2025年“微扰量子场论及其应用”前沿讲习班暨前沿研讨会

Collider probes for BSM physics
新物理对撞机图景

刘真

University of Minnesota

07/16/2025

Outline

All measurements are BSM probes!

Goal:

- Establish/Reenforce Collider Landscape
- Establish Basic Examples of BSM Searches
- Show how different physic goals give raise to vastly different BSM probes.

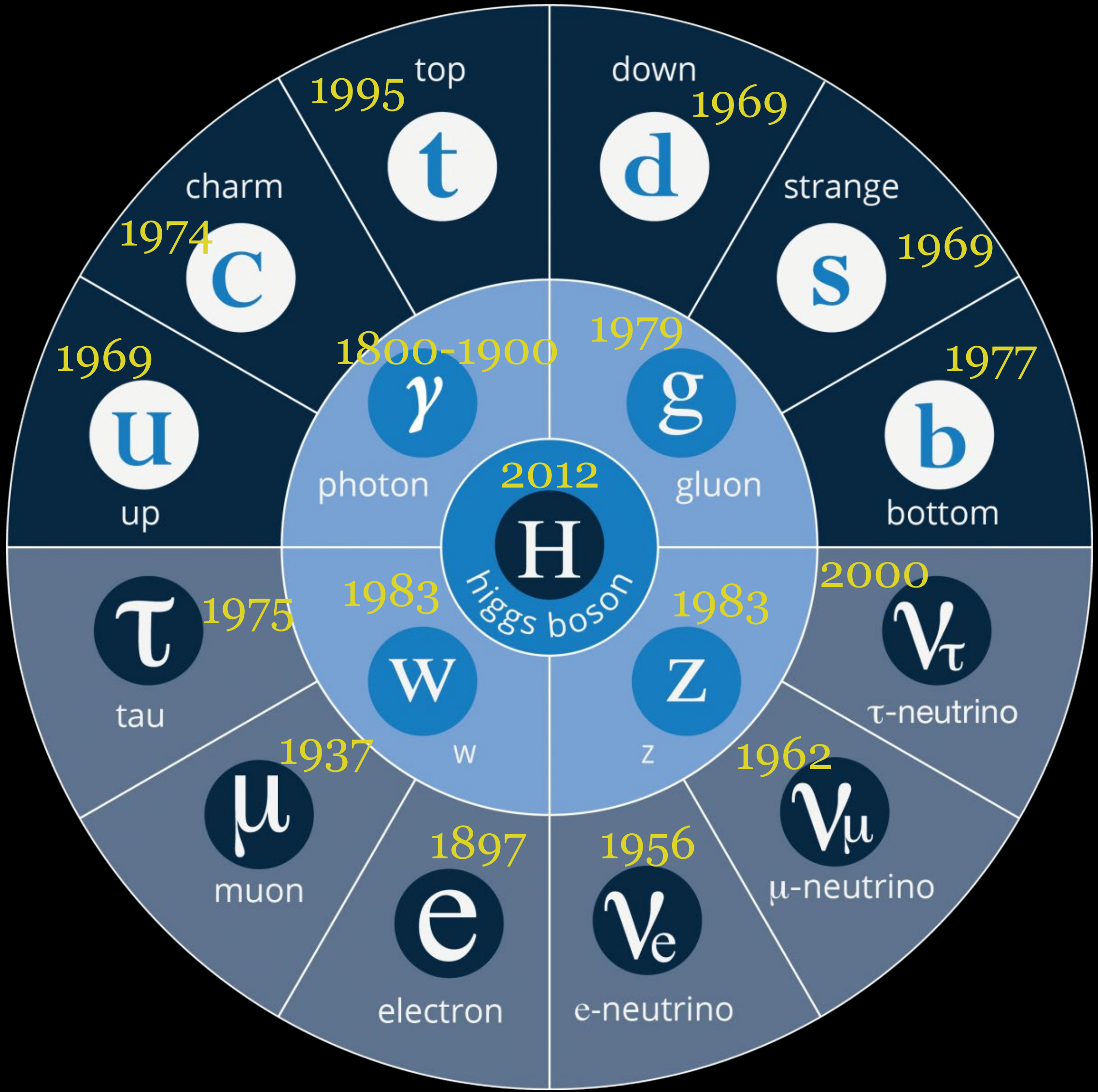
Please ask questions!
It will be more fun with them.

I will use English to deliver the lecture, but we can communicate in either Chinese or English.

Landscape of Colliders

HEP: Triumphant Endeavor of the past century

Quantum Gravity?



Beautiful Unification!

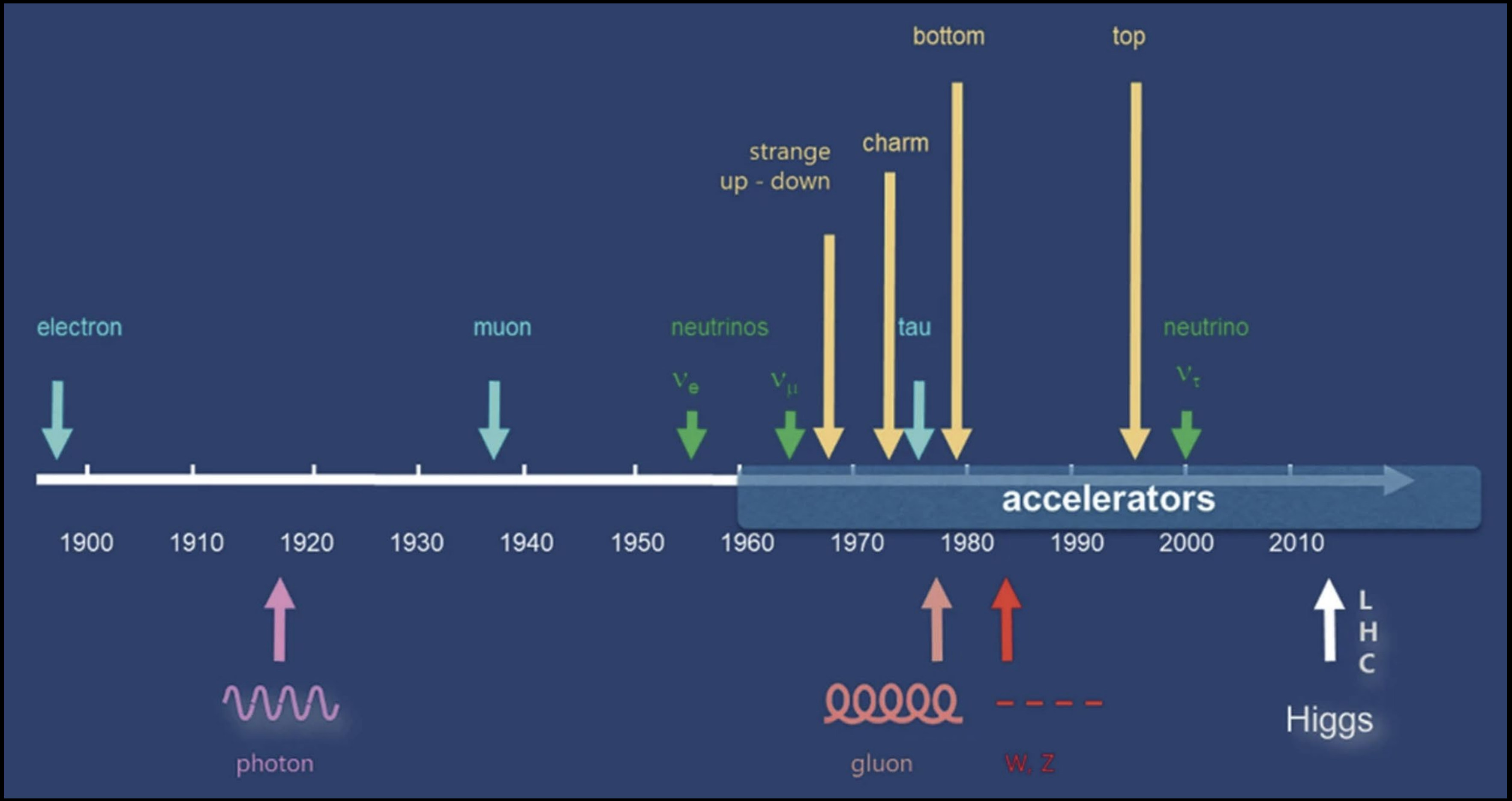
HEP Now: A vibrant and dynamical field

Quantum
Gravity?

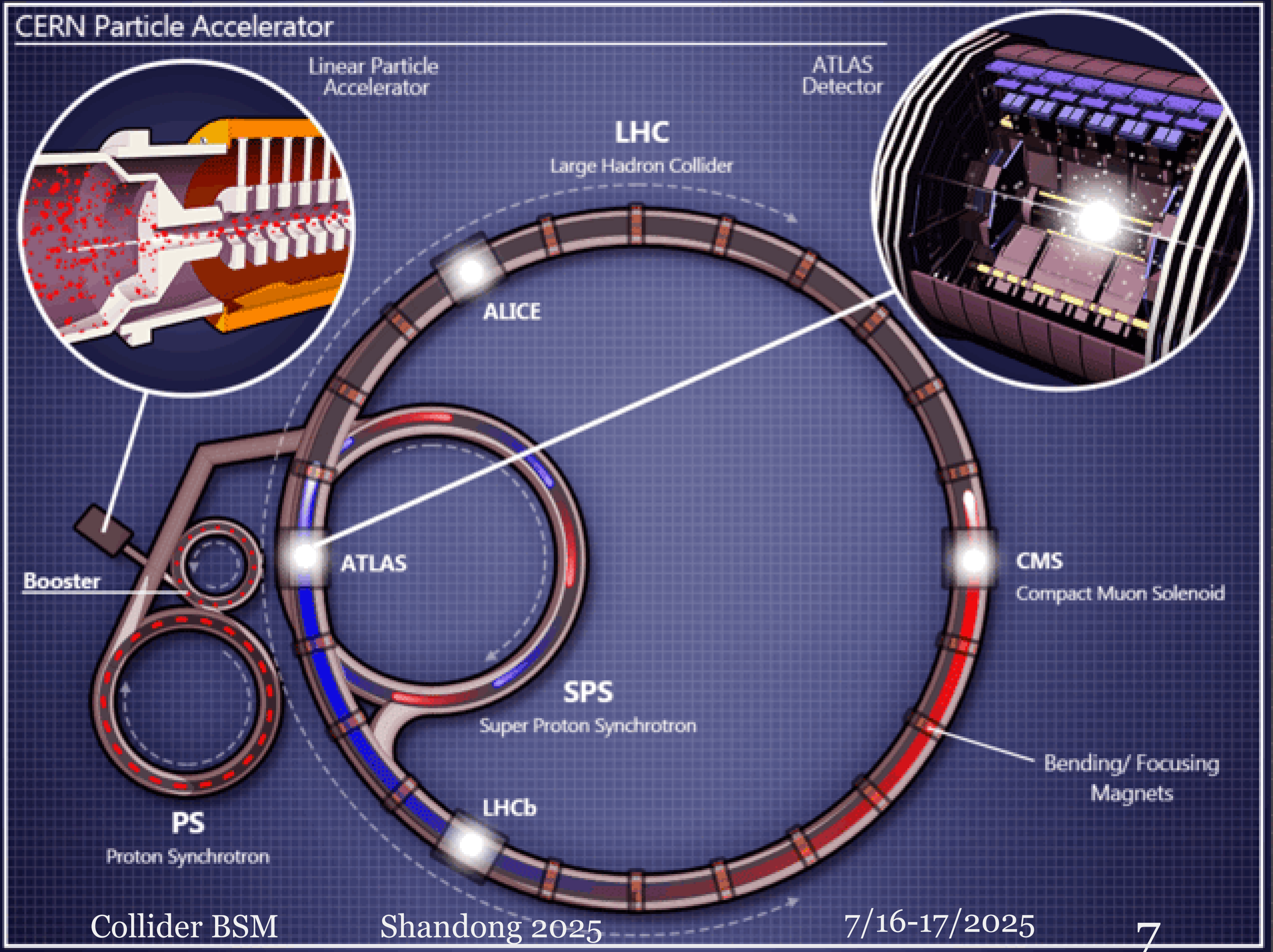
Explore the Unknown

HEP Now

Explore the Unknown



High Energy Collisions

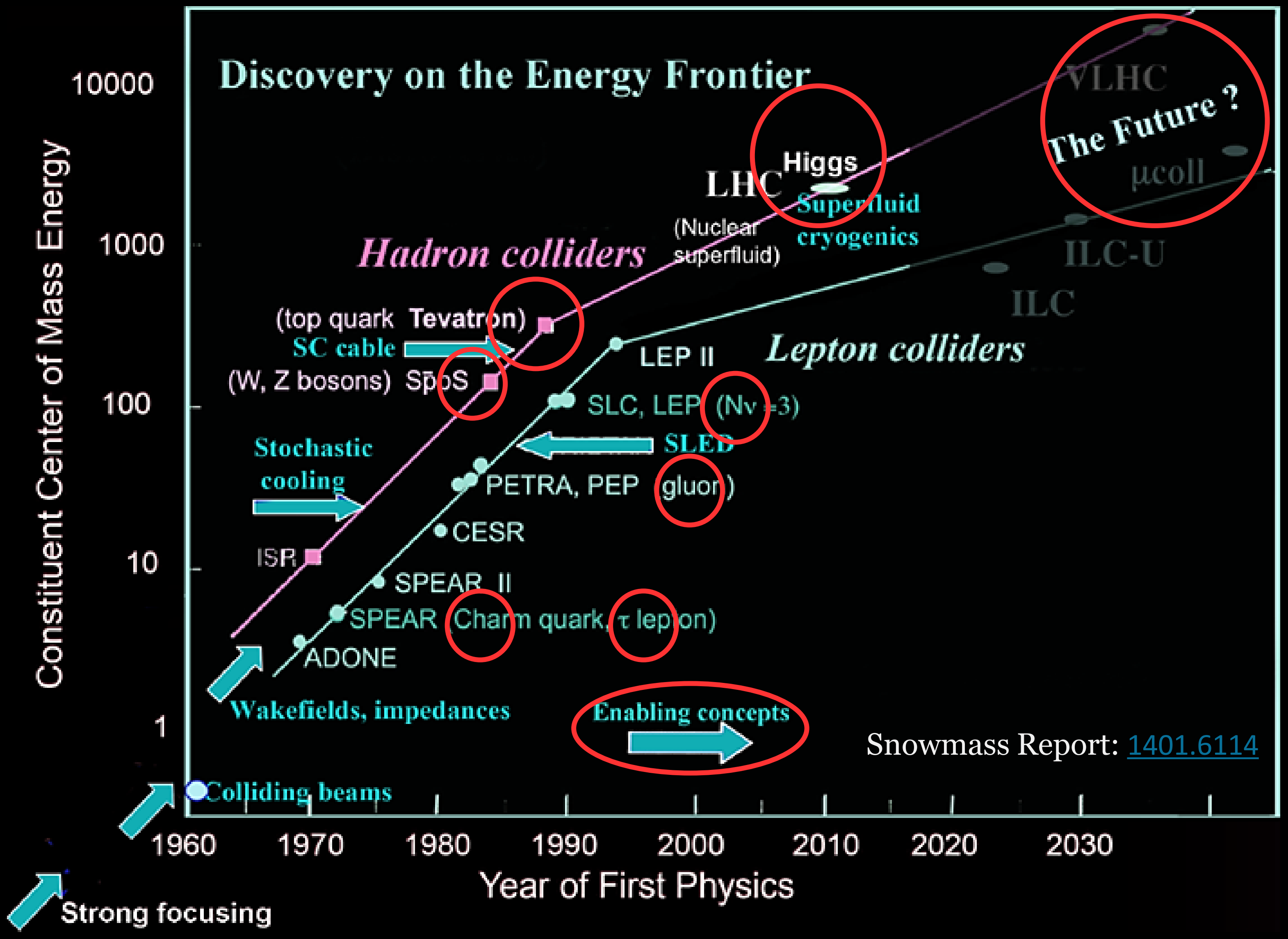


$$\text{Resolution} \propto 1/E_{cm}$$

Key for us to unveil the microscopic world

Large # of independent observables

High Energy Drives



Snowmass Report: 1401.6114

The forefront of tech & ambitions leads to discoveries.

The dream for high energy machines persists in our field.

Colliders are Omnipotent Experimental Platform

- Well-controlled initial states
- Well-measured final states
- Extreme resolution

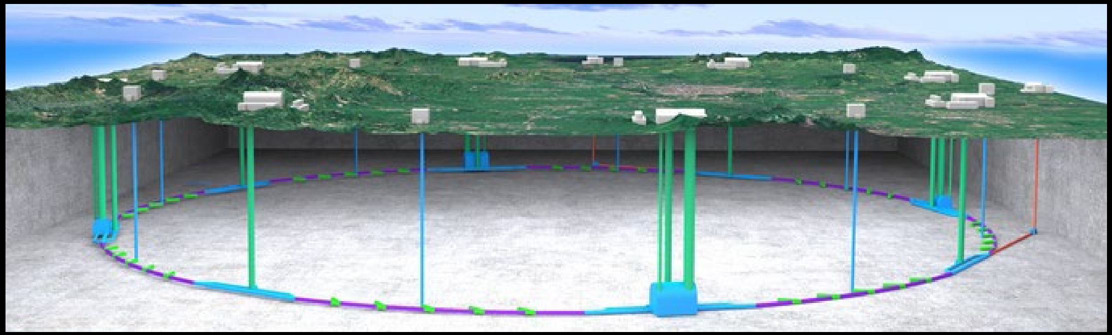
Thousands of search results, each containing (multiple) signal channels/regions/optimizations.

Now, many promising future collider plans

Future Colliders

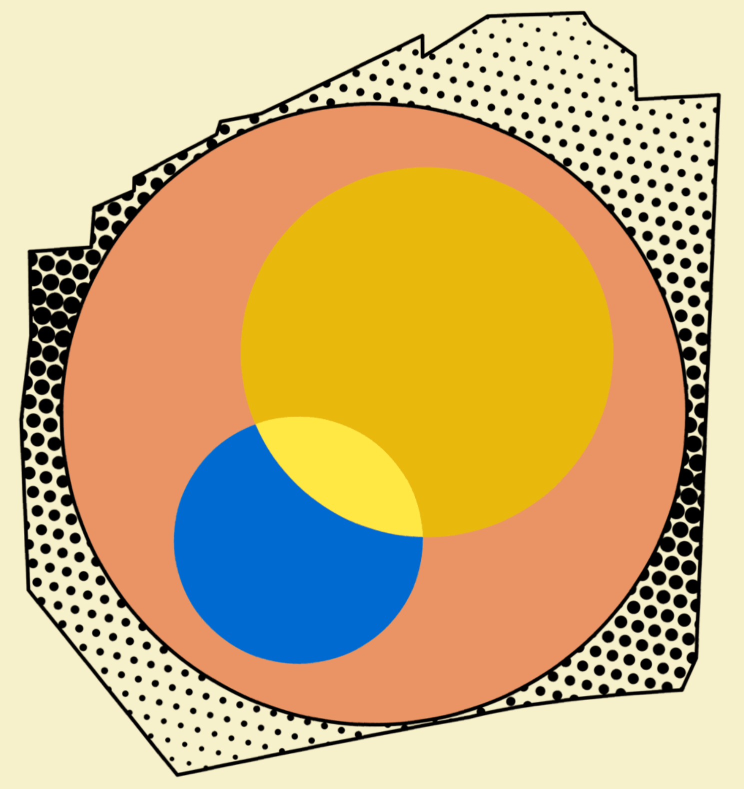
China

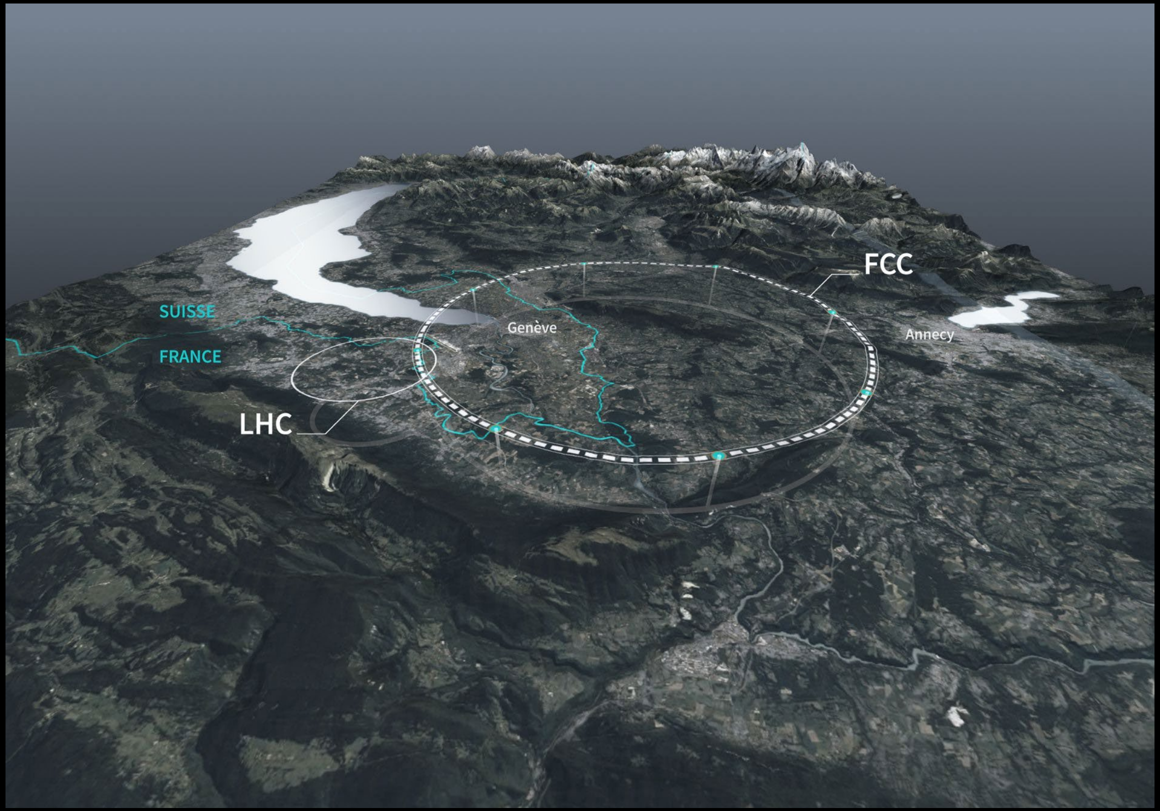
~CEPC (e^+e^-)
240 GeV
Higgs + pp
(~100 TeV)



USA?

Muon collider,
Higgs, 3~10 TeV

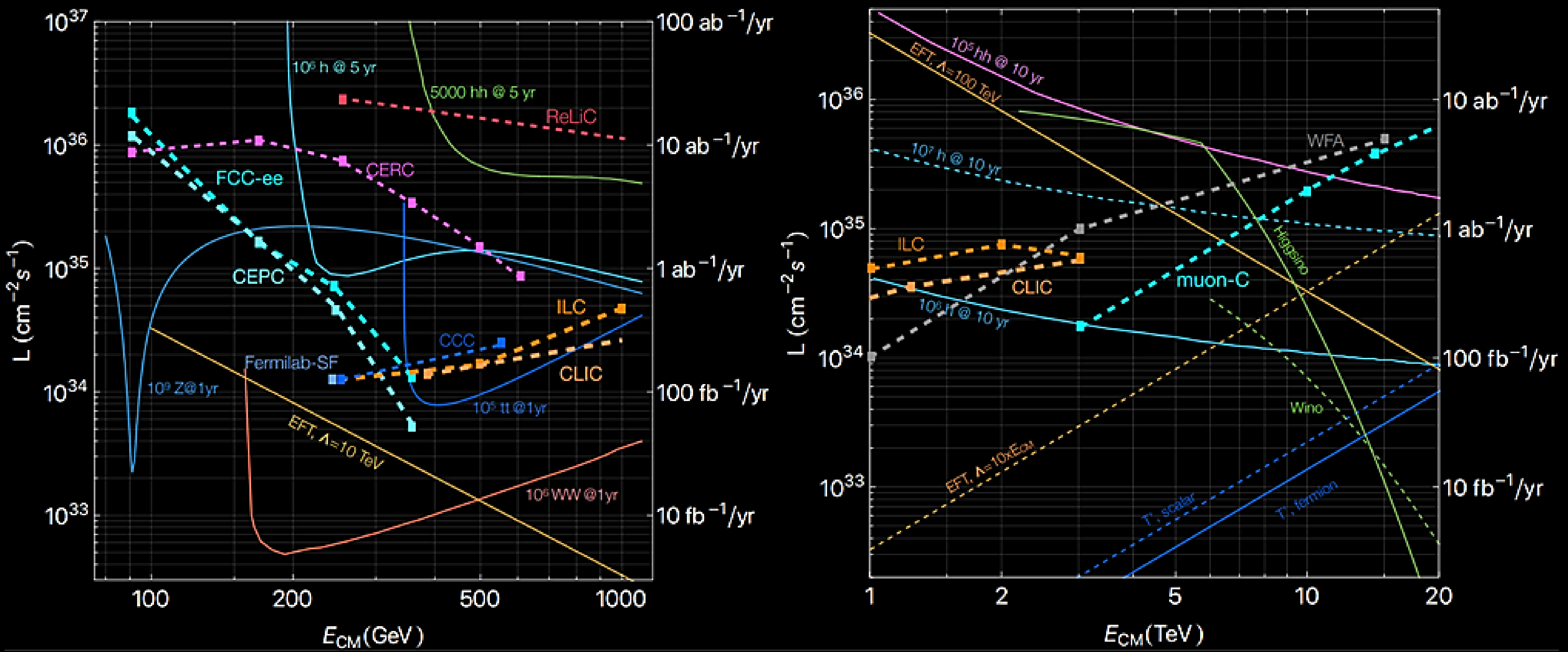




Europe ~100 km FCC
e^+e^- (Z factory, 240 GeV Higgs + 365 GeV Top)
ep, pp (~100 TeV)

And many others, ILC, μ-Tristan, Plasma Weak Field, etc…

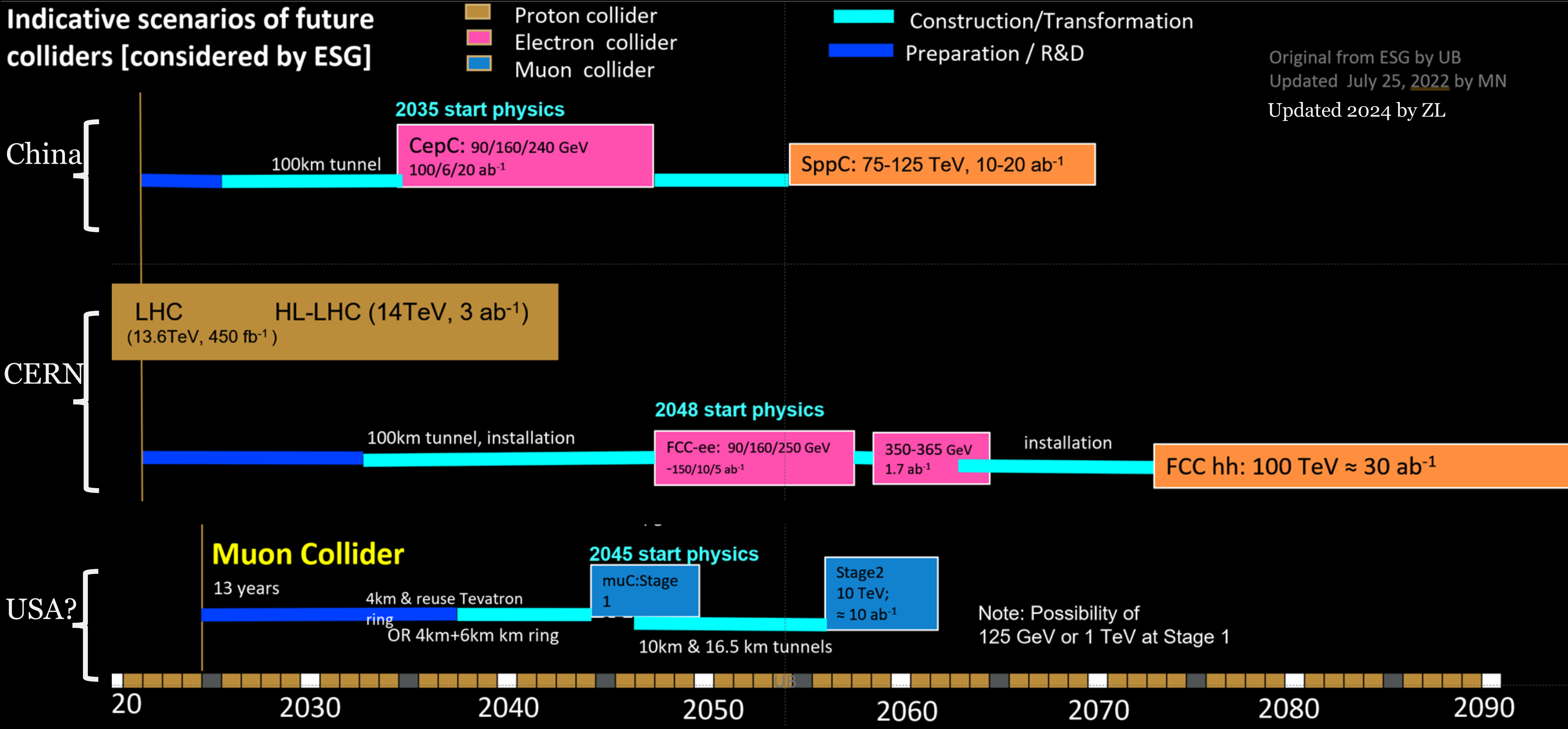
Many more future collider concepts



Many future collider options and excitement!

ZL, Wang, 2205.00031, also in ITF report, 2208.06030

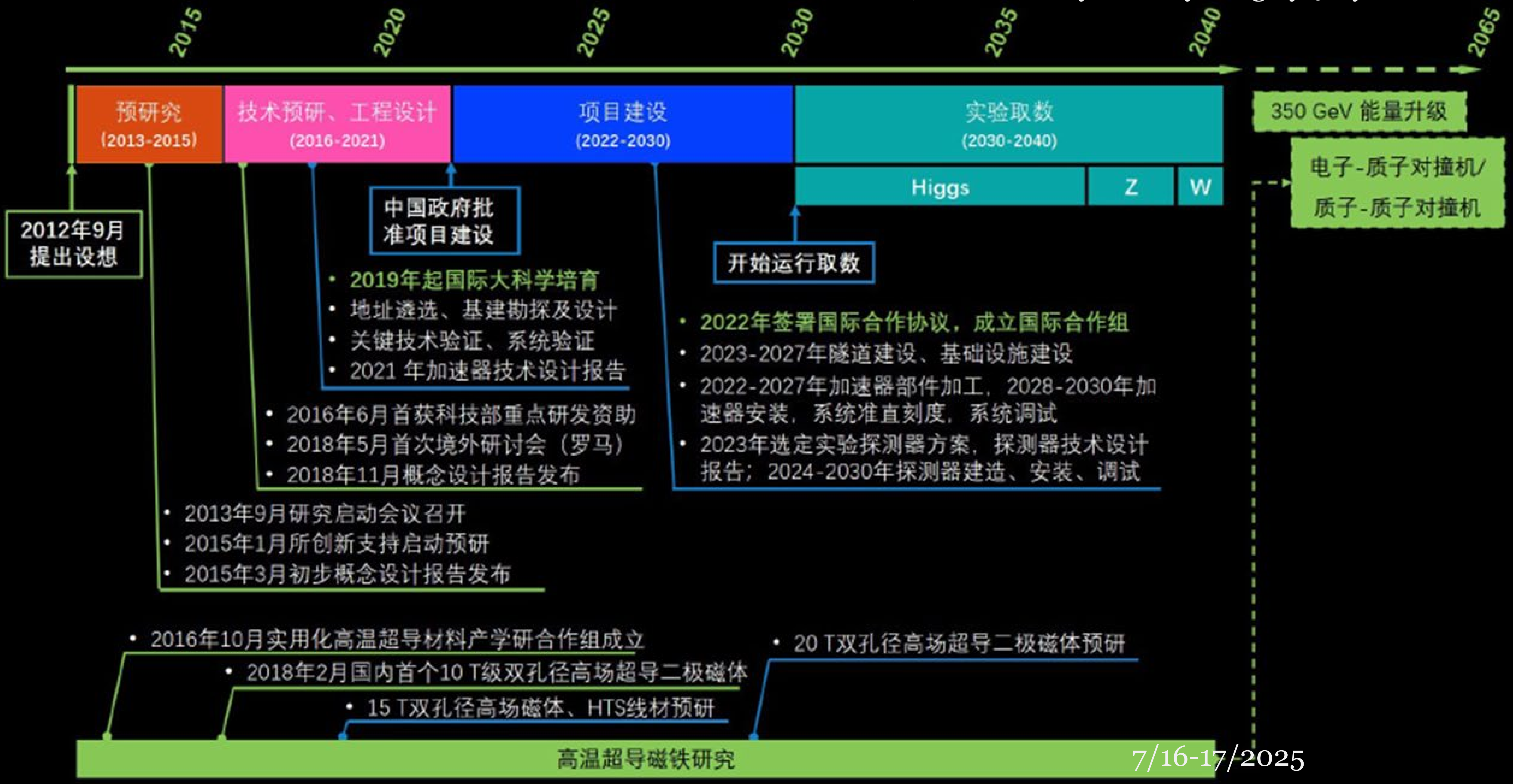
Indicative scenarios of future colliders [considered by ESG]



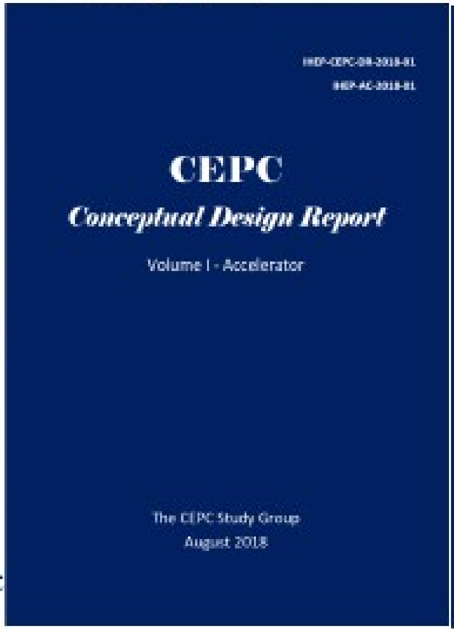
Promising CEPC

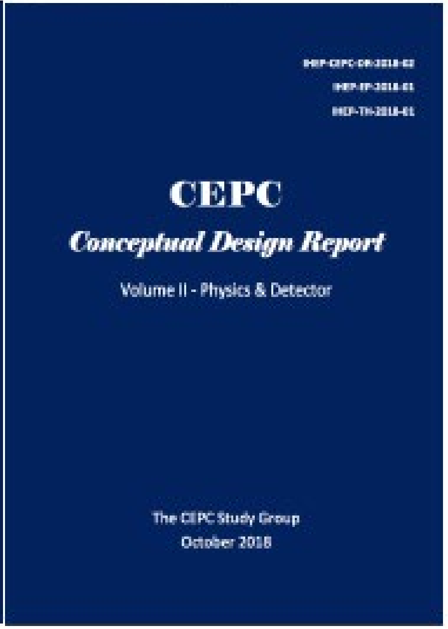
环形正负电子对撞机（CEPC）项目路线图

Timeline in 2020, but now
Of course, COVID delayed everything by 3+ yrs.



CDR released in Nov. 2018





Wang Yifang Wins 2019 Future Science Prize in Physical Science
Nov 19,2019
Prof. Wang Yifang, director of China's Institute of High Energy Physics and a member of the Chinese...

CEPC Design Report Released
Nov 14,2018
Scientists working on the Circular Electron Positron Collider (CEPC), a planned next-generation...

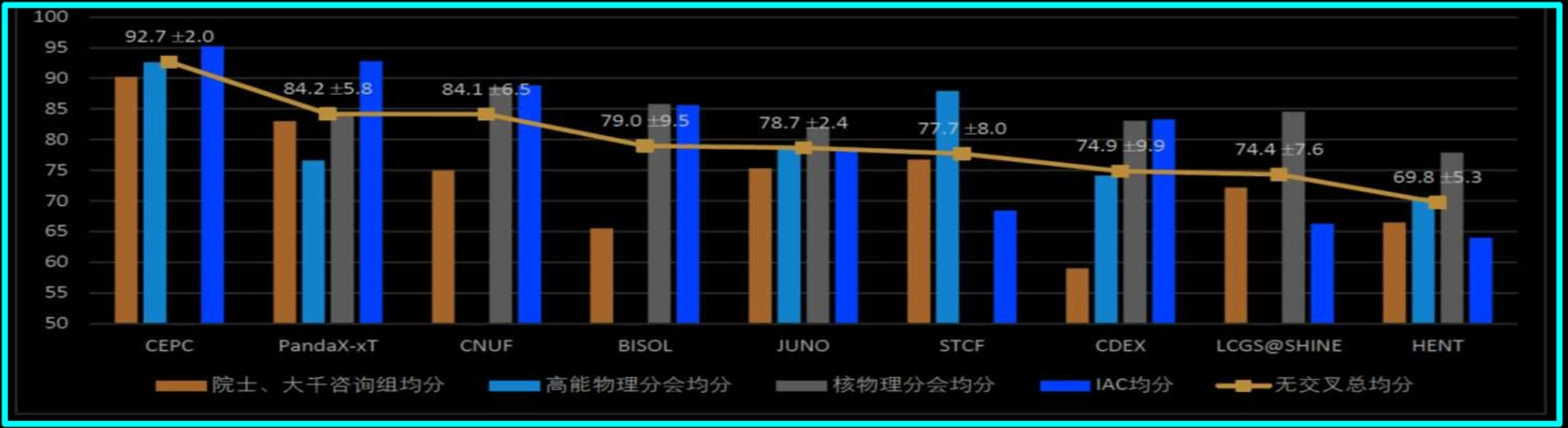
Did we make any progress? Many!

- Physics Estimations (pencil and paper)(throughout the process)
  - →pre-conceptual design report (pre-CDR)
  - →conceptual design report (CDR)
  - →technical design report (TDR)
  - →Engineering design report (EDR)
  - →Shovel
- From initial technological imagination to demonstration
- From design to product
- …

Many recent works to be cited here…

CEPC Project Development towards construction

- **TDR has been completed** (review + revision) to be **formally released on Dec. 25，2023.**
- **CAS is planning for the 15th 5-years plan for large science projects**, and a steering committee has been established, **chaired by the president of CAS**.
- **High energy physics and nuclear physics**, is one of the 8 groups (fields).
- **CEPC is ranked No. 1, with the smallest uncertainties, by every evaluation committee both domestic and international one** among all the collected proposals.
- **A final report has been submitted to CAS for consideration.**
- **The above mentioned actual process is within CAS and the following national selection process will be decisive.**



CEPC Site Preparations + several more sites considered.

The alignment of stars towards FCC-ee

Perfect alignment is being reached as we speak (2020-2024)

- **Politically, in China (CEPC):**

Current plans
- ❑ TDR release: Dec 2023
- ❑ Engineering Design Report: 2024-2027
- ❑ Application for 5-year funding: 2025
- ❑ Construction: 2027-2035
- ❑ Start of operation: 2036

From CERN DG New Year's address

Should we change our plans ? NO

Should we accelerate our planning ? YES

→ CERN Directorate will discuss these matters with the CERN Council in the coming months

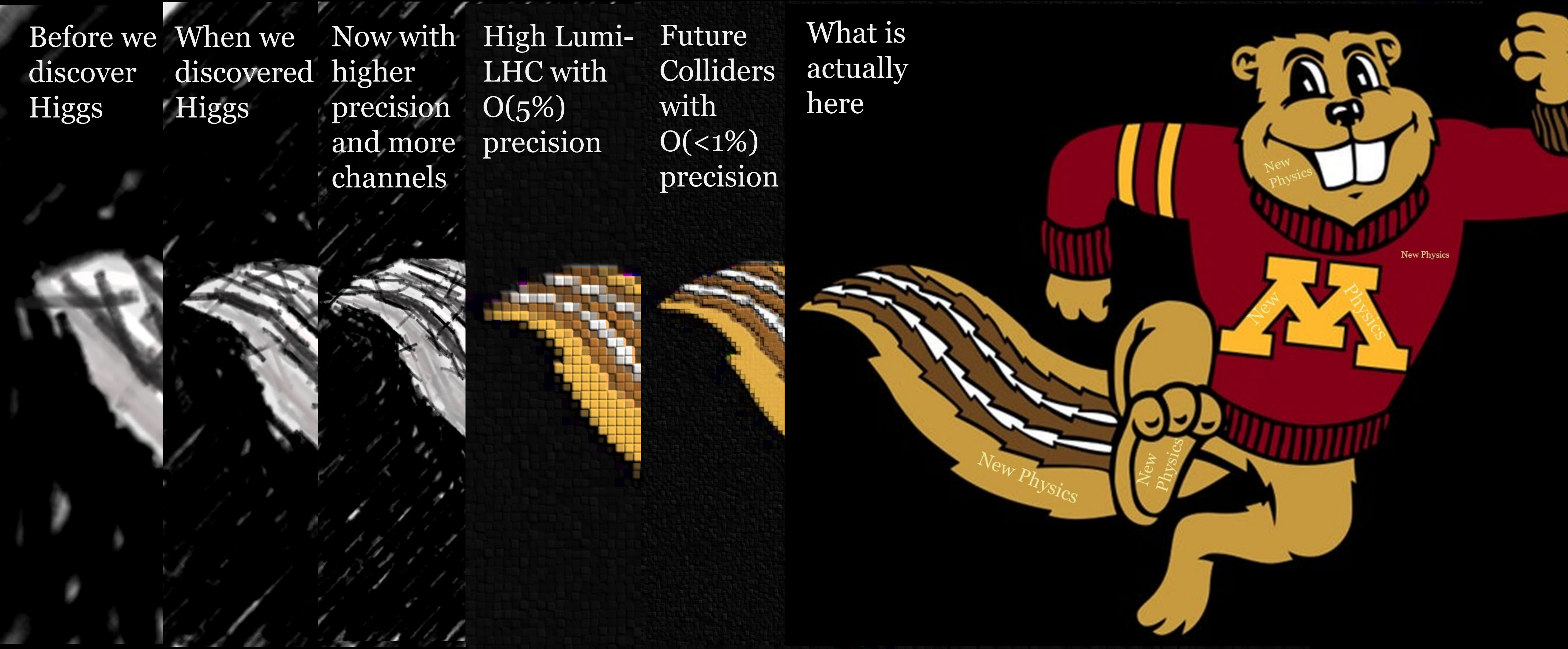
- First visible effects of this possible acceleration
  - Feasibility final report must be produced this year (and delivered beginning 2025)
  - Acceleration may come with more resources (or not)
  - But will certainly come with more work to do until the approval

Predictable future

- HL-LHC will continue to dominant until ~2040;
- FCC-ee has a stable plan to deliver physics in ~2048 for 15 years;
- CEPC could kick in and deliver physics by the late 2030s
- Muon Collider, a game-changer, the US community is actively engaged in
- DUNE flagship US particle physics until ~2045

Why do we care to measure?

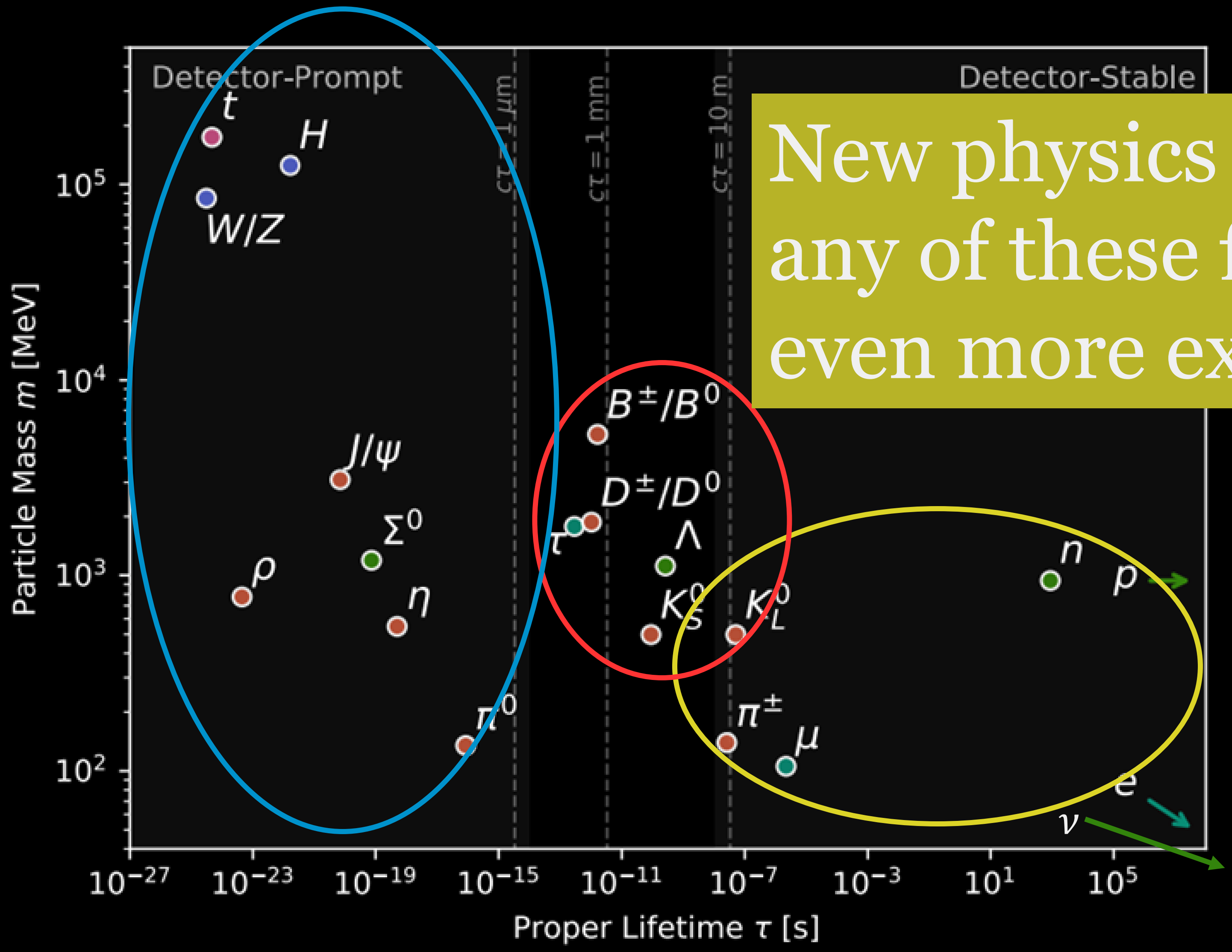
What can you Discover?



The BSM Formula is "Simple" & "Universal" (not only for collider)

- What are my Signals? (determined by the underlying theory you want to explore + your understanding of the experimental setup
- What are my Background? (determined by SM, Instrumentation)
- How to Optimize? (Is it even possible to carry out such a search? Will the result be meaningful?)

