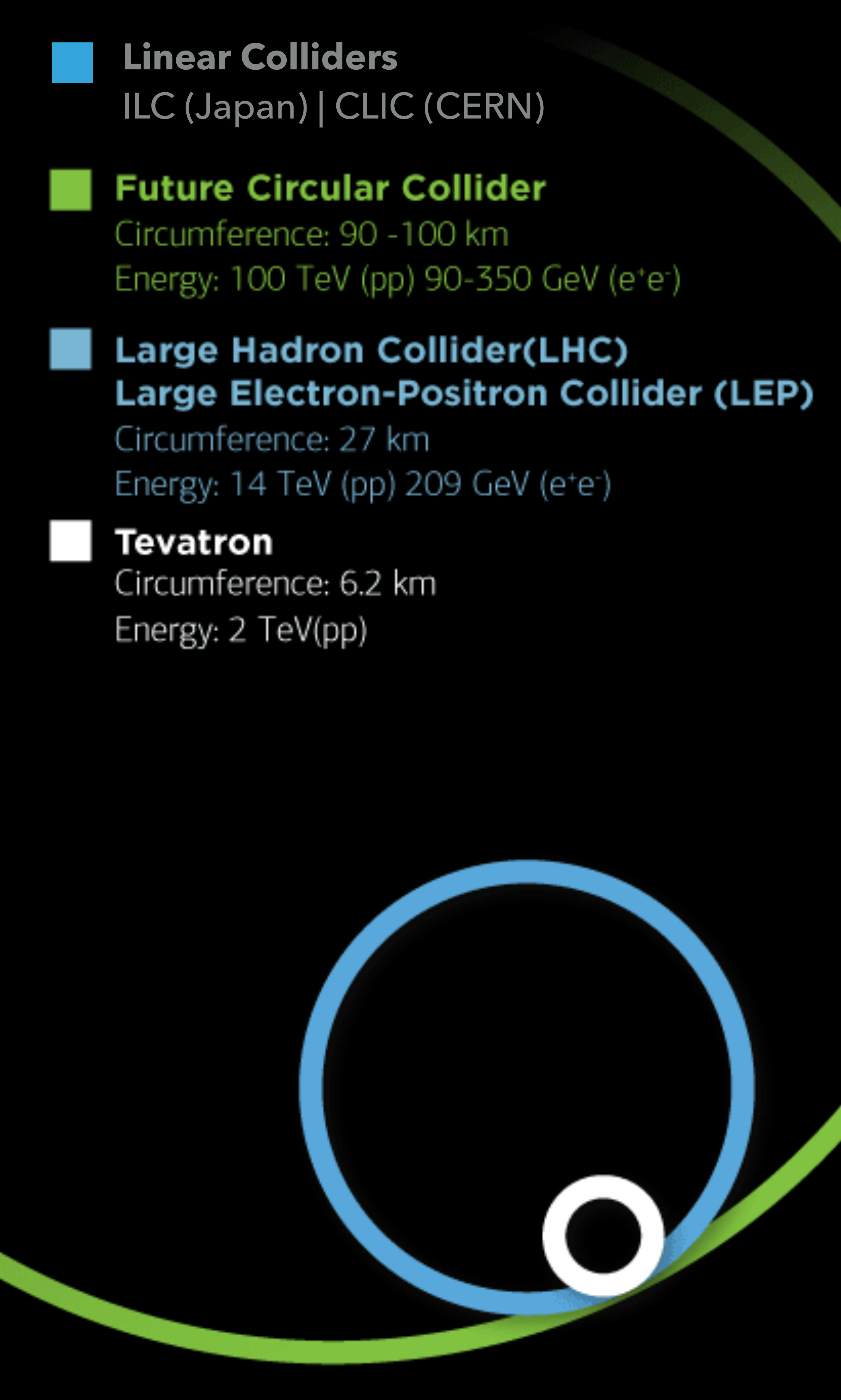


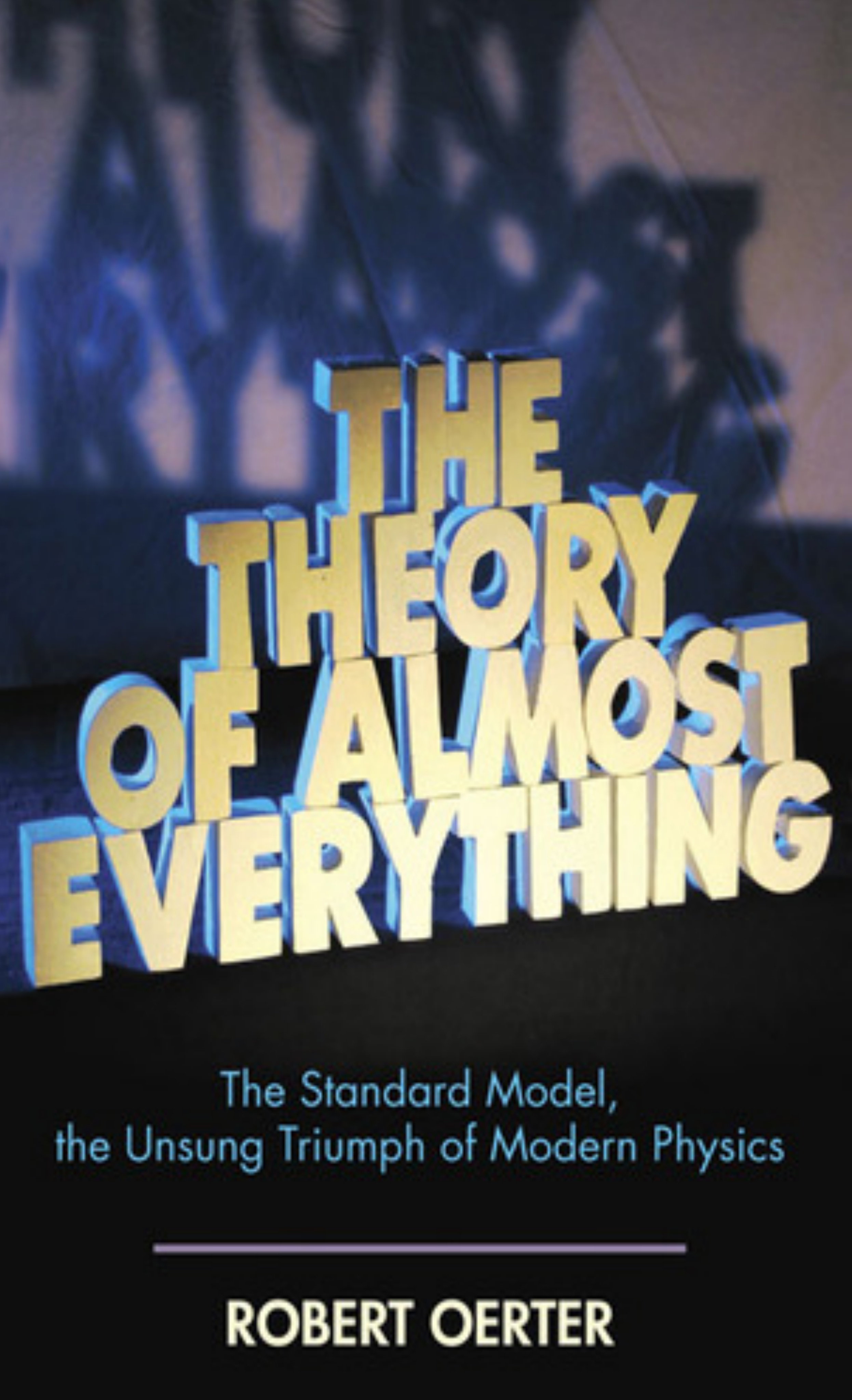
PERSPECTIVES IN PARTICLE PHYSICS AFTER LHC RUN2

Germán Rodrigo

IFIC INSTITUT DE FÍSICA CORPUSCULAR | EXCELENCIA SEVERO OCHOA | CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS | VNIVERSITAT DE VALÈNCIA

Red LHC España

3rd Workshop
Red Española del LHC
CIEMAT, Madrid, 6-8 May 2019



NO CLEAR BSM SIGNAL AT THE LHC SO FAR

- SM based in the simplest gauge symmetries: **SU(3)xSU(2)xU(1)**
- Also the **flavour sector very symmetric (GIM)**
- The **"natural"** theory at **"low" energies** (below the TeVs)
- We should expect that it will break at high energies: **departure scale undetermined | no theory guidance**

EXCELENCIA SEVERO OCHOA

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2019

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ 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	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	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	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	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 $G_{KK} \to WW/ZZ \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass 2.8 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	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 $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 4.4 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		1807.10473
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η^-_{LL}		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV η^-_{LL}		1707.02424
	CI $tttt$	≥1 e, μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\|C_{4t}\| = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV_{\chi\chi}$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \| T_{5/3} \to Wt + X$	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 $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	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	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	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	–	36.1	b^* mass 2.6 TeV		1805.09299
	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	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	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 $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	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	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\|q\| = 5e$	1812.03673
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\|g\| = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [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).

