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HINTS FOR NEW PHYSICS FROM PRECISION PHYSICS

X SERIES OF MAJORANA LECTURES, PHYSICS DEPT. UNIVERSITY OF NAPLES “FEDERICO II” - 21 APRIL 2021

NEW PHENO CHALLENGES AT THE LHC PRECISION FRONTIER

- **Lecture I:**
  “LHC Run III and the precision frontier”
- **Lecture II:**
  “New frontiers in the determination of the proton structure”
- **Lecture III:**
  “Hints for new physics from precision physics”

AIM: GIVE A PERSONAL PERSPECTIVE ABOUT WHAT I IDENTIFY AS MOST EXCITING CHALLENGES THAT MODERN COLLIDER PHENOMENOLOGY FACES.

DISCLAIMER: IMPOSSIBLE TO GO INTO ALL DETAILS THAT TOPICS DESERVE NOR TO COVER ALL RELEVANT TOPICS.

OUTLINE

- The hunt for new physics at the LHC
- Direct searches
    - ➡ Current status
    - ➡ Looking for a broader Higgs sector
    - ➡ How QCD helps searches
- Indirect searches
    - ➡ The SMEFT framework
    - ➡ Need for simultaneous fits
- Conclusions and outlook

1.

THE HUNT FOR NEW PHYSICS AT THE LHC

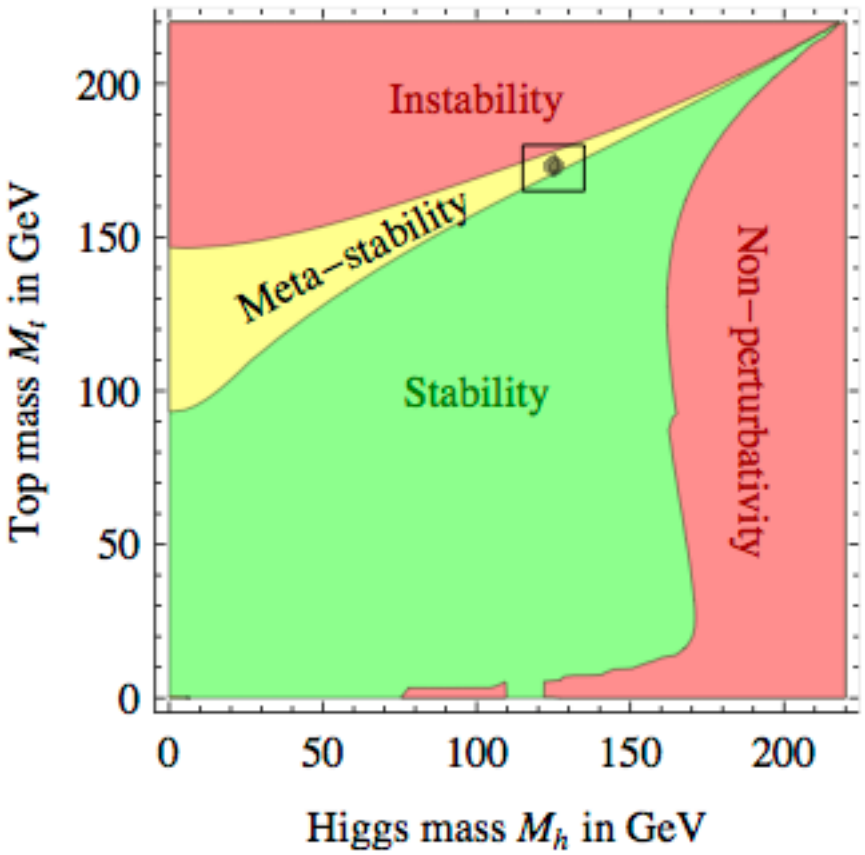
MANY FASCINATING OPEN QUESTIONS

Hierarchy problem:
Huge gap between EW scale (10^2 GeV) and Planck scale (10^{19} GeV)

Higgs Boson

Elementary or composite?
Additional Higgs bosons?

Is the vacuum of the universe stable?



Degrassi et al, 2012

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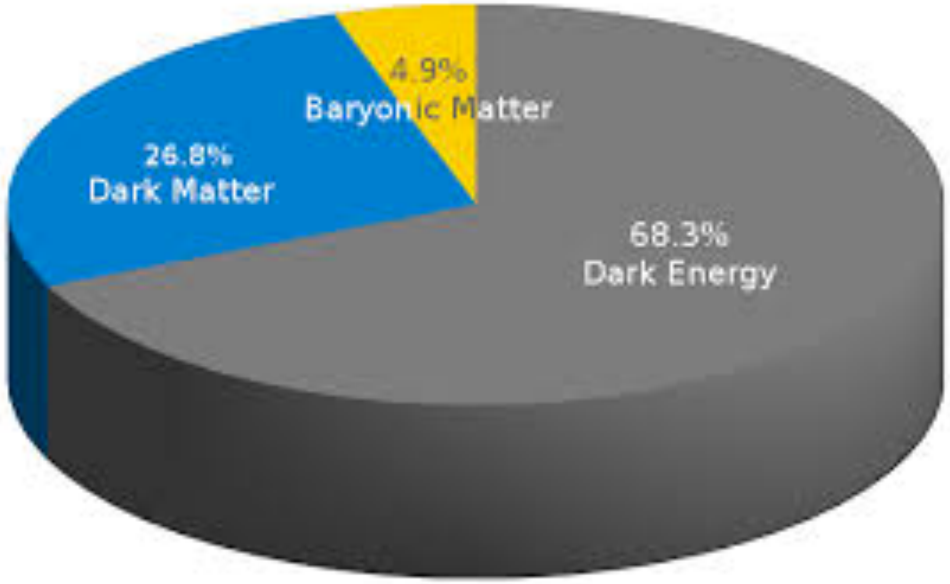
Dark Matter

Weakly-interacting massive particle?
Sterile neutrino?
Extremely light particle (axion)?
Alternative explanations?

Interaction with SM?
Self-interacting?



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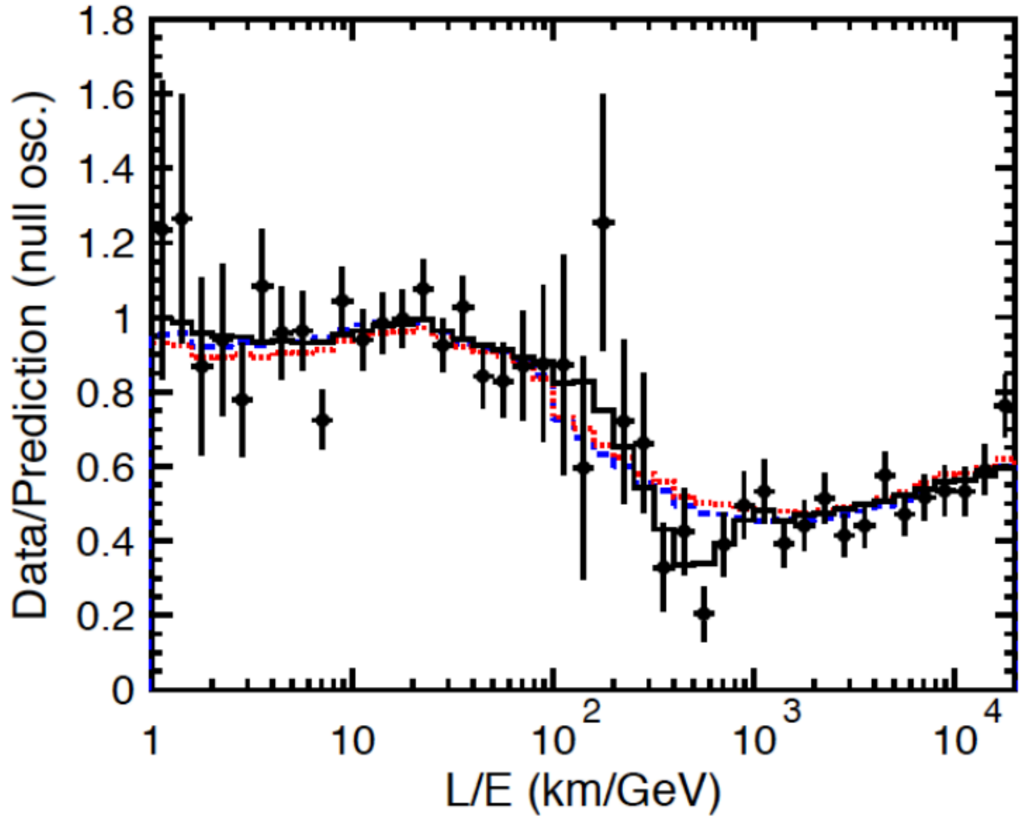
Quarks and leptons

- Are neutrinos Majorana or Dirac fermions?
- Origin of matter-antimatter asymmetry in the Universe?
- Flavour anomaly and (g-2) muon



Super-Kamiokande observation of neutrino oscillations, 2004

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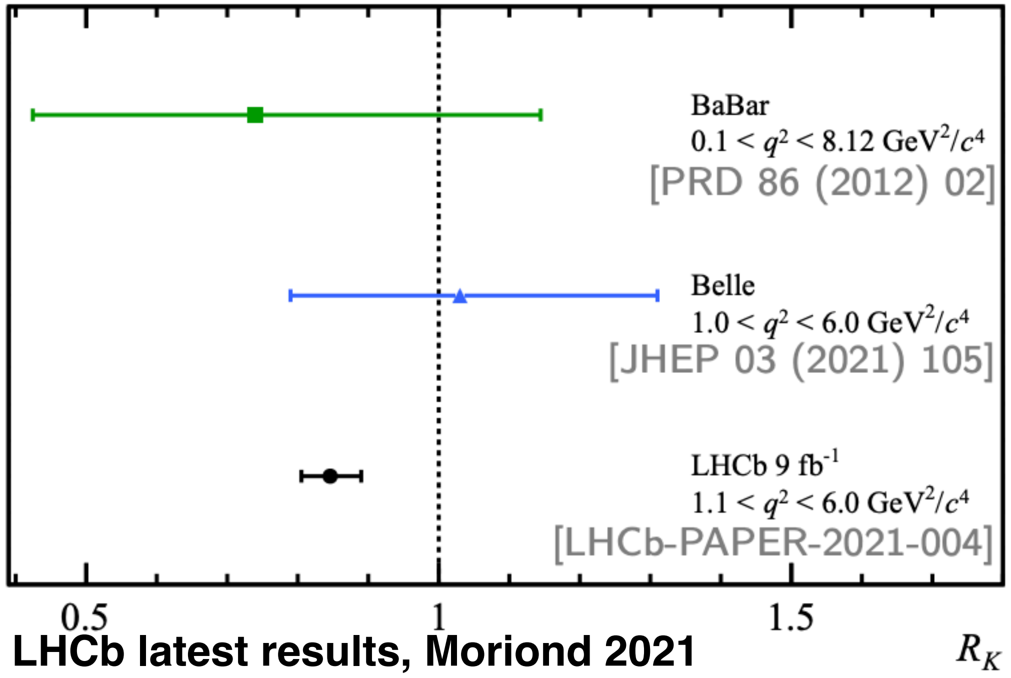
$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^+ \to K^+ \mu^+ \mu^-\right)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^+ \to K^+ e^+ e^-\right)}{\mathrm{d}q^2}\mathrm{d}q^2} \overset{\mathrm{SM}}{=} 1 \pm \mathcal{O}(10^{-2})\ \text{EM correction}^1$$



LHCb latest results, Moriond 2021

Quarks and leptons

Are neutrinos Majorana or Dirac fermions?

Origin of matter-antimatter asymmetry in the Universe?

Flavour anomaly and (g-2) muon

3.1σ tension with SM

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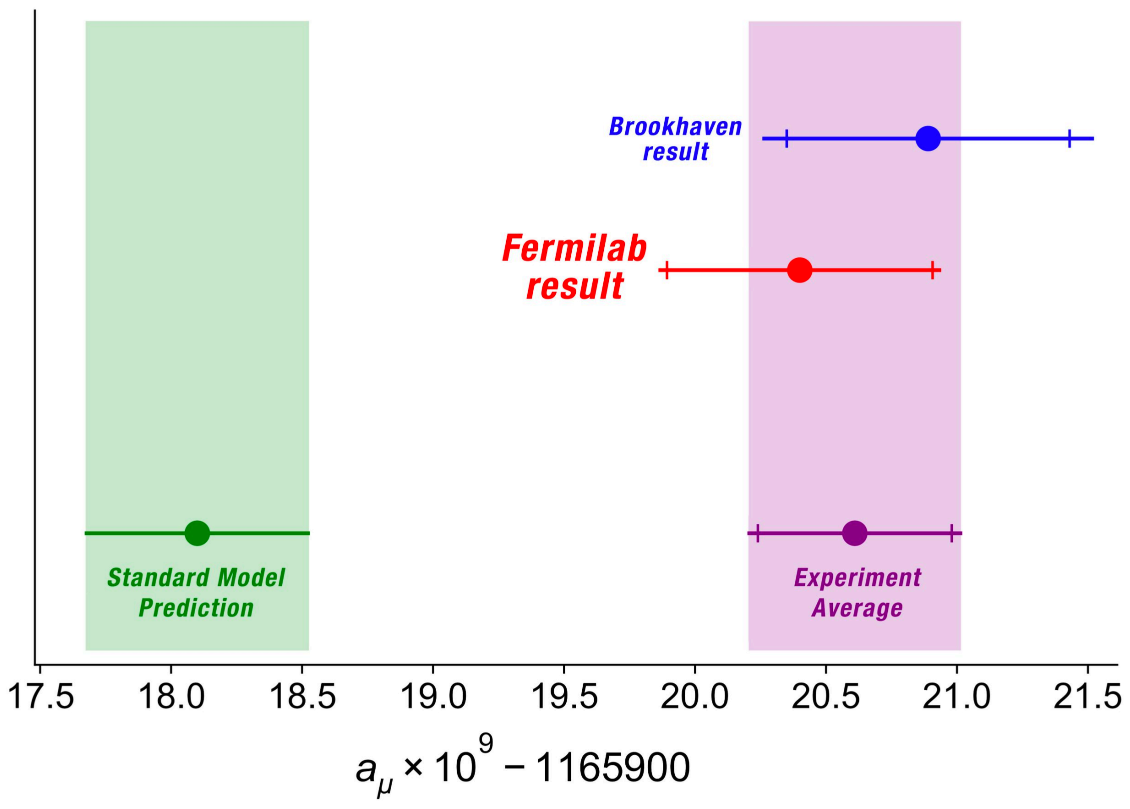


Quarks and leptons

Are neutrinos Majorana or Dirac fermions?

Origin of matter-antimatter asymmetry in the Universe?

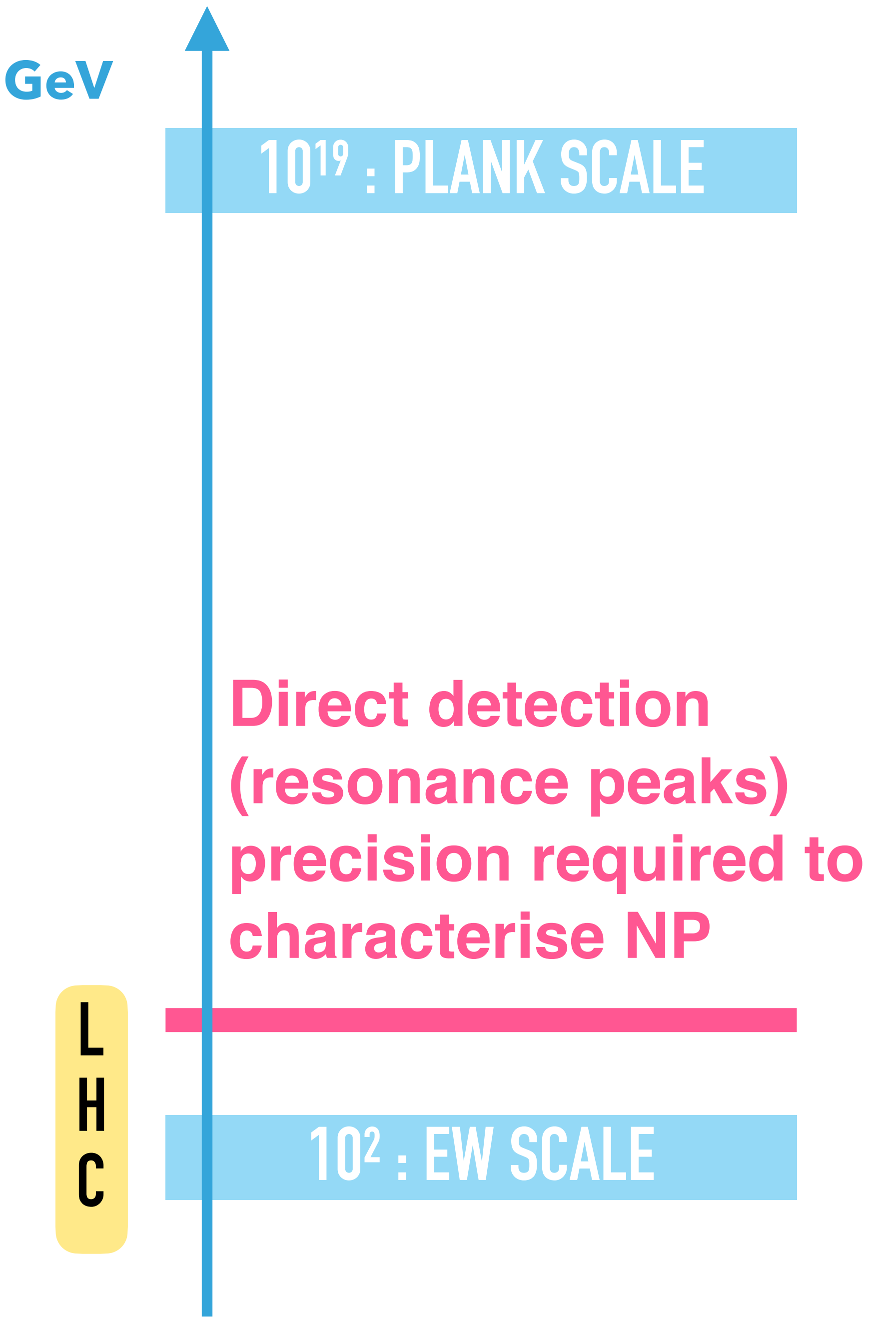
Flavour anomaly and (g-2) muon

4.2σ tension with SM

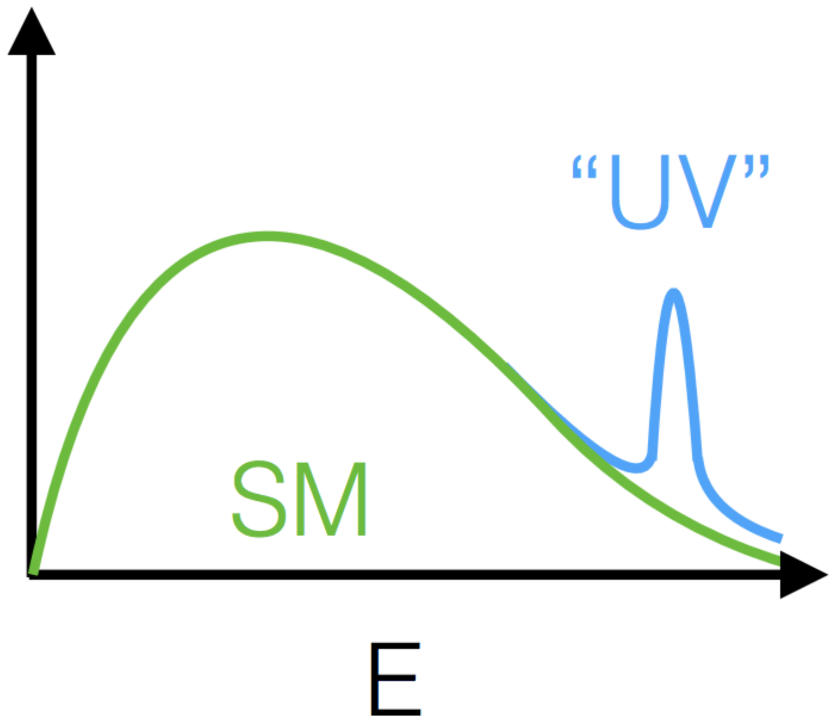
R. Postel, Fermilab/Muon g-s collaboration

ROLE OF PRECISION IN THE HUNT FOR NEW PHYSICS AT THE LHC

- Precision physics not only motivated by need of matching experimental precision
- Precision physics is key ingredient in the quest for new physics



Direct detection (resonance peaks) precision required to characterise NP



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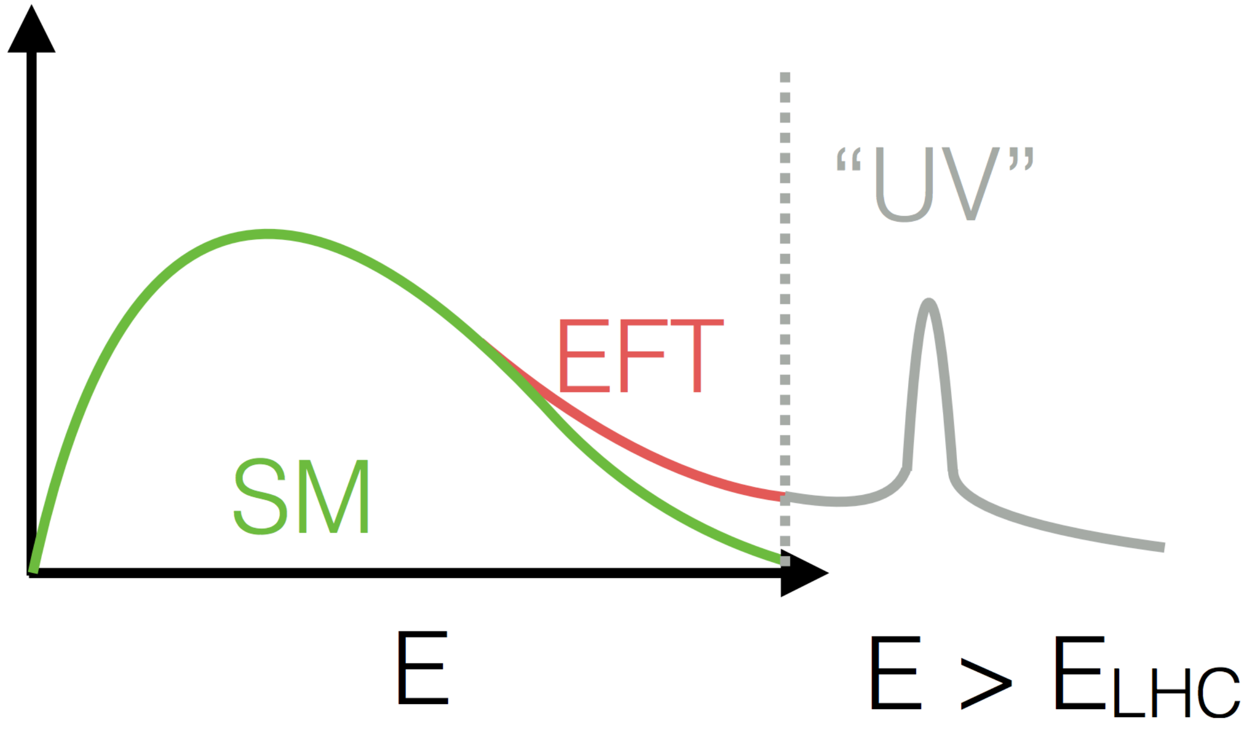
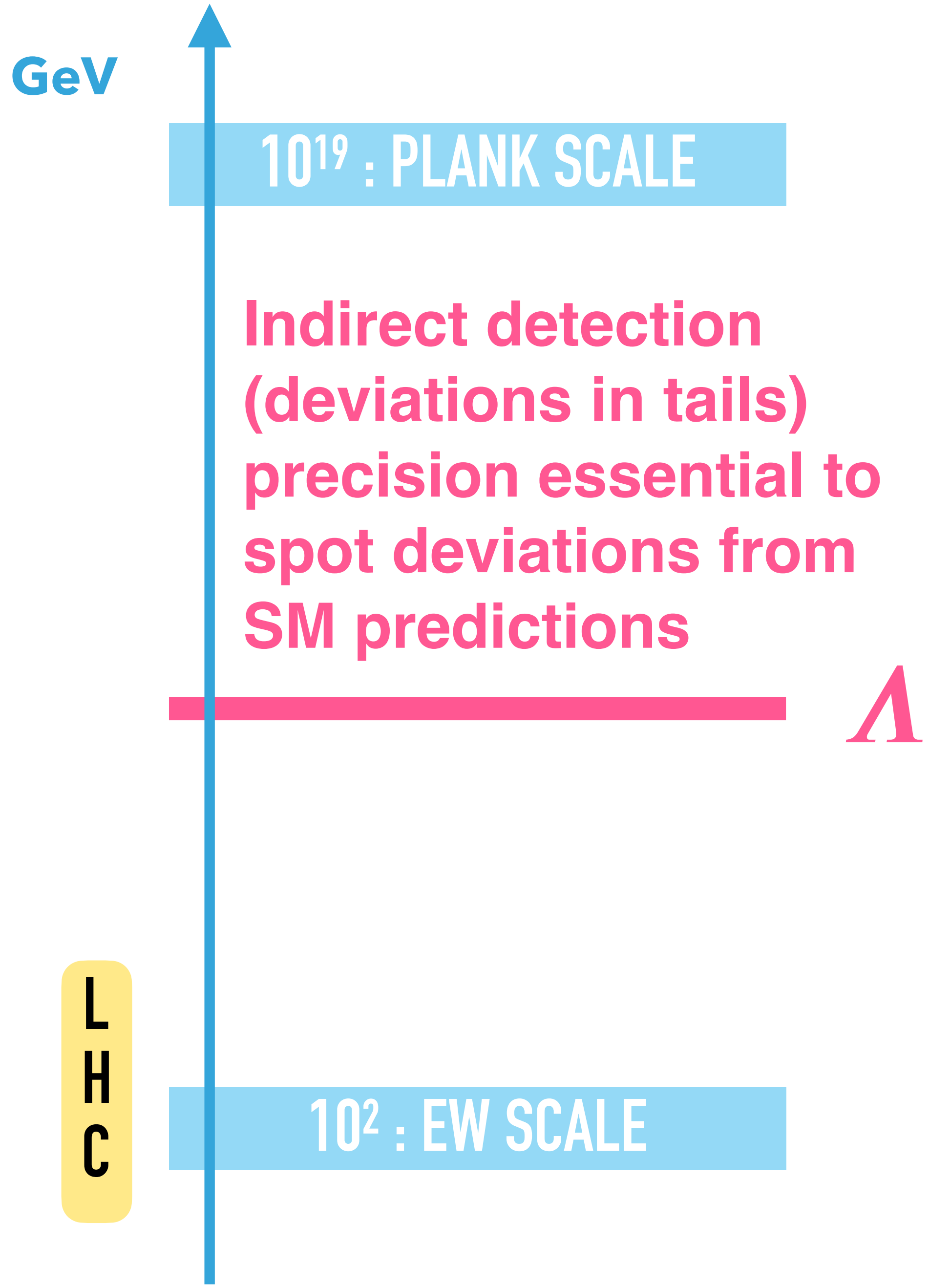




