Energy helps Accuracy
Precision at Hadron Colliders

DaMeSyFla Meeting - SISSA, Trieste - 16 Mar 2017

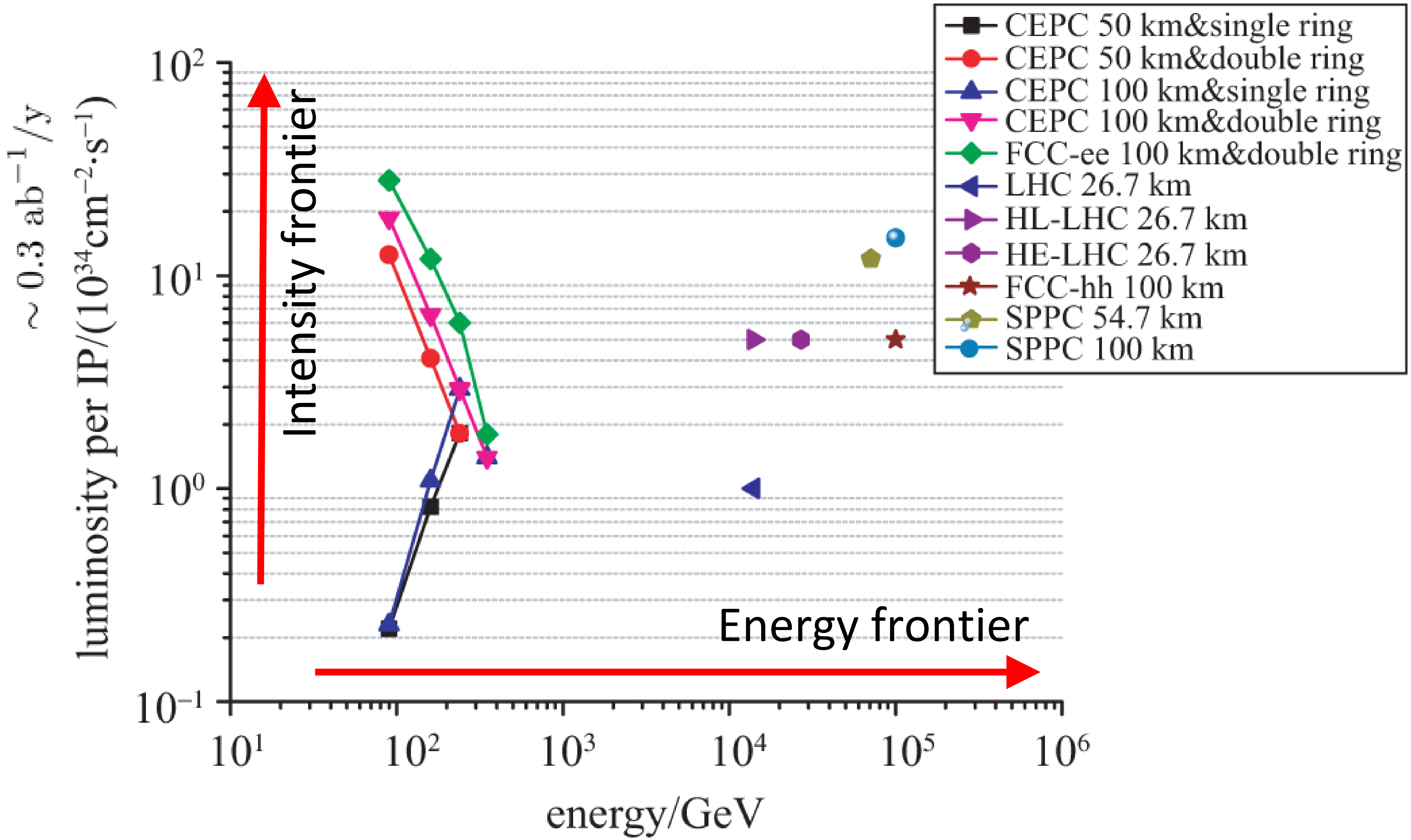
Riccardo Torre

EPFL Lausanne

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

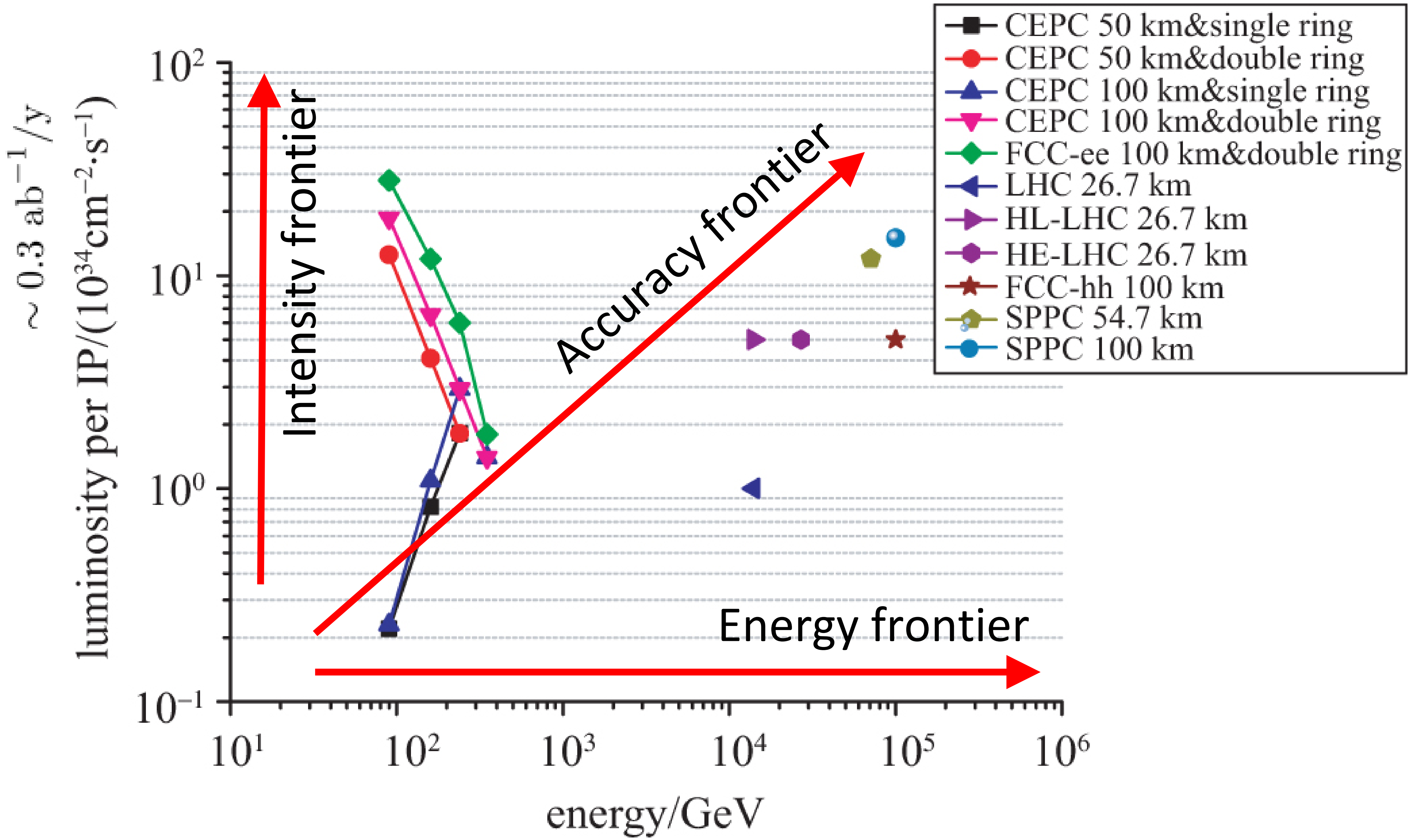
in collaboration with M. Farina, G. Panico, D. Pappadopulo, J.T. Ruderman, A. Wulzer, 1609.08157 [hep-ph]

Energy, intensity, and accuracy frontiers



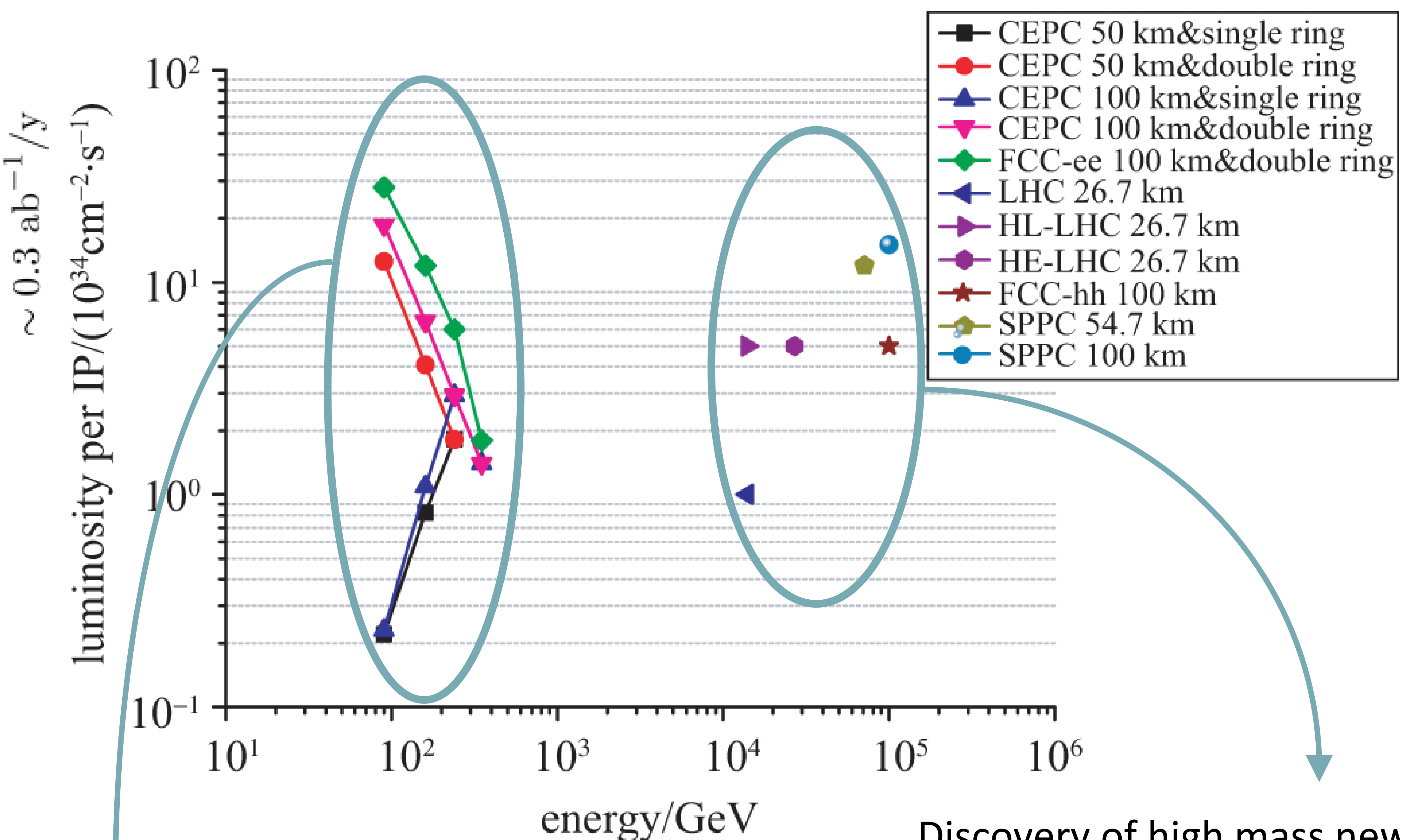
Energy and intensity frontiers usually considered complementary, but orthogonal

