Looking ahead

PREFIT school, DESY (2020)

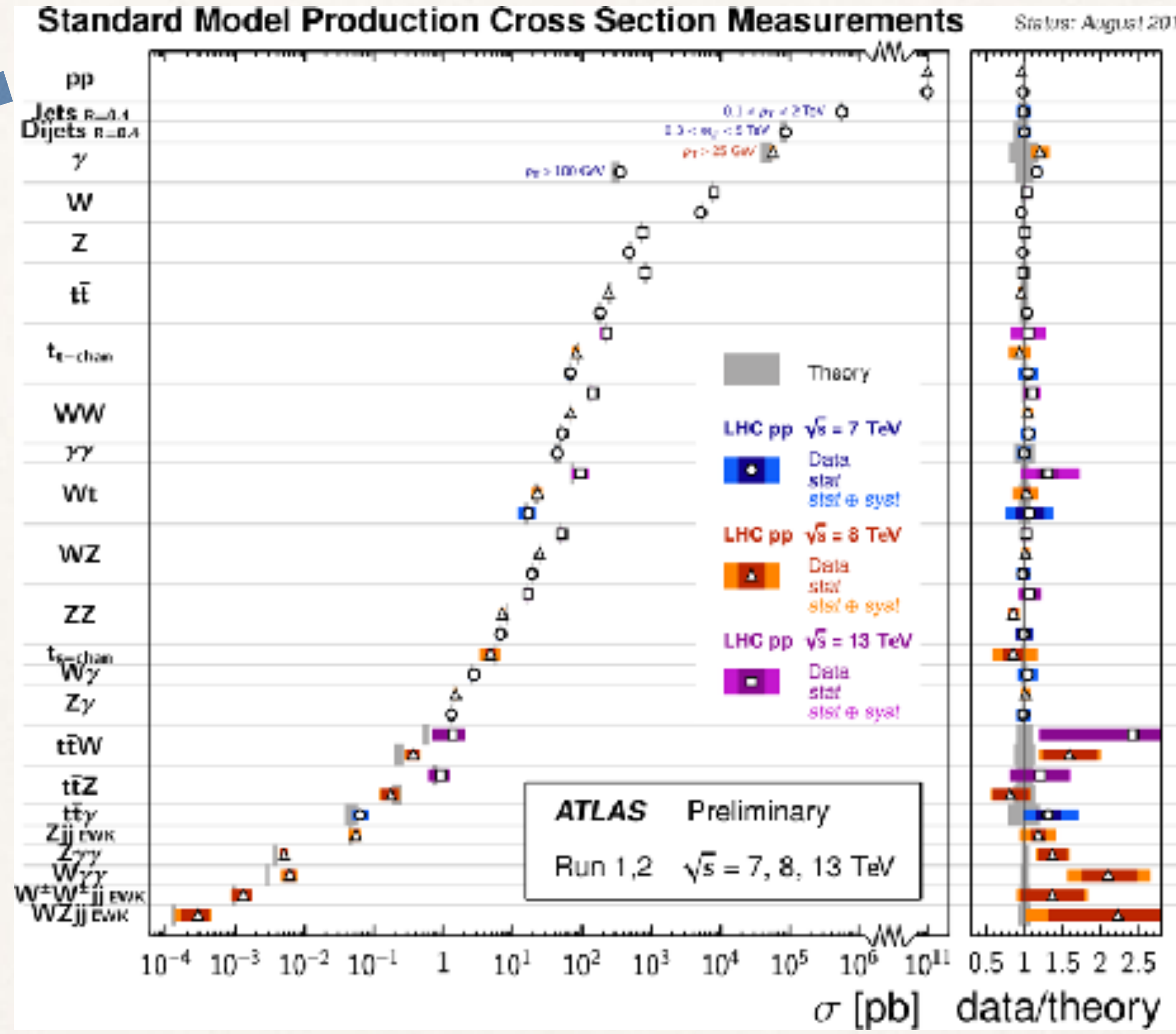
Veronica Sanz (Valencia & Sussex)

University of Sussex
Universitat de València
IFIC Institut de Física Corpuscular
CSIC Consejo Superior de Investigaciones Científicas

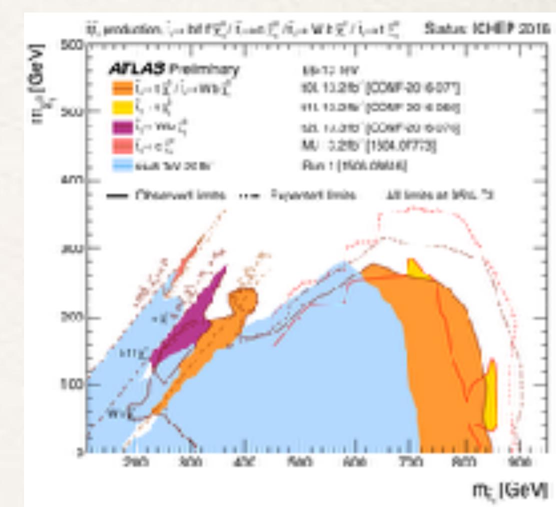
Let's start with the LHC

The LHC is in a mature stage, already providing precision tests for the SM in most channels (excl the Higgs)

Precise tests of the full structure of the SM, based on QFT, symmetries (global/gauge) and consistent ways to break them non-trivial tests of perturb.->non-perturb. QCD



Absence of excesses: interpreted as new physics exclusions



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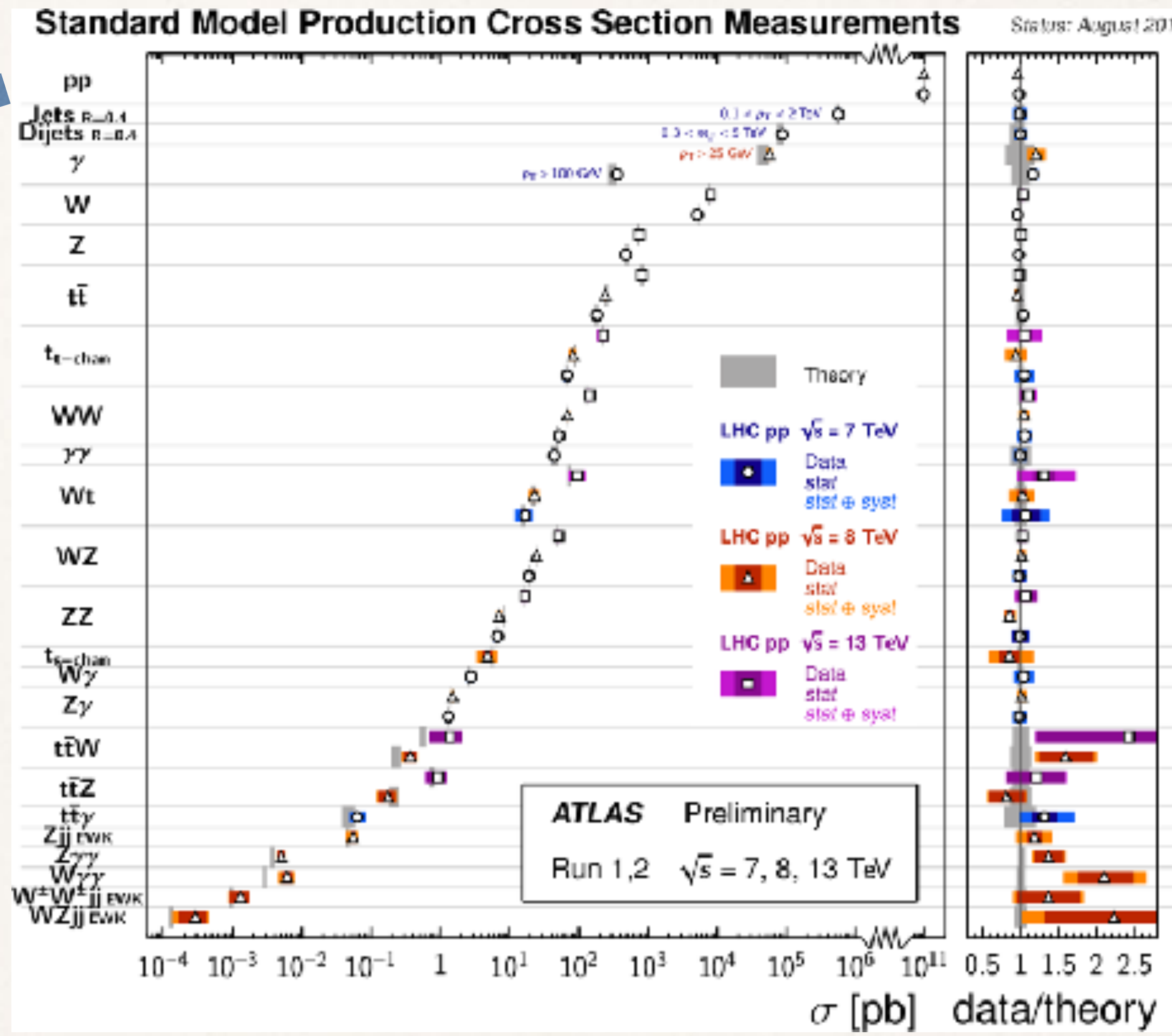

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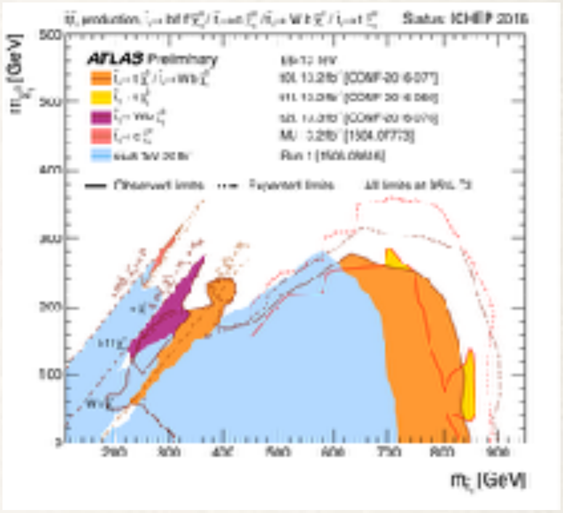


exclusions: rather impressive, many at the TeV
searches: outstanding coverage of possible topologies
any hints: (like in flavor) extremely tempting

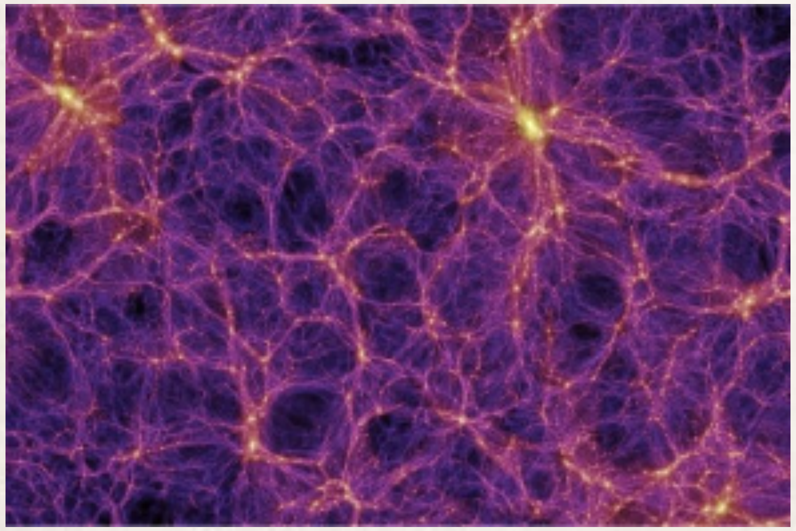
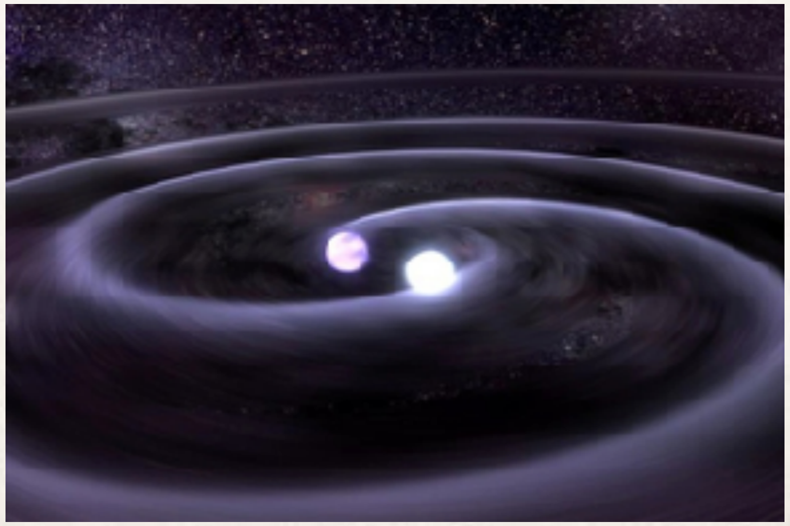
So here we are

What we would hope for

Special relativity
+
equivalence principle

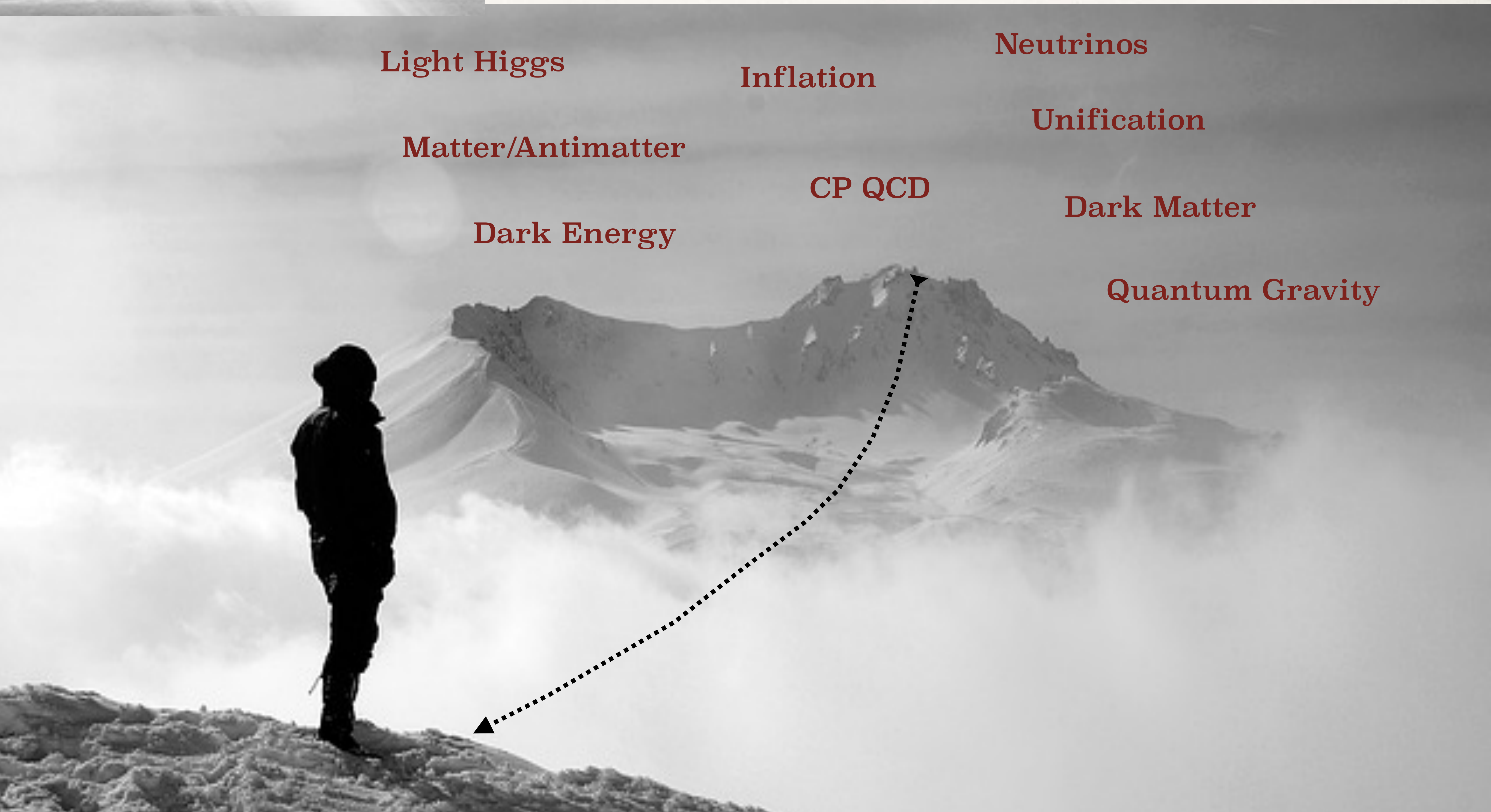
→ development of new, sophisticated mathematical framework

