Φαινό 2026

The 2026 Phenomenology Symposium

An odyssey through particle physics and related encounters in astrophysics and cosmology

University of Pittsburgh

May 11-13, 2026

indico.global/e/pheno26

New Directions in Collider Physics

Zhen Liu

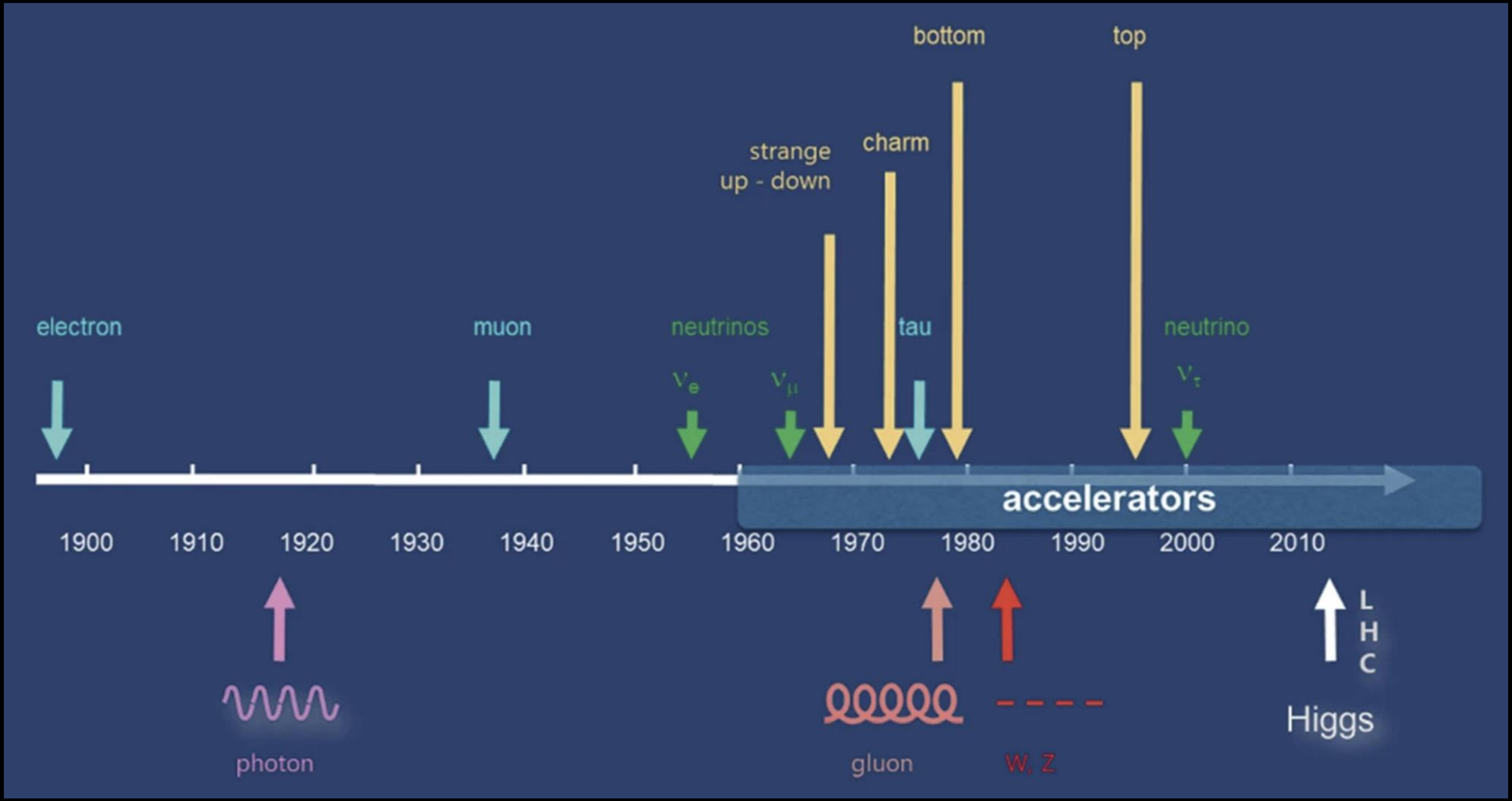
University of Minnesota

May 12, 2026

With financial support from the National Science Foundation and Department of Energy

Endeavor of HEP

Now: Explore the **Uncharted**



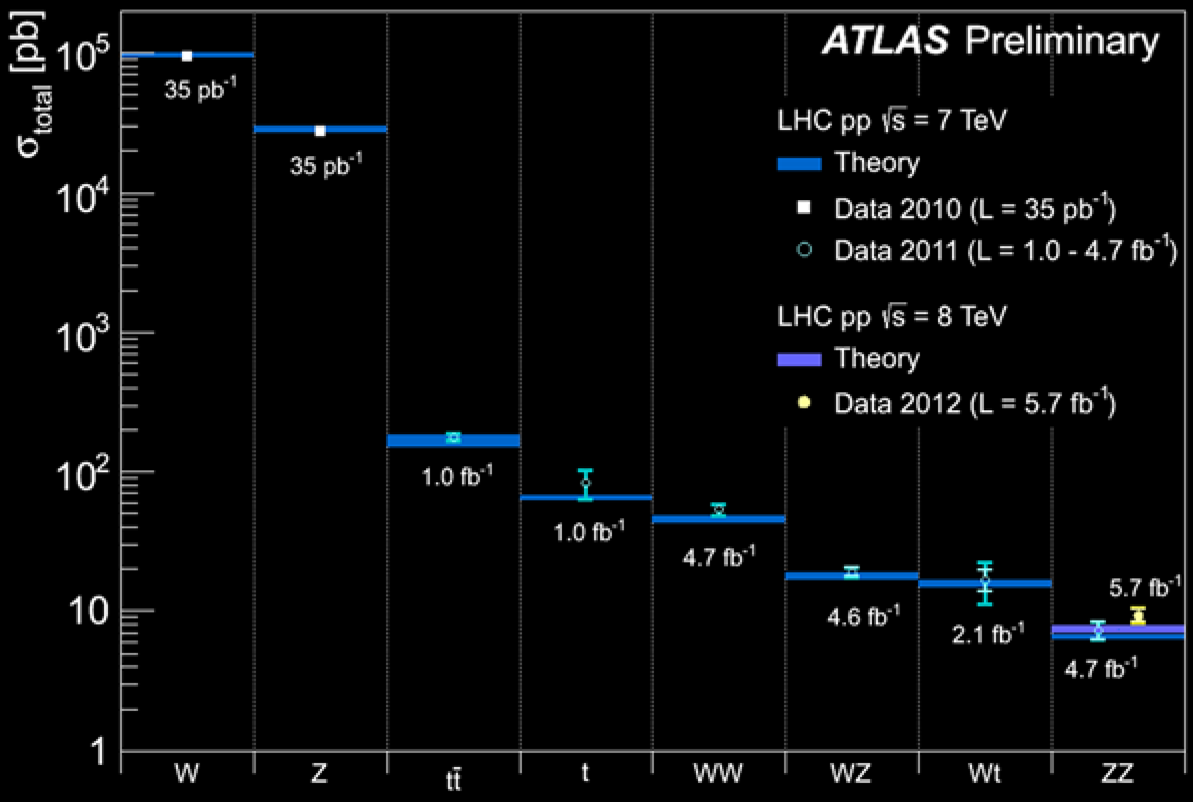
Resolution=1/E_{cm}

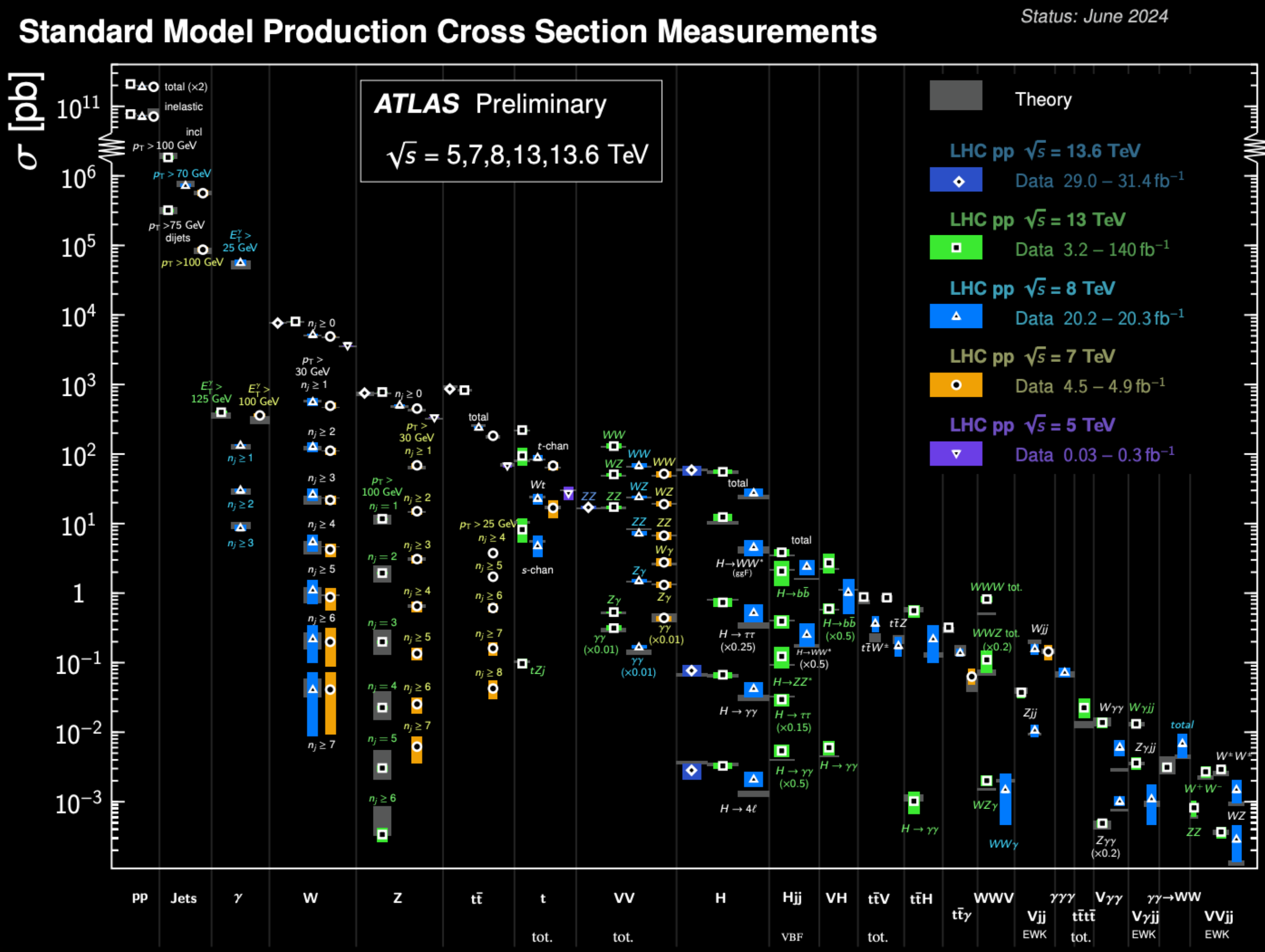
Large # of independent observables

Precise control + Background Rejection

LHC's successes

4 July 2012

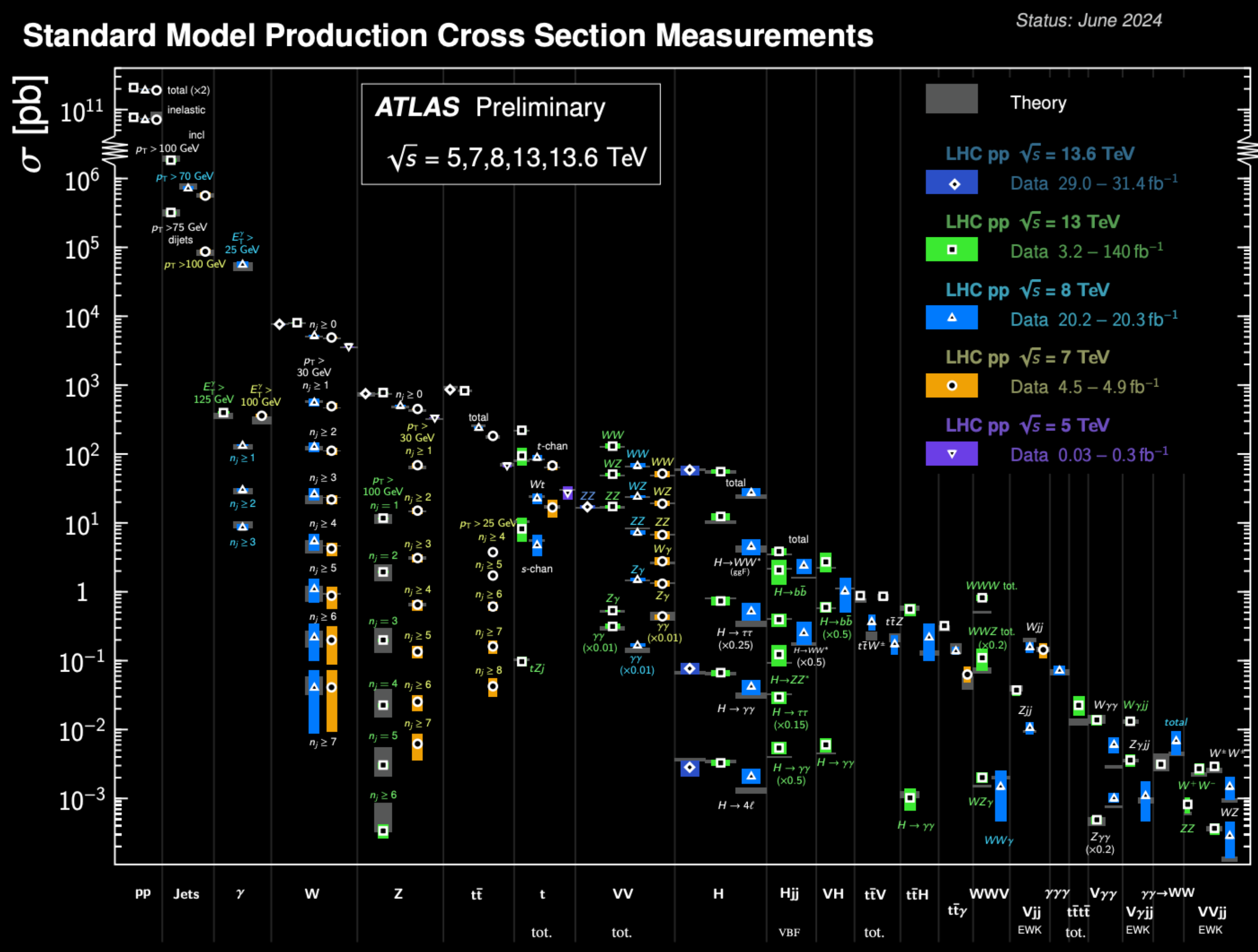




LHC's successes

- Higgs Discovery
- Precision measurements
- Direct searches on
  - Simplified models
  - SUSY
  - Extra Dim/Compositeness
  - …

+new upgrades in Energy, Detector, Trigger, Analysis methods



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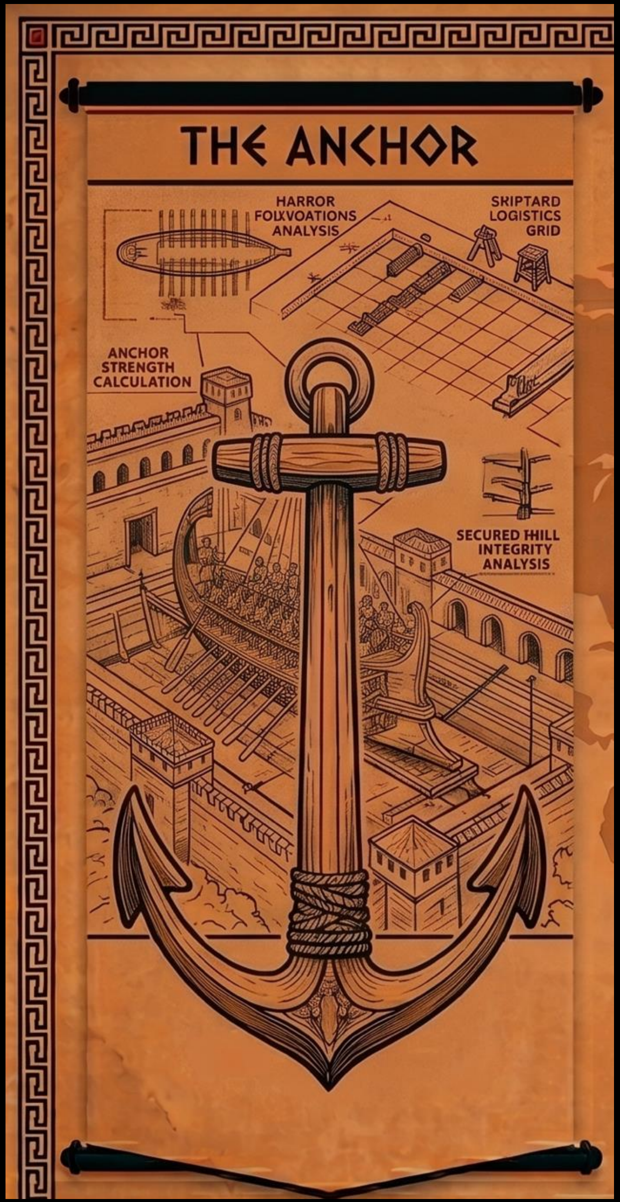
drove a paradigm shift

- (we become) humble (about how and where new physics would show up)
- more adventurous

Heavy Resonances



Where to look for heavy particles?

- For high scalar masses,

$$Br(S \to hh) = Br(S \to ZZ) = \frac{1}{2} Br(S \to WW)$$

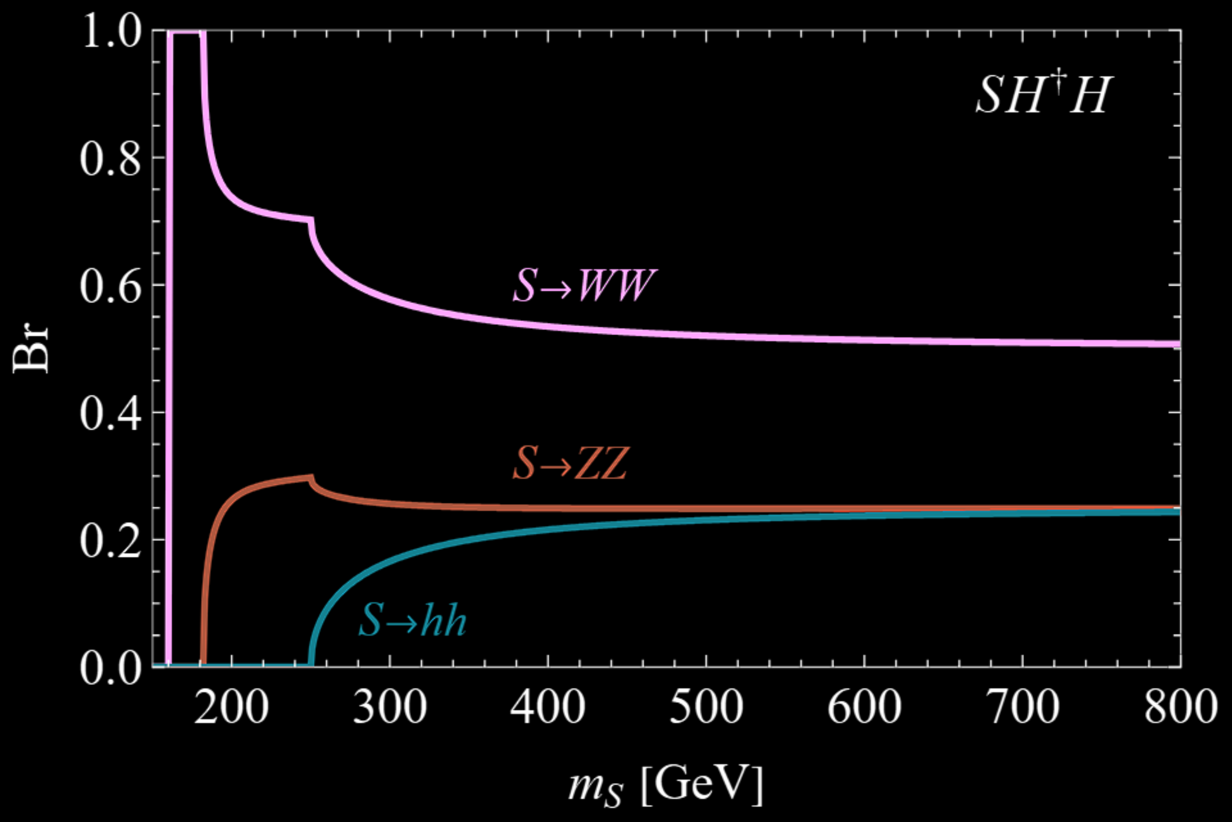
Goldstone Equivalence "generically" gives the above.

$$H^\dagger H = \frac{1}{2}(h+v)^2 + G^+G^- + \frac{1}{2}G^0G^0$$

Regardless whether one uses:

- S-h mass mixing: $\Lambda S(H^\dagger H)$
- S-h kinetic mixing: $\frac{1}{\Lambda}\partial_\mu S \partial^\mu (H^\dagger H)$
- SVV direct coupling: $\frac{1}{\Lambda} S|D_\mu H|^2$

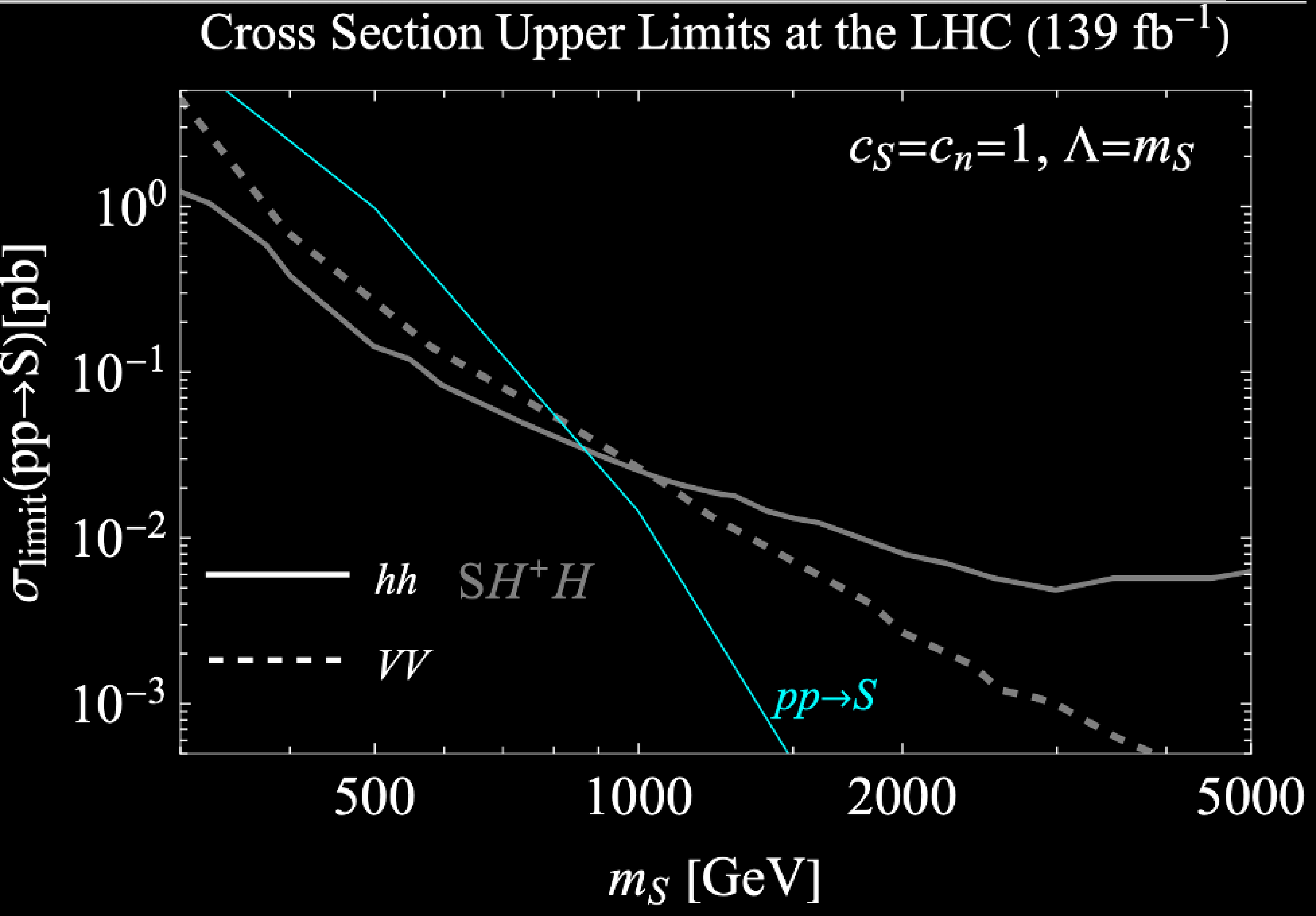
Similar plots for heavy fermions, heavy vectors…



Interplay between DiHiggs (hh) and DiBoson (VV)

- WW/ZZ (VV) has sizable leptonic channels, more clean
- hh has more hadronic decays, modern b-tagging makes resolved channels clean
- VV dominates high mass sensitivity

One can try to enhance hh branching for models with cascade decays or finite mass effects at E~v. See e.g., I. Lewis's talk yesterday.



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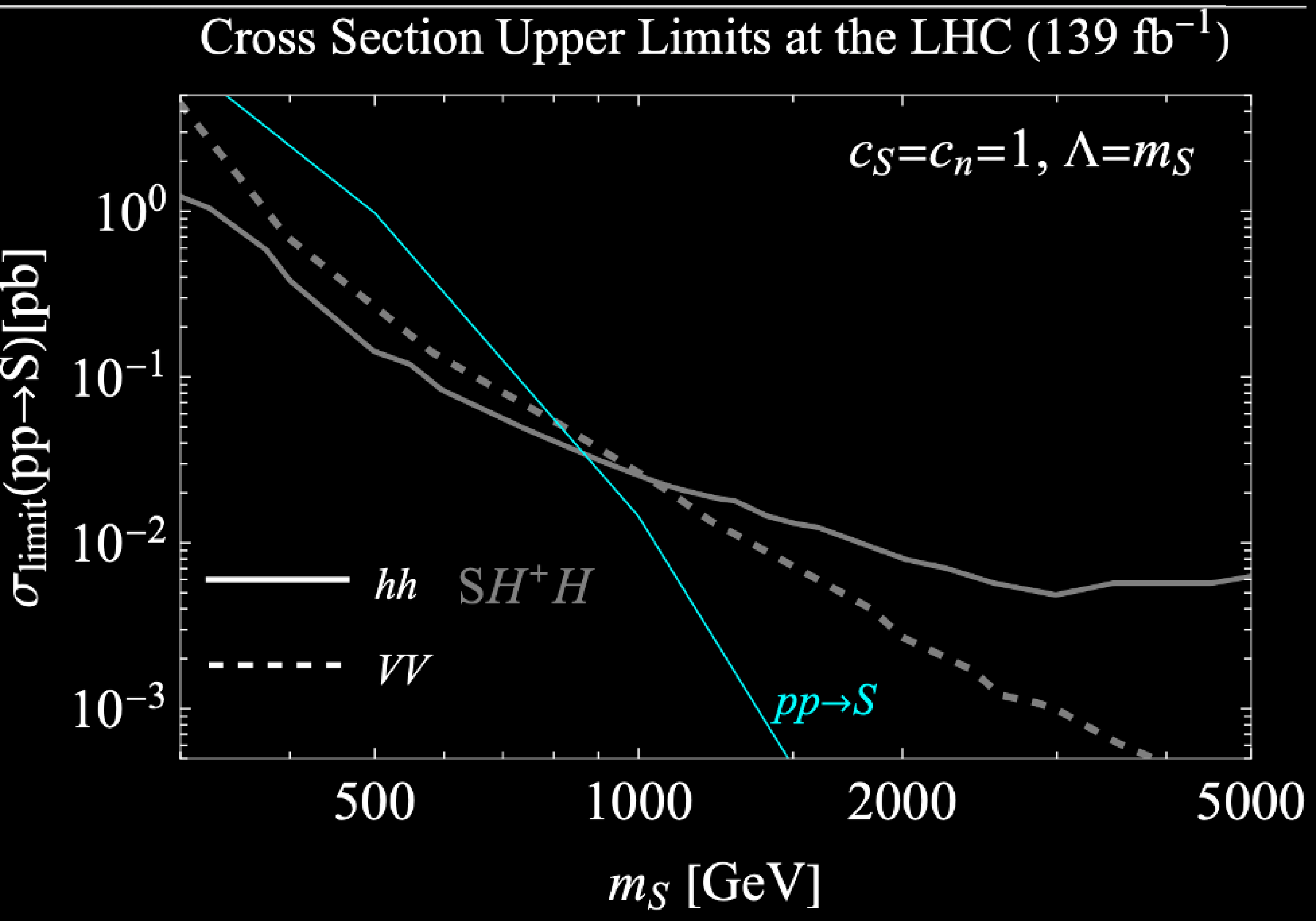

Can multi-Higgs be the leading discovery channel in general?

The busy Higgs mechanism: EWSB amplifies Higgs final states

P.R. Li, ZL, L.T. Wang 2604.14284

See P.R. Li's talk this afternoon

- After EWSB, expansion yields di-Higgs coupling ∝ n^2, while gauge couplings remain modest.
- Multi-Higgs can be the leading discovery channel; the same mechanism extends to fermions and vectors.

If the leading operator for S to SM Higgs is (or any similar format):

$$\frac{1}{\Lambda^{2n-3}} S\left(H^\dagger H\right)^n$$

$$\frac{\mathrm{BR}(S \to hh)}{\mathrm{BR}(S \to \mathrm{VV})} = (2n-1)^2$$

$$\frac{\mathrm{BR}(S \to hhh)}{\mathrm{BR}(S \to hh)} \sim \frac{1}{(4\pi)^2} \frac{2(n-1)^2}{3} \frac{m_S^2}{v^2}$$

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- After EWSB, expansion yields di-Higgs coupling ∝ n^2, while gauge couplings remain modest.
- Multi-Higgs can be the leading discovery channel; the same mechanism extends to fermions and vectors.
- Loop corrections stay under control; explicit UV models exist and are testable.

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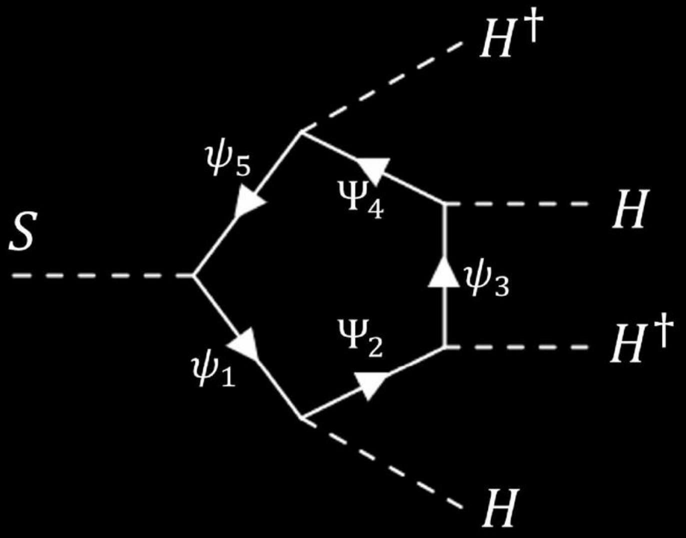
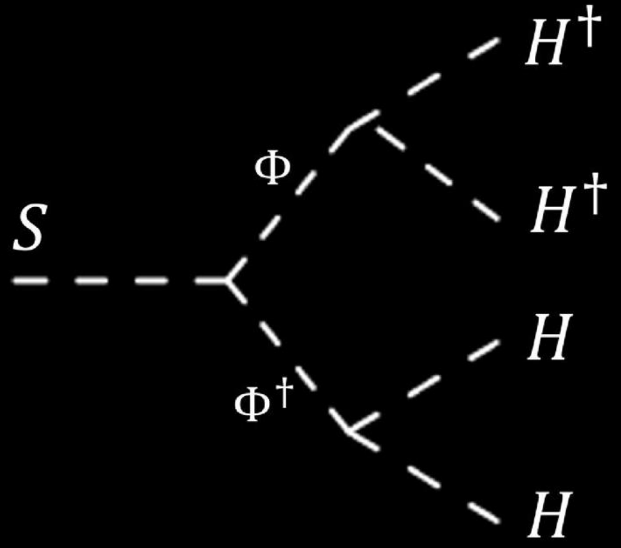
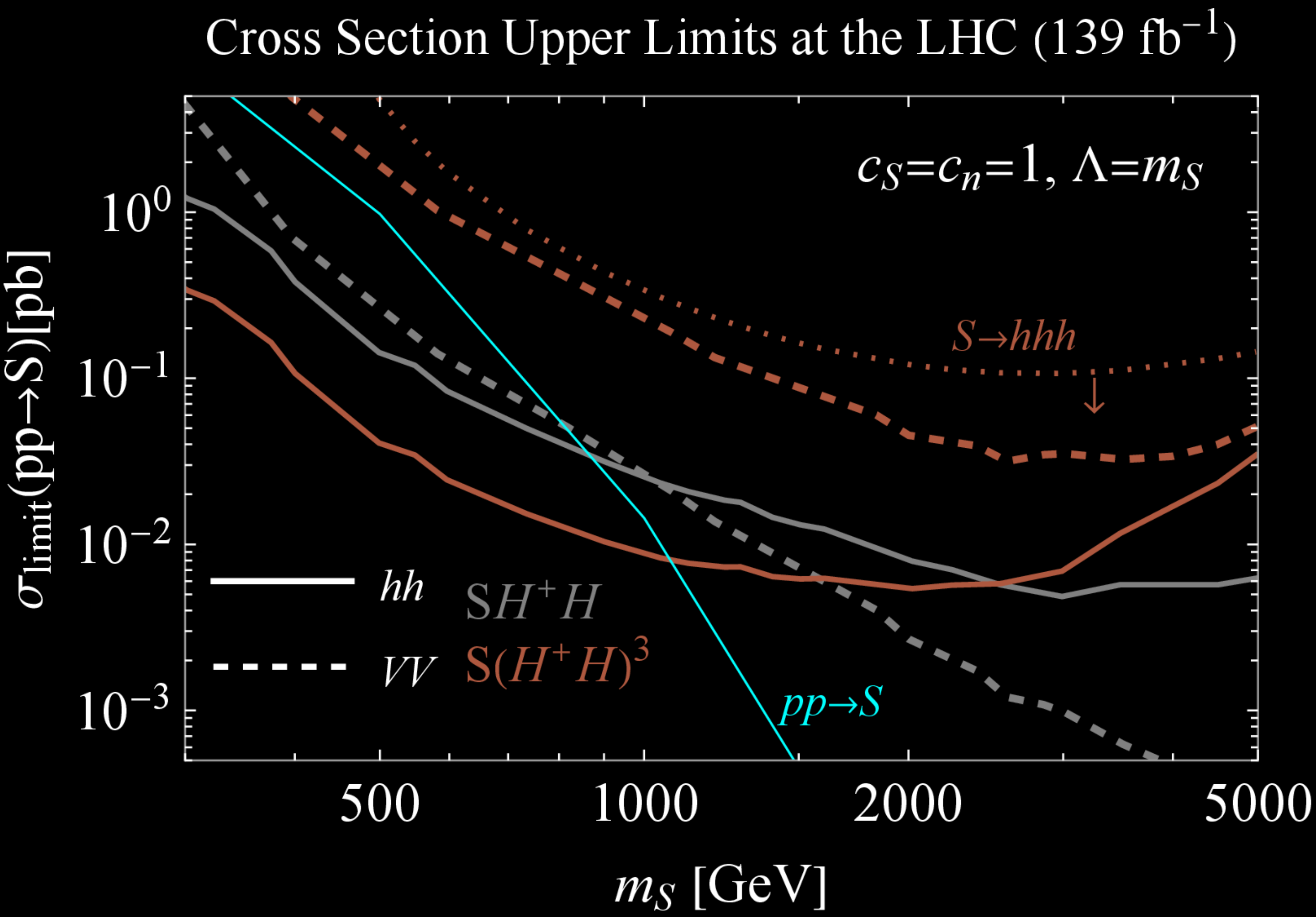




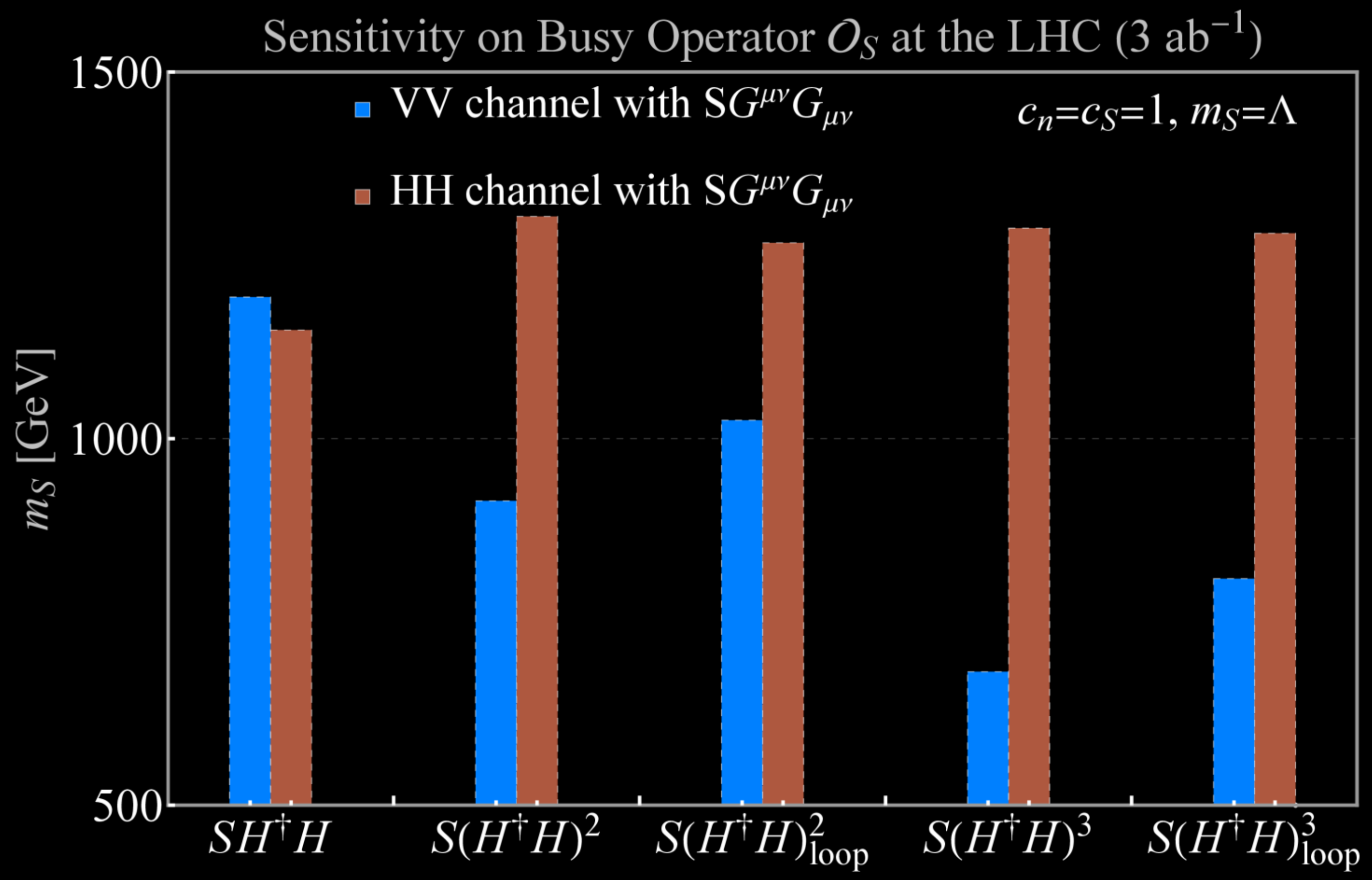
The busy Higgs paradigm: di-Higgs dominates the search landscape

- Large gap between solid (di-Higgs) and dashed (di-boson) curves for the busy operators.
- The busy Higgs mechanism transforms di-Higgs into the discovery channel for new heavy resonances
- We don't have resonance searches in hhh yet, so the limit is only the overall rate. It will dominate for high mass.



