

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

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

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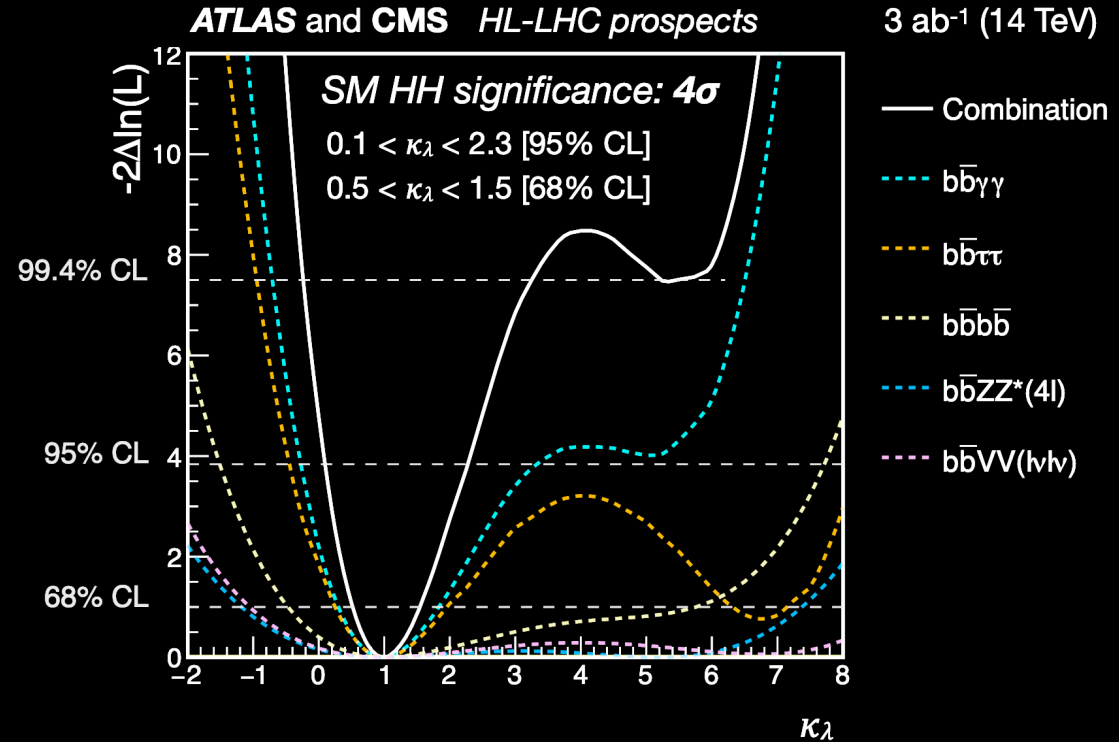
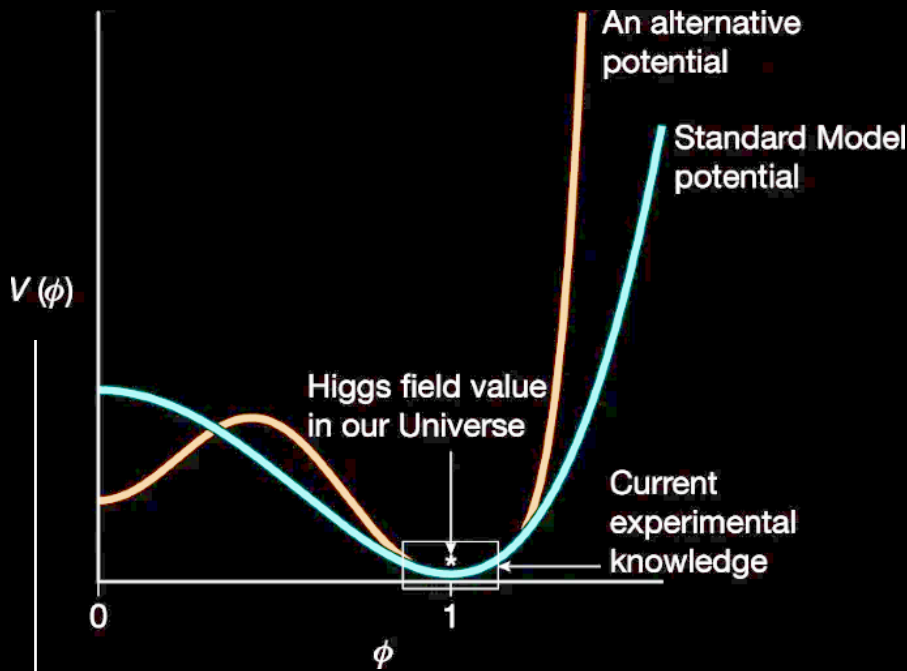
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1325 pages long

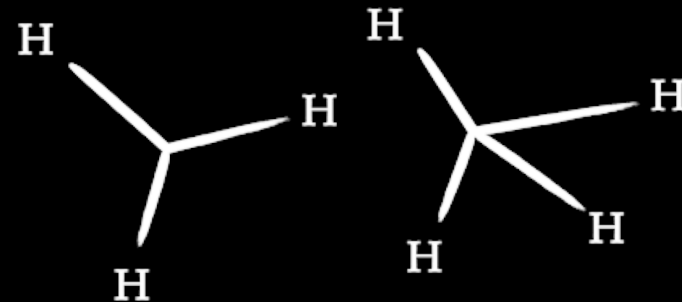
Spotlight

Tri-linear Higgs Couplings

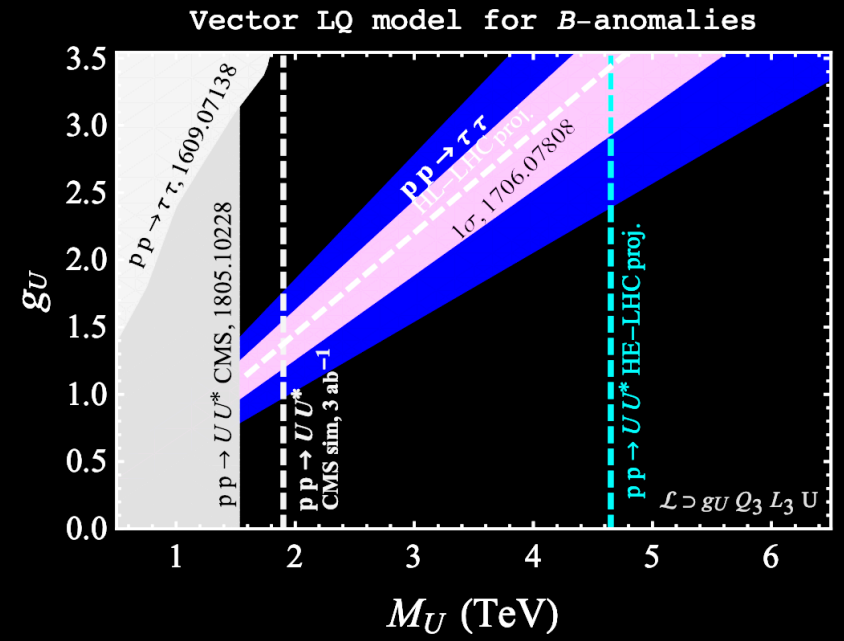
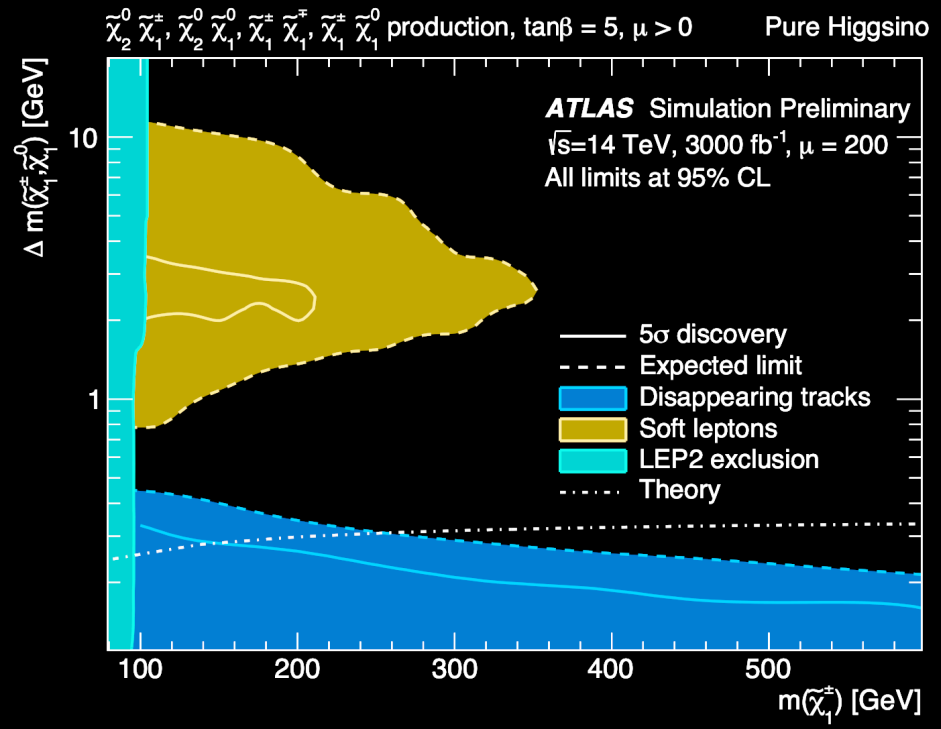
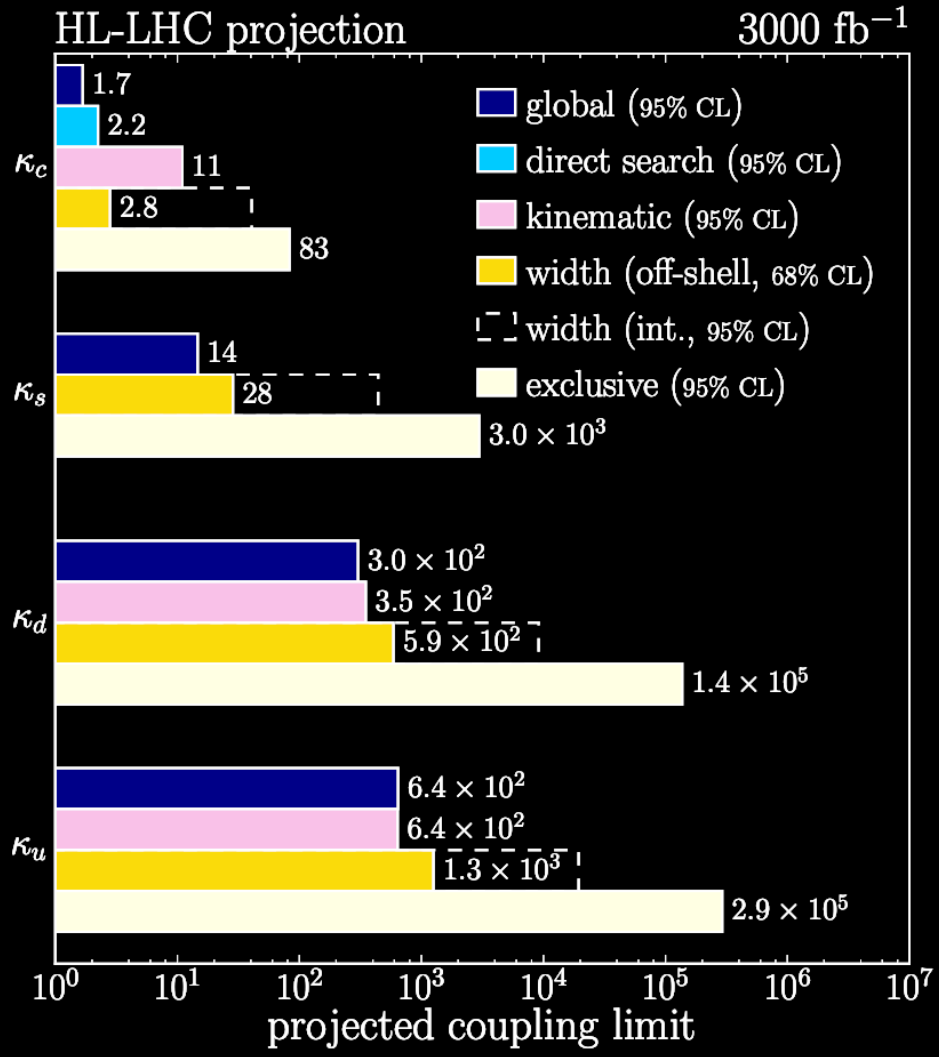
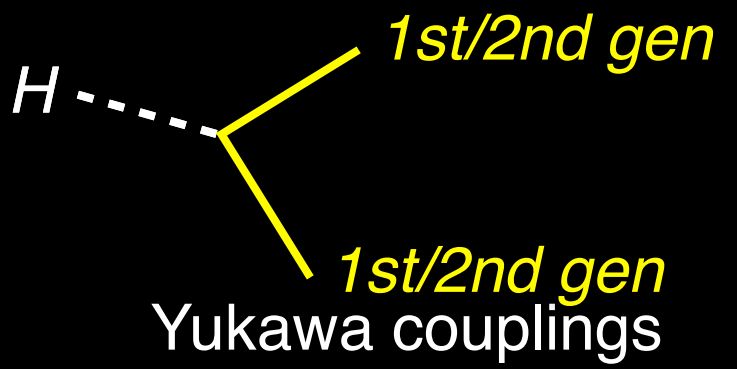
<https://www.nature.com/articles/s41586-022-04899-4>



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



Higgsino / Dark Matter



*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 opportunities in LHC future

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I cover some examples, indicative of my personal preference

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I did not cover all owing to lack of time

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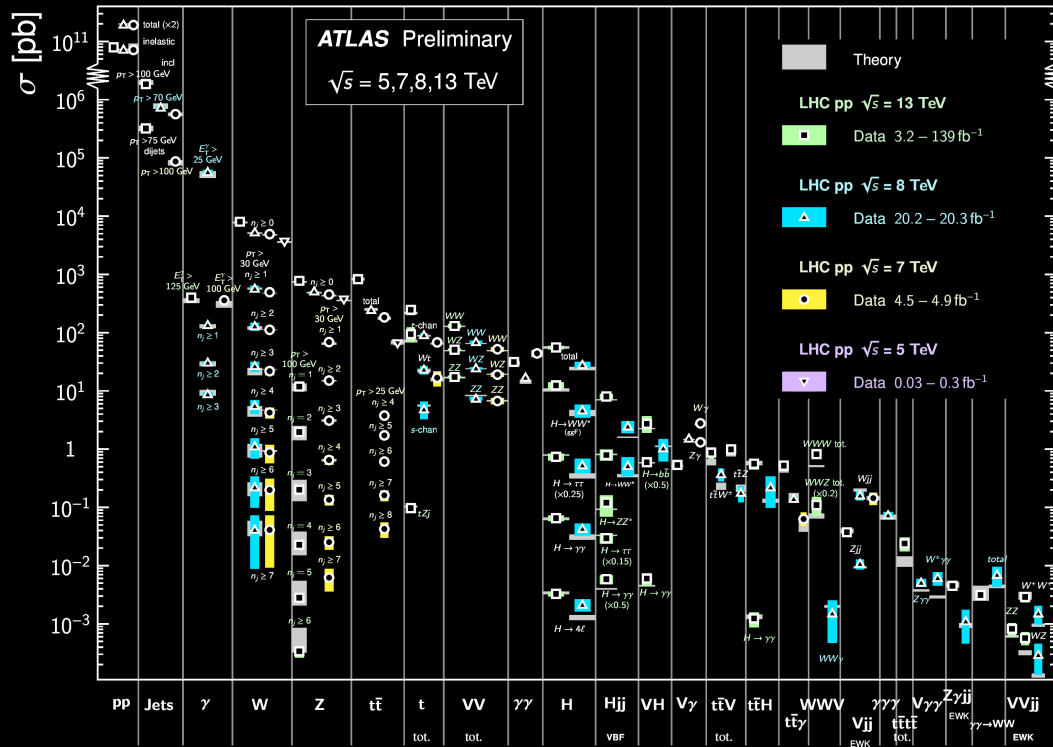
But largely I am gonna talk about my view...

Where we are now

Measurement

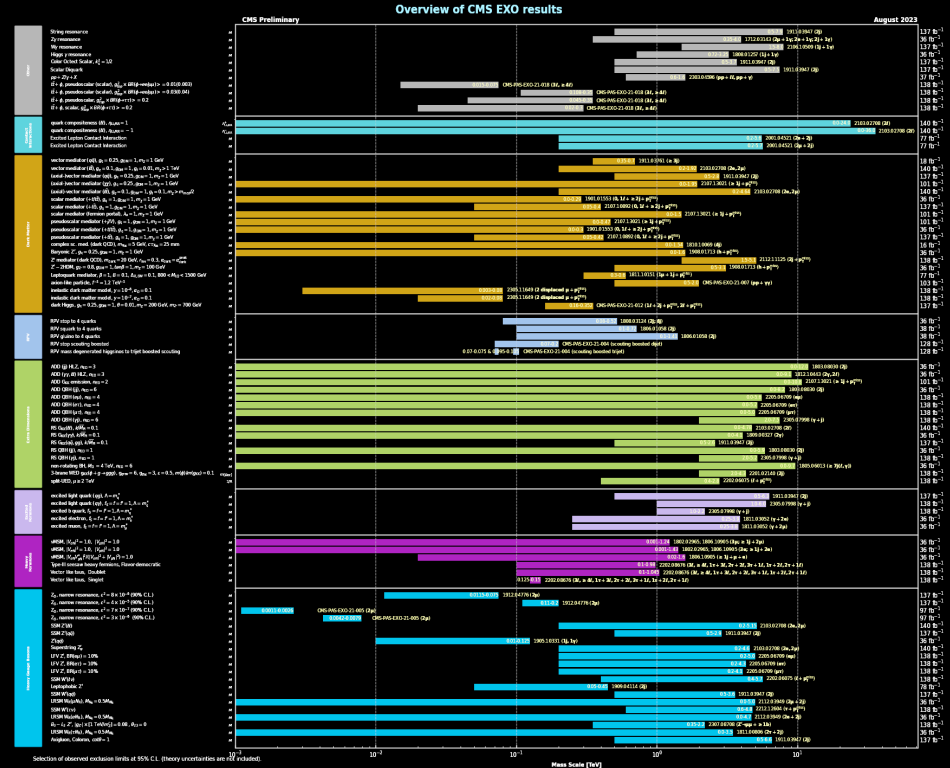
Standard Model Production Cross Section Measurements

