EWPT from Drell Yan at the LHC and beyond

LHCP 2017 - Shanghai - 17 May 2017

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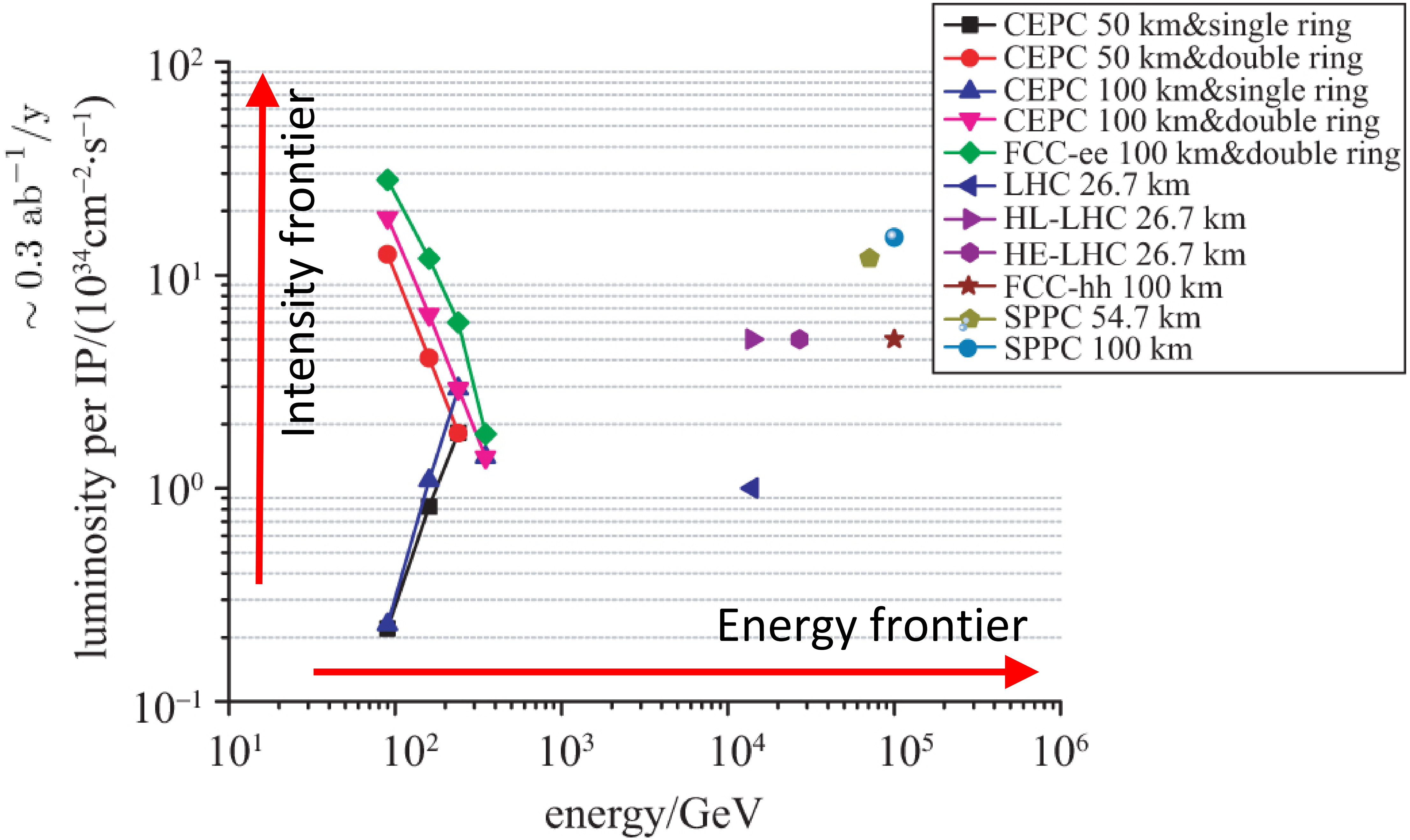
Energy, intensity, and accuracy frontiers