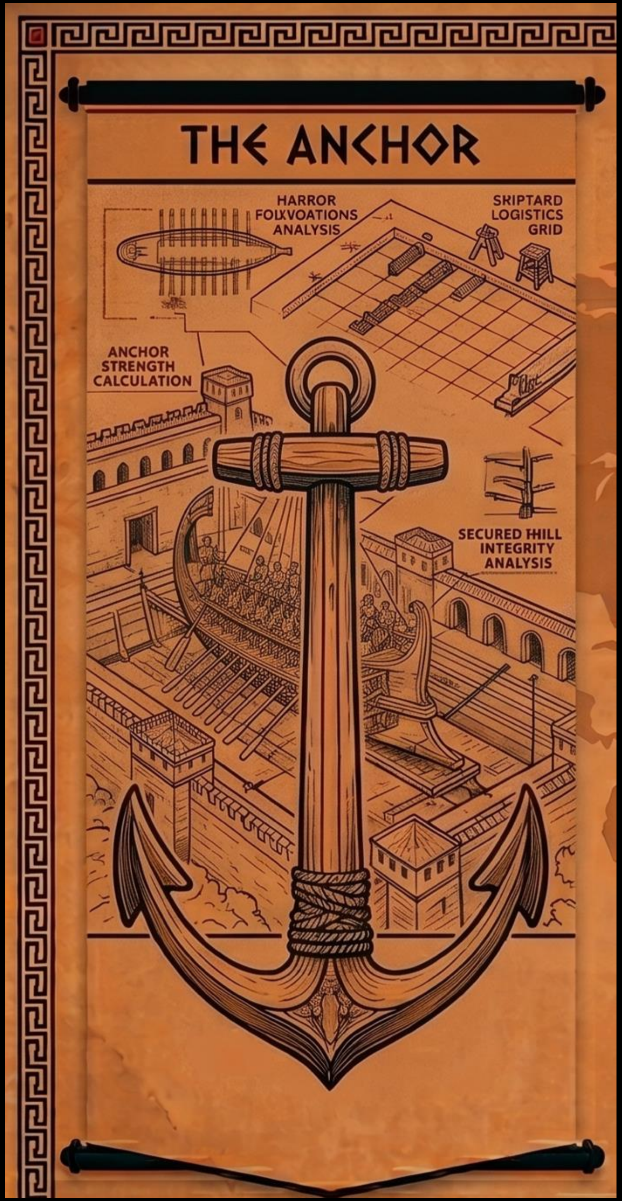
Busy Higgs Signals: HH reach far exceeds VV

- For $SH^\dagger H$, blue and orange are equal. For $S(H^\dagger H)^2$ and & $S(H^\dagger H)^3$, the orange bar extends much higher.
- Loop-induced low-dim operators changes the relative strength (branching) slightly.
- Di-Higgs searches probe busy scalar operators to significantly higher masses than di-gauge searches



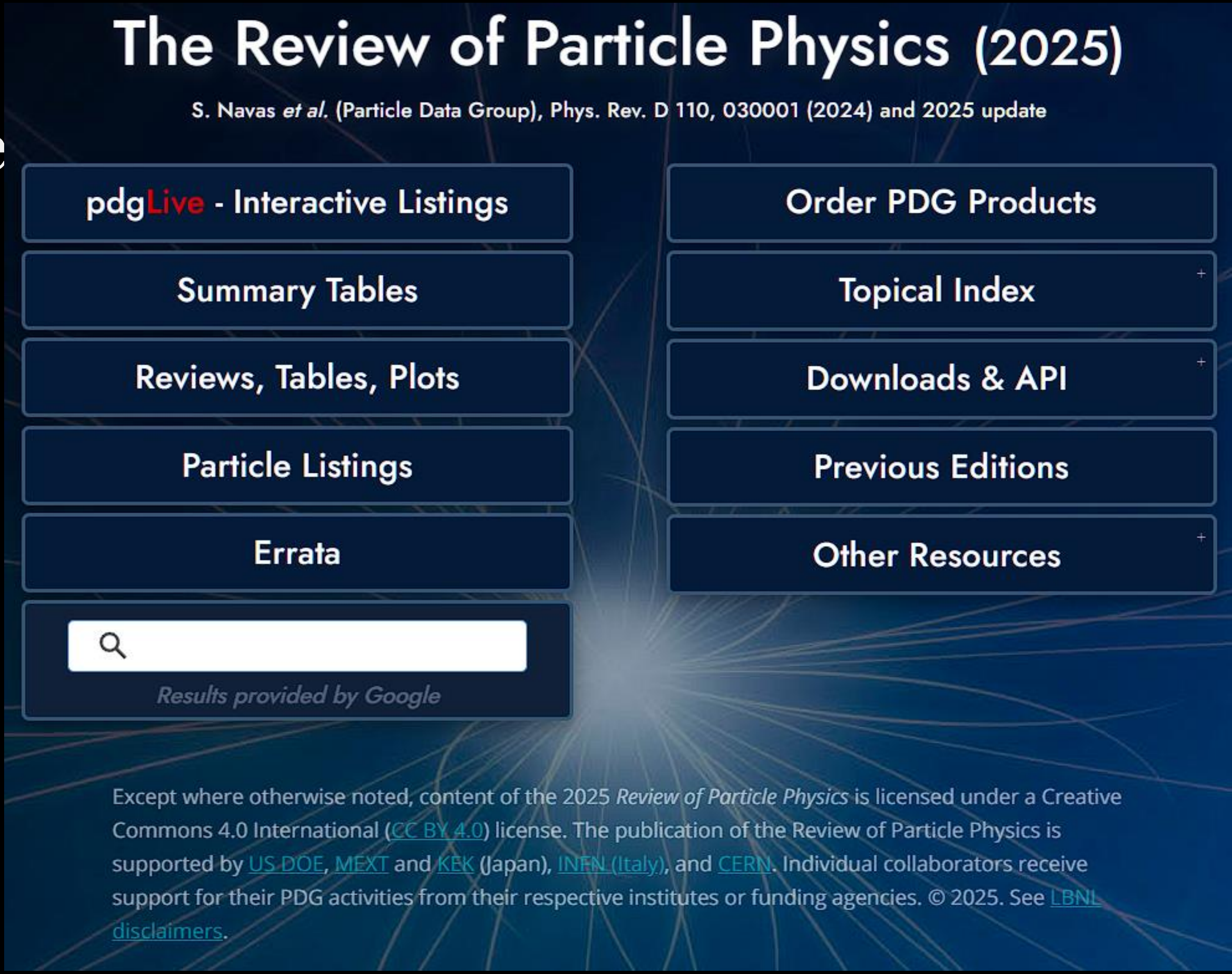
For further alignment suppression and cascade decays, see C. Wagner, S. Roy, in progress.

Old(Missed) Searches & (New) Results



Which fundamental boson has the fewest decays measured?

- Among W, Z, H
- Also adding pions, kaons, all those non-excited states etc.?



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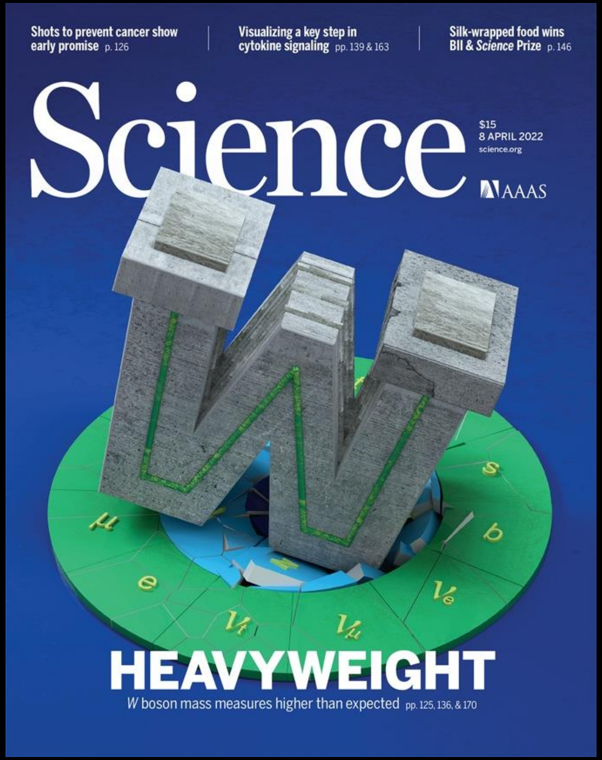
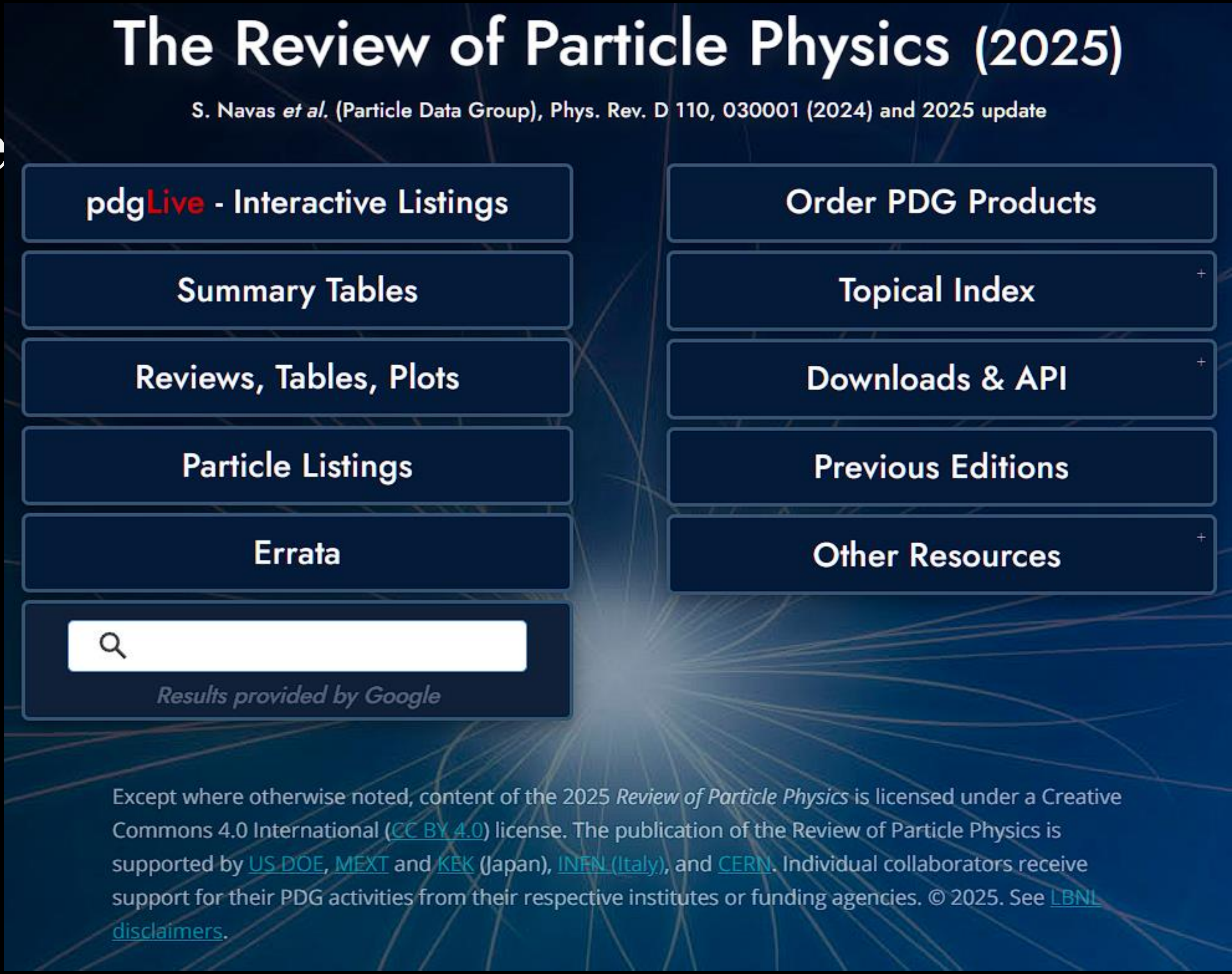




The most copious produced

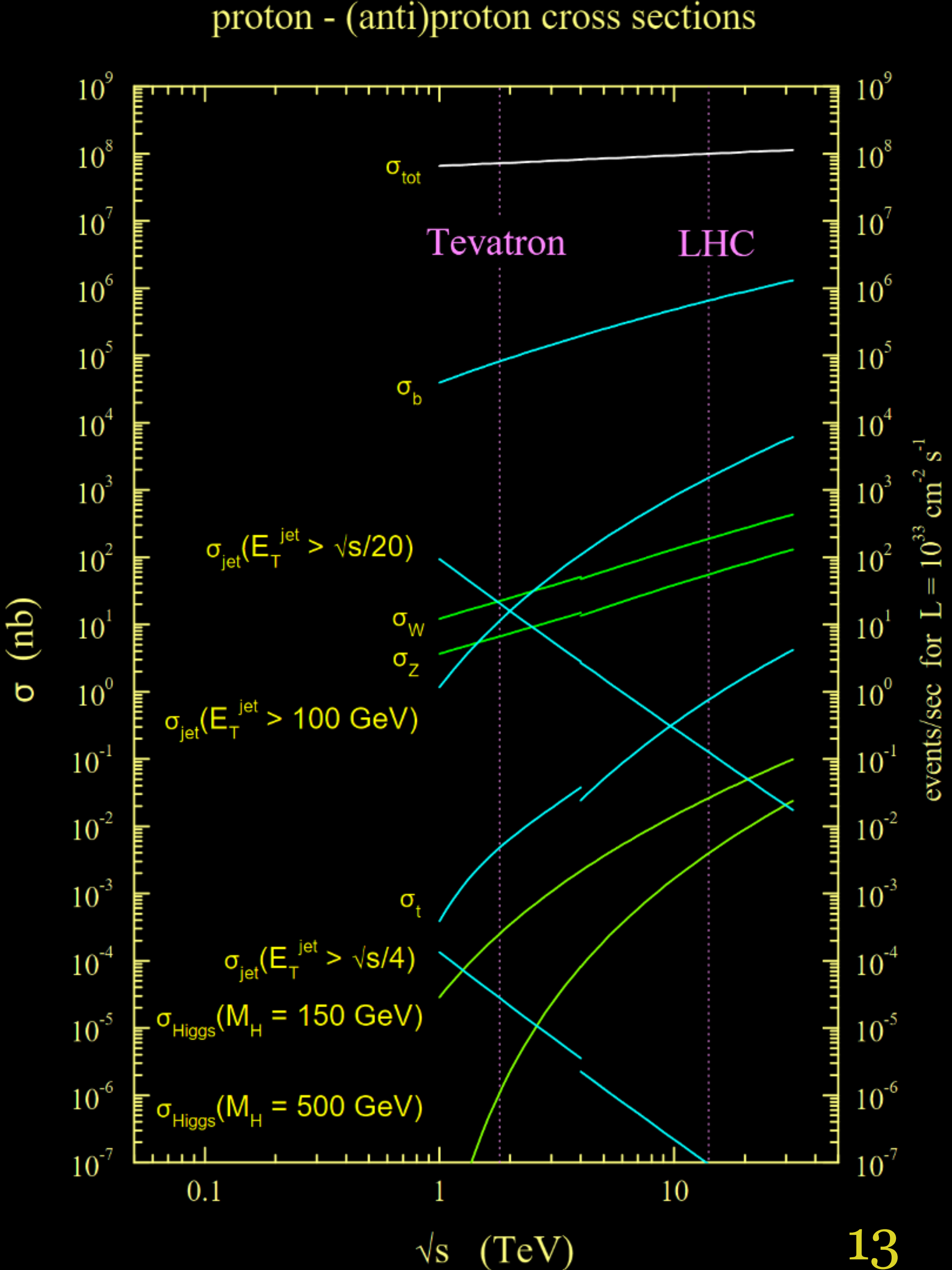
Did we overlook it fairly?

Is it too hard to detect?

W^+ **DECAY MODES**

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\ell^+\nu$	[2]	(10.86 ± 0.09) %		
Γ_2	$e^+\nu$		(10.71 ± 0.16) %		40185
Γ_3	$\mu^+\nu$		(10.63 ± 0.15) %		40185
Γ_4	$\tau^+\nu$		(11.38 ± 0.21) %		40165
Γ_5	hadrons		(67.41 ± 0.27) %		
Γ_6	$\pi^+\gamma$		$< 1.9 \times 10^{-6}$	CL=95%	40184
Γ_7	$\rho^+\gamma$		$< 5.2 \times 10^{-6}$	CL=95%	40181
Γ_8	$K^+\gamma$		$< 1.7 \times 10^{-6}$	CL=95%	40183
Γ_9	$D_s^+\gamma$		$< 6 \times 10^{-4}$	CL=95%	40160
Γ_{10}	$c\,X$		(33.3 ± 2.6) %		
Γ_{11}	$c\bar{s}$		(31^{+13}_{-11}) %		
Γ_{12}	invisible	[3]	(1.4 ± 2.8) %		
Γ_{13}	$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$	CL=95%	40184



We have a full and nice program for the Higgs boson

We've been calling the LHC

- Higgs factory
- Top factory
- QCD factory

A huge program around them

But LHC is also

- BSM explorer
- (and) EW factory!

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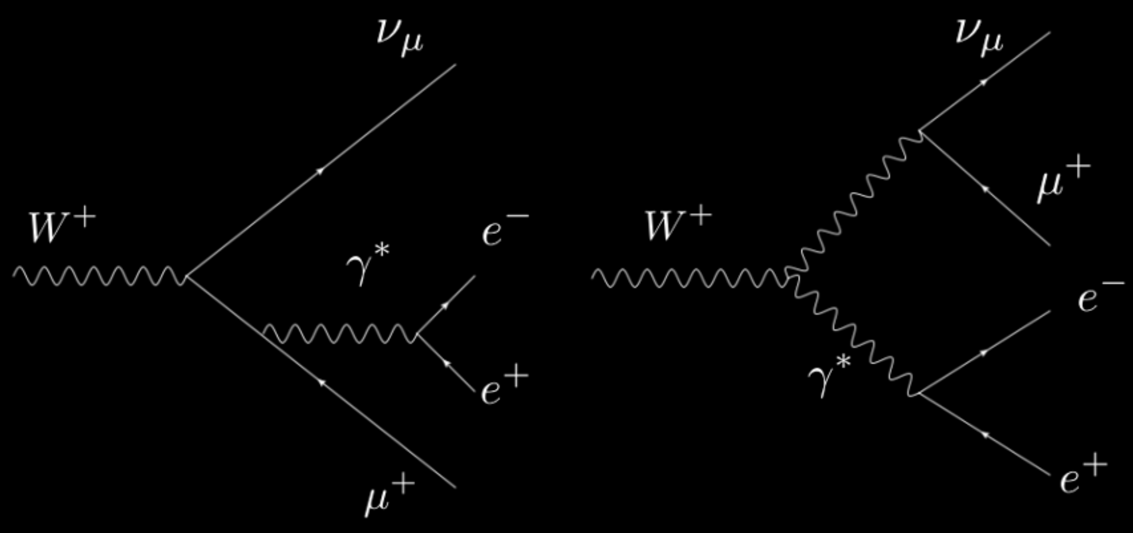
Maybe we should look into W and Z more. For instance:

$$W \to 3\ell + \nu$$
$$Z \to 2\ell + \gamma$$

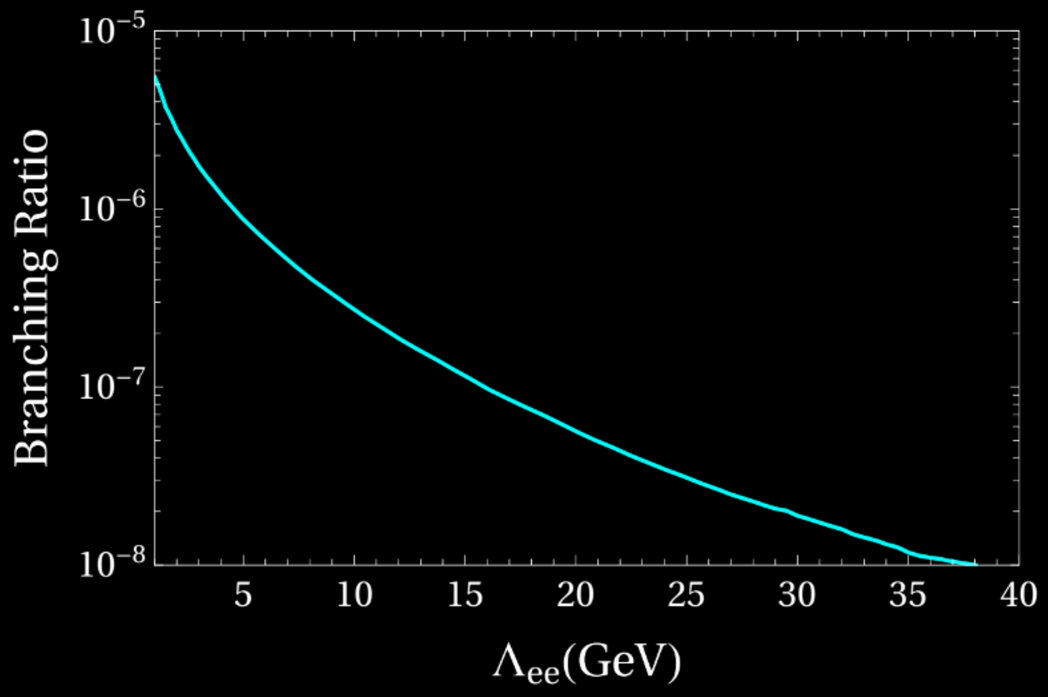
Y.F. Fei, P.R. Li, K.F. Lyu, ZL, M. Pospelov, 2407.15930.
Y.F. Fei, P.R. Li, ZL, M. Pospelov, 2604.13156

SM physics of $W \to 3\ell + \nu$



Signal process	cross section [pb]
$pp \to \ell^+\ell^-\ell^+\nu_\ell + (j),\ \mathrm{M}_{\ell\ell\ell\nu} \in \mathrm{OR}$	0.36
$pp \to \ell^+\ell^-\ell^-\bar{\nu}_\ell + (j),\ \mathrm{M}_{\ell\ell\ell\nu} \in \mathrm{OR}$	0.25

On-shell Region (OR) defined as: $m_W \pm 2\Gamma_W$



Subtilty: one cannot strictly separate on-shell W decay and off-shell W-decay. We define on-shell regime and compare the rate and kinematic distribution of a zero-width approximation W-decay.

Projected sensitivity

The SM Br on such a channel is at 10^{-6} level

Current LHC data (with current trigger and selection, 150 fb^{-1})

$$\delta Br(W \to 3\ell + \nu) = 6\%$$

HL-LHC data (with improved trigger on multileptons)

$$\delta Br(W \to 3\ell + \nu) = 0.6\%$$

A clean, high-statistics laboratory: $Z \to \mu\mu\gamma$ at the LHC

Γ_{58}	$e^+e^-\gamma$	[6]	$< 5.2 \times 10^{-4}$	CL=95%	45594	⌄
Γ_{59}	$\mu^+\mu^-\gamma$	[6]	$< 5.6 \times 10^{-4}$	CL=95%	45594	⌄
Γ_{60}	$\tau^+\tau^-\gamma$	[6]	$< 7.3 \times 10^{-4}$	CL=95%	45559	⌄

- The LHC produces billions of Z bosons; $Z \to \mu^+\mu^-\gamma$ is rare ($\sim 10^{-4}$) but exceptionally clean
- Final state: two opposite-sign muons + a hard photon — minimal hadronic background
- Fiducial branching ratio isolates a theoretically safe fixed-order regime
- Statistical precision: $\Delta\mathrm{Br}/\mathrm{Br} \sim 0.26\%$ (Run-2) and 0.04% (HL-LHC) — sub-percent SM test

Our re-interpretation of a Run-1 study

$$\mathrm{Br}^{\mathrm{fid}}(Z \to \mu\mu\gamma) = (3.34 \pm 0.016) \times 10^{-4}$$

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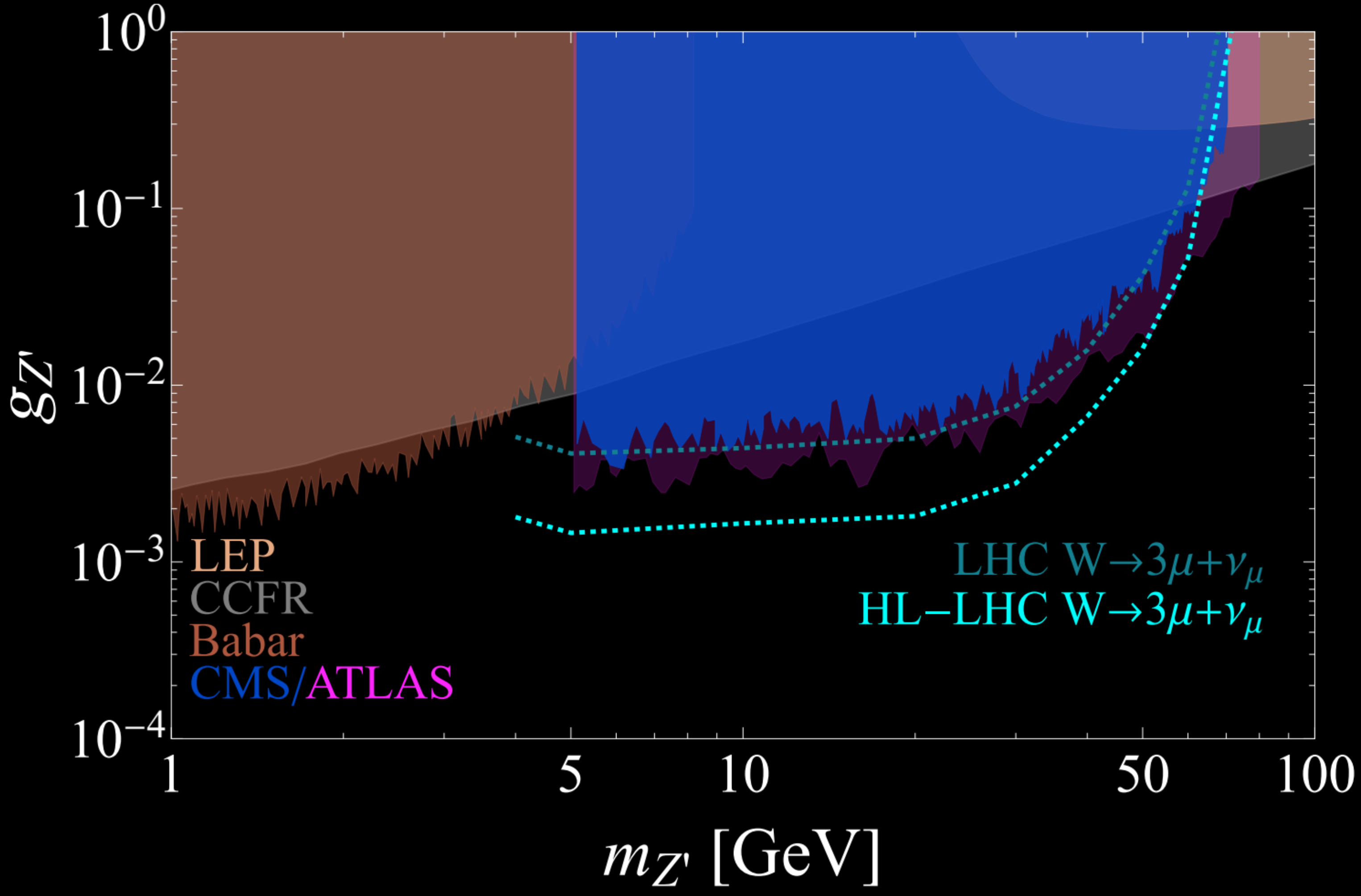
So, we can add a few more entries to PDG, then what?

One can also look for dark photon/Z, ALPs, SMEFT precision, subtle SM effects, in these channels.

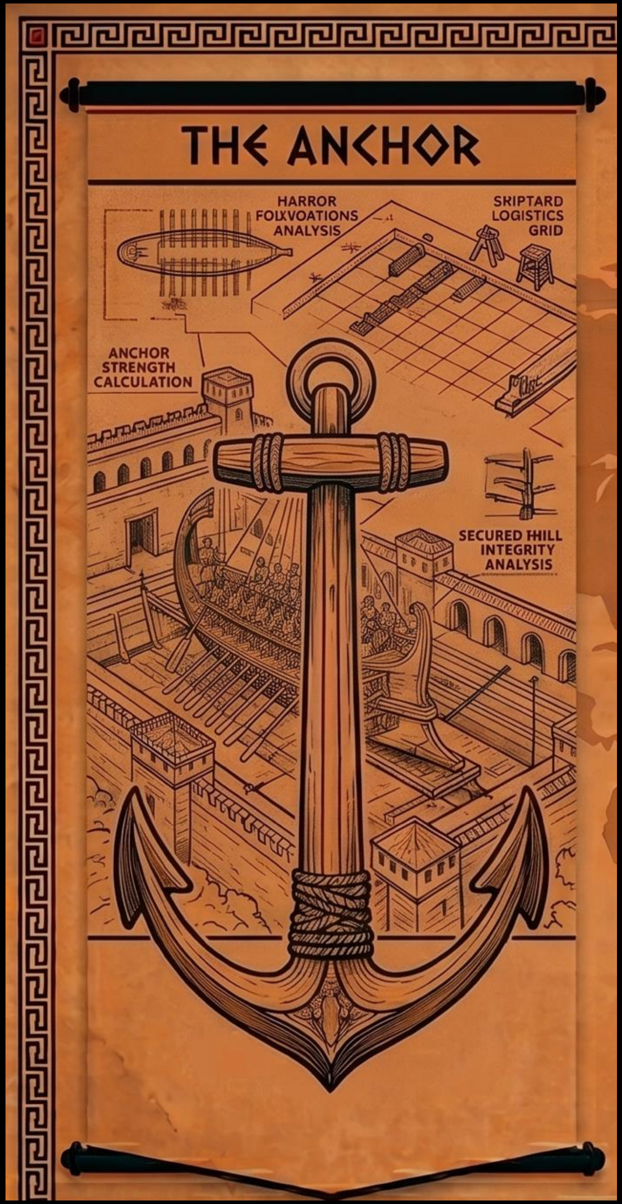
E.g., an $L_\mu - L_\tau$ Z'

- Standard search channel $Z \to 4\ell$.
- W rate is a factor of 4~5 larger than Z
- W leptonic branching fraction is a factor of 3 larger than Z

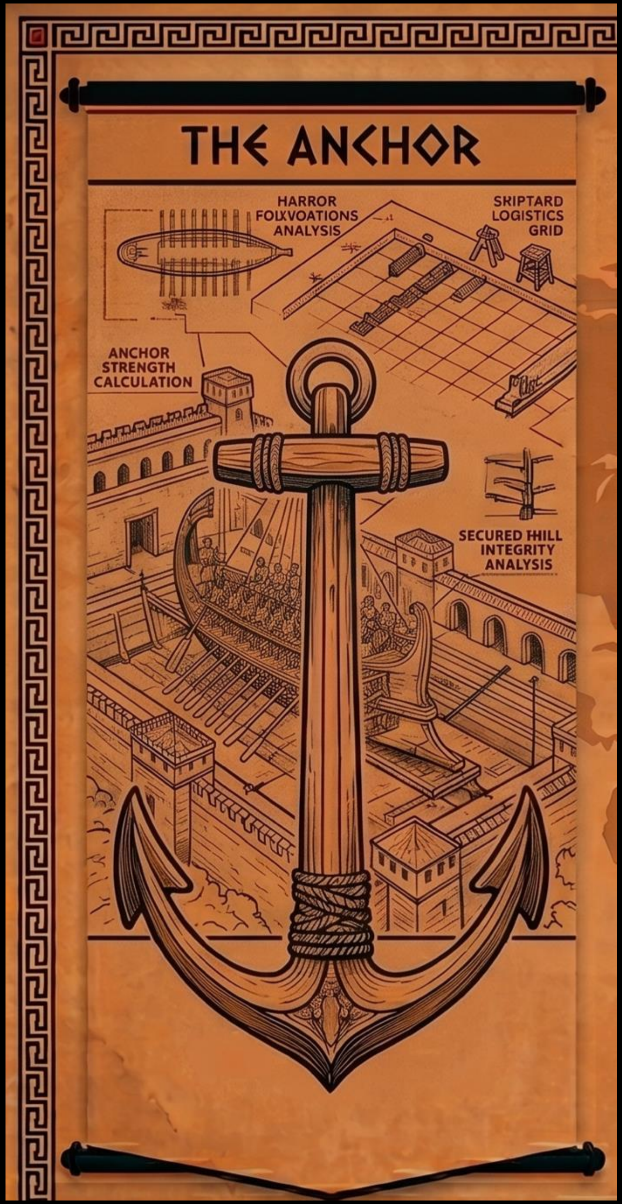
W exotic should be a **competitive** channel.



ATLAS Search: 2402.15212



Are we just hunting Bumps?



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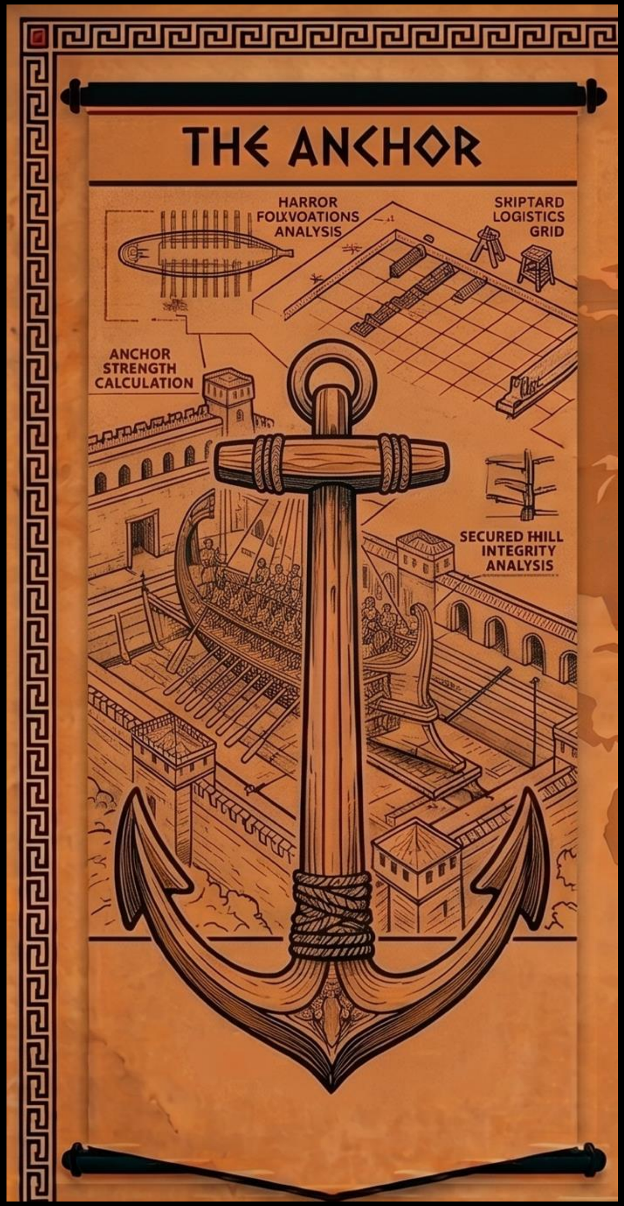
Many differential and precision measurements, some are QCD (such as recent studies on Energy-Energy correlators), some are EW (Higgs STXS). We are learning SM, QFT (e.g., positivity tests, J. Gu, C. Shu 2311.07663 K.F. Lyu, ZL, T. Wu, 2512.04336), flavor (Z. Ligeti's talk earlier), and stress testing the SM from all angles!



