The Energy **and** Accuracy Frontier

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Ideology

HEP before the Higgs

SUSY, etc.

Higgs

Top

W boson

HEP after the Higgs

Ideology

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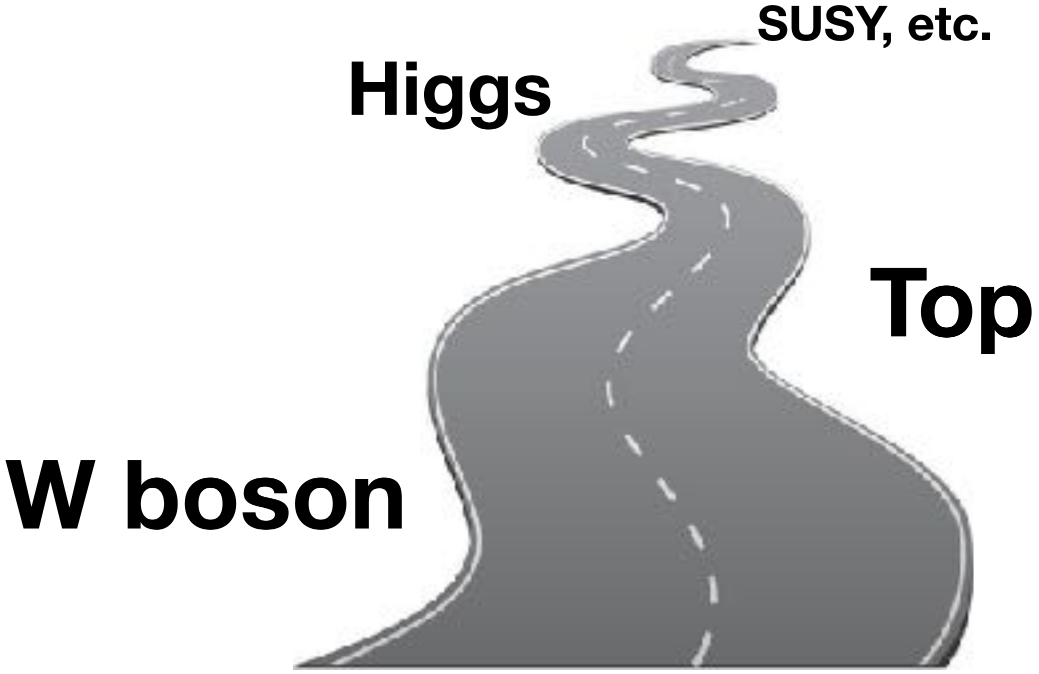


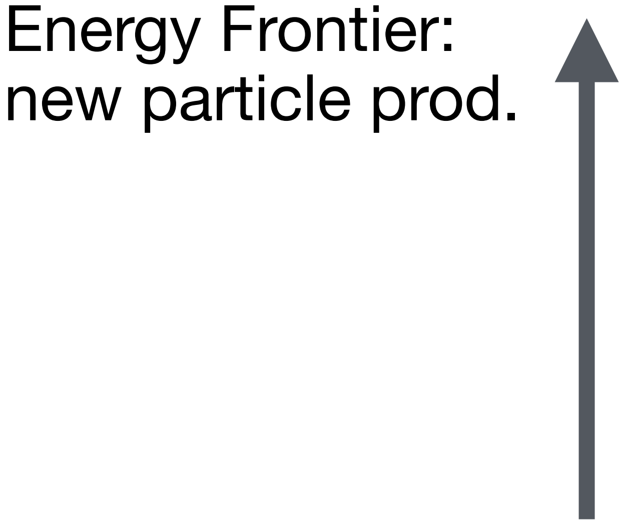
HEP after the Higgs

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

* Not necessarily a bad thing. Columbus left for his trip just because he had no idea of where he was going !!

Ideology

That is why we ended up with the concept of **frontiers:**



Energy Frontier:
new particle prod.

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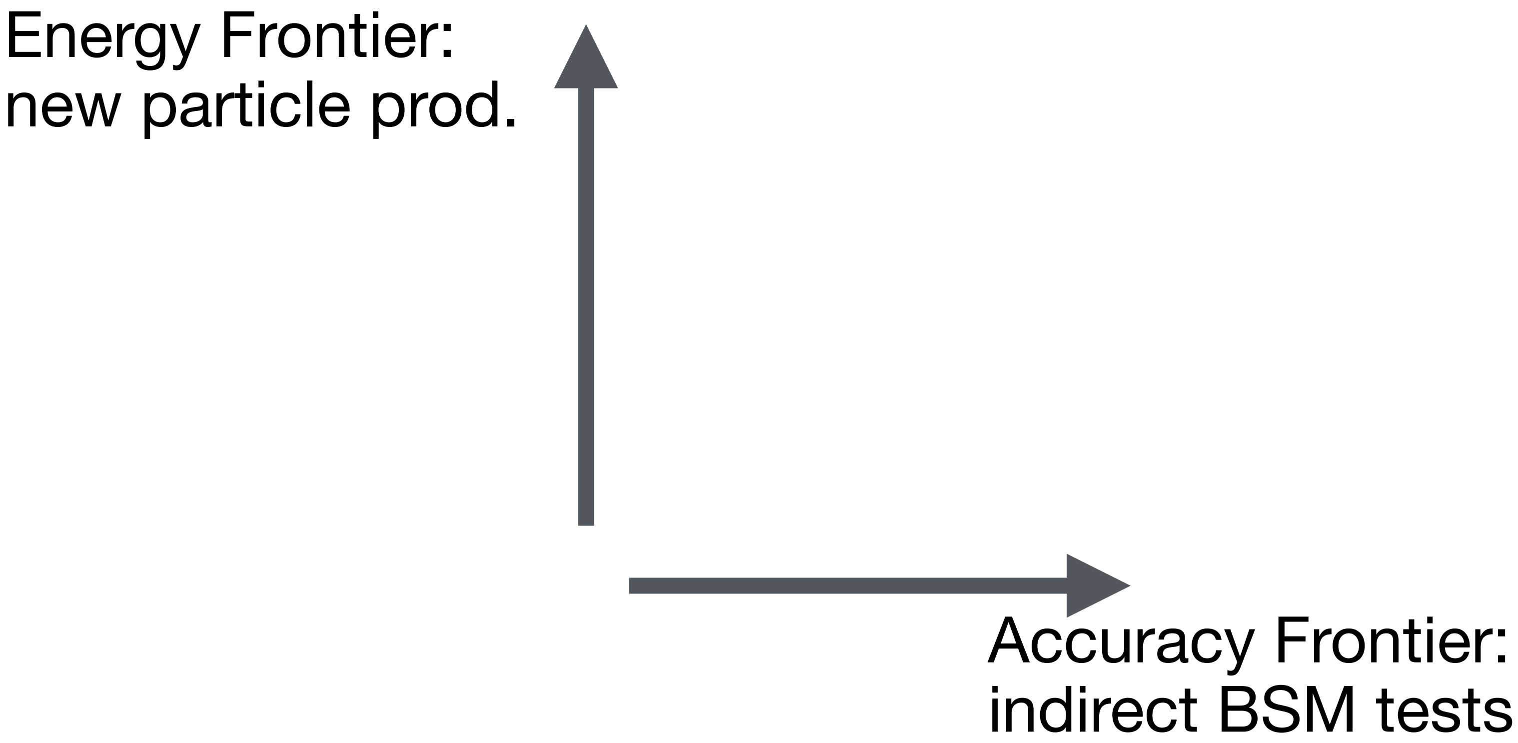

Energy Frontier:
new particle prod.

Accuracy Frontier:
indirect BSM tests

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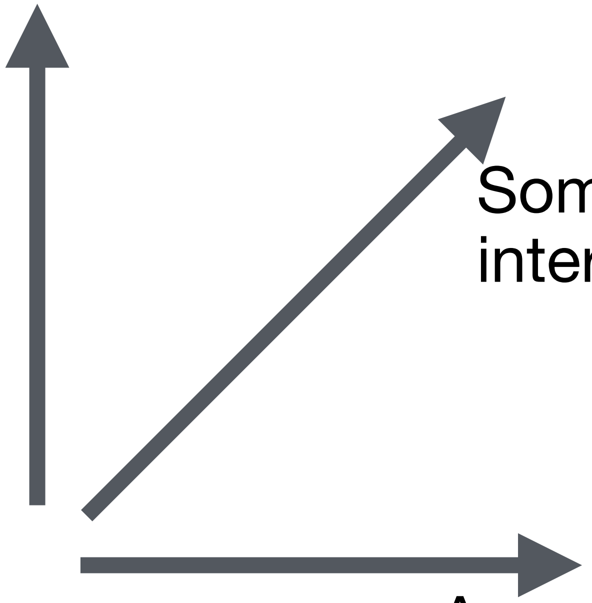

Energy Frontier:
new particle prod.

Something
interesting here?

Accuracy Frontier:
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Energy Frontier @ LHC: Direct Searches

The simplest and most common way to use LHC data …

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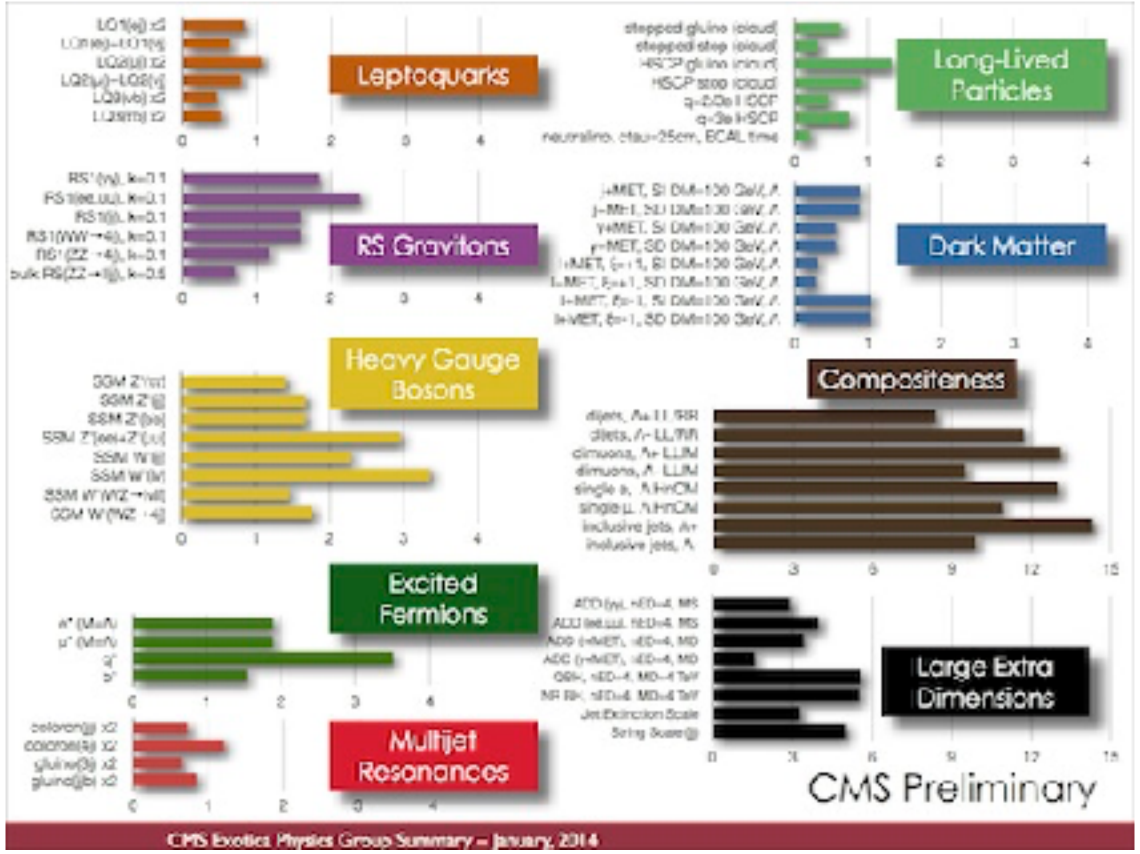