Status: February 2022



No crack

Searches

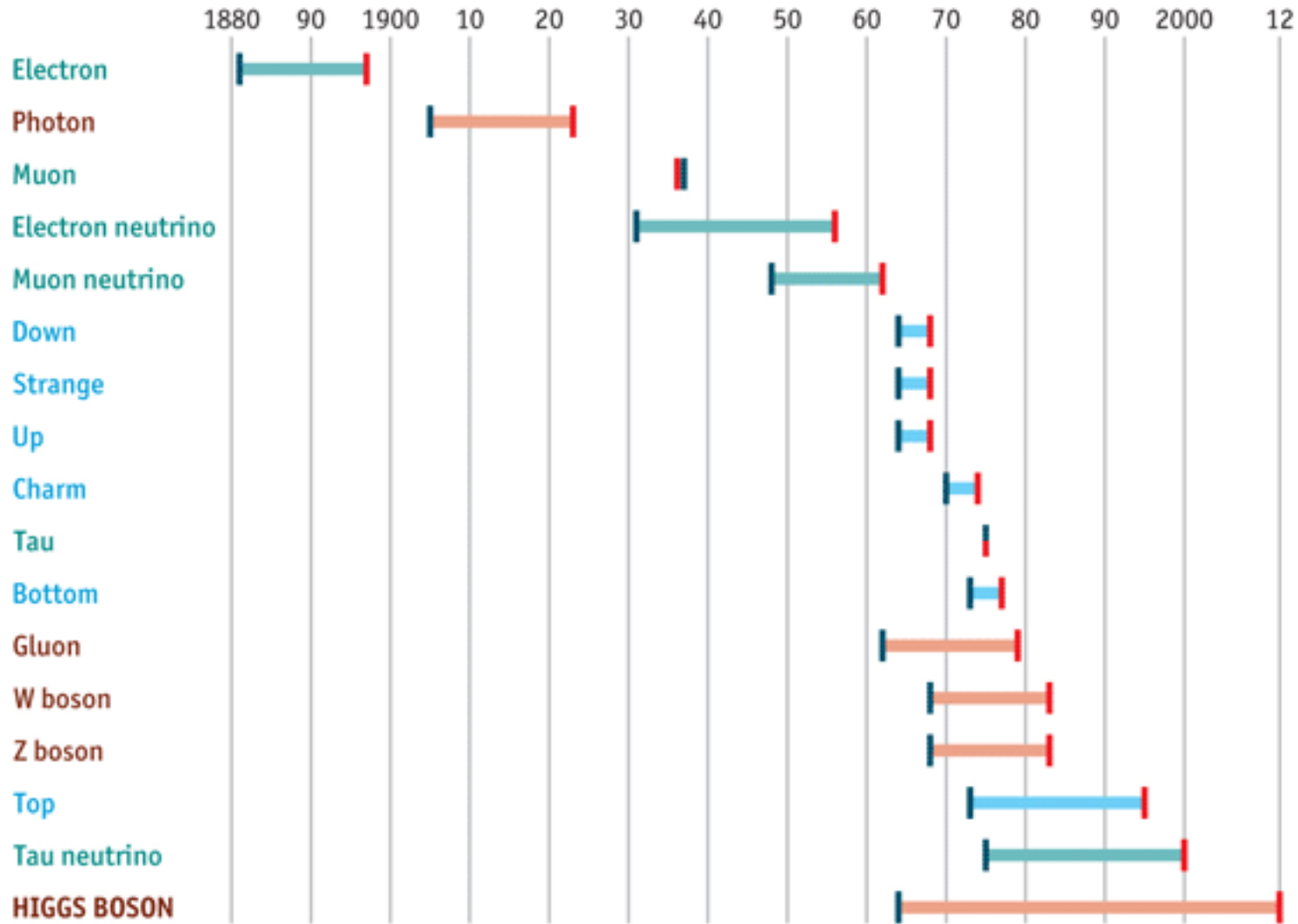


No excess

No significant deviations from SM

The Standard Model of particle physics

Years from concept to discovery



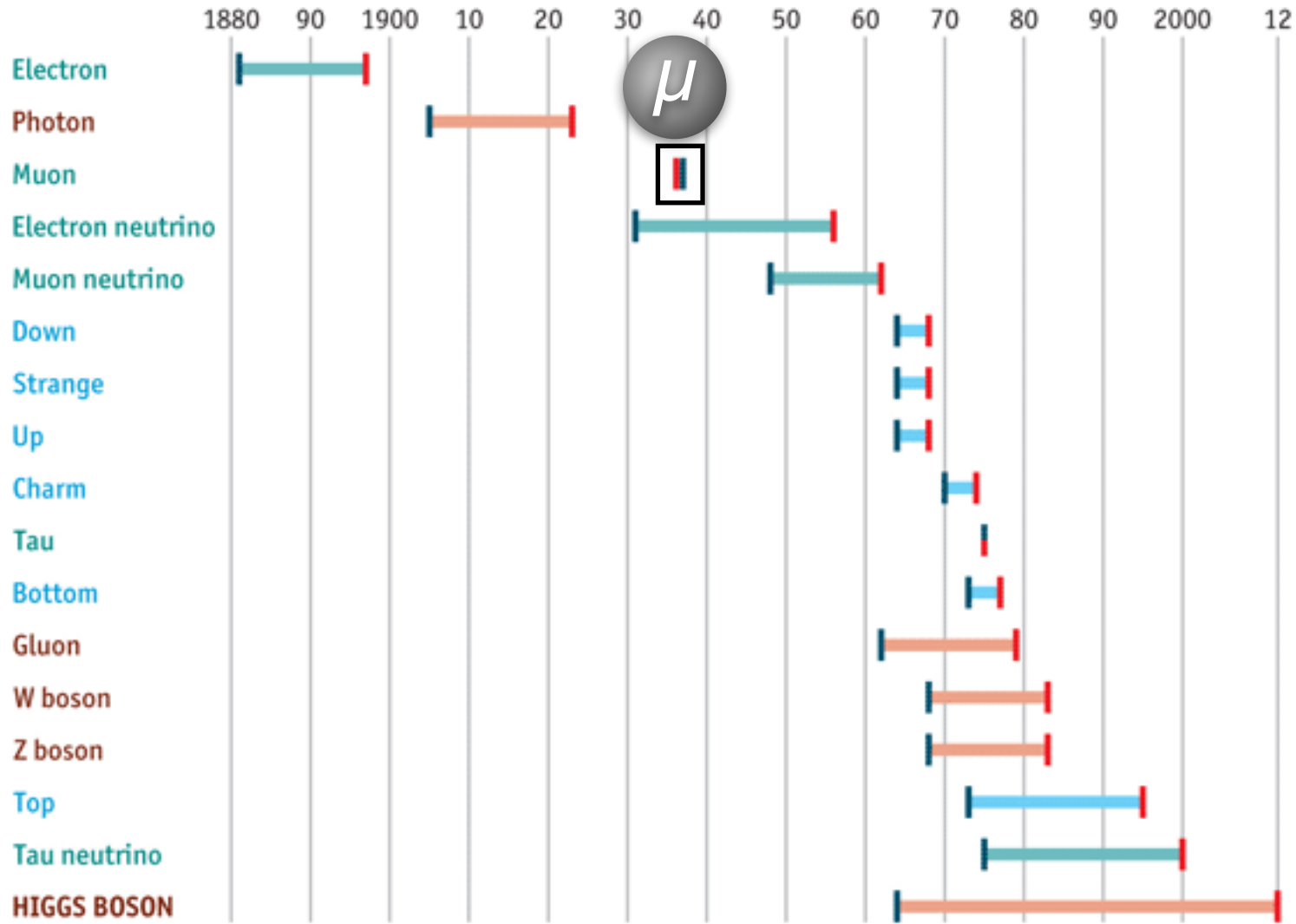
Source: *The Economist*

The Standard Model of particle physics

Years from concept to discovery

Leptons
Bosons
Quarks

Theorised/explained
Discovered



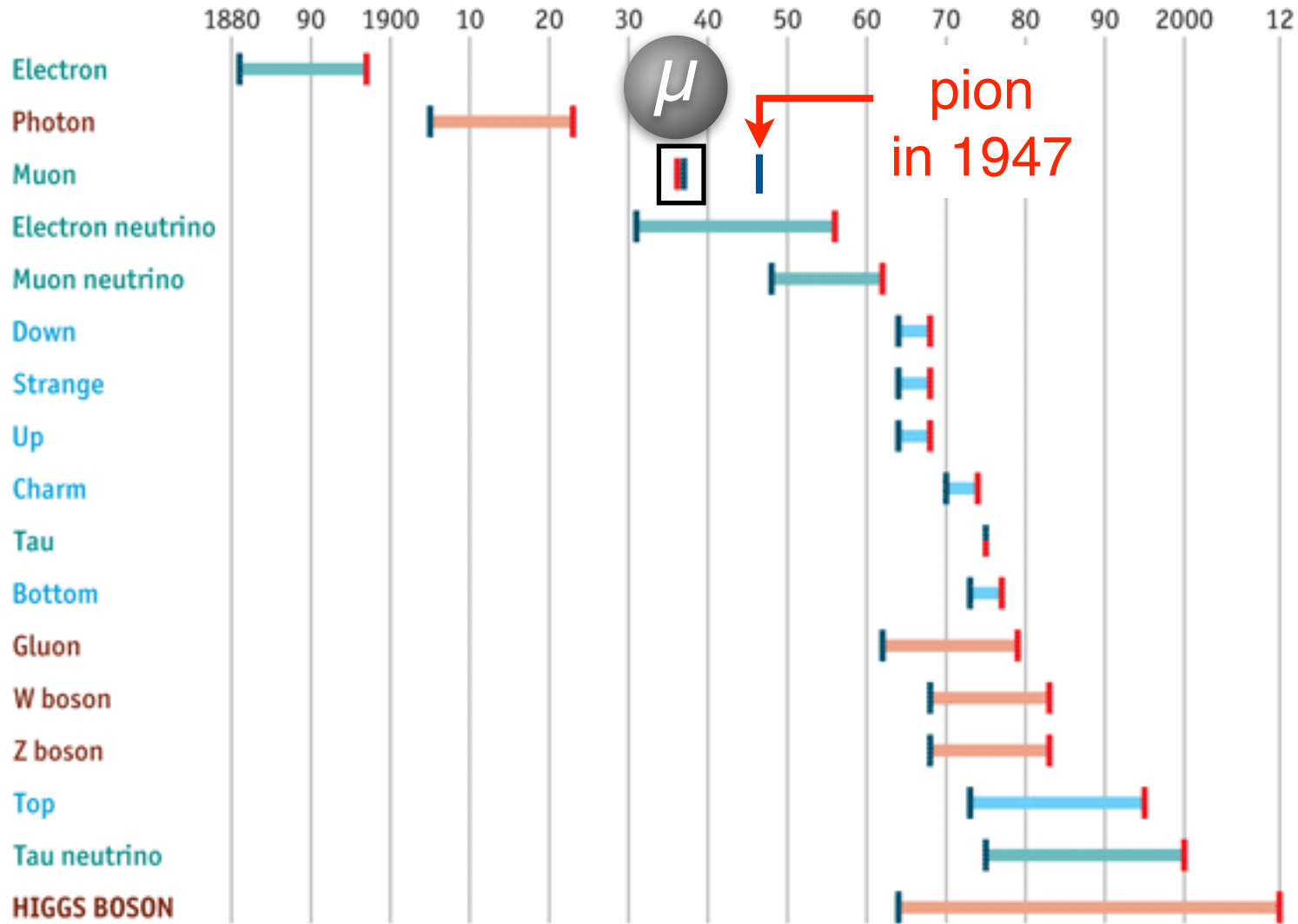
Source: *The Economist*

The Standard Model of particle physics

Years from concept to discovery

Leptons
Bosons
Quarks

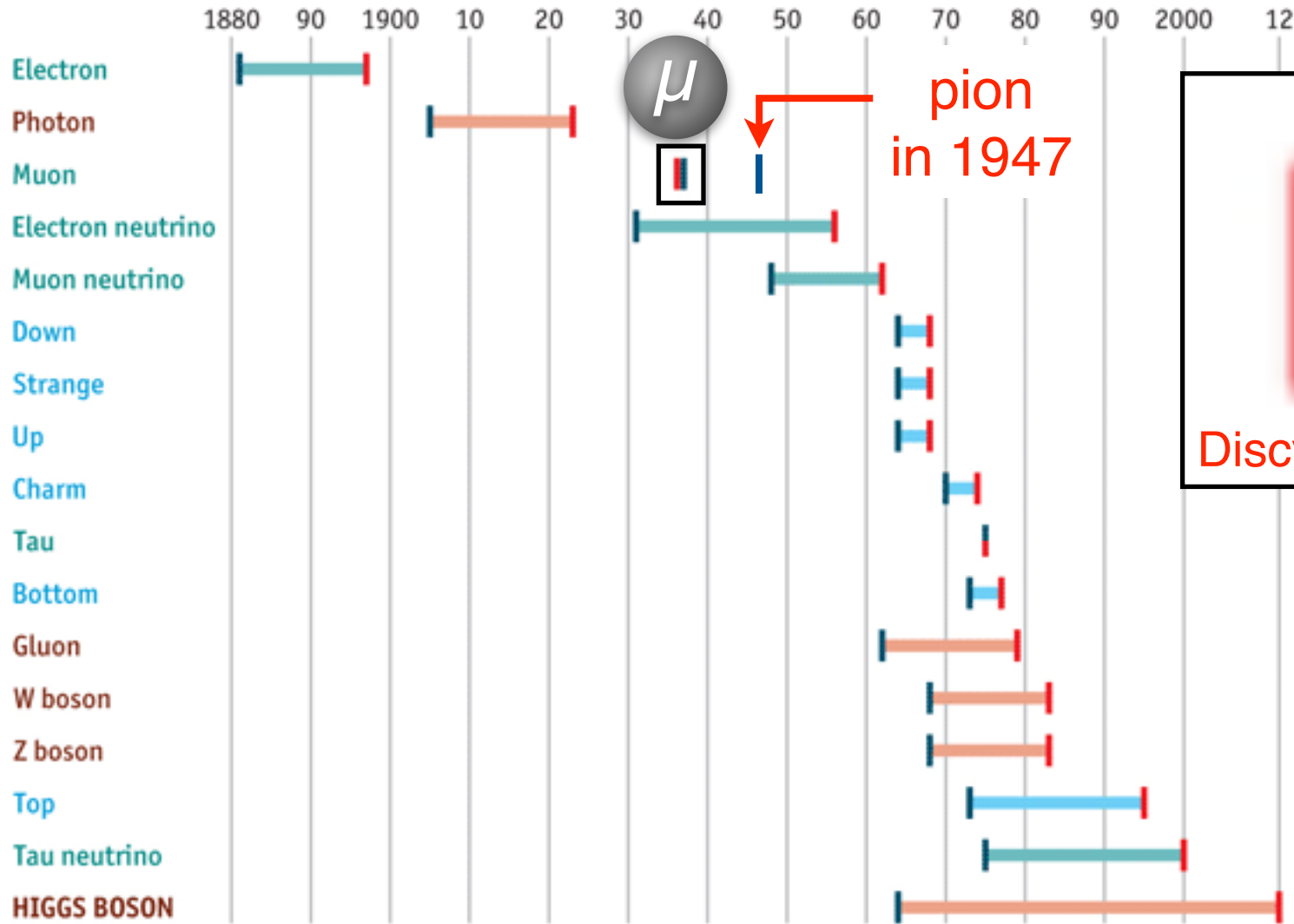
Theorised/explained
Discovered



Source: *The Economist*

The Standard Model of particle physics

Years from concept to discovery

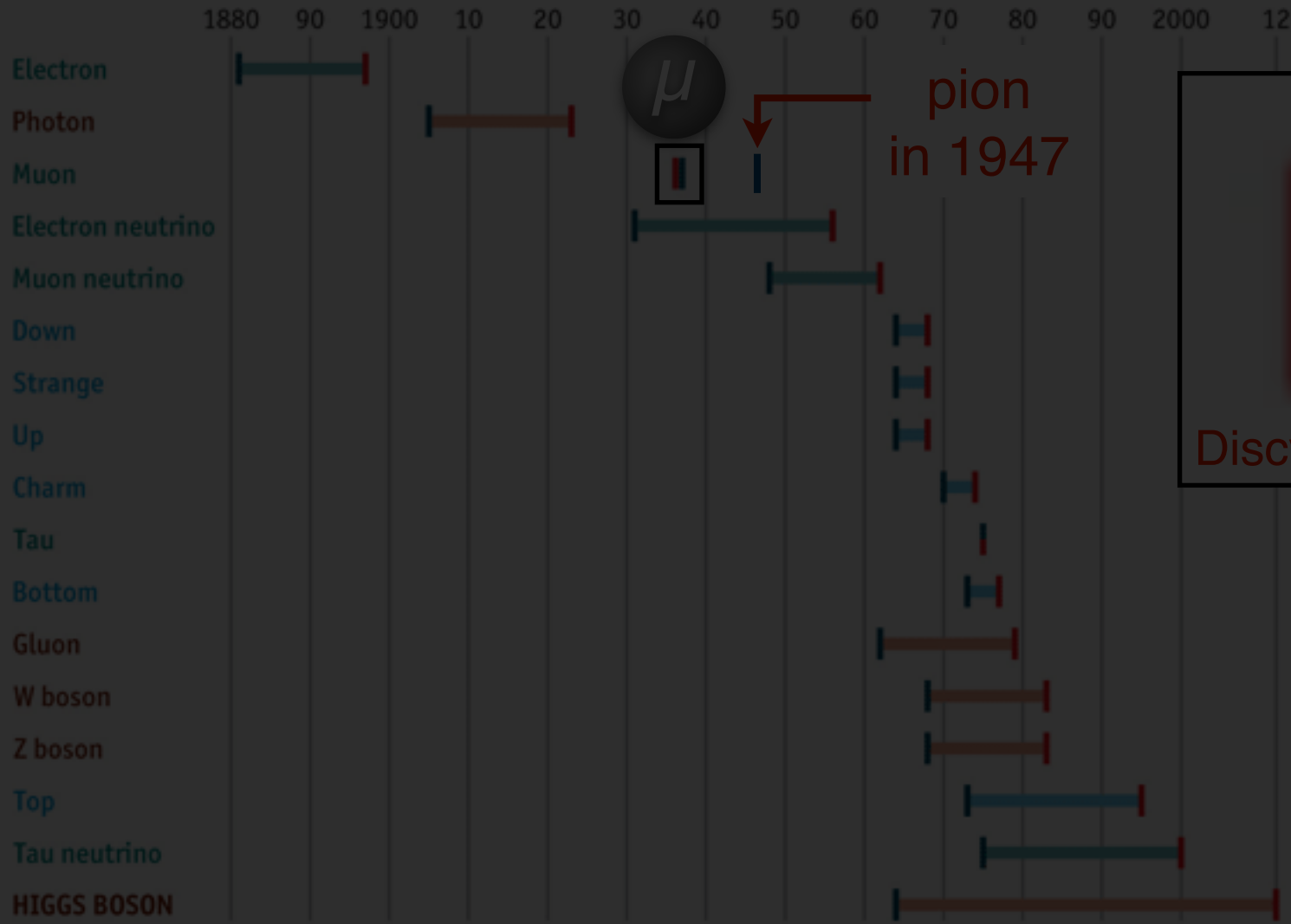


Source: *The Economist*

Discv. ⇒ Expl.

The Standard Model of particle physics

Years from concept to discovery

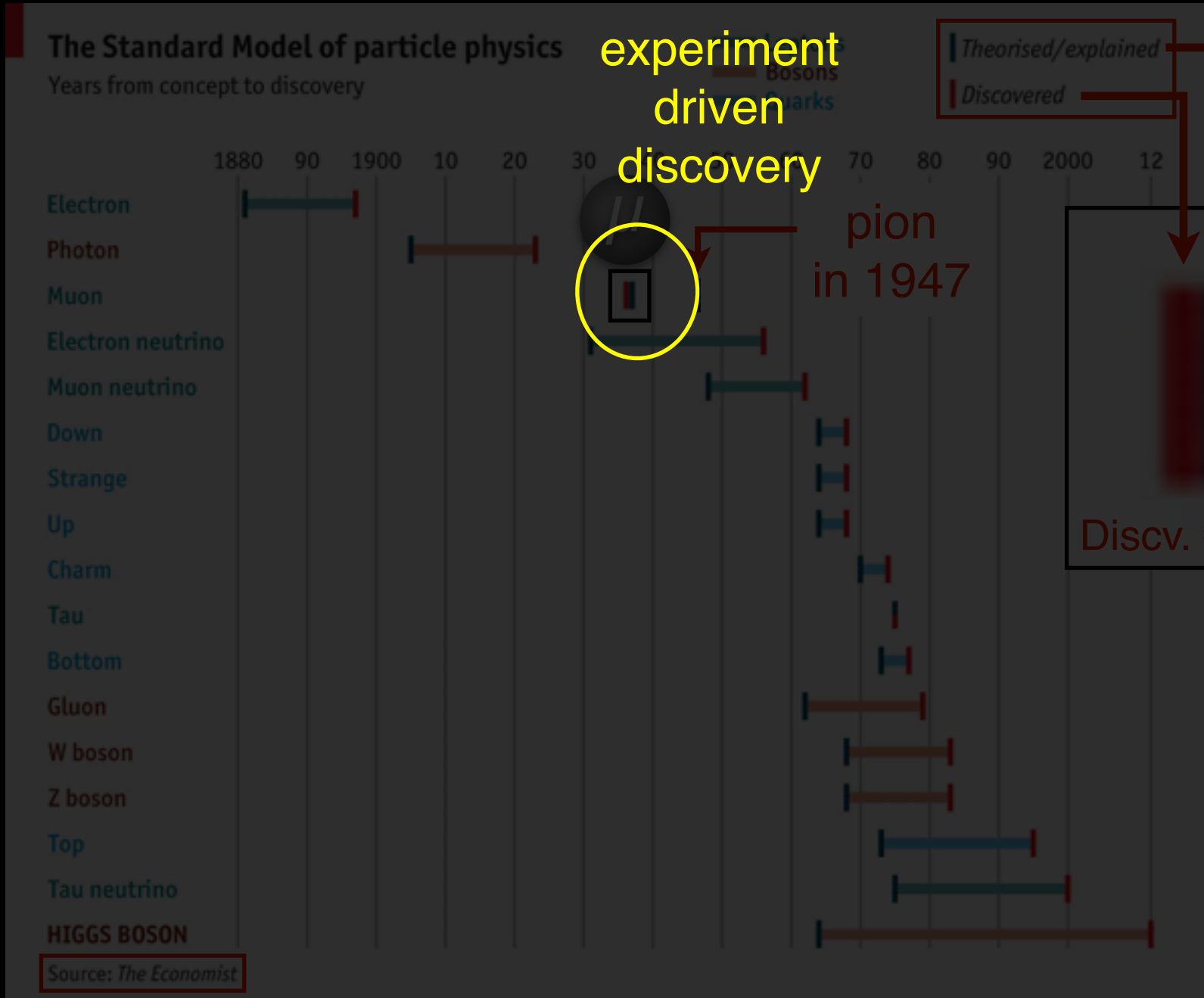


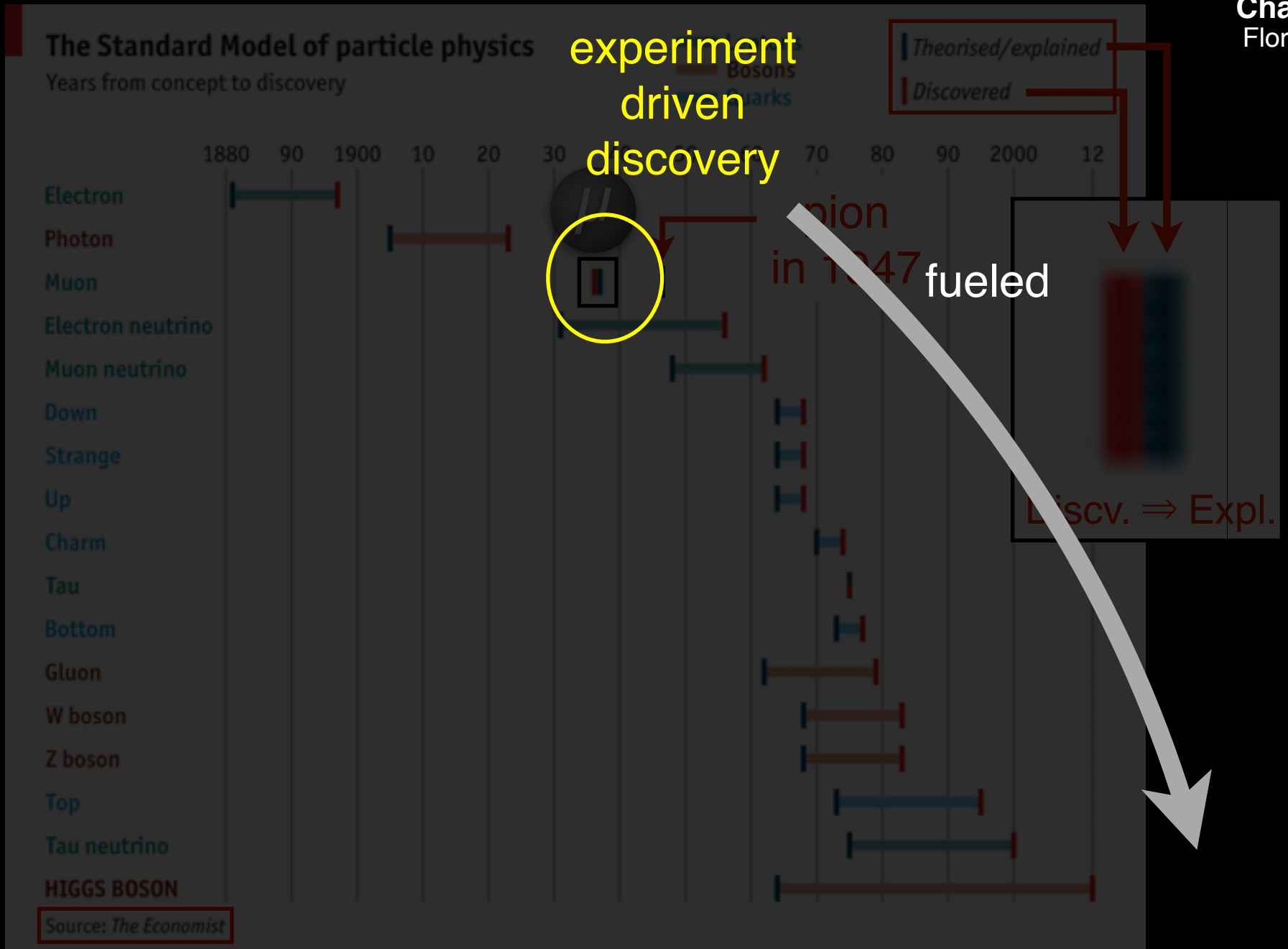
μ

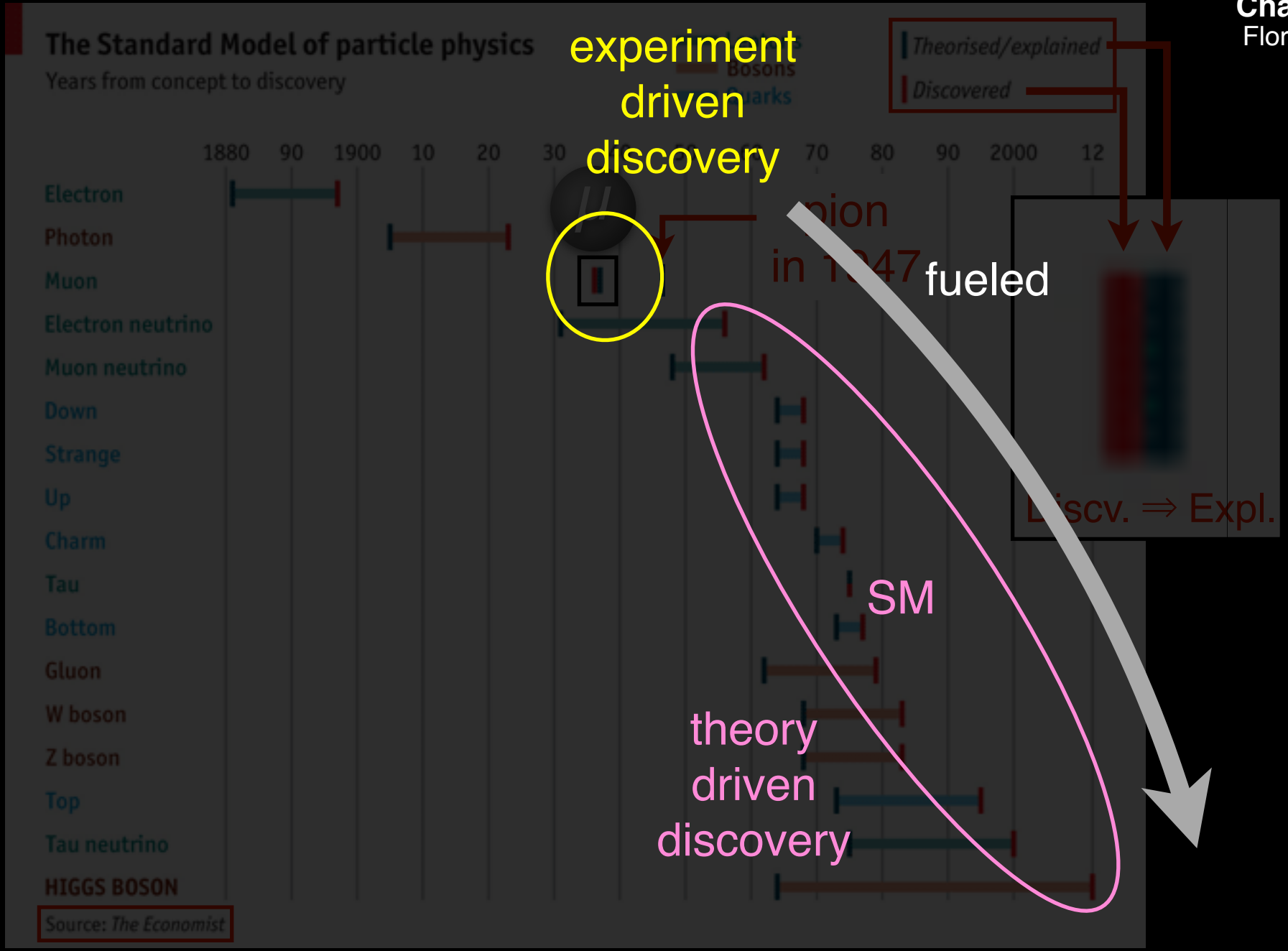
pion
in 1947

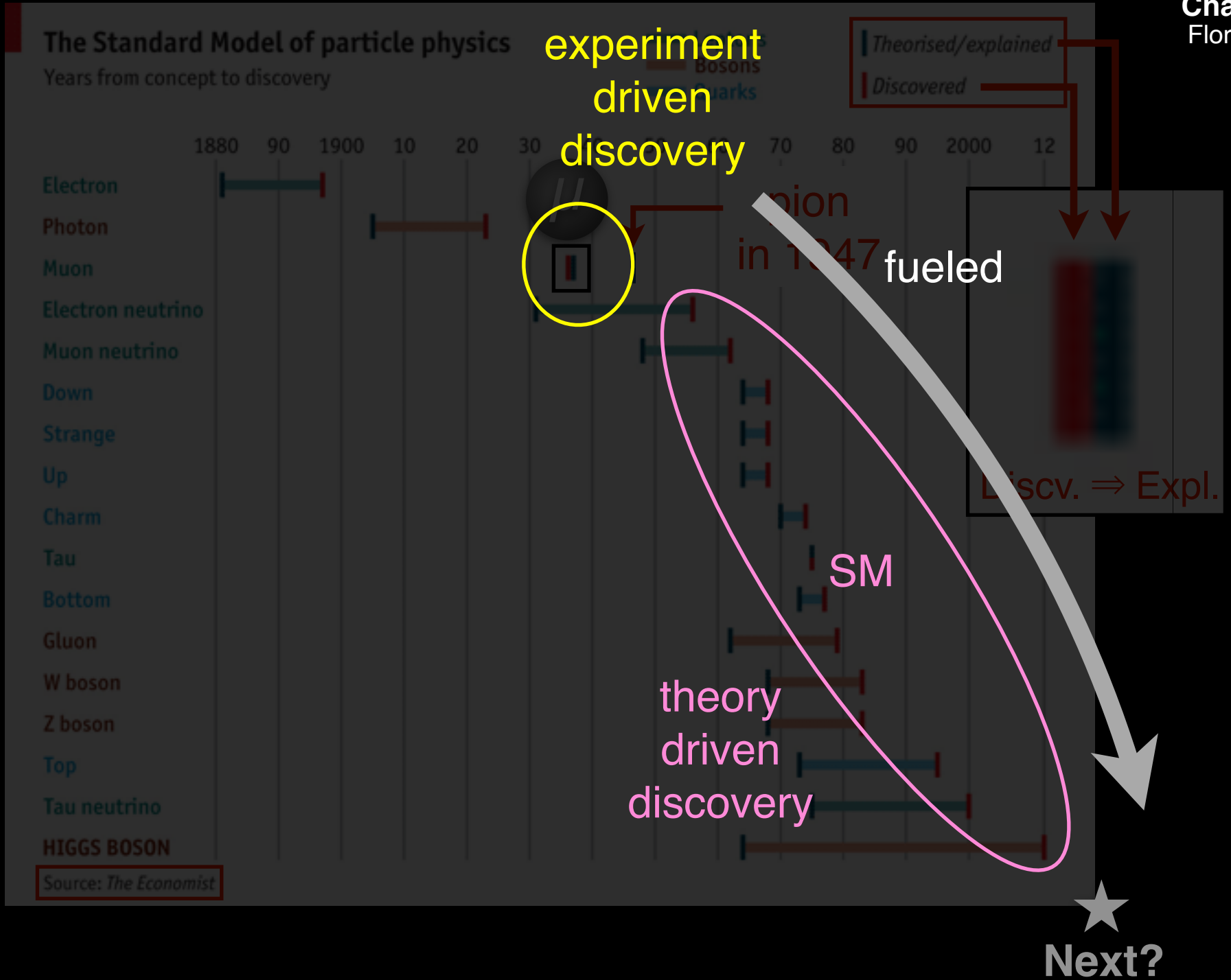
Discv. \Rightarrow Expl.

