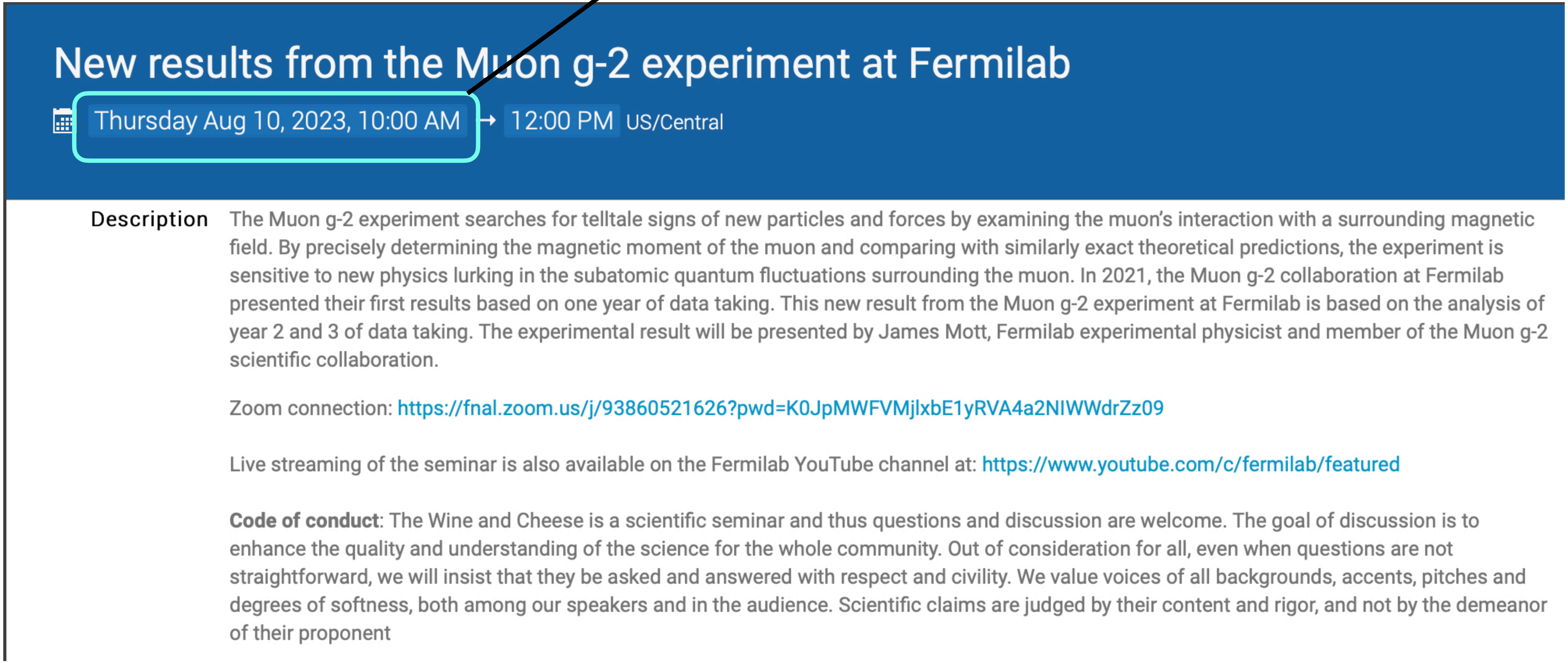
AMPLITUDES 2023

CERN, 7 - 11 AUGUST 2023

The LHC and beyond: where and what is new physics?

Michelangelo L. Mangano CERN TH

chicago time → that is now !!



New results from the Muon g-2 experiment at Fermilab

Thursday Aug 10, 2023, 10:00 AM → 12:00 PM US/Central

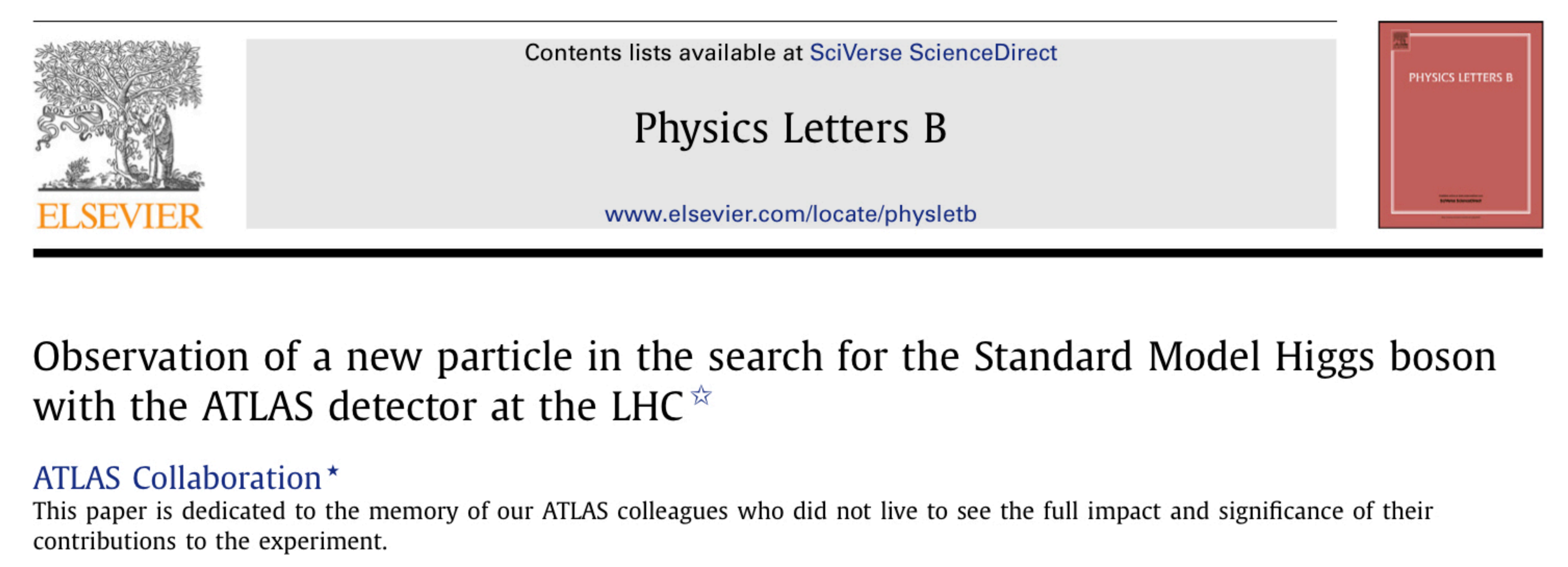
Description The Muon g-2 experiment searches for telltale signs of new particles and forces by examining the muon’s interaction with a surrounding magnetic field. By precisely determining the magnetic moment of the muon and comparing with similarly exact theoretical predictions, the experiment is sensitive to new physics lurking in the subatomic quantum fluctuations surrounding the muon. In 2021, the Muon g-2 collaboration at Fermilab presented their first results based on one year of data taking. This new result from the Muon g-2 experiment at Fermilab is based on the analysis of year 2 and 3 of data taking. The experimental result will be presented by James Mott, Fermilab experimental physicist and member of the Muon g-2 scientific collaboration.

Zoom connection: https://fnal.zoom.us/j/93860521626?pwd=K0JpMWFVMjlxbE1yRVA4a2NIWWdrZz09

Live streaming of the seminar is also available on the Fermilab YouTube channel at: https://www.youtube.com/c/fermilab/featured

Code of conduct: The Wine and Cheese is a scientific seminar and thus questions and discussion are welcome. The goal of discussion is to enhance the quality and understanding of the science for the whole community. Out of consideration for all, even when questions are not straightforward, we will insist that they be asked and answered with respect and civility. We value voices of all backgrounds, accents, pitches and degrees of softness, both among our speakers and in the audience. Scientific claims are judged by their content and rigor, and not by the demeanor of their proponent

2012


Contents lists available at SciVerse ScienceDirect

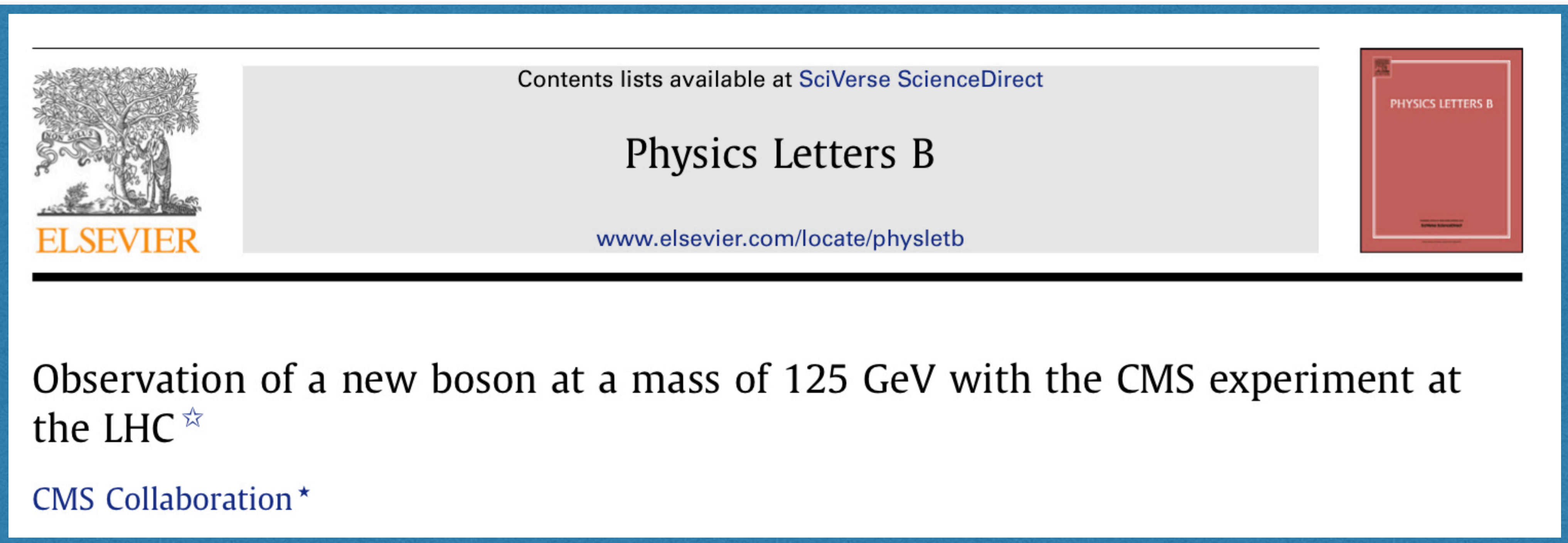
Physics Letters B

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.


Contents lists available at SciVerse ScienceDirect

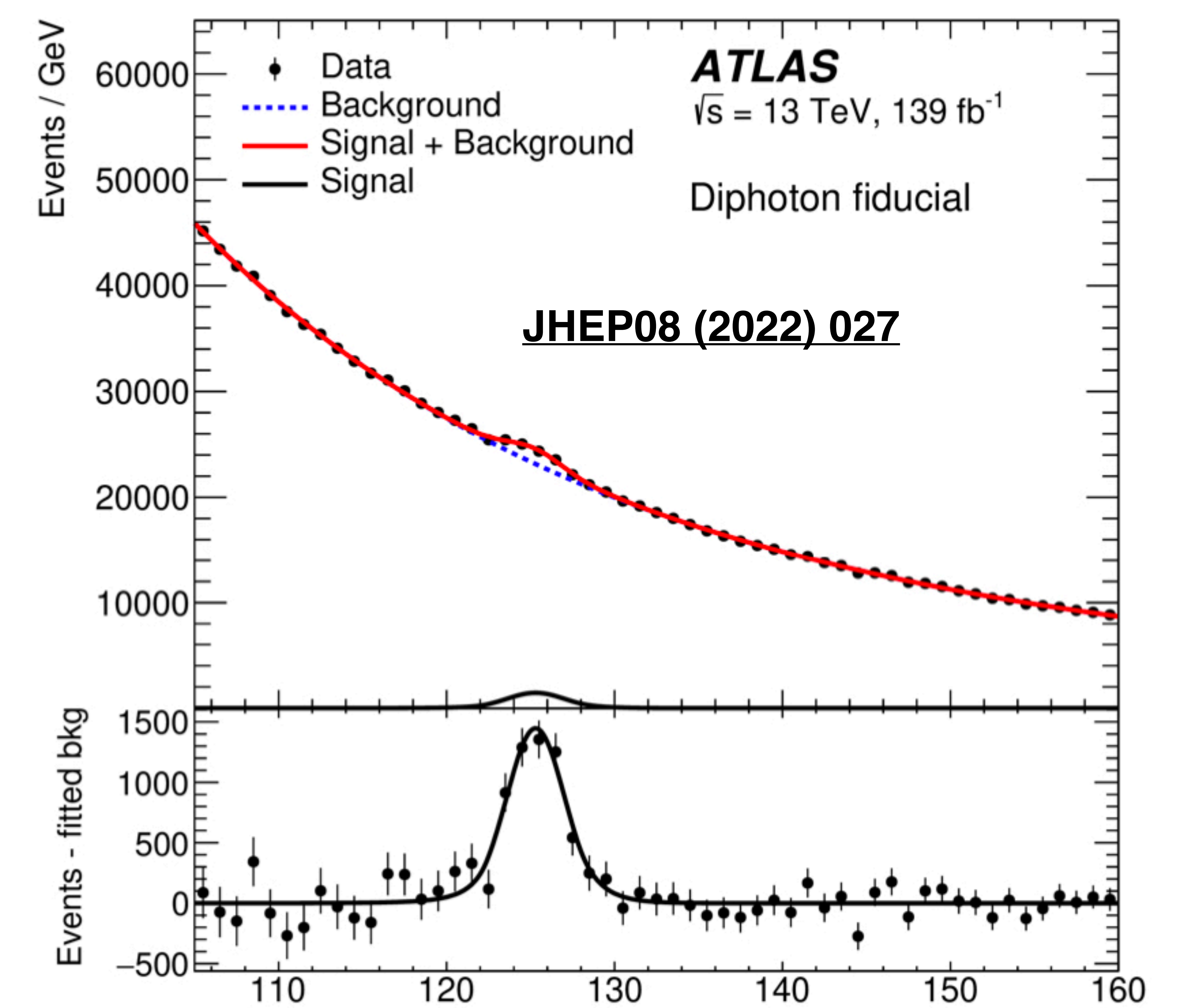
Physics Letters B

www.elsevier.com/locate/physletb

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

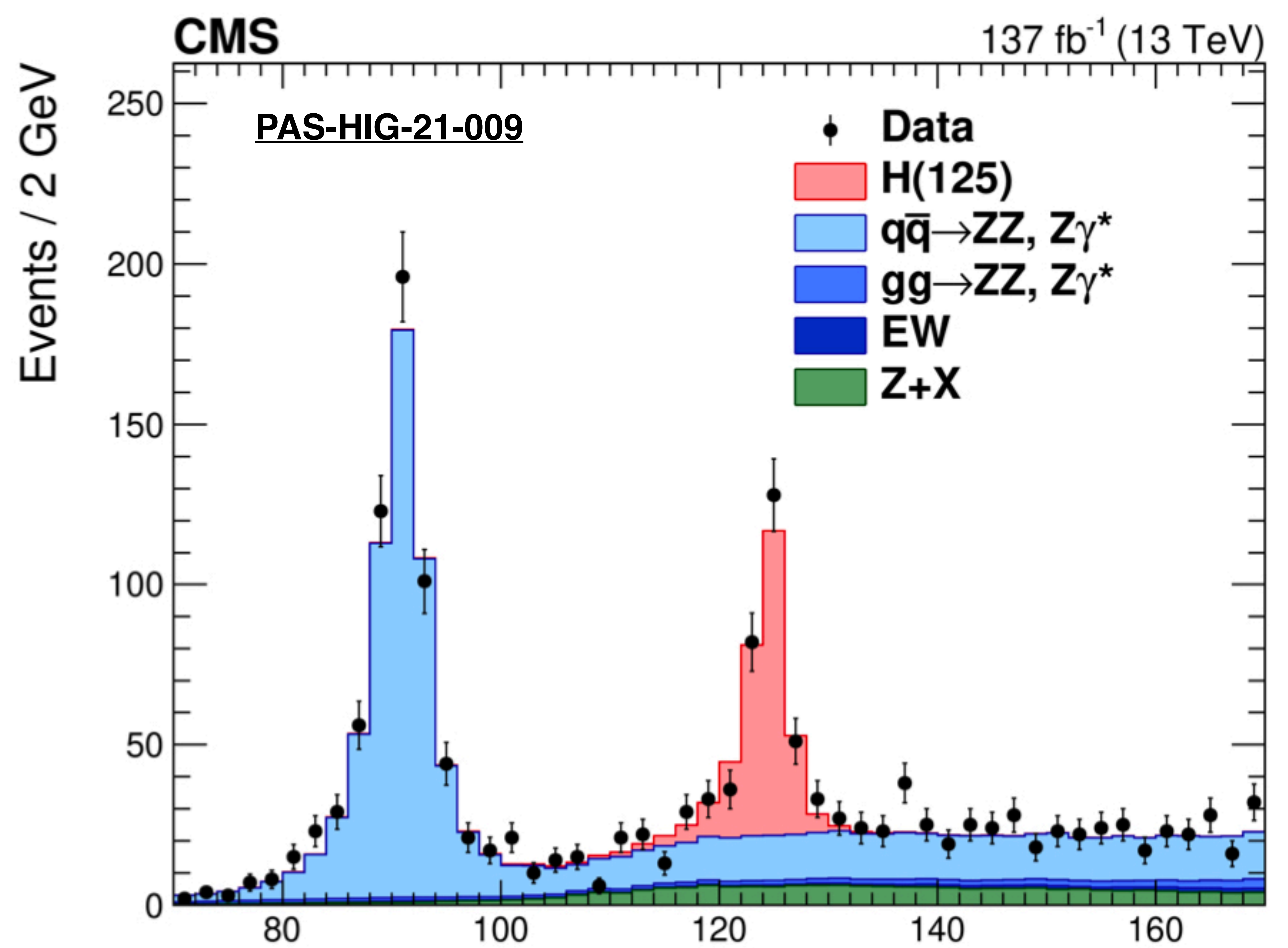
CMS Collaboration *

2023



JHEP08 (2022) 027

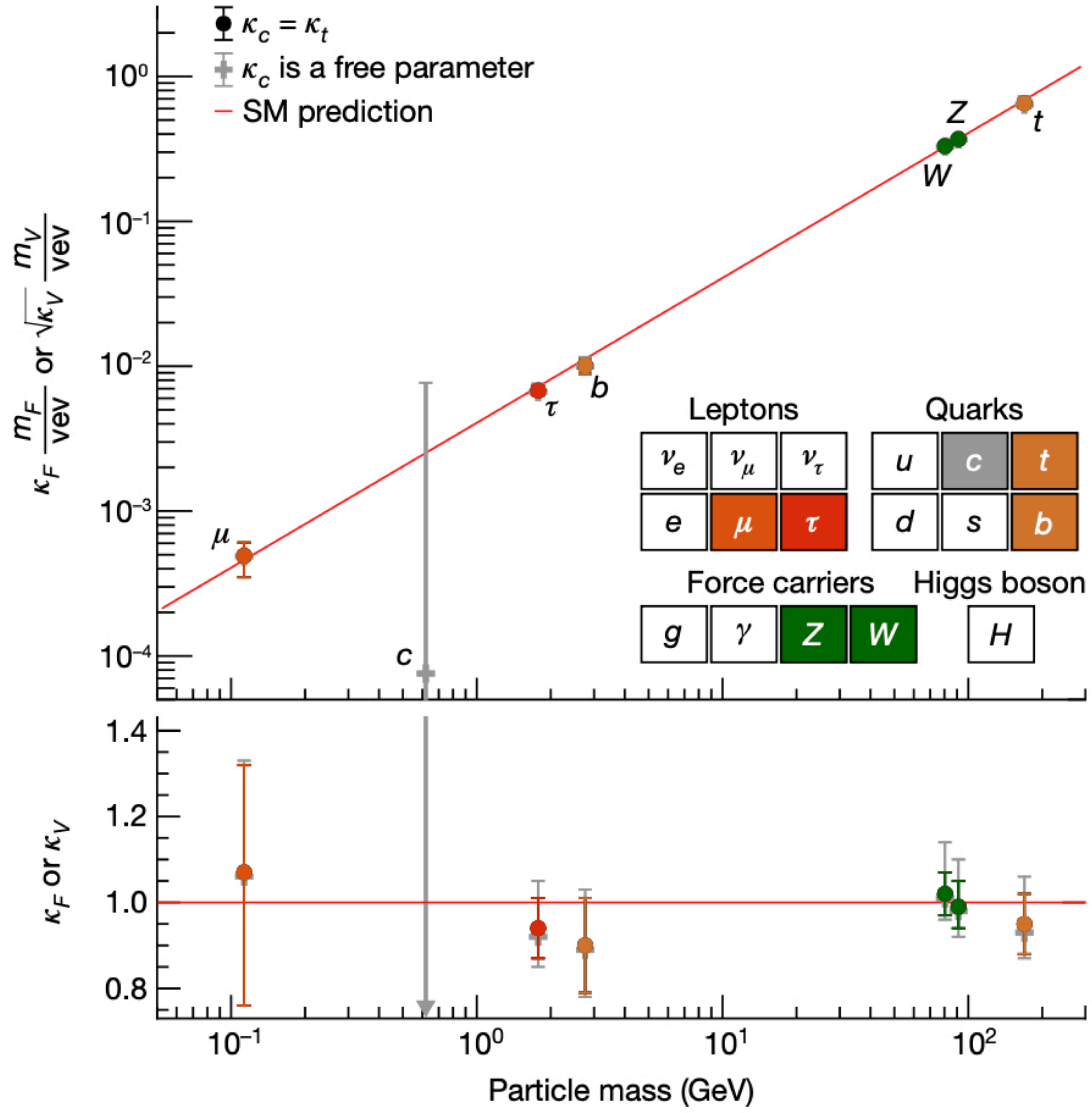
$H \rightarrow \gamma\gamma$

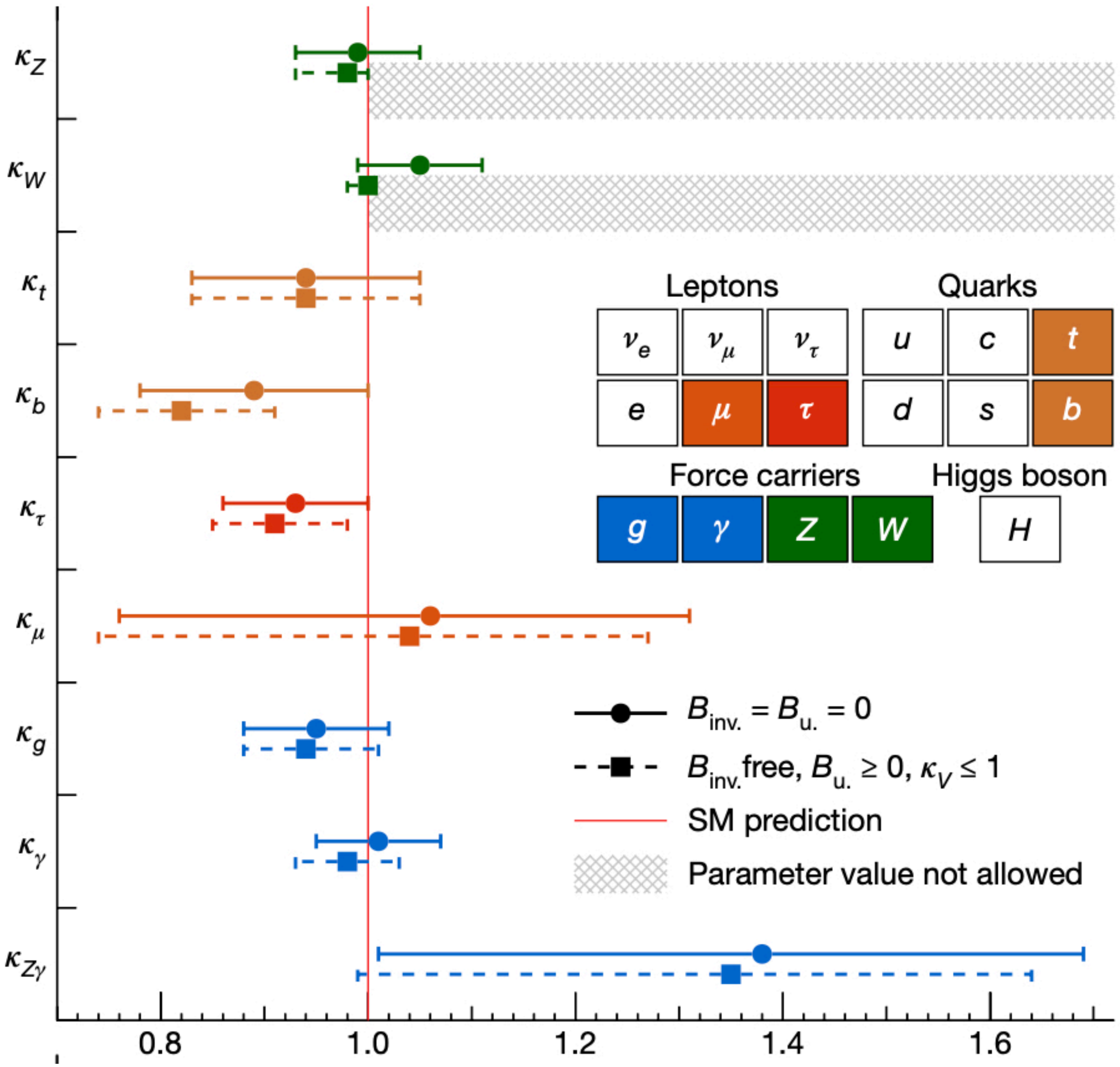


PAS-HIG-21-009

$H \rightarrow$ 4 leptons

General properties and couplings: OK



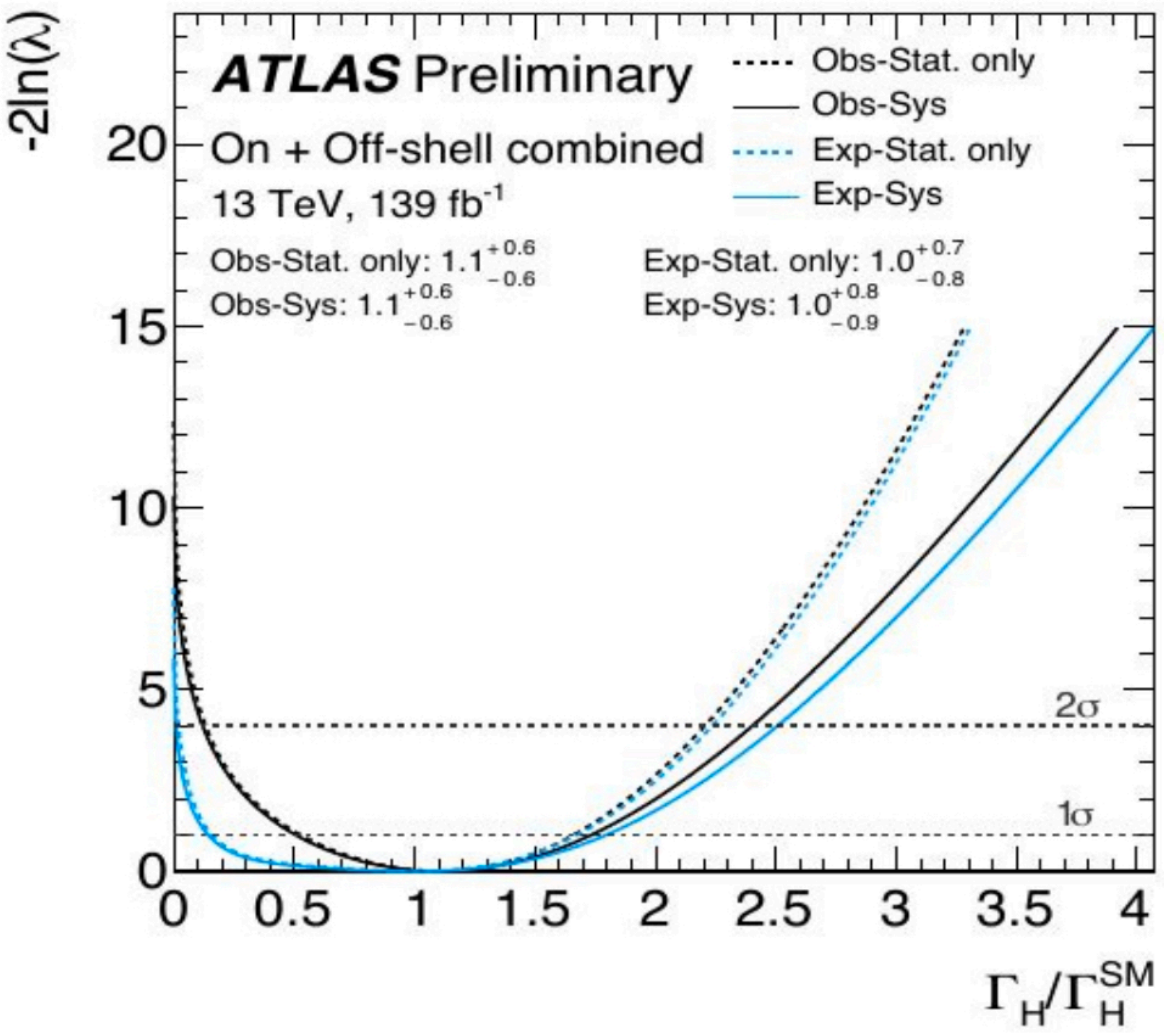


The ATLAS Collaboration Nature, 607, 52–59 (2022) , The CMS Collaboration Nature, 607, 60–68 (2022)