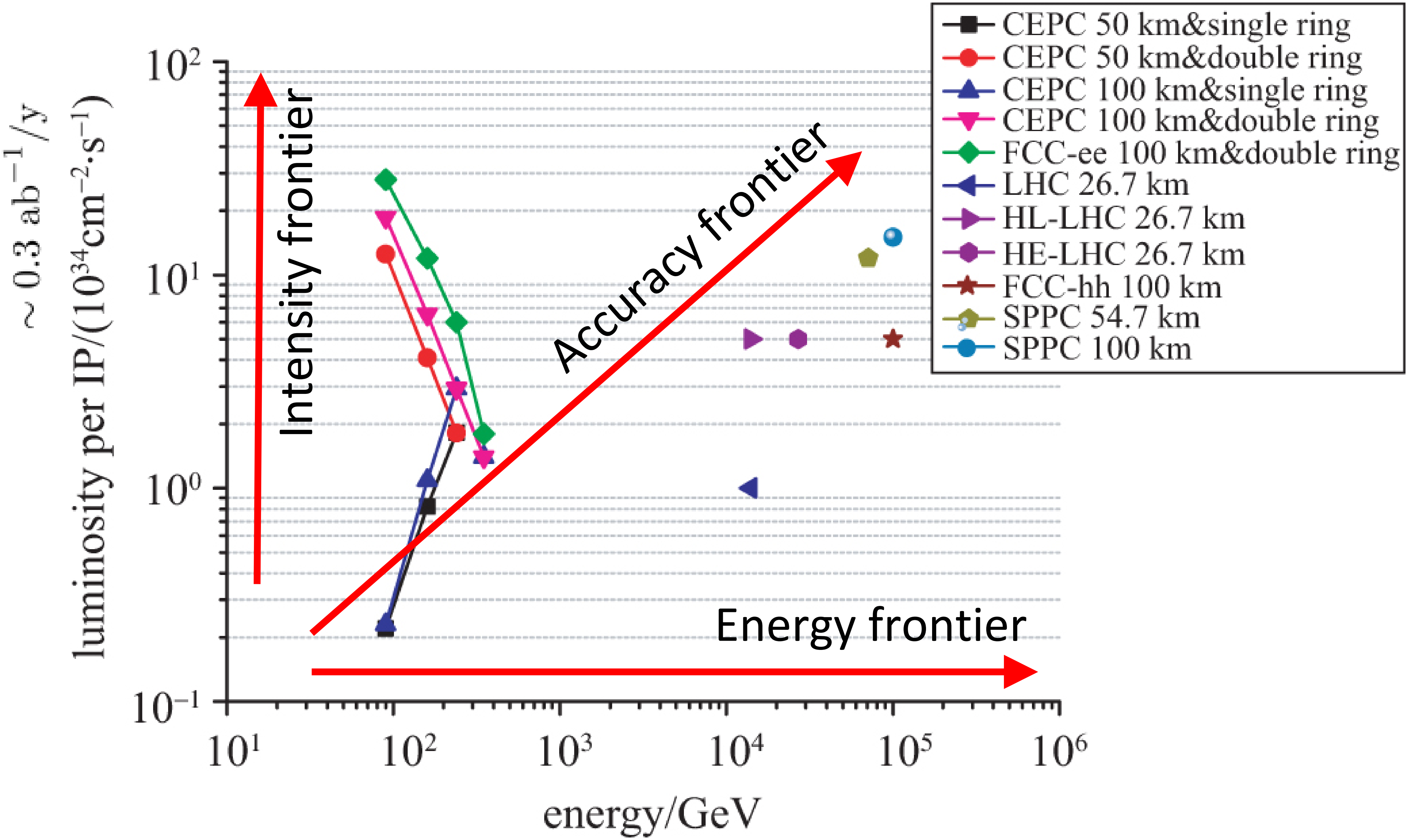


Intensity frontier

Energy frontier

Energy and intensity frontiers usually considered complementary, but orthogonal

Energy, intensity, and accuracy frontiers



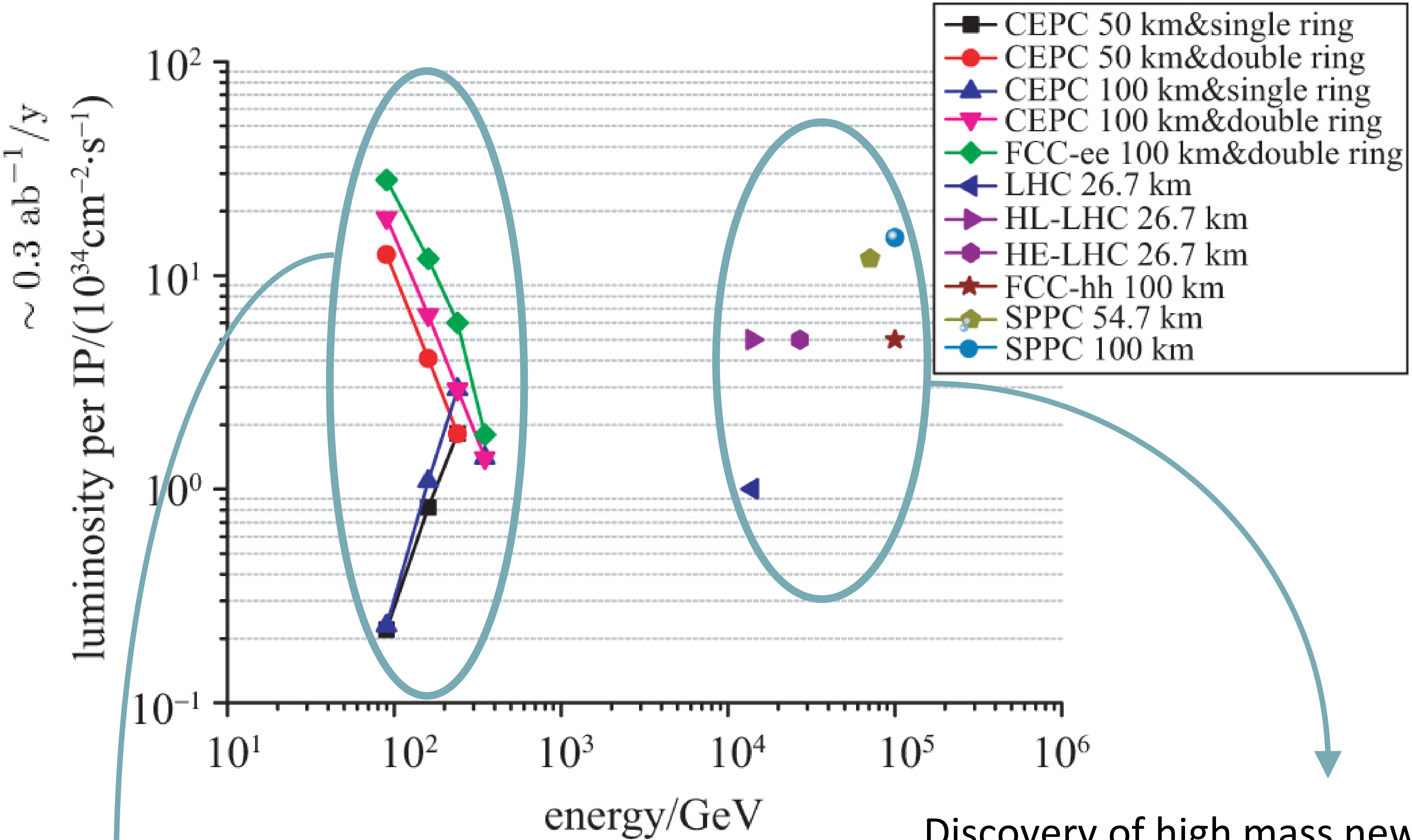
Intensity frontier

Accuracy frontier

Energy frontier

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

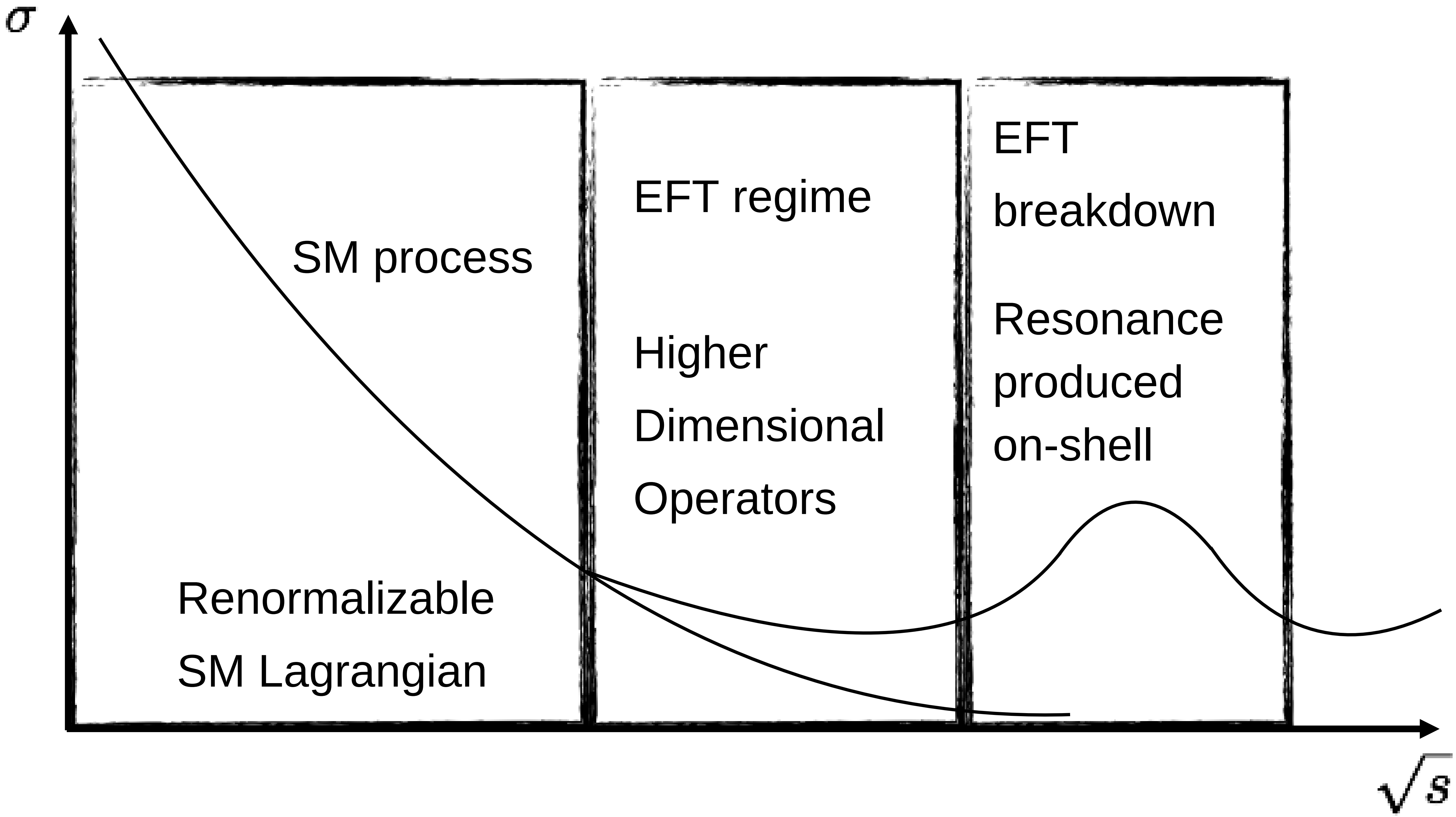
Energy, intensity, and accuracy frontiers