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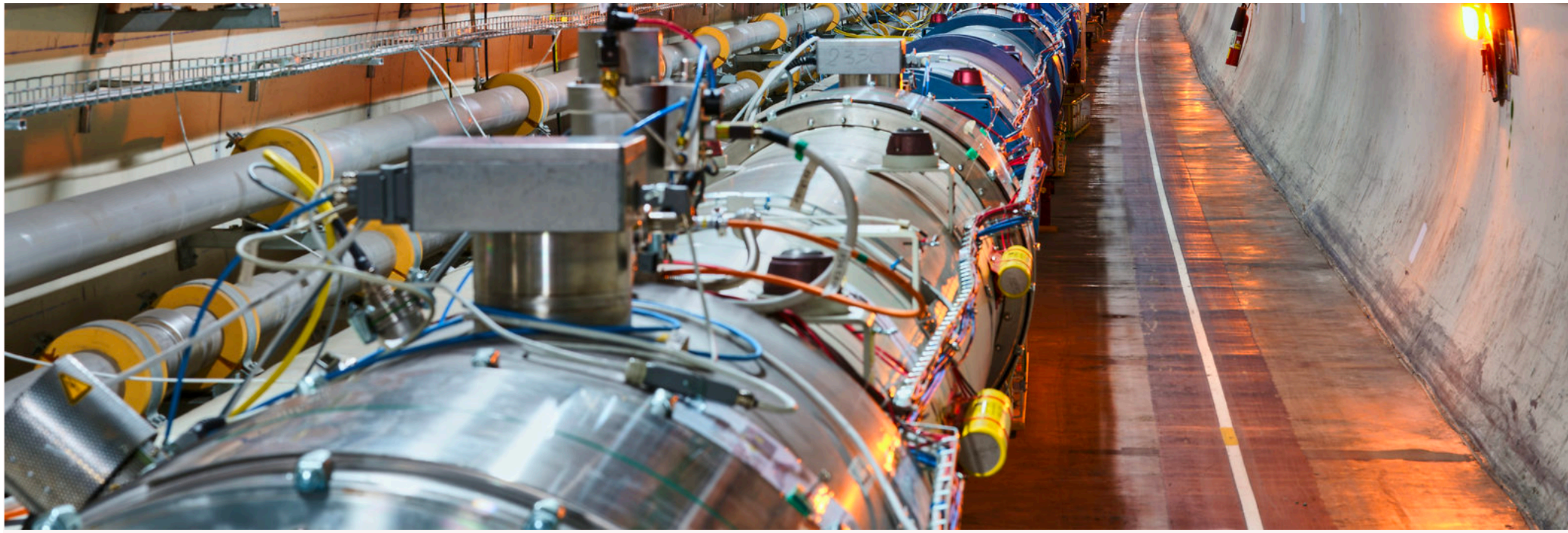
- Very unlikely to be visible in inclusive observables or total decay rates of known particles: the bulk of the contributions at "low energies", the characteristic hard scale is "low energy"

- Higher chances at the tail of differential distributions (not necessarily a clear bump) **"high energy"** characteristic hard scale: more sensitive to **quantum corrections** / missing quantum corrections can fake BSM symmetry topics



Maximilien Brice and Julien Marius Ordan, CERN

The unseen progress of the LHC

05/02/19 | By Sarah Charley

It's not always about what you discover.

"This work naturally pushes our search methods towards making more detailed and higher precision measurements that will help us constrain possible deviations by new physics," Willocq says.

The LHC Precision Program

At the LHC we can do more than searching for bumps !!

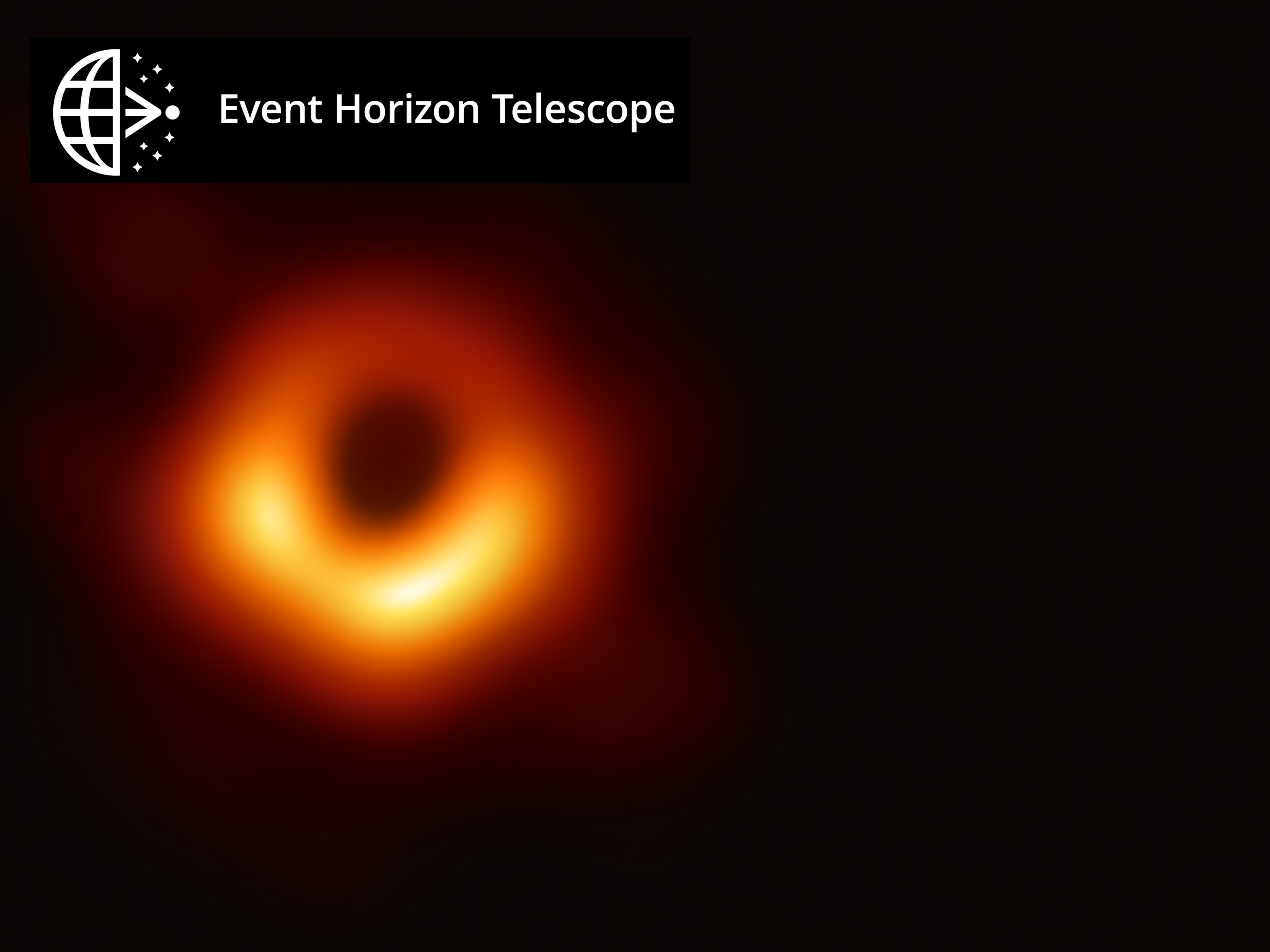
Because of **remarkable progresses** in:

pdf determination
high-order calculations
precise MC generators
analysis techniques

Precision is **not** bureaucratic **certification of SM** success !

Exciting tool to **discover BSM** indirectly. Same chance of success as direct search strategy used to have.