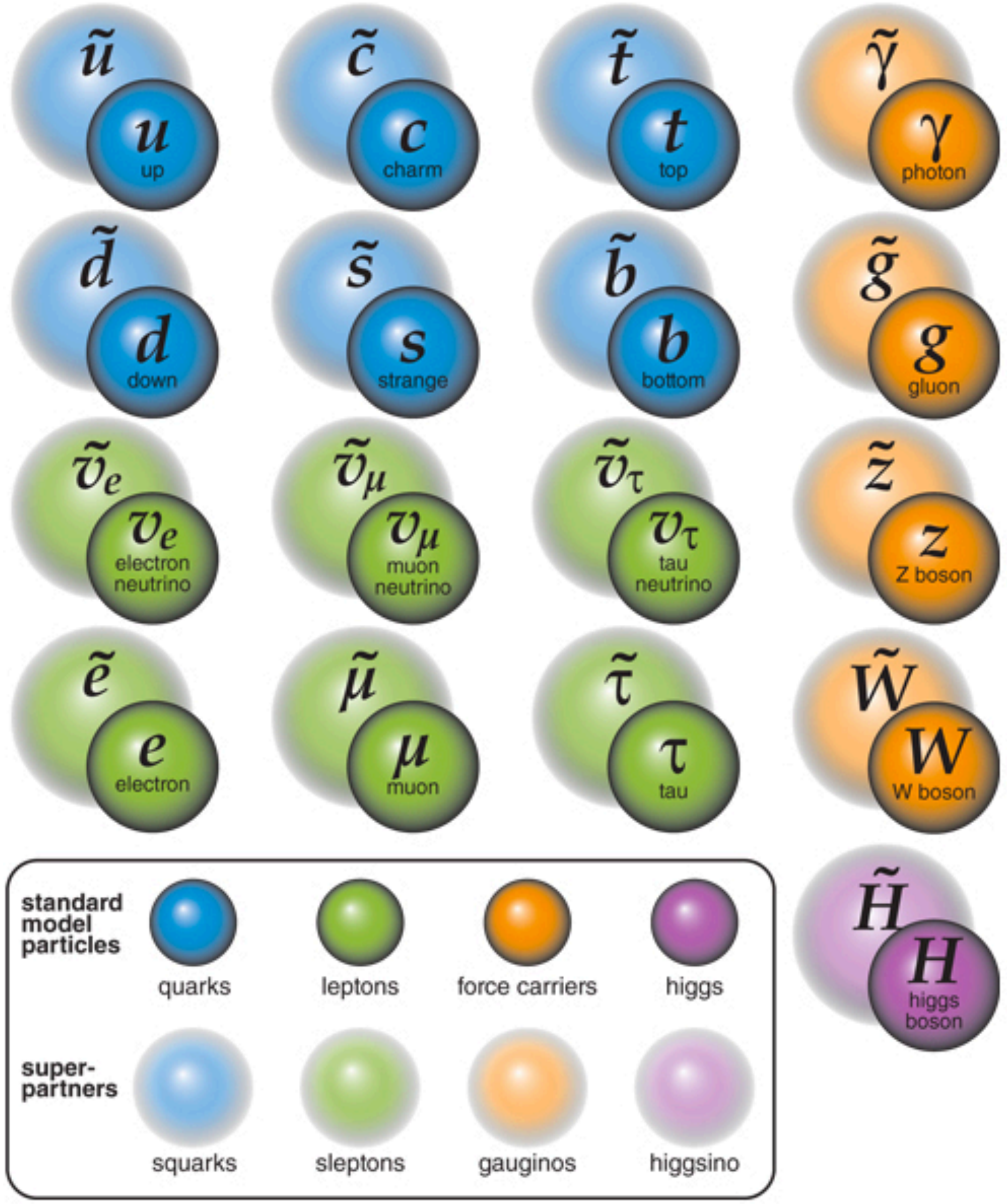
Indirect detection (deviations in tails) precision essential to spot deviations from SM predictions

II.

DIRECT SEARCHES

SEARCH STRATEGIES

- With a collider that is 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

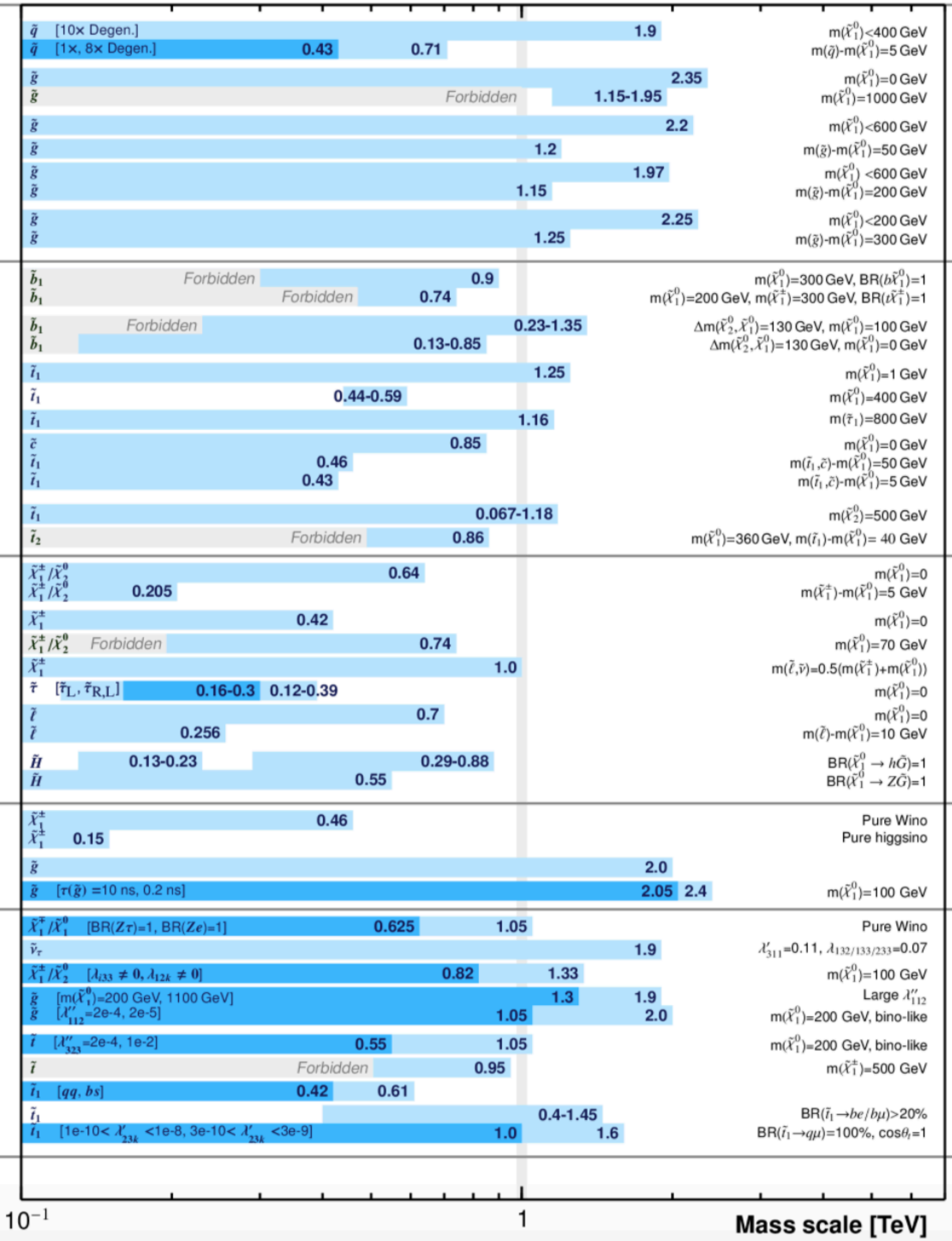


ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

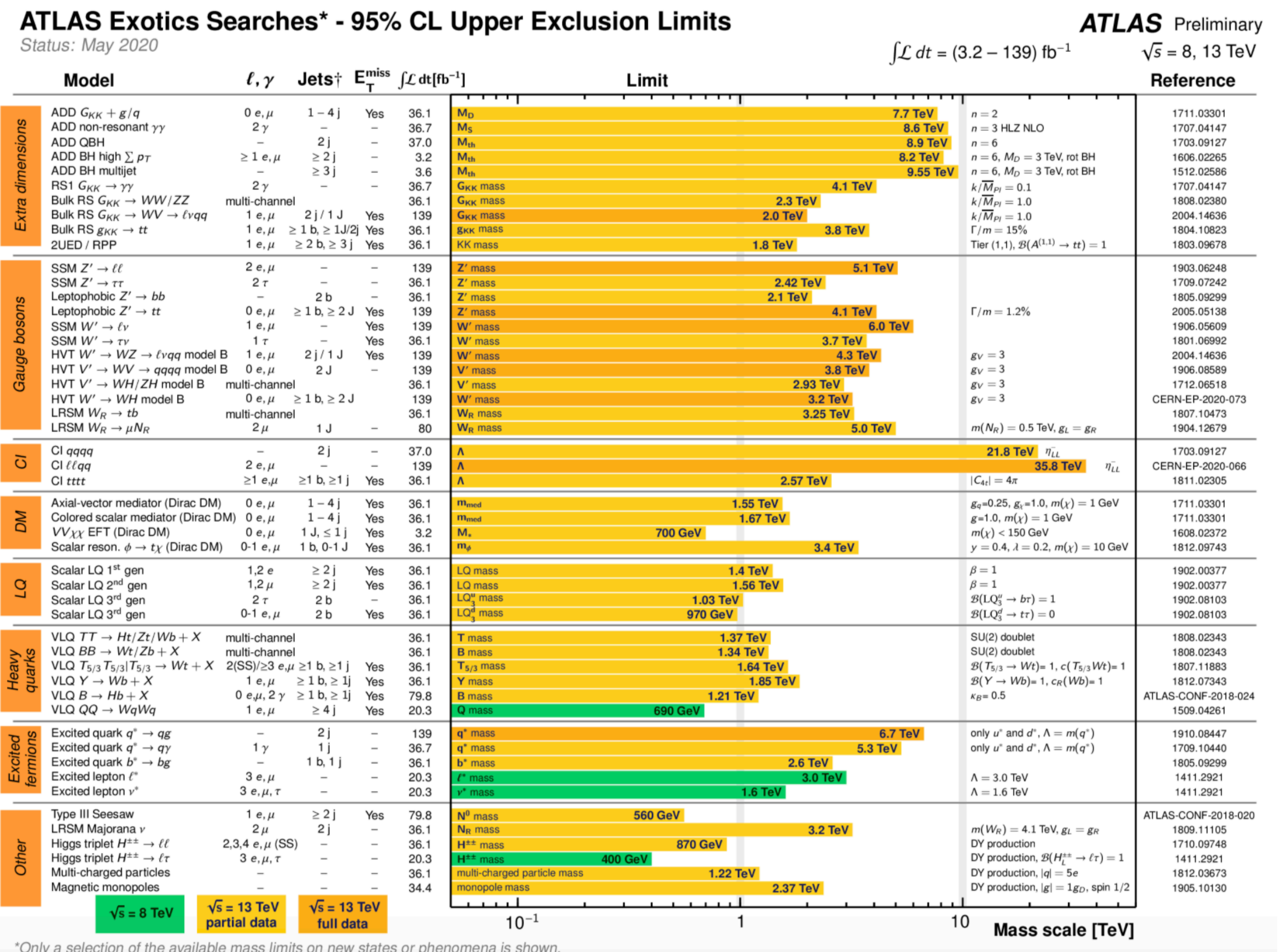
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [10× Degen.] 1.9	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$ 2.35	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		139	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$ 1.97	m($\tilde{\chi}_1^0$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	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
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$ Forbidden 0.74	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1909.08457
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$ 1.25	m($\tilde{\chi}_1^0$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ 0.44-0.59	m($\tilde{\chi}_1^0$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_2^0, \tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	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	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	3 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.64	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 0.42	m($\tilde{\chi}_1^0$)=0	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 0.74	m($\tilde{\chi}_1^0$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$ 1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$ 0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\to bbs$		$\geq 4b$		139	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956

*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.



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

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 $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV η_{LL}^-		CERN-EP-2020-066
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	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	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	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 $T_{5/3}T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$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, $\geq$ 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, $\geq$ 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^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	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, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

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

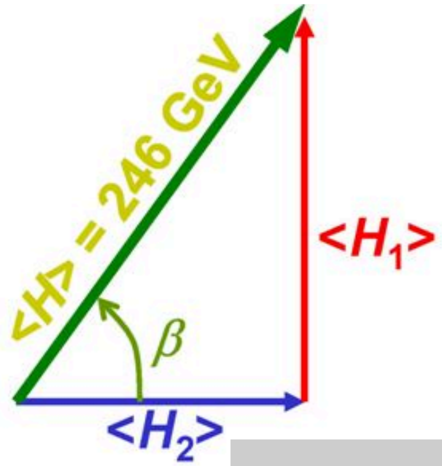
DIRECT SEARCHES FOR A BROADER HIGGS SECTOR

- 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 reacher scalar sector with more doublets or higher representations $\Longrightarrow$ Higgs might be the first of many new scalar states.

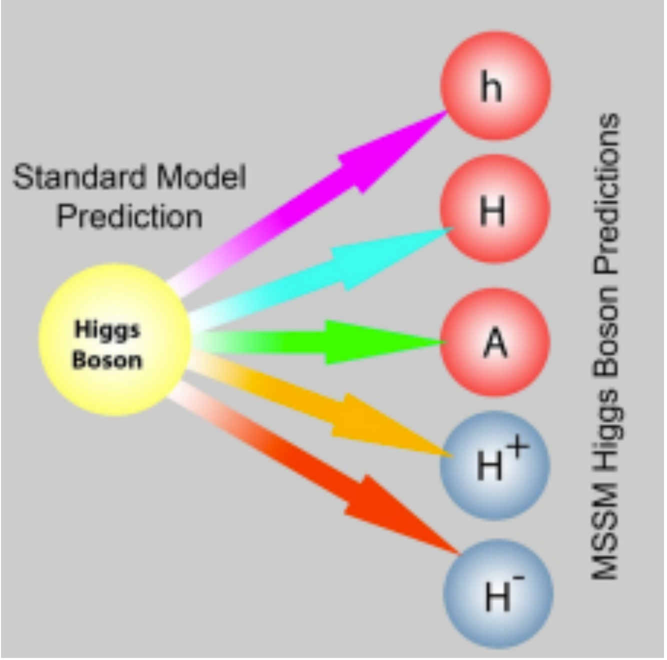
DIRECT SEARCHES FOR A BROADER HIGGS SECTOR

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

- 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 reacher scalar sector with more doublets or higher representations $\Longrightarrow$ 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)

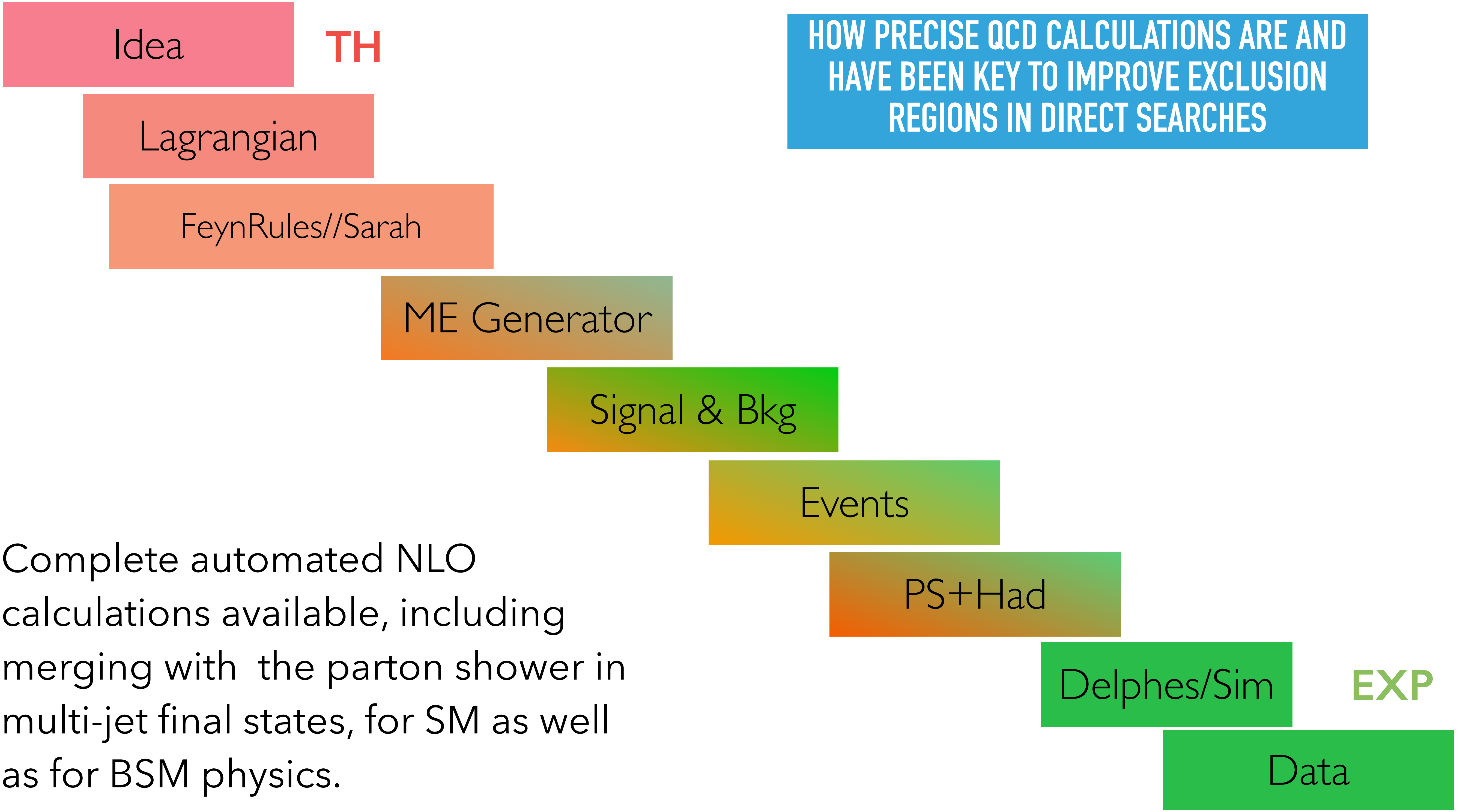


$$\tan\beta = \frac{v_2}{v_1}$$



- Observing a charged Higgs would be unmistakable sign of a broader Higgs sector

A FULLY AUTOMATED SIMULATION CHAIN…



TH

Idea

Lagrangian

FeynRules//Sarah

ME Generator

Signal & Bkg

Events

PS+Had

Delphes/Sim

Data

EXP

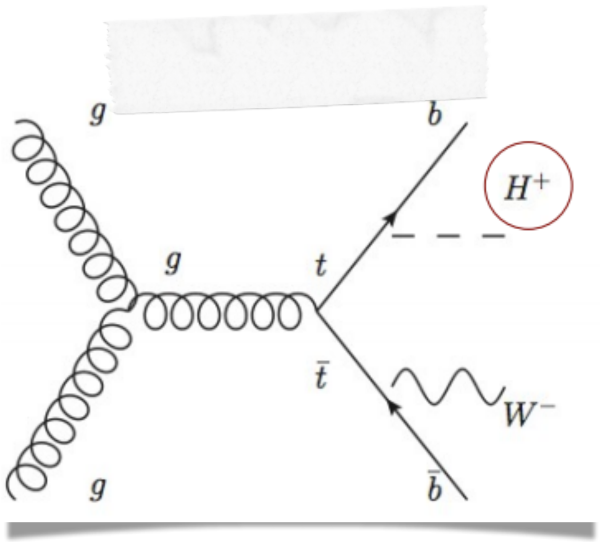
HOW PRECISE QCD CALCULATIONS ARE AND HAVE BEEN KEY TO IMPROVE EXCLUSION REGIONS IN DIRECT SEARCHES

Complete automated NLO calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics.

