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BEYOND THE STANDARD MODEL

OUTLINE

1. Physics beyond the Standard Model

- Motivation
- Model dependent and model independent strategies

2. Standard Model Effective Field Theory

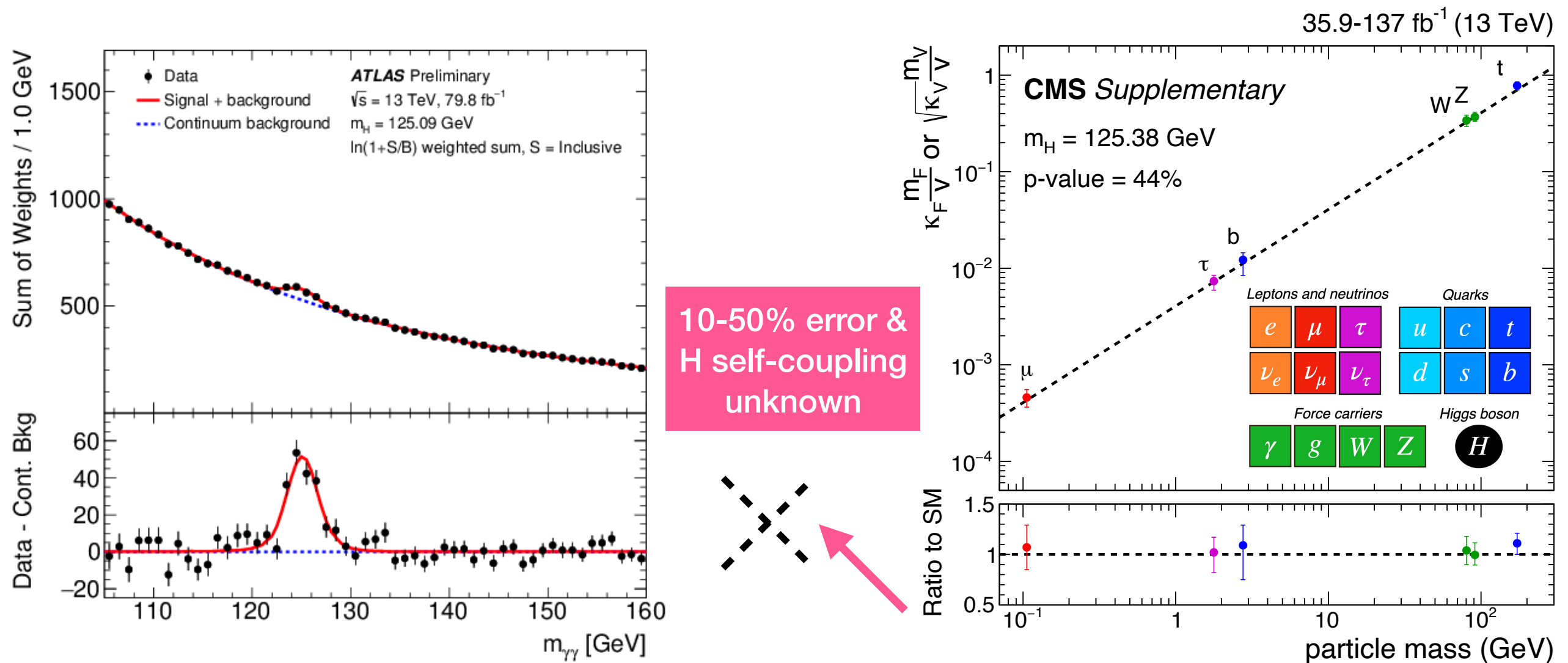
- Assumptions and basis
- Global SMEFT analyses at the LHC and EIC

3. Interplay between BSM physics and PDFs

- PDFs can absorb BSM physics: a few phenomenological examples
- LHC and EIC complementary constraints

1. PHYSICS BEYOND THE STANDARD MODEL

THE HIGGS DISCOVERY



- Discovery of the Higgs boson at the LHC in 2012 opened a new era of exploration of the high energy frontier at particle colliders with new Yukawa force still largely unknown.
- No bullet-proof theoretical argument to argue for the existence of New Physics between 8 and 13 TeV and even less so to prefer a NP model with respect to another.



IS THE HIGGS THE END OF THE STORY?

Definitely not!

GeV

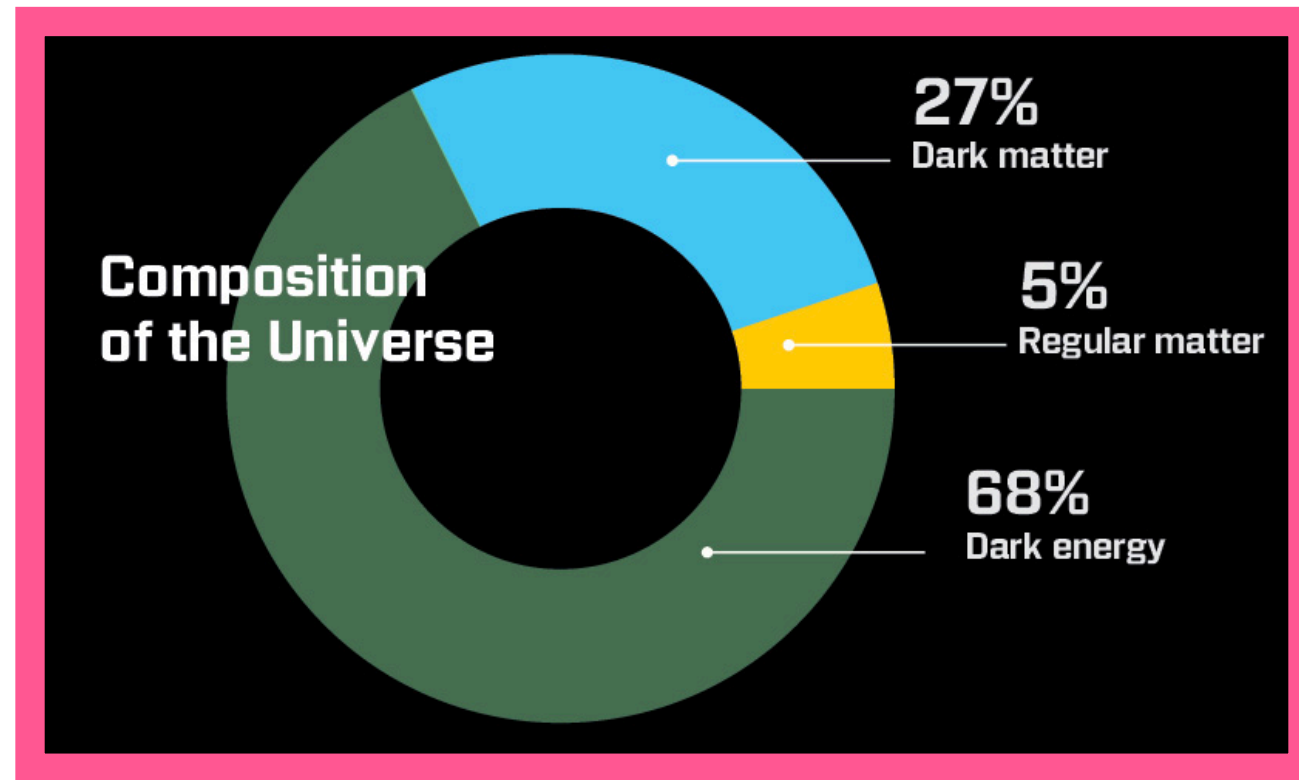
Gravity not in the SM

10^{19} : PLANK SCALE

10^2 : EW SCALE

**L
H
C**

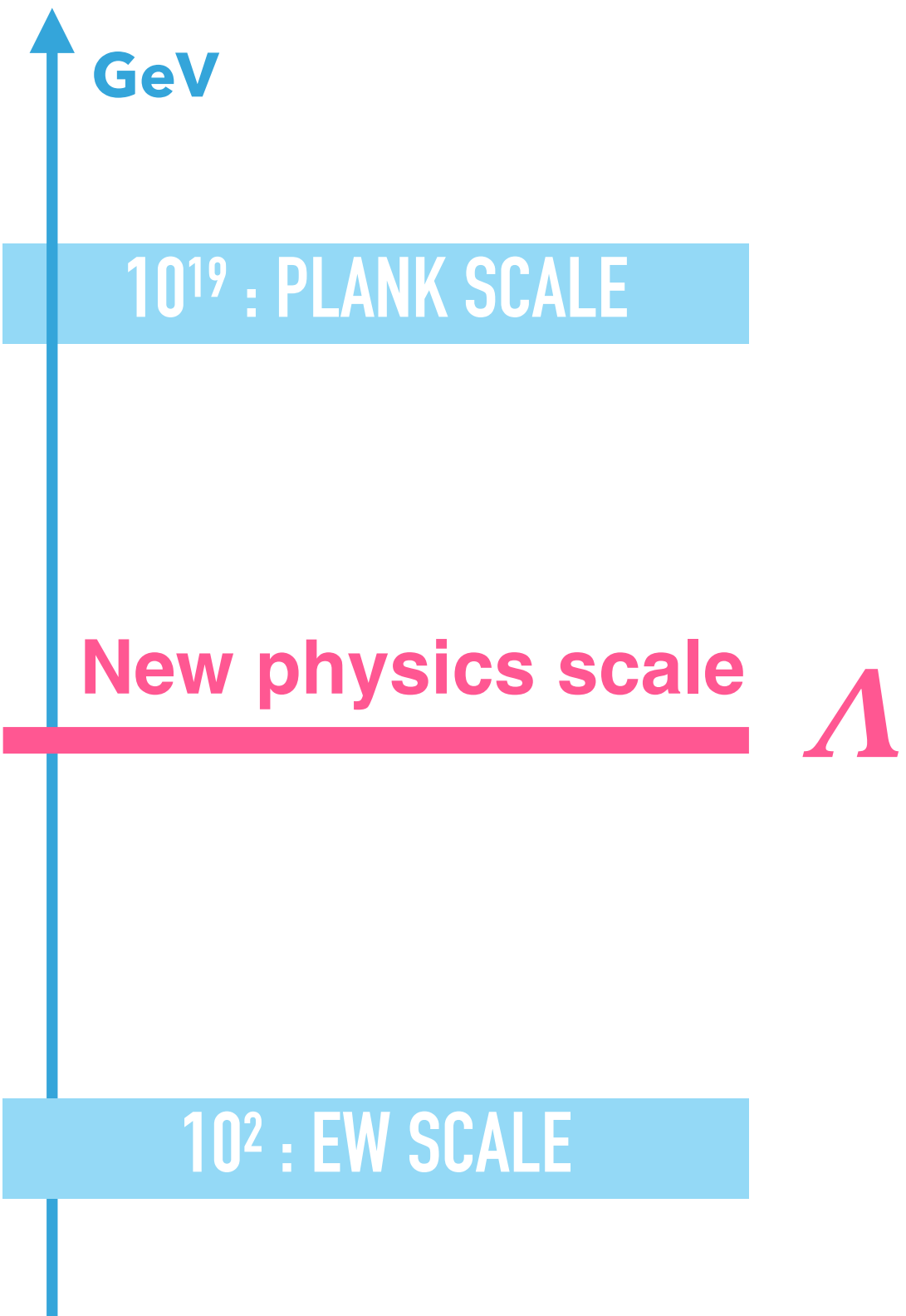
IS THE HIGGS THE END OF THE STORY?



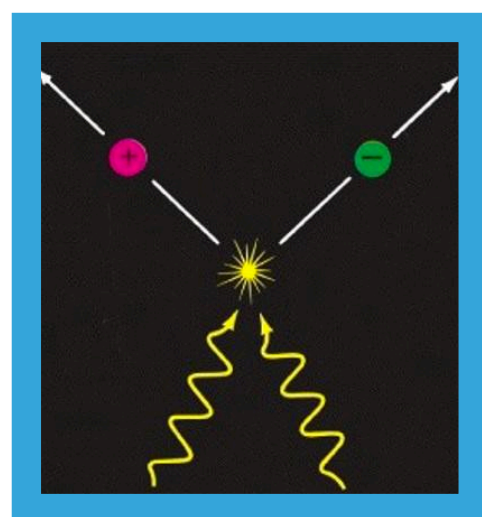
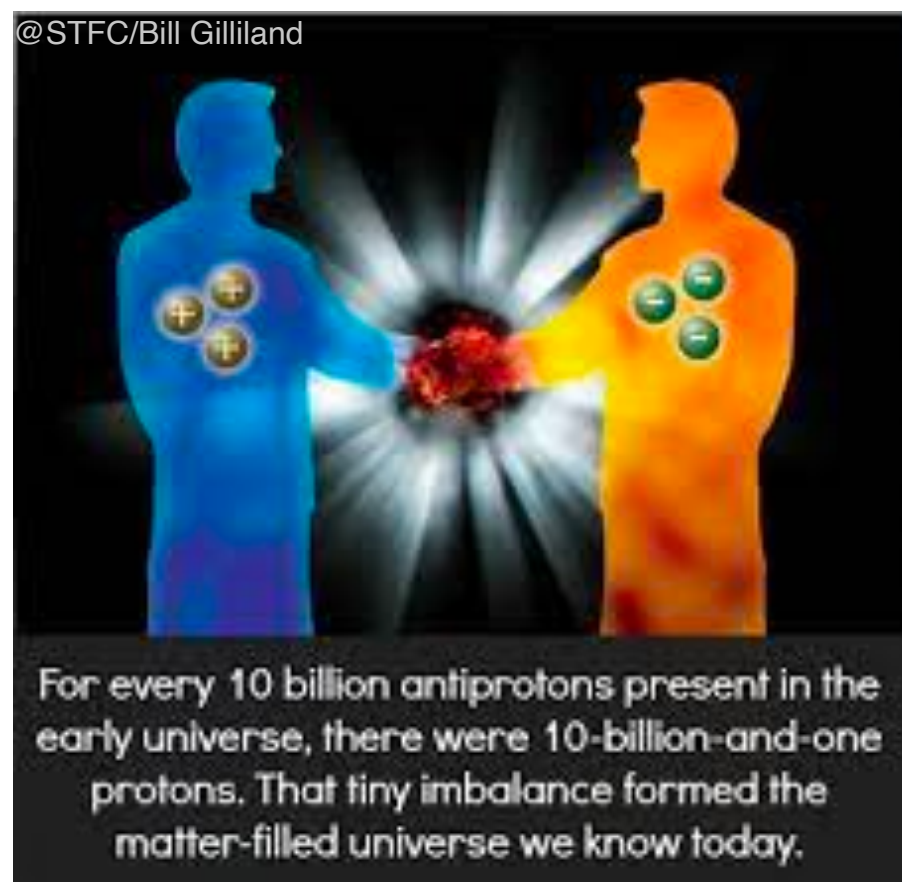
Degrassi et al, 2012

No Dark Matter candidate

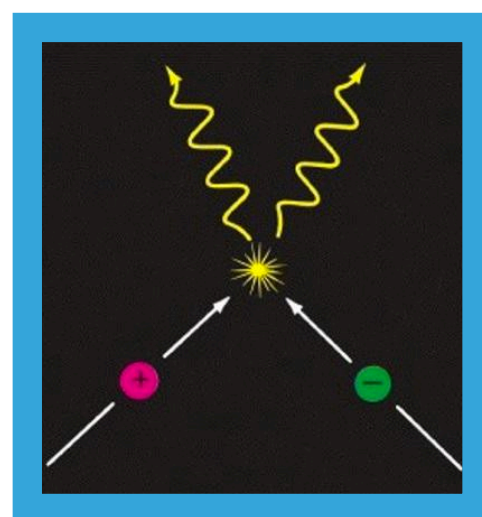
L
H
C



IS THE HIGGS THE END OF THE STORY?



≠



L
H
C

GeV

10^{19} : PLANK SCALE

New physics scale

Λ

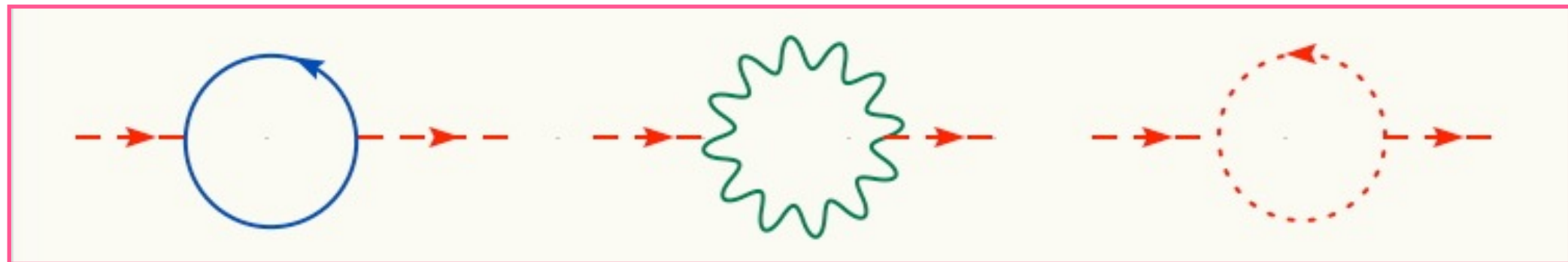
10^2 : EW SCALE

Not enough CP violation in SM to explain matter-antimatter asymmetry

THE HIGGS IS THE BEGINNING OF THE STORY

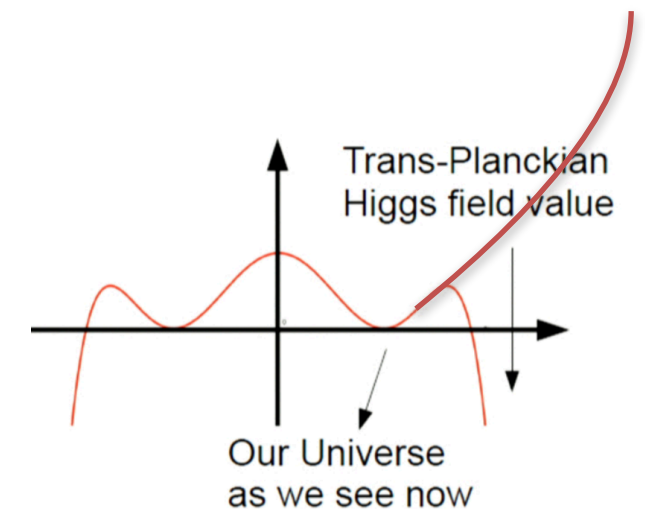
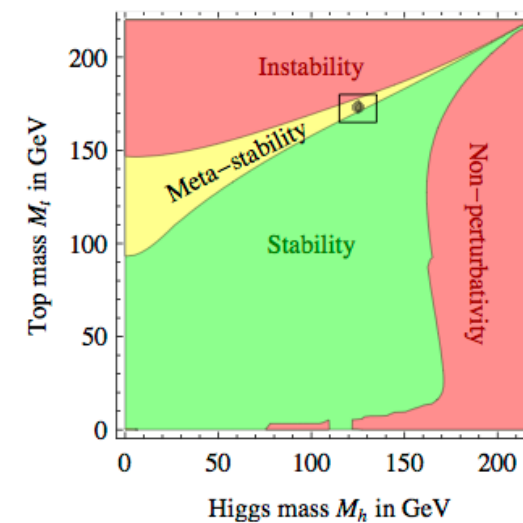
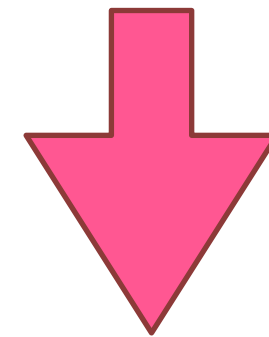
First spin-0 elementary particle ever discovered → its physics properties receive much stronger quantum corrections from virtual new particles than any other particle in the SM!

Higgs = portal to new physics



THE HIGGS IS THE BEGINNING OF THE STORY

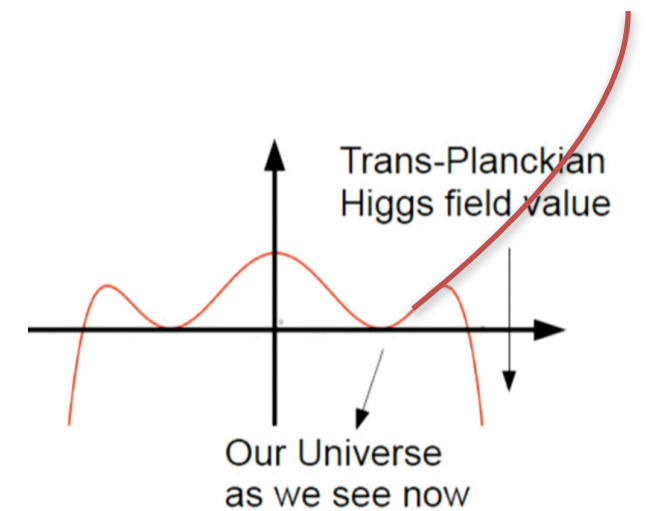
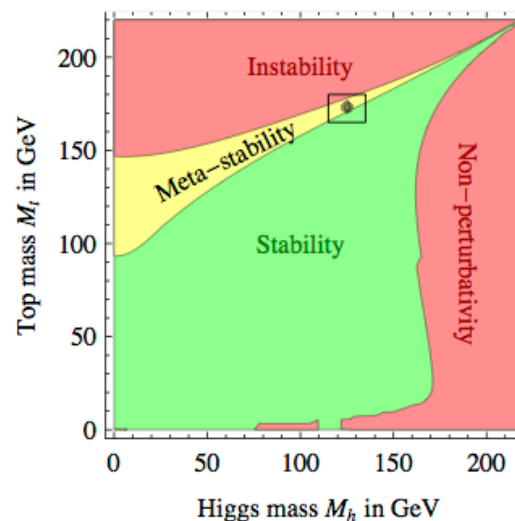
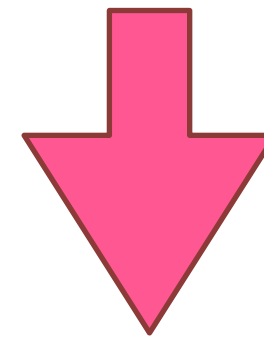
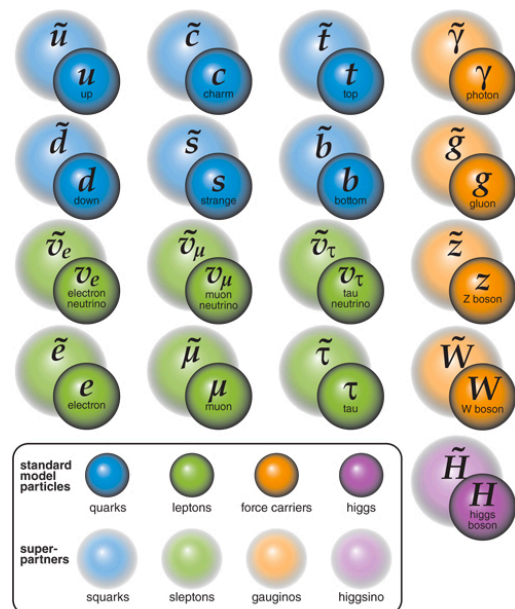
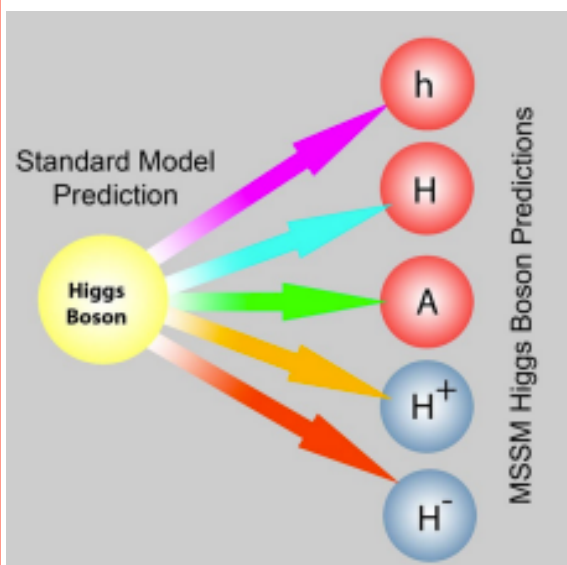
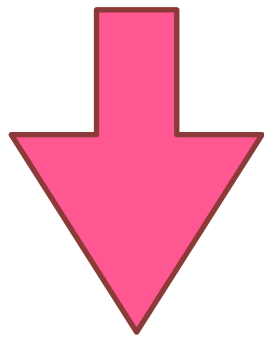
The fate of our universe is linked with the properties of the Higgs: are we going to quantum-tunnel into a completely different universe?



THE HIGGS IS THE BEGINNING OF THE STORY

From a theoretical point of view, it would be natural to have an extended Higgs sector and unveil new fundamental symmetries

The fate of our universe is linked with the properties of the Higgs: are we going to quantum-tunnel into a completely different universe?

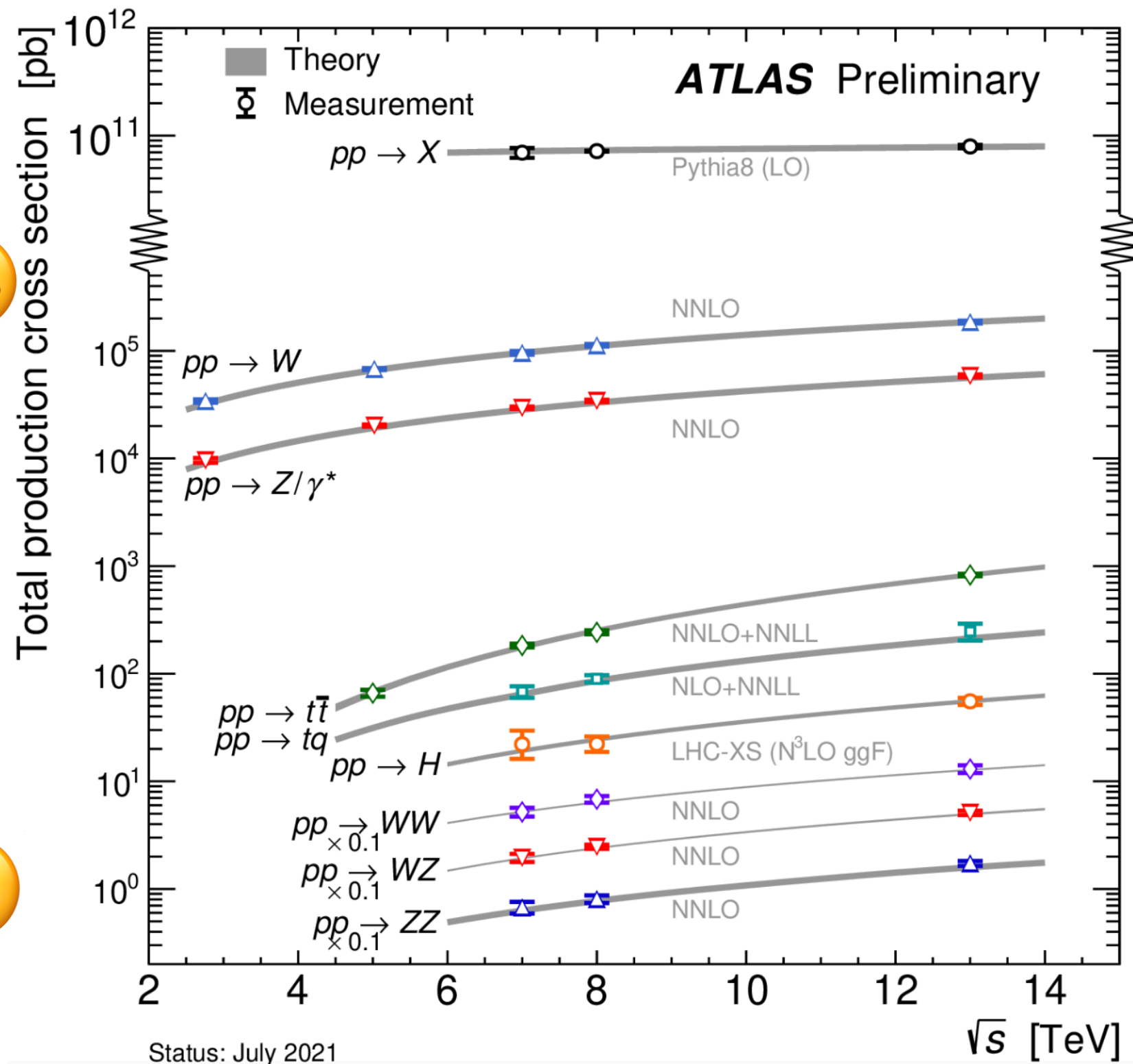


NEW PHYSICS, WHERE ARE THOU?

Thanks to the progress
in the theory
calculations predictions
have reached
impressive level of
precision!

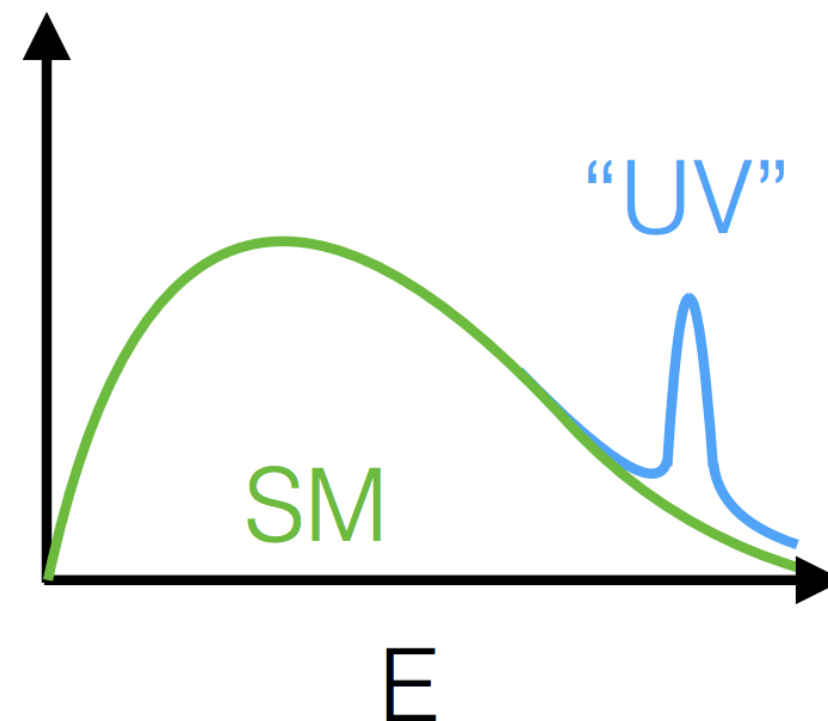
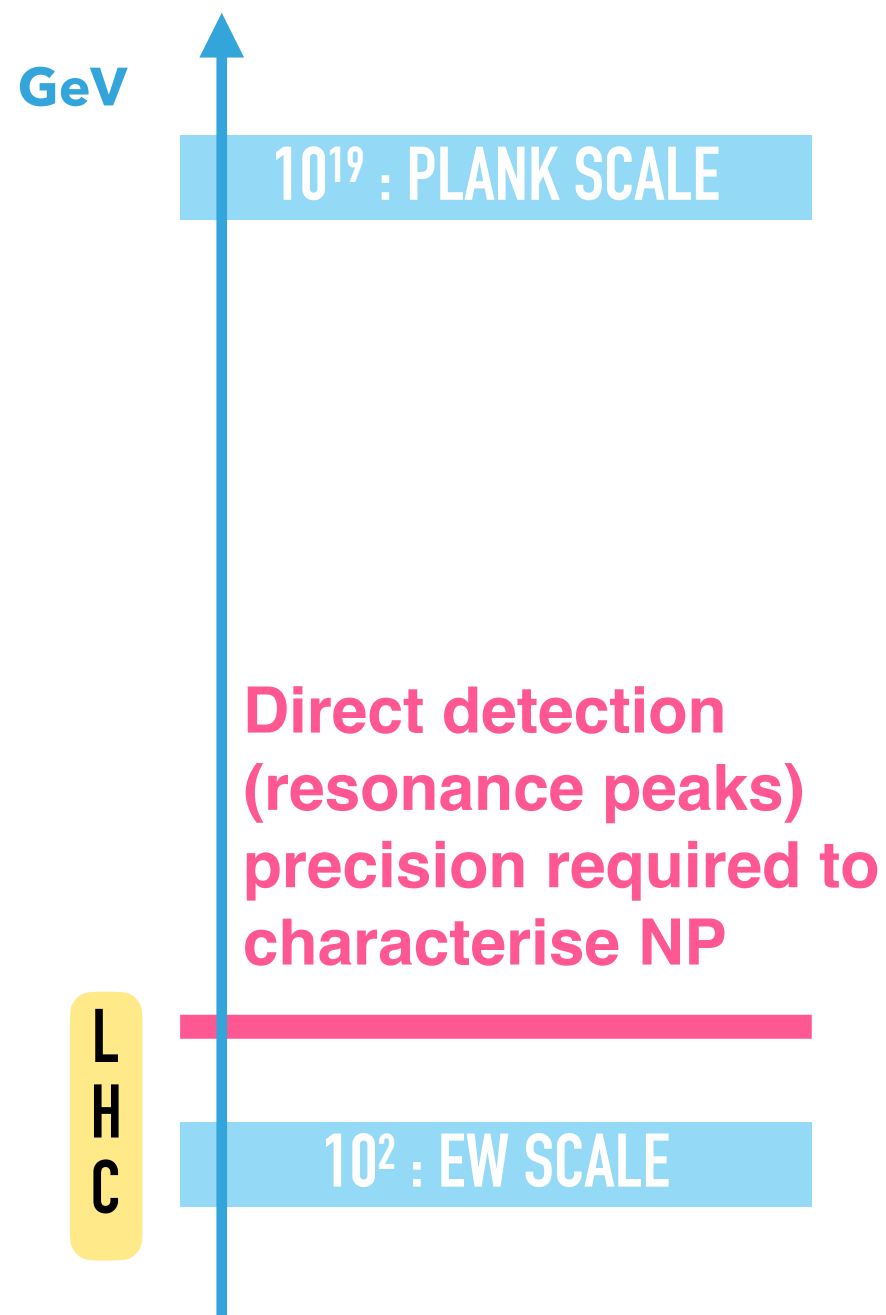


No strong evidence of
disagreement between
SM predictions and
experimental
measurements at the
LHC



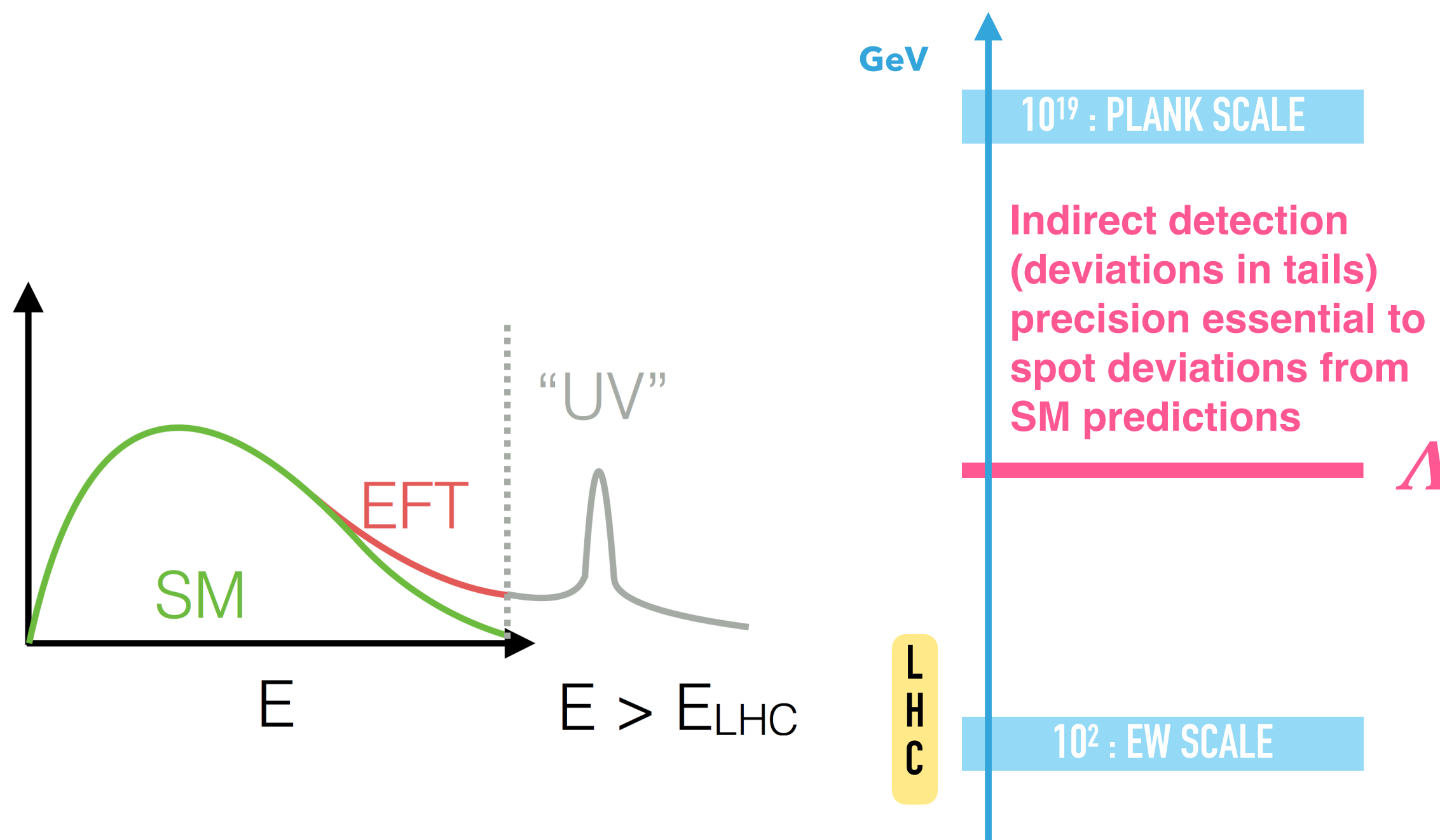
BSM PHENOMENOLOGY AT THE LHC

- Two complementary strategies have been pursued at the LHC for new physics searches
- Search for resonances (direct searches) and search for deviations (indirect searches)



BSM PHENOMENOLOGY AT THE LHC

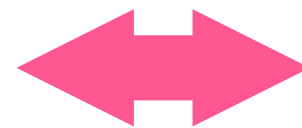
- Two complementary strategies have been pursued at the LHC for new physics searches
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NEW PHYSICS SEARCHES LANDSCAPE

Search for new states

specific models, simplified models

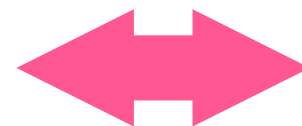


Search for new interactions

anomalous couplings, EFT...

Model-dependent

SUSY, 2HDM, ED,...



