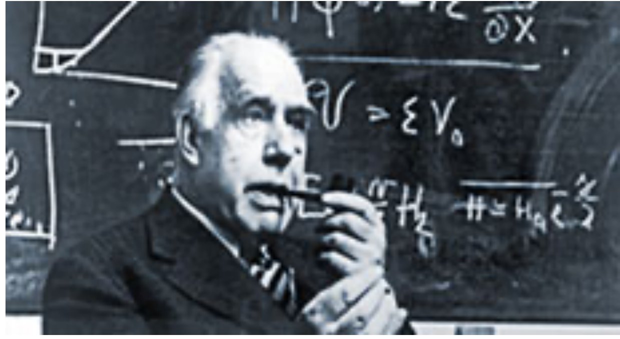
Niels Bohr Institute

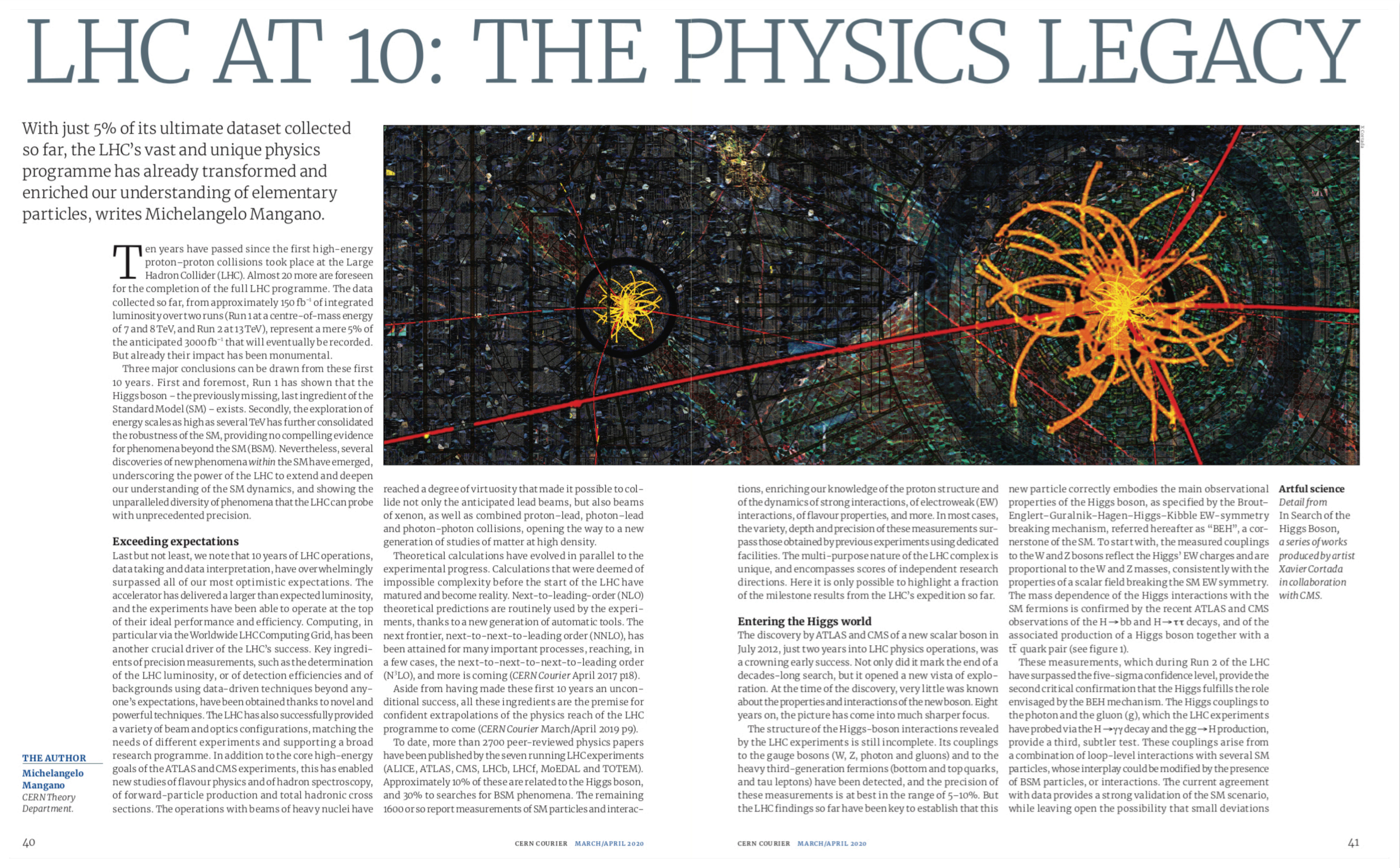


Physics at the LHC: the legacy so far, and beyond

Niels Bohr Lecture
NBI, Copenhagen
22 Febr 2023

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

CERN Courier March/April 2020
https://arxiv.org/abs/2003.05976



LHC AT 10: THE PHYSICS LEGACY

With just 5% of its ultimate dataset collected so far, the LHC's vast and unique physics programme has already transformed and enriched our understanding of elementary particles, writes Michelangelo Mangano.

Ten years have passed since the first high-energy proton–proton collisions took place at the Large Hadron Collider (LHC). Almost 20 more are foreseen for the completion of the full LHC programme. The data collected so far, from approximately 150 fb^{-1} of integrated luminosity over two runs (Run 1 at a centre-of-mass energy of 7 and 8 TeV, and Run 2 at 13 TeV), represent a mere 5% of the anticipated 3000 fb^{-1} that will eventually be recorded. But already their impact has been monumental.

Three major conclusions can be drawn from these first 10 years. First and foremost, Run 1 has shown that the Higgs boson – the previously missing, last ingredient of the Standard Model (SM) – exists. Secondly, the exploration of energy scales as high as several TeV has further consolidated the robustness of the SM, providing no compelling evidence for phenomena beyond the SM (BSM). Nevertheless, several discoveries of new phenomena *within* the SM have emerged, underscoring the power of the LHC to extend and deepen our understanding of the SM dynamics, and showing the unparalleled diversity of phenomena that the LHC can probe with unprecedented precision.

Exceeding expectations

Last but not least, we note that 10 years of LHC operations, data taking and data interpretation, have overwhelmingly surpassed all of our most optimistic expectations. The accelerator has delivered a larger than expected luminosity, and the experiments have been able to operate at the top of their ideal performance and efficiency. Computing, in particular via the Worldwide LHC Computing Grid, has been another crucial driver of the LHC's success. Key ingredients of precision measurements, such as the determination of the LHC luminosity, or of detection efficiencies and of backgrounds using data-driven techniques beyond anyone's expectations, have been obtained thanks to novel and powerful techniques. The LHC has also successfully provided a variety of beam and optics configurations, matching the needs of different experiments and supporting a broad research programme. In addition to the core high-energy goals of the ATLAS and CMS experiments, this has enabled new studies of flavour physics and of hadron spectroscopy, of forward-particle production and total hadronic cross sections. The operations with beams of heavy nuclei have reached a degree of virtuosity that made it possible to collide not only the anticipated lead beams, but also beams of xenon, as well as combined proton–lead, photon–lead and photon–photon collisions, opening the way to a new generation of studies of matter at high density.

Theoretical calculations have evolved in parallel to the experimental progress. Calculations that were deemed of impossible complexity before the start of the LHC have matured and become reality. Next-to-leading-order (NLO) theoretical predictions are routinely used by the experiments, thanks to a new generation of automatic tools. The next frontier, next-to-next-to-leading order (NNLO), has been attained for many important processes, reaching, in a few cases, the next-to-next-to-next-to-leading order (N^3LO), and more is coming (*CERN Courier* April 2017 p18).

Aside from having made these first 10 years an unconditional success, all these ingredients are the premise for confident extrapolations of the physics reach of the LHC programme to come (*CERN Courier* March/April 2019 p9).

To date, more than 2700 peer-reviewed physics papers have been published by the seven running LHC experiments (ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL and TOTEM). Approximately 10% of these are related to the Higgs boson, and 30% to searches for BSM phenomena. The remaining 1600 or so report measurements of SM particles and interactions, enriching our knowledge of the proton structure and of the dynamics of strong interactions, of electroweak (EW) interactions, of flavour properties, and more. In most cases, the variety, depth and precision of these measurements surpass those obtained by previous experiments using dedicated facilities. The multi-purpose nature of the LHC complex is unique, and encompasses scores of independent research directions. Here it is only possible to highlight a fraction of the milestone results from the LHC's expedition so far.

Entering the Higgs world

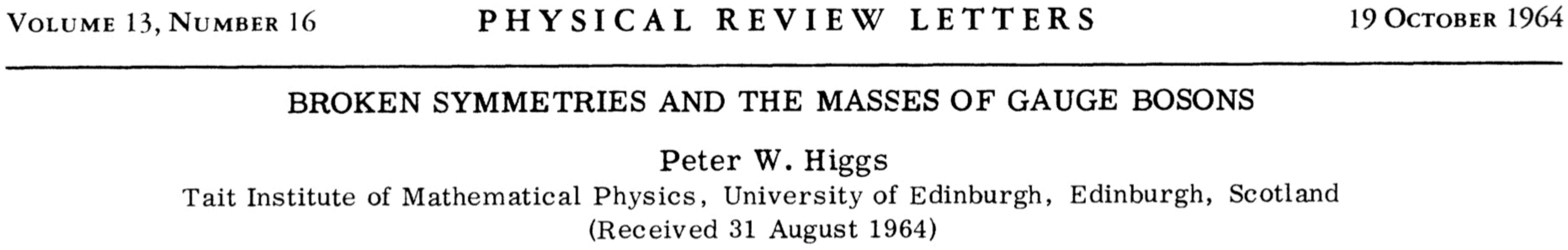
The discovery by ATLAS and CMS of a new scalar boson in July 2012, just two years into LHC physics operations, was a crowning early success. Not only did it mark the end of a decades-long search, but it opened a new vista of exploration. At the time of the discovery, very little was known about the properties and interactions of the new boson. Eight years on, the picture has come into much sharper focus.

The structure of the Higgs-boson interactions revealed by the LHC experiments is still incomplete. Its couplings to the gauge bosons (W, Z, photon and gluons) and to the heavy third-generation fermions (bottom and top quarks, and tau leptons) have been detected, and the precision of these measurements is at best in the range of 5–10%. But the LHC findings so far have been key to establish that this new particle correctly embodies the main observational properties of the Higgs boson, as specified by the Brout–Englert–Guralnik–Hagen–Higgs–Kibble EW-symmetry breaking mechanism, referred hereafter as "BEH", a cornerstone of the SM. To start with, the measured couplings to the W and Z bosons reflect the Higgs' EW charges and are proportional to the W and Z masses, consistently with the properties of a scalar field breaking the SM EW symmetry. The mass dependence of the Higgs interactions with the SM fermions is confirmed by the recent ATLAS and CMS observations of the $H \to bb$ and $H \to \tau\tau$ decays, and of the associated production of a Higgs boson together with a $t\bar{t}$ quark pair (see figure 1).

These measurements, which during Run 2 of the LHC have surpassed the five-sigma confidence level, provide the second critical confirmation that the Higgs fulfills the role envisaged by the BEH mechanism. The Higgs couplings to the photon and the gluon (g), which the LHC experiments have probed via the $H \to \gamma\gamma$ decay and the $gg \to H$ production, provide a third, subtler test. These couplings arise from a combination of loop-level interactions with several SM particles, whose interplay could be modified by the presence of BSM particles, or interactions. The current agreement with data provides a strong validation of the SM scenario, while leaving open the possibility that small deviations

Artful science *Detail from* In Search of the Higgs Boson, *a series of works produced by artist Xavier Cortada in collaboration with CMS.*

THE AUTHOR
Michelangelo Mangano
CERN Theory Department.

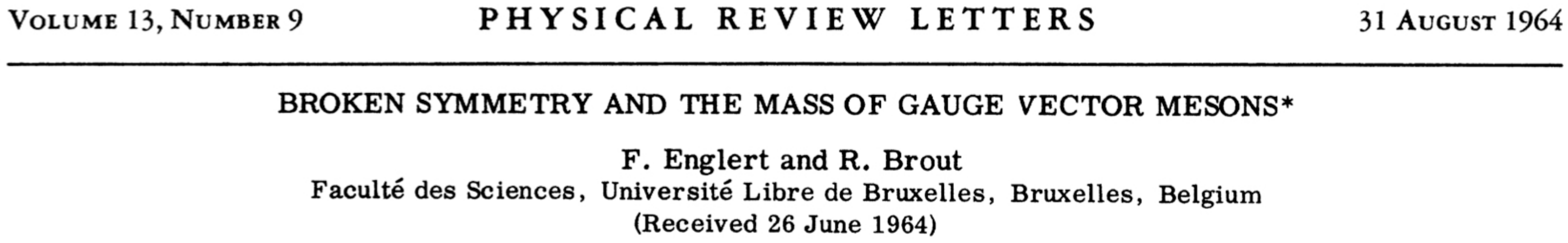


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

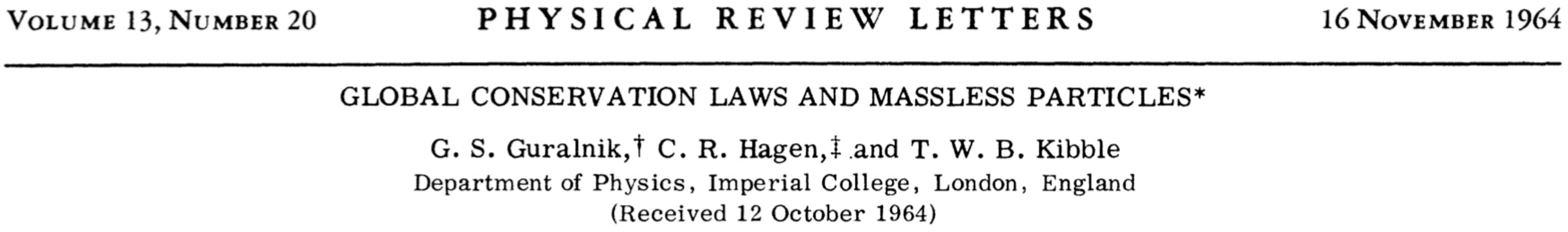


VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

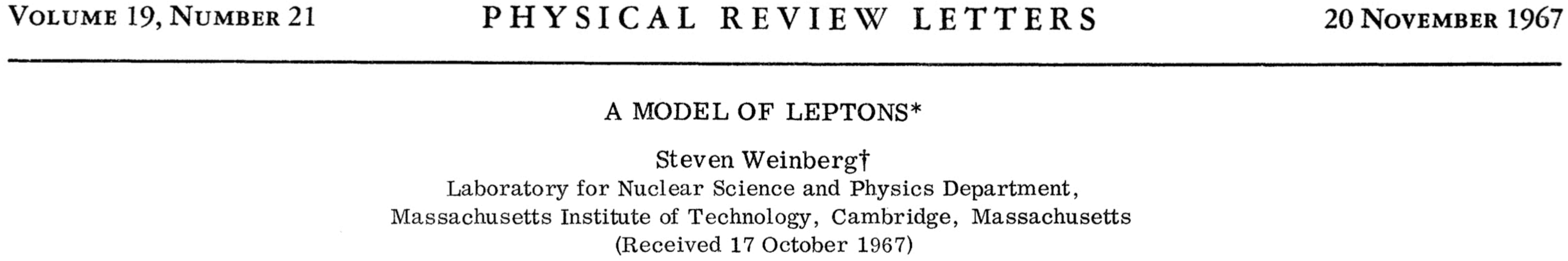


VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England

(Received 12 October 1964)



VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

Higgs et al (1964):

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - \boxed{V(\varphi_1^{\,2} + \varphi_2^{\,2})} - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

Let us suppose that $V'(\varphi_0^{\,2}) = 0$, $V''(\varphi_0^{\,2}) > 0$; then spontaneous breakdown of U(1) symmetry occurs.

$$\Rightarrow \quad \partial_\mu F^{\mu\nu} = -\boxed{e^2\varphi_o^2}A^\mu$$

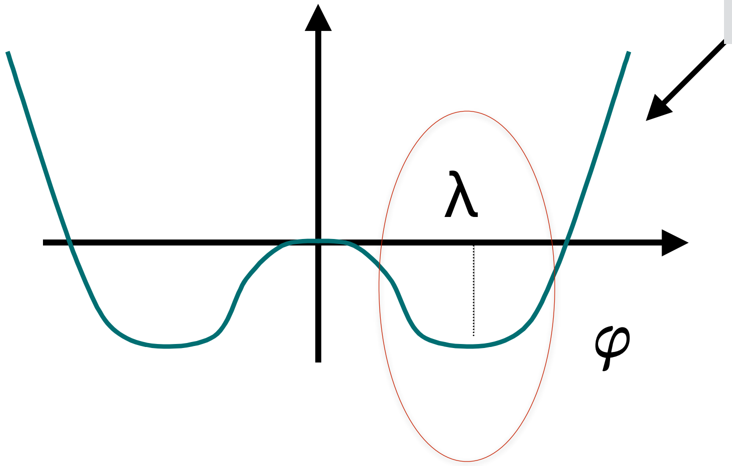
$$M_A = e\varphi_0$$

Weinberg (1967):

$$\mathcal{L} = -\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - \boxed{M_1^{\,2}\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2.} \qquad (4)$$

V(φ)



Weinberg (1967):

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$$-\tfrac{1}{2}|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 \boxed{-G_e(\bar{L}\varphi R} + \bar{R}\varphi^\dagger L) \boxed{-M_1^{\,2}\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2.} \quad (4)$$

$$\boxed{M_{electron} = G_e\lambda \Rightarrow G_e \sim O(10^{-6})}$$

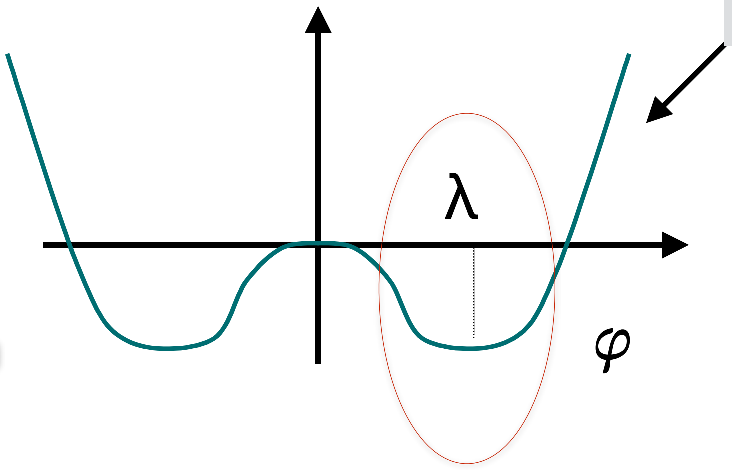
$$M_W = \tfrac{1}{2}\lambda g.$$

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2},$$

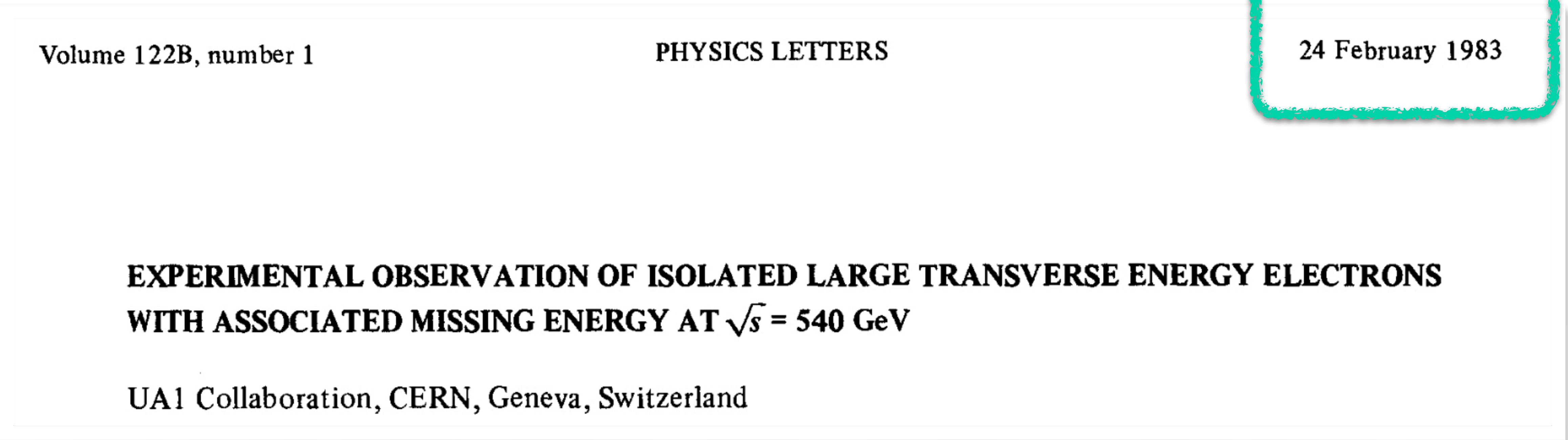
$$M_A = 0,$$

$$\langle\varphi\rangle = \lambda\begin{pmatrix}1\\0\end{pmatrix}.$$

V(φ)



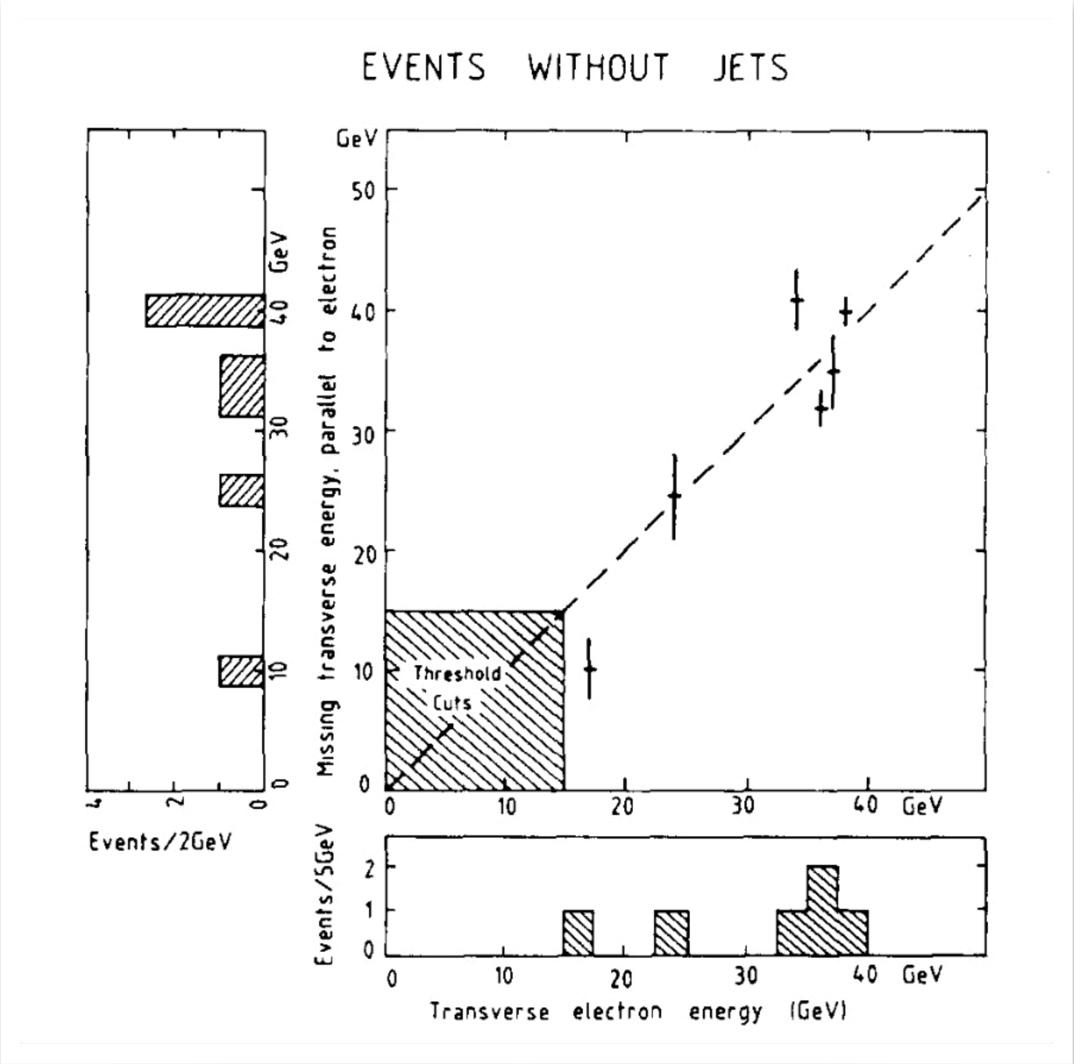
After ~15 yrs, 40 yrs on Friday …

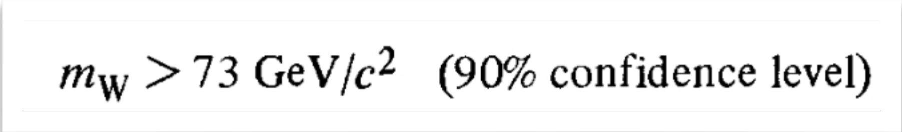


Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland





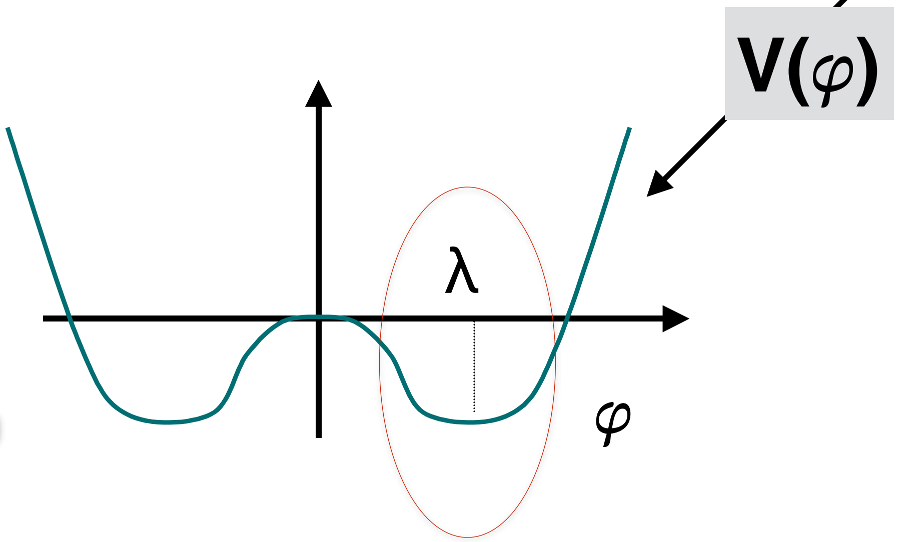
$m_W > 73$ GeV/c^2 (90% confidence level)

Weinberg (1967):

$$\mathfrak{L} = -\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 \boxed{-G_e(\bar{L}\varphi R} + \bar{R}\varphi^\dagger L) \boxed{-M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2.} \quad (4)$$

$$\boxed{M_{electron} = G_e\lambda \Rightarrow G_e \sim O(10^{-6})}$$



$$\langle\varphi\rangle = \lambda\binom{1}{0}.$$

$$M_W = \tfrac{1}{2}\lambda g.$$

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2},$$

$$M_A = 0,$$

$$M_\varphi = M_1$$

M₁ not constrained by known parameters like $M_{Z,W}$, G_F => no prediction for the Higgs mass …