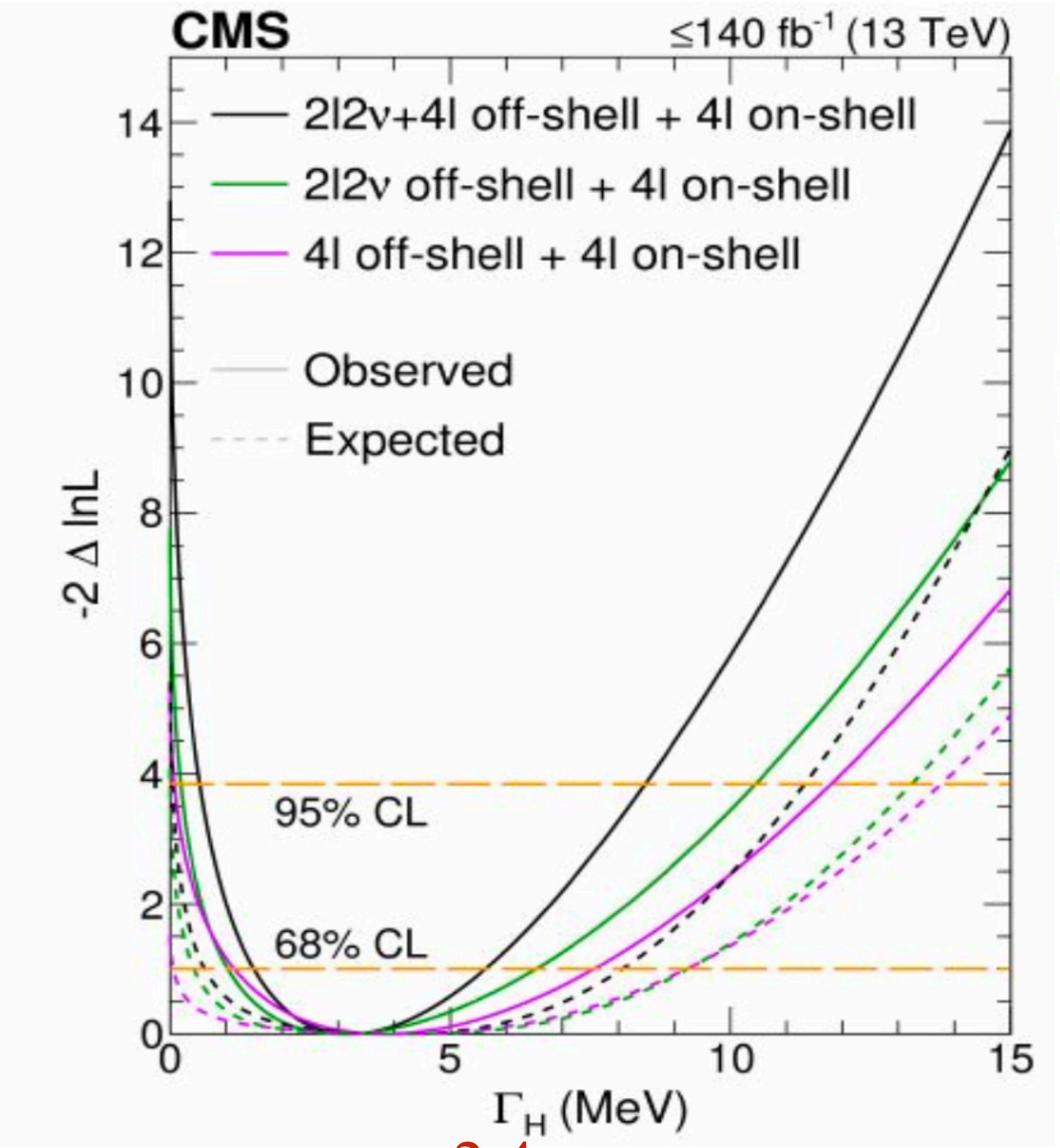
The Higgs width (SM: 4.1 MeV) : OK

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

ATLAS-CONF-2022-068



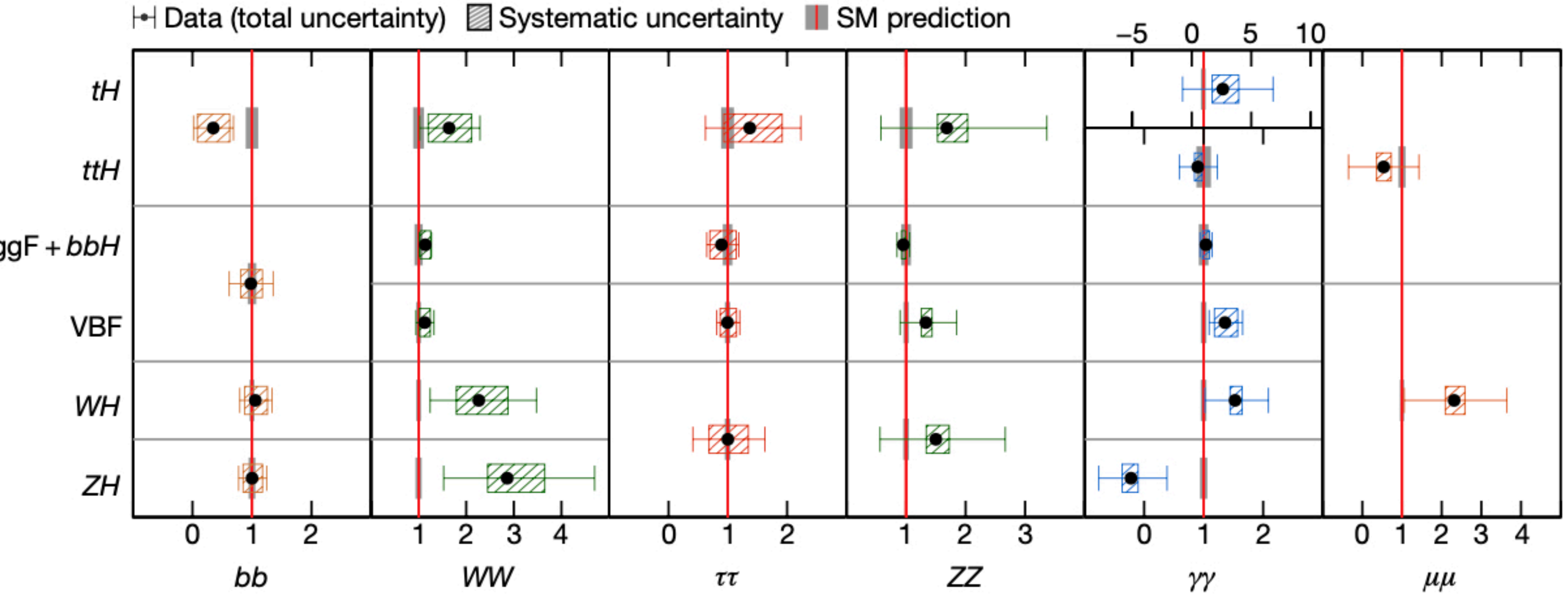
$$\Gamma_H = 4.6^{+2.6}_{-2.5}\ \text{MeV at } 68\,\%\, CL$$

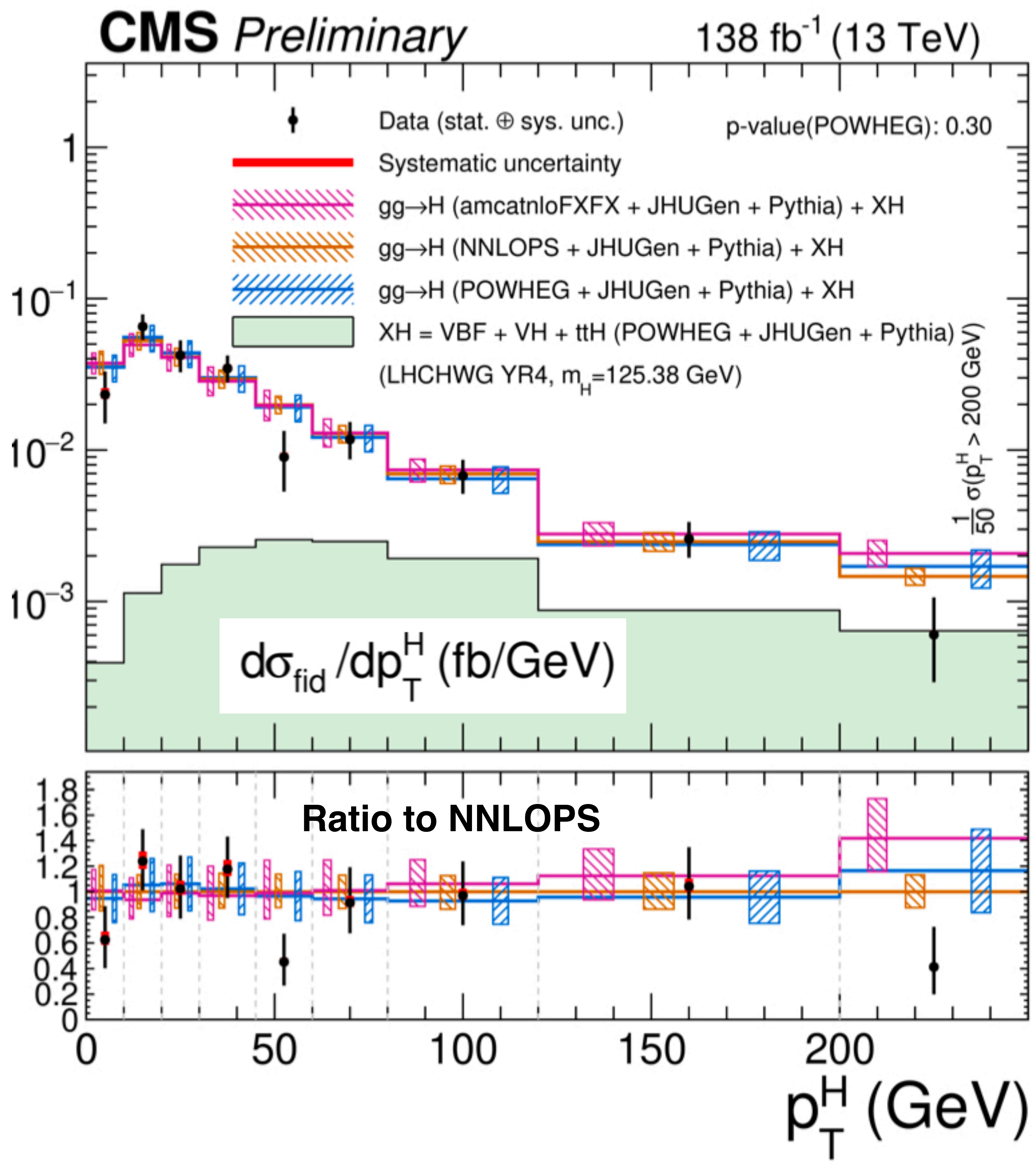


Nat. Phys. 18 (2022) 1329

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV at } 68\,\%\, CL$$

Production properties: OK





Is the Standard Model a model, a theory, or what ?

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Eg, from the Britannica Dictionary

Theory

1. an idea or set of ideas that is ***intended to explain*** facts or events
2. an idea that is suggested or presented as ***possibly true but that is not known or proven to be true***

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a set of ideas and numbers that ***describe*** the past, present, or future state of something

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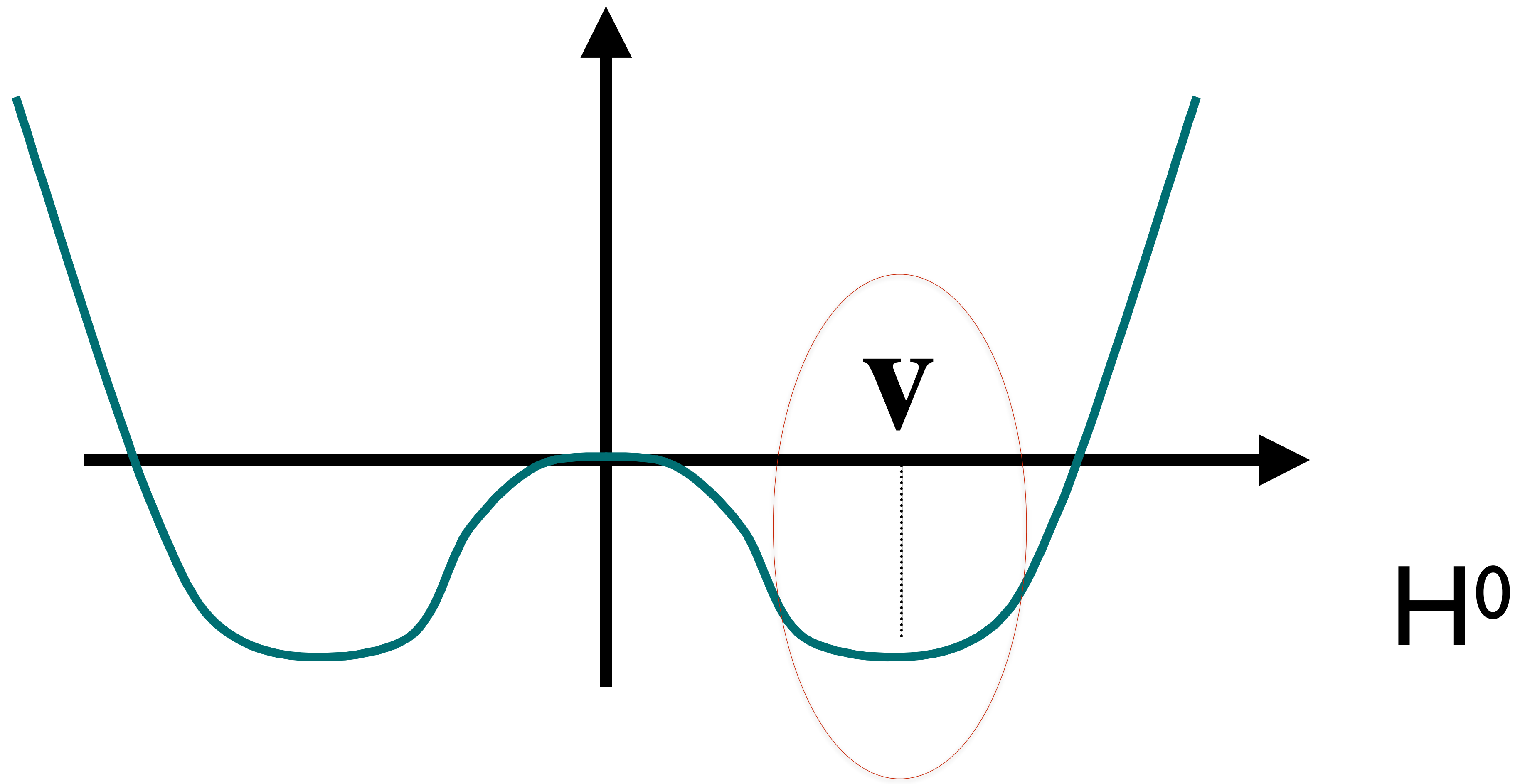
So, I’d rather stick to **Model….**

But there is a deeper reason why I believe the SM **still is** a model.

More precisely, I would actually define the SM as **the theory of** weak interactions, but just **a model for** electroweak symmetry breaking



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

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.

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How do we calculate m_H?

a historical example: superconductivity

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- 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.

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- 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

- …

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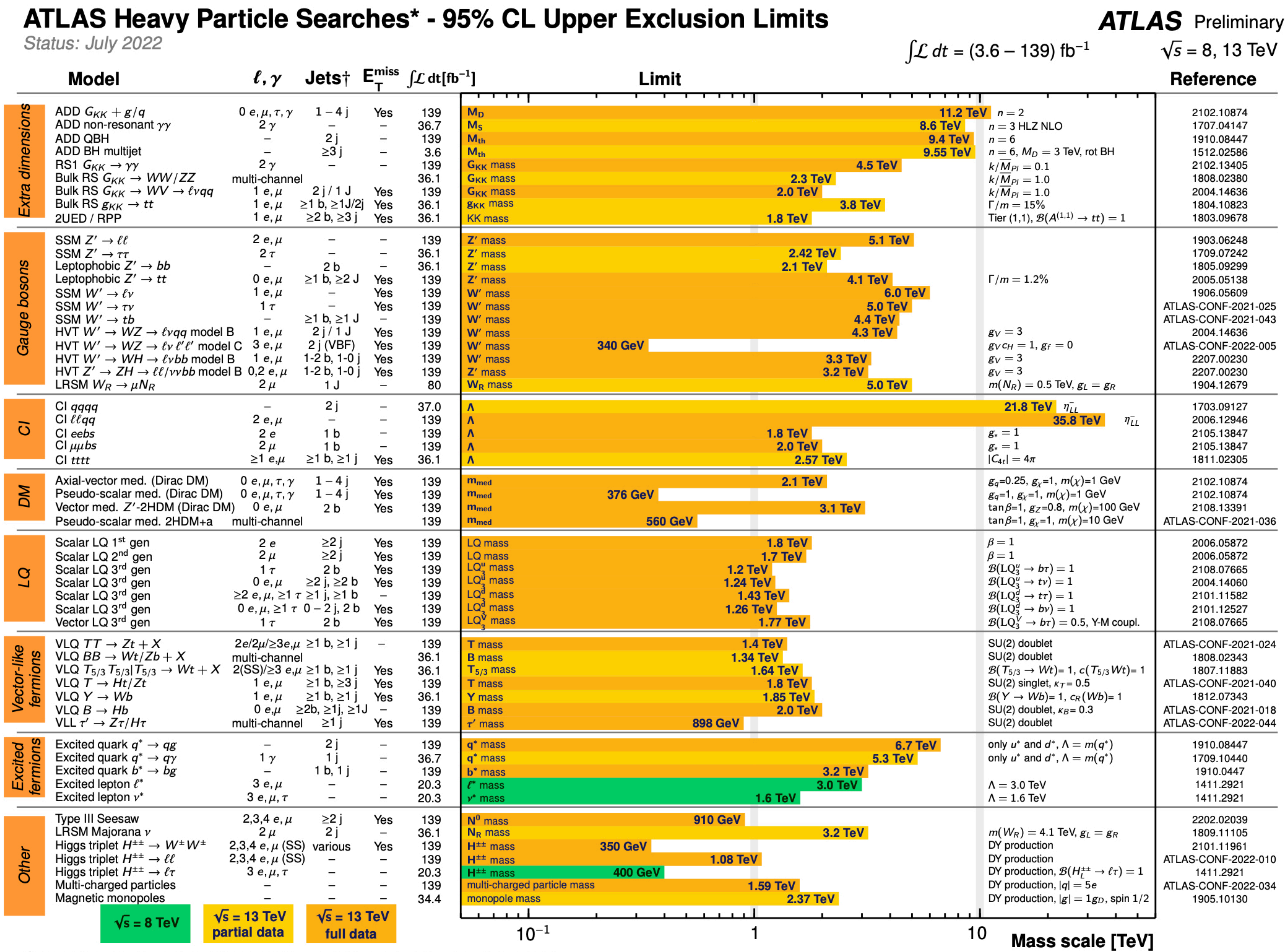
➡ the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties,
which can only rely on the LHC and on a future generation of colliders

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



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ 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, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n = 6$	1910.08447
	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	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	139	W' mass 3.3 TeV	$g_V = 3$	2207.00230
	HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B	0,2 e, μ	1-2 b, 1-0 j	Yes	139	Z' mass 3.2 TeV	$g_V = 3$	2207.00230
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	m_{med} 3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med} 560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.2 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^V mass 1.77 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb) = 1$, $c_R(Wb) = 1$	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.0447
	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	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	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
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV partial data 🟧 $\sqrt{s}$ = 13 TeV full data

*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).

Given no clear sign of BSM is there,
is there anything else interesting?

The serendipitous value of data: a few history lessons

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- Newton's law became the new Standard Model for planetary motions. Precision measurements of the Uranus orbit, in the first half of the XIX century, showed deviations from this "SM": was it a break-down of the SM, or the signal of a new ~~particle~~ planet?

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- Newton’s law became the new Standard Model for planetary motions. Precision measurements of the Uranus orbit, in the first half of the XIX century, showed deviations from this “SM”: was it a break-down of the SM, or the signal of a new ~~particle~~ planet?
    - assuming the validity of the SM, interpreting the deviations as due to perturbations by a yet unknown planet, Neptun was discovered (1846), implicitly giving stronger support to Newton’s SM

The serendipitous value of data: a few history lessons

- Tycho Brahe (1546-1601) spent his life measuring planets' positions more and more precisely
    - Johannes Kepler (1571-1630) used those data to extract a "phenomenological" interpretation, based on his 3 laws
    - Isaac Newton (1643-1727) discovered the underlying "theoretical" foundation of Kepler's laws … but it all started from Brahe's precision data!
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    - assuming the validity of the SM, interpreting the deviations as due to perturbations by a yet unknown planet, Neptun was discovered (1846), implicitly giving stronger support to Newton's SM
- Precision planetary measurements continued throughout the XIX century, revealing yet another SM deviation, in Mercury's motion. This time, it was indeed a beyond SM (BSM) signal: Einstein's theory of General Relativity!! Mercury's data did not motivate Einstein to formulate it, but once he had the equations, he used those precise data to confirm its validity!

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- We do not measure Higgs couplings precisely with the **goal to find** deviations from the SM. We measure them to **know** them, while being ready to detect deviations, if any…

- LEP’s success was establishing SM’s amazing power, by fully confirming its predictions!

- … and who knows how important a given measurement can become, to assess the validity of a future theory?
    - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

BOTTOM LINE:

- **you never know what data will lead to!**
- **there are no useless data, there is only <u>correct</u> data or <u>wrong</u> data**
- **physics progress builds on good data and powerful tools to interpret them (⇒ eg amplitudes!)**

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)… and the first papers are appearing by the new experiments started in Run 3 (FASER, SND@LHC)

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) →μμ
- 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 ?

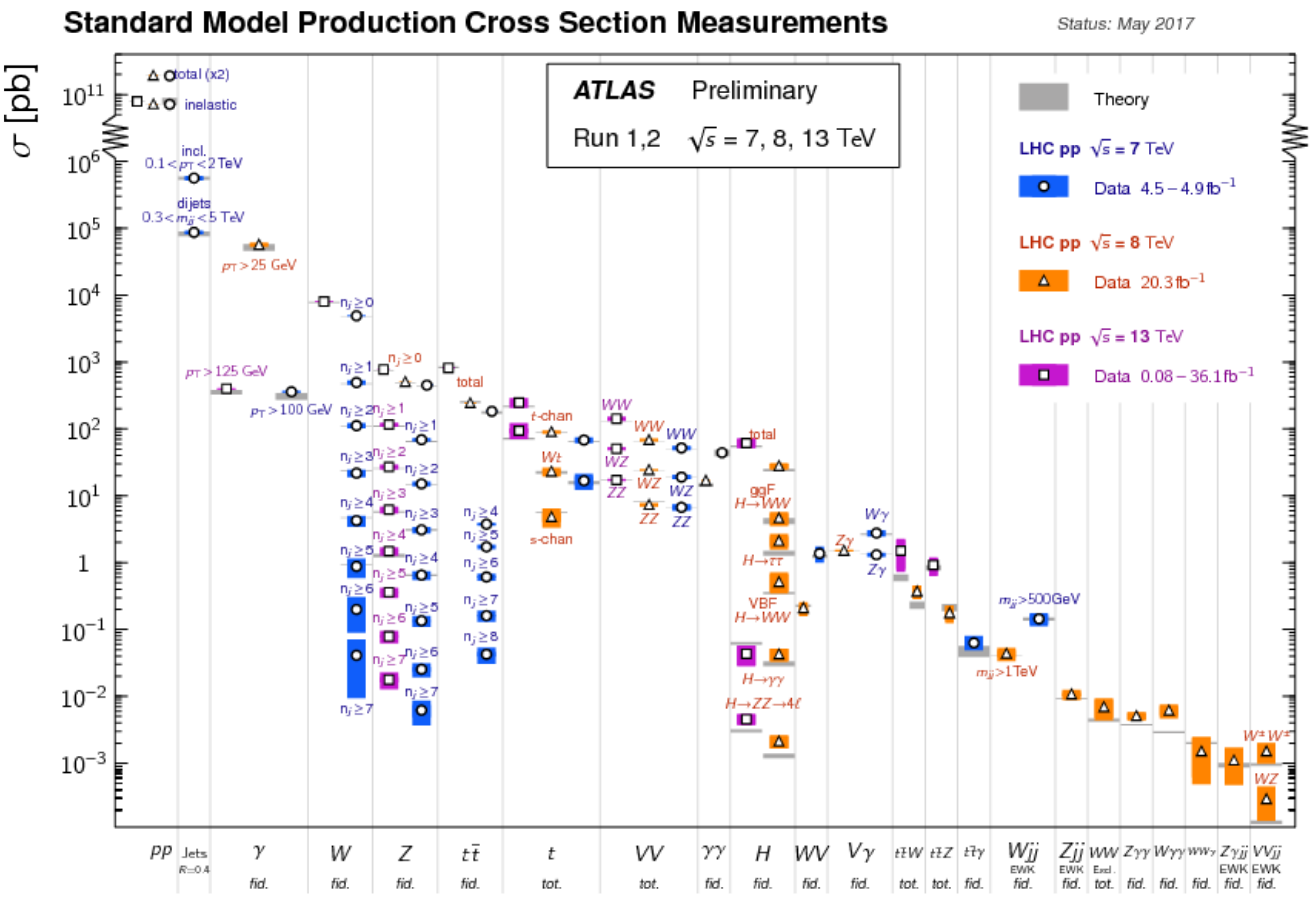
QCD dynamics

- 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, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

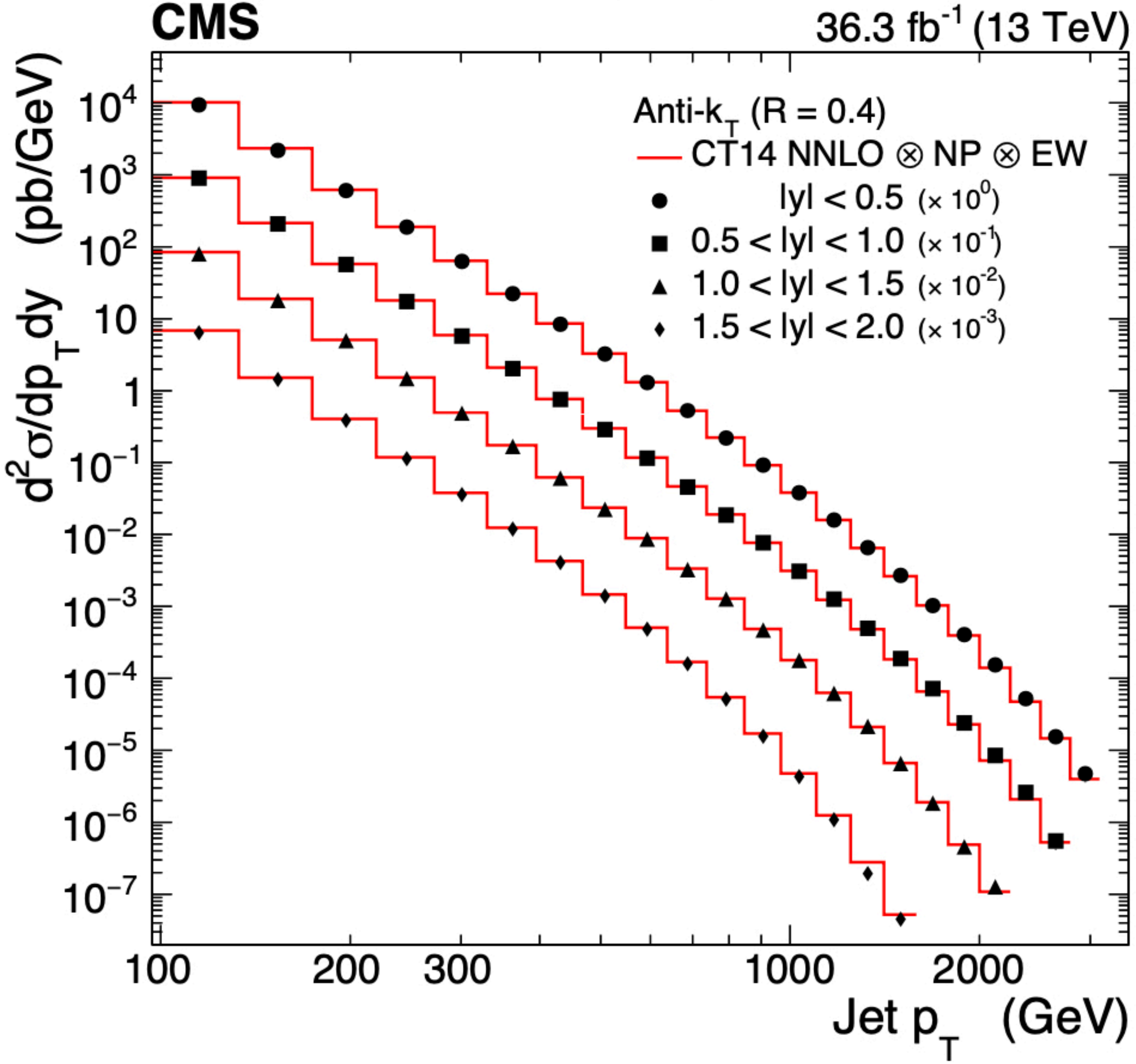
QCD production dynamics



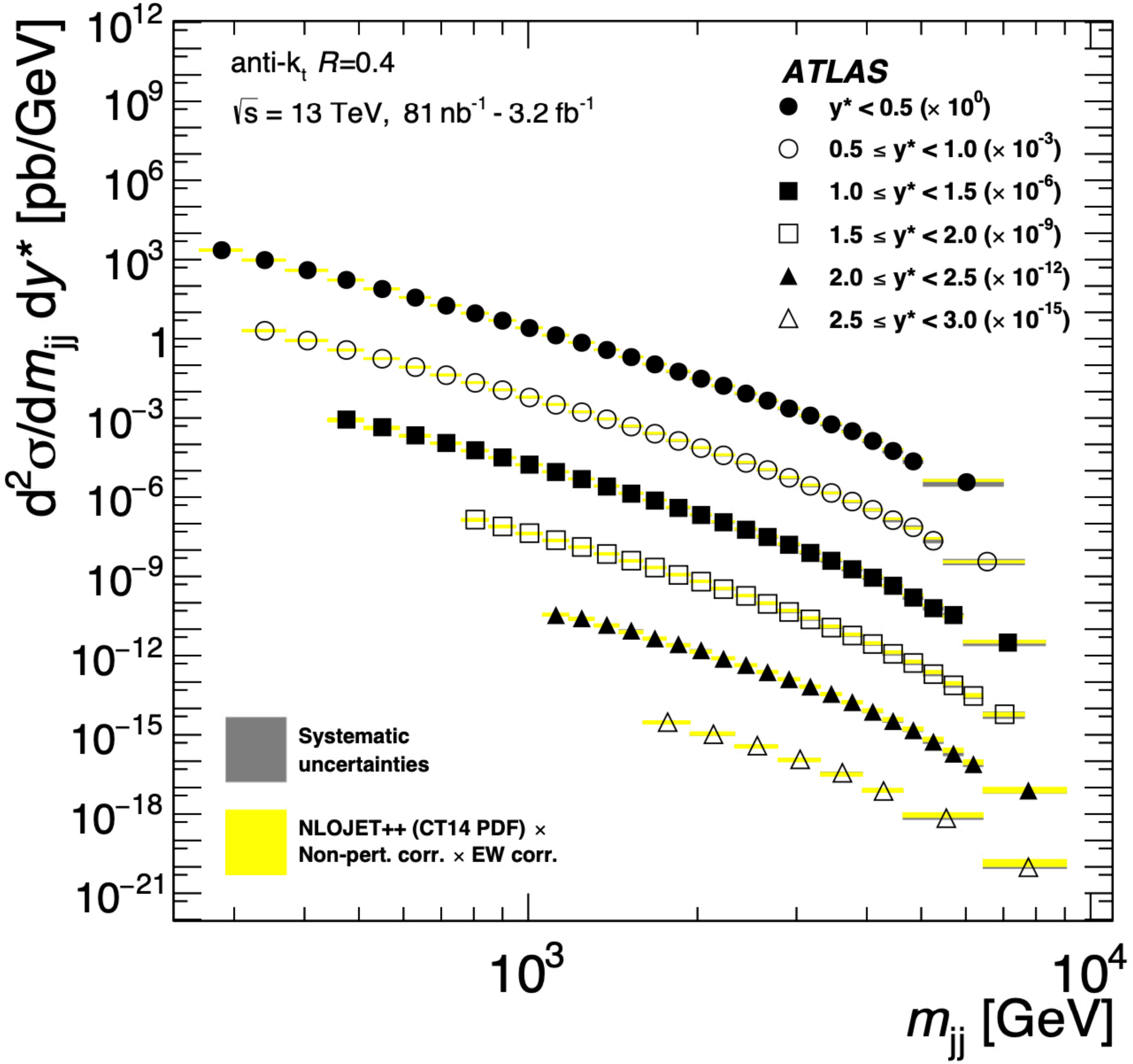
Excellent agreement between data and theoretical predictions, over 10 orders of magnitude, culminating 30 years of progress in higher-order perturbative calculations, which have now reached next-to-leading order as routine, NNLO as benchmark for most processes, and NNNLO available for only some (very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