Source: *The Economist*

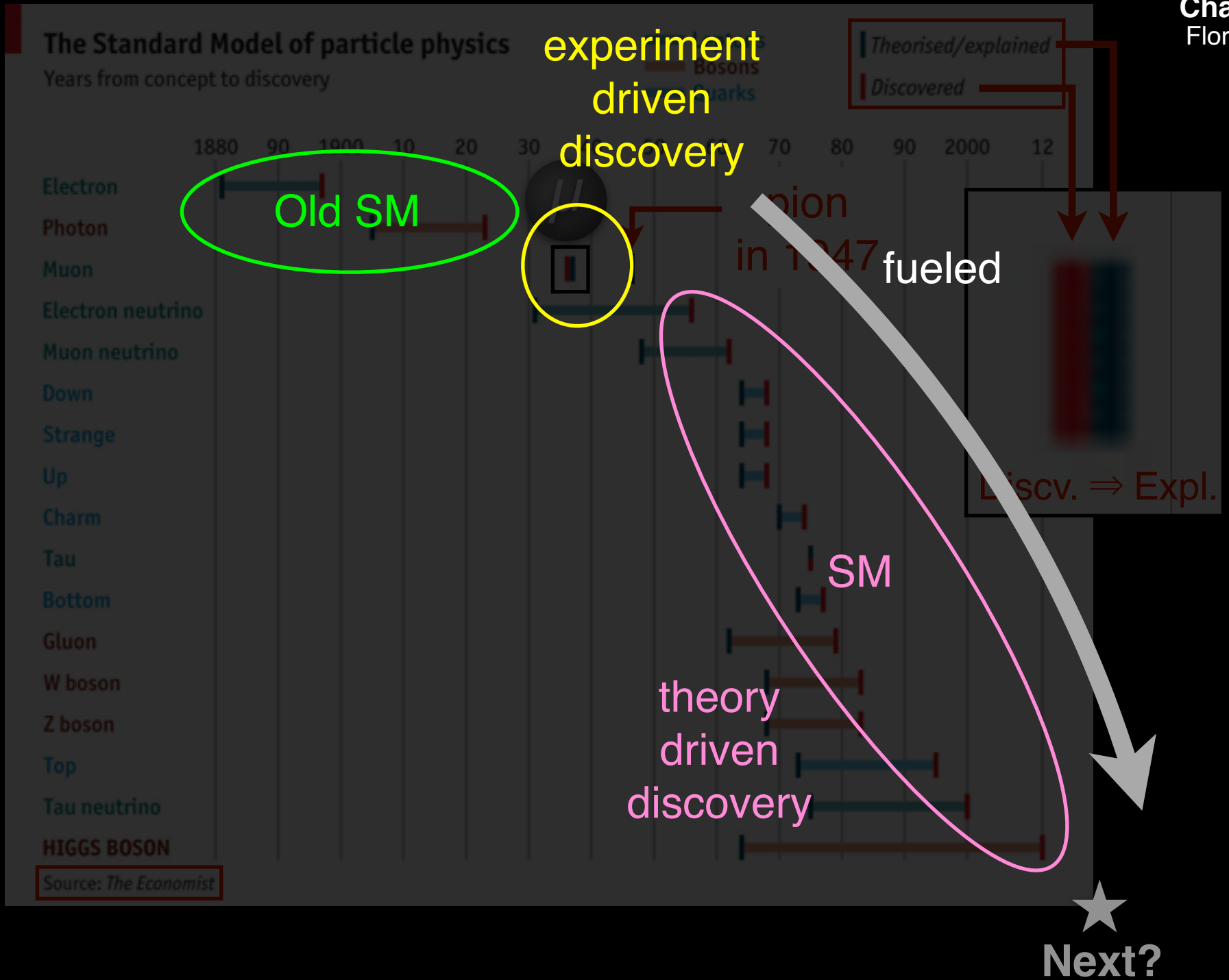


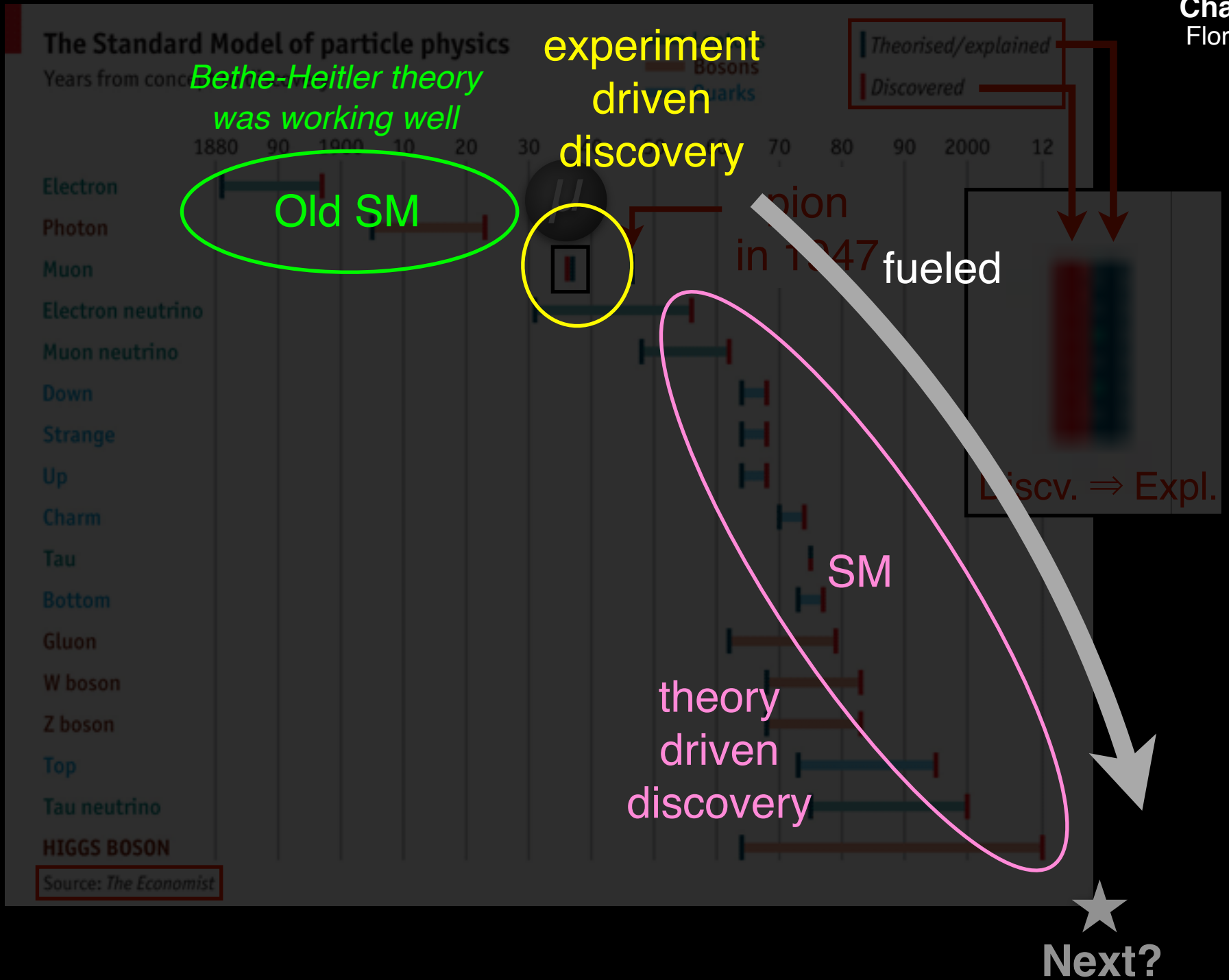






Source: *The Economist*

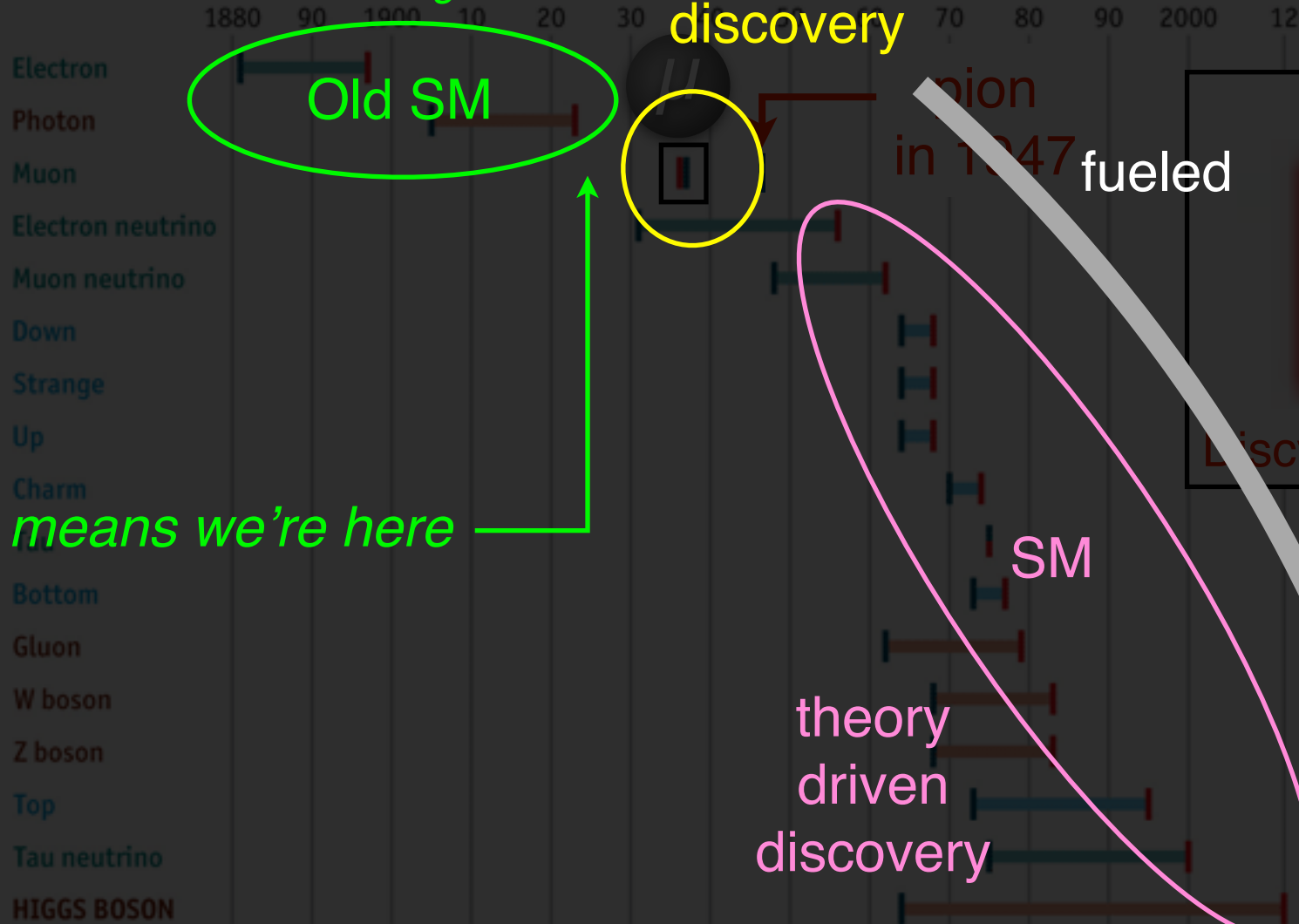




★
Next?

The Standard Model of particle physics

Years from conception



Bethe-Heitler theory was working well

Old SM

experiment driven discovery

1925

Theorised/explained
Discovered

fueled

Discv. \Rightarrow Expl.

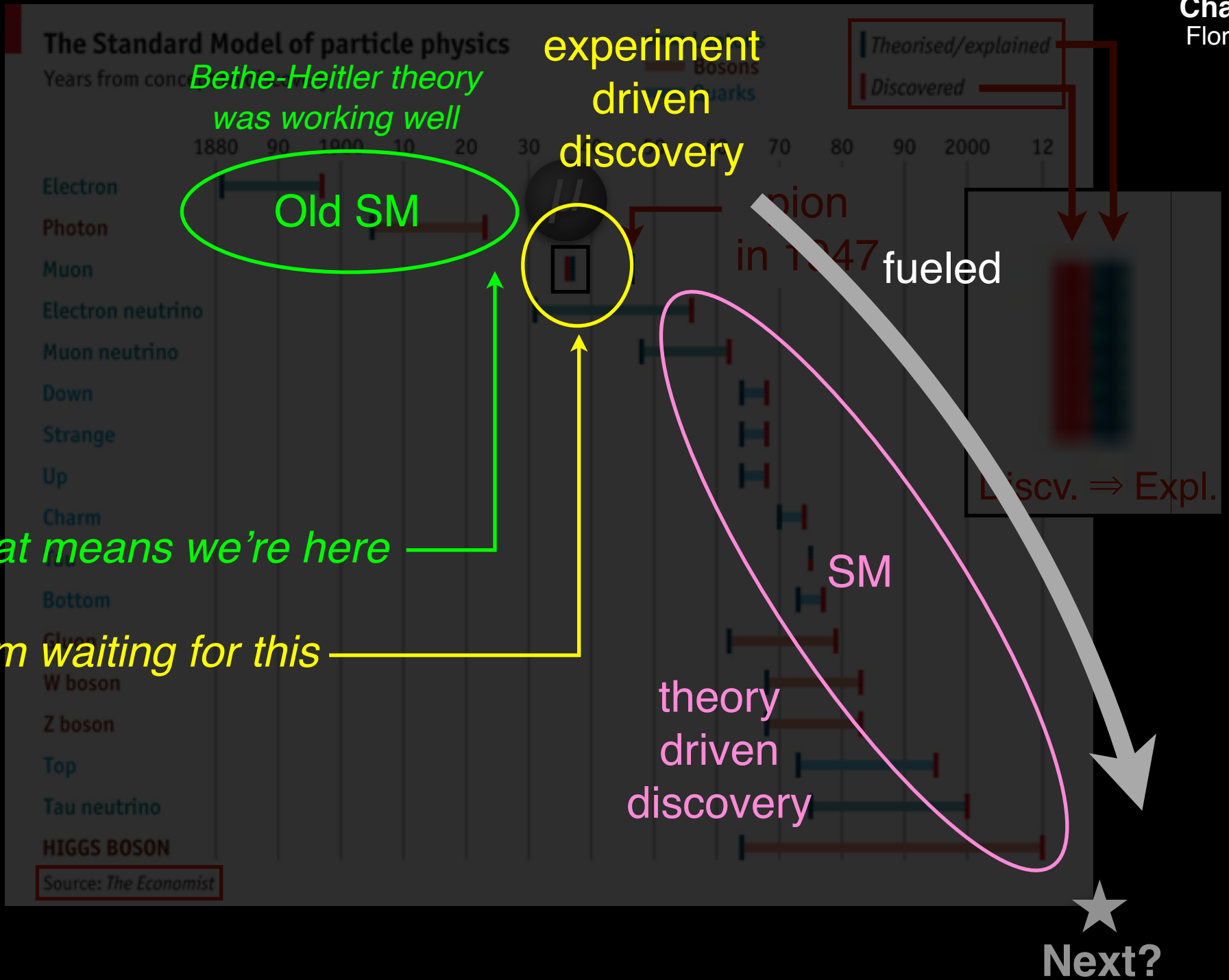
SM

theory driven discovery

That means we're here

★
Next?

Source: *The Economist*



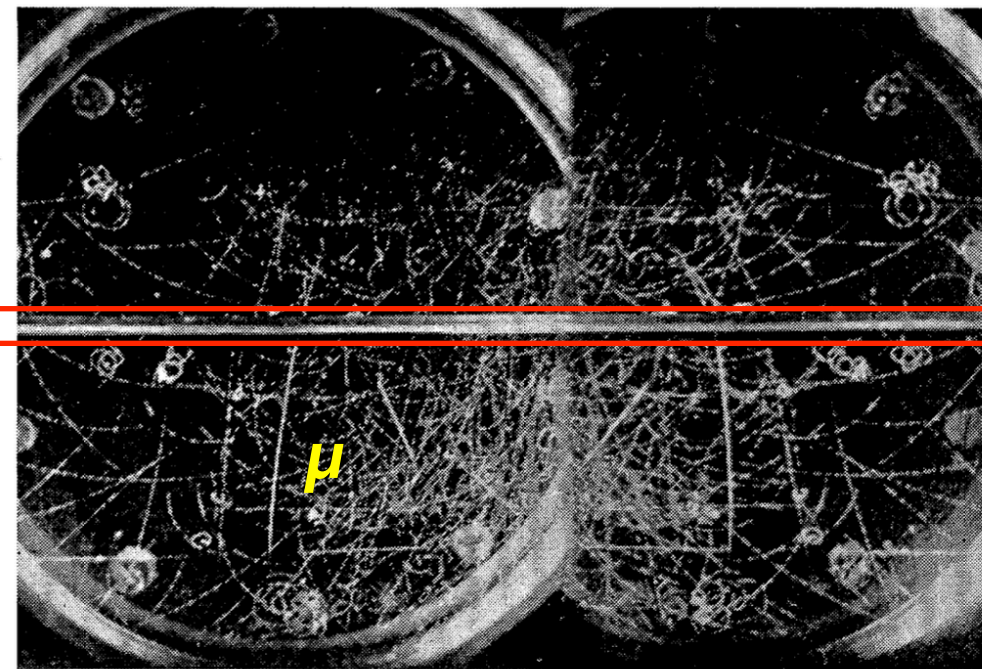
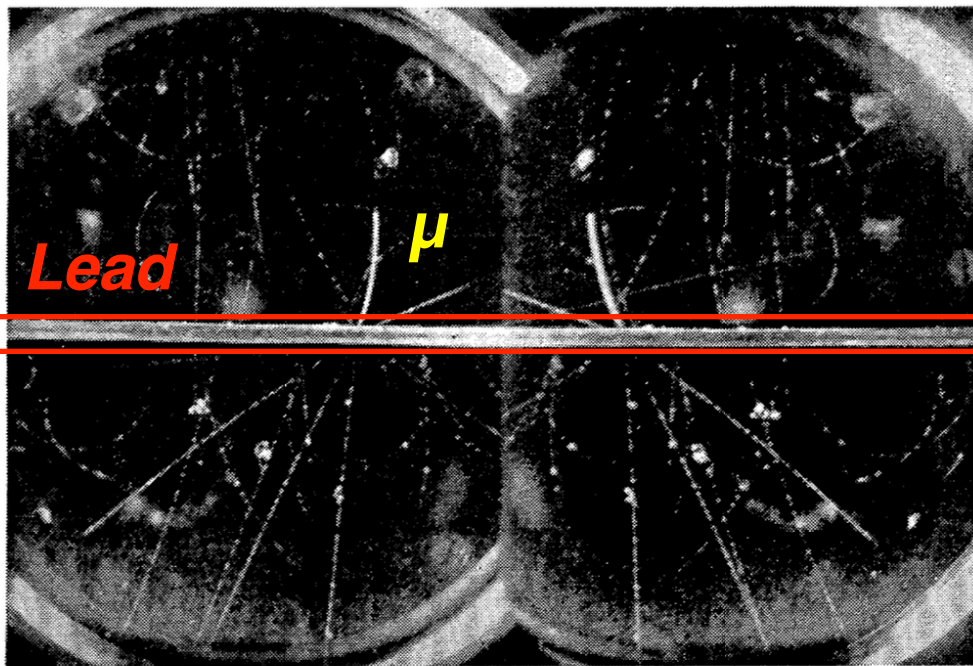
That means we're here

I am waiting for this

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)

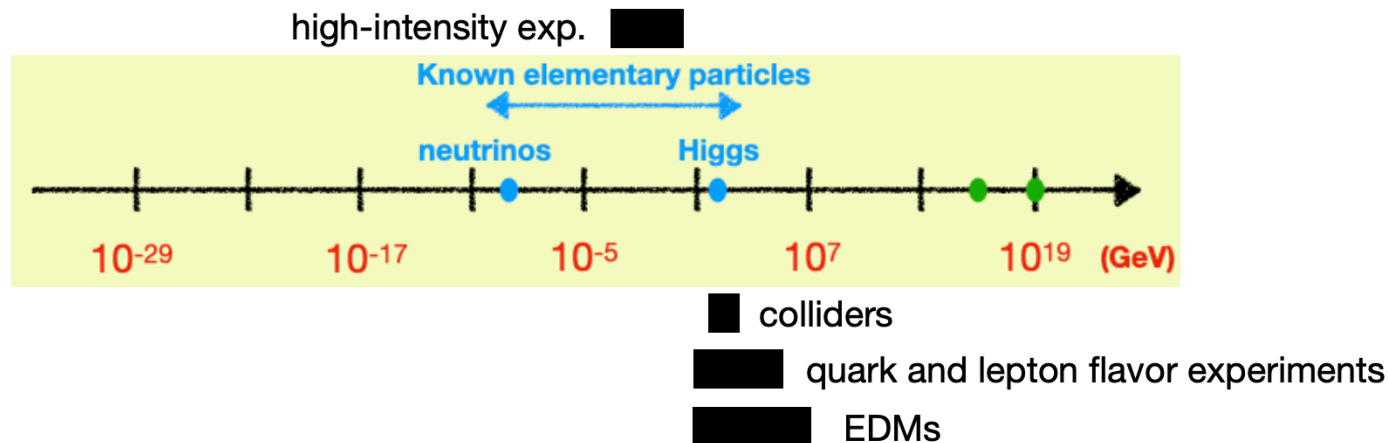
The Future of High Energy Physics: A New Generation, A New Vision

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?

$$S / \sqrt{B}$$

How do we proceed?

Need not be
theory driven

$$S / \sqrt{B}$$

How do we proceed?

Need not be
theory driven

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

How do we proceed?

Need not be
theory driven

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

How do we proceed?

Need not be
theory driven

non-zero preferred
but not required



How do we proceed?

Need not be
theory driven

non-zero preferred
but not required



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

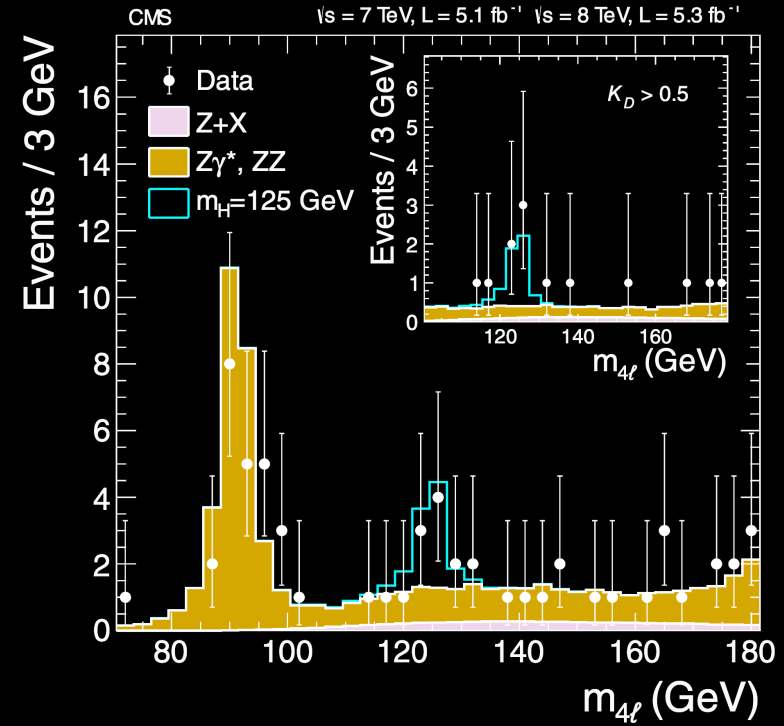
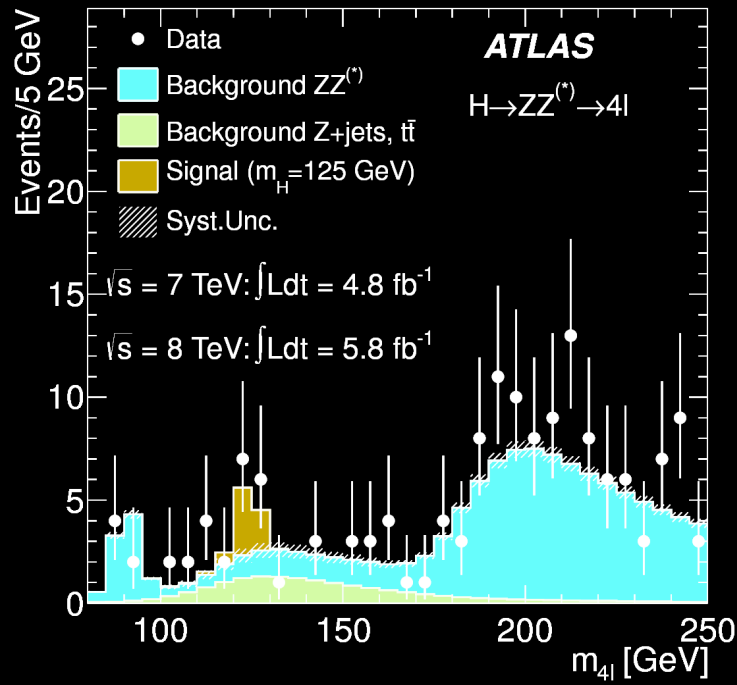
$$S / \sqrt{B} \longrightarrow 1 / \sqrt{B}$$

Focus on unexplored phase-space

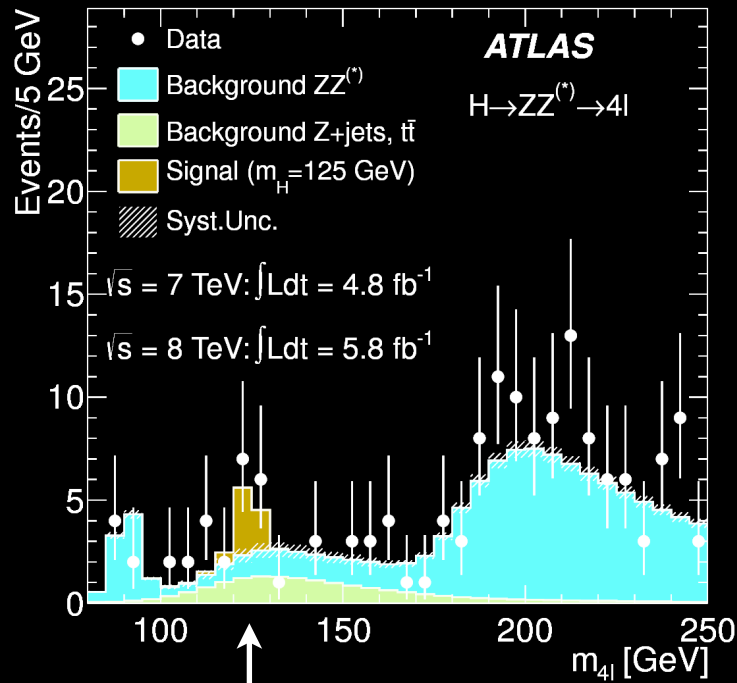
Test null-hypothesis (i.e. SM)

Surprises do happen!

How much of a surprise?



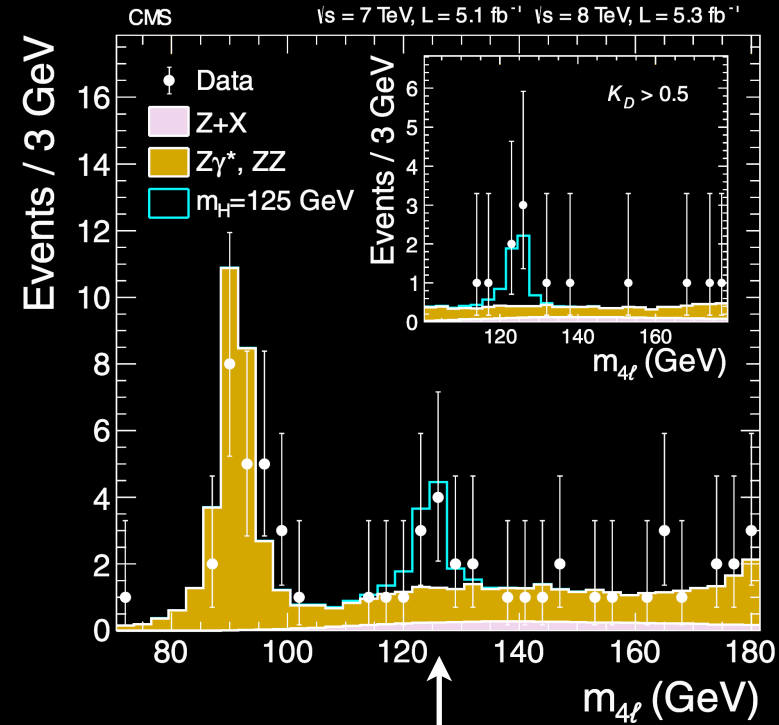
How much of a surprise?



~8 evt. excess

3.5σ

+

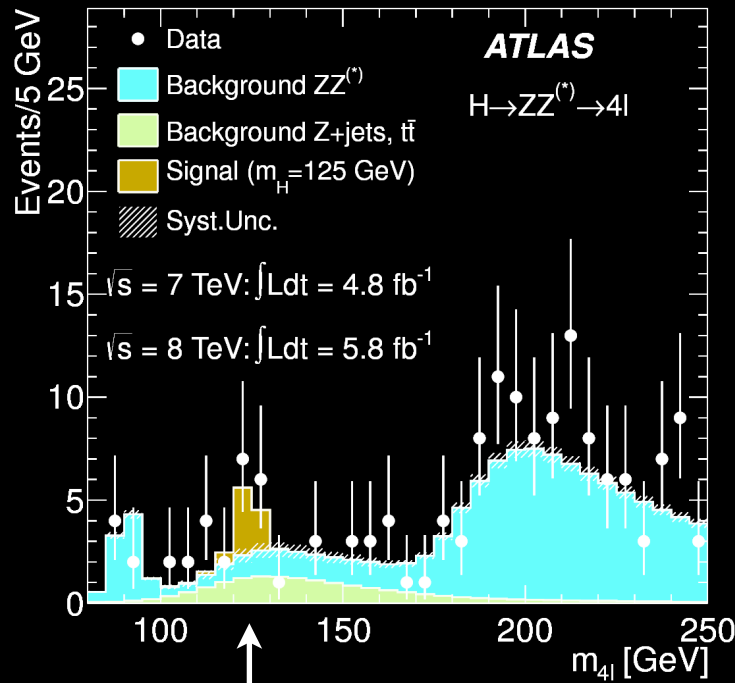


6 evt. excess

3.2σ

= 4.8σ

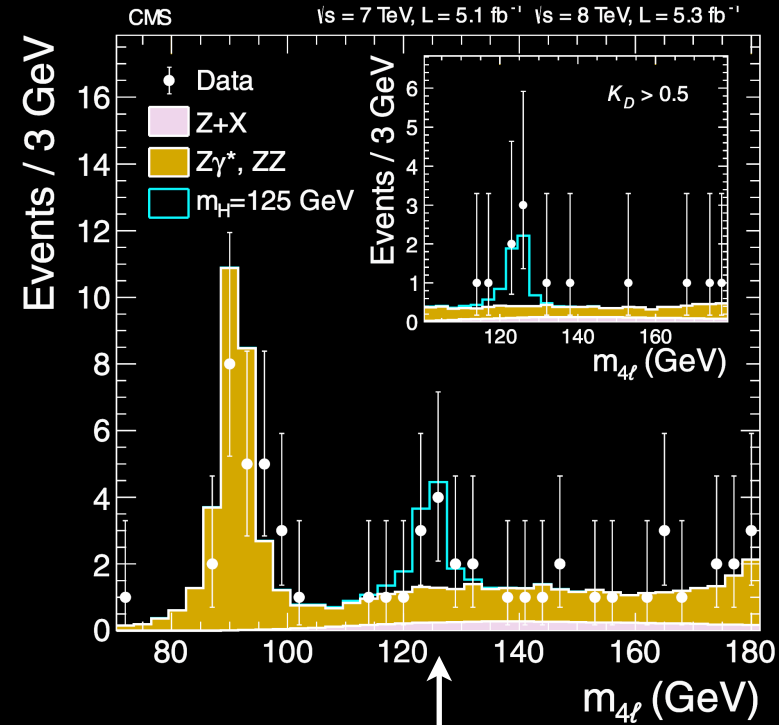
How much of a surprise?



~8 evt. excess

3.5σ

+



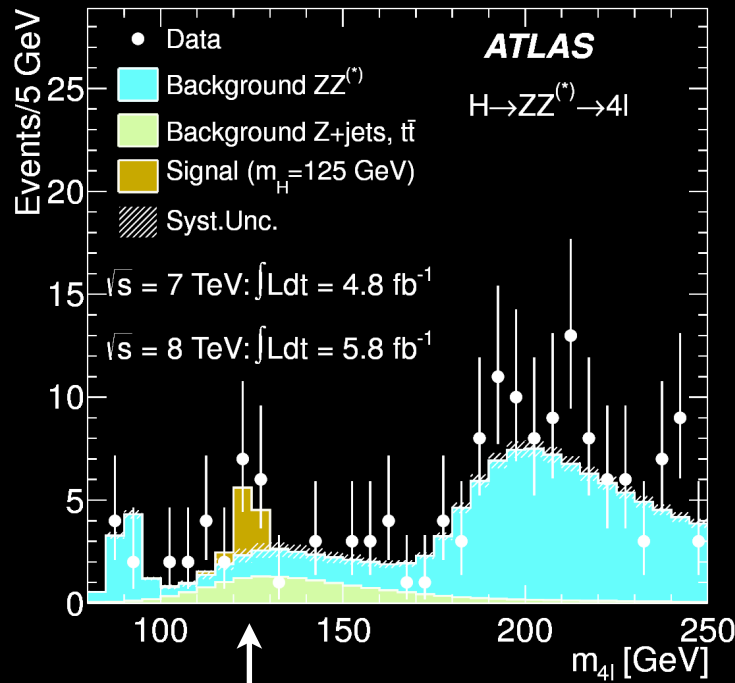
6 evt. excess

3.2σ

= 4.8σ

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

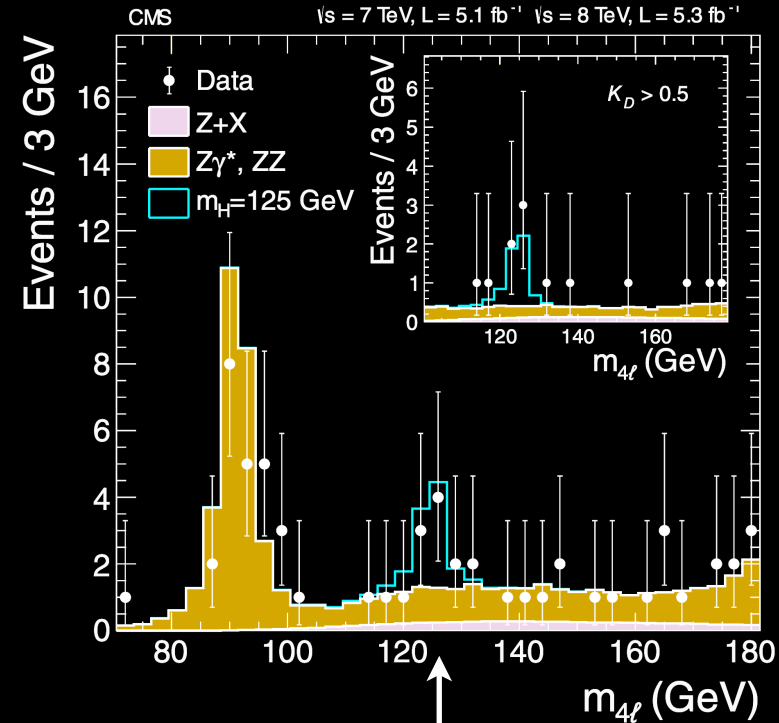
How much of a surprise?