→ **General relativity**

Universe's evolution	gravitational waves	black holes
		

Some years ago

String theory, *the* final theory
Mathematical consistency (anomalies, SUSY)
+guiding principles (QGrav, unification,3 families)
trickle down to the SM, a boundary condition



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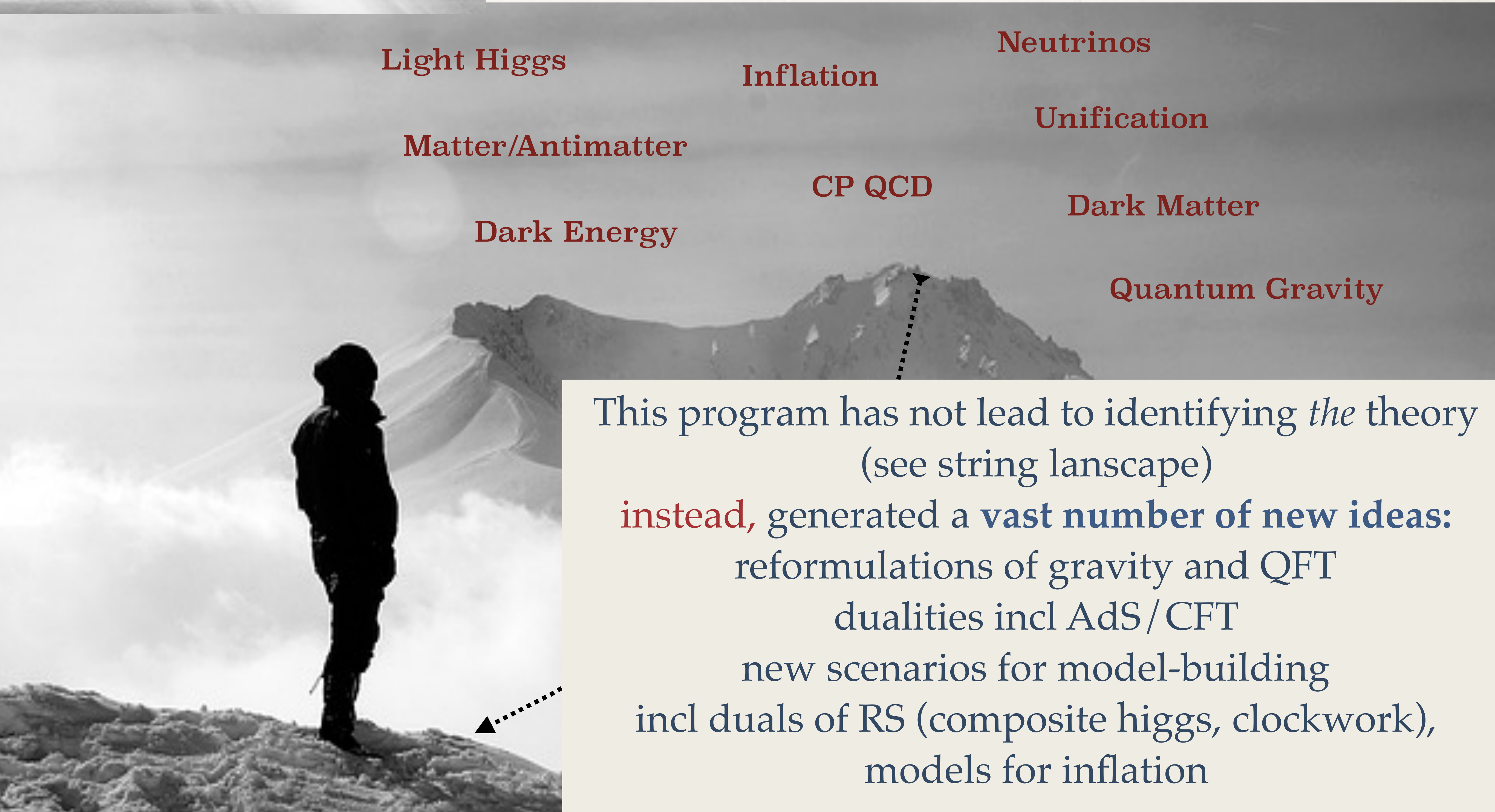
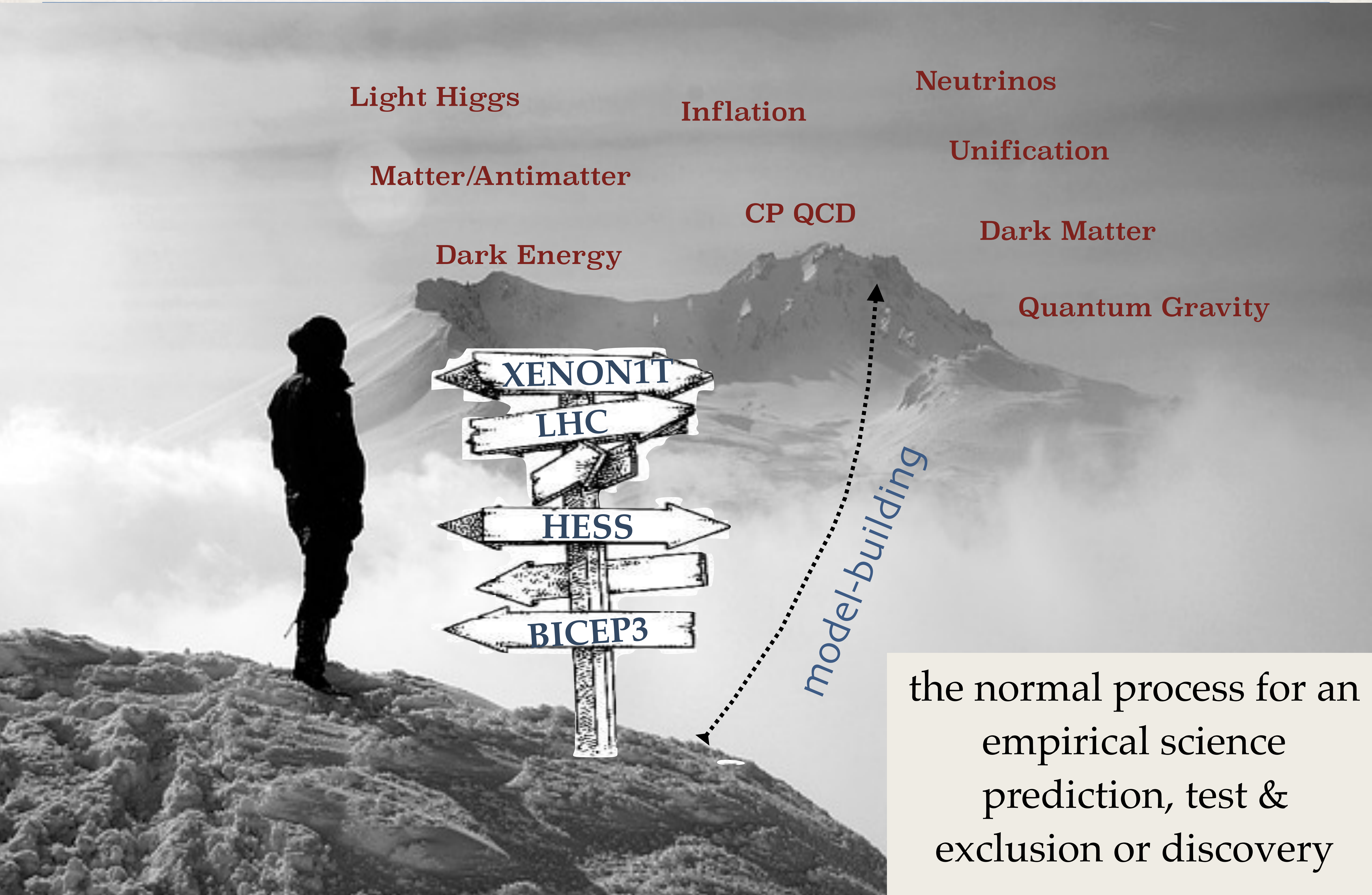


This program has not lead to identifying *the* theory
(see string lanscape)
instead, generated a **vast number of new ideas:**
reformulations of gravity and QFT
dualities incl AdS/CFT
new scenarios for model-building
incl duals of RS (composite higgs, clockwork),
models for inflation

So here we are again, post-LHC Run2



the normal process for an empirical science prediction, test & exclusion or discovery

One way forward: Connecting ideas/experiments

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

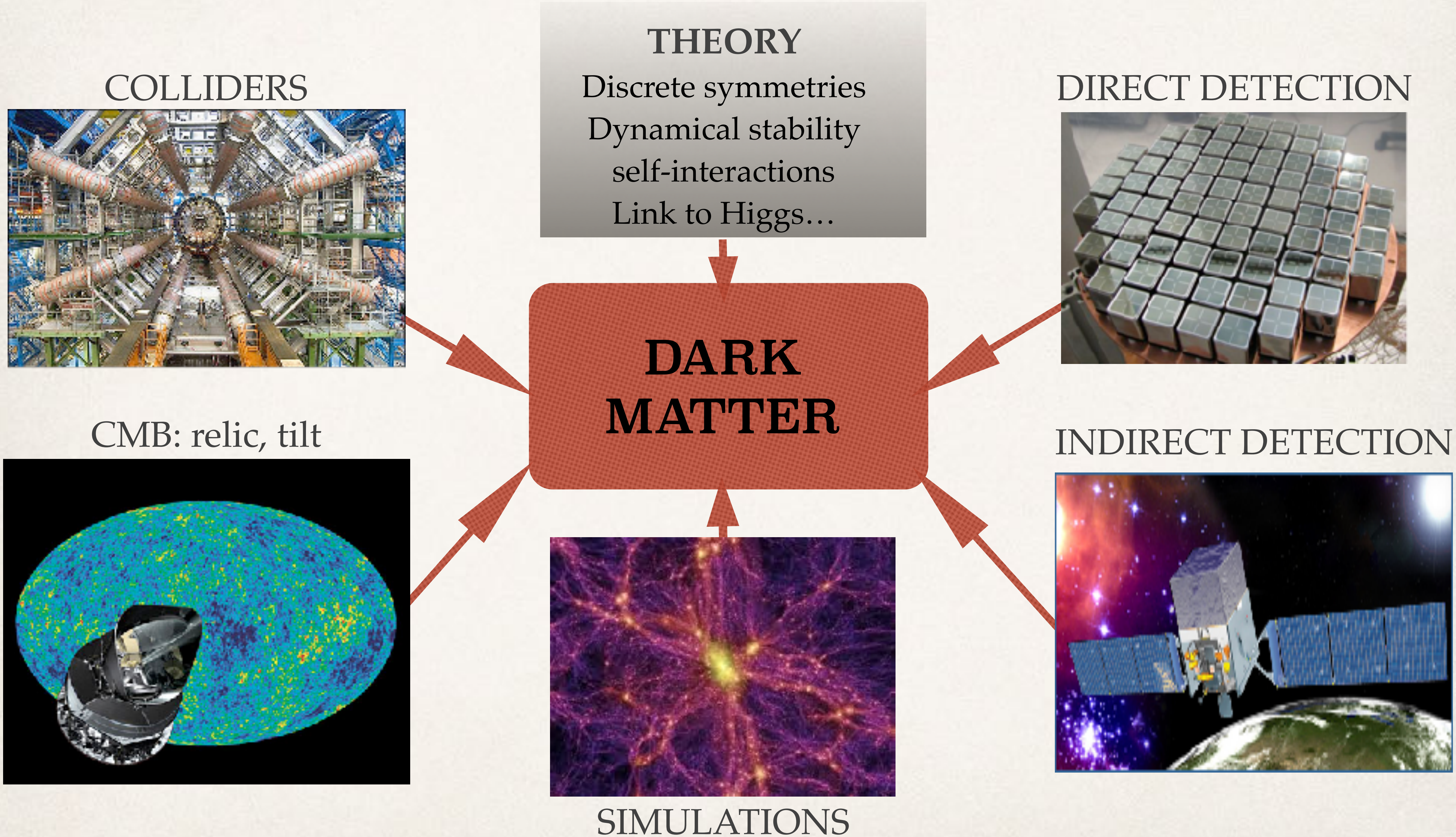
Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

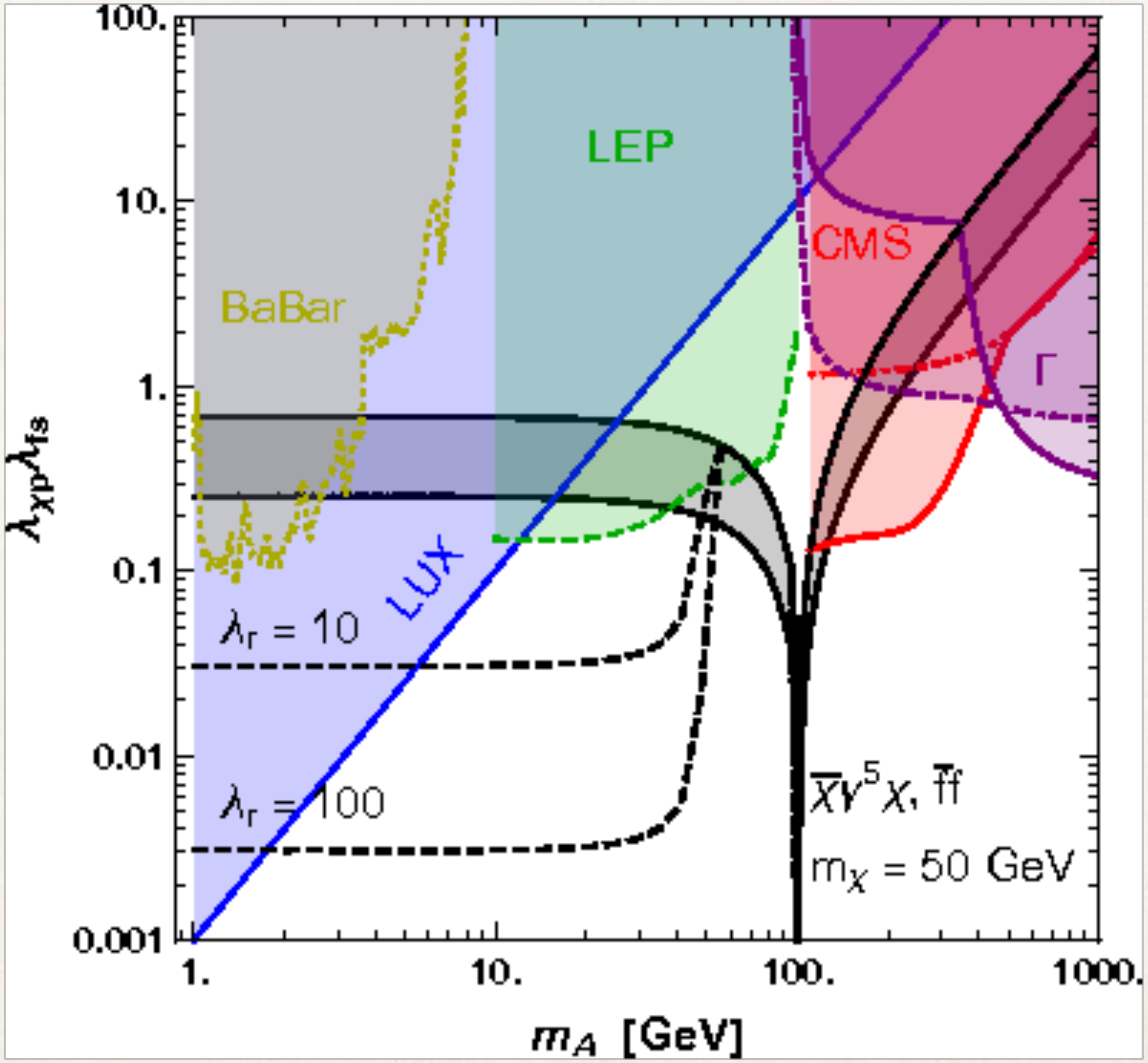
Similar story for Axions and ALPs, scalars are versatile

