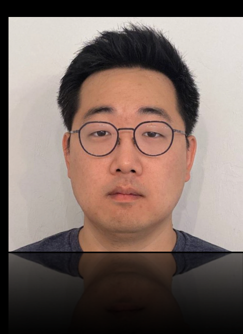
LHC Future Opportunities

(Energy Frontier)

The Future of High Energy Physics: A New Generation, A New Vision
Aspen Winter Conference



Philip Chang
University of Florida

Mar 26, 2024

HL-LHC projections

https://arxiv.org/pdf/1902.10229.pdf

Report on the Physics at the HL-LHC and Perspectives for the HE-LHC

Collection of notes from ATLAS and CMS

CERN-LPCC-2019-01

The ATLAS and CMS Collaborations

February 26, 2019

HL-LHC projections

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https://arxiv.org/pdf/1902.10229.pdf

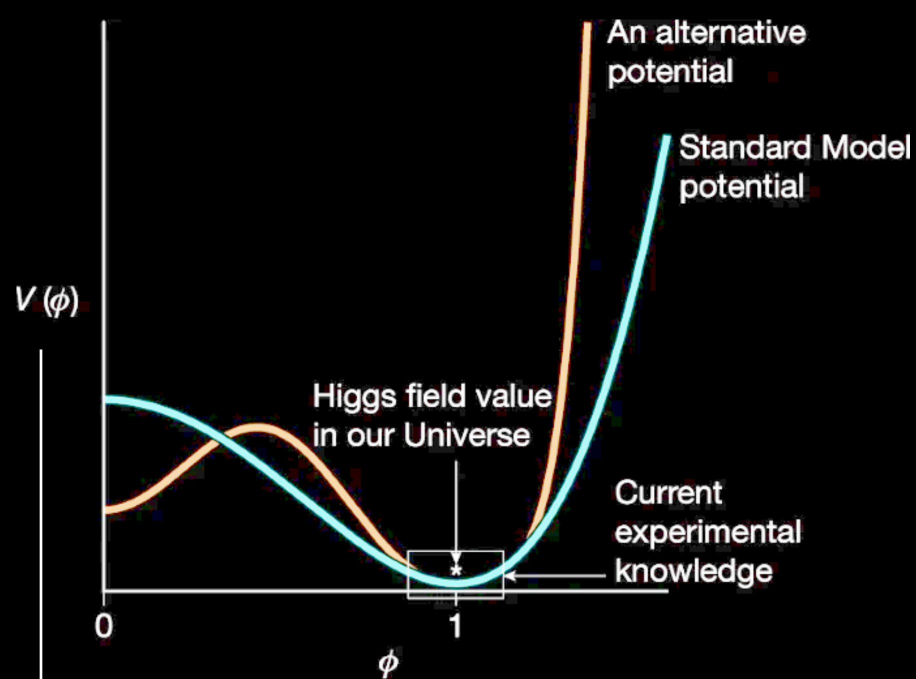
Contents

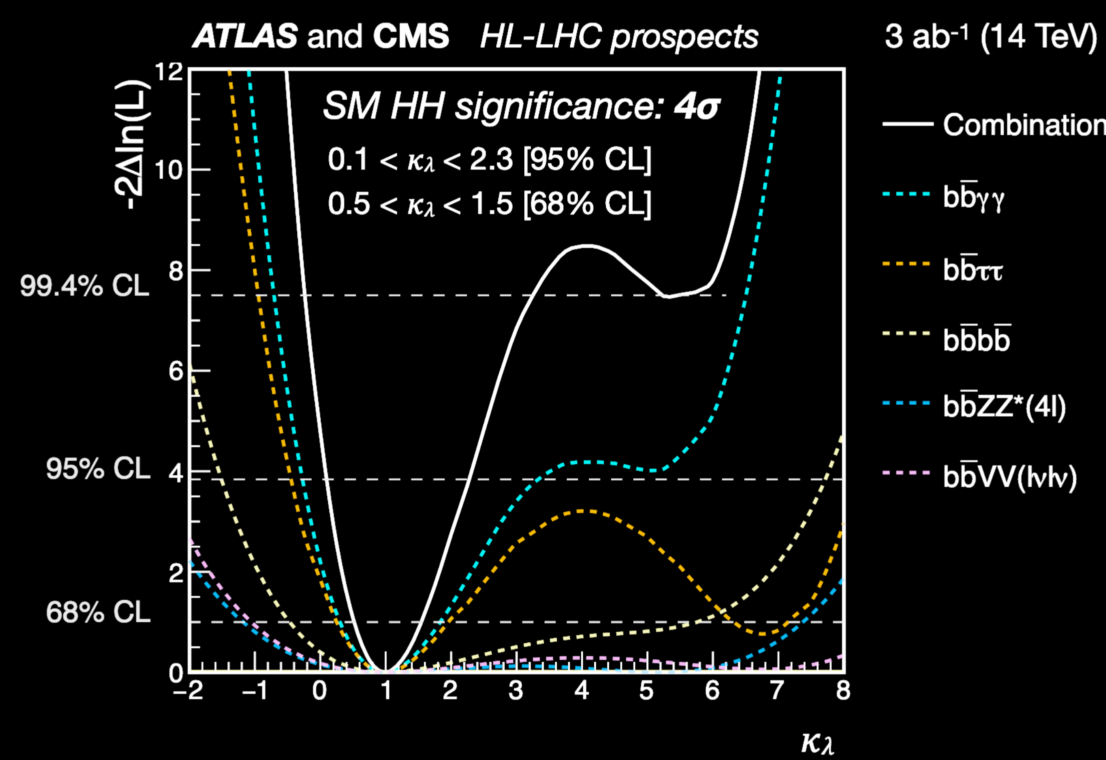
1325 pages long

Spotlight

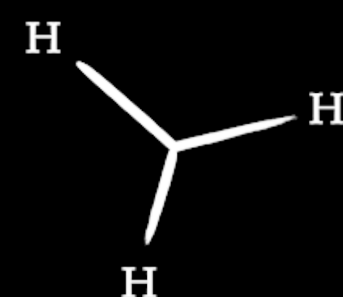
Tri-linear Higgs Couplings

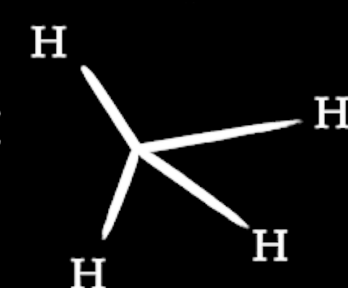
https://www.nature.com/articles/s41586-022-04899-4



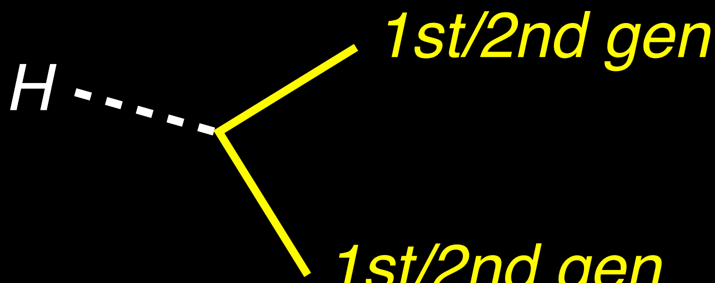


$$V(\phi) \sim \frac{1}{2}\mu^2(\phi^\dagger\phi) + \frac{1}{4}\lambda^4(\phi^\dagger\phi)^2$$

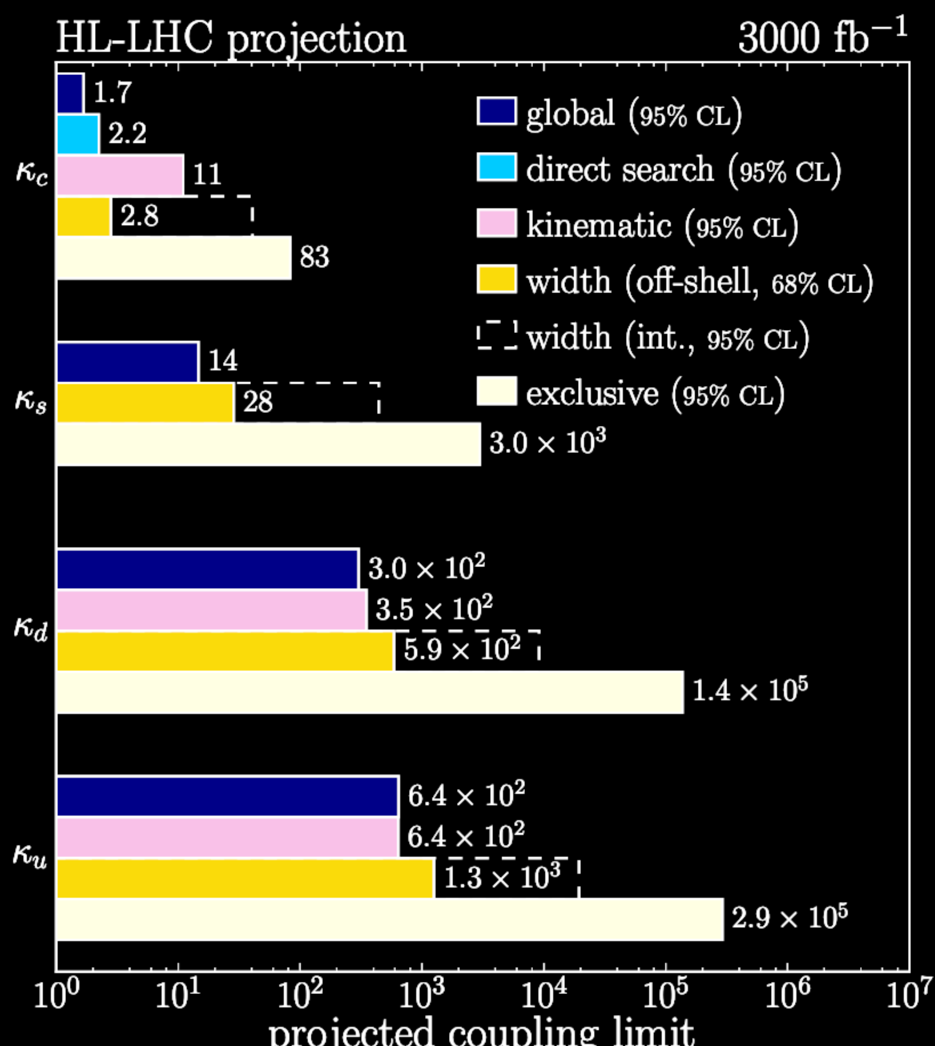


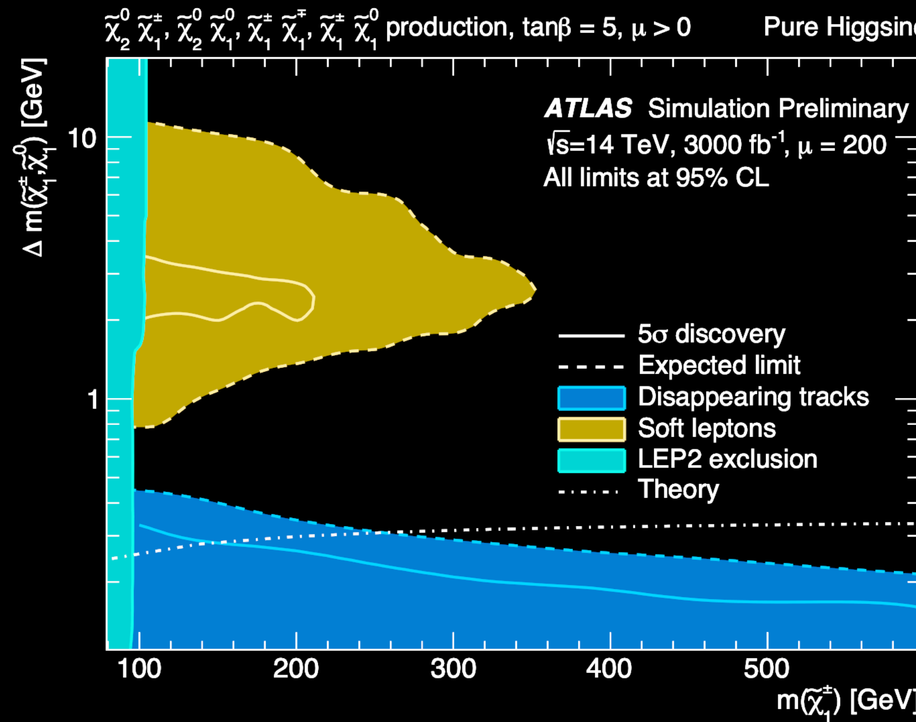


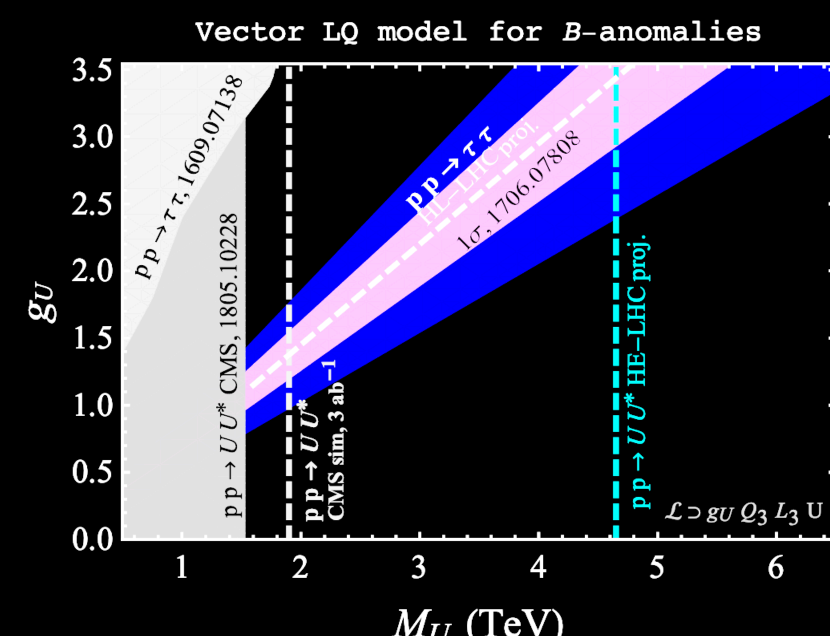
Higgsino / Dark Matter



Yukawa couplings







But there are myriads of talks you can find on why HL-LHC is important in great details

And I can't do justice in 20 minutes

Spoiler / Disclaimer:

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There are lots of opportunites in LHC future

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I cover some examples, indicative of my personal preference

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But largely I am gonna talk about my view…

Where we are now

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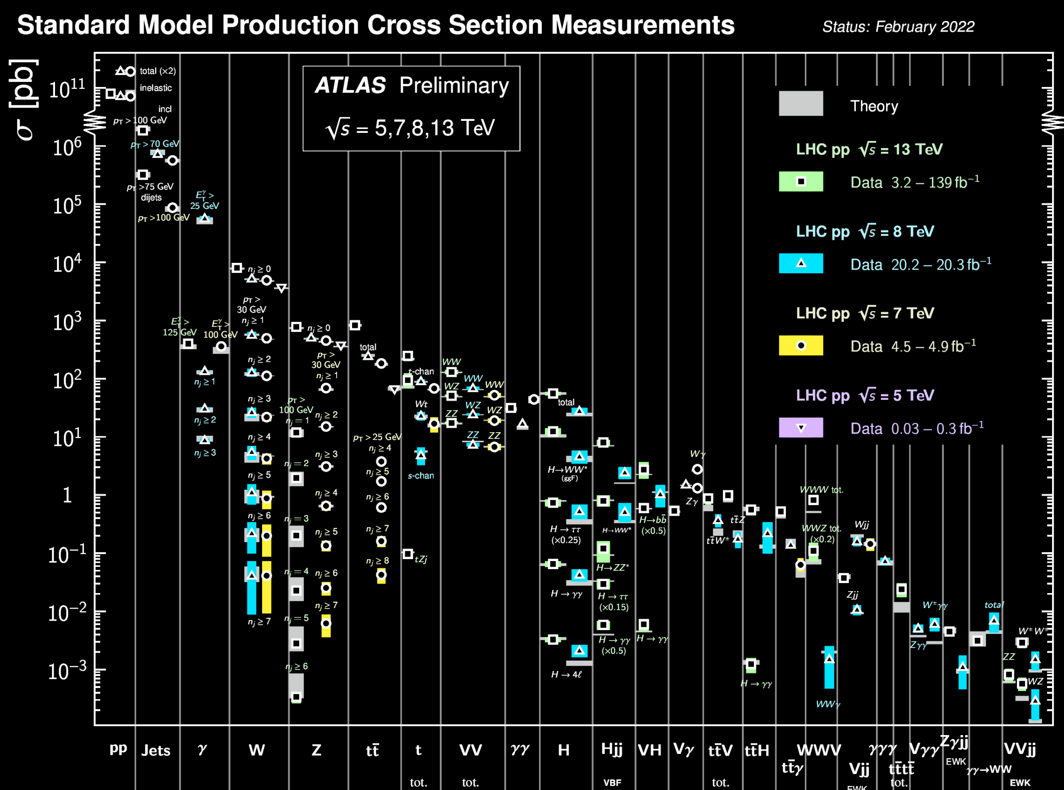
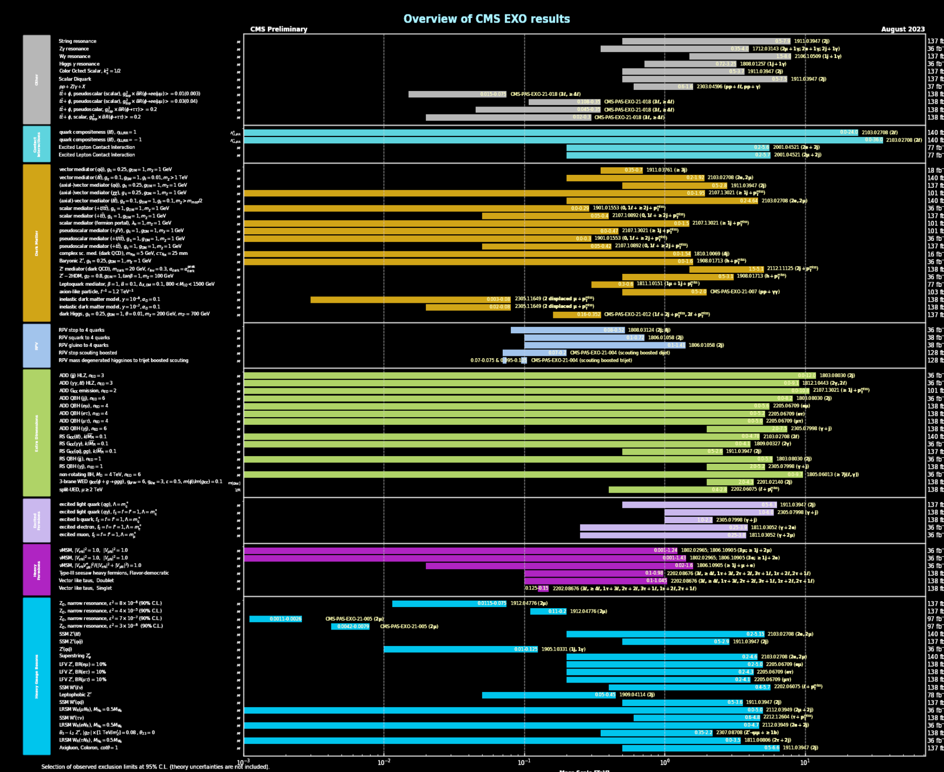
Measurement



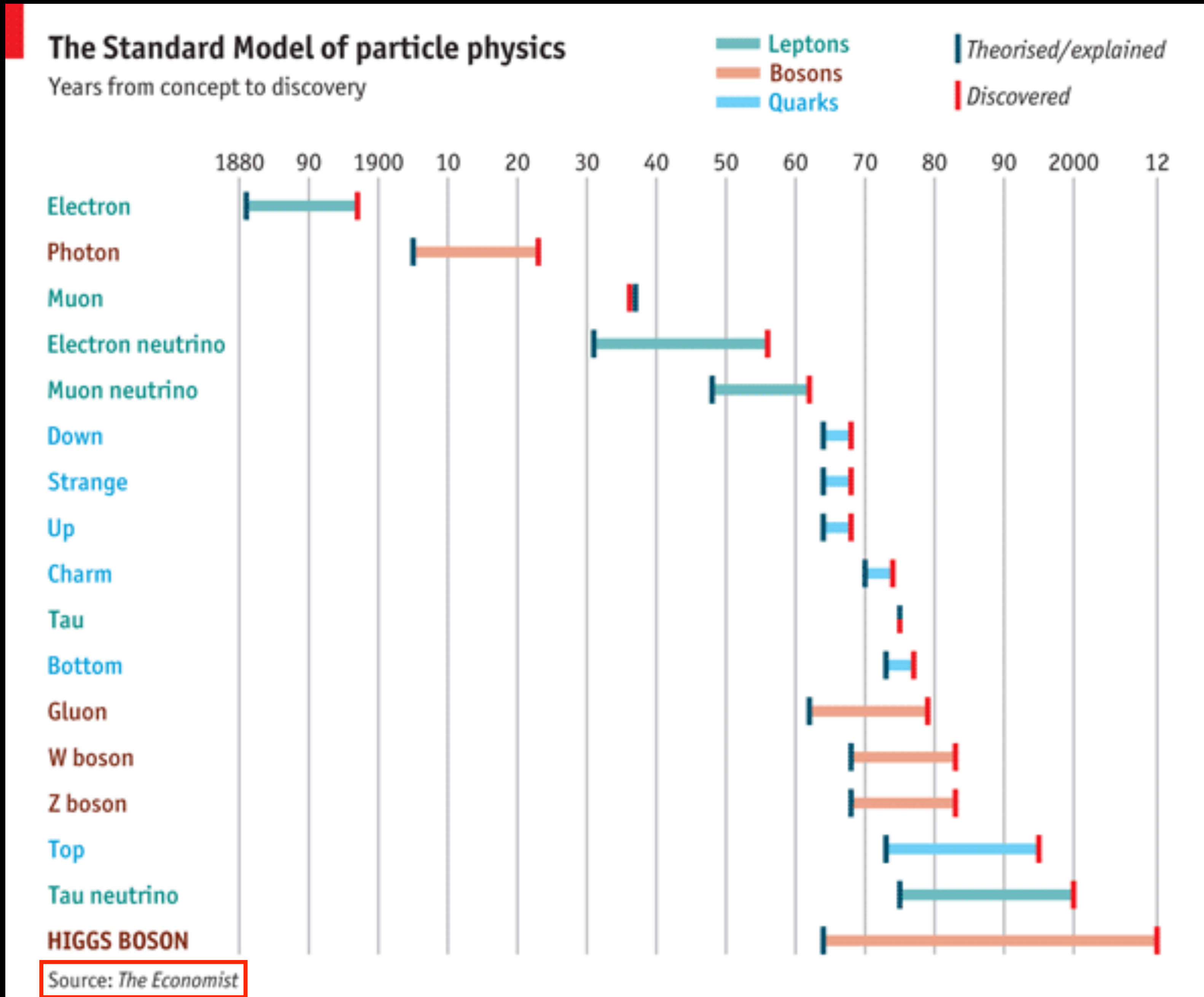
Searches



No crack

No excess

No significant deviations from SM


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
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Electron
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Muon
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Charm
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Gluon
W boson
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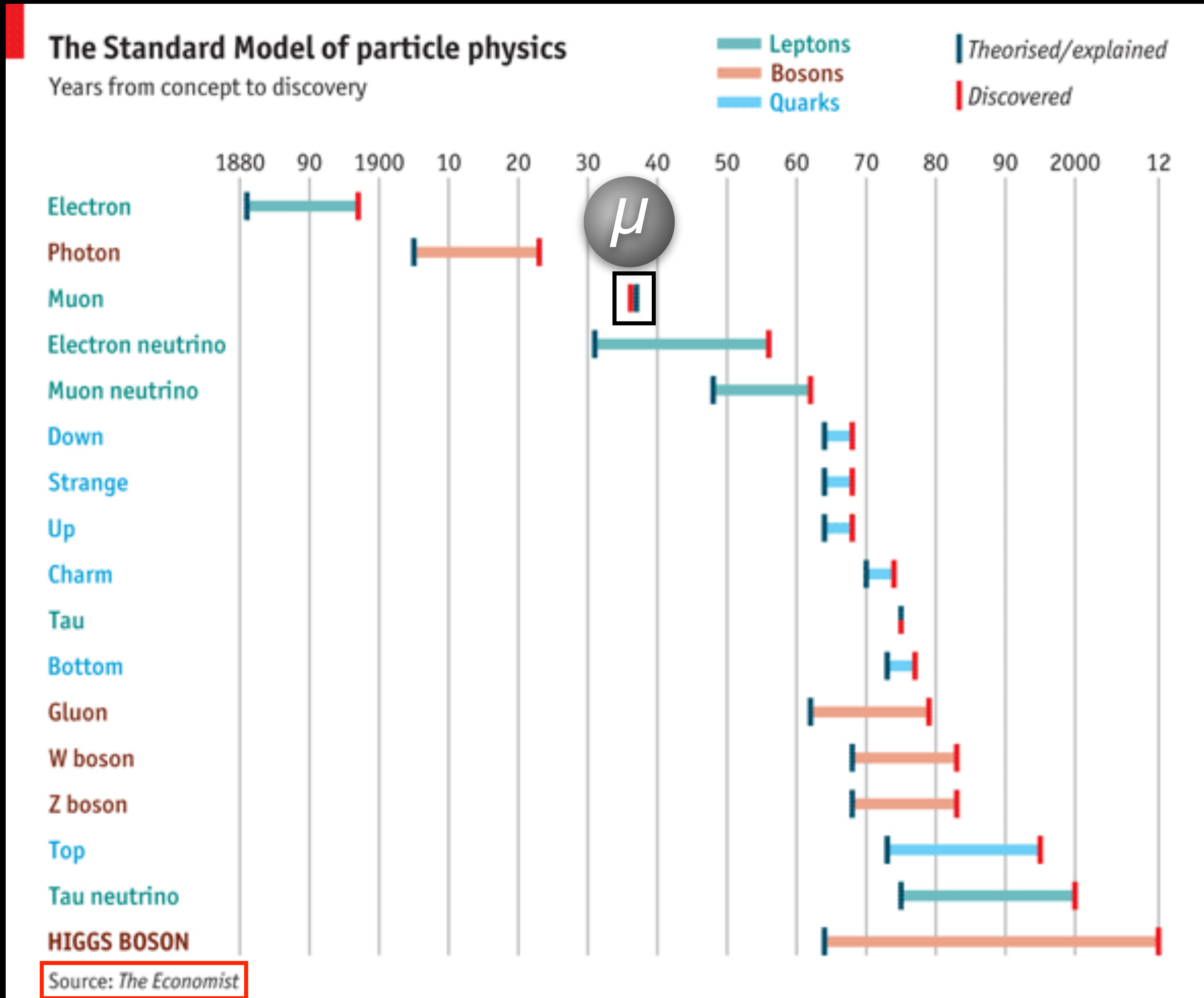
Tau neutrino
HIGGS BOSON
Source: The Economist



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Source: *The Economist*

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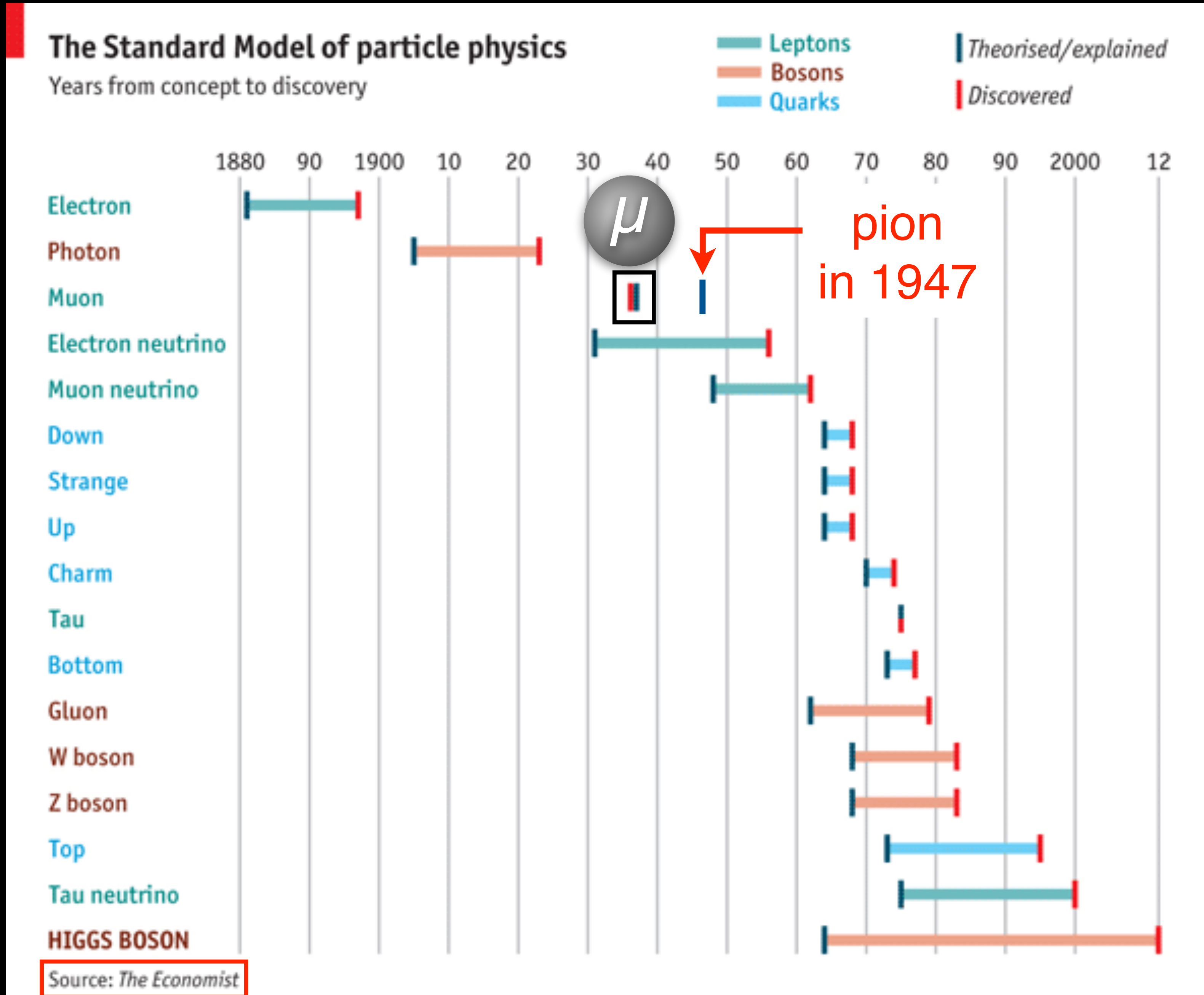