… TO SEARCH FOR CHARGED HIGGS

Charged Higgs main production mechanisms at the LHC:

LIGHT HIGGS
$m_{H\pm} < m_t$

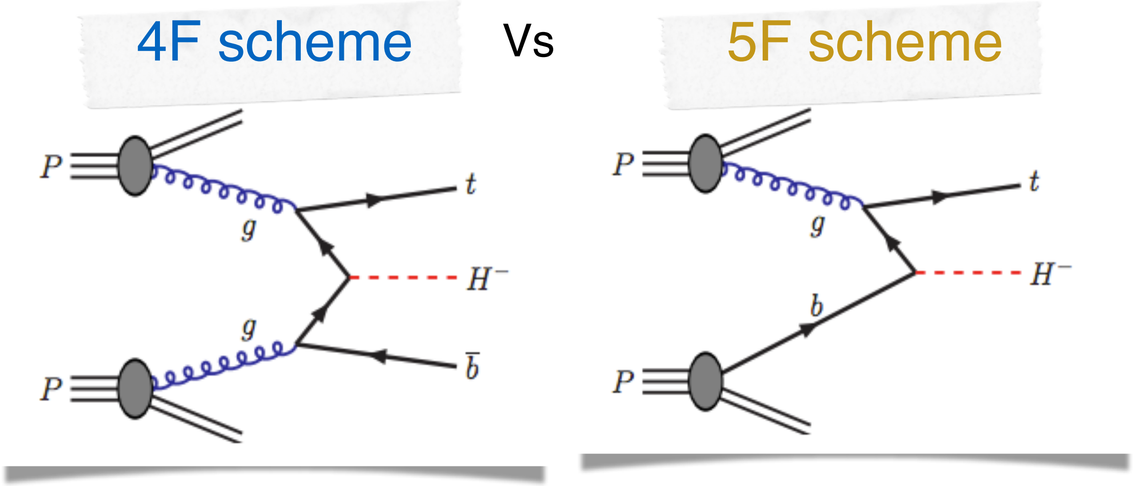


Precise predictions known for some time

INTERMEDIATE RANGE, $m_{H\pm} \sim m_t$

No searches in Run I due to lack of complex mass scheme calculation for resonant tops

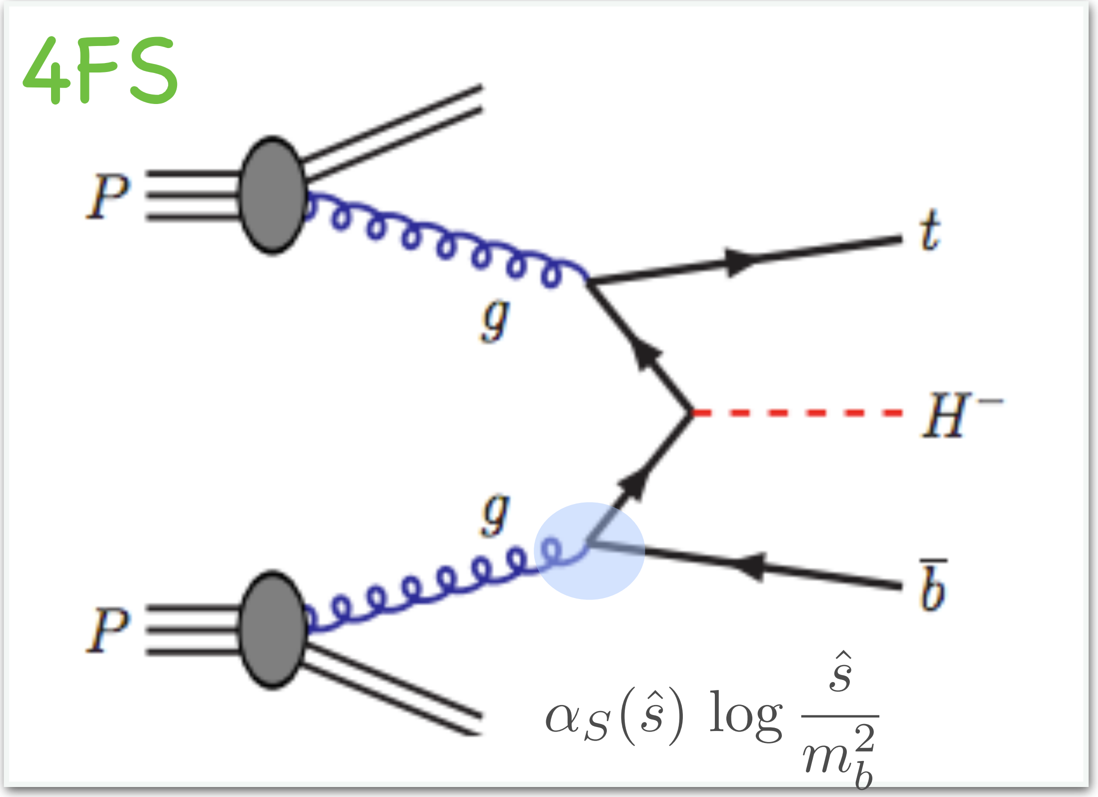
HEAVY HIGGS
$m_{H\pm} > m_t$



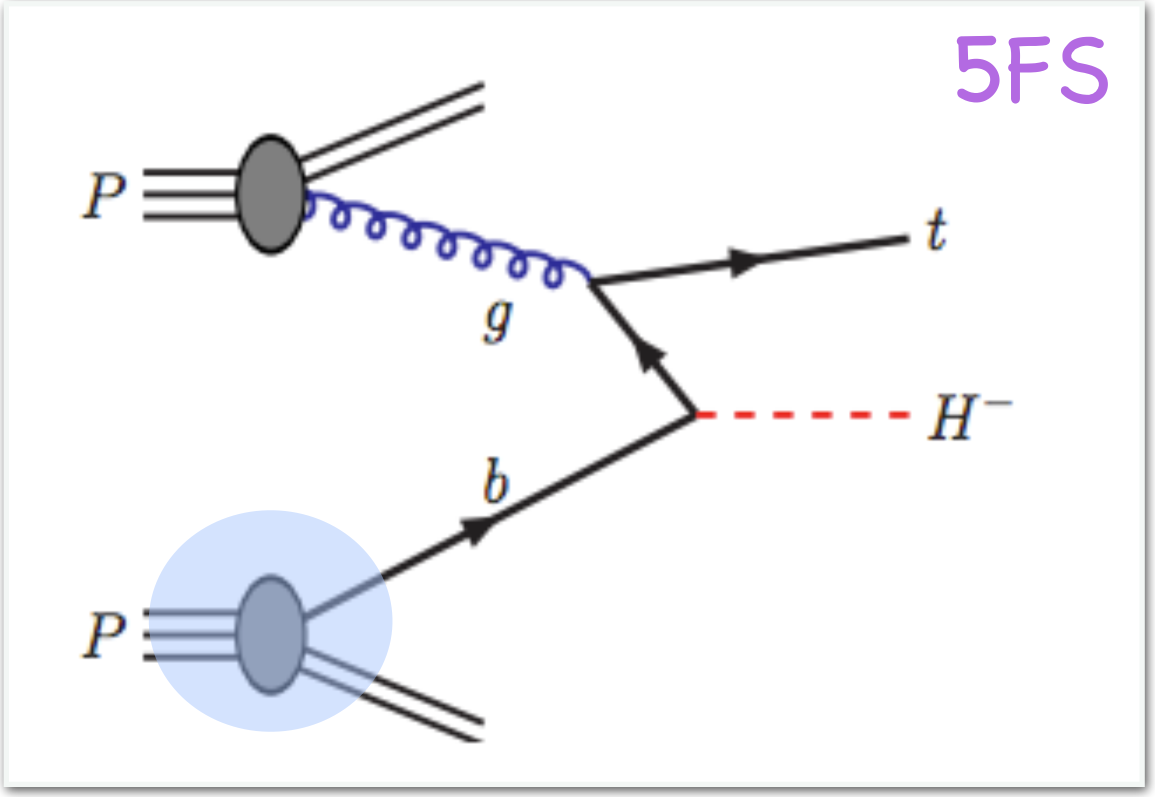
Large theoretical uncertainties due to ambiguity in choice of schemes

STATUS IN 2015

HEAVY CHARGED HIGGS



$\alpha_S(\hat{s}) \log \frac{\hat{s}}{m_b^2}$



✘ It does not resum possibly large $\log(Q/m_b)$, yet it has them explicitly
✘ Computing higher orders is more involved
✔ Mass effects are there at any order
✔ Straightforward implementation in MC event generators at LO and NLO

✔ It resums initial state large logs into b-PDFs leading to more stable predictions
✔ Computing higher orders is easier
✘ p_T of bottom enters at higher orders
✘ Implementation in MC depends on the gluon splitting model in the PS

HEAVY CHARGED HIGGS

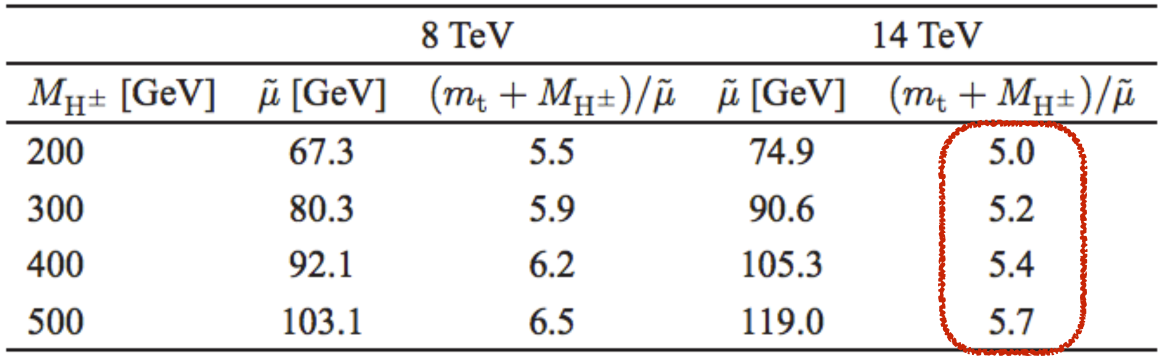
- For total cross section a matching of state-of-the-art 4FS and 5FS calculations performed

  Flechl, Klees, Kramer, Spira, MU, Phys.Rev. D91 (2015)

- All sources of uncertainties included (PDFs, m_b, α_s, scales, y_b) and scale settings for the 5FS motivated by kinematical study in

  Maltoni, Ridolfi, MU, JHEP 1207 (2012) 022

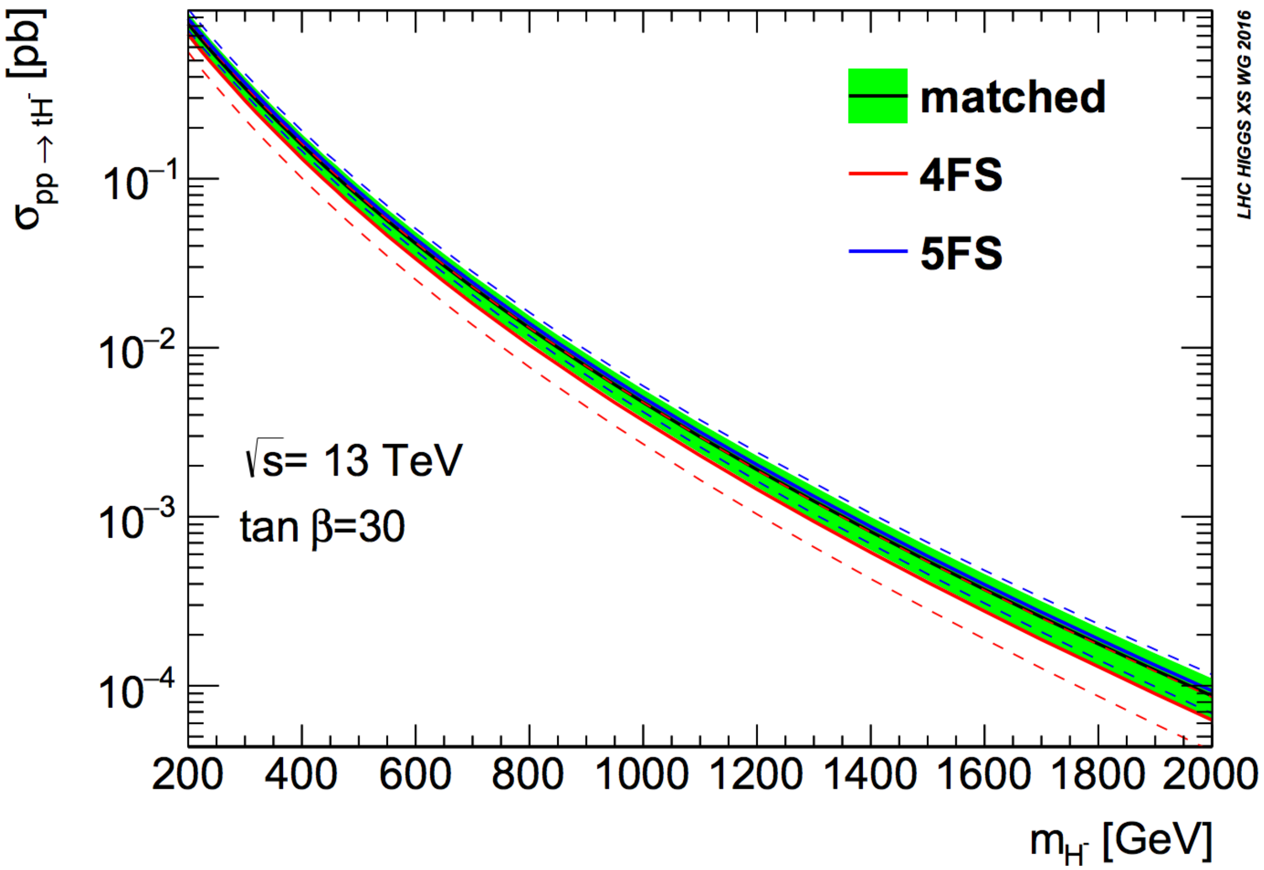
For **inclusive** xsec, where resummation nor b-quark mass effects are essential, 4FS and 5FS pictures are not too different, once judicious scales are chosen



	8 TeV		14 TeV	
$M_{H^\pm}$ [GeV]	$\tilde{\mu}$ [GeV]	$(m_t + M_{H^\pm})/\tilde{\mu}$	$\tilde{\mu}$ [GeV]	$(m_t + M_{H^\pm})/\tilde{\mu}$
200	67.3	5.5	74.9	5.0
300	80.3	5.9	90.6	5.2
400	92.1	6.2	105.3	5.4
500	103.1	6.5	119.0	5.7

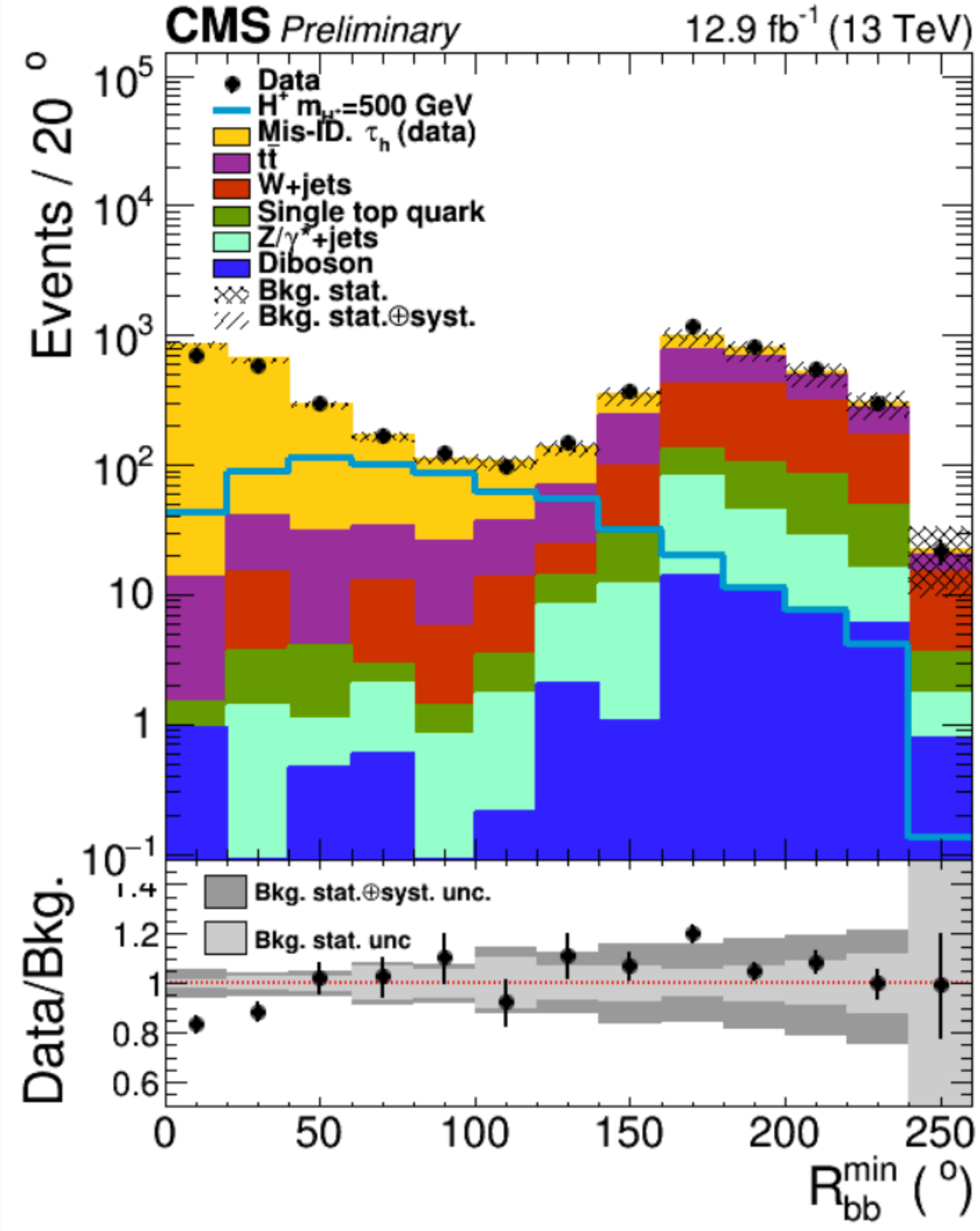
$\approx(m_{H+} + m_t)/5$

4FS versus 5FS



HEAVY CHARGED HIGGS

- To compare signal shapes with respect measured distributions, need fully differential predictions
- Until 2015, MC@NLO [Weydert et al, Eur.Phys.J. C67 (2010)] and POWHEG [Klasen et al, Eur.Phys.J. C72 (2012)] only available in the 5FS and differences between 4FS (leading order MG5_aMCatNLO + K-factor) and 5FS was big source of systematic uncertainty in charged Higgs searches



CMS-CR-2018-389

HEAVY CHARGED HIGGS

Implementation of 2HDM and charged Higgs production in the 4FS and 5FS schemes in the automatic framework provided by MadGraph5_aMC@NLO

Degrande, MU, Wiesemann, Zaro JHEP 1510 (2015)

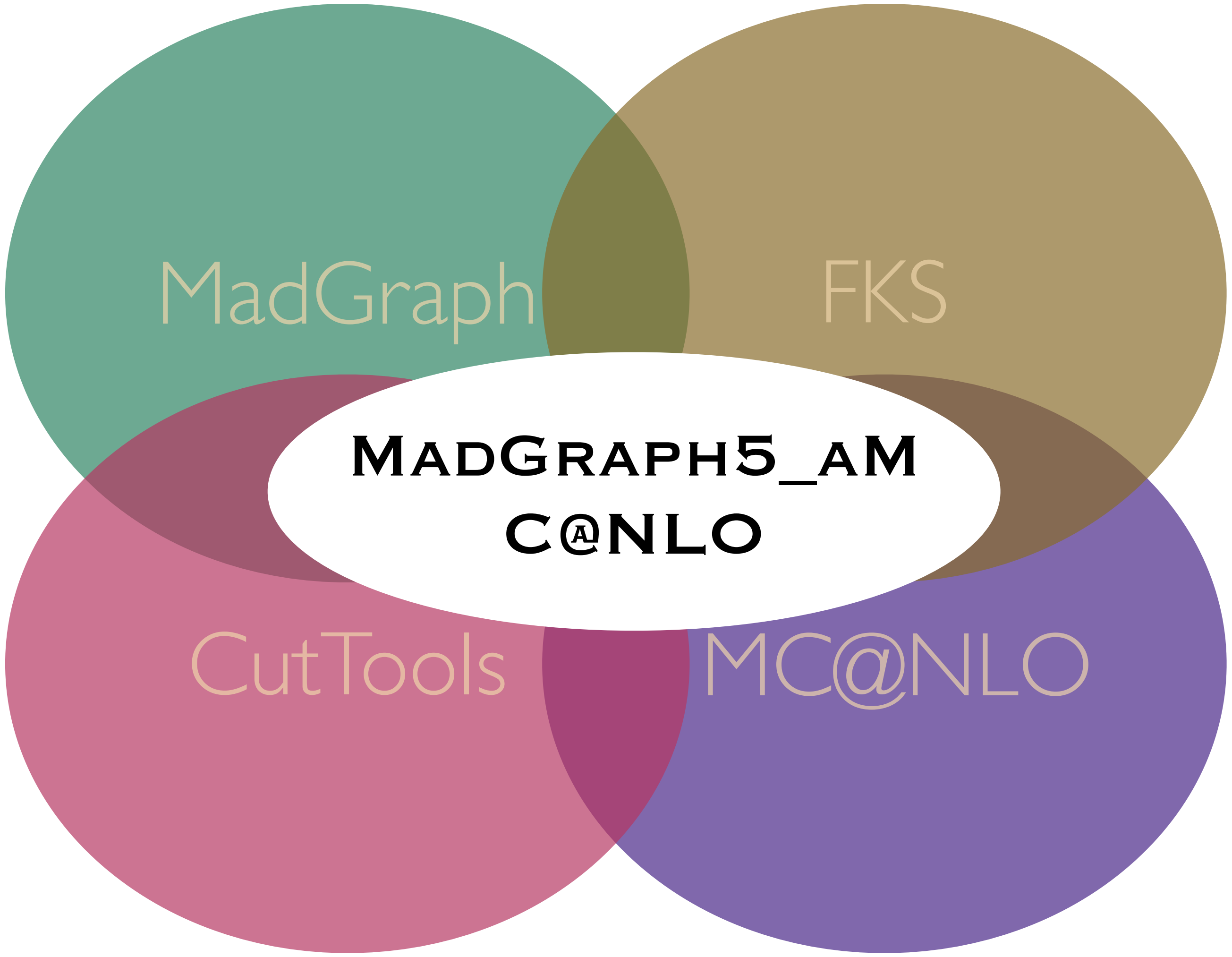
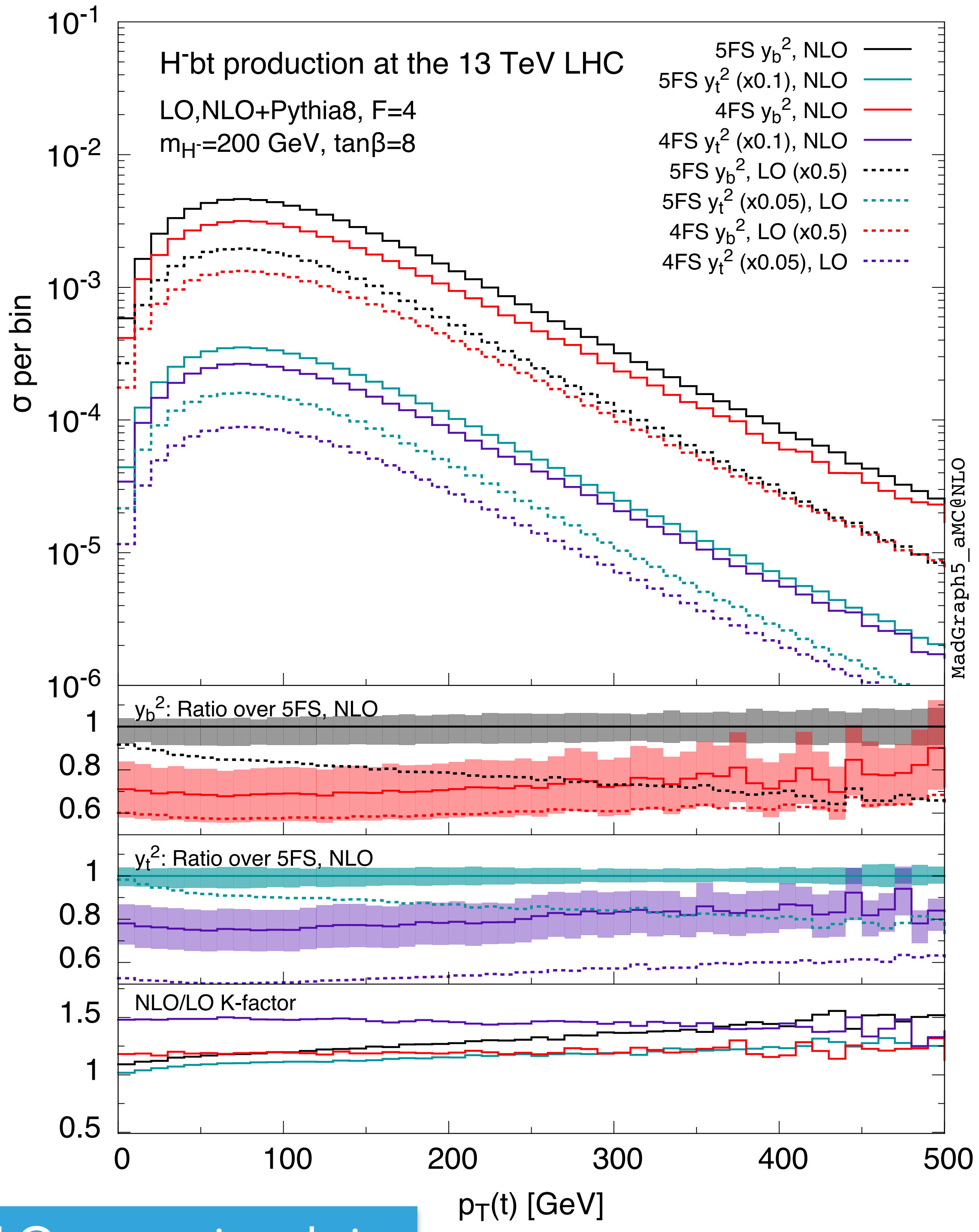


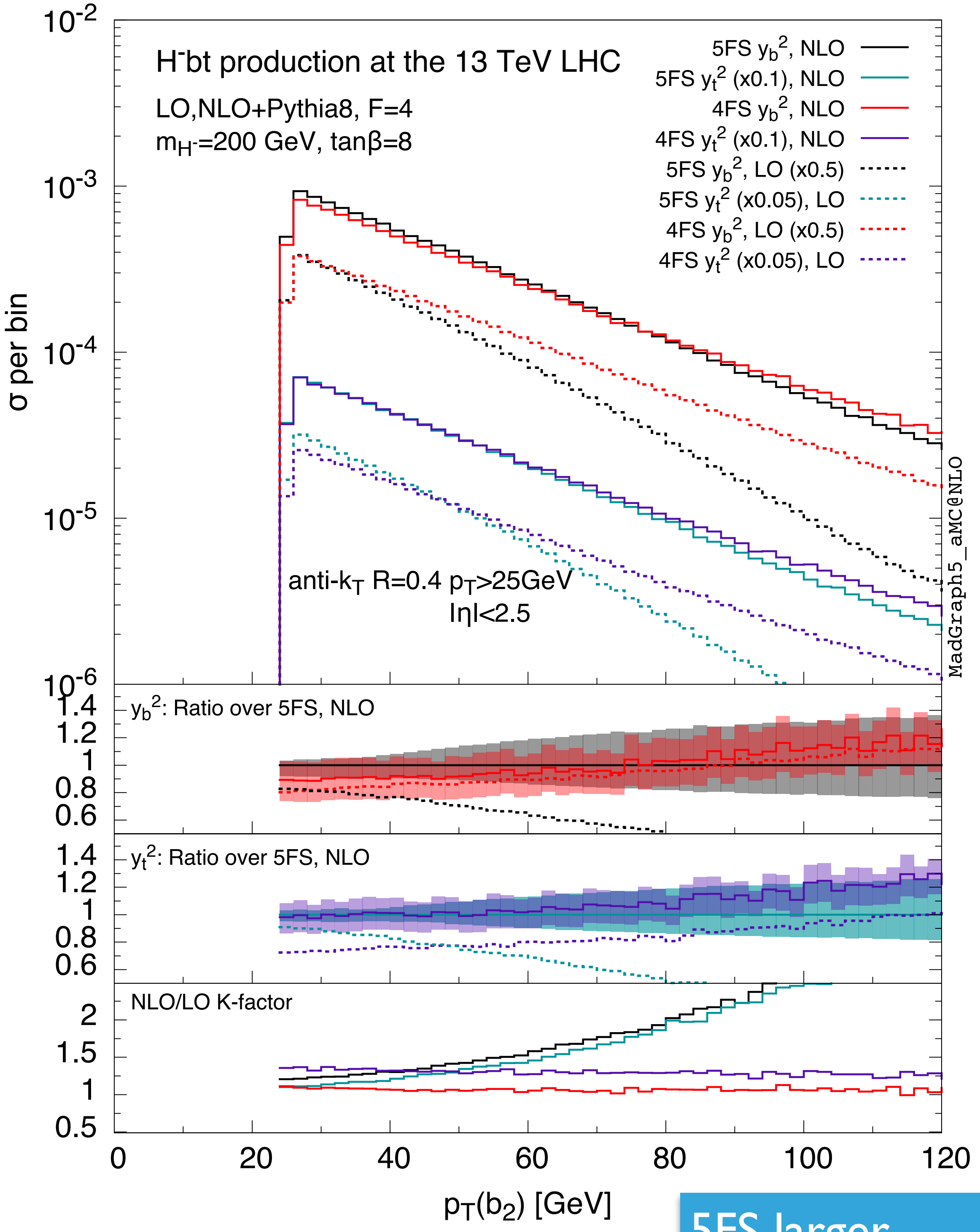
Illustration by M. Zaro

- NLO results: FKS method for IR subtraction and OPP integral-reduction procedure for one-loop matrix elements
- NLO+PS: MC@NLO method
- Scale and PDF uncertainties included
- Models resulting into a set of rules (UFO) are now generated automatically [C.Degrande 1406.3030]
- R2 and UV counter-terms automatically generated. Tested and validated in the 2HDM case