~8 evt. excess

3.5σ

+



6 evt. excess

3.2σ

= 4.8σ

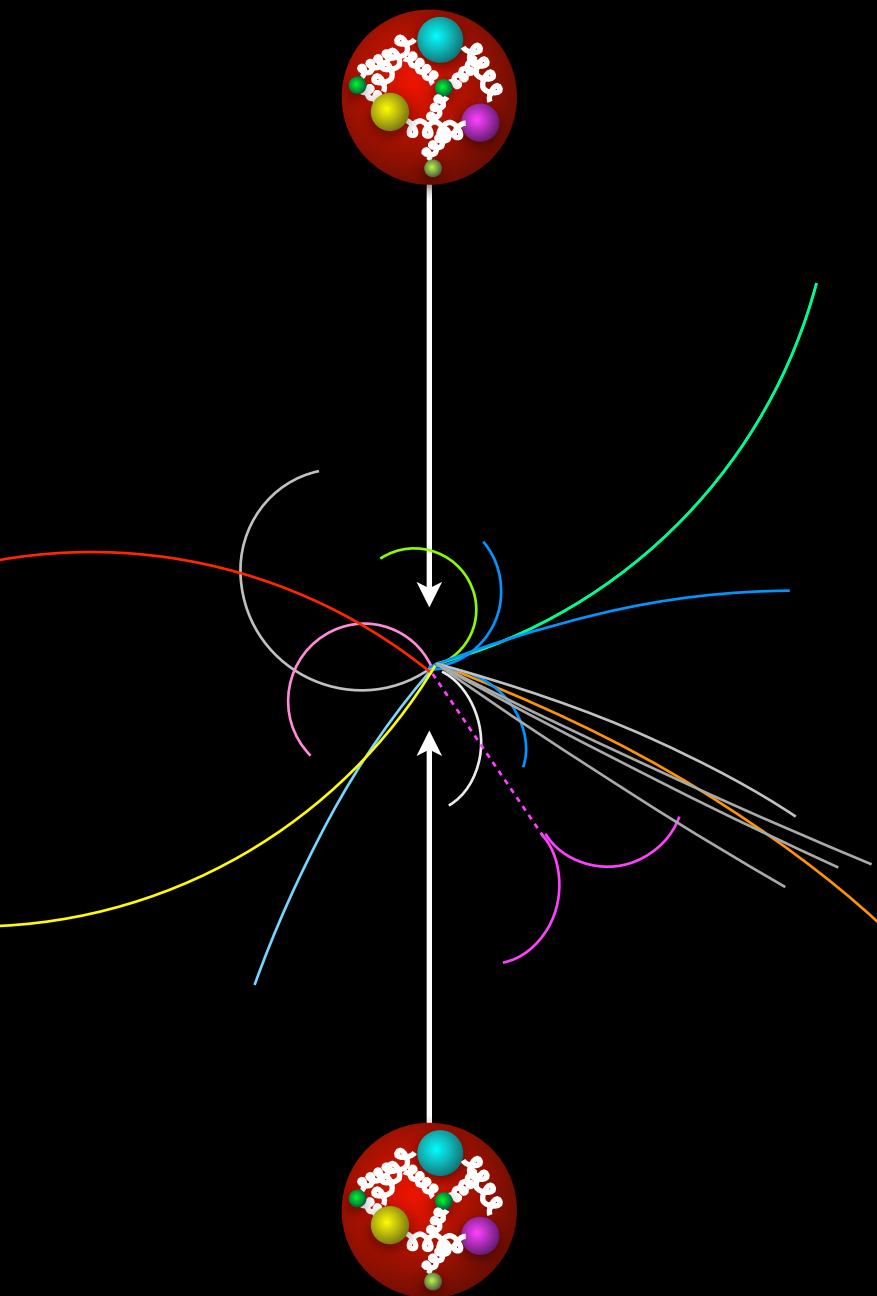
$3000 \text{ fb}^{-1} / 137 \text{ fb}^{-1} = 20$ times more data coming
(future) (today)

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

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

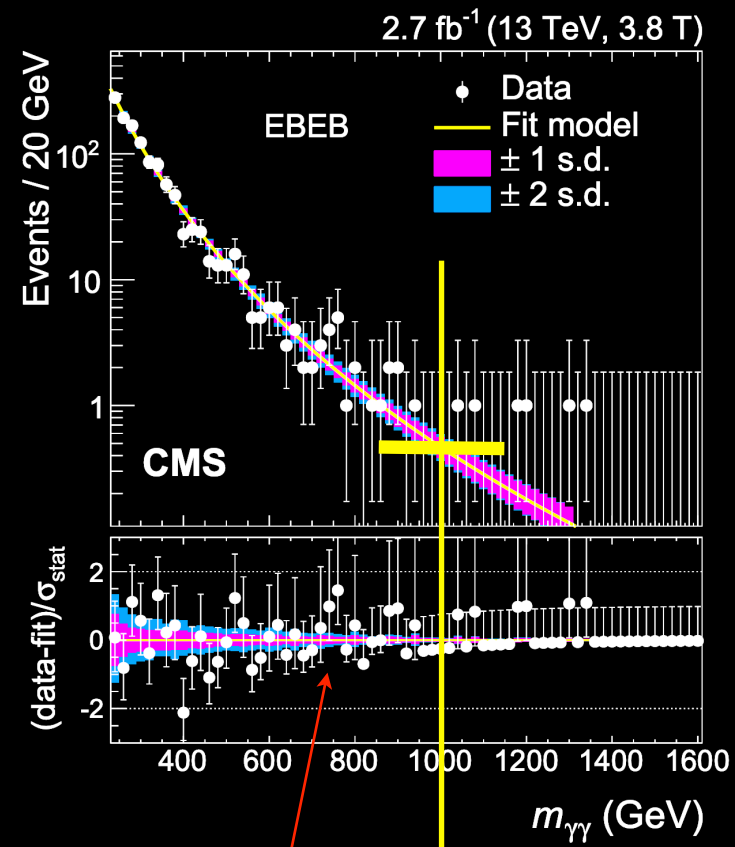
Phase-space

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



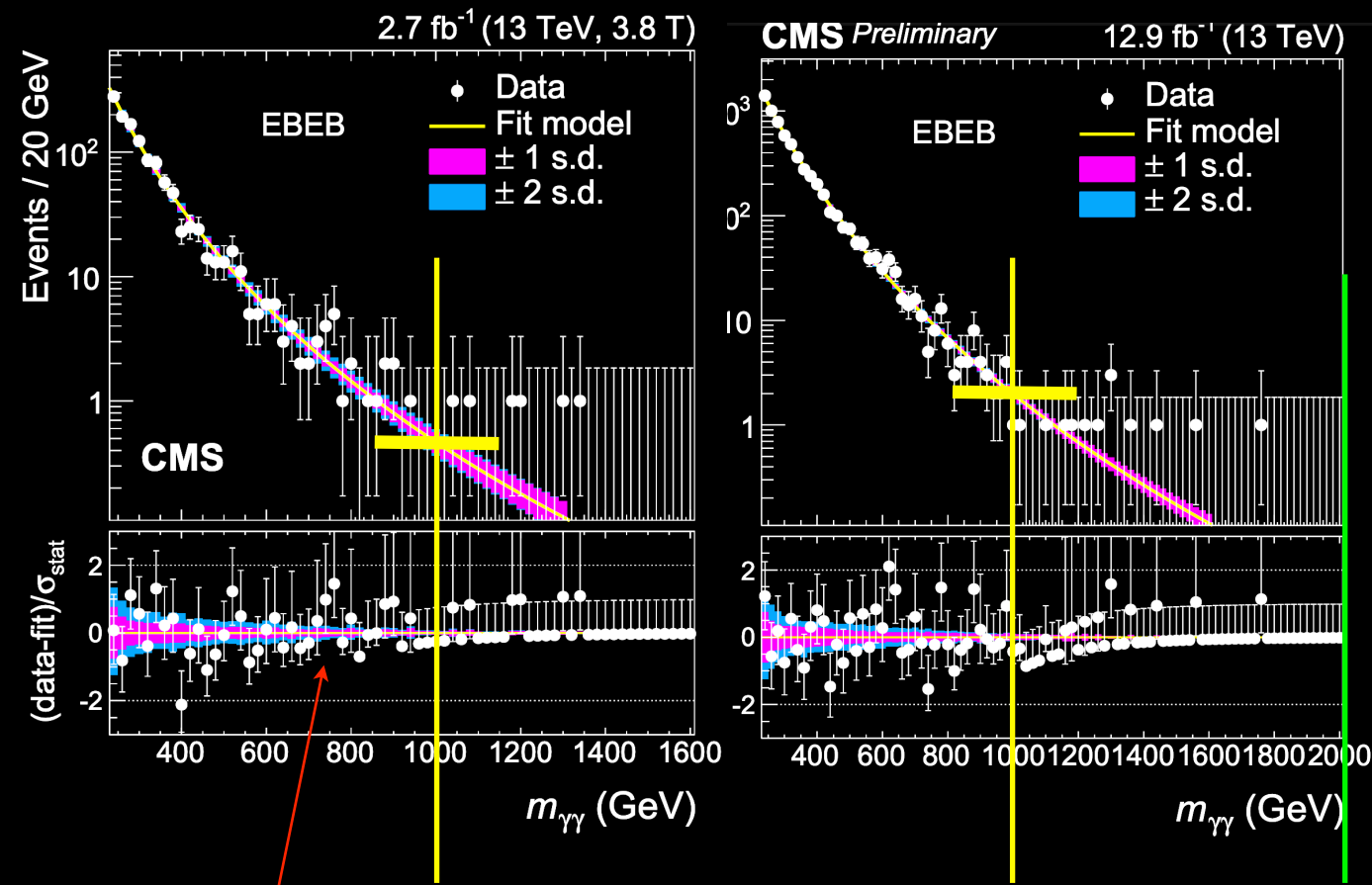
1. **Energy** of the final state particle
2. **Multiplicities**
3. **Angular correlation** (e.g. mass, substr.)
4. **Lifetime**

Pushing Energy



“750 GeV”

Pushing Energy

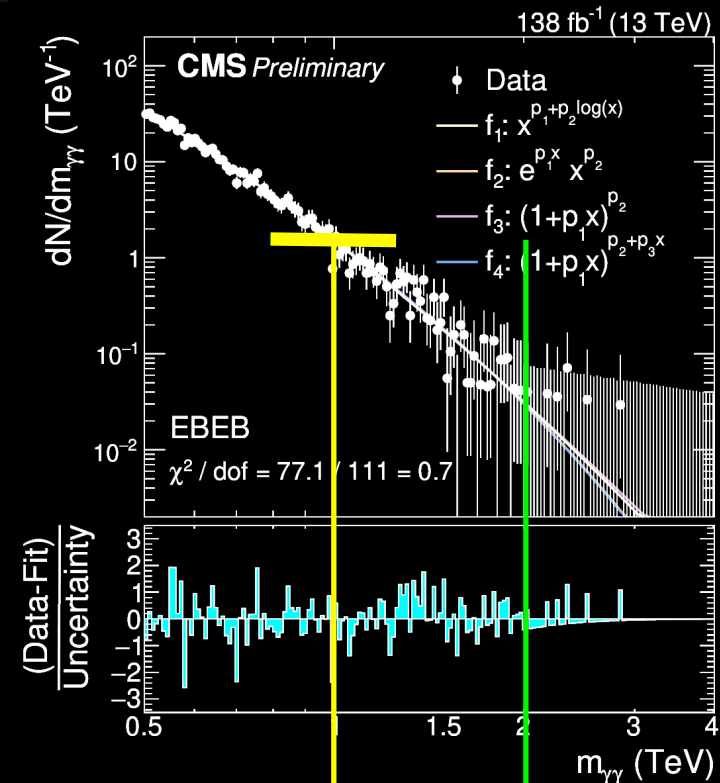
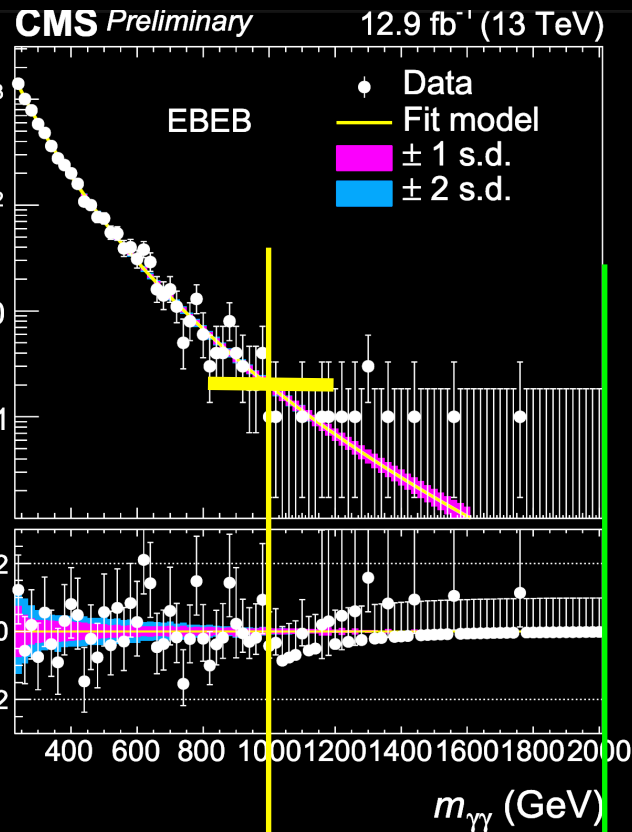
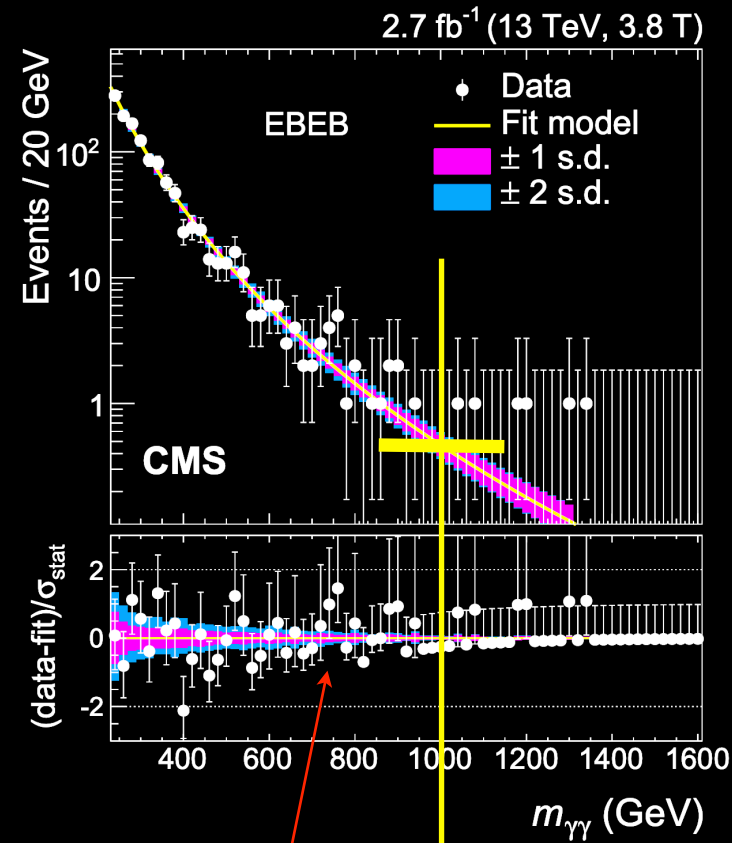


“750 GeV”

Pushing Energy

Yesterday

CMS-PAS-EXO-22-024

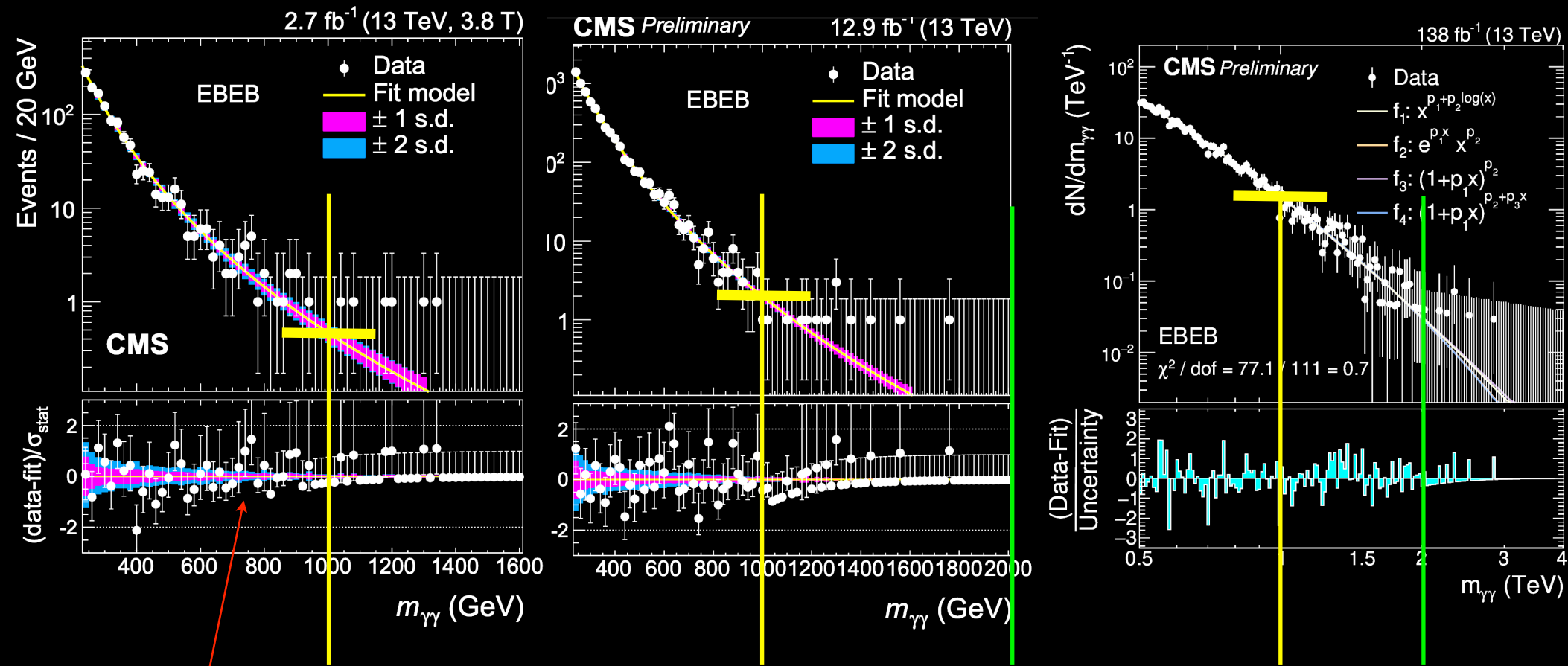


“750 GeV”

Pushing Energy

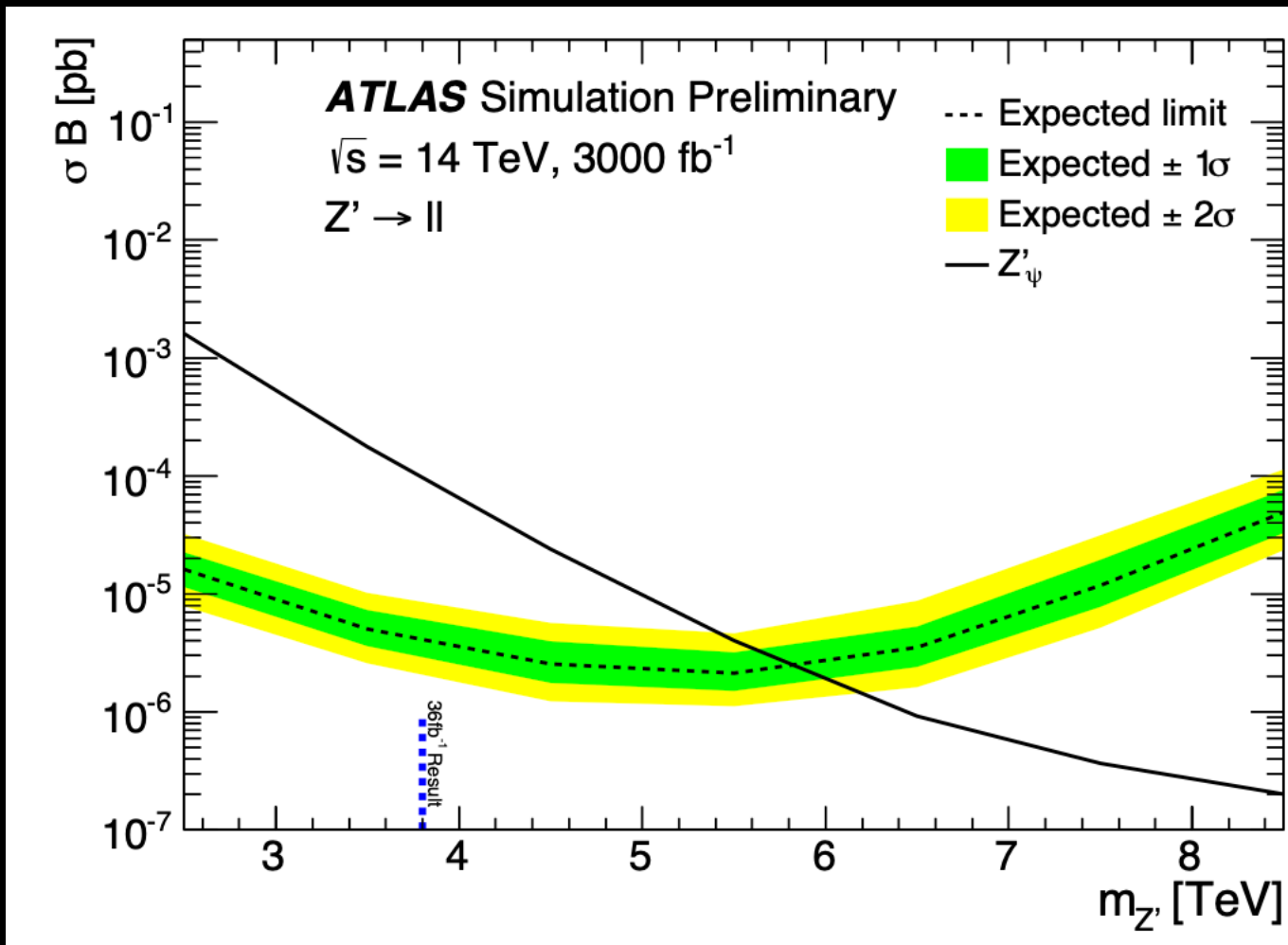
Yesterday

CMS-PAS-EXO-22-024

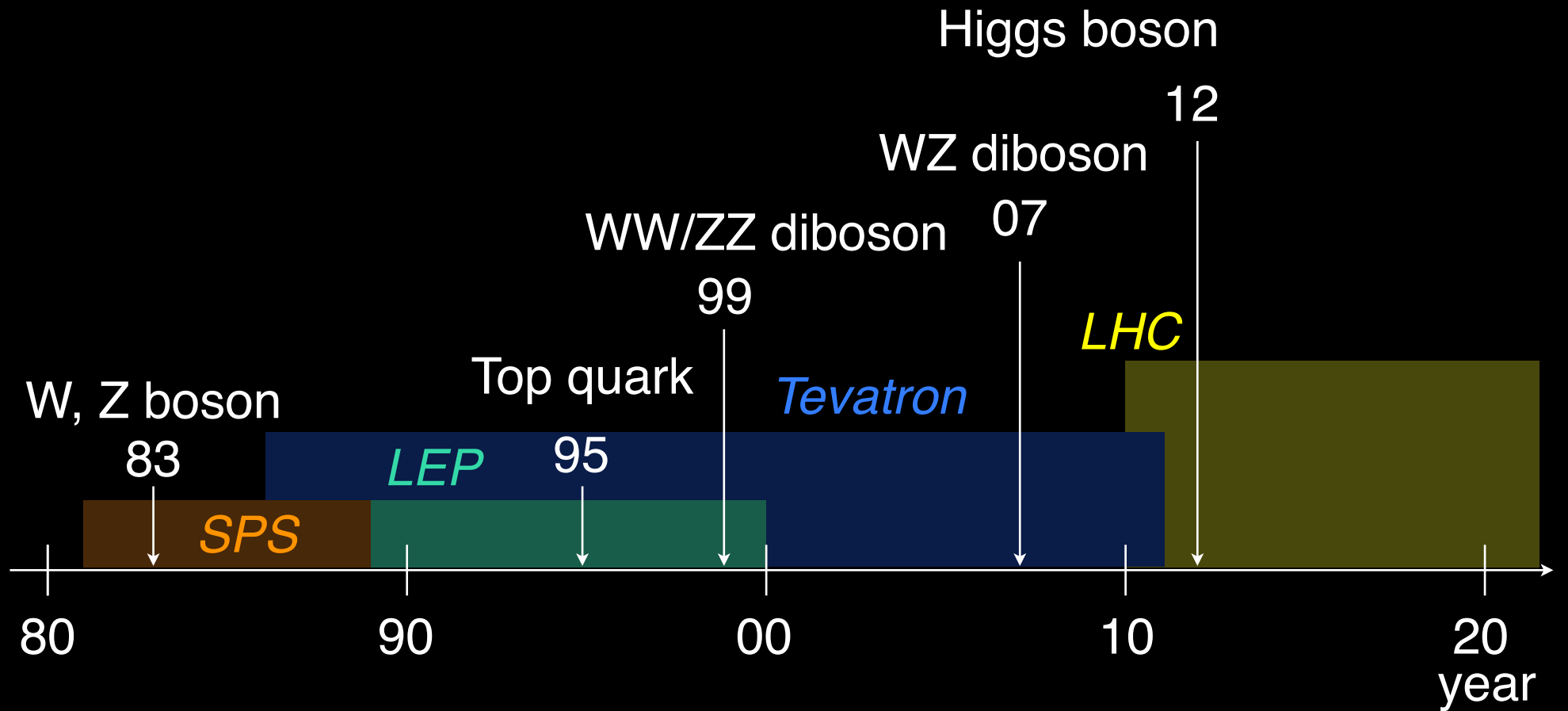


“750 GeV”

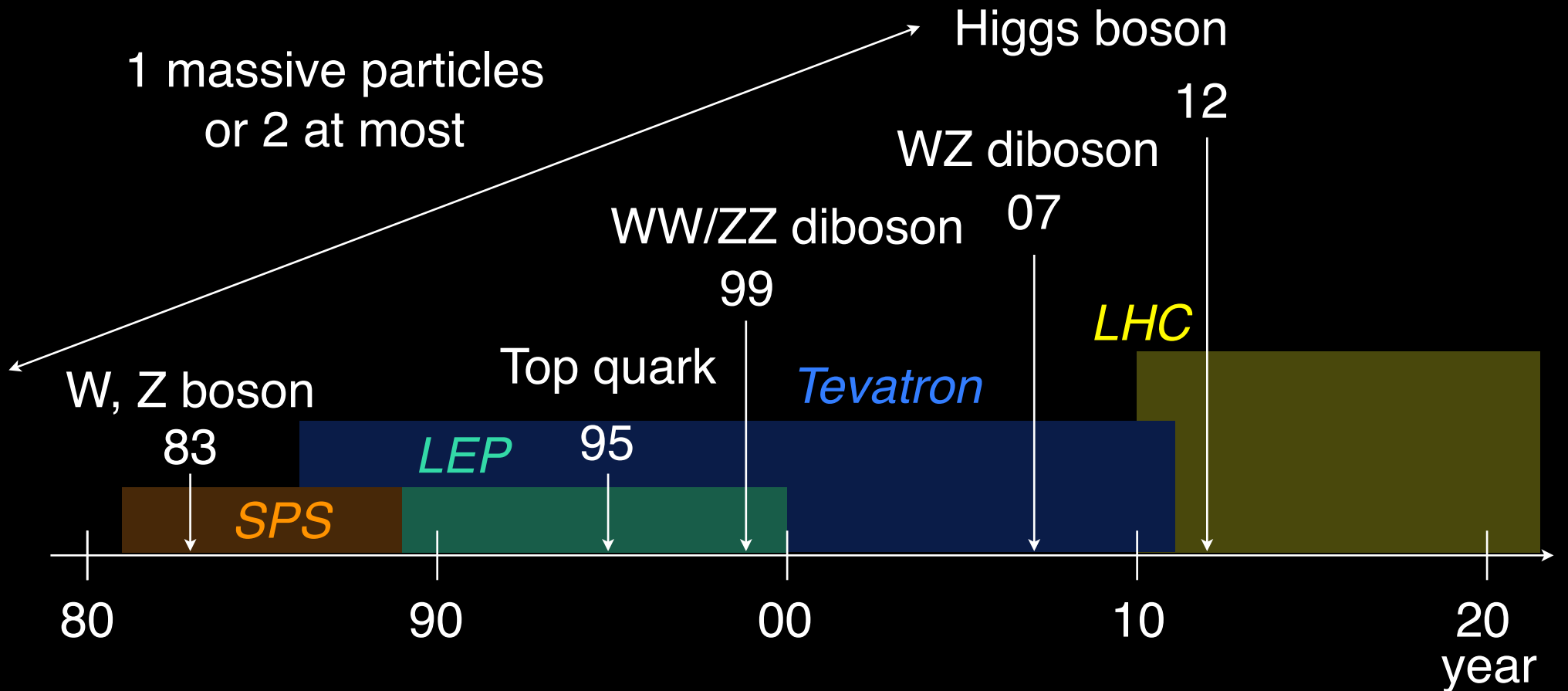
Same story for W' / Z' and various resonance searches



