Electroweak precision tests at hadron colliders

Giuliano Panico

IFAE Barcelona

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based on Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16
and in progress w/ Franceschini, Pomarol, Riva, Wulzer

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

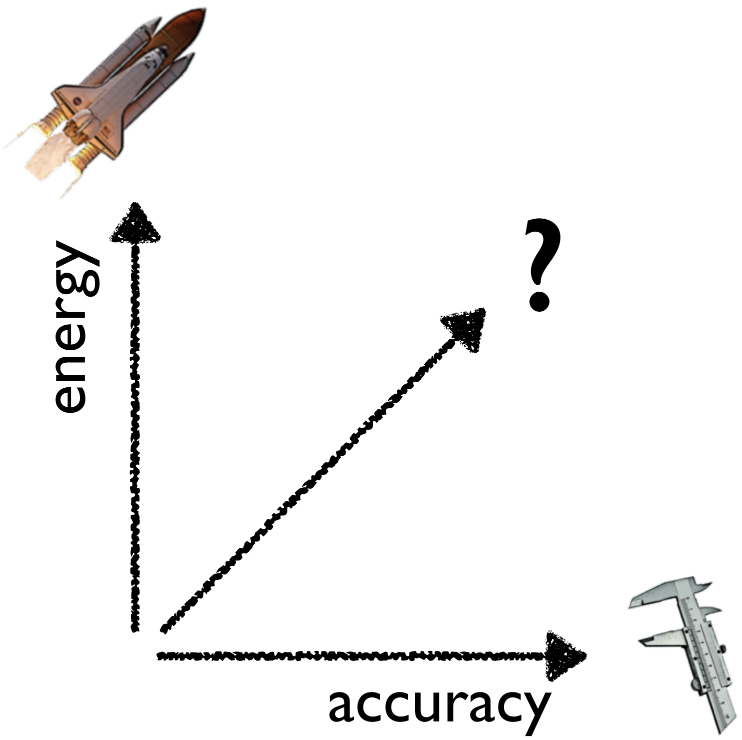
limited energy reach

high accuracy
(small systematics < %)

precision measurements
↓
indirect searches

Energy and accuracy

Can we take advantage of higher energy to improve precision tests?



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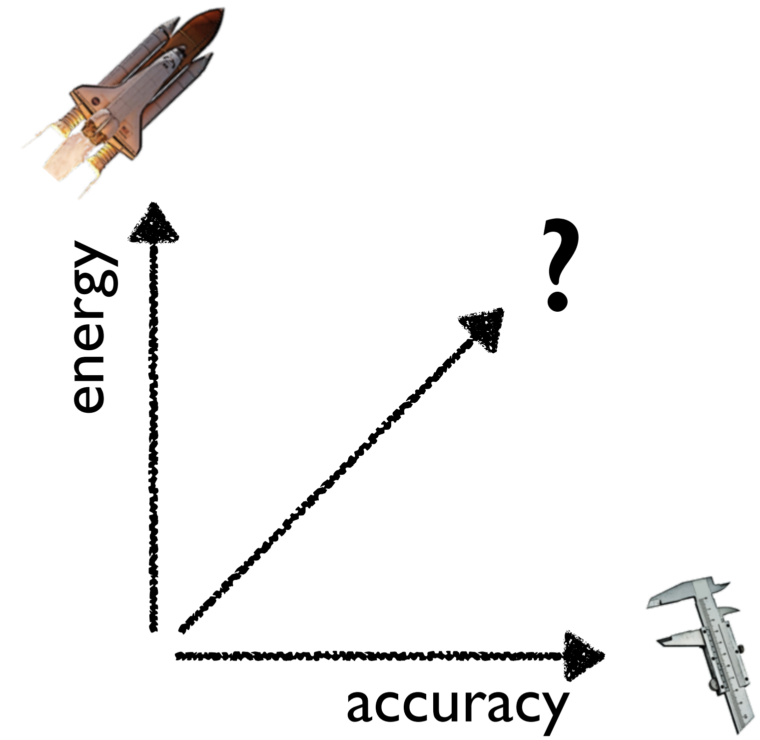


If new physics is heavy, low-energy effects are well described by the **EFT language**:

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

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

- 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

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

EFT validity

Corrections can not be arbitrarily large

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

Restrictions:

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

$\Big\}$ → $\dfrac{\delta\mathcal{A}}{\mathcal{A}_{\rm SM}} \lesssim 1$

✦ 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

✦ analysis must be restricted to events below the cut-off

Limitations: non-interference

Simplest channels: **$2 \to 2$ scattering**

Limitations: non-interference

Simplest channels: **2 → 2 scattering**

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

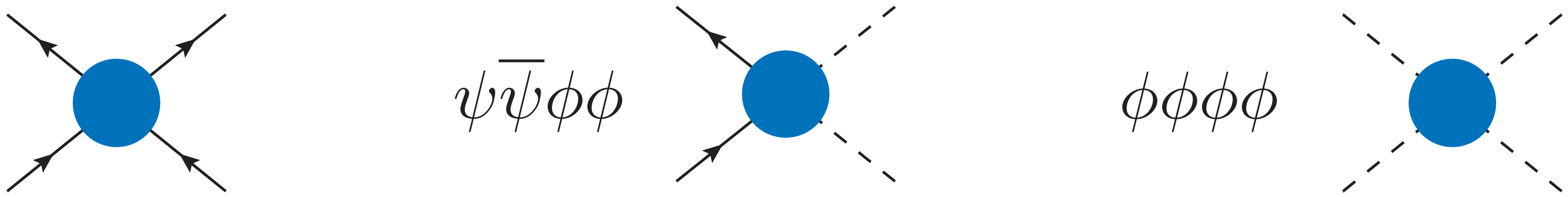
Limitations: non-interference

Simplest channels: **2 → 2 scattering**

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

✦ Only three channels interfere at **leading order** in $(\varepsilon_{\rm V})^0 = (m_{\rm V}/E)^0$

$\psi\overline{\psi}\psi\overline{\psi}$ $\psi\overline{\psi}\phi\phi$ $\phi\phi\phi\phi$ $(\,\phi = h, V_L\,)$



N.B. amplitudes with longitudinal modes accidentally suppressed

$$\sigma_{\rm SM}(\psi\overline{\psi} \to V_L V_L) \sim 0.002\ \sigma_{\rm SM}(\psi\overline{\psi} \to V_T V_T)$$
$$\sigma_{\rm SM}(V_L V_L \to V_L V_L) \sim 0.1\ \sigma_{\rm SM}(V_T V_T \to V_T V_T)$$