Alwall, Frederix, Frixione, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Hirschi, Zaro arXiv:1405.0301

HEAVY CHARGED HIGGS

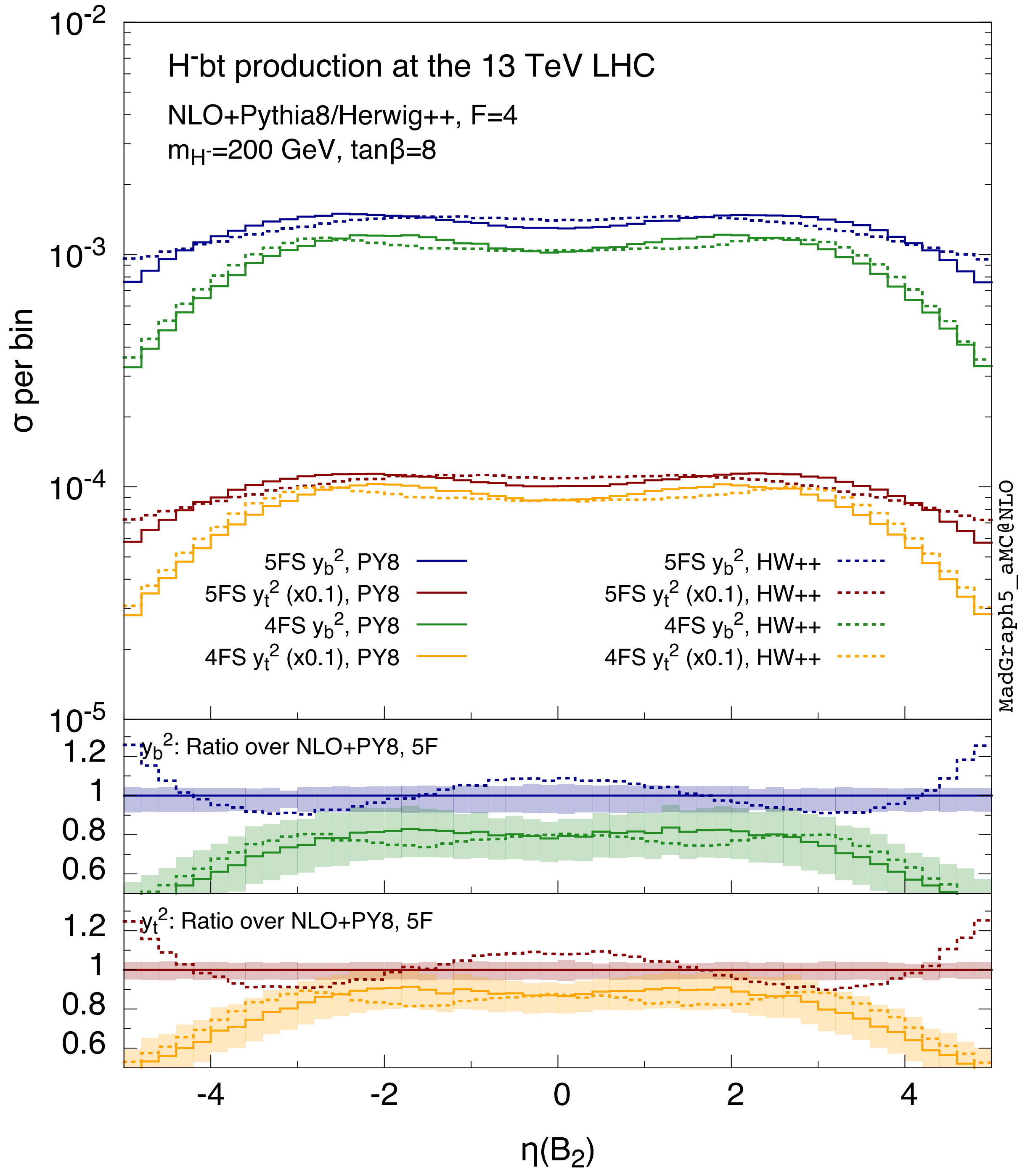


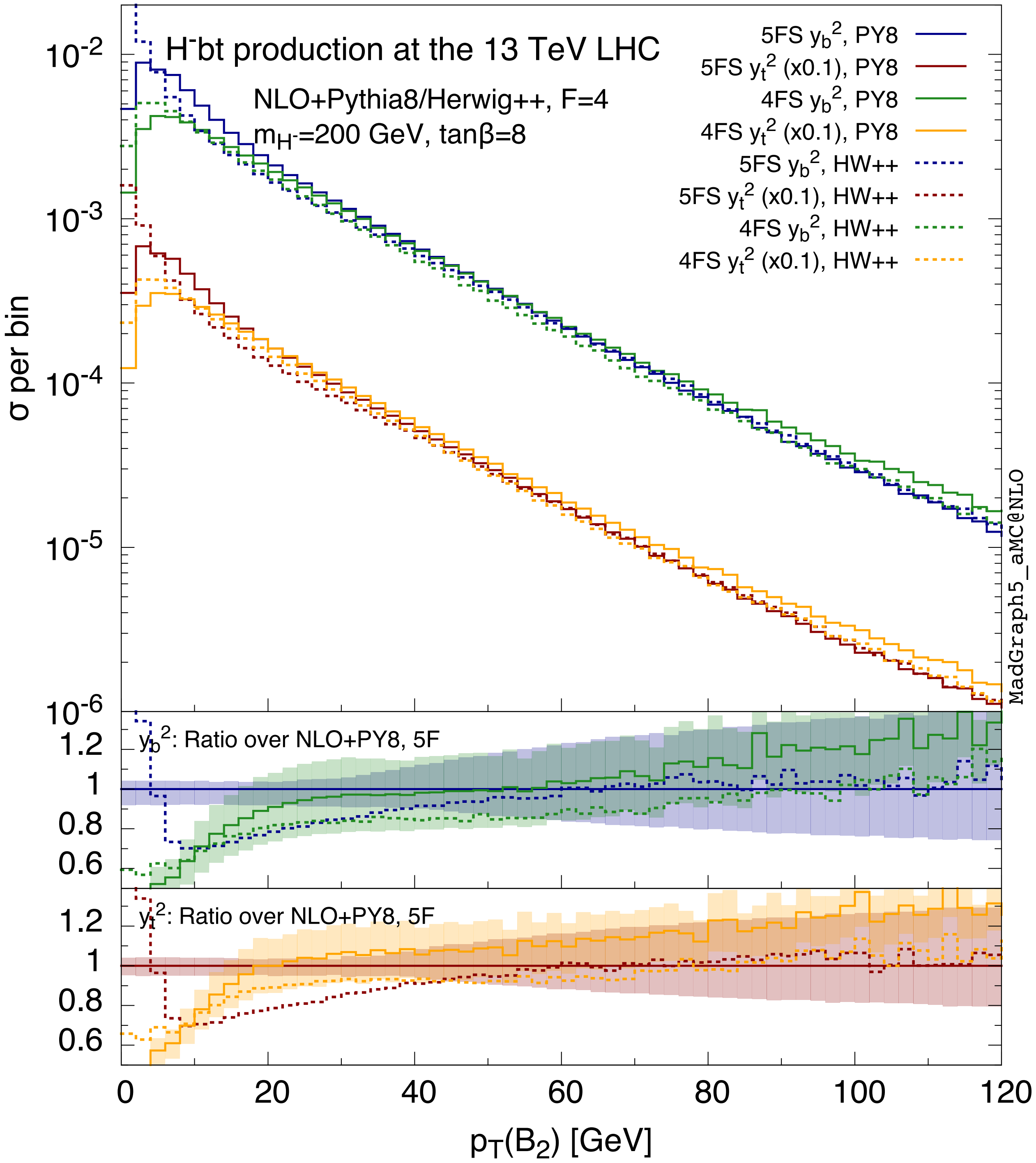


NLO corrections bring 4FS and 5FS close for inclusive observables

5FS larger uncertainties and K-factor

HEAVY CHARGED HIGGS

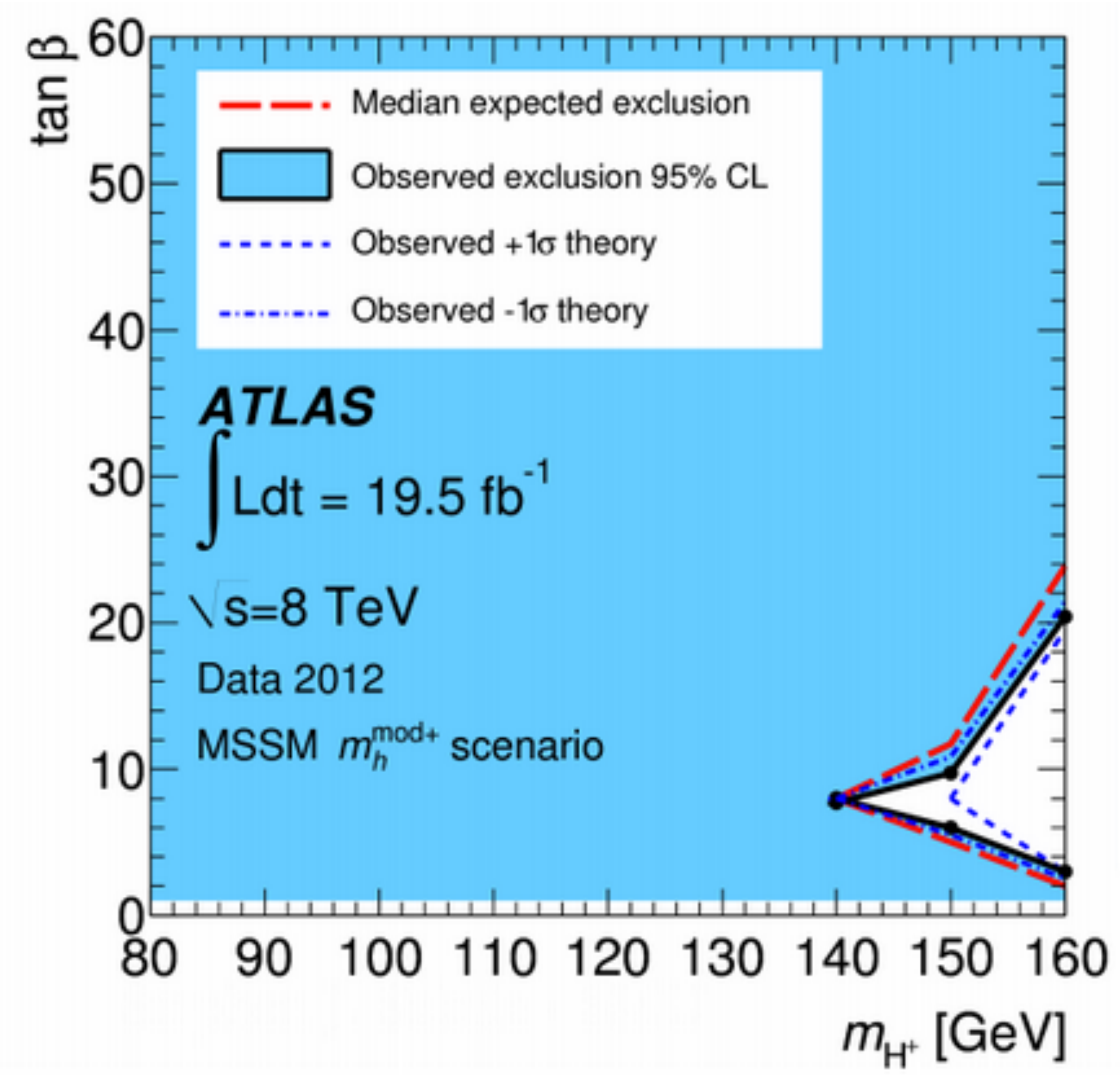




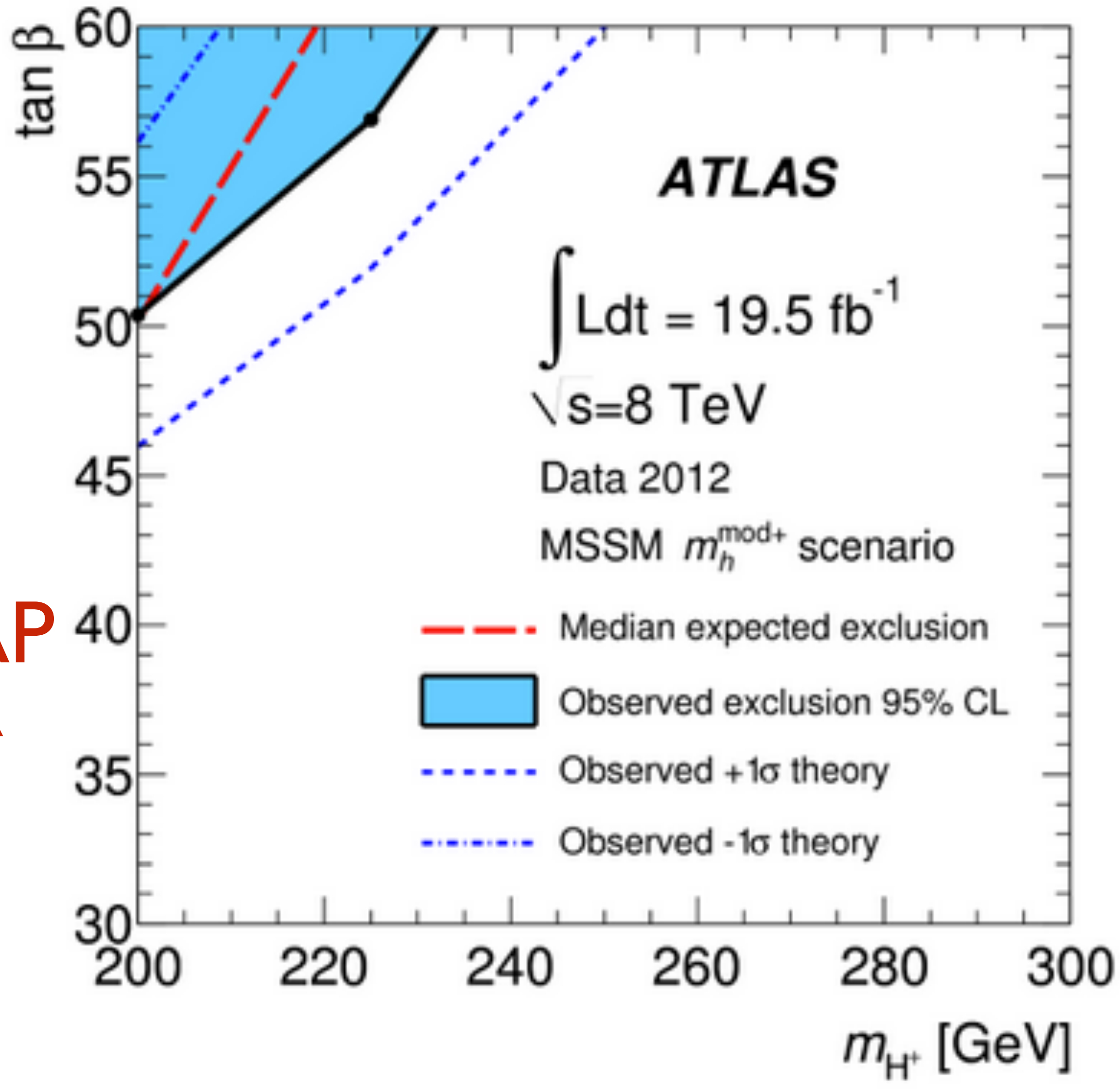
5FS exhibit stronger dependence on the Parton Shower for b-exclusive observables

4FS to be preferred for observables exclusive in b

INTERMEDIATE MASS CHARGED HIGGS



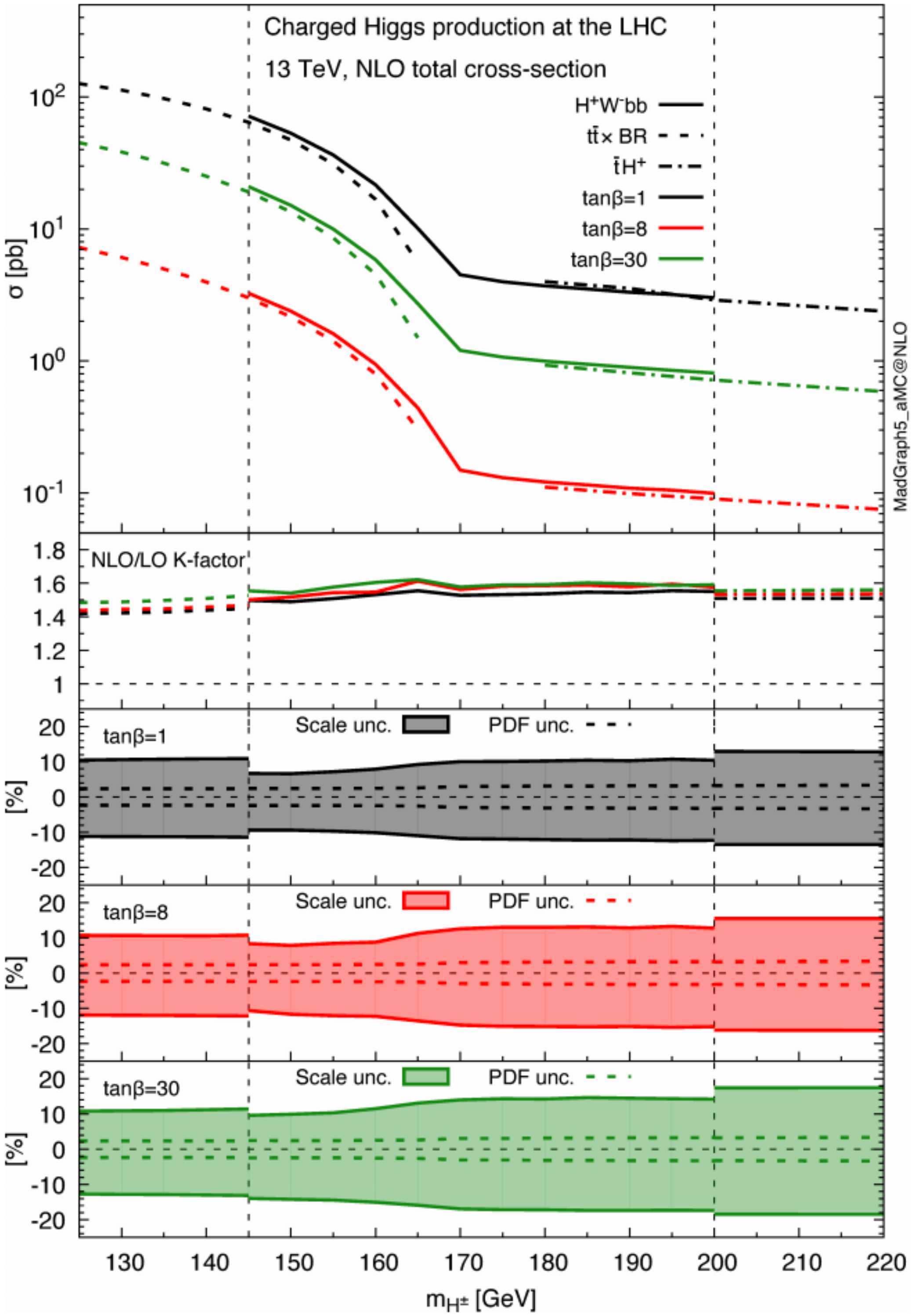
GAP

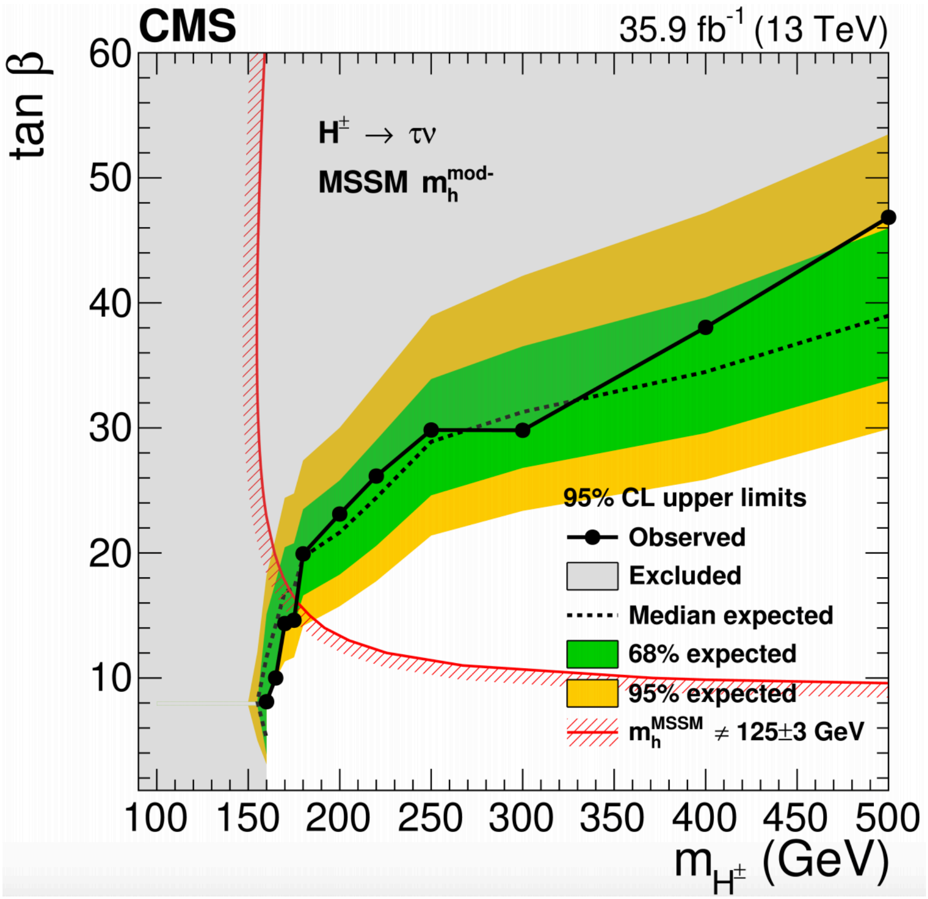


- Intermediate region has not been studied in the Run I
- LO total cross section has large (30-50%) theoretical errors. For accurate predictions one needs to compute NLO correction. Need a MC tool to simulate the signal in the region in which charged Higgs mass close to top mass.

INTERMEDIATE MASS CHARGED HIGGS

- Computation done with MadGraph5_aMC@NLO, improved with resonance-aware FKS subtraction
  Frederix et al. arXiv:1603:01178
- Complex top-mass (and Yukawa) scheme to include the top width in a gauge-invariant way. Γ_t computed at NLO for every ($m_{H\pm}$, tanβ) point
- Use massive bottom quarks (4FS).





III.