Many faces of Dark Matter



Complementarity

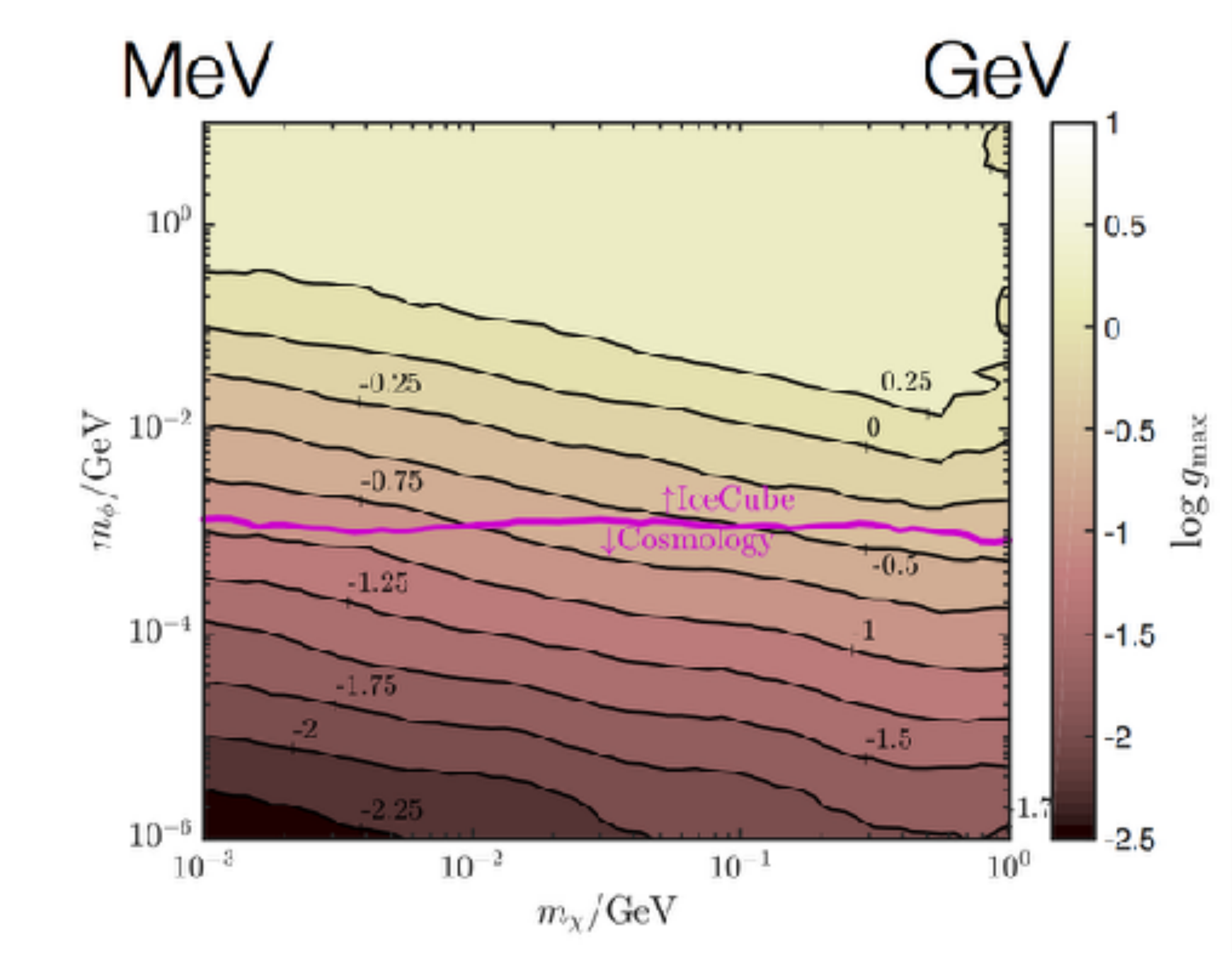
example: propose a solution to an astrophysical excess with a PP model



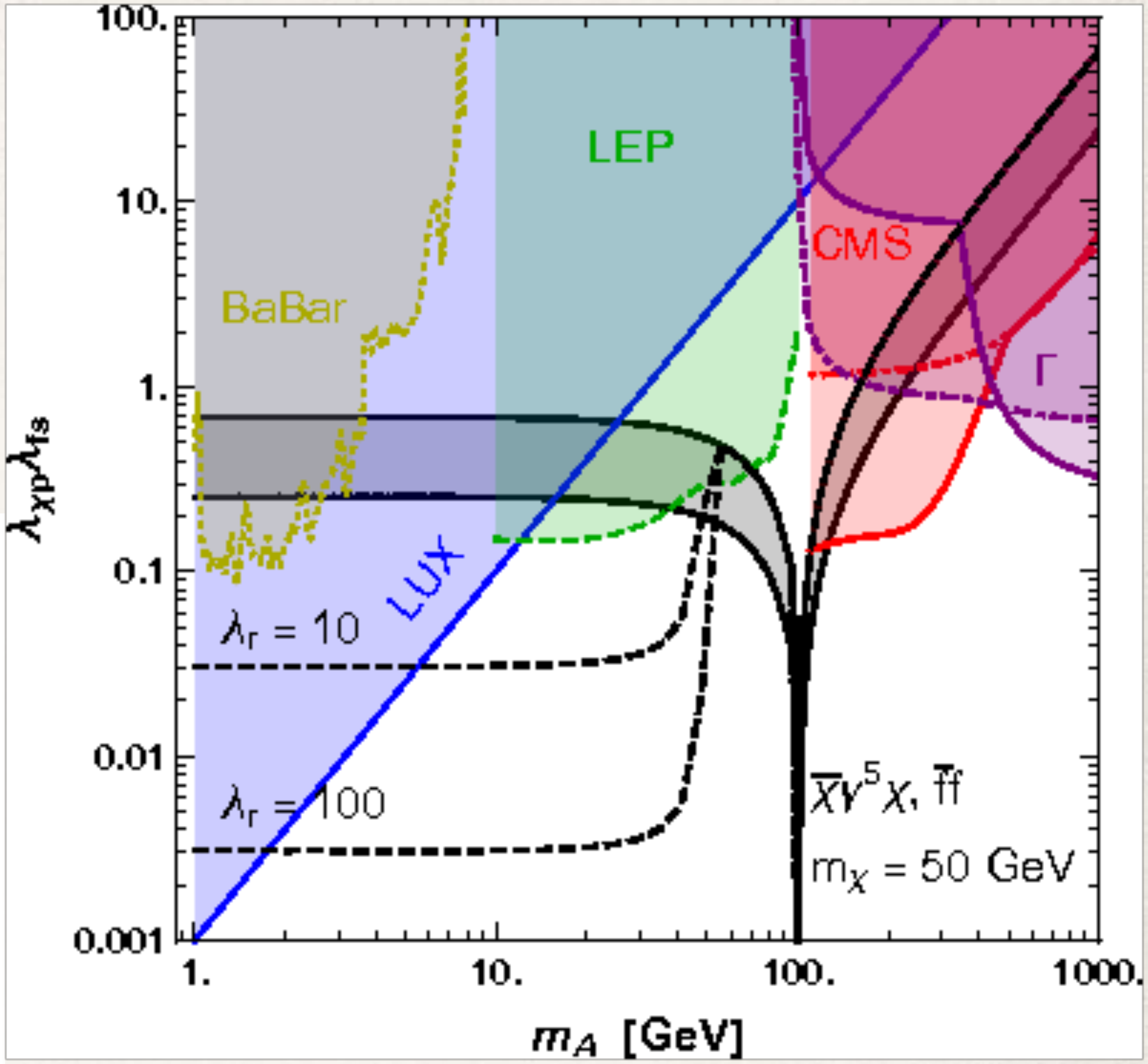
Escudero, Hooper, Witte. 1612.06462

Astrophysics/others

example: propose a solution to an astrophysical excess with a PP model, explore whether it is related to a coupling with neutrinos



Arguelles, Keirandish,Vincent. 1703.00451



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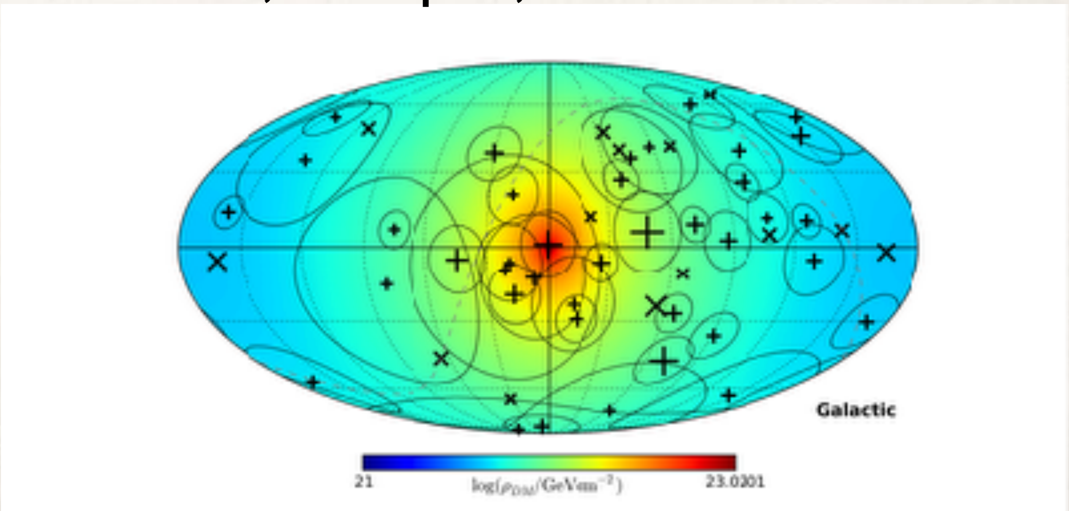
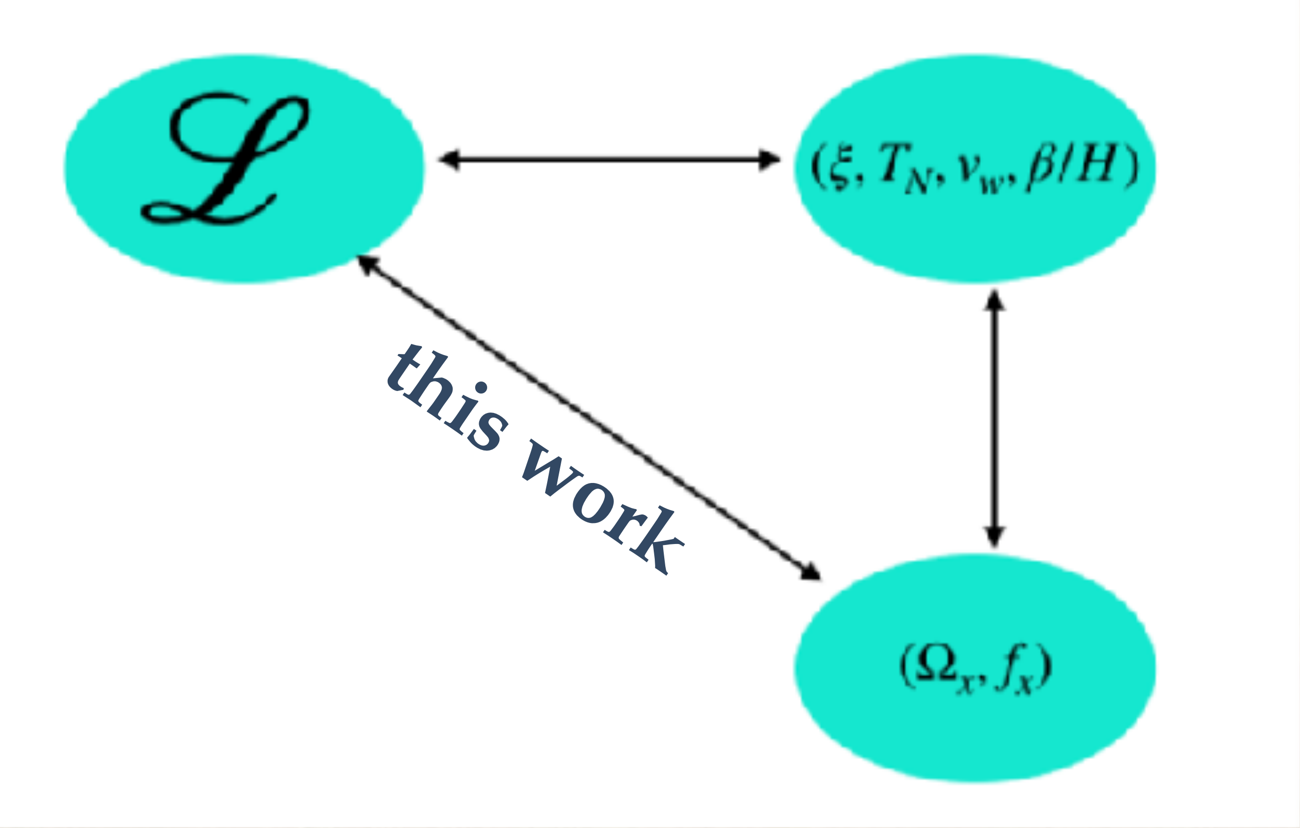


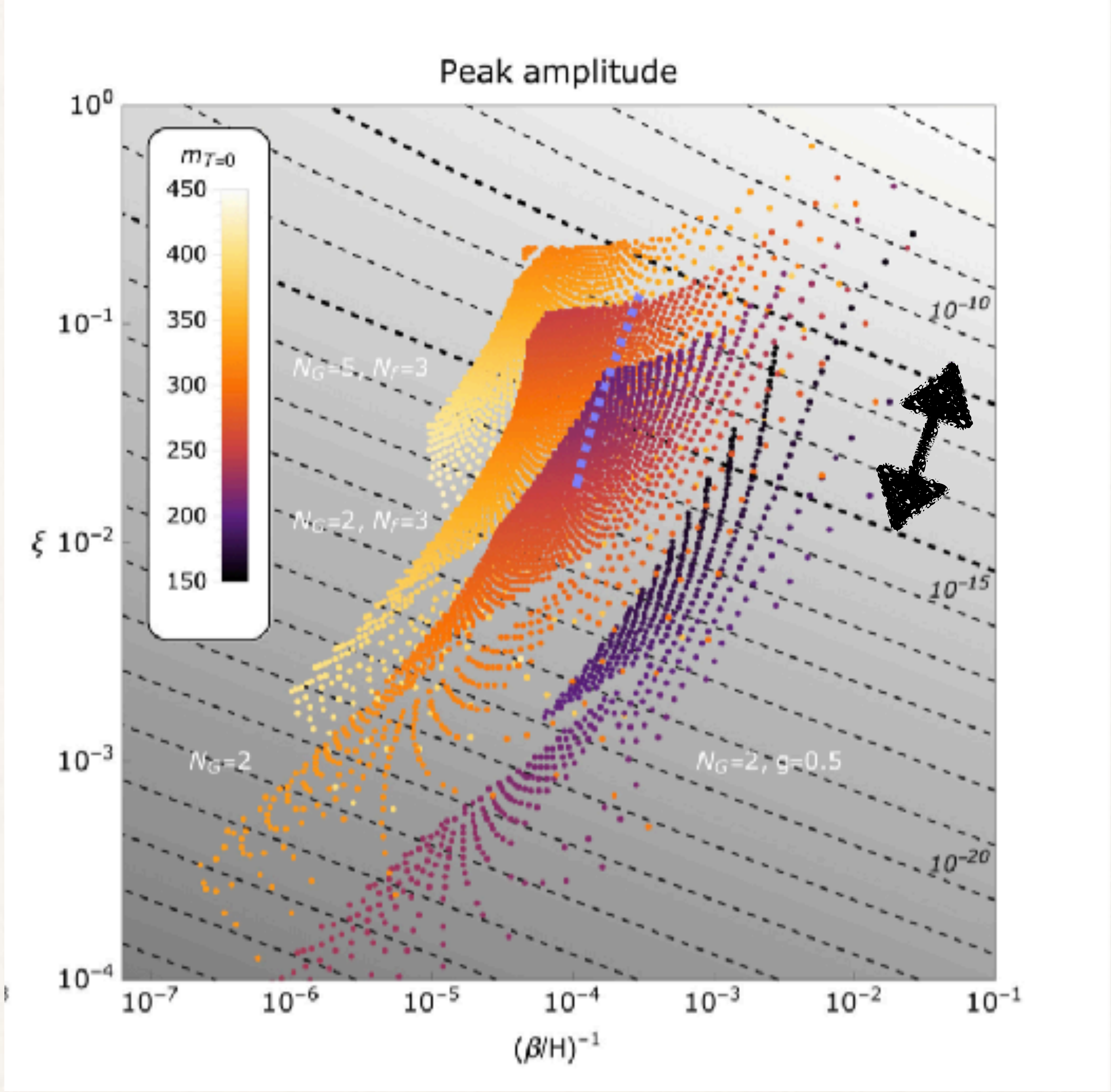
Gravitational waves/others

another example:

CROON, VS, WHITE. 1806.02332

Dark sectors and GWs. Classify sectors with 1st order PT and compute their GW signatures. Map onto DM models.

