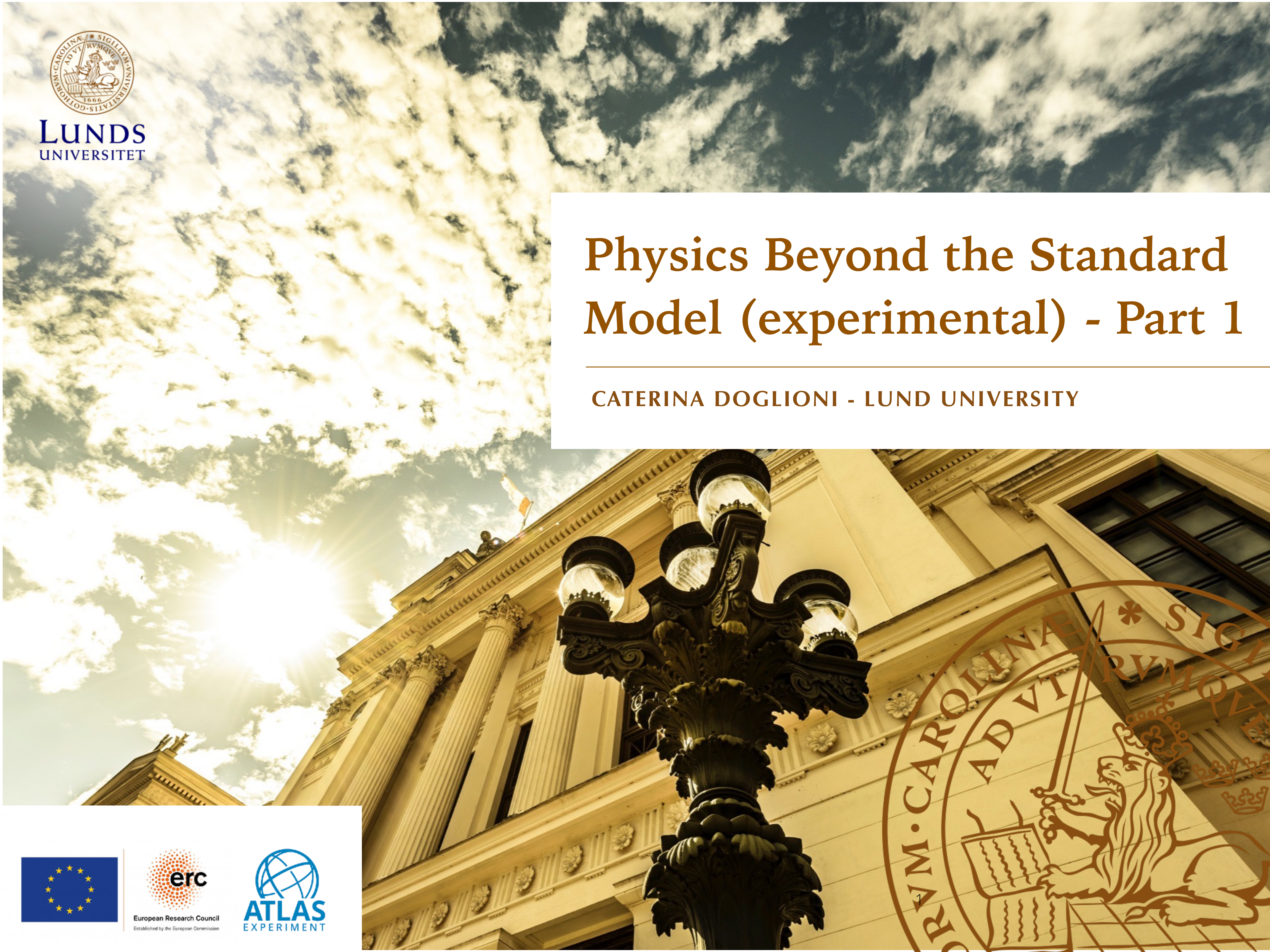


LUNDS UNIVERSITET

Physics Beyond the Standard Model (experimental) - Part 1

CATERINA DOGLIONI - LUND UNIVERSITY

European Research Council
Established by the European Commission

ATLAS EXPERIMENT

From an introduction that Eilam Gross asked all participants to his workshop

Will Kalderon, Eric Corrigan
Eva Hansen, CD, Alex Ekman

Caterina Doglioni

caterina.doglioni@hep.lu.se @CatDogLund
Senior Lecturer

My research:
I am a researcher at Lund University and a member of the ATLAS Collaboration at the LHC. I search for new physics phenomena that can be produced in proton-proton collisions, motivated by the presence of dark matter in our universe. I work on the DARKJETS ERC project together with a post-doctoral researcher and students, looking for the particles that mediate the interaction between known particles and Dark Matter particles. I am a PI in the INSIGHTS ITN on statistics and machine learning, and I am a member/WG convenor of the HEP Software Foundation.

My expertise is:
Dark matter, measurements and searches with hadronic jets, Trigger-Level Analysis in ATLAS

A problem I'm grappling with:
Synergies between particle, astroparticle and nuclear physics in terms of common tools and physics questions

I've got my eyes on:
Ways to discover weird jets from dark sector particle cascades, axion-like particles

I want to know more about:
Reproducible and understandable machine learning algorithms, autoencoders

Outline for these three BSM lectures

Lecture 1
The Standard Model has no apparent major problem!
Why should we look beyond, and how? Direct and indirect BSM searches

Lecture 2
The Standard Model has some problems!
Solving many problems at once: *supersymmetry*
Solving one problem at a time: *generic dark matter searches* (at the LHC, for today)

Lecture 3
Connecting DM@LHC with DM beyond the LHC (direct and indirect detection)
Darker matter: the rare and the unexpected (at the LHC and beyond)
Outline of other BSM theories & results
(Almost) back to the SM: neutrino physics

Some words about these lectures

Disclaimers: contiene una fonte di fenilalanina

This is not an exhaustive talk on all BSM physics that has ever been searched for

Inclusions (and omissions) are a matter of personal taste

There is some nice pedagogical literature out there to fill the gaps

Two recommendations out of many

- C. Csaki & F. Tanedo's BSM lectures: **https://arxiv.org/abs/1602.04228**
- H. Murayama's BSM paper: **http://arxiv.org/pdf/0704.2276v1.pdf**

What I expect from you: enough attention to ask questions, and feedback on lecture pace at the end of the first lecture so we can adapt the next ones

What you can expect from me: lectures (duh), answers to your questions, and follow-ups if I can't give answers right away

And because we're experimentalists, we'll have:

- Concepts for each lecture will be collectively summarized in a real-time mindmap (I will add that to the lecture slides afterwards)

Lecture 1

More detailed outline of lecture 1

The SM has no problems (for today)!

- Measurements and agreement with theory

✅Energy frontier => exploration of the unknown

"Generic" ***direct search strategies***:

look for (sizable) deviations signaling the presence of new particles

A simple BSM search in more detail

❌Energy frontier => but we're not upgrading the LHC energy anytime soon!

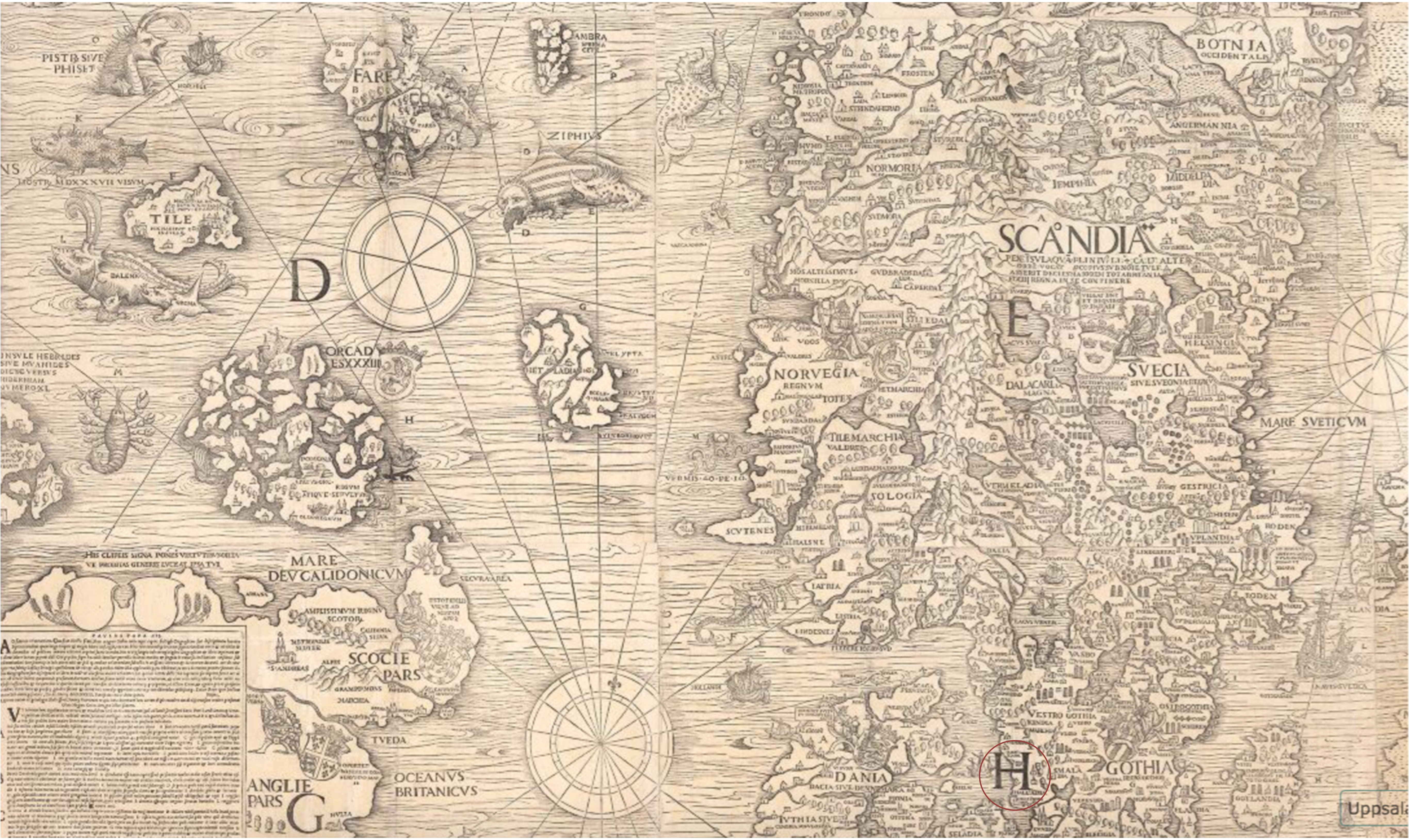
Indirect search strategies:

look for (small) deviations from the presence of new particles in loops

Standard Model? No problem!

A map of ~~Scandinavia~~ particle physics

Image from University of Uppsala



Re-charting known territories in Run 2

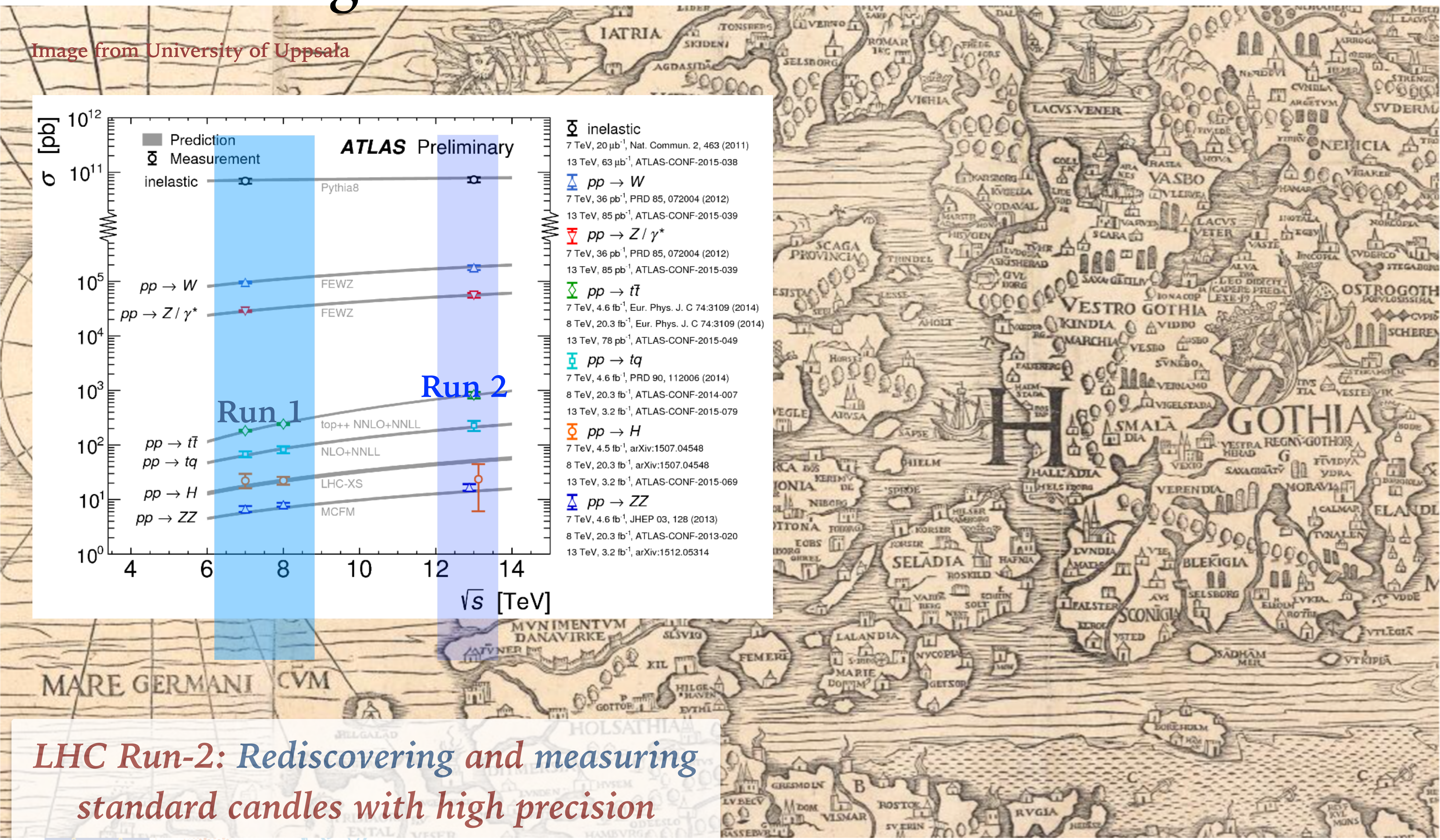
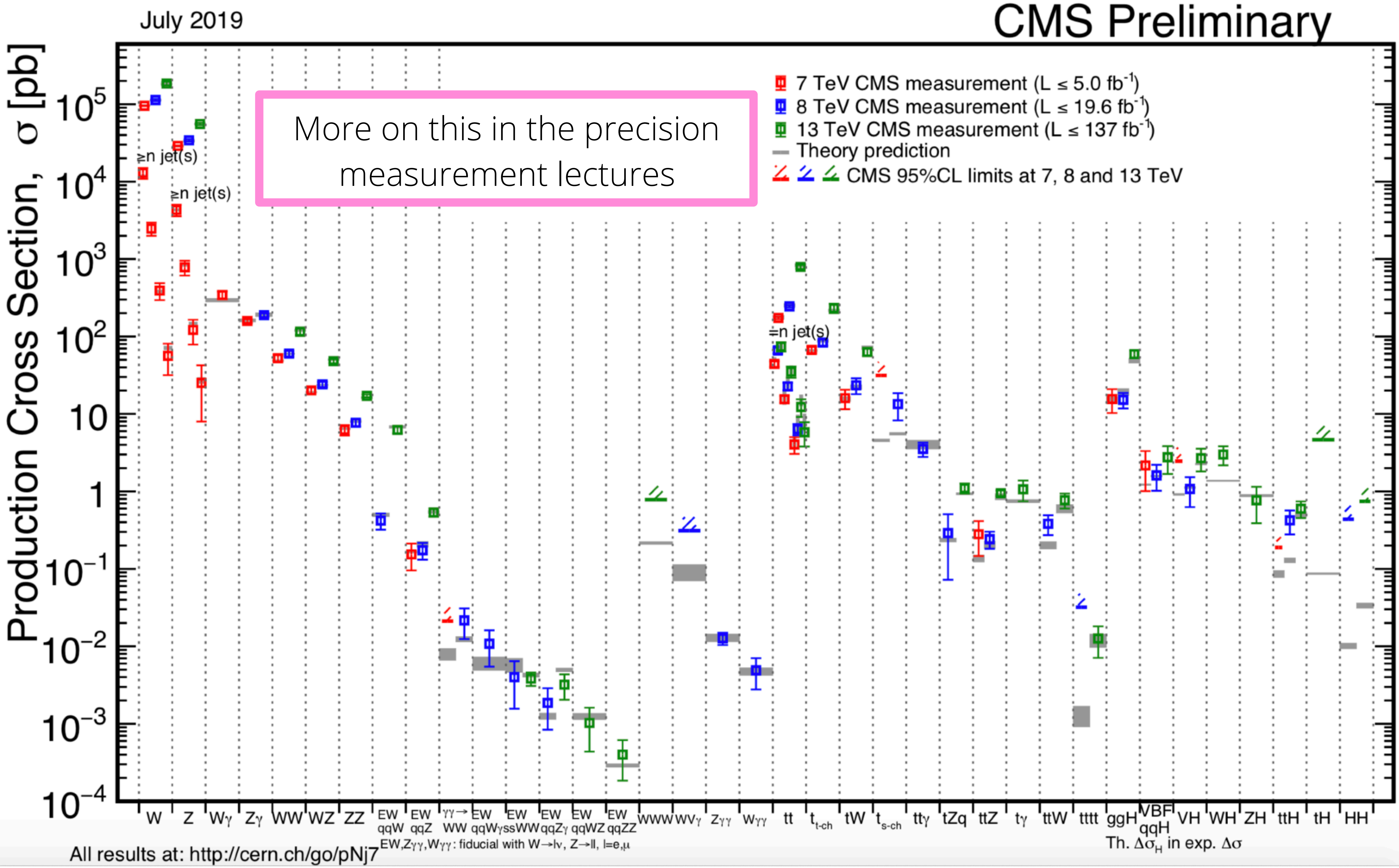


Image from University of Uppsala

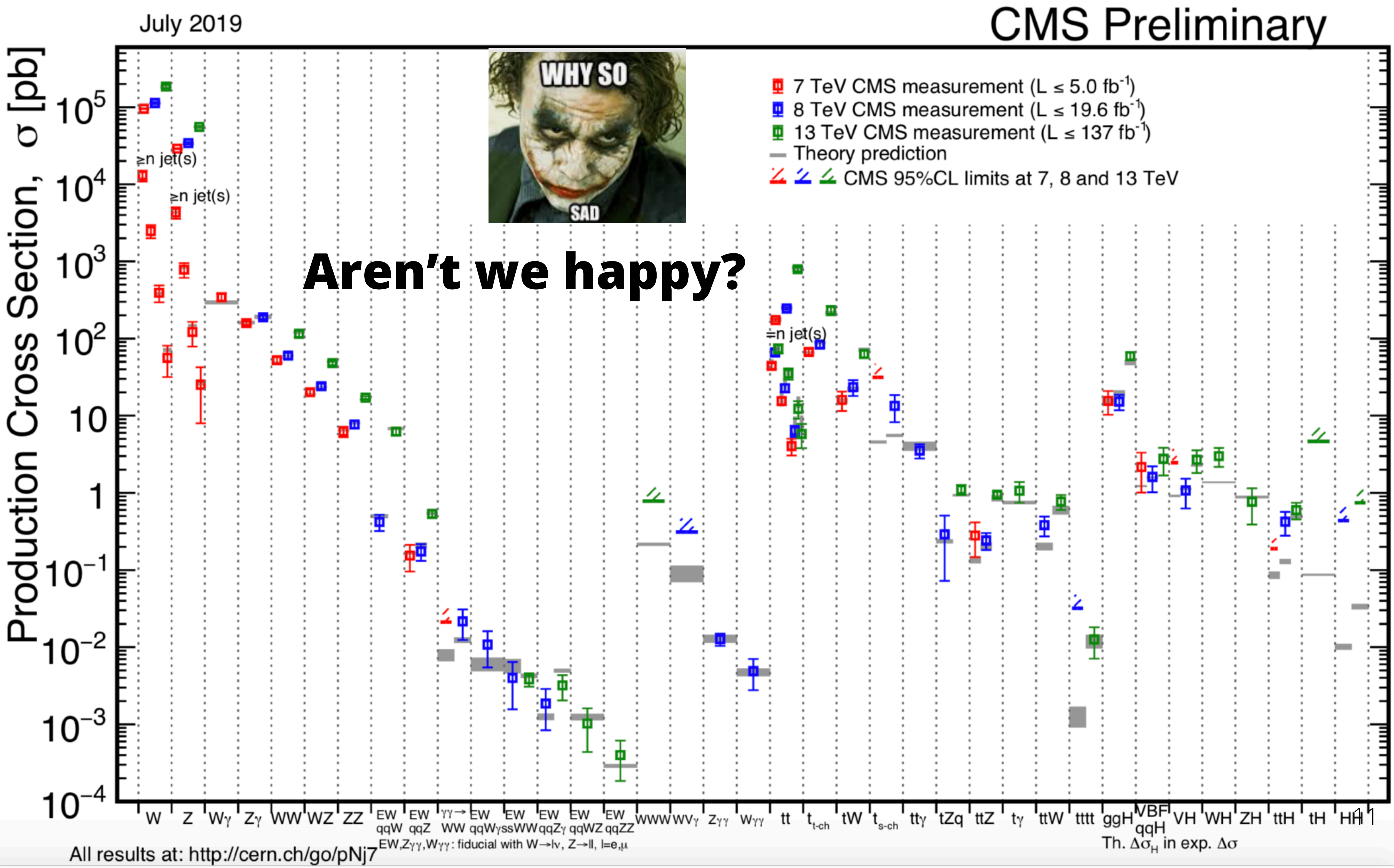
LHC Run-2: Rediscovering and measuring standard candles with high precision

The SM in its full experimental glory



More on this in the precision measurement lectures

The SM in its full experimental glory



Aren't we happy?

The SM in its full experimental glory

Aren't we happy?

https://science.sciencemag.org/content/313/5786/448.full

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See also: https://cosmosmagazine.com/mathematics/number-fascinates-physicists-above-all-others

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PERSPECTIVE | PHYSICS

A More Precise Fine Structure Constant

Daniel Kleppner*

+ See all authors and affiliations

Science 28 Jul 2006:
Vol. 313, Issue 5786, pp. 448-449
DOI: 10.1126/science.1131834

Article | Figures & Data | Info & Metrics | eLetters | PDF

Relativistic quantum electrodynamics (QED)—the theory that describes electromagnetic interactions between all electrically charged particles—is the most precisely tested theory in physics. In studies of the magnetic moment of the electron (a measure of its intrinsic magnetic strength), theory and experiment have been shown to agree within an uncertainty of only 4 parts per trillion. This astounding precision has just been improved. A new measurement by Odom *et al.* (1) has increased the experimental precision by a factor close to 6. In a parallel theoretical

Science
Vol 313, Issue 5786
28 July 2006
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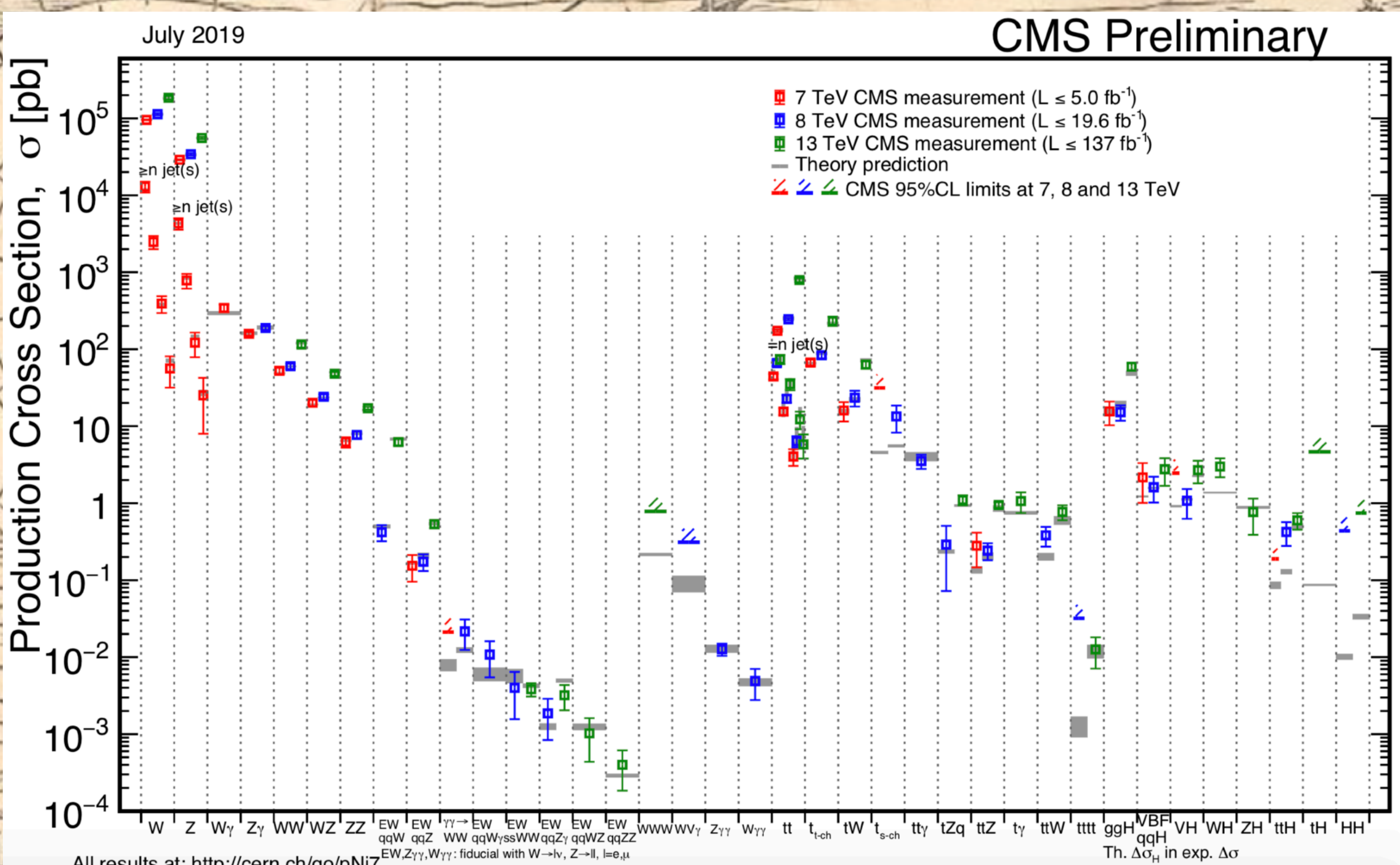
We should be even happier!

