BSM physics and reinterpretation of measurements

ATLAS SM Workshop - London - 6 Sep 2018

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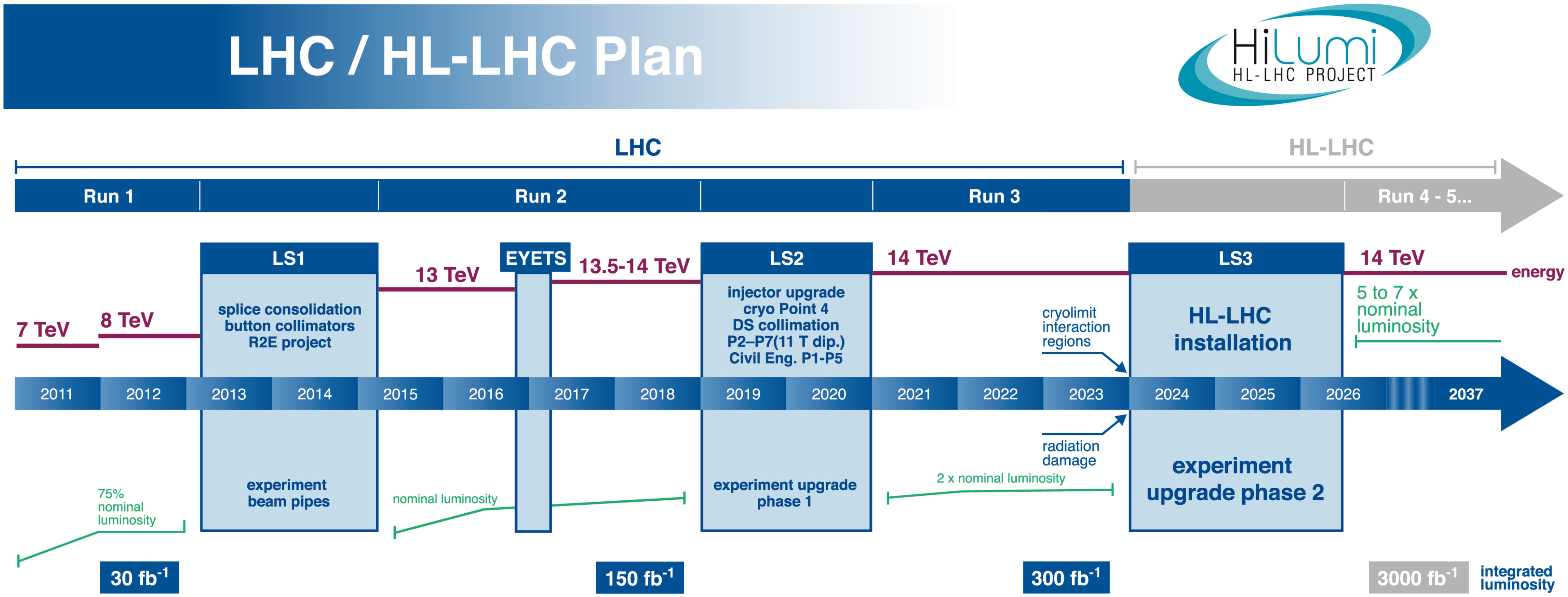
LHC physics program



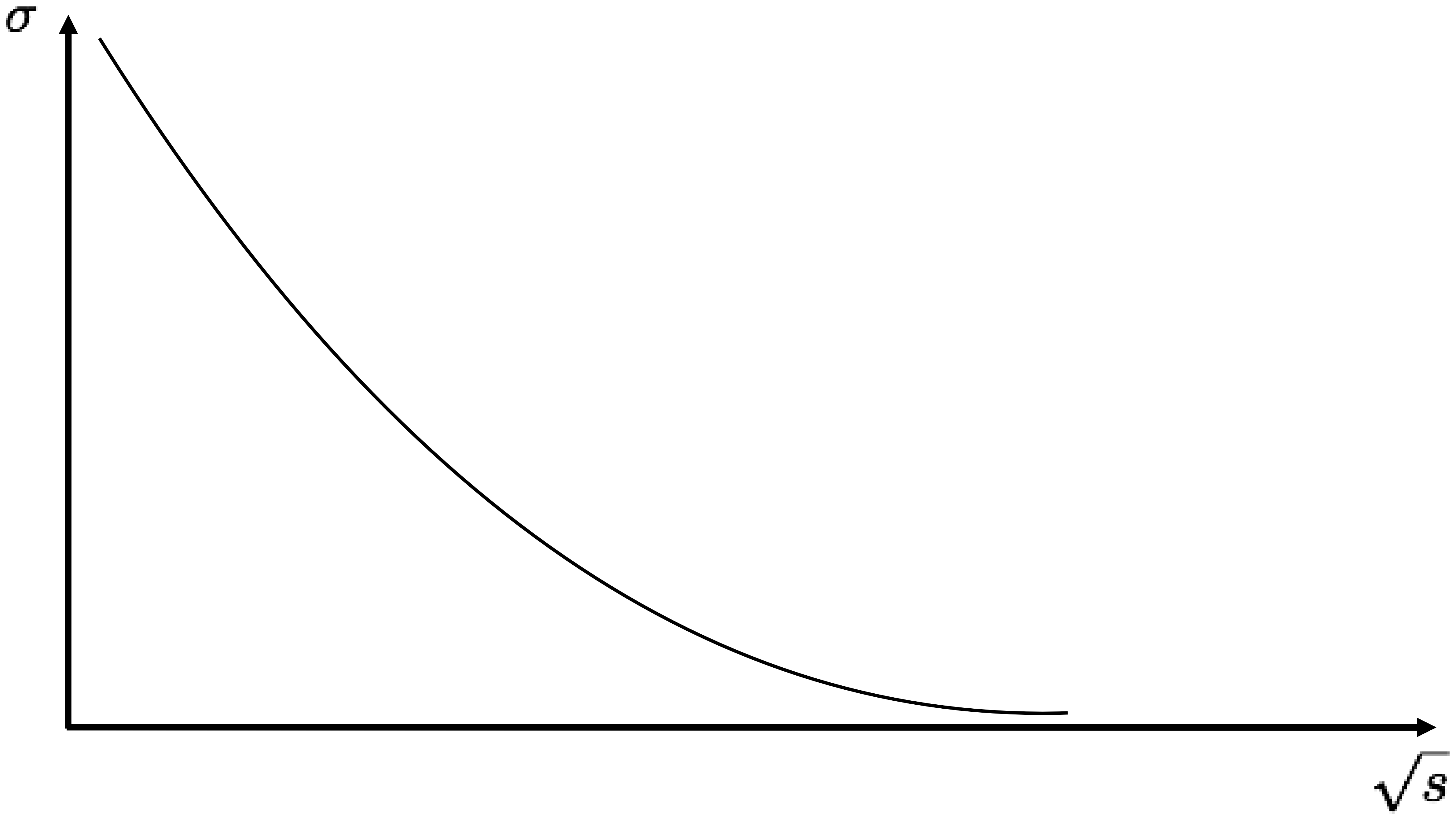
Main goal: Find signs of New Physics

direct searches

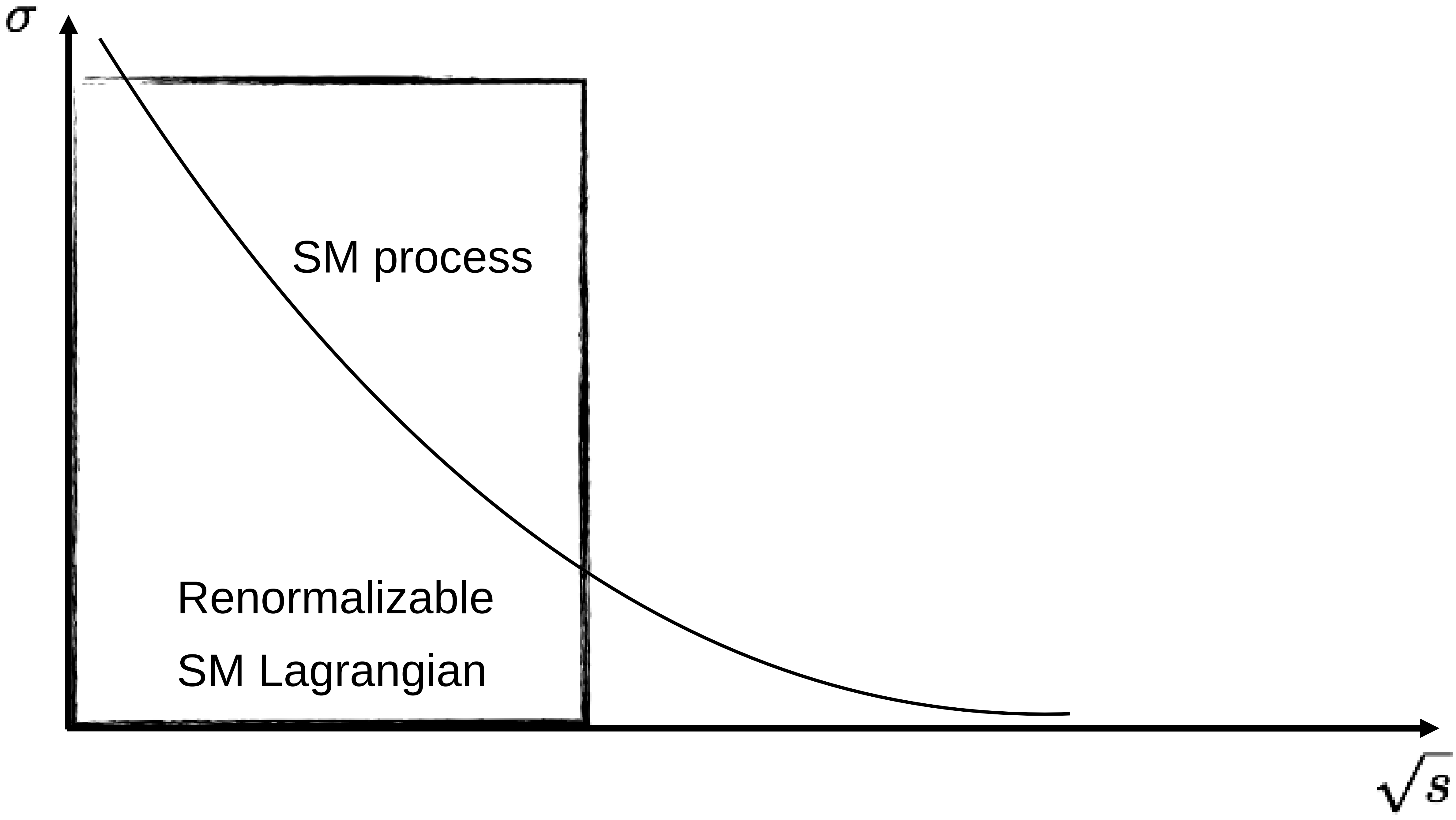
- directly: probing on-shell new physics
- indirectly: probing the effect of new physics on SM observables