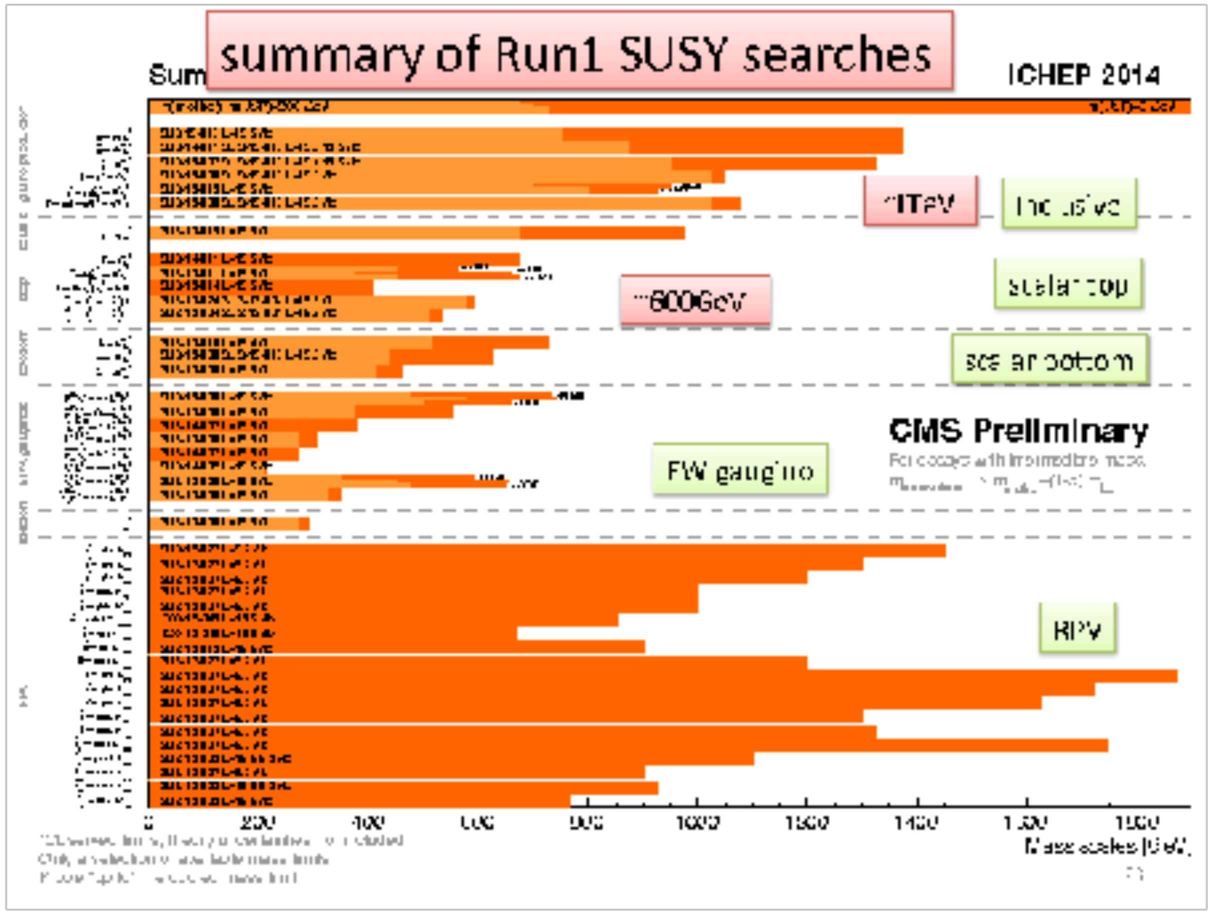

Energy Frontier @ LHC: Direct Searches

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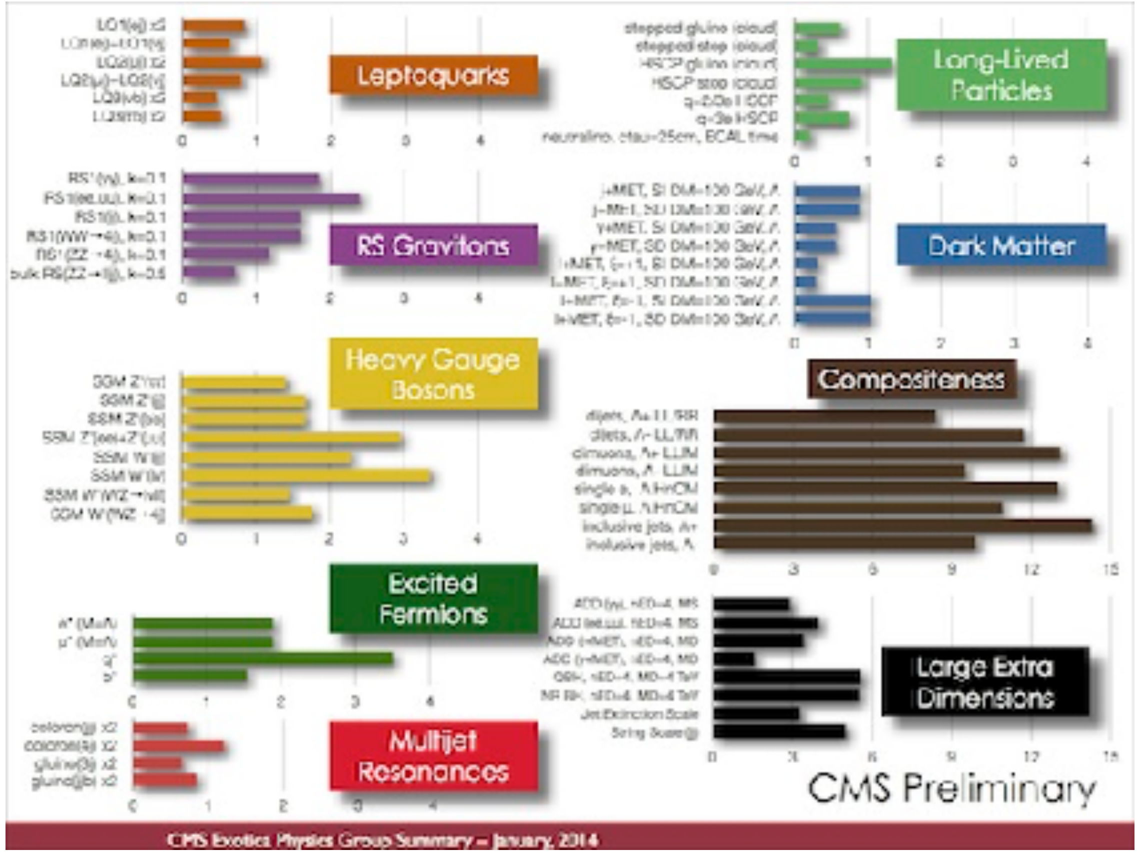

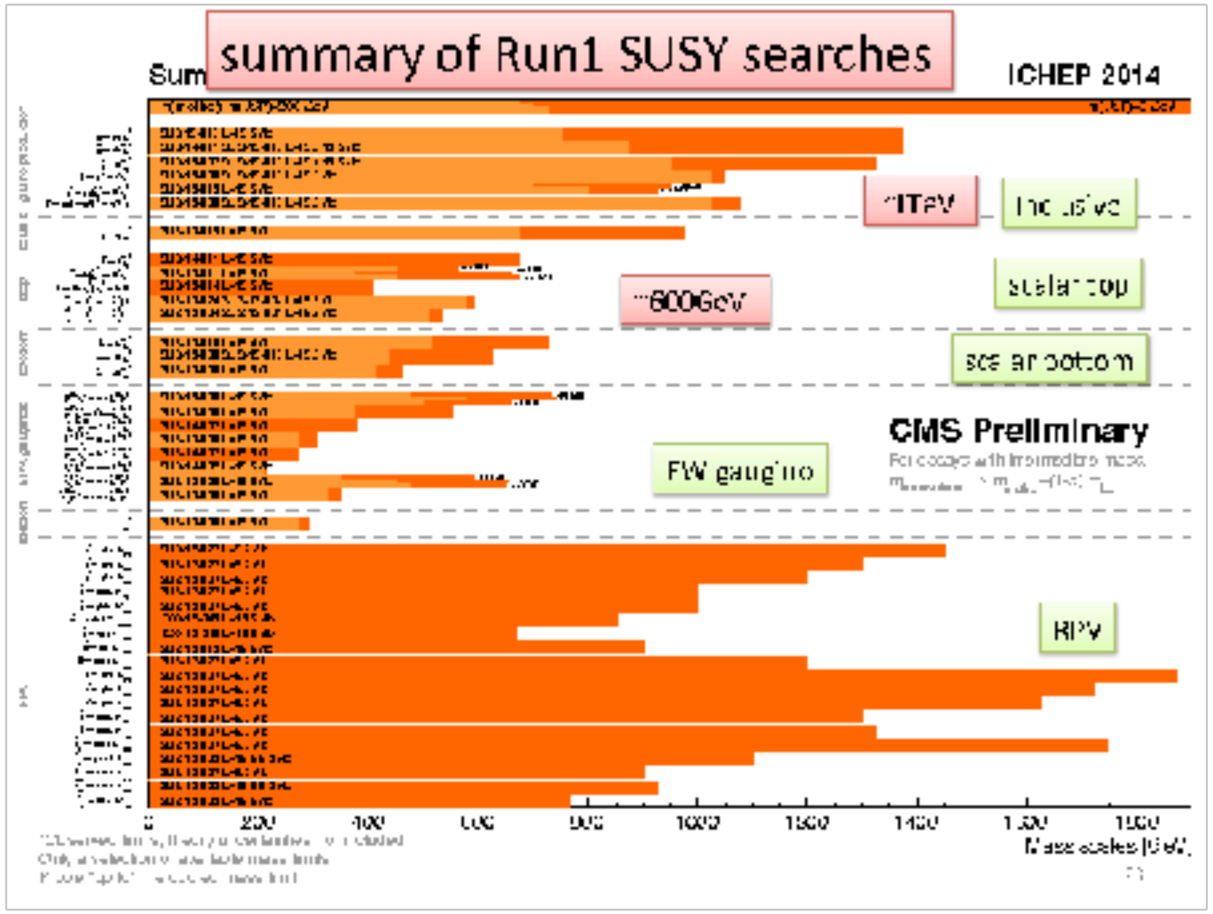

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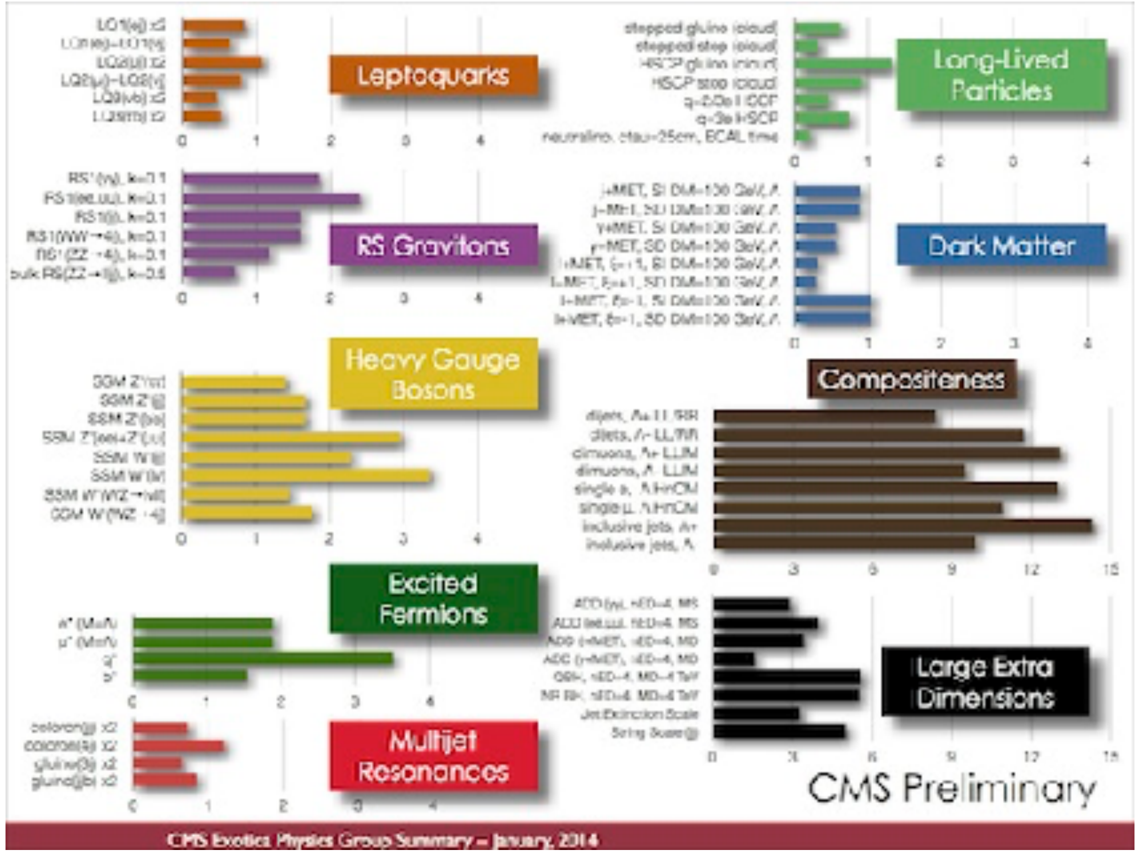