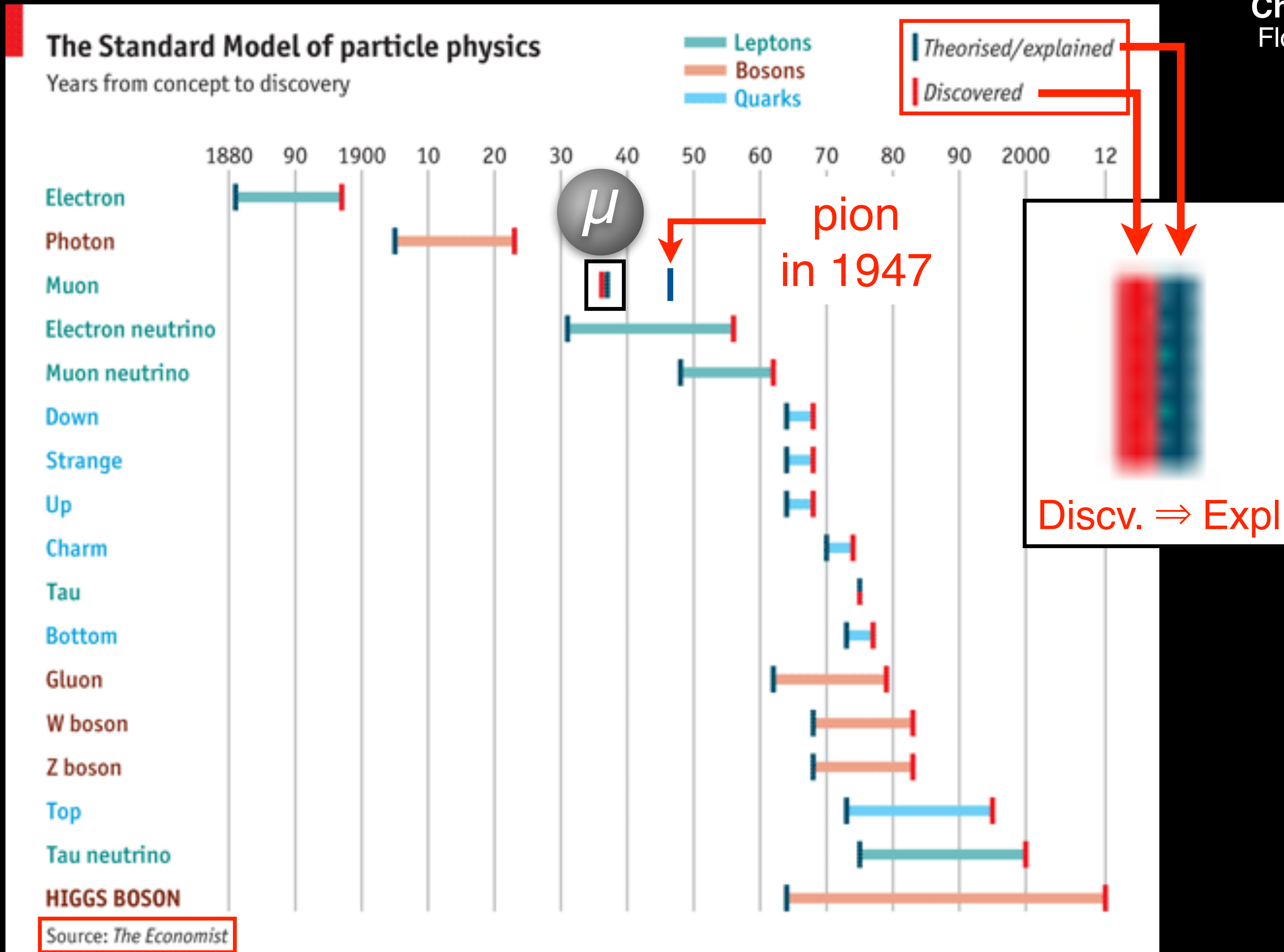
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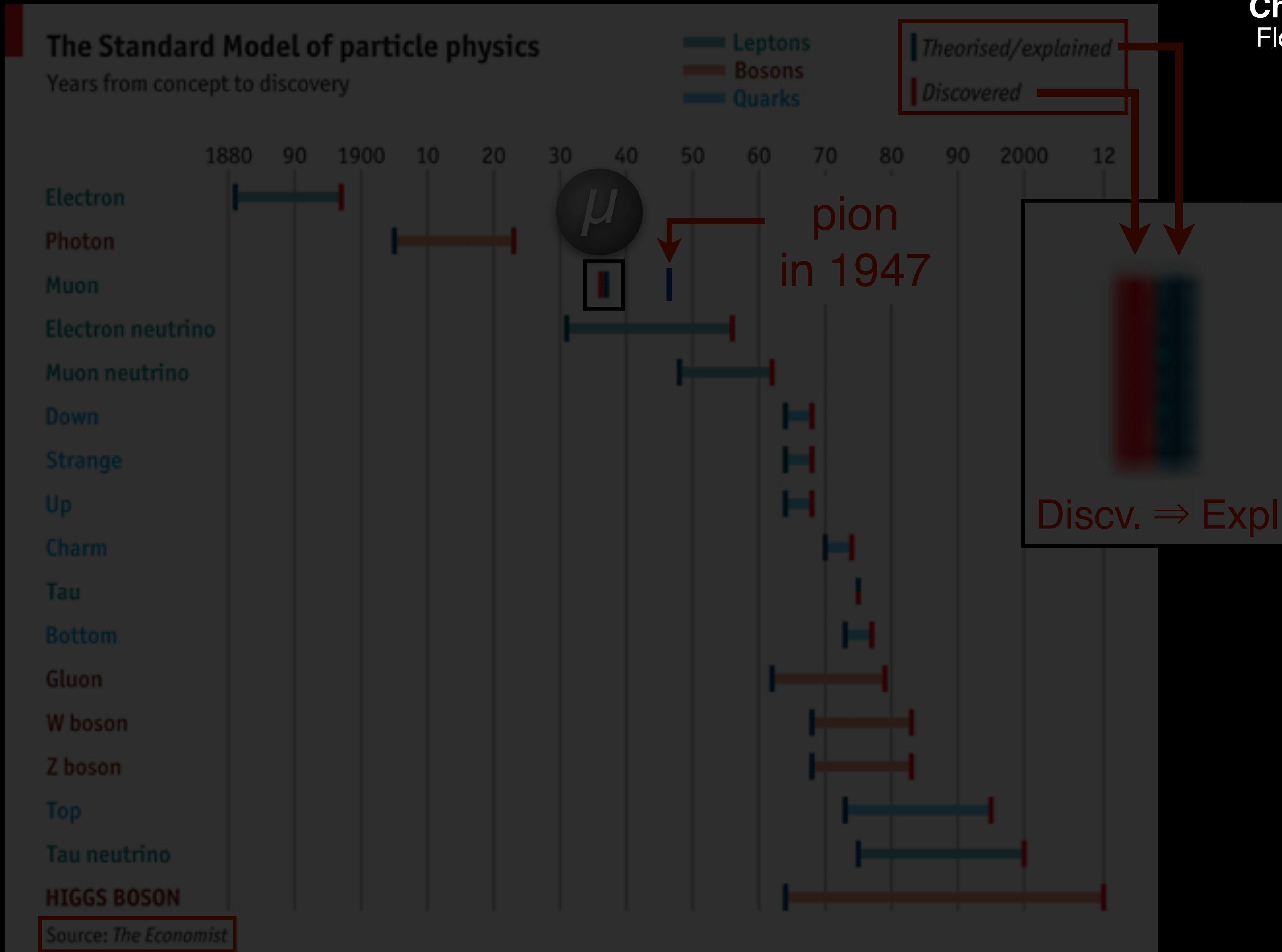
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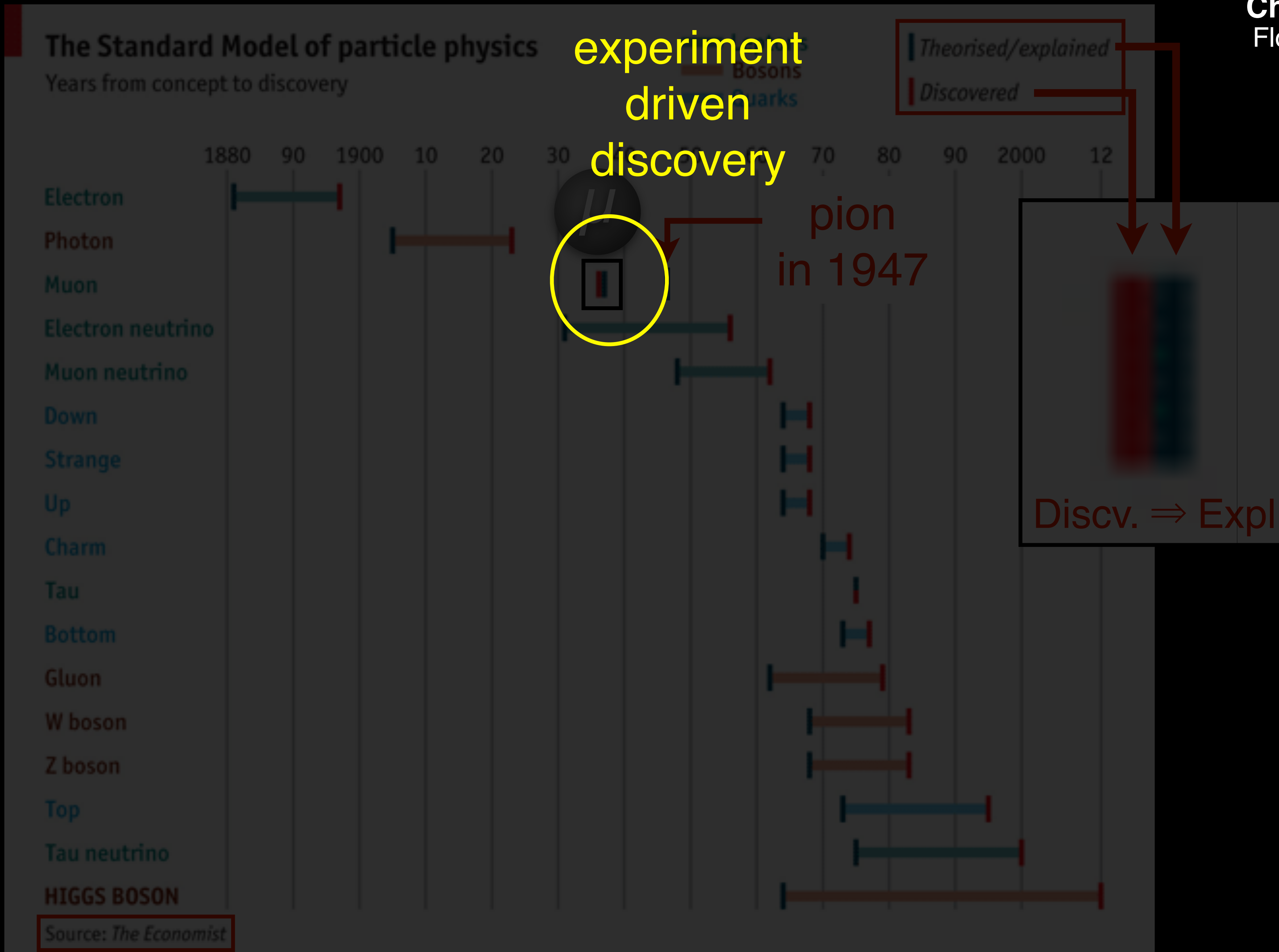

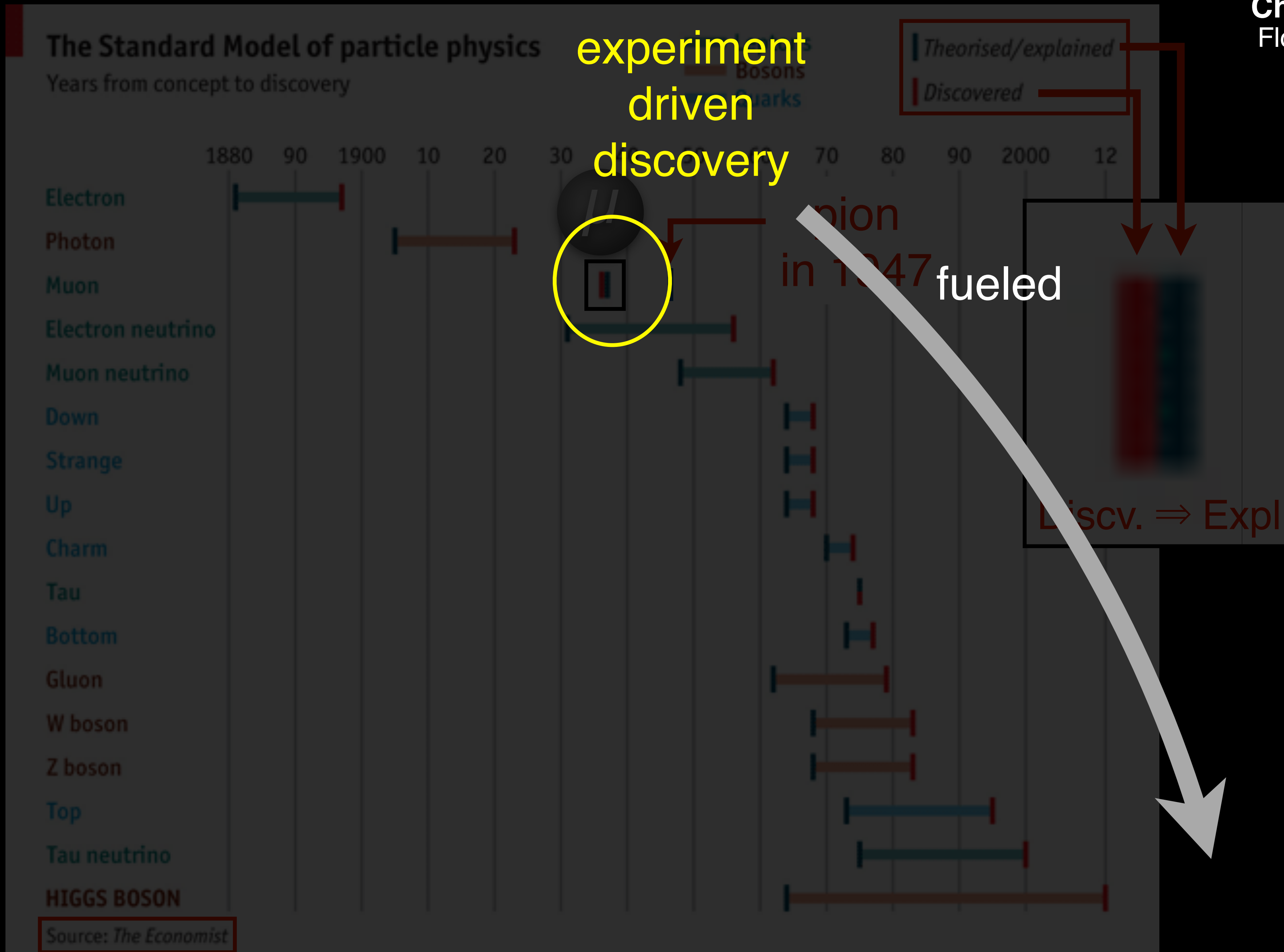
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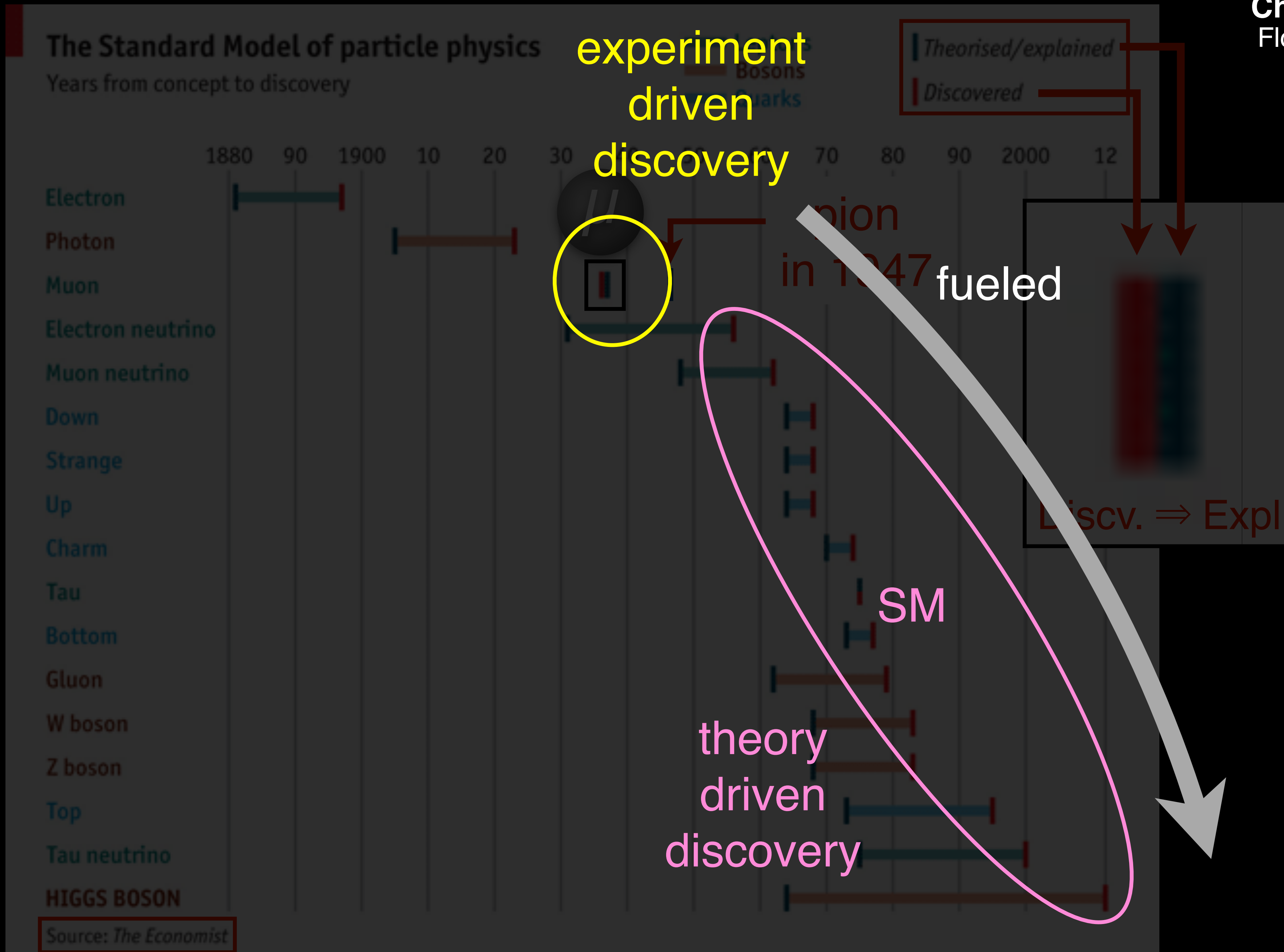

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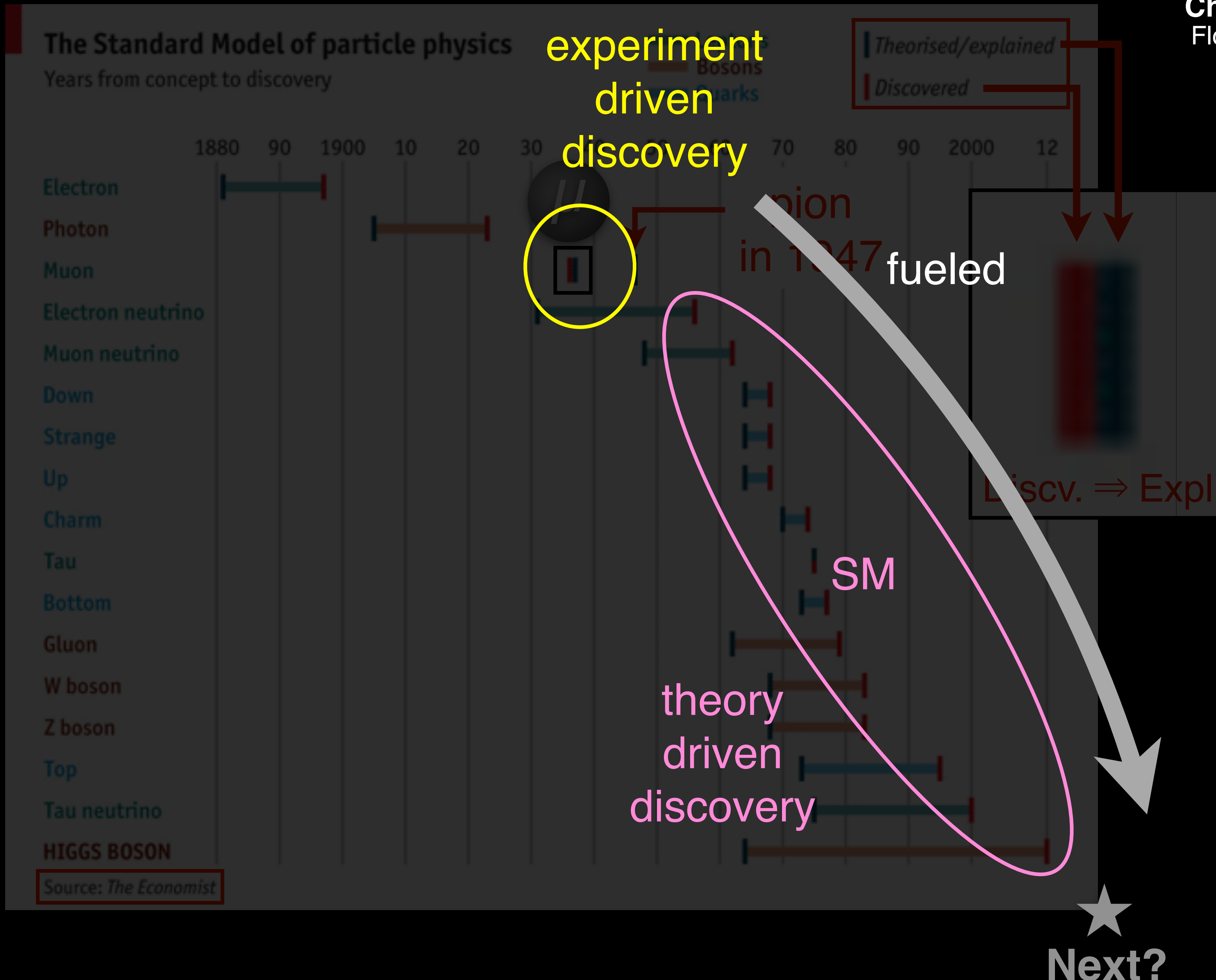
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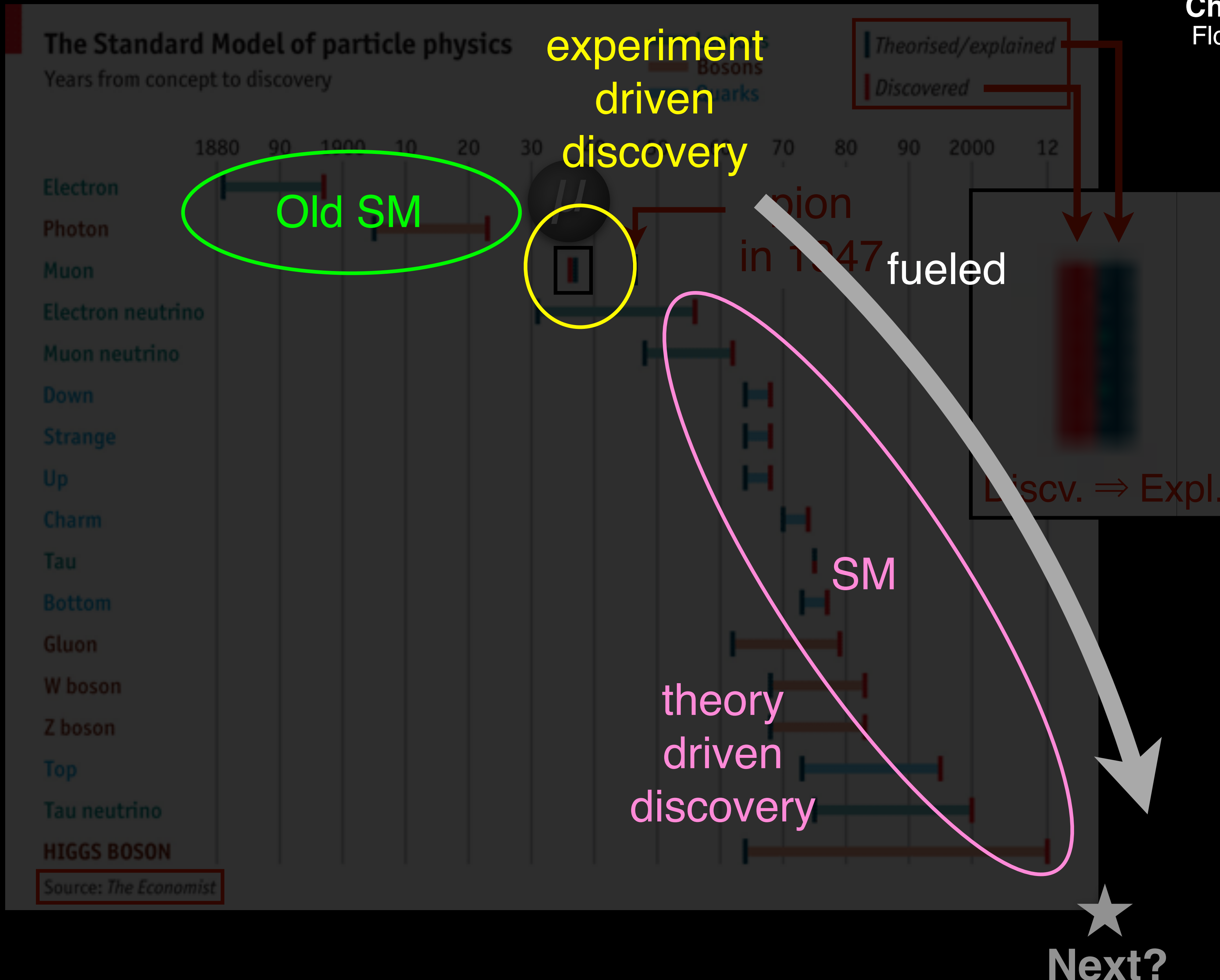
SM
theory
driven
discovery
Next?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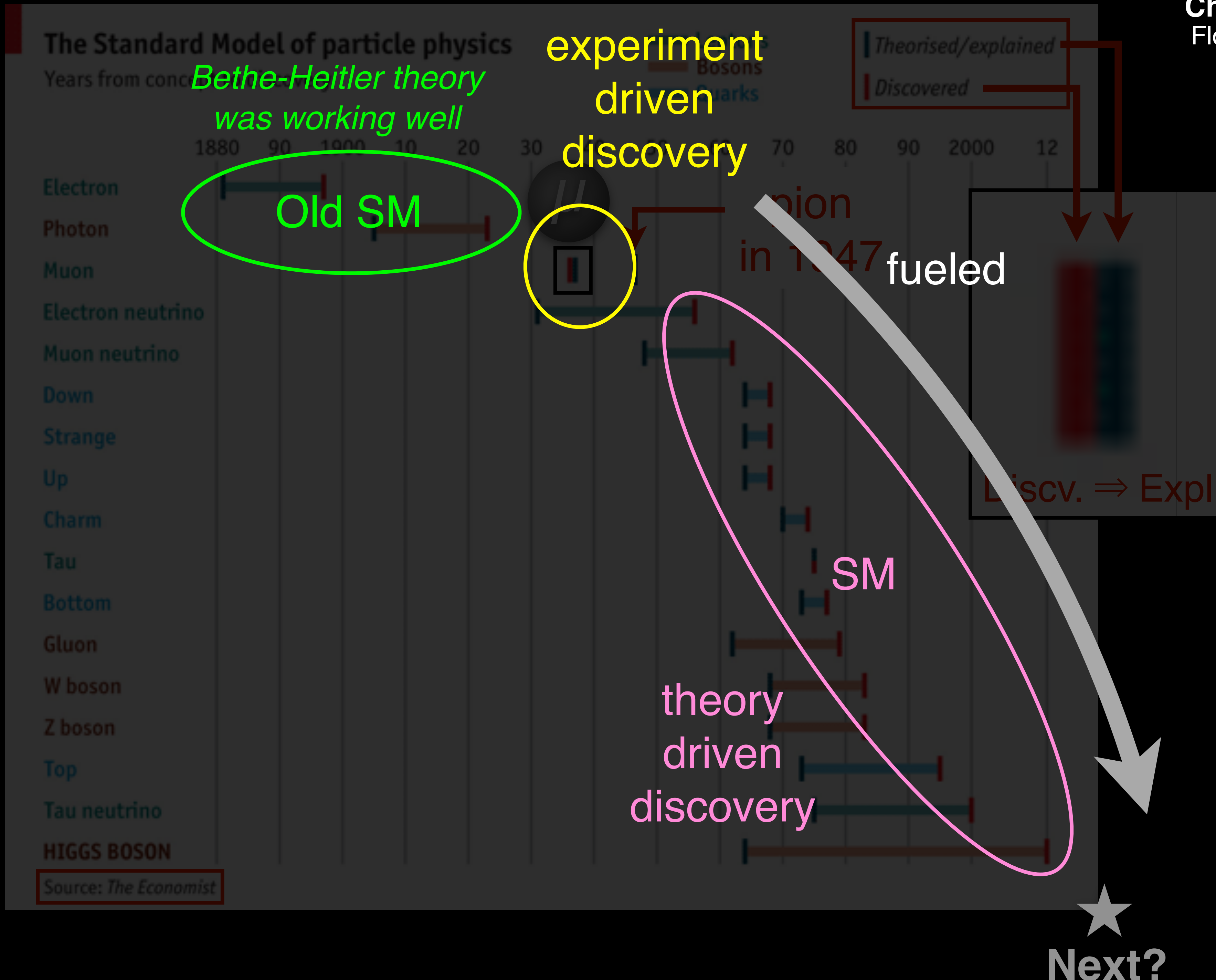
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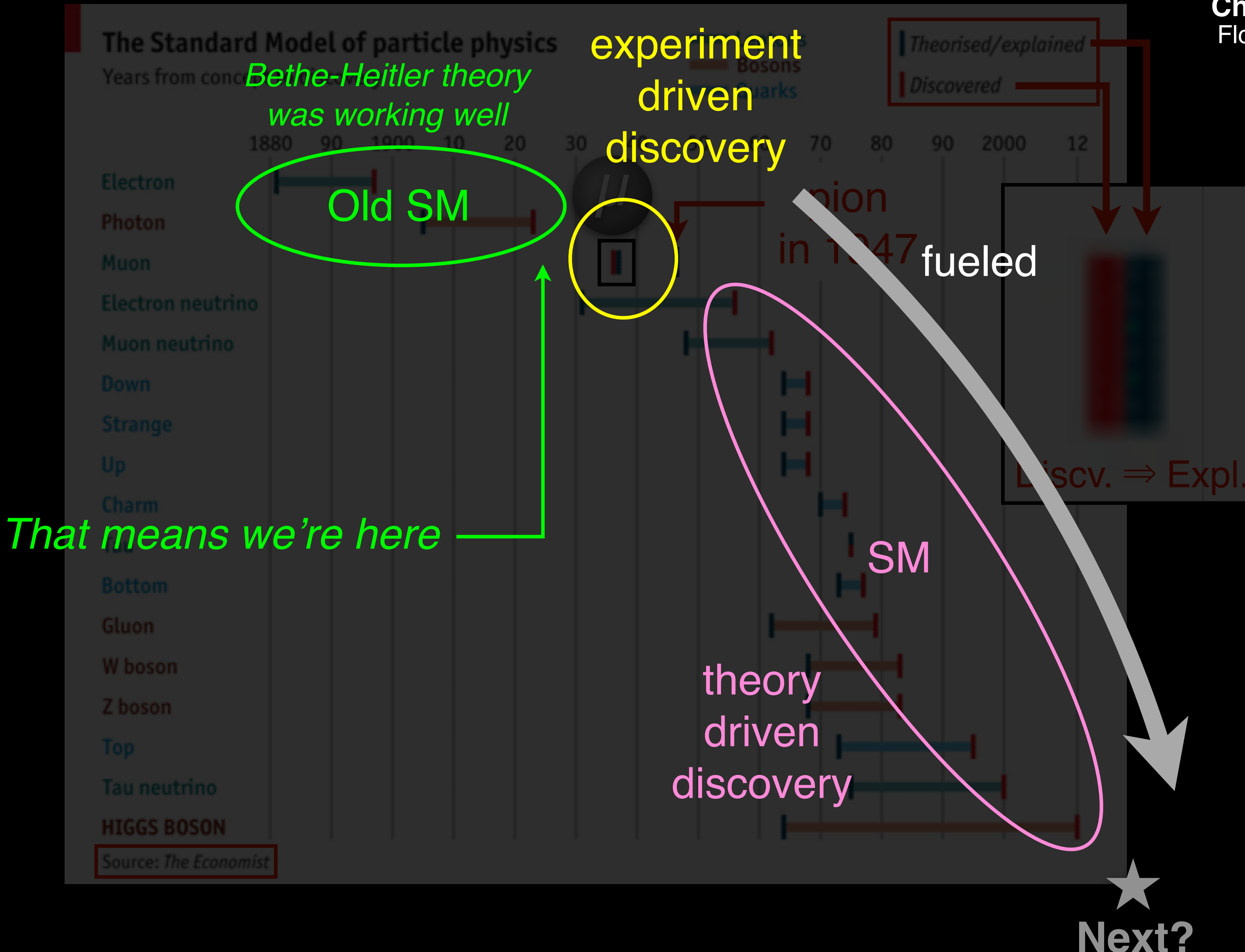
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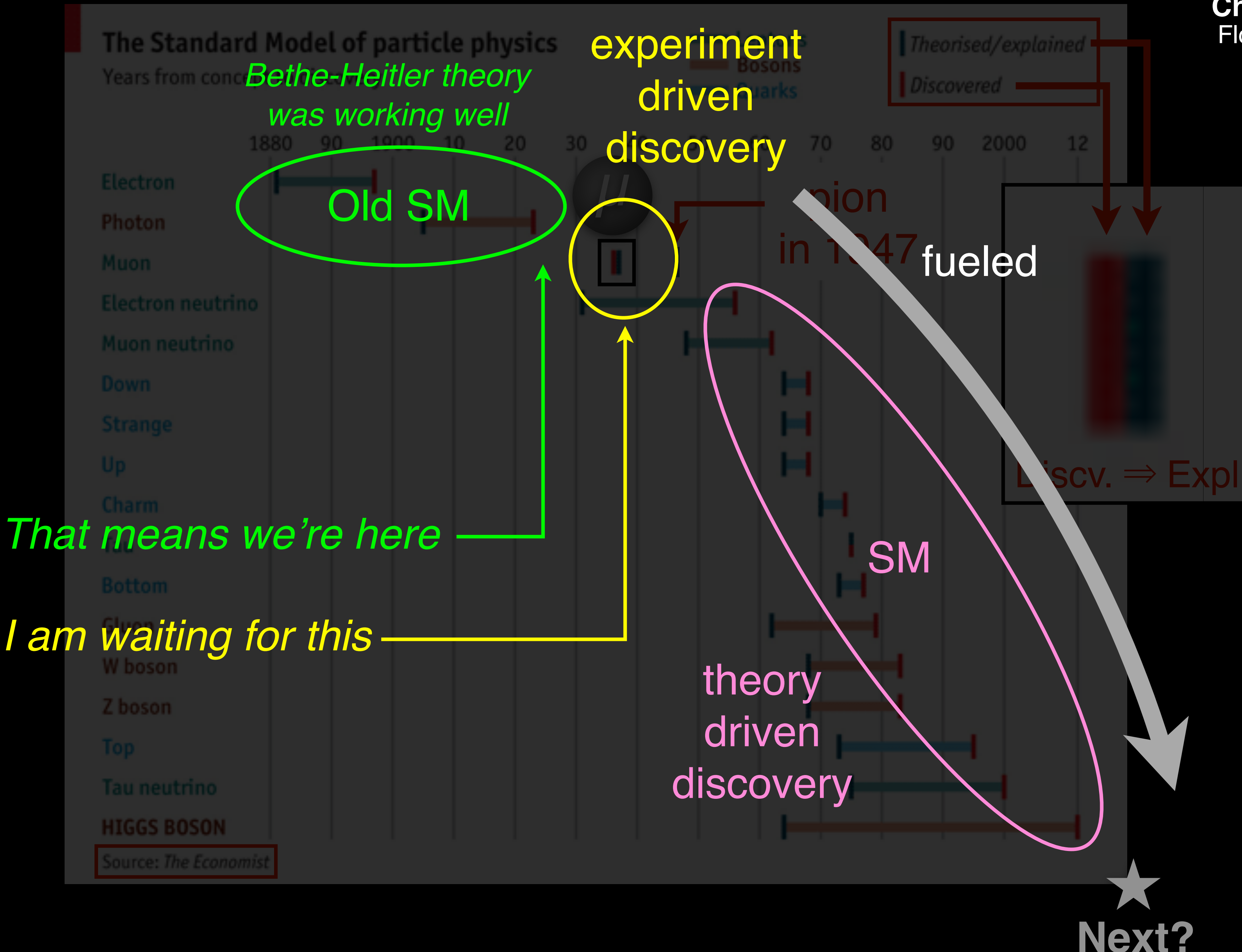
fueled
That means we're here
SM
theory
driven
discovery
Source: The Economist
Next?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That means we're here
I am waiting for this
SM
theory
driven
discovery
Source: The Economist
Next?