precision physics

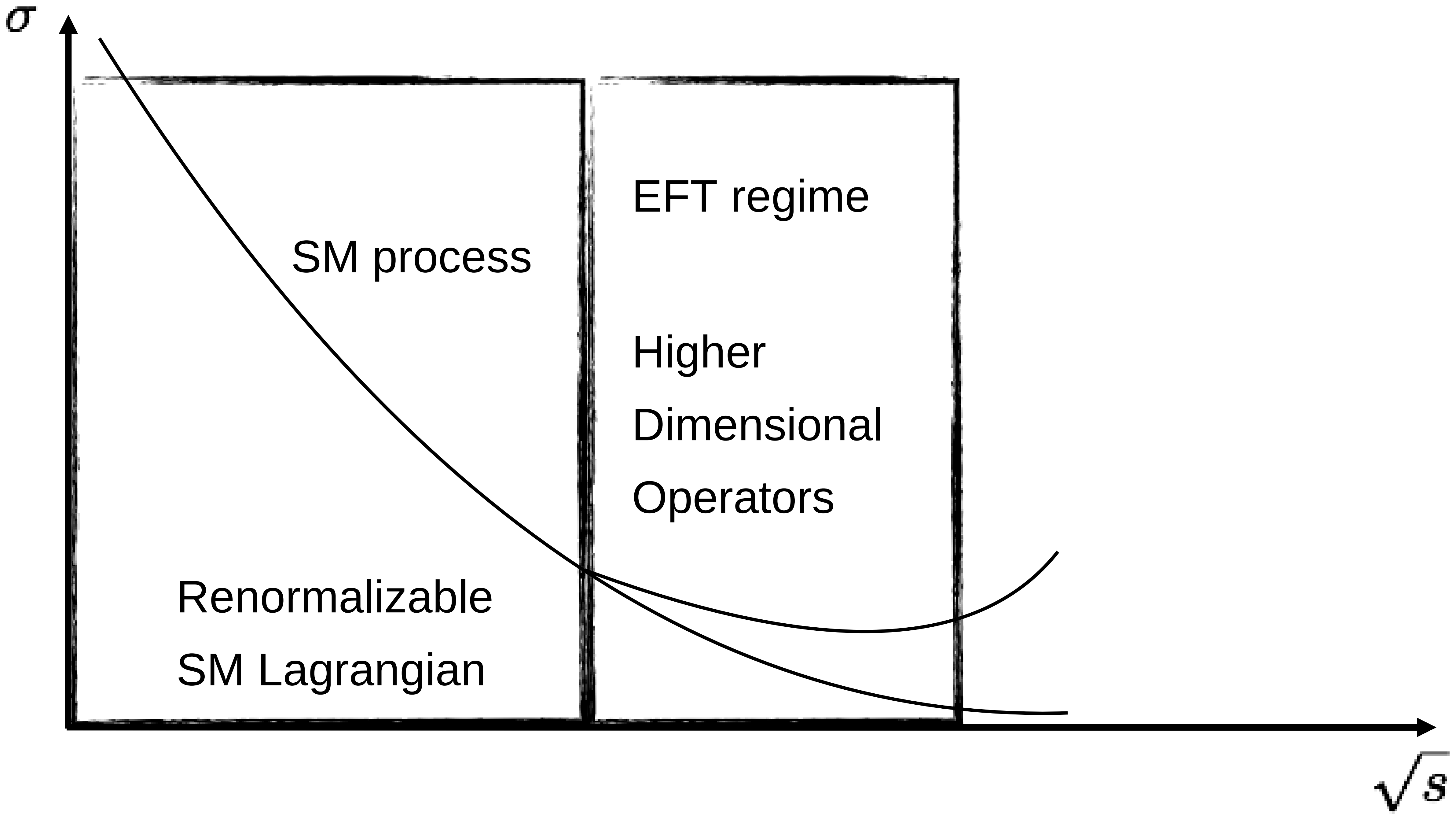
New physics: a pictorial representation



New physics: a pictorial representation



New physics: a pictorial representation



SM process

EFT regime

Higher

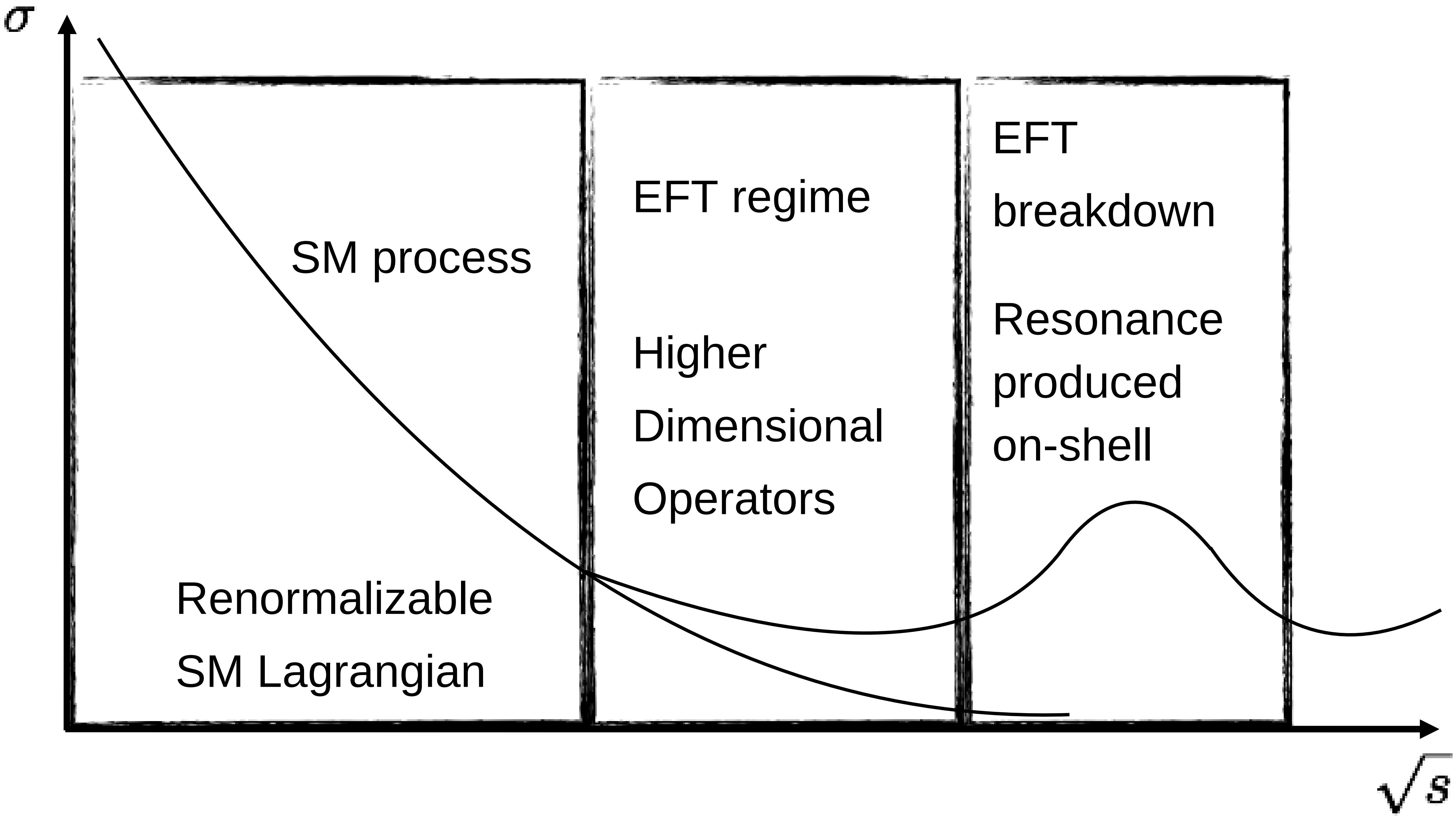
Dimensional

Operators

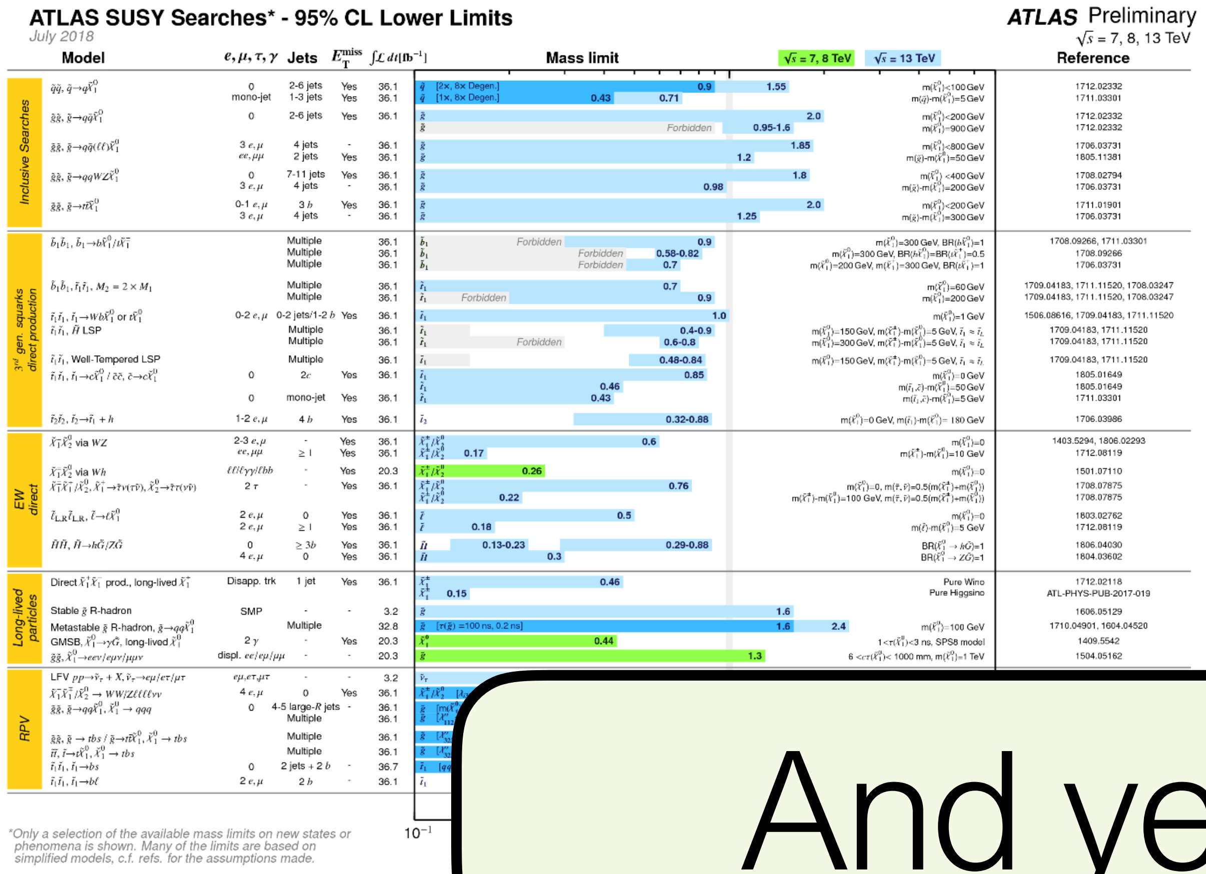
Renormalizable

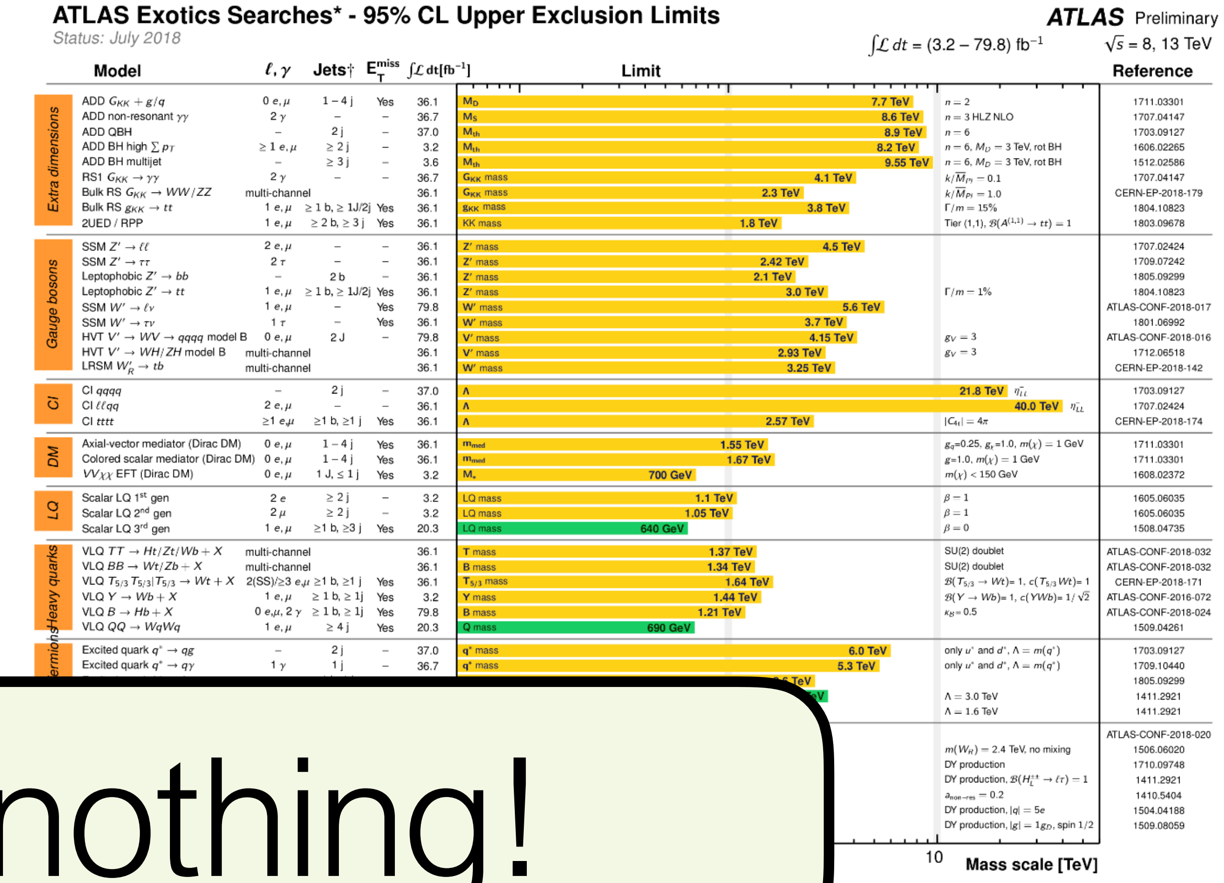
SM Lagrangian

New physics: a pictorial representation

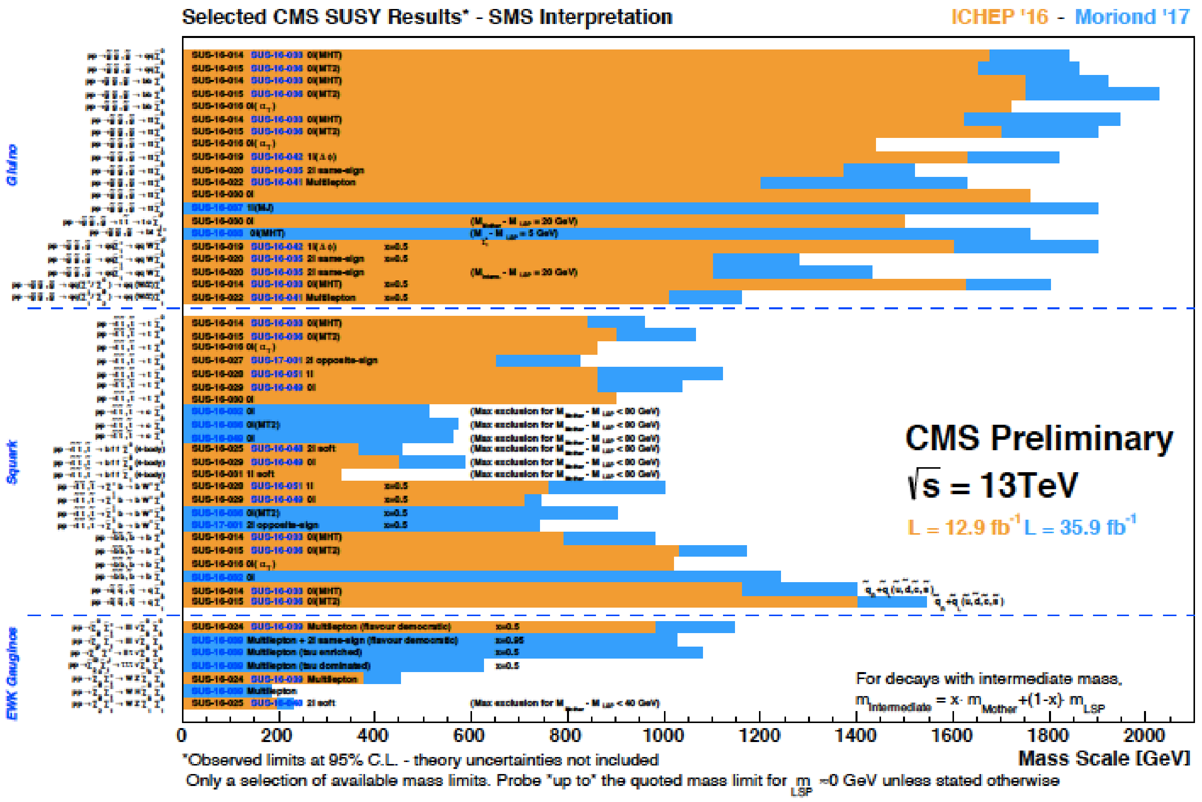


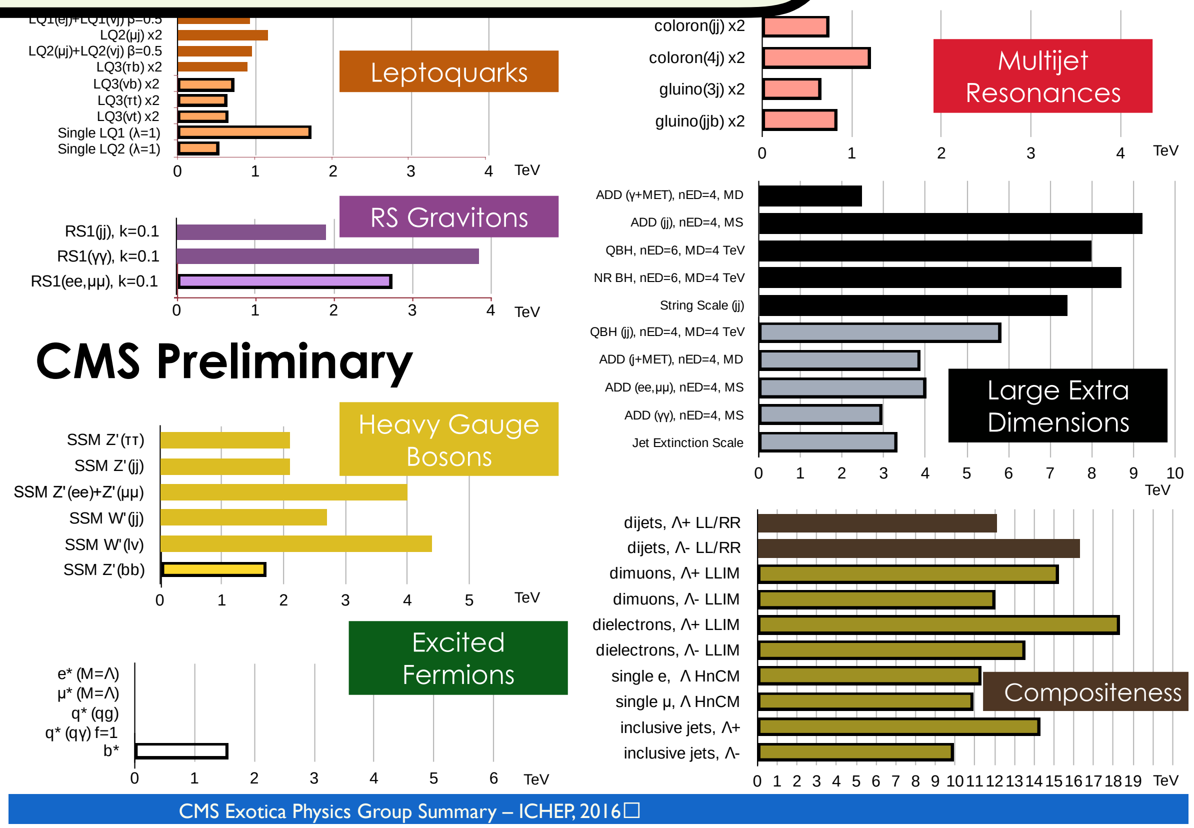
Direct searches





And yet nothing!





Precision physics: the LEP experience

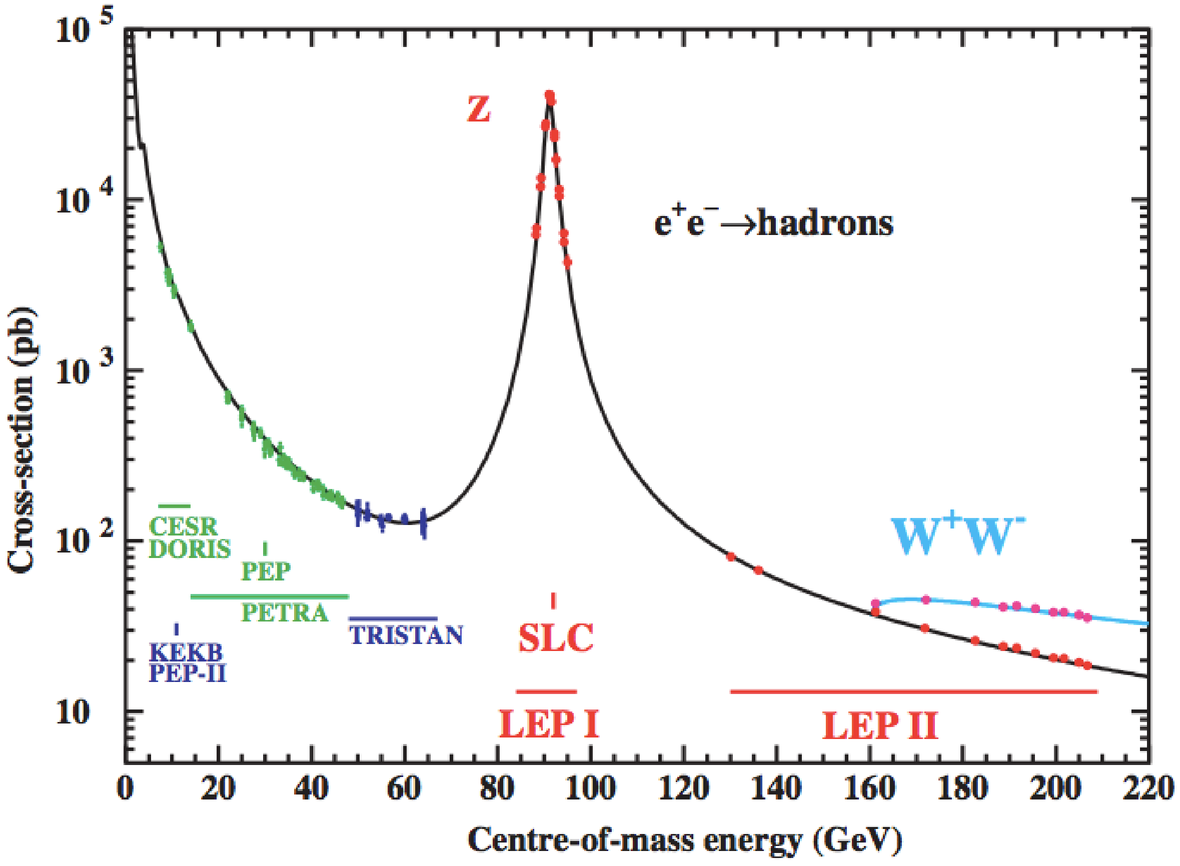
LEP is the prototypical example of a precision physics program

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: 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

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

Largest effects at high invariant masses

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 presence of precision measurements) is a requirement for EFT to be interesting, relevant and applicable!