“ Precise measurements of known particles and interactions are just as important as finding new particles


Event Horizon Telescope

Event Horizon Telescope

- **New Physics ?**

Event Horizon Telescope

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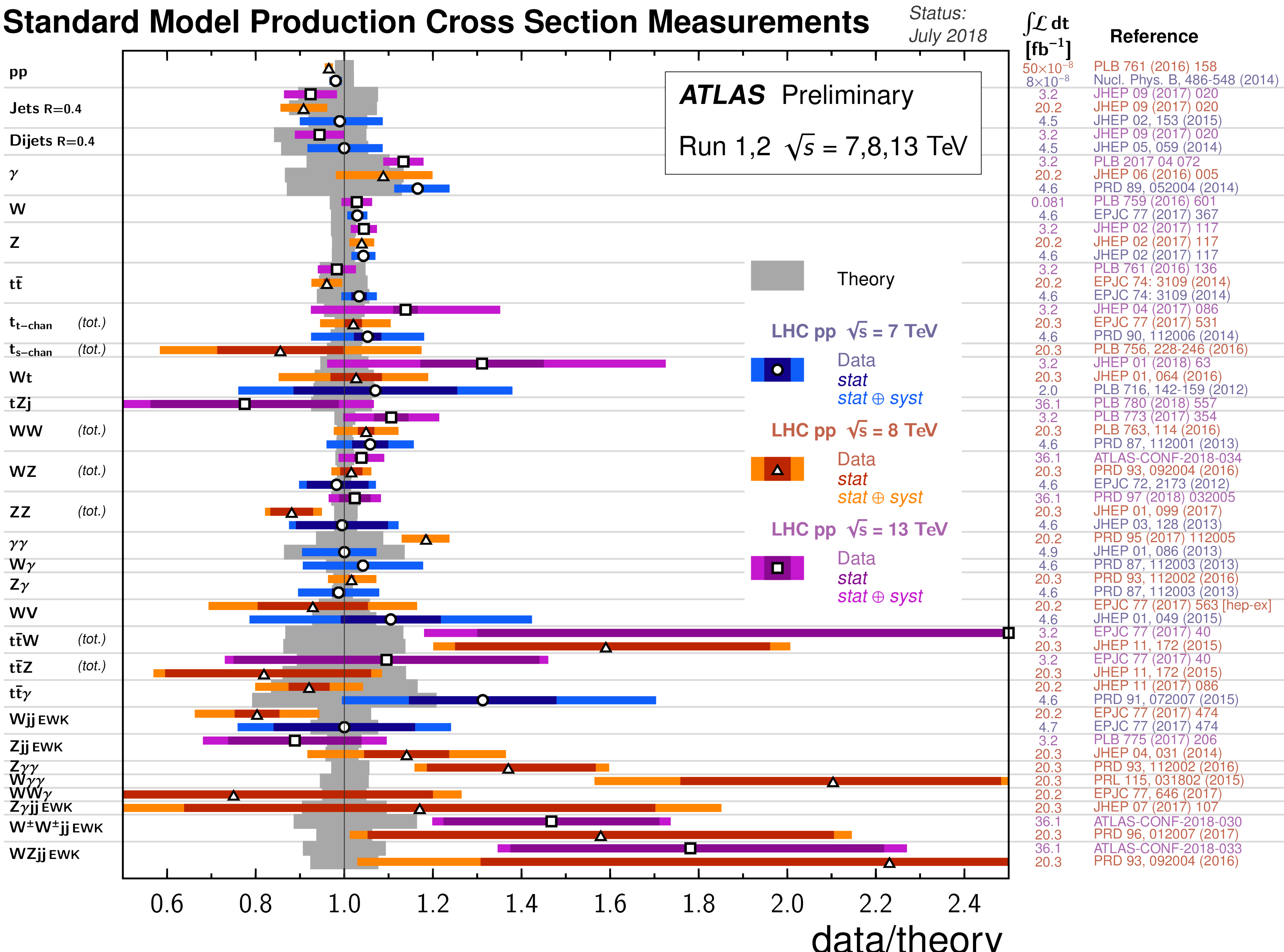
- **A global challenge:** a collaboration of radio telescopes around the world (200 researchers)