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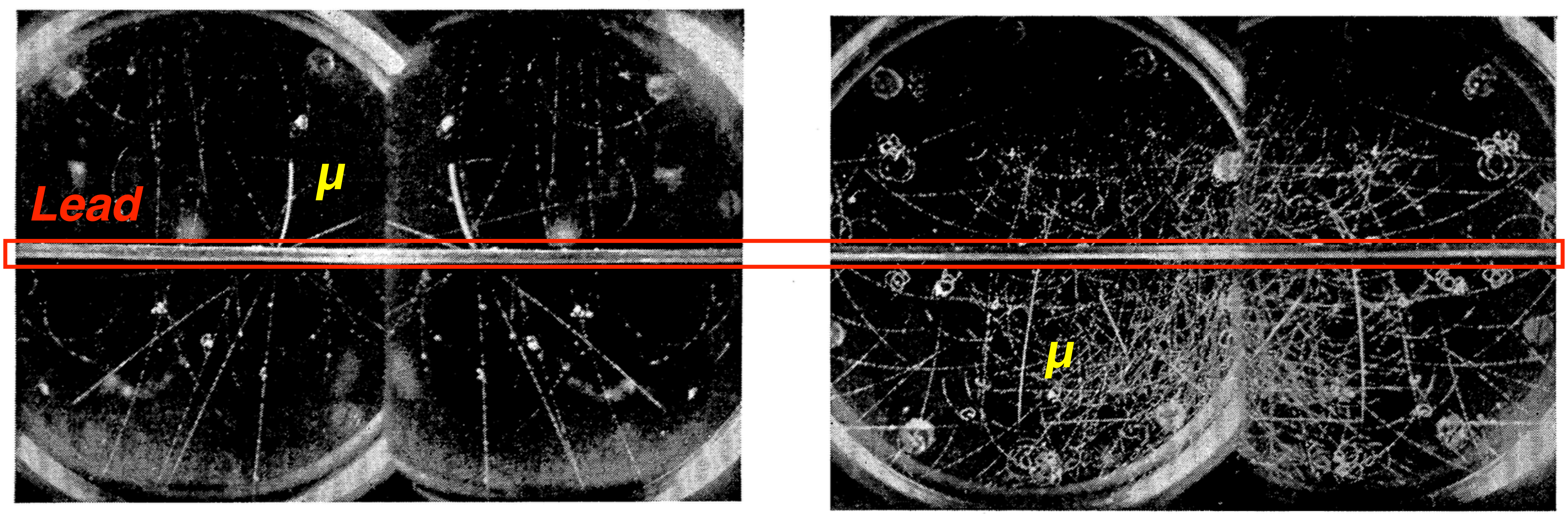
A study of … cosmic ray electron tracks, … has been made with the purpose of observing the interaction of these high energy particles with atomic nuclei and their external electrons.

270 C. D. ANDERSON AND S. H. NEDDERMEYER



Anderson and Neddermeyer, Phys. Rev. 50, 263 (1936)

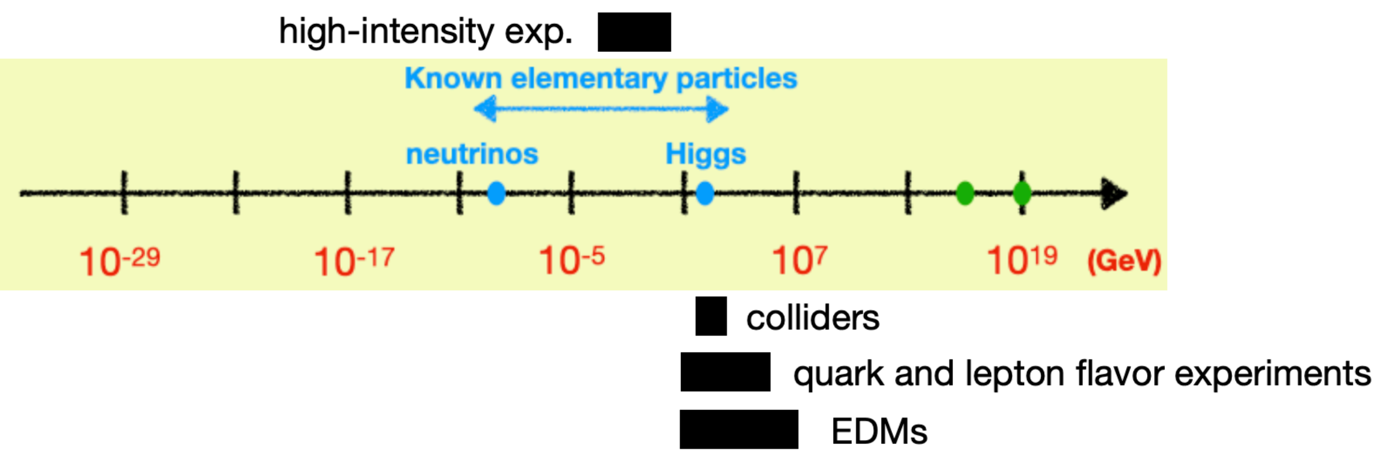
The Future of High Energy Physics: A New Generation, A New Vision

We are in an experimental driven discovery era

What's a discovery in particle physics

- Detecting for the first time a new fundamental process
- Discovering new particles (indirectly or directly)

We do not know what the next New Physics scale will be.



S. Gori

How do we proceed?

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$$S / \sqrt{B}$$

How do we proceed?

Need not be
theory driven

$S / \sqrt{B}$

How do we proceed?

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Need not be
theory driven

$S / \sqrt{B}$ →

How do we proceed?

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Need not be theory driven

$$S / \sqrt{B} \longrightarrow 1 / \sqrt{B}$$

How do we proceed?

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Need not be theory driven

non-zero preferred but not required

$$S / \sqrt{B} \longrightarrow 1 / \sqrt{B}$$

How do we proceed?

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Need not be theory driven

non-zero preferred but not required

$$S / \sqrt{B} \longrightarrow 1 / \sqrt{B}$$

Focus on unexplored phase-space

How do we proceed?

Need not be theory driven

non-zero preferred but not required

$$S / \sqrt{B} \longrightarrow 1 / \sqrt{B}$$

Focus on unexplored phase-space

Test null-hypothesis (i.e. SM)

How do we proceed?

Need not be theory driven

non-zero preferred but not required

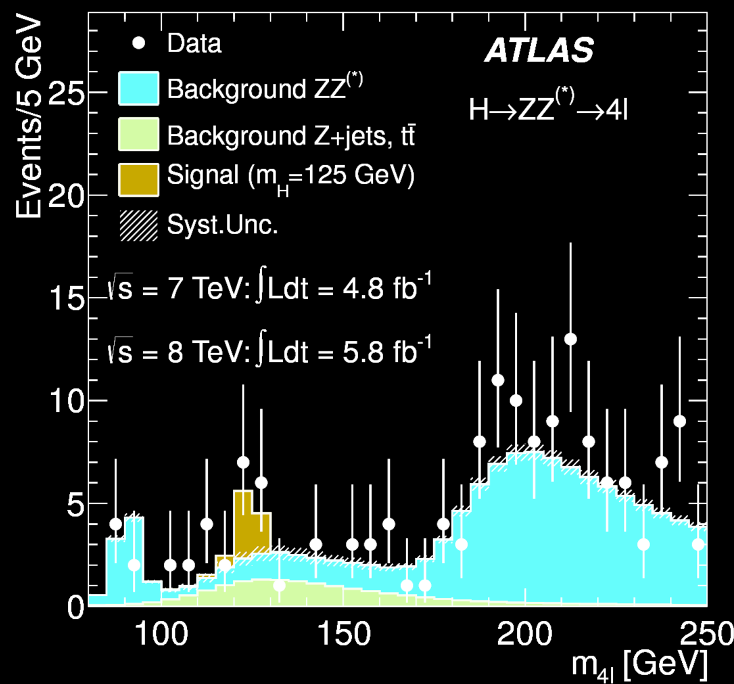
$S / \sqrt{B} \longrightarrow 1 / \sqrt{B}$

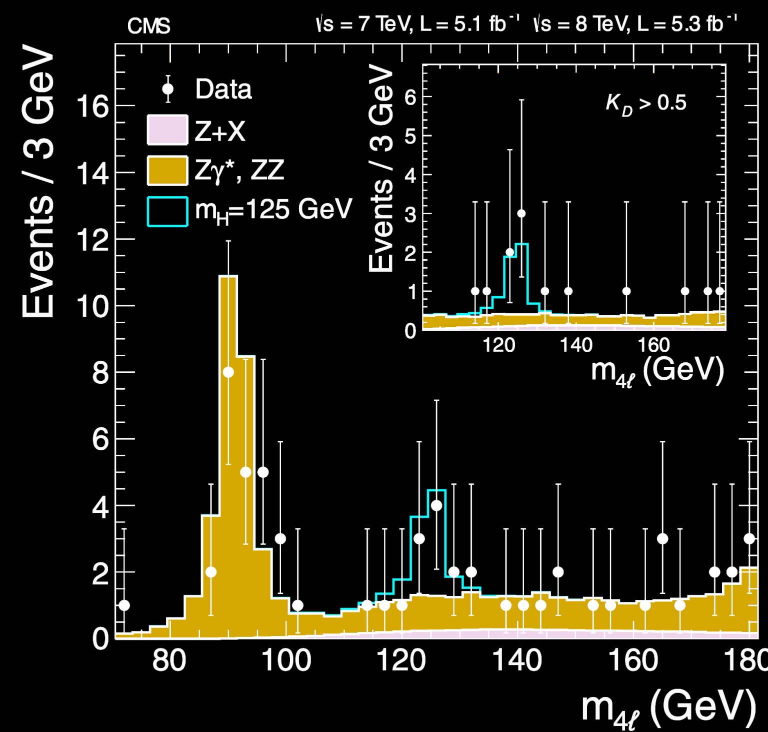
Focus on unexplored phase-space

Test null-hypothesis (i.e. SM)

Surprises do happen!

How much of a surprise?





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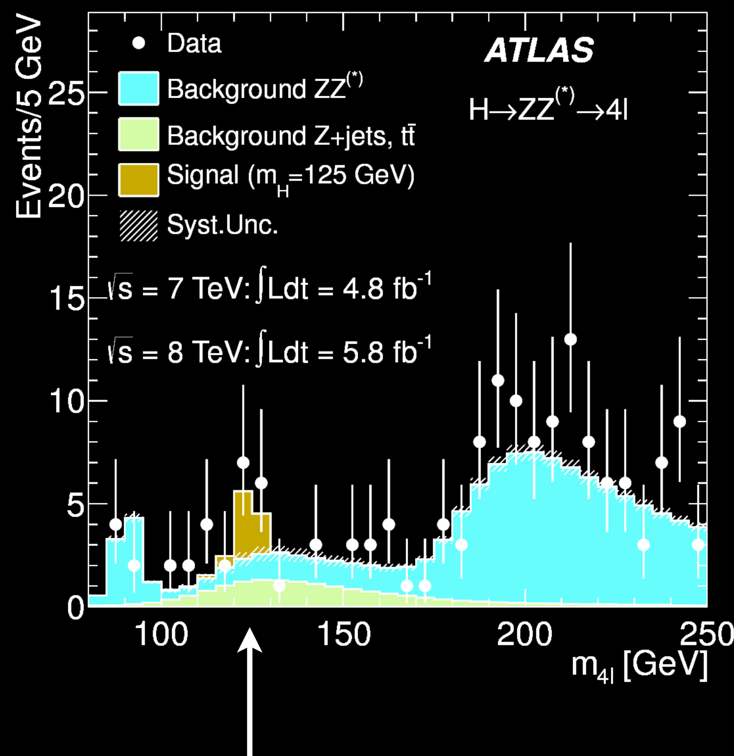
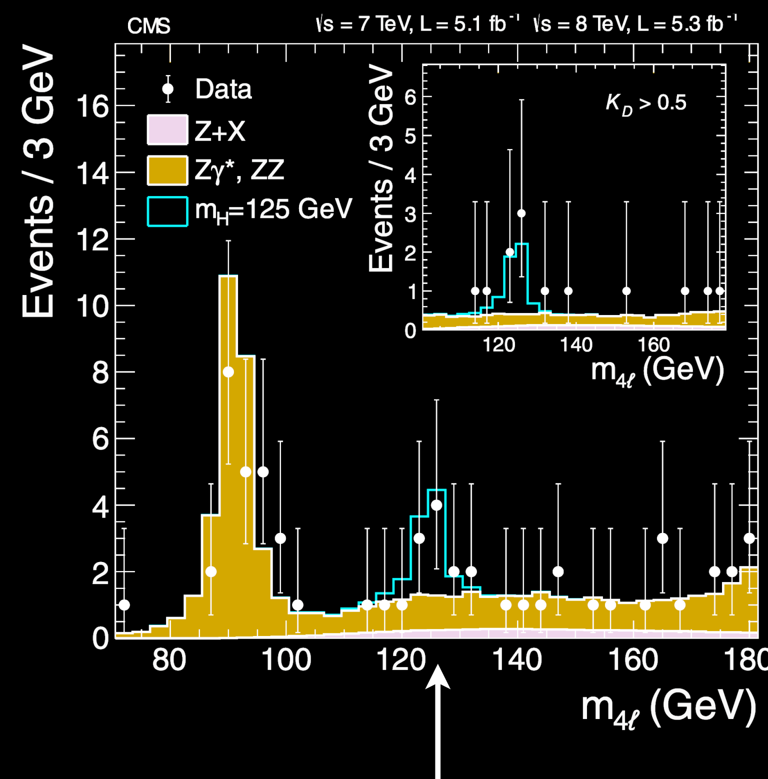




~8 evt. excess

3.5σ

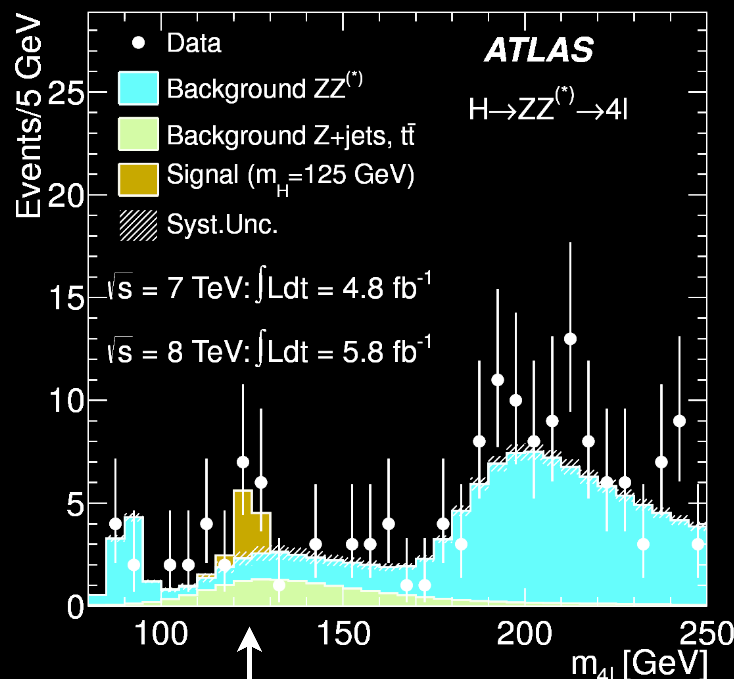
\+

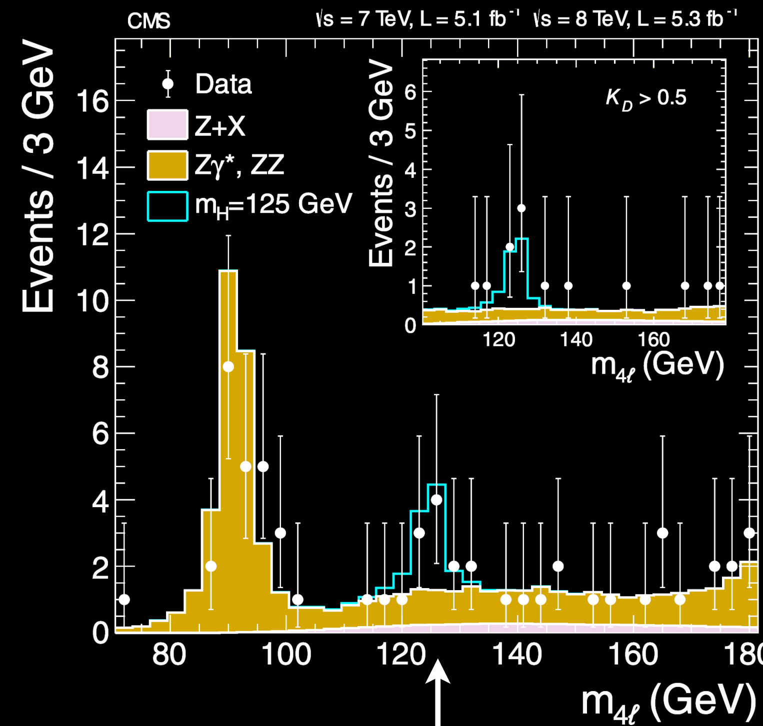
6 evt. excess

3.2σ

= 4.8σ

How much of a surprise?





~8 evt. excess — 6 evt. excess

3.5σ + 3.2σ = 4.8σ

3000 fb^{-1} (future) / 137 fb^{-1} (today) = 20 times more data coming

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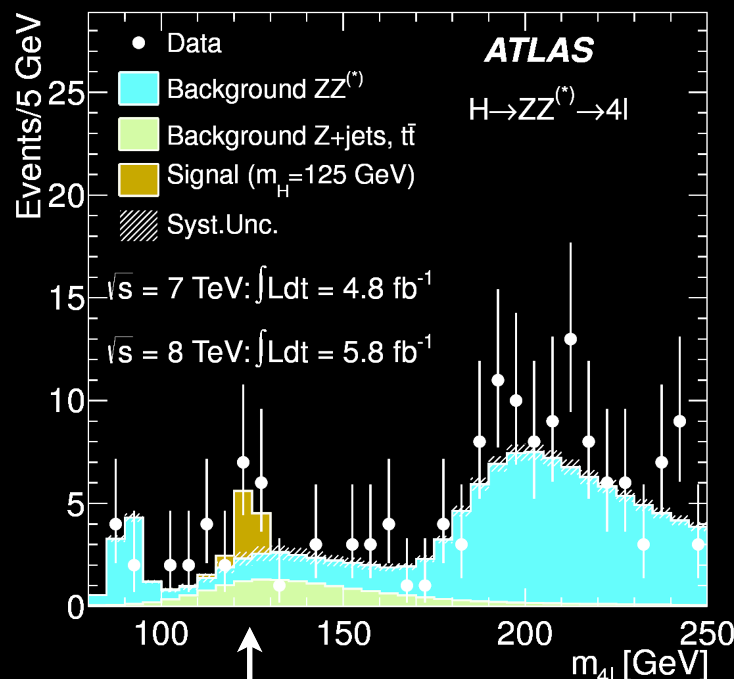
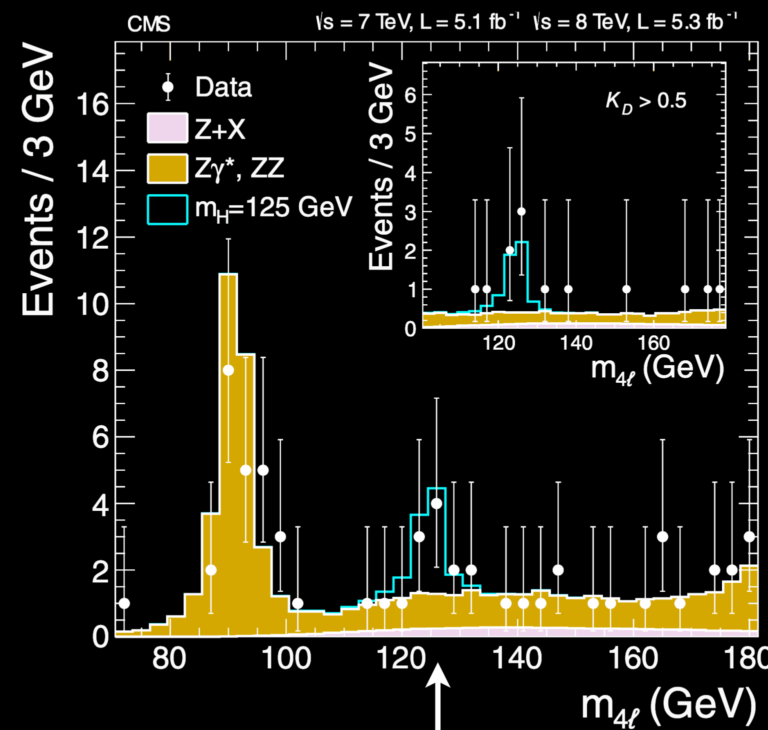
How much of a surprise?





~8 evt. excess

6 evt. excess

3.5σ + 3.2σ = 4.8σ

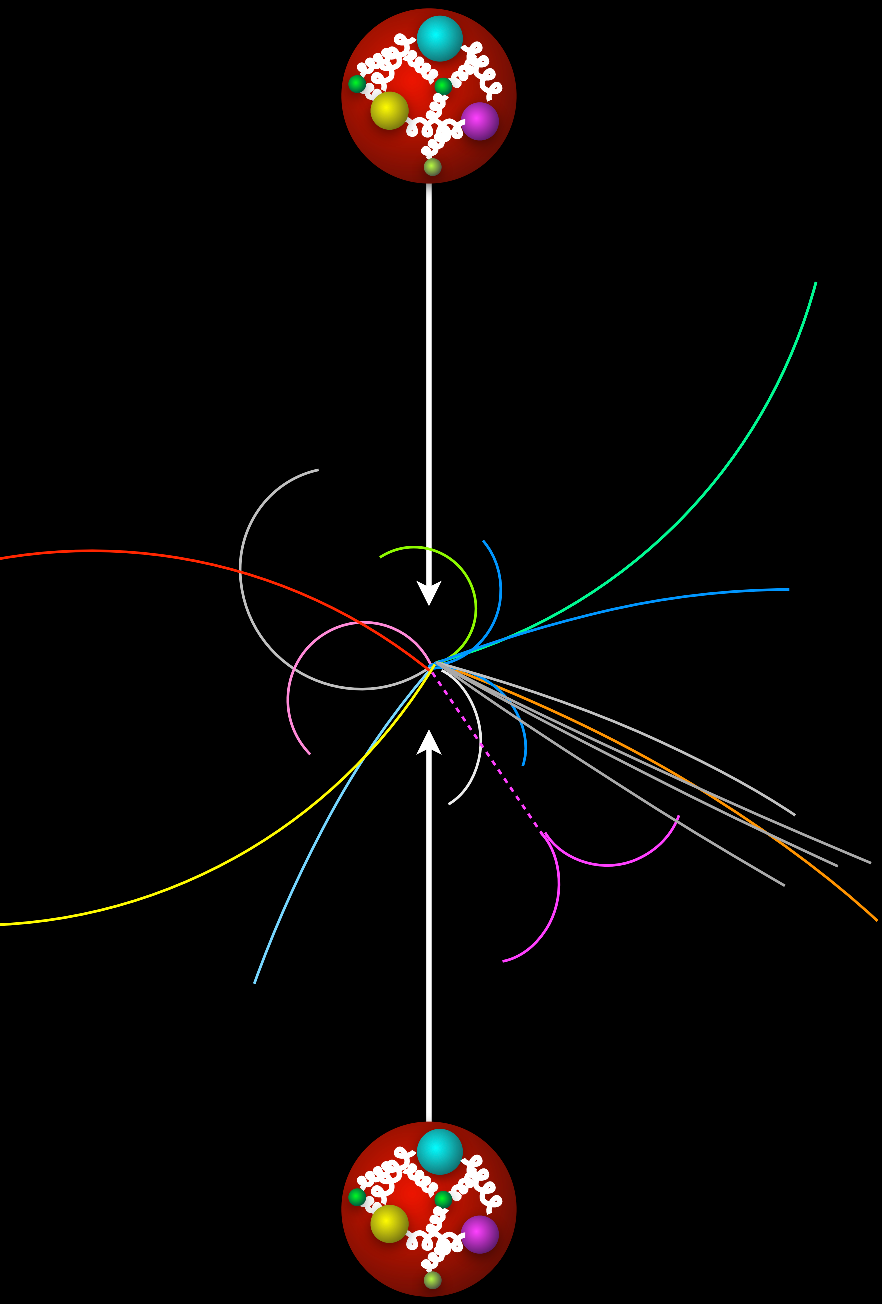
3000 fb^{-1} / 137 fb^{-1} = 20 times more data coming

(future) (today)

Today, we'd have seen < 0.5 event in each expt.

