Electroweak precision tests at hadron colliders

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based on Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16,
GP, Riva, Wulzer '17
Franceschini, GP, Pomarol, Riva, Wulzer '17

Hadron colliders vs Lepton colliders

Hadron and lepton colliders are **antithetical** machines

hadron colliders

high energy reach

limited accuracy
(large systematics $\gtrsim$ few %)

exploration
of new energy ranges
↓
direct searches

lepton colliders

limited energy reach

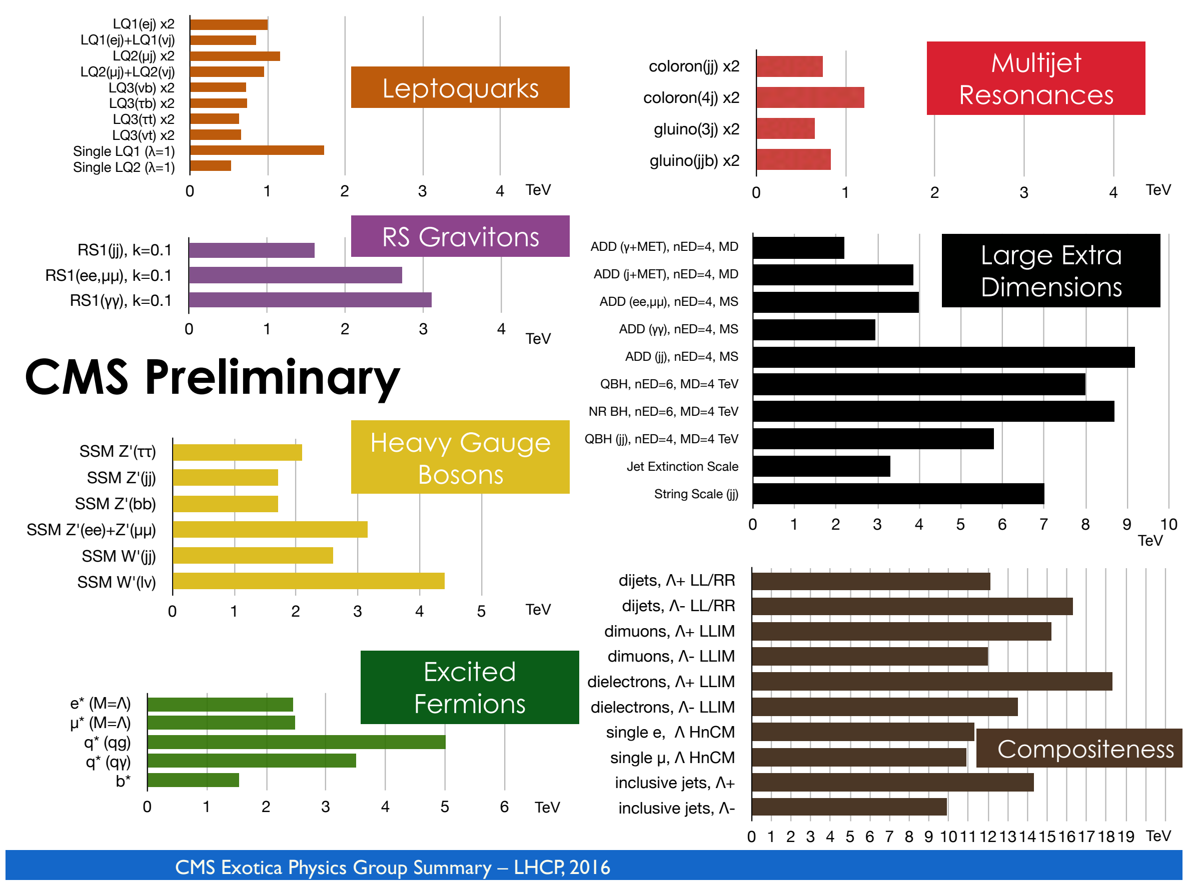
high accuracy
(small systematics < %)

precision measurements
↓
indirect searches

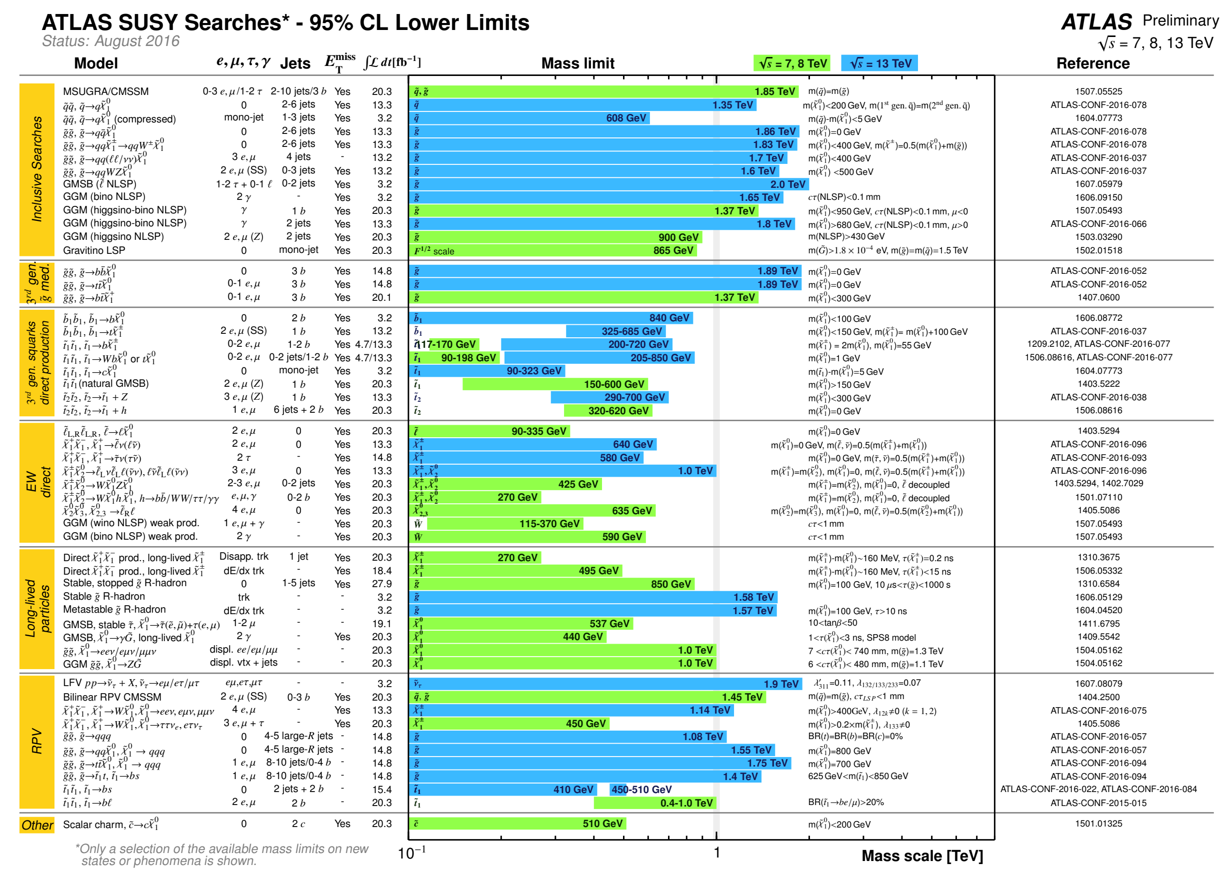
Energy frontier at LHC: direct searches

Simplest way to use LHC data

CMS Exotica summary



ATLAS SUSY summary



- ✦ quick progress at run 2
- ✦ slower improvement with high luminosity

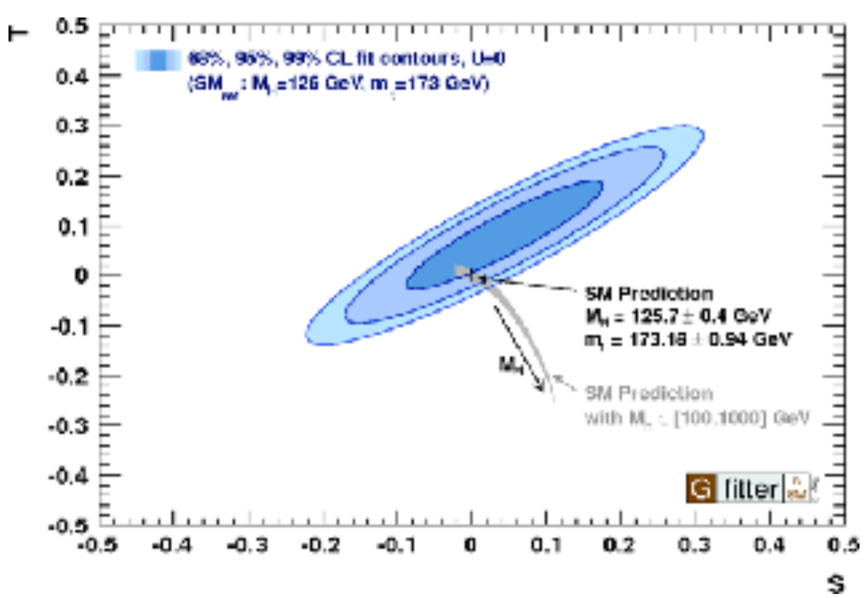
The LEP legacy

But indirect searches can also play an important role

Example: **oblique parameters** used to constrain **vector resonances**

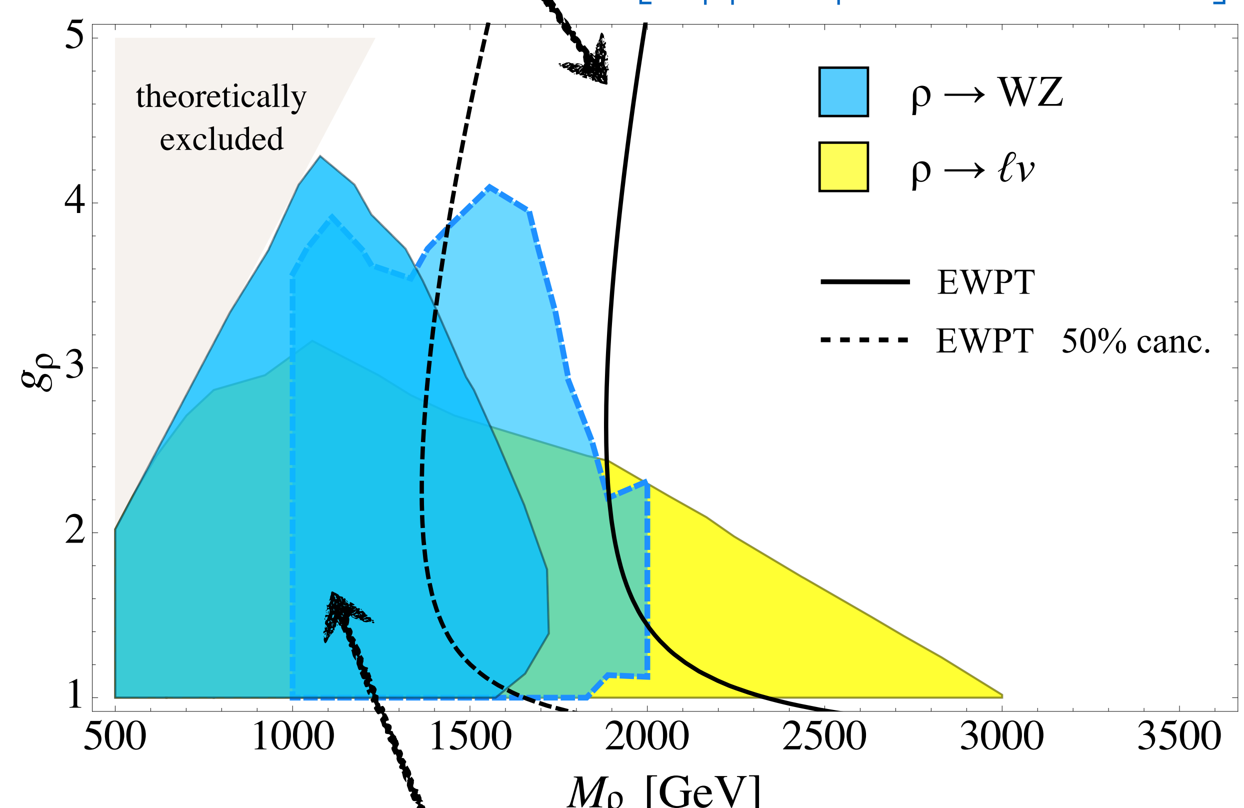
- ✦ bounds from LEP still competitive with 8 TeV LHC!

oblique parameters



bounds from S parameter

[Pappadopulo, Thamm et al.]



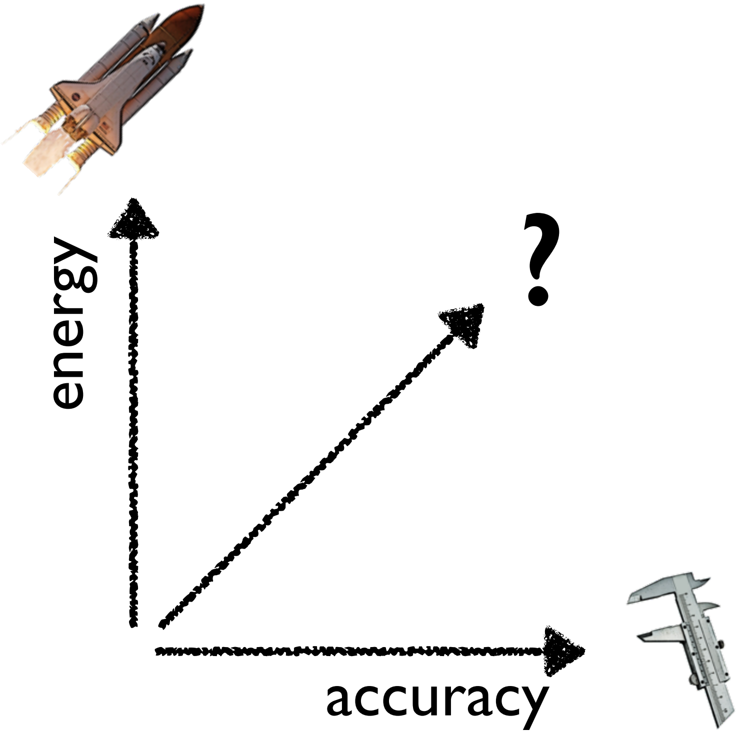
8 TeV LHC direct exclusions

Accuracy frontier at LHC

Can we perform "**precision measurements**" at the **LHC**?