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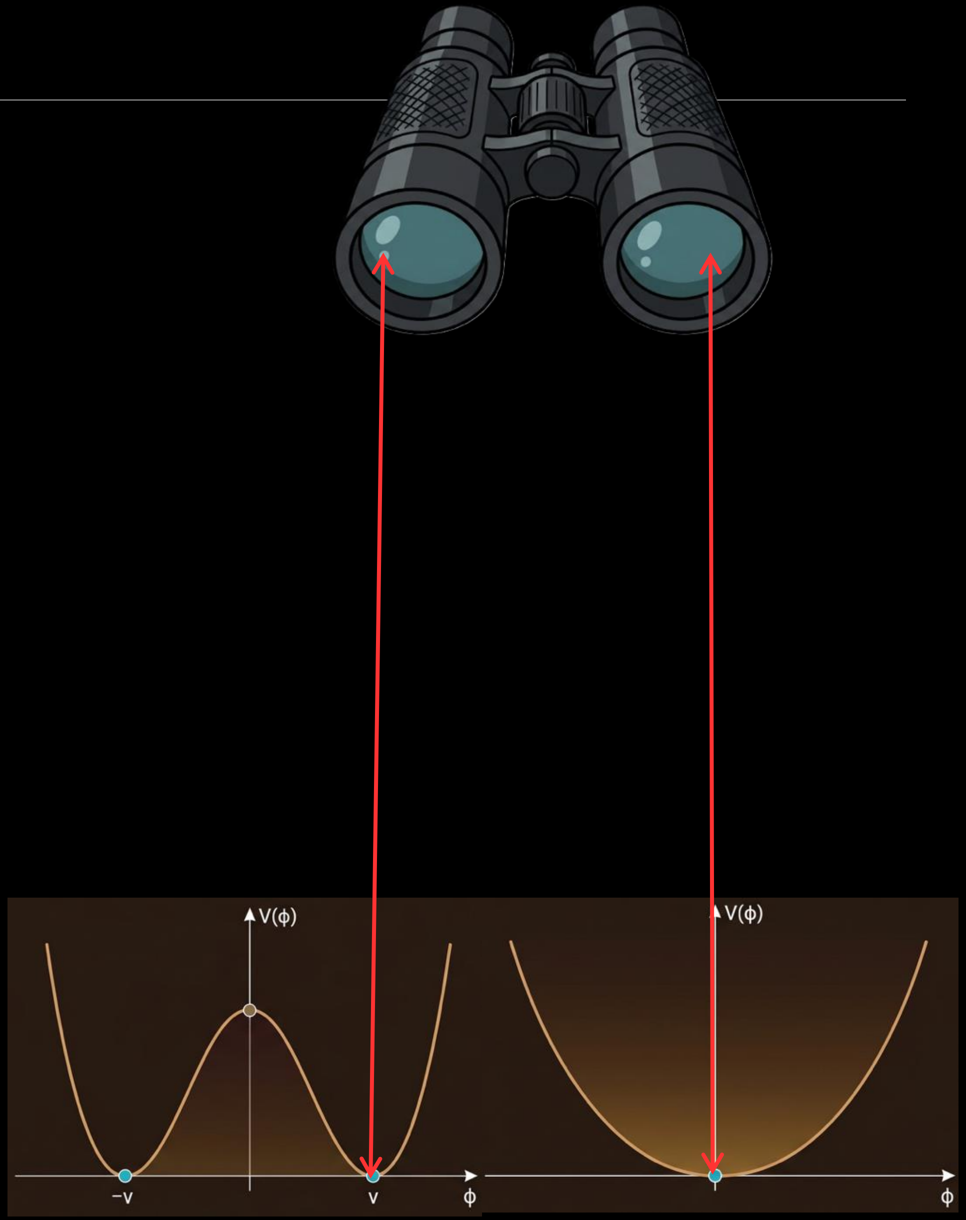
Quantum Entanglement angle: a vibrant direction, see F. Maltoni's talk next, also talk by R. Demina earlier.

Feature of High Energy Collisions: ~ EW symmetry (Electroweak Restoration)

- As a local scattering test, the difference between broken and non-broken scatterings is ordered by v/E.



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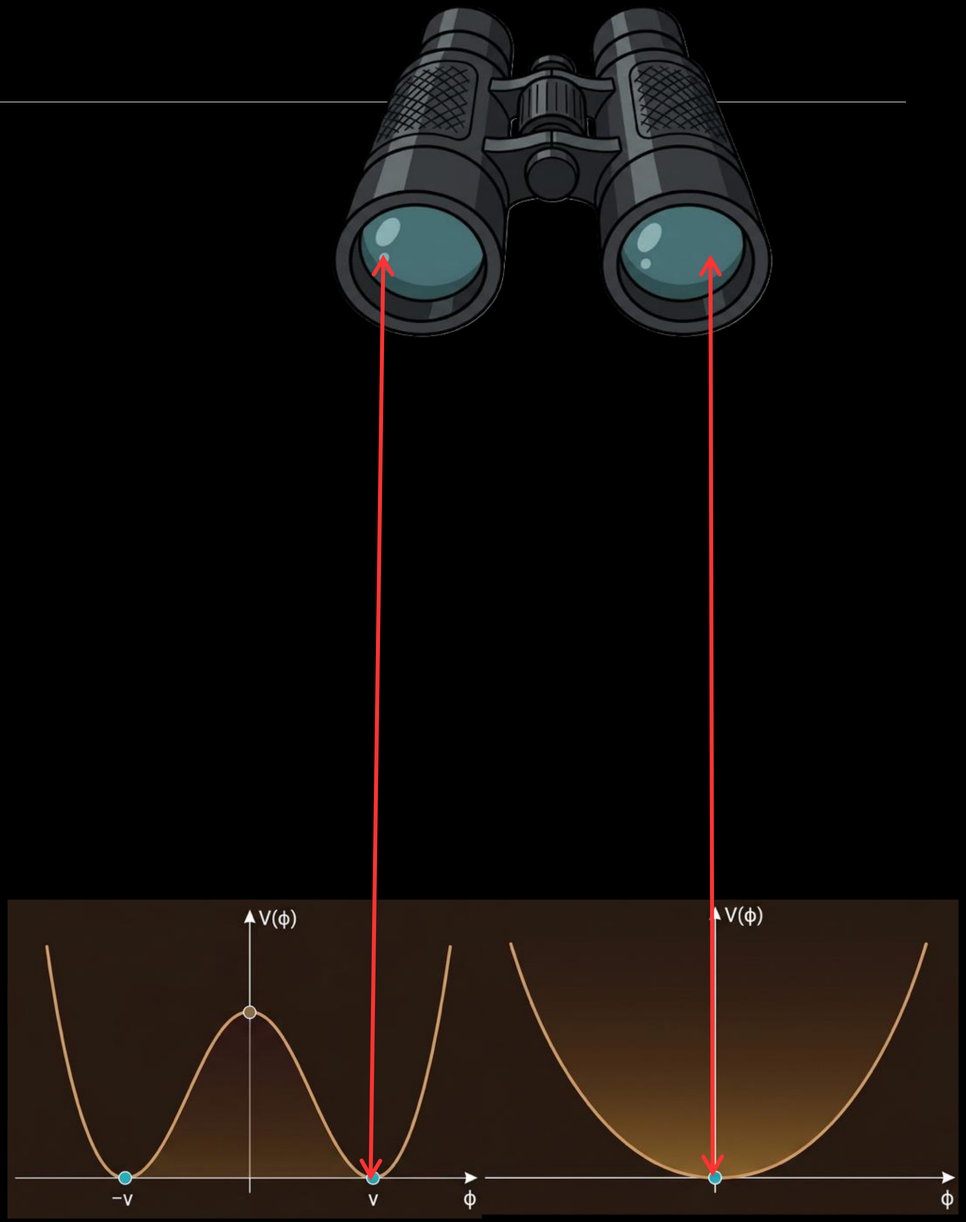

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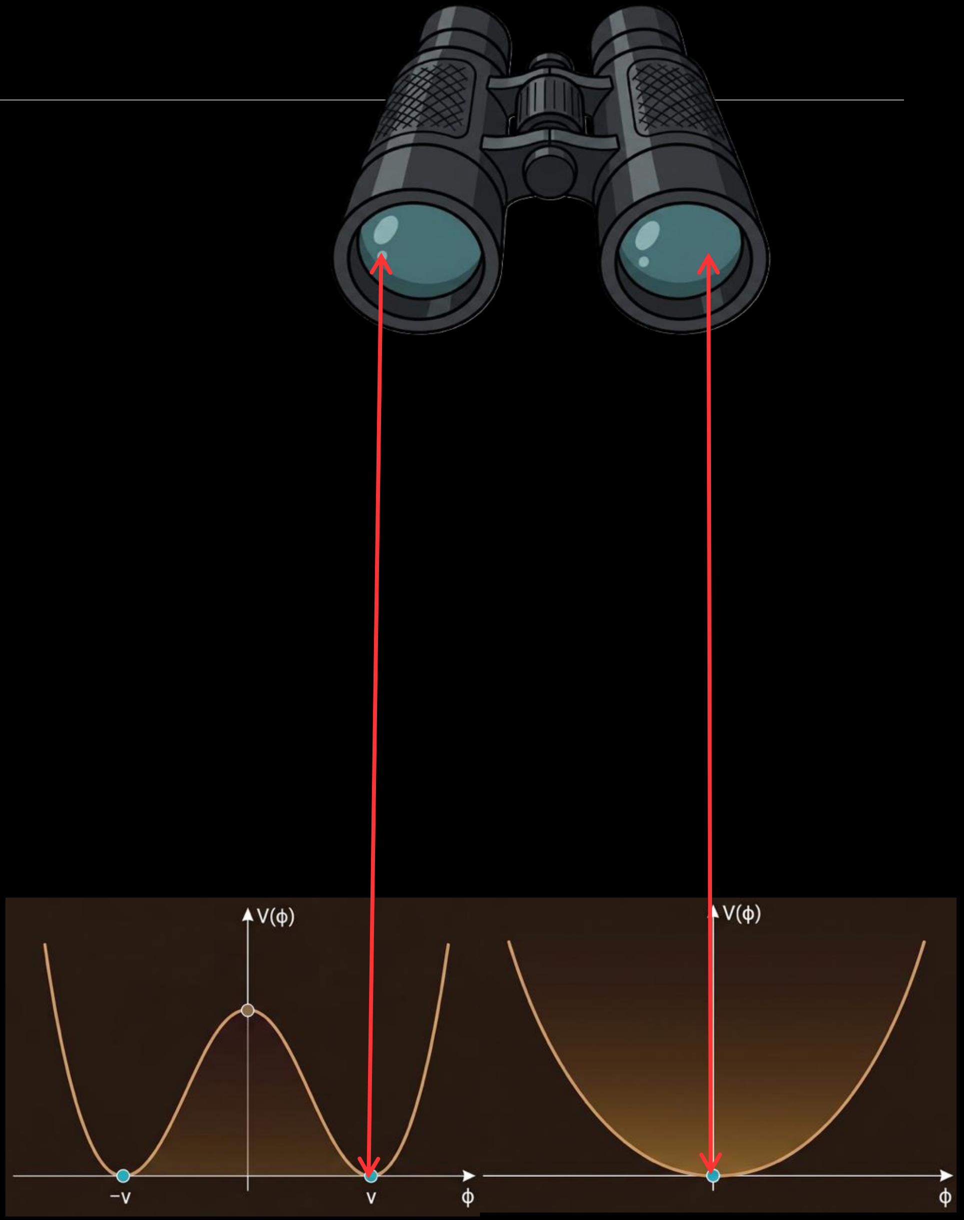
  - Higgs remembers its doublet nature



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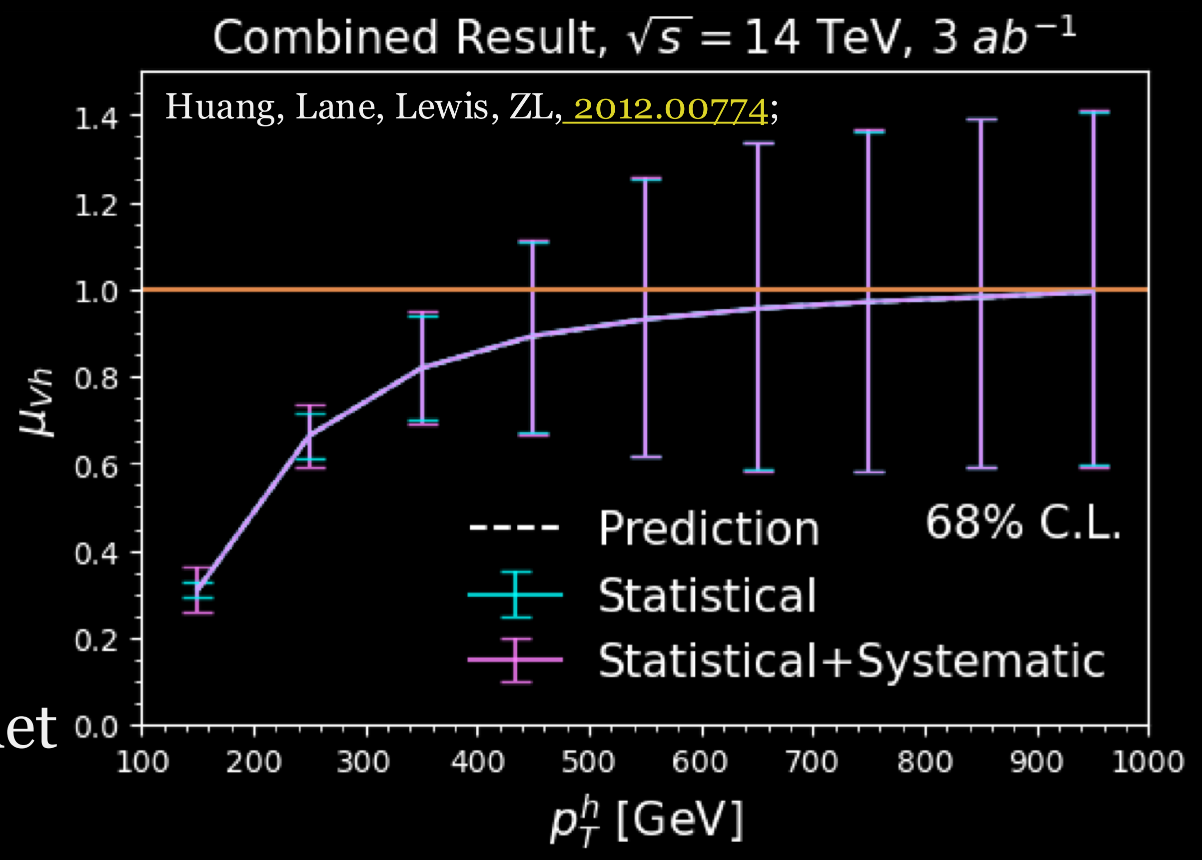
Seeing Goldstone Equivalence



See more discussions in R. Capdevilla, T. Han, 2412.12336

I. Lewis, ZL, I. Mahbub, 2605.08433

See I. Mahbub's talk this afternoon

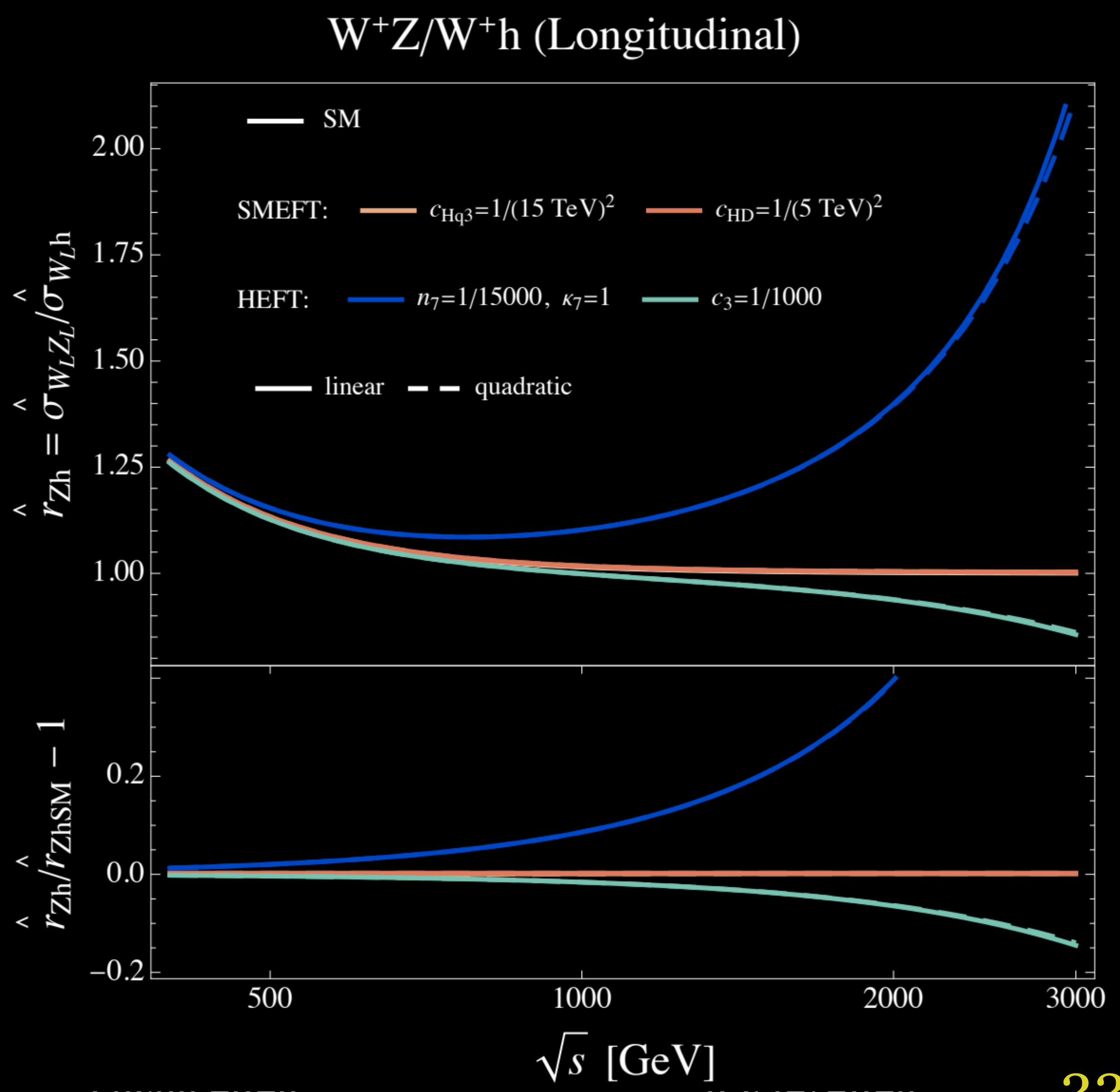
Testing of SM and BSM

Does Higgs remember its doublet nature?
Not necessarily.

We can quantify whether (corrections to) EWSB is linearly realized or non-linearly realized, by using SMEFT (Standard Model Effective Field Theory), HEFT (Higgs Effective Field Theory), respectively.

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}\, i\, G^{+} \\ v + h + i\, G^{0} \end{pmatrix} \qquad U(x) = \exp\left(\frac{i\, \sigma^I \pi^I(x)}{v} \right)$$

If EW restoration is true, some observables should remember h and Z are in an O(2).



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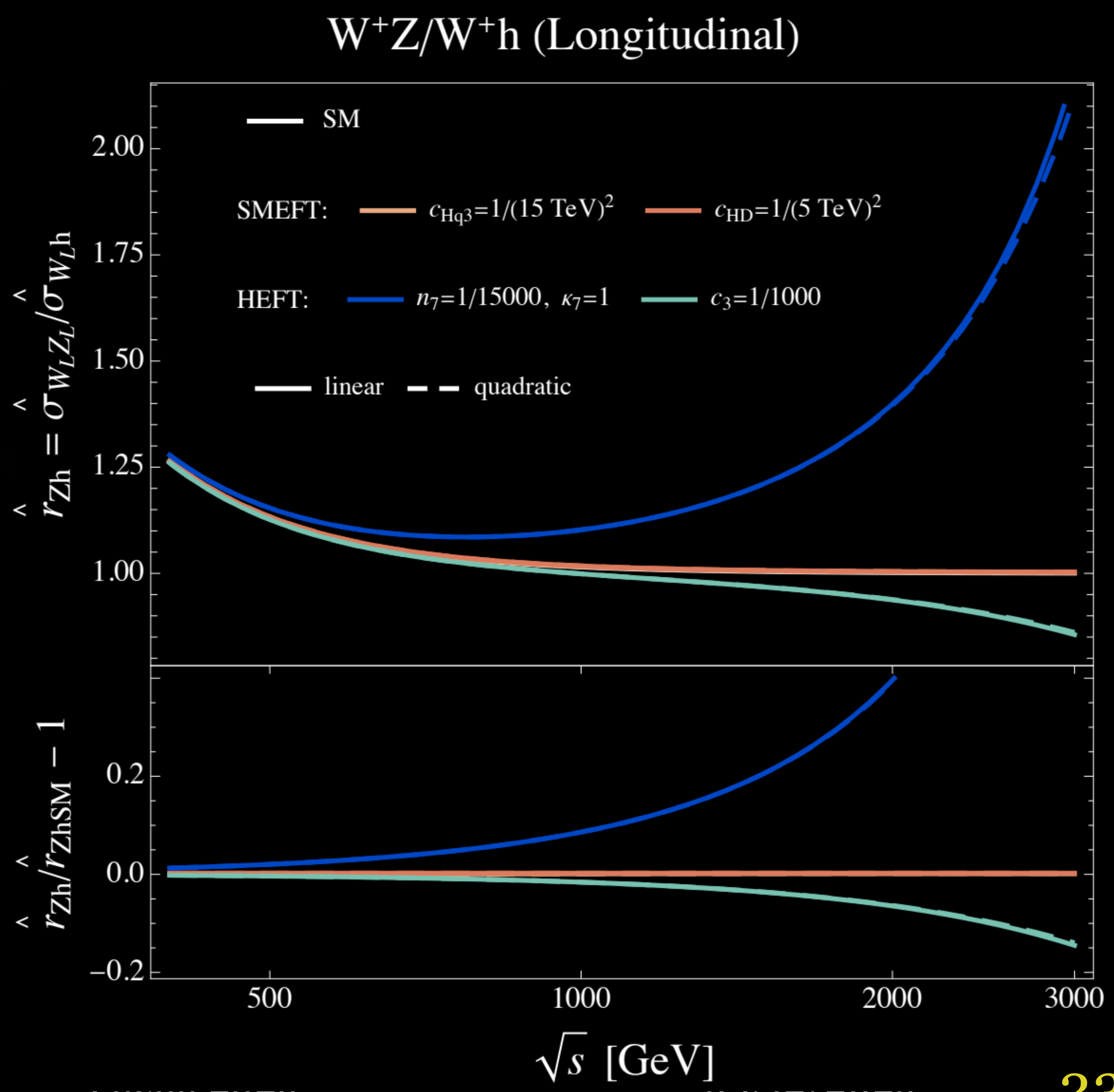
- EW restoration predicts universal amplitude ratios → only SM/SMEFT obey them
- HEFT generically violates these ratios, offering a clear discriminant
- Full set of cross section ratios to test linear/non-linear corrections to EWSB.



Clean discriminator: $W_L^+ Z_L / W_L^+ h$ ratio

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- EW restoration predicts universal amplitude ratios → only SM/SMEFT obey them
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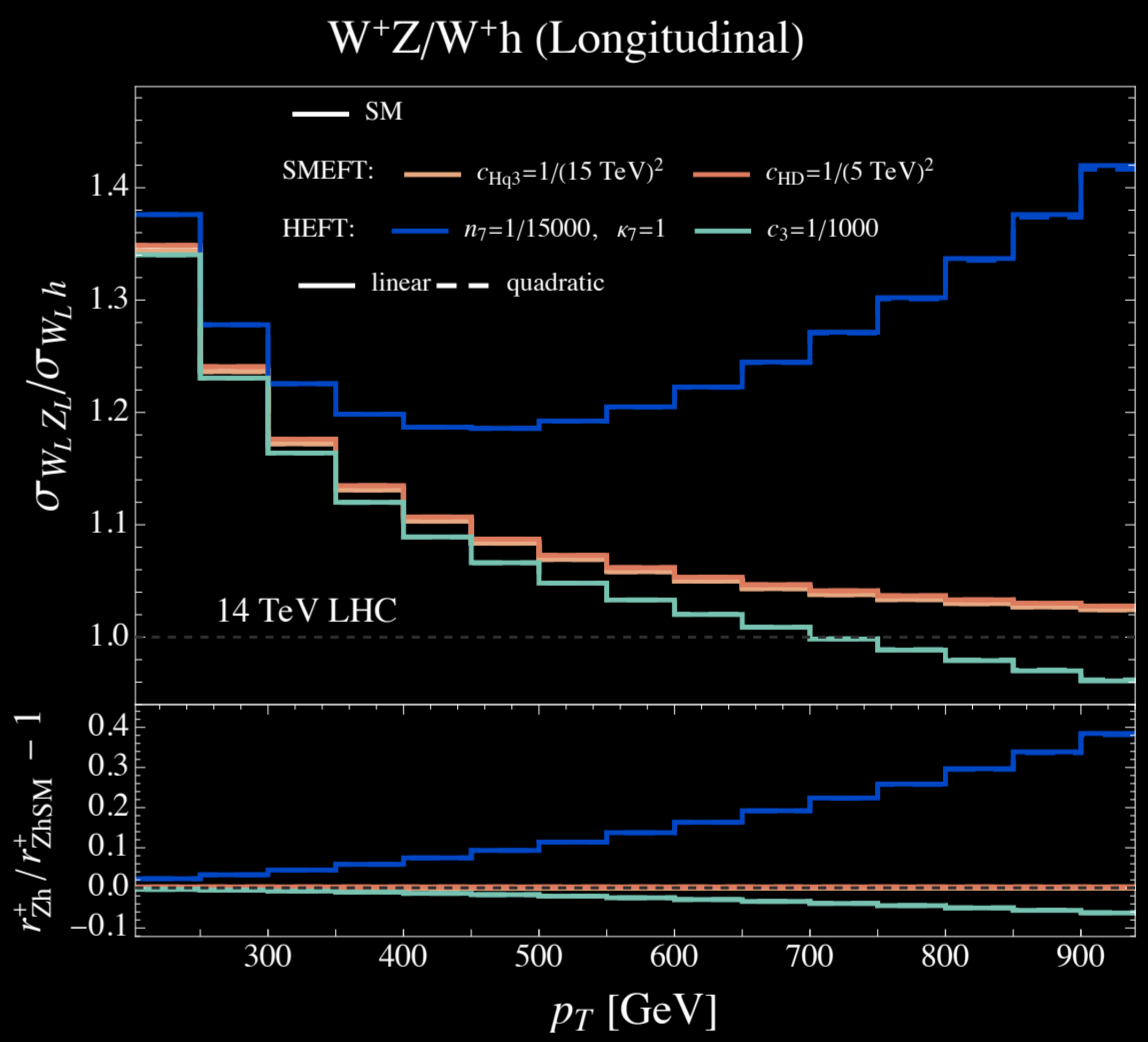
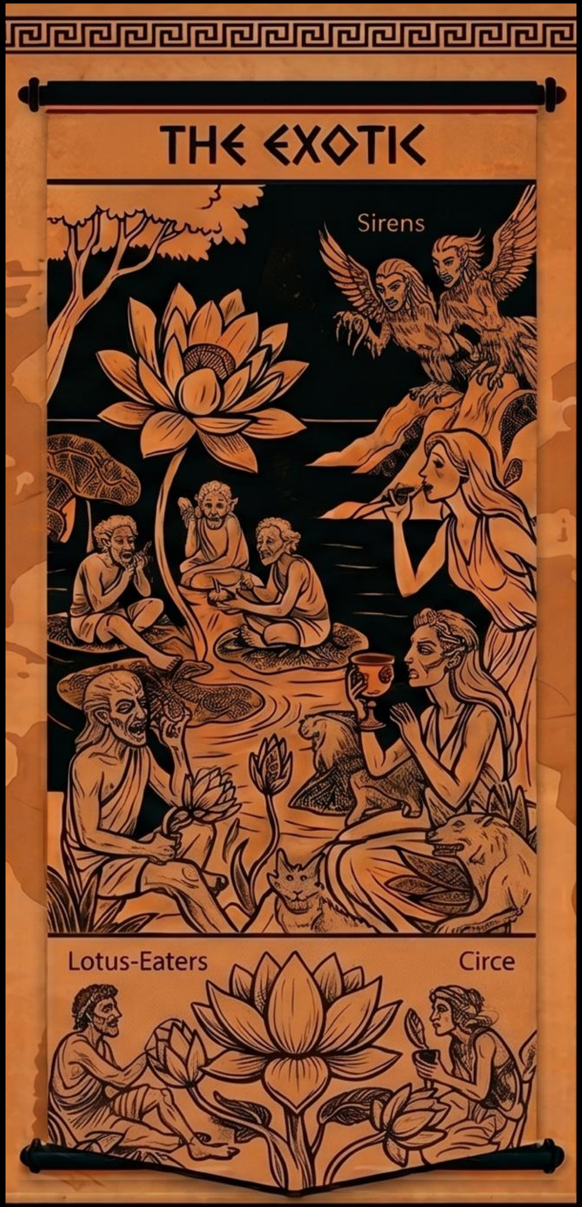
- Full set of cross section ratios to test linear/non-linear corrections to EWSB.
- Many more tests are possible at LHC and future colliders.



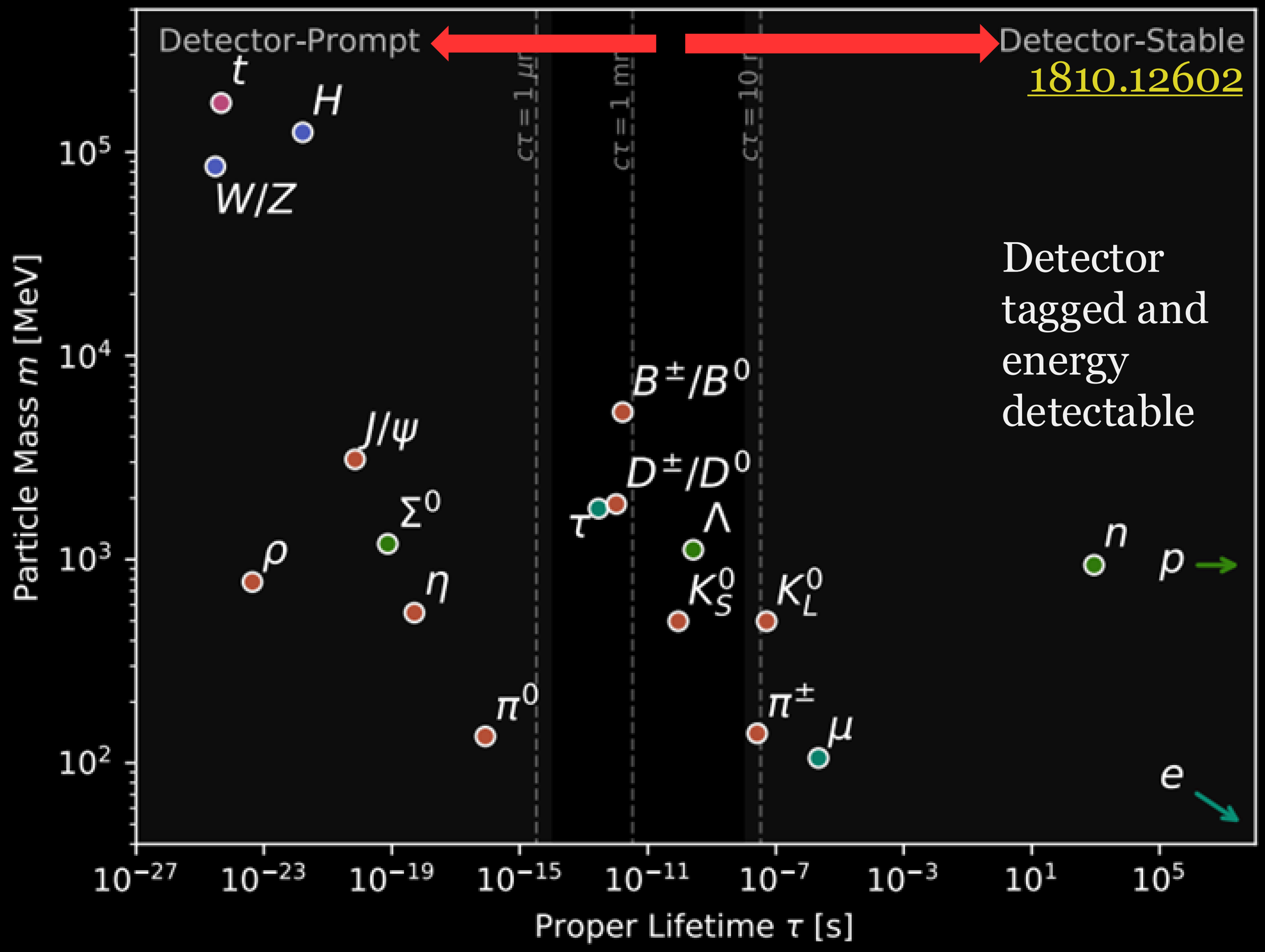
“Exotic”: Long-Lived Particles



What is LLP & Why searching for them?

