The legacy of HL-LHC for the high energy precision program

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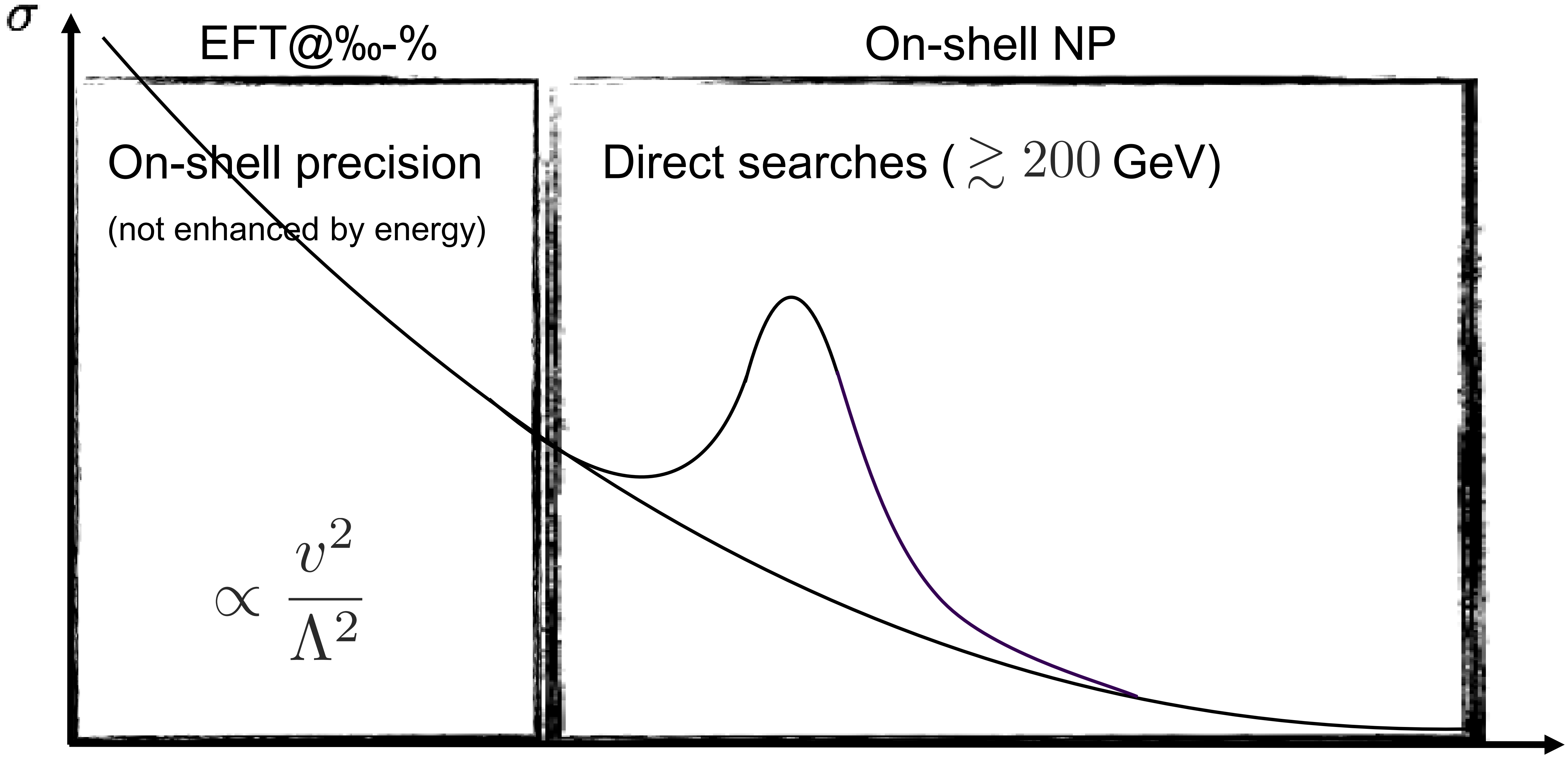
Partly based on [1609.08157](), [2008.12978](), and work in progress

LHC physics program

Main goal: Find signs of New Physics

- directly: probing on-shell new physics → direct searches
- indirectly: probing the effect of new physics on SM observables → precision physics

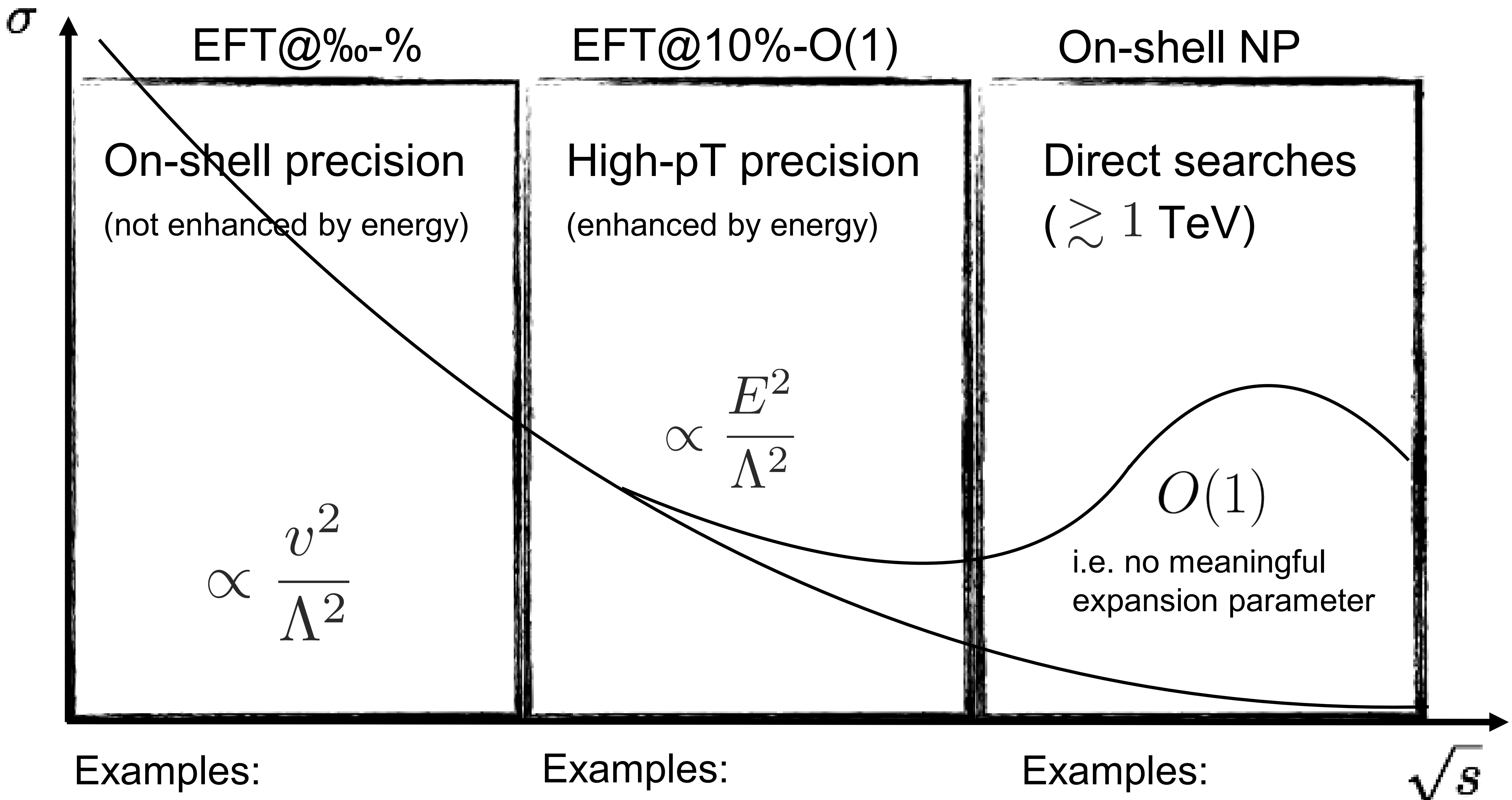
New Physics sketch: beginning of LHC



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

Examples:
- SUSY
- Top partners
- Resonances

New Physics sketch: now (after ~100/fb)



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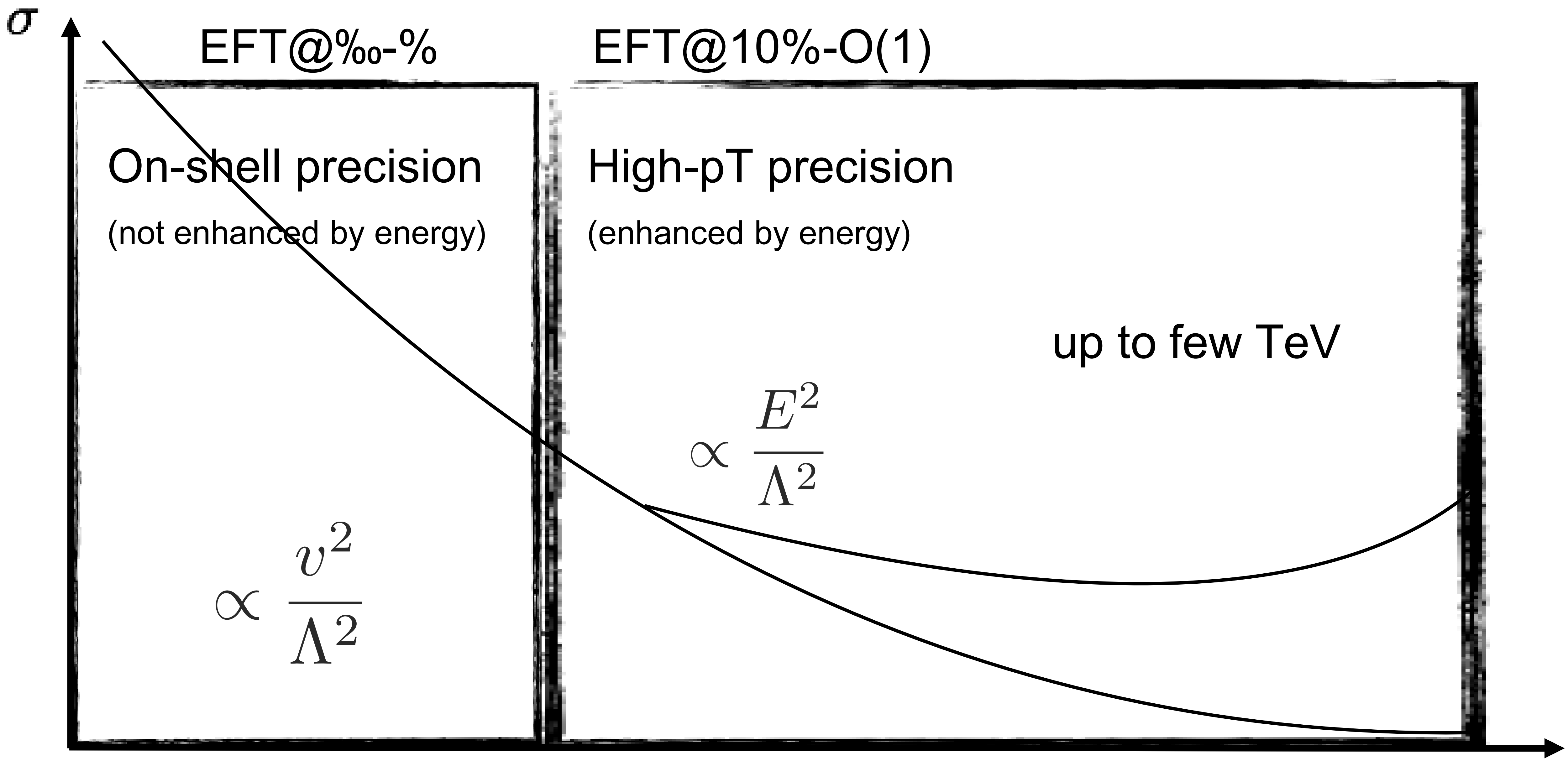
Examples:
- DY (e.g. W, Y, etc.)
- Di-bosons
- Di-jets
- Heavy quarks ($t\bar{t}$,…)

