
Genova Boccadasse

High pT observables impact on global fit

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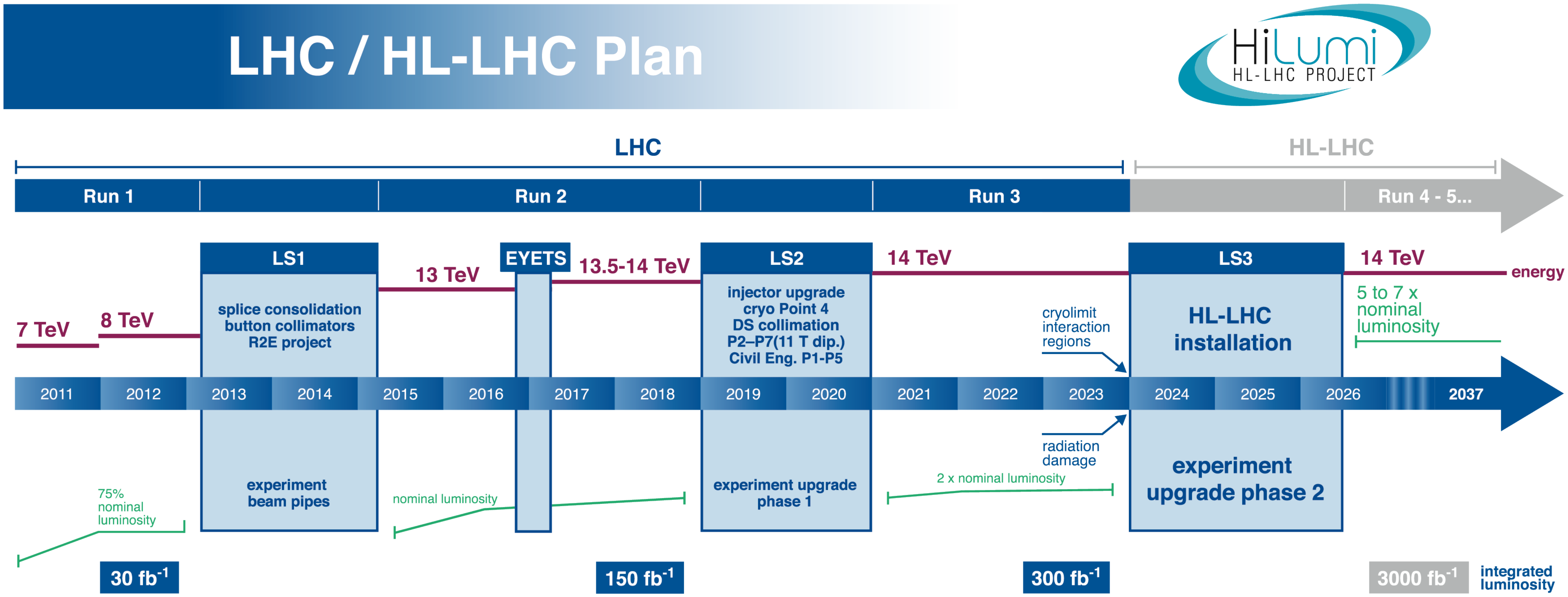
LHC physics program



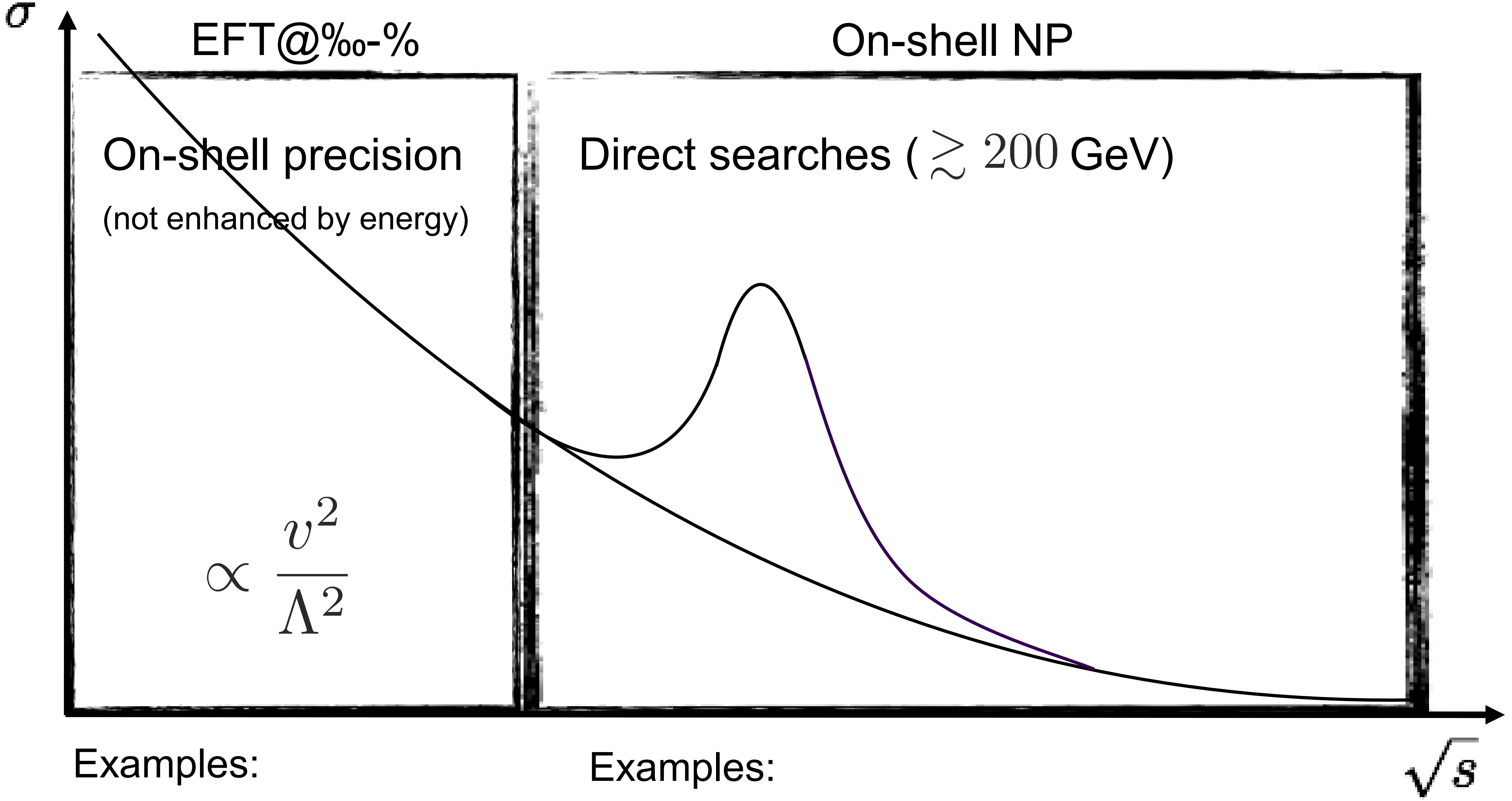
Main goal: Find signs of New Physics

direct searches

- directly: probing on-shell new physics
- indirectly: probing the effect of new physics on SM observables

precision physics

New Physics sketch: beginning of LHC



EFT@‰-%

On-shell NP

On-shell precision

(not enhanced by energy)