Moreover EFT is the simplest and more consistent way of parametrizing the different directions in which deviations from the SM can appear

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 aboves in a consistent way

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

Qualitative analysis, can one make it quantitative?

Two working examples

- Drell-Yan (neutral and charged)
- Di-jets (and inclusive jet)

Note: unfortunately cannot cover di-bosons. For references see, for instance: Franceschini, Panico, Pomarol, Riva, Wulzer, 1712.01310

The simplest case: DY

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

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

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

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

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

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

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

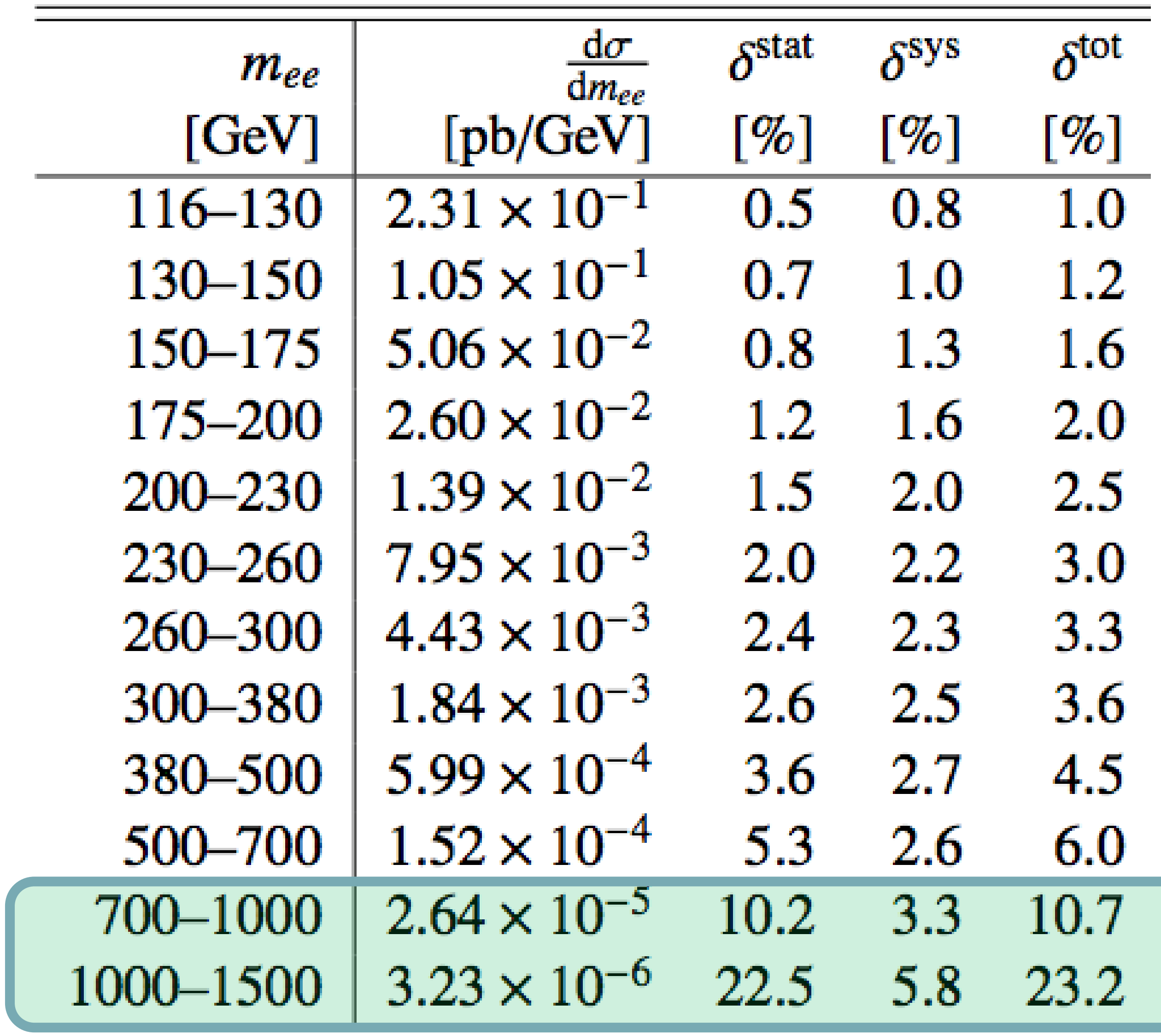
Projection

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)