Examples:
- SUSY
- Top partners
- Resonances

New Physics : end of (HL-)LHC



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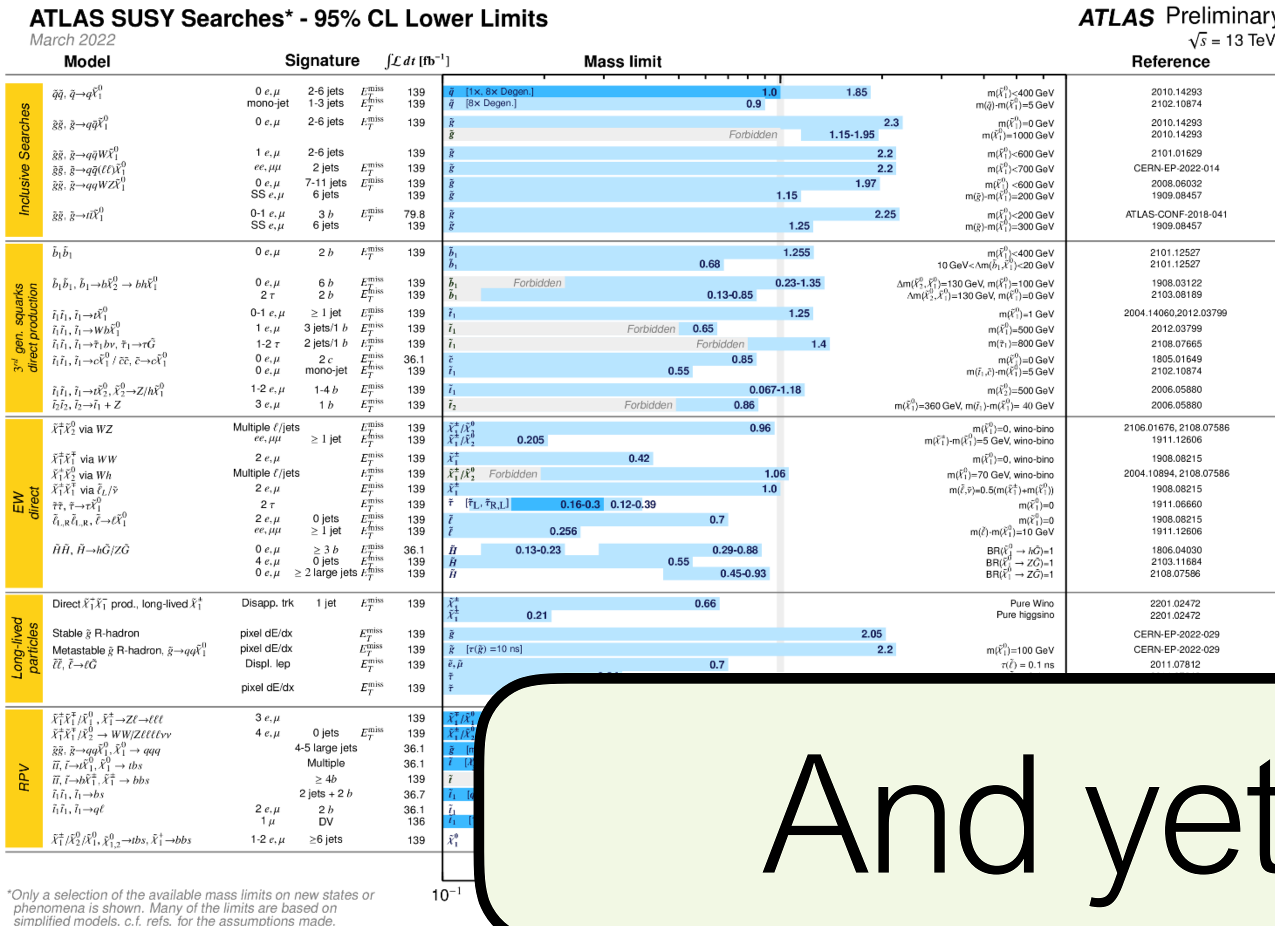
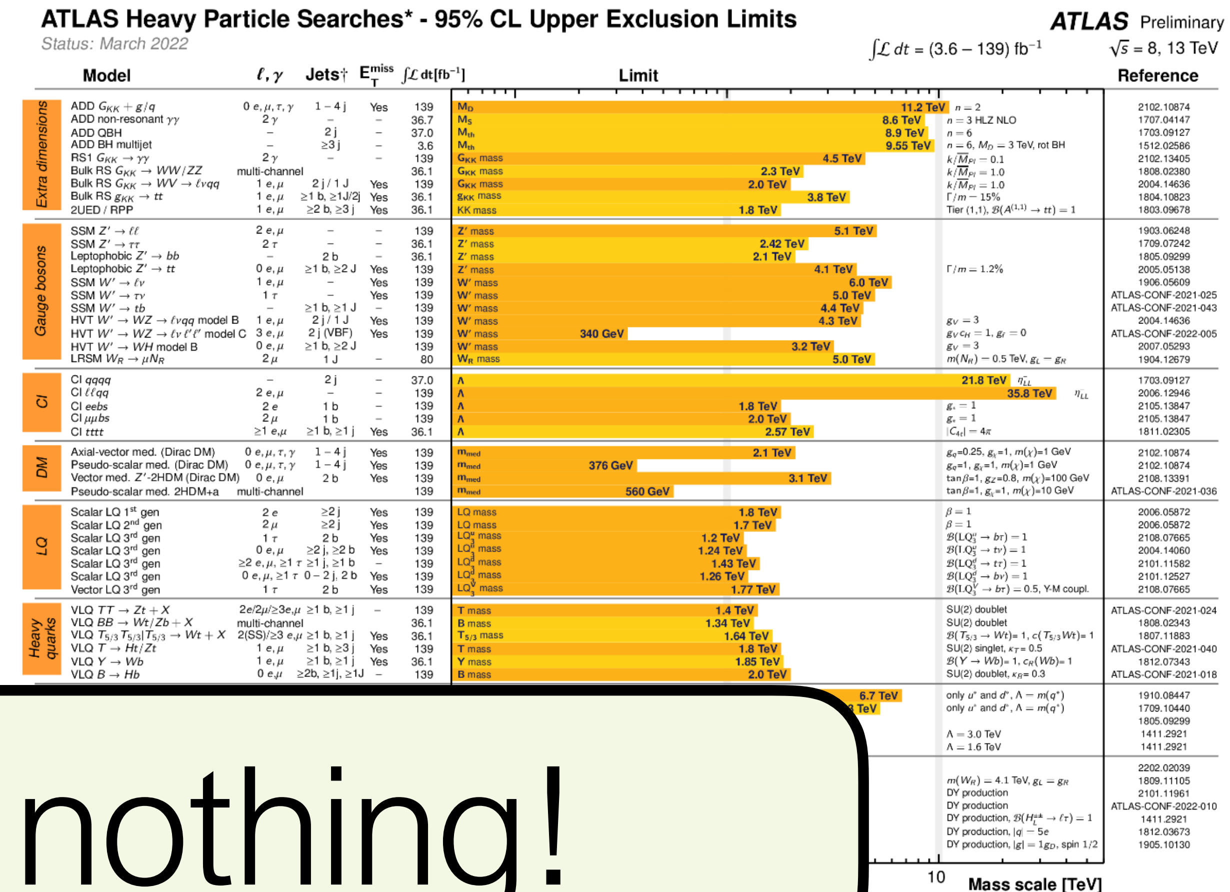
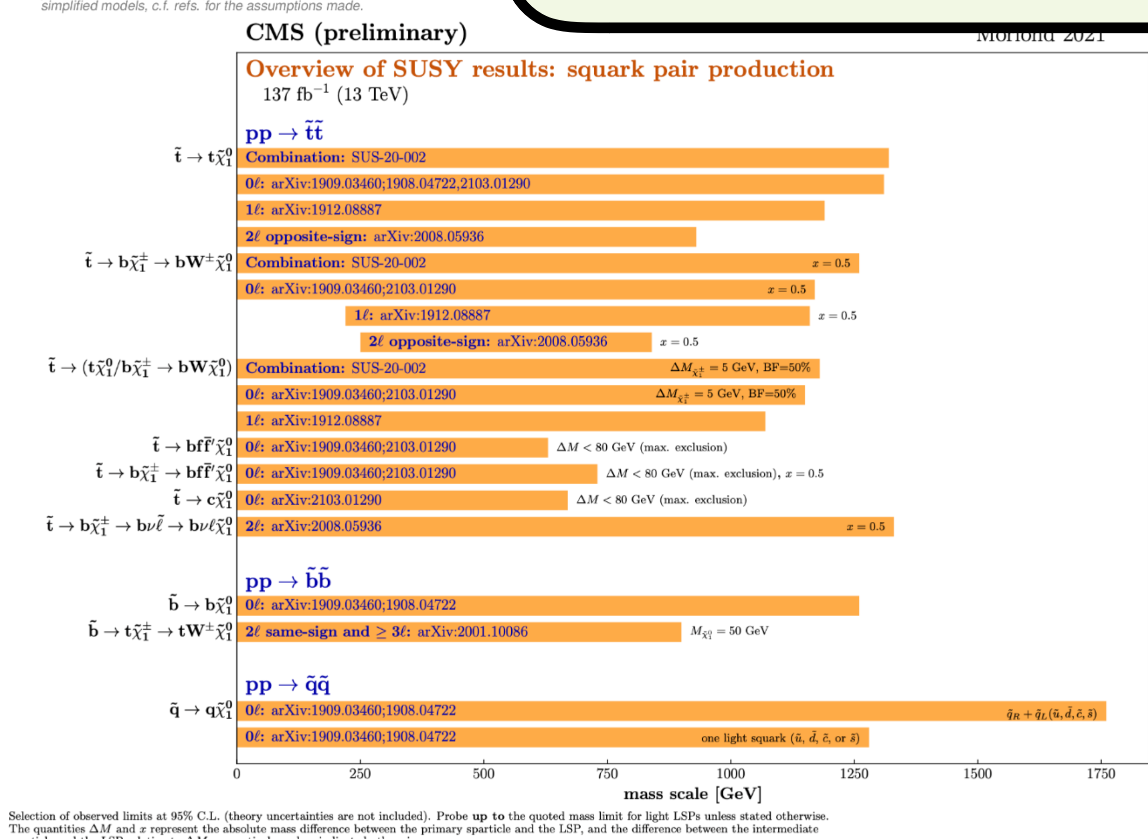
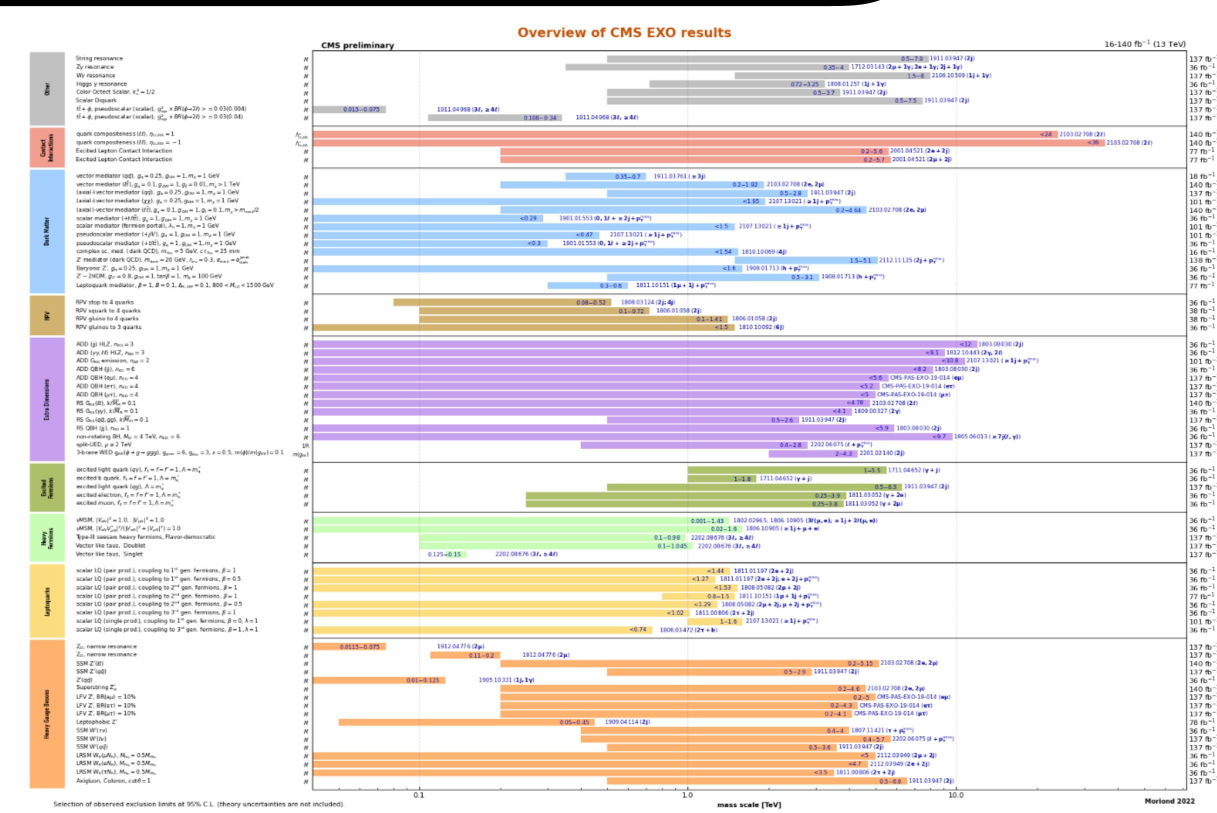
Direct searches









And yet nothing!

Measurements, searches, and global fits: 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 is confronted with a specific 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 usually 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 is given by fitting EFT and PDF together using DY data (see Greljo et al. 2104.02723)

The LHC legacy (in ~20 years) is to design and accomplish the final BSM measurement (which includes the 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 on “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). Multivatiate and ML could also provide a solution.
- **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. PDFs, HO, etc.). 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 is more severe, but theorists should try to get used to always deliver the full likelihood leading to their fits, that could be used by others and as input 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 robust statistical hypothesis test of the SM

Precision physics: the LEP experience

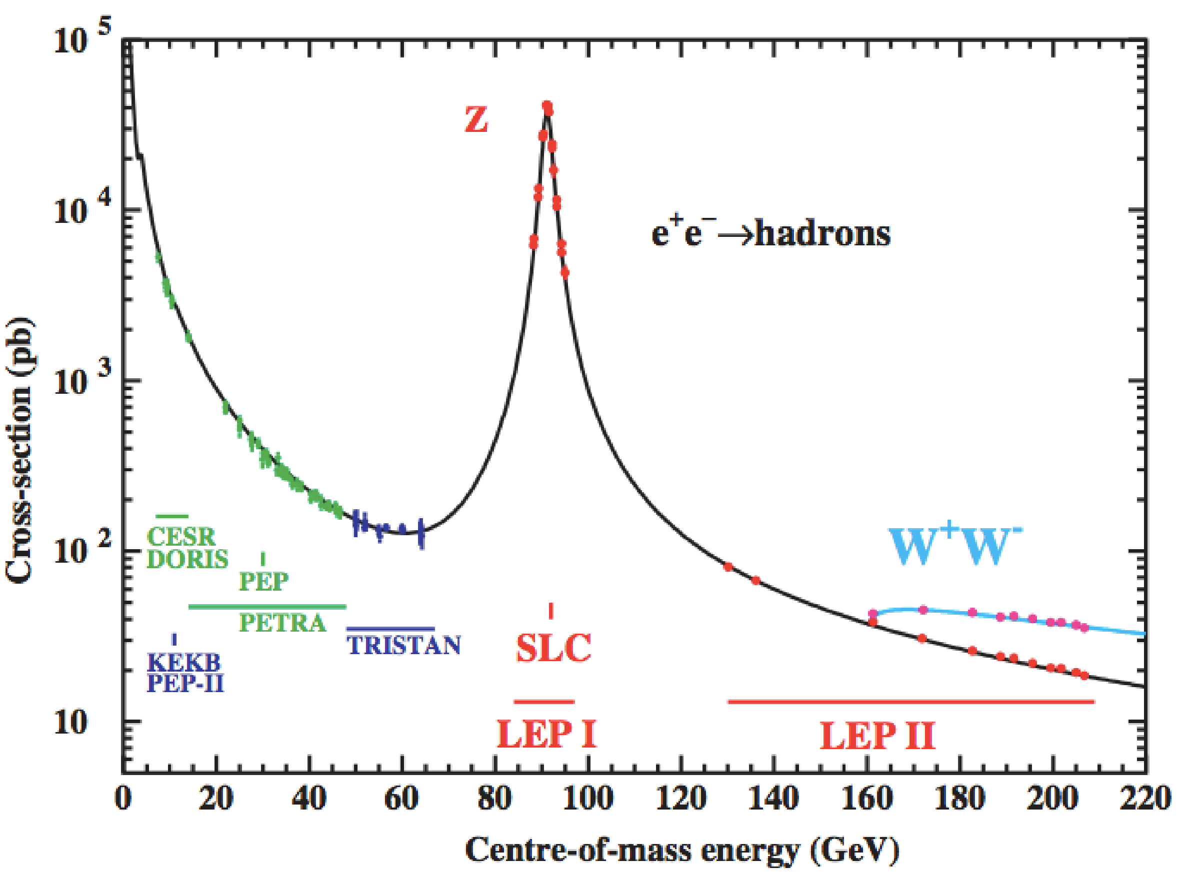
LEP is the prototypical example of a precision physics program

It measured with unprecedented accuracy SM observables allowing to perform precision tests of the SM electroweak sector

	Energy	Measurement	Precision
LEP-I	~ 91 GeV (Z peak)	Z properties	‰
LEP-II	from diboson thresholds up to ~208 GeV	off-shell Z properties, trilinear gauge interactions	%

LEP was sensitive to NP effects of the order of ‰ at the Z-pole and % off the Z-pole

- Clean experimental environment
- Small statistical uncertainties



Precision physics from high energy: the LHC

LHC environment completely different

No sensitivity to deviations from the SM of the order of % or below

At best 10% to O(1) effects (e.g. Higgs couplings)

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Precision@LHC requires new physics leading to large deviations but still unconstrained by LEP

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The best approach to indirect new physics is the framework of EFT

