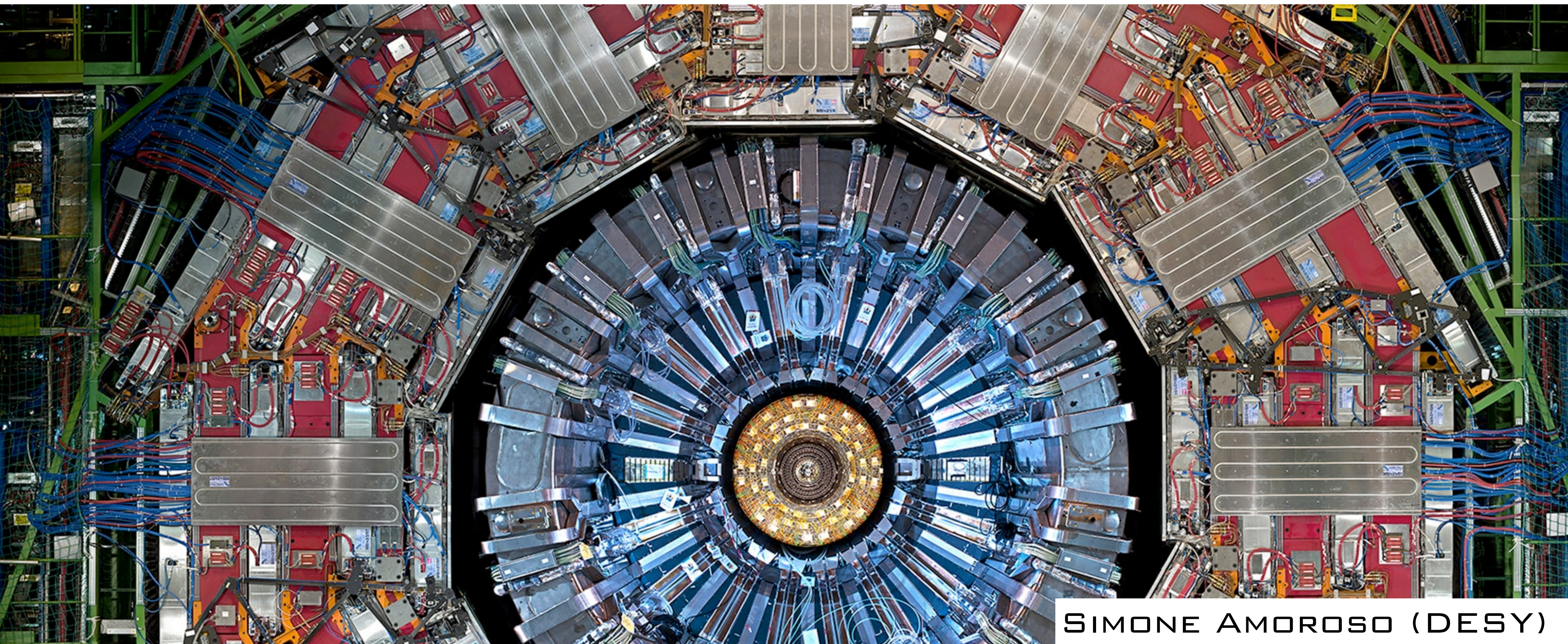
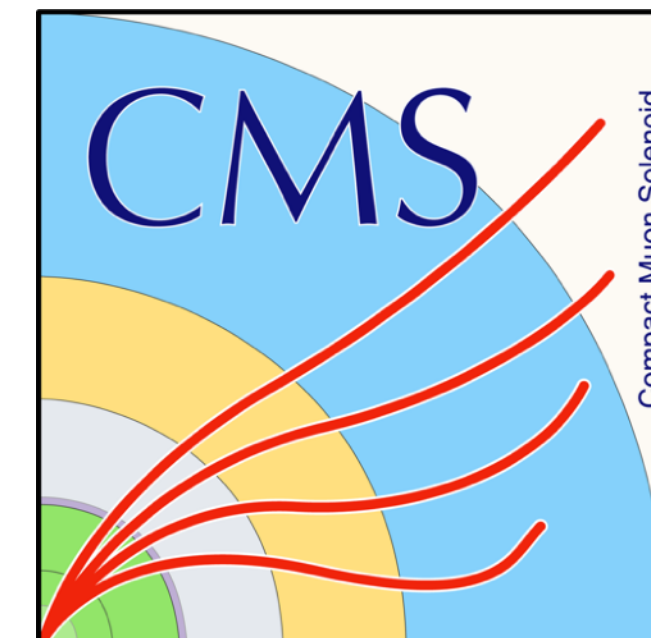




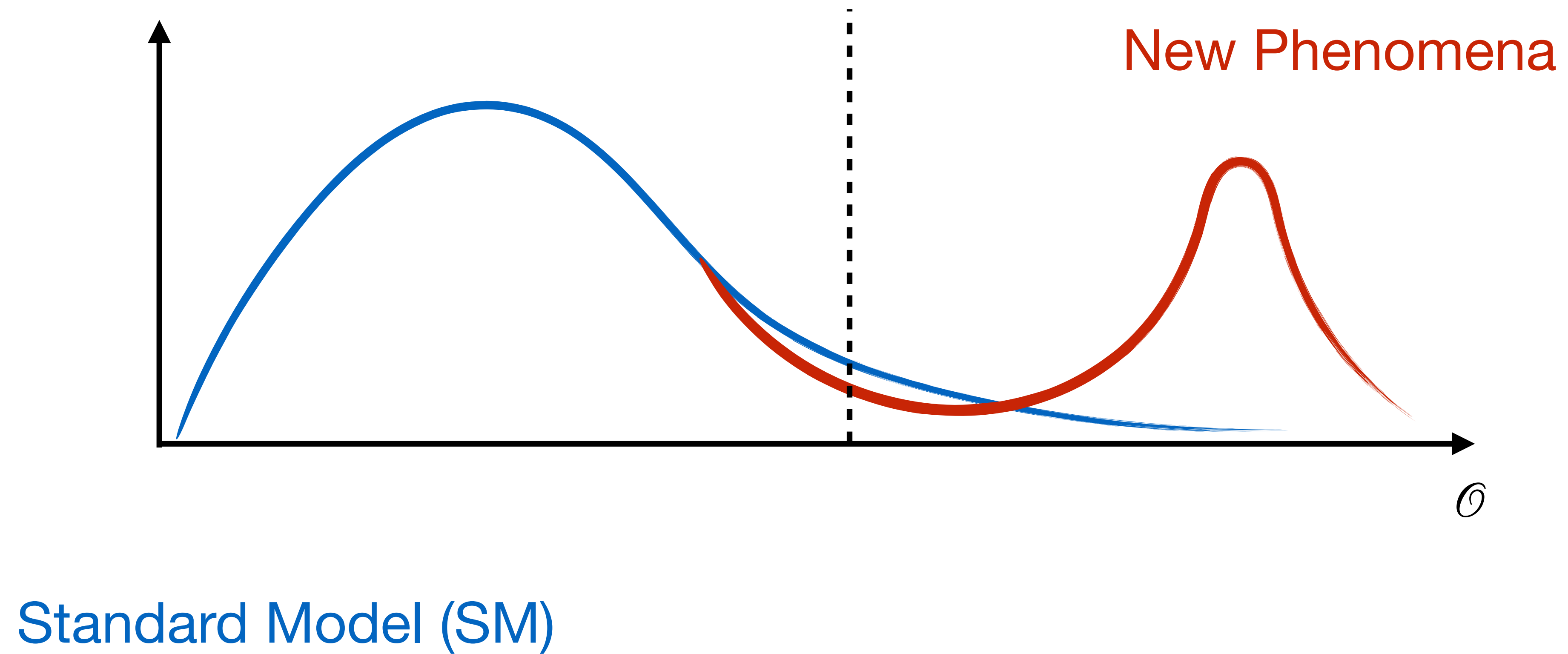
FROM THE PRECISION FRONTIER TO PHYSICS BEYOND THE STANDARD MODEL

M&U DAYS 2022 OCT. 21ST, 2022



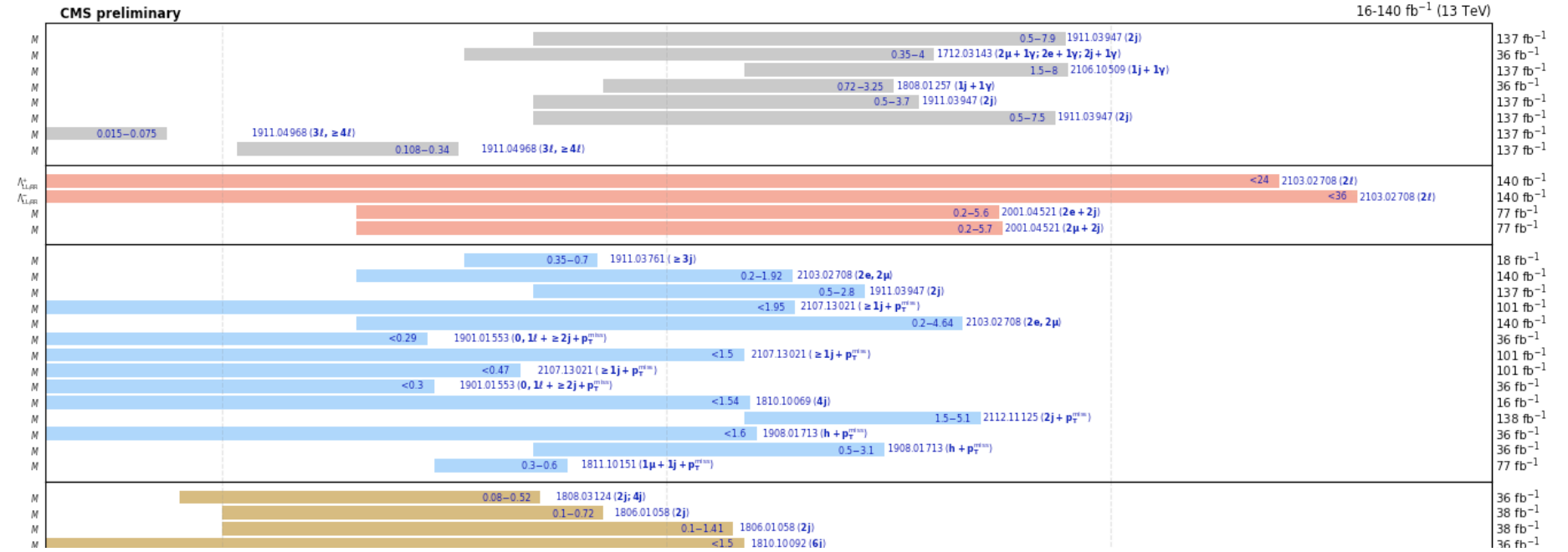
SIMONE AMOROSO (DESY)