INDIRECT SEARCHES

THE EFT APPROACH

- ➡ EFT is a powerful and model-independent approach.
- ➡ Assumption: new physics states are heavy
- ➡ Write the Lagrangian with only light SM particles
- ➡ BSM effects can be incorporated as a momentum expansion

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

BSM effects

SM particles

$$\hbar = c = 1$$
$$\dim A^\mu = 1$$
$$\dim \phi = 1$$
$$\dim \psi = 3/2$$

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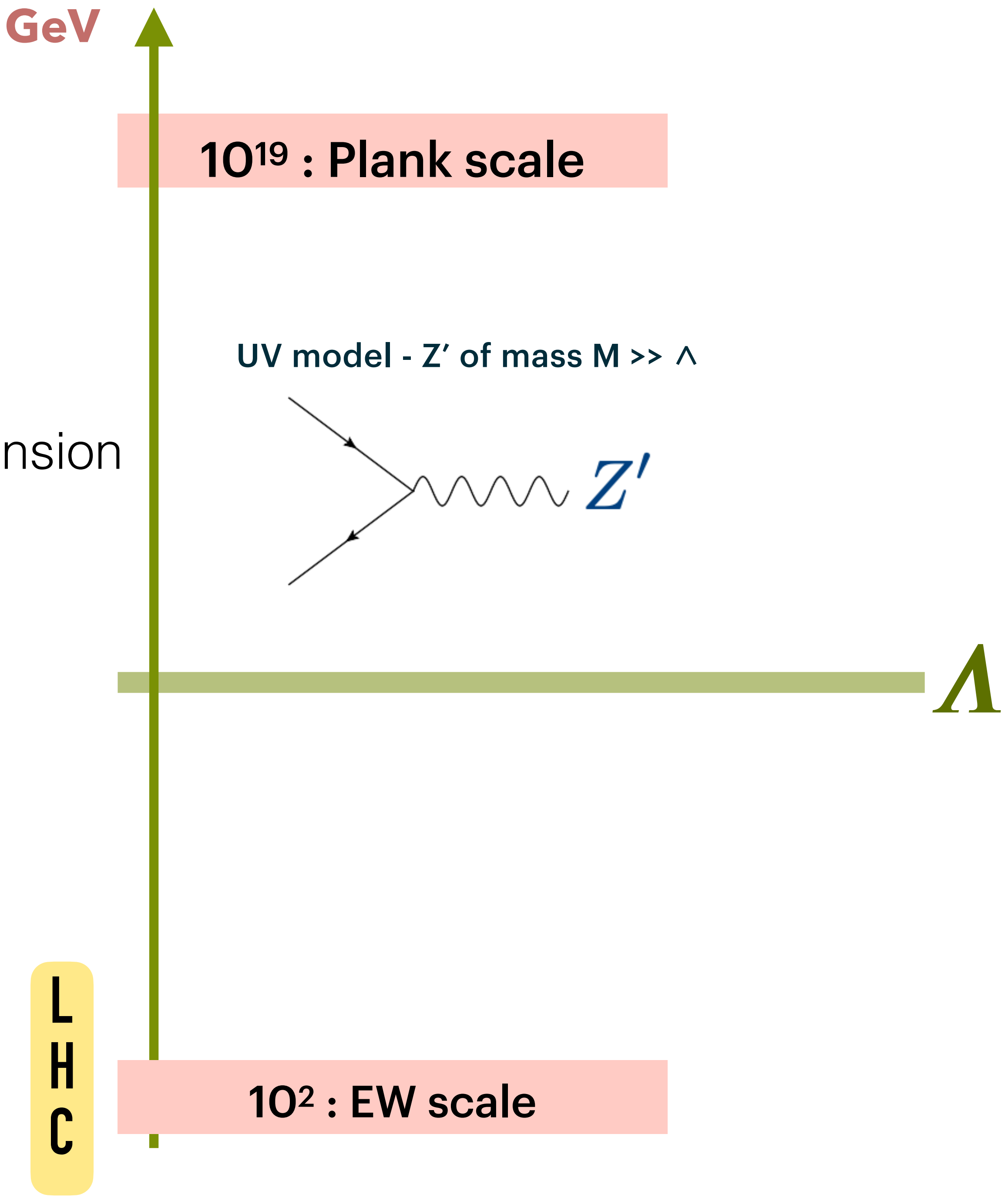

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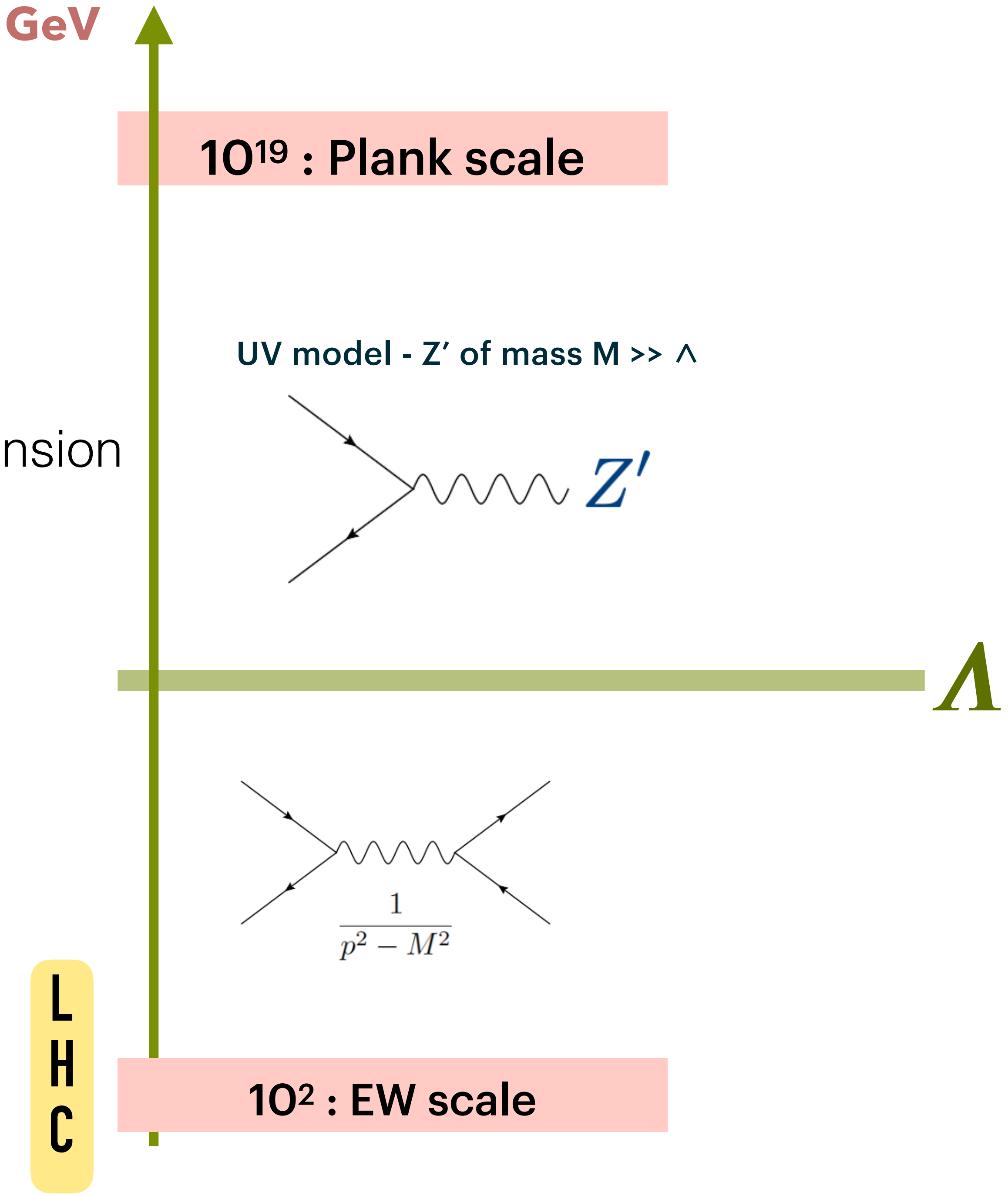
BSM effects

SM particles



GeV

10^{19} : Plank scale

UV model - Z′ of mass M >> Λ

Z'

Λ

$\frac{1}{p^2 - M^2}$

L H C

10^2 : EW scale

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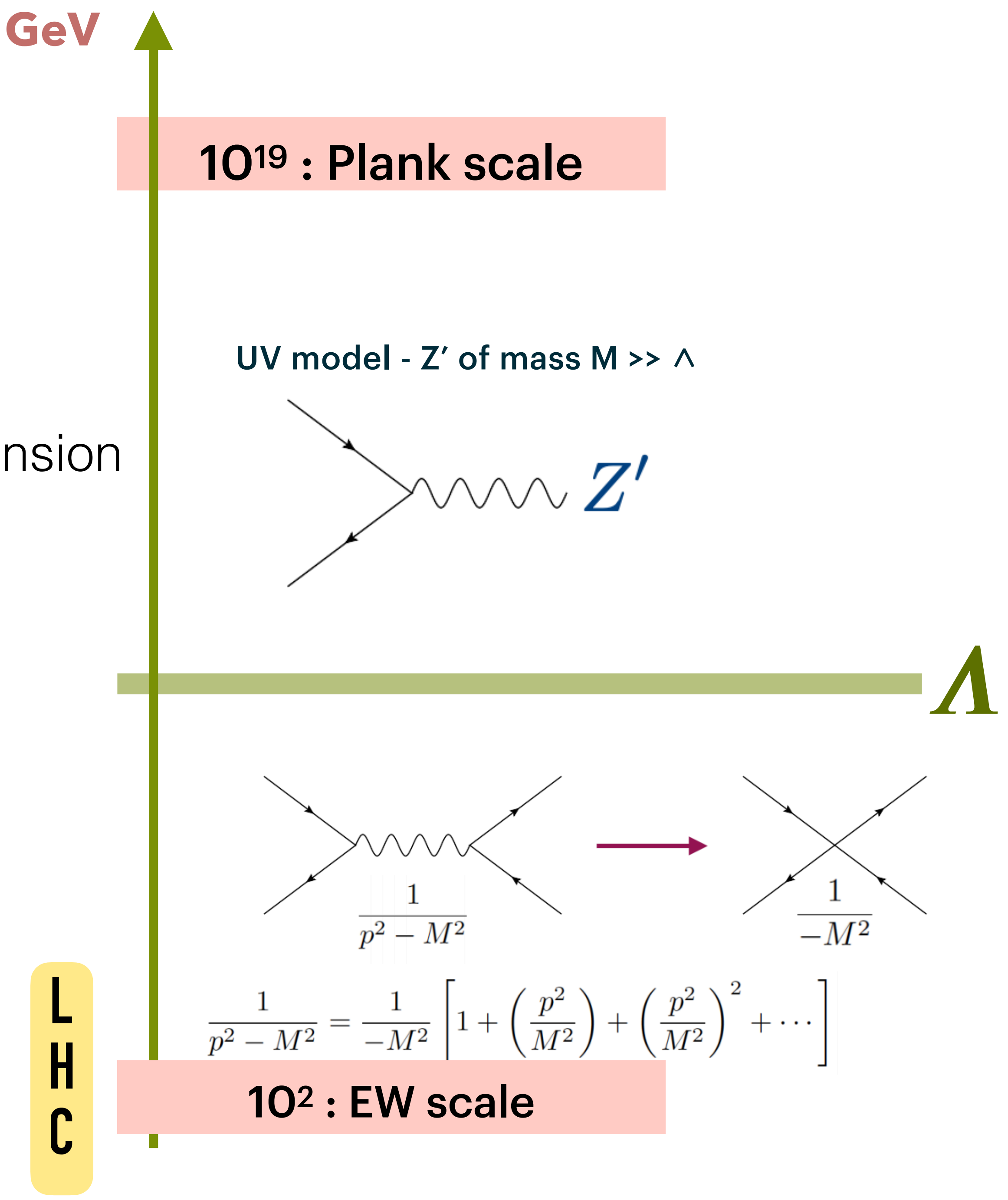
BSM effects

SM particles



$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

THE EFT APPROACH

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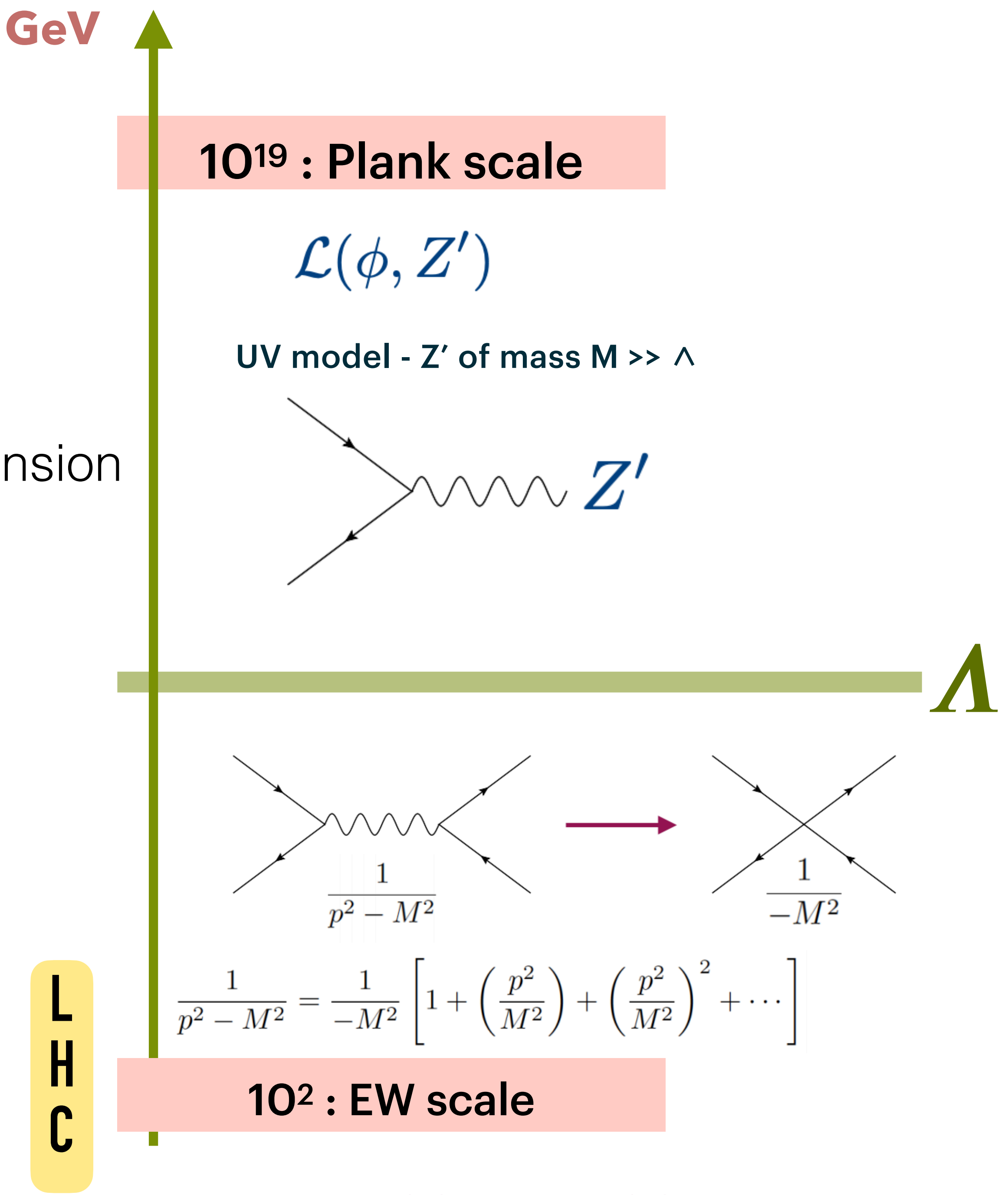
BSM effects

SM particles



GeV

10^{19} : Plank scale

$\mathcal{L}(\phi, Z')$

UV model - Z′ of mass M >> Λ

Λ

$\frac{1}{p^2 - M^2}$ → $\frac{1}{-M^2}$

$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

LHC

10^2 : EW scale

$$\mathcal{L}_{SM}(\phi) + \mathcal{L}_{dim6}(\phi) + \dots$$

$$\mathcal{L}_{dim6} = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

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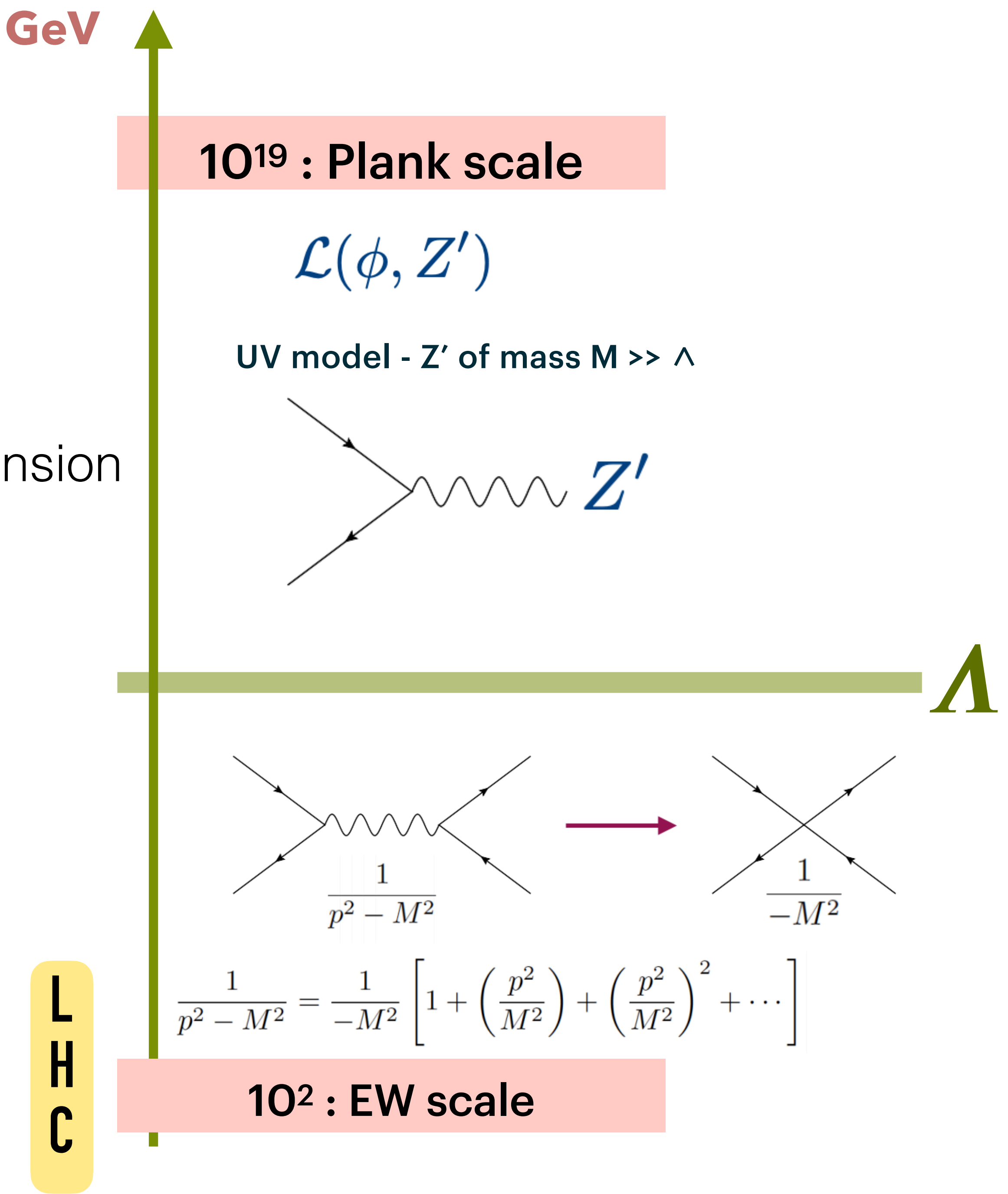
BSM effects

SM particles

BSM is a perturbation around the SM.
EFT reveals high energy physics through precise measurements at low energy.
Each operator can be improved at higher orders including QCD and EW corrections



$$\mathcal{L}_{SM}(\phi) + \mathcal{L}_{dim6}(\phi) + \dots$$

$$\mathcal{L}_{dim6} = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

THE STANDARD MODEL EFFECTIVE FIELD THEORY

#1 The basic framework is that of a relativistic quantum field theory, with interactions between particles described by a local Lagrangian.

#2 The Lagrangian is invariant under the linearly realised local SU(3)×SU(2)×U(1) symmetry

#3 The vacuum state of the theory preserves only $SU(3)_C \times U(1)_{em}$ local symmetry, as a result of the Brout-Englert-Higgs mechanism. The spontaneous breaking of the $SU(2)_L \times U(1)_Y$ symmetry down to $U(1)_{em}$ arises due to a vacuum expectation value (VEV) of a scalar field transforming as $(1, 2)_{1/2}$ under the local symmetry.

~~**#4** Interactions are renormalizable, which means that only interactions up to the canonical mass dimension 4 are allowed in the Lagrangian.~~

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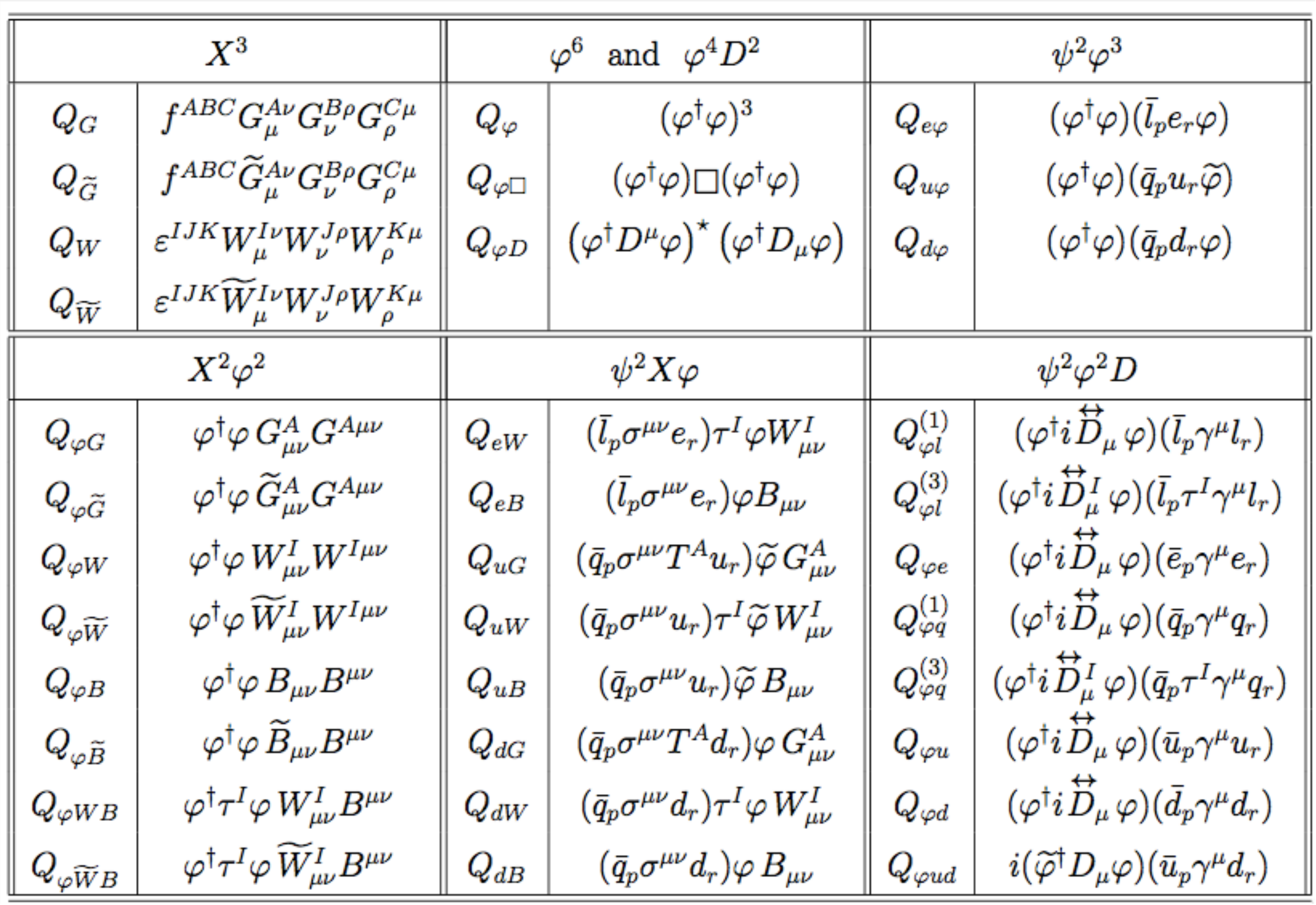
$$\mathcal{L}_{\rm eff} = \mathcal{L}^{\rm SM} + \mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \frac{1}{v^2}\sum_\alpha c_\alpha O_\alpha$$

O_α → complete basis of SU(3) × SU(2) × 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. Only 9 combinations of these operators will be relevant for a completely general description of the Higgs signal strength measurements at the LHC