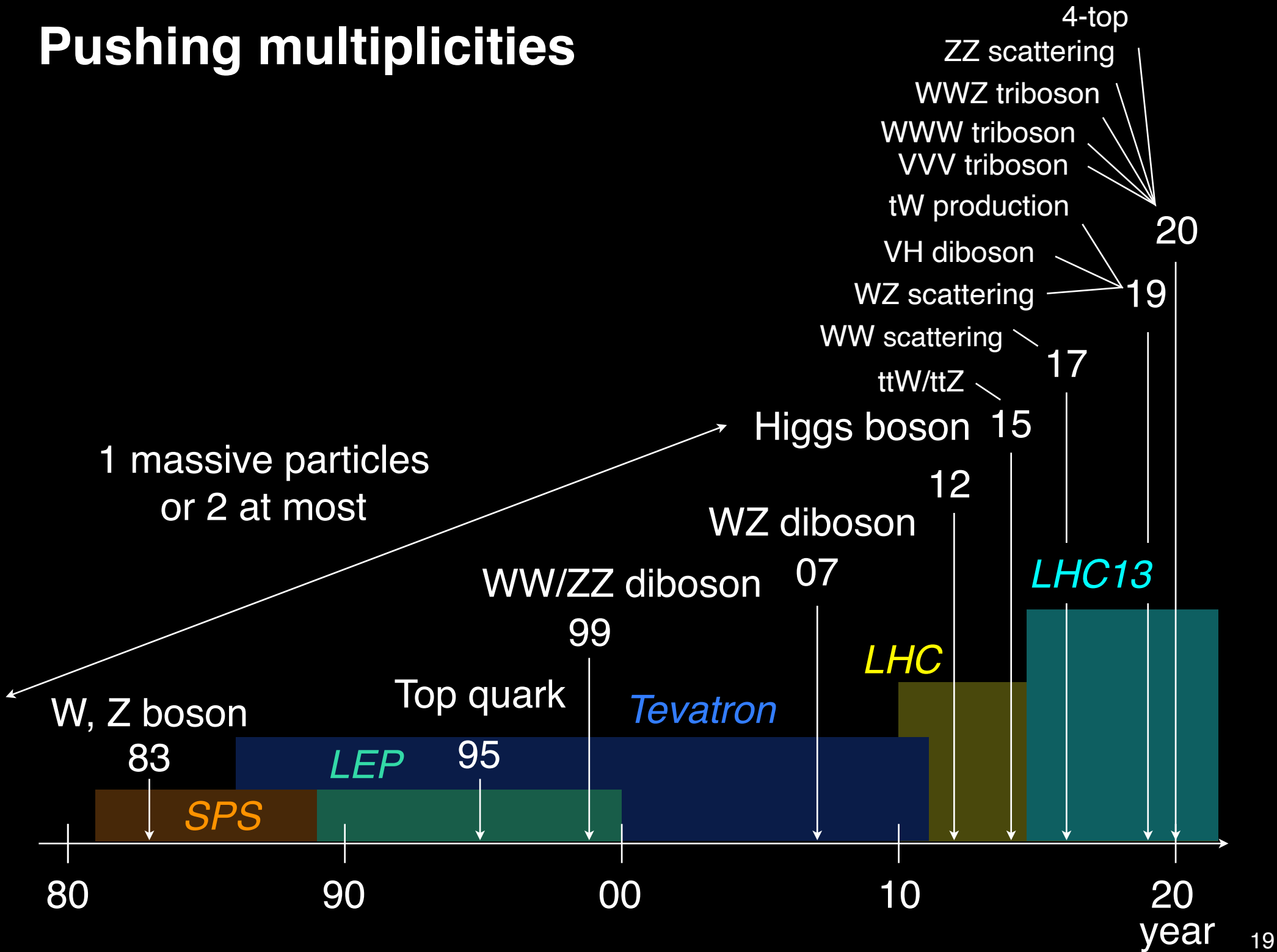
Pushing multiplicities



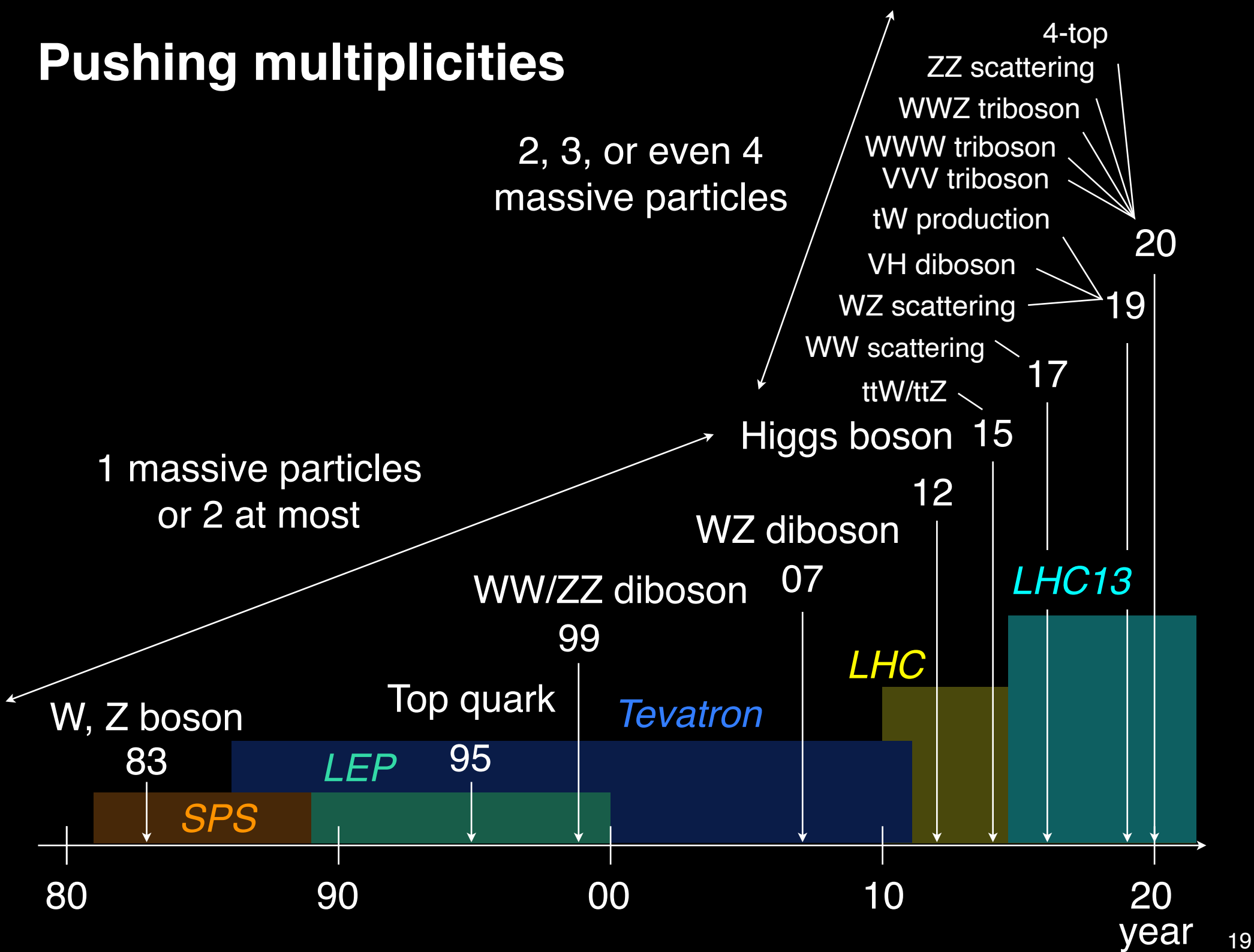
Pushing multiplicities



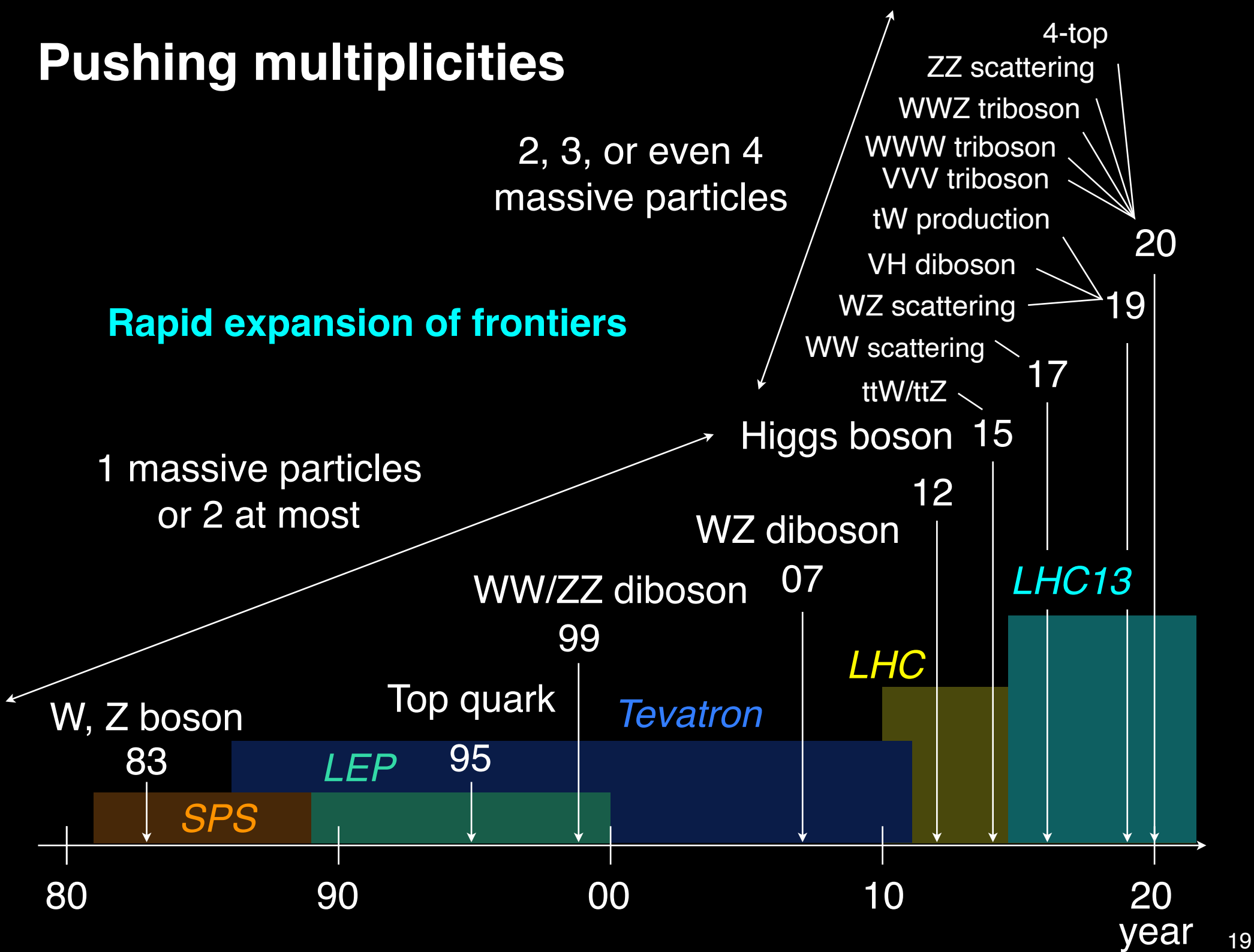
Pushing multiplicities



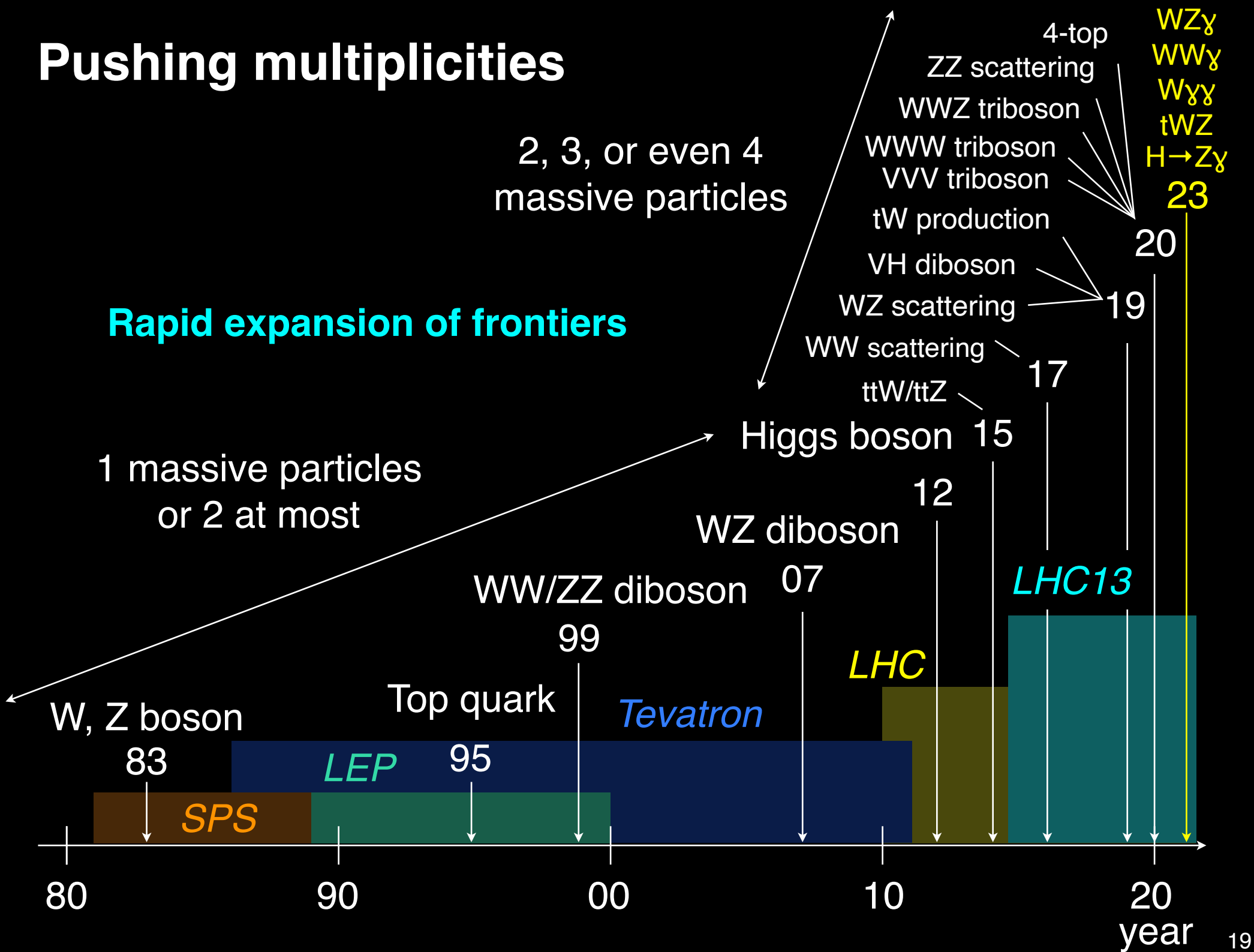
Pushing multiplicities



Pushing multiplicities



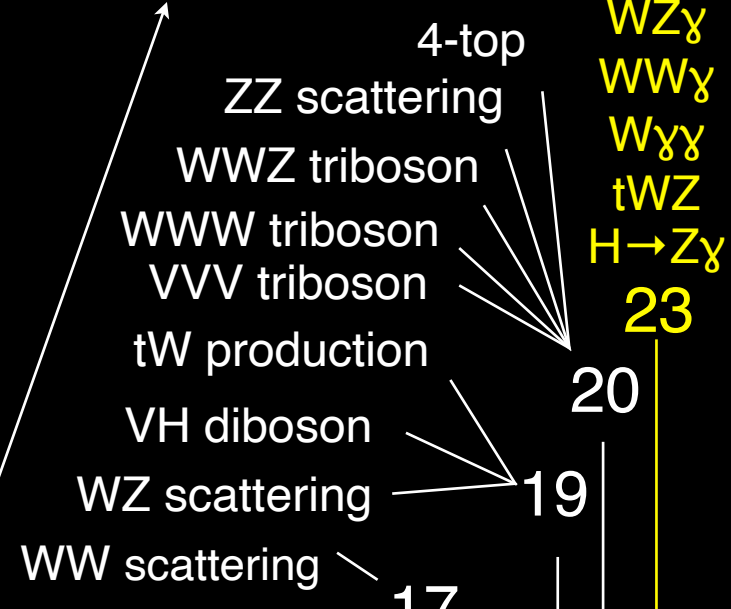
Pushing multiplicities



Pushing multiplicities

2, 3, or even 4 massive particles

Rapid expansion of frontiers

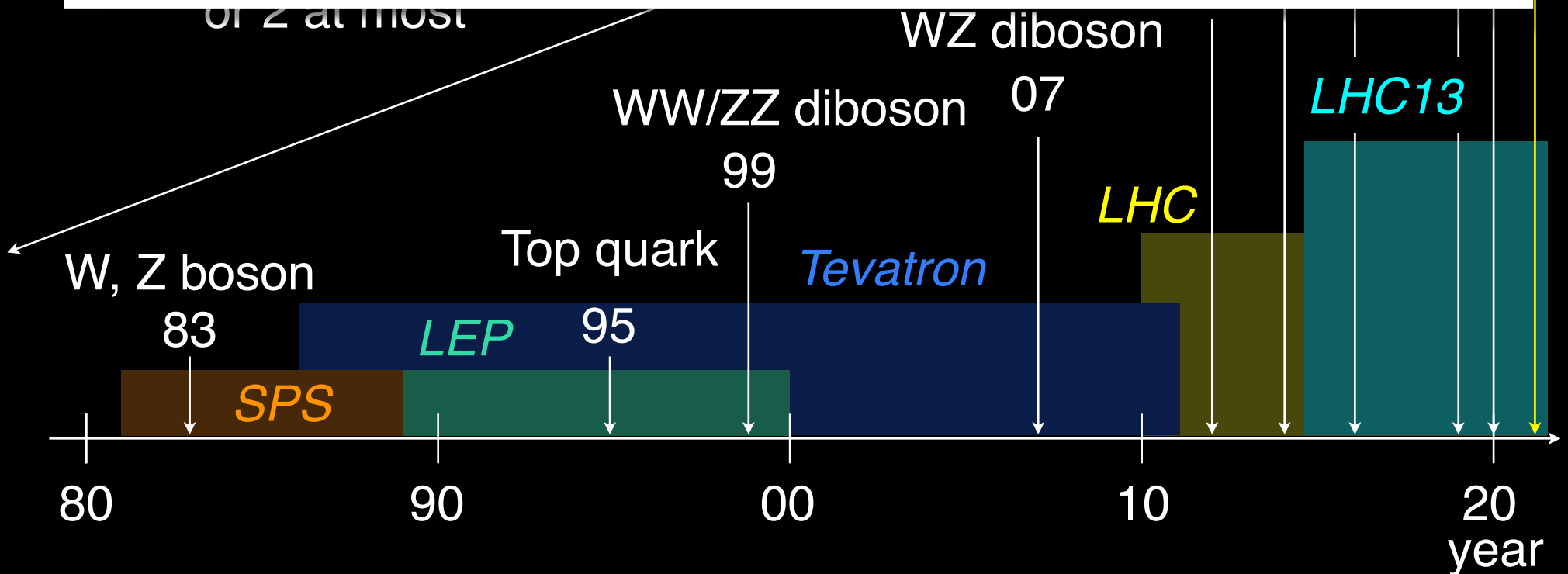


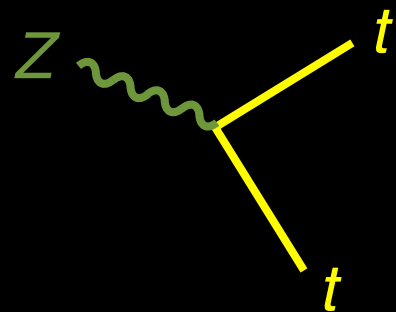
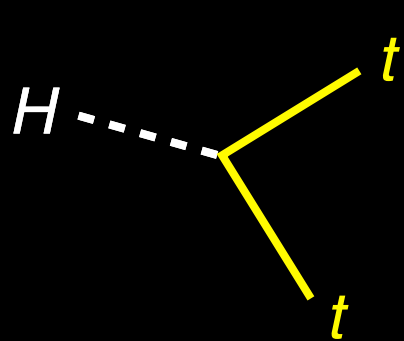
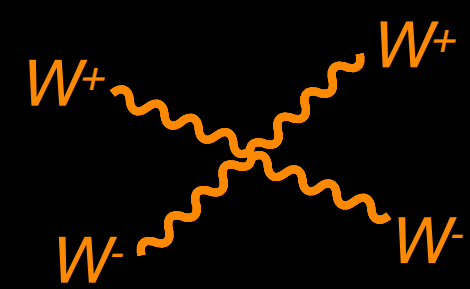
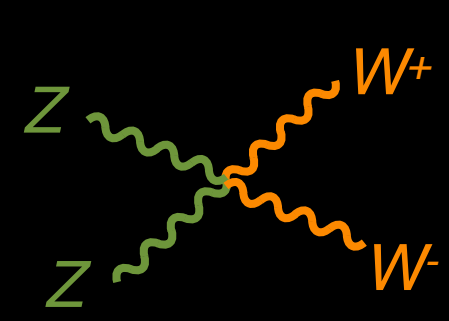
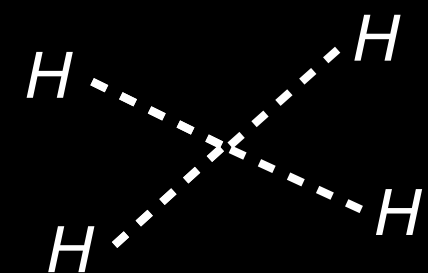
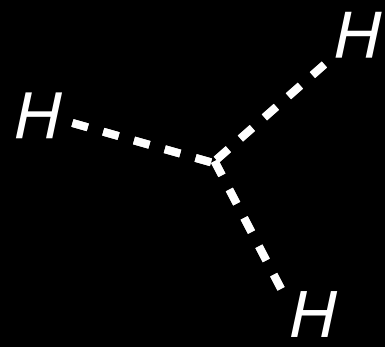
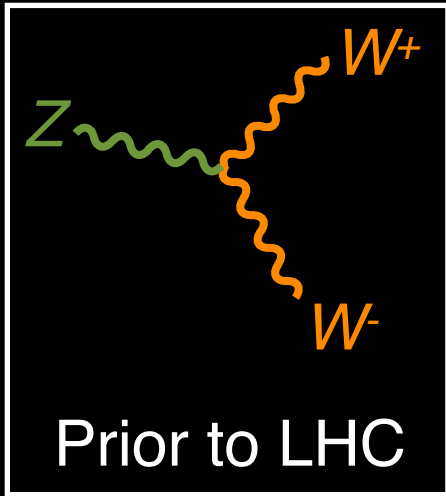
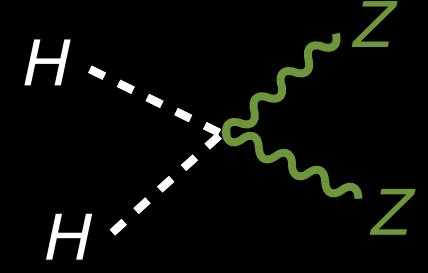
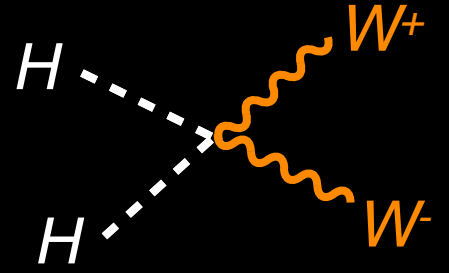
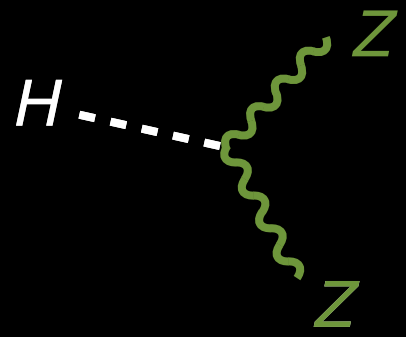
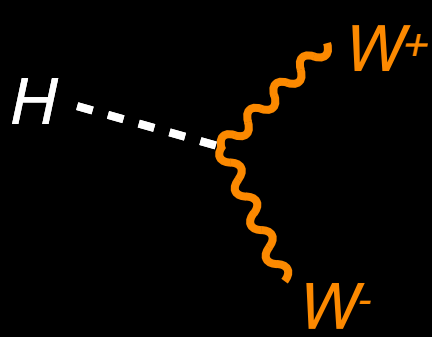
What's a discovery in particle physics