Long-lived particles in the standard model:
- approximate symmetries;
- kinematic suppressions;

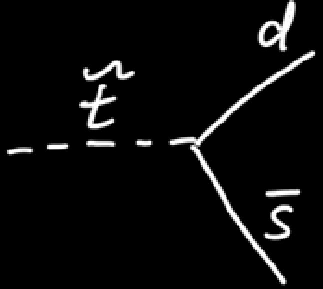
For BSM particles:
- Prompt particles being actively probed;
- Many scenarios give raise to long-lived signatures:
  - SUSY (GMSB, RPV, Split, etc.)
  - Hidden Sector Dynamics



SUSY as a Strawman (more towards heavy LLPs)

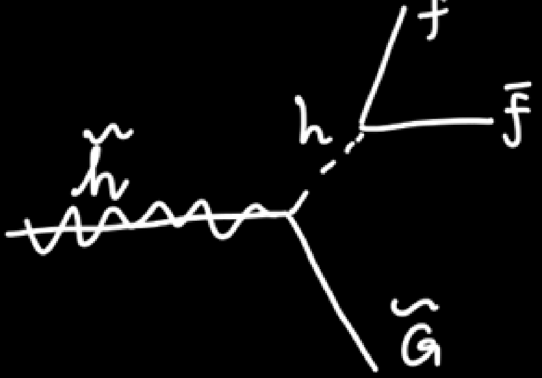
- R-Parity-Violating, small B/L-violating couplings

$$c\tau_{RPV} \sim 1\text{ m}\left(\frac{100\text{ GeV}}{\tilde{m}}\right)\left(\frac{10^{-8}}{\lambda_{RPV}}\right)^2$$



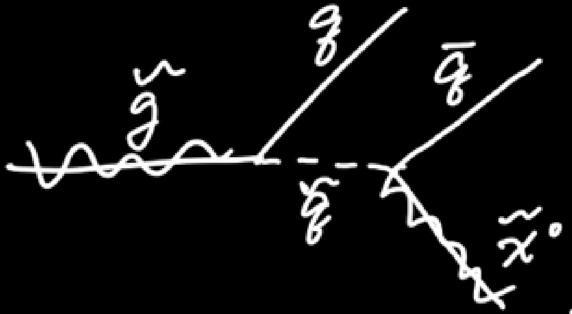
- Gauge mediation—suppressed couplings via SUSY breaking scale

$$c\tau_{\text{GMSB}} \sim 10\text{ m}\left(\frac{100\text{ GeV}}{\tilde{m}}\right)^5\left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4$$



- Mini-split spectrum—suppressed couplings through “decoupled” heavy particles

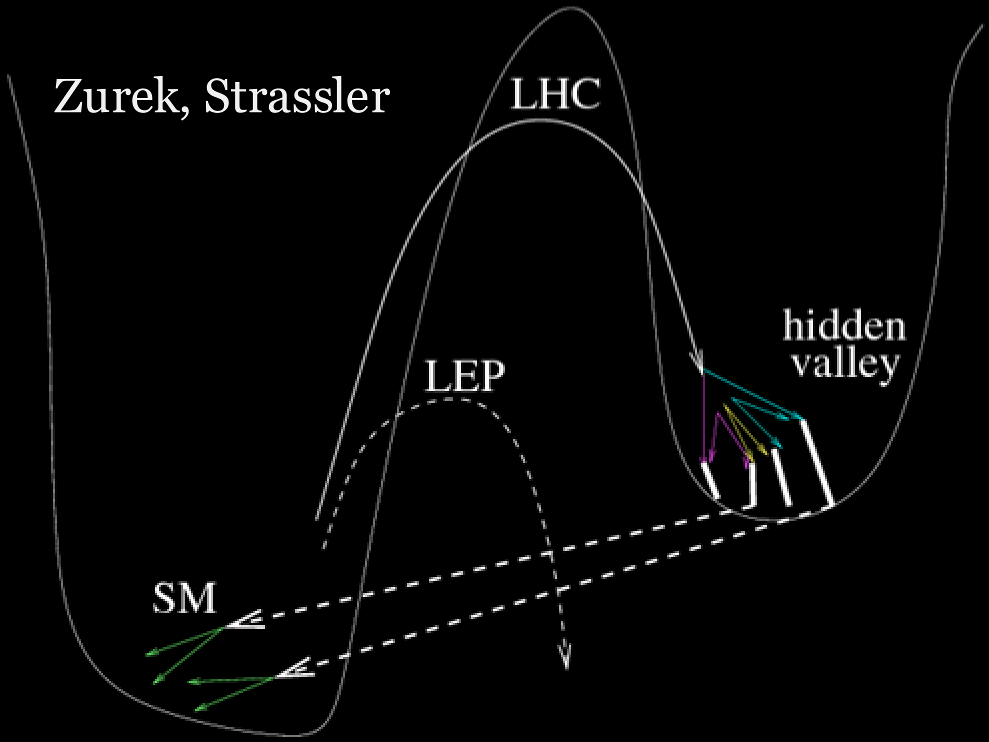
$$c\tau_{\text{milli-split}} \sim 1\text{ mm}\left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5\left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4$$

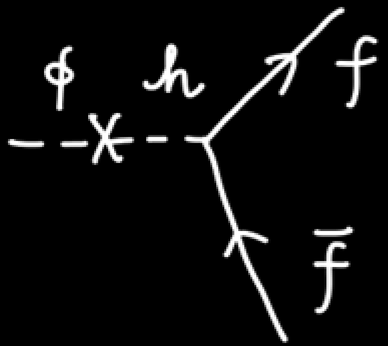


- Pure Wino/Higgsino–nearly degenerated, disappearing track

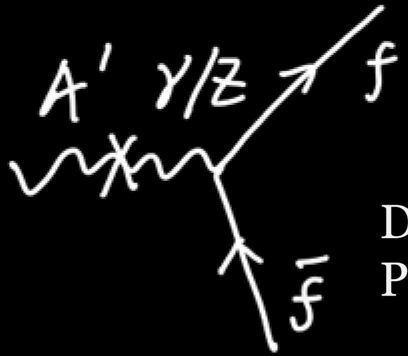
Hidden Sectors (more towards light LLPs)

Hidden sector feeble couplings to SM via various portals, suppressed by the smallness of the couplings



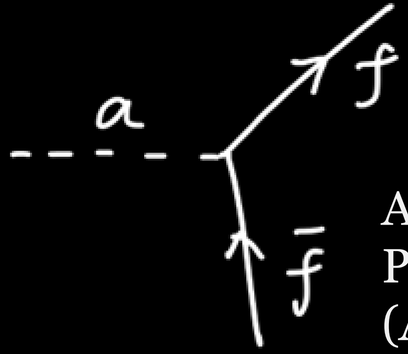


Higgs portal



Dark Photon

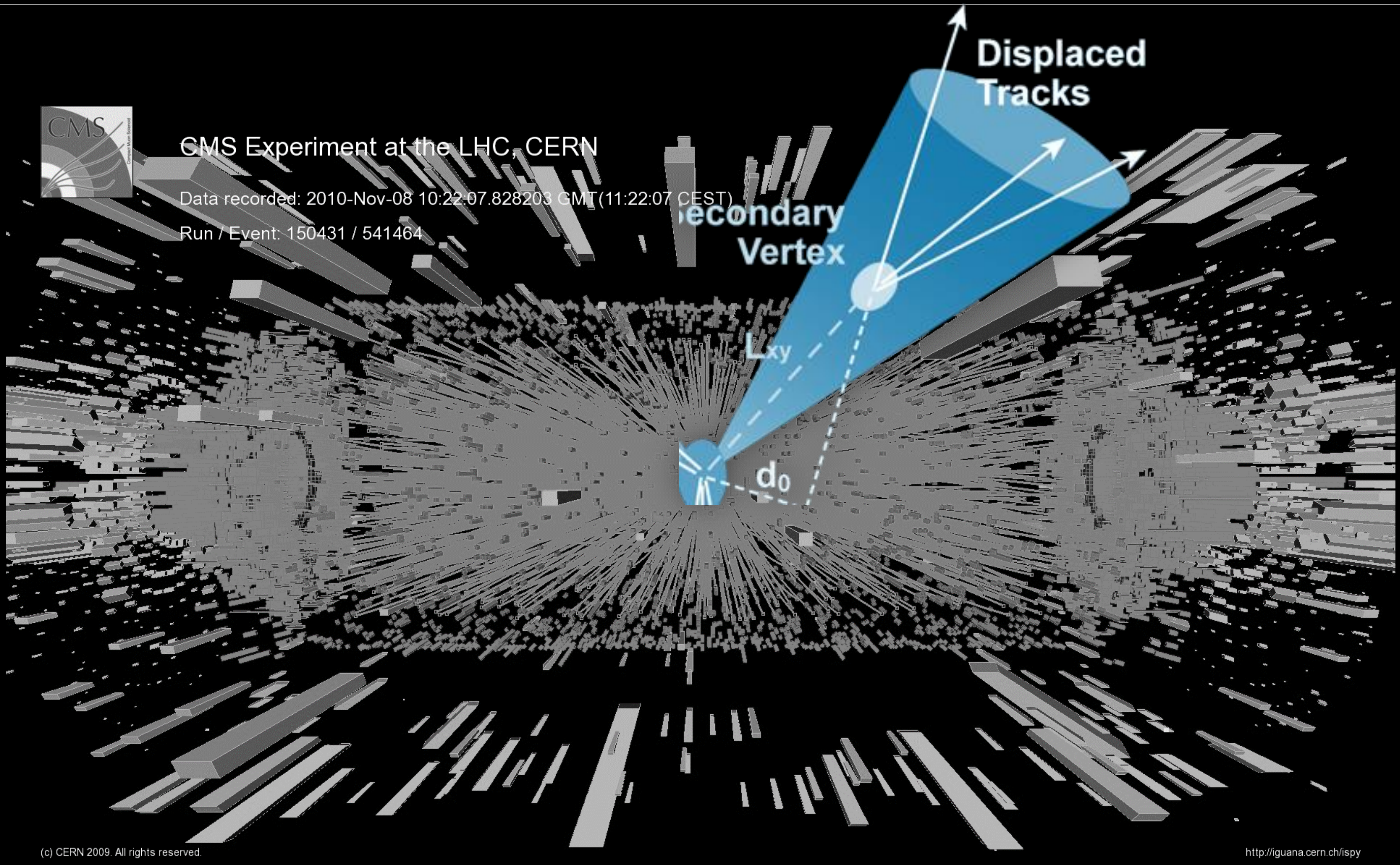
Heavy Neutral Leptons (HNLs)



Axion-Like-Particles (ALPs)

Fantastic Four or Amazing five (plus millicharged)

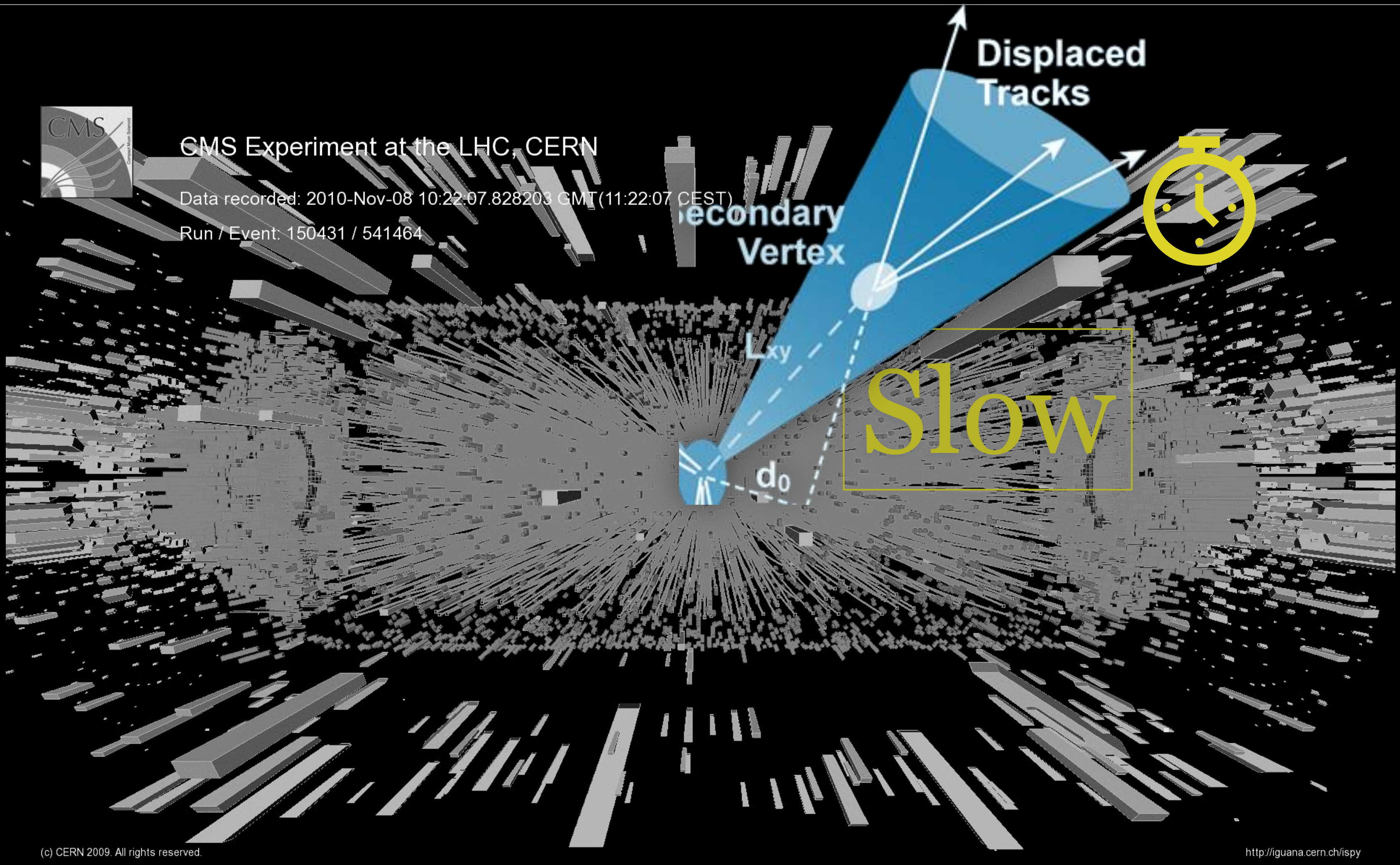
New Capability example: Timing



New Capability example: Timing

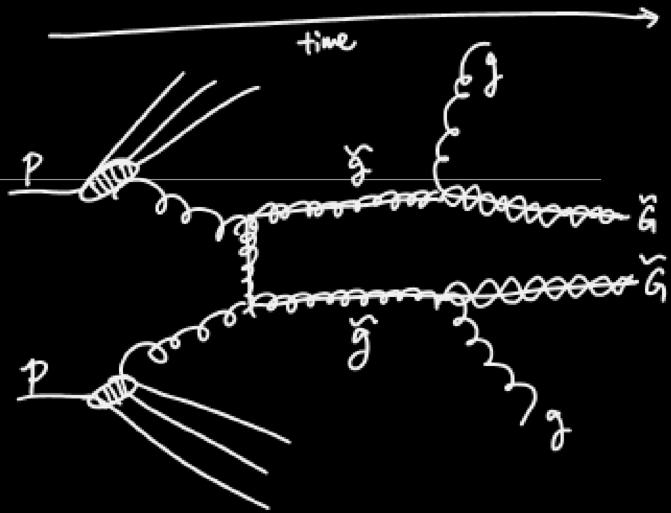
Delay is a universal feature of Long-Lived Particles*

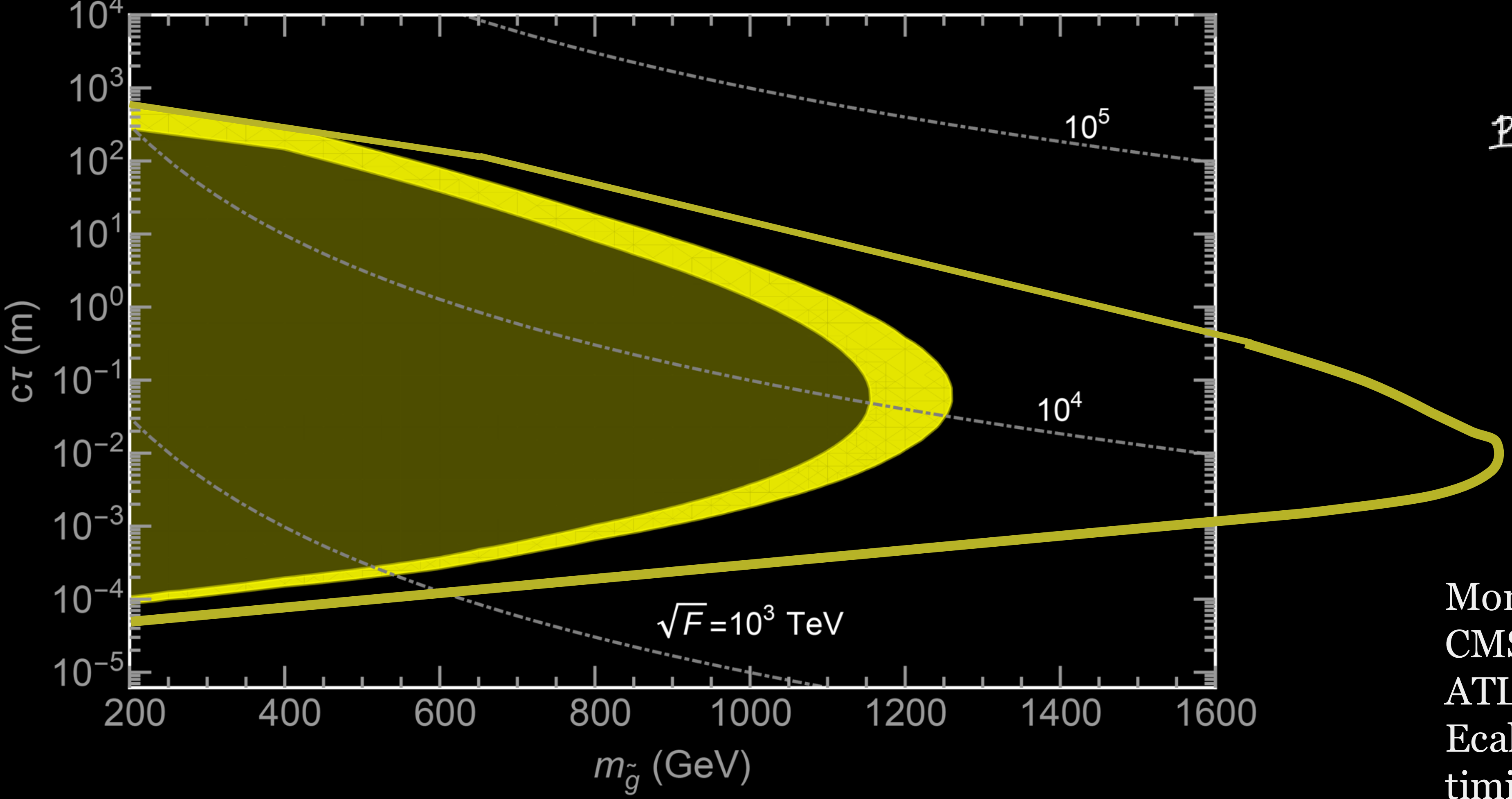
Liu, ZL, Wang, 1805.05957



*except for those hyper-boosted $\gamma \geq 7$

Late comers will be spotted easily





Displaced jet at 13 TeV, 39 fb^{-1}

More to come:
CMS MTD upgrade
ATLAS HGTD upgrade
Ecal, Muon system, HCal, timing information to be used

CMS search, 1906.06441
Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923

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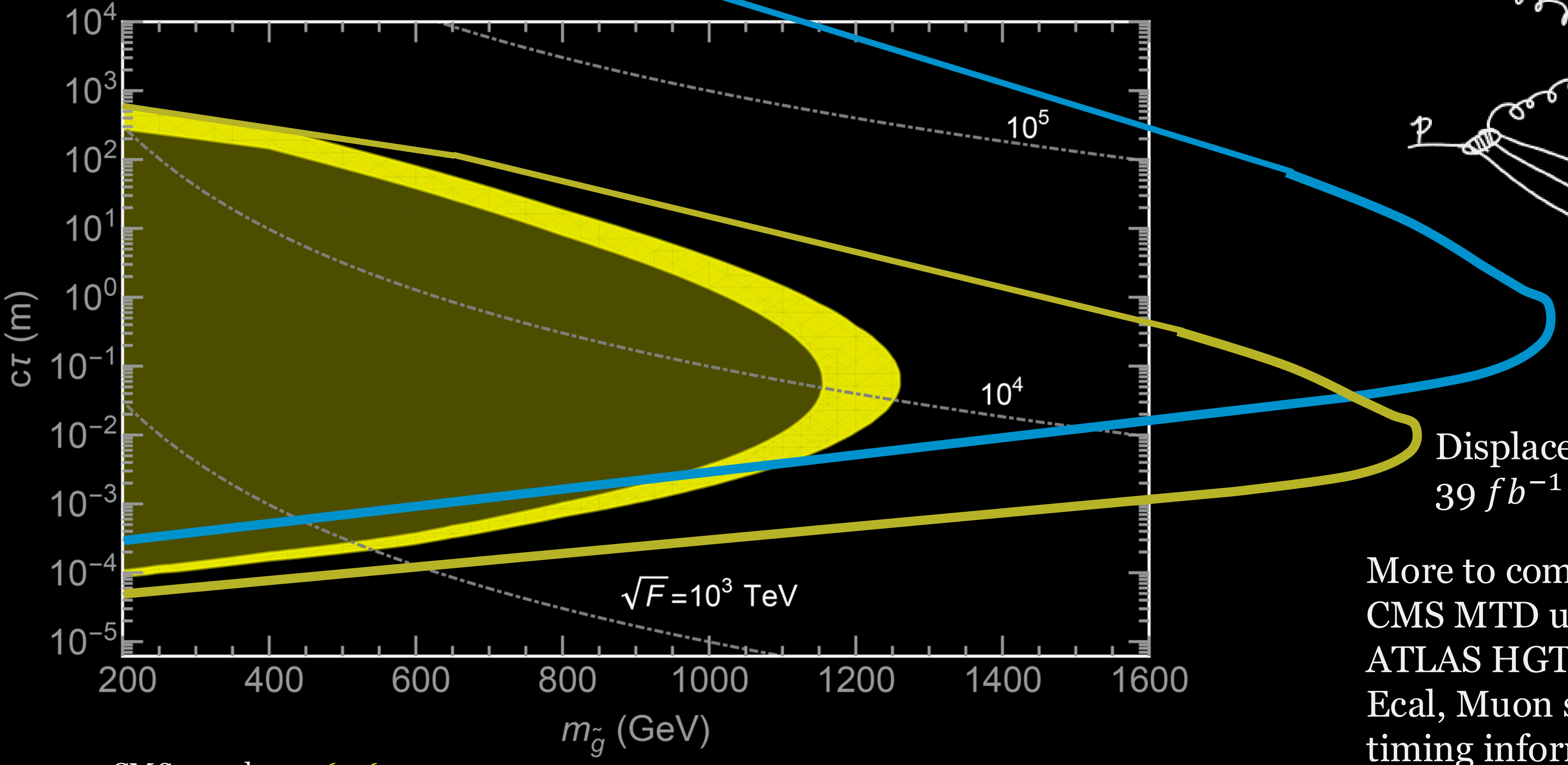

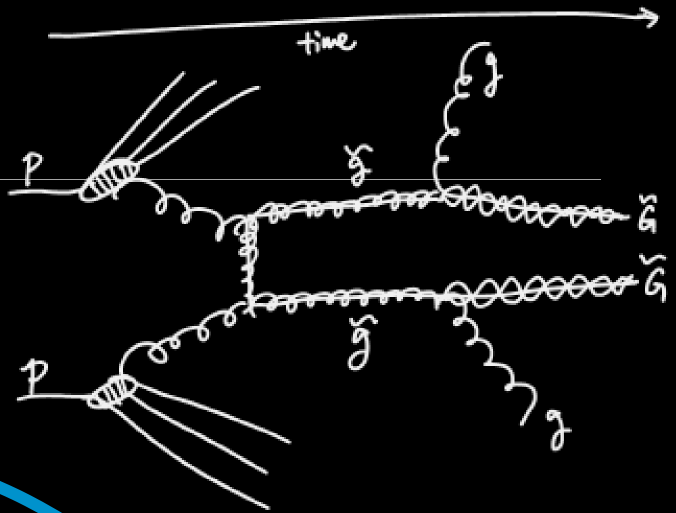

Delayed Jet analysis carried out by CMS, 139 fb^{-1}

Displaced jet at 13 TeV, 39 fb^{-1}

More to come:
CMS MTD upgrade
ATLAS HGTD upgrade
Ecal, Muon system, HCal, timing information to be used

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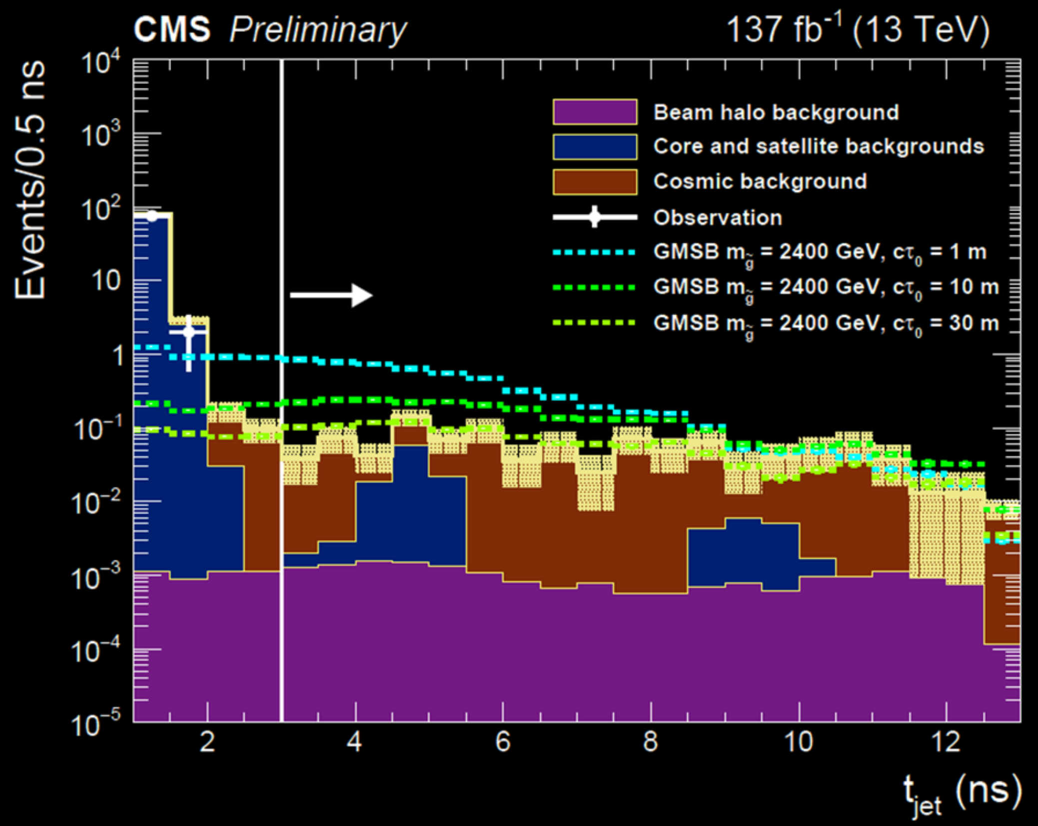
Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923

What is the time of a jet?

Theoretically and experimentally interesting



The pioneering delayed jet search used median time, clearly having a large room to improve.

$$t_J^{\{\text{median,hardest,random}\}} = t_{\{i_m,i_h,i_r\}} = \frac{r_T}{c}\cosh\eta_{\{i_m,i_h,i_r\}}$$

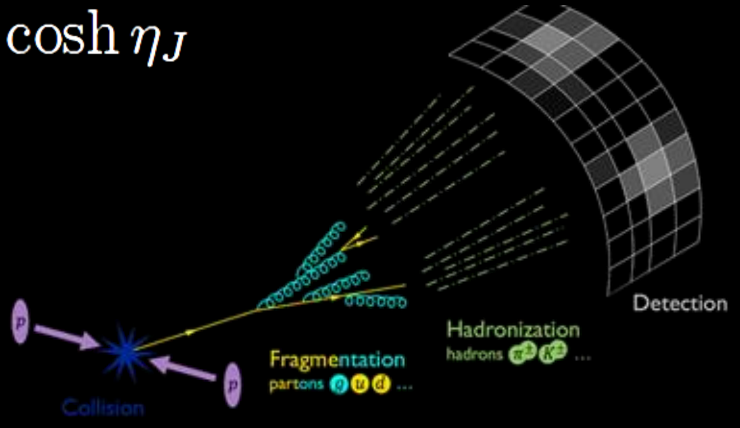
$$t_J^{\text{null}} = \frac{r_T}{c}\frac{|\vec{p}_J|}{p_{T,J}} = \frac{r_T}{c}\cosh\eta_J$$

$$t_J^{\text{kinematic}} = \frac{r_T}{c}\frac{E_J}{p_{T,J}}$$

$$t_J^{\text{average}} = \frac{1}{N}\sum_{i=1}^{N} t_i$$

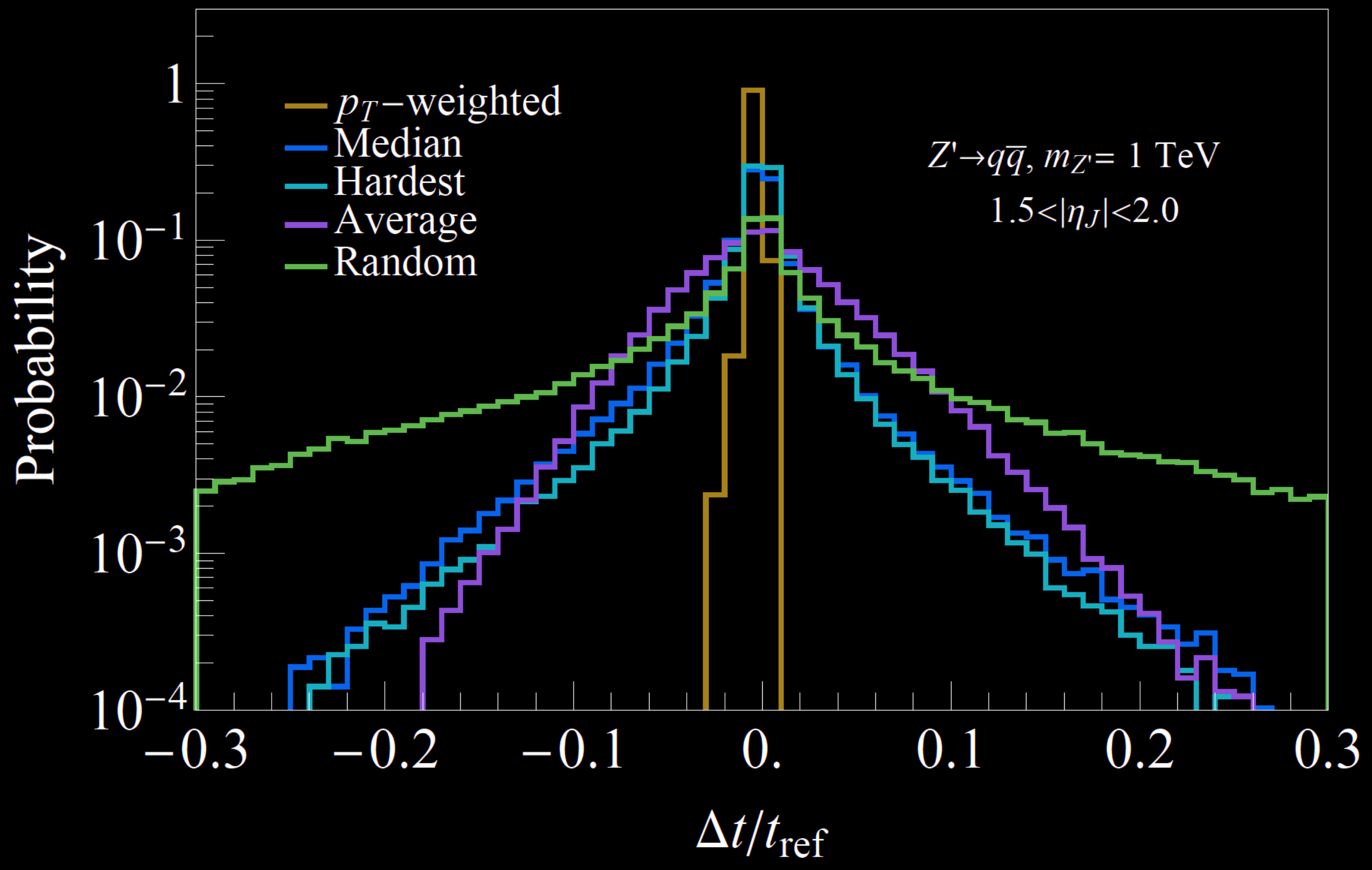
$$t_J^{p_T} = \frac{1}{p_{T,S}}\sum_{i=1}^{N} p_{T,i}t_i, \qquad p_{T,S} = \sum_{i=1}^{N} p_{T,i}$$

$$t_J^{(\alpha,\beta,\gamma)} \propto \sum_{i\in\text{jet}} (p_{T,i})^\alpha(\Delta R_i)^\beta t_i^\gamma$$



Chiu, ZL, Low, Wang, 2109.01682

Tackle Time: what is the time of a jet?



pT-weighted time provides the best convergence, and hence the quasi-optimal experimental definition of the jet time.

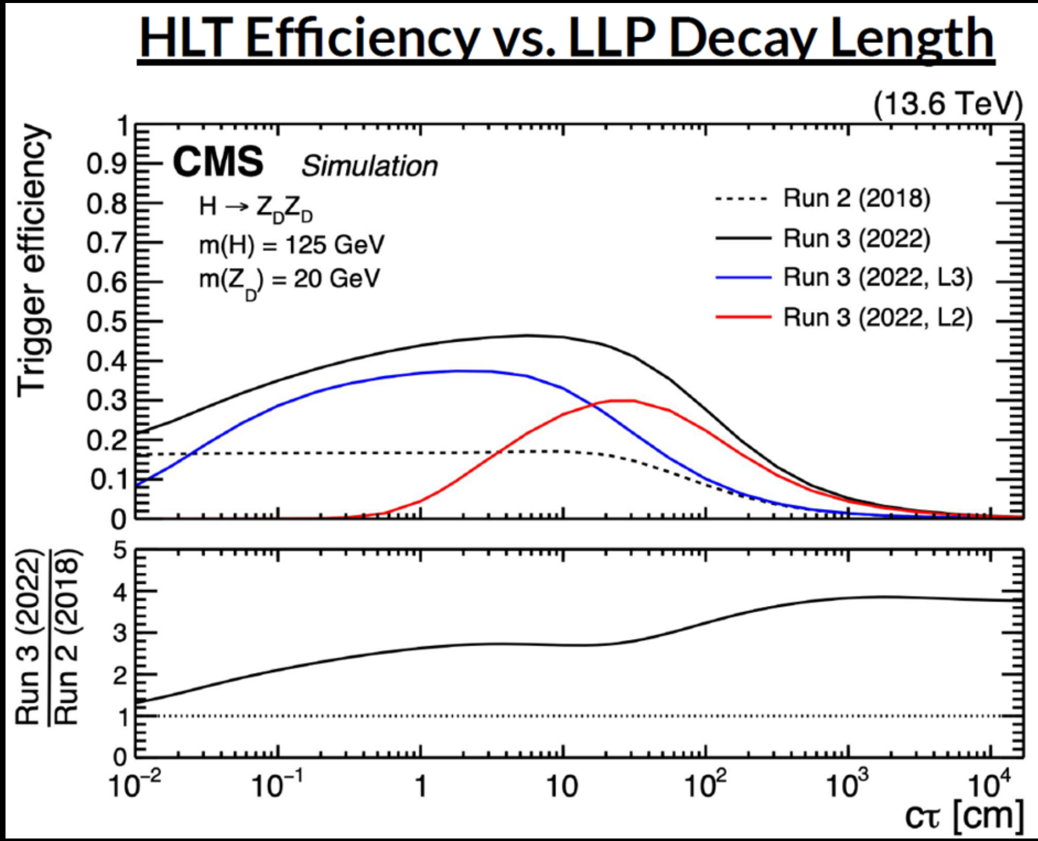
Other jet time definitions spread out driven by soft/colinear behaviors, further imprinted by geometrical effects.

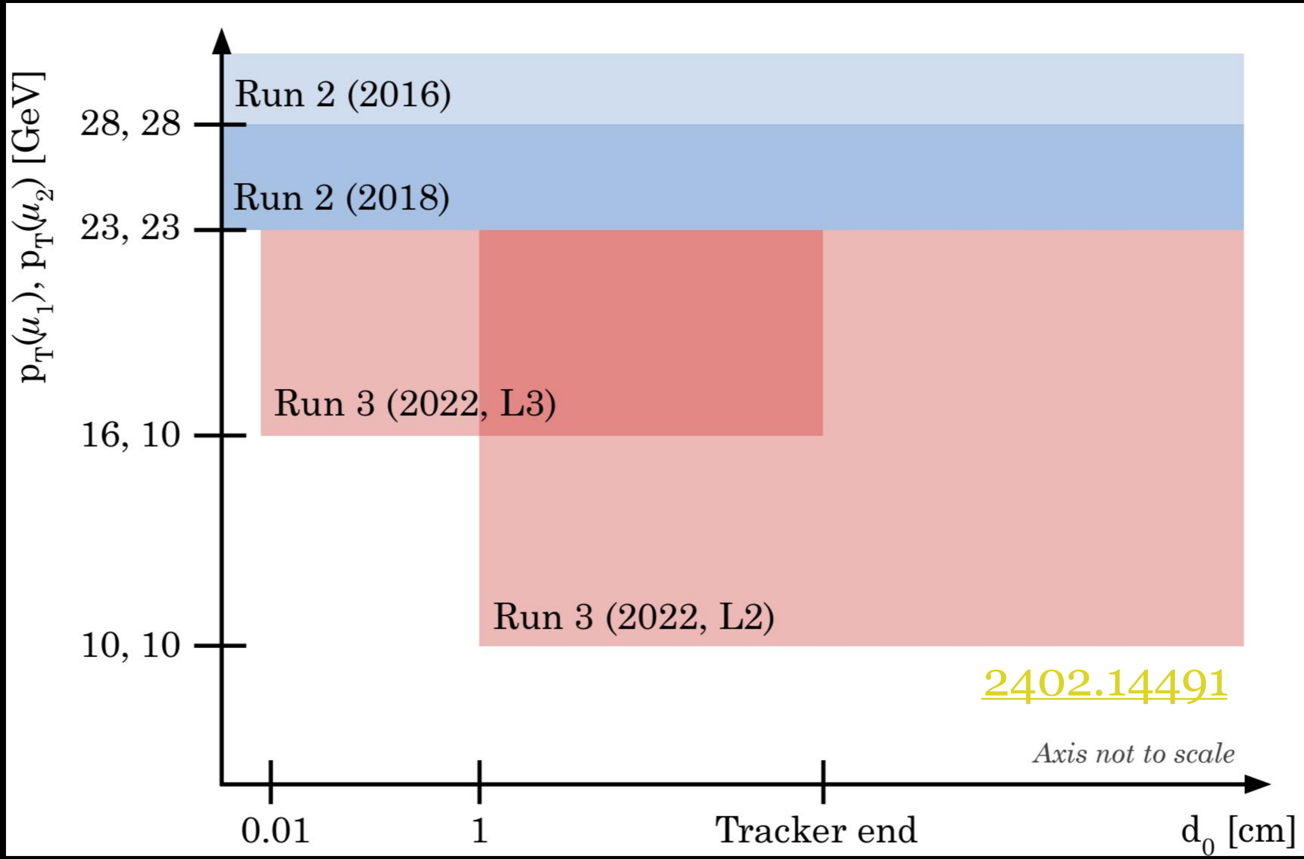
$$t_J^{(\alpha,\beta,\gamma)} \propto \sum_{i\in\mathrm{jet}} (p_{T,i})^{\alpha} (\Delta R_i)^{\beta} t_i^{\gamma}$$

Chiu, ZL, Low, Wang, 2109.01682
Chiu, Shen, ZL ongoing study with Machine Learning.