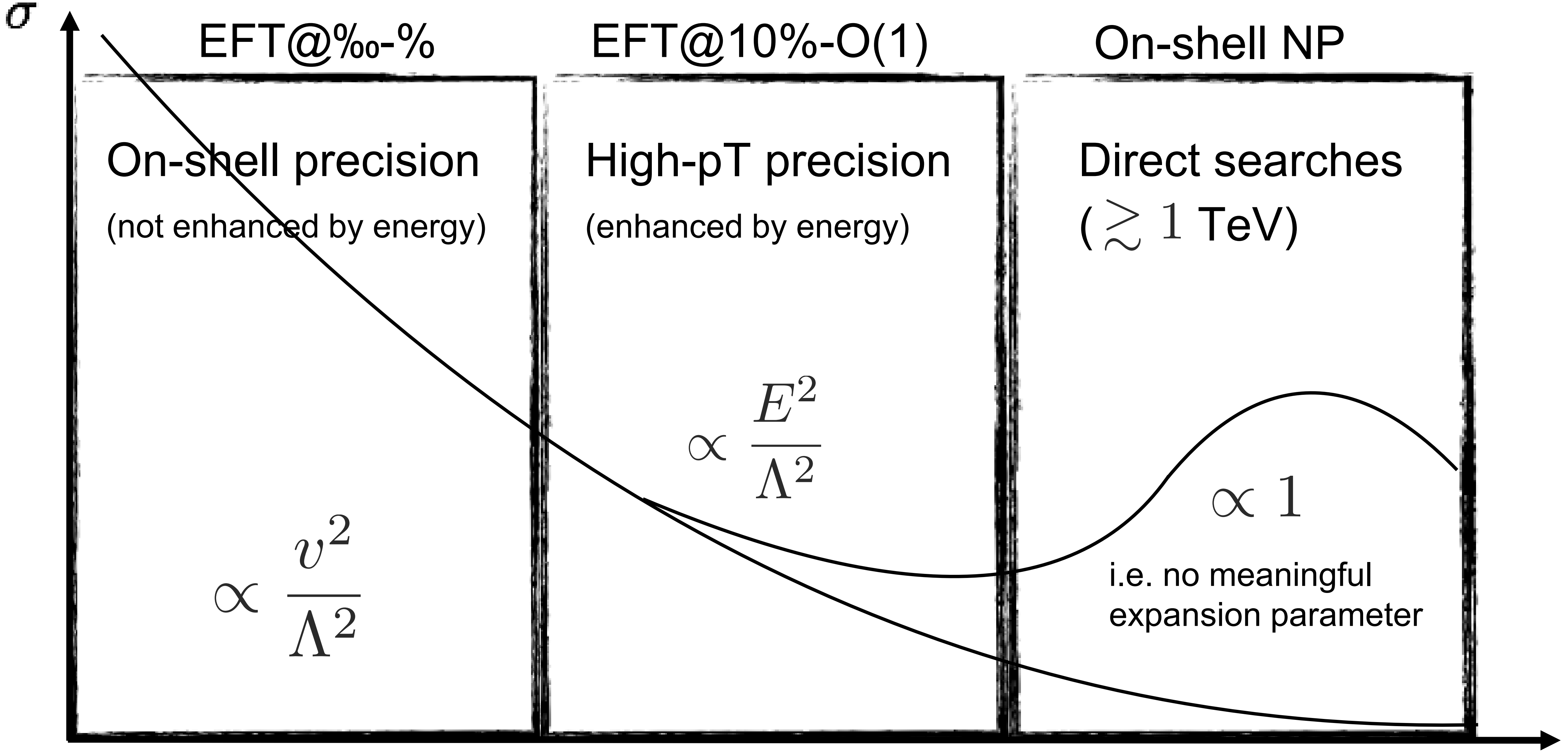
Direct searches ($\gtrsim 200$ GeV)

$$\propto \frac{v^2}{\Lambda^2}$$

Examples:
- SM parameters
- Pole observables
  e.g. $\hat{S}$, $\hat{T}$, etc.
- Higgs observables*

Examples:
- SUSY
- Top partners
- Resonances

New Physics sketch: now



EFT@‰-%

On-shell precision

(not enhanced by energy)

$\propto \frac{v^2}{\Lambda^2}$

EFT@10%-O(1)

High-pT precision

(enhanced by energy)

$\propto \frac{E^2}{\Lambda^2}$

On-shell NP

Direct searches

($\gtrsim 1$ TeV)

$\propto 1$

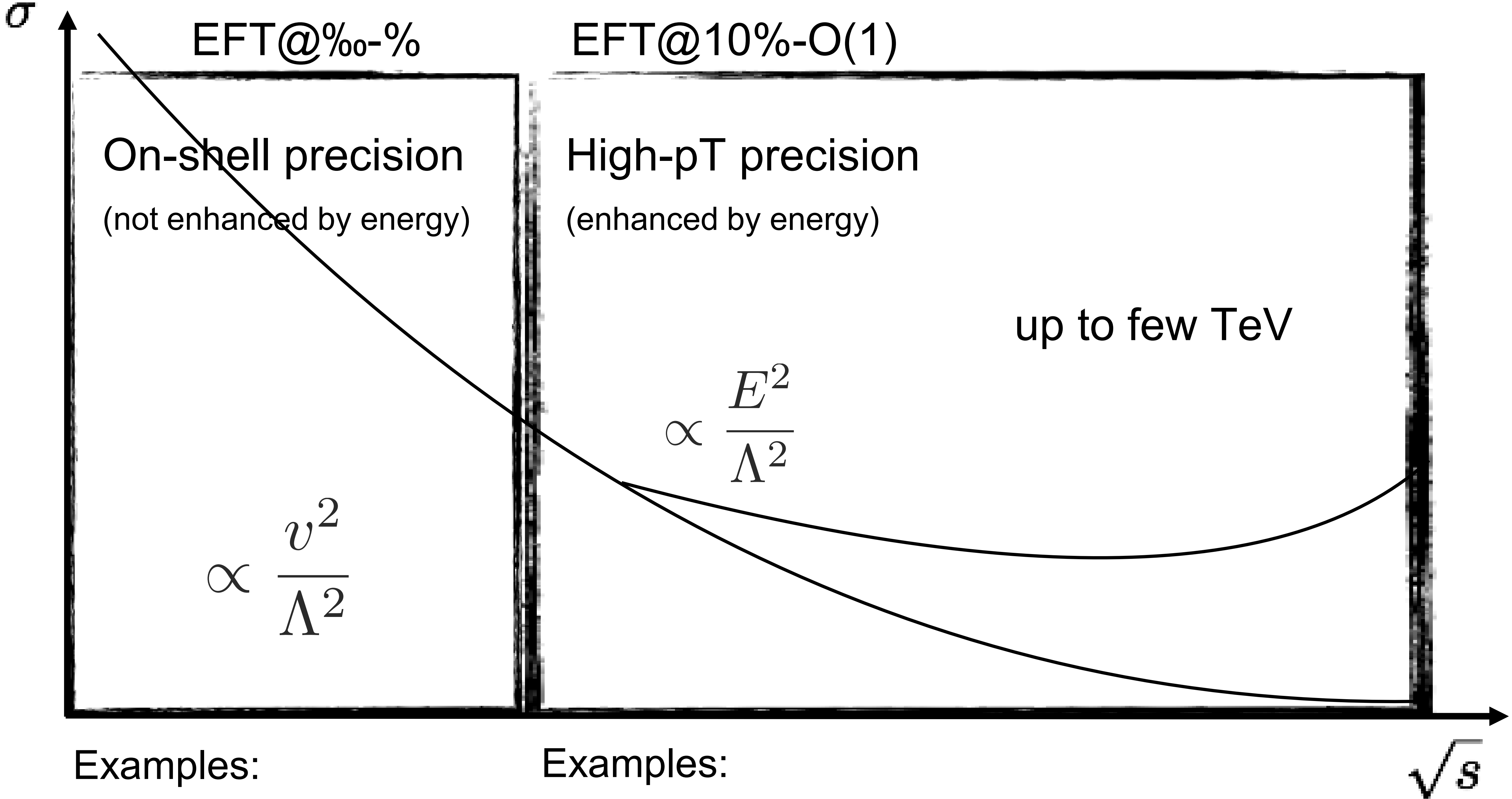
i.e. no meaningful expansion parameter

Examples:
- SM parameters
- Pole observables e.g. $\hat{S}$, $\hat{T}$, etc.
- Higgs observables

Examples:
- DY (e.g. W, Y, etc.)
- Di-bosons
- Di-jets
- Heavy quarks ($t\bar{t}$,…)

Examples:
- SUSY
- Top partners
- Resonances

New Physics : end of LHC



On-shell precision

(not enhanced by energy)

$$\propto \frac{v^2}{\Lambda^2}$$

High-pT precision

(enhanced by energy)