S. Gori

- Detecting for the first time a new fundamental process

or 2 at most





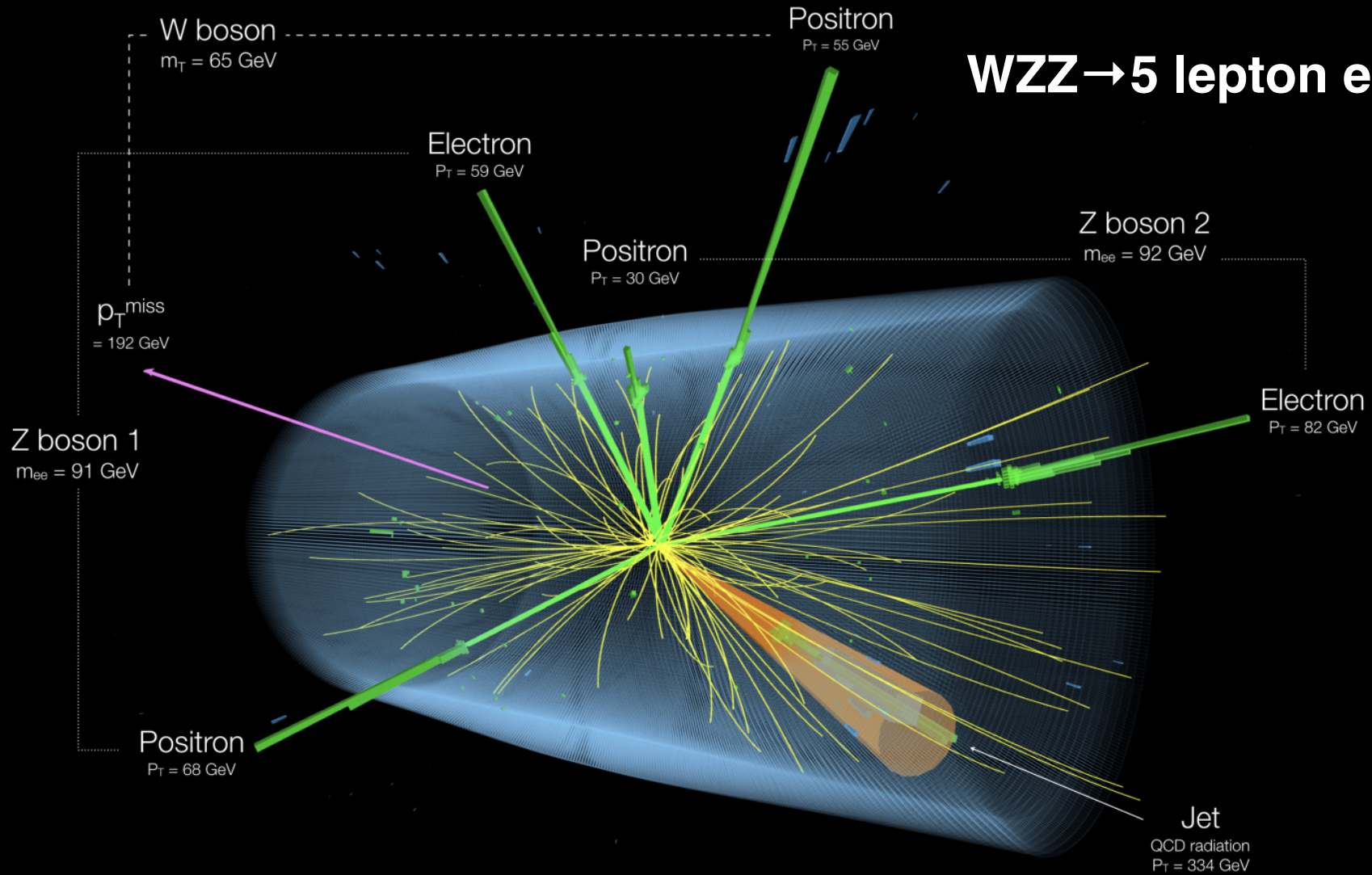
High multiplicities

$WZZ \rightarrow 5$ lepton event

CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491



$WZZ \rightarrow 5$ lepton events



5 electrons

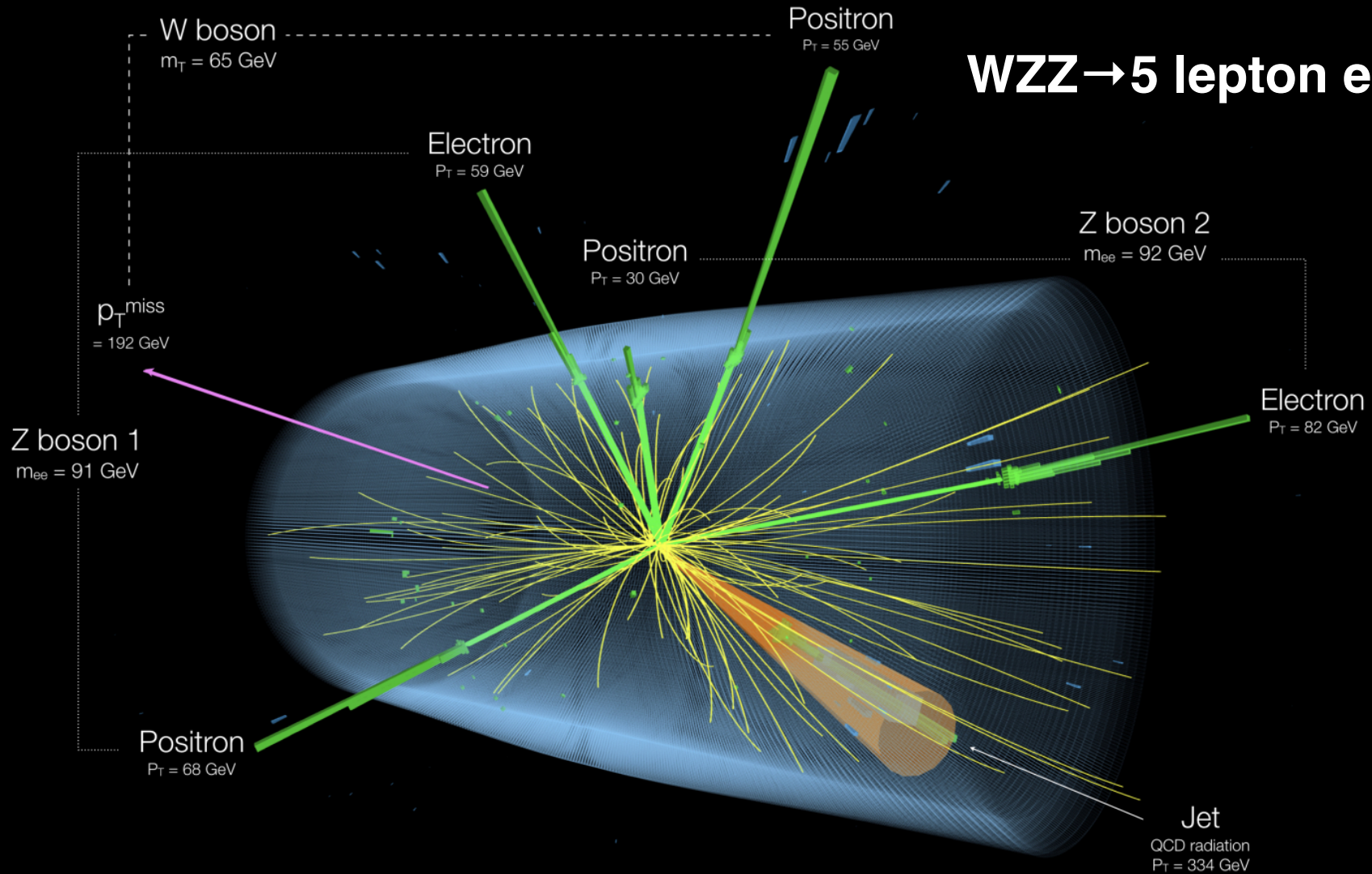
High multiplicities

$WZZ \rightarrow 5$ lepton event

CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491



$WZZ \rightarrow 5$ lepton events

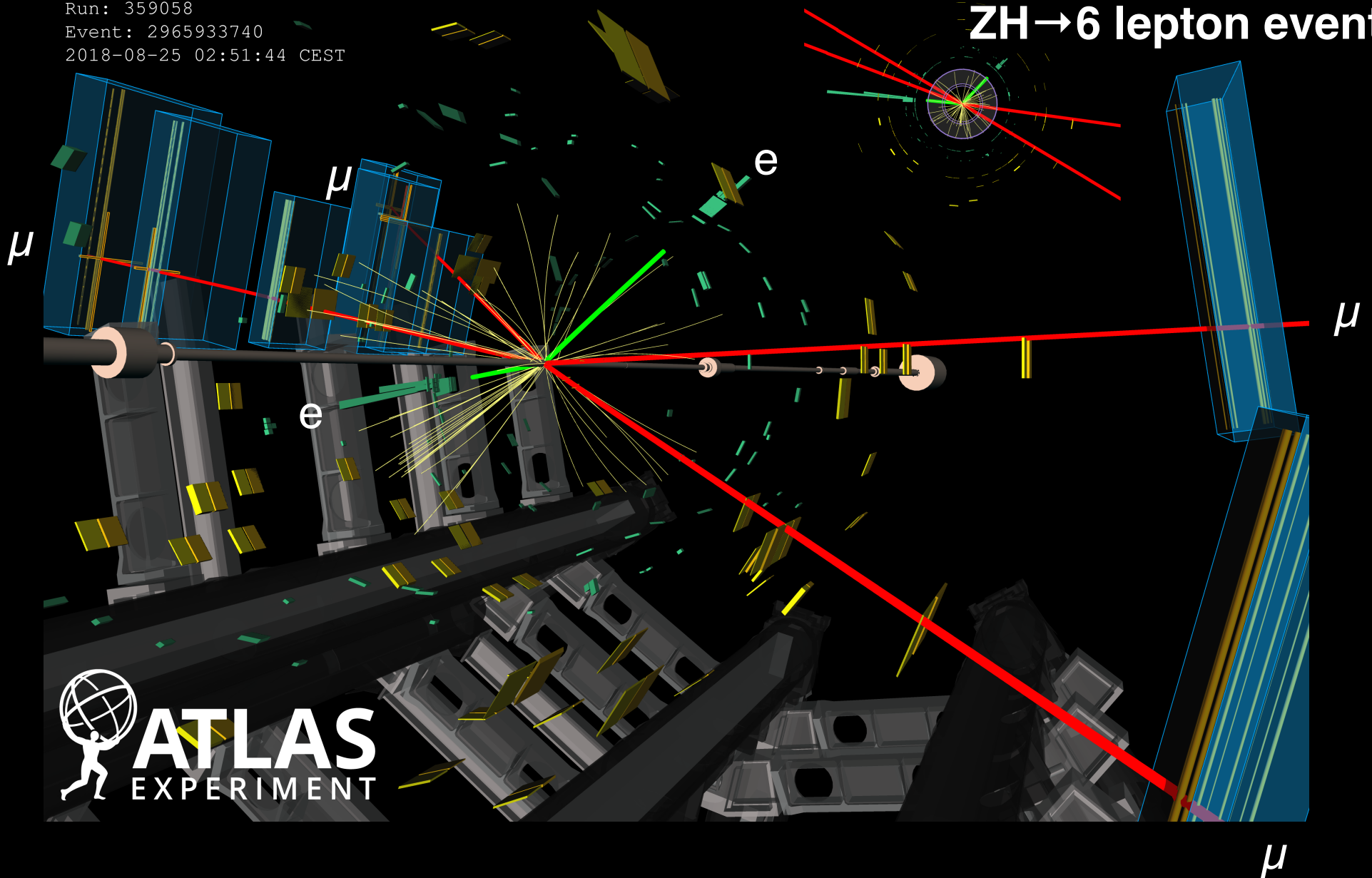


We expected ~ 1 event like this out of 15,000,000,000,000,000 collisions
5 electrons

High multiplicities

Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST

ZH → 6 lepton events


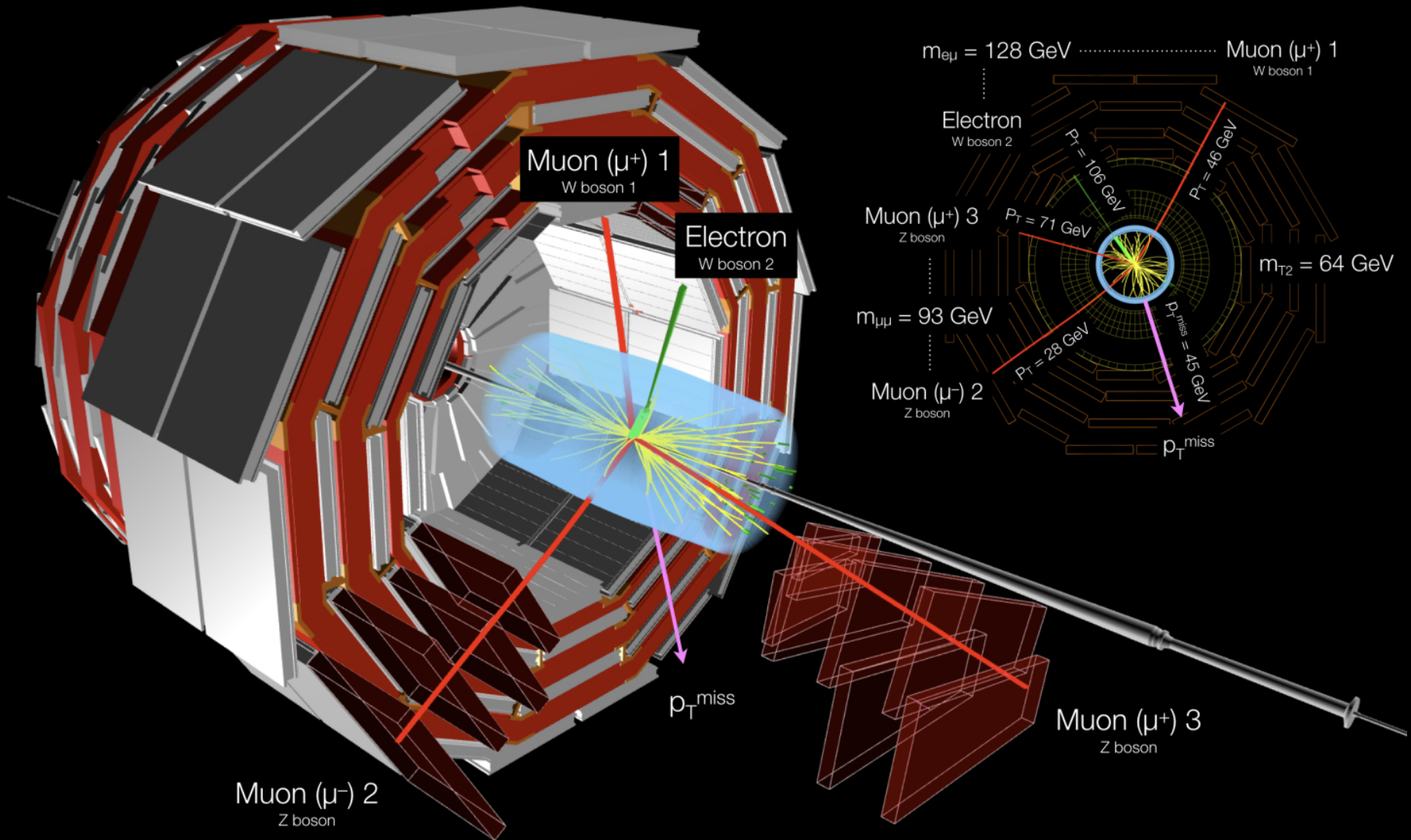


This event was also ~1 event expected

High multiplicity case study

WWZ → 4 lepton event

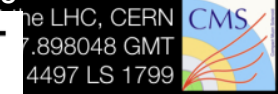
CMS experiment at the LHC, CERN
Data recorded: 2016-Jul-23 08:13:27.898048 GMT
Run 277168, Event No. 3219714497 LS 1799

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

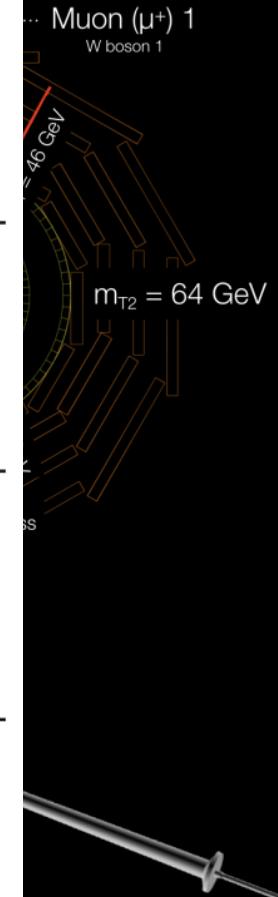
High multiplicity case study

arXiv:1902.10229



WWZ

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

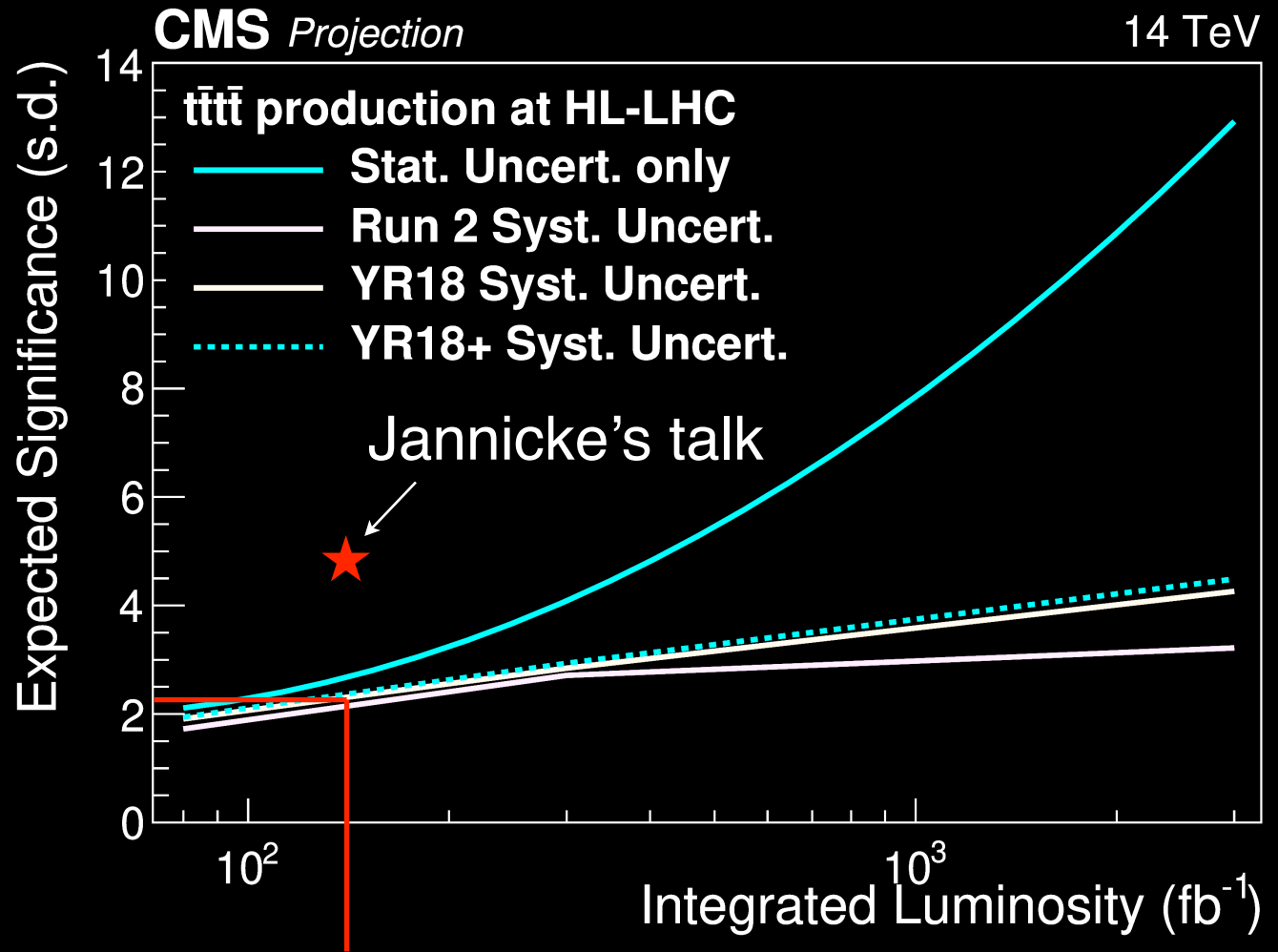
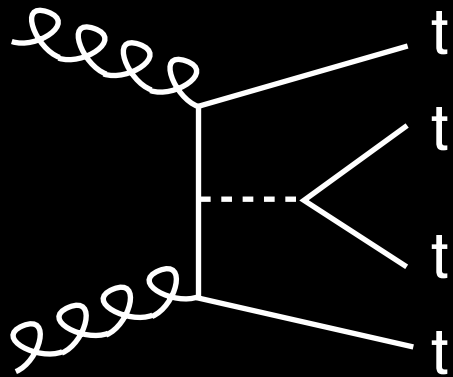


Expected to reach 3σ in 3000 fb⁻¹ → But we did it with 137 fb⁻¹

High multiplicity case study

arXiv:1902.10229

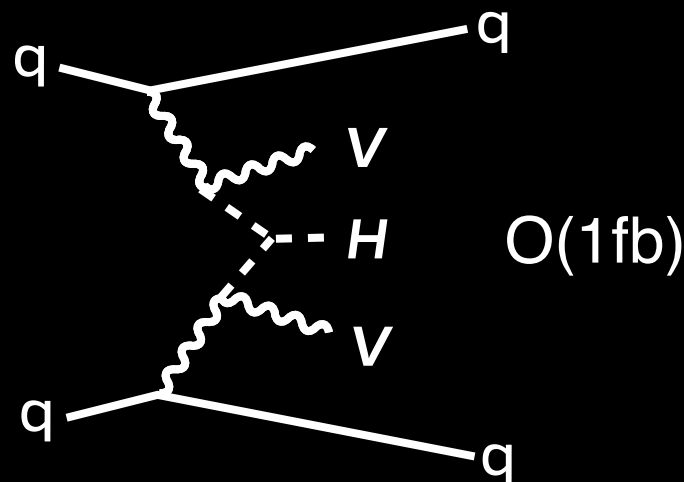
14 TeV



Many more multi-t,W,Z,H

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

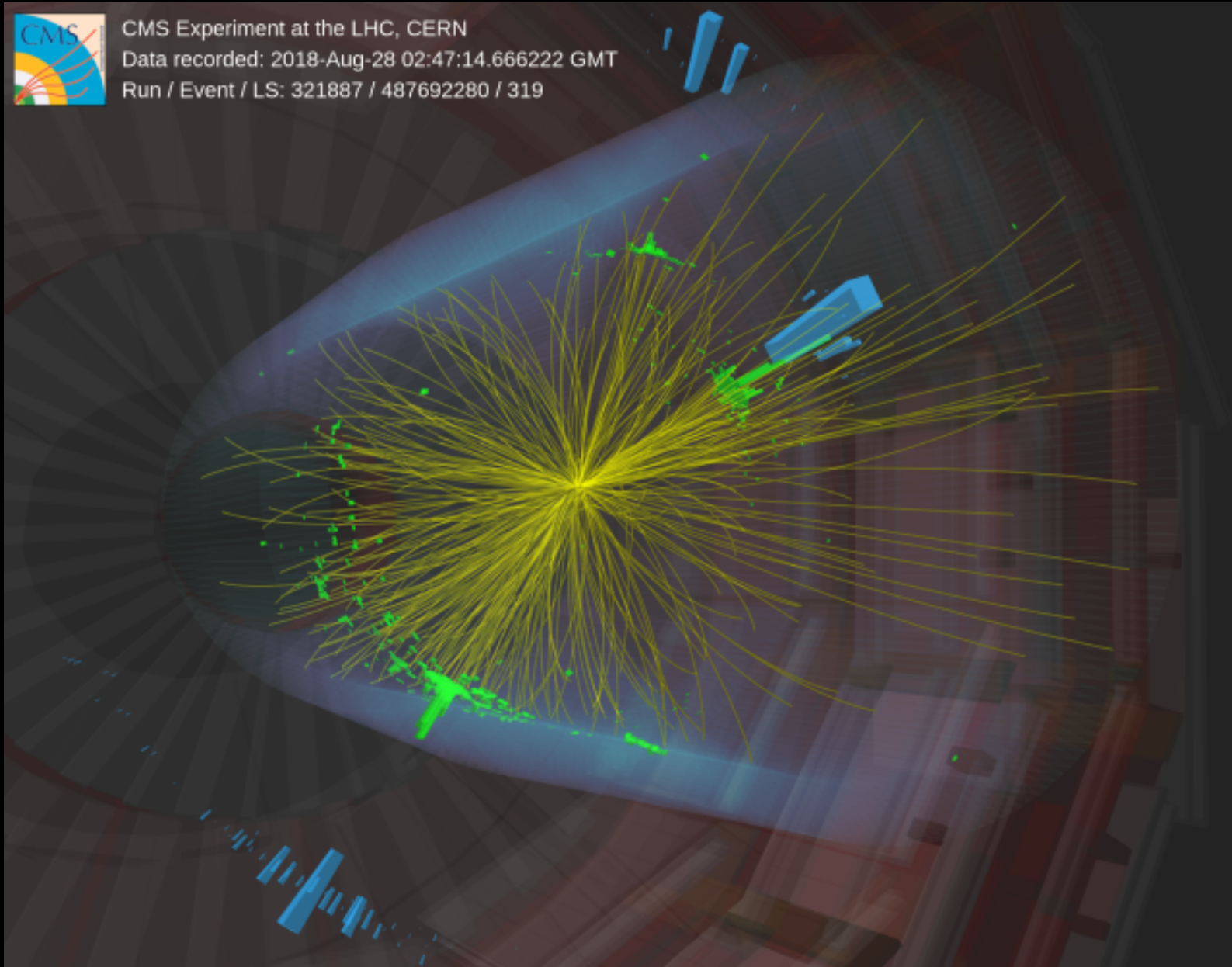
O(1fb)



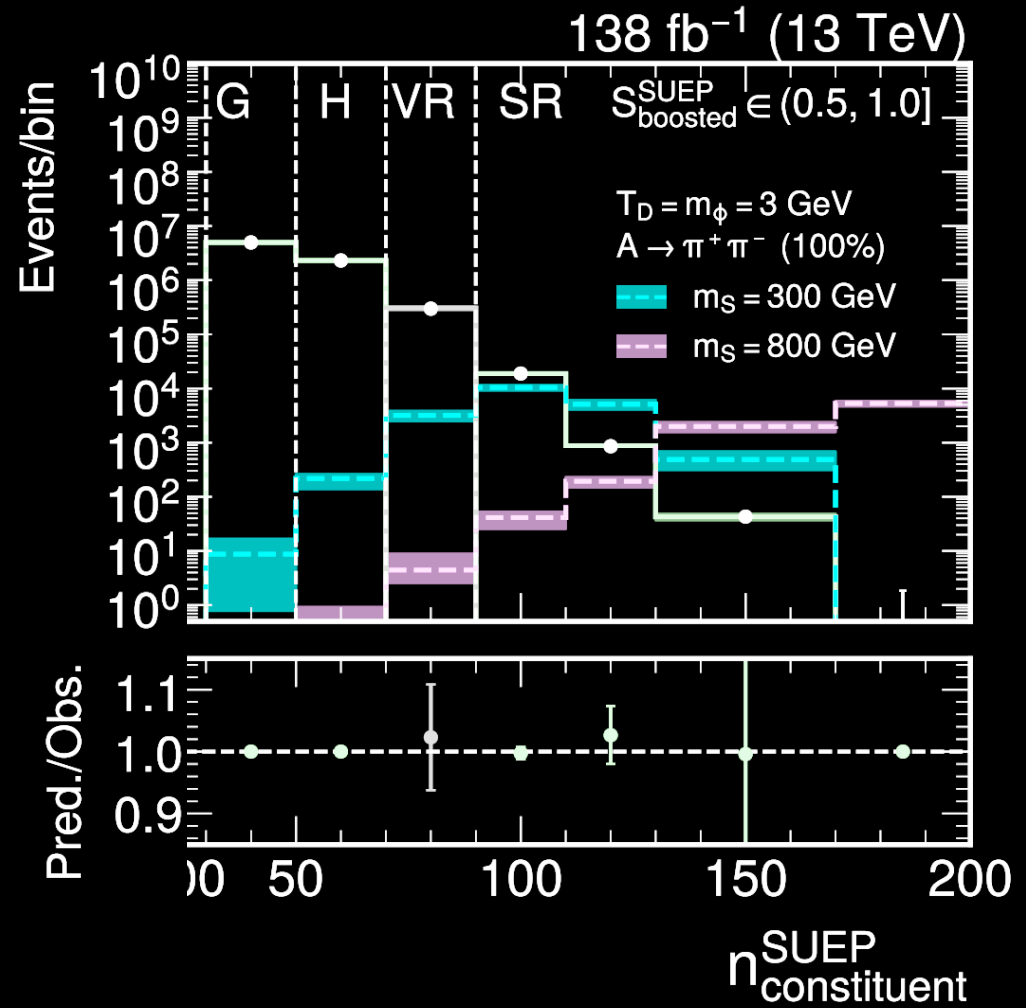
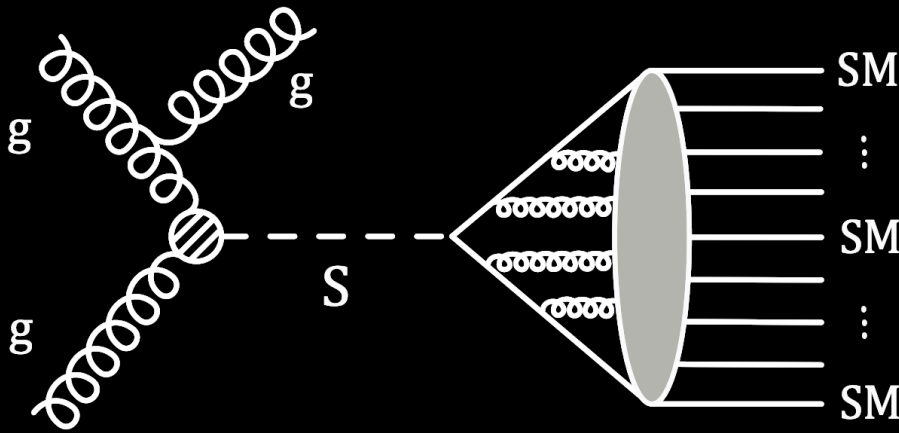
These phase-space would be possible to study

Pushing multiplicities even further

soft unclustered energy pattern (SUEP)

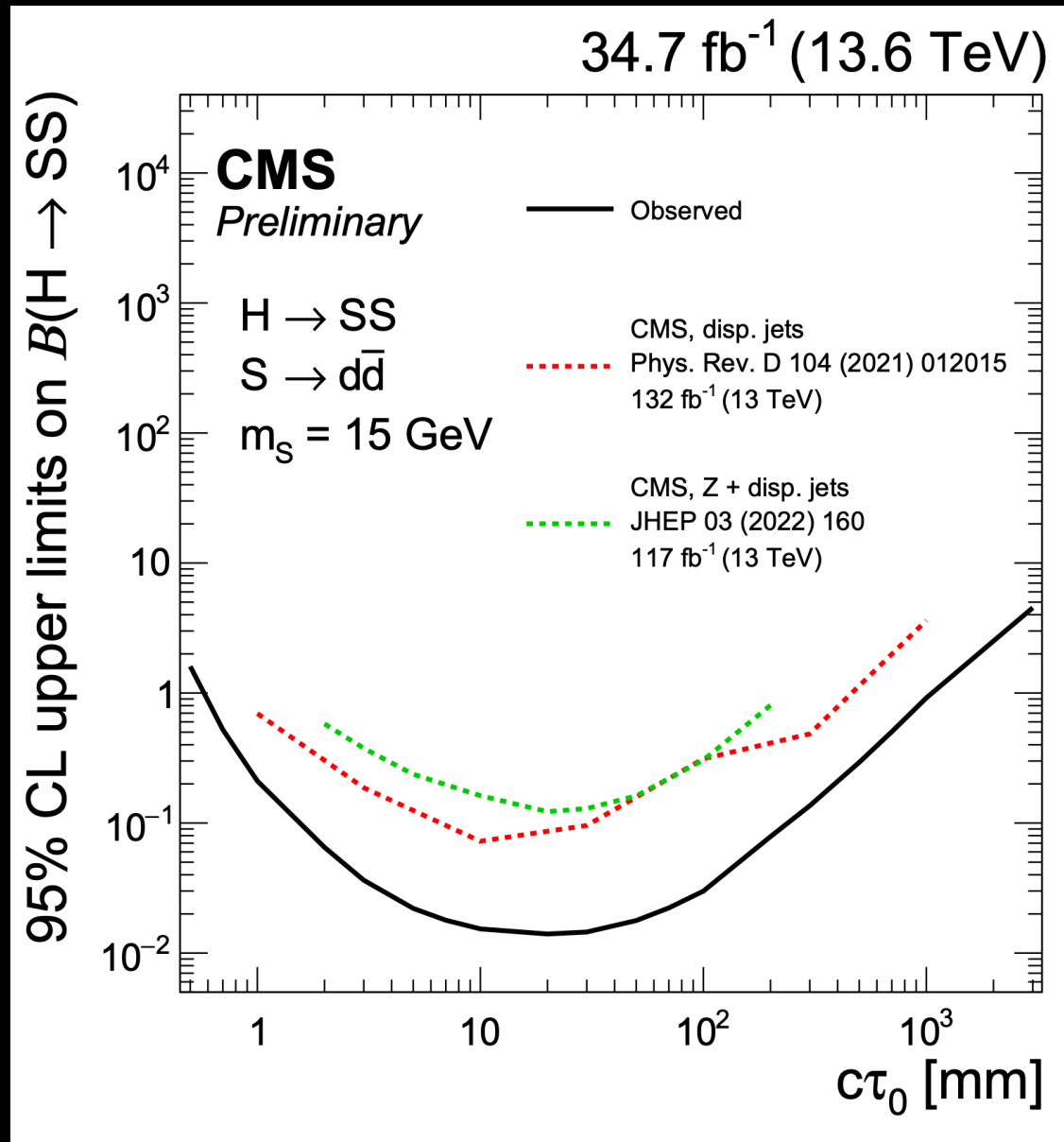
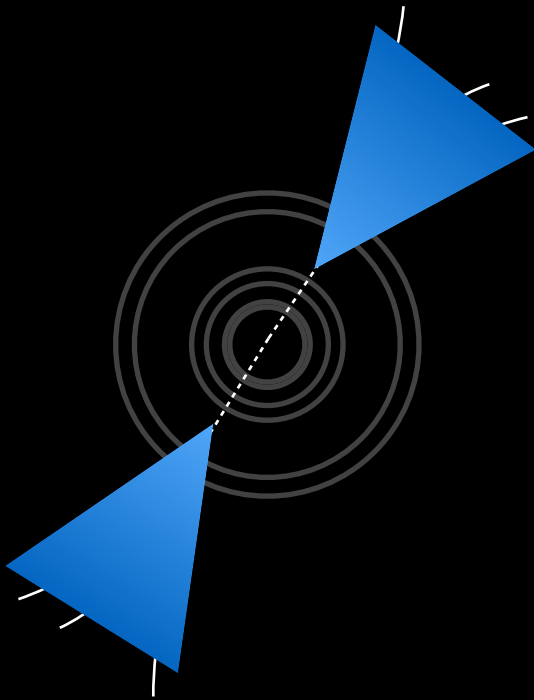