Many searches and measurements during first years of the LHC: mapping the Standard Model…



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

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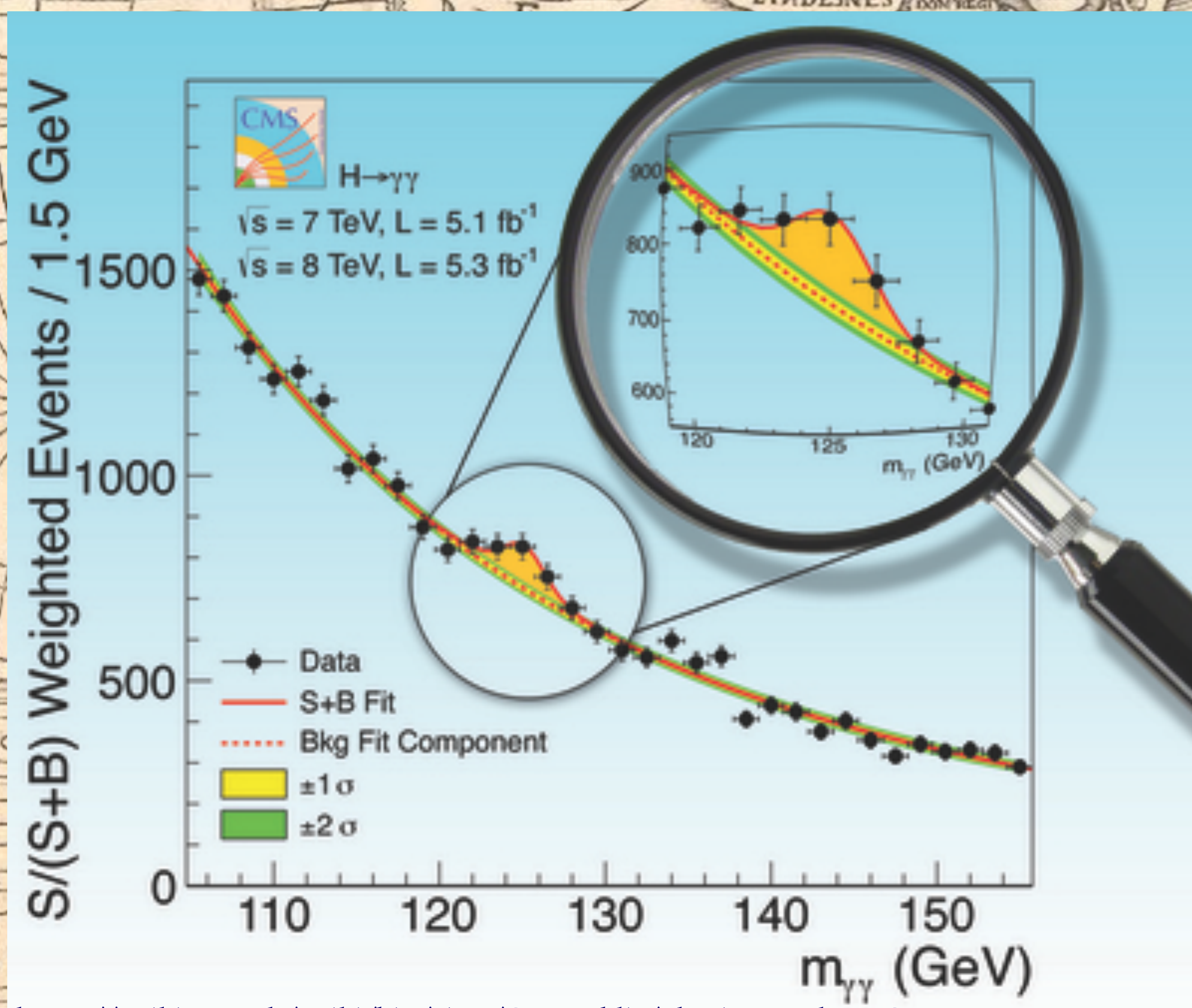


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

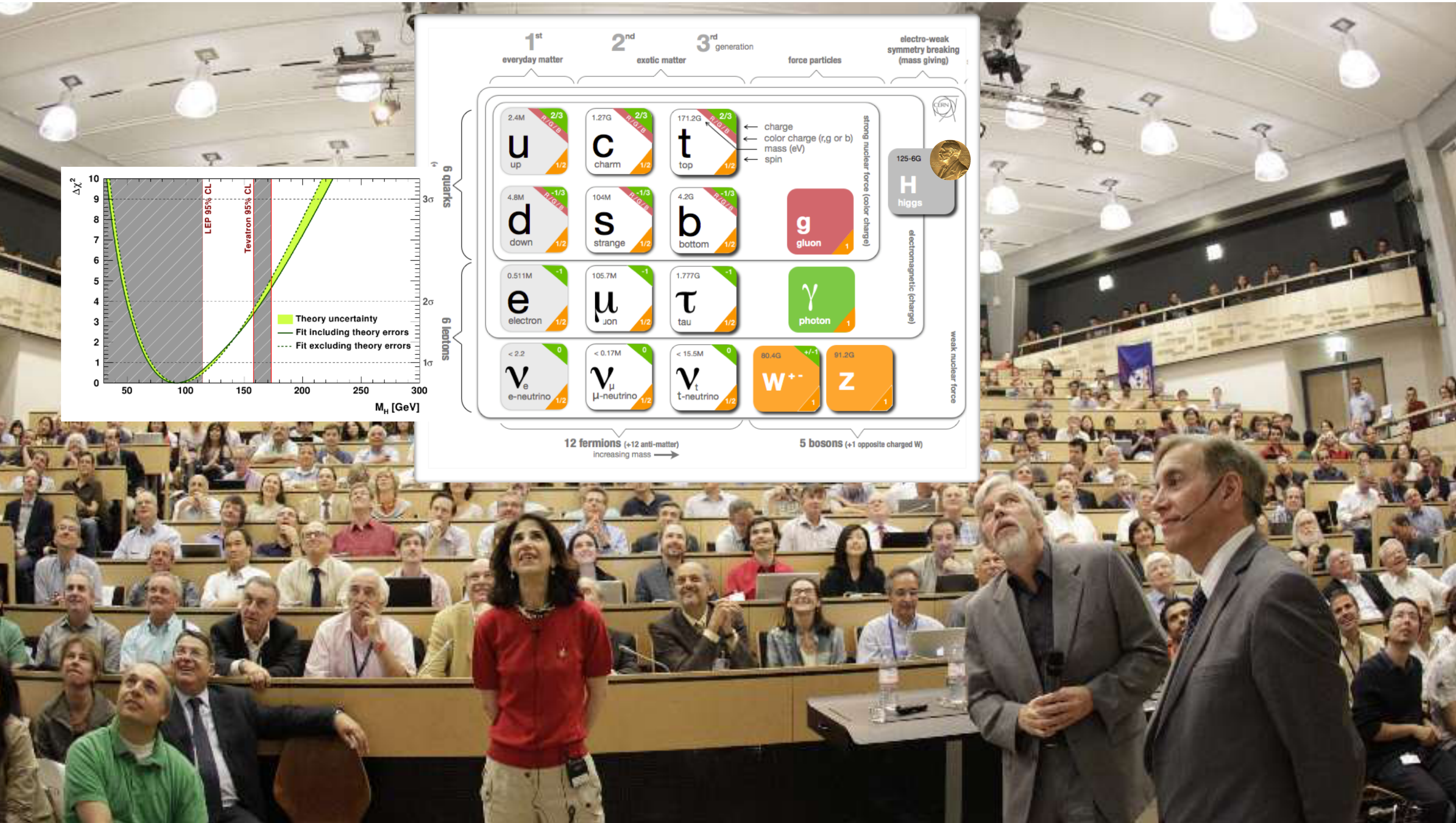
Higgs

arXiv:1503.07589

…and a milestone discovery

The LHC’s biggest discovery so far

Discovery of the Higgs boson: guided by **clues** from the **Standard Model**



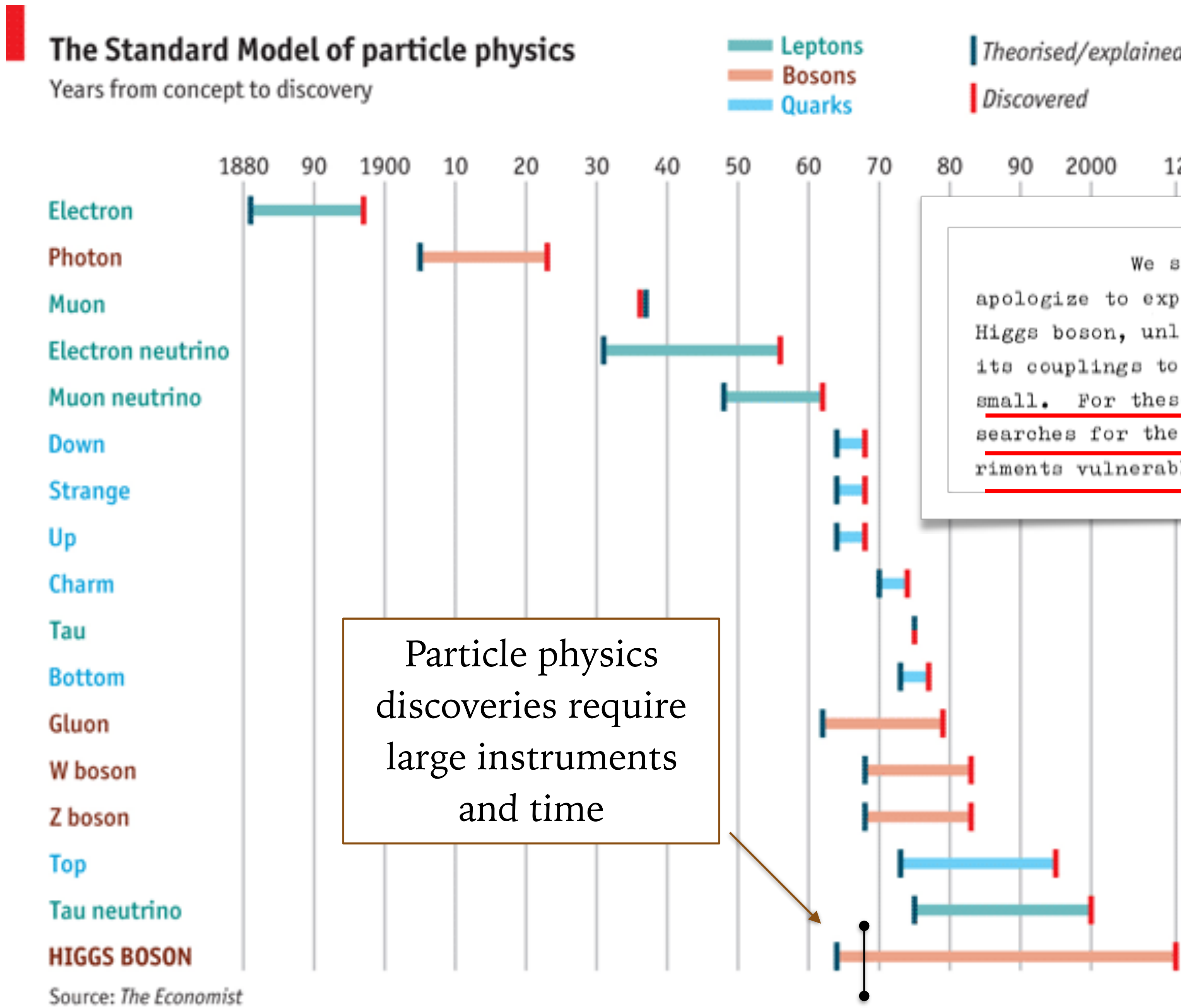
…it wasn't completely expected, for a while

https://cds.cern.ch/record/874049

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.

John Ellis

Expected and unexpected particle discoveries



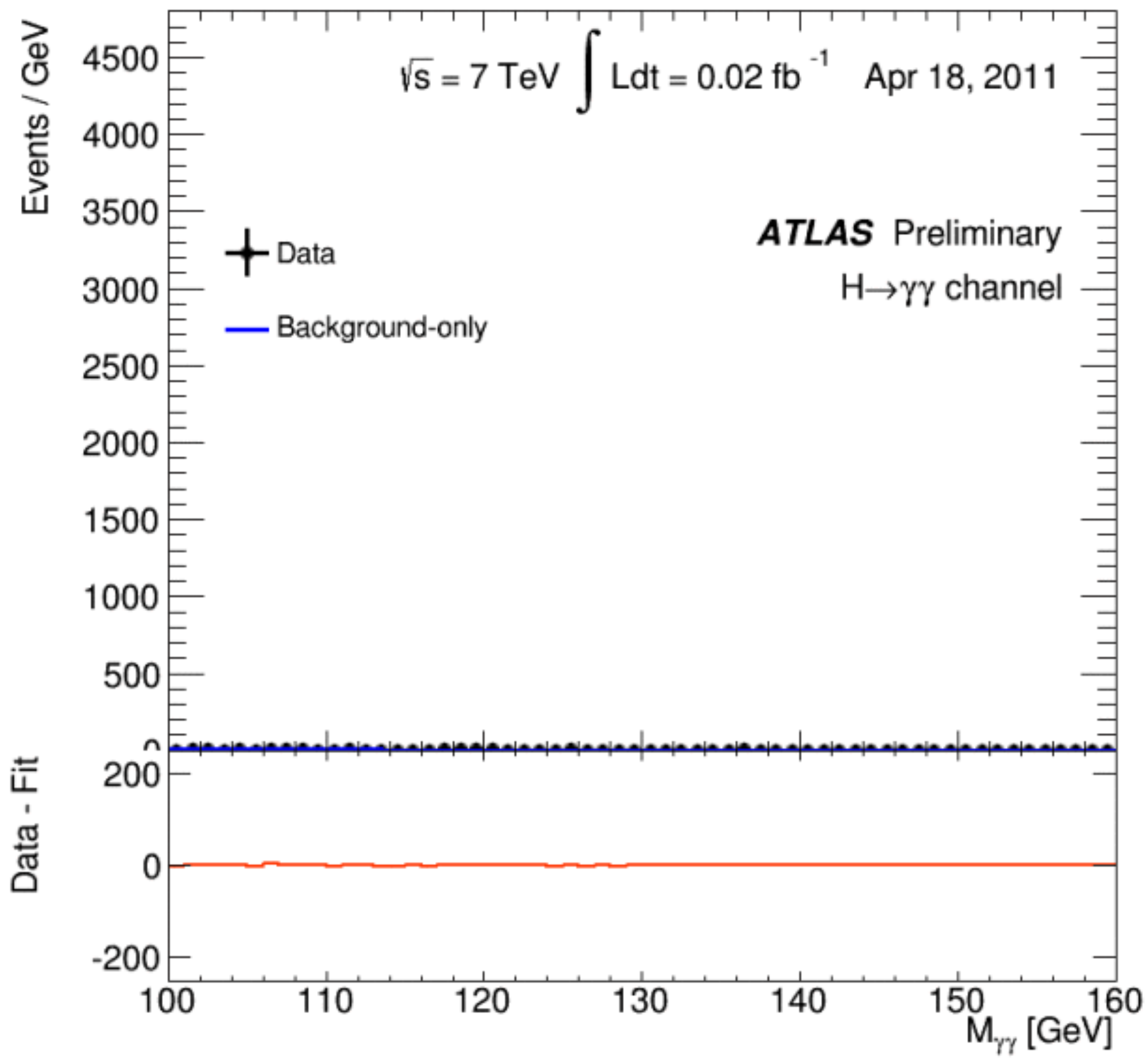
Particle physics discoveries require large instruments and time

https://cds.cern.ch/record/874049

> 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.

The Economist

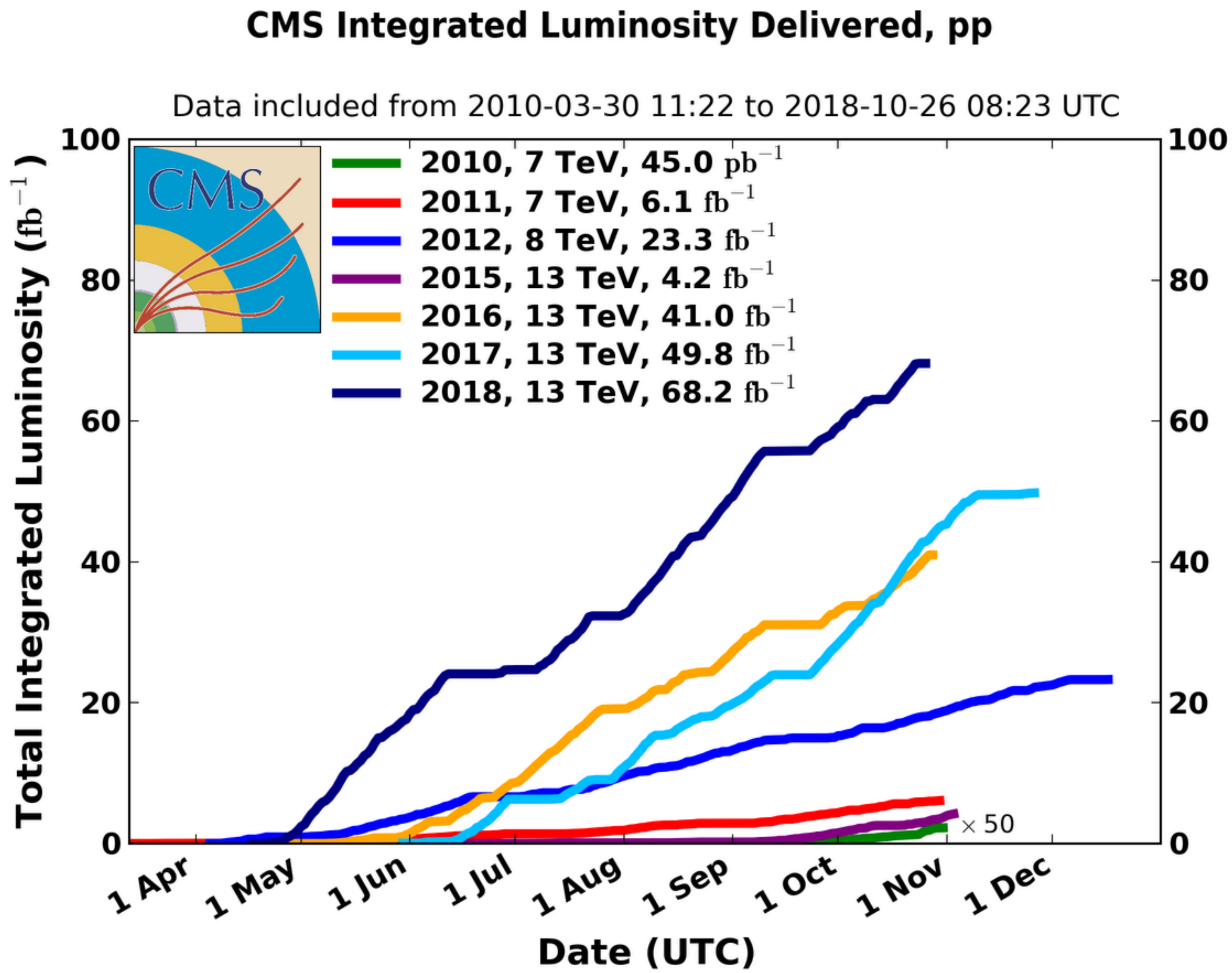
What does it take for a discovery?



- A particle **collider** (LHC)
  - 600000 collisions/second
  - Only one in 10^{13} may contain a Higgs boson
- **Detectors** able to select and precisely measure particles (photons)
  - ATLAS, CMS (LHCb, ALICE)
  - Millions of read-out channels
- Many **teams** that:
  - Operate the detector
  - Reconstruct and calibrate particles
  - Do the data analysis

More on this in the detector/ data analysis lectures

What does it take for a discovery? LHC data



√s = Centre of mass energy

More energy ⇔ can discover more massive particles ($E=mc^2$)

Luminosity = how much data is collected (proportional to # of collisions)

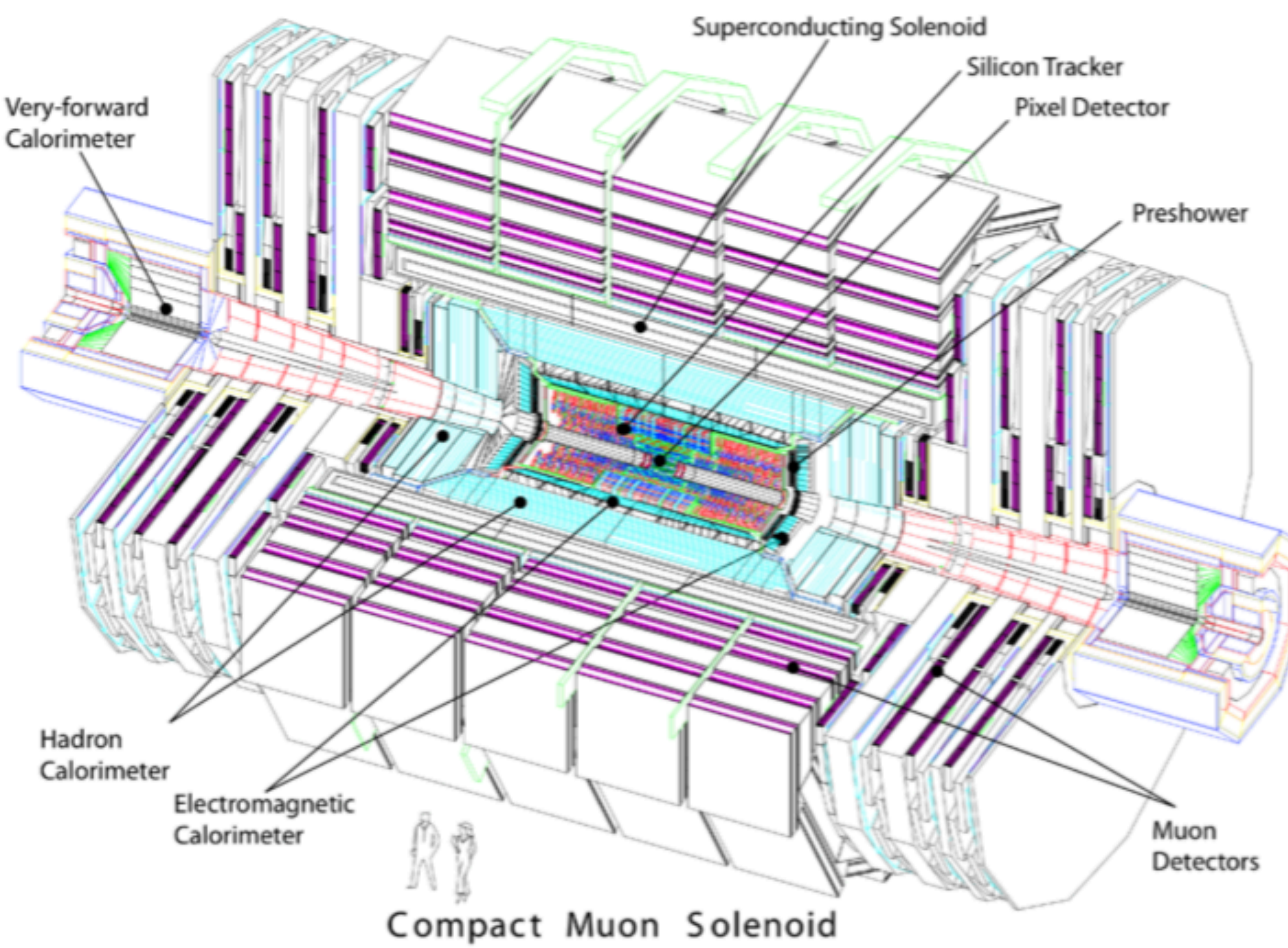
More data ⇔ more chances to see rare processes

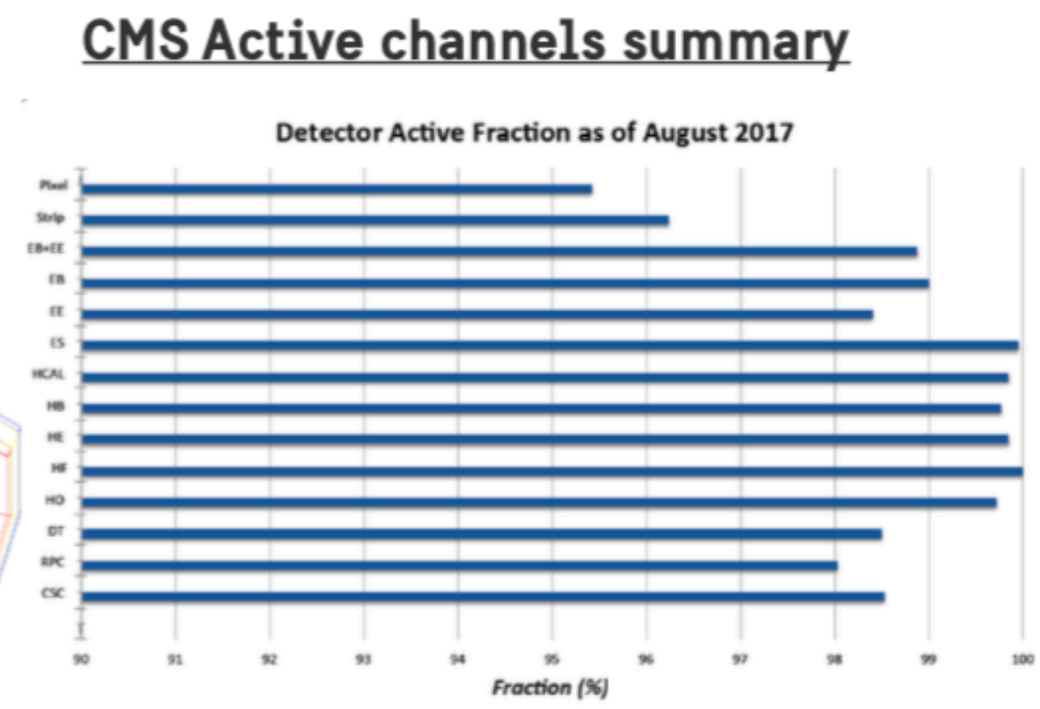
What does it take for a discovery? LHC data