How do we see SM particles



New physics can be of any of these forms and even more exotic

”

onstruction

vertex

“Reconstructable”

Missing (transverse) energy

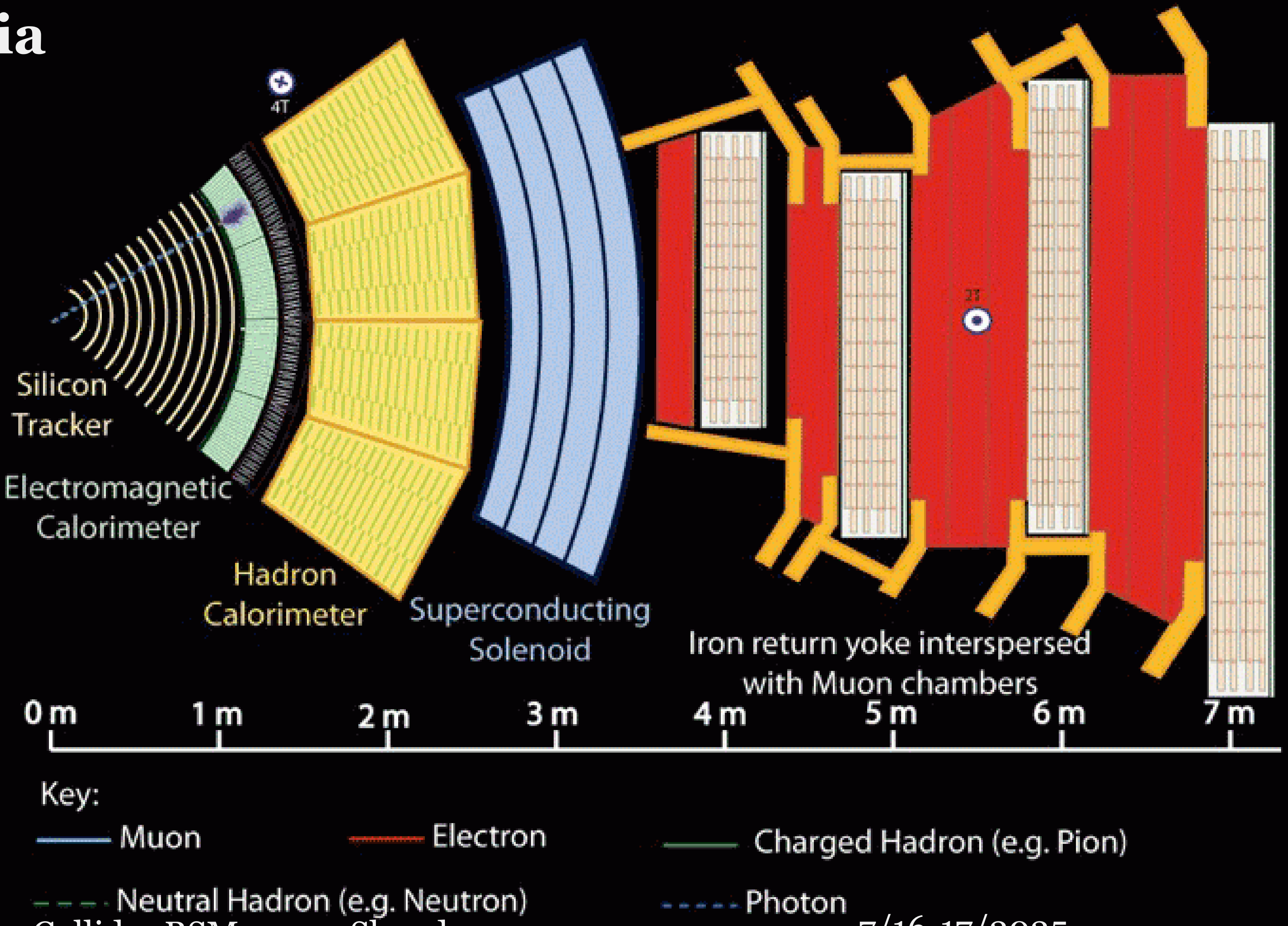
Directly Seen via

Tracker

ECal

HCal

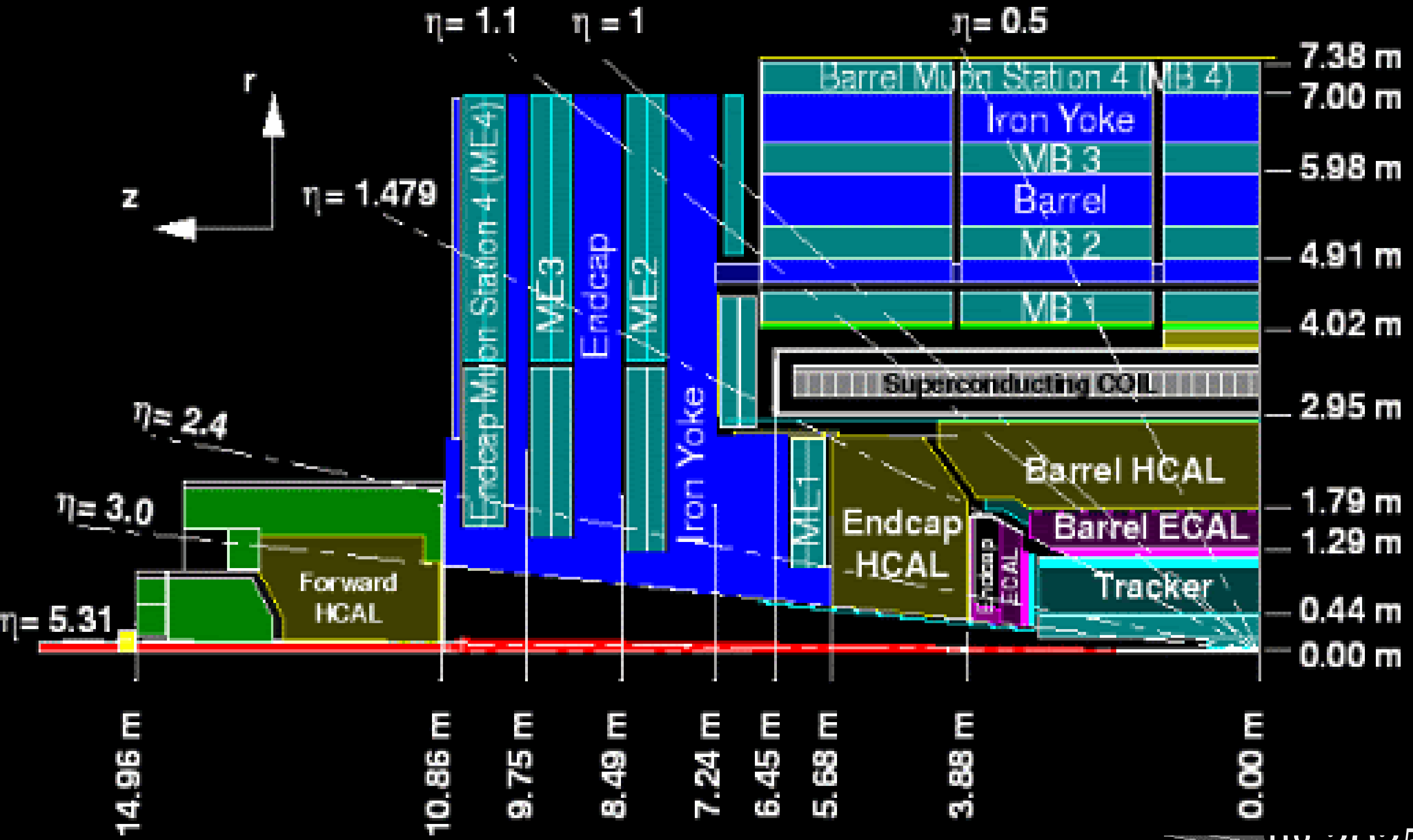
μ Chamber



Pseudo Rapidity representing Geometry

Pseudo-Rapidity:

$$\eta \equiv \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}\right) = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = \ln\left(\cot\frac{\theta}{2}\right)$$



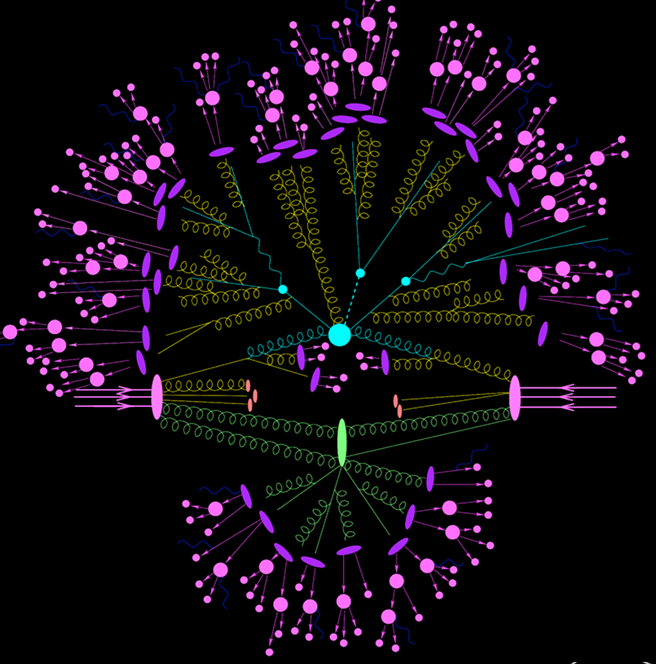
Experimentally, the hadron collider geometry are expressed in pseudo rapidity

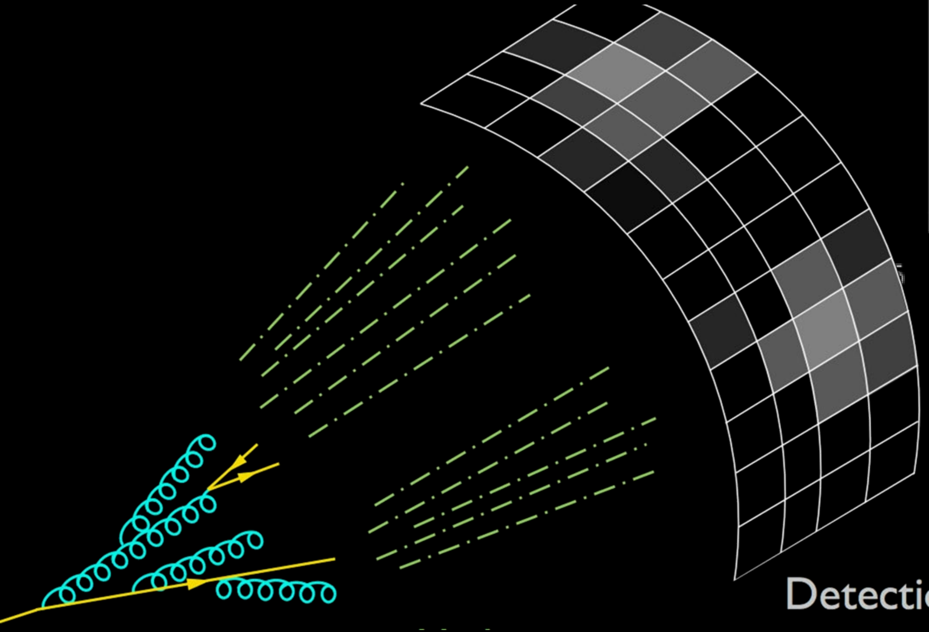
Typical high mass/energy events (central: Barrel & EndCap):

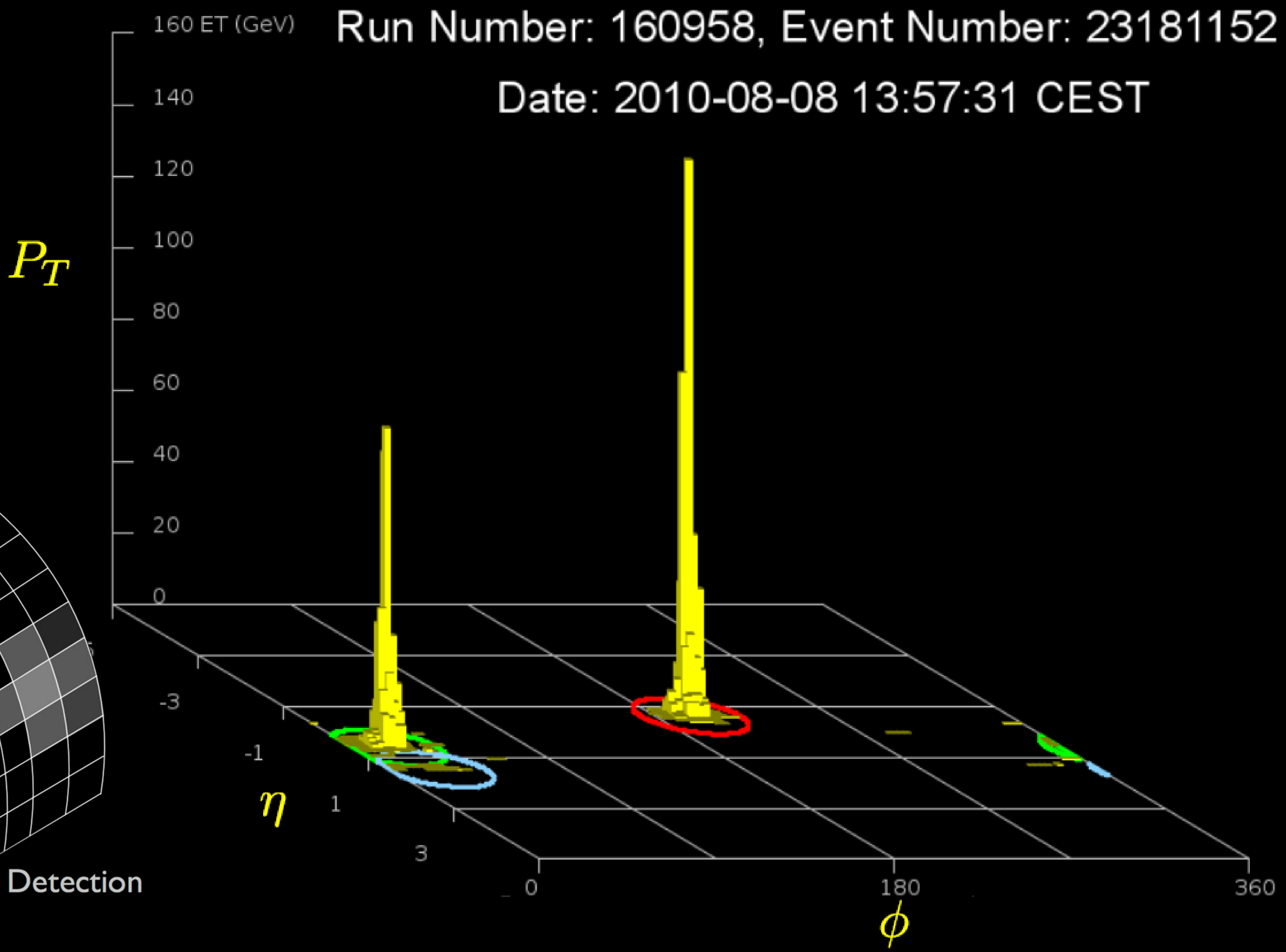
$$|\eta| < 3$$

Forward (lots of QCD background)

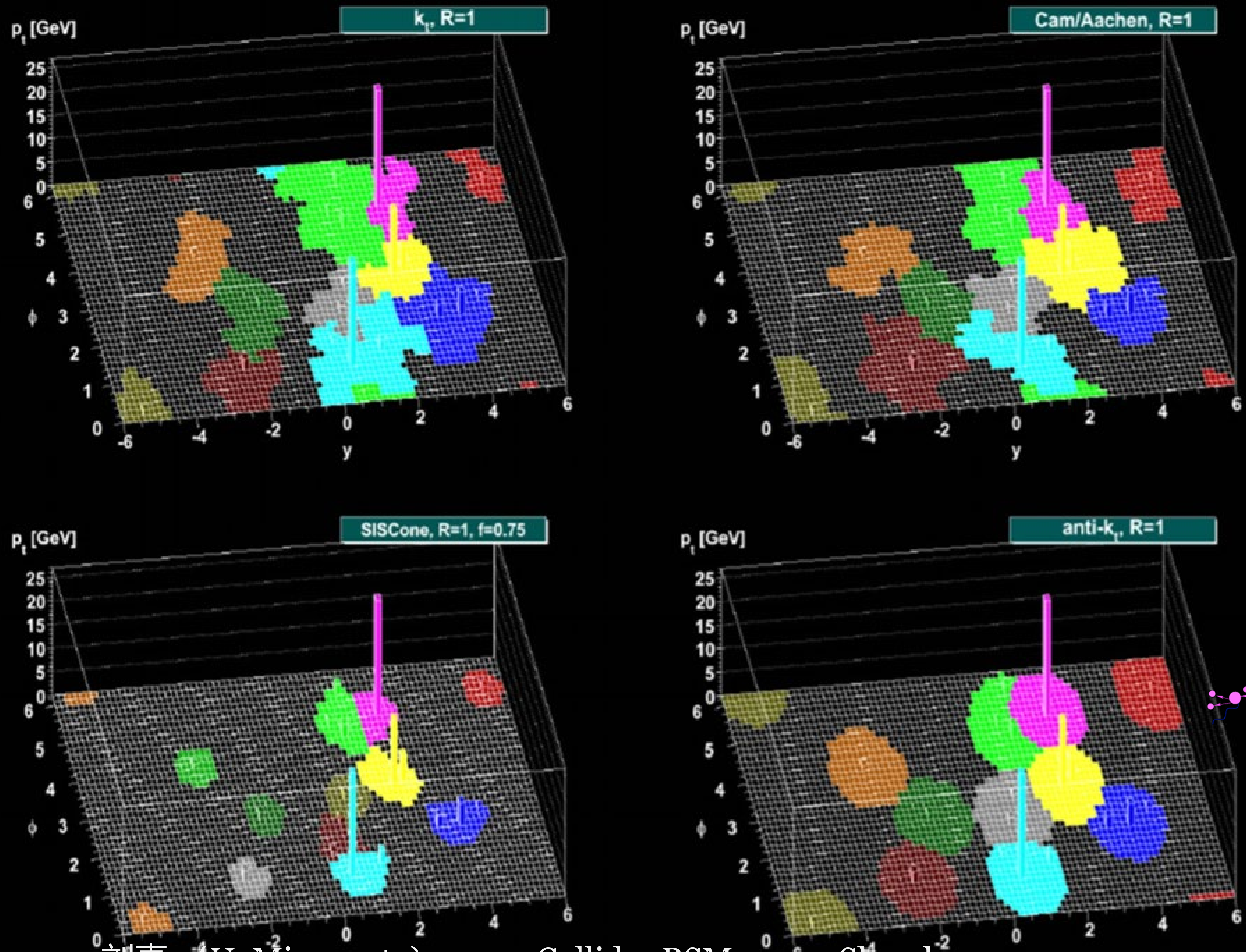
$$|\eta| > 3$$



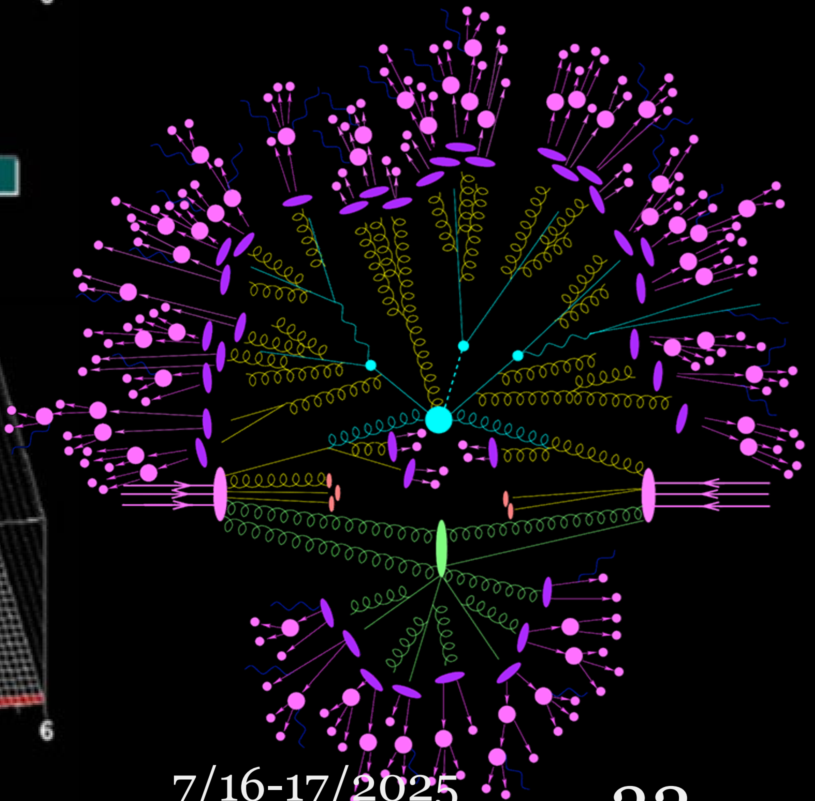




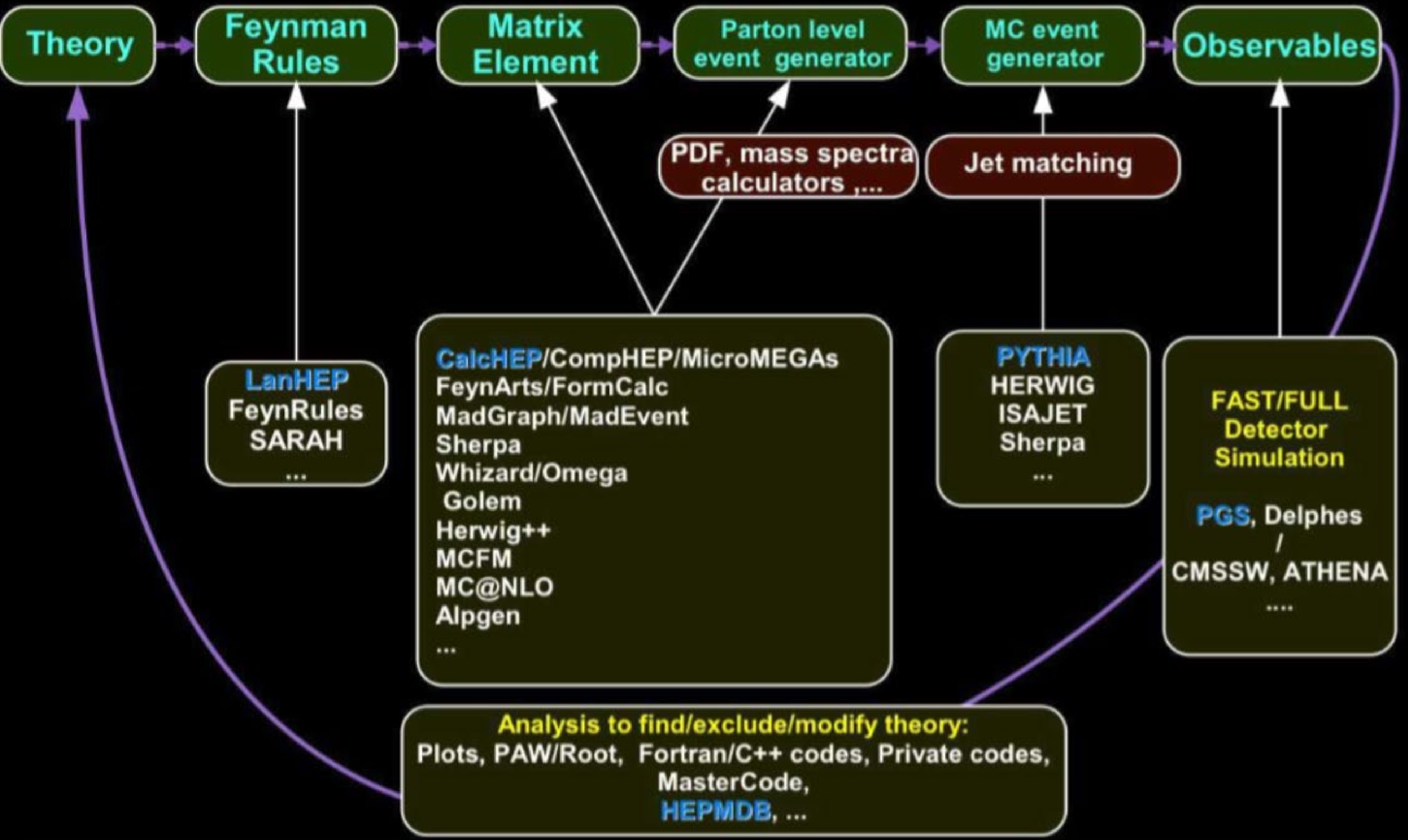
An Atlas event with two jets



Jet reconstruction algorithms
Pile-up removal
…



Phenomenological Studies

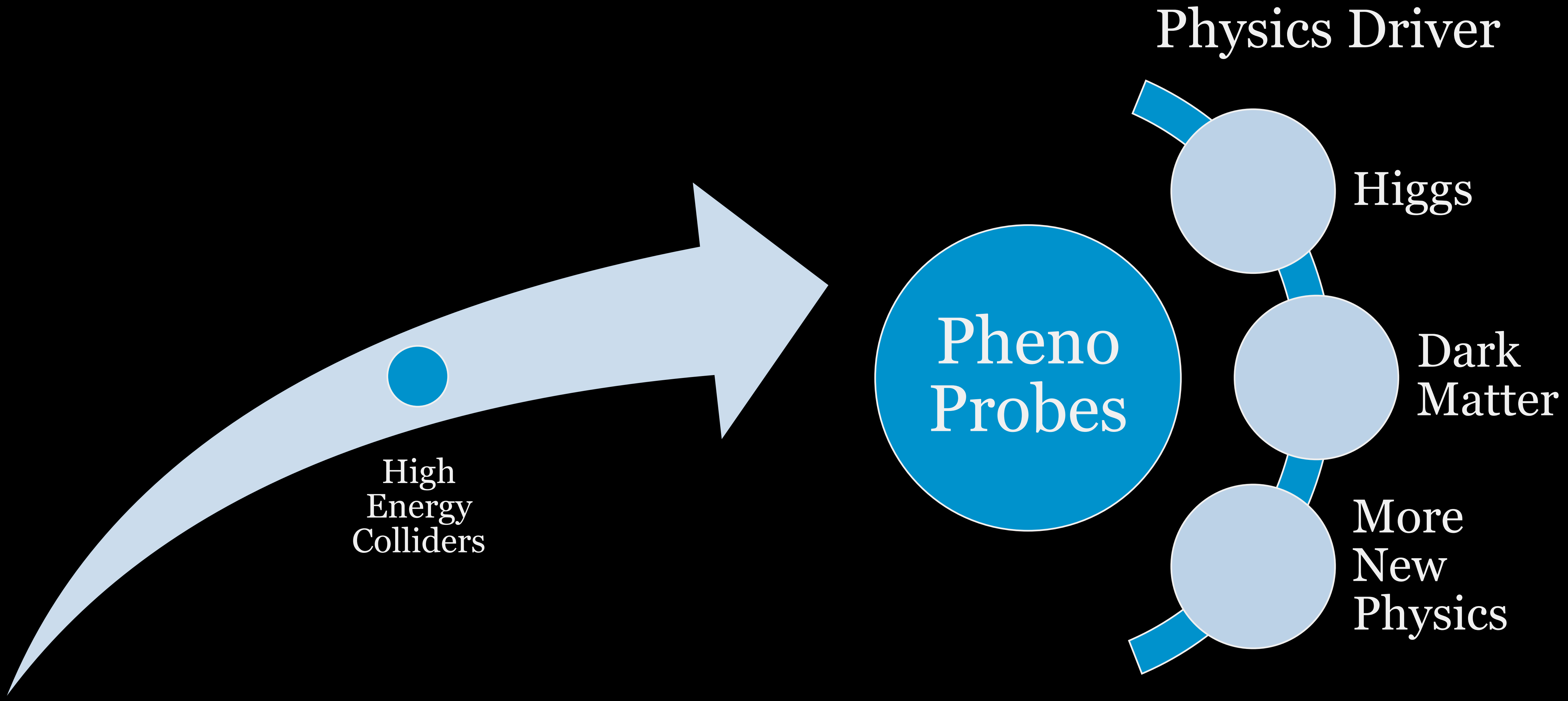


Recommend, use Madgraph and the tool-chains there*

Physics First (before trusting simulations due to complex nature of QFT).

*HELAS written at KEK

Landscape of High Energy Colliders



BSM @ LHC
A Snapshot

LHC rocks

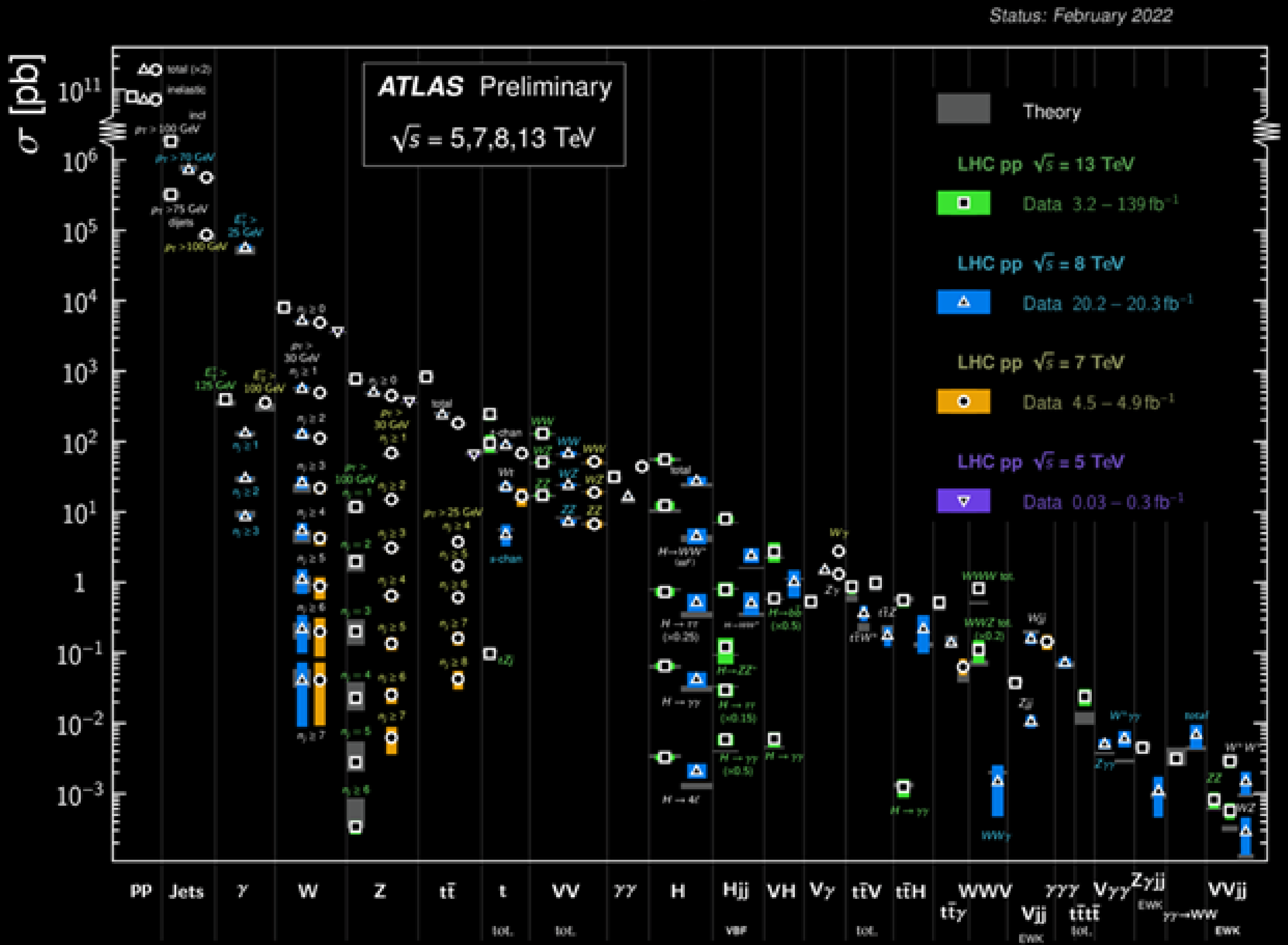
already revolutionized our understanding of microscopic world
and
will continue to deliver world-leading physics for the next ~20 yrs

LHC is running amazingly well

LHC's successes

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

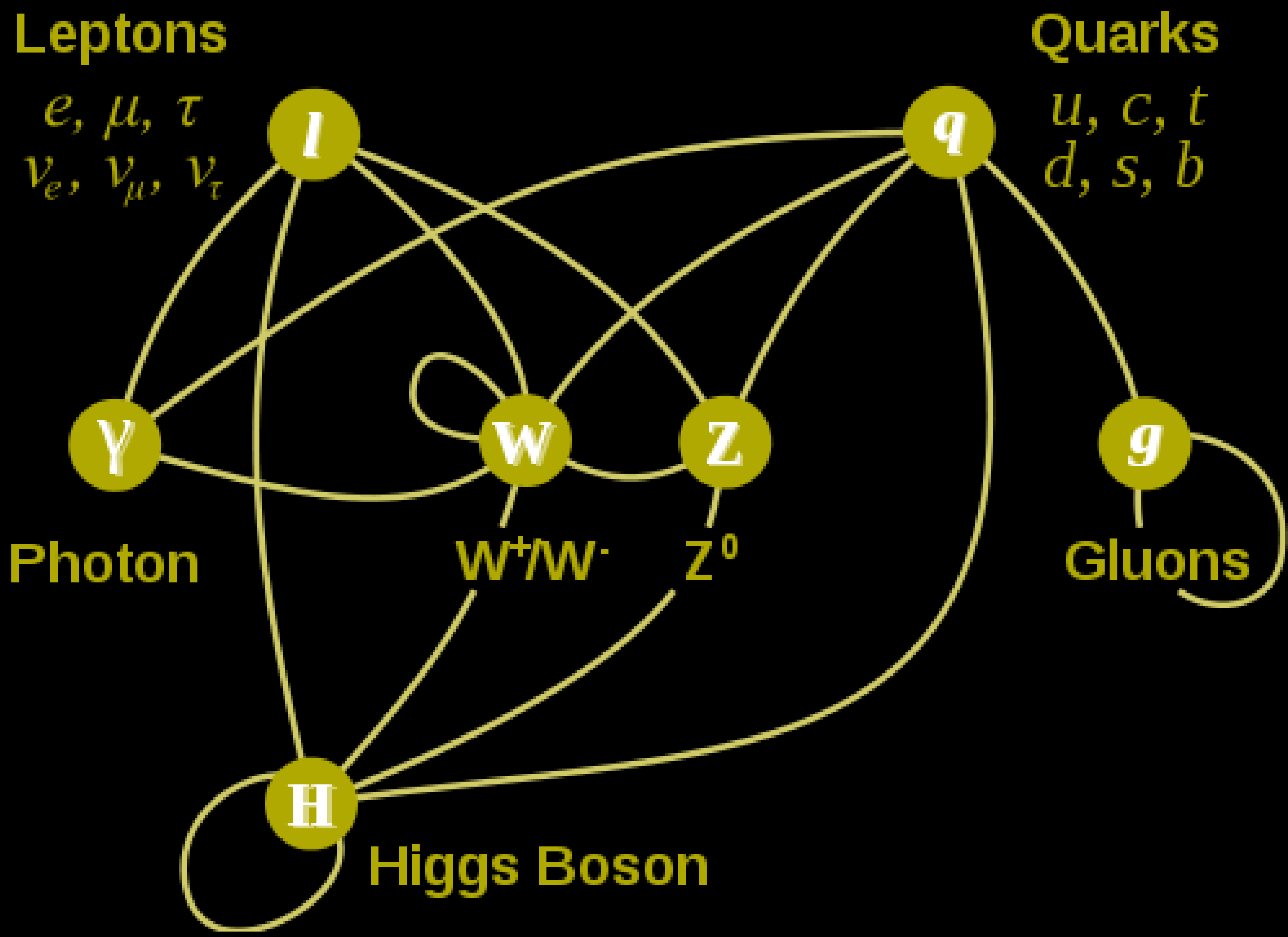
+new upgrades in Energy, Detector, Trigger, Analysis methods



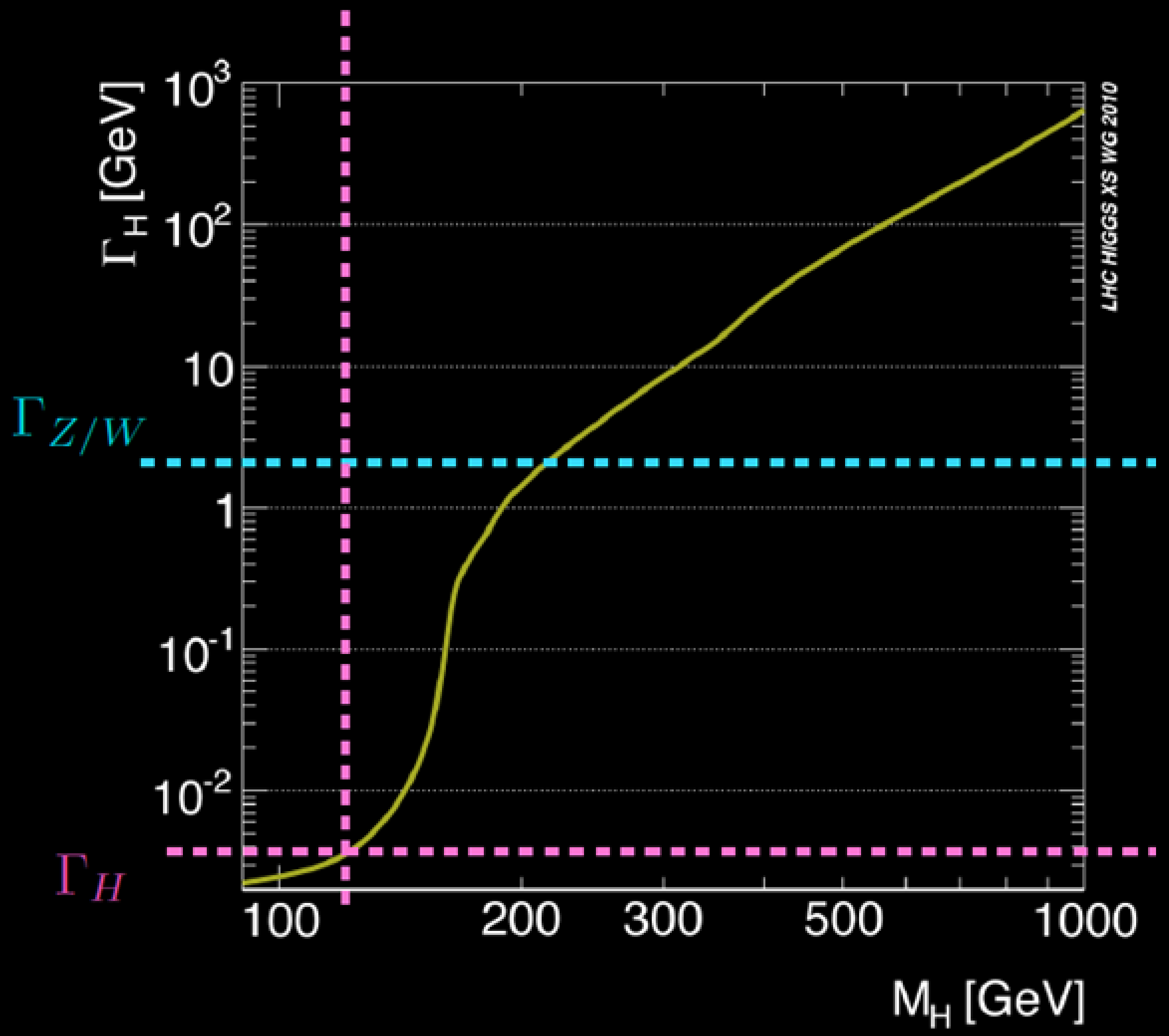
How did we DISCOVER Higgs?

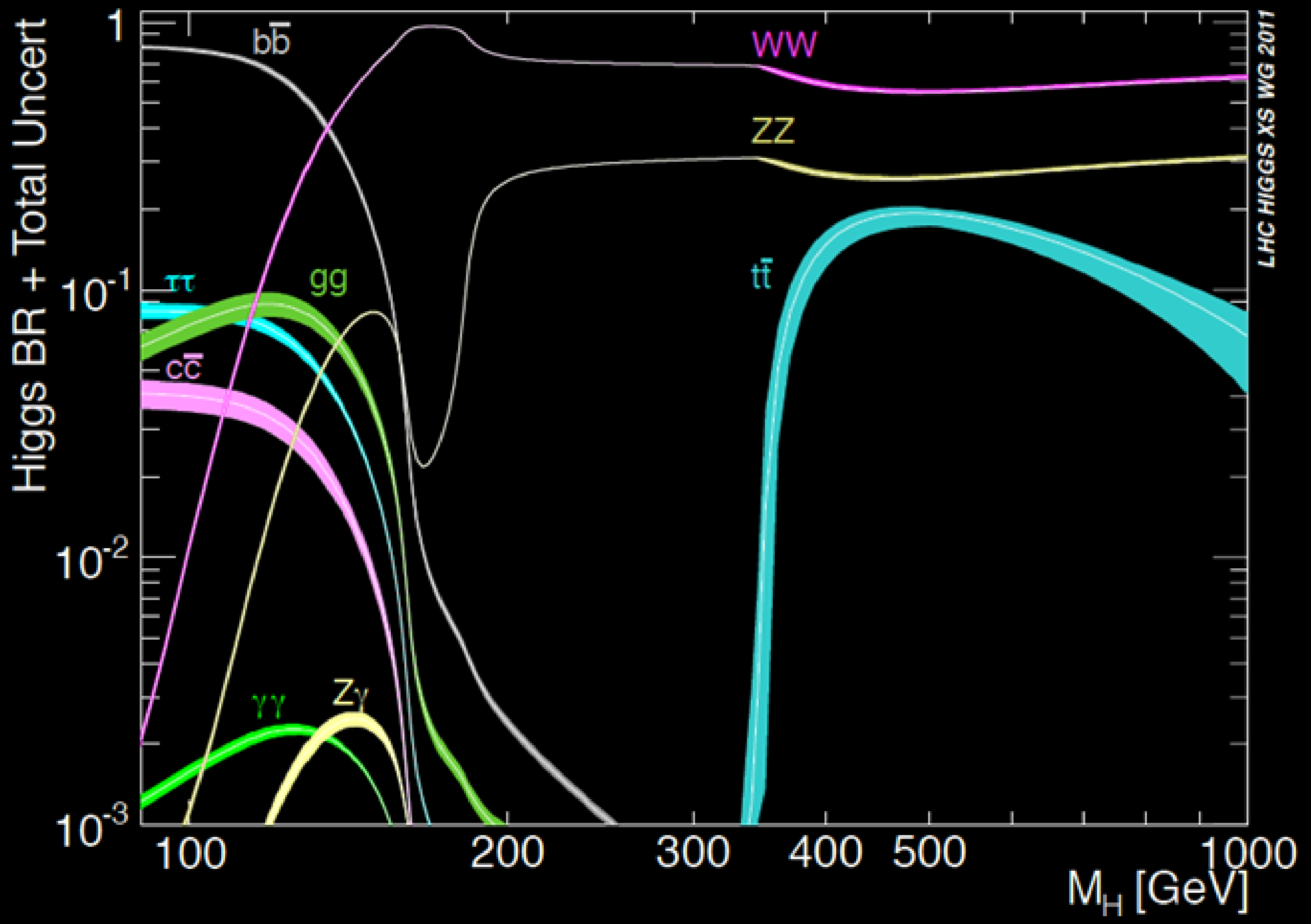
Higgs Couplings

- Gauge coupling
- Yukawa coupling—new forces (9+ Yukawas)
- Self coupling—new force
- Loop-induced (anomalous) couplings
  $H\gamma\gamma, Hgg, HZ\gamma, \ldots$



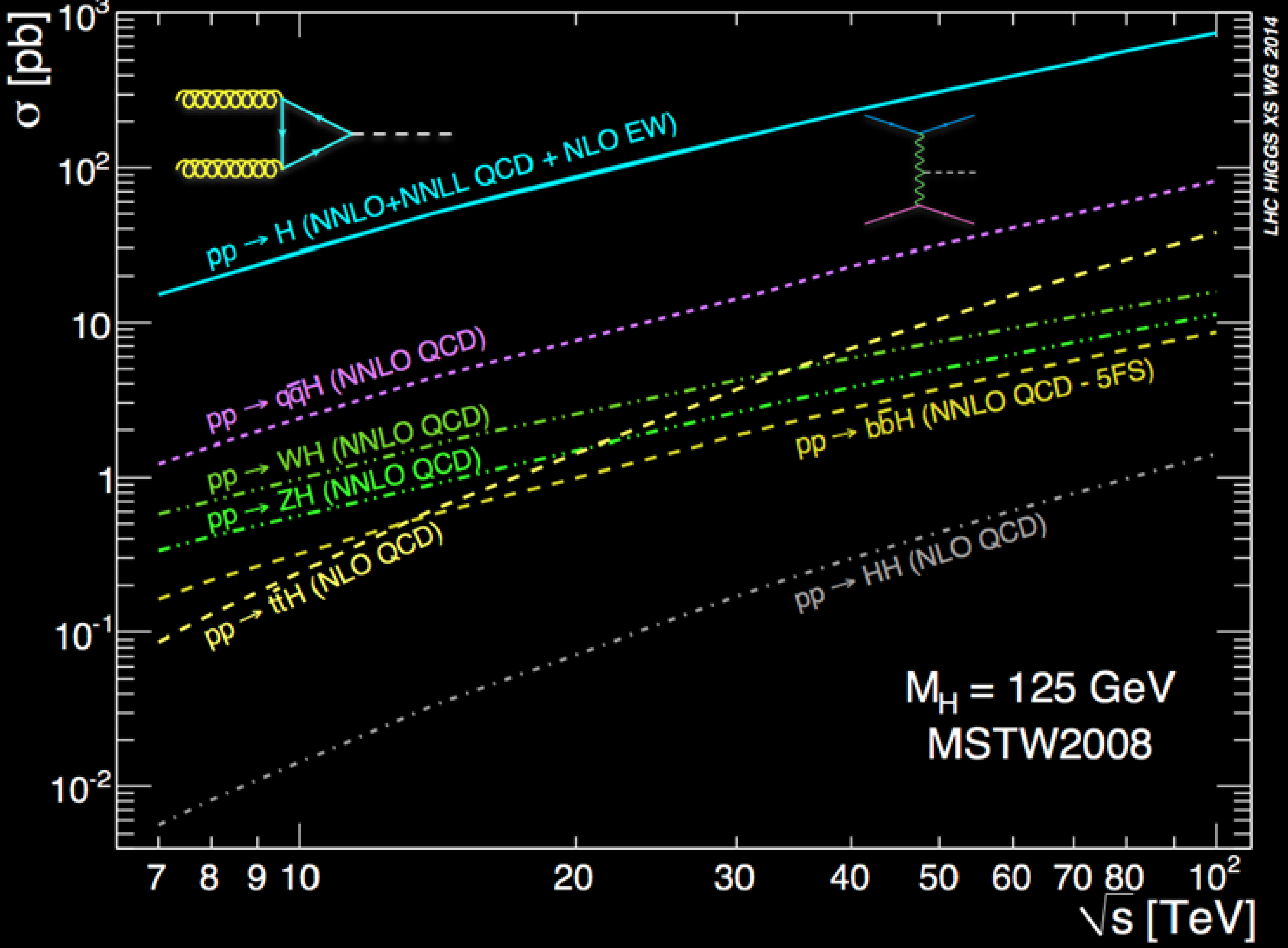
Higgs Width and Branching Fractions

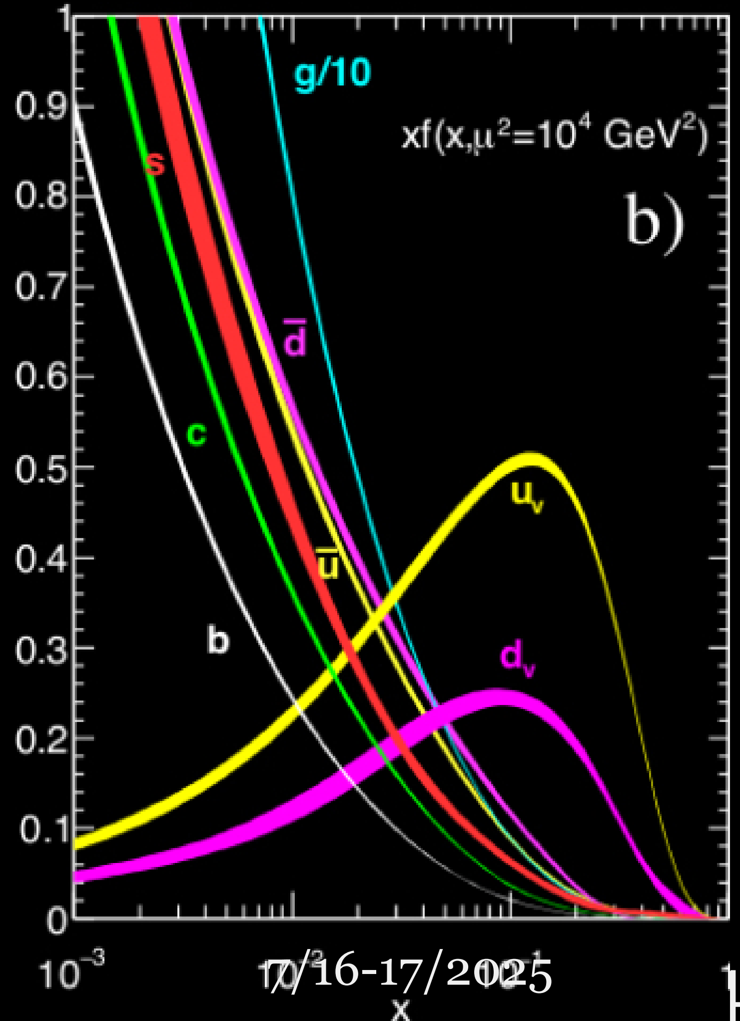




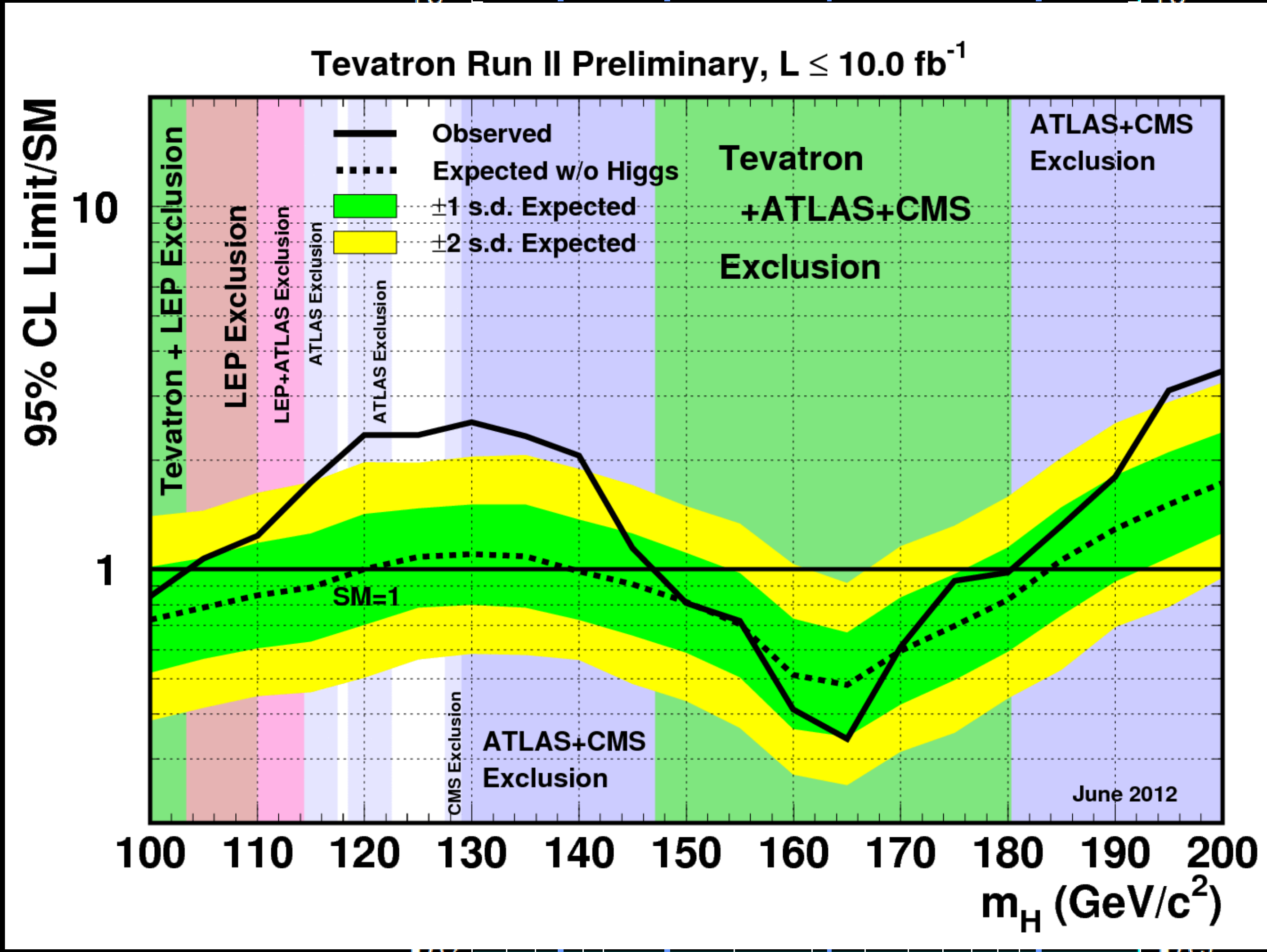
Higgs Physics

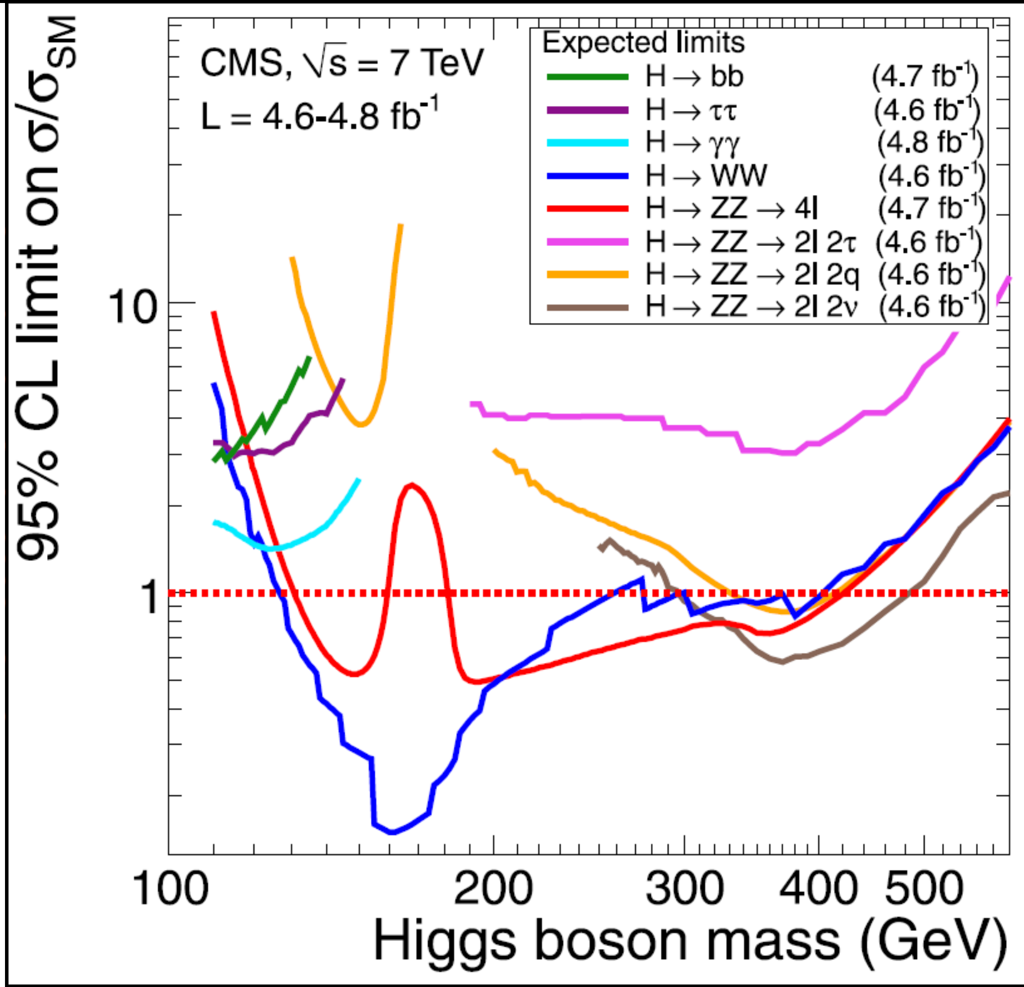
$$\sigma_{pp}^{NNLO}(gg \to H) = 12.937 \times (1 + 1.28 + 0.77)\, pb$$