Higher Dimensional Operators (HDO) lead to amplitudes that grow with energy

Largest effects at high invariant masses

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

Energy: ~100 GeV

Accuracy: ~‰-%

New physics effects not enhanced by energy

LHC

Energy: ~1 TeV

Accuracy: ~10%

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

Energy: ~100 GeV

Accuracy: ~‰-%

New physics effects not enhanced by energy

LHC

Energy: ~1 TeV

Accuracy: ~10%

New physics effects enhanced by $E^2_{\rm LHC}/E^2_{\rm LEP} \sim 100$

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 2quark-2lepton four fermion interactions)

De Blas et al., 1307.5068
Farina et al., 1609.08157
Alioli et al., 1712.02347
Alioli et al., 1804.07407
Fuentes-Martin et al., 2003.12421
RT et al., 2008.12978
Panico et al., 2103.10532
Greljo et al. 2104.02723
RT et al., in progress

➢ 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)

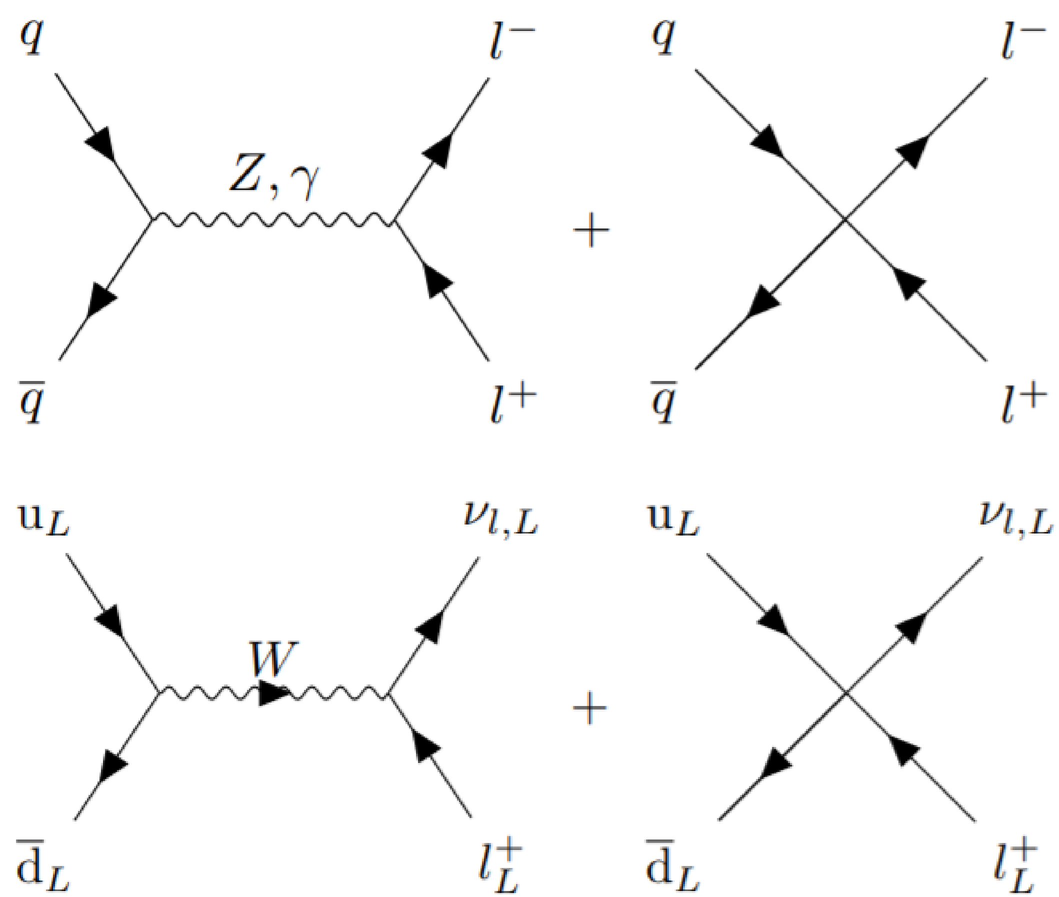
Farina et al., 1811.04084

➢ 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

➢ …

EFT for DY at LHC



Panico et al., 2103.10532

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

RT et al., 2008.12978

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

The simplest case: W&Y

Consider the SM EFT operators called "W"and "Y"

They contribute to DY at LHC (where few % precision is reached at high invariant masses)

	universal form factor ($\mathcal{L}$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

$$P_N = \begin{bmatrix} \frac{1}{q^2} - \frac{t^2\mathrm{W}+\mathrm{Y}}{m_Z^2} & \frac{t\big((\mathrm{Y}+\hat{\mathrm{T}})c^2+s^2\mathrm{W}-\hat{\mathrm{S}}\big)}{(c^2-s^2)\big(q^2-m_Z^2\big)} + \frac{t(\mathrm{Y}-\mathrm{W})}{m_Z^2} \\ \star & \frac{1+\hat{\mathrm{T}}-\mathrm{W}-t^2\mathrm{Y}}{q^2-m_Z^2} - \frac{t^2\mathrm{Y}+\mathrm{W}}{m_Z^2} \end{bmatrix}$$

$$P_C = \frac{1+\big((\hat{\mathrm{T}}-\mathrm{W}-t^2\mathrm{Y})-2t^2(\hat{\mathrm{S}}-\mathrm{W}-\mathrm{Y})\big)/(1-t^2)}{(q^2-m_W^2)} - \frac{\mathrm{W}}{m_W^2}$$

only modification of the gauge boson propagators

deviations entirely parametrized by 4 parameters:

$\hat{S}, \hat{T}, W, Y$

Contributions on the pole: LHC cannot surpass LEP

Contributions off the pole: LHC can surpass LEP

⇩

2 new physics parameters (W,Y) for 2 processes (neutral and charged DY)

If charged DY is not included there is a degeneracy, broken only by quadratic terms in W and Y (ellipse-like constraint)

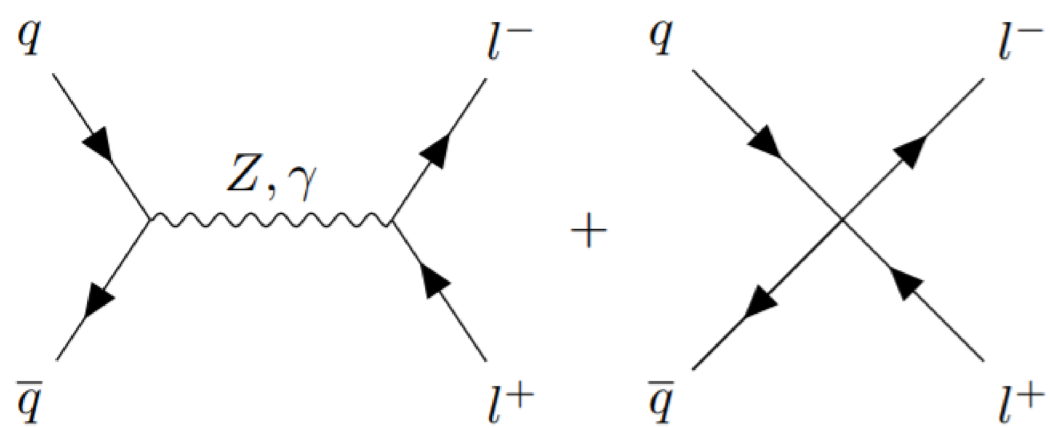
Precision in DY at LHC

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

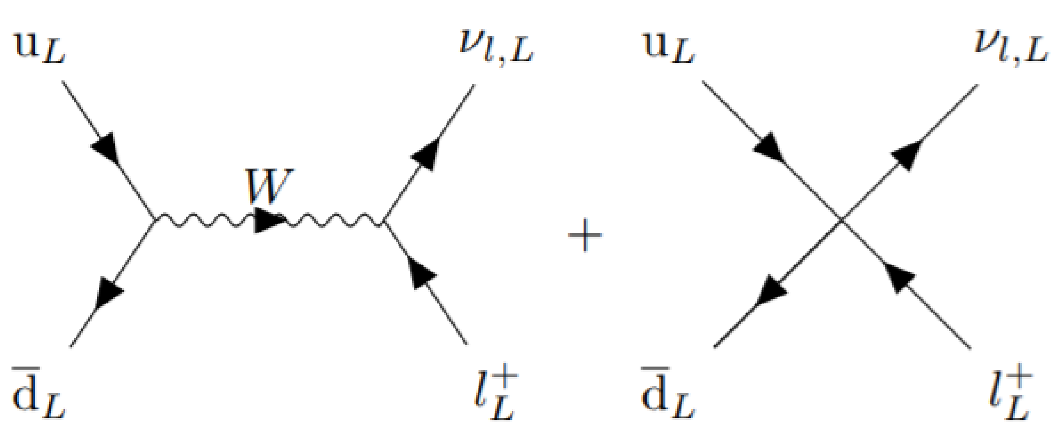
- LHC few percent experimental (statistic/systematic) uncertainties and fully differential cross section measurements (double differential for charged and triple differential for neutral)
- NLO QCD+NLO EW event generation matched to Parton Shower (e.g. POWHEG)
- NNLO QCD differential cross section (e.g. 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 from SM events including QCD and EW corrections with a simple analytic NP reweighting and do not require any scan over EFT parameters (making computationally trivial what would be extremely resource demanding)

NP factorization

- As stated before, new physics contributions factorize with respect to QCD corrections and leading-log EW corrections
- Nevertheless, this factorization depends on the type of the incoming quark and, in the case of the neutral channel, on the chiralities of the particles involved in the process



$$= i\,\mathcal{C}_0(q_{\chi_q}, l_{\chi_l})[\gamma^\mu P_{\chi_q}]_q[\gamma^\mu P_{\chi_l}]_l$$



$$= i\,\mathcal{C}_+(\{\mathrm{u},\mathrm{d}\}, l)[\gamma^\mu P_L]_q[\gamma^\mu P_L]_l$$

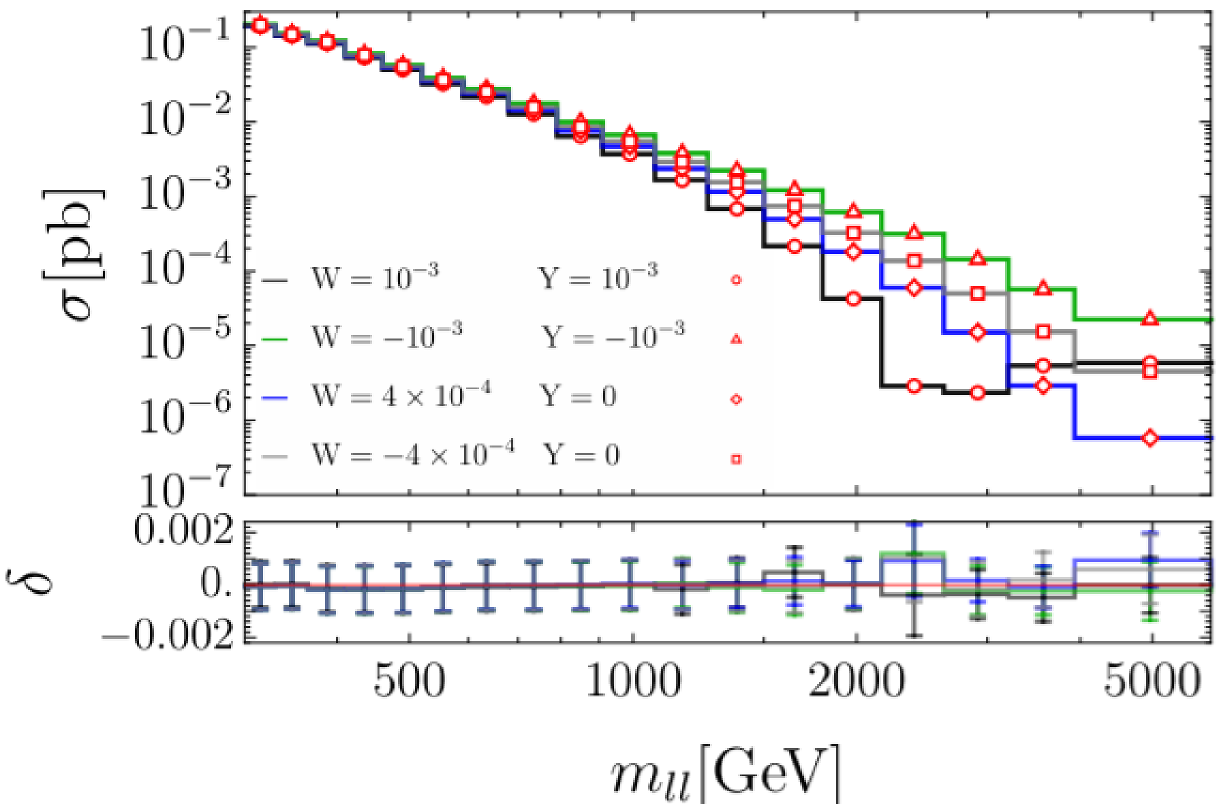
- While the charged process contains only the LL-LL chiral structure, the neutral one contains the four different structures LL-LL, LL-RR, RR-LL, RR-RR.

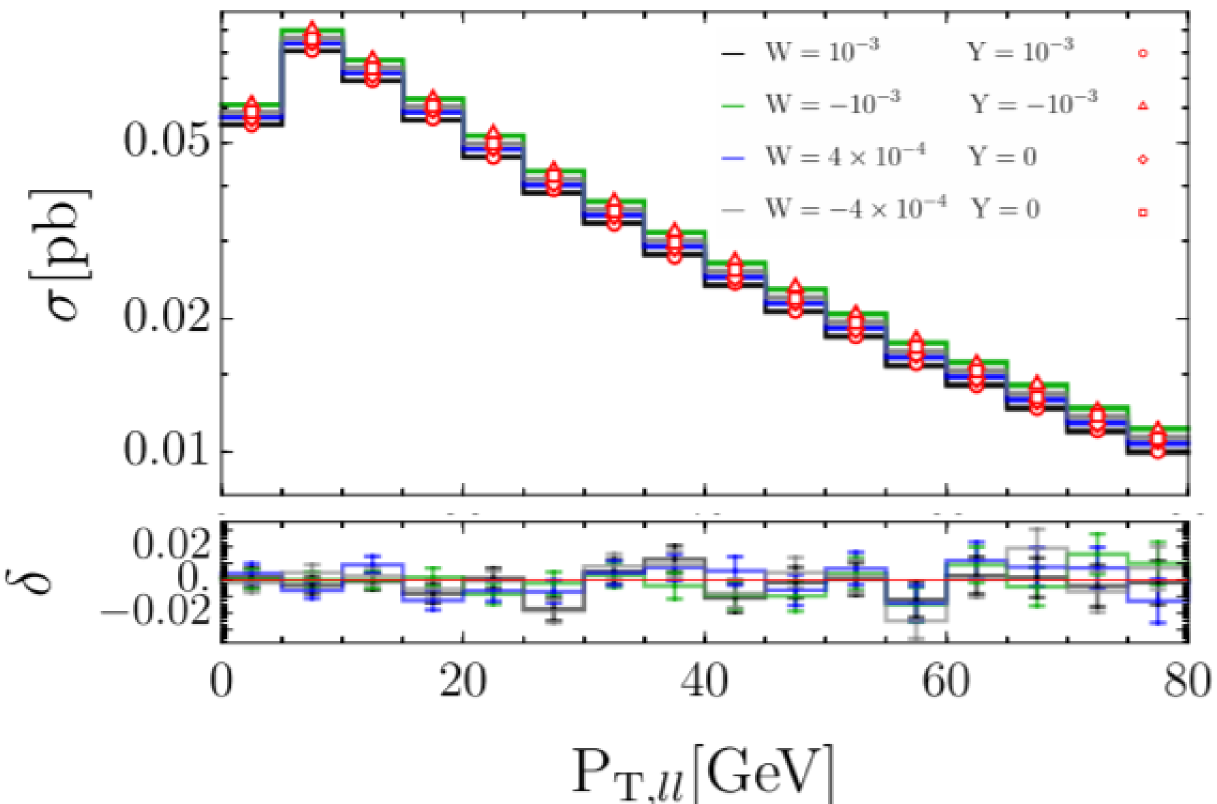
Our procedure

- We managed to trick the NLO QCD-only POWHEG model (Alioli et al., 0805.4802) to get simulations of SM events in the four non-vanishing chiarality channels (LL-LL,LL-RR,RR-LL,RR-RR)
- We add electroweak NLL contributions (to account for electroweak corrections)
- To each event we then attribute a weight that is an analytic function of the EFT parameters
- This gives events corresponding to the Monte Carlo simulation in an arbitrary point in the NP parameter space, with an error of the order of the sub-leading log and finite parts of the NLO EW part
- These events allow one to parametrize fully differential distributions for arbitrary values of the Wilson coefficients analytically
- In order to make predictions (or projections) we consider either data or BG only simulation as pseudo-data, and build a likelihood that is analytical in the NP parameters and allows to make inference (exclusion bounds) without any scan over EFT parameters
- We parametrize all relevant uncertainties with nuisance parameters (details later)
- To compare with experiments, we also consider the final state showering generated with PYTHIA and implement a photon recombination with the final state leptons

