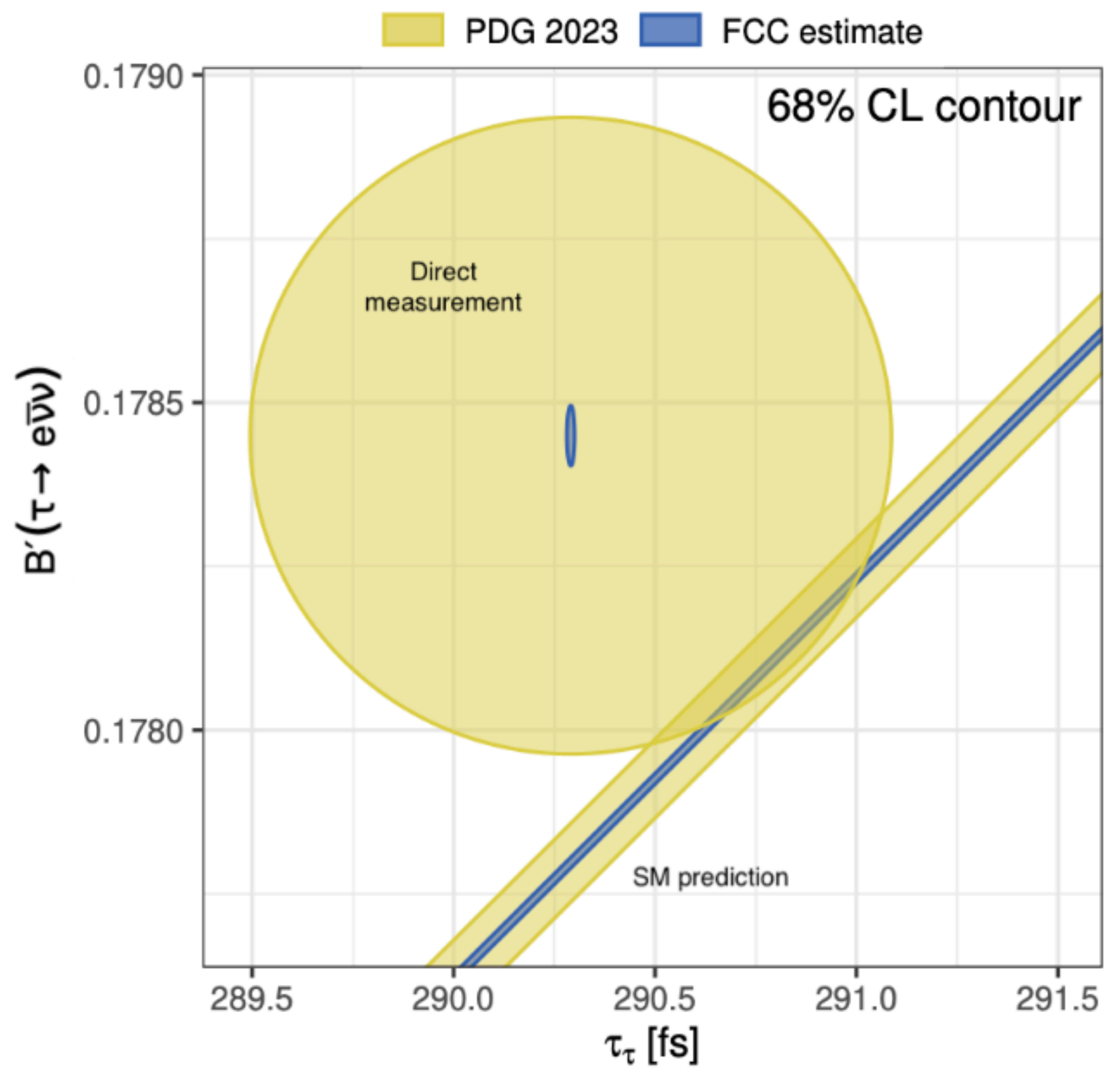
Key features

~10x more bb and cc pairs than total collected by Belle II

Boosted: Higher efficiency

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

* rare decays: b → τ transitions
* CP violating observables (b/c)
* Lepton Flavor violating tau decays (τ)
* Lepton Flavor Universality tests (τ)



Lepton Flavor Universality in tau decays

Heavy Neutral Leptons

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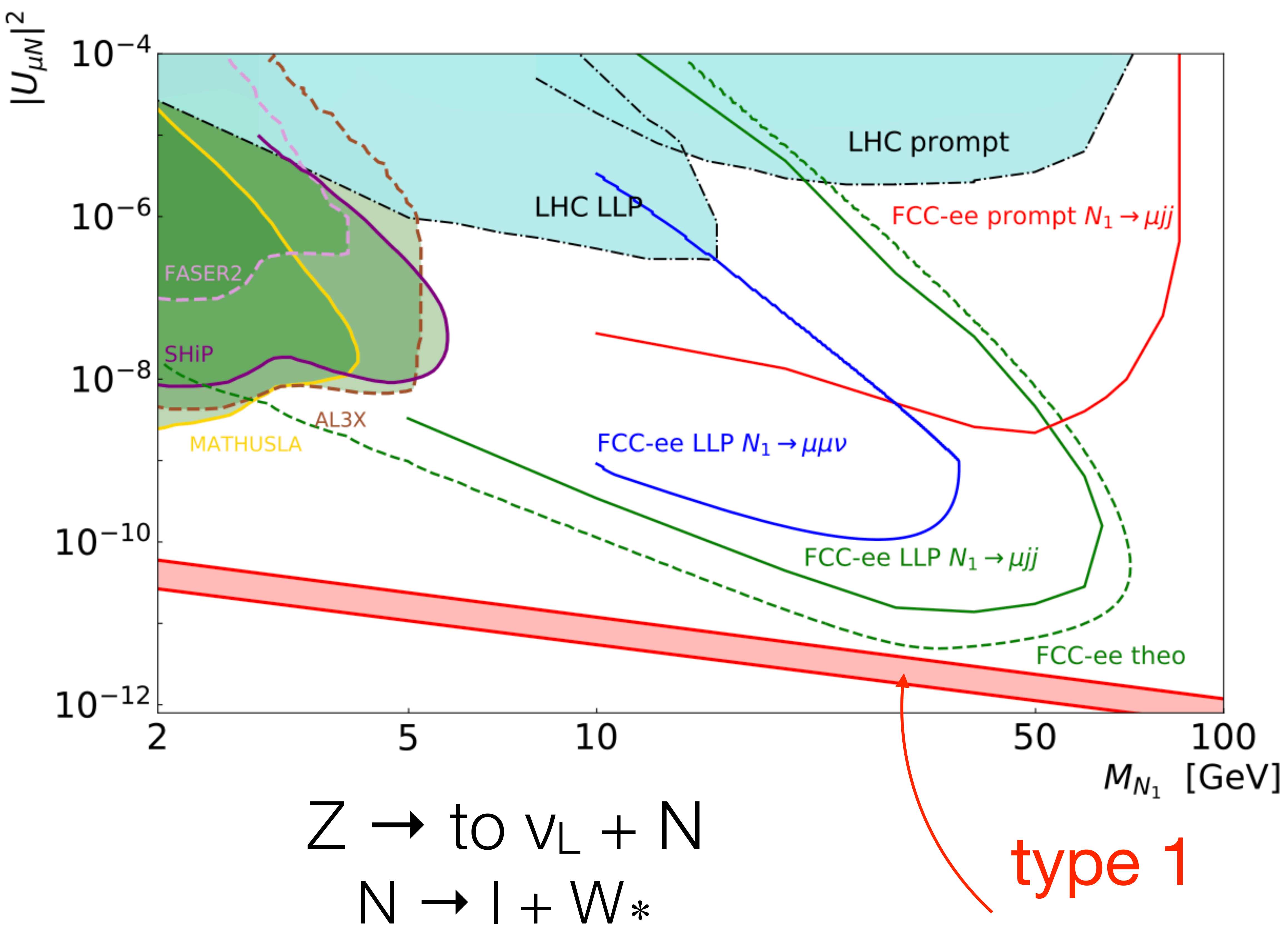
Great example of direct sensitivity to weakly coupled new physics

Right-handed/sterile neutrinos, N

Mix with ν_L via Yukawa interactions mediated by the Higgs field

Motivated by small neutrino masses & leptogenesis



$Z \to$ to $\nu_L + N$

$N \to l + W*$

$N \to \nu + Z*$

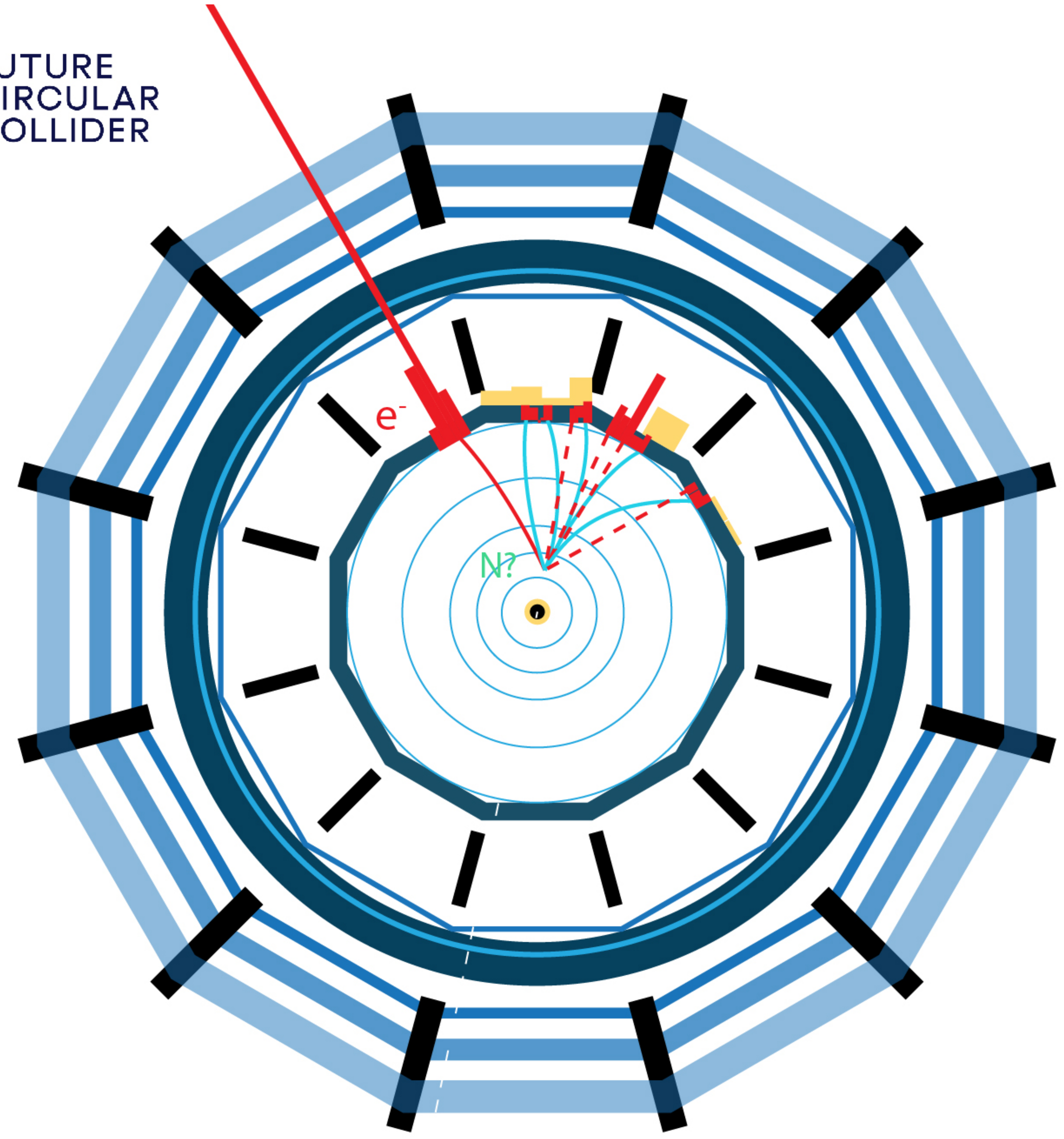
Detector needs

2502.21223

- Require excellent p & E resolution!
  - Low density precision trackers
  - Time of flight for particle ID
  - Hadronic W/Z/h separation
  - Precision beam monitoring & luminosity

- Challenge: collision environment
  - Rate of Zs ~200 kHz
  - Beam backgrounds ~200 MHz/cm^2
  - Radiation
    - Total ionizing dose ~ 1 Mrad
    - Fluence ~10^{14} MeV neq/cm^2

FUTURE CIRCULAR COLLIDER



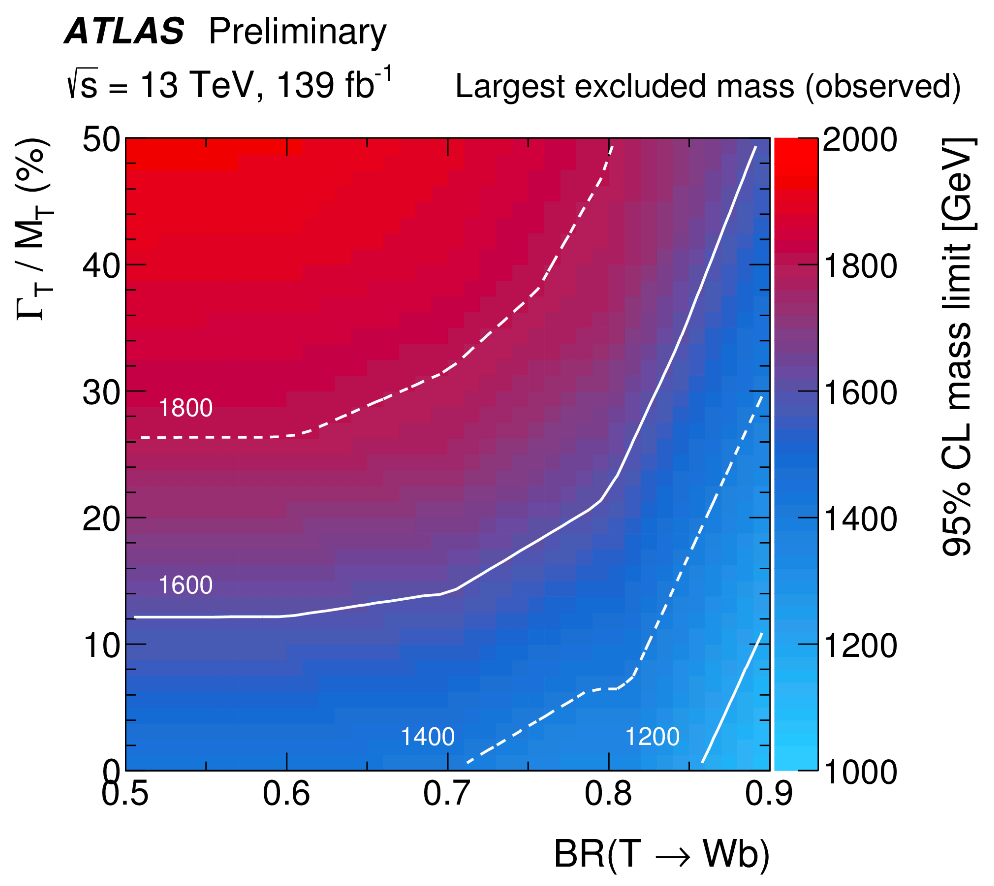
Opportunities to contribute to design in simulation and R&D in the lab


10 TeV Scale
Colliders

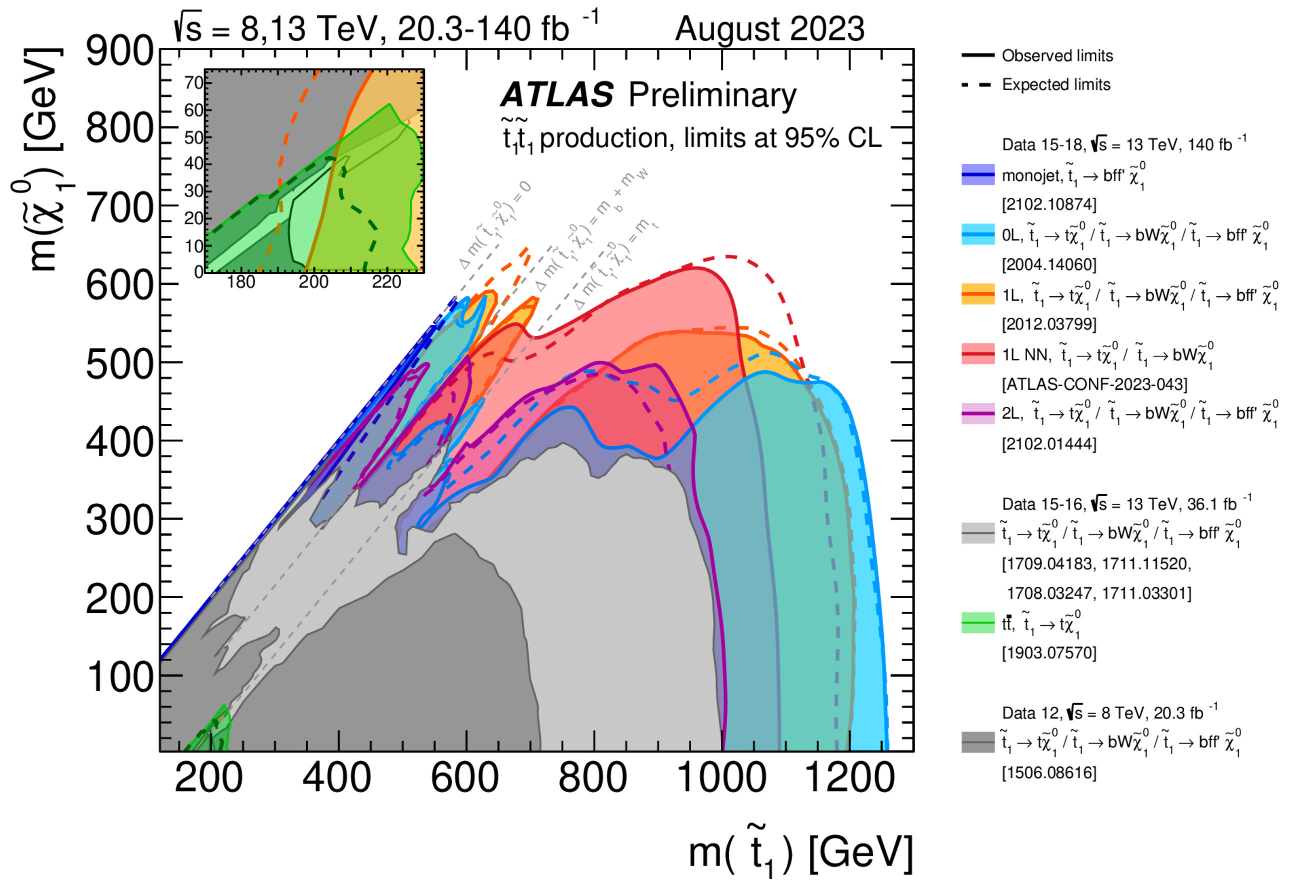
Metric: Microscopic nature of the higgs

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

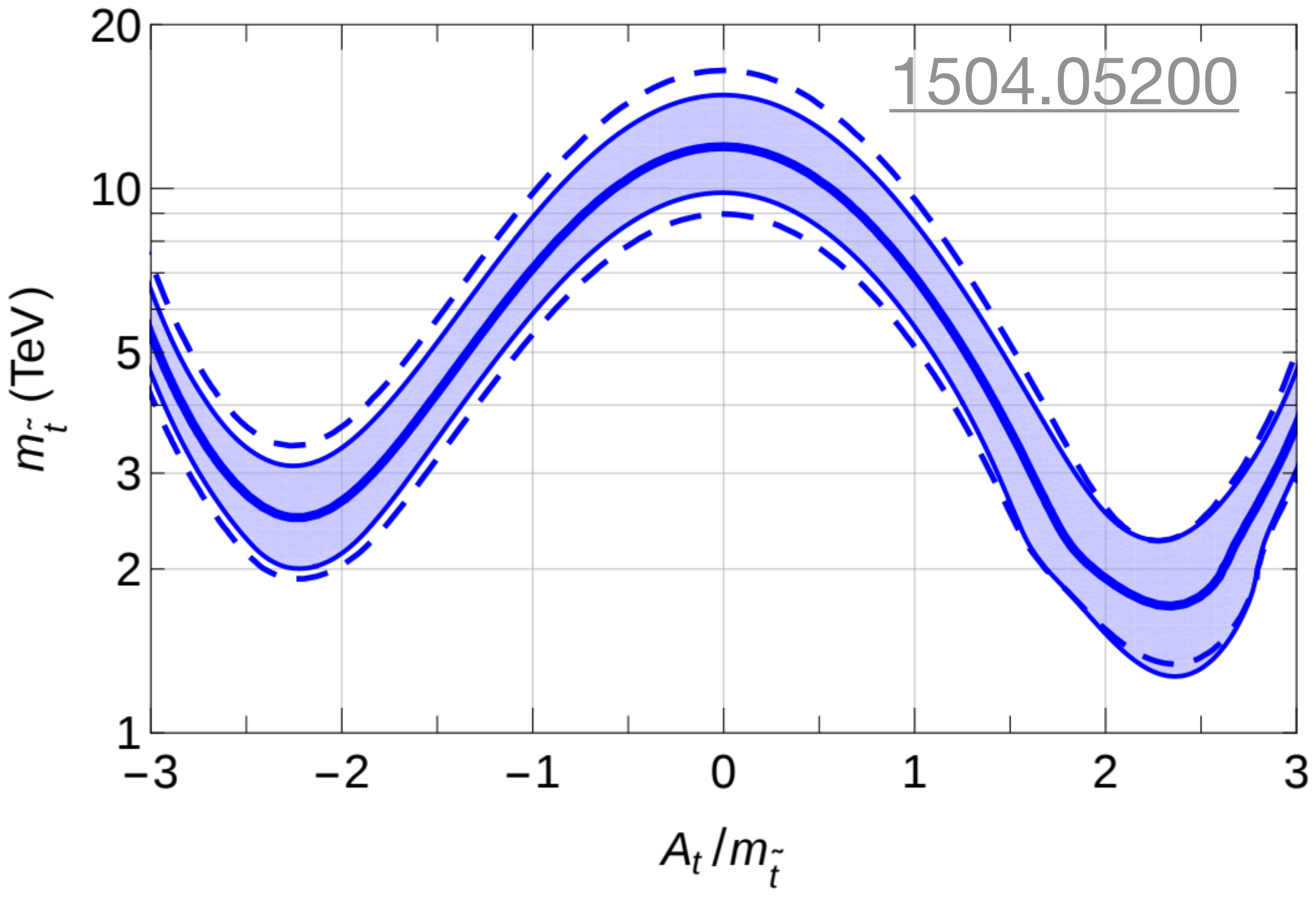
e.g. composite Higgs, like the pion?



e.g. new symmetry & additional particles?