<u>Obvious answer:</u>

yes, for previously "**untested**" observables



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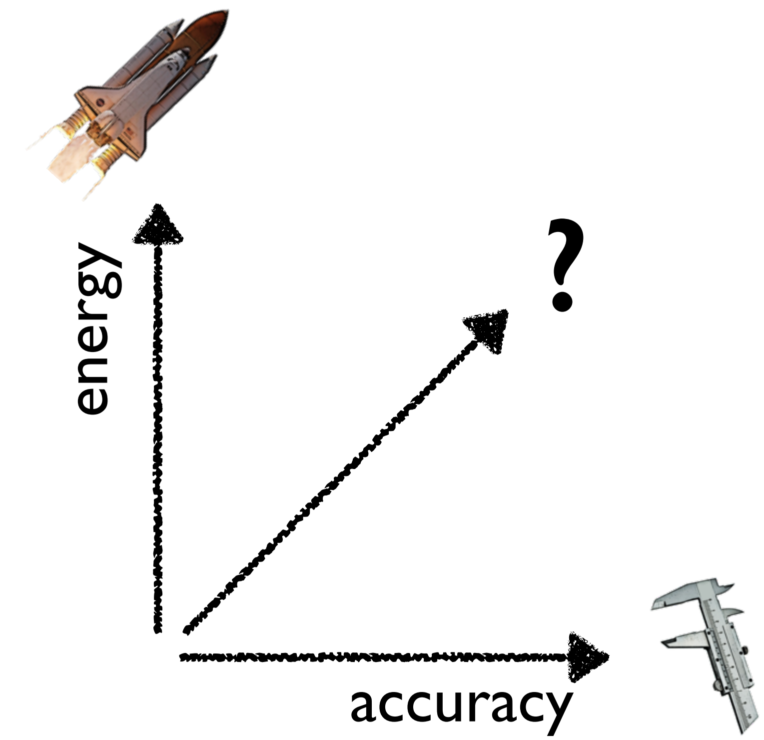
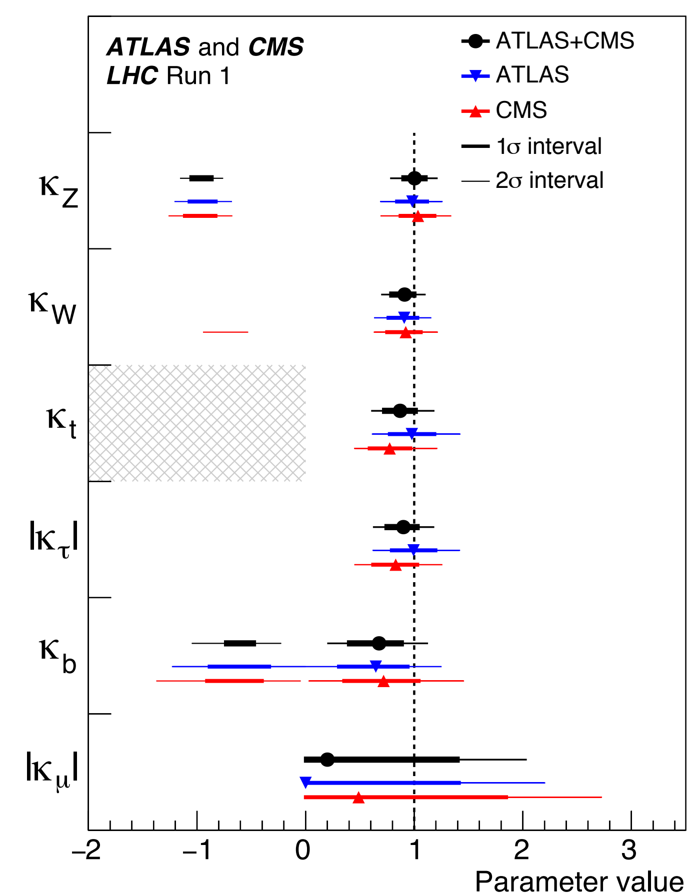


Obvious answer:

yes, for previously "**untested**" **observables**

Example: precision measurements of the **Higgs couplings**

- deviations expected in several BSM scenarios (eg. SUSY and composite Higgs)
- useful to derive constraints



Accuracy at LHC: the Higgs

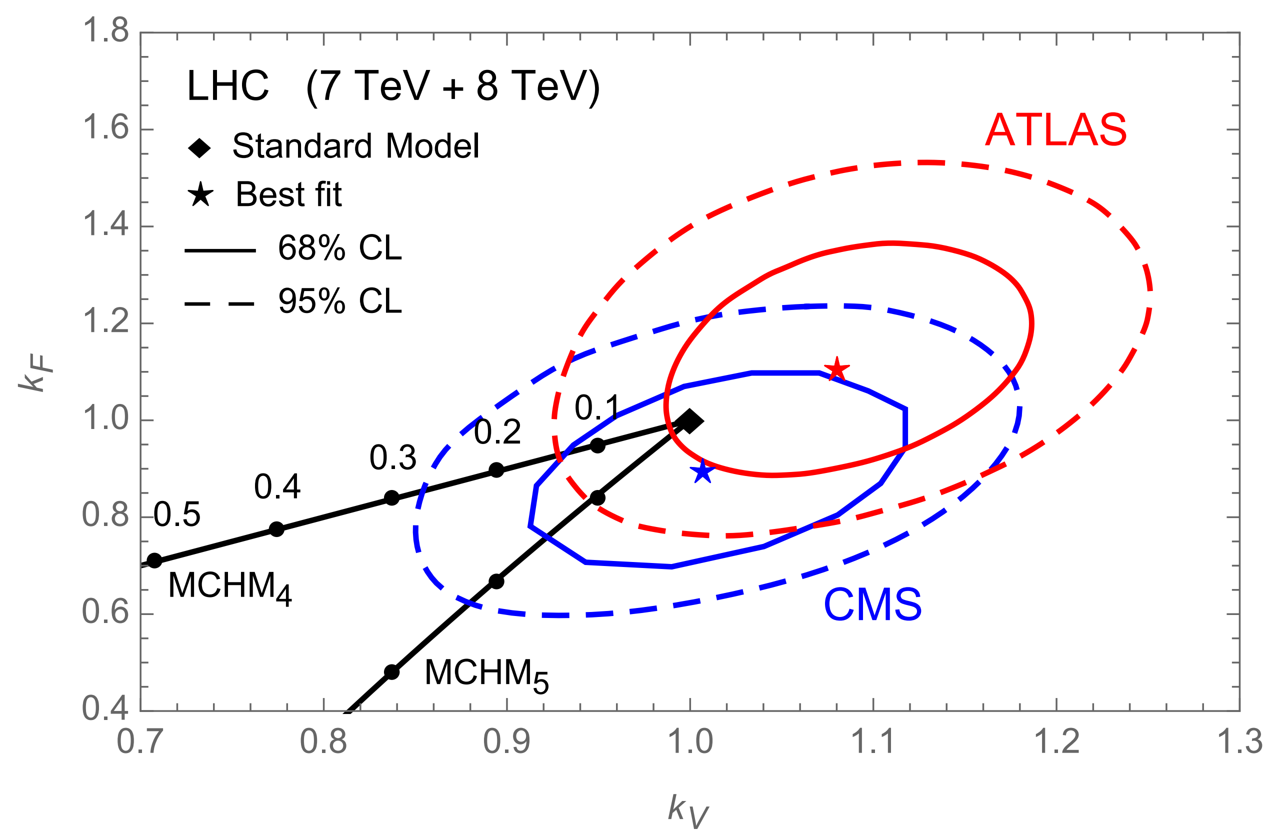
Composite Higgs couplings:

- ✦ model-independent predictions (based on symmetries)

Higgs-vectors $k_V = \sqrt{1-\xi}$ **Higgs-fermions** $\begin{cases} \text{MCHM}_{5,14} & k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}} \\ \text{MCHM}_{4,10} & k_F = \sqrt{1-\xi} \end{cases}$

- ✦ direct connection with tuning $\qquad \xi = \dfrac{v^2}{f^2} \qquad \Delta \gtrsim \dfrac{1}{\xi}$
  (f Goldstone Higgs decay constant)

- current bounds $\quad \xi \gtrsim 0.1$
- not much improvement expected with next runs
  (if central value goes to SM)



Accuracy at LHC: the Higgs

Slow progress on Higgs couplings in future runs

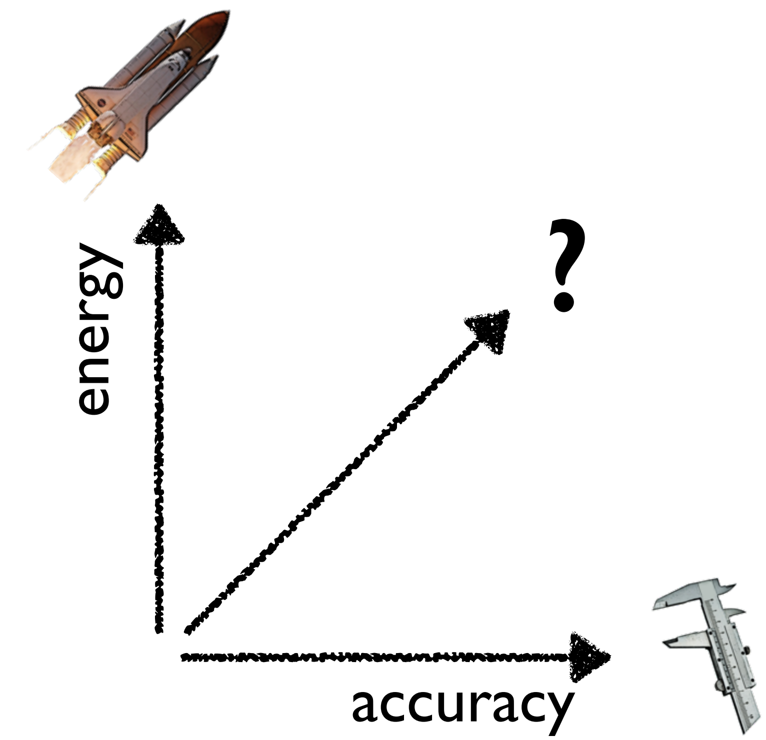
Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

[CERN-CMS-NOTE-2012-006]

Close to threshold due to systematics

Energy and accuracy: EW precision

Are there other precision observables we can access at the LHC?



Can we take advantage of high energy to improve **EW precision measurements**?

Energy and accuracy: EW precision

If new physics is heavy, low-energy effects are well described by the **EFT language**:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

leading corrections from dimension-6 operators $\mathcal{O}_i^{(6)}$

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leading corrections from dimension-6 operators $\mathcal{O}_i^{(6)}$

- deviations from SM typically **grow with energy**

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

- LHC could match LEP sensitivity by going at **high energy**

$$0.1\ \% \quad \text{at} \quad 100\ \text{GeV} \longrightarrow 10\ \% \quad \text{at} \quad 1\ \text{TeV}$$

EFT validity

Corrections can not be arbitrarily large

$$\frac{\mathcal{A}_{\mathrm{SM+BSM}}}{\mathcal{A}_{\mathrm{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

Restrictions:

- necessary condition: $E \lesssim \Lambda \;\Rightarrow\; (E^2/\Lambda^2) \lesssim 1$
- in many cases: $\# < 1$

$$\left.\begin{array}{l} E \lesssim \Lambda \;\Rightarrow\; (E^2/\Lambda^2) \lesssim 1 \\ \# < 1 \end{array}\right\} \longrightarrow \frac{\delta\mathcal{A}}{\mathcal{A}_{\mathrm{SM}}} \lesssim 1$$

✦ leading effects are linear in BSM (from interference with SM)

✦ a meaningful bound can be obtained only if the precision is better than the SM

⟶ **clean channels** with low syst. and stat. errors

✦ pay attention to the **cut-off!** (restrict analysis to valid region)

Examples of analyses

A proof of principle: oblique parameters at the LHC

- ✦ Di-lepton Drell-Yan production

Going beyond: more challenging channels

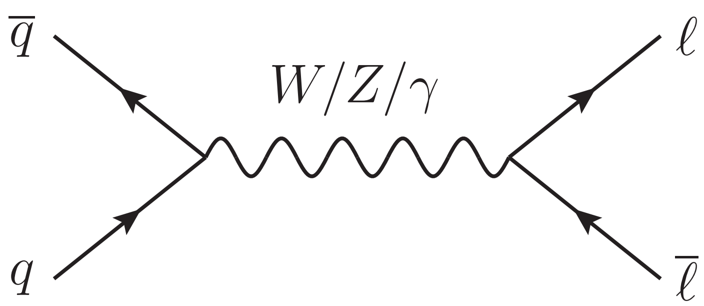
- ✦ Di-boson production (WZ and $W\gamma$)

A proof of principle: oblique parameters

Di-lepton DY production

Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16

Oblique parameters at LHC



Drell-Yan production ($\ell^+\ell^-$or $\ell\nu$)

- Large cross section and interference at leading order with SM

→ ideal process to test new physics

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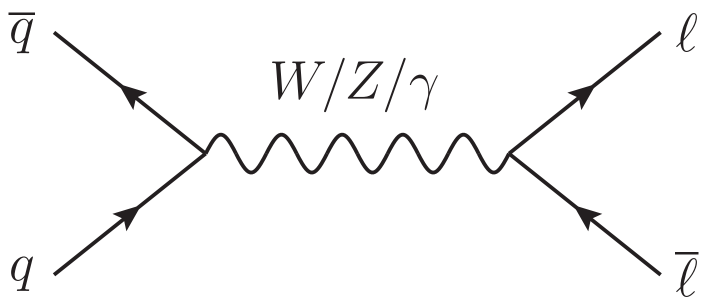


Drell-Yan production ($\ell^+\ell^-$ or $\ell\nu$)

- Large cross section and interference at leading order with SM

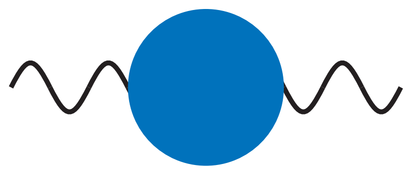
  → ideal process to test new physics

Simple BSM effects: **<u>oblique parameters</u>**

- Deformation of the gauge propagators from dim.-6 operators

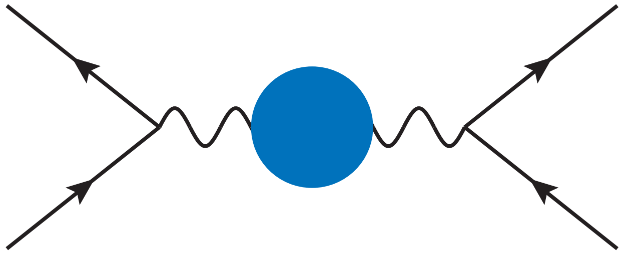
$$\frac{gg'\hat{S}}{16m_W^2}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \qquad -\frac{g^2\hat{T}}{2m_W^2}|H^\dagger D_\mu H|^2$$

$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \qquad -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



→ **LEP** bounds at the **0.1% level**

Oblique parameters at LHC



Drell-Yan production ($\ell^+\ell^-$or $\ell\nu$)

Simple BSM effects: **oblique parameters**

$$P_{\rm N} = \begin{bmatrix} \frac{1}{q^2} - \frac{t_{\rm W}^2 W + Y}{m_{\rm Z}^2} & \frac{t_{\rm W}((Y+\hat{T})c_{\rm W}^2 + s_{\rm W}^2 W - \hat{S})}{(c_{\rm W}^2 - s_{\rm W}^2)(q^2 - m_{\rm Z}^2)} + \frac{t_{\rm W}(Y-W)}{m_{\rm Z}^2} \\ \star & \frac{1+\hat{T}-W-t_{\rm W}^2 Y}{q^2 - m_{\rm Z}^2} - \frac{t_{\rm W}^2 Y + W}{m_{\rm Z}^2} \end{bmatrix}$$

$$P_{\rm C} = \frac{1+((\hat{T}-W-t_{\rm W}^2 Y) - 2t_{\rm W}^2(\hat{S}-W-Y))/(1-t_{\rm W}^2)}{q^2 - m_{\rm W}^2} - \frac{W}{m_{\rm W}^2}$$

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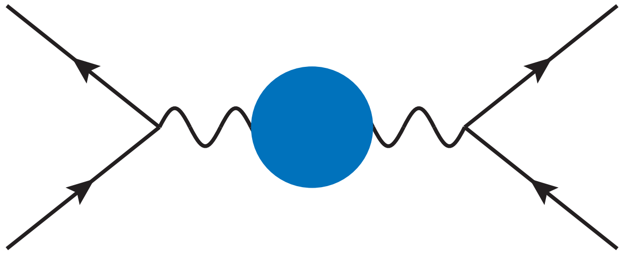

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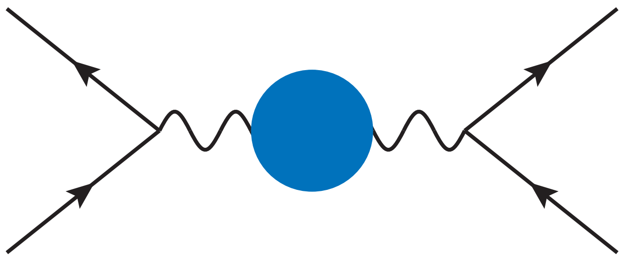
- $\hat{S}$ and $\hat{T}$: only affect pole residues (i.e. total cross-section)
  LHC measurements (% from syst.) **not competitive**