✦ Channels with transverse vectors interfere only at **subleading order**

eg. $\mathcal{A}_{\rm SM}(\psi\overline{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^0$ $\mathcal{A}_{{\rm BSM}_6}(\psi\overline{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^2$

Three examples

In the following, three examples:

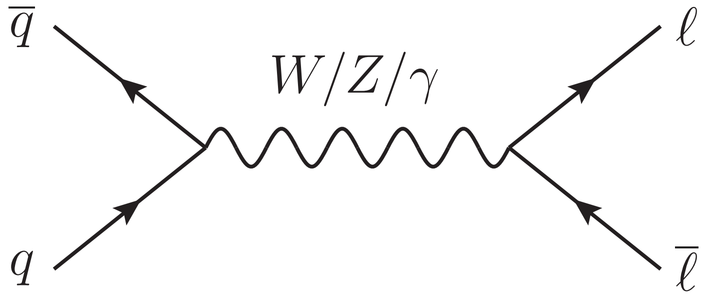
- ✦ Di-lepton Drell-Yan production
- ✦ WZ production
- ✦ $W\gamma$ production

An easy example: leading interference

Di-lepton DY production

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

Oblique parameters at LHC



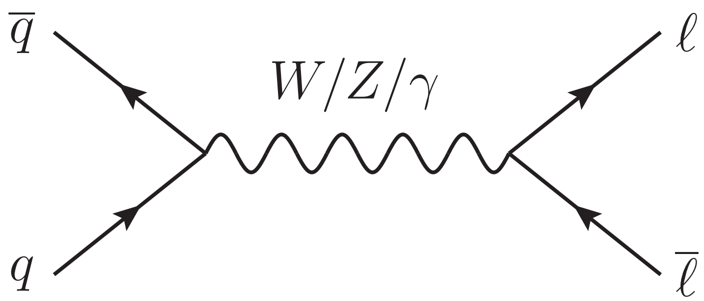
Drell-Yan production ($\ell^+\ell^-$ or $\ell\nu$)

Simple BSM effects: **oblique parameters**

- Large cross section and interference at leading order with SM

  → ideal process to test new physics

Oblique parameters at LHC



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

Simple BSM effects: **oblique parameters**

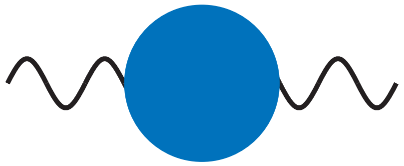
- Large cross section and interference at leading order with SM

  → ideal process to test new physics

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

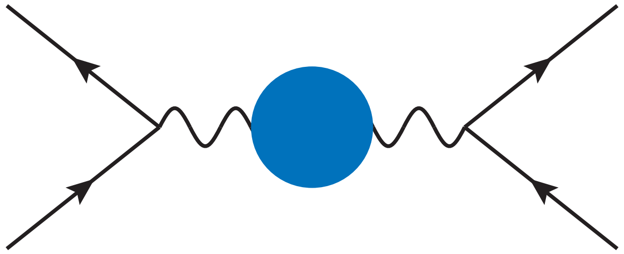
$$\frac{gg'\hat{S}}{16m_W^2}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \qquad -\frac{g^2\hat{T}}{2m_W^2}|H^\dagger D_\mu H|^2$$

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



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

Oblique parameters at LHC



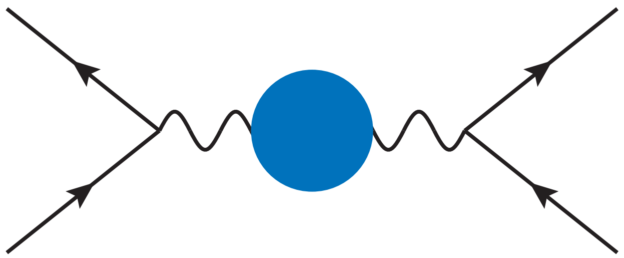
Drell-Yan production ($\ell^+\ell^-$ or $\ell\nu$)

Simple BSM effects: **oblique parameters**

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

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

Oblique parameters at LHC



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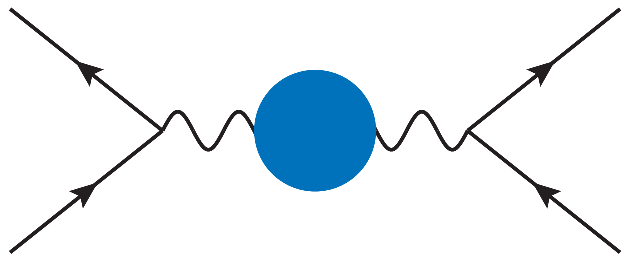
✦ $\hat{S}$ and $\hat{T}$: only affect pole residues (i.e. total cross-section)
LHC measurements (% from syst.) **not competitive**