m_h =125 GeV → multi-TeV top-partners

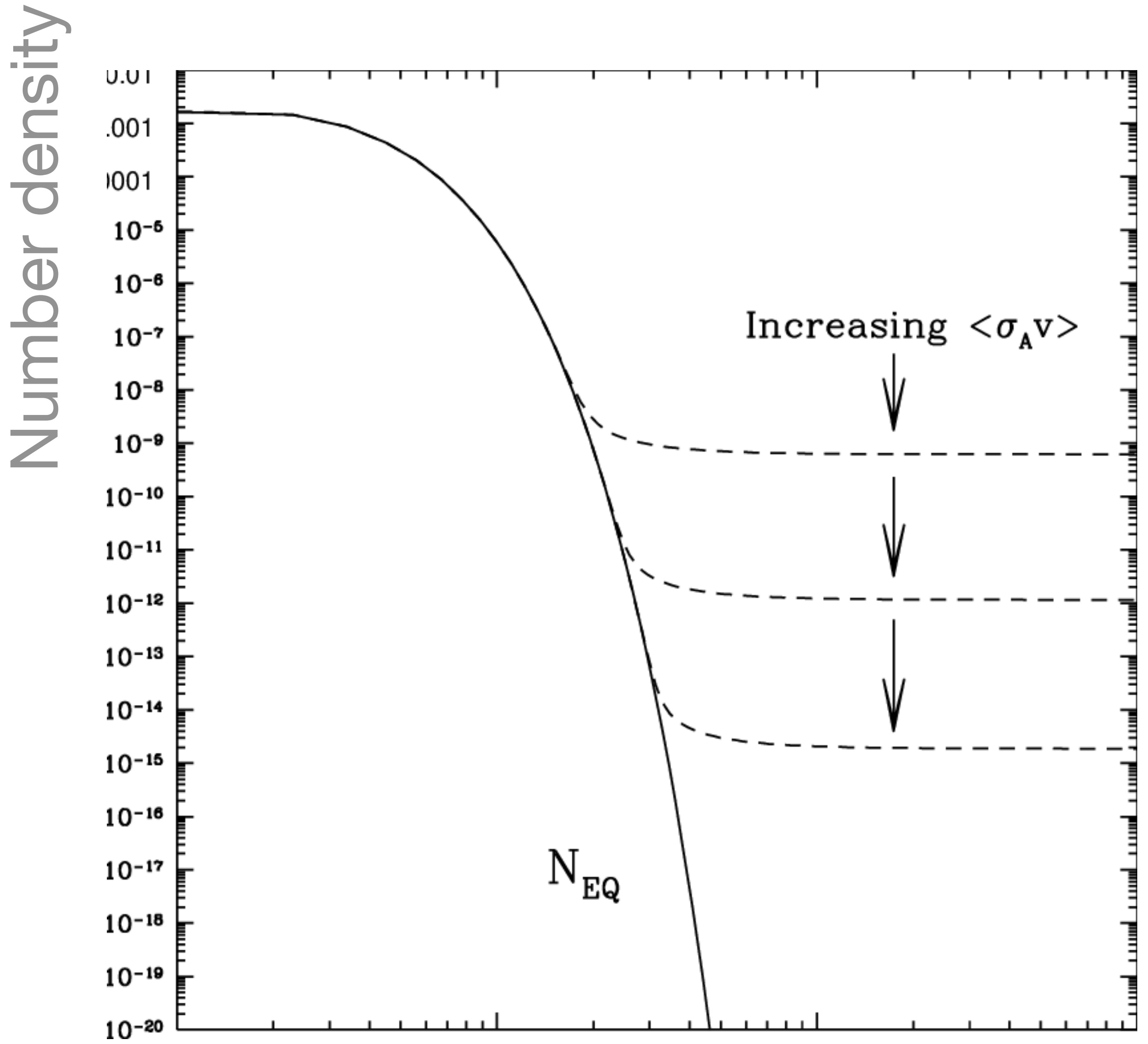


Data & theory suggest any strongly coupled particles <u>> 1 TeV</u>

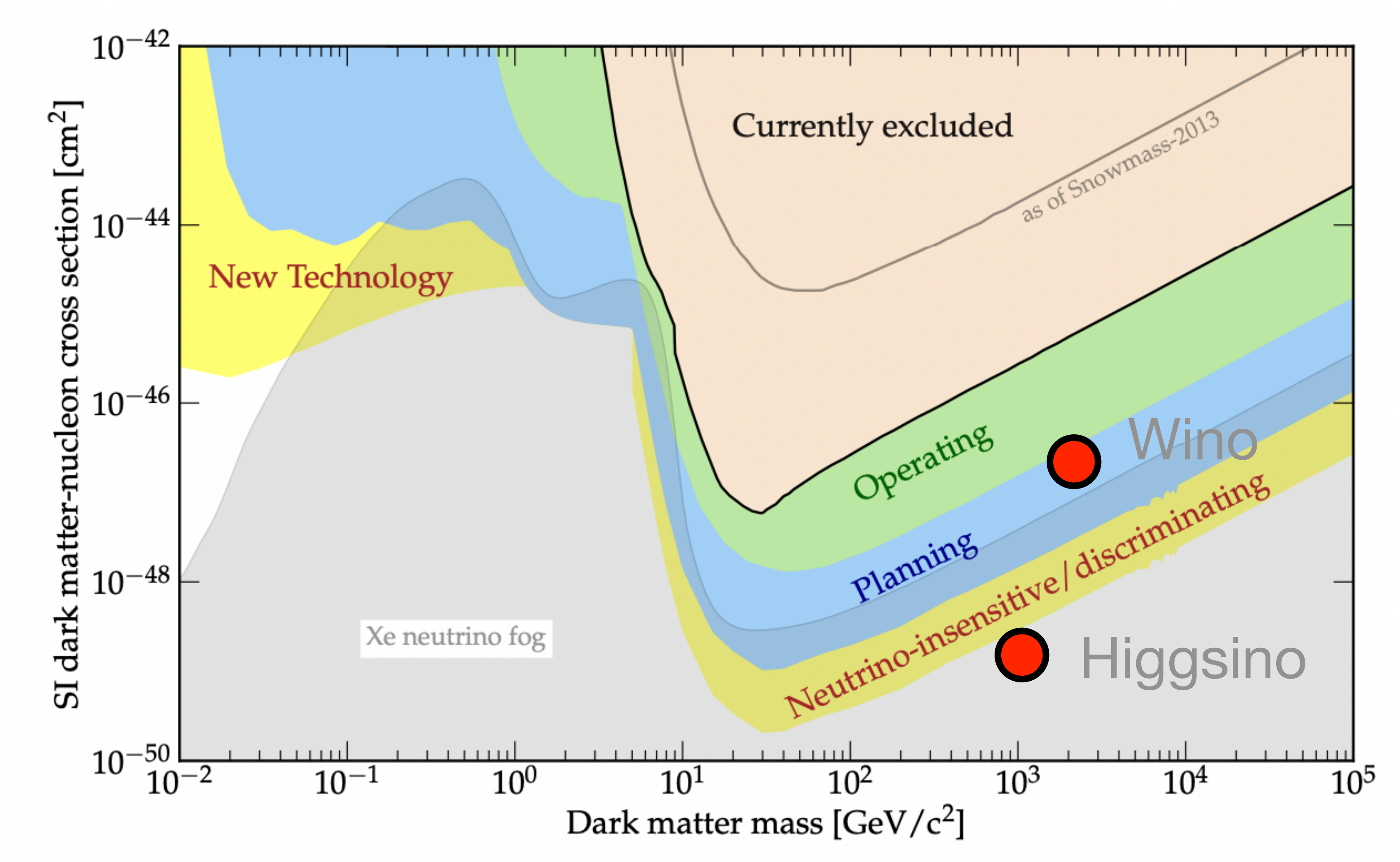
Metric: Minimal Dark Matter

DM Complementarity Report: 2211.07027

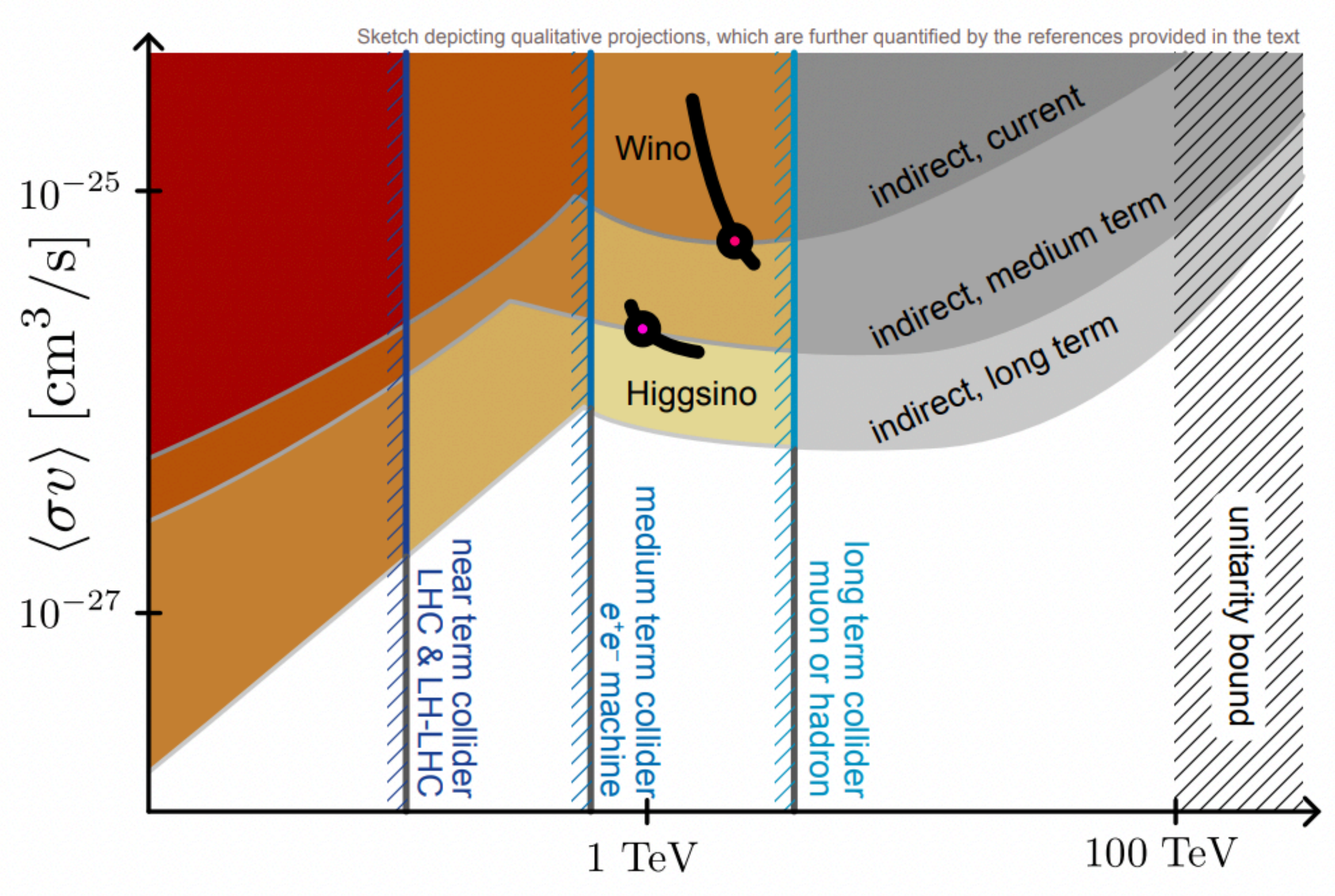
We've yet to probe WIMPs up to their thermal targets



Pure higgsino under neutrino floor!



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



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

Hadron collider constraints

Colliding composite particles

Quarks and gluons carry a fraction of proton momentum
Probe a range energies at once
High rate of “messy” backgrounds - need a trigger

Energy reach given by
Collider size
High field dipoles

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

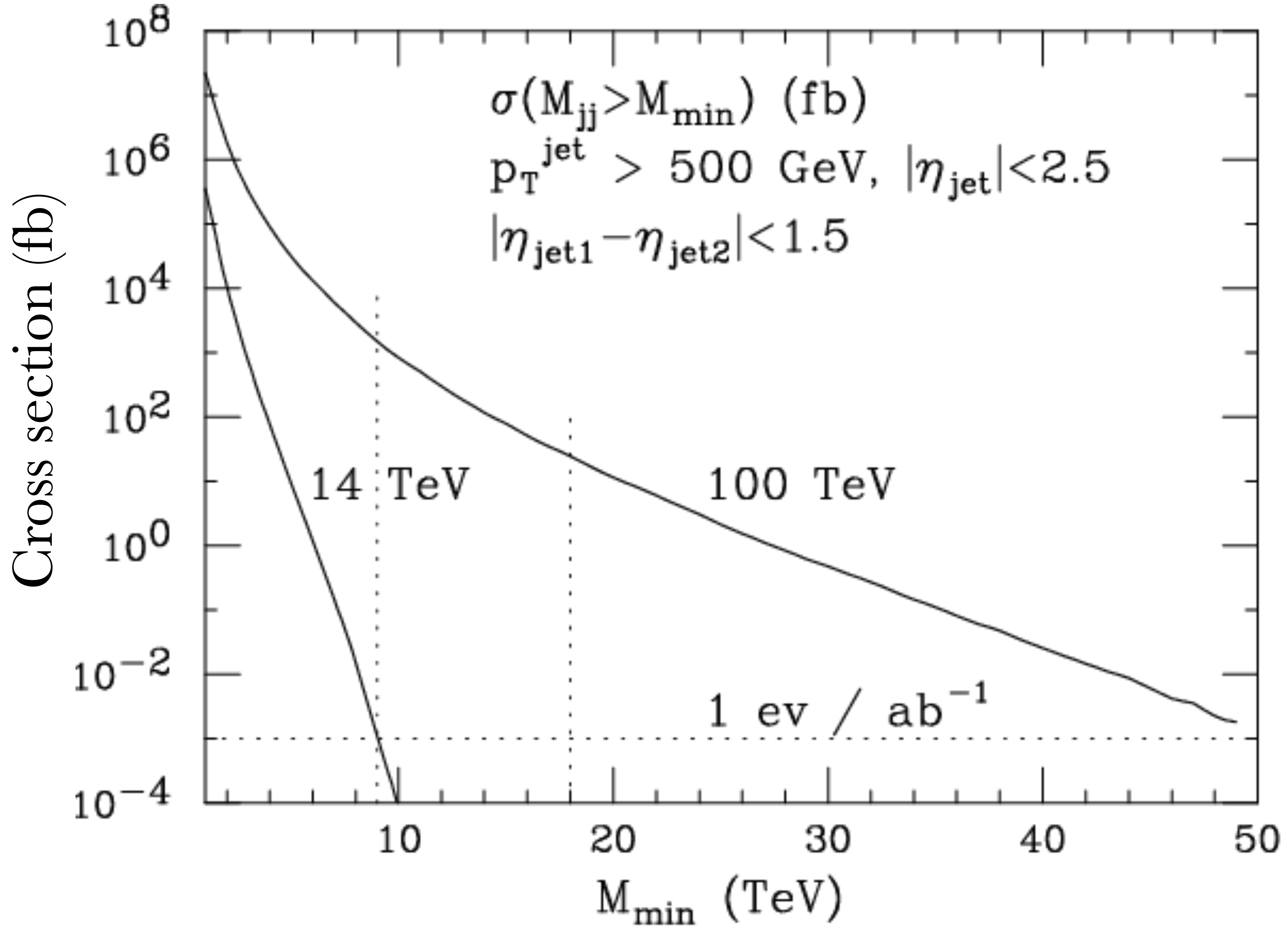
		LHC tunnel	FCC tunnel
Circumference [km]		27.0	90.0
COM [TeV]	LHC NbTi - 8.3 T	14	46
	Record NbSn3 - 14 T	23	78
	Future HTS - 18 T	30	100

Physics reach with 100 TeV hadrons

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

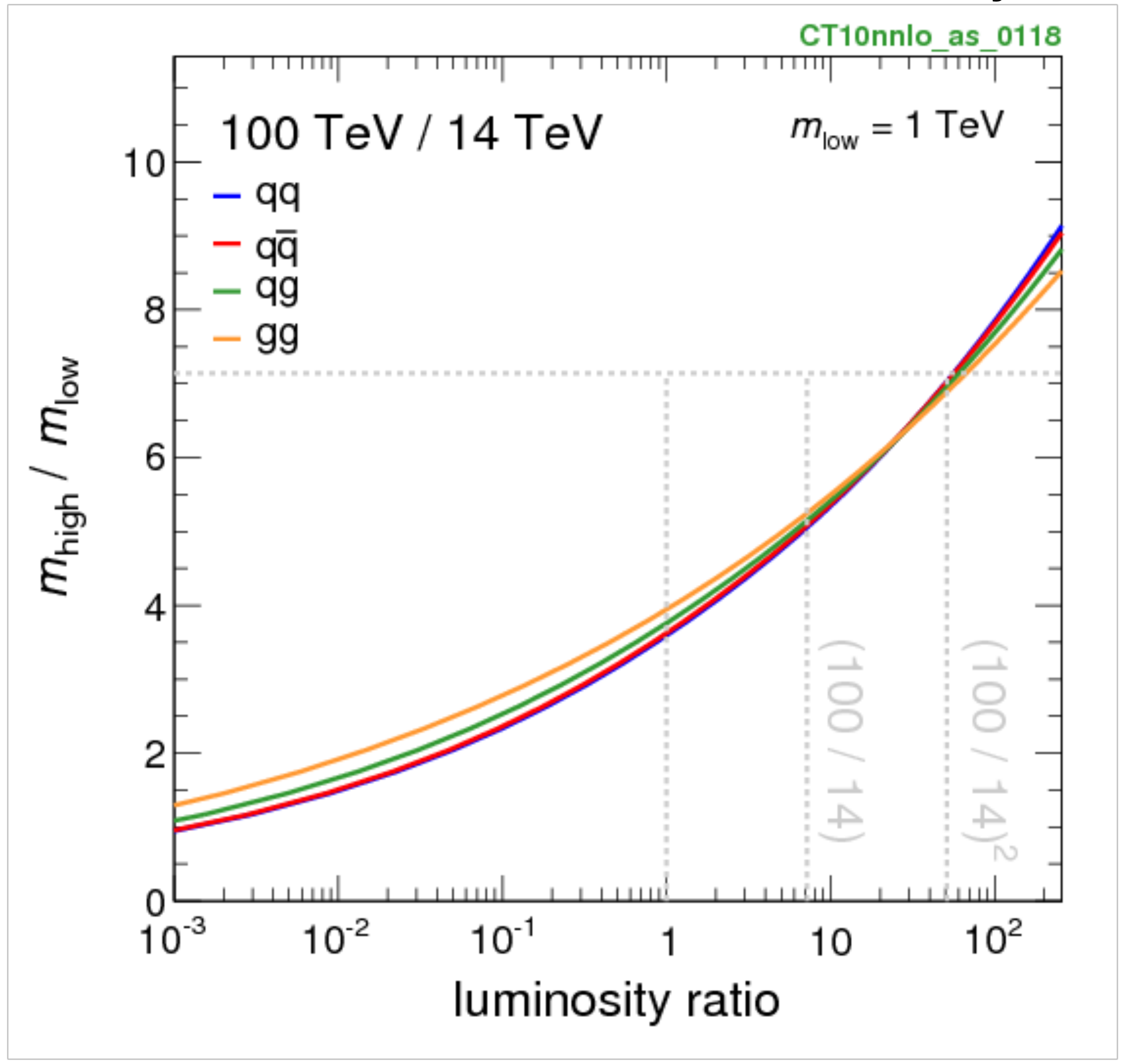
For higher mass ~O(10) TeV

Large increase in XS means direct BSM sensitivity almost immediately



Lower mass ~O(1) TeV

Smaller increase in XS means need at least 10x luminosity



Plan is to run for 25 years

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 & 30 ps res
  - ~2x granularity
  - ~3x timing resolution per track
  - Data rates: 1000 TB/s
  - Radiation: ~10^2 x HL-LHC

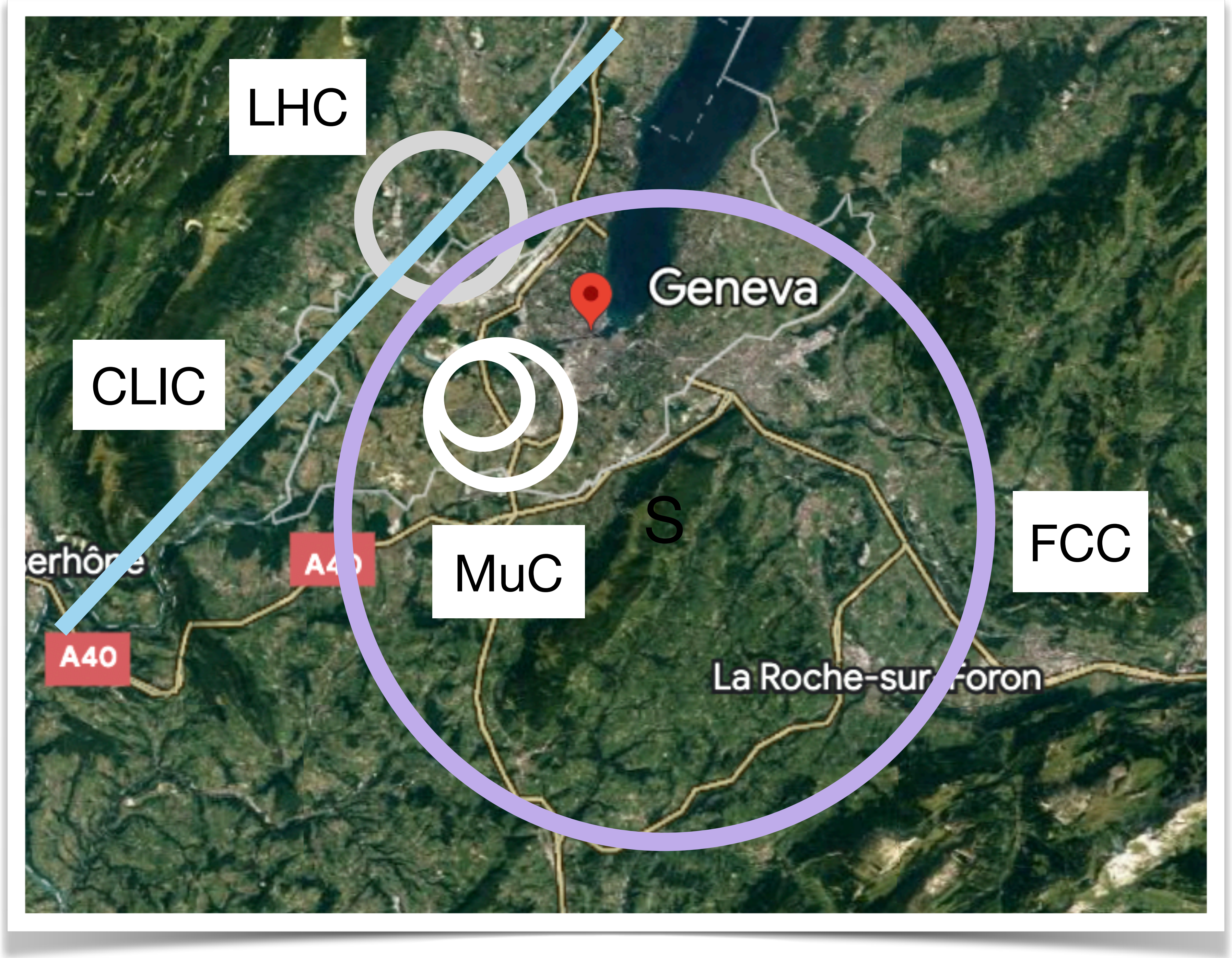
We are *many* decades away from being able to build these detectors

Also need forward coverage $|\eta|$=4-6 and larger detectors/magnets

What about muons?

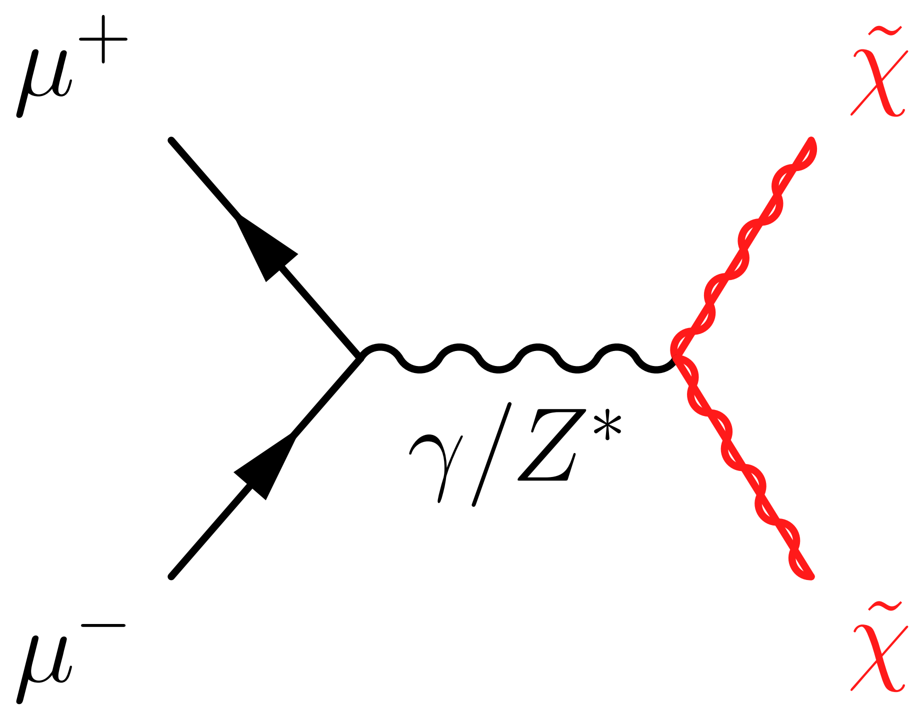
Break the traditional paradigm of larger and larger e^+e^- and hadron colliders

- Compact & power-efficient
  - Massive → no synchotron radiation
  - Leptons → 2 E_{beam}=$E_{collision}$
  - Luminosity/Power increases with E