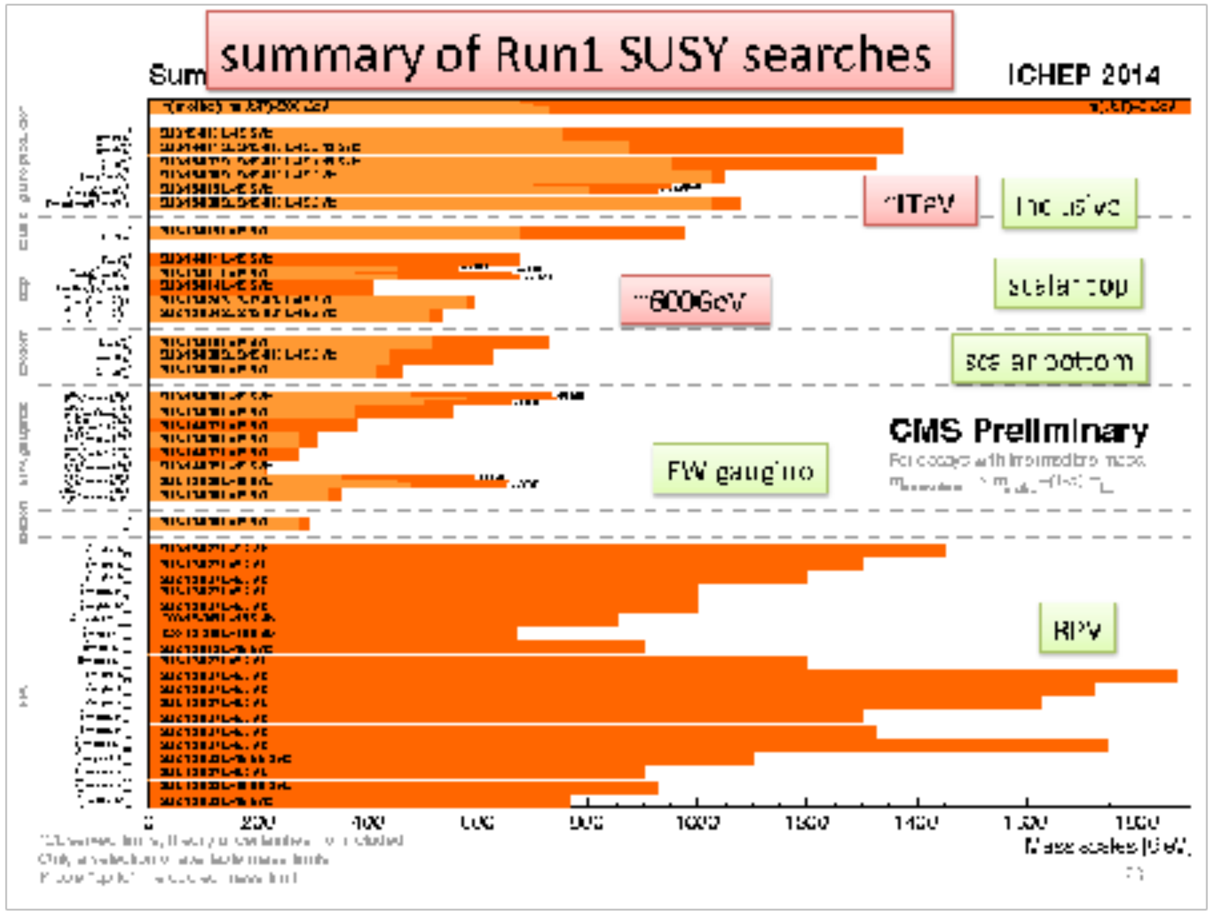

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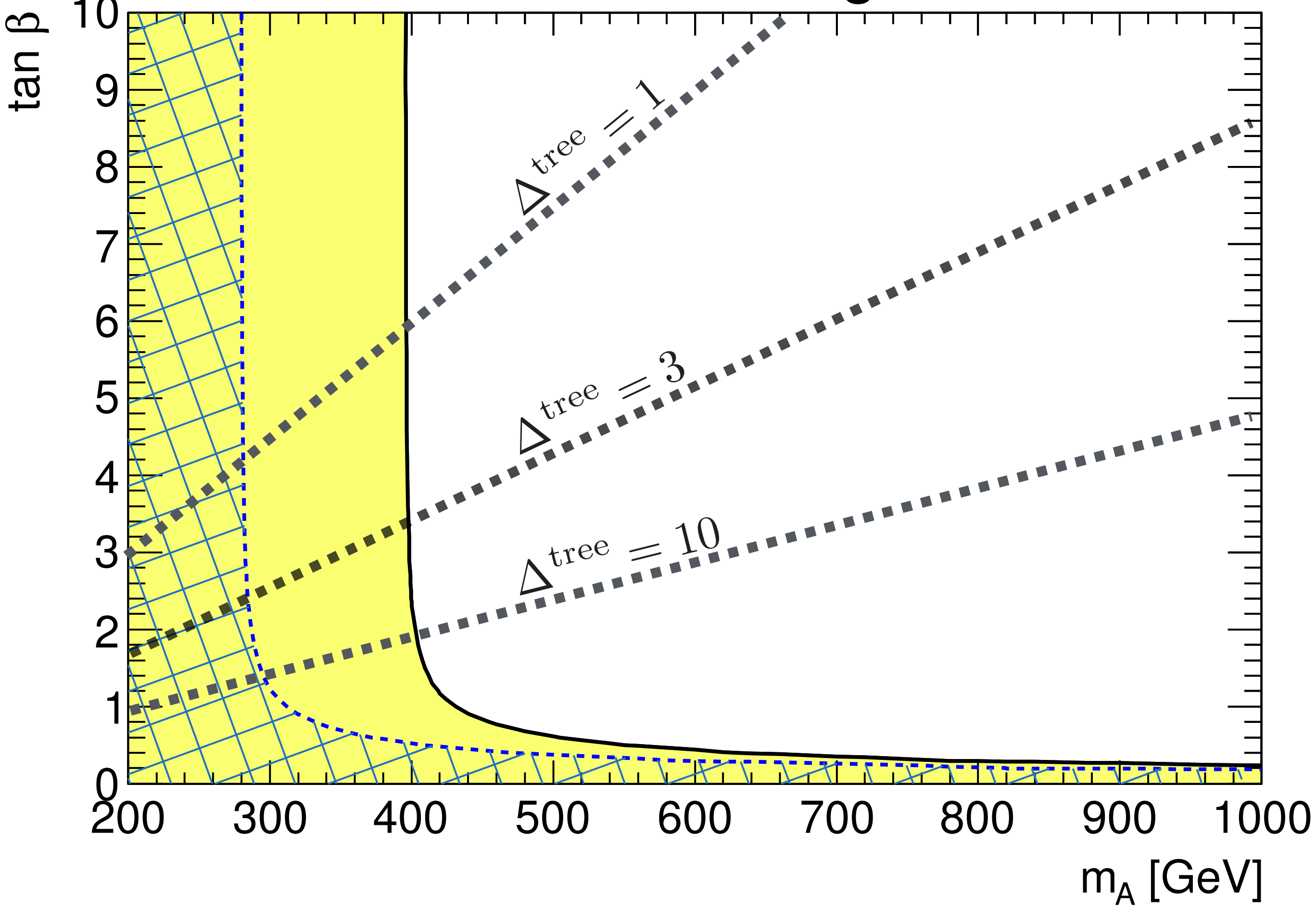
Not much improvement at run-3 and at HL-LHC

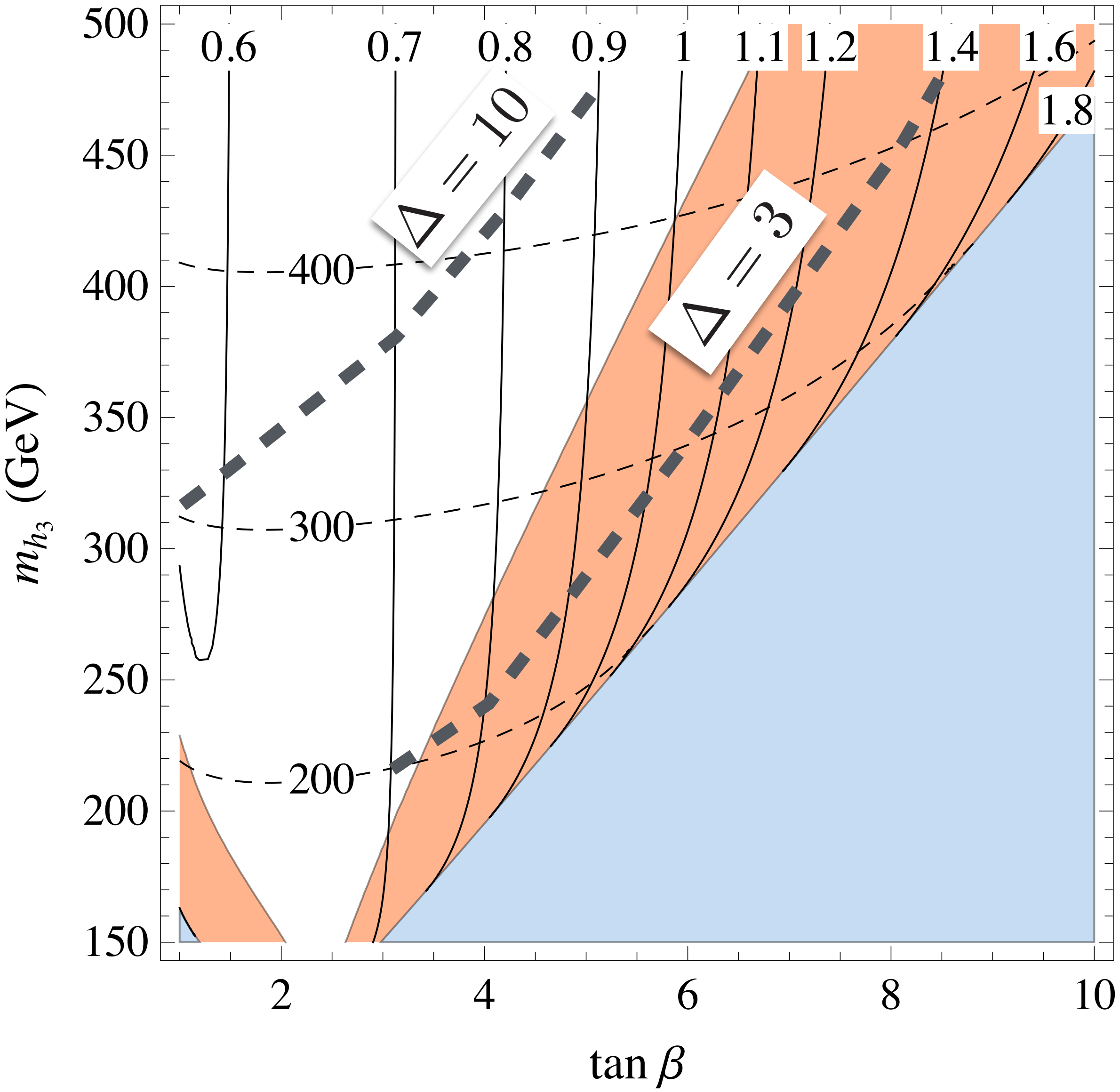
Accuracy Frontier @ LHC: Higgs

Higgs couplings probe many BSM scenarios, among which **SUSY** and **Composite Higgs**