Oblique parameters at LHC



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- $\hat{S}$ and $\hat{T}$: only affect pole residues (i.e. total cross-section)
  LHC measurements (% from syst.) **not competitive**
- W and Y: induce constant terms
  quadratically enhanced at high energy

Experimental uncertainty

Good experimental accuracy

Neutral DY at 8 TeV [ATLAS 1606.01736]

$m_{\ell\ell}$ [GeV]	$\frac{d\sigma}{dm_{\ell\ell}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]
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
1000–1500	2.66×10^{-6}	17.05	2.95	17.31

~10% accuracy at 1 TeV

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~**10% accuracy** at 1 TeV

run-1 error dominated by **statistics**

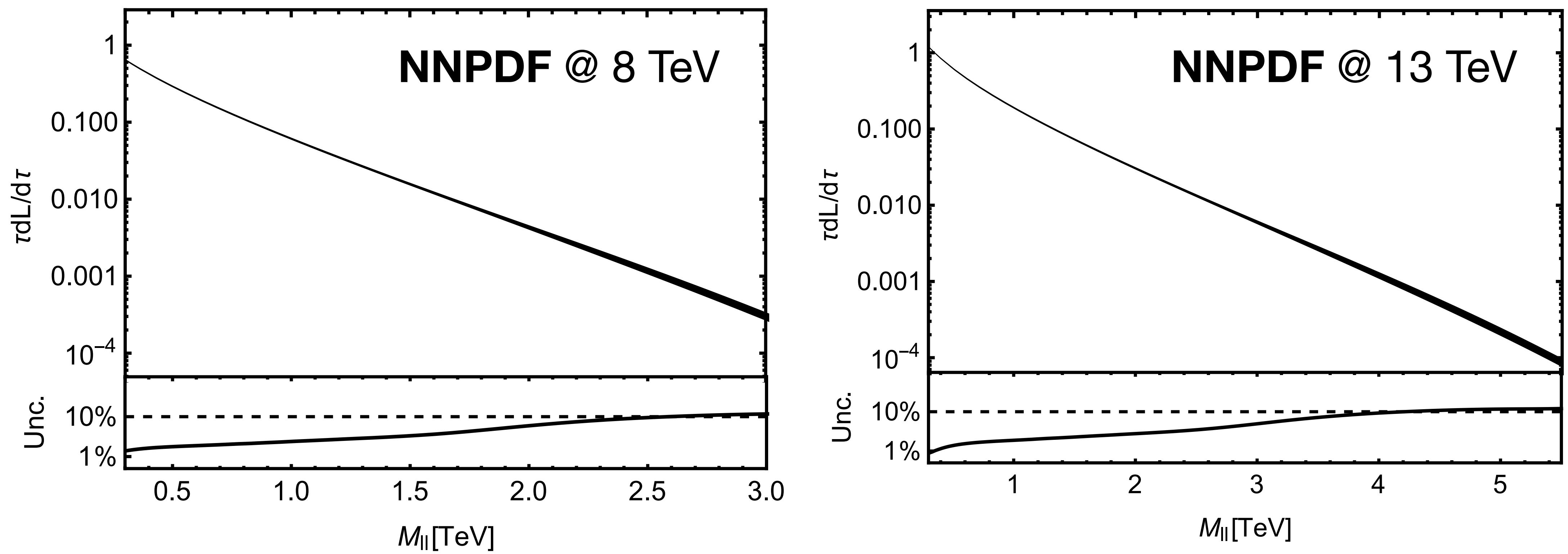
↓

large **improvement** possible at run-2 **systematic error ~2%**

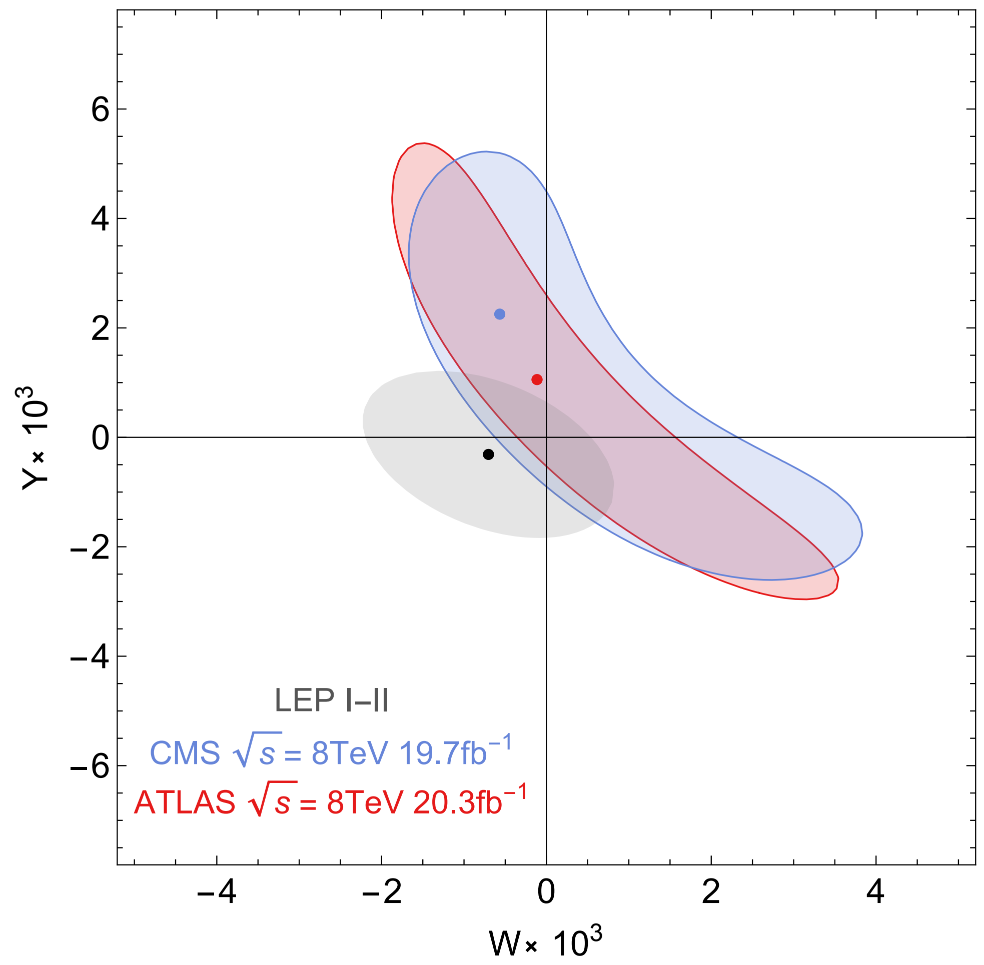
Theory uncertainty

Theory errors well under control

- ✦ accurate cross section computations
  - NNLO QCD accuracy (<1% scale variation error) [FEWZ]
  - NLO EW corrections known
- ✦ small photon pdf uncertainty [Manohar, Nason, Salam, Zanderighi '16]
- ✦ small q-$\bar{q}$ pdf uncertainty (error $\lesssim$10% for E$\lesssim$3 - 4 TeV)



Oblique parameters at the LHC



✦ Neutral DY at **8 TeV** is roughly competitive with LEP

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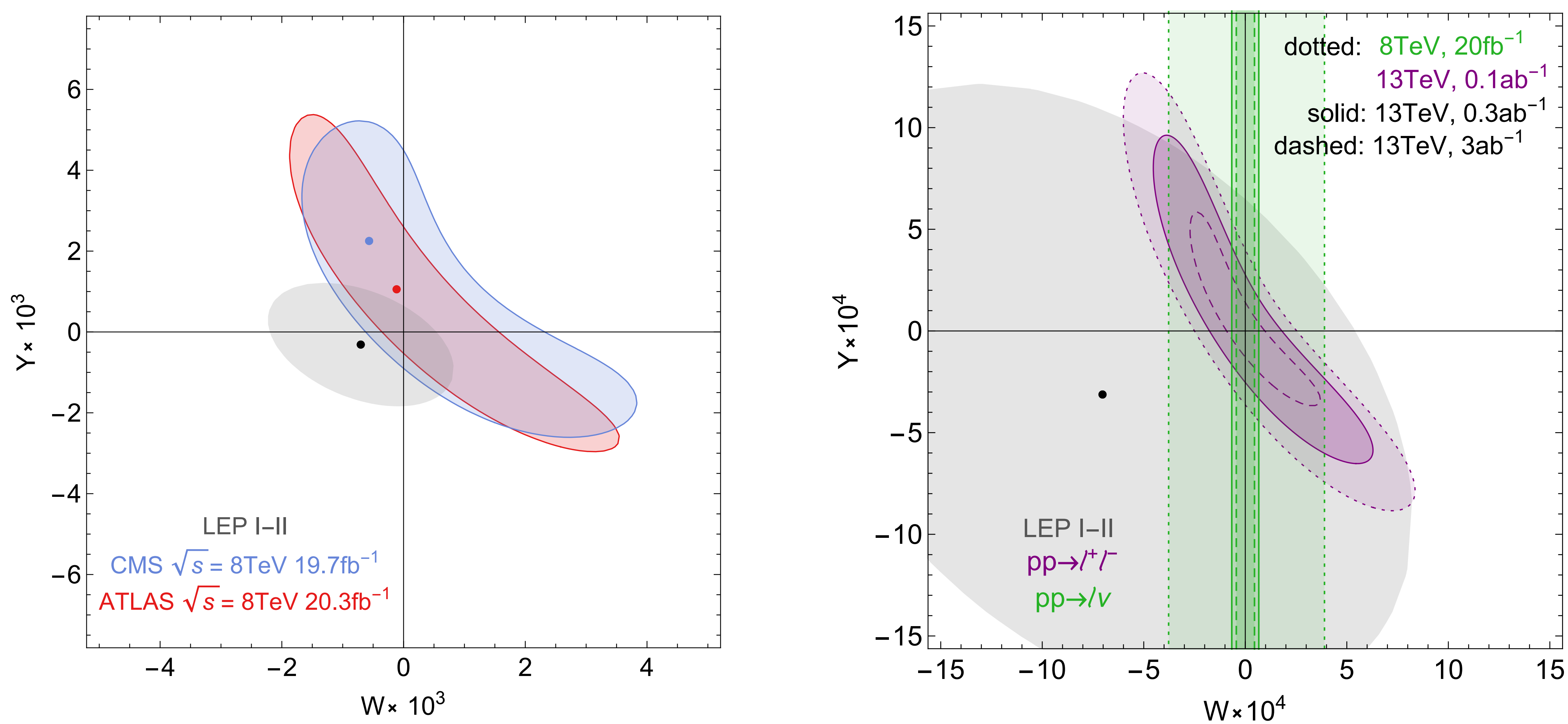
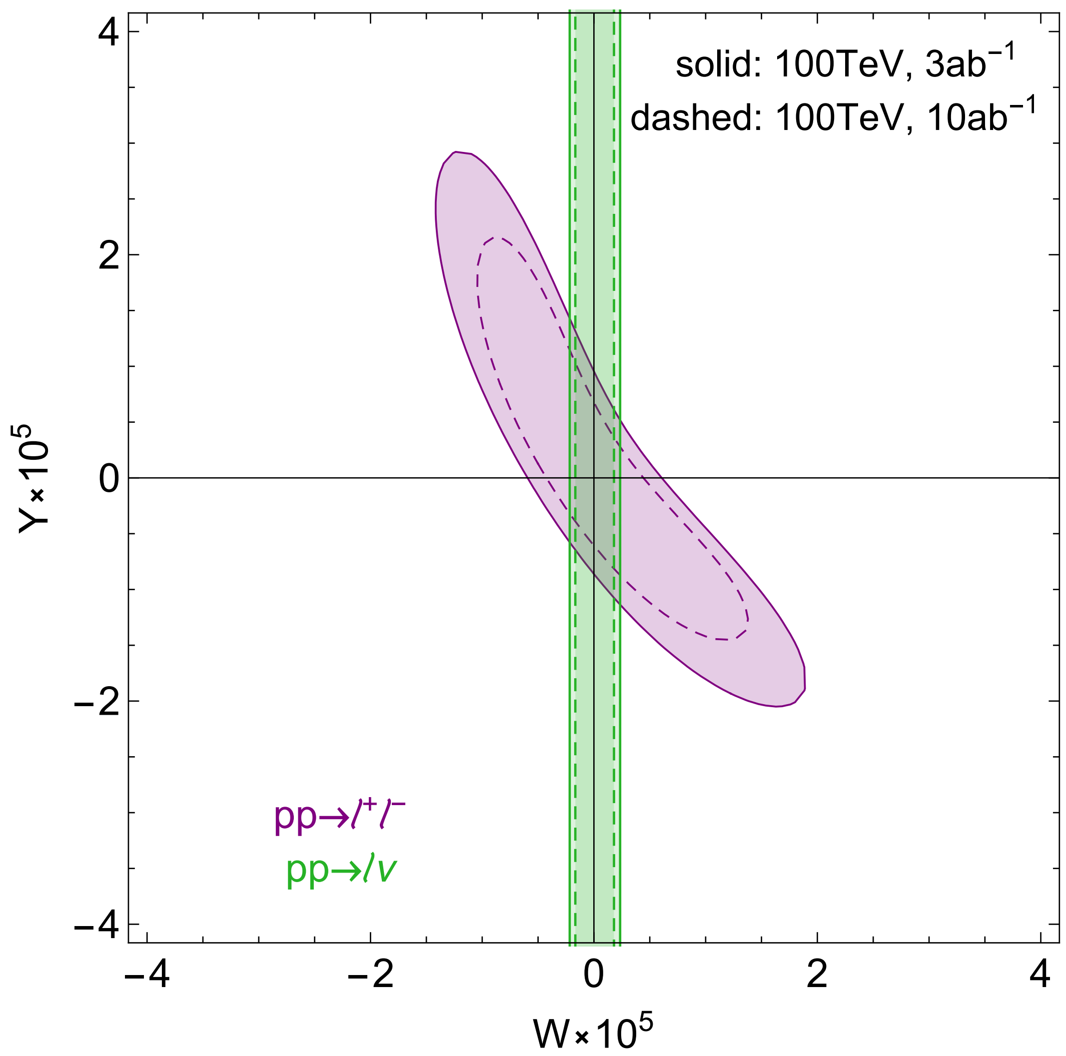


- Neutral DY at **8 TeV** is roughly competitive with LEP
- Charged DY at **8 TeV** could **improve** LEP bound on W
  (experimental analysis not available, our extrapolation assumes 5% syst.)
- **13 TeV** measurements will be **much better than LEP**