Energy, intensity, and accuracy frontiers



Real interplay is given by the accuracy frontier, which is not orthogonal to them

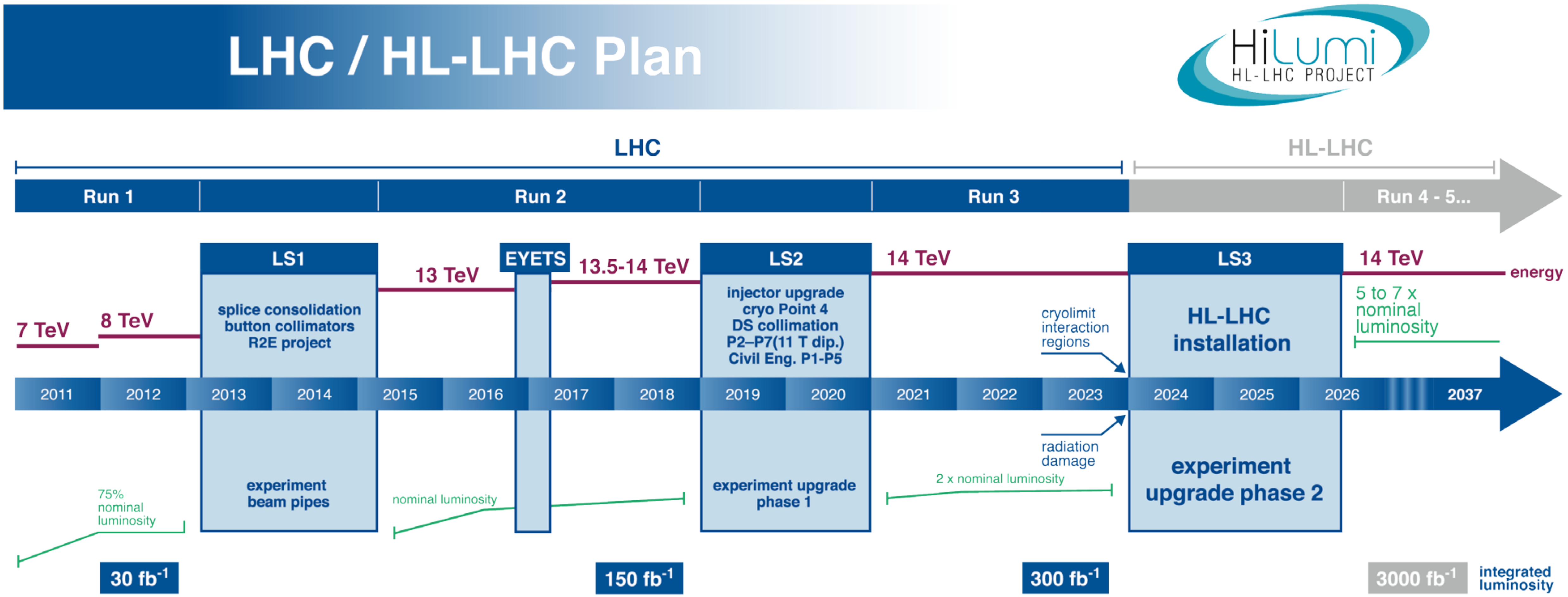
Energy, intensity, and accuracy frontiers



Precision at SM thresholds in high luminosity lepton colliders: Z, H, ZZ, WW, ZH, HH, tt

Discovery of high mass new physics in high energy hadron colliders…
… but also precision physics at and above SM thresholds