Pushing multiplicities even further



Pushing lifetime

displaced di-jet



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

Pushing "Angles"

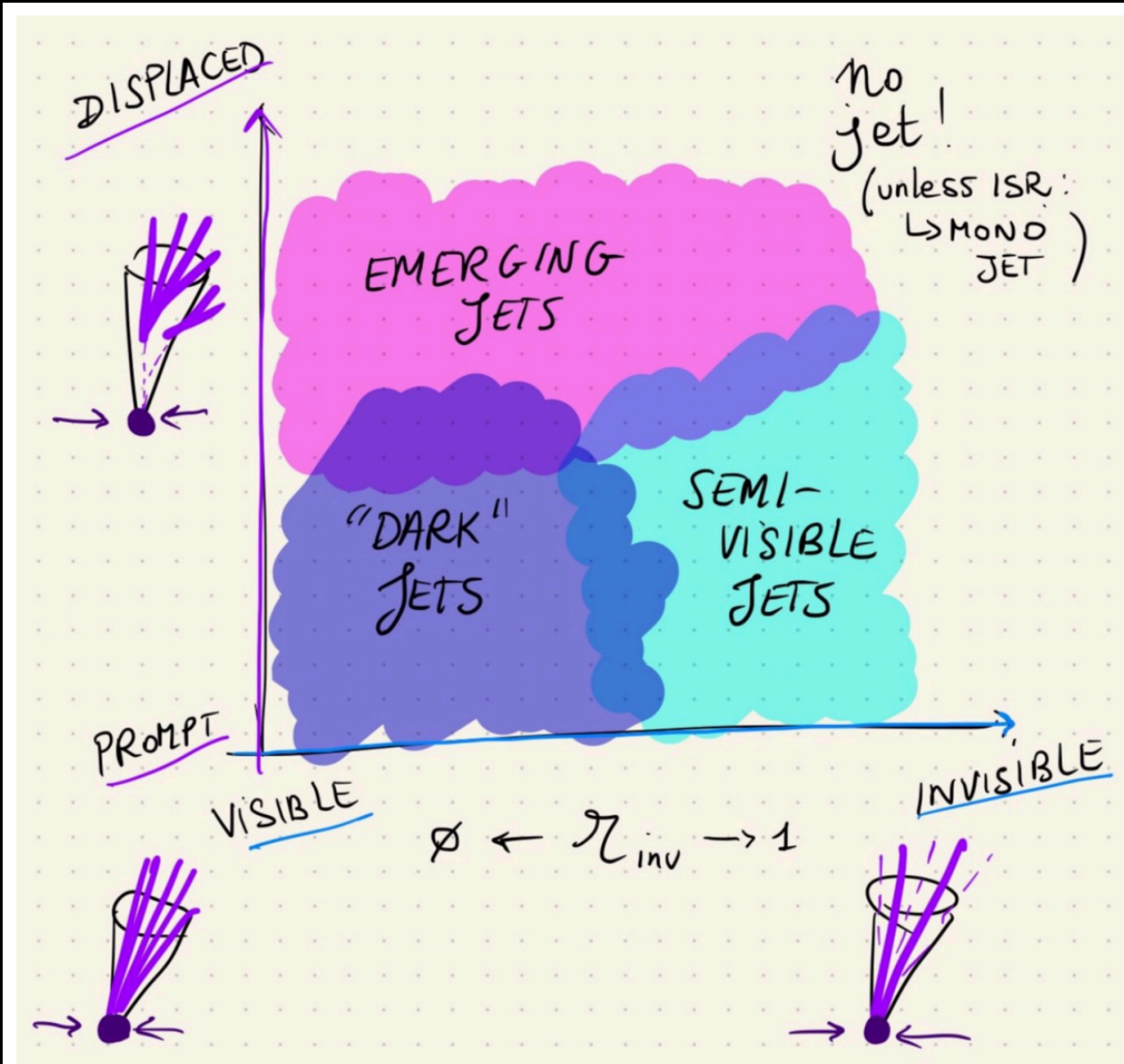
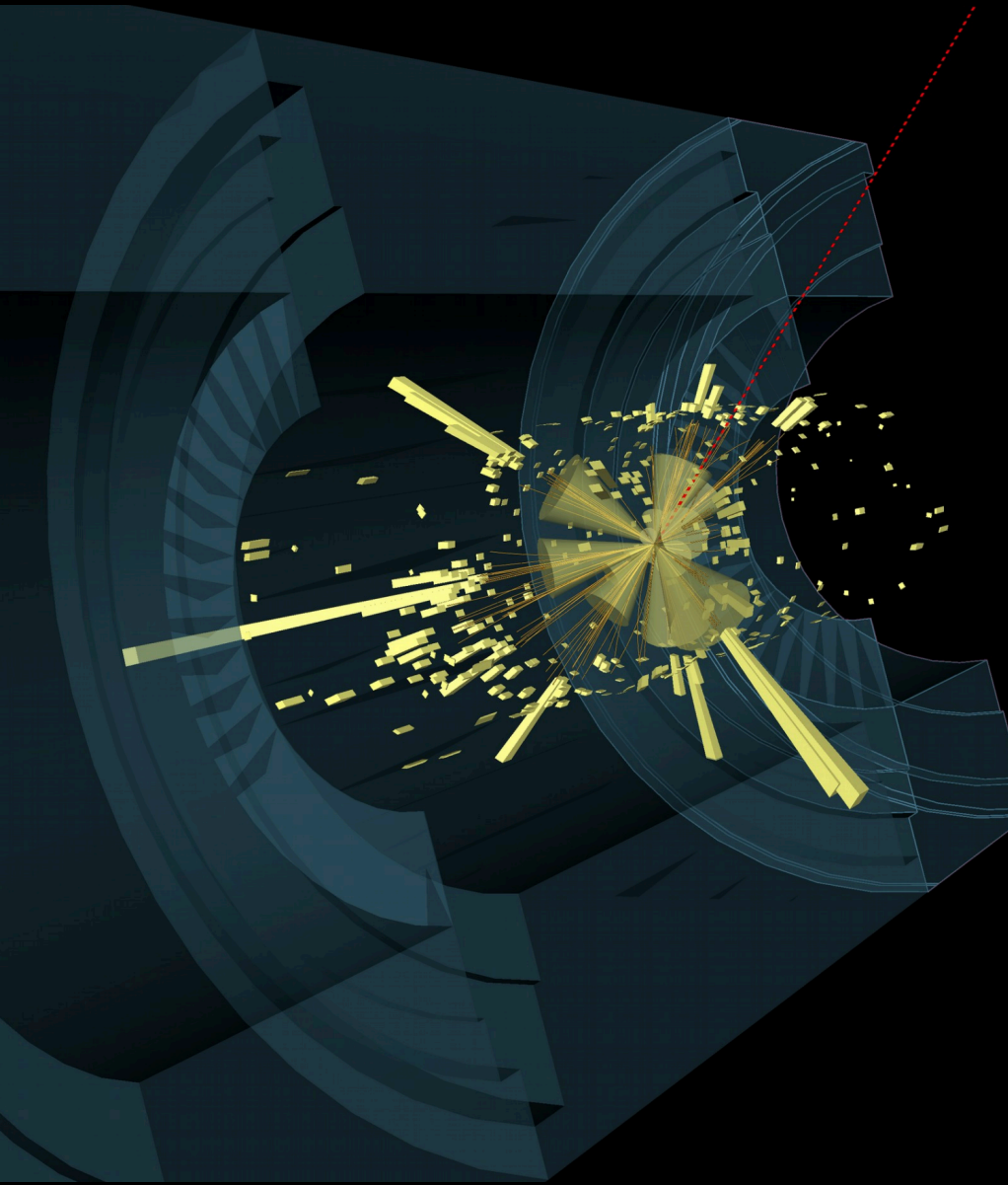
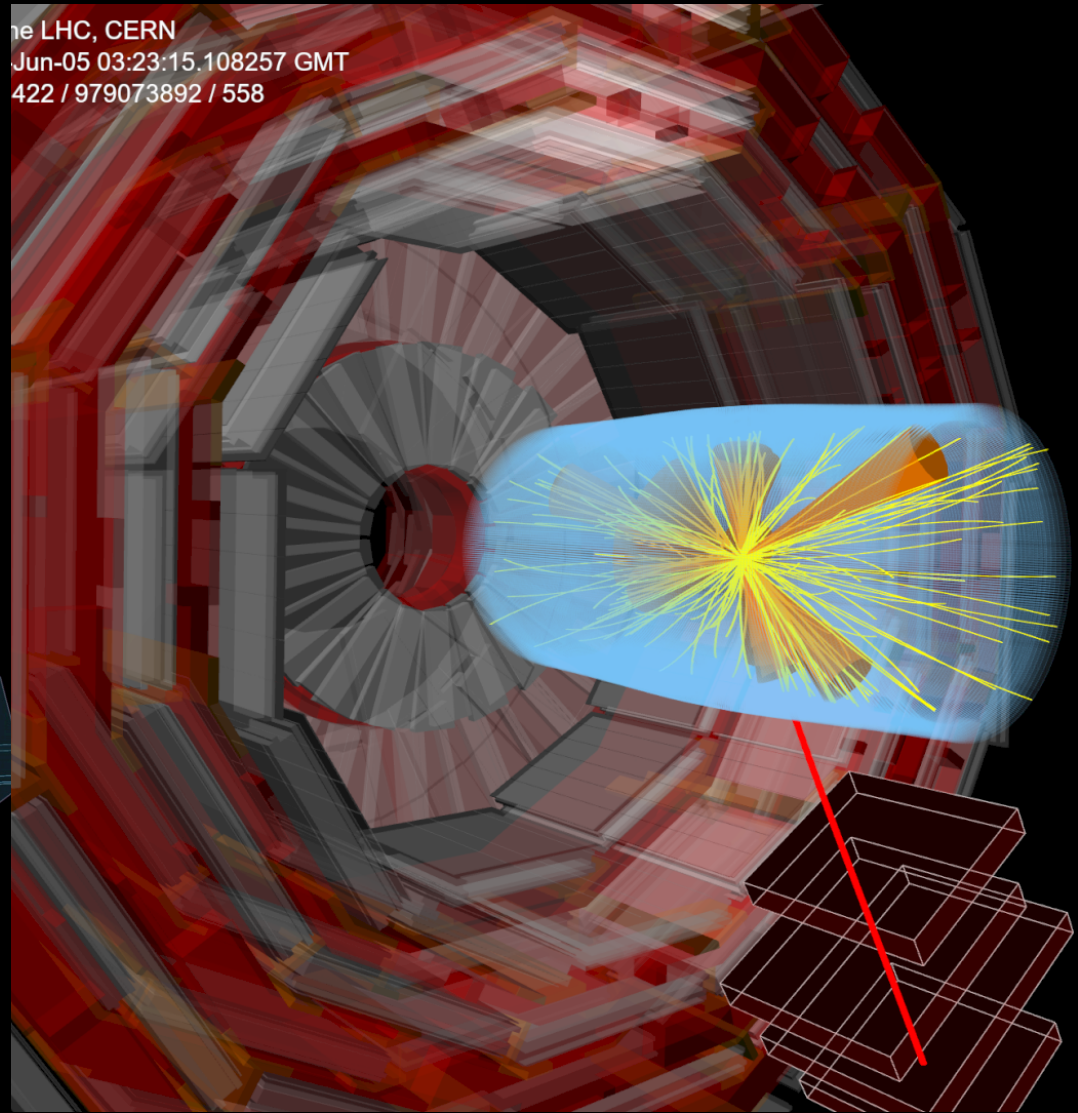


Image C. Doglioni

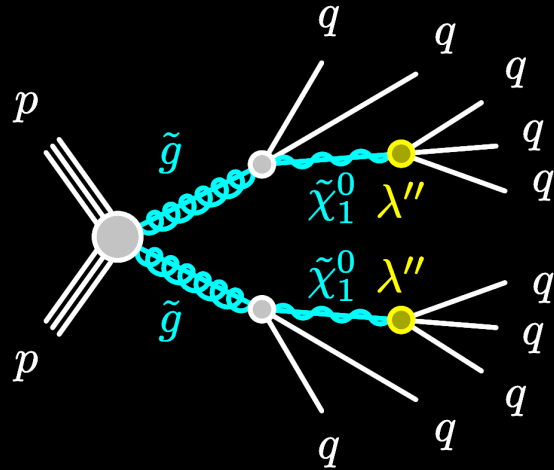
Many jets



the LHC, CERN
Jun-05 03:23:15.108257 GMT
422 / 979073892 / 558

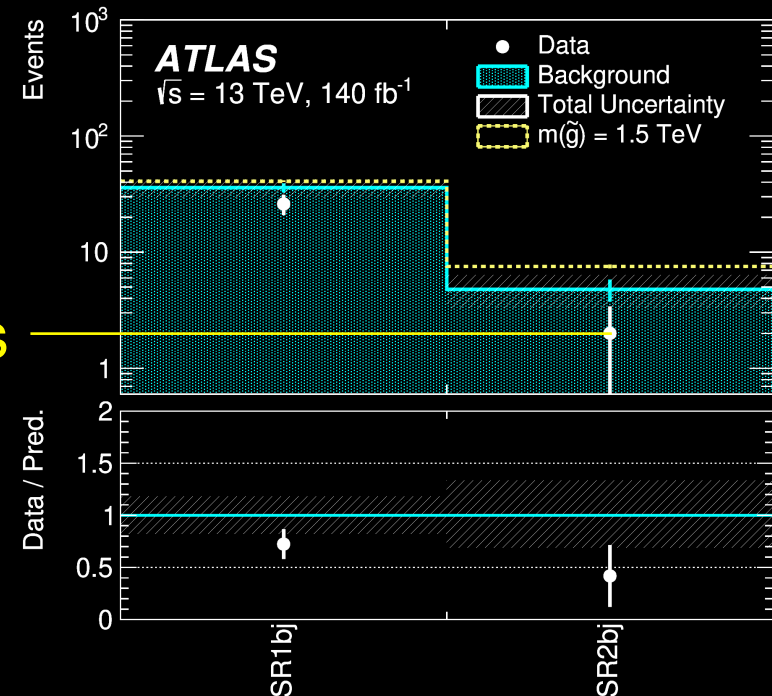
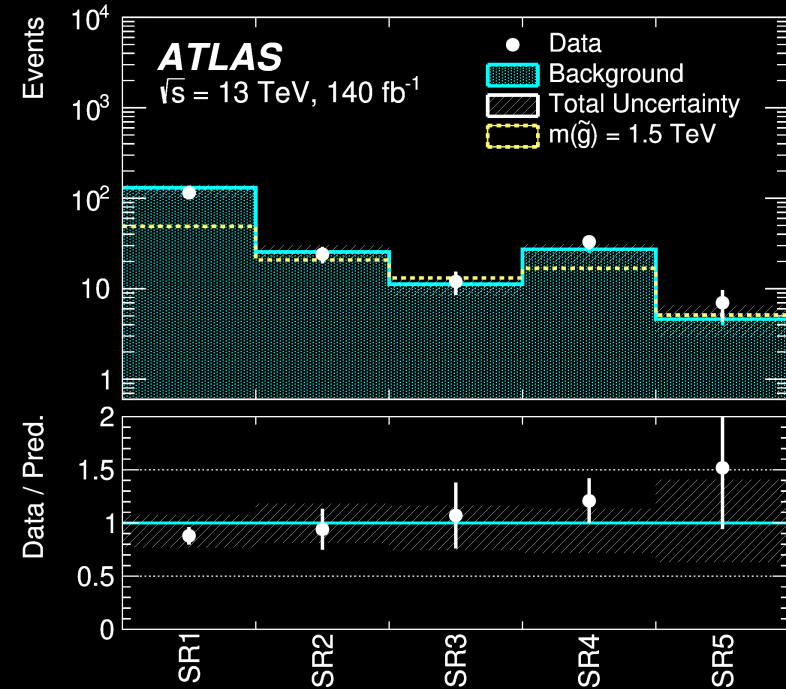


Many jets



	n_{jets}	$p_{\text{T}}(j)$ [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



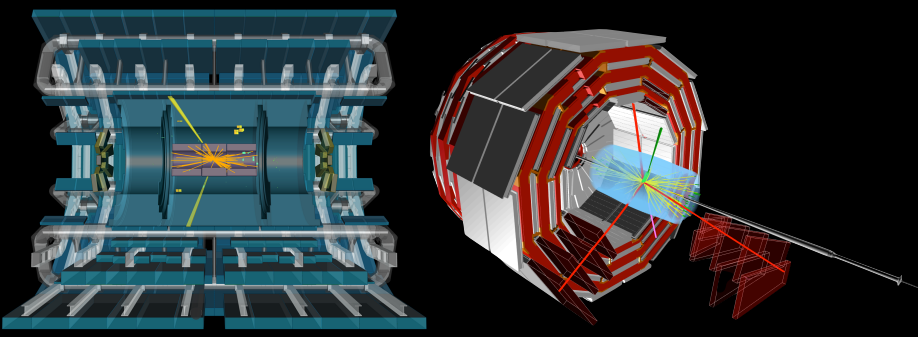
It did not use mass because too little evt. but in HL-LHC you could

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

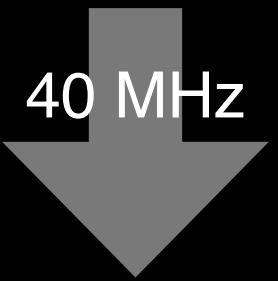
CARL D. ANDERSON AND SETH H. NEDDERMEYER, *Norman Bridge Laboratory of Physics, California Institute of Technology*
(Received June 9, 1936)

Observations of N same-charged lepton events ($l^+l^+l^+, l^+l^+l^+l^+, \dots$) ?

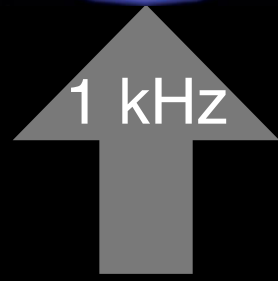
Go down deeper into the weeds



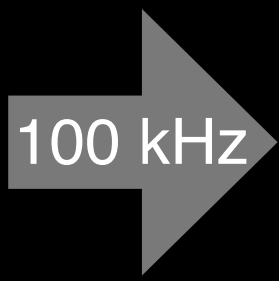
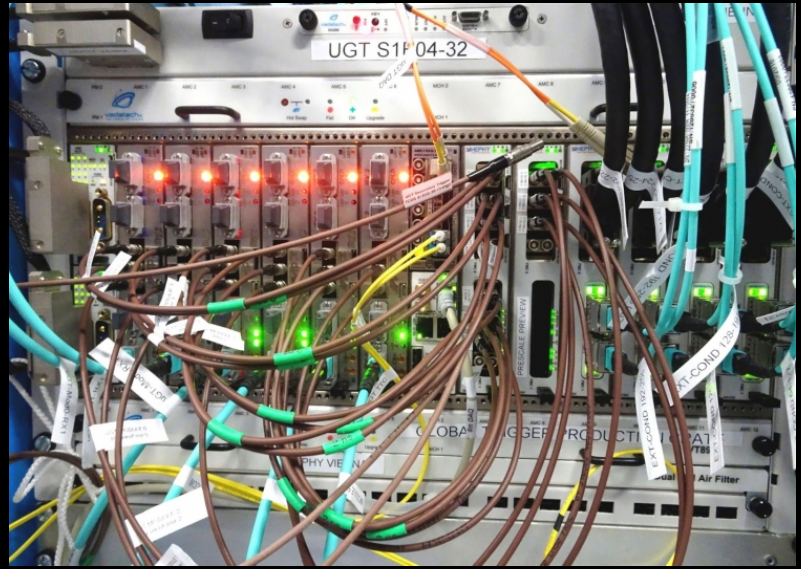
Analysis



40 MHz



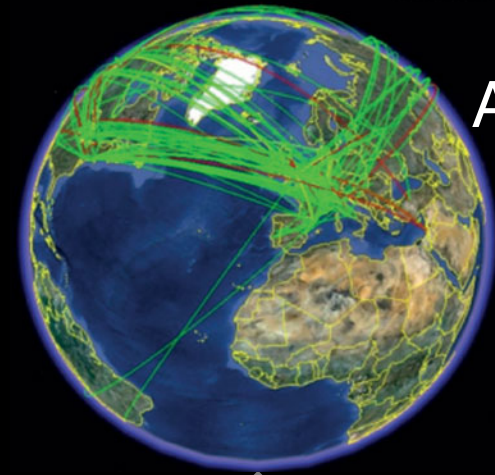
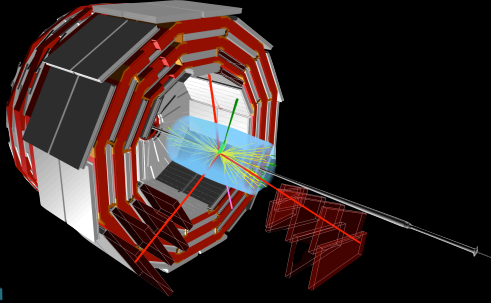
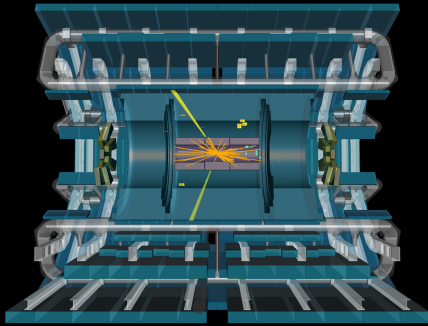
1 kHz



100 kHz



Go down deeper into the weeds

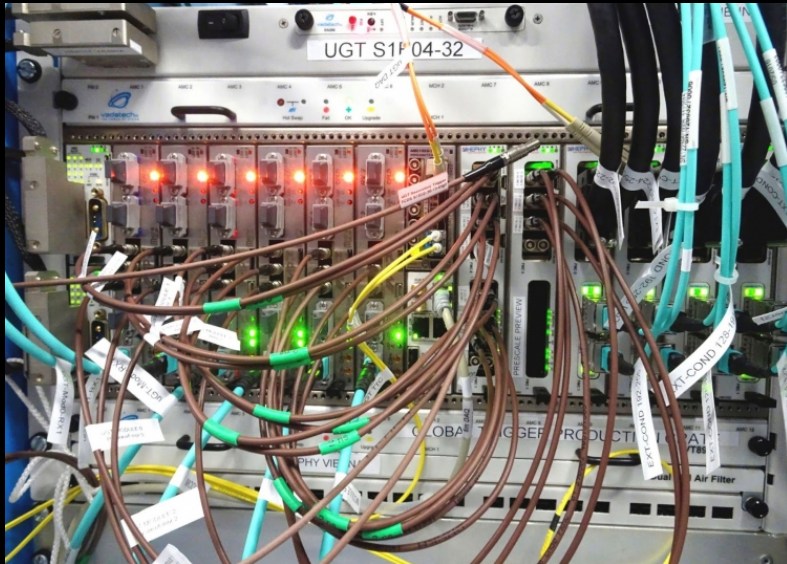


Analysis

40 MHz

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

1 kHz

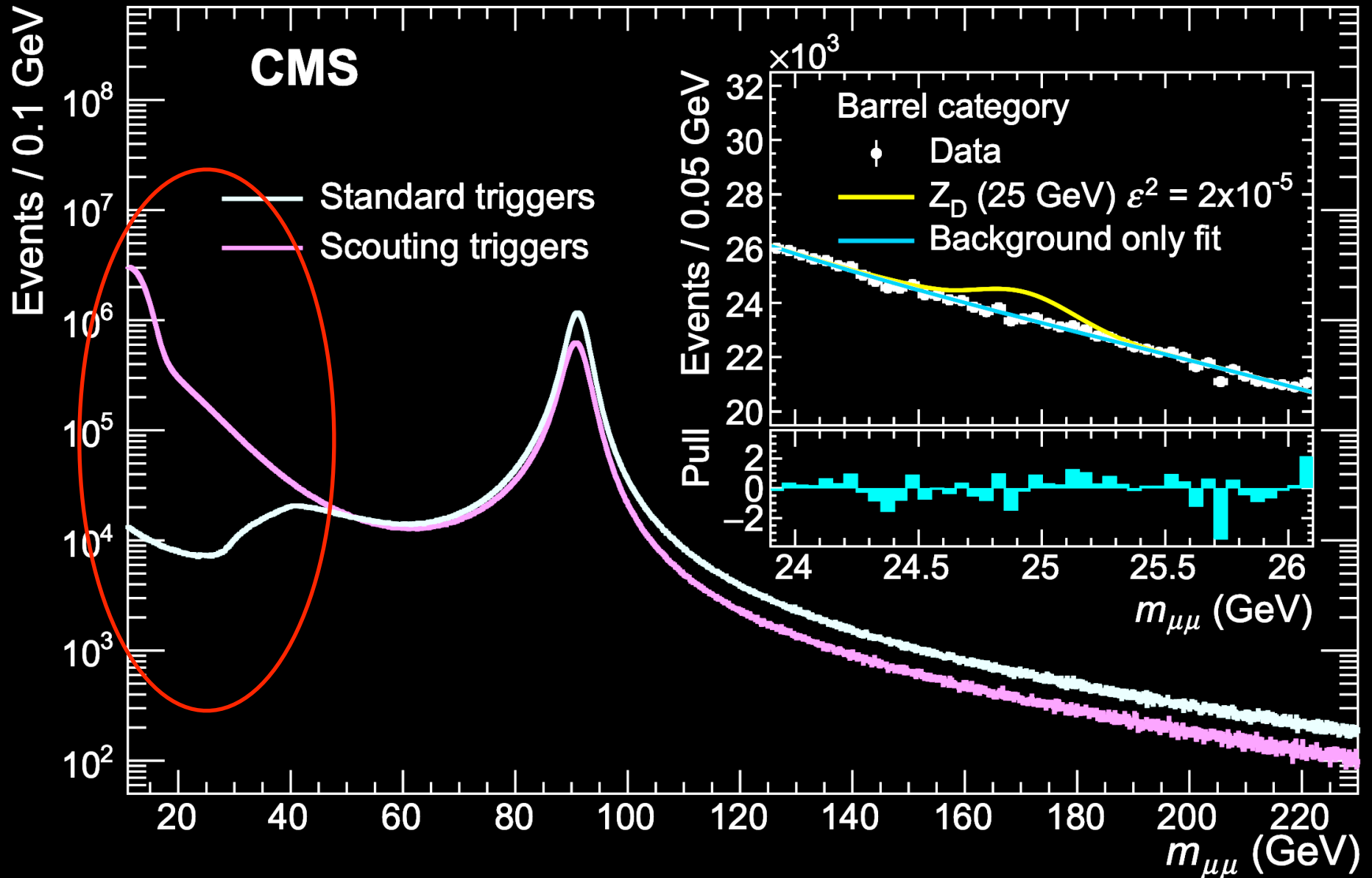


100 kHz



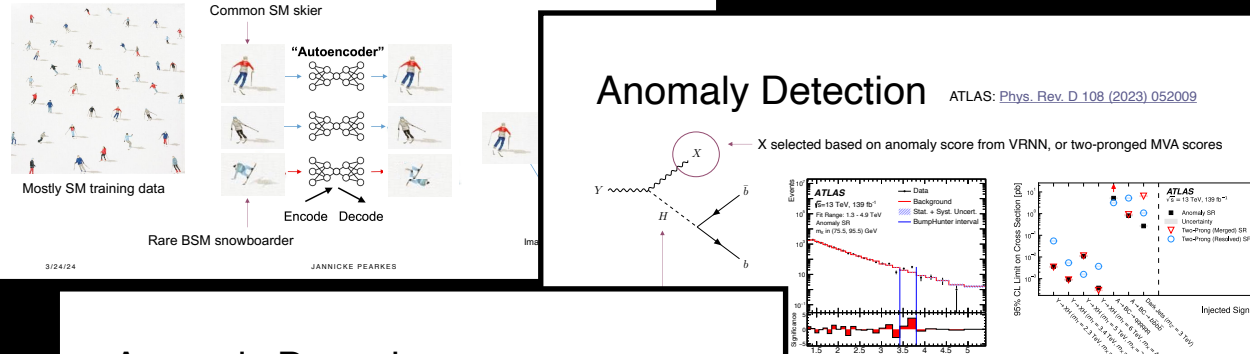
Go down deeper into the weeds

137 fb⁻¹ (standard triggers) and 96.6 fb⁻¹ (scouting triggers) (13 TeV)

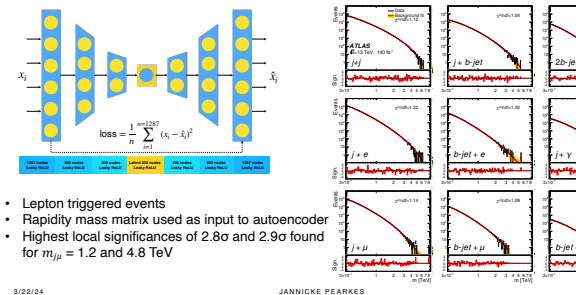


Anomaly detection

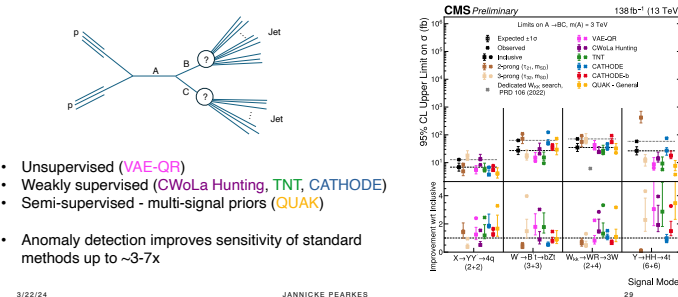
Anomaly Detection with with Unsupervised Machine Learning



Anomaly Detection



Anomaly Detection



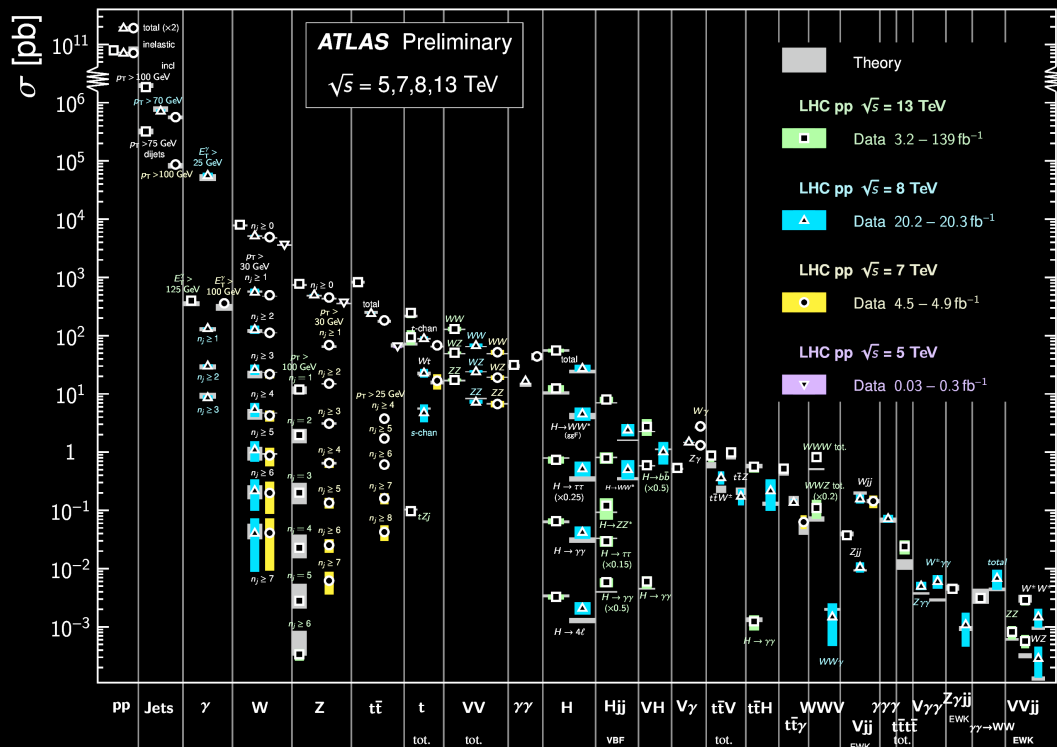
See Jannicke's slides

But what if you still....