Oblique parameters at FCC_{100}

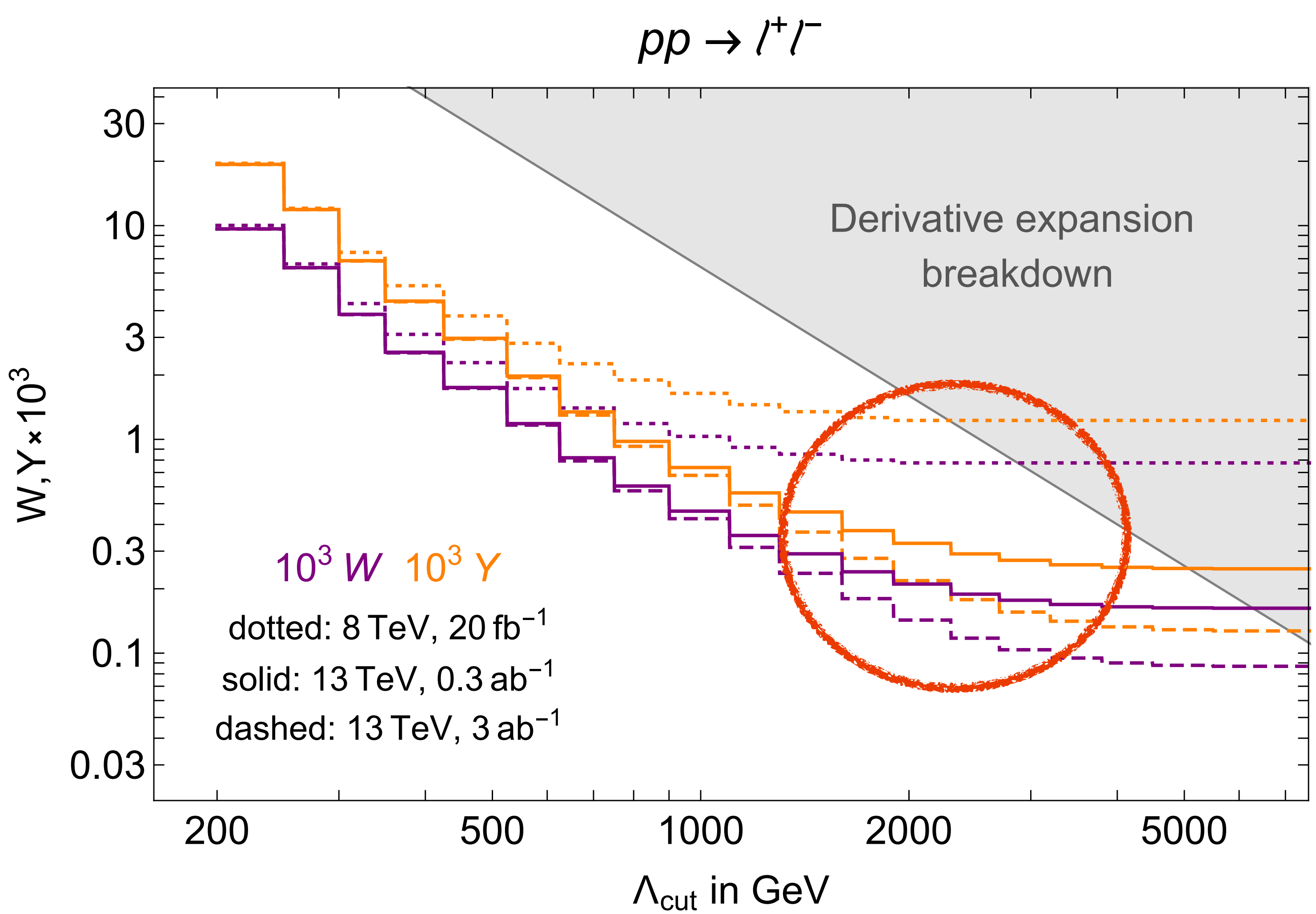


- FCC_{100} could improve the LHC bound by more than one order of magnitude

The relevant energy range

exclusion limits
as a function
of the **energy cut**

$$\sqrt{\hat{s}} < \Lambda_{cut}$$



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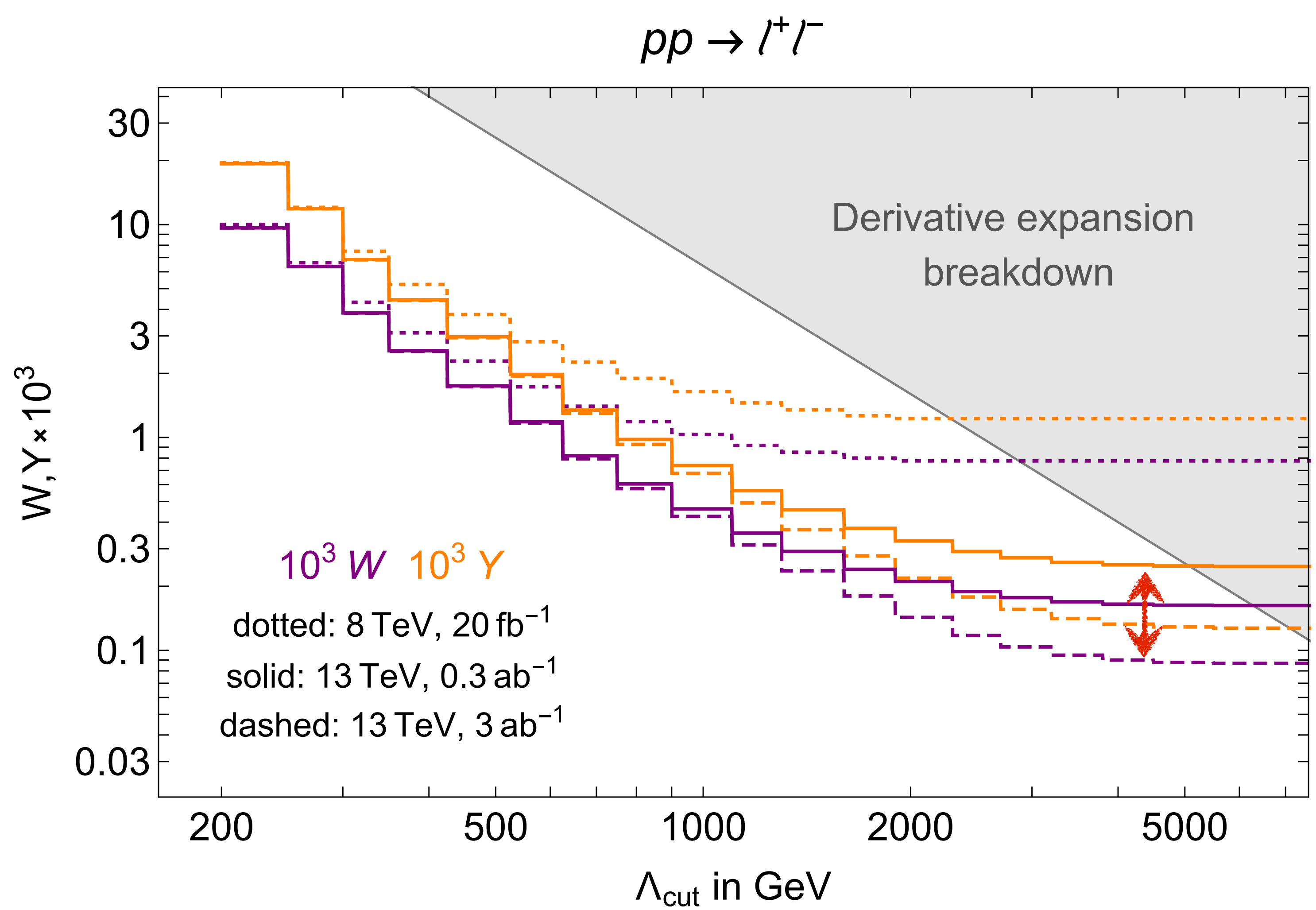


- Energy bins up to ~ 3 TeV are relevant for the bounds
  (at higher energies statistics quickly degrades due to pdf's)

- Limits at LHC-300 still statistically dominated
  HL-LHC benefits from larger statistics at high energy

Validity of the EFT description

Important to assess the **range of validity** of the EFT

- the cut-off is a **free parameter** of the EFT
  (encodes information on the UV theory)

- bounds must be set as a function of the cut-off
  (considering only data below the cut-off)

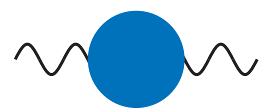
- cut-off can not be arbitrarily large:
  maximal cut-off depending on the effective description

Validity of the EFT description

alternative descriptions of W and Y in terms of dim.-6 operators

form factor picture

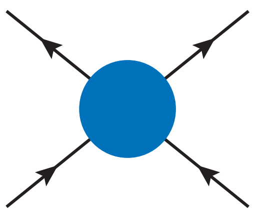
$$-\frac{W}{4m_{\rm W}^2}(D_\rho W^a_{\mu\nu})^2 \qquad -\frac{Y}{4m_{\rm W}^2}(\partial_\rho B_{\mu\nu})^2$$



new physics coupled only
to SM gauge bosons
(eg. composite Higgs with vector resonances)

contact interactions picture

$$-\frac{g^2 W}{2m_{\rm W}^2} J_{L\,\mu}^{\ a} J_{L\,a}^{\ \mu} \qquad -\frac{g'^2 Y}{2m_{\rm W}^2} J_{Y\,\mu} J_Y^{\ \mu}$$



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fermions with "universal" couplings
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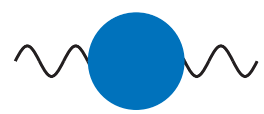

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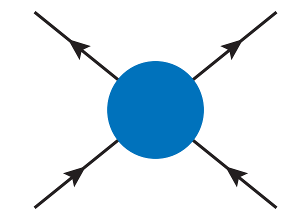


new physics directly coupled to SM
fermions with "universal" couplings
(not fully motivated)

maximal cut-off is different!

$$\Lambda_{max} = \frac{m_{\rm W}}{\max(\sqrt{W}, \sqrt{Y})}$$

new operators smaller than SM kinetic terms
BSM < SM always

$$\Lambda'_{max} = \frac{4\pi m_{\rm W}/g}{\max(\sqrt{W}, t_{\rm W}\sqrt{Y})} \gg \Lambda_{max}$$

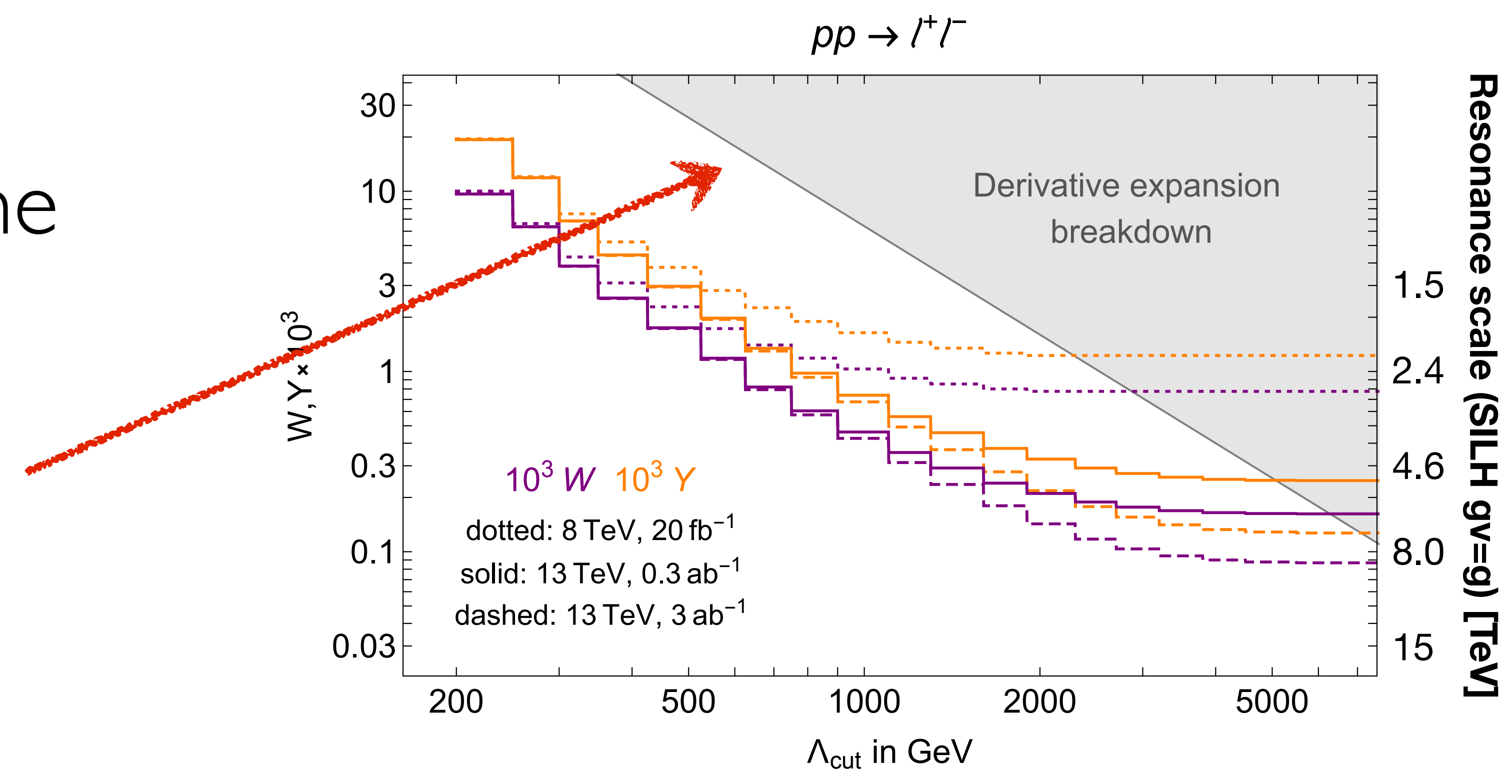
perturbativity bound
BSM can be larger than SM

✦ the two pictures are equivalent only at low energy

Validity of the EFT description

maximal cut-off limits the range of validity

$$\Lambda_{max} = \frac{m_{\mathrm{W}}}{\max(\sqrt{W}, \sqrt{Y})}$$



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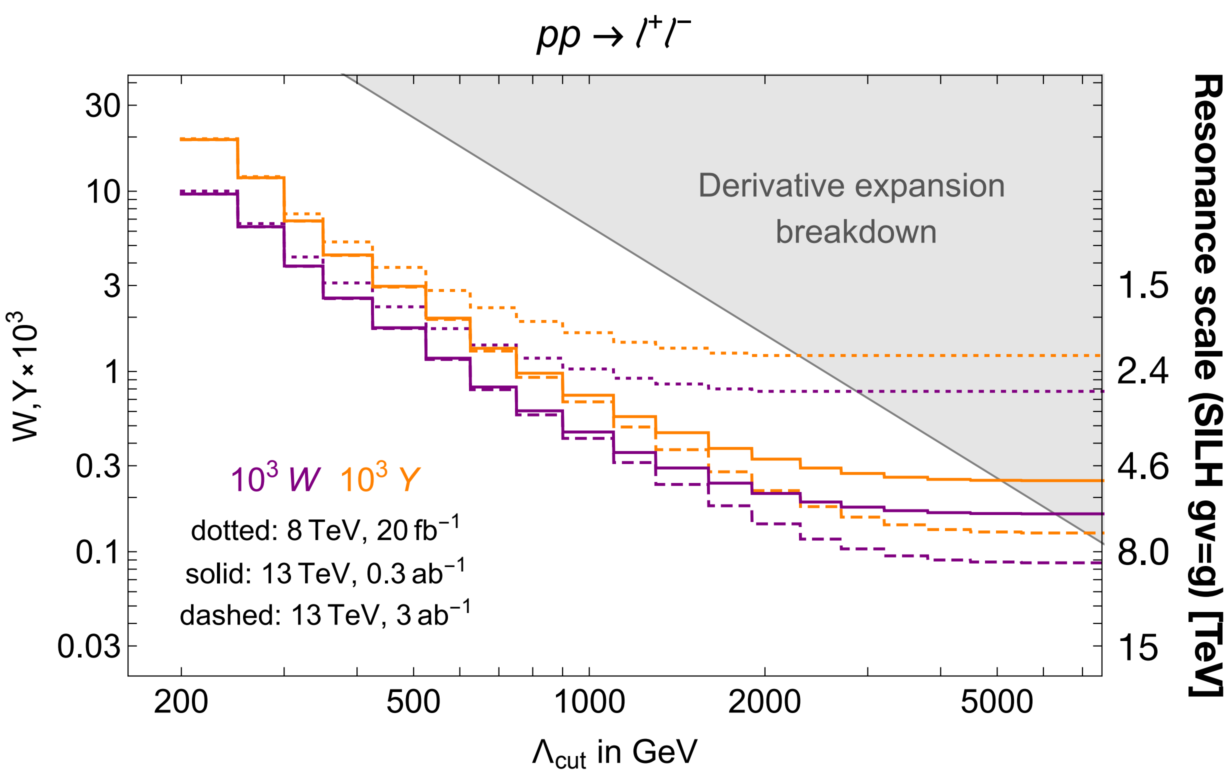
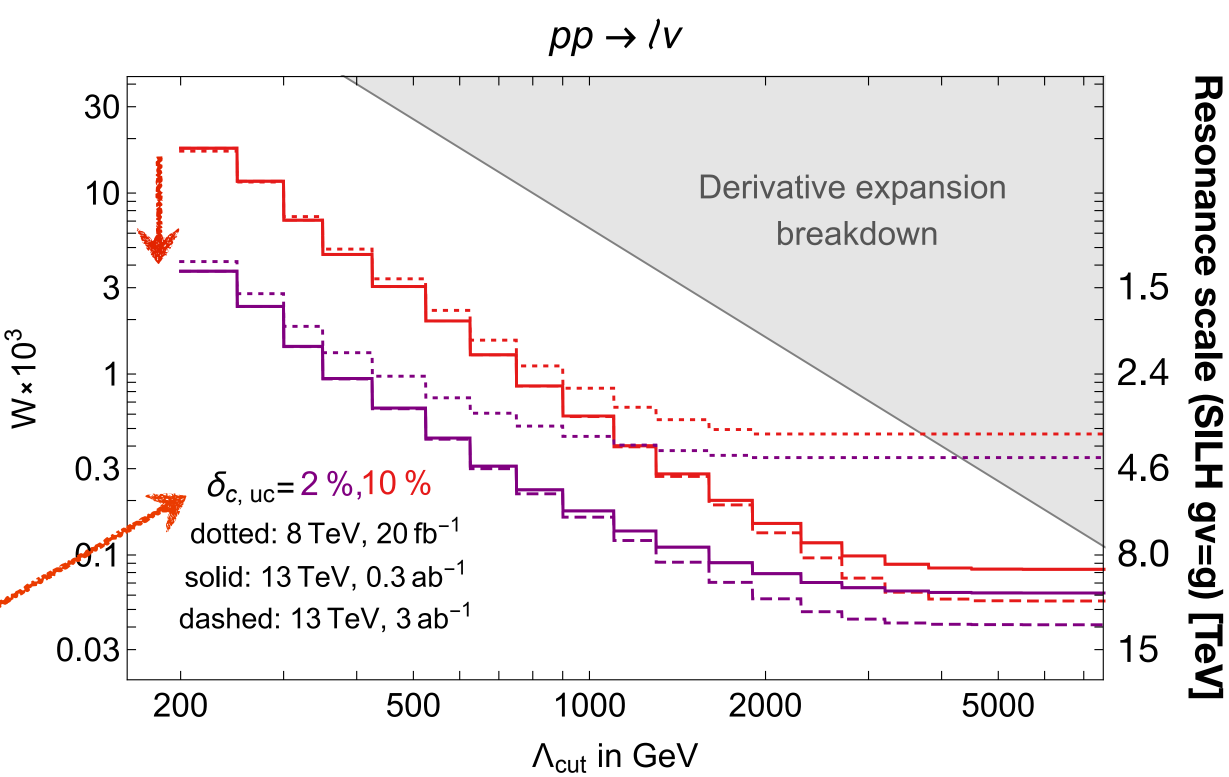