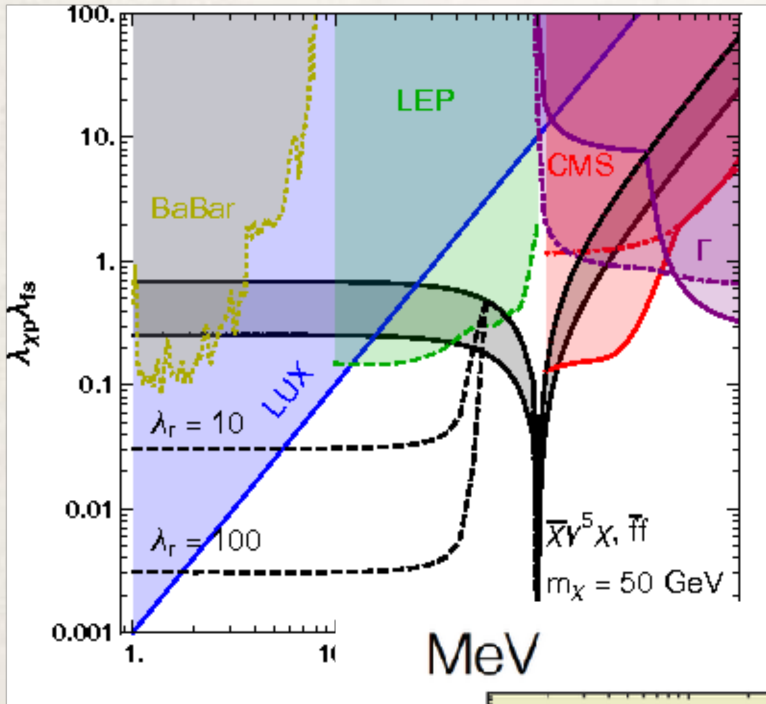


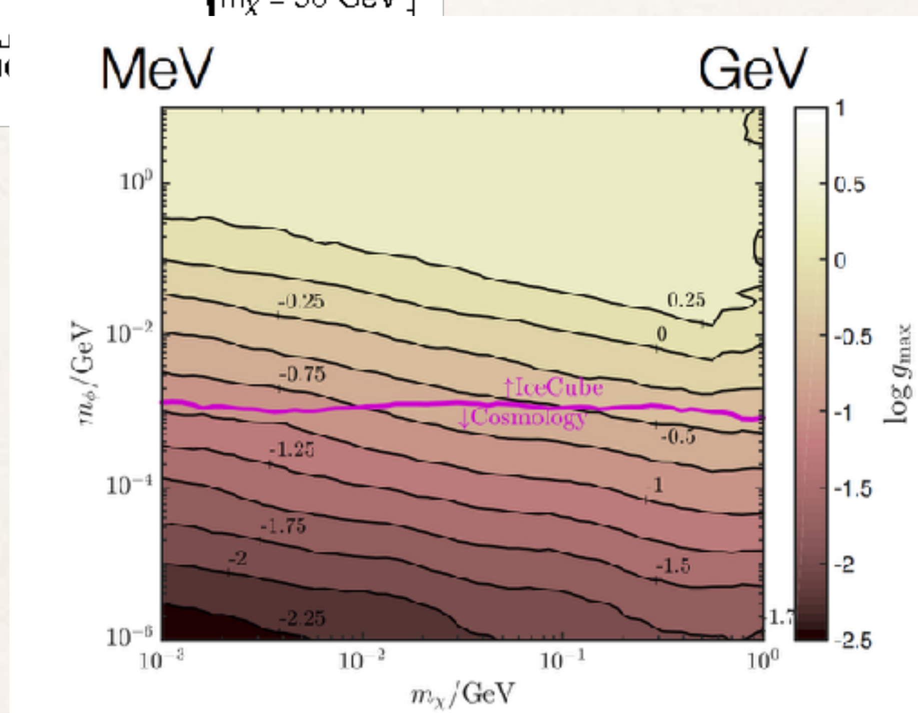


Regions: different dark sectors

Arrow: ~ region LISA (1yr)

These days we think a lot more about **complementarity**





1. New experiments, ways they present results, access to data

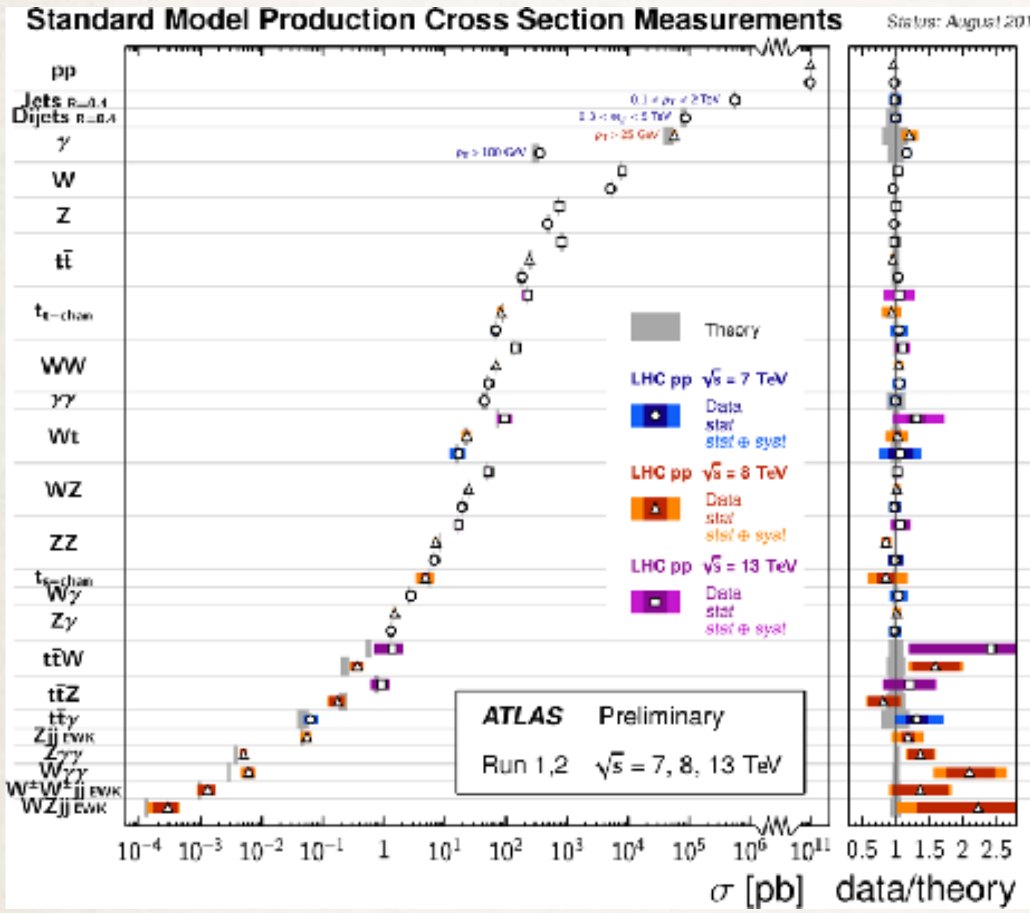
2. Simple straw-man models

3. Development of public tools, or recasting, so we can tackle complex processes and focus on the fundamental ideas

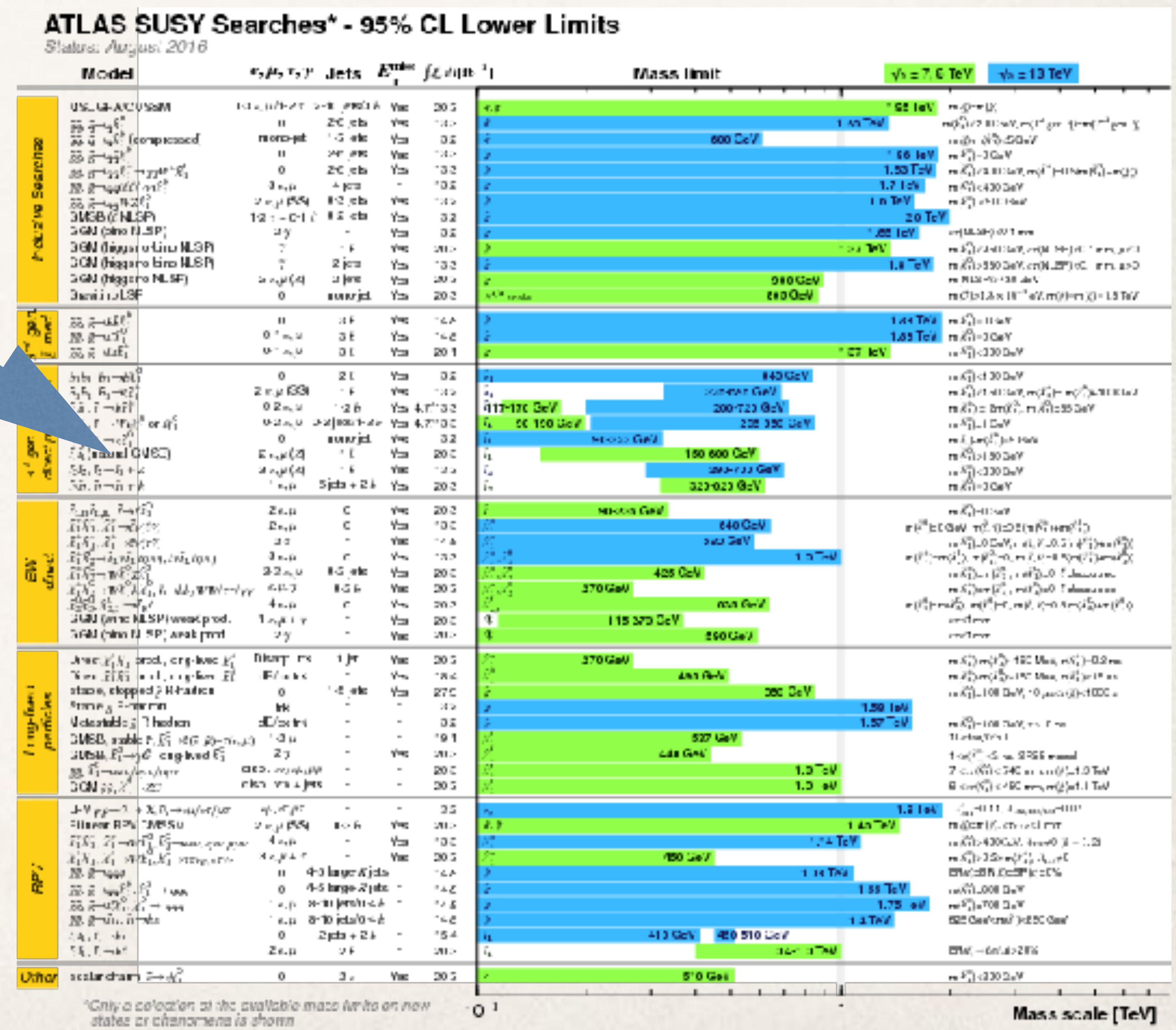
Back to the LHC:
Direct versus indirect searches

Direct searches for new phenomena

consistency of data vs
SM predictions

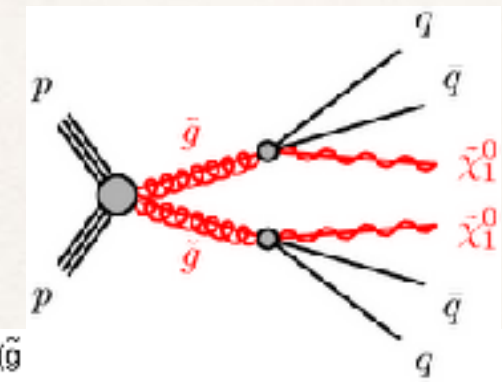


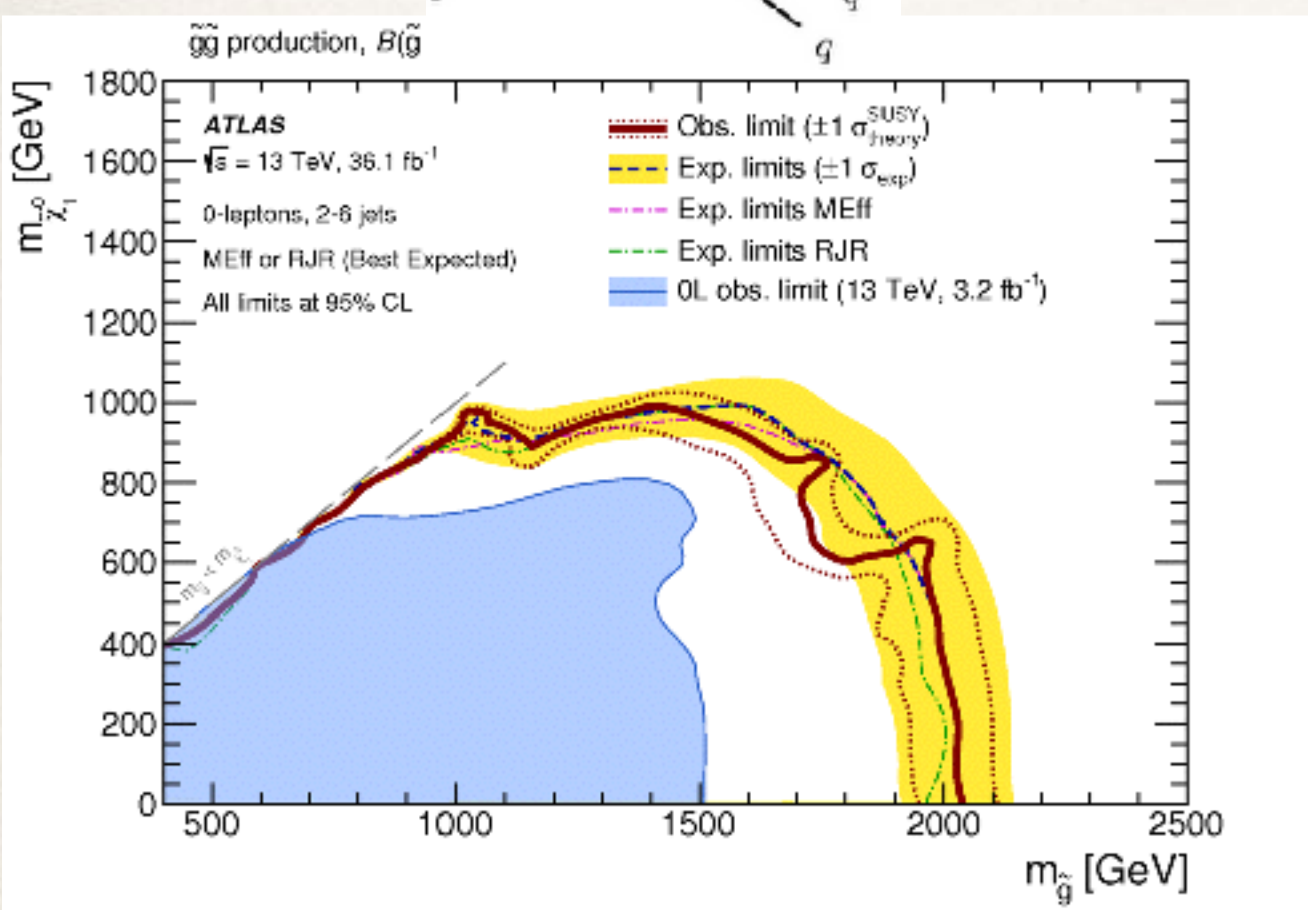
Interpretation in models:
exclusion regions