MSSM: not that interesting



NMSSM: better



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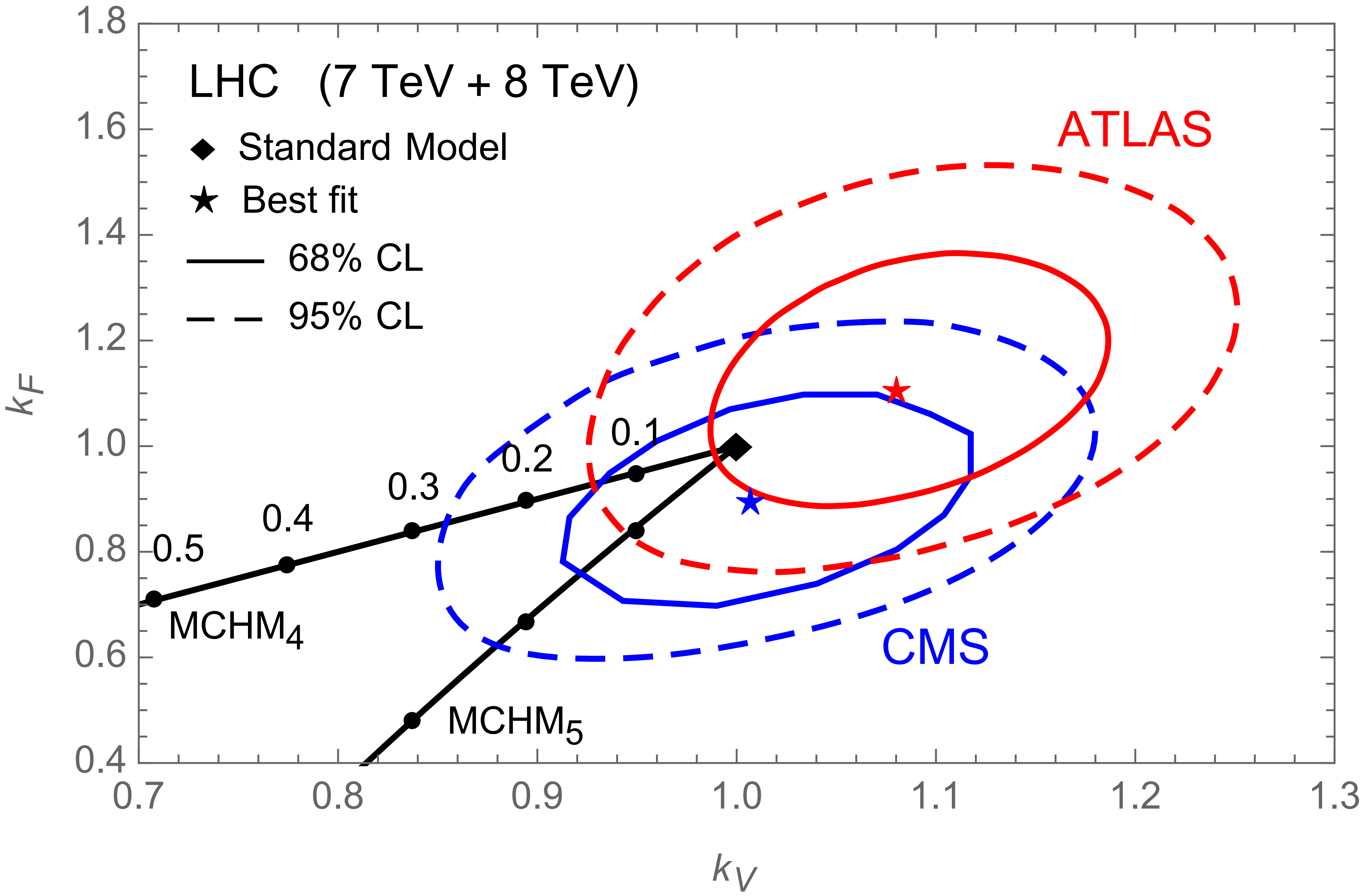

Accuracy Frontier @ LHC: Higgs

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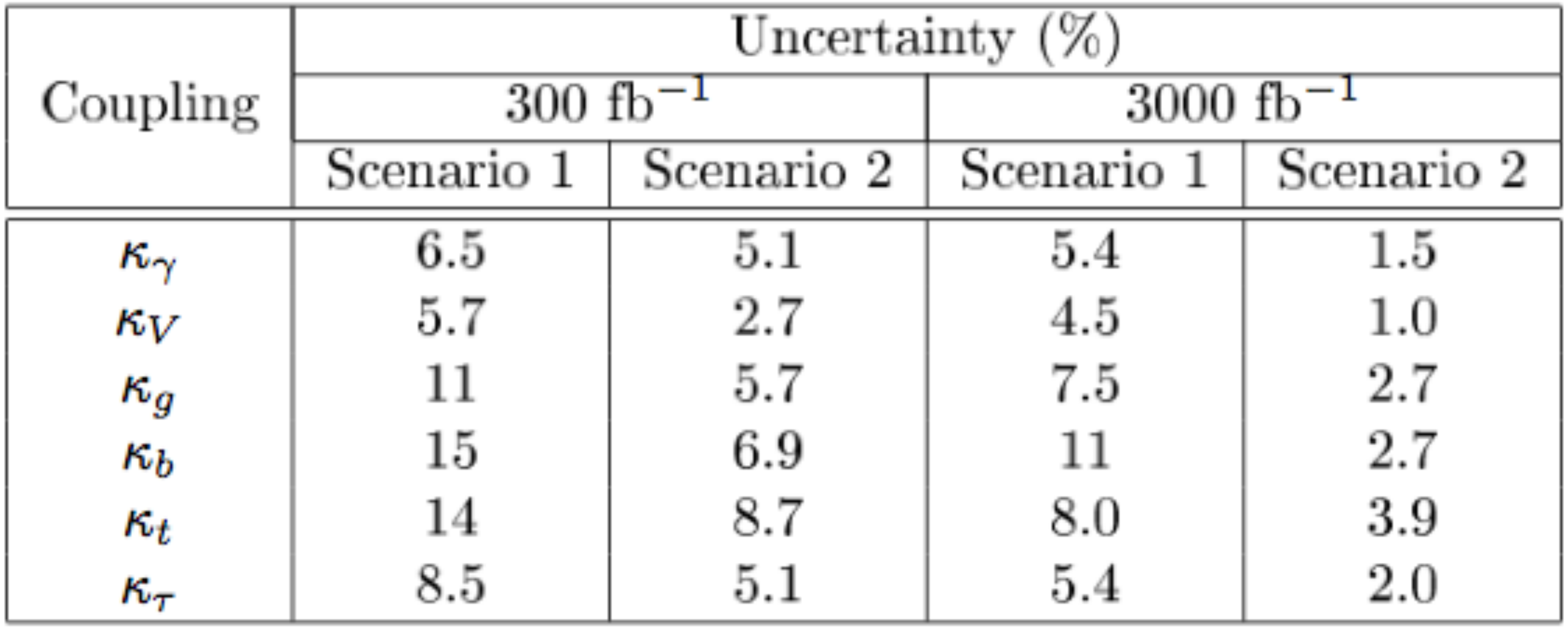
But run-2,3,HL-LC progresses will be **slow:**



Coupling	Uncertainty (%)			
	$300\ \mathrm{fb}^{-1}$		$3000\ \mathrm{fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

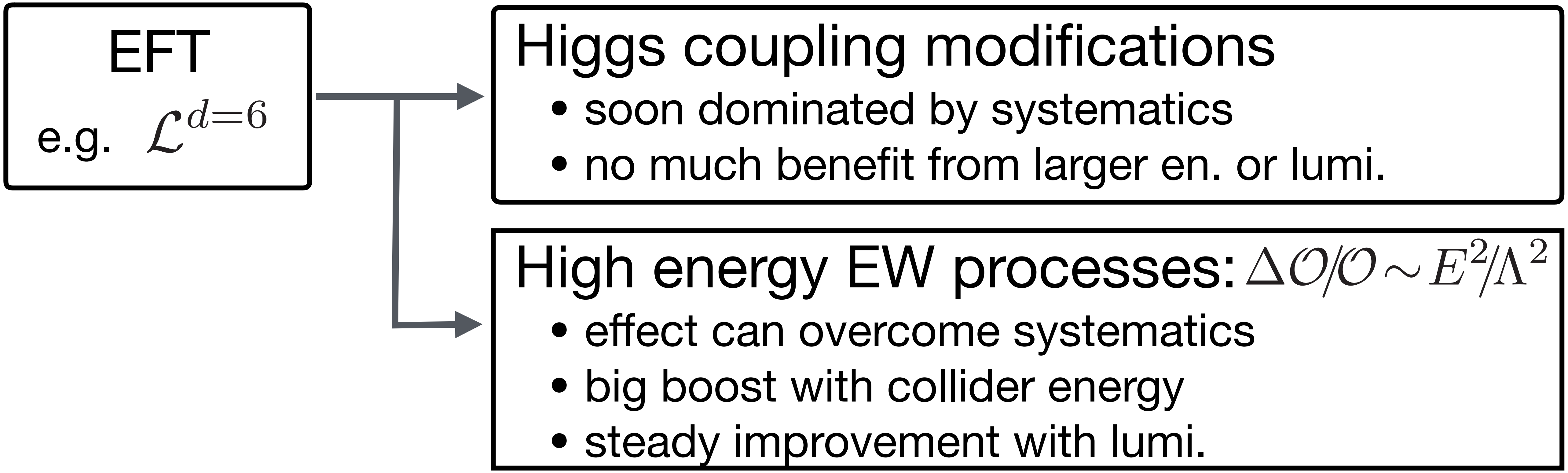
from CERN-CMS-NOTE-2012-006

Close to the threshold due to systematics

Beyond Higgs couplings

Physics modifying couplings also affects other EW obs.

In EFT description: (appropriate if BSM is heavy)



EFT

e.g. $\mathcal{L}^{d=6}$

Higgs coupling modifications

- soon dominated by systematics
- no much benefit from larger en. or lumi.

High energy EW processes: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- effect can overcome systematics
- big boost with collider energy
- steady improvement with lumi.

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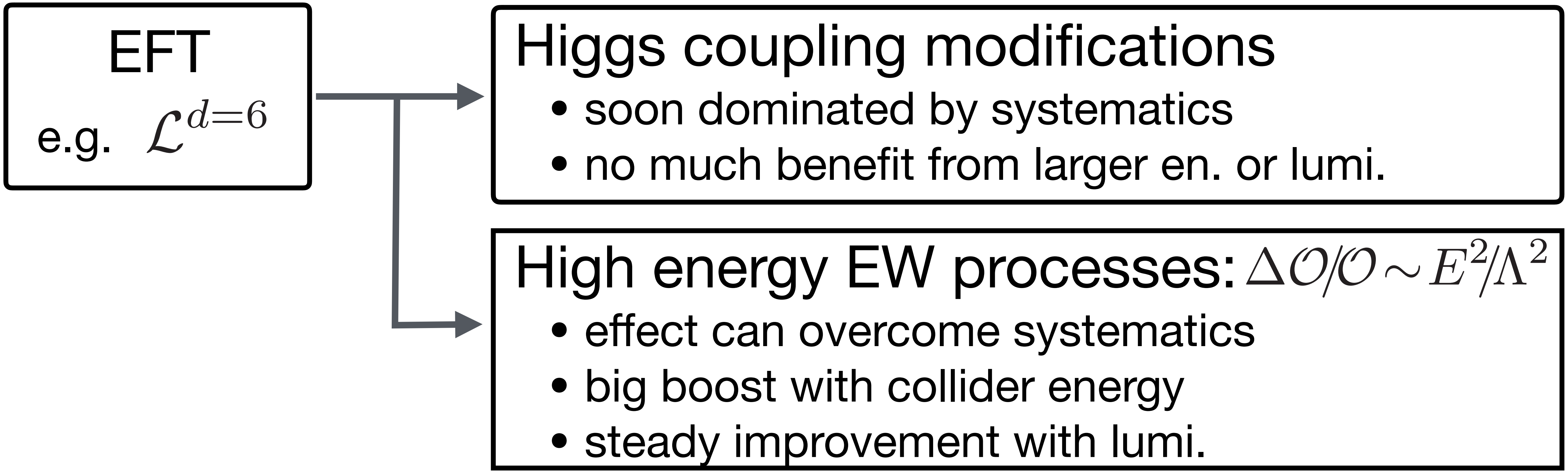

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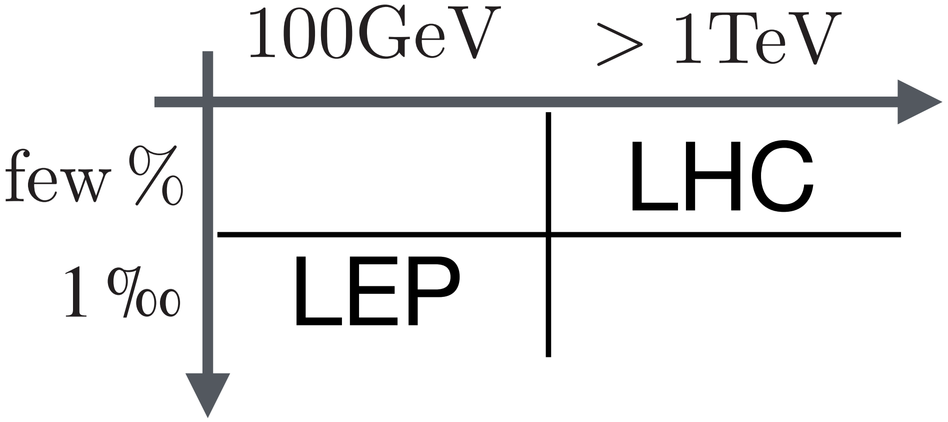
$$1‰ \ @ \ 100\,\mathrm{GeV} \ \sim \ 10\% \ @ \ 1\,\mathrm{TeV}$$

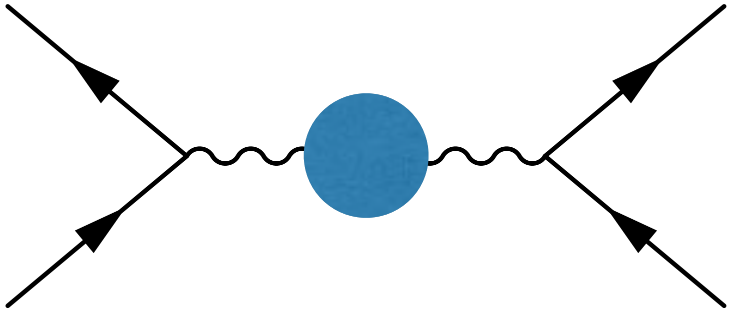


LHC better than LEP on some EWPT par.?