- Bunch crossing frequency: up to 30 MHz
  - A collision of bunches **every 25 nanoseconds**
- **Consequences:** Detectors need fast electronics, good buffering

- Up to 2808 bunches of protons per proton beam
  - Each of them with up to 10^{11} protons
  - Leading to **600 million proton-proton collisions per second**
- **Consequences:** many simultaneous collisions (pile-up)
  - Current data taking: up to 70
  - High-Luminosity LHC (2025-2035): up to 200
  - Usually only the most energetic is selected

What does it take for a discovery? Detectors





Many **sub-detectors** used to measure different particle properties

Information from sub-detectors combined in **reconstruction**

Experimental physicists analyze the collections of **events recorded**

What does it take for a discovery? Collaborations

ATLAS

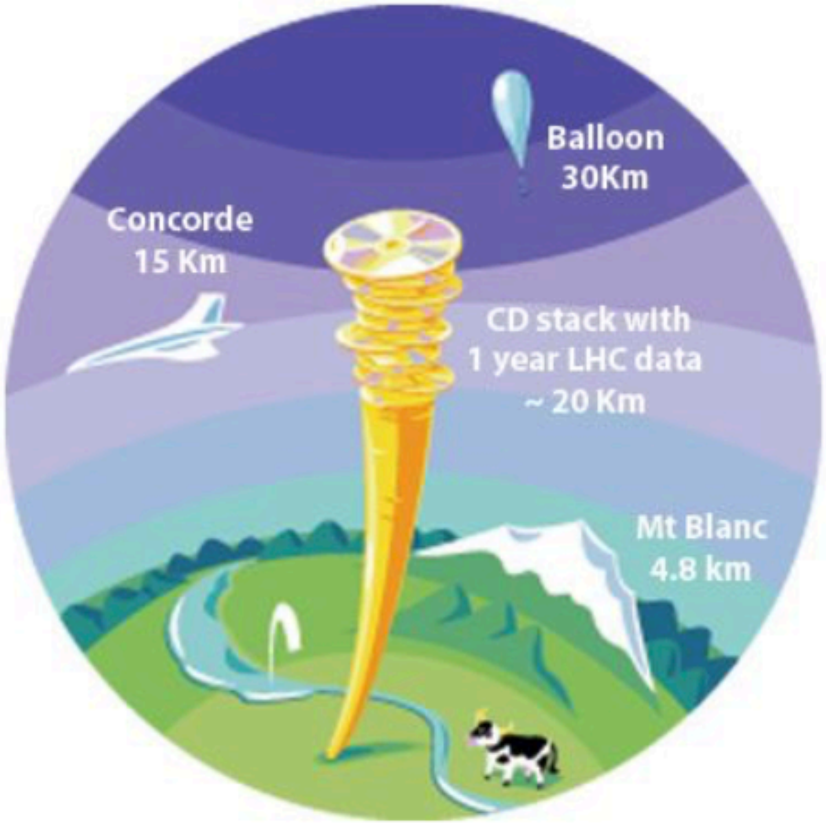
CMS

LHCb

ALICE

Selecting interesting data at the LHC

- If everything was recorded at the LHC:
  - up to 30 million collisions/second (MHz)
  - 1-1.5 MB/data per collision
  - 30 MHz * 1 MB = 30 TB/s
  - 30 TB/s * 10e+6 s/year (day & night) ~ 0.05 ZB/year
- facebook
  - 600 TB/day ~ 200 PB/year [Facebook 2014]
- **"There's always a bigger fish"** [C. Tully's talk @ siRTDM18]
- But bigger fish also have bigger money… cost-effectiveness important for scientific instruments!

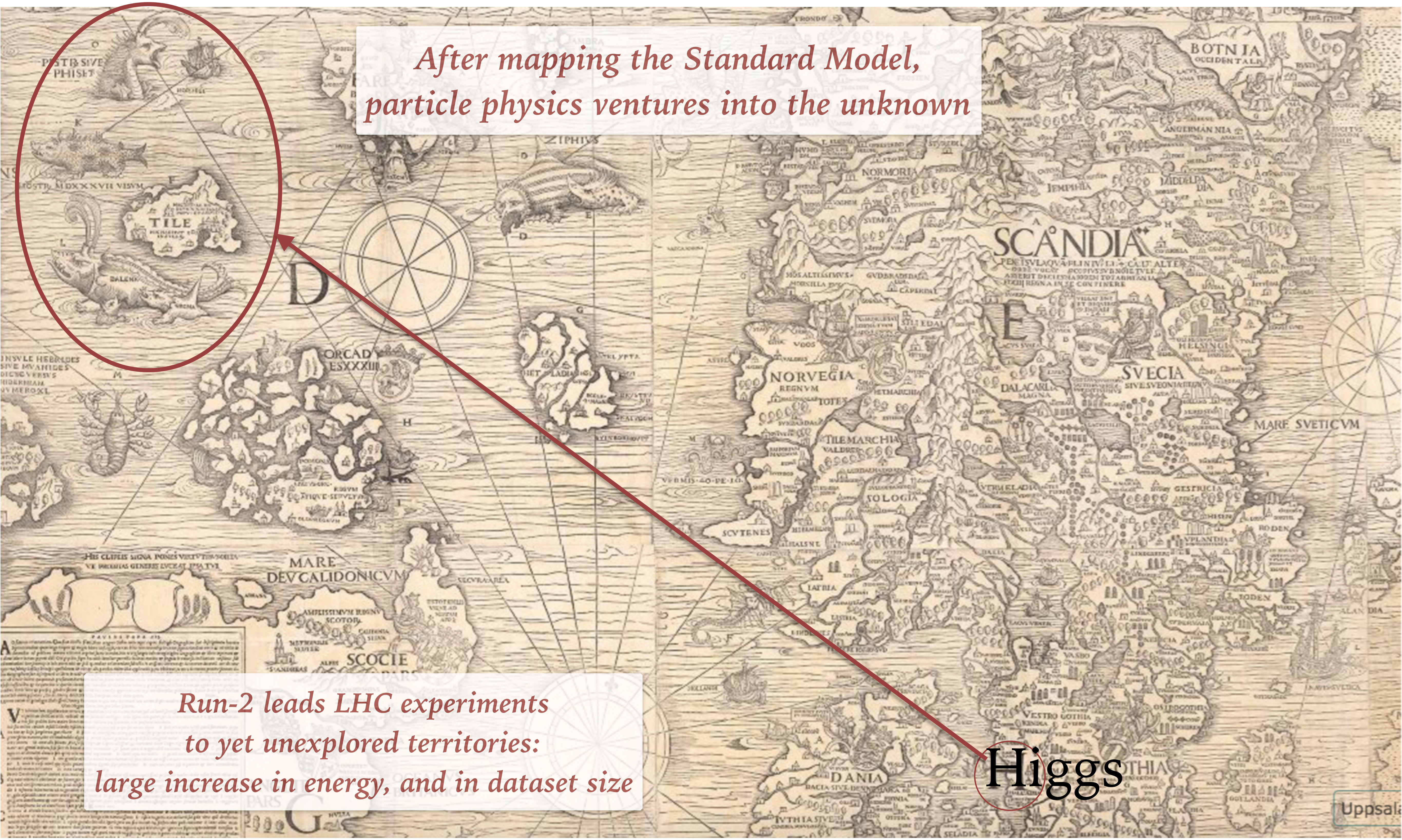


This picture is after selection of "interesting" data: with all data, the stack of CDs reaches to the moon

LHC experiments need to select "interesting" events **in real-time** (milli/microseconds) - more on this later

Where to go after the Higgs? Uncharted!

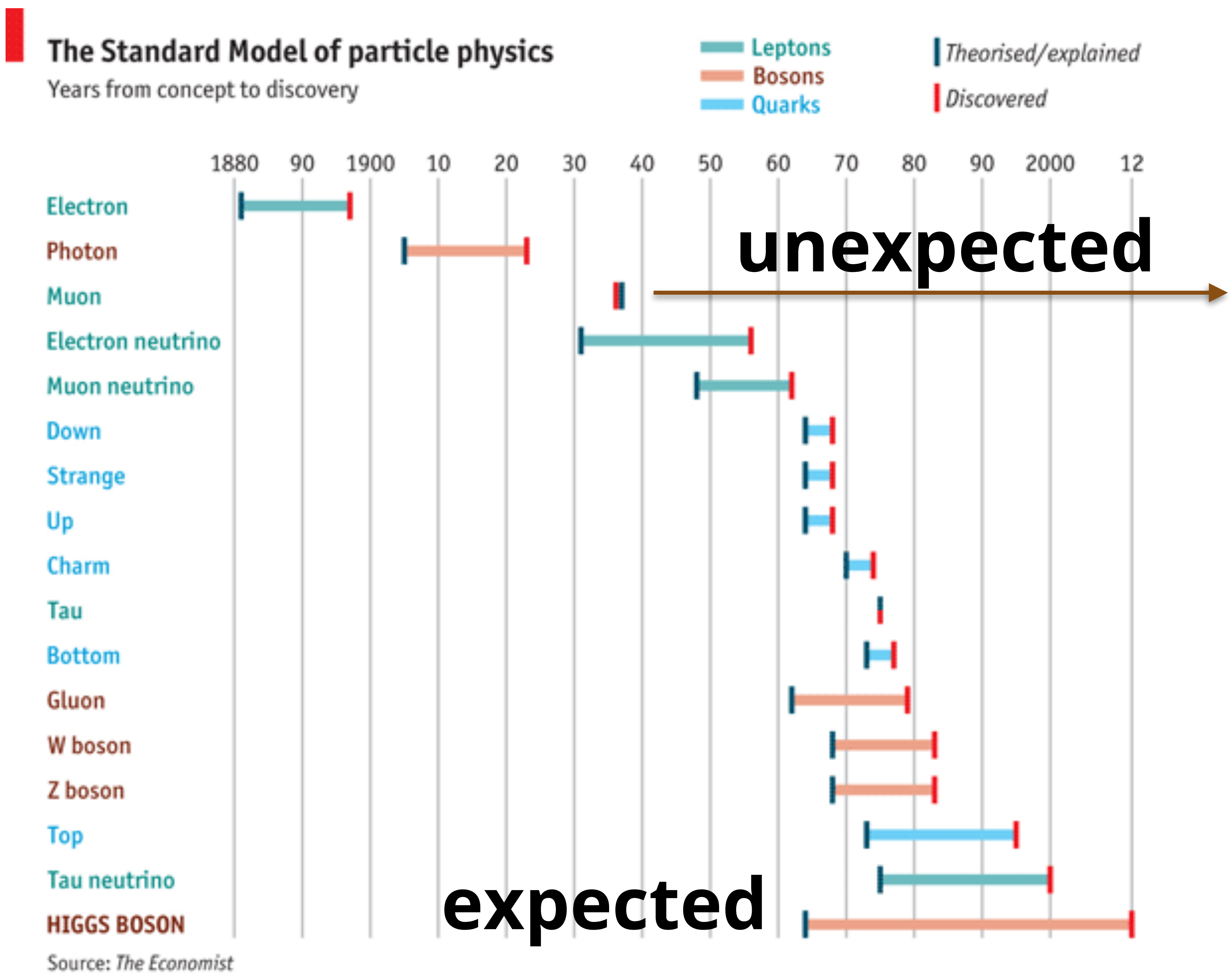
Image from University of Uppsala



After mapping the Standard Model, particle physics ventures into the unknown

Run-2 leads LHC experiments to yet unexplored territories: large increase in energy, and in dataset size

Expected & unexpected discoveries



The Economist

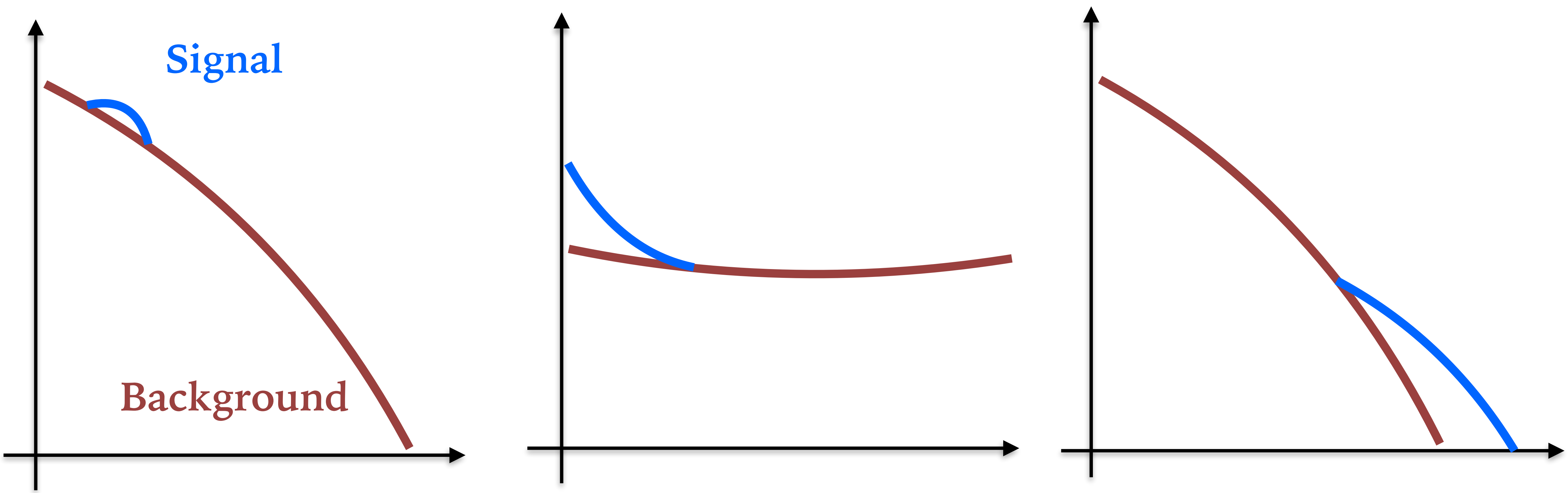
Take-home point #1:

one don't necessarily needs a motivation
to search for new physics,
it may just be that the SM is what nature gave us
and new physics is *just there* on top of it

Once we have a high-energy collider +
experiments, we can look for the unexpected!

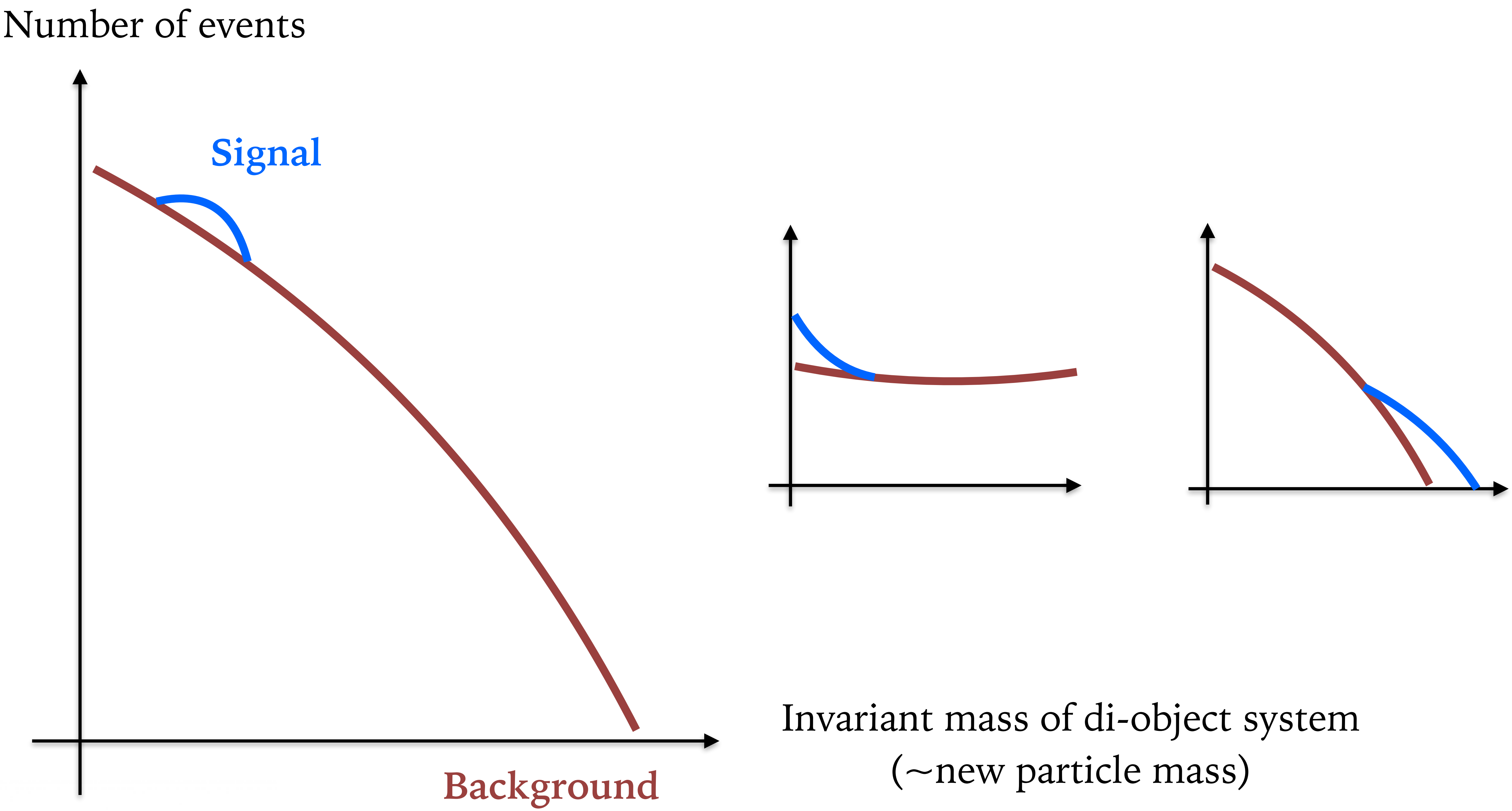
Generic direct search strategies

How would new phenomena manifest?



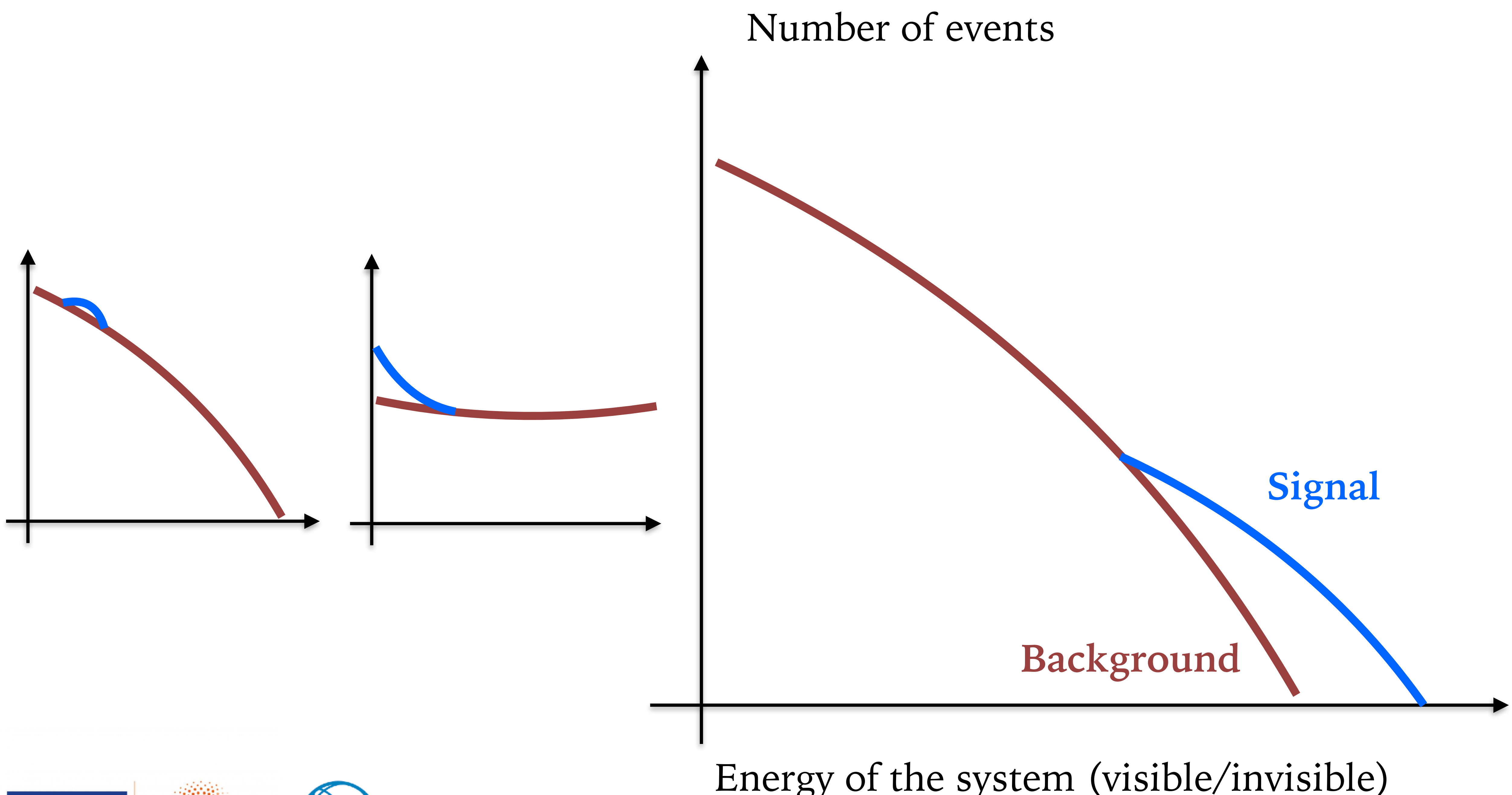
These are just **examples** of distributions analysed in searches at ATLAS and CMS

How would new phenomena manifest?



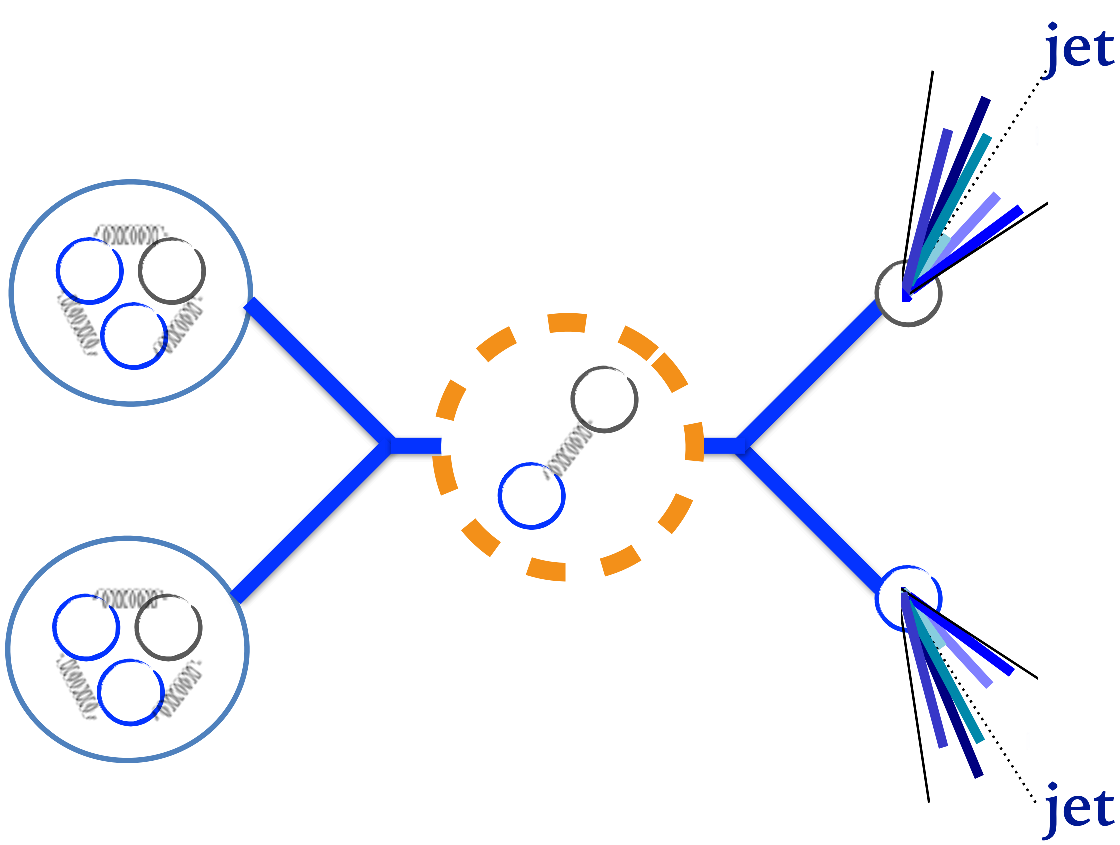
How would new phenomena manifest?