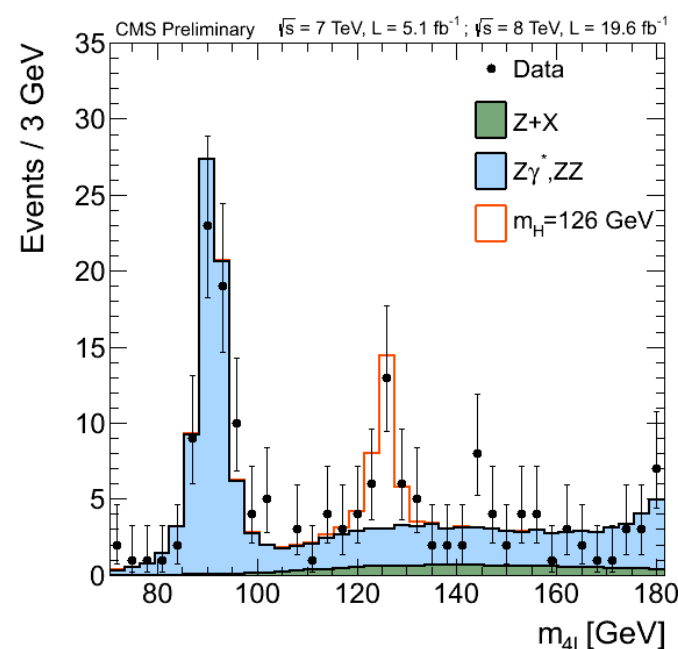
Model-independent

simplified models, EFT, ...

NEW PHYSICS SEARCHES LANDSCAPE

Search for new states

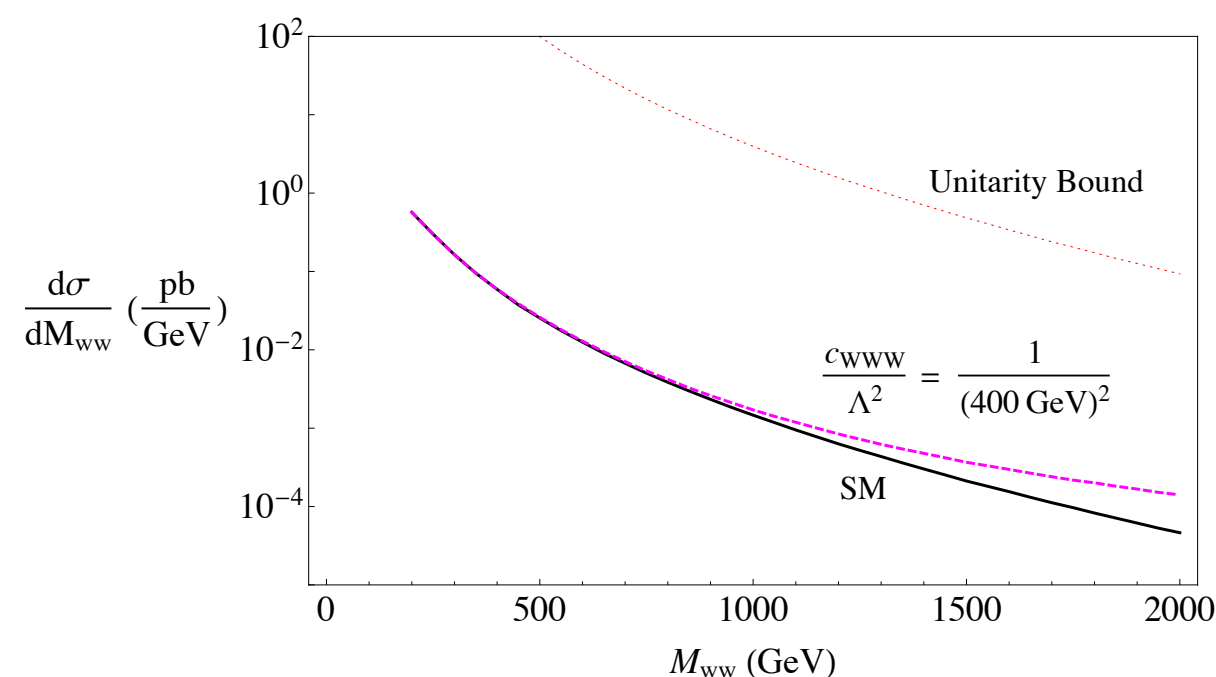
specific models, simplified models



“Peak” or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Search for new interactions

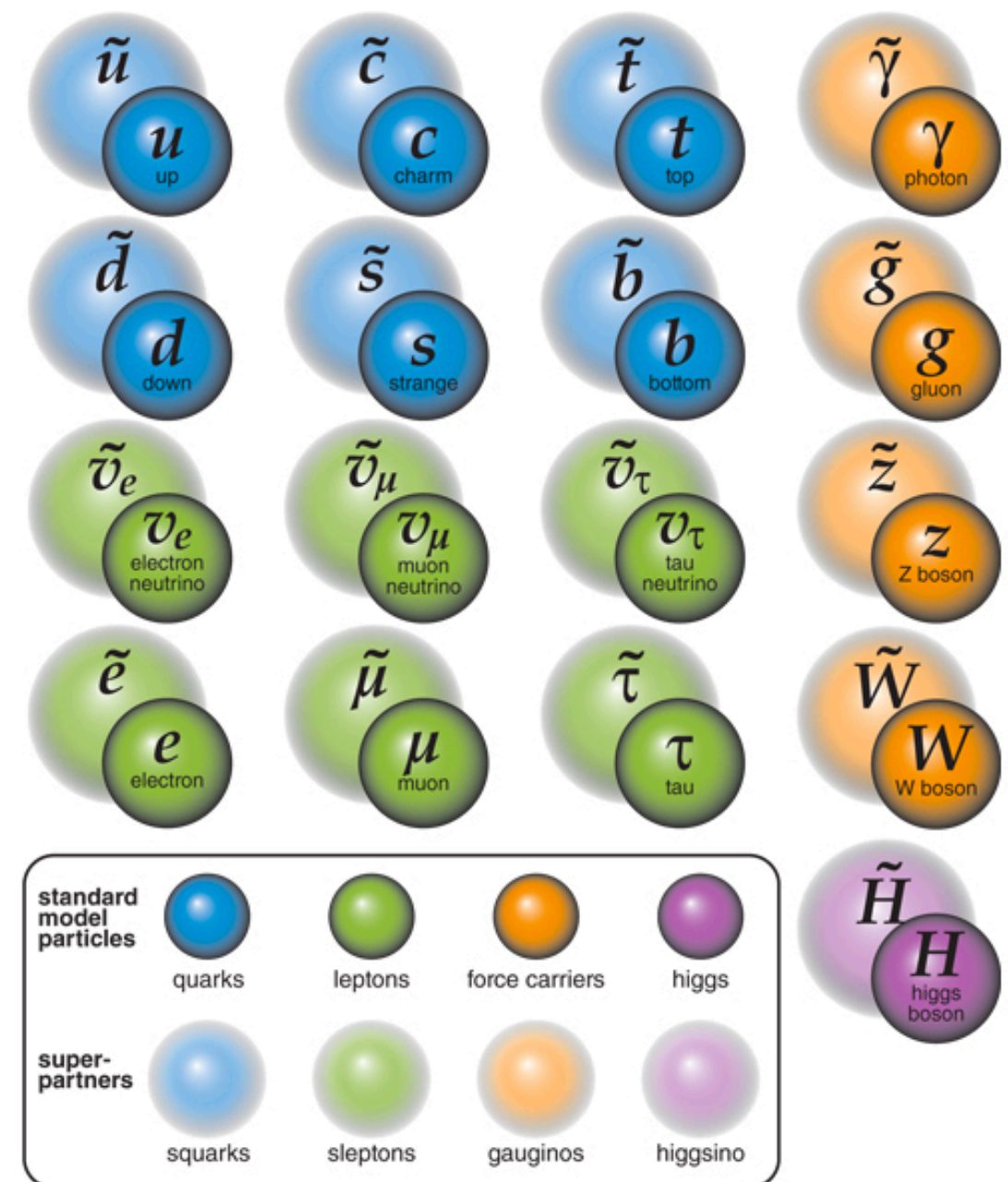
anomalous couplings, EFT...



Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

DIRECT SEARCHES

- With LHC reaching unexplored energy scales, searches for new physics should aim at being sensitive to the highest possible energy scale and no stone should be left unturned.
- LHC strategy: look for New Physics by covering the widest range of theoretically or experimentally motivated searches



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

√s = 13 TeV

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}	140 140	$\tilde{q}$ [1x, 8x Degen.] $\tilde{q}$ [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0)<400$ GeV $m(\tilde{q})\text{-}m(\tilde{\chi}_1^0)=5$ 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}	140	$\tilde{g}$ $\tilde{g}$	 Forbidden	 1.15-1.95	$m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{\chi}_1^0)=1000$ 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		140	$\tilde{g}$		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}	140	$\tilde{g}$		2.2	$m(\tilde{\chi}_1^0)<700$ GeV	2204.13072	
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets	E_T^{miss} E_T^{miss}	140 140	$\tilde{g}$ $\tilde{g}$		1.97 1.15	$m(\tilde{\chi}_1^0)<600$ GeV $m(\tilde{g})\text{-}m(\tilde{\chi}_1^0)=200$ GeV	2008.06032 2307.01094	
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} E_T^{miss}	140 140	$\tilde{g}$ $\tilde{g}$		2.45 1.25	$m(\tilde{\chi}_1^0)<500$ GeV $m(\tilde{g})\text{-}m(\tilde{\chi}_1^0)=300$ GeV	2211.08028 1909.08457	
	3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	140	$\tilde{b}_1$ $\tilde{b}_1$		1.255 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
		$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_2^0\rightarrow bh\tilde{\chi}_1^0$	0 e, μ 2 τ	6 b 2 b	E_T^{miss} E_T^{miss}	140 140	$\tilde{b}_1$ $\tilde{b}_1$	Forbidden	0.23-1.35 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ 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}	140	$\tilde{t}_1$		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}	140	$\tilde{t}_1$	Forbidden	1.05	$m(\tilde{\chi}_1^0)=500$ GeV	2012.03799, 2401.13430	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1\rightarrow \tau\tilde{G}$		1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden	1.4	$m(\tilde{\tau}_1)=800$ GeV	2108.07665	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c}\rightarrow c\tilde{\chi}_1^0$		0 e, μ 0 e, μ	2 c mono-jet	E_T^{miss} E_T^{miss}	36.1 140	$\tilde{c}$ $\tilde{t}_1$		0.85 0.55	$m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{t}_1, \tilde{c})\text{-}m(\tilde{\chi}_1^0)=5$ 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}	140	$\tilde{t}_1$		0.067-1.18	$m(\tilde{\chi}_2^0)=500$ GeV	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow \tilde{t}_1+Z$		3 e, μ	1 b	E_T^{miss}	140	$\tilde{t}_2$	Forbidden	0.86	$m(\tilde{\chi}_1^0)=360$ GeV, $m(\tilde{t}_1)\text{-}m(\tilde{\chi}_1^0)=40$ GeV	2006.05880	
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet	E_T^{miss} E_T^{miss}	140 140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.96 0.205	$m(\tilde{\chi}_1^0)=0$, wino-bino $m(\tilde{\chi}_1^\pm)\text{-}m(\tilde{\chi}_1^0)=5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e, μ		E_T^{miss}	140	$\tilde{\chi}_1^\pm$		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		E_T^{miss}	140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden	1.06	$m(\tilde{\chi}_1^0)=70$ GeV, wino-bino	2004.10894, 2108.07586	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ		E_T^{miss}	140	$\tilde{\chi}_1^\pm$		1.0	$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\rightarrow\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_R\tilde{\tau}_R$]	0.35	0.5	$m(\tilde{\chi}_1^0)=0$	2402.00603	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	140 140	$\tilde{\ell}$ $\tilde{\ell}$		0.7 0.26	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\ell})\text{-}m(\tilde{\chi}_1^0)=10$ GeV	1908.08215 1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ 0 e, μ 2 e, μ	≥ 3 b 0 jets ≥ 2 large jets ≥ 2 jets	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	140 140 140 140	$\tilde{H}$ $\tilde{H}$ $\tilde{H}$ $\tilde{H}$		0.94 0.55 0.45-0.93 0.77	$\text{BR}(\tilde{\chi}_1^0\rightarrow h\tilde{G})=1$ $\text{BR}(\tilde{\chi}_1^0\rightarrow Z\tilde{G})=1$ $\text{BR}(\tilde{\chi}_1^0\rightarrow Z\tilde{G})=1$ $\text{BR}(\tilde{\chi}_1^0\rightarrow Z\tilde{G})=\text{BR}(\tilde{\chi}_1^0\rightarrow h\tilde{G})=0.5$	2401.14922 2103.11684 2108.07586 2204.13072	
	Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$		0.66 0.21	Pure Wino Pure higgsino	2201.02472 2201.02472
Stable $\tilde{g}$ R-hadron		pixel dE/dx		E_T^{miss}	140	$\tilde{g}$		2.05		2205.06013	
Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$		pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ [$\tau(\tilde{g})=10$ ns]		2.2	$m(\tilde{\chi}_1^0)=100$ GeV	2205.06013	
$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\rightarrow\ell\tilde{G}$		Displ. lep		E_T^{miss}	140	$\tilde{e}, \tilde{\mu}$ $\tilde{\tau}$		0.74 0.36	$\tau(\tilde{\ell})=0.1$ ns $\tau(\tilde{\ell})=0.1$ ns	ATLAS-CONF-2024-011 ATLAS-CONF-2024-011	
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})=10$ ns	2205.06013	
RPV		$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm\rightarrow Z\ell\rightarrow\ell\ell\ell$	3 e, μ			140	$\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ [$\text{BR}(Z\tau)=1, \text{BR}(Ze)=1$]	0.625	1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\rightarrow WW/Z\ell\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.95	1.55	$m(\tilde{\chi}_1^0)=200$ GeV	2103.11684	
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow qq q$		≥ 8 jets		140	$\tilde{g}$ [$m(\tilde{\chi}_1^0)=50$ GeV, 1250 GeV]		1.6	Large λ''_{112}	2401.16333	
	$\tilde{t}\tilde{t}, \tilde{t}\rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow tbs$		Multiple		36.1	$\tilde{t}$ [$\lambda''_{323}=2\text{e-}4, 1\text{e-}2$]	0.55	1.05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003	
	$\tilde{t}\tilde{t}, \tilde{t}\rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\rightarrow bbs$		$\geq 4b$		140	$\tilde{t}$	Forbidden	0.95	$m(\tilde{\chi}_1^\pm)=500$ GeV	2010.01015	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42	0.61		1710.07171	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow q\ell$	2 e, μ 1 μ	2 b DV		140 136	$\tilde{t}_1$ $\tilde{t}_1$ [$1\text{e-}10<\lambda'_{23k}<1\text{e-}8, 3\text{e-}10<\lambda'_{23k}<3\text{e-}9$]		0.4-1.85 1.0	$\text{BR}(\tilde{t}_1\rightarrow be/b\mu)>20\%$ $\text{BR}(\tilde{t}_1\rightarrow q\mu)=100\%, \cos\theta_{\ell_i}=1$	2406.18367 2003.11956	
	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0\rightarrow tbs, \tilde{\chi}_1^\pm\rightarrow bbs$	1-2 e, μ	≥ 6 jets		140	$\tilde{\chi}_1^0$	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.

10⁻¹

1

Mass scale [TeV]

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

	Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1 - 4 j$	Yes	36.1	M_D 7.7 TeV	$n = 2$ 1711.03301
	ADD non-resonant $\gamma\gamma$	2γ	—	—	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 $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	—	3.2	M_{th} 8.2 TeV	$n = 6, M_D = 3 \text{ TeV}$, rot BH 1606.02265
	ADD BH multijet	—	$\geq 3 j$	—	3.6	M_{th} 9.55 TeV	$n = 6, M_D = 3 \text{ TeV}$, rot BH 1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	—	—	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$ 1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	—	—	36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$ 1808.02380
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 J$	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$ 2004.14636
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$ 1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	—	—	139	Z' mass 5.1 TeV	$\Gamma/m = 1.2\%$ 1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	—	—	36.1	Z' mass 2.42 TeV	1709.07242
	Leptophobic $Z' \rightarrow bb$	—	$2 b$	—	36.1	Z' mass 2.1 TeV	1805.09299
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV	2005.05138
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	—	Yes	139	W' mass 6.0 TeV	1906.05609
	SSM $W' \rightarrow \tau\nu$	1τ	—	Yes	36.1	W' mass 3.7 TeV	1801.06992
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 4.3 TeV	$g_V = 3$ 2004.14636
	HVT $V' \rightarrow WV \rightarrow qq qq$ model B	$0 e, \mu$	$2 J$	—	139	V' mass 3.8 TeV	$g_V = 3$ 1906.08589
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	—	—	36.1	V' mass 2.93 TeV	$g_V = 3$ 1712.06518
	HVT $W' \rightarrow WH$ model B	$0 e, \mu$	$\geq 1 b, \geq 2 J$	—	139	W' mass 3.2 TeV	$g_V = 3$ CERN-EP-2020-073
	LRSW $W_R \rightarrow tb$	multi-channel	—	—	36.1	W_R mass 3.25 TeV	1807.10473
	LRSW $W_R \rightarrow \mu N_R$	2μ	$1 J$	—	80	W_R mass 5.0 TeV	$m(N_R) = 0.5 \text{ TeV}$, $g_L = g_R$ 1904.12679
CI	Cl $qqqq$	—	$2 j$	—	37.0	Λ 21.8 TeV η_{LL}^-	1703.09127
	Cl $\ell\ell qq$	$2 e, \mu$	—	—	139	Λ 35.8 TeV η_{LL}^-	CERN-EP-2020-066
	Cl $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV $ C_{4t} = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	m_{med} 1.55 TeV	$g_q=0.25, g_\chi=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	m_{med} 1.67 TeV	$g=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	VV $\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	M_* 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1608.02372
	Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	$0-1 e, \mu$	$1 b, 0-1 J$	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$ 1812.09743
LQ	Scalar LQ 1 st gen	$1, 2 e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 2 nd gen	$1, 2 \mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 3 rd gen	2τ	$2 b$	—	36.1	LQ ₃ ^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$ 1902.08103
	Scalar LQ 3 rd gen	$0-1 e, \mu$	$2 b$	Yes	36.1	LQ ₃ ^d mass 970 GeV	$\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$ 1902.08103
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	—	—	36.1	T mass 1.37 TeV	SU(2) doublet 1808.02343
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	—	—	36.1	B mass 1.34 TeV	SU(2) doublet 1808.02343
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$ 1807.11883
	VLQ $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ 1812.07343
	VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$ ATLAS-CONF-2018-024
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	—	$2 j$	—	139	q^* mass 6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	—	36.7	q^* mass 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow bg$	—	$1 b, 1 j$	—	36.1	b^* mass 2.6 TeV	1805.09299
	Excited lepton ℓ^*	$3 e, \mu$	—	—	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton ν^*	$3 e, \mu, \tau$	—	—	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	N^0 mass 560 GeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ ATLAS-CONF-2018-020
	LRSW Majorana ν	2μ	$2 j$	—	36.1	N_R mass 3.2 TeV	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	—	—	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production 1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	—	—	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$ 1411.2921
	Multi-charged particles	—	—	—	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q = 5e$ 1812.03673
	Magnetic monopoles	—	—	—	34.4	monopole mass 2.37 TeV	DY production, $ g = 1g_D$, spin 1/2 1905.10130
		$\sqrt{s} = 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$ partial data	$\sqrt{s} = 13 \text{ TeV}$ full data		10 ⁻¹ 1 10	Mass scale [TeV]

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

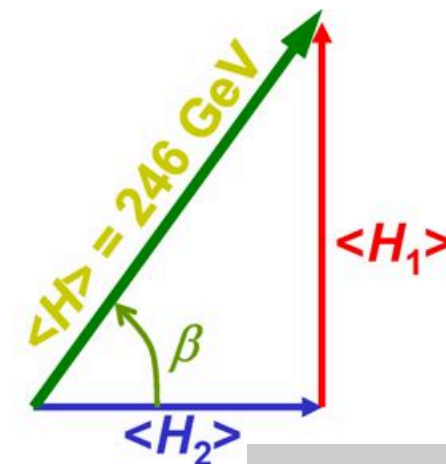
EXAMPLE: DIRECT SEARCH FOR A BROADER HIGGS SECTOR

- The Higgs provides a privileged searching ground. It has just been discovered. Some of its properties are either just been measured or completely unknown. A plethora of production and decay modes available.
- First “elementary” scalar ever : carrier of a new Yukawa force, whose effects still need to be measured.
- Several motivations to have a richer scalar sector with more doublets or higher representations $\Rightarrow$ Higgs might be the first of many new scalar states.

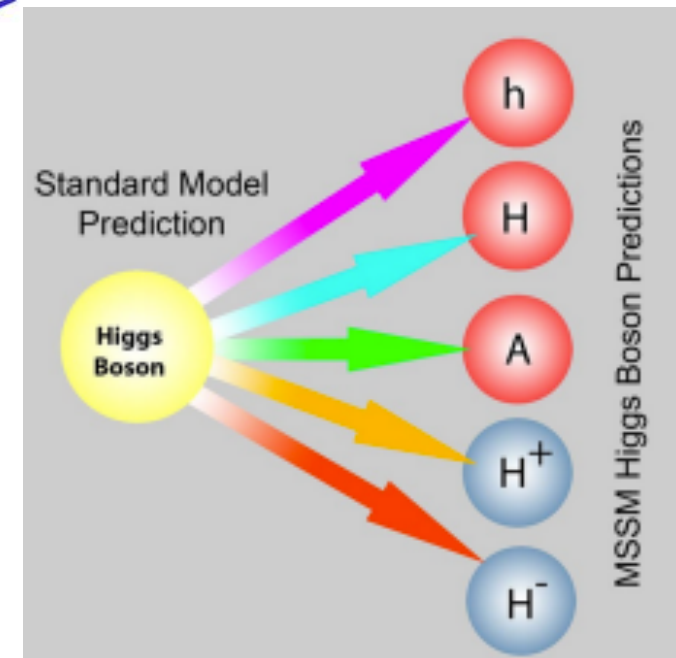
EXAMPLE: DIRECT SEARCH FOR A BROADER HIGGS SECTOR

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- Several motivations to have a richer scalar sector with more doublets or higher representations $\Rightarrow$ Higgs might be the first of many new scalar states.
- 2HDM simplest extension of SM Higgs sector two Higgs doublets, leading to five physical scalar Higgs bosons.
- Simplified model that embeds several specific models (like MSSM)
- Observing a charged Higgs would be unmistakable sign of a broader Higgs sector

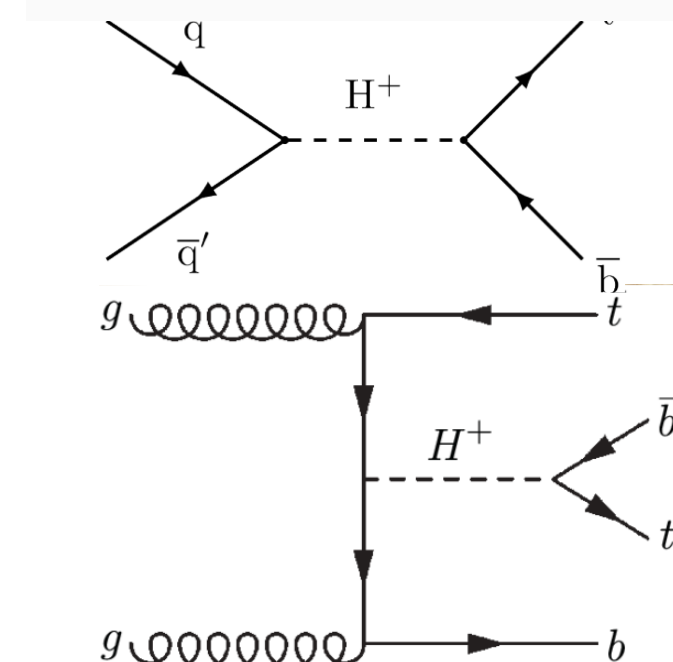
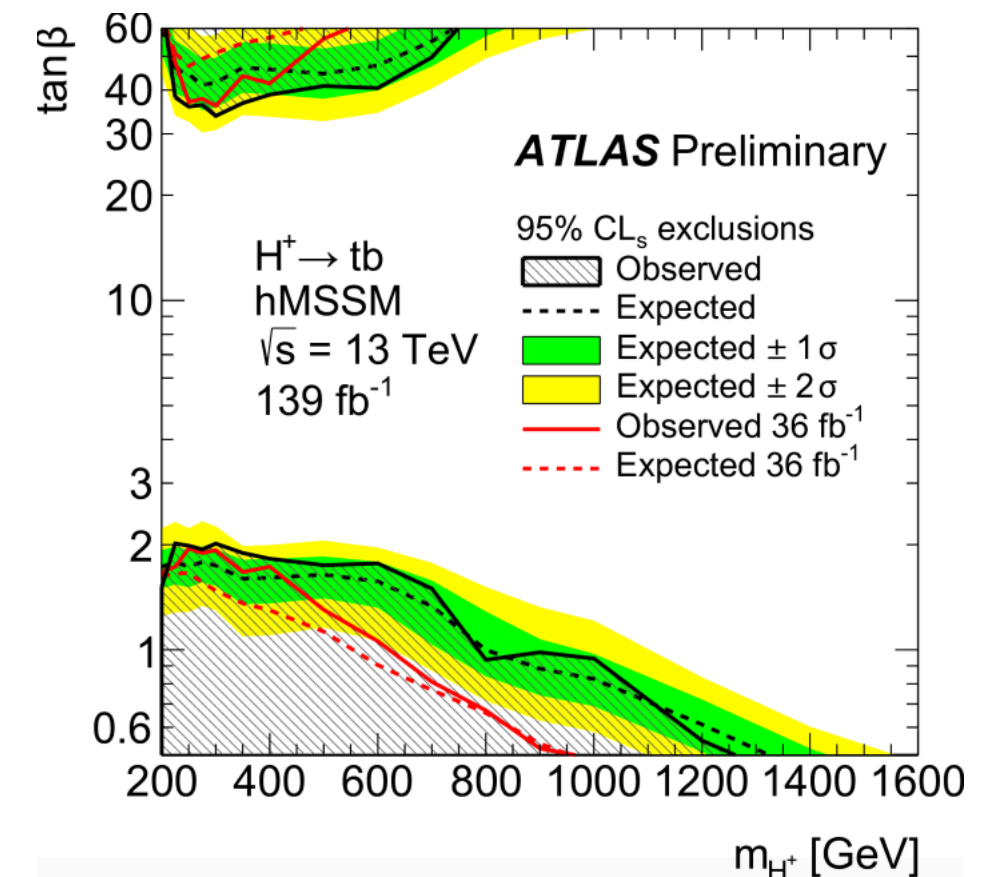
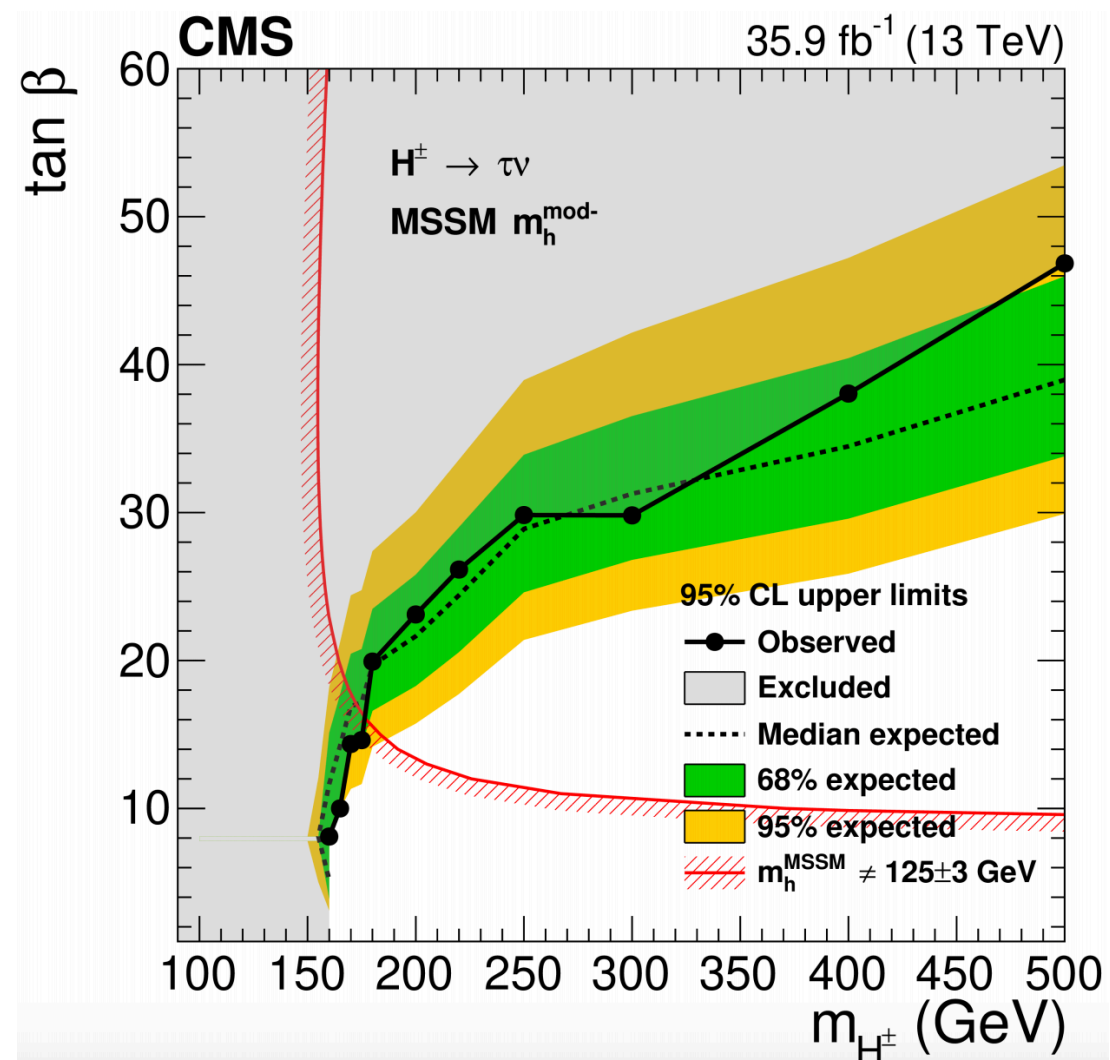
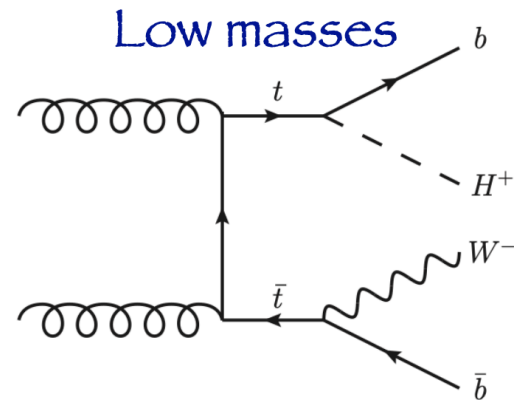
$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$



$$\tan \beta = \frac{v_2}{v_1}$$

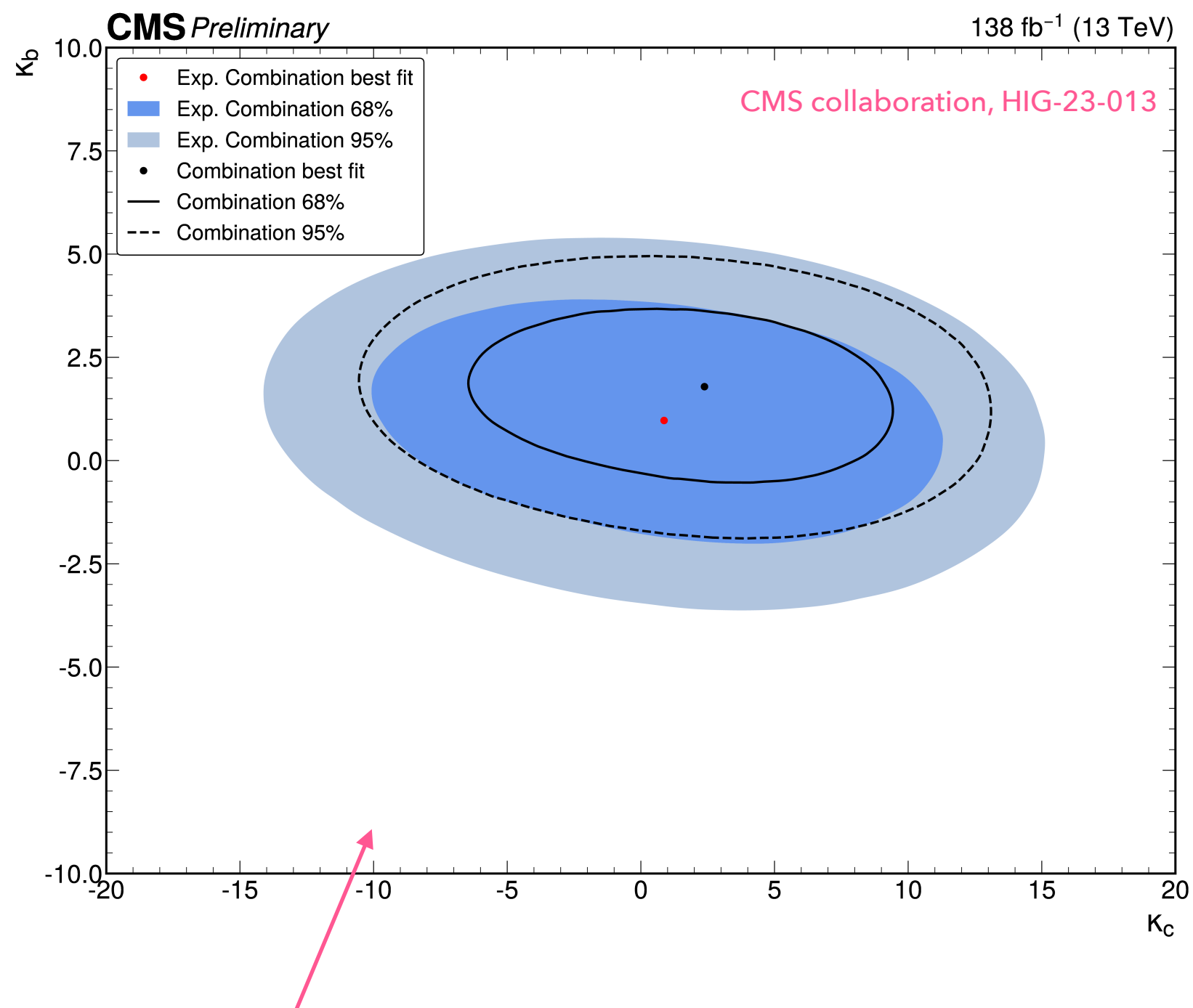


DIRECT SEARCHES FOR A CHARGED HIGGS



EXAMPLES OF INDIRECT SEARCHES

- Simplest framework for indirect searches is the **kappa framework**
- Assumes there is a single Higgs boson, with a mass of 125 GeV, and that any possible new physics effects that can be seen in these measurements affect only the couplings between the Higgs boson and other particles.
- These possible new physics effects are then parametrised in terms of coefficients κ .

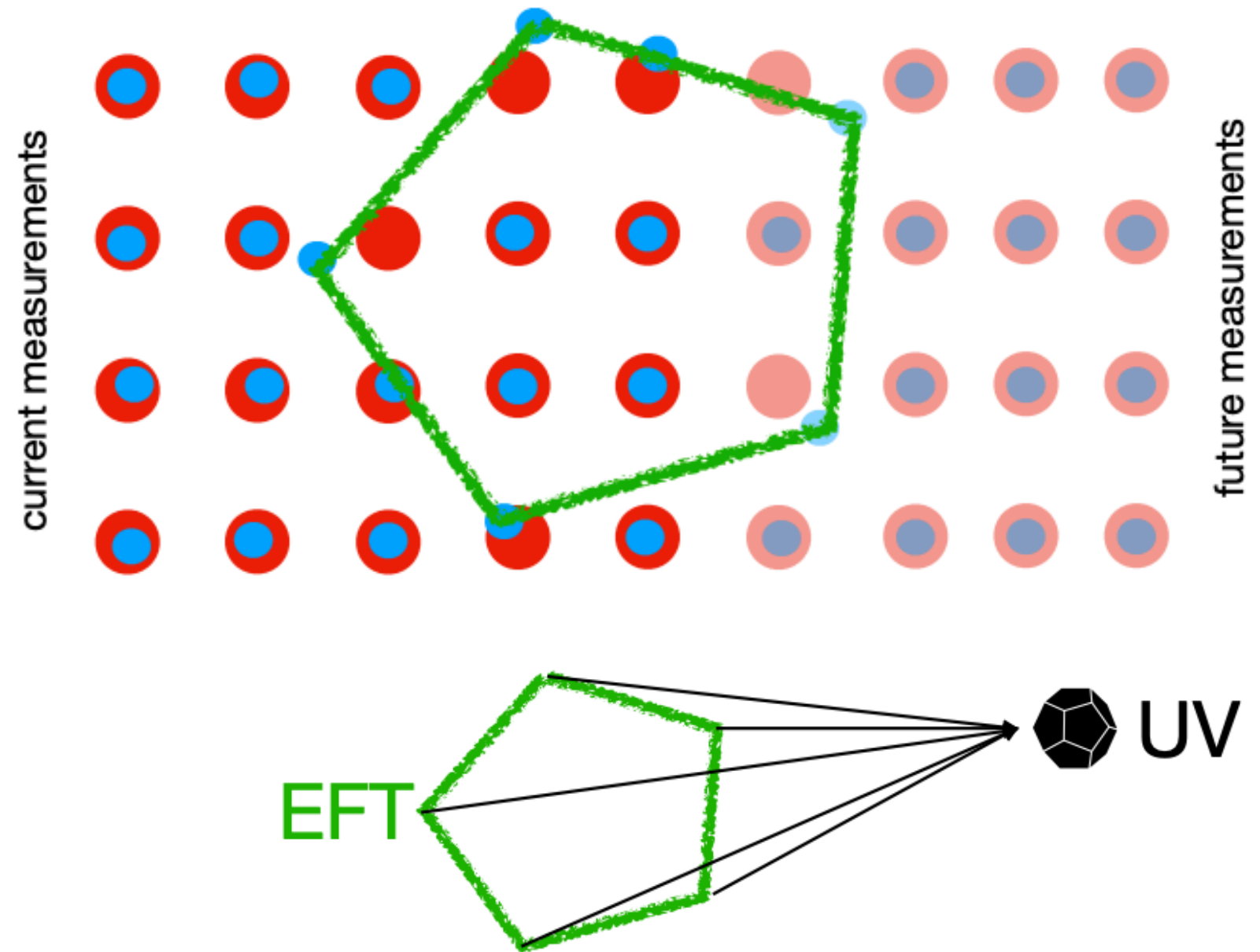


Constraints on Higgs boson coupling to charm and bottom quarks from Higgs transverse momentum measurements by CMS @ 13 TeV

2. STANDARD MODEL EFFECTIVE FIELD THEORY

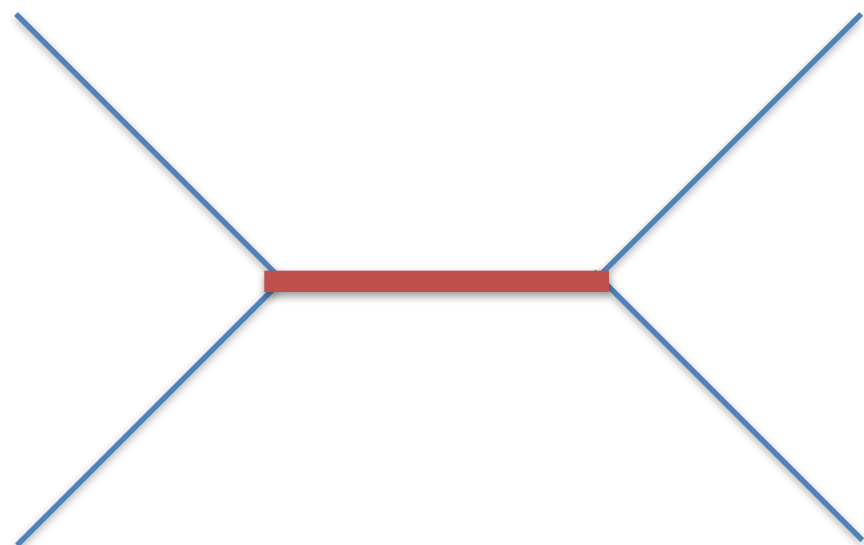
THE IDEA BEHIND EFT

- As more precise data and SM theoretical predictions become available, we can identify patterns of small differences induced by new physics and from there deduce what is the new model that causes a given pattern!
- Want to be as agnostic and general as possible: EFT formalism

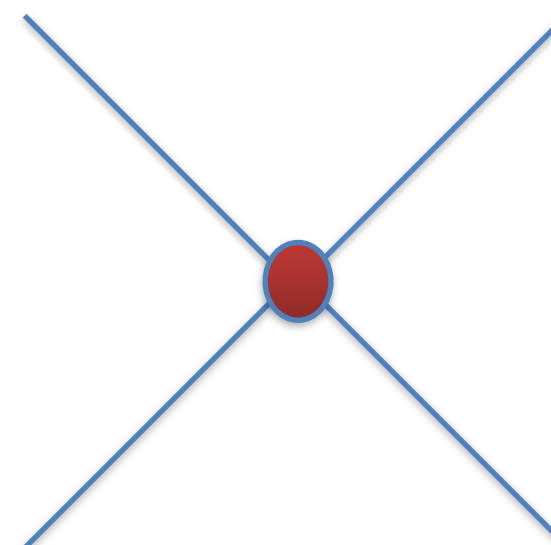
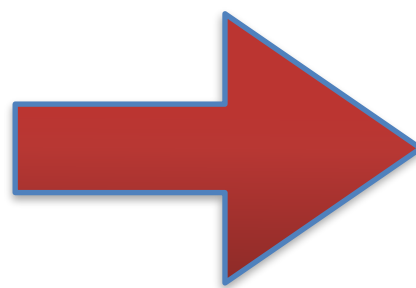


THE IDEA BEHIND EFT

- Beta decay of a neutron into proton and electron plus missing energy (neutrino) was perfectly described by Fermi theory (Fermi, 1934) as the interaction of the four particles involved. Only in 1983 the W boson mediating the interaction was discovered.