Inclusive jet p_T and dijet mass distributions

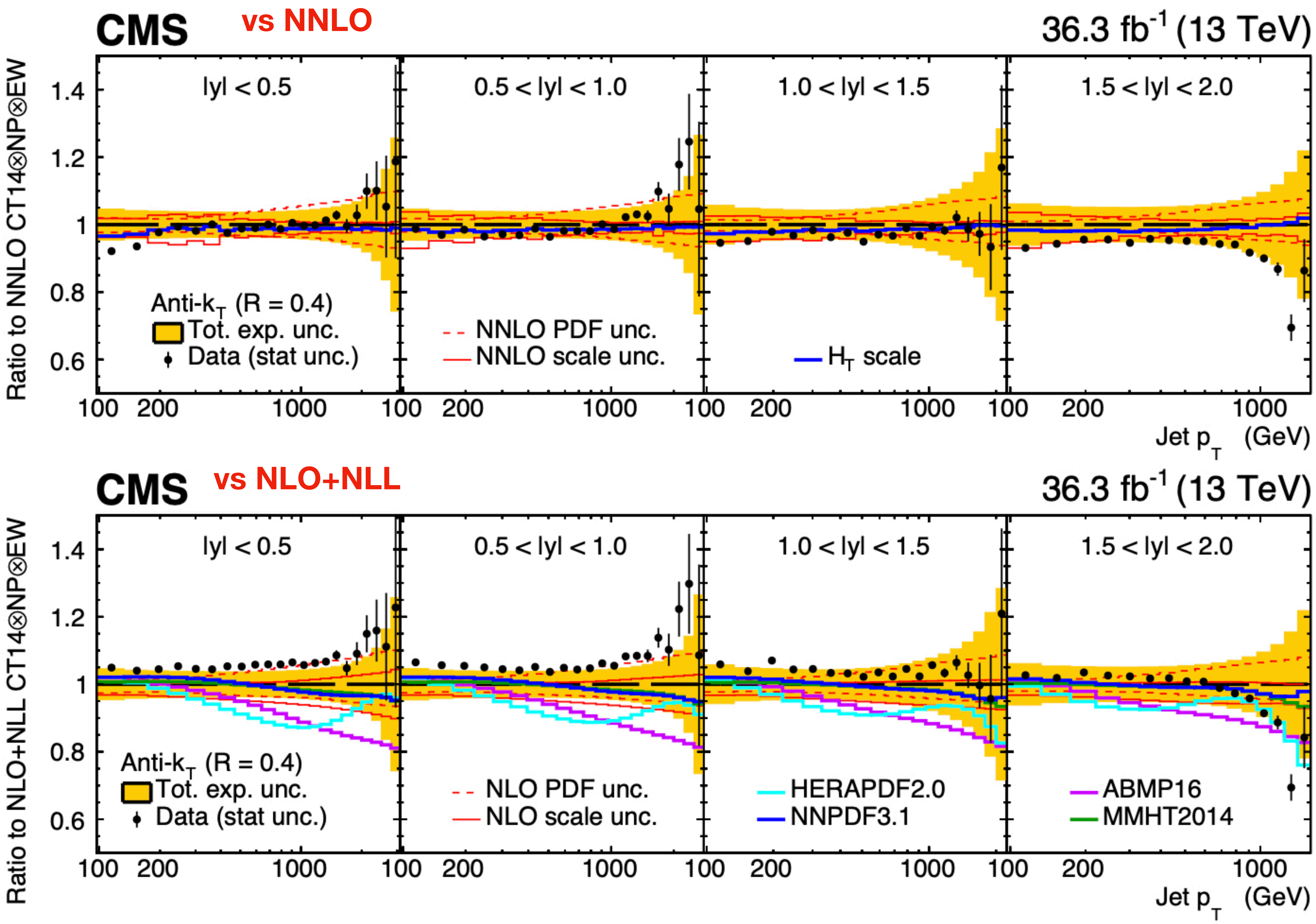
CMS, JHEP 02 (2022) 142



ATLAS, JHEP 05 (2018) 195



Comparison with QCD

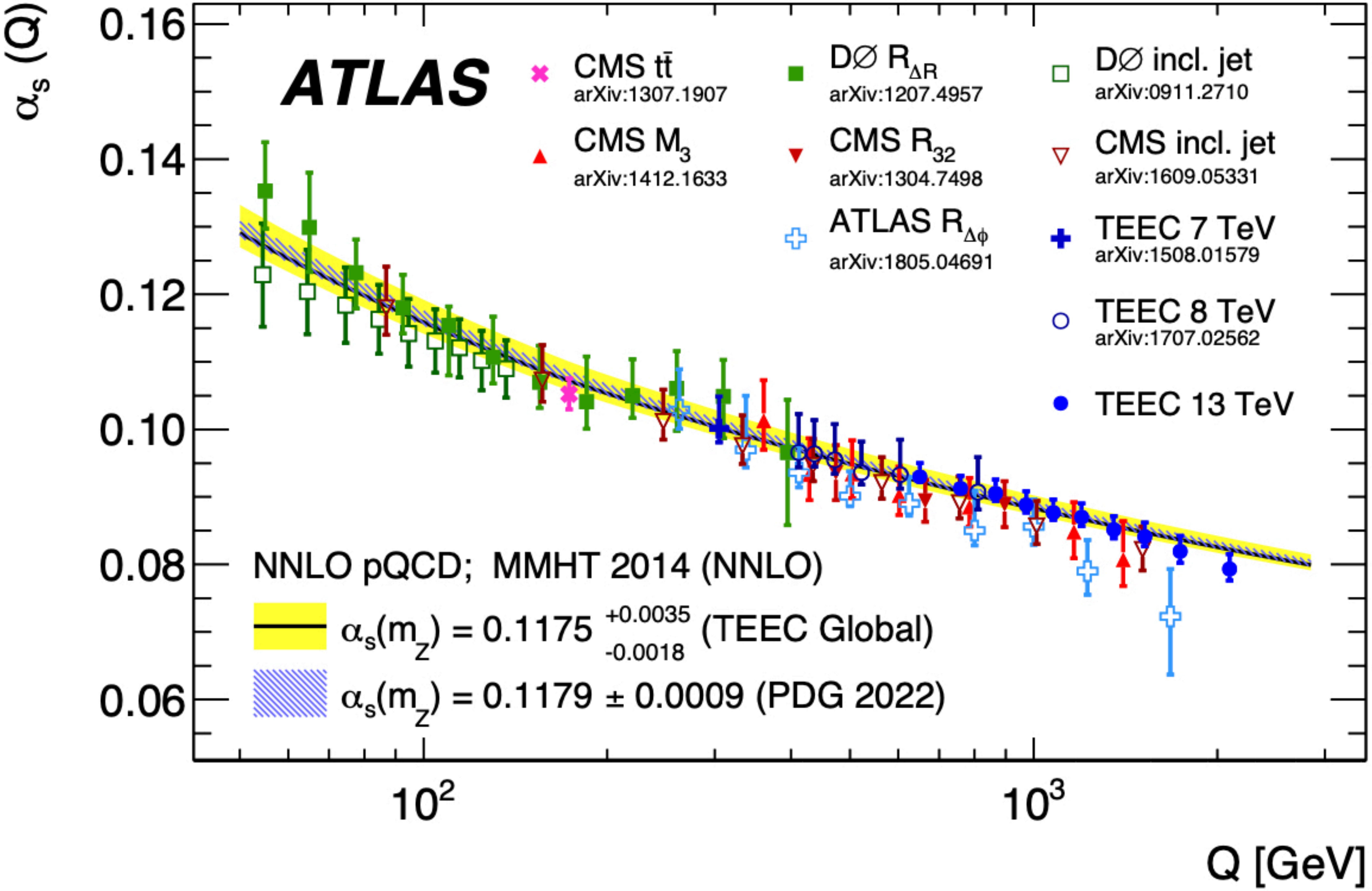


- Overall excellent agreement at the 5% level, and within exptl systematics
- NNLO improves over NLO
- PDF systematics remains dominant, esp at large p$_T$

α_S measurements from jets

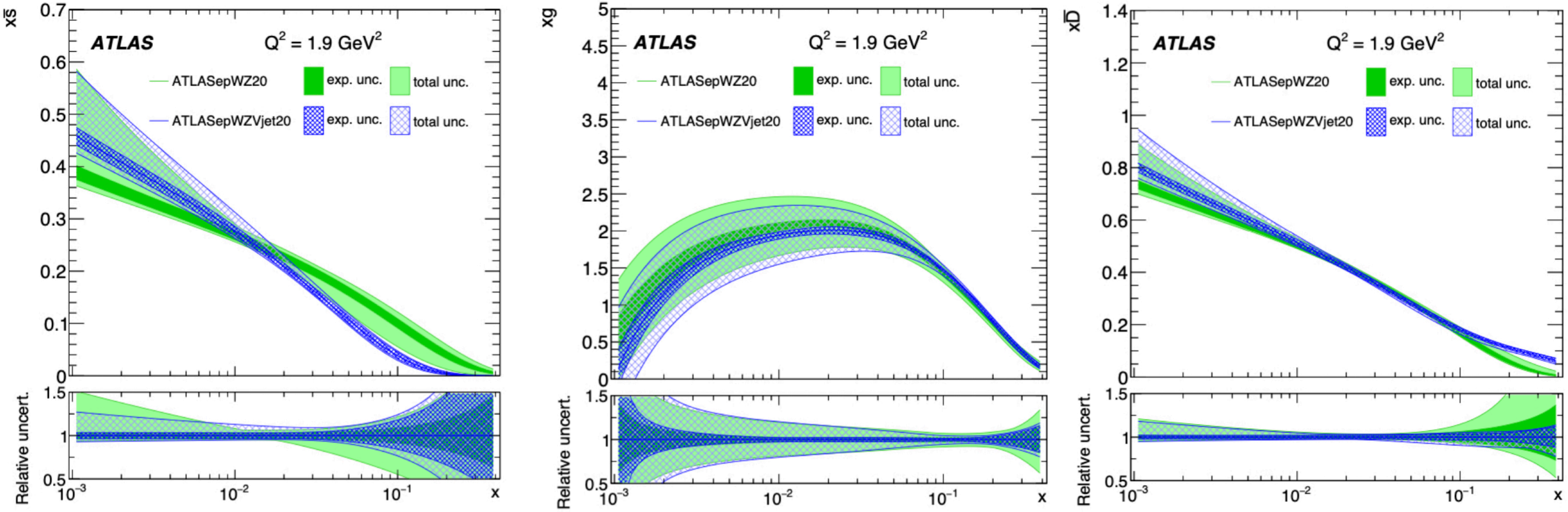
Transverse energy-energy correlations (TEEC):

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$



The impact of V + jets data on PDF determinations

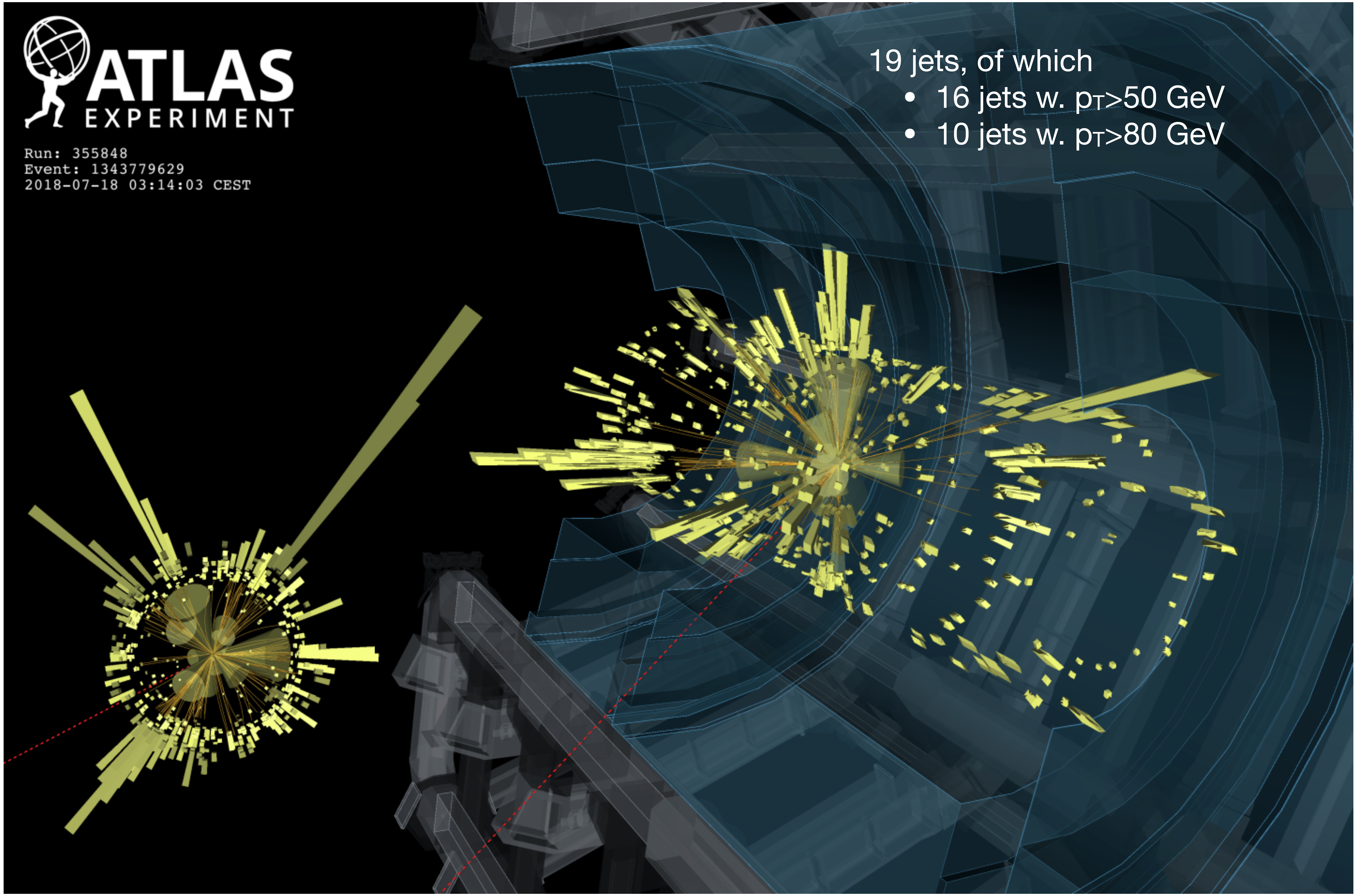
ATLAS, JHEP 07 (2021) 223



ATLASepWZ20: PDF fits using HERA ep and LHC W/Z inclusive production data

ATLASepWZVjet20: as ATLASepWZ20, plus W/Z+jets data

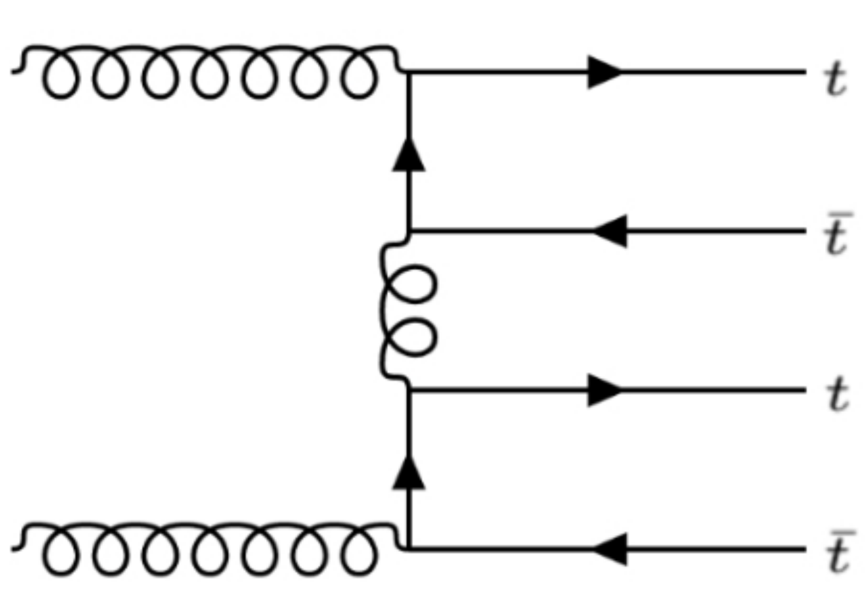
Multijet final states

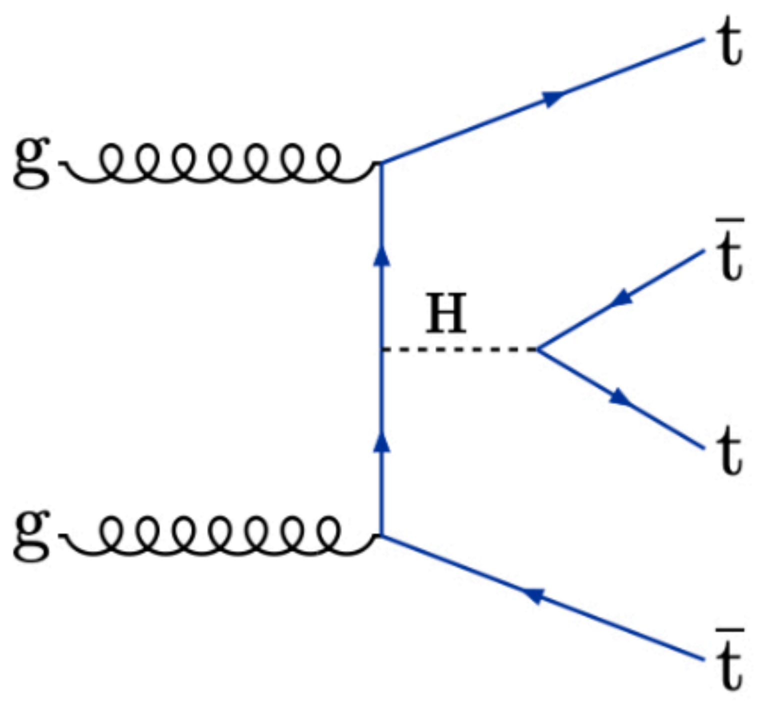


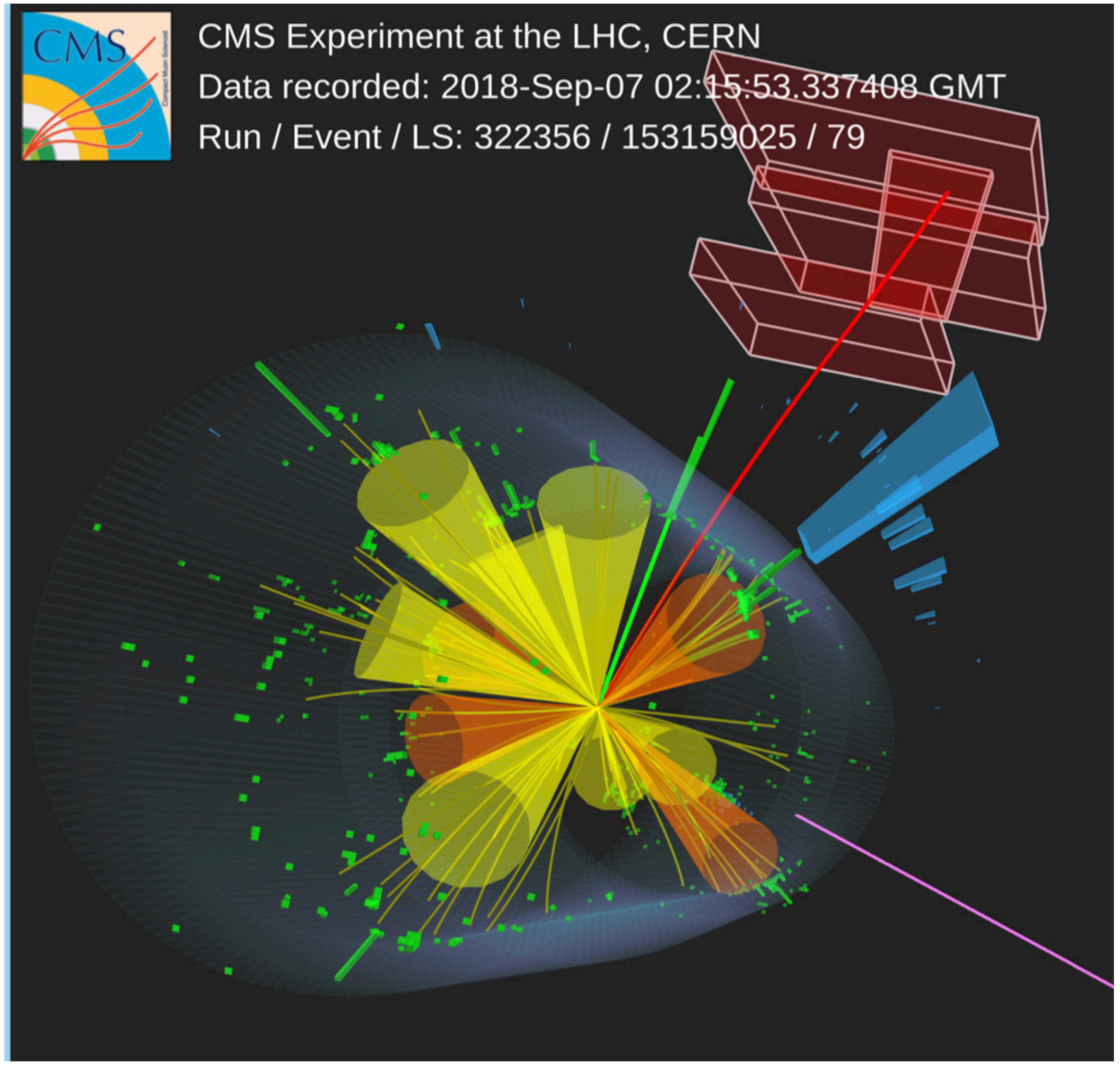
19 jets, of which

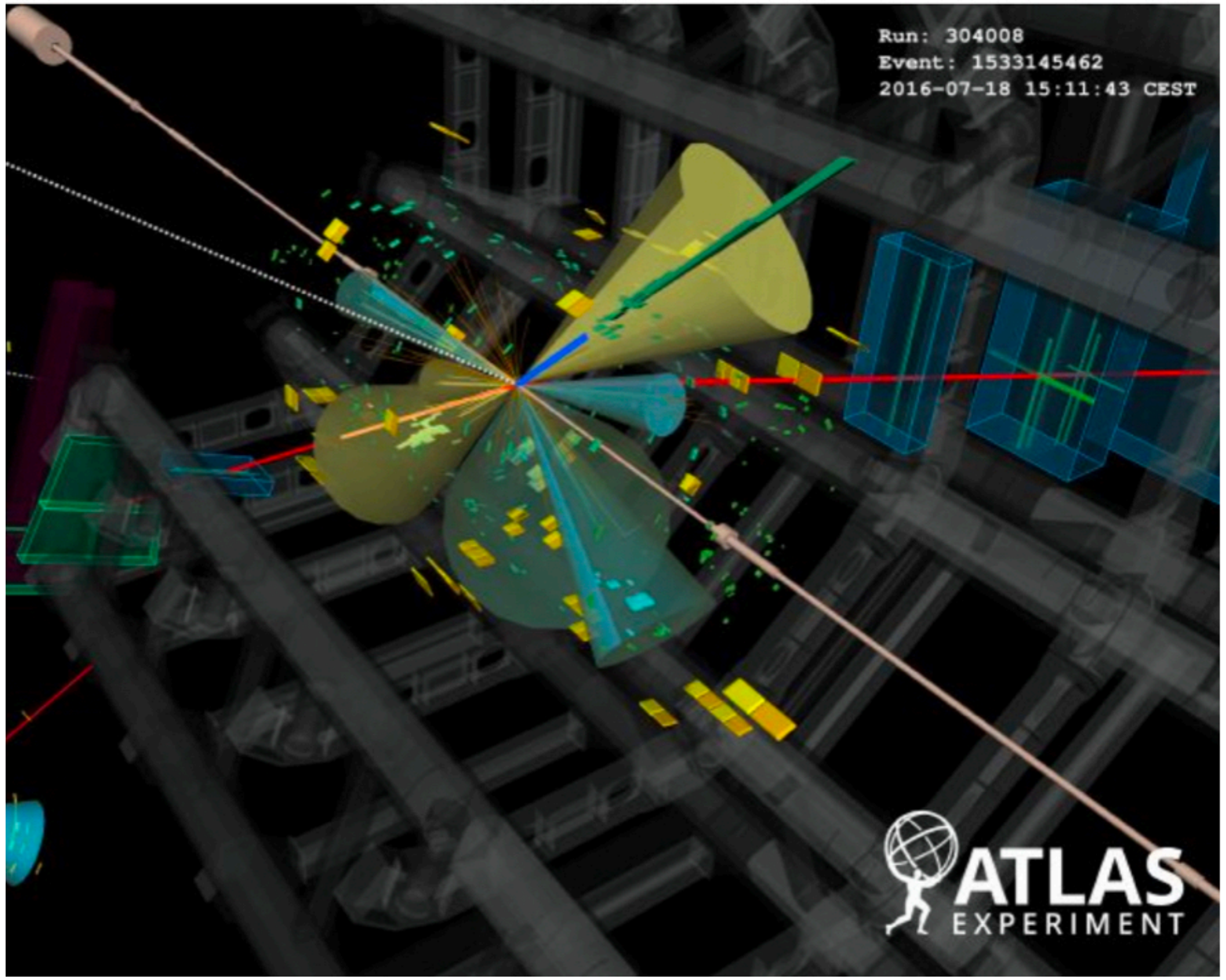
- 16 jets w. p_T>50 GeV
- 10 jets w. p_T>80 GeV