Experimental uncertainties

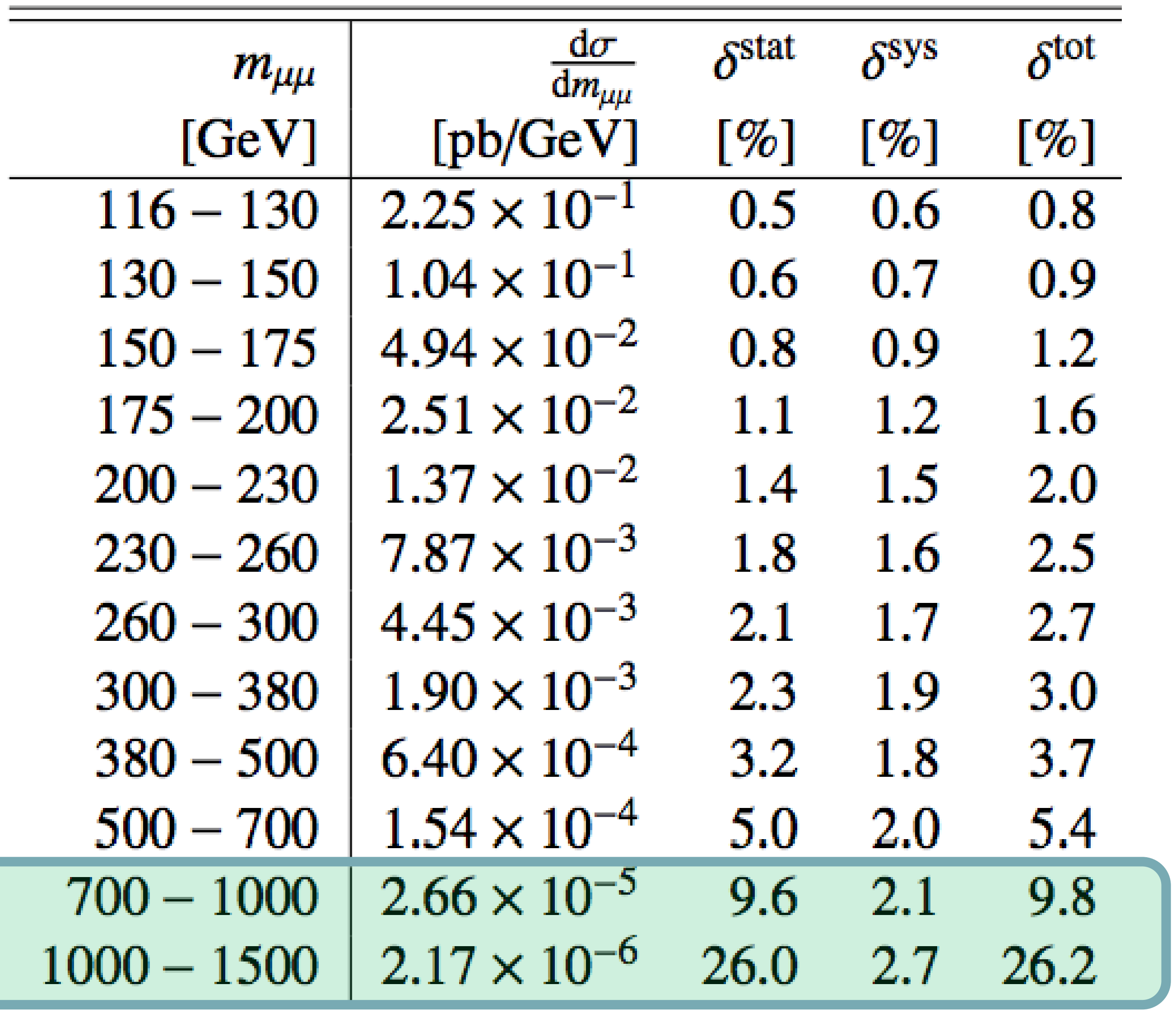
ATLAS, 1606.01736

Electrons



m_{ee} [GeV]	$\frac{d\sigma}{dm_{ee}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]
116–130	2.31×10^{-1}	0.5	0.8	1.0
130–150	1.05×10^{-1}	0.7	1.0	1.2
150–175	5.06×10^{-2}	0.8	1.3	1.6
175–200	2.60×10^{-2}	1.2	1.6	2.0
200–230	1.39×10^{-2}	1.5	2.0	2.5
230–260	7.95×10^{-3}	2.0	2.2	3.0
260–300	4.43×10^{-3}	2.4	2.3	3.3
300–380	1.84×10^{-3}	2.6	2.5	3.6
380–500	5.99×10^{-4}	3.6	2.7	4.5
500–700	1.52×10^{-4}	5.3	2.6	6.0
700–1000	2.64×10^{-5}	10.2	3.3	10.7
1000–1500	3.23×10^{-6}	22.5	5.8	23.2

Muons



$m_{\mu\mu}$ [GeV]	$\frac{d\sigma}{dm_{\mu\mu}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]
116 – 130	2.25×10^{-1}	0.5	0.6	0.8
130 – 150	1.04×10^{-1}	0.6	0.7	0.9
150 – 175	4.94×10^{-2}	0.8	0.9	1.2
175 – 200	2.51×10^{-2}	1.1	1.2	1.6
200 – 230	1.37×10^{-2}	1.4	1.5	2.0
230 – 260	7.87×10^{-3}	1.8	1.6	2.5
260 – 300	4.45×10^{-3}	2.1	1.7	2.7
300 – 380	1.90×10^{-3}	2.3	1.9	3.0
380 – 500	6.40×10^{-4}	3.2	1.8	3.7
500 – 700	1.54×10^{-4}	5.0	2.0	5.4
700 – 1000	2.66×10^{-5}	9.6	2.1	9.8
1000 – 1500	2.17×10^{-6}	26.0	2.7	26.2

Statistic uncertainties still dominating in the interesting region

Main systematic uncertainty is energy scale (corr) around 2% around 1 TeV

Systematic uncertainty under control within (or below) 2-3% around 1 TeV

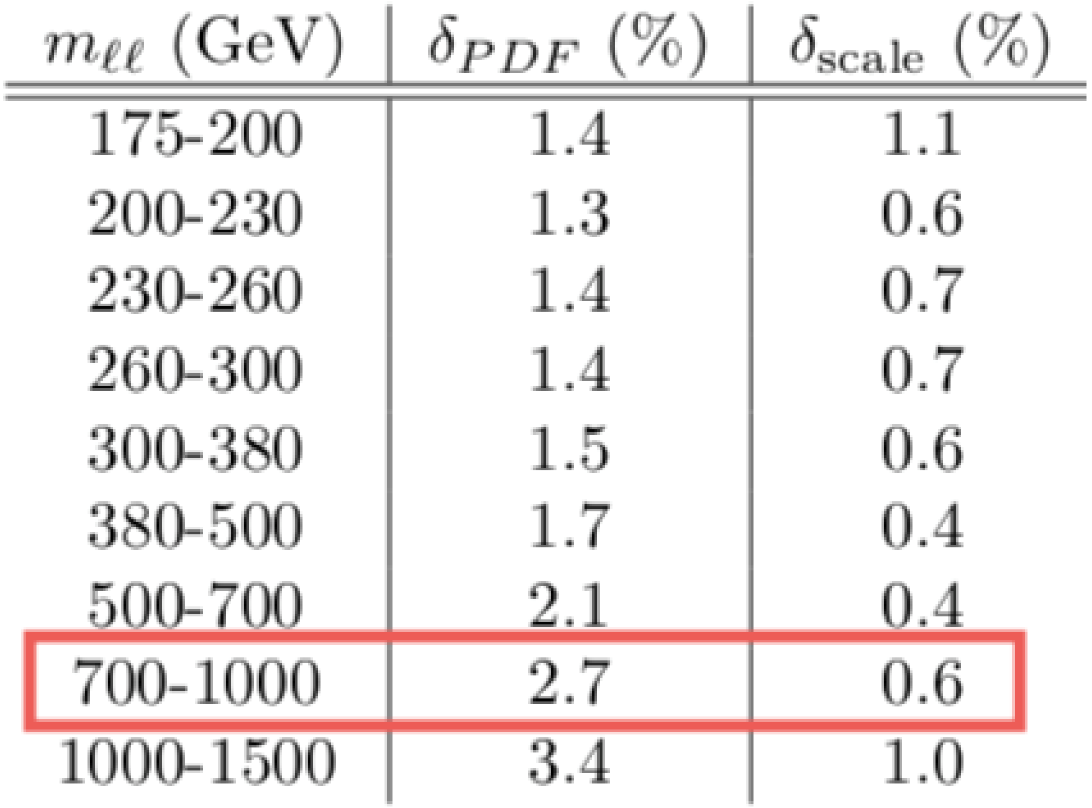
Theory uncertainties

Farina et al., 1609.08157

We computed NNLO QCD prediction with FEWZ using NNPDF2.3@NNLO

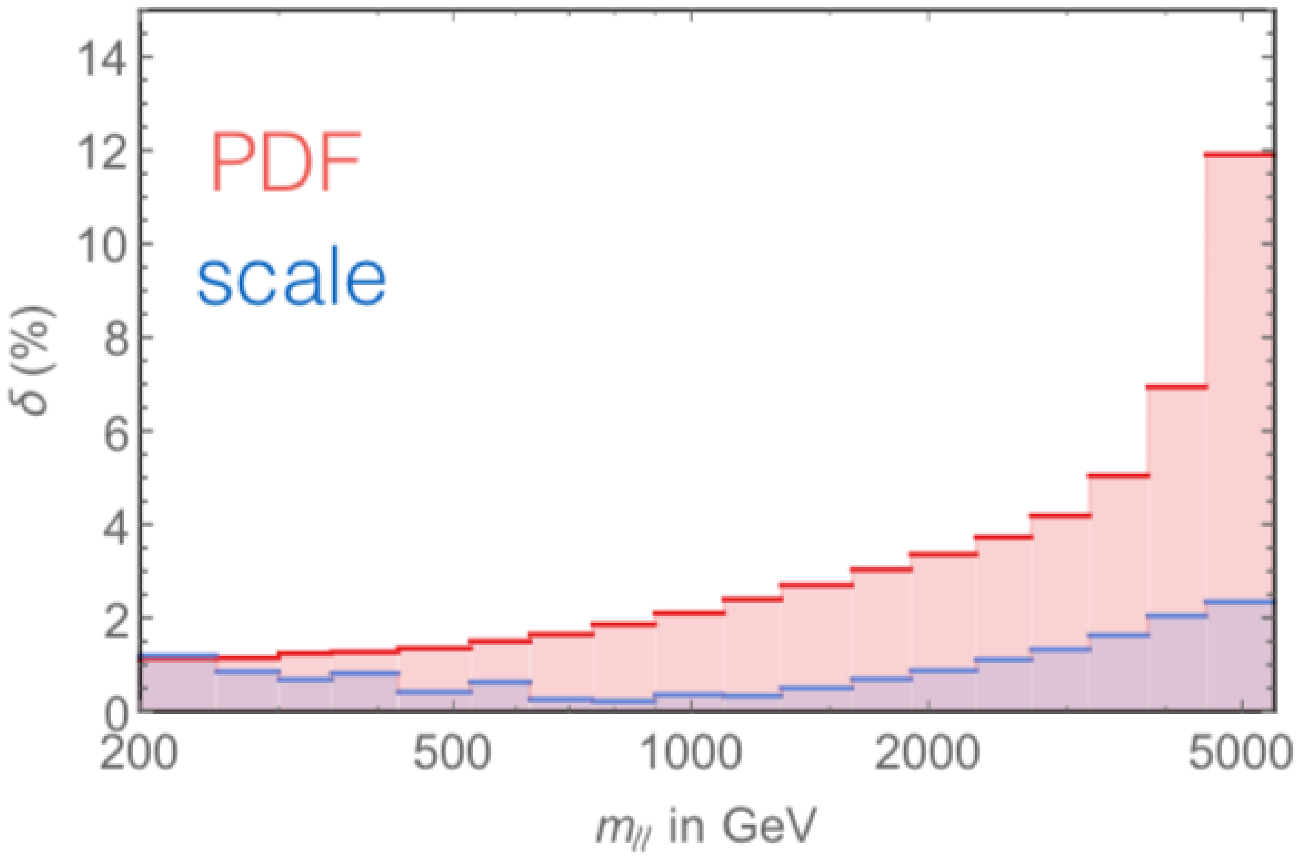
Main uncertainty from PDFs (correlated)

Scale uncertainties correlated across all bins



$m_{\ell\ell}$ (GeV)	δ_{PDF} (%)	δ_{scale} (%)
175-200	1.4	1.1
200-230	1.3	0.6
230-260	1.4	0.7
260-300	1.4	0.7
300-380	1.5	0.6
380-500	1.7	0.4
500-700	2.1	0.4
700-1000	2.7	0.6
1000-1500	3.4	1.0