DIM-6 OPERATORS

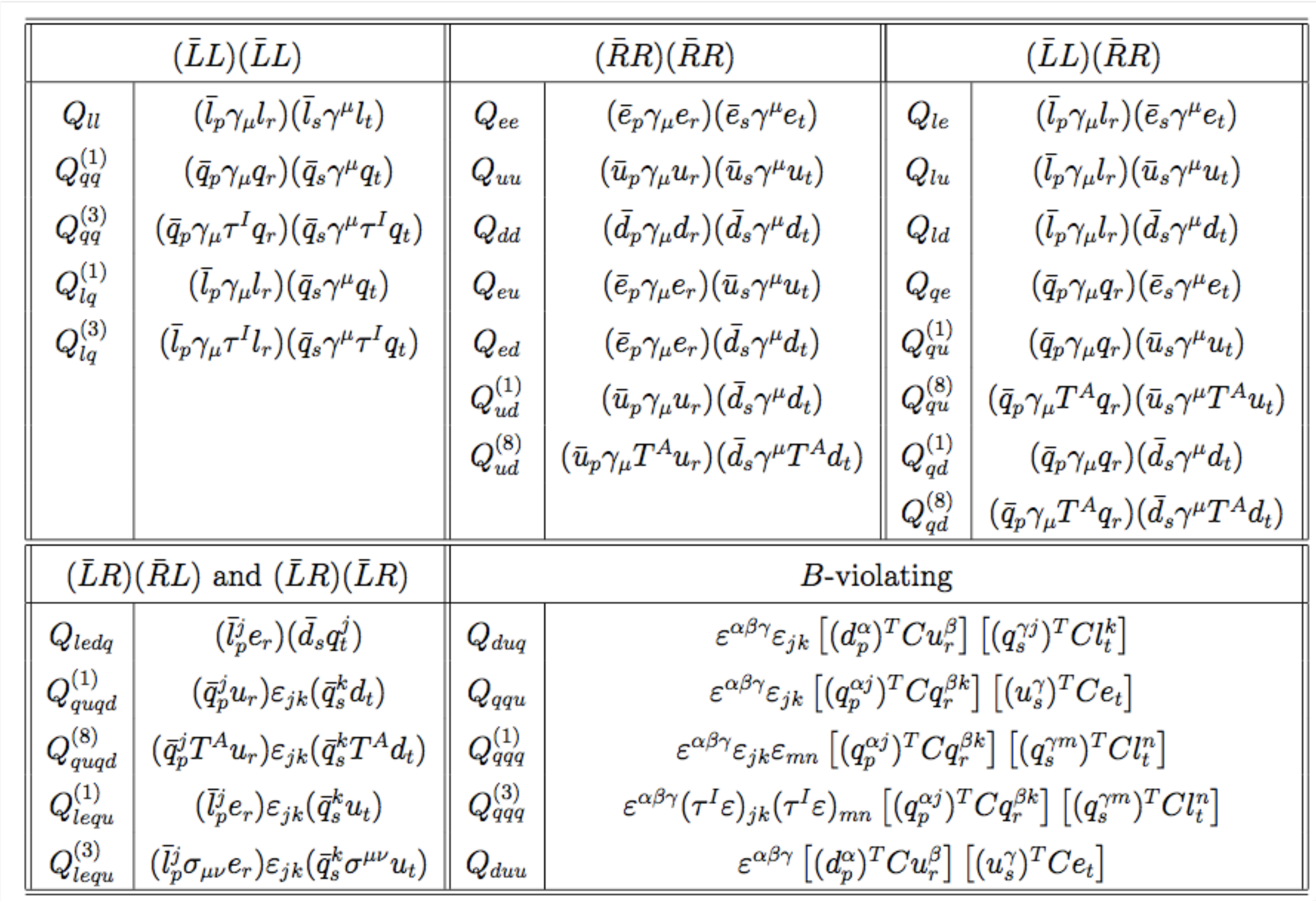


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

[Buchmuller and Wyler, 86]

[Grzadkowski et al, 10]

DIM-6 OPERATORS



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

[Buchmuller and Wyler, 86]

[Grzadkowski et al, 10]

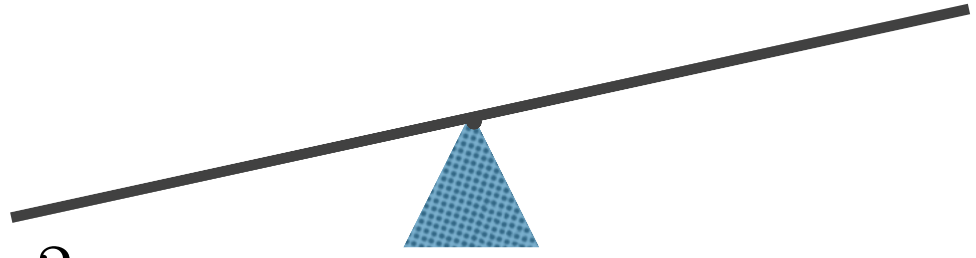
CONSTRAINING THE SMEFT AT THE LHC

- 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.

s is a generic scale, which is process and operator dependent

$$\mathrm{Obs}_i = \mathrm{Obs}_i^{\mathrm{SM}} + M_{ij} \cdot \frac{s}{\Lambda^2} c_j$$

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

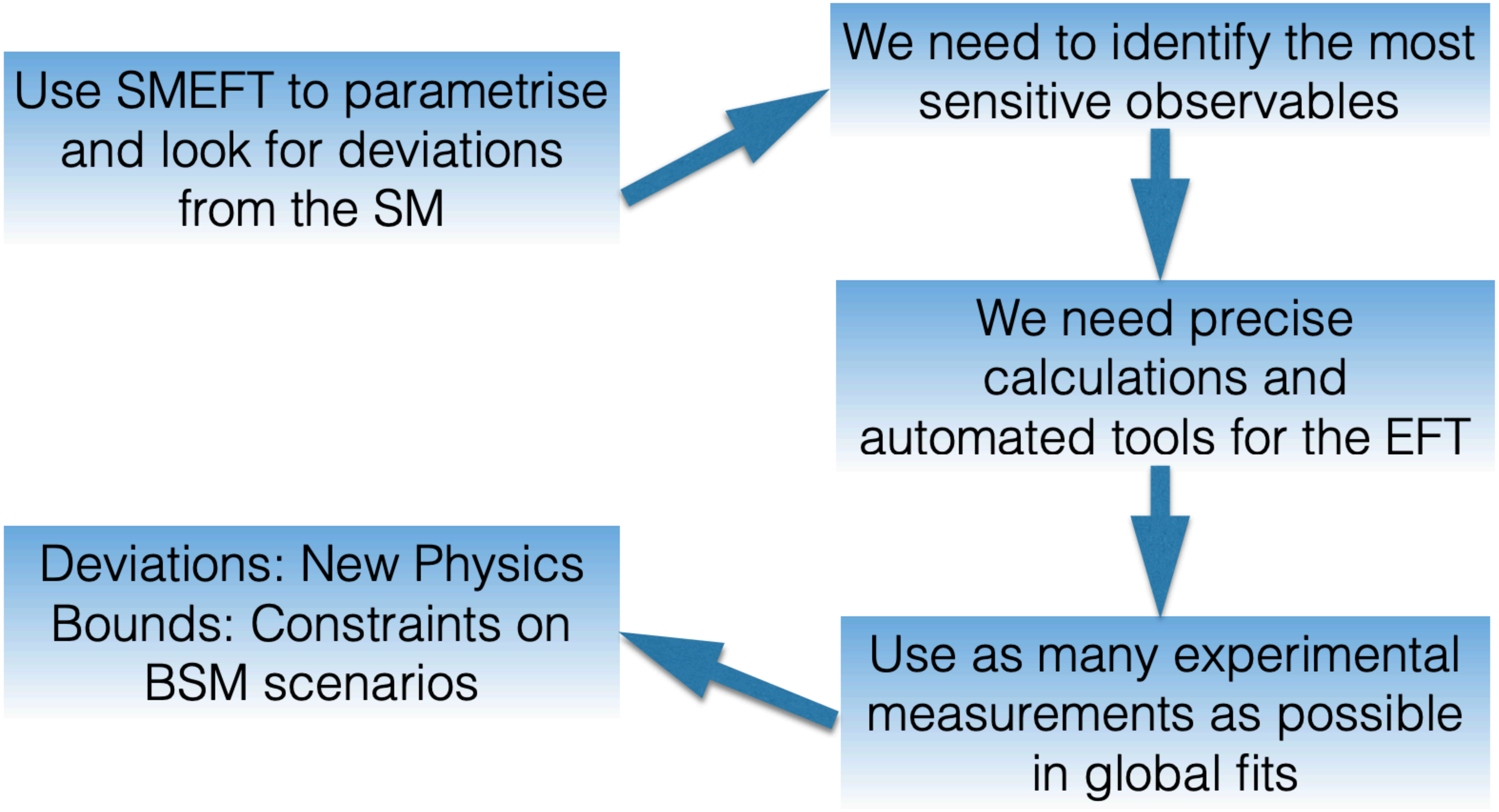


$$|c_i| s/\Lambda^2 < \delta$$

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

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.



Use SMEFT to parametrise and look for deviations from the SM

We need to identify the most sensitive observables

We need precise calculations and automated tools for the EFT

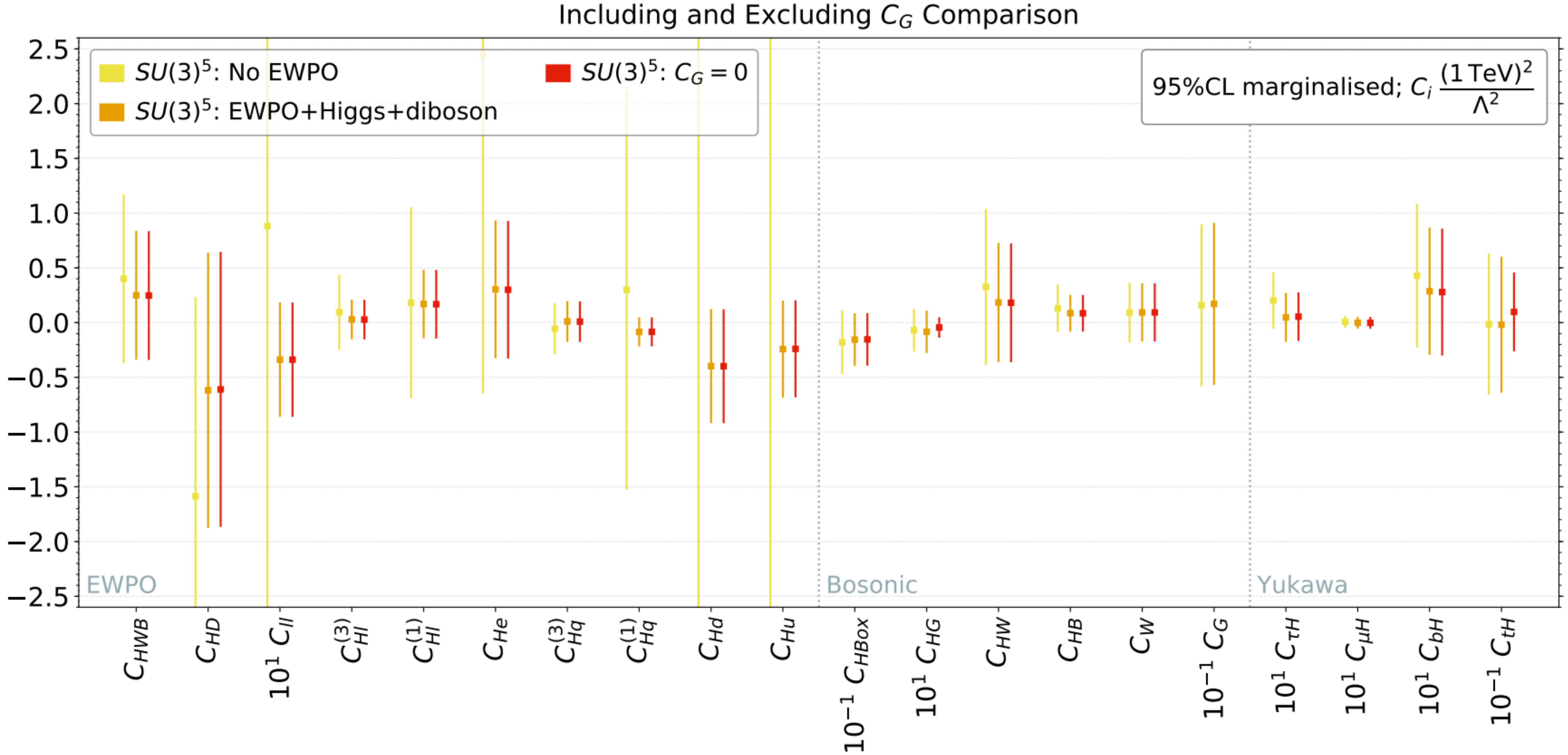
Use as many experimental measurements as possible in global fits

Deviations: New Physics
Bounds: Constraints on BSM scenarios

E. Vryonidou, RECFA meeting 2019

CONSTRAINING THE SMEFT AT THE LHC

arXiv:2012.02779



➡ Most fits of SMEFT coefficients are restricted to a few observables or sectors, thus reducing the number of dim-6 operators involved.

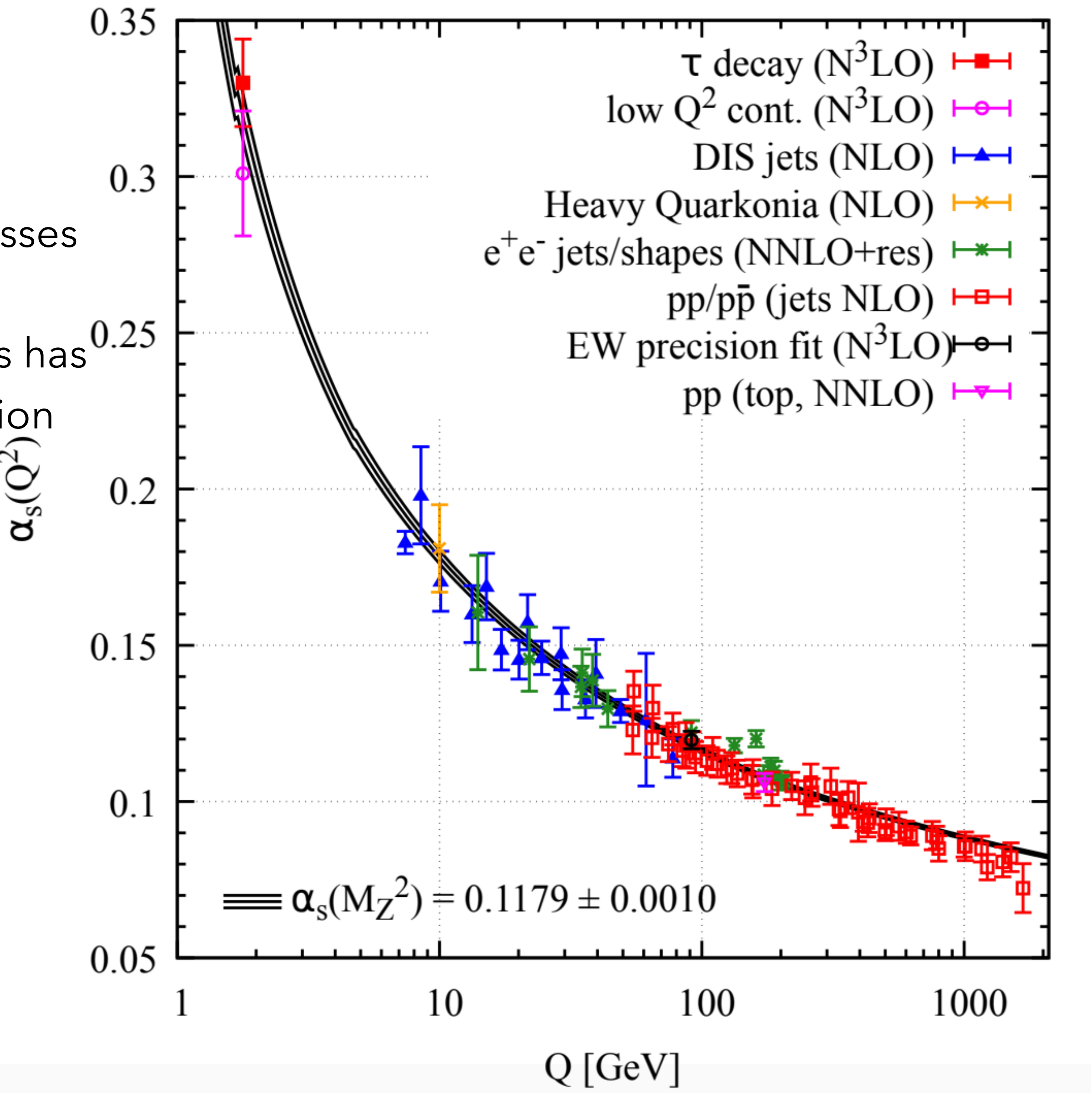
➡ Possibly the most global fit so far includes 34 dim-6 operators (linearly) and include EW precision observable, diboson production at LEP and LHC, LHC Run I and II Higgs, Tevatron and LHC top data for a total of ~300 measurements

[Ellis, Madigan, Mimasu, Sanz, You arXiv: 2012.02779]

NEED FOR SIMULTANEOUS FITS?

A SHORT DIGRESSION: PDFS AND α_S

- ➡ PDFs and α_s strongly correlated (PDF evolution with the scale and hard cross sections)
- ➡ Cleanest determinations of α_s from processes that do not require knowledge of the PDFs
- ➡ A determination of α_s jointly with the PDFs has advantage that it is driven by the combination of many experimental measurements from several different processes.



PDG 2020

A SHORT DIGRESSION: PDFS AND α_S

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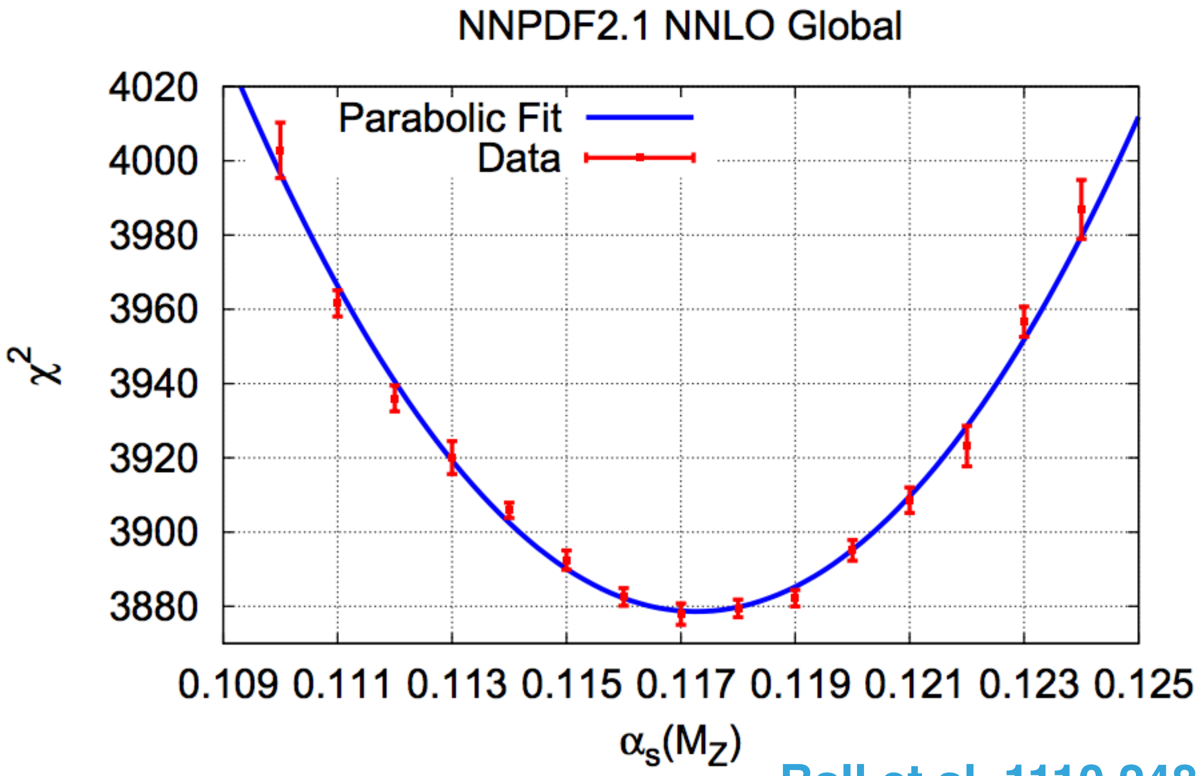
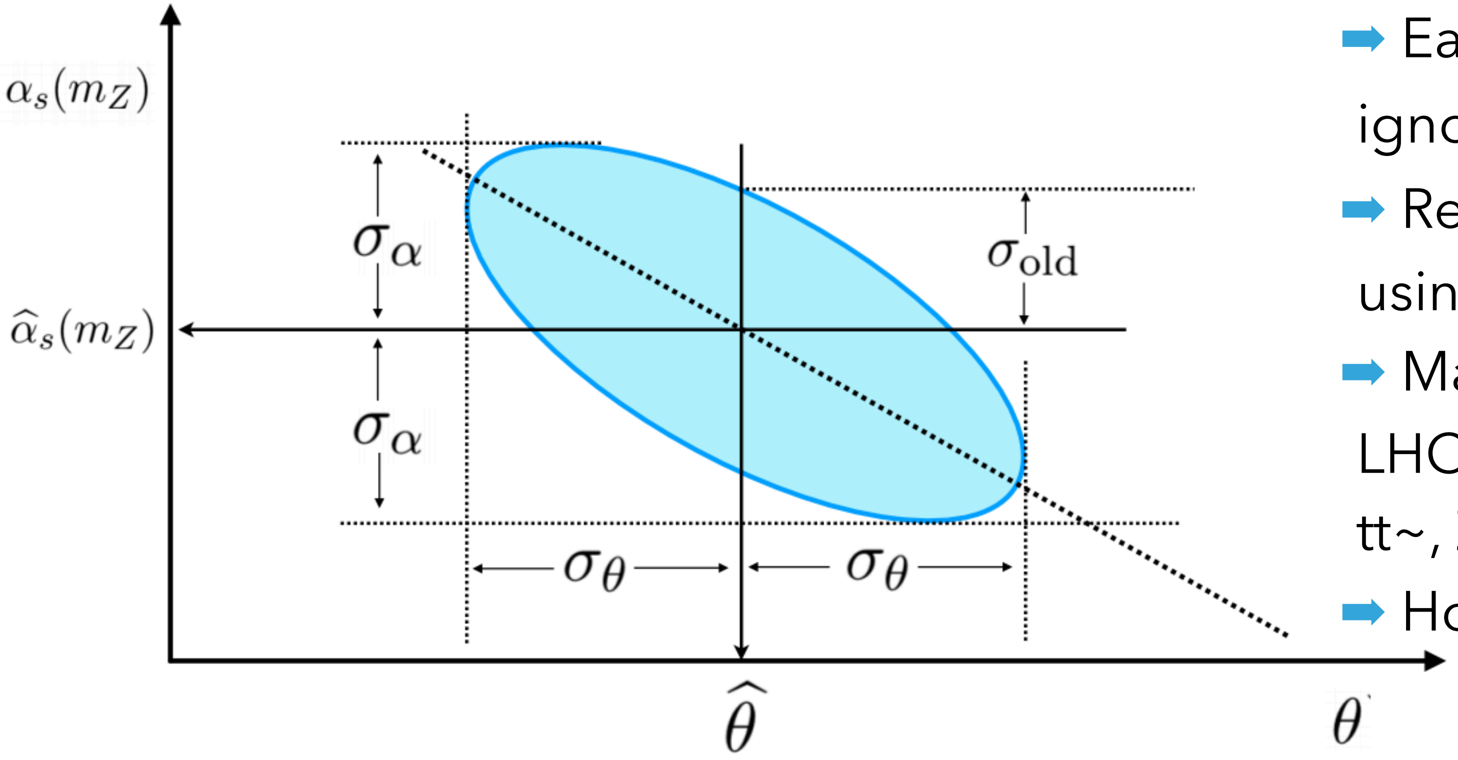


Ball et al, 1110.2483

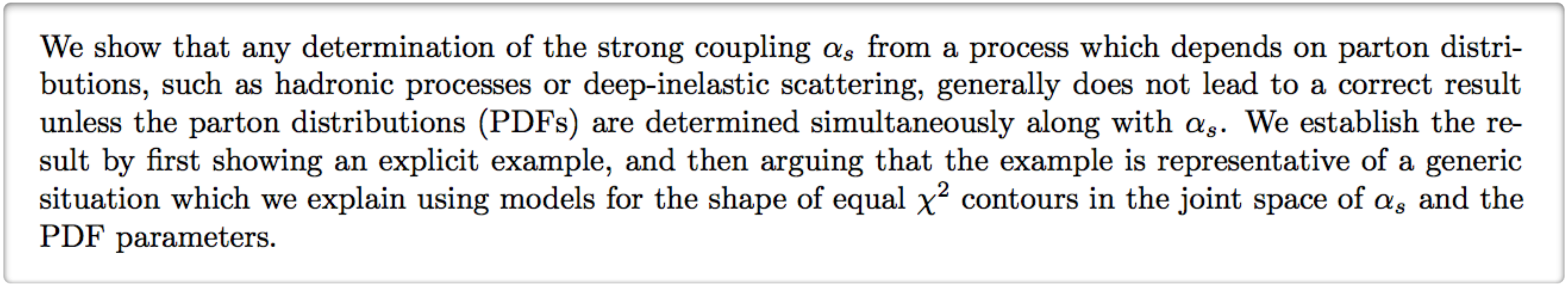


- ➡ Early determinations involve a scan over α_s and ignored PDF and α_s correlation in the fit
- ➡ Recent simultaneous determination of PDF and α_s using correlated replica method
- ➡ Many determination of α_s from analyses of specific LHC processes have been published recently (from tt~, Z and W production, jets)
- ➡ How reliable are such partial determination of α_s ?