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

New physics: a pictorial representation



SM process

Renormalizable
SM Lagrangian

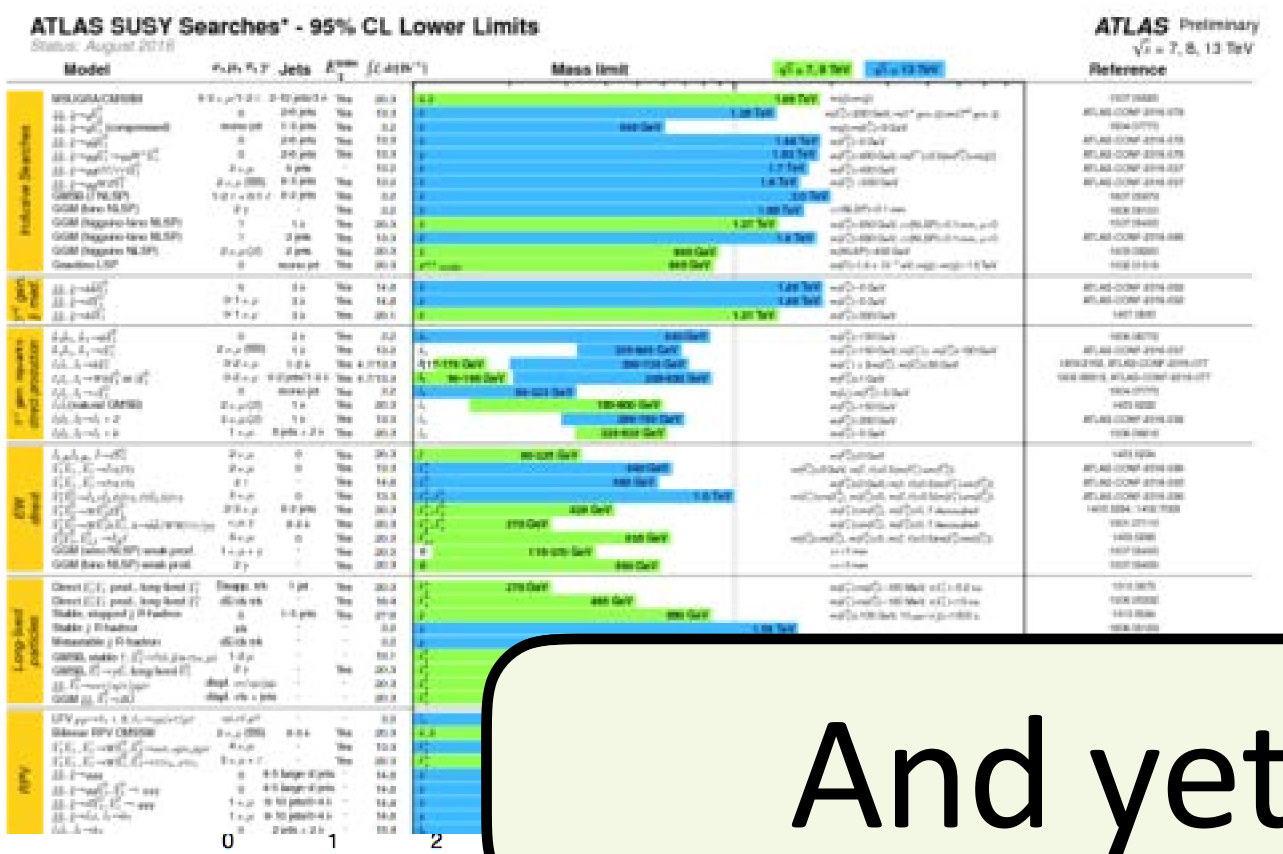
EFT regime

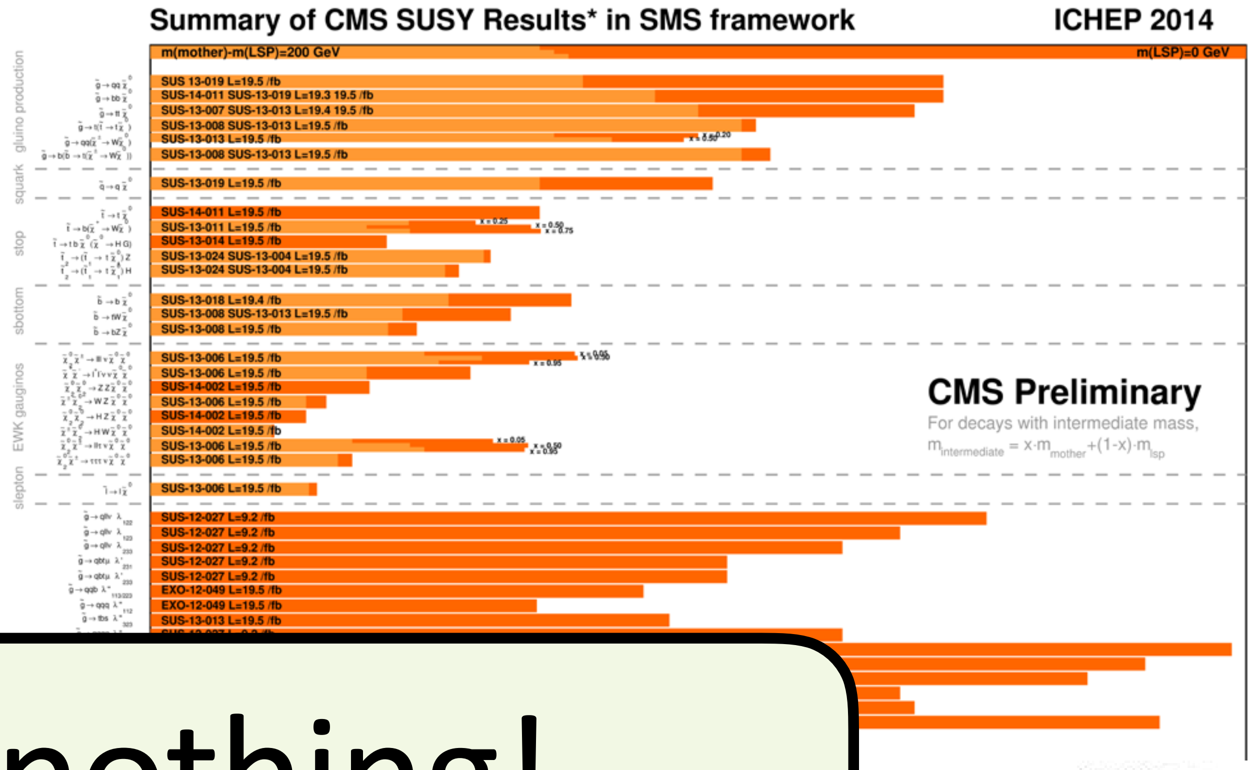