DATA/THEORY I INCLUSIVE OBSERVABLES 5-20% THEORETICAL ACCURACY



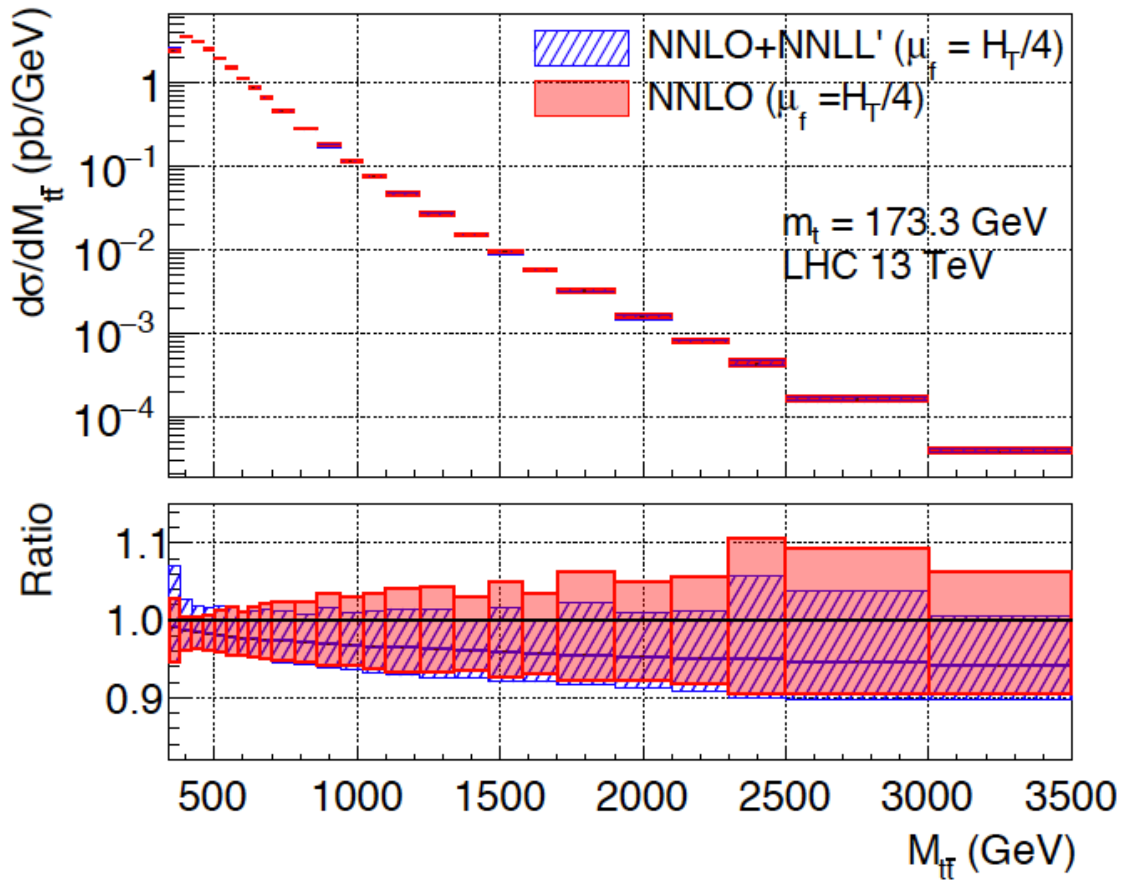
G. Rodrigo, Red LHC 2019

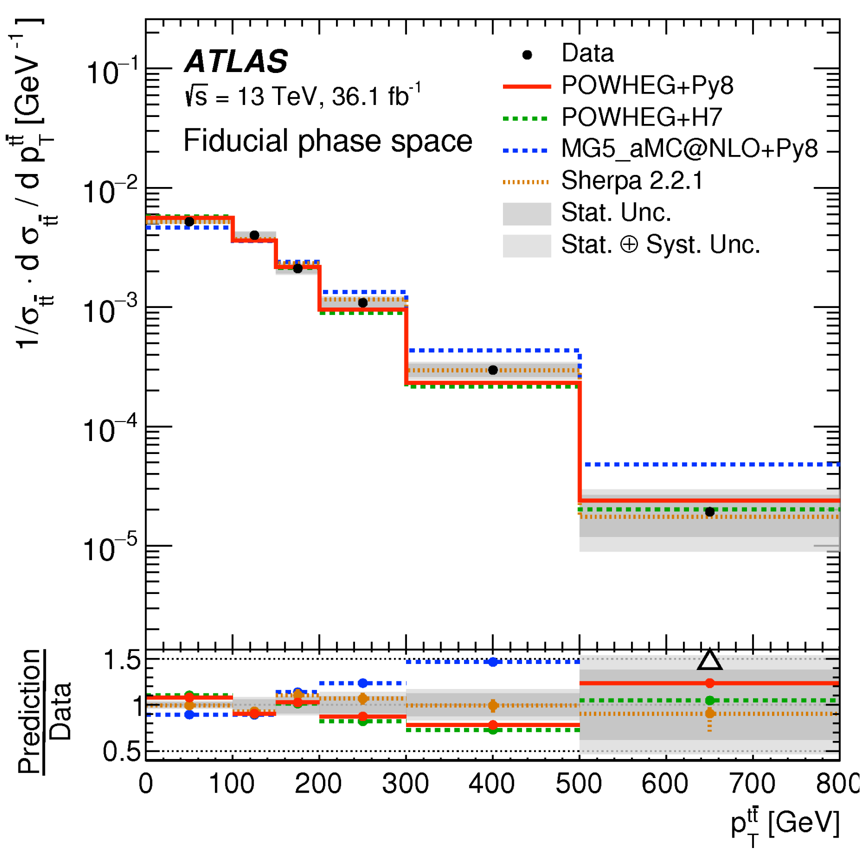
IFIC

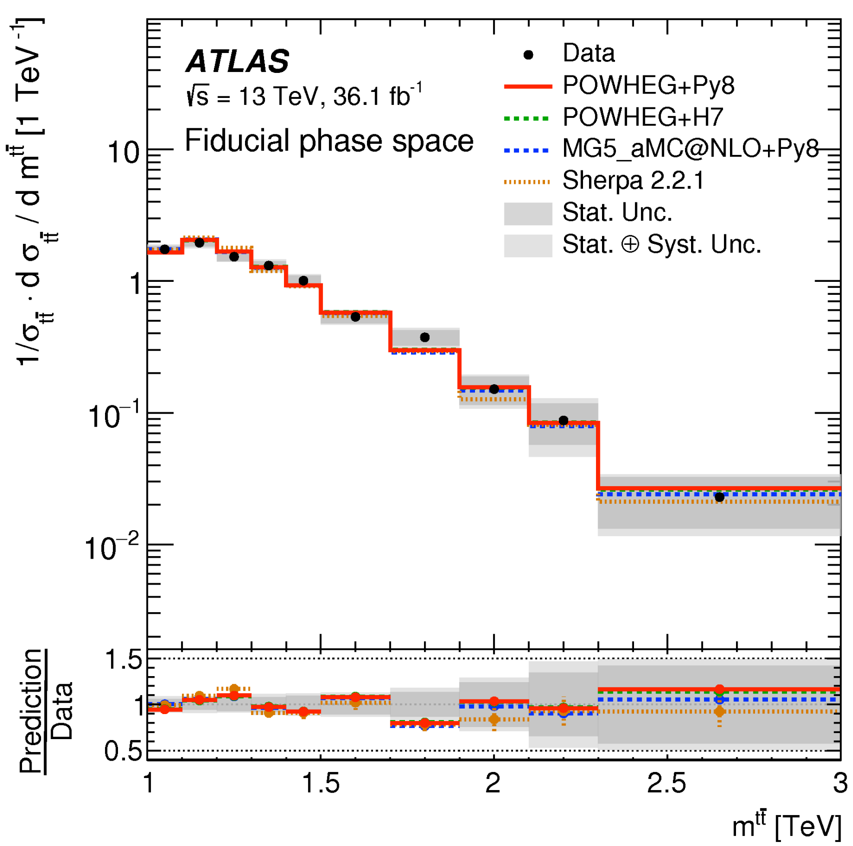
EXCELENCIA SEVERO OCHOA

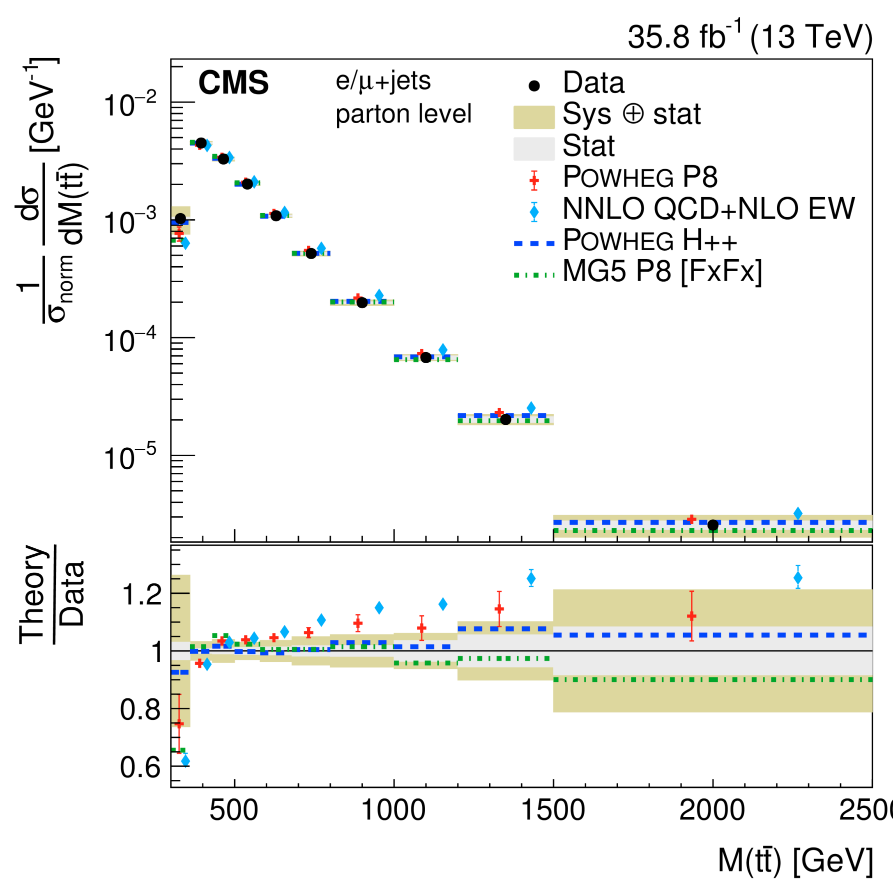
Czakon et al., arXiv:1803.07623

10%, 20%, 50% IS THE MOST COMMON UNCERTAINTY FOR HADRONIC COLLISIONS IN THE TAILS









STUNNING PROGRESS IN THEORETICAL CALCULATIONS IN THE PAST YEARS

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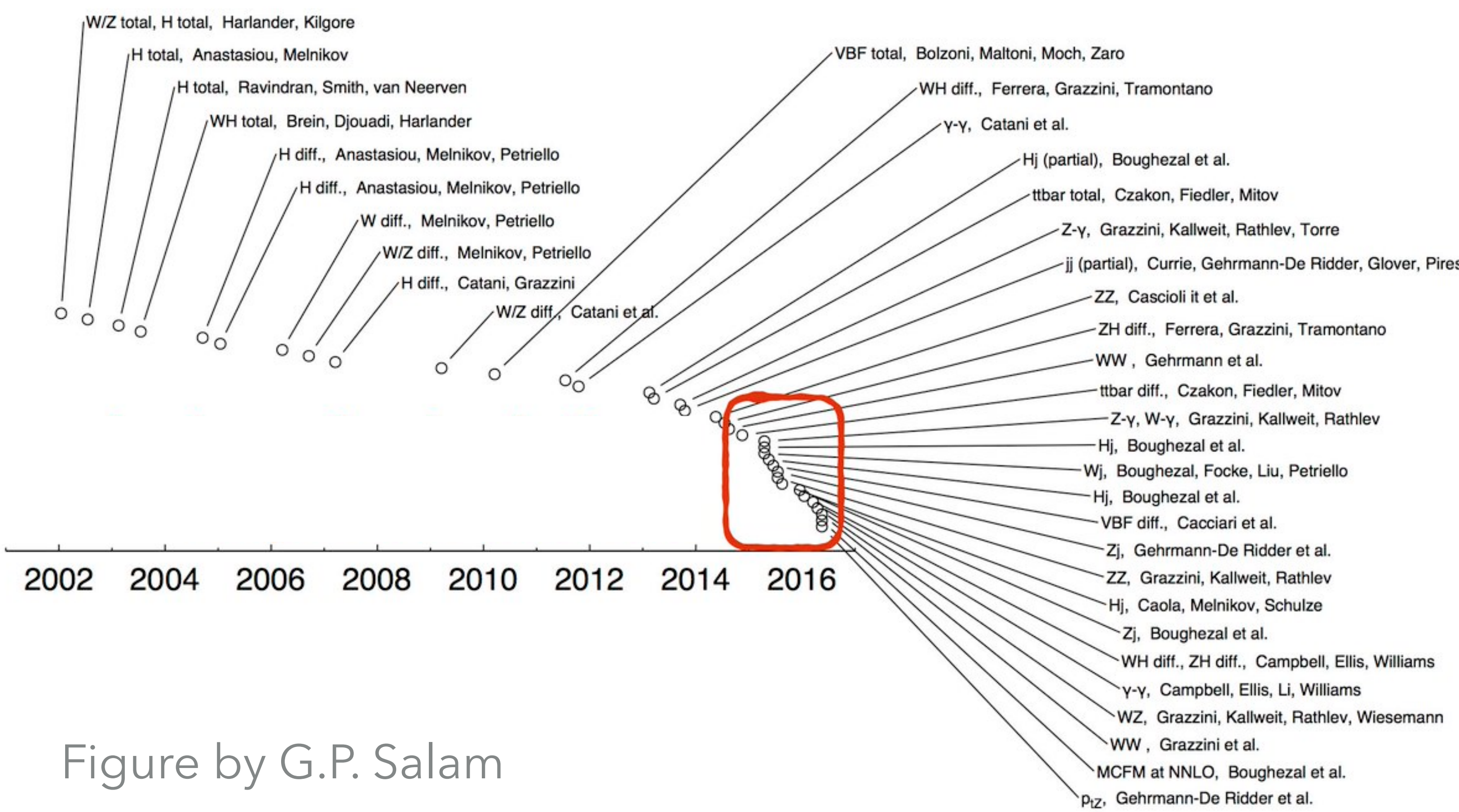