PHYSICS AT THE LARGE HADRON COLLIDER



A DEDICATED SEARCH PROGRAM

Overview of CMS EXO results



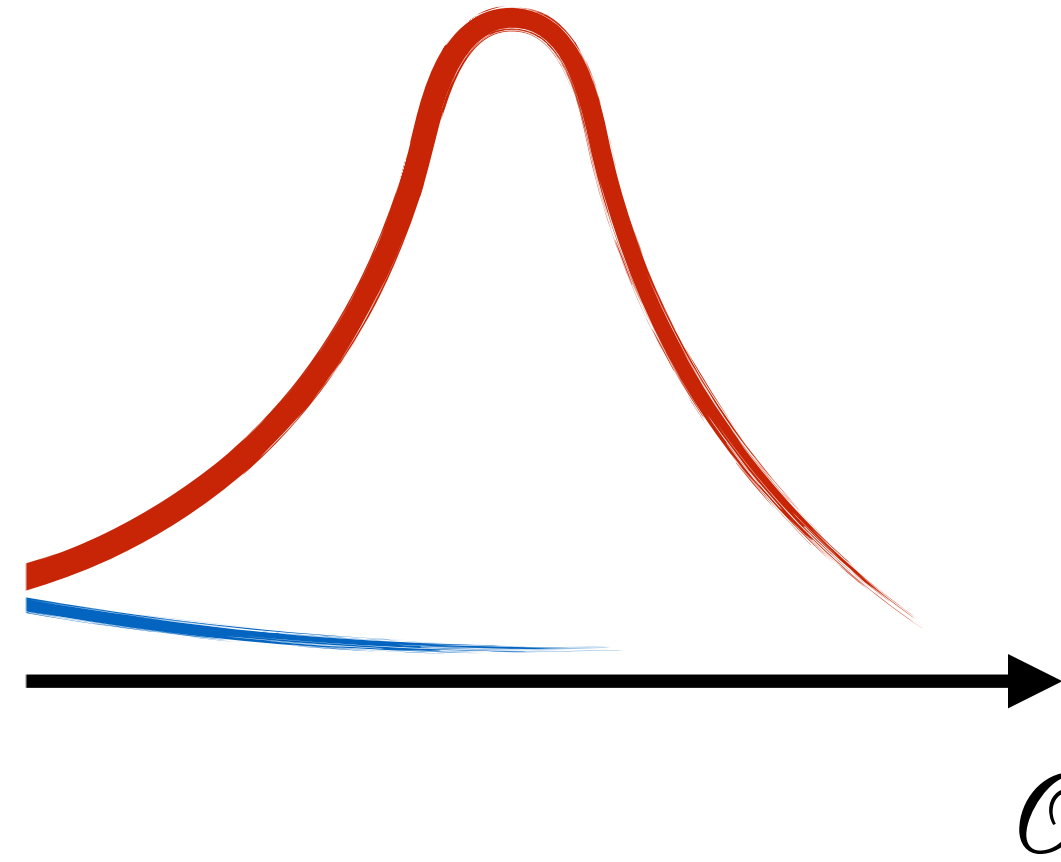
ATLAS SUSY Searches* - 95% CL Lower Limits
March 2022

	Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$]	Mass limit	Reference			
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	139 139	\tilde{q} [1 \times , 8 \times Degen.] 1.0 \tilde{q} [8 \times Degen.] 0.9 $m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q})-m(\tilde{\chi}_1^0)=5$ GeV	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g} 2.3 $m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{g})=1000$ GeV	2010.14293 2010.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g} 2.2 $m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	E_T^{miss}	139	\tilde{g} 2.2 $m(\tilde{\chi}_1^0) < 700$ GeV	CERN-EP-2022-014	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ	7-11 jets	E_T^{miss}	139	\tilde{g} 1.97 $m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS e, μ	6 jets	E_T^{miss}	139	\tilde{g} 1.5 $m(\tilde{g})-m(\tilde{\chi}_1^0)=200$ GeV	1909.08457	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	E_T^{miss}	79.8	\tilde{g} 2.25 $m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2018-041	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	SS e, μ	6 jets	E_T^{miss}	139	\tilde{g} 1.25 $m(\tilde{g})-m(\tilde{\chi}_1^0)=300$ GeV	1909.08457	
	3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	139	\tilde{b}_1 1.255 \tilde{b}_1 0.68 $m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV < $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{h}\tilde{\chi}_1^0$		0 e, μ 2 τ	6 b 2 E_T^{miss}	E_T^{miss} E_T^{miss}	139 139	\tilde{b}_1 23-1.35 $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=0$ GeV	1908.03122 2103.08189	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$		0-1 e, μ	≥ 1 jet	E_T^{miss}	139	\tilde{t}_1 1.25 $m(\tilde{\chi}_1^0)=1$ GeV	2004.14060,2012.03799	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 e, μ	3 jets/1 b	E_T^{miss}	139	\tilde{t}_1 0.65 $m(\tilde{\chi}_1^0)=500$ GeV	2012.03799	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{\tau} \rightarrow \tau\tilde{G}$		1-2 τ	2 jets/1 b	E_T^{miss}	139	\tilde{t}_1 1.4 $m(\tilde{\chi}_1^0)=800$ GeV	2108.07665	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / c\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$		0 e, μ	2 c mono-jet	E_T^{miss} E_T^{miss}	36.1 139	\tilde{t}_1 0.85 $m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{t}_1, \tilde{\chi}_1^0)=5$ GeV	1805.01649 2102.10874	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$		1-2 e, μ	1-4 b	E_T^{miss}	139	\tilde{t}_1 0.067, 1.18 $m(\tilde{\chi}_2^0)=500$ GeV	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\tilde{\chi}_1^0 + Z$		3 e, μ	1 b	E_T^{miss}	139	\tilde{t}_2 0.86 $m(\tilde{\chi}_1^0)=360$ GeV, $m(\tilde{t}_1), m(\tilde{\chi}_1^0)=40$ GeV	2006.05880	
EW direct		$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ via WZ	Multiple ℓ/jets	$ee, \mu\mu$	E_T^{miss} E_T^{miss}	139 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0/\tilde{\chi}_2^0$ 0.96 $\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ 0.205 $m(\tilde{\chi}_1^0)=0$, wino-bino $m(\tilde{\chi}_1^0)-m(\tilde{\chi}_1^0)=5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
		$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ via WW	2 e, μ	≥ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.42 $m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets	$ee, \mu\mu$	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 1.0 $m(\tilde{\chi}_1^0)=70$ GeV, wino-bino	2004.10894, 2108.07586	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	≥ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 1.0 $m(\tilde{\chi}_1^0)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{\chi}_2^0))$	1908.08215	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\ell}$ 0.16-0.3 0.12-0.39 $m(\tilde{\chi}_1^0)=0$	1911.06660	
	$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7 $m(\tilde{\chi}_1^0)=0$	1908.08215	
	$\tilde{e}\tilde{e}, \mu\mu$	≥ 1 jet	E_T^{miss}	139	$\tilde{\ell}$ 0.256 $m(\tilde{\chi}_1^0)=10$ GeV	1911.12606		
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ	$\geq 3 b$	E_T^{miss}	36.1	\tilde{H} 0.13-0.23 0.55 0.29-0.88 $BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$	1806.04030	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	4 e, μ	0 jets	E_T^{miss}	139	\tilde{H} 0.55 $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	2103.11684	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ	≥ 2 large jets	E_T^{miss}	139	\tilde{H} 0.45-0.93 $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	2108.07586	
Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.66 $\tilde{\chi}_1^{\pm}$ 0.21 Pure Wino Pure higgsino	2201.02472 2201.02472	
	Stable \tilde{g} R-hadron	pixel dE/dx		E_T^{miss}	139	\tilde{g} 2.05 $m(\tilde{\chi}_1^0)=100$ GeV	CERN-EP-2022-029	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	139	\tilde{g} 2.2 $\tau(\tilde{g})=0.1$ ns	CERN-EP-2022-029	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{\ell}, \tilde{\mu}$ 0.7 $\tau(\tilde{\ell})=0.1$ ns	2011.07812	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	pixel dE/dx		E_T^{miss}	139	$\tilde{\ell}, \tilde{\mu}$ 0.34 0.36 $\tau(\tilde{\ell})=10$ ns	2011.07812 CERN-EP-2022-029	
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0/\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow Z\ell\ell$	3 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ 0.625 1.0 $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [BR(Z τ)=1, BR(Z e)=1] $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [A ₃₃ \neq 0, A ₁₂₃ \neq 0]	Pure Wino $m(\tilde{\chi}_1^0)=200$ GeV	2011.10543 2103.11684
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0/\tilde{\chi}_2^0 \rightarrow WWZZ\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.95 1.55 Large A ₁₁₂	1804.03568	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	4-5 large jets		E_T^{miss}	36.1	\tilde{g} 1.3 1.9 $m(\tilde{\chi}_1^0)=200$ GeV, 1100 GeV	ATLAS-CONF-2018-003	
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s$	Multiple		E_T^{miss}	36.1	\tilde{t} 0.55 1.0 $A_{33} \approx 2\text{e-}4, 1\text{e-}2$ $m(\tilde{\chi}_1^0)=200$ GeV, bino-like	2010.01015	
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow b\tilde{b}s$	$\geq 4b$		E_T^{miss}	139	\tilde{t} 0.95 Forbidden $m(\tilde{\chi}_1^0)=500$ GeV	1710.07171	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b		E_T^{miss}	36.7	\tilde{t}_1 [eq. b.s.] 0.42 0.61 \tilde{t}_1 0.4-1.45 \tilde{t}_1 [1e-10 < A ₃₃ < 1e-8, 3e-10 < A ₃₃ < 3e-9]	1710.05544	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, μ	2 b	E_T^{miss}	36.1	\tilde{t}_1 1.0 BR($\tilde{t}_1 \rightarrow b\ell$)/ $\text{br}(p) > 20\%$	2003.11956	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	1 μ	DV	E_T^{miss}	136	\tilde{t}_1 1.0 BR($\tilde{t}_1 \rightarrow q\mu$)=100%, cos $\theta=1$	2106.09609	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s, \tilde{\chi}_1^0 \rightarrow b\tilde{b}s$	1-2 e, μ	≥ 6 jets	E_T^{miss}	139	$\tilde{\chi}_1^0$ 0.2-0.32 Pure higgsino	2106.09609	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