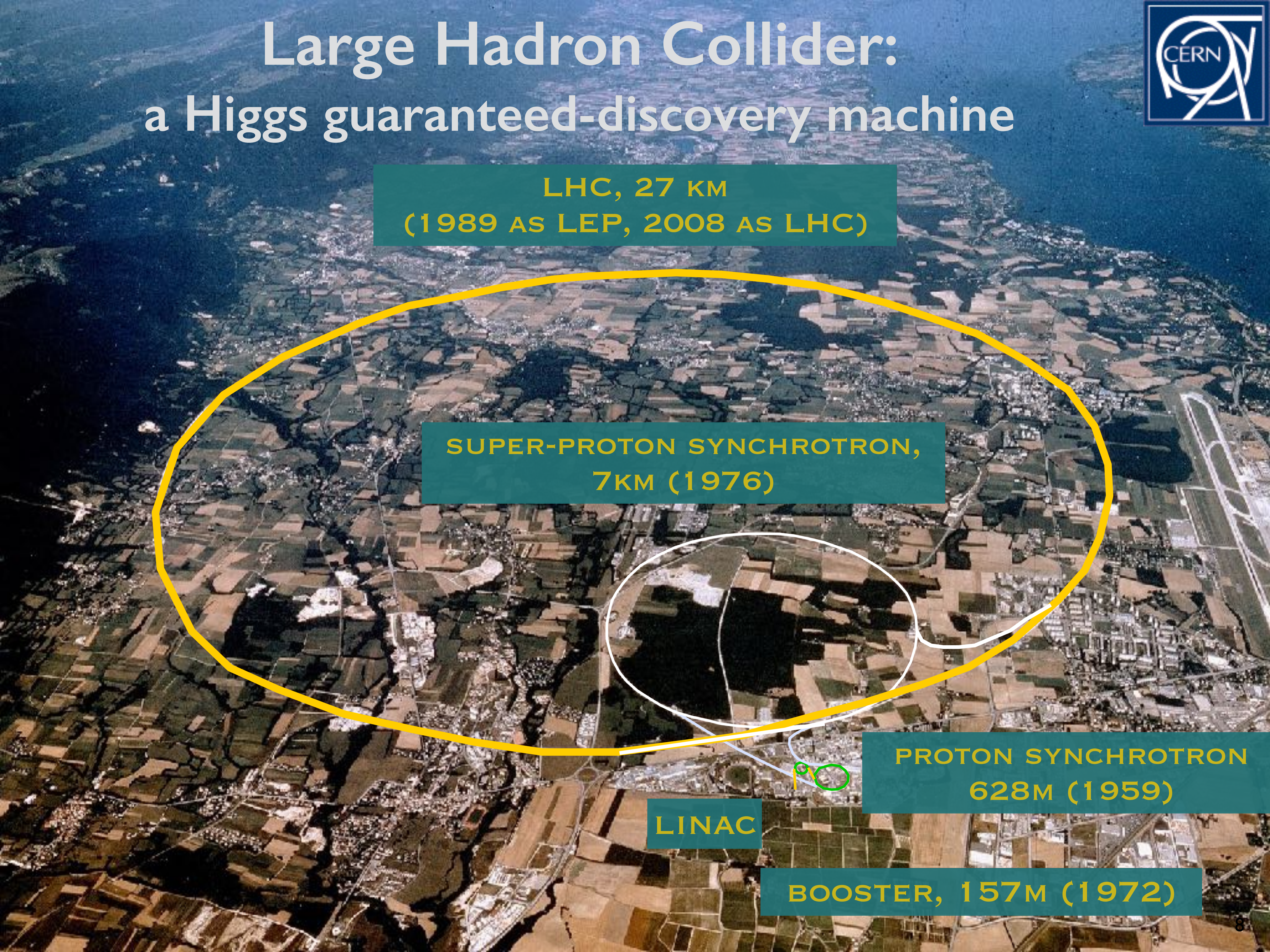
$$M_\varphi^2 \sim h/G_F < h^{max}_{unitarity}/G_F$$

=> … except for a unitarity-driven upper limit, O(TeV)

NB in Weinberg's notation ***h*** is the Higgs self-coupling strength, from $h\varphi^4$

Large Hadron Collider:

a Higgs guaranteed-discovery machine



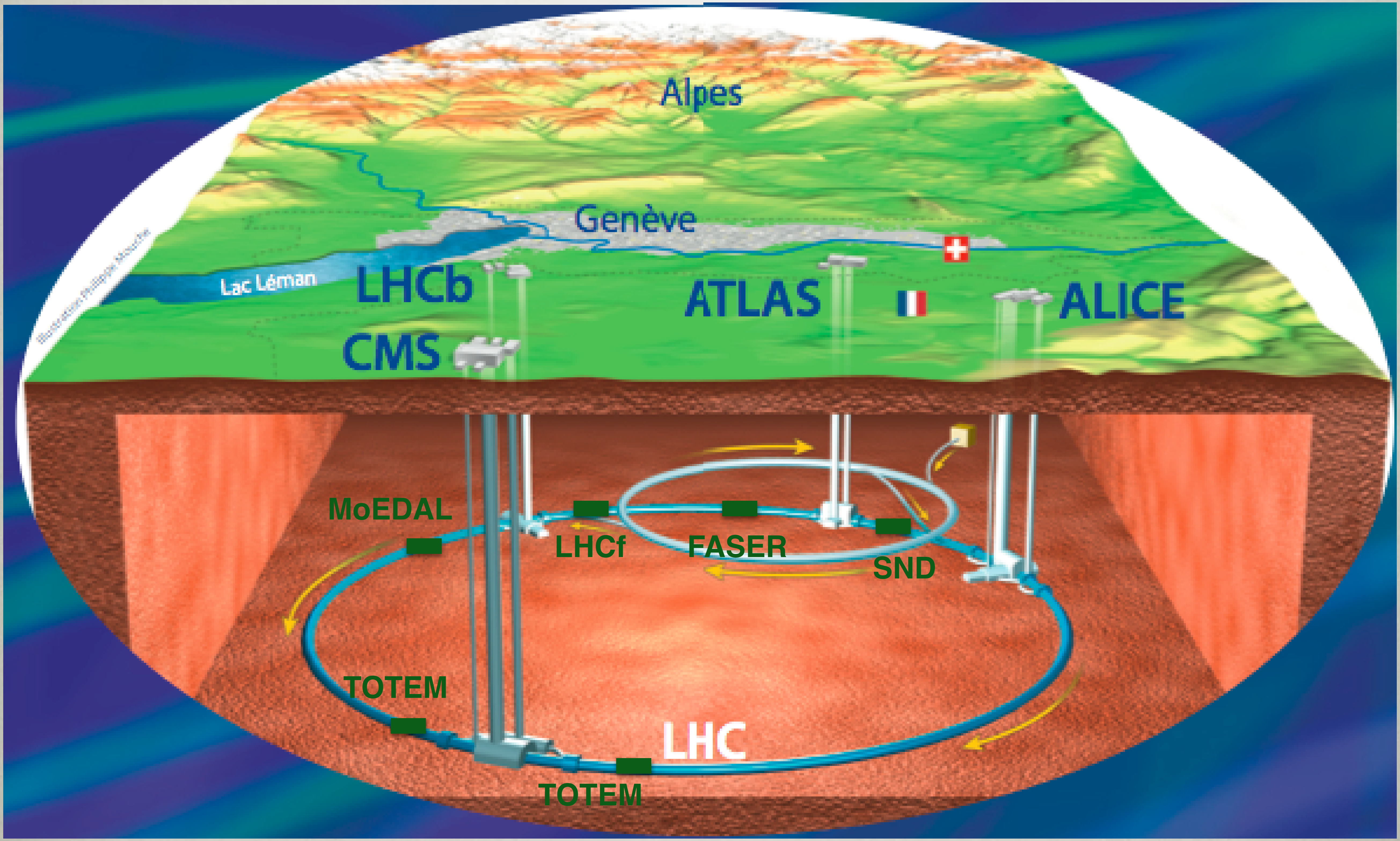
LHC, 27 km
(1989 as LEP, 2008 as LHC)

Super-proton synchrotron,
7km (1976)

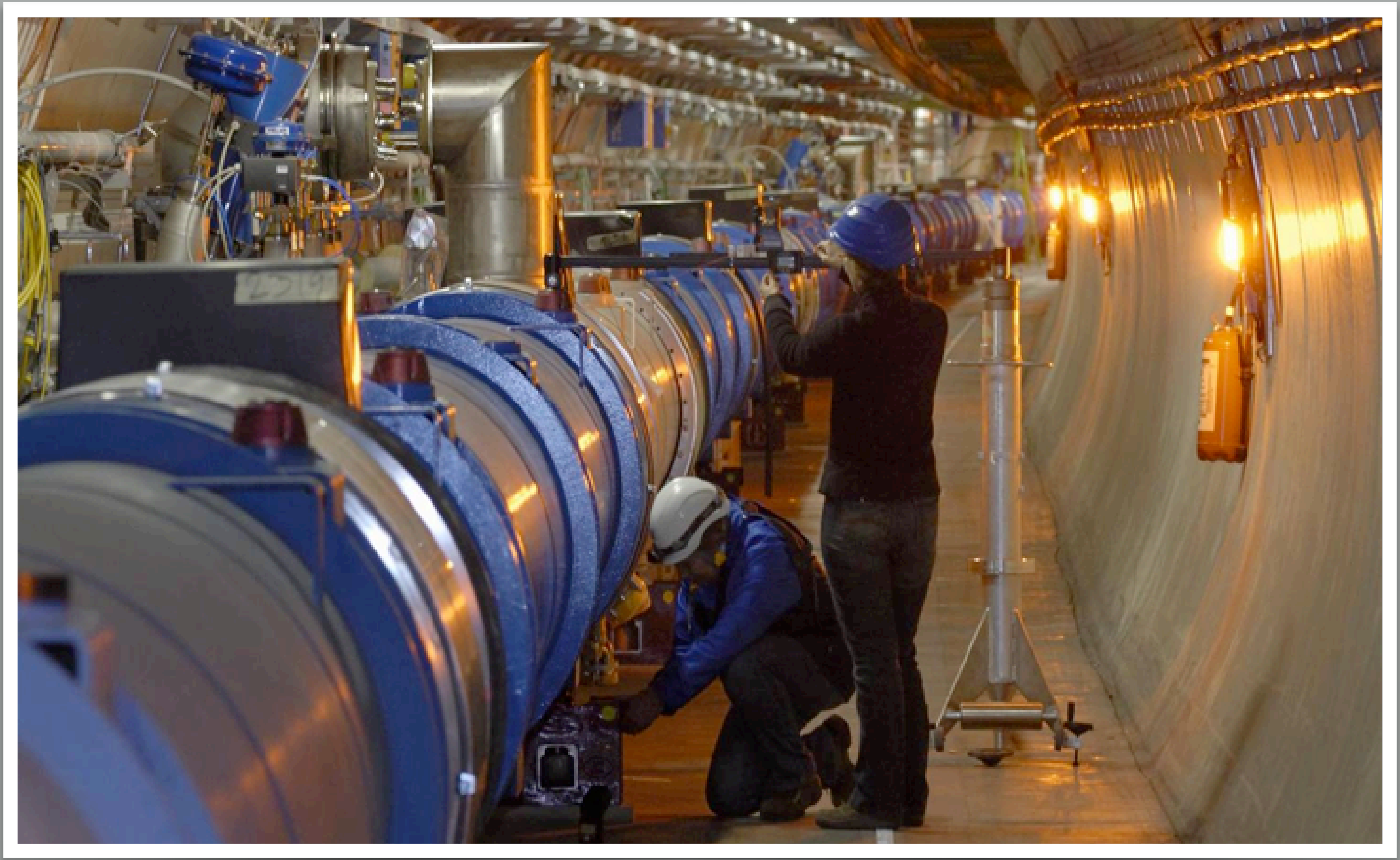
Proton synchrotron
628m (1959)

Linac

Booster, 157m (1972)


Alpes
Genève
Lac Léman
LHCb
CMS
ATLAS
ALICE
MoEDAL
LHCf
FASER
SND
TOTEM
LHC
TOTEM

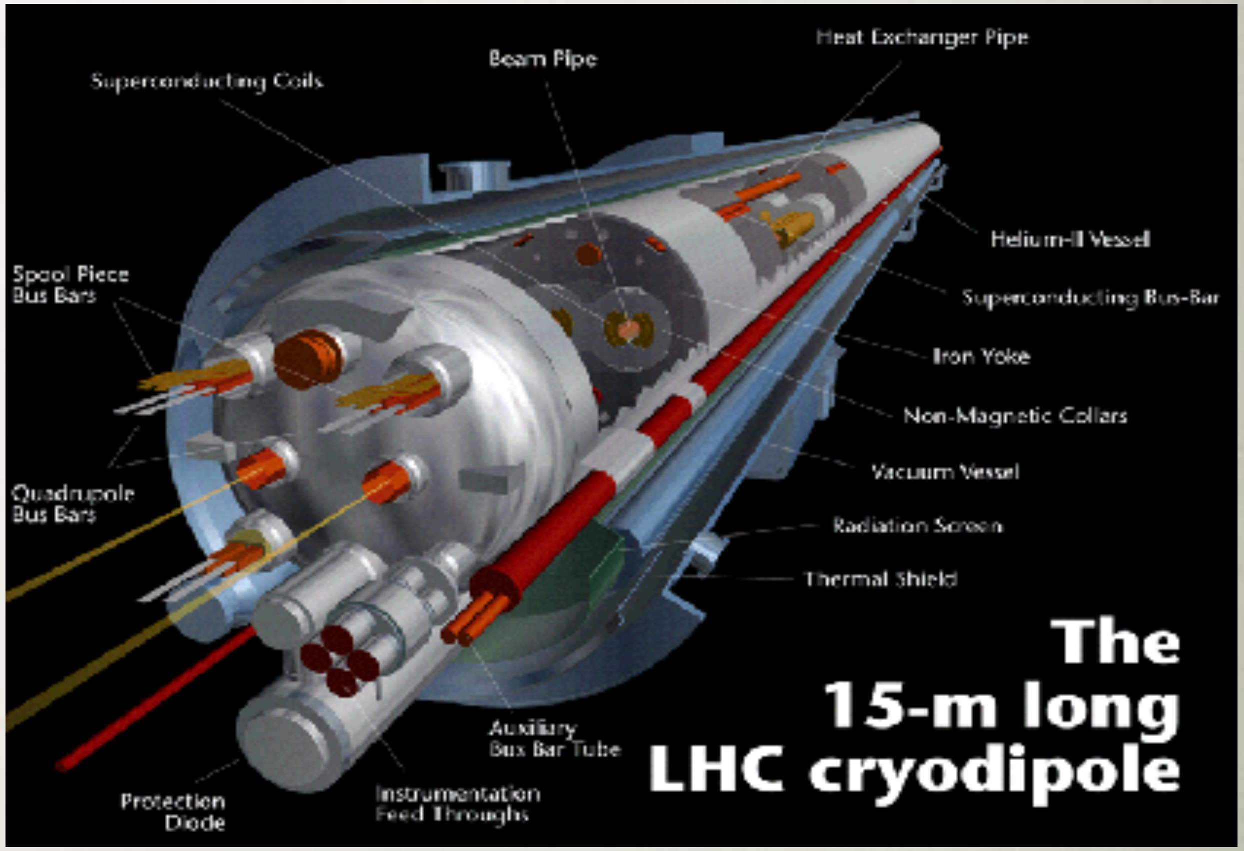
THE LHC



THE LHC DIPOLE

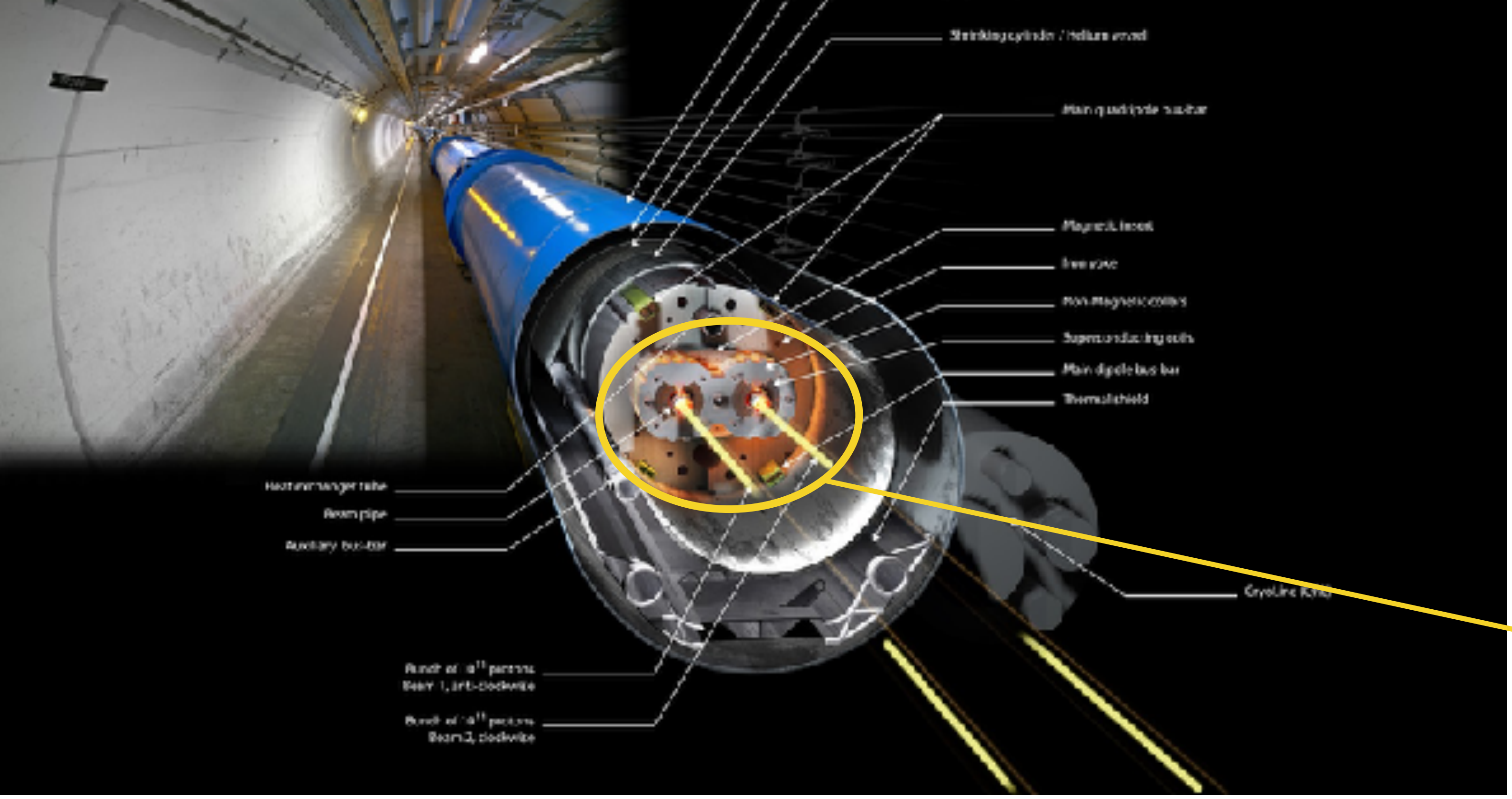
- B field = 83,000 Gauss
  - Ni Ti SC cable

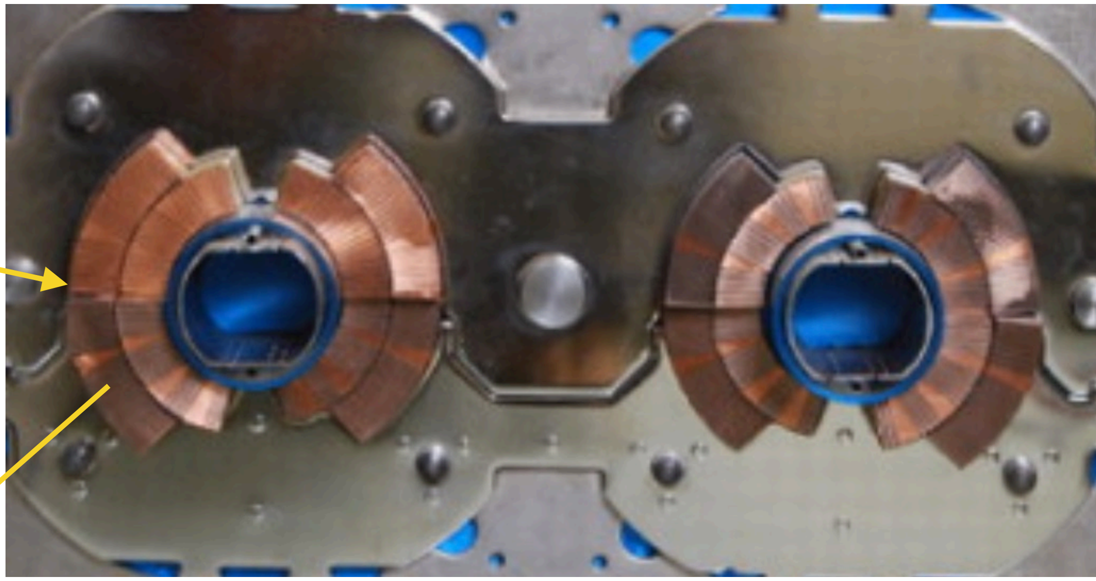
(Earth's field ~ 0.5 Gauss)

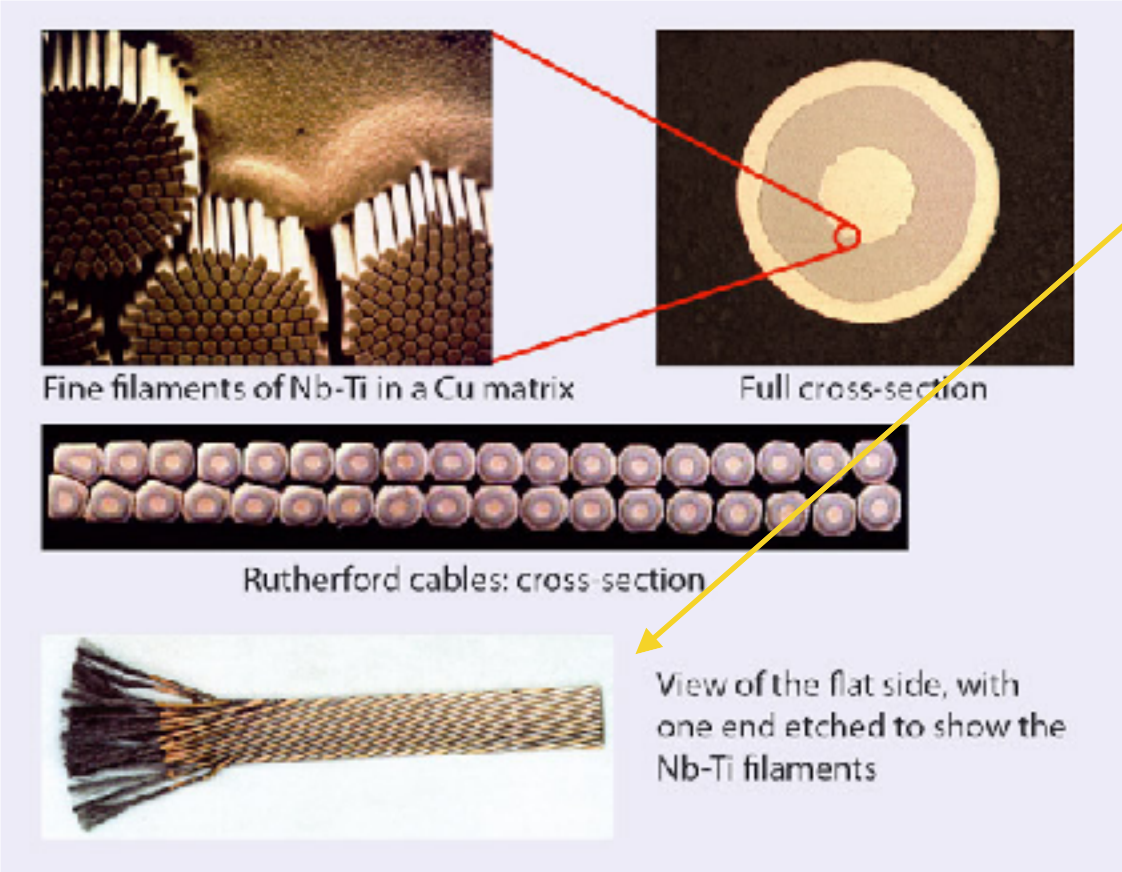


- T = $1.9K^0$ = – 456 F
  - superfluid liquid Helium
- 35 tonnes
- 50 ft long
- Stress at the collar: 150 MPa
  - ~ 22,000 psi
  - ~ 1,500 kg/cm^2
- Stored energy: 7 MJoule

More, but simple, facts about LHC dipoles:
http://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.magnetic_dipoles





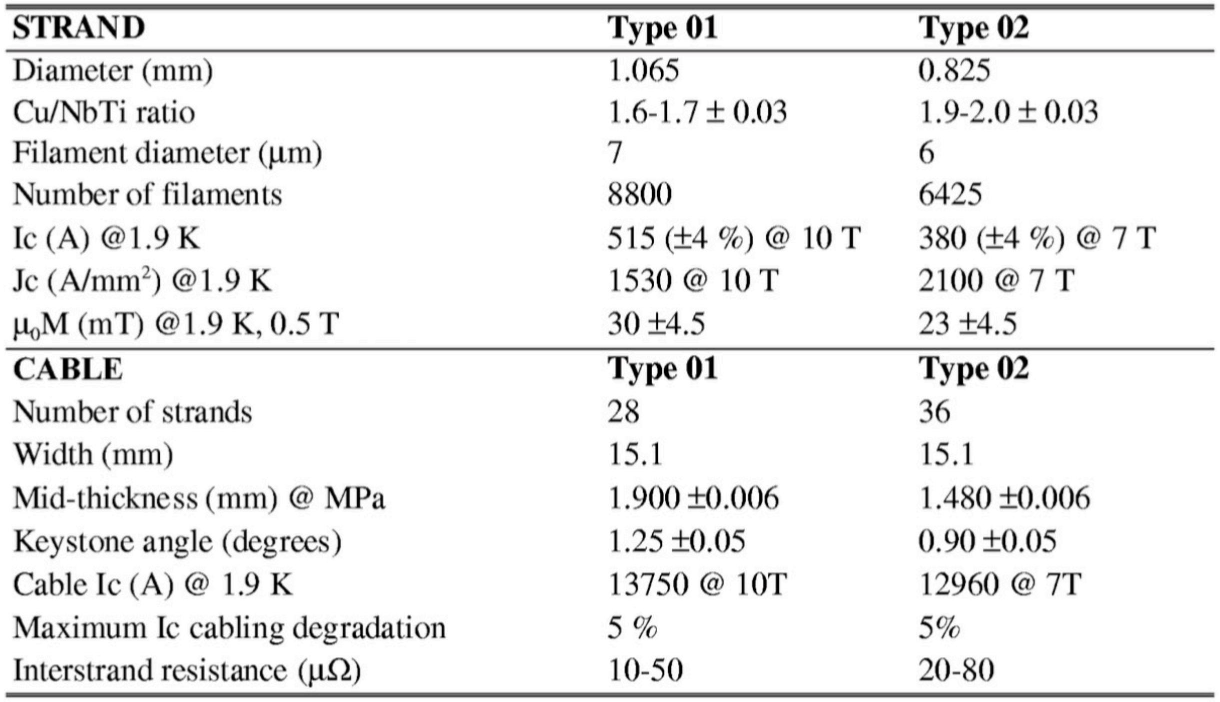


Fine filaments of Nb-Ti in a Cu matrix

Full cross-section

Rutherford cables: cross-section

View of the flat side, with one end etched to show the Nb-Ti filaments



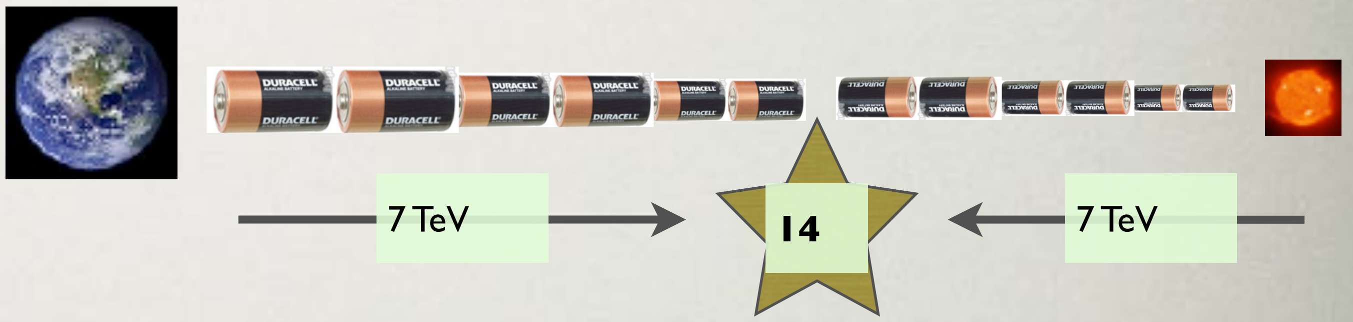
STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (µm)	7	6
Number of filaments	8800	6425
Ic (A) @1.9 K	515 (±4 %) @ 10 T	380 (±4 %) @ 7 T
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm) @ MPa	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Maximum Ic cabling degradation	5 %	5%
Interstrand resistance (µΩ)	10-50	20-80