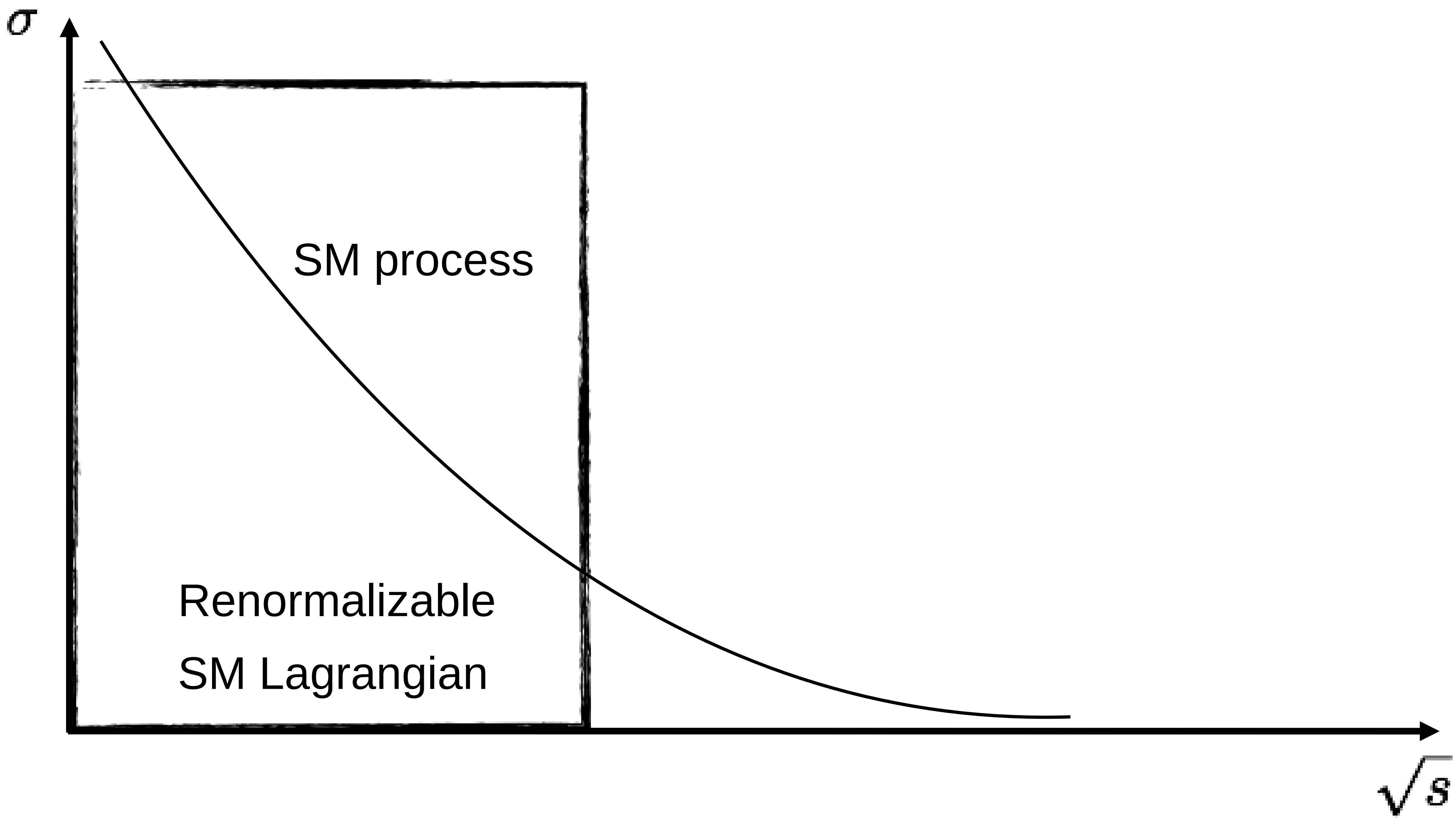
LHC physics program



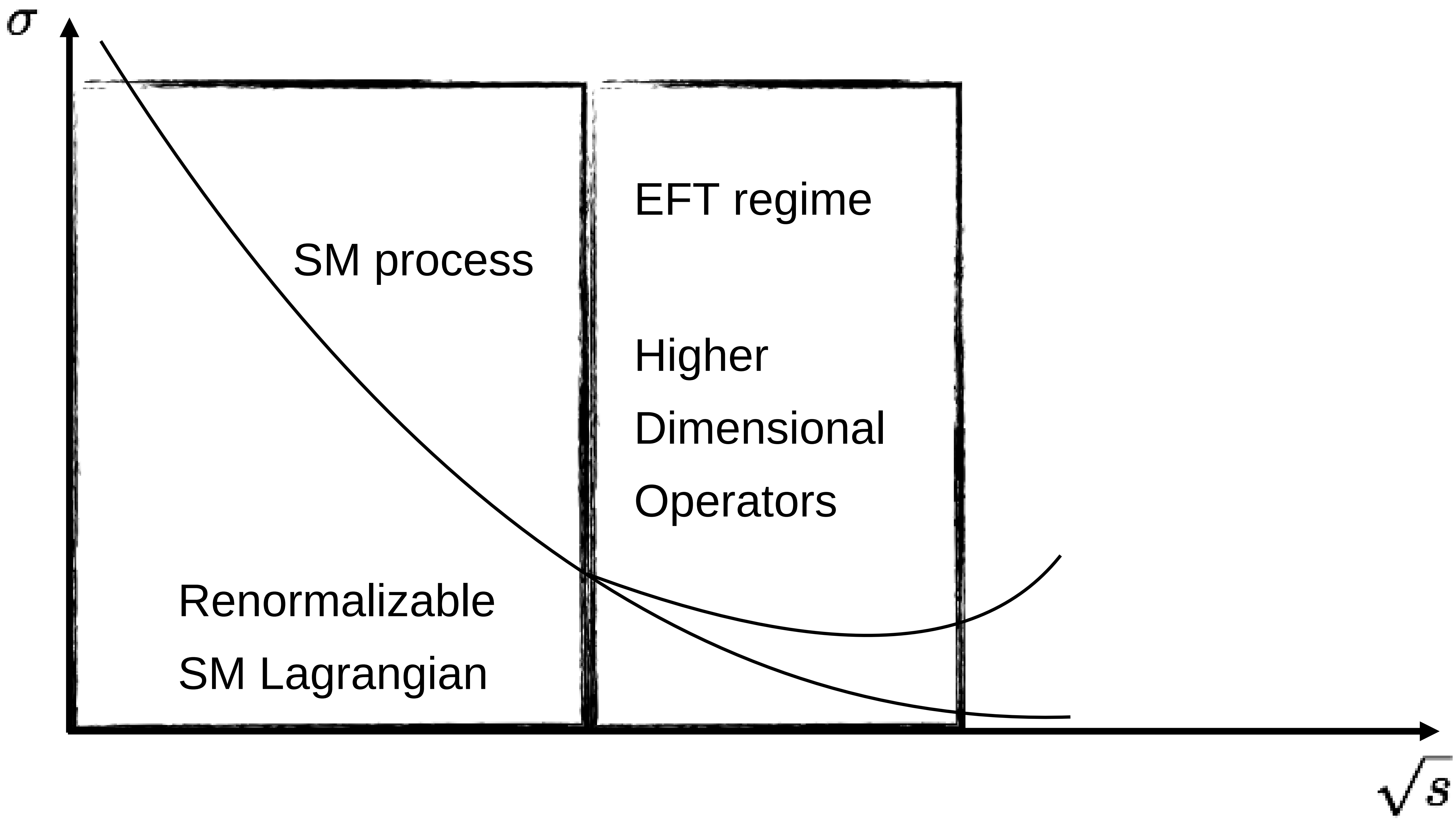
Main goal: Find signs of New Physics

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

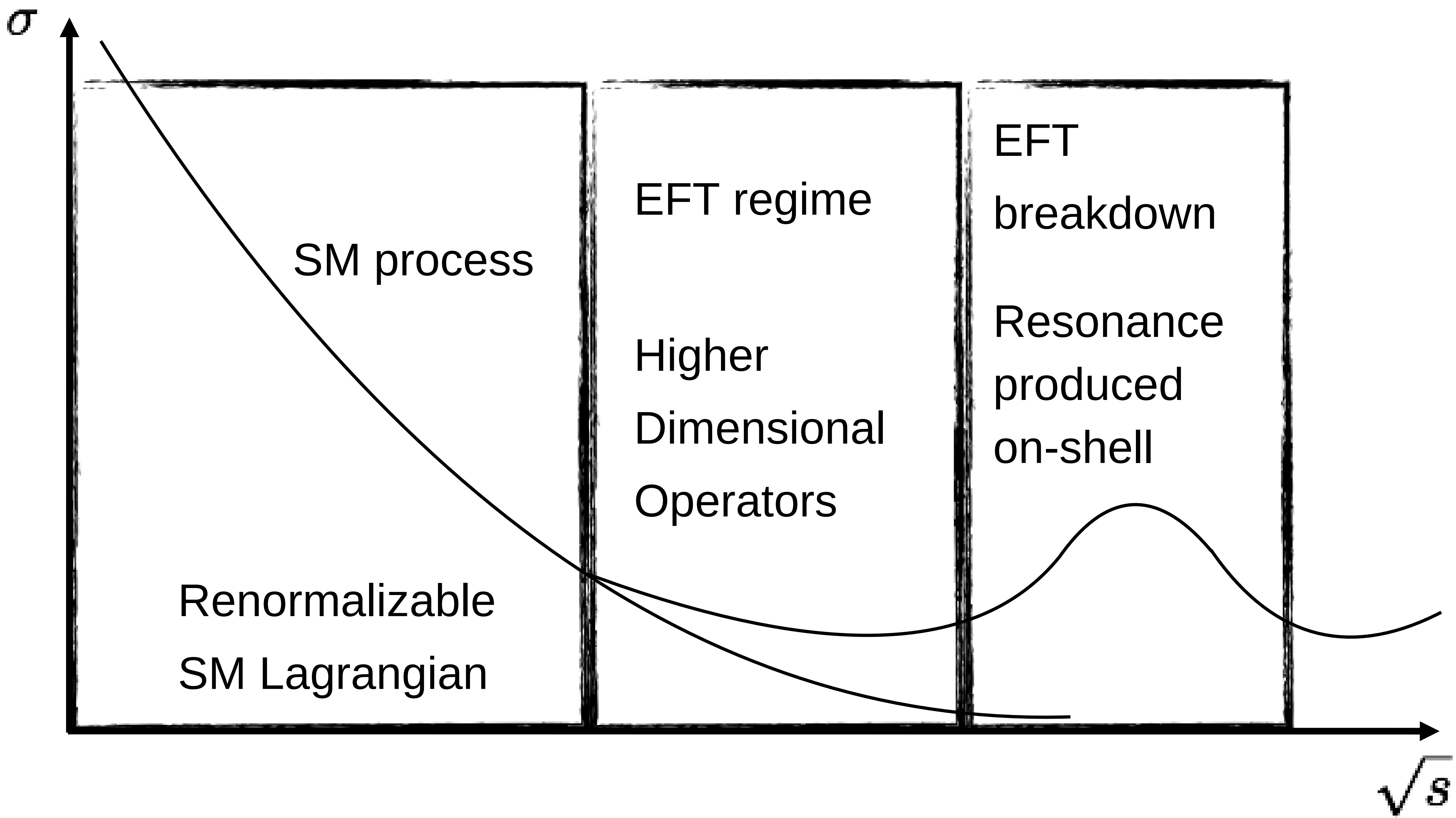
New physics: a pictorial representation