Recent Trigger Improvement: Displaced Dimuon

Run3 improved trigger: trigger efficiency increased by a factor of 2-4



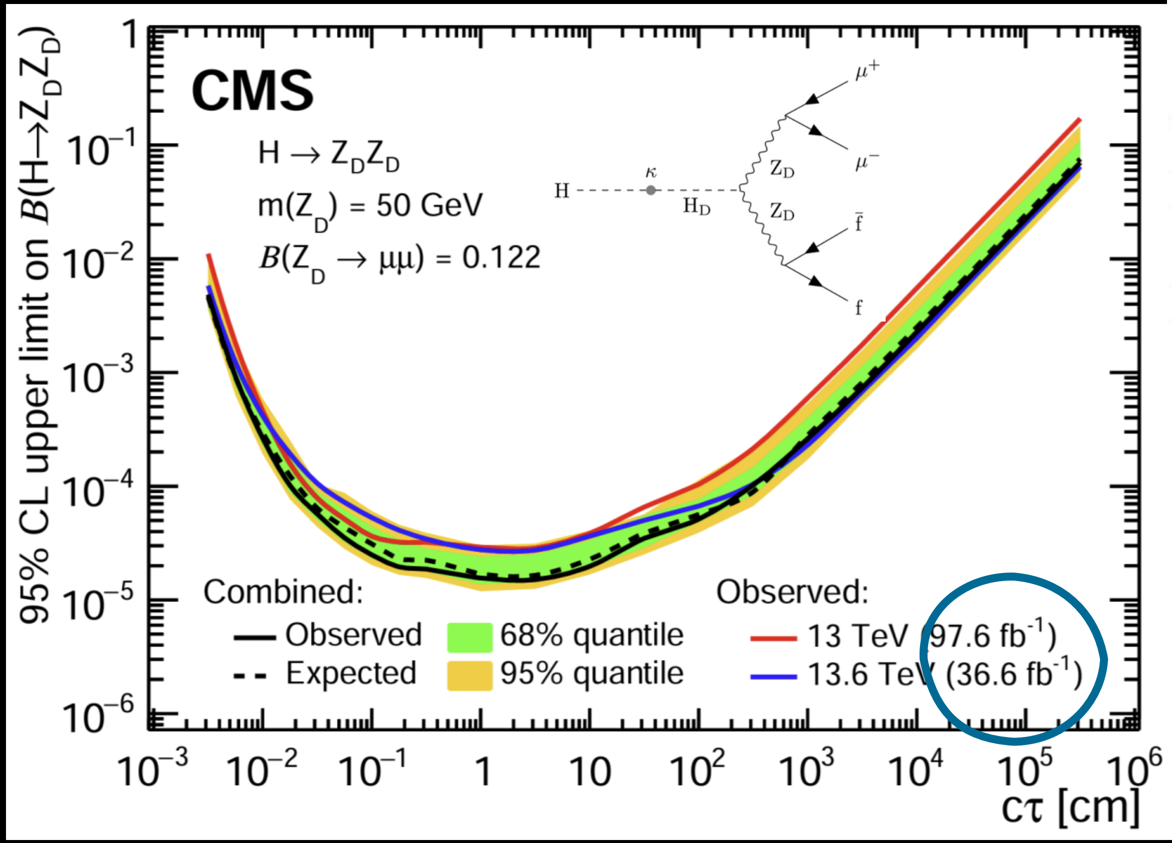


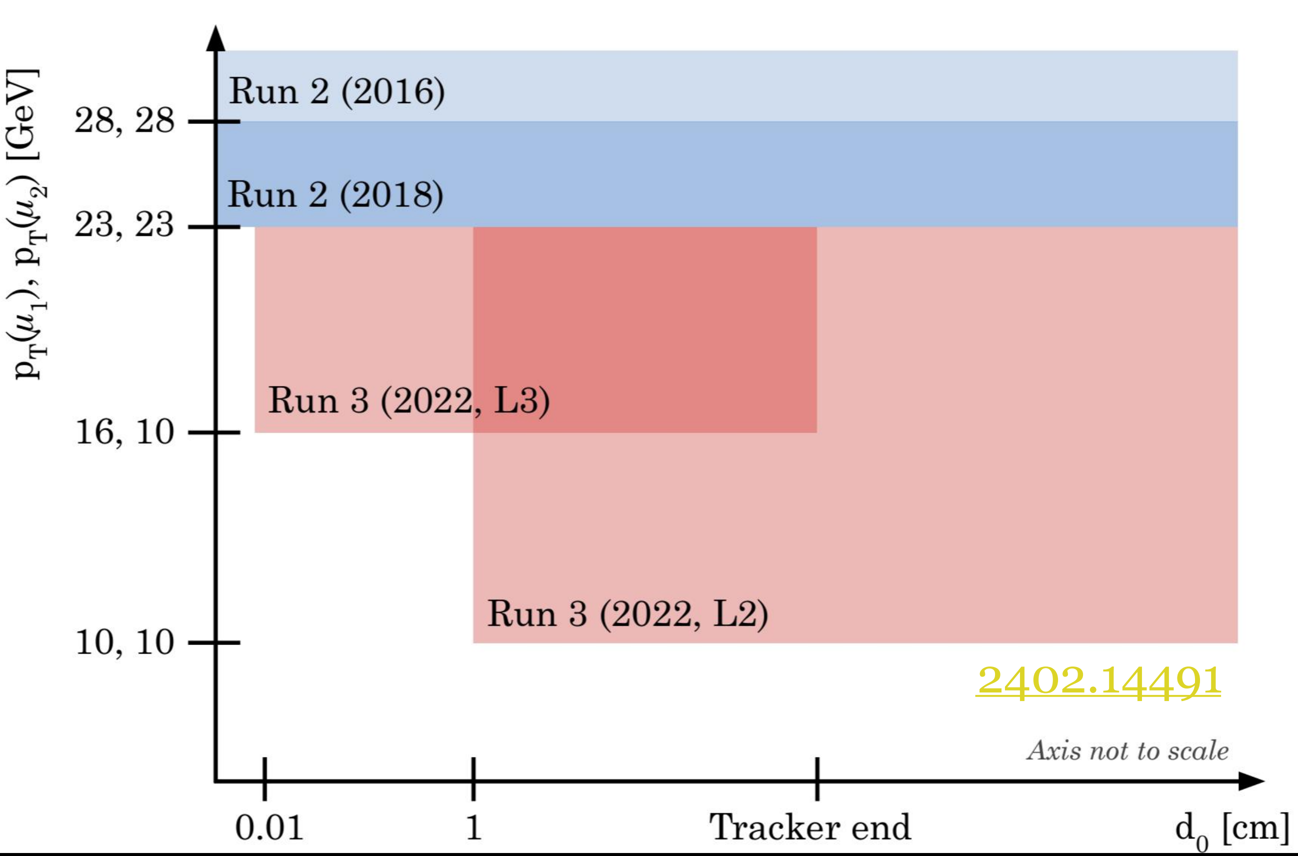
L2: Muon system only, newly added long-lived trigger

L3: Muon system plus tracking, newly added longlived trigger

Recent Trigger Improvement: Displaced Dimuon

Run3 improved trigger: trigger efficiency increased by a factor of 2-4



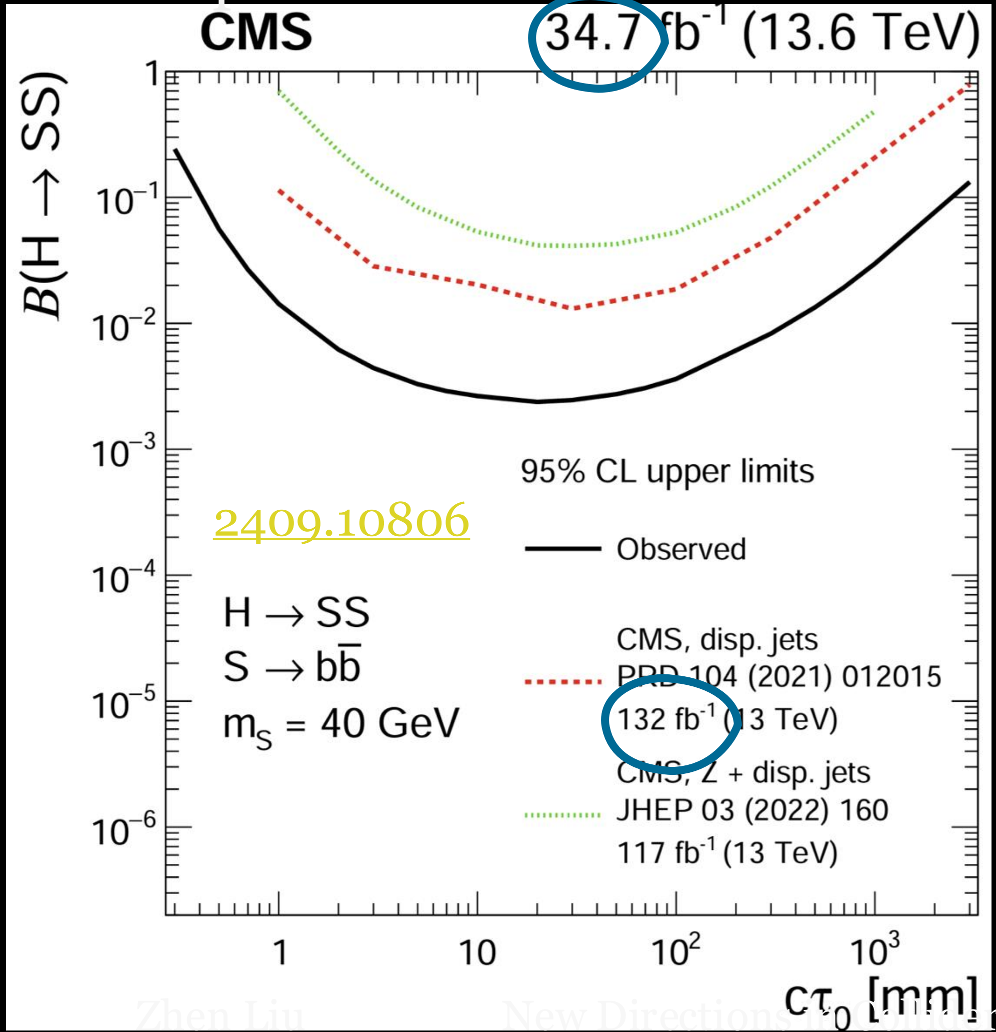


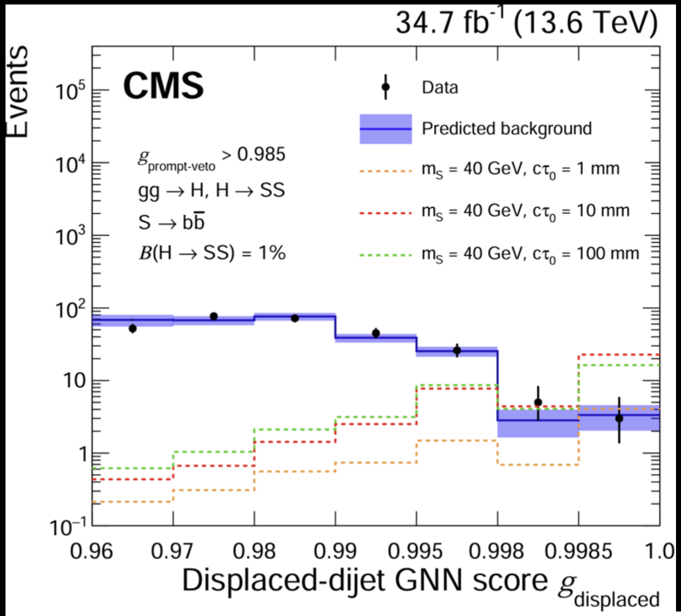
2402.14491

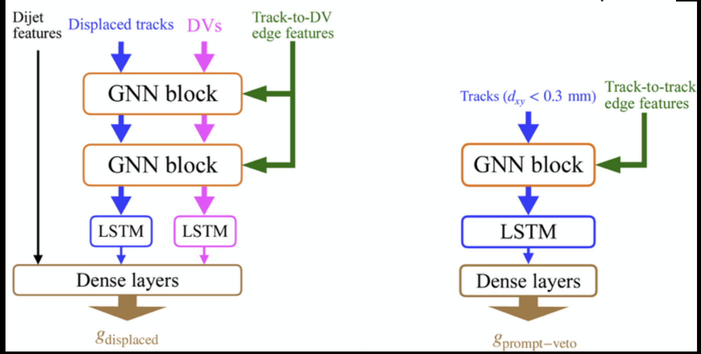
Better sensitivity with 1/3 the luminosity due to the improved trigger.

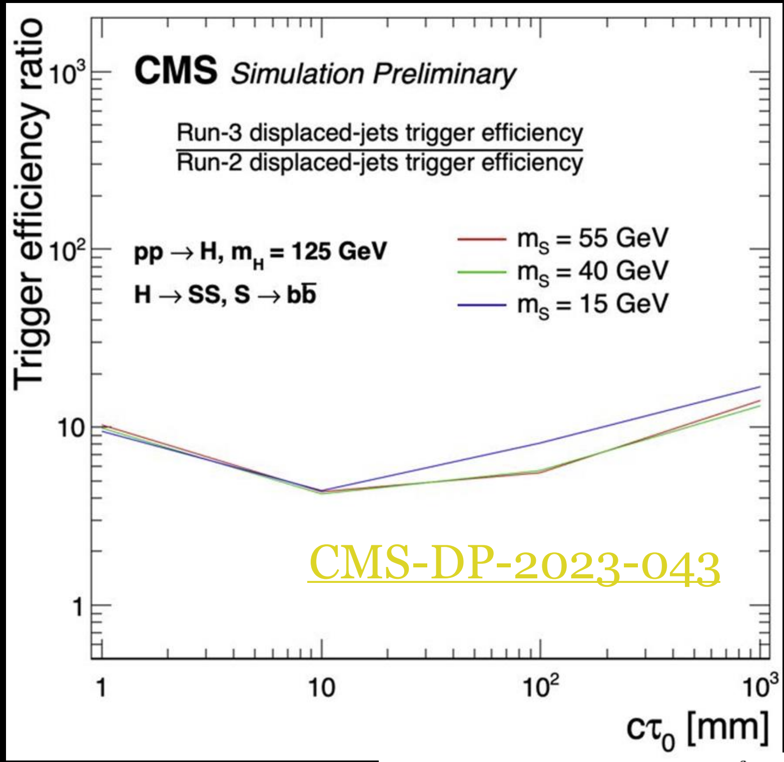
Recent Trigger Improvement: Displaced jets in tracker

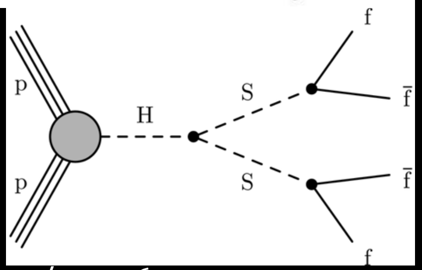
Run3 improved trigger: trigger efficiency by around 10, then with analysis improvement









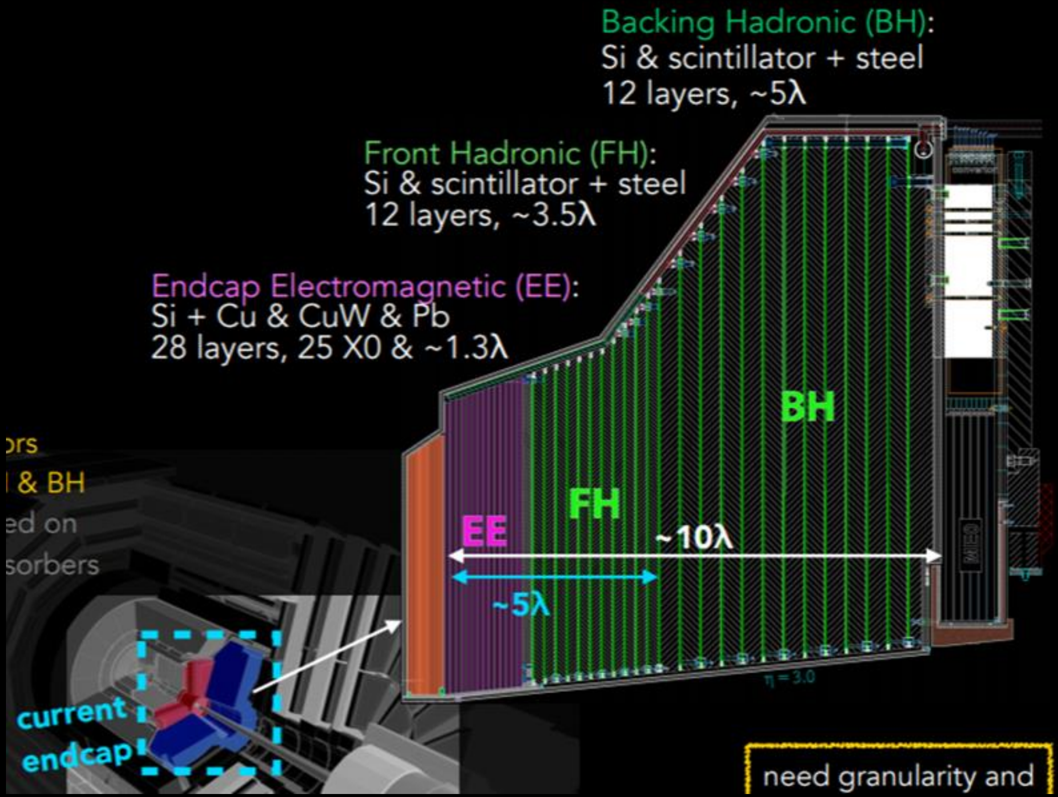


Realize the true power of LHC

Displaced tracks trigger, Timing in trigger

LLP searches in all subsystems, e.g.,

- muon spectrometer
- HGCal, HGTD, Mip Timing Detector



Look for LLPs in HGCAL, Liu, ZL, Wang, Wang, 2005.10836; Displaced Trigger, Gershtein 1705.04321, Gerstein, Kanpen, 1907.00007, Gerstein, Knapen, Redigolo 2012.07864 ; Linthorne, Stolarski, 2103.08620; Guo, He, Liu, Wang, 2111.01164; Chekanov et al., 2203.07286 +…

Realize the true power of LHC

Displaced tracks trigger, Timing in trigger
LLP searches in all subsystems, e.g.,

- muon spectrometer
- HGCal, HGTD, Mip Timing Detector

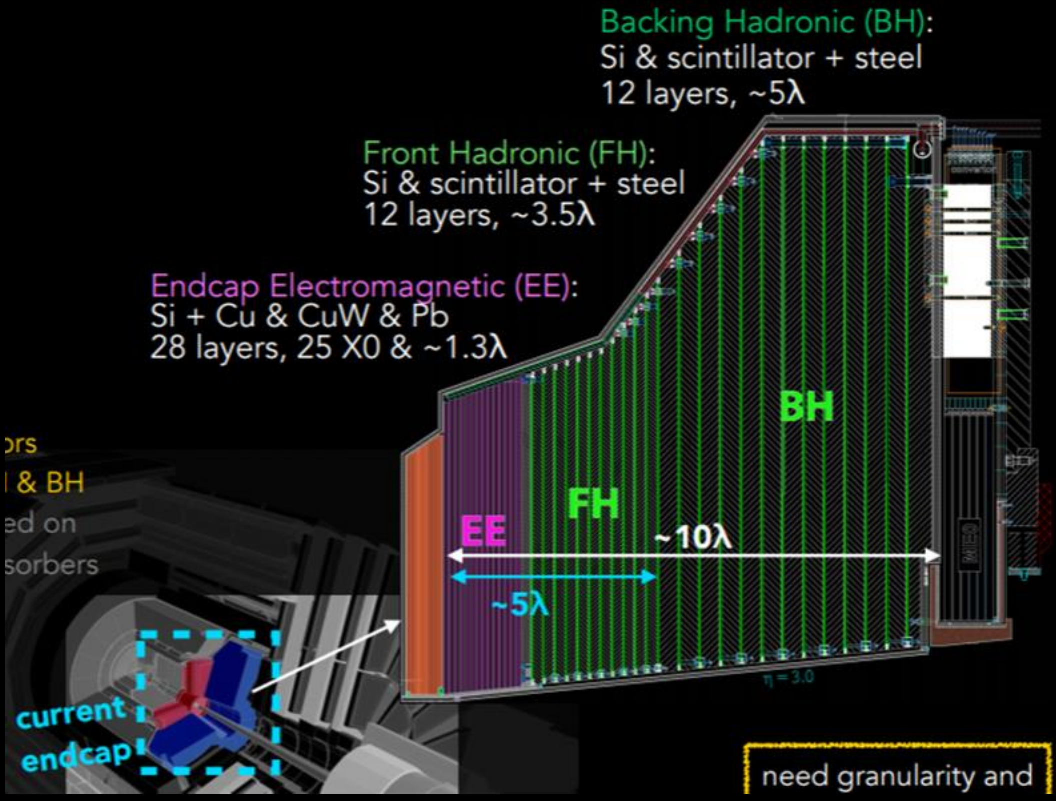
Expanding LHC program

MATHUSLA, Codex-B, AL3X, ANUBIS — Central/Hard LLPs

FASER, FPF, (SND), SHiP, NA62, SeaQuest, … — Forward/light LLPs; Beamdump experiments

MoEDAL, MilliQan — monopole, millicharged particles

→ Search for LLPs



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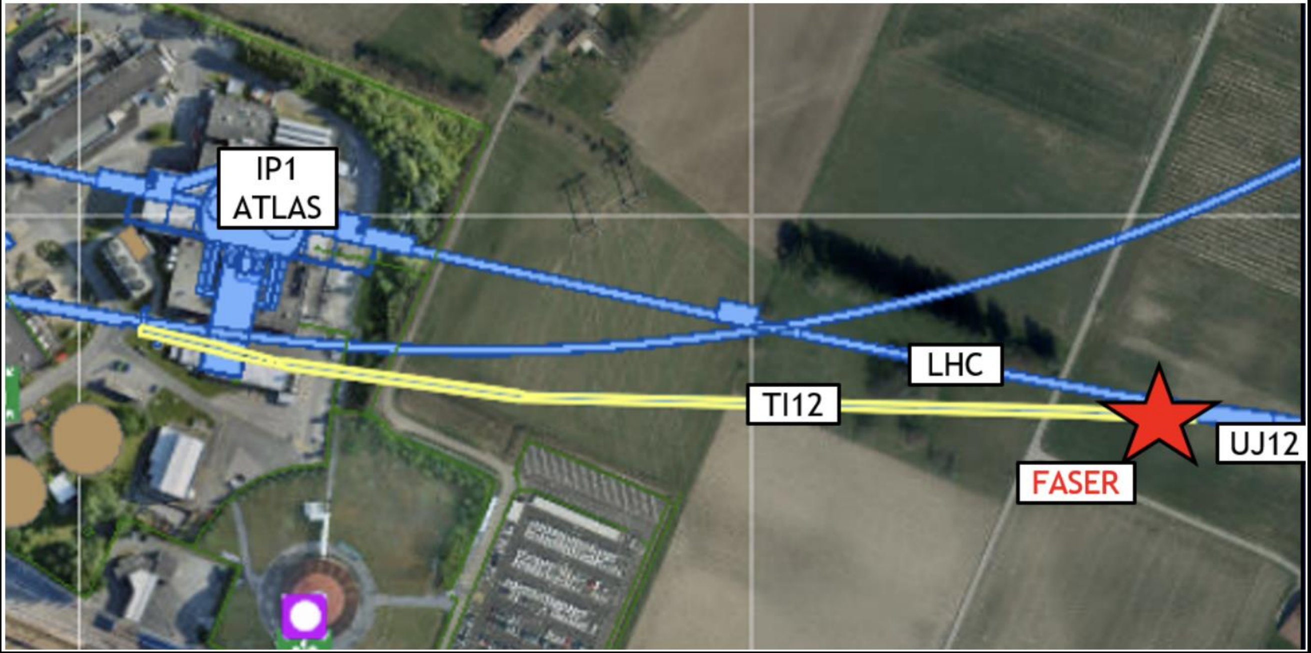
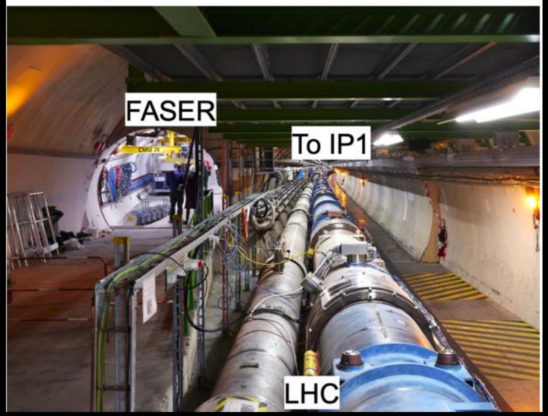
Forward Physics

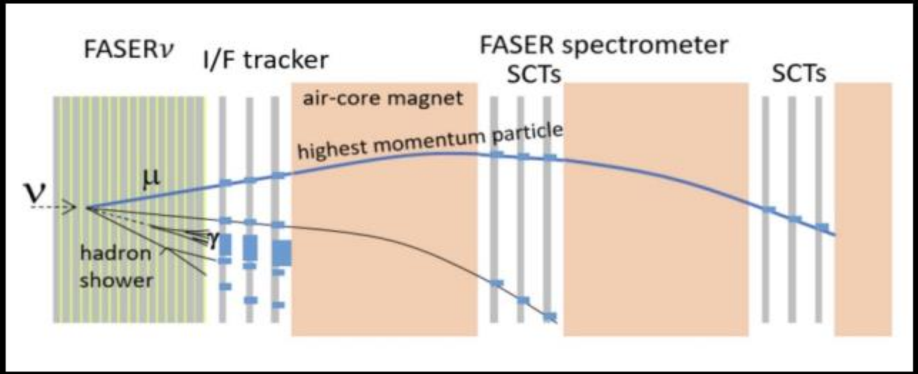
Forward Physics



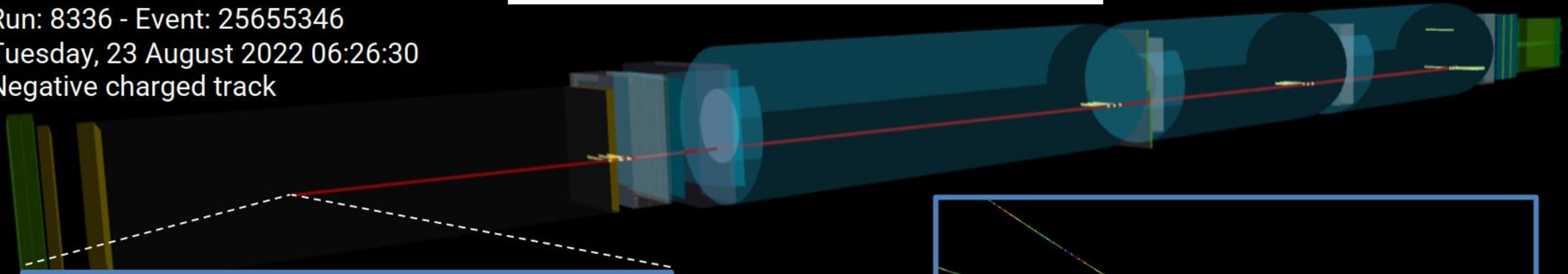


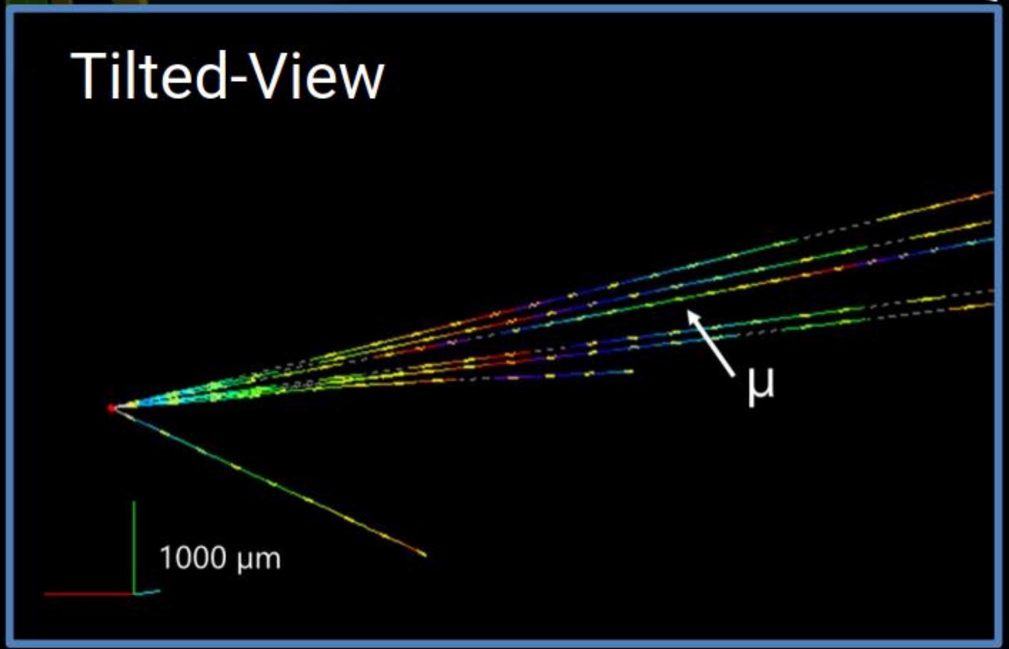
From FASER talk at Moriond26 by Hu & Queitsch-Maitland

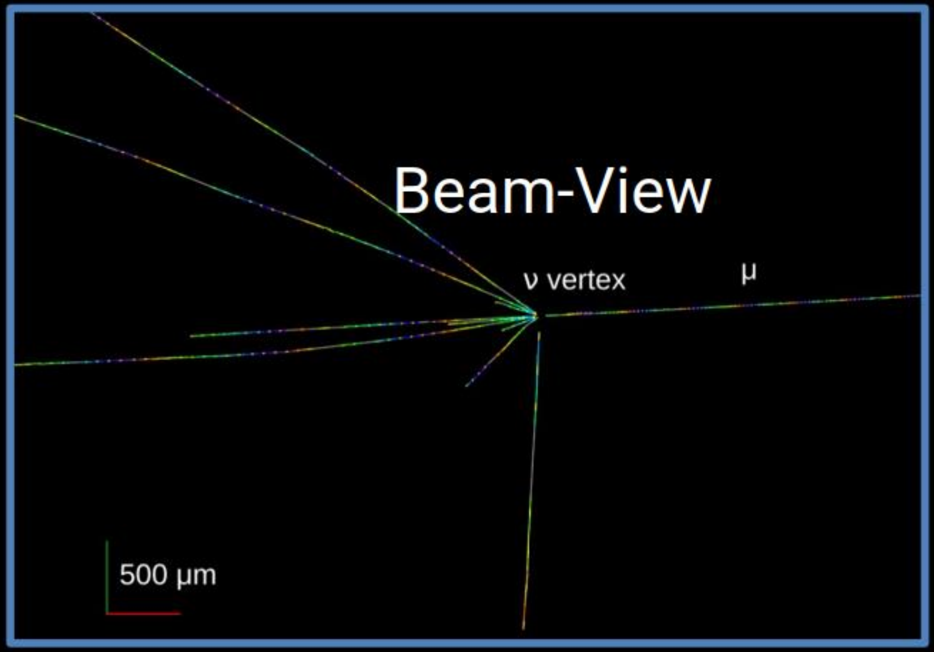
FASER Preliminary



Run: 8336 - Event: 25655346
Tuesday, 23 August 2022 06:26:30
Negative charged track