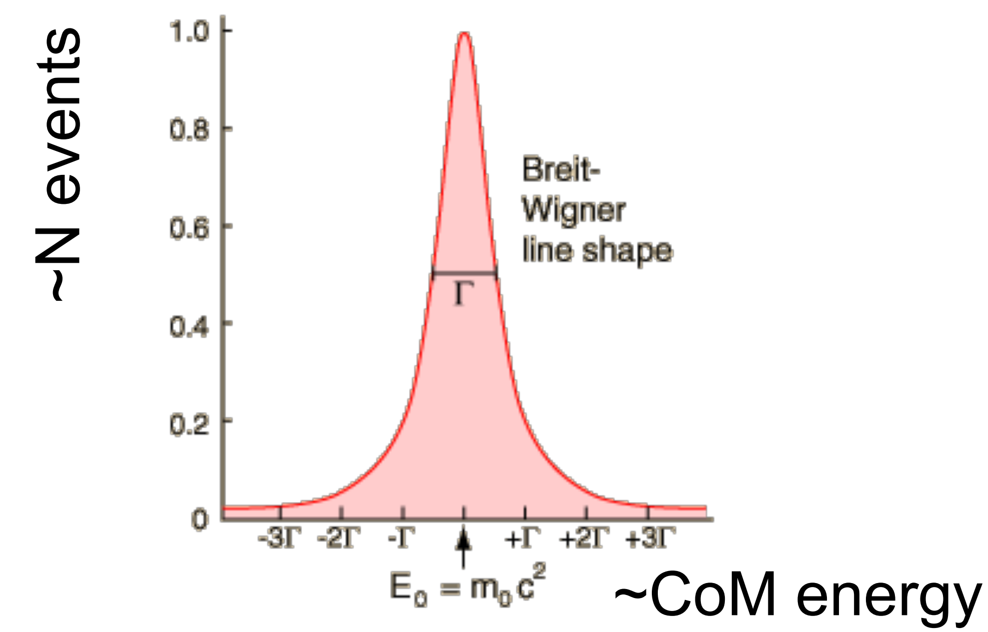
New particles and states: larger multiplicity of objects at high masses



How do new phenomena look like?

New unstable particles with narrow width (resonances) ↔ **Breit-Wigner-shaped invariant mass of decay products**





$$f(E) = \frac{k}{(E^2 - M^2)^2 + M^2\Gamma^2}$$

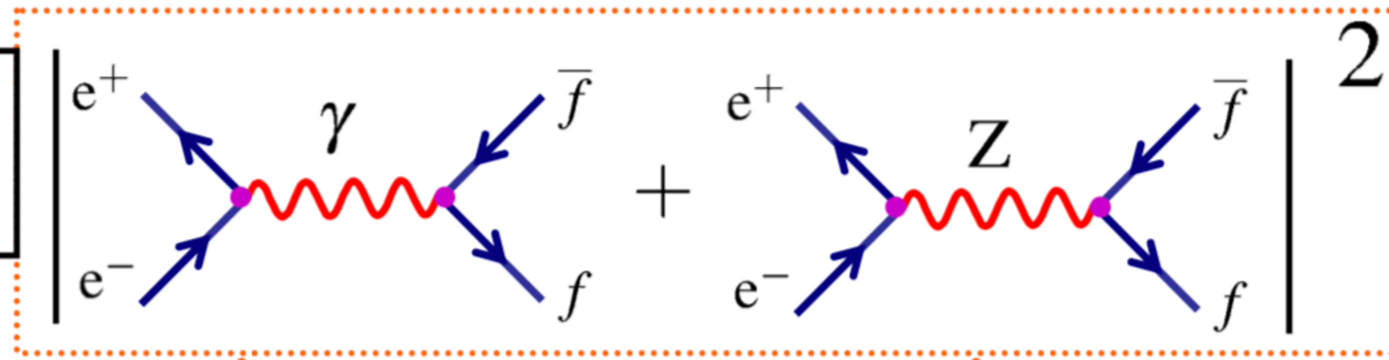
energy (of the collider) — mass — decay width (of the particle)

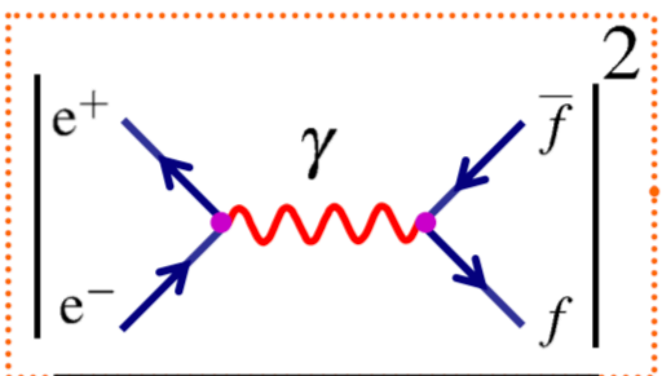
Think of the Z boson...

$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\Gamma_{ee}\Gamma_{ff}$$

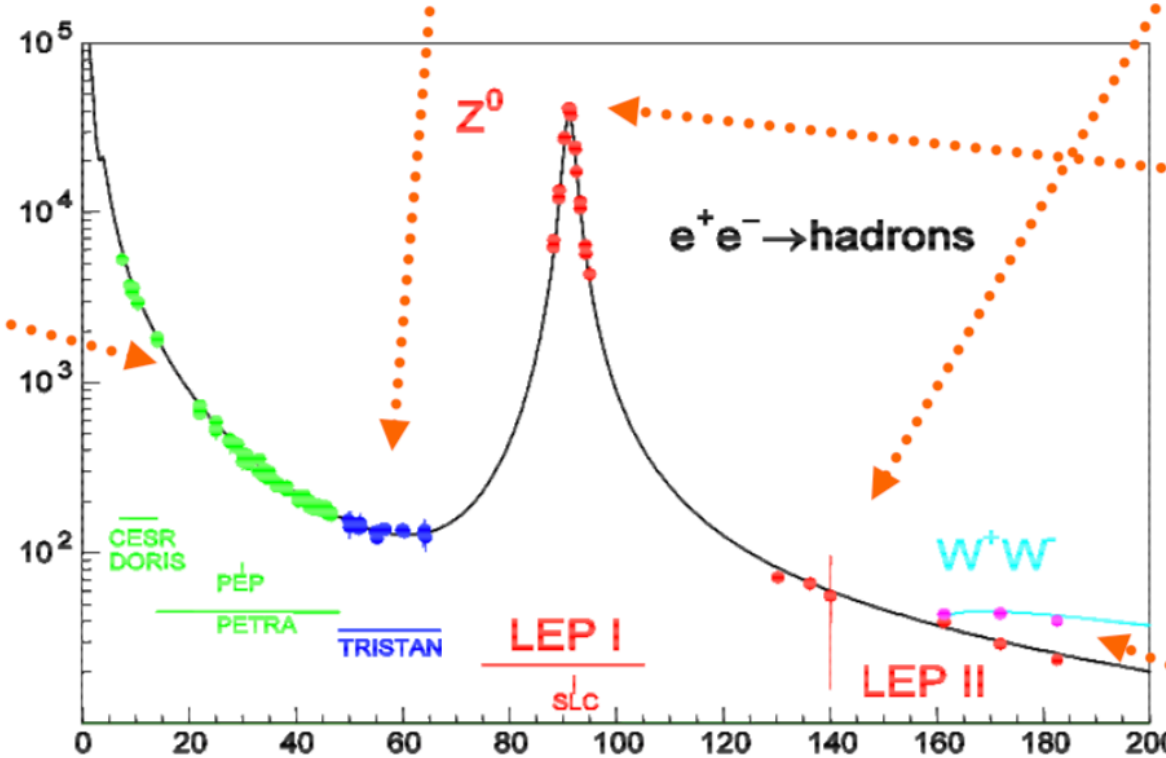
M. Thomson's lectures, Cambridge, 2009

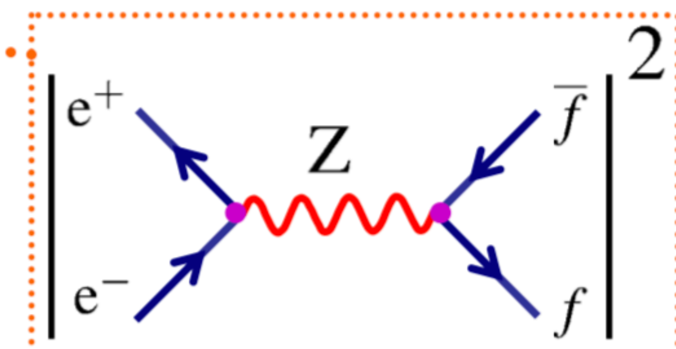
In general e^+e^- annihilation involves both photon and Z exchange : + interference





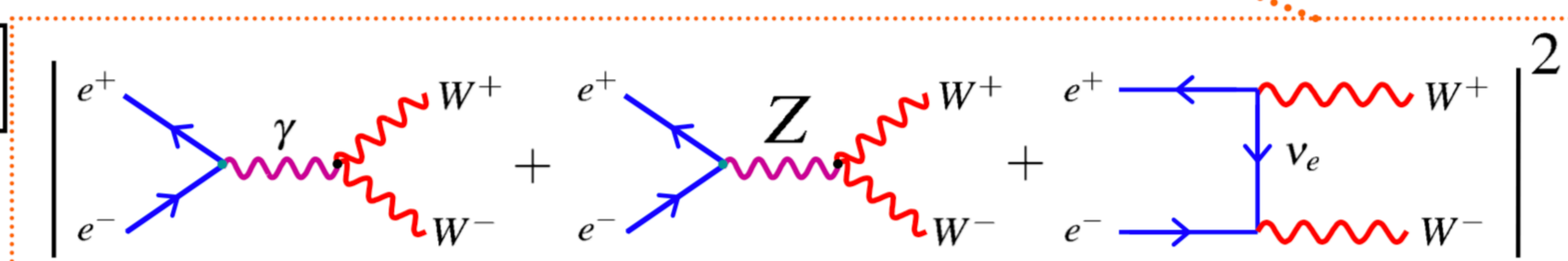
Well below Z: photon exchange dominant





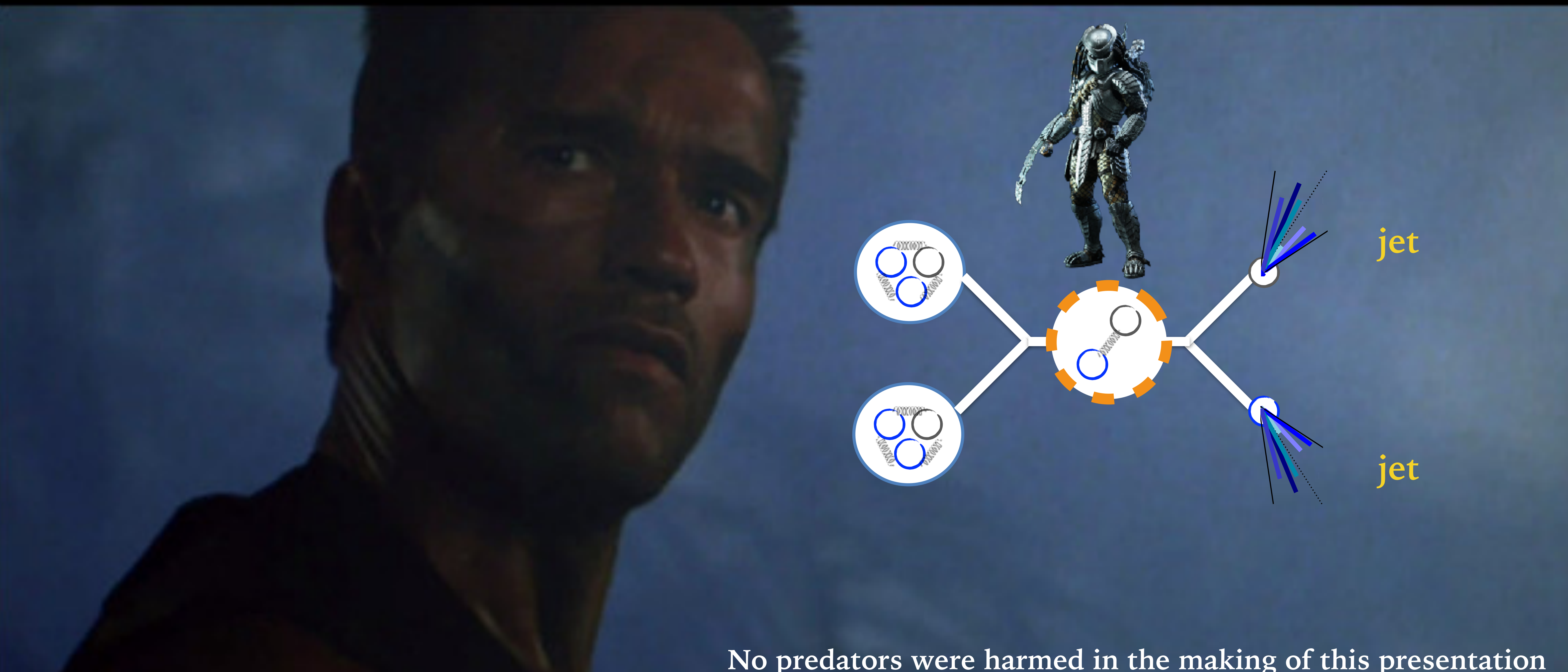
At Z resonance: Z exchange dominant

High energies: WW production



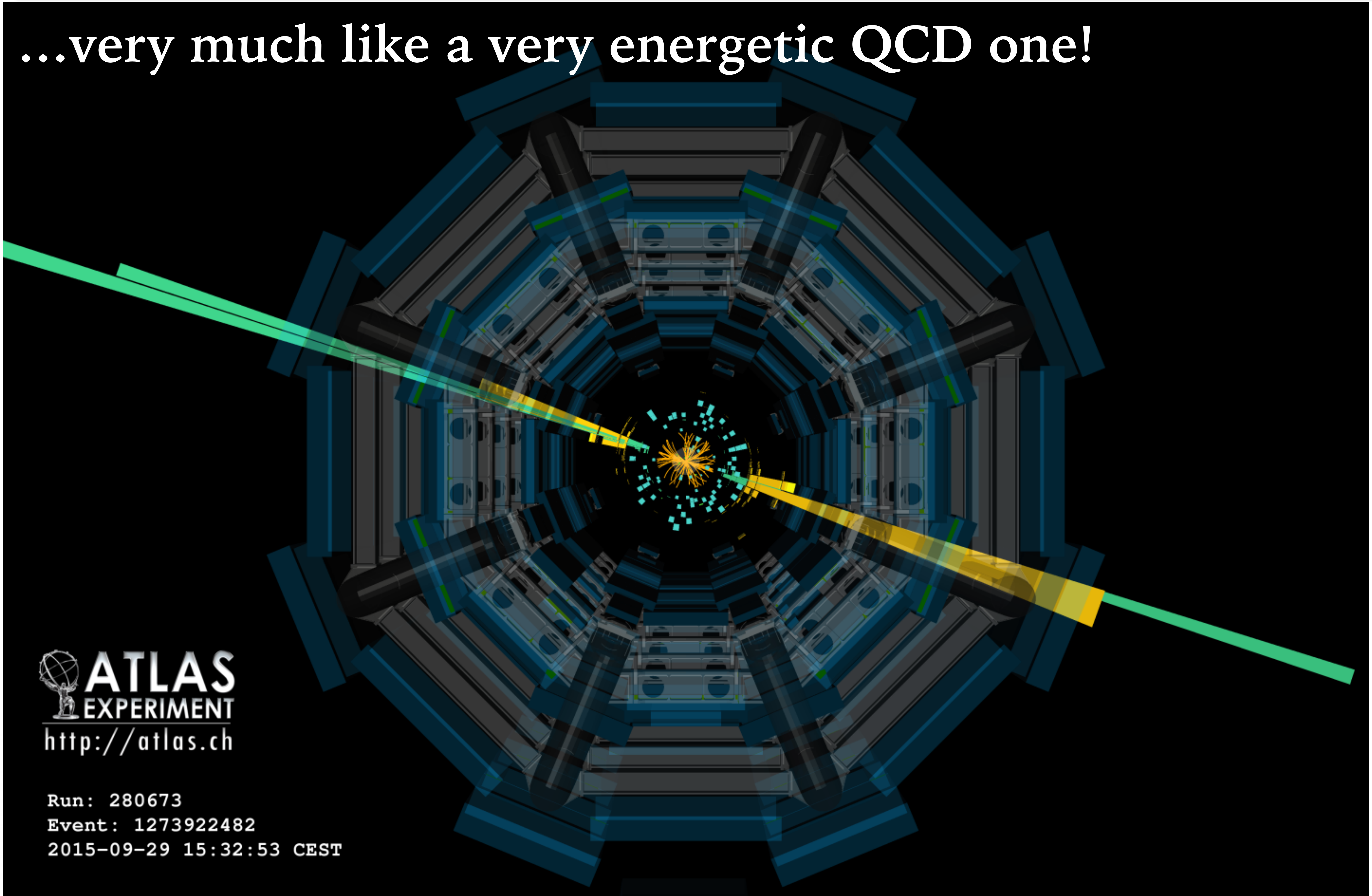
…then think of the LHC as a discovery machine

IF IT ~~BLEEDS~~ IS PRODUCED FROM QUARK INTERACTIONS



WE CAN ~~KILL IT~~ DISCOVER IT IN FINAL STATES WITH JETS

How does a new resonant particle event look like?



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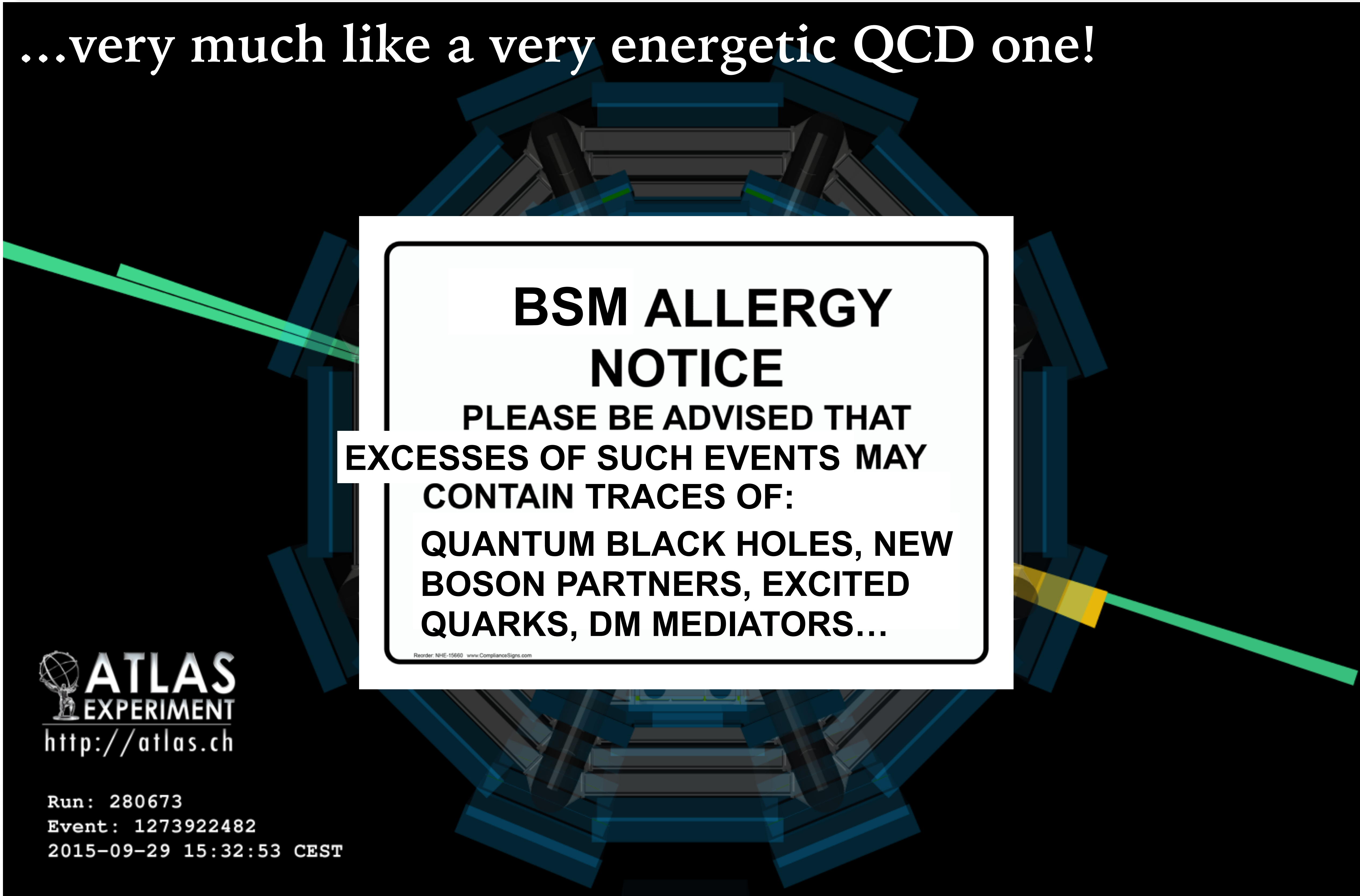
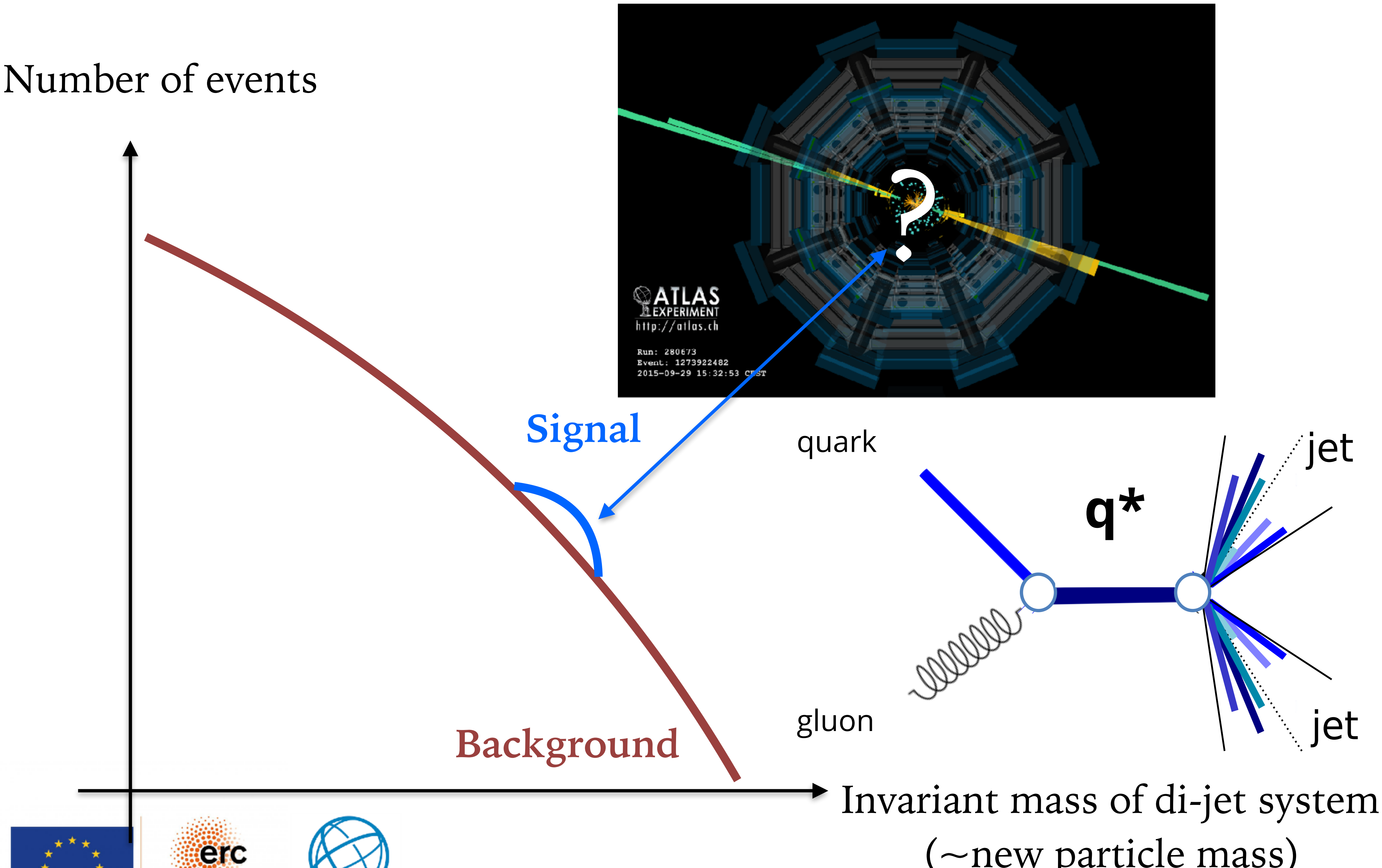


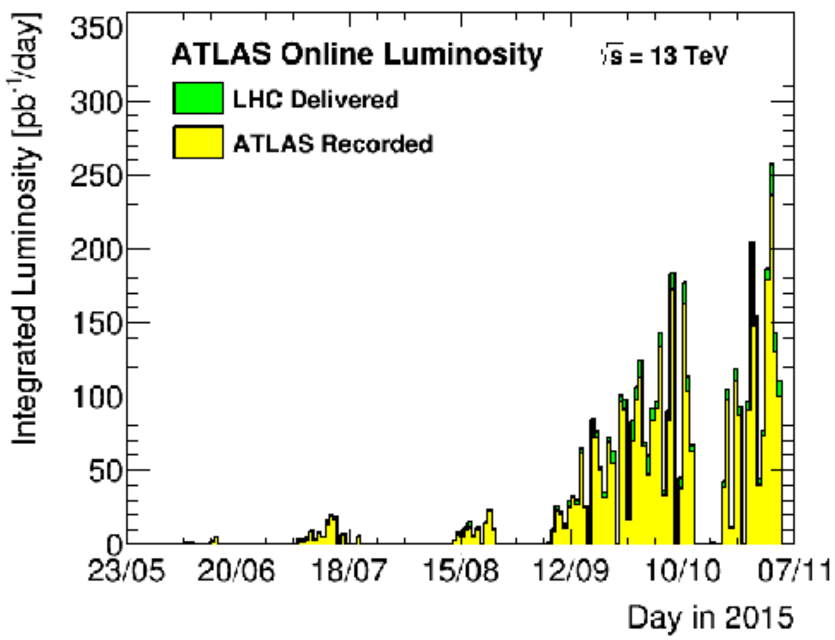
How would new phenomena manifest?

New particles: resonant excess (bump) over Standard Model background



How keen are experimentalists to do these searches?

Very! 1 month after first Run-2 data...