Figure by G.P. Salam

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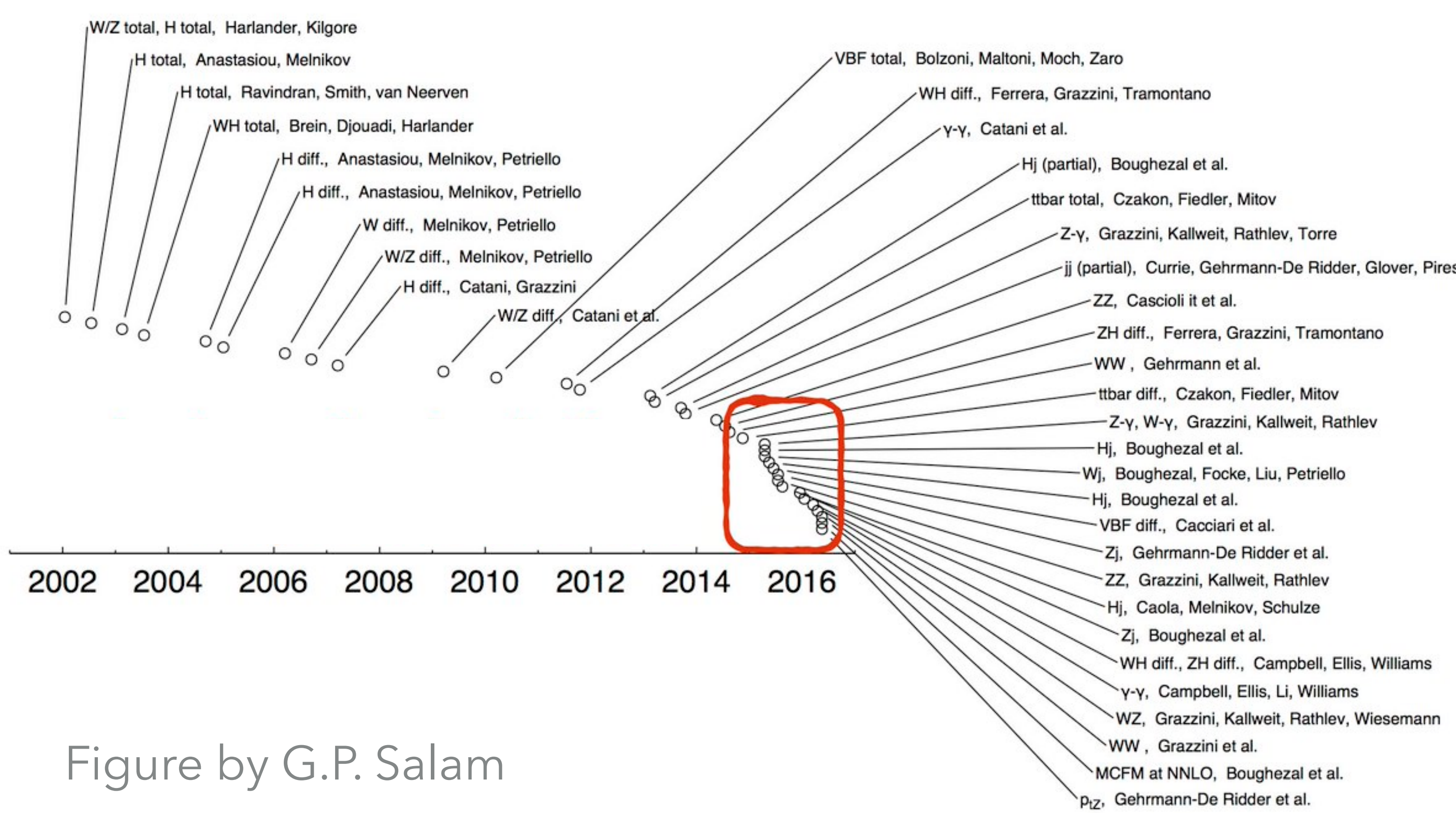
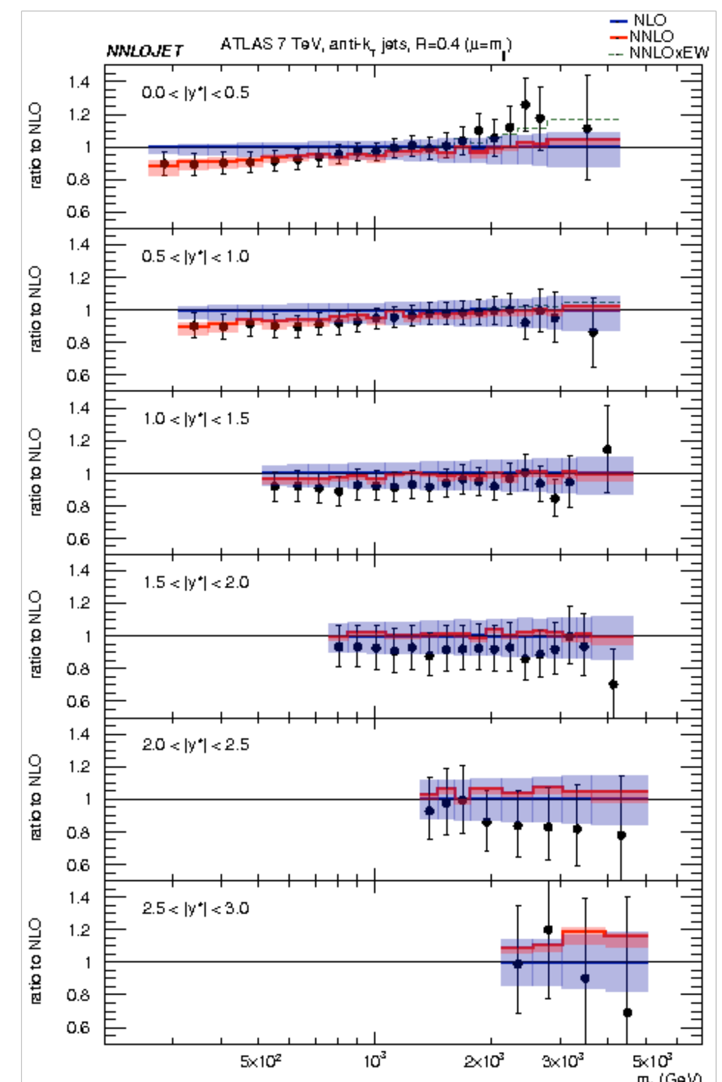