Measurement

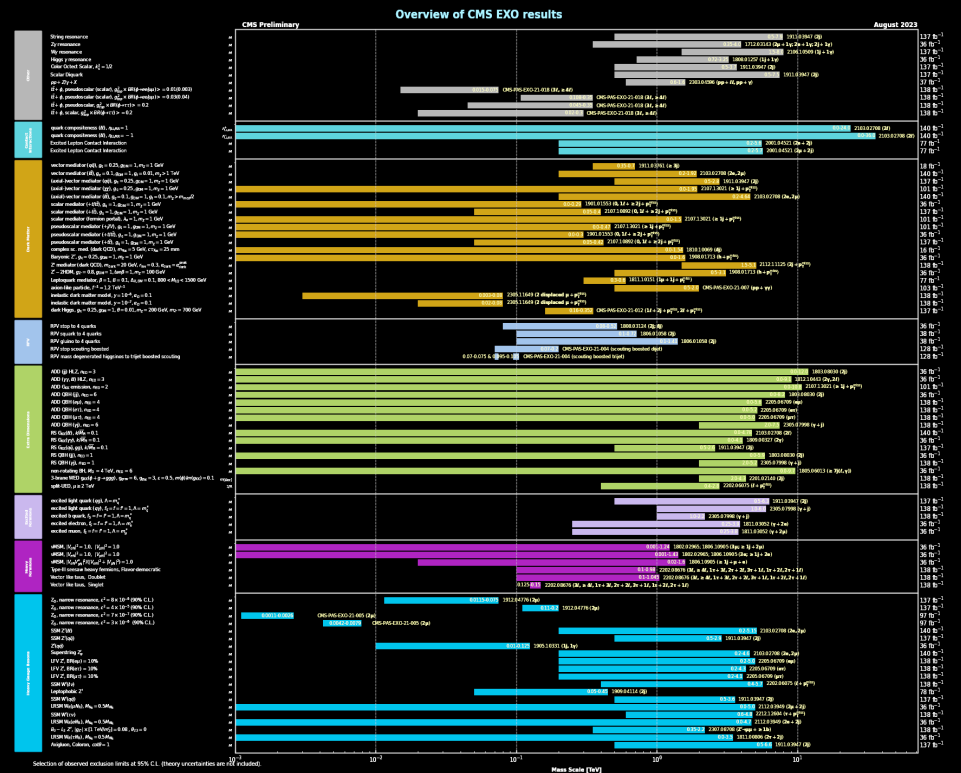
Standard Model Production Cross Section Measurements

Status: February 2022



No crack

Searches

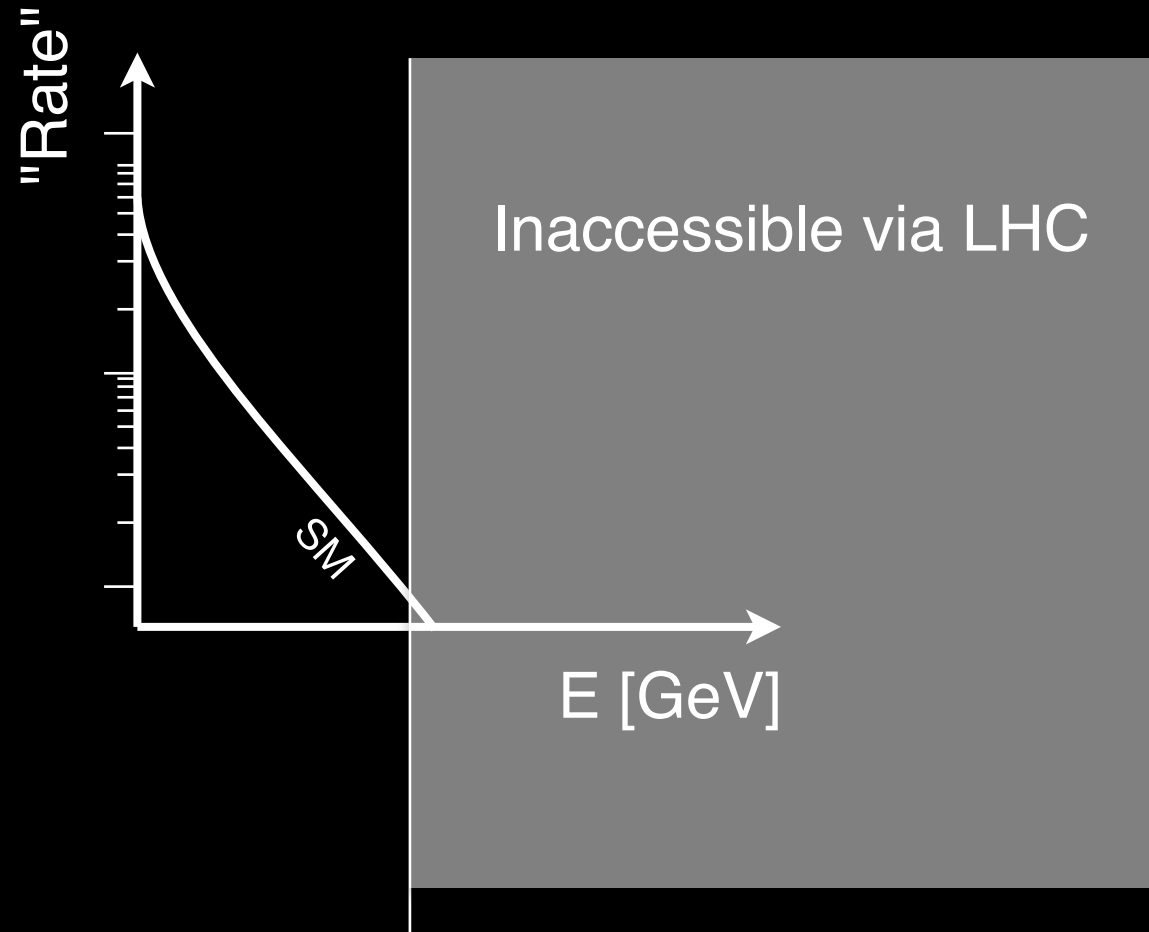


No excess

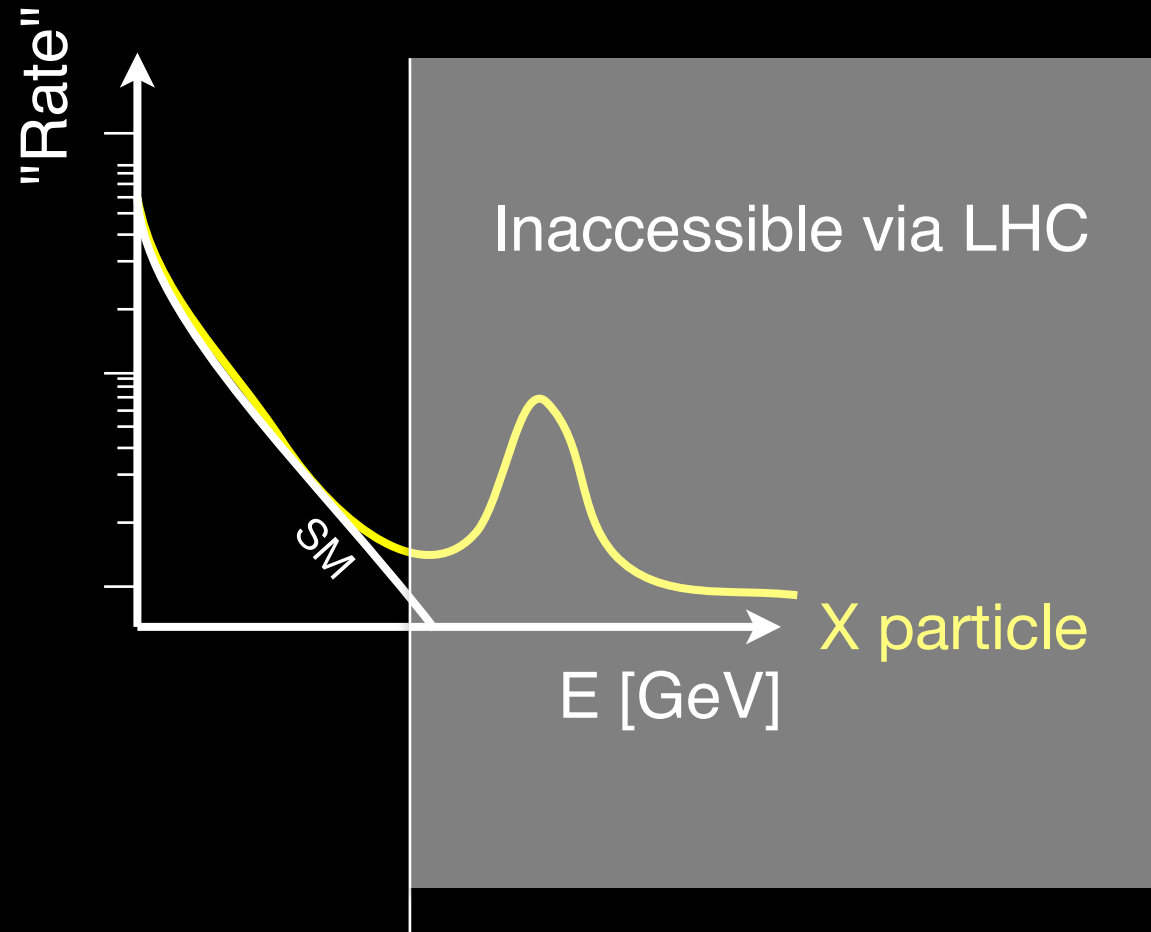
Effective Field Theory

Inaccessible via LHC

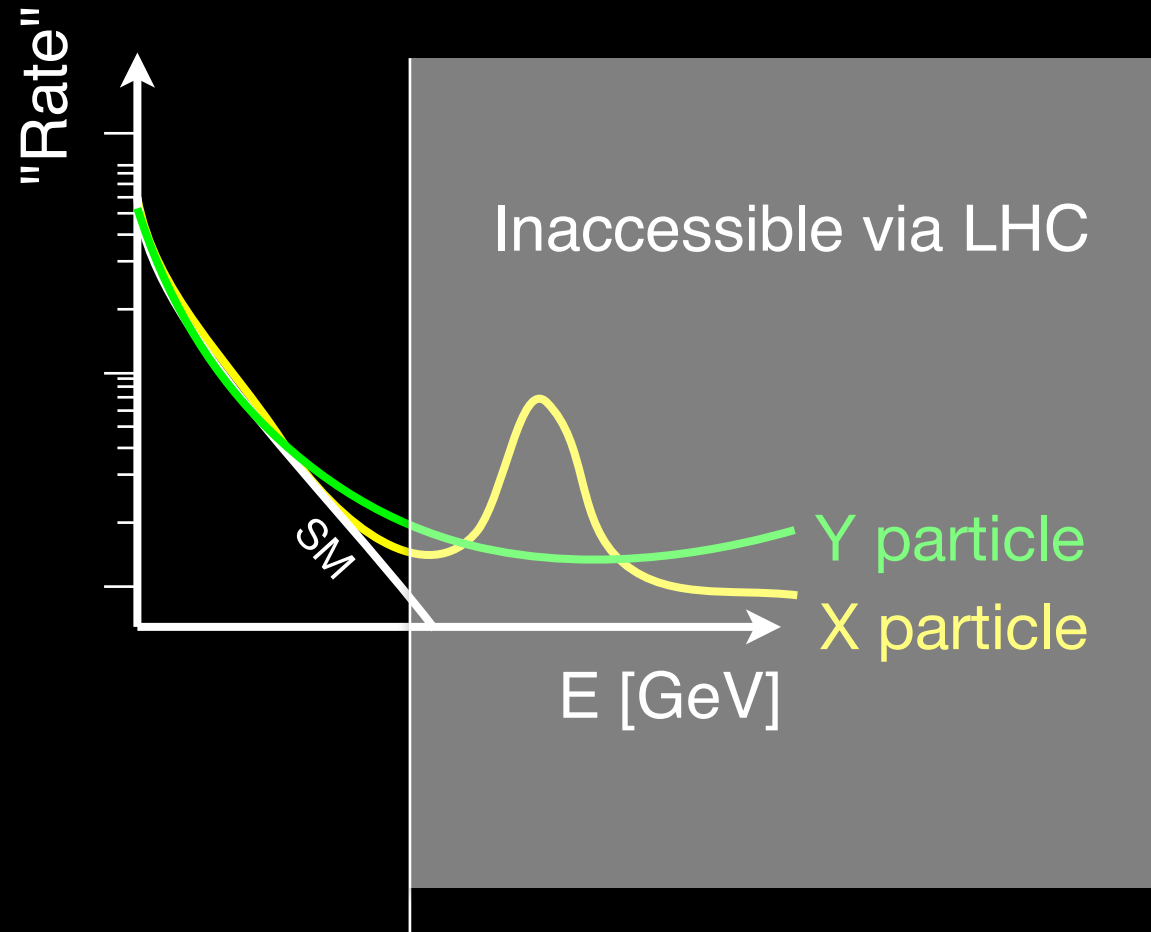
Effective Field Theory



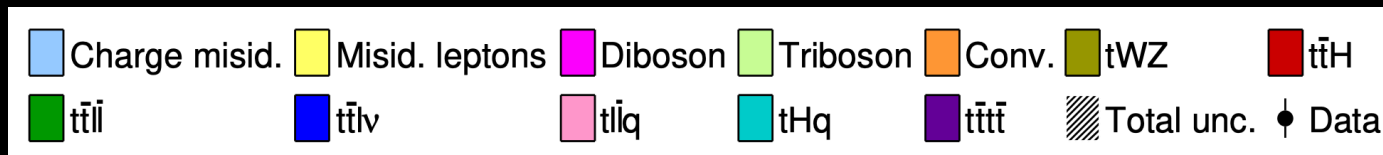
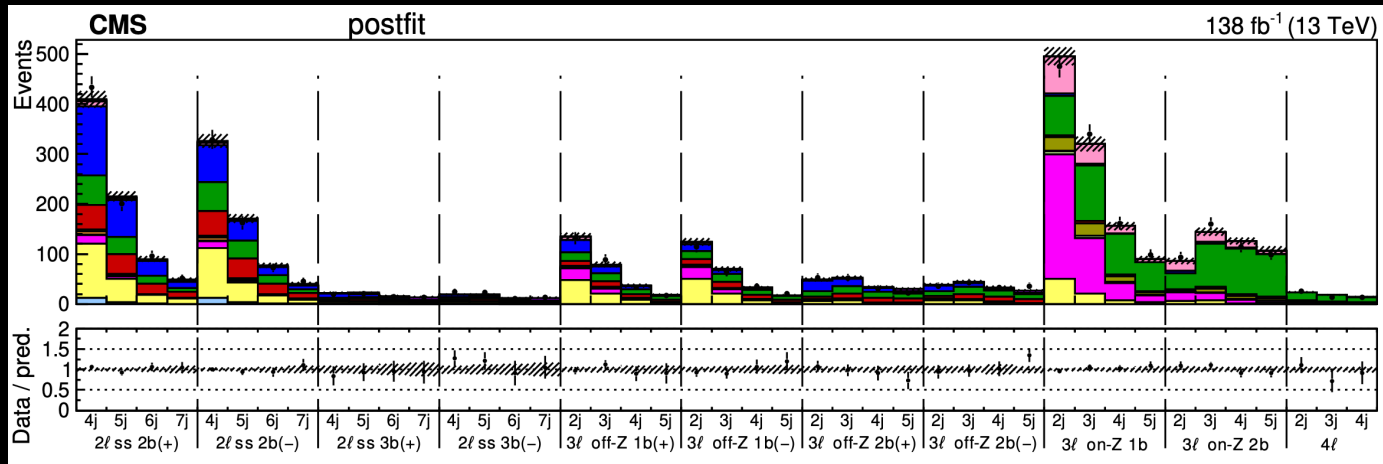
Effective Field Theory



Effective Field Theory

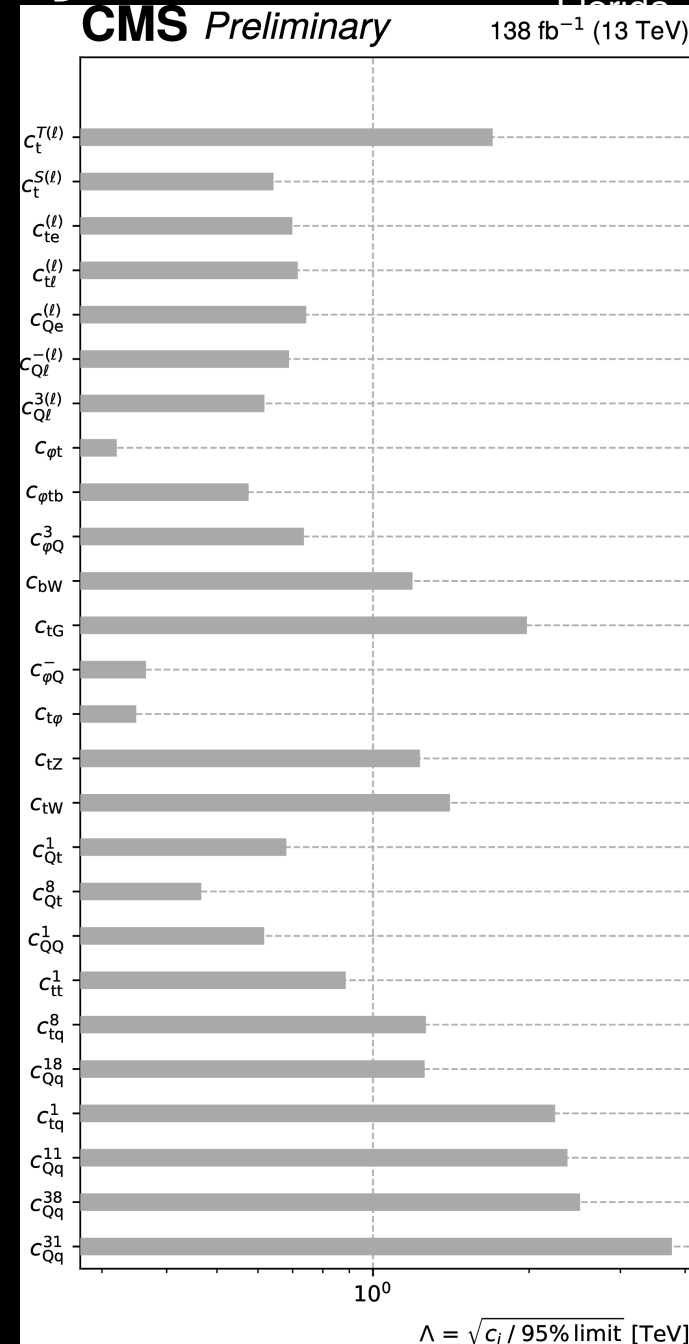


Effective Field Theory



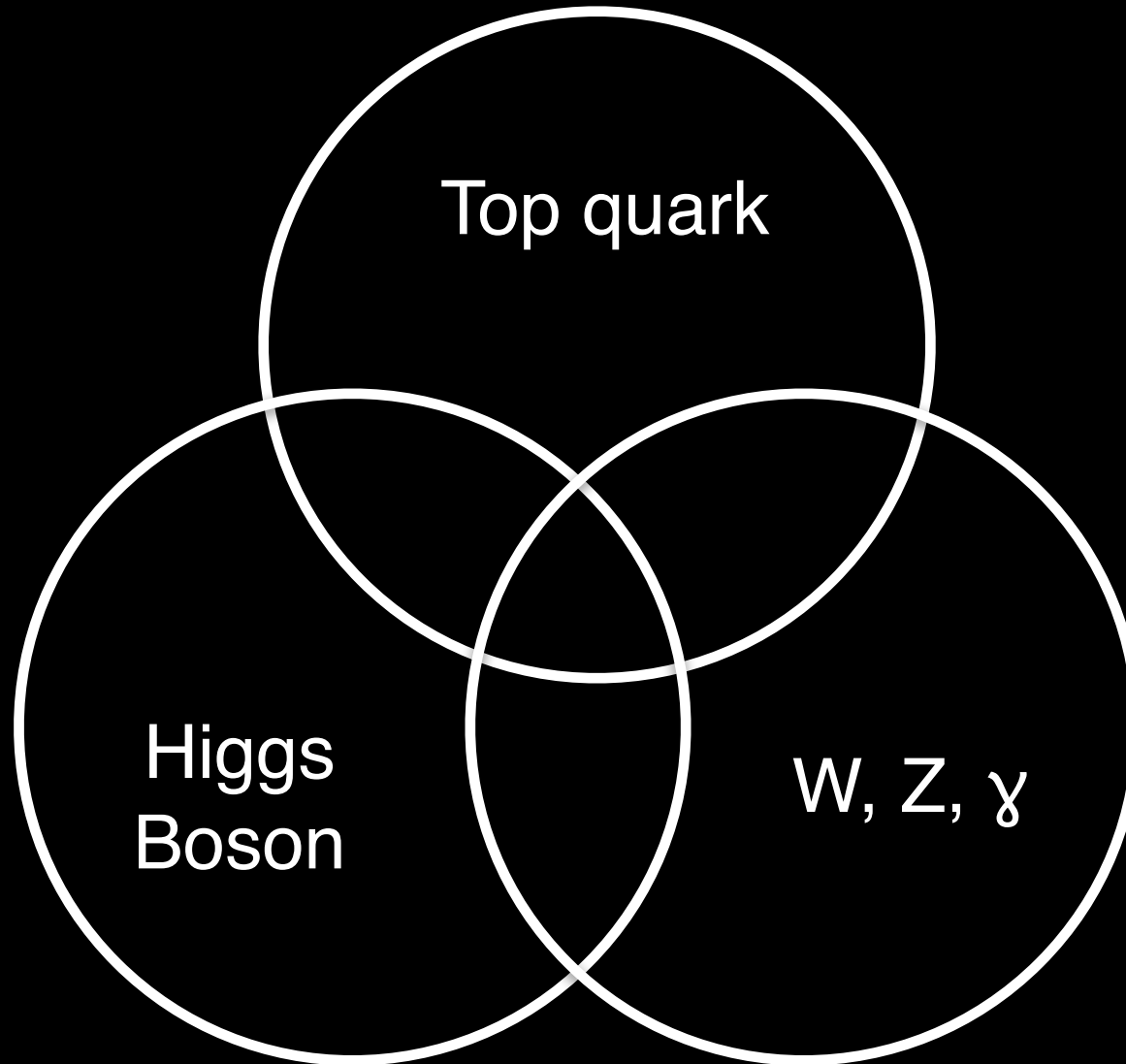
$$L_{\text{LEFT}} = L_{\text{SM}} + \sum \frac{C_i}{\Lambda^2} O_{i,\text{dim6}} + \dots$$

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

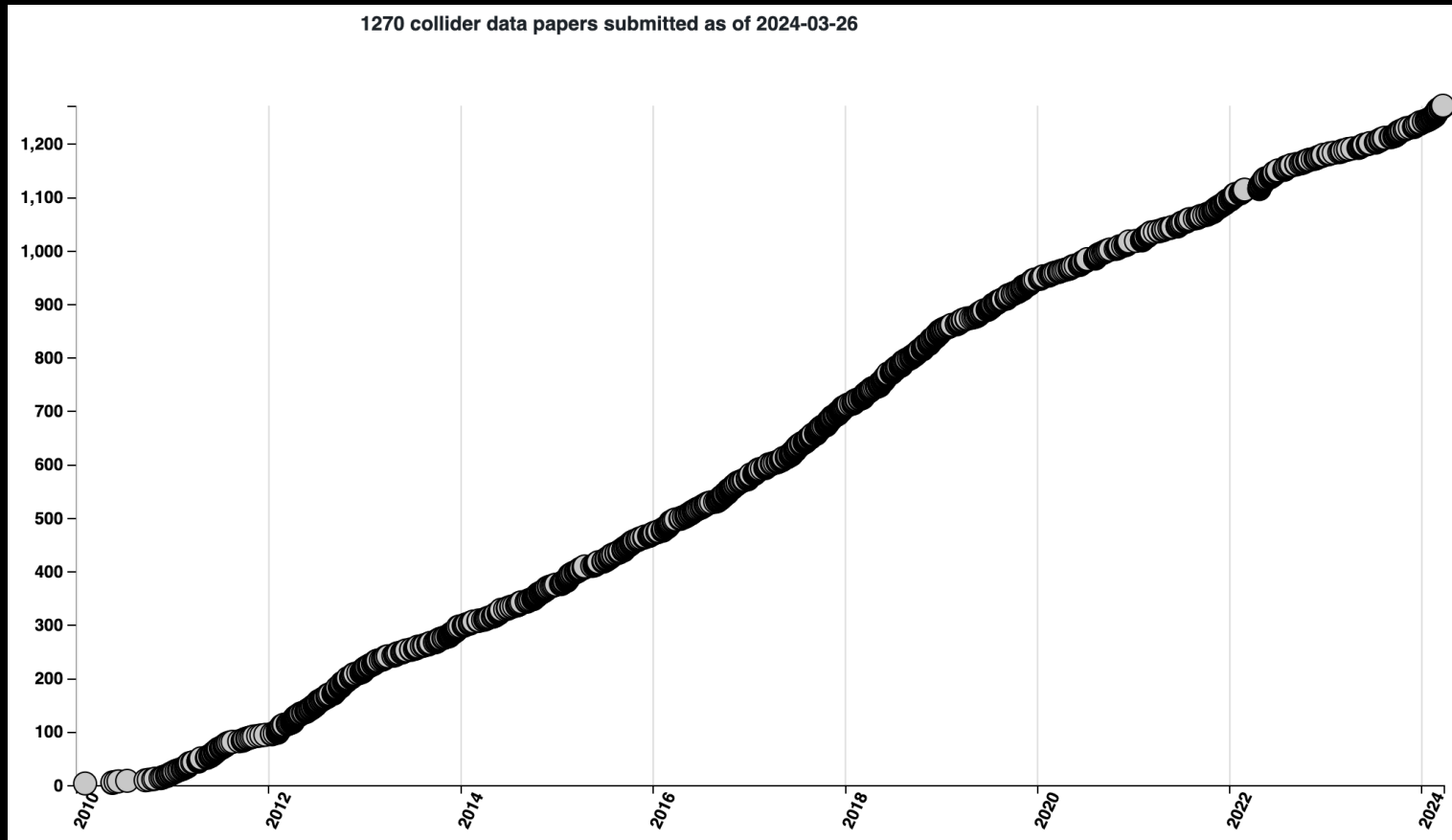


$\Lambda = \sqrt{C_i / 95\% \text{ limit}} \text{ [TeV]}$

Interpretation



Remarkable collaborations



1270 CMS
1278 ATLAS

Diverse particle physics topics being covered by general purpose detector experiments

Summary

We are in an experimental driven discovery era

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