4 top production



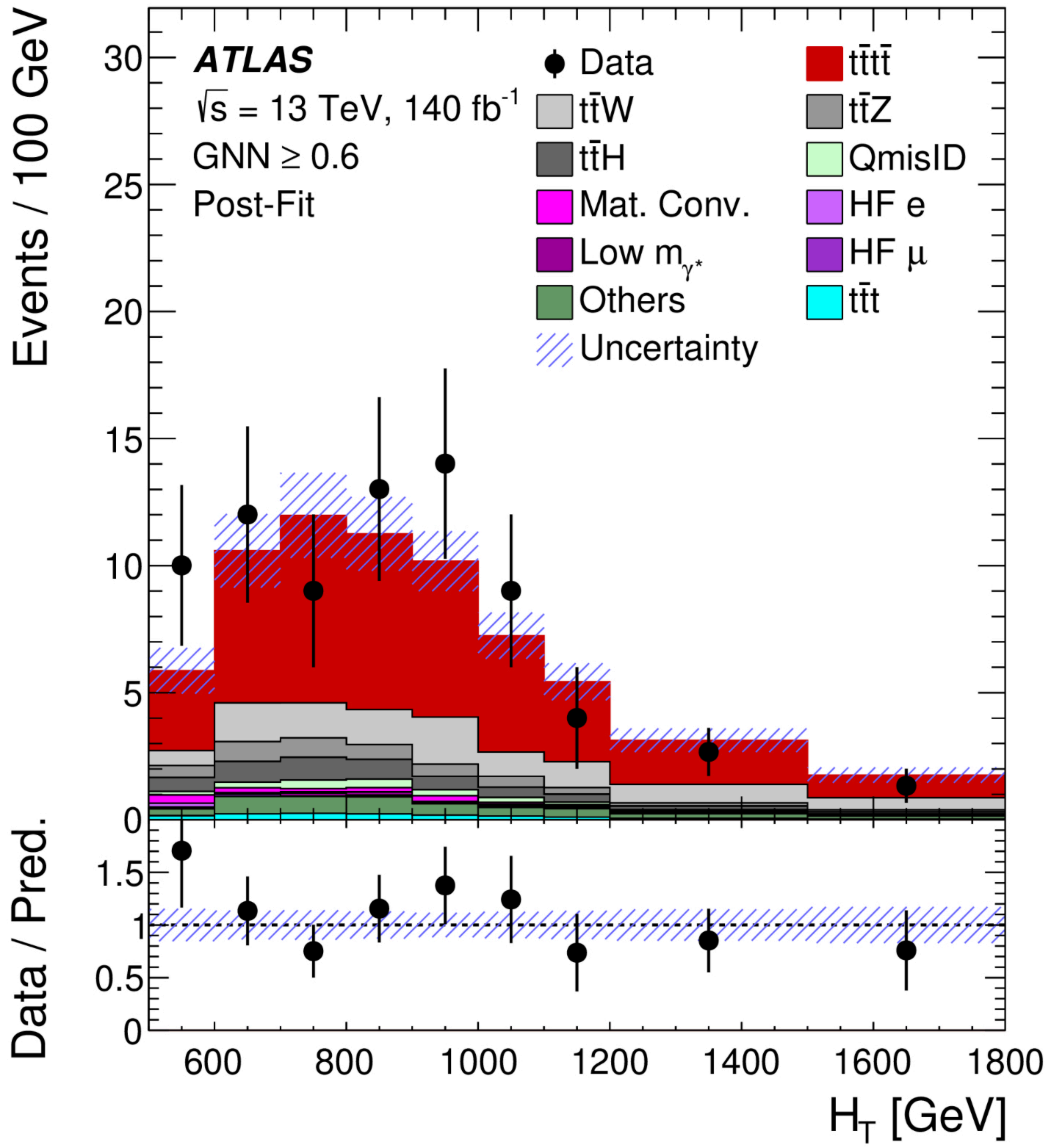


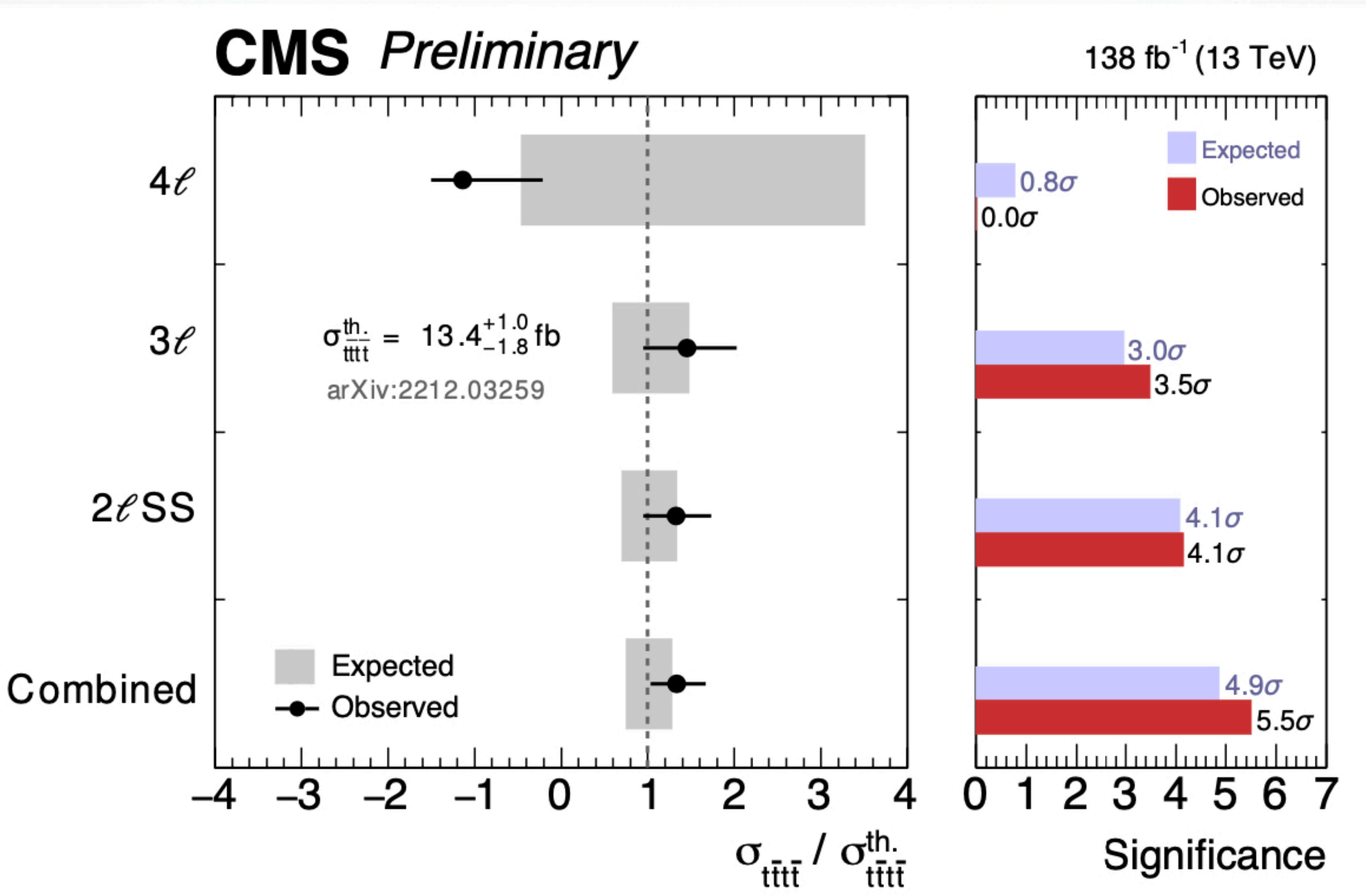




https://arxiv.org/abs/2303.15061

https://cds.cern.ch/record/2853304





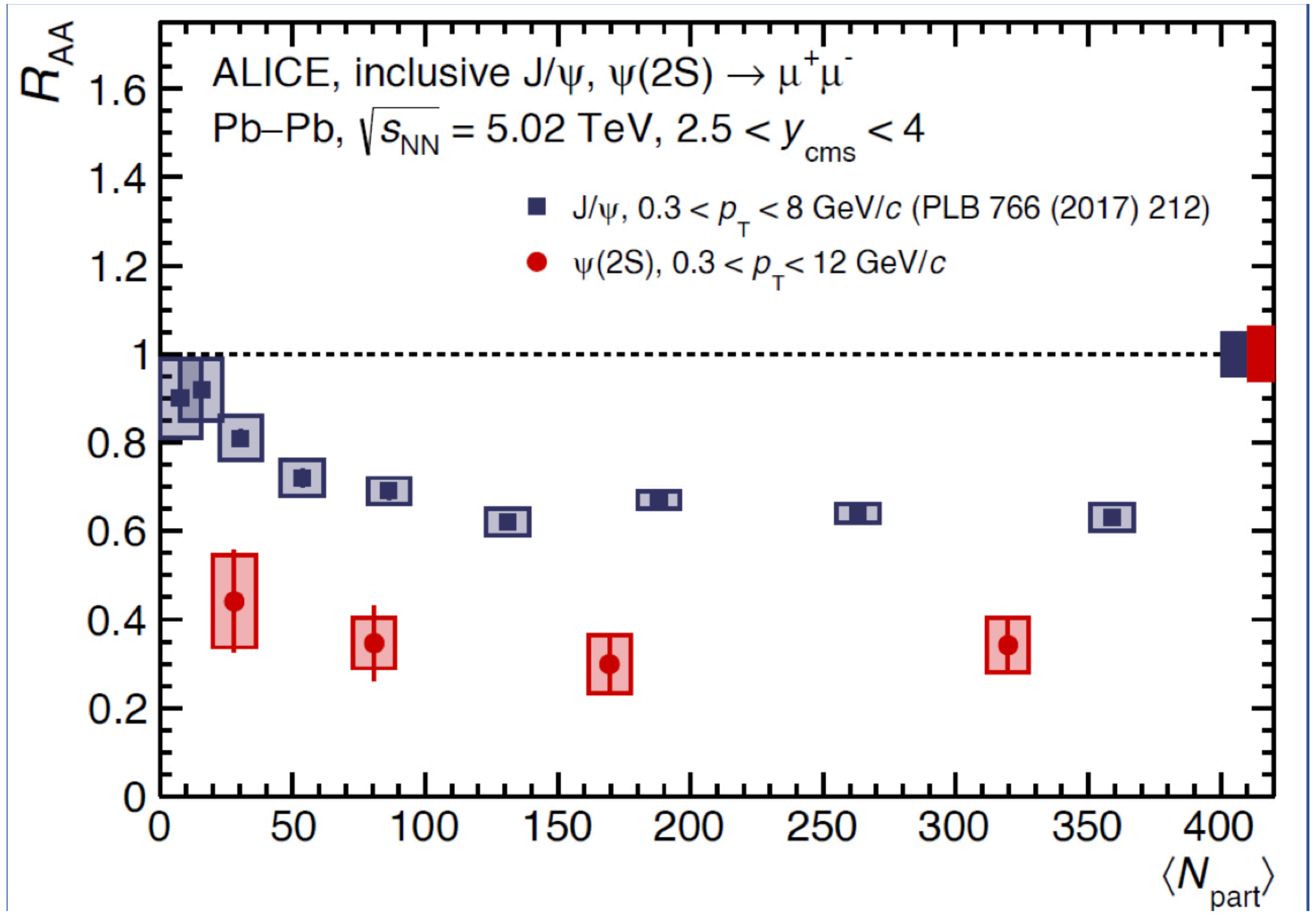
$$\sigma_{exp} = 22.5^{+6.6}_{-5.5}\ \text{fb} \quad \text{vs} \quad \sigma_{SM} = 12.0 \pm 2.4\ \text{fb}$$

$$\sigma_{exp} = 17.0^{+3.7}_{-3.5}{}_{stat}{}^{+2.4}_{-2.1}{}_{syst}\ \text{fb} \quad \text{vs} \quad \sigma_{SM} = 13.4^{+1.0}_{-1.8}\ \text{fb}$$

Study of QCD in new 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)



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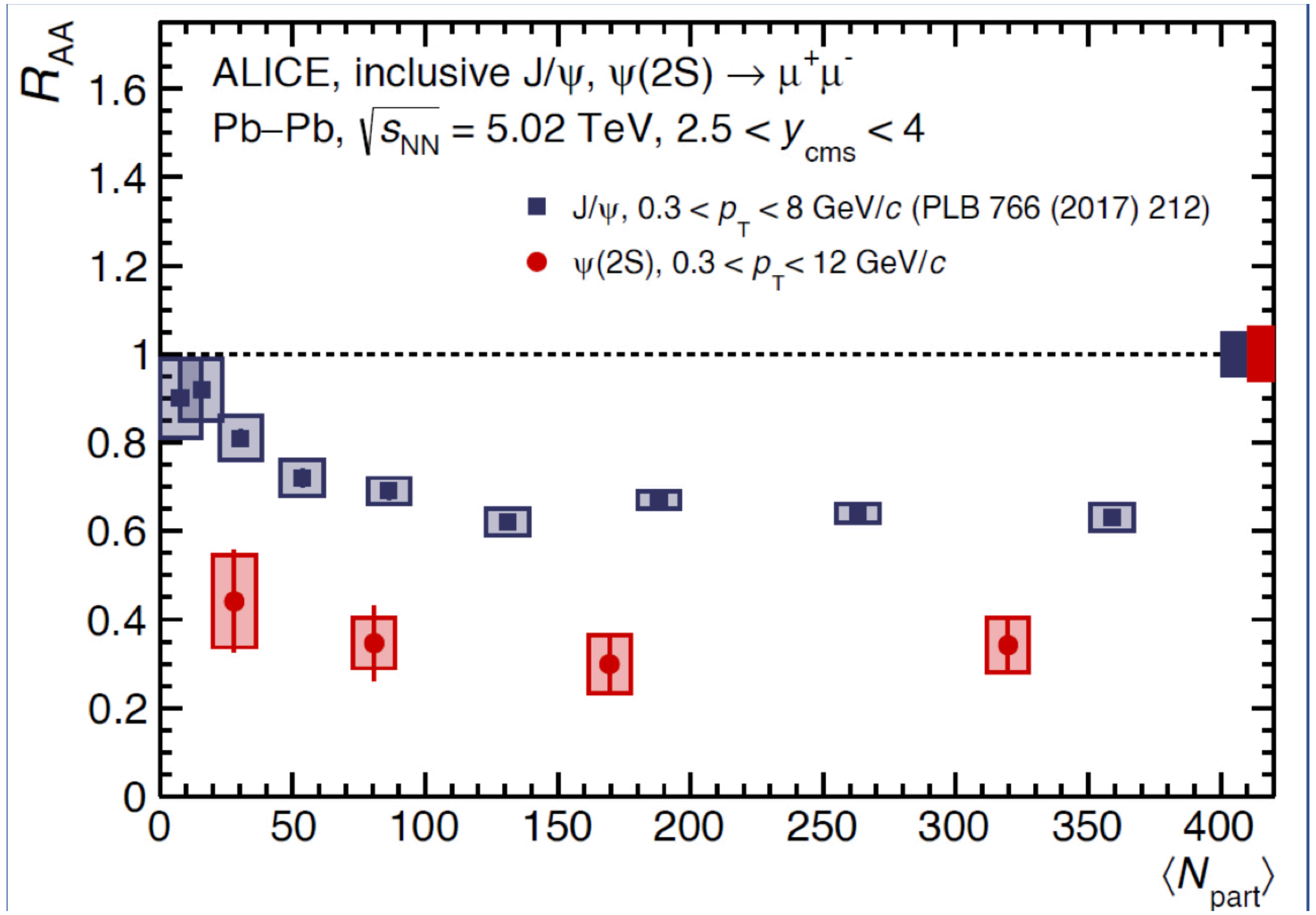
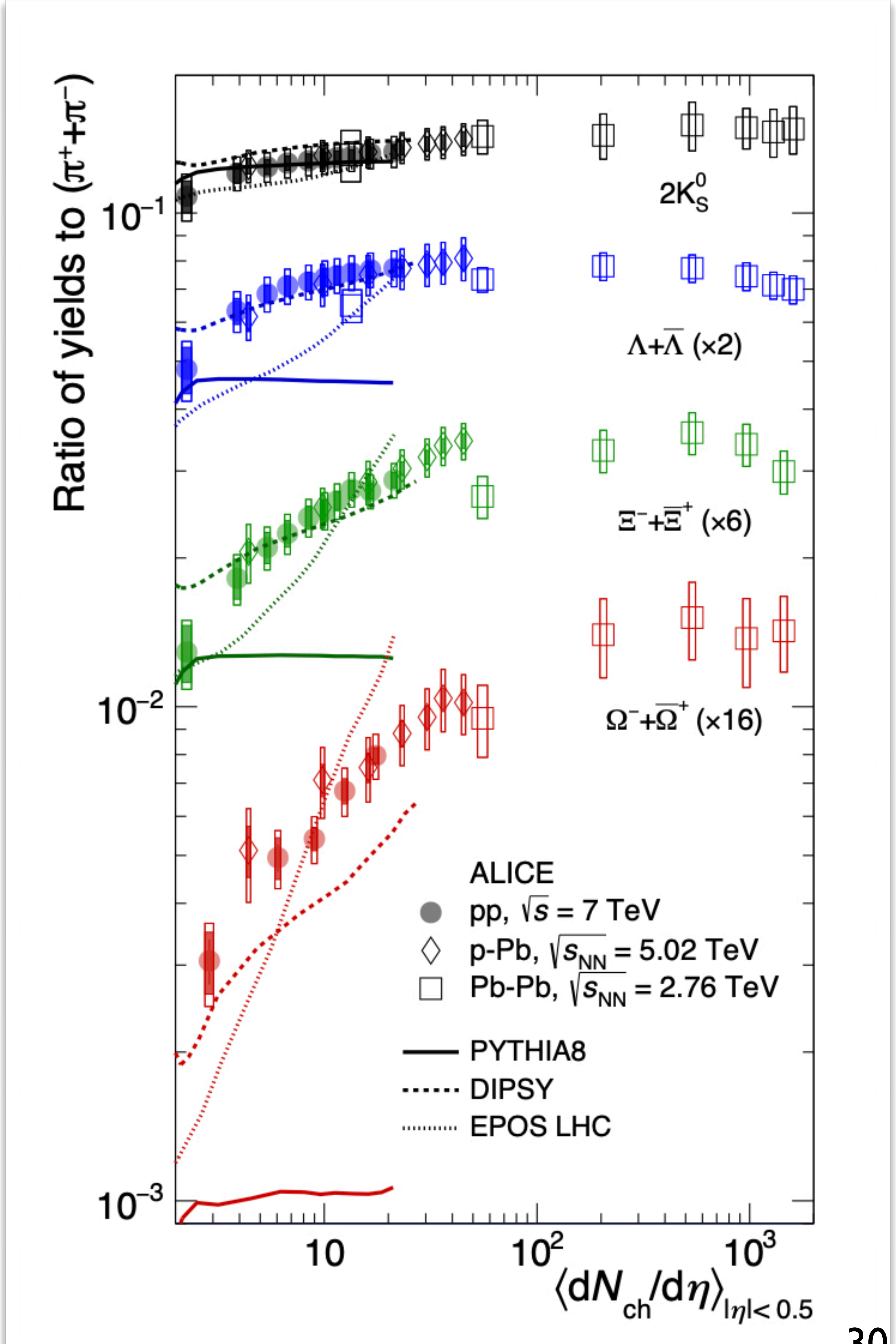


discovery of new dynamical behaviour, with collective phenomena typical of QGP appearing already in high-multiplicity final states of pp and pA

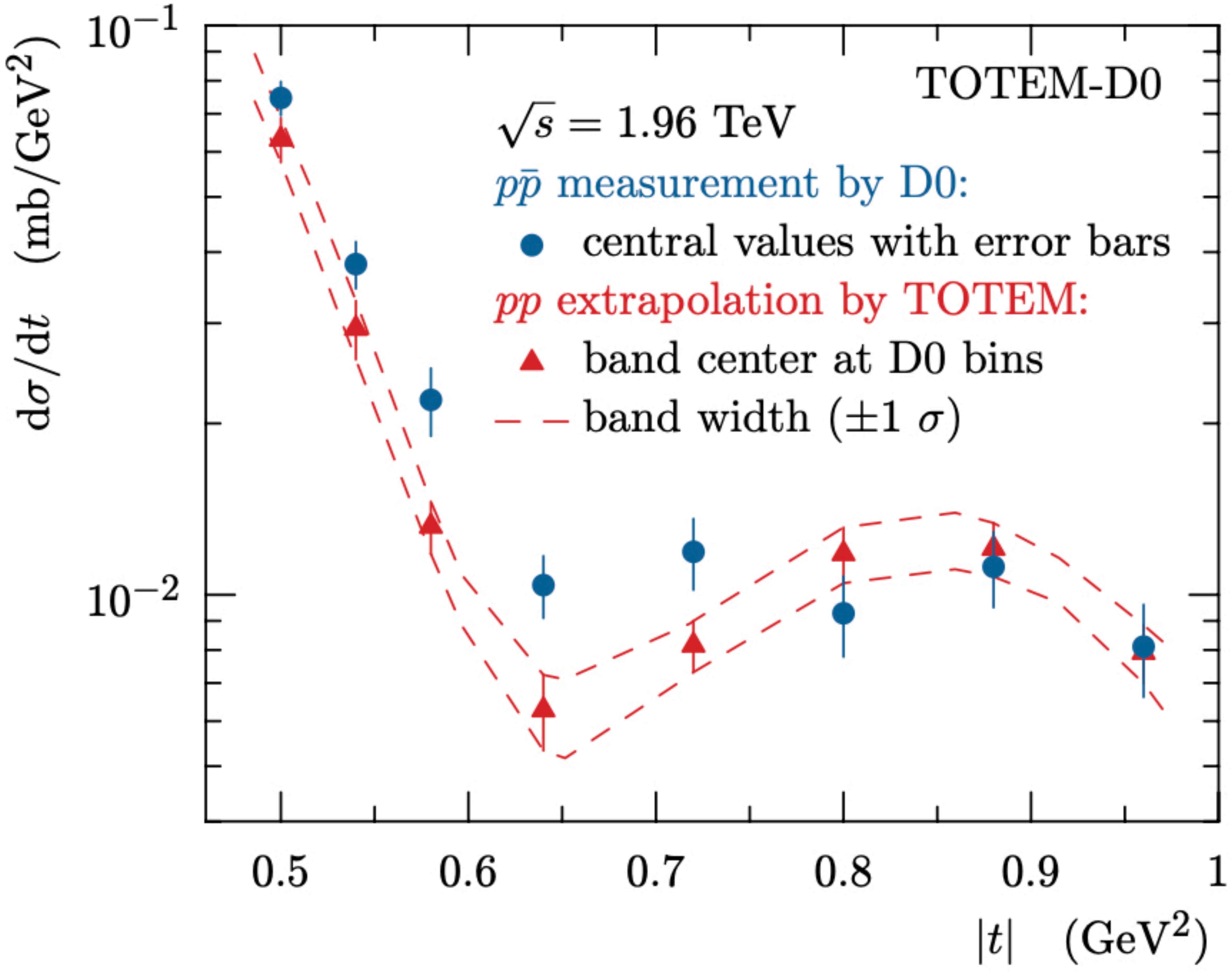


First experimental evidence for odderon exchange made possible by comparison of pp TOTEM data with ppbar D0 data

hadron-hadron elastic scattering dominated by exchange of leading Regge poles:

- pomeron (CP even, contributes w. same sign to pp and ppbar amplitudes)
- odderon (CP odd, contribute w. opposite signs to pp and ppbar amplitudes)

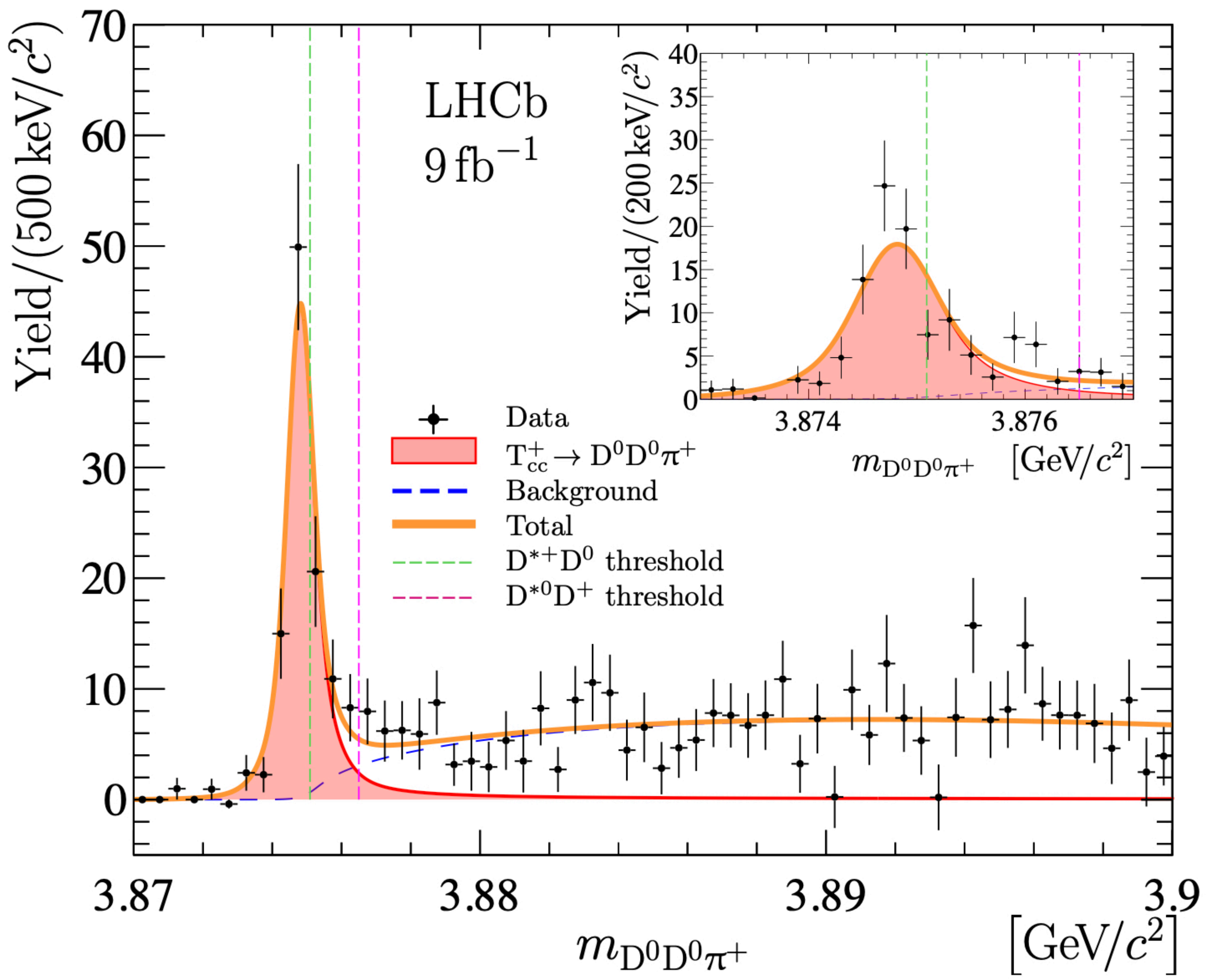
Phys.Rev.Lett. 127 (2021) 6, 062003



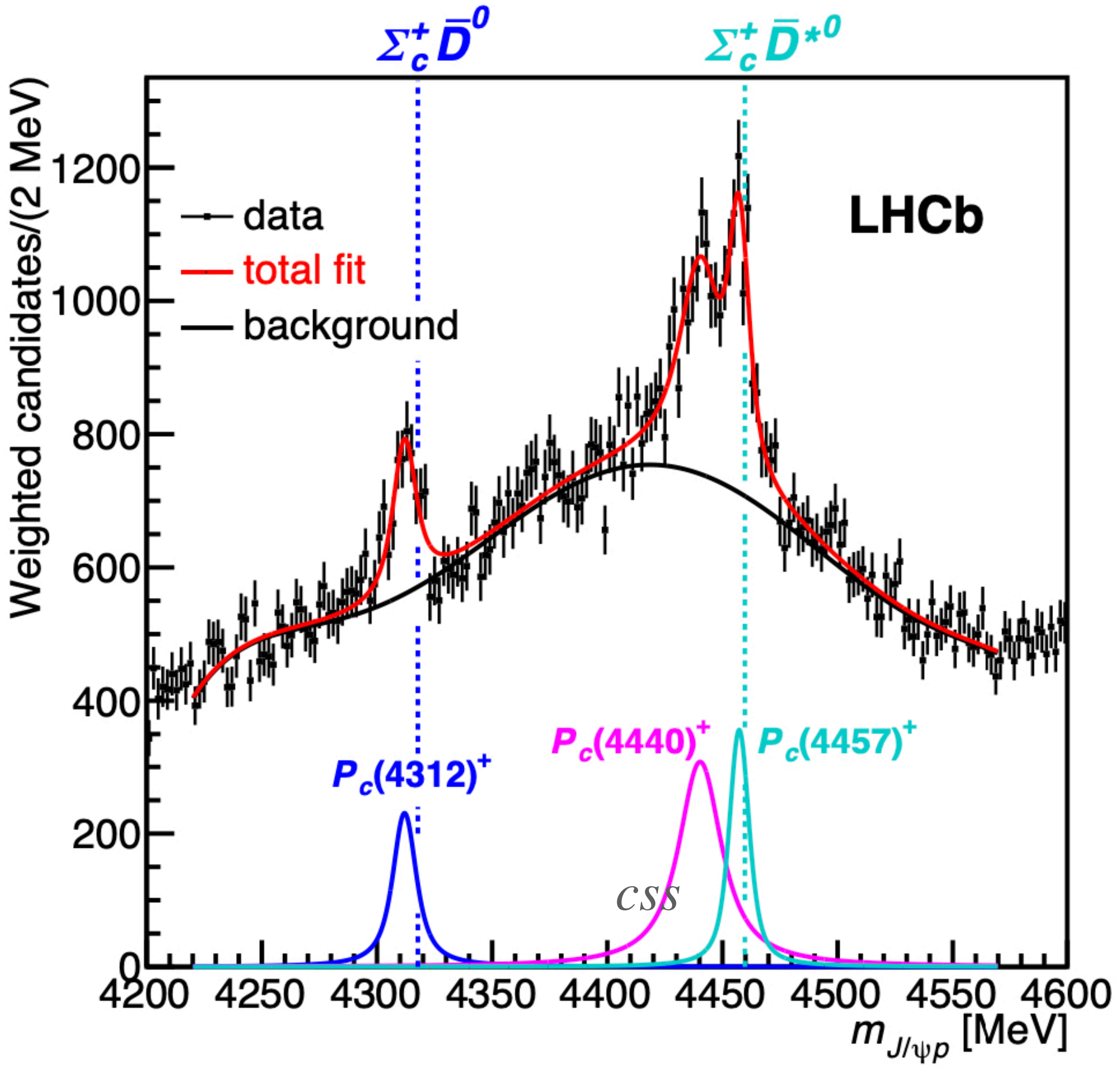
Exotic Spectroscopy, nuclear physics and more