1 TeV

New Phenomena

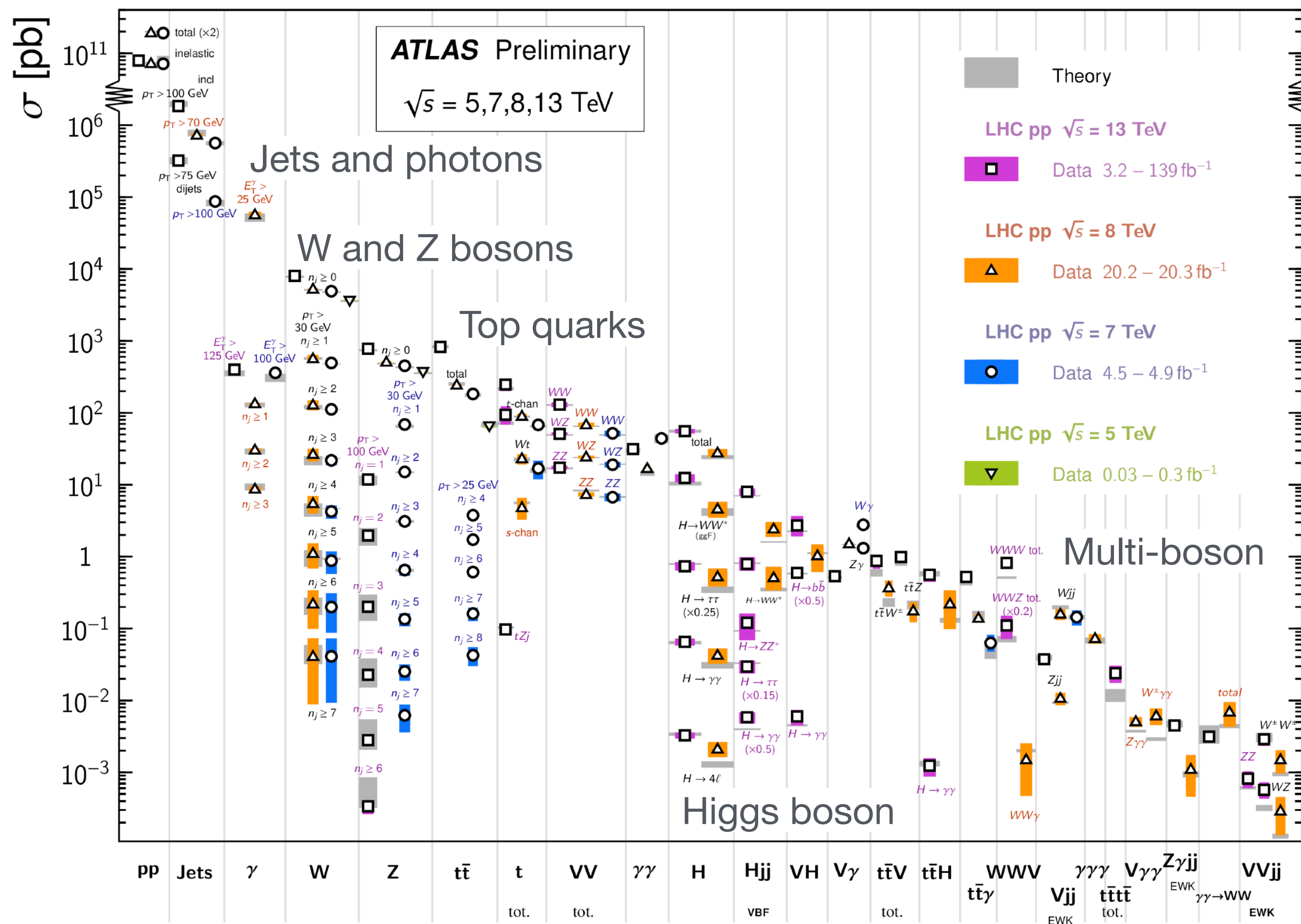


- Extensive (~1000 results)
- Signature/model driven
- Fast → detector level

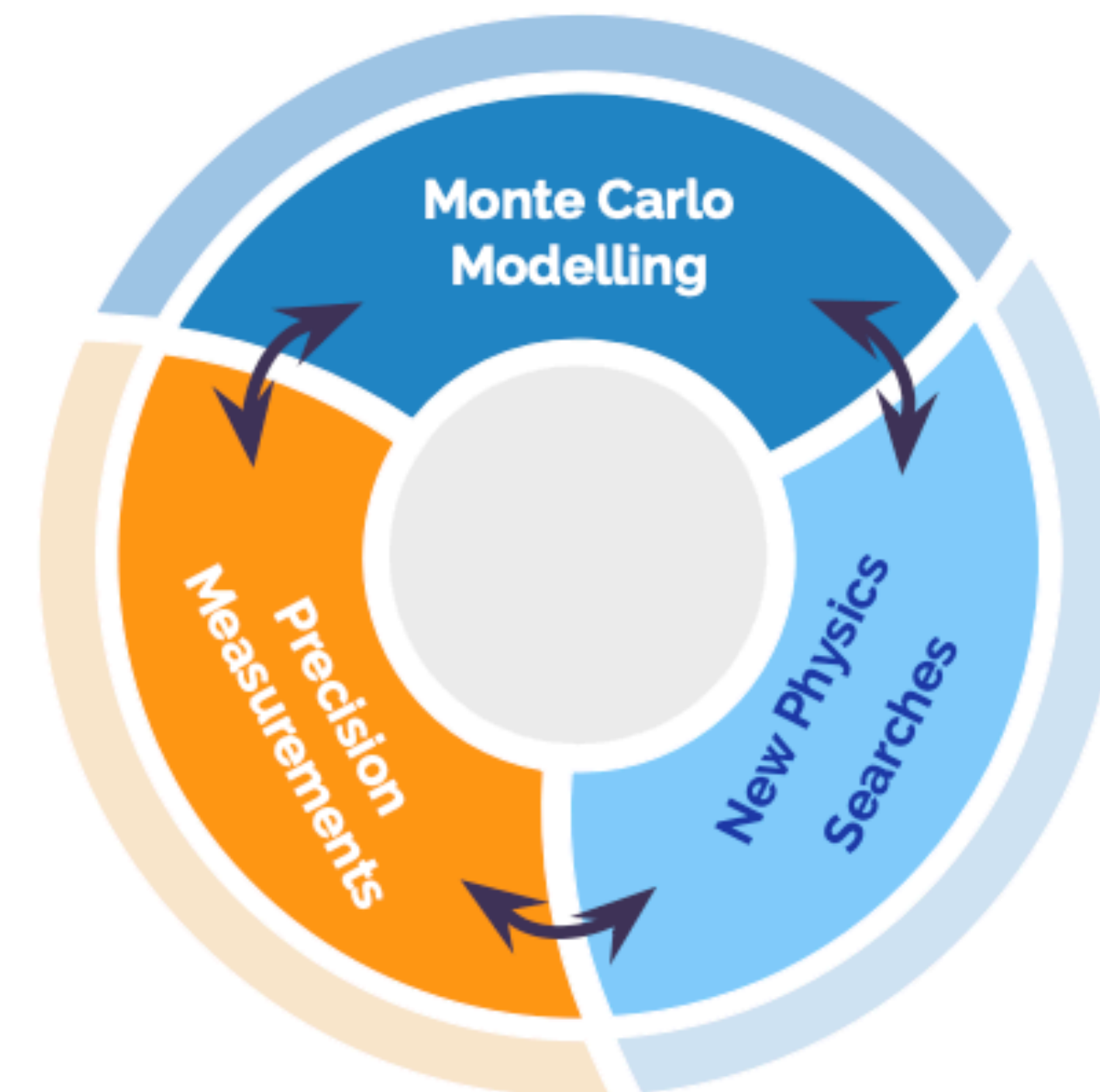
STANDARD MODEL MEASUREMENTS

Standard Model Production Cross Section Measurements

Status: February 2022



- ▶ SM process driven
- ▶ Detector-corrected
- ▶ Focus on precision/longevity

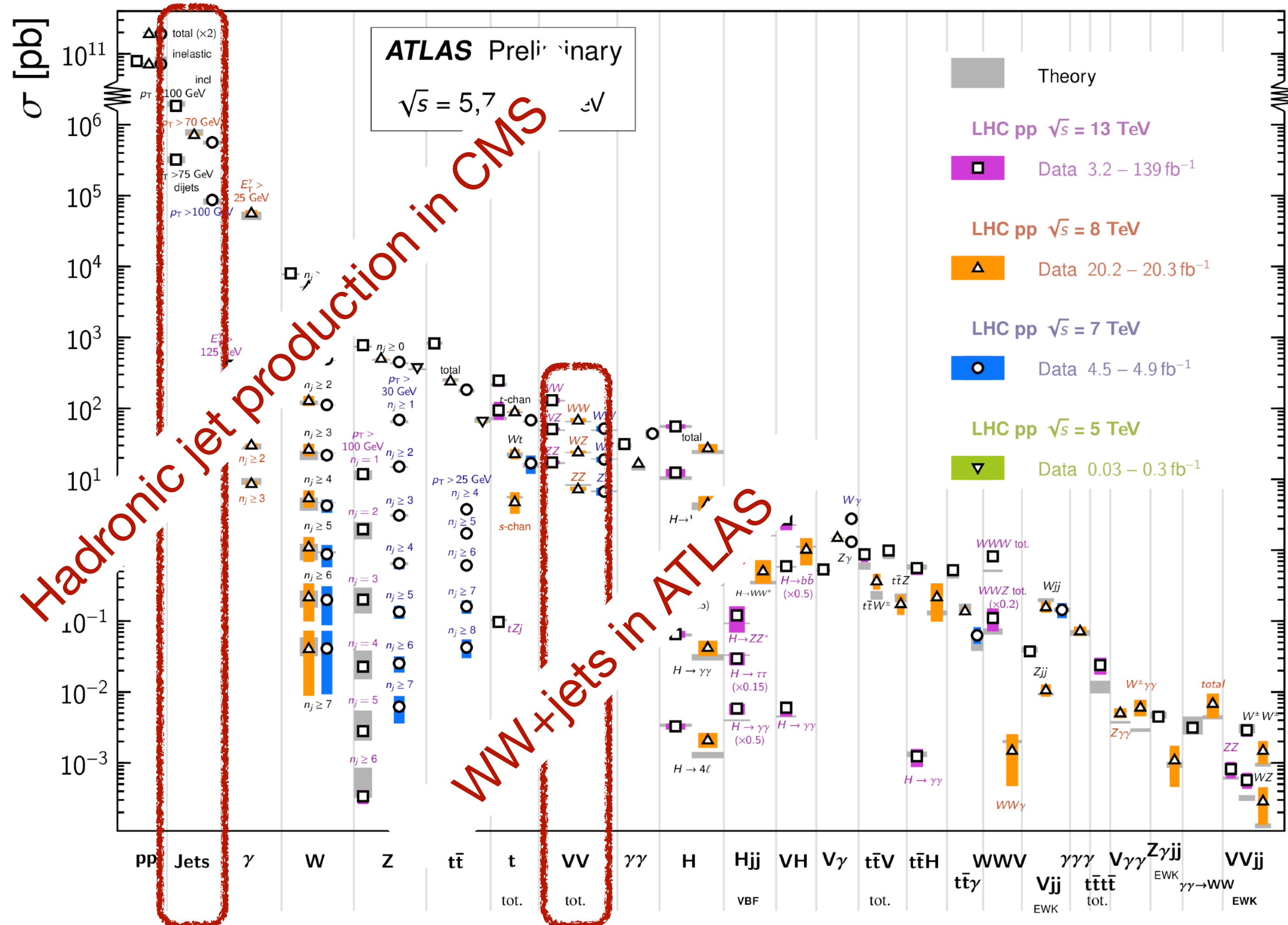


<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/>

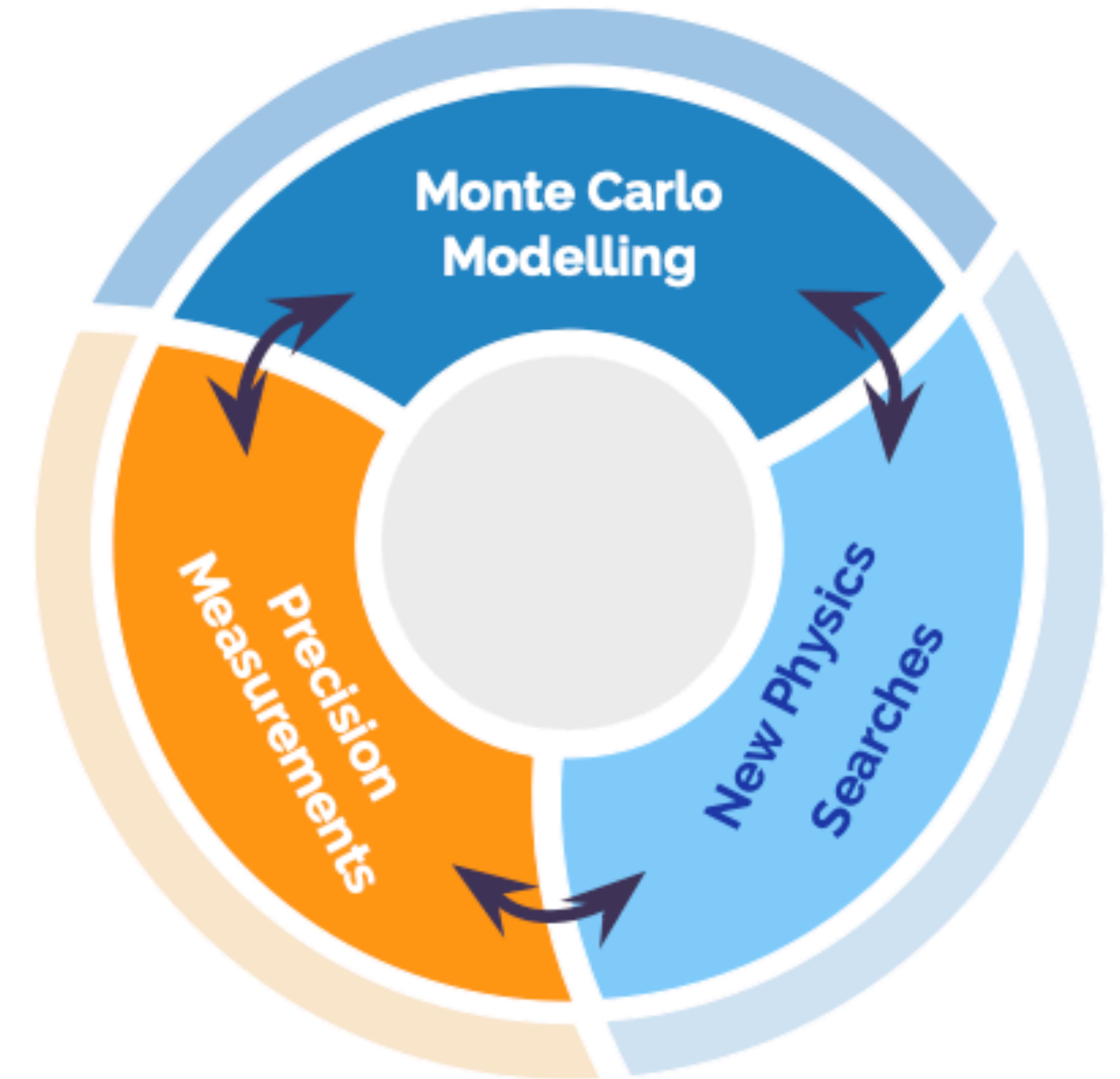
STANDARD MODEL MEASUREMENTS

Standard Model Production Cross Section Measurements

Status: February 2022