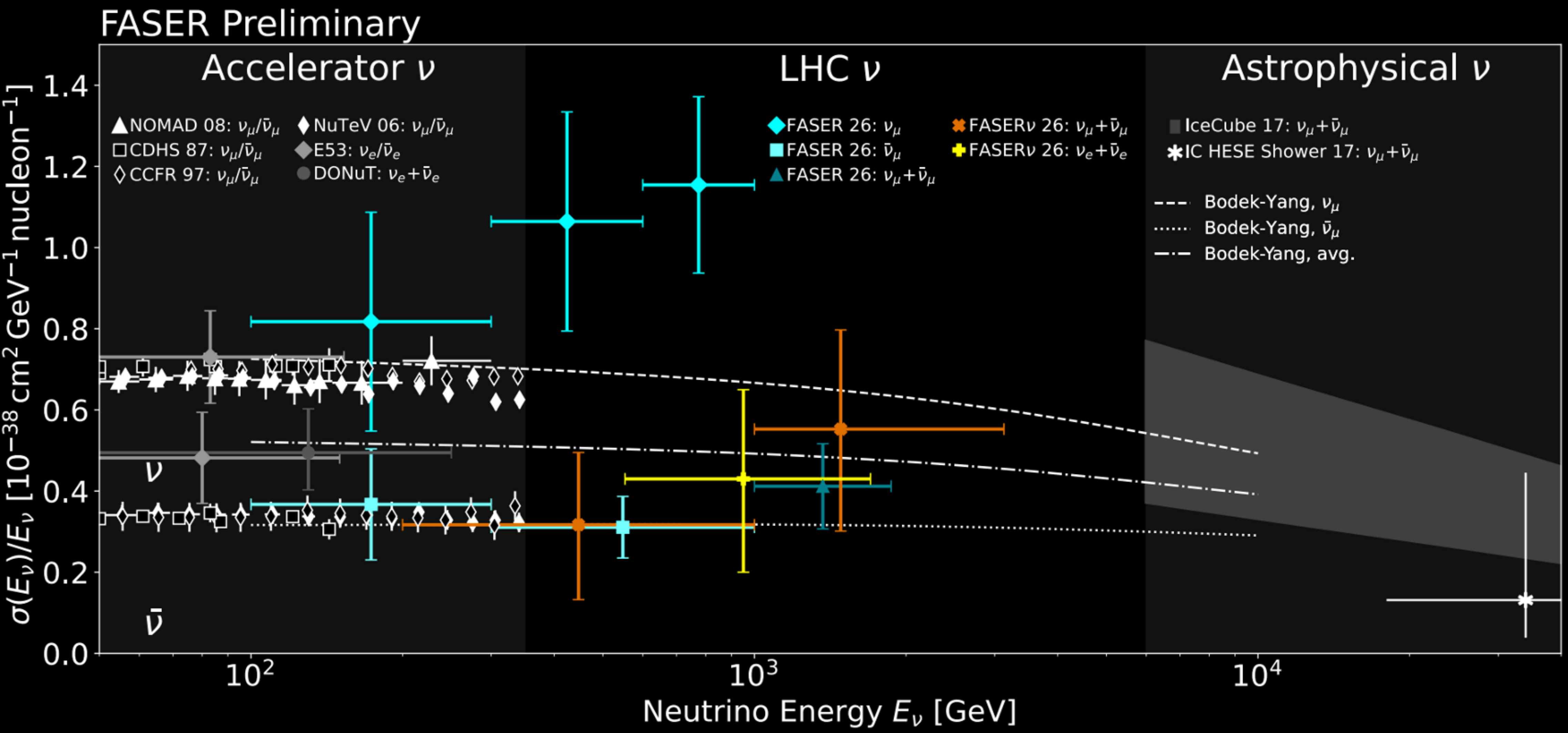




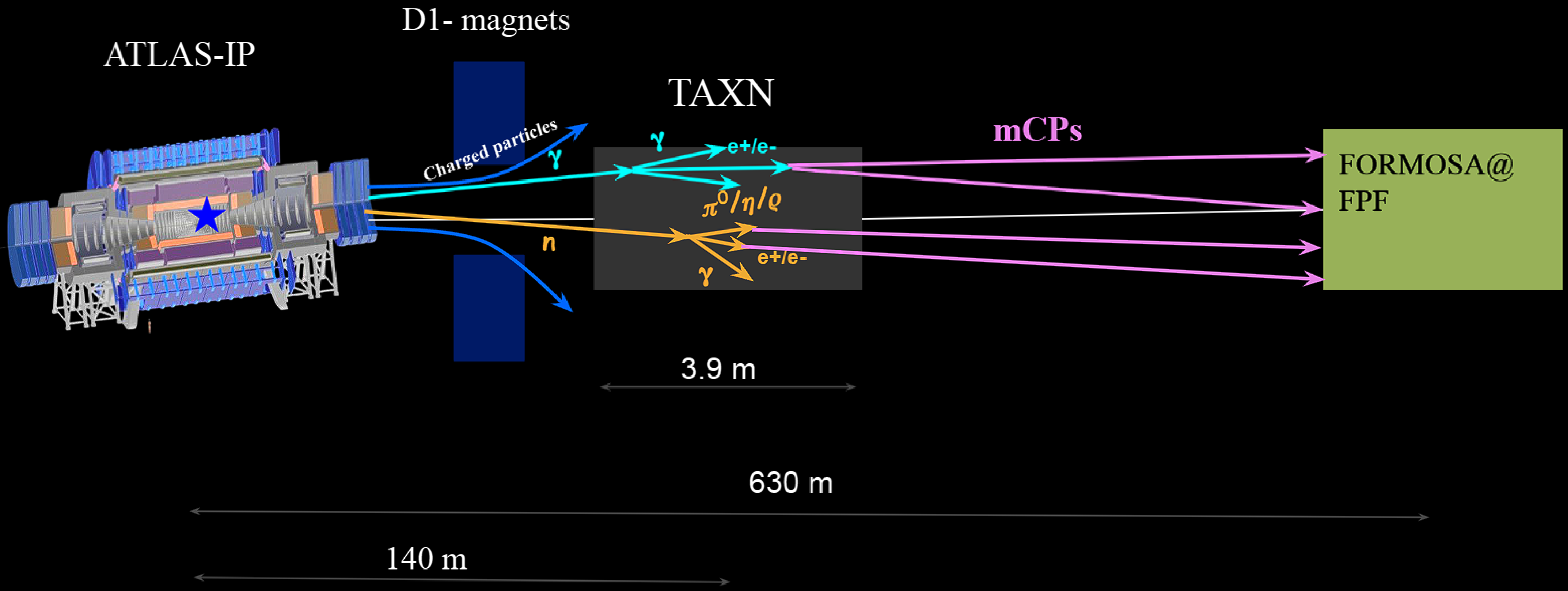


 https://faser-public-plots.app.cern.ch

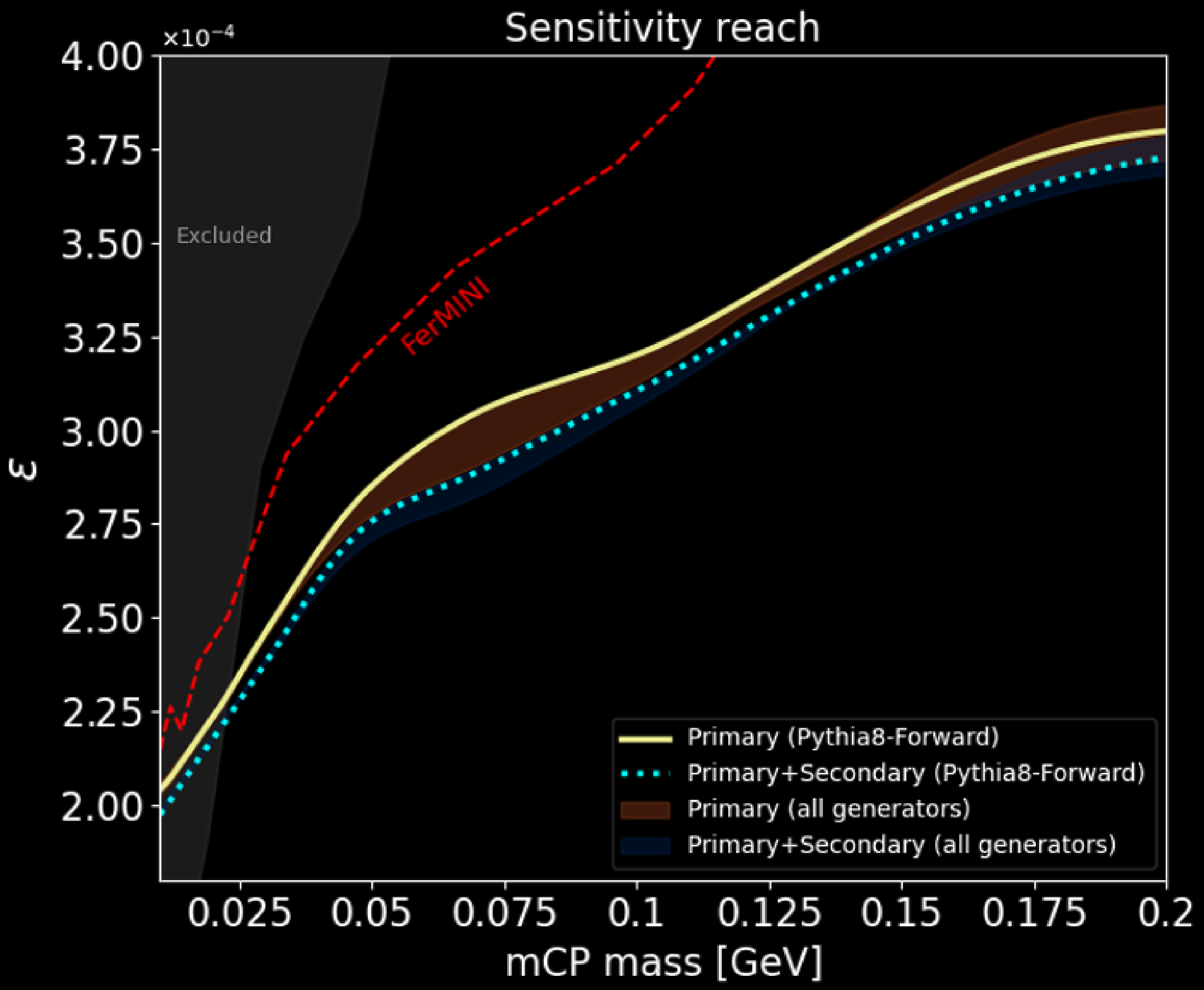
2026 FASER results

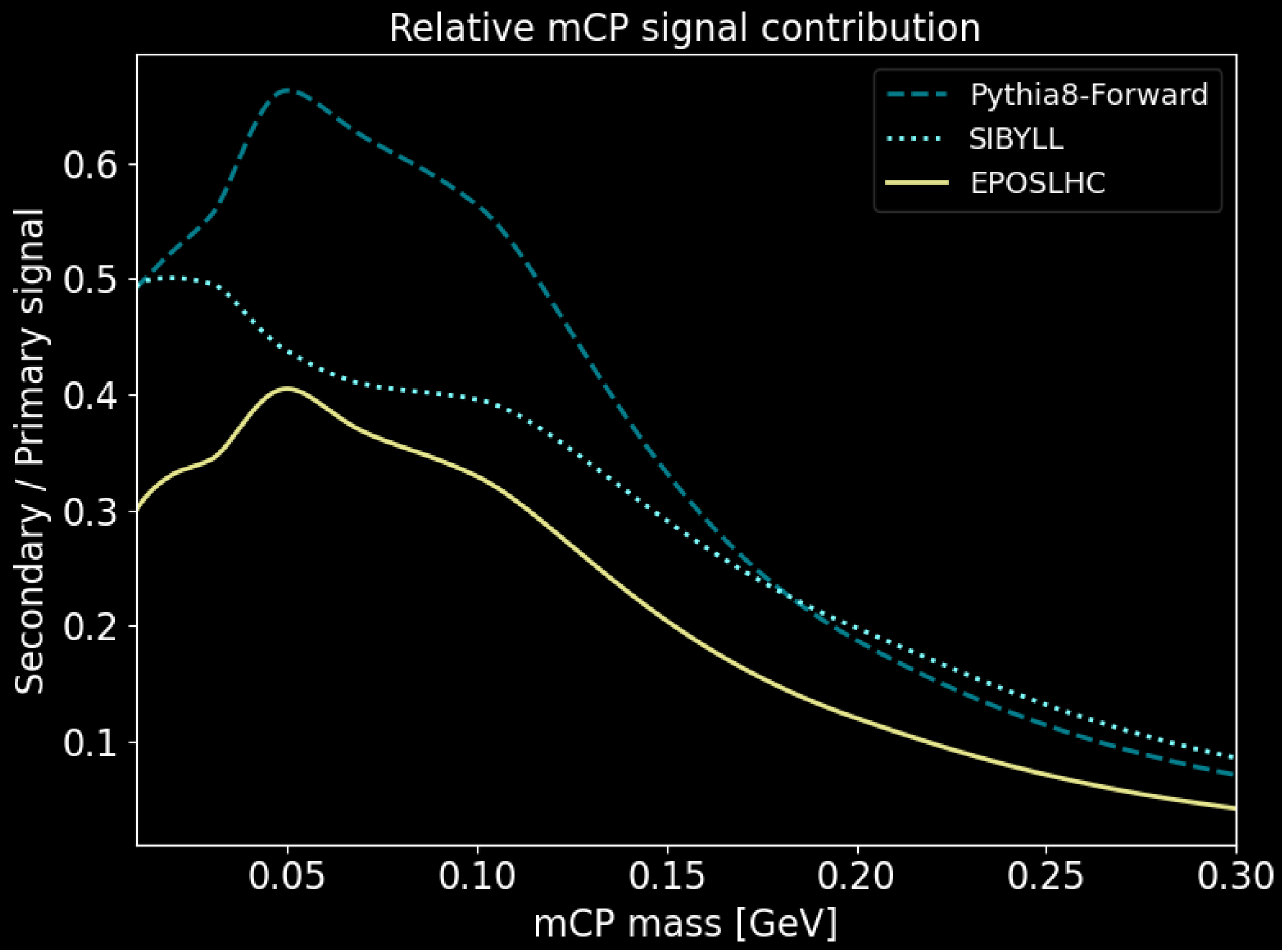


One can also look for dark sector particles such as millicharged particles



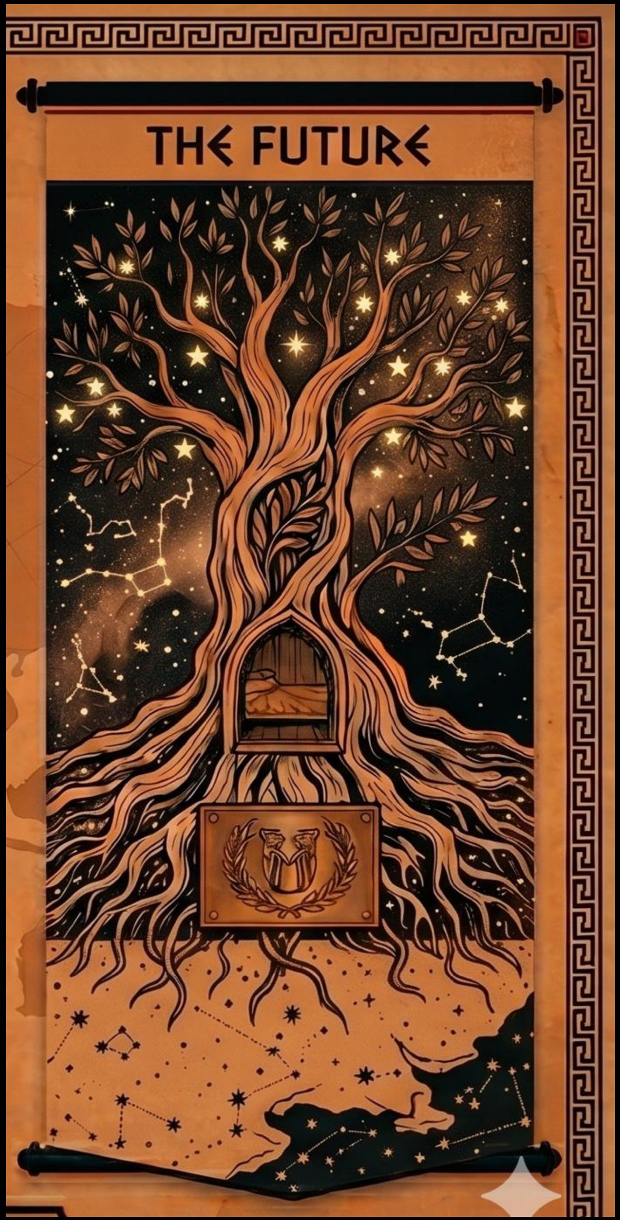
Showers Can Boost mCP Signals by 40–60%



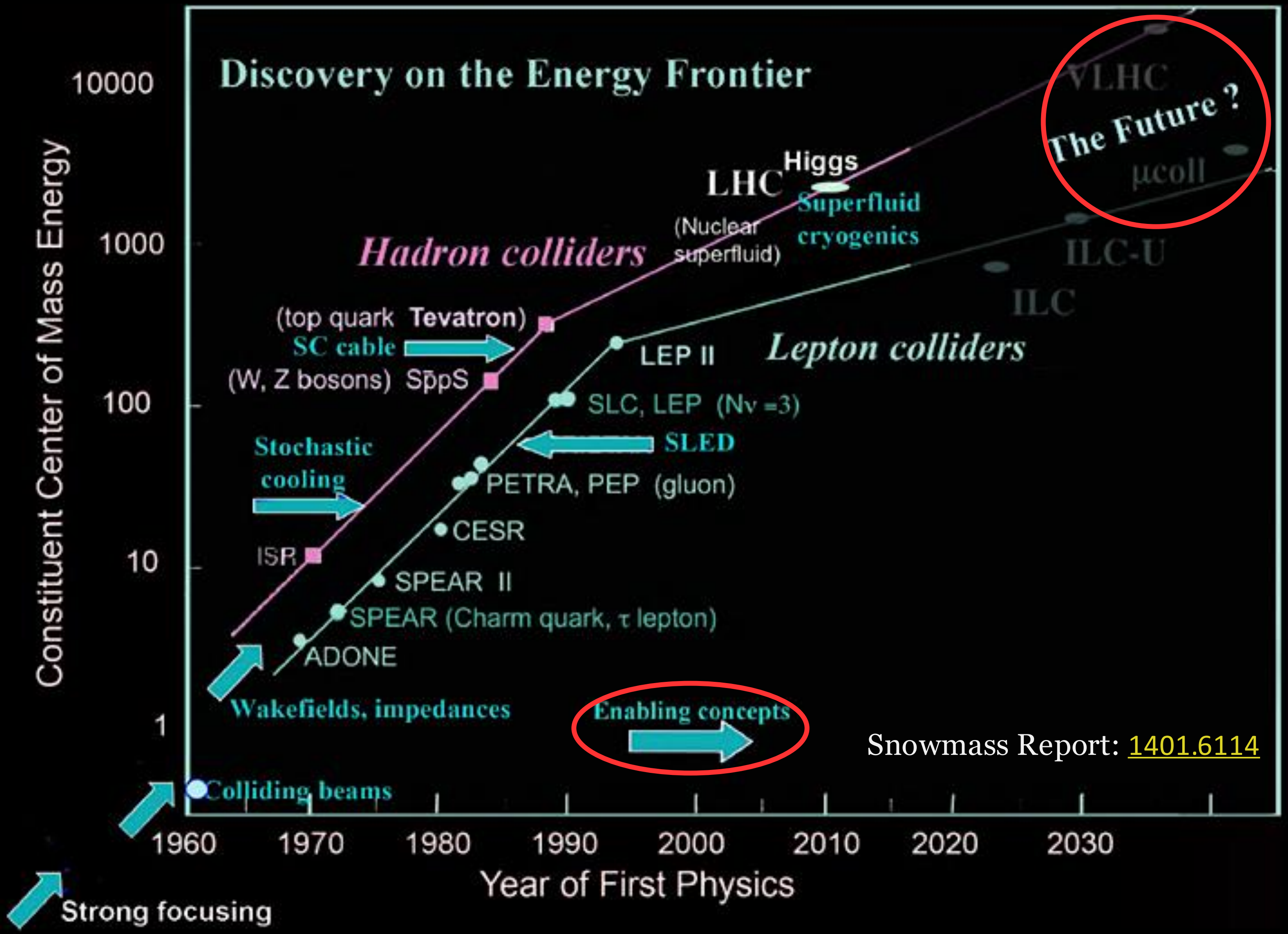


J. Adhikary, P.R. Li, ZL, S. Trojanowski, A. Zabihi, to appear

Future



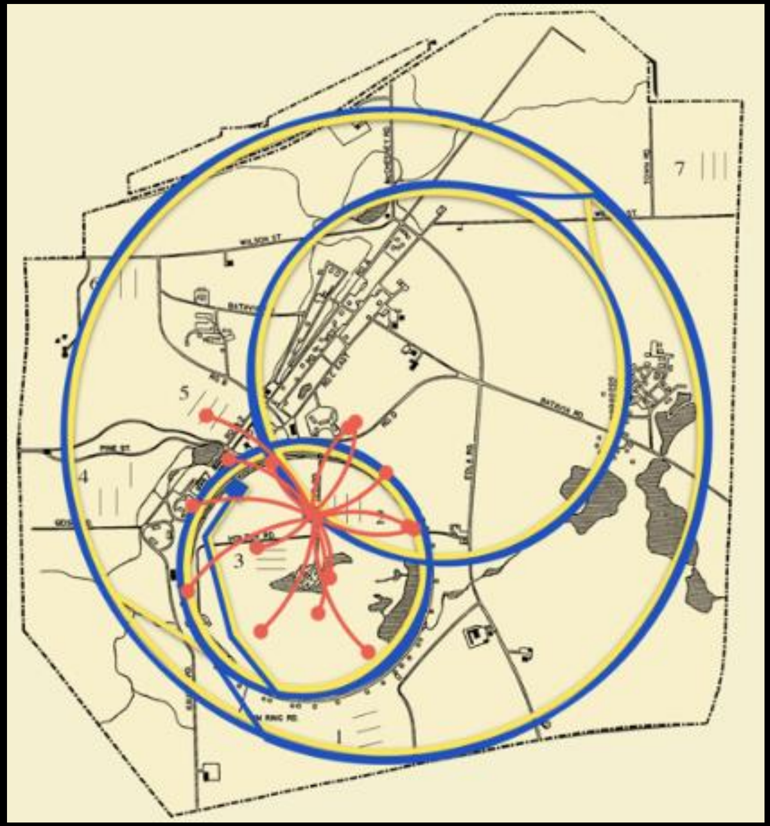
High Energy & Precision Drives



Snowmass Report: [1401.6114](1401.6114)

The forefront of tech & ambitions leads to discoveries.

A clear and persistent desire for high energy machines.

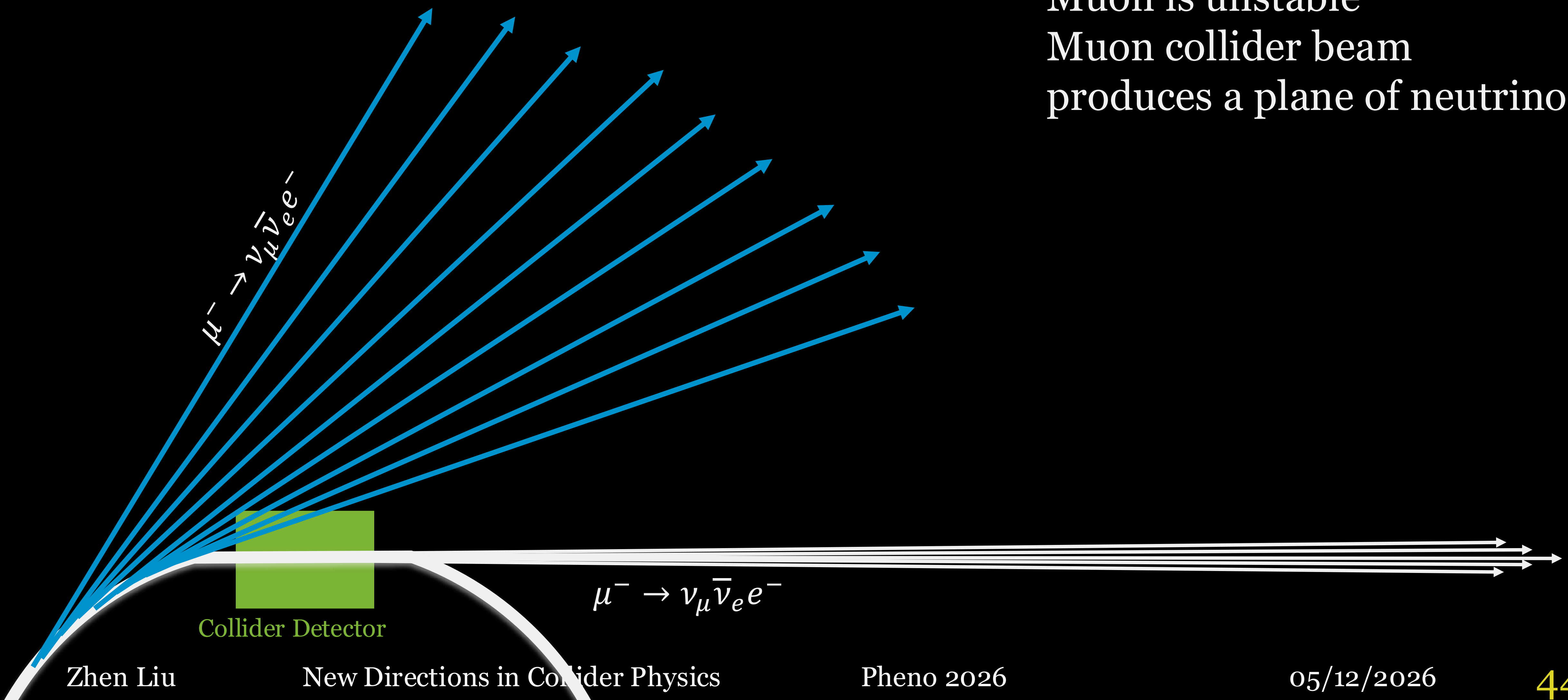


GIF from US muon collider meeting: https://indico.fnal.gov/event/64493/

Muon Beam Induced Neutrinos

More on future colliders & vision M. Carena's talk tomorrow, S. Demers's talk earlier.

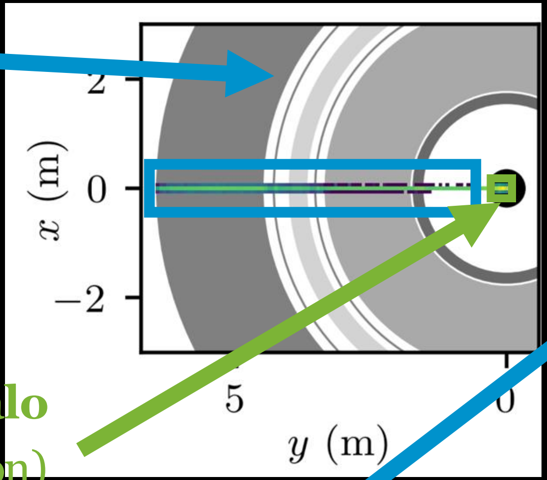
Muon is unstable
Muon collider beam
produces a plane of neutrinos

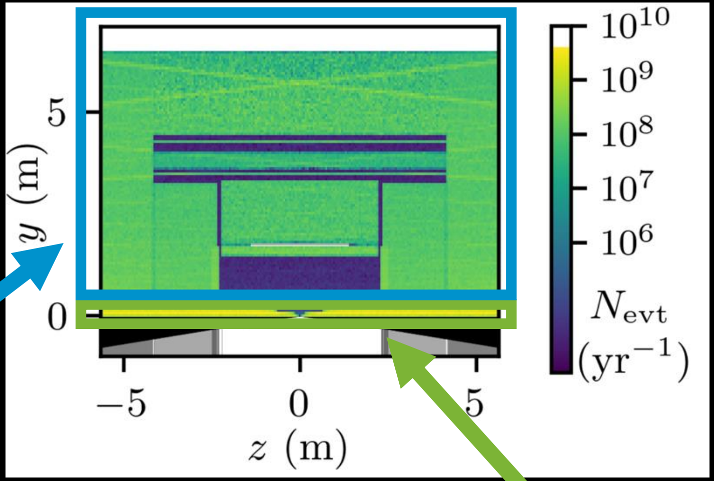


L. Bojorquez-Lopez, M. Hostert, C. Argüelles, ZL 2412.14115

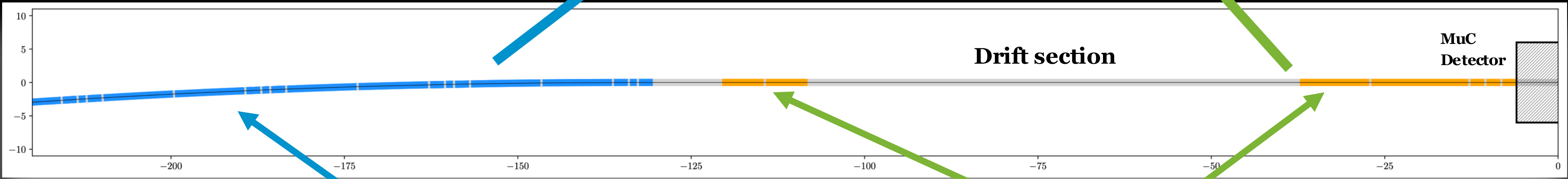
Beam-induced Neutrinos (BINs)

Neutrino Slice
(mostly from main ring)





Neutrino Halo
(mostly from straight section)
Vast majority goes down the pipe



Bending magnets

Focusing magnets

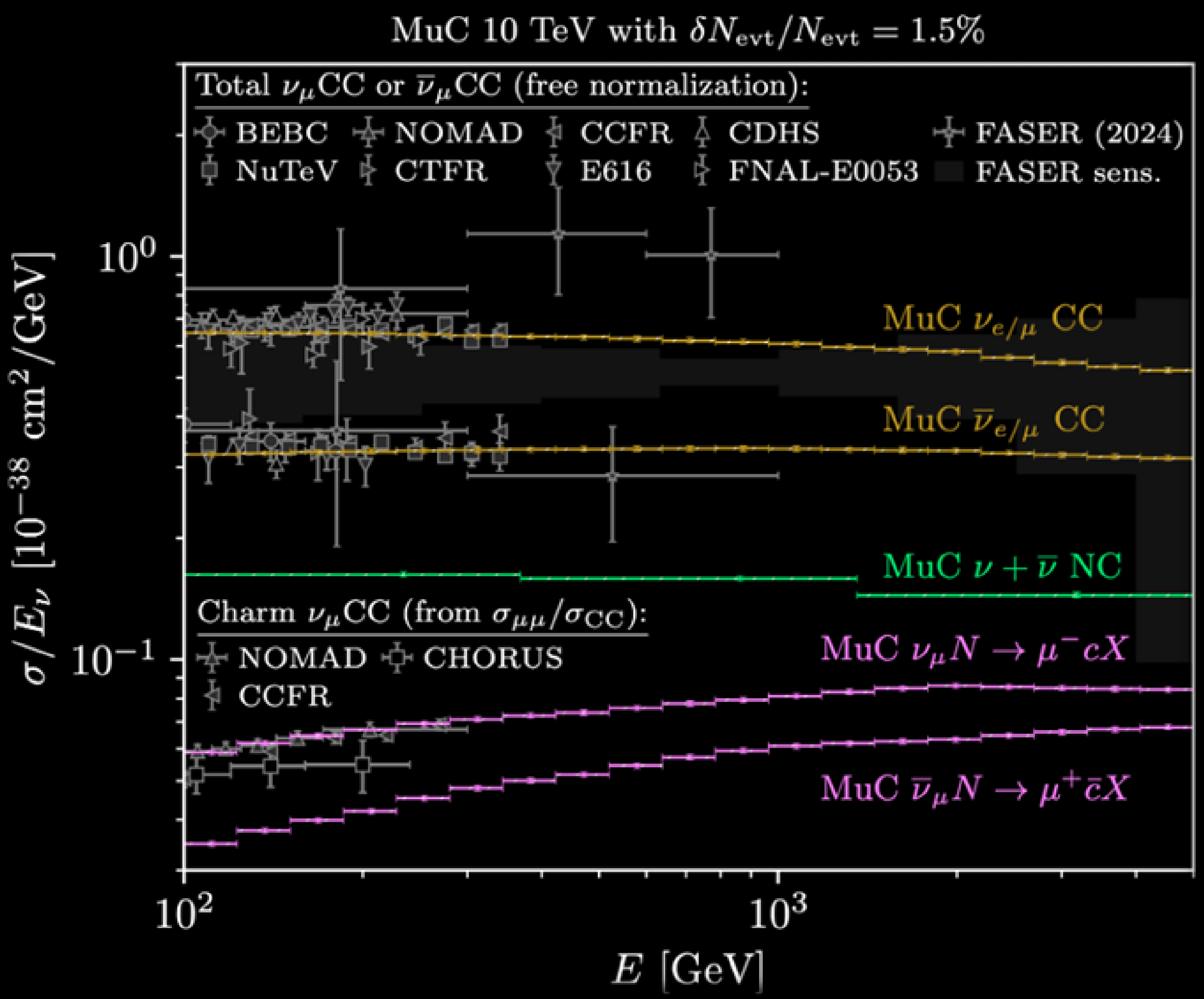
See M. Hostert's talk tomorrow

Beam-induced Neutrinos (BINs)

This is what a 1.5% **uncertainty on TeV neutrino cross sections would look like:**

Clearly, more work is required to understand if it is feasible at the neutrino slice. (Ogoing collaboration with T. Holmes, L. Lee et al)

Many other physics, such as beam polarization monitoring, Weinberg angle from the neutrino sector, rare neutrino-nucleus process, neutrino effective interactions, etc.

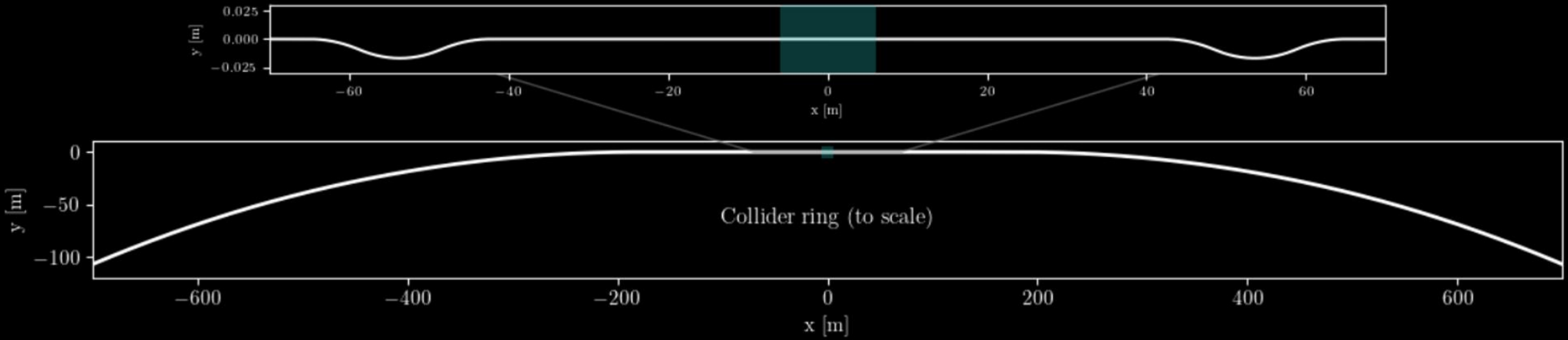


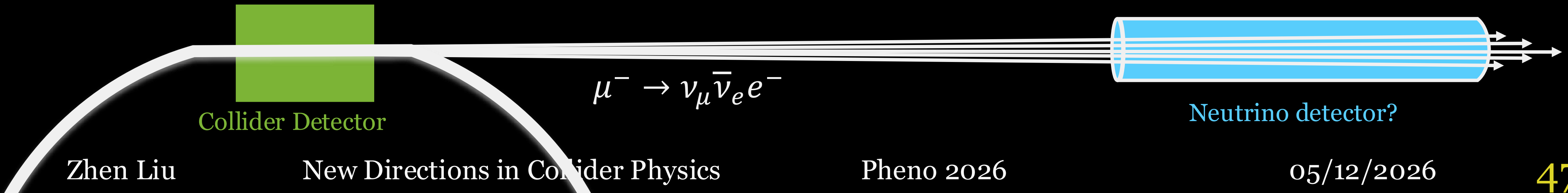
Adhikary, Kelly, Kling, Trojanowski, 2412.10315
Kling, Ma, Mękała, Reuter, Tabrizi, 2508.00761

Forward Detection of BINs

Ongoing study with J. Choi, M. Hostert, and P.R. Li
Muon Inducted Neutrino Tool (MINT)

Straight section neutrino flux is extremely collimated. No need for a big detector — event rate is enormous.





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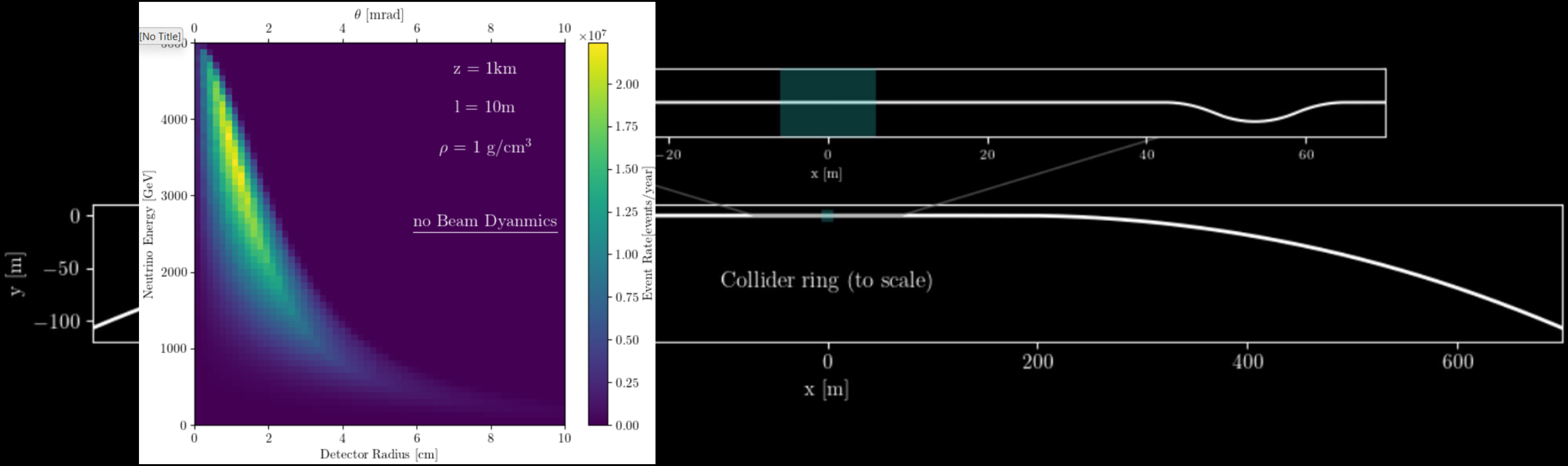