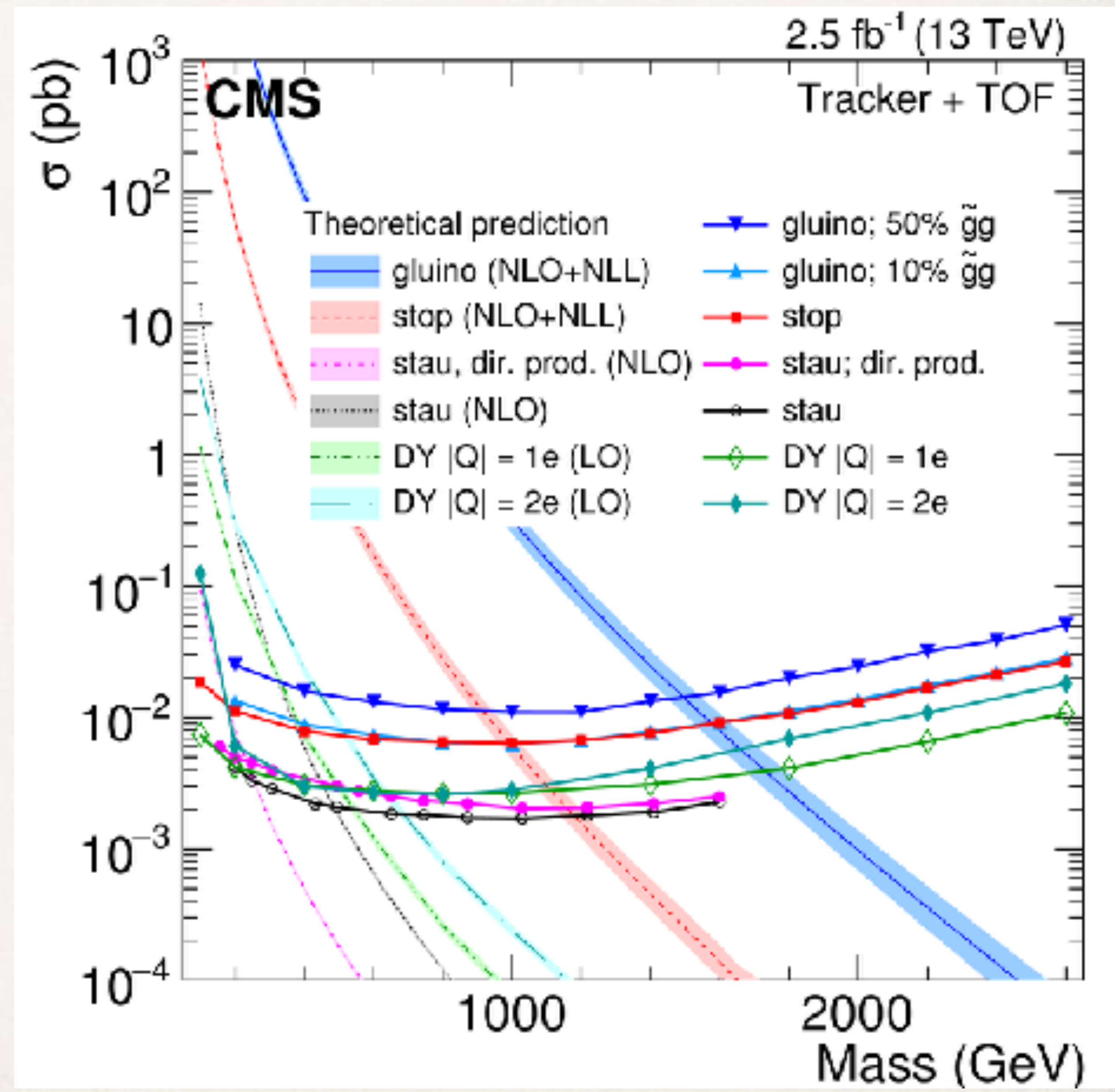


Coloured states to the very exotic

SUSY Benchmark **Jets+MET** **some-SUSY** **HSCPs**





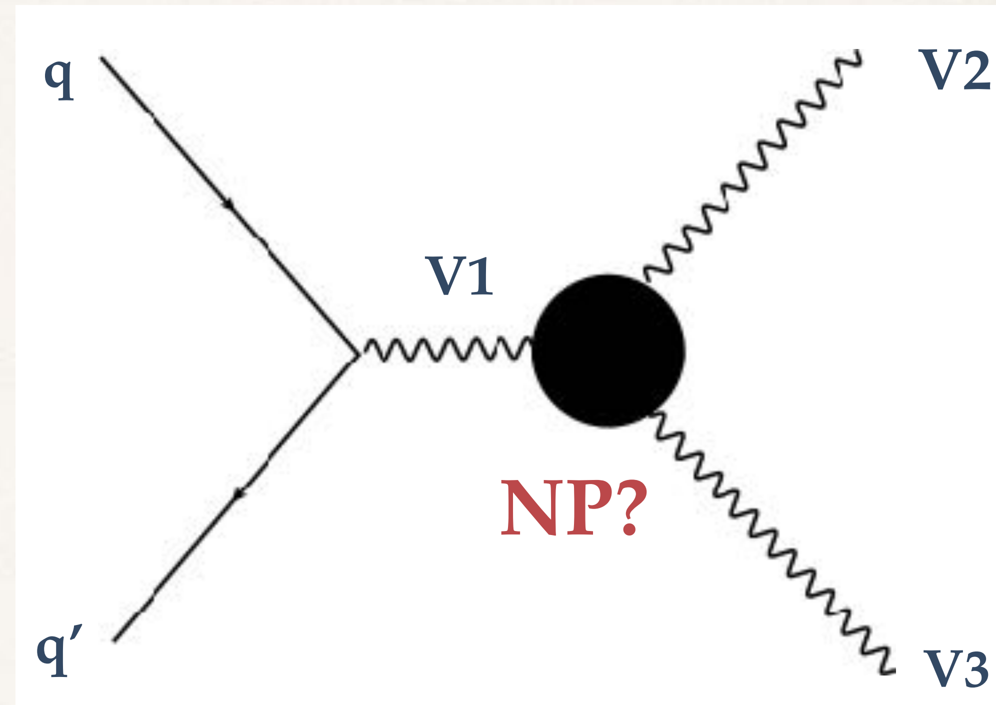


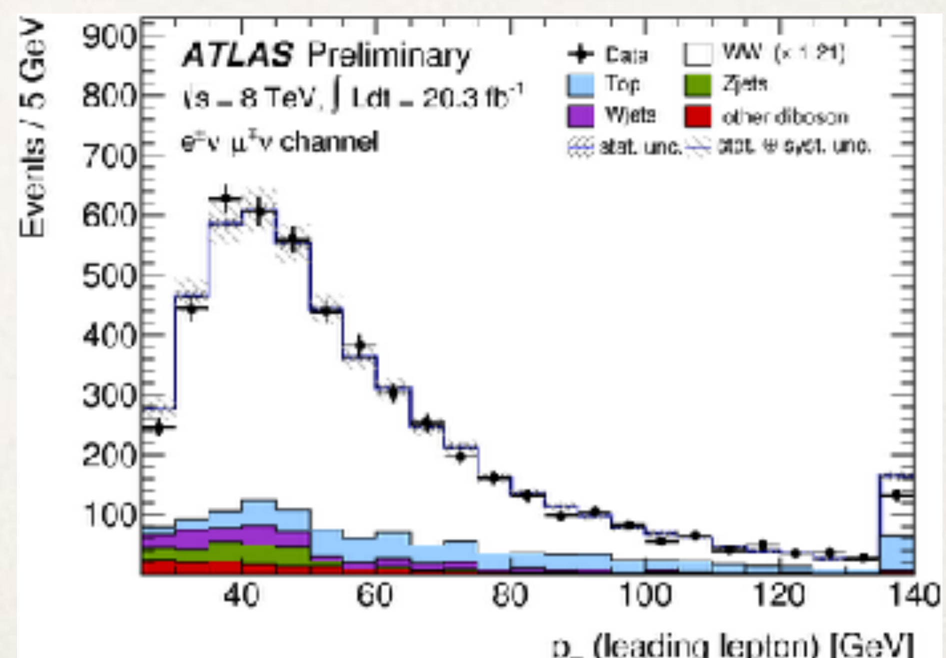
Indirect searches

Focus on SM particles' behaviour
precise determination of couplings and kinematics
comparison with SM,
search for deviations

Indirect searches using the Higgs
since 2012, relatively new
Higgs as a window to NP
expect deviations in its behaviour
Run2 data and beyond
precision Higgs Physics