Submission history

From: Atlas Publications [view email]

[v1] Fri, 4 Dec 2015 20:15:47 GMT (778kb,D)

https://arxiv.org/abs/1512.01530

Submission history

From: The CMS Collaboration [view email]

[v1] Thu, 3 Dec 2015 20:49:43 GMT (1357kb,D)

http://arxiv.org/abs/1512.01224

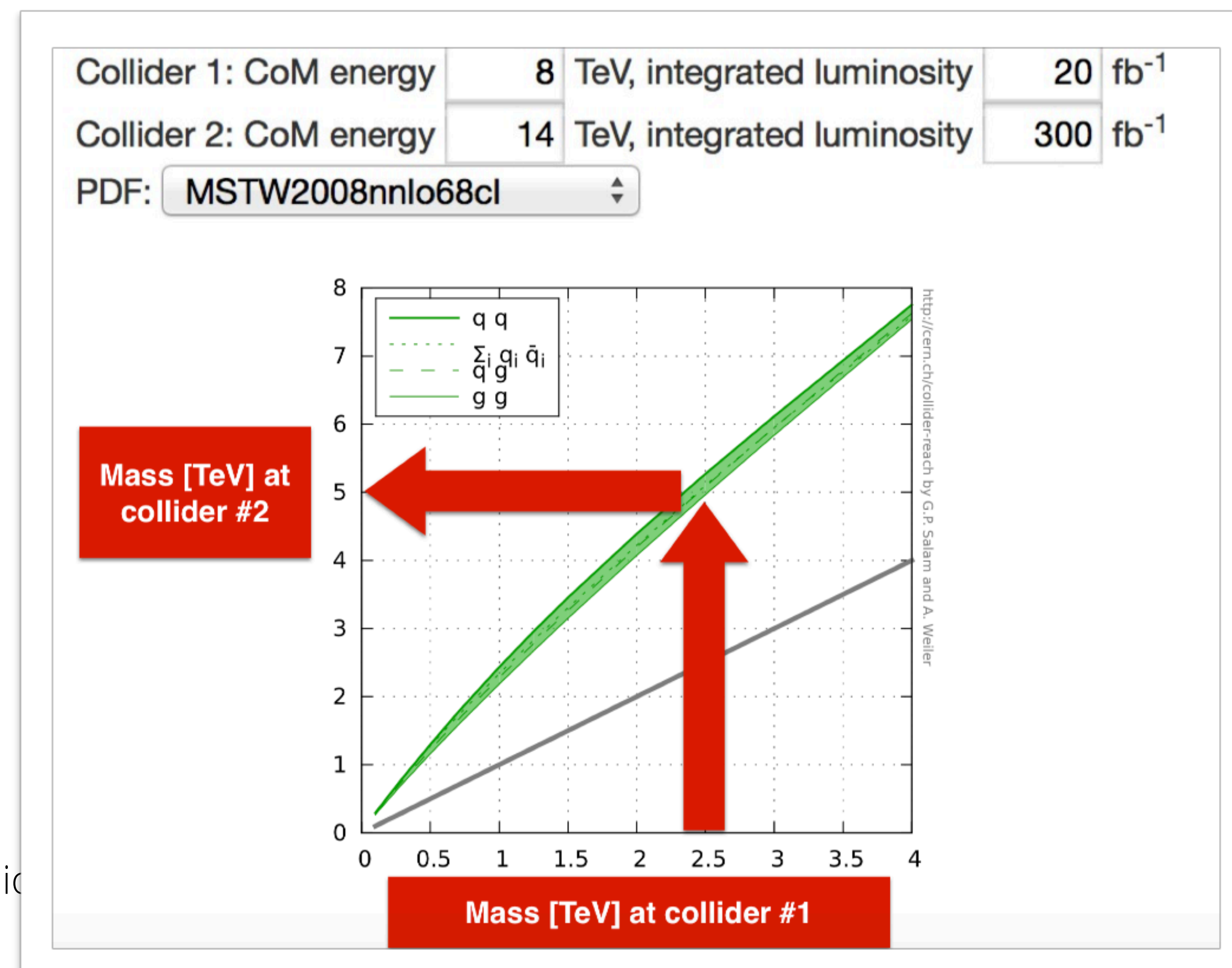
Increase in LHC energy

⇩

Greater discovery potential for new high-mass states

Details in G. Salam's talk on Collider Reach tools

Try it yourself at http://collider-reach.web.cern.ch/collider-reach/



How to search for ~~bumps~~ new physics 101

Record interesting LHC events

Calibrate objects & build distributions of **interesting observables**

Search: compare data and background

see any deviations?

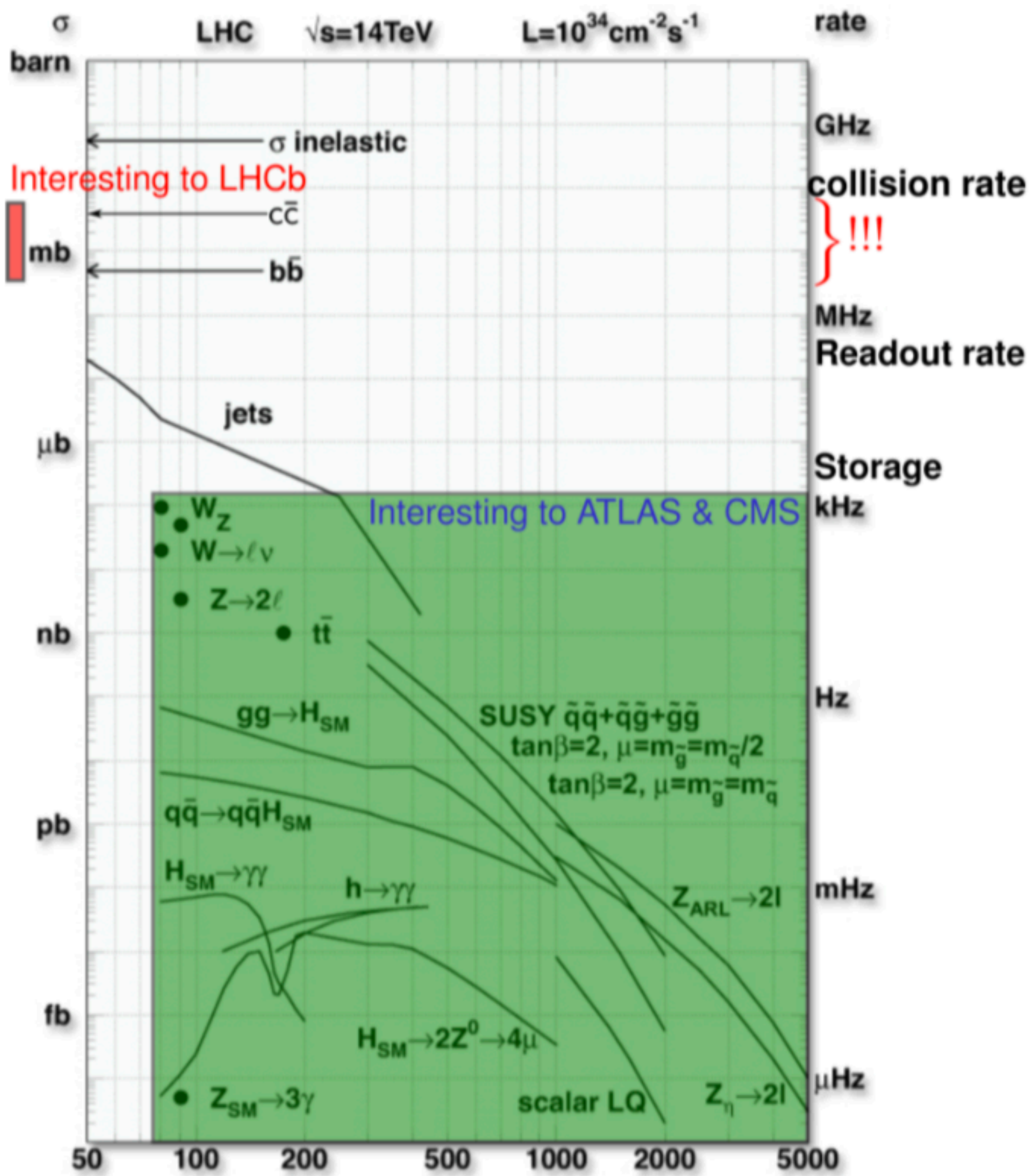
No

Yes

Set limits and constrain new physics models

What is interesting at the LHC?

J. Stirling / C. Fitzpatrick



Cross-section

Particle energy or mass

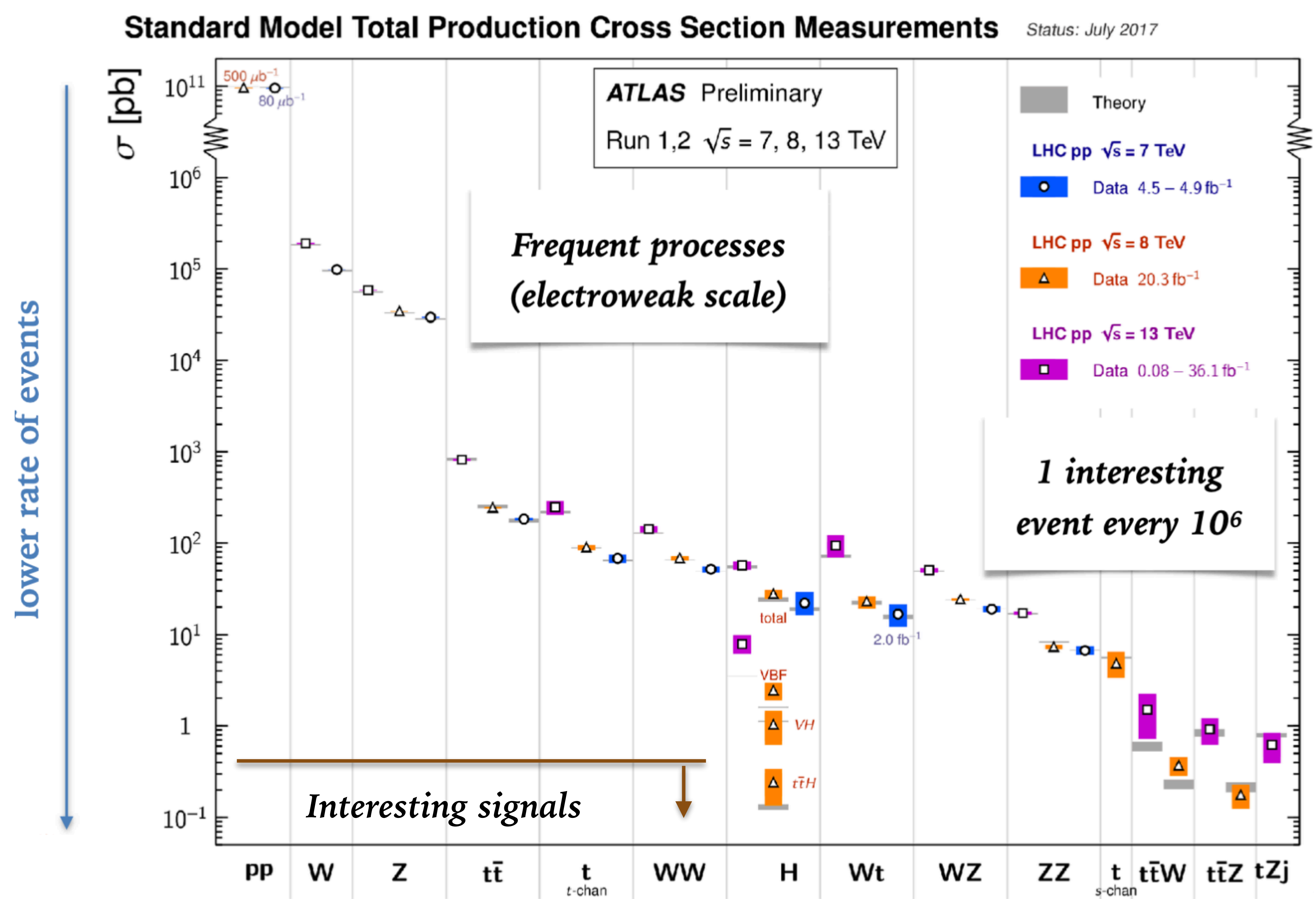
Cross-section * Luminosity
= number of events produced

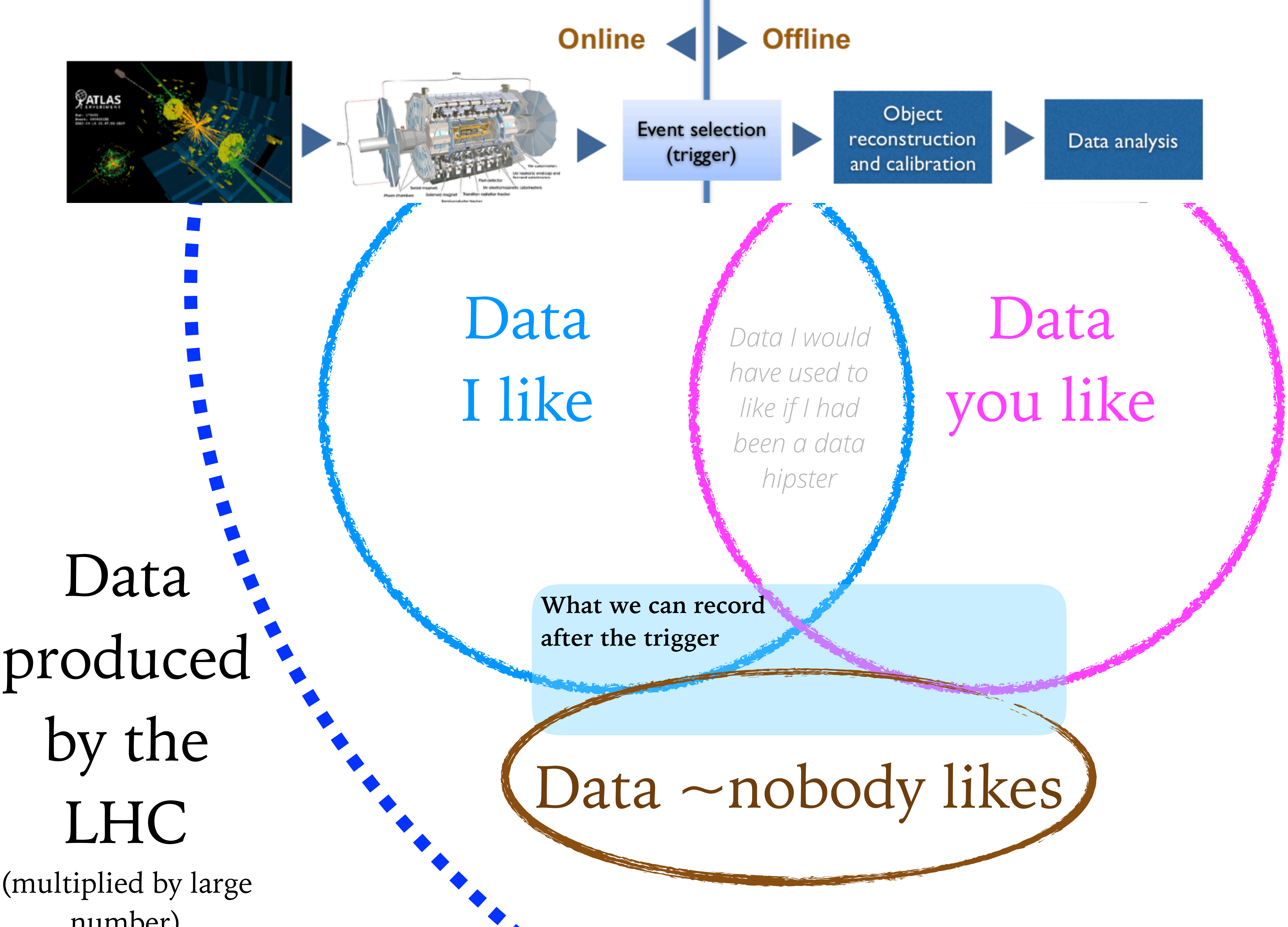
Challenges:

The **definition of "interesting"** changes experiment by experiment

Rare signal processes that are buried in **high-rate backgrounds** have to be discarded

Another look at the Standard Model




Online
Offline
ATLAS
Event selection (trigger)
Object reconstruction and calibration
Data analysis
Data I like
Data I would have used to like if I had been a data hipster
Data you like
What we can record after the trigger
Data ~nobody likes
Data produced by the LHC
(multiplied by large number)

Deciding what to record: trigger menu

Trigger menu decided in advance of data taking period

Example for **ATLAS**:

Year	2012		2015		
$\sqrt{s}$	8 TeV		13 TeV		
Peak luminosity	7.7×10^{33} cm^{-2} s^{-1}		5.0×10^{33} cm^{-2} s^{-1}		
	p_T threshold [GeV], criteria				
Category	L1	HLT	L1	HLT	Offline
Single electron	18	24i	20	24	25
Single muon	15	24i	15	20i	21
Single photon	20	120	22i	120	125
Single tau	40	115	60	80	90
Single jet	75	360	100	360	400
Single *b*-jet	n/a	n/a	100	225	235
E_T^{miss}	40	80	50	70	180

- More or less flexible to adjustments (changes need very good reasons!)
  - Follows priorities dictated by experiment's physics strategy
  - **LHCb**: using MVA to optimize selections and rates

Risks: **not recording** enough events, **missing** whole classes of events

How LHC collaborations make the most of the data

Interesting time for high energy physics:
we don't know what to expect from new physics
(but we know it should be somewhere)
we have the **LHC running now**,
and the data we discard is **gone forever**

1. Analyze as much data as possible, **as fast as possible**
2. Save data for **further reconstruction, later**
3. Implement more refined algorithms to **look for the unexpected**
   - Including unsupervised searches / novelty detection
     - See e.g. this talk by M. Pierini for more details

More on this in the next lectures

How to search for ~~bumps~~ new physics 101

Record interesting LHC events

Calibrate objects & build distributions of **interesting observables**

Search: compare data and background

see any deviations?

No

Set limits and constrain new physics models

Yes

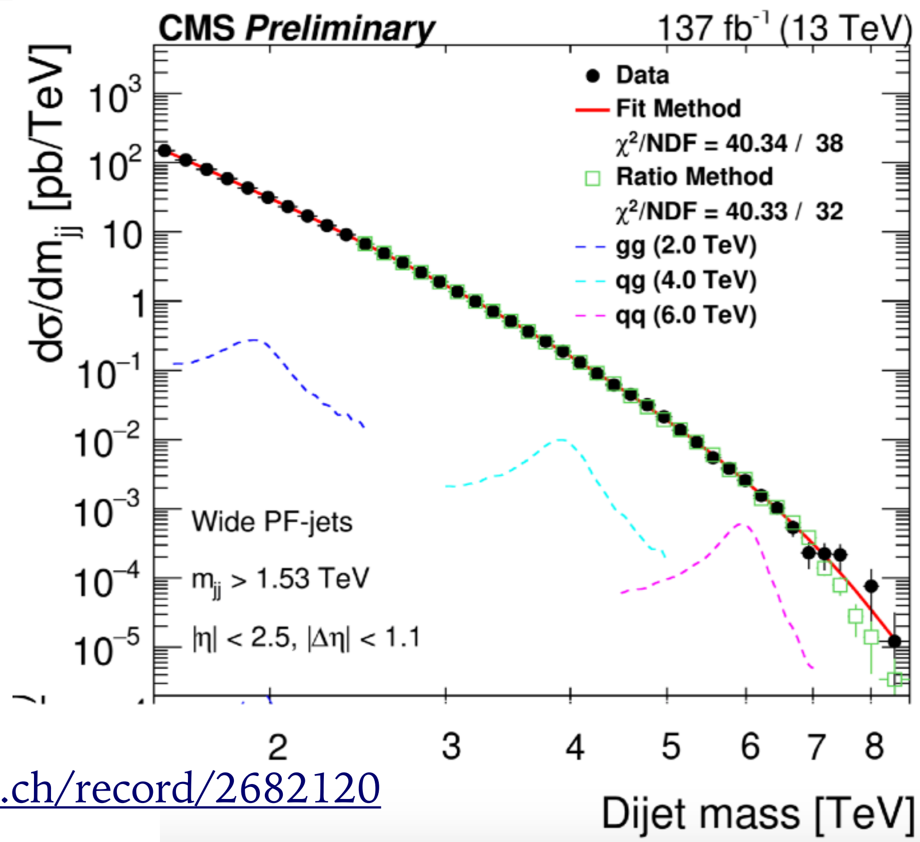
Take-home point #2:

having a good calibration & performance of physics objects is an integral (and essential) part of any search / measurement

[this also applies for good detector operations, data taking and computing to process and analyse the data]

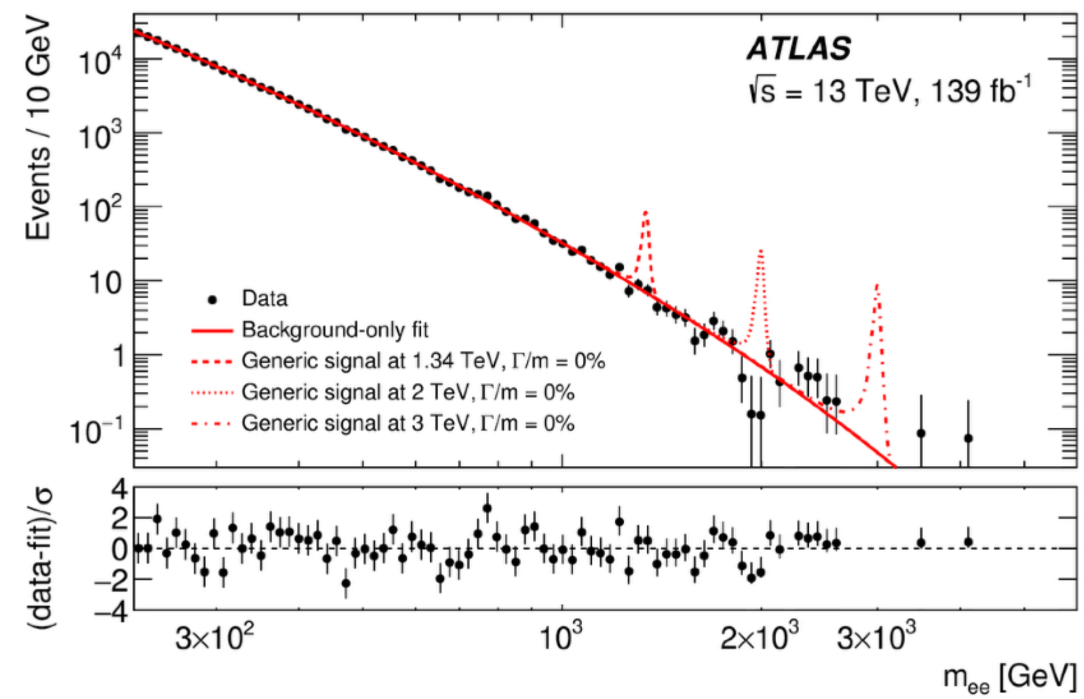
Searching for bumps in the … invariant mass distribution

di-jet

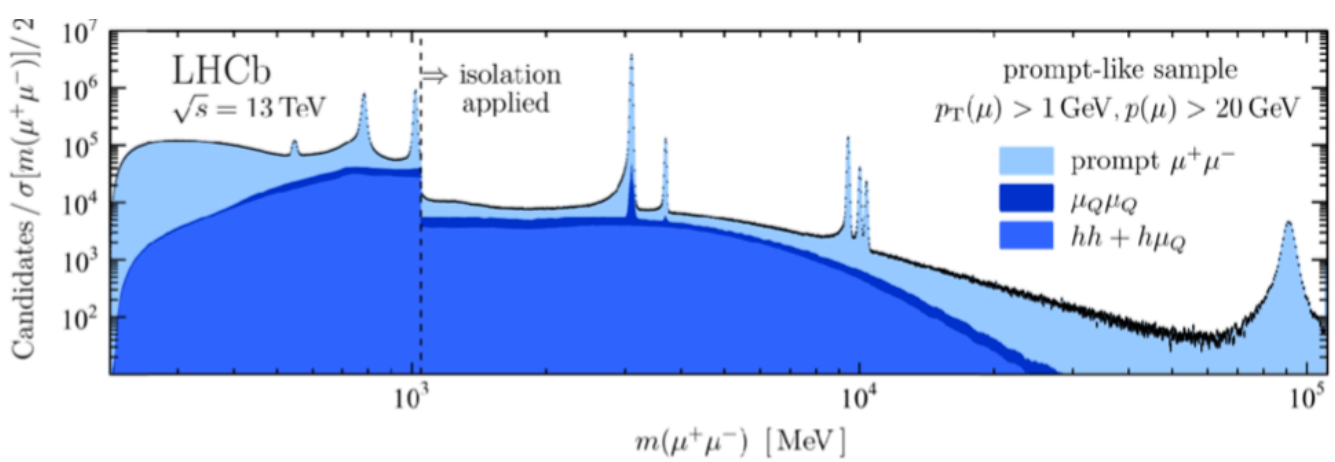


https://cds.cern.ch/record/2682120

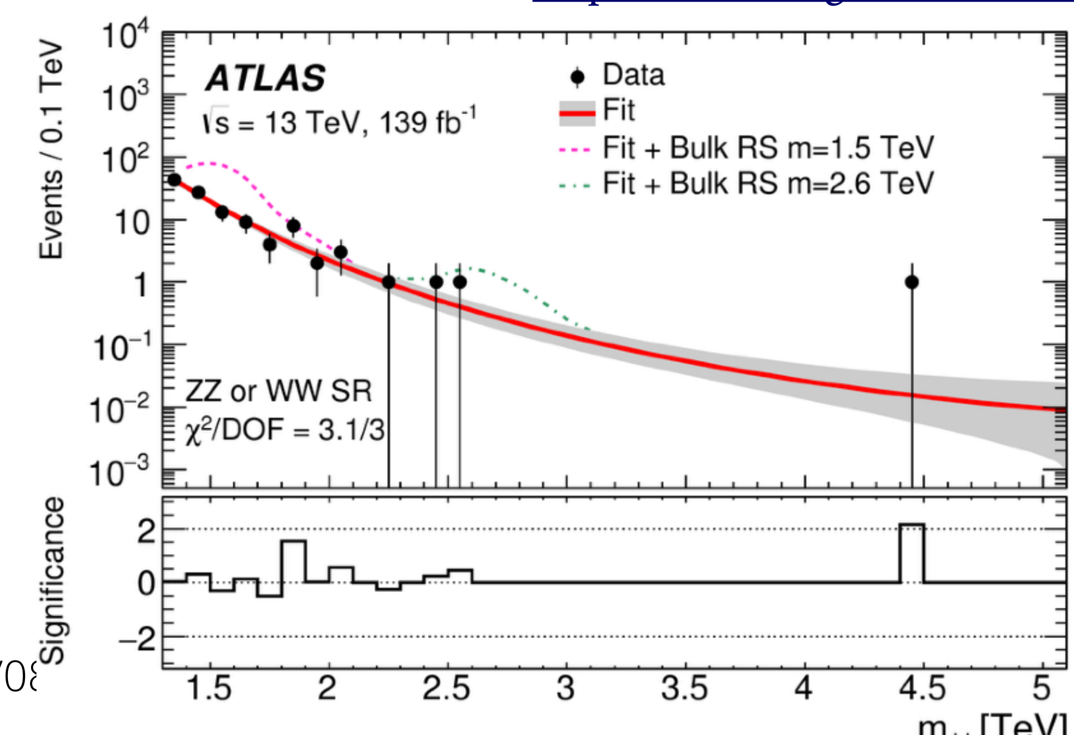
di-electron https://arxiv.org/abs/1903.06248



di-muon https://arxiv.org/abs/1710.02867



diboson https://arxiv.org/abs/1906.08589



Also: di-photon, weird jets….