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**

↓

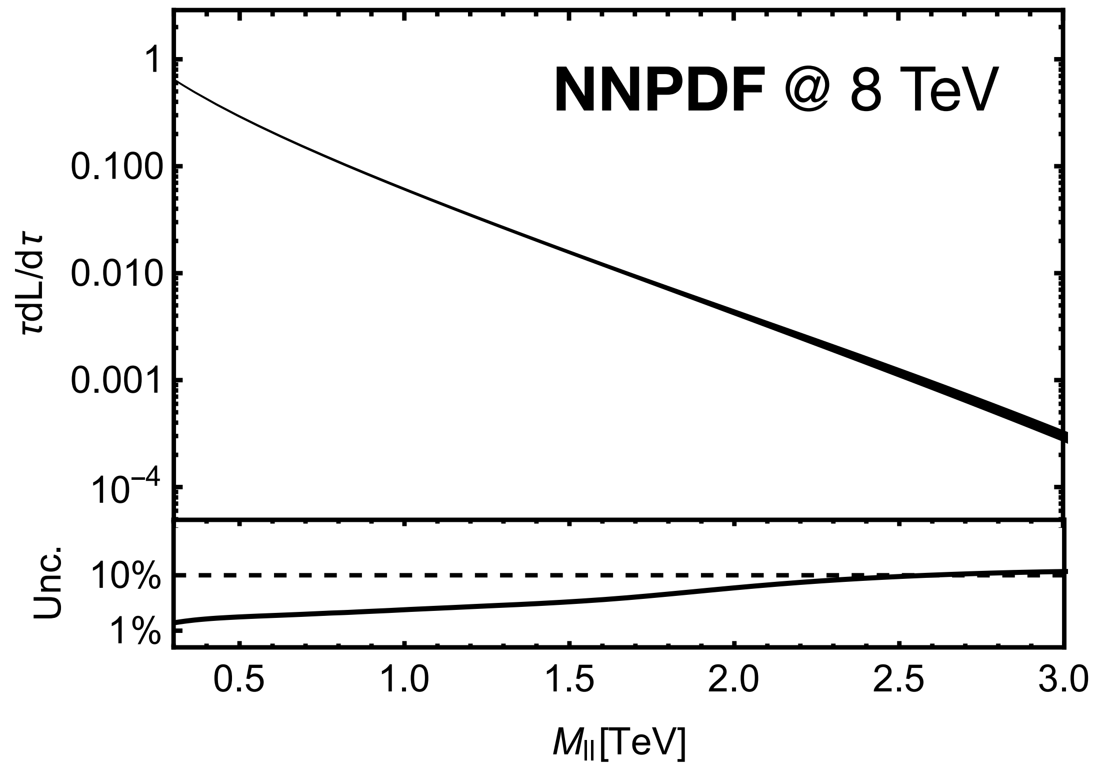
large **improvement** possible at run-2

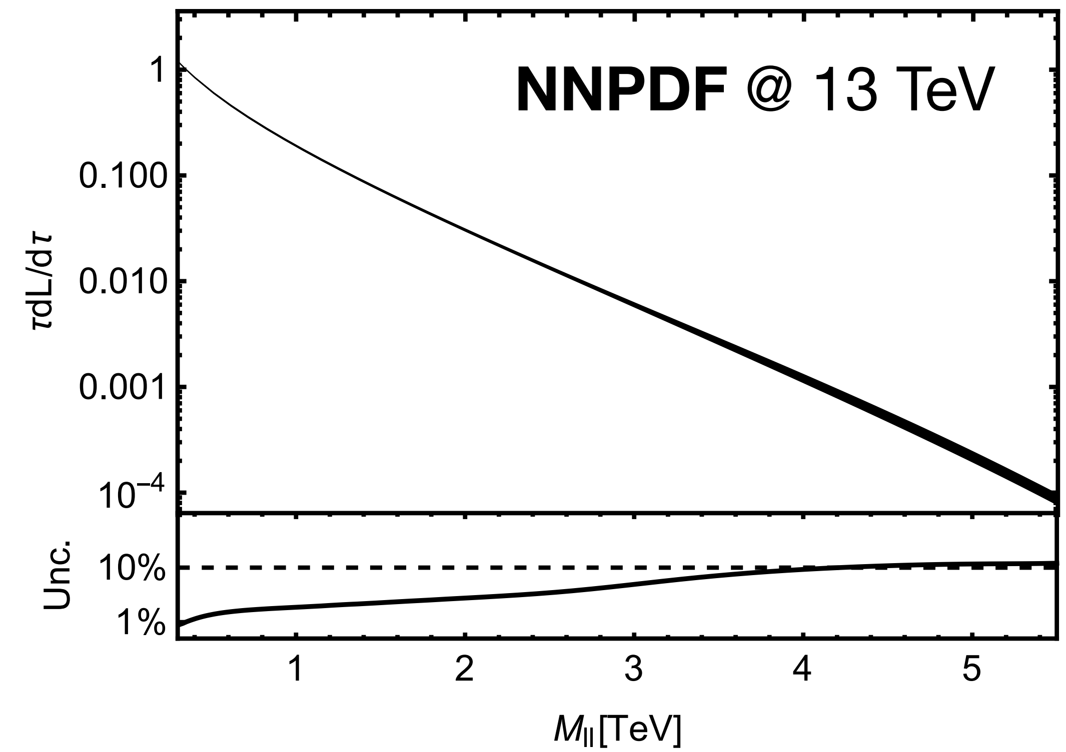
systematic error ~2%

Theory uncertainty

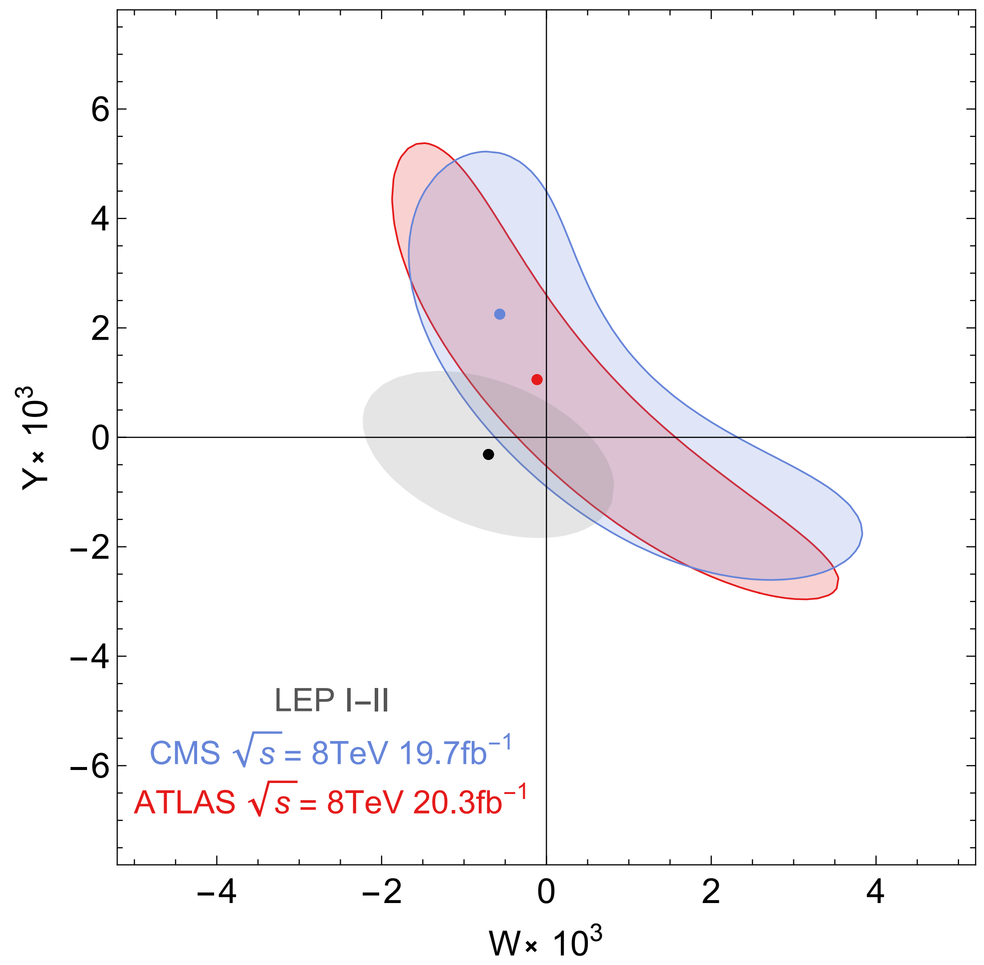
Theory errors well under control

- ✦ 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)