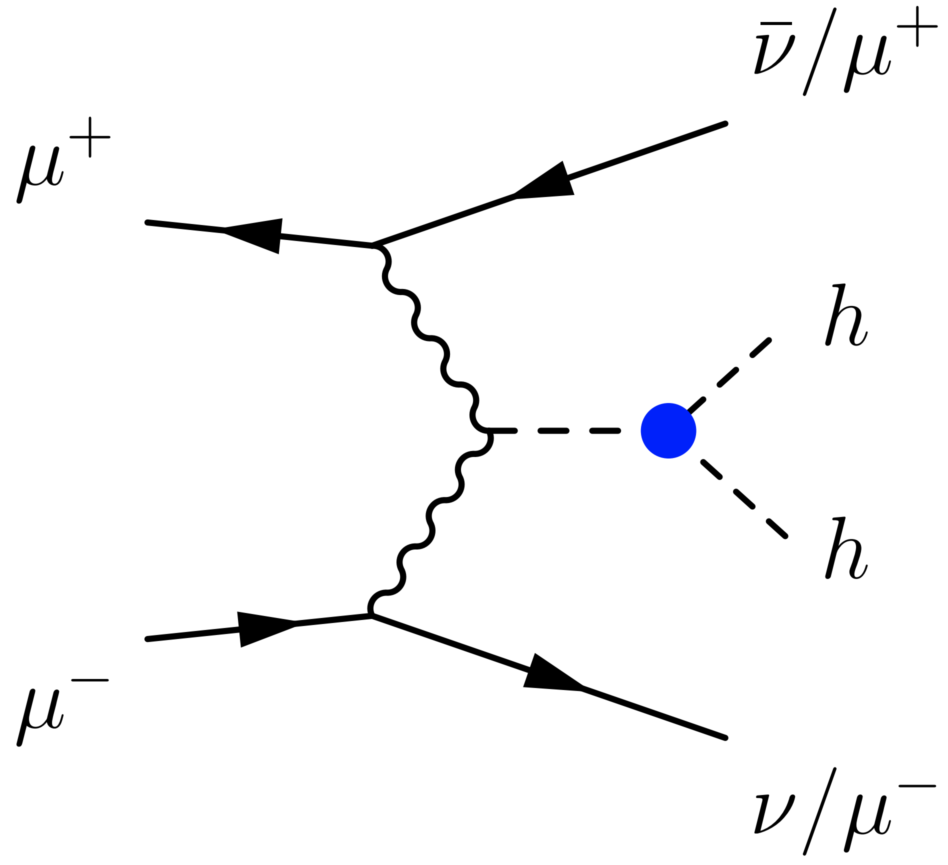
Muon Collider Physics

BSM reach & precision electroweak in same experiment - without QCD backgrounds



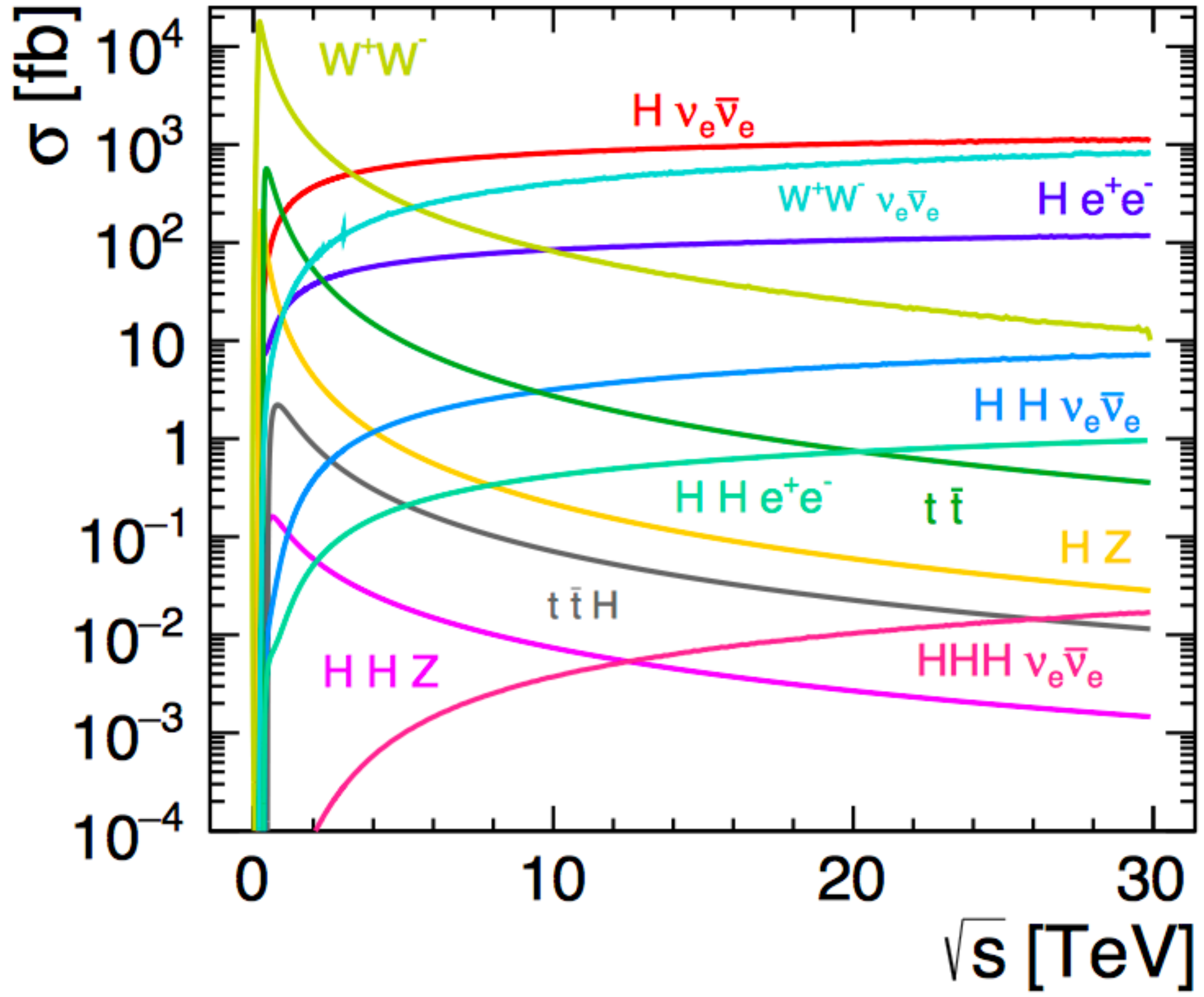
$$\sigma \sim \frac{1}{E^2}$$

s-channel
multi-TeV objects



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

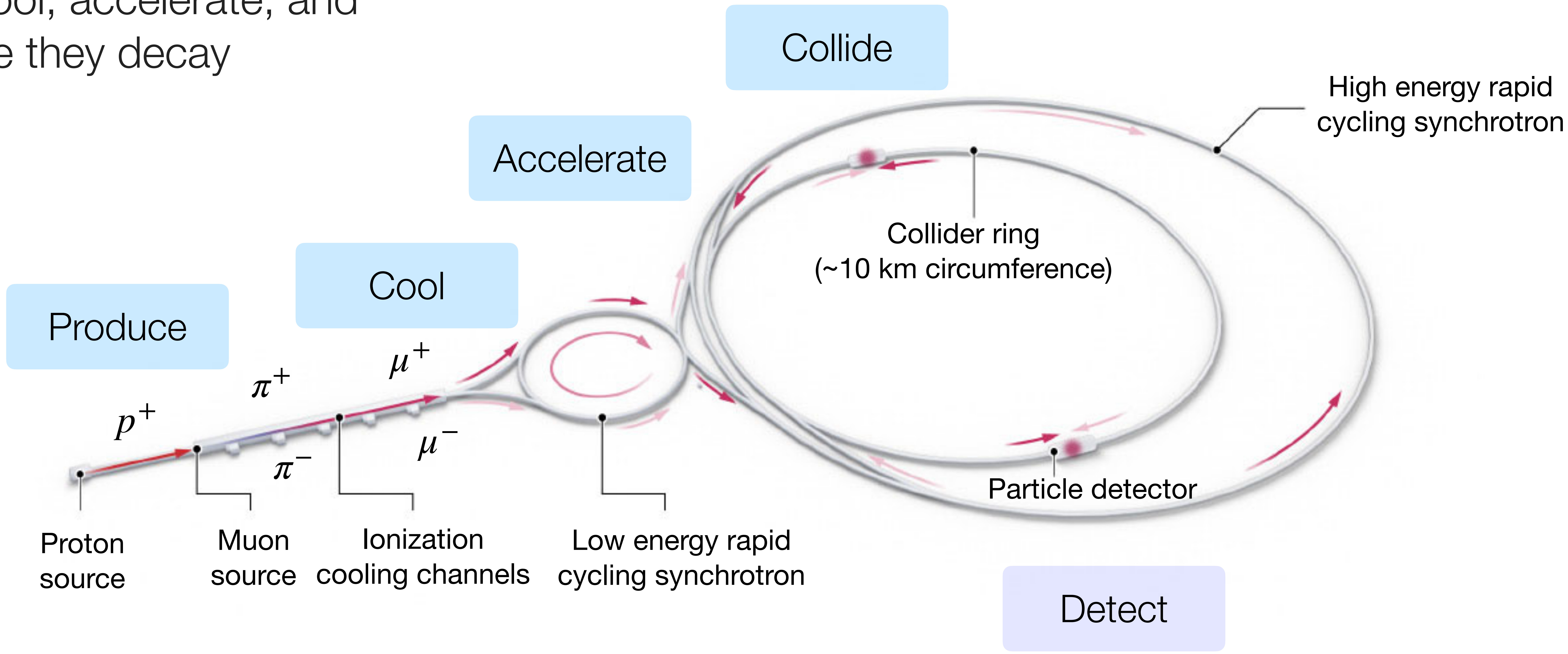
Vector boson fusion
~100 GeV objects
forward ν/μ



The Challenge

Muon lifetime τ=2.2 μs

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



Unique collision environment

Set by energy, physics goals, and cross-sections

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

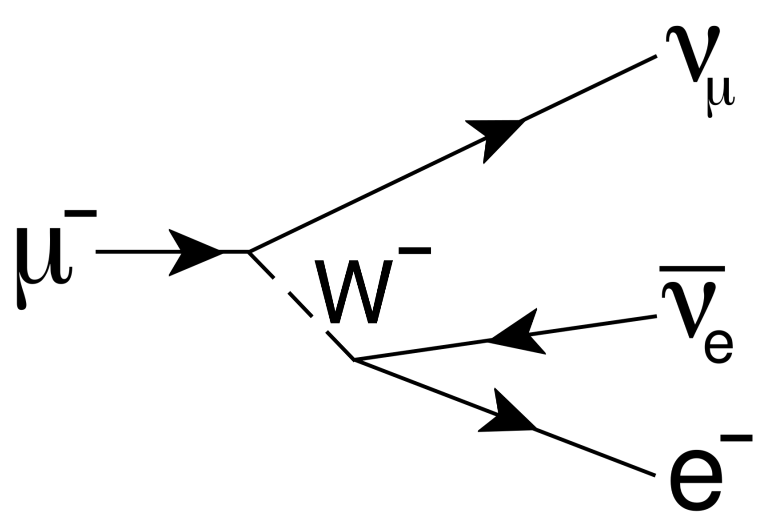
Aim for 10 ab^{-1} in 5 years

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

Set $n_b = 1$ and maximize N_μ per bunch	~$2 \cdot 10^{12}$ N_μ
Minimize circumference, maximize f	30 kHz
Minimize beam size, aim for	$\sigma_x \sigma_y$ ~20 μm, σ_z ~1.5 mm
Re-inject muons every βγτ	100 ms
Decays w/in 20 m of detector	*10^7*
Total energy from μ decays	*~10 EeV*

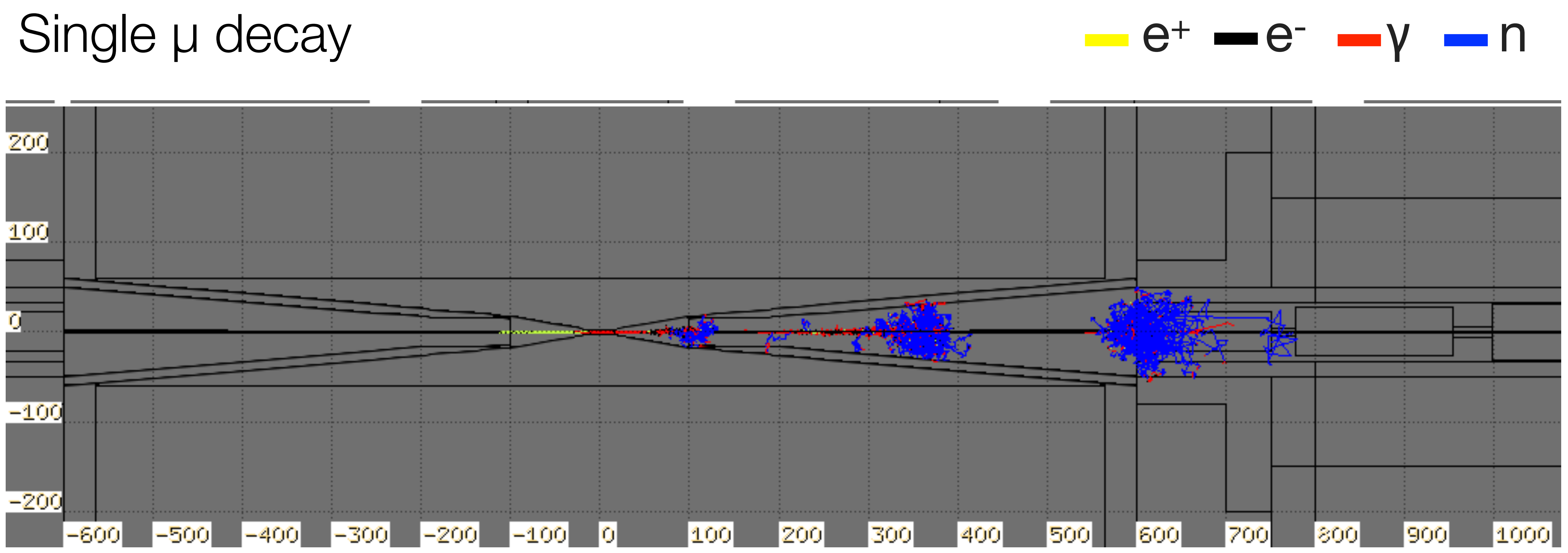
Tungsten Nozzles

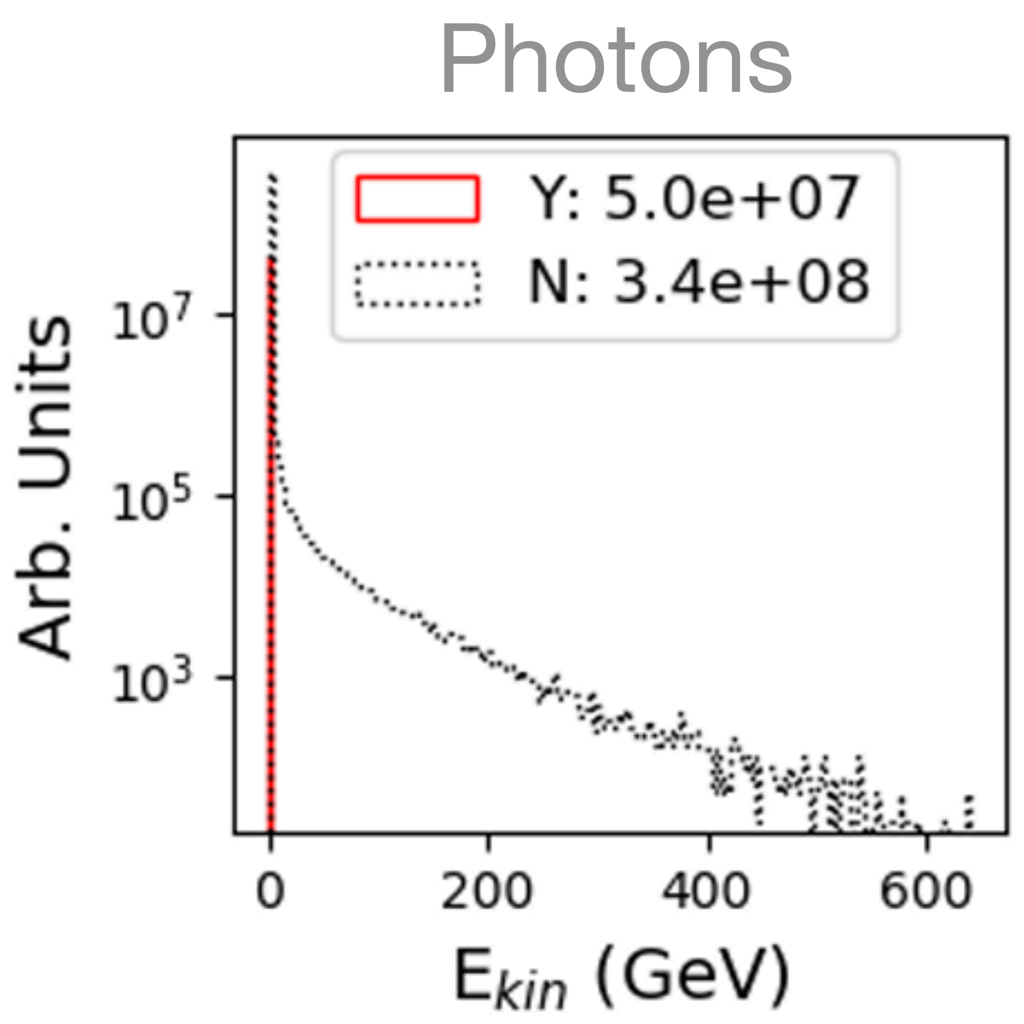
Suppress high energy component

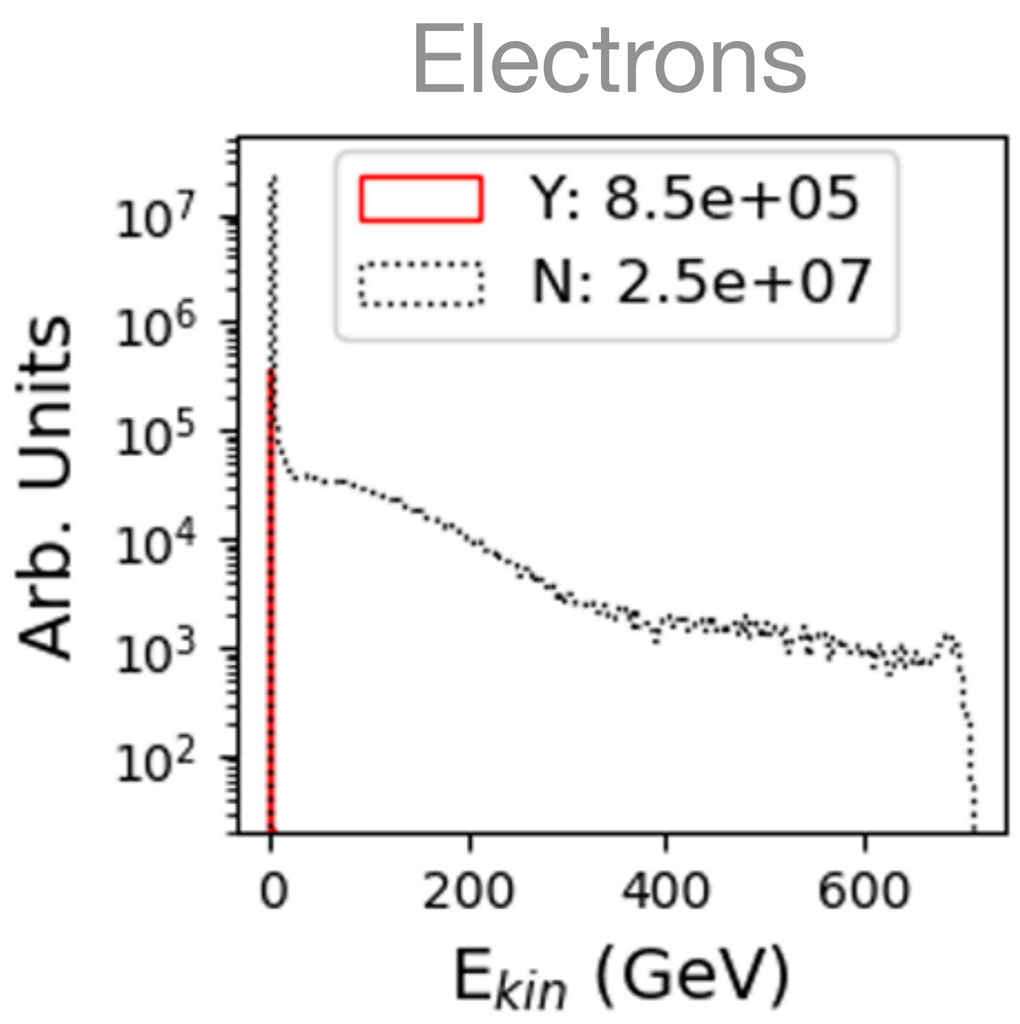


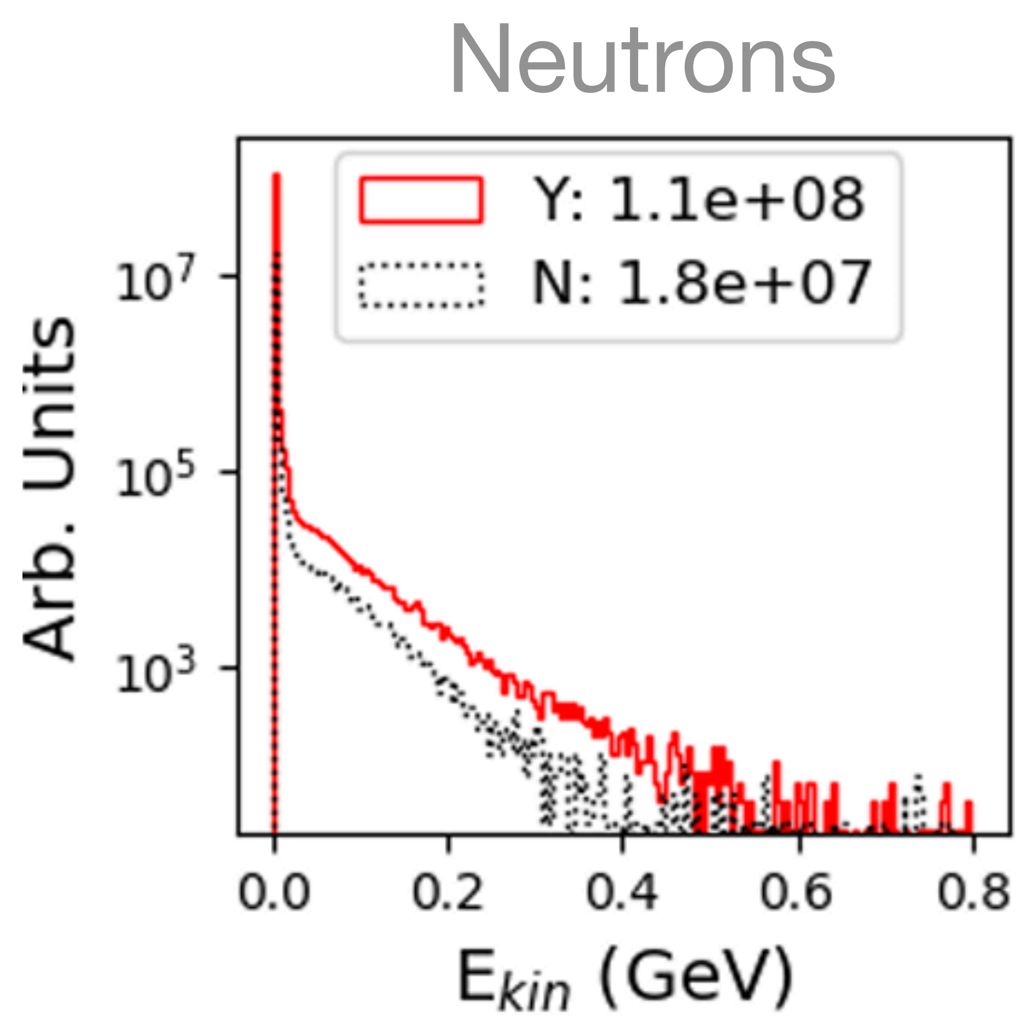
Tradeoff: increase in low energy neutrons

Single μ decay









Background properties

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

Exact details depend on beam energy, collider lattice, nozzle, and solenoid

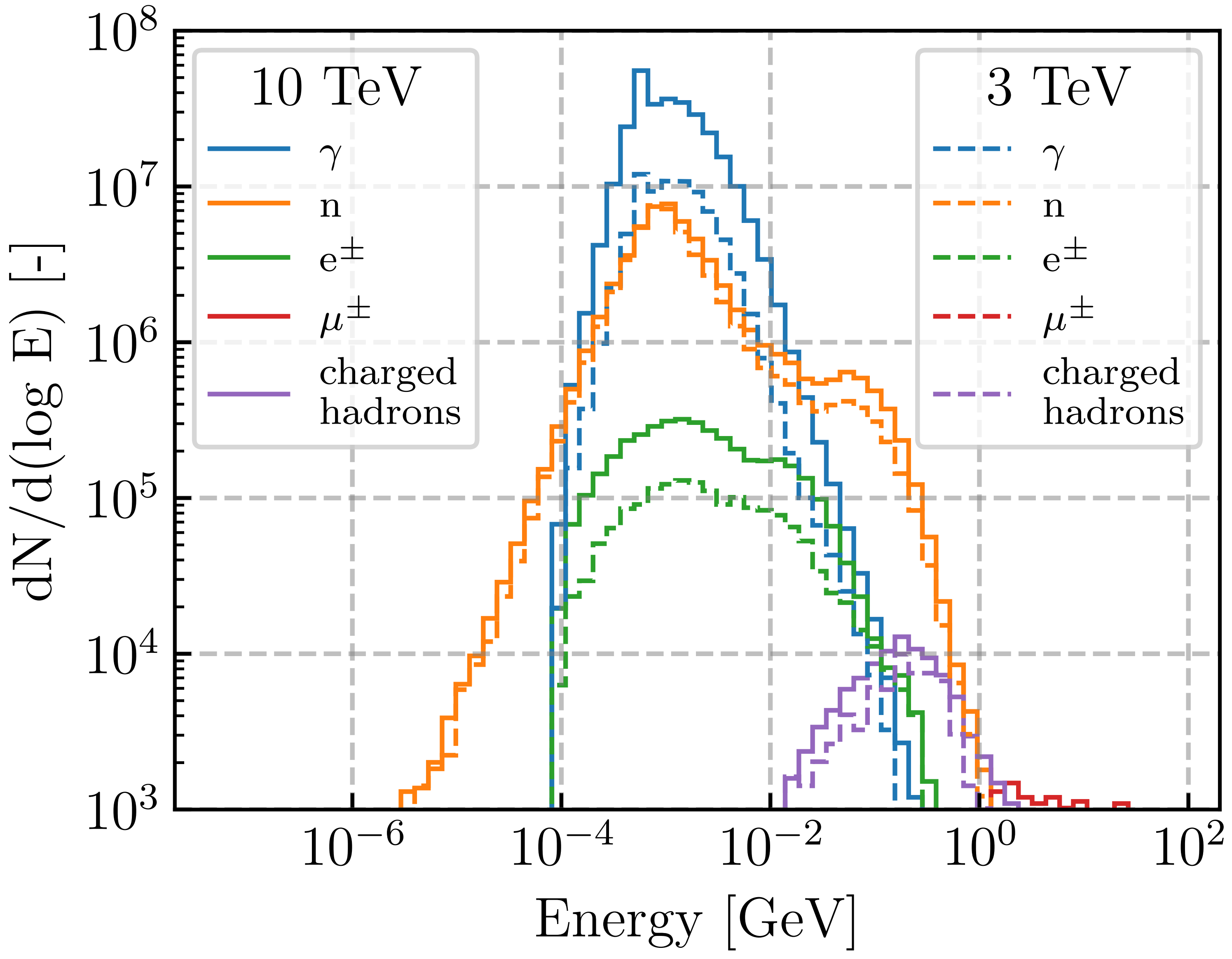
But this background looks very different from signal!