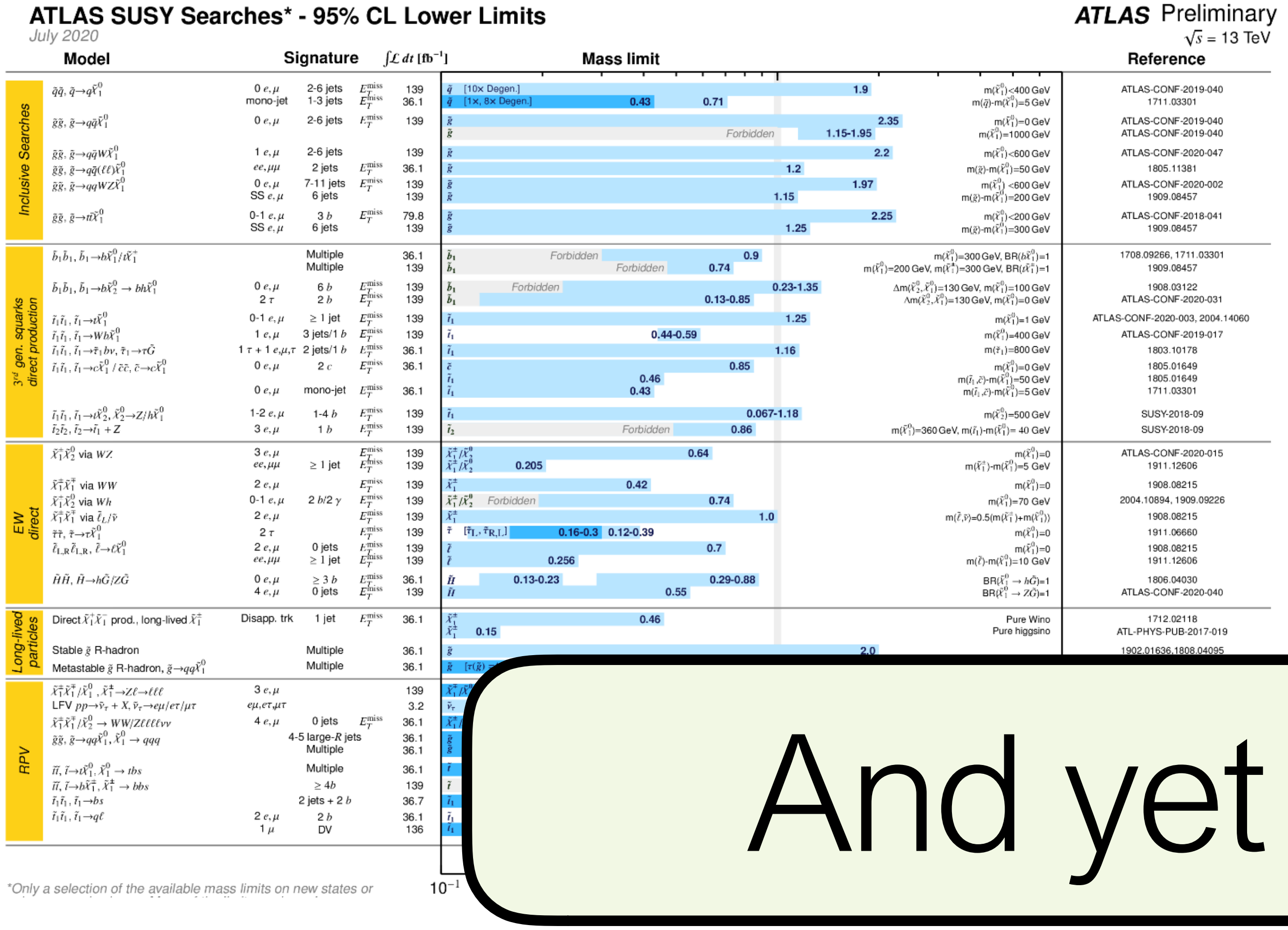
up to few TeV

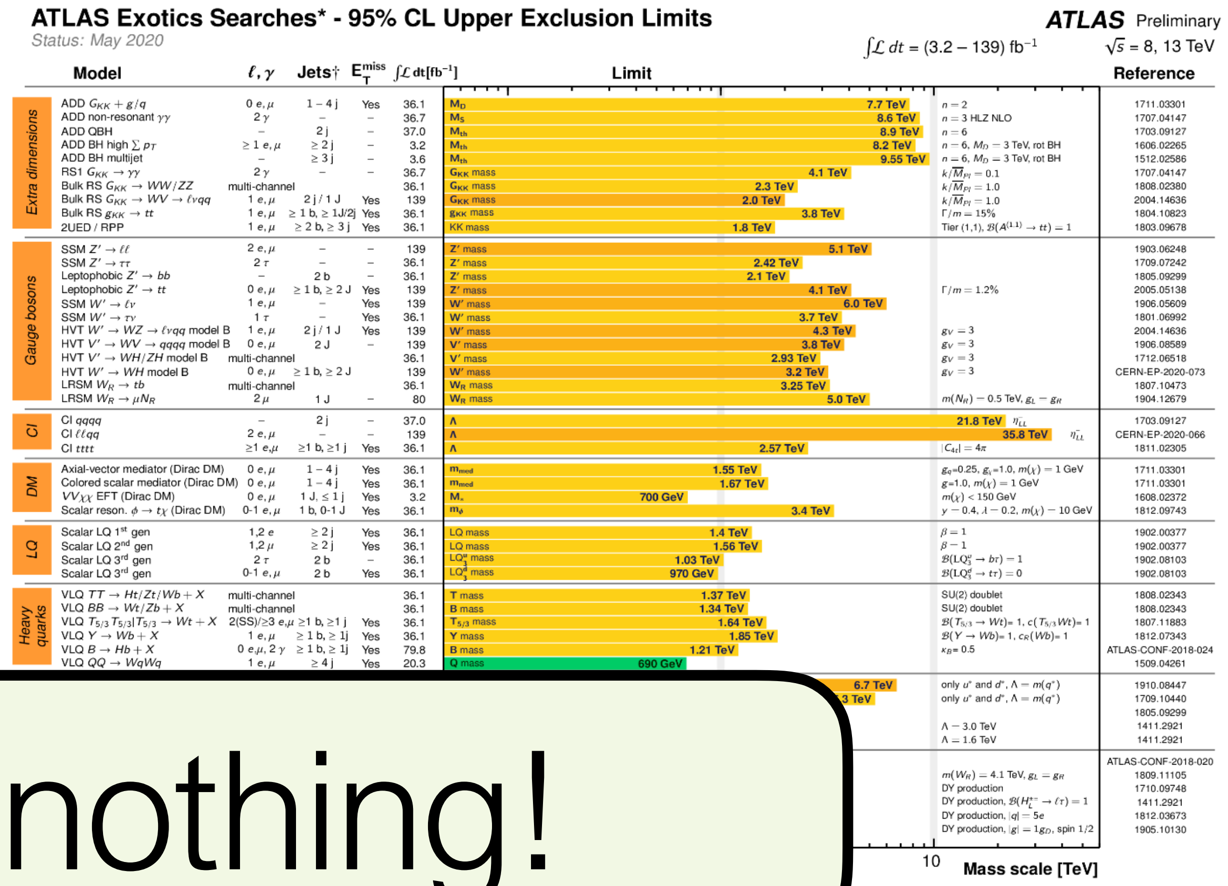
$$\propto \frac{E^2}{\Lambda^2}$$

Examples:
- SM parameters
- Pole observables e.g. $\hat{S}$, $\hat{T}$, etc.
- Higgs observables

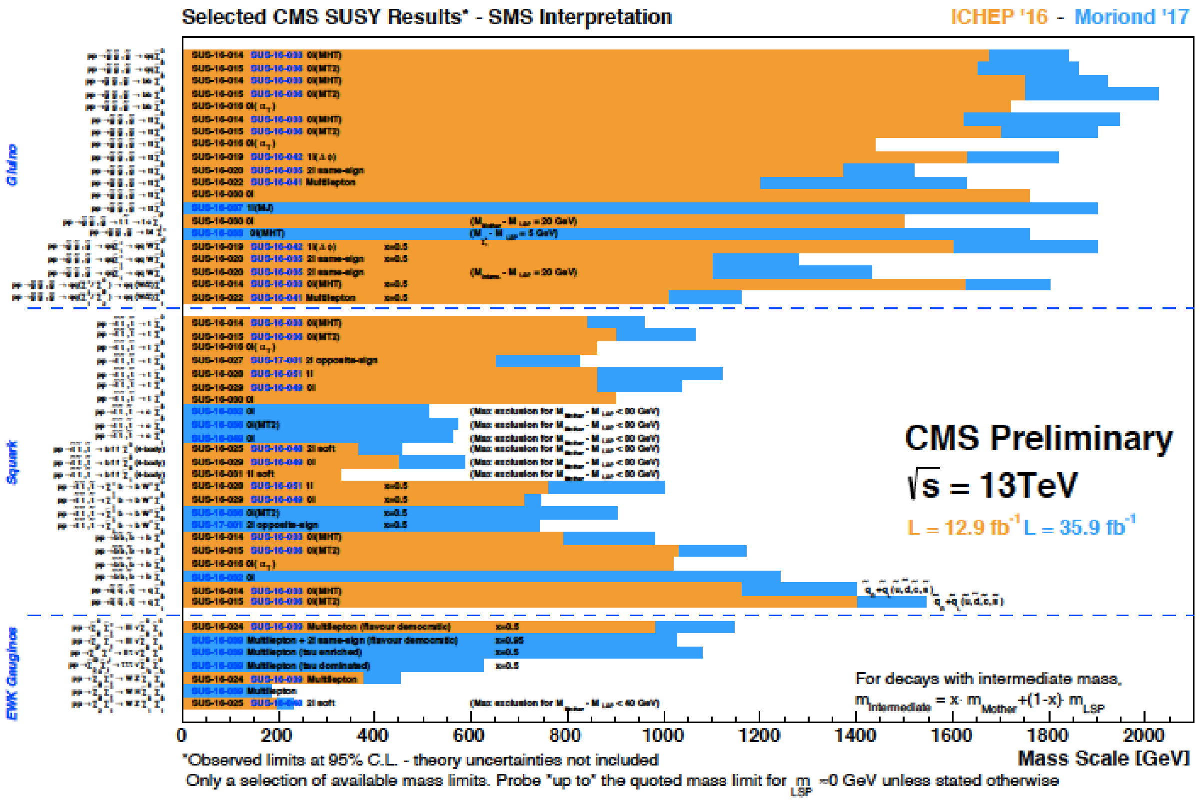
Examples:
- DY (e.g. W, Y, etc.)
- Di-bosons
- Di-jets
- Heavy quarks ($t\bar{t}$,…)