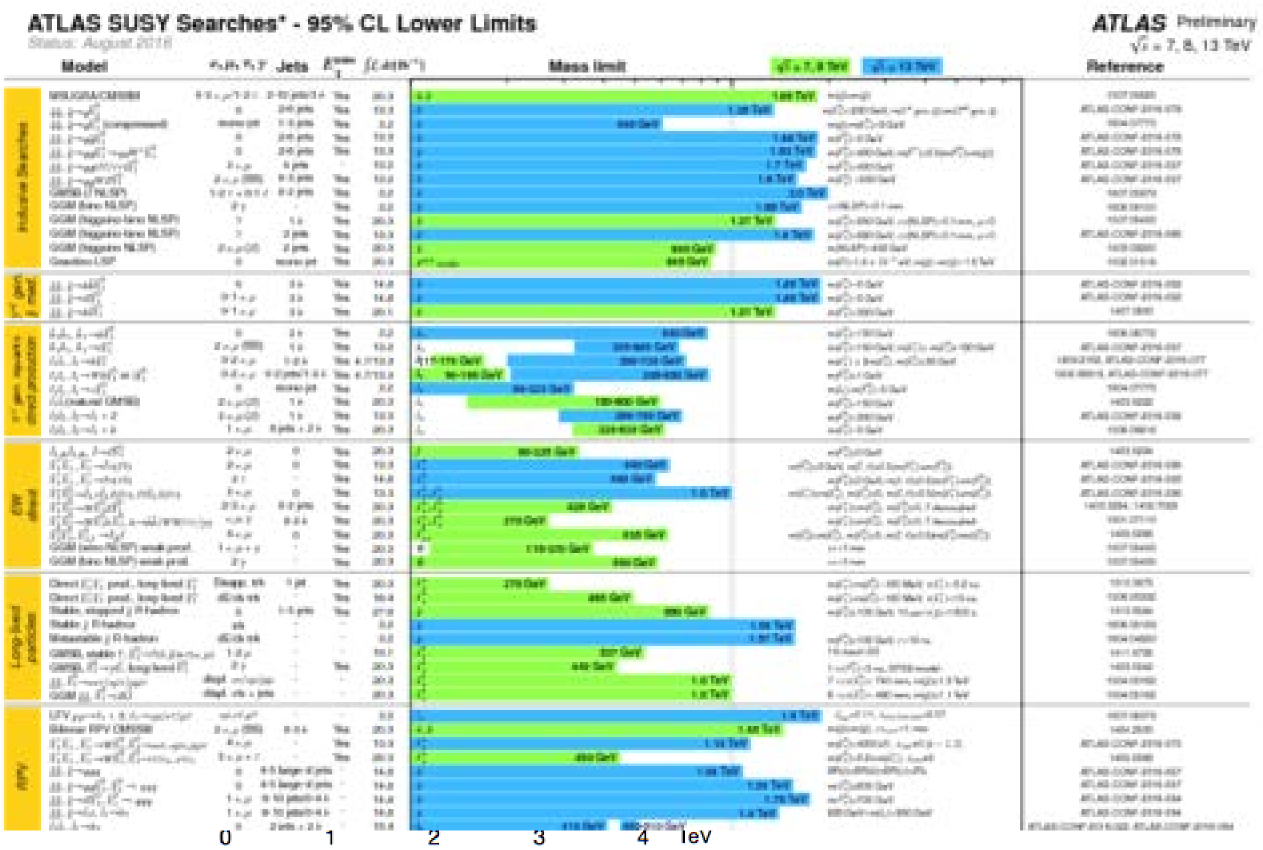
New physics: a pictorial representation

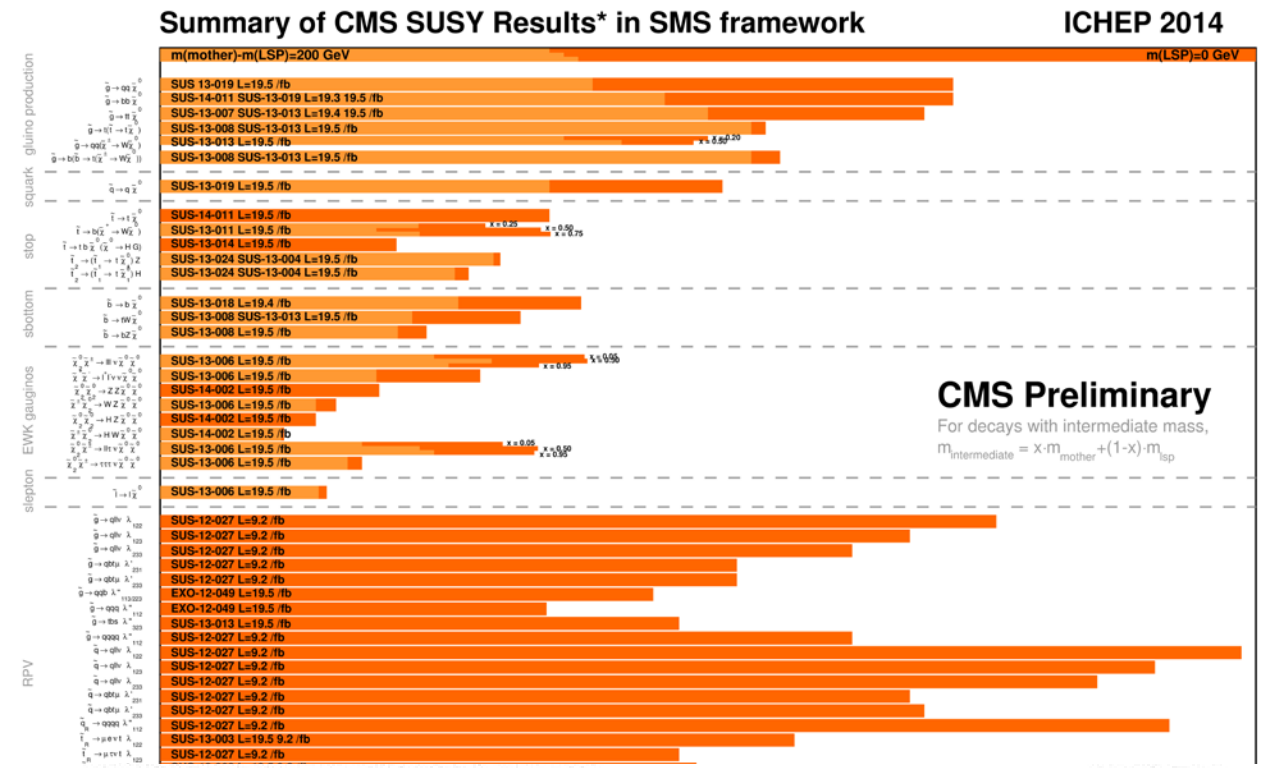


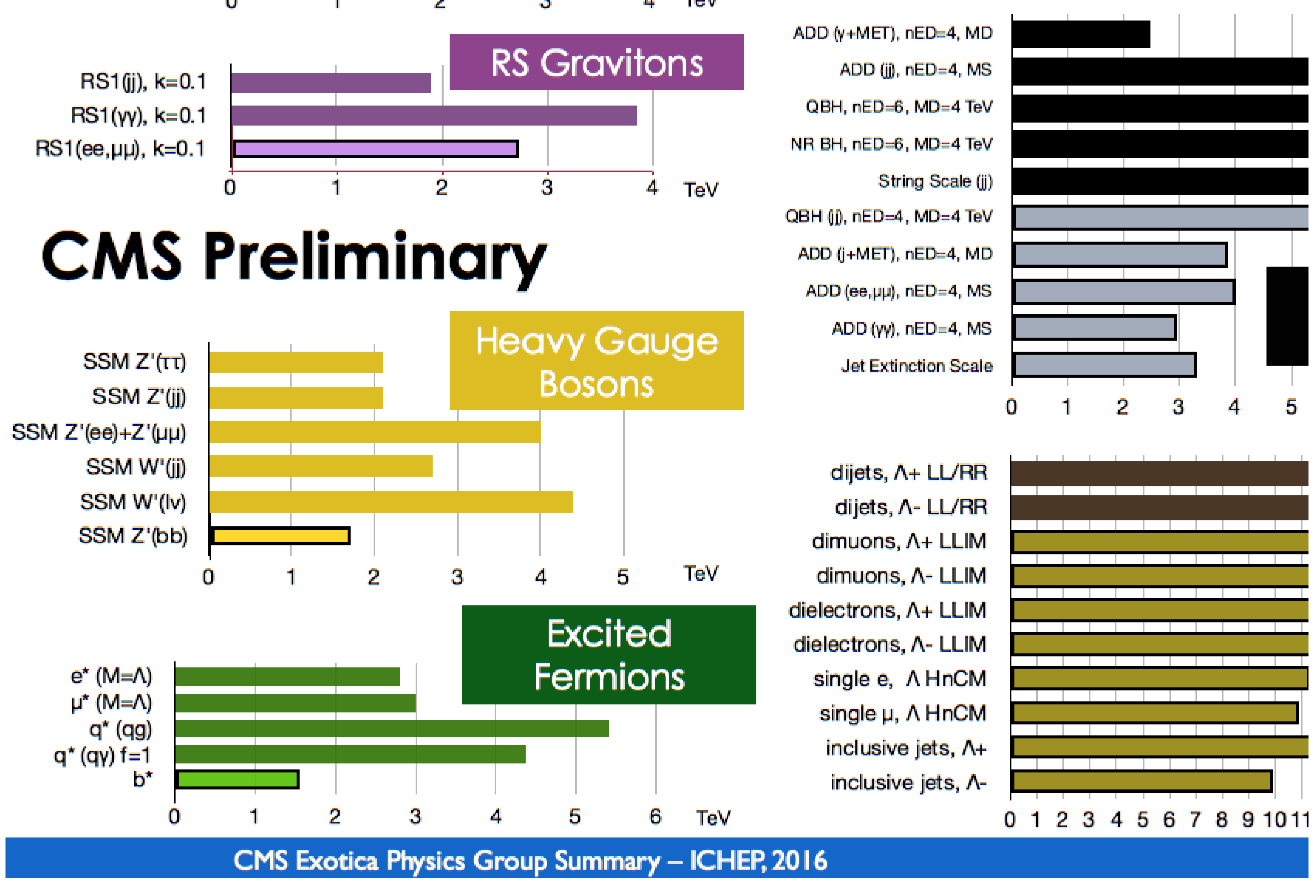
New physics: a pictorial representation

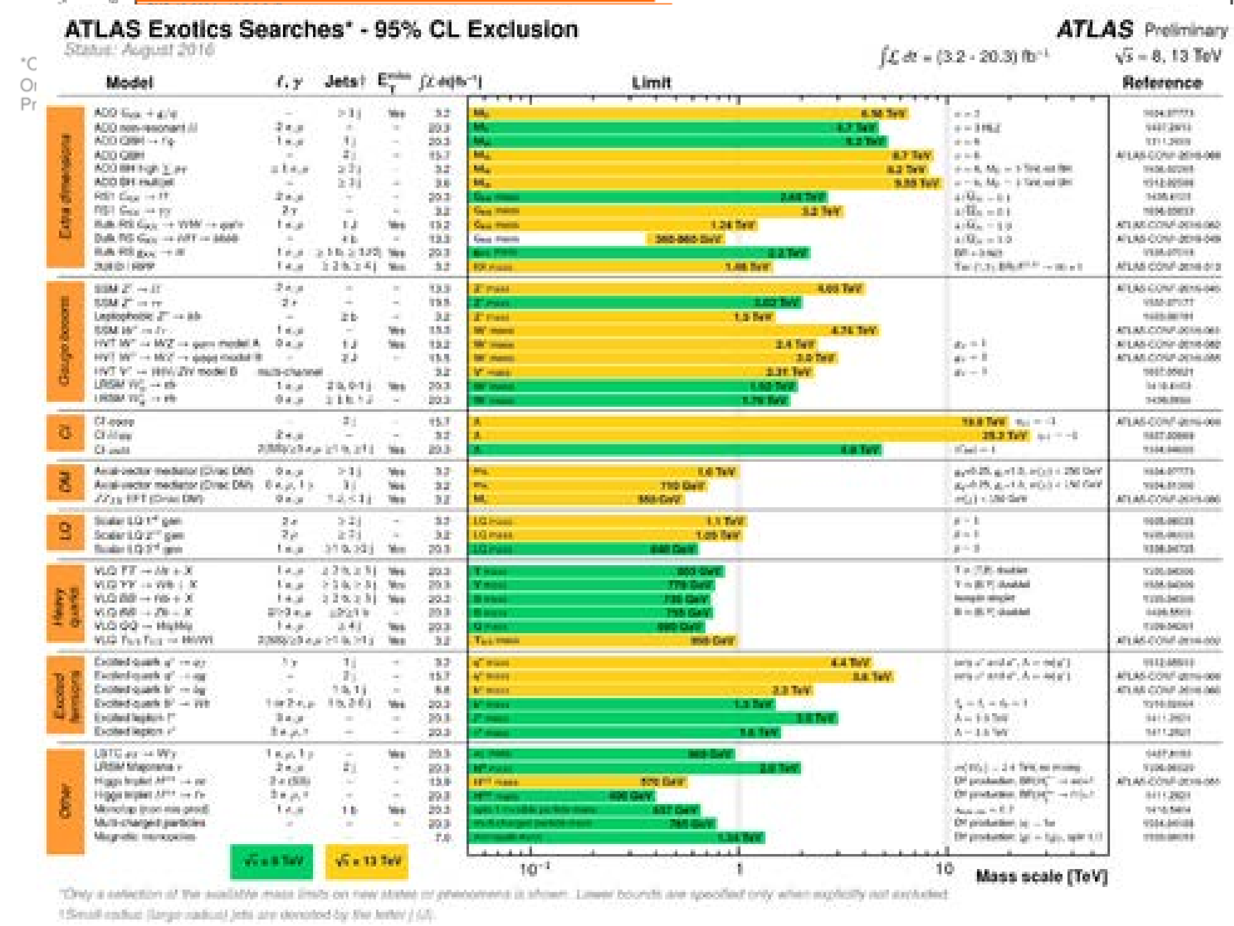


Direct searches









Direct searches

Yet nothing!