emerges from nozzles

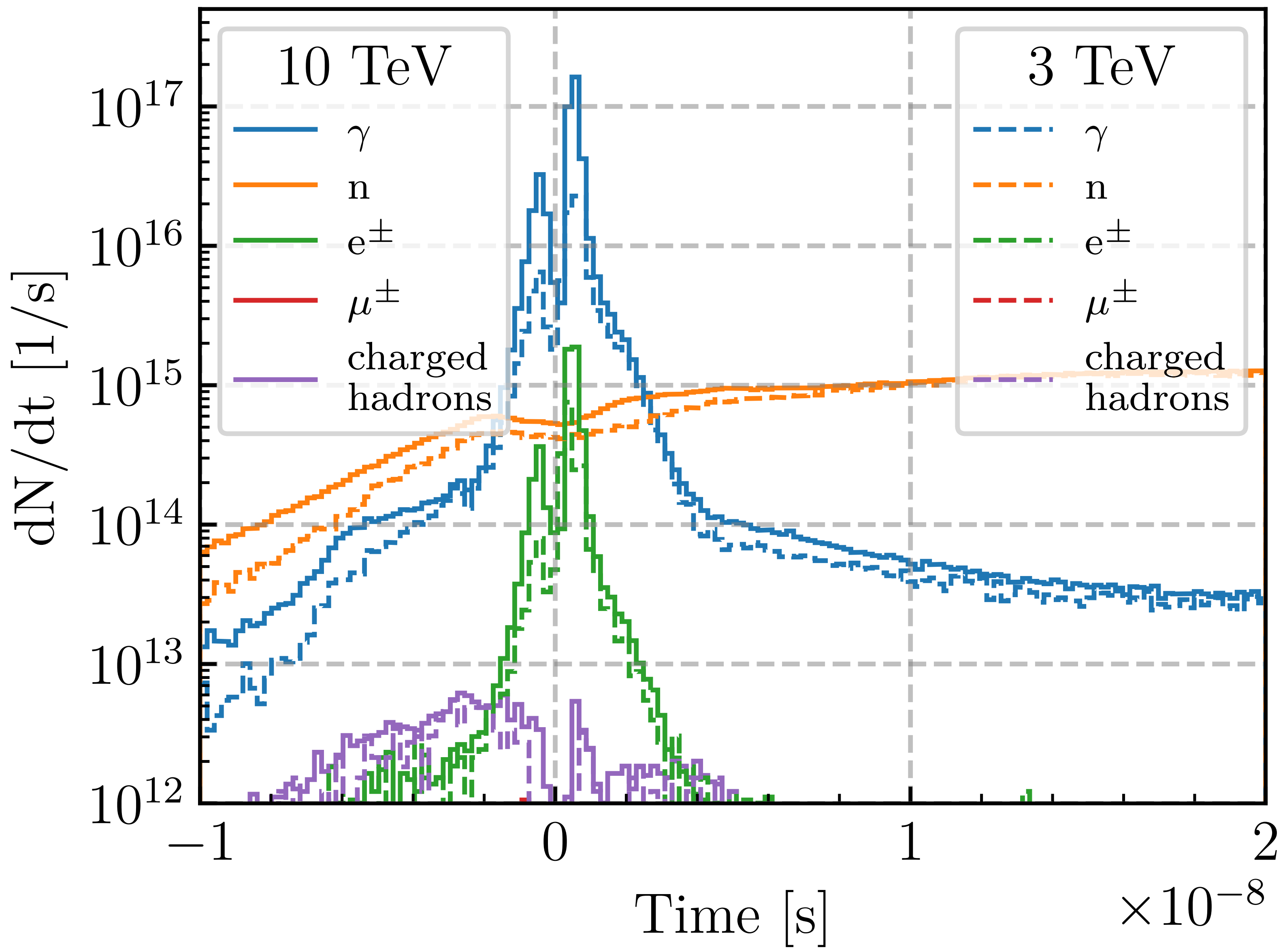
arrives largely out-of-time

extremely low energy

Low energy, ~10 MeV



Large out of time tail



What this all means for detector

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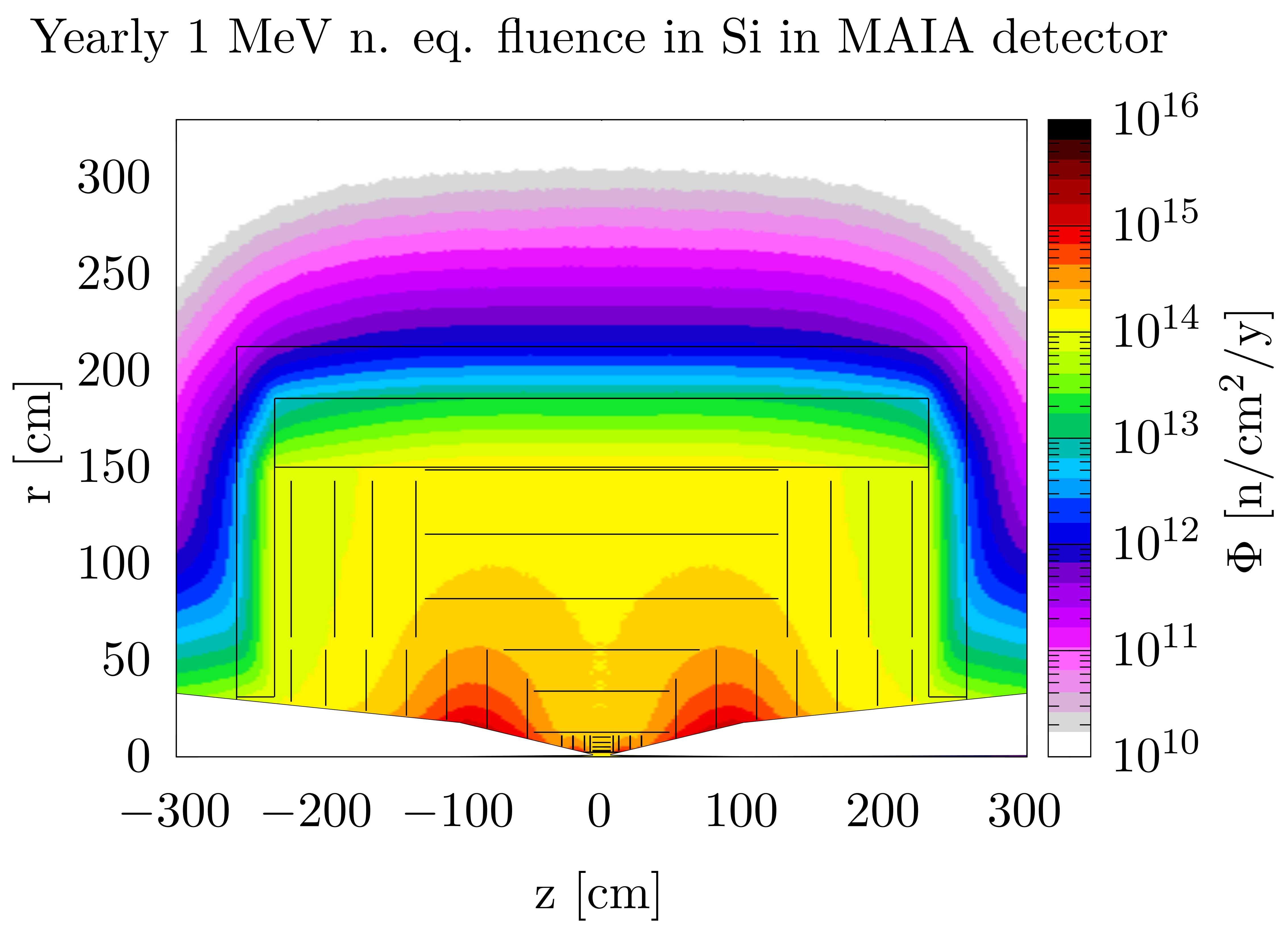
Compared to HL-LHC

~10 x hit density

~1/1000 event rate

Similar dose & fluence

Requirements are a natural evolution from HL-LHC



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

Comparing muons & hadrons

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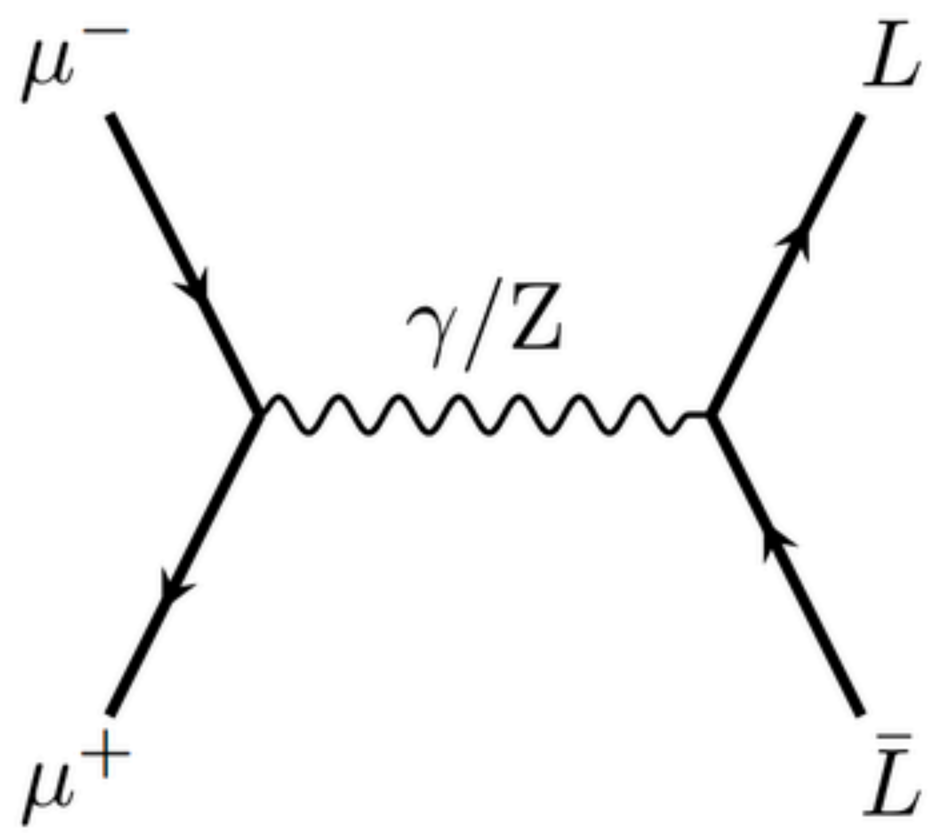
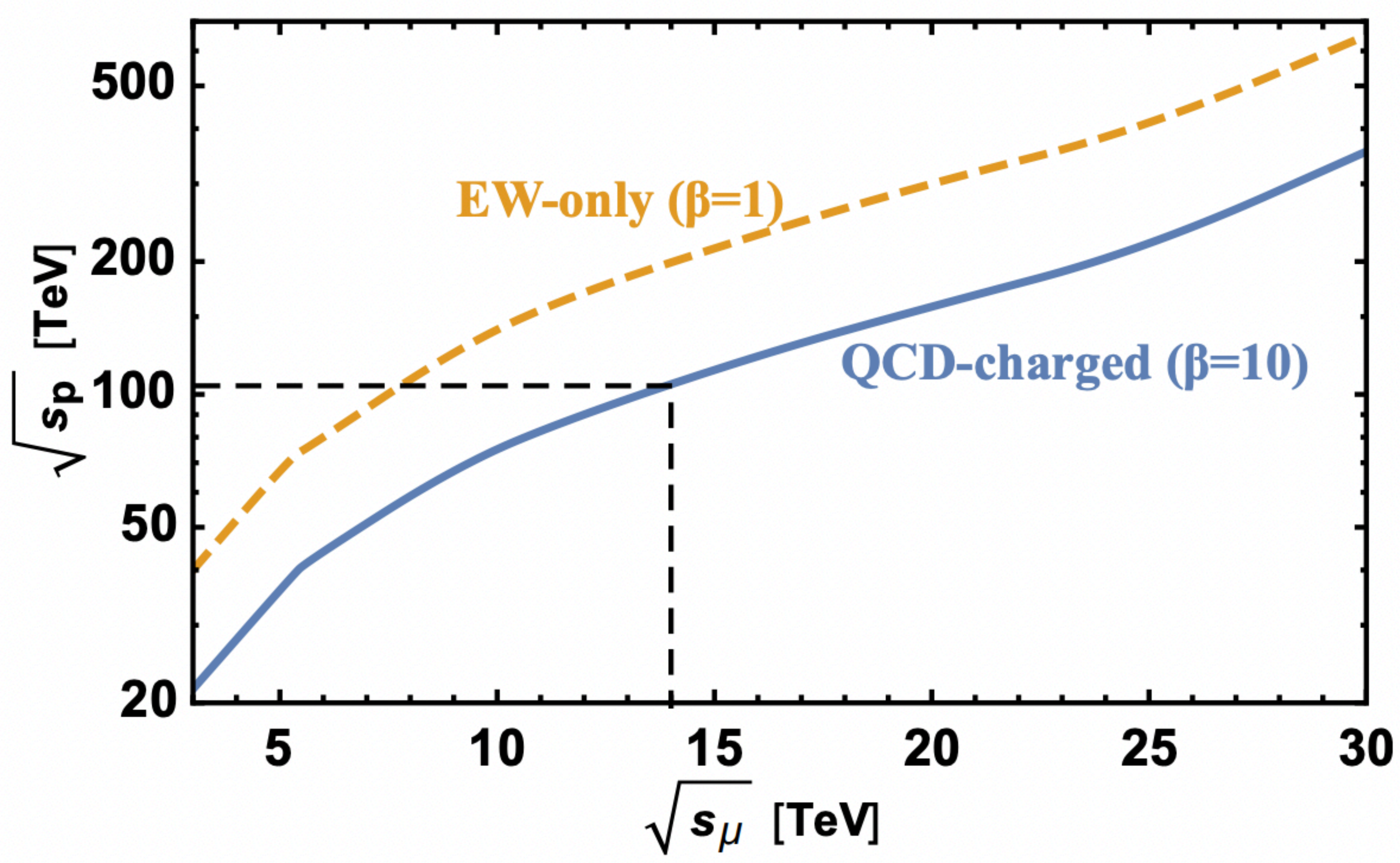
More complicated than 10 TeV μμ ~ 100 TeV pp

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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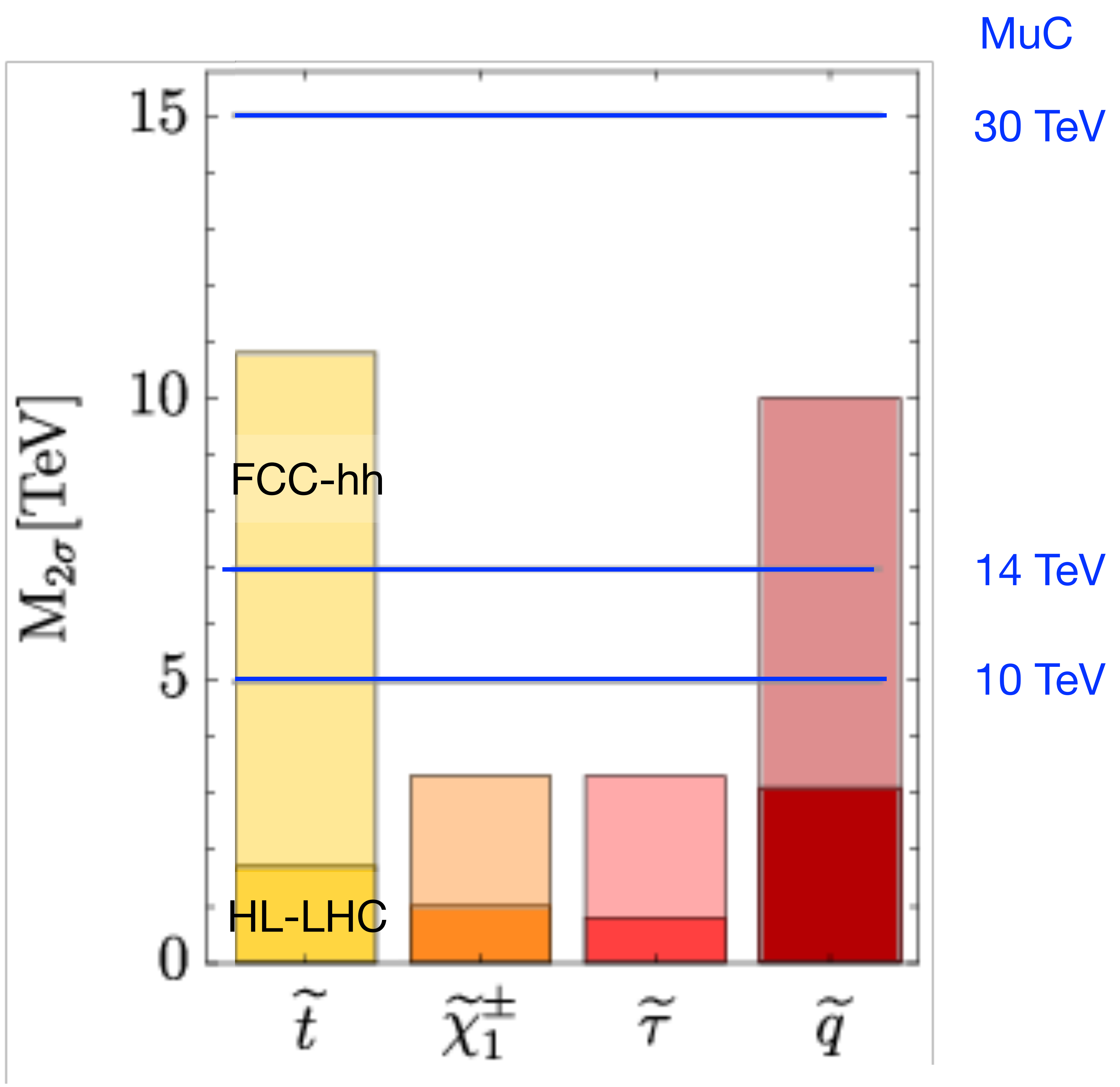
Example: Supersymmetry

MuC: pair-production up to √s/2

FCC-hh: better for stops (color charge)

But, most <u>realistic</u> models have TeV scale sleptons/electroweakinos



Comparing indirect reach

2303.08533

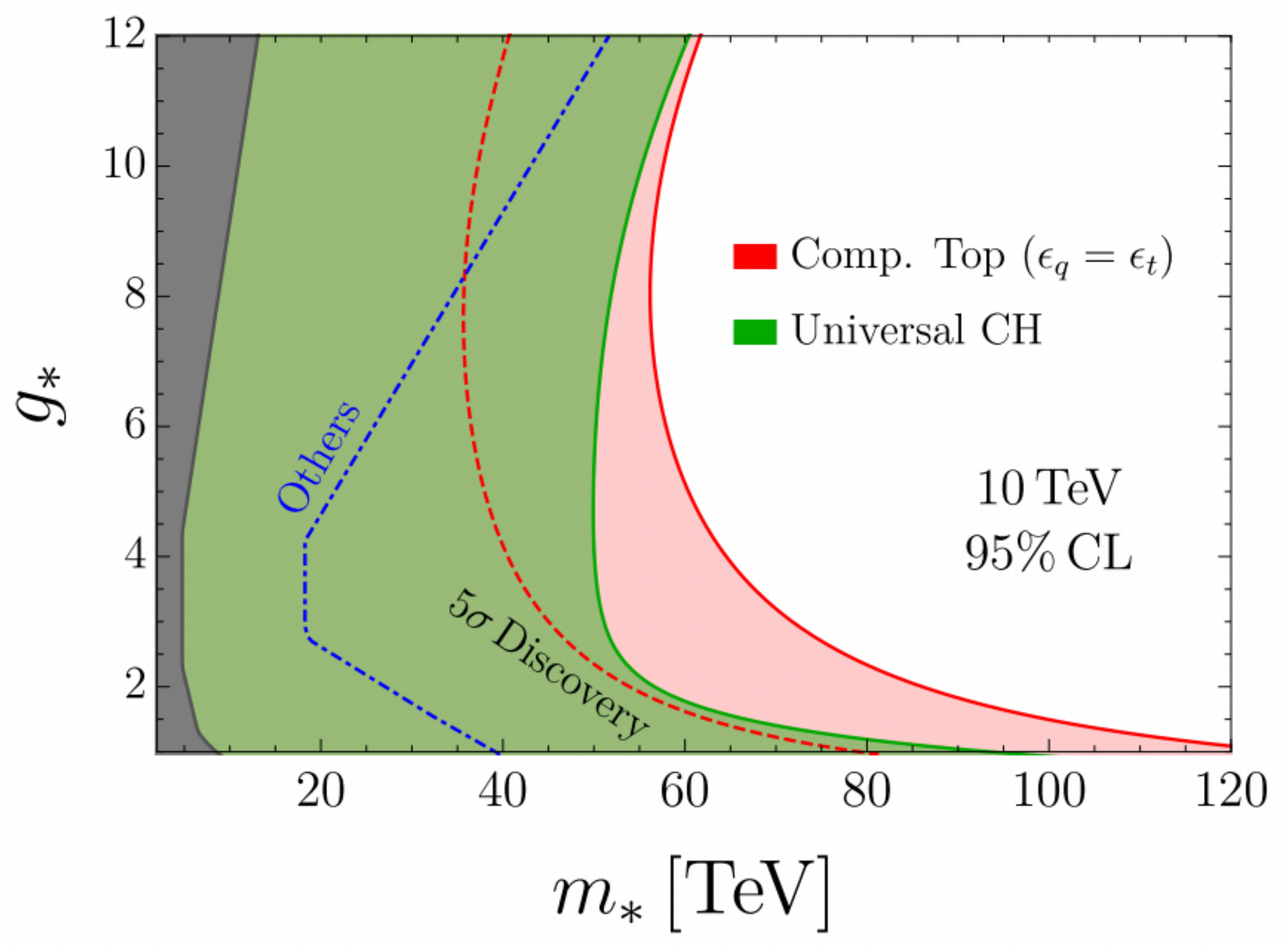
Example: Higgs Compositeness

Diboson & di-fermion final states

MuC: sensitivity scales with √s

FCC-hh: lower effective parton luminosity

Low energy **e+e-** Doesn't compare

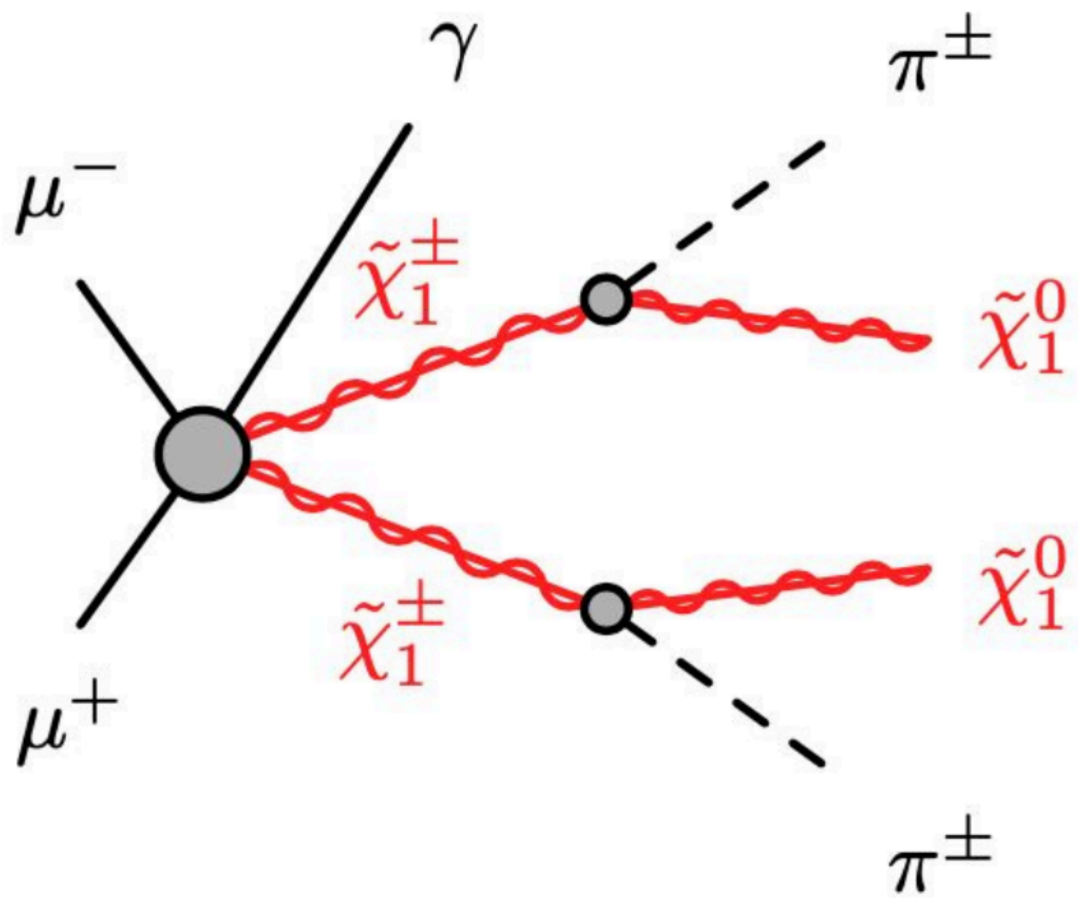


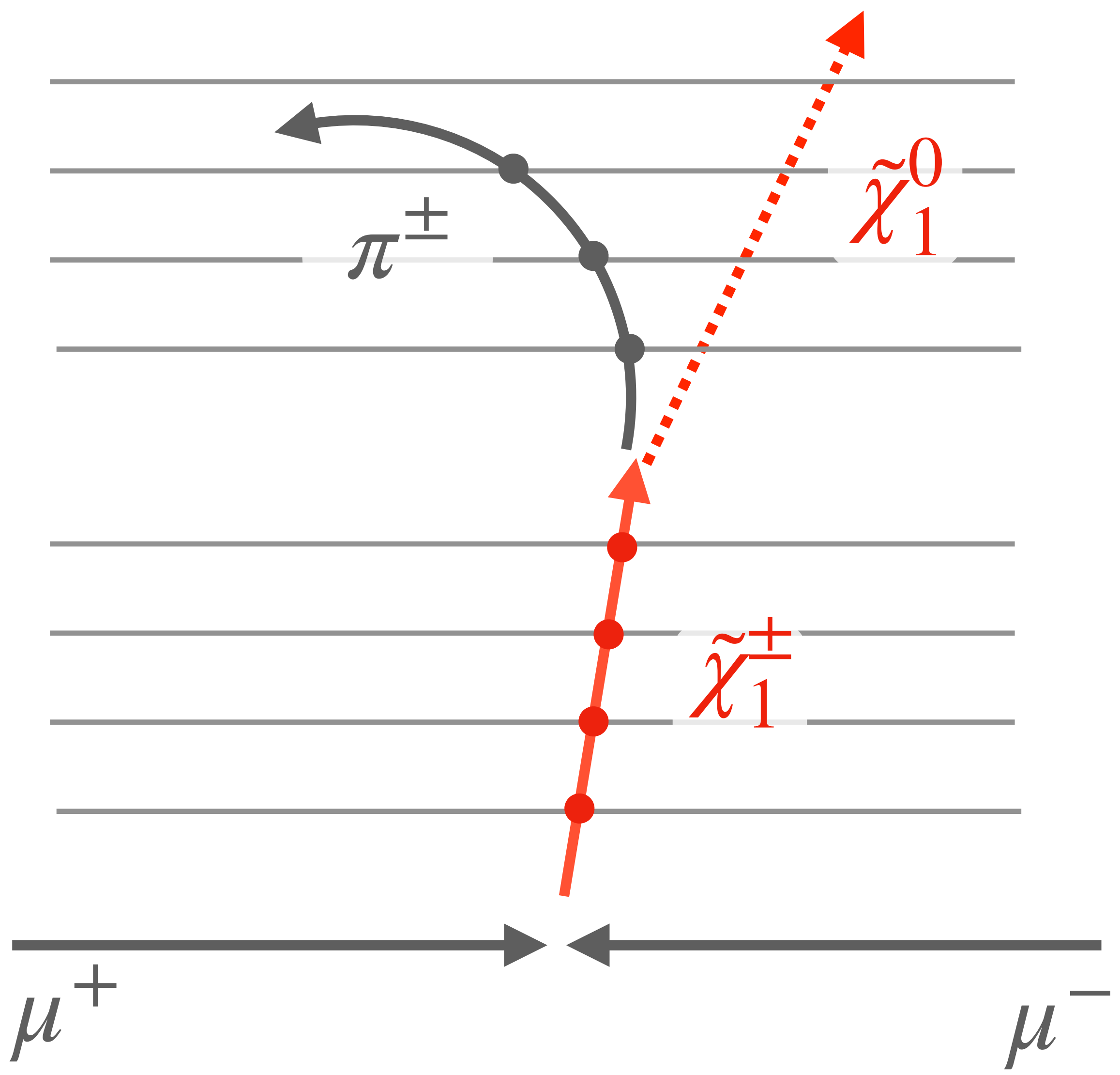
Challenge for both: retaining sensitivity to WIMPs

2504.21417

One of our most important physics targets

Challenging signatures: mono-X, disappearing track, soft track





$\tilde{\chi}_1^{\pm}$ is *slowly* moving!