accuracy allows to test a wider range of theories

(moving the bounds away from the maximal cut-off)

syst. error



Comparison with future colliders

Bounds on W and Y at different colliders

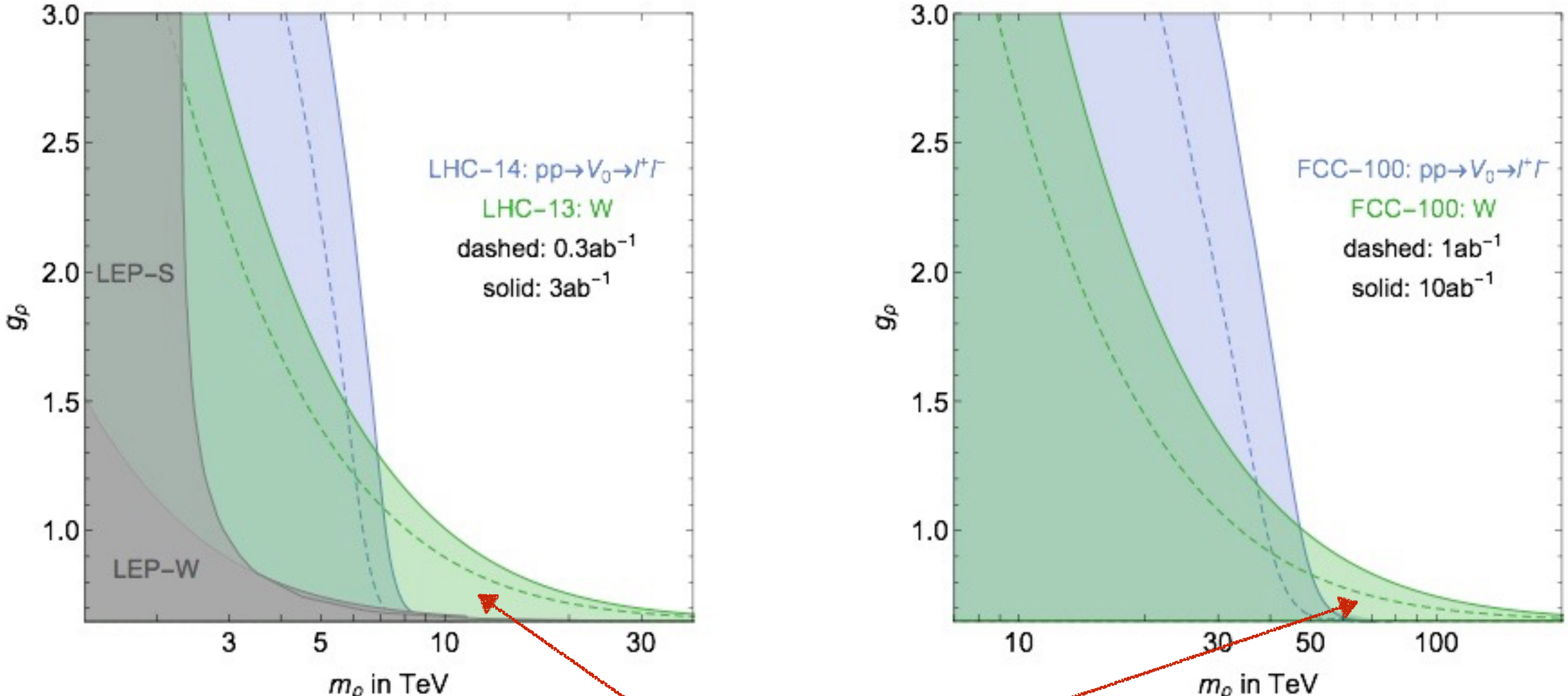
	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2 \times 10^7\ Z$	$0.3/\text{ab}$	$3/\text{ab}$	$10/\text{ab}$	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	$3/\text{ab}$	$1/\text{ab}$	$1/\text{ab}$
W $\times 10^4$	$[-19, 3]$	± 0.7	± 0.45	± 0.02	± 4.2	± 1.2	± 3.6	± 0.3	± 0.5	± 0.15
Y $\times 10^4$	$[-17, 4]$	± 2.3	± 1.2	± 0.06	± 1.8	± 1.5	± 3.1	± 0.2	$\sim \pm 0.5$	$\sim \pm 0.15$

- HL-LHC comparable with TLEP
- FCC_{100} much better than ILC 500 GeV and CLIC 3 TeV

Comparison with direct searches

Competitive with direct searches on new vector states

Example: massive W' mixing with SM (eg. composite vector state)



constraints from W stronger
than direct searches

More challenging channels

Di-boson processes

GP, Riva, Wulzer '17
Franceschini, GP, Pomarol, Riva, Wulzer '17

More channels for precision

Which other channels can we exploit for EW precision?

Required features:

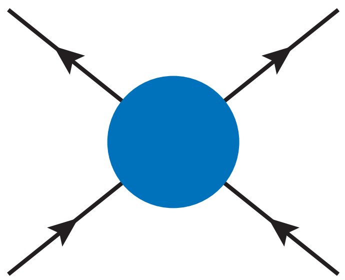
- ✦ sizable cross section (low statistical error)
- ✦ small background and good theory understanding (low systematic error)
- ✦ good sensitivity to new physics (corrections growing with energy)

Natural candidates: **$2 \rightarrow 2$ scattering processes**

2 → 2 scattering

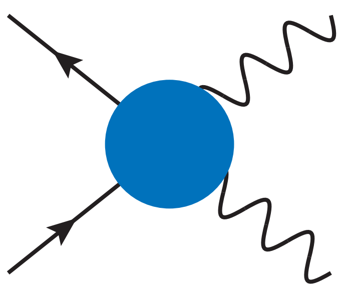
There are three main classes of $2 \to 2$ processes:

$ff \to ff$



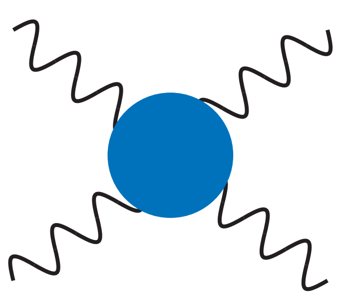
- large cross section
- background ok in lepton channels
- large new-physics effects

$ff \to VV$
$(VV \to ff\,,\;\; fV \to fV)$



- good cross section
- background ok in lepton channels
  (pay branching fractions)

$VV \to VV$



- small cross section
- need "dirty" channels for statistics

Growth vs non-growth

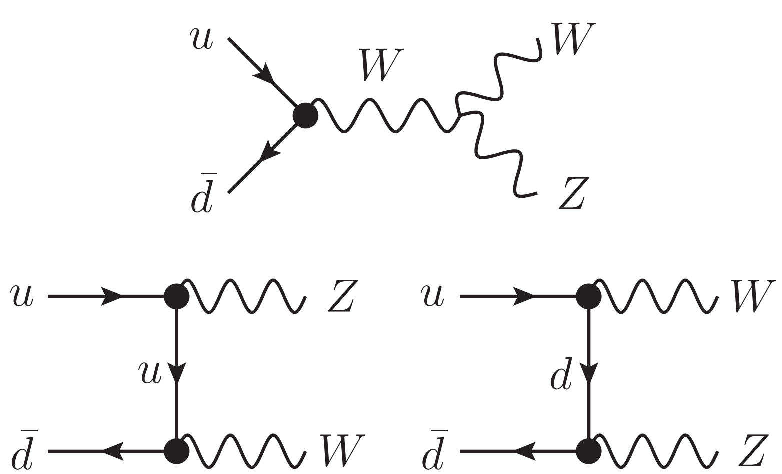
All dim. 6 operators induce a growth …but **not** in all channels!

Example: the **WZ channel**

Triplet operator

$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

- corrections to W and Z interactions

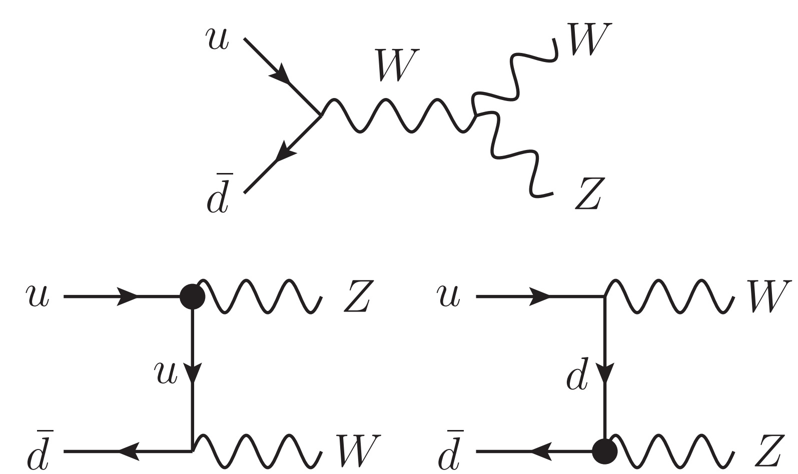


- growth with E^2

Singlet operator

$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(i H^\dagger \overleftrightarrow{D}_\mu H)$$

- corrections to Z interactions



- **no growth!**

✦ difficult to guess the growth/no-growth in unitary gauge

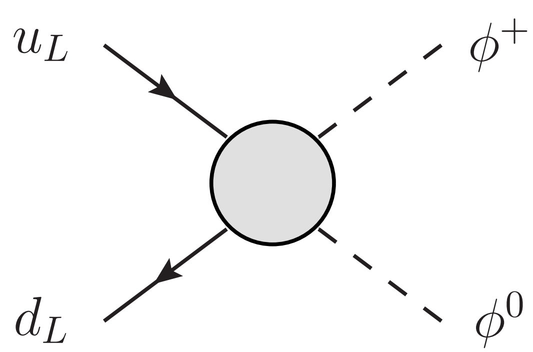
Growth vs non-growth

Easier to understand growth with equivalence theorem:

- at **high energy** gauge fields can be "traded" for Higgs **Goldstones**

Triplet operator

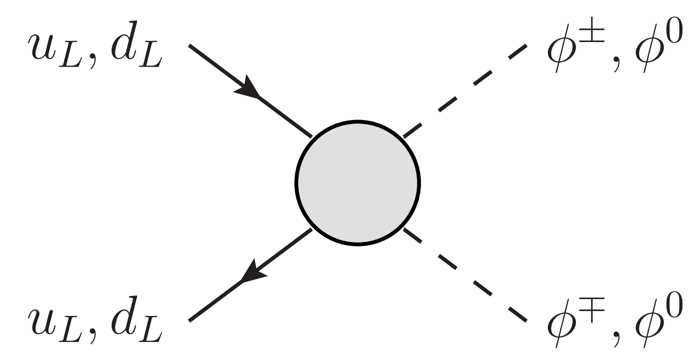
$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$



- contributes to p p → W Z

Singlet operator

$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(i H^\dagger \overleftrightarrow{D}_\mu H)$$



- does **not** contribute to p p → W Z

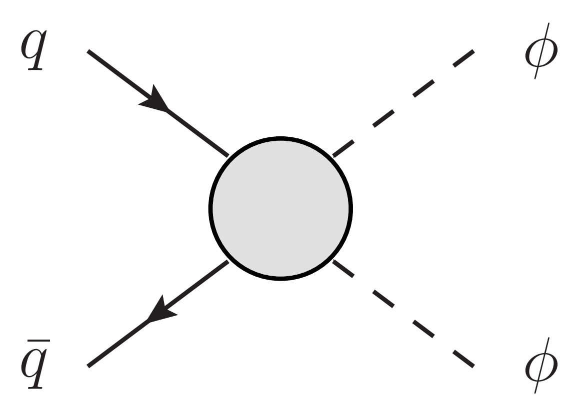
  (contributes only to neutral channels WW and ZH)

Growth vs non-growth

Easier to understand growth with equivalence theorem:

- at **high energy** gauge fields can be "traded" for Higgs **Goldstones**

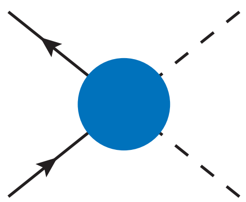
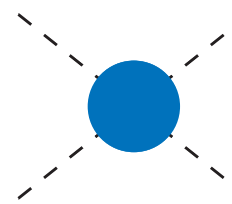
- probing di-boson at high-energy is a way to test **the Higgs dynamics!**



Limitations: non-interference

Limitation: at high-energy interference of dim.-6 with SM only in few helicity channels [Azatov, Contino, Machado, Riva '16]

- ✦ only **longitudinal** channels interfere at **LO** in $(\varepsilon_{\rm V})^0 = (m_{\rm V}/E)^0$

$\psi\overline{\psi}V_L V_L$  $V_L V_L V_L V_L$ 

  - **growth** at high energy

- ✦ **transverse** channels interfere only at subleading order

  eg. $\mathcal{A}_{\rm SM}(\psi\overline{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^0 \qquad \mathcal{A}_{\rm BSM_6}(\psi\overline{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^2$

  - no growth at high energy

    → … but see later for a "trick" to get interference in transverse channels

Which operators in di-boson?