Tetraquarks, pentaquarks, double-heavy baryons, exotics, …

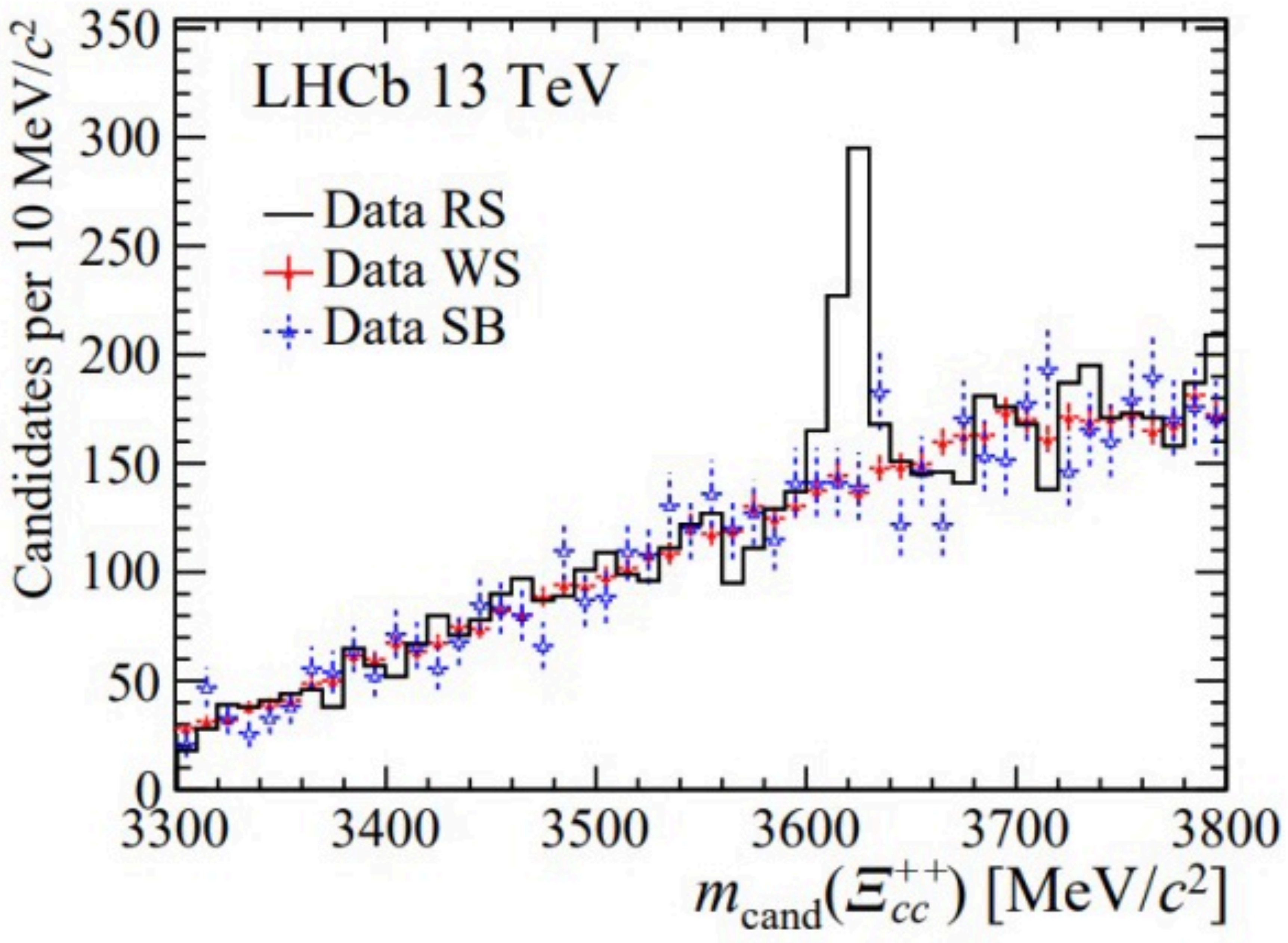
$cc\bar{u}\bar{d}$



$duuc\bar{c}$



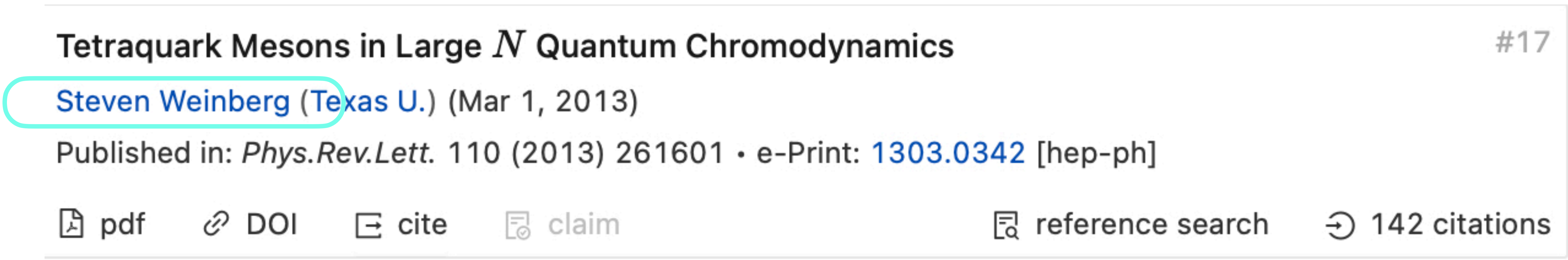
ccu



A Theory of Scalar Mesons #1

G. 't Hooft (Utrecht U.), G. Isidori (Pisa, Scuola Normale Superiore and Frascati), L. Maiani (Rome U. and INFN, Rome), A.D. Polosa (INFN, Rome), V. Riquer (INFN, Rome) (Jan, 2008)

Published in: *Phys.Lett.B* 662 (2008) 424-430 • e-Print: 0801.2288 [hep-ph]

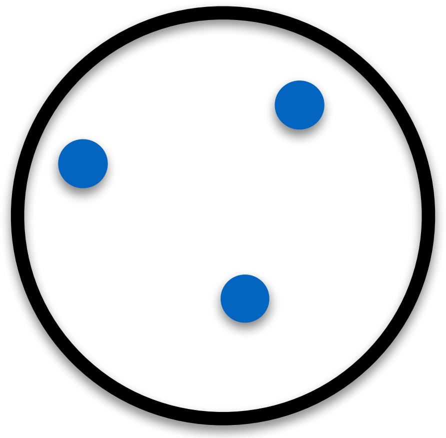


Tetraquark Mesons in Large N Quantum Chromodynamics #17

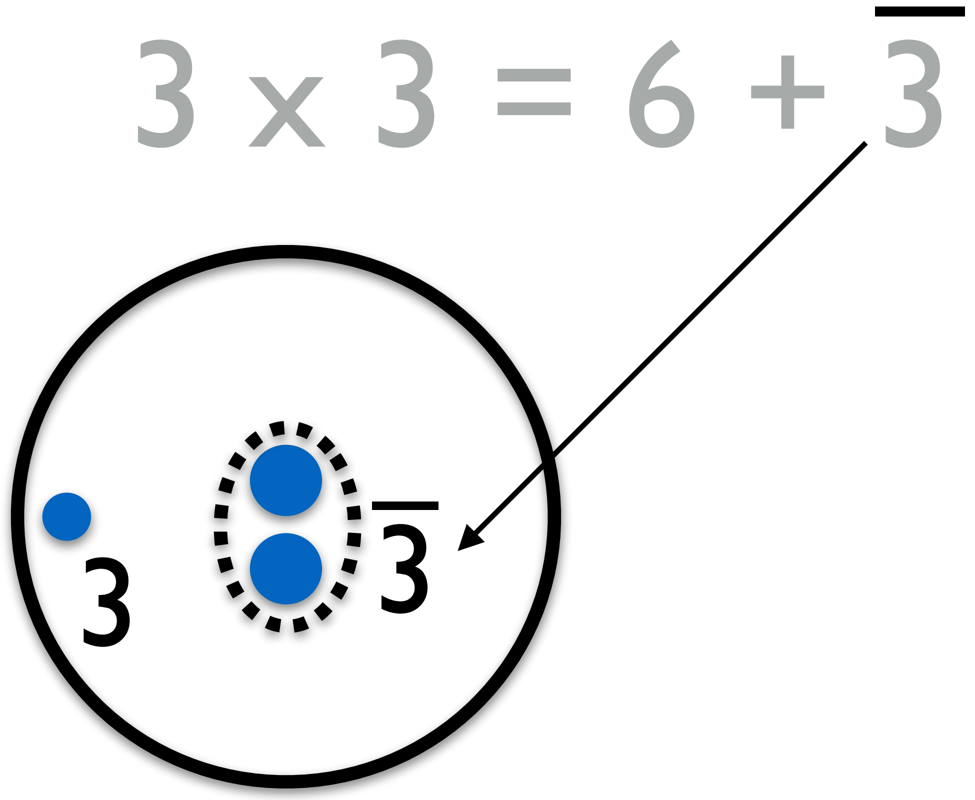
Steven Weinberg (Texas U.) (Mar 1, 2013)

Published in: *Phys.Rev.Lett.* 110 (2013) 261601 • e-Print: 1303.0342 [hep-ph]

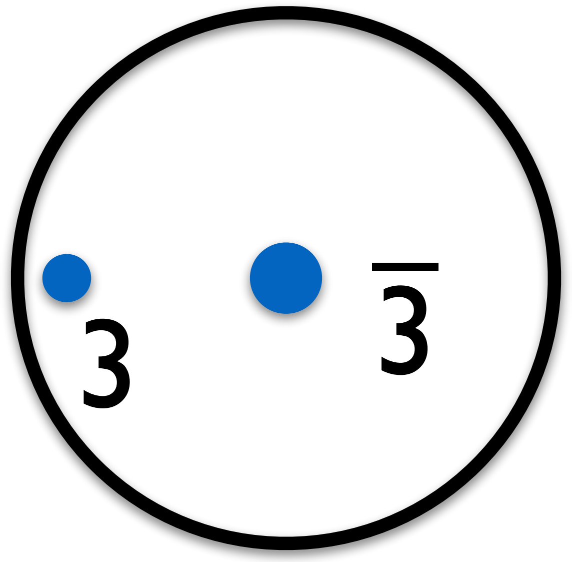
A usual baryon:



A baryon with two heavy q's:

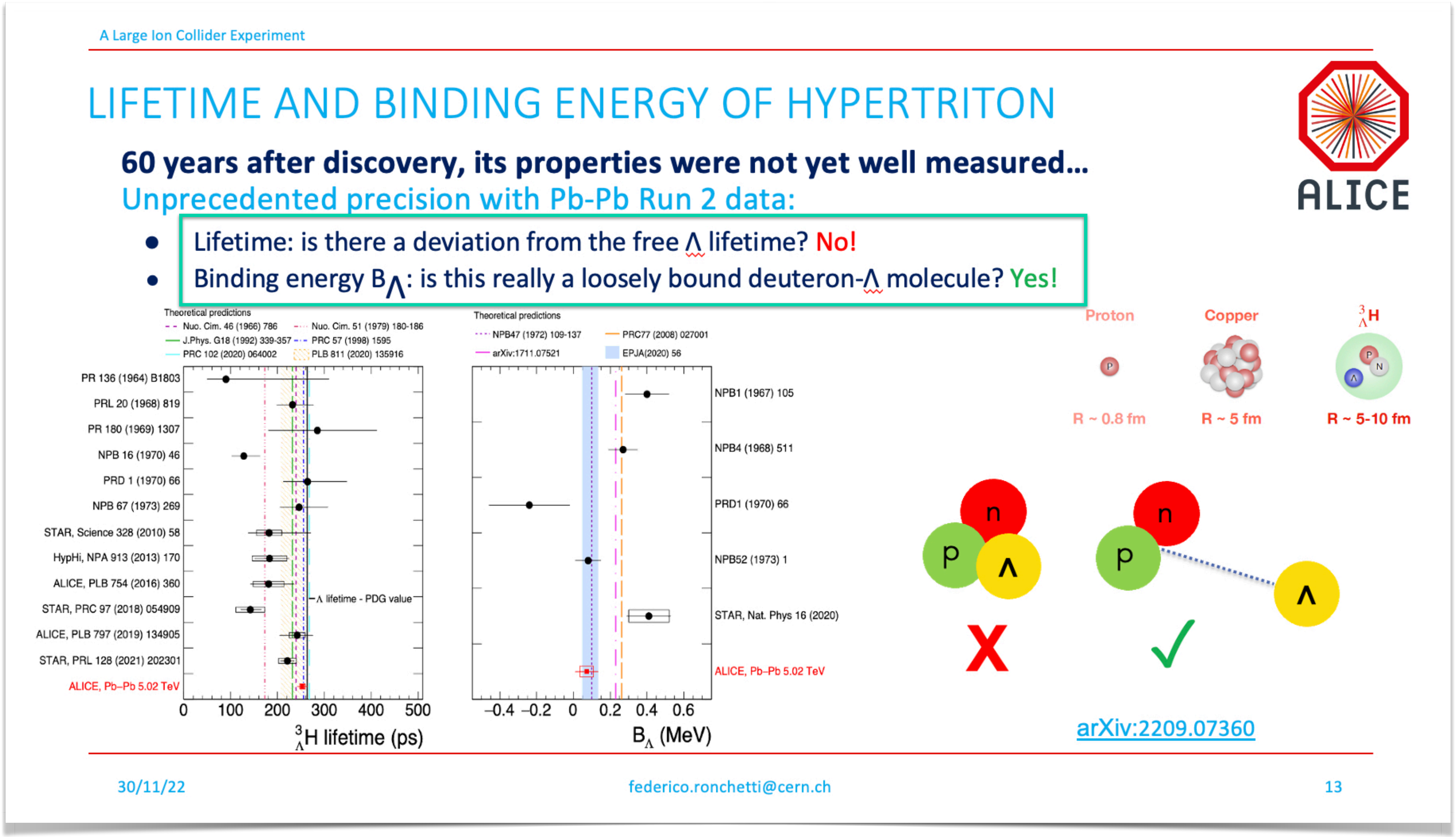

$$3 \times 3 = 6 + \bar{3}$$

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!!



A Large Ion Collider Experiment

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

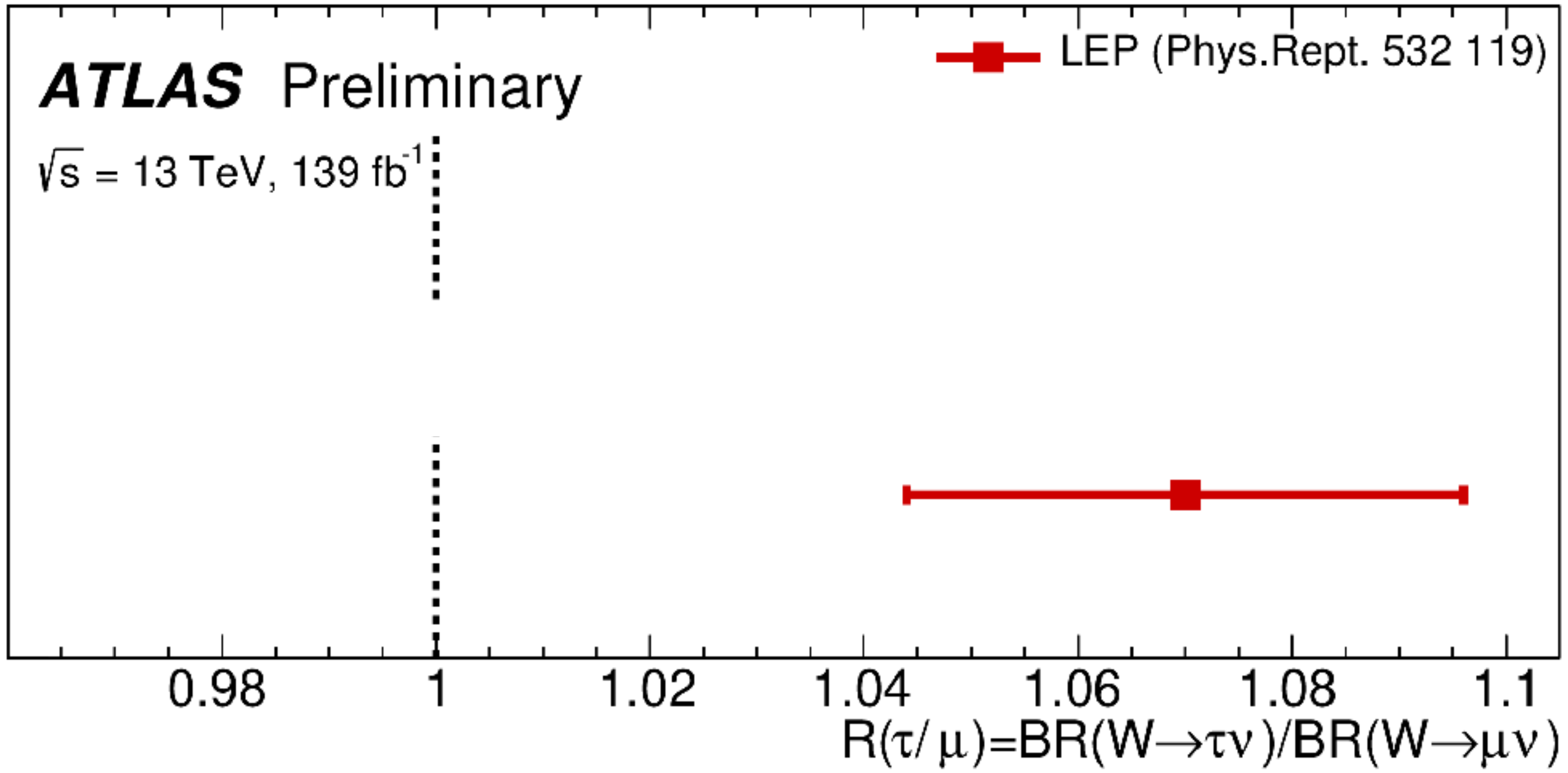
30/11/22

federico.ronchetti@cern.ch

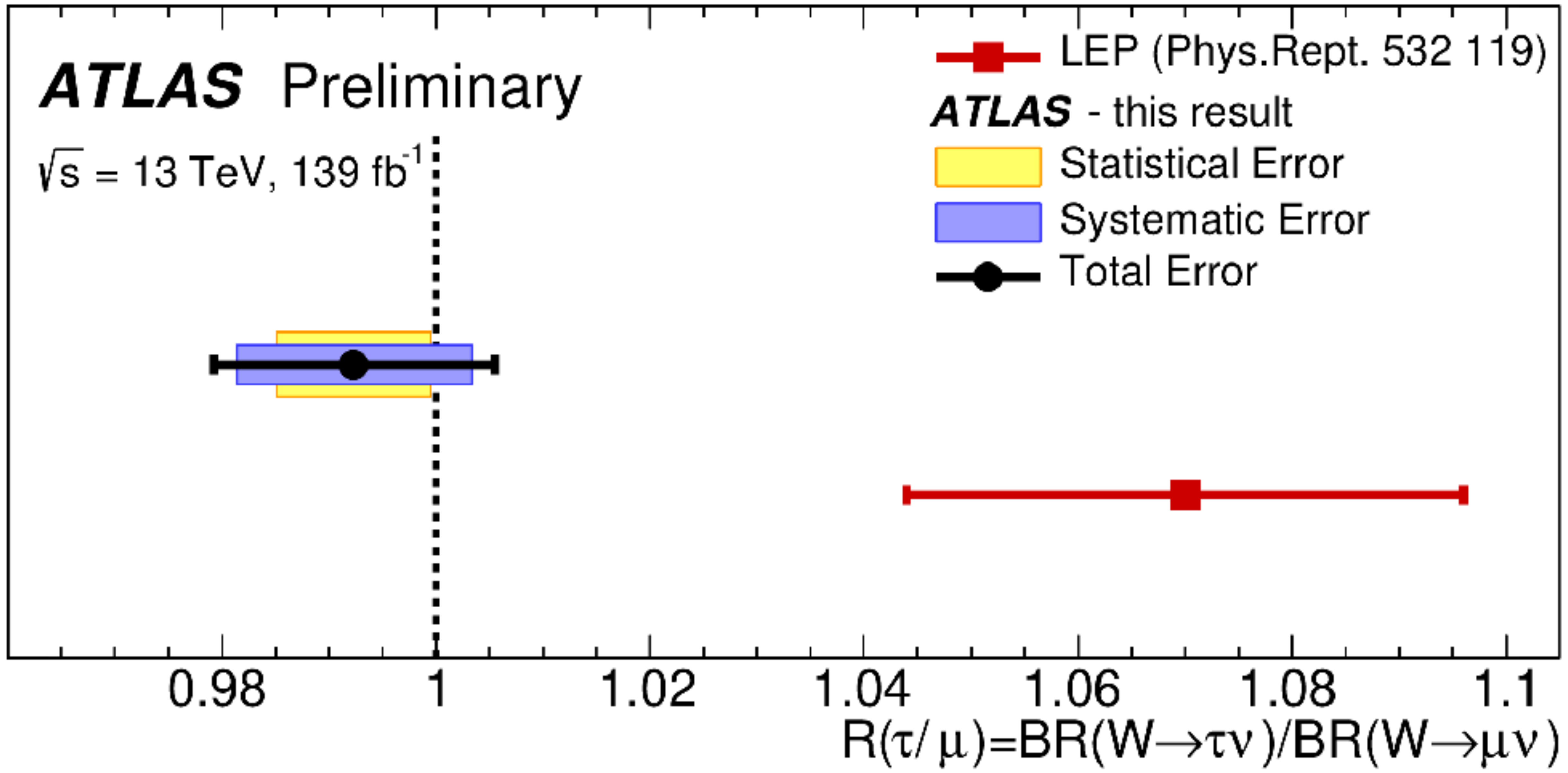
13

EW physics

Lepton universality of W couplings



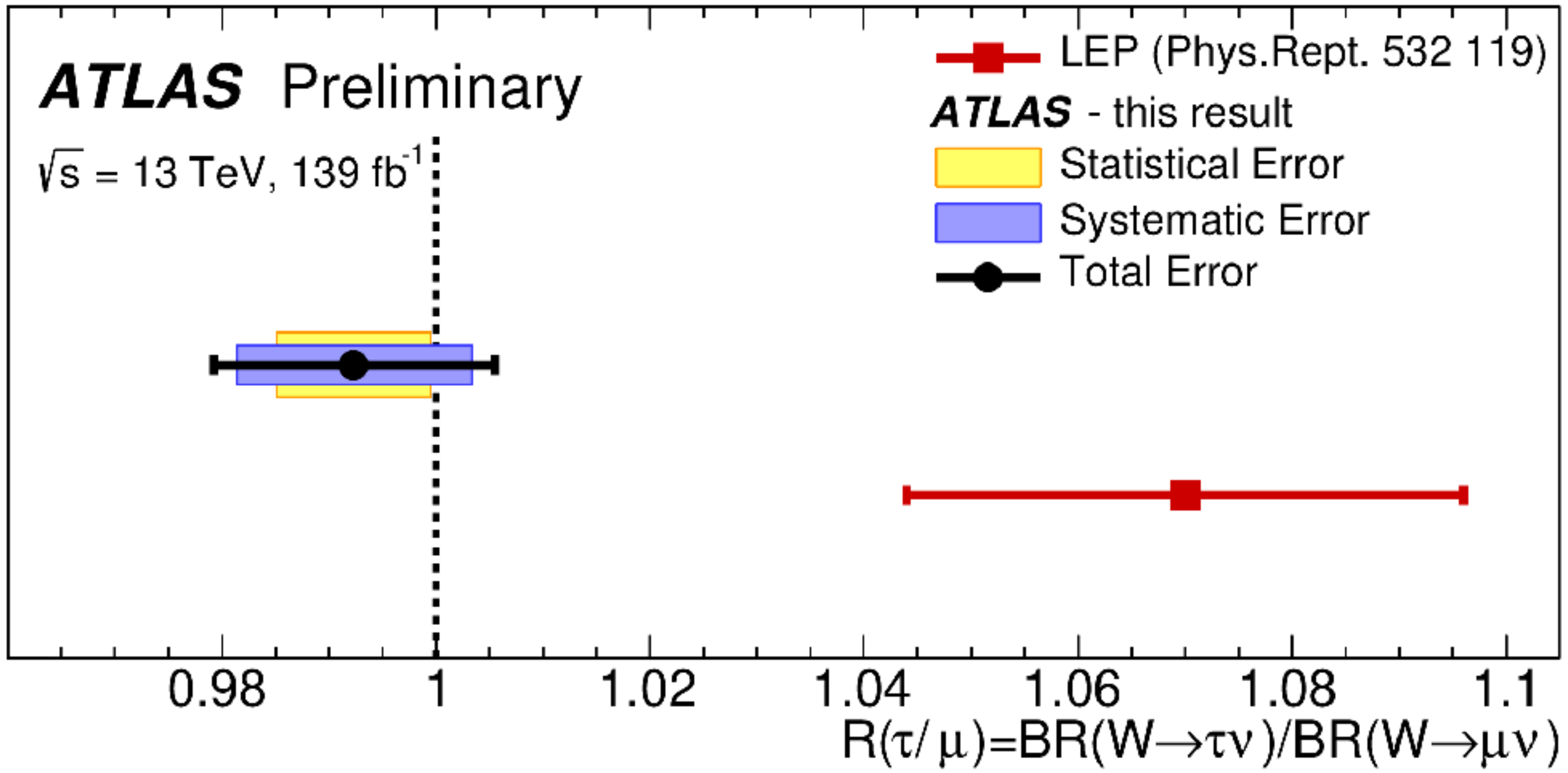
Lepton universality of W couplings

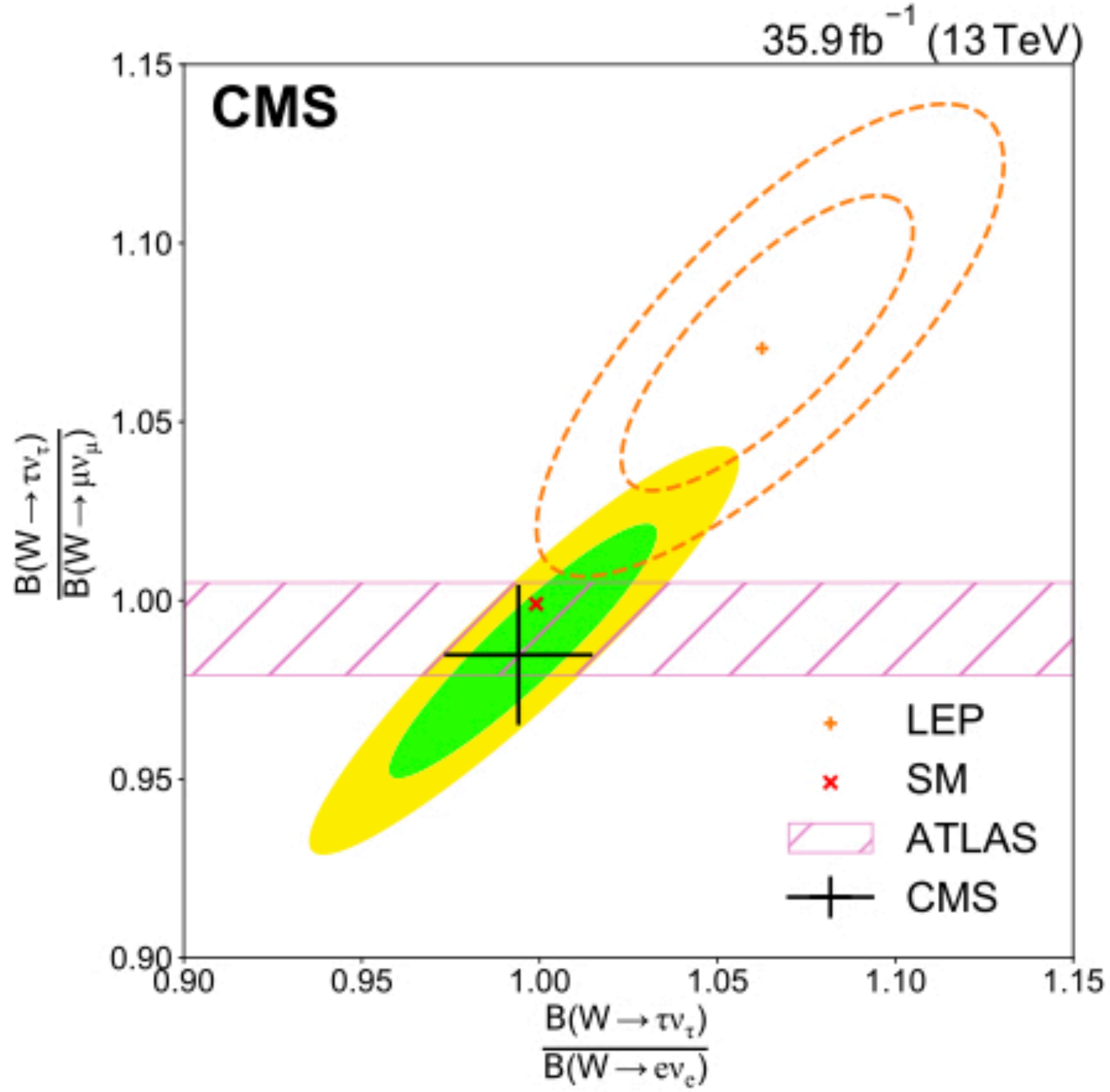


Lepton universality of W couplings

ATLAS 2020: arXiv:2007.14040

CMS 2022: arXiv:2201.07861





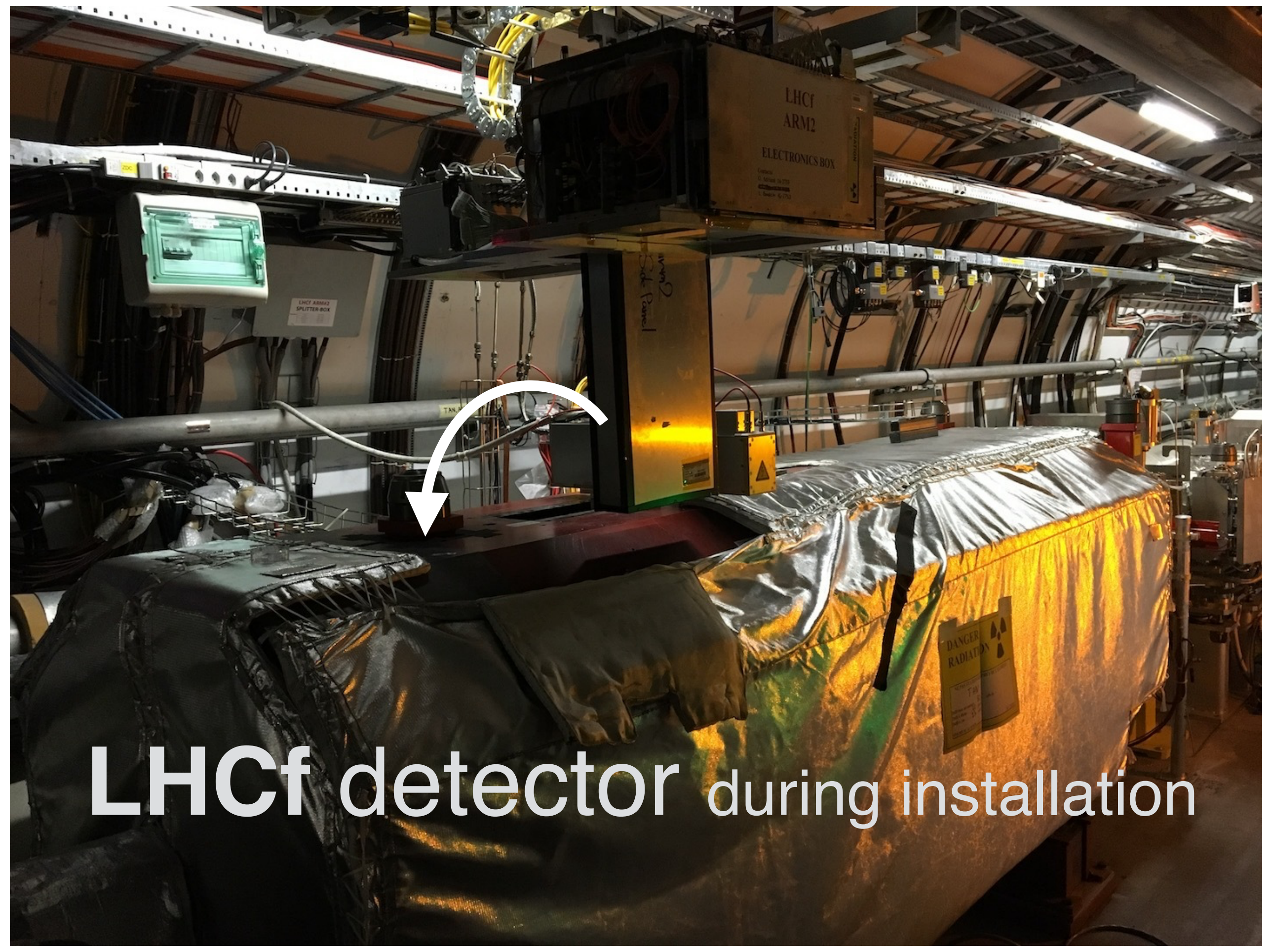
LEP:
***BR*(W→τν)/*BR*(W→μν) = 1.066 ± 0.025**