Higher
Dimensional
Operators

EFT
breakdown

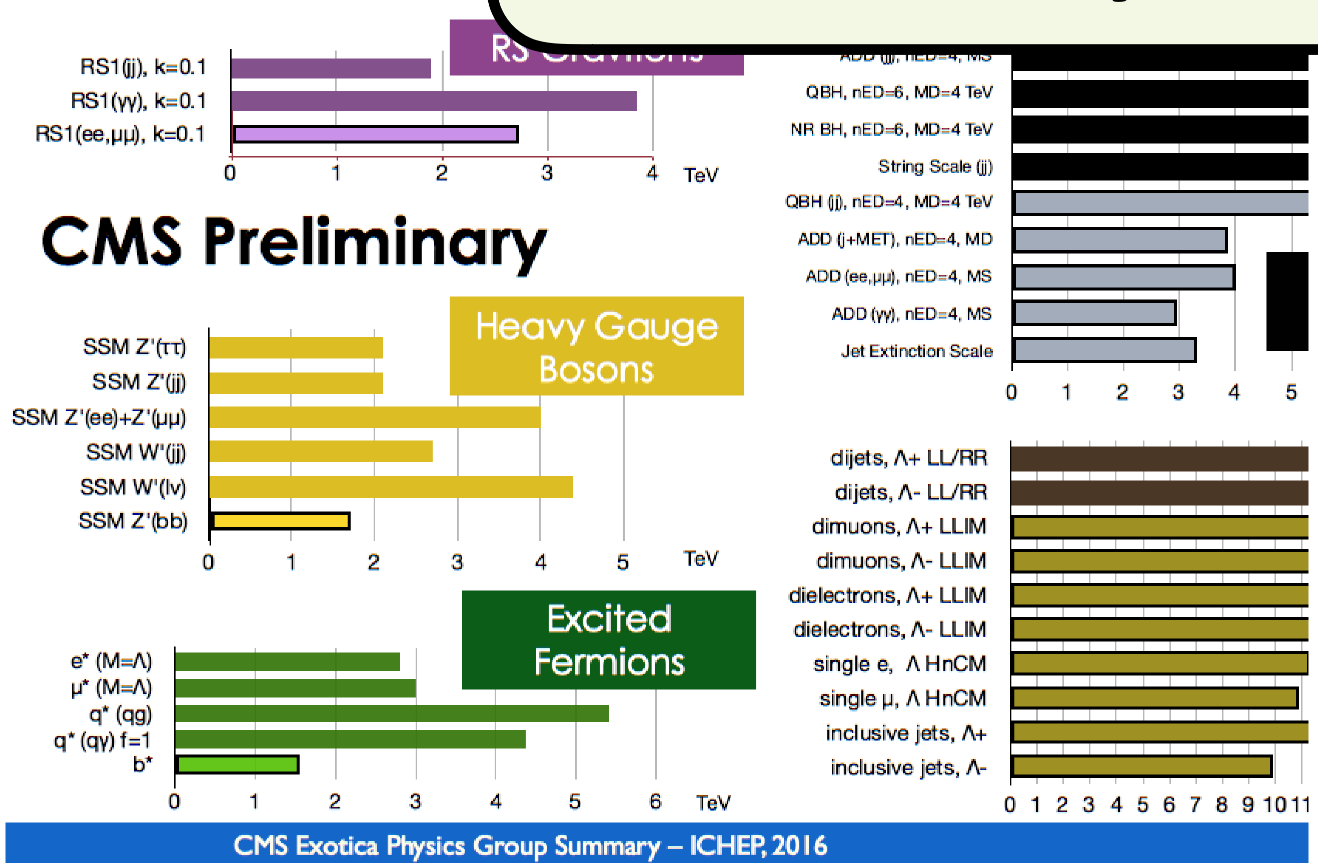
Resonance
produced
on-shell

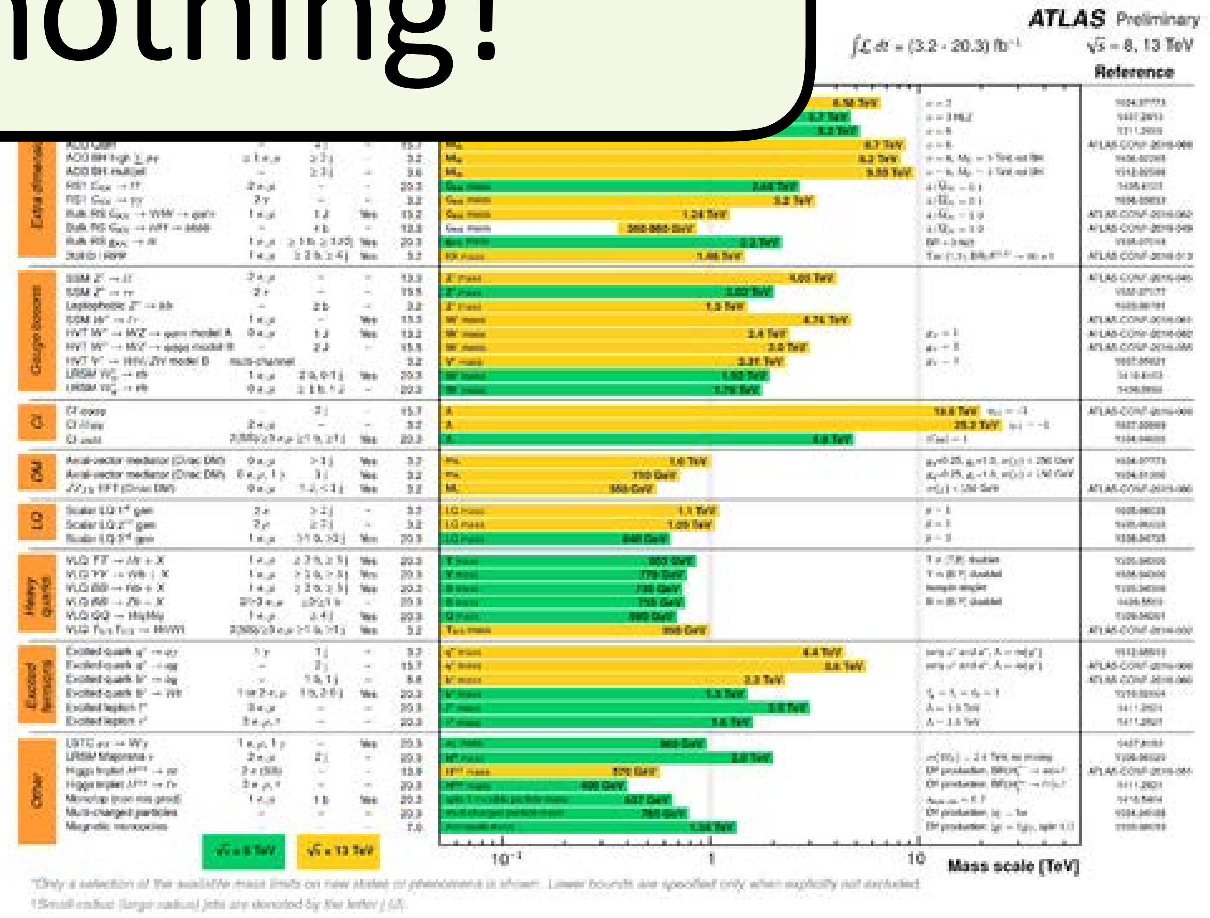
Direct searches





And yet nothing!