8 TeV



13 TeV

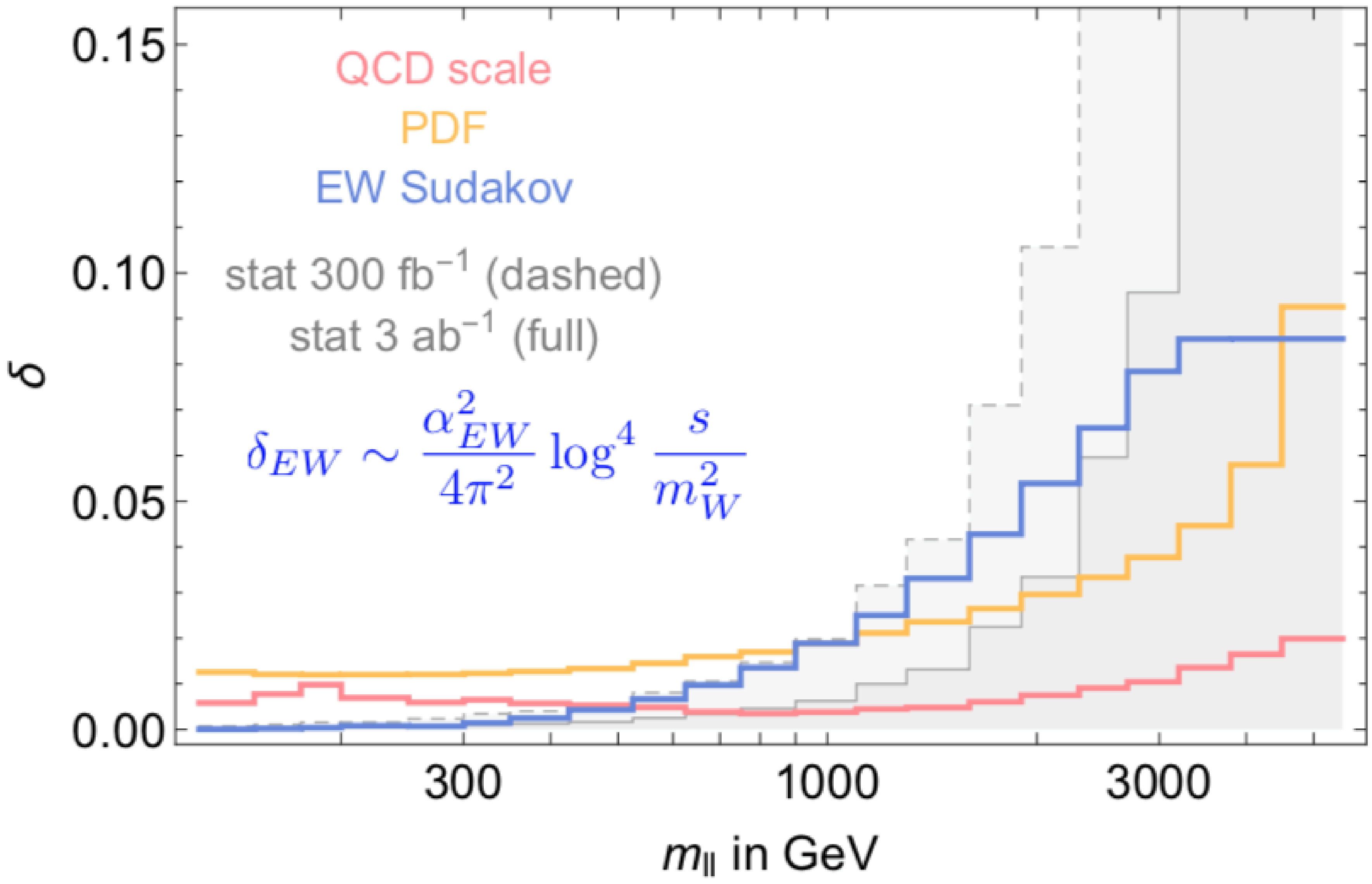
Theory uncertainties

Farina et al., 1609.08157

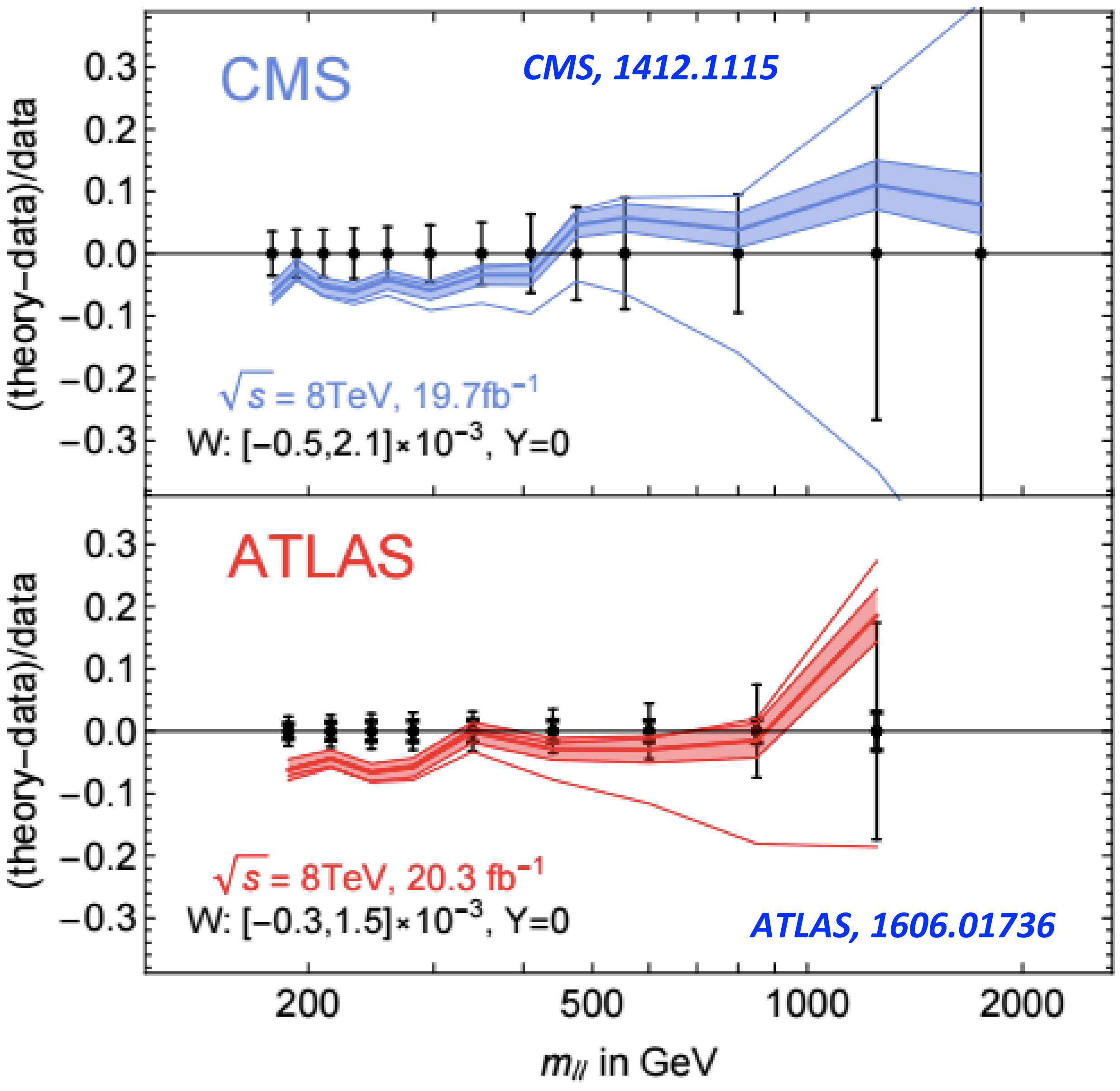
Additional source of TH uncertainty we did not include is NLO EW

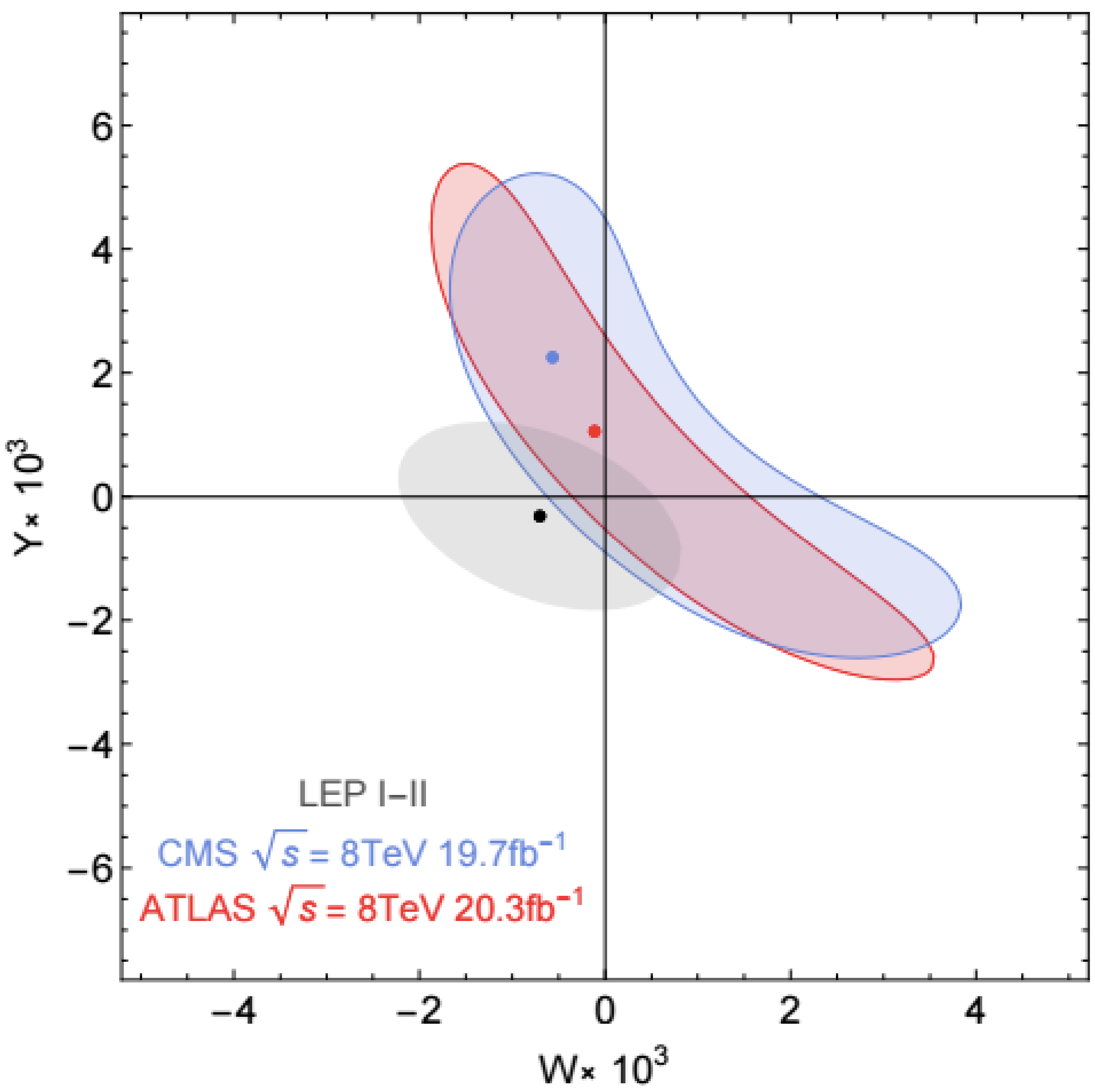
The effect can become large at large invariant masses (large Sudakov logs)

However, at most comparable with other uncertainties and in the high mass region subdominant compared to stat uncertainty