(e.g. 1 fb * 10% (BR) * 3% (acc.) * 137 fb^{-1} = 0.4 events)

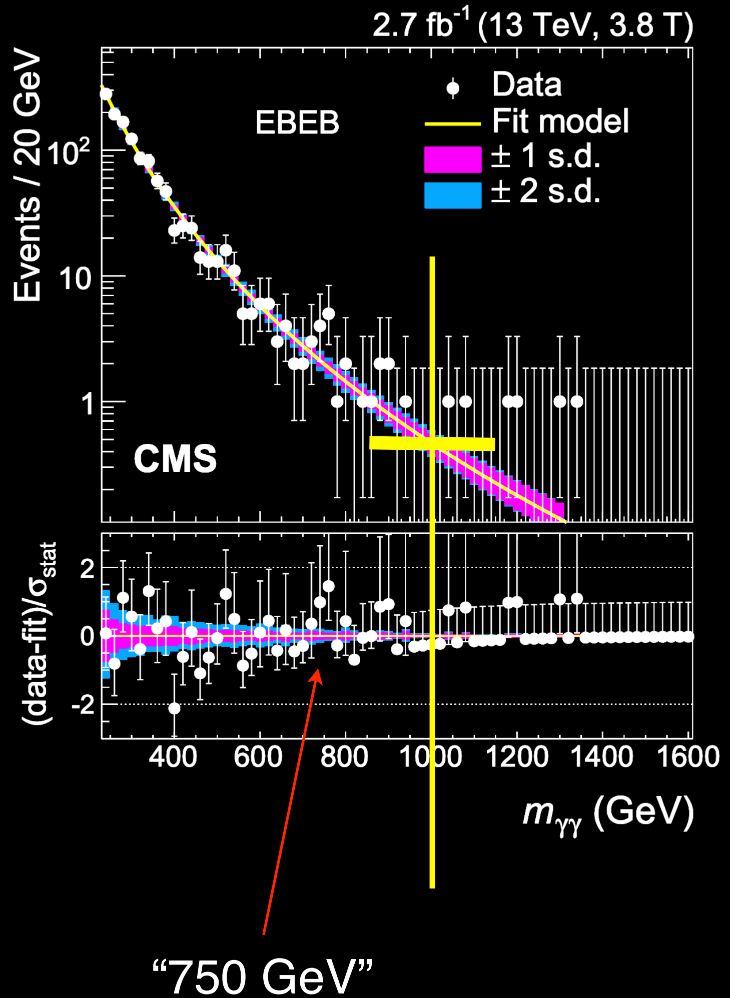
Phase-space



"How do we make sure we don't leave things on the table?"

1. **E**nergy of the final state particle
2. **M**ultiplicites
3. **A**ngular correlation (e.g. mass, substr.)
4. **L**ifetime

Pushing Energy



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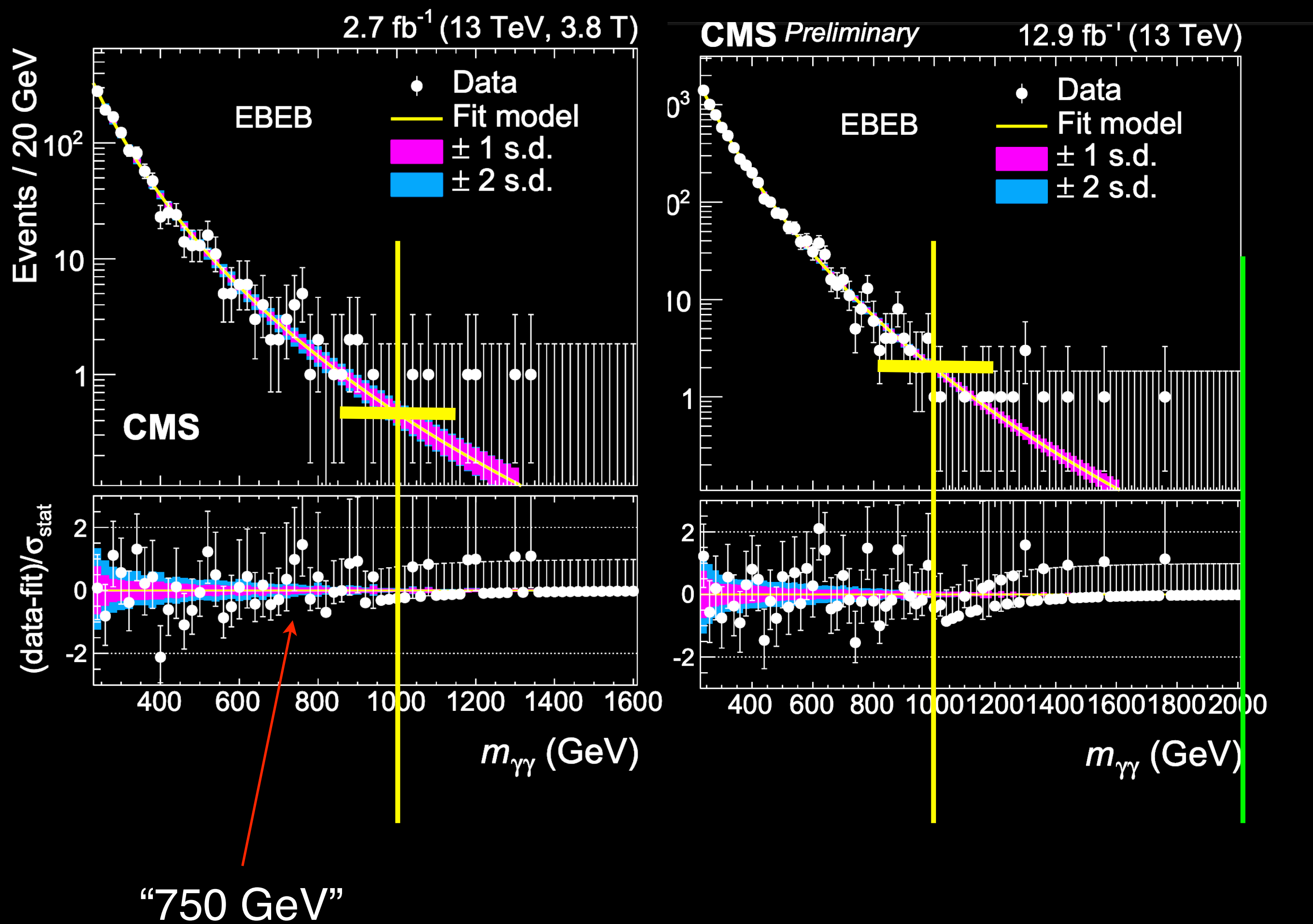

Pushing Energy

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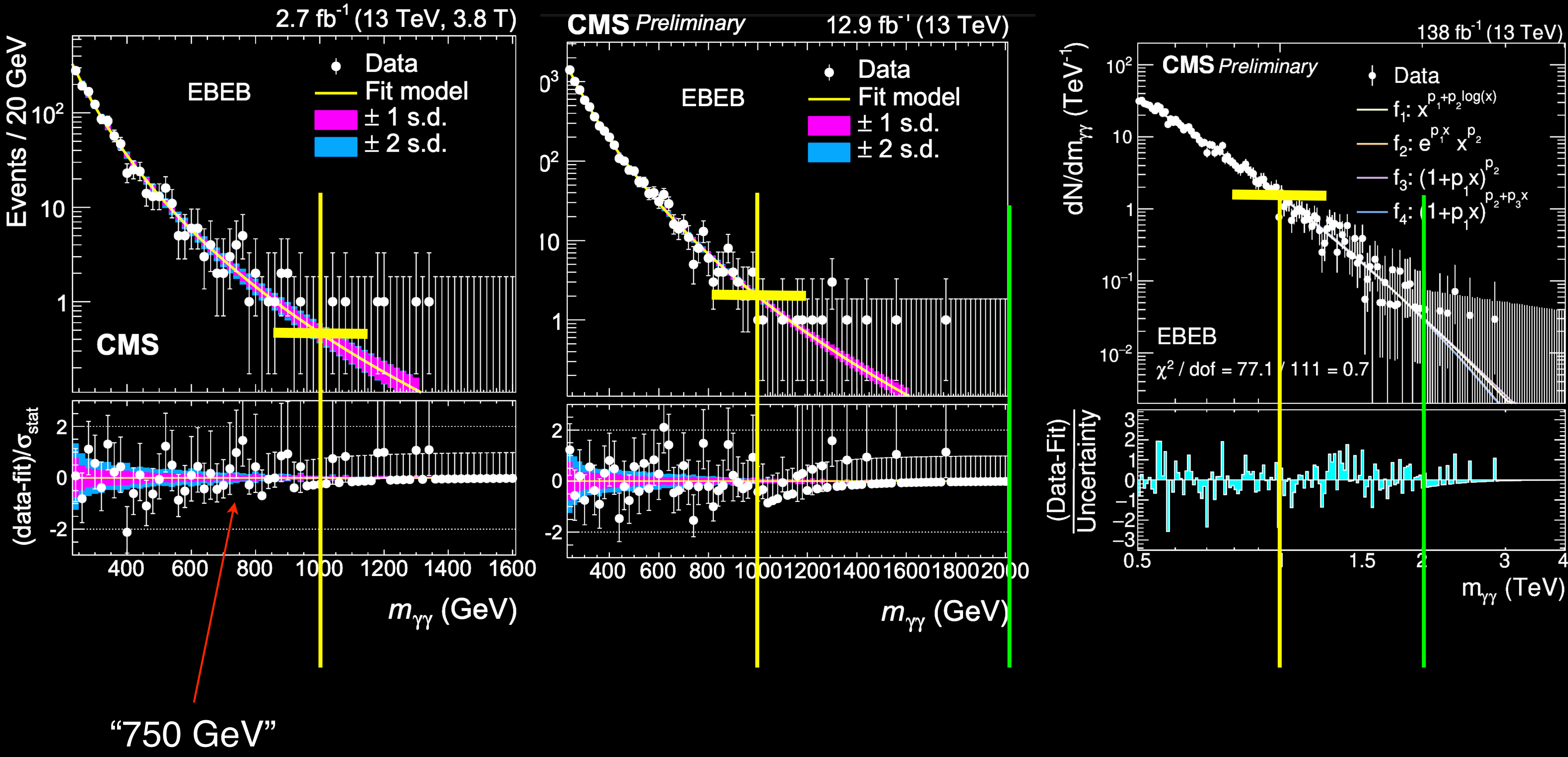
Yesterday

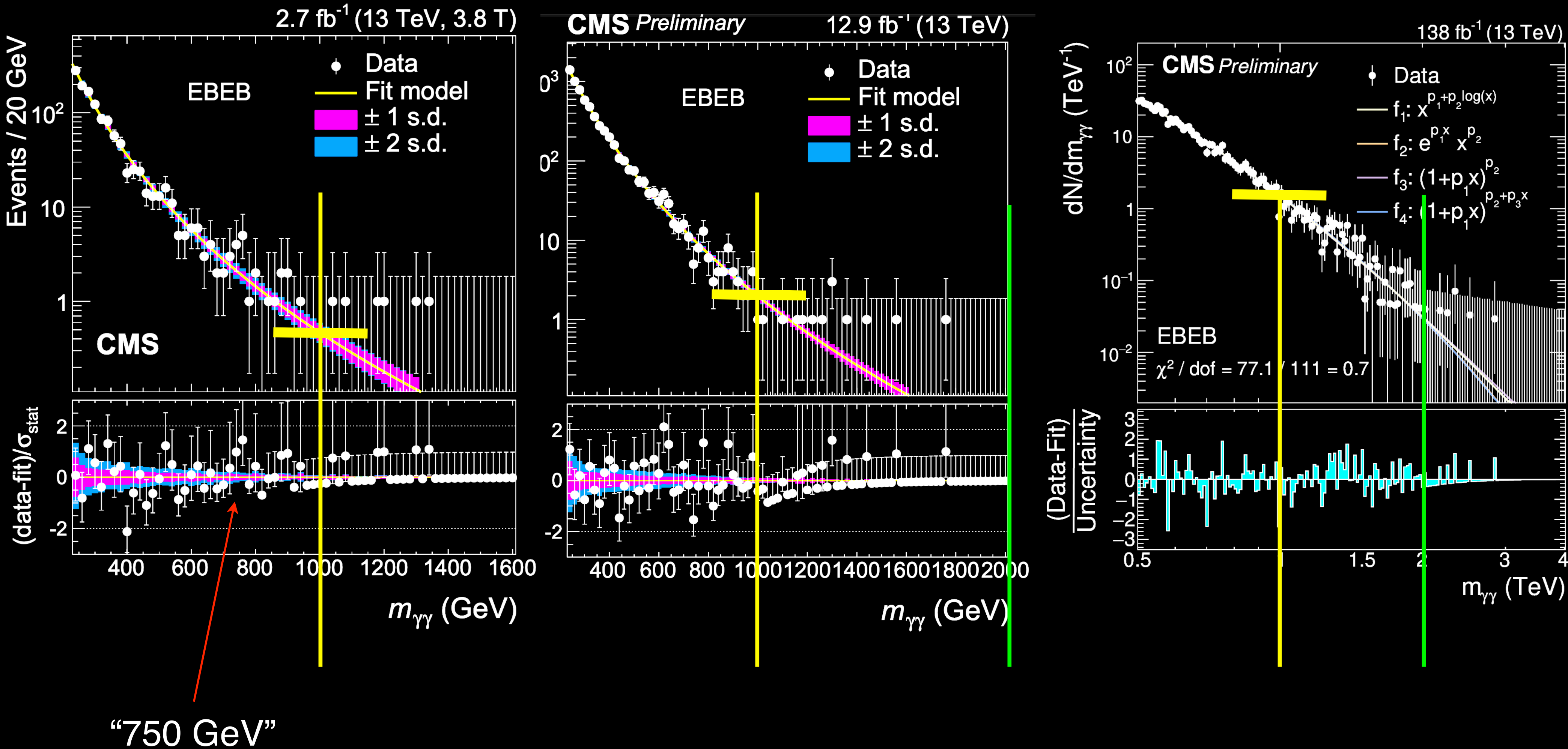
CMS-PAS-EXO-22-024



Pushing Energy

Yesterday

CMS-PAS-EXO-22-024



Same story for W' / Z' and various resonance searches

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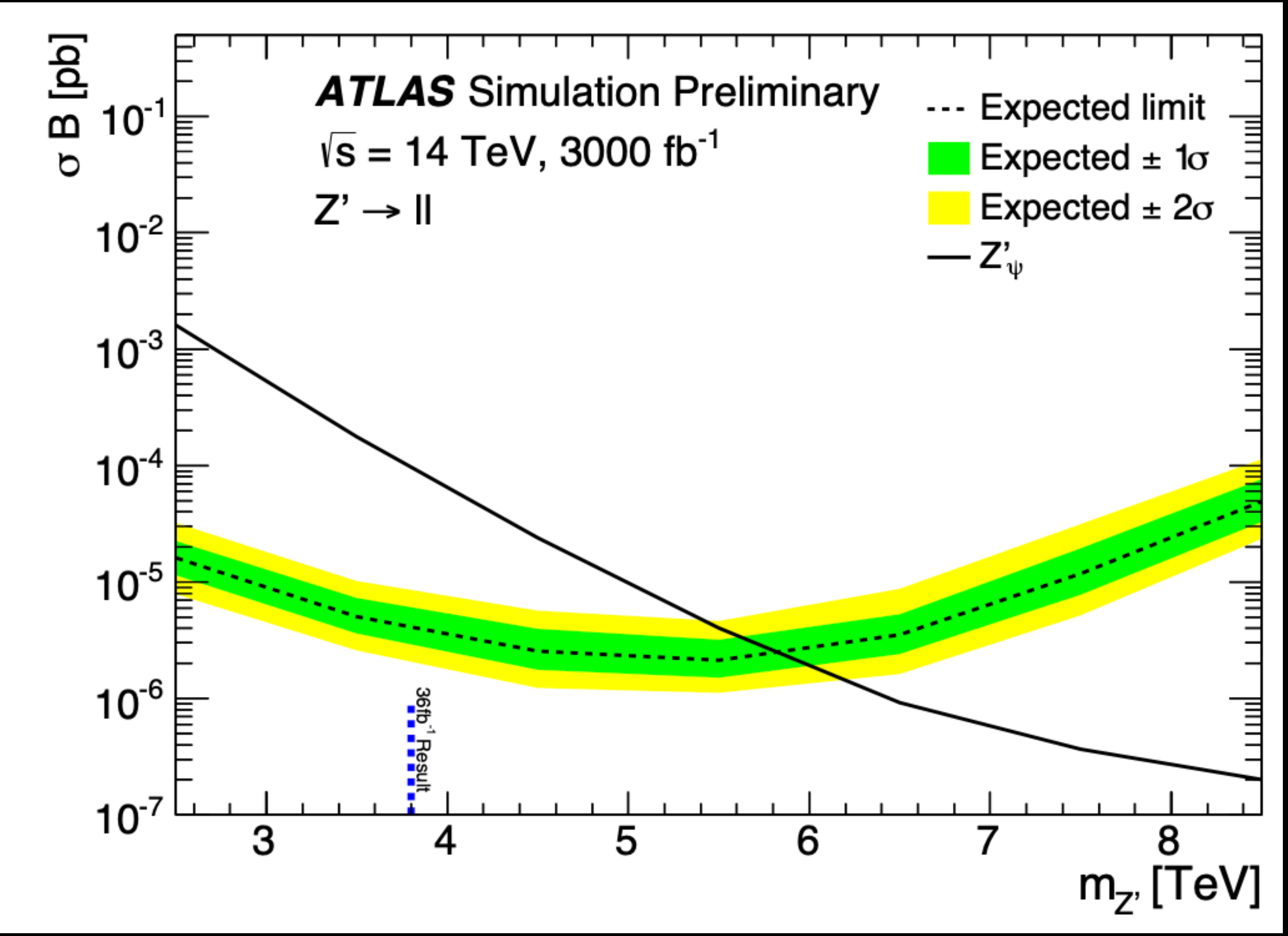
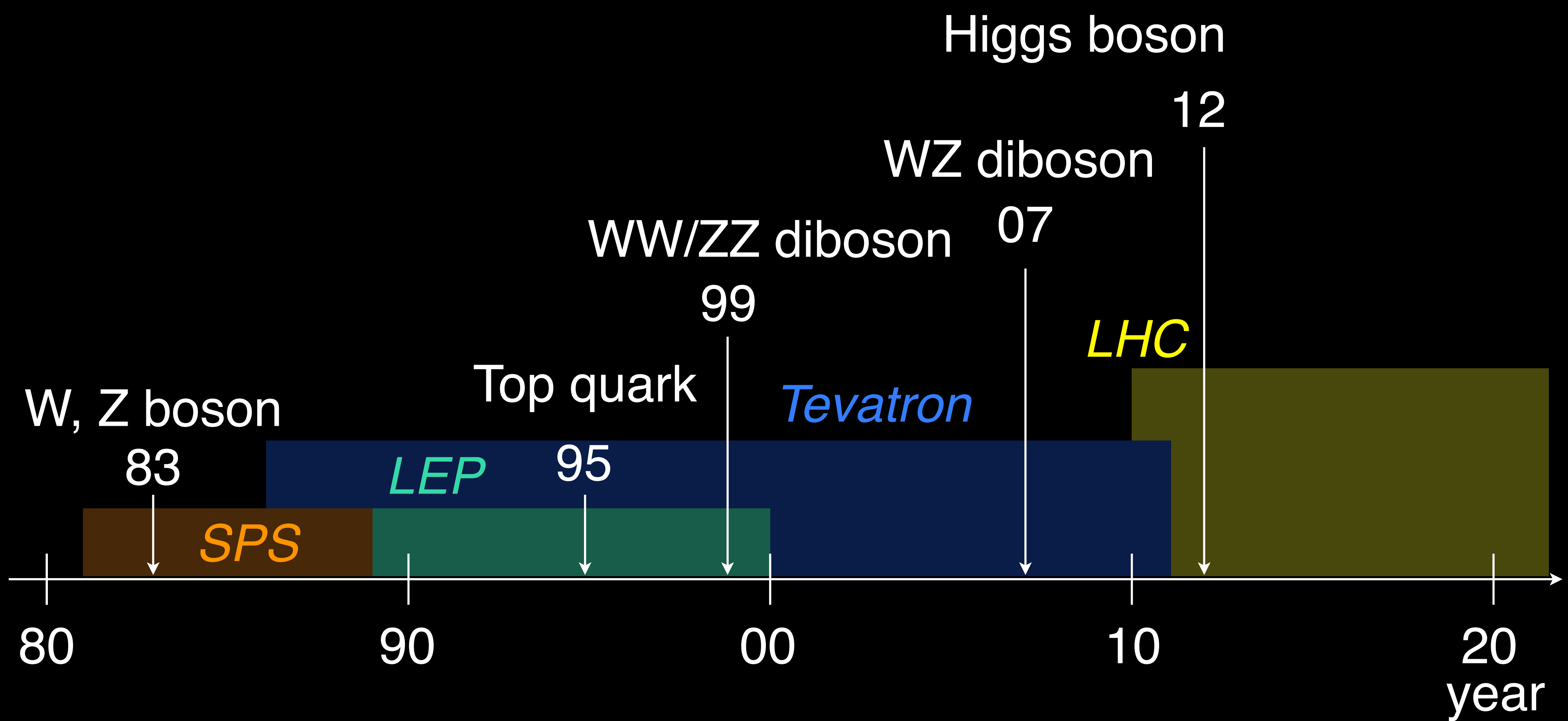


Pushing multiplicities



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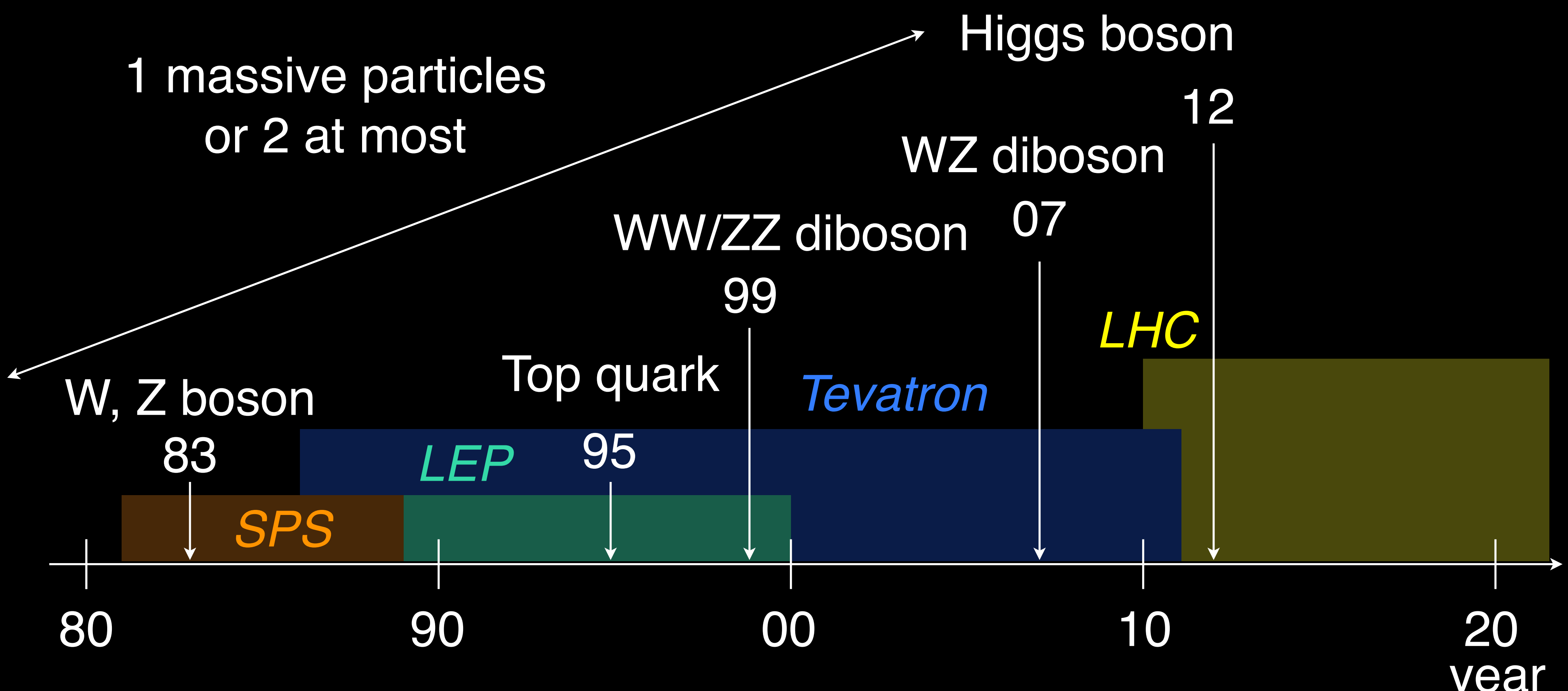

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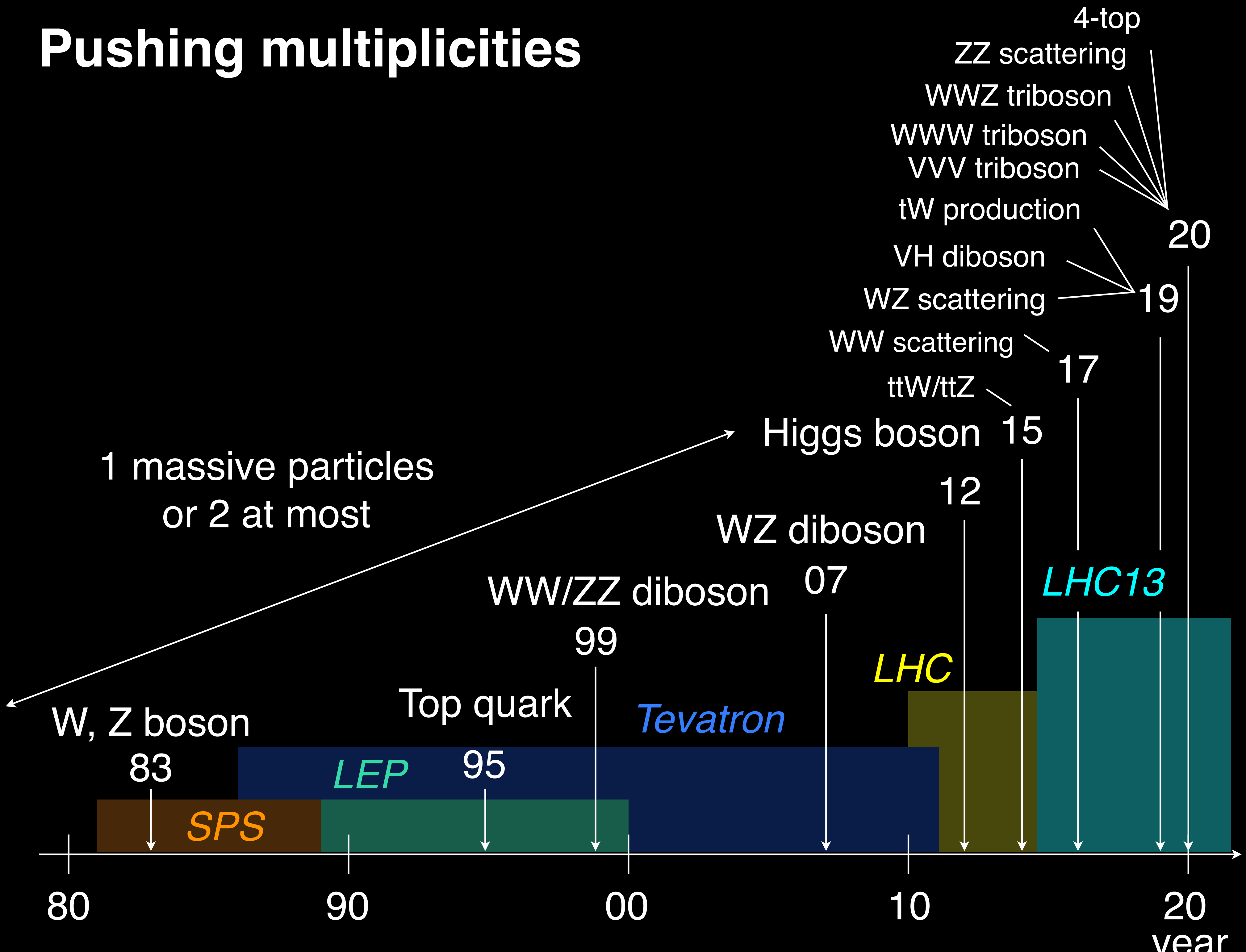