If intermediate particle much heavier than energy of the system...

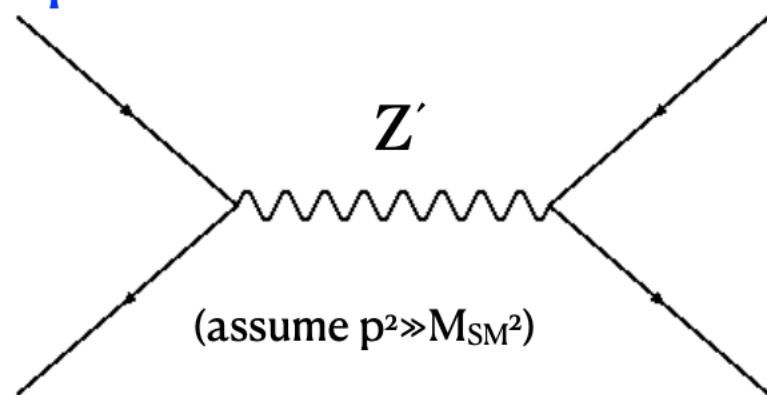


... it is integrated out and its effect is only an “effective interaction”

EXAMPLES OF UV TO EFT MATCHING

- Can match explicit BSM models to the effective field theories in a straightforward way. Each model leads to different low energy behaviour hence a different pattern of Wilson coefficients.

Example 1:



$$\sim -\frac{g_{Z'}^2}{p^2 - M_{Z'}^2} \approx \frac{g_{Z'}^2}{M_{Z'}^2} + \frac{g_{Z'}^2 p^2}{M_{Z'}^4} + \dots$$

dim-6 ↓ dim-8 ↓

$$\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\text{Re}[\mathcal{M}_6 \mathcal{M}_{SM}^*] + \frac{1}{\Lambda^4} \{ |\mathcal{M}_6|^2 + 2\text{Re}[\mathcal{M}_8 \mathcal{M}_{SM}^*] \}$$

$$\frac{g_{SM}^4}{p^4}$$

$$\frac{g_{SM}^2 g_{Z'}^2}{p^2 M_{Z'}^2}$$

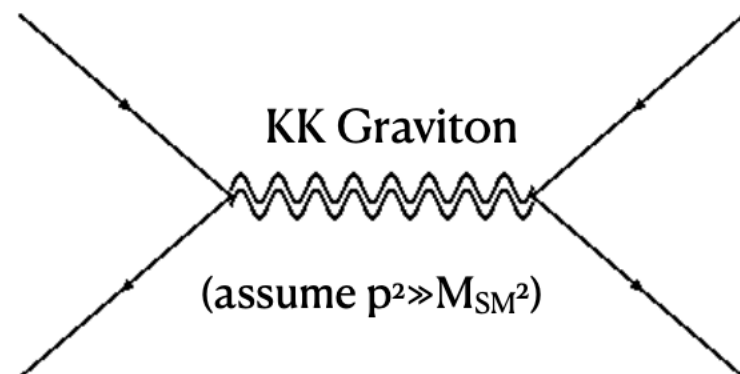
$$\frac{g_{Z'}^4}{M_{Z'}^4}$$

$$\frac{g_{SM}^2 g_{Z'}^2}{M_{Z'}^4}$$

EXAMPLES OF UV TO EFT MATCHING

- Can match explicit BSM models to the effective field theories in a straightforward way. Each model leads to different low energy behaviour hence a different pattern of Wilson coefficients.

Example 2:



$$\sim \overset{\text{dim-6}}{\downarrow} 0 + \overset{\text{dim-8}}{\downarrow} \frac{p^2}{M_S^4} + \dots$$

Han, Lykken, Zhang (1998)

$$\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\text{Re}[\mathcal{M}_6 \mathcal{M}_{SM}^*] + \frac{1}{\Lambda^4} \{ |\mathcal{M}_6|^2 + 2\text{Re}[\mathcal{M}_8 \mathcal{M}_{SM}^*] \}$$

$$\frac{g_{SM}^4}{p^4}$$

$$0$$

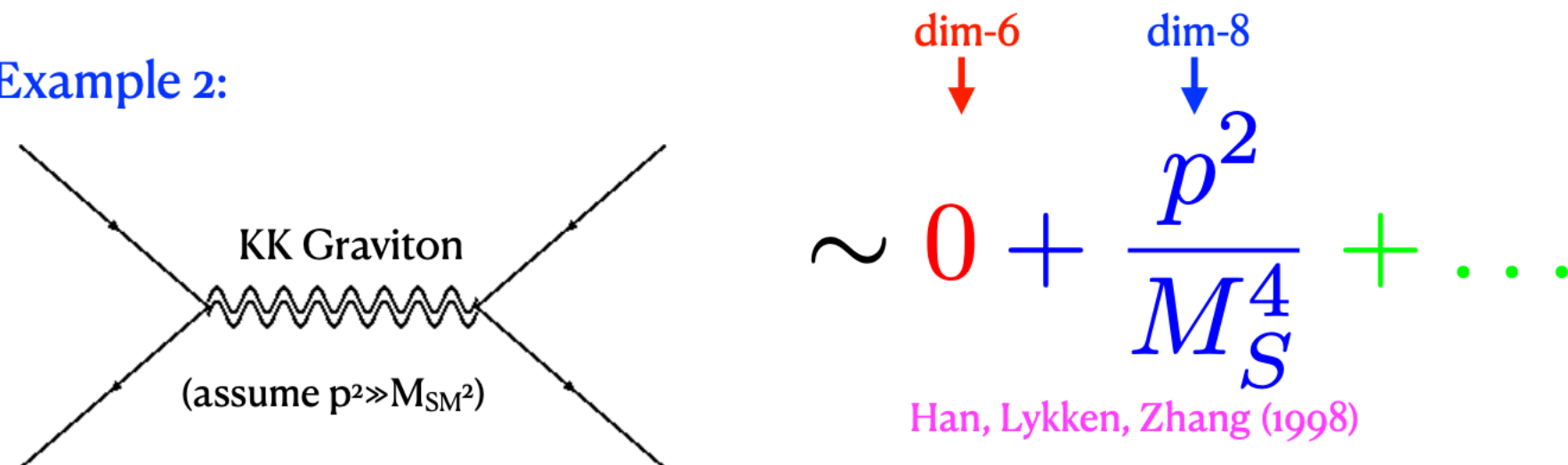
$$0$$

$$\frac{g_{SM}^2}{M_S^4}$$

EXAMPLES OF UV TO EFT MATCHING

- Can match explicit BSM models to the effective field theories in a straightforward way. Each model leads to different low energy behaviour hence a different pattern of Wilson coefficients.

Example 2:



$$\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\text{Re}[\mathcal{M}_6 \mathcal{M}_{SM}^*] + \frac{1}{\Lambda^4} \{ |\mathcal{M}_6|^2 + 2\text{Re}[\mathcal{M}_8 \mathcal{M}_{SM}^*] \}$$

$\frac{g_{SM}^4}{p^4}$
 0
 0
 $\frac{g_{SM}^2}{M_S^4}$

Crucial to have tools that match a UV Lagrangian to the corresponding EFT, where all heavy degrees of freedom have been integrated out.

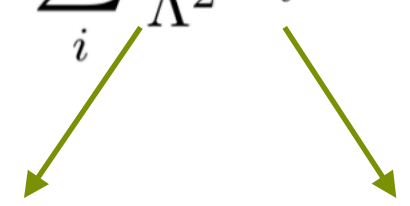
MatchMakerEFT Carmona et al 2112.10787

Matchete Fuentes-Martin et al 2212.04510

STANDARD MODEL EFFECTIVE FIELD THEORY

- EFT is a well-defined theoretical approach for indirect searches
- Assumption: new physics states are heavy
- Write the Lagrangian with only light SM particles
- BSM effects can be incorporated as a momentum expansion
- Each operator can be improved at higher orders including QCD and EW corrections
- SMEFT: assume SM field content and gauge symmetries (apart from accidental)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$



BSM effects SM particles

$$\begin{aligned}\hbar &= c = 1 \\ \dim A^\mu &= 1 \\ \dim \phi &= 1 \\ \dim \psi &= 3/2\end{aligned}$$

STANDARD MODEL EFFECTIVE FIELD THEORY

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Complete basis of $SU(3) \times SU(2) \times U(1)$ invariant $D = 6$ operators constructed out of the SM fields. In general 2499 independent operators after imposing baryon and lepton number conservation. Flavor universality, 76 operators.

DIM-6 BASIS

Pure gauge
interactions

Gauge-Higgs
and Higgs-Higgs
interaction

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	Q_{φ}	$(\varphi^{\dagger} \varphi)^3$	$Q_{e\varphi}$	$(\varphi^{\dagger} \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^{\dagger} \varphi) \Box (\varphi^{\dagger} \varphi)$	$Q_{u\varphi}$	$(\varphi^{\dagger} \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$	$Q_{\varphi D}$	$(\varphi^{\dagger} D^{\mu} \varphi)^* (\varphi^{\dagger} D_{\mu} \varphi)$	$Q_{d\varphi}$	$(\varphi^{\dagger} \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^{\dagger} \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{l}_p \gamma^{\mu} l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^{\dagger} \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu}^I \varphi)(\bar{l}_p \tau^I \gamma^{\mu} l_r)$
$Q_{\varphi W}$	$\varphi^{\dagger} \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{e}_p \gamma^{\mu} e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^{\dagger} \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{q}_p \gamma^{\mu} q_r)$
$Q_{\varphi B}$	$\varphi^{\dagger} \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu}^I \varphi)(\bar{q}_p \tau^I \gamma^{\mu} q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^{\dagger} \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{u}_p \gamma^{\mu} u_r)$
$Q_{\varphi WB}$	$\varphi^{\dagger} \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{d}_p \gamma^{\mu} d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^{\dagger} \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^{\dagger} D_{\mu} \varphi)(\bar{u}_p \gamma^{\mu} d_r)$

Fermion-Higgs-Gauge
interaction

DIM-6 BASIS

Four fermion
interactions

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B -violating			
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s^j q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^{\gamma m})^T C l_t^n]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^{\gamma m})^T C l_t^n]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		

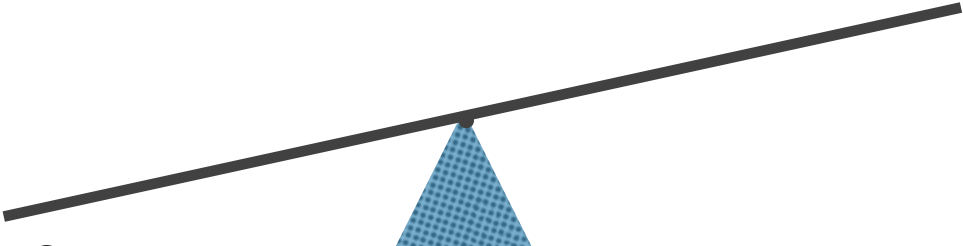
B violation

CONSTRAINING THE SMEFT AT THE LHC

- Large number of operators, yet a plethora of observables and final states to measure.
- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.
- Validity issues arise, as well as for the interpretation in terms of UV models.

$\mathcal{S}$ is a generic scale, which is process and operator dependent

$$\text{Obs}_i = \text{Obs}_i^{\text{SM}} + M_{ij} \cdot \frac{\mathcal{S}}{\Lambda^2} c_j$$



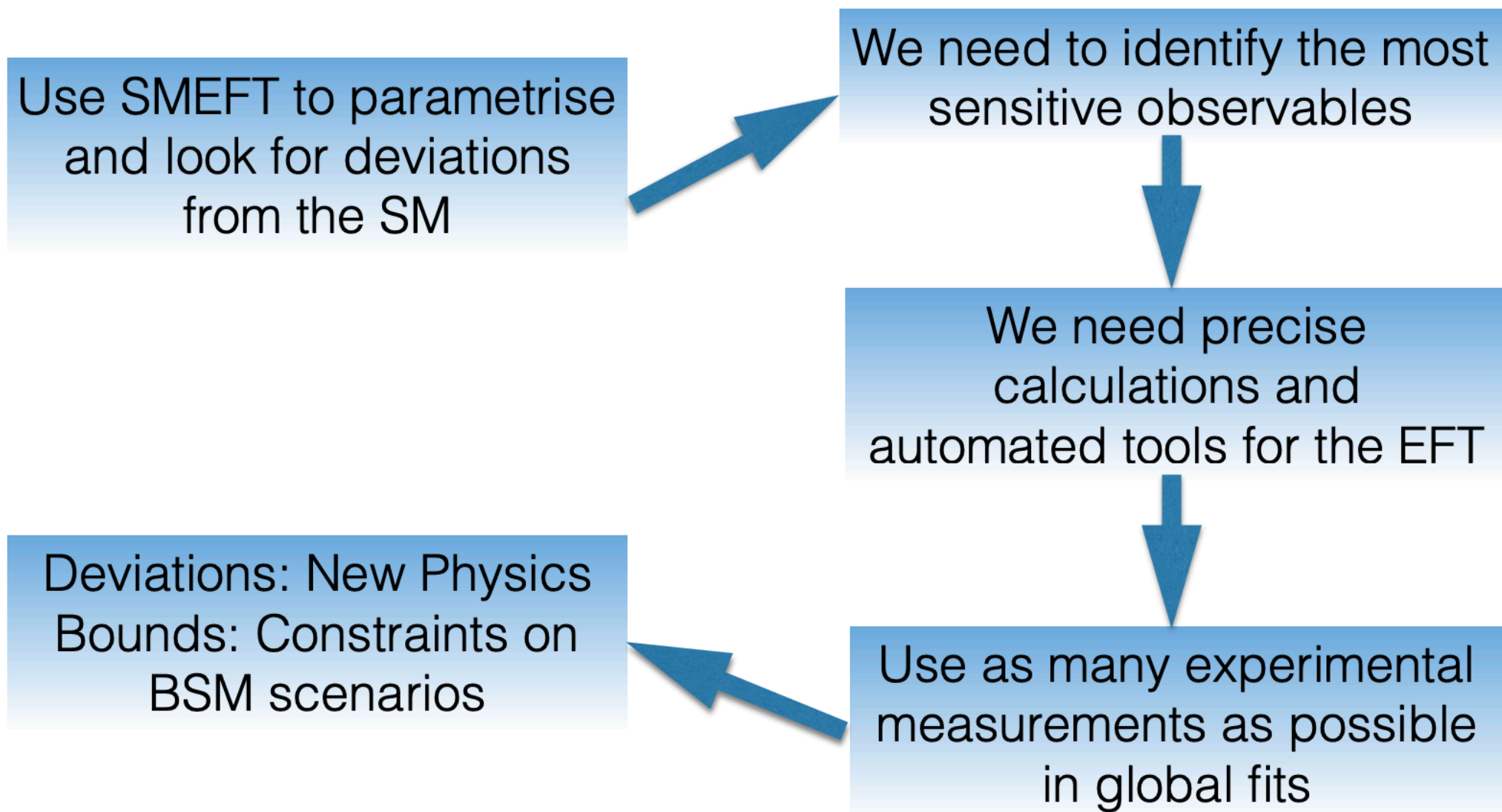
$$\Lambda > \sqrt{s} \sqrt{|c_i|/\delta}$$

$$|c_i|s/\Lambda^2 < \delta$$

$$\sqrt{s} < \Lambda$$

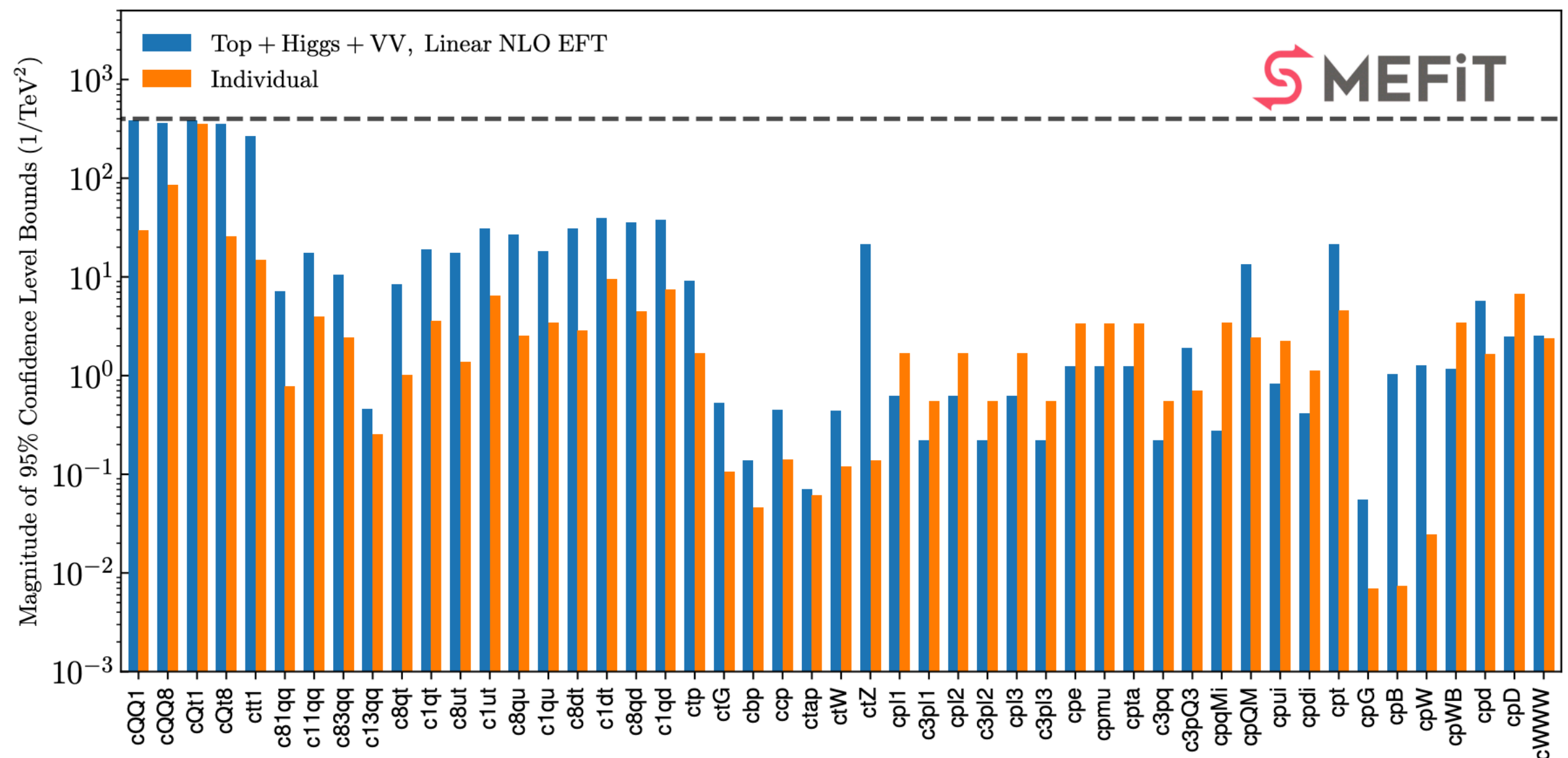
CONSTRAINING THE SMEFT AT THE LHC

- ➔ A **global constraining strategy** needs to be employed
- ➔ Identify the operators entering predictions for each observable (LO, NLO,..)
- ➔ Find enough observables (cross sections, BR's, distributions,...) to constrain all operators.



CONSTRAINING THE UNSEEN AT THE LHC

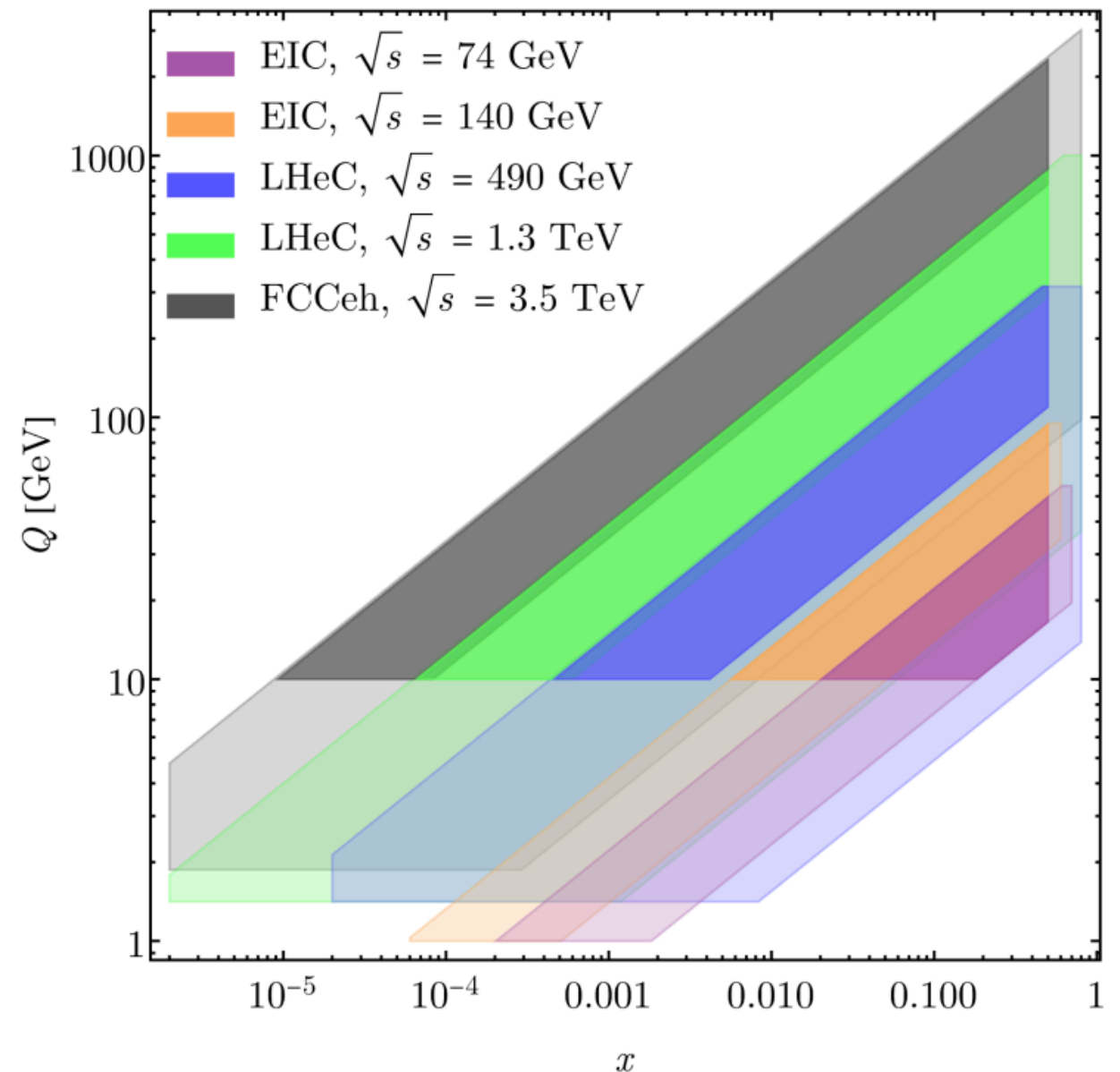
- ➡ Most fits of SMEFT coefficients are restricted to a few observables or sectors, thus reducing the number of dim-6 operators involved.
- ➡ Recently several more global fits appeared: careful with individual versus marginalised fits



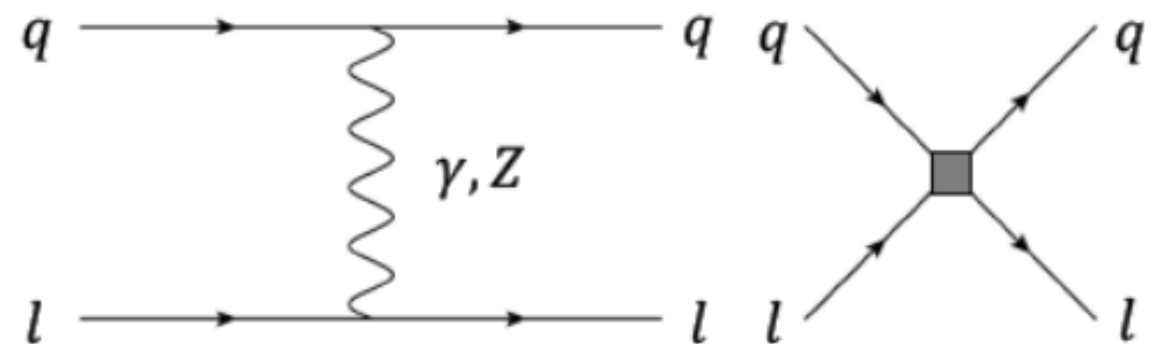
SMEFT ANALYSES AT THE EIC

- Another possibility of probing the SMEFT parameter space is with DIS experiments.
- Host of facilities spanning low and high energies are planned for both the near and far future.

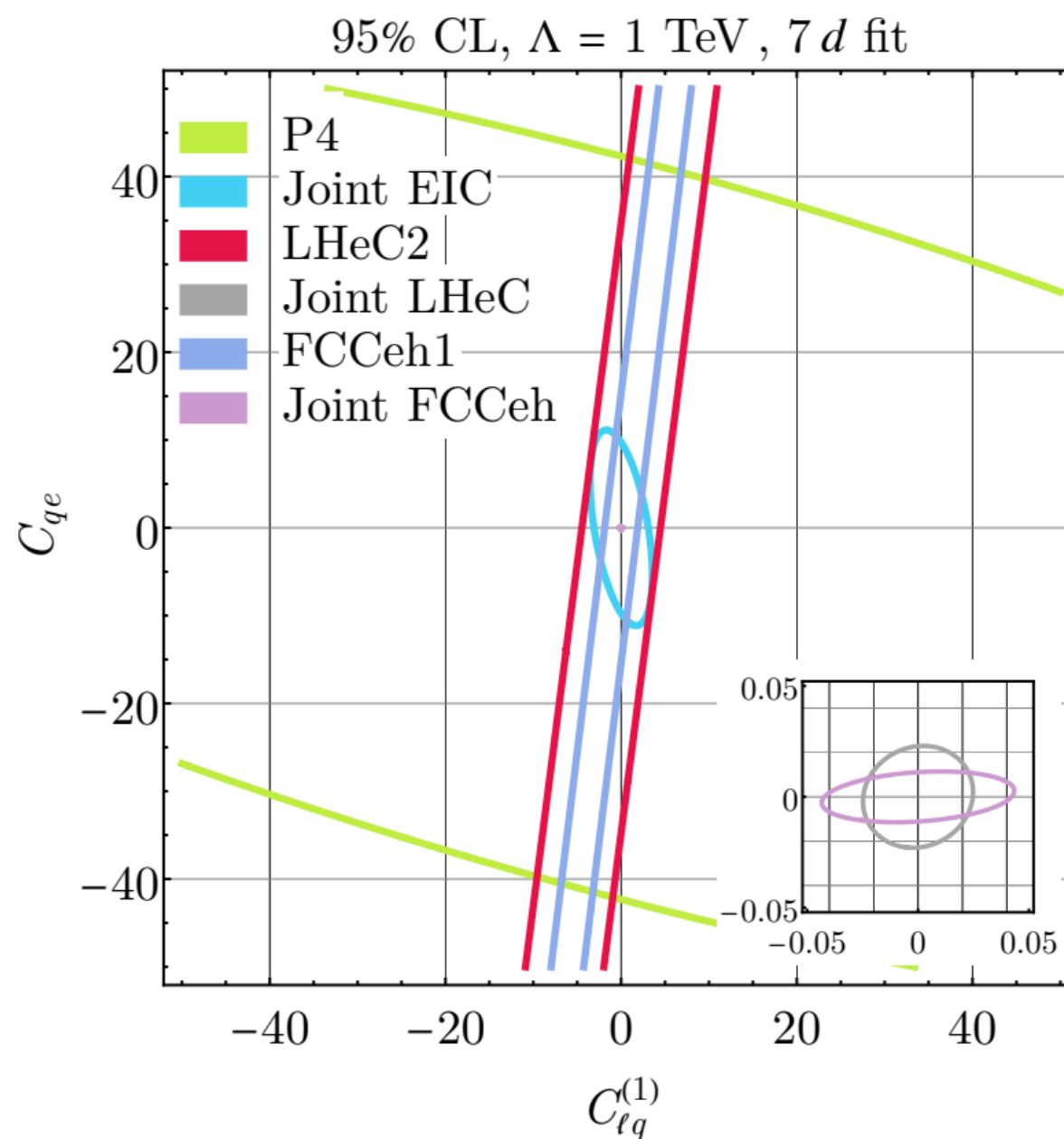
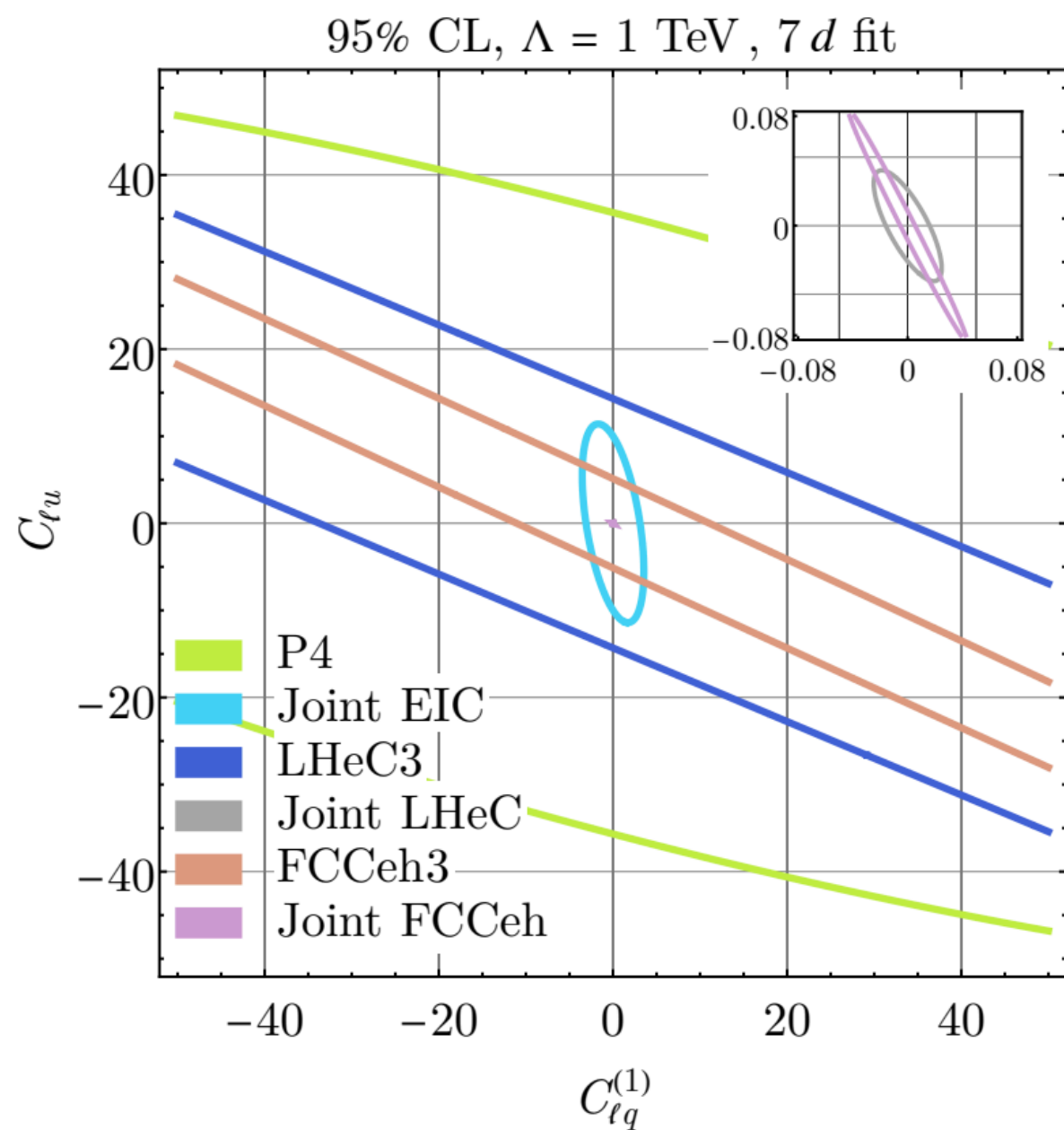
Past: HERA $\sqrt{s} \sim 320$ GeV
 Near future: EIC $\sqrt{s} \sim 140$ GeV
 Future: LHeC $\sqrt{s} \sim 1.3$ TeV
 FCC-eh $\sqrt{s} \sim 3.4$ TeV



Sensitive to the same operators as the Drell-Yan process at the LHC



SMEFT ANALYSES AT THE EIC

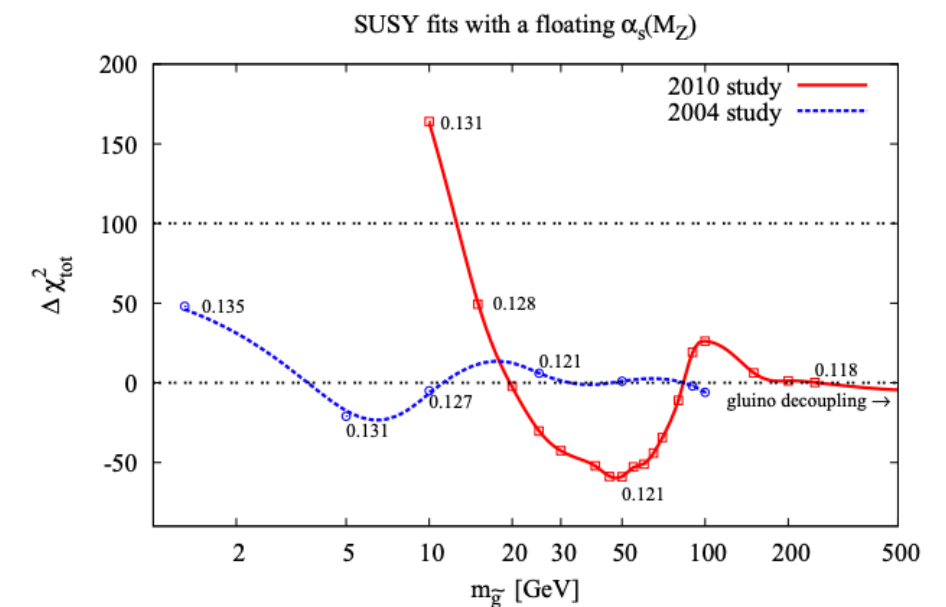
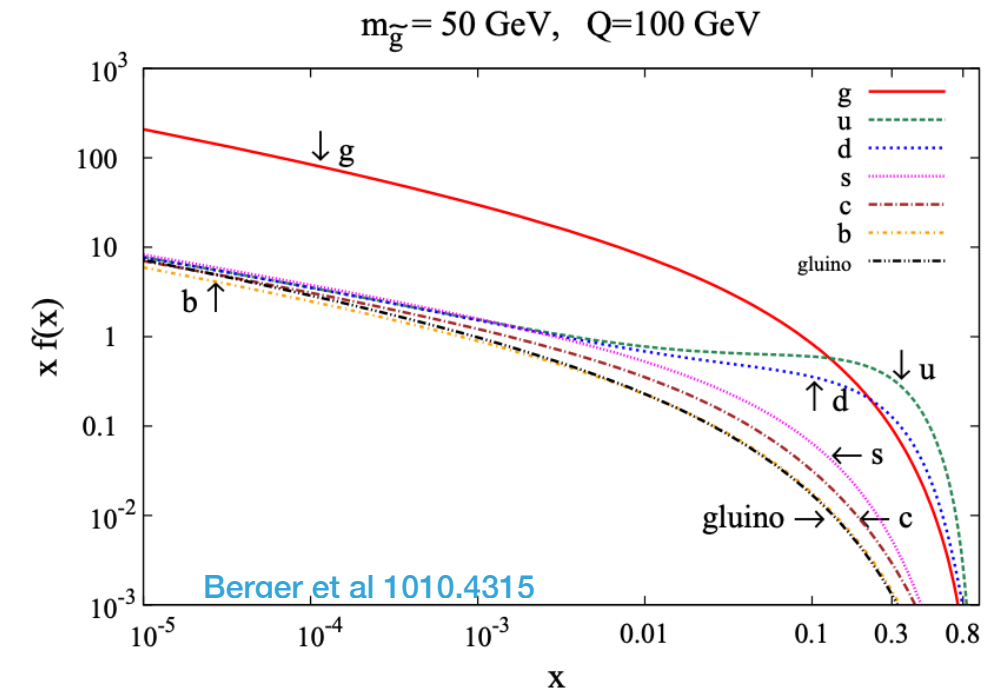
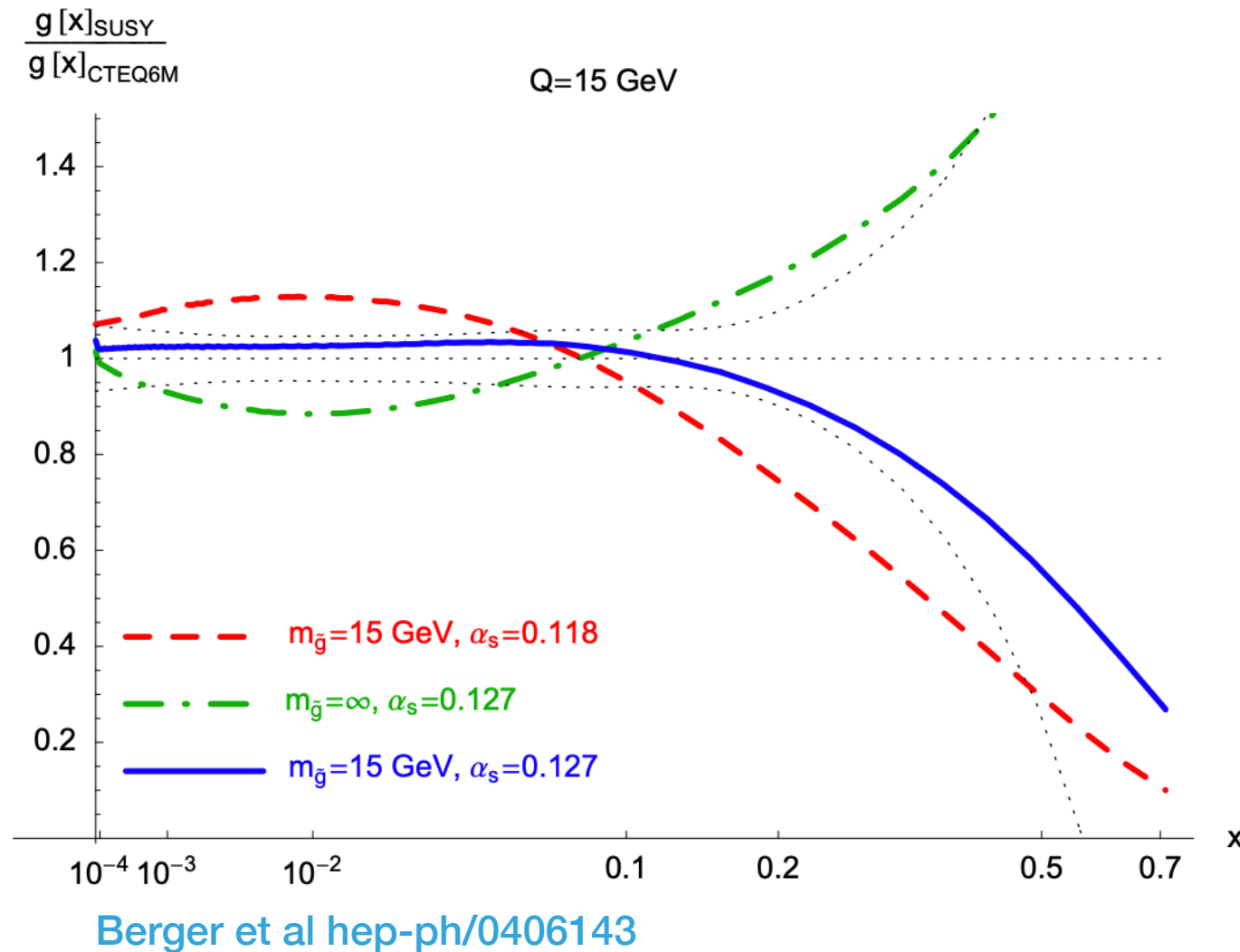


Boughezal et al 2204.07557

Bissolotti, Boughezal, Simsek 2306.05564

3. INTERPLAY BETWEEN BSM PHYSICS AND PDFS

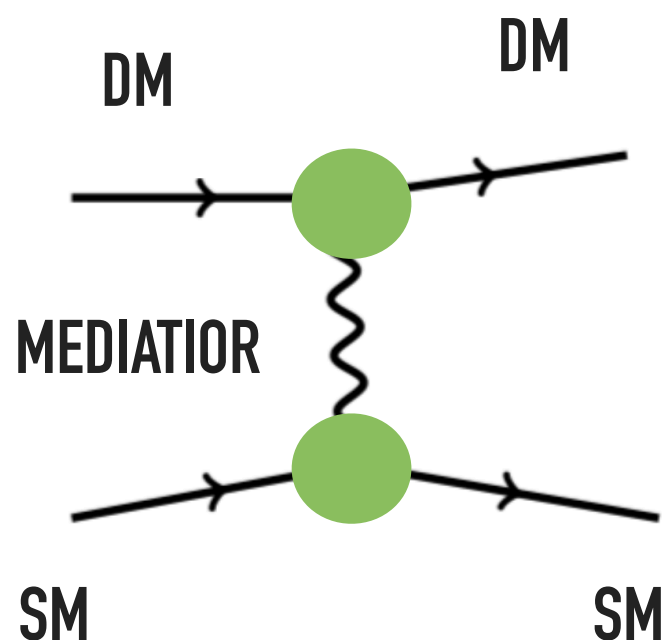
NEW PARTONS?