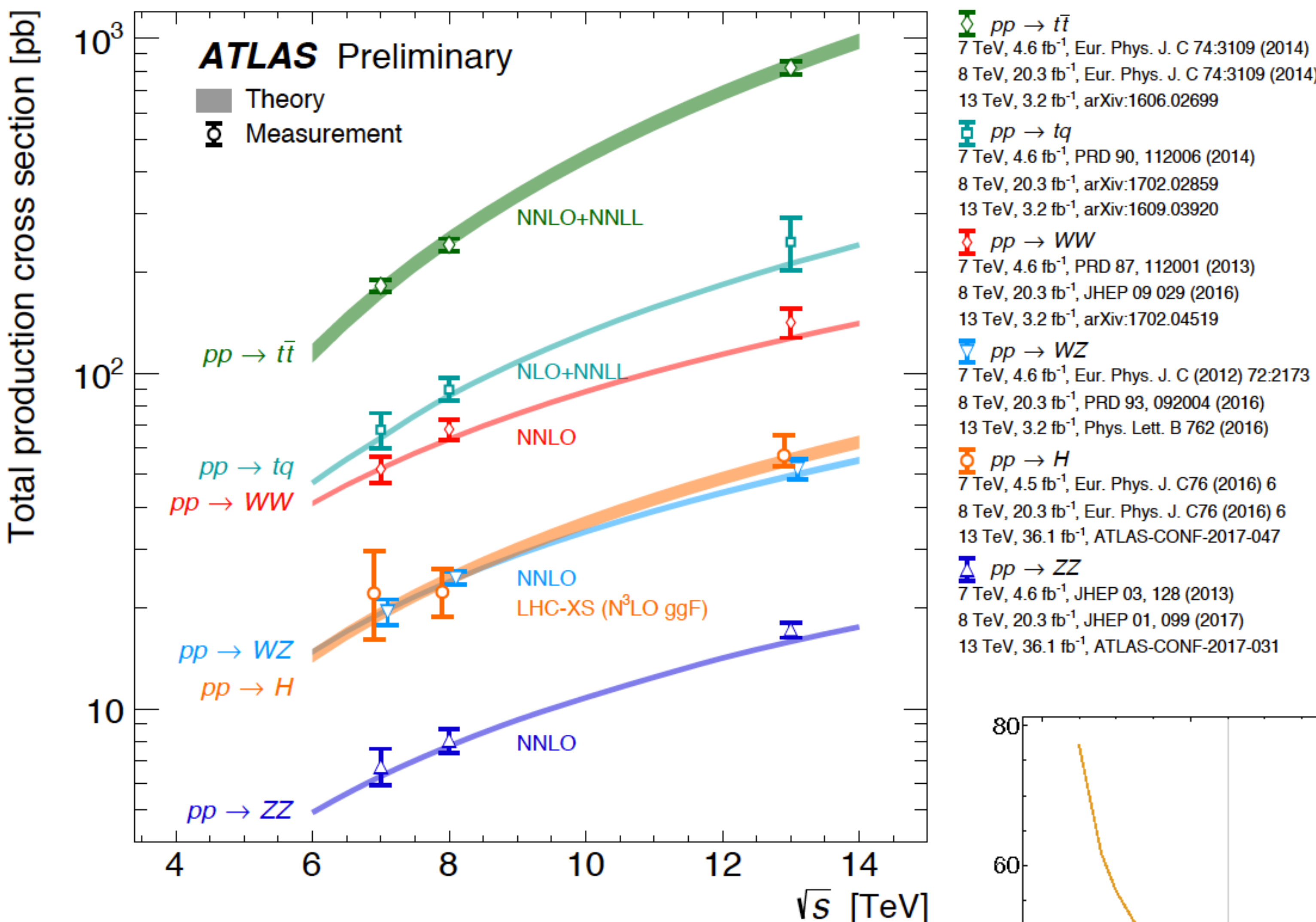
Figure by G.P. Salam

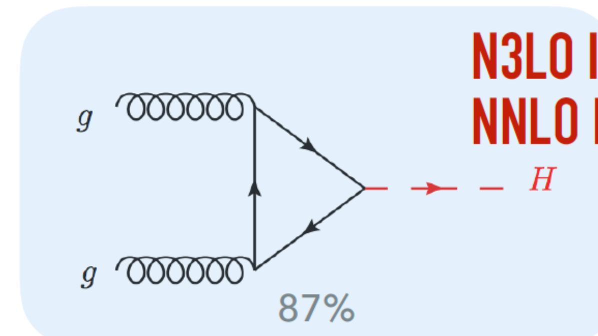


e.g. dijet production
data prefer NNLO

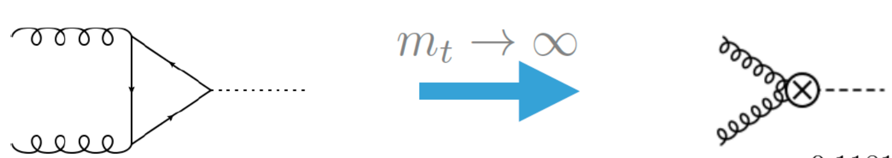
STUNNING PROGRESS IN THEORETICAL CALCULATIONS IN THE PAST YEARS

- **N3LO** ggH (2➔1): 5% th+3% (PDF- α_S) [Anastasiou et al., 2016]