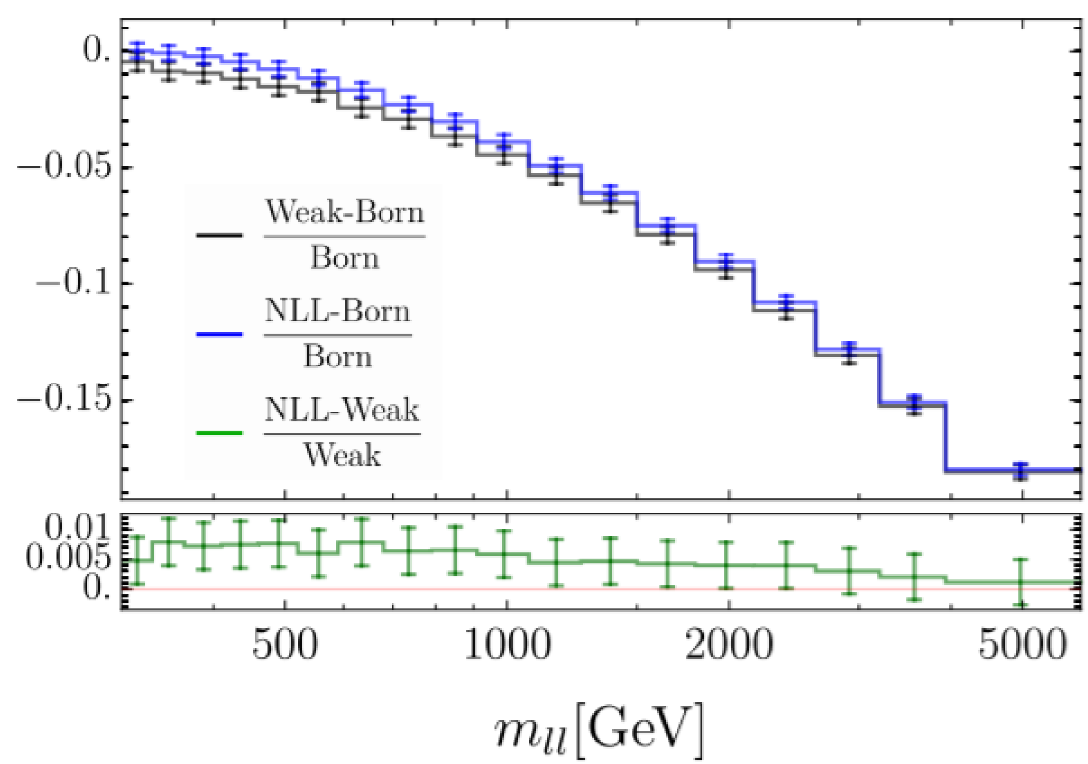
Validation

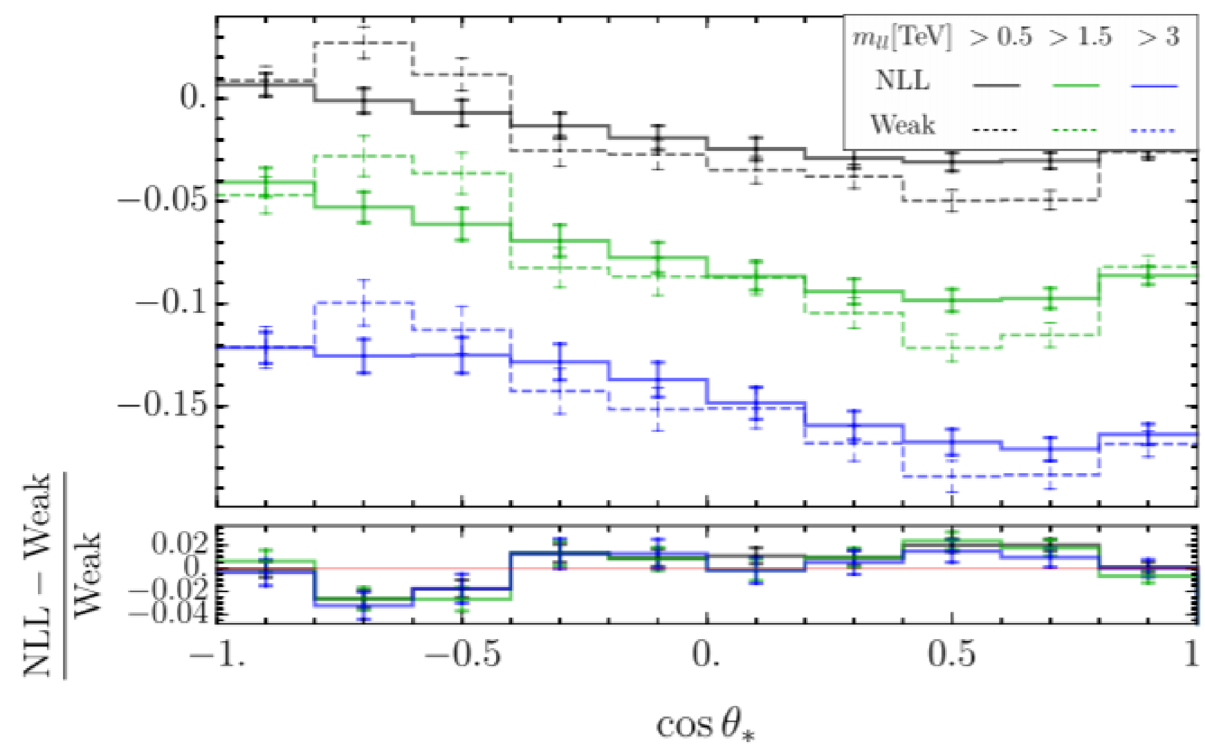
NLO QCD validation





NLL EW validation





The theoretical cross section

- In order to build a general Likelihood for the DY process we need a suitable parametrization of the cross section in each bin “I” in terms of NP parameters and nuisance parameters (which describe uncertainties)
- In the case of the W&Y operators the cross section is a quadratic polynomial in W and Y, which can be conveniently parametrized using the Cholesky decomposition

$$\sigma_I^{\mathrm{th}}(\mathrm{W},\mathrm{Y}) = \overline{\sigma}_I^{\mathrm{SM}} c_{0,I}^2 \left| \begin{pmatrix} 1 & c_{1,I} & c_{3,I} \\ 0 & c_{2,I} & c_{4,I} \\ 0 & 0 & c_{5,I} \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \mathrm{W} \\ \mathrm{Y} \end{pmatrix} \right|^2$$

$$= \overline{\sigma}_I^{\mathrm{SM}} c_{0,I}^2 [1 + 2c_{1,I}\mathrm{W} + 2c_{3,I}\mathrm{Y} + (c_{1,I}^2 + c_{2,I}^2)\mathrm{W}^2 + \left(c_{3,I}^2 + c_{4,I}^2 + c_{5,I}^2\right)\mathrm{Y}^2 + 2(c_{1,I}c_{3,I} + c_{2,I}c_{4,I})\mathrm{WY}] \,.$$

- Provided that $c_{0,I}$, $c_{2,I}$, and $c_{5,I}$ are positive, this ensures a strictly positive cross section
- This is an analytic function giving the cross section in each bin for every value of W&Y
- The c coefficients are computed from simulation using our analytic reweighting
- All relevant uncertainties are then implemented allowing the c coefficients to vary according to well defined probability distributions
- Monte Carlo statistical uncertainty is completely negligible both for SM and NP (which, due to the analytic reweighting, has the same relative uncertainty as the SM)

Uncertainties: α_S

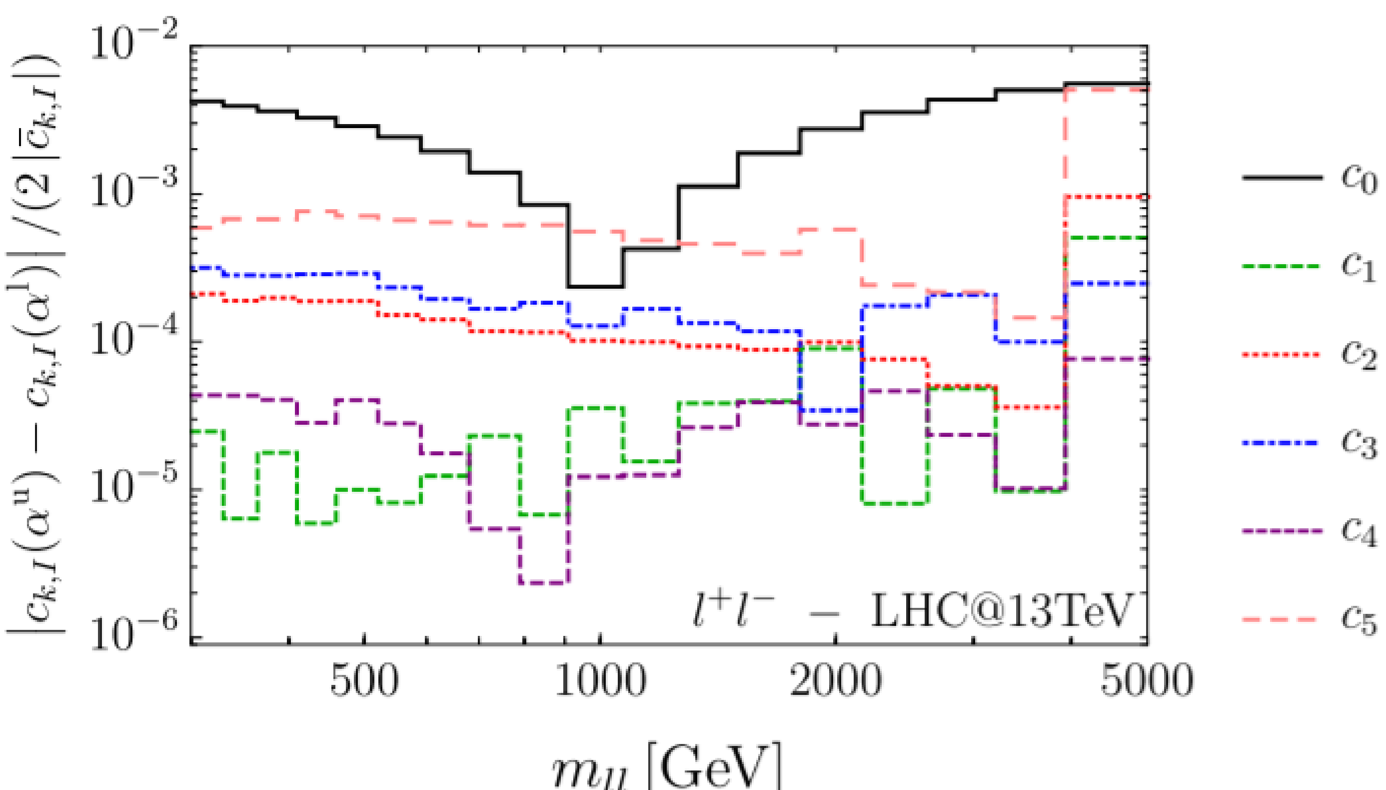
- POWHEG simulations include, on top of a "central" weight obtained for $\alpha_S = 0.1180$, also a reweighting for $\alpha_S^l = 0.1165$ and $\alpha_S^u = 0.1195$. These values correspond to different values of the c coefficients, that are used to parametrize the uncertainty through a linear dependence of the c's from a single standard normally distributed nuisance parameter θ^{α_S}

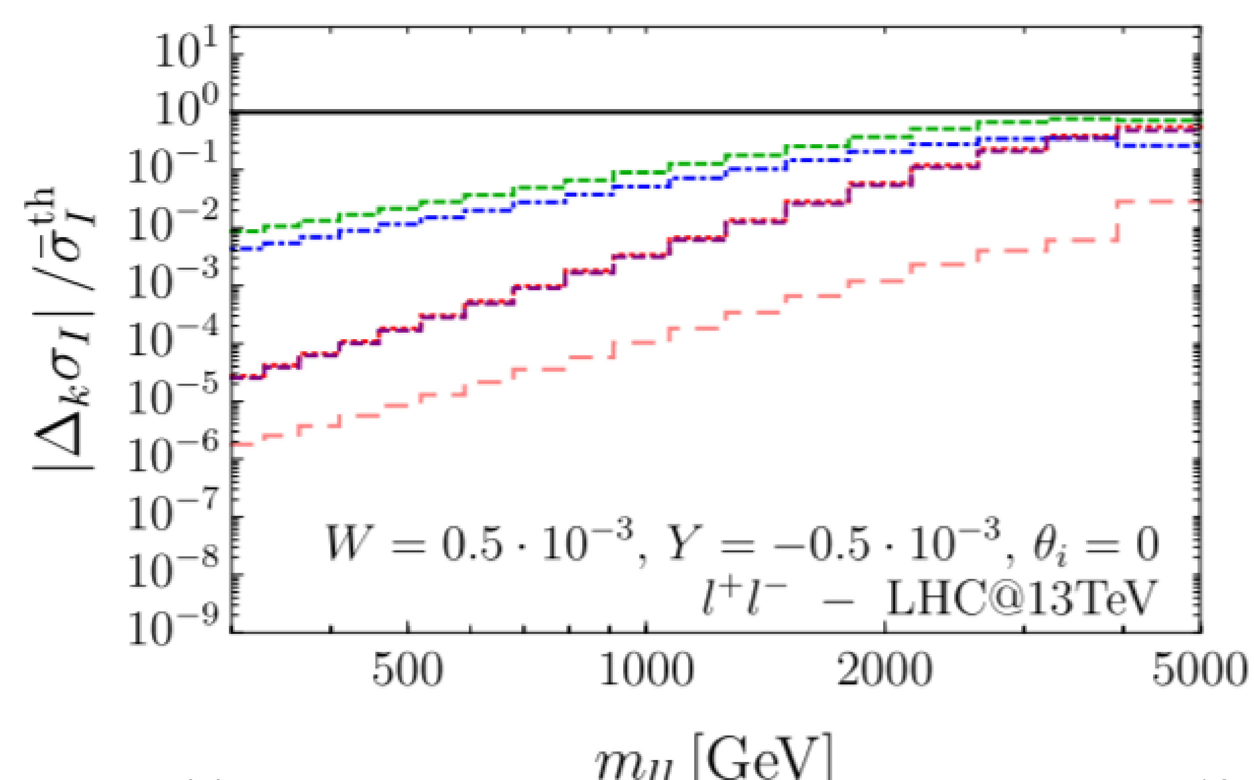
$$c_{0,I} = c_{0,I}\left(\theta^{\alpha_\mathrm{s}}\right) = \bar{c}_{0,I} + \kappa_I^{\alpha_\mathrm{s}}\theta^{\alpha_\mathrm{s}} = 1 + \kappa_I^{\alpha_\mathrm{s}}\theta^{\alpha_\mathrm{s}}$$

$$k_I^{\alpha_\mathrm{s}} = \max\left(\left|c_{0,I}(\alpha_\mathrm{s}^\mathrm{u}) - \bar{c}_{0,I}\right|, \left|c_{0,I}(\alpha_\mathrm{s}^\mathrm{l}) - \bar{c}_{0,I}\right|\right)$$

$$f_{\alpha_\mathrm{s}}\left(\theta^{\alpha_\mathrm{s}}\right) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\theta^{\alpha_\mathrm{s}}\right)^2}$$