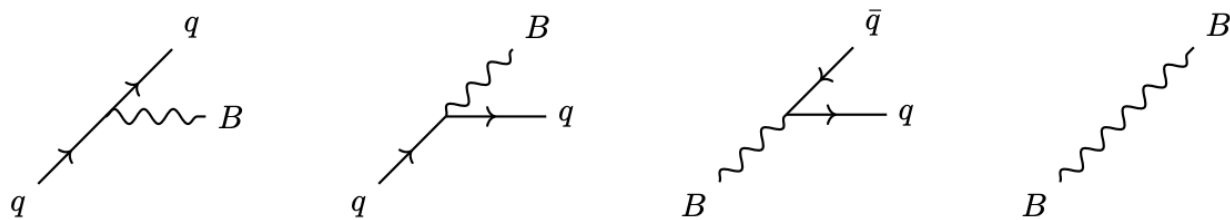
- Pre-LHC studies: what is there was a light SUSY coloured partner?
- A light SUSY Parton would modify DGLAP equation and running of α_s
- Comparison to data excludes any light coloured parton on increasing mass range as more (and more precise) data are included in the global PDF fits.

NEW PARTONS?

- Idea: now PDFs are known very precisely, and their uncertainties will continue to reduce in the near future with the HL-LHC, could we do the same for a colourless particle too?
- Can we link it to dark matter?
- Hidden-sector Dark Matter is a natural generalisation of the Weakly Interacting Matter Particles idea to include interactions through a new force rather than just SM forces.



NEW PARTONS?



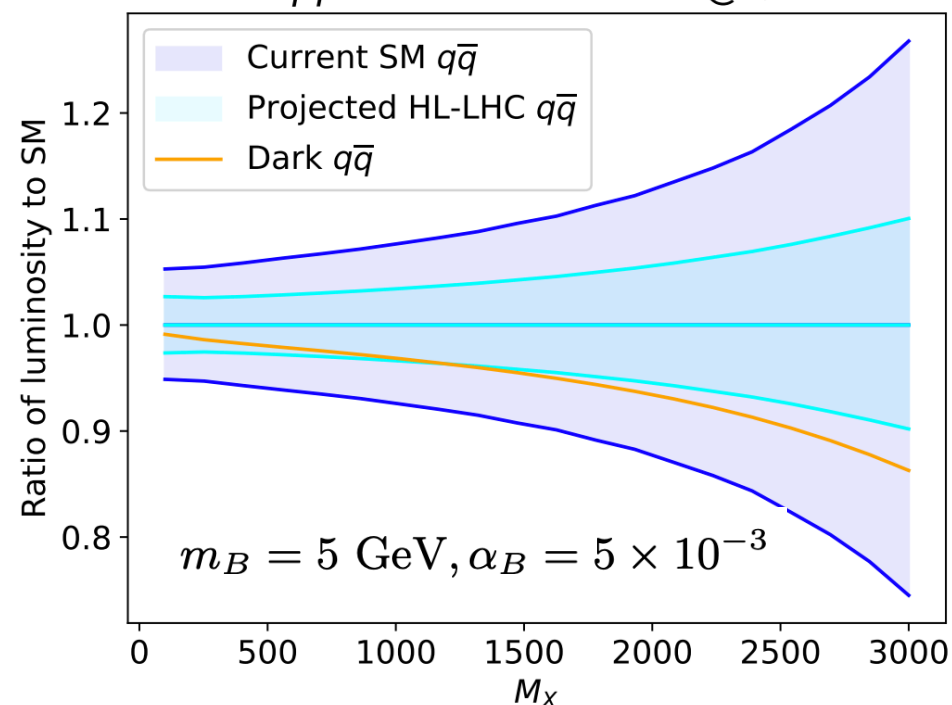
$$\mathbf{q}^S = \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Delta_\Sigma \\ B \end{pmatrix} \quad Q^2 \frac{\partial \mathbf{q}^S}{\partial Q^2} = \begin{pmatrix} \ddots & \ddots & 0 \\ \ddots & \ddots & 0 \\ 0 & 0 & P_{Bq} & 0 \\ 0 & 0 & P_{qB} & P_{BB} \end{pmatrix} \otimes \mathbf{q}^S.$$

- If there was a lepto-phobic dark photon weakly coupled to quarks, it would appear among the partons of the proton.

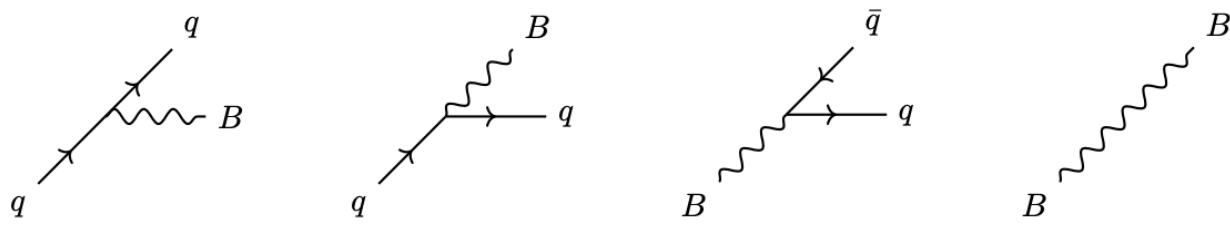
$$\mathcal{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \not{B} q$$

- The presence of the dark Parton would modify the evolution of standard quarks and gluon.

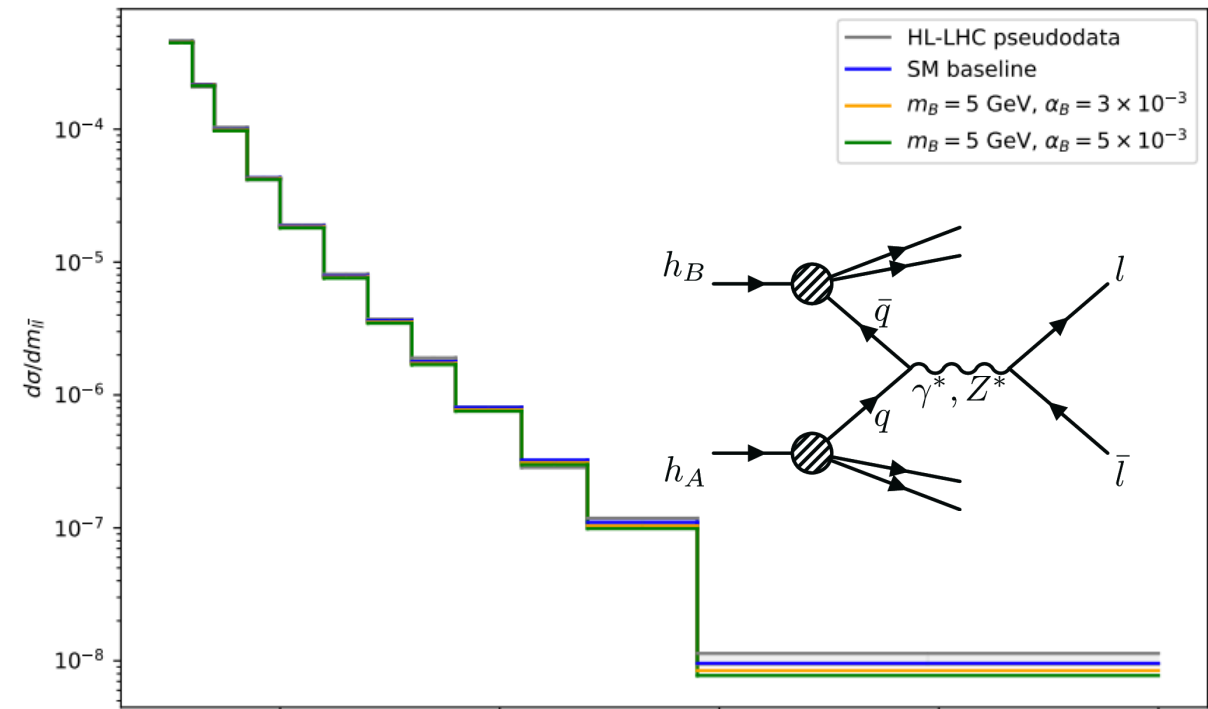
Ratios of $q\bar{q}$ luminosities to SM @ $\sqrt{s}=14$ TeV



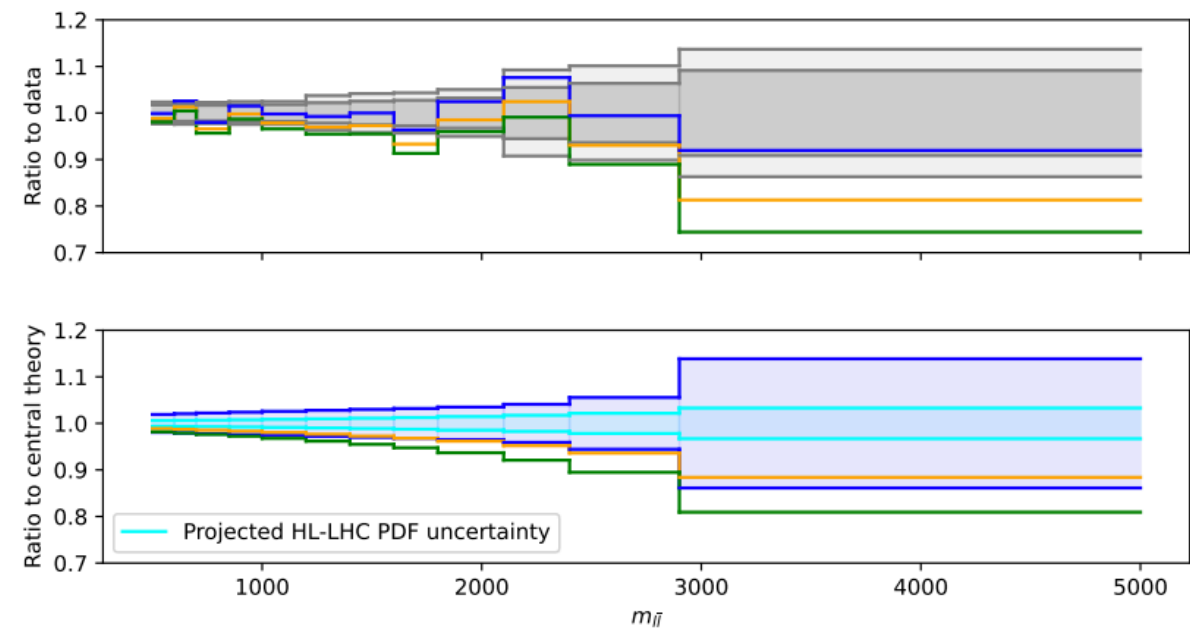
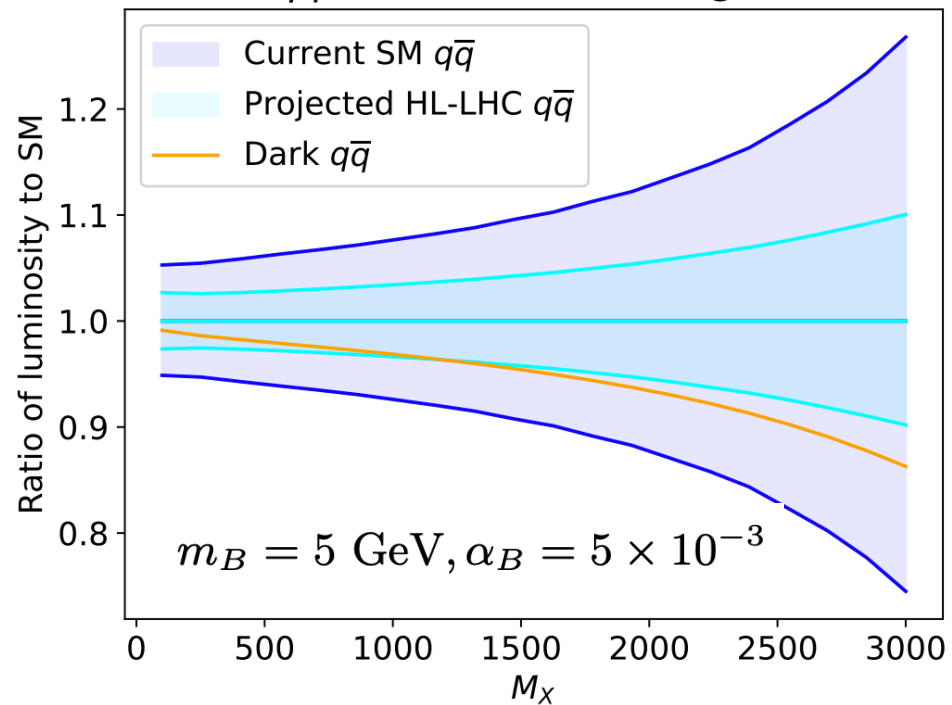
NEW PARTONS?



$$\mathbf{q}^S = \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Delta_\Sigma \\ B \end{pmatrix} \quad Q^2 \frac{\partial \mathbf{q}^S}{\partial Q^2} = \begin{pmatrix} \ddots & \ddots & 0 \\ \ddots & \ddots & 0 \\ 0 & 0 & P_{Bq} \\ 0 & 0 & P_{Bq} \\ 0 & 0 & P_{BB} \end{pmatrix} \otimes \mathbf{q}^S$$



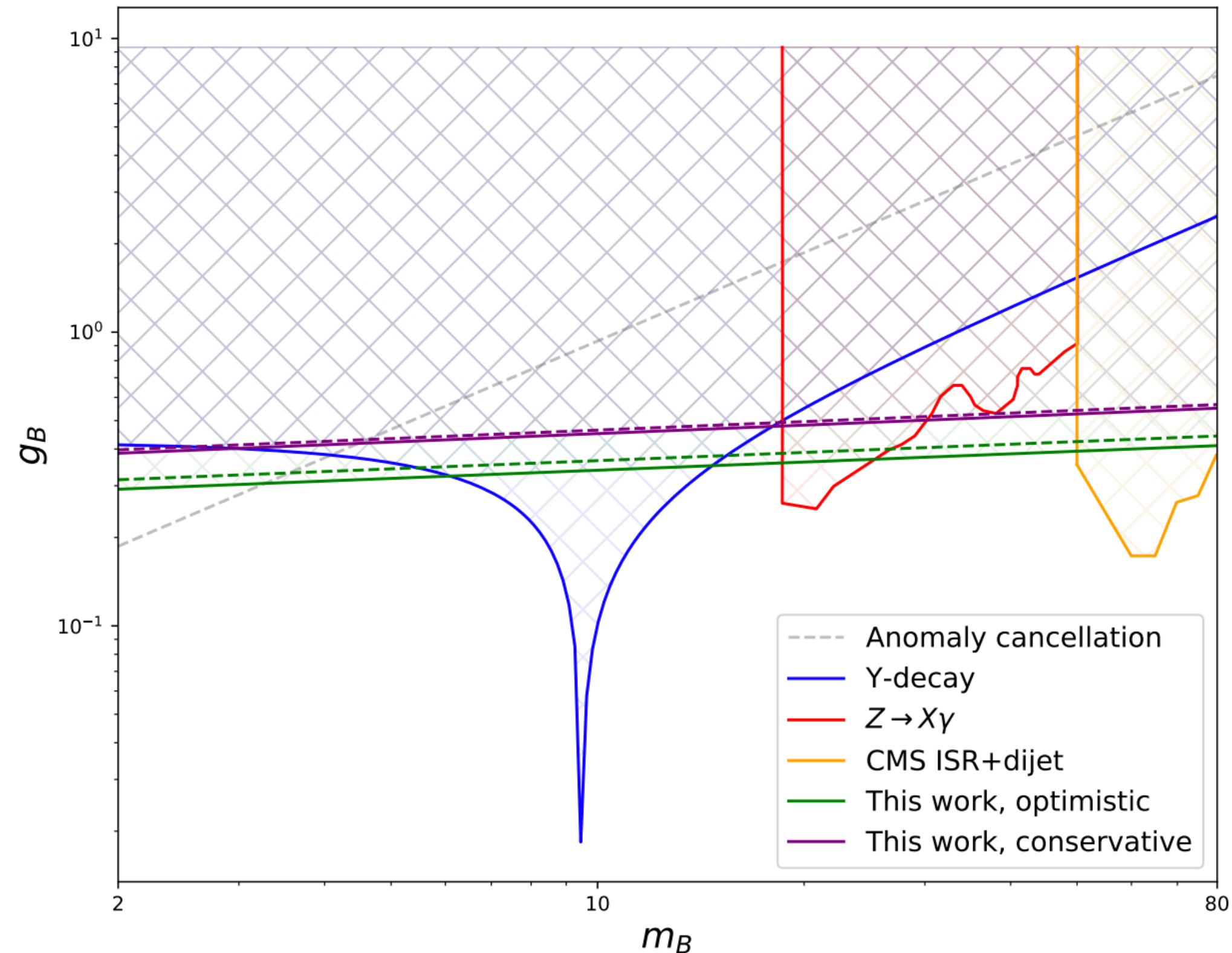
Ratios of $q\bar{q}$ luminosities to SM @ $\sqrt{s}=14$ TeV



M. McCullough, J. Moore, MU, arXiv:2203.12628

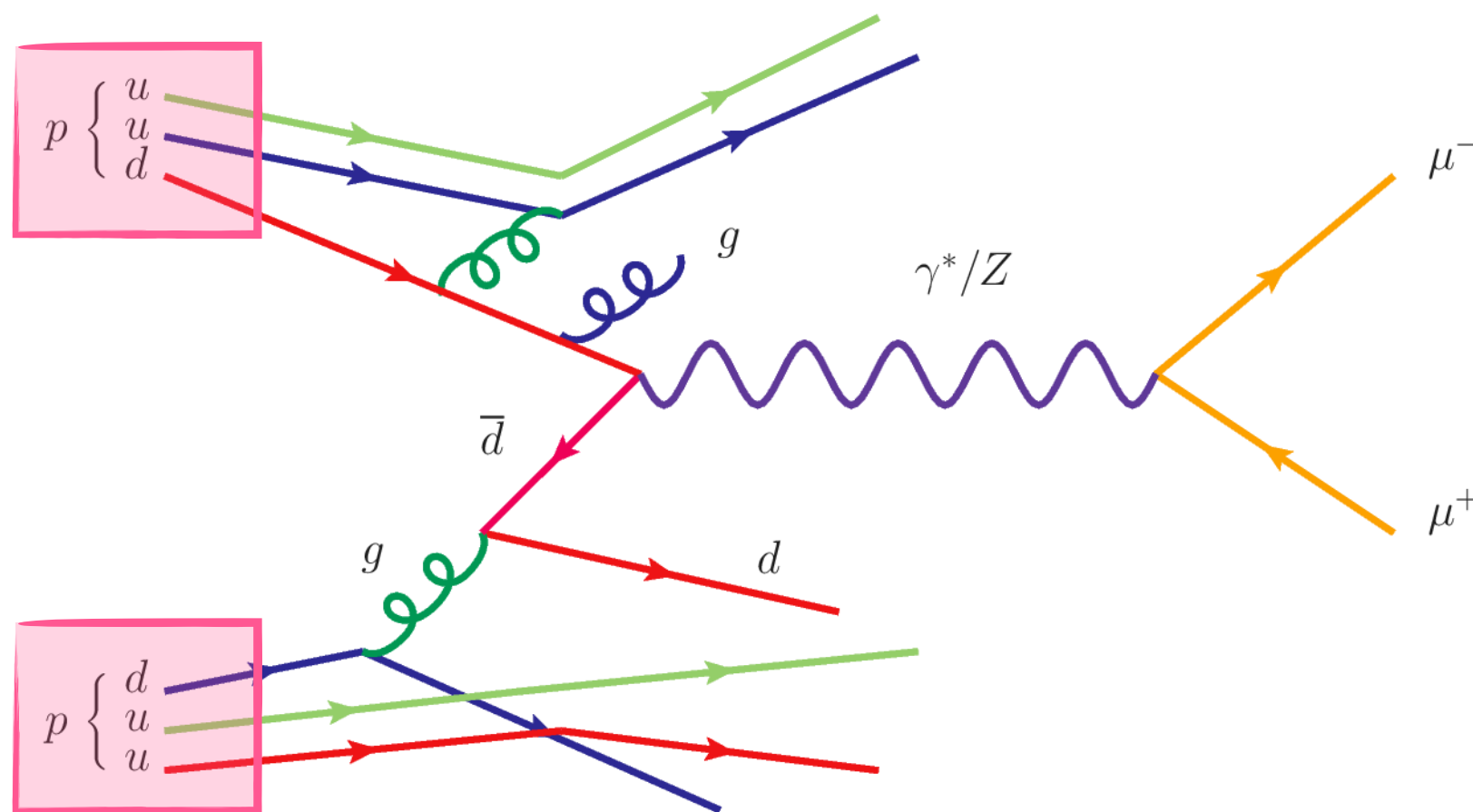
DARK PHOTON CONSTRAINTS

M. McCullough, J. Moore, MU, arXiv:2203.12628



Precise LHC data can indirectly constrain parameter space of the dark photon in a competitive way compared to direct searches

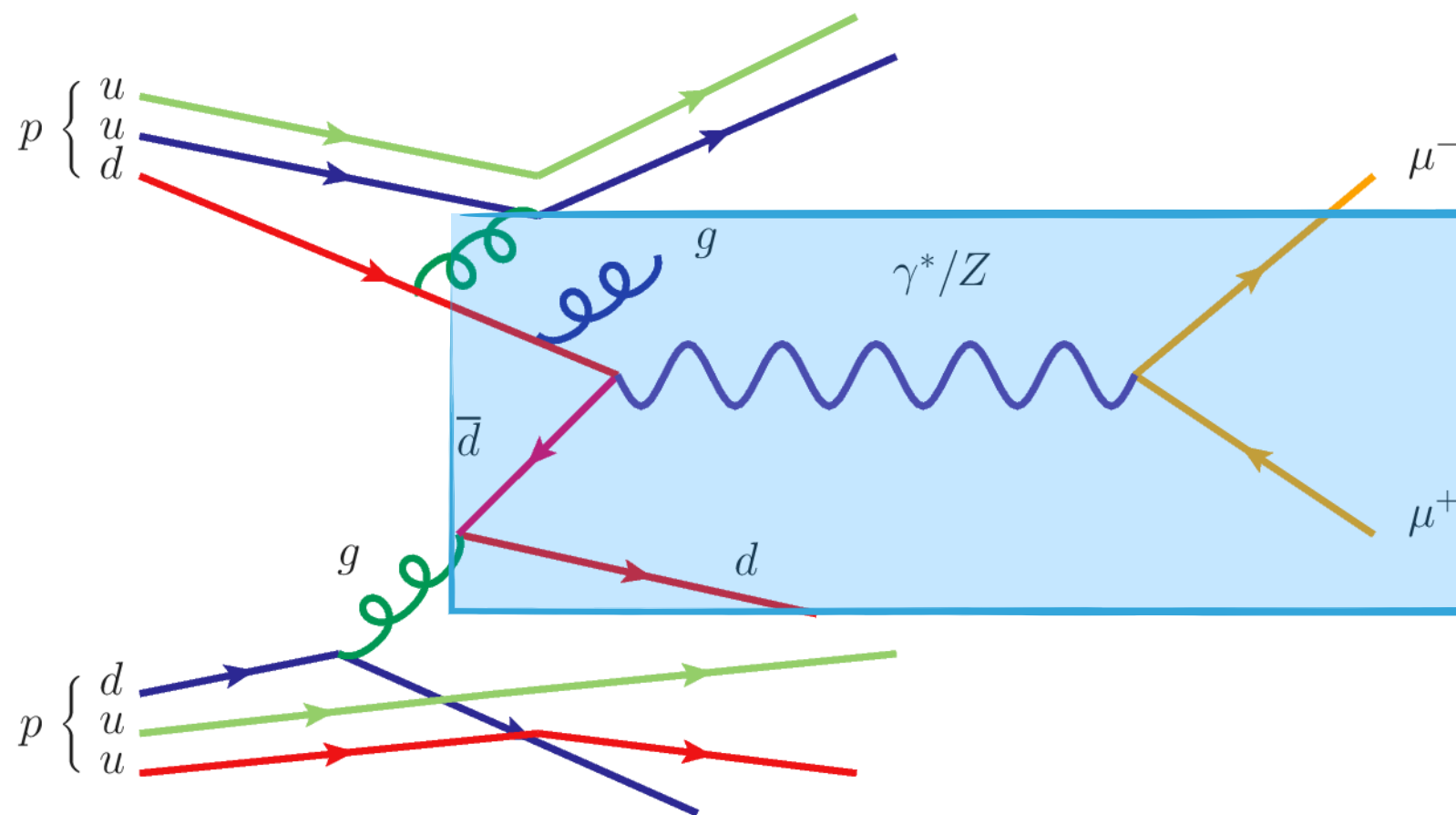
SIMULTANEOUS VERSUS SEPARATE FITS



$$d\sigma^{pp \rightarrow ab} \stackrel{\substack{\uparrow \\ \text{+ LHC Data}}}{=} \sum_{i,j} \boxed{f_i \otimes f_j} \otimes d\hat{\sigma}^{ij \rightarrow ab} + \dots \stackrel{\substack{\rightarrow \\ \text{Fit of PDF} \\ \text{Coefficients} \\ \{\theta_i\}}}{}$$

$f_i(\{\theta_k\})$

SIMULTANEOUS VERSUS SEPARATE FITS



(LHC) Data $\uparrow$

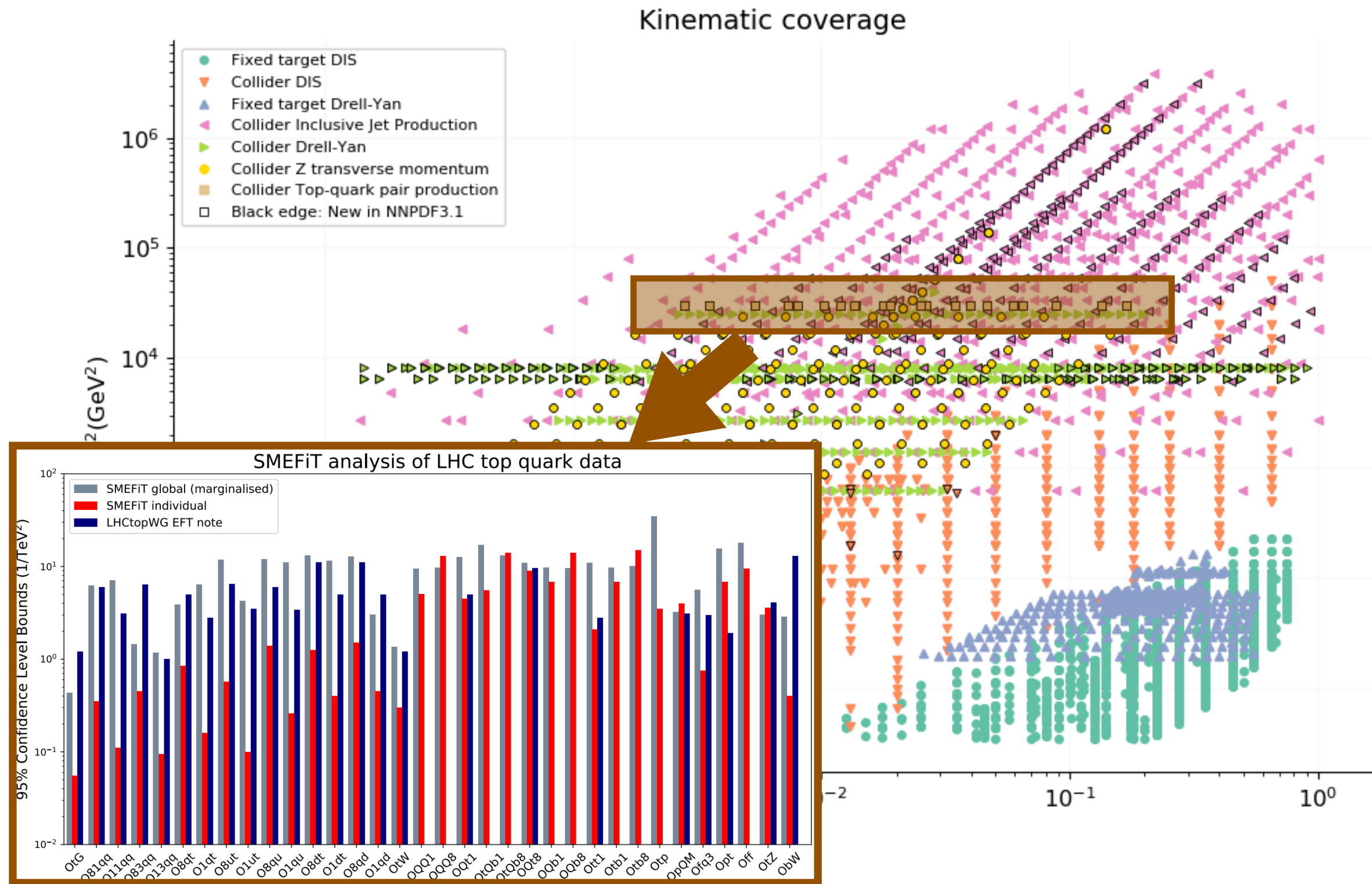
$$d\sigma^{pp \rightarrow ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij \rightarrow ab} + \dots$$