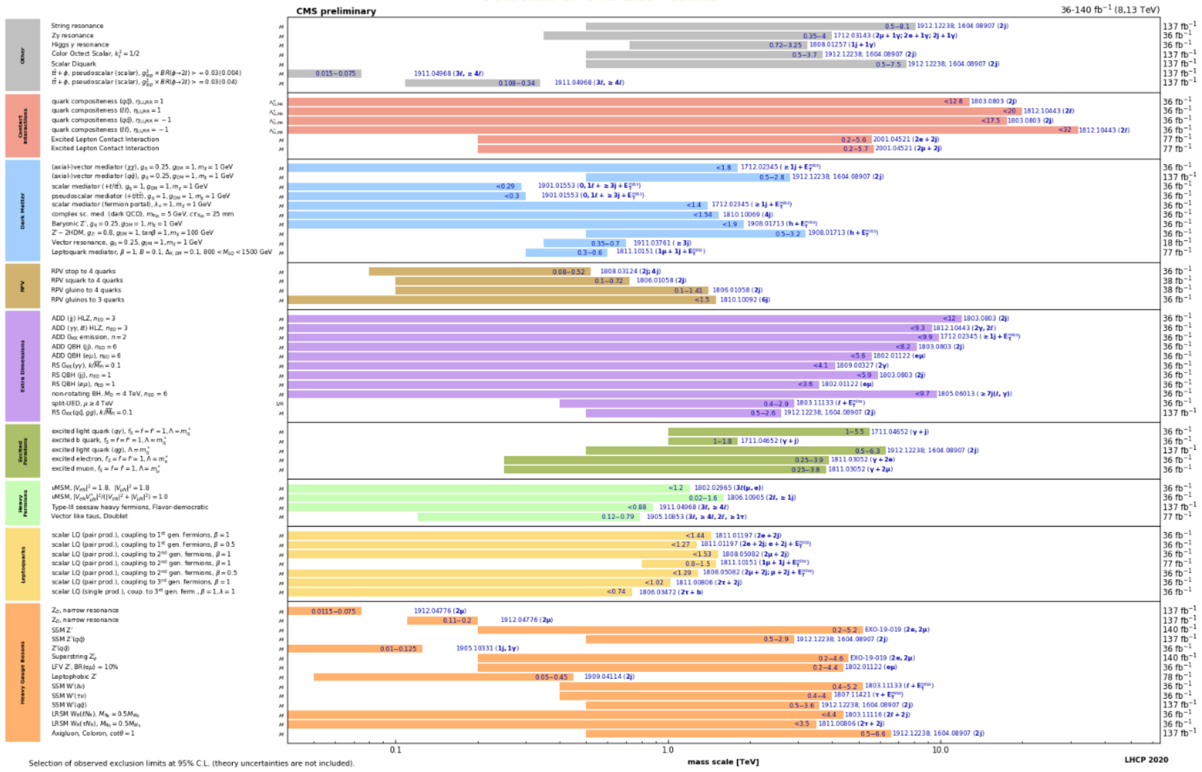
Direct searches





And yet nothing!





Measurements, searches, and global fit: a statistical perspective

Measurement

- What is usually called a “measurement” can be defined as **parameter estimation** within the SM hypothesis
- This quantifies precisely “what you see” (SM), but says nothing about “what you do not see” (NP)
- Used to extract SM inputs to searches and global fits

Search (or direct search)

- This usually refers to “direct searches” where, through a statistical **hypothesis test**, the SM gets confronted with an alternative hypothesis
- It gives some information on how much your data prefer the SM vs a well defined alternative model

Fit (or global fit or indirect search)

- This consists of either **parameter estimation** beyond the SM or a **hypothesis test** with a general enough alternative hypothesis (e.g. EFT)
- It gives information on ”what you see” and “what you do not see”
- Notice that only BSM parameters are fit, while SM ones are taken from **measurements**

The (HL-)LHC legacy

“BSM measurements” (aka global fit v2.0: SM+EFT)

- It is known that uncertainties on some SM inputs is what limits the extraction of BSM parameters and, conversely, the presence of NP may affect extraction of SM parameters

  Examples: PDFs vs DY, multi-jet vs alphaS, etc.

- As the knowledge of the SM increases (better predictions and more analyses become available) and the large EFT parameter space gets a “good coverage” (several channels are measured and can be combined with each others) one can build a combined likelihood of SM+EFT
- Analyses that were targeting direct searches need to be turned into “measurements”, which require a higher level of precision (e.g. di-bosons)
- A simple (and interesting) example could be given by fitting EFT and PDF together using DY data

The LHC legacy (in ~20 years) is to design and accomplish the final BSM measurement (which includes SM!)

(New) Challenges

- **Combination and correlation**: combining experimental analyses is still a big issue at the LHC, where uncertainties are parametrized differently and correlations are not known (there is a slow progress but huge work ahead)
- **Defining observables**: observables related to precision measurements are often targeted at “SM measurements”. It is necessary to extend and optimize them towards multi-differential “BSM measurement” oriented observables (e.g. recent triple differential DY cross section)
- **Large parameter space**: when the number of parameters > a few, many studies become unfeasible (a lot of work in this direction: MEM, ML techniques, MadMiner, analytic reweighting, etc.)
- **EFT in backgrounds**: EFT effects may be relevant, especially for reducible BGs
- **Theory errors**: a further complication arises when statistical uncertainties become “negligible” and theory errors start to dominate (e.g. missing HO). Including theory errors in statistical analysis presents conceptual issues that need to be addressed
- **Result presentation**: not only experimental analyses, but also theory results are still shown in an ad-hoc and incomplete way (e.g. 2D contours, etc). For experiments the issue il more severe, but theorists should try to get used to always deliver the full likelihood leading to their fit, that could be used by others and as inputs to global fits

Still a long way to go, but the path is clear

The EFT direction(s)

EFT for the SM seems like a rather “new” topic for theorists

Many theorists have abandoned model building in favor of EFT

This is not a psychological effect due to the absence of new physics

⇓

Absence of new physics (and the existence of precision measurements) is a requirement for EFT to be interesting, relevant and applicable!

EFT is the simplest and most consistent way of parametrizing the different directions in which deviations from the SM can appear (SM deformations)

It is incredibly powerful at determining what “is possible”, what “is impossible”, what “is likely” and what “is unlikely”

Measurements (and especially precision measurements) in high energy physics have little meaning if one cannot quantify the above in a consistent way

In other words, EFT provides the “alternative hypothesis” necessary for a statistical hypothesis test of the SM

Precision: LHC vs LEP

Compare for instance LEP and LHC sensitivity to an interaction of the form

Z-pole observable

$$-\frac{\hat{S}}{4m_W^2}(H^\dagger \tau^a H)W^a_{\mu\nu}B^{\mu\nu}$$

LEP	**LHC**
Energy: ~100 GeV	Energy: ~1 TeV
Accuracy: ~‰-%	Accuracy: ~10%
New physics effects not enhanced by energy	New physics effects not enhanced by energy

LHC cannot compete with LEP

off Z-pole observable

$$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

LEP	**LHC**
Energy: ~100 GeV	Energy: ~1 TeV
Accuracy: ~‰-%	Accuracy: ~10%
New physics effects not enhanced by energy	New physics effects enhanced by $E^2_{\mathrm{LHC}}/E^2_{\mathrm{LEP}} \sim 100$

LHC comparable with (or better than) LEP

Generalization of this reasoning is what defines the high pT LHC precision program

State of the art

- Drell-Yan (neutral and charged)

  (aka quark-quark-lepton-lepton four fermion interactions)

De Blas et al., 1307.5068
Farina et al., 1609.08157
Alioli et al., 1712.02347
Fuentes-Martin et al., 2003.12421
RT et al., 2008.12978

- Di-jets and multi-jets (and inclusive jet)

  (aka 4quark four fermion interactions)

Alioli et al., 1706.03068

- Di-tops

  (aka 2quark-2t four fermion interactions)

Farina et al., 1811.04084

- Di-bosons (including VH)

Biekötter et al., 1406.7320
Falkowski et al. 1508.00581
Butter et al., 1604.03105
Zhang, 1610.0618
Green et al., 1610.07572
Baglio et al., 1708.03332
Panico et al., 1708.07823
Franceschini et al. 1712.01310
Liu et al., 1804.08688
Banerjee et al., 1807.01796
Grojean et al., 1810.05149
Henning et al., 1812.09299
Ethier et al., 2101.03180

Conclusions

- The (HL)-LHC legacy may be given by “BSM measurements” which extend the concepts of SM measurement, NP search, and global fit
- There are several issues to be addressed (precise theory predictions, combination of experimental analyses, definition of observables, large parameter space and signal generation, EFT in backgrounds, treatment of TH uncertainties, etc.) but the path is clear
- LHC has the unique opportunity of doing precision in the high-pT region, which allows to set unprecedented constraints on a large class of EFT operators
- The high-pT precision program is a clear BSM direction complementary to (on-shell) Higgs properties and “low energy” precision (Z-pole EW, flavour, etc.)
- Some results already exist for DY, di-jet, ttbar, dibosons, but this only consists of a handful of studies and most of the work has yet to be done