Only **4** <u>High-Energy Primaries</u> inducing **LO interference** and **growth with energy:**

$$WZ,\ WH:\ a_q^{(3)}, a_u, a_d$$

$$WW,\ ZH:\ a_q^{(3)}, a_q^{(1)}, a_u, a_d$$

Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f

- parametrize BSM contribution: $\delta\mathcal{A}(q'\bar{q} \to VV') = a\, E^2 \sin\theta^*$
- can be connected with explicit basis, eg. with Warsaw basis:

$$\begin{cases} \mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) \\ \mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(i H^\dagger \overleftrightarrow{D}_\mu H) \end{cases}$$

$$\begin{cases} \mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(i H^\dagger \overleftrightarrow{D}_\mu H) \\ \mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(i H^\dagger \overleftrightarrow{D}_\mu H) \end{cases}$$

Estimate of reach in diboson

Estimate of the reach on $a_q^{(3)}$ in diboson channels at HL-LHC

Channel	Bound without bkg.	Bound with bkg.
Wh	$[-0.0096, 0.0096]$	$[-0.036, 0.031]$
Zh	$[-0.030, 0.028]$	–
WW	$[-0.012, 0.011]$	$[-0.044, 0.037]$
WZ	$[-0.013, 0.012]$	$[-0.023, 0.021]$

boosted Higgs analysis from [Butterworth et al. 1506.04973]
main bkgs.: Wbb, tt, Wt, WZ

only events with longitudinal polarizations

bkg. estimate includes only transverse polarizations

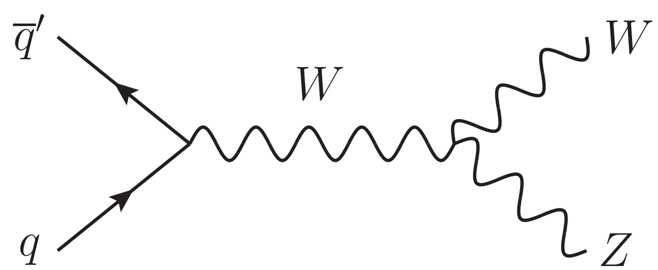
- WZ channel more promising, followed by WH

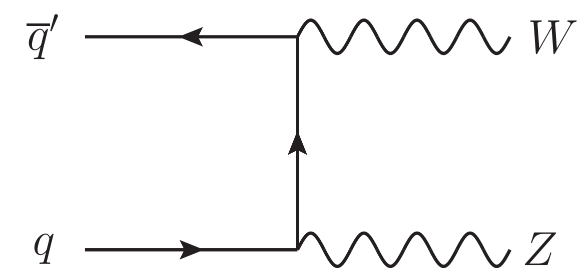
Looking for subleading channels

The WZ *process*

Franceschini, GP, Pomarol, Riva, Wulzer '17

WZ production





Clean fully-leptonic final state: $q\bar{q} \to WZ \to (\ell\nu)(\ell\ell)$

- ✦ small background
- ✦ systematic uncertainties under control ($\lesssim$ few %)

[ATLAS Phys. Rev. D 93 (2016)]

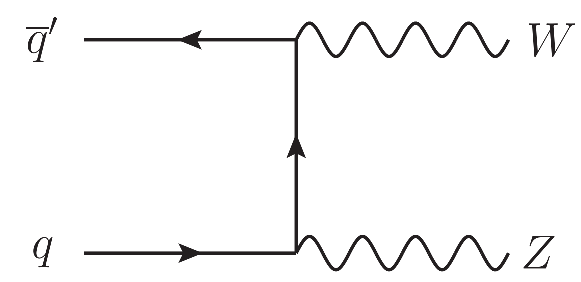
Energy enhanced new-physics effects in **longitudinal channel**

$$\frac{\mathcal{A}_{LL}^{\mathrm{SM}\,+\,\mathrm{BSM}}(q\bar{q} \to WZ)}{\mathcal{A}_{LL}^{\mathrm{SM}}(q\bar{q} \to WZ)} \sim 1 + a_q^{(3)} E^2$$

WZ production

… but **transverse** channels **dominate** the SM cross section

large cross section
due to t-channel singularity
(only there for transverse)



cross sections with standard acceptance cuts:

	σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
8 TeV	12 pb	0.73 pb	6%
13 TeV	25 pb	1.5 pb	

(BR for fully-leptonic decay not included $\mathrm{BR}(WZ \to (\ell\nu)(\ell\ell)) \simeq 1.5\%$)

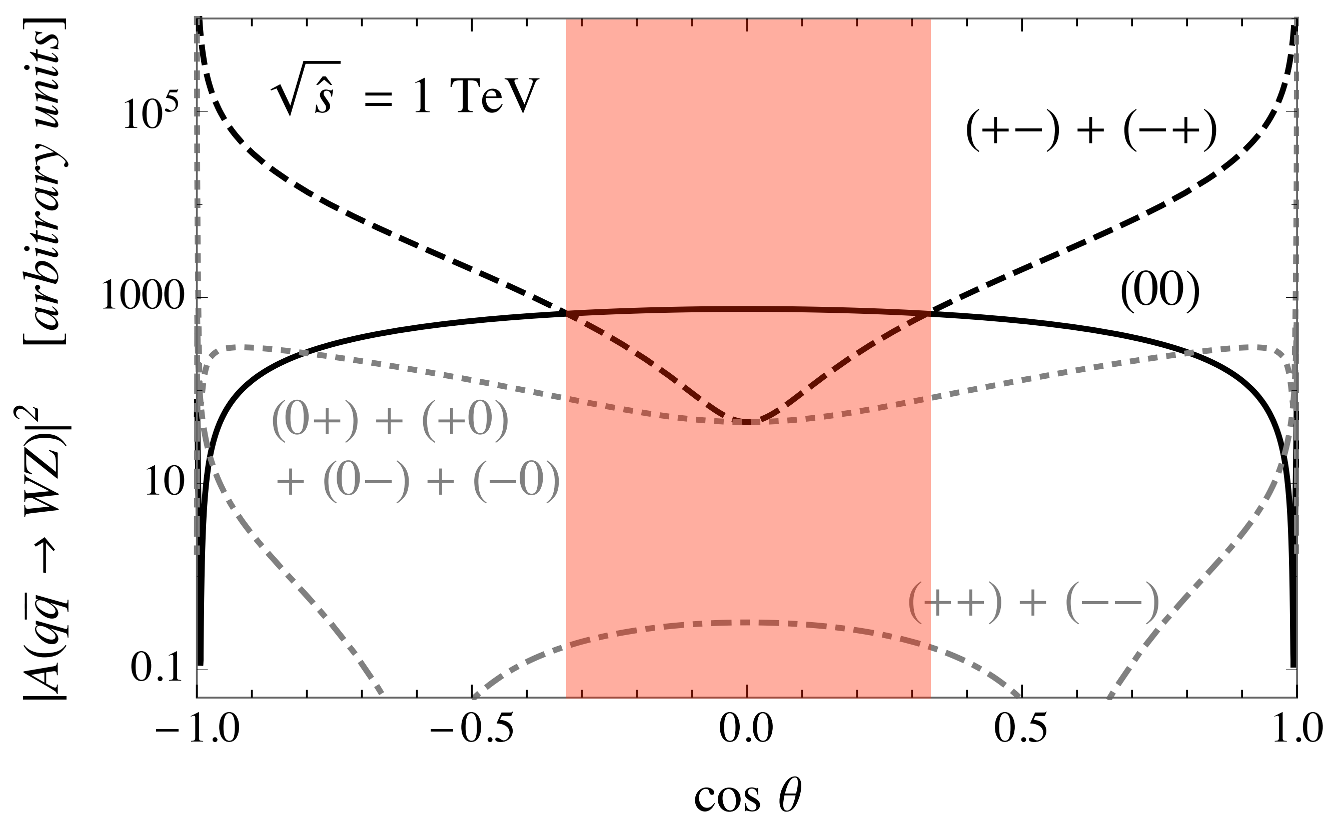
Extracting the longitudinal channel

Transverse amplitudes vanish for (nearly) central scattering

[Baur, Han, Ohnemus '94]

$$A_{(+-)}(u\bar{d} \to WZ)\,, \quad A_{(-+)}(u\bar{d} \to WZ) \propto \cos\theta - \frac{1}{3}\tan\theta_W$$

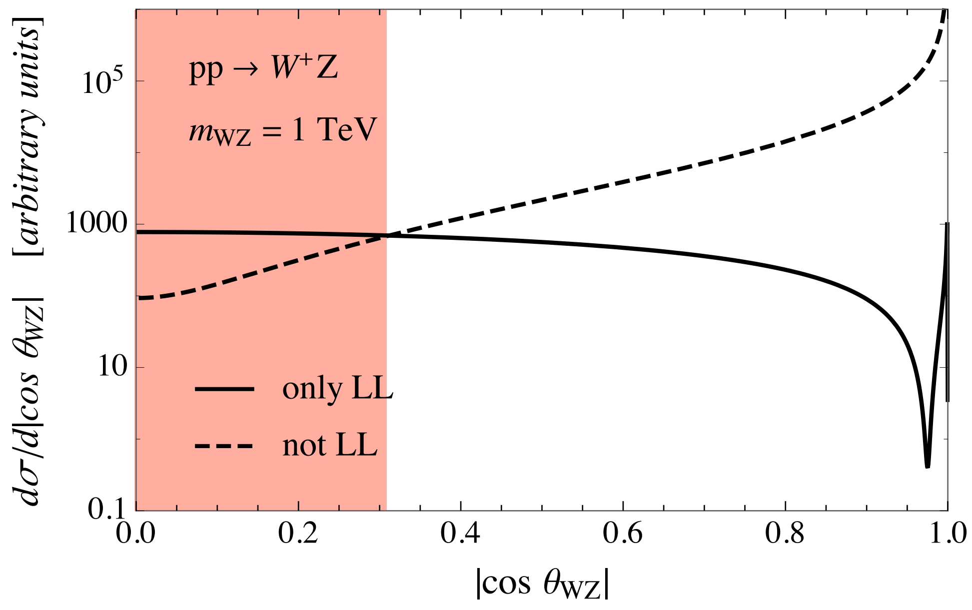
- longitudinal amplitude dominates for $\theta \sim 90^\circ$
- cuts in $\hat{s}$ and $\cos\theta$ can be used to isolate the longitudinal channel

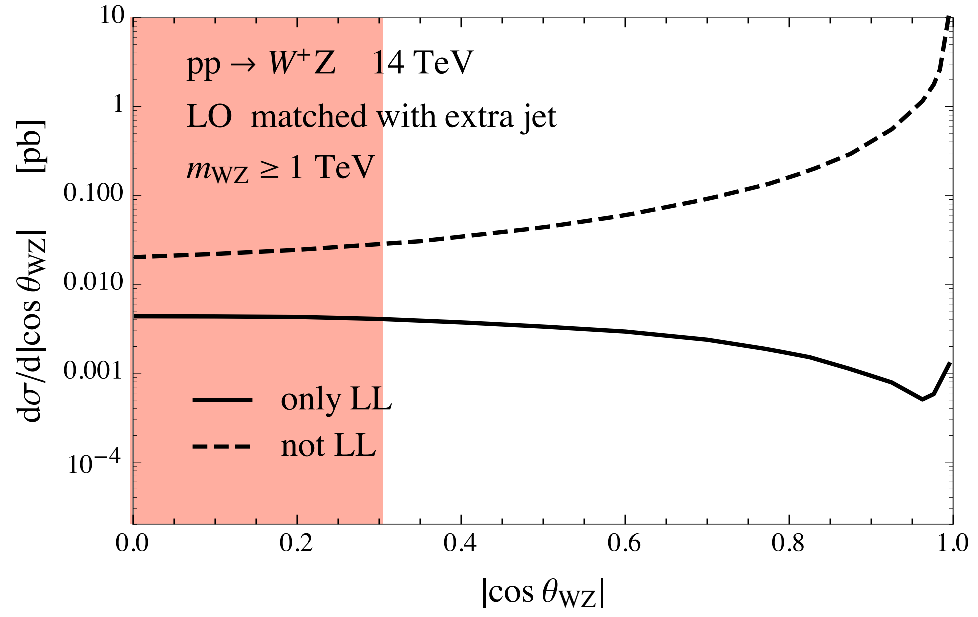


13 TeV		σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
$\lvert\cos\theta\rvert < 0.5$	$\sqrt{\hat{s}} > 300$ GeV	630 fb	230 fb	37%
$\lvert\cos\theta\rvert < 0.5$	$\sqrt{\hat{s}} > 500$ GeV	80 fb	34 fb	42%

A realistic analysis

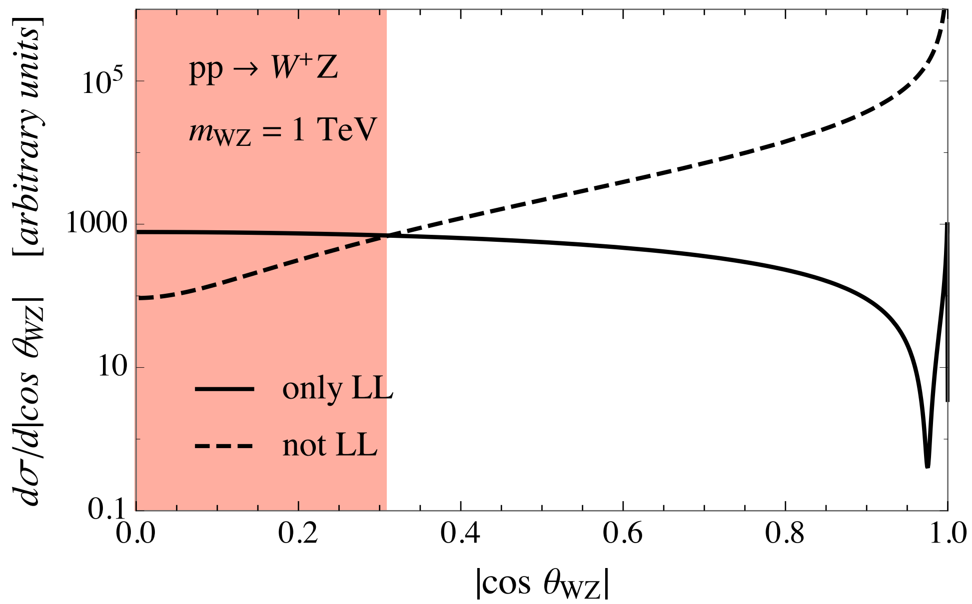
- NLO corrections partially spoil the LO zeroes (mainly due to real emission)

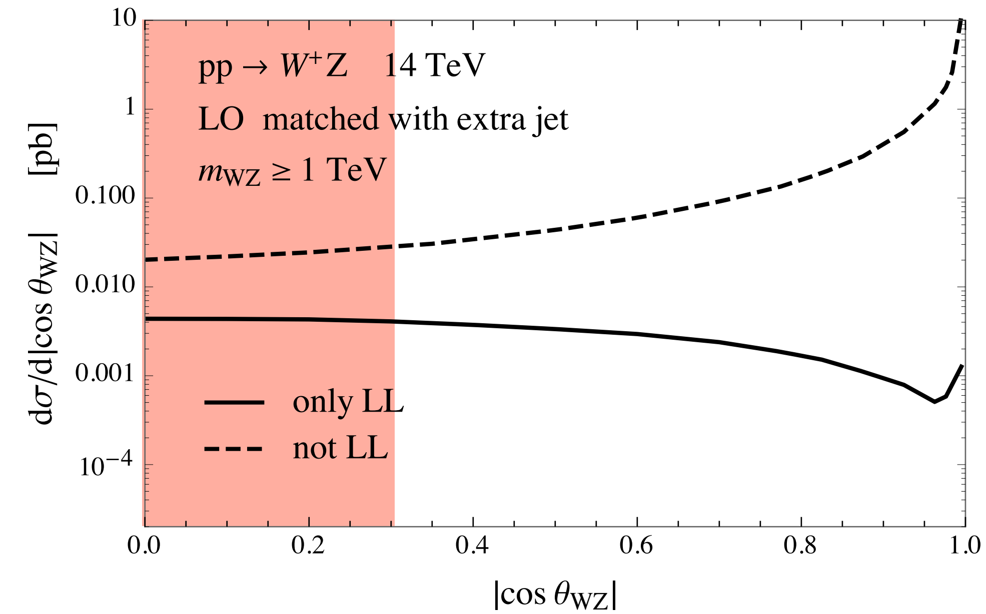




A realistic analysis

✦ NLO corrections partially spoil the LO zeroes (mainly due to real emission)