$\uparrow$

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

Fit of
Wilson
Coefficients
 $\{c_i\}$

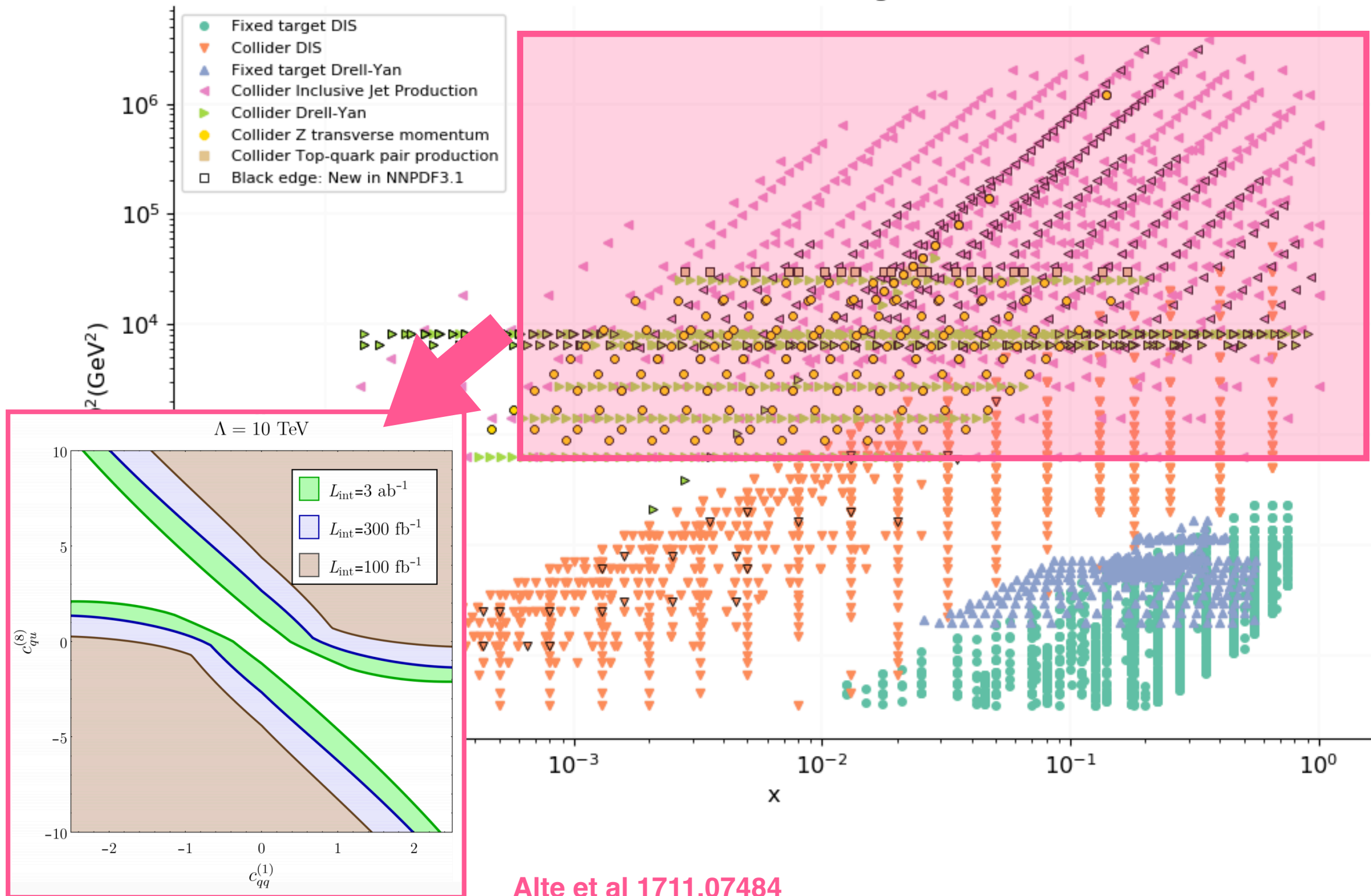
EXPERIMENTAL OVERLAP



Hartland et al 1901.05965

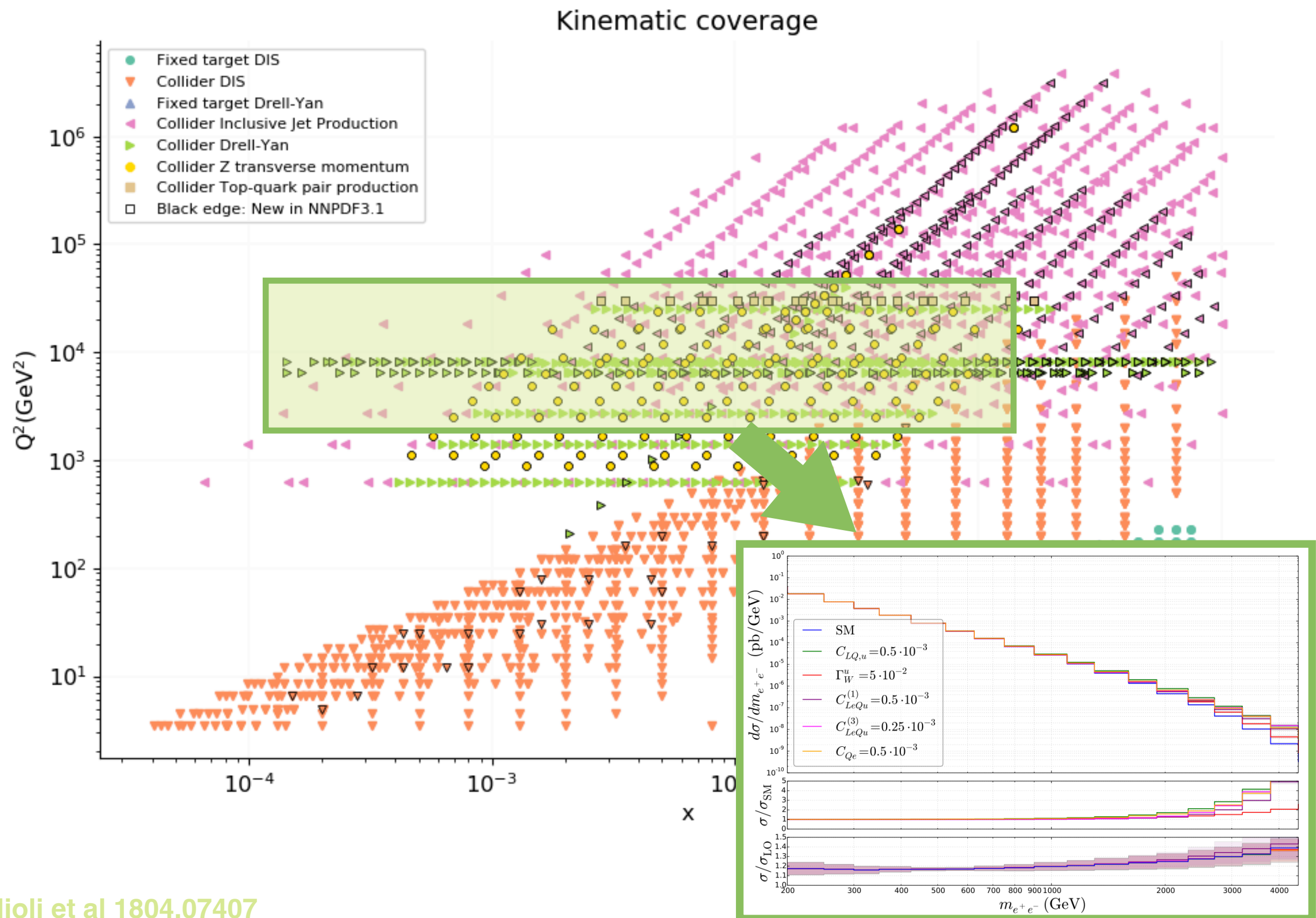
EXPERIMENTAL OVERLAP

Kinematic coverage

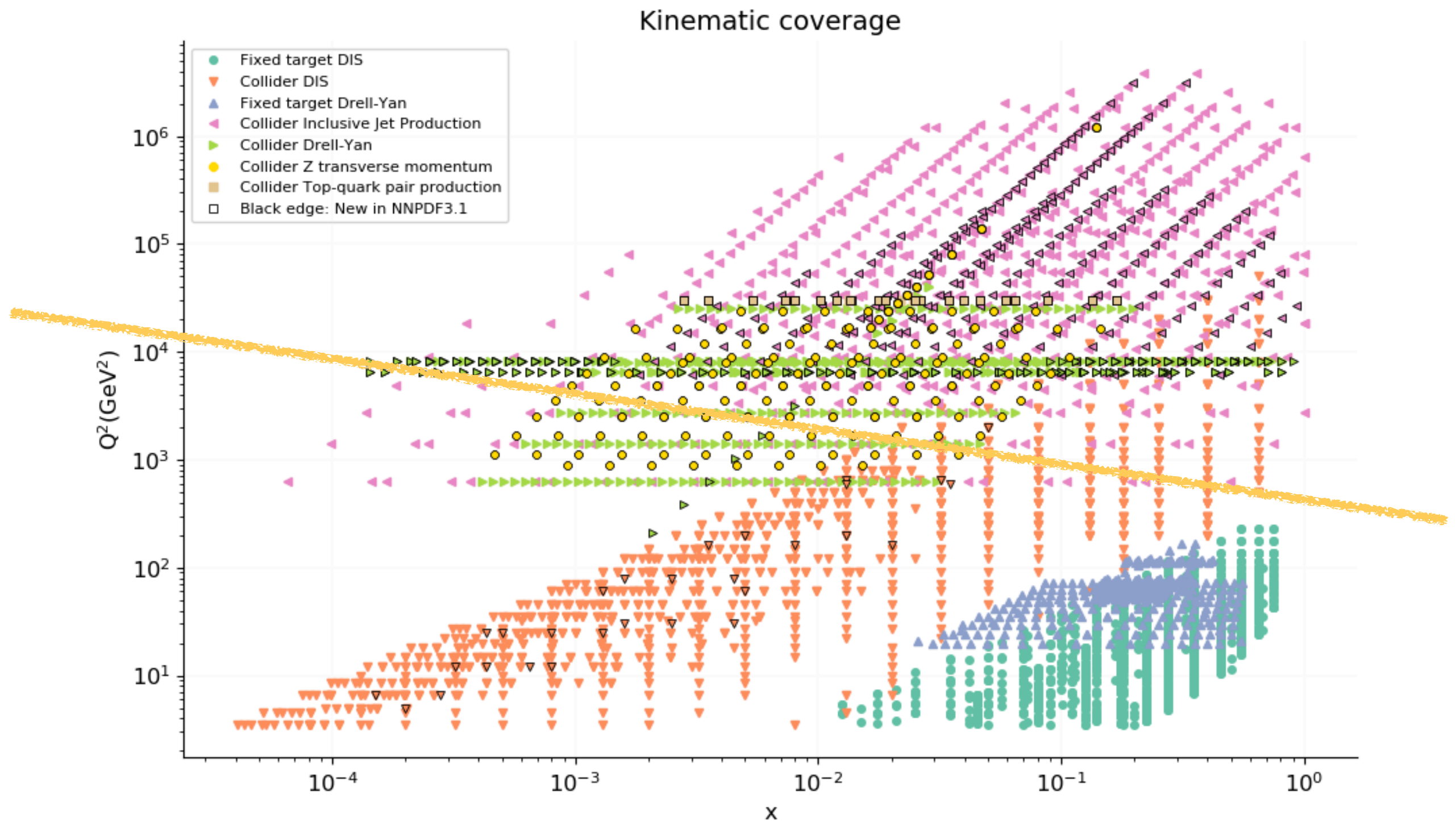


Alte et al 1711.07484

EXPERIMENTAL OVERLAP

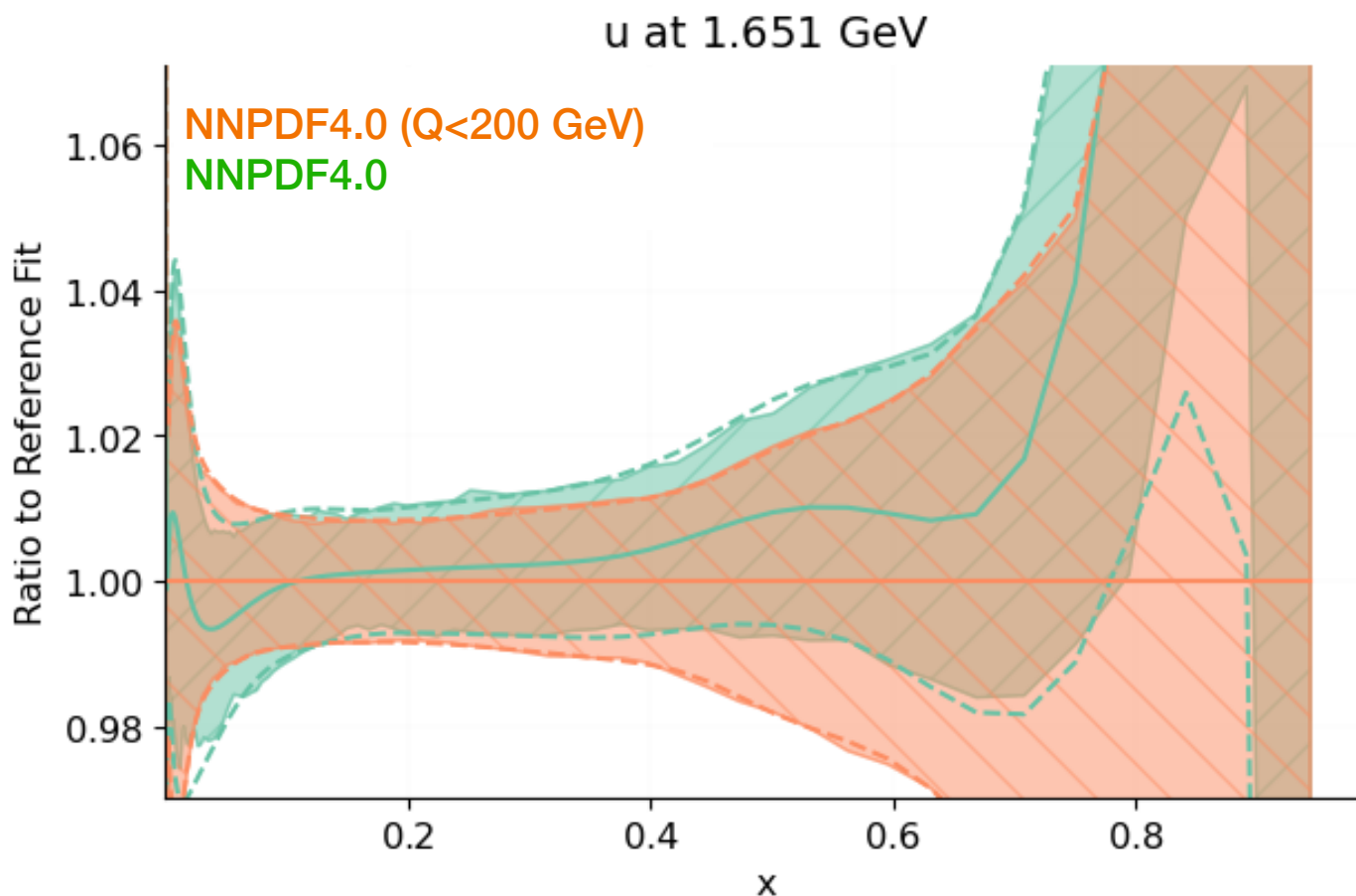


CONSERVATIVE PDFS



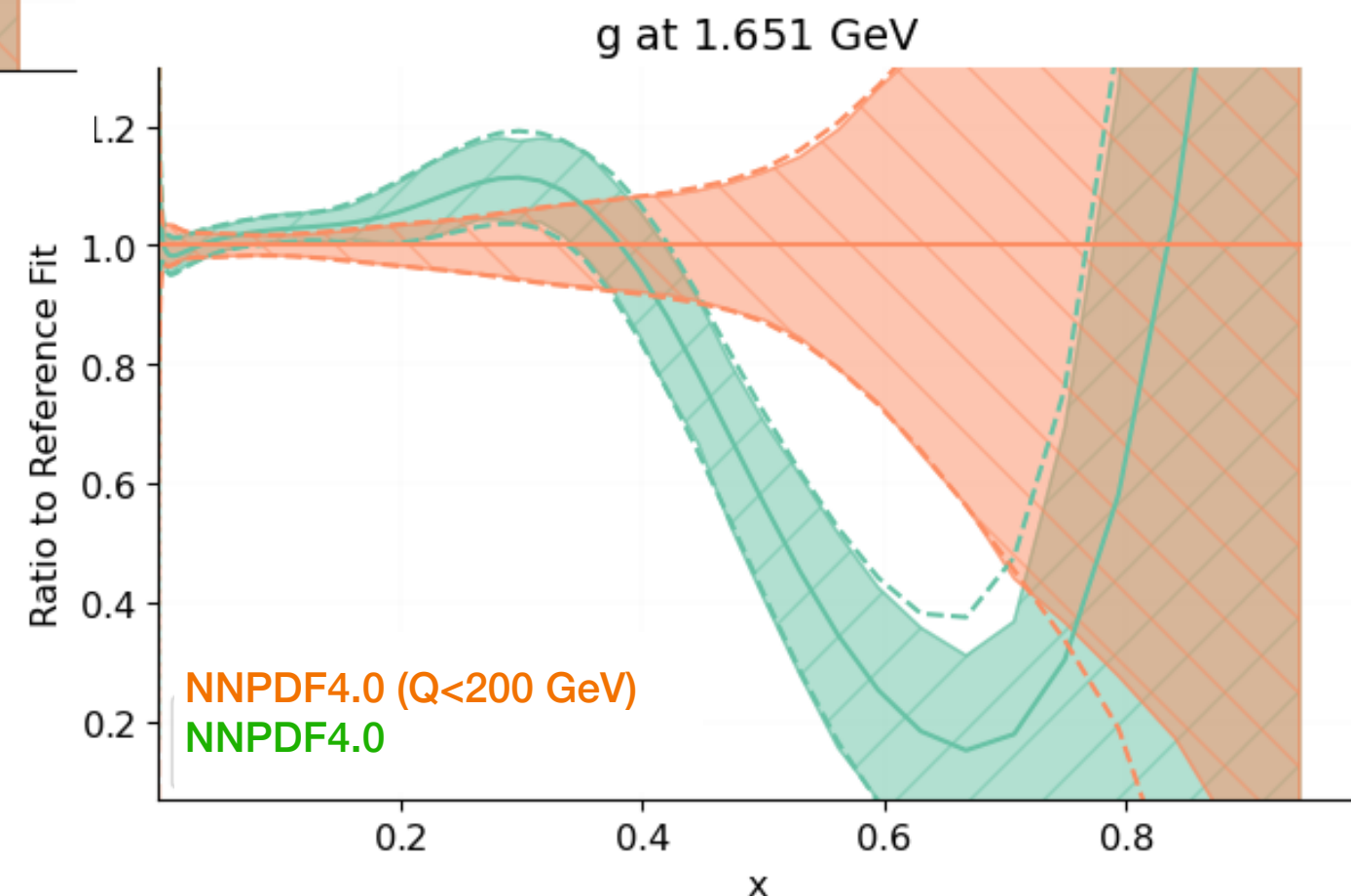
- ➡ Hot to disentangle effects?
- ➡ Cut data? Conservative partons?

CONSERVATIVE PDFS

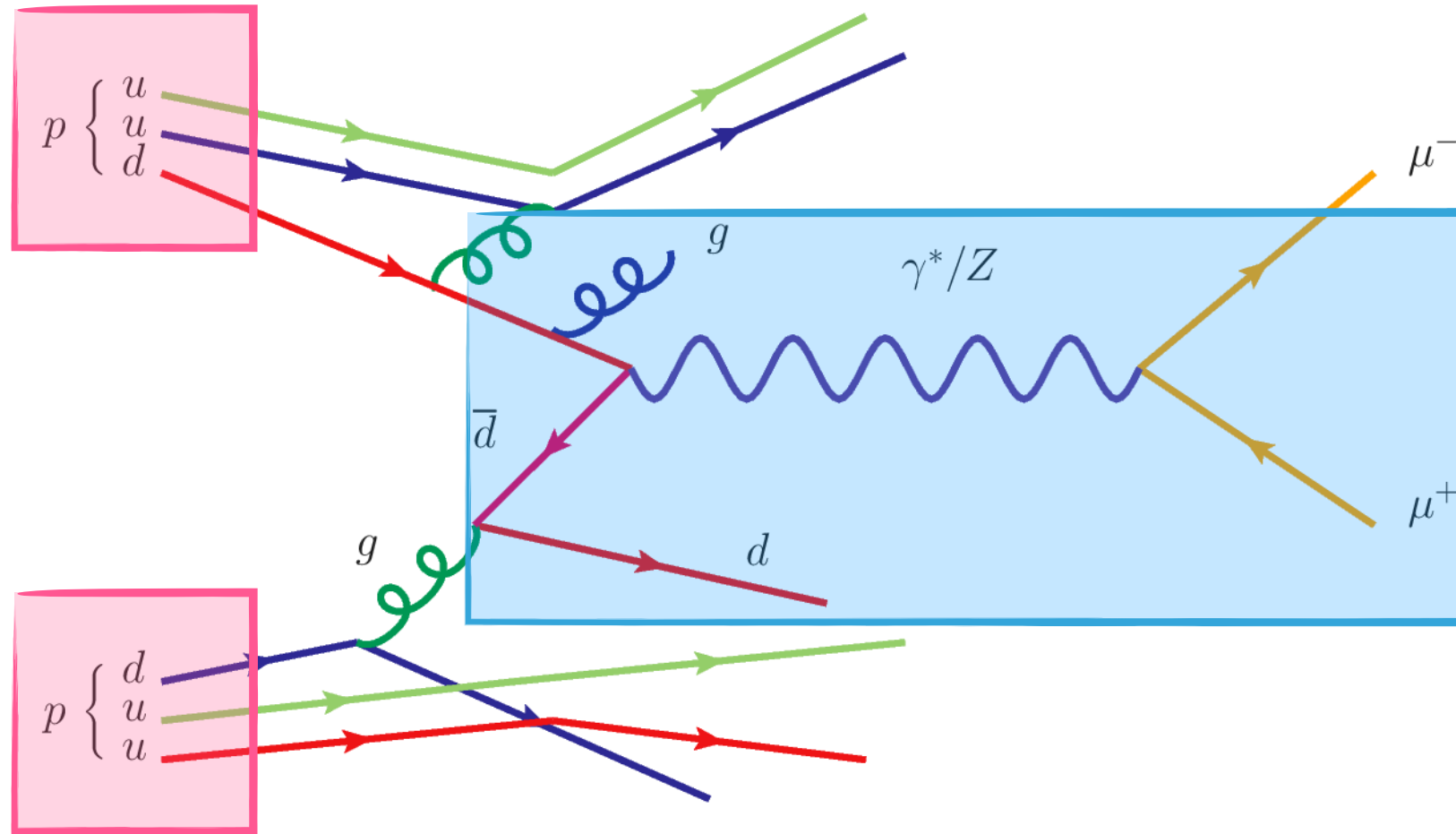


- Cutting high Q data would shift some PDFs significantly
→ rely on old data and on extrapolation of PDF fits

- Cutting high Q data would increase PDF uncertainties
→ less precise theory predictions at the LHC



SIMULTANEOUS PDF AND SMEFT FITS



$d\sigma^{pp \rightarrow ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij \rightarrow ab} + \dots$

LHC Data $\uparrow$ $f_i(\{\theta_k\})$ $\uparrow$ $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$

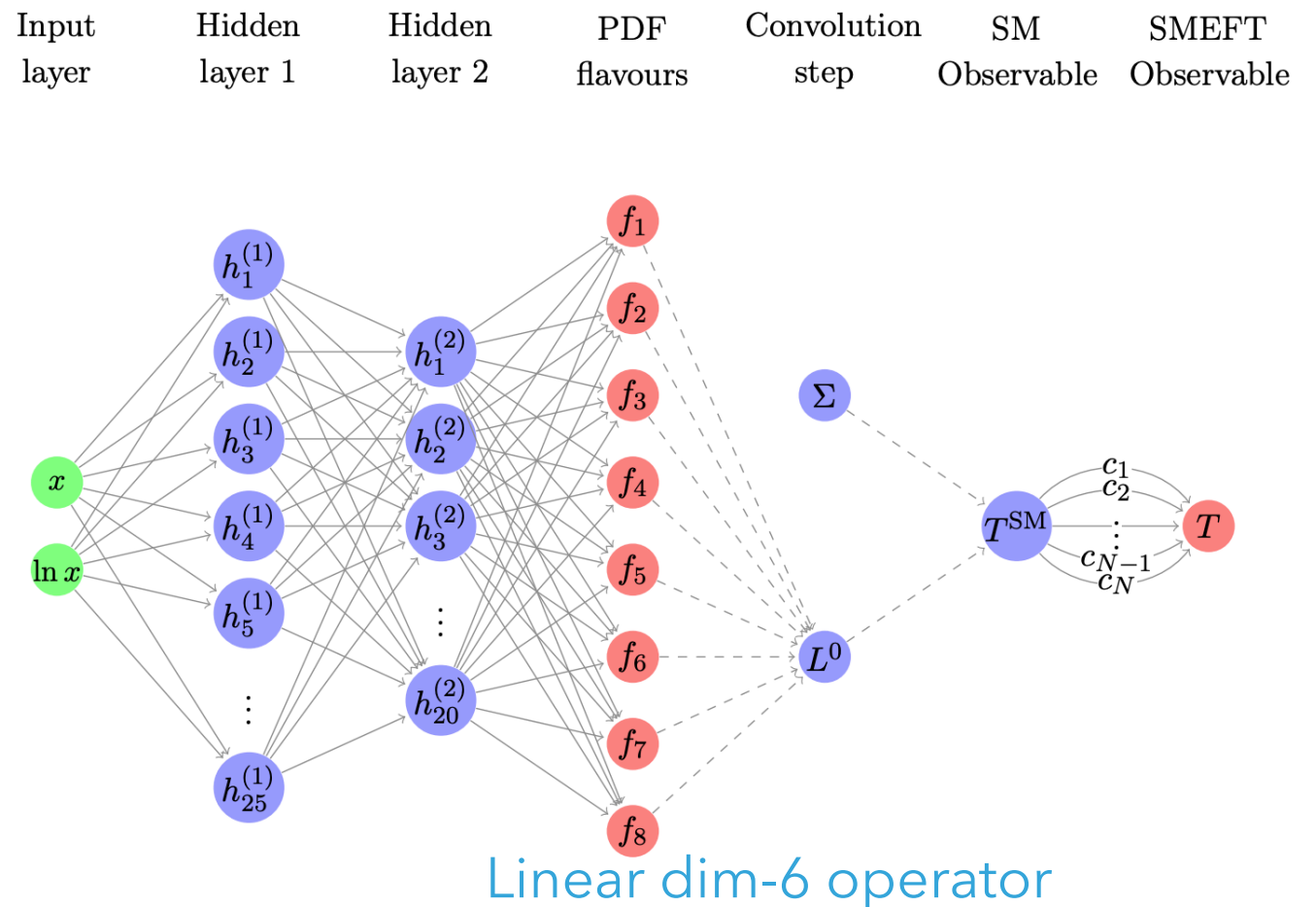
What's the interplay?

SIMULTANEOUS PDF AND SMEFT FITS

- ▶ The idea: take a PDF fit based on NNPDF methodology and make dependence of observables on physics parameters $\{c_i\}$ explicit via fast interface before computing the loss function (e.g. adding SMEFT corrections, expanding observables in terms of SM precision parameters)
- ▶ Perform minimisation of loss function over

$$\hat{\theta} = \theta \cup \{c_i\}$$

by adding new layer to the deep neural network used in NNPDF



$$T(\hat{\theta}) = \Sigma(\{c_n\}) \cdot L^0(\theta) = T^{\text{SM}}(\theta) \cdot \left(1 + \sum_{n=1}^N c_n R_{\text{SMEFT}}^{(n)} \right)$$

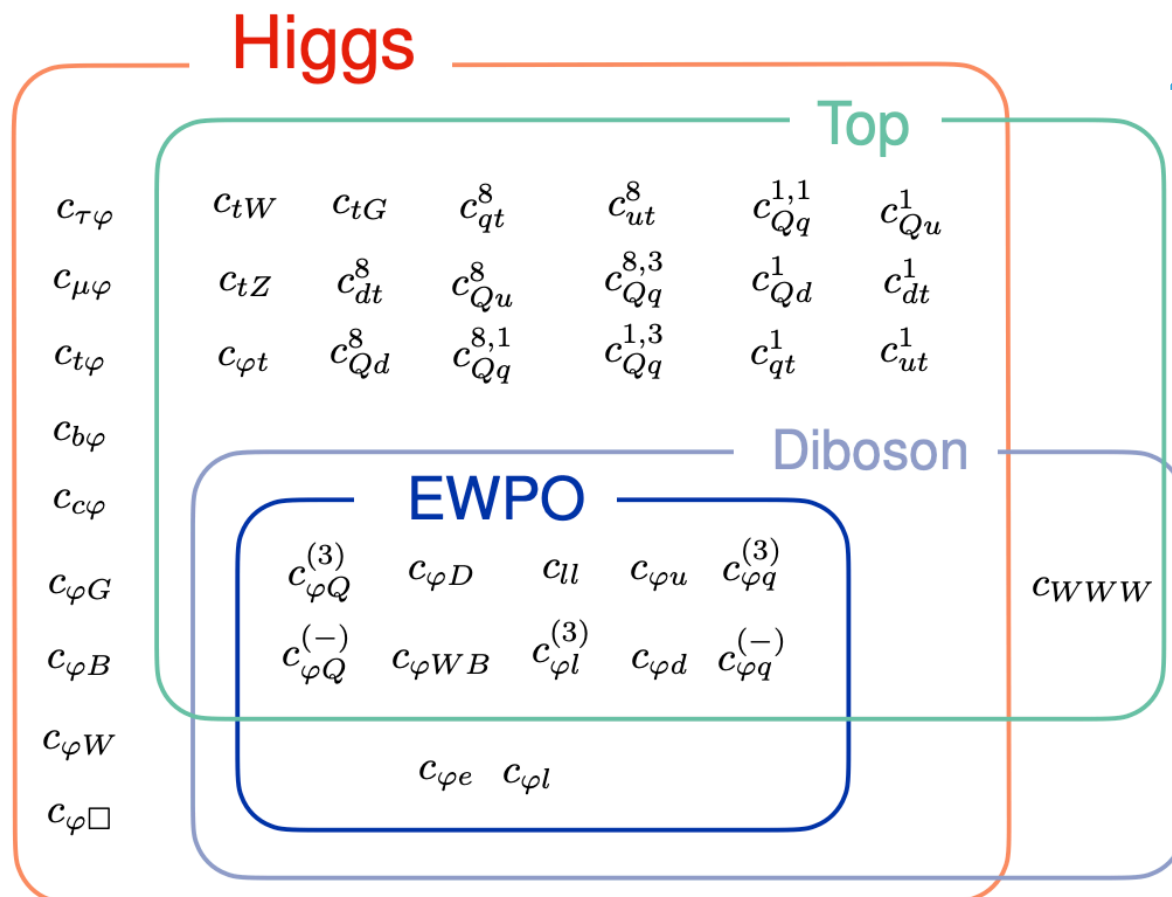
SIMUNET: A GLOBAL PDF AND SMEFT ANALYSIS

SimuNET released open-source with detailed documentation & allow users

<https://github.com/HEP-PBSP/SIMUnet>

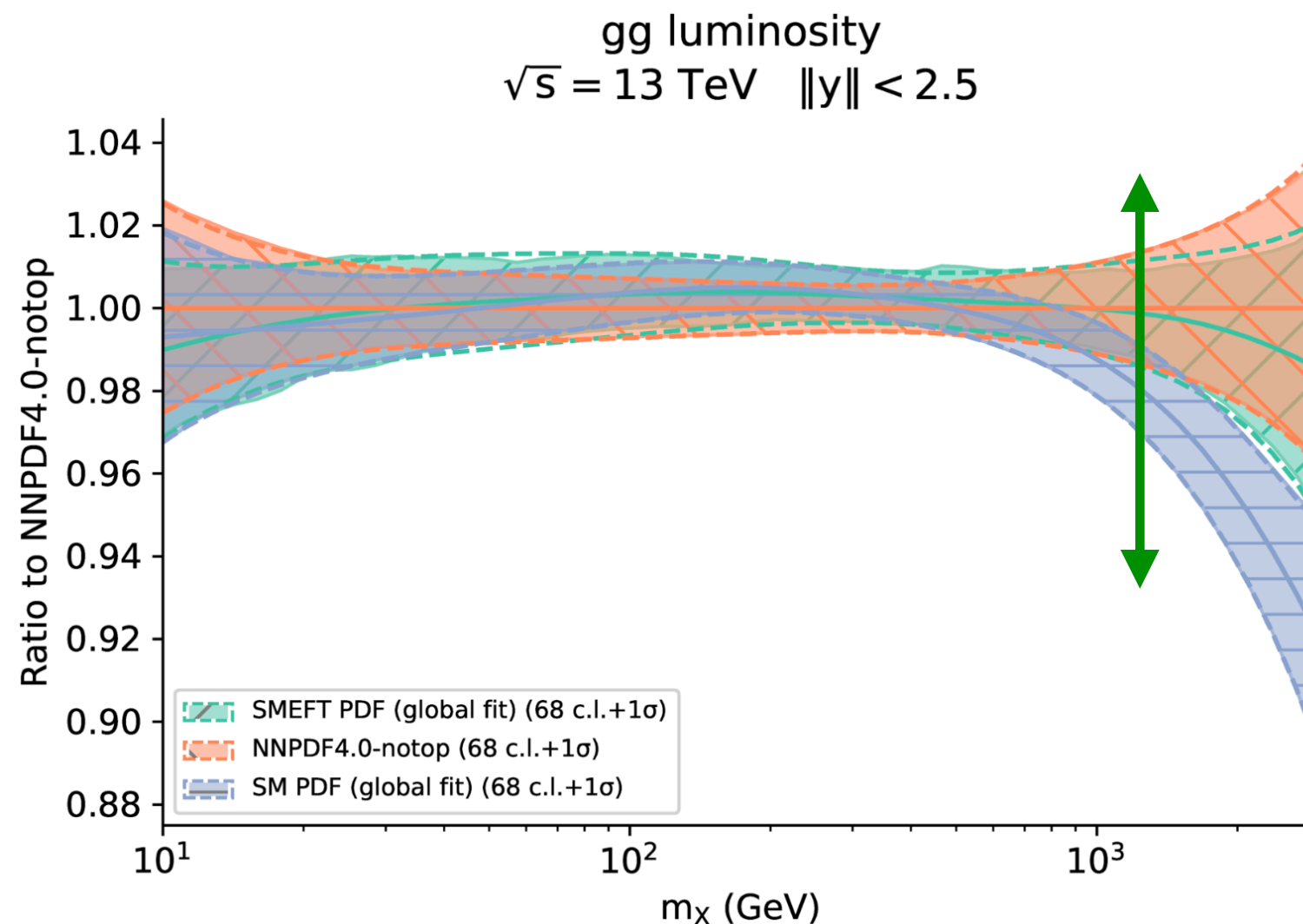
- ✓ PDF only fits [NNPDF]
- ✓ SMEFT only fits - linear SMEFT
- ✓ Simultaneous SMEFT & PDFs - linear SMEFT

```
dataset_inputs:
- {dataset: NMC, frac: 0.75}
- {dataset: ATLASTTBARTOT7TEV, cfac: [QCD], simu_fac: "EFT_NLO"}
- {dataset: CMS_SINGLETOPW_8TEV_TOTAL, simu_fac: "EFT_NLO", use_fixed_predictions: True}
```



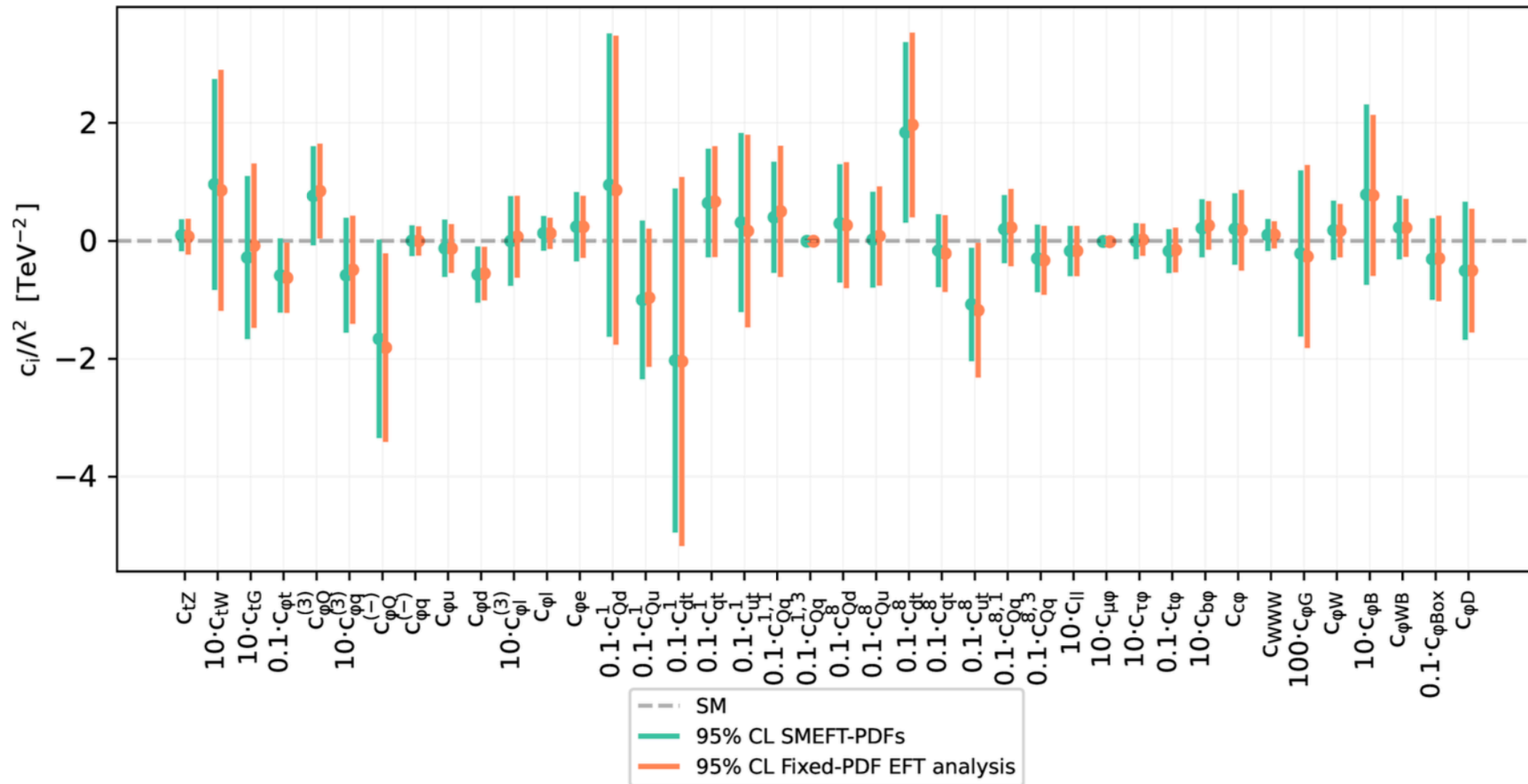
40 SMEFT operators can be fitted alongside PDFs

SIMUNET: A GLOBAL PDF AND SMEFT ANALYSIS



- ✓ Simultaneous analysis of PDFs and 40 operators in the **top+Higgs+EWPO+di-boson sector** using simuNET method shows that WCs are stable, while PDF uncertainties broaden and PDF fitted simultaneously alongside WCs sits nicely between PDF-only fit without top data and PDF fit including all data [Costantini, Hammou, Madigan, Mantani, Moore, Morales, MU - arXiv: 2402.03308]

SIMUNET: A GLOBAL PDF AND SMEFT ANALYSIS



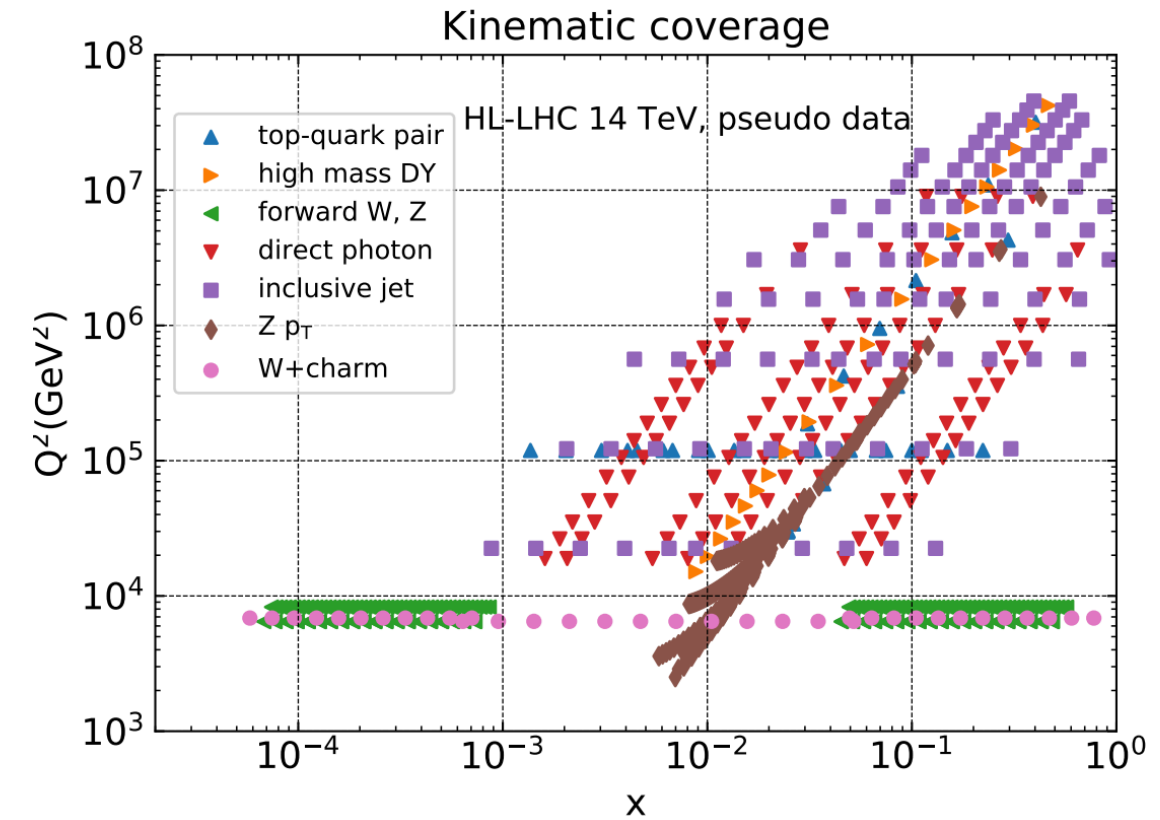
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LOOKING FORWARD: HL-LHC