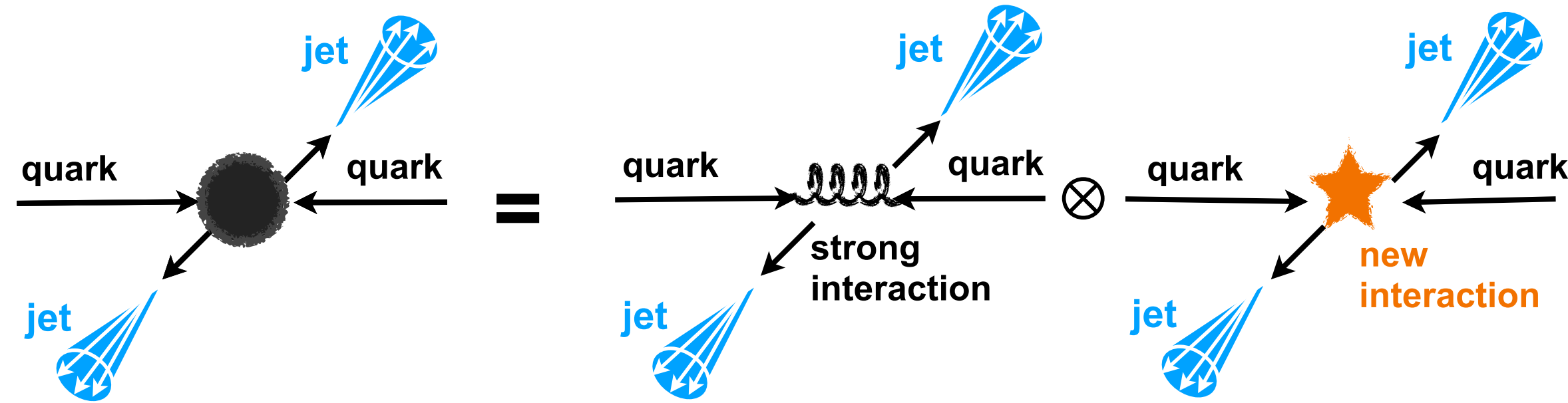


- ▶ SM process driven
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<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/>

HADRONIC JETS AS PROBE OF THE STRONG FORCE



* Sensitive to the proton structure (PDFs)

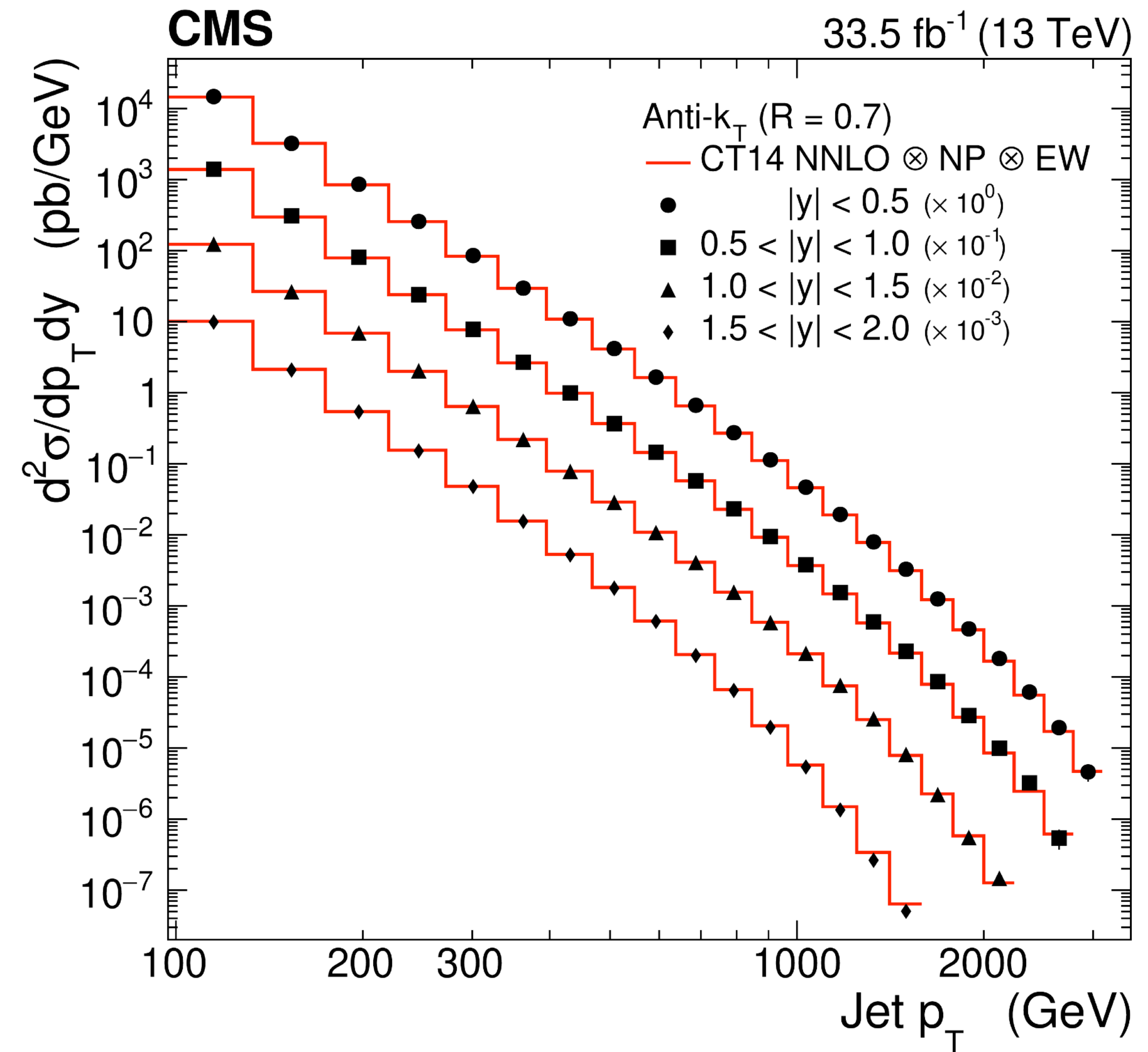
* Extract strong coupling $\alpha_s(m_Z)$,
least well known fundamental constant:
 $\alpha_s(m_Z) = 0.1170 \pm 0.0017$

Most precise $\alpha_s(m_Z)$ from a hadron collider experiment

* Probe physics beyond the SM

► Parametrised with effective couplings c_i
valid up to new physics scale Λ (EFT)