The LHC accelerator

- 1232 LHC dipoles, plus ~600 other smaller magnets

- E_{beam} = 7000 GeV ~ $7\text{x}10^{12}$ eV ~ 5 trillions 1.5V batteries

~ 100 M km of batteries, about d[Earth-Sun]



- E_{beam} = 7000 GeV ~ 7500 $m_{\text{proton}}\, c^2$
  - $E=mc^2 / \sqrt{[1-v^2/c^2]}$ ➪ v = 0.999 999 99 c

- N_{proton} ~ 10^{11}/bunch x 2800 bunches/beam x 2 beams ~ 10^{14}

- Energy stored ~ 350 MJ ~ 200 lb of TNT ~ Train running full speed

The general targets of a collider experiment

(a) measure fundamental properties of elementary particles:

- mass, spin and the coupling strength of their interactions

(b) extract information on the interaction dynamics

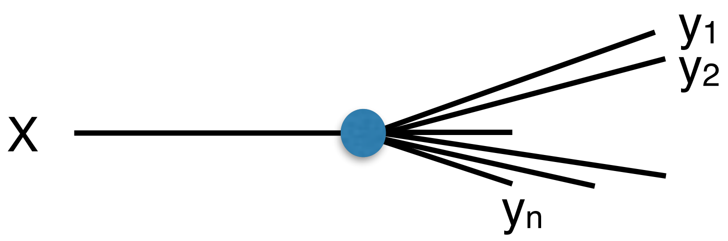
- electroweak and strong interactions, in various regimes of energy, distance, collectivity

(c) identify possible departures from Standard Model expectations:

- unexpected dynamical features of known interactions
- detection of new fundamental interactions
- detection of previously unknown particles

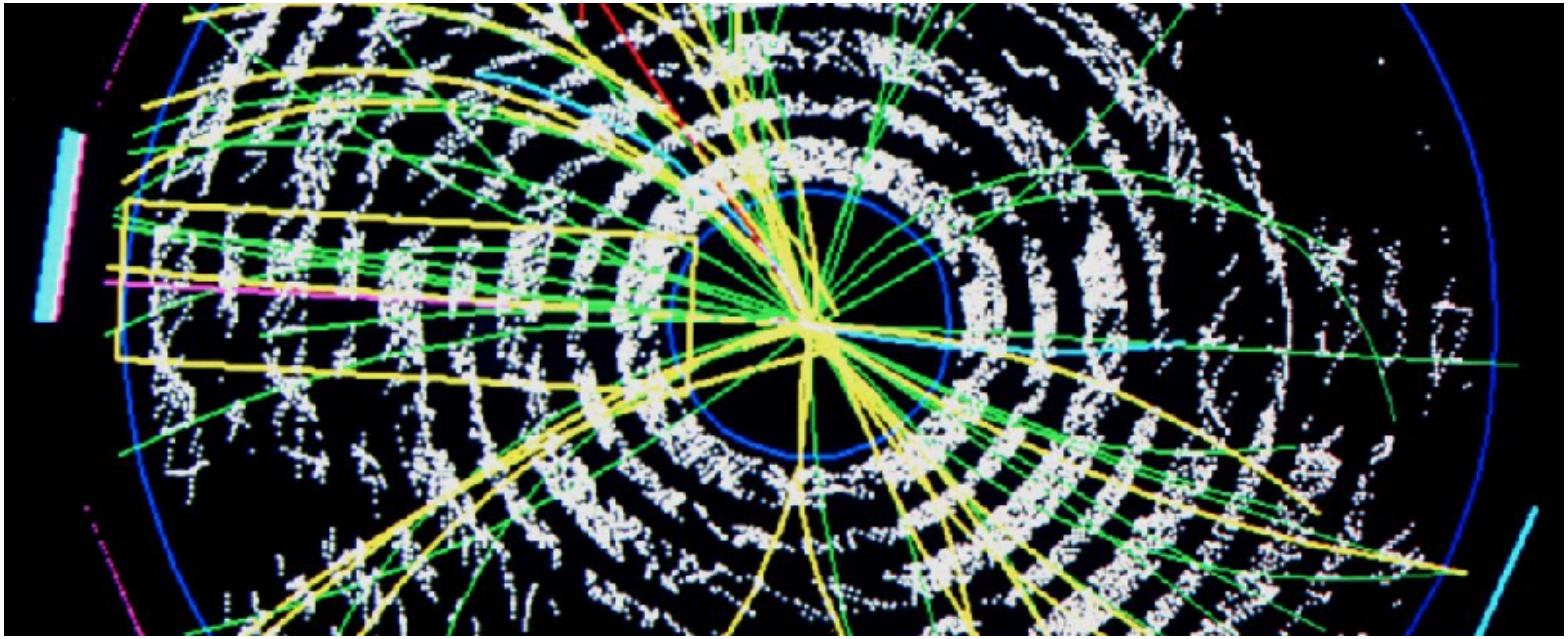
Example, measure the **mass**: reconstruct decays, and use $M=\sqrt{P^2}$.

Need to fully contain/detect/identify all decay products, and precisely measure their 4-momentum



$$M_X^2 = P_X^2 = \left(\sum_{i=1,n} p(y_i) \right)^2$$

Example: decay products of a top + antitop quark pair



Example, **couplings**: measure production rates, or decay modes and fractions.

X=specific process

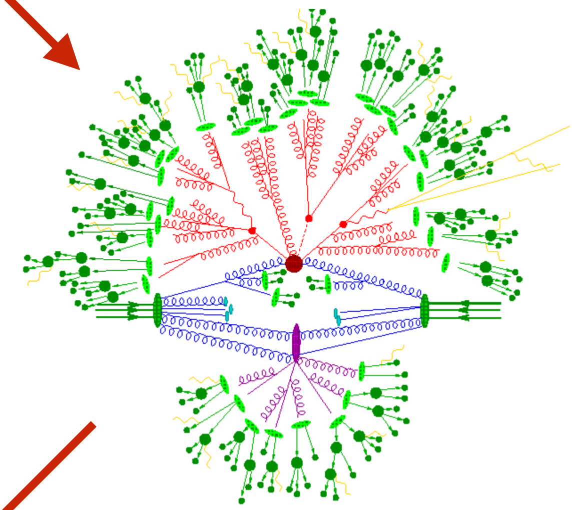
m=mass,
g=coupling strengths,
PDF=distribution of quarks/
gluons inside individual proton

Accelerator+Exp
detailed modeling of the beam geometry and population, evolution as fill evolves, non-linear dependence on beam density, dynamics, cross-talk, accelerator/detector interface, etc.etc. Interplay of accelerator and experiment, δ_{syst} today at sub-% level

ATLAS, https://arxiv.org/abs/2212.09379

$$\mathrm{Prob}_{TH}(\text{X in det acceptance}\,|\,\underline{m, g, PDF}) \times N(pp\ \text{collisions}) \boxed{=} N_{exp}(\text{X in det acceptance})$$

extract params by
fitting this equality

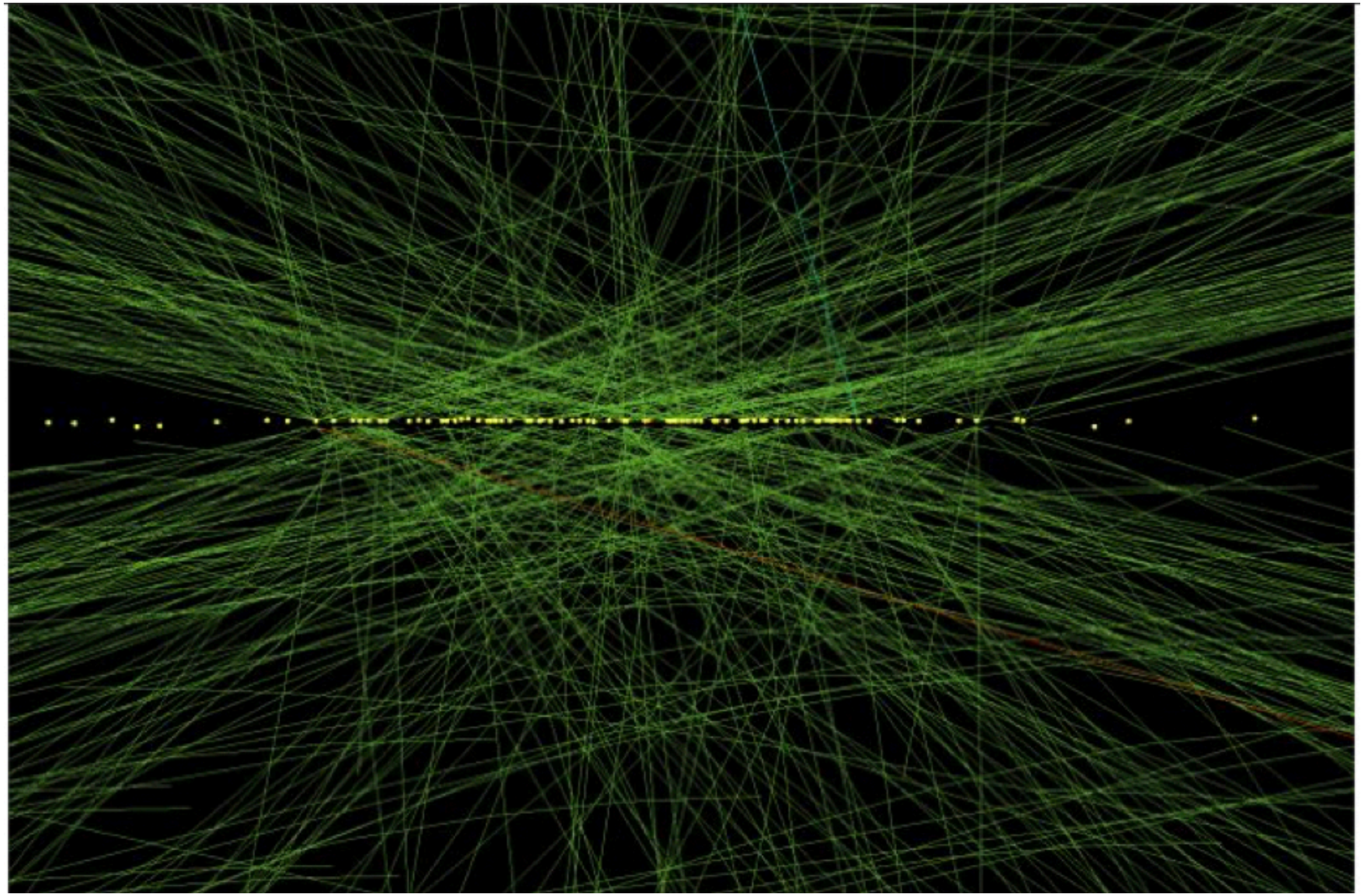


TH:
Theoretical calculation of relevant matrix elements, higher-order calculations for complex processes typically involve millions of Feynman diagrams.

δ_{syst} ~ few percent from perturbative, PDF and parametric uncertainties

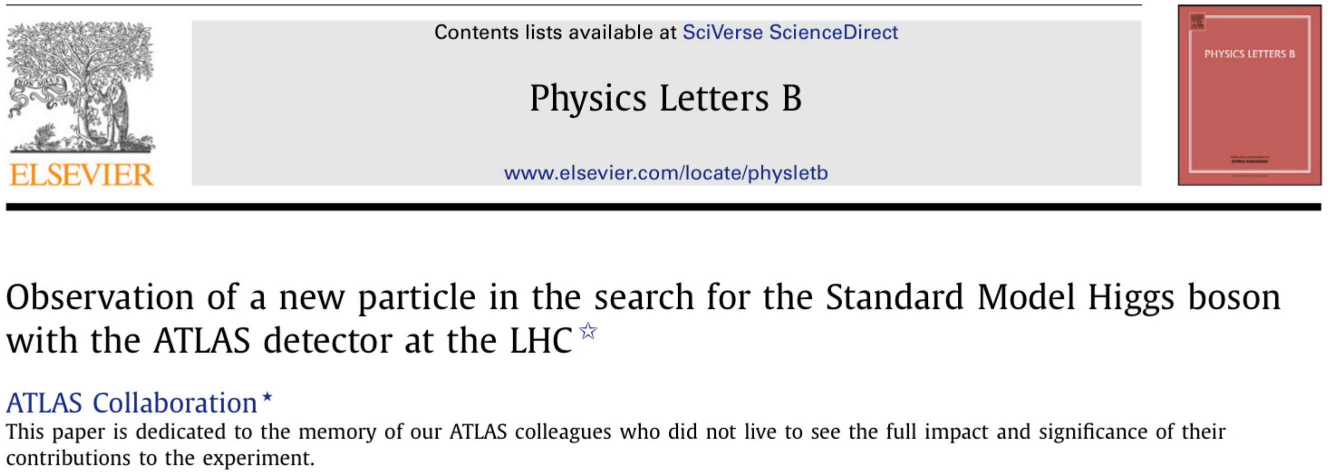
EXP:
understand detection efficiency, particle identification, measure momenta to define fiducial phase-space region, etcetc
Typical δ_{stat} as small as permille, δ_{syst} ~ percent

…to be done in the context of events looking like this (here 78 individual pp interactions in a single bunch crossing — CMS)



- bunch collisions frequency: 40 MHz
- event size: ~ 2 MB => event storage rate O(kHz)
- time to decide whether the event is of potential interest for storage and further analysis: ~ O(µsec)

Fast forward to 2012



Contents lists available at SciVerse ScienceDirect

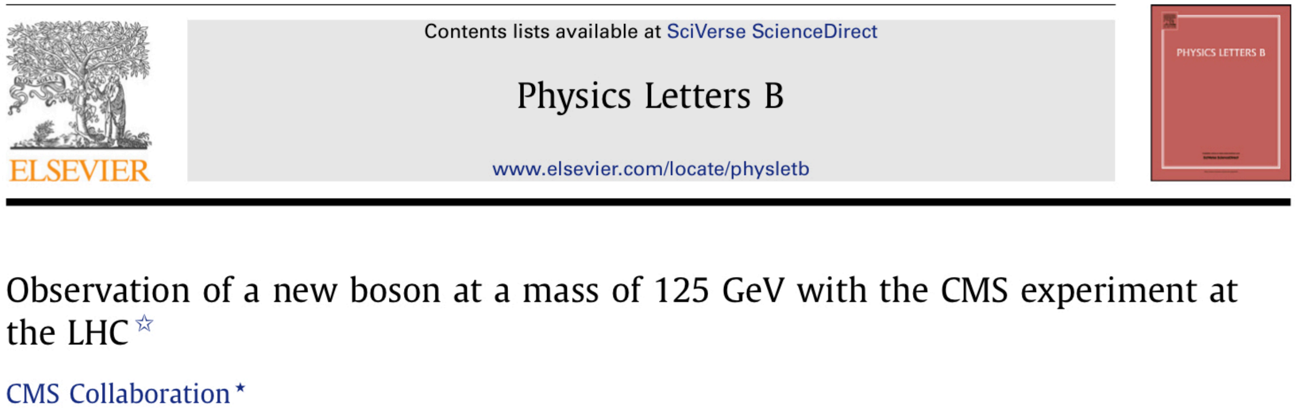
Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.



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Physics Letters B

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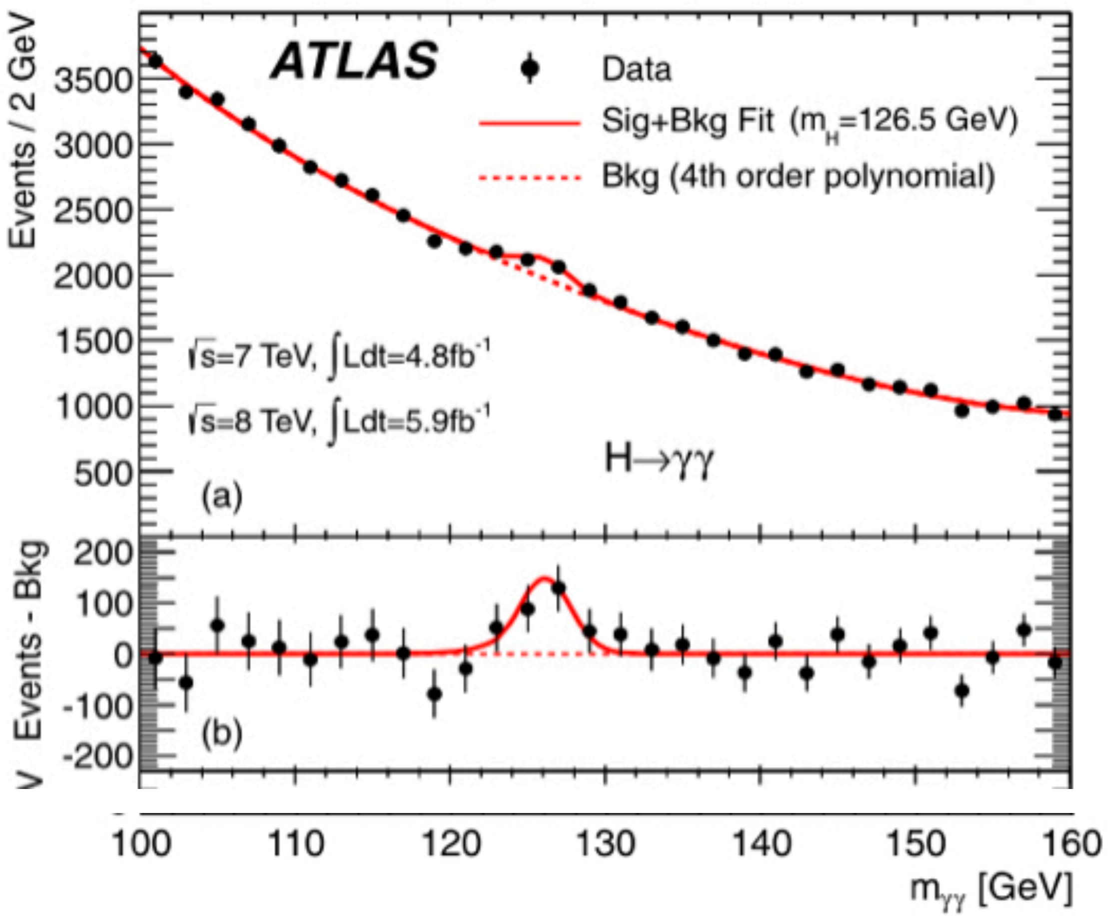
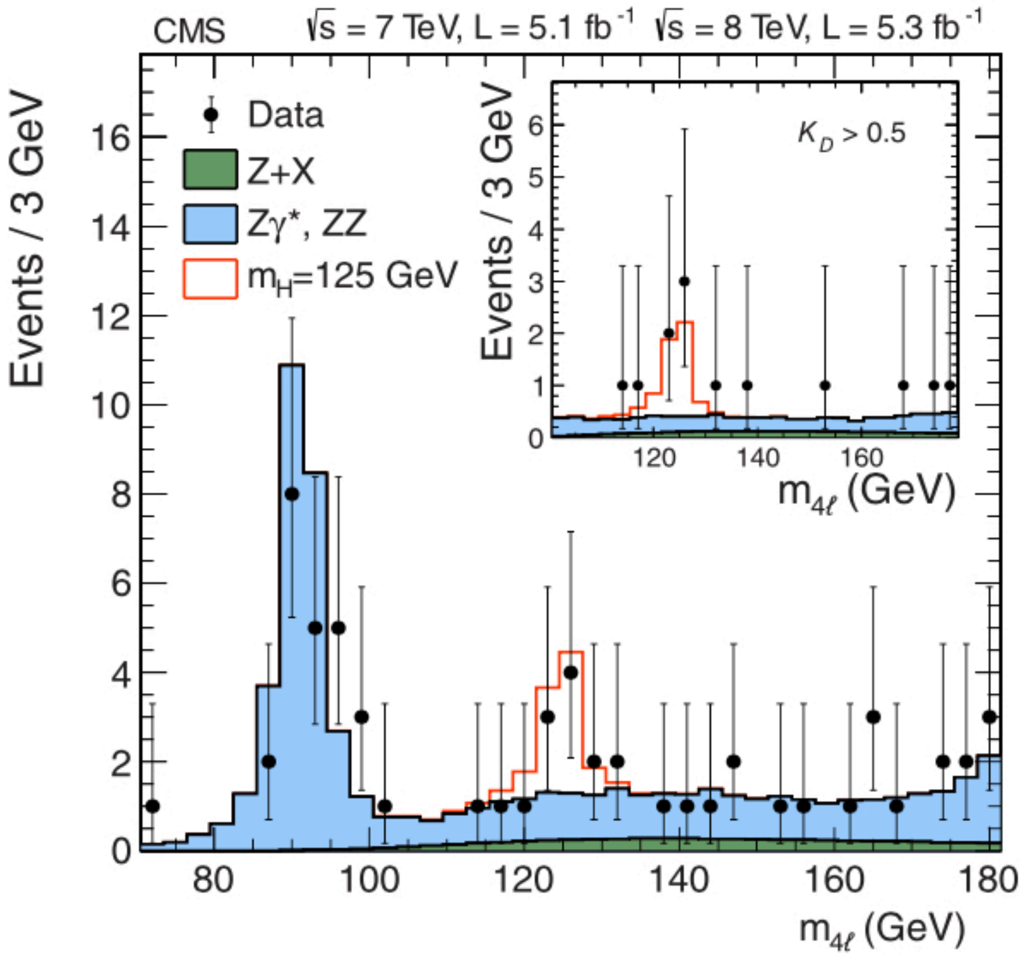
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