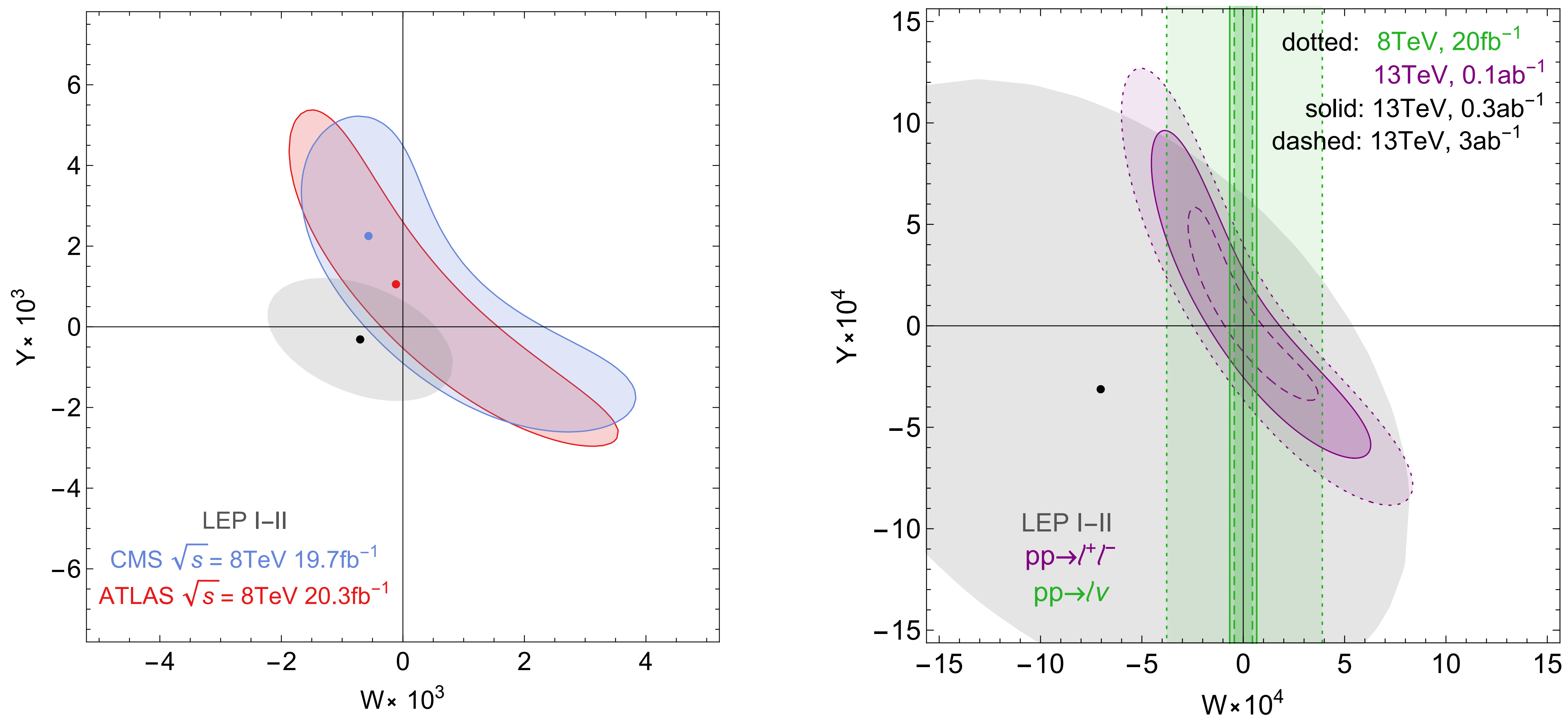


Oblique parameters at the LHC



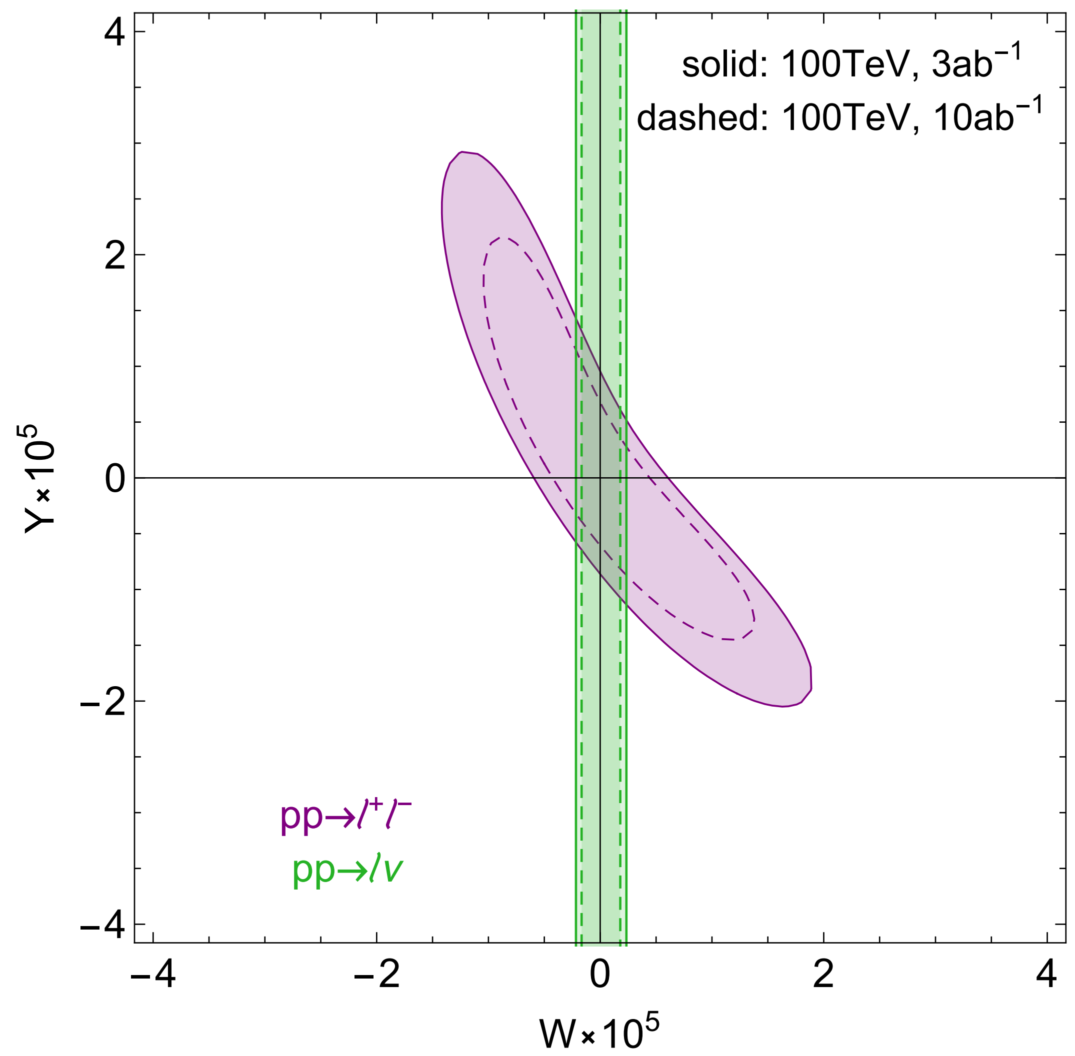
✦ Neutral DY at **8 TeV** is roughly competitive with LEP