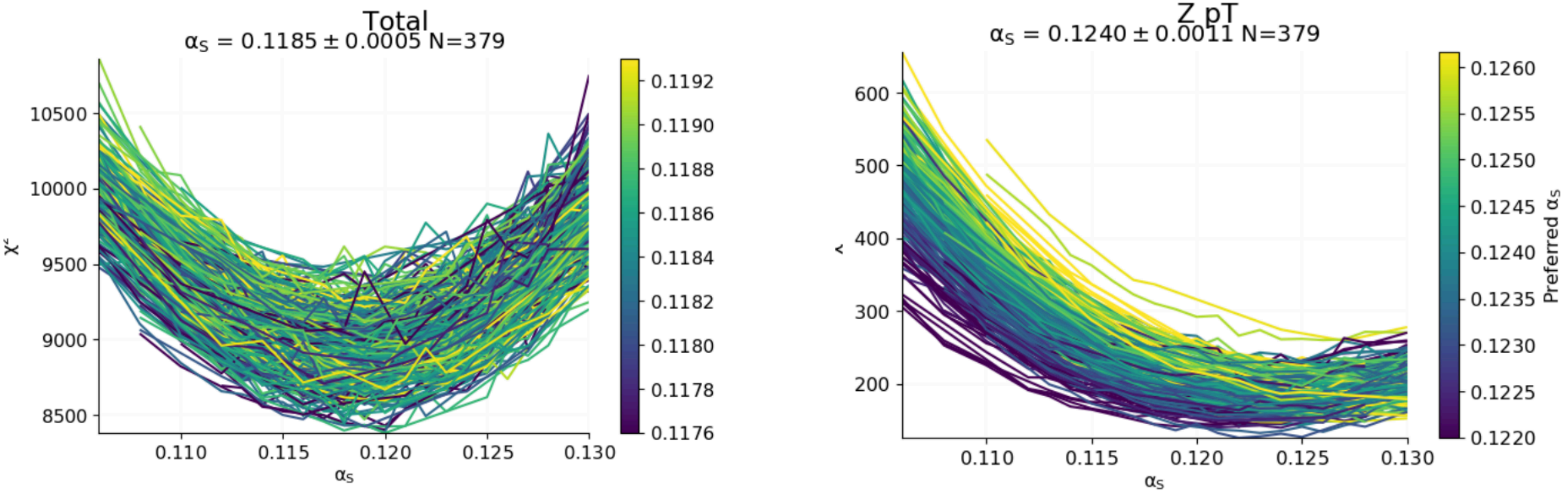
Ball, Carrazza, Del Debbio, Forte, Kassabov, Rojo, Slade, MU 1802.03398

A SHORT DIGRESSION: PDFS AND α_S

Forte, Kassabov 2001.04986

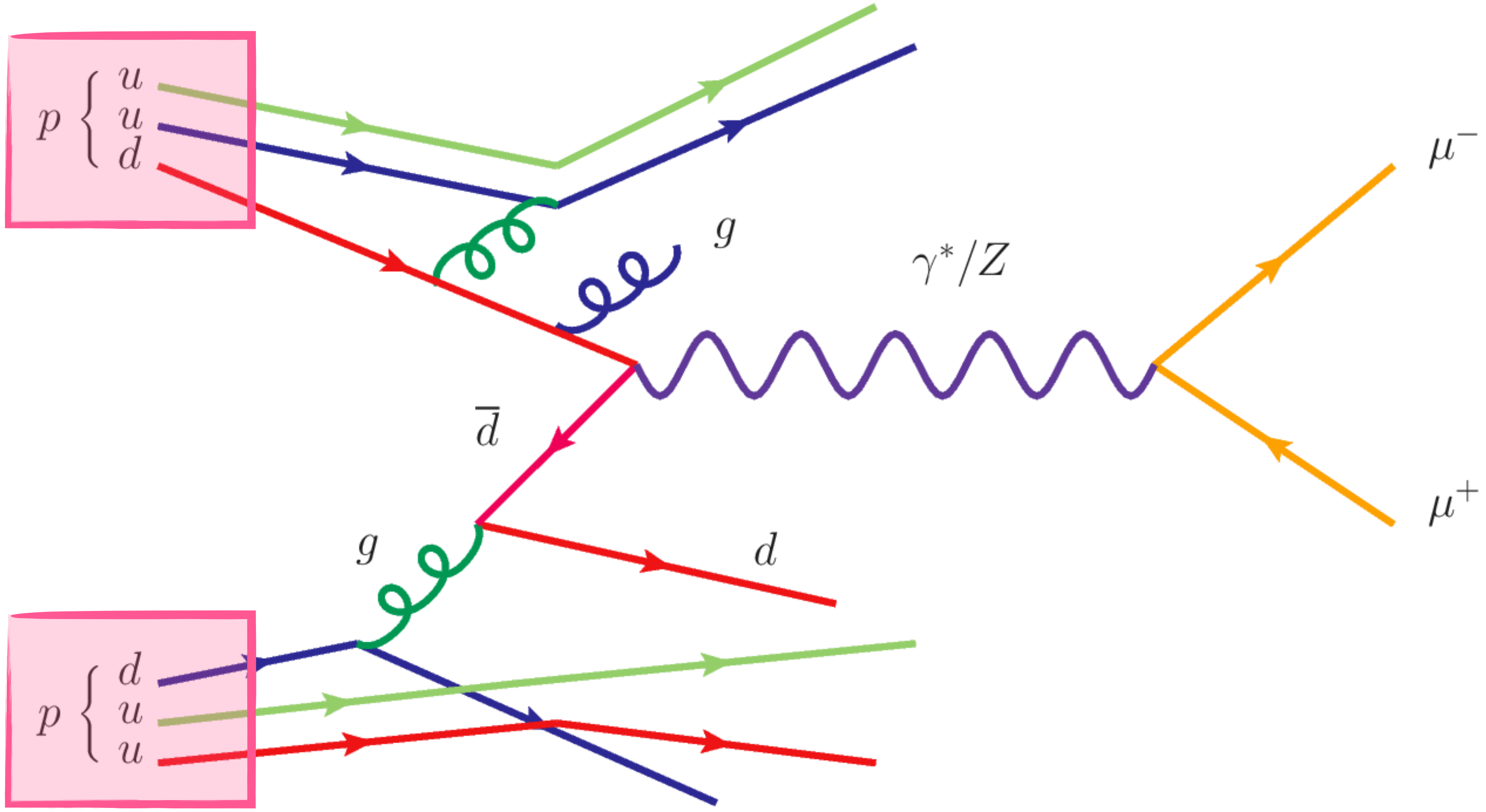


We show that any determination of the strong coupling α_s from a process which depends on parton distributions, such as hadronic processes or deep-inelastic scattering, generally does not lead to a correct result unless the parton distributions (PDFs) are determined simultaneously along with α_s. We establish the result by first showing an explicit example, and then arguing that the example is representative of a generic situation which we explain using models for the shape of equal χ^2 contours in the joint space of α_s and the PDF parameters.



These results point towards the need of new generation of global fits, in which all ingredients that enter theoretical predictions are treated consistently.

WHAT ABOUT PDF FITS AND SMEFT FITS?



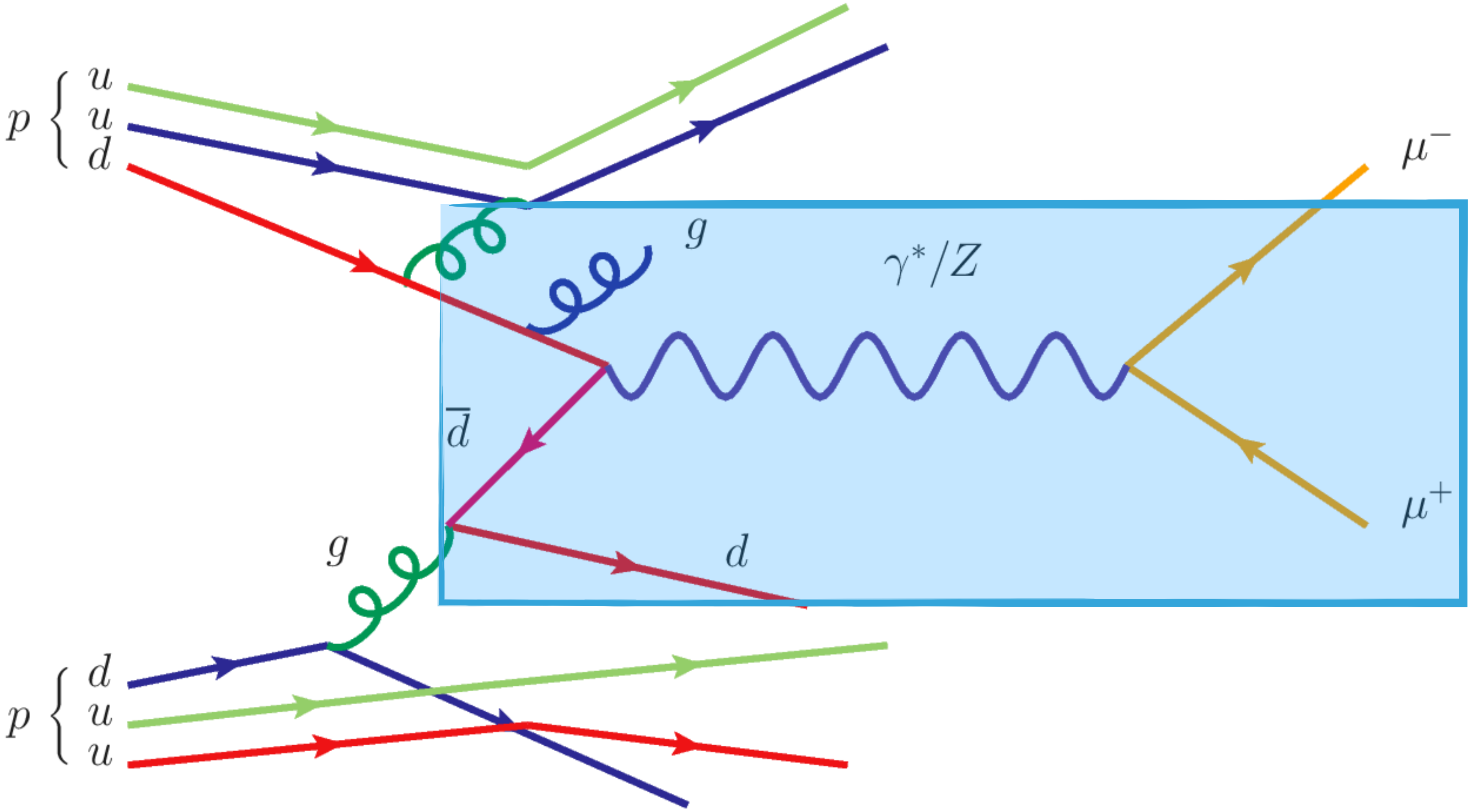
$$d\sigma^{pp\to ab} = \sum_{i,j} \boxed{f_i \otimes f_j} \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

Fit of PDF Coefficients $\{\theta_i\}$

+ LHC Data

$f_i(\{\theta_k\})$

WHAT ABOUT PDF FITS AND SMEFT FITS?



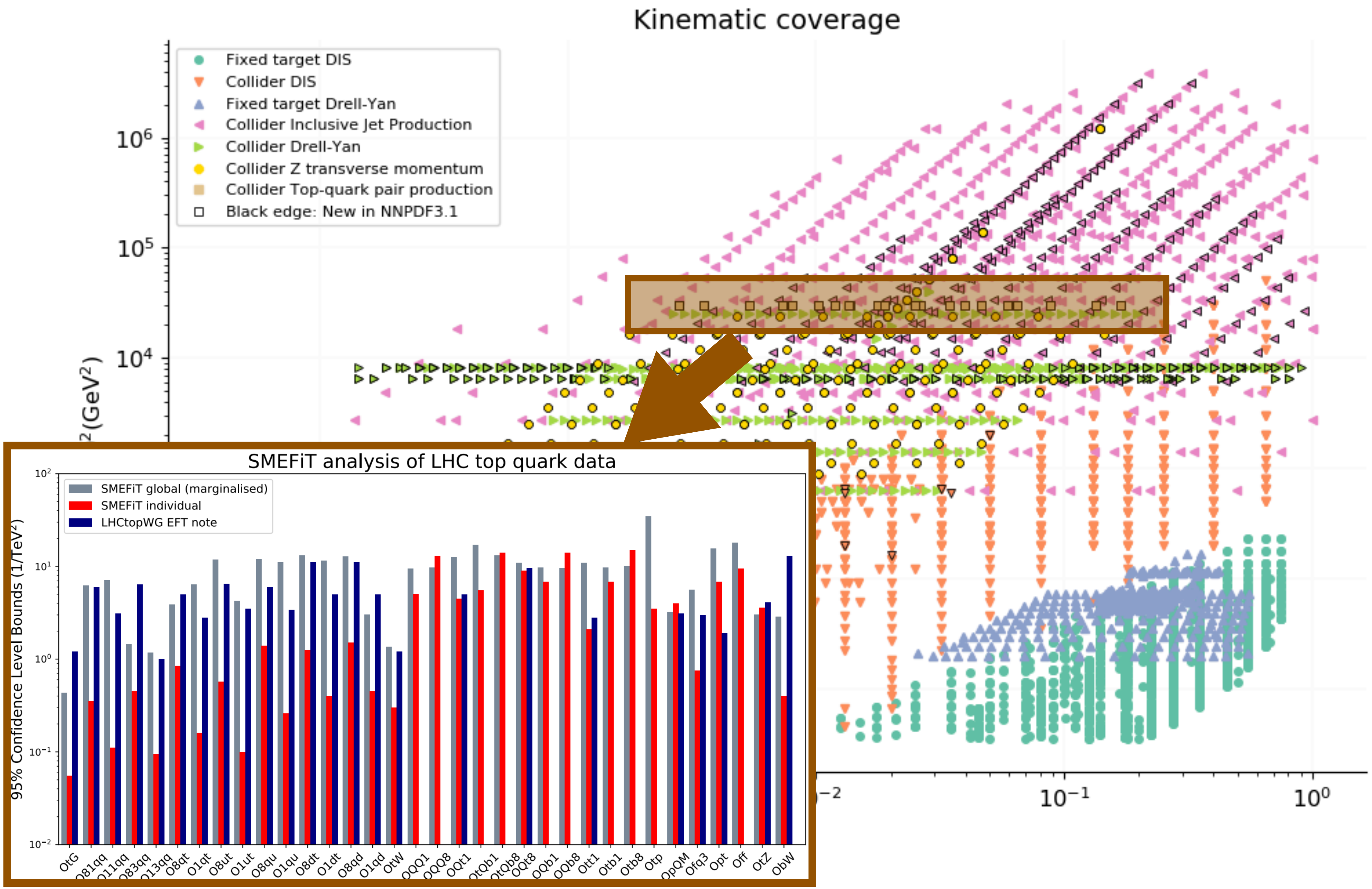
$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes \boxed{d\hat{\sigma}^{ij\to ab}} + \ldots$$