(and small improvement expected)

Precision physics: the LEP experience

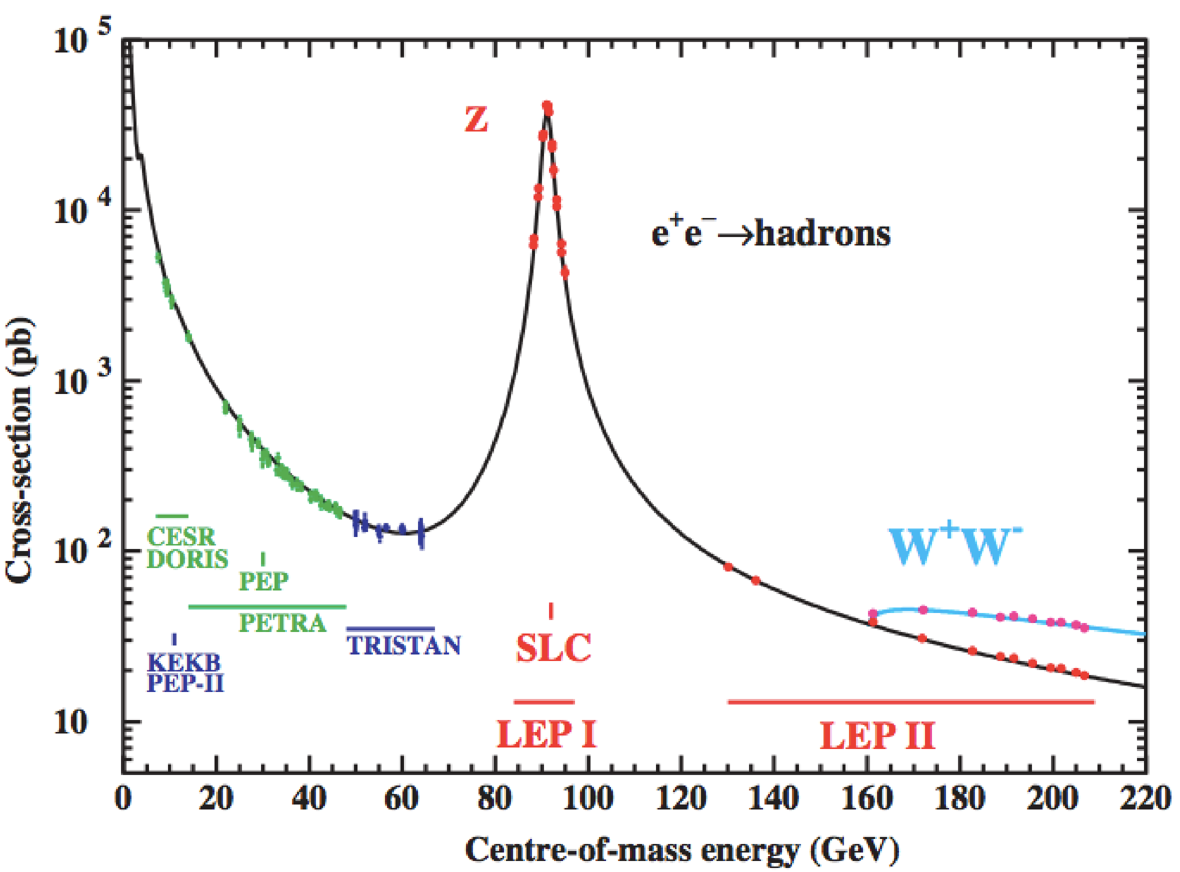
LEP is the main example of a precision physics program

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: the LHC

LHC environment completely different

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

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

⇓

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

⇓

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

HDO lead to amplitudes that grow with energy

Largest effects at high invariant masses

Precision in the SM

SM Sector	Current precision	
$\mathcal{L} \supset m_V^2 V V,\, g_V V_\mu J_f^\mu$	$\sim$ ‰	LEP-I, Tevatron
$\mathcal{L} \supset g_V V V \partial V$	$\sim \%$	LEP-II , Tevatron
$\mathcal{L} \supset g_V^2 v H V V$	$\sim 10\%$	LHC
$\mathcal{L} \supset y_f H f f$	$\sim \mathcal{O}(1)$	LHC (only b and tau)
$\mathcal{L} \supset H^3, H^4$	$\sim \mathcal{O}(10)$	LHC (only trilinear)

Given a set of assumption all the SM sectors can be studied within the SM EFT

Precision in the SM at the LHC

These interactions can still give large deviations in on-shell physics

They are therefore within the precision capabilities of hadron colliders and by now mostly limited by statistics

This is the Higgs precision program of the LHC (and of future hadron colliders)

$\mathcal{L} \supset g_V^2 v H V V$	$\sim 10\%$	LHC
$\mathcal{L} \supset y_f H f f$	$\sim \mathcal{O}(1)$	LHC (only b and tau)
$\mathcal{L} \supset H^3, H^4$	$\sim \mathcal{O}(10)$	LHC

Precision in the SM at the LHC

$\mathcal{L} \supset m_V^2 VV,\ g_V V_\mu J_f^\mu$	$\sim$ ‰	LEP-I, Tevatron
$\mathcal{L} \supset g_V VV\partial V$	$\sim$ %	LEP-II , Tevatron

These interactions are too strongly constrained to be studied at the LHC with on-shell physics

However, the SM EFT contains operators that correct these interactions and lead to observable effects that grow with the energy

For some of these interactions one can expect large deviations in high energy tails of cross sections leading to effects that can be observed even with the precision limits of hadron colliders

This is the EW precision program of the LHC (and of future hadron colliders)

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: ~100 GeV

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 $E_{\rm LHC}/E_{\rm LEP} \sim 100$

LHC comparable with (or better than) LEP

Qualitative analysis, can one make it quantitative?

Assumptions

As already mentioned, the use of the EFT requires assumptions, here an example

	universal form factor ($\mathcal{L}$)	contact operator ($\mathcal{L}'$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$	$-\frac{g_2^2\mathrm{W}}{2m_W^2} J_L{}^a_\mu J_L{}^\mu_a$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2\mathrm{Y}}{2m_W^2} J_Y{}_\mu J_Y{}^\mu$

These two theories are obtained one from the other using equations of motion

However, they are radically different for three reasons:

- They are related by e.o.m. at linear order, but they differ at the level of dim-8 operators (correction to processes that depend on the square of W and Y)
- Deviations in 4-fermion interactions can be described by many more parameters, while universal form factors assume that all these parameters are equal
- They correspond to theories with different maximal cut-offs:

$$\Lambda' \equiv \frac{4\pi m_W/g_2}{\max(\sqrt{\mathrm{W}}, t\sqrt{\mathrm{Y}})}, \quad \Lambda \equiv \frac{m_W}{\max(\sqrt{\mathrm{W}}, \sqrt{\mathrm{Y}})} < \Lambda'$$

The simplest case

To make our statements quantitative and make a clear case for EW precision at the LHC we consider the simplest case of universal new physics effect on Drell-Yan (DY) process

LHC reaches percent-level precision in this channel

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

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

only modification of the gauge boson propagators

deviations entirely parametrised 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@LHC

DY@LHC profits of great precision

- LHC few percent experimental (statistical/systematic) uncertainties
- NNLO QCD theory calculation (FEWZ)
- Parton Distribution Functions (NNPDF2.3@NNLO)

$$\sigma = \sigma_{\rm SM}\left(1 + \sum_i a_i O_i + \sum_{i,j} a_{ij} O_i O_j\right), \qquad O = \{W, Y\}$$

The “a” coefficients vary bin by bin (in the invariant or transverse mass)

We compare the cross section integrated in the bins with observations using a χ^2 test