Precision physics: the LEP experience

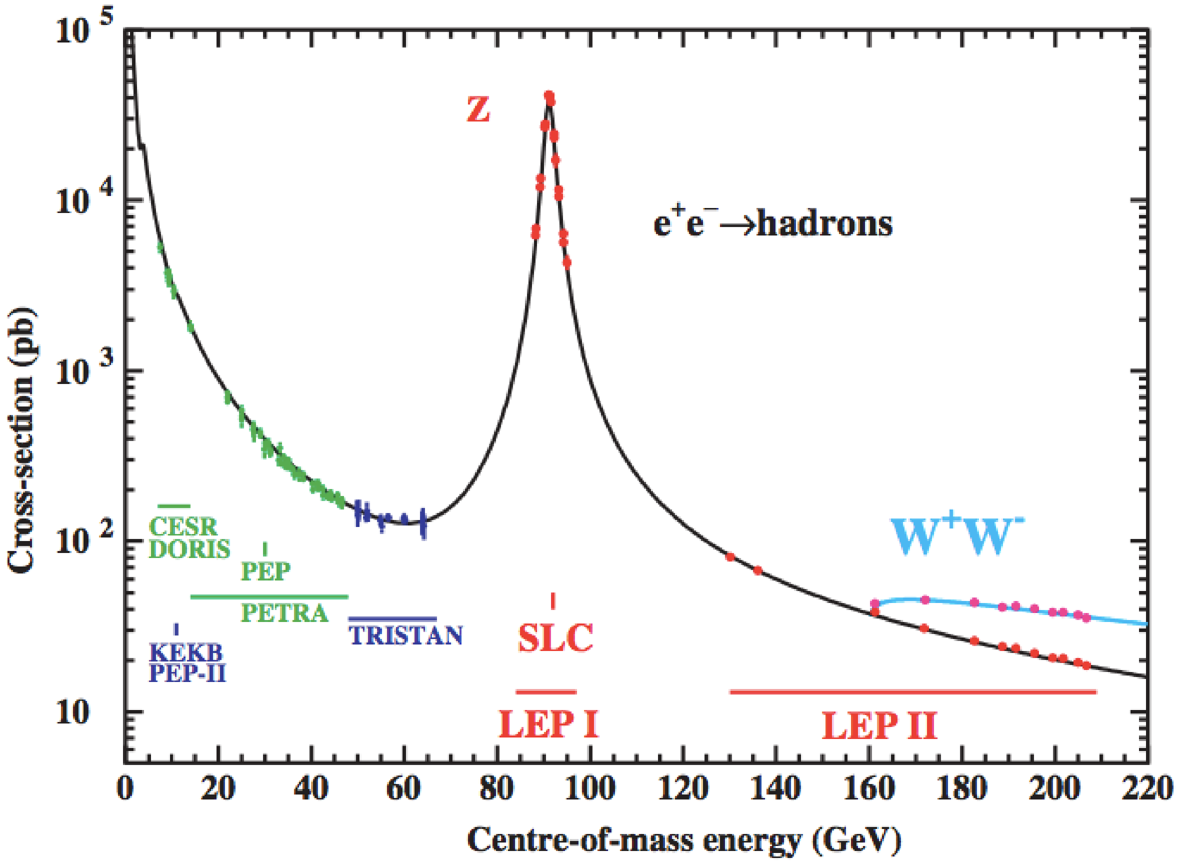
LEP is the main example of a precision physics program

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 10% 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

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

LHC comparable with (or better than) LEP

Qualitative analysis, can one make it quantitative?

The simplest case

To answer the question 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

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

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

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 at 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