Fit of Wilson Coefficients {ci}

(LHC) Data

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

A SIGNIFICANT OVERLAP

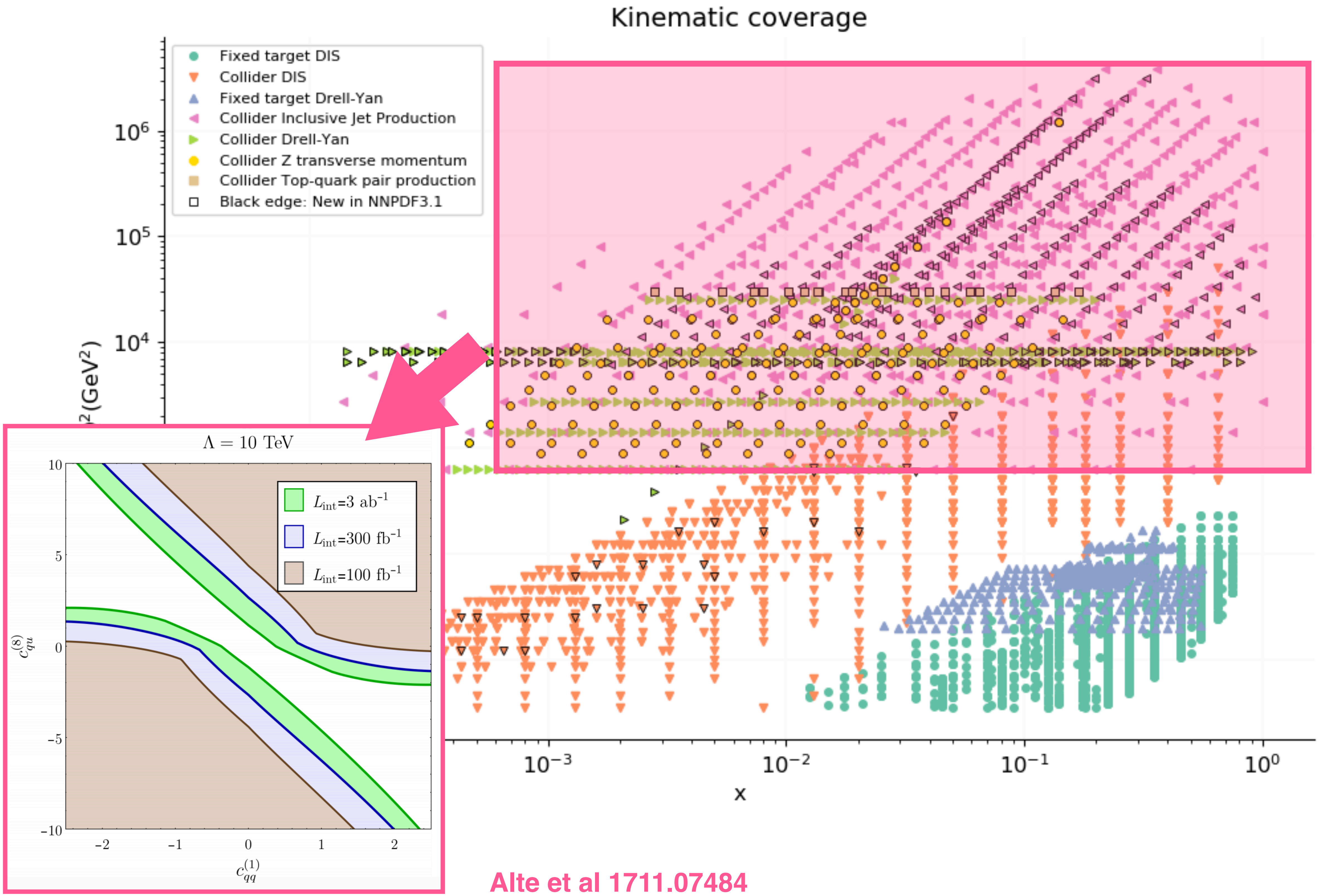


Kinematic coverage

SMEFiT analysis of LHC top quark data

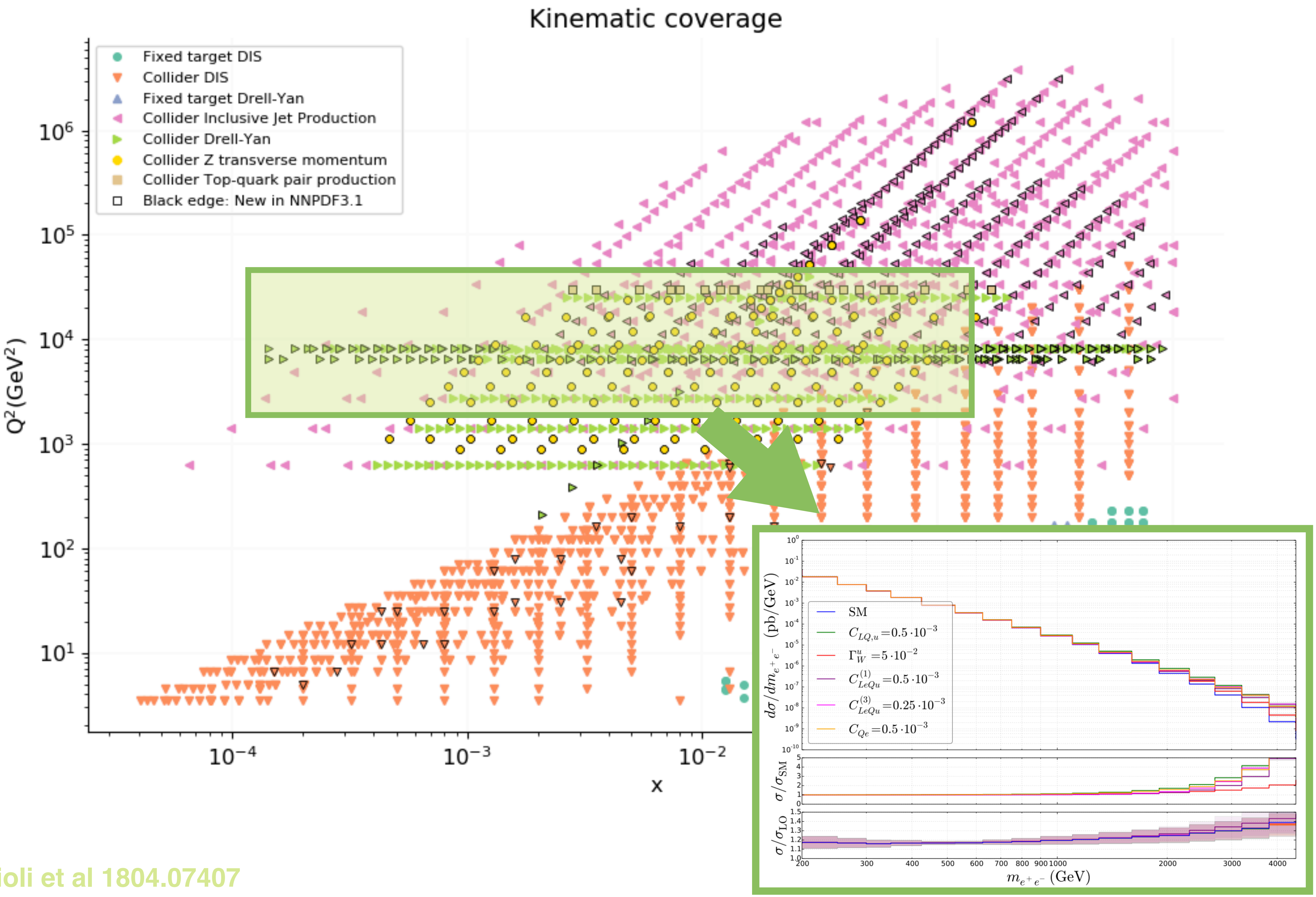
Hartland et al 1901.05965

A SIGNIFICANT OVERLAP



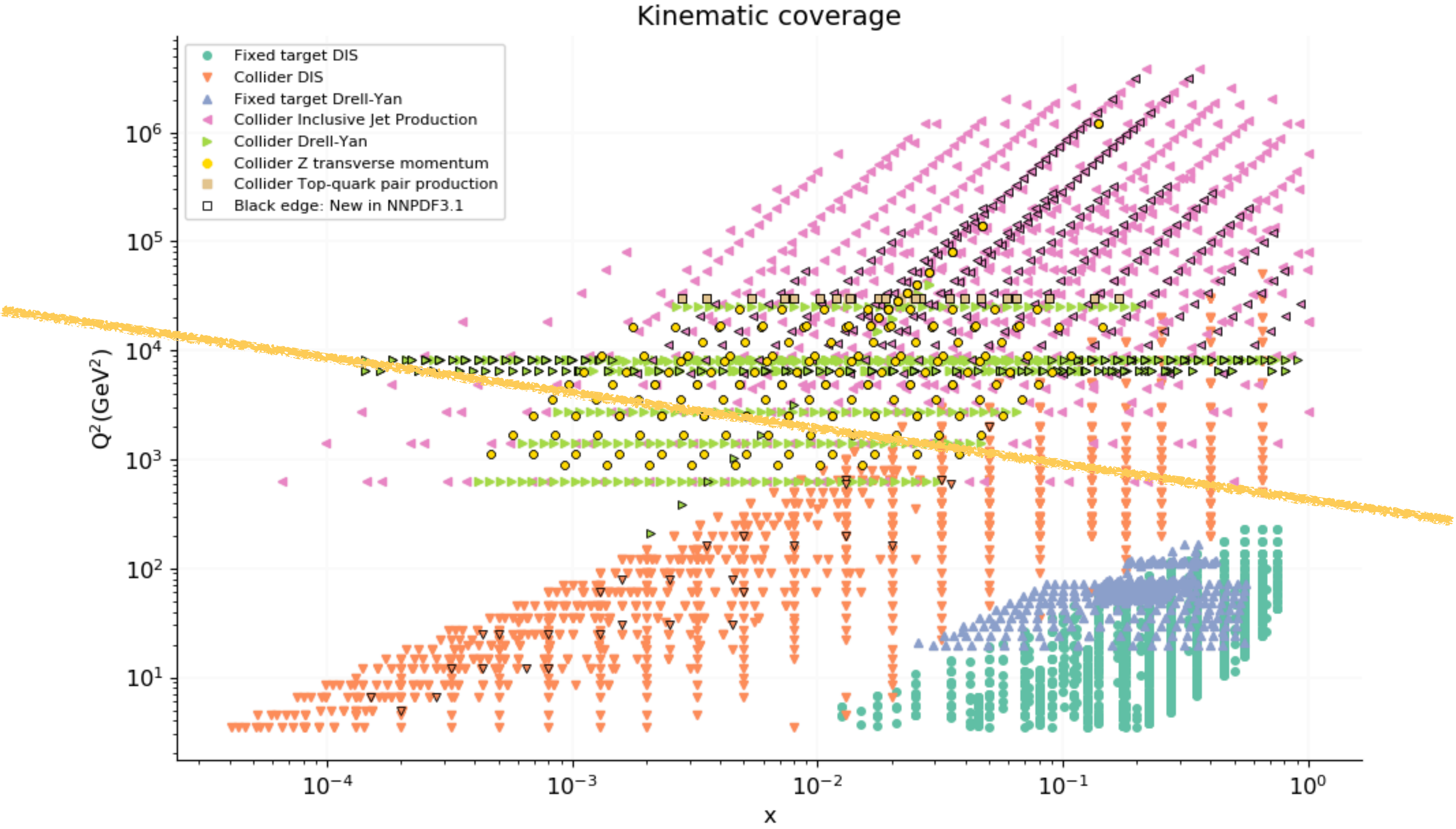
Alte et al 1711.07484

A SIGNIFICANT OVERLAP



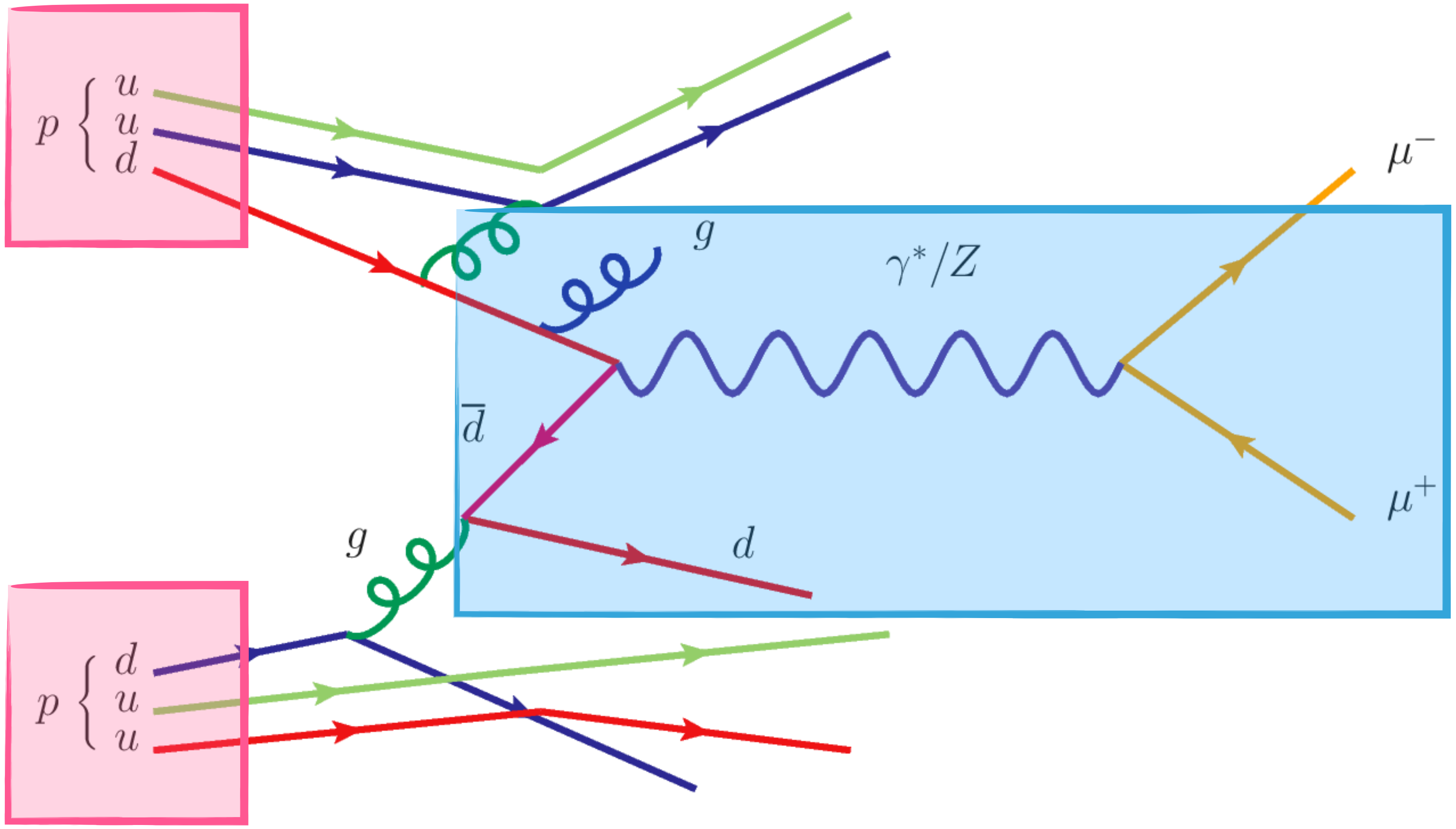
Alioli et al 1804.07407

HOW TO DISENTANGLE THE EFFECTS?



- Cuts?
- Conservative partons?

SIMULTANEOUS FITS



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

What’s the interplay? Simultaneous fits

LHC Data

$f_i(\{\theta_k\})$

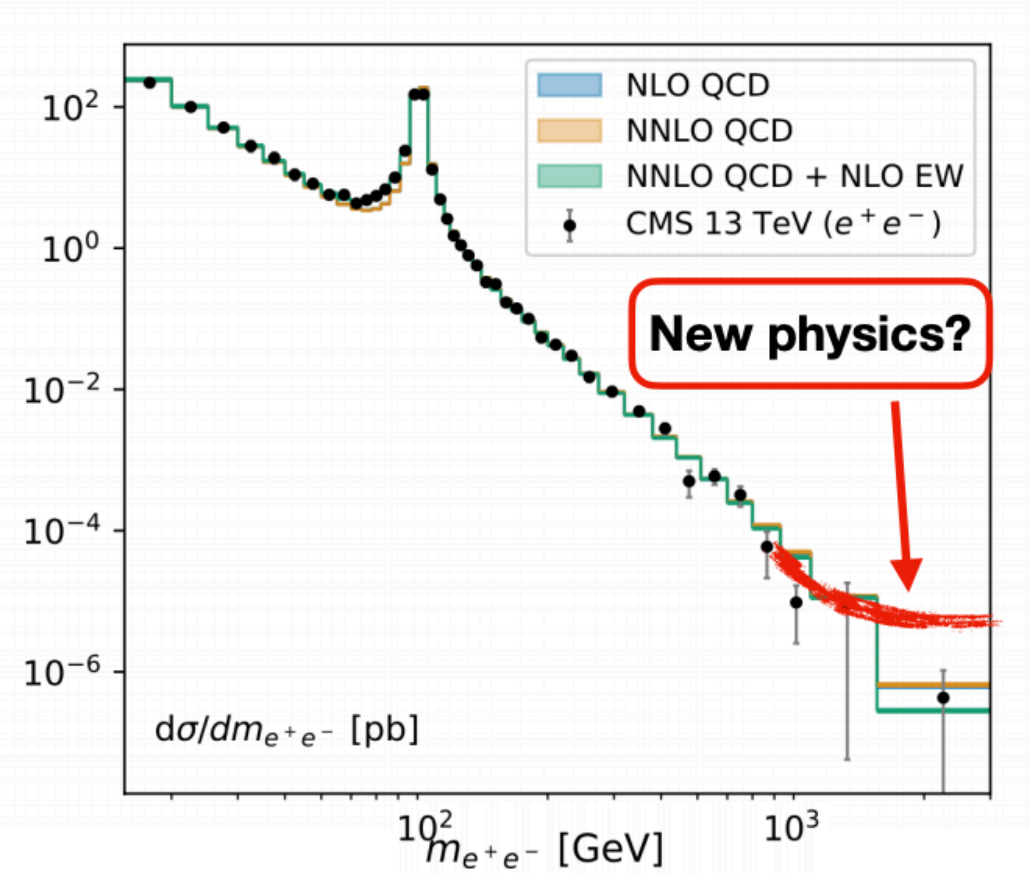
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

Carrazza, Degrande, Iranipour, Rojo, MU, Phys.Rev.Lett. 123 (2019) no.13, 132001
Greljo, Iranipour, Kassabov, Madigan, Moore, Rojo, MU, Voisey, arXiv:2104.02723

DRELL-YAN HIGH-ENERGY TAILS

- Drell-Yan (DY) tails, a.k.a. **high-mass DY**
- DY used in **both PDF and EFT determinations**:

  1. **Important constraints** on $q\bar{q}$
  2. New physics could **distort tails**



From Cameron Voisey’s talk at HEFT2021

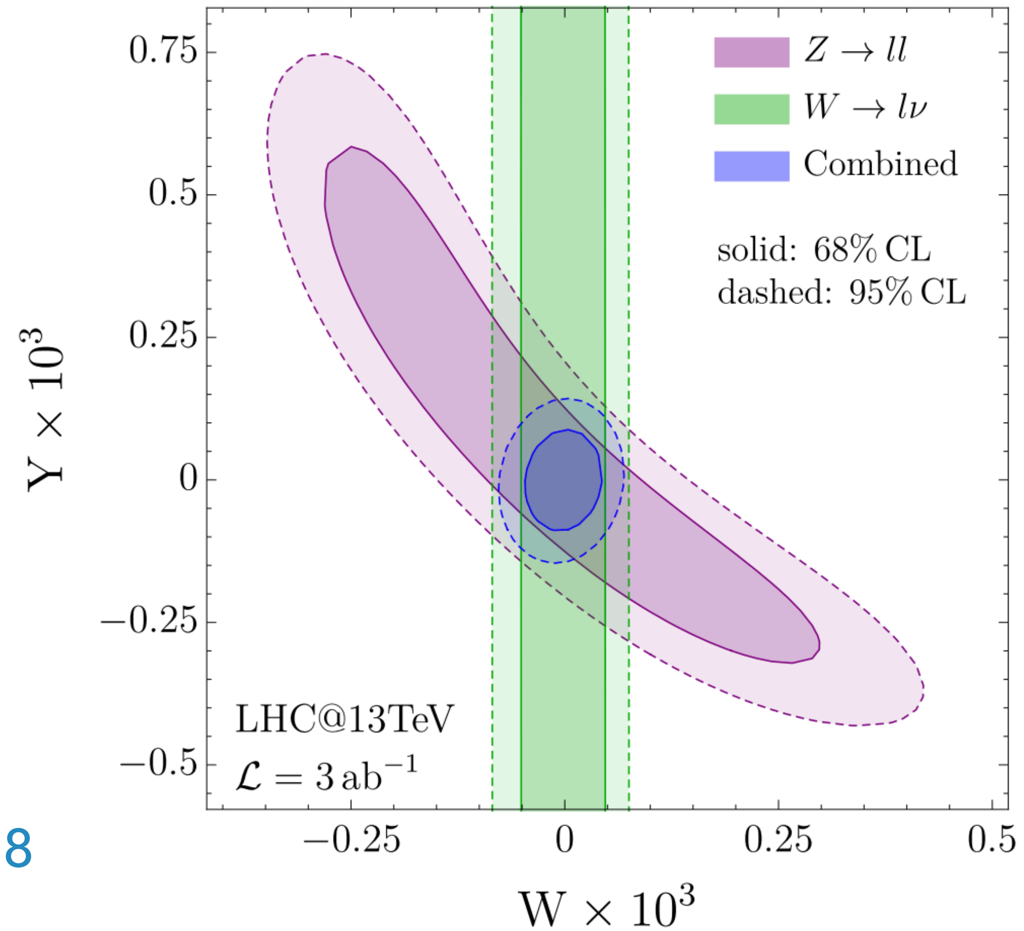
OBLIQUE CORRECTIONS

$$\mathscr{L}_{\rm SMEFT} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

Studied in e.g. arXiv: 1609.08157, 2008.12978

- Electroweak (EW) oblique corrections: **parametrise self-energy of EW gauge bosons**
- Four operators that can be matched to dim-6 in SMEFT: $\hat{S}, \hat{T}, \hat{W}, \hat{Y}$

  - $\hat{S}, \hat{T}$ **well constrained**, **weaker q^2-dependence**



R. Torre et all 2008.12978

SM PDFS VERSUS SMEFT PDFS

Standard procedure: SM PDFs

1. Take data, make predictions accounting for operators with **fixed SM PDF set**
2. Compute χ^2 for set of Wilson coefficients (WCs)

$$\boxed{\chi^2 = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} (D_i - T_i)\,({\rm cov}^{-1})_{ij}\,(D_j - T_j)}$$

3. Fit function
4. Extract bounds

$$\boxed{T = f_{1,\rm SM} \otimes f_{2,\rm SM} \otimes \hat{\sigma}_{\rm BSM}}$$

Our procedure: SMEFT PDFs

- Same as previously, but…
- For each value of WC do a **consistent PDF fit** $\Rightarrow \mathrm{N}_{\rm WCs}$ **SMEFT PDF sets**

$$\boxed{T = f_{1,\rm BSM} \otimes f_{2,\rm BSM} \otimes \hat{\sigma}_{\rm BSM}}$$

ANALYSIS SETTINGS

Data

- **DIS & low-mass/on-shell DY** data from NNPDF3.1
- Plus **high-mass DY**:
  - **LHC NC data**: ATLAS 7, 8 TeV; CMS 7, 8, 13 TeV
  - **HL-LHC** projections (later)

Theory: SM

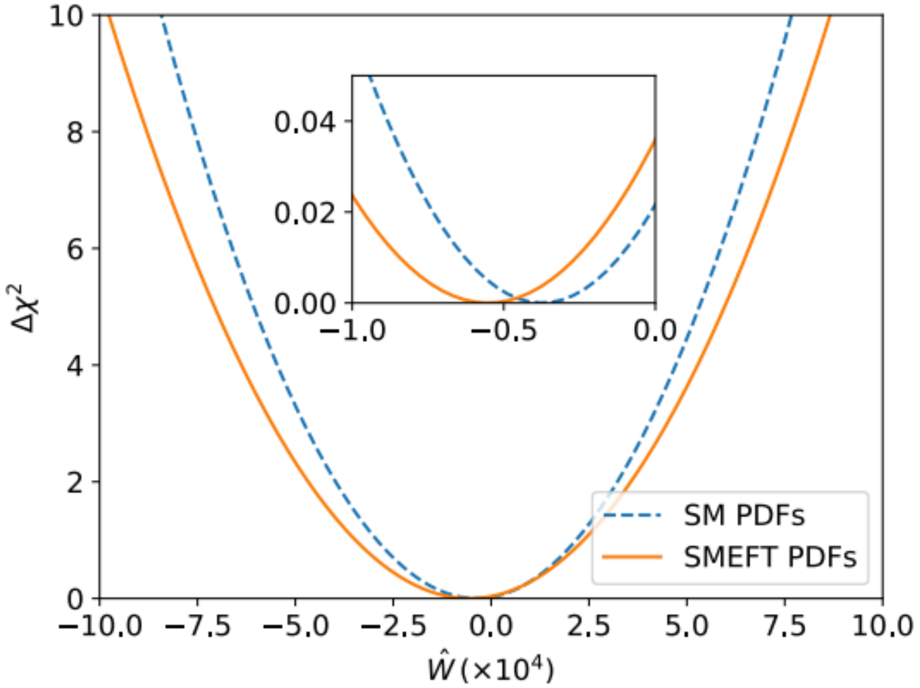
- **NNLO QCD + NLO EW**

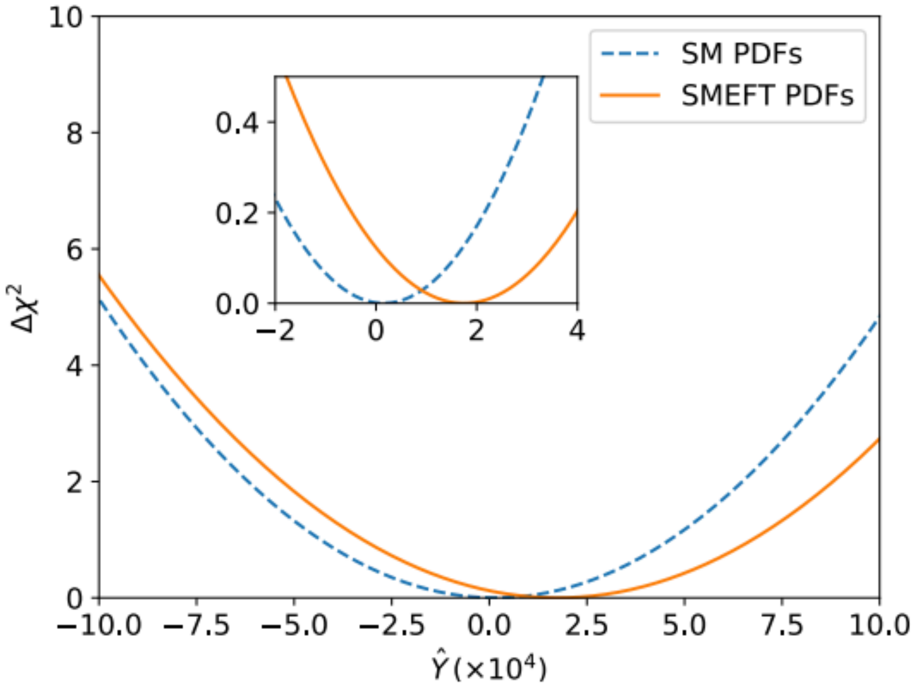
SMEFT

- **K-factor approach**, $d\sigma_{\text{SMEFT}} = d\sigma_{\text{SM}} \times K_{\text{EFT}}$
- **Linear (dim-6)** for $\hat{W}, \hat{Y}$
- Applied to **DIS & DY**

From Cameron Voisey’s talk at HEFT2021

RESULTS: CURRENT DATA





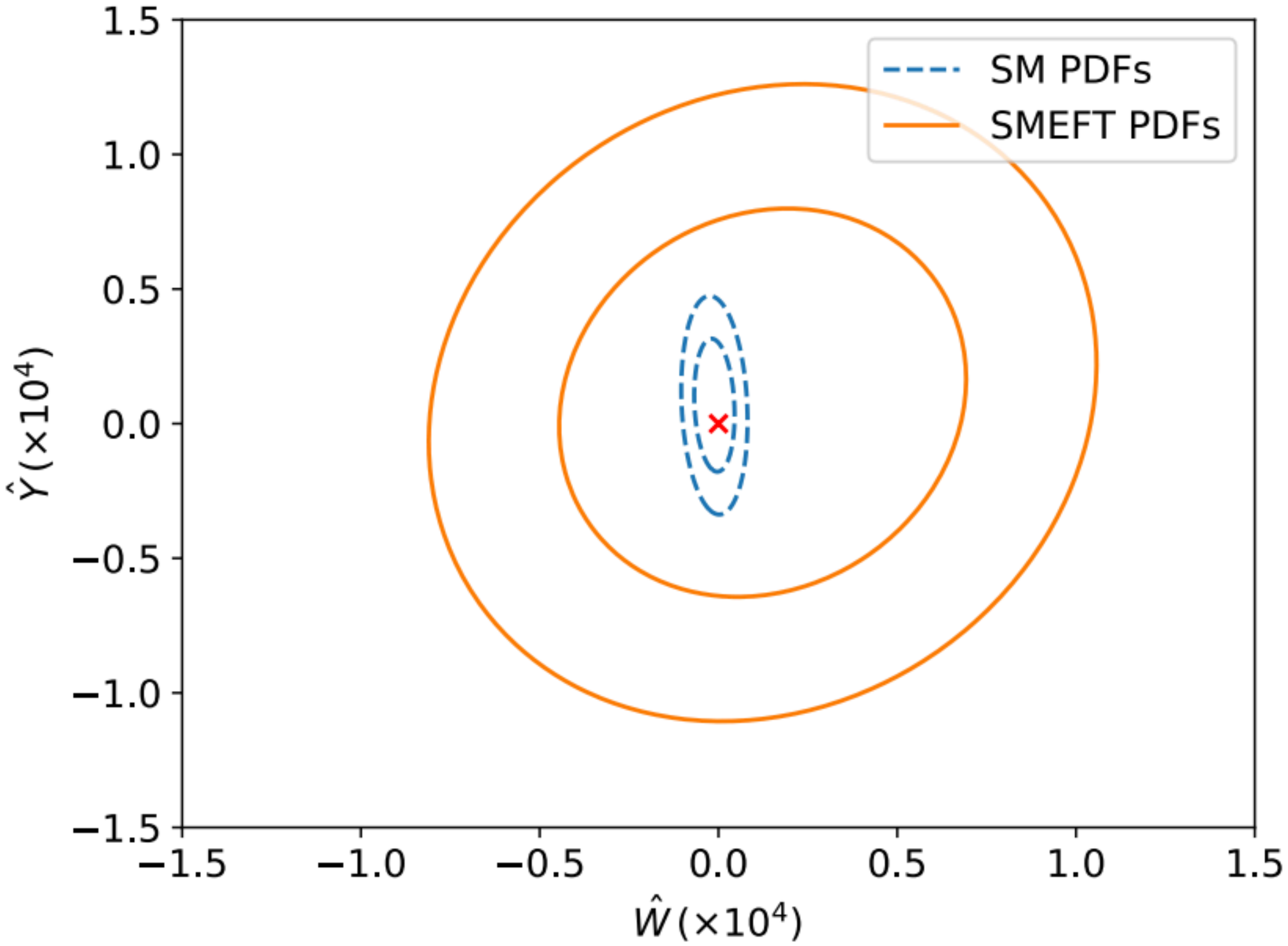
- 95% CL bounds:

  - **broaden** by **15% ($\hat{W}$), 12% ($\hat{Y}$)**

- PDF unc. included:

  - becomes **shrinking** by **11% ($\hat{W}$), 13% ($\hat{Y}$)**

RESULTS: HL-LHC PROJECTIONS



- 95% CL bounds:

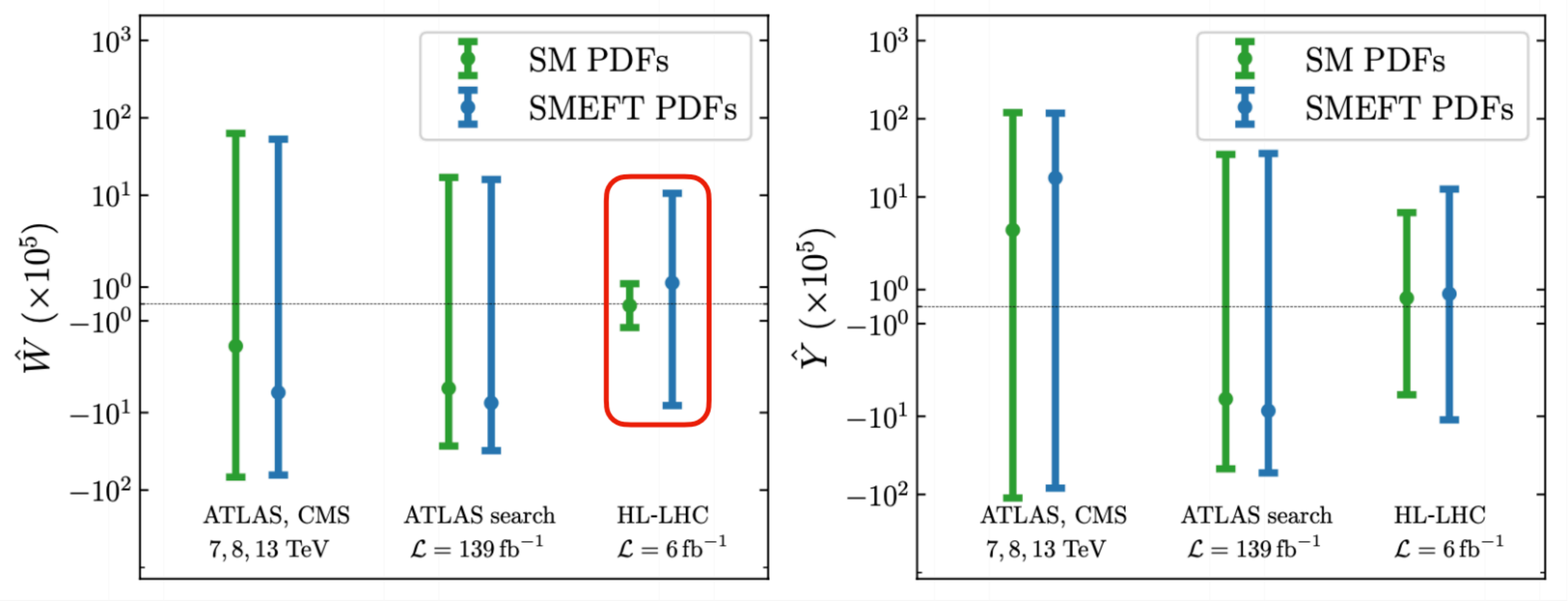
  - **broaden** by **940%** ($\hat{W}$), **190%** ($\hat{Y}$)

- PDF unc. included:

  - **broaden** by **620%** ($\hat{W}$), **110%** ($\hat{Y}$)

- **Neglecting PDF-EFT interplay** would lead to **significant underestimate** of uncertainty on EFT parameters

RESULTS: HL-LHC PROJECTIONS



Using **SM PDFs** to find optimal reach leads to **significant underestimate of uncertainties** — **consistent treatment** suggests only **mild improvement versus current bounds**!

CONCLUSIONS

- Precision physics opens up new fascinating challenges
- Precise and accurate predictions are key to make progress in comparing theoretical predictions predictions to experimental data
- QCD precision physics helps direct searches and is essential for indirect searches
- A robust framework to globally interpret all subtle deviations from the SM predictions that might arise is uttermost needed.
- The terms precision and discovery have characterised the 10-year LHC legacy and will become even more predominant in the 20+ years ahead.

THANK YOU FOR YOUR ATTENTION!