► For vector-like couplings new physics scale $\Lambda > 32 \text{ TeV}$

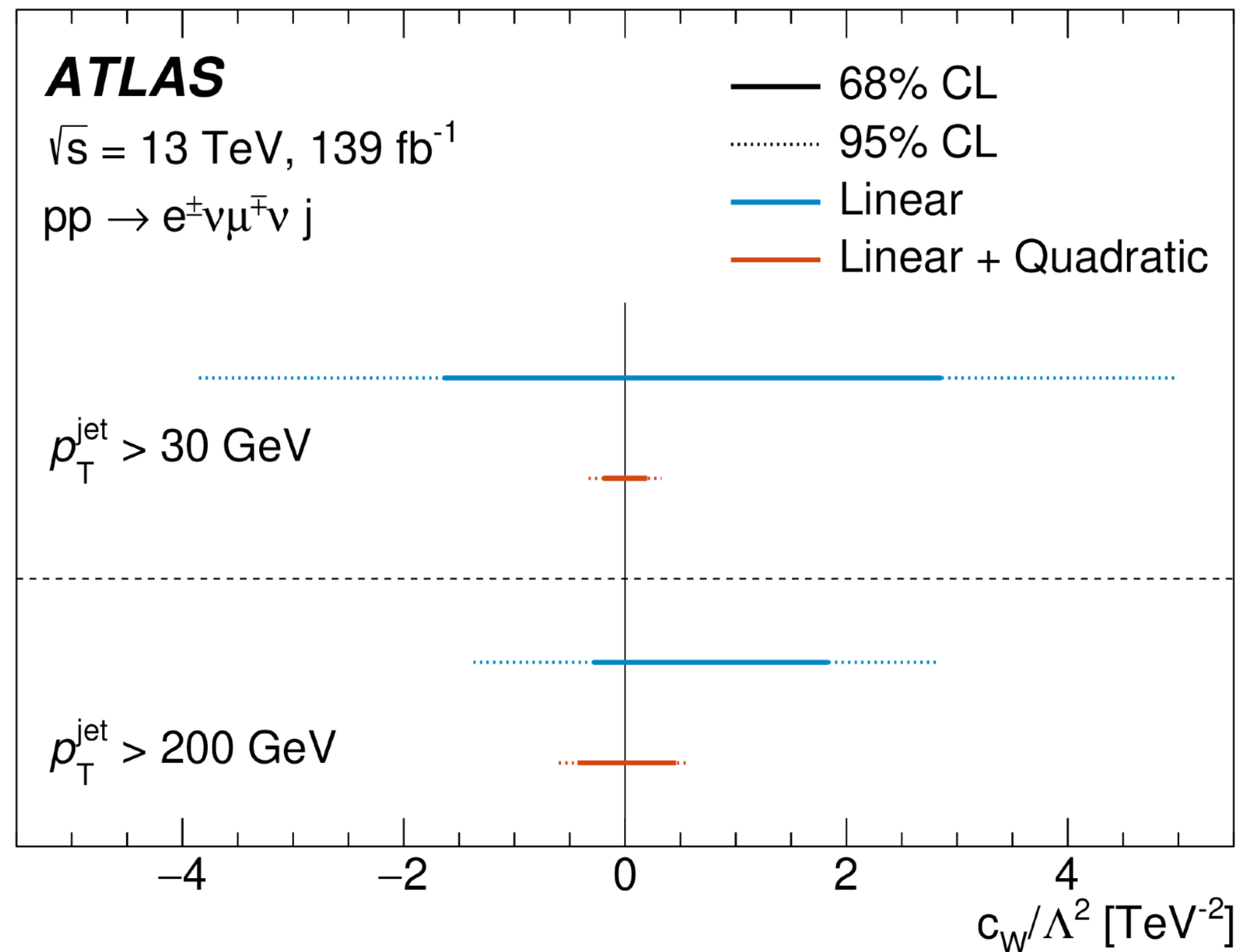


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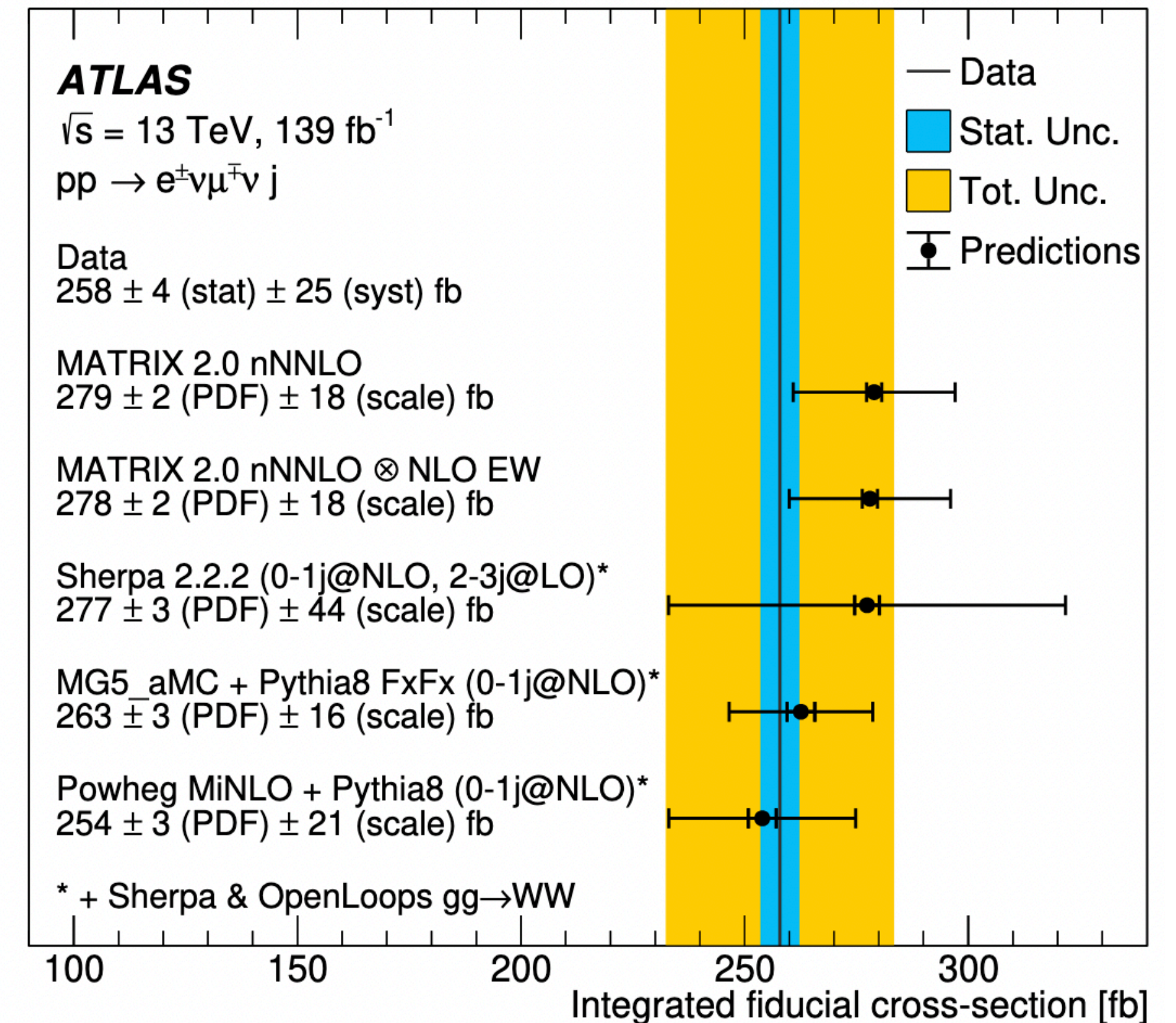
ELECTROWEAK INTERACTIONS IN $WW+JETS$

* ATLAS precise measurement of $pp \rightarrow e^\pm \nu \mu^\pm \nu j$

- Sensitive to electroweak boson self-interactions and higher orders in the strong coupling



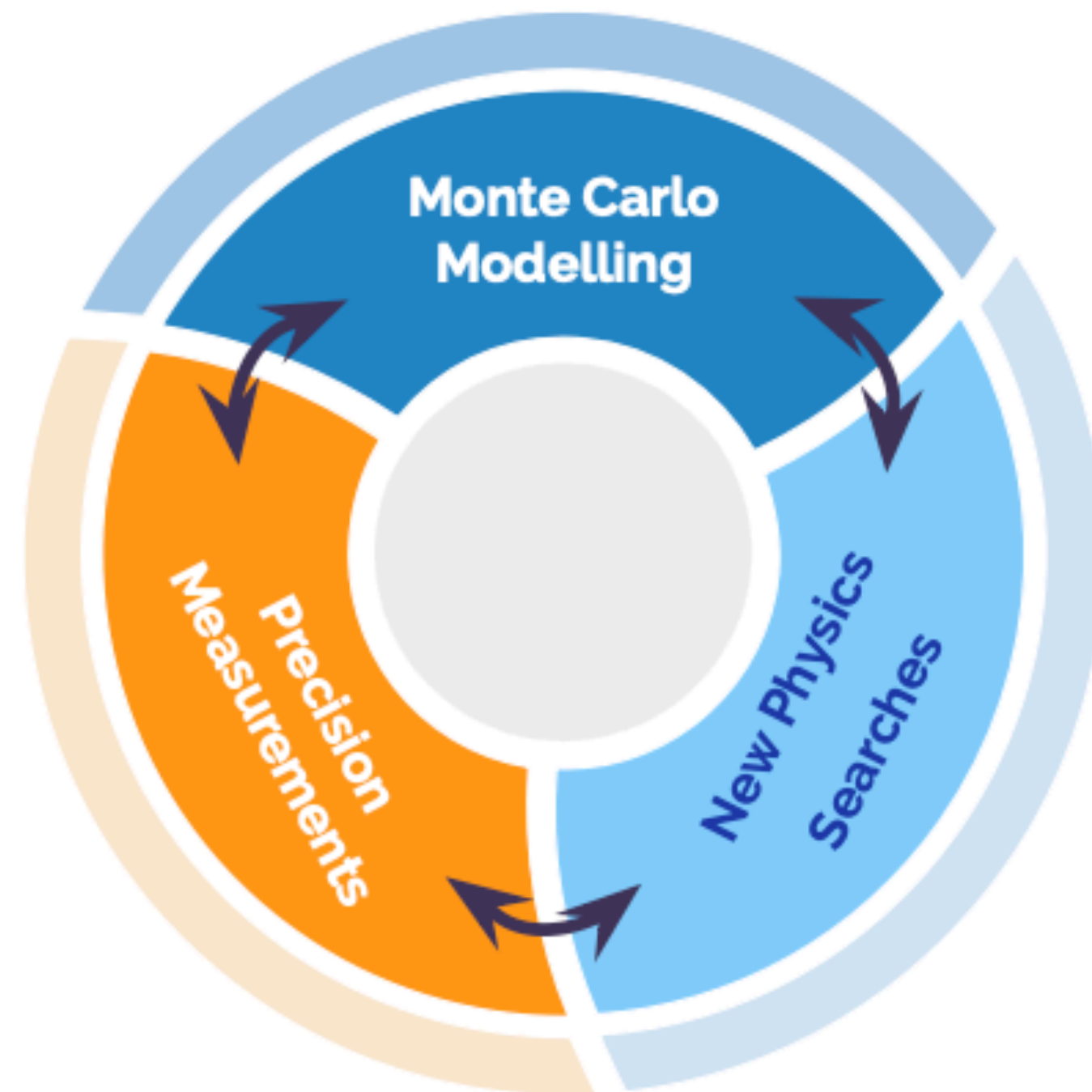
JHEP 06 (2021) 003



- Compared to state-of-the-art theoretical predictions
- Differential distributions constrain **effective couplings**