Oblique parameters at the LHC



- 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}

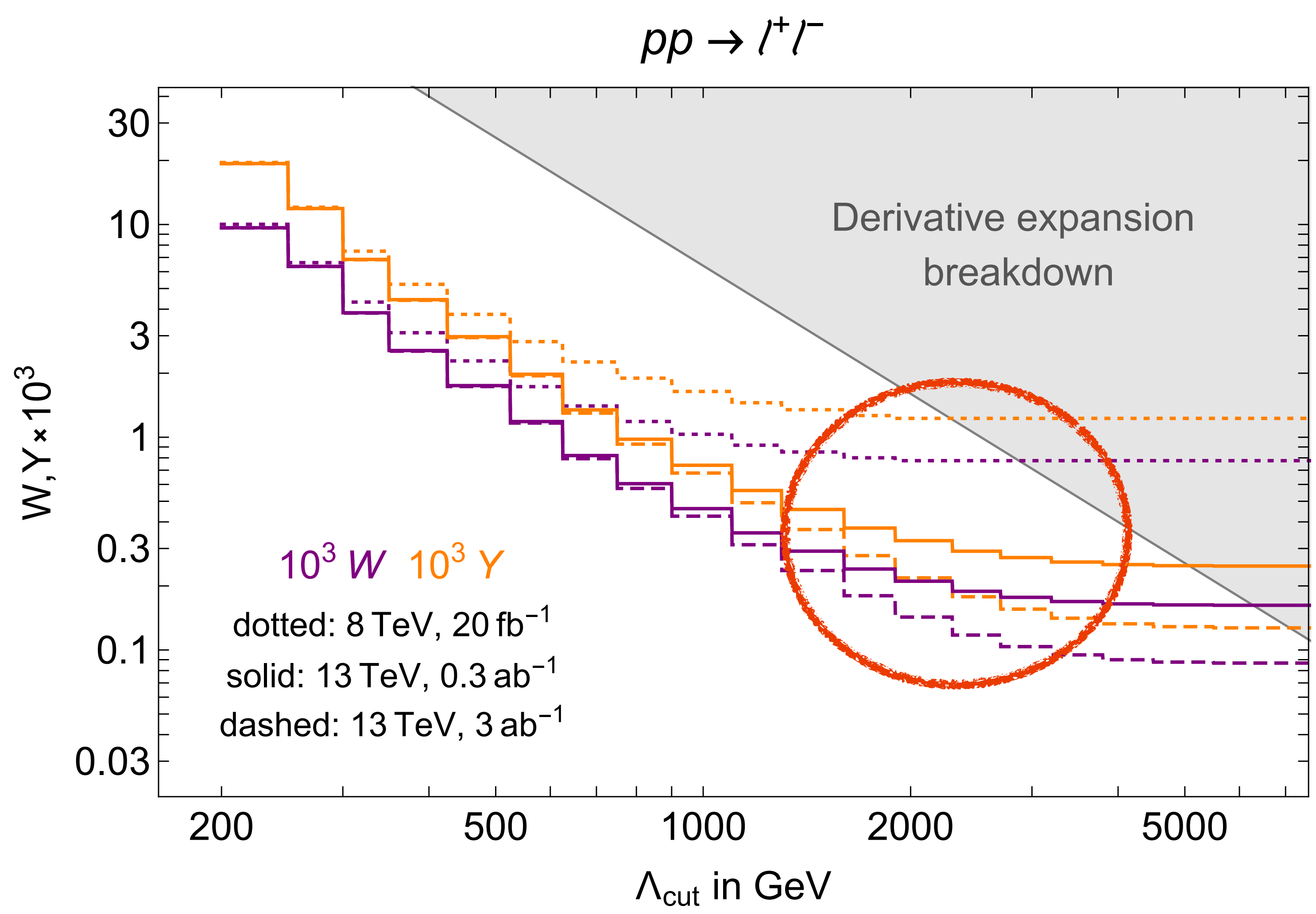


- FCC_{100} could improve the LHC bound by more than one order of magnitude

The relevant energy range

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

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



- Energy bins up to ~ 3 TeV are relevant for the bounds
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The relevant energy range