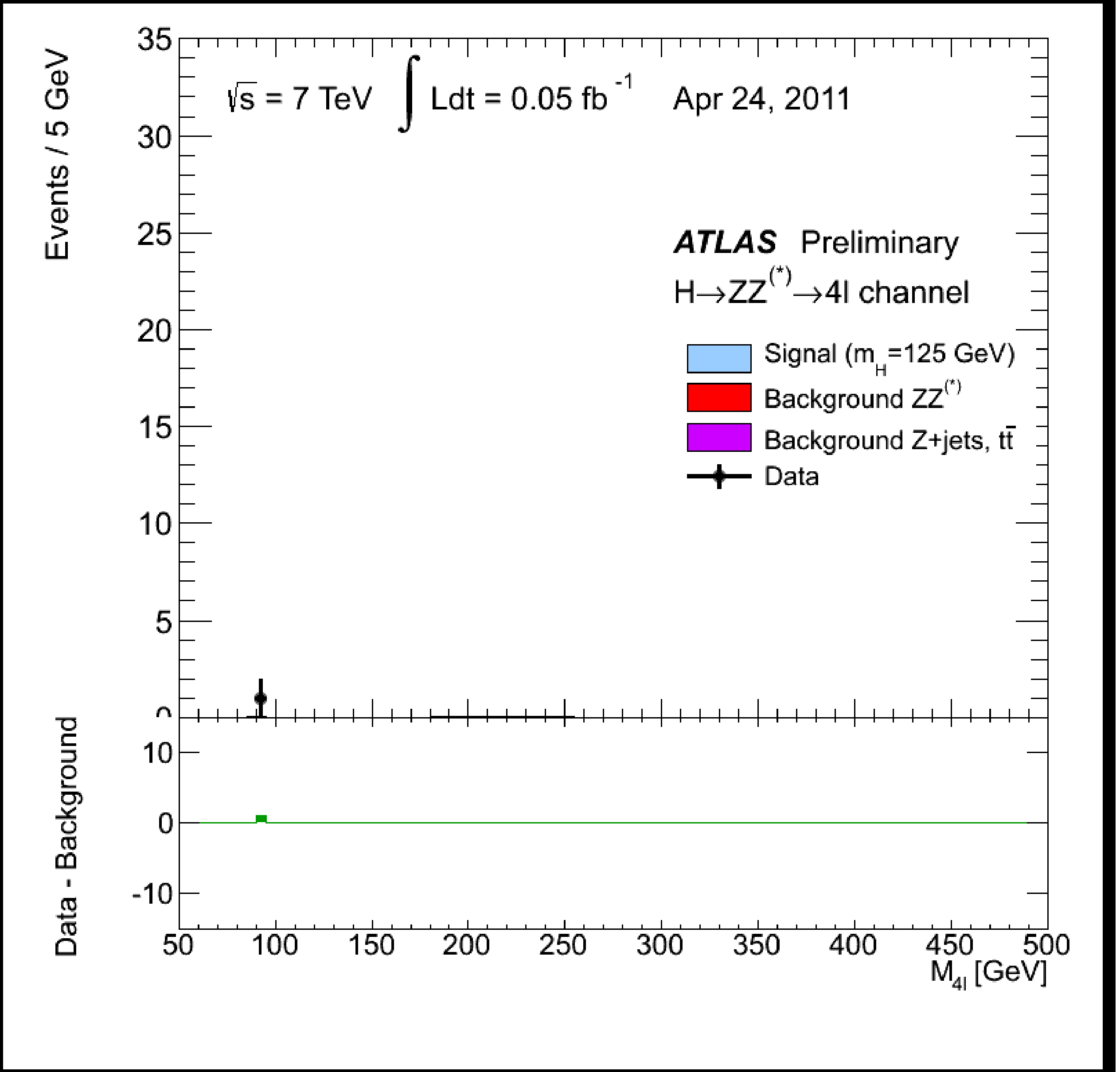


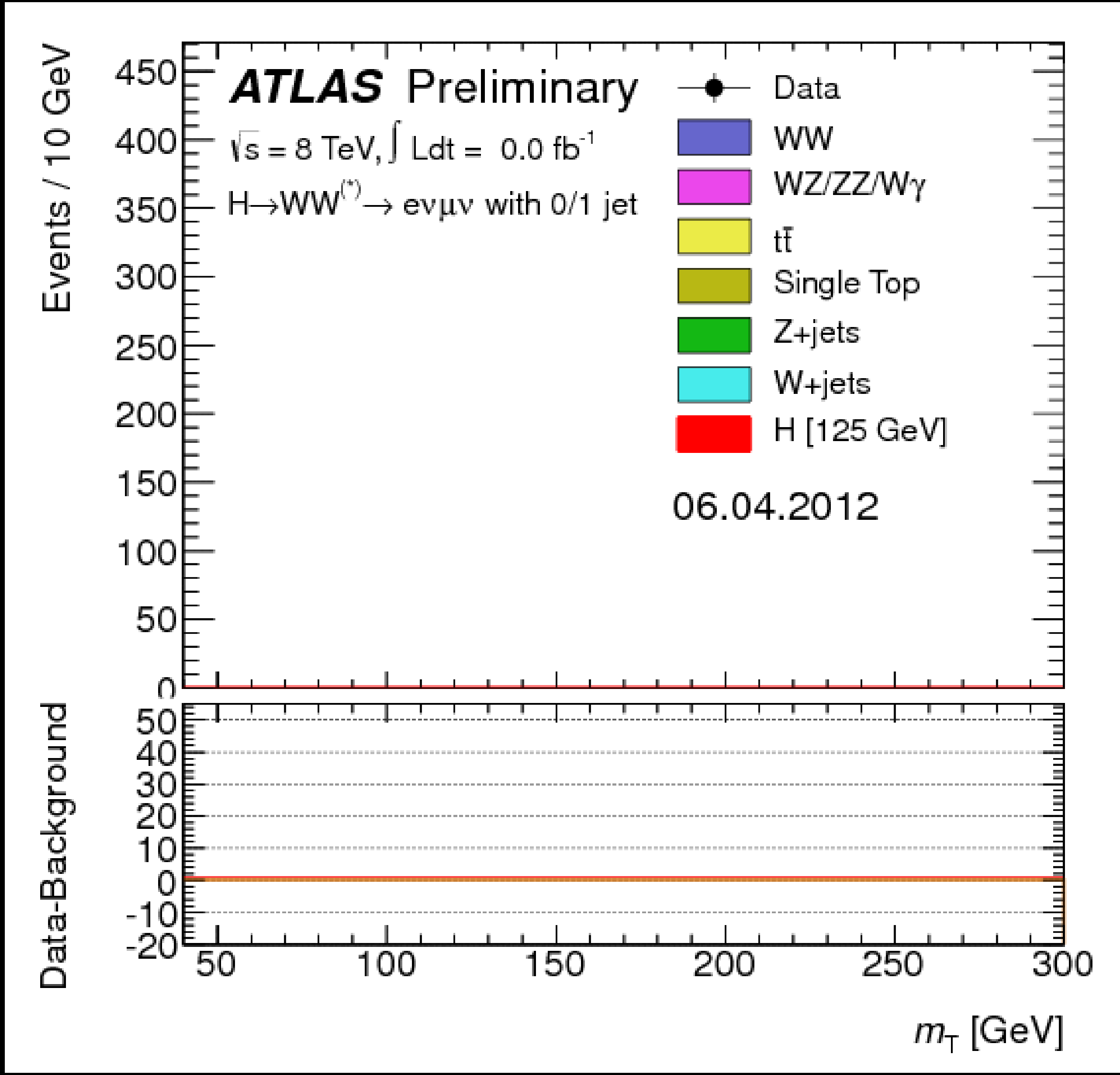


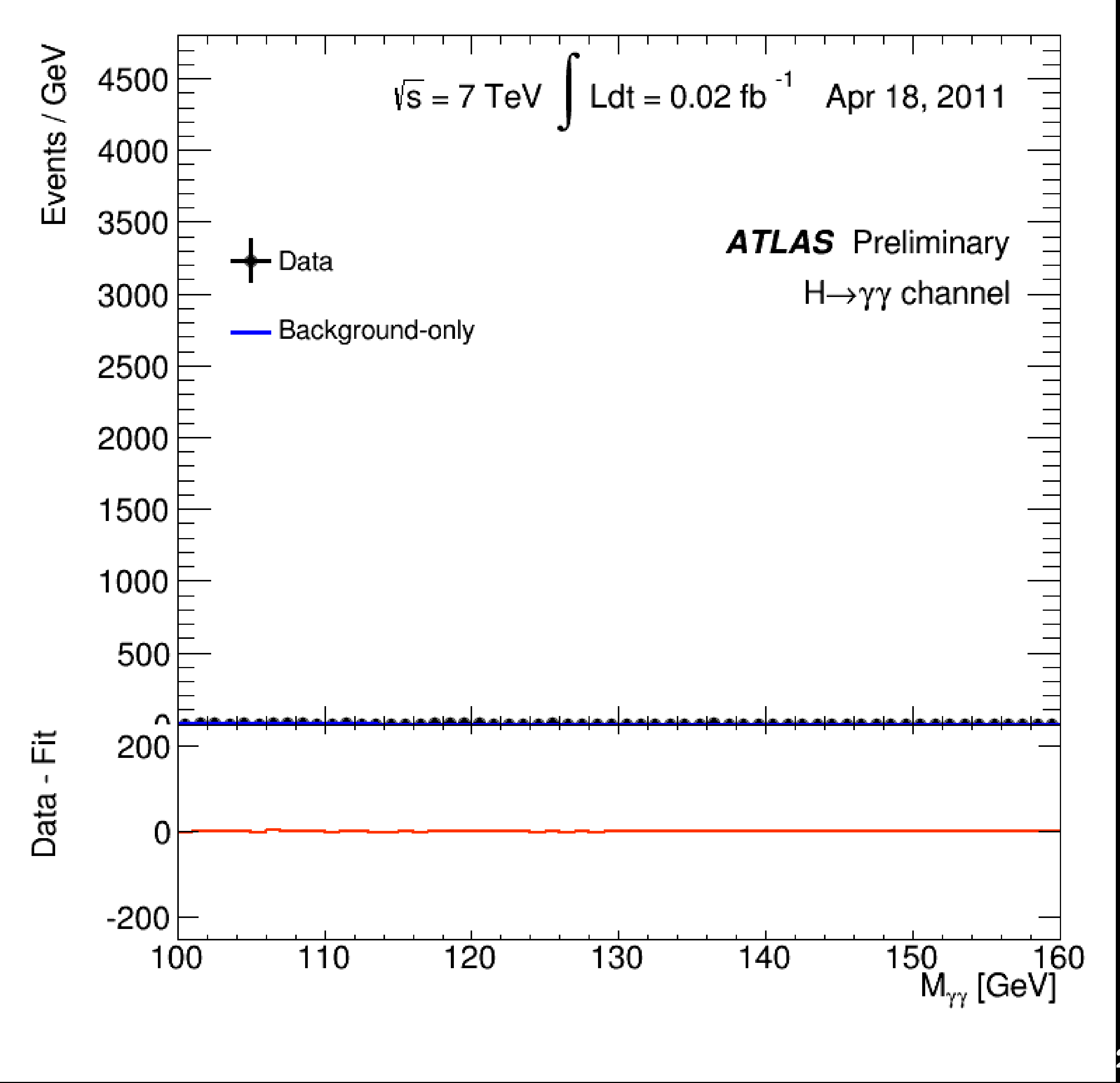
A snapshot before discovery






√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

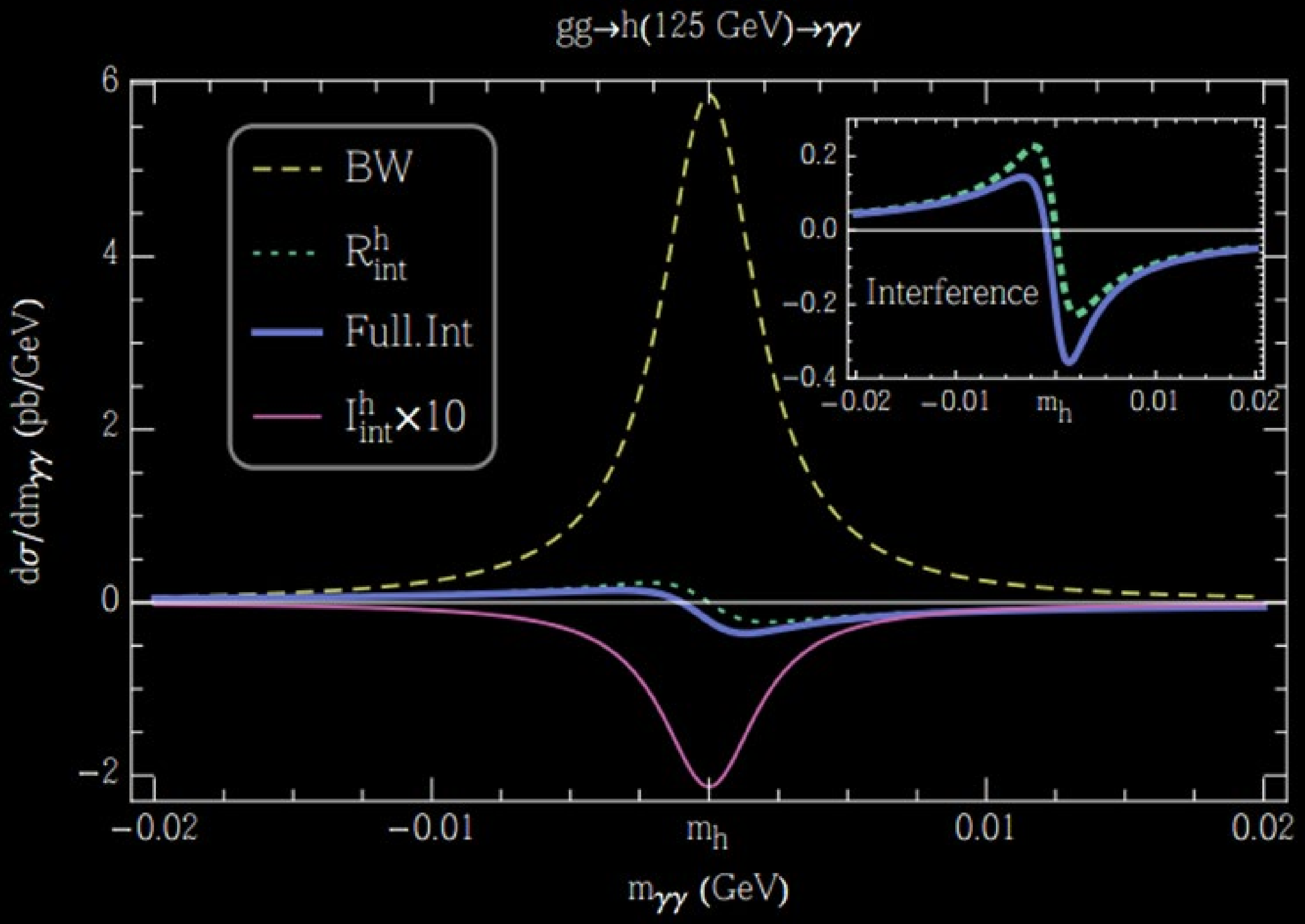

ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 0.0 fb-1
H→WW(*)→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
tt̄
Single Top
Z+jets
W+jets
H [125 GeV]
06.04.2012
Events / 10 GeV
Data-Background
mT [GeV]



$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

Did we do it right?
Will it be right?

More to explore, e.g., Higgs on-shell interference



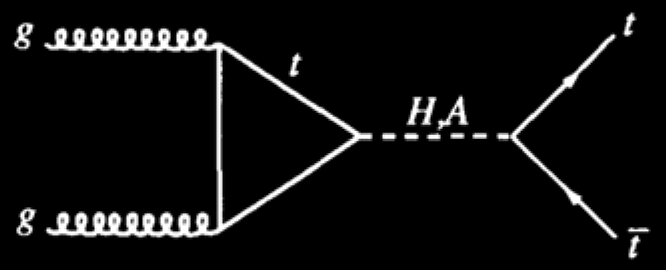
Non-factorizable into signal and background calculation, Pole-behavior matters (not standard EFT friendly);
Gain new information about width and strong & weak phase;
Interesting test for Interference.
Non-trivial quantum interference for on-shell states (which are typically ignored for heavy particles).

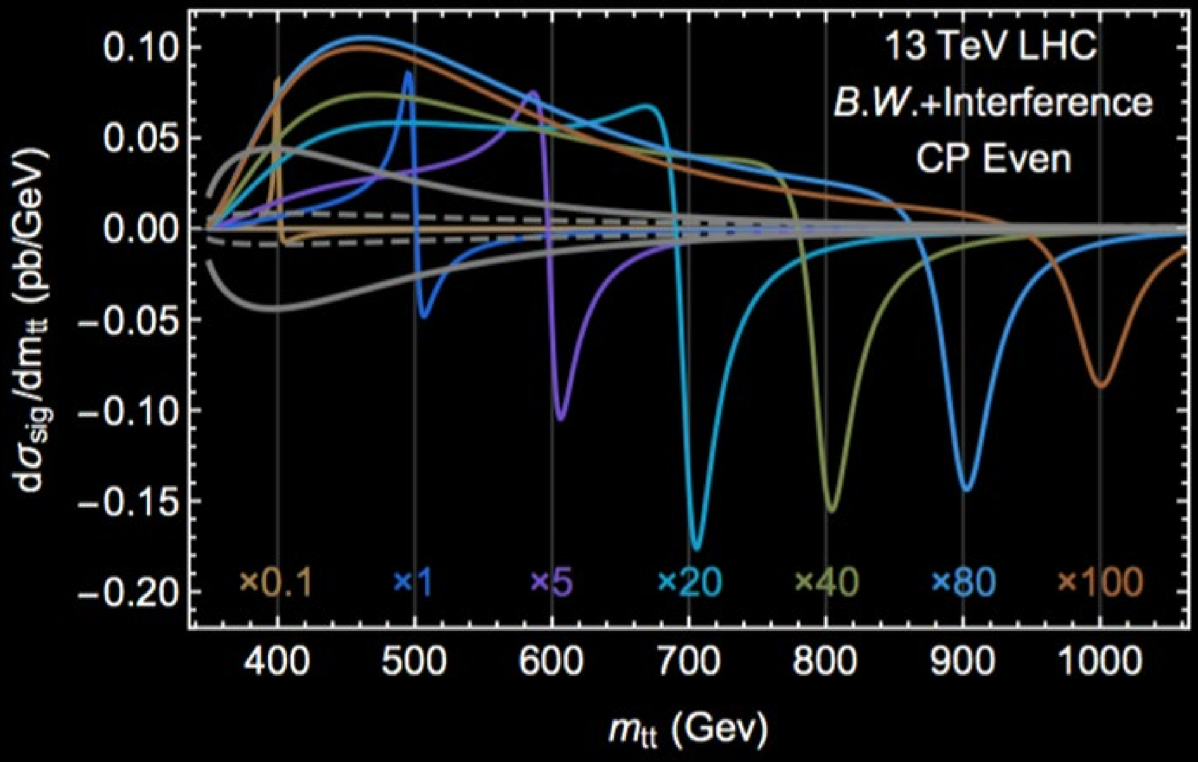
J. Campbell, M. Carena, R. Harnik, ZL, *PRL 18'*
Collaborating with R. Rusack group on CMS

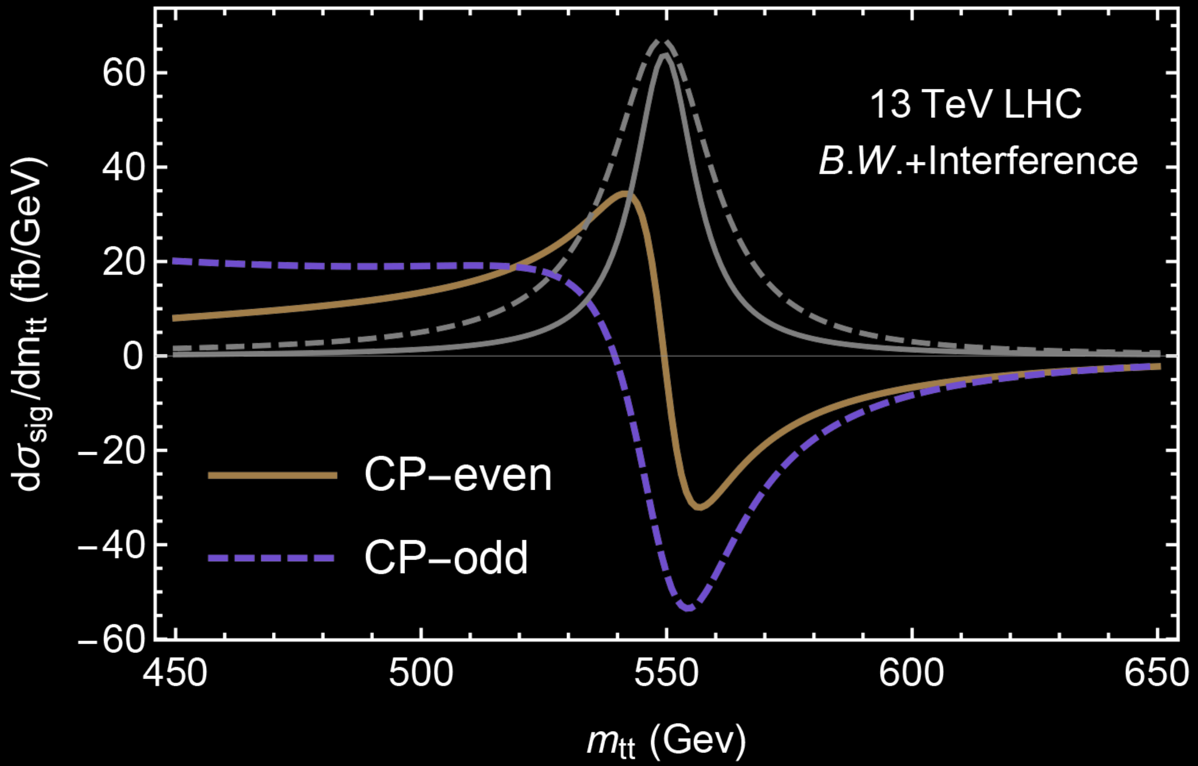
New scalar with constructive interference
M. Carena, ZL, M. Riembau, *PRD 18'*

New colored states with interference patterns
T. Han, I. Lewis, H.K. Liu, ZL, X. Wang, *JHEP 23'*

One Key ingredient (recent $\phi \to t\bar{t}$ search)

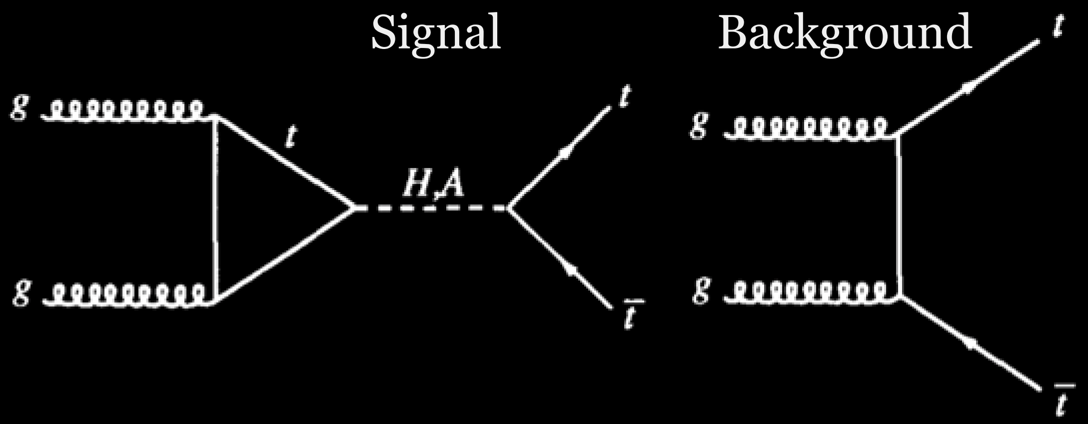


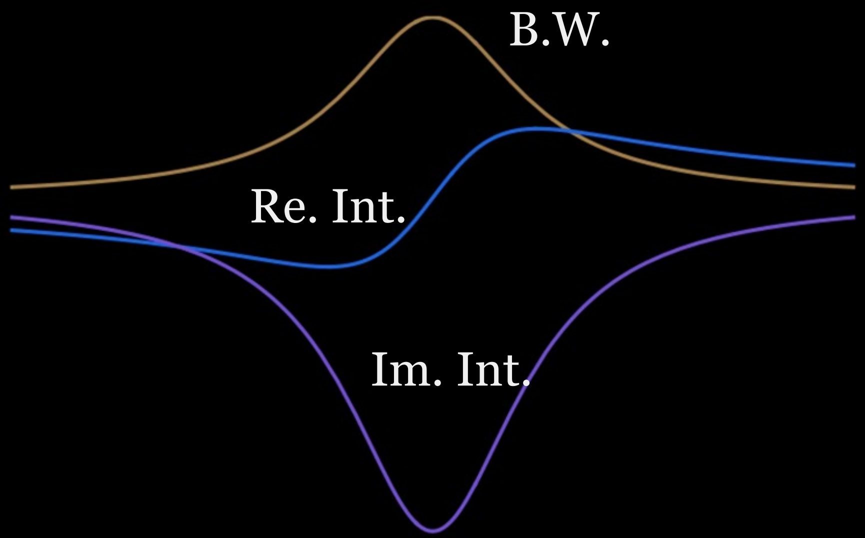


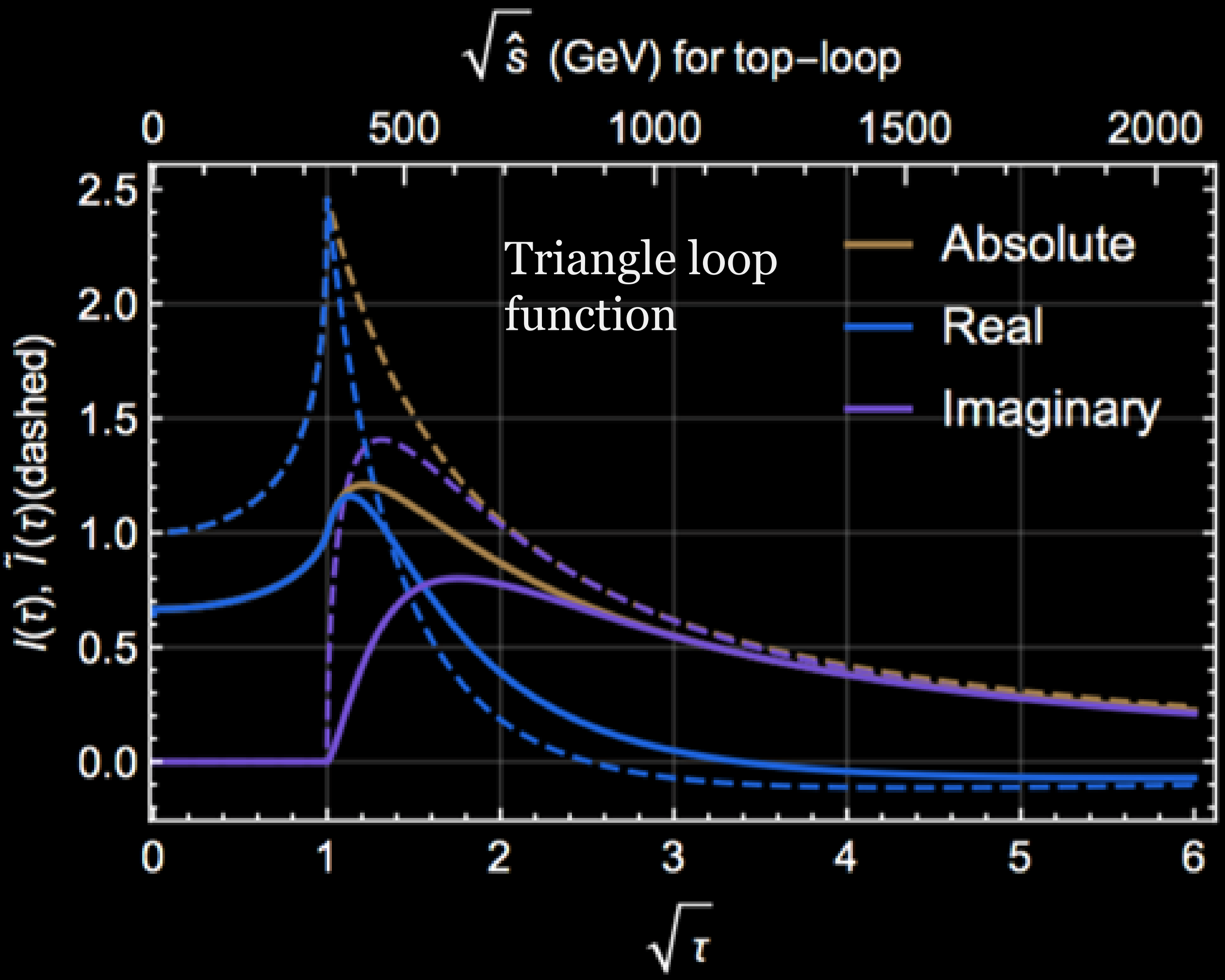


D. Dicus, A. Stange, S. Willenbrock, hep-ph/9404359, Focusing on ttbar @LHC, **M. Carena, ZL, arXiv:1608.07282** Other channels and effects, including ttH, tH (see in N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang arXiv:1504.04630 and J. Hajer, Y.-Y. Li, T. Liu J. Shiu arXiv:1504.07617, S. Gori, 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, and how stable such effects are against QCD corrections (see a case study in W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer arXiv:1511.05584), ttbar differential observables (W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer arXiv:1702.06063; W. Bernreuther, L. Chen, Z.-G. Si, [illegible]), Machine Learning,

Unfamiliar look of heavy Scalars

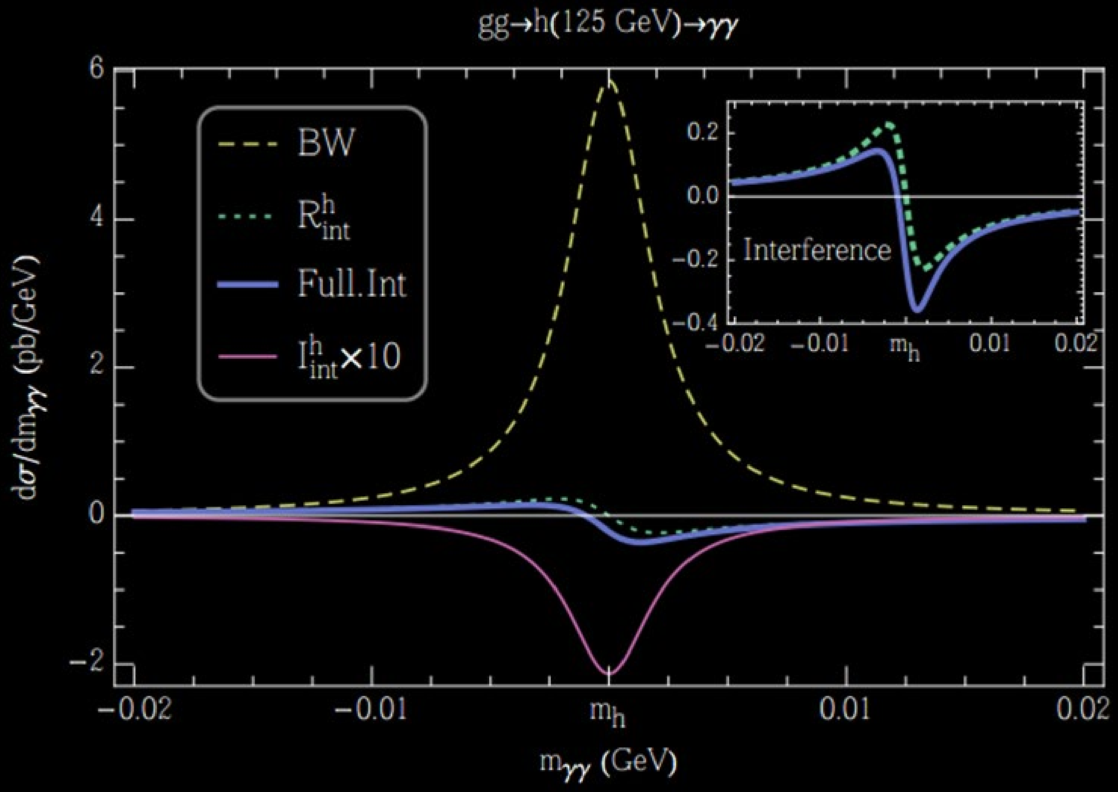




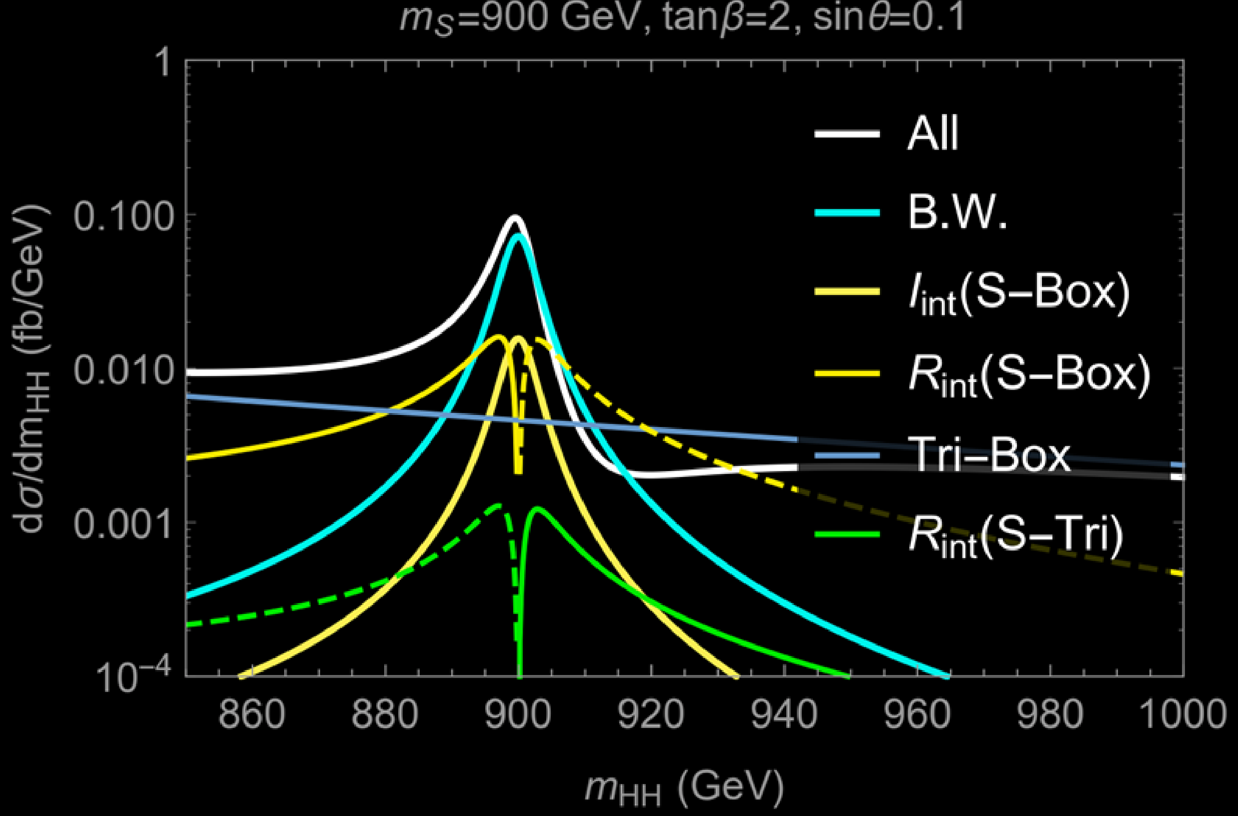


Interferences onsite

Non-factorizable into signal and background calculation, either described by standard EFT;
Gain new information about width and strong & weak phase;
Interesting test for Interference.



Dixon, Siu, hep-ph/0302233
Campbell, Carena, Harnik, ZL, 1704.08259
Cjeri, Coradeschi, de Florian, Fidanza, 1706.07331
Maltoni, Mandal, Zhao, 1812.08703
Chen, Heinrich, Jahn, Jones, Kerner, Schlenk, Yokoya 1911.09314
Hoche et al, in progress
Also (real-part interference): Dixon, Li, 1305.3854



Carena, ZL, Riembau, 1801.00794
Kauer, Lind, Maierhoefer, Song, 1905.03296
Other channels: Jung, Sung, Yoon, arXiv:1510.03450, arXiv:1601.00006, (dijets) Martin, 1606.03026, Bhattipirolu, Martin, 2004.06181 see Bhattiprolu's talk yesterday.

Physics-wise: where are we now?

A paradigm shift driven by LHC

Models solving multiple puzzle of Nature at once

➔

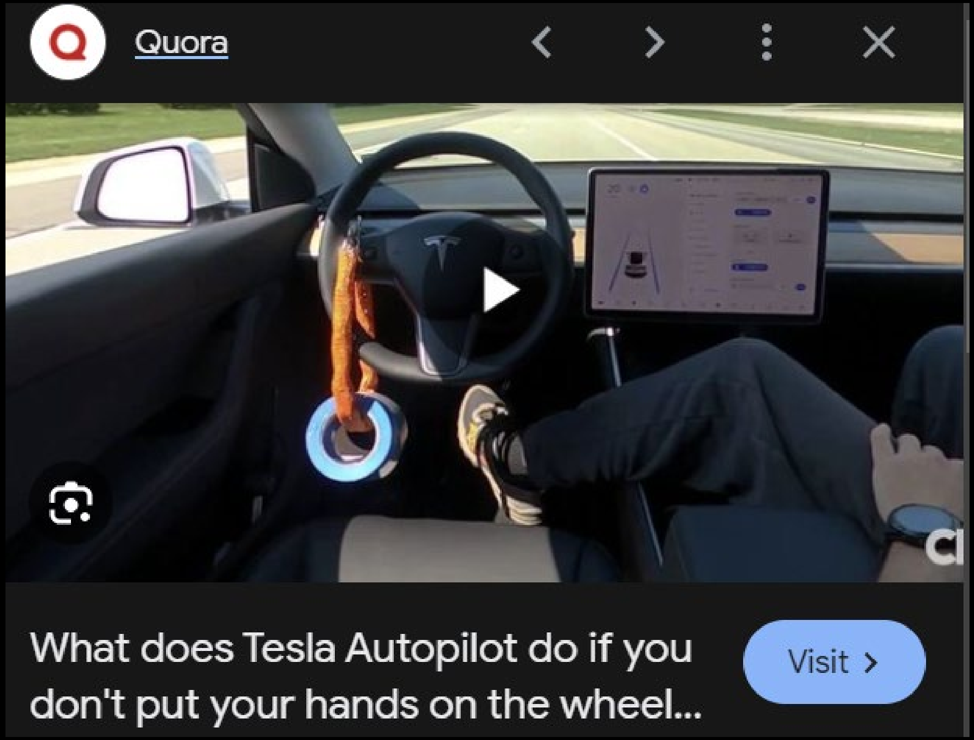
Models solving >=0 puzzles *but* raising new signatures that can be probed by experiments

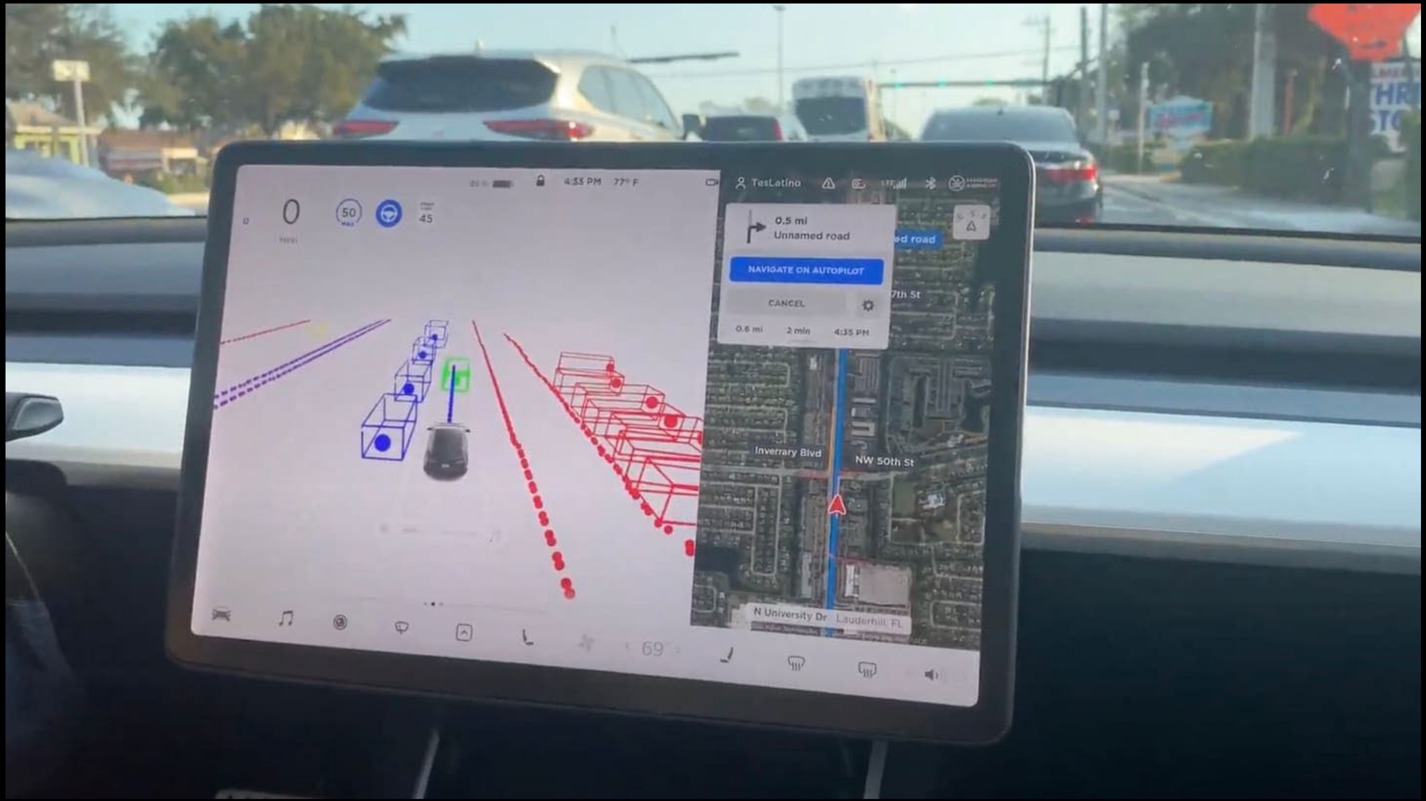
LHC experimental colleagues have been working hard and creatively on the more established model paradigms, steady & impressive progress all the time;

Our job becomes to Identify:

- new opportunities that are missed or overlooked;
- new important questions that could be answered;
- new interesting questions about particle physics;

Theorists now





But, LHC runs until 2040, we shall explore if we can get more from its precious data!

- Working hard to improve the theory prediction precision
- Laid back to be called for new results and anomalies
- (As it seems) There is nothing much more we can do (for the LHC)...
- Working hard planning and enabling future colliders

2025 年“微扰量子场论及其应用”前沿讲习班暨前沿研讨会

Collider probes for BSM physics
新物理对撞机图景

刘真

University of Minnesota

07/17/2025

Which boson* is least measured?