N3LO INCLUSIVE
NNLO DIFFERENTIAL

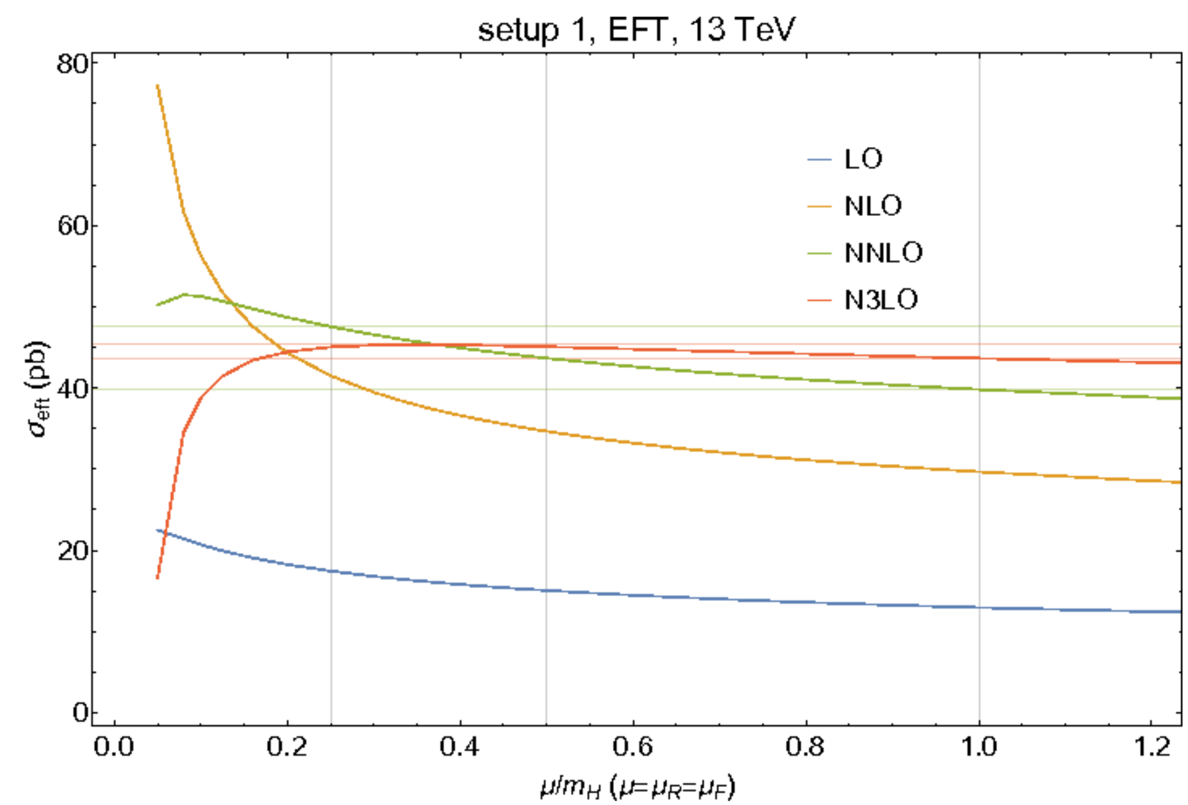


$\alpha_S = 0.1181 \pm 1\%$

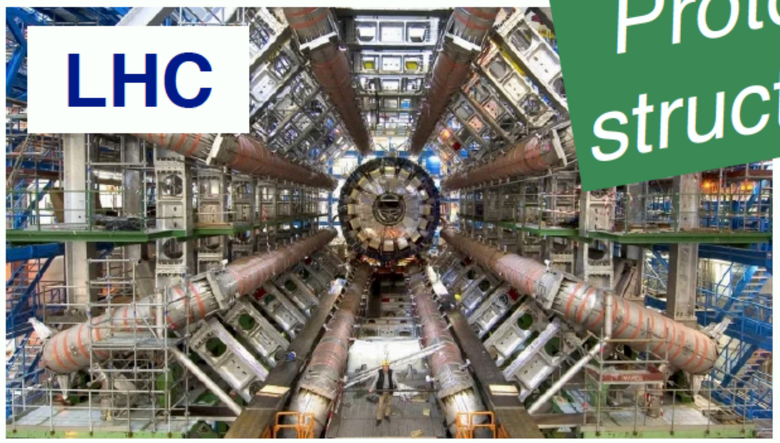
$$\hat{\sigma} = \alpha_s^2 \sigma^{\rm LO} + \alpha_s^3 \sigma^{\rm NLO} + \alpha_s^4 \sigma^{\rm NNLO} + \alpha_s^5 \sigma^{\rm N3LO}$$

✓ ✓ ✓ ✓

[Dulat at PASCOS2018]



From colliders to the cosmos

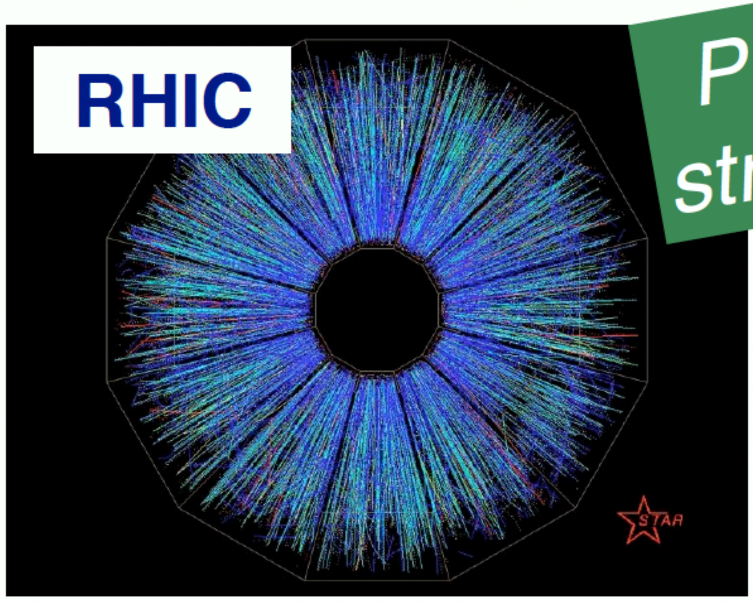


Proton structure

New **elementary particles** beyond the **Standard Model?**

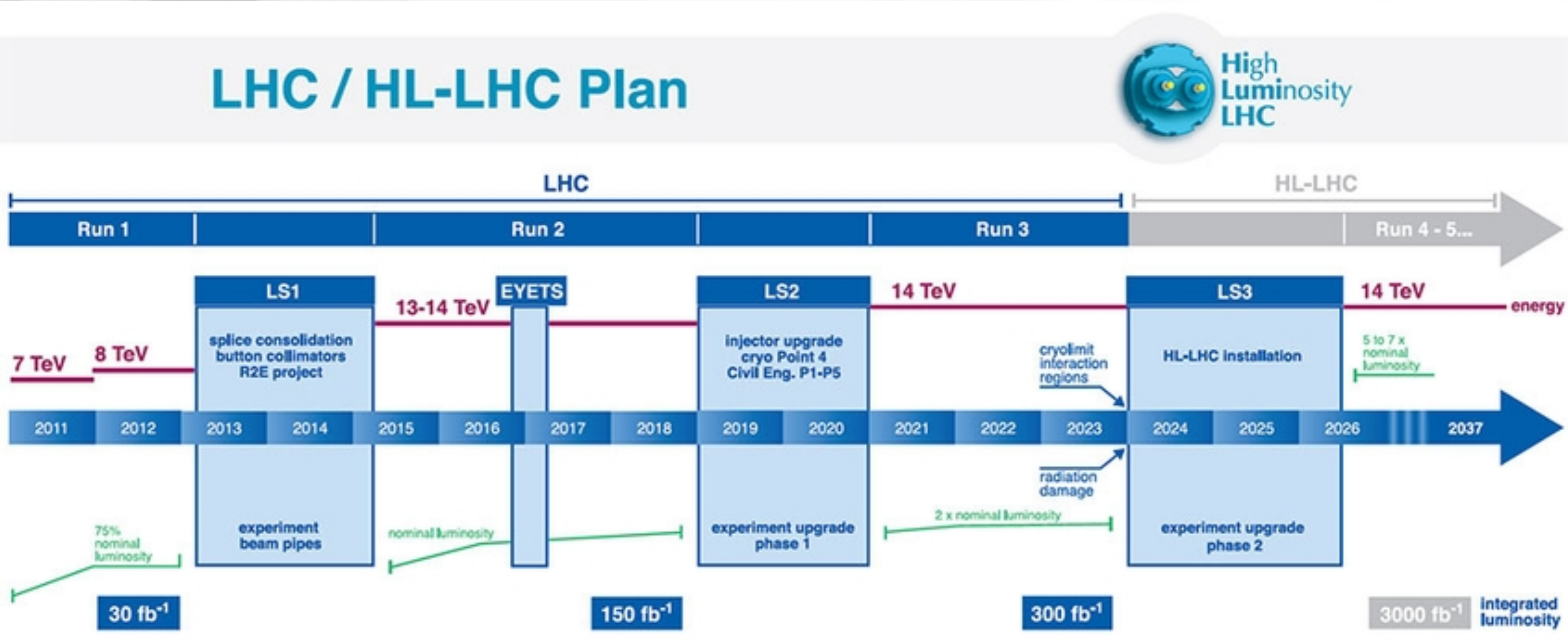
Proton structure

Origins and properties of **cosmic neutrinos**?

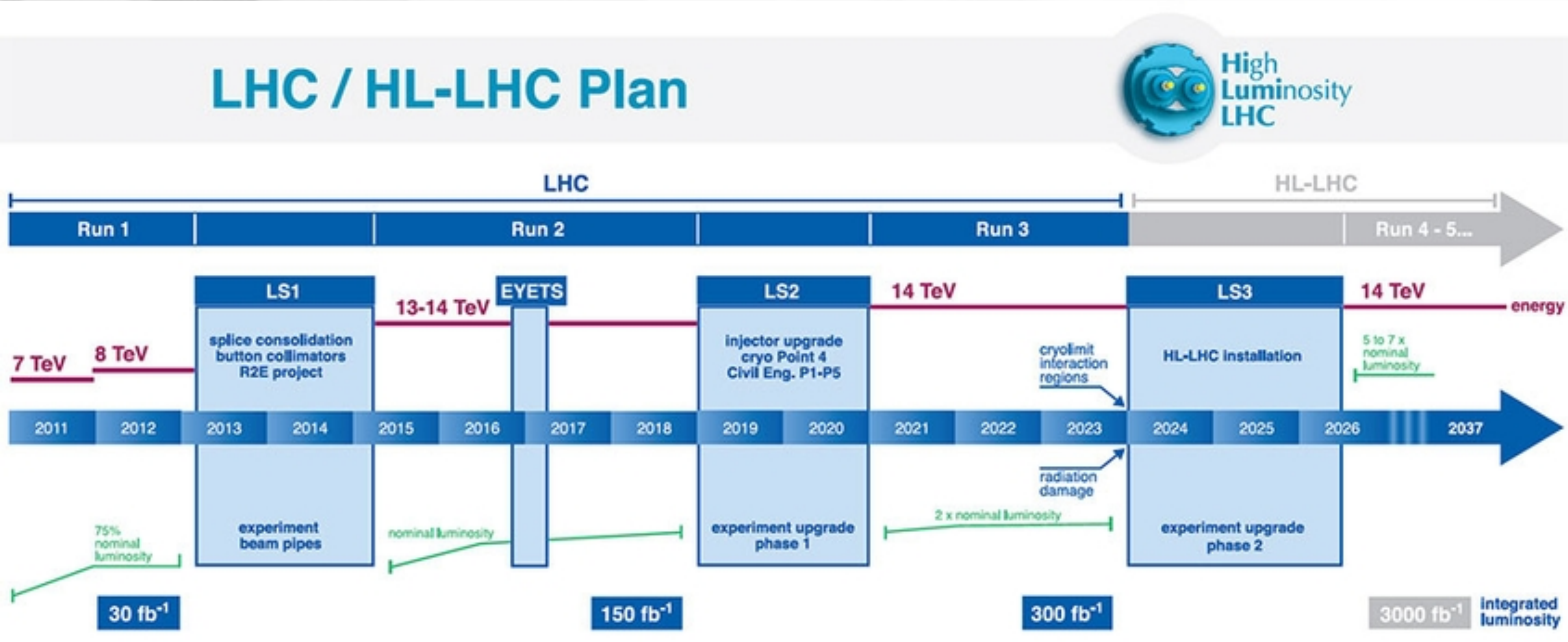


Proton structure

Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**



- **150 fb^{-1}** today (only ~ 1/4 analysed)
- **300 fb^{-1}** by 2023
- **3000 fb^{-1}** by 2037