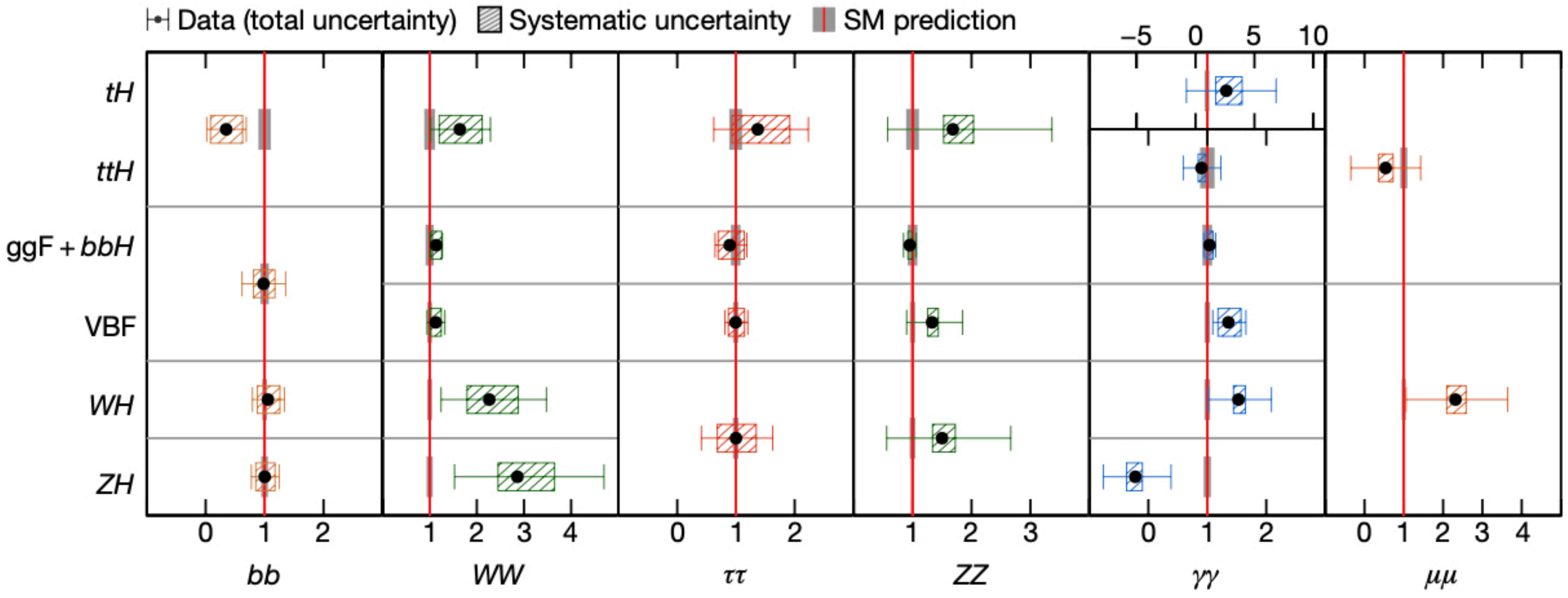


$H \to \gamma\gamma$



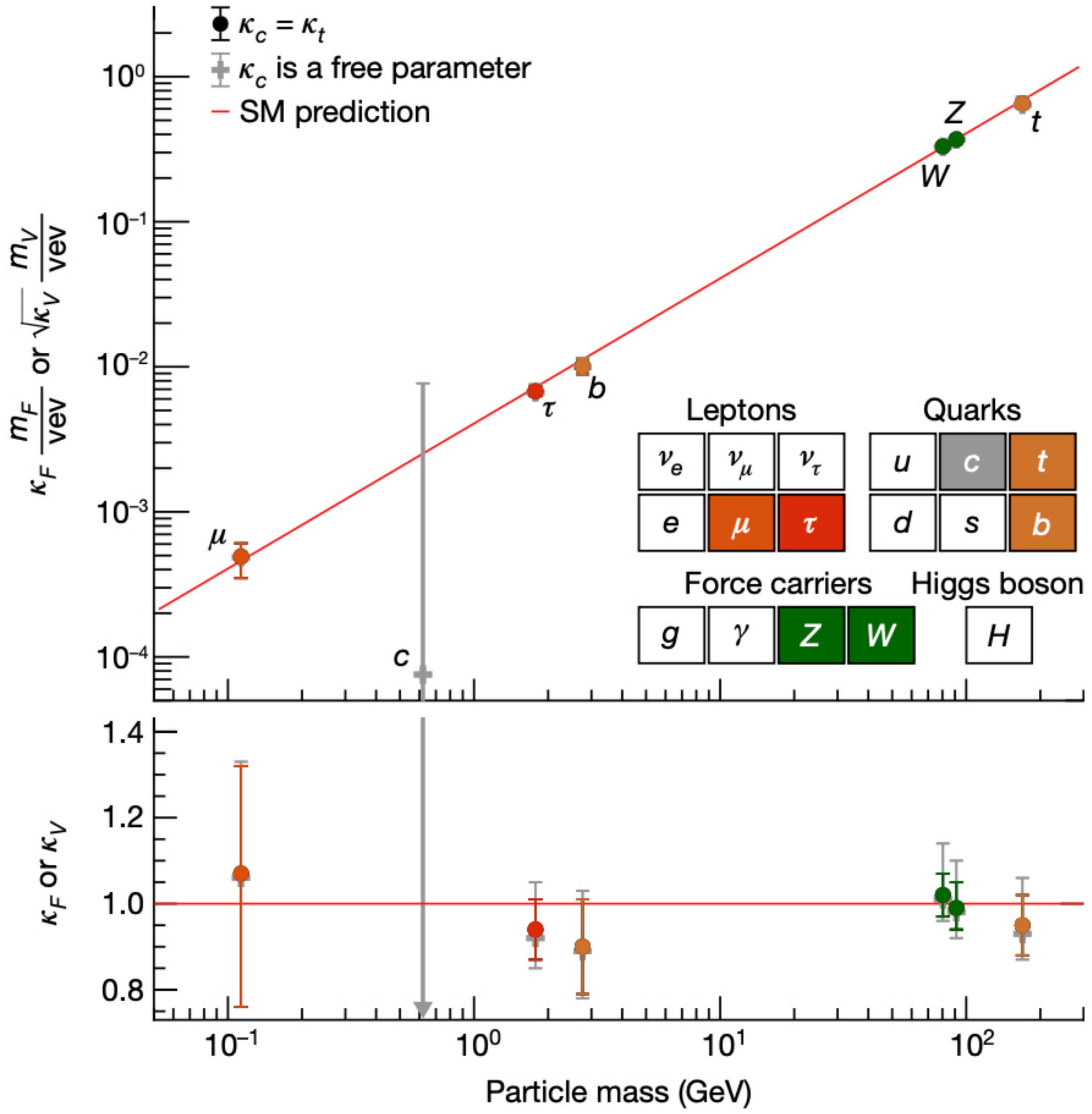
$H \to 4$ leptons

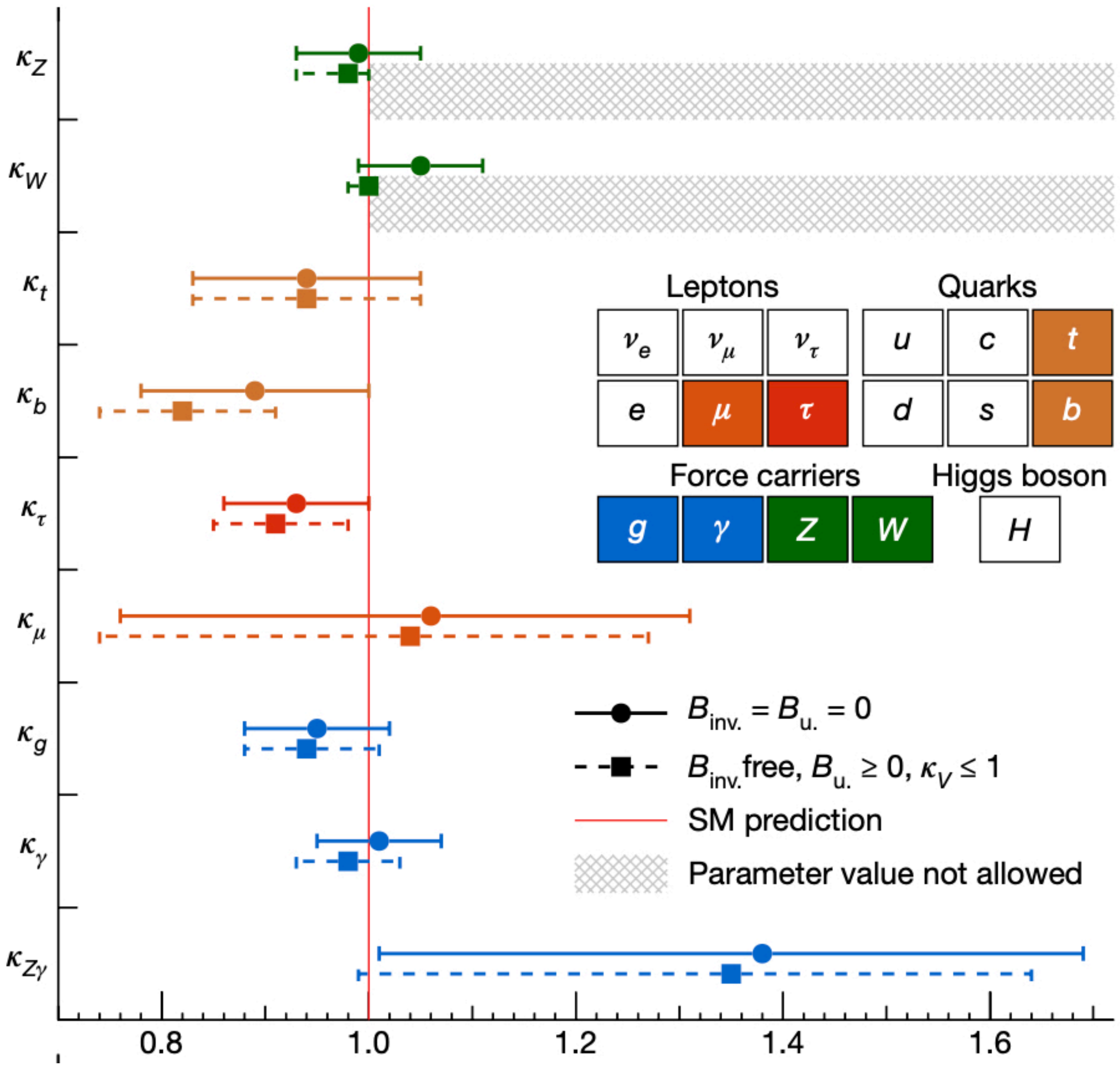
by 2022:



The ATLAS Collaboration
Nature, 607, 52–59 (2022)

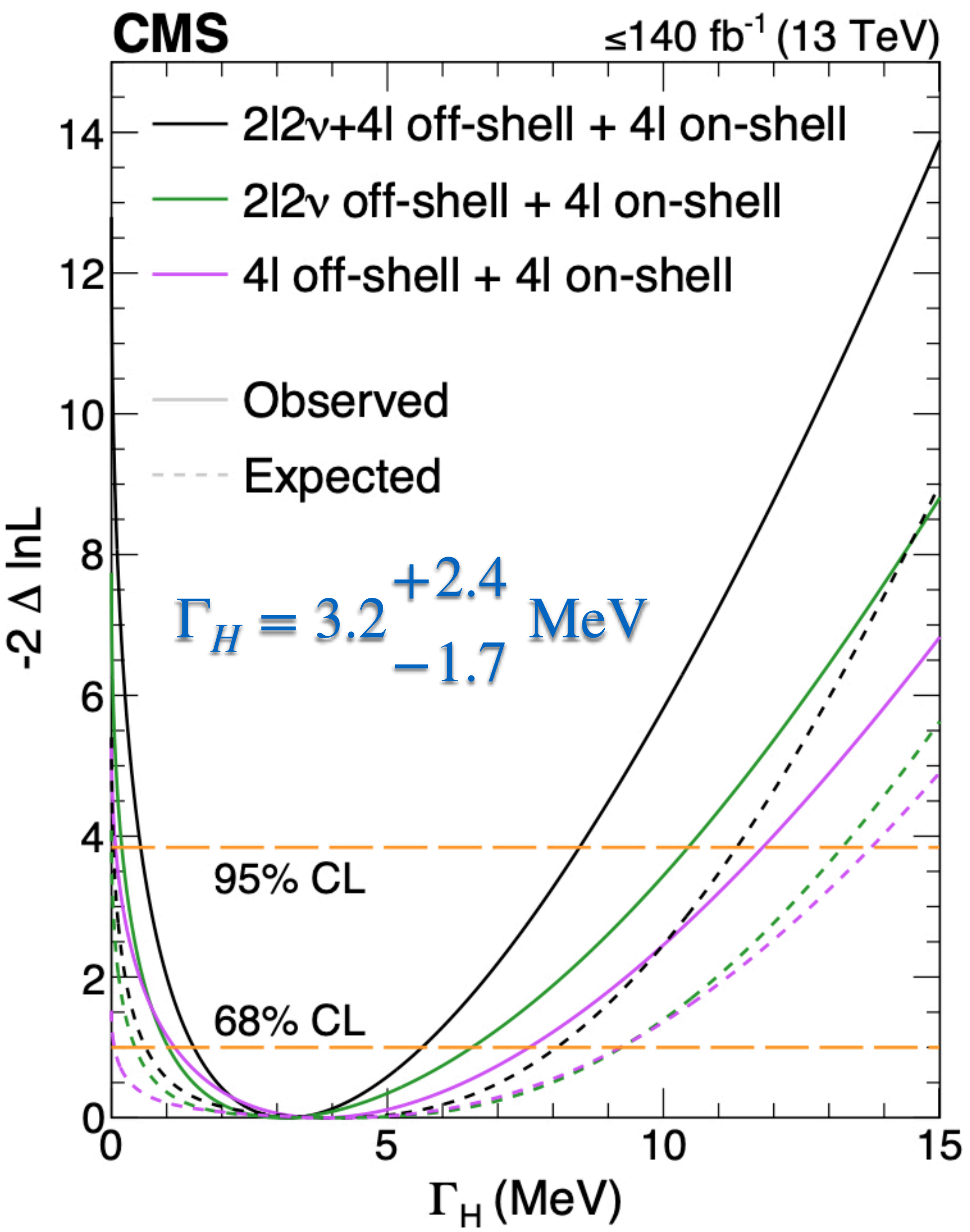
The CMS Collaboration
Nature, 607, 60–68 (2022)



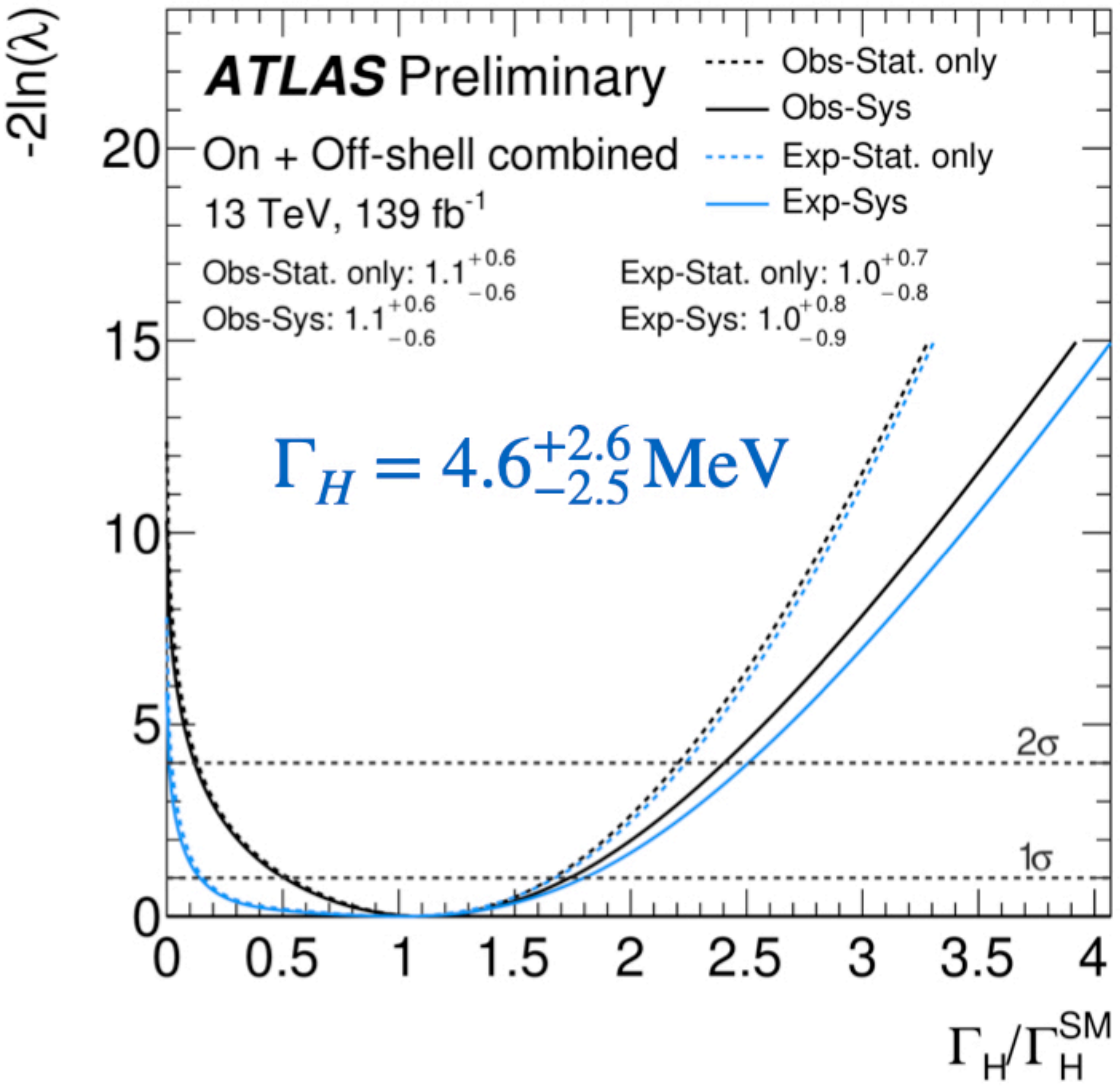


The Higgs width (SM: 4.1 MeV)

$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}}g^2_{\text{HZZ}}}{m_H\Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}}g^2_{\text{HZZ}}}{m^2_{ZZ}}$$



$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV



$\Gamma_H = 4.6^{+2.6}_{-2.5}\,\text{MeV}$

The key lessons

- The LHC works, and is more powerful than expected !
- The experiments work, and are more precise than expected !
- Theory works, and is more reliable than expected !
- The Higgs exists …
- … and nothing else beyond the Standard Model showed up …
- … but the spectrum of physics emerged from the LHC is far richer than expected !

The value of diversity in collider physics

LHC scientific production

Over 3000 papers published/submitted to refereed journals by the 7 experiments that operated in Run 1 and 2 (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)

Not only Higgs and exotic searches !

Flavour physics

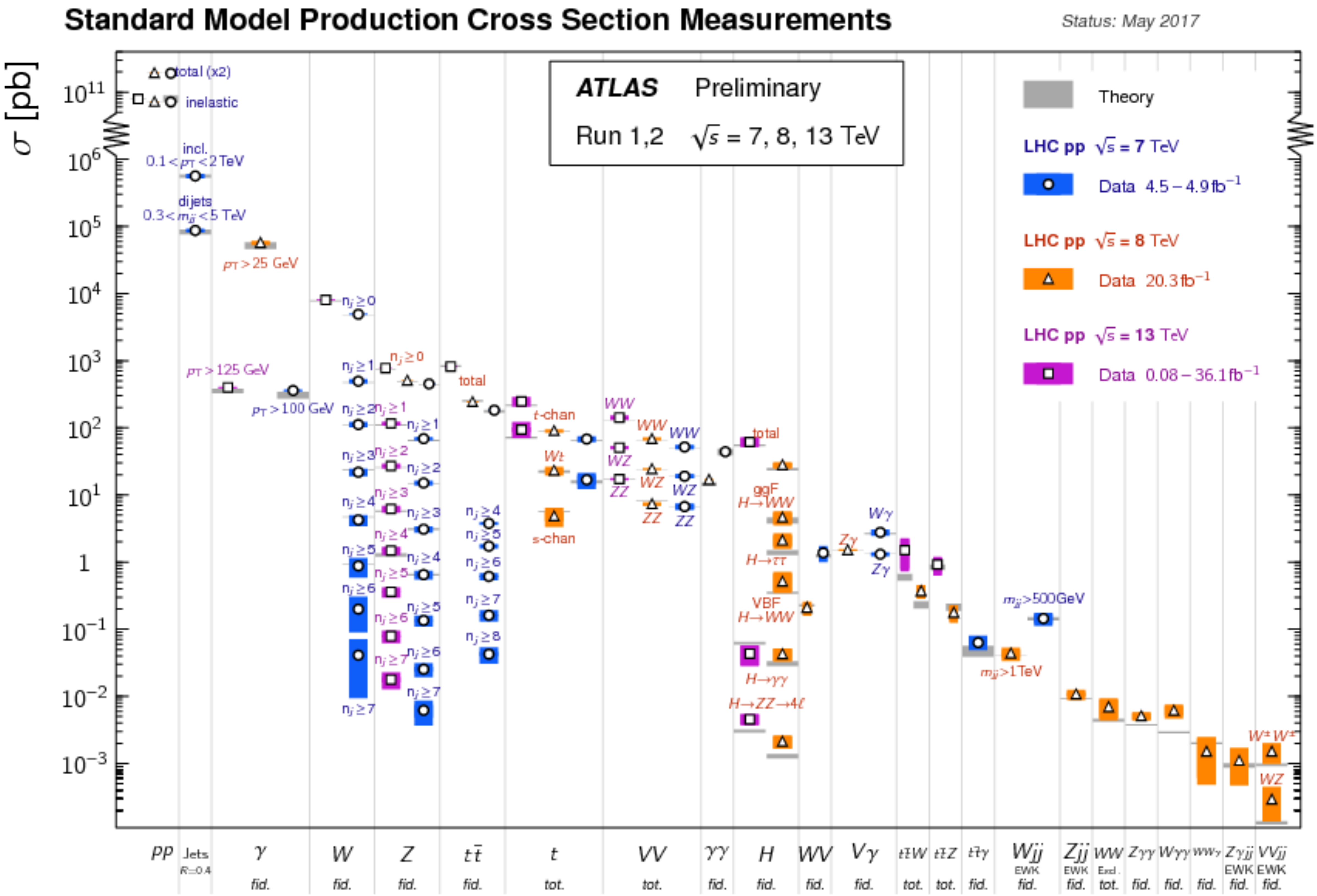
- B(s) $\rightarrow\mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase ϕs, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW param's and dynamics

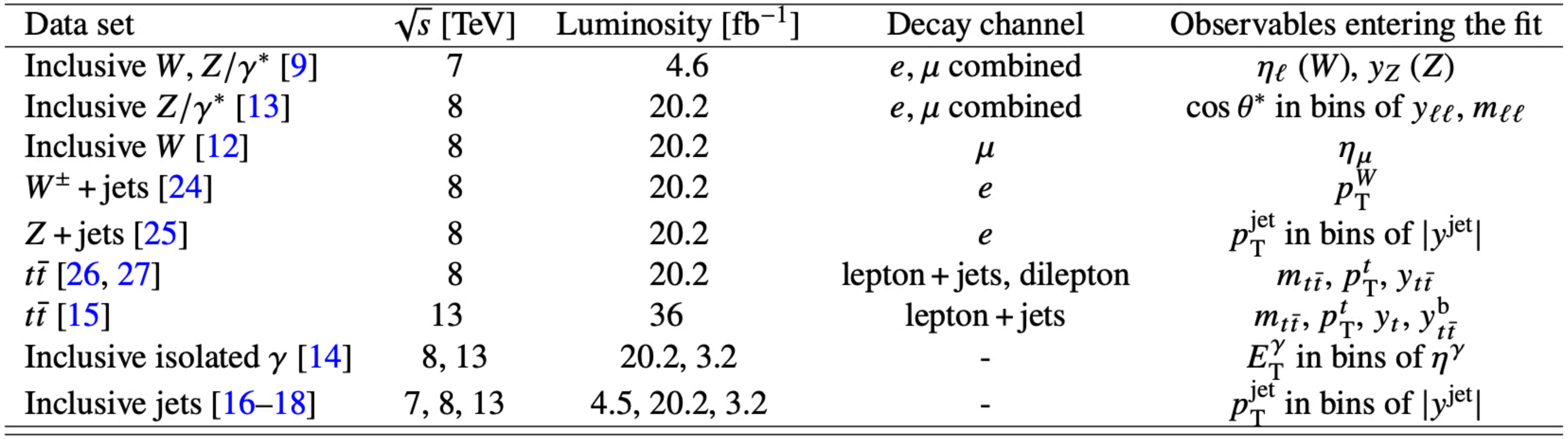
- m_W, m_{top} 171.77 ± 0.37 GeV, (CMS https://arxiv.org/pdf/2302.01967.pdf) $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)



Excellent agreement between data and theoretical predictions, over 10 orders of magnitude, culminating 30 years of progress in higher-order perturbative calculations, which have now reached next-to-leading order as routine, NNLO as benchmark for most processes, and NNNLO available for only some (very important!) cases, but rapidly expanding beyond

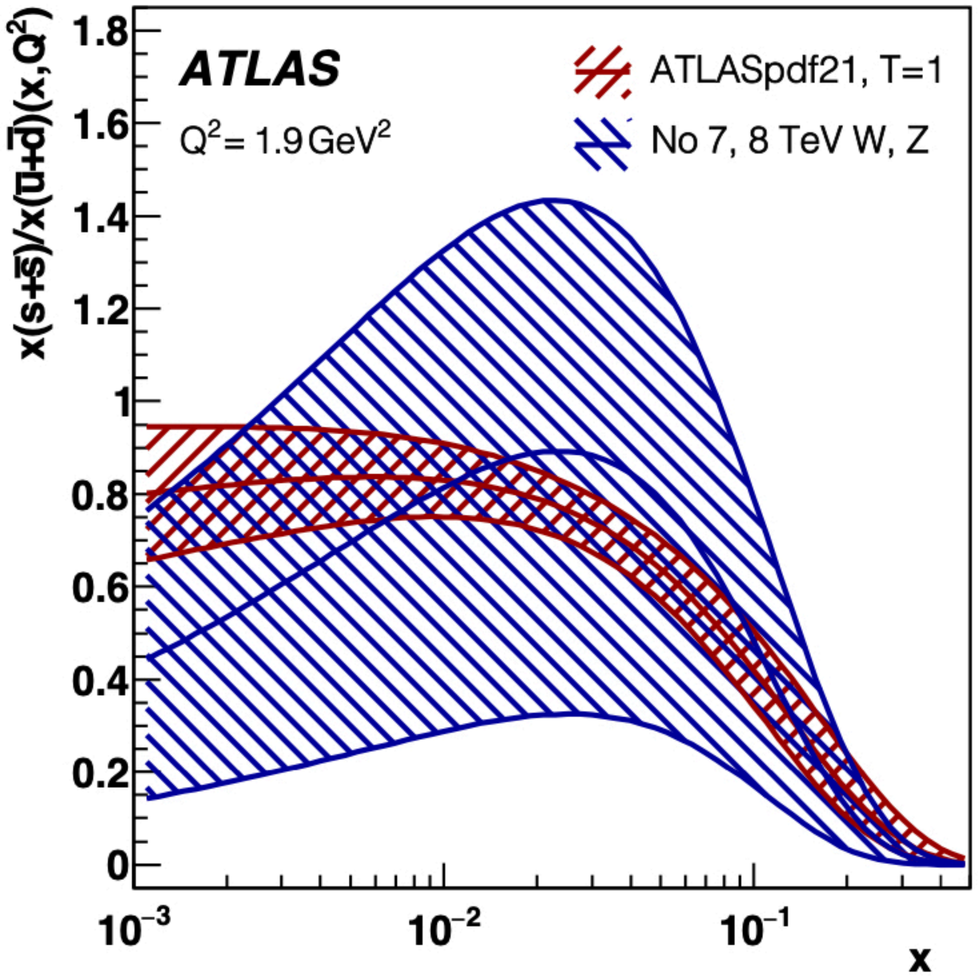
Example: PDF fits from LHC data

ATLASpdf21 fit, https://arxiv.org/pdf/2112.11266.pdf including HERA and ATLAS data

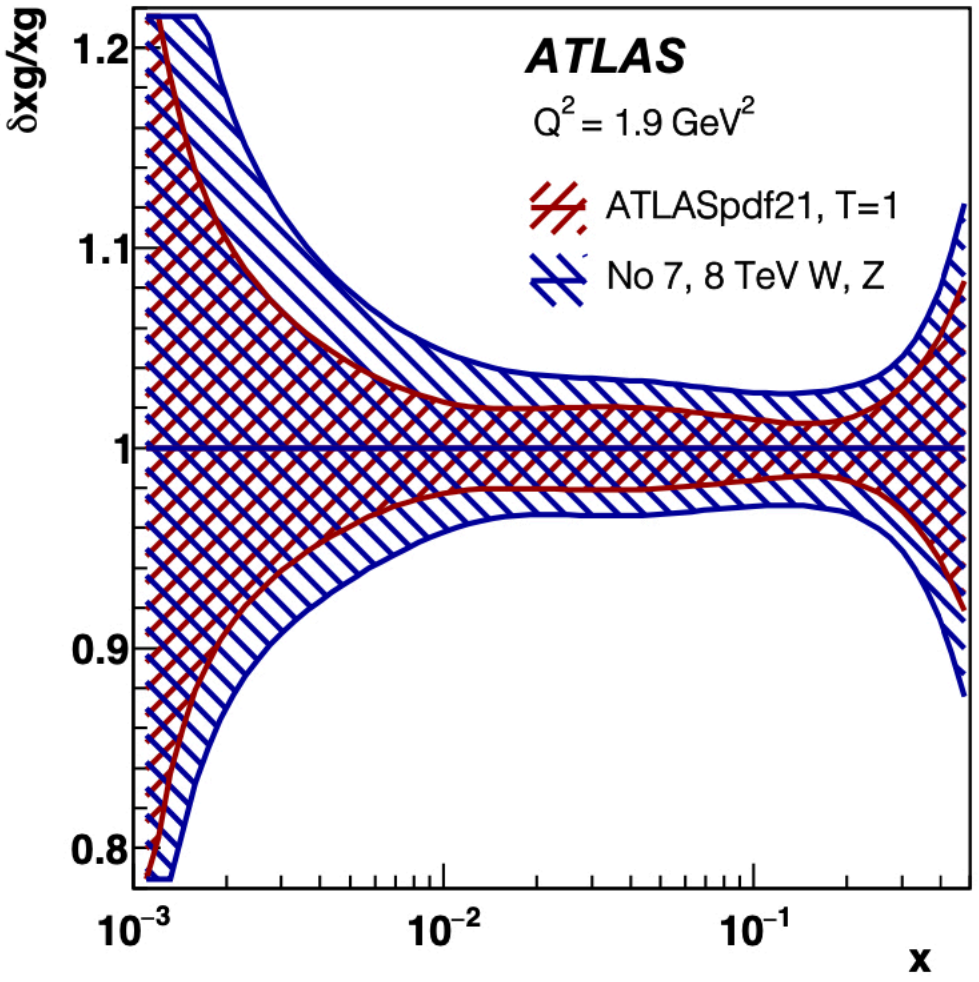


Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^* [13]	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}, m_{\ell\ell}$
Inclusive W [12]	8	20.2	μ	η_μ
$W^\pm$ + jets [24]	8	20.2	e	p_{T}^W
Z + jets [25]	8	20.2	e	$p_{\mathrm{T}}^{\mathrm{jet}}$ in bins of $\lvert y^{\mathrm{jet}}\rvert$
$t\bar{t}$ [26, 27]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}, p_{\mathrm{T}}^t, y_{t\bar{t}}$
$t\bar{t}$ [15]	13	36	lepton + jets	$m_{t\bar{t}}, p_{\mathrm{T}}^t, y_t, y_{t\bar{t}}^{\mathrm{b}}$
Inclusive isolated γ [14]	8, 13	20.2, 3.2	-	E_{T}^γ in bins of η^γ
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	-	$p_{\mathrm{T}}^{\mathrm{jet}}$ in bins of $\lvert y^{\mathrm{jet}}\rvert$