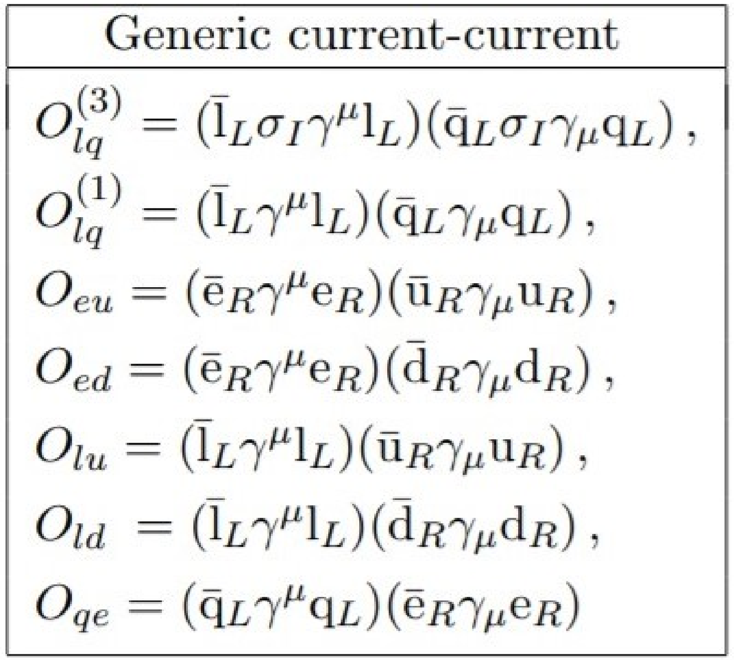
THANK YOU

BACKUP

Precision in DY at LHC

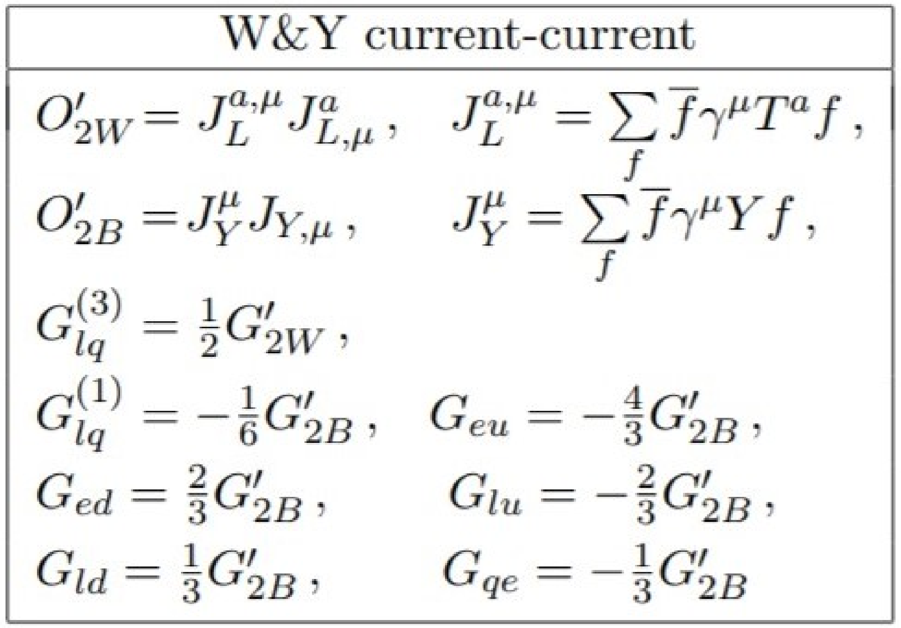
DY@LHC profits of great precision (is the most precise channel at LHC)

- LHC few percent experimental (statistic/systematic) uncertainties
- NLO QCD+NLO EW theory calculation (e.g. POWHEG)
- NNLO QCD theory calculation (e.g. FEWZ)
- NNLO PDFs (both MC ensembles and Hessian reduction)
- NP contributions (from qqll current-current operators) factorize with respect to QCD corrections and leading-log EW corrections
- This means that signal events can be generated including QCD and EW corrections with a simple analytic reweighting and do not require any scan over EFT parameters



Generic current-current

$$\begin{aligned}
O_{lq}^{(3)} &= (\bar{\mathrm{l}}_L\sigma_I\gamma^\mu \mathrm{l}_L)(\bar{\mathrm{q}}_L\sigma_I\gamma_\mu \mathrm{q}_L)\,,\\
O_{lq}^{(1)} &= (\bar{\mathrm{l}}_L\gamma^\mu \mathrm{l}_L)(\bar{\mathrm{q}}_L\gamma_\mu \mathrm{q}_L)\,,\\
O_{eu} &= (\bar{\mathrm{e}}_R\gamma^\mu \mathrm{e}_R)(\bar{\mathrm{u}}_R\gamma_\mu \mathrm{u}_R)\,,\\
O_{ed} &= (\bar{\mathrm{e}}_R\gamma^\mu \mathrm{e}_R)(\bar{\mathrm{d}}_R\gamma_\mu \mathrm{d}_R)\,,\\
O_{lu} &= (\bar{\mathrm{l}}_L\gamma^\mu \mathrm{l}_L)(\bar{\mathrm{u}}_R\gamma_\mu \mathrm{u}_R)\,,\\
O_{ld} &= (\bar{\mathrm{l}}_L\gamma^\mu \mathrm{l}_L)(\bar{\mathrm{d}}_R\gamma_\mu \mathrm{d}_R)\,,\\
O_{qe} &= (\bar{\mathrm{q}}_L\gamma^\mu \mathrm{q}_L)(\bar{\mathrm{e}}_R\gamma_\mu \mathrm{e}_R)
\end{aligned}$$