Plus of course measuring operators not constrained by LEP

Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]



Simplest EW process: Drell-Yan (l+l- or lnu)

Simplest BSM effects: Oblique corrections

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

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

4 par.s, with **‰ limit** from **very accurate, low energy** (LEP) measurements

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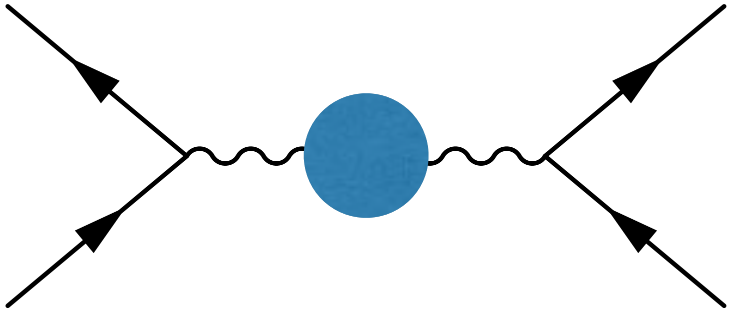

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$\hat{\mathrm{S}}$ and $\hat{\mathrm{T}}$: only affect pole residues, i.e., tot. X-sec.
LHC measurements (%, from syst.) **are not competitive**

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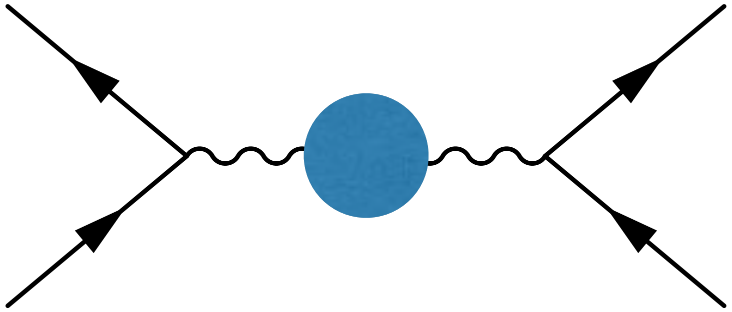

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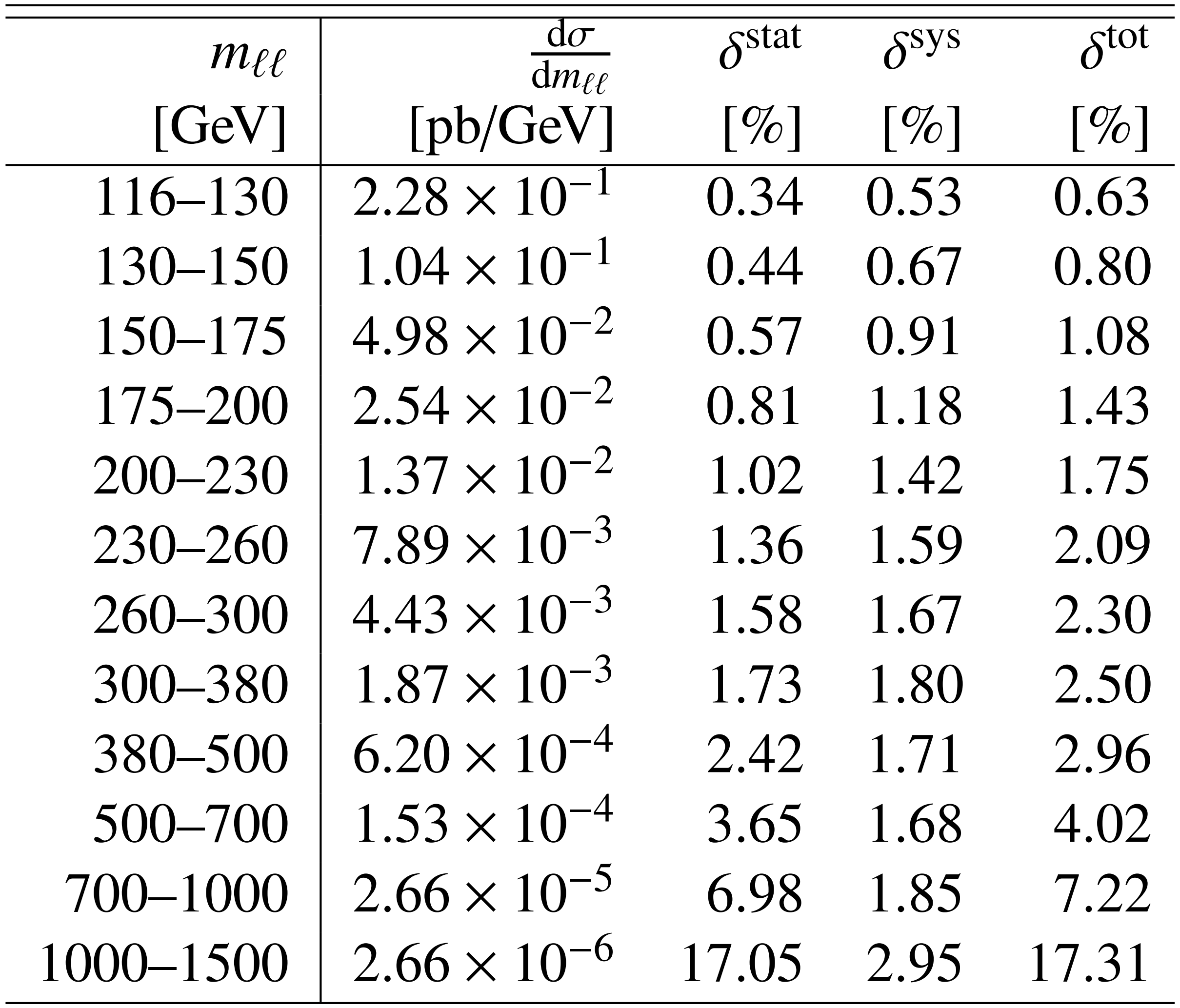
W and Y: produce constant terms.
quadratically enhanced at high mass. What can LHC do?

Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

Accurate experimental measurement:

Run-I (8 TeV) neutral DY (from ATLAS)



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116–130	2.28×10^{-1}	0.34	0.53	0.63
130–150	1.04×10^{-1}	0.44	0.67	0.80
150–175	4.98×10^{-2}	0.57	0.91	1.08
175–200	2.54×10^{-2}	0.81	1.18	1.43
200–230	1.37×10^{-2}	1.02	1.42	1.75
230–260	7.89×10^{-3}	1.36	1.59	2.09
260–300	4.43×10^{-3}	1.58	1.67	2.30
300–380	1.87×10^{-3}	1.73	1.80	2.50
380–500	6.20×10^{-4}	2.42	1.71	2.96
500–700	1.53×10^{-4}	3.65	1.68	4.02
700–1000	2.66×10^{-5}	6.98	1.85	7.22
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~ 1 TeV measured at **~ 10%**

Reach comparable with LEP ?

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Reach comparable with LEP ?

Statistically dominated error

>> X-sec (at high mass) @ run-2

Run-2 will surpass LEP ?

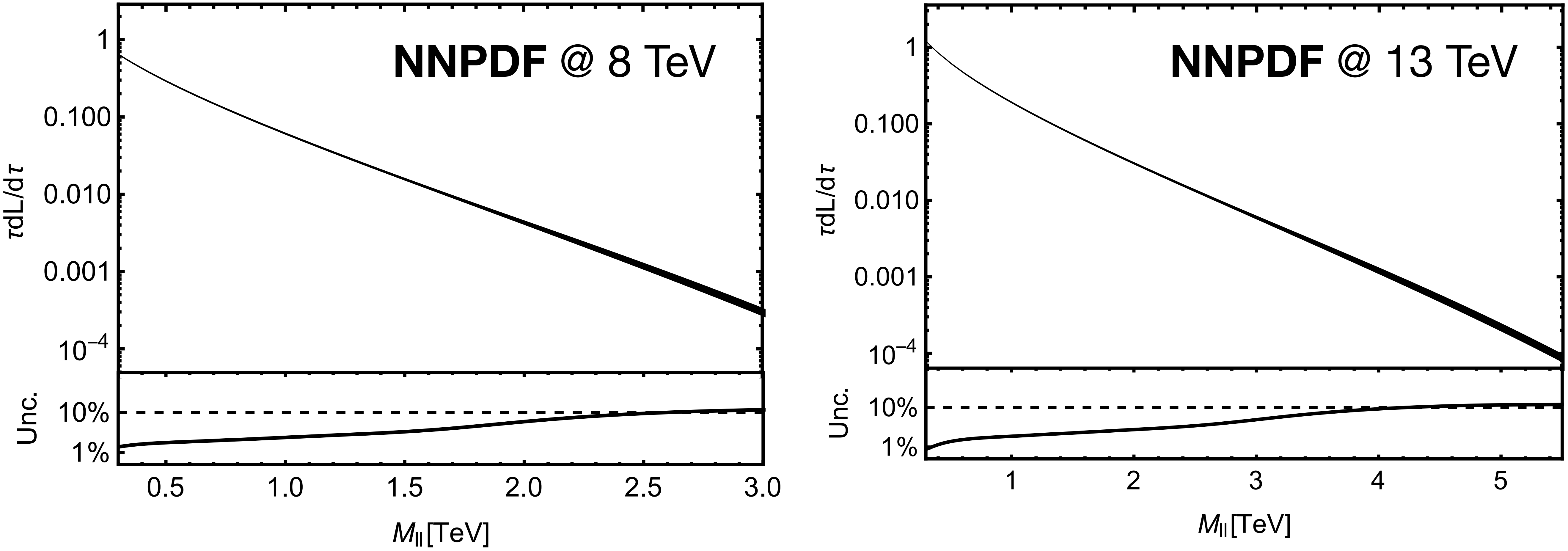
Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

Accurate experimental measurement: Syst. ~ 2%

Theory errors are well under control:

- q-qbar PDF error < 10% below 3 (4) TeV @ run-1 (run-2)



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- NLO EW known and under control
- photon PDF uncertainty safely small [Manohar,Nason,Salam,Zanderighi, 2016]