e.g. Anomalous trilinear gauge couplings, aka **TGCs**

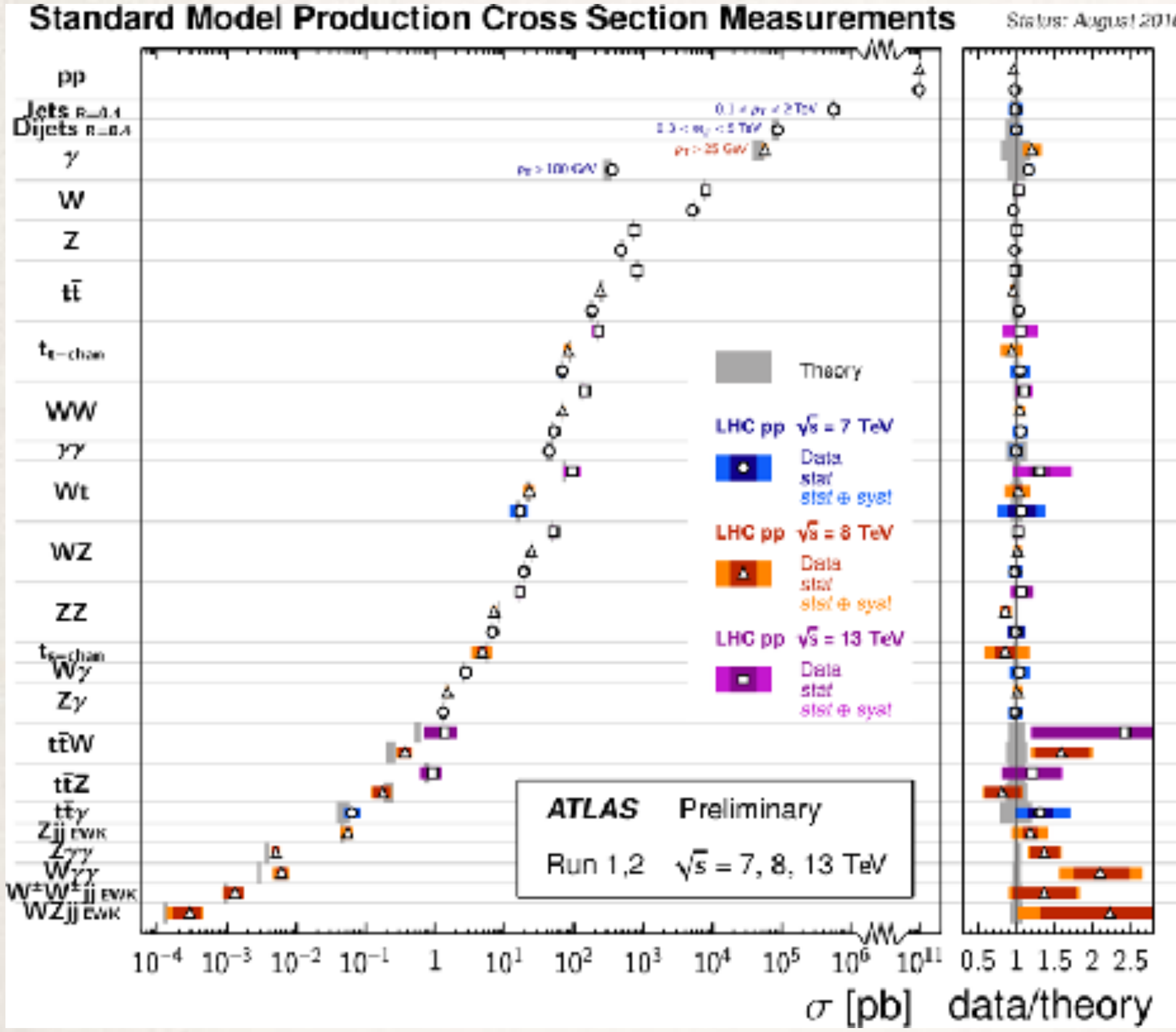


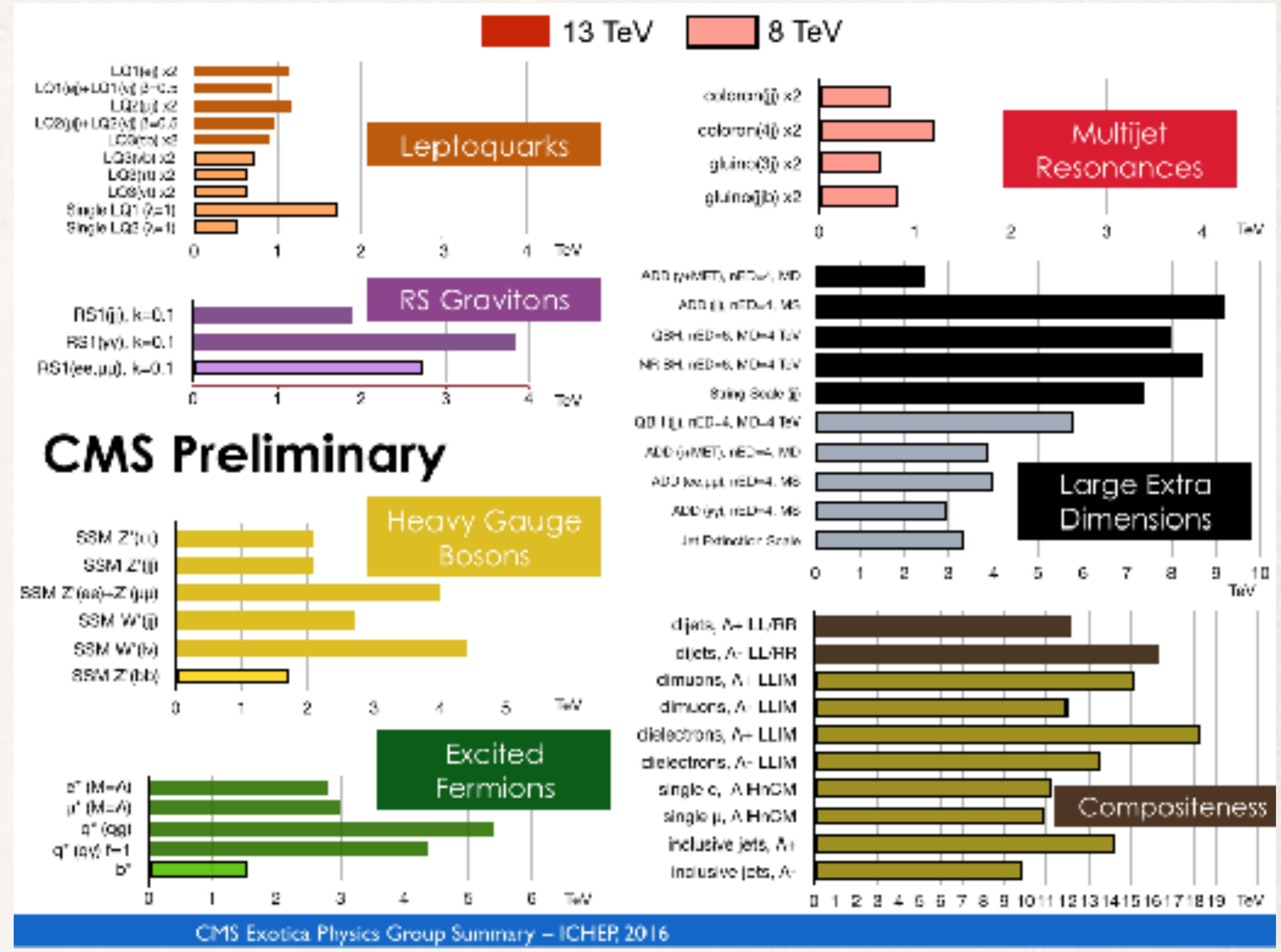


LEP, Tevatron, LHC

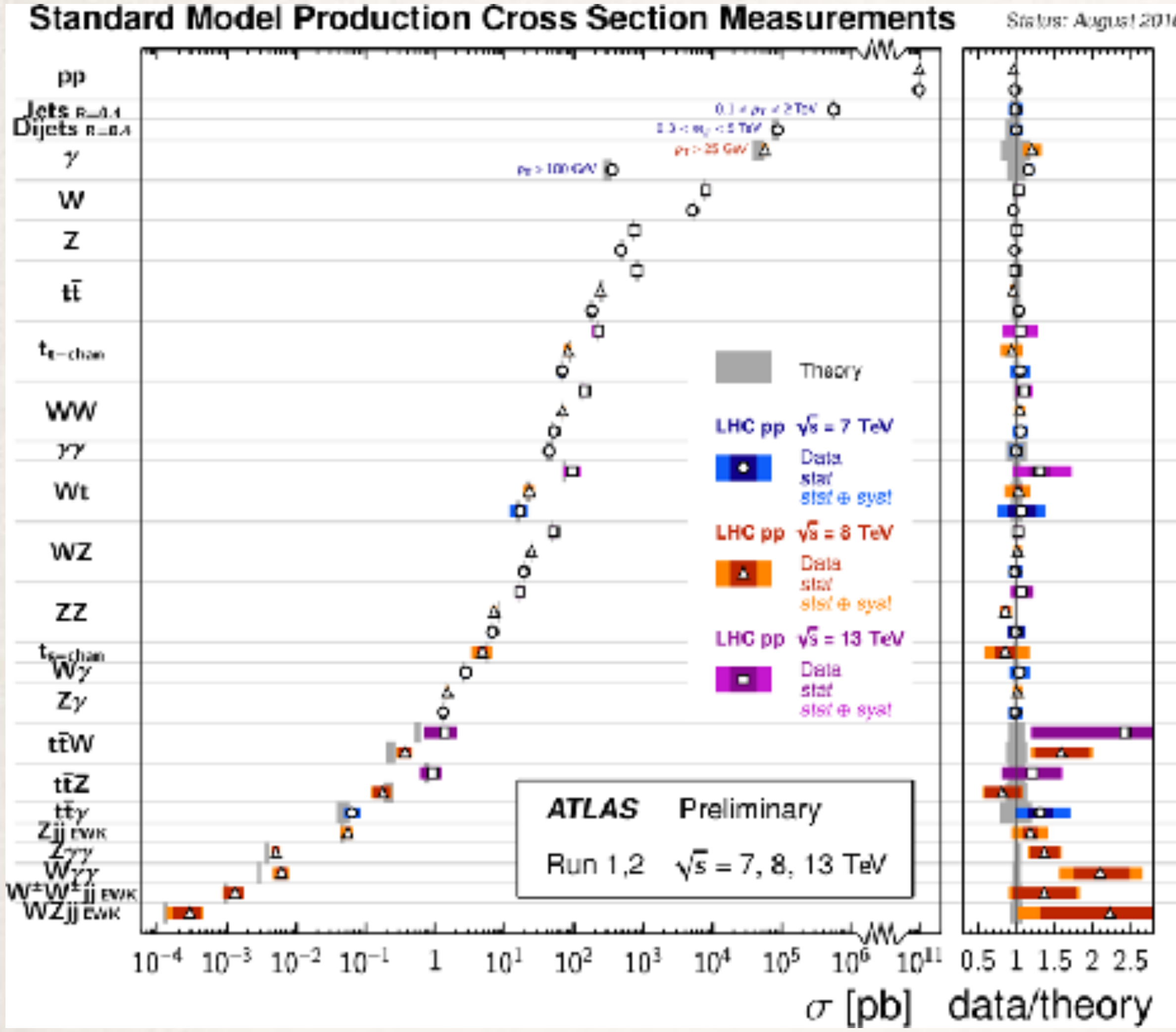
Casting a wide net: the *new* SM

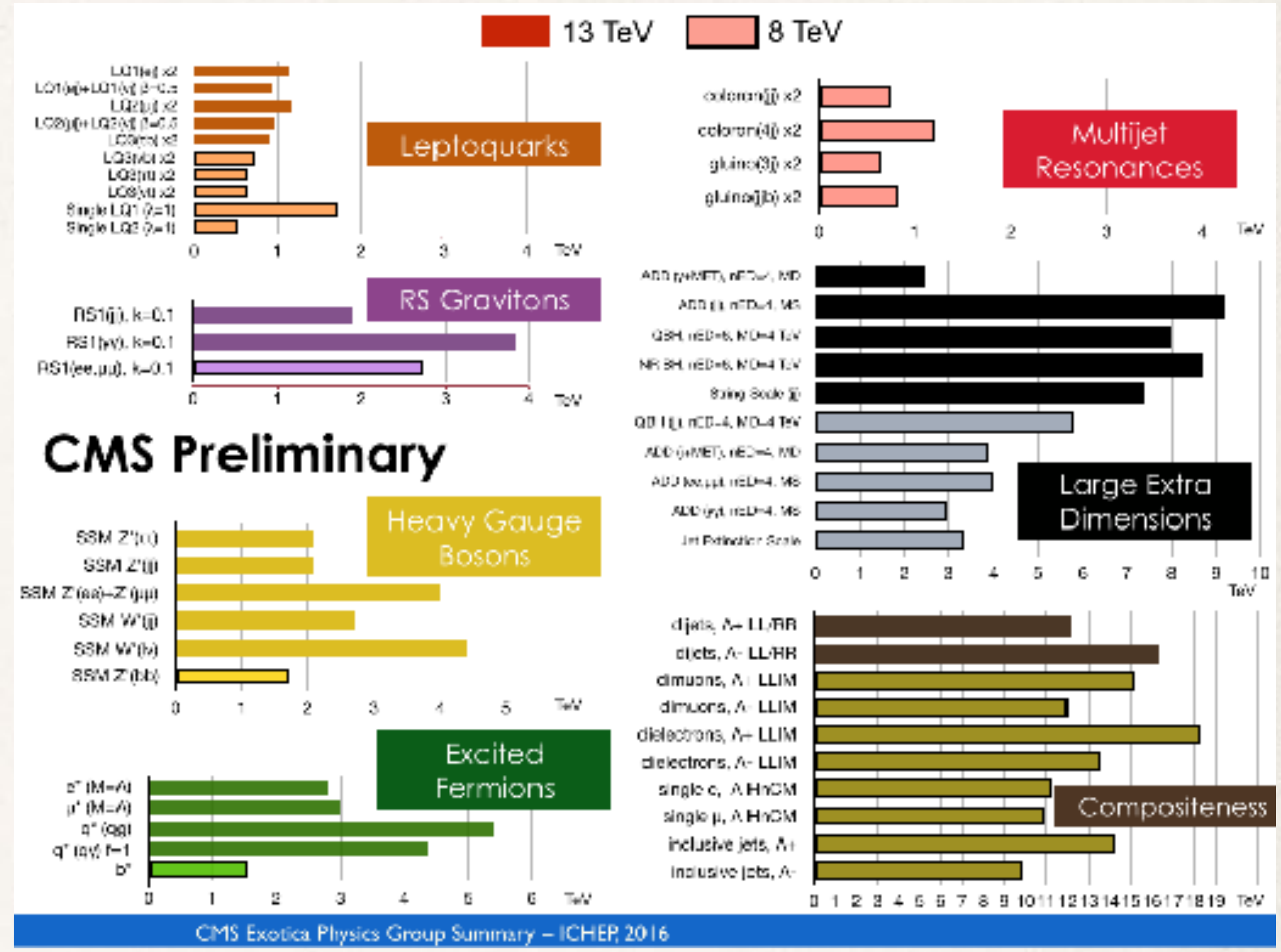
Why EFT?


Standard Model Production Cross Section Measurements
pp
Jets
Dijets
W
Z
WW
Wt
WZ
ZZ
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
σ [pb]
data/theory


13 TeV
8 TeV
Leptoquarks
Multijet Resonances
RS Gravitons
CMS Preliminary
Large Extra Dimensions
Heavy Gauge Bosons
Excited Fermions
Compositeness
TeV
CMS Exotica Physics Group Summary – ICHEP, 2016

Why EFT?





The SM is a good description of Nature at the LHC

==> new resonances/phenomena may be **heavy**

==> Our hopes for simple/natural models are not realised

==> We should adopt a more **model-independent** strategy when interpreting data

EFT approach

Well-defined theoretical approach

Assumes New Physics states are heavy

Write Effective Lagrangian with only light (SM) particles

BSM effects can be incorporated as a momentum expansion

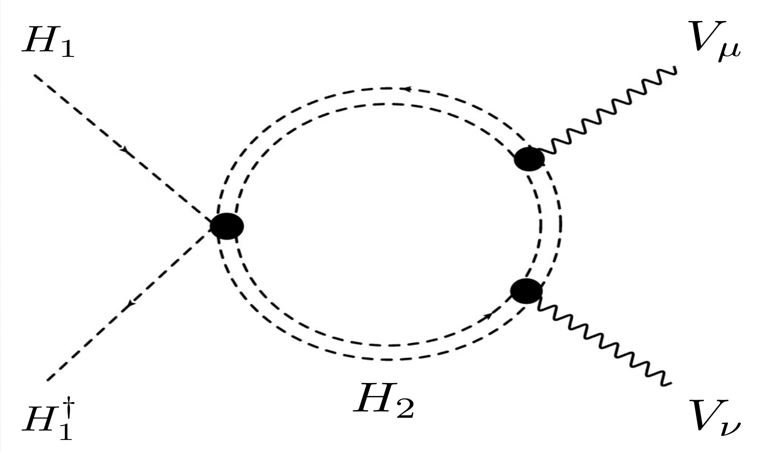
dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\,\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\,\mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

example:

2HDM



$$\frac{ig}{2m_W^2}\bar{c}_W \left[\Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi\right] D_\nu W^{k,\mu\nu}$$

where $\bar{c}_W = \dfrac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$

EFT approach

THEORY

Model-independent parametrization deformations respect to the SM

Well-defined theory
can be improved order by order in momentum expansion
consistent addition of higher-order QCD and EW corrections

Connection to models is straightforward

EXPERIMENT

Beyond kappa-formalism: Allows for a richer and generic set of kinematic features

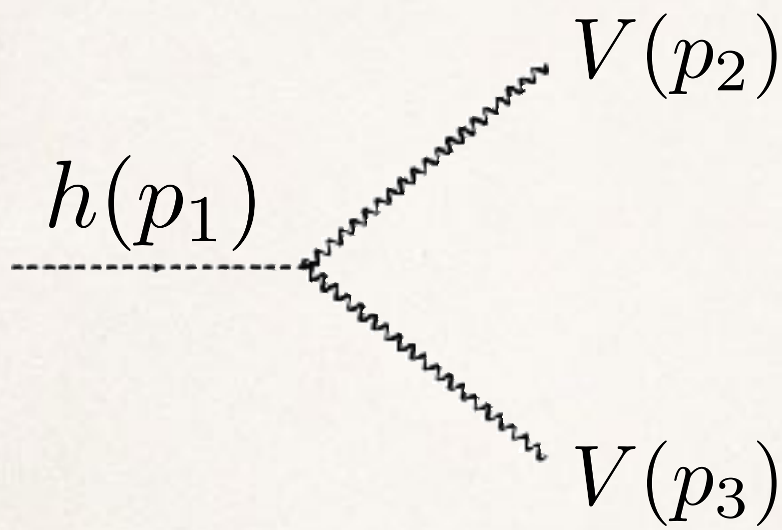
Higher-order precision in QCD/EW

Can treat EFT effects on backgrounds and signal consistently

The way to combine all Higgs channels and EW production

EFT and differential information

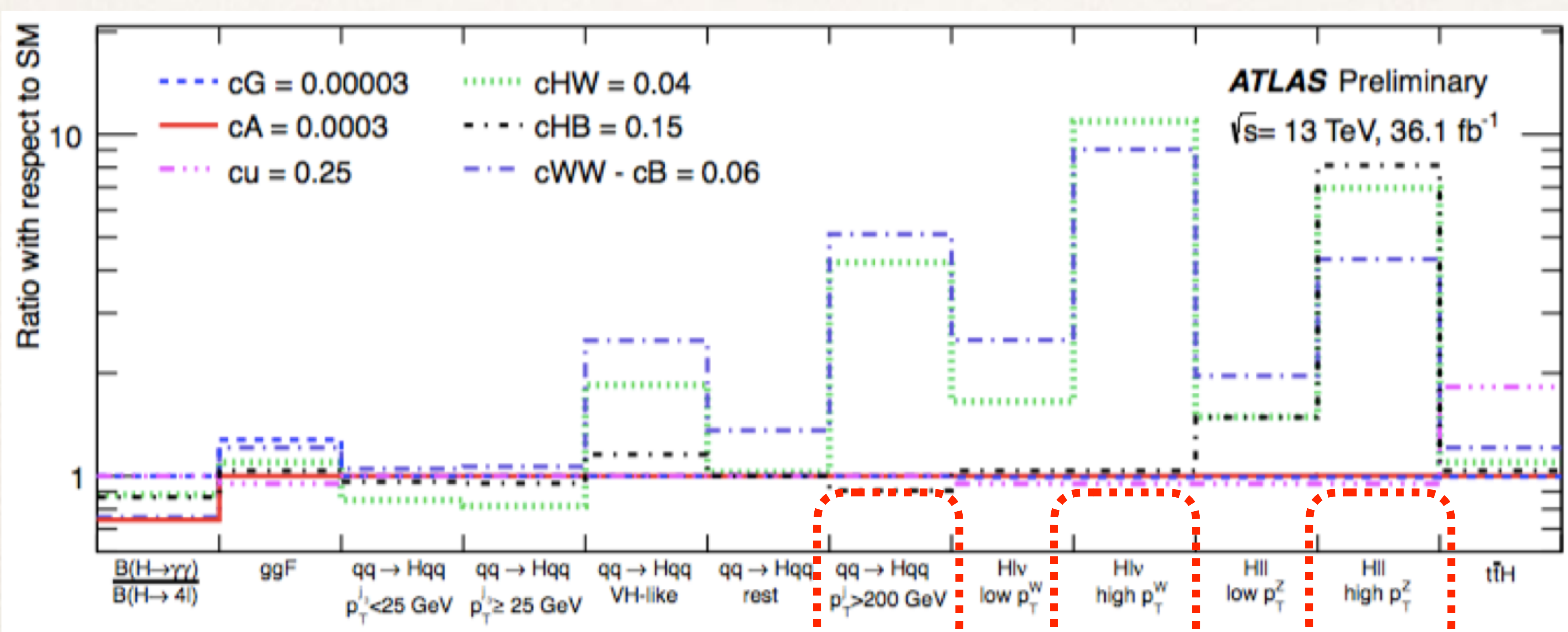
$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_\nu \partial_\mu V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$



$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

$$-i g^{(1)}_{hVV} p_3^\mu p_2^\nu \quad -i\tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

+ off-shell pieces



Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

$$\bar{c}_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right]\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right)\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2)\,\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

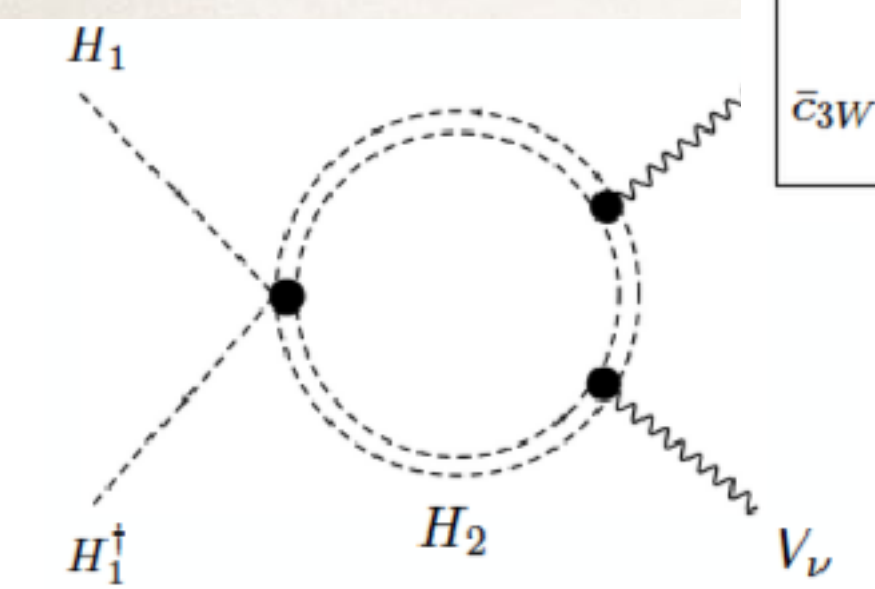
$$c_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = \frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