- This uncertainty is only relevant for the $c_{0,I}$ coefficients





Uncertainties: scale variation

- Scale variation uncertainty parametrizes the unknown value of the missing higher orders
- Missing higher orders in QCD are parametrized reweighting the simulation for different values of the factorization and renormalization scales. We consider a central value of such scales $\overline{\mu}_F = \overline{\mu}_R = \sqrt{s}$ and vary them by multiplicative factors 1, $2^{\pm 1}$, and $2^{\pm 1/2}$ for a total of 24 different weights
- These uncertainties are also reduced by taking into account that the full NNLO QCD calculation is available, for instance in FEWZ
- Missing higher EW orders are estimated looking at the relative impact of the leading 2-loop IR logs. Their contribution is small enough that, after including them in our rescaling procedure, we could neglect the uncertainty from missing EW contributions
- The final scale uncertainty that we consider is 1/10 of the NLO QCD one and we only consider it for the SM contribution (for NP it turns out to be totally negligible)
- We parametrize this uncertainty with a nuisance parameter per bin, distributed according to a standard normal distribution (similarly to α_S), with the c's coefficients given by

$$c_{0,I} = \bar{c}_{0,I} + \frac{(c_{k,I}^{\max} - c_{k,I}^{\min})}{2}\theta_I^{\mathrm{TU}}$$

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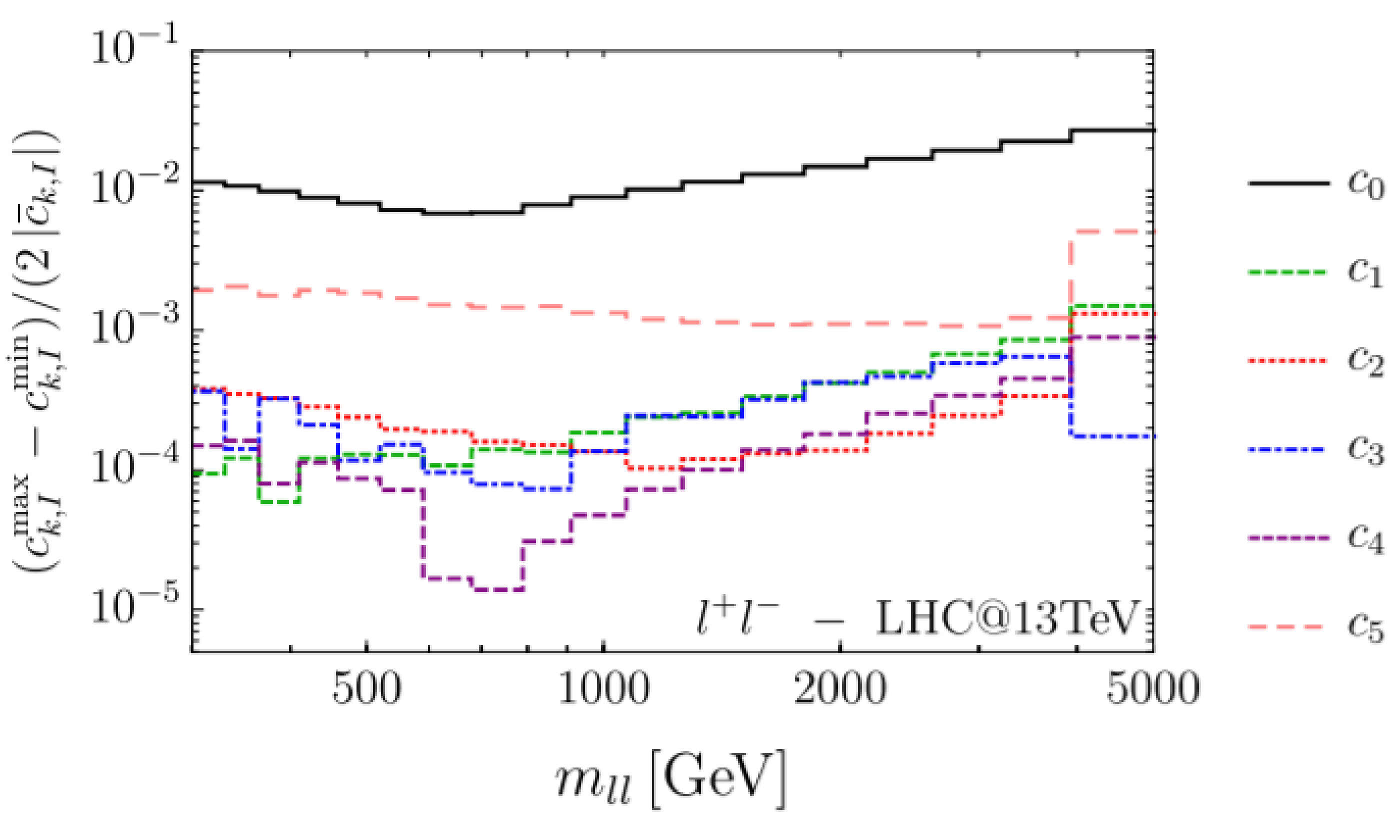
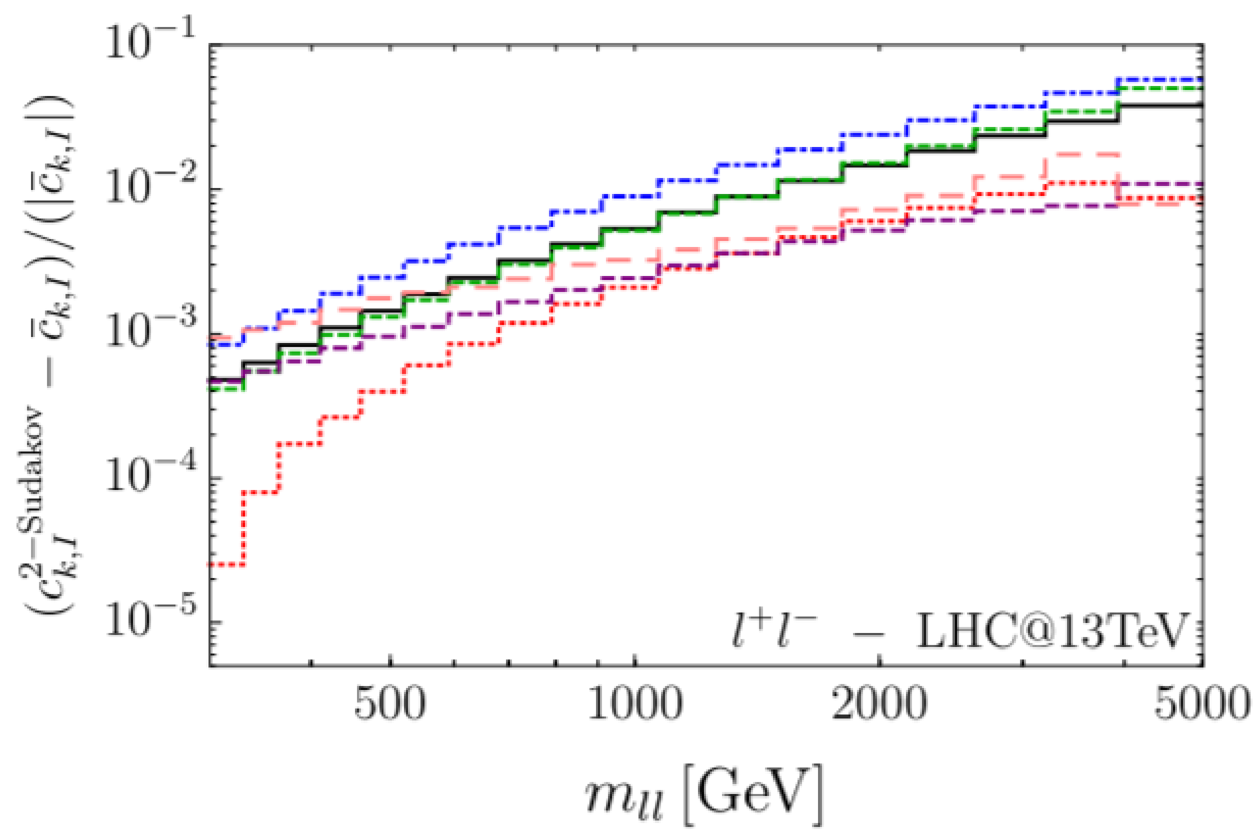




Uncertainties: PDFs

- We used the PDF set PDF4LHC15_nlo_30_pdfas, which correspond to the Hessian reduction of the PDF uncertainties to 30 uncorrelated nuisance parameters with standard normal distributions

$$f_{\mathrm{PDF}}\left(\theta_i^{\mathrm{PDF}}\right) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\theta_i^{\mathrm{PDF}}\right)^2}, \qquad i = 1, \ldots, 30$$

- This allows us to uniform the treatment of PDFs uncertainties among the neutral and charged channels
- The use of the Hessian set is motivated by the fact that we look at small deviations from the SM with no on-shell new physics
- The choice of 30 replicas is motivated by a study we made with a pdf Monte Carlo ensemble that allowed us to find about 20 uncertainty eigenvectors with uncertainty above permille
- For the strictly positive Cholesky we employed an exponential parametrization, while for the others we just used a linear one

$$X(\theta_i^{\mathrm{PDF}}) = \overline{X} \exp\left[\sum_{i=1}^{30} \frac{X^{(i)} - \overline{X}}{\overline{X}} \theta_i^{\mathrm{PDF}}\right], \quad \text{for} \quad X = \{c_{0,I}, c_{2,I}, c_{5,I}\}$$

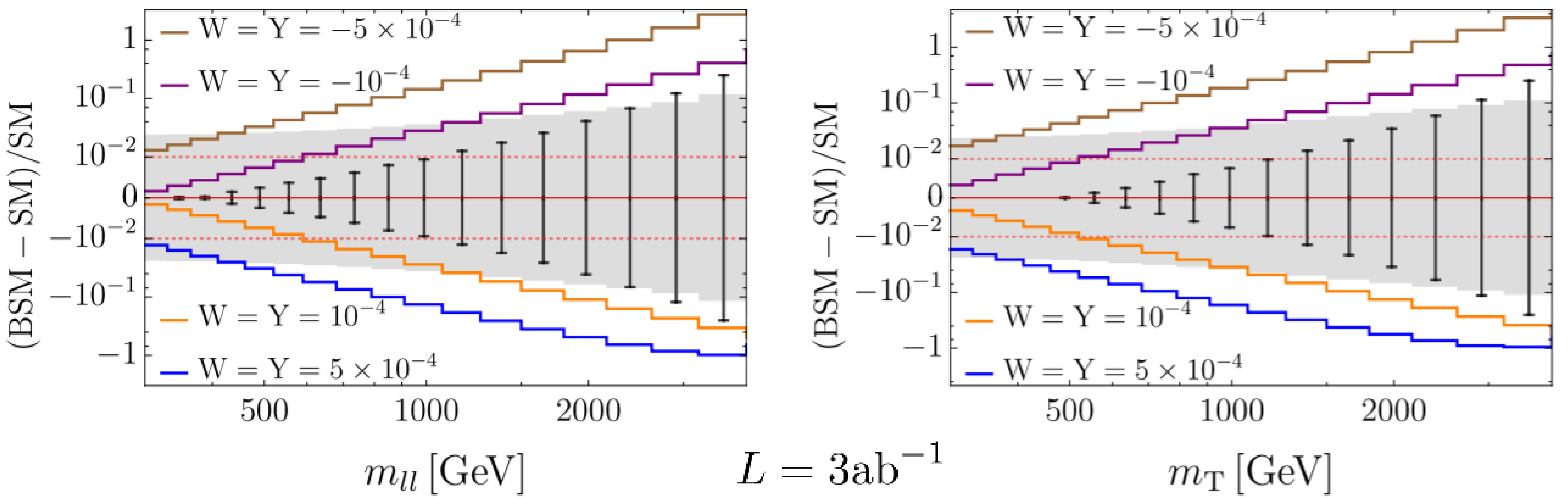
$$X(\theta_i^{\mathrm{PDF}}) = \overline{X} + \sum_{i=1}^{30} (X^{(i)} - \overline{X}) \theta_i^{\mathrm{PDF}}, \quad \text{for} \quad X = \{c_{1,I}, c_{3,I}, c_{5,I}\}$$

Likelihood and experimental uncertainties

We parametrize the DY binned (18 log-spaced bins) likelihood (in the W&Y case) as