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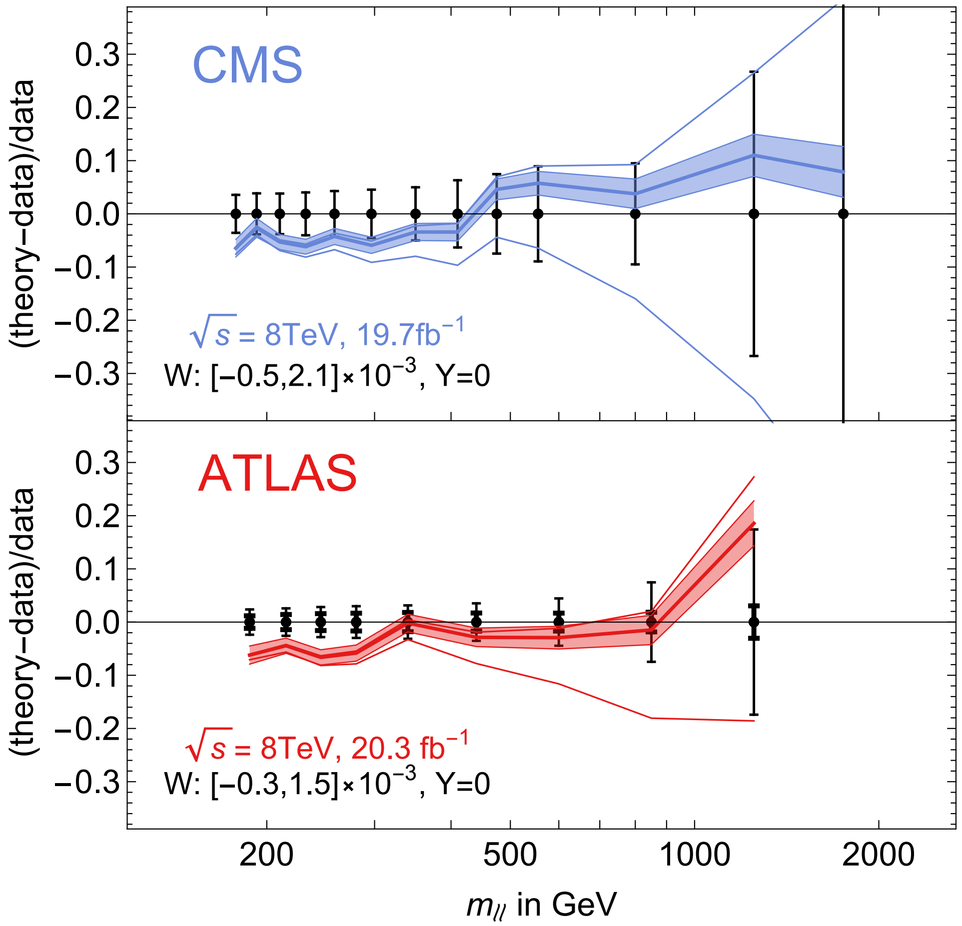
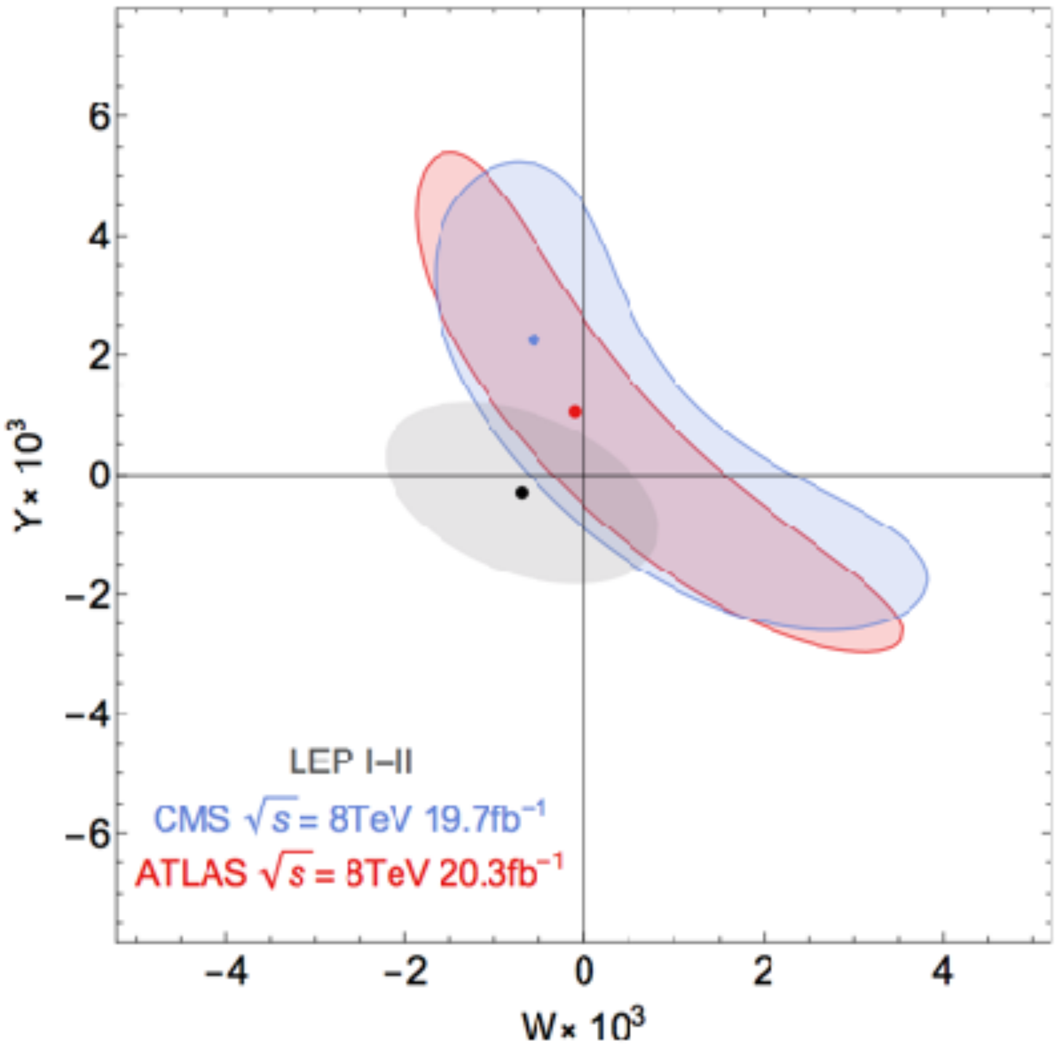


SM prediction reproduces data

Well-visible effect of ‰-sized W/Y in the high-mass region

Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]



Neutral DY @ **run-1** is **competitive with LEP**

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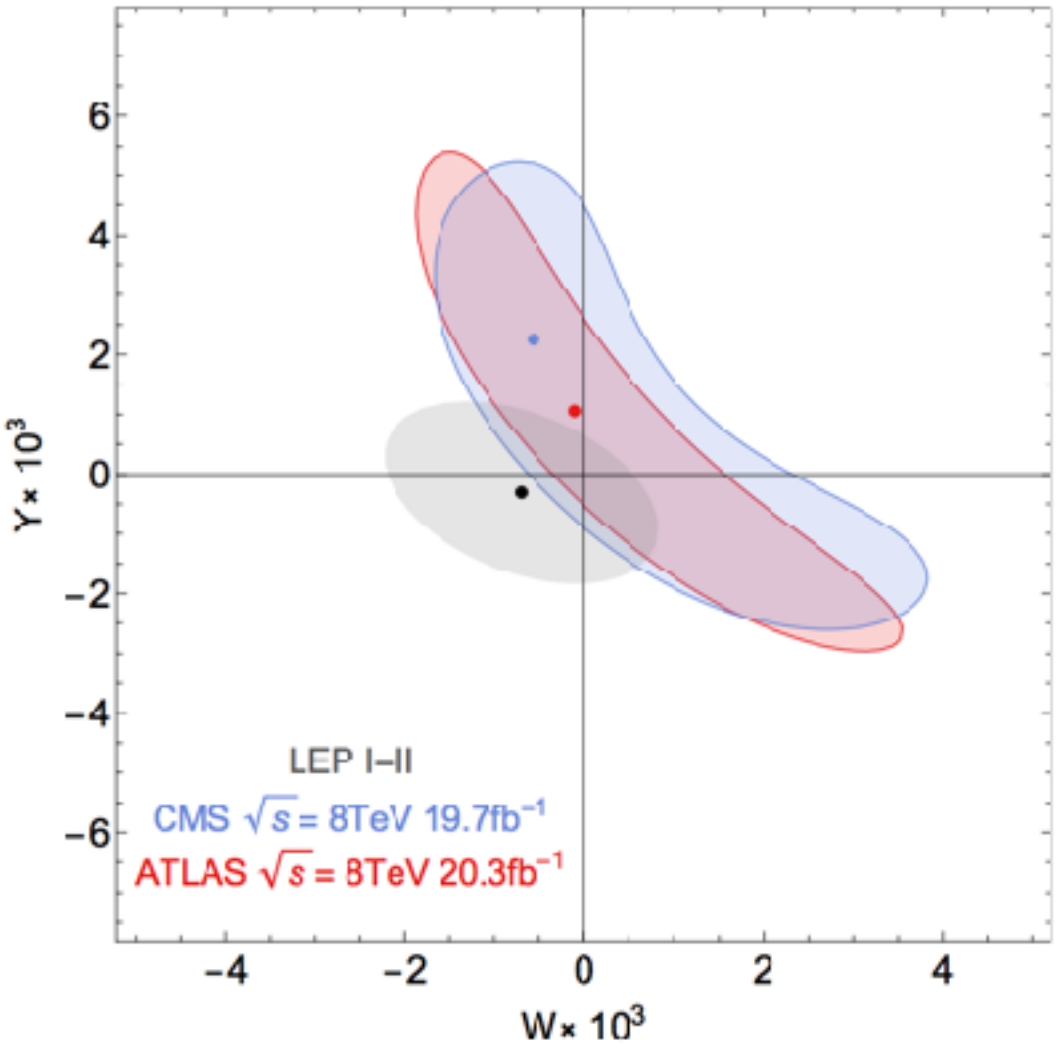