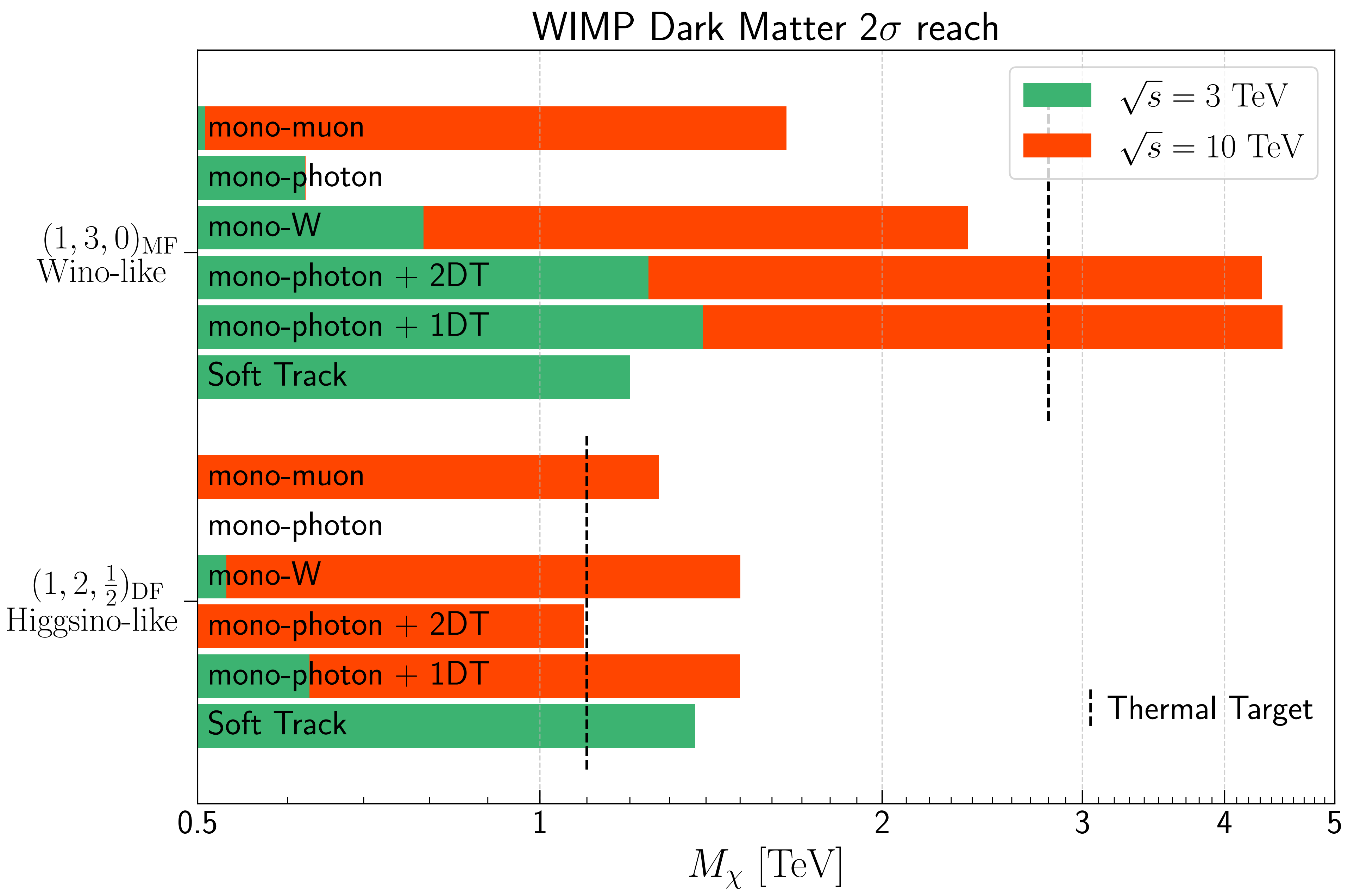
Takeaway: Can we do physics?

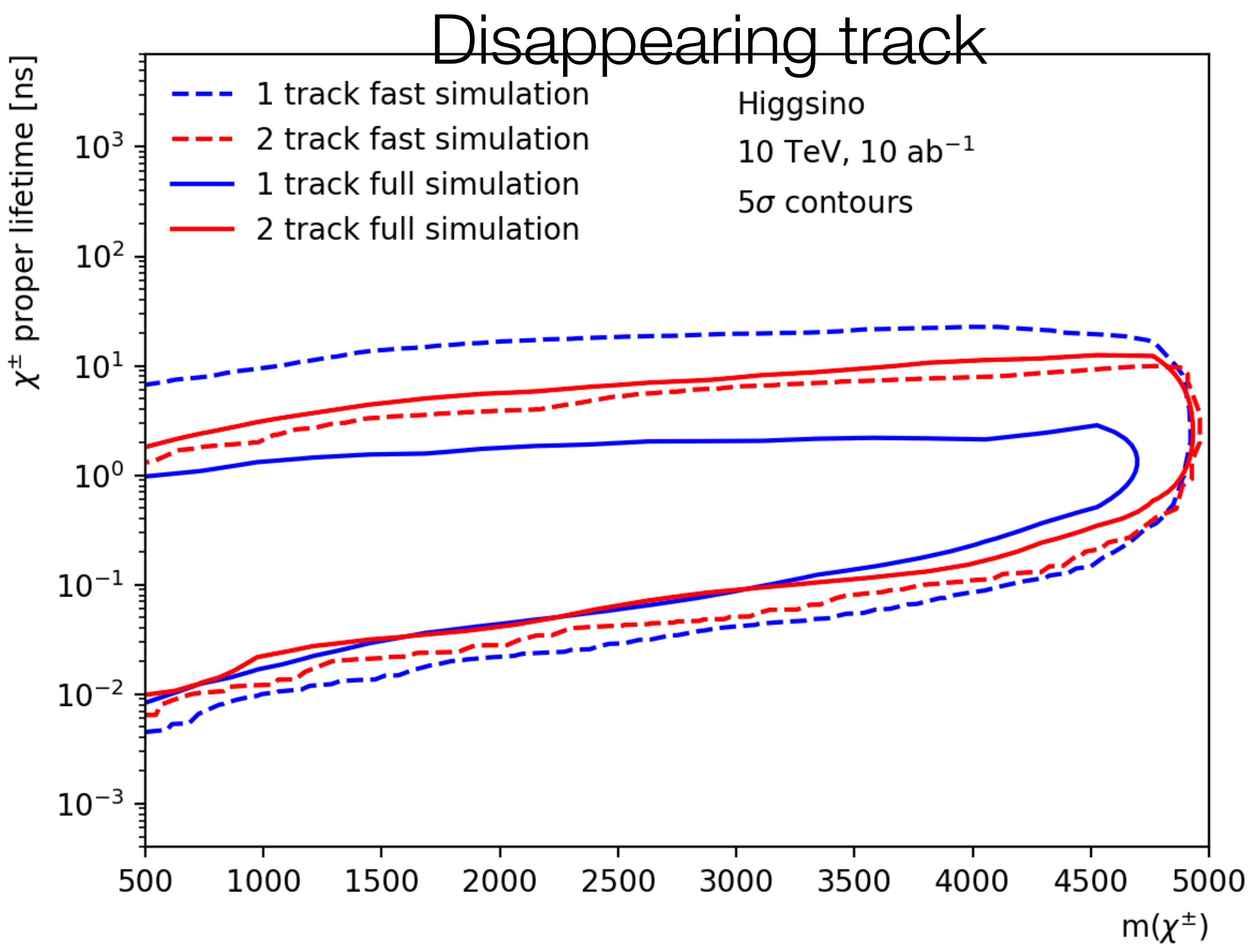
2303.08533

Real test: baseline detector design in full simulation based on near term technology

We've done this for a Muon Collider - with work in progress can likely do better!

Hadron colliders - we're more familiar with detector principles, but technology isn't ready





Conclusions

- We have a strong physics case for future colliders
- Decision making processes on going
  - An e+e- machine to follow the HL-LHC
  - And rigorous accelerator R&D towards the 10 TeV scale
- Regardless - there are many commonalities across different proposals
  - Physics complementarity, detector design in simulation & technology R&D
- Get involved!

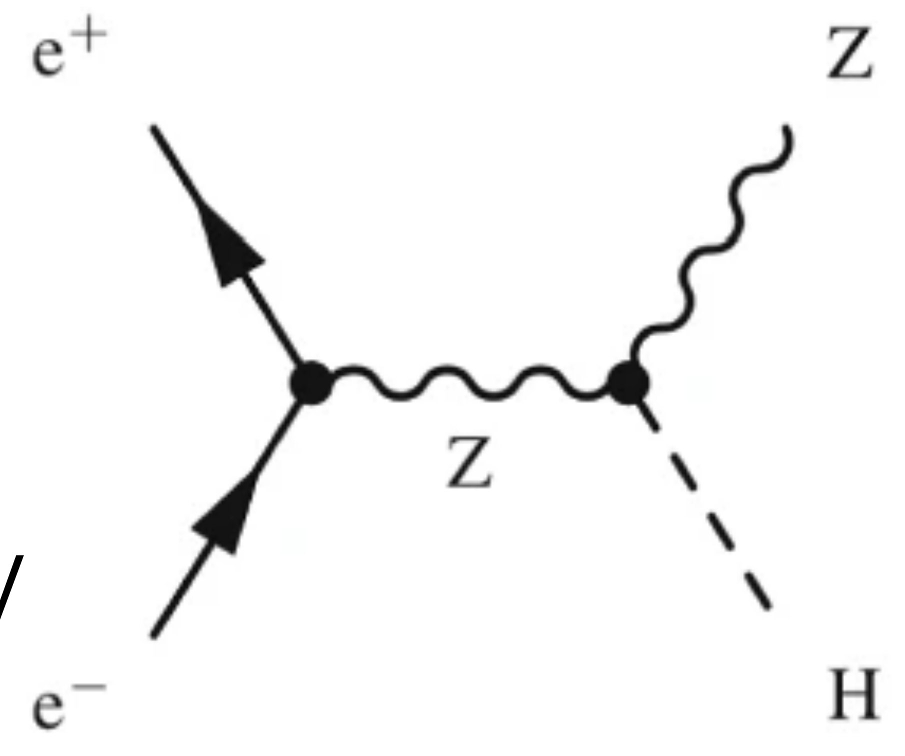
Backup

Karri Folan DiPetrillo
The University of Chicago
Brookhaven Forum
22 October 2025