- Focus on HL-LHC projections for both NC and CC high-mass Drell-Yan in PDF fits

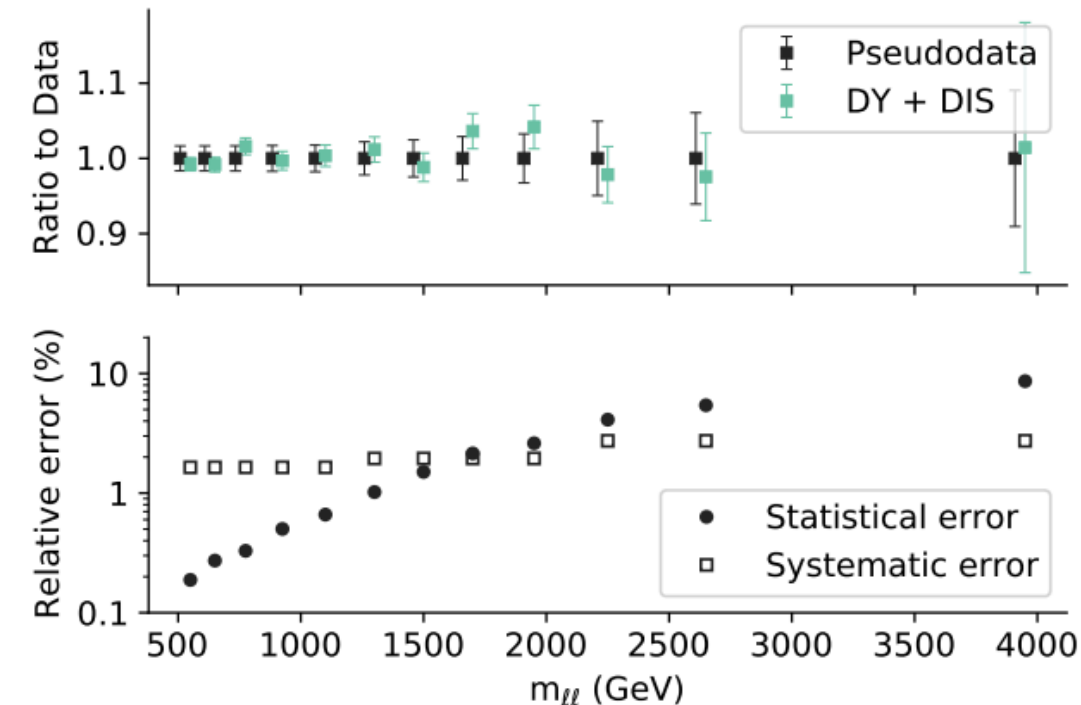
$$\sigma_i^{\text{hllhc}} \equiv \sigma_i^{\text{th}} \left(1 + \lambda \delta_{\mathcal{L}}^{\text{exp}} + r_i \delta_{\text{tot},i}^{\text{exp}} \right), \quad i = 1, \dots, n_{\text{bin}}$$

$$\delta_{\text{tot},i}^{\text{exp}} = \left((\delta_i^{\text{stat}})^2 + \sum_{j=1}^{n_{\text{sys}}} \left(f_{\text{red},j} \delta_{i,j}^{\text{sys}} \right)^2 \right)^{1/2}$$

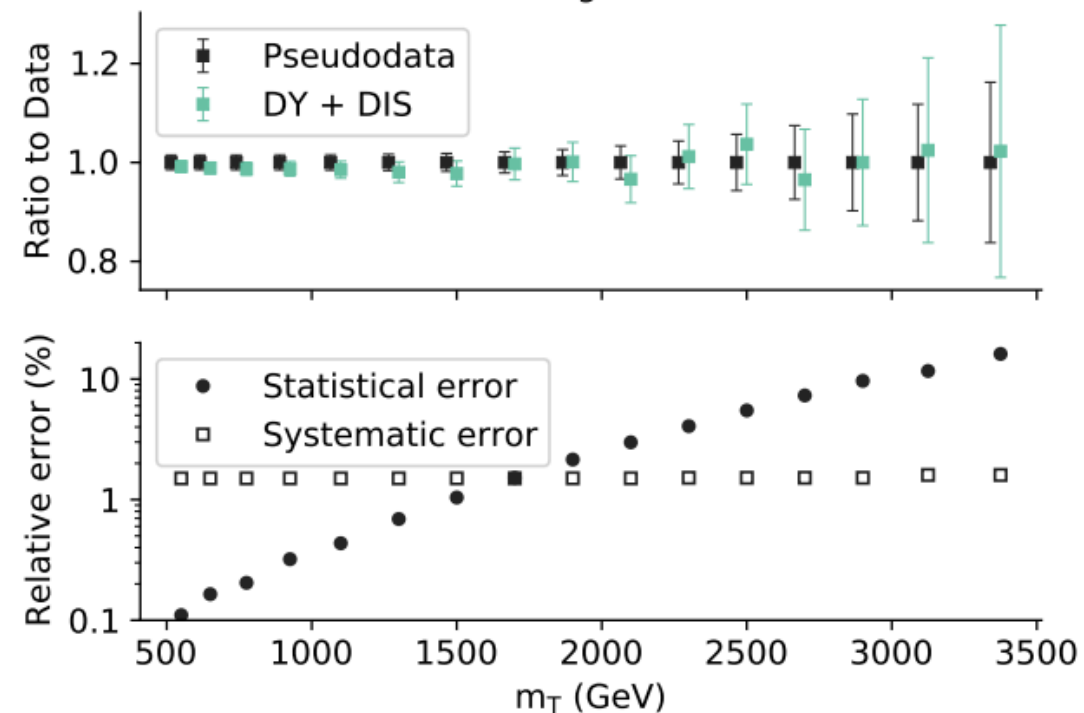


Abdul-Khalek et al, 1810.03639

HL-LHC HM DY 14 TeV - neutral current - electron channel



HL-LHC HM DY 14 TeV - charged current - electron channel



+ muon
channel

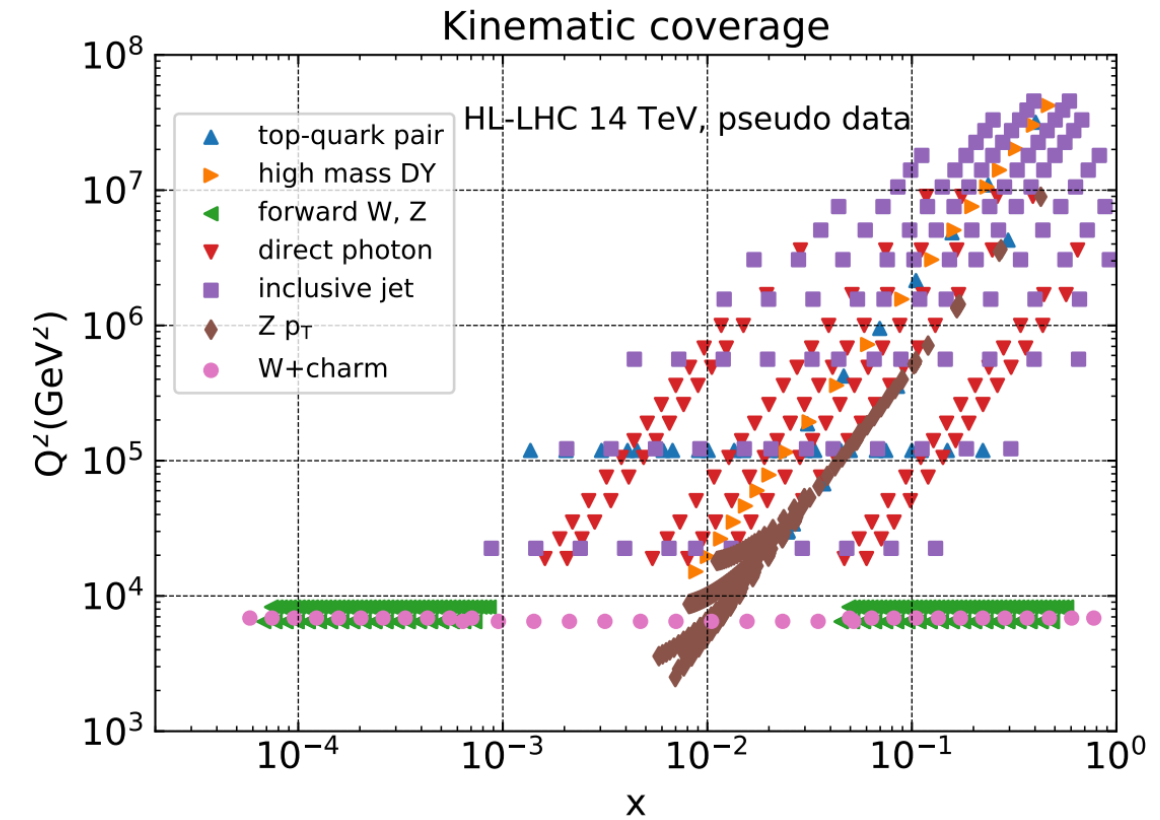
Greljo et al, arXiv:2104.02723

LOOKING FORWARD: HL-LHC

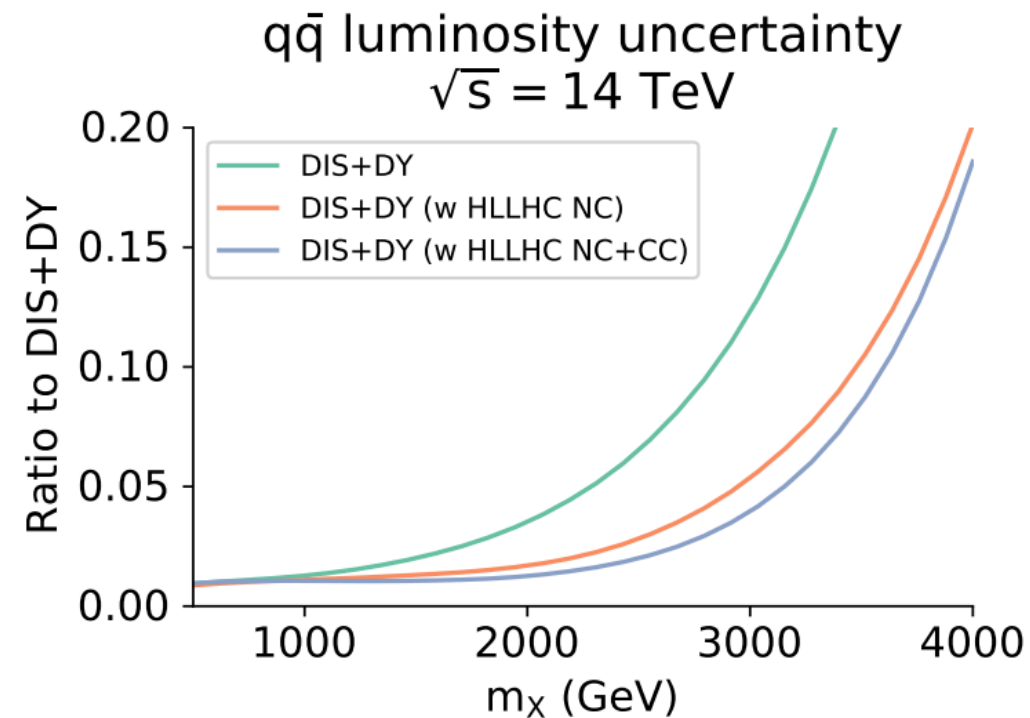
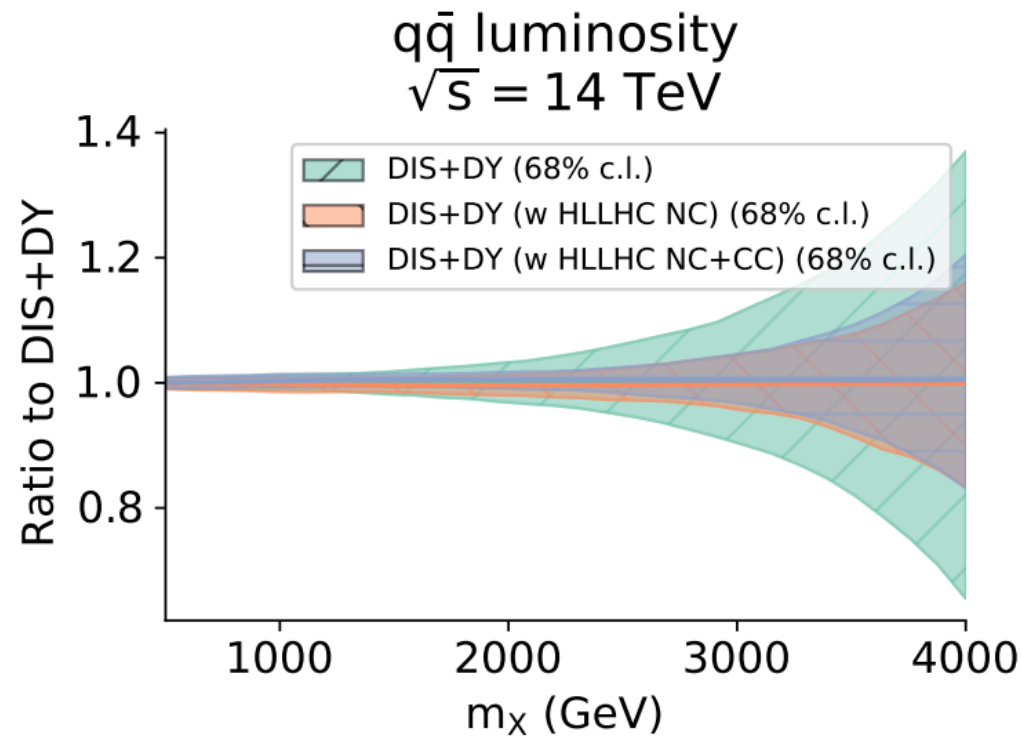
- Focus on HL-LHC projections for both NC and CC high-mass Drell-Yan in PDF fits

$$\sigma_i^{\text{hllhc}} \equiv \sigma_i^{\text{th}} \left(1 + \lambda \delta_{\mathcal{L}}^{\text{exp}} + r_i \delta_{\text{tot},i}^{\text{exp}} \right), \quad i = 1, \dots, n_{\text{bin}}$$

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Abdul-Khalek et al, 1810.03639



Greljo et al, arXiv:2104.02723

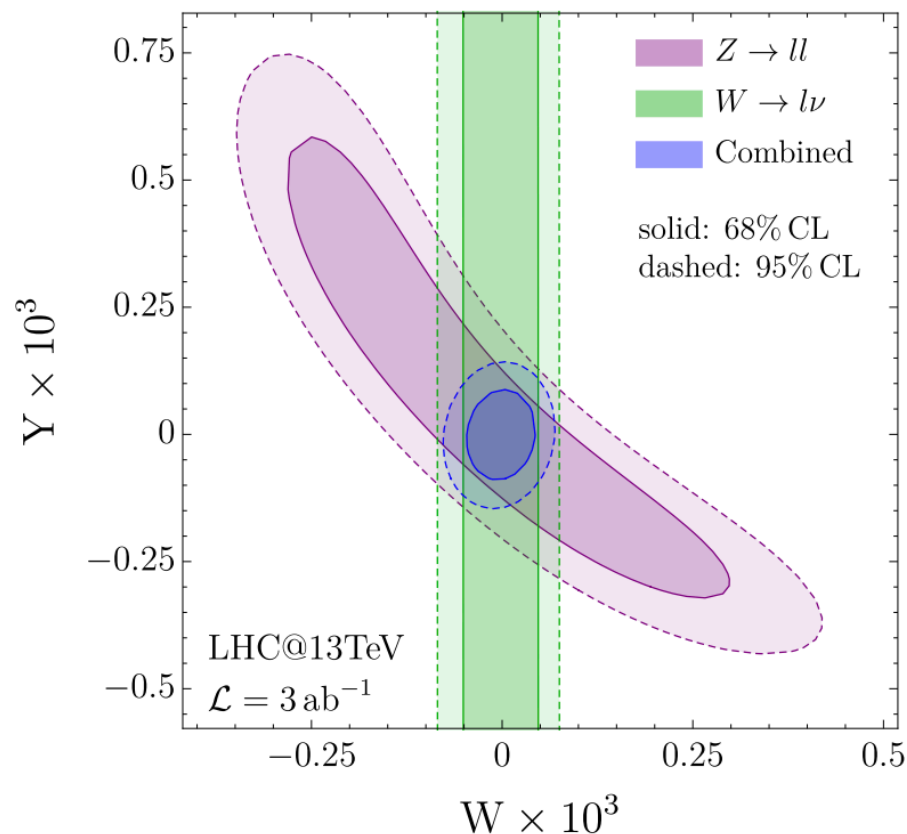
FLAVOR-UNIVERSAL MODELS AND DRELL-YAN TAILS

- Energy-growing EW oblique corrections in high-mass NC and CC Drell-Yan tails.
- W and Y parametrise the self-energy of gauge bosons: powerful probes of quark-lepton contact interactions that produce effects that grow with energy

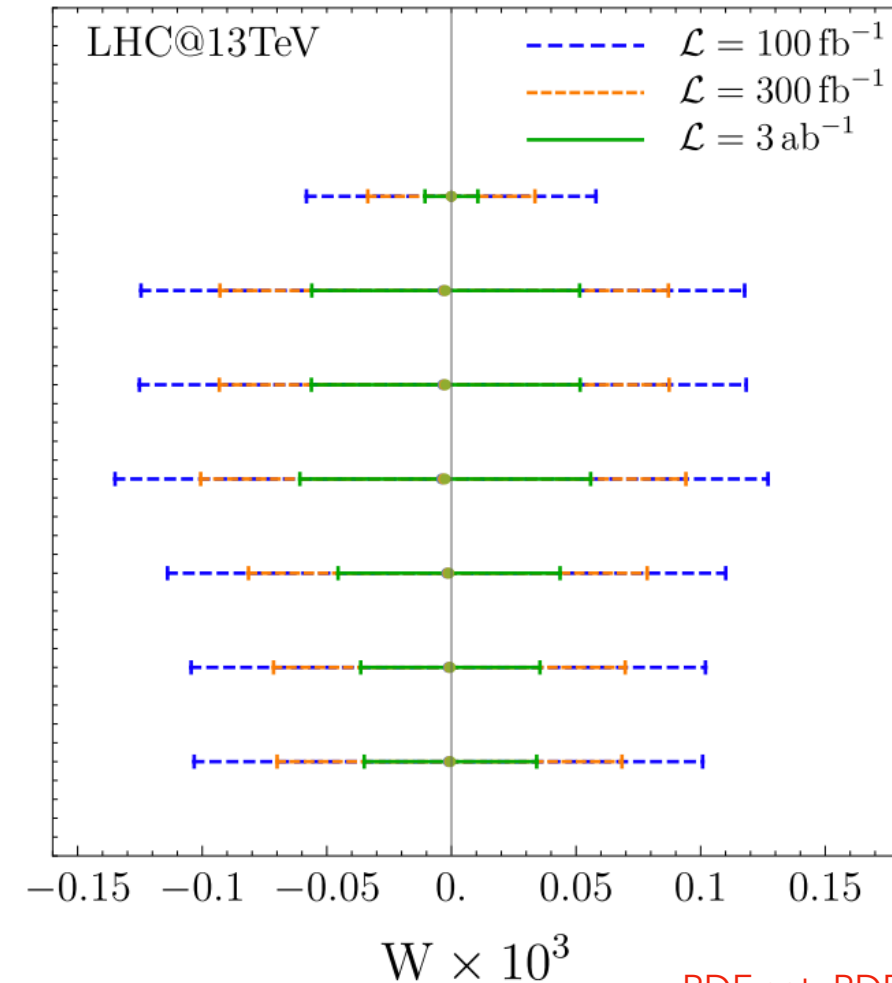
[Torre et al, 2008.12978]

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W_{\mu\nu}^a)^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} - \frac{g^2 \hat{W}}{4m_W^2} \mathcal{O}_{lq}^{(3)} - \frac{g_Y^2 \hat{Y}}{m_W^2} \left(Y_l Y_d \mathcal{O}_{ld} + Y_l Y_u \mathcal{O}_{lu} + Y_l Y_q \mathcal{O}_{lq}^{(1)} + Y_e Y_d \mathcal{O}_{ed} + Y_e Y_u \mathcal{O}_{eu} + Y_e Y_q \mathcal{O}_{qe} \right)$$



Combined bound



Only Stat

No Exp

No Syst

Baseline

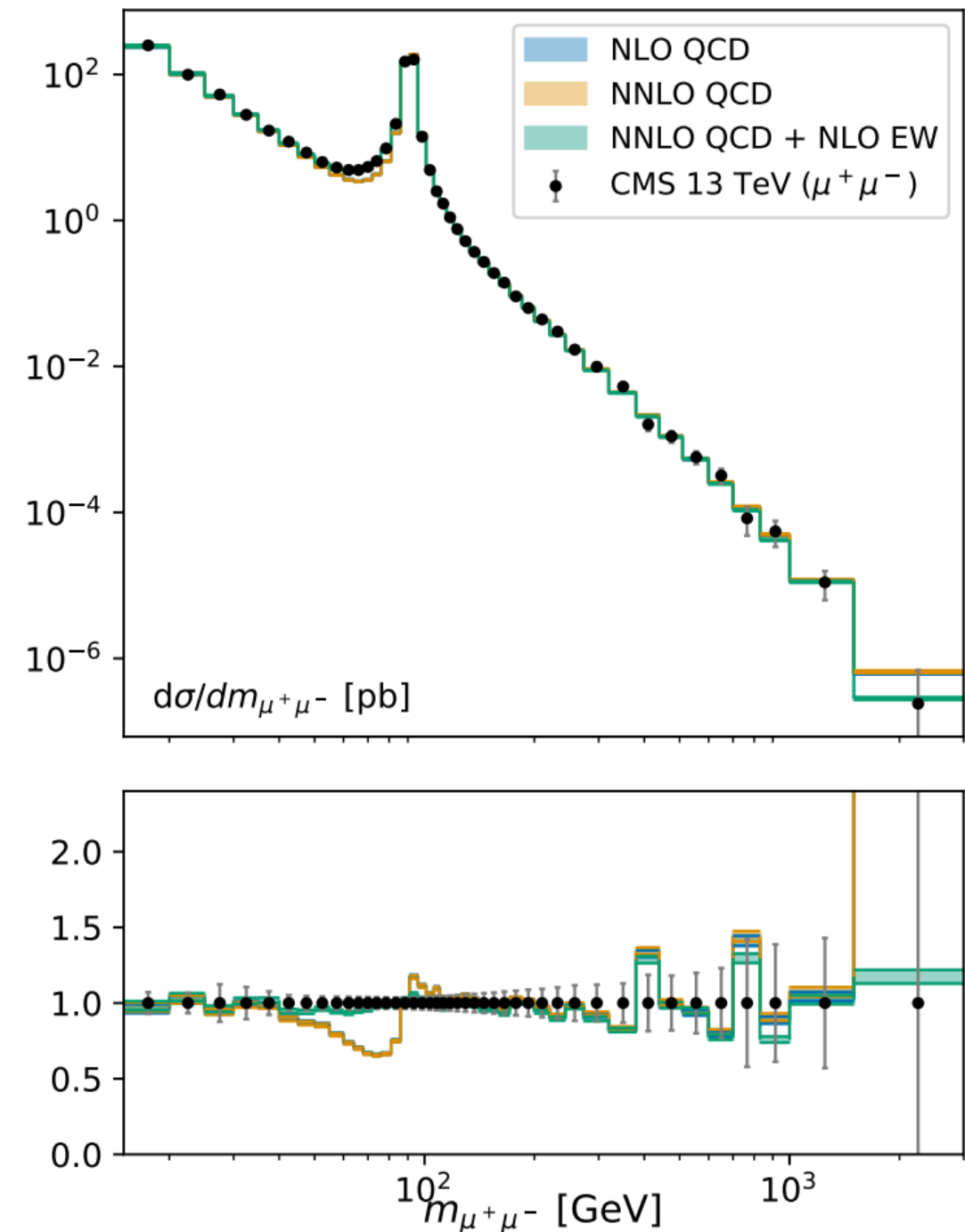
Half PDF

No PDF

No TH

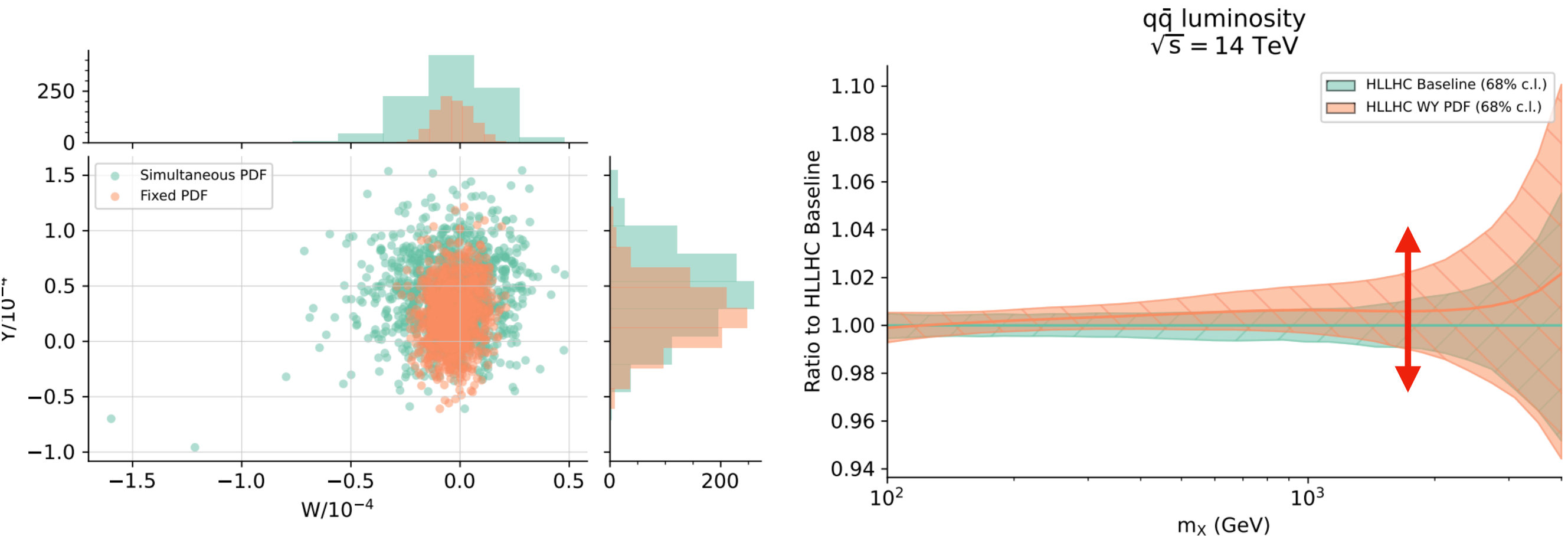
FLAVOR-UNIVERSAL MODELS AND DRELL-YAN TAILS

- Similar analysis as in Torre et al, now with emphasis on PDF and their interplay with bounds on oblique operators
[Greljo, Iranipour, Kassabov, Madigan, Moore, Rojo, MU, Voisey: 2104.02723]
- Settings:
 - ➔ PDF fit based on DIS (~ 3000 data points), Drell-Yan on-shell and low-mass data from ATLAS, CMS and LHCb (~ 600 data points)
 - ➔ + Run I and II ATLAS and CMS high mass NC Drell-Yan data (~ 300 data points)
 - ➔ + HL-LHC projections
 - ➔ SM predictions at NNLO QCD + NLO EW



RESULTS IN THE DRELL-YAN SECTOR

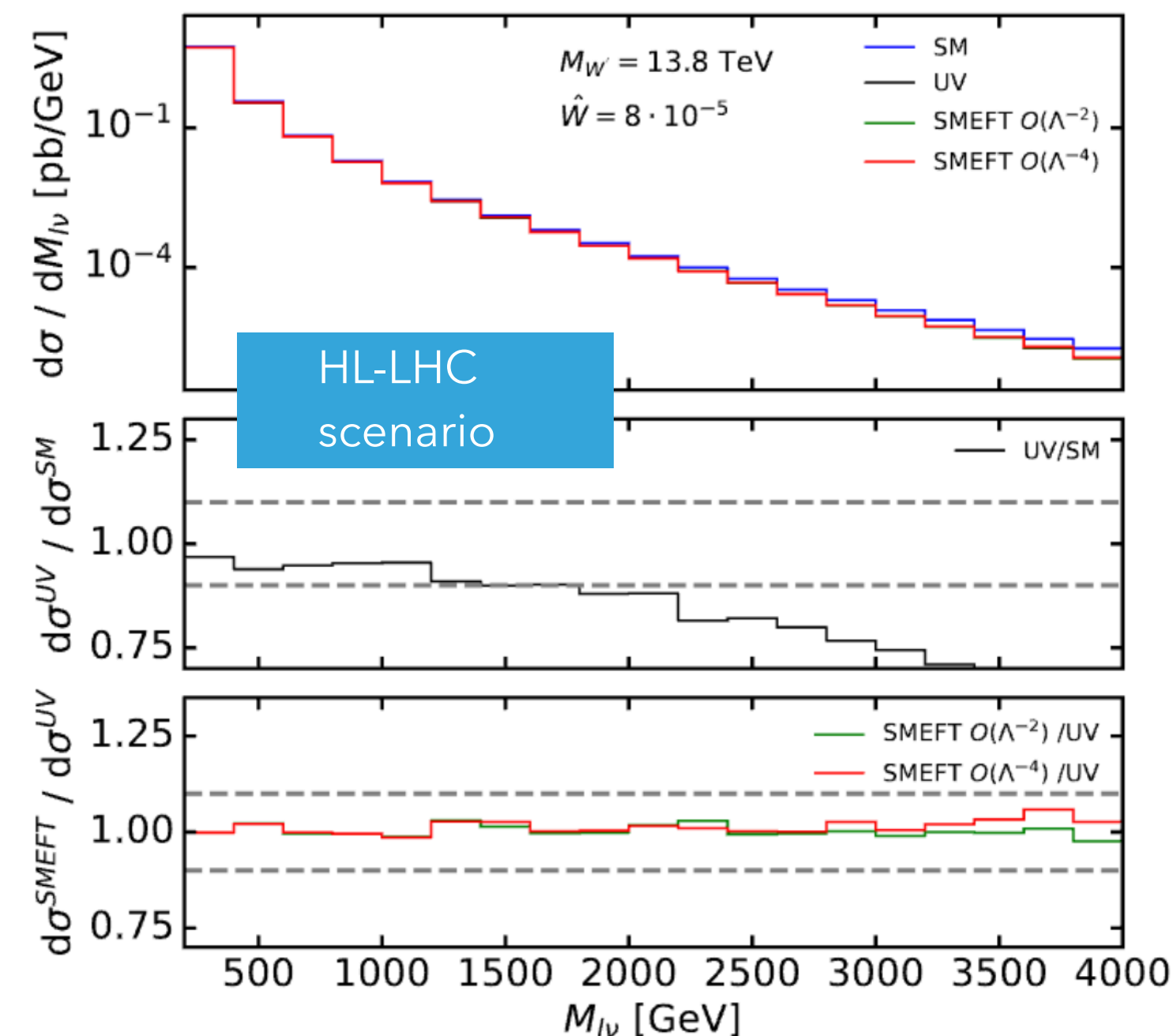
HL-LHC MC data generated assuming law of Nature = SM



- ✓ Simultaneous analysis of PDFs and **Drell-Yan sector** Wilson coefficient in the context of universal parameters of DIS + DY (including HL-LHC projections) using simuNET method shows if HL-LHC projections were generated by using a SM model, then WCs bounds broaden and PDF uncertainties change significantly once SMEFT effects allowed in theory predictions entering PDF fit

[Greljo et al 2104.02723] [Iranipour, MU 2201.07240]

CAN PDFS ABSORB NEW PHYSICS?



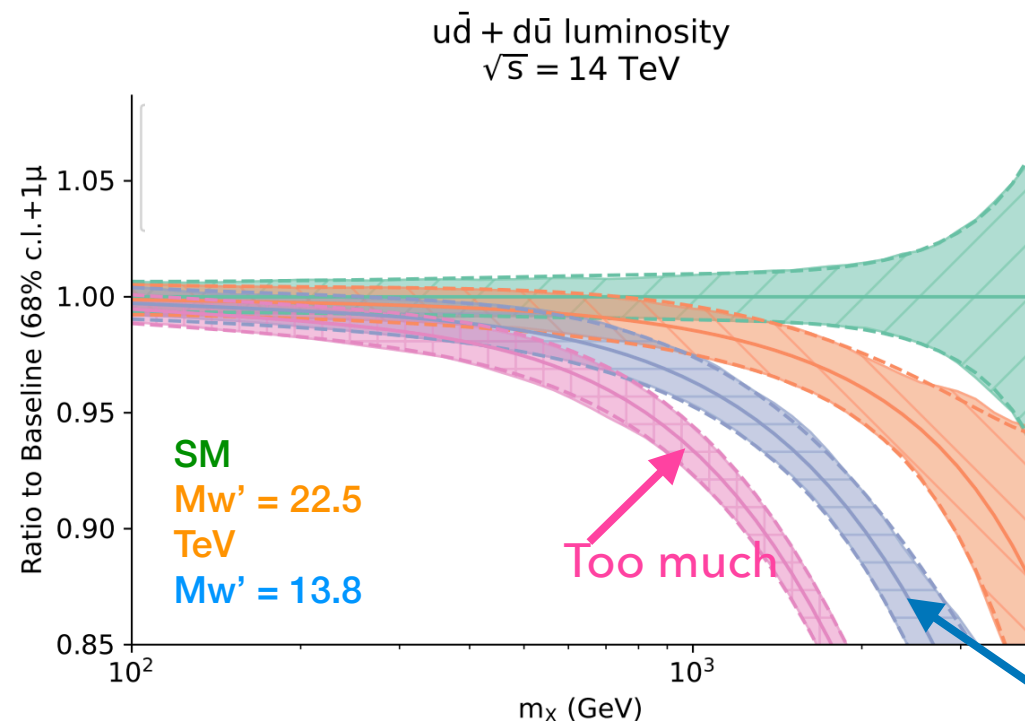
- Imagine instead to generate artificial data injecting a given underlying law:
"True" law of nature =
"True" PDFs + "True" BSM model
- Can inject directly UV model or W/Y SMEFT parametrisation in the region in which SMEFT approximation is good
- Fit PDFs **assuming SM**
- If fit quality of BSM (data) with SM (theory) does not deteriorate with respect to SM (data) with SM (theory) and PDFs deviate from SM PDFs then the BSM signal is absorbed by the PDFs!

$$\checkmark \quad \mathcal{L}_{\text{SMEFT}}^{W'} = \mathcal{L}_{\text{SM}} - \frac{g_{W'}^2}{2M_{W'}^2} J_L^{a,\mu} J_{L,\mu}^a \quad J_L^{a,\mu} = \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L$$

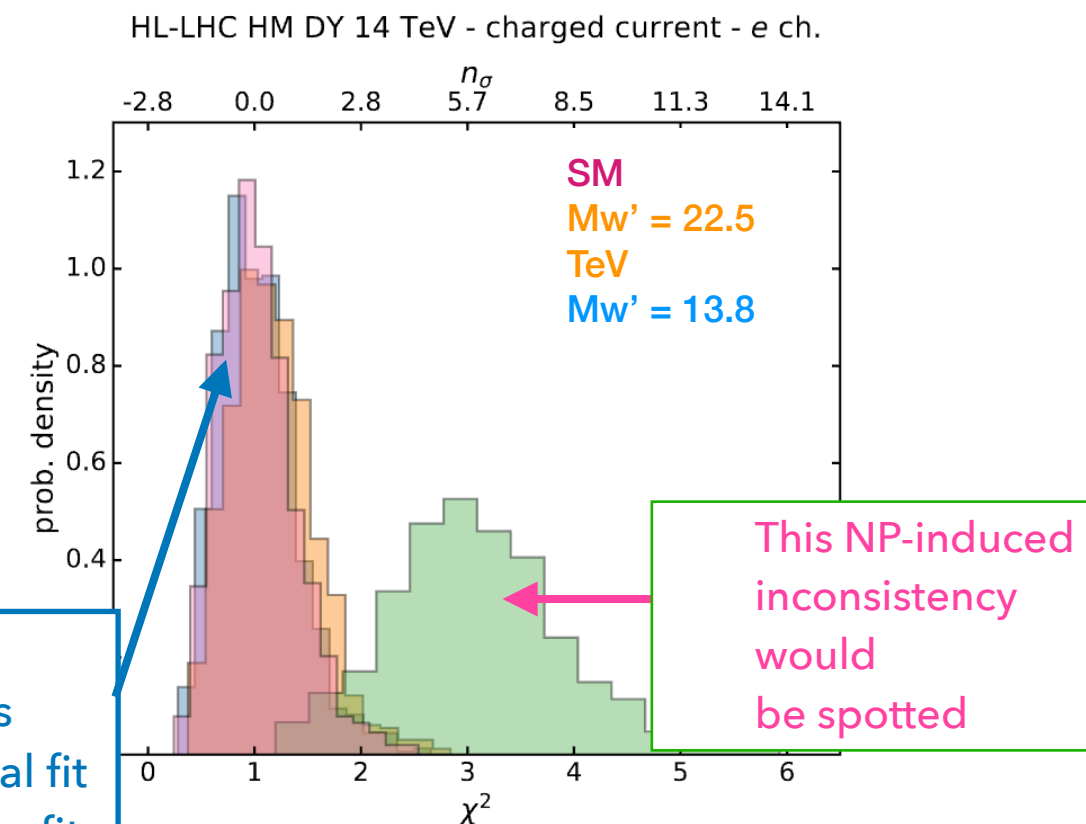
$$\times \quad \mathcal{L}_{\text{SMEFT}}^{Z'} = \mathcal{L}_{\text{SM}} - \frac{g_{Z'}^2}{2M_{Z'}^2} J_Y^\mu J_{Y,\mu} \quad J_Y^\mu = \sum_f Y_f \bar{f} \gamma^\mu f$$

CAN PDFS ABSORB NEW PHYSICS? YES!

- The fit-quality of the global fit is unchanged even with signal from $M_{w'} = 13.8$ TeV injected in all data (mostly visible in HL-LHC NC and CC Drell-Yan data)
- Once we go beyond this point, the fit-quality deteriorates due to the HL-LHC neutral current and charged current Drell-Yan artificial data.
- Already for $M_{w'} = 13.8$ TeV the $qq \sim$ luminosity shifts far beyond the PDF uncertainties because anti-quark PDFs at large- x compensate or “fit away” the effect of New Physics and we would not know in a real fit.