ATLAS:
***BR*(W→τν)/*BR*(W→μν) = 0.992 ± 0.013**

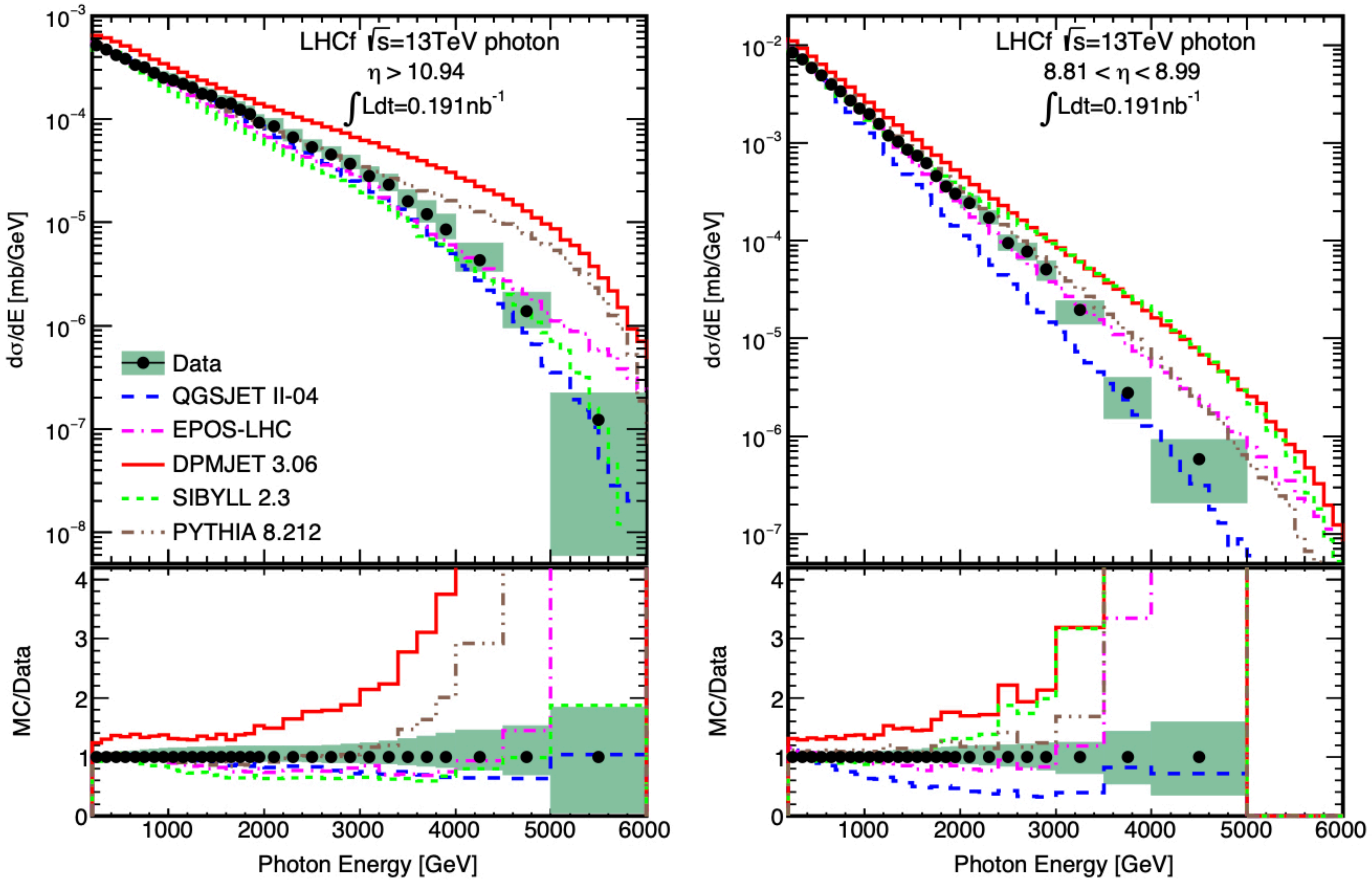
Impact on astroparticle physics

countless searches for dark matter candidates covering a huge domain of plausible model space

… plus:

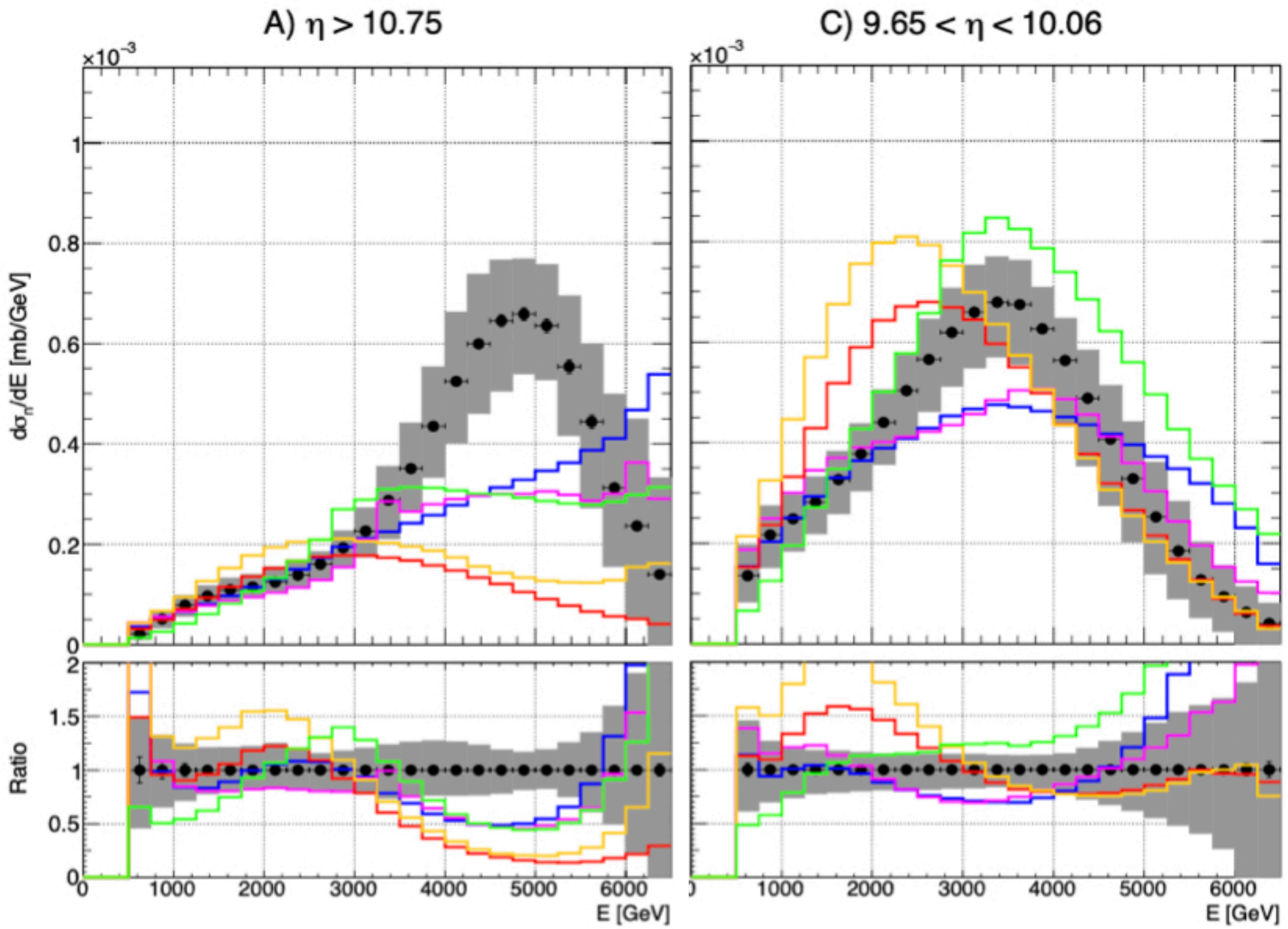

LHCf detector during installation

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



photons~π⁰~π⁺⁻

Phys.Lett.B 780 (2018) 233



neutrons

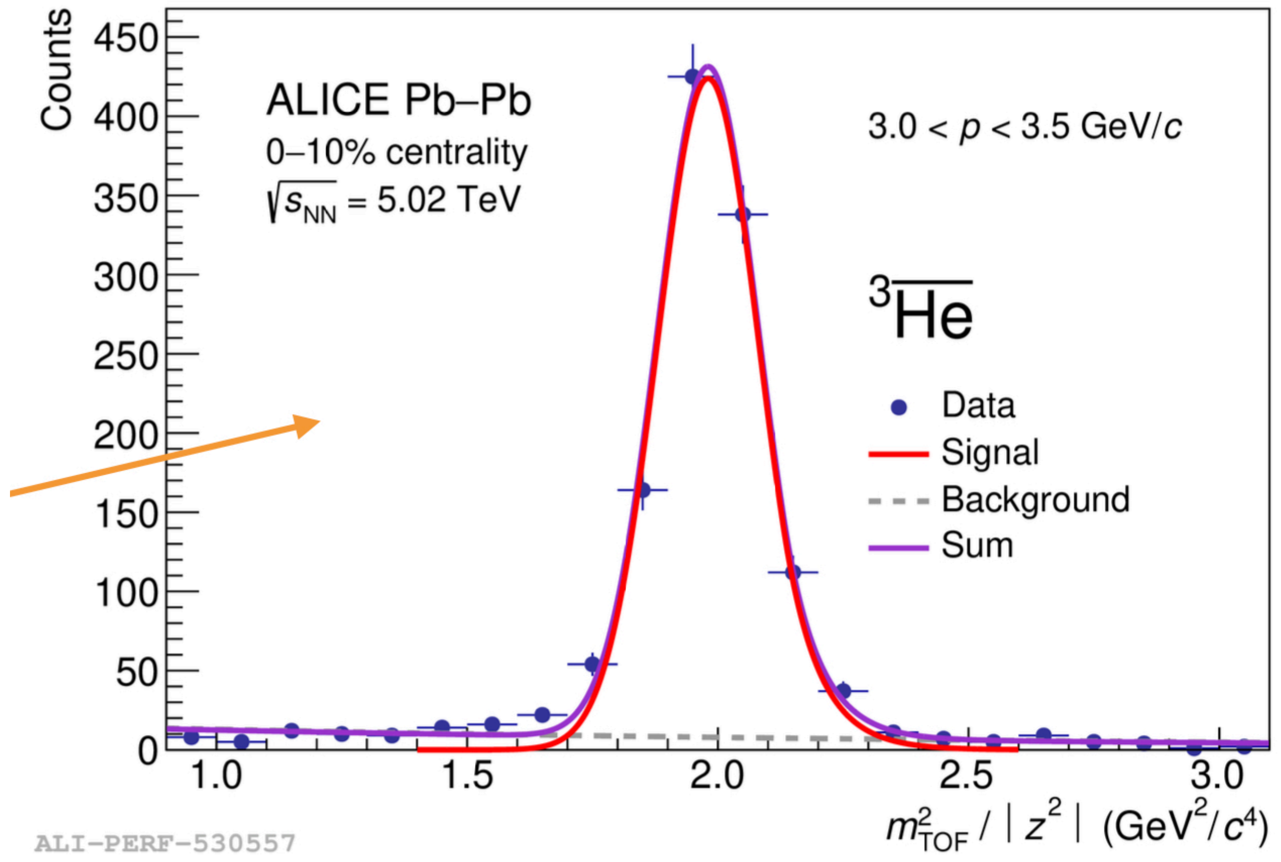
JHEP 07 (2020) 016

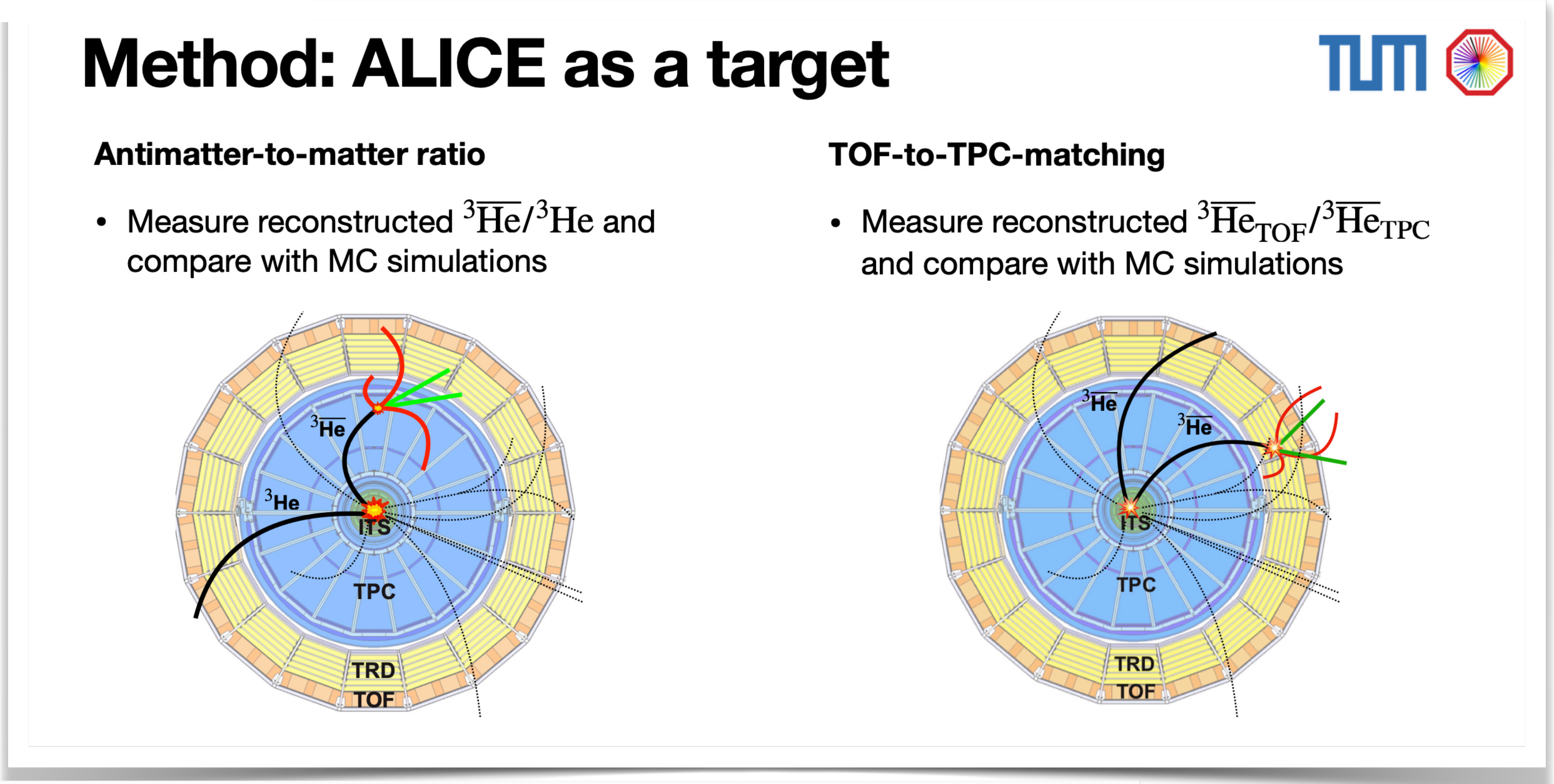
Article https://doi.org/10.1038/s41567-022-01804-8

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





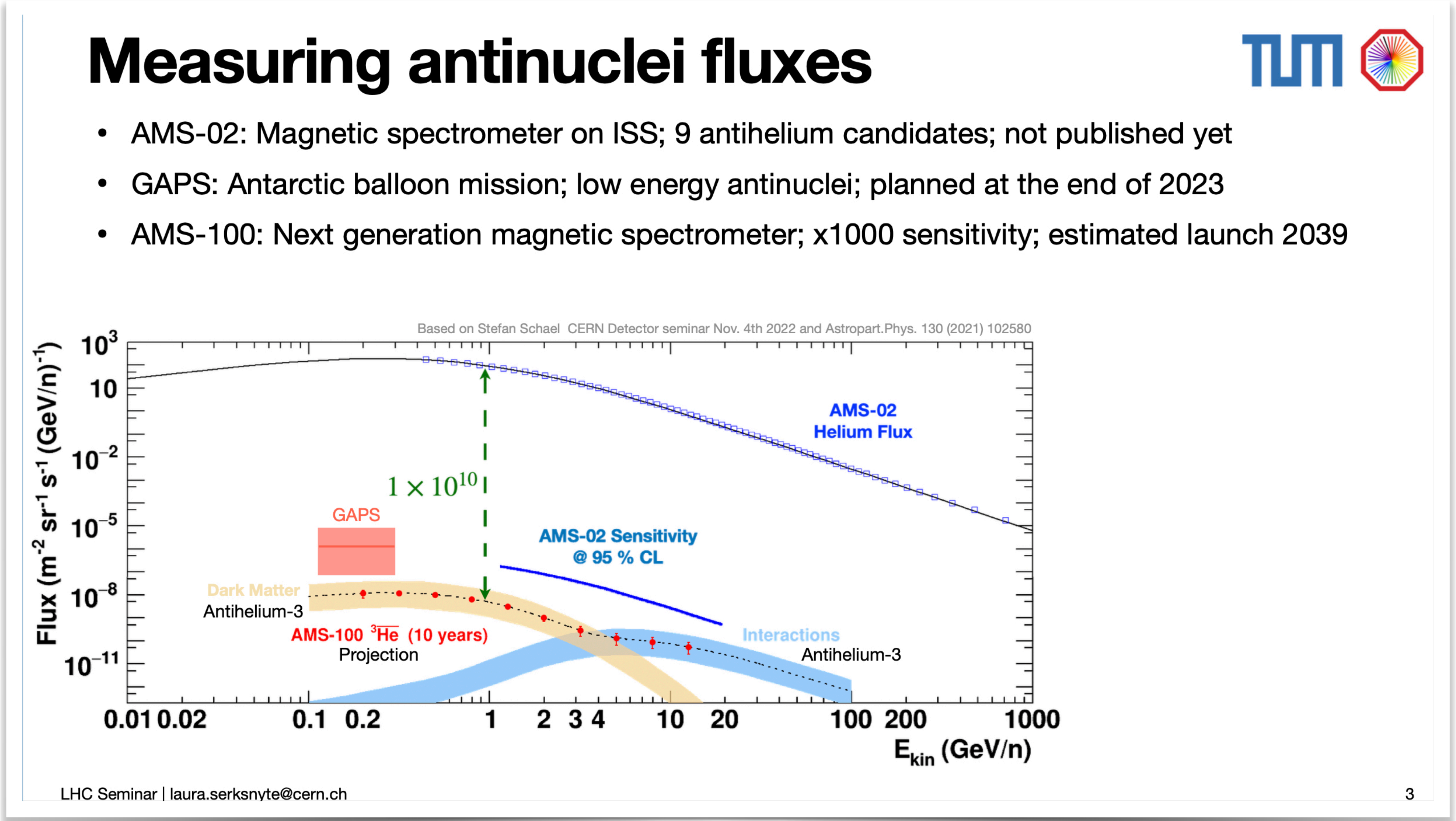
Method: ALICE as a target

Antimatter-to-matter ratio

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

TOF-to-TPC-matching

- Measure reconstructed $^3\overline{He}_{TOF}/^3\overline{He}_{TPC}$ 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

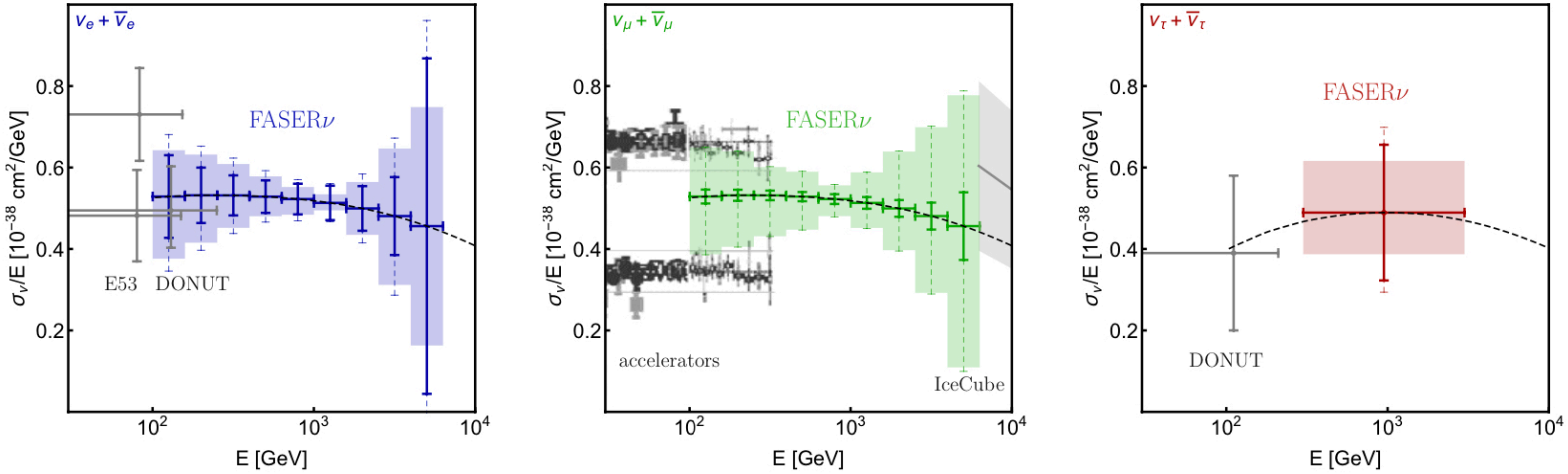
Based on Stefan Schael CERN Detector seminar Nov. 4th 2022 and Astropart.Phys. 130 (2021) 102580

LHC Seminar | laura.serksnyte@cern.ch

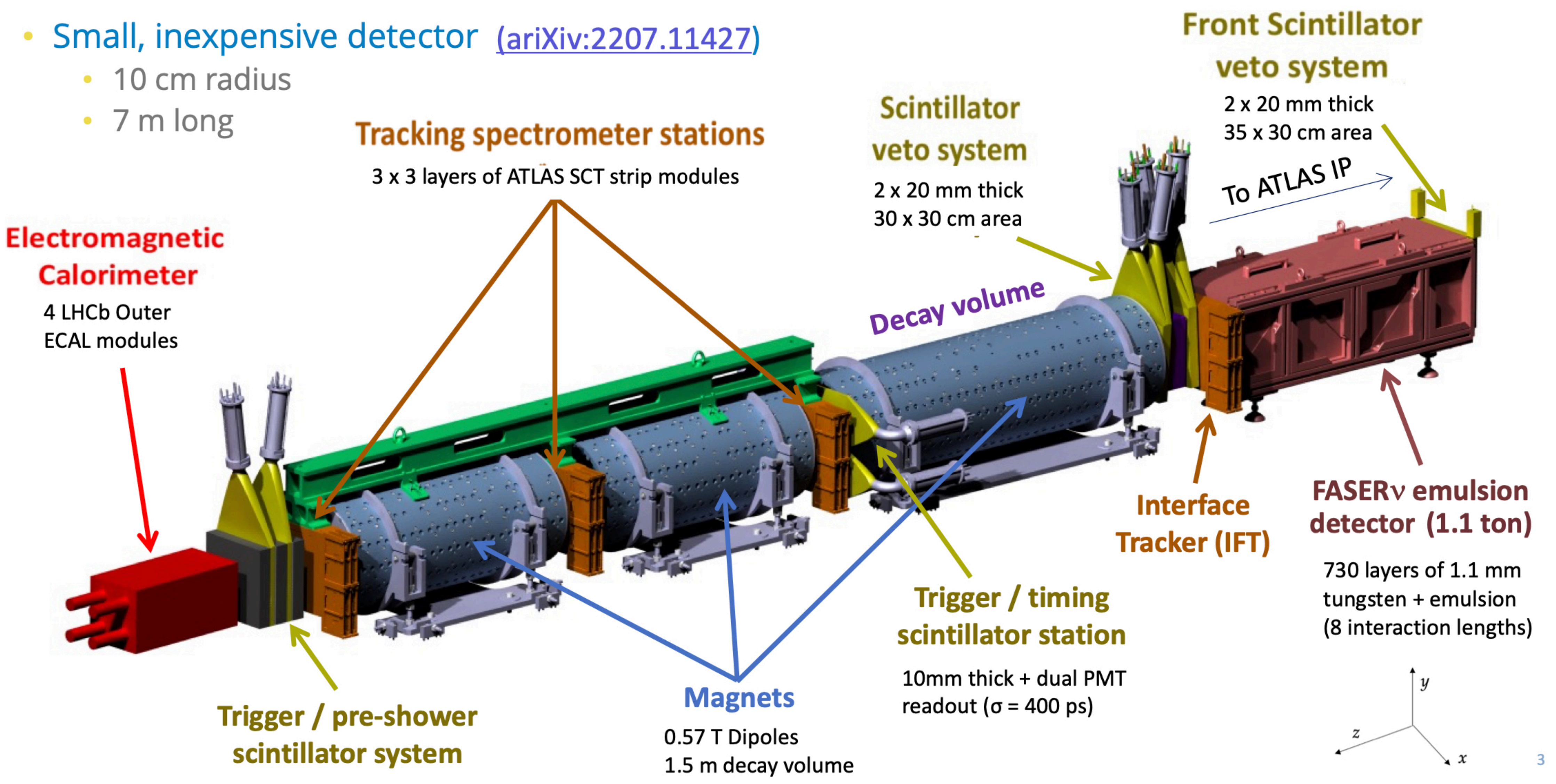
3

Neutrino Physics: FASERν and SND@LHC

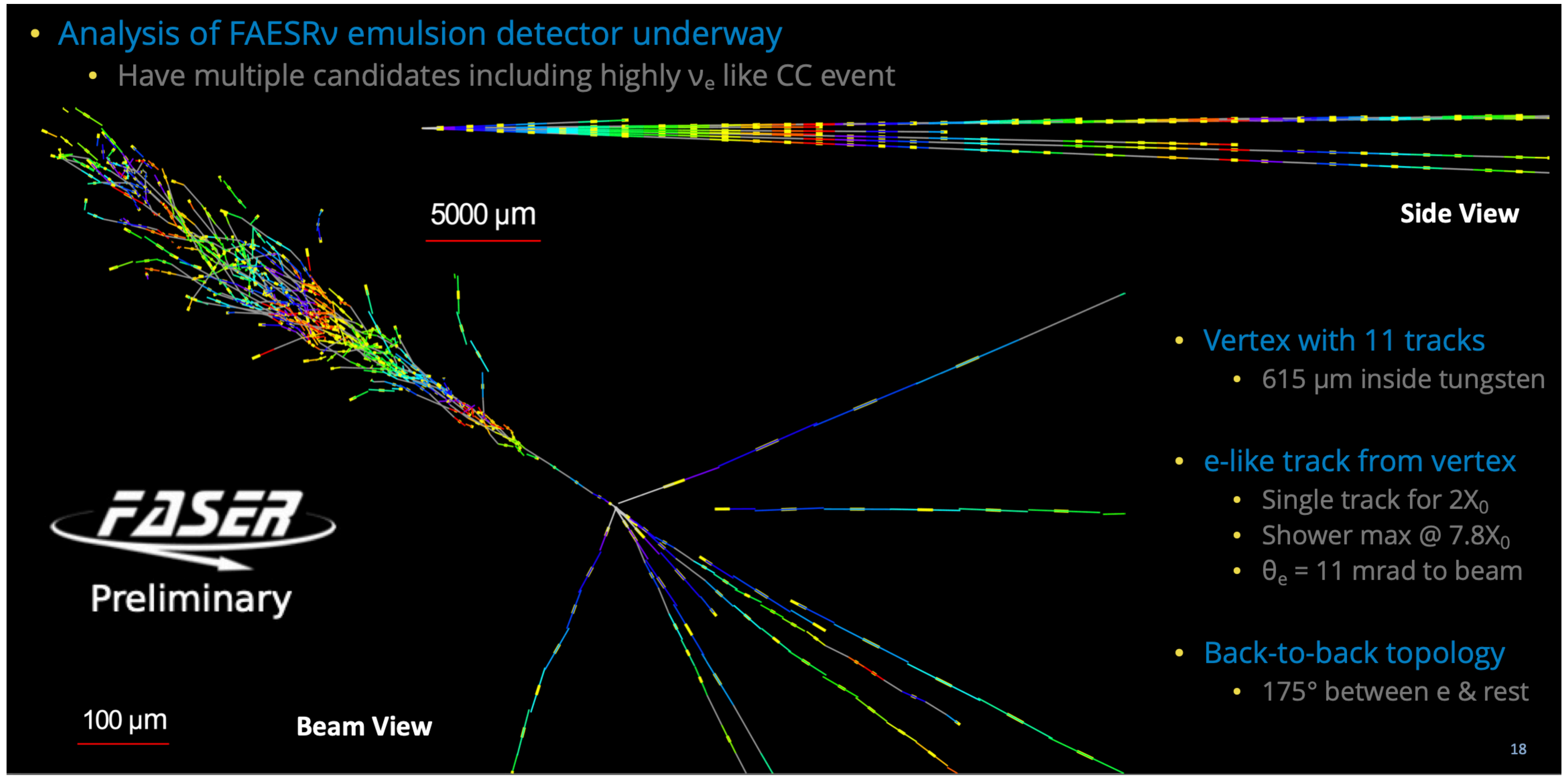
Among other goals:
measure neutrino cross sections in energy ranges never explored before, of relevance to cosmic neutrino studies, and flavour-tagged