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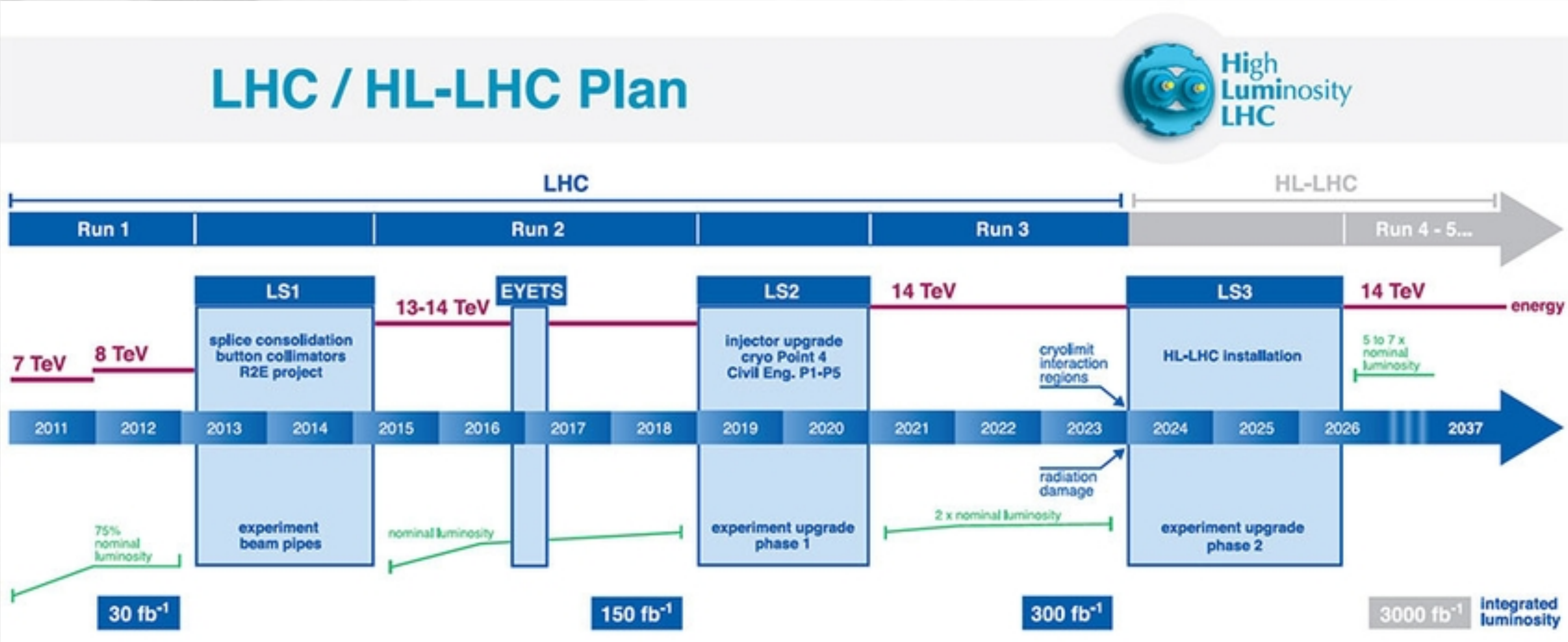

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LHC PHYSICS AT % PRECISION ?

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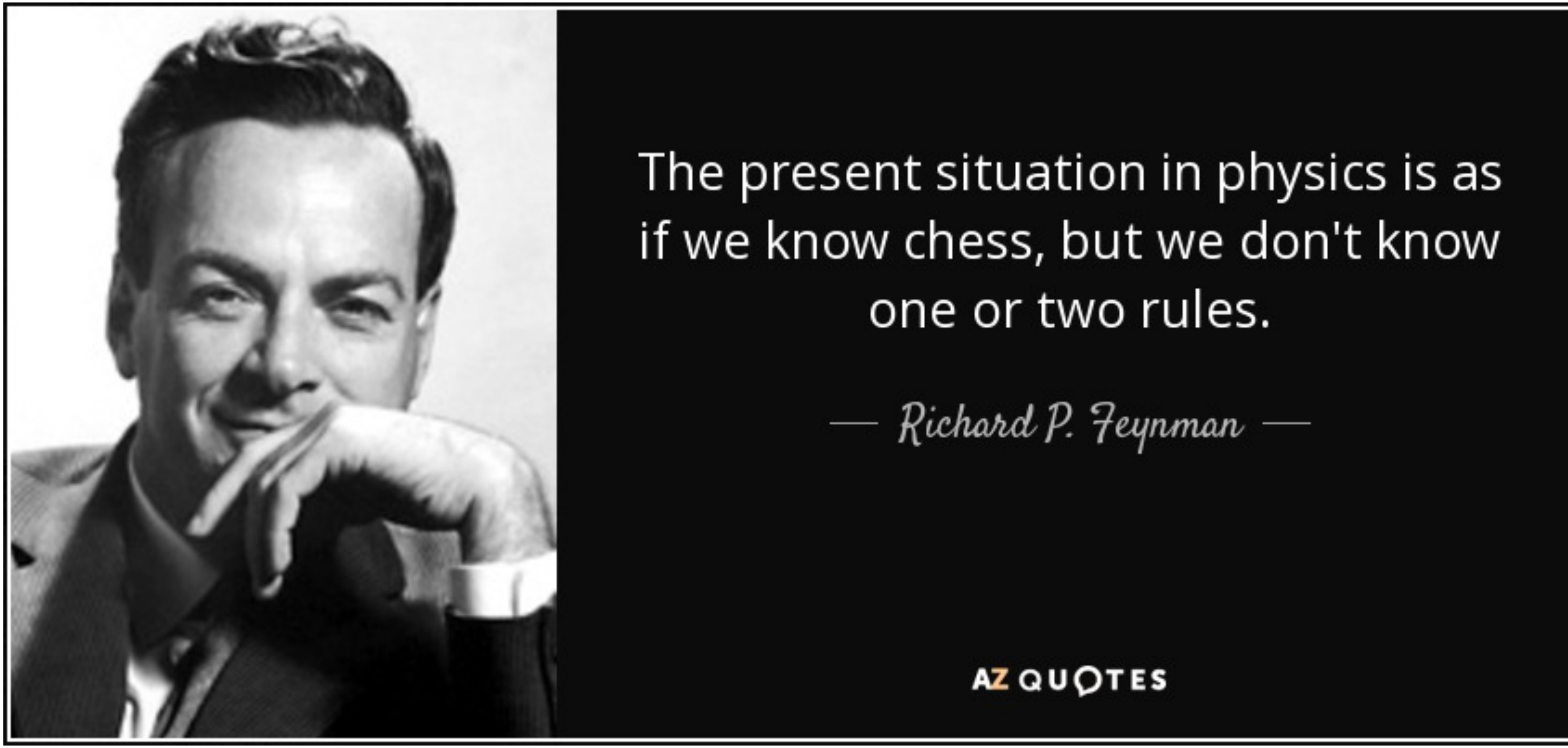
- **Change focus:** not only discovery, quest for **precision** at the forefront for better physics | **global challenge**
- It requires to challenge our current understanding of QFT in many different aspects
- **% physics** still far away (2037?), but promising landscape given the recent successful developments in the field


The present situation in physics is as if we know chess, but we don't know one or two rules.
— Richard P. Feynman —
AZ QUOTES