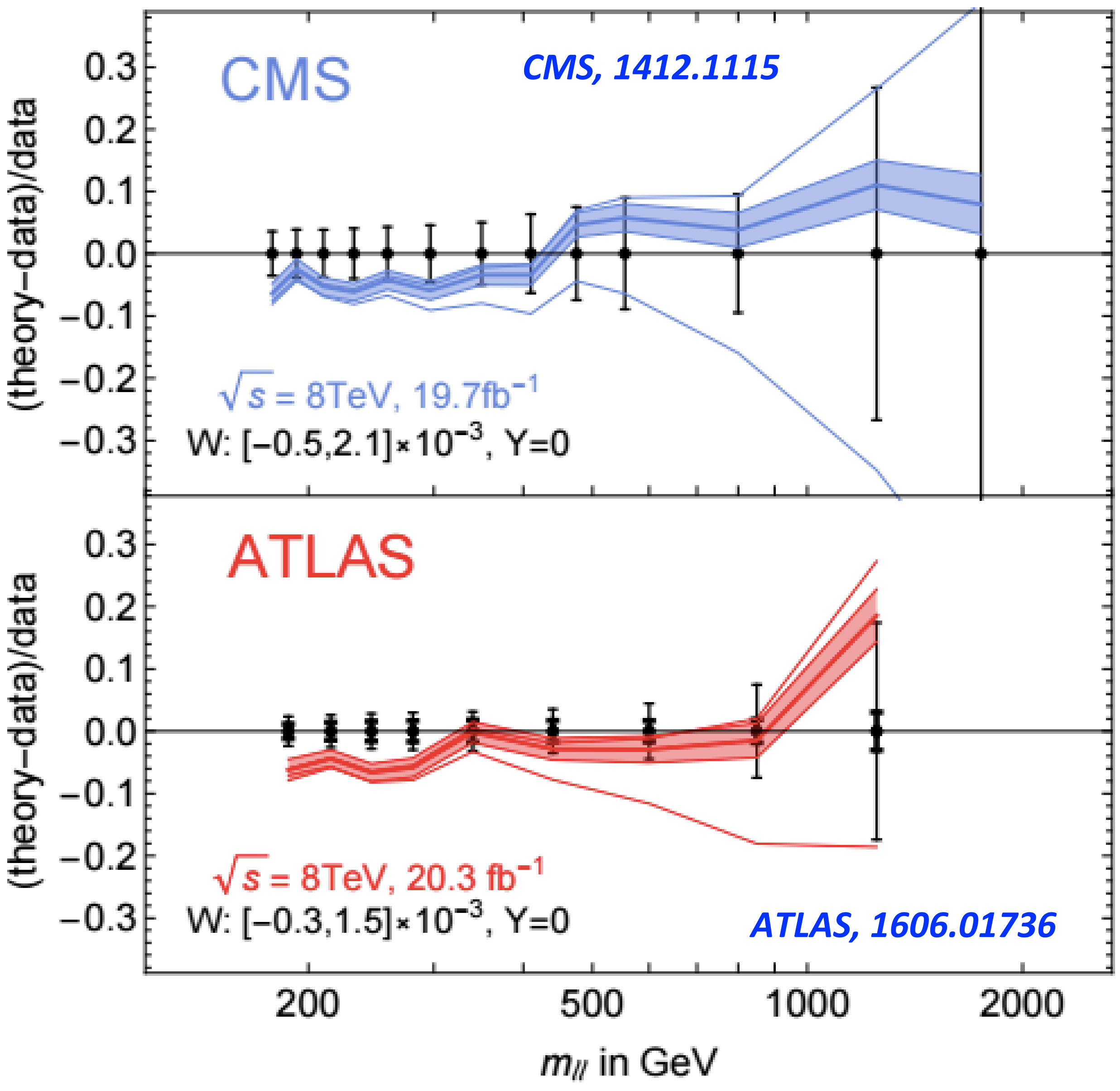
Data

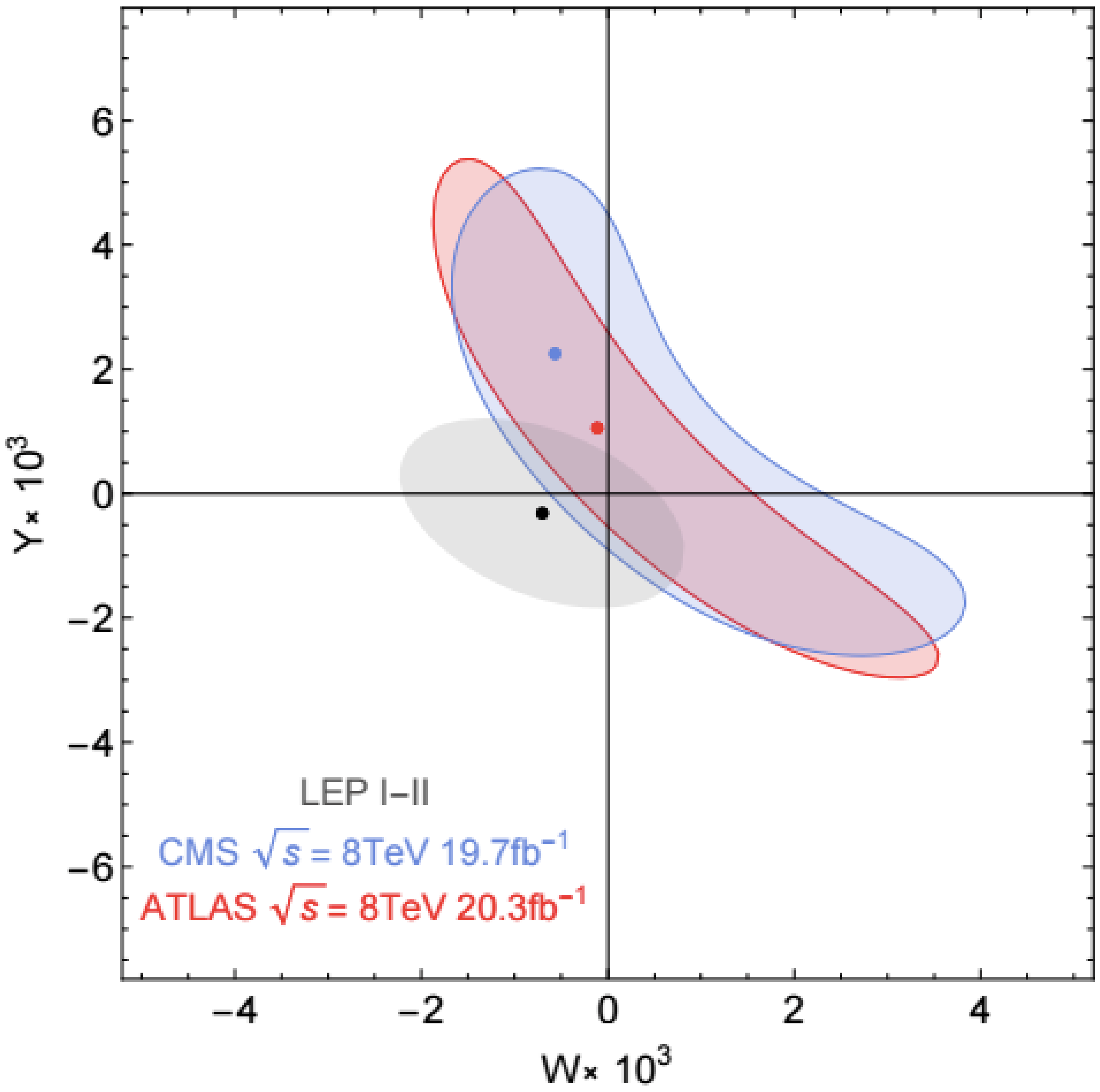
We use neutral DY data from ATLAS (1606.01736) and CMS (1412.1115) and consider uncertainties with their full correlation matrices

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)