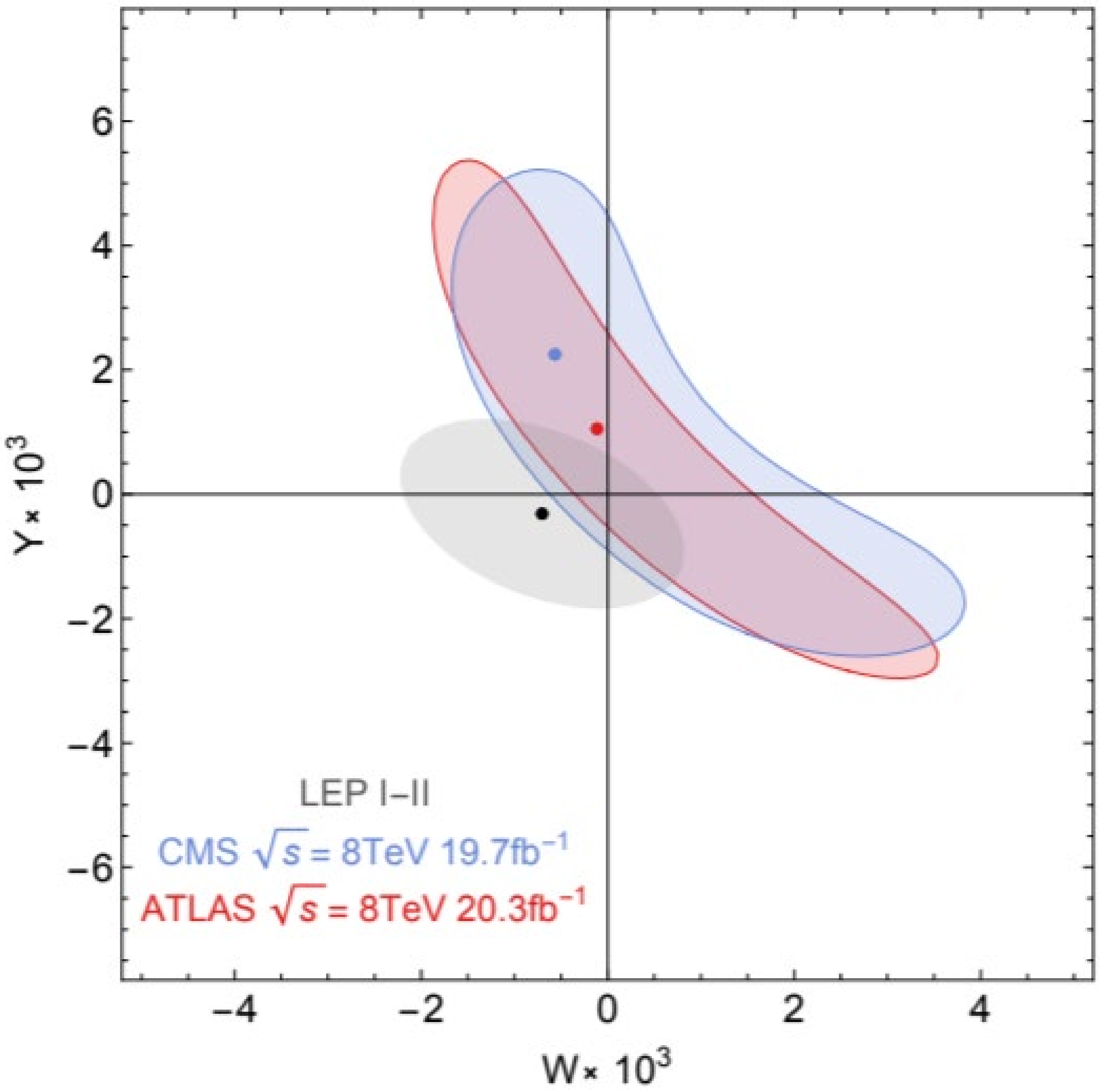
$$\mathscr{L}\left(W, Y, \theta^{\alpha_s}, \theta_i^{\mathrm{PDF}}, \theta_I^{\mathrm{TU}}, \theta_I^{\mathrm{exp}}, \theta^{\mathrm{L}}\right) = \prod_{I=1}^{N} \mathrm{Poisson}\left[n_I | \mu_I\left(W, Y, \theta^{\alpha_s}, \theta_i^{\mathrm{PDF}}, \theta_I^{\mathrm{TU}}, \theta_I^{\mathrm{exp}}, \theta^{\mathrm{L}}\right)\right] \times f_{\alpha_s}(\theta^{\alpha_s}) f_{\mathrm{PDF}}(\theta^{\mathrm{PDF}}) f_{\mathrm{TU}}(\theta_I^{\mathrm{TU}}) f_{\mathrm{exp}}(\theta^{\mathrm{exp}}) f_{\mathrm{L}}(\theta^{\mathrm{L}})\,.$$

$$\mu_I = \sigma_I^{\mathrm{th}}\left(1 + \sum_J \left[\sqrt{\Sigma^{\mathrm{exp}}}\right]_{IJ} \theta_J^{\mathrm{exp}} + 0.02\theta^L\right)$$



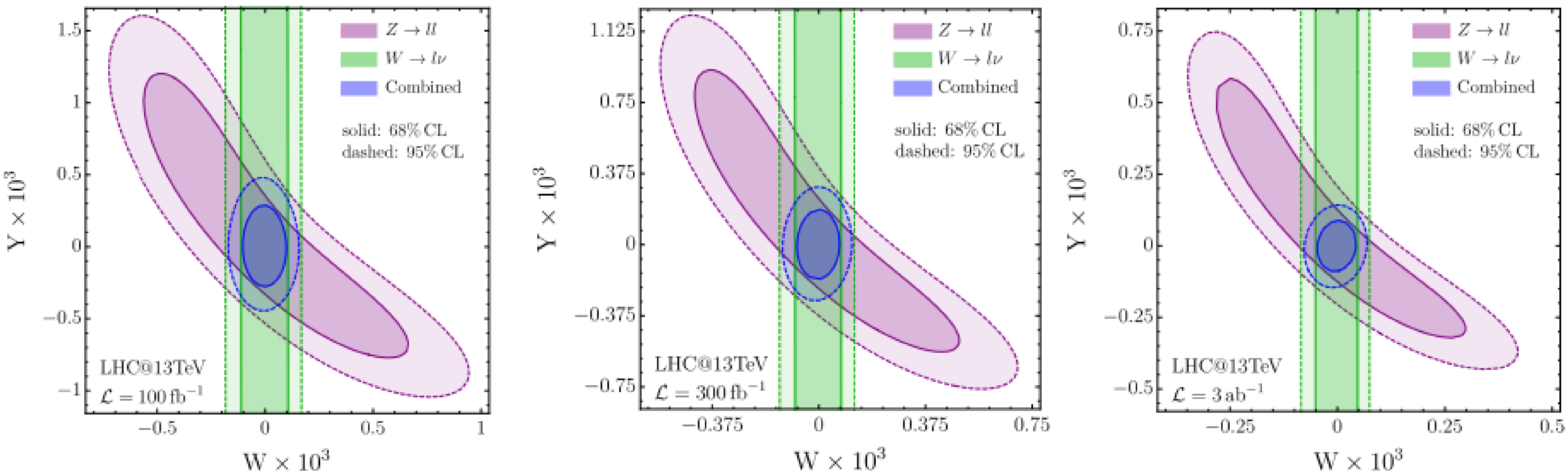
Results: data

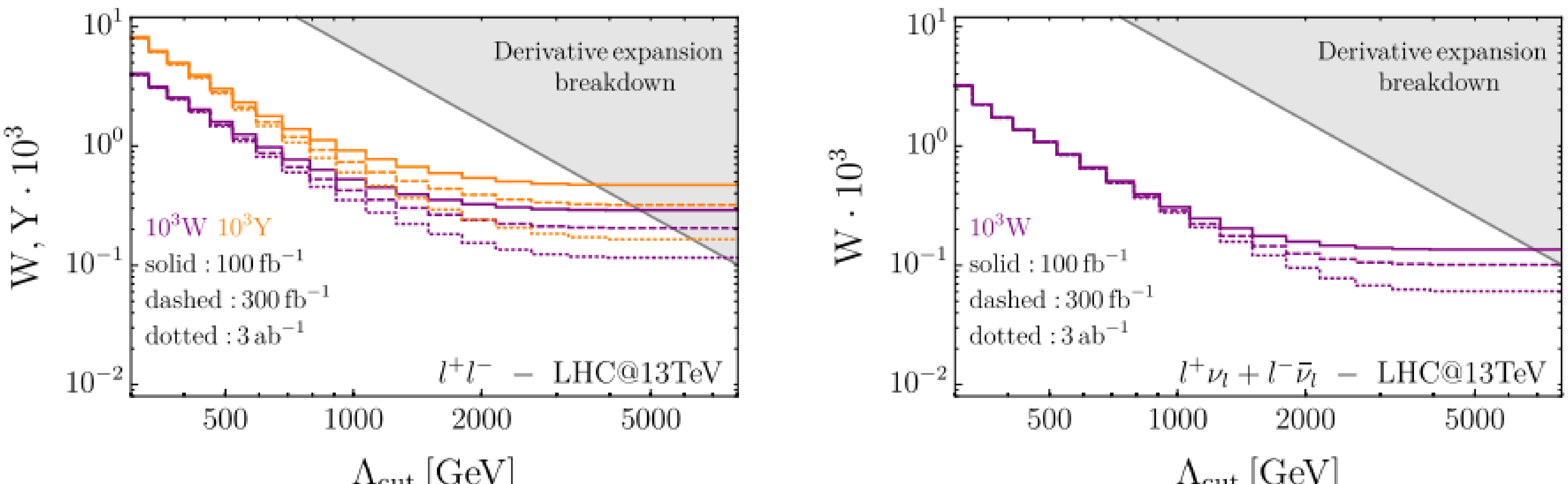
Farina et al., 1609.08157



Considering only neutral DY at 8 TeV the LHC is already competitive with LEP

Results: projections

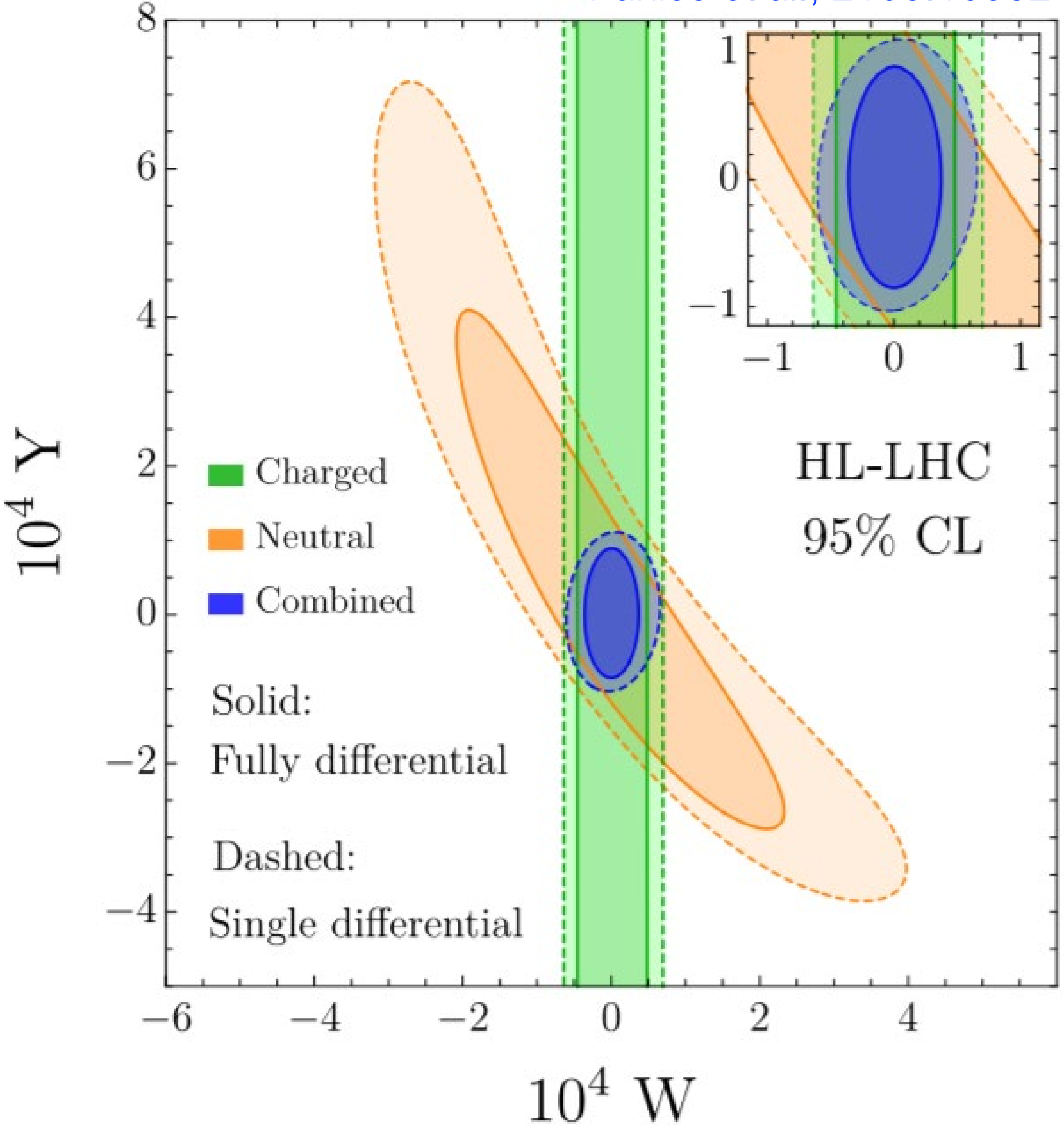




Results: W&Y single vs triple differential

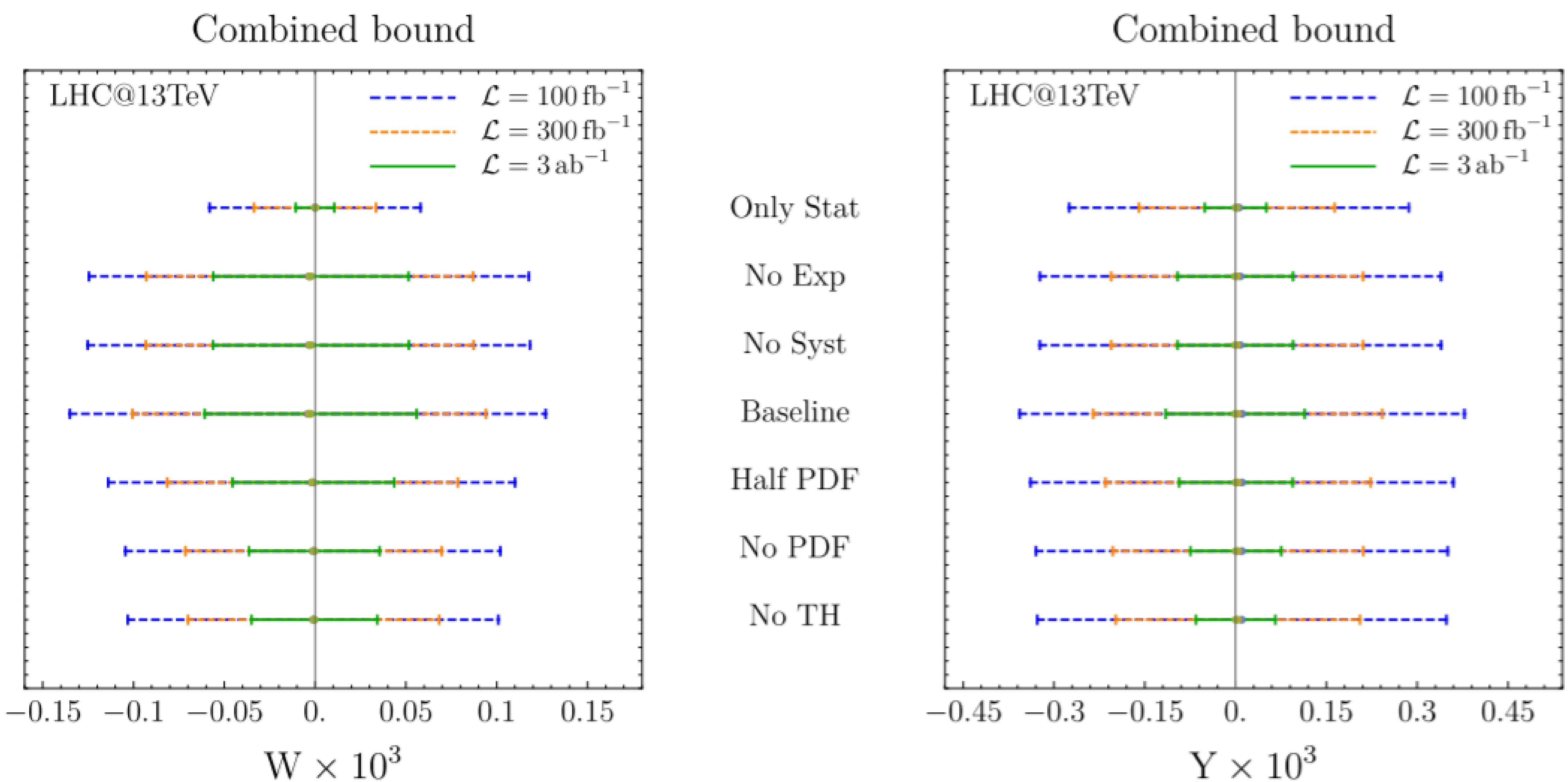
The results further improve when using the fully differential information instead of the single differential one