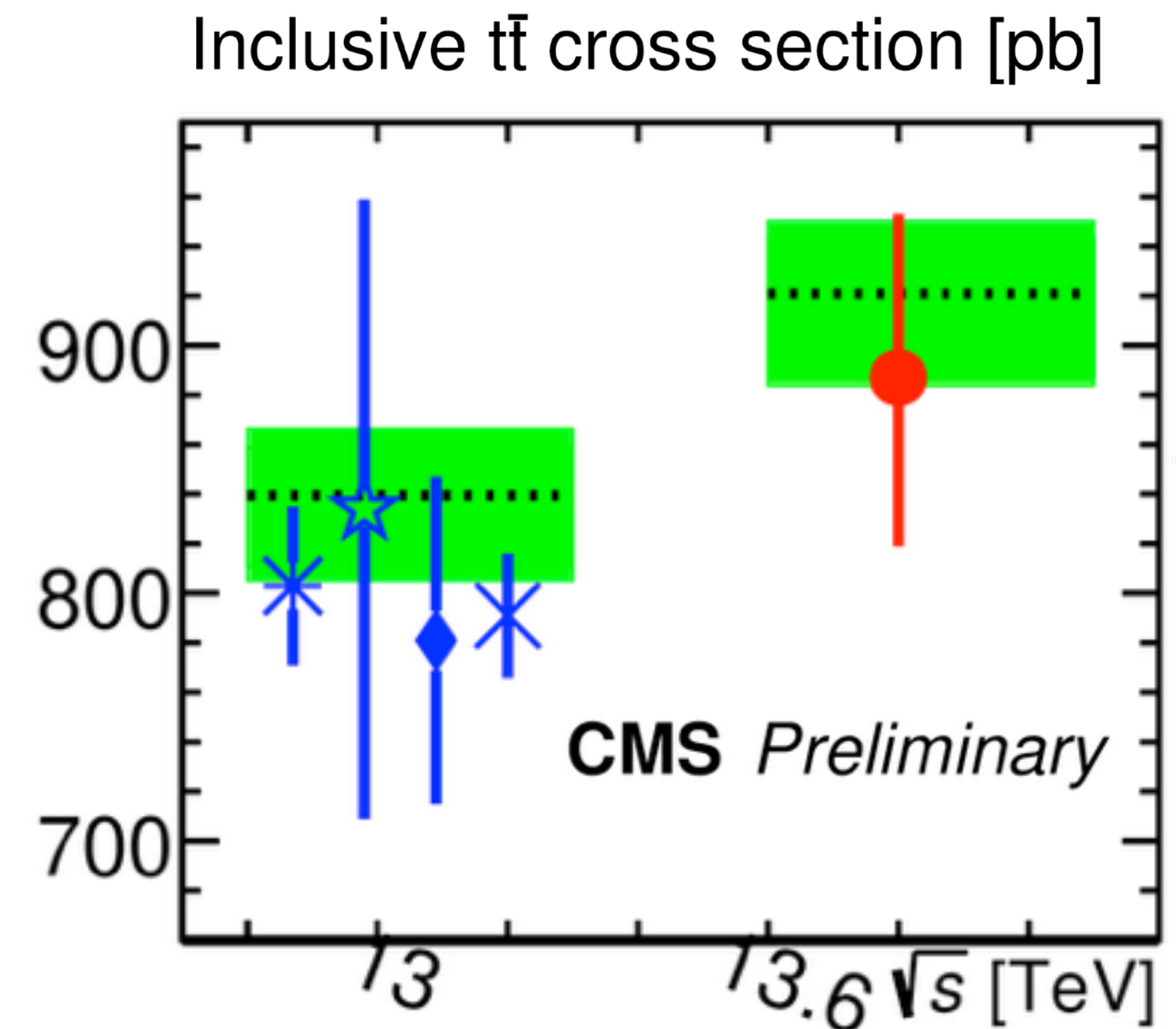
SUMMARY

- * We have only scraped the surface of the potential of the LHC data



- * SM measurements constraint BSM physics beyond the LHC direct reach

- * Only touched upon two 13 TeV results, but Run3 data is already with us



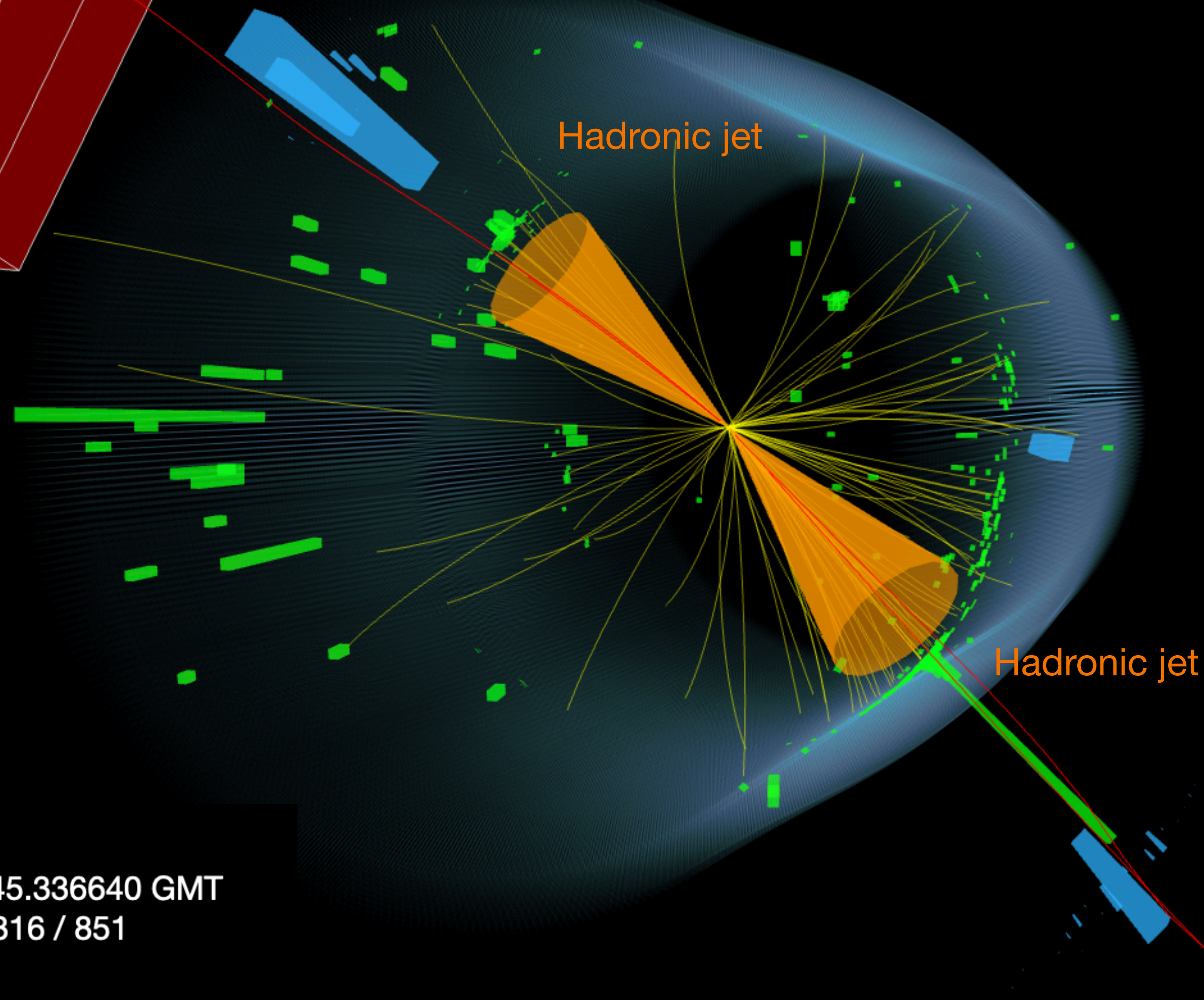
CMS-TOP-22-012

BACKUP

Display of a two jet
event in CMS



CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-27 14:40:45.336640 GMT
Run / Event / LS: 281707 / 1353407816 / 851



INCLUSIVE JETS AND $\alpha_s(m_Z)$

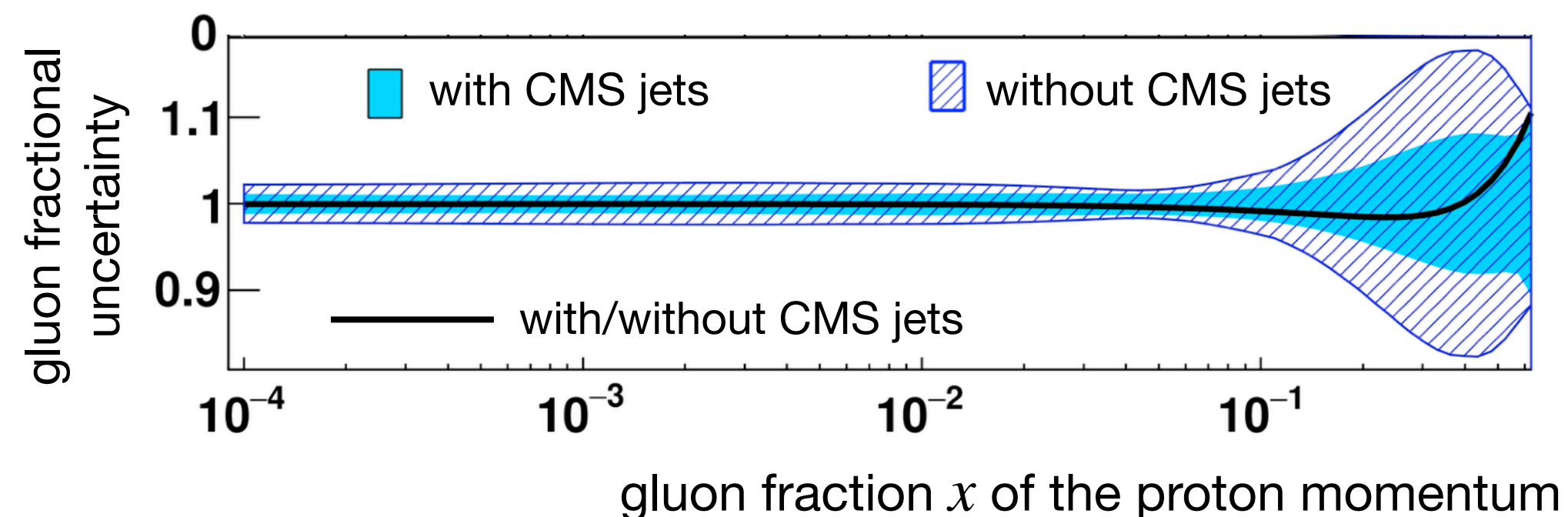
* QCD analysis at NNLO QCD

- ▶ Joint determination of the proton PDFs and $\alpha_s(m_Z)$ using the CMS jet and HERA2 DIS data
- ▶ Avoid circularity: jets \rightarrow gluon PDF, jets $\rightarrow \alpha_s(m_Z)$

$$\alpha_s(m_Z) = 0.1170 \pm 0.0014(\text{fit}) \pm 0.0007(\text{model}) \pm 0.0008(\text{scale}) \pm 0.0001(\text{parametrisation})$$