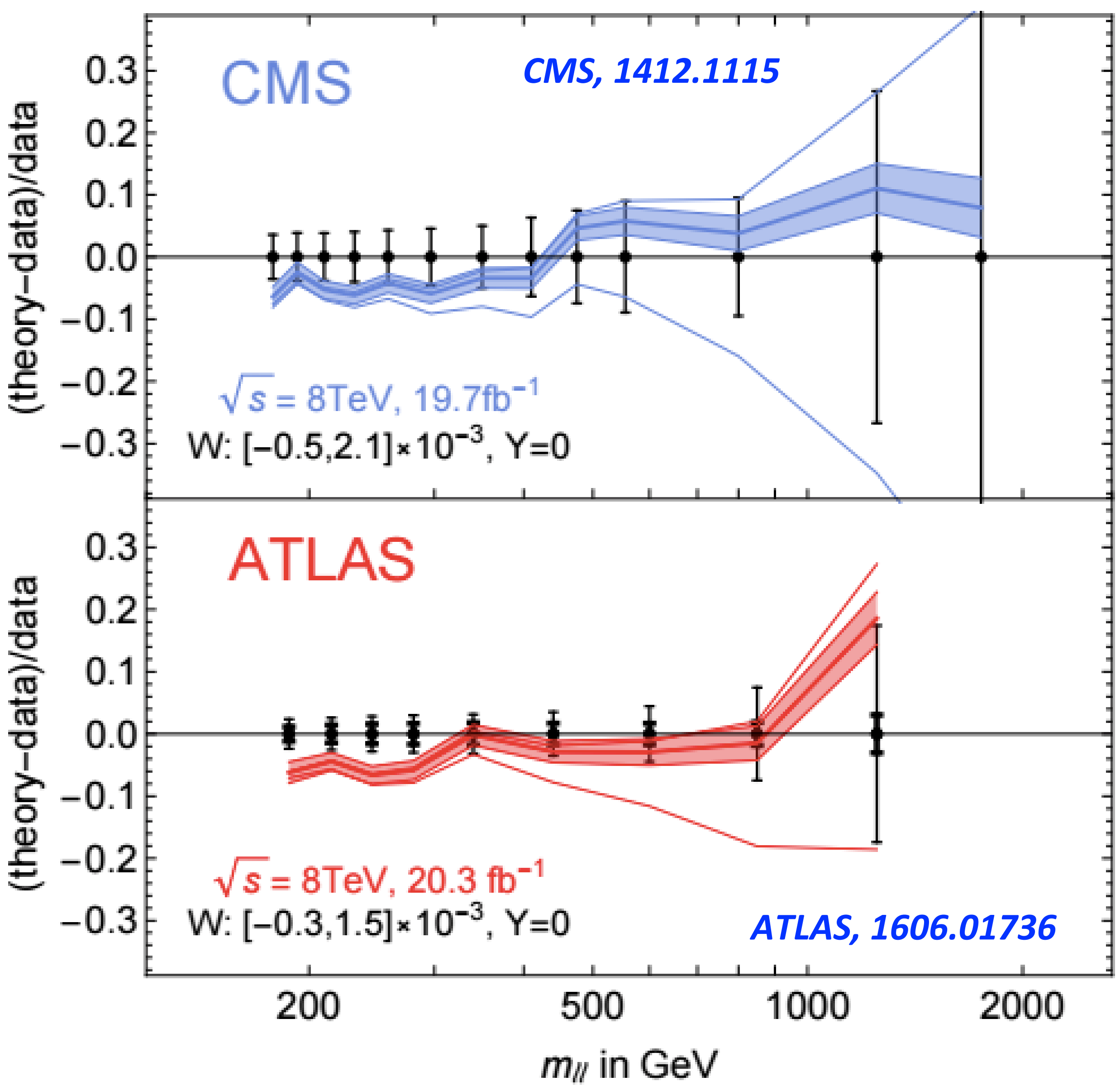
Data

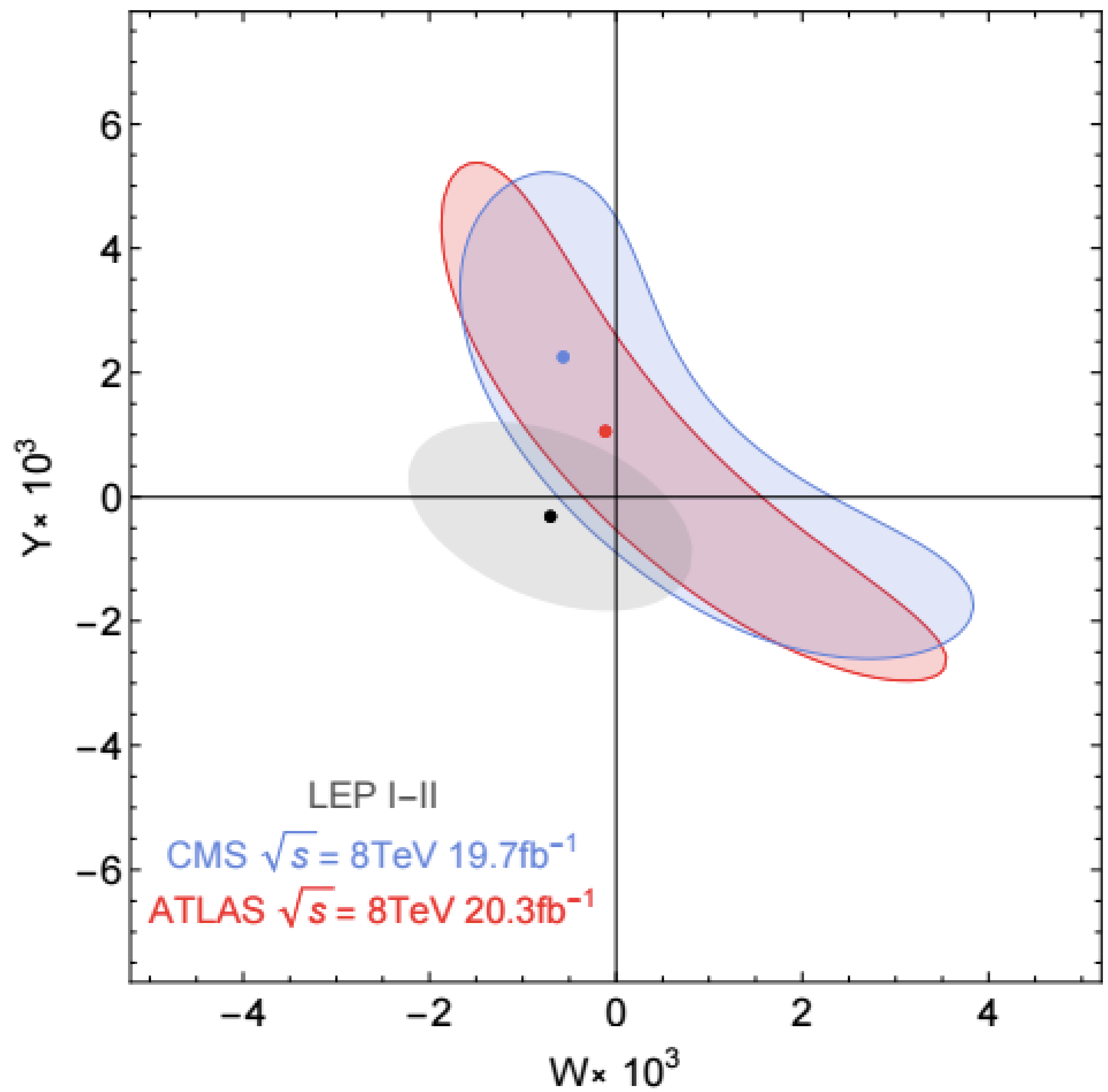
We use neutral DY data from ATLAS (1606.01736) and CMS (1412.1115) and consider uncertainties with their full correlation matrices

Projection

We make projections for charged DY (not yet studied by experiments) and higher energy/luminosity including estimates of systematic uncertainties divided into fully correlated and uncorrelated ones (2% for neutral DY and 5% for charged DY)