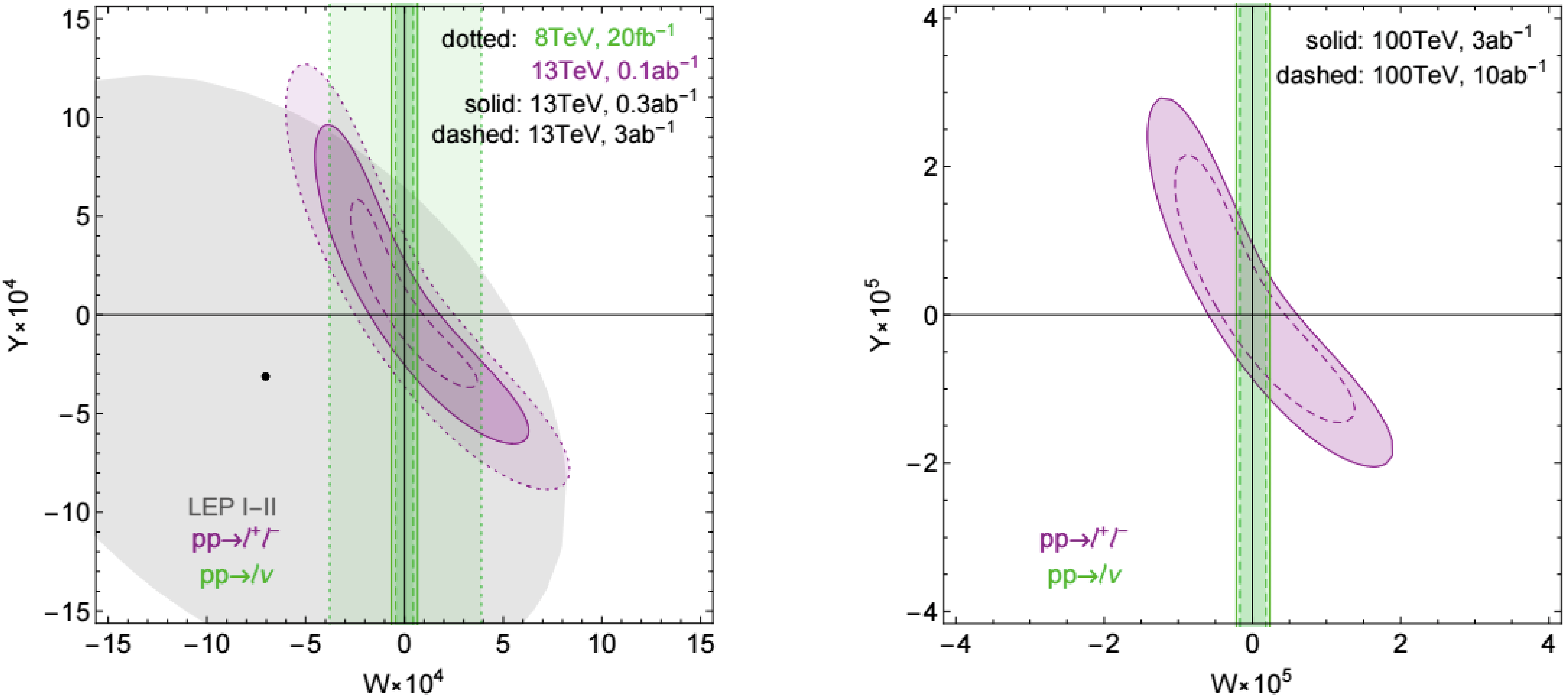
Results: data





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

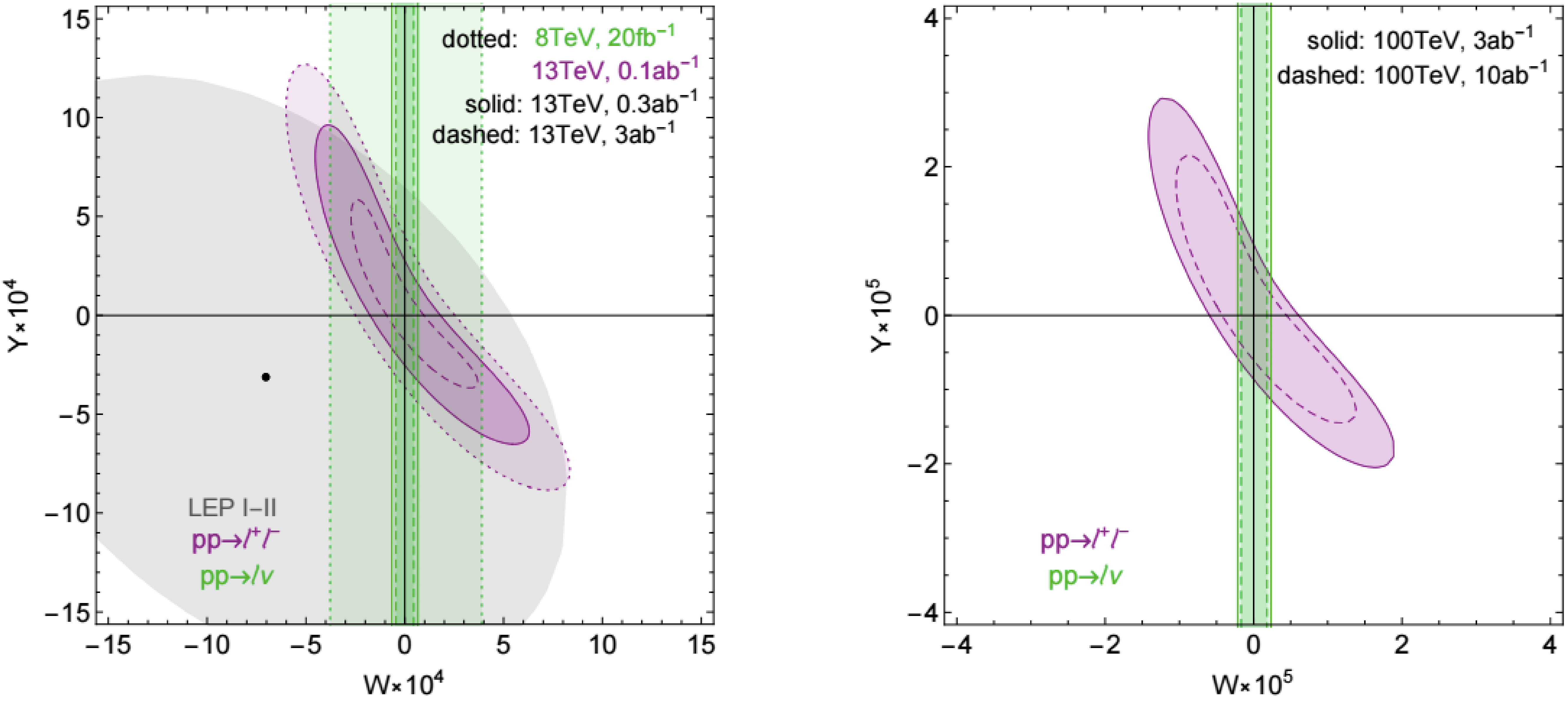
Results: projections



Including 8 TeV charged DY LHC should already surpass LEP

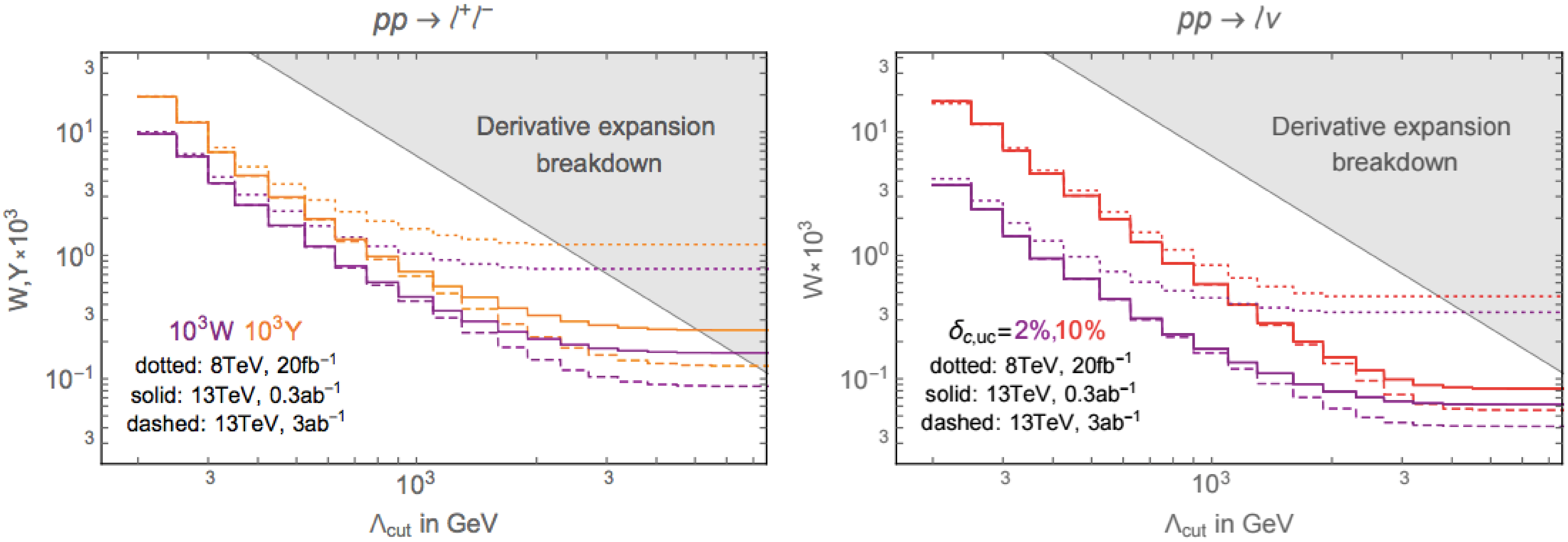
13 TeV LHC can improve by up to a factor of 5, HL-LHC by a factor of 10 and a futue 100 TeV collider by a factor of 100

Results: projections



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

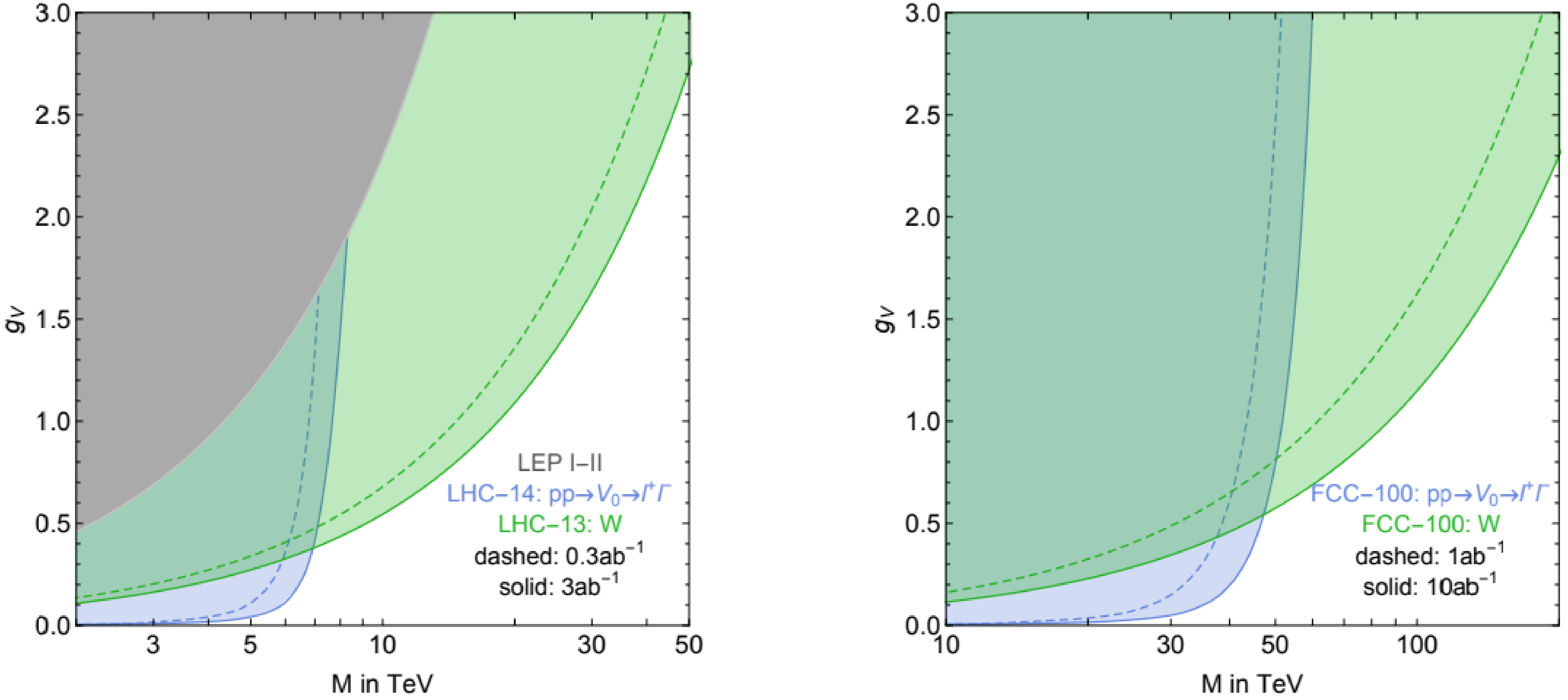
Therefore, as expected, in this channel we are testing ~10% deviations

Constraints on new physics

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

An example can be a triplet of heavy vectors (HVT)

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



Beyond leptons: jets

Alioli et al., 1706.03068

A similar exercise can be done using di-jet distributions

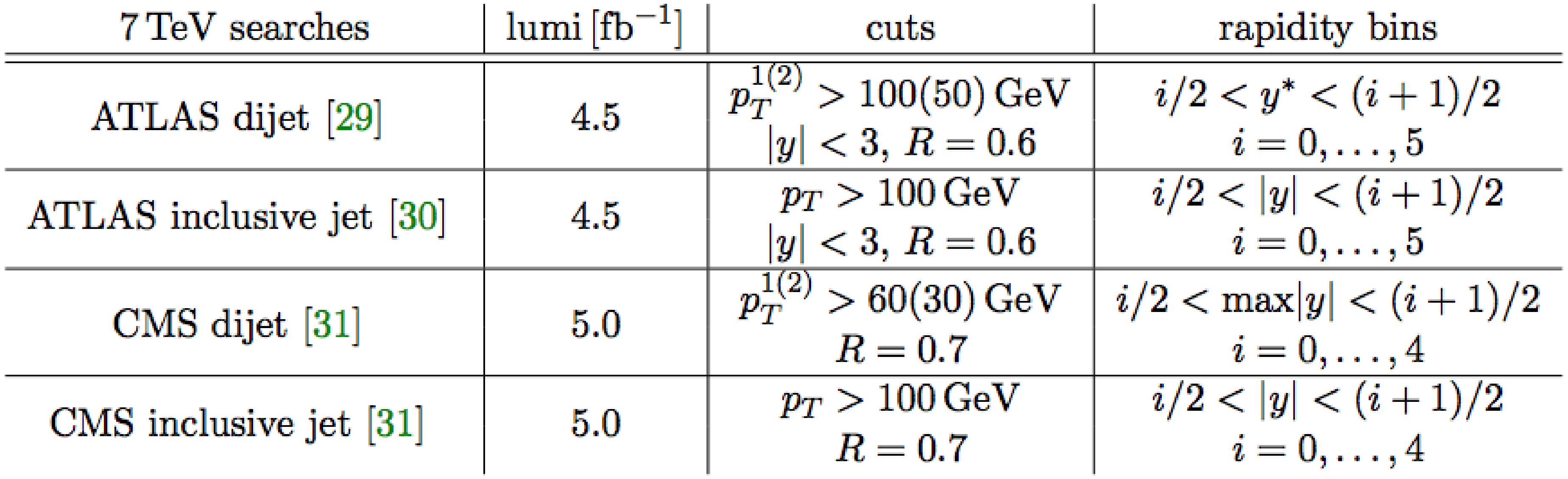
Can consider in the SM EFT the operator

$$-\frac{Z}{4m_W^2}\left(D_\rho G^A_{\mu\nu}\right)^2$$

Modifies the gluon propagator at high energy (enhancement in jet cross sections at high invariant masses)

More challenging due to larger uncertainties, but under control within 10% in the interesting region (at large masses theory uncertainty dominated by PDFs)

The analysis proceeds in a similar way as for di-leptons



7 TeV searches	lumi [fb^{-1}]	cuts	rapidity bins
ATLAS dijet [29]	4.5	$p_T^{1(2)} > 100(50)$ GeV $\lvert y\rvert < 3$, $R = 0.6$	$i/2 < y^* < (i+1)/2$ $i = 0, \ldots, 5$
ATLAS inclusive jet [30]	4.5	$p_T > 100$ GeV $\lvert y\rvert < 3$, $R = 0.6$	$i/2 < \lvert y\rvert < (i+1)/2$ $i = 0, \ldots, 5$
CMS dijet [31]	5.0	$p_T^{1(2)} > 60(30)$ GeV $R = 0.7$	$i/2 < \max\lvert y\rvert < (i+1)/2$ $i = 0, \ldots, 4$
CMS inclusive jet [31]	5.0	$p_T > 100$ GeV $R = 0.7$	$i/2 < \lvert y\rvert < (i+1)/2$ $i = 0, \ldots, 4$