Strange quark / light antiquarks ratio

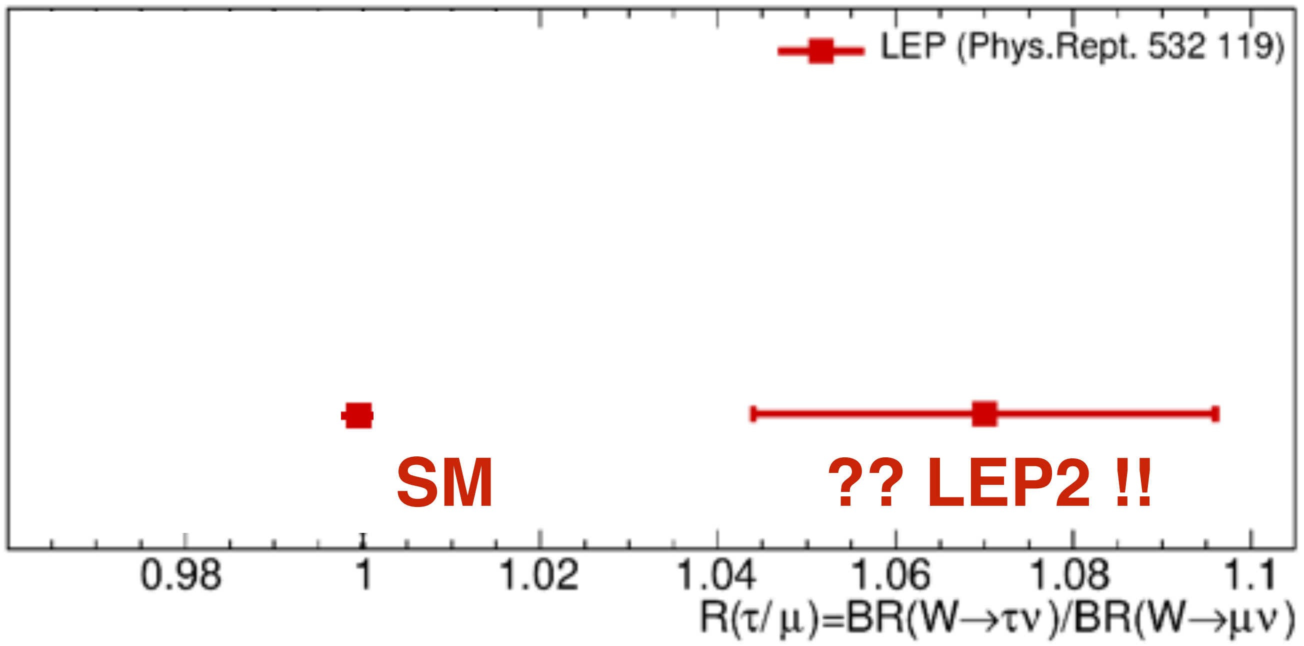


Gluon PDF



Precision W physics

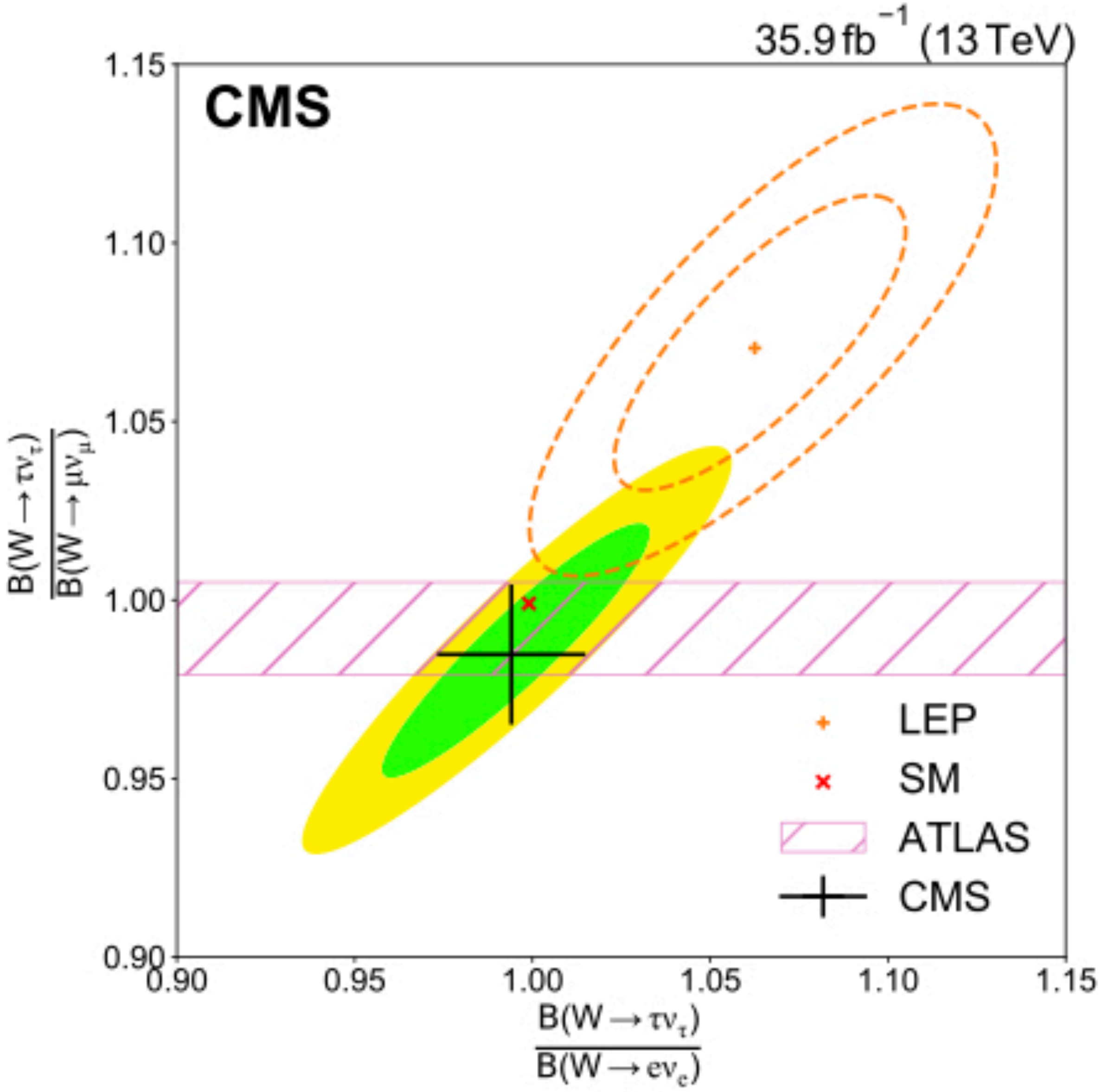
ATLAS 2020: arXiv:2007.14040



LEP:
$BR(W\to\tau\nu)/BR(W\to\mu\nu) = 1.066 \pm 0.025$

ATLAS:
$BR(W\to\tau\nu)/BR(W\to\mu\nu) = 0.992 \pm 0.013$

CMS 2022: arXiv:2201.07861

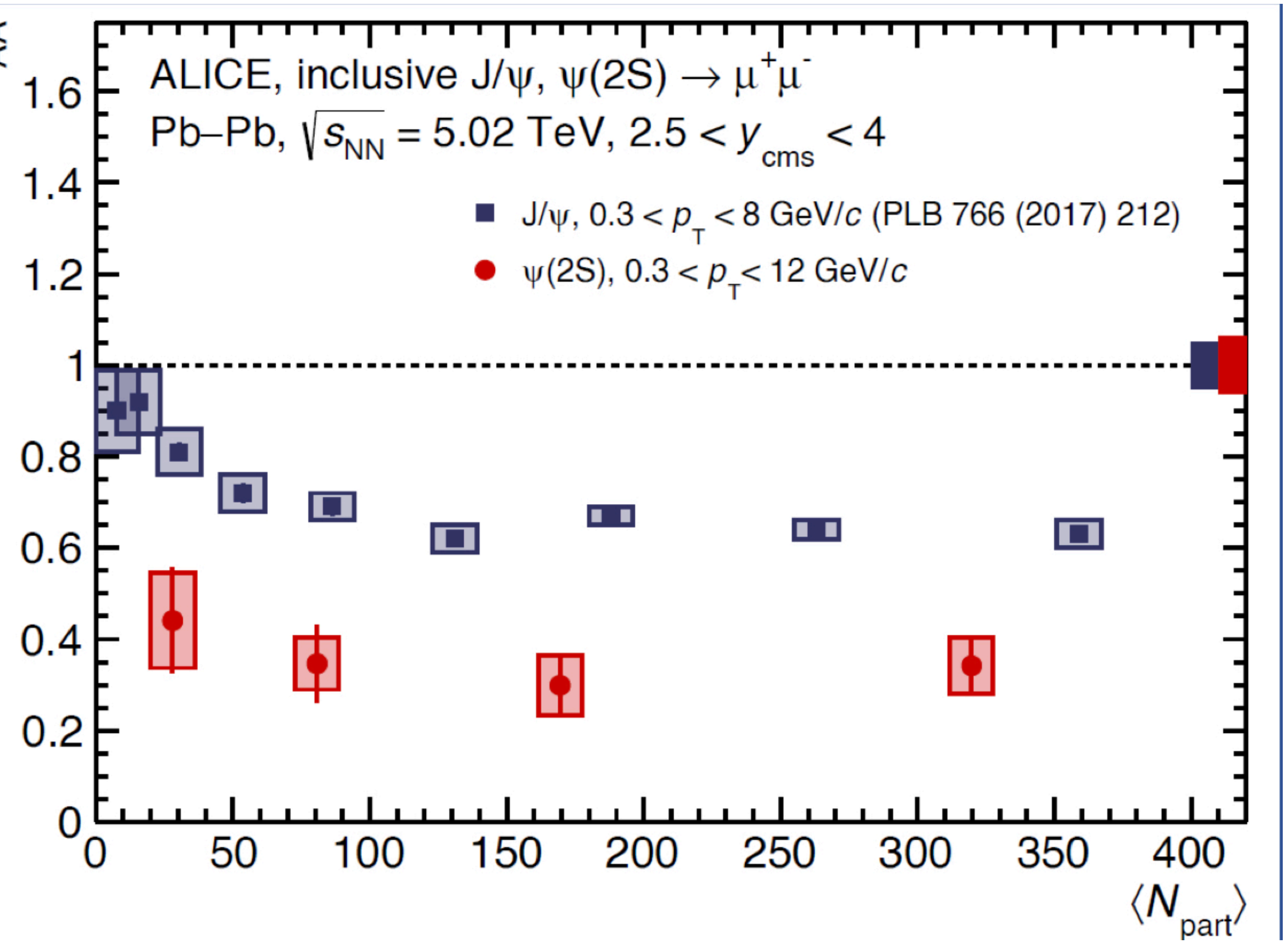


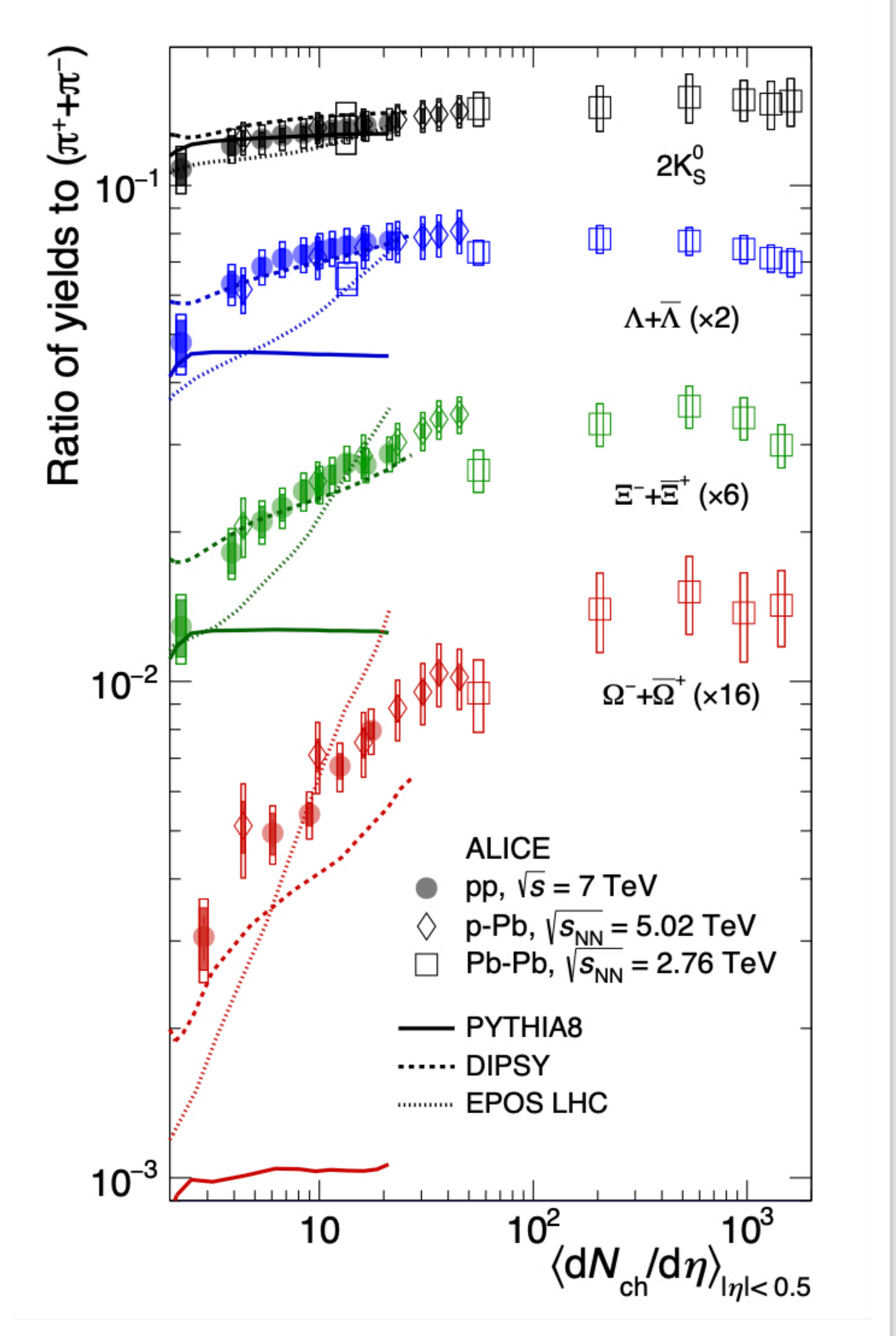
Study of QCD dynamics in previously unexplored dynamical regimes

Collective QCD phenomena in high-T, high-density and other extreme environments

consolidation of known phenomena, with higher precision and broader coverage:
(ALICE, https://inspirehep.net/literature/2165947)

discovery of new dynamical behaviour, with collective phenomena typical of QGP appearing already in high-multiplicity final states of pp and pA

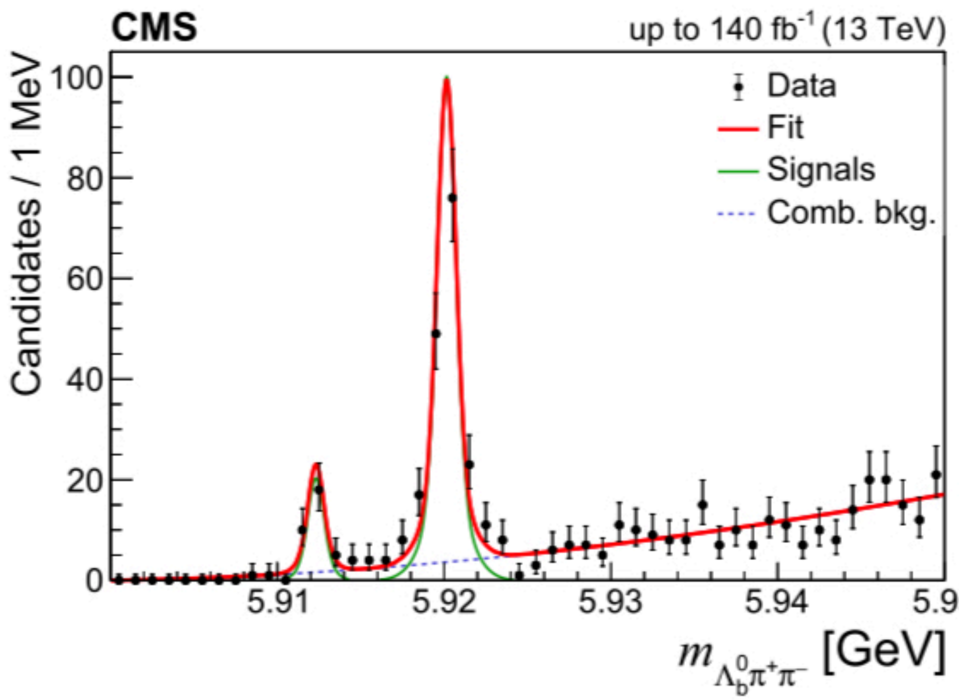


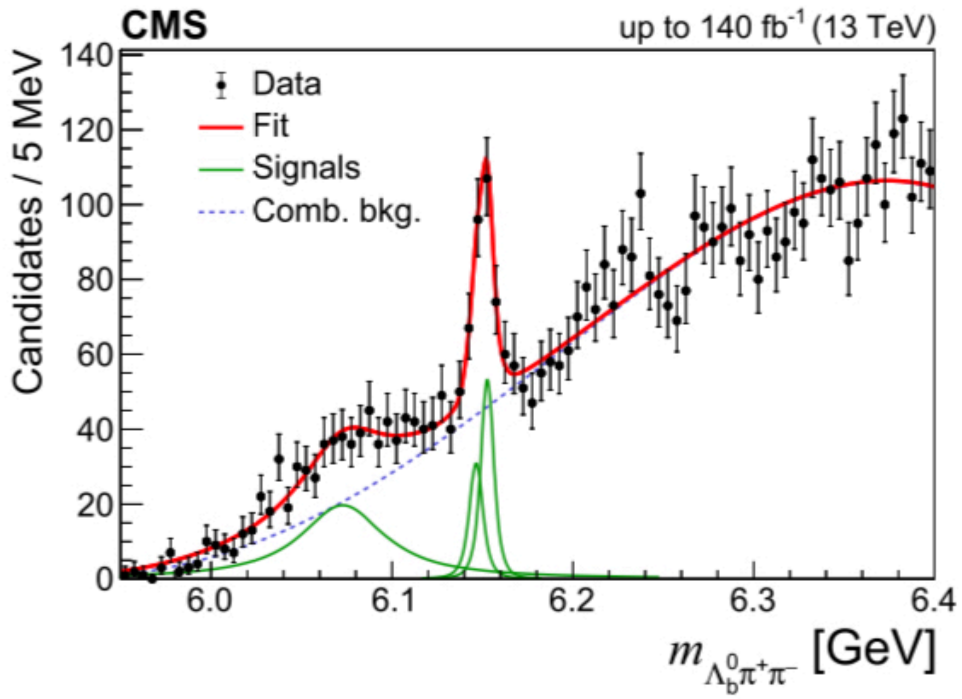


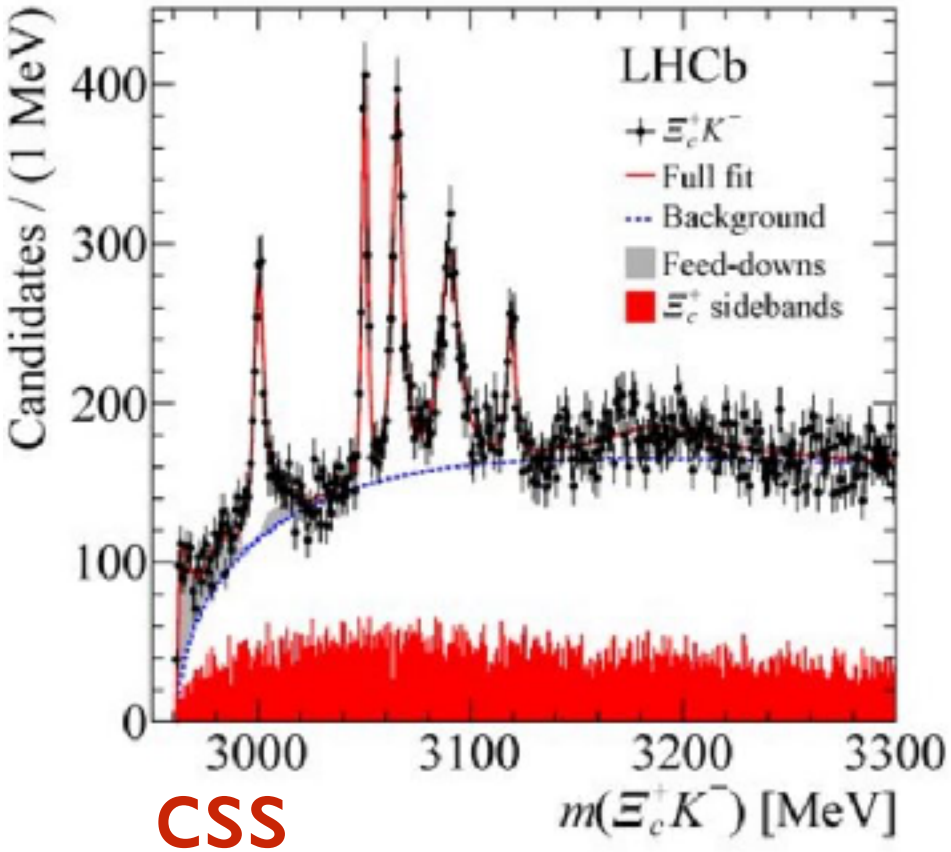
Exotic Spectroscopy, nuclear physics and more

Continued progress, and novelties, in spectroscopy

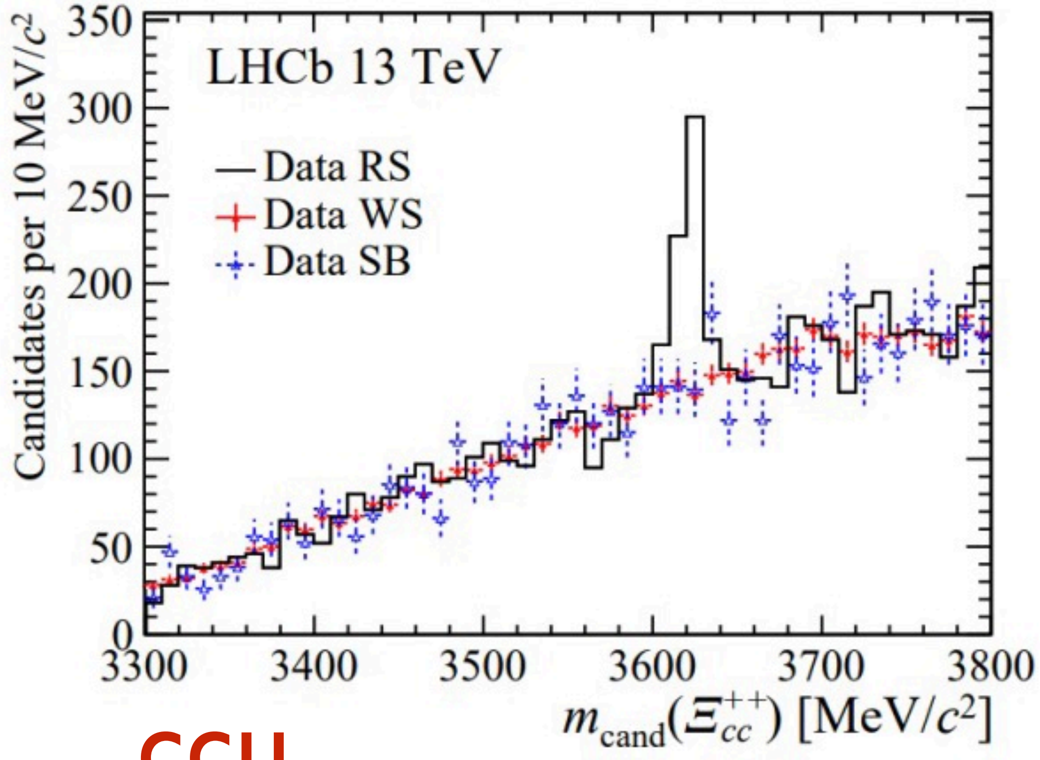
CMS, Phys. Lett. B 803 (2020) 135345





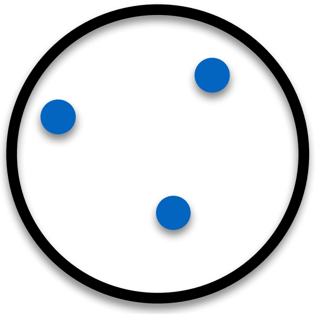


CSS

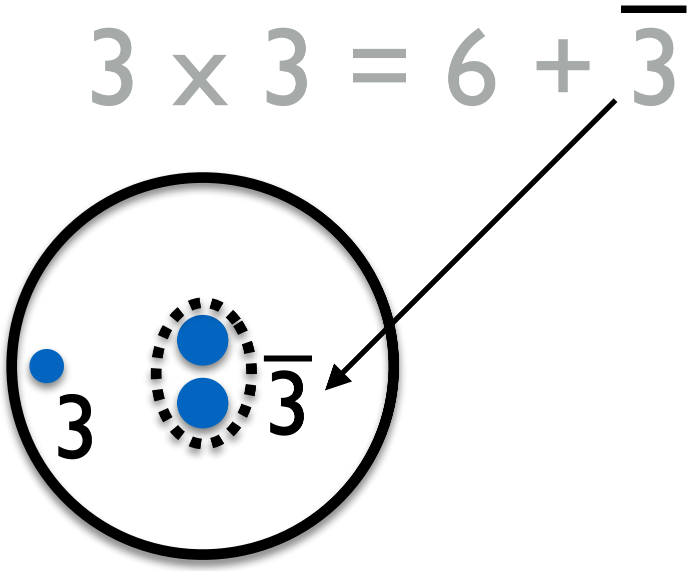


CCU

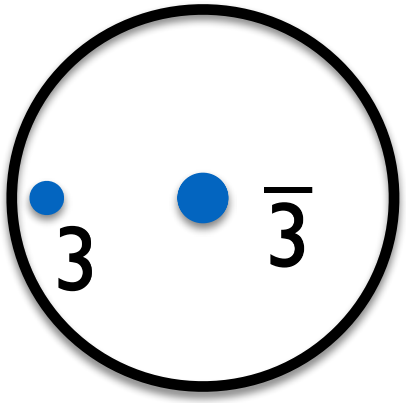
A usual baryon:



A baryon with two heavy q's:

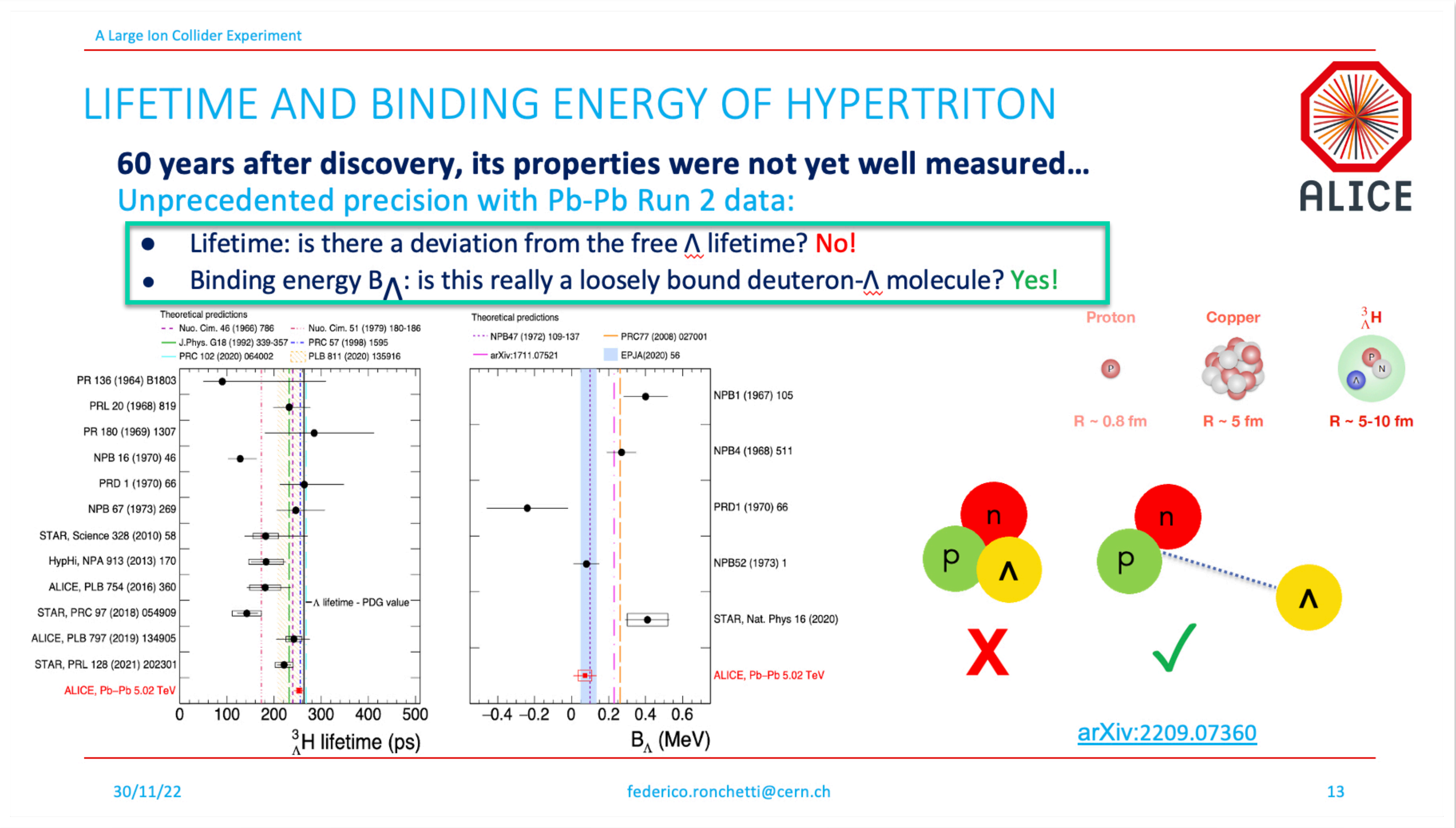

$3 \times 3 = 6 + \bar{3}$

Similar to a heavy meson, eg B_u



but here the core is a fermion, while in a doubly-heavy baryon the core is a boson (different hyperfine splitting structures, etc)

⇒ rewarding for theory and experiment to challenge each other's ability to predict/measure!!



LIFETIME AND BINDING ENERGY OF HYPERTRITON

60 years after discovery, its properties were not yet well measured…

Unprecedented precision with Pb-Pb Run 2 data:

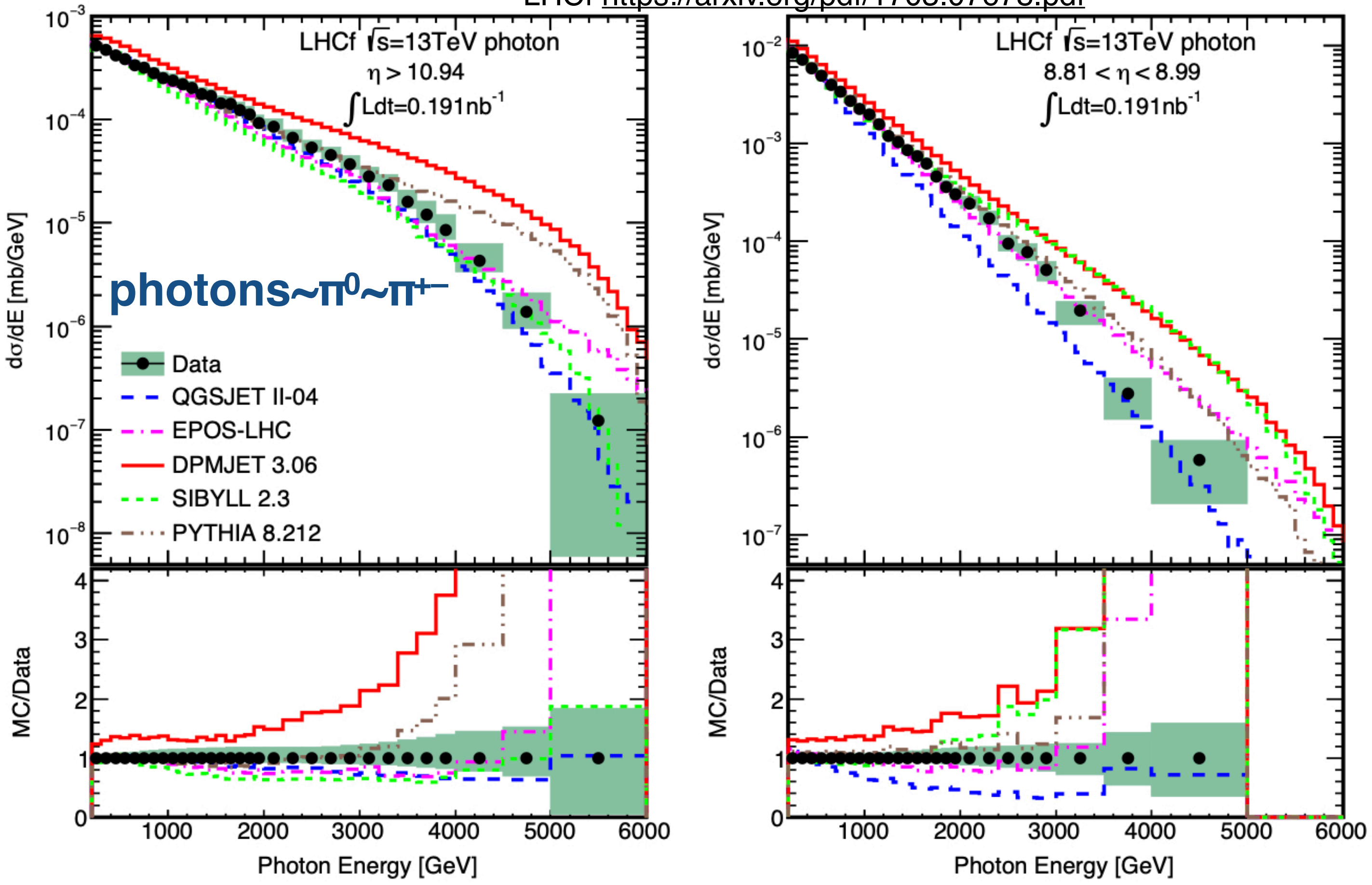
- Lifetime: is there a deviation from the free Λ lifetime? No!
- Binding energy B_{Λ}: is this really a loosely bound deuteron-Λ molecule? Yes!

arXiv:2209.07360

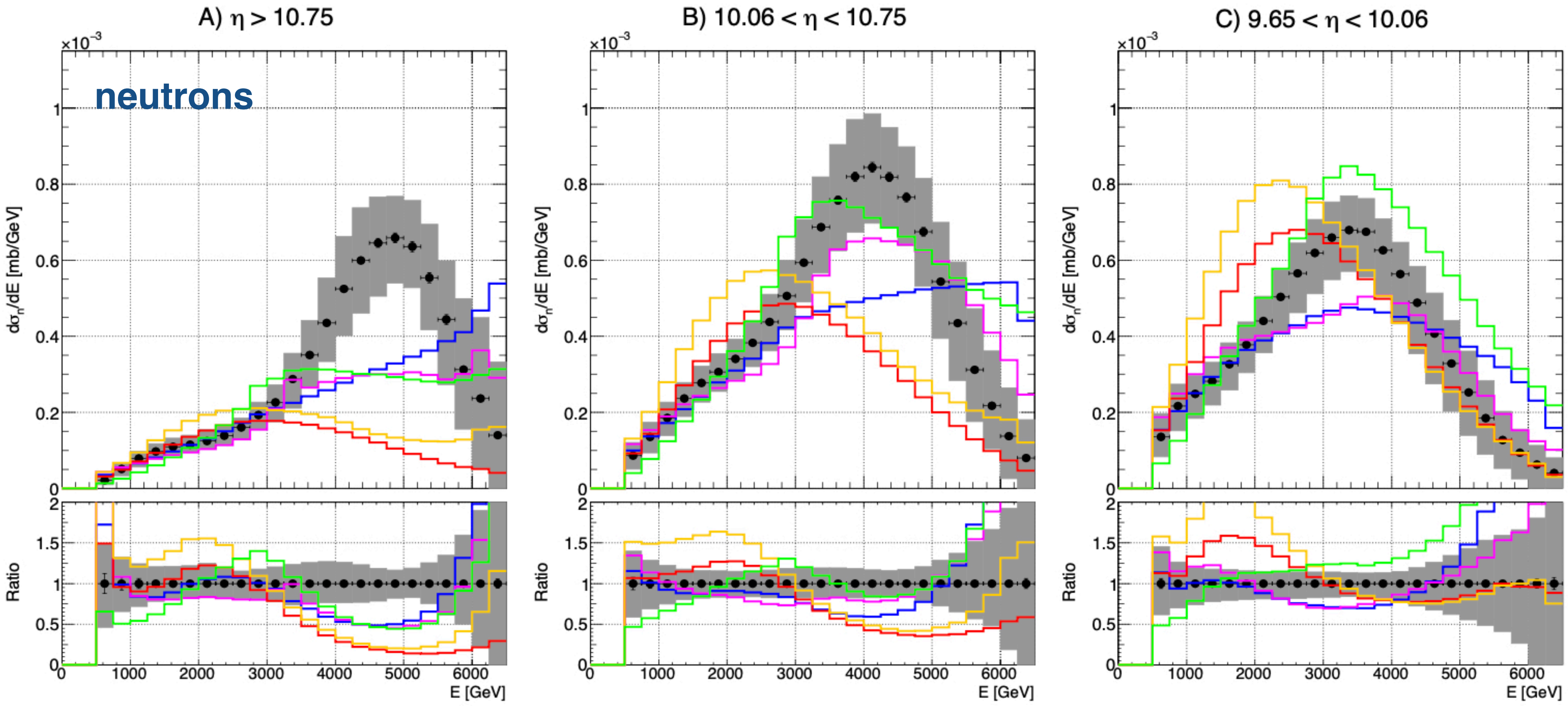
federico.ronchetti@cern.ch

Impact on astroparticle physics

LHCf https://arxiv.org/pdf/1703.07678.pdf

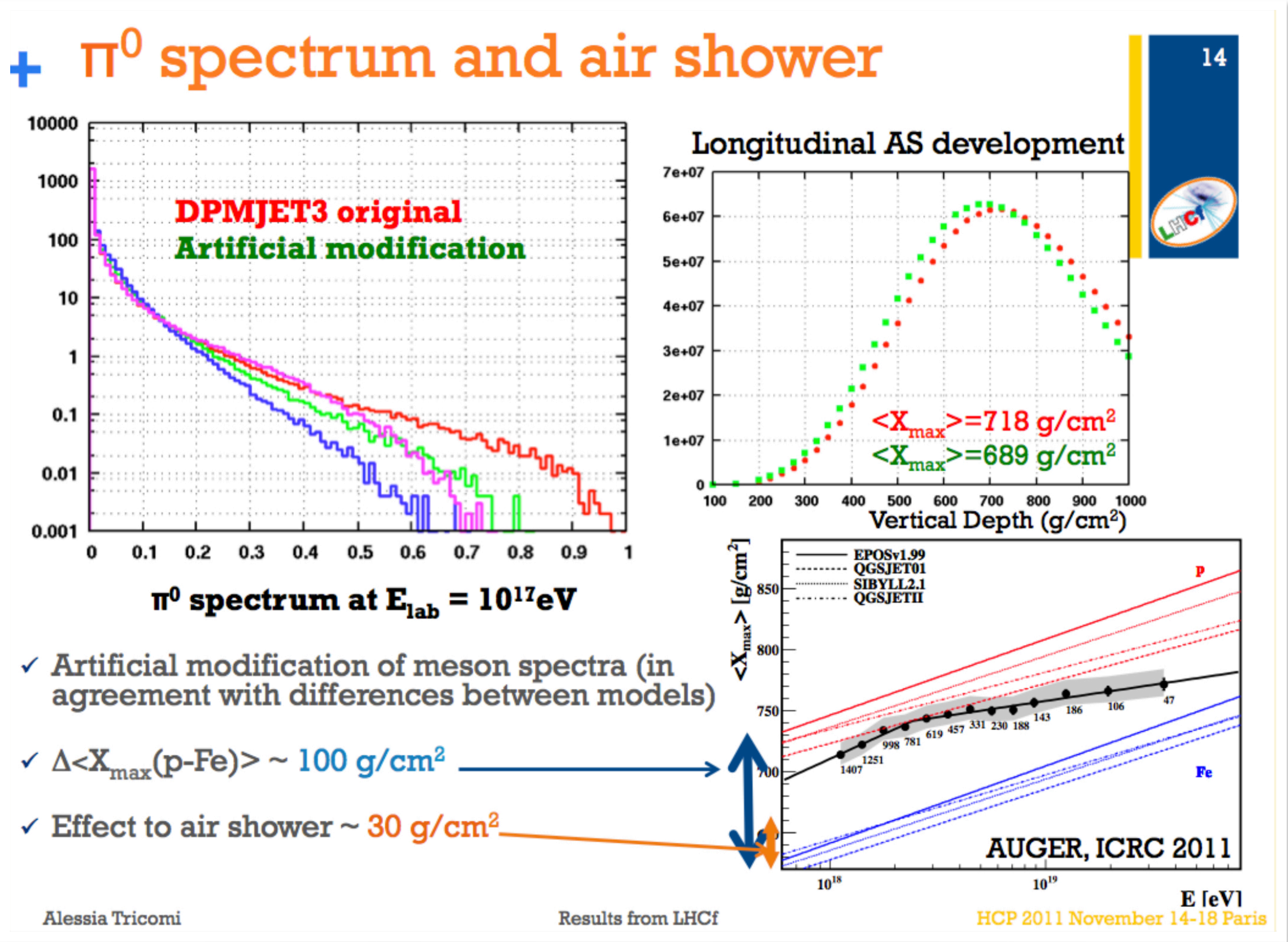


LHCf https://arxiv.org/pdf/2003.02192.pdf



Probing the spectrum of most energetic particles forward-produced => model development of highest-energy cosmic ray showers in the atmosphere

π^0 spectrum and air shower



π^0 spectrum at $E_{lab} = 10^{17}$eV

- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta \langle X_{max}(p\text{-}Fe) \rangle \sim 100\ g/cm^2$
- ✓ Effect to air shower ~ 30 g/cm²

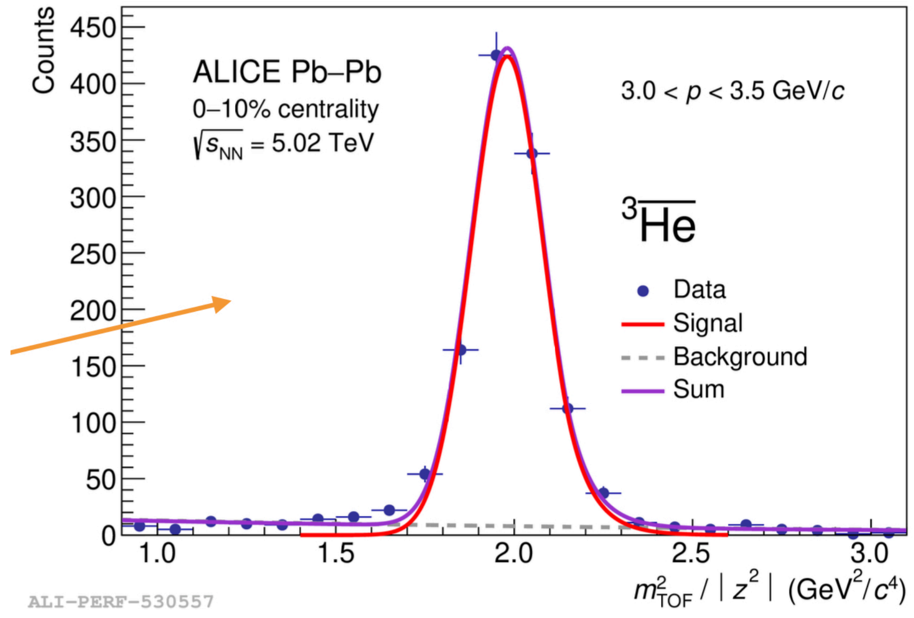
Article

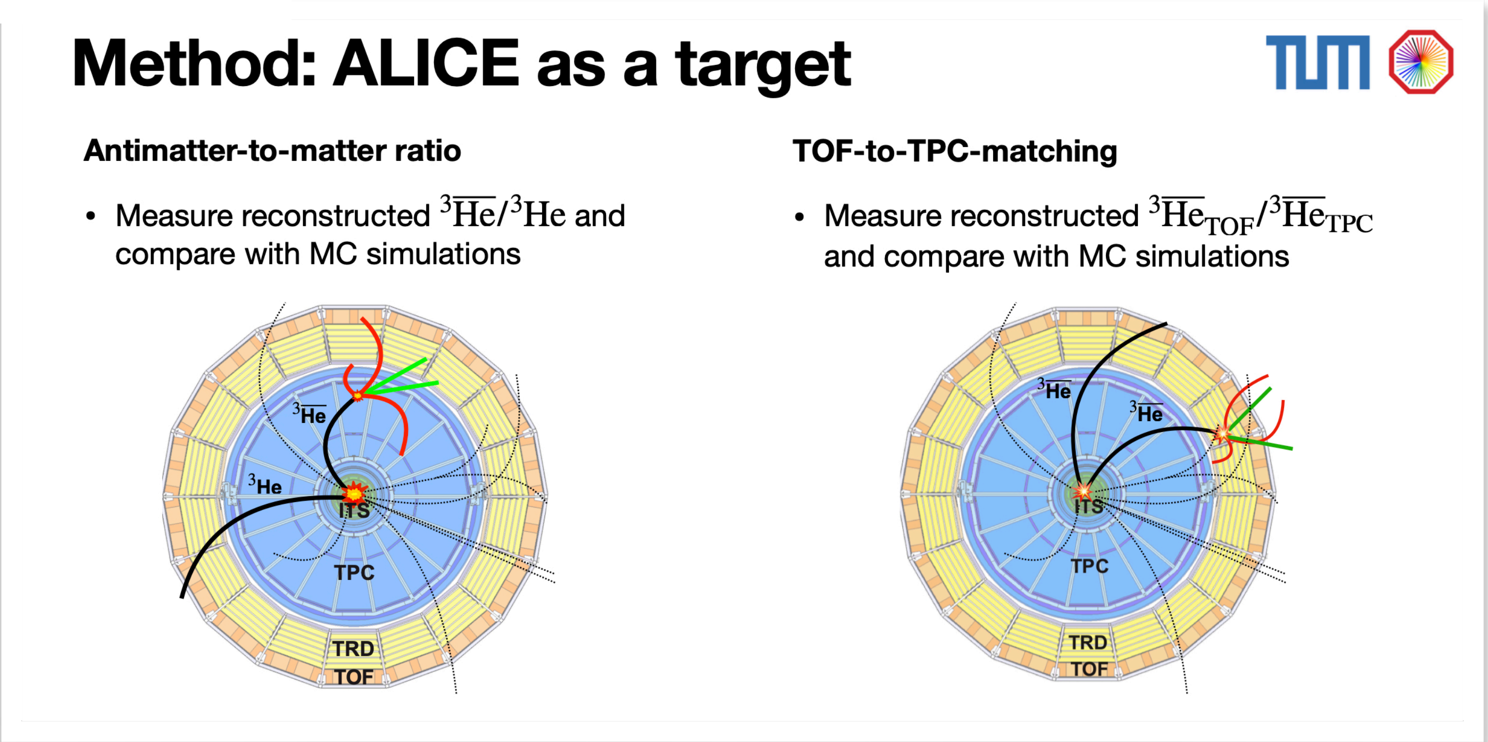
https://doi.org/10.1038/s41567-022-01804-8

Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

ALICE https://doi.org/10.1038/s41567-022-01804-8

Laura Šerkšnytė CERN seminar





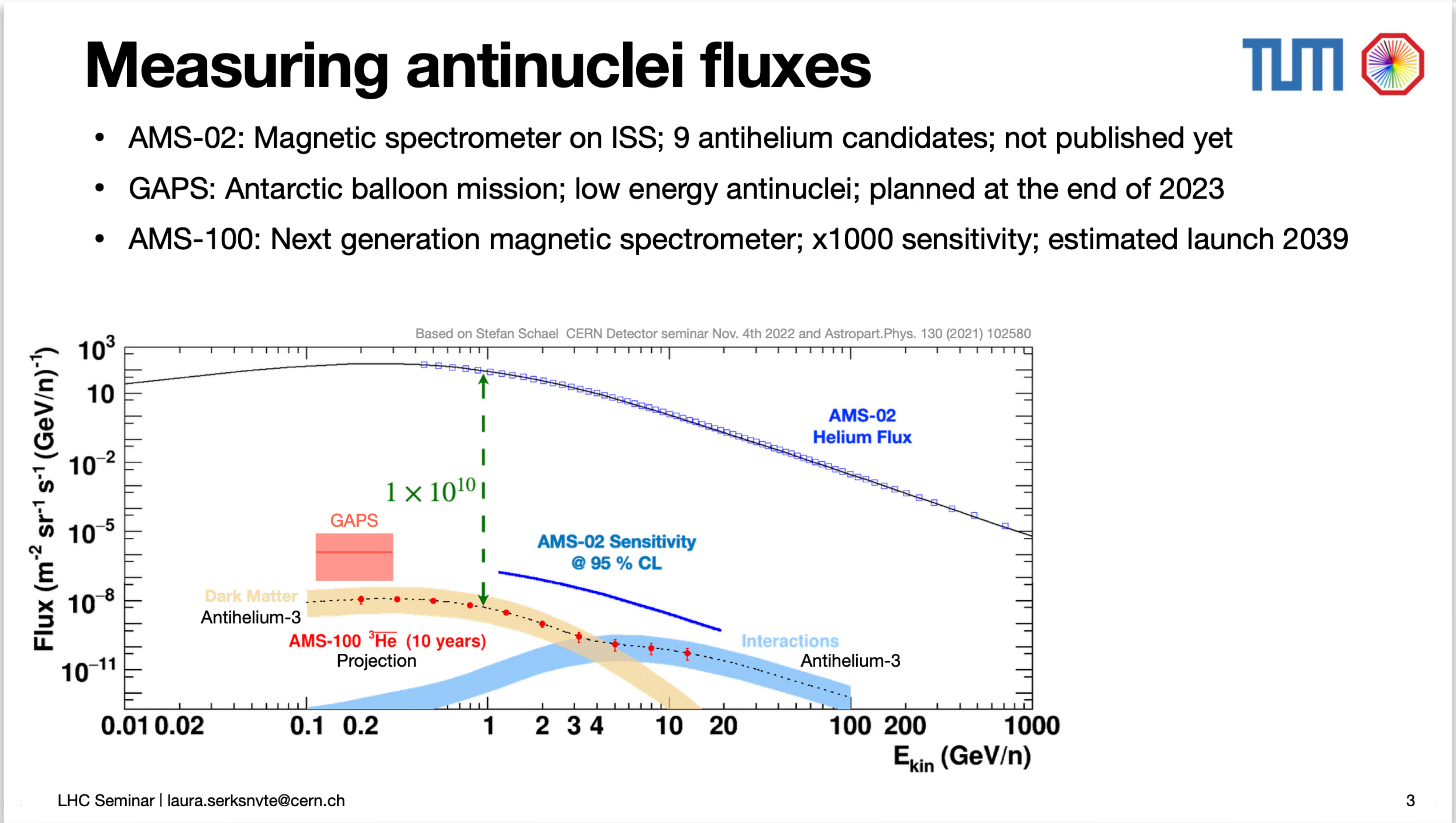
Method: ALICE as a target

Antimatter-to-matter ratio

- Measure reconstructed $^3\overline{\text{He}}/^3\text{He}$ and compare with MC simulations

TOF-to-TPC-matching

- Measure reconstructed $^3\overline{\text{He}}_{\text{TOF}}/^3\overline{\text{He}}_{\text{TPC}}$ and compare with MC simulations