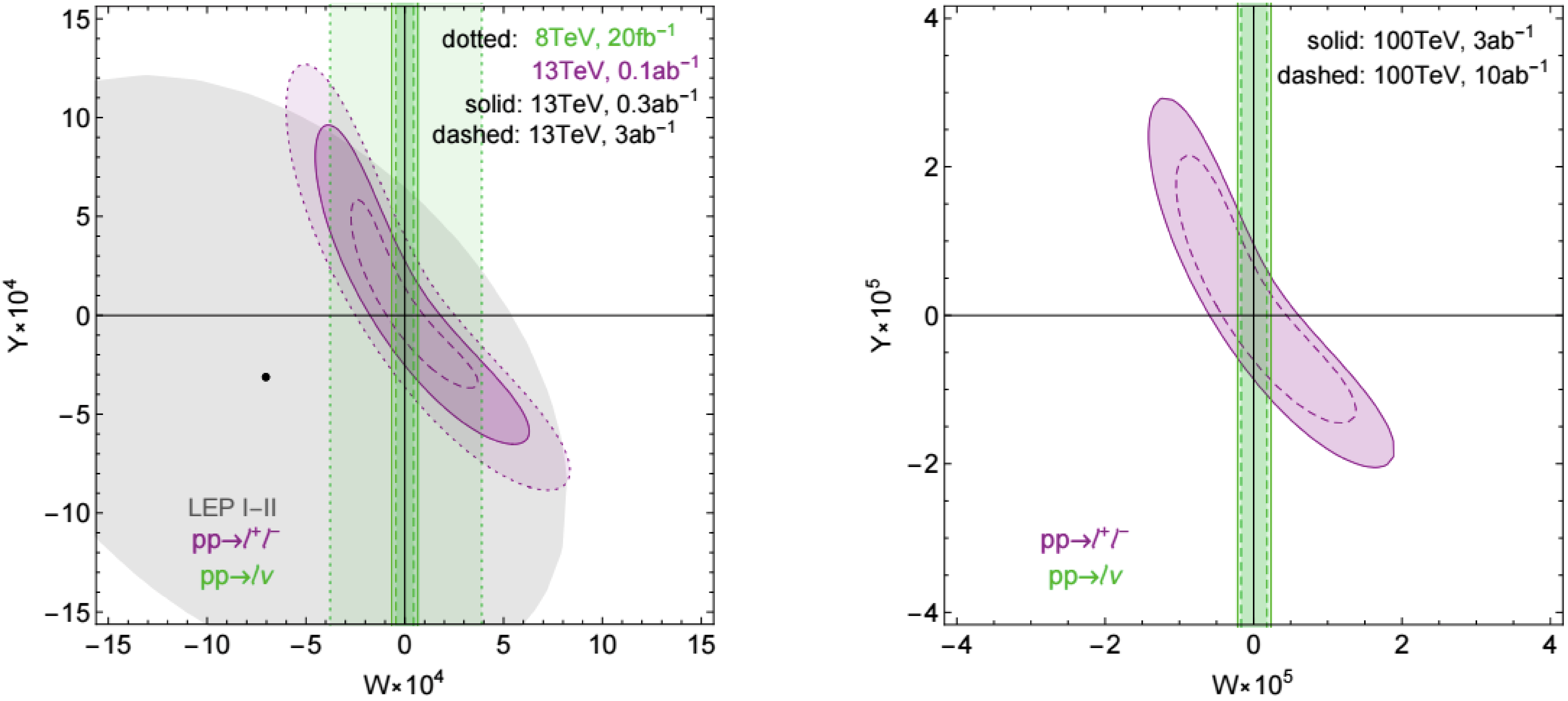
Results: data





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

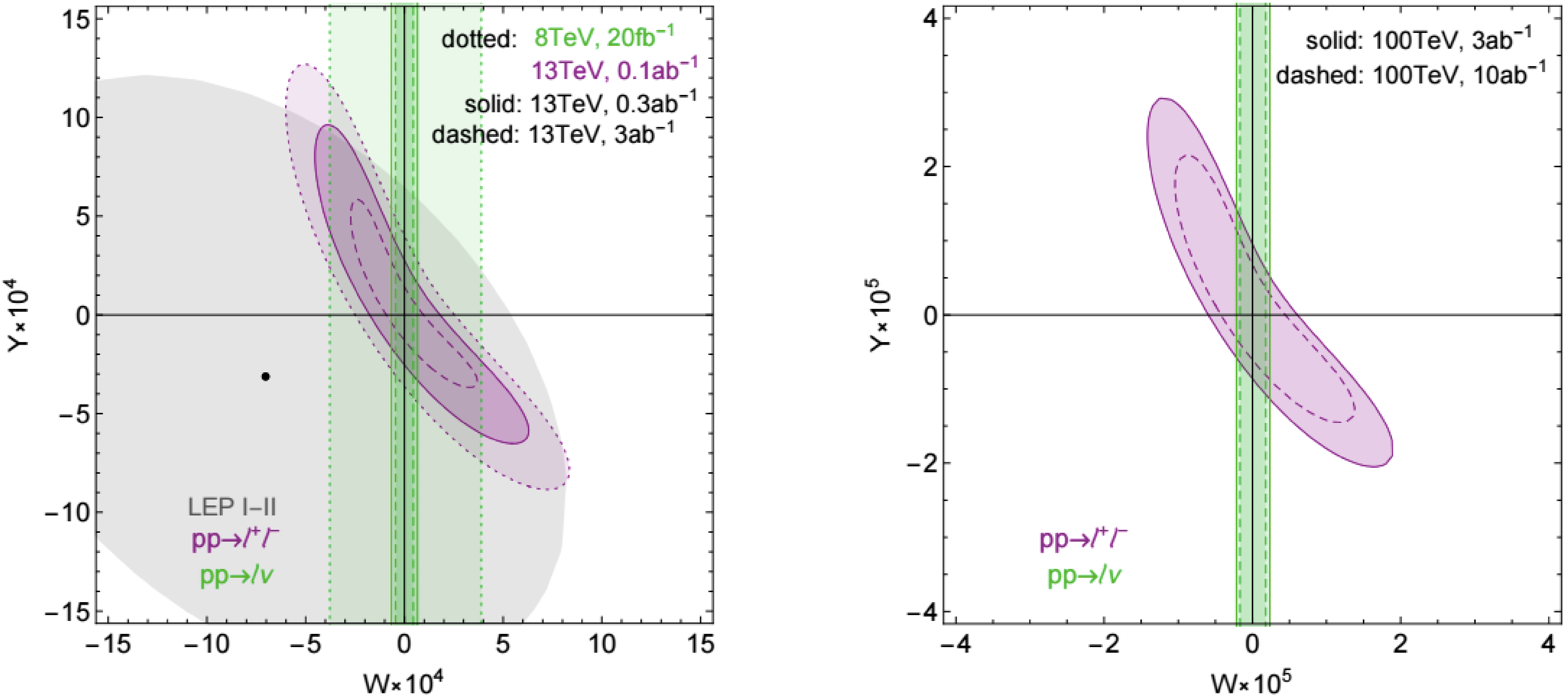
Results: projections



Including 8 TeV charged DY LHC should already surpass LEP

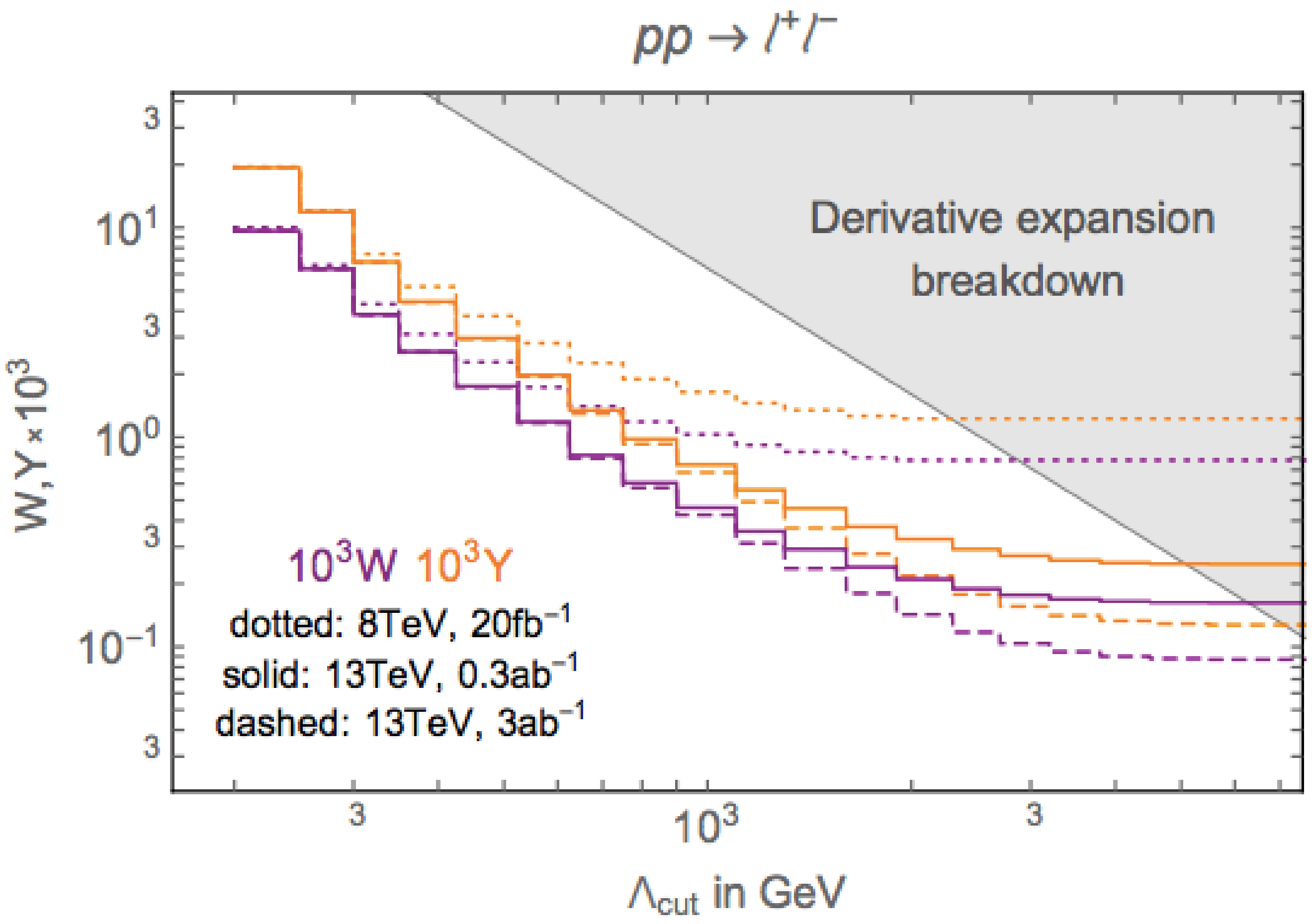
13 TeV LHC can improve by up to a factor of 5, HL-LHC by a factor of 10 and a futue 100 TeV collider by a factor of 100