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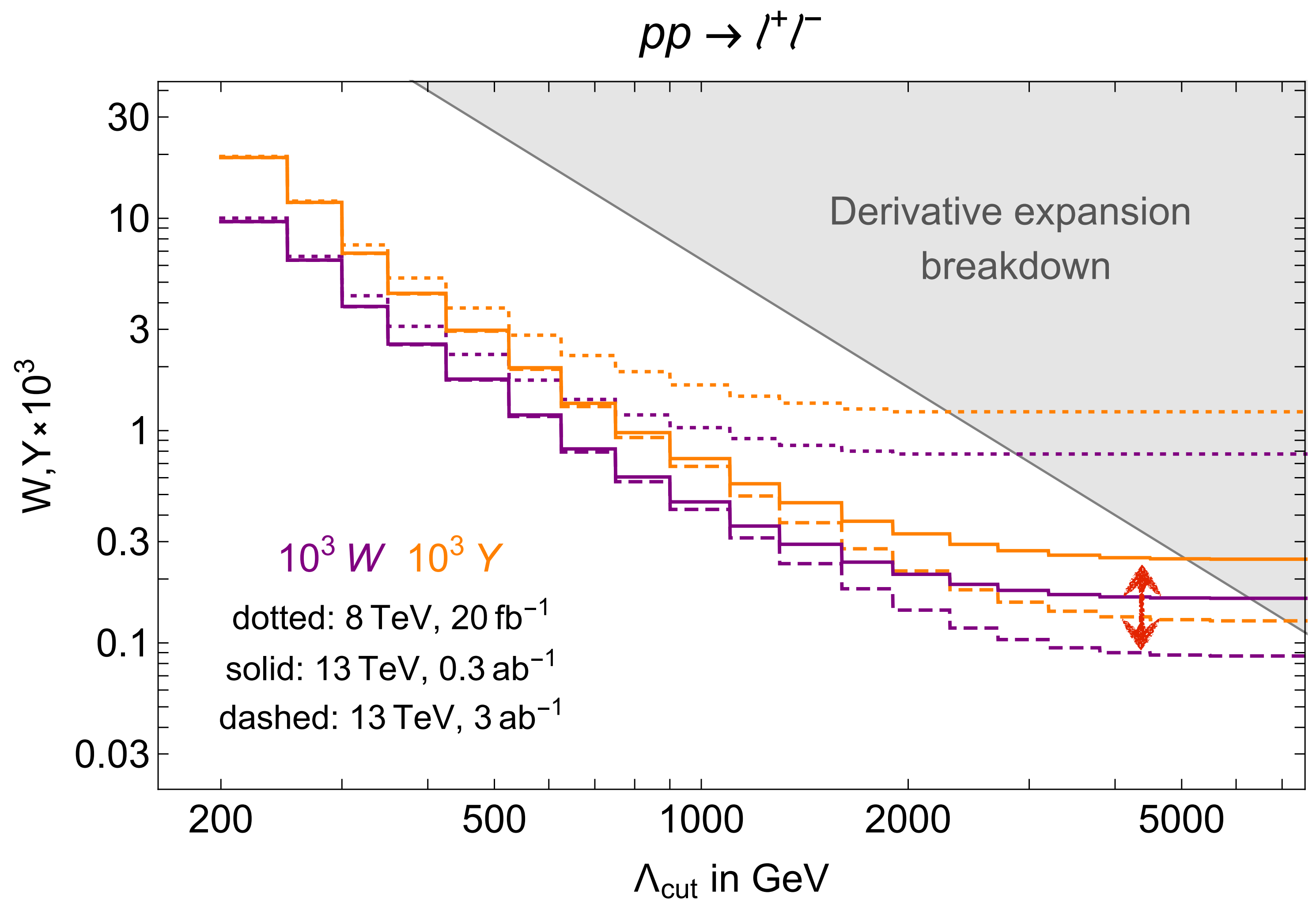


- Energy bins up to ~ 3 TeV are relevant for the bounds
  (at higher energies statistics quickly degrades due to pdf's)

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

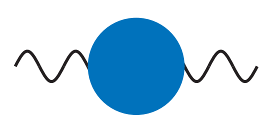
Validity of the EFT description

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

<u>**form factor picture**</u>

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

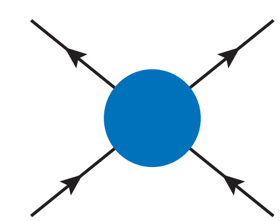


$$\Lambda_{max} = \frac{m_{\rm W}}{\max(\sqrt{W}, \sqrt{Y})}$$

(new operators smaller than SM kinetic terms)

<u>**contact interactions picture**</u>

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



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

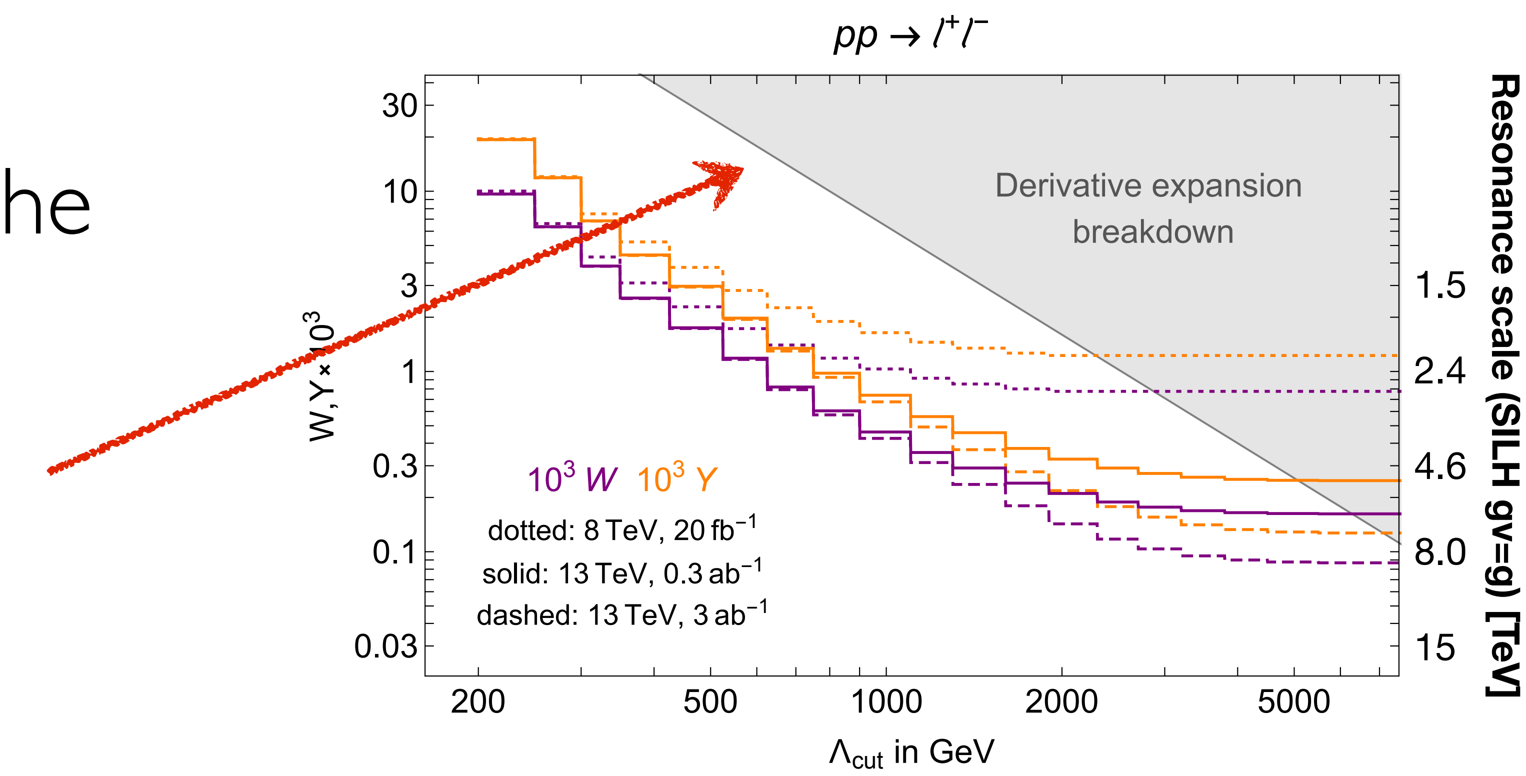
(perturbativity bound)

maximal cut-off is different!