ATLAS, 1312.3524

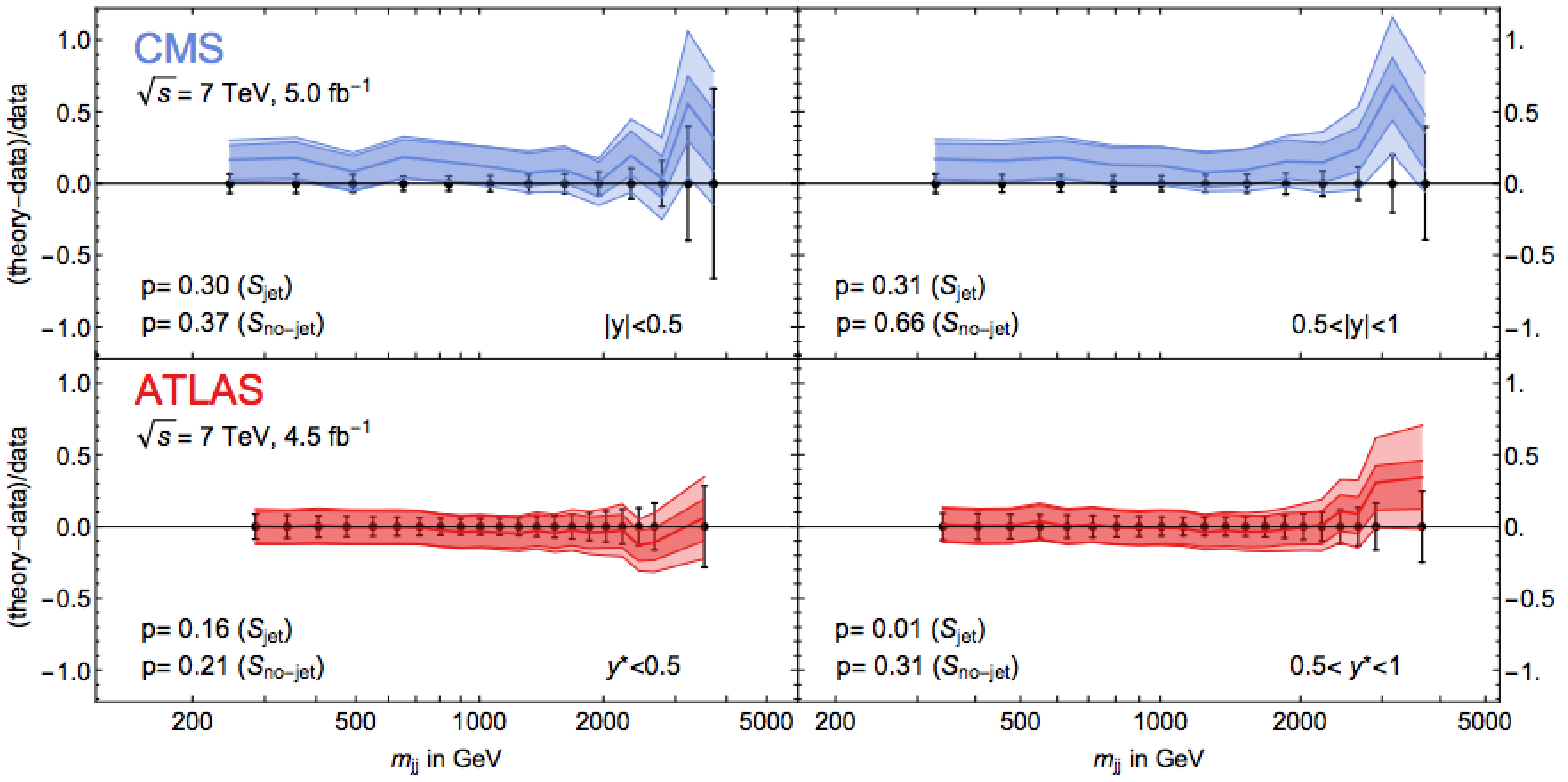
ATLAS, 1410.8857

CMS, 1212.6660

Prediction vs data

Alioli et al., 1706.03068

Dijet



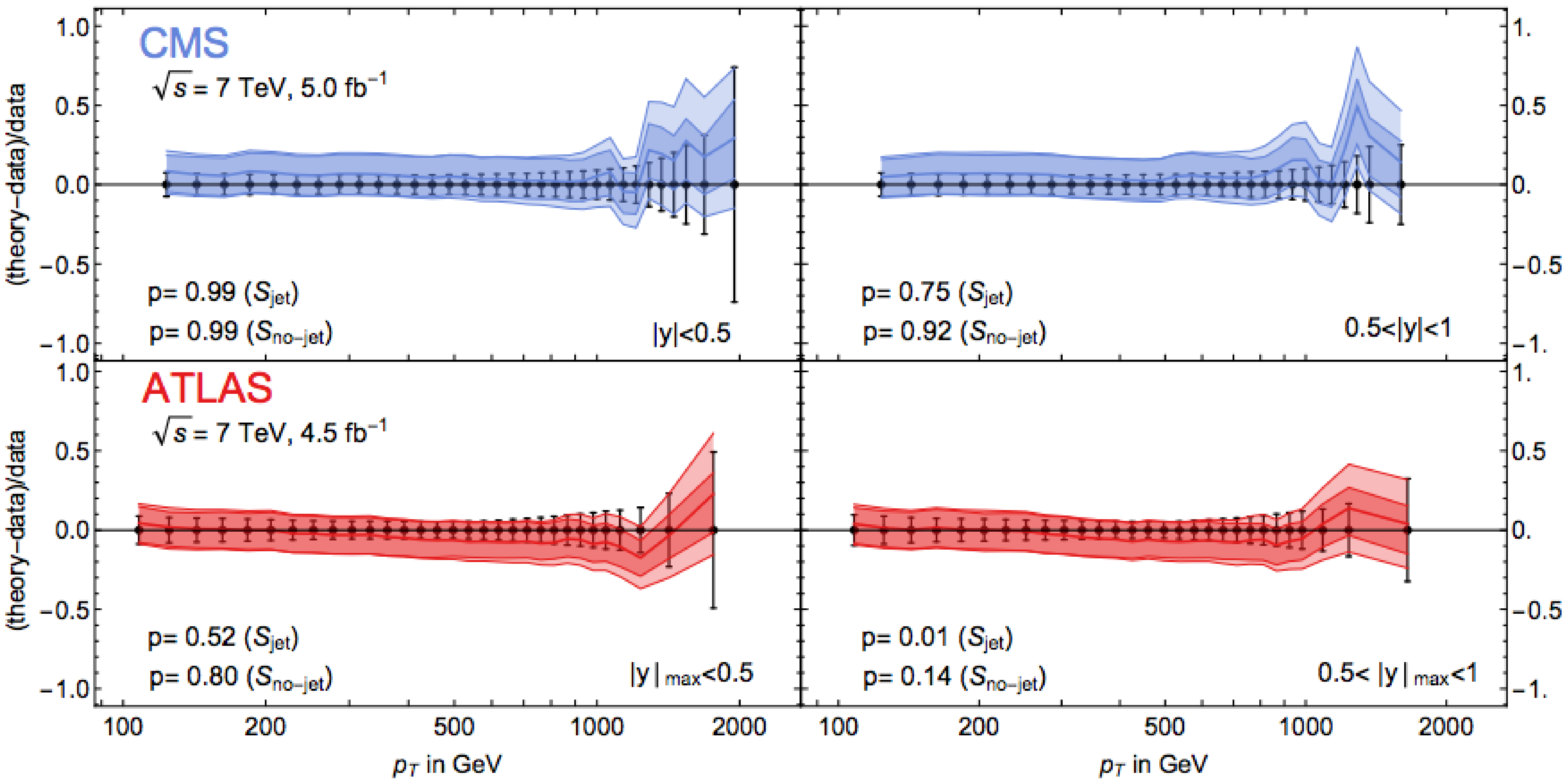
🟦🟥 NNPDF30_NLO_AS_0118 including jet data

🟦🟥 NNPDF30_NLO_AS_0118_nojet not including jet data (LHC & Tevatron)

Prediction vs data

Alioli et al., 1706.03068

Inclusive jet



▨ NNPDF30_NLO_AS_0118 including jet data

■ NNPDF30_NLO_AS_0118_nojet not including jet data (LHC & Tevatron)

Results using 7 TeV data

Alioli et al., 1706.03068

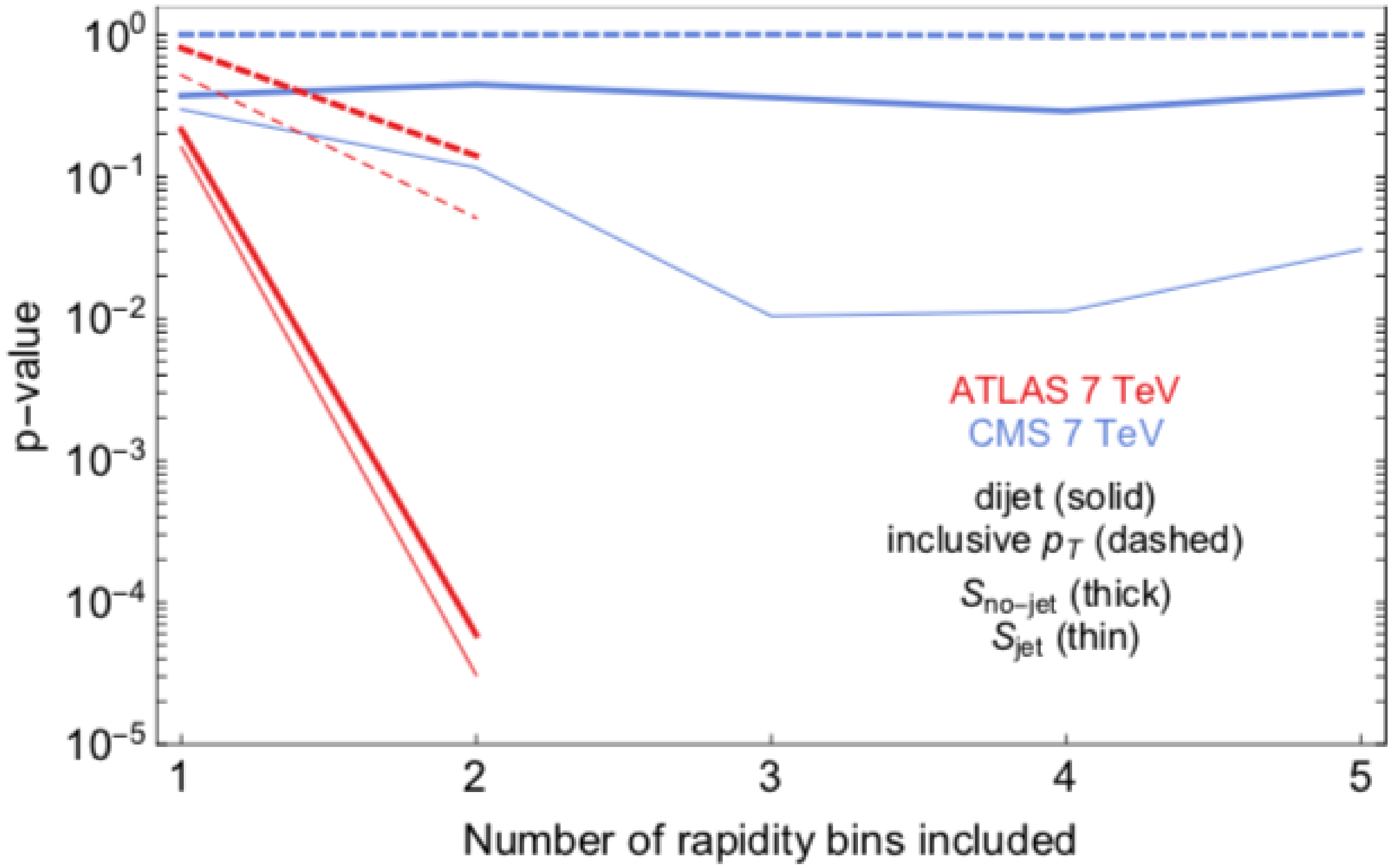
95% CL bounds on $Z \times 10^4$

Analysis	$\mathcal{S}_{\text{no-jet}}$ - 1bin	$\mathcal{S}_{\text{no-jet}}$ - 2bins	$\mathcal{S}_{\text{jet}}$ - 1bin
ATLAS dijet	[-19.8,+3.9]	*[+4.1,+9.3]	[-5.4,+4.3]
ATLAS inclusive jet	[-18.7,+8.7]	[-6.5,+1.3]	[-3.2,+8.0]
CMS dijet	[-18.3,+6.0]	[-2.3,+5.5]	[-5.5,+2.8]
CMS inclusive jet	[-18.9,+3.1]	*[-8.6,-0.4]	[-8.0,+1.9]

* excludes the SM at 95% CL

Already observed by ATLAS that the double differential fit is bad

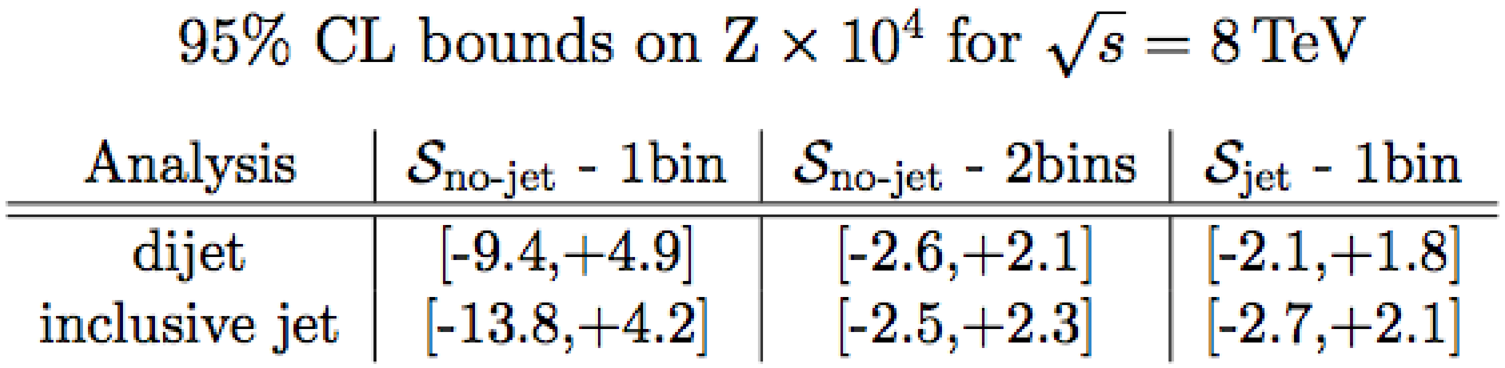
Suggests (reasonably) that theory prediction may not be under control (NNLO needed?)