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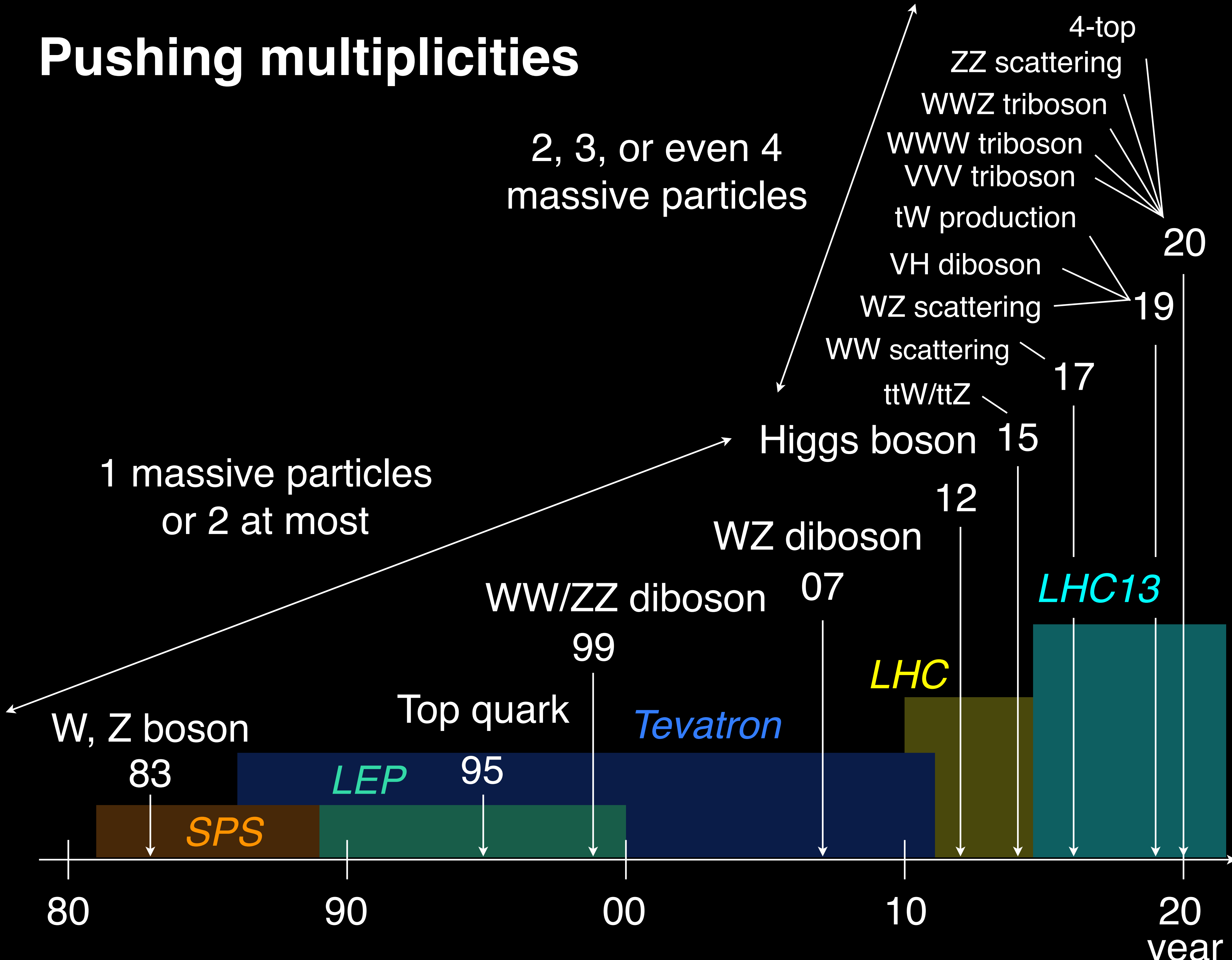

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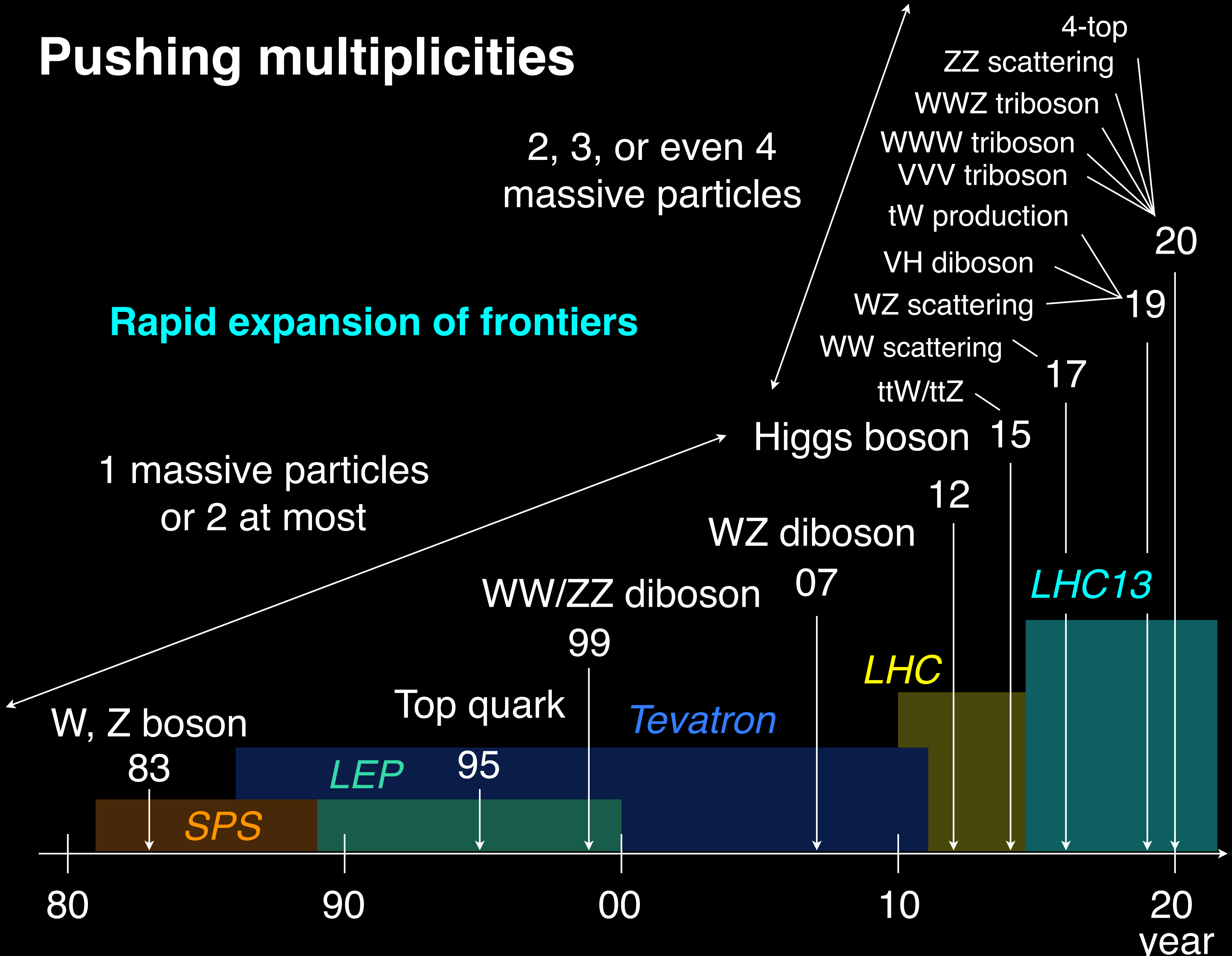

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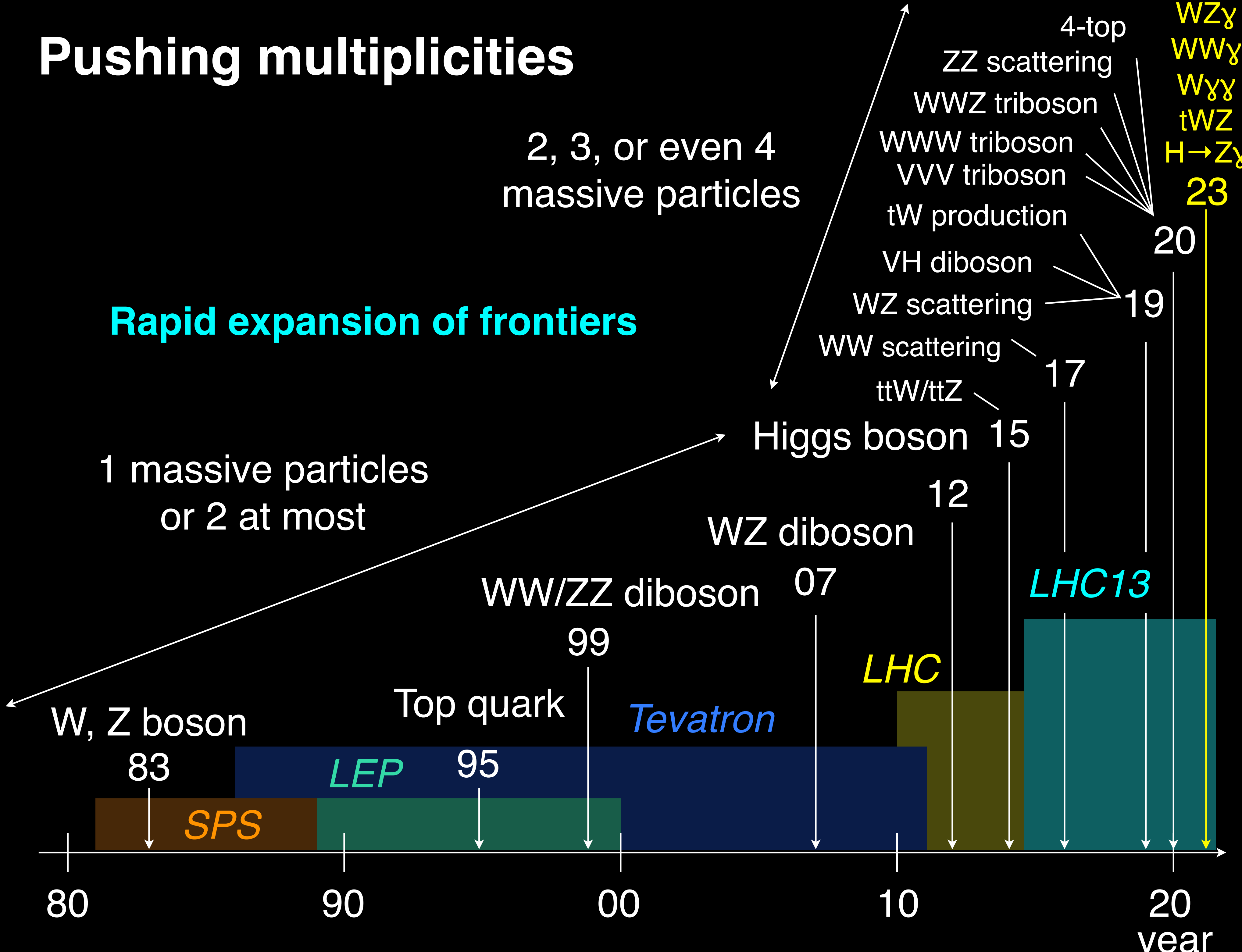
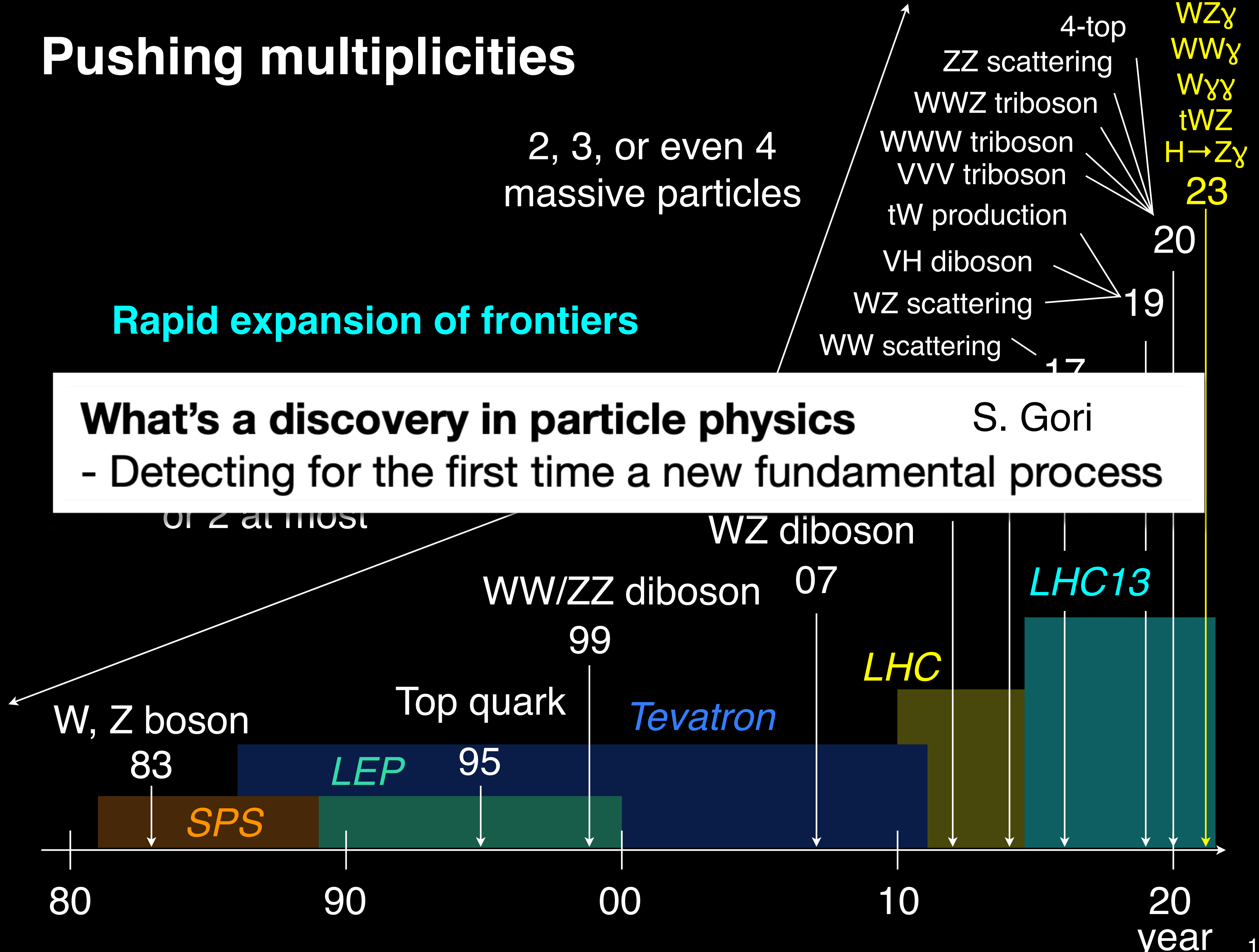


Pushing multiplicities



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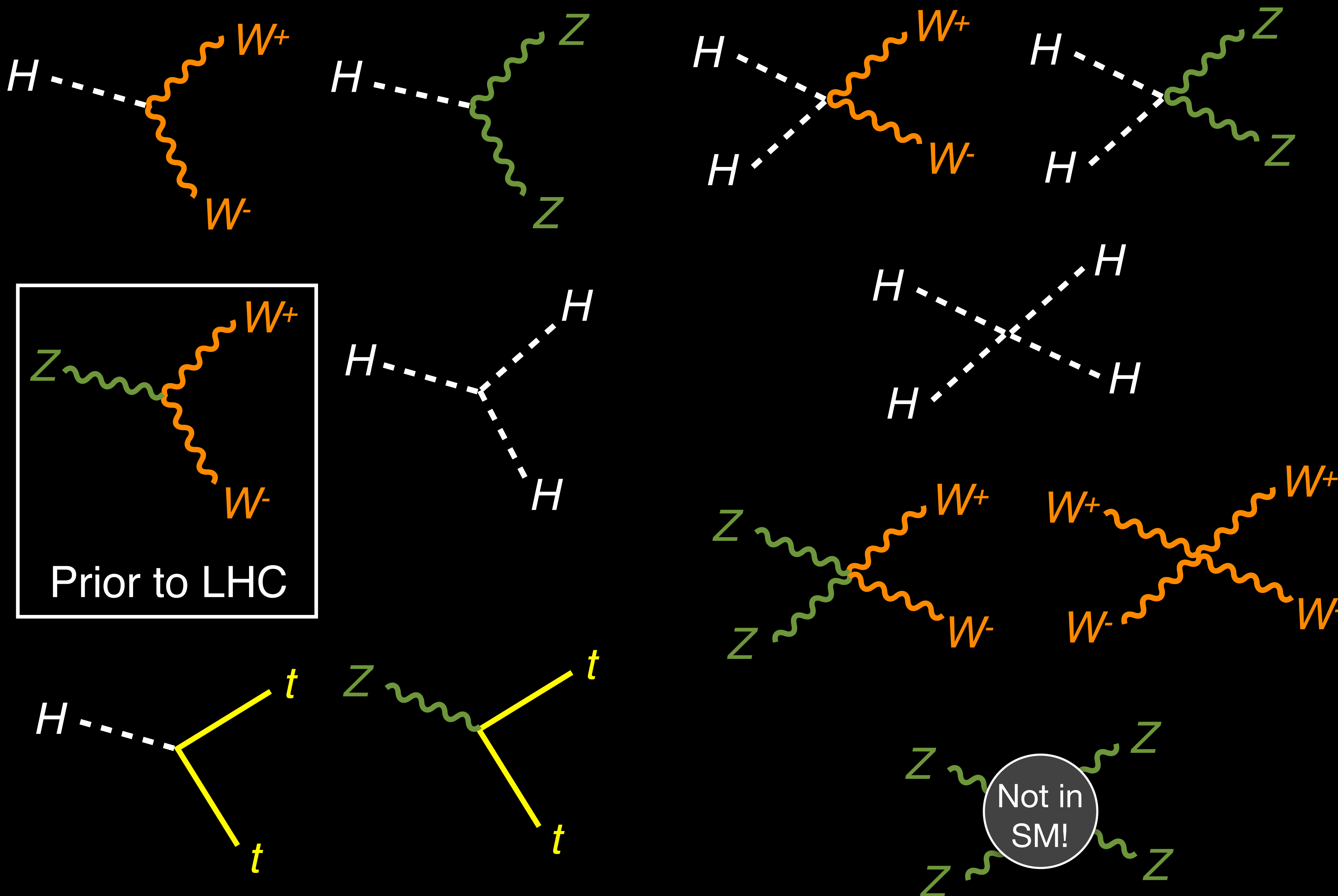

High multiplicities

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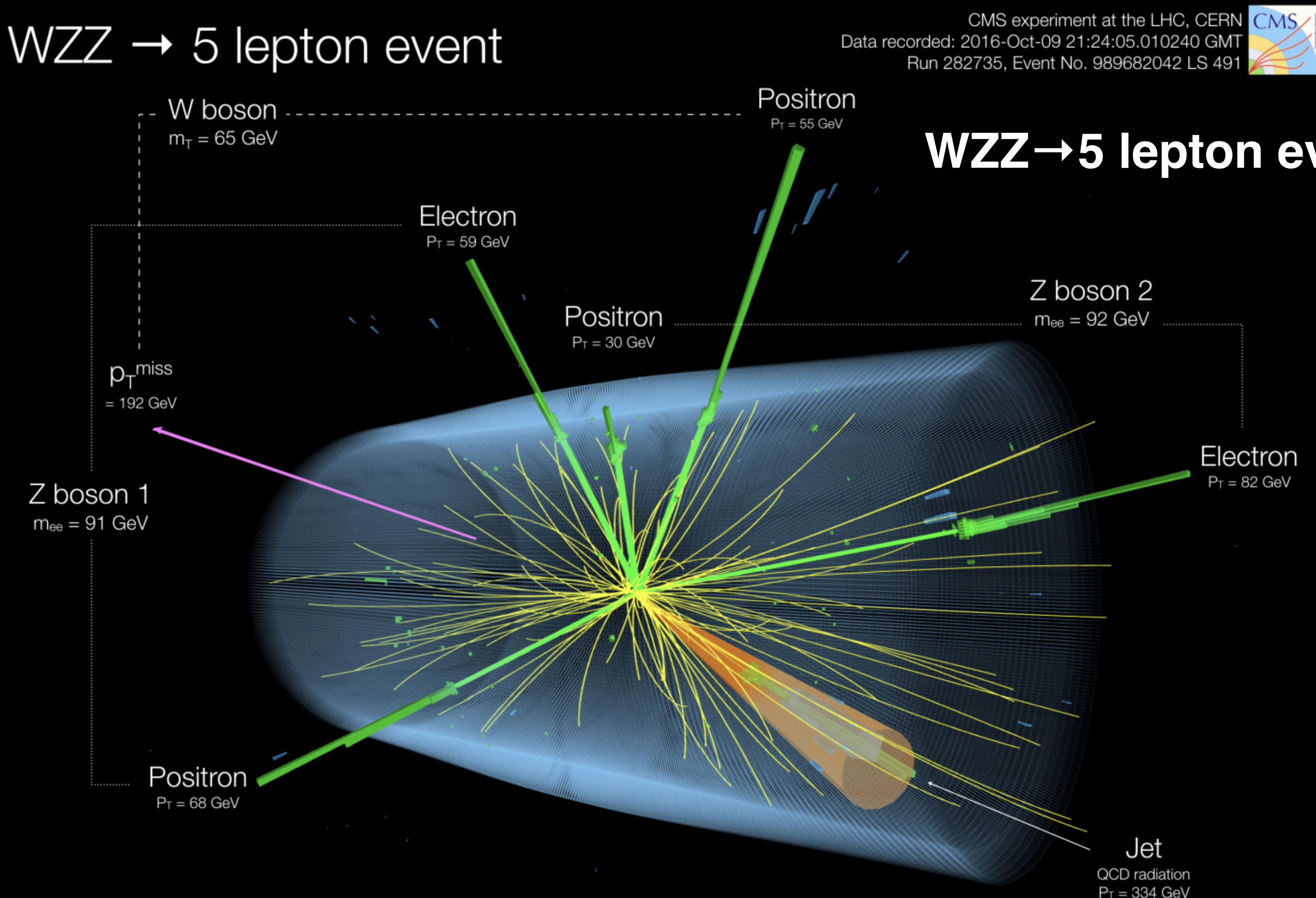
WZZ→5 lepton events



5 electrons

High multiplicities

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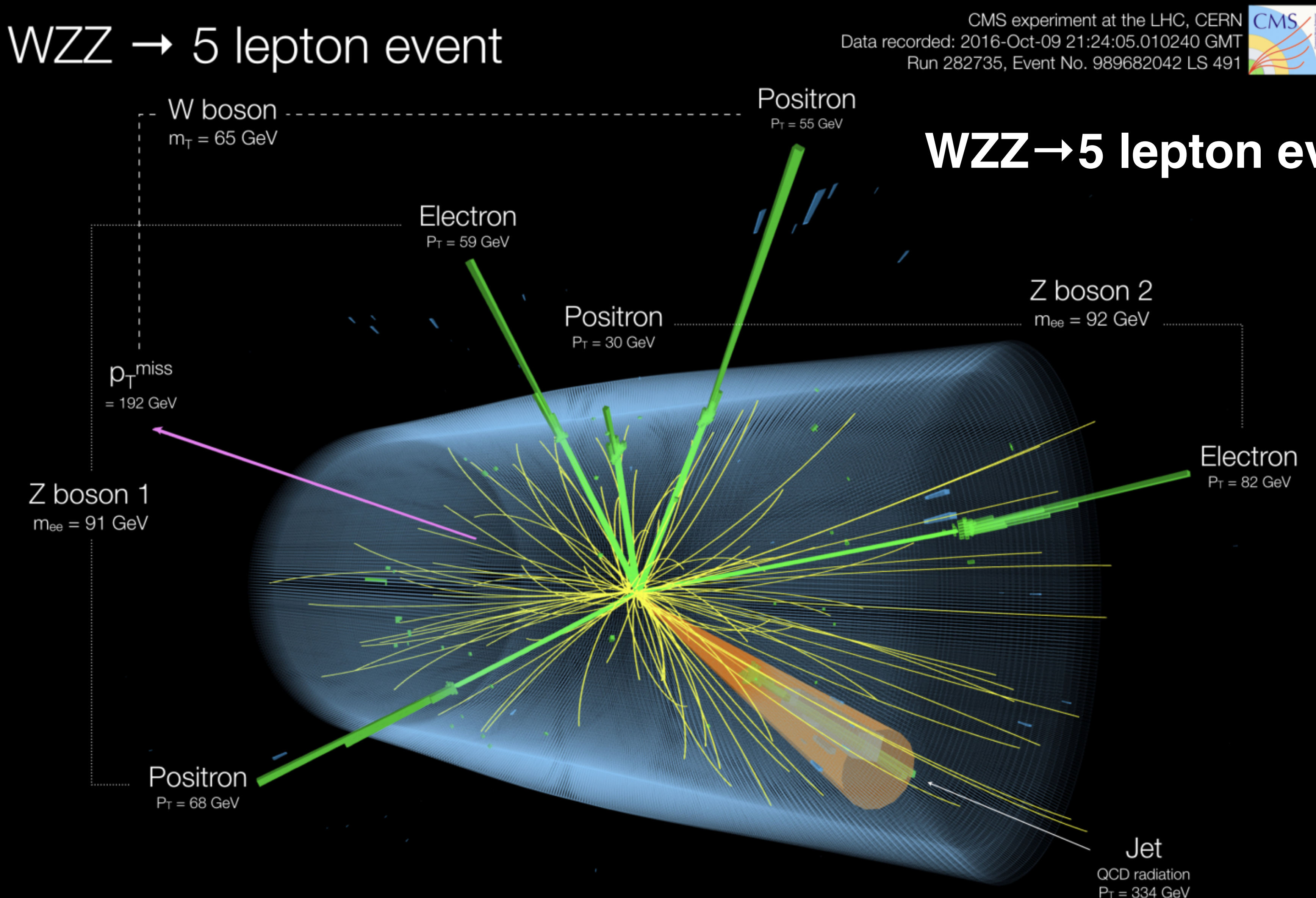
WZZ→5 lepton events



We expected ~1 event like this out of 15,000,000,000,000,000 collisions

5 electrons

High multiplicities

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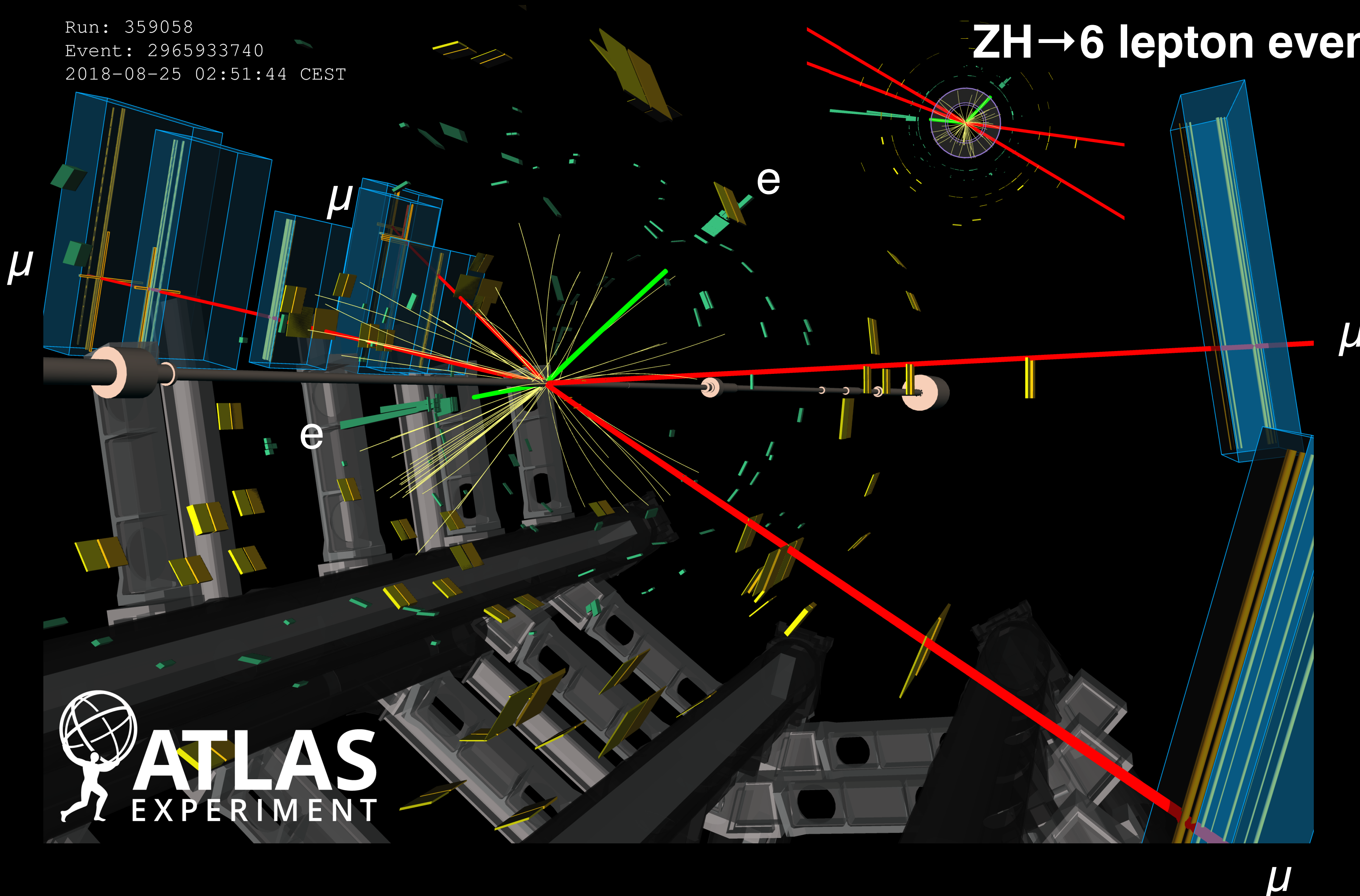
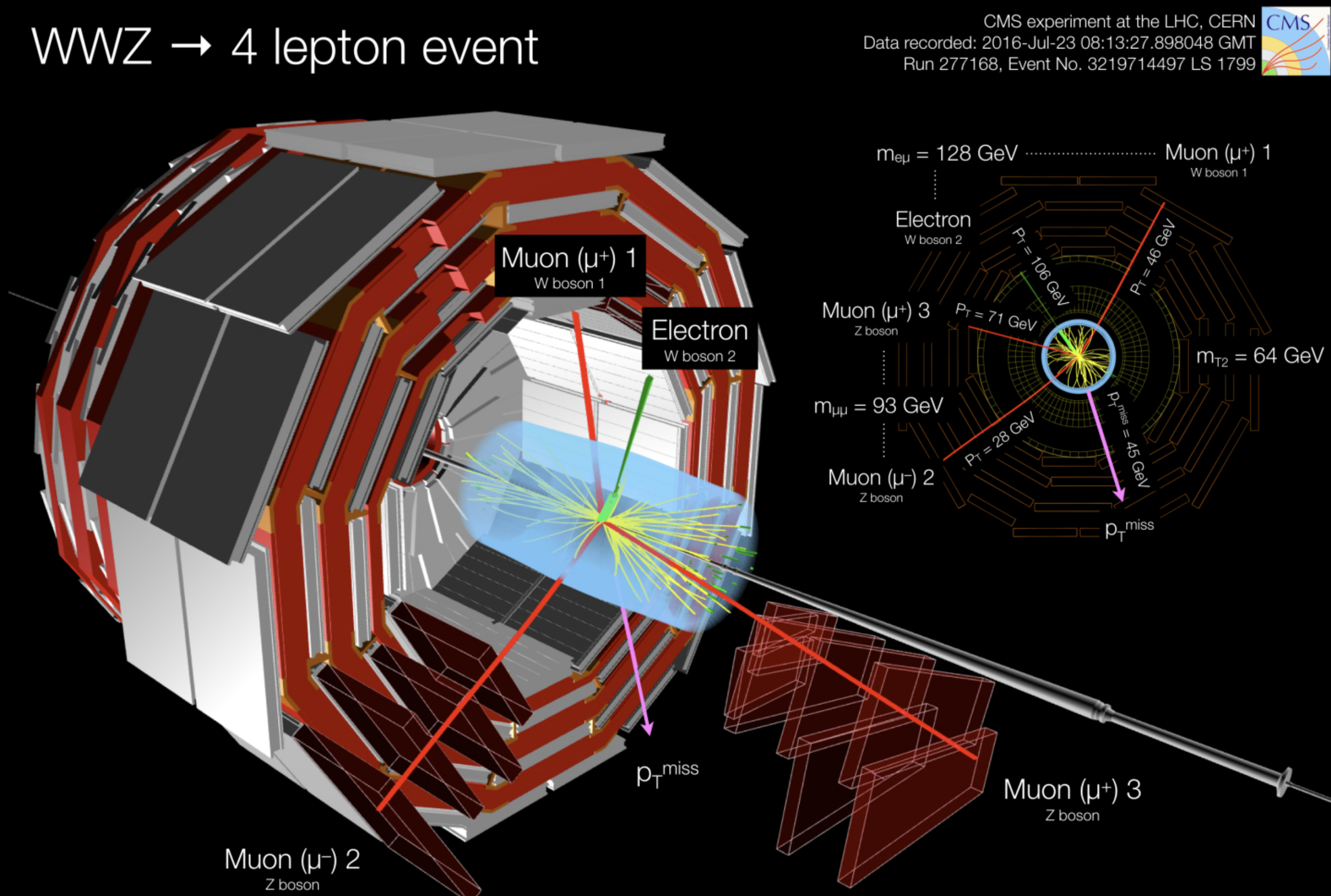