Validity of the EFT description

maximal cut-off limits the range of validity

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



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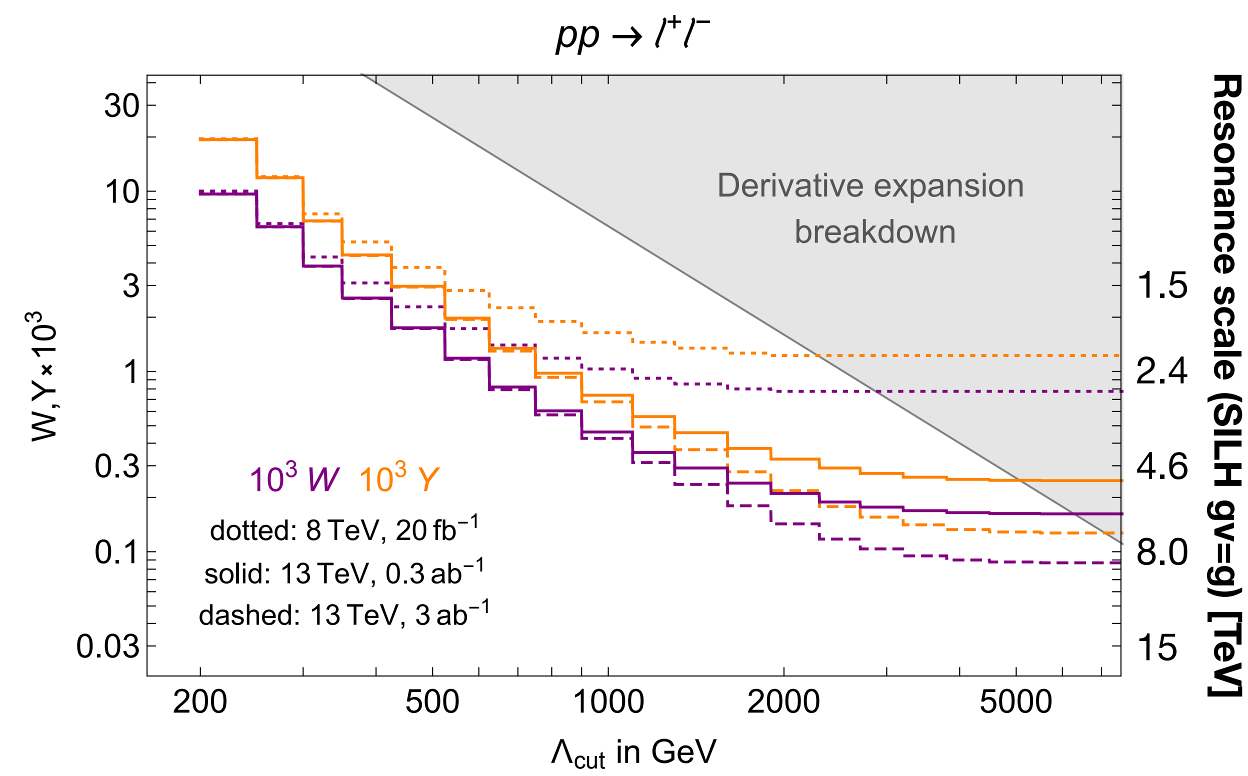
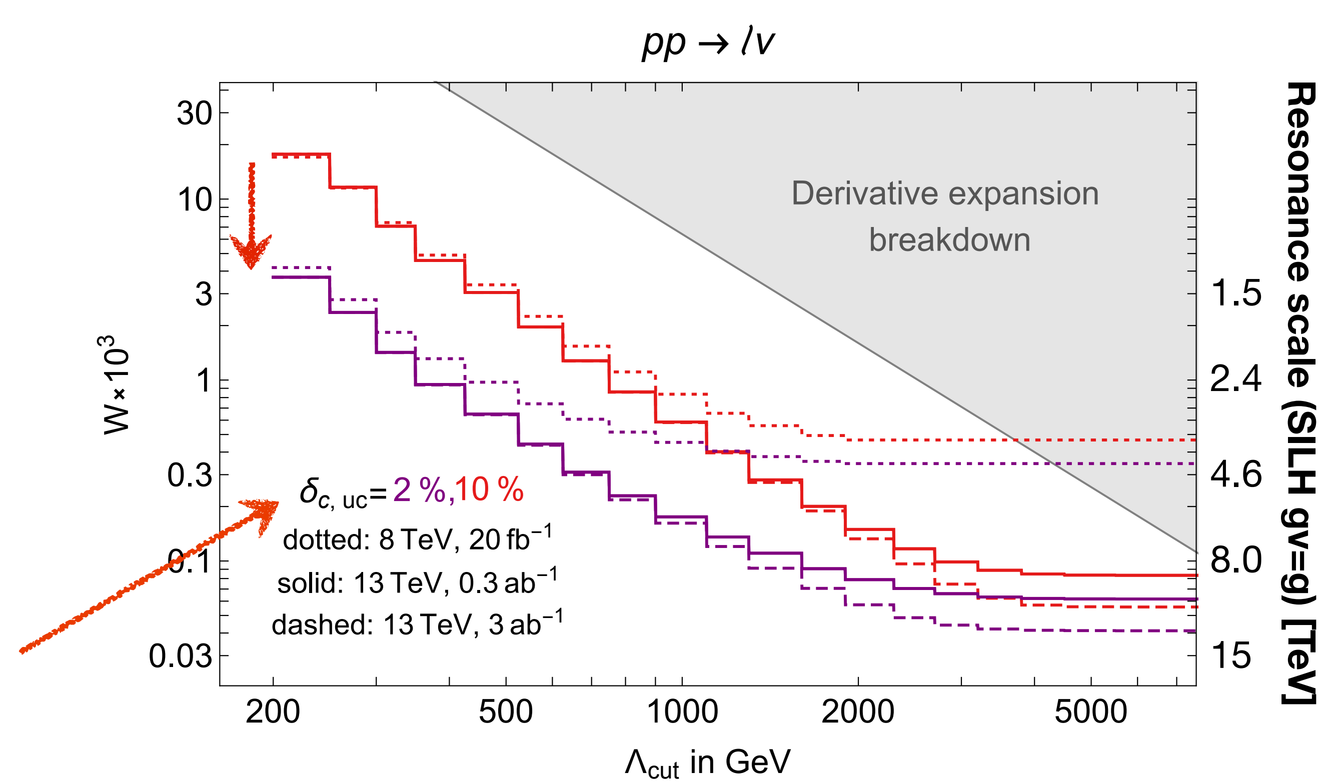