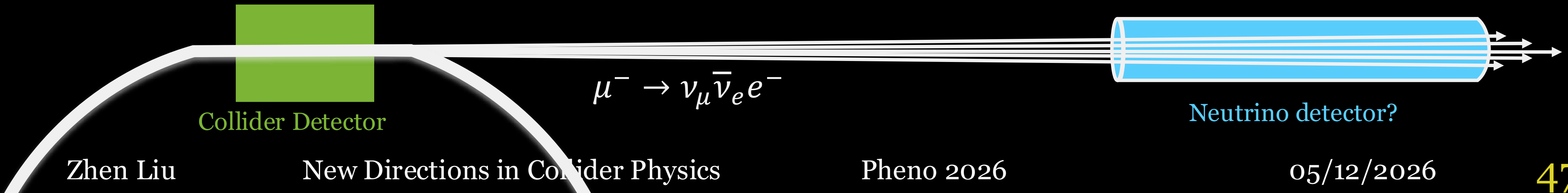

$\mu^- \to \nu_\mu \bar{\nu}_e e^-$

Adhikary, Kelly, Kling, Trojanowski, 2412.10315
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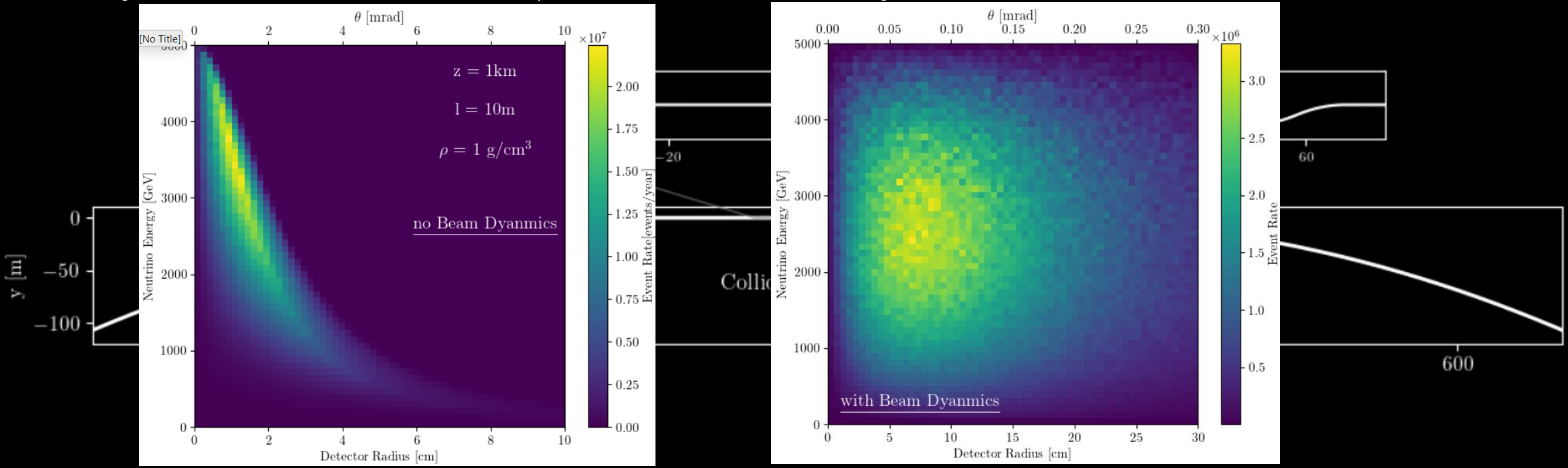
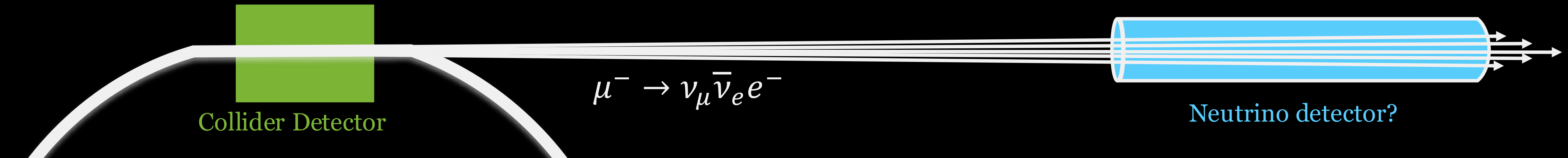
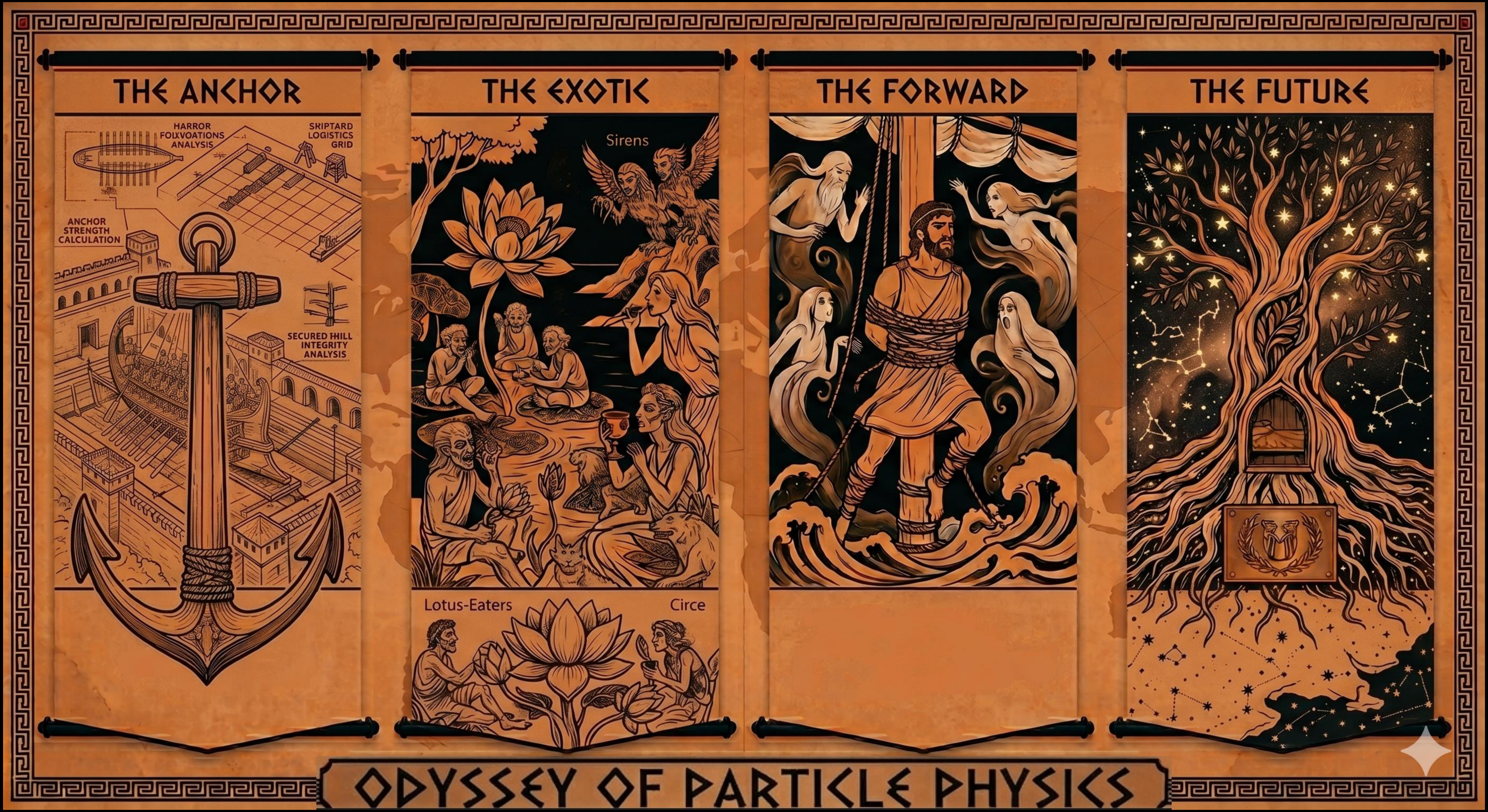
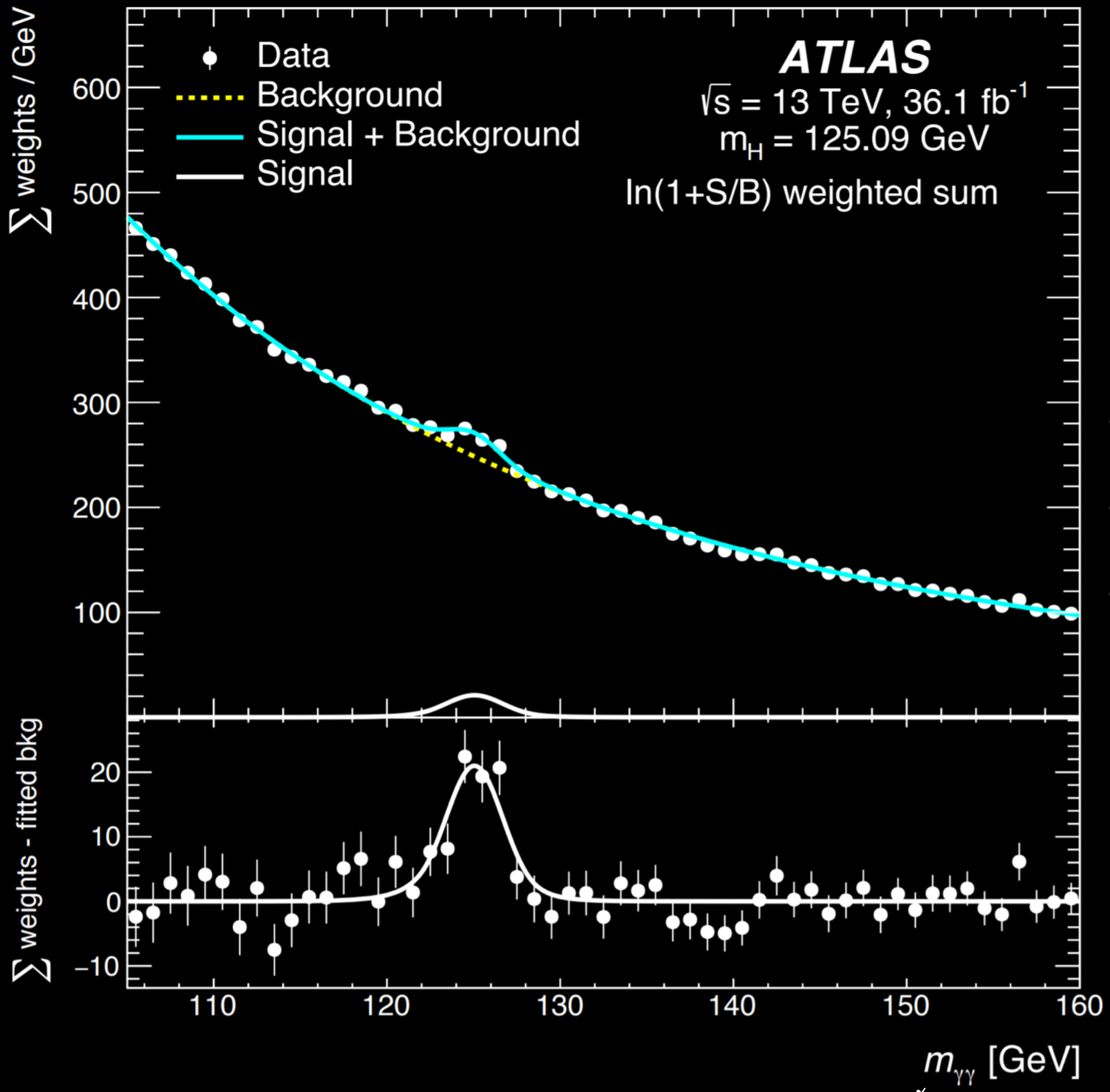


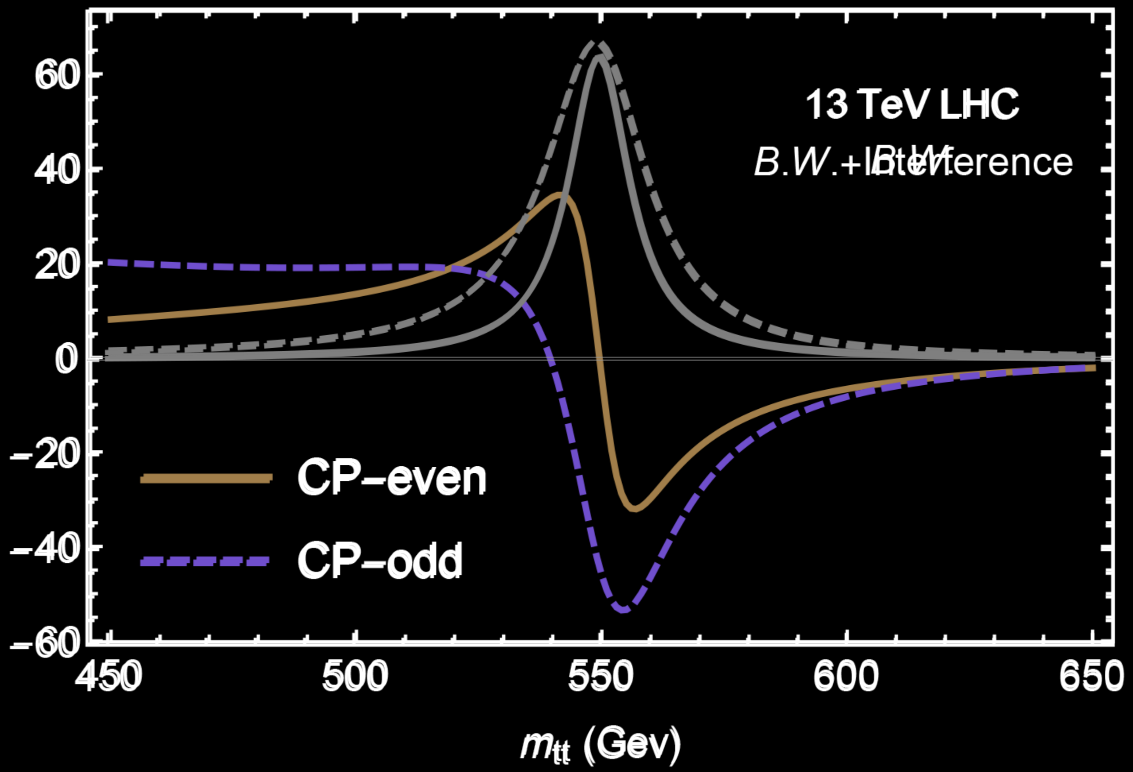


$\mu^- \to \nu_\mu \bar{\nu}_e e^-$


THE ANCHOR
HARROR FOLXVOATIONS ANALYSIS
SRIPTARD LOGISTICS GRID
ANCHOR STRENGTH CALCULATION
SECURED HILL INTEGRITY ANALYSIS
THE EXOTIC
Sirens
Lotus-Eaters
Circe
THE FORWARD
THE FUTURE
ODYSSEY OF PARTICLE PHYSICS

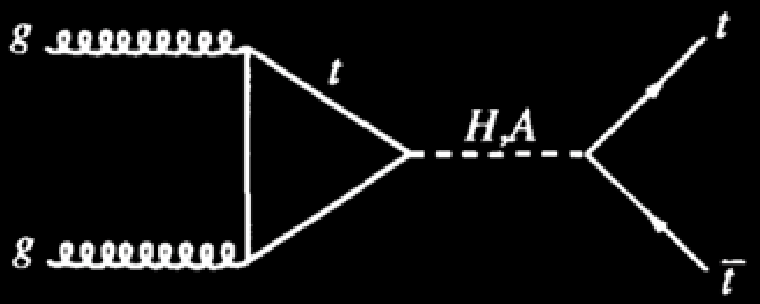
Also Dips

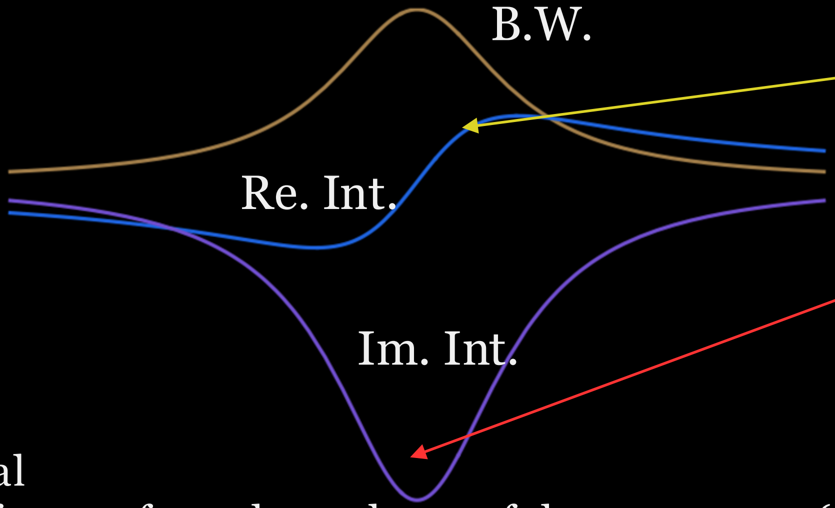


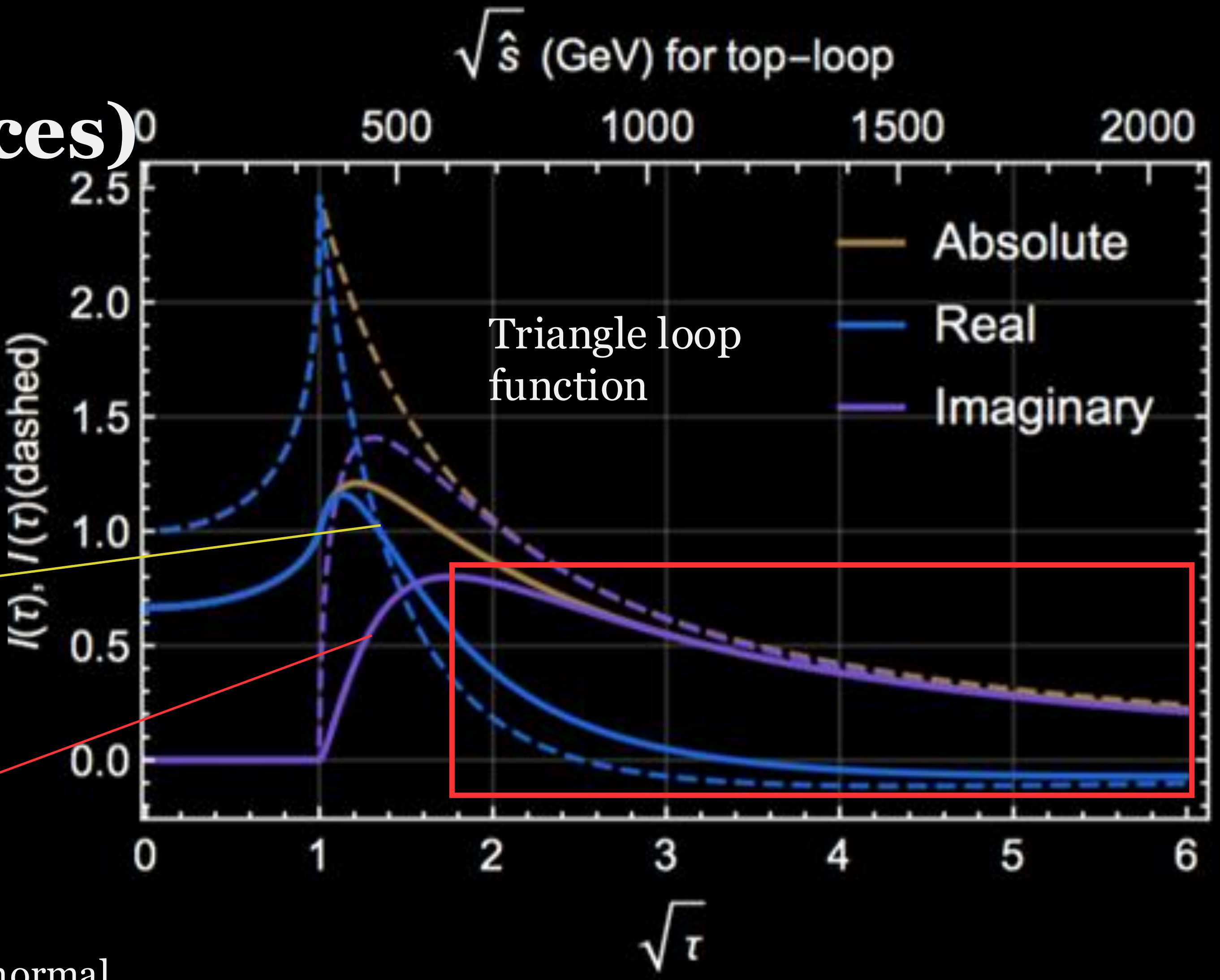


D. Dicus, A. Stange, S. Willenbrock, hep-ph/9404359, Focusing on ttbar @LHC, M. Carena, ZL, arXiv:1608.07282
Other channels and effects, including ttH, tH (see in N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang arXiv:1504.04630 and J. Hajer, Y.-Y. Li, T. Liu J. Shiu arXiv:1504.07617, S. Gori, I.-W. Kim, N. Shah, K. Zurek arXiv:1602.02782 , N. Craig, J. Hajer, Y. Li, T. Liu, H. Zhang, arXiv:1605.08744, B. Hespel, F. Maltoni, E. Vryonidou arXiv:1606.04149, W.S. Hou, M. Kohda, T. Modak 1710.07260, 1906.09703), H+jet, charged Higgs searches. More recently, the ttbar bound state studies' interpretations by ATLAS and CMS.

Challenges (interferences)



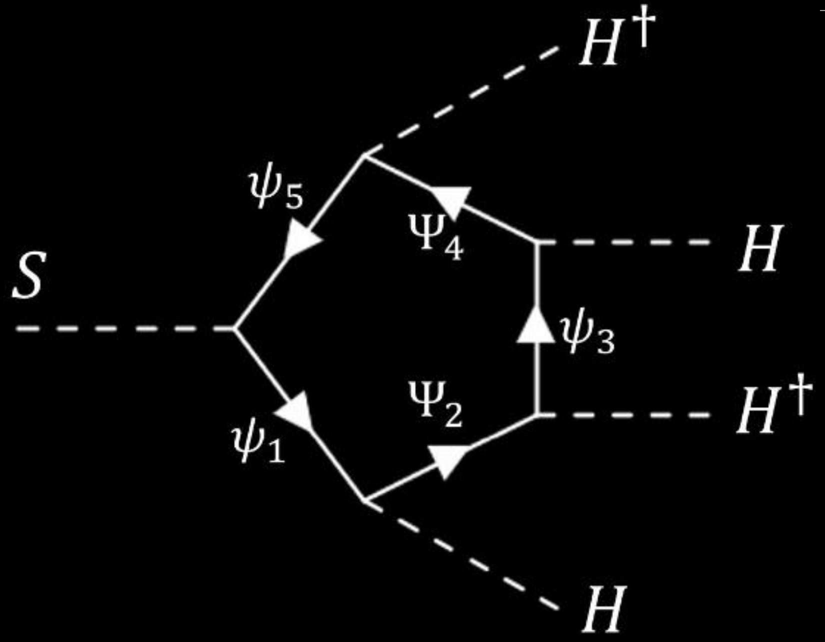


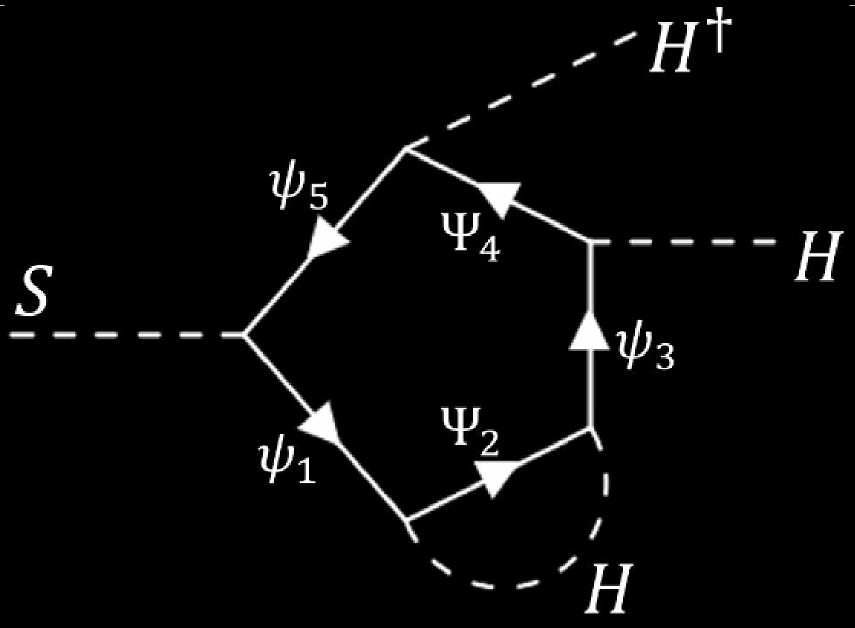


Background real
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

Once across the threshold, imaginary piece arises drastically and the real piece decreases.

A strong phase
``insensitive"* to phase in the Yukawa as the signal amplitudes is proportional to $|y_t|^2$.
*subject to difference in loop functions. Very typical in hadron physics, also used in leptogenesis





$$\mathcal{O}_{\rm EFT} = \frac{|\kappa|^2\mu}{M_\Phi^4} S(H^\dagger H)^2$$

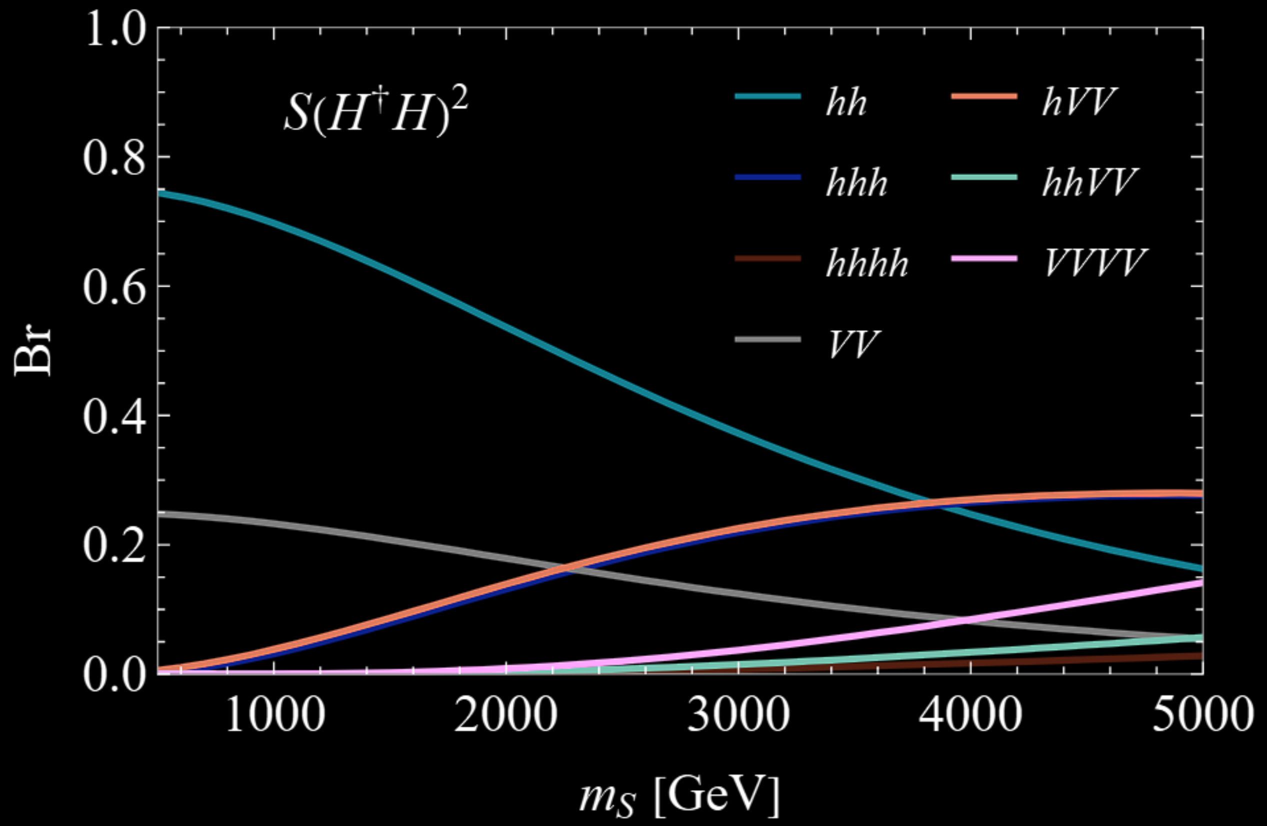
$$\mathcal{O}_{\rm loop} \sim \frac{4}{16\pi^2}\frac{|\kappa|^2\mu}{M_\Phi^2} S H^\dagger H$$

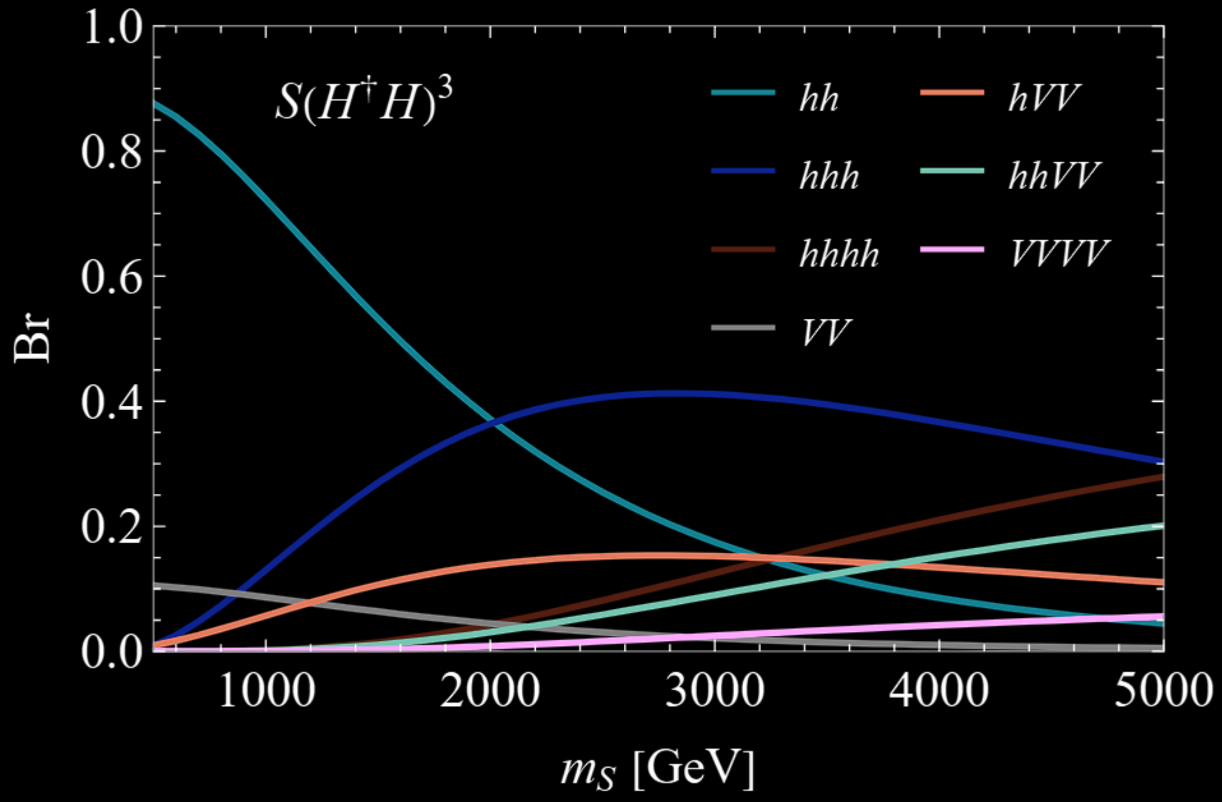
TABLE I. Flavor charge assignment

	ψ_1	Ψ_2	ψ_3	Ψ_4	ψ_5	H_u	H_d	Φ
$U(1)$ flavor charge	1	2	3	4	5	1	1	-4
SM $U(1)_Y$	0	$\frac{1}{2}$	0	$\frac{1}{2}$	0	$\frac{1}{2}$	$-\frac{1}{2}$	0
SM $SU(2)_L$	0	$\frac{1}{2}$	0	$\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	0

$$\frac{\Gamma(S \to hh)}{\Gamma(S \to a_i a_i)} = (2n-1)^2, \quad \frac{\Gamma(S \to hhh)}{\Gamma(S \to h a_i a_i)} = (2n-1)^2/3,$$

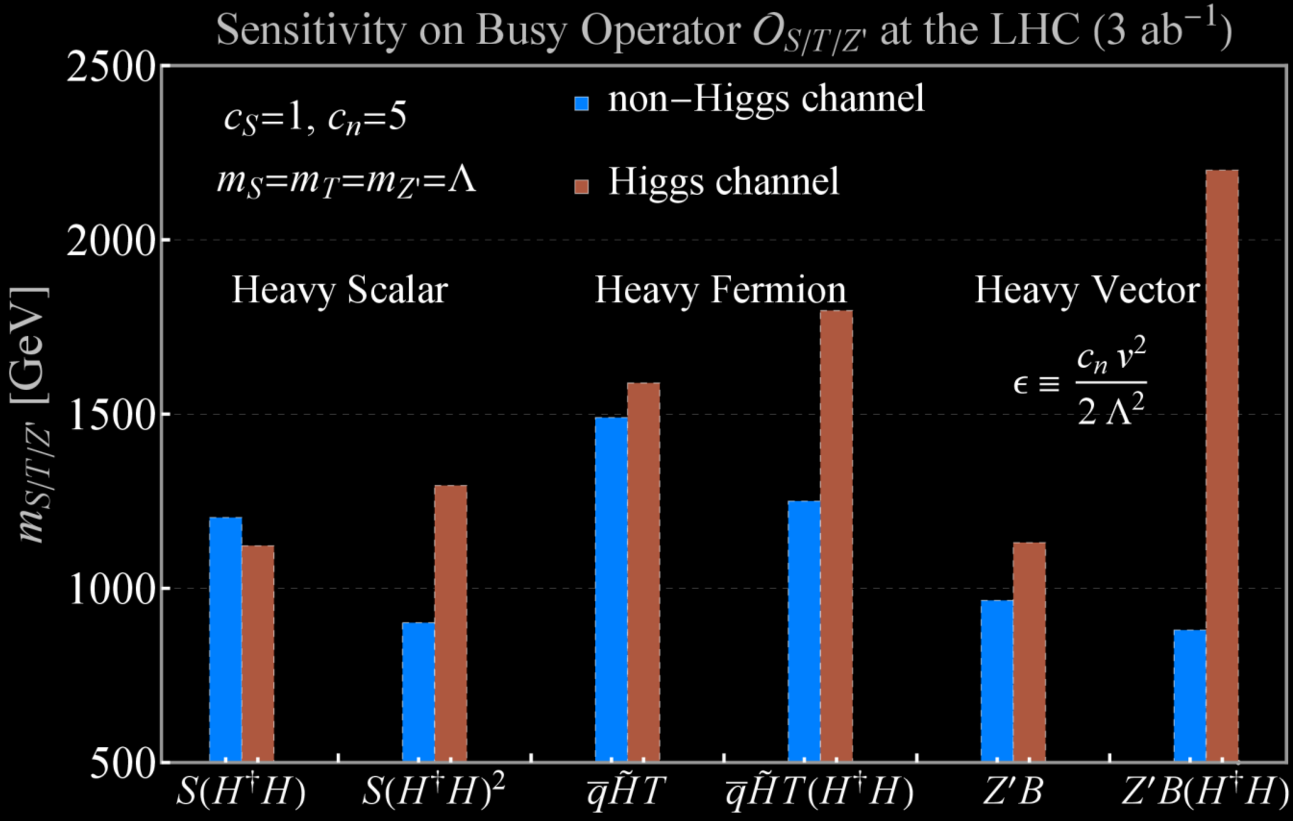
$$\Gamma(S \to 4h) : \Gamma(S \to hh a_i a_i) : \Gamma(4a_i) : \Gamma(a_i a_i a_j a_j) = (2n-1)^2(2n-3)^2/6 : (2n-3)^2 : 3/2 : 1$$



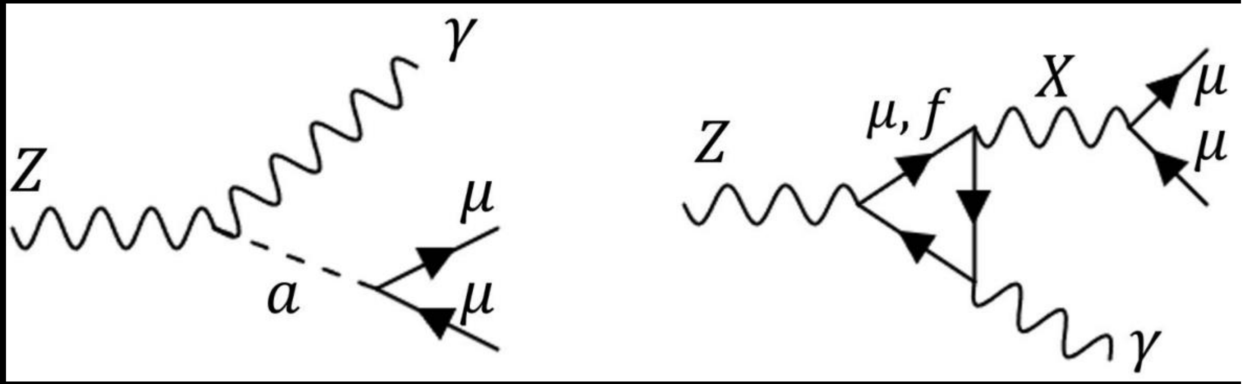


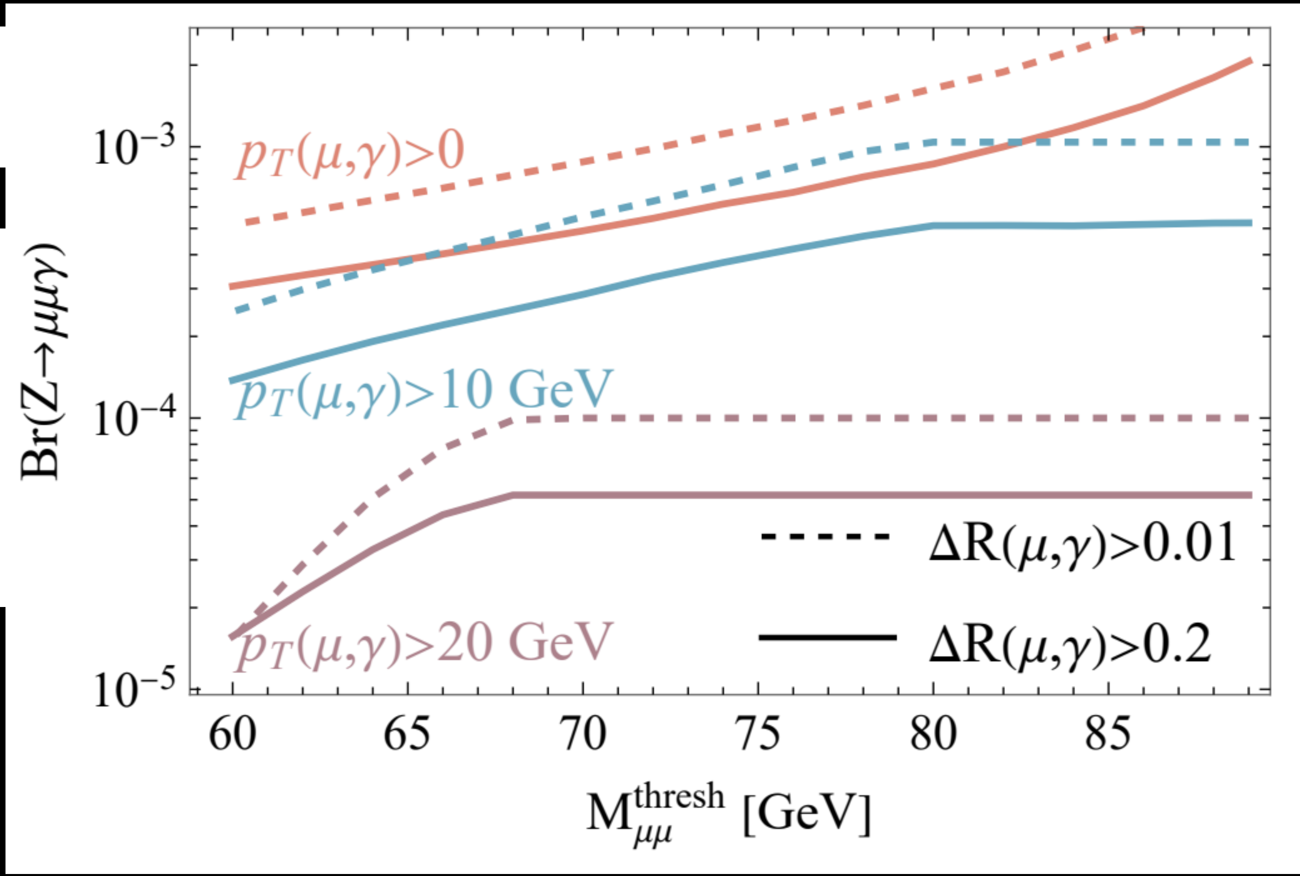
HL-LHC reach: Higgs final states dominate across spins

- Each pair of bars compares minimal (left) vs busy (right) coupling. The blue bar in the busy case far exceeds the orange bar. For the heavy vector Z′, busy operator pushes the reach from ≈1 TeV to 2.5 TeV via Zh.
- Higgs final states, not dibosons, become the primary discovery channels in the busy Higgs framework across scalar, fermion, and vector resonances.
- The same underlying mechanism extends to heavy fermionic and vector resonances, where it can similarly enhance channels such as ht, Zh, and γh.
- Projected 95% C.L. mass reach at HL-LHC (3 ab^{-1}) for heavy scalars, fermions, and vectors. Minimal operators ($SH^\dagger H$, …) vs. busy operators. Orange: best non-Higgs channel; blue: best Higgs final state. Benchmark: c_n=5, m=Λ, ϵ≡c_n v²/(2Λ²).