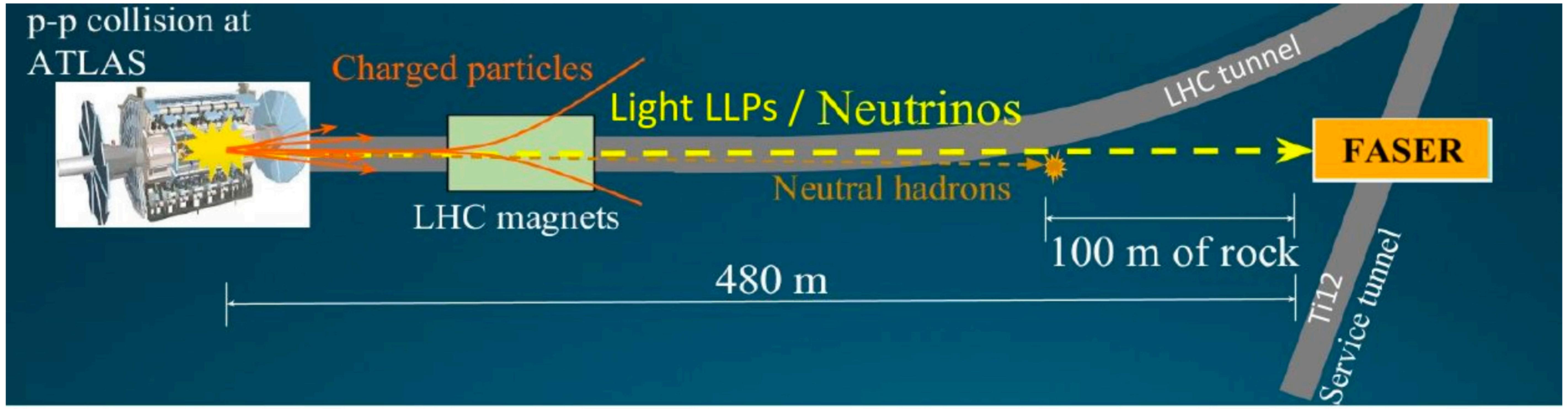
FASER/FASERν



- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long

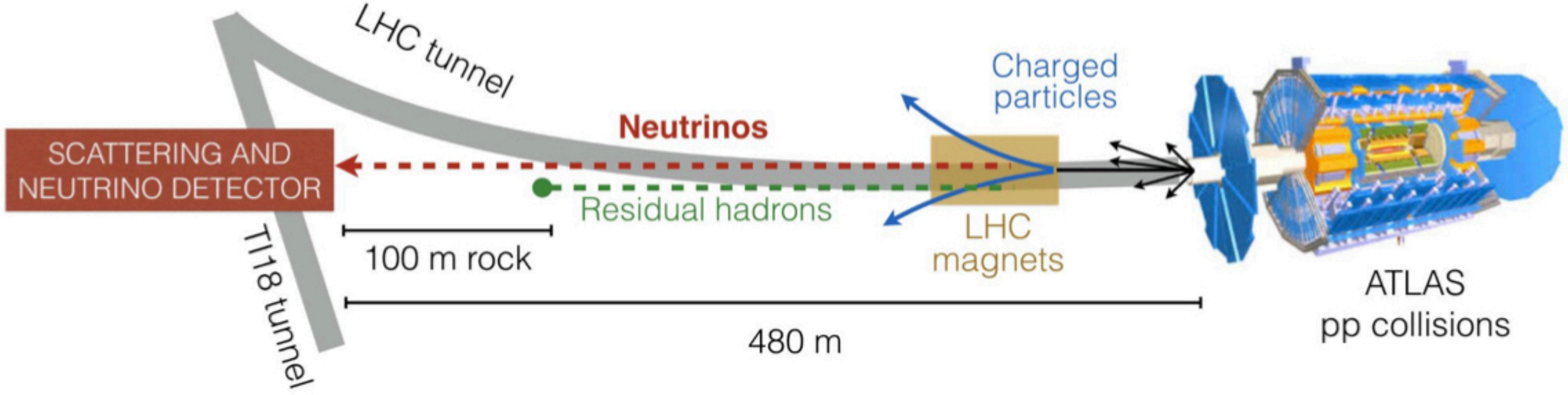


- Analysis of FAESRν emulsion detector underway
  - Have multiple candidates including highly ν_e like CC event
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest



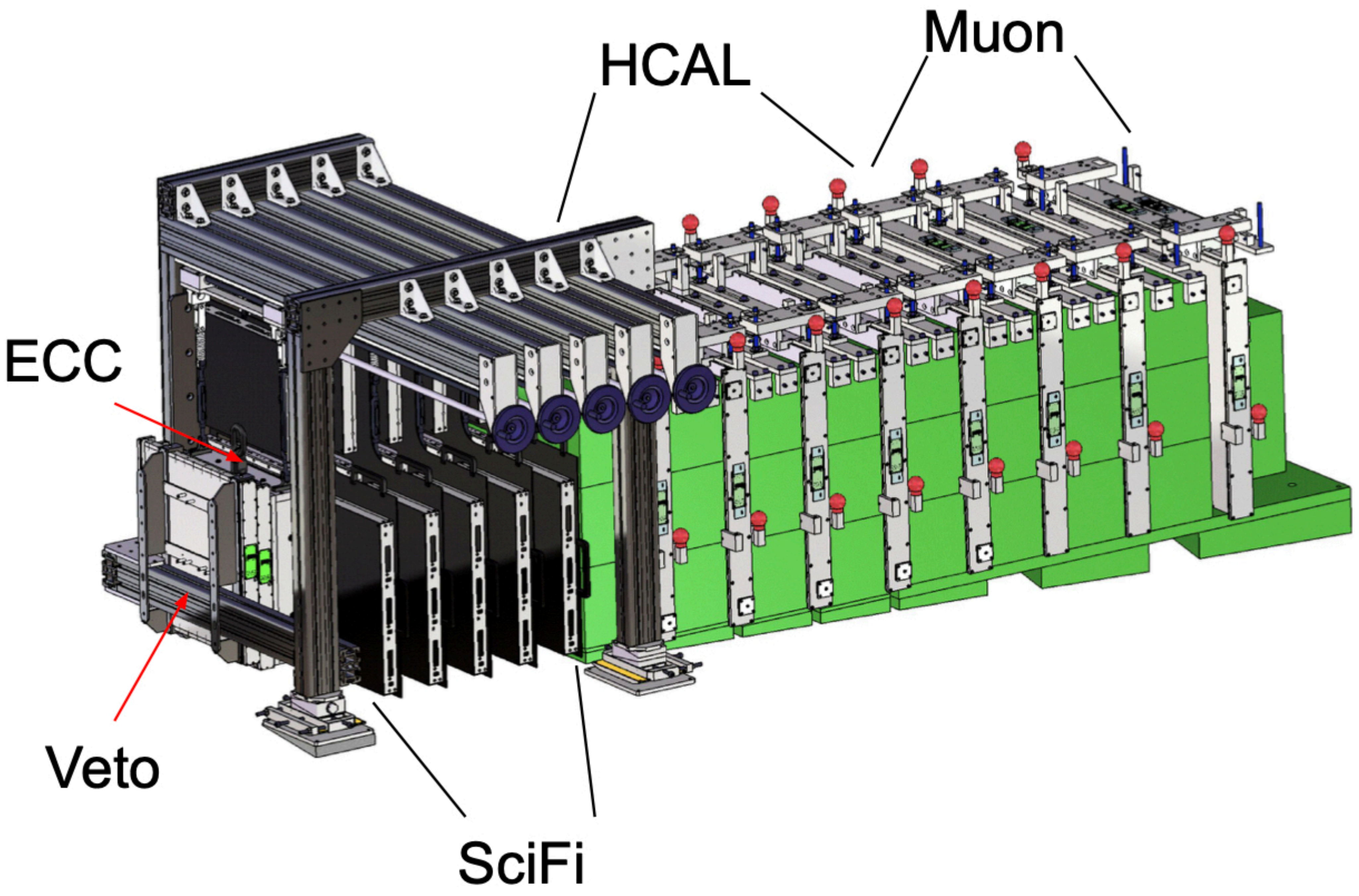
Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

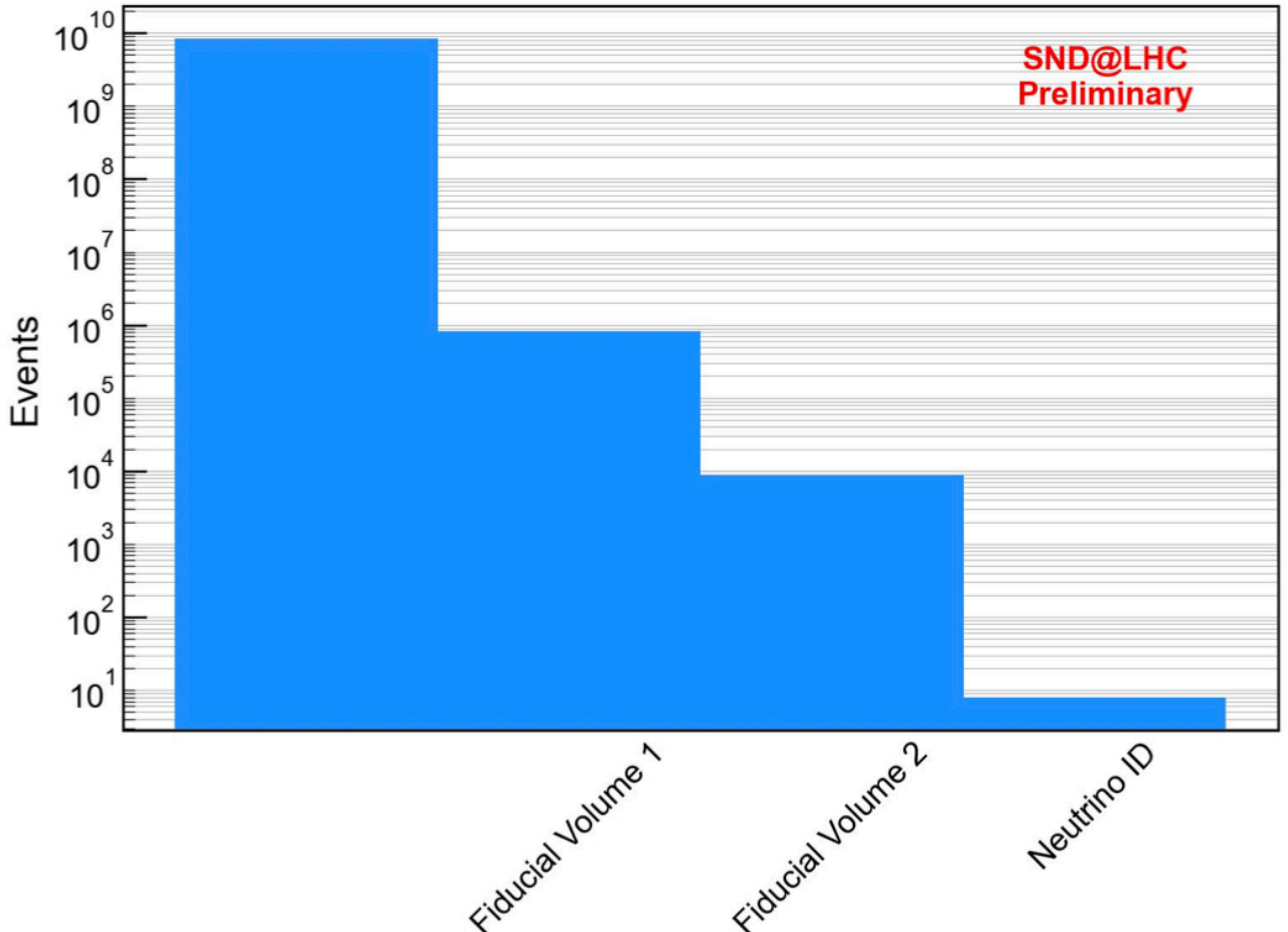
SND@LHC



- About 480 m from ATLAS interaction point
- TI18 tunnel
  - Used in the past as transfer line from SPS to LEP
- Shielded by 100 m of rock and LHC magnet deflection
- Angular acceptance: $7.2 < \eta < 8.4$
- First phase: collect 250 fb^{-1} in Run 3

Observed ν_μ **candidates**: 8 (expected 5)
Preliminary estimate of background yield: 0.2





2022 run:

8 ν_μ candidates (exp 5)

estimated bg 0.2

- Those 3000 papers reflects the immense potential of LHC to probe the fundamental dynamics of the SM. A diversity that 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

A question of perspective

- If new data with lepton pairs at high mass become available, and their analysis shows no deviation from the SM, the message should not be
  - **we succeeded in correctly predicting the cross section of lepton pairs at previously unexplored energies 😀 👏**
- and not
  - **we failed to detect a Z’ or an inconsistency in the SM ☹️ 👎**

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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!

New BSM search paradigms

- model-specific searches vs model-independent “object” searches
- direct probes (eg resonances) vs indirect probes (eg EFT)

- The late 70’s - early 80’s witnessed the establishment of the SM (’79 Nobel prize, success of QCD, W/Z discovery, …) and the expansion of confidence in the gauge and symmetry paradigm (GUT’s and SUSY), with a flourishing of models for extensions of the SM and the identification of the ultimate theory. This was a cataclysmic philosophical shift, putting theory ahead of experiments.

- Experiments started focusing on tests of specific models, searching for proton decay, SUSY particles, preons, etc

- The **hierarchy problem** was identified as a serious conceptual limitation of the SM early on (’t Hooft ’79), but it exploded as a main driver of BSM speculation as the SM itself became more firmly established at LEP, shifting the focus towards the search of its **natural** solution

- A first example of model-independent exploration of the SM limitations emerged at LEP, driven by the powerful indirect sensitivity to new physics enabled by the accurate measurements, with the introduction of the S,T,U ($\varepsilon_{1,2,3}$) parameters (similar EFT approaches were in parallel pursued before that at low energy, eg in the study of c/b hadrons)

- But searches and analyses at the Tevatron, and in the the planning for LHC, remained focused on the direct search of new particles, thanks to the powerful energy and mass reach

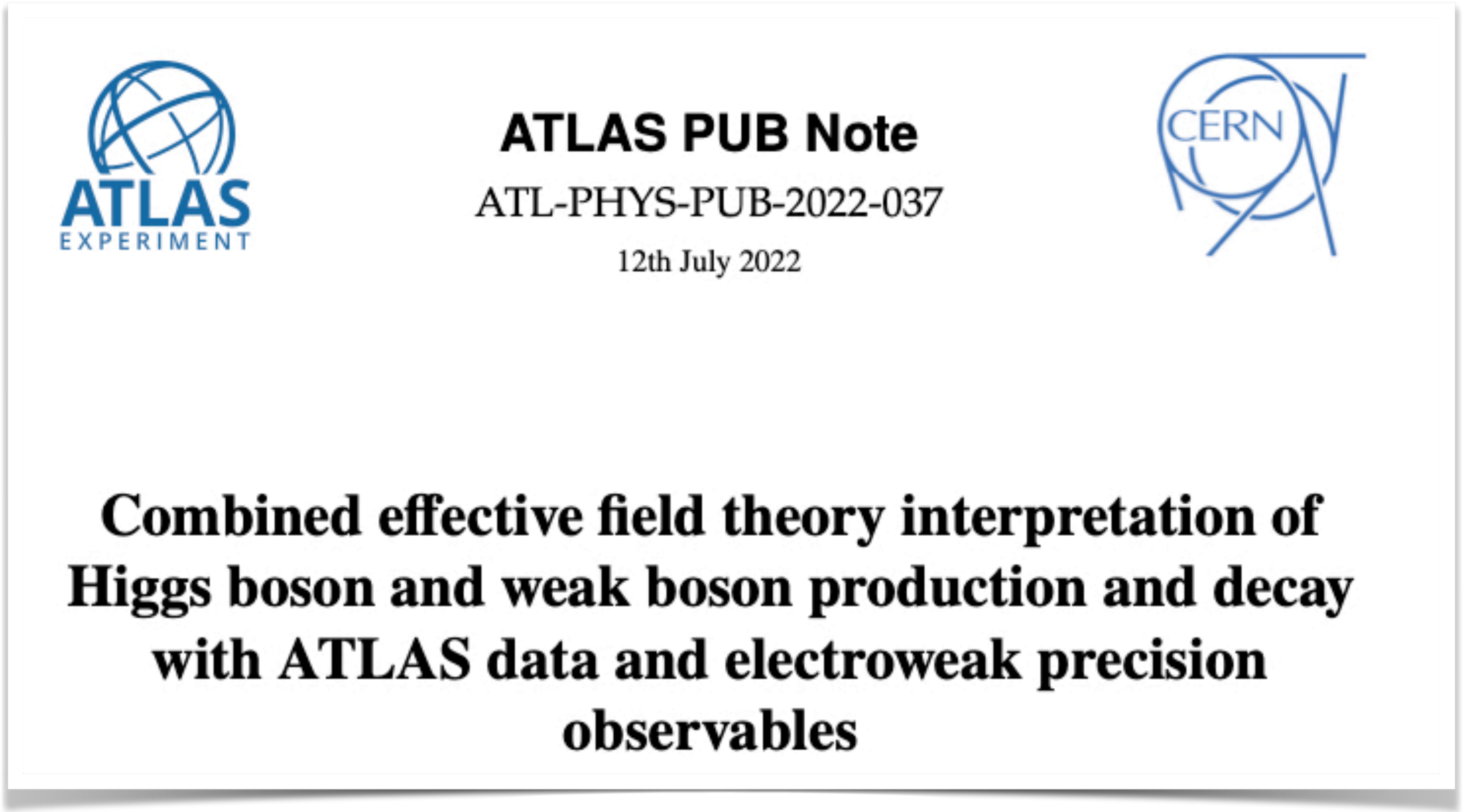
- With the LHC approaching, it became clear that any discovery would have been a “model-independent” one: the observation of a new phenomenon was not going to single out at first a specific model, but at best to provide evidence for general properties (eg multijets or missing ET signatures). The task of identifying a specific model relied on the solution of the “inverse problem”, something more easily done with a structured model-independent approach, whereby many models at the same time could be tested against the features of the new data.

- This approach was particularly justified by the realization that the class of BSM scenarios discussed in the 90’s was too limited, followed by the explosion of new and phenomenologically diverse models to address naturalness (extra dimensions, Higgs-less theories, …)

- **Simplified models** and **EFTs** became the new paradigm.

    - the former to parametrize specific final state features, characteristic of BSM signatures, such as missing energy, high-pt leptons, heavy quarks, multijets, etc

    - the latter covering indirect signals, possibly manifest through precision measurements of slight deviations from predicted SM behaviours



ATLAS PUB Note

ATL-PHYS-PUB-2022-037

12th July 2022

Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables

https://inspirehep.net/literature/2134693

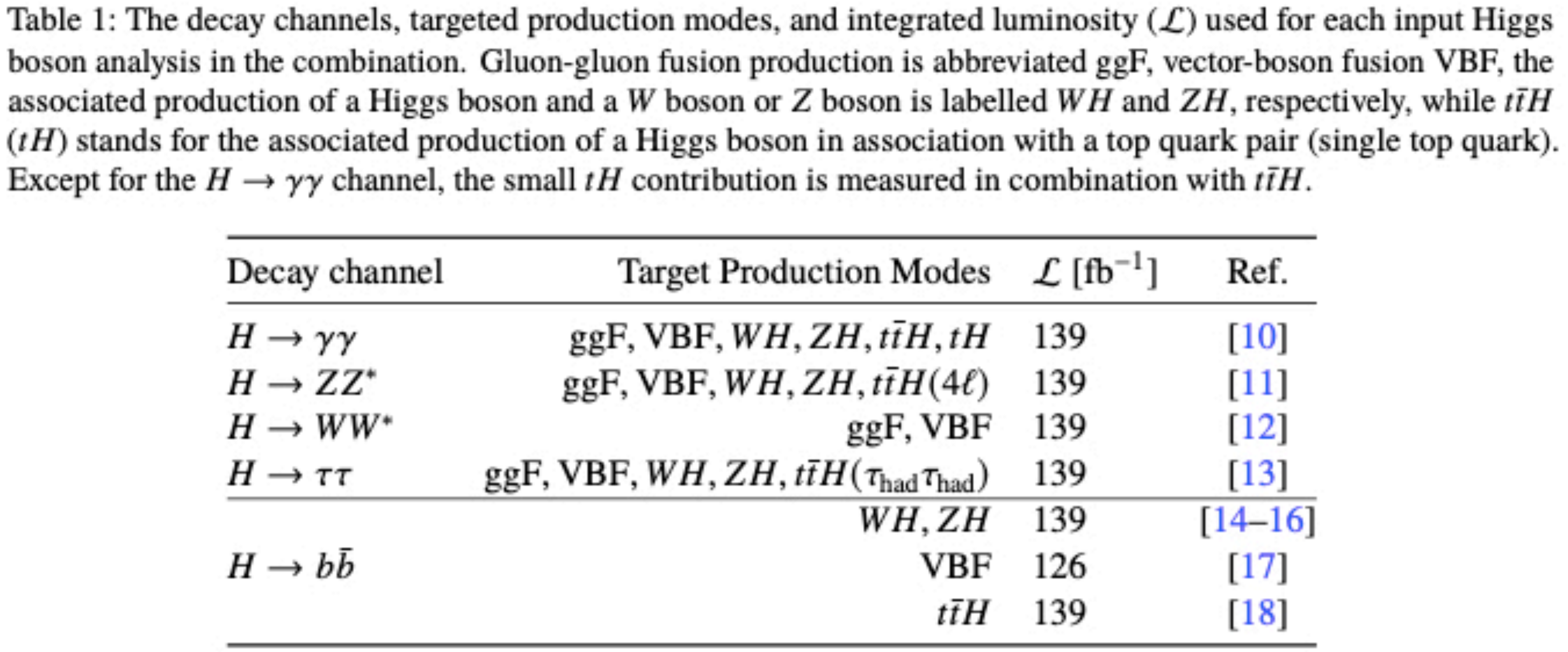
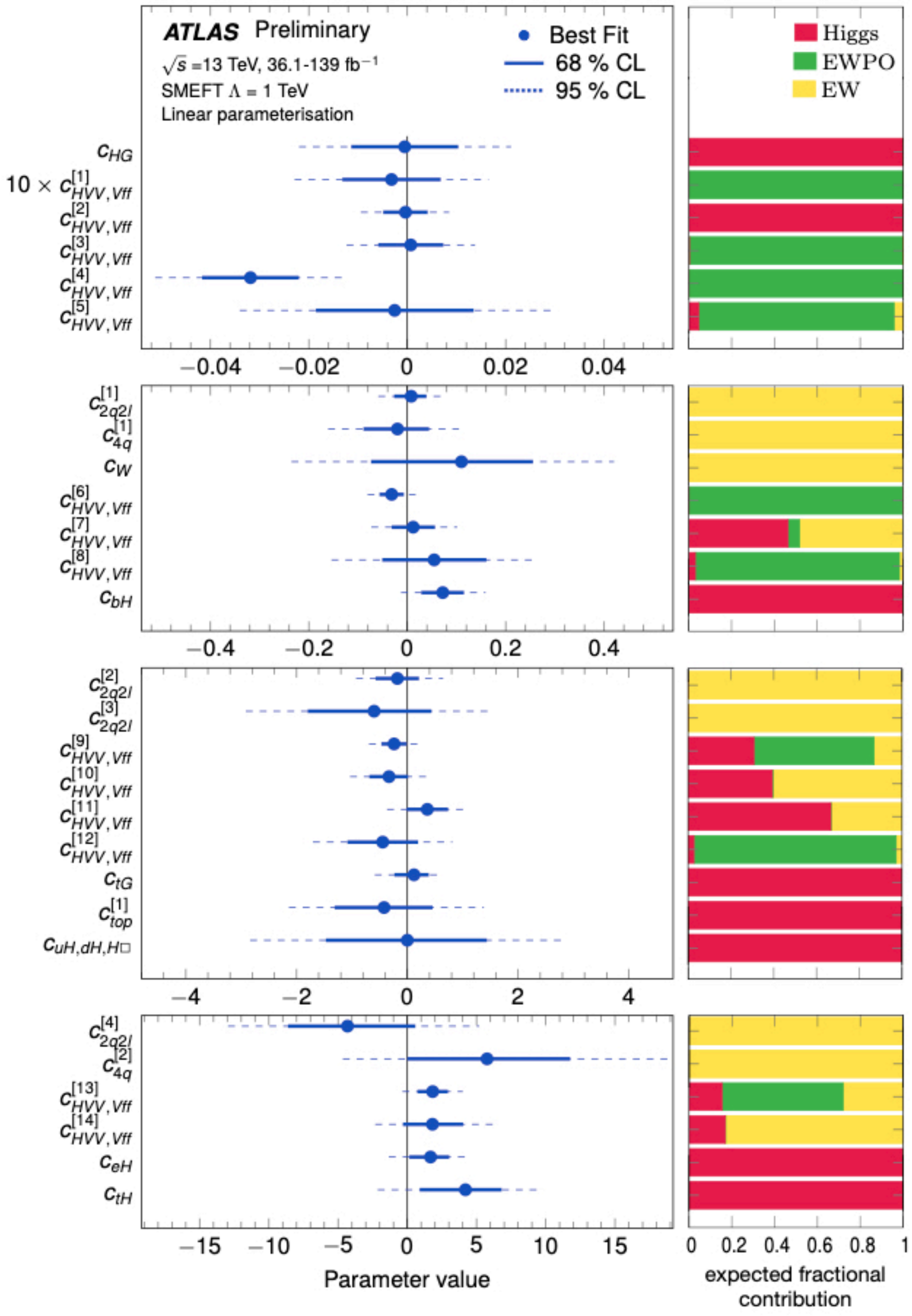


Table 1: The decay channels, targeted production modes, and integrated luminosity ($\mathcal{L}$) used for each input Higgs boson analysis in the combination. Gluon-gluon fusion production is abbreviated ggF, vector-boson fusion VBF, the associated production of a Higgs boson and a W boson or Z boson is labelled WH and ZH, respectively, while $t\bar{t}H$ (tH) stands for the associated production of a Higgs boson in association with a top quark pair (single top quark). Except for the $H \to \gamma\gamma$ channel, the small tH contribution is measured in combination with $t\bar{t}H$.