Results: projections

Alioli et al., 1706.03068

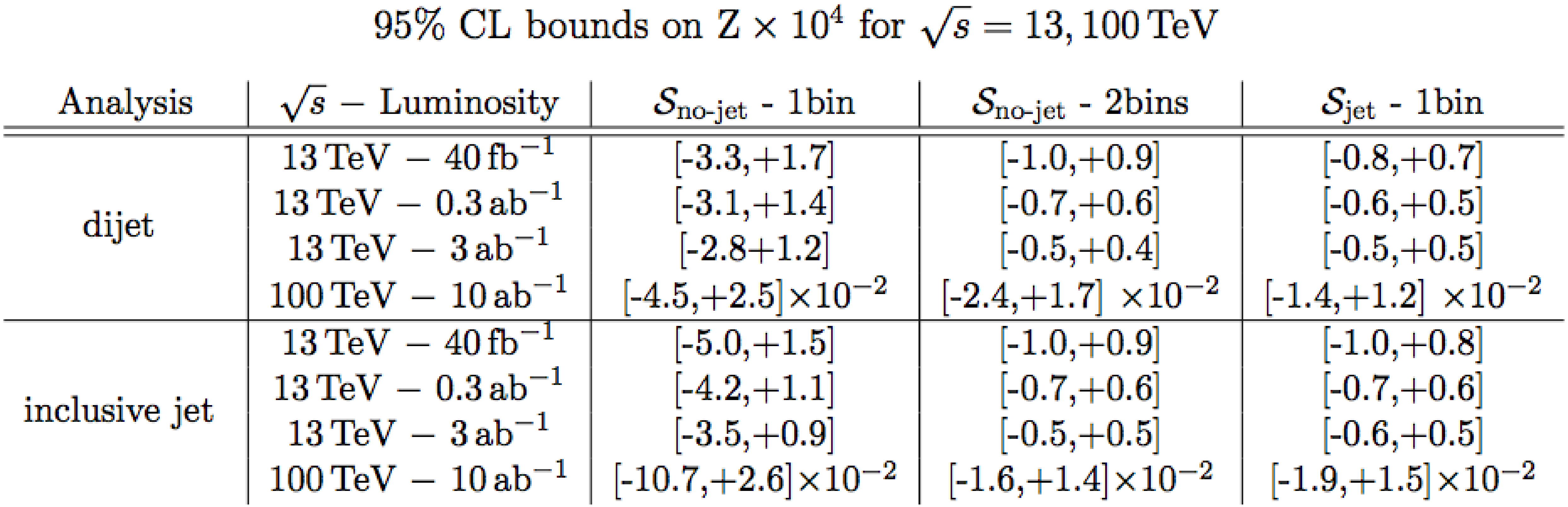
8 TeV



95% CL bounds on Z × 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]

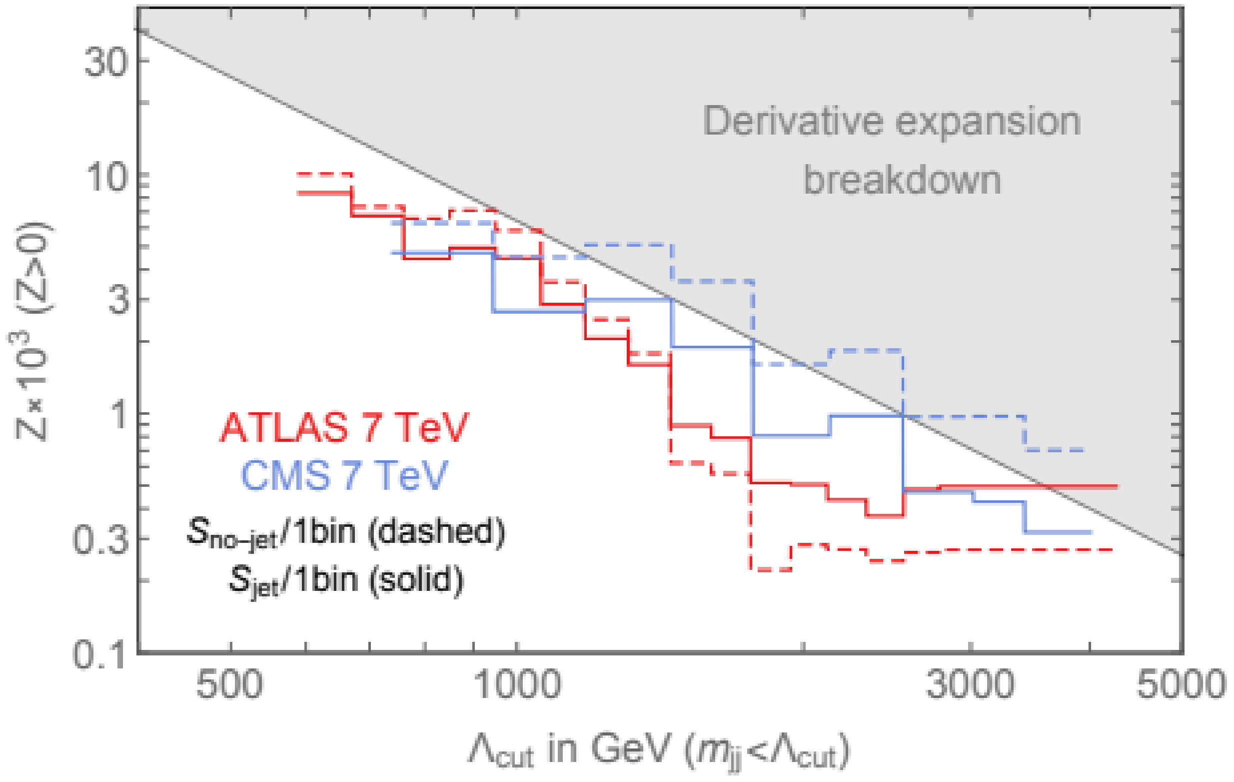
13/100 TeV

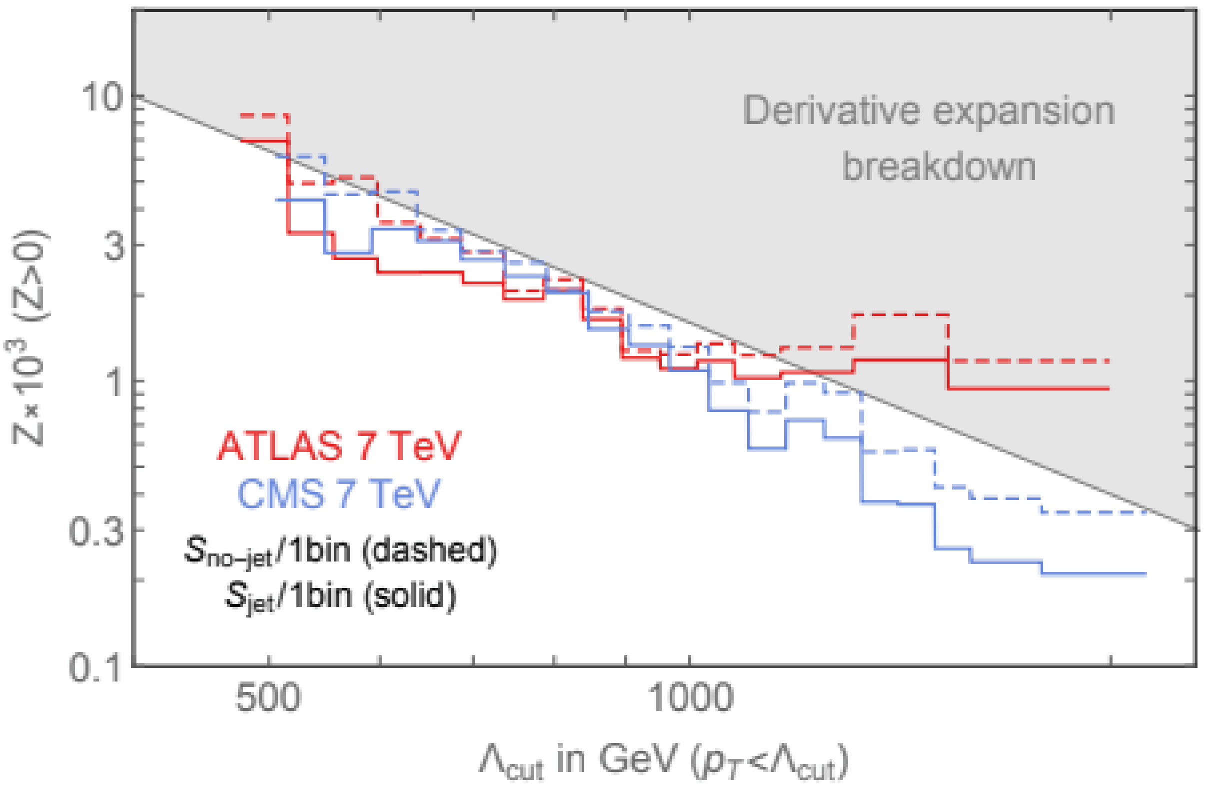


95% CL bounds on Z × 10^4 for $\sqrt{s} = 13, 100\,\text{TeV}$

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]×10^{-2}	[-2.4,+1.7] ×10^{-2}	[-1.4,+1.2] ×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]×10^{-2}	[-1.6,+1.4]×10^{-2}	[-1.9,+1.5]×10^{-2}

Validity of the EFT





Differently from DY here constraint barely within EFT validity

At 7 TeV does not yet reach the saturation (which would appear at few TeV)

The constraints is close to the scale of breakdown of the perturbative expansion, which corresponds to O(1) NP effects

Therefore, as expected, in this channel we are testing O(1) deviations

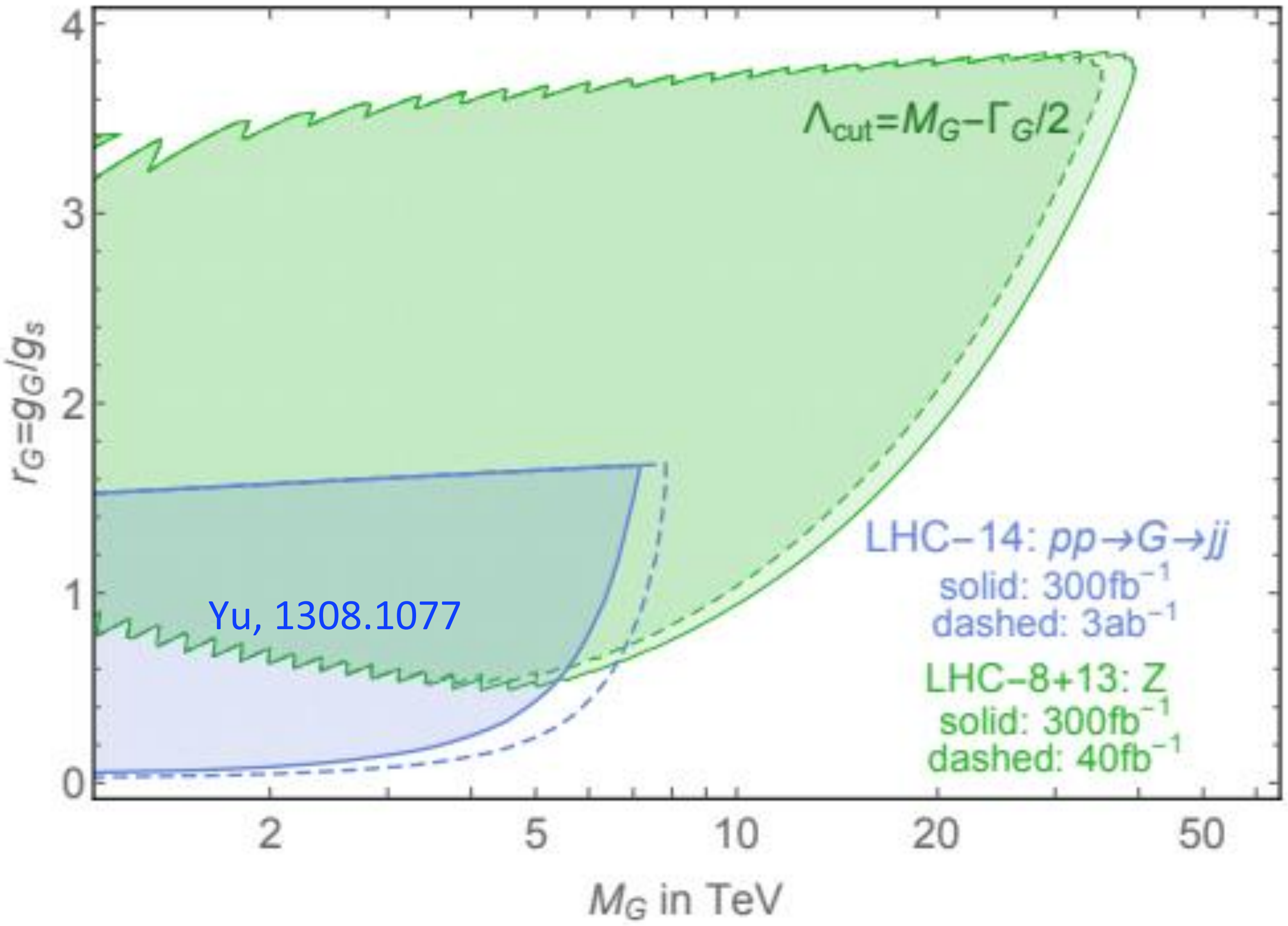
Improving on uncertainties (especially PDF one) would improve EFT validity

Constraints on new physics

Universal constraints on Z can be translated for instance in bound on heavy gluon

Alioli et al., 1706.03068

$$\Delta\mathscr{L}_{\mathcal{G}} = -\frac{1}{4} D_{[\mu}\mathcal{G}^A_{\nu]} D^{[\mu}\mathcal{G}^{\nu]A} + \frac{M^2}{2}\mathcal{G}^A_\mu \mathcal{G}^{A\mu} - g_{\mathcal{G}}\mathcal{G}^A_\mu \sum_q \bar{q}\gamma^\mu T^A q.$$



Yu, 1308.1077

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 operators in the SM EFT, 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% (the goal being %), which requires a joint effort from the theory (NLO-NNLO calculations) and experimental (smart analyses technique) communities

- DY is a very simple example, where uncertainties are small and the LHC can compete with and surpass LEP in constraining certain observables

- Di(multi)-jet is a more challenging example, that highlights the role of experimental accurcay

- The precision capabilities of the LHC can be extended to future hadron colliders making more interesting their comparison with future leptonic machines

THANK YOU