Some differences in production

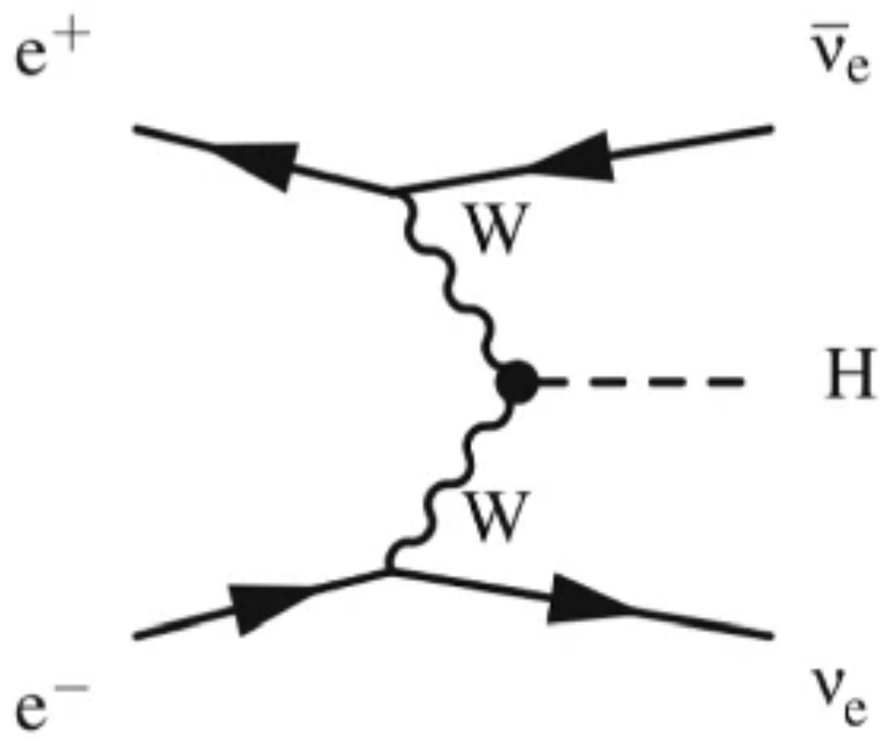
Higgsstrahlung

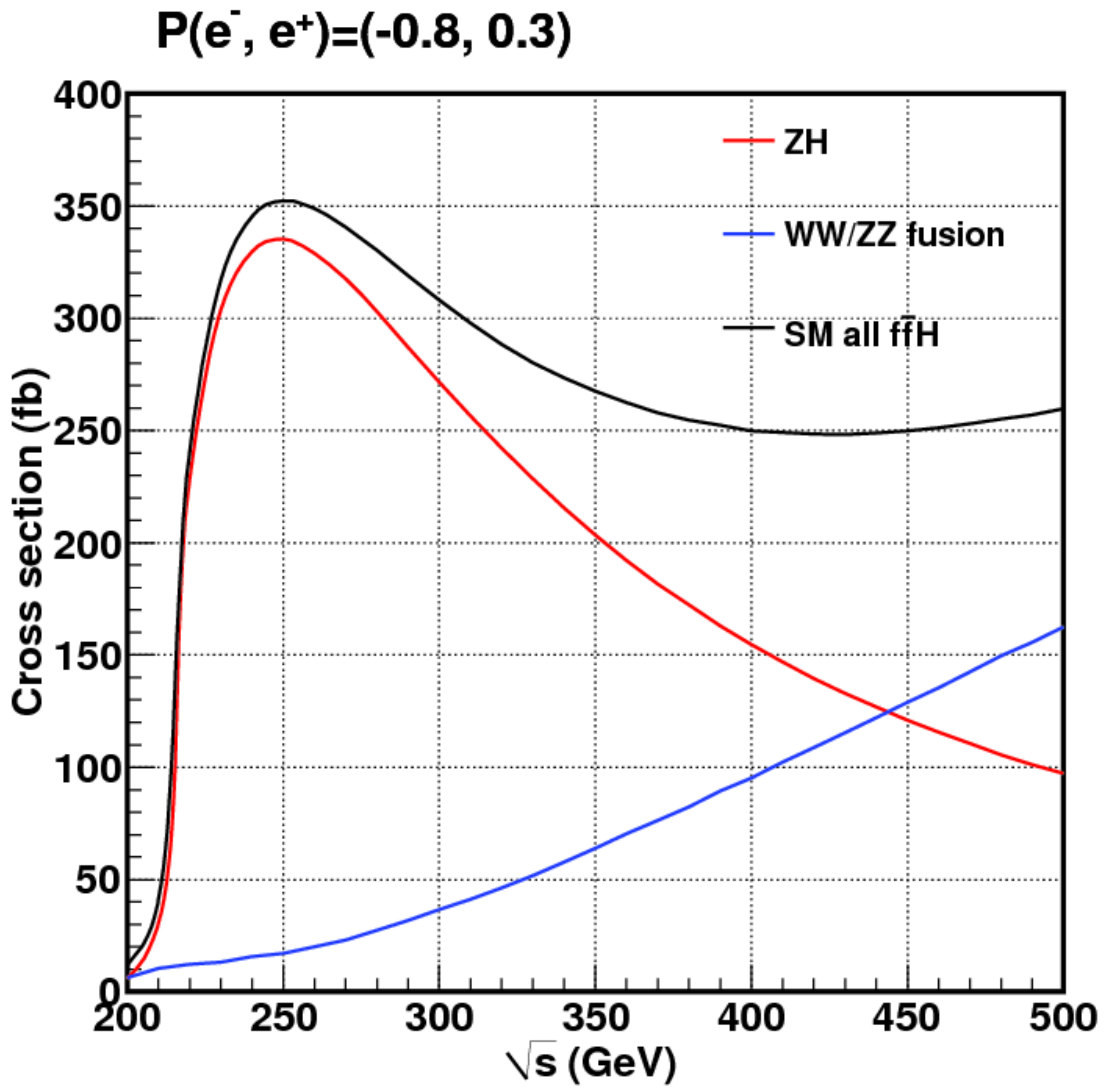
Peaks at 240 GeV



WW fusion

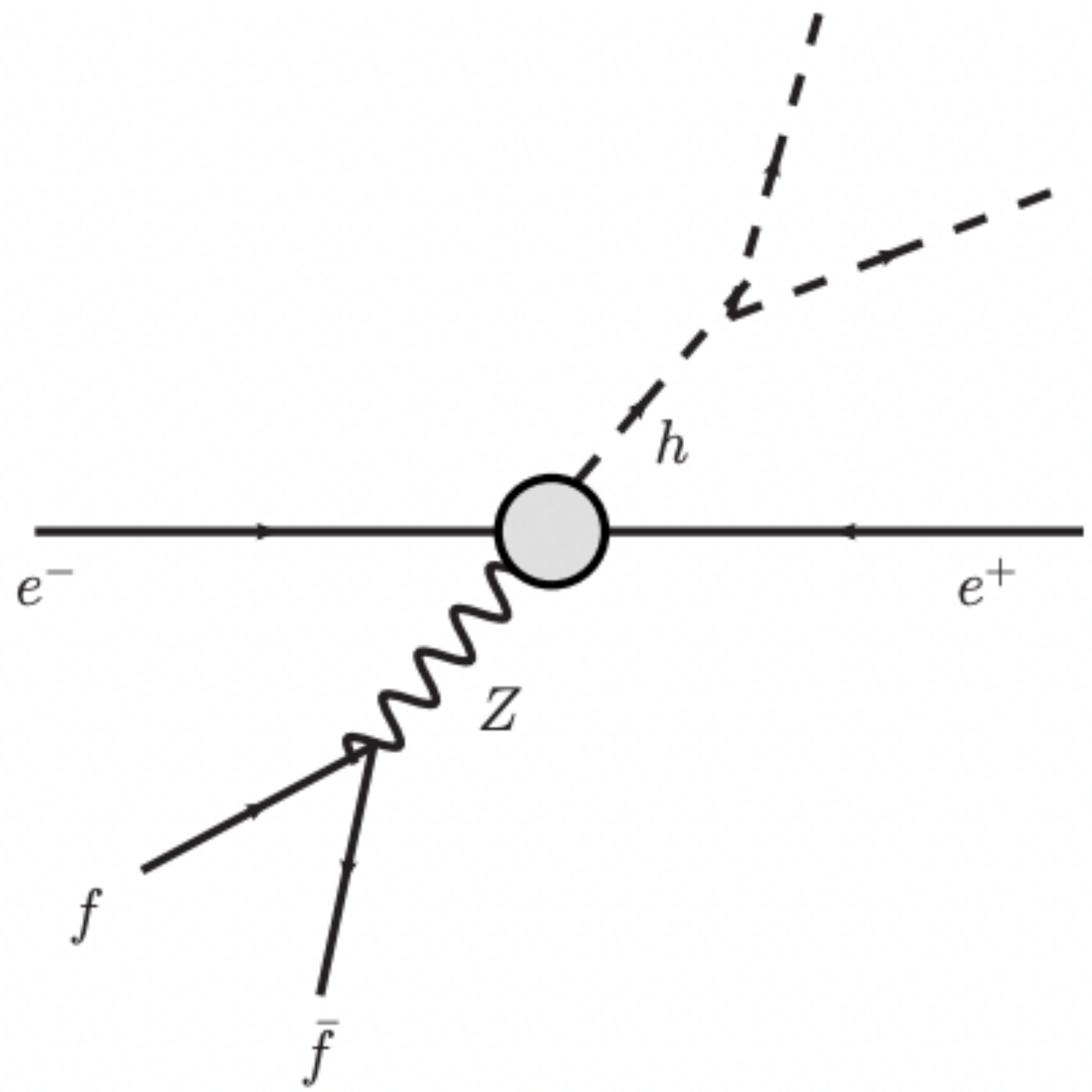
Takes over at higher E



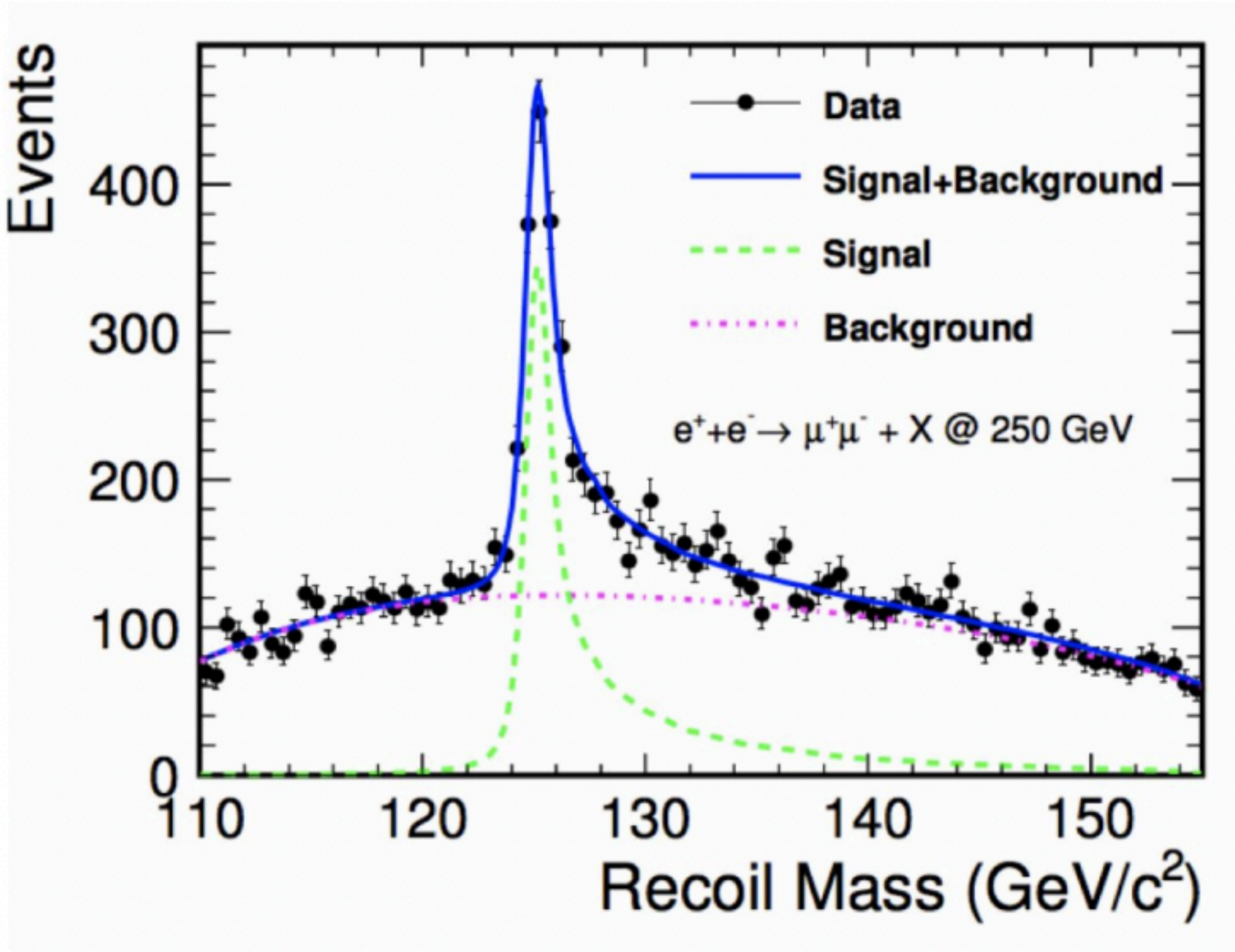


Unique feature: Higgs recoil

Know initial collision energy

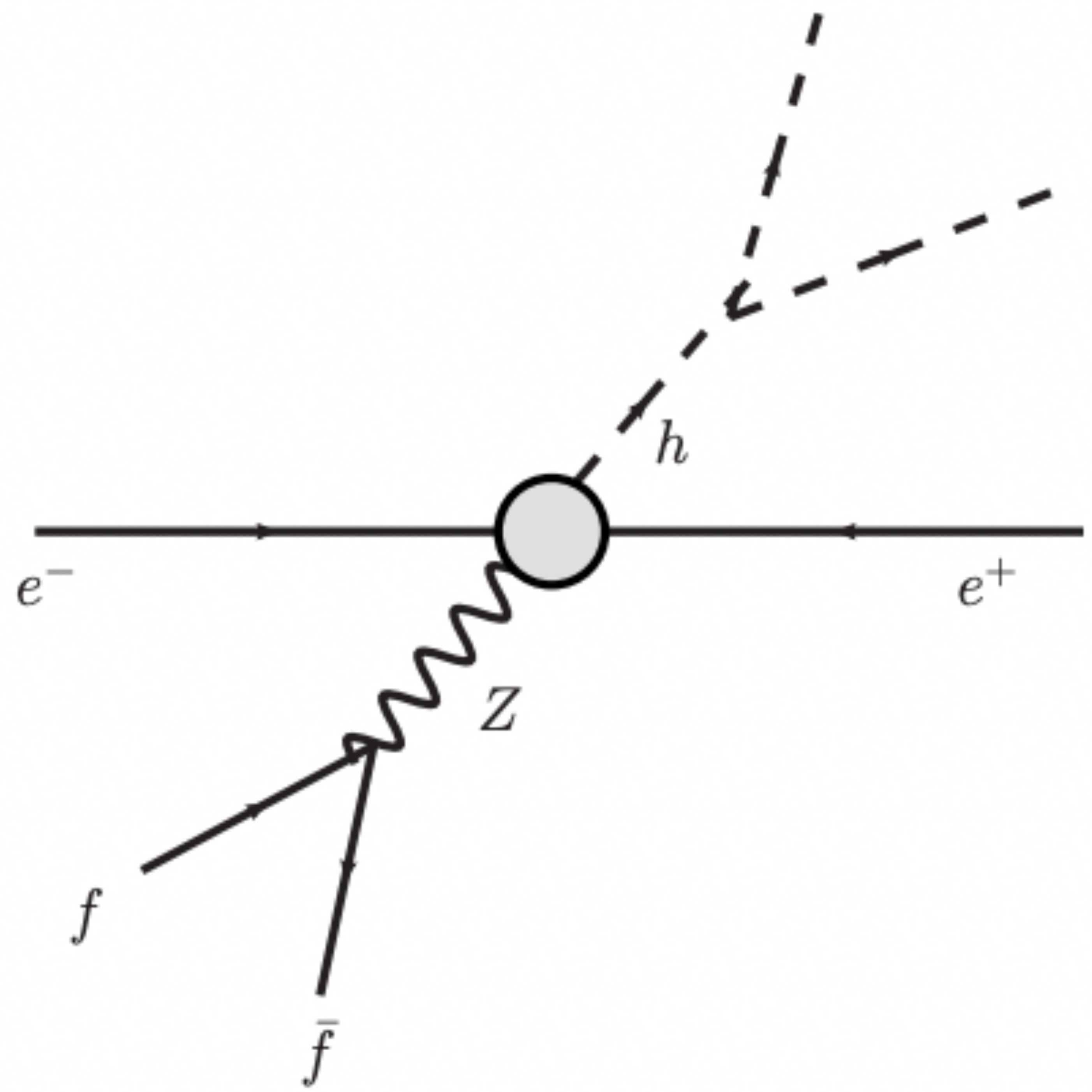


→ reconstruct the Higgs boson without identifying decaying products



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

Unique feature: Higgs recoil



Useful for

Higgs→invisible

Higgs→rare/unconventional

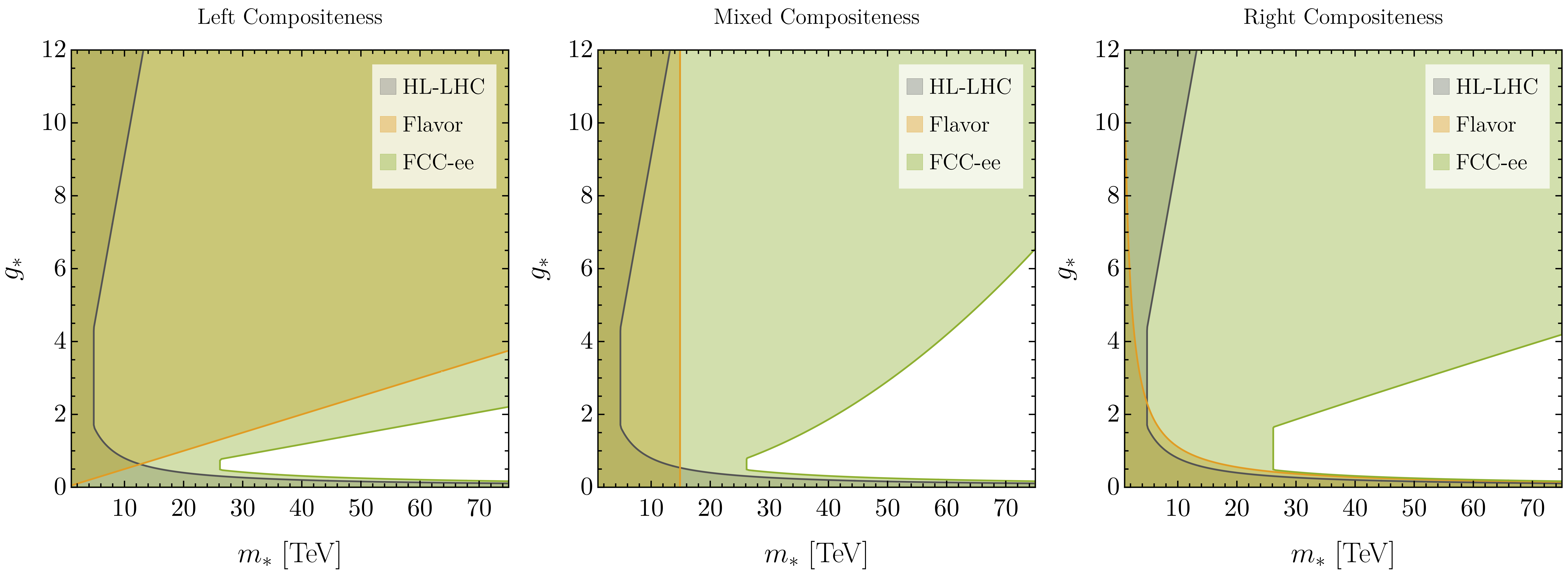
And Total Higgs width

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

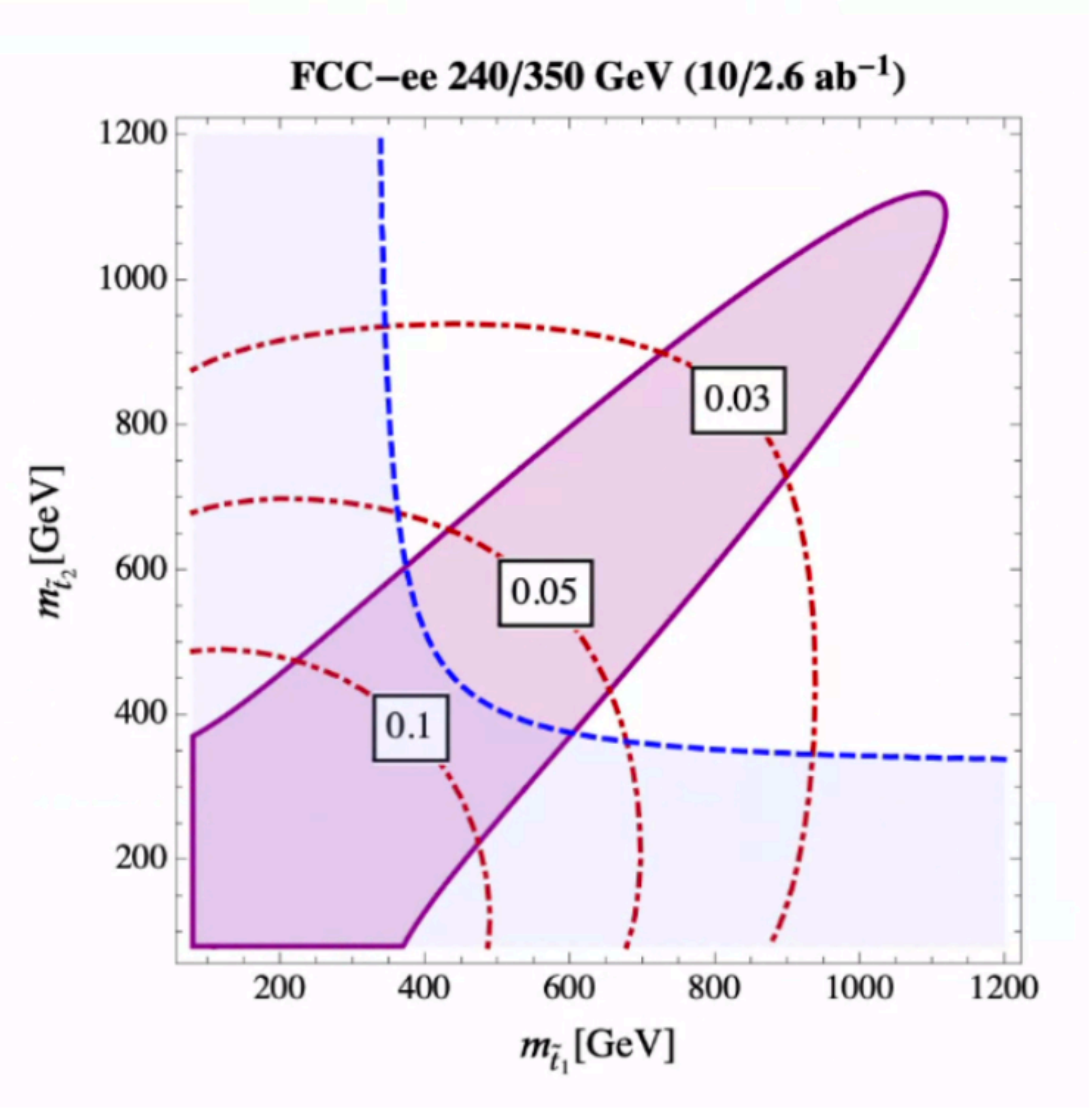
Or with h→WW and WW fusion

FCC-ee Composite Higgs

Sensitivity to BSM up to ~10 TeV scale



FCC-ee Supersymmetry



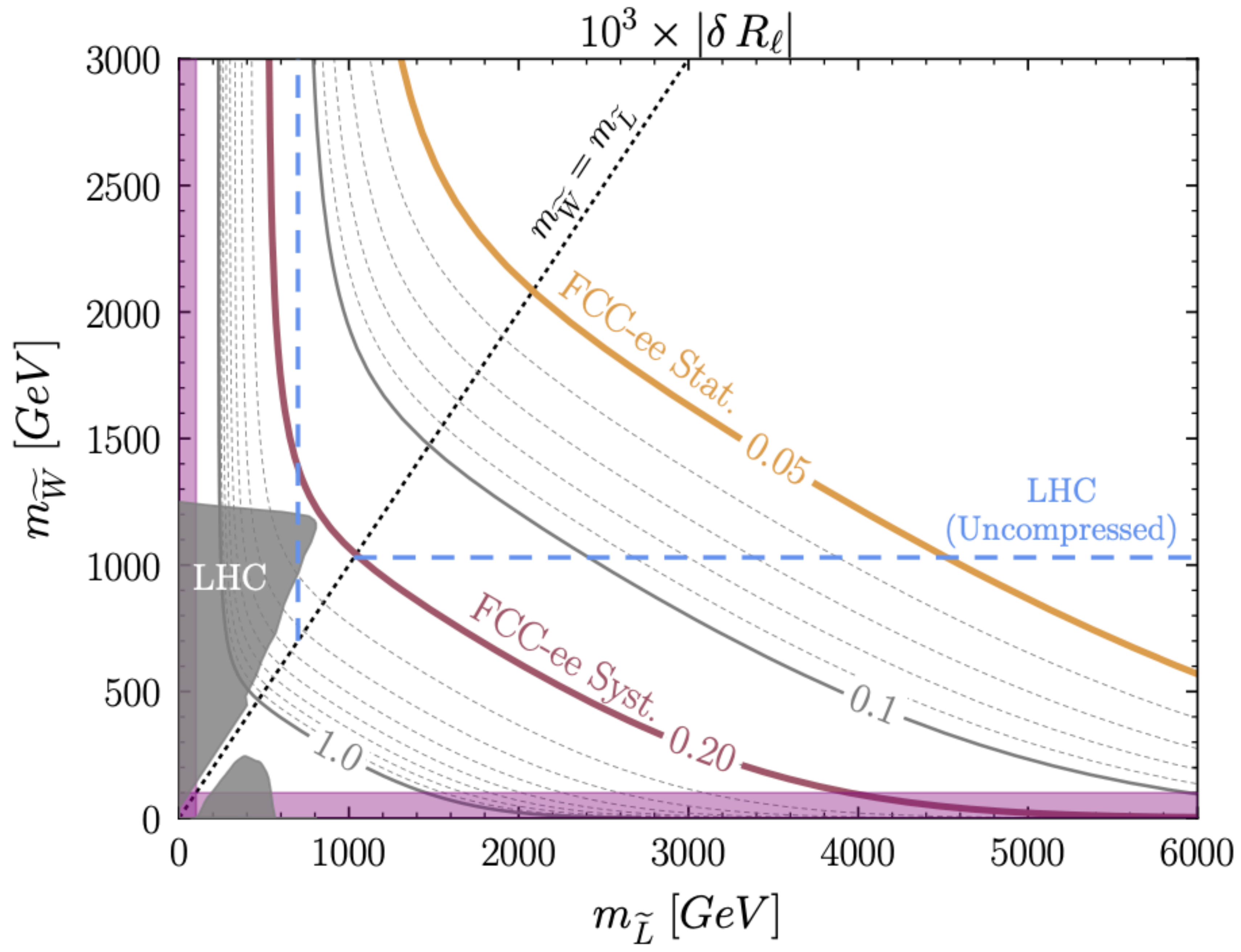
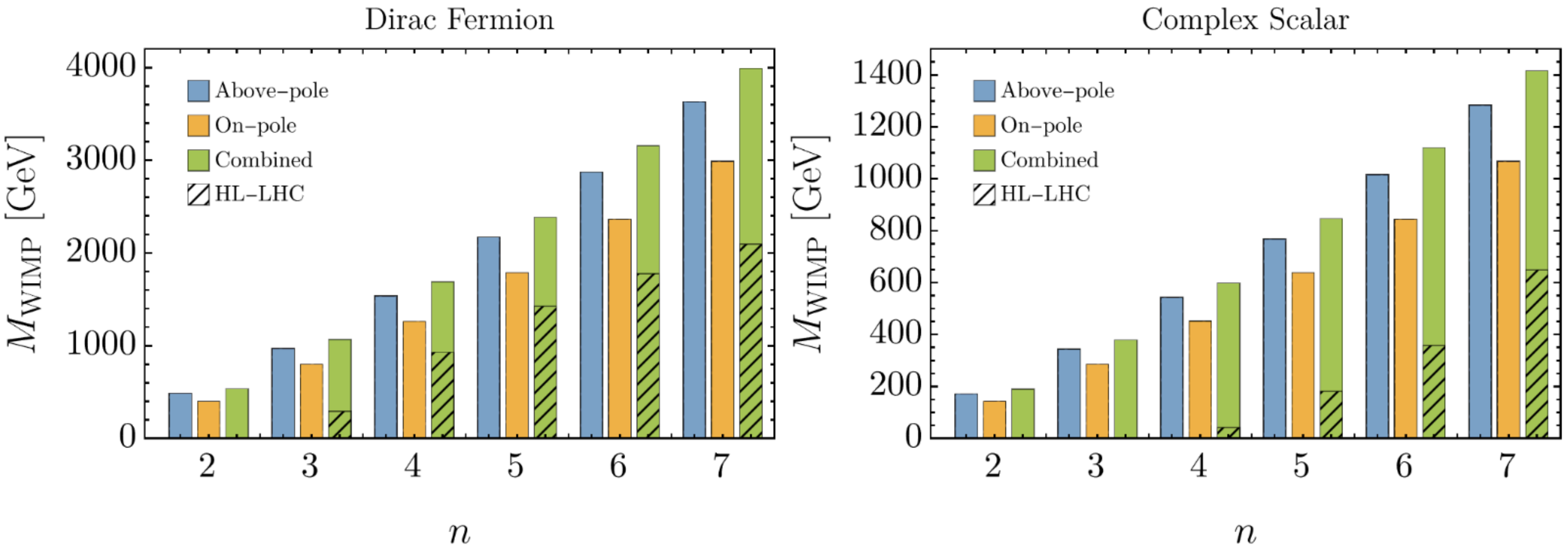


Fig. 27: Left: Projected 2σ sensitivity of Higgs couplings to stops at FCC-ee in the parameter space of stop masses $m_{\tilde{t}_1}$ vs. $m_{\tilde{t}_2}$; from Ref. [112]. Right: FCC-ee Z branching ratio projected statistical and systematic 1σ uncertainties in the left-handed selectron mass vs. pure wino mass plane; from Ref. [104] scaled to the baseline luminosities.

FCC ee WIMPs



Classic WIMPs Thermal Targets

Dirac fermion doublet (Higgsino ~1 TeV)

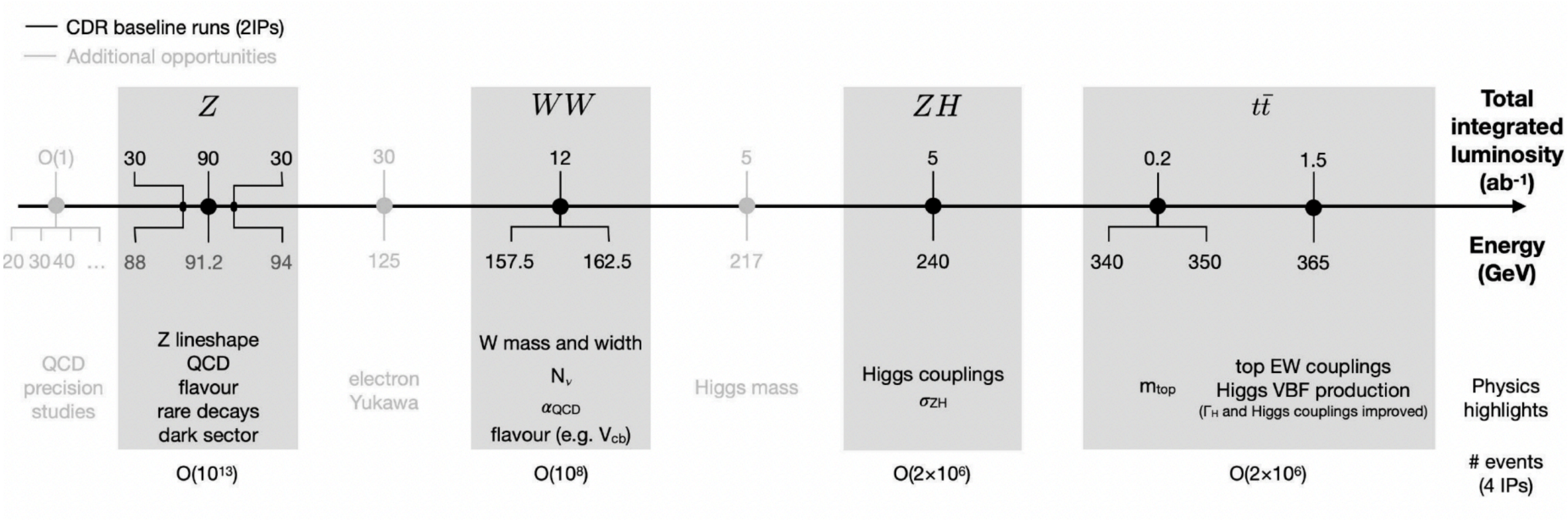
Majorana fermion triplet (Wino ~3 TeV)

Next up: High Luminosity LHC

ATLAS/CMS Highlights on the Higgs for European Strategy Update 2026

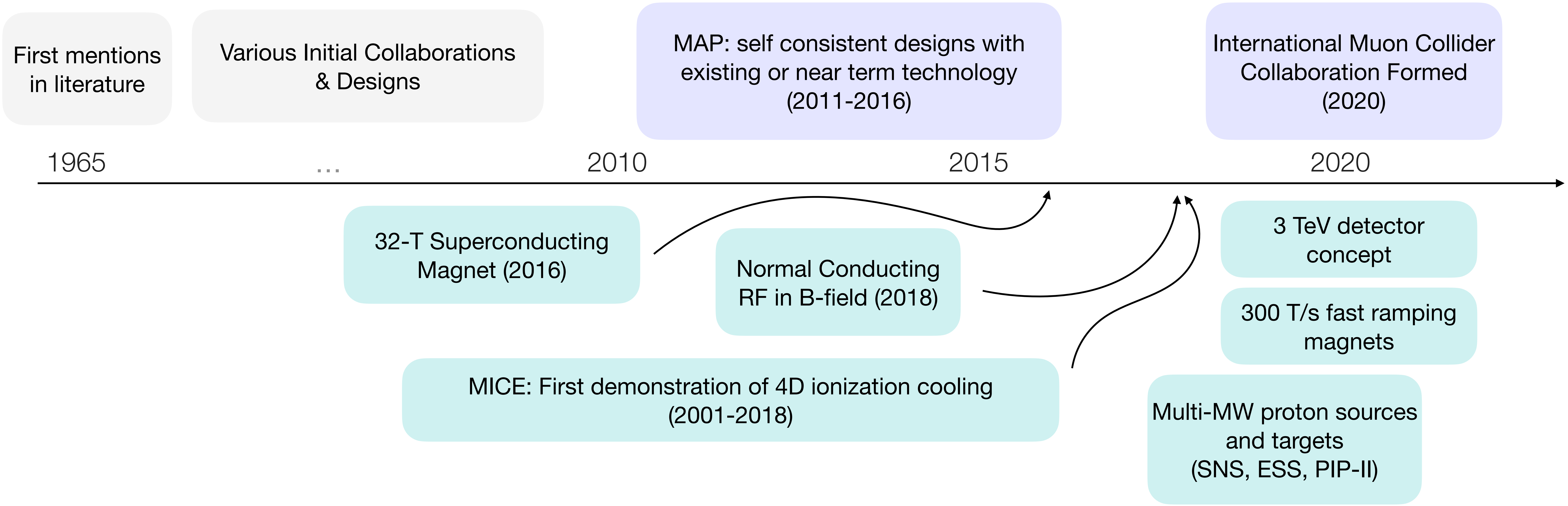
- The observation of the $H \to \mu^+\mu^-$ and $H \to Z\gamma$ rare processes and the determination of the corresponding couplings with a precision of 3 and 7%, respectively;
- The measurement of the other main Higgs boson couplings to fermions and vector bosons (including loop-induced and Standard Model (SM) suppressed couplings to the photon and the gluons) with a precision between 1.6 and 3.6%, assuming only known Higgs boson interactions;
- A sensitivity to the charm Yukawa coupling of 1.5 times the SM value at 95% Confidence Level (CL);
- The observation of the SM di-Higgs-boson production with a significance exceeding 7σ;
- The measurement of the Higgs boson trilinear self-coupling λ_3 with a precision better than 30%;

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

Vertex Detector at a circular e+e- collider

Physics Requirements

$$\sigma(d_0) \sim 3 \oplus \frac{15}{p \sin^{3/2}\theta}\ \mu m$$

Aim to keep systematics < 10^{-5}

Tera-Z environment

Rate of Zs ~200 kHz

Beam backgrounds ~200 MHz/cm^2

Radiation ~10^{14} MeV neq/cm^2

Detector Requirements

Single hit resolution	Pixel size	25 x 25 µm
Multiple scattering	Pixel thickness	50 µm
	Material Budget	0.3% X_0/layer
Challenges	Power	<50 mW/cm^2
	Integration time	~1 µs