This event was also ~1 event expected

High multiplicity case study

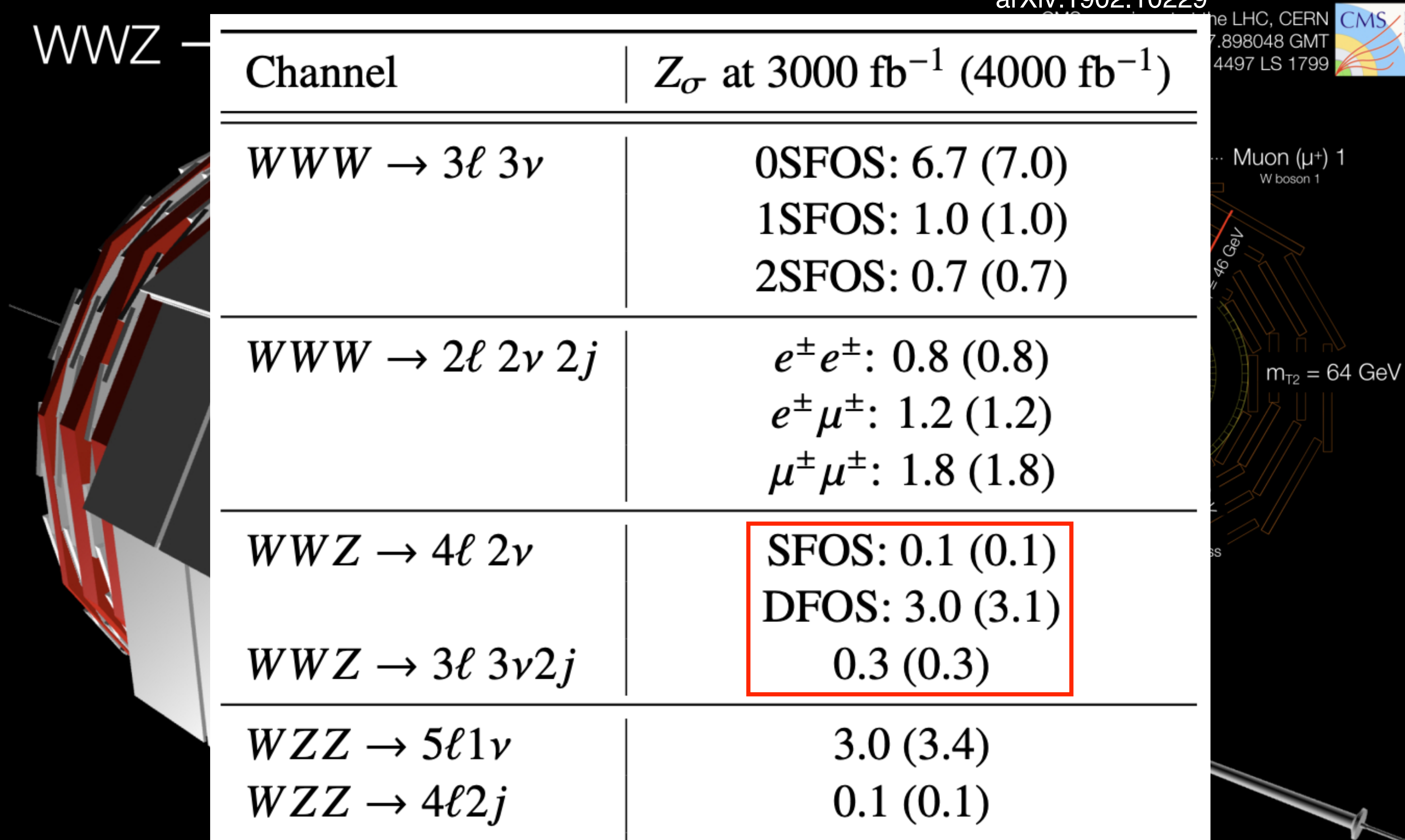
WWZ → 4 lepton event



Expected to reach 3σ in 3000 fb^{-1} → But we did it with 137 fb^{-1}

High multiplicity case study

arXiv:1902.10229



Channel	Z_σ at 3000 fb^{-1} (4000 fb^{-1})
$WWW \to 3\ell\, 3\nu$	0SFOS: 6.7 (7.0) 1SFOS: 1.0 (1.0) 2SFOS: 0.7 (0.7)
$WWW \to 2\ell\, 2\nu\, 2j$	$e^\pm e^\pm$: 0.8 (0.8) $e^\pm \mu^\pm$: 1.2 (1.2) $\mu^\pm \mu^\pm$: 1.8 (1.8)
$WWZ \to 4\ell\, 2\nu$	SFOS: 0.1 (0.1) DFOS: 3.0 (3.1)
$WWZ \to 3\ell\, 3\nu 2j$	0.3 (0.3)
$WZZ \to 5\ell 1\nu$	3.0 (3.4)
$WZZ \to 4\ell 2j$	0.1 (0.1)
$WZZ \to 3\ell 3\nu$	0.03 (0.03)
$WZZ \to 3\ell 1\nu 2j$	0.04 (0.04)

Expected to reach 3σ in 3000 fb^{-1} → But we did it with 137 fb^{-1}

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High multiplicity case study

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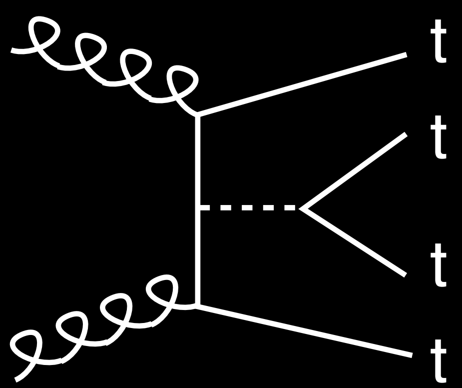
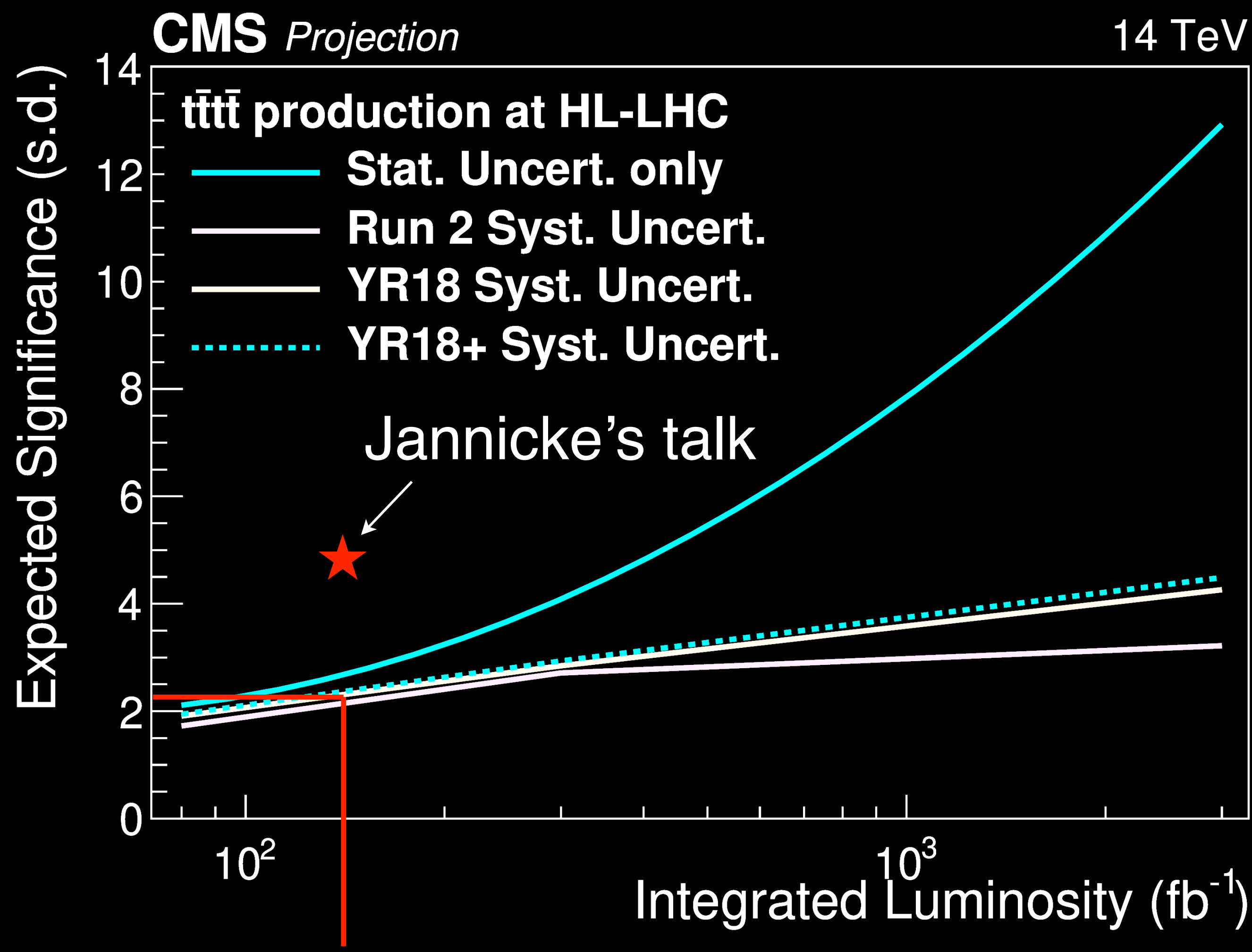


arXiv:1902.10229



Many more multi-t,W,Z,H

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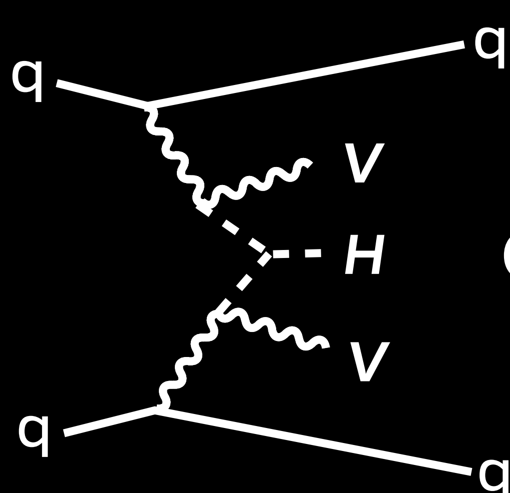
	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
	Four vector bosons					
c.21*	$pp \to W^+W^-W^+W^-$ (4f)	`p p > w+ w- w+ w-`	$5.721 \pm 0.014 \cdot 10^{-4}$	$^{+3.7\%}_{-3.5\%}$ $^{+2.3\%}_{-1.7\%}$	$9.959 \pm 0.035 \cdot 10^{-4}$	$^{+7.4\%}_{-6.0\%}$ $^{+1.7\%}_{-1.2\%}$
c.22*	$pp \to W^+W^-W^\pm Z$ (4f)	`p p > w+ w- wpm z`	$6.391 \pm 0.076 \cdot 10^{-4}$	$^{+4.4\%}_{-4.1\%}$ $^{+2.4\%}_{-1.8\%}$	$1.188 \pm 0.004 \cdot 10^{-3}$	$^{+8.4\%}_{-6.8\%}$ $^{+1.7\%}_{-1.2\%}$
c.23*	$pp \to W^+W^-W^\pm \gamma$ (4f)	`p p > w+ w- wpm a`	$8.115 \pm 0.064 \cdot 10^{-4}$	$^{+2.5\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.546 \pm 0.005 \cdot 10^{-3}$	$^{+7.9\%}_{-6.3\%}$ $^{+1.5\%}_{-1.1\%}$
c.24*	$pp \to W^+W^-ZZ$ (4f)	`p p > w+ w- z z`	$4.320 \pm 0.013 \cdot 10^{-4}$	$^{+4.4\%}_{-4.1\%}$ $^{+2.4\%}_{-1.7\%}$	$7.107 \pm 0.020 \cdot 10^{-4}$	$^{+7.0\%}_{-5.7\%}$ $^{+1.8\%}_{-1.3\%}$
c.25*	$pp \to W^+W^-Z\gamma$ (4f)	`p p > w+ w- z a`	$8.403 \pm 0.016 \cdot 10^{-4}$	$^{+3.0\%}_{-2.9\%}$ $^{+2.3\%}_{-1.7\%}$	$1.483 \pm 0.004 \cdot 10^{-3}$	$^{+7.2\%}_{-5.8\%}$ $^{+1.6\%}_{-1.2\%}$
e.13*	$pp \to t\bar{t}W^-W^+$ (4f)	`p p > t t~ w+ w-`	$6.675 \pm 0.006 \cdot 10^{-3}$	$^{+30.9\%}_{-21.9\%}$ $^{+2.1\%}_{-2.0\%}$	$9.904 \pm 0.026 \cdot 10^{-3}$	$^{+10.9\%}_{-11.8\%}$ $^{+2.1\%}_{-2.1\%}$
e.14*	$pp \to t\bar{t}W^\pm Z$	`p p > t t~ wpm z`	$2.404 \pm 0.002 \cdot 10^{-3}$	$^{+26.6\%}_{-19.6\%}$ $^{+2.5\%}_{-1.8\%}$	$3.525 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-10.8\%}$ $^{+2.3\%}_{-1.6\%}$
e.15*	$pp \to t\bar{t}W^\pm \gamma$	`p p > t t~ wpm a`	$2.718 \pm 0.003 \cdot 10^{-3}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.3\%}_{-1.8\%}$	$3.927 \pm 0.013 \cdot 10^{-3}$	$^{+10.3\%}_{-10.4\%}$ $^{+2.0\%}_{-1.5\%}$
e.16*	$pp \to t\bar{t}ZZ$	`p p > t t~ z z`	$1.349 \pm 0.014 \cdot 10^{-3}$	$^{+29.3\%}_{-21.1\%}$ $^{+1.7\%}_{-1.5\%}$	$1.840 \pm 0.007 \cdot 10^{-3}$	$^{+7.9\%}_{-9.9\%}$ $^{+1.7\%}_{-1.5\%}$
e.17*	$pp \to t\bar{t}Z\gamma$	`p p > t t~ z a`	$2.548 \pm 0.003 \cdot 10^{-3}$	$^{+30.1\%}_{-21.5\%}$ $^{+1.7\%}_{-1.6\%}$	$3.656 \pm 0.012 \cdot 10^{-3}$	$^{+9.7\%}_{-11.0\%}$ $^{+1.8\%}_{-1.9\%}$
g.12*	$pp \to HW^+W^-$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^\pm \gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^\pm$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$

O(1fb)

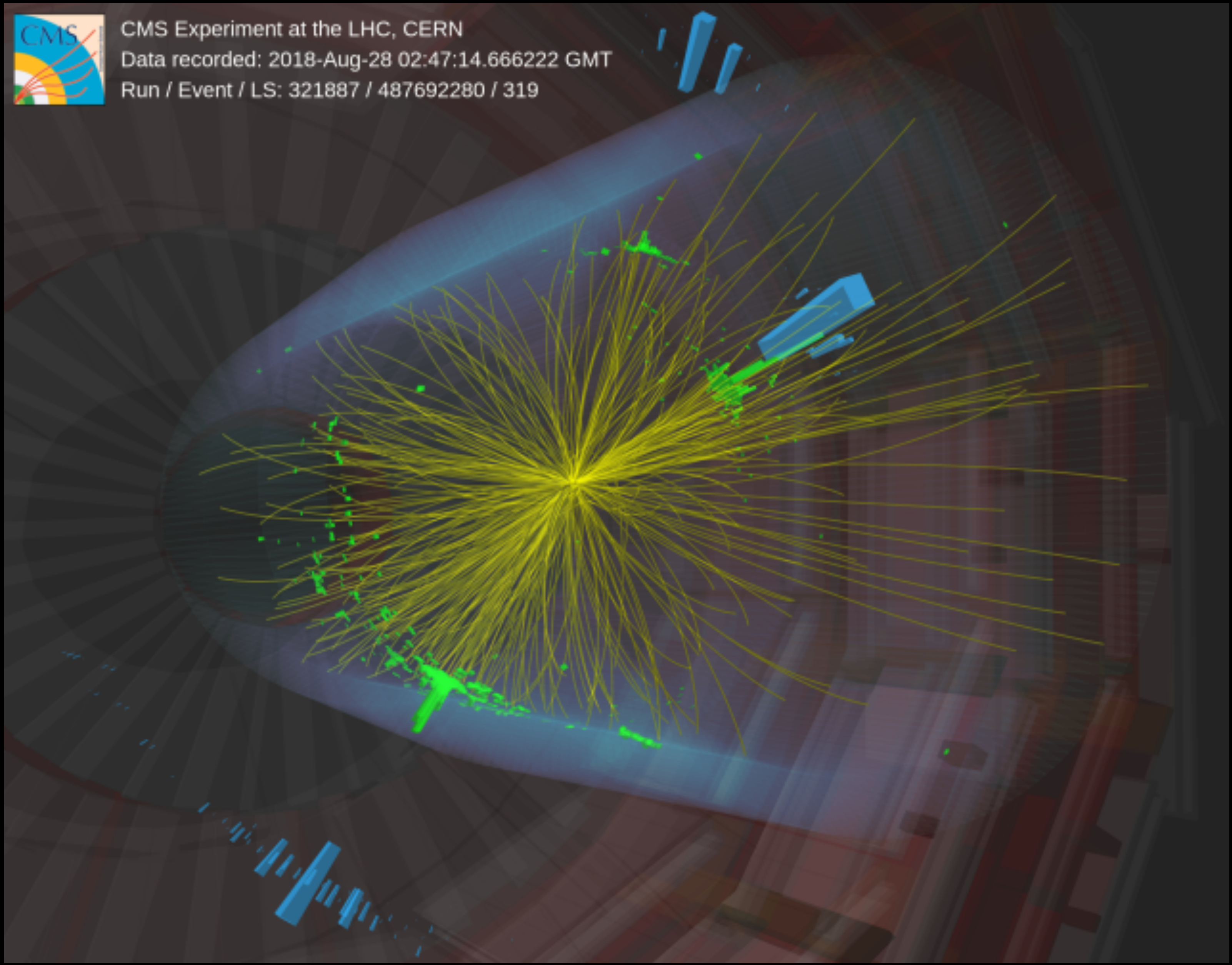


O(1fb)

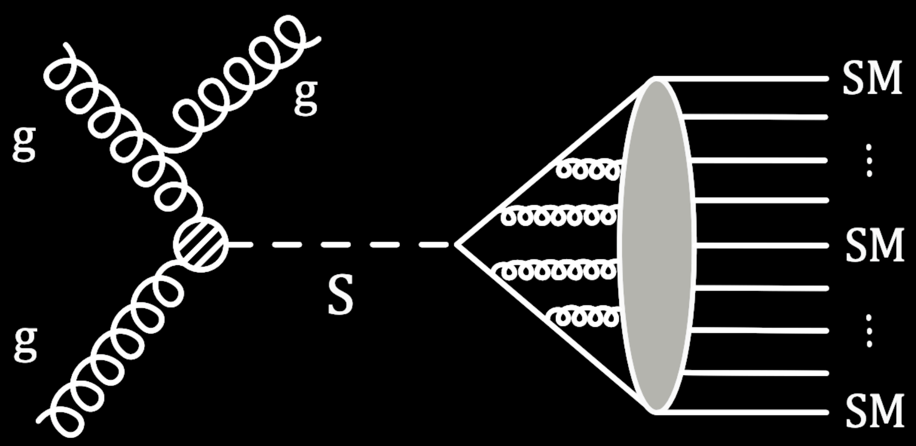
These phase-space would be possible to study

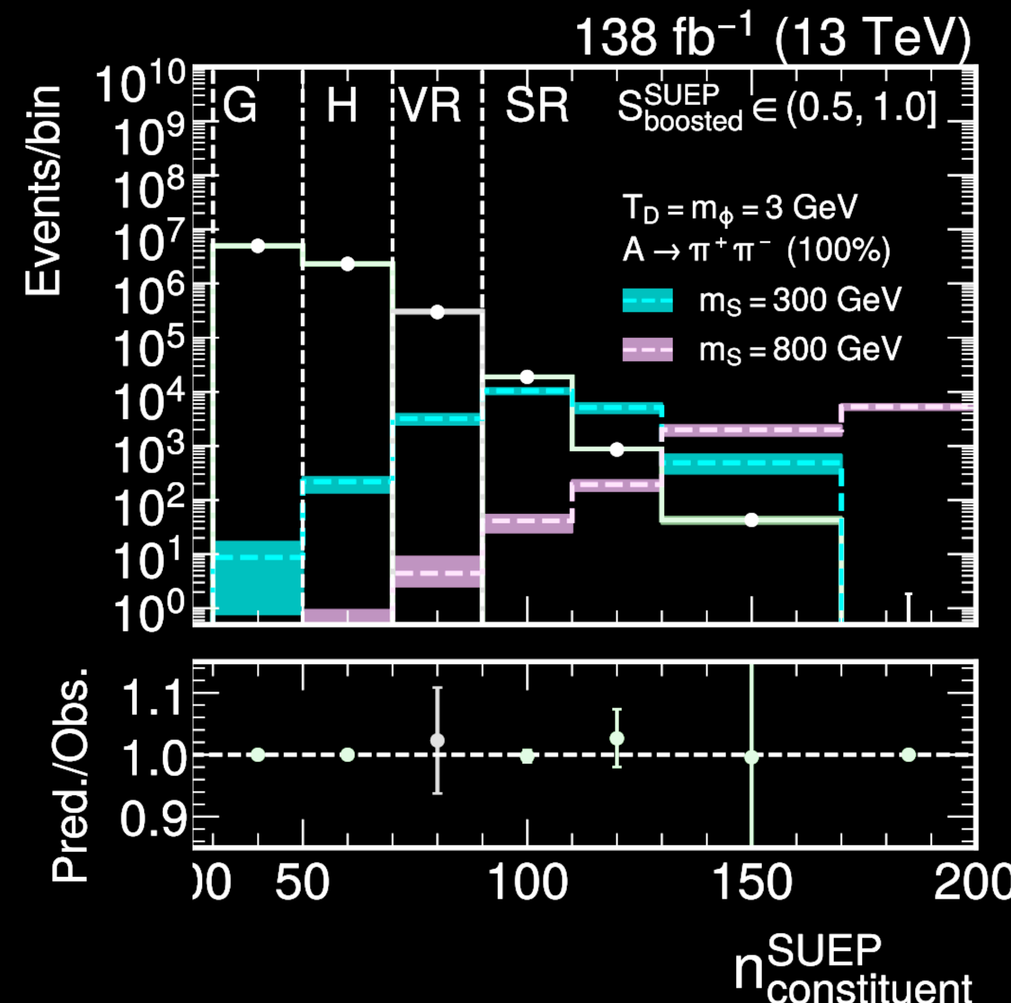
Pushing multiplicites even further

soft unclustered energy pattern (SUEP)



Pushing multiplicites even further





Pushing lifetime

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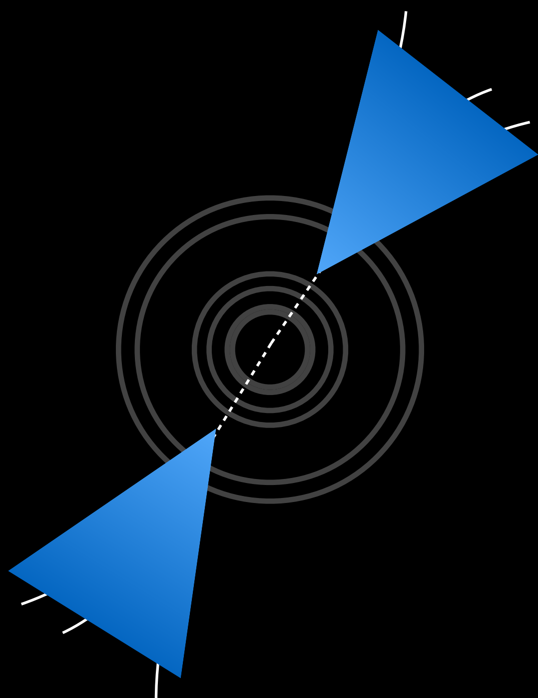
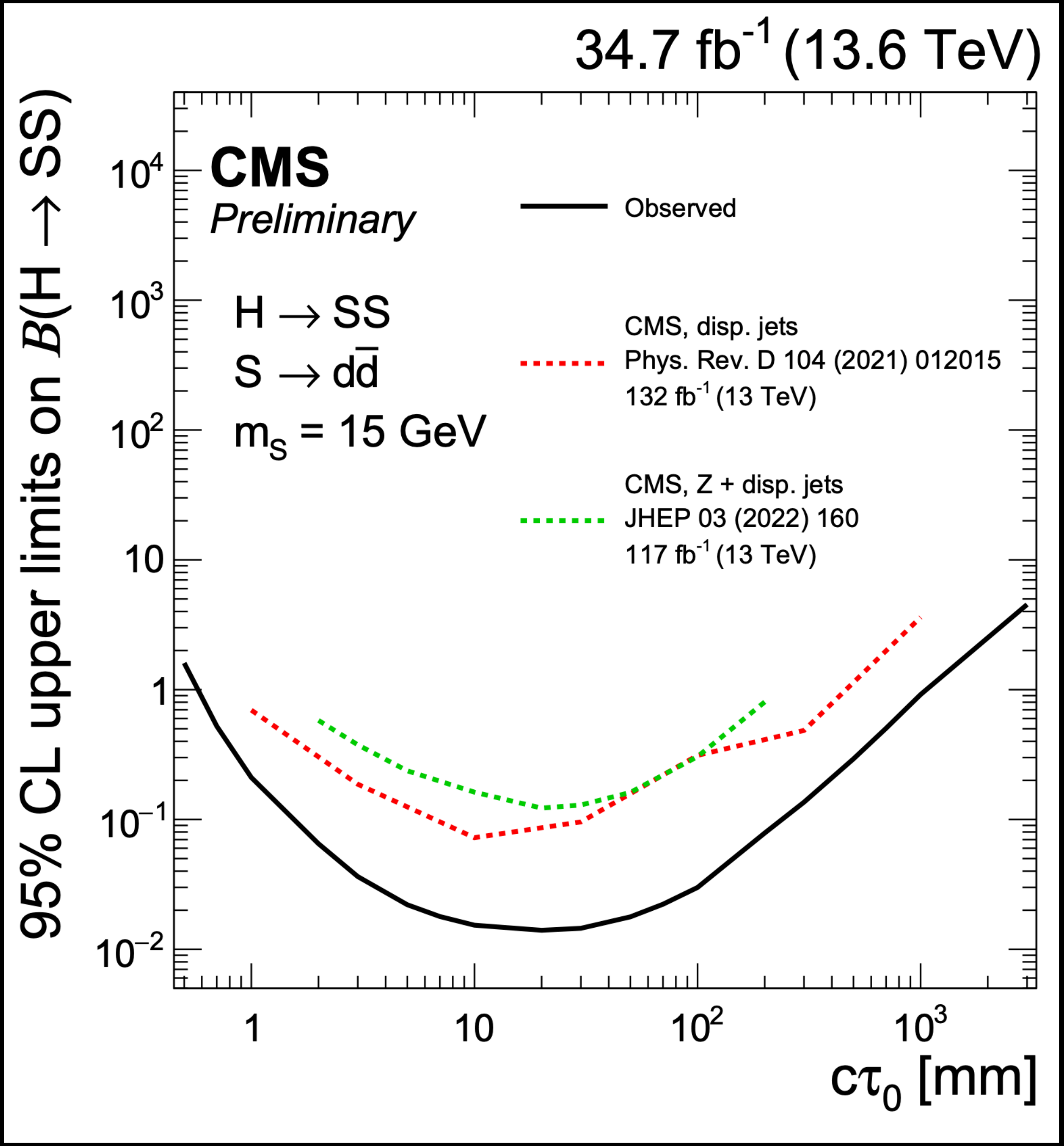
displaced di-jet





https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-23-013/index.html

Pushing “Angles”