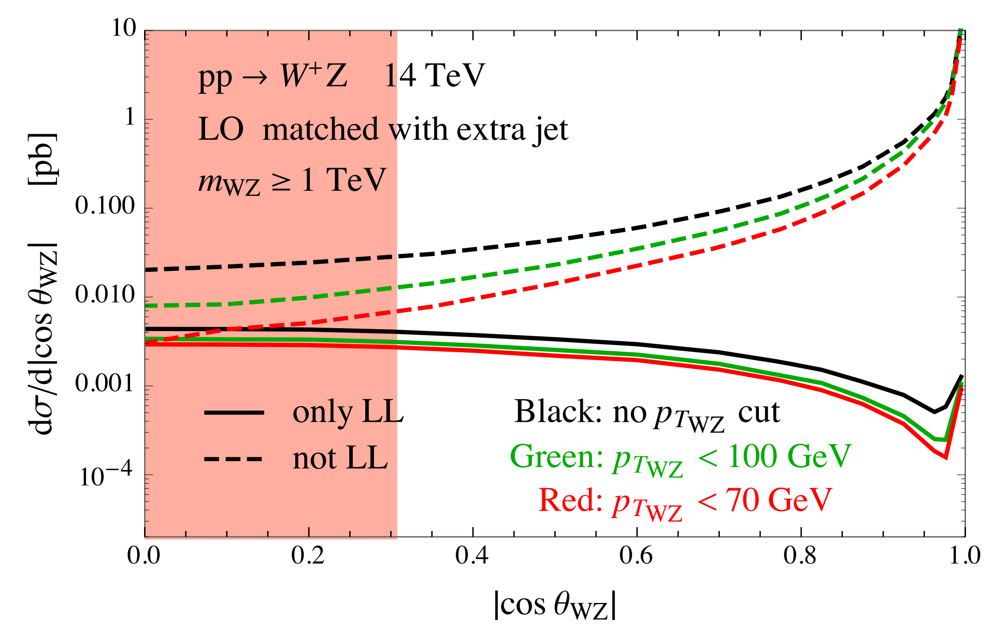




➔ NLO effects can be kept under control with a cut on the transverse momentum of the WZ system (safer than jet veto)

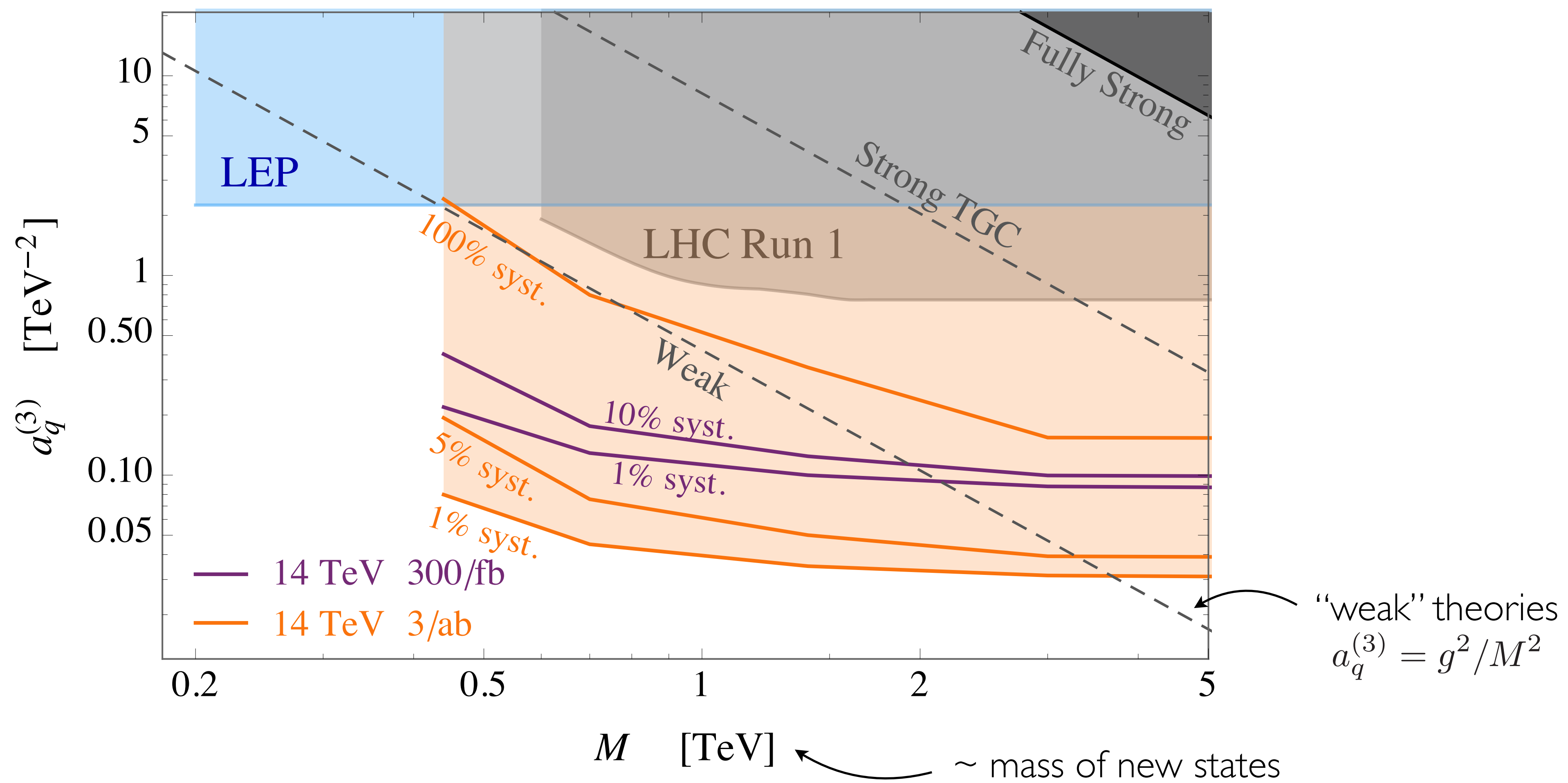
possible choice:

$$p_{T_{WZ}} < 70 \text{ GeV}$$



Reach at LHC

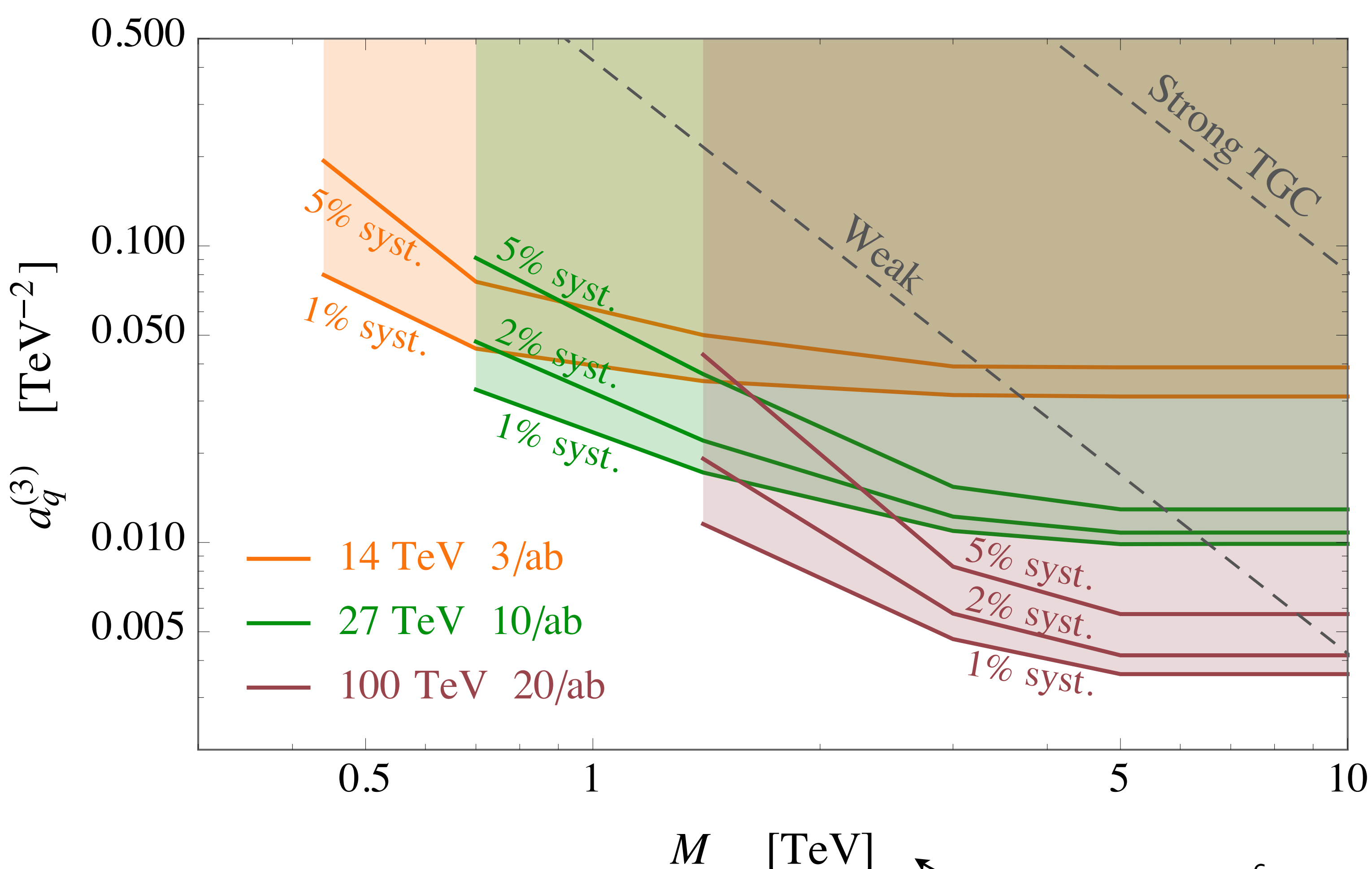
Estimates of the bounds on $a_q^{(3)}$



- drastic improvement from LEP and "naive" LHC analysis
- systematics play an important role in the precision reach
- bounds cover wide range of weakly-coupled new physics
  (accuracy is important to access these theories)

Reach at future colliders

Estimates of the bounds on $a_q^{(3)}$

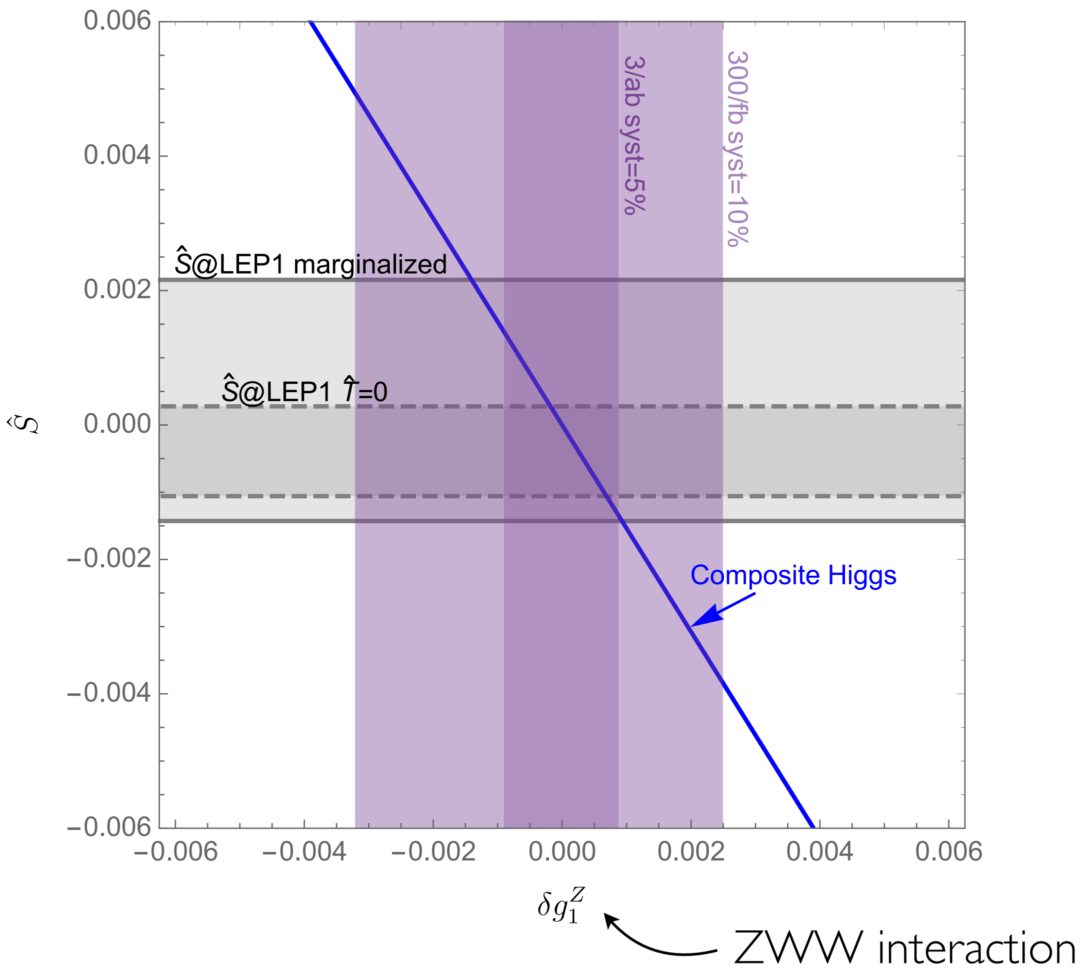


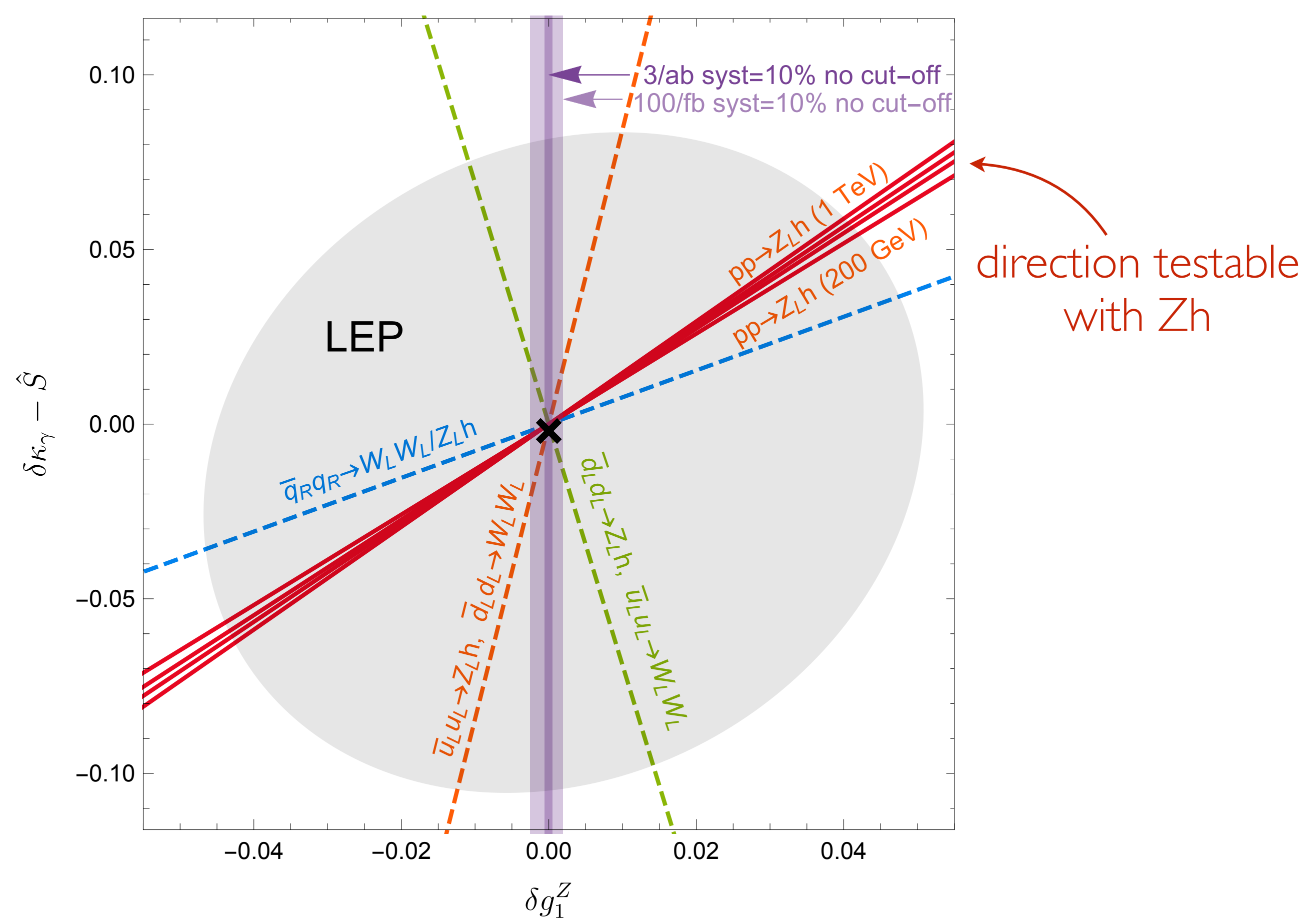
~ mass of new states

- additional improvement possible at future colliders
- reach at FCC-hh comparable with CLIC see [Ellis, Roloff, Sanz, You '17]