Towards 4D trackers for future colliders

μμ/hh need precision space O(5 μm) and timing O(30 ps) in every layer

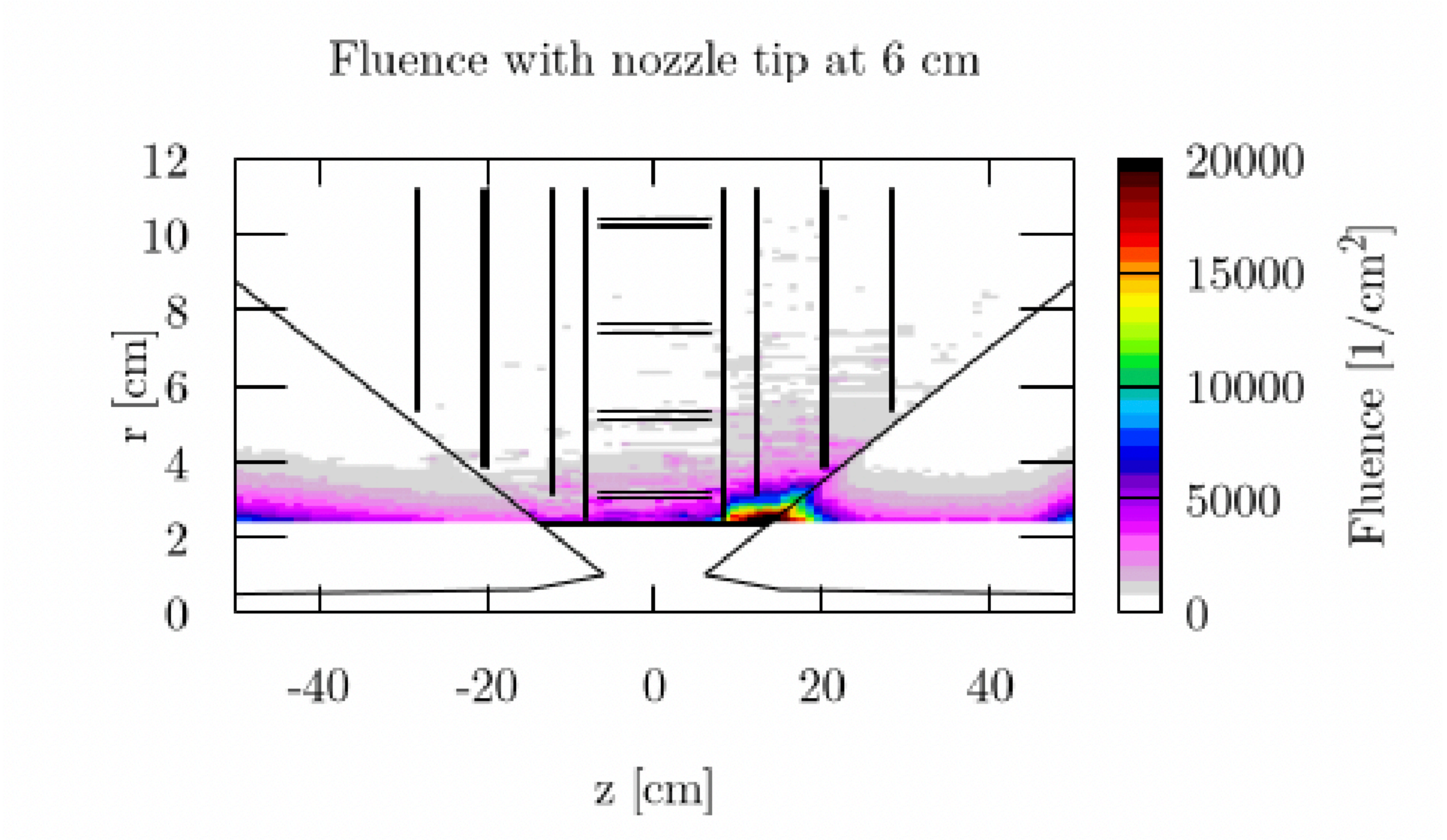
Sensor R&D thrusts: smaller granularity & radiation hardness

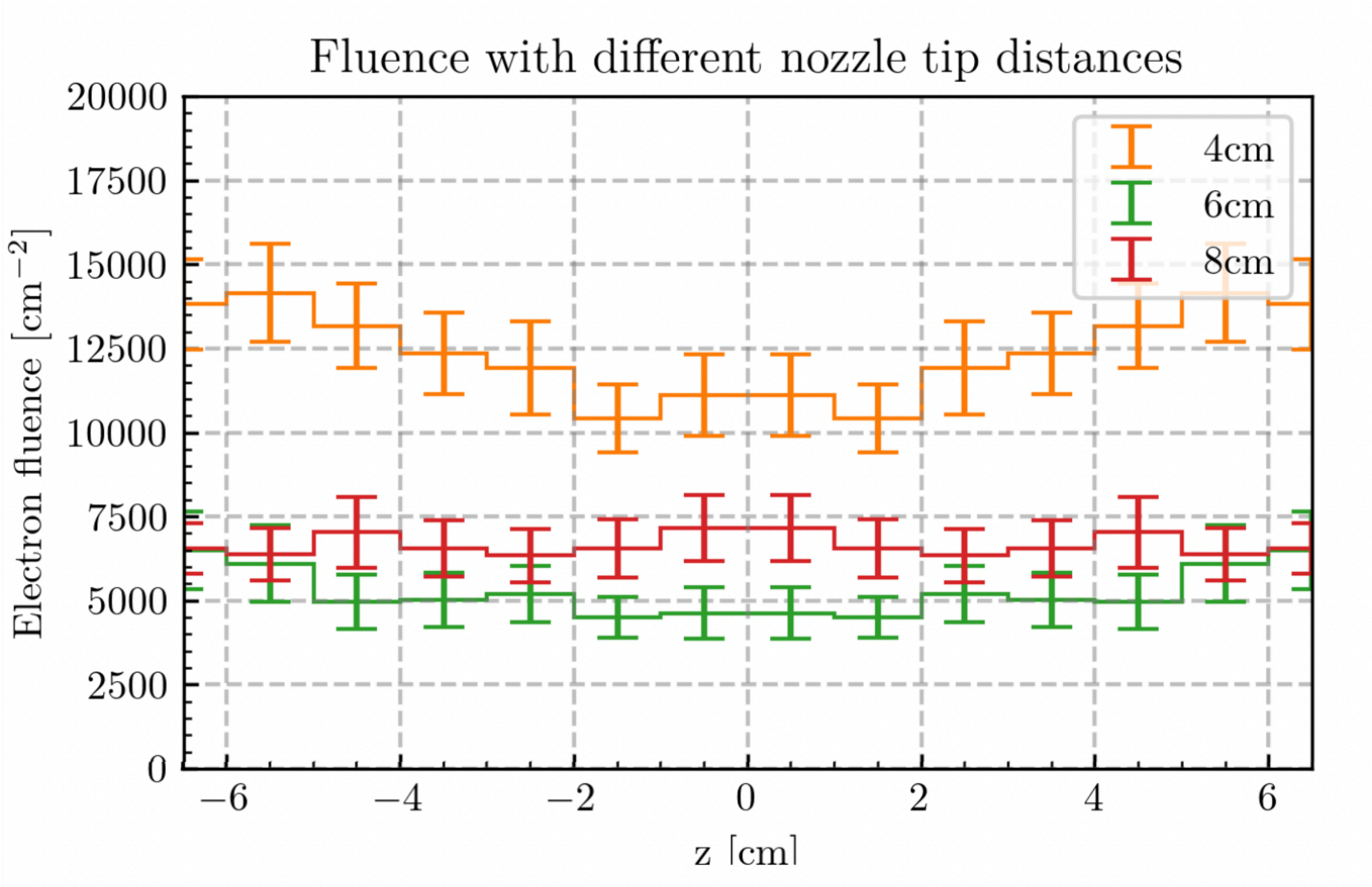
	HL-LHC	Future μμ	Future hh
Physics need	pile-up	BIB rejection	pile-up
Time resolution	30 ps/track	30-60 ps/hit	5 ps/track, 30 ps/hit
Location	outermost layer	every layer	~every layer
Granularity	1x1 mm^2	~25x25 μm^2	~25x25 μm^2
Fluence (n_{eq}/cm^2)	$2 \cdot 10^{15}$	$\sim 10^{16}$	$>5 \cdot 10^{17}$

μC Work in progress: Machine detector interface

<u>D. Calzorlari</u>

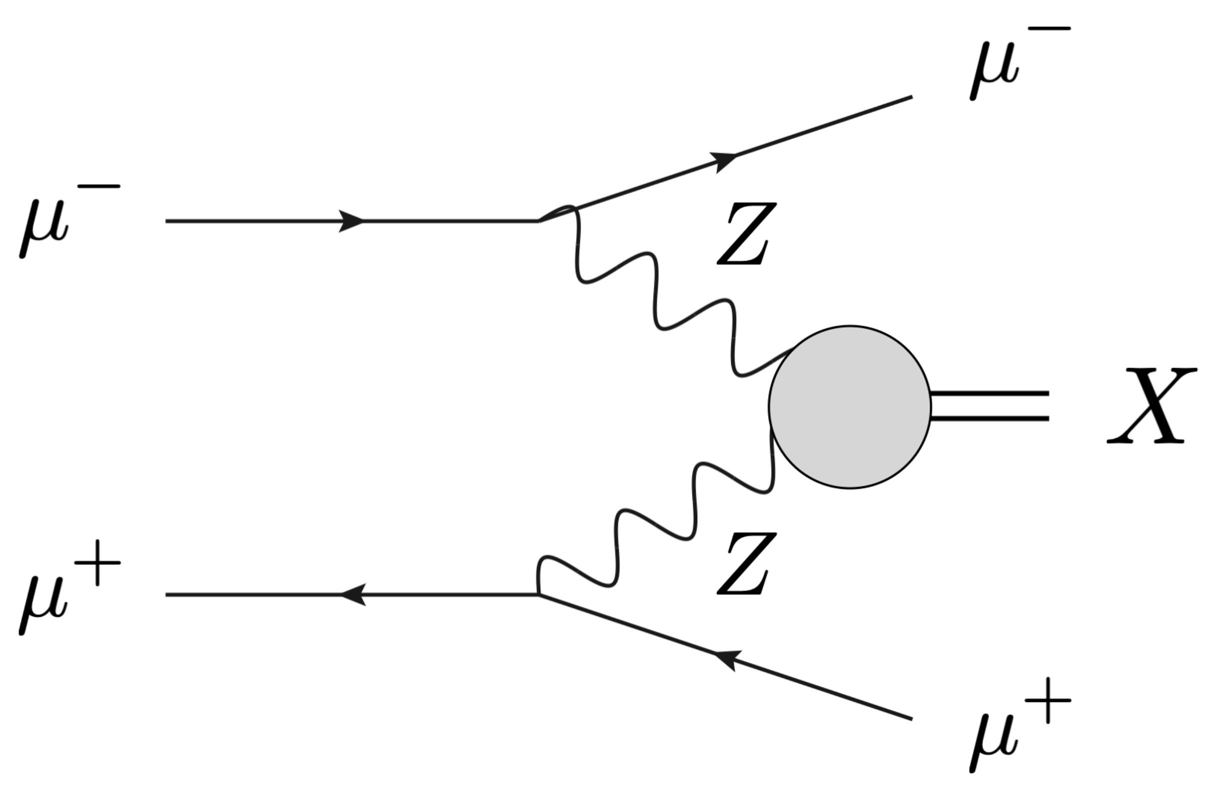
Beam induced background highly dependent on nozzle configuration
Systematic optimization in progress!





μC 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}

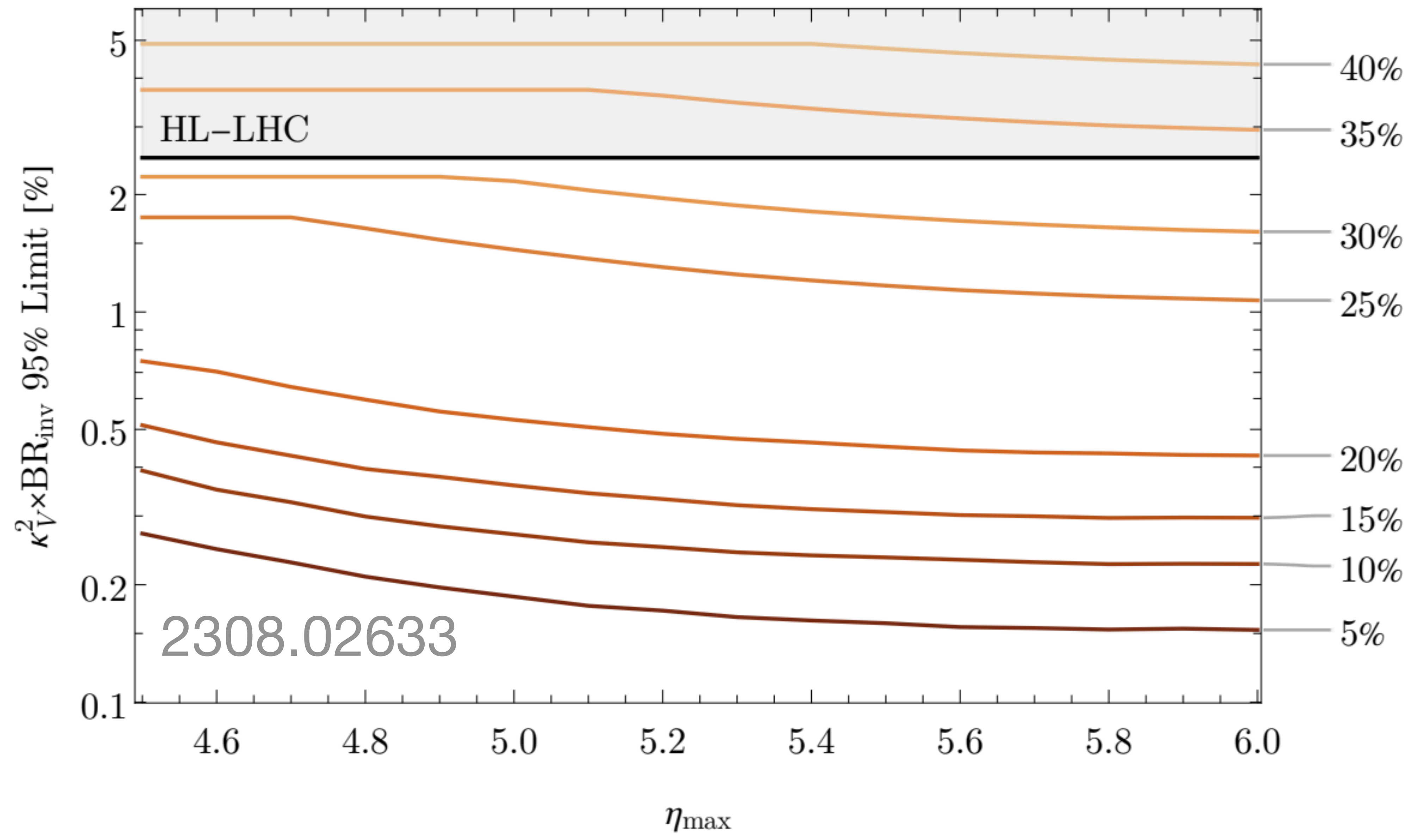
Γ_h via inclusive rate

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

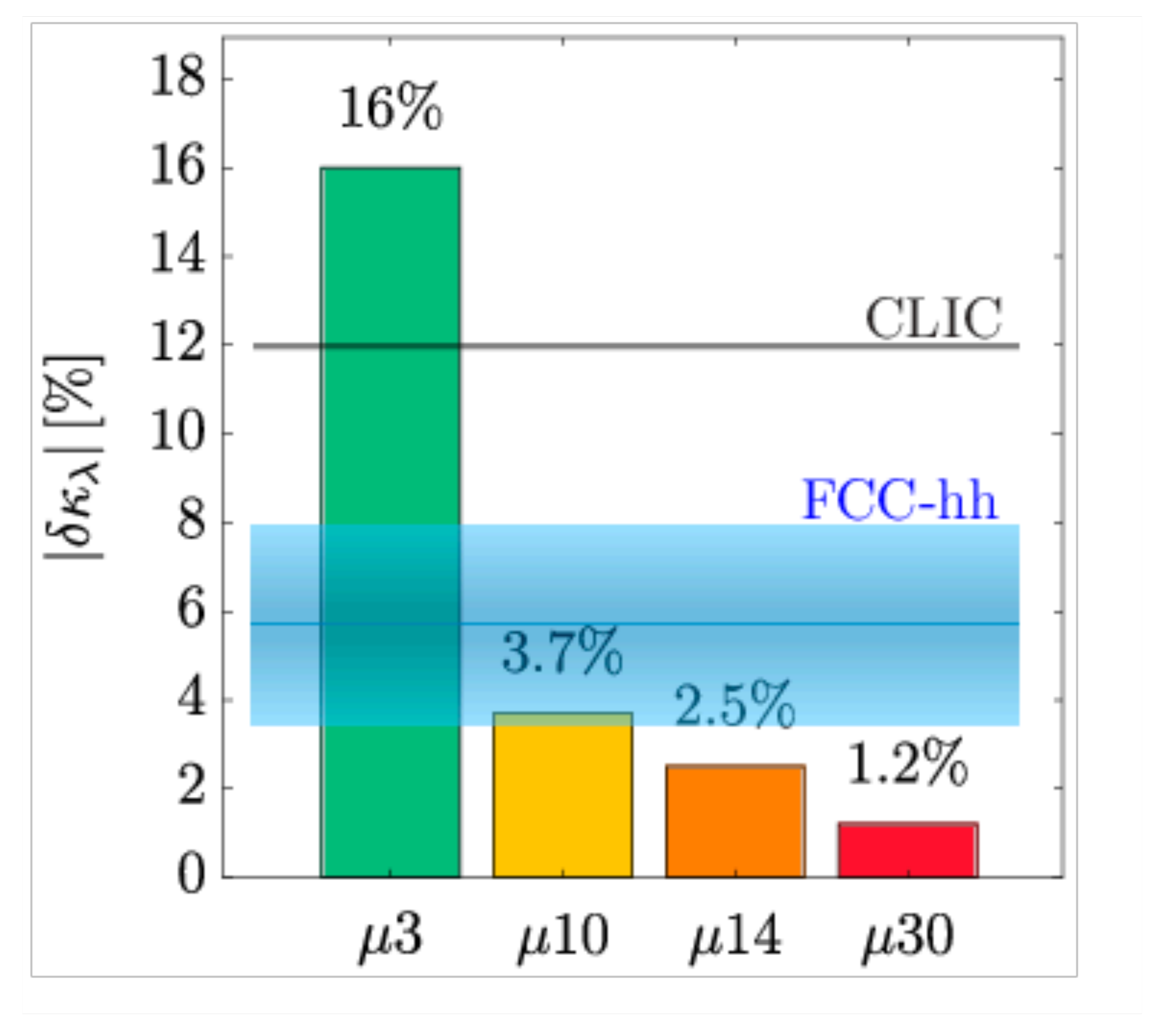


μC Takeaway: Can we do physics?