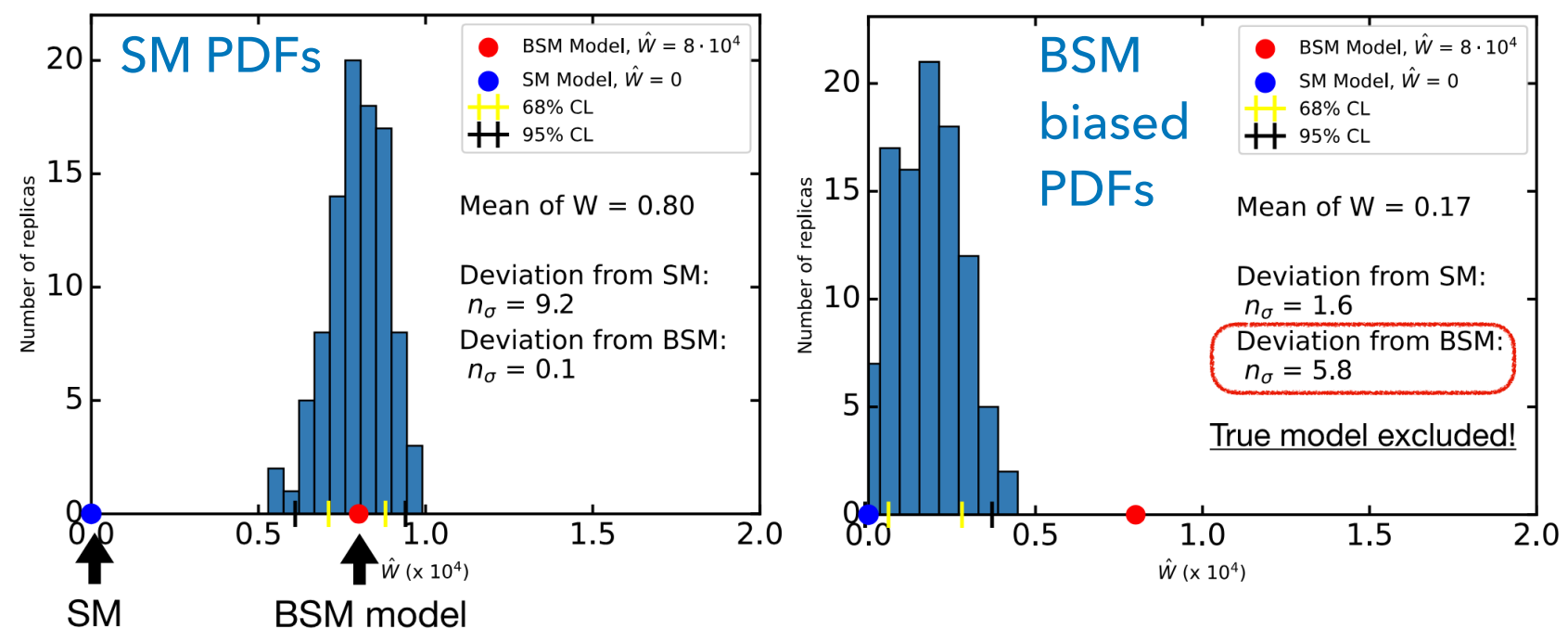
Max BSM bias allowed for this model by global fit without spoiling fit quality



PHENOMENOLOGICAL CONSEQUENCES

- The fit-quality of the global fit is unchanged even with signal from $M_{w'} = 13.8$ TeV injected in all data (mostly visible in HL-LHC NC and CC Drell-Yan data)
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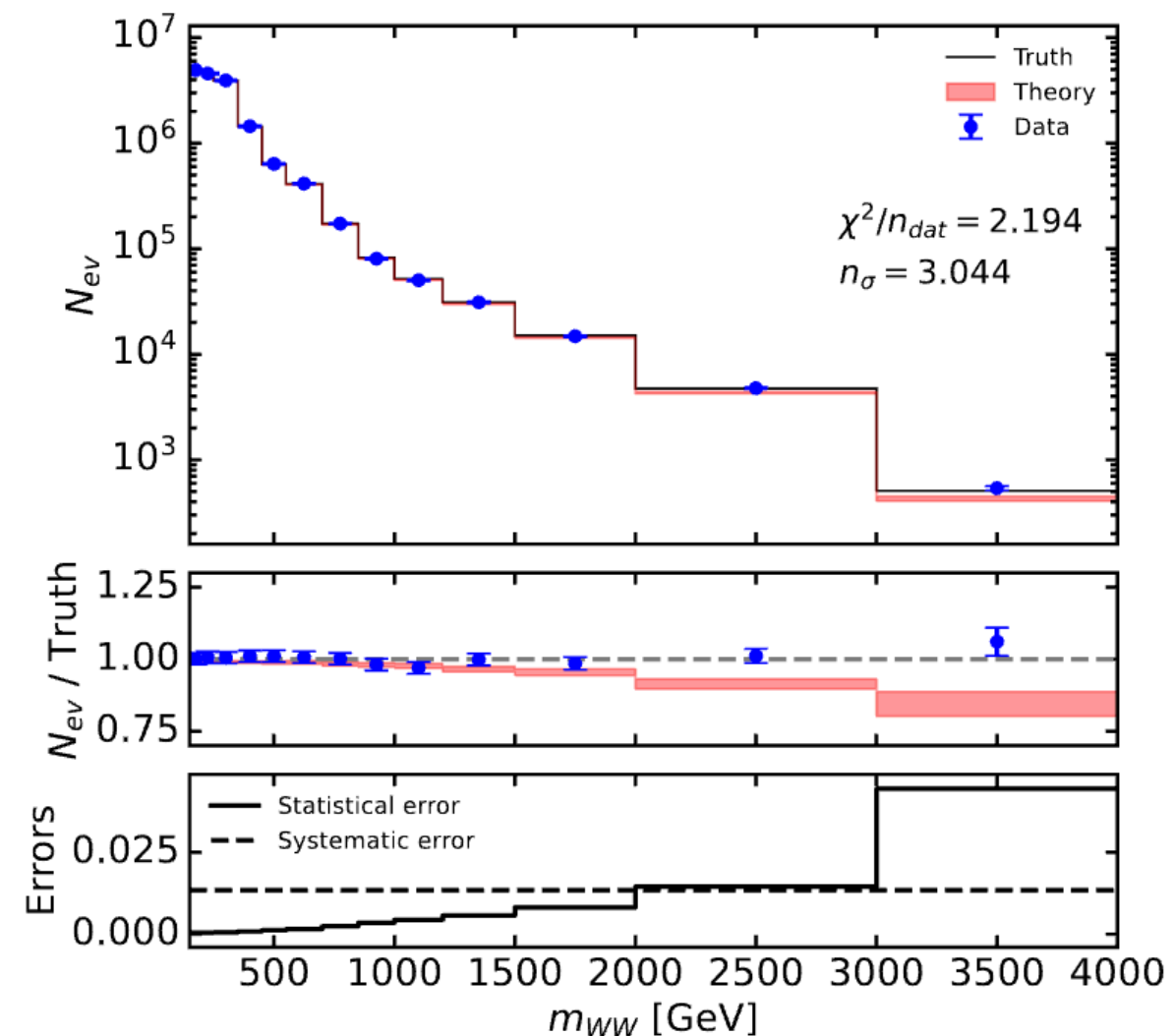
Consequence #1:
Would not see indirect effect of new physics as we would find SMEFT bounds compatible with the SM!



PHENOMENOLOGICAL CONSEQUENCES

- The fit-quality of the global fit is unchanged even with signal from $M_{W'} = 13.8$ TeV injected in all data (mostly visible in HL-LHC NC and CC Drell-Yan data)
- Once we go beyond this point, the fit-quality deteriorates due to the HL-LHC neutral current and charged current Drell-Yan artificial data.
- Already for $M_{W'} = 13.8$ TeV the $qq \sim$ luminosity shifts far beyond the PDF uncertainties because anti-quark PDFs at large- x compensate or “fit away” the effect of New Physics and we would not know in a real fit.

Consequence #2:
Would see New Physics
effects where there are none
(for example in WW)



HOW TO AVOID NEW PHYSICS “CONTAMINATION”?

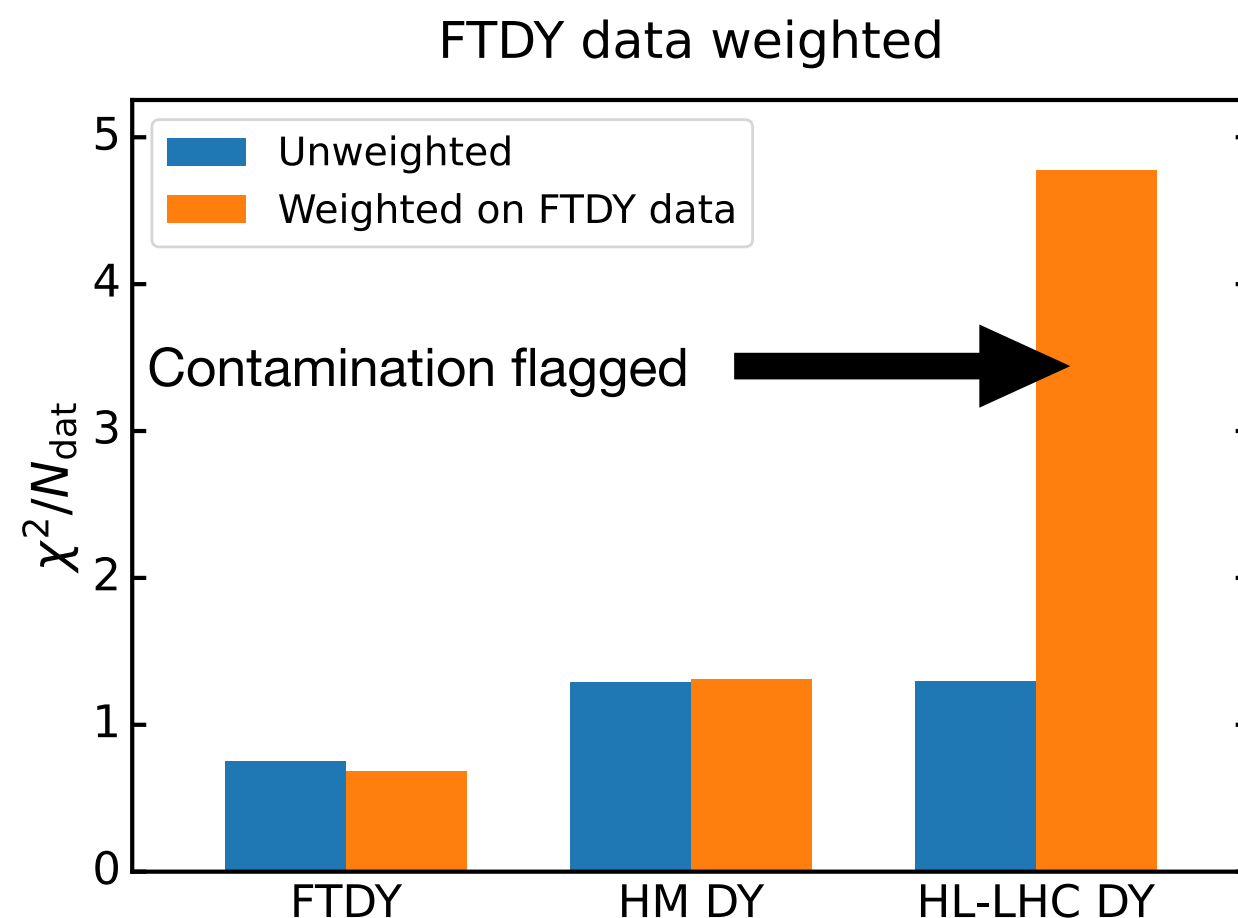
- LHCb on-shell at high rapidity data do not help as quark probed at large x , antiquark at small x
- If we fit giving more weight (artificially increasing statistics) of fixed-target DY data on proton/deuteron the BSM-induced inconsistency would be flagged
- Need more accurate low-energy/large- x constraining measurements to really disentangle such effects

Flat direction in the anti-quark at large- x :

- ➔ Accommodates PDFs to artificial data with BSM injected
- ➔ Allows for BSM bias in $q\bar{q}$ luminosity

Including lower-energy large- x data:

- Constrain large- x region
- Safe from BSM contamination

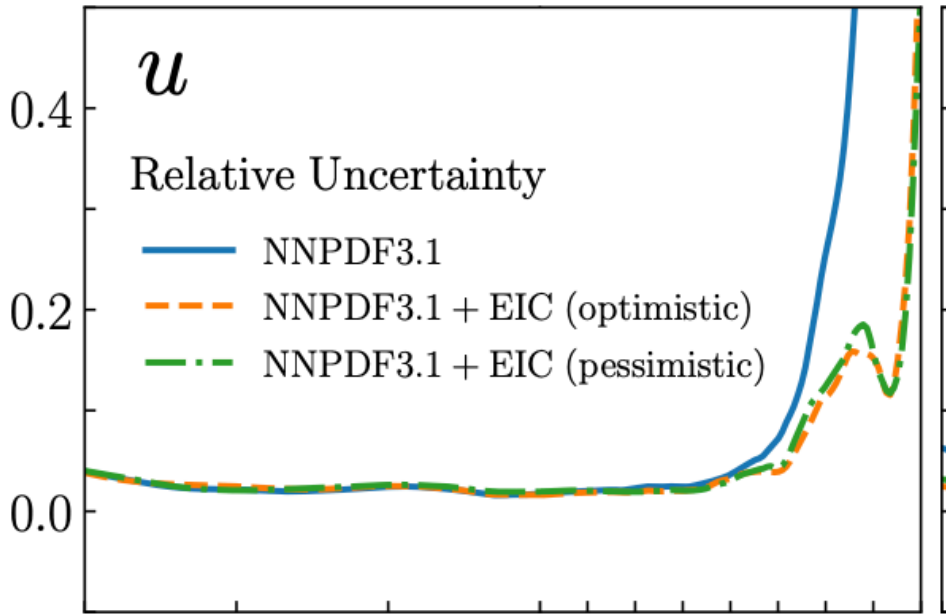
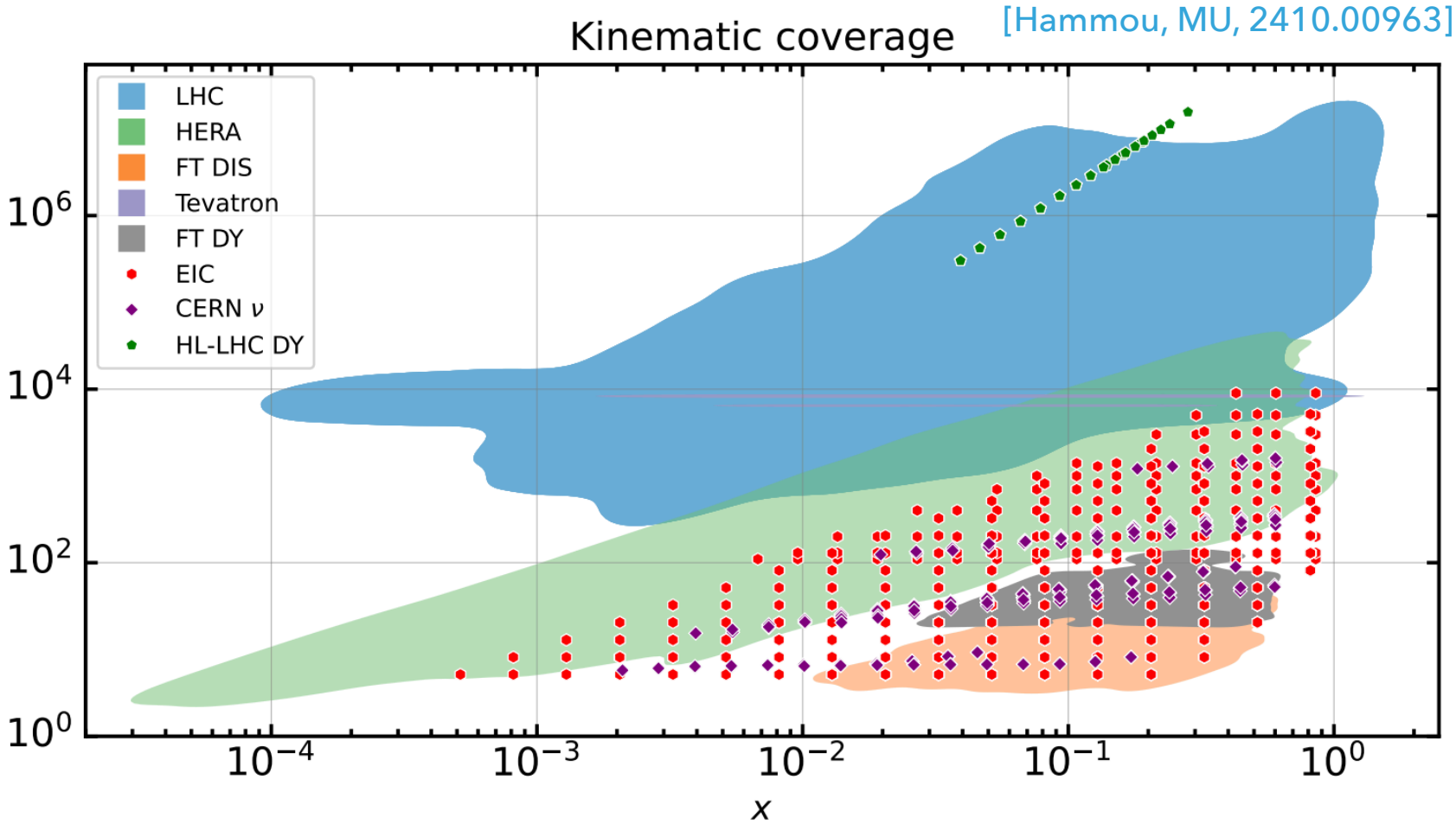


EIC TO THE RESCUE

Observable	N_{dat}	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb ⁻¹]
Charged Current			
$\tilde{\sigma}(e^- + p \rightarrow \nu + X)$	89 (89)	140.7	100
$\tilde{\sigma}(e^+ + p \rightarrow \bar{\nu} + X)$	89 (89)	140.7	10
Neutral Current (proton)			
$\tilde{\sigma}(e^- + p \rightarrow e^- + X)$	181 (131)	140.7	100
	181 (131)	63.2	100
	126 (91)	44.7	100
	87 (76)	28.6	100
$\tilde{\sigma}(e^+ + p \rightarrow e^+ + X)$	181 (131)	140.7	10
	181 (131)	63.2	10
	126 (91)	44.7	10
	87 (76)	28.6	10
Neutral Current (deuteron)			
$\tilde{\sigma}(e^- + d \rightarrow e^- + X)$	116 (116)	89.0	10
	107 (107)	66.3	10
	76 (76)	28.6	10
$\tilde{\sigma}(e^+ + d \rightarrow e^+ + X)$	116 (116)	89.0	10
	107 (107)	66.3	10
	76 (76)	28.6	10

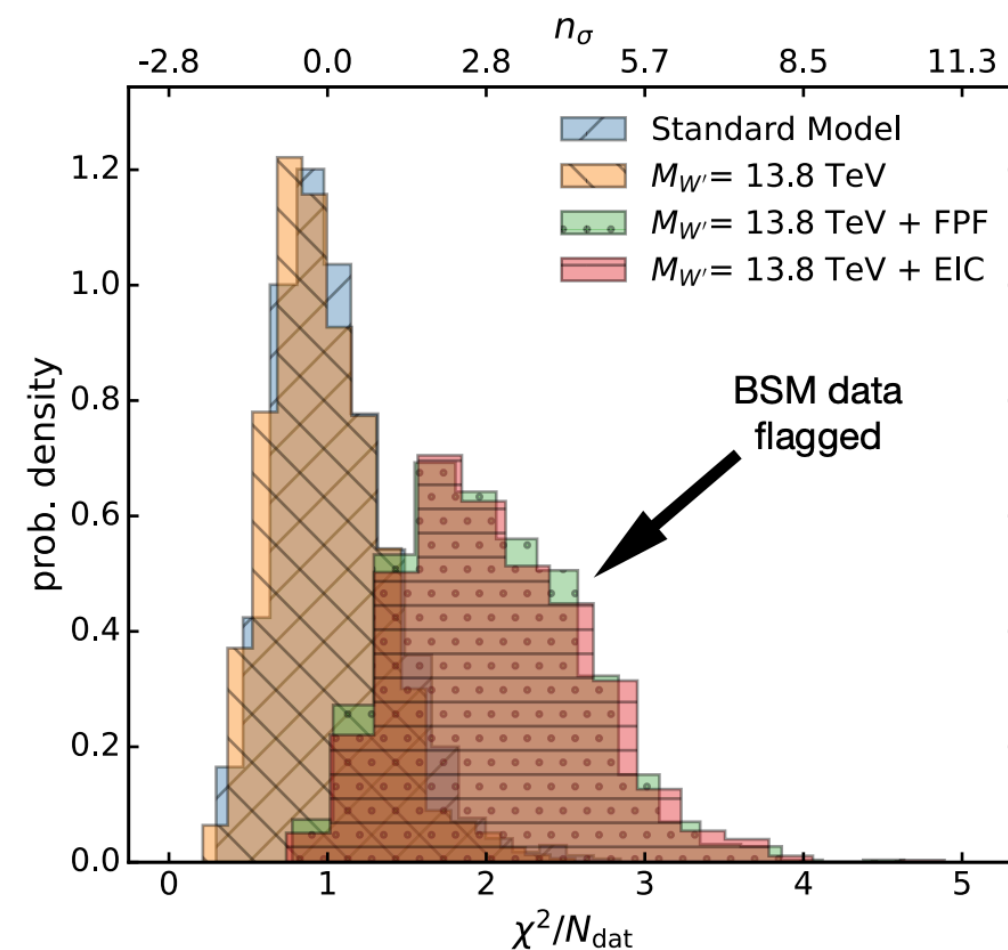
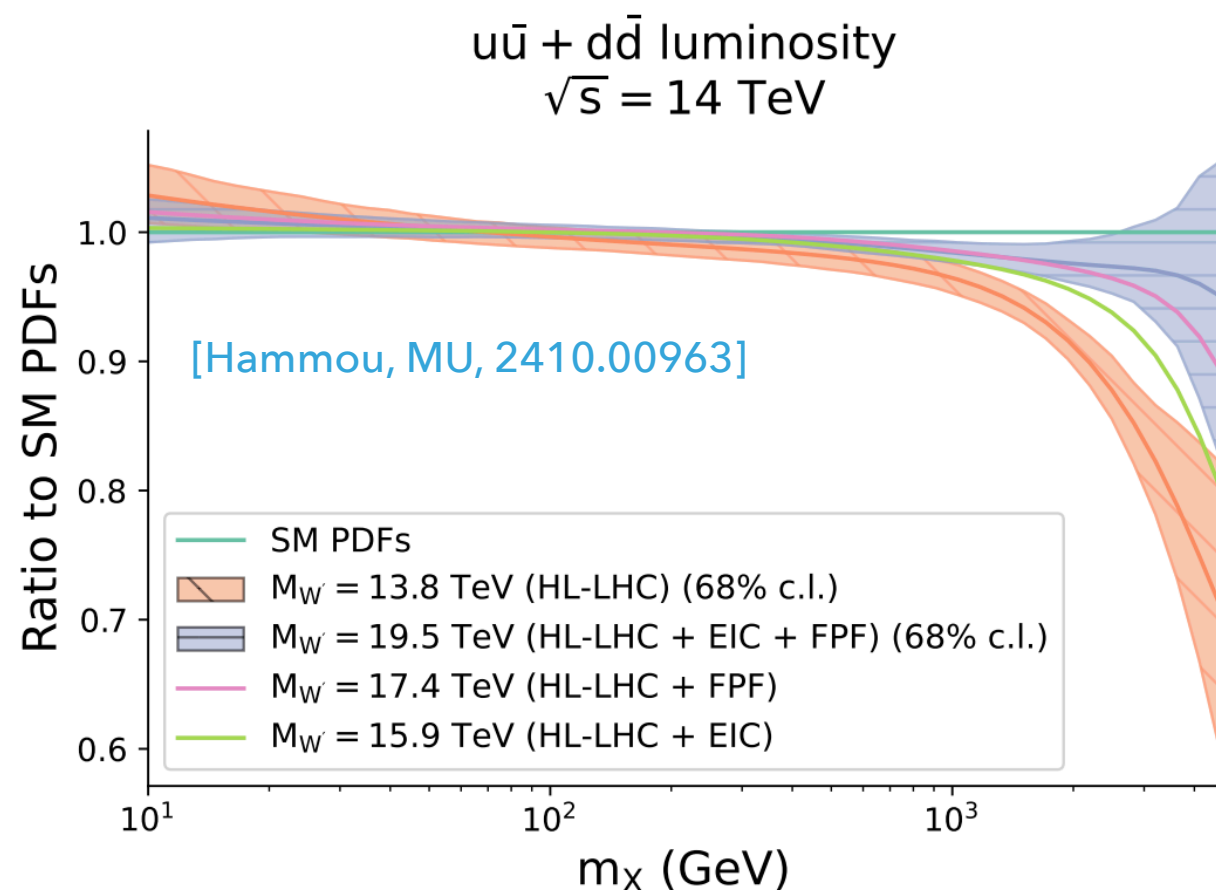
Optimistic scenario

Pessimistic scenario



• NC and CC DIS measurements at the EIC would provide handles on up and down quarks at medium-large-x

EIC TO THE RESCUE



- Including the EIC artificial data alongside the HL-LHC ones reduces the BSM-bias in PDF luminosity
- The HL-LHC data with $M_{W'} = 13.8$ TeV injected would be excluded from the fit as their theoretical description with the SM would be too poor and the data would be considered inconsistent
- EIC inclusion would push the threshold of BSM bias up to $M_{W'} \sim 20$ TeV and would make the effect on PDFs much smaller

EIC TO THE RESCUE

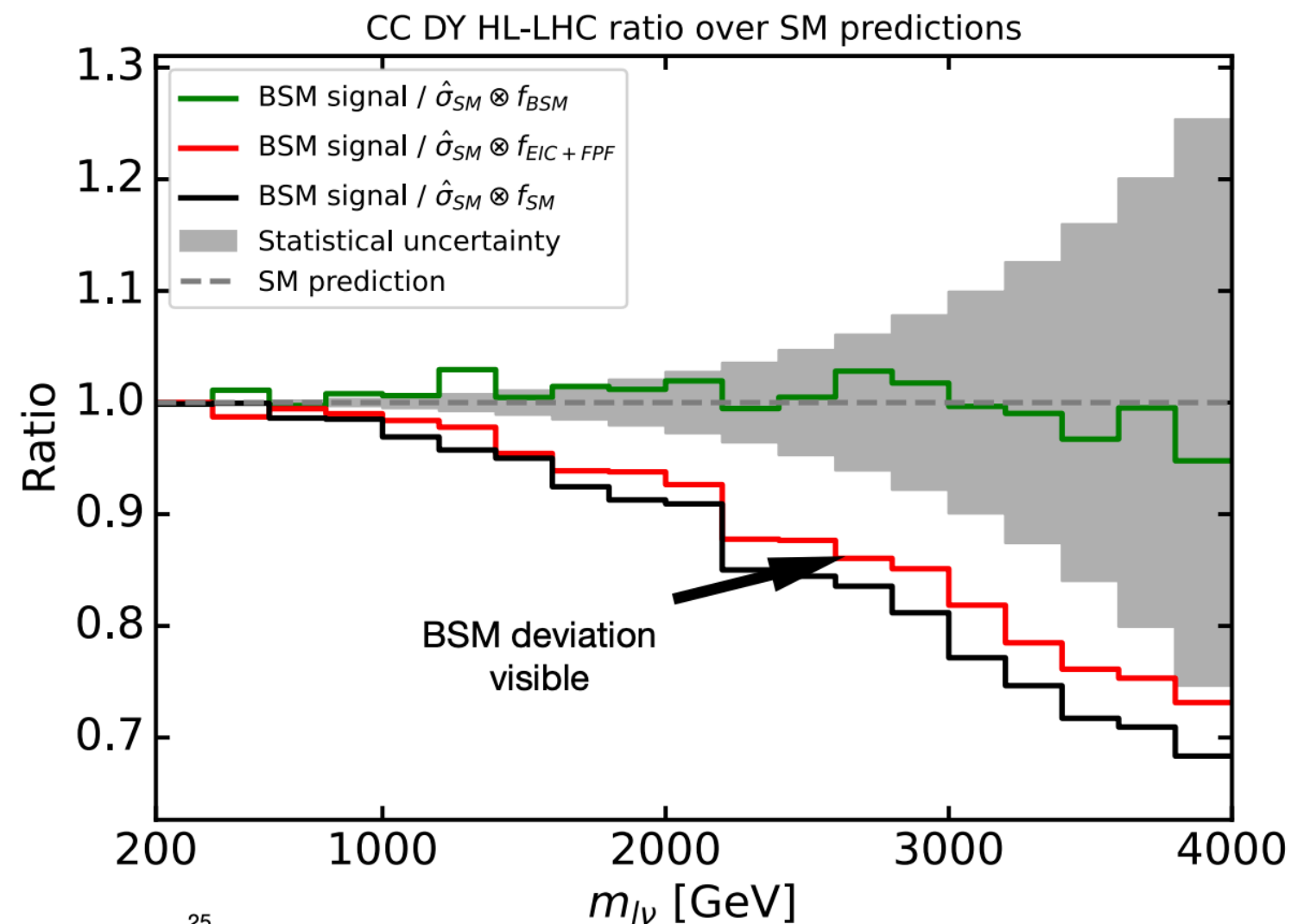
- ✓ Potential BSM effects, which might otherwise be absorbed into the PDFs, can be disentangled in high-energy measurements by incorporating EIC measurements in a global PDF analysis
- ✓ This minimises the risk of BSM-induced bias in PDF fits and allow for more consistent identification of BSM effects in high energy data, which can then be analysed separately.

$$\hat{\sigma}_{BSM} \otimes \mathcal{L}_{SM} \approx \hat{\sigma}_{SM} \otimes \mathcal{L}_{BSM}$$

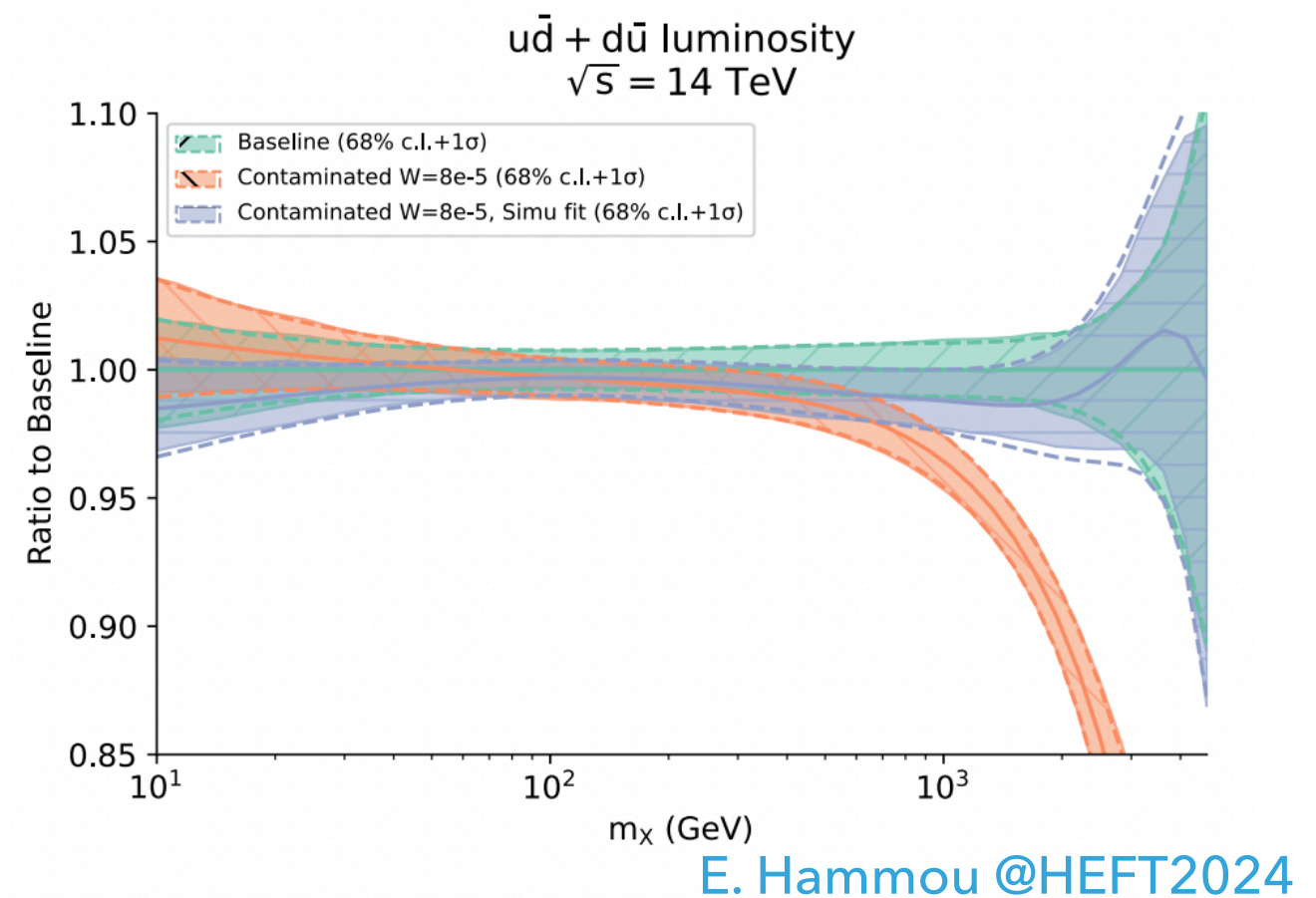
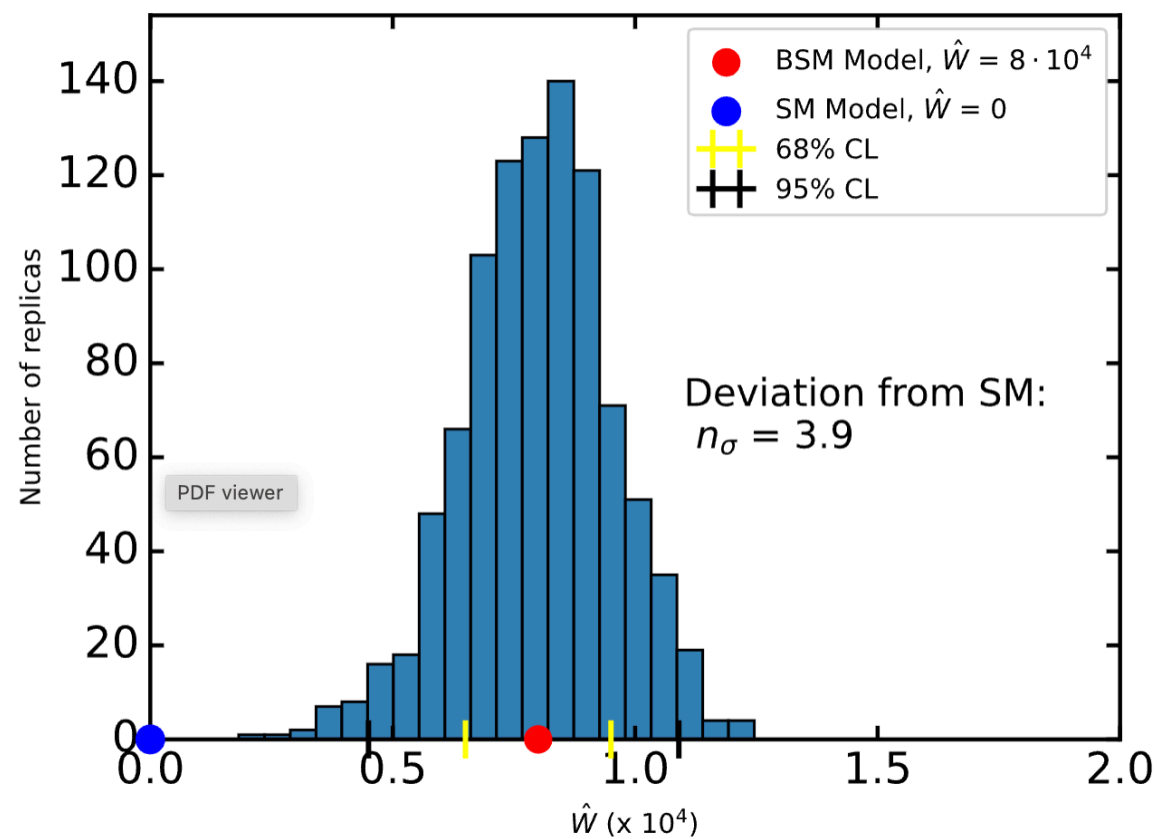


$$\hat{\sigma}_{BSM} \otimes \mathcal{L}_{SM} \neq \hat{\sigma}_{SM} \otimes \mathcal{L}_{EIC+FPF}$$

$$M_{W'} : 13.8 \text{ TeV}$$



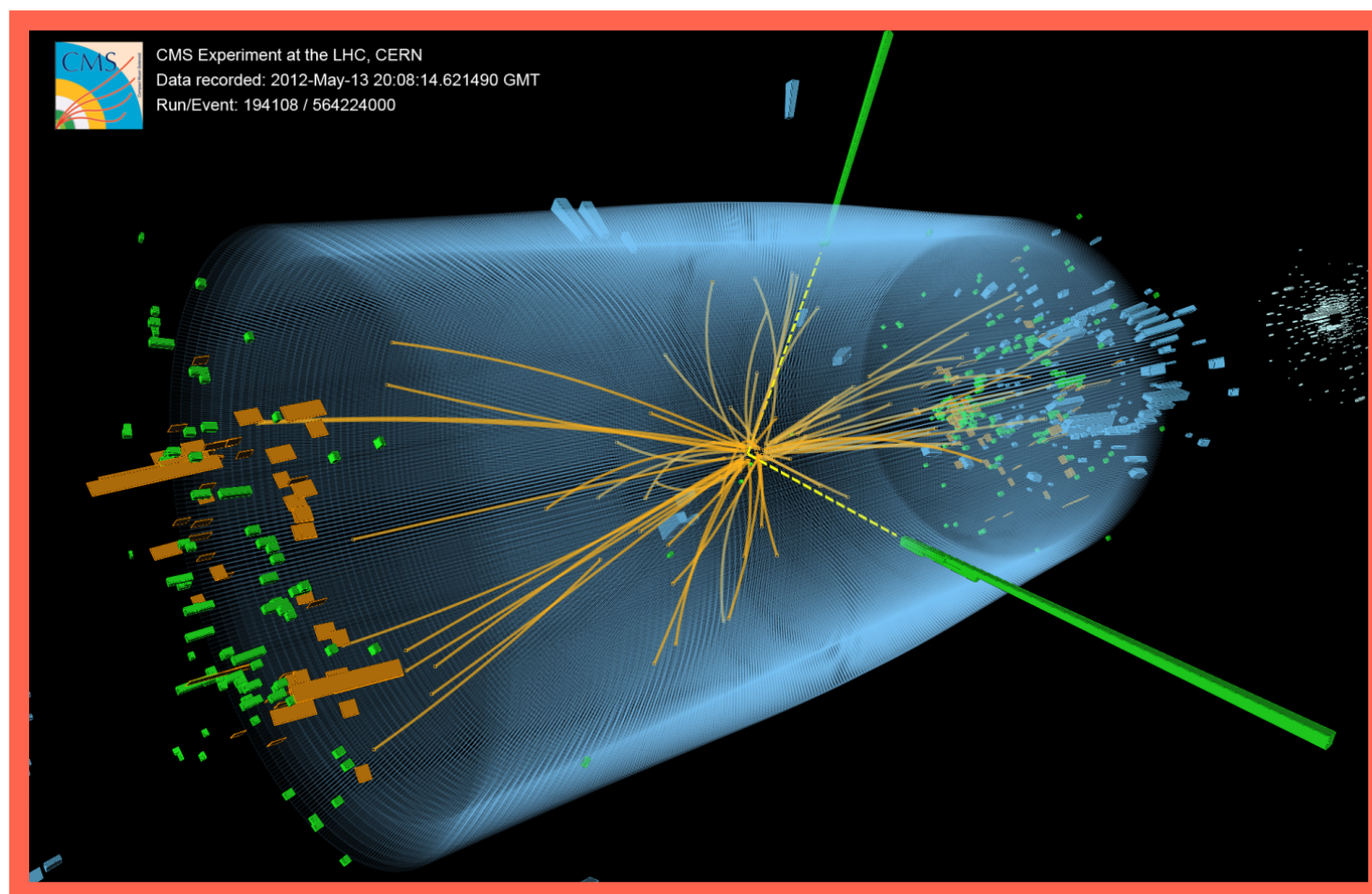
SIMULTANEOUS FIT TO THE RESCUE



✓ Simultaneous analysis of PDFs and **Drell-Yan sector** Wilson coefficient in the context of universal parameters of DIS + DY (including HL-LHC projections) using simuNET method shows that if HL-LHC projections were generated by using a W' BSM model, the simultaneous fit would be able to find the “true” SM PDFs and the “true” SMEFT value!