How to search for ~~bumps~~ new physics 101

Record interesting LHC events

Calibrate objects & build distributions of **interesting observables**

Search: compare data and background

see any deviations?

No

Set limits and constrain new physics models

Yes

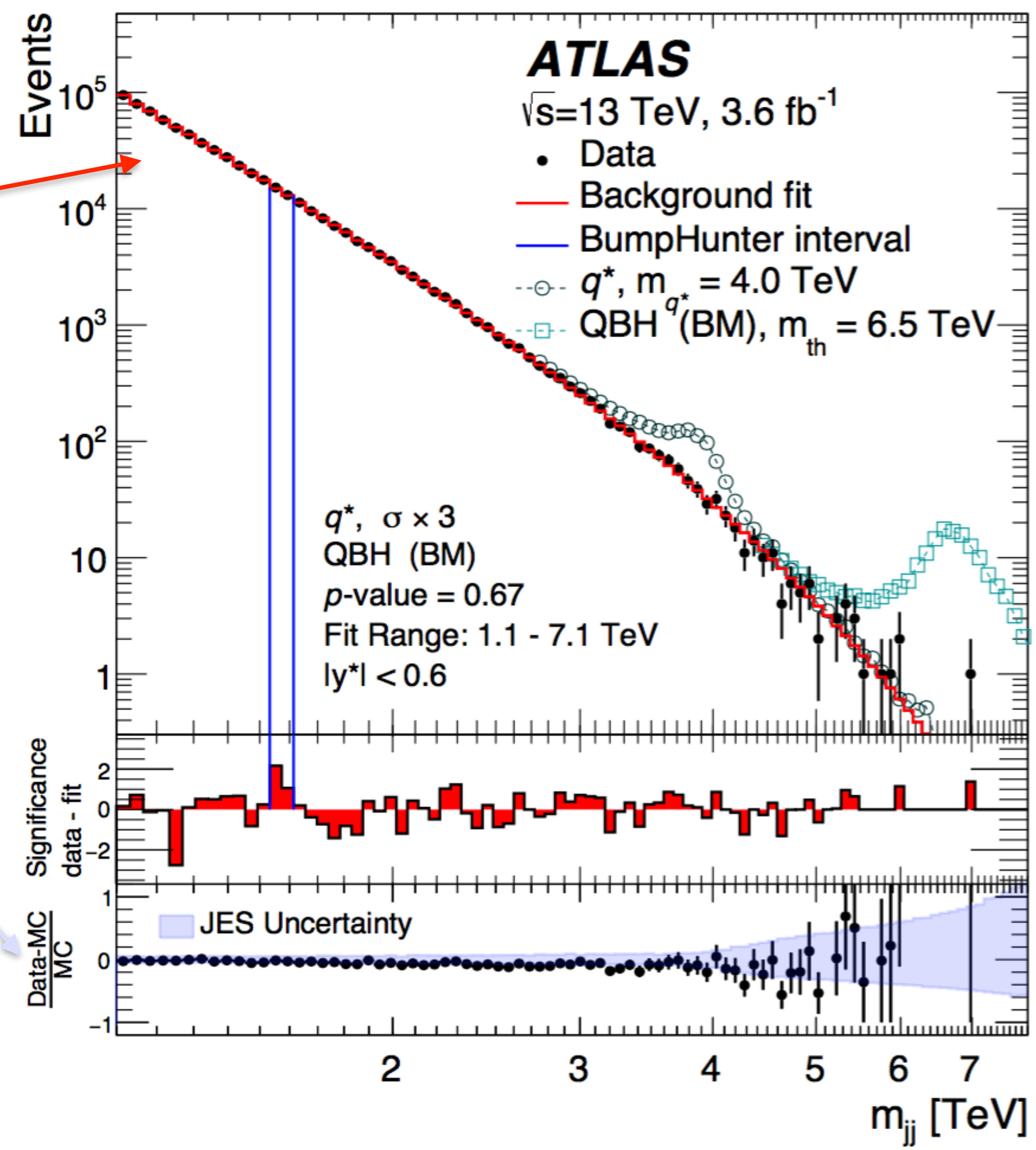
Search phase: compare data and background

Simplest way: compare **data** with **smooth QCD-inspired fit, e.g.:**

$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

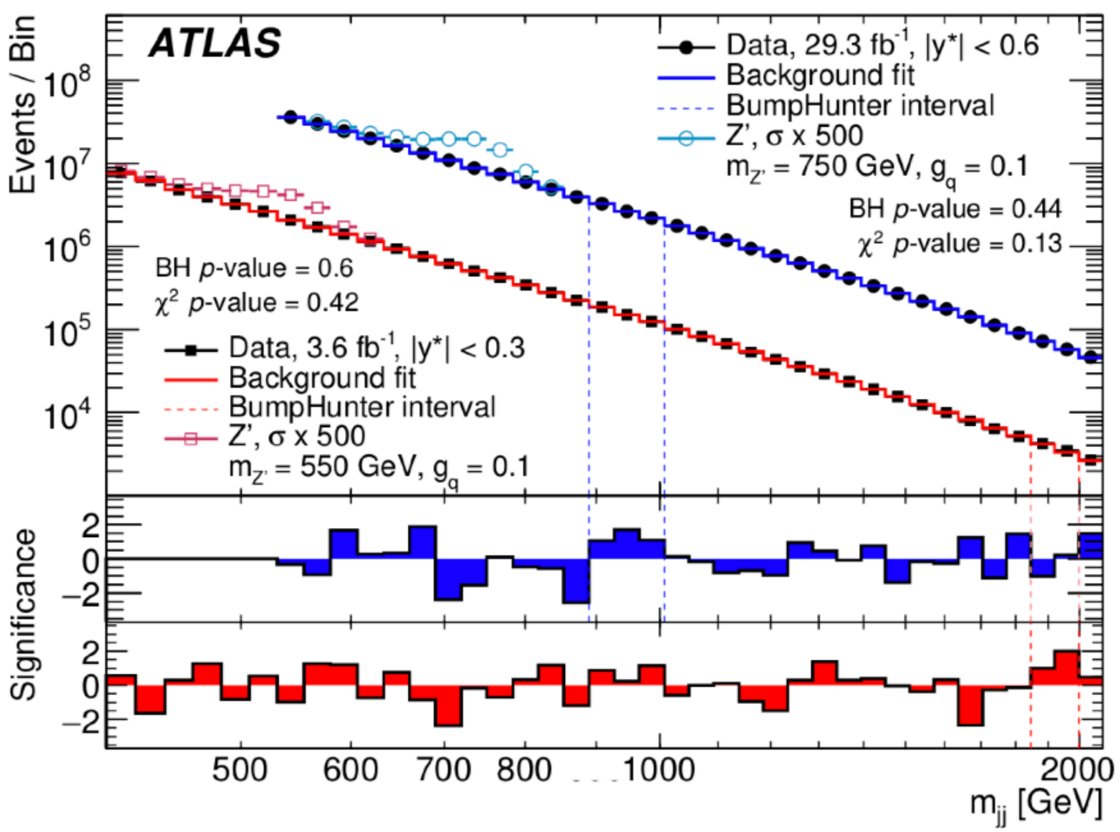
More complex techniques: today PM

Compare **data** with **simulation** (Pythia), but mostly as a cross-check



Searching with *BumpHunter*

https://arxiv.org/abs/1804.03496



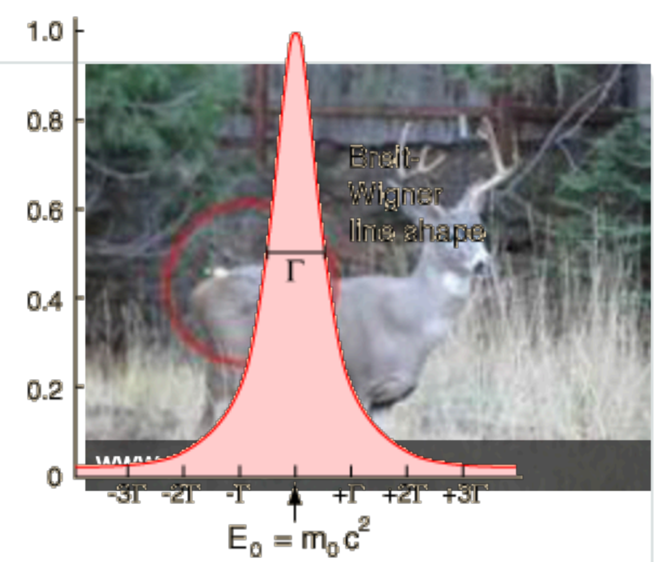
"Searching for new physics"
= obtaining a quantitative estimate
of the data *disagreeing*
with a background-only model

Example of model-agnostic method:
BumpHunter

Many more on the market / in statistics lectures

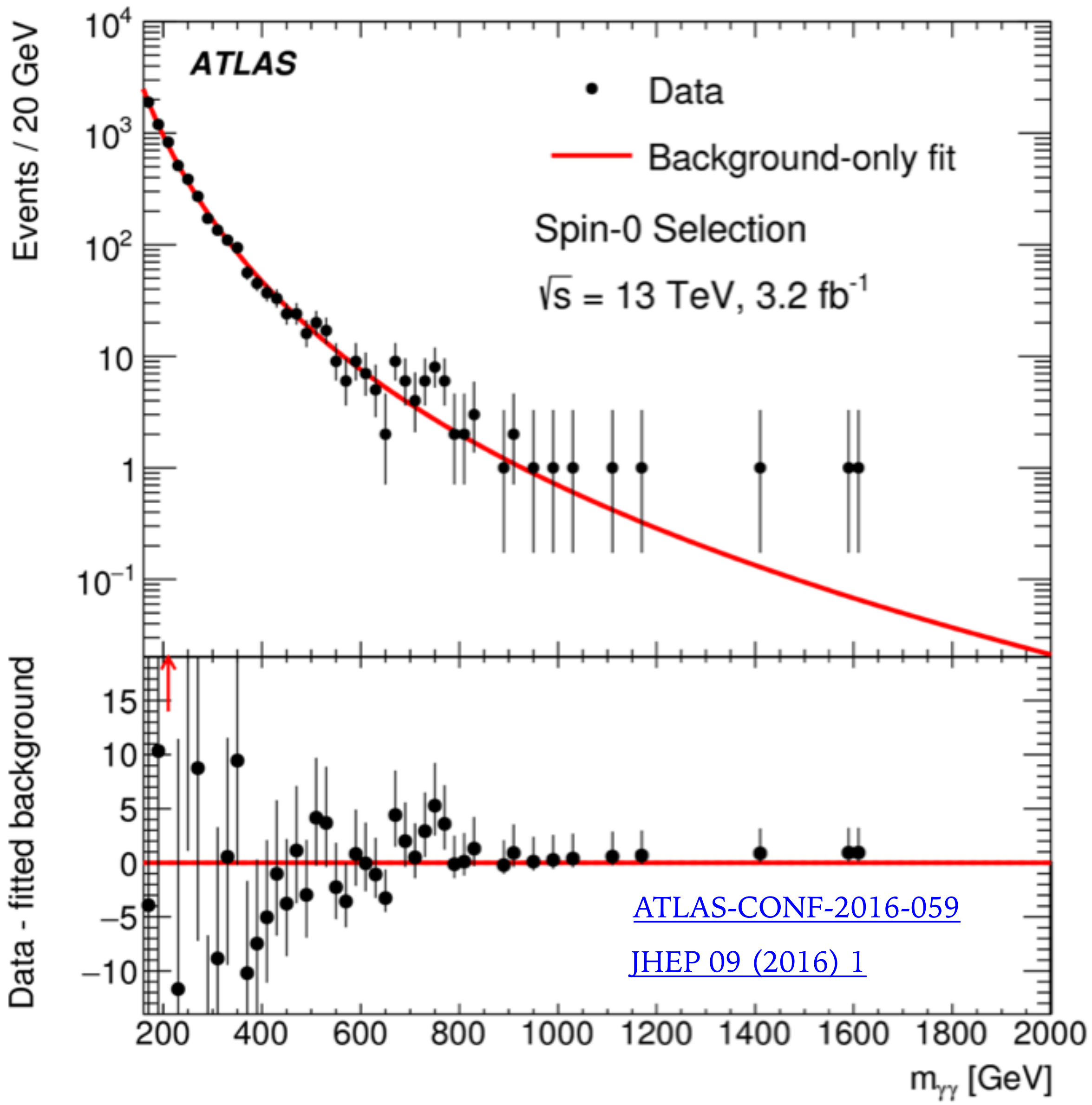
Bump- Hunting is cruel and socially unjustifiable. Thousands of models die as victims of this 'sport' every year. The **cruelty** of **hunting** involves the causing of pain towards phenomenologists

Bump Hunting | BSM search | Equality



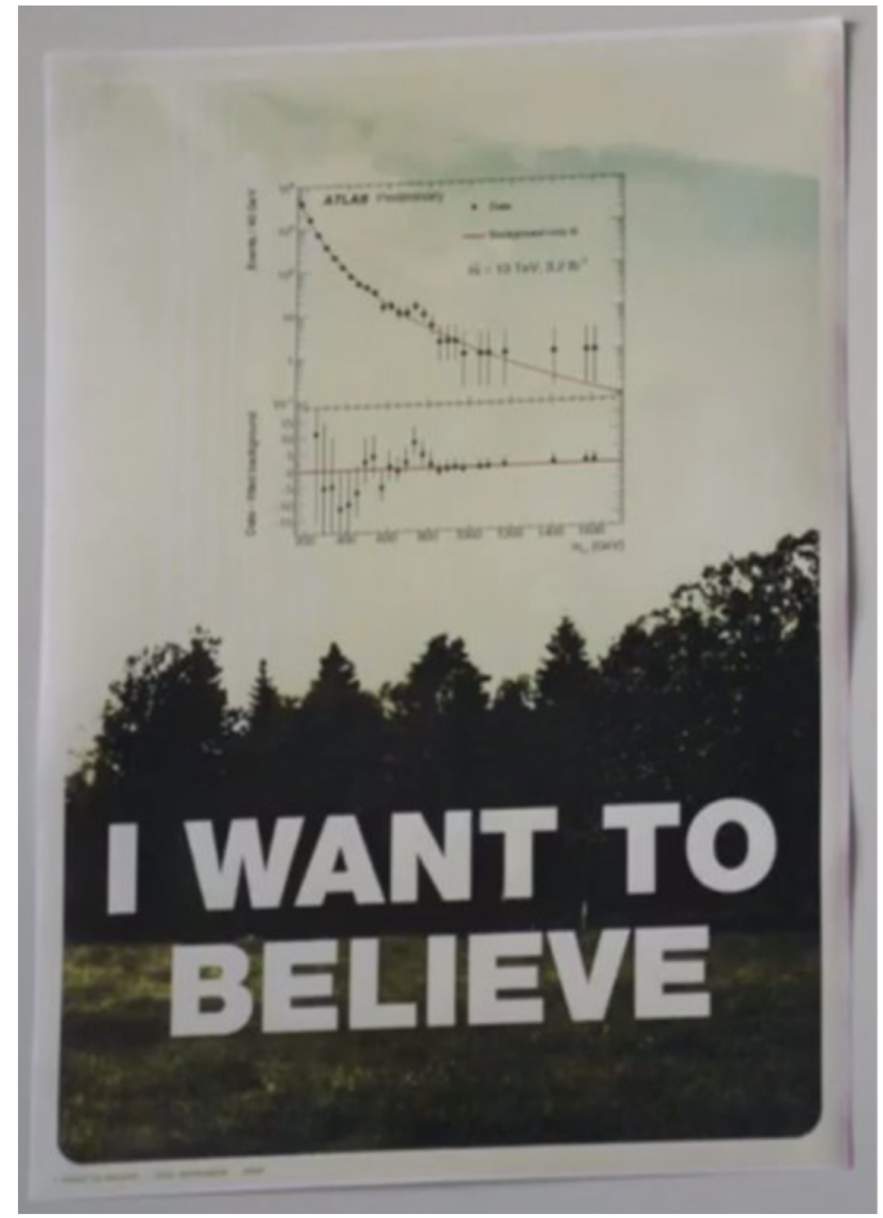
Note: my personal views align with no-hunting in general even when I make fun of physics lingo
also see this set of slides for another perspective on this kind of physics lingo

Care with statistics & enthusiasm needed: diphoton



Di-photon, December 2015:

(small) overall excess over background, more data was needed

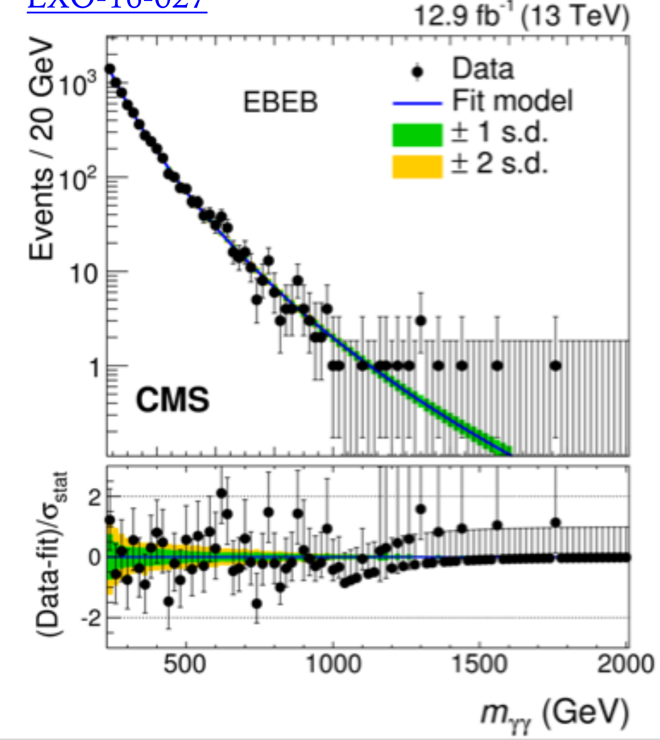


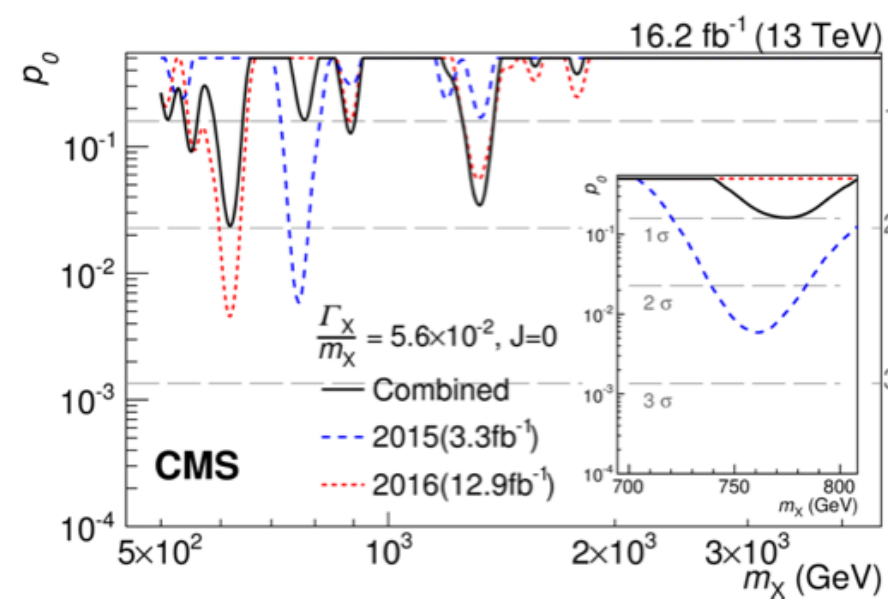
Poster on the wall of an experimental physicist at CERN
Source: BBC documentary

Care with statistics & enthusiasm needed: diphoton

Waste bin in a theoretical physicist's office at CERN
Source: twitter

EXO-16-027





Di-photon:

the (small) overall excess over background is gone with more data

How to search for ~~bumps~~ new physics 101

Record interesting LHC events

Calibrate objects & build distributions of **interesting observables**

Search: compare data and background

see any deviations?

No

Set limits and constrain new physics models

Yes

How to read an example LHC limit plot

~~How to make a LHC limit plot~~

More on this in stats lectures

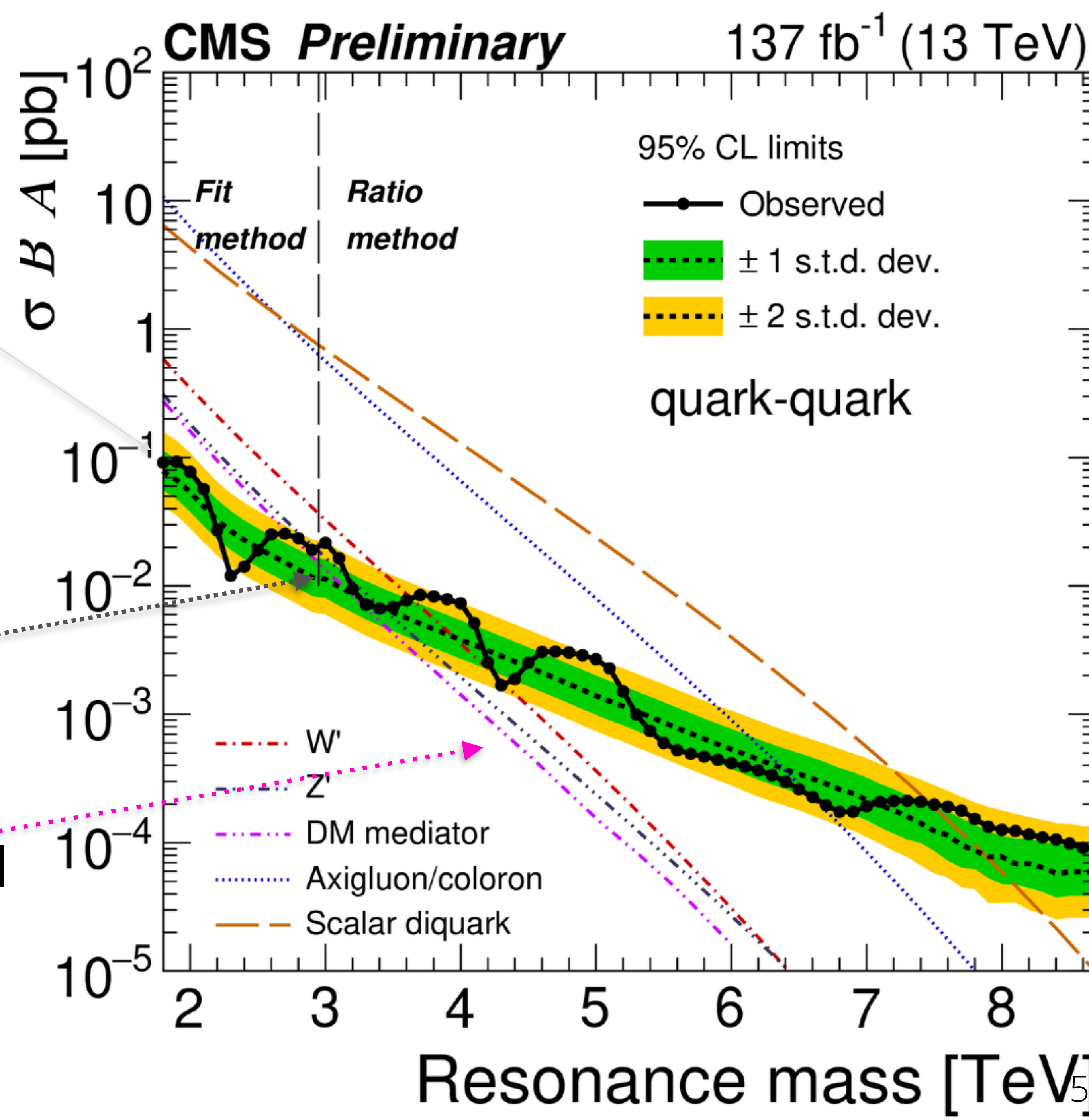
or these slides

Exclusion **observed** from data of:

- the cross-section (~ N of events) for a given di-object process
- with a certain BR ***B*** to the final state in the search
- after acceptance **A** of experimental selection
- considering experimental (in)efficiencies (ϵ)

Exclusion **expected** from bkg-only, together with uncertainty bands

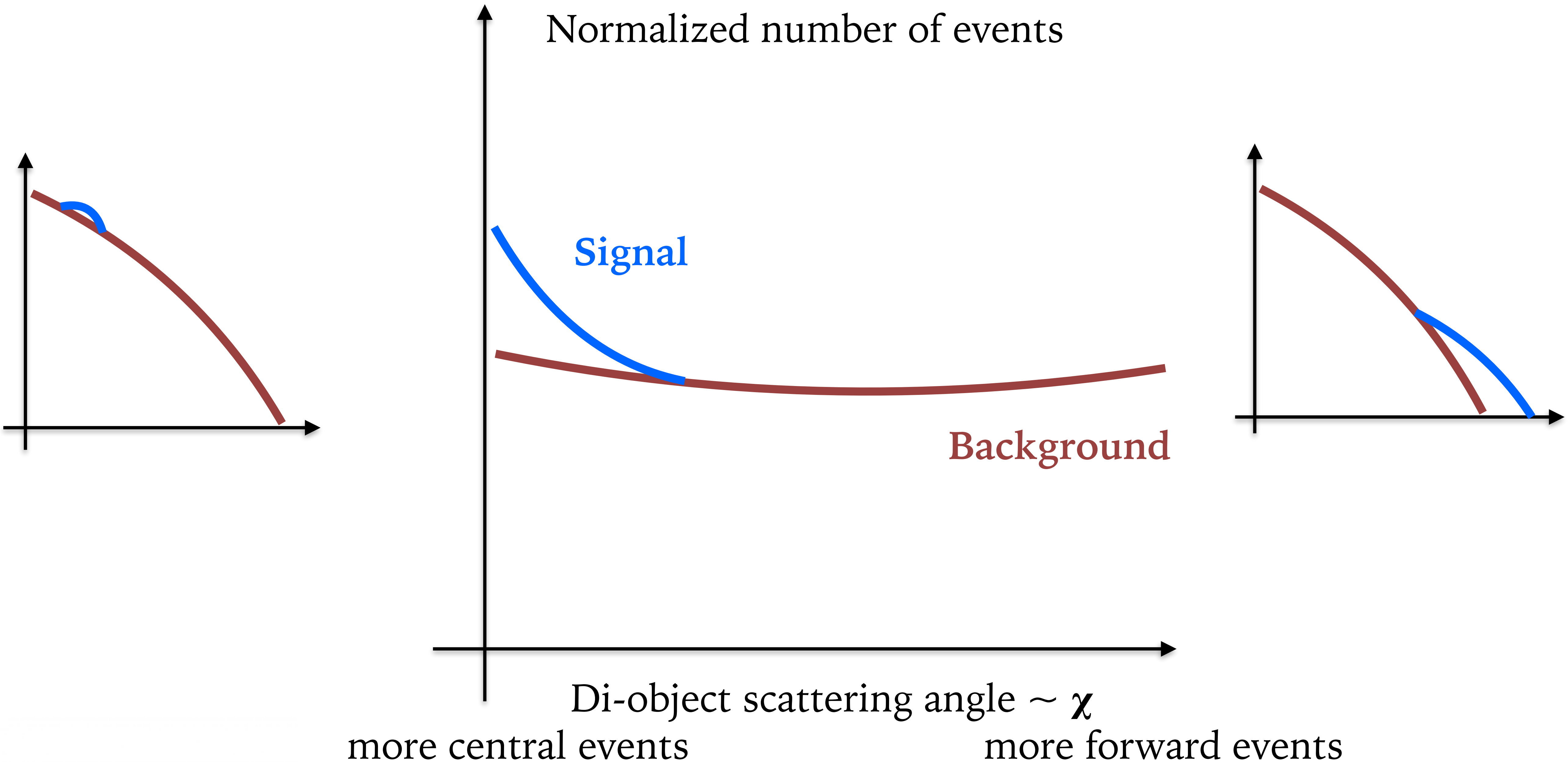
Theoretical cross-sections for selected models, accounting for **B**, **A**, ϵ



https://cds.cern.ch/record/2682120

How would new phenomena manifest?