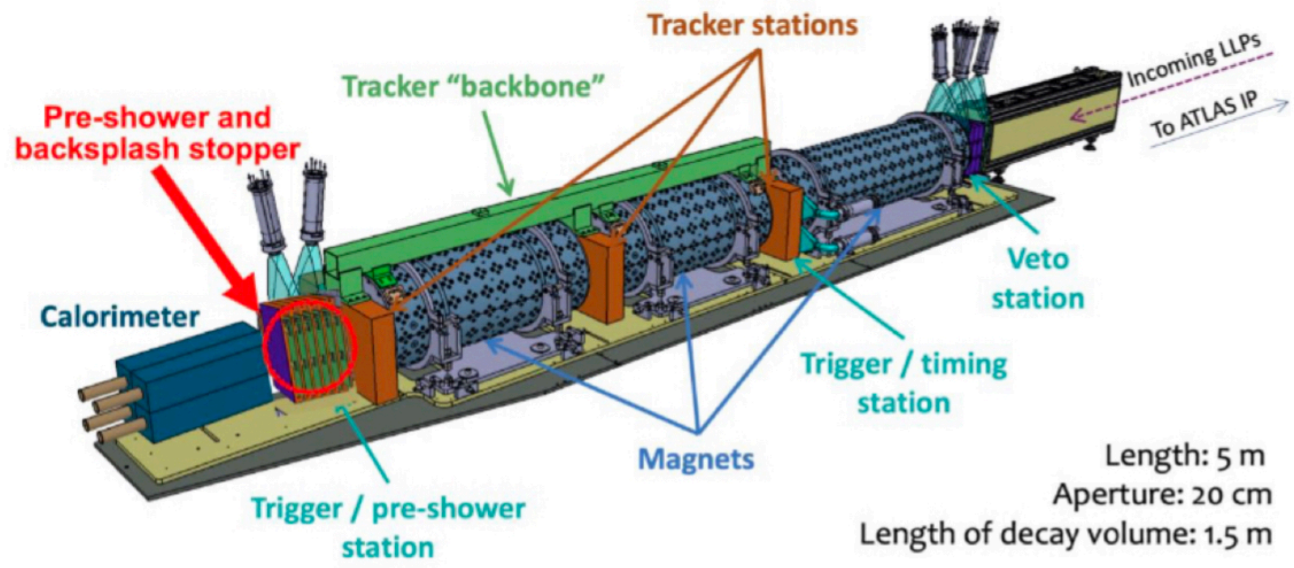
Measuring antinuclei fluxes

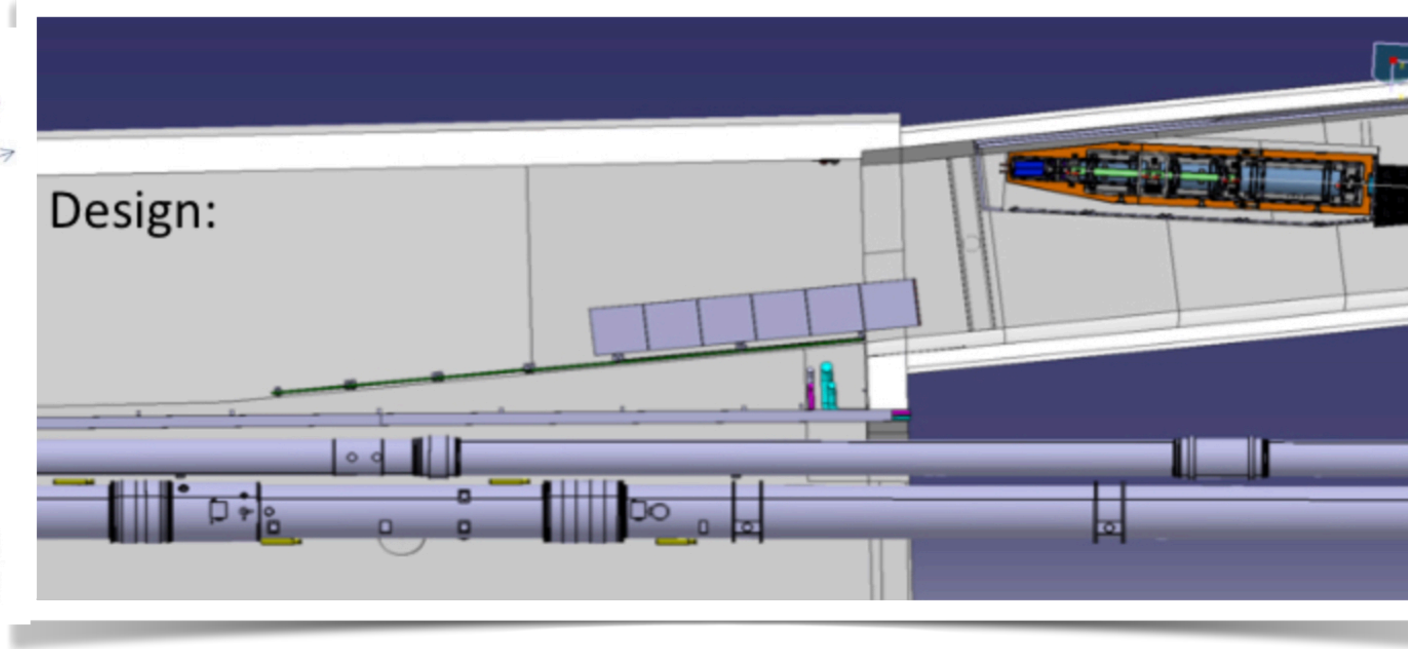
- AMS-02: Magnetic spectrometer on ISS; 9 antihelium candidates; not published yet
- GAPS: Antarctic balloon mission; low energy antinuclei; planned at the end of 2023
- AMS-100: Next generation magnetic spectrometer; x1000 sensitivity; estimated launch 2039

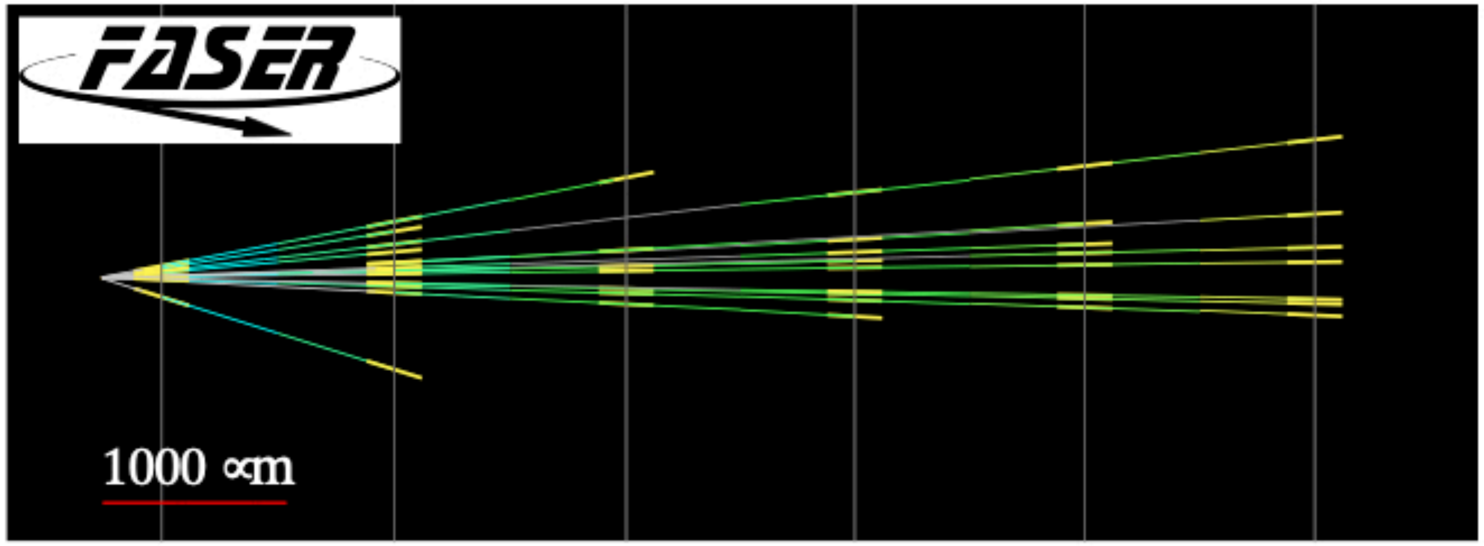
Based on Stefan Schael CERN Detector seminar Nov. 4th 2022 and Astropart.Phys. 130 (2021) 102580

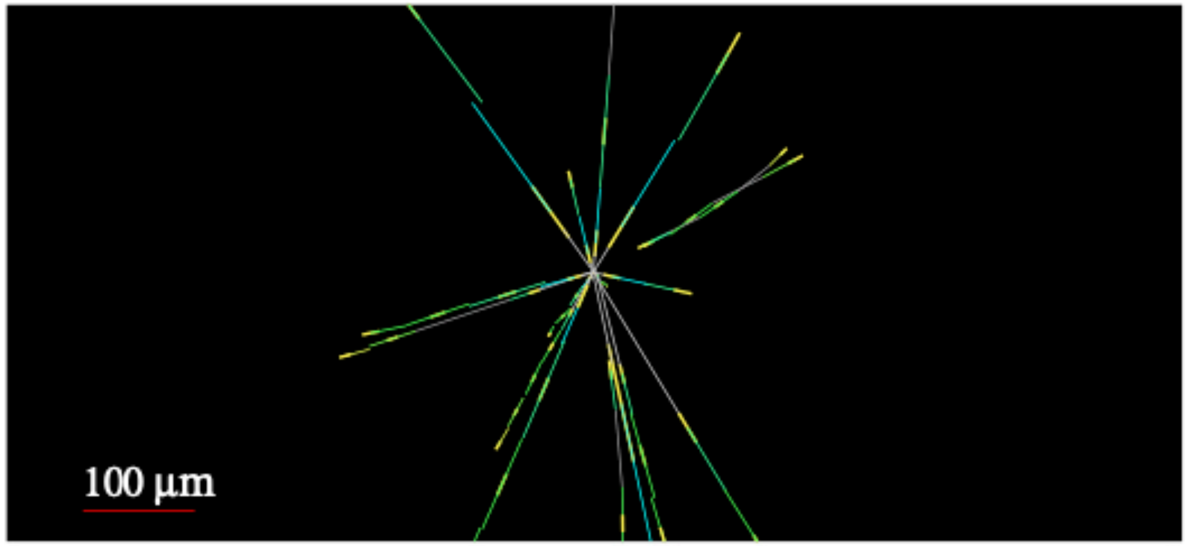
Neutrino physics

First detection of neutrinos produced by the LHC

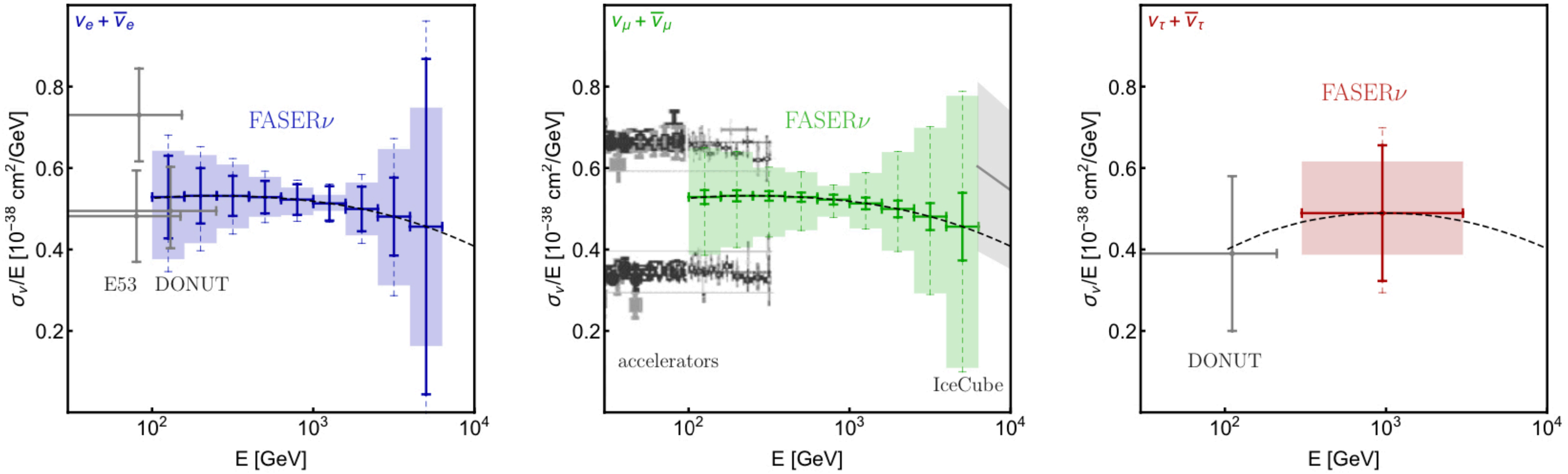




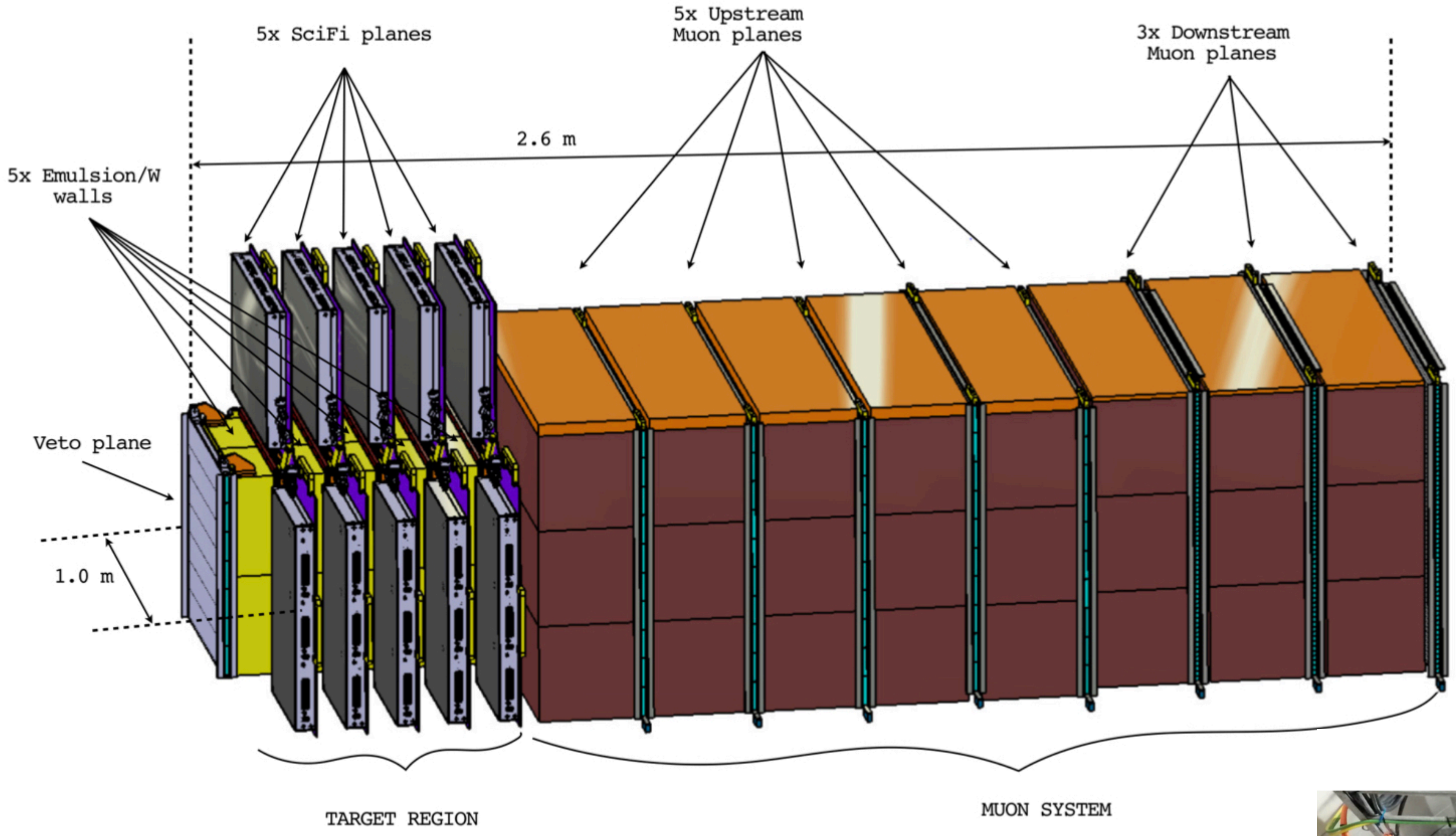




The goal: measure neutrino cross sections in energy ranges never explored before, of relevance to cosmic neutrino studies, and flavour-tagged



SND@LHC



March 8th

Remarks

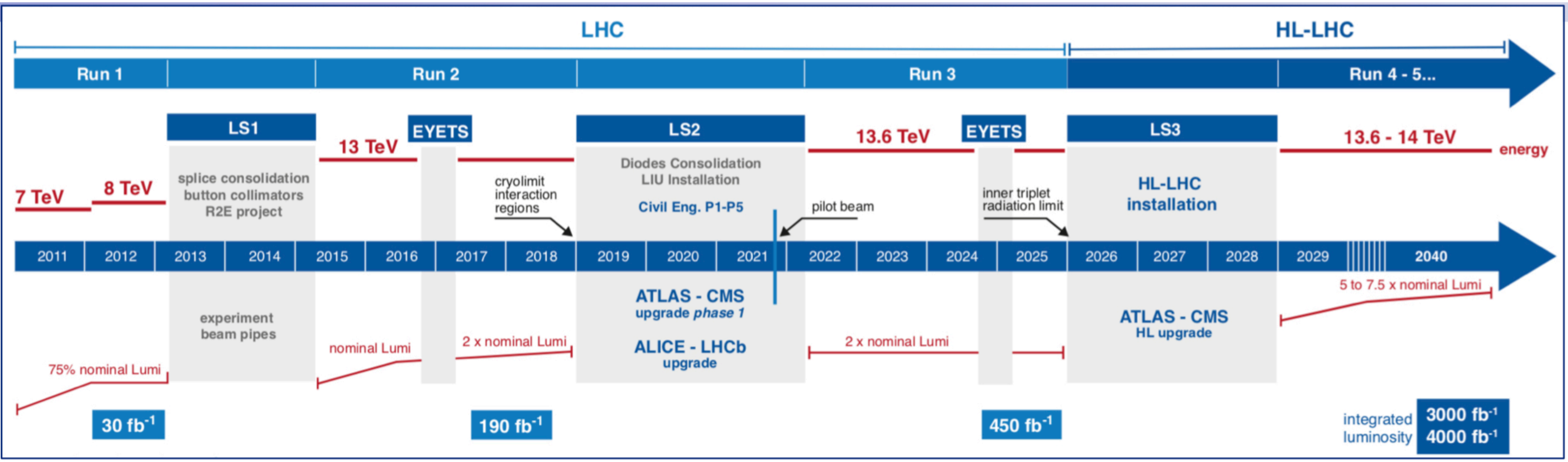
- These 3000 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc
- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

I have a broad concept of "*new physics*", which includes SM phenomena, emerging from the data, that are unexpected, surprising, or simply poorly understood.

I consider as "new", and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

"New physics" is emerging every day at the LHC!

What’s next for the LHC, and beyond?


LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
2 x nominal Lumi
ATLAS - CMS
HL upgrade
5 to 7.5 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1

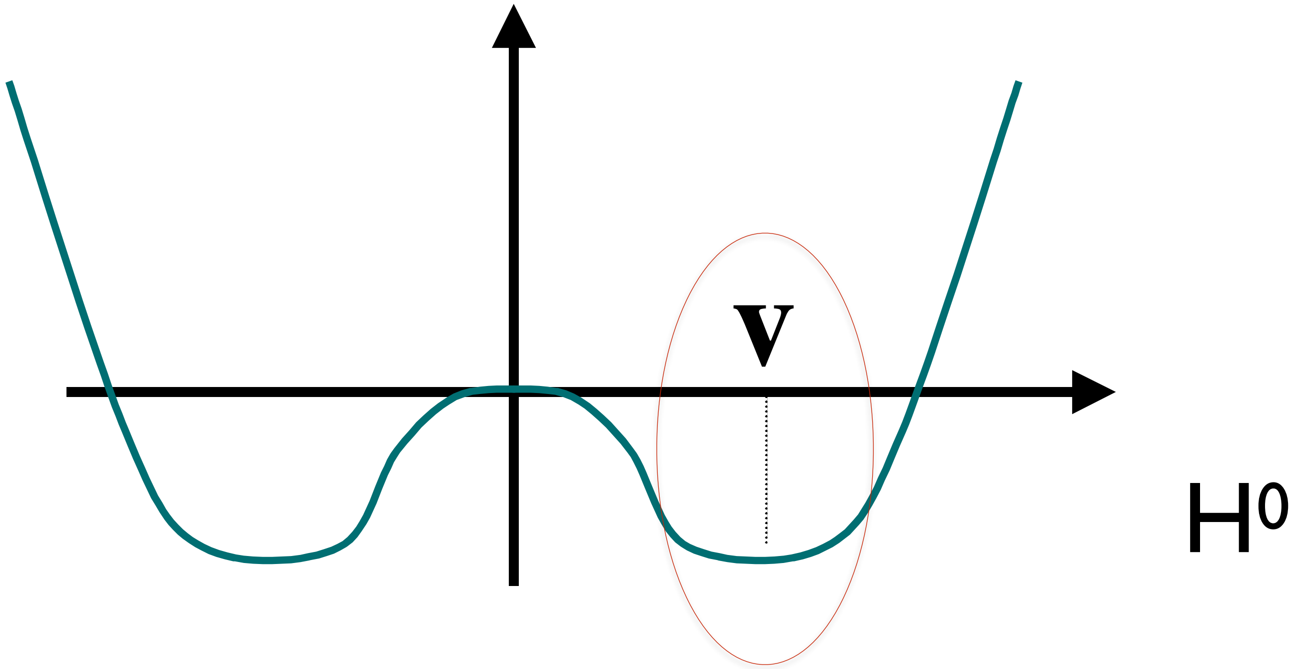
beyond the Higgs: the important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Origin of inflation
  - …
  - Quantum gravity

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- *Two examples:*
  - **DM:** could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - *a vast array of expts* is needed, even though most of them will end up empty-handed…
  - **Neutrino masses:** could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, *a broad range of options* to explore, to find the right clues
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

But there is one central question to the progress of HEP, which can only be addressed by colliders



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don’t know, the SM doesn’t tell us …

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object

- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2 + g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking

- …

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

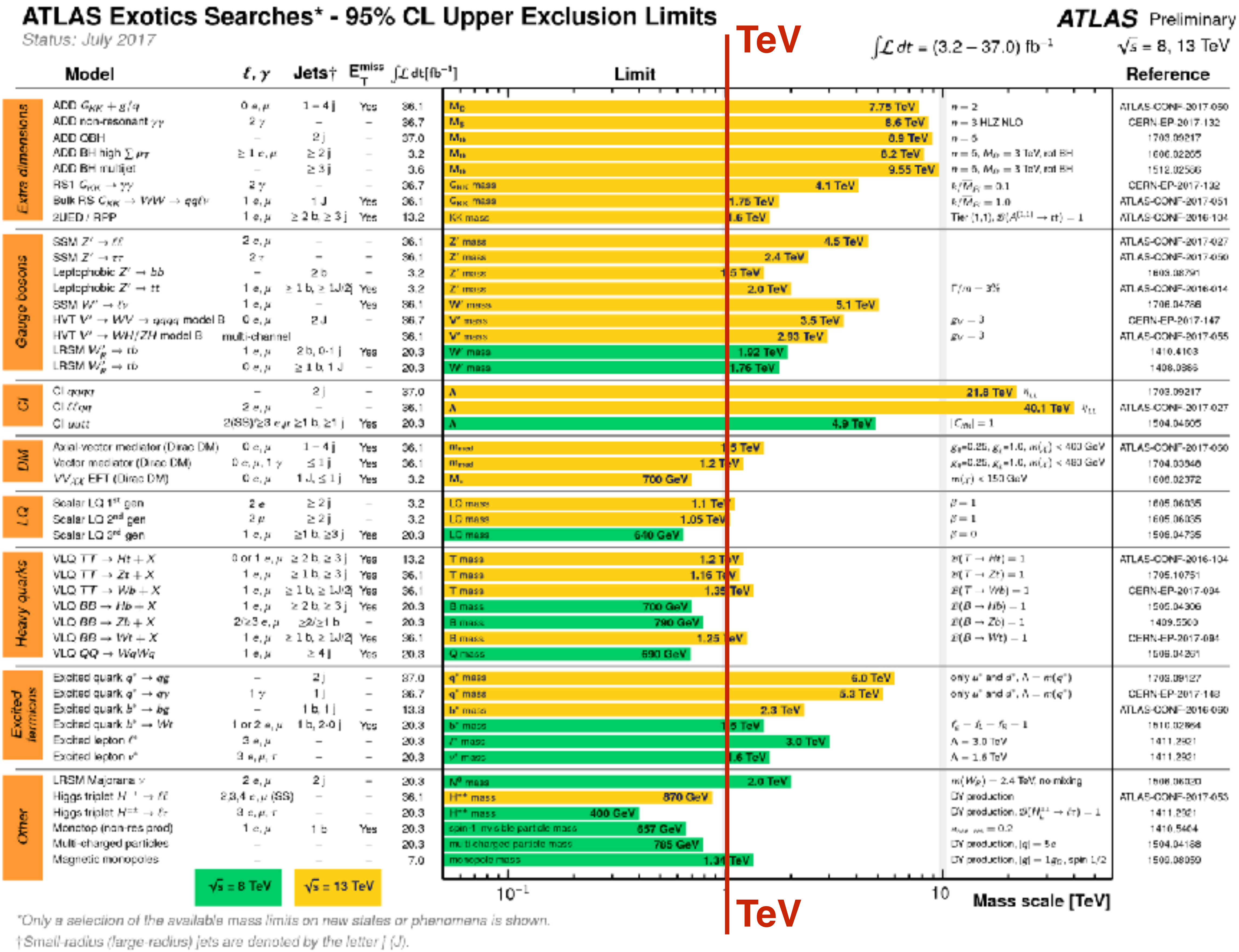
In search of the origin of known departures from the SM

- **Dark matter, long lived particles**
- **Neutrino masses**
- **Matter/antimatter asymmetry of the universe**

To explore alternative extensions of the SM

- **New gauge interactions (Z’, W’) or extra Higgs bosons**
- **Additional fermionic partners of quarks and leptons, leptoquarks, …**
- **Composite nature of quarks and leptons**
- **Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, …)**
- **Extra dimensions**
- **New flavour phenomena**
- **unanticipated surprises …**

So far, no *conclusive* signal of physics beyond the SM



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8,\ 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 − 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI qqqq	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV η_{LL}^-		ATLAS-CONF-2017-027
	CI uutt	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

➡ ***the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can only rely on a future generation of colliders***

The importance of the in-depth exploration of the Higgs properties was acknowledged by the 2020 update of the European Strategy for Particle Physics:

“An electron-positron Higgs factory is the highest-priority next collider”

Key question for the future developments of HEP: Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision ⇒ higher statistics, better detectors and experimental conditions*