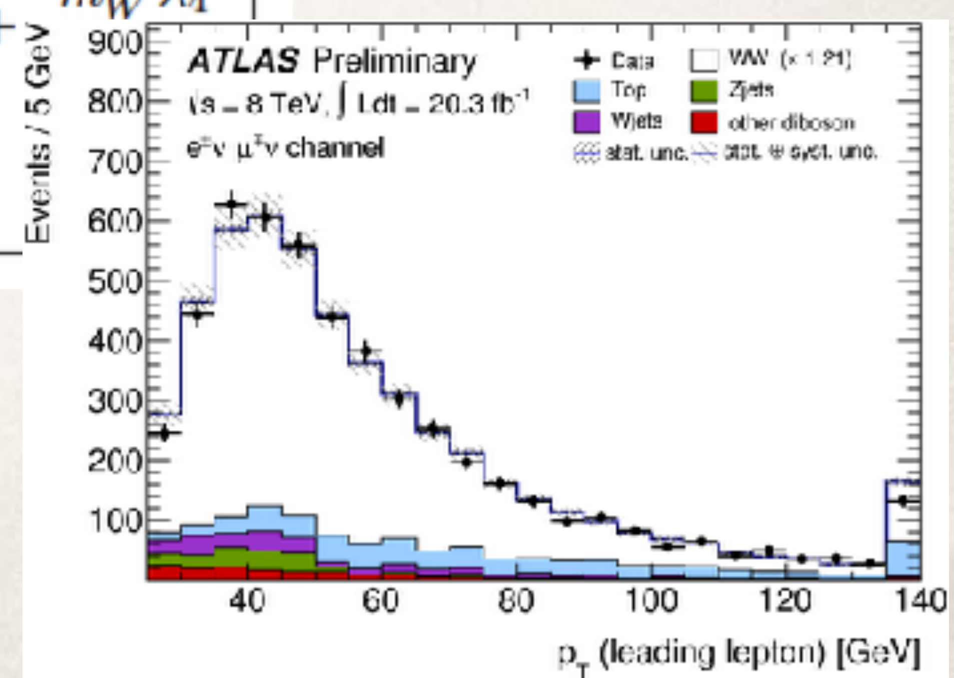
$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{\ldots}$$

$$\bar{c}_{3W} = \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde{\mu}_2^2}$$

MODELS



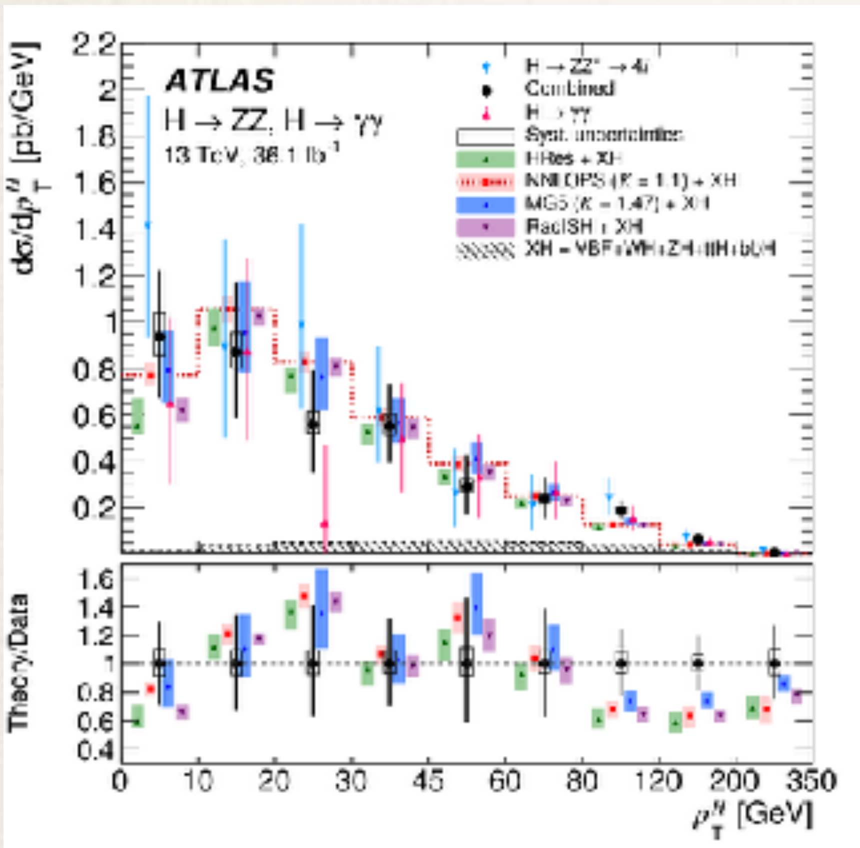
DATA



Advantages

- **Combination**: LHC Higgs and EW production, low energy, EWPTs
- **Precision:** higher-order EW and QCD, dimension-eight, chiral logs
- **Consistency:** Backgrounds and signal
- **Reduces model biases:** explore theories beyond known paradigms
- **Matching:** Direct connection to models

EFTs in PP are an old friend



Maybe you have been working on
low-E flavour/CPV/BLV physics
precision calculations or simply using bounds
What's different for the EFT@EW scale?

We're testing it using a *hadron* collider
flavour physics: heavy means heavy
EW EFT: we are in this border between kinematic reach and precision
& parameter space is very large

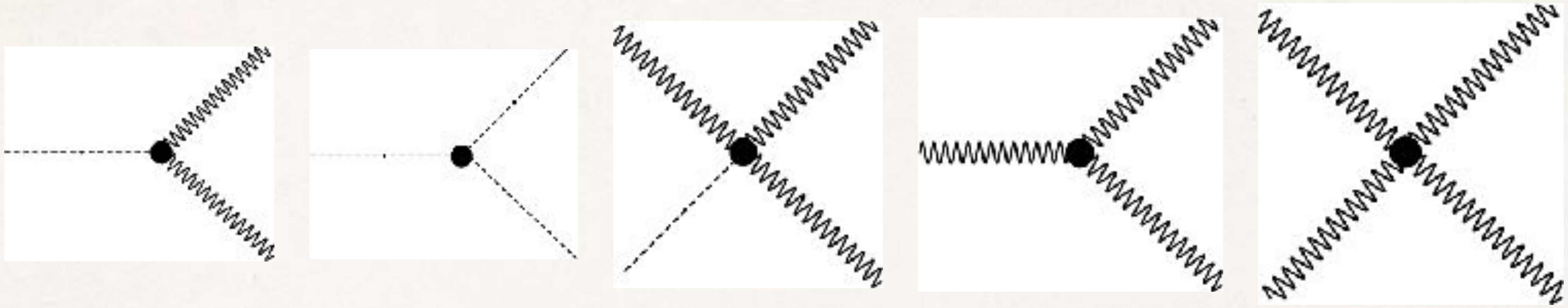
Disadvantages

- **Assumptions**: Only SM light states
- **Complexity:** Large number of parameters
- **Validity:** EFT cannot be used in regions of energies ~ scale of new resonances

Combination of data — SMEFT

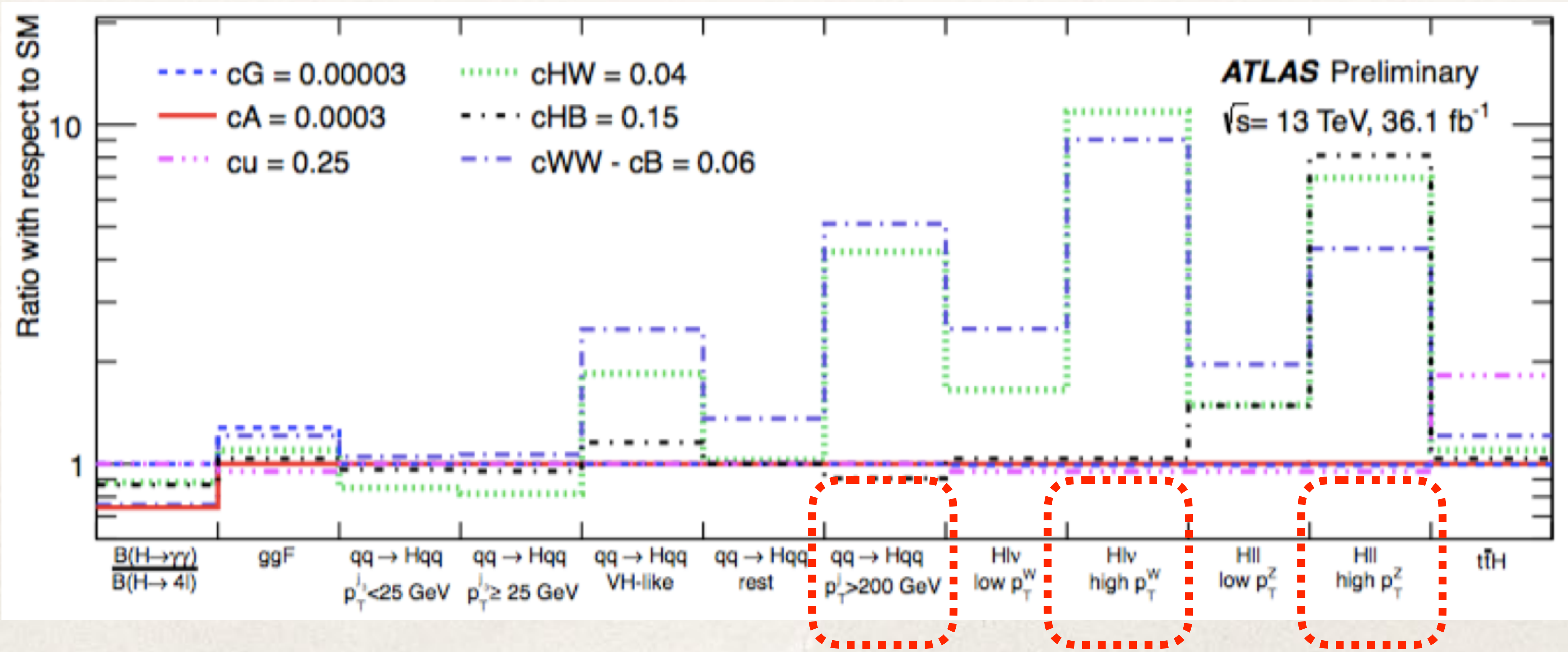
Global analyses using EFTs

EFTs induce effects in many channels, ideal framework for **combination**



ALLOUL, FUKS, VS. 1310.5150,
GORBAHN, NO, VS. 1502.07352

key use of differential information



SMEFT global analysis

ELLIS, MURPHY, VS, YOU. 1803.03252

In this work:

Use EWPT, Higgs and diboson data, incl use STXS

Assume linear EWSB, CP-conservation and MFV

Present results in Warsaw and SILH bases, 20 operators

Matching to simplified UV models

e.g. **WARSAW**

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$+ \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2}H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$
$$+ \frac{\bar{C}_{Hq}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}_{Hq}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$$

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H})$$
$$+ \frac{\bar{C}_G}{v^2}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\, G^A_{\mu\nu}$$
$$+ \frac{\bar{C}_{HW}}{v^2}H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2}H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.$$

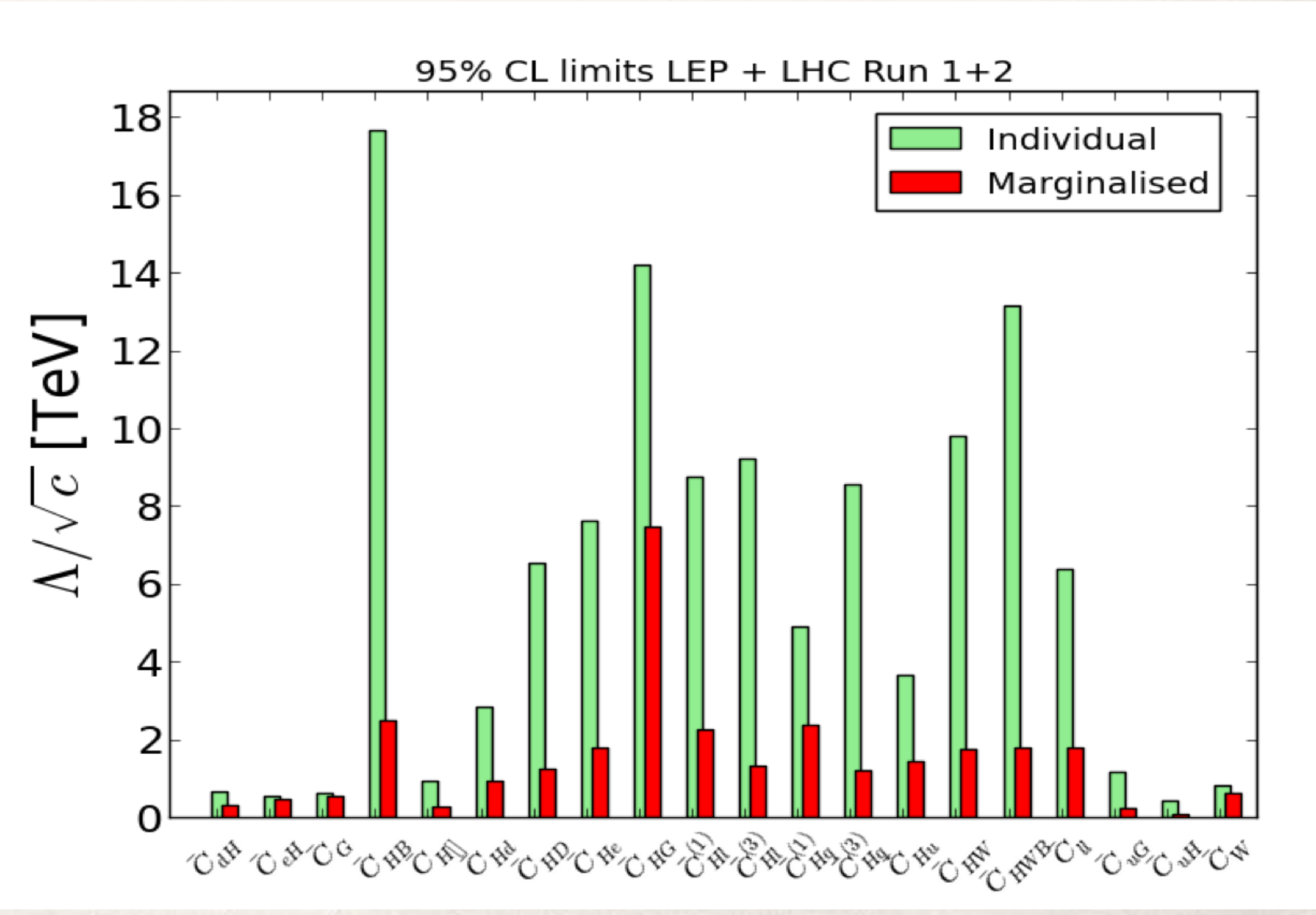
SMEFT global analysis

ELLIS, MURPHY, VS, YOU. 1803.03252

Theory	χ^2	χ^2/n_d	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564

SMEFT: 20 deformations
SMEFT*: 13 deformations
(weakly coupled and renormalizable)