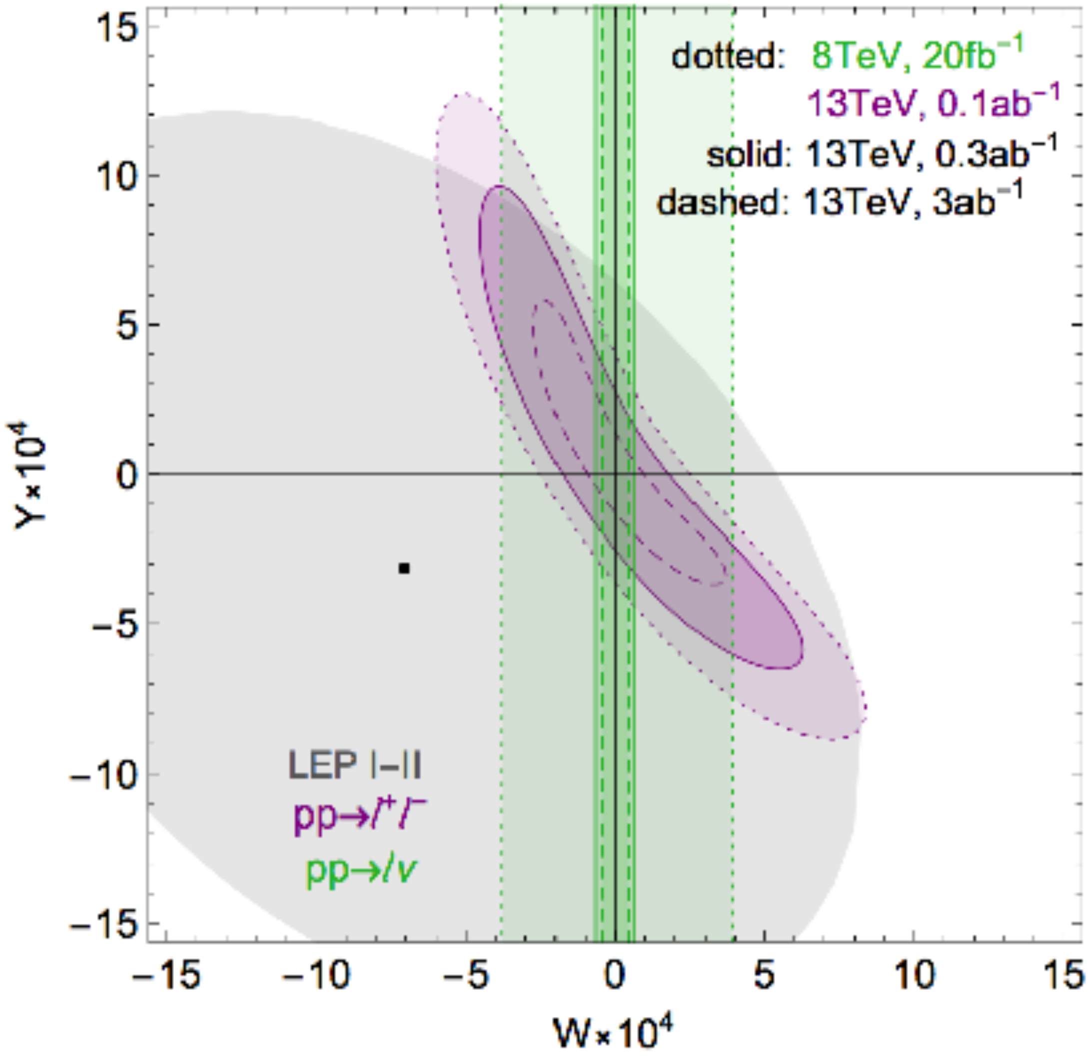

Neutral DY @ **run-1** is **competitive with LEP**

Charged DY @ **run-1 would surpass LEP**

No measurement available, extrapolation assumes (conservative) 5% systematic

Oblique Parameters at the LHC

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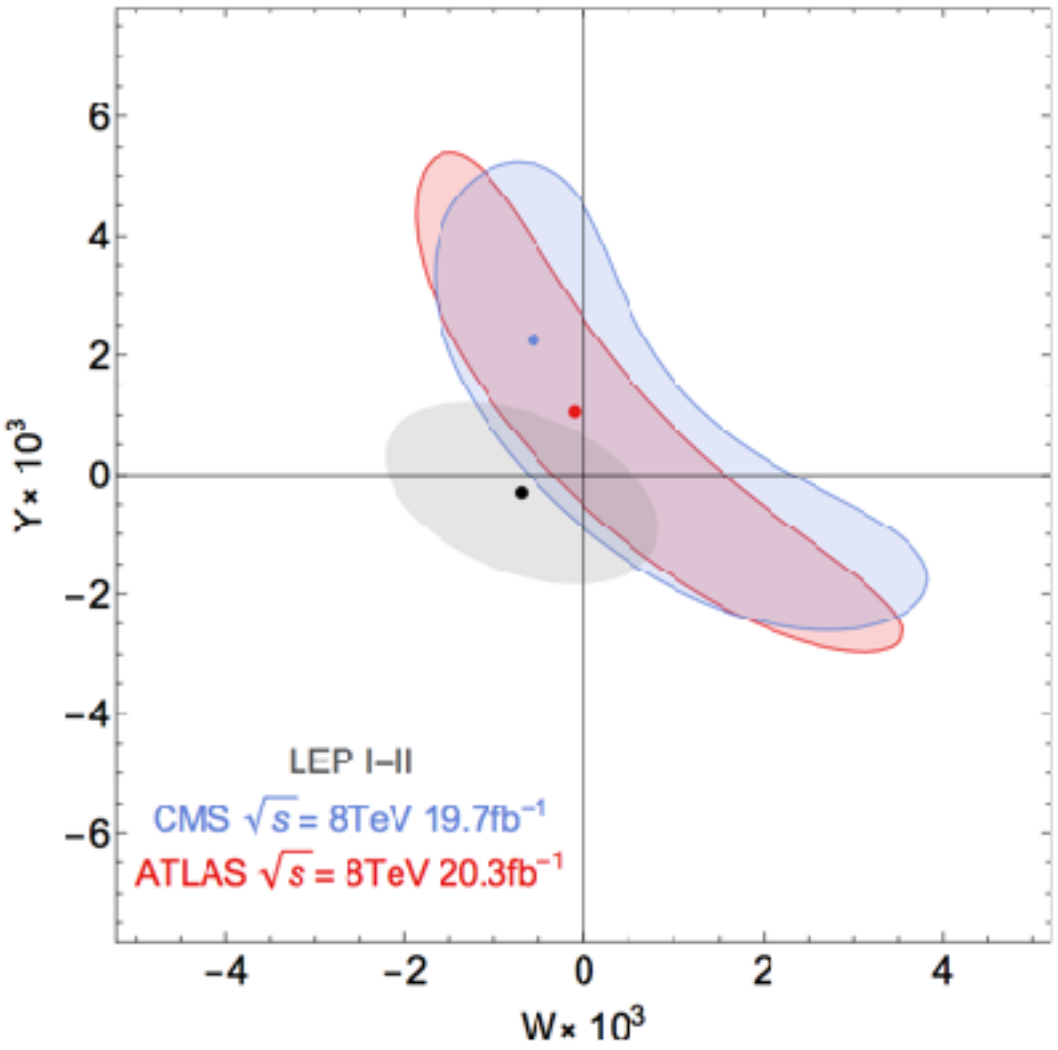

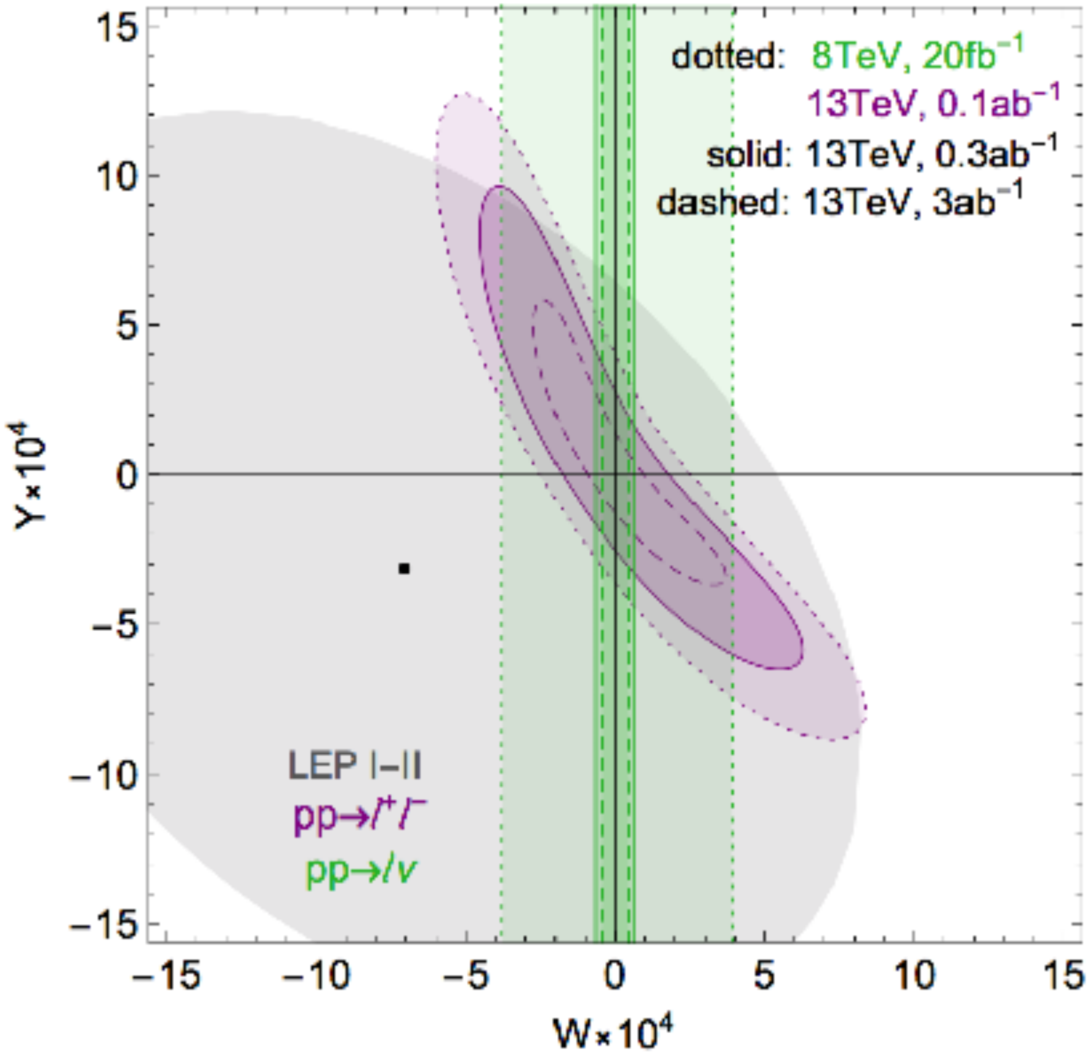

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Neut./Ch. DY @ **run-2/3 is much better than LEP**

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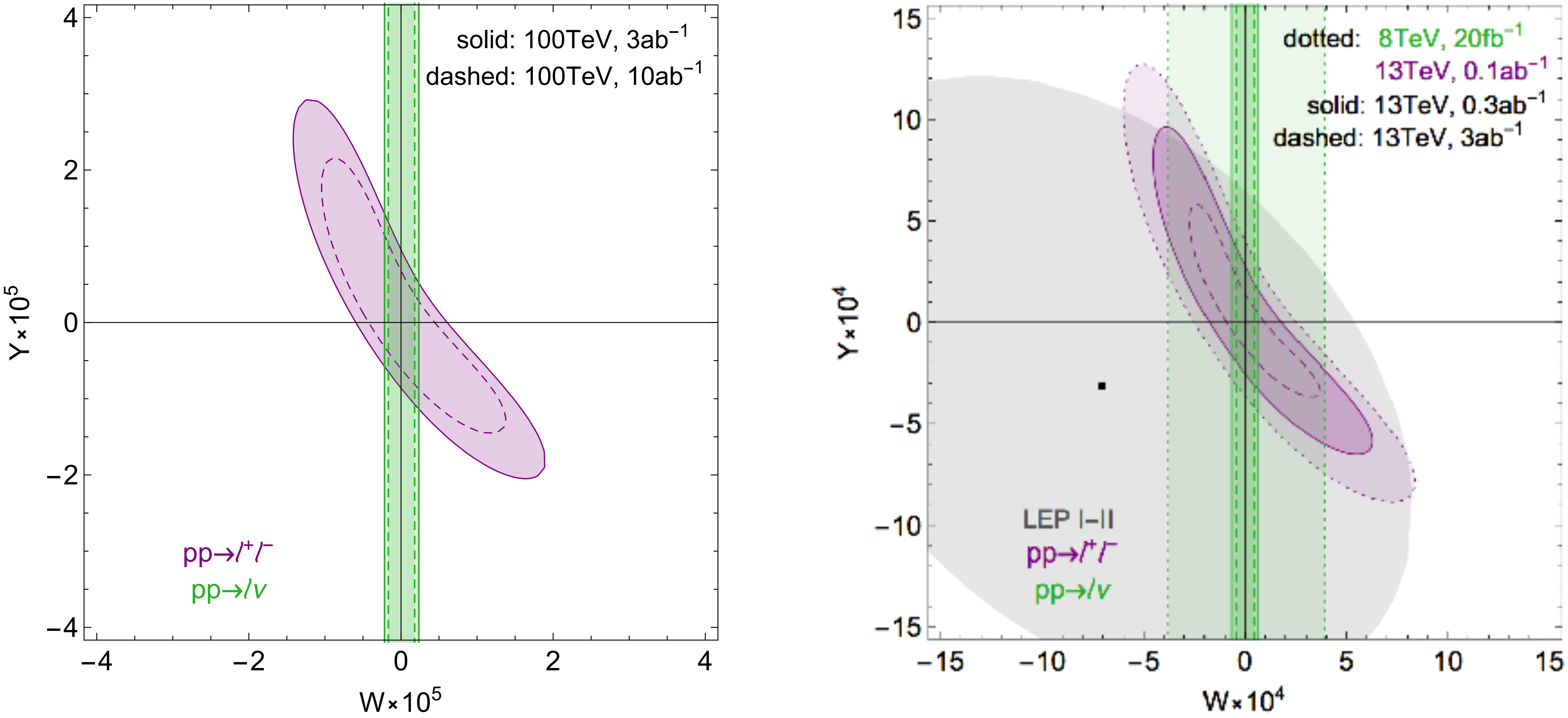