*To be more specific, which elementary (in the SM) unstable boson, candidates are W, Z, H

Z Boson

Z $J = 1$

See related reviews:

- Z Boson PDF
- Anomalous $ZZ\gamma$, $Z\gamma\gamma$, and ZZV Couplings PDF
- Anomalous W/Z Quartic Couplings (QGCs) PDF

Expand all sections

Z MASS	91.1876 ± 0.0021 GeV
Z WIDTH	2.4955 ± 0.0023 GeV
AVERAGE PARTICLE MULTIPLICITIES IN HADRONIC Z DECAY	
Z HADRONIC POLE CROSS SECTION	41.4802 ± 0.0325 nb
Z VECTOR COUPLINGS	
Z AXIAL-VECTOR COUPLINGS	
Z COUPLINGS TO NEUTRAL LEPTONS	
Z ASYMMETRY PARAMETERS	
TRANSVERSE SPIN CORRELATIONS IN $Z \to \tau^+\tau^-$	
FORWARD-BACKWARD $e^+ e^- \to f\bar{f}$ CHARGE ASYMMETRIES	
CHARGE ASYMMETRY IN $e^+ e^- \to q\bar{q}$	
CHARGE ASYMMETRY IN $p\,\bar{p} \to Z \to e^+ e^-$	
ANOMALOUS $ZZ\gamma$, $Z\gamma\gamma$, AND ZZV COUPLINGS	
ANOMALOUS W/Z QUARTIC COUPLINGS	
a_0/Λ^2, a_c/Λ^2	

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	e^+e^-	[1]	$(3.3632 \pm 0.0042)\%$		45594
Γ_2	$\mu^+\mu^-$	[1]	$(3.3662 \pm 0.0066)\%$		45594
Γ_3	$\tau^+\tau^-$	[1]	$(3.3696 \pm 0.0083)\%$		45559
Γ_4	$\ell^+\ell^-$	[2][1]	$(3.3658 \pm 0.0023)\%$		
Γ_5	$\mu^+\mu^-\mu^+\mu^-$				45593
Γ_6	$\ell^+\ell^-\ell^+\ell^-$	[3]	$(4.55 \pm 0.17) \times 10^{-6}$		45594
Γ_7	invisible	[1]	$(20.000 \pm 0.055)\%$		
Γ_8	hadrons	[1]	$(69.911 \pm 0.056)\%$		
Γ_9	$(u\bar{u} + c\bar{c})/2$		$(11.6 \pm 0.6)\%$		
Γ_{10}	$(d\bar{d} + s\bar{s} + b\bar{b})/3$		$(15.6 \pm 0.4)\%$		
Γ_{11}	$c\bar{c}$		$(12.03 \pm 0.21)\%$		
Γ_{12}	$b\bar{b}$		$(15.12 \pm 0.05)\%$		
Γ_{13}	$b\bar{b}b\bar{b}$		$(3.6 \pm 1.3) \times 10^{-4}$		
Γ_{14}	ggg		$< 1.1\%$	CL=95%	
Γ_{15}	$\pi^0\gamma$		$< 2.01 \times 10^{-5}$	CL=95%	45594
Γ_{16}	$\eta\gamma$		$< 5.1 \times 10^{-5}$	CL=95%	45592
Γ_{17}	$\rho^0\gamma$		$< 2.5 \times 10^{-5}$	CL=95%	45591
Γ_{18}	$\omega\gamma$		$< 6.5 \times 10^{-4}$	CL=95%	45590
Γ_{19}	$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	CL=95%	45589
Γ_{20}	$\phi\gamma$		$< 9 \times 10^{-7}$	CL=95%	45588
Γ_{21}	$\gamma\gamma$		$< 1.46 \times 10^{-5}$	CL=95%	45594
Γ_{22}	$\pi^0\pi^0$		$< 1.52 \times 10^{-5}$	CL=95%	45594
Γ_{23}	$\gamma\gamma\gamma$		$< 2.2 \times 10^{-6}$	CL=95%	45594
Γ_{24}	$\pi^\pm W^\mp$	[4]	$< 7 \times 10^{-5}$	CL=95%	10169
Γ_{25}	$\rho^\pm W^\mp$	[4]	$< 8.3 \times 10^{-5}$	CL=95%	10143
Γ_{26}	$J/\psi(1S)$ X		$(3.51^{+0.23}_{-0.25}) \times 10^{-3}$	S=1.1	

Z Boson

	Mode		Ref.	Fraction	Confidence level	
Γ_{55}	Ξ_b X			seen		
Γ_{56}	b -baryon X		[5]	$(1.38 \pm 0.22)\%$		
Γ_{57}	anomalous γ + hadrons		[6]	$< 3.2 \times 10^{-3}$	CL=95%	
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
Γ_{61}	$\ell^+\ell^-\gamma\gamma$		[7]	$< 6.8 \times 10^{-6}$	CL=95%	
Γ_{62}	$q\bar{q}\gamma\gamma$		[7]	$< 5.5 \times 10^{-6}$	CL=95%	
Γ_{63}	$\nu\bar{\nu}\gamma\gamma$		[7]	$< 3.1 \times 10^{-6}$	CL=95%	45594
Γ_{64}	$e^\pm\mu^\mp$	*LF*	[4]	$< 7.5 \times 10^{-7}$	CL=95%	45594
Γ_{65}	$e^\pm\tau^\mp$	*LF*	[4]	$< 5.0 \times 10^{-6}$	CL=95%	45576
Γ_{66}	$\mu^\pm\tau^\mp$	*LF*	[4]	$< 6.5 \times 10^{-6}$	CL=95%	45576
Γ_{67}	pe	*B, L*		$< 1.8 \times 10^{-6}$	CL=95%	45589
Γ_{68}	$p\mu$	*B, L*		$< 1.8 \times 10^{-6}$	CL=95%	45589

	Mode	Ref.	Fraction	Confidence level	
Γ_{27}	$J/\psi(1S)\gamma$		$< 1.4 \times 10^{-6}$	CL=95%	45541
Γ_{28}	$\psi(2S)$ X		$(1.60 \pm 0.29) \times 10^{-3}$		
Γ_{29}	$\psi(2S)\gamma$		$< 4.5 \times 10^{-6}$	CL=95%	45519
Γ_{30}	$J/\psi(1S)\ell^+\ell^-$				45541
Γ_{31}	$J/\psi(1S)J/\psi(1S)$		$< 2.2 \times 10^{-6}$	CL=95%	45489
Γ_{32}	$\chi_{c1}(1P)$ X		$(2.9 \pm 0.7) \times 10^{-3}$		
Γ_{33}	$\chi_{c2}(1P)$ X		$< 3.2 \times 10^{-3}$	CL=90%	
Γ_{34}	$\Upsilon(1S)$ X $+\Upsilon(2S)$ X $+\Upsilon(3S)$ X		$(1.0 \pm 0.5) \times 10^{-4}$		
Γ_{35}	$\Upsilon(1S)$ X		$< 4.4 \times 10^{-5}$	CL=95%	
Γ_{36}	$\Upsilon(1S)\gamma$		$< 2.8 \times 10^{-6}$	CL=95%	45103
Γ_{37}	$\Upsilon(2S)$ X		$< 1.39 \times 10^{-4}$	CL=95%	
Γ_{38}	$\Upsilon(2S)\gamma$		$< 1.7 \times 10^{-6}$	CL=95%	45043
Γ_{39}	$\Upsilon(3S)$ X		$< 9.4 \times 10^{-5}$	CL=95%	
Γ_{40}	$\Upsilon(3S)\gamma$		$< 4.8 \times 10^{-6}$	CL=95%	45006
Γ_{41}	$\Upsilon(1,2,3S)\Upsilon(1,2,3S)$		$< 1.5 \times 10^{-6}$	CL=95%	
Γ_{42}	$(D^0/\overline{D}^0)$ X		$(20.7 \pm 2.0)\%$		
Γ_{43}	$D^\pm$ X		$(12.2 \pm 1.7)\%$		
Γ_{44}	$D^*(2010)^\pm$ X	[4]	$(11.4 \pm 1.3)\%$		
Γ_{45}	$D_{s1}(2536)^\pm$ X		$(3.6 \pm 0.8) \times 10^{-3}$		
Γ_{46}	$D_{sJ}(2573)^\pm$ X		$(5.8 \pm 2.2) \times 10^{-3}$		
Γ_{47}	$D^{*\prime}(2629)^\pm$ X		searched for		
Γ_{48}	B X				
Γ_{49}	B^* X				
Γ_{50}	B^+ X	[5]	$(6.08 \pm 0.13)\%$		
Γ_{51}	B_s^0 X	[5]	$(1.59 \pm 0.13)\%$		
Γ_{52}	B_c^+ X		searched for		
Γ_{53}	Λ_c^+ X		$(1.54 \pm 0.33)\%$		
Γ_{54}	Ξ_c^0 X		seen		

Higgs Boson

H DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	WW^*		$(25.7 \pm 2.5)\%$		
Γ_2	ZZ^*		$(2.80 \pm 0.30)\%$		
Γ_3	$\gamma\gamma$		$(2.50 \pm 0.20) \times 10^{-3}$		62625
Γ_4	$b\bar{b}$		$(53 \pm 8)\%$		
Γ_5	e^+e^-		$< 3.6 \times 10^{-4}$	CL=95%	62625
Γ_6	$\mu^+\mu^-$		$(2.6 \pm 1.3) \times 10^{-4}$		62625
Γ_7	$\tau^+\tau^-$		$(6.0^{+0.8}_{-0.7})\%$		62600
Γ_8	$Z\gamma$		$(3.2 \pm 1.5) \times 10^{-3}$		29431
Γ_9	$Z\rho(770)$		$< 1.21\%$	CL=95%	29423
Γ_{10}	$Z\phi(1020)$		$< 3.6 \times 10^{-3}$	CL=95%	29417
Γ_{11}	$Z\eta_c$				29315
Γ_{12}	ZJ/ψ				29306
Γ_{13}	$J/\psi\gamma$		$< 3.5 \times 10^{-4}$	CL=95%	62587
Γ_{14}	$J/\psi J/\psi$		$< 1.8 \times 10^{-3}$	CL=95%	62548
Γ_{15}	$\psi(2S)\gamma$		$< 2.0 \times 10^{-3}$	CL=95%	62571
Γ_{16}	$\Upsilon(1S)\gamma$		$< 4.9 \times 10^{-4}$	CL=95%	62268
Γ_{17}	$\Upsilon(2S)\gamma$		$< 5.9 \times 10^{-4}$	CL=95%	62224
Γ_{18}	$\Upsilon(3S)\gamma$		$< 5.7 \times 10^{-4}$	CL=95%	62197
Γ_{19}	$\Upsilon(nS)\Upsilon(mS)$		$< 1.4 \times 10^{-3}$	CL=95%	
Γ_{20}	$\rho(770)\gamma$		$< 8.8 \times 10^{-4}$	CL=95%	62623
Γ_{21}	$\phi(1020)\gamma$		$< 4.8 \times 10^{-4}$	CL=95%	62621
Γ_{22}	$e\mu$	LF	$< 6.1 \times 10^{-5}$	CL=95%	62625
Γ_{23}	$e\tau$	LF	$< 2.2 \times 10^{-3}$	CL=95%	62612
Γ_{24}	$\mu\tau$	LF	$< 1.5 \times 10^{-3}$	CL=95%	62612
Γ_{25}	invisible		$< 13\%$	CL=95%	
Γ_{26}	γ invisible		$< 2.9\%$	CL=95%	

H MASS	125.25 ± 0.17 GeV (S = 1.5)
H SPIN AND CP PROPERTIES	
H DECAY WIDTH	$3.2^{+2.4}_{-1.7}$ MeV
H SIGNAL STRENGTHS IN DIFFERENT CHANNELS	
Combined Final States	1.03 ± 0.04
WW^* Final State	1.00 ± 0.08
ZZ^* Final State	1.02 ± 0.08
$\gamma\gamma$ Final State	1.10 ± 0.07
$c\bar{c}$ Final State	8 ± 22 (S = 1.9)
$b\bar{b}$ Final State	0.99 ± 0.12
$\mu^+\mu^-$ Final State	1.21 ± 0.35
$\tau^+\tau^-$ Final State	0.91 ± 0.09
$Z\gamma$ Final State	
$\gamma^*\gamma$ Final State	1.5 ± 0.5
Higgs couplings	
Fermion coupling (κ_F)	0.95 ± 0.05
Gauge boson coupling (κ_V)	1.035 ± 0.031
W boson coupling (κ_W)	
Z boson coupling (κ_Z)	
top Yukawa coupling (κ_t)	
bottom Yukawa coupling (κ_b)	
charm Yukawa coupling (κ_c)	
tau Yukawa coupling (κ_τ)	
muon Yukawa couping (κ_μ)	
photon effective coupling (κ_γ)	
gluon effective coupling (κ_{gluon})	
$Z\gamma$ effective coupling ($\kappa_{Z\gamma}$)	
OTHER H PRODUCTION PROPERTIES	
$t\bar{t}H$ Production	1.10 ± 0.18
HH Production Cross Section in pp Collisions	
Higgs trilinear self coupling modifier κ_λ	
Higgs-gauge boson quartic coupling modifier κ_{2V}	
tH production	6 ± 4
H Production Cross Section in pp Collisions at $\sqrt{s}$ = 13 TeV	56.9 ± 3.4 pb

W is less studied, somehow…

W $J = 1$

See related reviews:

Mass and Width of the W Boson PDF

Extraction of Triple Gauge Couplings (TGC's) PDF

PDF

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	$\ell^+\nu$	[1]	$(10.86 \pm 0.09)\%$		
Γ_2	$e^+\nu$		$(10.71 \pm 0.16)\%$		40188
Γ_3	$\mu^+\nu$		$(10.63 \pm 0.15)\%$		40188
Γ_4	$\tau^+\nu$		$(11.38 \pm 0.21)\%$		40169
Γ_5	hadrons		$(67.41 \pm 0.27)\%$		
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	CL=95%	40188
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	CL=95%	40164
Γ_8	c X		$(33.3 \pm 2.6)\%$		
Γ_9	$c\bar{s}$		$(31^{+13}_{-11})\%$		
Γ_{10}	invisible	[2]	$(1.4 \pm 2.9)\%$		
Γ_{11}	$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$	CL=95%	40188

[1] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[2] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p< 200 MeV.

[1] 80.377 ± 0.012 GeV

0.88145 ± 0.00013

10.811 ± 0.012 GeV

-0.029 ± 0.028 GeV

2.085 ± 0.042 GeV

ONIC W DECAY

15.70 ± 0.35

2.20 ± 0.19

0.92 ± 0.14

19.39 ± 0.08

$0.984^{+0.018}_{-0.020}$

0.982 ± 0.042

-0.022 ± 0.019

0.92 ± 0.06

-0.09 ± 0.06

-0.07 ± 0.09 (S = 1.1)

-0.30 ± 0.17

$-0.12^{+0.06}_{-0.04}$

-0.09 ± 0.07

$2.22 \pm 0.20\ e/2m_W$

c_{WWW}/Λ^2, c_W/Λ^2, c_B/Λ^2

ANOMALOUS W/Z QUARTIC COUPLINGS

a_0/Λ^2, a_c/Λ^2, a_n/Λ^2, κ_0^W/Λ^2, κ_c^W/Λ^2, $f_{T,0}/\Lambda^4$, $f_{M,i}/\Lambda^4$, α_4, α_5, $F_{S,i}/\Lambda^4$, $F_{M,i}/\Lambda^4$, $F_{T,i}/\Lambda^4$

But most copious produced

Did we overlook it fairly?

Is it too hard to detect?

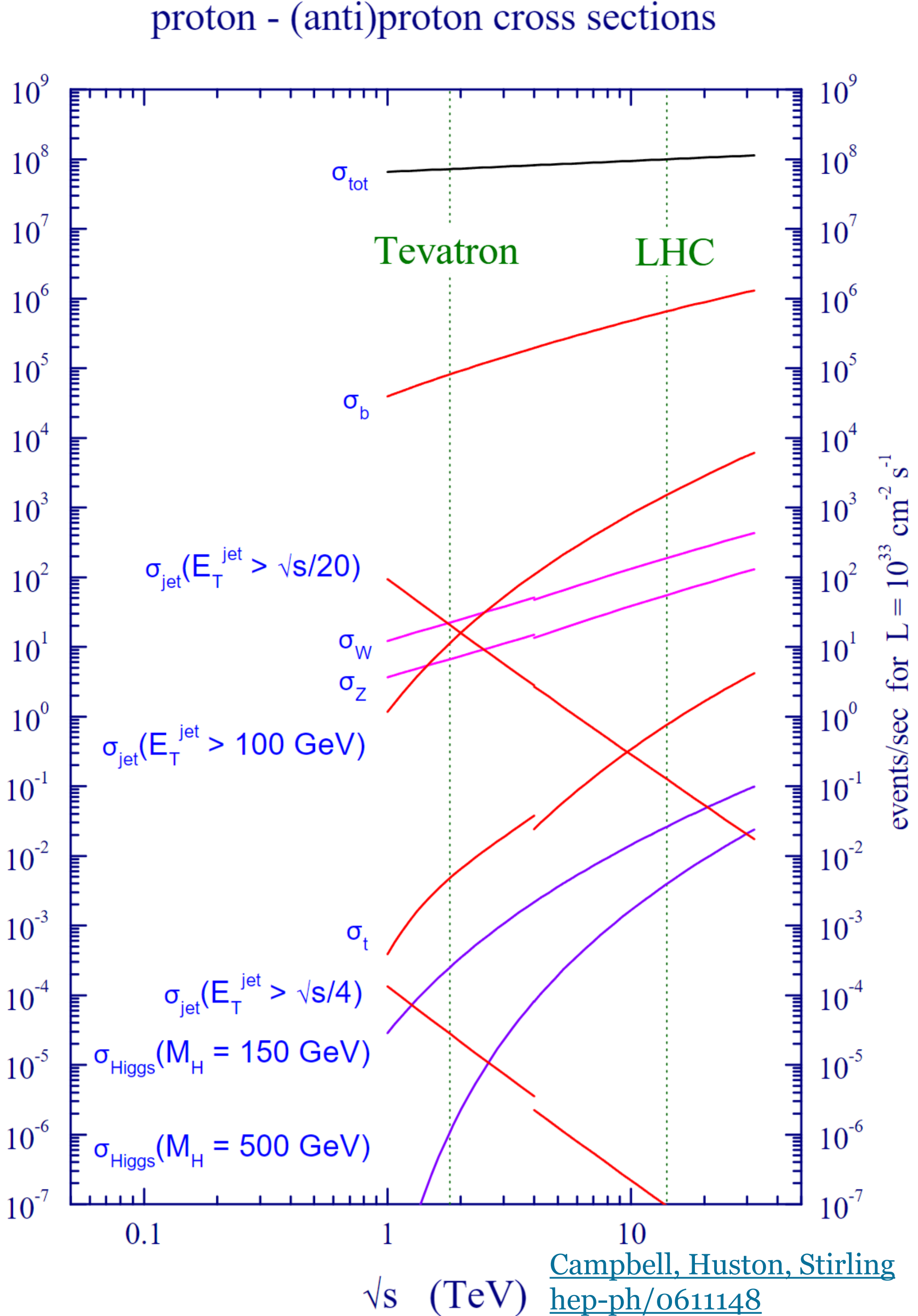
W^+ **DECAY MODES**

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

	Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\ell^+\nu$	[1]	$(10.86 \pm 0.09)\%$		
Γ_2	$e^+\nu$		$(10.71 \pm 0.16)\%$		40188
Γ_3	$\mu^+\nu$		$(10.63 \pm 0.15)\%$		40188
Γ_4	$\tau^+\nu$		$(11.38 \pm 0.21)\%$		40169
Γ_5	hadrons		$(67.41 \pm 0.27)\%$		
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	CL=95%	40188
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	CL=95%	40164
Γ_8	c X		$(33.3 \pm 2.6)\%$		
Γ_9	$c\bar{s}$		$(31^{+13}_{-11})\%$		
Γ_{10}	invisible	[2]	$(1.4 \pm 2.9)\%$		
Γ_{11}	$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$	CL=95%	40188

[1] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[2] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p< 200 MeV.



Campbell, Huston, Stirling hep-ph/0611148

David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g]
David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

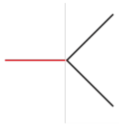
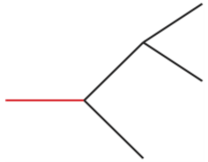
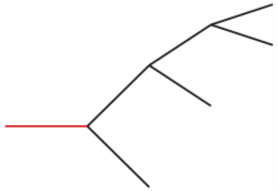
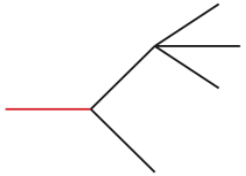
Higgs exotic decays program

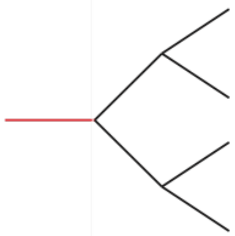
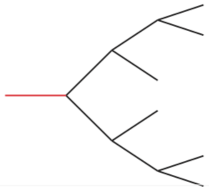
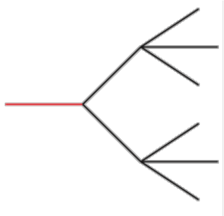
1312.4992

Table from ZL, L.-T. Wang, H. Zhang, 1612.09284

Still a lot of uncharted territory for new searches!

Can be conquered using upcoming LHC runs with advanced **analysis tools** and **new detectors**.
For existing searches, there are new possibilities such as unequal masses, etc.

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

We have a full and nice program for the Higgs boson

We've been calling the LHC

- Higgs factory
- Top factory

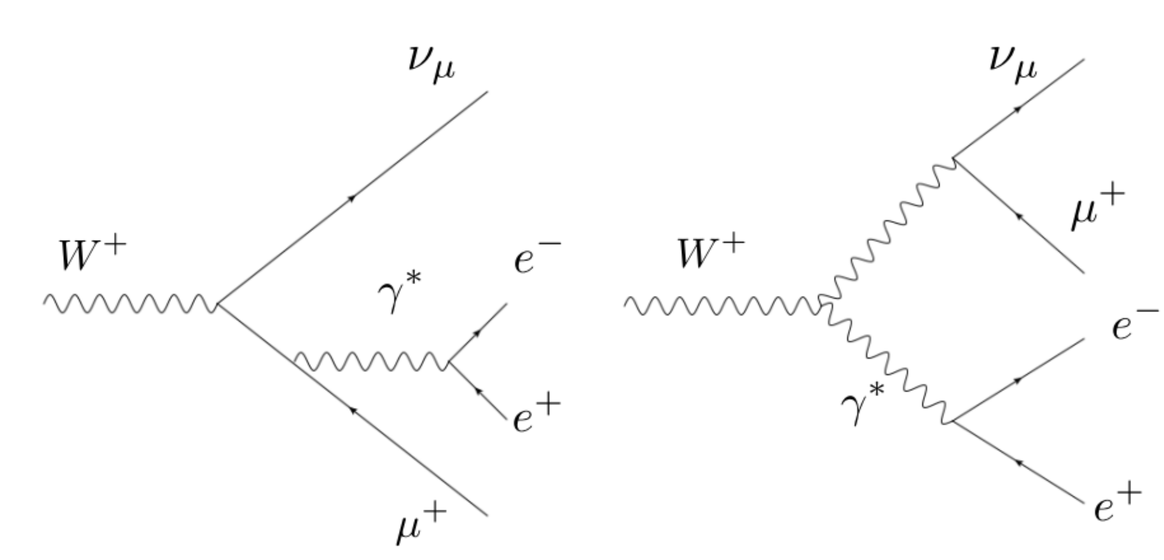
But I think LHC

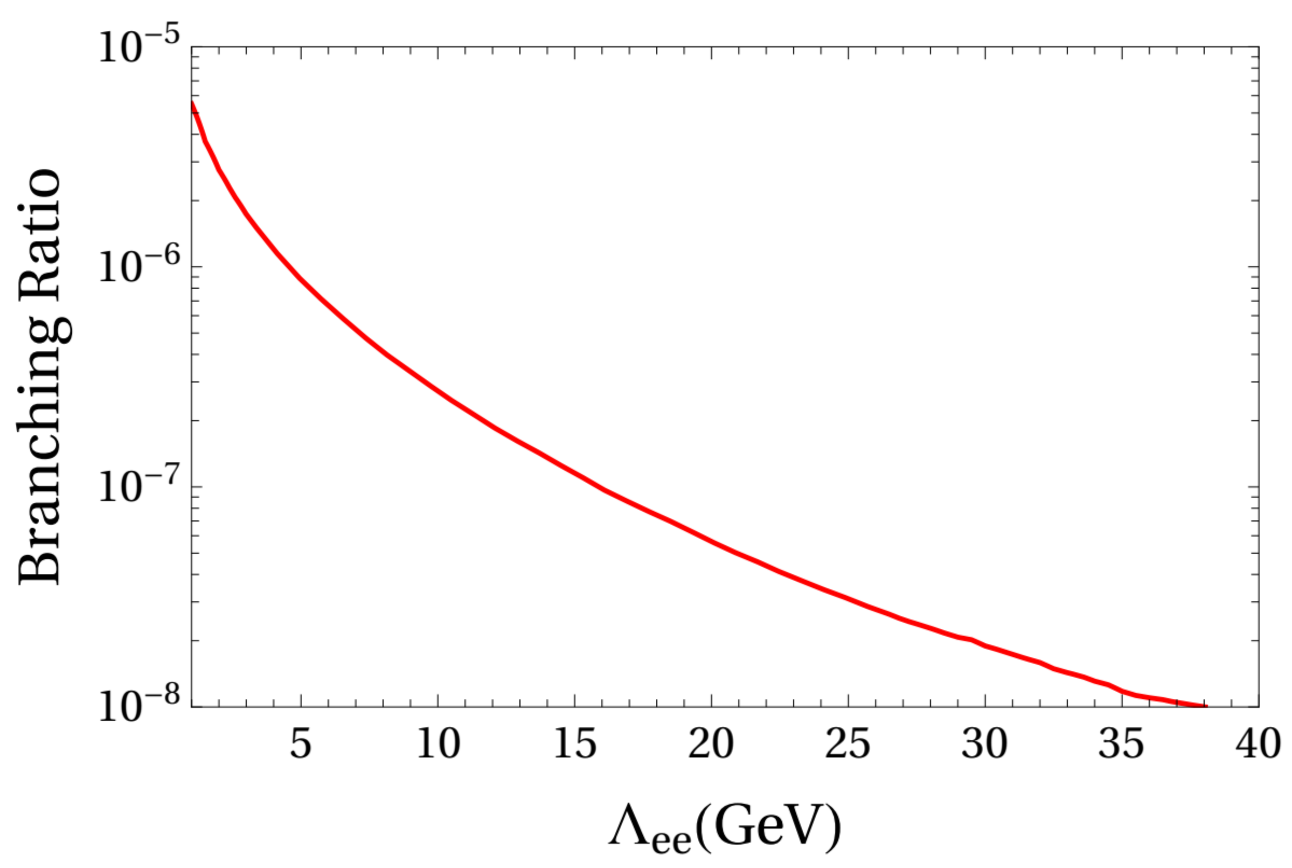
- BSM explorer
- (AND) SM factory!

Maybe we should look into W more.
Hence, as a first example, we propose to study the W exotic decay into $3\ell + \nu$

in collaboration with Y.F. Fei, P.R. Li, K.F. Lyu, M. Pospelov, 24'

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



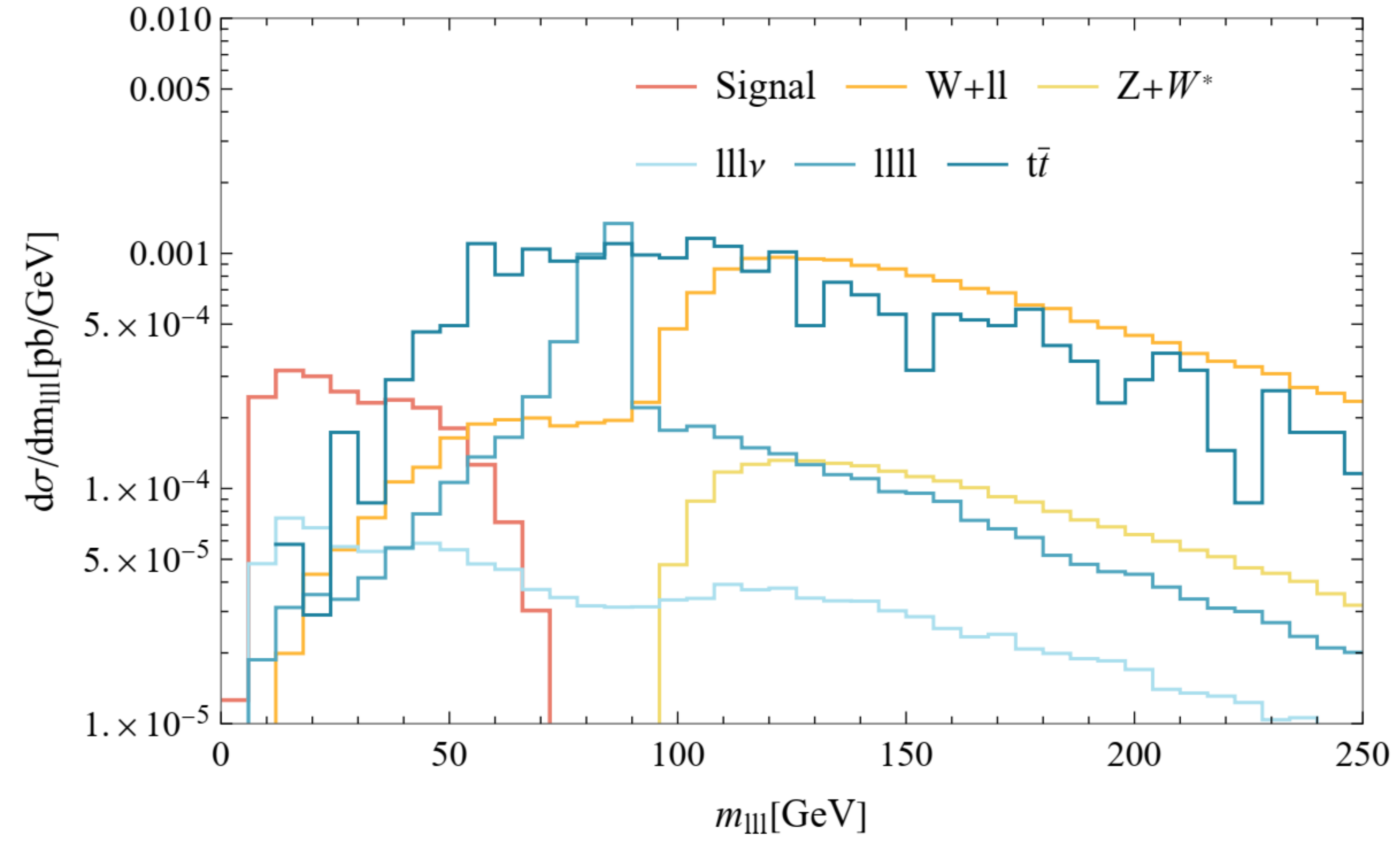


Signal process	cross section [pb]
$pp \to \ell^+\ell^-\ell^+\nu_\ell + (j),\ \mathrm{M}_{\ell\ell\ell\nu} \in \mathrm{OR}$	0.36
$pp \to \ell^+\ell^-\ell^-\bar{\nu}_\ell + (j),\ \mathrm{M}_{\ell\ell\ell\nu} \in \mathrm{OR}$	0.25

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.

SM background



Parton level pre-selection

$p_T(j) > 20$ GeV, $p_T(\ell) > 3$ GeV,
$\eta(\ell) < 5.0(2.5)$, $\eta(j) < 5.0$, $\Delta R(\ell\ell) > 0.2$.

Background process	cross section [pb]
$pp \to \ell\ell\ell\nu_\ell + (j)$, $M_{\ell\ell\ell\nu} \notin$ OR	0.95
$pp \to \ell\ell\ell\ell + (j)$	0.34
$pp \to t\bar{t} + (j)$	6.88×10^2

Detector level initial-selection

$\eta(\mu) < 2.8$, $\eta(e, j) < 4$, $\Delta R(\ell\ell, j\ell) > 0.2$,
$n(\ell) = 3$, $p_T(\ell) > 5$ GeV,
$n(j) \leq 2$ with $p_T(j) > 20$ GeV, $M_{\ell\ell} > 4$ GeV

Projected sensitivity

Cross-section [pb]	Parton-level	$n(\ell) = 3$	$n(j) \leq 2$, $M_{\ell\ell} > 4$ GeV	$M_{\ell\ell\ell} < 80$ GeV	Cut-based result $M_{\ell\ell\ell} < 60$ GeV	ML result DNN selection
Signal	0.61(100%)	0.036(5.9%)	0.021(3.5%)	0.021(3.5%)	0.021(3.4%)	0.017(2.7%)
$pp \to \ell\ell\ell\nu,\ M_{\ell\ell\ell\nu} \notin$ OR	0.95(100%)	0.22(23%)	0.2(21%)	0.013(1.4%)	8×10^{-3}(0.87%)	0.(0.3%)
$pp \to \ell\ell\ell\ell$	0.34(100%)	0.068(20%)	0.061(18%)	0.017(5%)	7.2×10^{-3}(2.1%)	3.2×10^{-3}(0.95%)
$pp \to t\bar{t} + (j)$	688(100%)	0.19(0.027%)	0.11(0.016%)	$0.023(3 \times 10^{-5})$	$0.01(1 \times 10^{-5})$	$2.1 \times 10^{-3}(3 \times 10^{-6})$

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

Current LHC data (with current trigger and selection)

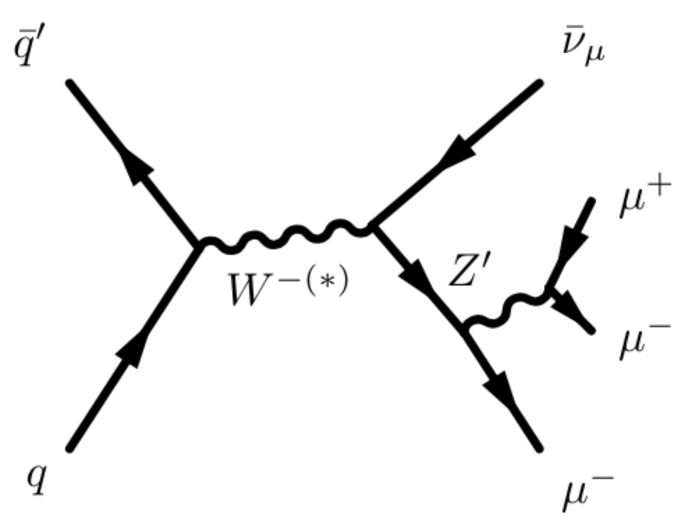
$$\delta Br(W \to 3\ell + \nu) = 6\%$$

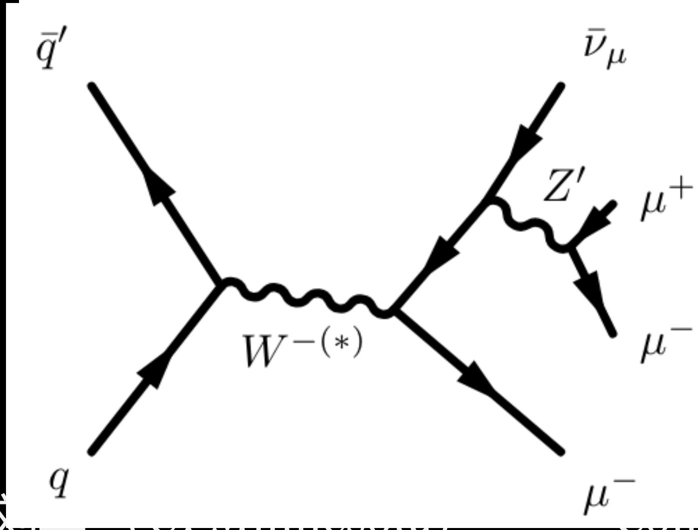
HL-LHC data (with improved trigger on multileptons)

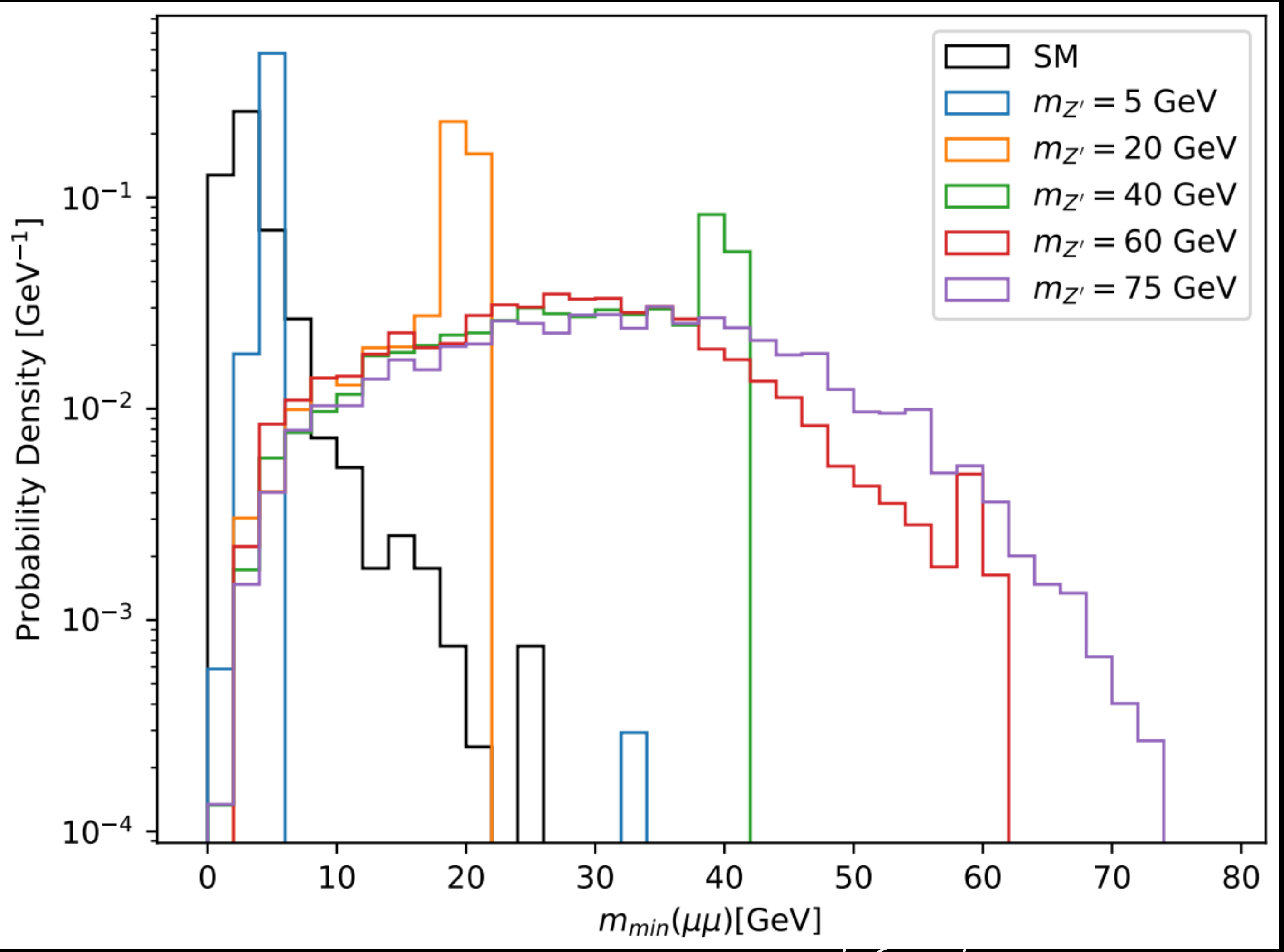
So we can add one more entry to PDG, what else?

One can also look for Z’

Taking the gauged $L_\mu - L_\tau$ example:

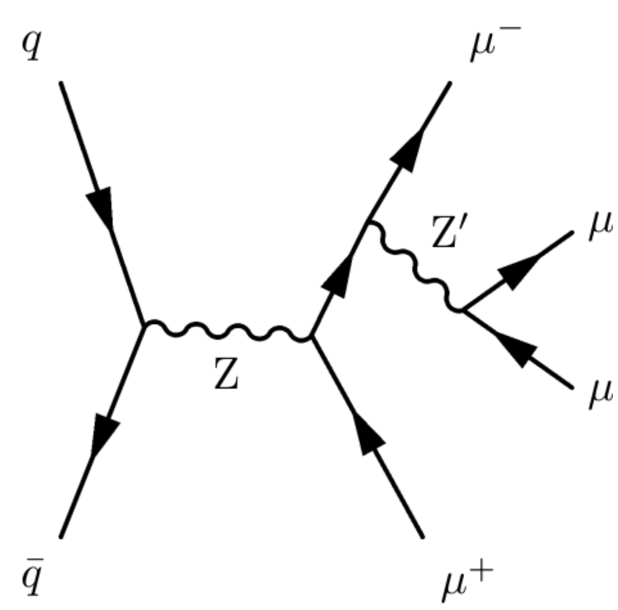


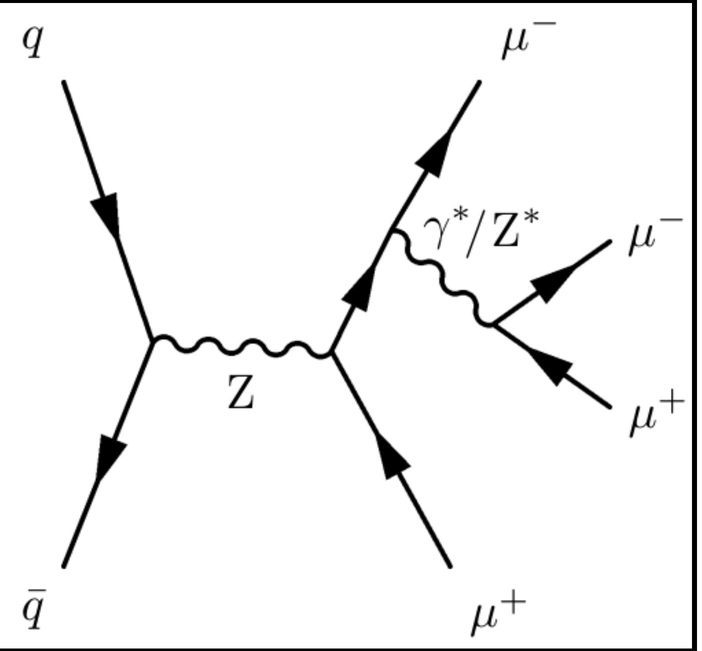


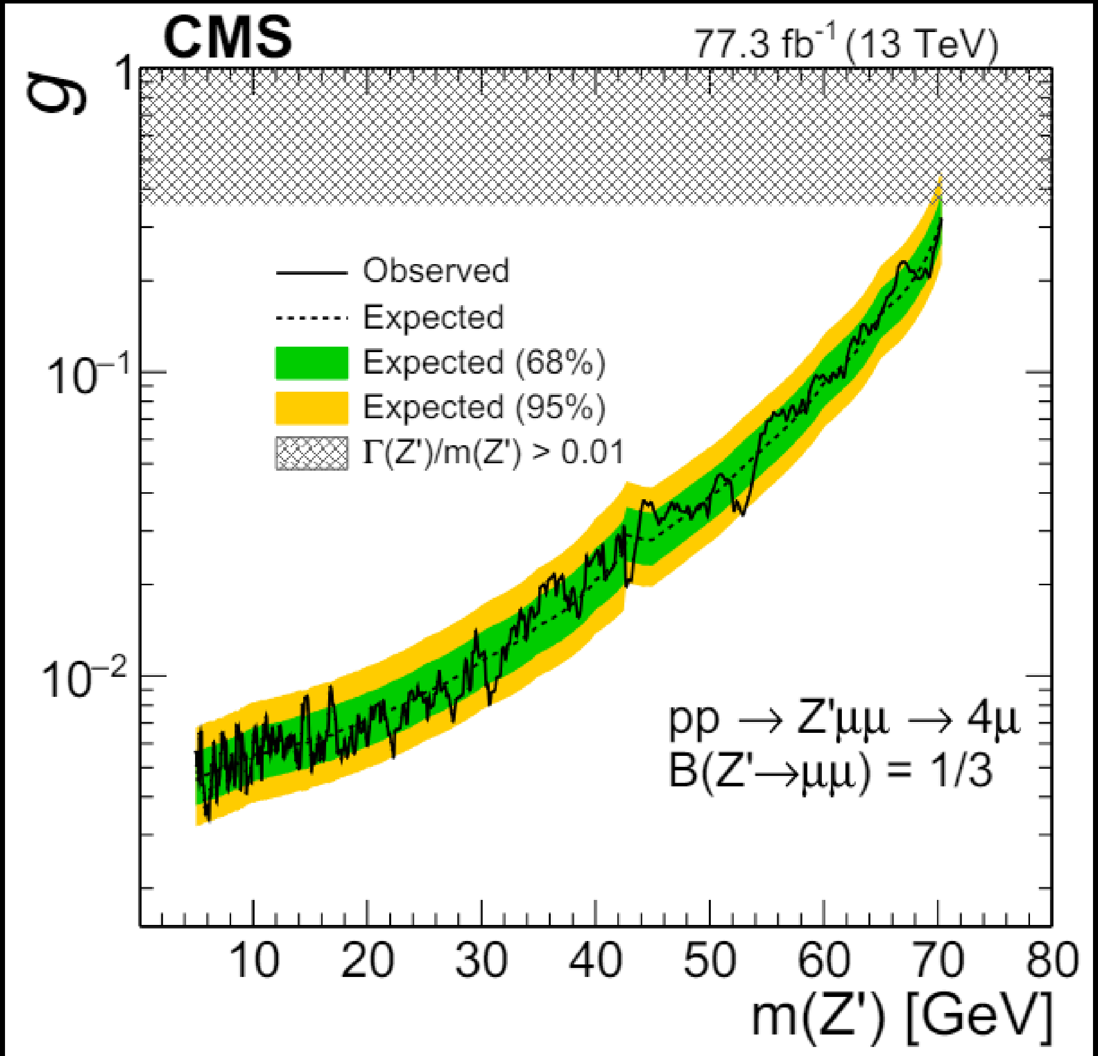


Shouldn't we already have a great limit from $Z \to 4\ell$?

Yes.







Shouldn't we already have a great limit from $Z \to 4\ell$?

But,

W rate is a factor of 4~5 larger than Z

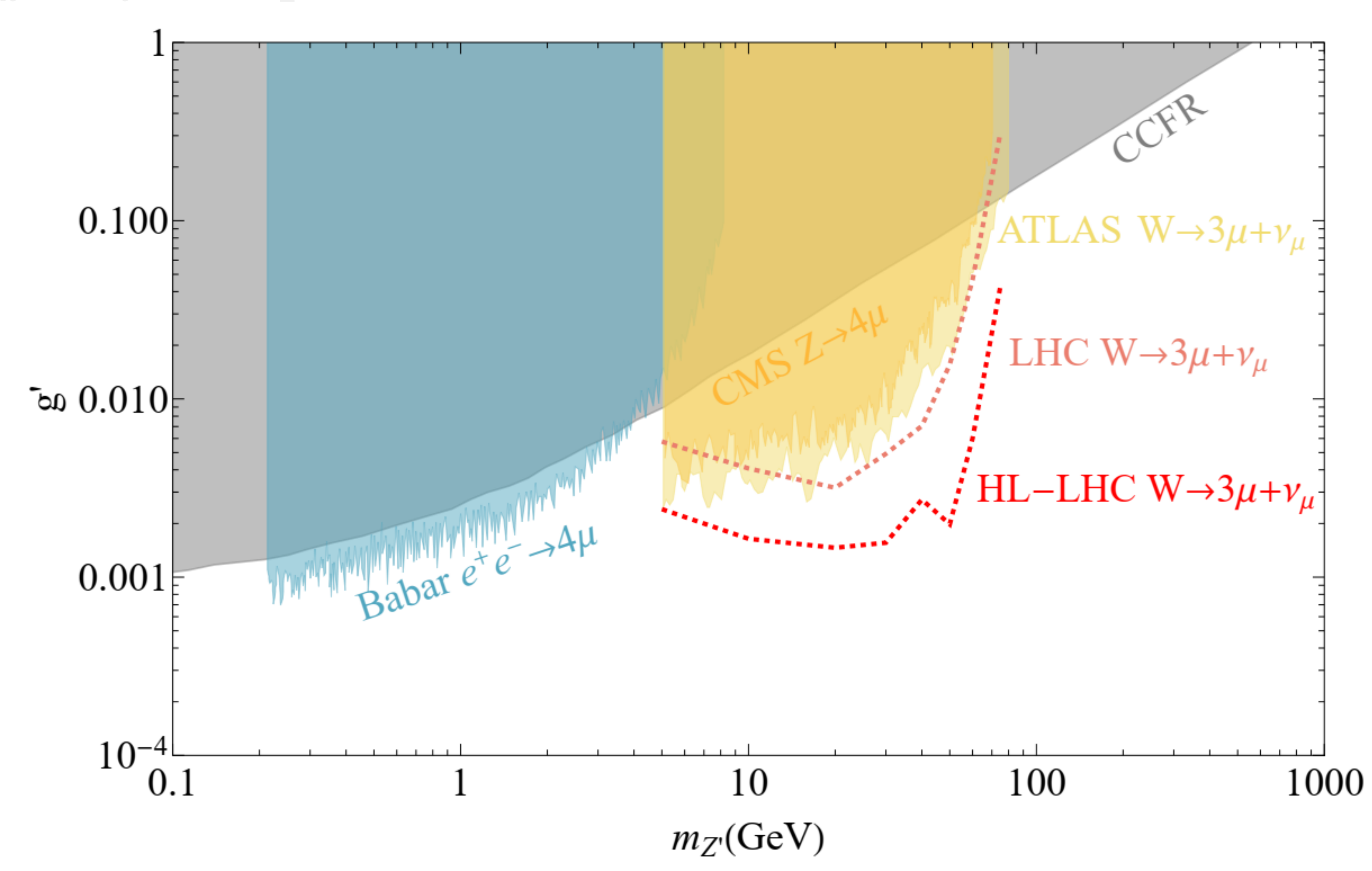
W leptonic branching fraction is a factor of 3 larger than Z

So this channel have O(10) higher rate for the signal.

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

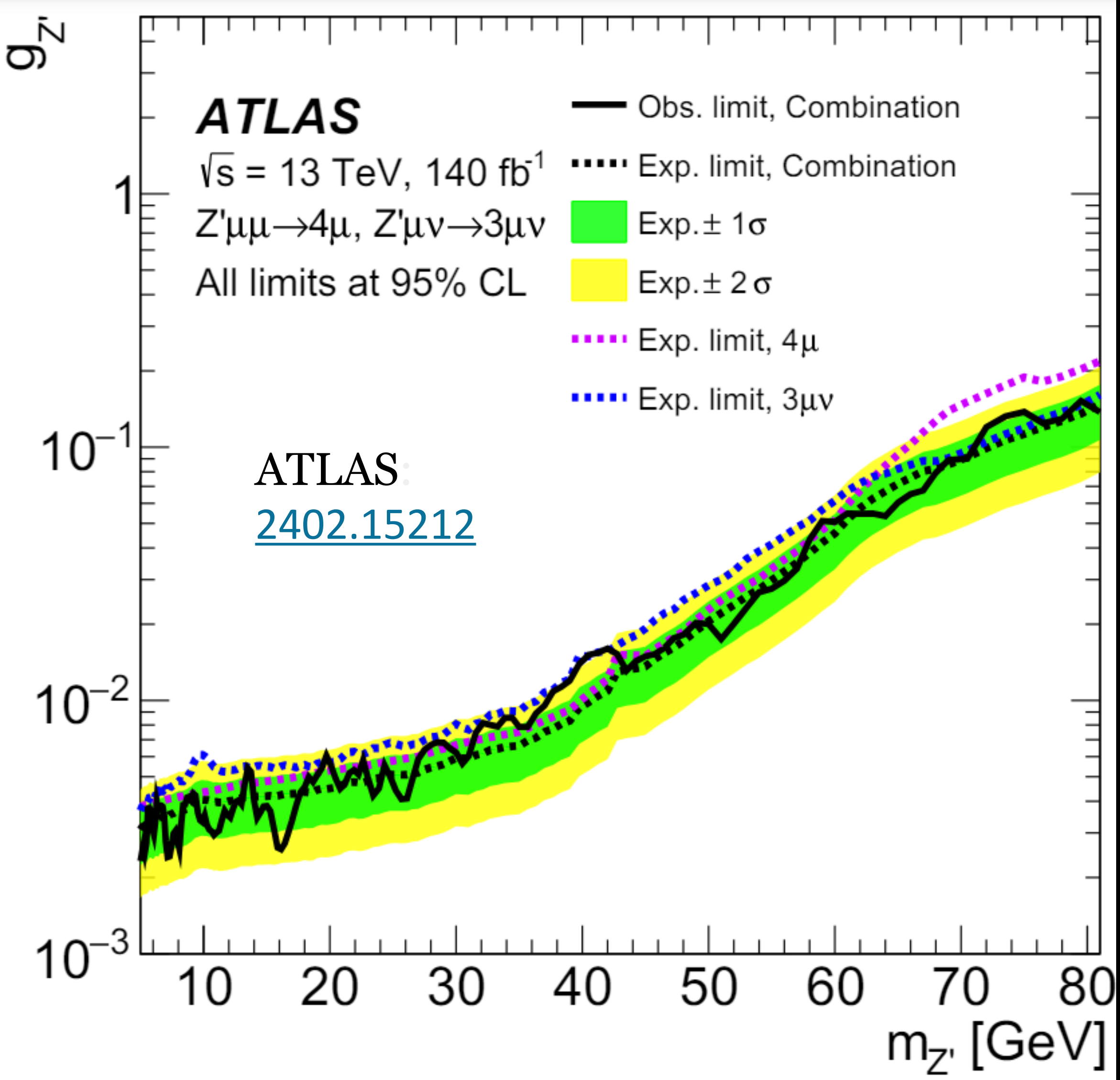
Z' projection

Gauged $L_\mu - L_\tau$ example:



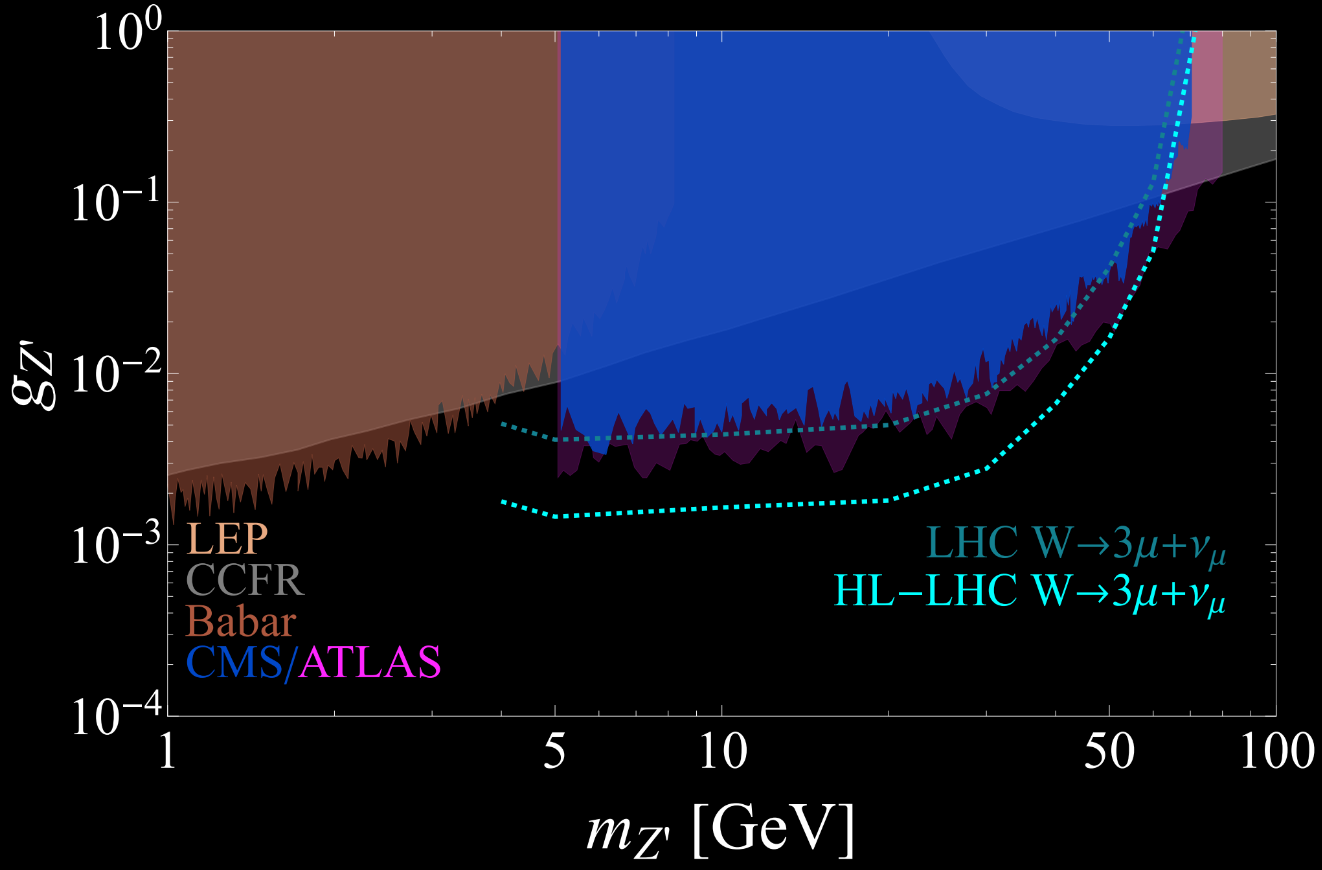
Ahh, experimentalists went partially ahead of us…

- We are quite compatible
- But the SM value was never extracted (they just called it the background)!
- More new physics:
  - Anomalous Z'
  - SMEFT
  - SM Z contribution
  - …



ATLAS
2402.15212

More to explore, e.g., LHC as weak boson factory



The LHC is not only a powerful machine on Higgs, top, and QCD, but also a powerful machine in weak bosons. The physics potential has not been realized and we are pointing out many new physics that can be done regarding weak bosons.