SEE ALSO **MORE RECENT**
GONZALEZ-GARCIA ET AL
1812.01009
PLEHN ET AL.
1812.07587
SIMILAR RESULTS



SMEFT global analysis

ELLIS, MURPHY, VS, YOU. 1803.03252

Constraints on simple extensions of the SM

Model	χ^2	$\chi^2/n_{\rm d}$	Coupling	Mass / TeV
SM	157	0.987	-	-
$\mathcal{S}_1$	156	0.986	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9) \cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.0,\ 49)$
φ, Type I	156	0.986	$Z_6 \cdot \cos\beta = -0.64 \pm 0.59$	$M_\varphi = (0.9,\ 4.3)$
Ξ	155	0.984	$\lvert \kappa_\Xi\rvert^2 = (4.2 \pm 3.4) \cdot 10^{-3}$	$M_\Xi = (12,\ 35)$
N	155	0.978	$\lvert \lambda_N\rvert^2 = (1.8 \pm 1.2) \cdot 10^{-2}$	$M_N = (5.8,\ 13)$
$\mathcal{W}_1$	155	0.984	$\left\lvert \hat{g}^{\phi}_{\mathcal{W}_1}\right\rvert^2 = (3.3 \pm 2.7) \cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
E	156.9	0.993	$\lvert \lambda_E\rvert^2 = (2.0 \pm 9.7) \cdot 10^{-3}$	$M_E = (9.2,\ \infty)$
Δ_3	156	0.990	$\lvert \lambda_{\Delta_3}\rvert^2 = (0.8 \pm 1.1) \cdot 10^{-2}$	$M_{\Delta_3} = (7.3,\ \infty)$
Σ	156.7	0.992	$\lvert \lambda_\Sigma\rvert^2 = (0.9 \pm 2.0) \cdot 10^{-2}$	$M_\Sigma = (5.9,\ \infty)$
Q_5	156	0.990	$\lvert \lambda_{Q_5}\rvert^2 = 0.08 \pm 0.10$	$M_{Q_5} = (2.4,\ \infty)$
T_2	156.8	0.992	$\lvert \lambda_{T_2}\rvert^2 = (2.0 \pm 5.1) \cdot 10^{-2}$	$M_{T_2} = (3.8,\ \infty)$
$\mathcal{S}$	157	0.993	$\lvert y_{\mathcal{S}}\rvert^2 < 0.32$	$M_{\mathcal{S}} > 1.8$
Δ_1	157	0.993	$\lvert \lambda_{\Delta_1}\rvert^2 < 5.7 \cdot 10^{-3}$	$M_{\Delta_1} > 13$
Σ_1	157	0.993	$\lvert \lambda_{\Sigma_1}\rvert^2 < 7.3 \cdot 10^{-3}$	$M_{\Sigma_1} > 12$
U	157	0.993	$\lvert \lambda_U\rvert^2 < 2.8 \cdot 10^{-2}$	$M_U > 6.0$
D	157	0.993	$\lvert \lambda_D\rvert^2 < 1.4 \cdot 10^{-2}$	$M_D > 8.4$
Q_7	157	0.993	$\lvert \lambda_{Q_7}\rvert^2 < 7.7 \cdot 10^{-2}$	$M_{Q_7} > 3.6$
T_1	157	0.993	$\lvert \lambda_{T_1}\rvert^2 < 0.13$	$M_{T_1} > 3.0$
$\mathcal{B}_1$	157	0.993	$\left\lvert \hat{g}^{\phi}_{\mathcal{B}_1}\right\rvert^2 < 2.4 \cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

Classification by DE BLAS, CRIADO, PEREZ-VICTORIA, SANTIAGO 1711.10391

EFT precision — next steps

- incorporate higher-order QCD and EW effects
- quantify higher-order EFT effects (dimension-8)

Lots of progress on this front, some projects involved in

NLO QCD MC

POWHEG-BOX

MIMASU, VS, WILLIAMS. 1512.02572

aMC@NLO

DEGRANDE, FUKS, MAWATARI, MIMASU, VS.
1609.04833

NEW: CP-VIOLATING TERMS— REQUEST

DIMENSION-EIGHT

Feynrules—> UFO—> aMC@NLO

HAYS, MARTIN, VS, SETFORD. 1808.00442

Warsaw—>Other using *Rosetta*

MIMASU ET AL. 1508.05895

incorporate these tools to the experimental analyses

Putting it all together

WHAT'S NEXT?

Capture *subtle* details, can be expressed as images

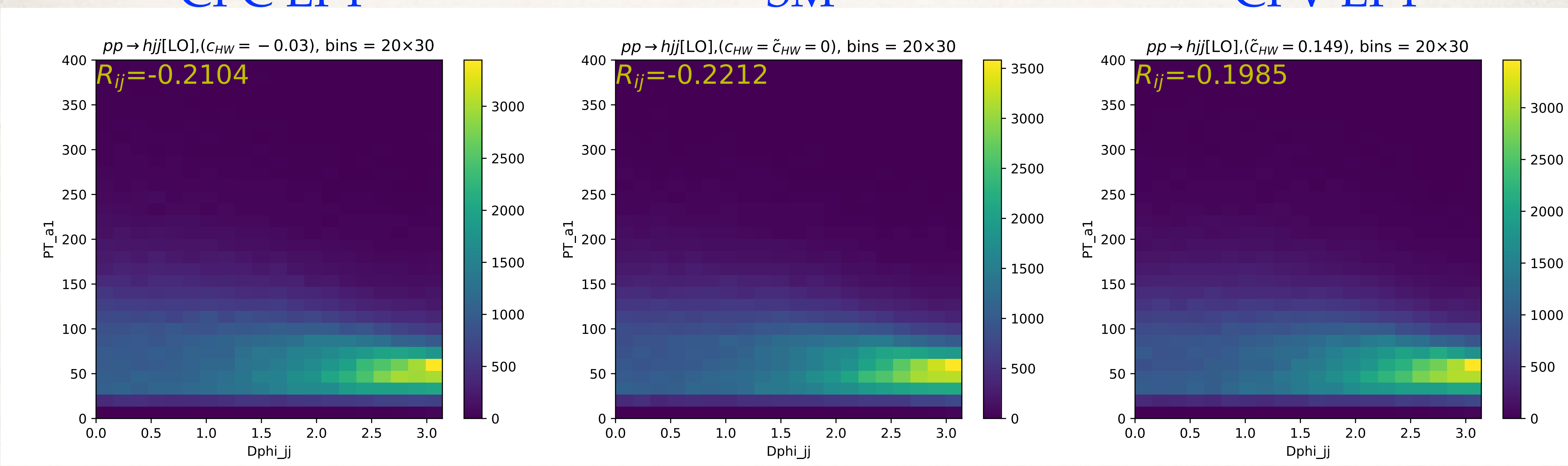
machine learning techniques

supervised or anomaly detection

lots of activity in the last months

e.g. CPV vs CPC EFT effects in VBF

CPC EFT | SM | CPV EFT

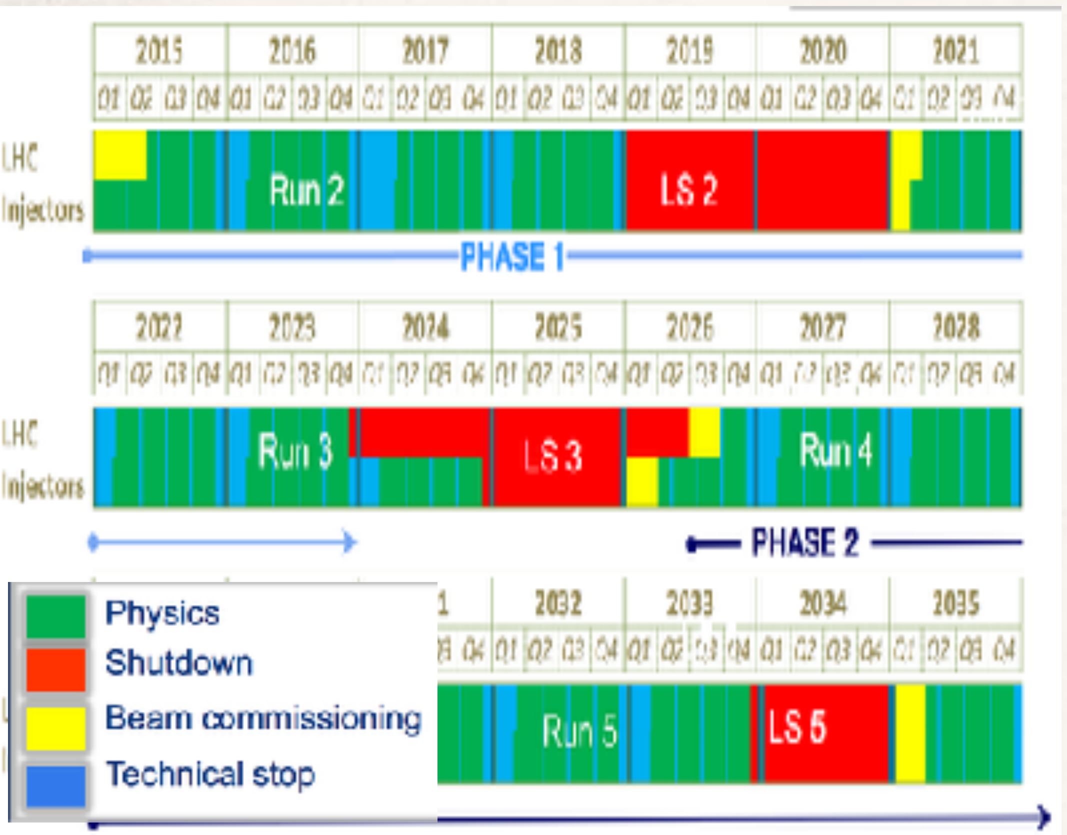


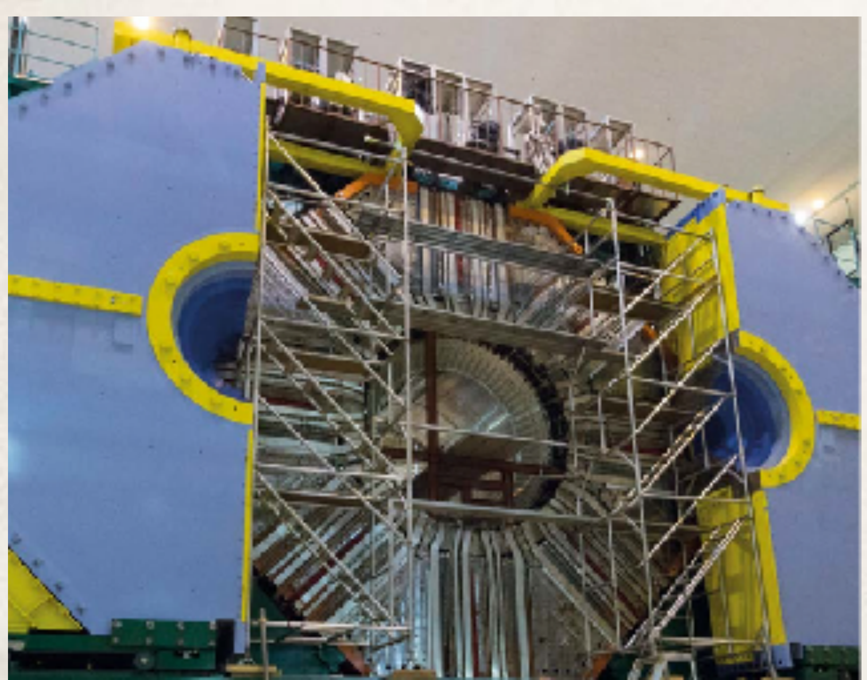
FREITAS, FUKS, MIMASU, VS. IN PREP

Experiments keep coming in:
There is a lot to explore ahead of us

For the LHC, this is just the beginning

HL-LHC (High-Luminosity) LHC approved, to deliver 3000 inverse fb of data.
Funding ensured until 2035.





LHC hopefuls

gains from more data and better understanding of the environment

Testing non-standard kinematic features
Reaching high-precision in Higgs physics
Searches for invisible particles (monoX)
Blind spots (DV, disap. tracks, quirks)

and, of course, FLAVOUR
with Belle-II, NA62 complementing LHCb

Smaller experiments may be key

Narrower focus

BUT

cheaper, shorter time-scale

develop creative experimental techniques

often enlarge the initial physics focus

And what about the cool/crazy stuff?

Dark Energy and its interaction with us

Alternatives to space-time symmetries (e.g. emergent gravity)

Very light dark matter (new exp techniques)

Dark moments in the Universe's history, pre-BBN

Connections between IR and UV physics, e.g. BHs

We need to *challenge* the well-stablished paradigms,
may be quickly ruled out
but one **always** learn something new from these explorations

Conclusions

- Here we are, looking for a way to advance our understanding of nature, to reach discovery

- Scaling back from an ambitious program to find *the* theory of everything. Facing the challenges/opportunities that more data brings

- Use of simplified models to organize/interpret searches, less model biased, and suitable to complementarity studies. Yet theoretical advances require more than simplified models, asking difficult questions from model building

- Keeping at the edge of the interpretation of data: bringing many towards precision (akin to SM) and to Artificial Intelligence techniques (NNs and the likes), but we should not lose track of our core mission:

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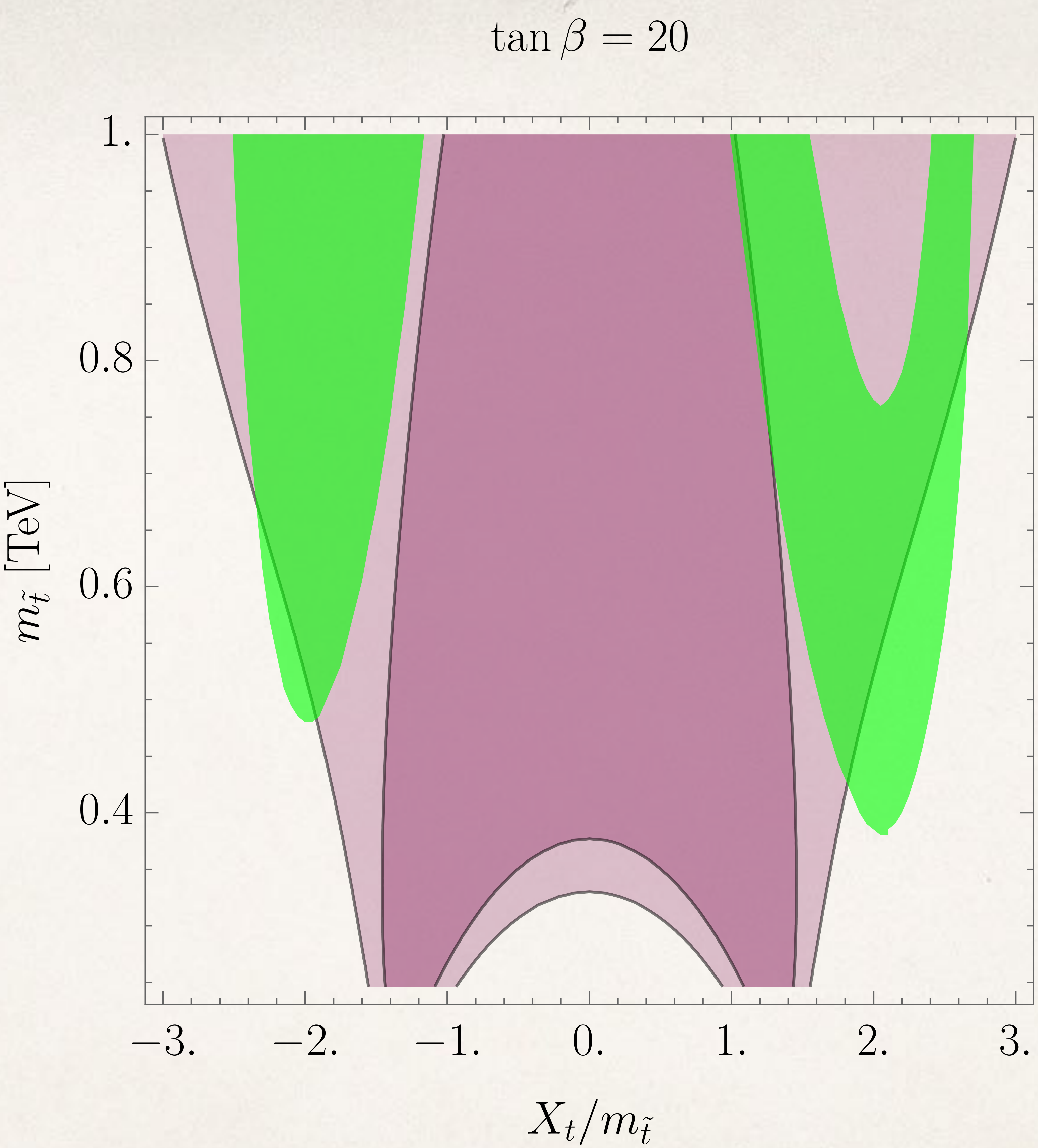
Understanding Nature

(and having fun on the way!)



$\tan\beta = 20$
1.
0.8
0.6
0.4
$m_{\tilde{t}}$ [TeV]
−3.
−2.
−1.
0.
1.
2.
3.
$X_t/m_{\tilde{t}}$