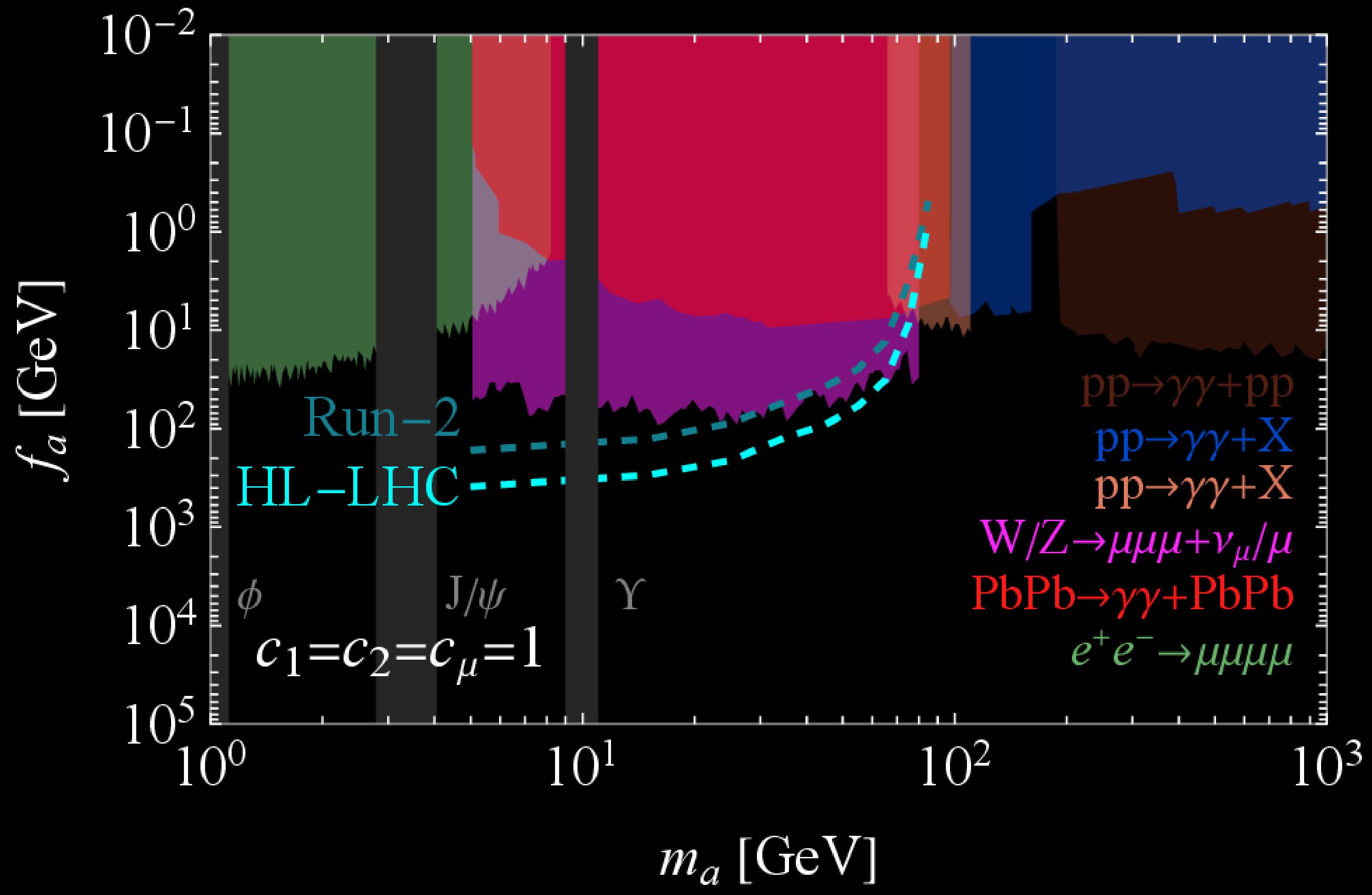


$$\mathrm{Br}^{\mathrm{fid}} = \frac{\sigma^{\mathrm{fid}}(pp \to Z \to \mu\mu\gamma)}{\sigma(pp \to Z)} = \frac{\epsilon^{\mathrm{cuts}} \times \sigma(pp \to Z \to \mu\mu\gamma)}{\sigma(pp \to Z)}$$



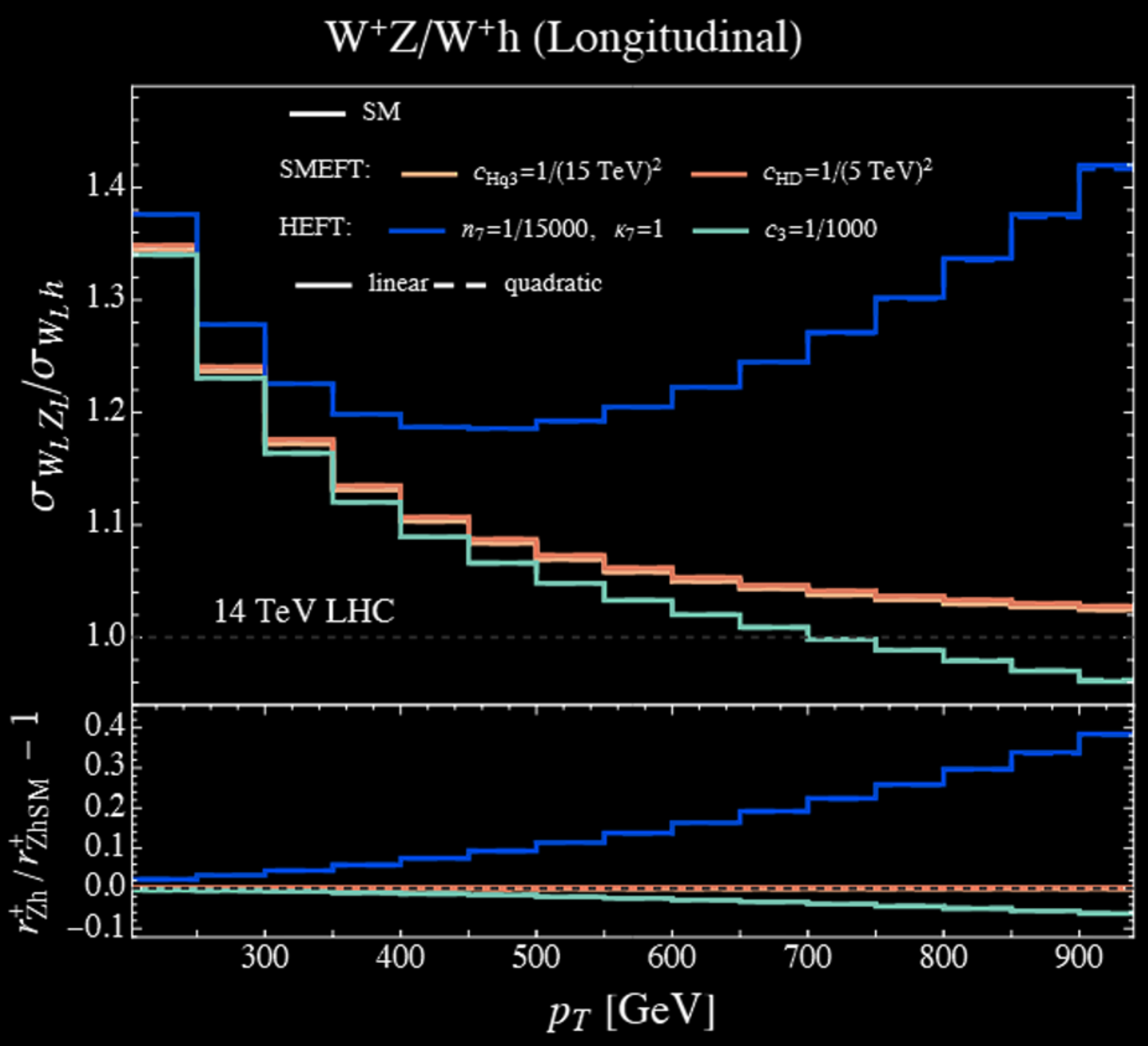


ALP reach: $Z \to \mu\mu\gamma$ probes decay constants f_a beyond existing limits



The clean discriminator: longitudinal W^+Z/W^+h ratio

- Why this artifact: This final ratio plot, focusing only on longitudinal bosons, provides the sharpest separation between linear and non-linear EW symmetry realizations.
- How to read it: The ratio $r^+_{ZH} = \sigma(W^+_L Z_L)/\sigma(W^+_L h)$ is plotted against p_T^W. The SM curve approaches 1 at high p_T; SMEFT curves also converge to 1, but HEFT curves (yellow, maroon) do not.
- Takeaway: The longitudinal $W^\pm Z_L / W^\pm h$ ratio is a nearly theory-independent probe of the Higgs doublet nature.
- Paper caption excerpt: Ratio r^+_{ZH} for purely longitudinal final states as a function of transverse momentum. SM (black), SMEFT (dark/light blue), and HEFT (yellow, maroon) predictions are overlaid.



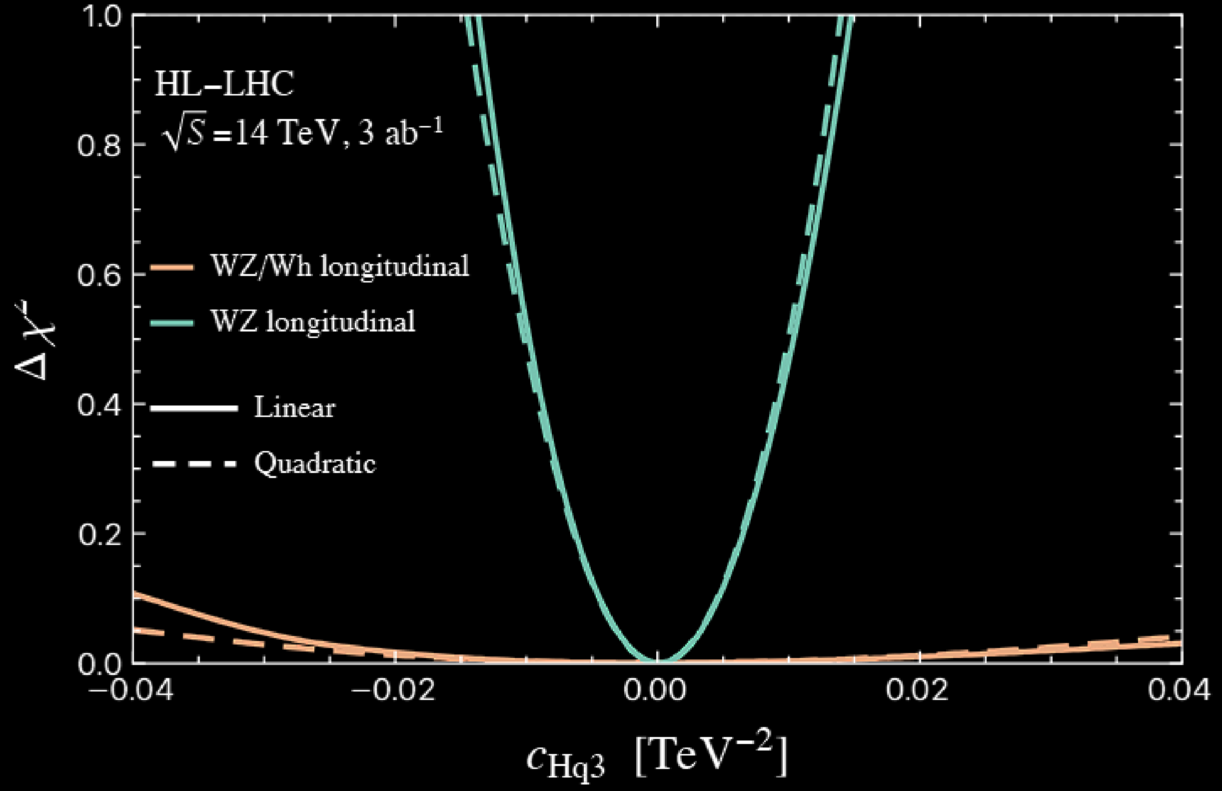
To $\mathcal{O}(m^2/s)$	SM	SMEFT	HEFT
$\frac{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	± 1	± 1	$\mp \frac{c_3 g - 8\pi\,(n_1^Q + n_7^Q)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$-\sqrt{2}\left(T_3^q + \frac{s_W^2}{c_W^2} Y_L^q\right)$	$-\frac{C_{Hq}^{(1)} + 2\,T_3^q C_{Hq}^{(3)}}{\sqrt{2}\,C_{Hq}^{(3)}}$	$\sqrt{2}\frac{8\pi\,n_5^Q + T_3^q\left(c_3 g - 8\pi\,(n_1^Q - 3n_7^Q)\right)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$\sqrt{2}\frac{g_L^{Zq}}{c_W^2}$	$-\frac{C_{Hq}^{(1)} - 2\,T_3^q C_{Hq}^{(3)}}{\sqrt{2}\,C_{Hq}^{(3)}}$	$\sqrt{2}\frac{\kappa_5 n_5^Q + T_3^q(\kappa_1 n_1^Q + \kappa_7 n_7^Q)}{\kappa_1 n_1^Q - \kappa_7 n_7^Q}$
$\frac{\mathcal{M}(q_+\bar{q}_- \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}$	$-\frac{s_W^2 Y_R^q}{c_W^2 T_3^q + s_W^2 Y_L^q}$	$-\frac{C_{Hq}}{C_{Hq}^{(1)} + 2\,T_3^q C_{Hq}^{(3)}}$	$-\frac{8\pi\,(n_6^Q + T_3^q(n_2^Q + n_8^Q))}{8\pi\,n_5^Q + T_3^q(c_3 g - 8\pi\,(n_1^Q - 3n_7^Q))}$
$\frac{\mathcal{M}(q_+\bar{q}_- \to Z_L h)}{\mathcal{M}(q_-\bar{q}_+ \to Z_L h)}$	$-\frac{g_R^{Zq}}{g_L^{Zq}}$	$-\frac{C_{Hq}}{C_{Hq}^{(1)} - 2\,T_3^q\,C_{Hq}^{(3)}}$	$-\frac{\kappa_6 n_6^Q + T_3^q(\kappa_2 n_2^Q + \kappa_8 n_8^Q)}{\kappa_5 n_5^Q + T_3^q(\kappa_1 n_1^Q + \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_+\bar{q}'_- \to W_L^{-(+)} Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^{-(+)} Z_L)}$	0^*	$\frac{C_{Hud}^{(*)}}{2C_{Hq}^{(3)}}$	$-8\,\pi\frac{n_2^Q - n_8^Q + (-)2\,i\,n_4^Q}{c_3 g - 8\pi(n_1^Q + n_7^Q)}$
$\frac{\mathcal{M}(q_+\bar{q}'_- \to W_L^{-(+)} h)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^{-(+)} h)}$	0^*	$-\frac{C_{Hud}^{(*)}}{2\,C_{Hq}^{(3)}}$	$-\frac{\kappa_2 n_2^Q - \kappa_8 n_8^Q + (-)2\,i\,\kappa_4 n_4^Q}{\kappa_1 n_1^Q - \kappa_7 n_7^Q}$

To $\mathcal{O}(m^2/s)$	SM	SMEFT	HEFT
$\dfrac{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	± 1	± 1	$\mp \dfrac{c_3 g - 8\pi\,(n_1^Q + n_7^Q)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\dfrac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) - \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\sqrt{2}\,\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$2\,T_3^q$	$2\,T_3^q$	$-\dfrac{8\pi(1-\kappa_5)n_5^Q + T_3^q\left(c_3 g - 8\pi\left[(1+\kappa_1)n_1^Q + (\kappa_7 - 3)n_7^Q\right]\right)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\dfrac{\mathcal{M}(q_+\bar{q}_- \to W_L^+ W_L^-)}{\mathcal{M}(q_+\bar{q}_- \to Z_L h)}$	1	1	$\dfrac{n_6^Q + T_3^q(n_2^Q + n_8^Q)}{\kappa_6 n_6^Q + T_3^q(\kappa_2 n_2^Q + \kappa_8 n_8^Q)}$
$\dfrac{\mathcal{M}(q_+\bar{q}'_- \to W_L^\pm Z_L)}{\mathcal{M}(q_+\bar{q}'_- \to W_L^\pm h)}$	–	∓ 1	$\mp \dfrac{n_2^Q - n_8^Q \mp 2\,i\,n_4^Q}{\kappa_2 n_2^Q - \kappa_8 n_8^Q \mp 2\,i\,\kappa_4 n_4^Q}$
$\dfrac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) - \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) + \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}$	$-\dfrac{g^2 T_3^q}{g'^2 Y_L^q}$	$-2\,T_3^q \dfrac{C_{Hq}^{(3)}}{C_{Hq}^{(1)}}$	$-\dfrac{8\pi(1-\kappa_5)n_5^Q + T_3^q\left(c_3 g - 8\pi\left[(1+\kappa_1)n_1^Q + (\kappa_7 - 3)n_7^Q\right]\right)}{8\pi(1+\kappa_5)n_5^Q + T_3^q\left(c_3 g - 8\pi\left[(1-\kappa_1)n_1^Q - (\kappa_7 + 3)n_7^Q\right]\right)}$

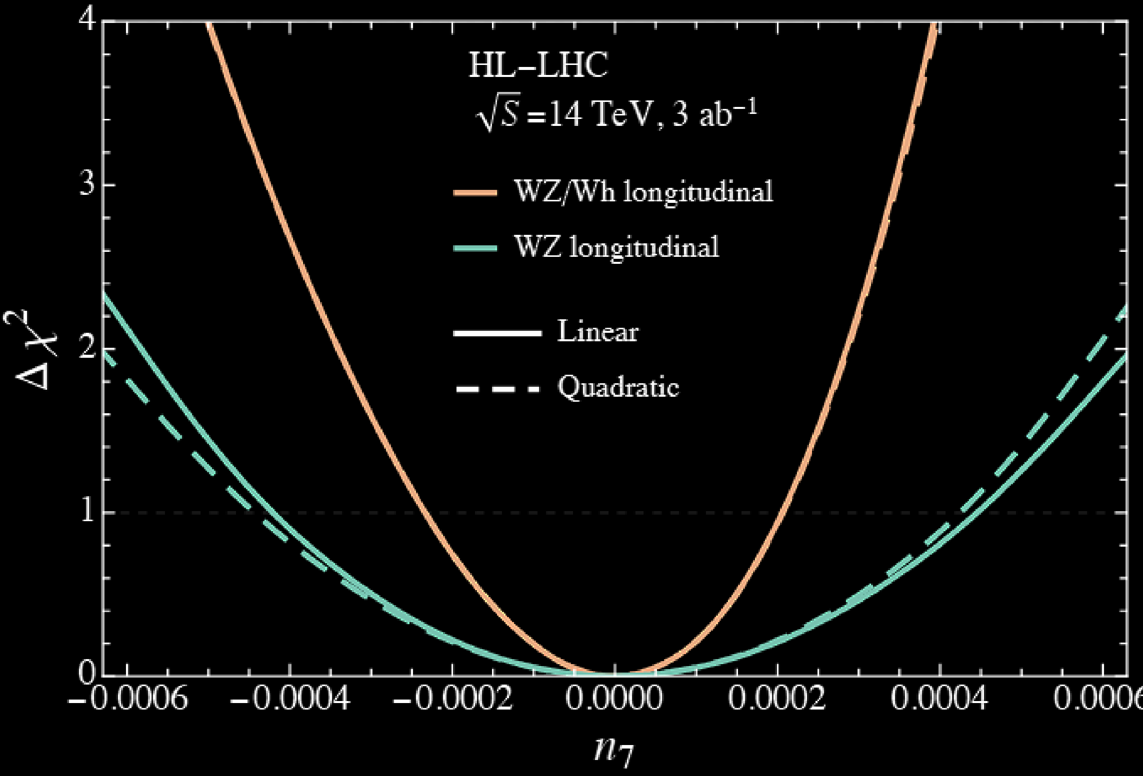
$$r_{Zh}^{\pm} \equiv \frac{d\sigma(pp \to W^{\pm}Z)/dp_T^W}{d\sigma(pp \to W^{\pm}h)/dp_T^W} ,$$

$$r_{Zh} \equiv \frac{\sum_{W^{\pm}} d\sigma(pp \to W^{\pm}Z)/dp_T^W}{\sum_{W^{\pm}} d\sigma(pp \to W^{\pm}h)/dp_T^W} ,$$

SMEFT



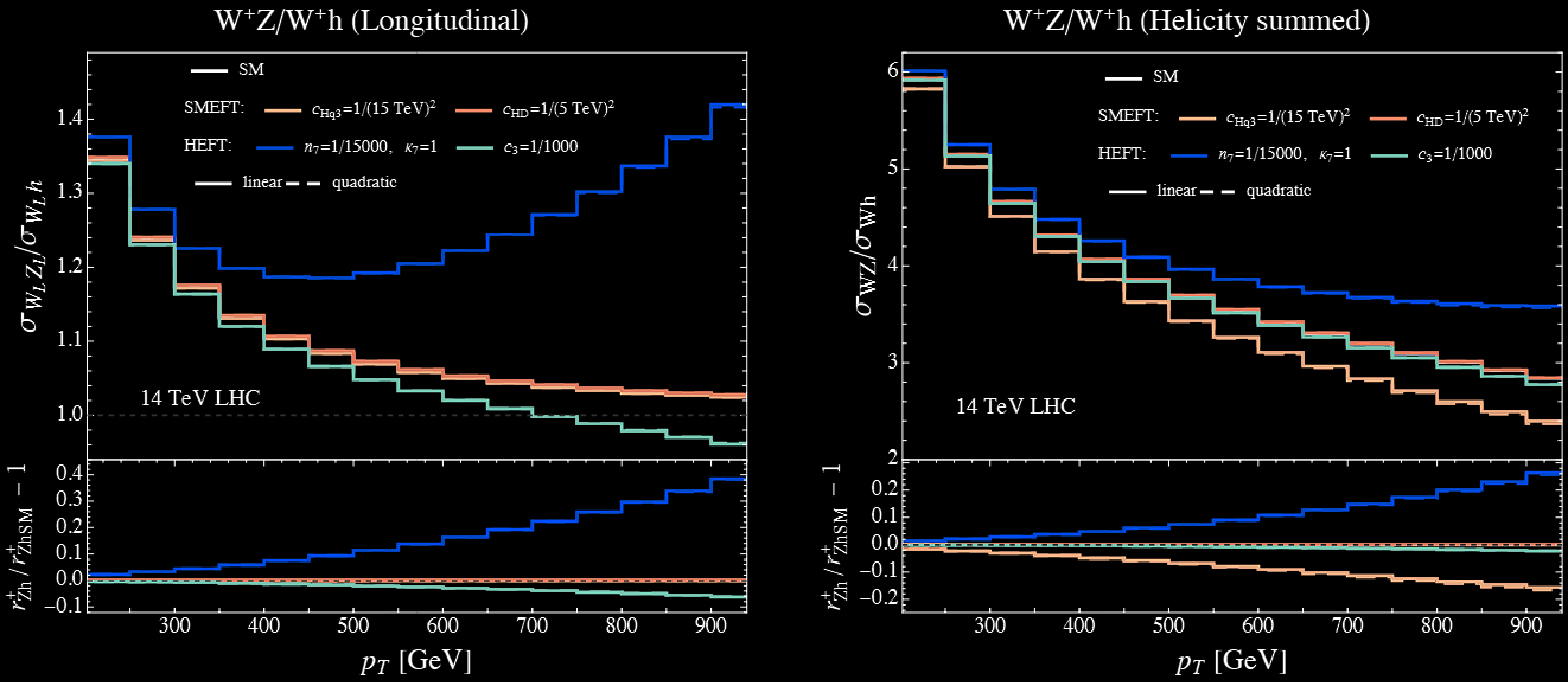
HEFT

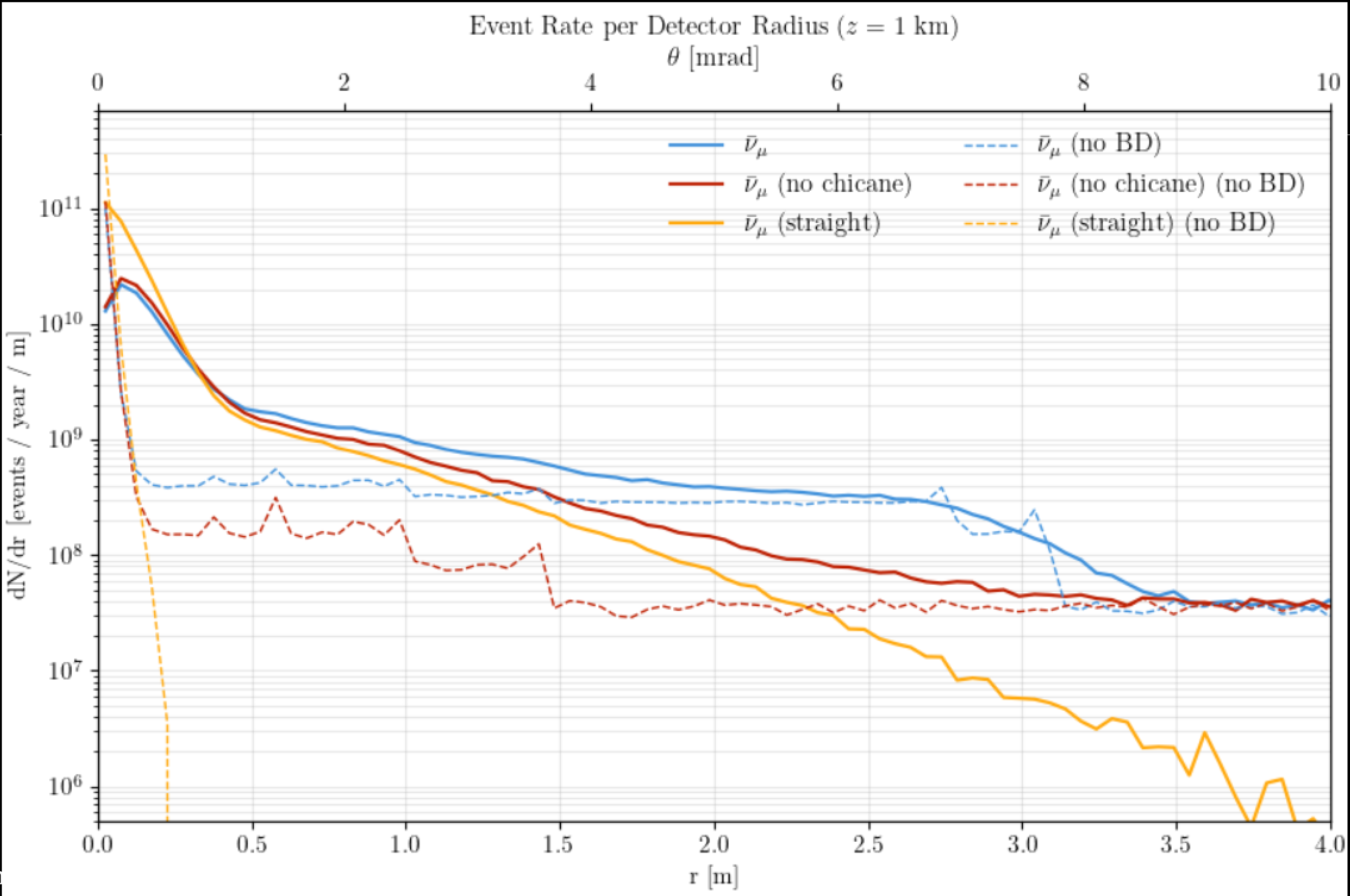


$$\mathcal{Q}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)\,(\bar{q}_R \gamma^\mu q_R)\,,$$
$$\mathcal{Q}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)\,(\bar{Q}_L \gamma^\mu Q_L)\,,$$
$$\mathcal{Q}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)\,(\bar{Q}_L \sigma^I \gamma^\mu Q_L)\,,$$
$$\mathcal{Q}_{Hud} = (\widetilde{H}^\dagger i \overleftrightarrow{D}_\mu H)\,(\bar{u}_R \gamma^\mu d_R)\,,$$
$$\mathcal{Q}_{HD} = (H^\dagger D_\mu H)^*\,(H^\dagger D_\mu H)\,,$$

$$\mathcal{F}_i(h) = \left(1 + 2\kappa_i \frac{h}{v} + \kappa_i^{(2)} \frac{h^2}{v^2} + \mathcal{O}(h^3)\right)$$

$$\mathcal{N}_1^Q(h) = i\,\bar{Q}_L \gamma^\mu V_\mu Q_L\, \mathcal{F}_1(h),$$
$$\mathcal{N}_2^Q(h) = i\,\bar{Q}_R \gamma^\mu U^\dagger V_\mu U\, Q_R\, \mathcal{F}_2(h),$$
$$\mathcal{N}_4^Q(h) = \bar{Q}_R \gamma_\mu U^\dagger [V^\mu, T] U Q_R F_4(h)$$
$$\mathcal{N}_5^Q(h) = i\,\bar{Q}_L \gamma_\mu \{V^\mu, T\} Q_L\, F_5(h)$$
$$\mathcal{N}_6^Q(h) = i\,\bar{Q}_R \gamma_\mu U^\dagger \{V^\mu, T\} U Q_R F_6(h)$$
$$\mathcal{N}_7^Q(h) = i\,\bar{Q}_L \gamma^\mu T V_\mu T\, Q_L\, \mathcal{F}_7(h),$$
$$\mathcal{N}_8^Q(h) = i\,\bar{Q}_R \gamma^\mu U^\dagger T V_\mu T U\, Q_R\, \mathcal{F}_8(h)$$
$$\mathcal{P}_3(h) = \frac{i}{4\pi}\,\mathrm{Tr}\big(W_{\mu\nu}[V^\mu, V^\nu]\big)\,\mathcal{F}_3(h).$$

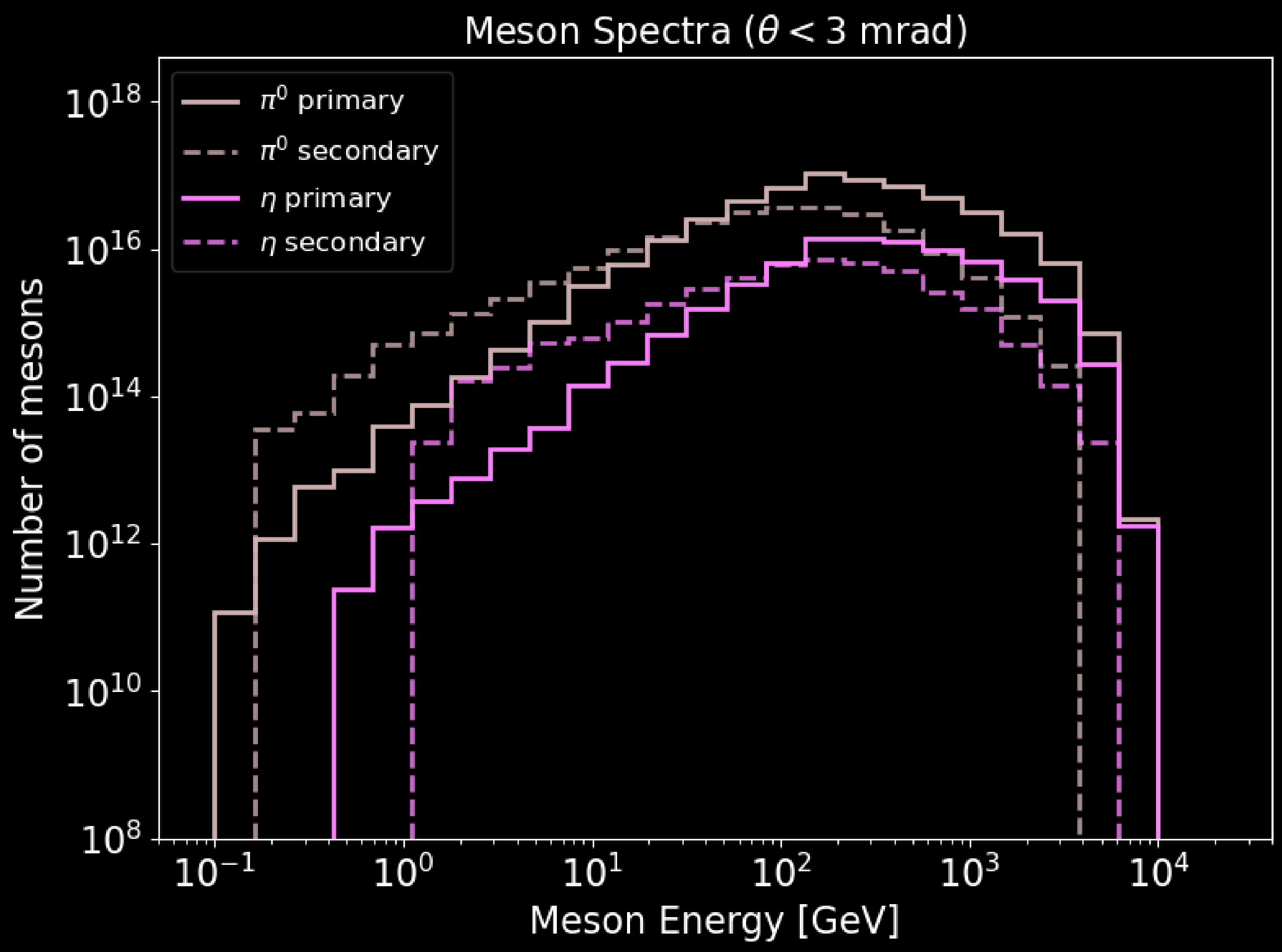

W⁺Z/W⁺h (Longitudinal)
SM
SMEFT: $c_{Hq3}=1/(15\ \text{TeV})^2$ $c_{HD}=1/(5\ \text{TeV})^2$
HEFT: $n_7=1/15000$, $\kappa_7=1$ $c_3=1/1000$
linear quadratic
14 TeV LHC
$\sigma_{W_L Z_L}/\sigma_{W_L h}$
$r^+_{Zh}/r^+_{ZhSM}-1$
p_T [GeV]
W⁺Z/W⁺h (Helicity summed)
SM
SMEFT: $c_{Hq3}=1/(15\ \text{TeV})^2$ $c_{HD}=1/(5\ \text{TeV})^2$
HEFT: $n_7=1/15000$, $\kappa_7=1$ $c_3=1/1000$
linear quadratic
14 TeV LHC
σ_{WZ}/σ_{Wh}
$r^+_{Zh}/r^+_{ZhSM}-1$
p_T [GeV]


Event Rate per Detector Radius (z = 1 km)
θ [mrad]
dN/dr [events / year / m]
r [m]
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$ (no chicane)
$\bar{\nu}_\mu$ (straight)
$\bar{\nu}_\mu$ (no BD)
$\bar{\nu}_\mu$ (no chicane) (no BD)
$\bar{\nu}_\mu$ (straight) (no BD)

Zh

Secondary Showers Produce Abundant Light Mesons and EM Activity

- Why this artifact: This figure directly shows the secondary particle yields that ultimately convert into the mCP signal – the missing link between the primary neutrals and the extra mCPs at the detector.
- How to read it: Left panel: neutral meson spectra (π^0, η, etc.) from hadronic showers. Right panel: electrons/positrons from electromagnetic cascades. Compare the order-of-magnitude yields: meson production is copious at 1–100 GeV, precisely the regime that feeds mCP generation.
- Takeaway: The secondary cascades generate large fluxes of η, π^0, and e^+e^-, providing multiple production channels for millicharged particles beyond what primary collisions alone give.
- Context anchor: Predicted energy spectra of secondary neutral mesons (left) and electromagnetic shower products (right) produced within θ < 3 mrad with respect to the LHC beam collision axis.
- Paper caption excerpt: Spectra of secondary neutral mesons (left) and electromagnetic shower products (right) within θ < 3 mrad, forward-tuned Pythia8, 3 ab^{-1}.



Beam-induced Neutrinos (BINs)

More neutrinos than we have ever detected by >3 orders of magnitude.

O(1) events per bunch crossing.

About 0.1 large-R (HCal/ECal) events per bunch crossing.

Collider	MuC 10 TeV	MuC 3 TeV	μTRISTAN
Beams	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^+$
Muons/bunch	1.8×10^{12}	1.8×10^{12}	1.4×10^{10}
bunches/cycle	1	1	40
f_{inj}	5 Hz	5 Hz	50 Hz
C	8.7 km	4.3 km	4.3 km
BIN exclusive reactions in HCAL and ECAL/year			
Total NC	1.5×10^9	4.6×10^8	3.4×10^9
Total ν_e CC	4.7×10^9	1.4×10^9	1.1×10^{10}
Total ν_μ CC	5.4×10^9	1.7×10^9	1.1×10^{10}
ES $\nu_\mu e \to \nu_\mu e$	3.8×10^5	1.1×10^5	0
ES $\bar{\nu}_e e \to \bar{\nu}_e e$	8.6×10^5	2.5×10^5	0
ES $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	3.4×10^5	9.9×10^4	1.9×10^6
QE $\nu n \to \ell^- p^+$	2.6×10^6	2.5×10^6	2.8×10^7
QE $\bar{\nu} p^+ \to \ell^+ n$	2.7×10^6	2.5×10^6	3.2×10^7
Coh π^0	3.0×10^5	2.9×10^5	3.5×10^6
Res $\bar{\nu}_e e \to \rho^-$	4.2×10^5	7.7×10^5	0
Res $\bar{\nu}_e e \to K^{*-}$	2.6×10^4	4.4×10^4	0
IMD $\nu_\mu e \to \nu_e \mu^-$	4.2×10^6	1.2×10^6	0
IMD $\bar{\nu}_e e \to \bar{\nu}_\mu \mu^-$	1.2×10^6	3.5×10^5	0
ITD $\bar{\nu}_e e \to \bar{\nu}_\tau \tau^-$	9.4×10^3	0	0
Trident e^+e^-	1.2×10^6	2.9×10^5	1.7×10^6
Trident $\mu^\pm e^\mp$	2.9×10^6	6.7×10^5	5.0×10^6
[illegible]	[illegible]	[illegible]	[illegible]