Panico et al., 2103.10532



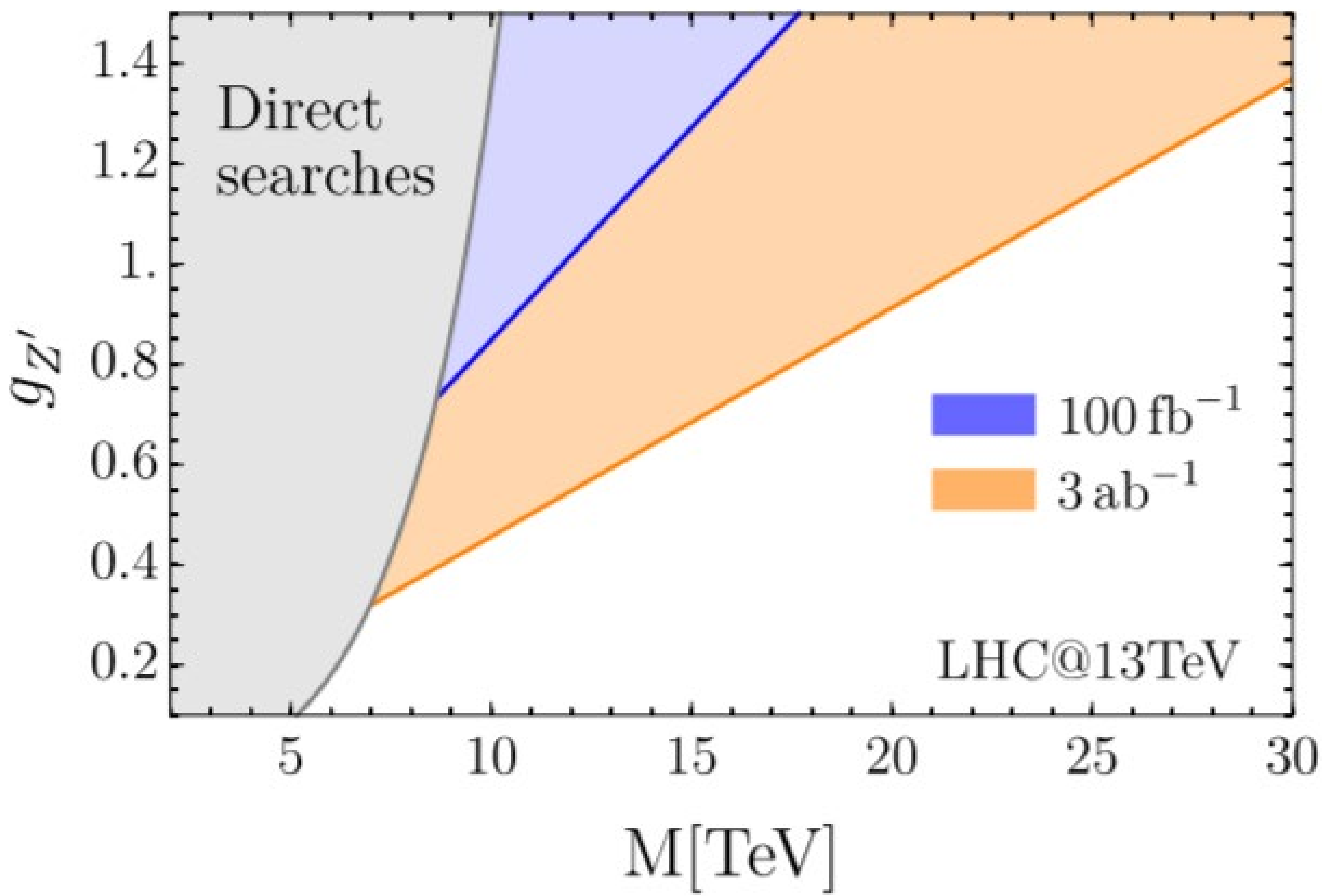
Impact of uncertainties

To quantify the impact of the various sources of uncertainties we have performed one-parameter fits for W and Y for different hypotheses on the uncertainties



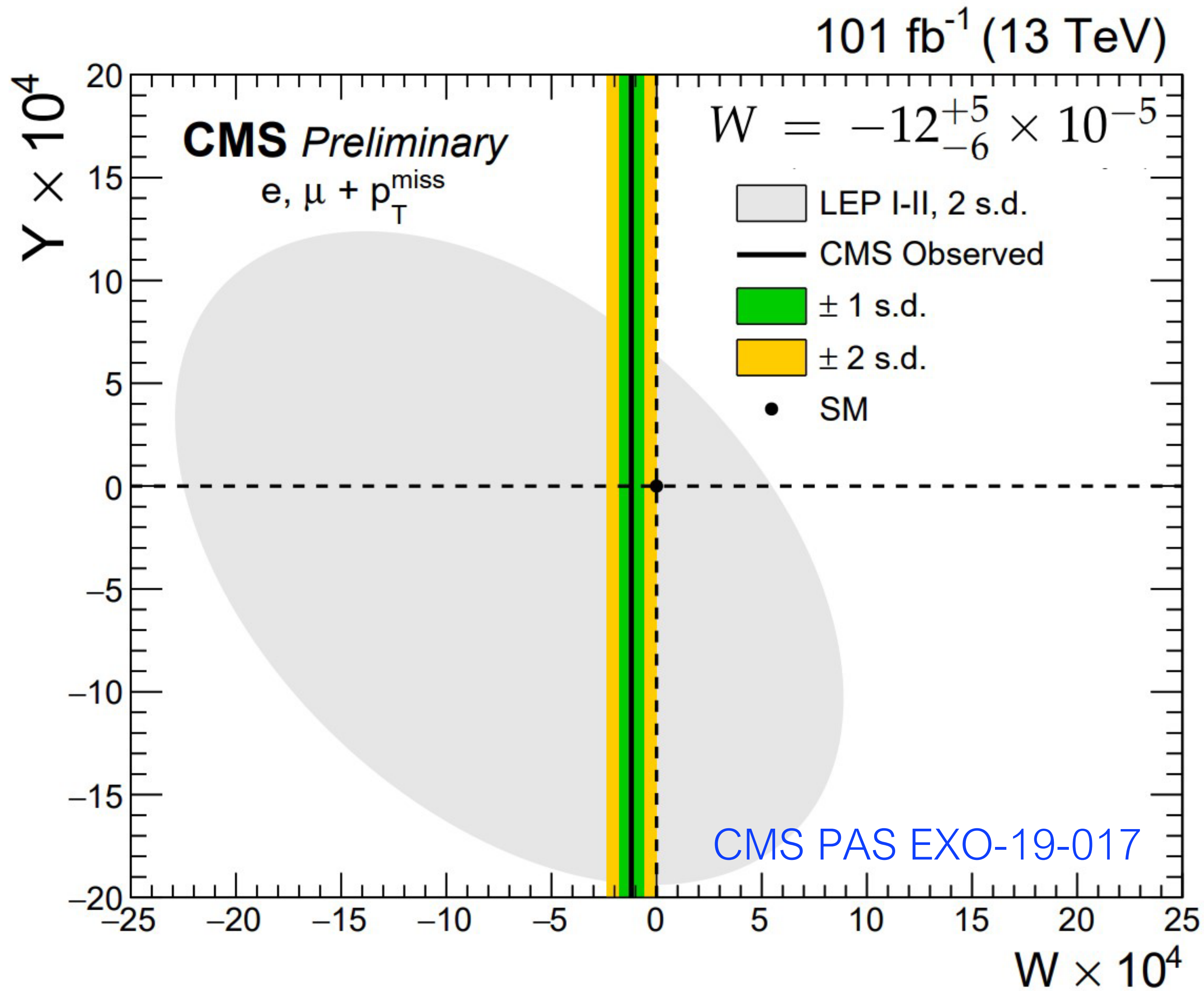
Comparison with direct search projections

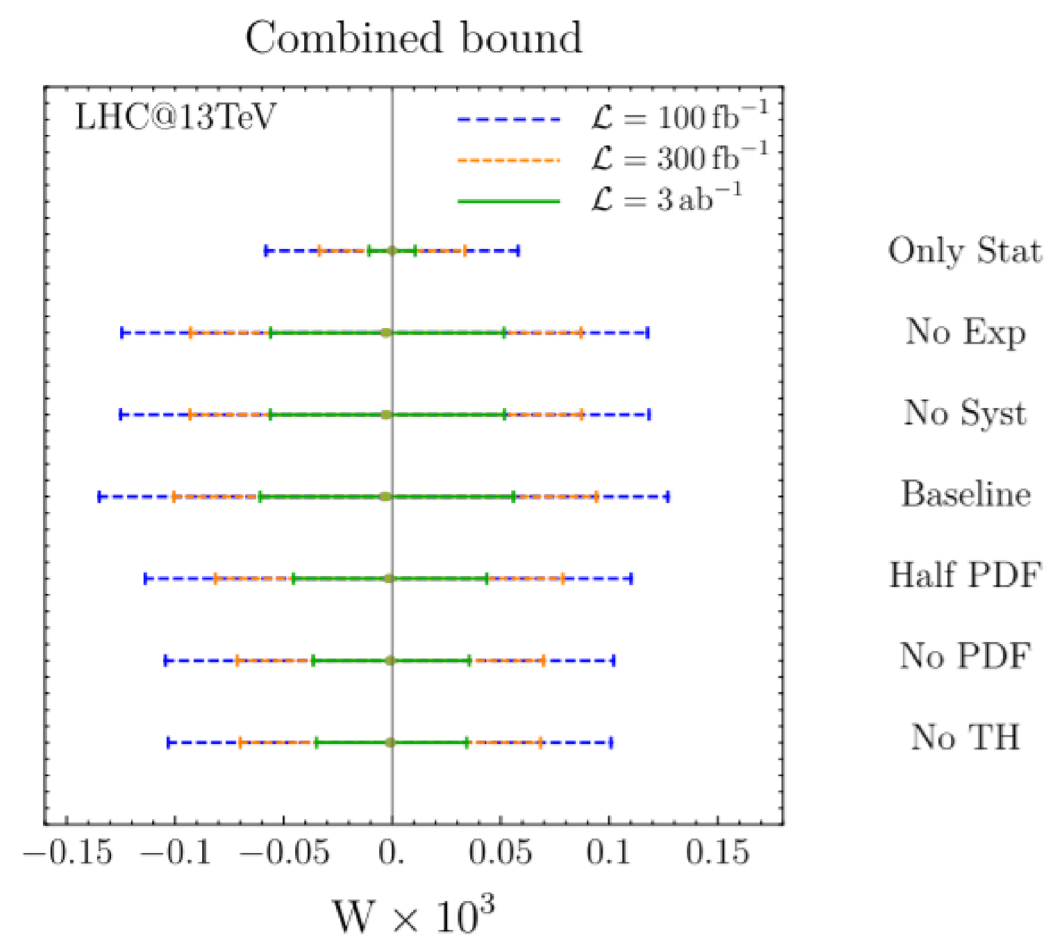
A simple Z’ model would generate a Y parameter, making direct vs indirect constraints complementary



Comparison with updated bound on W

CMS recently released a fit of the W parameter, done in the context of a W' search. The bound overcomes the LEP bound by more than one order of magnitude





Bounds on general 4-fermion

Panico et al., 2103.10532

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

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

A fully differential (double differential for charged and triple differential for neutral) analysis allows to constrain more directions and is essential for the general 4-fermion case

95%CL	single parameter			profiled		
$[10^{-3}\,\mathrm{TeV}^{-2}]$	fully diff.	fully diff. lin.	single diff.	fully diff.	fully diff. lin.	single diff.
$G_{lq}^{(3)}$	$[-1.09, 1.03]$	$[-1.06, 1.06]$	$[-1.35, 1.25]$	$[-1.19, 1.06]$	$[-1.30, 1.30]$	$[-1.51, 1.27]$
$G_{lq}^{(1)}$	$[-4.68, 7.51]$	$[-5.66, 5.66]$	$[-5.11, 10.64]$	$[-8.62, 10.56]$	$[-35.6, 35.6]$	$[-9.72, 13.5]$
G_{qe}	$[-4.71, 8.62]$	$[-6.57, 6.57]$	$[-6.11, 10.9]$	$[-7.23, 9.37]$	$[-375, 375]$	$[-10.9, 11.3]$
G_{lu}	$[-4.22, 6.42]$	$[-5.01, 5.01]$	$[-5.88, 10.6]$	$[-6.05, 10.3]$	$[-187, 187]$	$[-11.6, 13.7]$
G_{ld}	$[-16.3, 10.2]$	$[-18.0, 18.0]$	$[-19.2, 12.5]$	$[-16.9, 14.9]$	$[-419, 419]$	$[-20.2, 20.9]$
G_{eu}	$[-3.10, 3.54]$	$[-3.30, 3.30]$	$[-3.29, 3.83]$	$[-6.20, 10.3]$	$[-46.9, 46.9]$	$[-7.25, 11.7]$
G_{ed}	$[-13.5, 8.18]$	$[-10.3, 10.3]$	$[-15.5, 8.69]$	$[-16.9, 16.0]$	$[-121, 121]$	$[-17.9, 18.7]$

LHC@14TeV

300/fb

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 poorly constrained 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.)