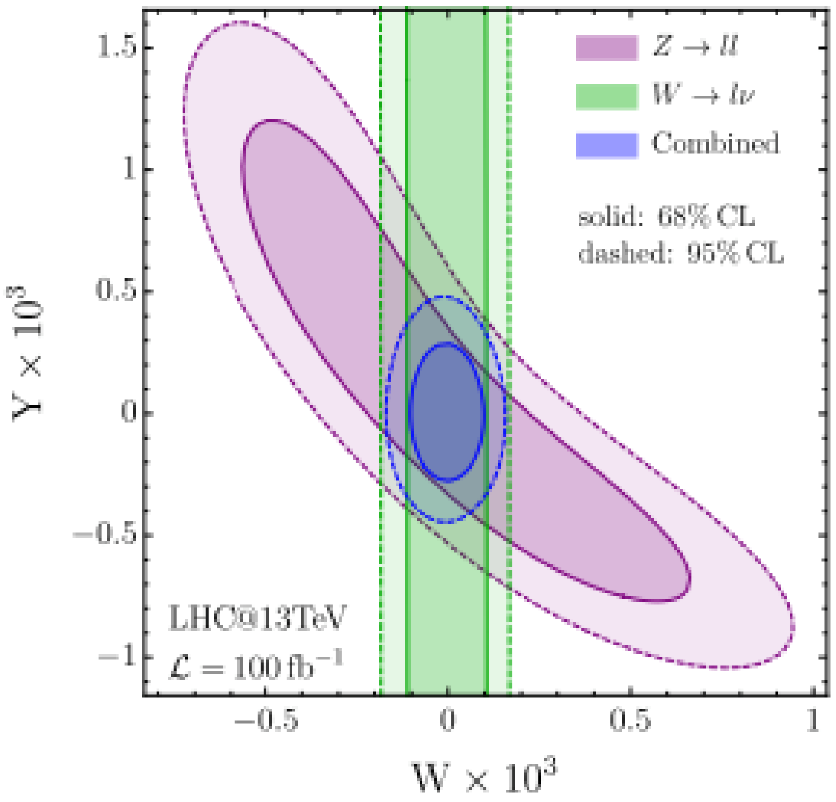


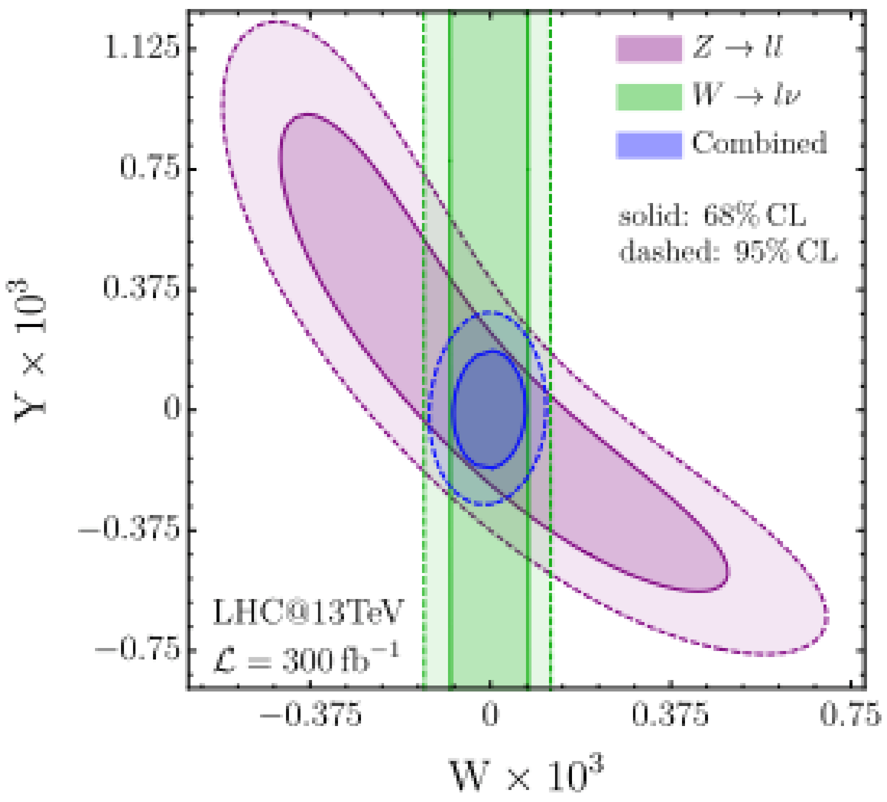
W&Y current-current

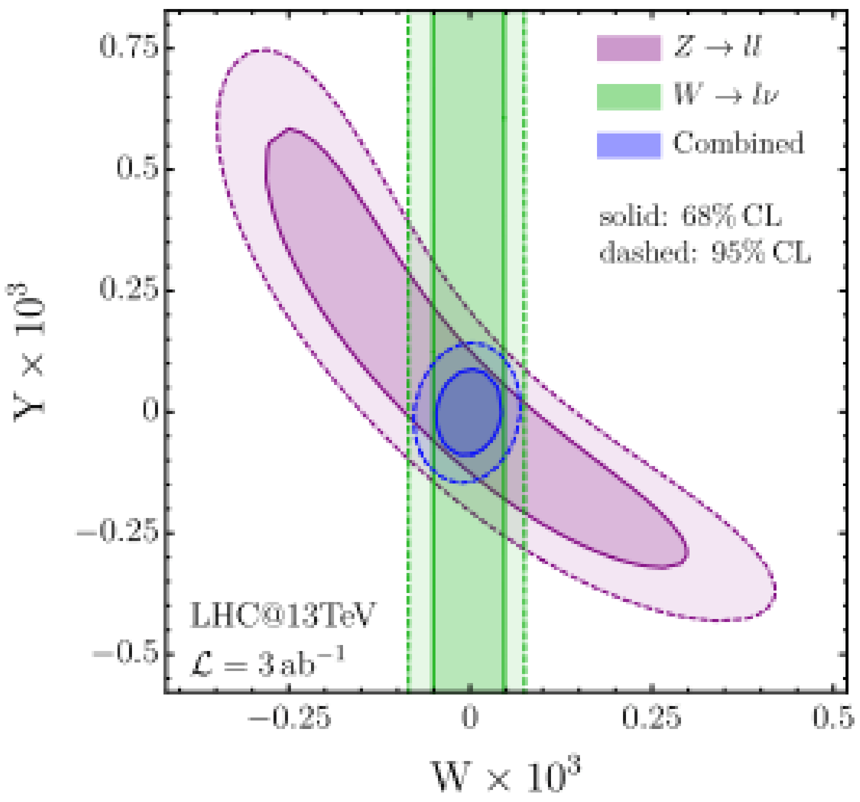
$$\begin{aligned}
O'_{2W} &= J_L^{a,\mu} J^a_{L,\mu}\,, \quad J_L^{a,\mu} = \sum_f \bar{f}\gamma^\mu T^a f\,,\\
O'_{2B} &= J_Y^\mu J_{Y,\mu}\,, \quad J_Y^\mu = \sum_f \bar{f}\gamma^\mu Y f\,,\\
G_{lq}^{(3)} &= \tfrac{1}{2} G'_{2W}\,,\\
G_{lq}^{(1)} &= -\tfrac{1}{6} G'_{2B}\,, \quad G_{eu} = -\tfrac{4}{3} G'_{2B}\,,\\
G_{ed} &= \tfrac{2}{3} G'_{2B}\,, \quad G_{lu} = -\tfrac{2}{3} G'_{2B}\,,\\
G_{ld} &= \tfrac{1}{3} G'_{2B}\,, \quad G_{qe} = -\tfrac{1}{3} G'_{2B}
\end{aligned}$$