Bounds on universal theories

Comparison with LEP bounds on universal theories





- ✦ LHC is probing an independent direction from LEP
  - comparable sensitivity in many theories (eg. composite Higgs $\widehat{S} \simeq -\delta g_1^Z$)
- ✦ big improvement on δg_1^Z with respect to global fit at LEP

“Interference resurrection”

The $W\gamma$ *process*

GP, Riva, Wulzer ‘17

“Switching on” the interference

The **non-interference theorem** applies only if we are dealing with final states with definite helicity

when the gauge bosons decay helicities get “mixed”

↓

interference between transverse and longitudinal channels gives rise to **azimuthal correlations!**

Important features:

- interference affects only the **exclusive** cross section:
  it modifies only the **azimuthal distribution** of the decay products
- interference is erased by integrating over the decay angles

Wγ production

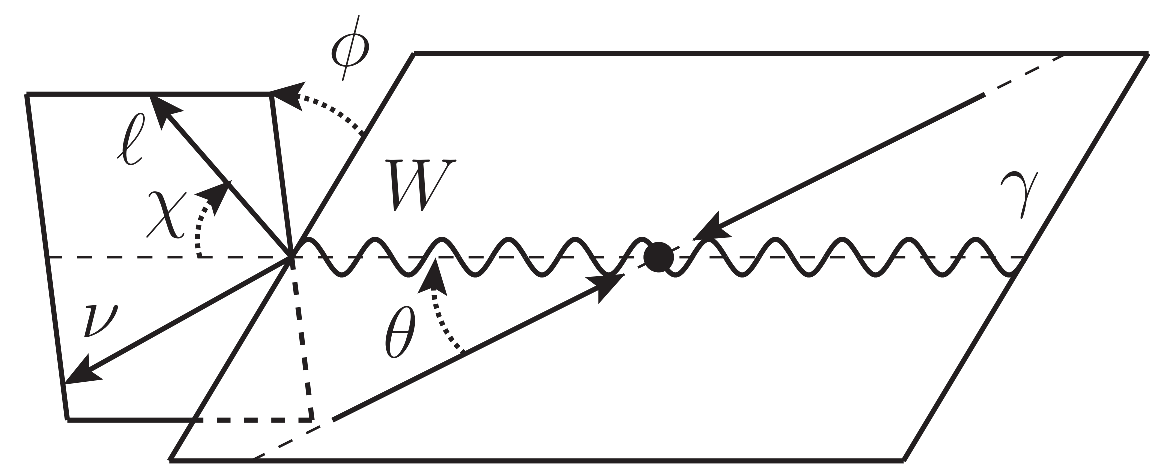
A simple process to explore interference is $W\gamma$ production

Polarized **production**:

$$\begin{cases} \mathcal{A}^{\rm SM}_{(+-)}\,,\mathcal{A}^{\rm SM}_{(-+)} \sim 1 \\ \mathcal{A}^{\rm SM}_{(0\pm)} \sim \dfrac{m_{\rm W}}{E} \\ \mathcal{A}^{\rm SM}_{(++)}\,,\mathcal{A}^{\rm SM}_{(--)} \sim \dfrac{m^2_{\rm W}}{E^2} \end{cases}$$

Polarized W **decay**:

$$\begin{cases} \mathcal{A}_{(+)} \sim (1+\cos\chi)e^{i\phi} \\ \mathcal{A}_{(-)} \sim (-1+\cos\chi)e^{-i\phi} \\ \mathcal{A}_{(0)} \sim -\sqrt{2}\sin\chi \end{cases}$$



- azimuthal phase depending on W polarization

Wγ production: the amplitude

Total amplitude:

$$
\begin{aligned}
|\mathcal{A}_{tot}|^2 \sim\, & (1+c_\chi)^2|\mathcal{A}_{(+\pm)}|^2 + (1-c_\chi)^2|\mathcal{A}_{(-\pm)}|^2 + 2s_\chi^2|\mathcal{A}_{(0\pm)}|^2 \\
& -2s_\chi^2\,\mathrm{Re}[\mathcal{A}_{(+\pm)}\mathcal{A}^*_{(-\pm)}e^{2i\phi}] \\
& -2\sqrt{2}(1+c_\chi)s_\chi\,\mathrm{Re}[\mathcal{A}_{(+\pm)}\mathcal{A}^*_{(0\pm)}e^{i\phi}] \\
& +2\sqrt{2}(1-c_\chi)s_\chi\,\mathrm{Re}[\mathcal{A}_{(-\pm)}\mathcal{A}^*_{(0\pm)}e^{-i\phi}]
\end{aligned}
$$

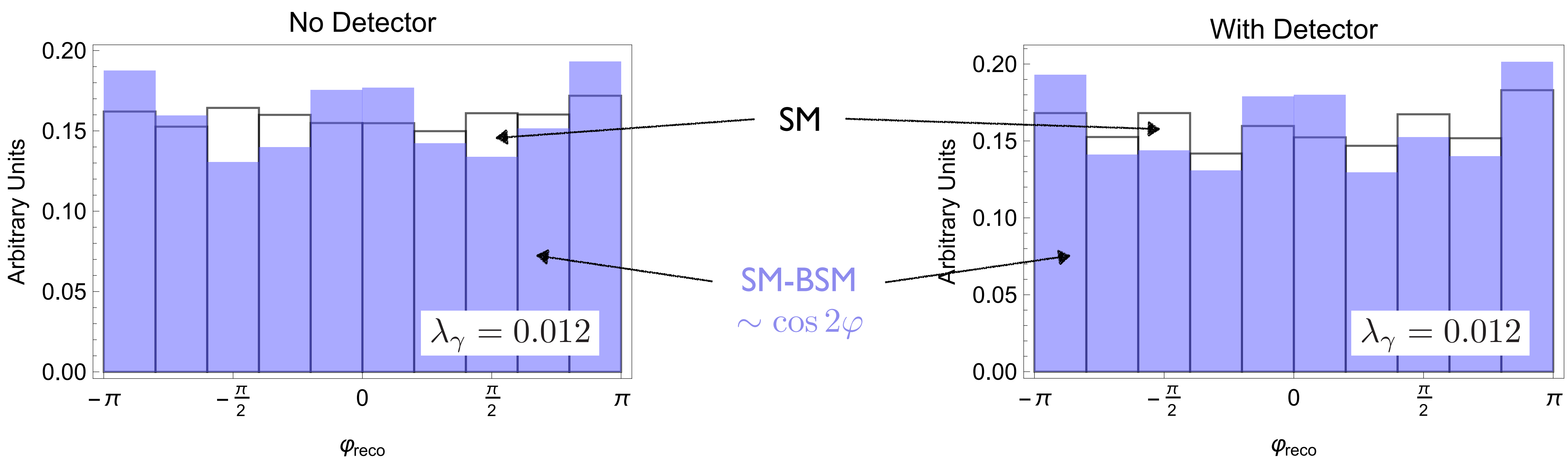
no interference (first line)

interference: **azimuthal correlations** (remaining lines)

→ interference terms lead to non-trivial dependence on ϕ

Wγ production: TGC corrections

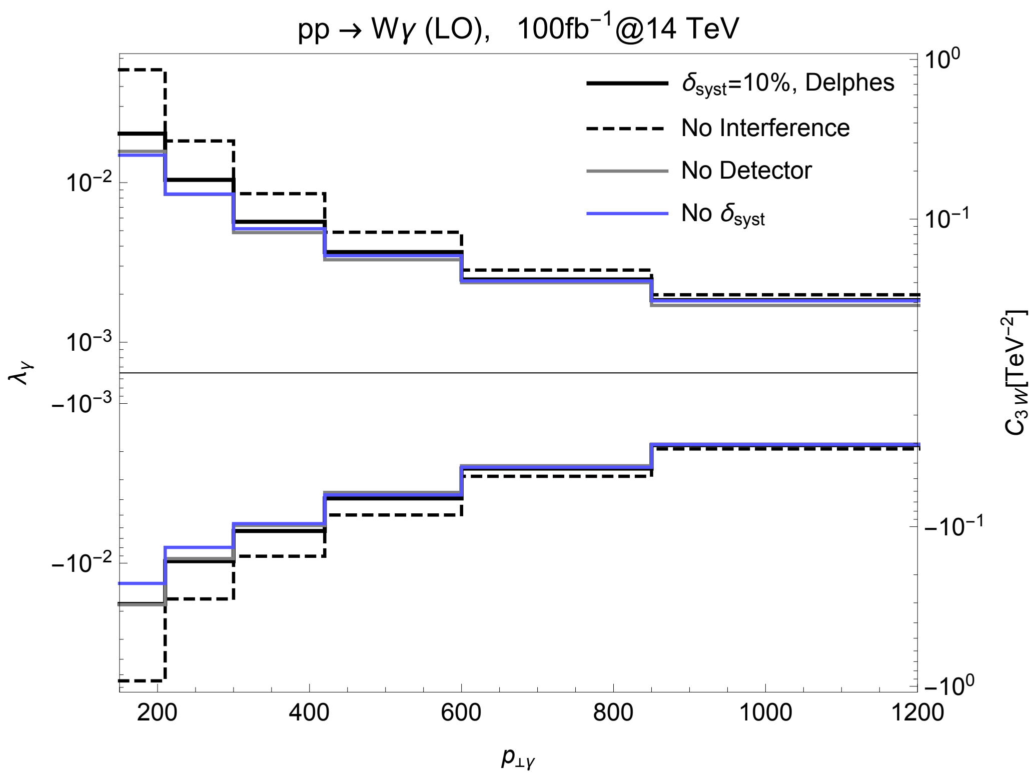
<u>Example</u>: corrections to TGC's: $\frac{ie}{m_{\mathrm{W}}^2}\lambda_\gamma W_\mu^{+\nu} W_\nu^{-\rho} A_\rho^{\ \mu}$

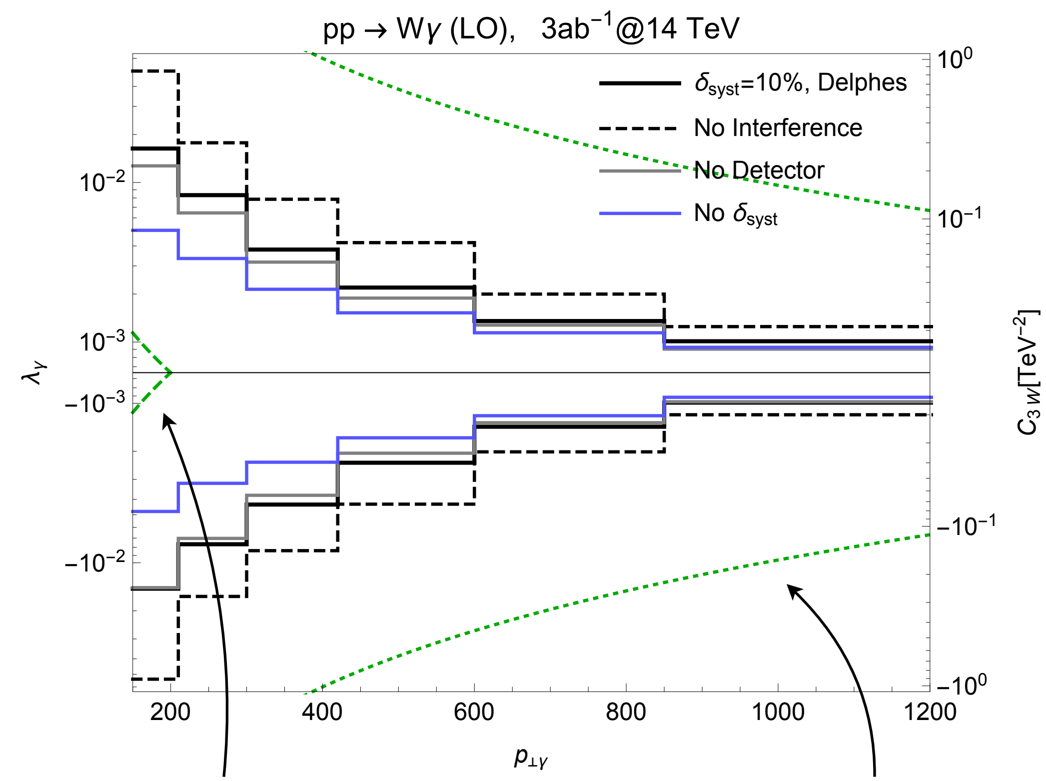


- ✦ BSM effects from interference clearly visible
  - neutrino reconstruction induces small uncertainty
  - detector effects under control

Sensitivity reach

"Interference resurrection" improves the bounds at LHC





one-loop new-physics $\lambda_\gamma \sim 6g^2/(16\pi^2)\, m_W^2/\Lambda^2$

weakly-coupled new-physics $\lambda_\gamma \sim 6\, m_W^2/\Lambda^2$

- ✦ largest effects in low-energy bins (factor ~2 improvement)
- ✦ significant improvement also on overall bound at HL-LHC

$$|\lambda_\gamma| < 1.0 \times 10^{-3}$$

$|\lambda_\gamma| < 1.3 \times 10^{-3}$ w/o interference

$|\lambda_\gamma| < 0.9 \times 10^{-3}$ no syst. error

- ✦ sensitive to tree-level weakly-coupled new physics

Conclusions

Conclusions

Hadron colliders can be used to get **precision EW measurements**

- exploit energy growth of new-physics effects

Challenges:

- accessing **high-energy tails**, good statistics (eg. $2 \to 2$ scattering)
- **accuracy**, low systematic uncertainties (eg. leptonic final states)

LHC can be **competitive** or even **better than LEP**

- di-lepton DY production (test of universal W and Y)
- di-boson production (test trilinear gauge couplings; analogous of S)

Outlook (in progress):

- exploit full kinematic distributions
- enhance new-physics with "interference resurrection"