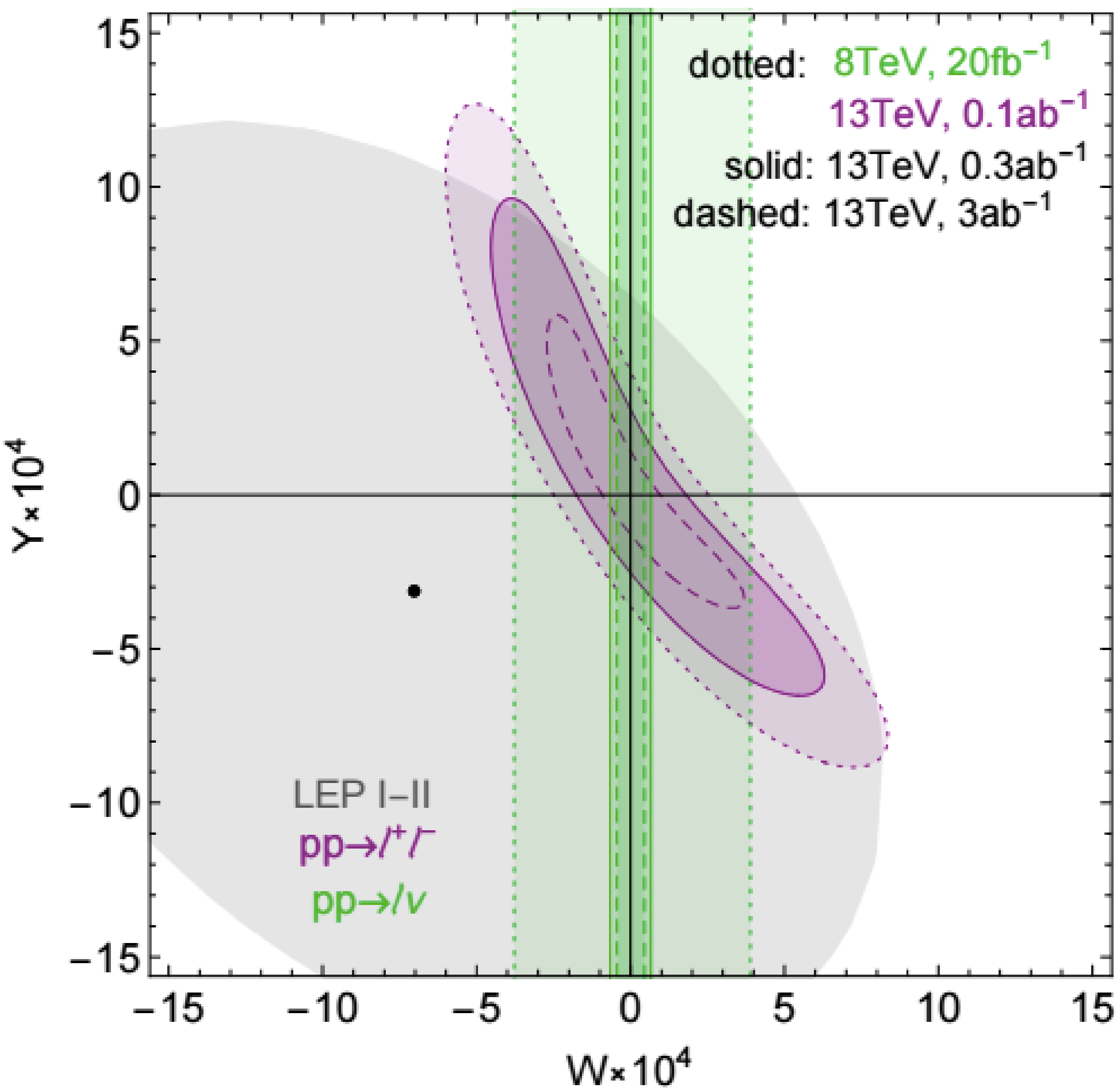
Results: data

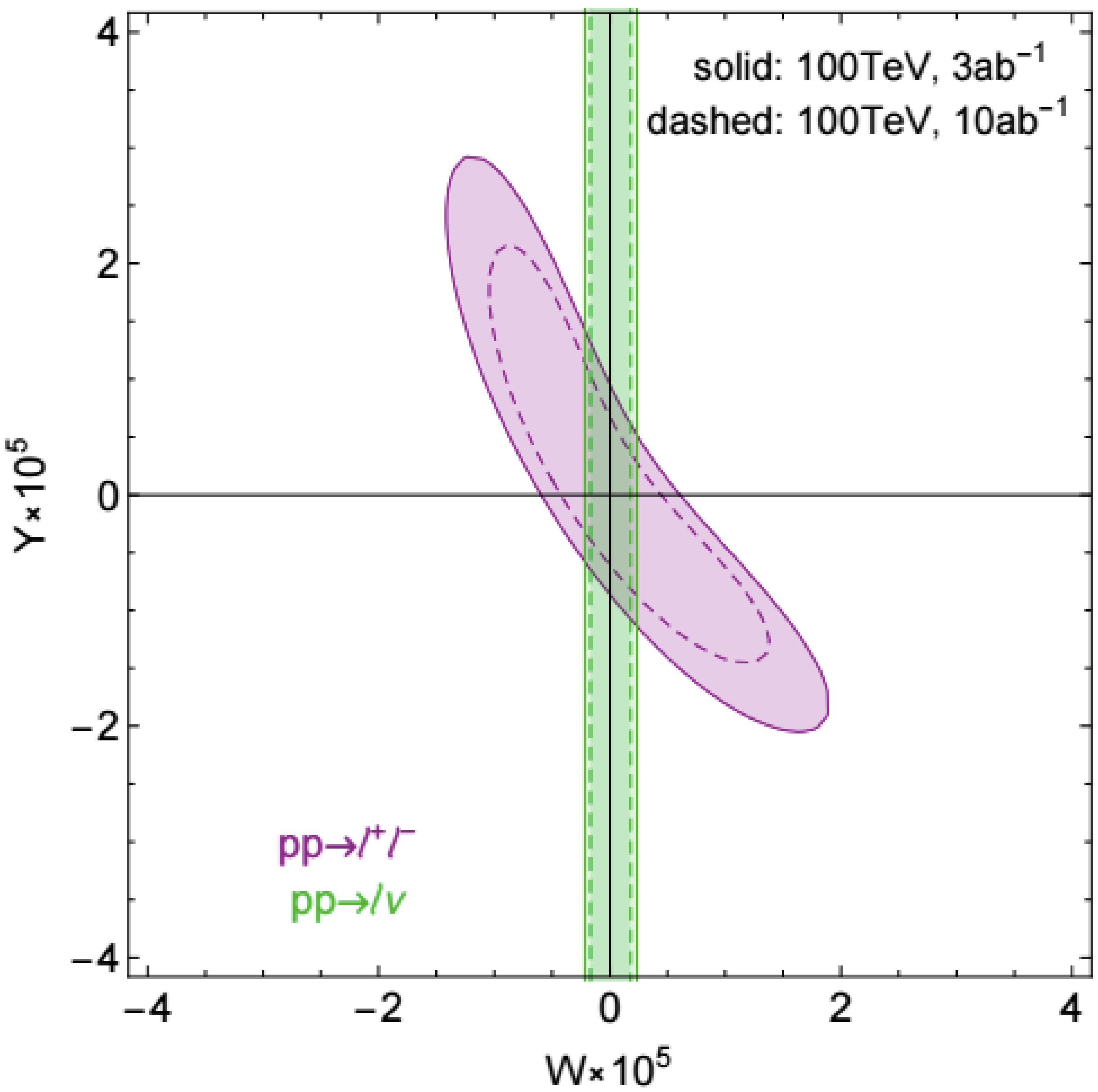




Considering only neutral DY at 8 TeV the LHC is already competitive with LEP

Results: projections

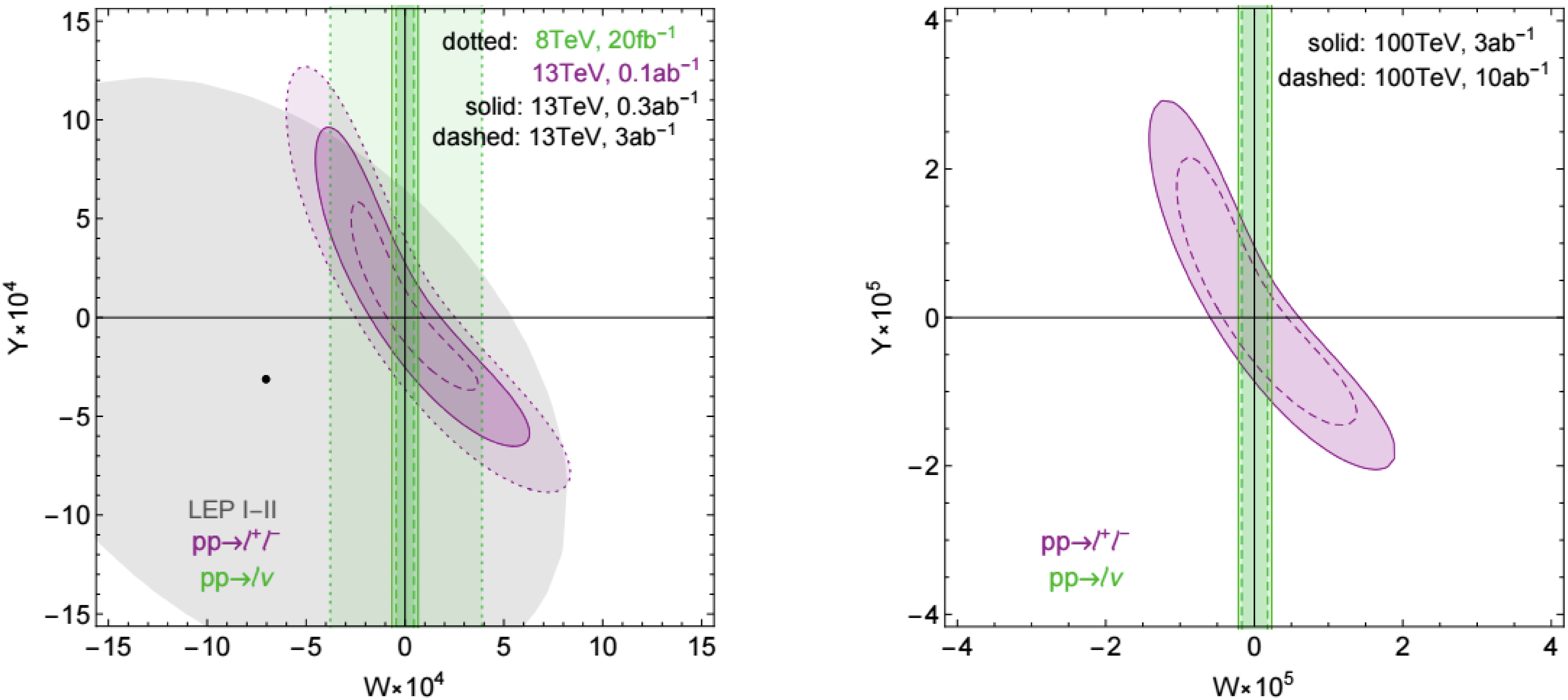




Including 8 TeV charged DY LHC should already surpass LEP

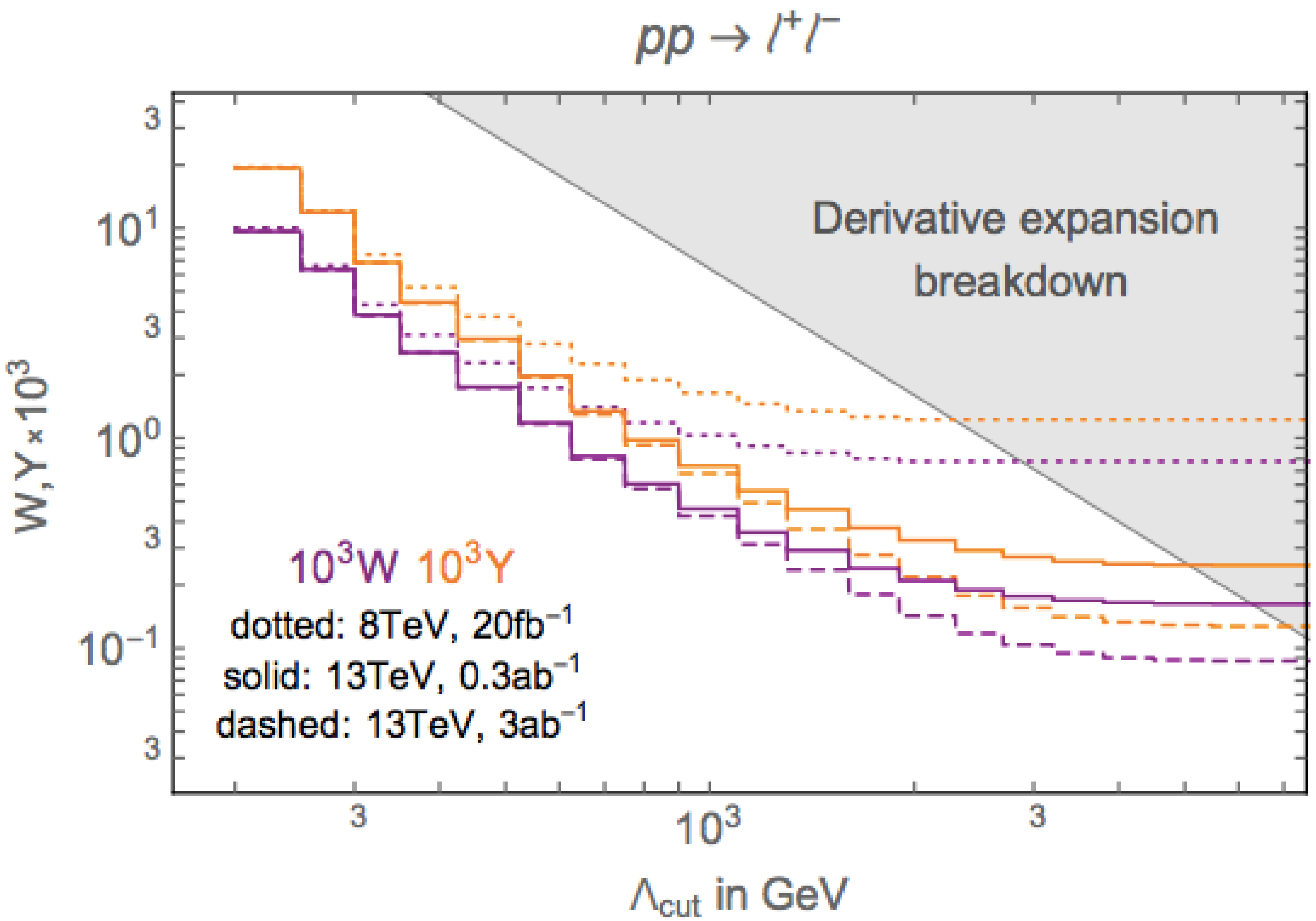
13 TeV LHC can improve by up to a factor of 5, HL-LHC by a factor of 10 and a futue 100 TeV collider by a factor of 100