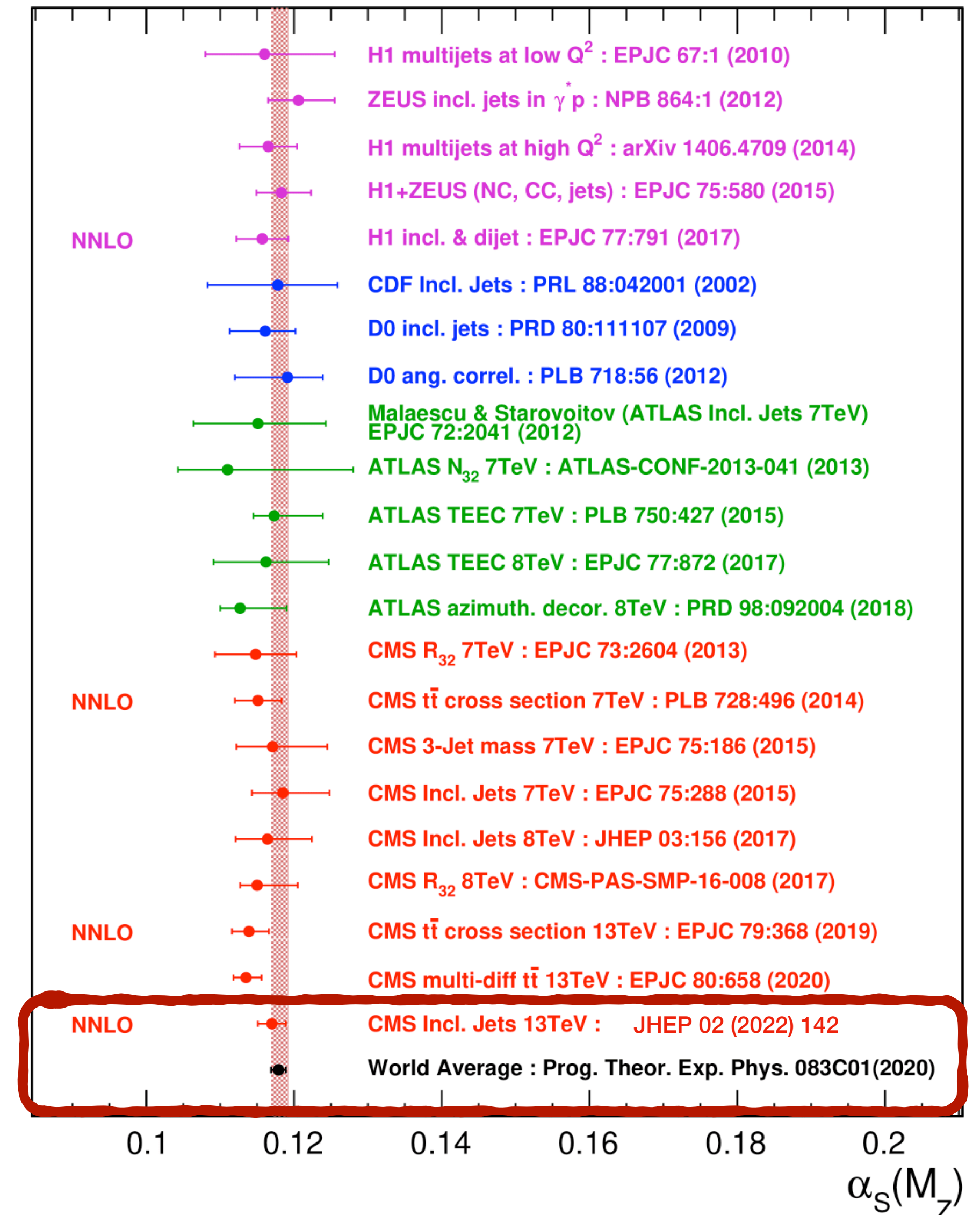
Data statistics Parametric uncertainties

QCD scale variations PDF functional form



- * Most precise $\alpha_s(m_Z)$ from single experiment, in agreement with world average

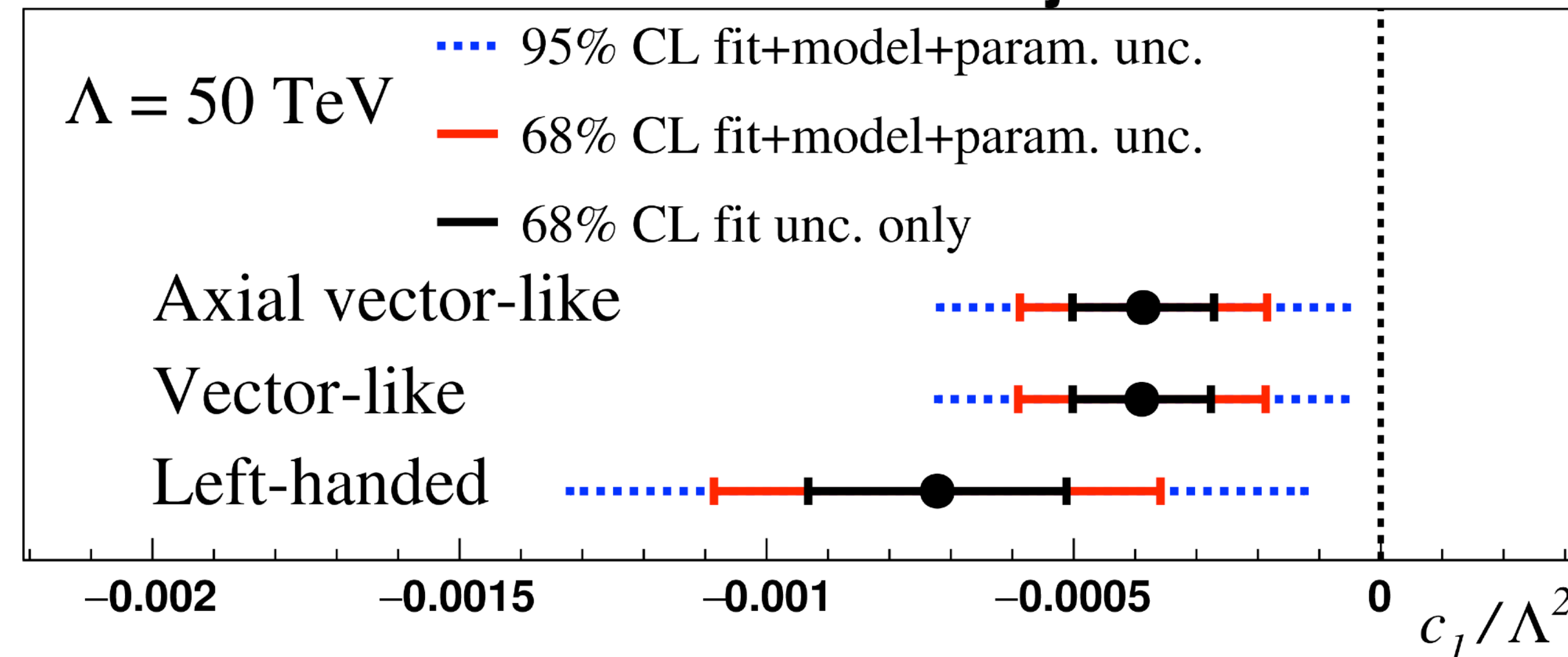
$\alpha_s(m_Z)$ at hadron collider from jets data



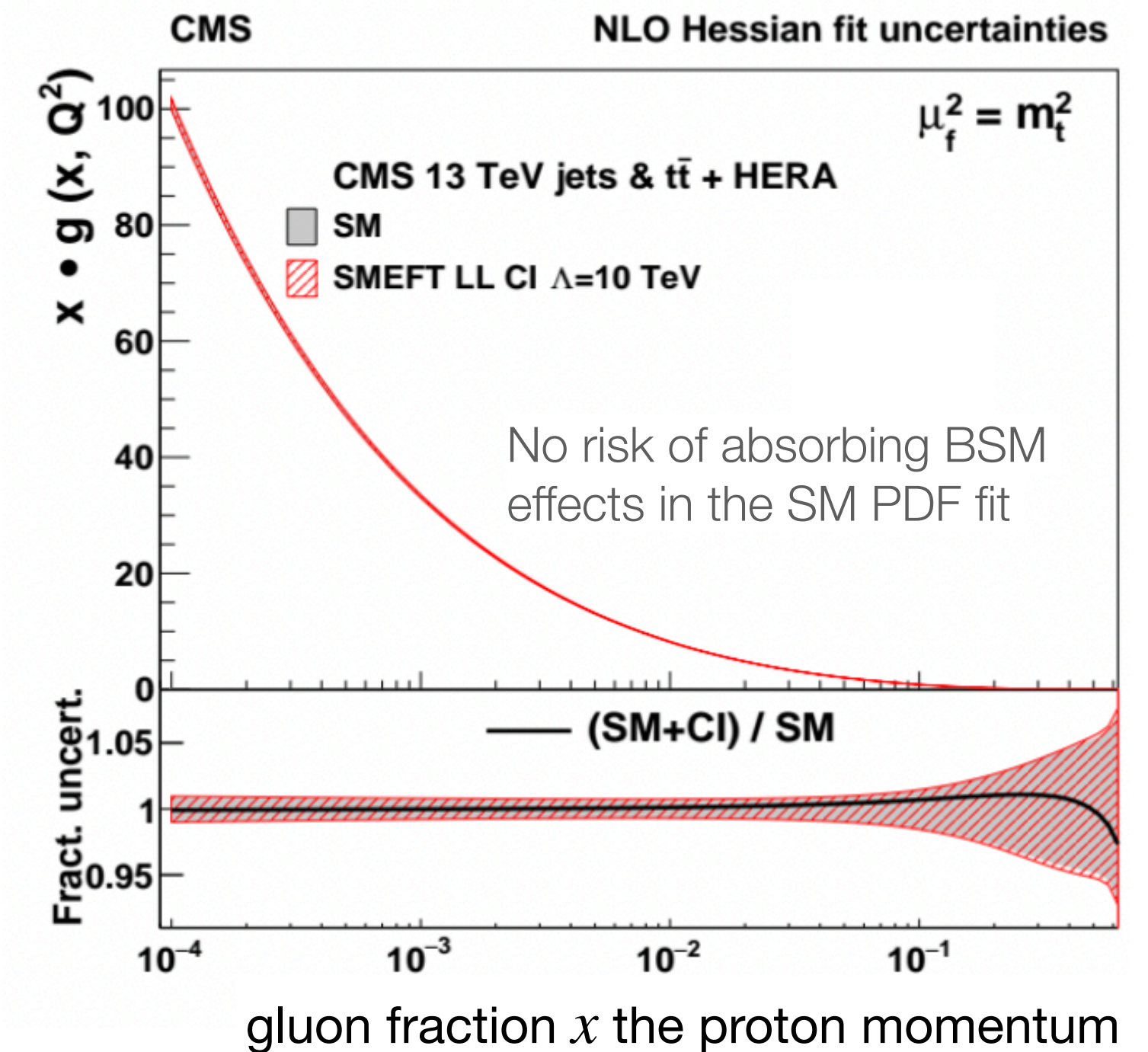
JETS & NEW PHYSICS

- * Unbiased search for Contact Interactions in high- p_T jets
 - **Issue:** SM prediction based on PDFs including LHC jet data
 - **Solution:** BSM effects are not absorbed into the PDFs by determining them in a simultaneous fit