W boson exotic decay

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

W boson mass speculations

J.Y. Gu, ZL, T. Ma, J. Shu, *CPC 22'*

Z boson exotic decay, in progress

Electroweak restoration and goldstone equivalence test

L. Huang, S. Lane, I. Lewis, ZL, *PRD 21' (editor's suggestion)*

Higgs exotic decays

S. Jung, ZL, L.T. Wang, K.P. Xie, *PRD 22'*

Long-Lived Particles:

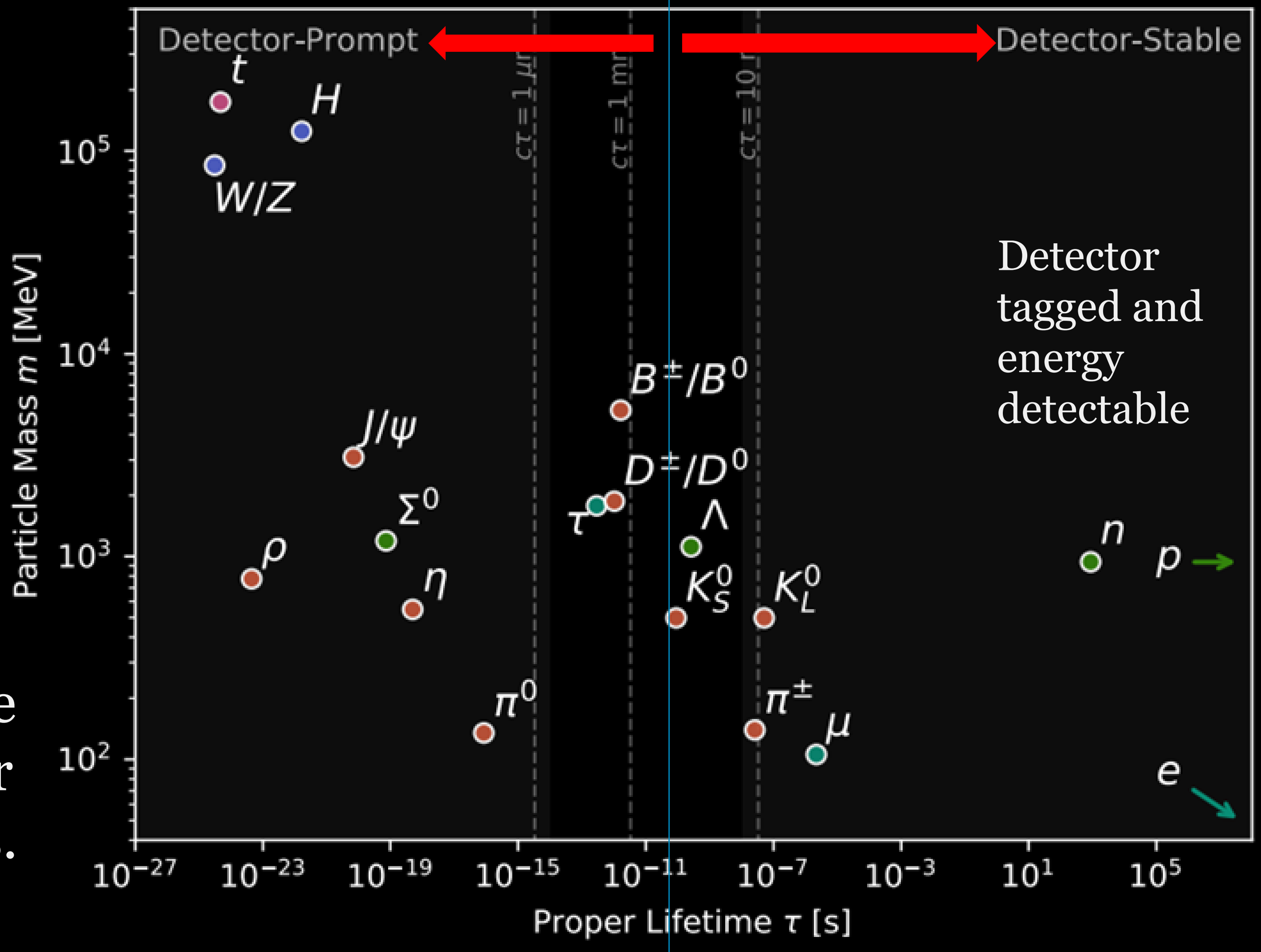
A vivid example of BSM pheno considerations and search developments

What is LLP?

Long-lived particles in the standard model:

- approximate symmetries;
- kinematic suppressions;

First pixel layer (first layer of detector)



Detector tagged and energy detectable

For BSM particles:

- Prompt particles being actively probed;
- Detector Stable particles are probed as missing energy or EM charged stable particles.

Fig. credit: L. Lee @ ATLAS

Why Long-Lived BSM Particles? Supersymmetry

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

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

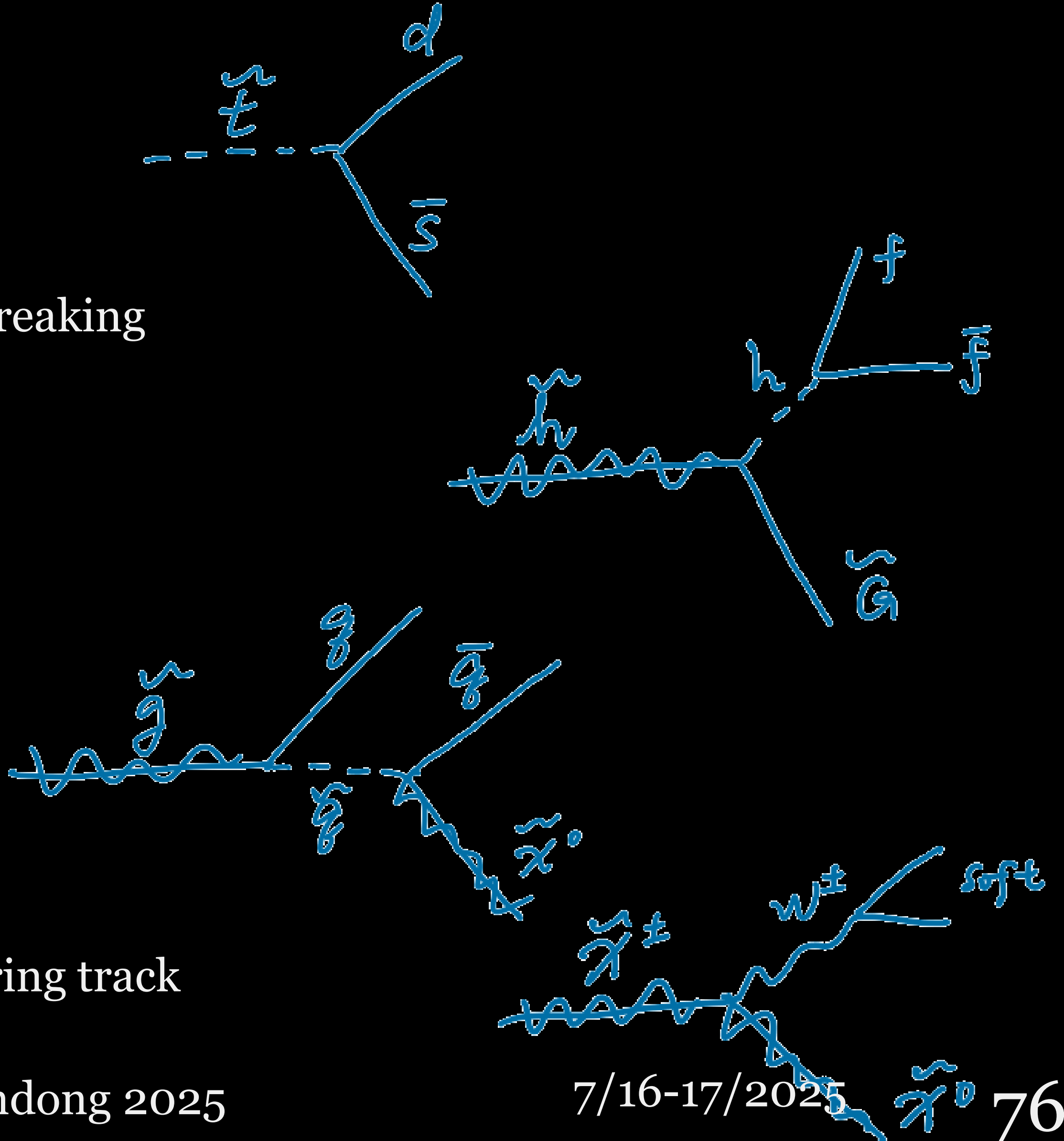
- Gauge mediation—suppressed couplings via SUSY breaking scale

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

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

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

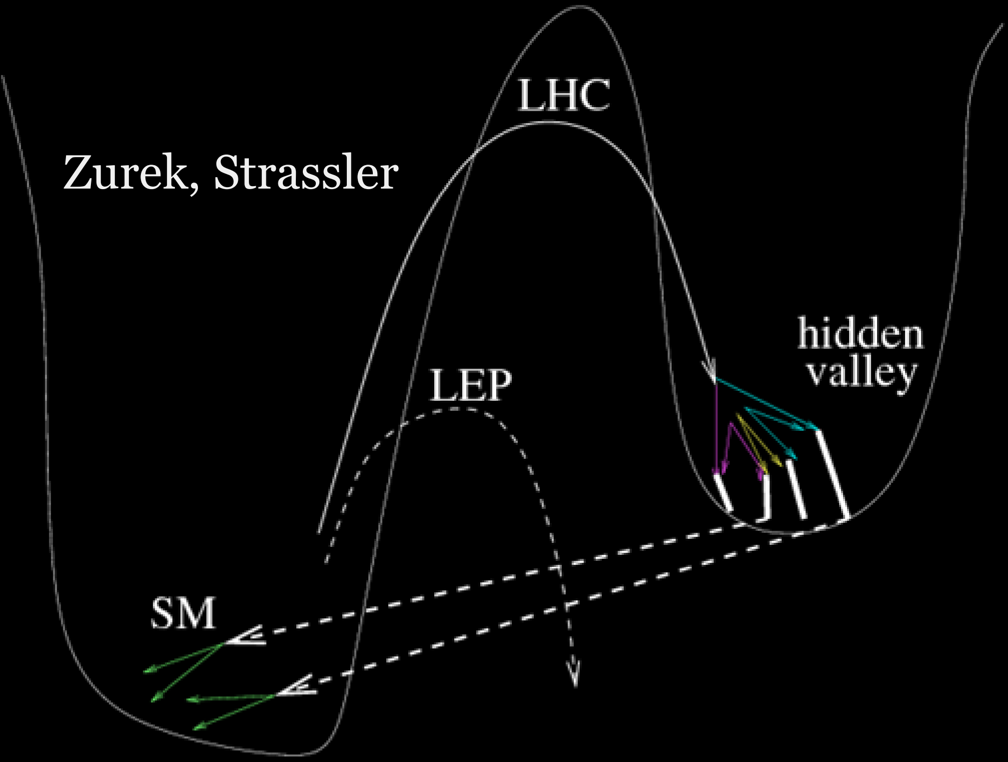
- Pure Wino/Higgsino–nearly degenerated, disappearing track



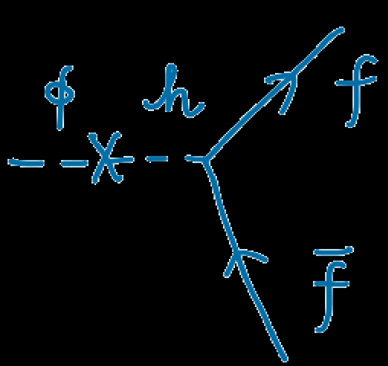
Why Long-Lived BSM Particles? Hidden Valley

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

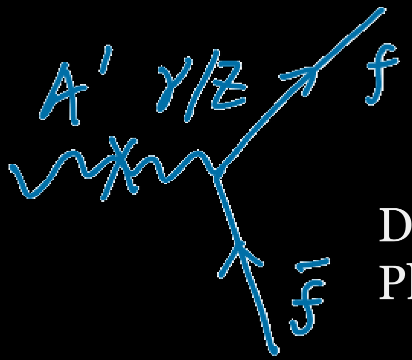
Zurek, Strassler



Higgs portal

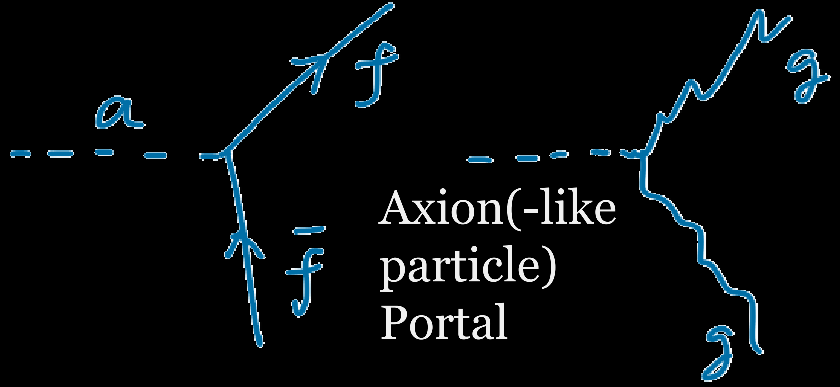


Dark Photon/Z



Neutrino Portal

Axion(-like particle) Portal



LLP: A rich program

LHC detectors designed for prompt signals. For LLPs:

☹trigger
☹reconstruction
☺standard model background
☹non-standard background

Huge uncharted well-motivated territories to explore!

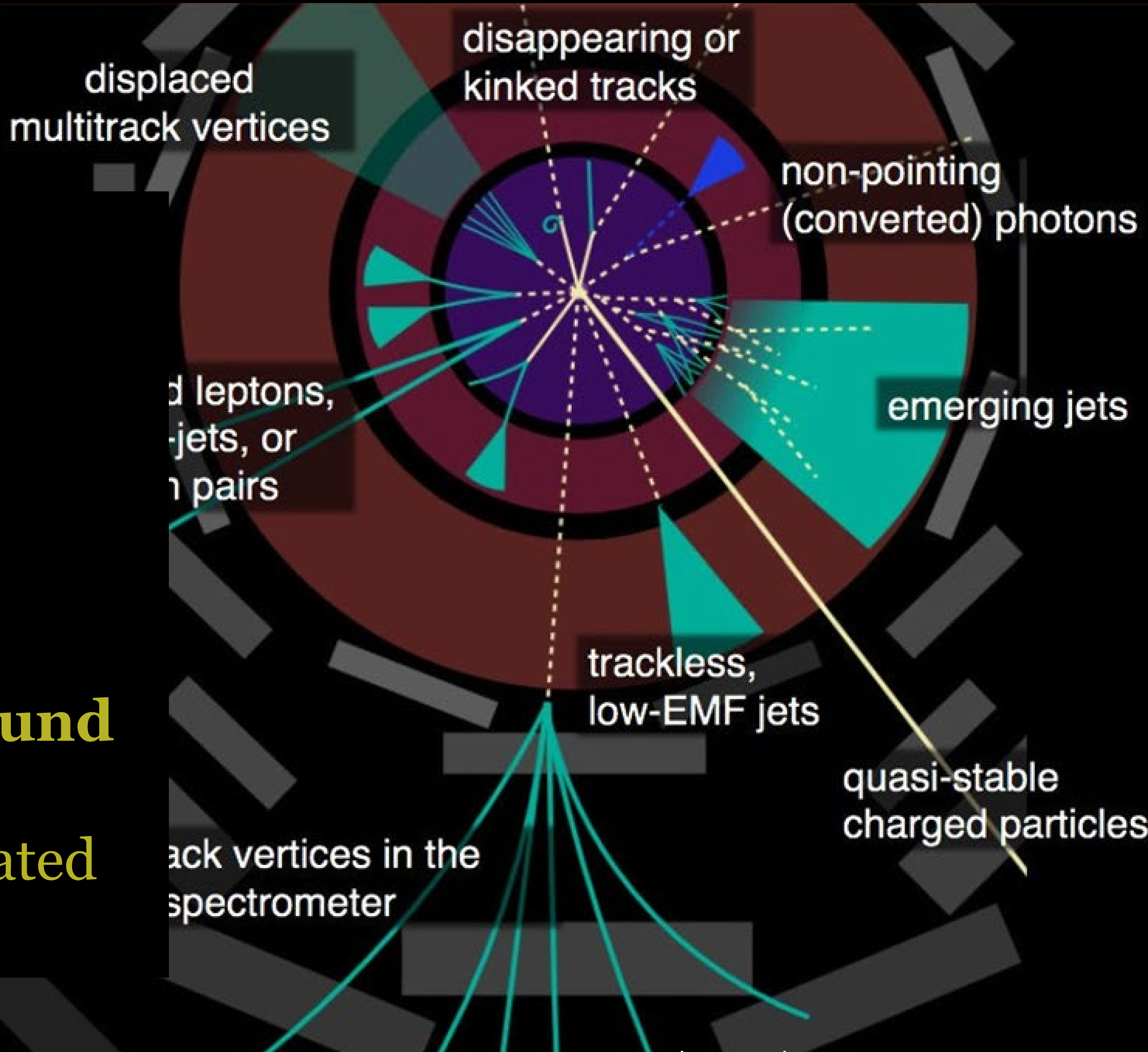
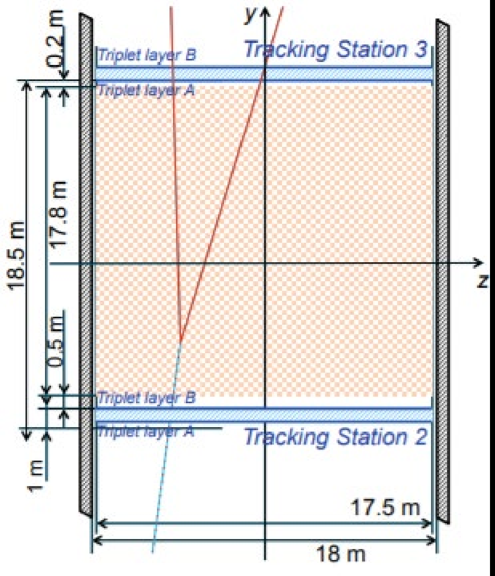


Fig. credit: Heather Russel @ ATLAS

Forward Spectrometer



Expanding the LHC program

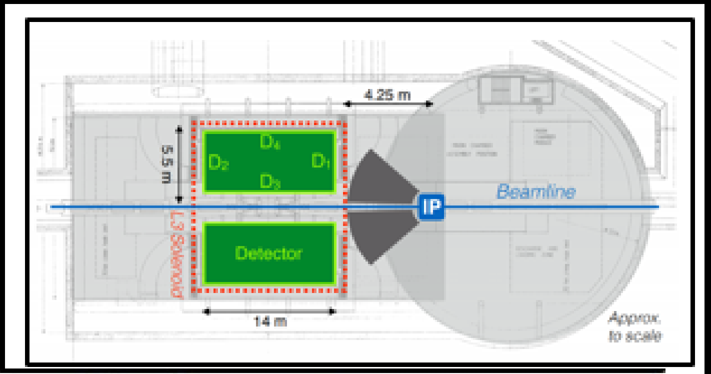
MATHUSLA
Codex-B
AL3X
ANUBIS
} Central/Hard LLPs

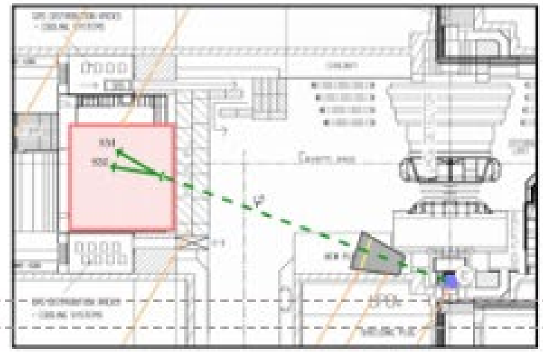
FASER
SHiP
NA62
SeaQuest
} Forward/lighter LLPs
} Beamdump experiments

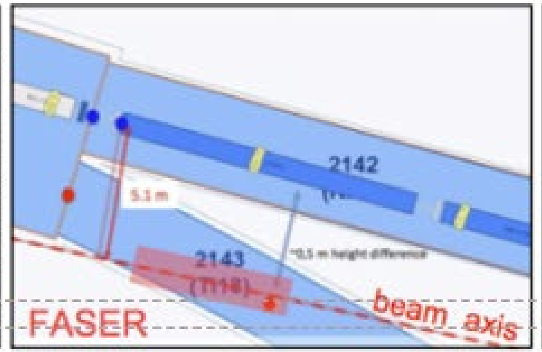
...

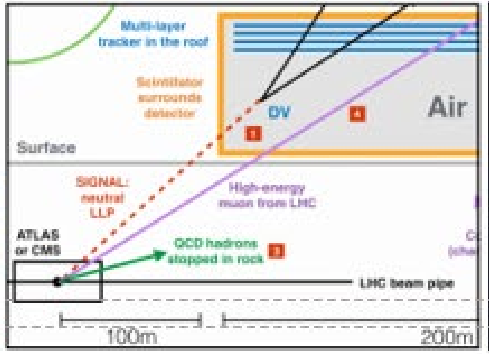
MoEDAL
MilliQan
} monopole
millicharged particles

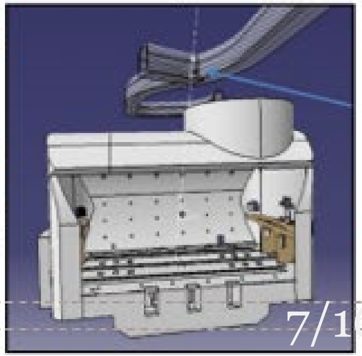
} Search for LLPs

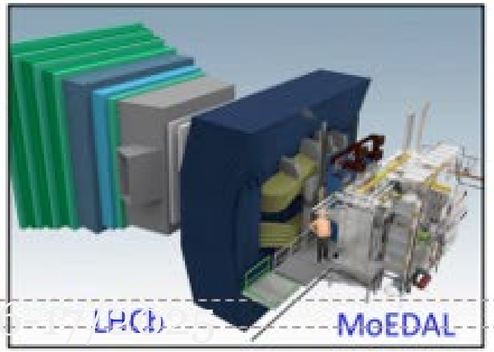




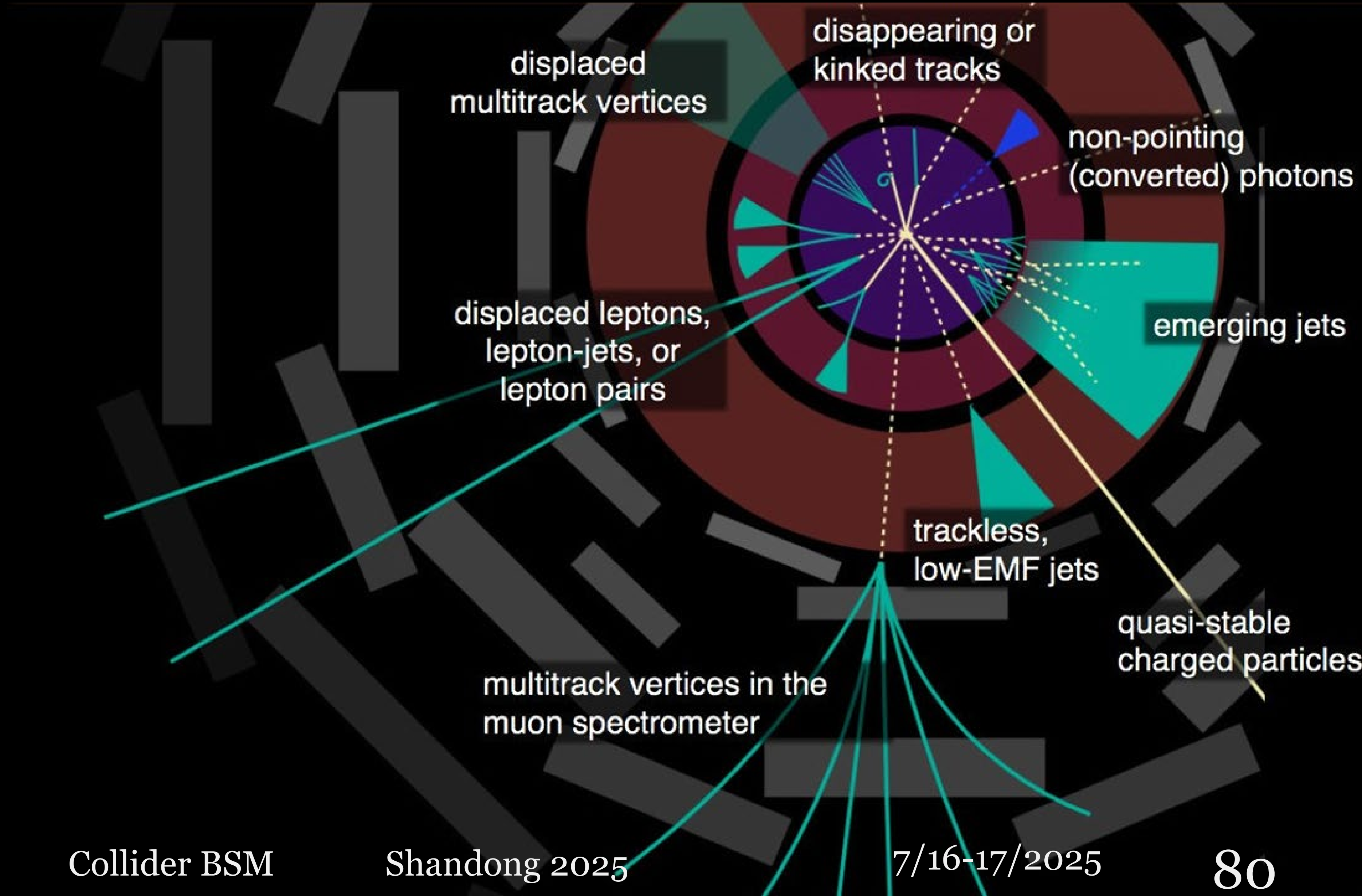








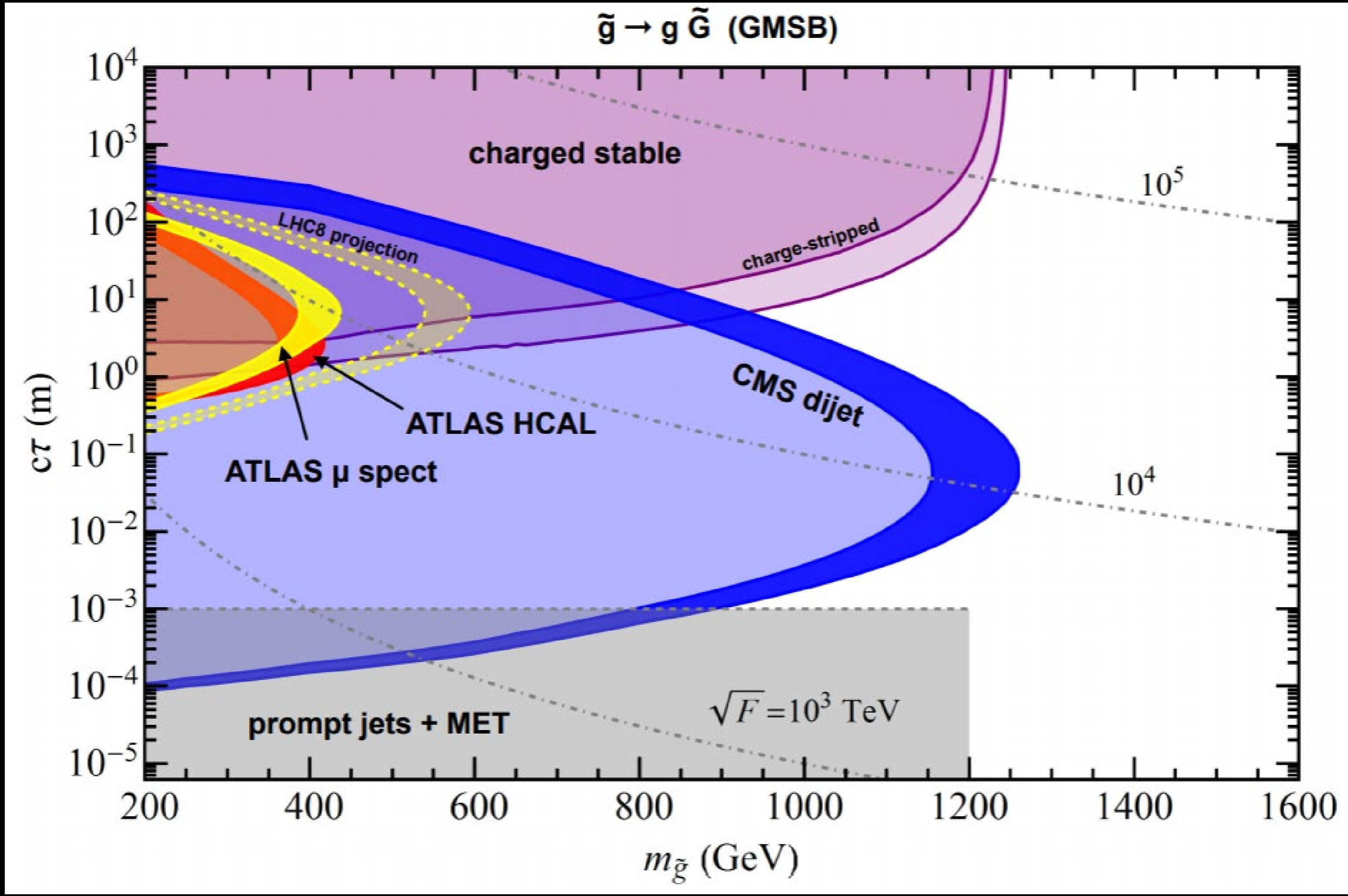
Generalize: search for hidden sector particles



LLPs around 2015

We have a new Lifetime Frontier

8 TeV result by ZL, B. Tweedie, 1503.05923



- <10 LLP searches
- 1 (or 2) LLP trigger(s)
- LLP are viewed as highly-tuned strange cases specialized for a particular model's particular parameter space.

With our reinterpretation work, we showed:

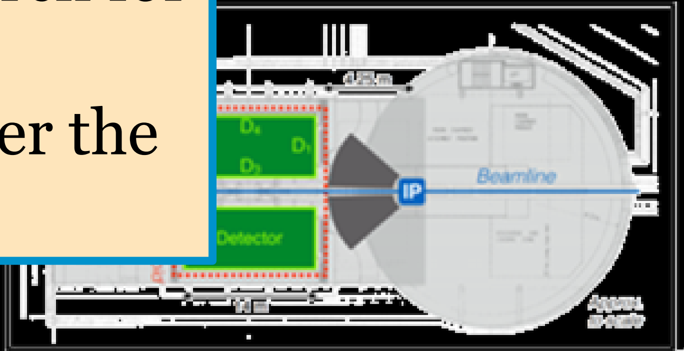
- LLPs are motivated by large class of models/parameters
- LLP searches are "inclusive" that one can interpret in broad class of models
- We identified many gaps and opportunities

Since 2015:
A Renaissance of Long-Lived Particles

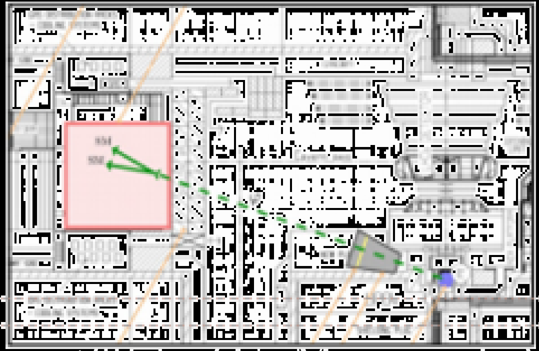
MATHUSLA
Codex-B
AL3X
Anubis
FASER
SHiP
NA62
SeaQue
MoEDA
MilliQan

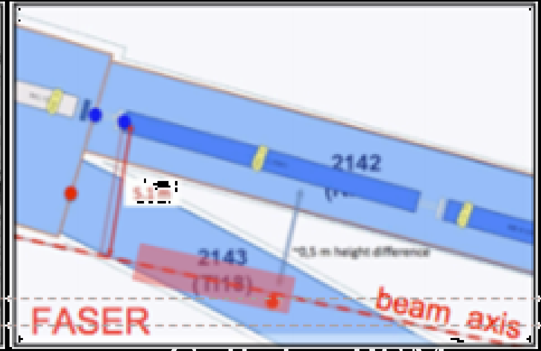
Lesson 1: The models and signature landscape changes as the theory motivations/emphasis/focus and experimental discoverability changes (with respect to data). We should be prepared to search for exotic signatures.
Lesson 1*: there will be many proposals to cover the gap, we should think about them carefully.

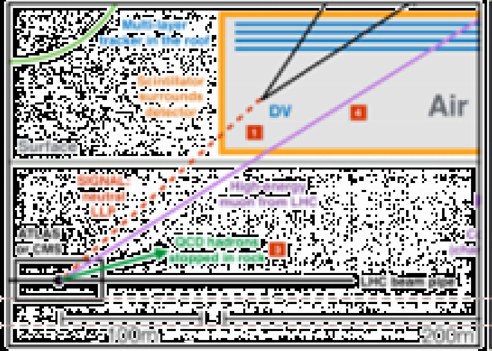
r LLPs

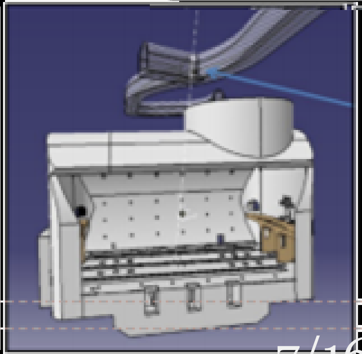


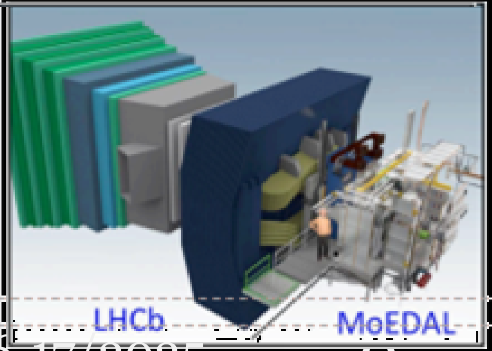
millicharged particles







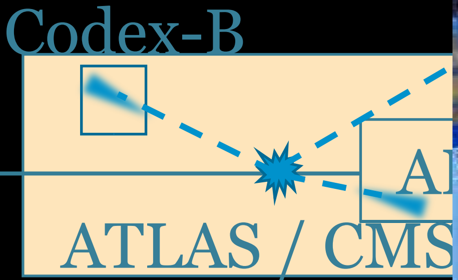


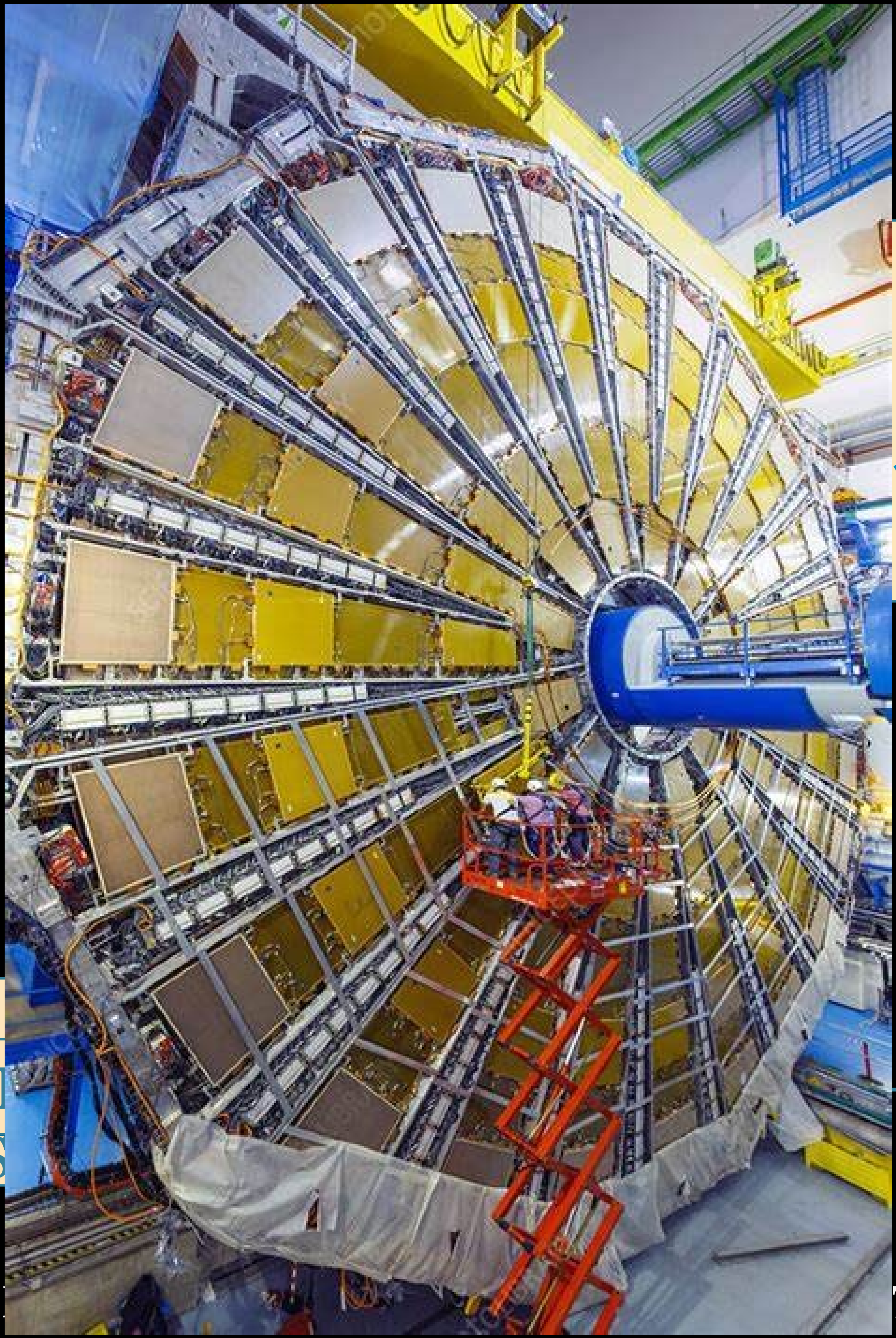


How to think about LLP searches?

Just to get some idea

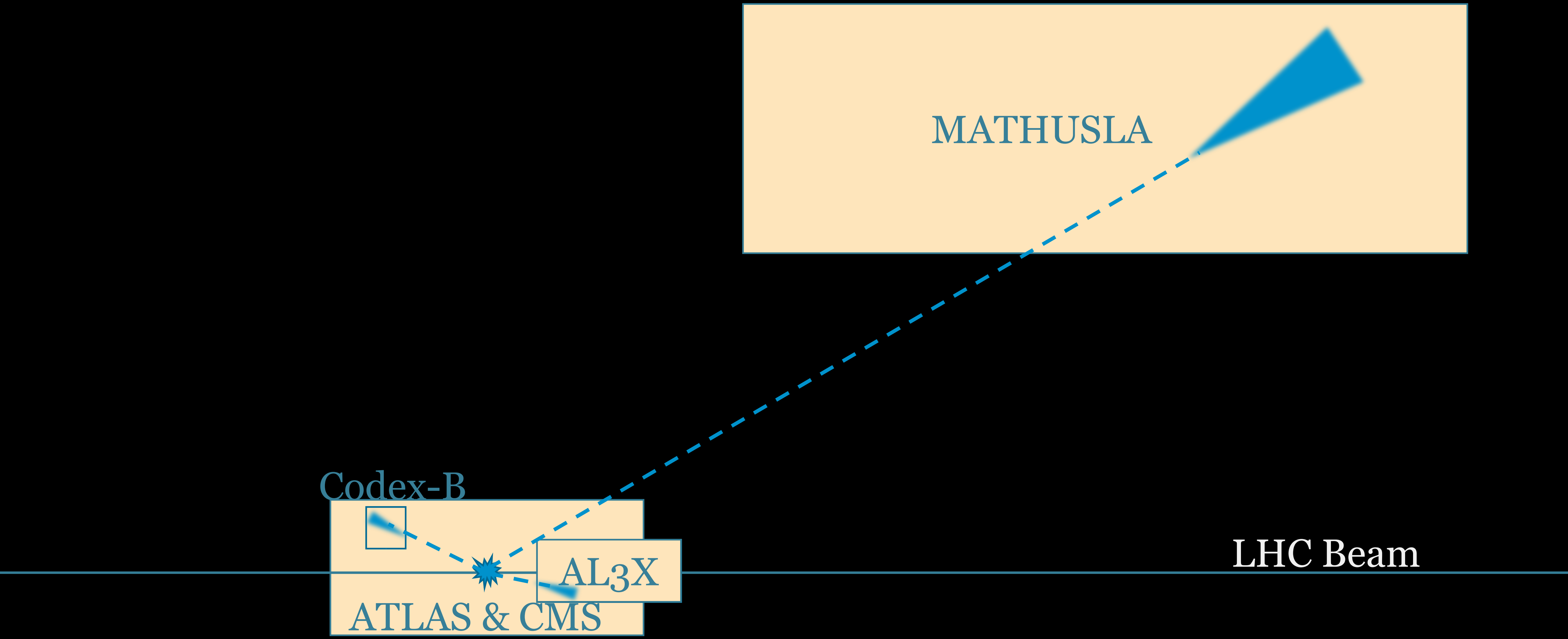
I do not necessarily mean exactly these proposals but rather they are representatives of various auxiliary detector concepts.



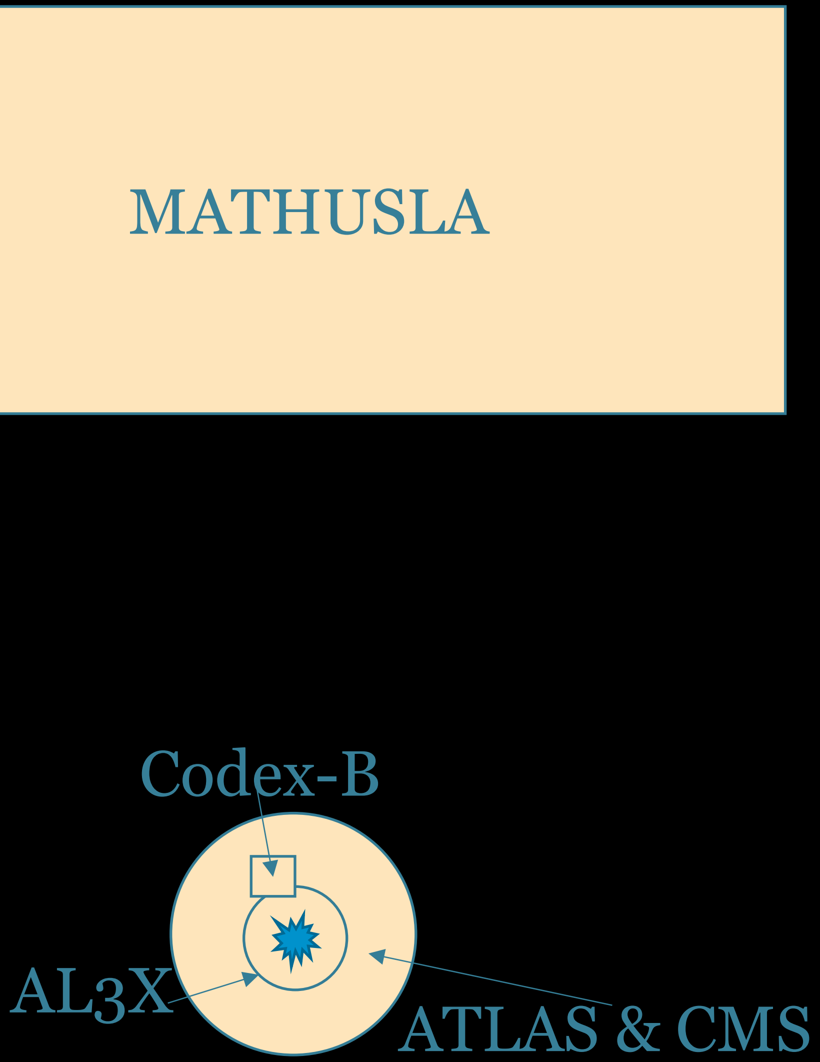


LHC Beam

What are these proposals?



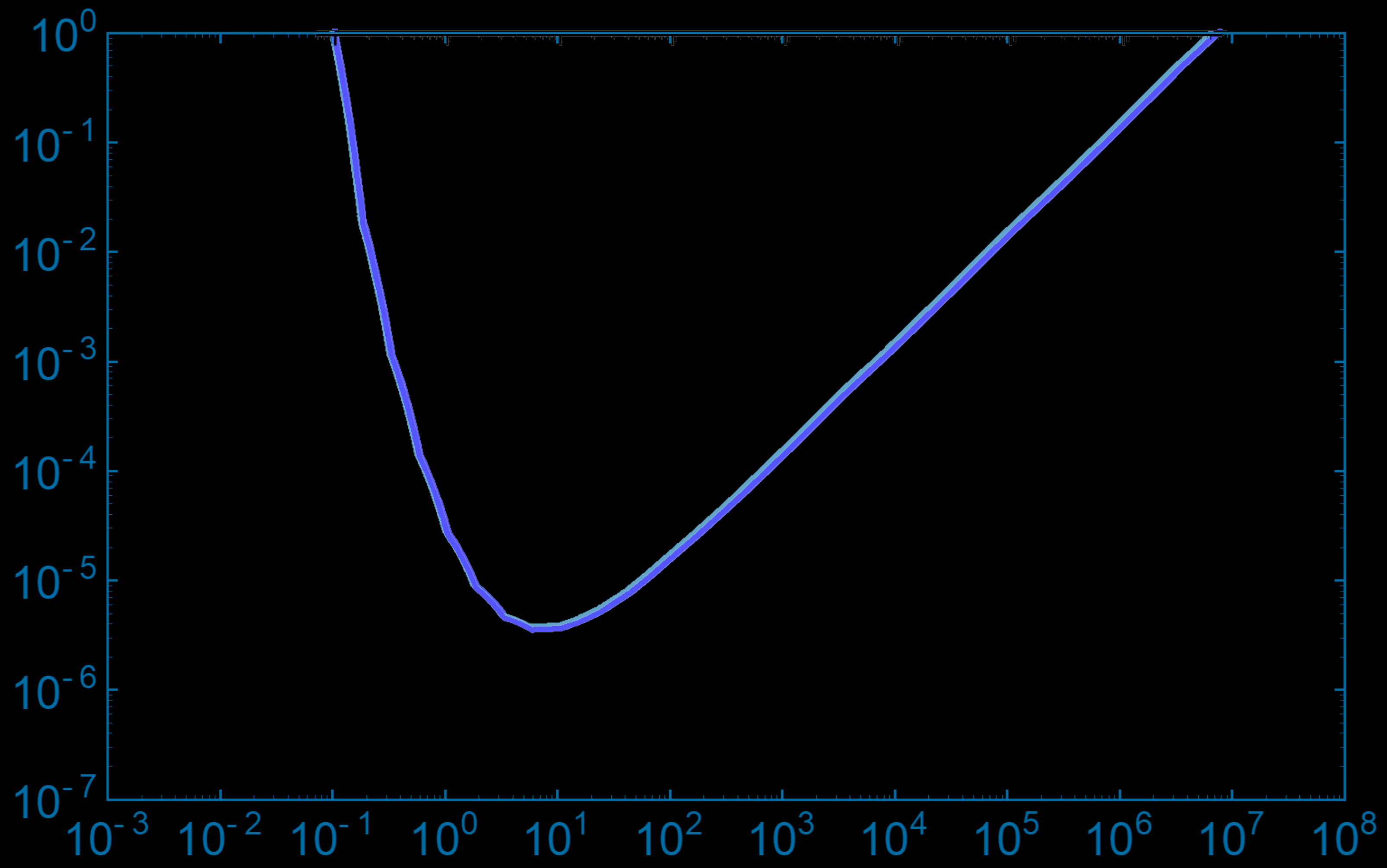
What are these proposals?