Neutral DY @ **run-1** is **competitive with LEP**

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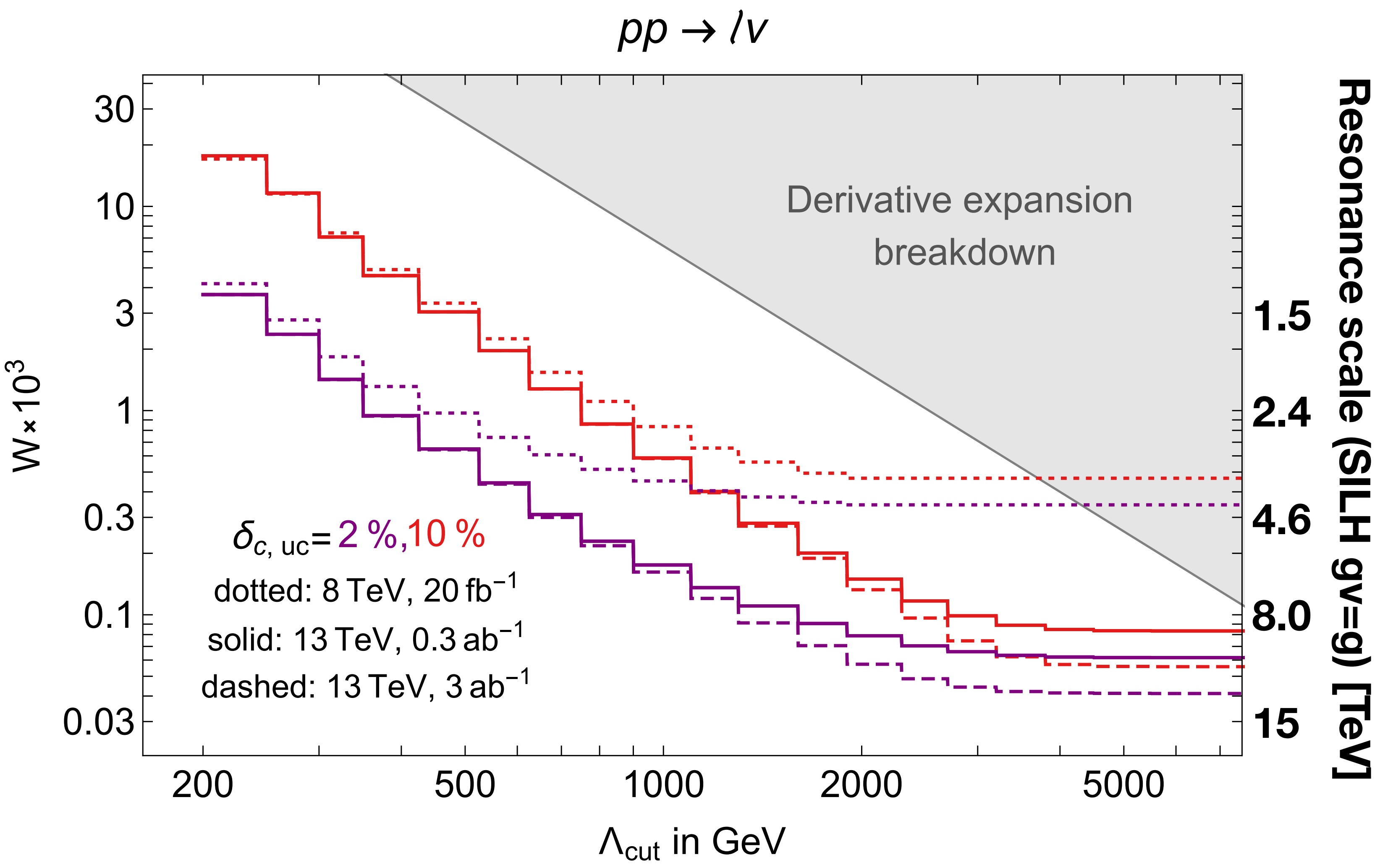
Raising **energy better** than raising **lumi** (part.lumi boost)

Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

Basic Sanity Check: Limit from scales (2-3 TeV) well below cutoff



Mass limit competitive or stronger than direct searches for small-coupling SILH realisation or for W-compositeness “remedios” power-counting

More model-independent limits, better from “exploration” view-point.

Di-Bosons

[Franceschini, Panico, Pomarol, Riva, AW, in progress]

W/Y limits easily evaded by strongly-coupled SILH:

$$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \qquad -\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \quad \sim \quad \frac{g_W^2}{g_*^2}\cdot\frac{1}{m_*^2}$$

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Some un-suppressed operators: $\sim 1\cdot\dfrac{1}{m_*^2}$

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

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

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W/Y limits easily evaded by strongly-coupled SILH:

$$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad -\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \quad \sim \quad \frac{g_W^2}{g_*^2}\cdot\frac{1}{m_*^2}$$

Some un-suppressed operators: $\sim 1\cdot\dfrac{1}{m_*^2}$

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

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

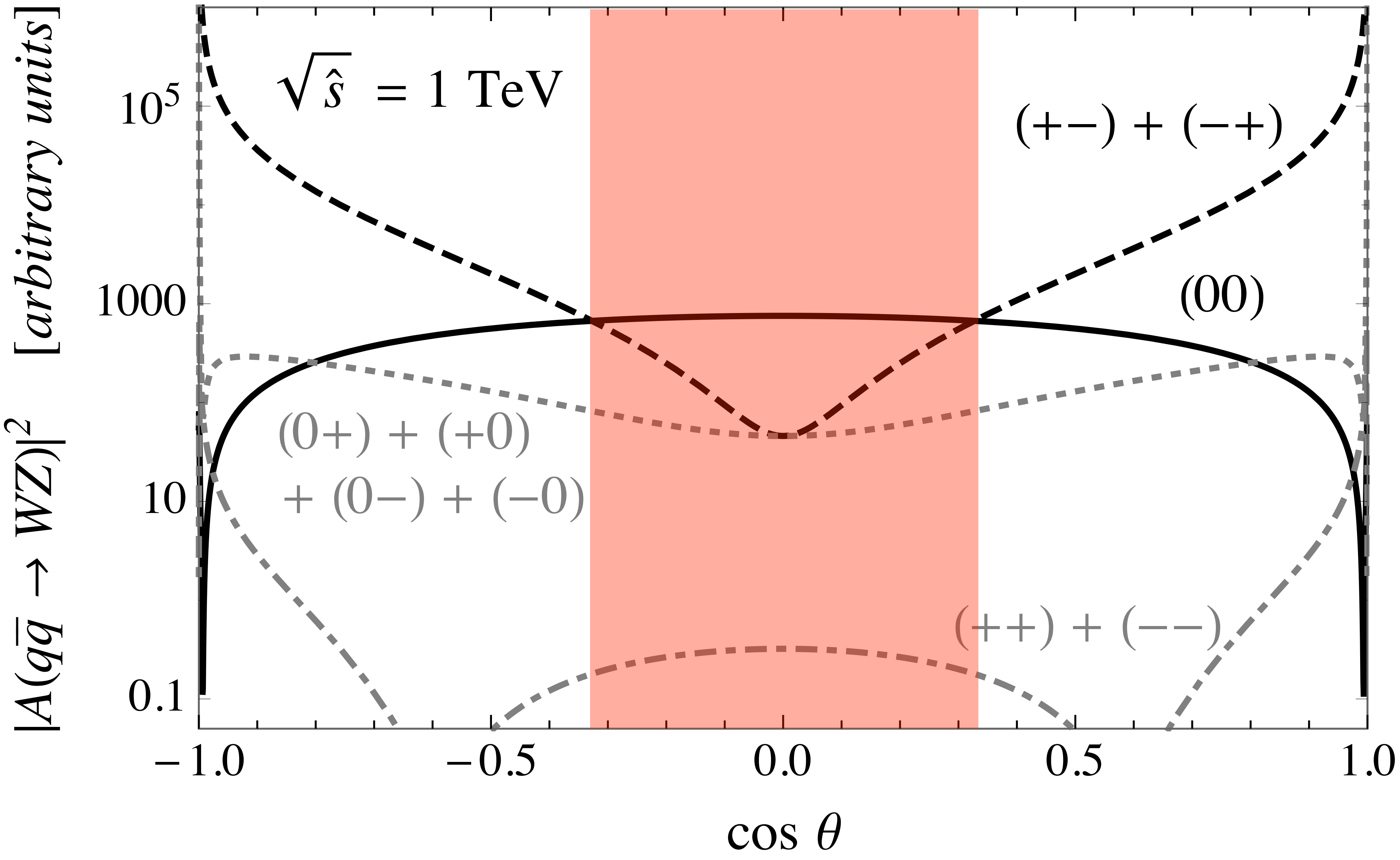
Channel	**Challenge**
$WW\ \ WZ$	Transverse background
$WH\ \ ZH$	Boosted Higgs

Di-Bosons

[Franceschini, Panico, Pomarol, Riva, AW, in progress]

Our attempt: fully leptonic WZ

Exploit (~accidental) ~vanishing transverse amplitude at $\theta = \pi/2$



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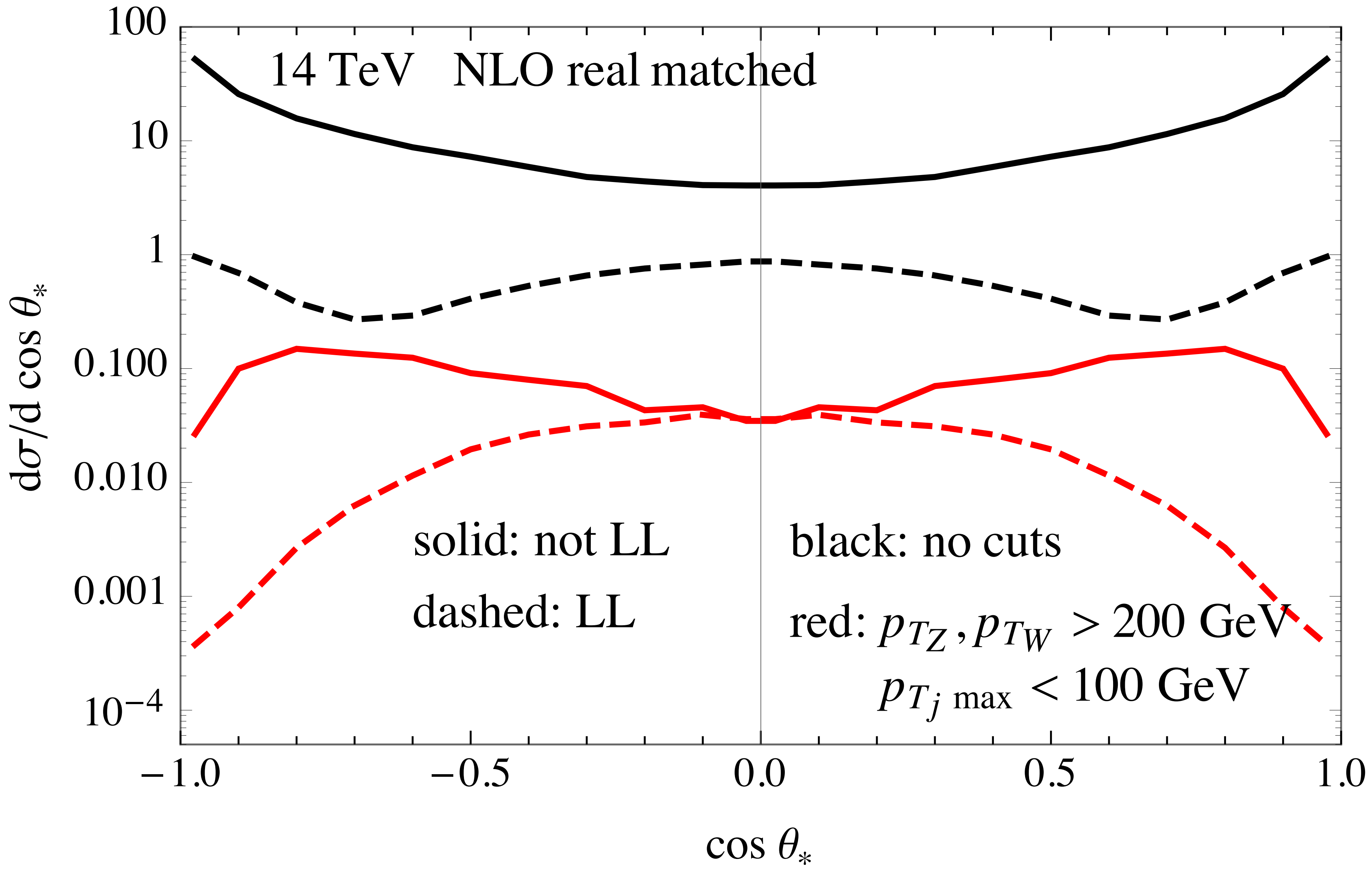

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HL-LHC reach (preliminary!):

$$\frac{c_W + c_{HW}}{m_*^2} \sim \left(\frac{1}{3\,\mathrm{TeV}}\right)^2$$

Comparable with LEP S-par., but on different operator combination

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Further improvements (?)

- Vector boson polar decay angles to tell L from T
- **Interference resurrection** from azimuthal angles

Conclusions

- EWPT’s are possible at the LHC

  Exploiting **energetic and accurate** measurements

- LHC will be better than LEP in W and Y determination

  Most sensitive probes of W-compositeness “remedios” scenario, and of Heavy (composite) spin-1 resonances at low coupling

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- Direct (same observable) future colliders comparison:

		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	—	—	—

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- Can we do more than W and Y?

  Diboson channels under **preliminary** investigation.
  Cooperation with **exp./QCD** communities will be **essential** to get the best out of this program