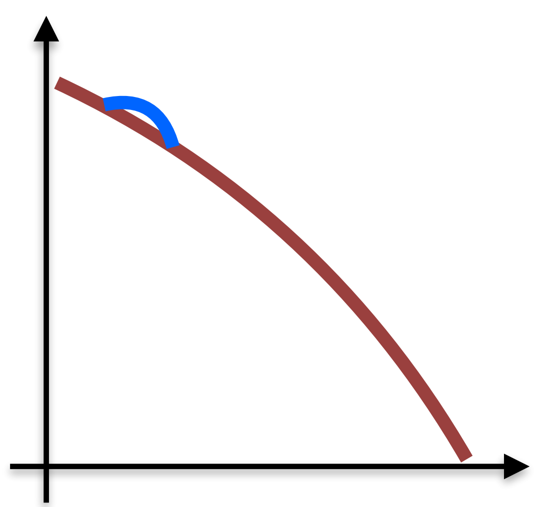
New interactions: more central production with respect to backgrounds

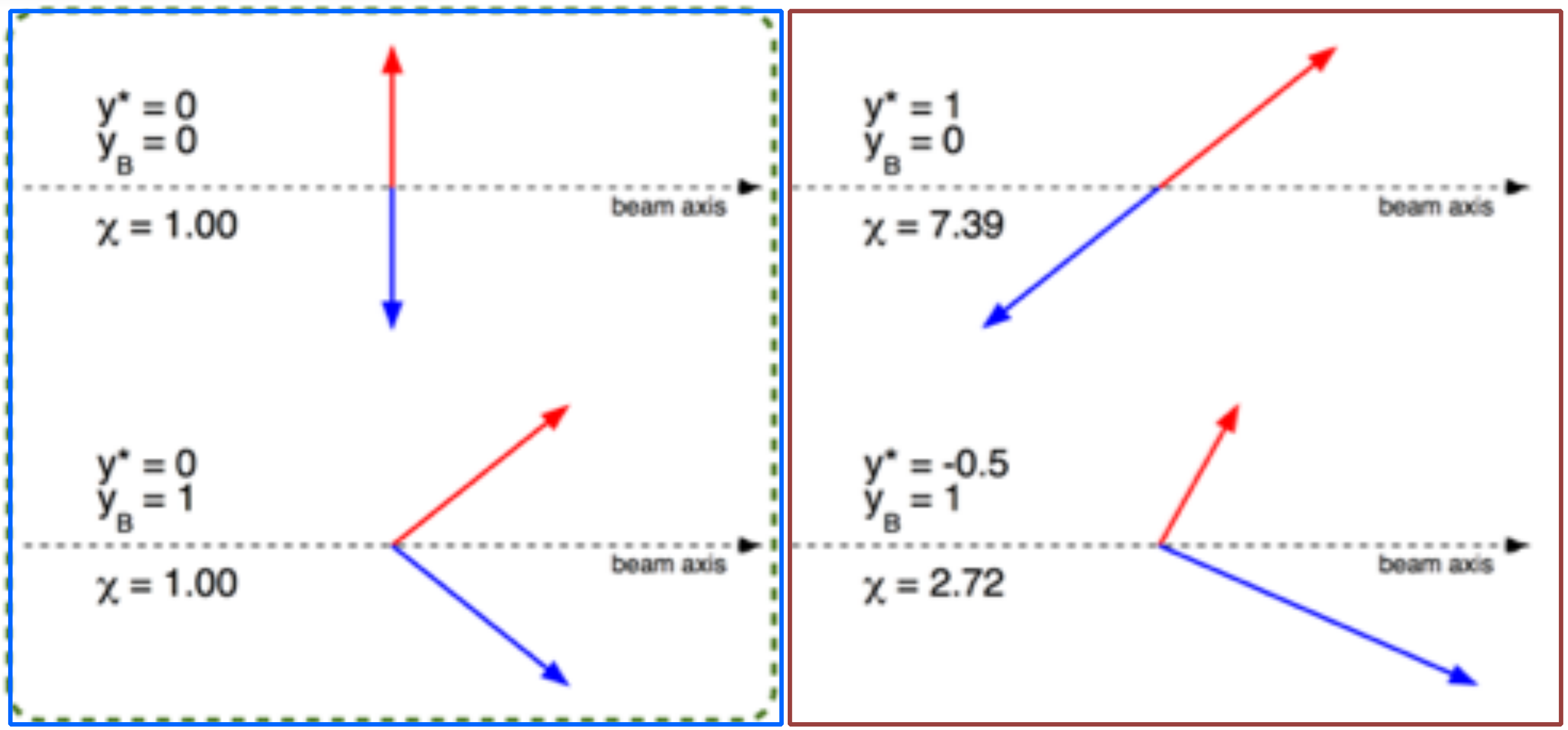


How would new phenomena manifest?

New interactions: more central production with respect to backgrounds

Dag Gillberg, ICHEP 2012





signal:
more central events

background:
more forward events

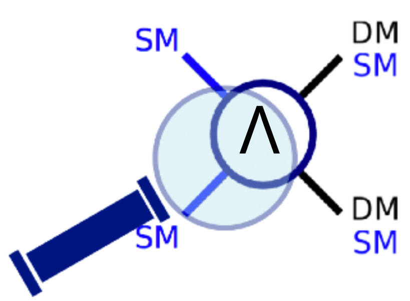
For the theory: think Rutherford & read L. Bryngemark's thesis

Selected results of angular analyses, and more

Signal: contact interactions (CI)

$$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)\right].$$

CI: a way to encapsulate new physics at a higher energy scale Λ



Valid approach as long as CoM energy << Λ

Λ	$(\eta_{LL}, \eta_{RR}, \eta_{RL})$
$\Lambda^{\pm}_{LL}$	$(\pm1, 0, 0)$
$\Lambda^{\pm}_{RR}$	$(0, \pm1, 0)$
$\Lambda^{\pm}_{VV}$	$(\pm1, \pm1, \pm1)$
$\Lambda^{\pm}_{AA}$	$(\pm1, \pm1, \mp1)$
$\Lambda^{\pm}_{(V-A)}$	$(0, 0, \pm1)$

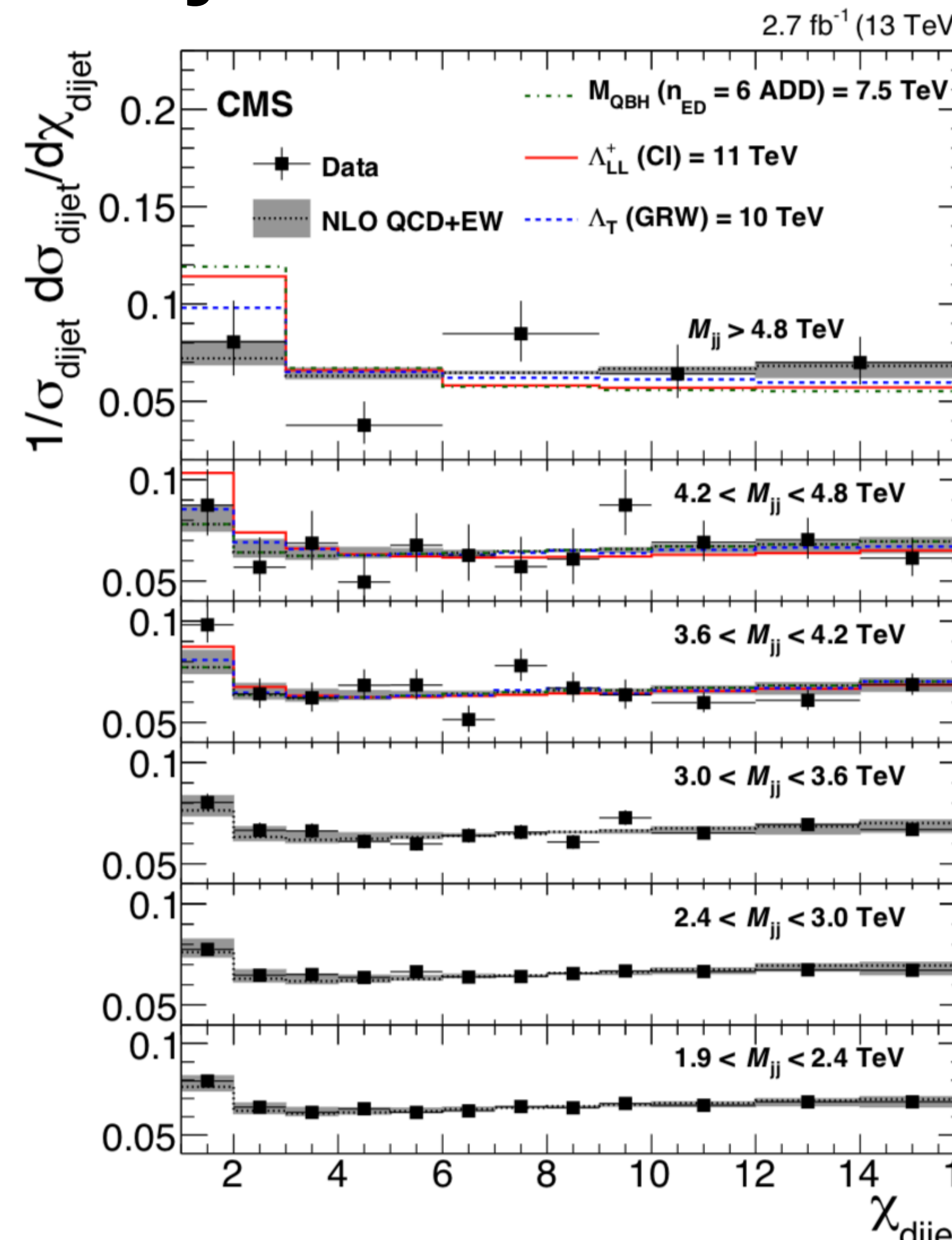
+ : constructive interference

- : destructive interference

https://arxiv.org/abs/1703.09986

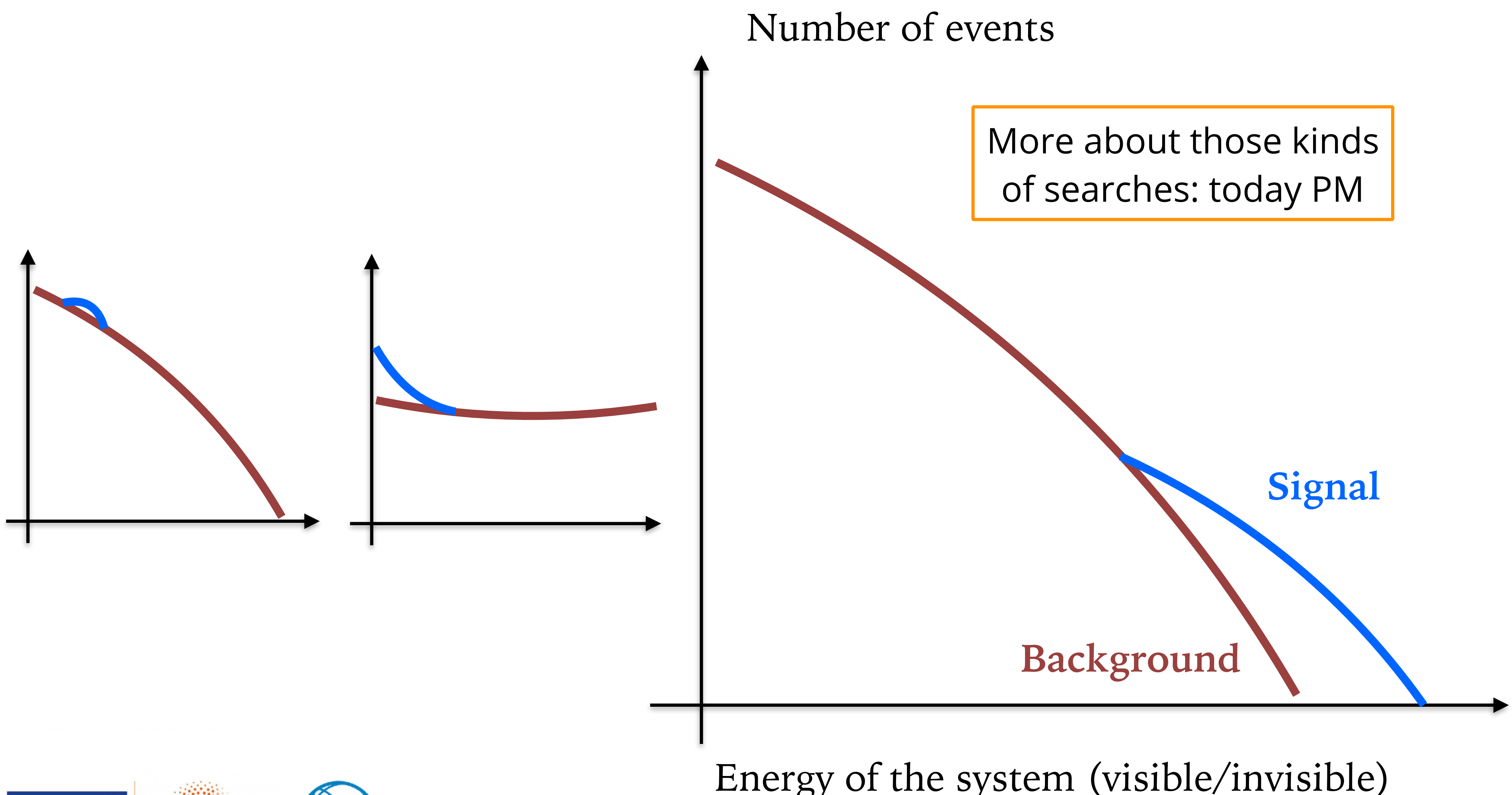
di-jet

Note: unfolded for detector effects



How would new phenomena manifest?

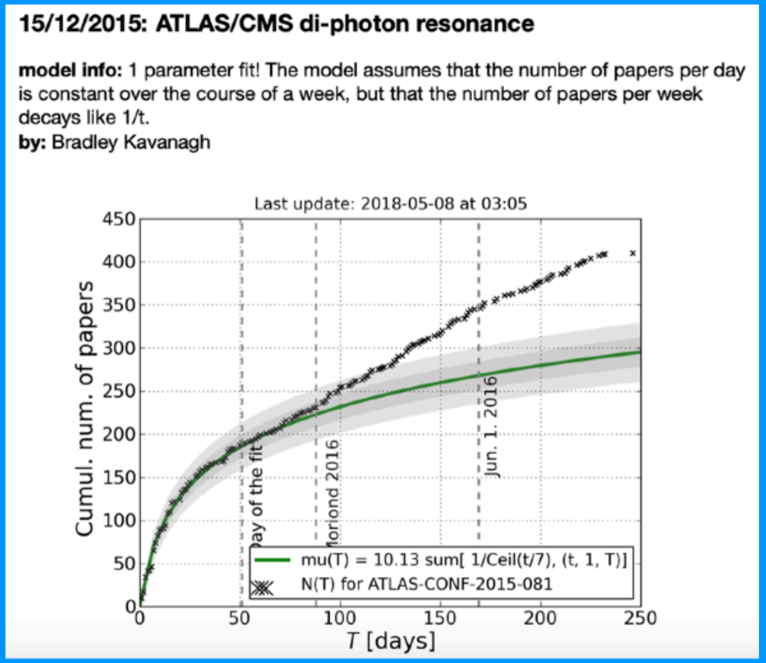
New particles and states: larger multiplicity of objects at high masses



Take-home point #3:

Generic searches for new particles, especially at a new center-of-mass energy, can catch a wide range of new phenomena

(and if an unexpected particle is found, a model that accommodates it will be found soon after the discovery)



https://cp3.irmp.ucl.ac.be/~mbackovic/

Two mega bummer slides

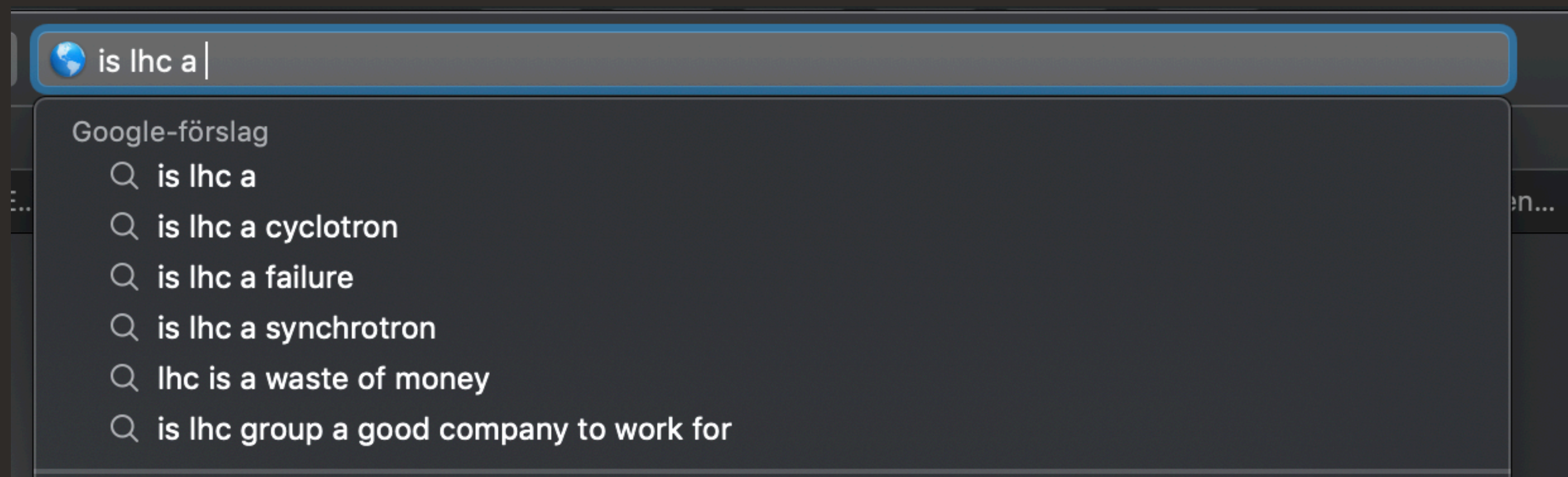
Have we found any unexpected new particles yet?

Two mega bummer slides

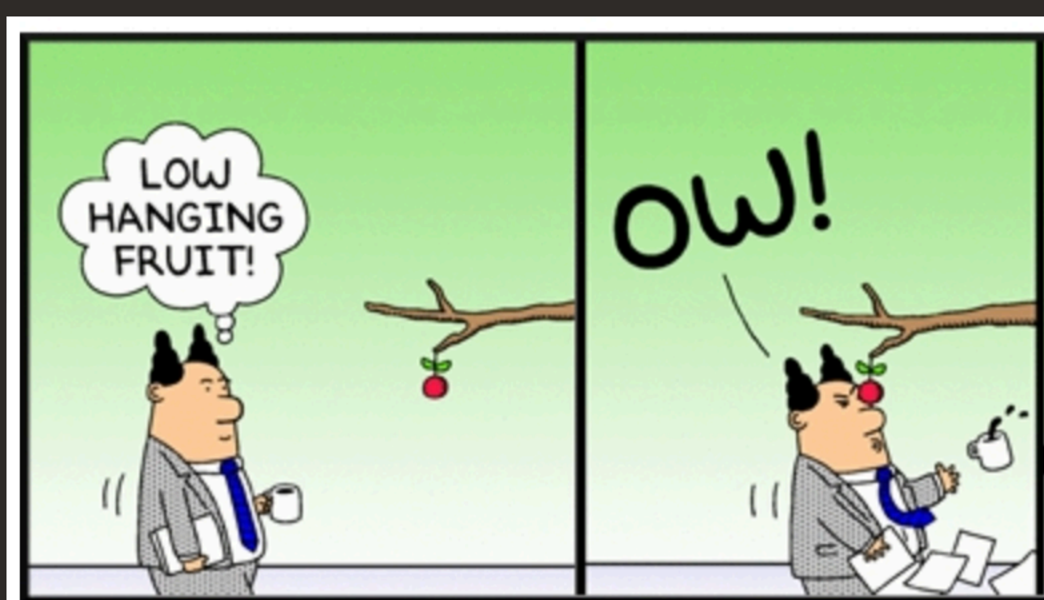
No.

And the LHC isn't upgrading to a much higher energy scale anytime soon

Naysayer’s feeling about future LHC physics:



My feeling about future LHC physics:



Dilbert comics

Let’s keep looking!

New physics could still manifest in:

1. deviations through precision
2. rare, unusual processes

Plus, the SM actually has some unexplained issues[see lecture this PM]

Indirect searches for new particles
(very very short, deferred to flavor lectures)

Searching for new particles in loops

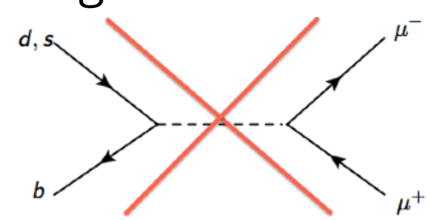
Similarly to **contact interactions**

quantum loops let us look for new particles at energies >> collider

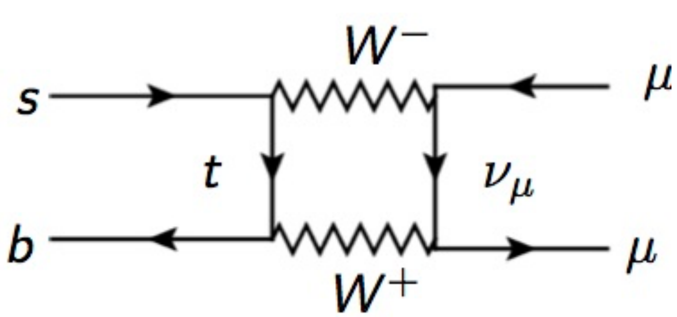
(can violate energy conservation for a very short time)

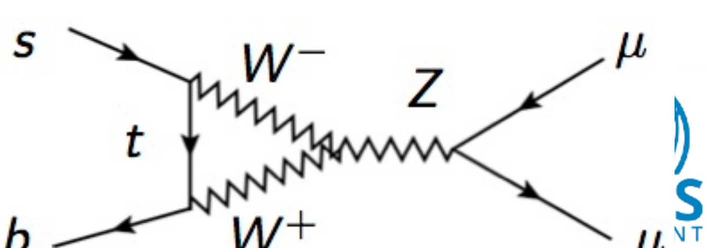
How to look: **precision** measurements, e.g. Bs -> mumu

Leading order: forbidden (FCNC)

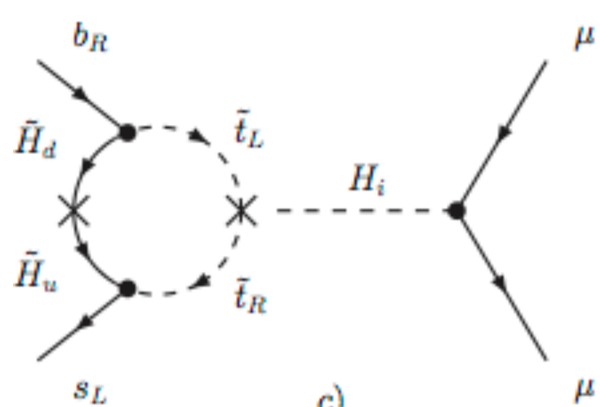


Loop: very rare!