CMS SMEFT NLO 13 TeV jets & $t\bar{t}$ + HERA



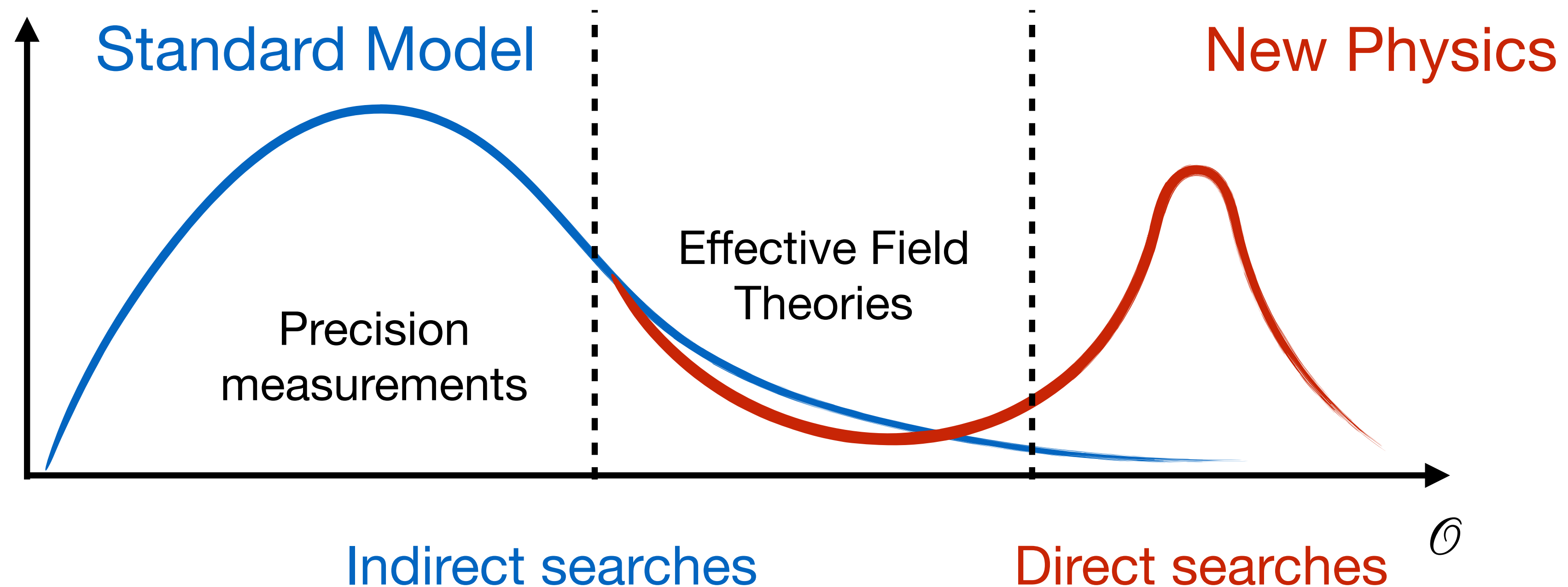
JHEP 02 (2022) 142



- * Results consistent with the SM
- * Constrain new physics scale Λ assuming $c_1 = -1$
 - $\Lambda > 32 \text{ TeV}$ for vector-like coupling

PHYSICS AT THE LHC

- * Physics Beyond the Standard Model more elusive than expected
- * Time to *rethink our approaches*



- * Effective Field Theory: parametrise high scale physics at low energies
- * Access energy scales much higher than those directly accessible

EFFECTIVE FIELD THEORIES

- * If BSM physics is heavy we can “*integrate it out*”, leaving higher dimensional operators in the Lagrangian - an EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}^{(6)} + \dots$$

c_i Wilson coefficient

$\mathcal{O}_i^{(d)}$ operator of dimension d

Λ scale of new physics

Fitted to experimental measurements

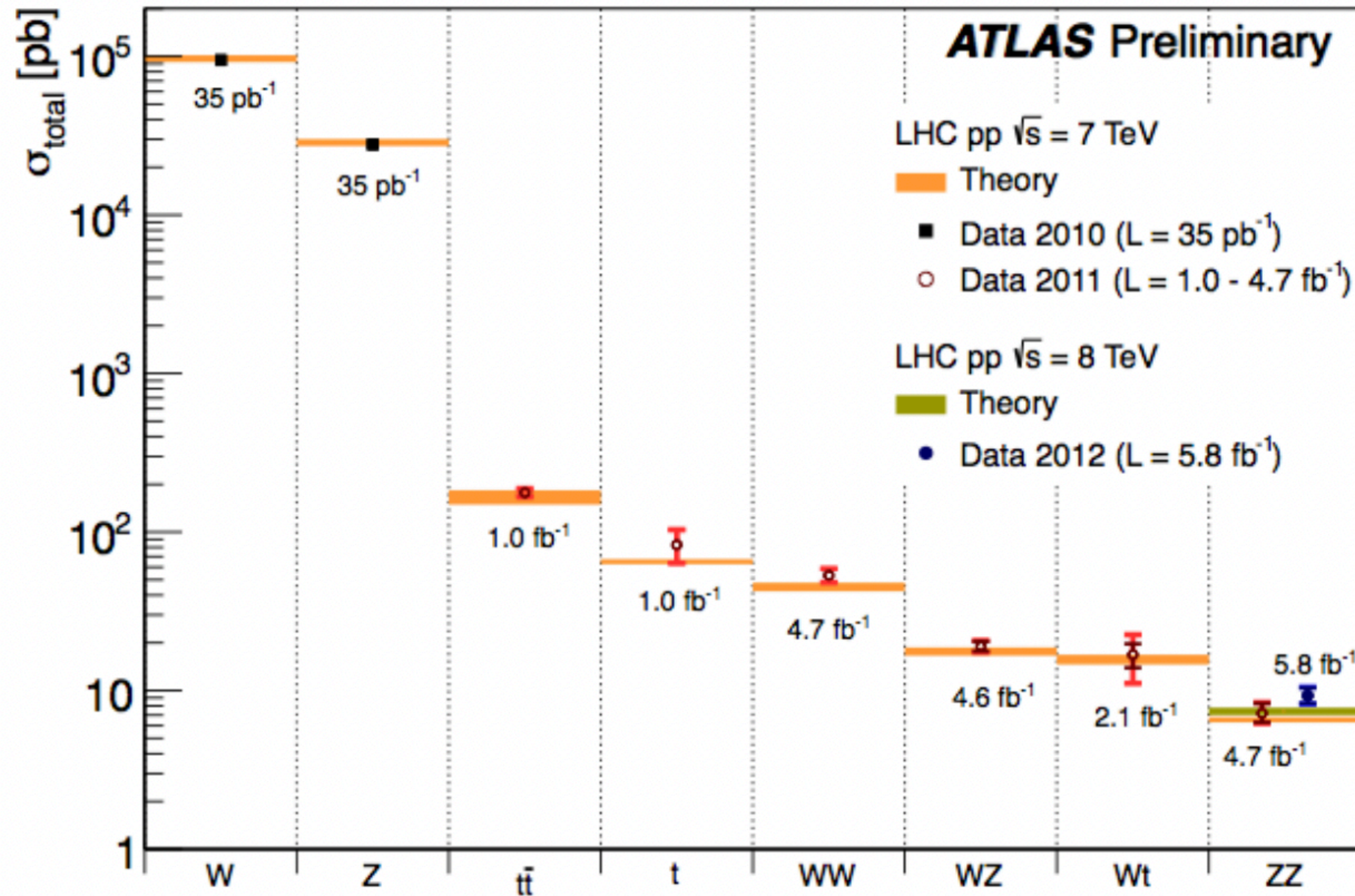
New physics to show up as $c_i \neq 0$

- * Contribution of certain operators grows with partonic center-of-mass energy
 - Increased sensitivity in TeV region
- * Dim-6: 1000s of operators, complex phase space to explore
- * Complementarity between different measurements and processes

STANDARD MODEL AT THE LHC: THE BEGINNINGS

Standard Model Production Cross Section Measurements

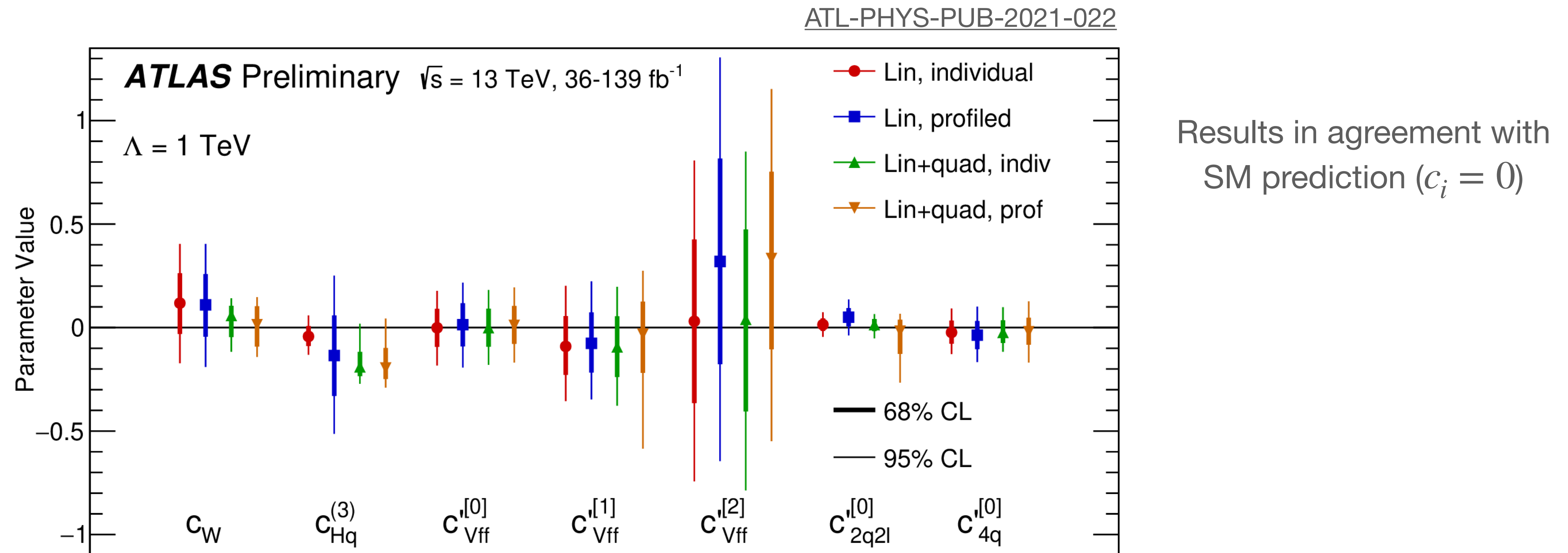
Status: March 2013



- Discovery of the Higgs
- Precision measurements of QCD and EW processes
- Exploration of BSM physics via direct and indirect searches

GLOBAL EFT FIT TO DIBOSON DATA

- * ATLAS combined interpretation of WW, WZ, ZZ, and VBF Z measurements
 - Allows to constrain more flat directions in the EFT space



- * First step towards global EFT interpretations of multiple processes