[Costantini, Hammou et al - in preparation]

SUMMARY AND OUTLOOK

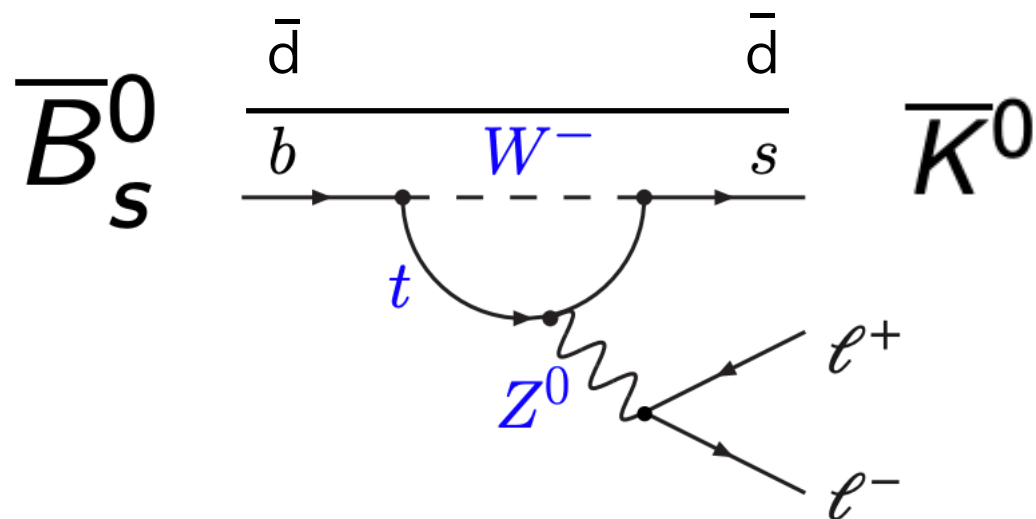


“ Great discoveries,
which seem to mark
the end of a story,
mark in fact the
beginning of a new,
more extraordinary
one”

G. Ilioupoulos

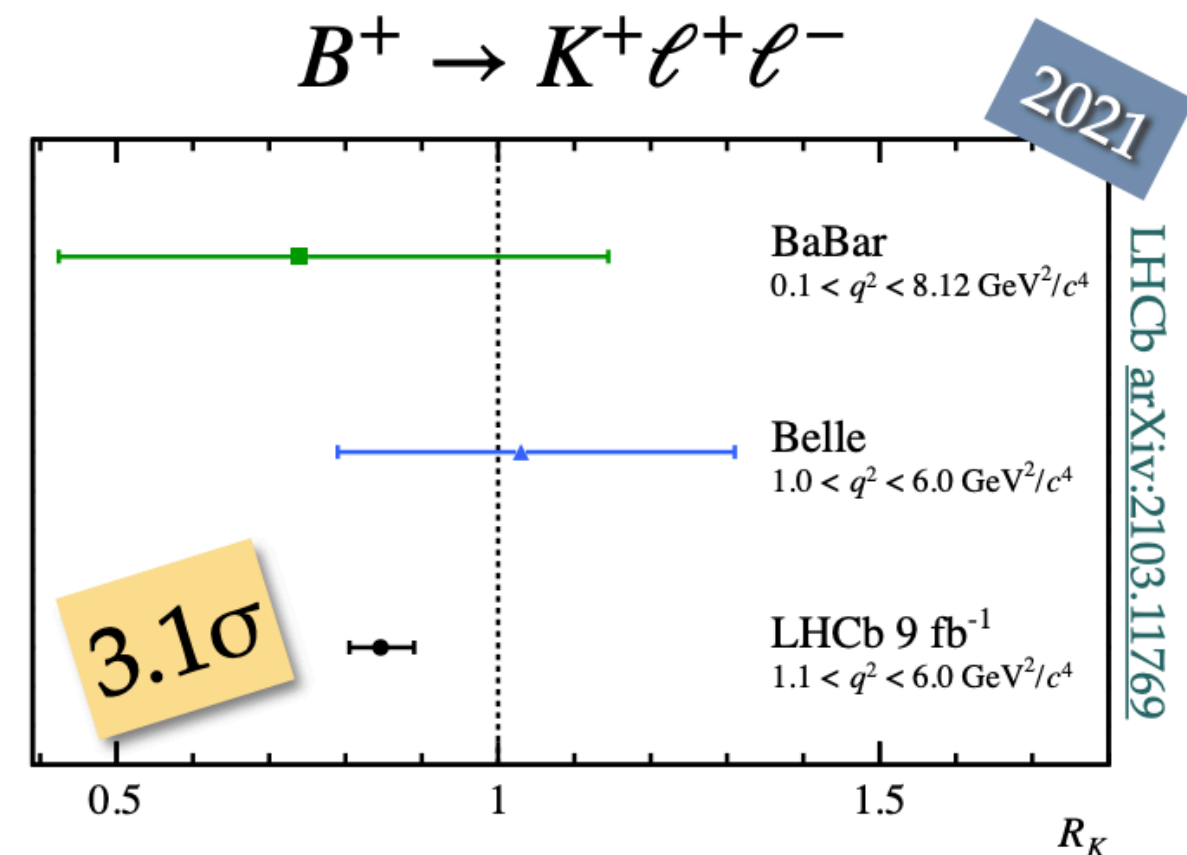
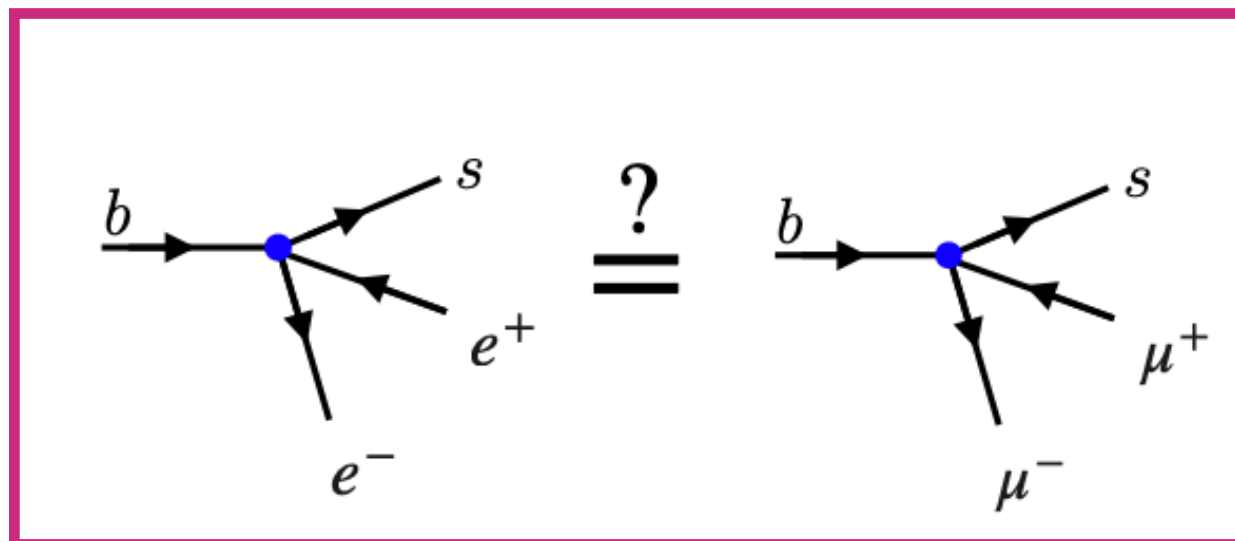
With about one billion events per second and more than 20 years of data taking from now on and so many data still to analyse, surprising understanding & new discoveries might be just around the corner!

HINTS IN LEPTON FLAVOUR UNIVERSALITY VIOLATION



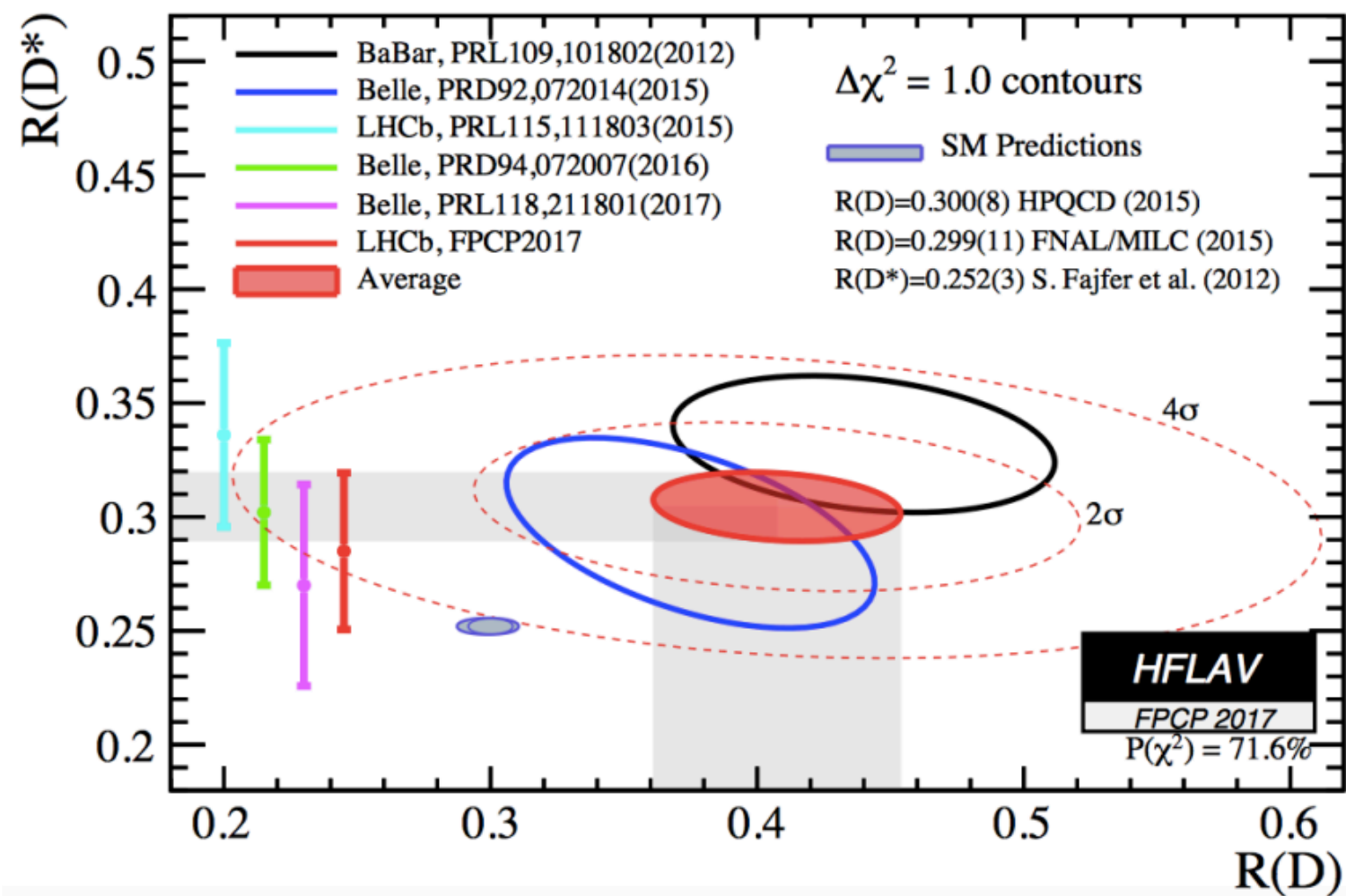
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}$$

$$R_H = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H e^+ e^-)}{dq^2} dq^2} \stackrel{\text{SM}}{\approx} 1$$



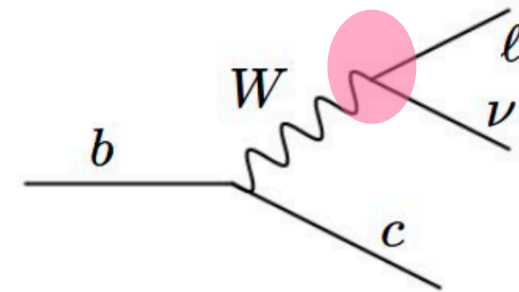
➔ Similar deviation pattern observed in bottom-strange-, bottom-down-, bottom-up-leptons

HINTS IN LEPTON FLAVOUR UNIVERSALITY VIOLATION



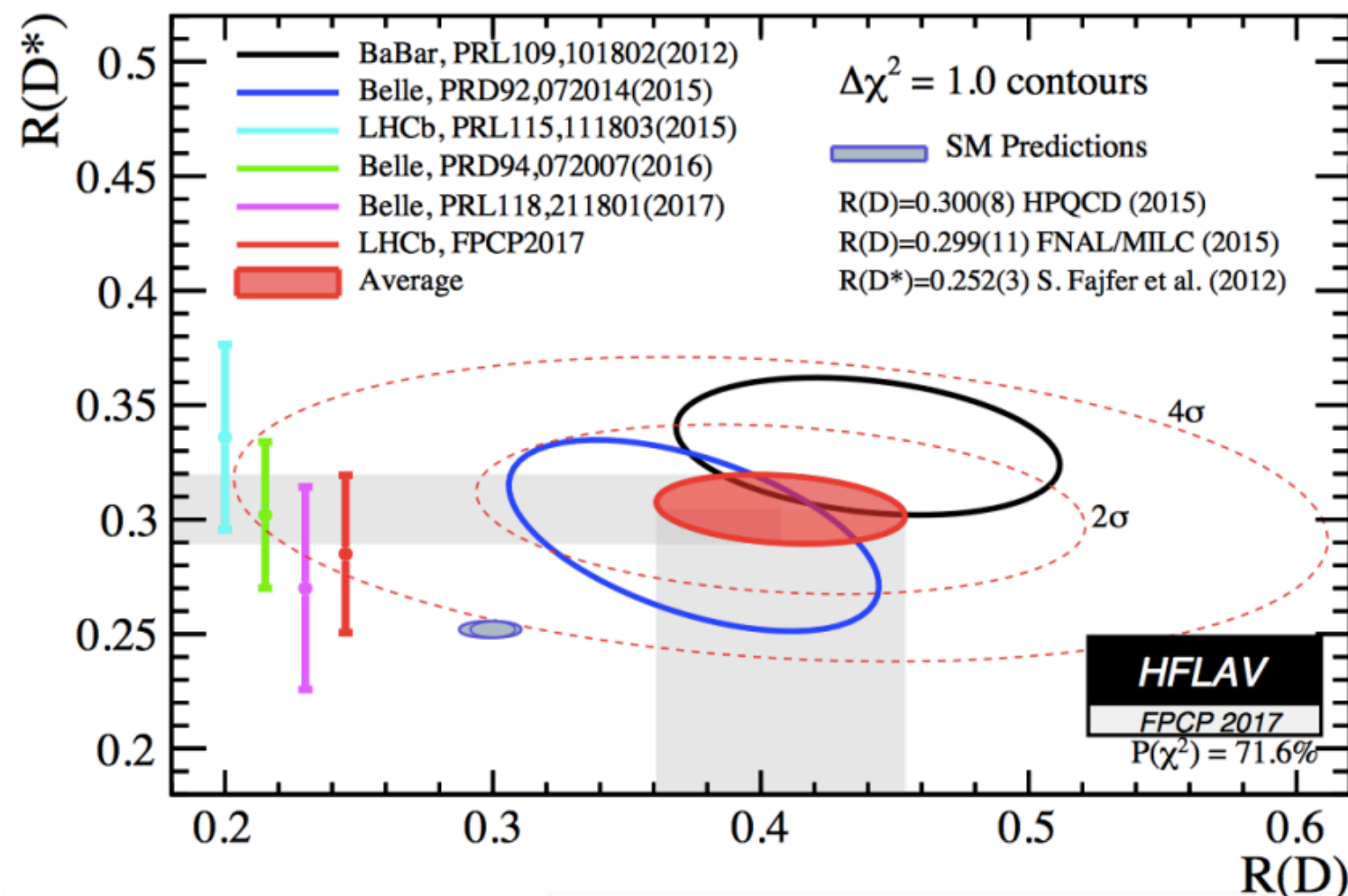
➔ Same tension in the charged current channel (no loops involved)

$$R_{D^*} \equiv \frac{\mathcal{B}(B \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^* \mu \nu_\mu)}$$



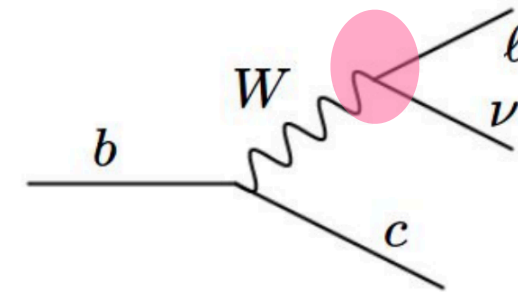
**GLOBAL TENSION WITH THE
SM OF ABOUT 3.1σ**

HINTS IN LEPTON FLAVOUR UNIVERSALITY VIOLATION



➔ Same tension in the charged current channel (no loops involved)

$$R_{D^*} \equiv \frac{\mathcal{B}(B \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^* \mu \nu_\mu)}$$



GLOBAL TENSION WITH THE SM OF ABOUT 3.1 σ

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$

$$a_\mu \equiv ((g - 2)_\mu)/2$$

Lepton magnetic moment $\vec{\mu}$:

$$\vec{\mu} = -g \frac{e}{2m} \vec{s}$$

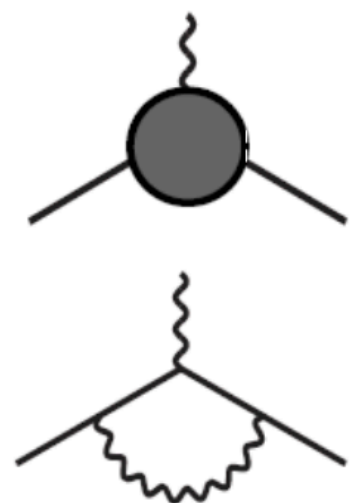
$$\mathcal{H} = -\vec{\mu} \cdot \vec{B}$$

$$(\vec{s} = \frac{1}{2} \vec{\sigma} \text{ (spin)}, \quad g = 2 + 2F_2(0))$$

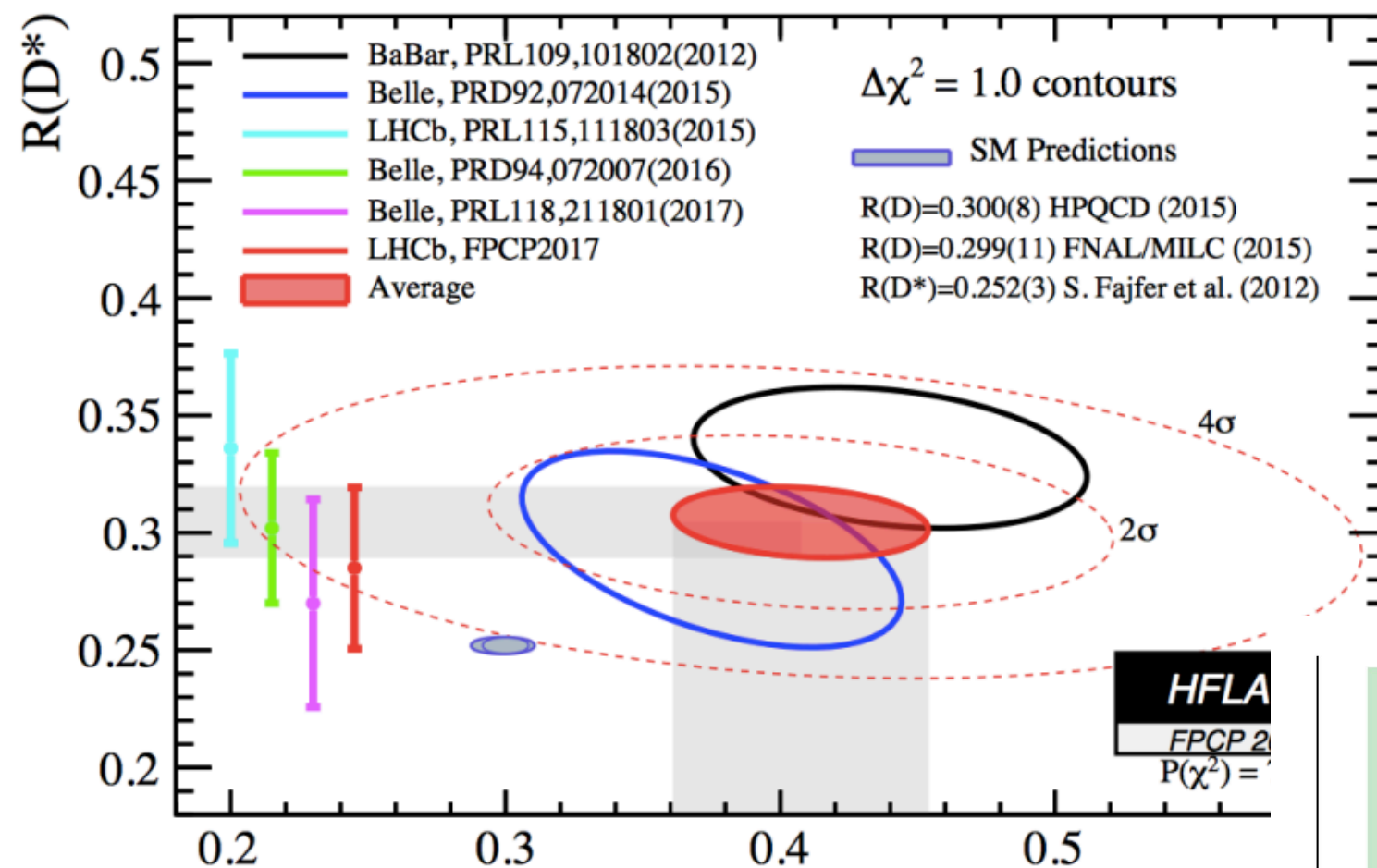
where

$$\bar{u}(p+q)\Gamma^\mu u(p) = \bar{u}(p+q) \left(\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2m} F_2(q^2) \right) u(p)$$

Anomalous magnetic moment: $a \equiv (g - 2)/2 (= F_2(0))$



HINTS IN LEPTON FLAVOUR UNIVERSALITY VIOLATION



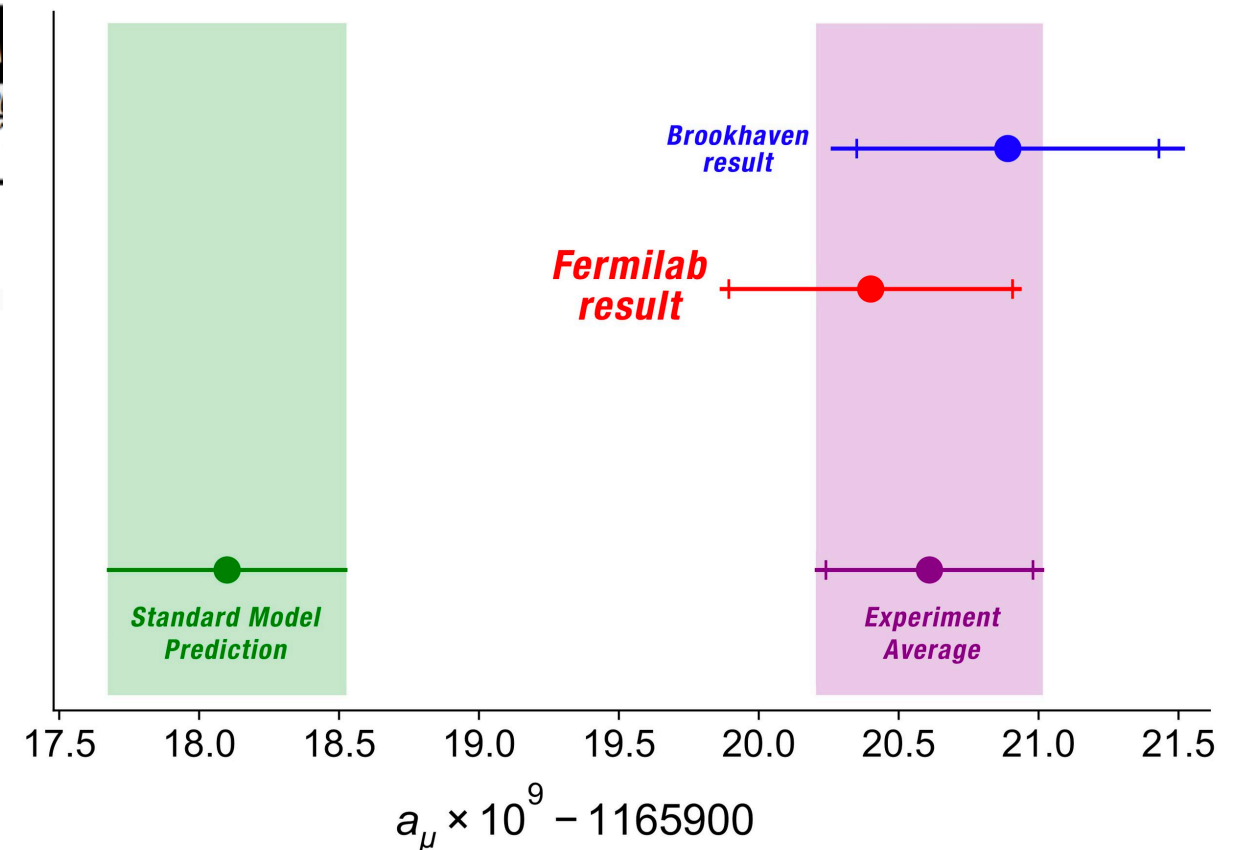
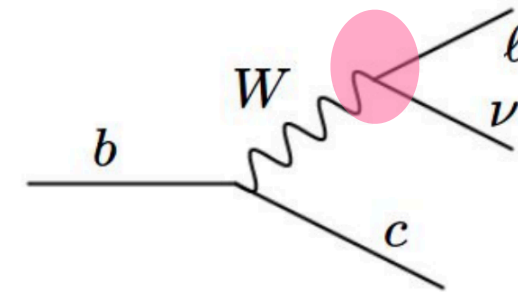
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$

$$a_\mu \equiv ((g - 2)_\mu)/2$$

**COMBINED RESULTS SHOW 4.2 σ
TENSION WITH THE SM**

→ Same tension in the charged current channel (no loops involved)

$$R_{D^*} \equiv \frac{\mathcal{B}(B \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^* \mu \nu_\mu)}$$

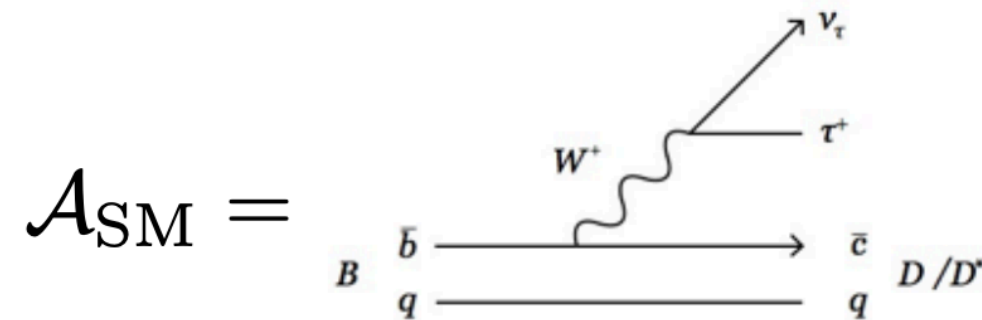


LEPTONS IN THE SM

(1) Flavour changing charged current

$$|C_{\tau}^{\text{NP}}| \gg |C_{\mu}^{\text{NP}}|, |C_e^{\text{NP}}|$$

$$b \rightarrow c \ell \nu_{\ell} \quad (B \rightarrow D^{(*)} \tau \nu, \dots)$$

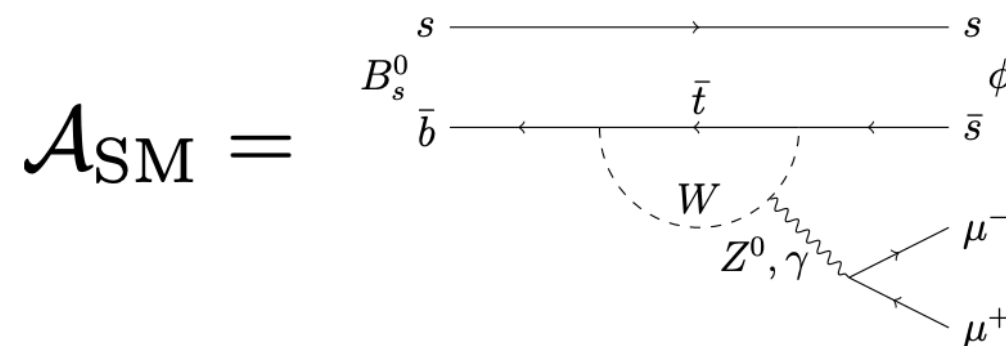


(2) Flavour changing neutral current

$$|C_{\mu}^{\text{NP}}| \gg |C_e^{\text{NP}}|$$

$$(|C_{\mu}^{\text{NP}}| \neq |C_e^{\text{NP}}|)$$

$$b \rightarrow s \ell \ell$$



(3) (g-2) of the muon versus (g-2) of the electron

$$|C_{\mu}^{\text{NP}}| \gg |C_e^{\text{NP}}|$$

SIMPLIFIED MODELS

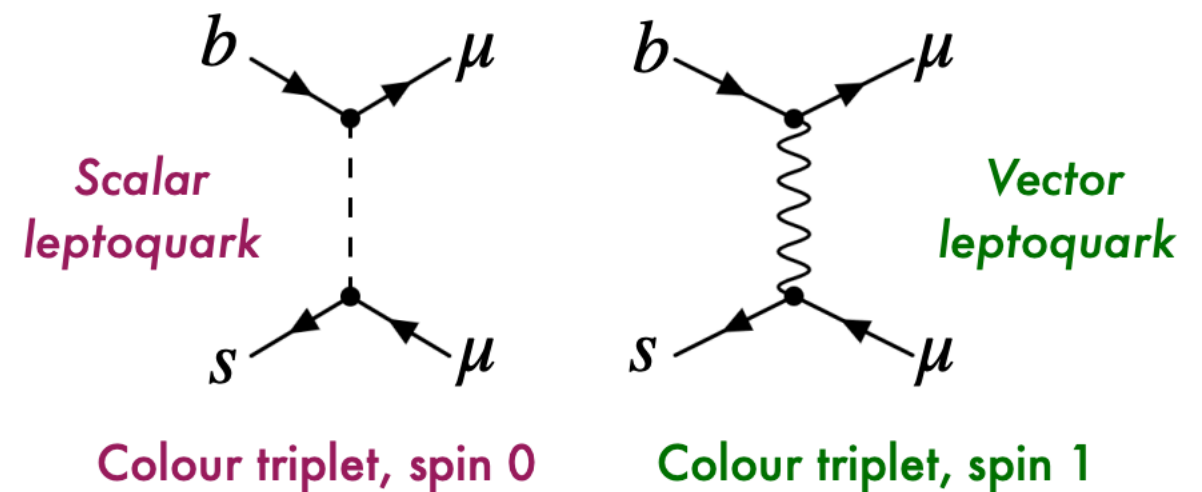
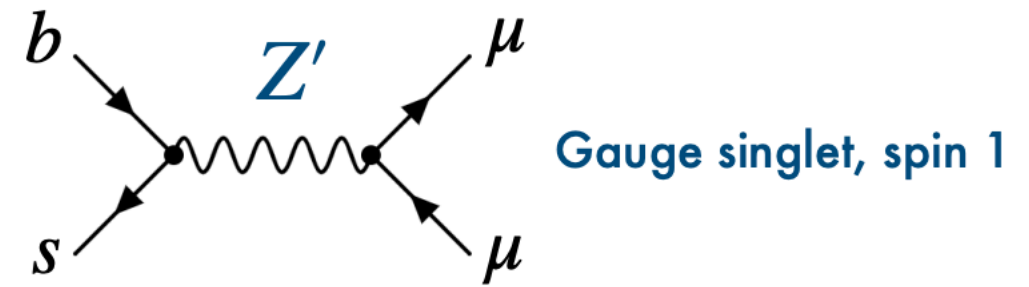
$$\frac{1}{\Lambda^2} (\bar{Q}_L \gamma^\mu Q_L) (\bar{L}_L \gamma_\mu L_L)$$

$$\frac{1}{\Lambda^2} (\bar{Q}_L \gamma^\mu \sigma^A Q_L) (\bar{L}_L \gamma_\mu \sigma^A L_L)$$

$$\Lambda \approx 30 \text{ TeV}$$

$$\frac{\Delta_{bs} \Delta_{\mu\mu}}{m_{Z'}^2} \approx \frac{1}{(30 \text{ TeV})^2}$$

$$\frac{\lambda_{b\mu} \lambda_{s\mu}}{m_\Pi^2} \approx \frac{1}{(30 \text{ TeV})^2}$$



SIMPLIFIED MODELS

$$\frac{1}{\Lambda^2} (\bar{Q}_L \gamma^\mu Q_L) (\bar{L}_L \gamma_\mu L_L)$$

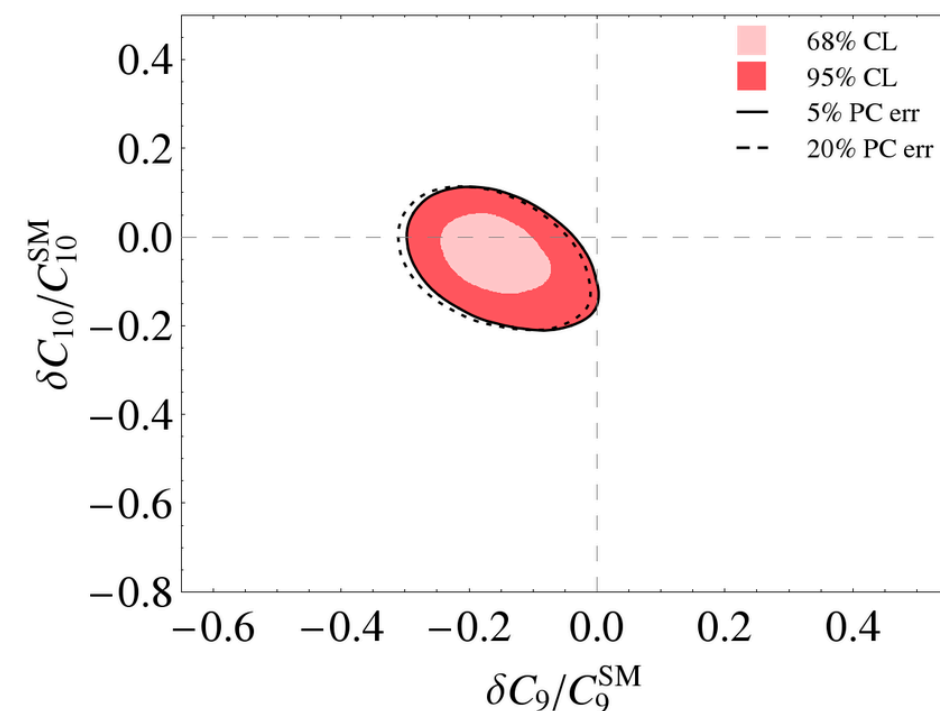
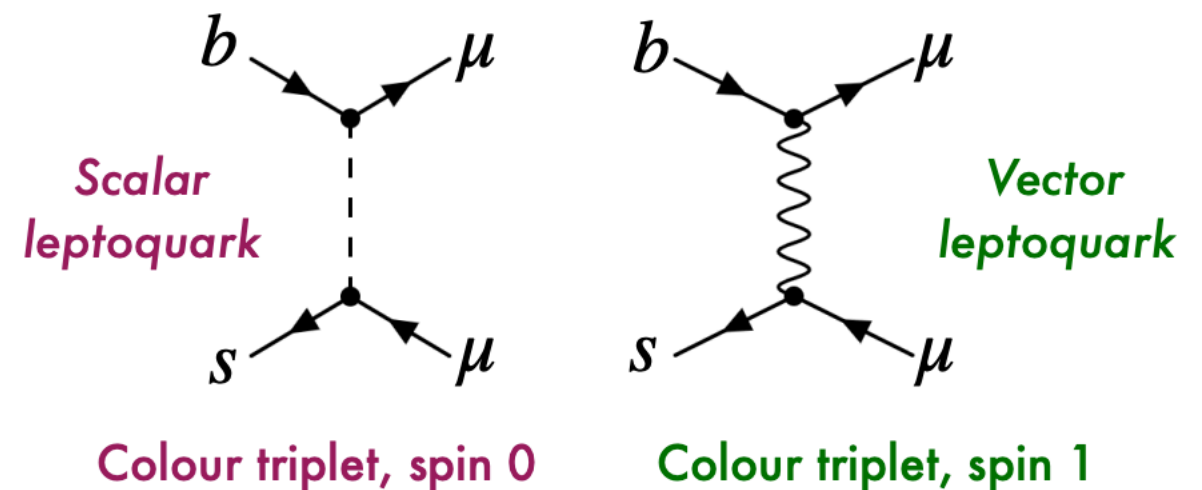
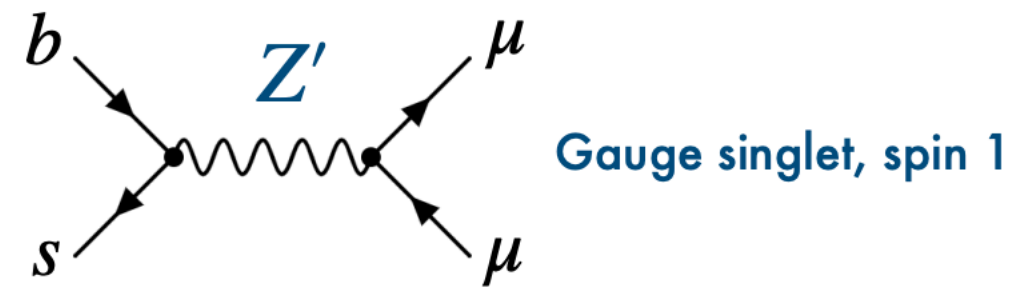
$$\frac{1}{\Lambda^2} (\bar{Q}_L \gamma^\mu \sigma^A Q_L) (\bar{L}_L \gamma_\mu \sigma^A L_L)$$

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EXAMPLE OF A SMEFT FIT
FOCUSSED ON TWO OPERATORS



A FULLY AUTOMATED SIMULATION CHAIN