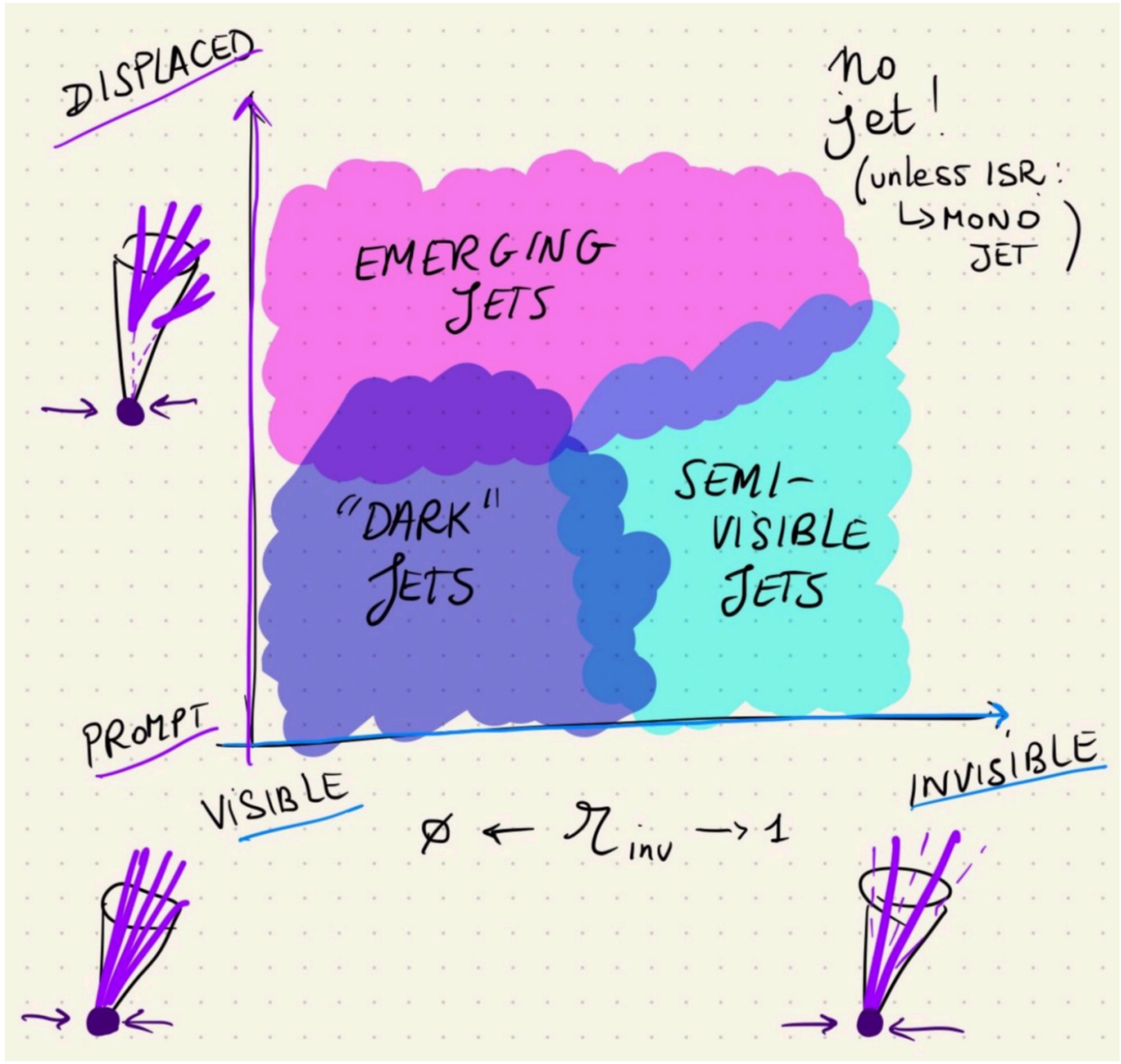


Image C. Doglioni

Many jets

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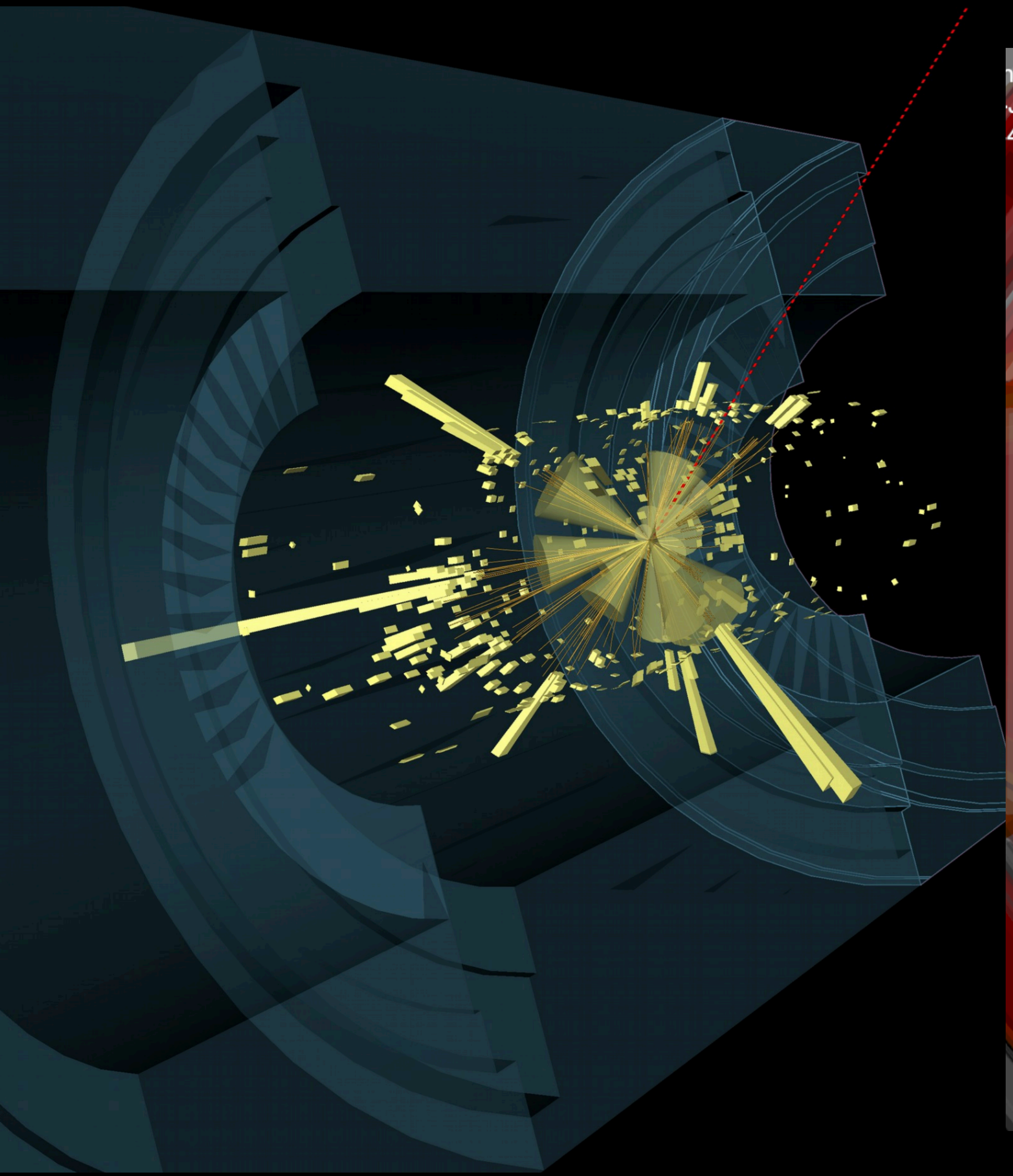

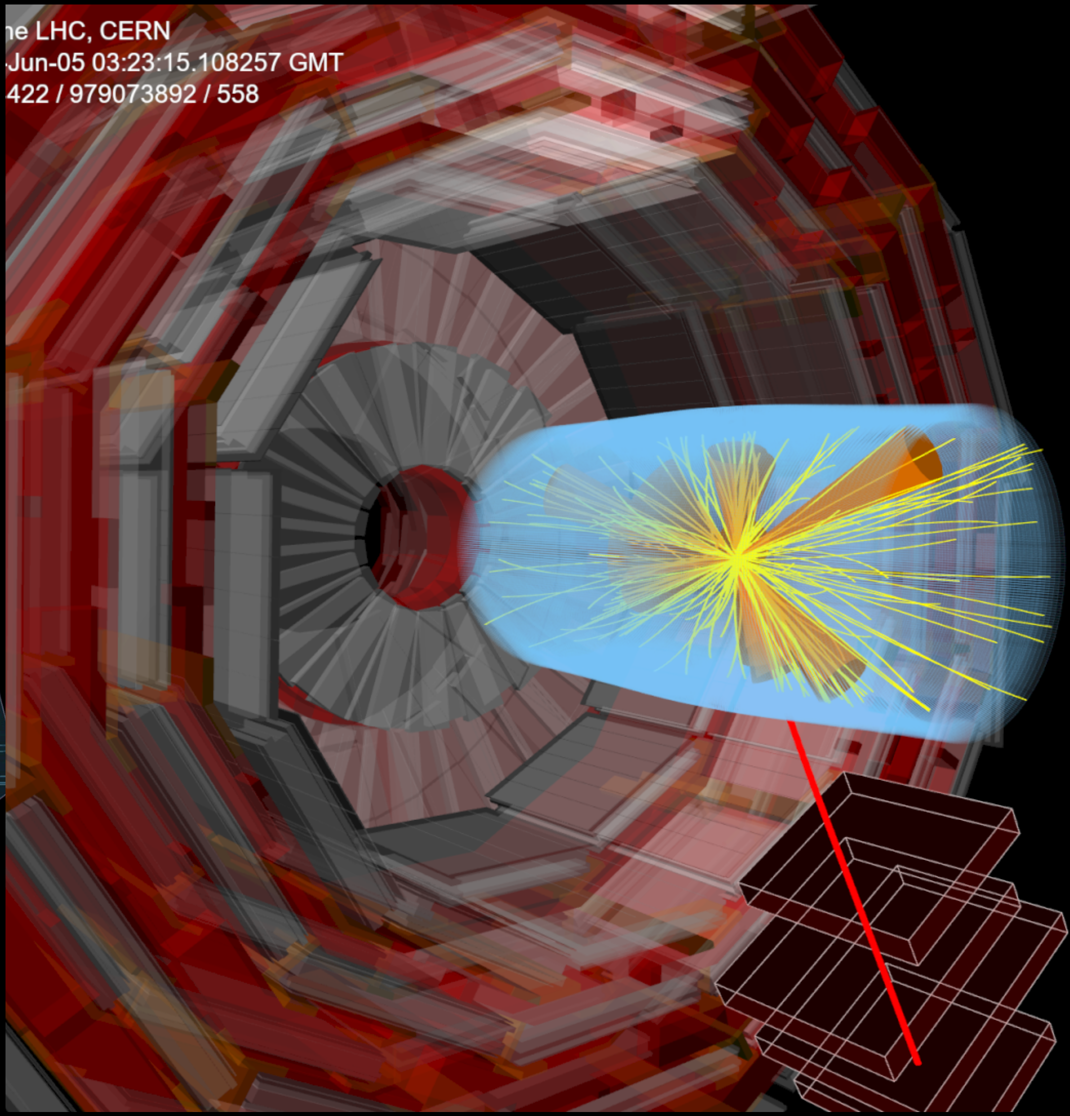

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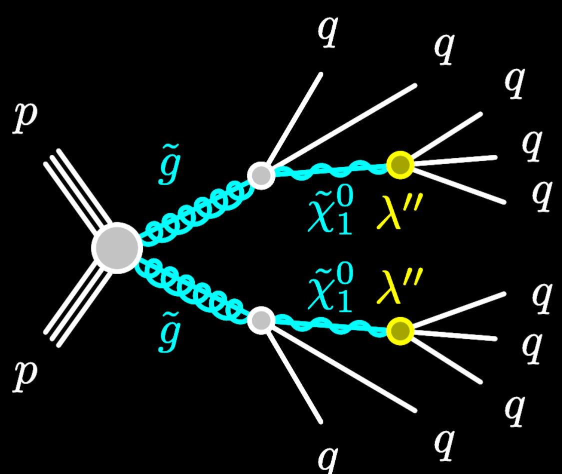
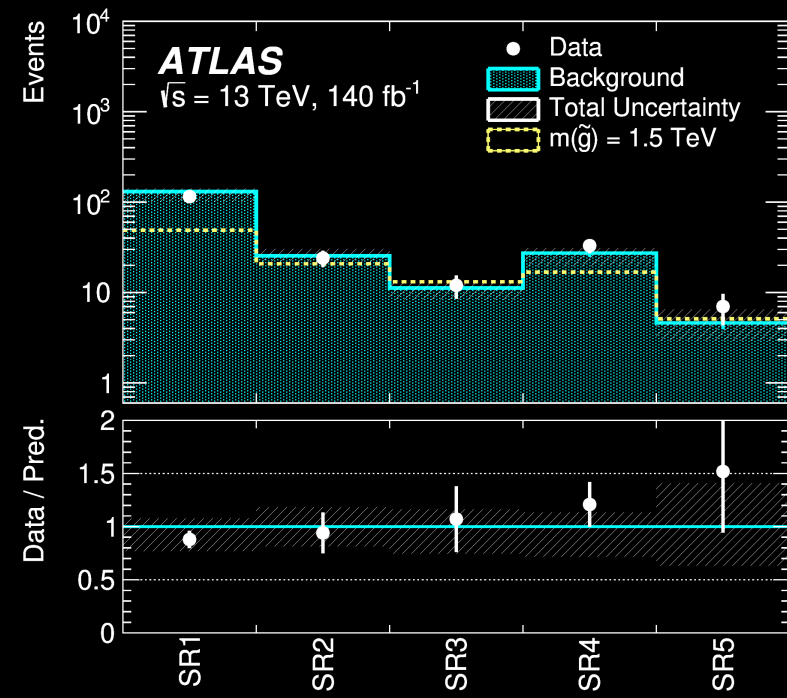
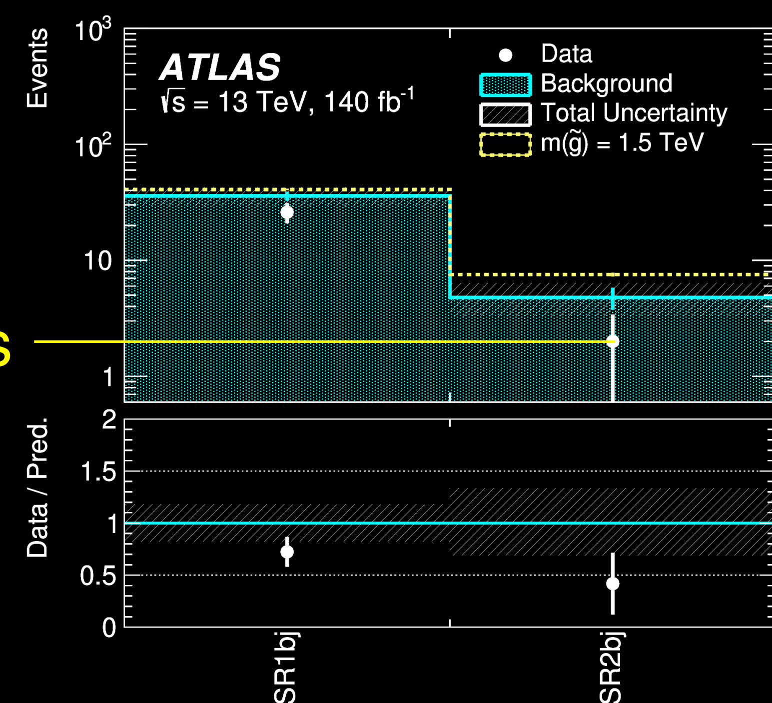
Many jets



	n_{jets}	$p_T(j)$ [GeV]	C	$n_{b-\text{jets}}$
SR1	≥ 7	≥ 180	≥ 0.90	–
SR2	≥ 7	≥ 220	≥ 0.90	–
SR3	≥ 7	≥ 240	≥ 0.90	–
SR4	≥ 8	≥ 180	≥ 0.85	–
SR5	≥ 8	≥ 210	≥ 0.85	–
SR1bj	≥ 7	≥ 180	≥ 0.85	≥ 2
SR2bj	≥ 8	≥ 180	≥ 0.85	≥ 2



2 events



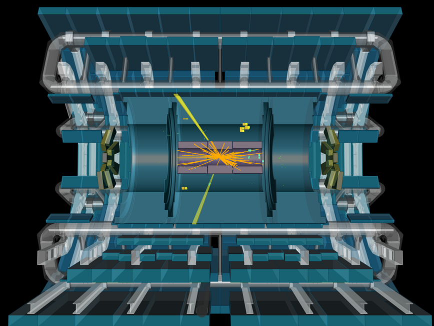
It did not use mass because too little evt. but in HL-LHC you could

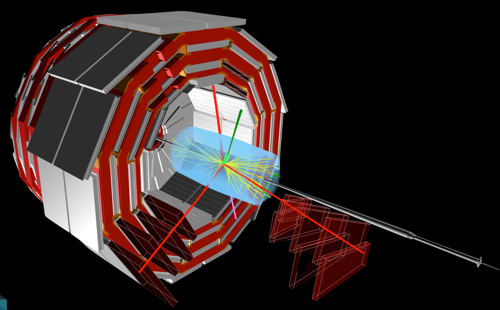
Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

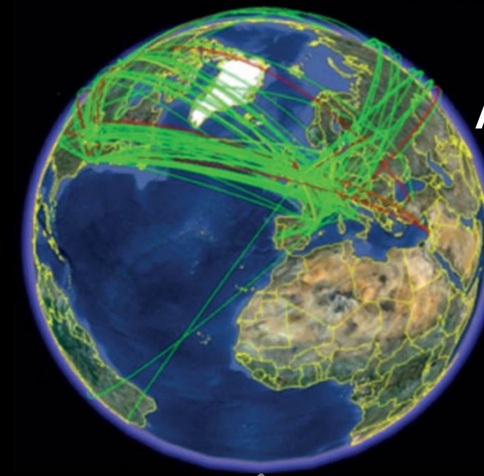
Carl D. Anderson and Seth H. Neddermeyer, *Norman Bridge Laboratory of Physics, California Institute of Technology*
(Received June 9, 1936)

Observations of N same-charged lepton events ($\ell^\pm\ell^\pm\ell^\pm$,$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$,…) ?

Go down deeper into the weeds



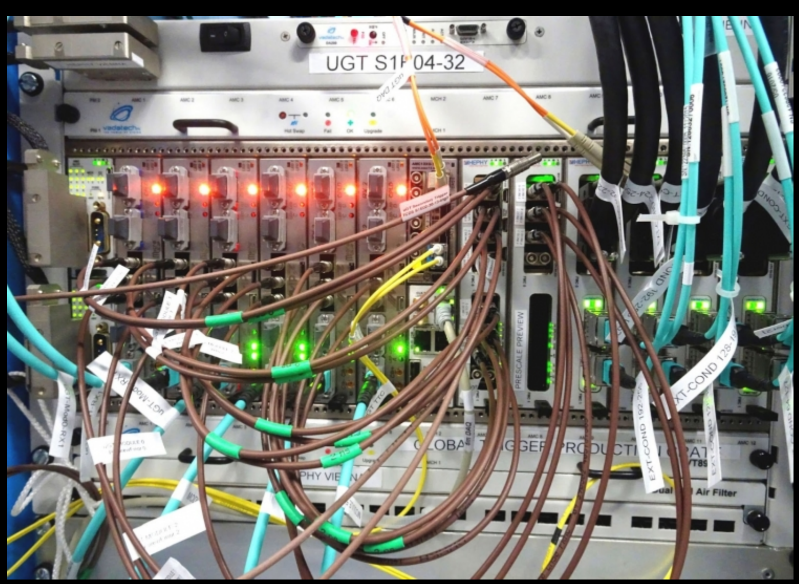




Analysis

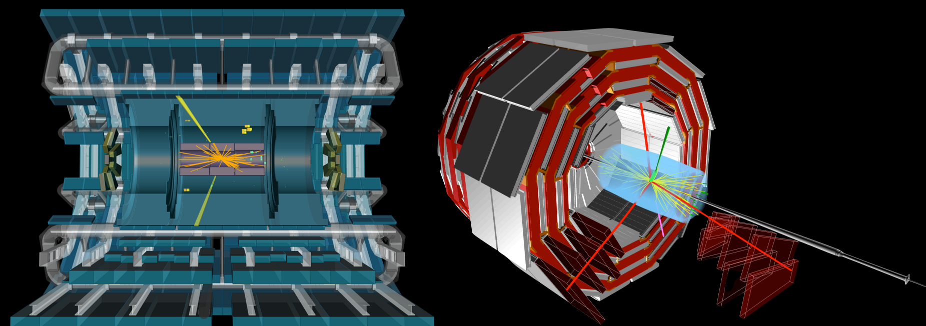
40 MHz

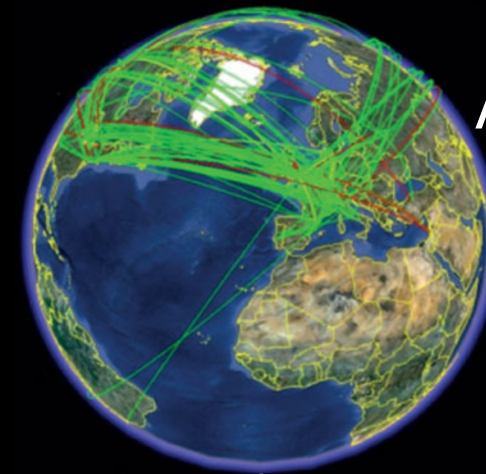
1 kHz



100 kHz

Go down deeper into the weeds



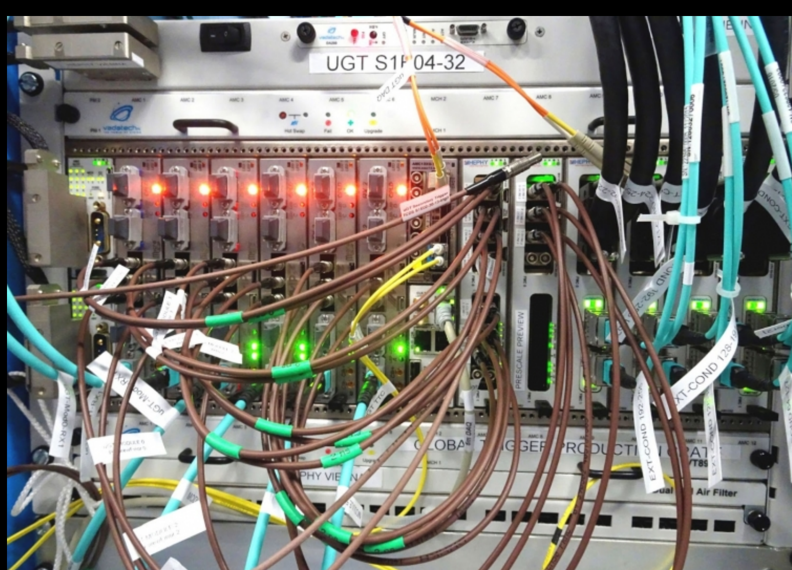


Analysis

40 MHz

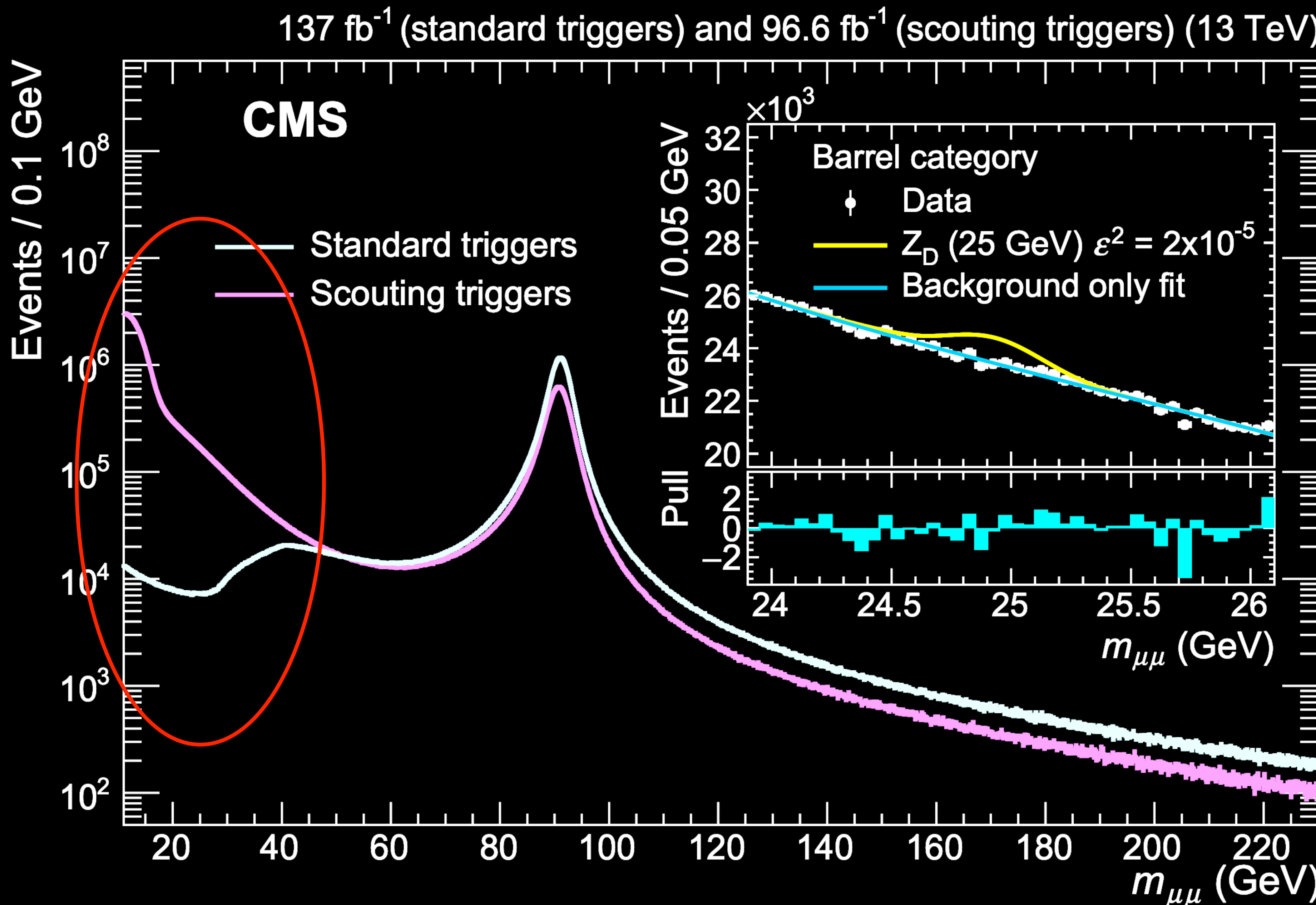
***40,000x events lost
we don't get to analyze
them in details***

1 kHz

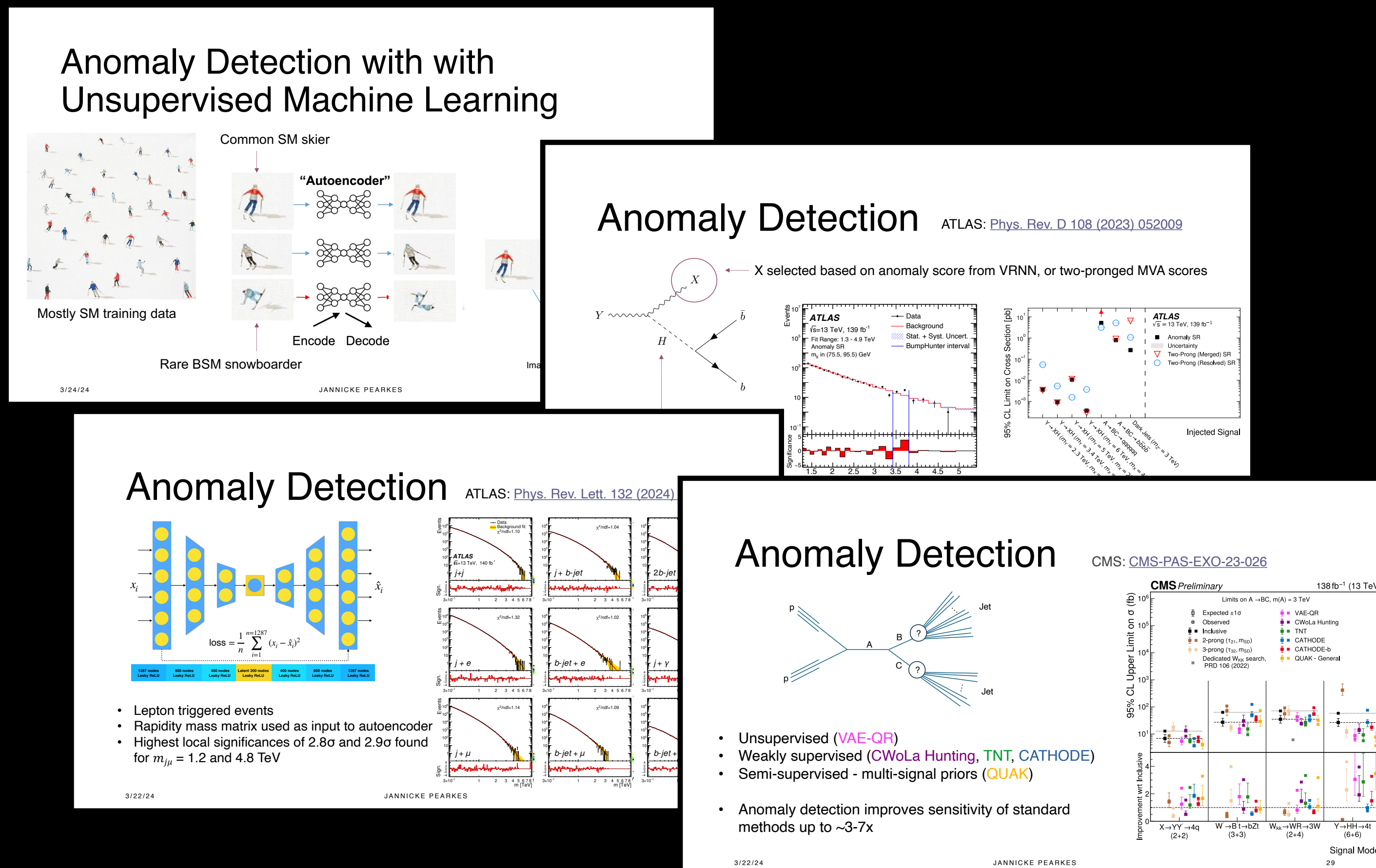


100 kHz

Go down deeper into the weeds



Anomaly detection



See Jannicke's slides

But what if you still….