Universal features of LLPs: a typical reach plot

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

Better sensitivity



Log scale in proper lifetime

Universal features of LLPs: understanding shapes

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

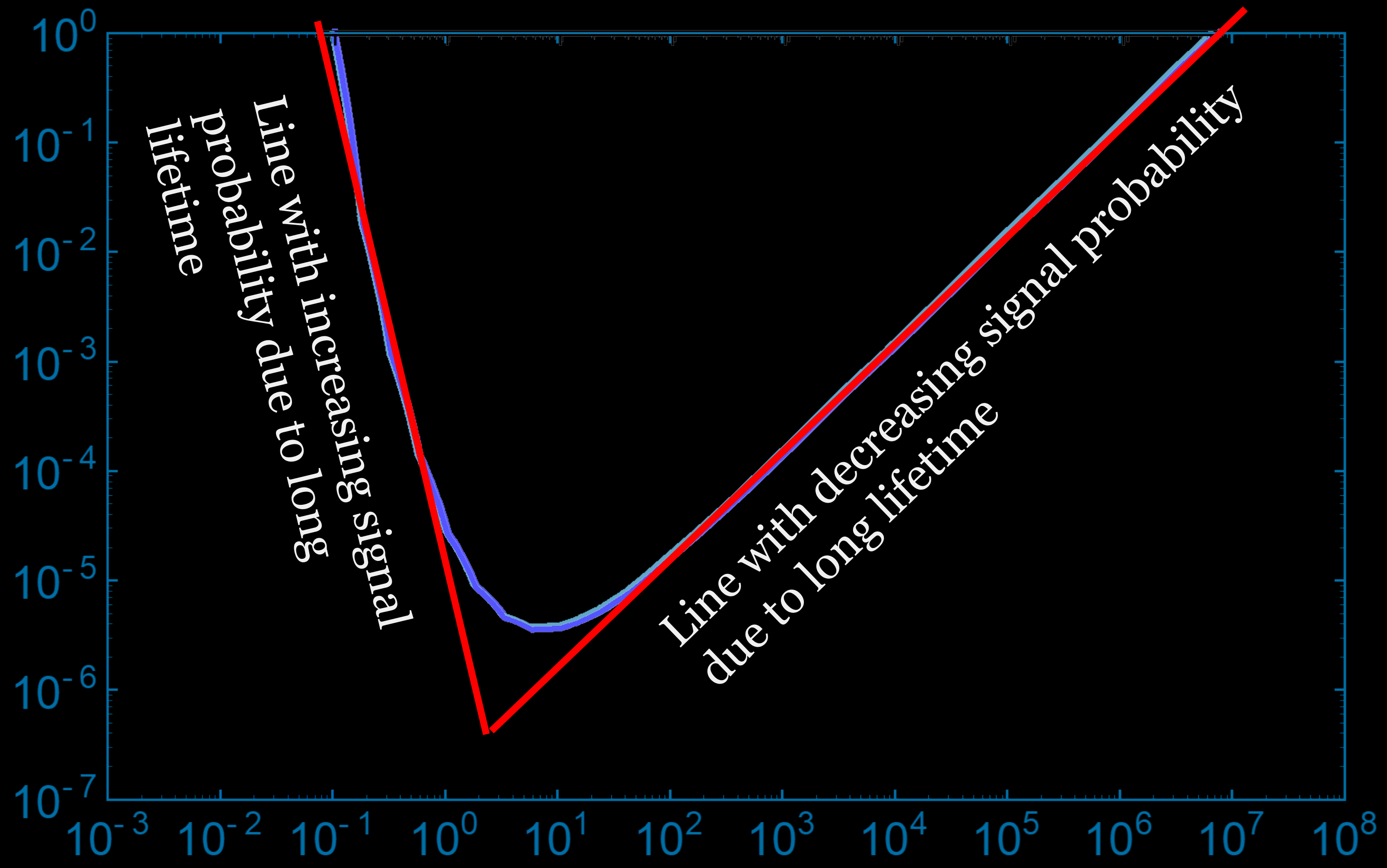
Geometrical acceptance P_{in}

$$P_{\rm in} = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d}$$

$$\approx \frac{\Delta\Omega}{4\pi} \; e^{-L_1/d} \; \frac{L_2 - L_1}{d}$$

$d = c\tau\gamma\beta$

Better sensitivity



Log scale in proper lifetime

Universal features of LLPs: understanding shapes

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

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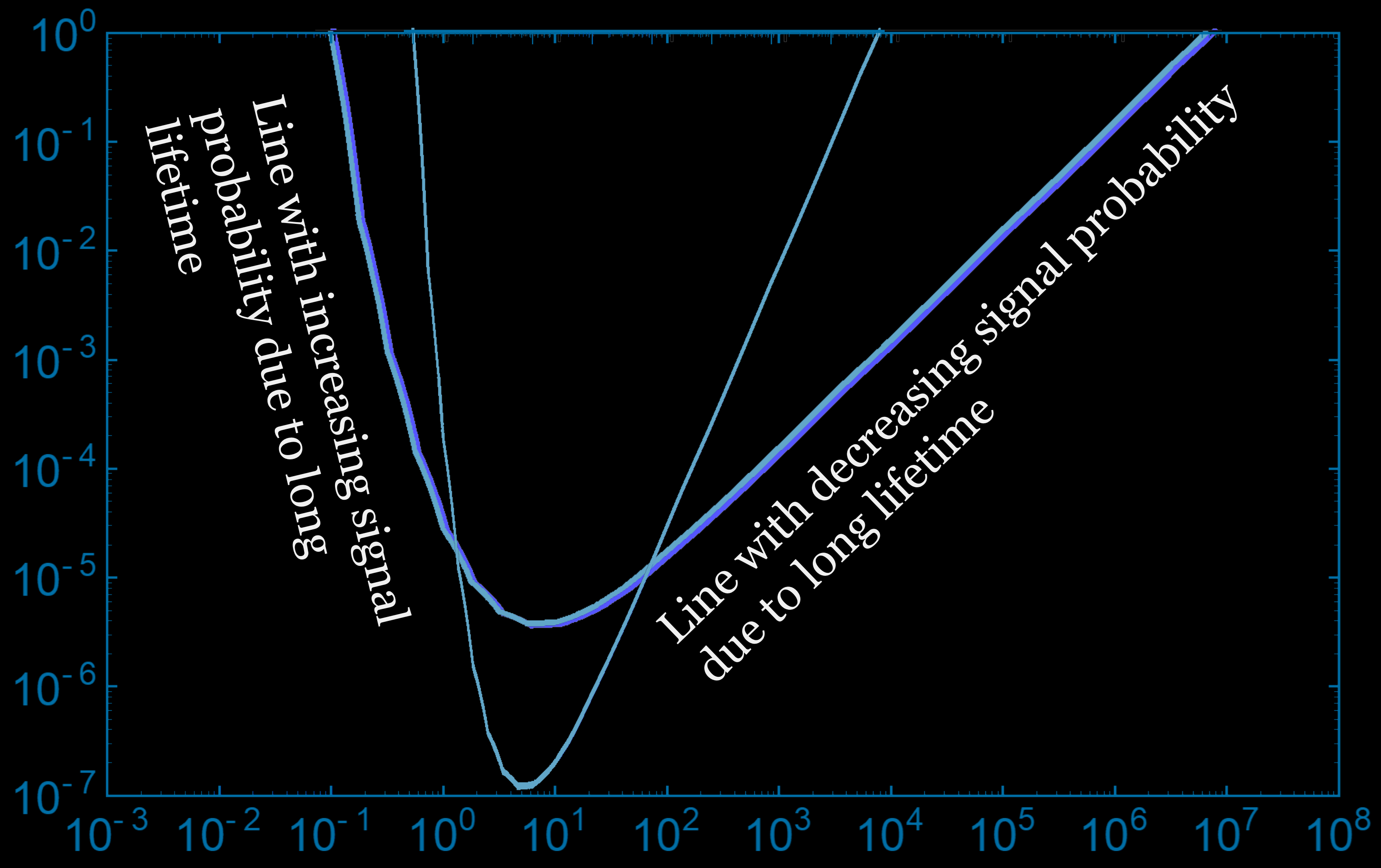
$$P_{in} = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d}$$

$$\approx \frac{\Delta\Omega}{4\pi} \; e^{-L_1/d} \; \frac{L_2 - L_1}{d}$$

$d = c\tau\gamma\beta$

Double LLPs: P_{in}^2

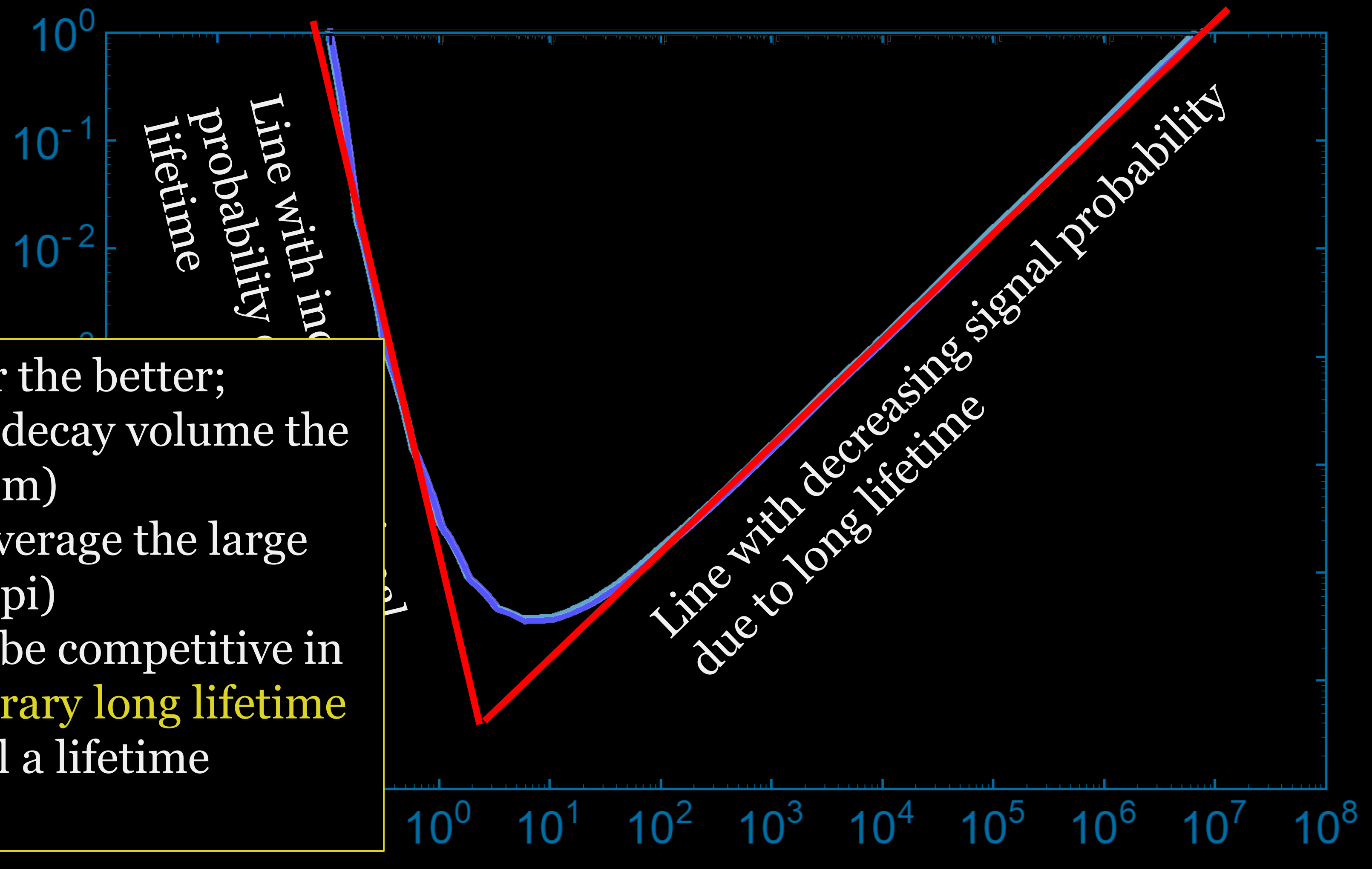
Better sensitivity



Log scale in proper lifetime

Countering one's intuition

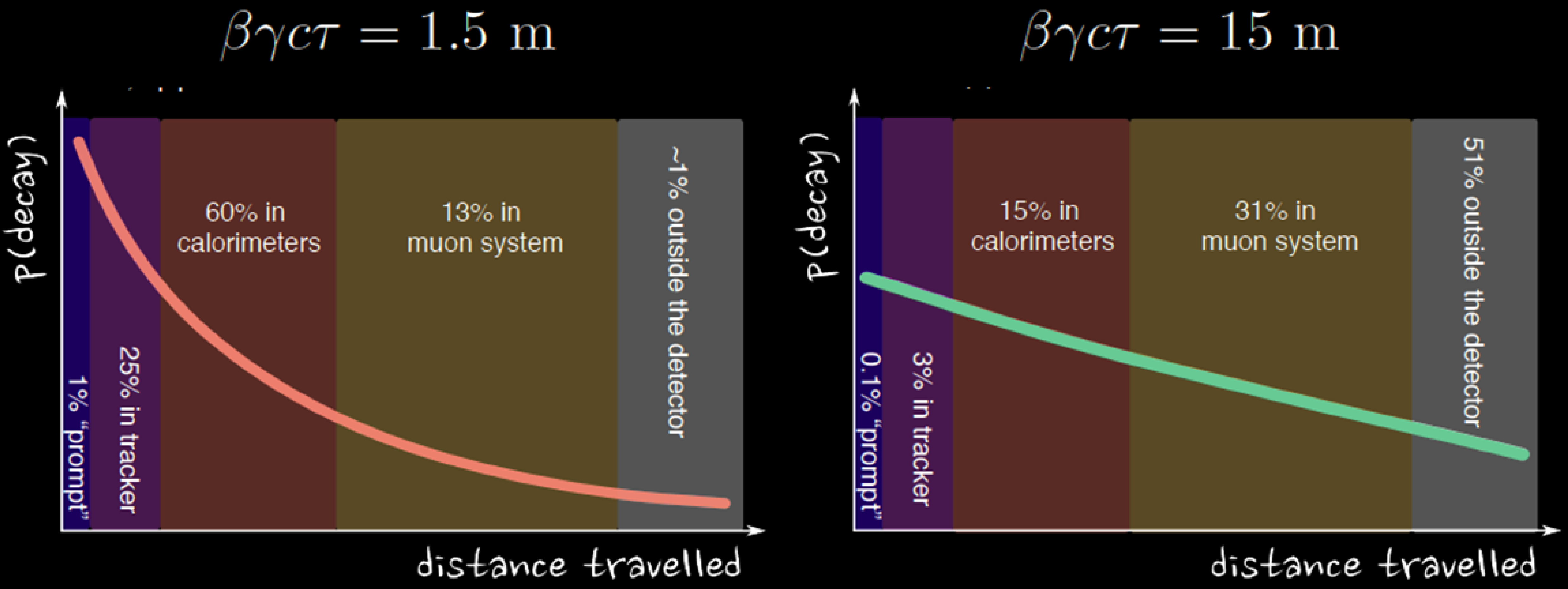
Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)



- For short lifetime: the closer the better;
- For long lifetime: the larger decay volume the better (CMS/ATLAS is 6-10 m)
- For any lifetime: angular coverage the large the better (CMS/ATLAS is 4pi)
- LHC main detectors should be competitive in any lifetime (including arbitrary long lifetime limit; some times people call a lifetime frontier)!

Log scale in proper lifetime

For the case of long lifetime...



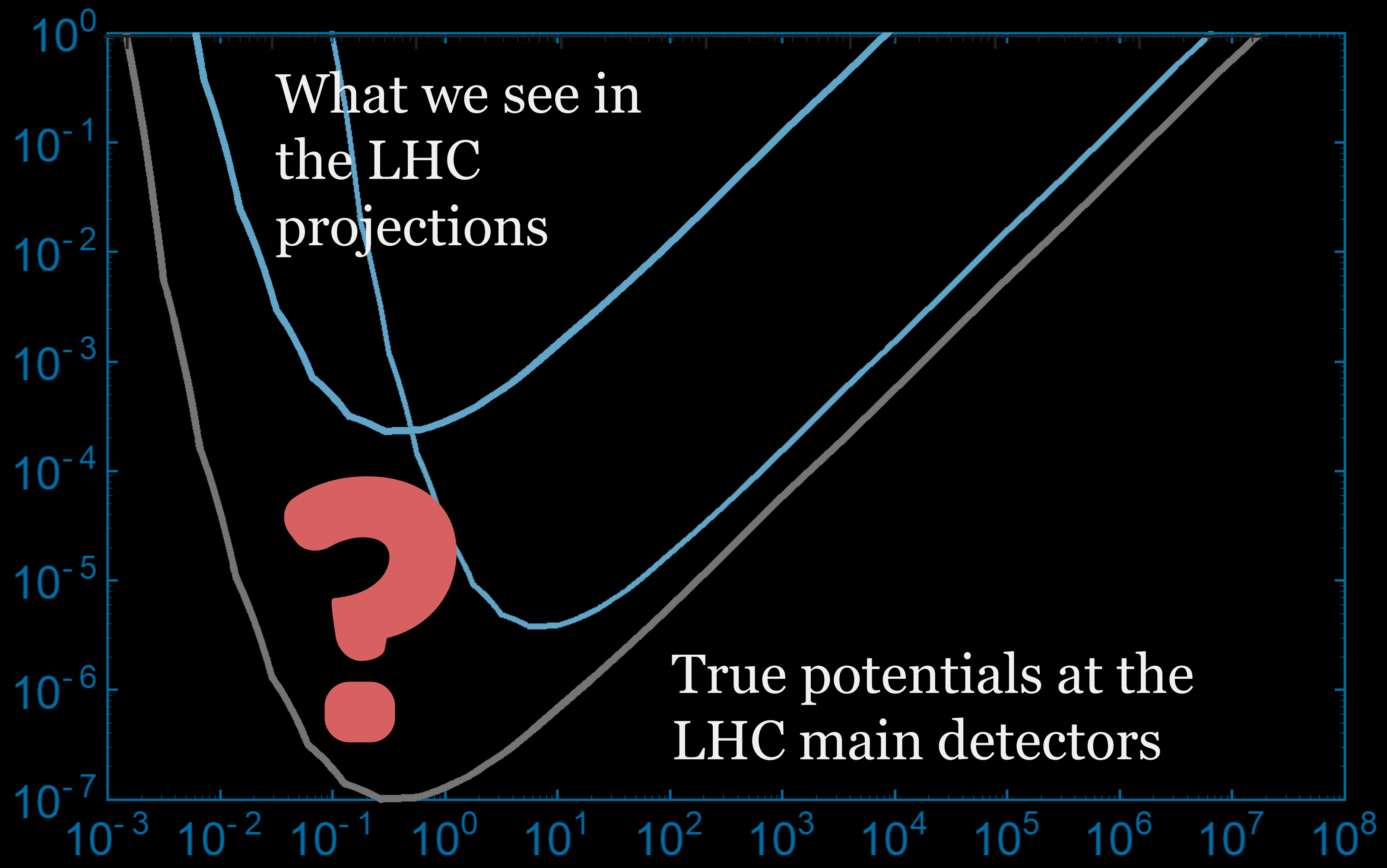
H. Russell, LHC LLP Community workshop, 2017; based on ATLAS geometry

Not decaying in LHC main detectors ≠ will decay in other detectors

Rebuilding intuition: True Potential of main detectors

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

Better sensitivity



Log scale in proper lifetime (m)

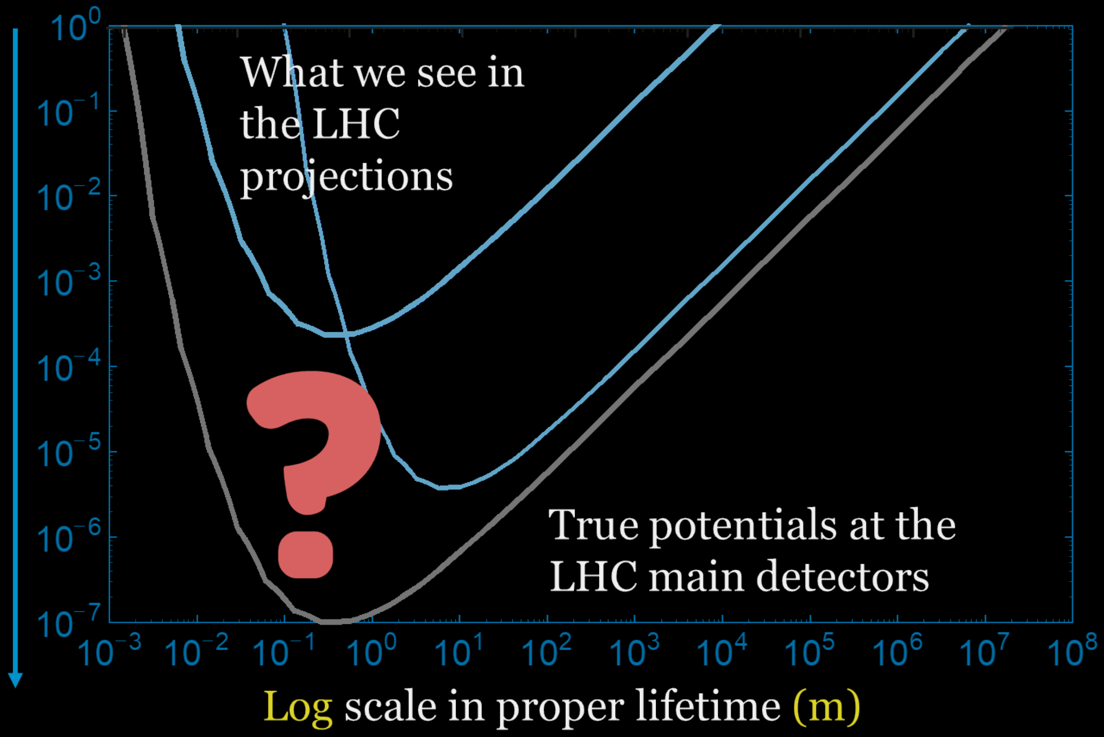
Reexamining intuition: Identifying the challenge

e.g.,
C. Csaki, E. Kuflik, S. Lombardo, O. Slone, 1508.01522 shows Higgs to LLPs typical trigger efficiency <1%;
ZL, B.Tweedie, 1503.05923, O(100 GeV) LLPs have typical efficiency ~1%;

$$n_{sig} = N_{prod} \times P_{in} \times \epsilon_{trigger*selection} \times \epsilon_{bkg}^{penalty}$$

O(1%) — 20-50% for dedicated LLP trigger

1-100% — Energy threshold, reconstruction efficiency, etc.



Opportunities with Lessons

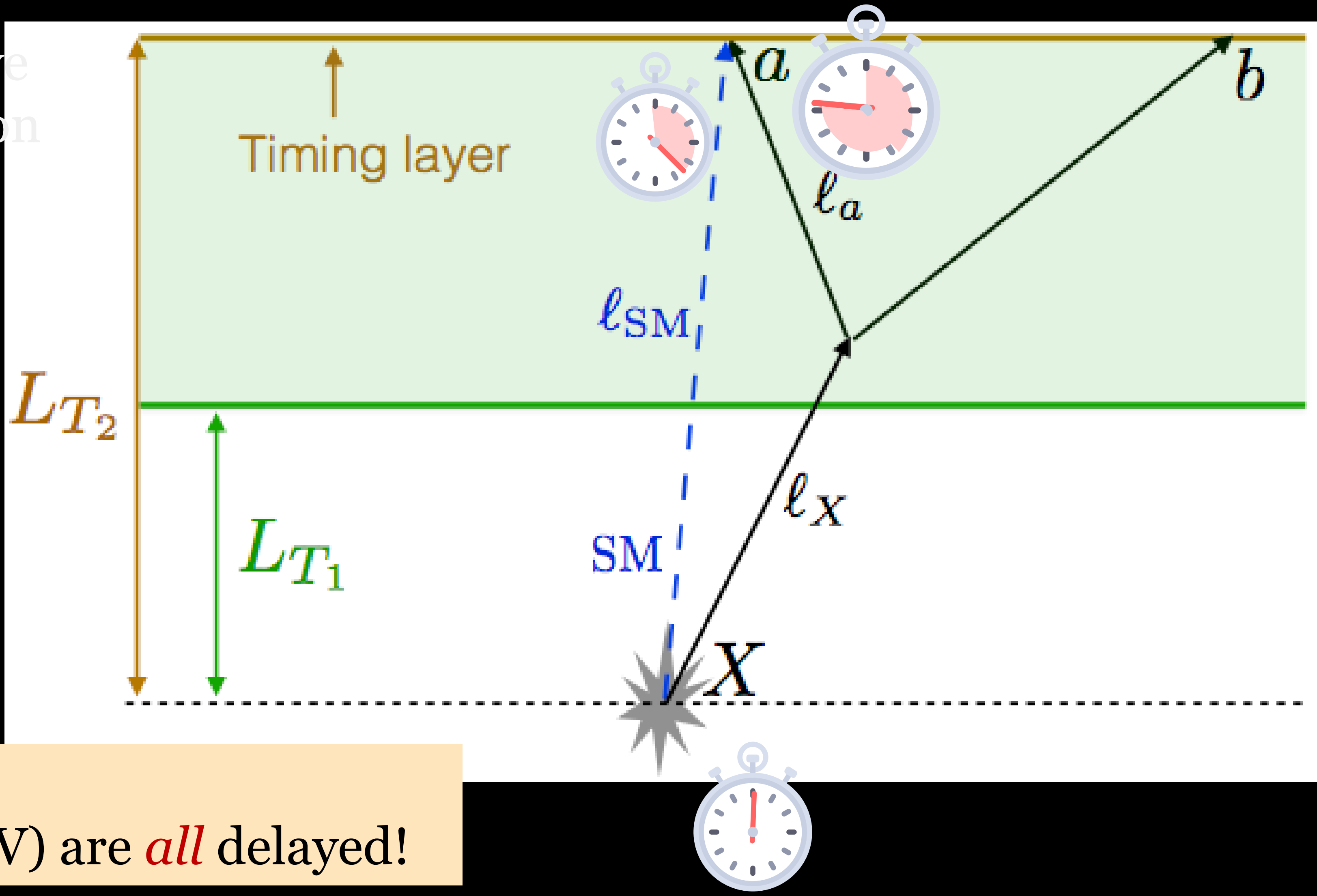
- Search Ideals:
  Timing the LLP Opportunity

Overcoming the difficulties: Timing LLPs

ATLAS, CMS, LHCb all have upgrade plans with precision timing (for pile-up suppression) of order ~30 picosecond

$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}}$$

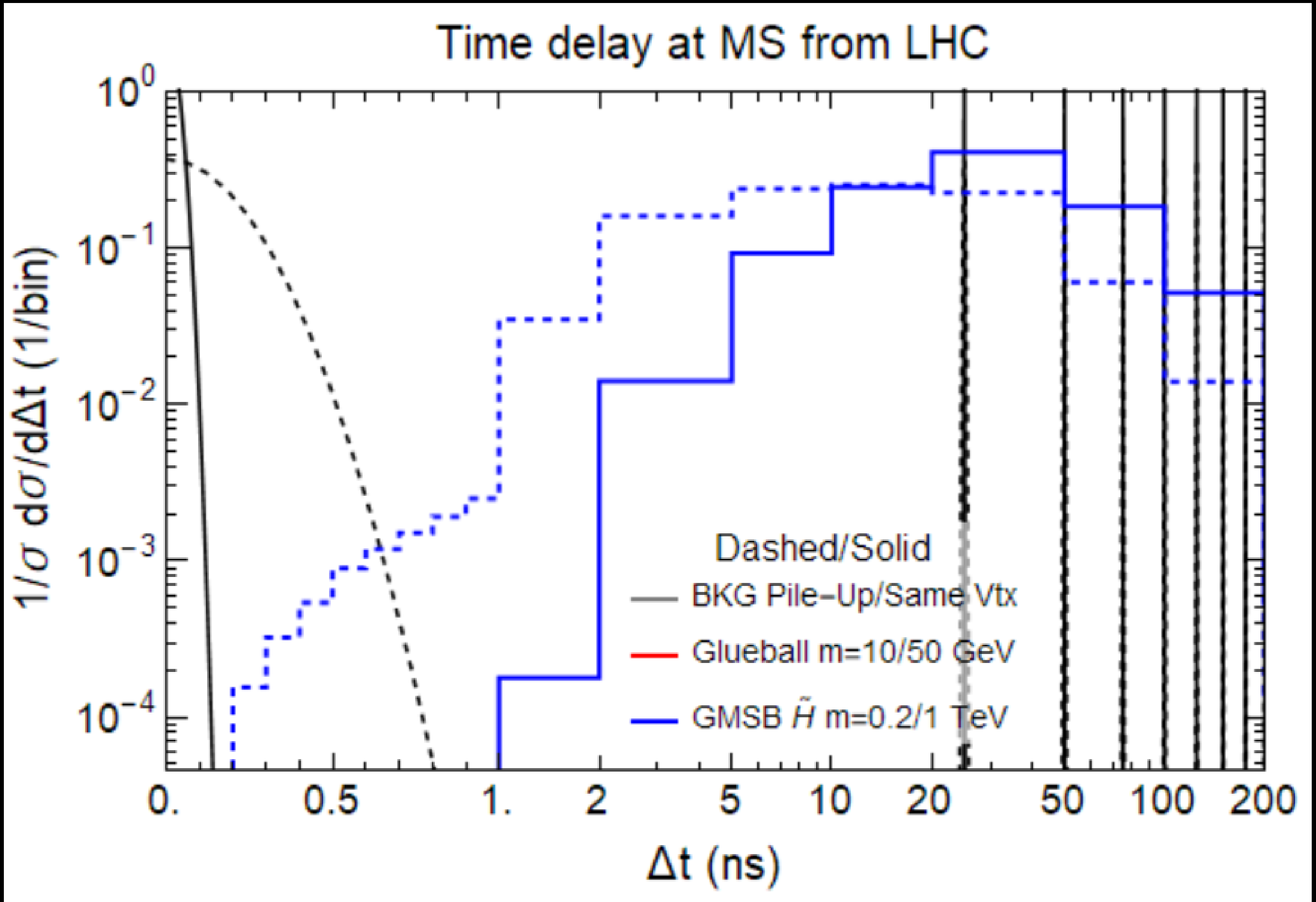
signal arrival time — background arrival time

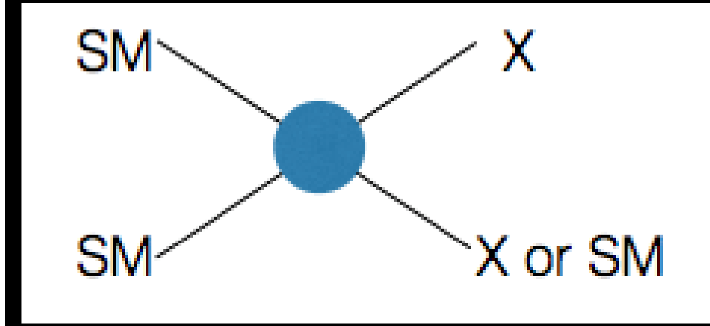


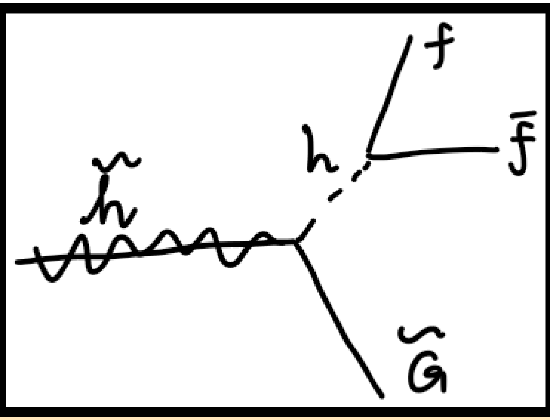
1% delay can be spotted
LLP (with mass > 10s of GeV) are *all* delayed!

J. Liu, ZL, LT Wang, 1805.05957
Chiu, ZL, Low, Wang, 2109.01682
Chiu, ZL, Shen, et al, ongoing

Pair-produced LLPs are significantly delayed



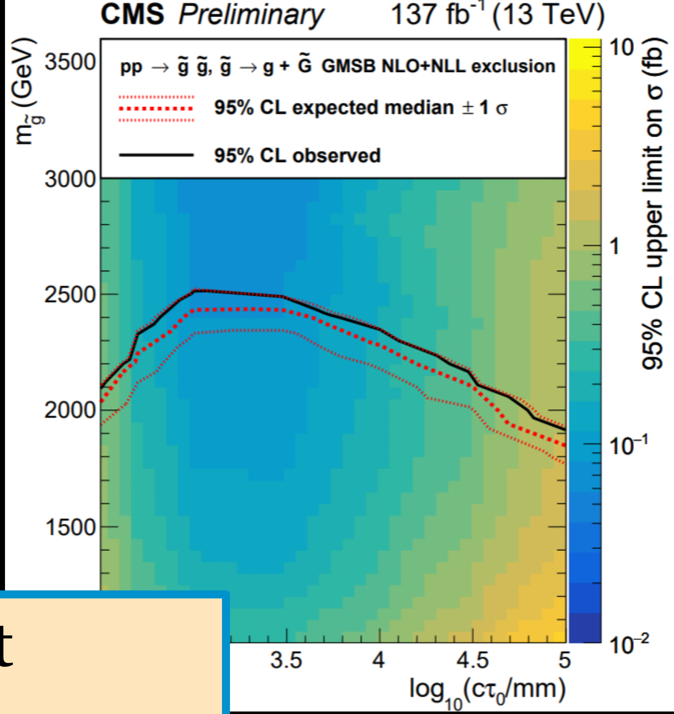


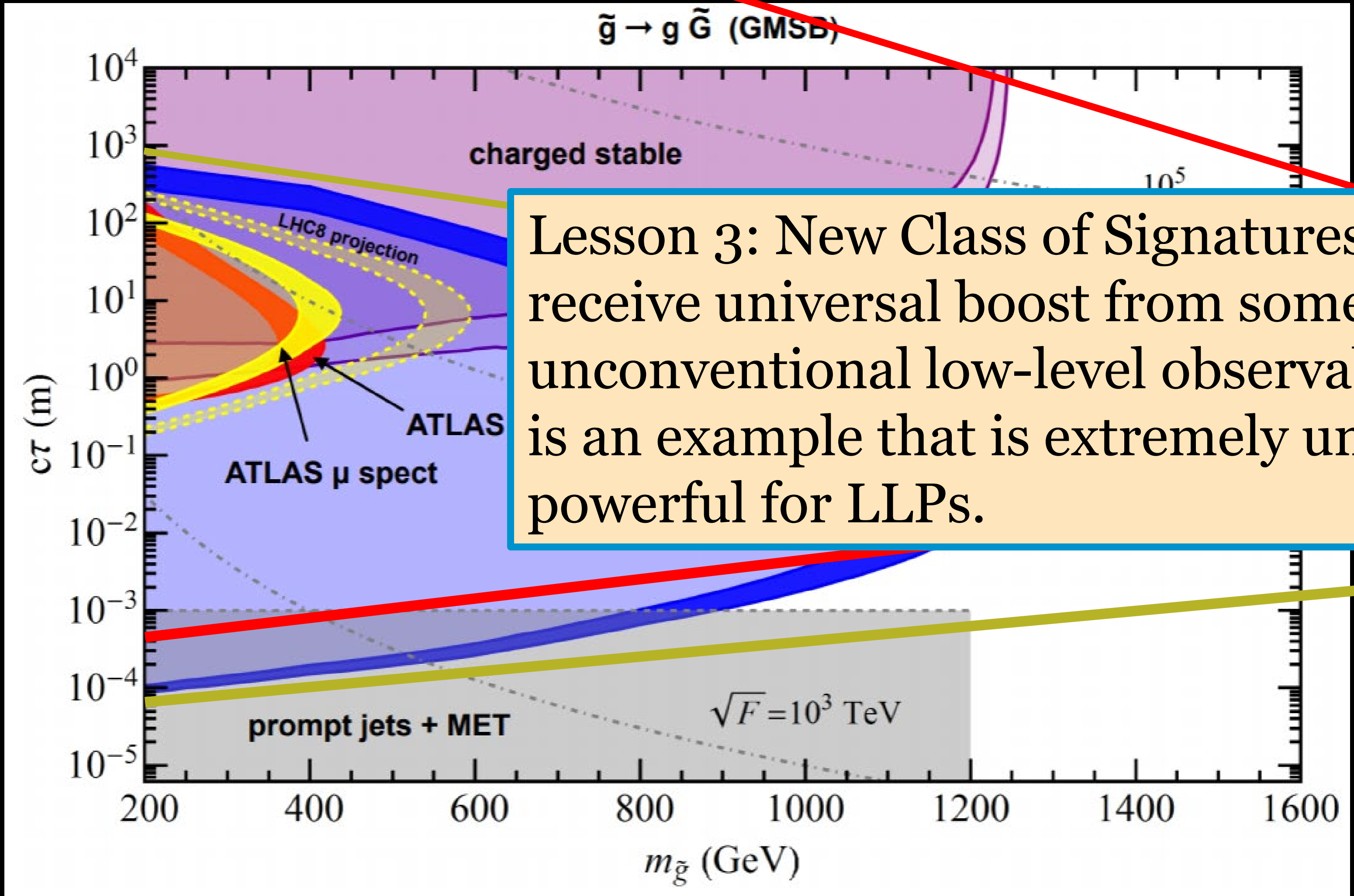


Representative of LLP pair production:
All severely delayed

Delayed jet

Used traditional 300 GeV MET trigger but rely on the time delays of the trackless **minimal jet (50 GeV pT)** , start probing new regime!





Lesson 3: New Class of Signatures might receive universal boost from some unconventional low-level observables. Timing is an example that is extremely universally powerful for LLPs.

New LLP searches now often consider timing information as part of the analysis/search.

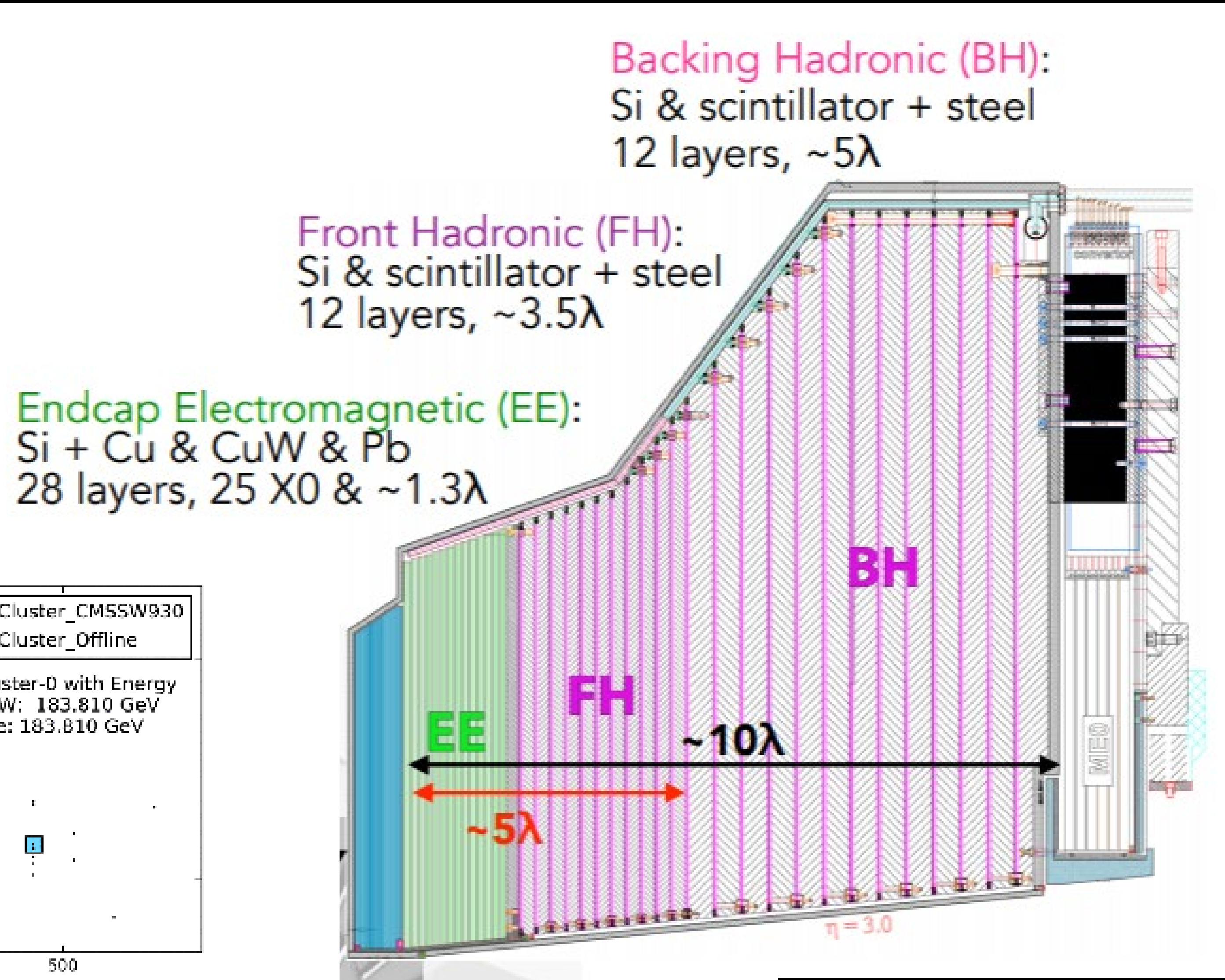
Opportunities with Lessons

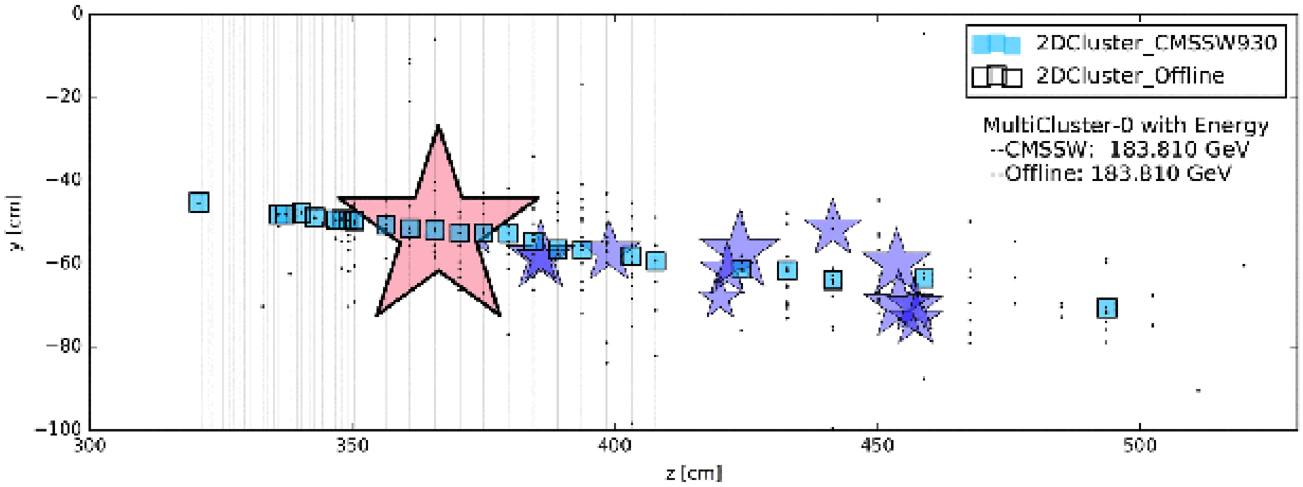
- Search Ideals:
  Vertexing with Calorimetry

More ideas: using substructures in the calorimetry

HL upgrade:
Directional resolution milliradian,
Temporal resolution 30 ps
(for pT > 30 GeV):

Allowing jet & shower

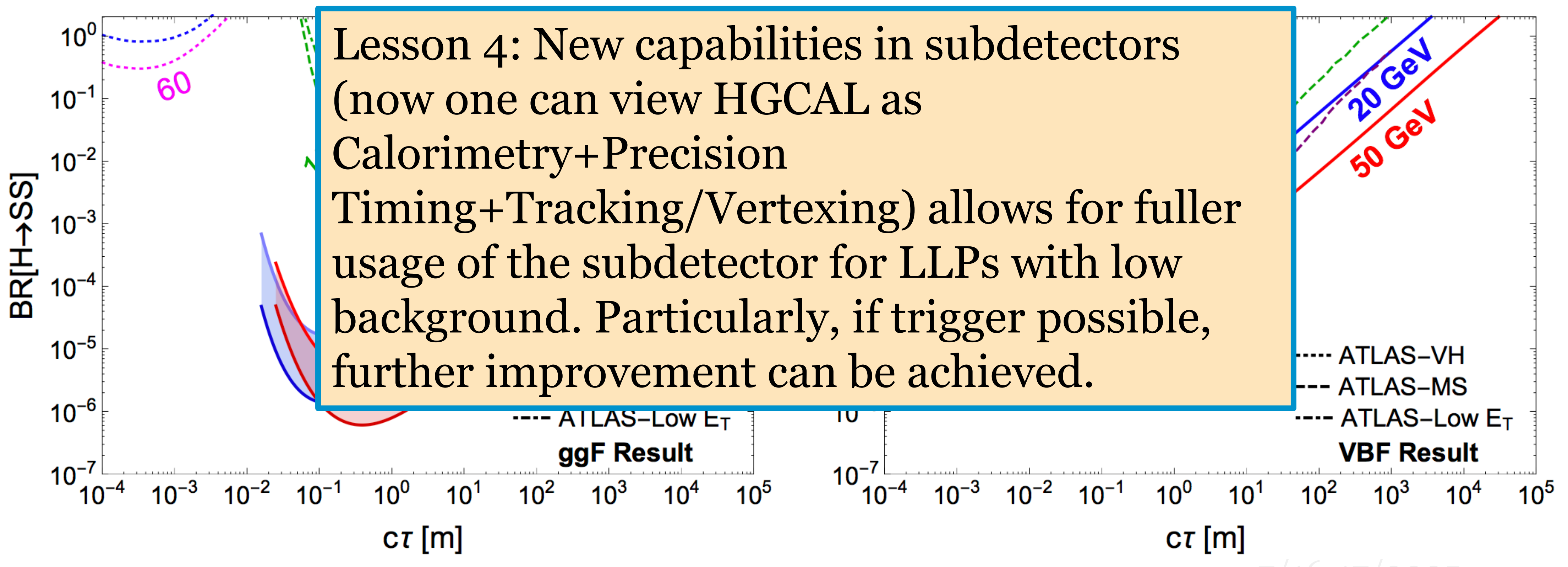




Projected sensitivity for HL-LHC

With a similar (in concept but different in details) vertexing selection as the previous axion example

- ggF result: with/without high H_T trigger requirement
- VBF result: standard VBF trigger



Lesson 4: New capabilities in subdetectors (now one can view HGCAL as Calorimetry+Precision Timing+Tracking/Vertexing) allows for fuller usage of the subdetector for LLPs with low background. Particularly, if trigger possible, further improvement can be achieved.