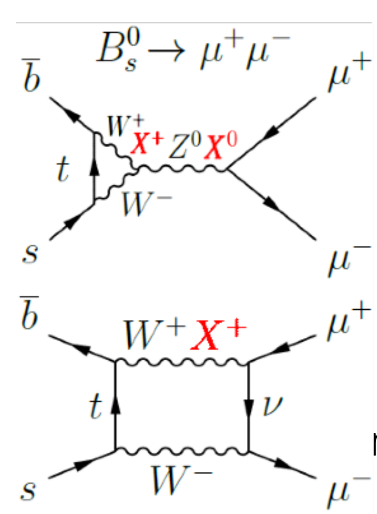




New particles: take your pick!

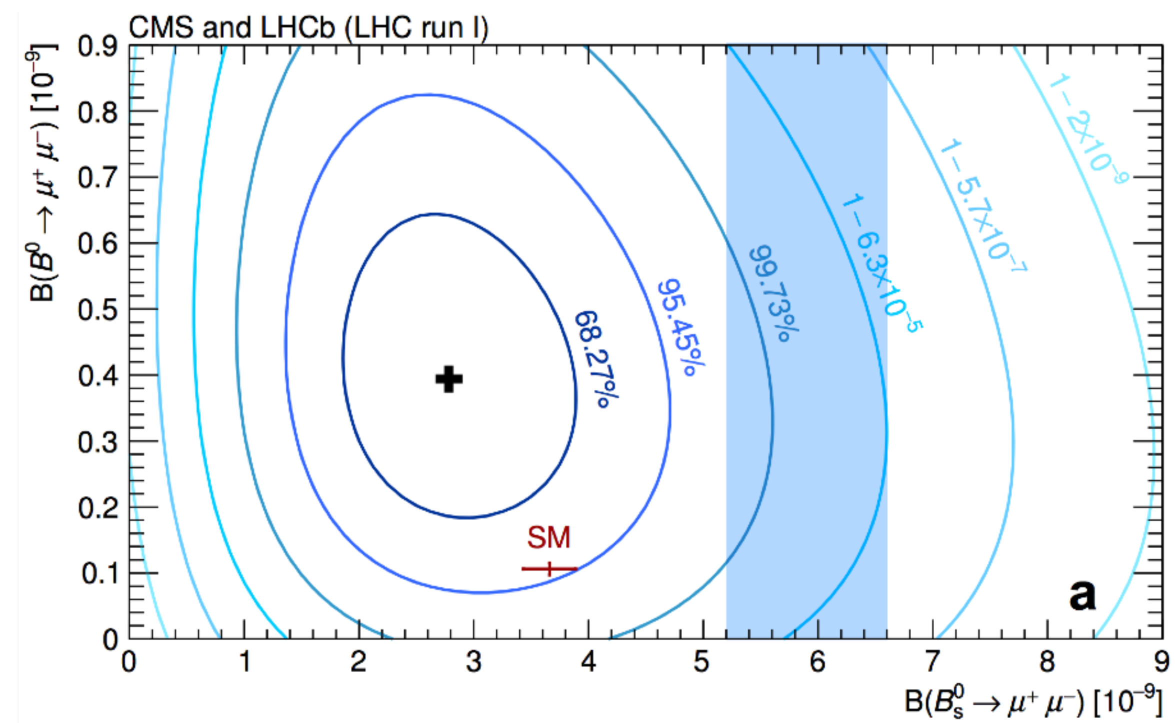


arXiv:1611.07864.pdf



arXiv:1504.06519

Method: measure branching fractions



New CMS and ATLAS results available

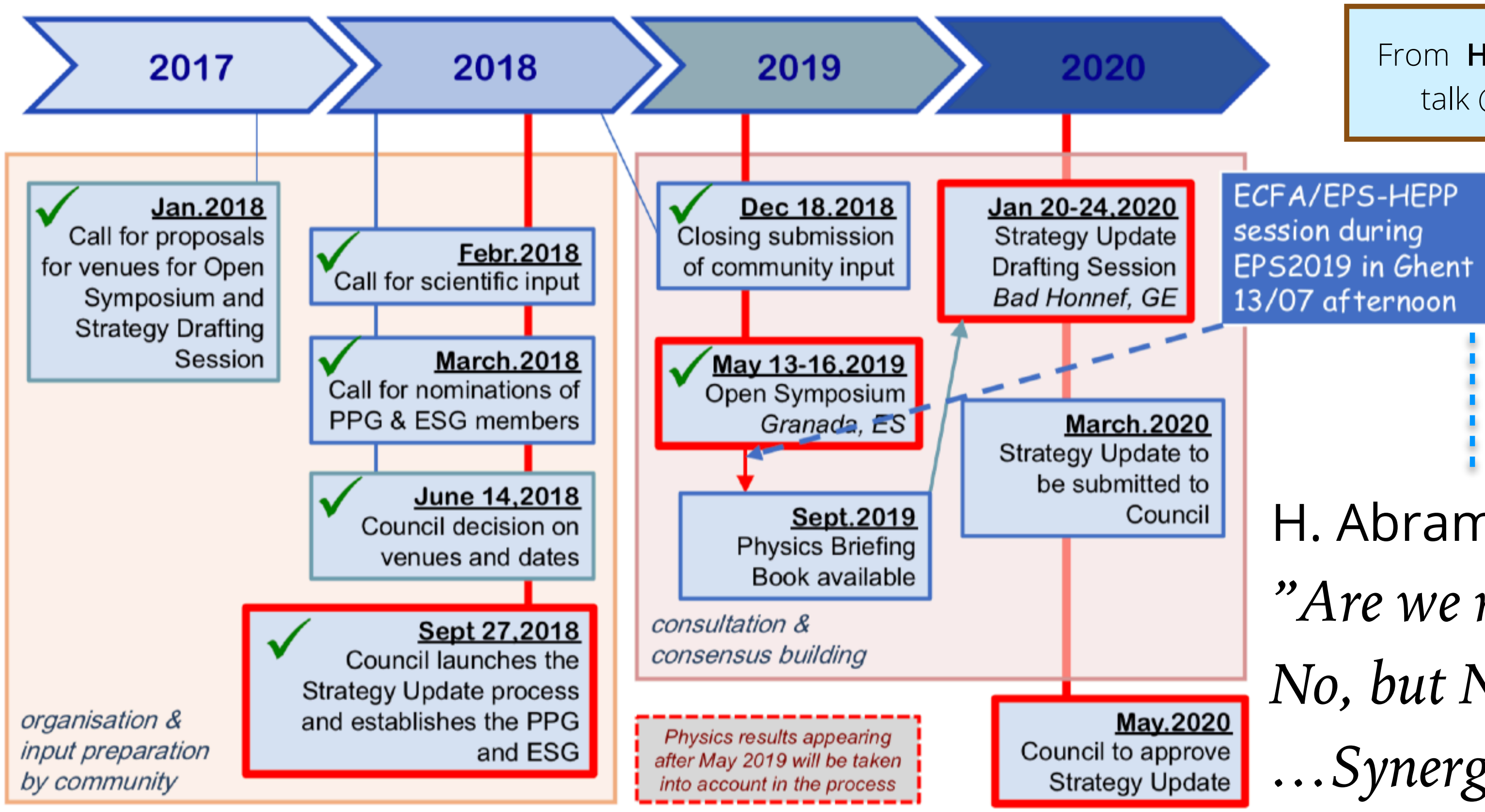
Looking to future colliders

(continuing from Andre David's thoughts)

Context: update of the European Strategy of Particle Physics

https://europeanstrategyupdate.web.cern.ch/about

The European Strategy for Particle Physics provides a clear prioritisation of European ambitions in advancing the particle physics science. The Strategy is due to be updated by May 2020 to guide the direction of the field to the mid-2020s and beyond.



From **H. Abramowicz**'s talk @ EPSHEP'19

H. Abramowicz, 2019/07/13:

"Are we ready to recommend a future facility in Europe?"

No, but National Inputs [recommend]:

...Synergies with Astroparticle Physics" → dark matter!

More on this in the next lecture

Future colliders: reminder of possibilities

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

https://arxiv.org/abs/1905.03764

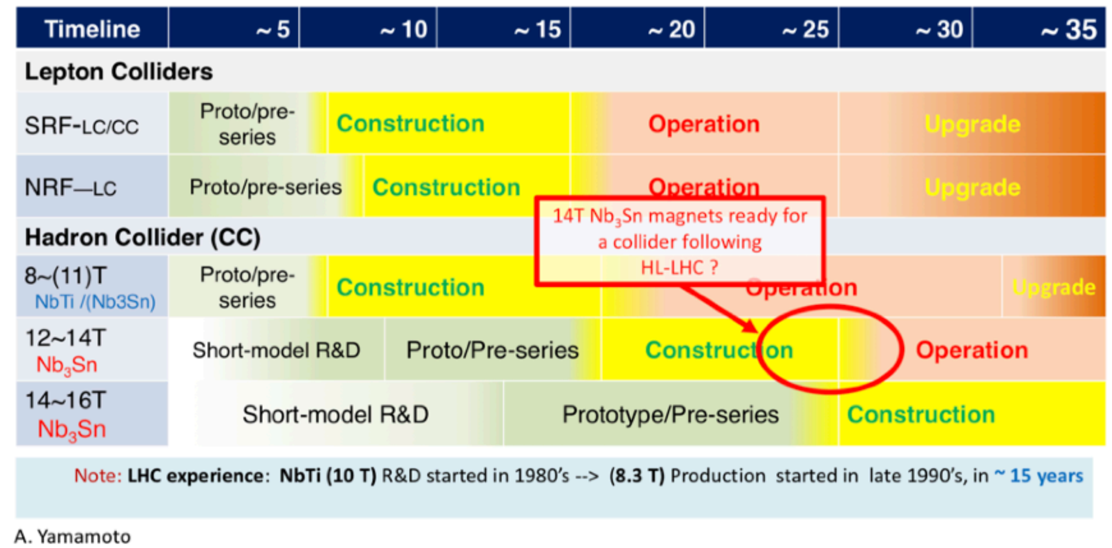
Full programs include earlier versions / CoM energies

More on this in the accelerator lectures

Future collider timelines

- Technology for lepton colliders ready earlier than for high-energy hadron colliders
- Example: magnets & accelerators

From **C. Biscari**'s talk @ EPSHEP'19



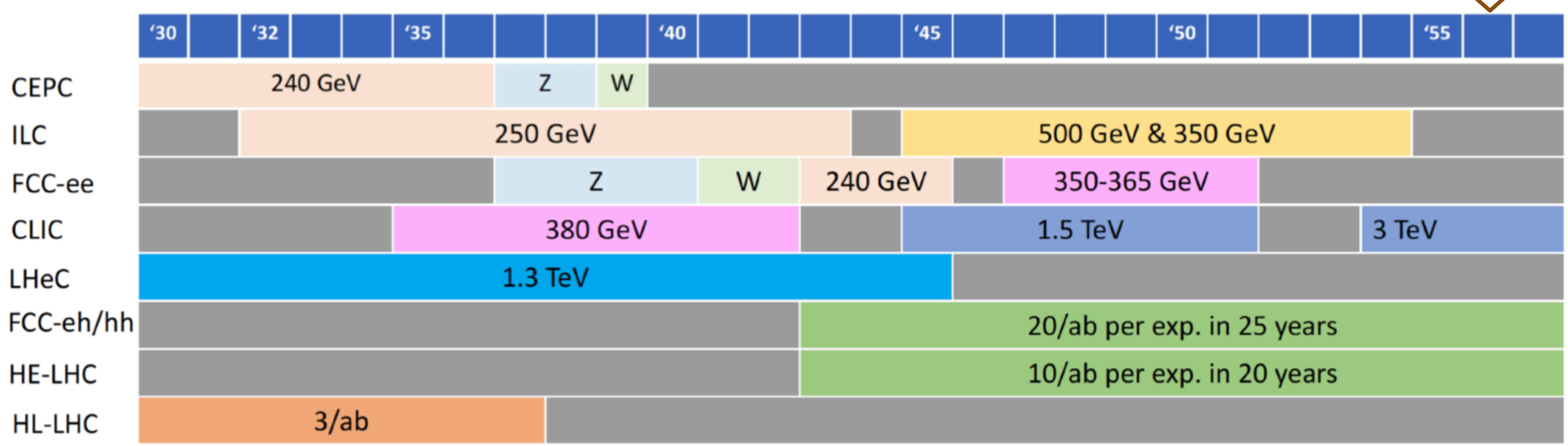
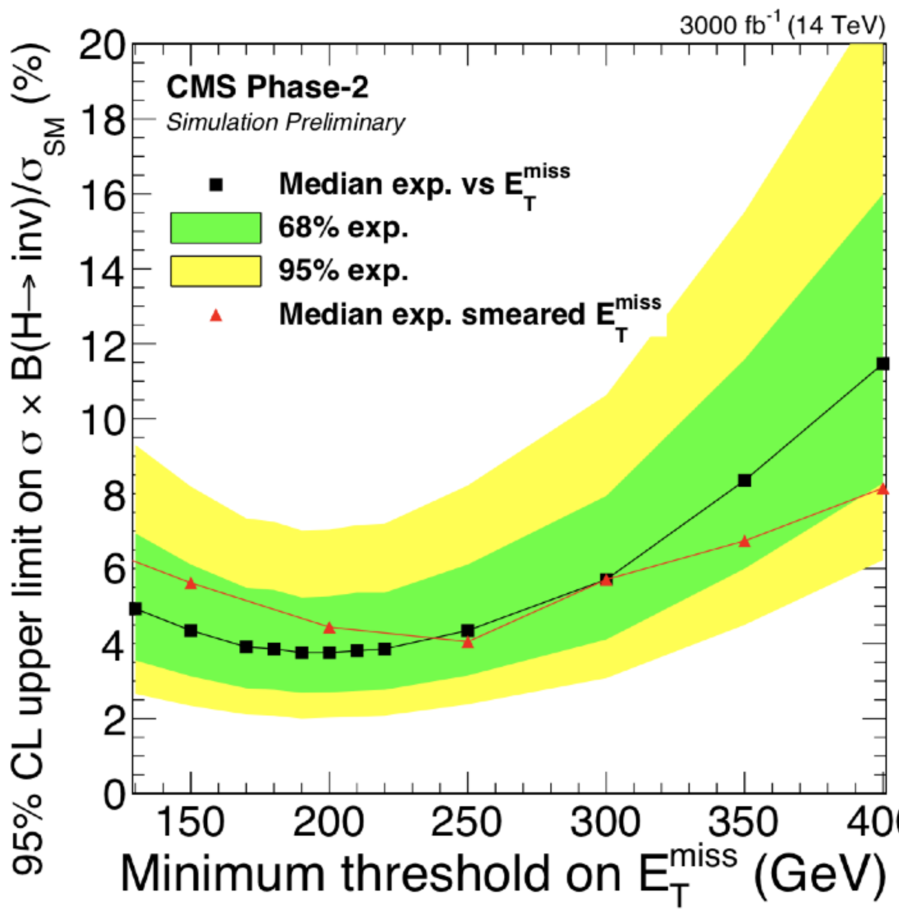


Figure 13. Sketch of timeline of various collider projects starting at the "earliest start time" stated in the respective documents. For FCC-eh/hh this figure assumes that it is not preceeded by FCC-ee. If it comes after FCC-ee it would start in the early 2060s.

Opportunities and challenges for BSM @ hadron colliders

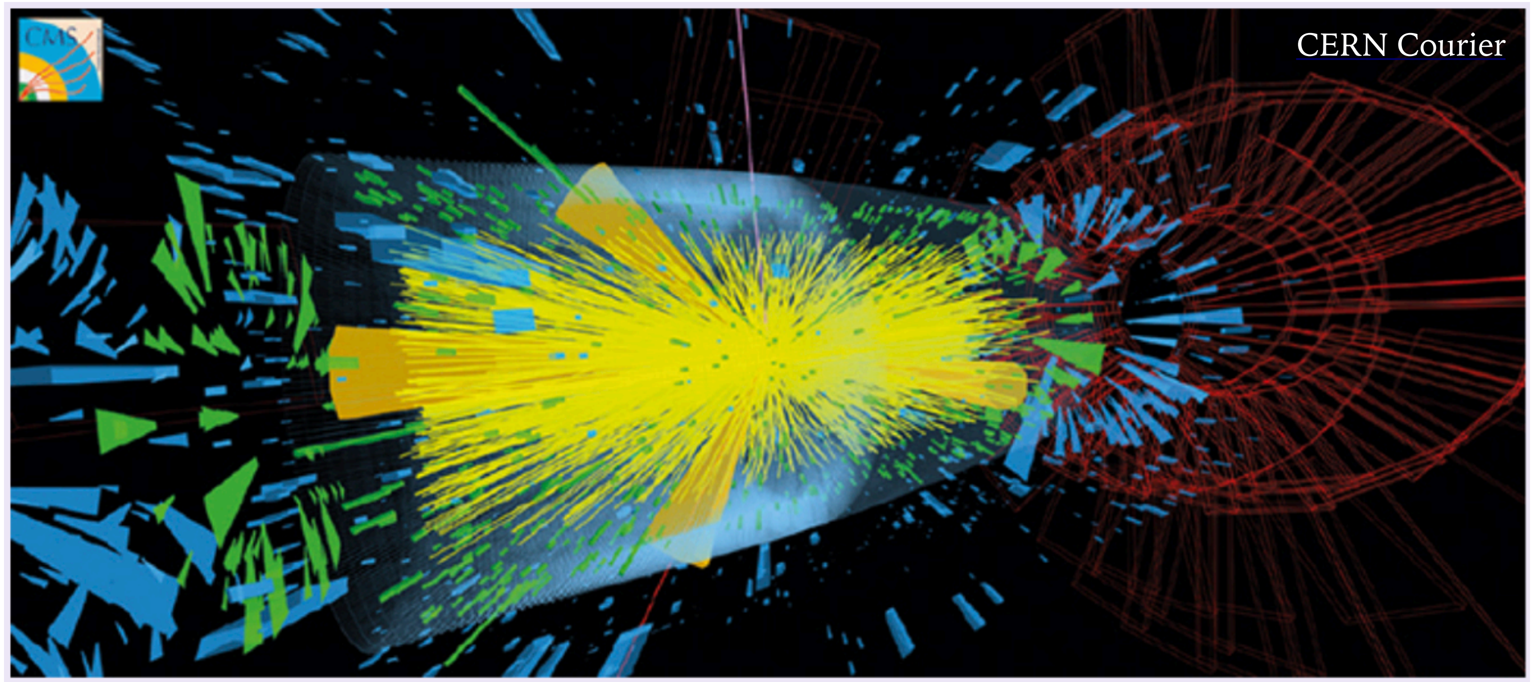
- Generally best reach for direct discovery of high-mass states
- Challenges: online data taking thresholds, simultaneous collisions (pile-up)

arXiv:1902.10229 and CMS-PAS-FTR-18-016



MET threshold influences search sensitivity
(trade-off between higher backgrounds and acceptance)

Higgs decays to invisible (VBF) + 200 pile-up collisions



HL-LHC uncertainty on Higgs to invisible BR (VBF)
depends on pile-up rejection method

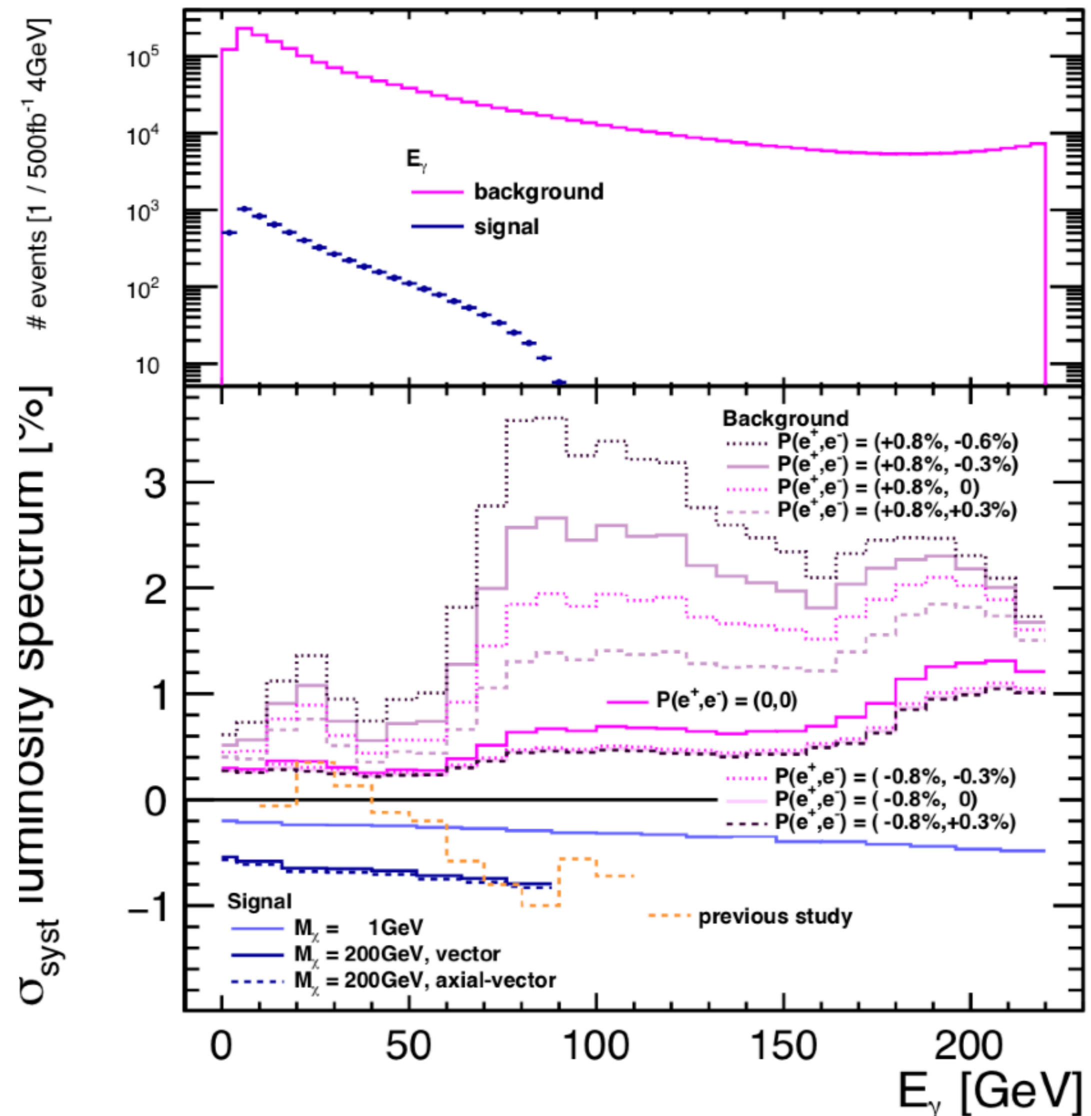
arXiv:1902.10229 and ATL-PHYS-PUB-2018-038

- Main experimental uncertainties: energy scales, simulation modeling, luminosity

Opportunities and challenges for BSM @ lepton colliders

- Limited by CoM energy but clean environment
  → still good reach for new energy scales
- Lower backgrounds
  → ILC/CLIC could run *untriggered*
  - Can probe lower mass objects, or search for other theory benchmarks at a later stage
- Specific strengths of lepton colliders:
  - clearer tagging for BSM involving Higgs
  - beam polarization can enhance/help identify signal
- Main experimental uncertainties: luminosity, electron identification (theory also similar magnitude)

S. Campana's talk
G. Stewart's talk



M. Habermehl's PhD thesis

Take-home point #4:

Direct and indirect searches for new physics complement each other (and therefore so do different kinds of future colliders)

Recap of Lecture 1
& wordclouds & a poll

Go to www.menti.com and use the code 57 32 87

Take-home point #1:

one don’t necessarily needs a motivation
to search for new physics,
it may just be that the SM is what nature gave us
and new physics is *just there* on top of it

Once we have a high-energy collider +
experiments, we can look for the unexpected!

Take-home point #2:

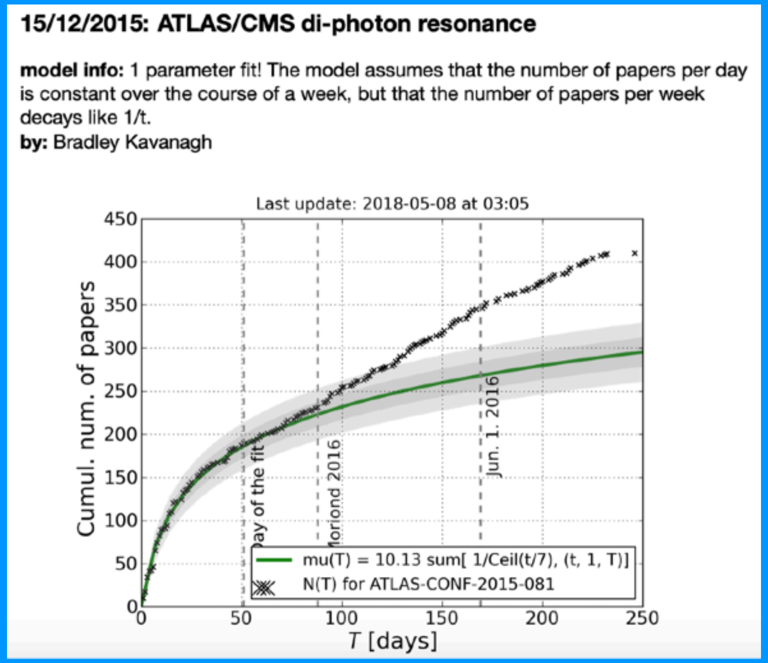
having a good calibration & performance of physics objects is an integral (and essential) part of any search / measurement

[this also applies for good detector operations, data taking and computing to process and analyse the data]

Take-home point #3:

Generic searches for new particles, especially at a new center-of-mass energy, can catch a wide range of new phenomena

(and if an unexpected particle is found, a model that accommodates it will be found soon after the discovery)



https://cp3.irmp.ucl.ac.be/~mbackovic/

Take-home point #4:

Direct and indirect searches for new physics complement each other (and therefore so do different kinds of future colliders)