- *sensitivity (to elusive signatures) ⇒ ditto*

- ***extended energy/mass reach ⇒ higher energy***

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

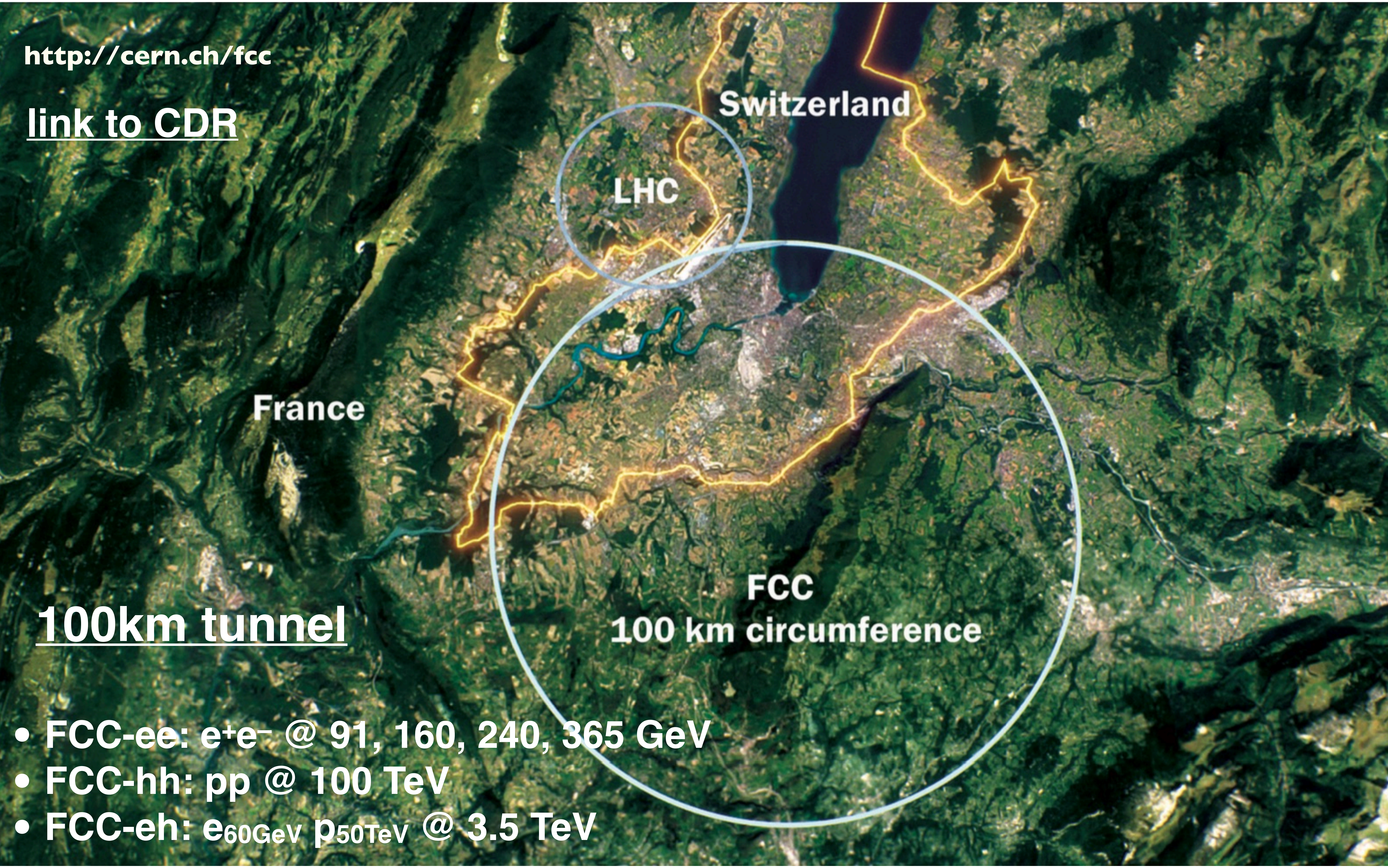
- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

Future Circular Collider



http://cern.ch/fcc

link to CDR

100km tunnel

- FCC-ee: e^+e^- @ 91, 160, 240, 365 GeV
- FCC-hh: pp @ 100 TeV
- FCC-eh: $e_{60\mathrm{GeV}}\ p_{50\mathrm{TeV}}$ @ 3.5 TeV

Event rates: examples

FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←Z)
	10^6	$5\ 10^{12}$	10^8	10^6	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

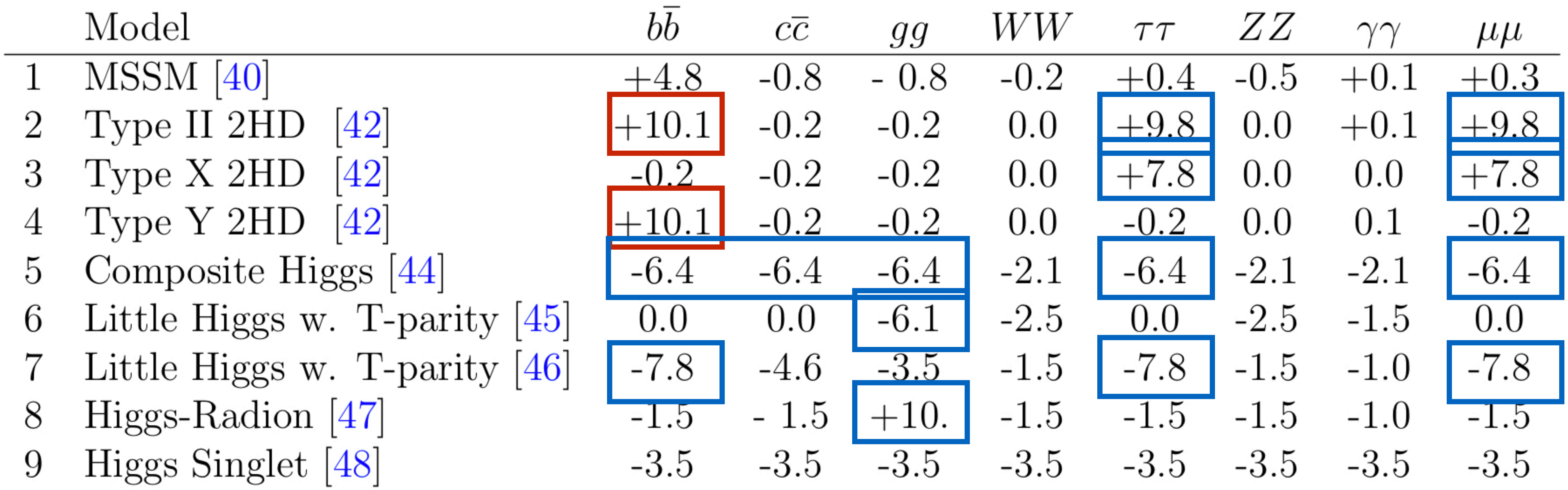
FCC-hh	H	b	t	W(←t)	τ(←W←t)
	$2.5\ 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5\ 10^6$	$2\ 10^7$

(1) guaranteed deliverables: Higgs properties

Coupling deviations for various BSM models, likely to remain unconstrained by direct searches at HL-LHC

https://arxiv.org/pdf/1708.08912.pdf



	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

🟦 5 – 10 %

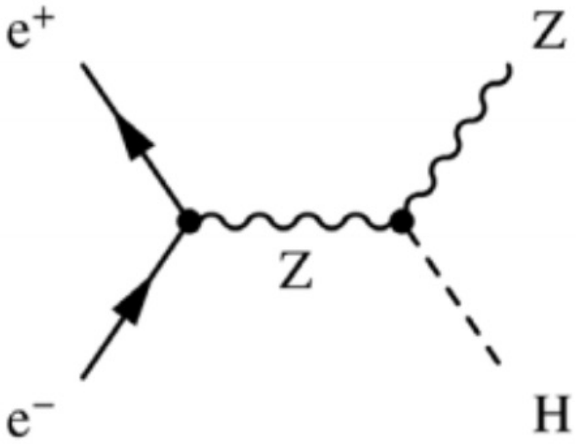
🟥 > 10%

NB: when the b coupling is modified, BR deviations are smaller than the square of the coupling deviation. Eg in model 5, the BR to b, c, tau, mu are practically SM-like

(sub)-% precision must be the goal to ensure 3-5σ evidence of deviations, and to cross-correlate coupling deviations across different channels

The absolutely unique power of $e^+e^- \rightarrow ZH$ (circular or linear):

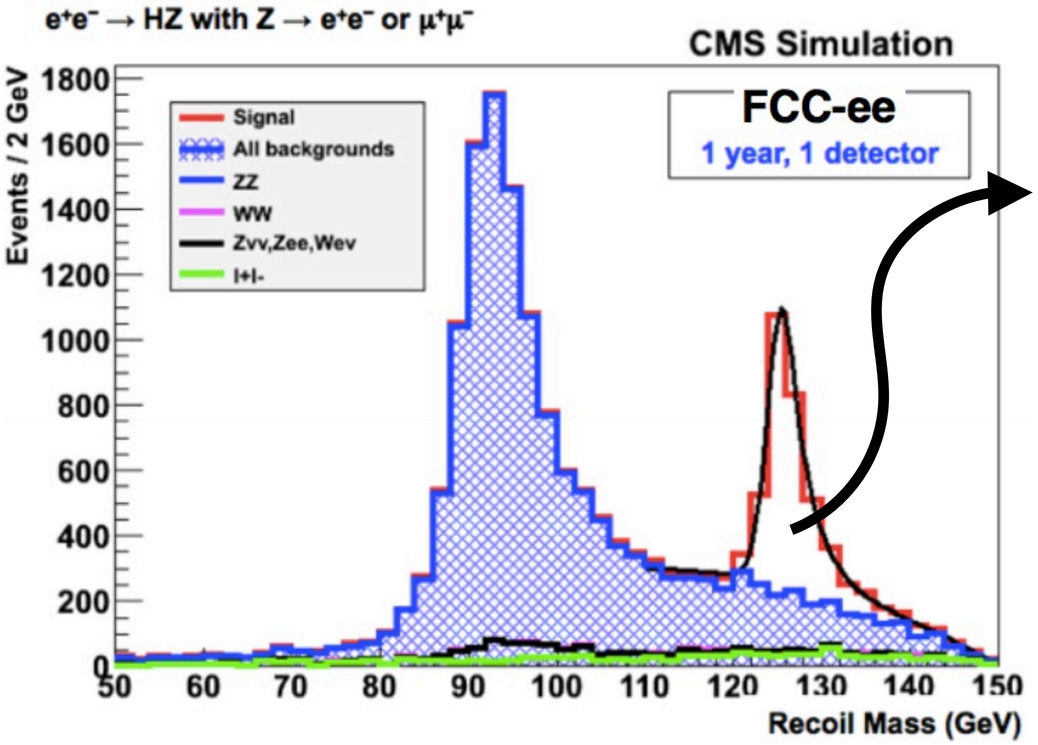
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\, p(e^-e^+) - p(Z)\,]^2$ **peaks at** $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!



$m_{recoil} = \sqrt{[\, p(e^-e^+) - p(Z)\,]^2}$

$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\rightarrow ZZ]) \propto$

$\sigma(ZH) \times BR(H \rightarrow ZZ) \propto$

$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

=> **absolute measurement of width and couplings**

Higgs couplings after FCC-ee

	HL-LHC	**FCC-ee**
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**

NB

BR(H→Zγ,γγ) ~O(10^{-3}) ⇒ **O(10^{7}) evts for Δ_{stat}~%**

BR(H→μμ) ~O(10^{-4}) ⇒ **O(10^{8}) evts for Δ_{stat}~%**

The absolutely unique power of pp → H+X:

- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling

- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	gg→H	**VBF**	**WH**	**ZH**	**ttH**	**HH**
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

BR(H→Zγ,γγ) $\sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for $\Delta_{stat}\sim\%$**

BR(H→μμ) $\sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for $\Delta_{stat}\sim\%$**

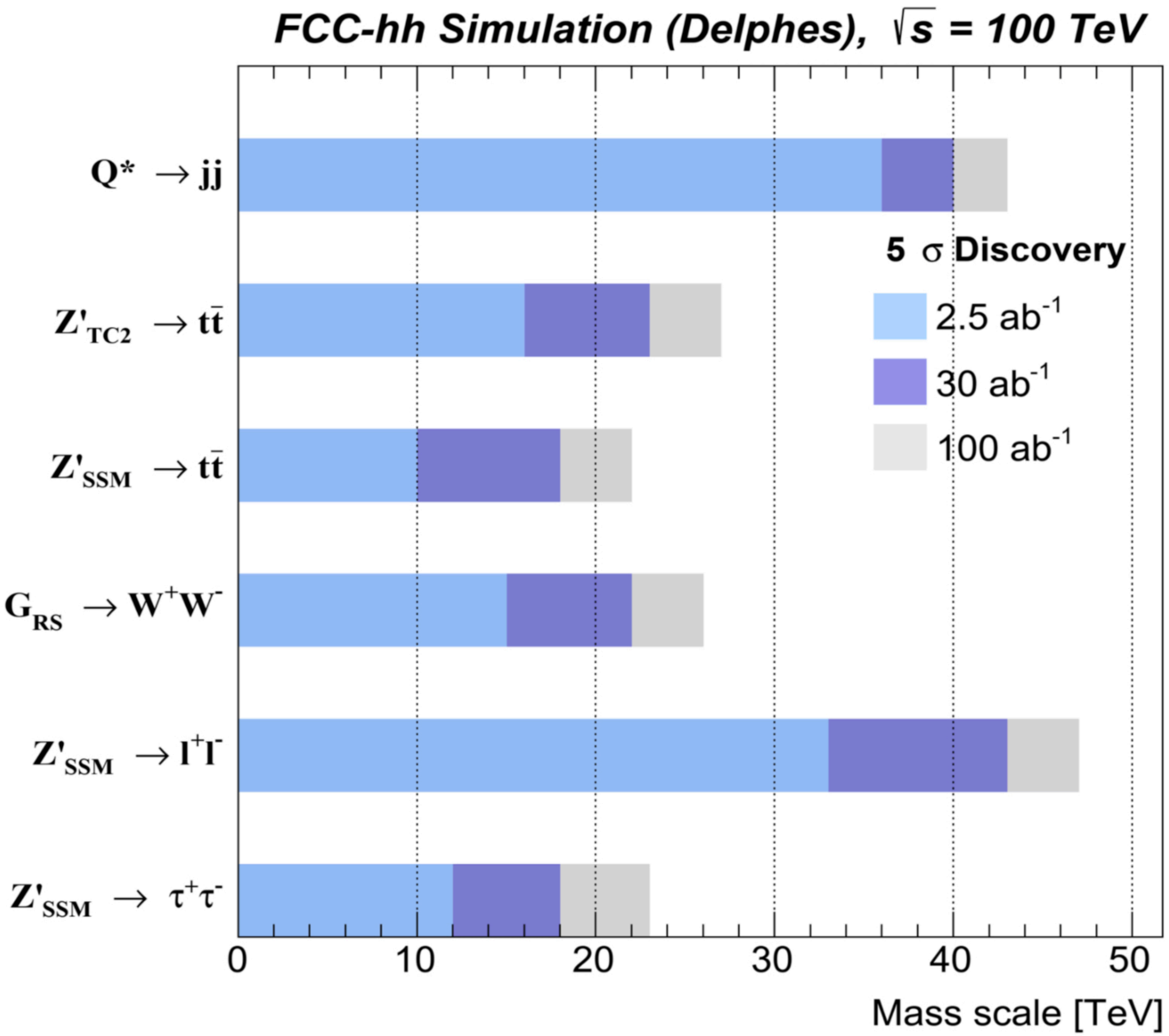
pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt B(H→ZZ*) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

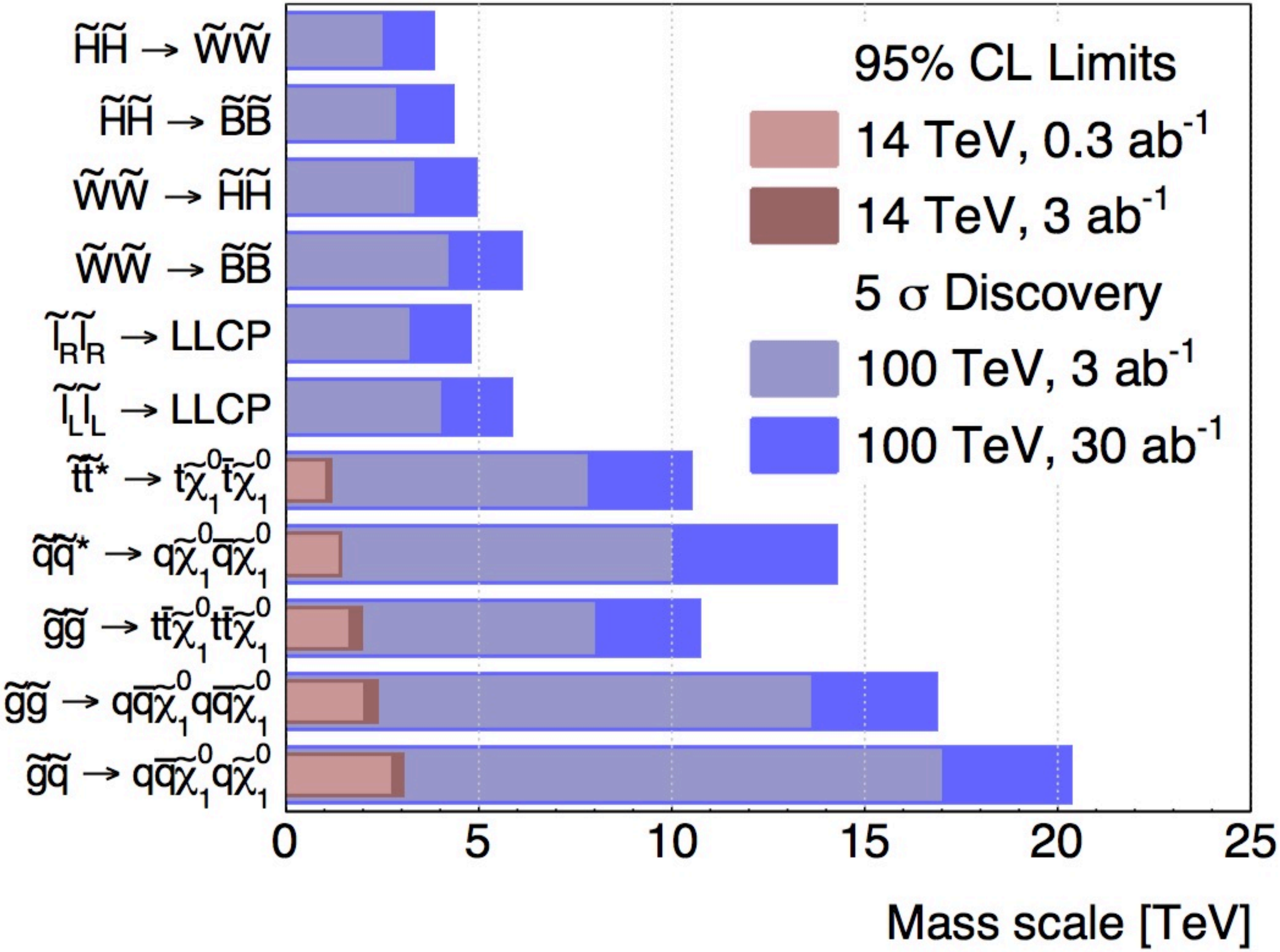
(2) Direct discovery reach at high mass: the power of 100 TeV

s-channel resonances



100 TeV allow to directly access the mass scales revealed indirectly by precision EW and H measurements at the future e+e– factory

SUSY reach at 100 TeV



15-20 TeV squarks/gluinos would require a lepton collider in the ECM range of 30-50 TeV

(3) The potential for yes/no answers to important questions

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\mathrm{DM}} h^2 \sim \frac{10^9 \mathrm{GeV}^{-1}}{M_{\mathrm{pl}}} \frac{1}{\langle \sigma v \rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

$$\langle \sigma v \rangle \sim g_{\mathrm{eff}}^4 / M_{\mathrm{DM}}^2$$

$$\Omega_{\mathrm{DM}} h^2 \sim 0.12 \times \left(\frac{M_{\mathrm{DM}}}{2\ \mathrm{TeV}} \right)^2 \left(\frac{0.3}{g_{\mathrm{eff}}} \right)^4$$

$$\Omega_{wimp}\, h^2 \lesssim 0.12$$

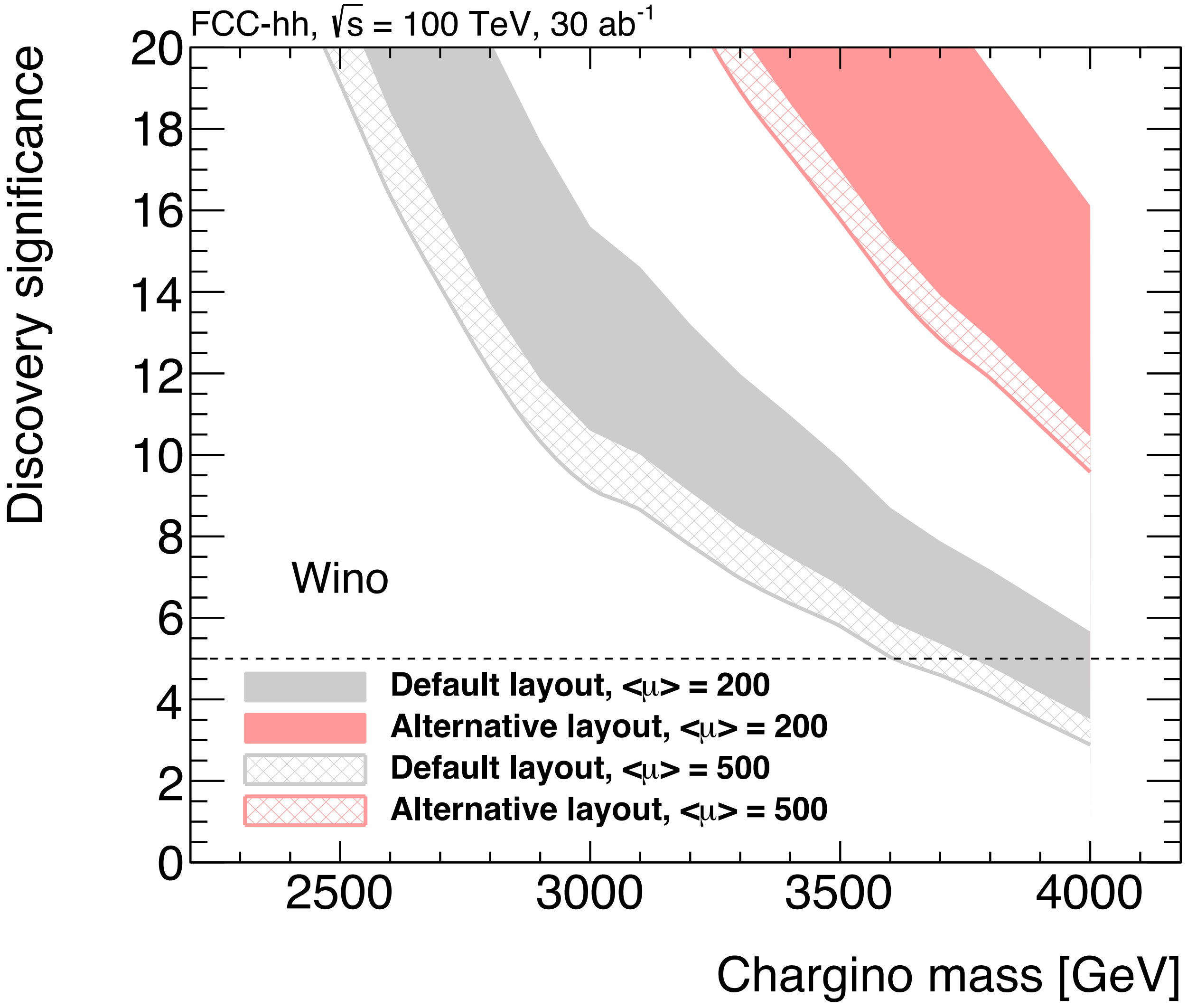
$$M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3} \right)^2$$

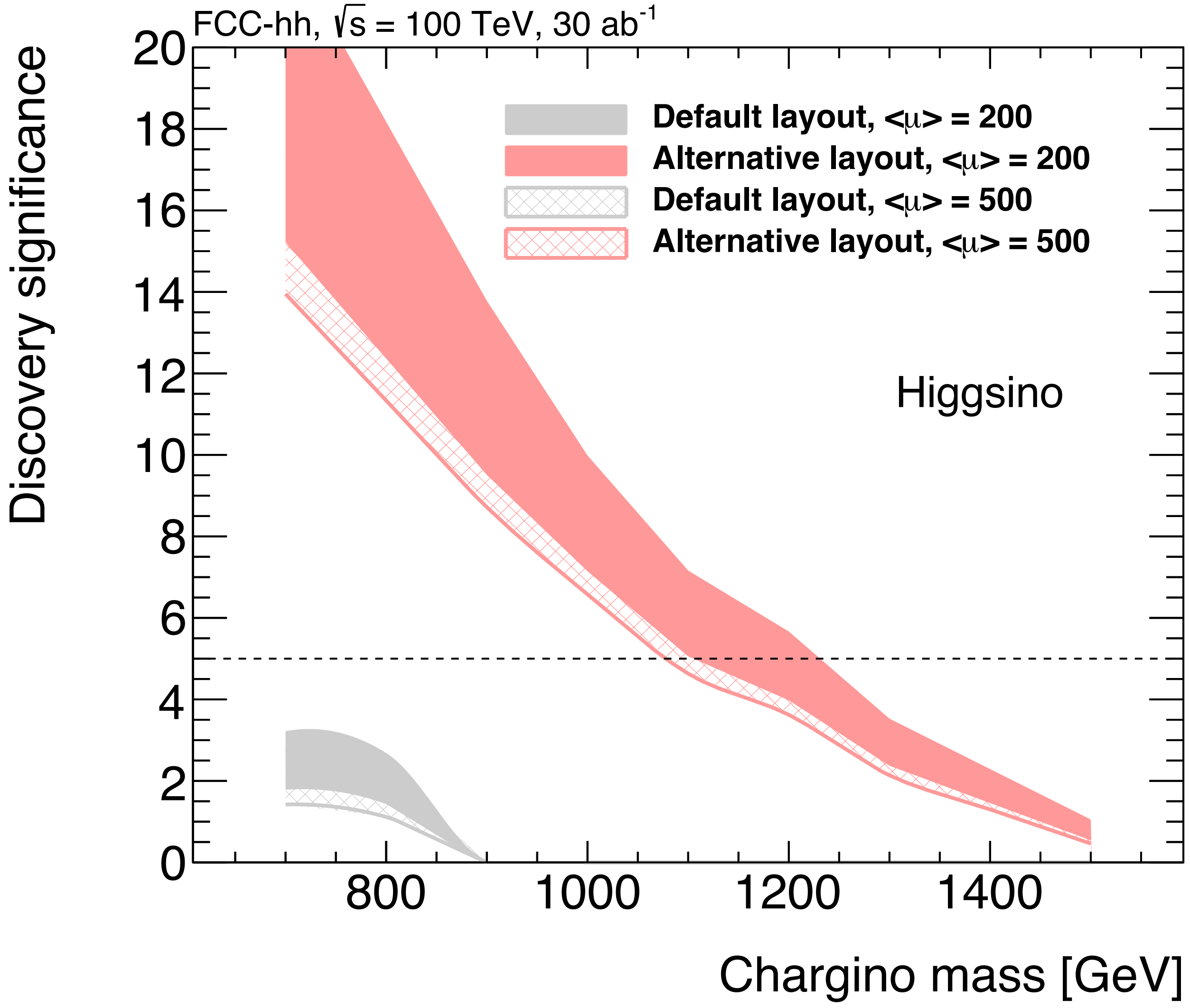
K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

(at ~full pileup)





=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3}\right)^2$$

Final remarks

- The LHC has proven the immense and unique versatility and precision of a high-energy pp collider. Its forthcoming upgrades in luminosity and detector performance open the way to possible discoveries, and more surprises
- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- The exptl program possible at a future collider facility, combining a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, offers unmatchable breadth and diversity: concrete, compelling and indispensable Higgs & SM measurements, a unique direct & indirect discovery potential, and continued exploration of dynamics in the most diverse contexts, with impact on a broad range of fields beyond colliders
- The technological, financial and sociological challenges are immense, and will test our community ability to build and improve on the experience of similar challenges in the past.
- The next 5-6 years, before the next review of the European Strategy for Particle Physics, will be critical to reach the scientific consensus and political support required to move forward