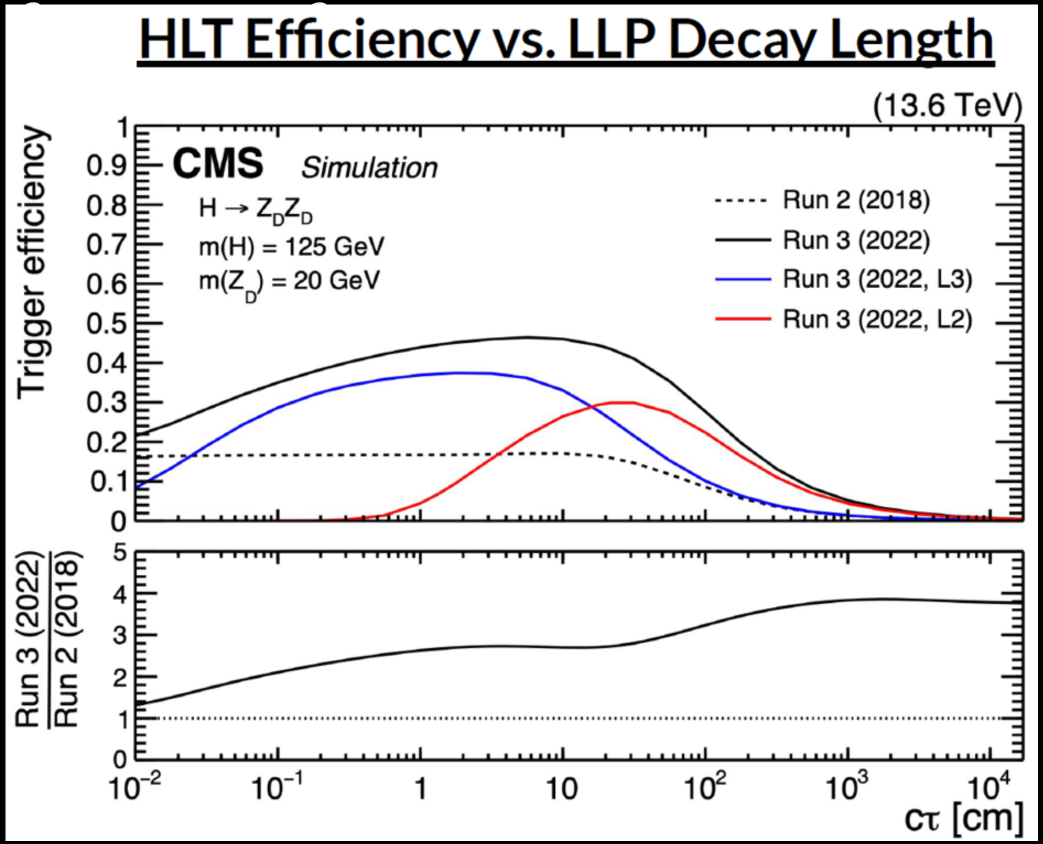
Opportunities with Lessons

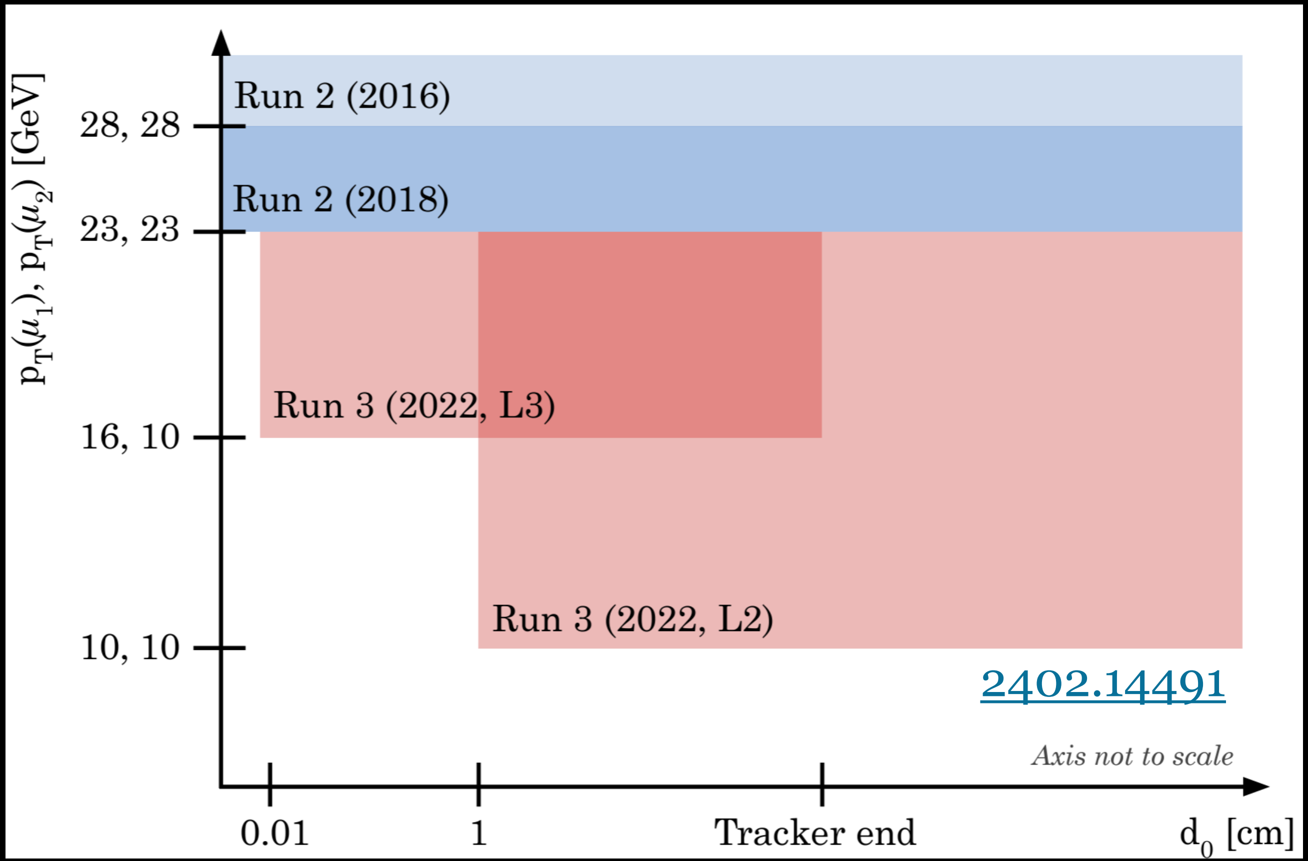
- New triggers

Many New Improvements in the past few years and many more to implement

Recent Trigger Improvement: Displaced Dimuon

- Run3 improved trigger: trigger efficiency increased by a

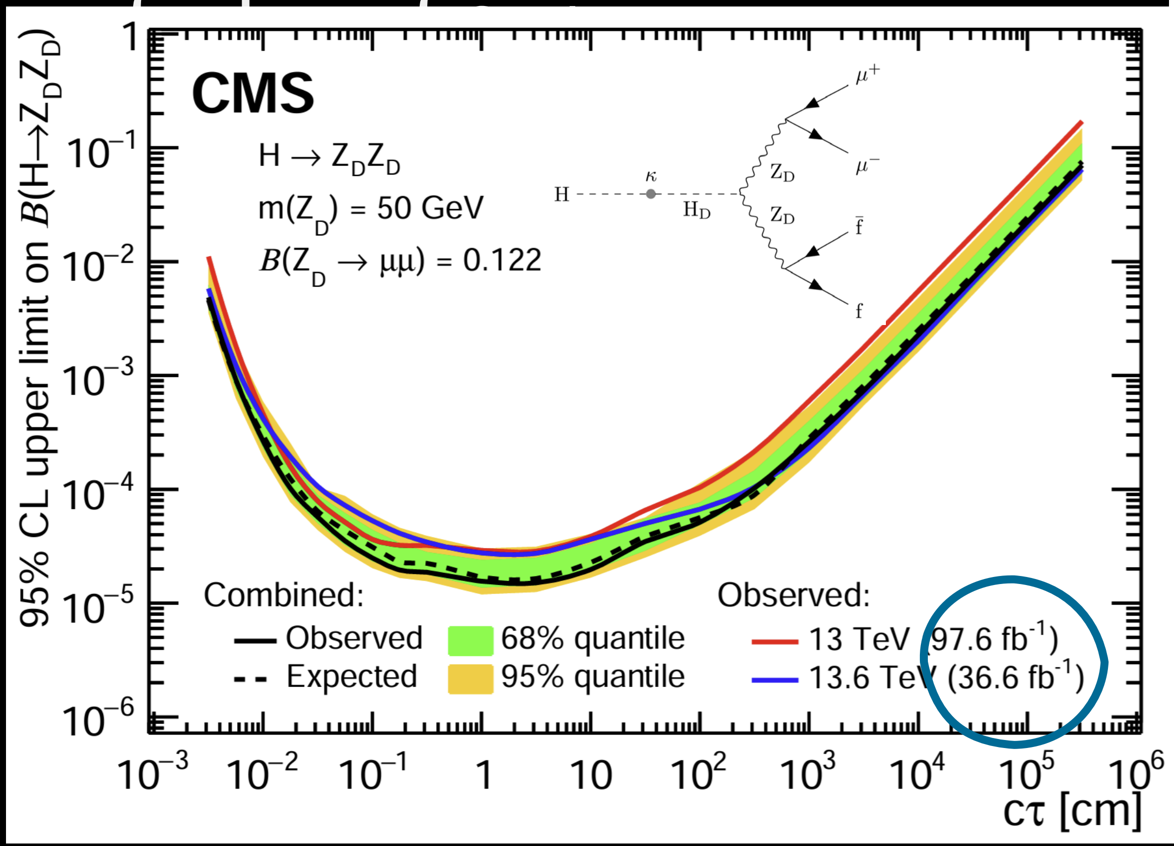


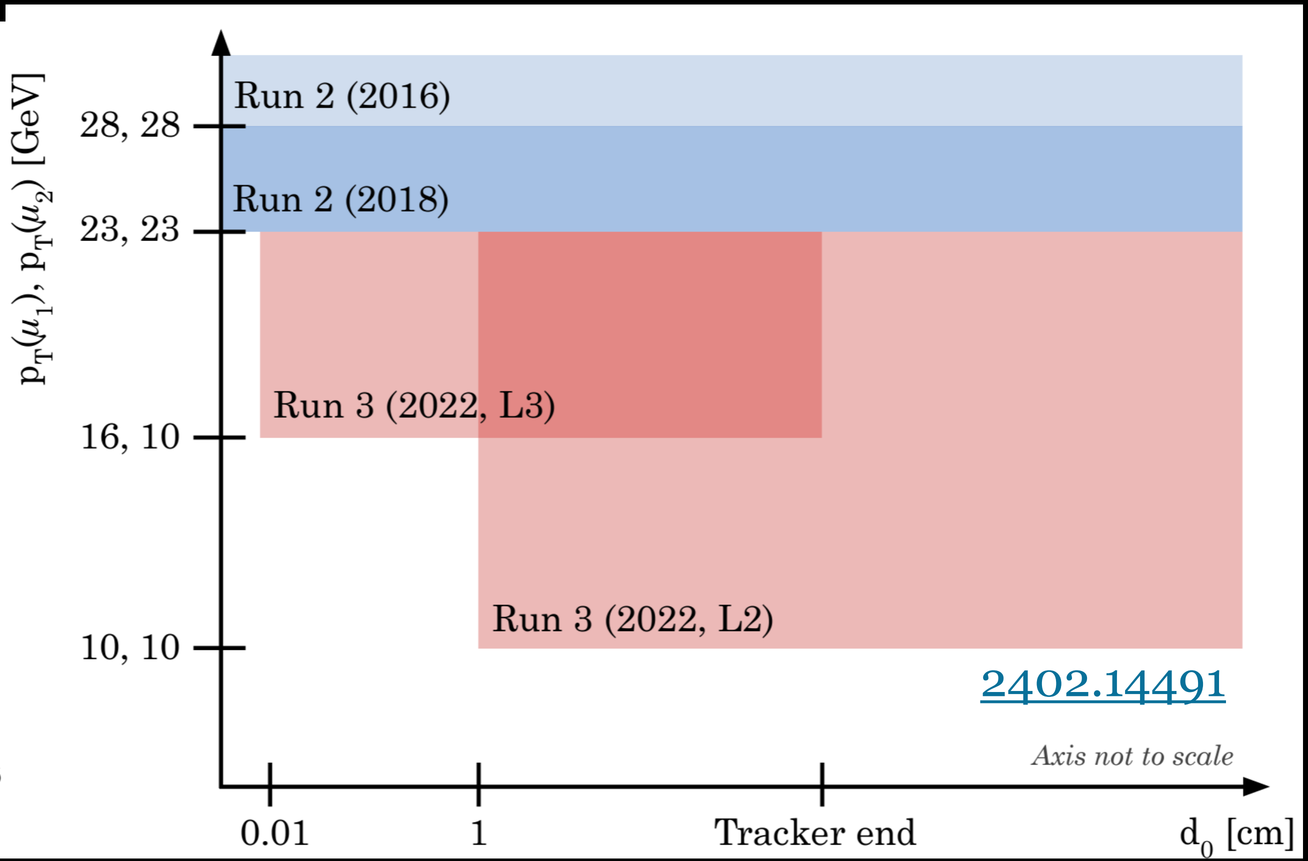


L2: Muon system only, newly added long-lived trigger
L3: Muon system plus tracking, newly added longlived trigger

Recent Trigger Improvement: Displaced Dimuon

- Run3 improved trigger: trigger efficiency increased by a

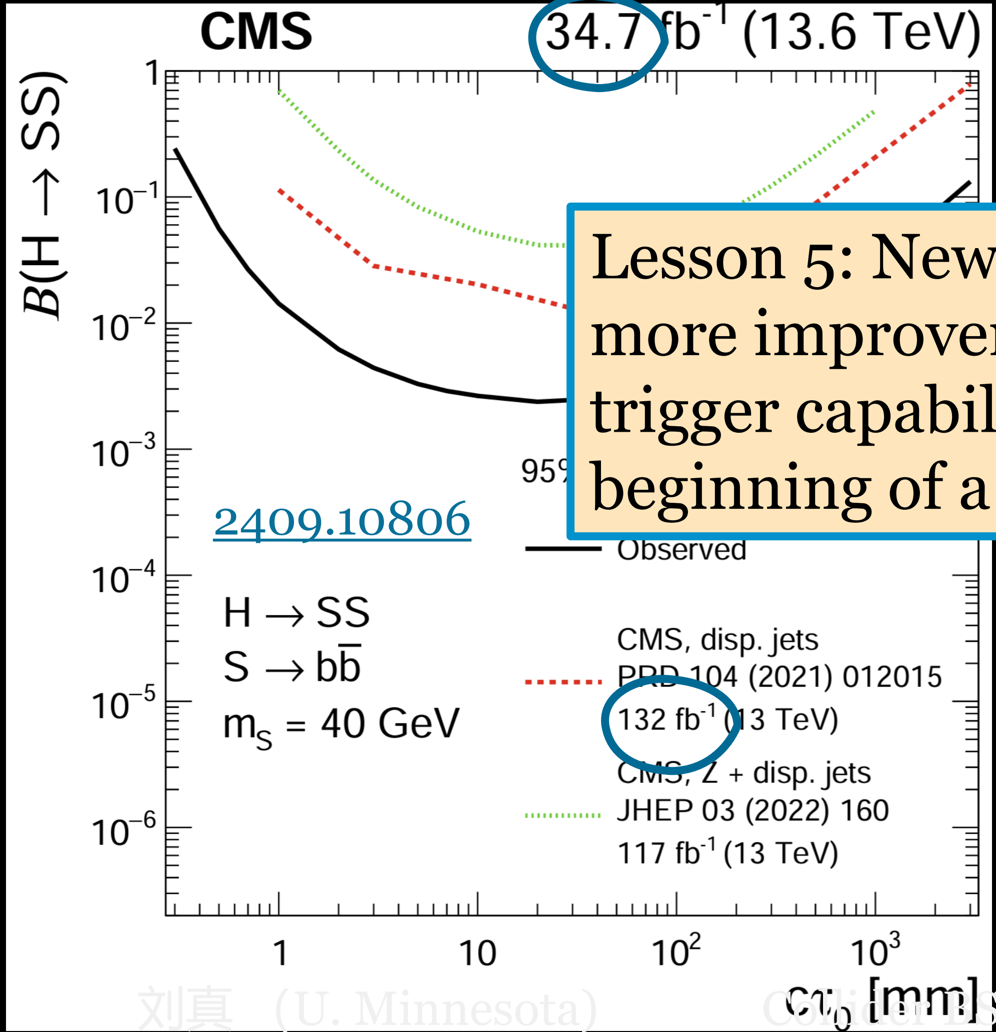


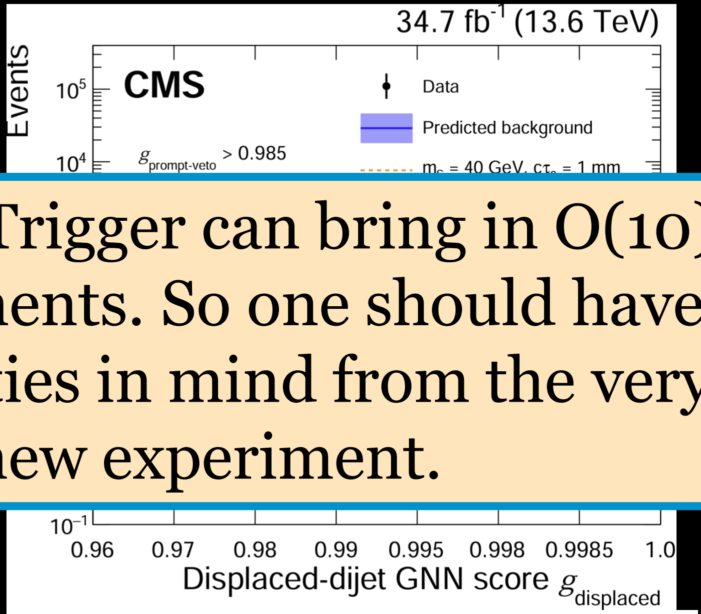


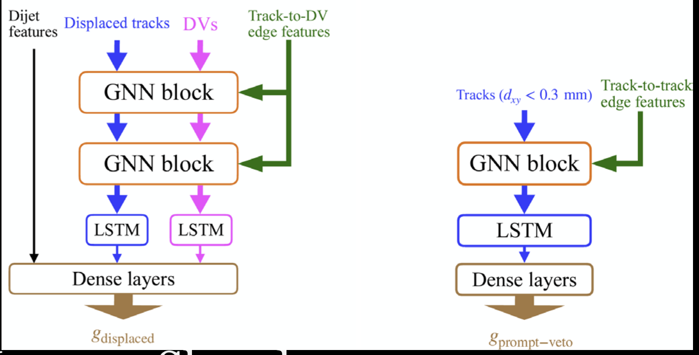
Better sensitivity with 1/3 the luminosity due to the improved trigger.

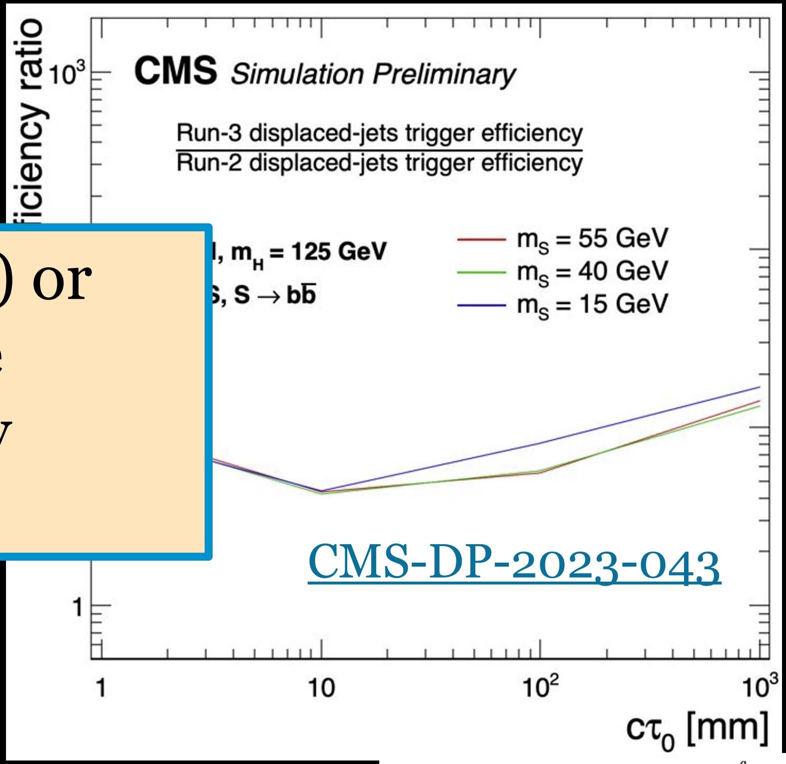
Recent Trigger Improvement: Displaced jets in tracker

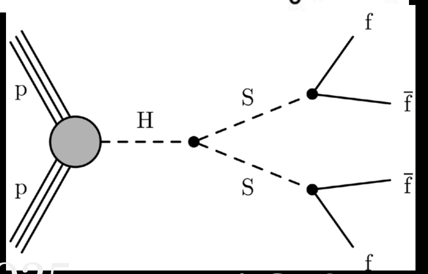
- Run3 improved trigger: trigger efficiency by around 10, then with analysis improvement











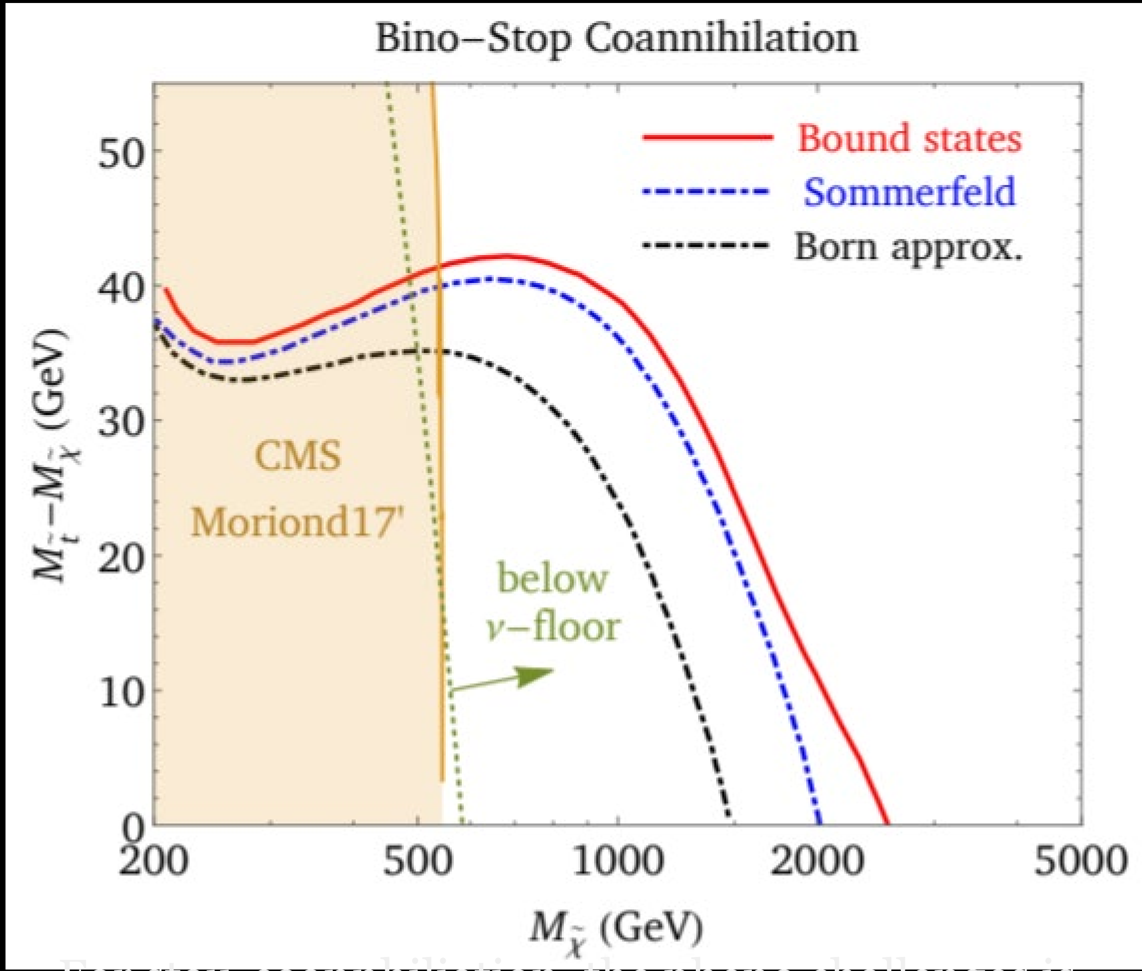
Lesson 5: New Trigger can bring in O(10) or more improvements. So one should have trigger capabilities in mind from the very beginning of a new experiment.

Opportunities with Lessons

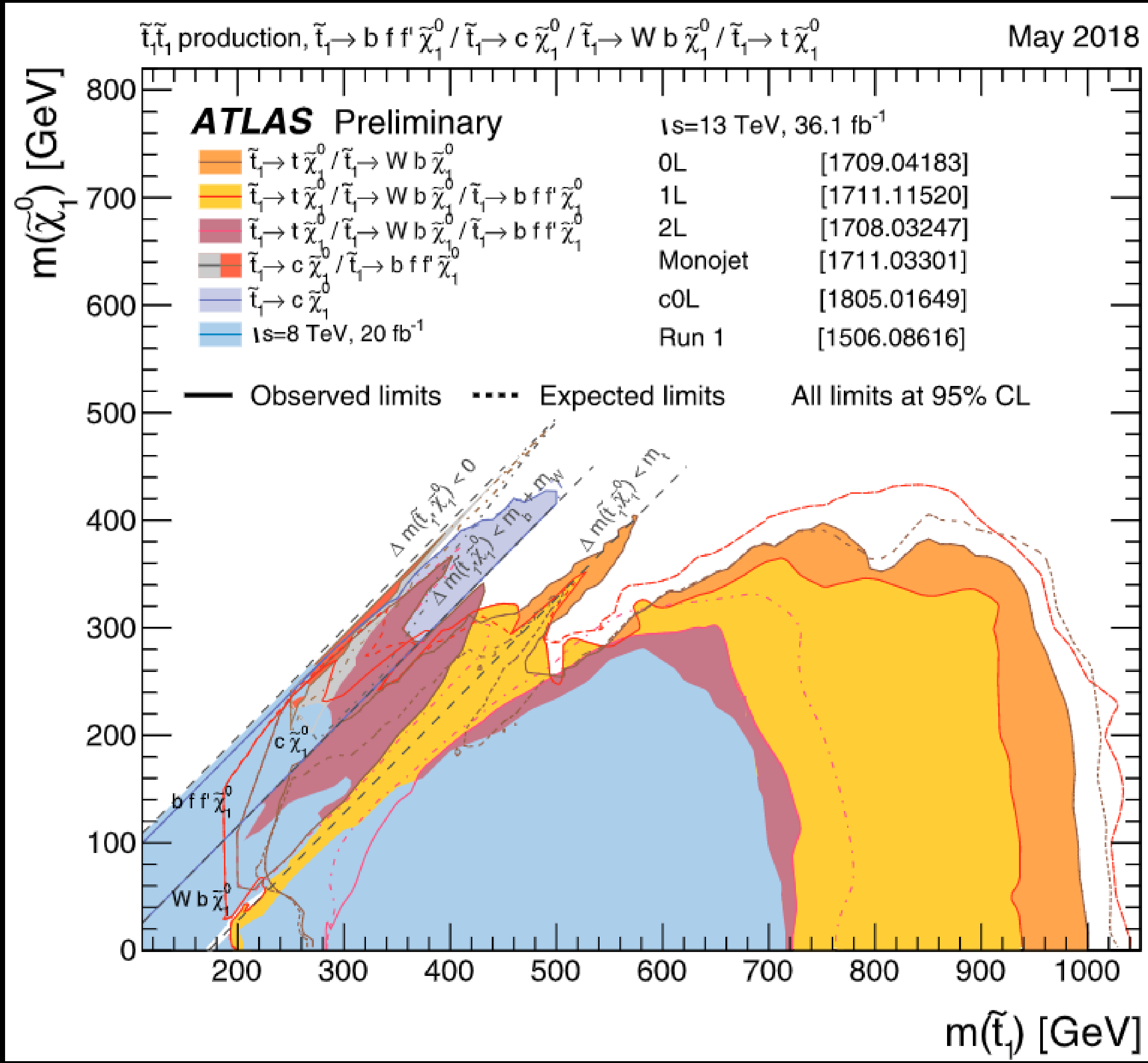
- New Challenging Signals

Mono-jet + (soft) displaced tracks

Coannihilation and LLP



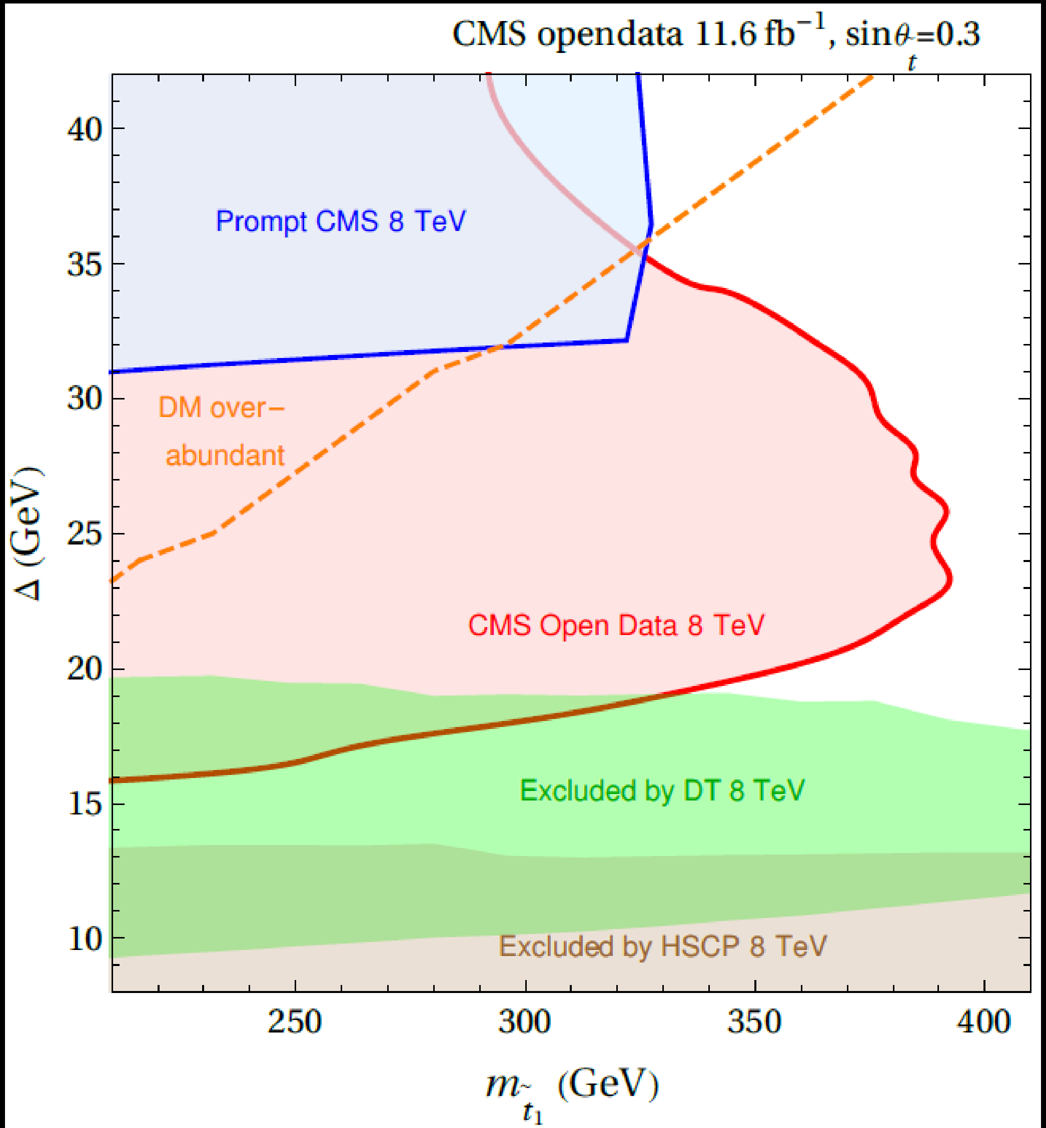
For stau-coannihilation, the pheno challenges is with soft and prompt tau leptons.

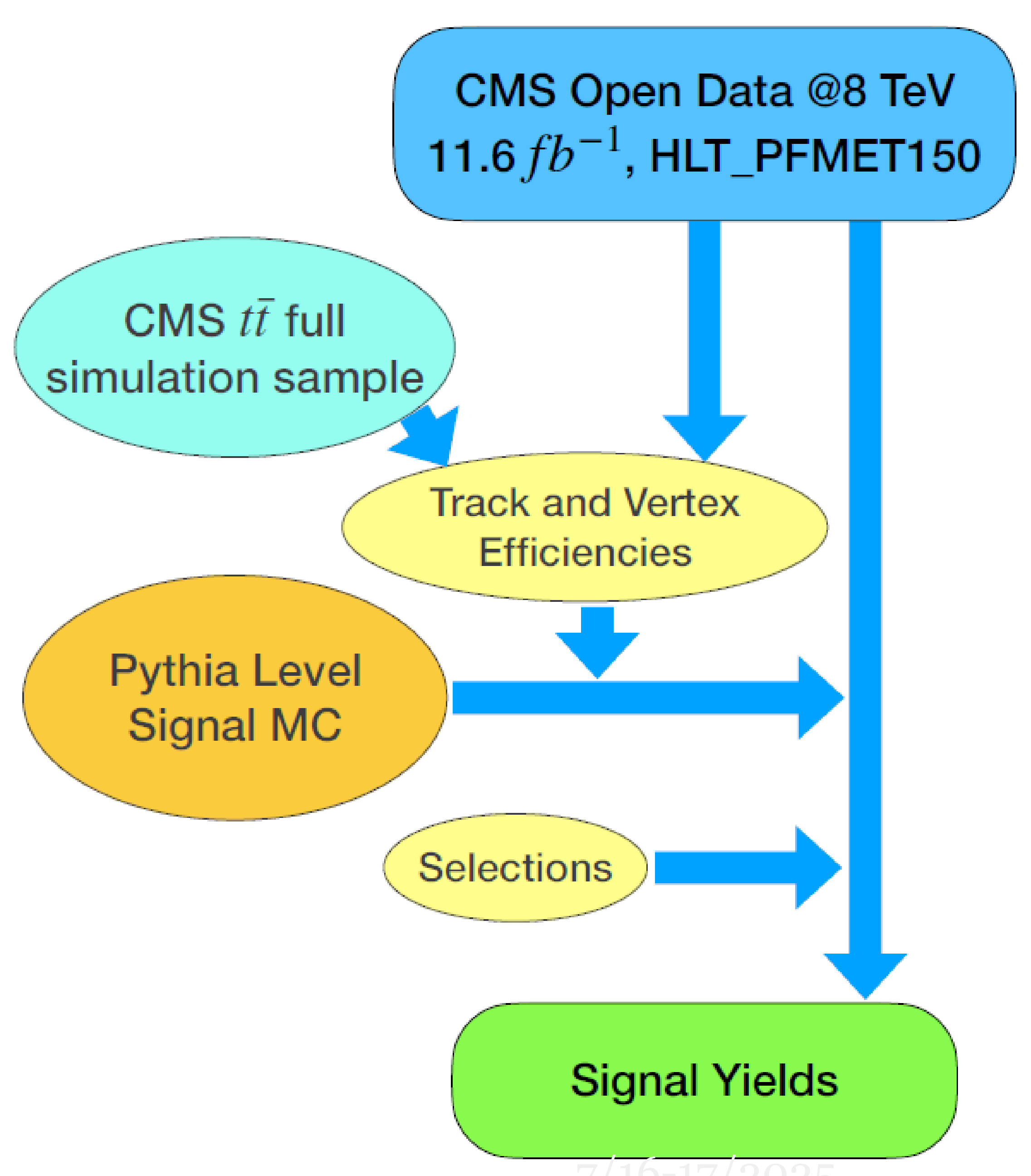


T. Han, ZL, A. Natarajan, 1303.3040

An, Hu, ZL, Yang, [2107.11405]

With OpenData, we showed MET+soft tracks are feasible





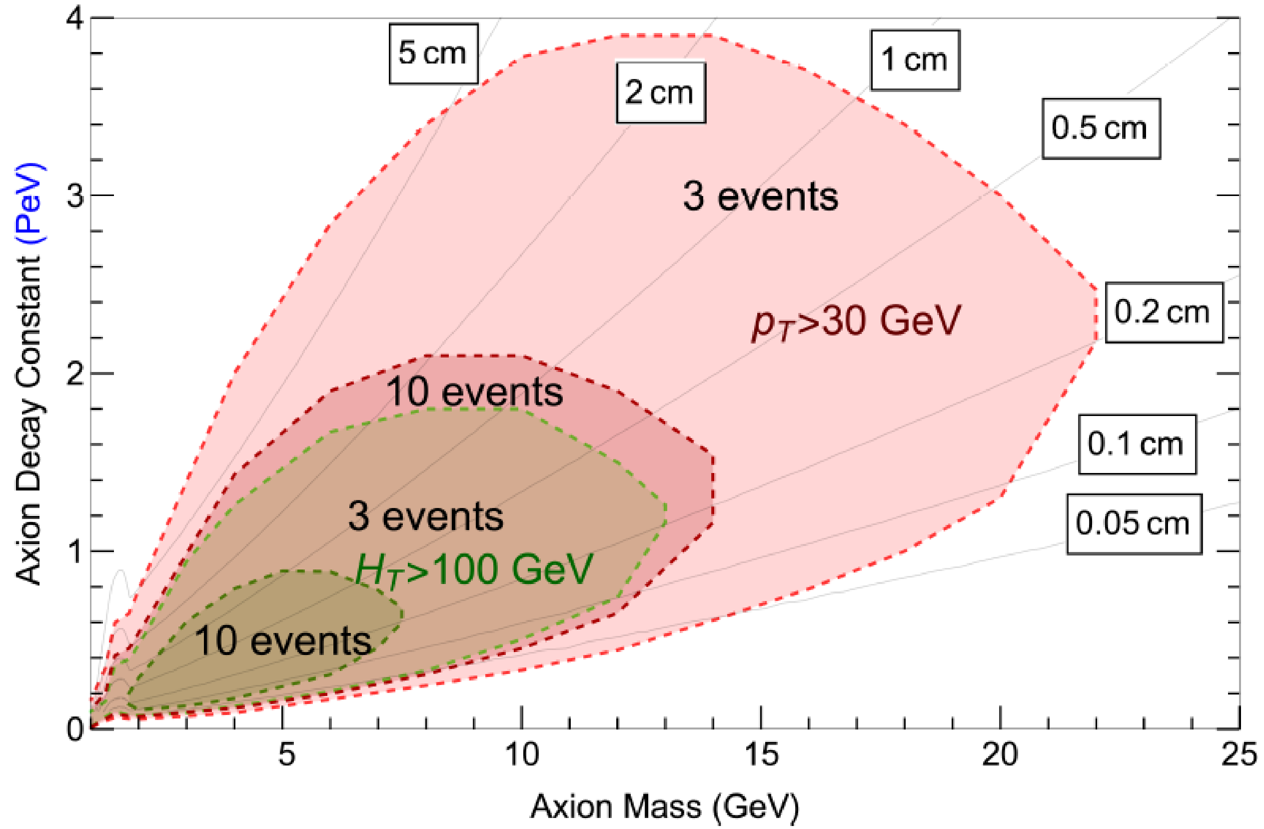
Hook, Kumar, ZL, Sundrum, 1911.12364; ZL, Kumar, et al on various possibilities, 2011.05995, 2210.02462, 2207.08448, Knapen, Kumar, Redigolo, 2112.07720

A displaced track trigger enables searches for axions

Unique singly produced LLPs making the LHC main detectors the major place to look for them:

Long lifetime = low production rate

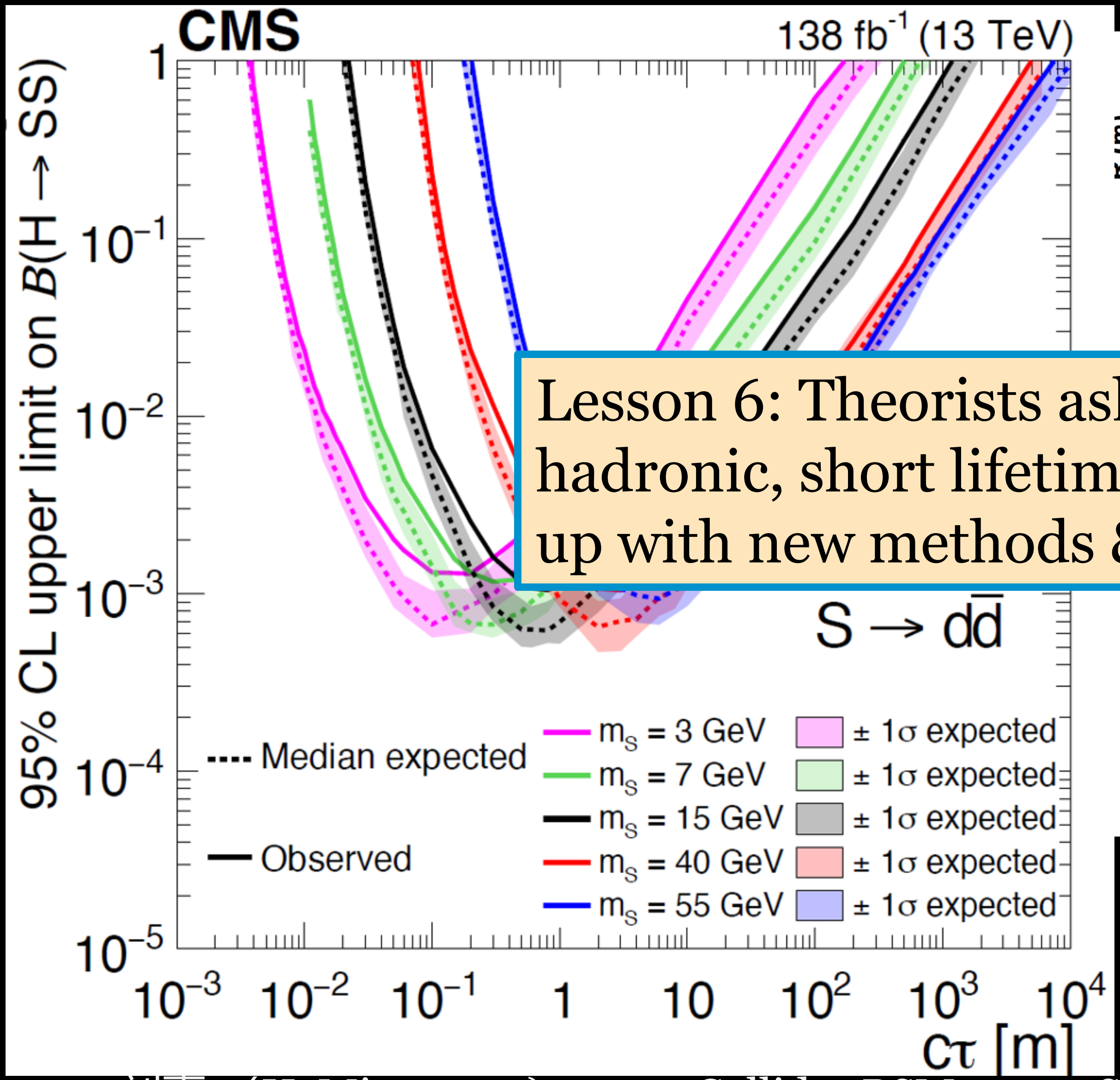
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

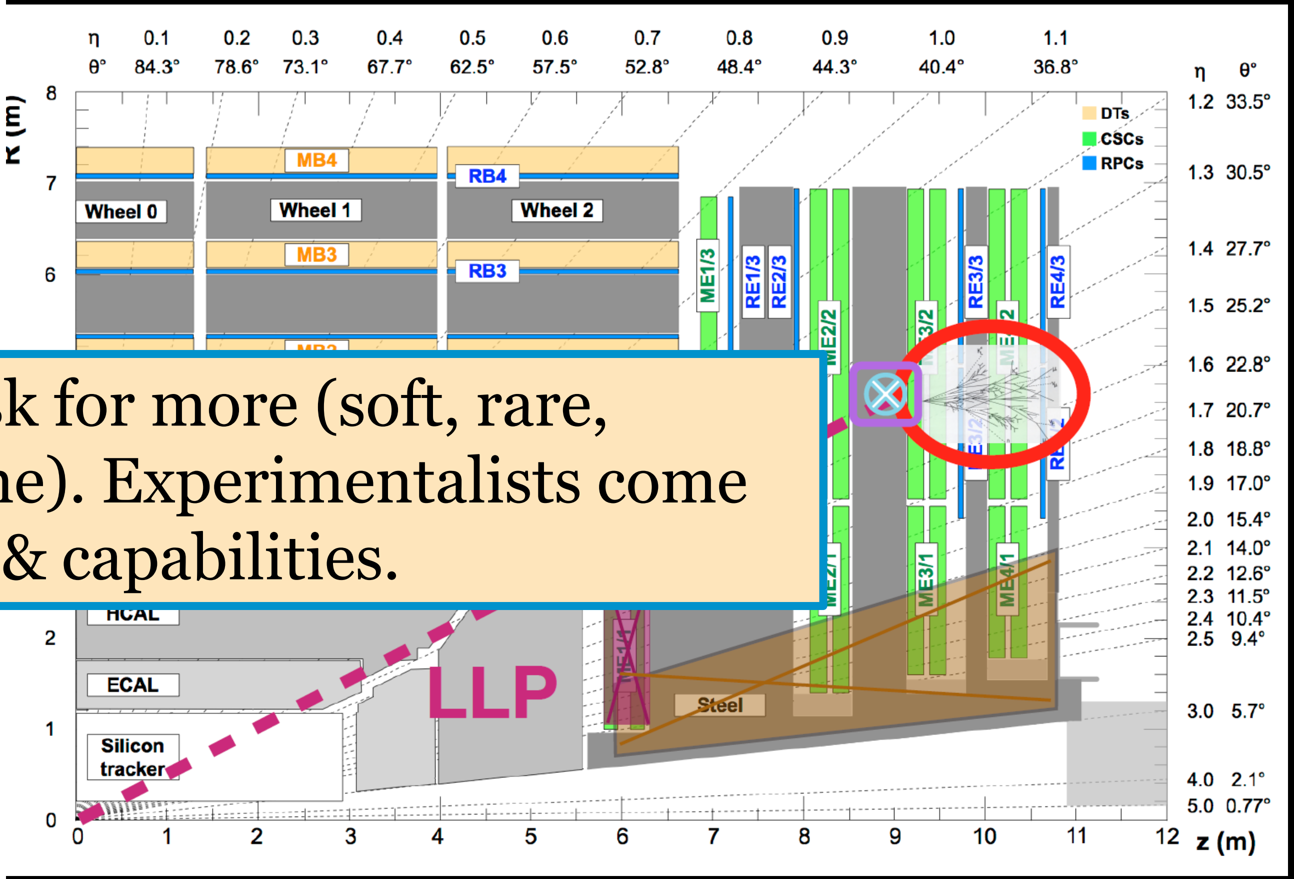


A 2D-4D vertexing selection for displaced jet to veto the fake track background, demonstrating the plausibility of this search.

Trigger: Y. Gershtein, 1705.04321, CMS-PAS-FTR-18-018

Our experimental colleagues also creatively handle those low mass (but not soft) objects





Lesson 6: Theorists ask for more (soft, rare, hadronic, short lifetime). Experimentalists come up with new methods & capabilities.

Opportunities with Lessons

- Future Collider Benchmark: Higgsino DM

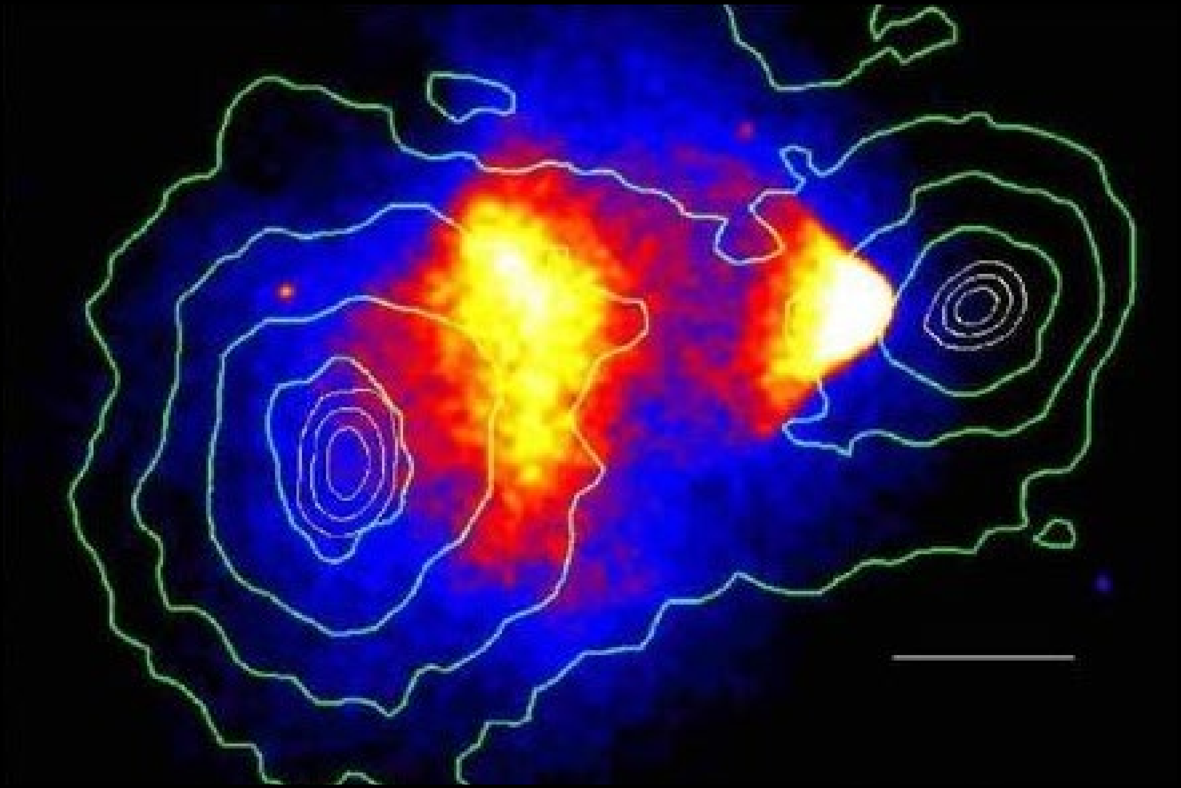
WIMP Dark Matter

Compelling, simple, predictive explanation for thermal, cold dark matter.

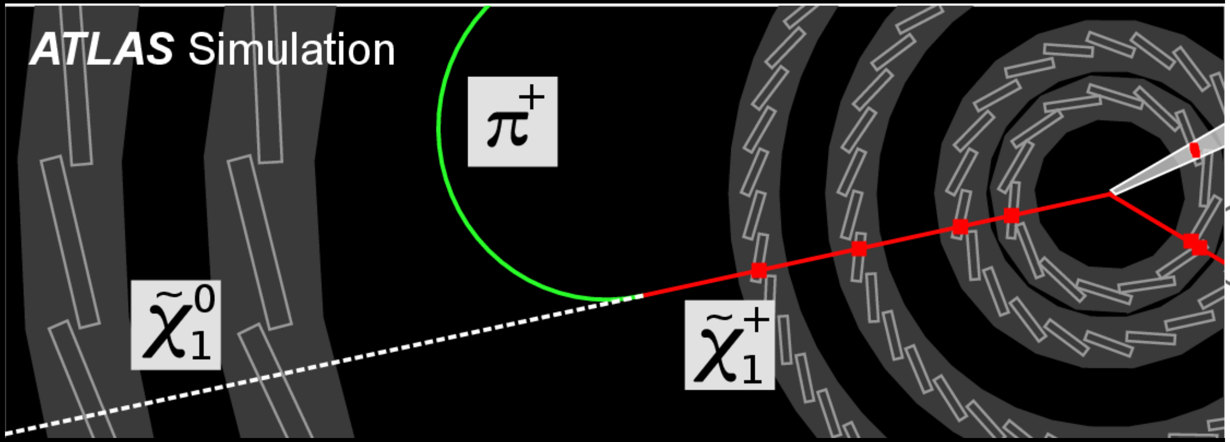
Amongst those, a pure electroweak doublet (SUSY Higgsino) is particularly motivated and challenging.

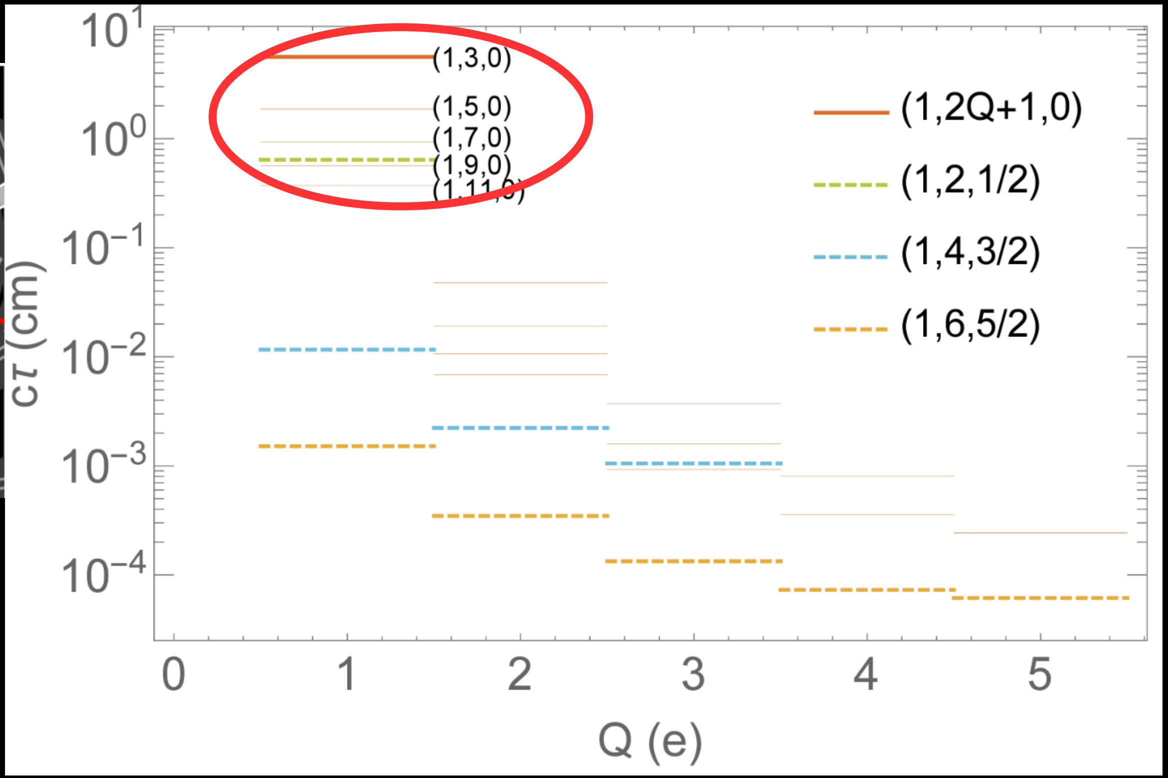
$$\Omega h^2 \simeq 0.1 \times (\frac{2 \times 10^{-26}\mathrm{cm}^3/\mathrm{sec}}{< \sigma_{\mathrm{eff}} v >_{\mathrm{freeze-out}}})$$

$$< \sigma_{\mathrm{eff}} v >_{\chi\bar{\chi}\to VV} \simeq \frac{\pi \alpha_\chi^2}{m_\chi^2}$$



Disappearing Tracks: next to minimal signatures





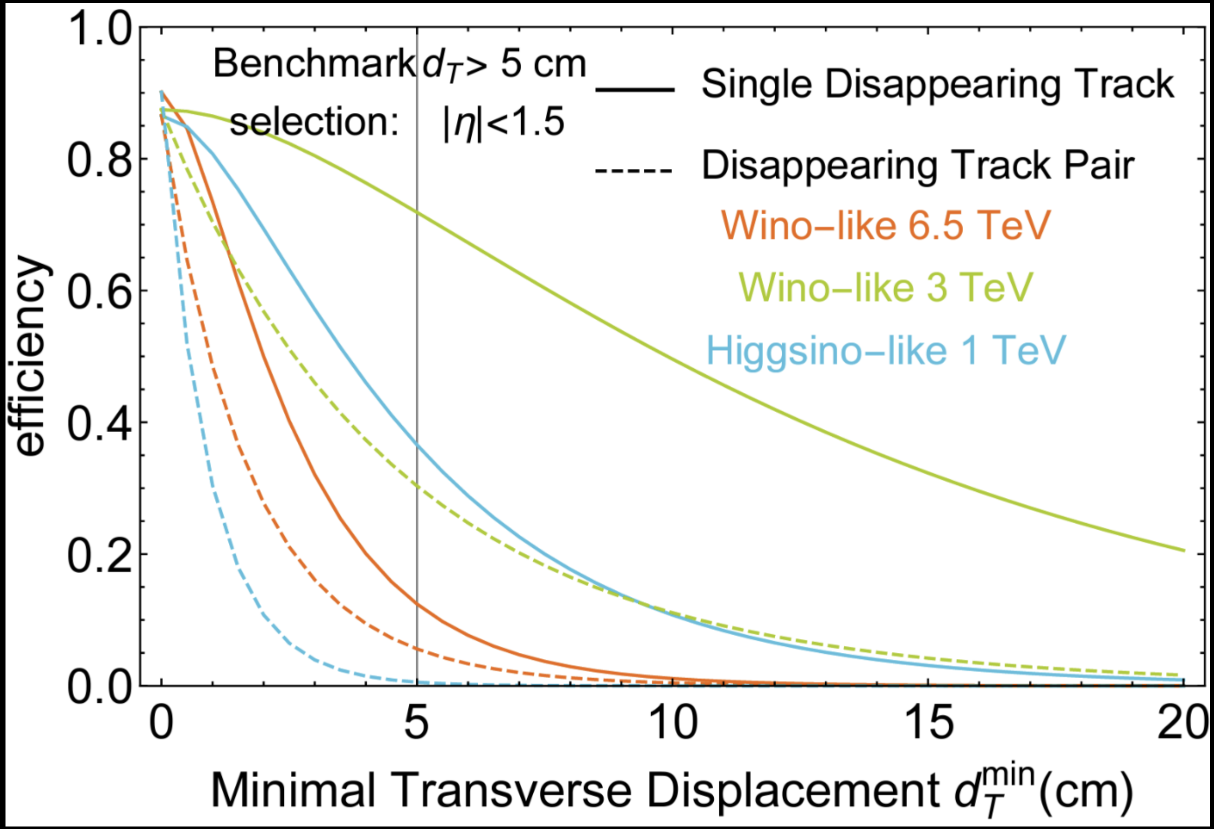
- Only useful for searches using charge 1 states
- Still, all higher charged states will cascade back to charge 1 states promptly
- Use all the production rates of charged states
- Mono-photon+disappearing tracks
- Beam Induced Background

Pure Higgsinos with 360 MeV mass splitting, 6mm lifetime, low production rate and 1.1 TeV target mass, very challenging.