Results: projections

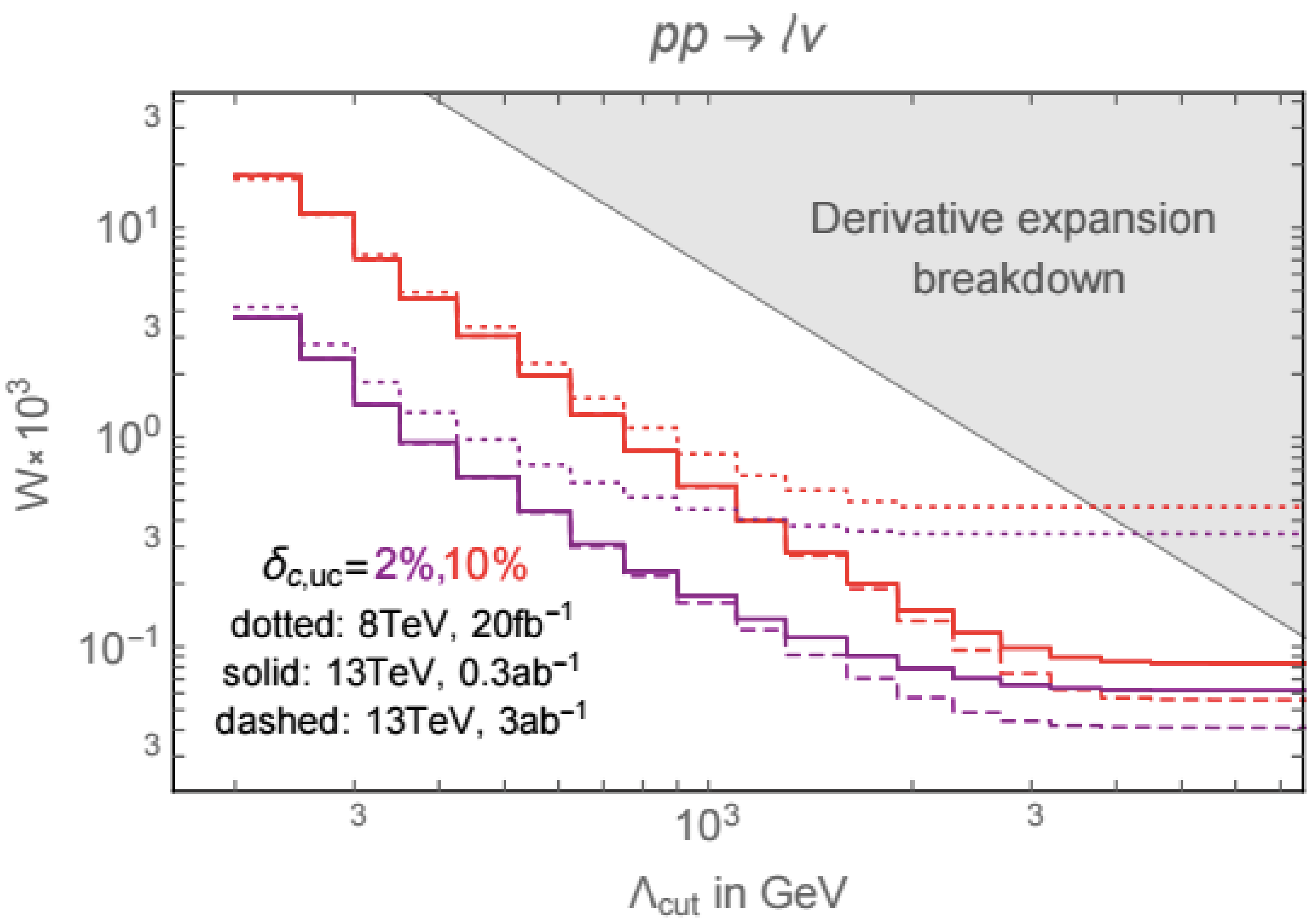


		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2\times10^7\,Z$	$19.7\,\mathrm{fb}^{-1}$	$20.3\,\mathrm{fb}^{-1}$	$0.3\,\mathrm{ab}^{-1}$	$3\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$10^9\,Z$	$10^{12}\,Z$	$3\,\mathrm{ab}^{-1}$
NC	$\mathrm{W}\times10^4$	$[-19,3]$	$[-3,15]$	$[-5,22]$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

Validity of the EFT



$pp \to l^+l^-$



$pp \to l\nu$

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

Constraints on new physics

Universal constraints on W and Y are applicable to different NP scenarios

Examples:

Compositeness of EW gauge bosons

Compositeness of the electroweak gauge bosons corresponds to the scales

$$\Lambda_1 \approx m_W/\sqrt{Y} \qquad \Lambda_2 \approx m_W/\sqrt{W}$$

$\Lambda_2 \geq 4$ TeV charged DY at LHC@8TeV

$(\Lambda_2, \Lambda_1) \geq (6.5, 5)$ TeV neutral DY at LHC@13TeV with 300 fb^{-1}

Heavy vectors

Scenarios with heavy vectors, e.g. triplets under the SM SU(2), can surpass constraints from direct searches for

$3.5\ \mathrm{TeV} < m_{W'} < 4\ \mathrm{TeV}\,,\ g_V \sim g_2$ charged DY at LHC@8TeV

$6.5\ \mathrm{TeV} < m_{W'} < 10\ \mathrm{TeV}\,,\ g_V \lesssim 2g_2$ neutral DY at LHC@13TeV with 300 fb^{-1}

Conclusions

- The precision LHC program can extend beyond Higgs precision and include EW precision (oblique parameters, four fermion interactions, 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 (smart 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
- The precision capabilities of the LHC can be extended to future hadron colliders making more interesting their comparison with future leptonic machines

THANK YOU