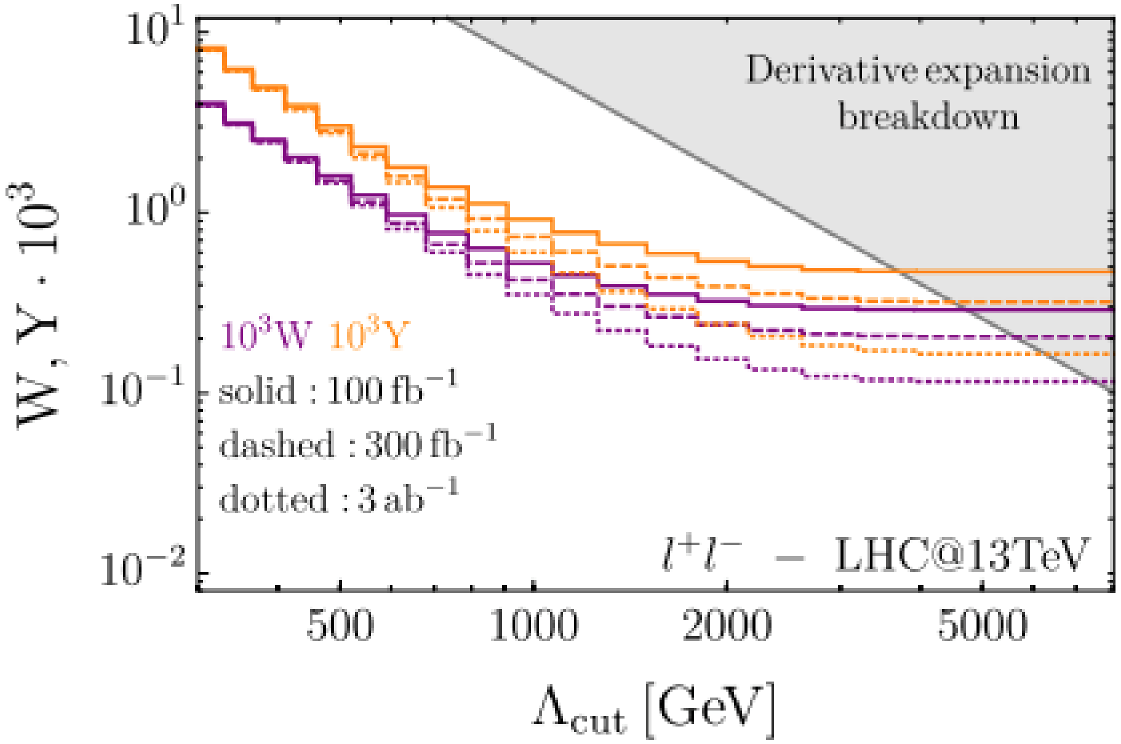
Precision in DY at LHC: W&Y

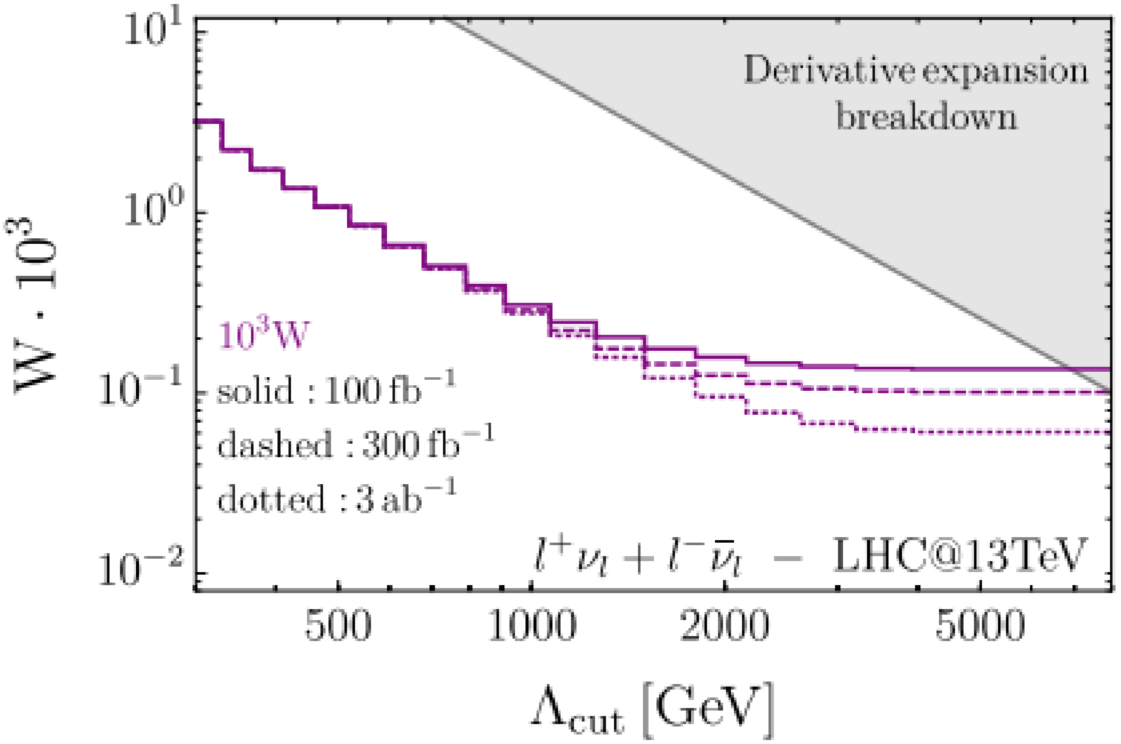
RT et al., 2008.12978











Precision in di-jet at LHC: Z

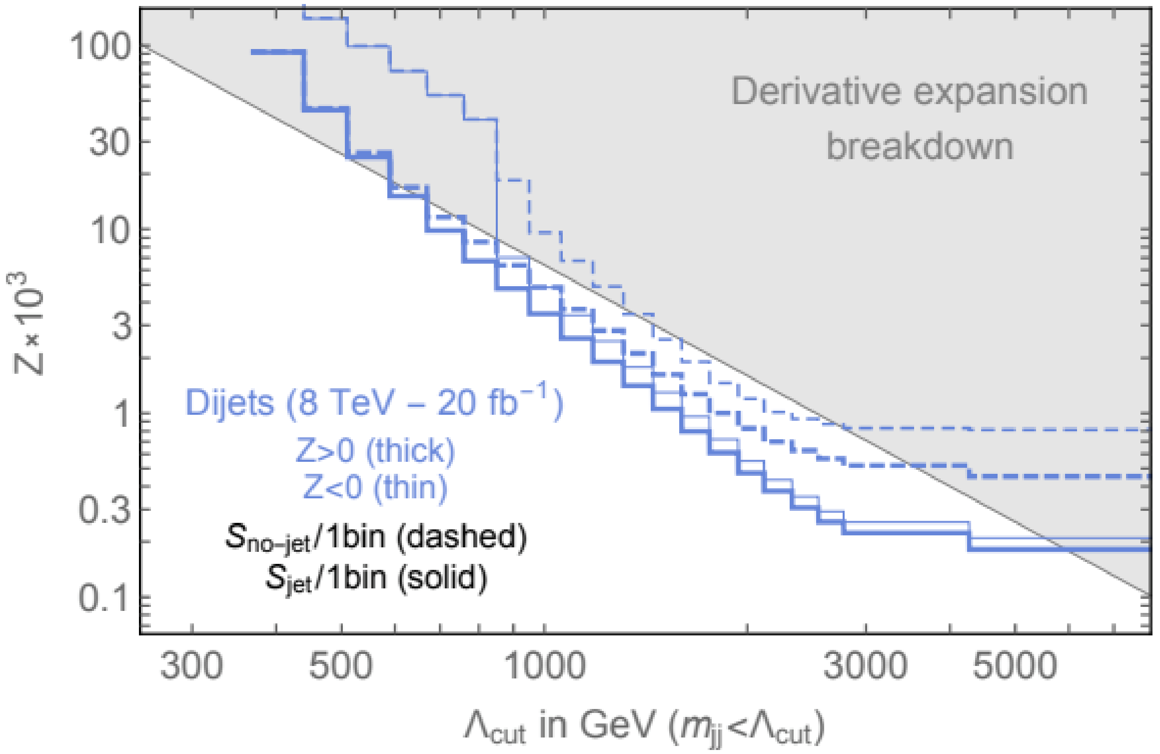
Alioli et al., 1712.02347

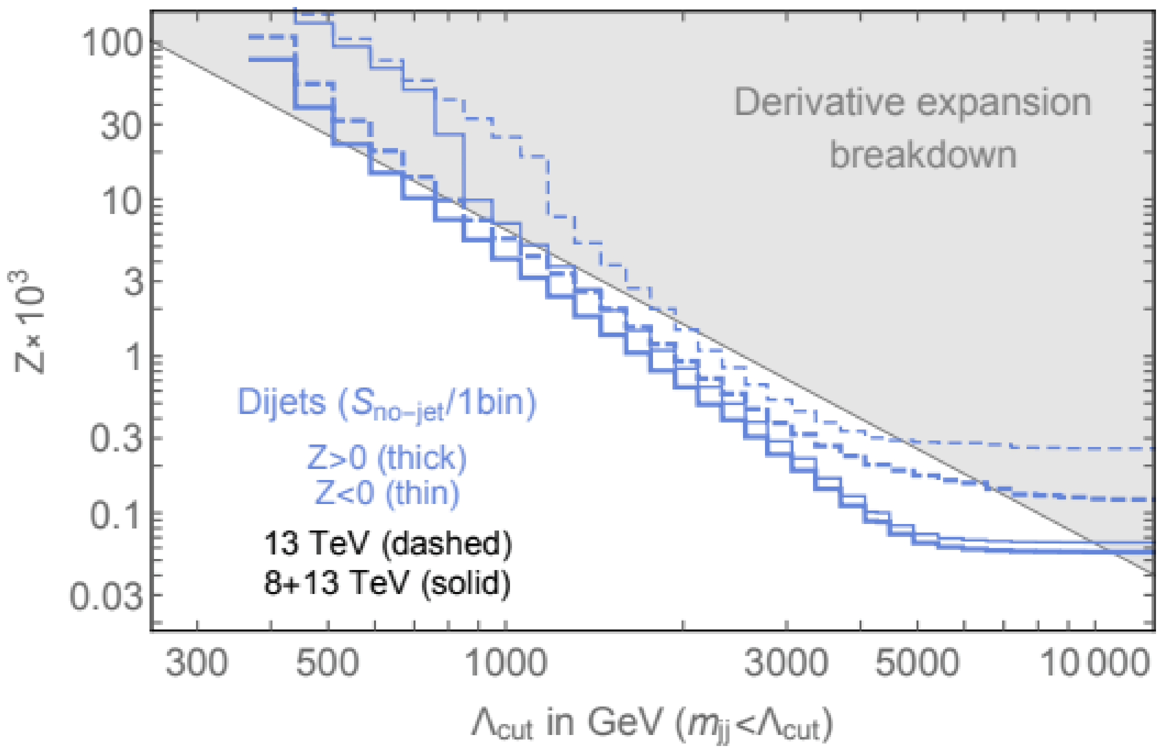
95% CL bounds on $Z \times 10^4$ for $\sqrt{s} = 8\,\text{TeV}$

Analysis	$\mathcal{S}_{\text{no-jet}}$ - 1bin	$\mathcal{S}_{\text{no-jet}}$ - 2bins	$\mathcal{S}_{\text{jet}}$ - 1bin
dijet	[-9.4,+4.9]	[-2.6,+2.1]	[-2.1,+1.8]
inclusive jet	[-13.8,+4.2]	[-2.5,+2.3]	[-2.7,+2.1]

95% CL bounds on $Z \times 10^4$ for $\sqrt{s} = 13, 100\,\text{TeV}$

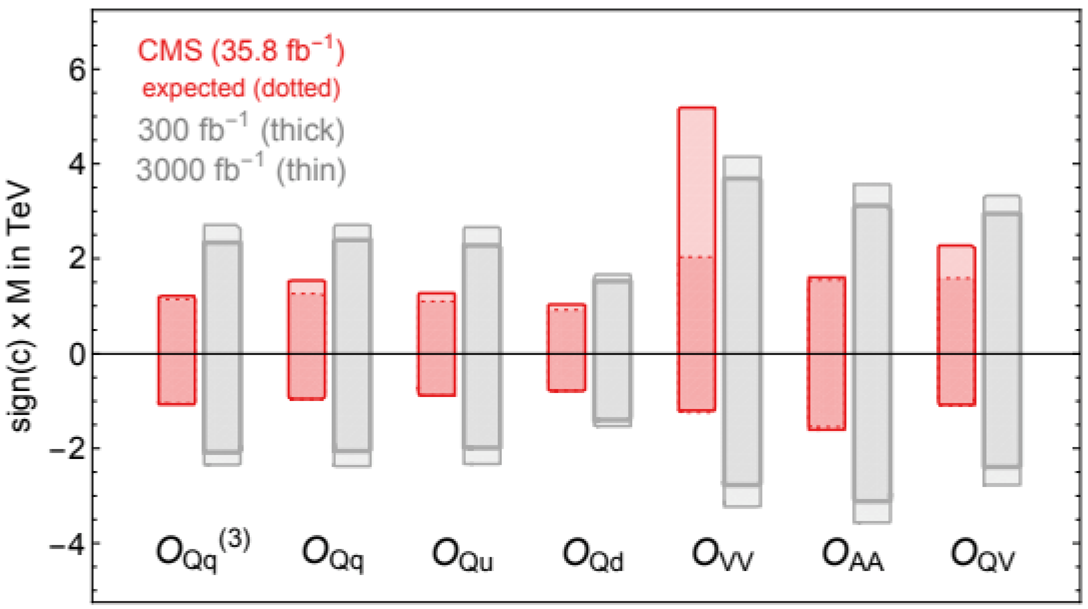
Analysis	$\sqrt{s}$ – Luminosity	$\mathcal{S}_{\text{no-jet}}$ - 1bin	$\mathcal{S}_{\text{no-jet}}$ - 2bins	$\mathcal{S}_{\text{jet}}$ - 1bin
dijet	13 TeV – 40 fb^{-1}	[-3.3,+1.7]	[-1.0,+0.9]	[-0.8,+0.7]
	13 TeV – 0.3 ab^{-1}	[-3.1,+1.4]	[-0.7,+0.6]	[-0.6,+0.5]
	13 TeV – 3 ab^{-1}	[-2.8+1.2]	[-0.5,+0.4]	[-0.5,+0.5]
	100 TeV – 10 ab^{-1}	[-4.5,+2.5]$\times 10^{-2}$	[-2.4,+1.7] $\times 10^{-2}$	[-1.4,+1.2] $\times 10^{-2}$
inclusive jet	13 TeV – 40 fb^{-1}	[-5.0,+1.5]	[-1.0,+0.9]	[-1.0,+0.8]
	13 TeV – 0.3 ab^{-1}	[-4.2,+1.1]	[-0.7,+0.6]	[-0.7,+0.6]
	13 TeV – 3 ab^{-1}	[-3.5,+0.9]	[-0.5,+0.5]	[-0.6,+0.5]
	100 TeV – 10 ab^{-1}	[-10.7,+2.6]$\times 10^{-2}$	[-1.6,+1.4]$\times 10^{-2}$	[-1.9,+1.5]$\times 10^{-2}$