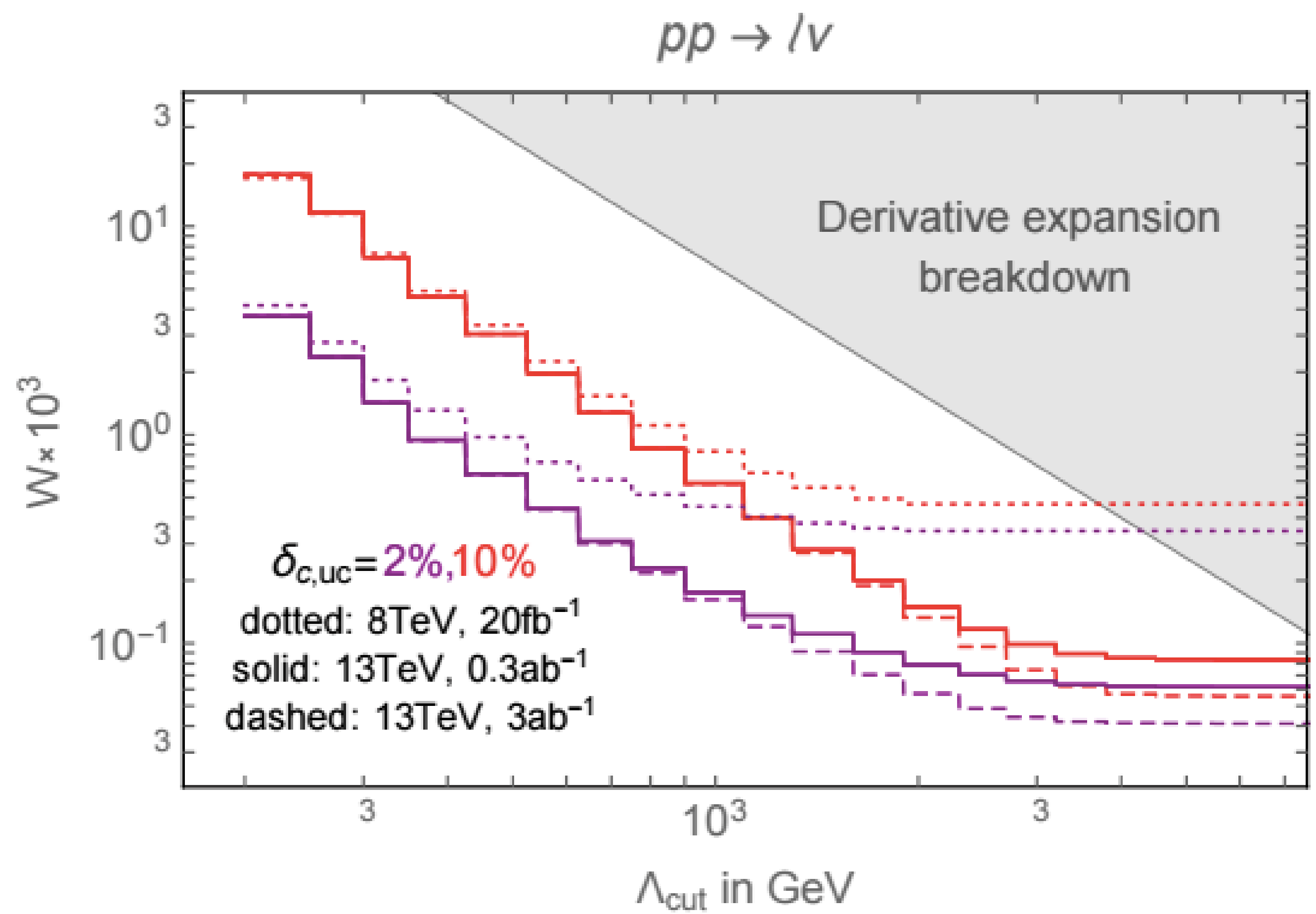
Results: projections



		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2\times10^7\,Z$	$19.7\,\text{fb}^{-1}$	$20.3\,\text{fb}^{-1}$	$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$10^9\,Z$	$10^{12}\,Z$	$3\,\text{ab}^{-1}$
NC	$W\times10^4$	[−19, 3]	[−3, 15]	[−5, 22]	±1.5	±0.8	±0.04	±3	±0.7	±0.3
	$Y\times10^4$	[−17, 4]	[−4, 24]	[−7, 41]	±2.3	±1.2	±0.06	±4	±1	±0.2
CC	$W\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—	—	—

Validity of the EFT





The strongest constraints comes from high energy events

Constraints saturated around 1(3) TeV for the LHC at 8(13) TeV

The constraints is about a factor of 10 below the scale of breakdown of the perturbative expansion, which corresponds to O(1) NP effects

Therefore, as expected, in this channel we are testing ~10% deviations

Example of application: HVT

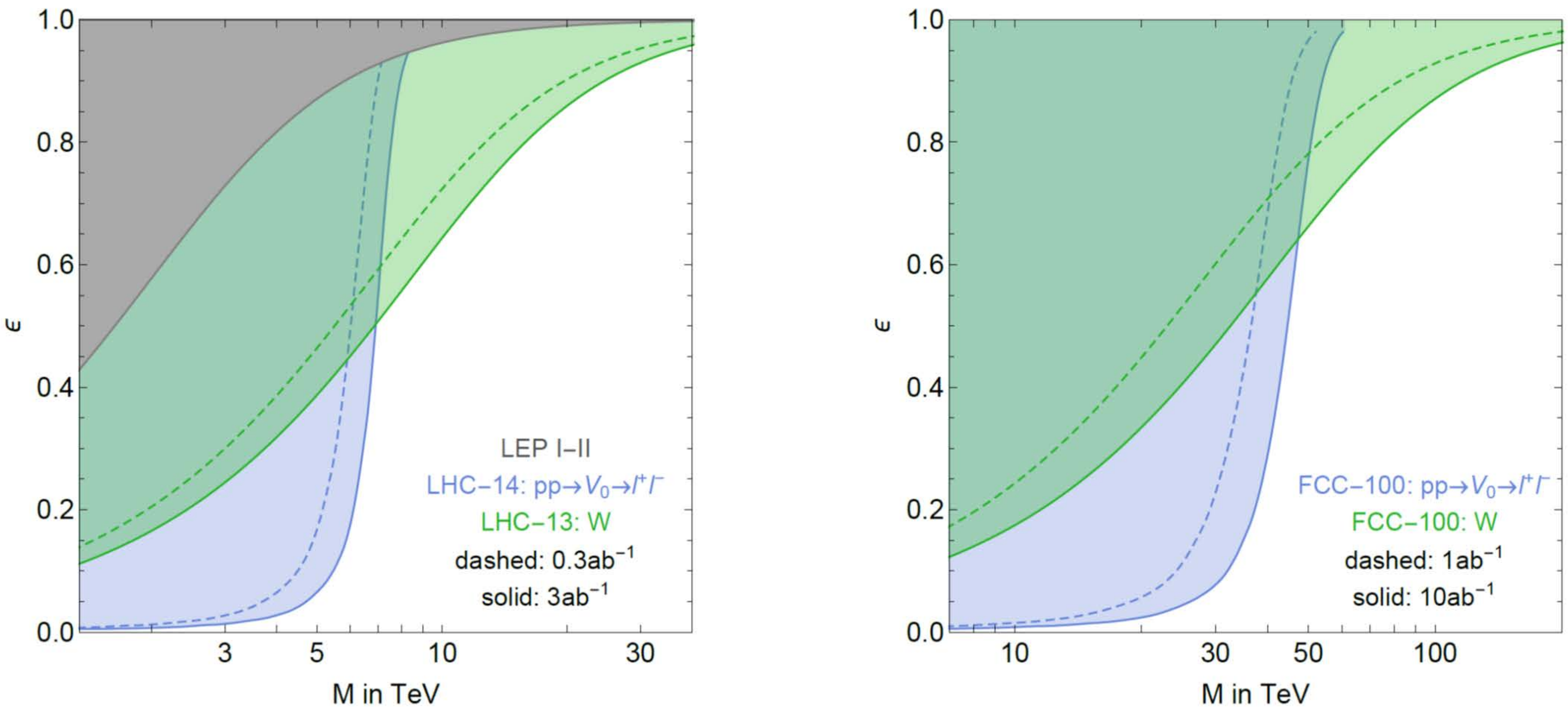
A weak triplet massive vector field generates a universal correction to W

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{a\nu]} + \frac{M^2}{2} V^a_\mu V^{a\mu} - \frac{\epsilon}{2} D_{[\mu} V^a_{\nu]} W^{a\mu\nu}$$

Such vector can arise in weakly coupled as long as strongly coupled UV completions of the SM

Integrating out the triplet generates a contribution to W which depends on the mass of the vector and its "kinetic mixing" with the SM W boson

$$\mathrm{W} = \frac{\epsilon^2}{1-\epsilon^2} \frac{m_W^2}{M^2} + O(\mathrm{W}^2)$$



Conclusions

- The precision LHC program can extend beyond Higgs precision and include EW precision (oblique parameters, anomalous trilinear gauge couplings, etc.)
- The growth with energy of HDO, which enhances new physics effects to 10%-O(1) is essential to perform EW precision at LHC
- It is crucial that systematic, statistical and theoretical uncertainties are kept below the 10% region (the goal being %), which requires a joint effort from the theory (NLO-NNLO calculations) and experimental (improved analyses techniques) communities
- DY is a very simple example, where uncertainties are small and the LHC can compete with and surpass LEP in constraining certain observables (actually being sensitive to rather weakly coupled heavy new physics)
- The precision capabilities of the LHC can be extended to future hadron colliders making more interesting their comparison with future leptonic machines

THANK YOU