- I gave an extensive example of this direction for the simplest process: neutral and charged DY (work still in progress to release a full DY likelihood)

- Some results already exist also for di-jet, ttbar, di-bosons, but this only consists of a handful of studies and most of the work has yet to be done

THANK YOU

BACKUP

Precision in di-jet at LHC: Z

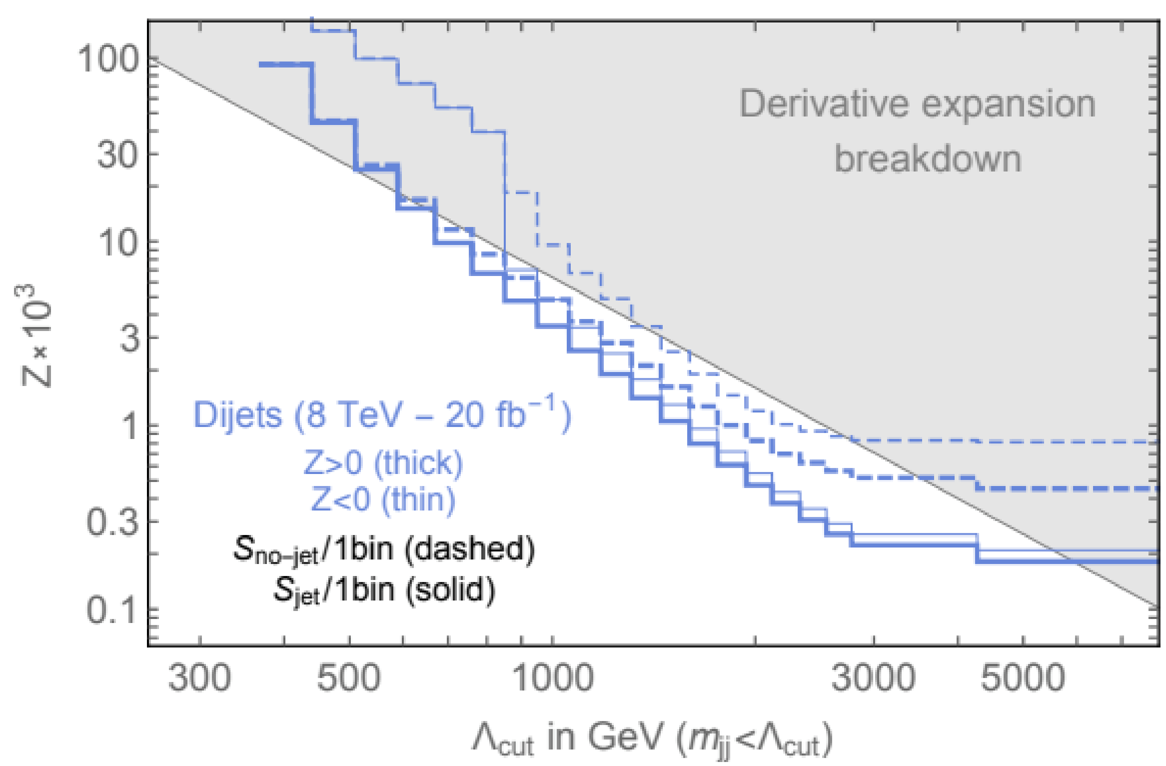
95% CL bounds on $Z \times 10^4$ for $\sqrt{s} = 8\,\text{TeV}$

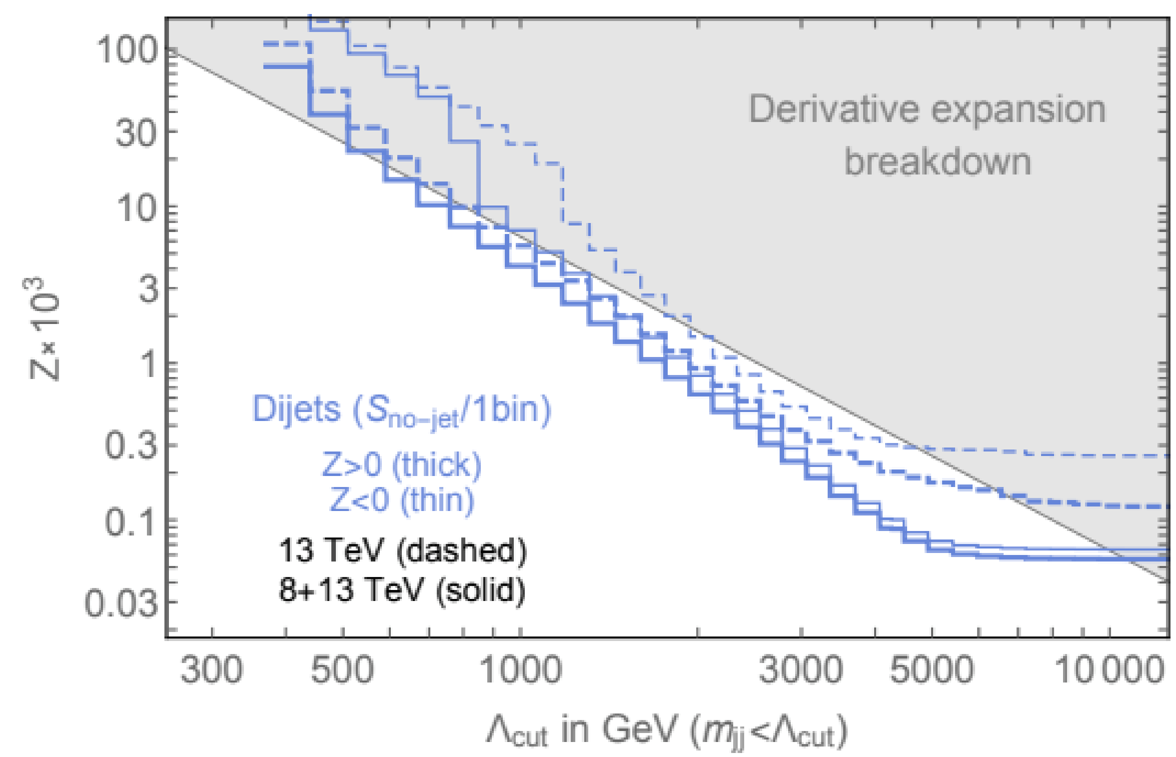
Alioli et al., 1712.02347

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 $\sqrt{s} = 13, 100\,\text{TeV}$

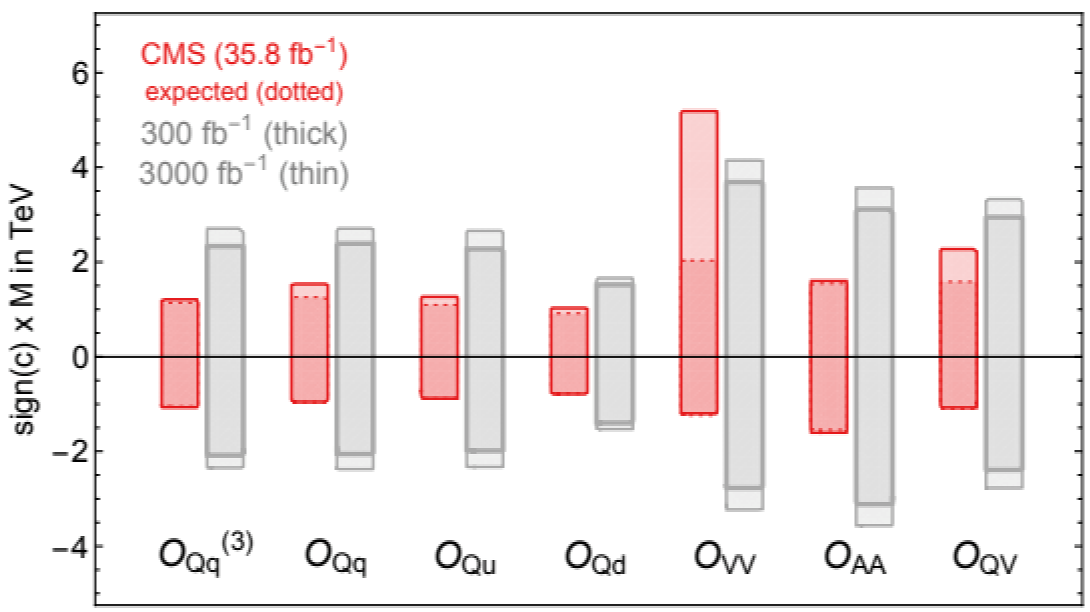
Analysis	$\sqrt{s}$ – Luminosity	$\mathcal{S}_{\text{no-jet}}$ - 1bin	$\mathcal{S}_{\text{no-jet}}$ - 2bins	$\mathcal{S}_{\text{jet}}$ - 1bin
dijet	13 TeV – 40 fb^{-1}	[-3.3,+1.7]	[-1.0,+0.9]	[-0.8,+0.7]
	13 TeV – 0.3 ab^{-1}	[-3.1,+1.4]	[-0.7,+0.6]	[-0.6,+0.5]
	13 TeV – 3 ab^{-1}	[-2.8+1.2]	[-0.5,+0.4]	[-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]$\times 10^{-2}$

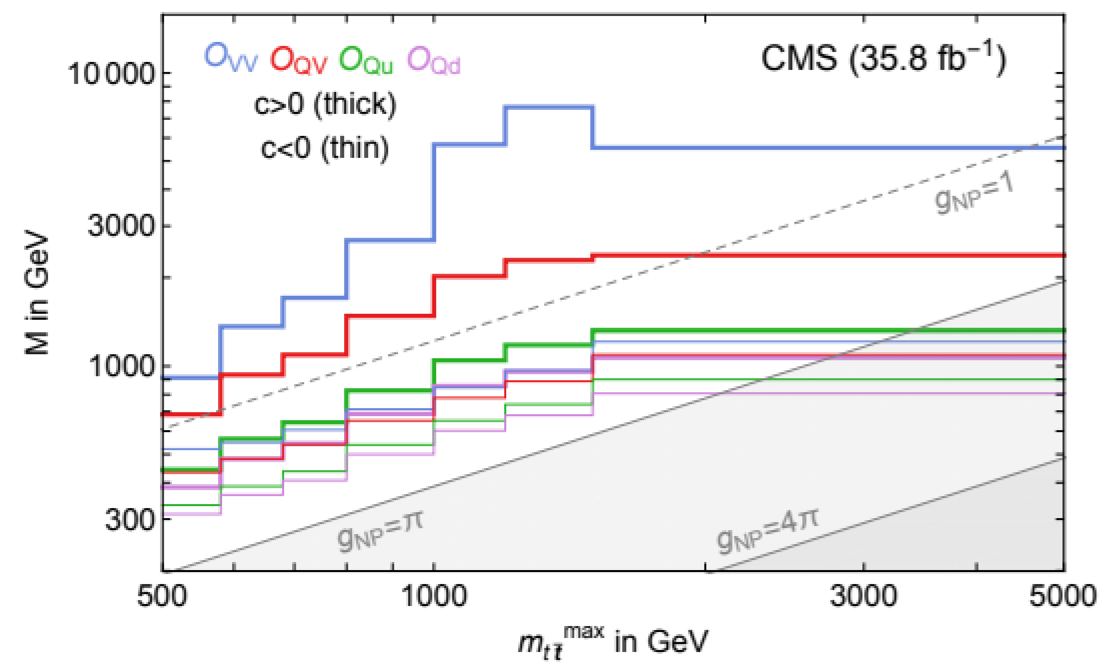


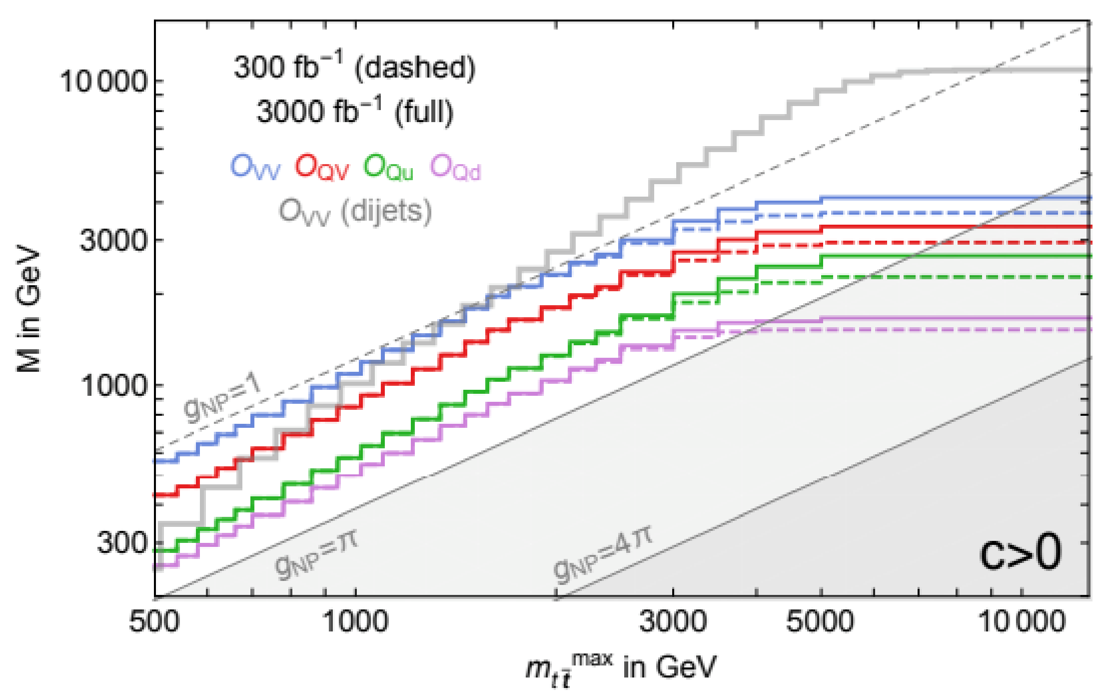


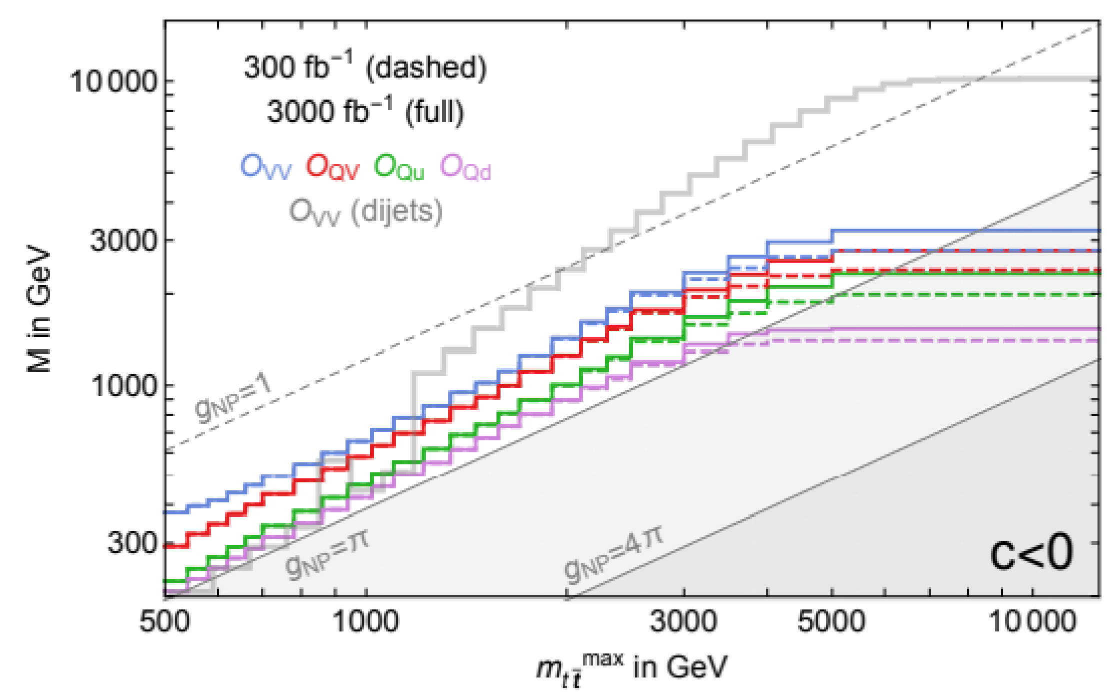
Precision in ttbar at LHC

Farina et al., 1811.04084









Precision in di-bosons at LHC

Franceschini et al., 1712.01310

SILH Basis

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

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

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

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

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

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

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

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

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