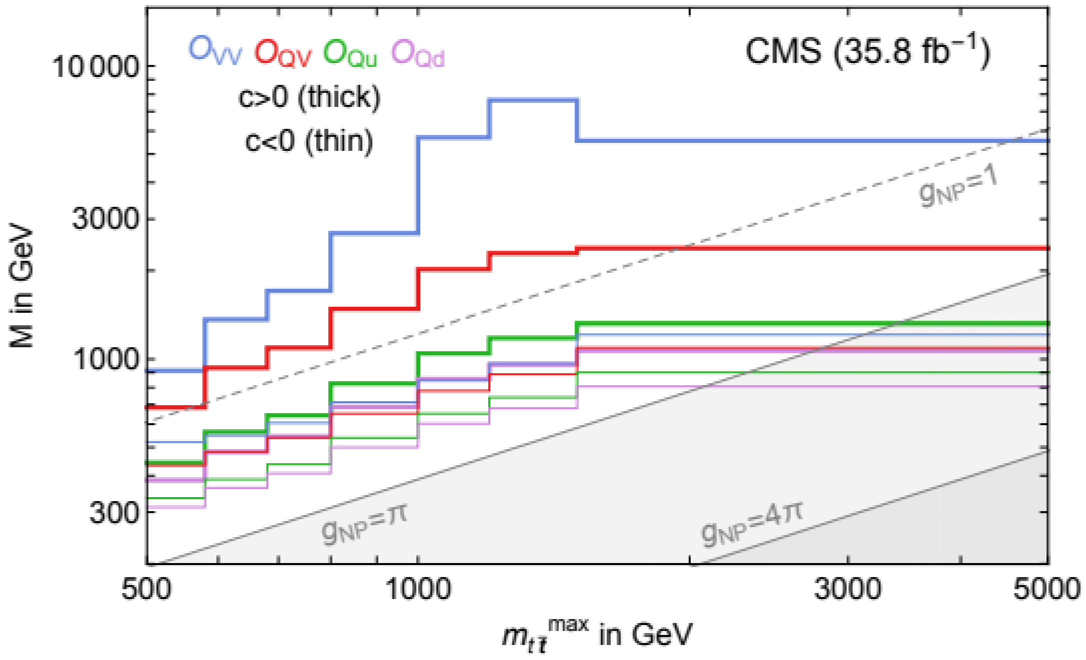


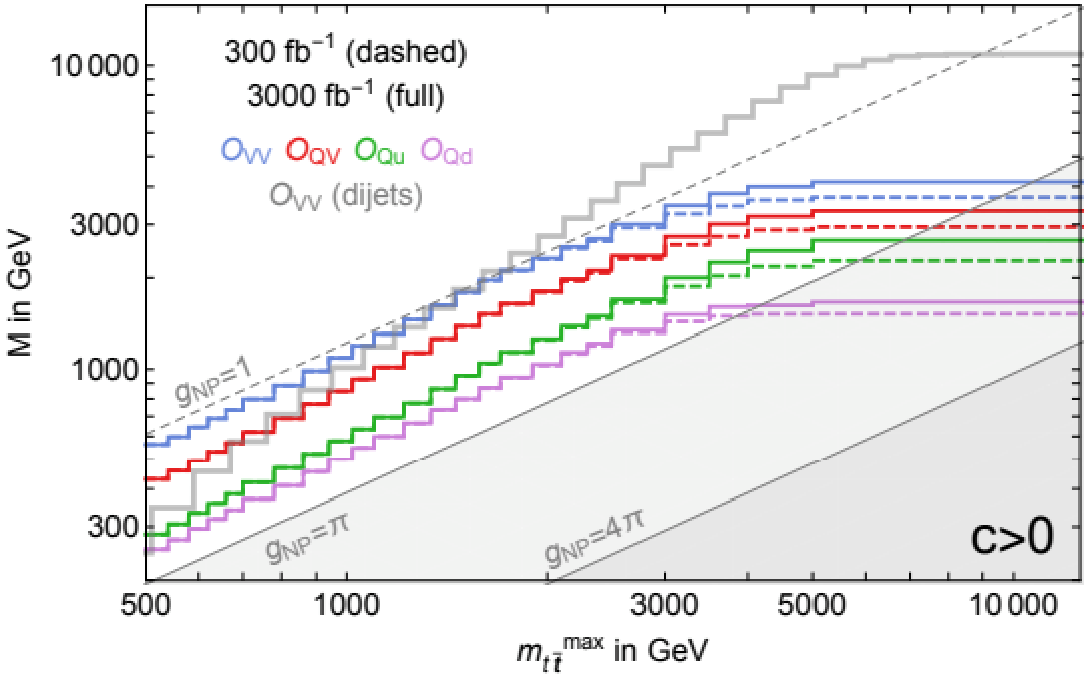


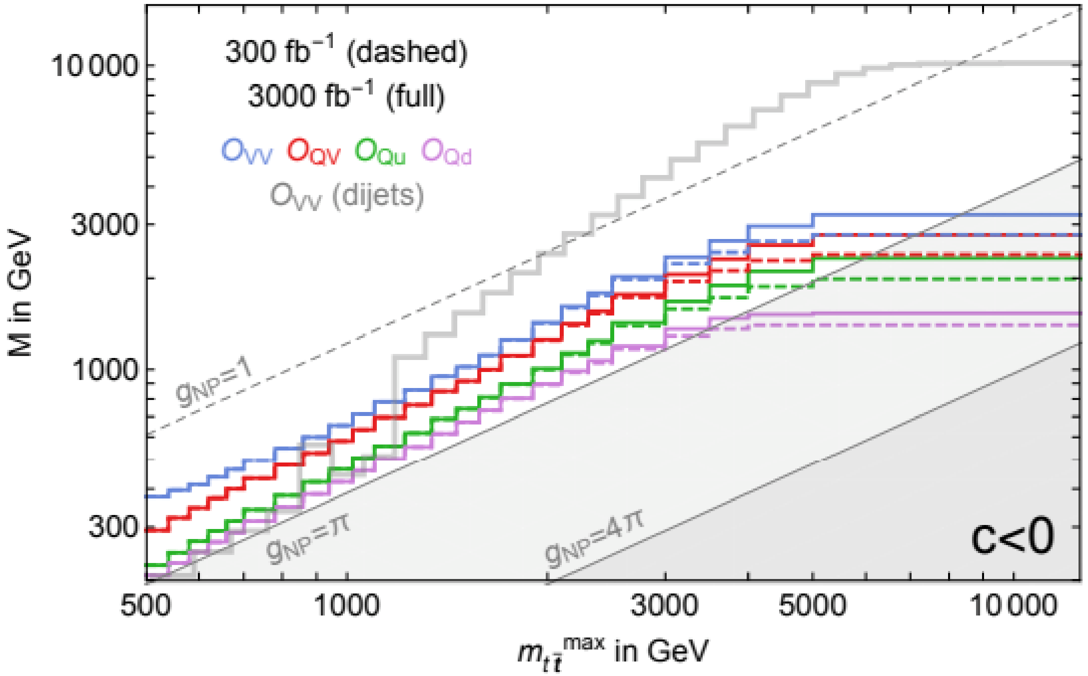
Precision in ttbar at LHC

Farina et al., 1811.04084









Precision in di-bosons at LHC

SILH Basis

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$

$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$

Franceschini et al., 1712.01310

Example of constraint on a BSM “high-energy primary” from WZ

$$A^{hW^+}_{u_-\bar{d}_+} = A^{ZW^+}_{u_-\bar{d}_+} = A^{hW^-}_{d_-\bar{u}_+} = -A^{ZW^-}_{d_-\bar{u}_+} = \sqrt{2}a_q^{(3)}$$

$$a_q^{(3)} = \frac{g^2}{M^2}(c_W + c_{HW} - 2c_{2W}) = -\frac{g^2}{m_W^2}(c^2_{\theta_W}\delta g_1^Z + W)$$