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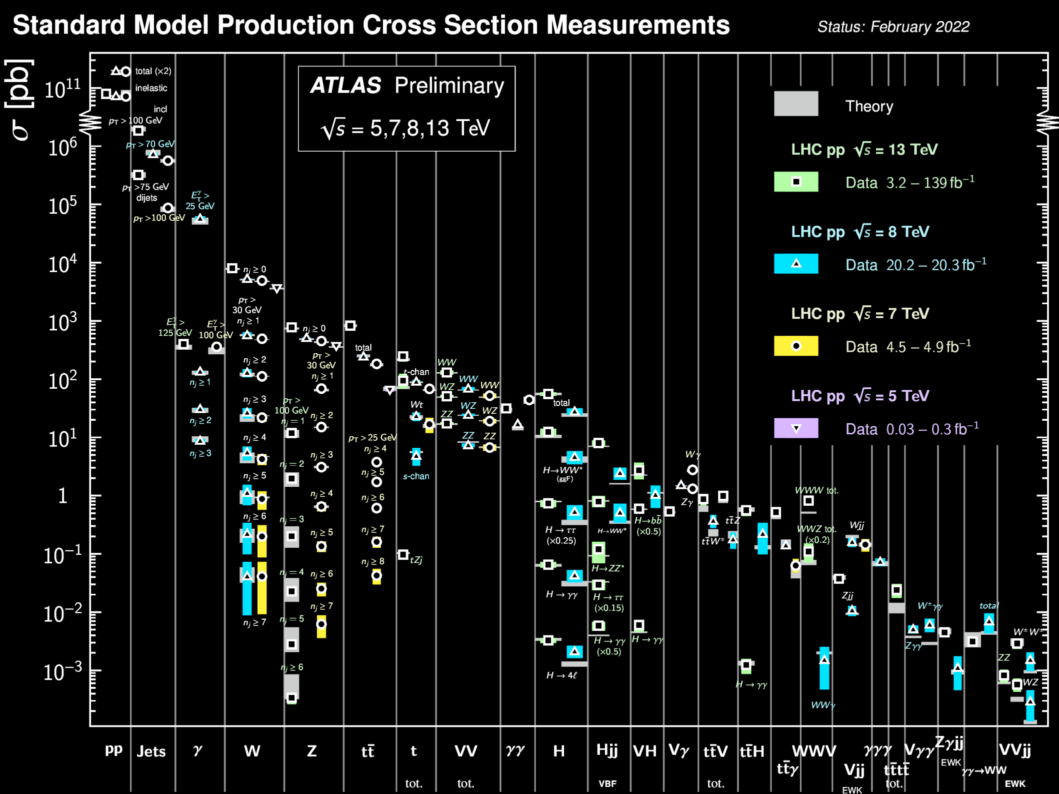
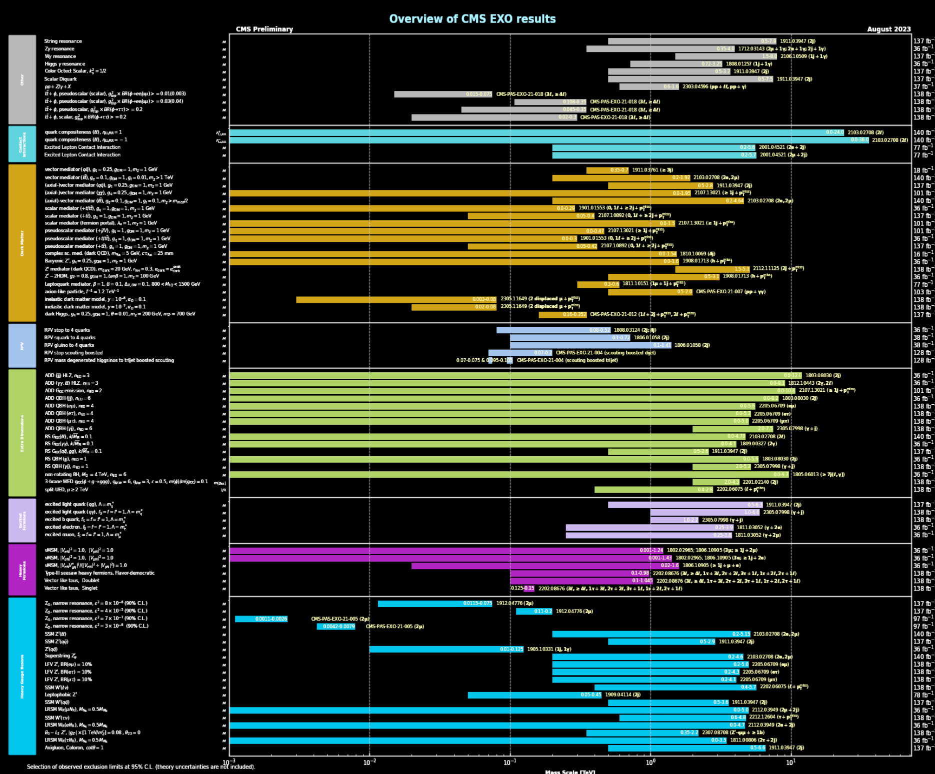
Measurement



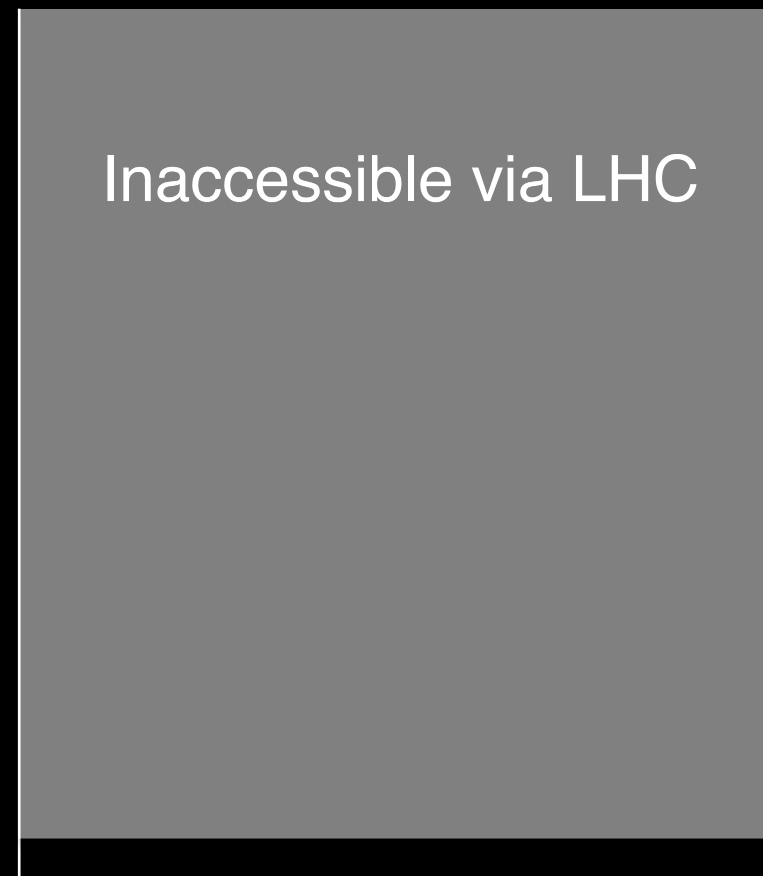
No crack

Searches



No excess

Effective Field Theory



Effective Field Theory

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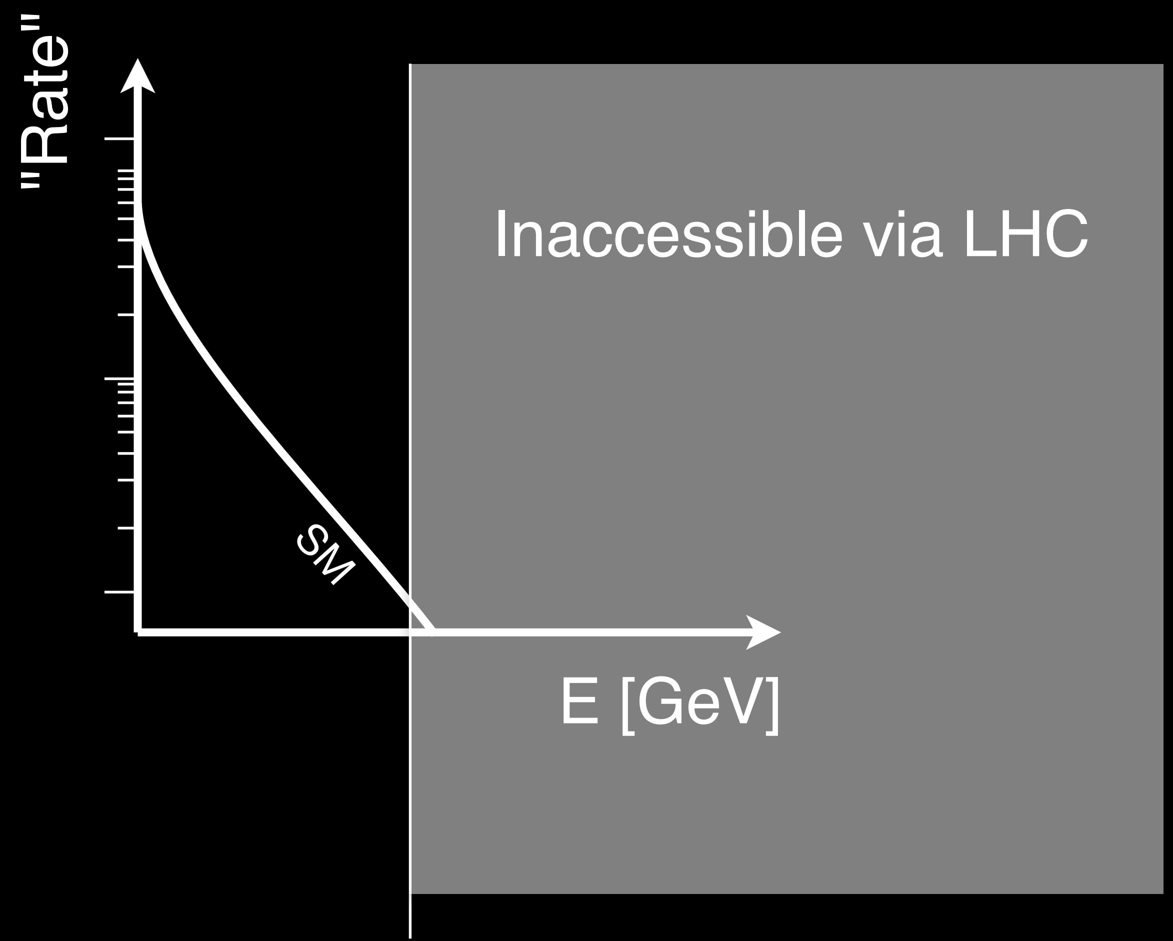
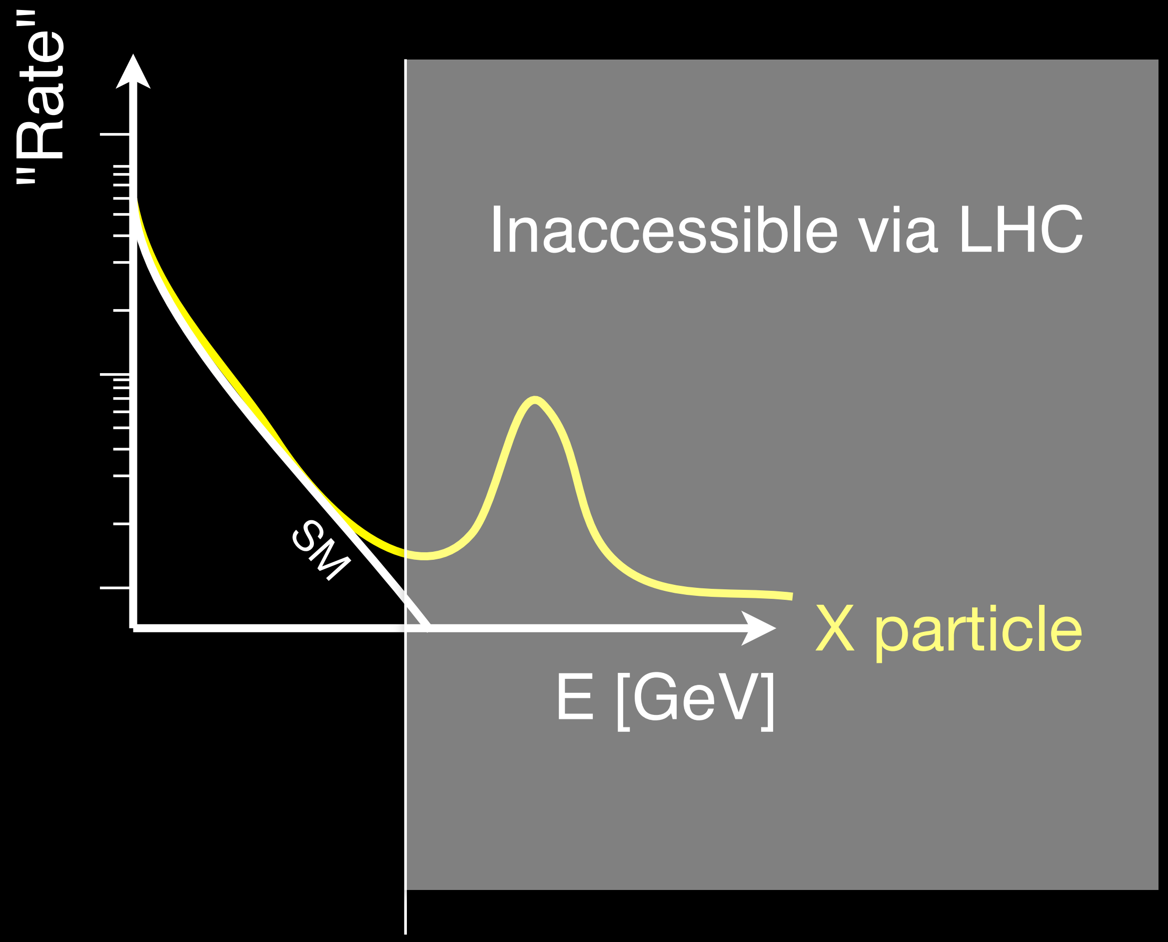
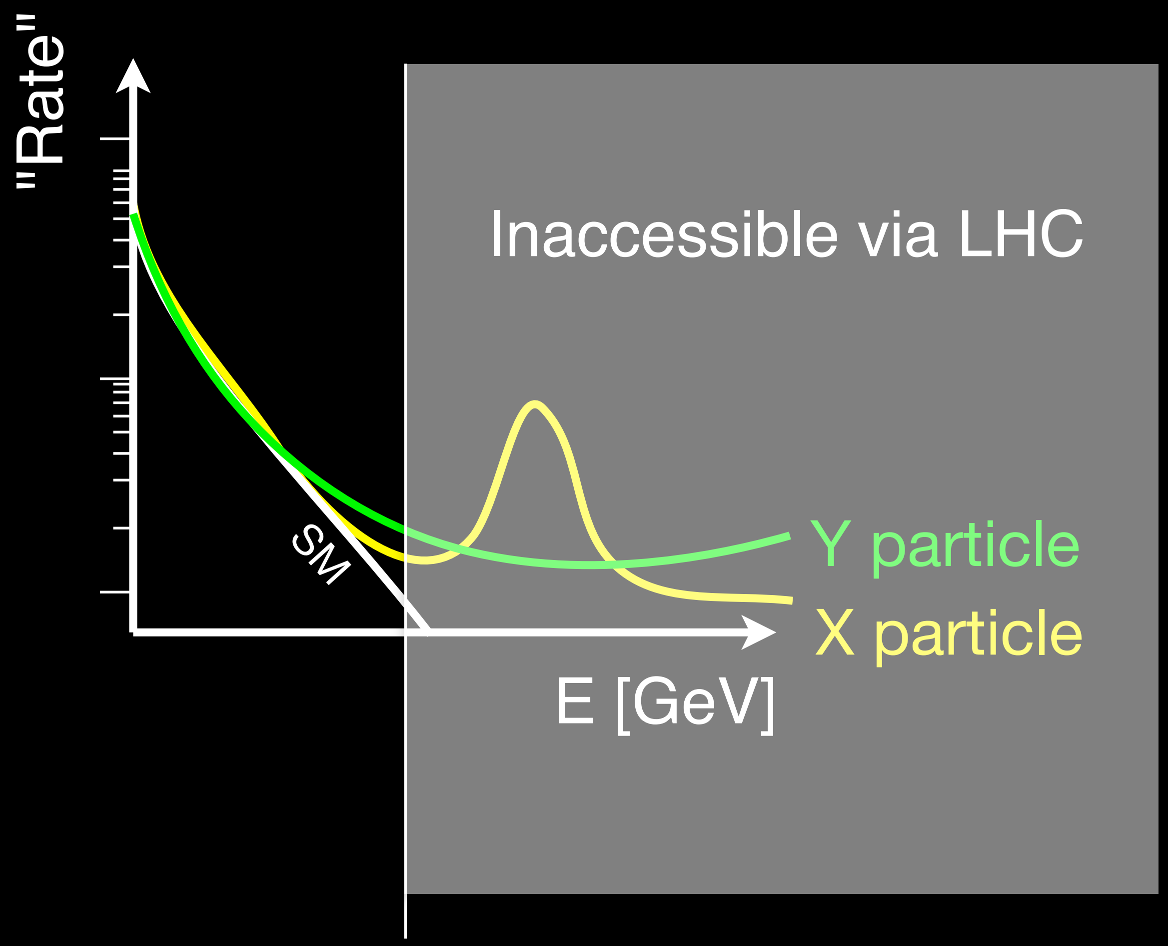


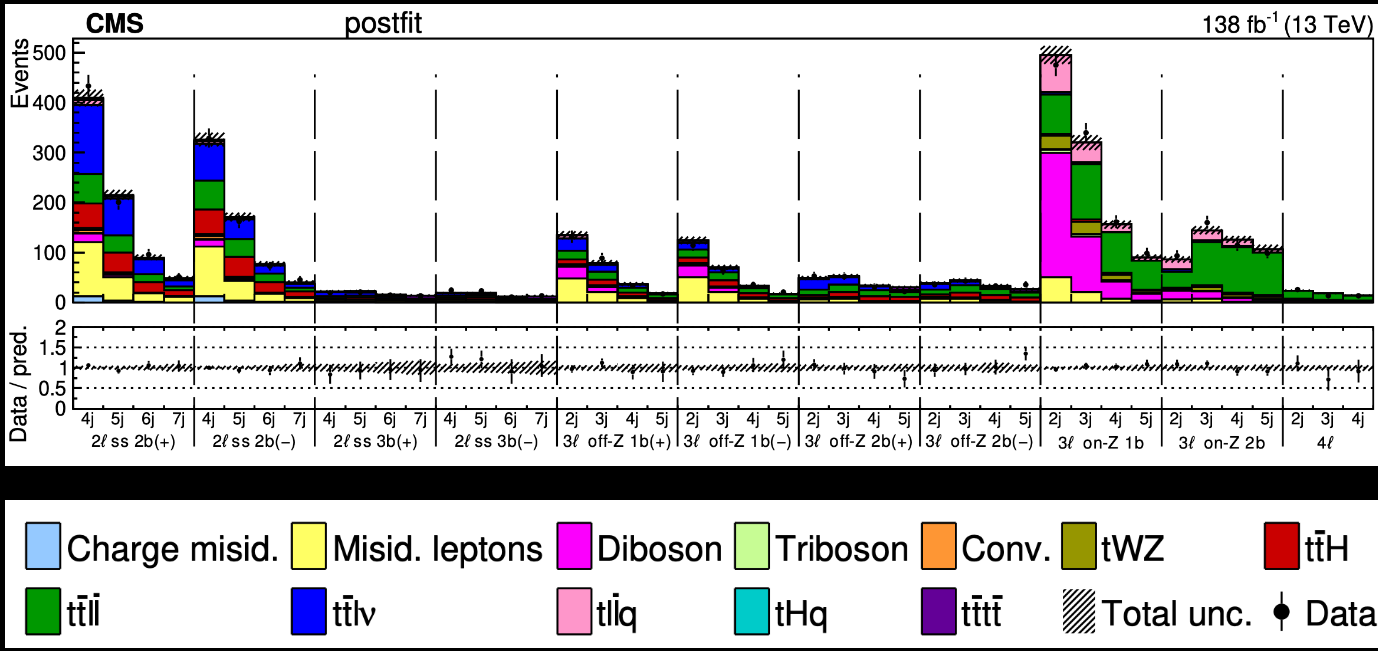
Effective Field Theory

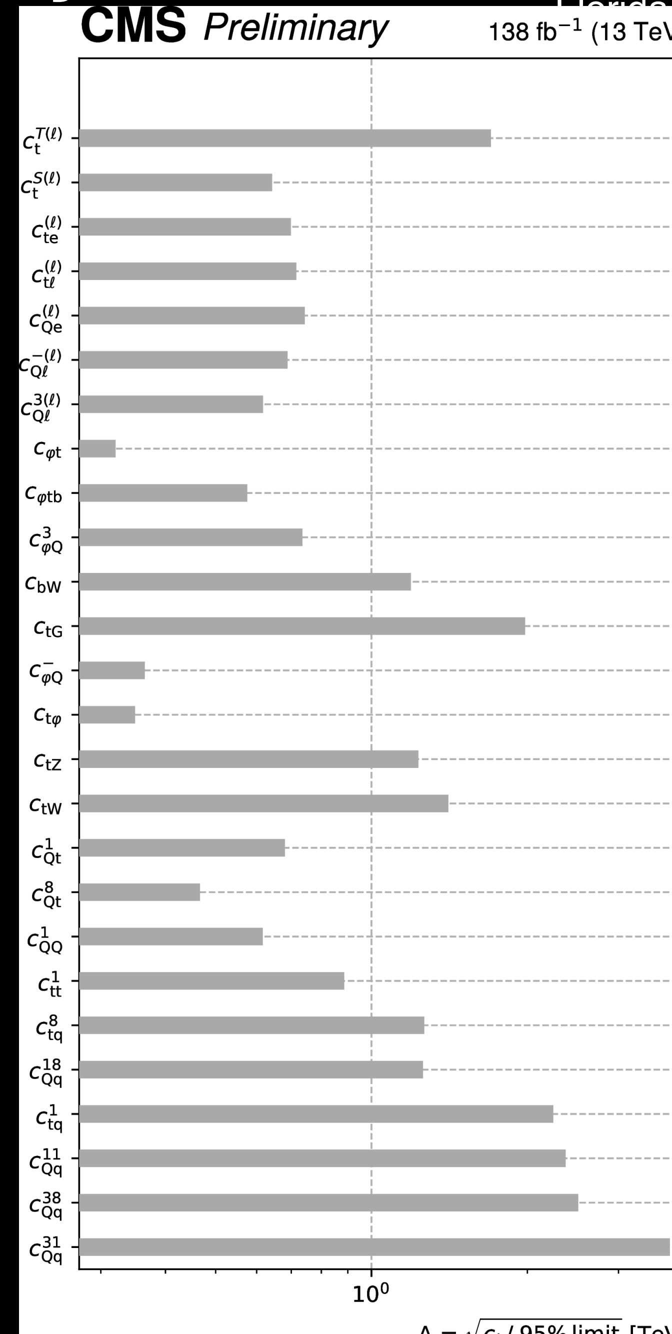


Effective Field Theory



Effective Field Theory

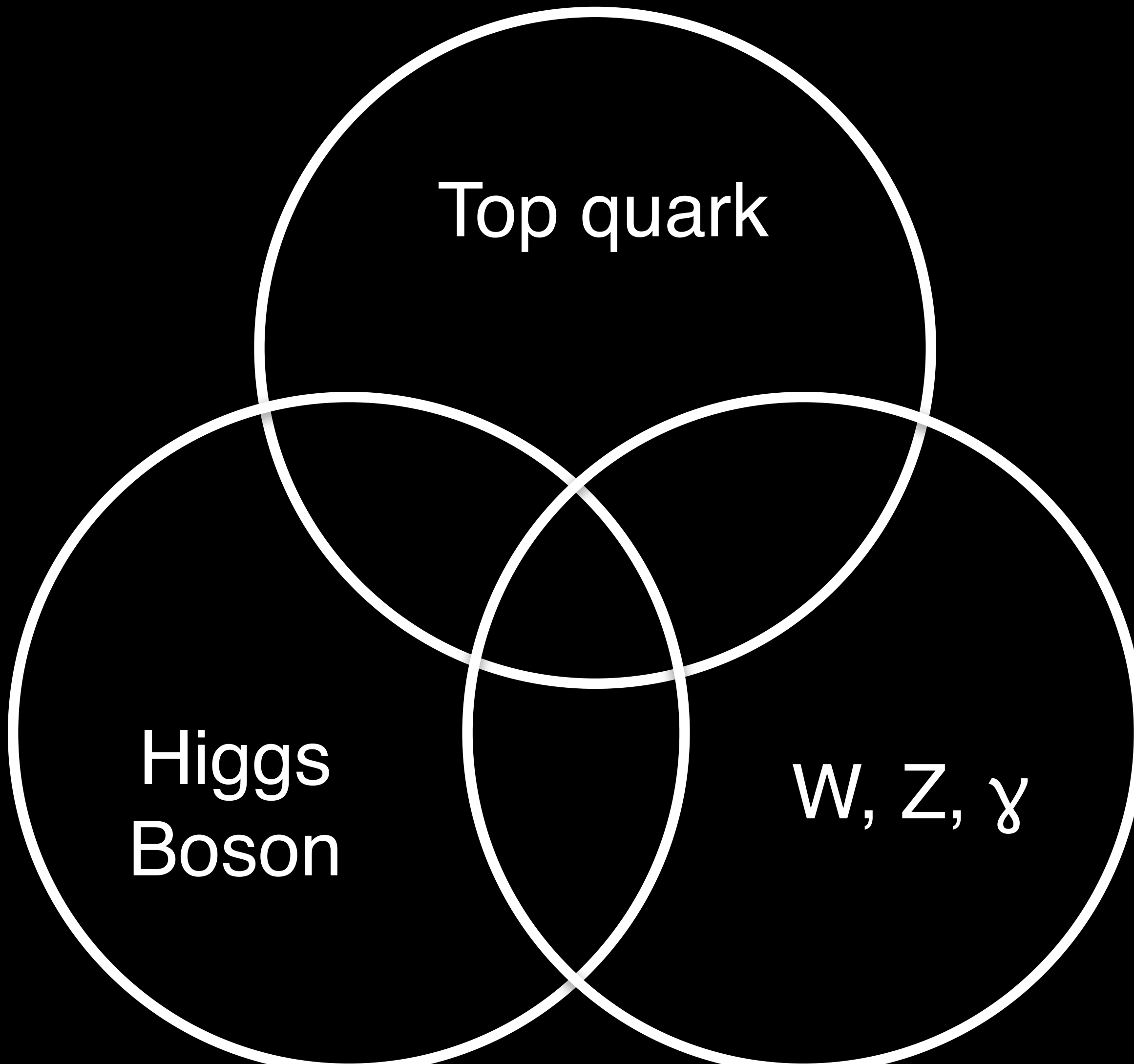




$$L_{EFT} = L_{SM} + \sum \frac{c_i}{\Lambda^2} O_{i,dim6} + \ldots$$

Global combination to interpret comprehensively for possible new physics (Including all sectors)

Interpretation



Remarkable collaborations

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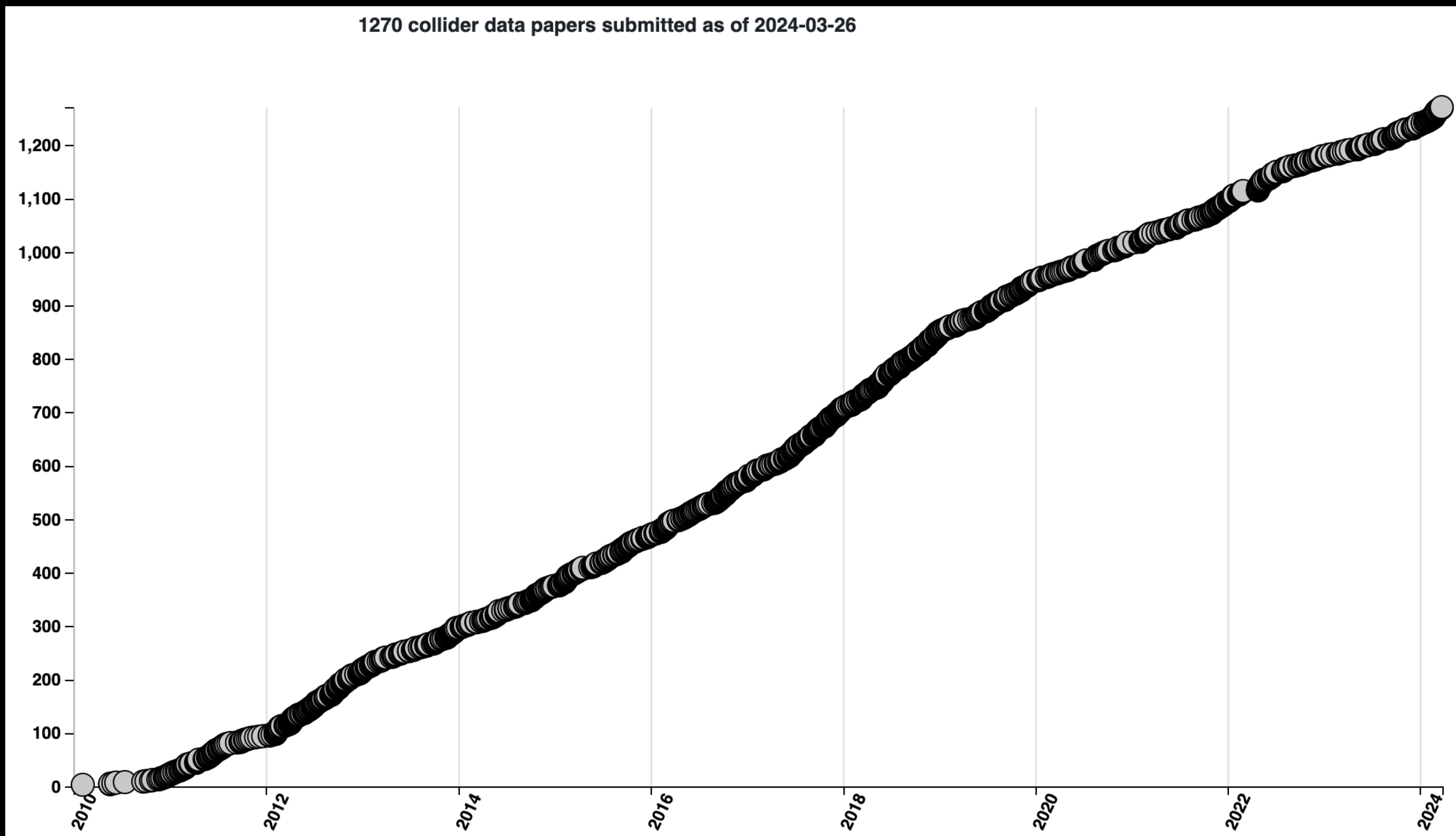

1270 CMS
1278 ATLAS

Diverse particle physics topics being covered by general purpose detector experiments

Summary

<u>We are in an experimental driven discovery era</u>

Many phase-space boundaries are still being pushed and we are expanding frontiers