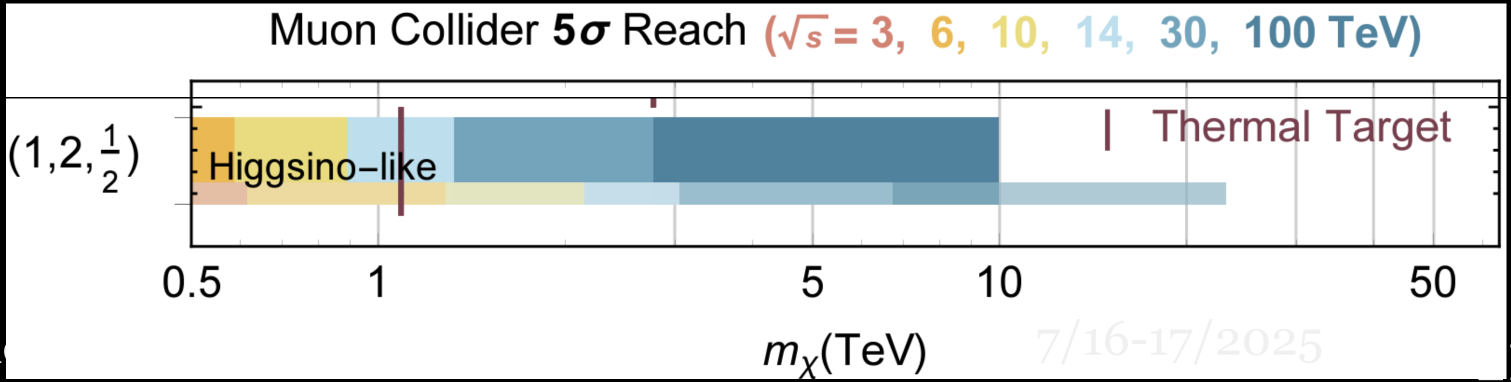
Han, ZL, Wang, Wang, 2009.11287, 2203.07351

Minimal transverse displacement

- Only use the central tracks, |eta|<1.5
- We assume at least two-layers of trackers can be placed before **r=5cm**
- Show both pair reconstruction or single reconstruction results
- We conservatively required 50 signal events for discovery



Recent optimization work looking for soft pions, achieving sensitivity to Higgsino at 3TeV MuC, Capdevilla, Meloni, Zurita, 2405.08858



Lots of studies at CEPC

- Main detectors
- Auxiliary detectors (LAYCAST, FD3)

CEPC New Physics Potentials

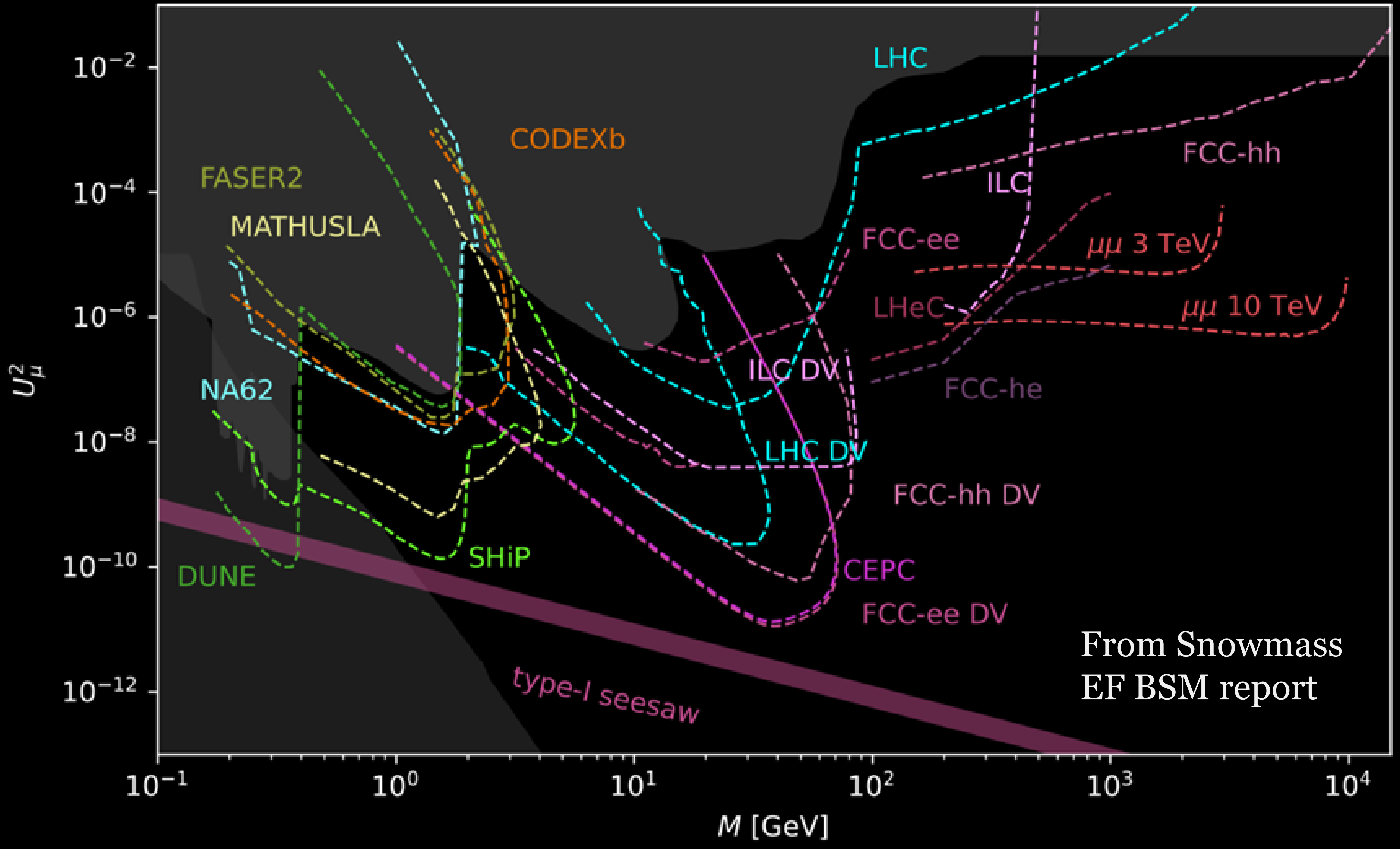
Prepared for the CEPC BSM white paper

CEPC BSM Physics Study Group

VI. LONG-LIVED PARTICLE SEARCHES (LIANG LI, YING-NAN MAO, KECHEN WANG, ZEREN SIMON WANG)

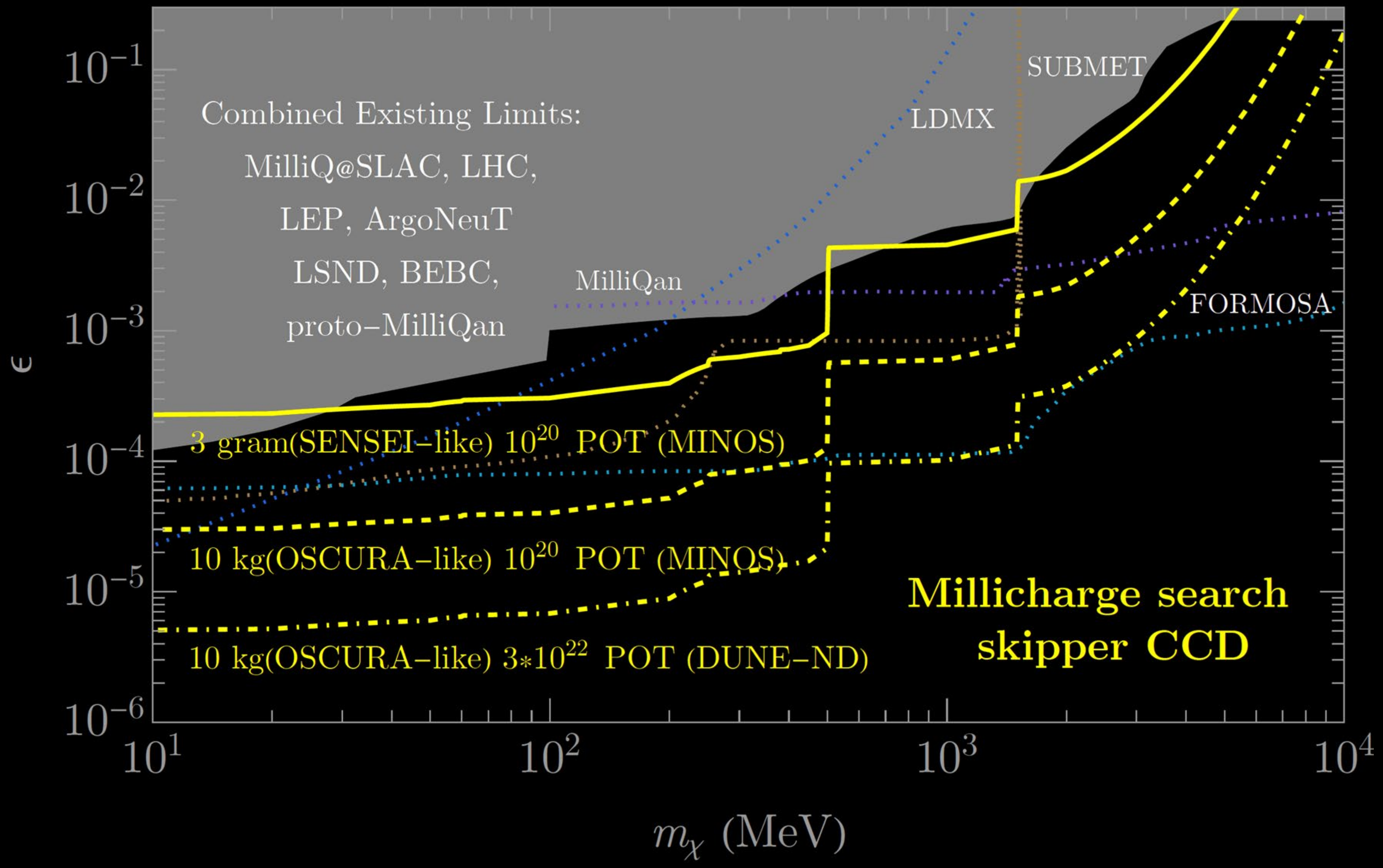
LLP Type	Signal Signature	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [ab^{-1}]	Detector	Sensitivities on parameters [Assumptions]	Figs.	Refs.
New scalar particles (X)	$Z(\to \text{incl.})\, h(\to XX)$, $X \to q\bar{q}/\nu\bar{\nu}$	240	20	ND	$\text{Br}(h \to XX) \sim 10^{-6}$ [$m \in (1, 50)$ GeV, $\tau \in (10^{-3}, 10^{-1})$ ns]	38	[80]
	$Z(\to \text{incl.})\, h(\to XX)$, $X \to \text{incl.}$	240	5.6	ND	$\text{Br}(h \to XX) \sim 3 \times 10^{-6}$ [$m = 0.5$ GeV, $c\tau \sim 5 \times 10^{-3}$ m]	50	[86]
				FD3	$\text{Br}(h \to XX) \sim 7 \times 10^{-5}$ [$m = 0.5$ GeV, $c\tau \sim 1$ m]	50	[86]
				LAYCAST	$\text{Br}(h \to XX) \sim 5 \times 10^{-6}$ [$m = 0.5$ GeV, $c\tau \sim 10^{-1}$ m]	50	[257]
RPV-SUSY neutralinos ($\tilde{\chi}_1^0$)	$Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \text{incl.}$	91.2	150	ND	$\lambda'_{112}/m_{\tilde{f}}^2 \in (2 \times 10^{-14}, 10^{-8})\ \text{GeV}^{-2}$ [$m \sim 40$ GeV, $\text{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$]	44	[86]
				FD3	$\lambda'_{112}/m_{\tilde{f}}^2 \in (10^{-14}, 10^{-9})\ \text{GeV}^{-2}$ [$m \sim 40$ GeV, $\text{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$]	51	[86]
				LAYCAST	$\lambda'_{112}/m_{\tilde{f}}^2 \in (7 \times 10^{-15}, 10^{-9})\ \text{GeV}^{-2}$ [$m \sim 40$ GeV, $\text{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$]	51	[257]
ALPs (a)	$Z^{(*)} \to \mu^- \mu^+ a$	91	150	ND	$f_a/C^A_{\mu\mu} \lesssim 950$ GeV	45	[85]
	γa, $a \to \gamma\gamma$	91.2	150	ND	$C_{\gamma\gamma}/\Lambda \sim 10^{-3}\ \text{TeV}^{-1}$ [$C_{\gamma Z} = 0$, $m \sim 2$ GeV]	52	[257]
				FD3	$C_{\gamma\gamma}/\Lambda \sim 6 \times 10^{-3}\ \text{TeV}^{-1}$ [$C_{\gamma Z} = 0$, $m \sim 0.3$ GeV]	52	[258]
				LAYCAST	$C_{\gamma\gamma}/\Lambda \sim 2 \times 10^{-3}\ \text{TeV}^{-1}$ [$C_{\gamma Z} = 0$, $m \sim 0.7$ GeV]	52	[257]
Hidden valley particles (π_V^0)	$Z\, h(\to \pi_V^0 \pi_V^0)$, $\pi_V^0 \to b\bar{b}$	350	1.0	ND	$\sigma(h) \times \text{BR}(h \to \pi_v^0 \pi_v^0) \sim 10^{-4}$ pb [$m \in (25, 50)$ GeV, $\tau \sim 10^2$ ps]	42	[259]
Dark photons (γ_D)	$Z(\to q\bar{q})\, h(\to \gamma_D \gamma_D)$, $\gamma_D \to \ell^- \ell^+/q\bar{q}$	250	2.0	ND	$\text{Br}(h \to \gamma_D \gamma_D) \sim 10^{-5}$, [$m \in (5, 10)$ GeV, $\tau \sim 10^2$ ps, $\epsilon \in (10^{-6}, 10^{-7})$]	43	[83]

Heavy Neutrino Portal



From Snowmass
EF BSM report

Millicharged Particles from Colliders



Future projections:

SENSEI@MINOS

DUNE-ND

LDMX

Etc.

ZL's estimation.
Also updated with various more realistic considerations with SENSEI and OSCURA collaboration (2304.08625 , 2305.04964).

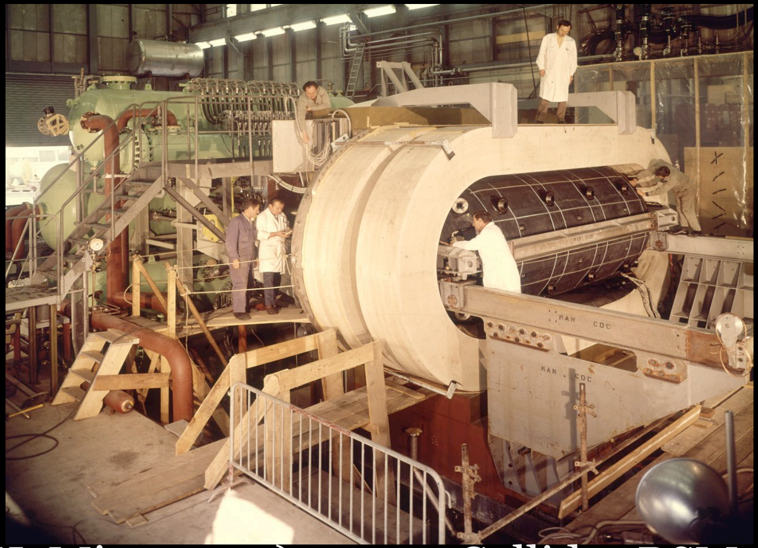
Looking into the Future: Lessons from History

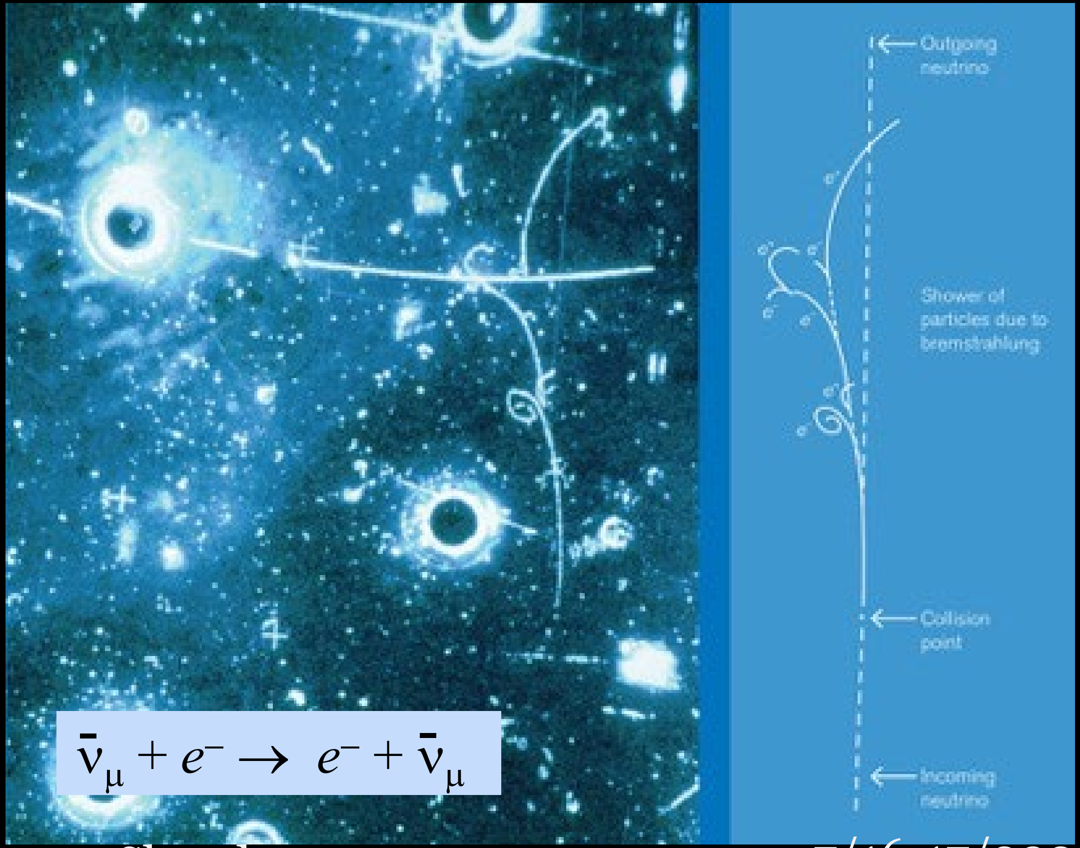
42 Years of W boson Discovery

Claudia-Elisabeth Wulz
Institute of High Energy Physics
Austrian Academy of Sciences, Vienna

Neutral currents and Weinberg angle

1973	Discovery of neutral currents at CERN with neutrino interactions in the Gargamelle bubble chamber, supporting electroweak theory
~1977	Measurements of Weinberg angle from cross-section ratios between neutral and charged current interactions -> prediction for W mass M_W ~ 60 – 80 GeV
~1980	More precise measurements of Weinberg angle -> M_W = 82.0 ± 2.4 GeV

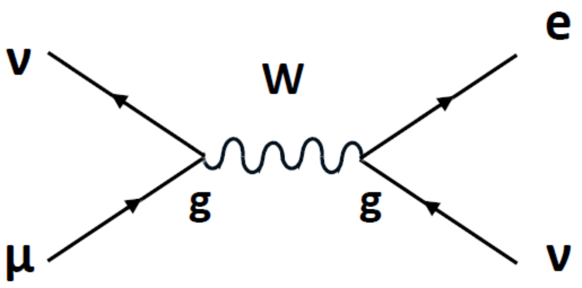




$$\bar{\nu}_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu$$

The W turns 40
Theoretical background and implications
Michelangelo Mangano

Before 1983

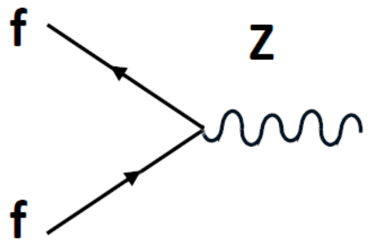


$$\Gamma(\mu \to e\nu\bar{\nu}) \propto G_F = \frac{\pi}{\sqrt{2}} \frac{g^2}{M_W^2}$$ ➡ **known**

SM:

$$g = e/\sin\theta_W$$

$$M_W = M_Z \cos\theta_W$$



$$g_V = T_3 - 2Q\sin^2\theta_W$$

$$g_A = T_3$$

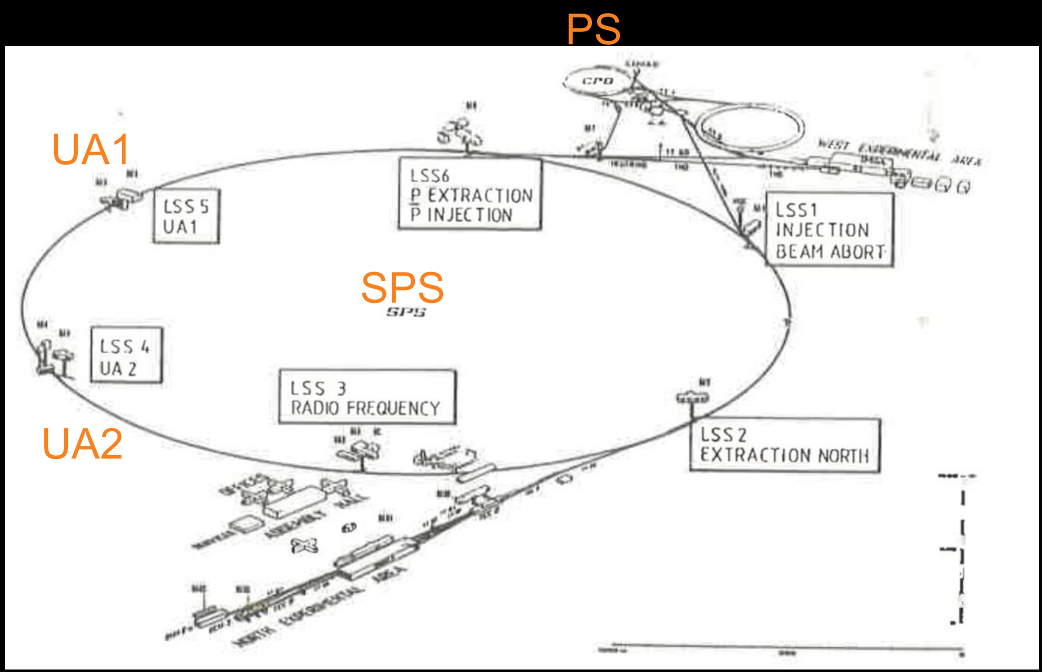
➡ **measure** $\sin\theta_W$ **in NC/CC DIS**

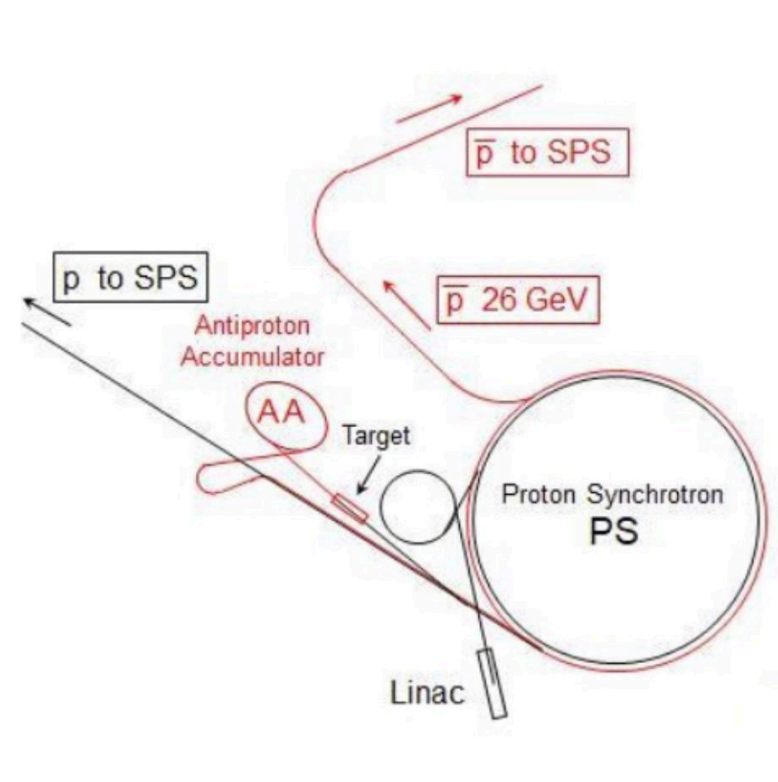
➡ **predict** (up to rad corr's) $$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_F \sin^2\theta_W}$$ **and** $$M_Z = M_W / \cos\theta_W$$

Claudia-Elisabeth Wulz
Institute of High Energy Physics
Austrian Academy of Sciences, Vienna

Timeline leading to the W discovery

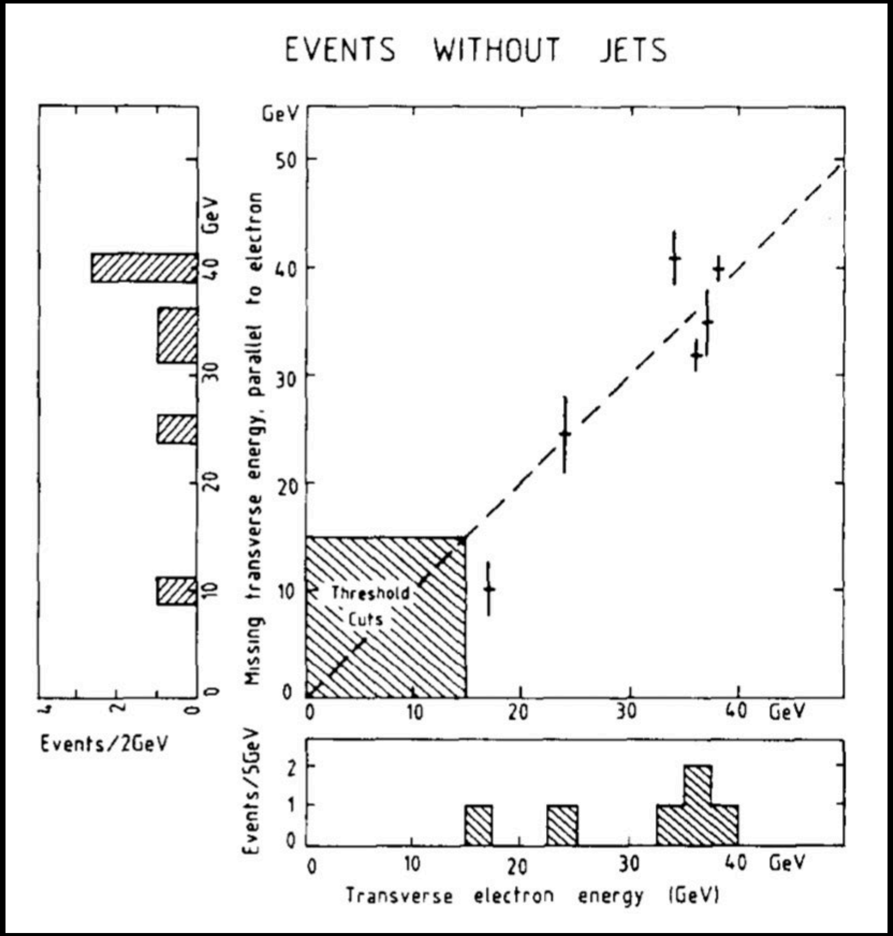
1976	First beam in the CERN Super Proton Synchrotron (SPS)
1976	Cline, McIntyre, Rubbia propose conversion of existing machine into a $p\bar{p}$ collider
1978	Decision to convert the SPS into the Super Proton-Antiproton Synchrotron ($Sp\bar{p}S$)
1981	First proton-antiproton collisions at $\sqrt{s}$ = 540 GeV
1982	Experiments UA1 and UA2 have acquired enough data to enable the W discovery
1983	Announcement of W discovery



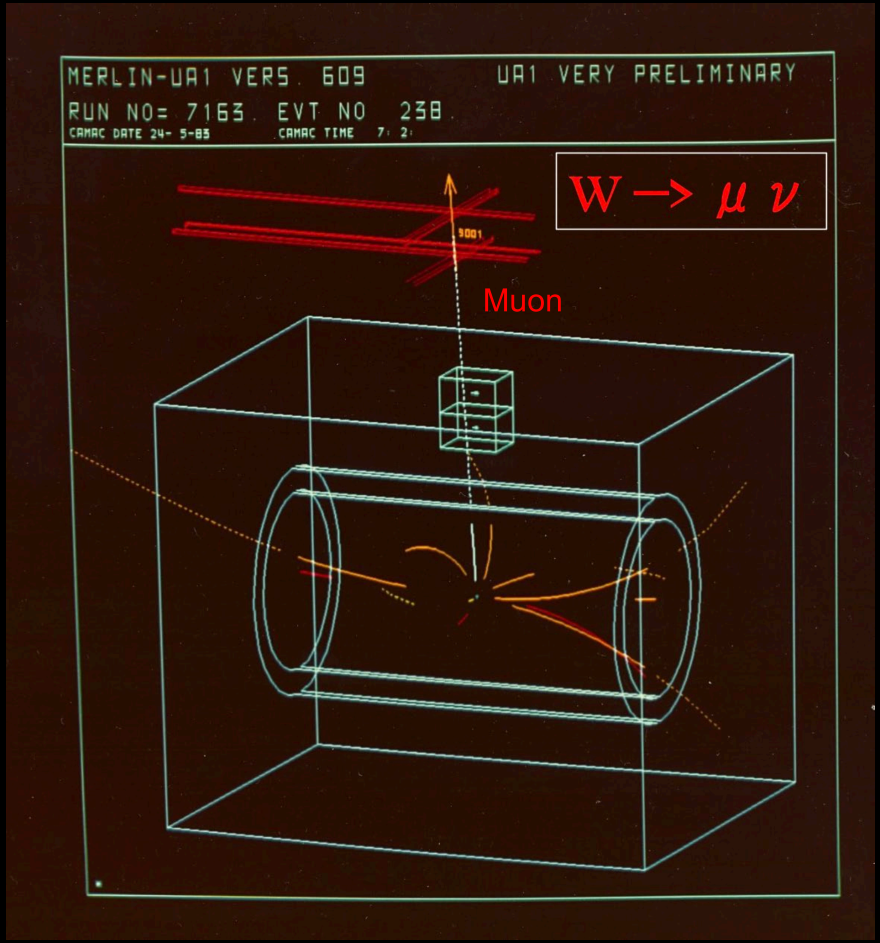


W events in UA1

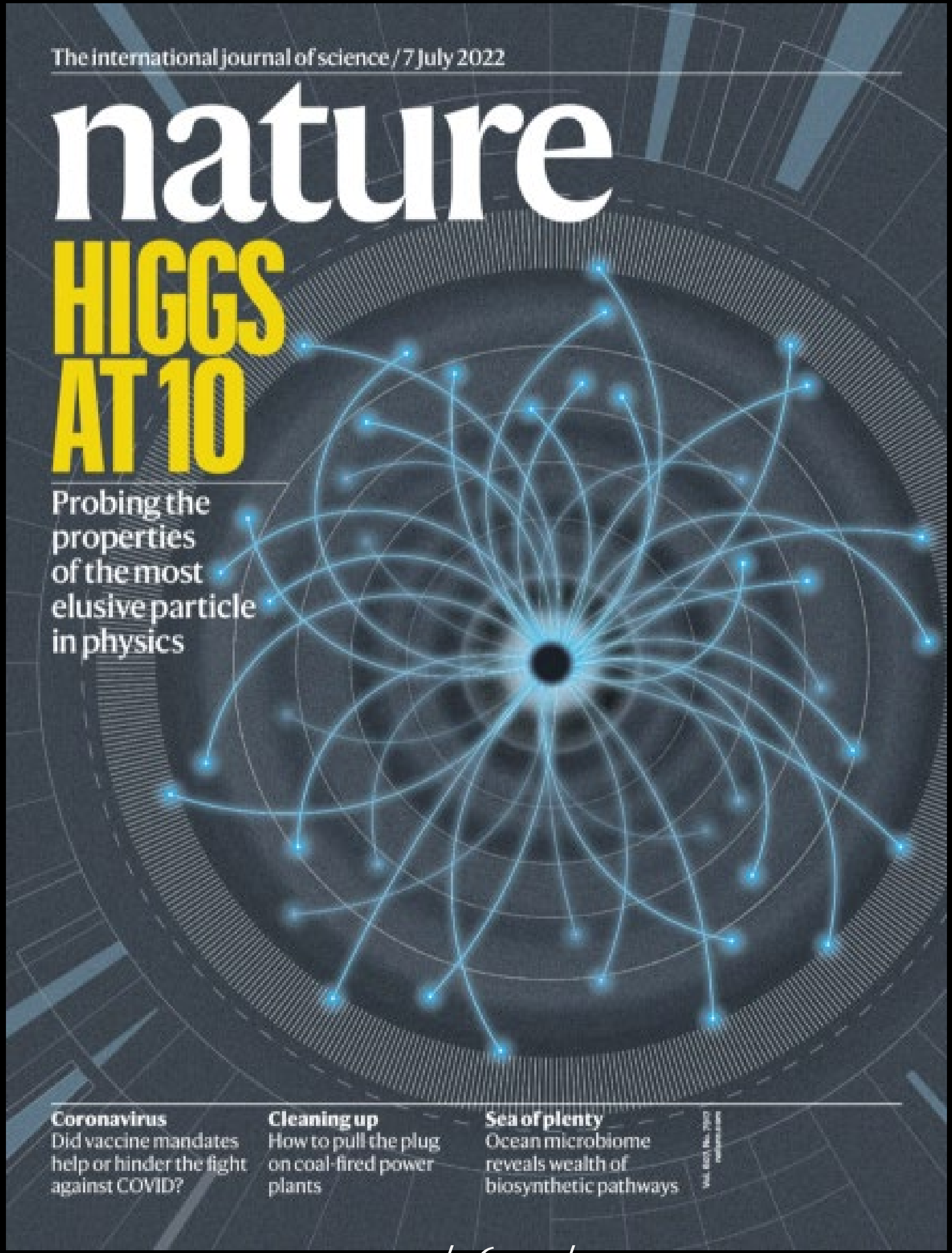
Electron events



Muon event (not in discovery paper)



13 years of Higgs Discovery

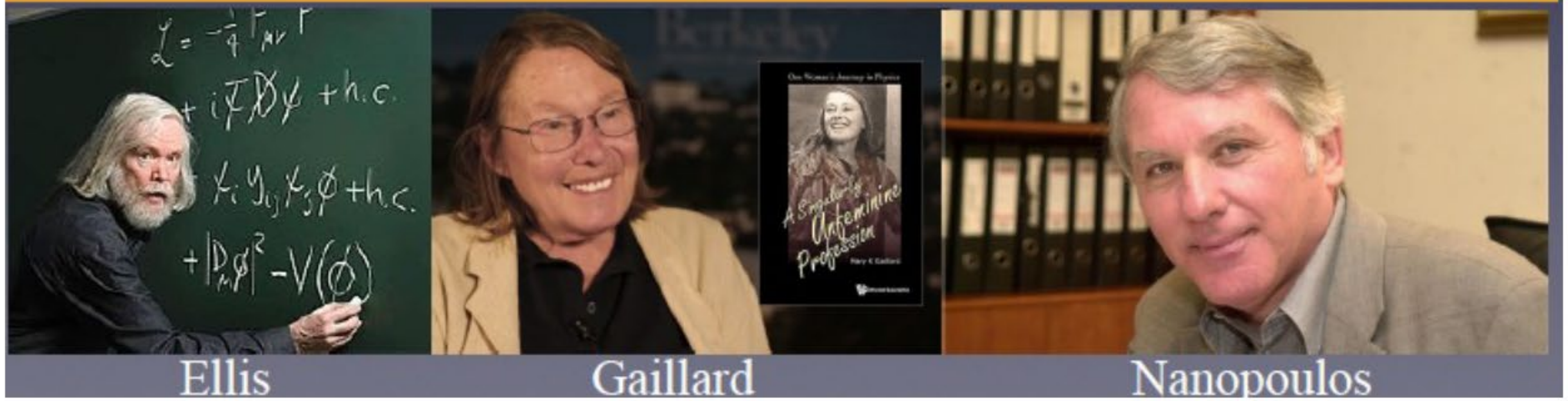


We all take Higgs for granted, but

First Study of the Higgs, 1976

- The beginning of Higgs phenomenology

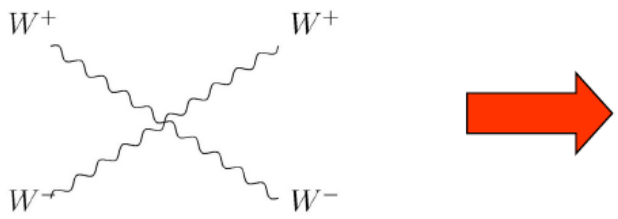
> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



Slide from S. Dawson

Unitarity, 1977

- We did know something about the Higgs mass
- Either $M_H < 800$ GeV or perturbative unitarity violated around 3 TeV



Cross sections grow with energy without Higgs

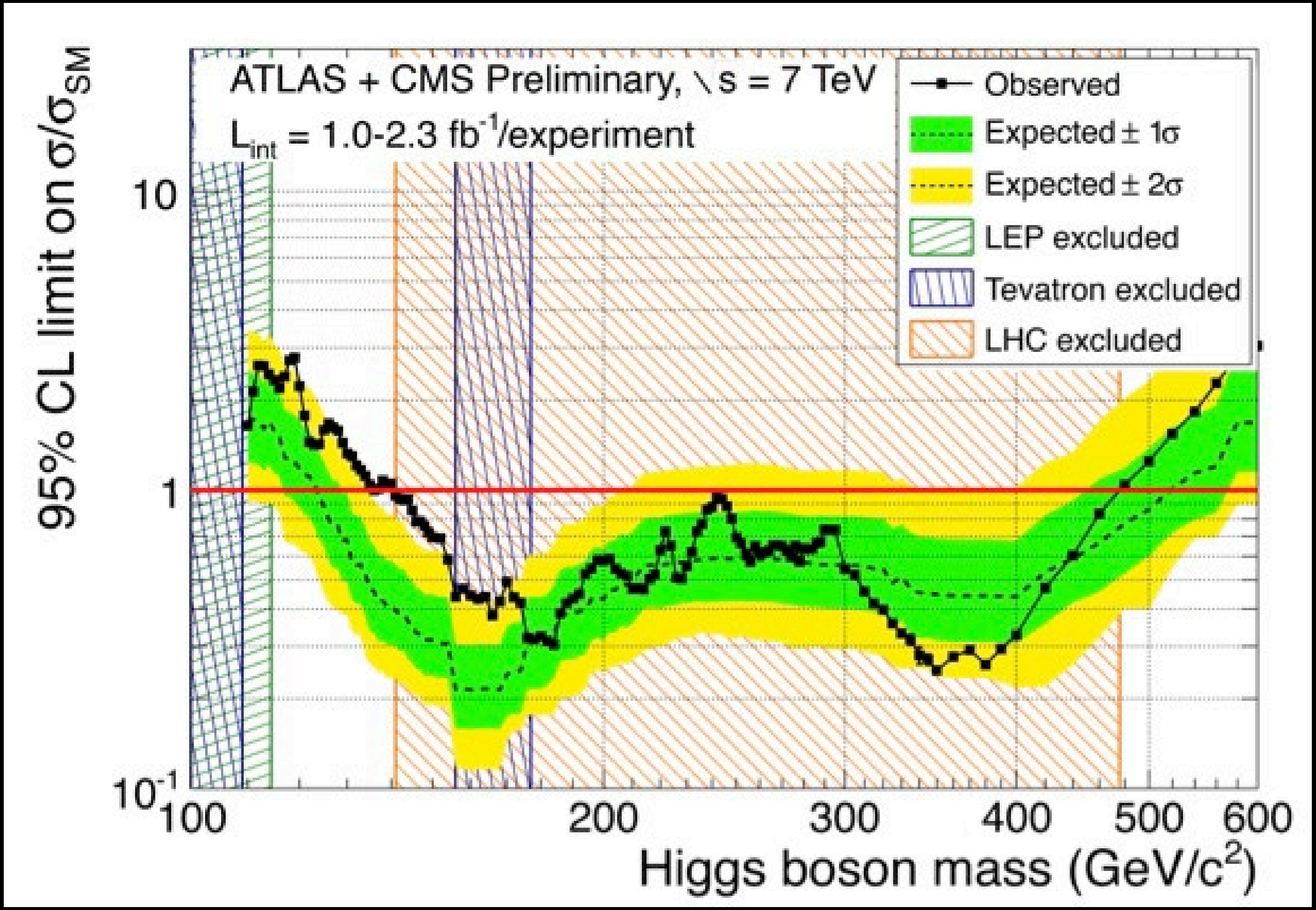
- Led to the powerful idea of a ”no-lose” theorem
- “The LHC had to find a Higgs or something else at an accessible scale”

Lee, Quigg, and Thacker

And SSC

Slide from S. Dawson

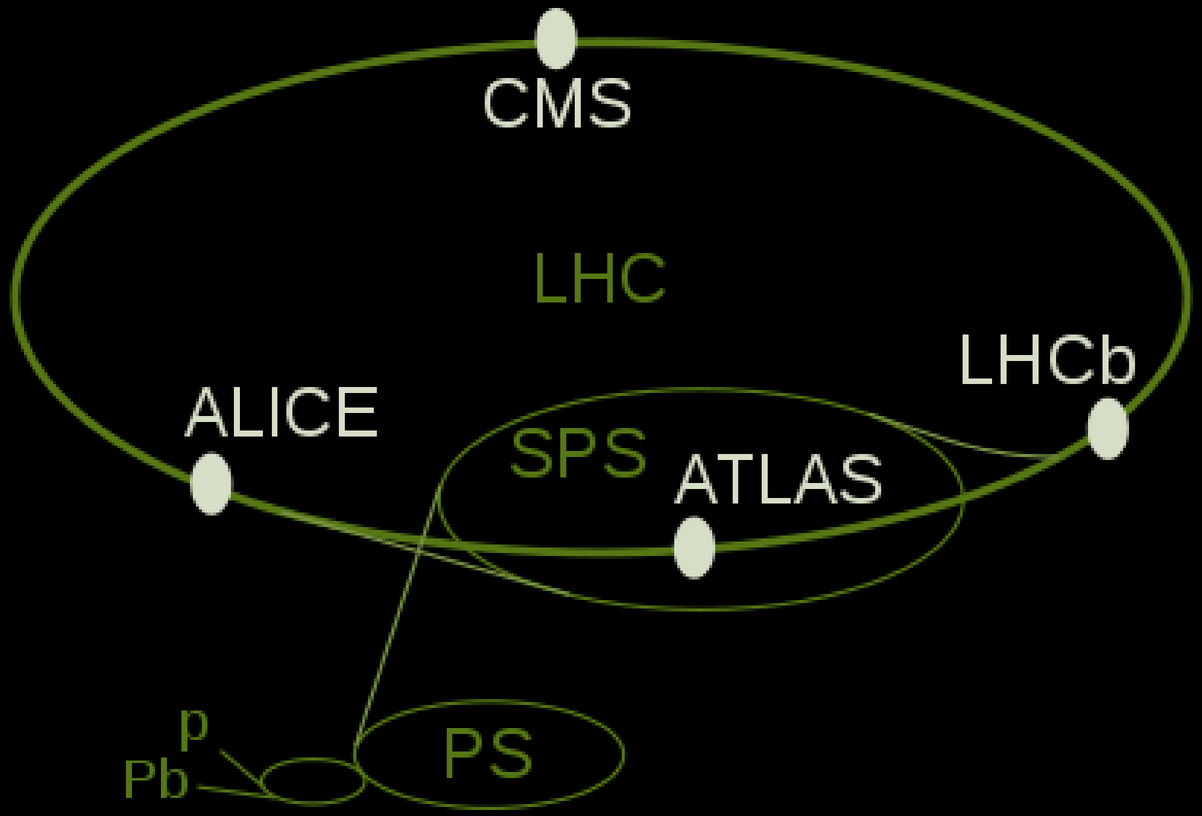
Higgs is not that obvious



I felt lucky to witness a bit of pre-Higgs era:

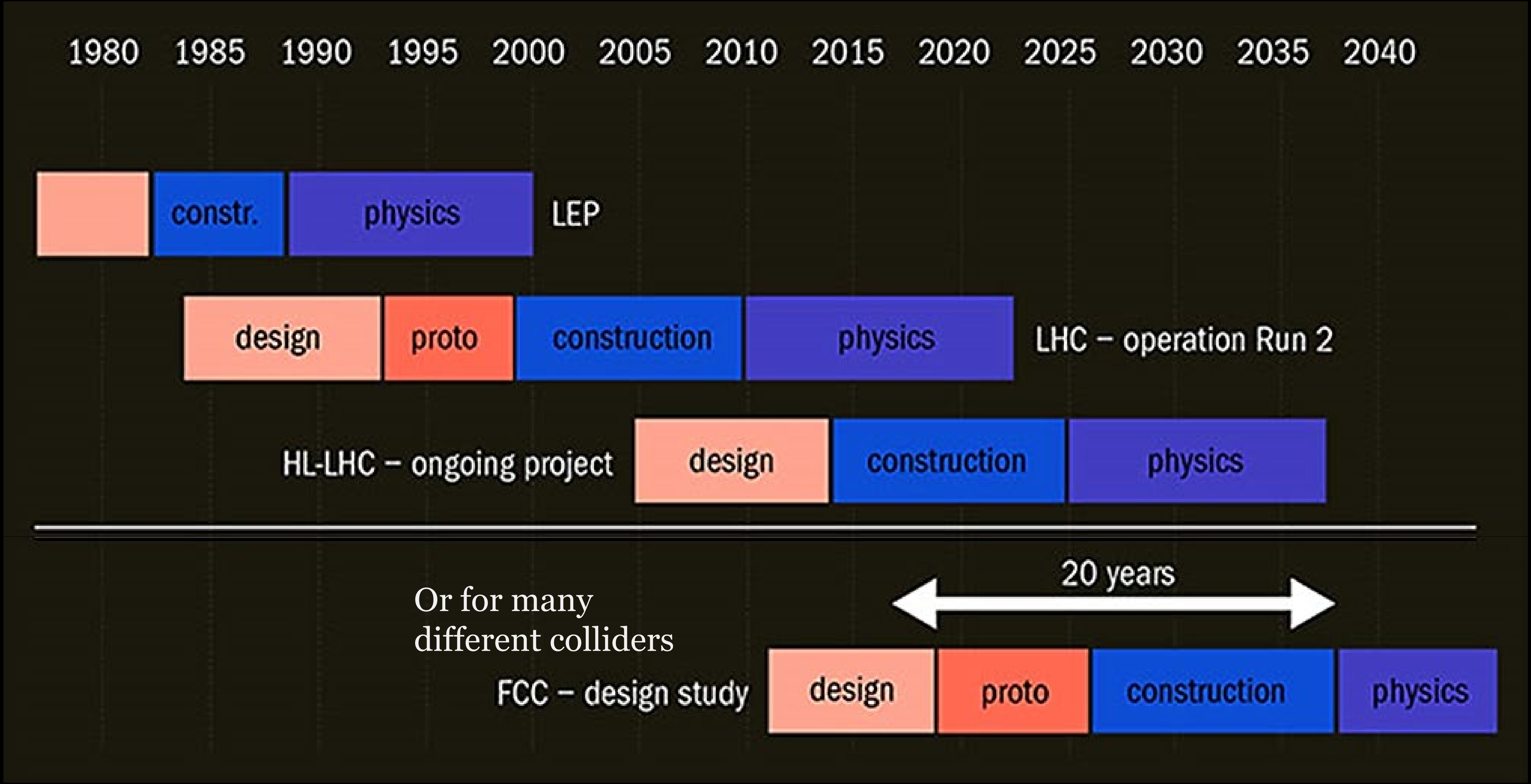
- New regions immediately covered by the LHC between 160-500 GeV
- Still, we didn't know where Higgs or New Physics would show up
- Higgsless theories were still motivated
- Higgs discovery was a huge step forward

Higgs was then Discovered in 2012 at the LHC



Does this ring look familiar?

The Lifespans of HEP programs are long…



Or for many
different colliders

But I also think these discoveries spoiled us

We knew:

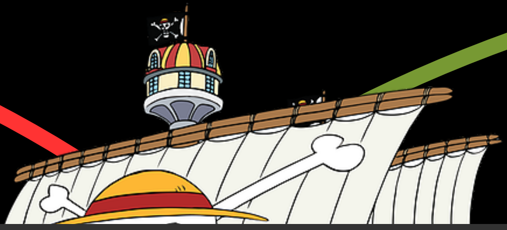
- W is there with already a target mass before searching;
- Top quark is there
- Higgs is there, or new physics enters before 800 GeV (no-lose theorem)

But, research is about the unknown, and we shall not over-promise.

All measurements are BSM probes!

Goal:

- Establish/Reenforce Collider Landscape
- Establish Basic Examples of BSM Searches
- Show how different physic goals give raise to vastly different BSM probes.



BSM Opportunities

Around the Higgs
Go Exotic
Have Fun

Theoretica
plausible

rimentally
sible