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139	[10]
$H \to ZZ^*$	ggF, VBF, WH, ZH, $t\bar{t}H(4\ell)$	139	[11]
$H \to WW^*$	ggF, VBF	139	[12]
$H \to \tau\tau$	ggF, VBF, WH, ZH, $t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]
$H \to b\bar{b}$	WH, ZH	139	[14–16]
	VBF	126	[17]
	$t\bar{t}H$	139	[18]



caveats…

$$L_{eff} = L_0 + \sum_n \frac{c_n}{\Lambda^n} L_n$$

- What is constrained by precision observables in EFT approaches are ratios of a coupling strength (the generic c_n above) and the scale of the new physics Λ:

$$c / \Lambda < 1/\Lambda_{max} \Longrightarrow \Lambda > c\, \Lambda_{max}$$

- If c = O(1), $\Lambda \gtrsim \Lambda_{max}$, maximizing the energy reach for strongly-coupled BSM scenarios. For weakly coupled theories, or for loop-induced BSM effects, $c \ll 1$ and sets poorer limits on Λ

- Strong limits on forbidden decays, such as K→μe or μ→eγ , interpreted in the context of c=O(1), give limits in the range of several hundreds TeV … but in practice most models for, eg, μ→eγ, are constrained by data at the level of few hundred GeV

- LEP EW precision tests properly established the mass range for both the top quark and the Higgs boson, well above LEP's reach for their direct discovery. However, the same tests could not constrain the mass scale of SUSY particles above the direct production limits. SUSY particles could have been behind the corner, without leaving a trace in the EFT analysis, given the available precision

- EFT is the best tool to analyze and document in a model-independent way the outcome of precision measurements. But its use to establish constraints on high-mass phenomena, and to project the sensitivity to new physics, is strongly dependent on the concrete examples of new physics one is considering, and it cannot be used to set universal model-independent constraints on the scale of new physics

- This issue should enter more prominently in the discussions about the future of accelerator physics, where its neglect or consideration lead to different weights in the assessment of different strategies.

A model-independent "sort-of-EFT" analysis of Mercury's orbit anomaly

$$V_{eff}(M,R) = -\,G_N \frac{M}{R}\left[1 + \sum_{n\geq 1} v_n \left(\frac{R_S}{R}\right)^n\right]$$

with $R_S = 2G_N M/c^2$ and $R_S/R \sim (v/c)^2$

- This could have been done before Einstein's **General Relativity**, as a GR EFT precursor
- The precise study of Mercury's perihelion precession would have given values of v_n coefficients consistent with General Relativity results.
- However out of this exercise we would not have recovered the full "non-perturbative" version of the underlying theory, or even predicted the deflection of light by the gravitational field.
- Even Eddington's experimental input may not have helped, as it's not obvious (not to me at least!) how to connect the EFT coefficients above to light's deflection in the gravitational field of the Sun
- Here the "new physics" is General Relativity, and uncovering the full theory required a quantum leap that seems to go beyond a basic model-independent approach to canonical observables and expansion parameters

➡ ***an intrinsic limitation of the power of EFTs or model-independent searches for new physics?***

- **NB** In the analysis of the Sun-Mercury 2-body problem, the expansion in powers of R_S/R is equivalent to an expansion in powers of $(v/c)^2 \sim GM/R$ ==> see today's non-relativistic EFTs

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:

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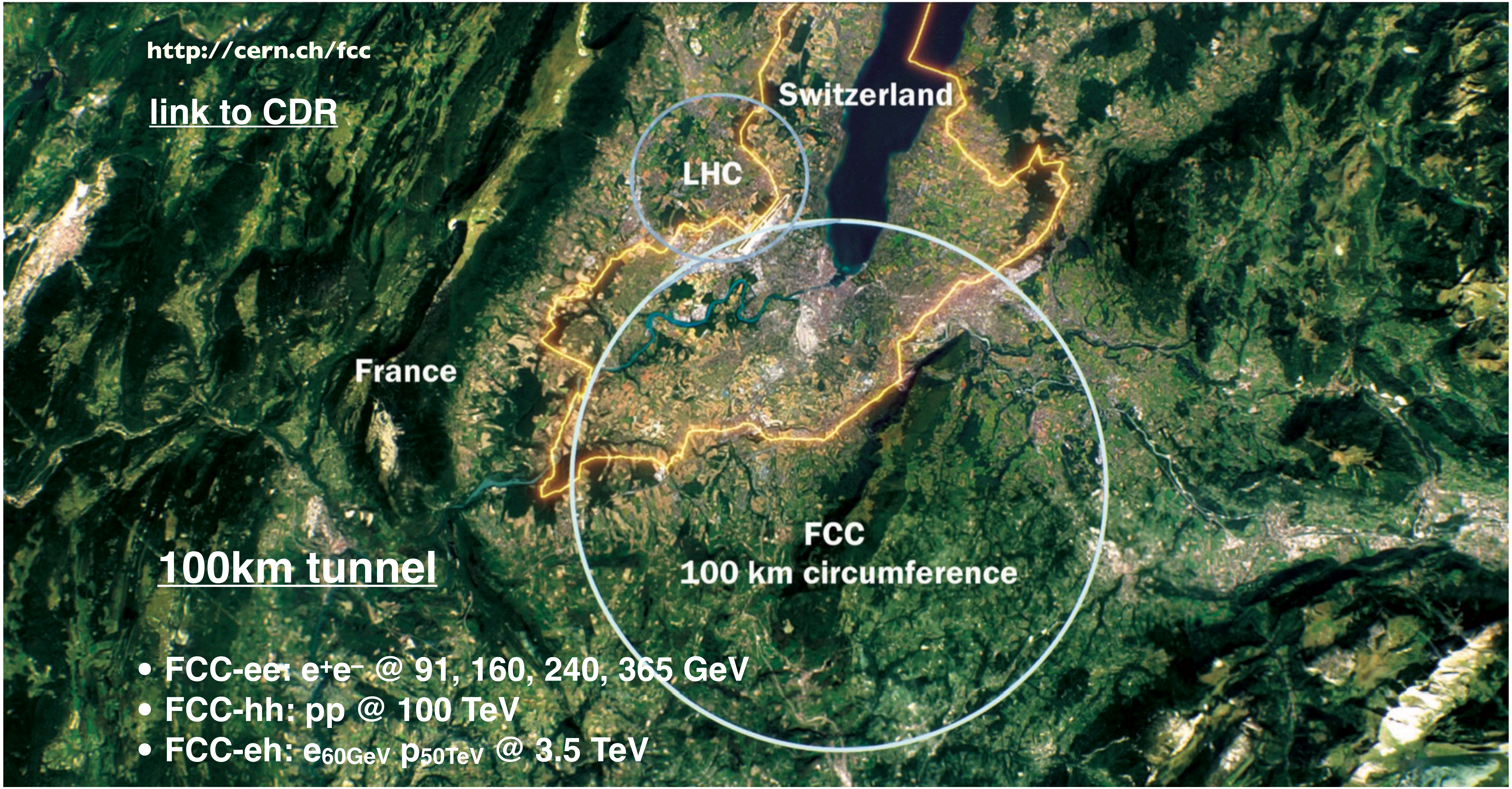
(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

CERN, beyond the LHC: 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_{60GeV} p_{50TeV} @ 3.5 TeV

Event rates: examples

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

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

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

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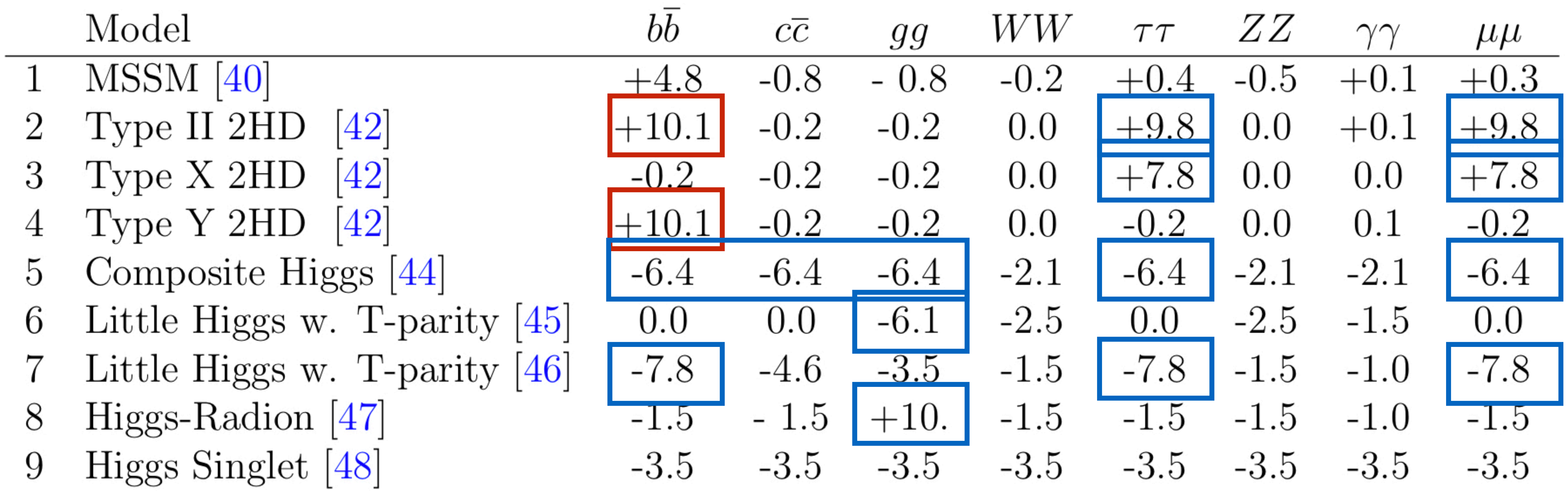
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Guaranteed deliverables: Higgs properties

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

T. Barklow et al, 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

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) ~O(10^{-3}) ⇒ **O(10^{7}) evts for Δ_{stat}~%**

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

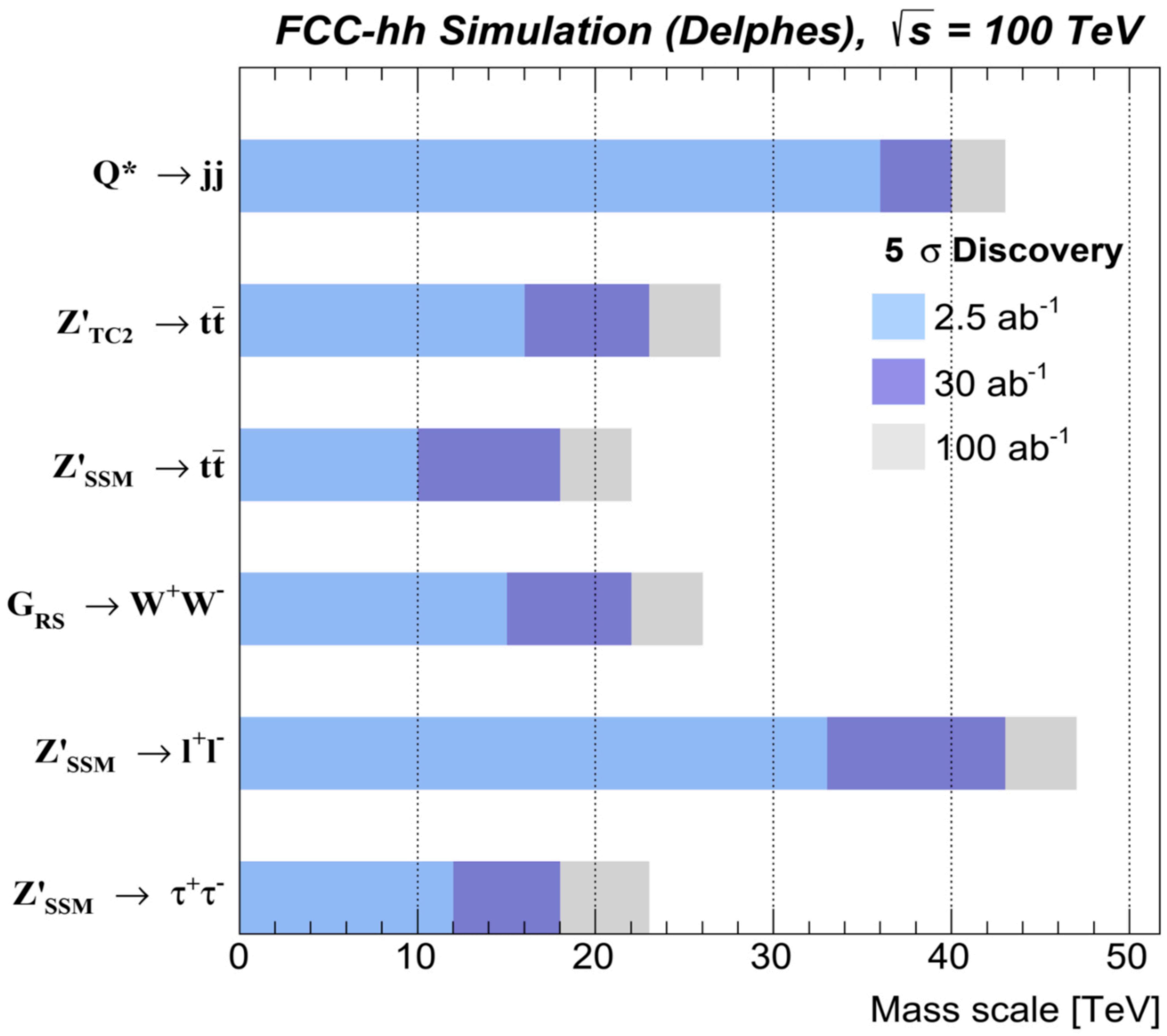
pp collider is essential to beat the % target, since no proposed lepton collider can produce more than O(10^{6}) H's

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

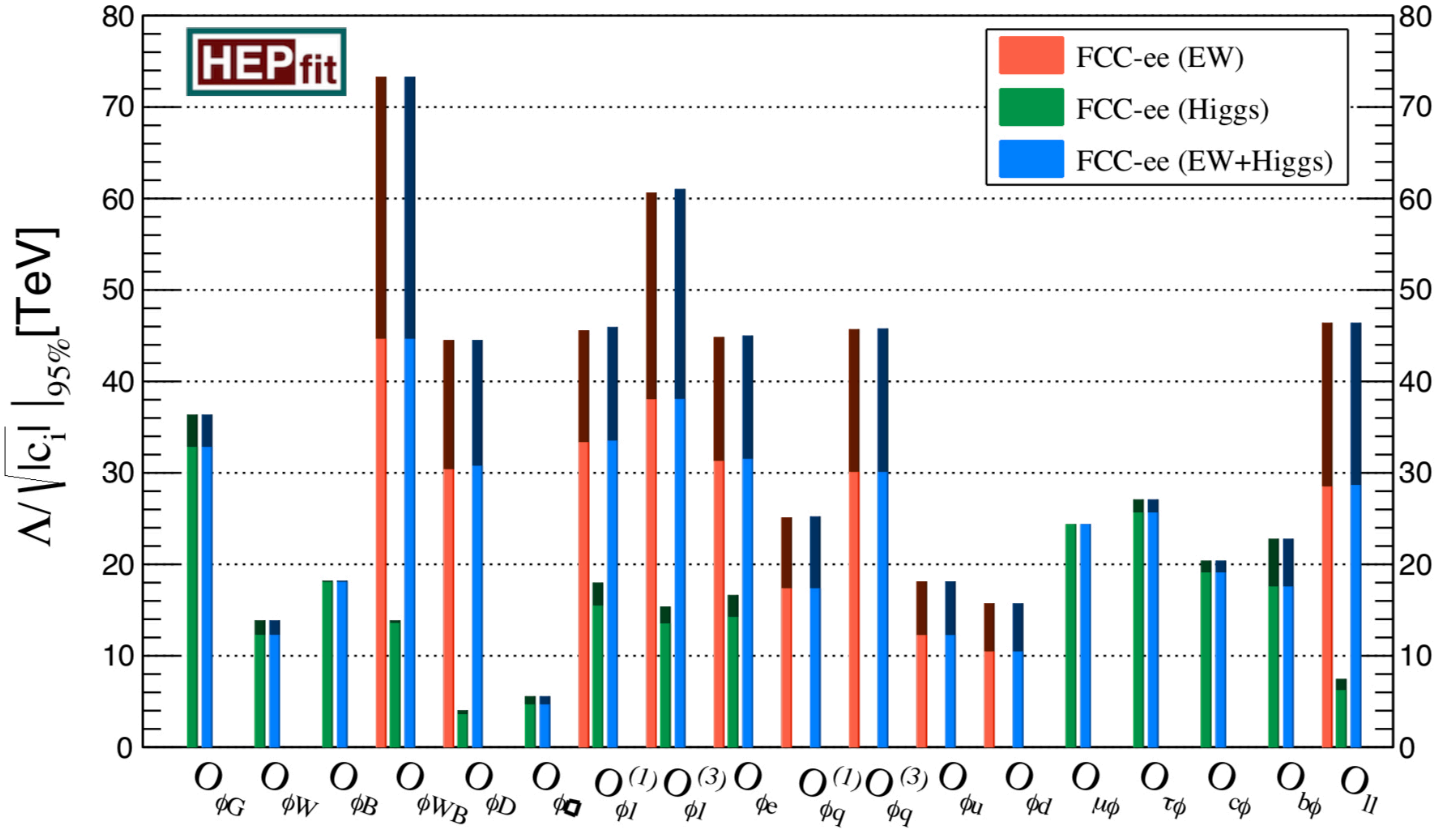
** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

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

s-channel resonances

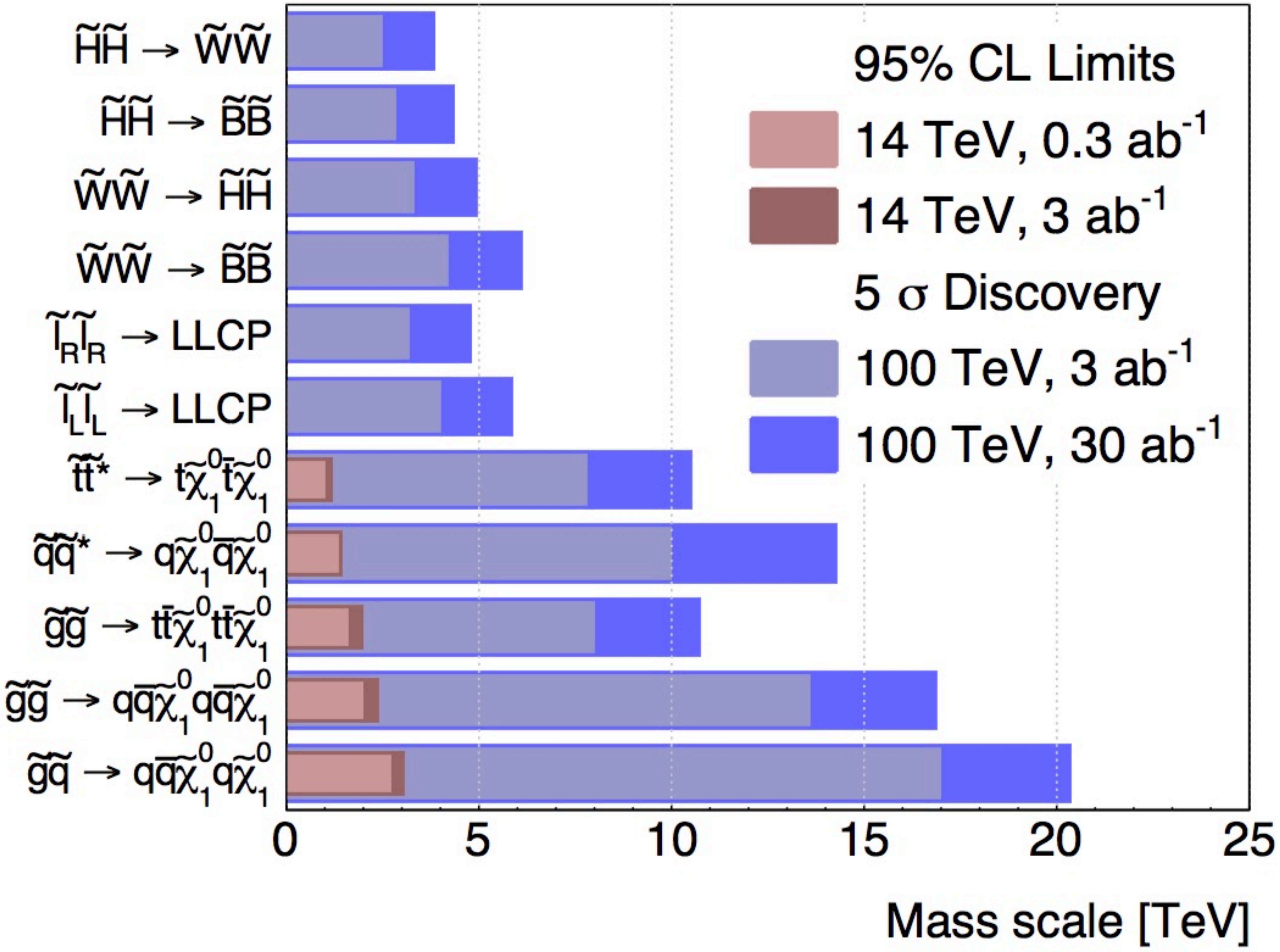


100 TeV allow to directly access the mass scales revealed indirectly by precision EW and H measurements at the future e+e– factory



Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

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)

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

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

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

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

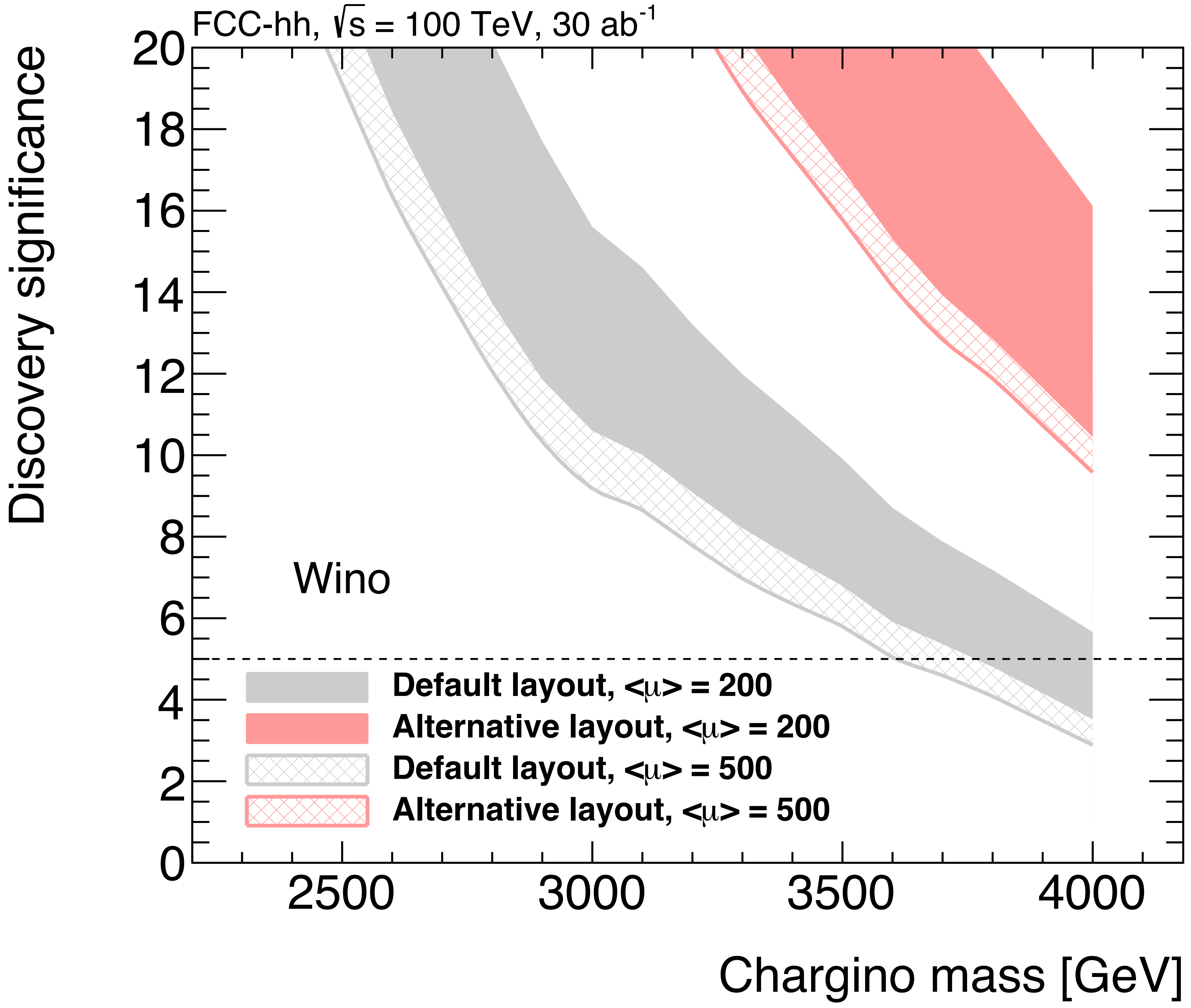
$$\Omega_{wimp}\ h^2 \lesssim 0.12$$

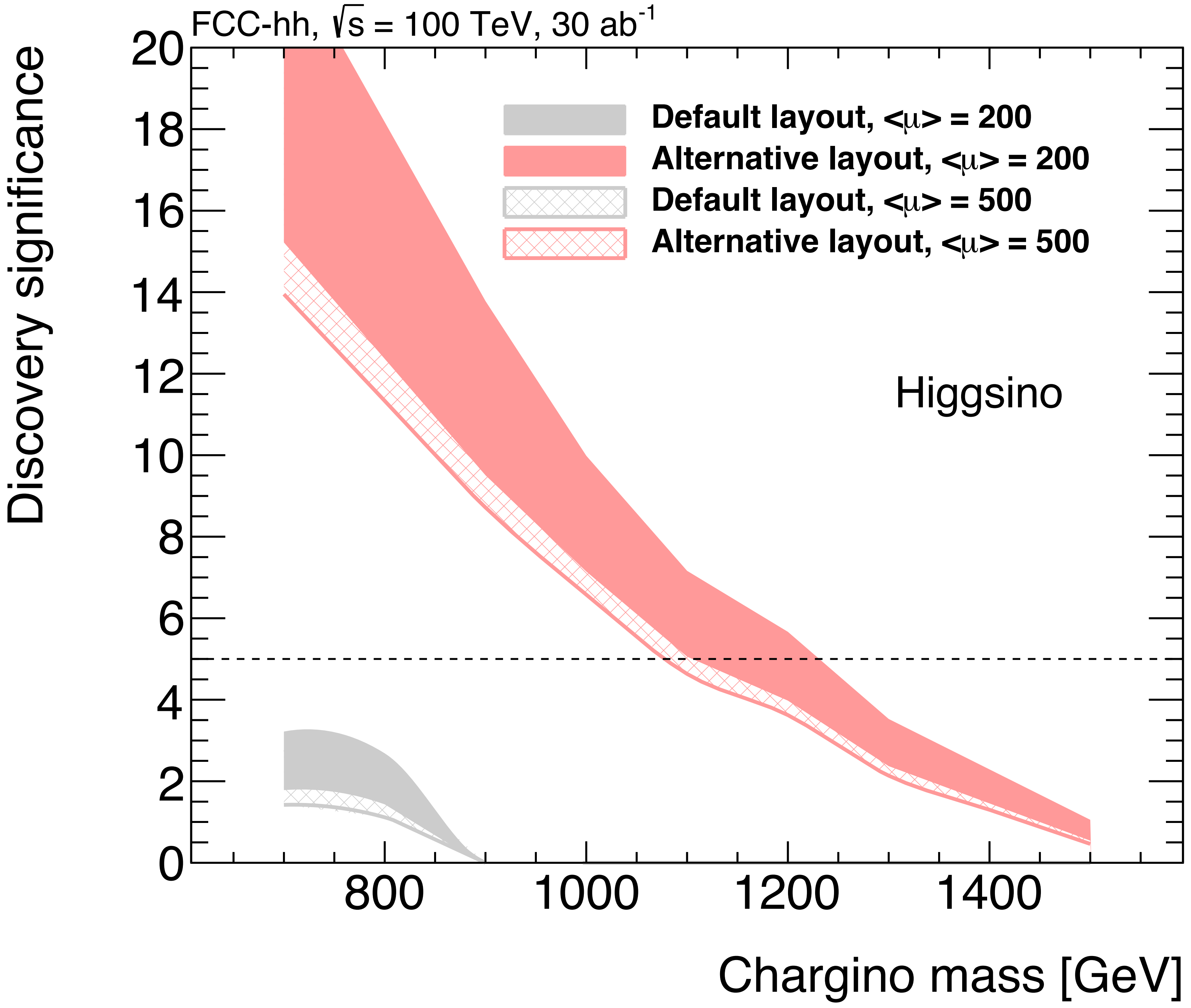
$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3}\right)^2$$

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.

Disappearing charged track analyses

(at ~full pileup)





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

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

Final words

- Understanding the origin of the Higgs and EWSB is a key task, which only colliders — to the best or our current knowledge — can undertake
- The diverse collider phenomenology —particularly the hadronic one —probes a huge dynamical range of phenomena, challenging the theoretical understanding, both at the level of fundamental understanding and of computational complexity.
- The goal of measuring and theoretically describing " SM data " goes hand in hand with the search for BSM physics, whether directly or via precision SM tests.

It provides the motivational challenge and the intellectual reward to ensure the continued progress of collider physics for the next decades