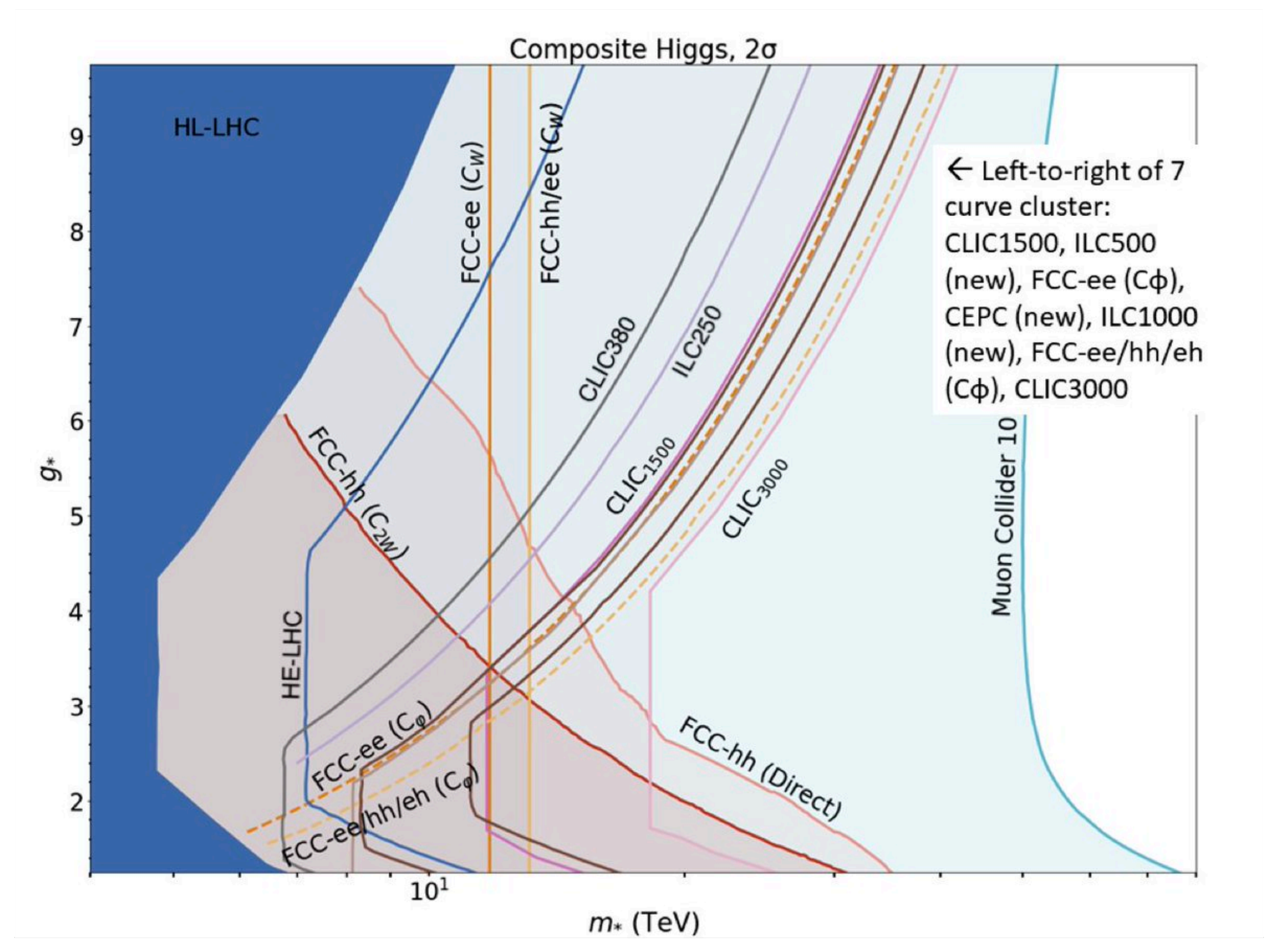
2303.08533

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

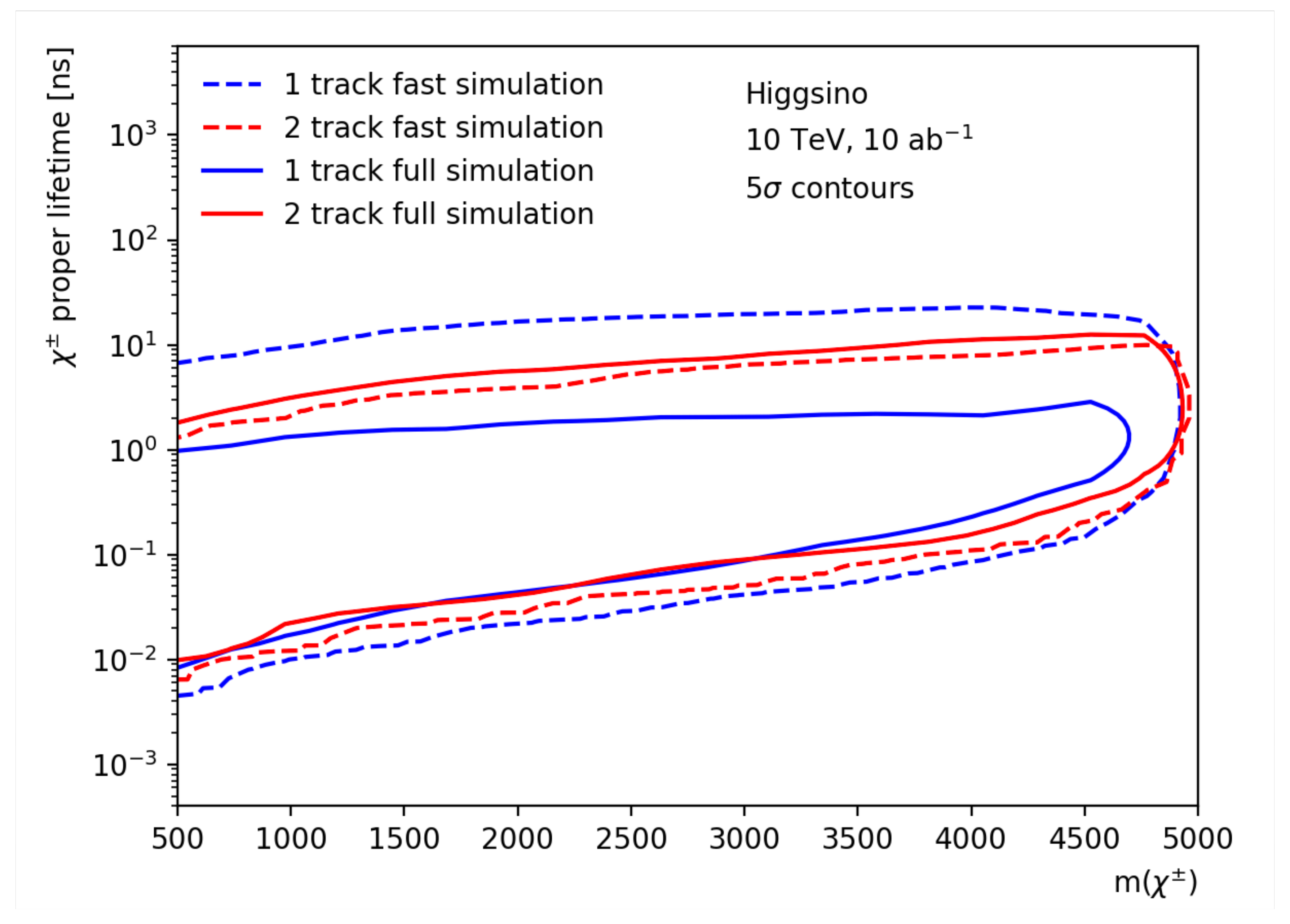
Higgs self-coupling



Composite Higgs Scenarios



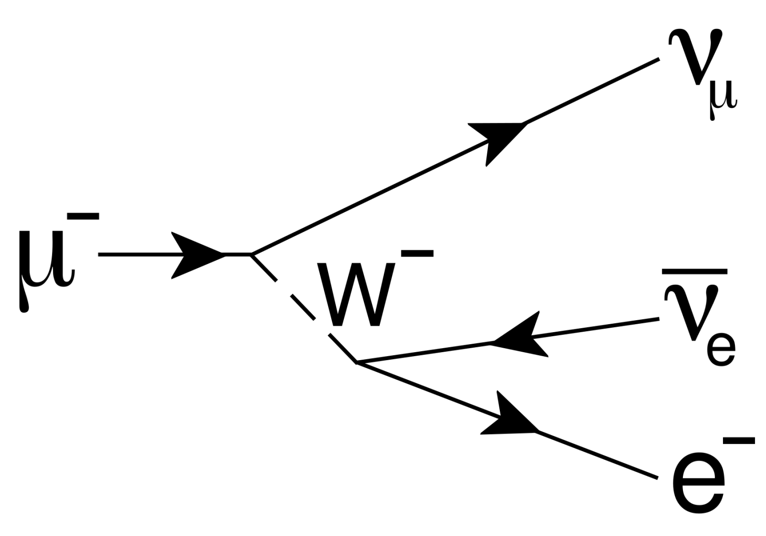
WIMPs/Disappearing track



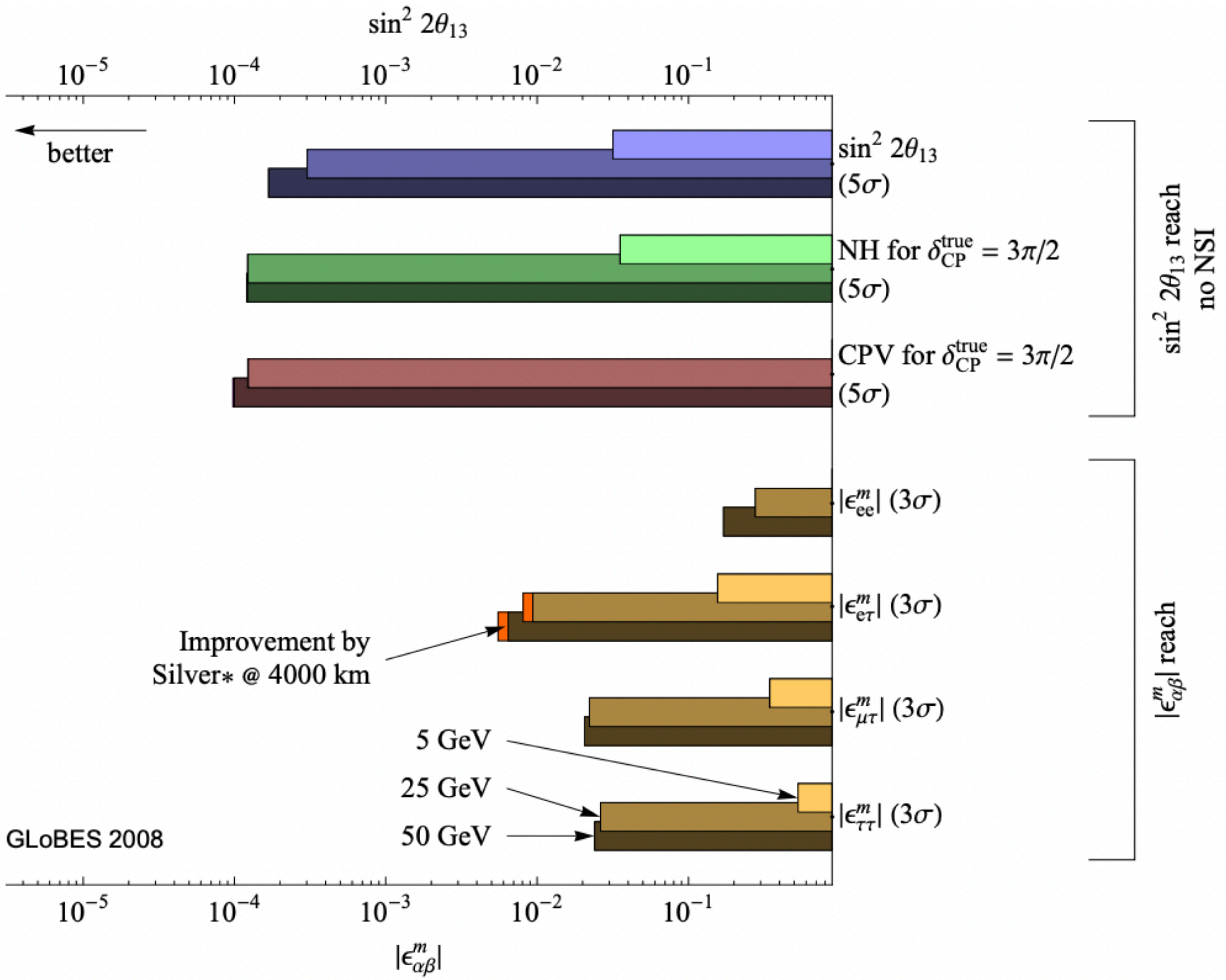
Muon-neutrino synergies

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?



Muon Collider Trigger/DAQ challenges

2508.06239

It's a lepton collider - we want to keep every event

Triggerless readout seems feasible

- Large event sizes: 80 MB
- Modest event rates: 30 kHz
- Similar to CMS HLT input at HL-LHC: ~100 TB/s

Open questions

- where should data be reduced?
- requirements on front-end electronics?
- DAQ and offline processing and storage?

Loose hit-time window → Data rate/FE with [-0.5, 5] ns; Tight hit-time window → Data rate/FE with $[-3\sigma_T, 5\sigma_T]$

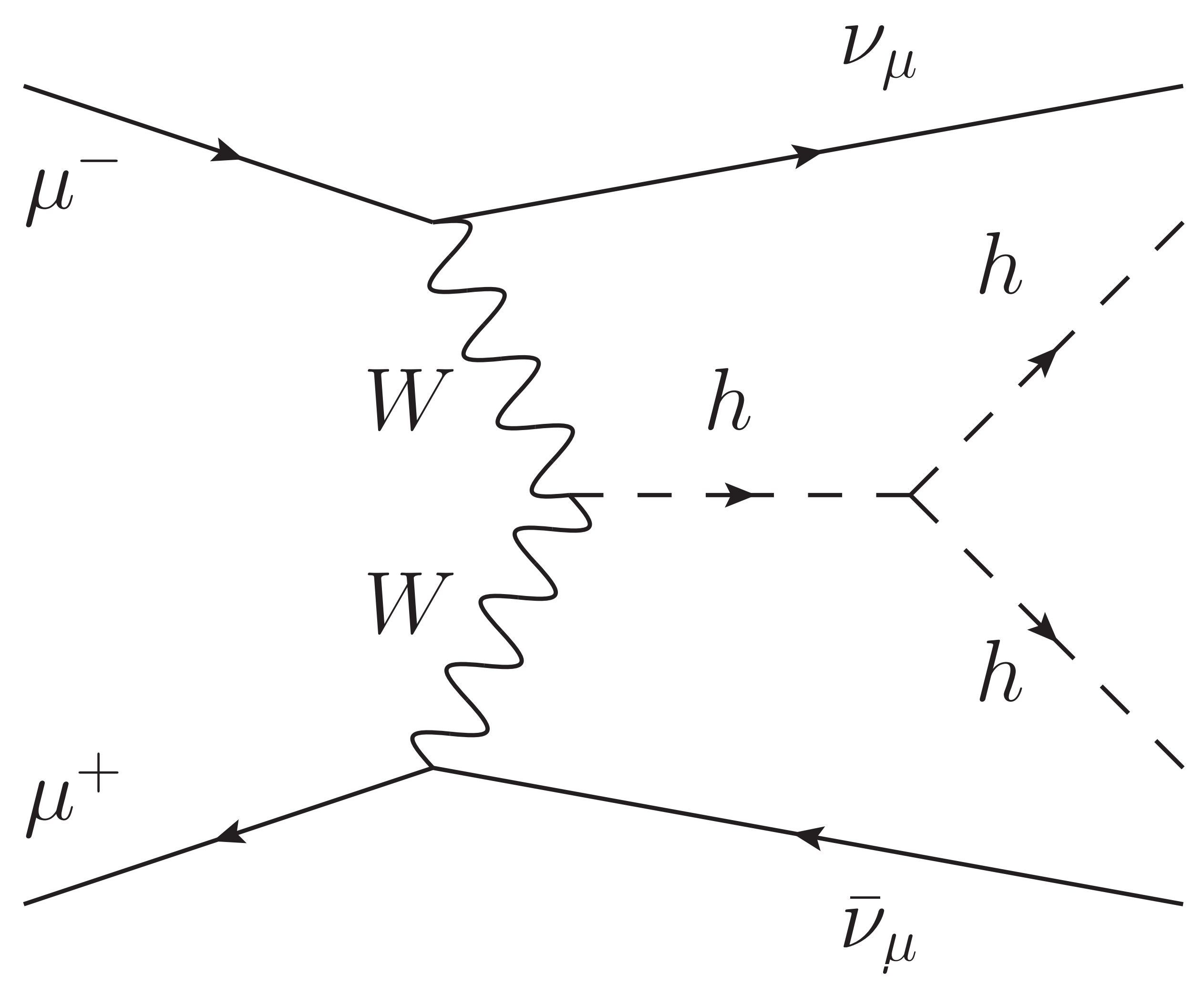
Sub-detector layer	Occupancy (hits/BX/cm²) with [-0.5, 5] ns	Occupancy (hits/BX/cm²) with $[-3\sigma_T, 5\sigma_T]$	RAW data size (/FE/BX) (kB) with [-0.5, 5] ns	Data rate/FE (Gbps) with [-0.5, 5] ns	Data rate/FE (Gbps) with $[-3\sigma_T, 5\sigma_T]$
VXB L0 (σ_T=30 ps)	15422 (40%)	3600 (10%)	300	73.6	16.8
VXE L5 (σ_T=30 ps)	5541	1979	110	26.4	9.6
ITB L0 (σ_T=60 ps)	528	373	10	2.4	1.6
ITE L0 (σ_T=60 ps)	145	114	2.9	0.7	0.5
OTB L0 (σ_T=60 ps)	25	11	0.5	0.1	0.05
OTE L0 (σ_T=60 ps)	10	7.4	0.2	0.05	0.03

Challenge: vertex detector pushes up against FE/optical readout bandwidth constraints

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!

Which collider(s) should we build?

Total projected cost

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

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

Three categories of machines

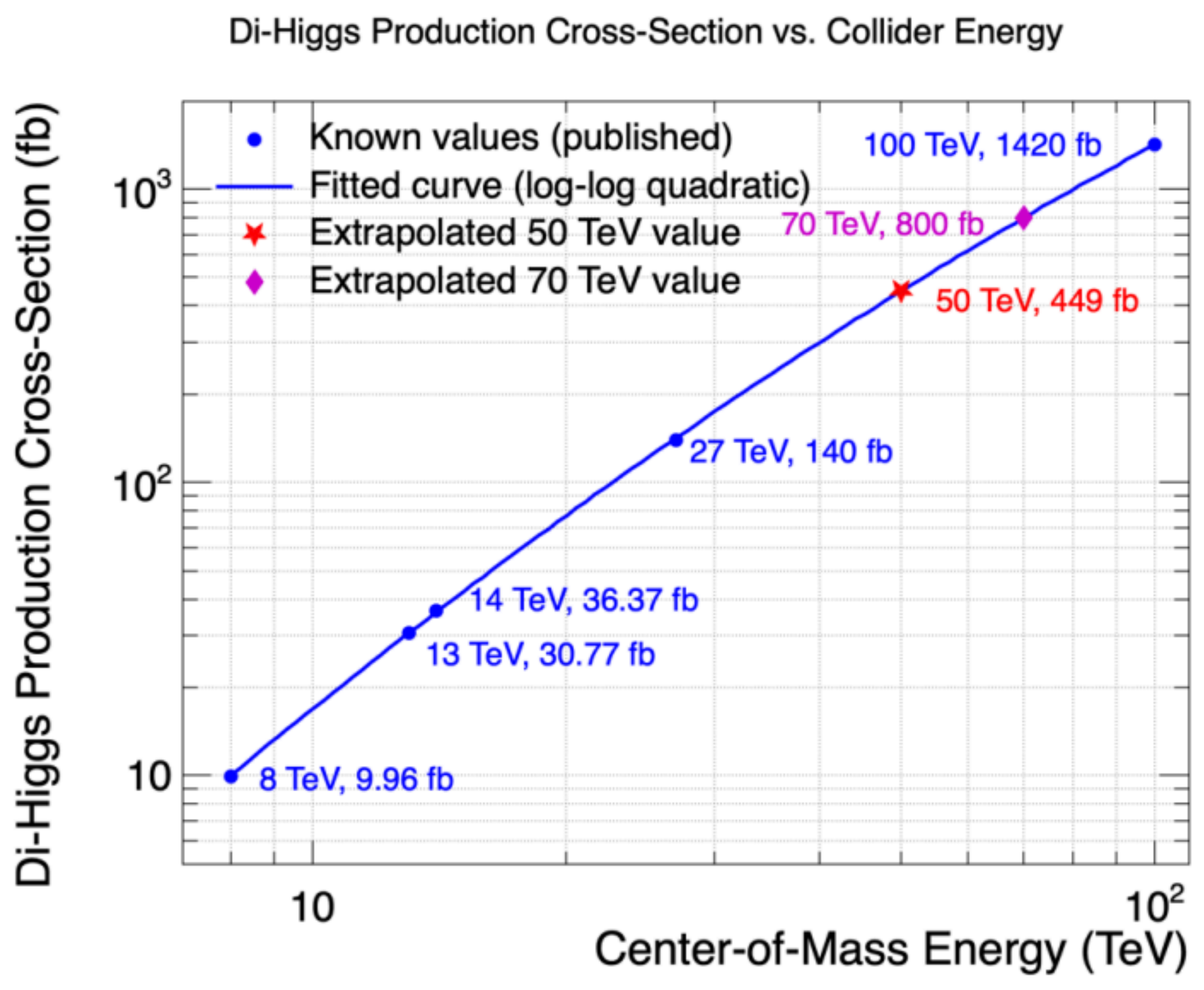
Collider	√s (TeV)	Tunnel (km)	Power (MW)	Cost ($B)	Time to start (yrs)
ILC e+e-	0.24	20	140	7-12	<12
FCC-ee	0.24	100	290	12-18	13-18
MuC-3	3	10	230	7-12	19-24
CLIC	3	50	550	18-30	19-24
MuC-10	10	16	300	12-18	>25
FCC-hh	100	100	560	30-50	>25

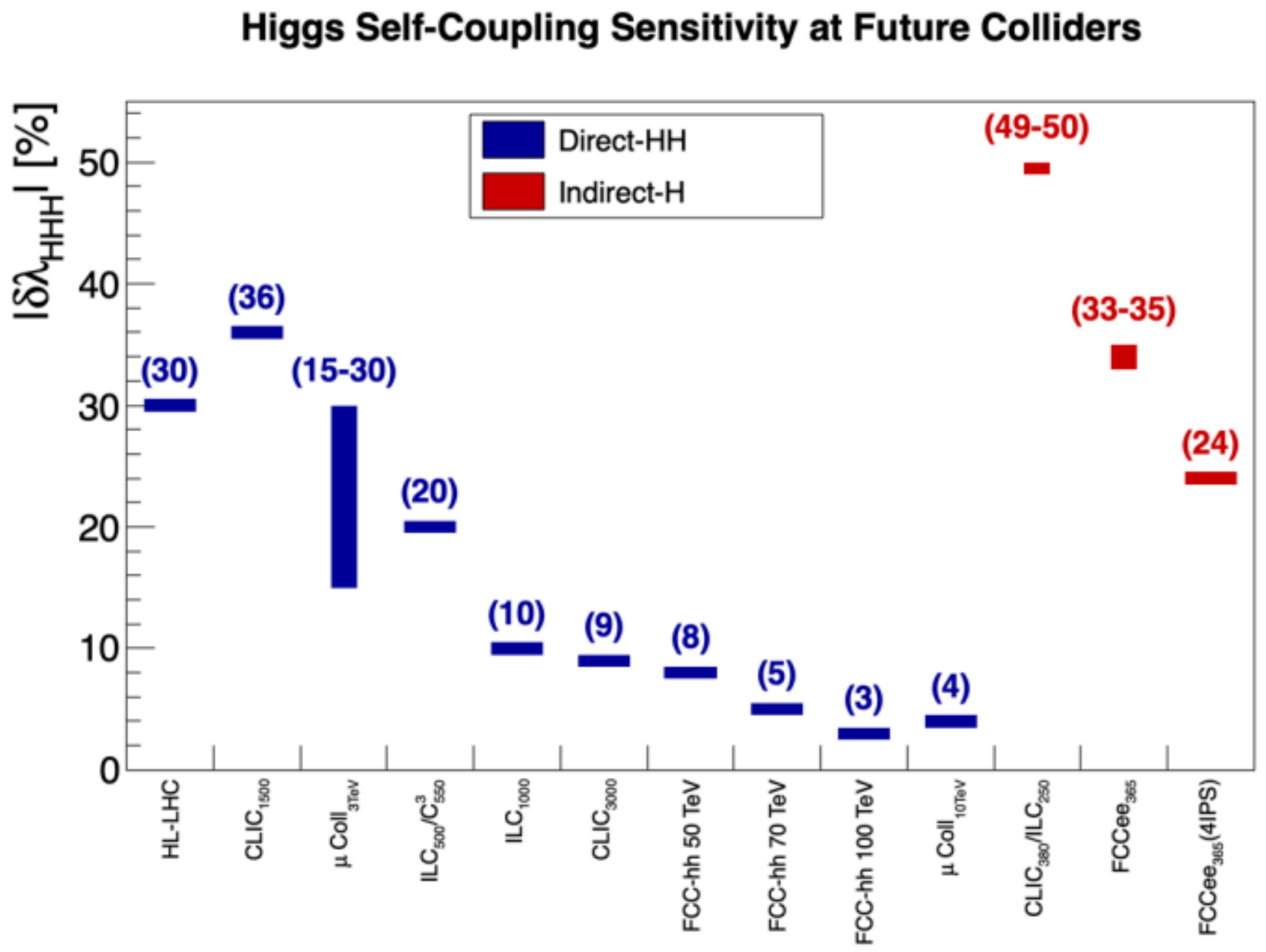
*Cost without contingency/escalation
**Technically limited timelines
***No staging assumed

Higgs self-coupling

2504.00951

Measuring higgs self coupling to a few% = test of electroweak phase transition and vacuum stability



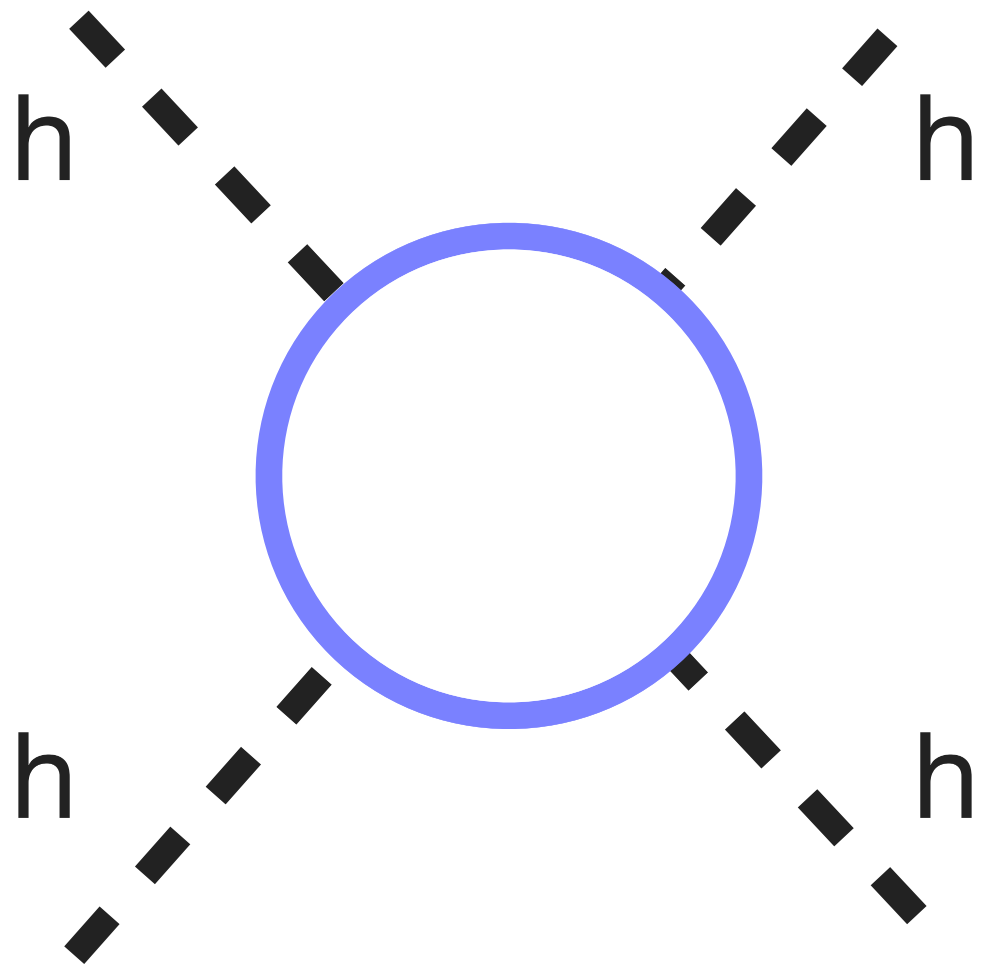


Producing enough di-higgs events requires **~10 TeV scale collider**

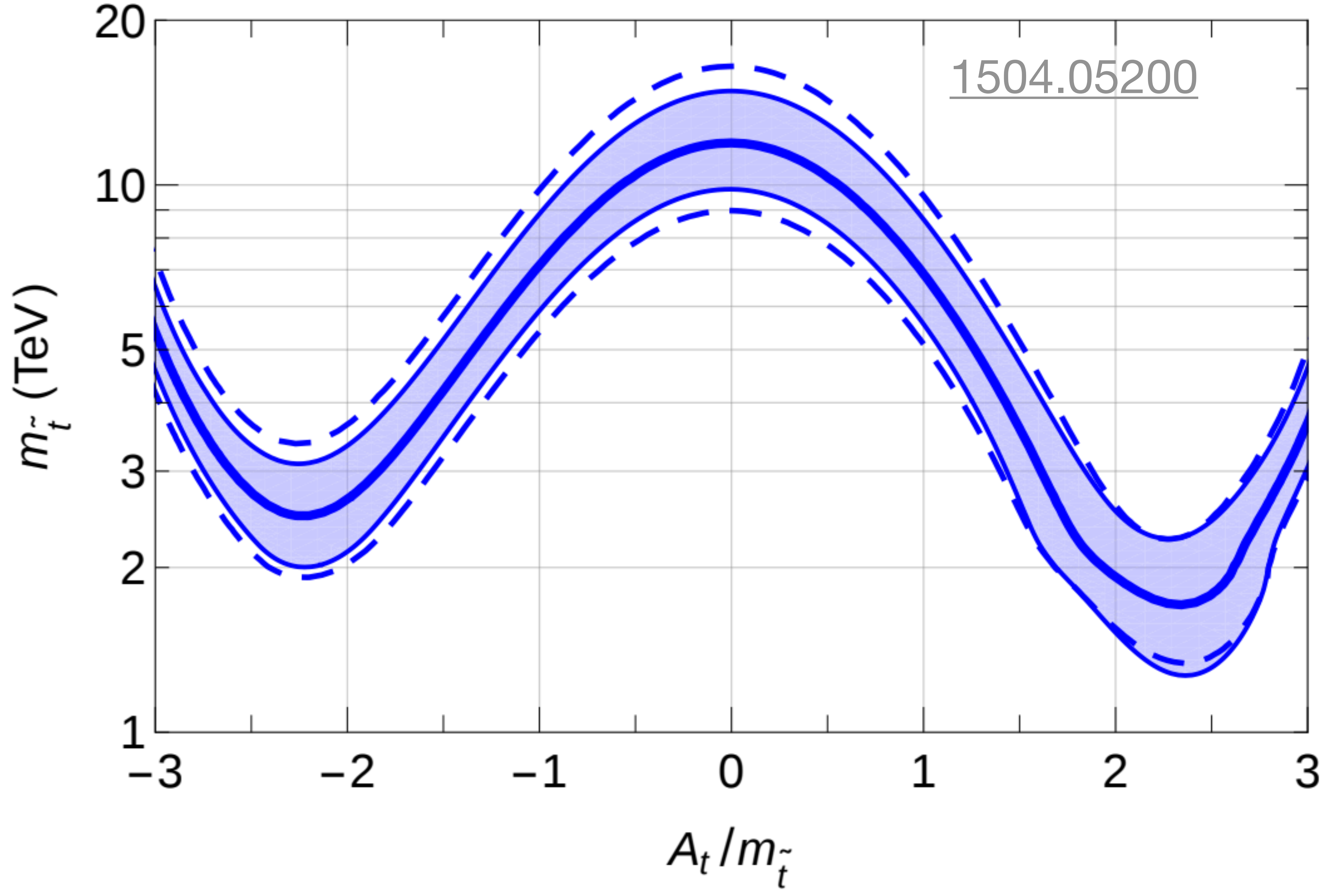
We don't have the technology in hand yet

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