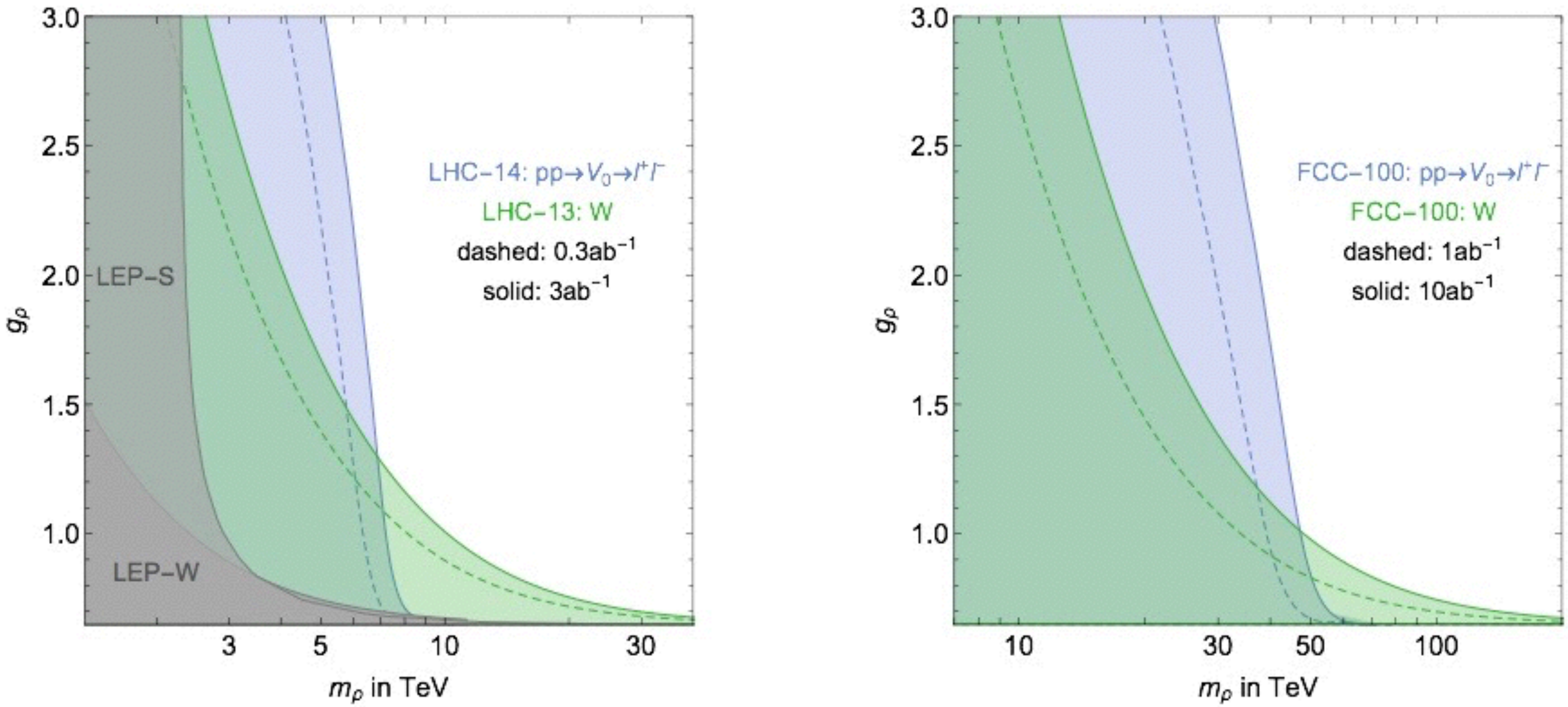
accuracy moves the bounds away from the maximal cut-off

syst. error



Comparison with direct searches

competitive with direct searches on new vector states with O(1) couplings

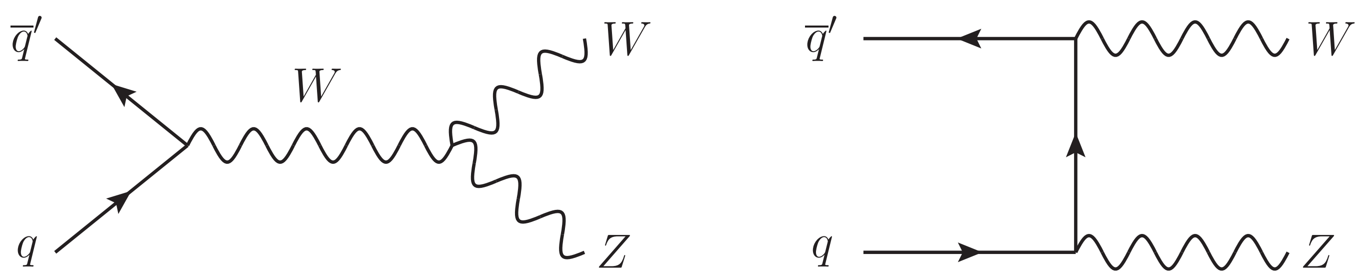


Looking for subleading channels

The WZ process

in progress w/ Franceschini, Pomarol, Riva, Wulzer

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**
(no enhancement in transverse channels due to non-interference theorem)

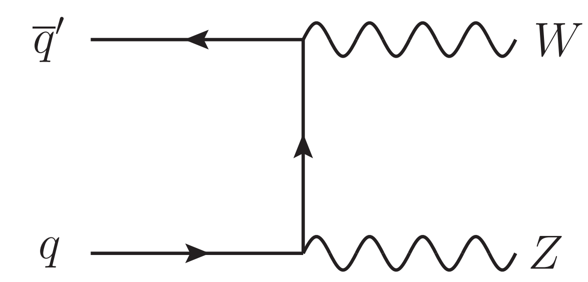
$$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\overline{q}_L \sigma^a \gamma^\mu q_L) \longrightarrow \frac{\mathcal{A}_{00}^{\mathrm{SM+BSM}}(q\bar{q} \to WZ)}{\mathcal{A}_{00}^{\mathrm{SM}}(q\bar{q} \to WZ)} = 1 + 4\frac{s}{\Lambda^2} c_L^{(3)}$$

leading correction from interference with SM

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 $\mathrm{BR}(WZ \to (\ell\nu)(\ell\ell)) \simeq 1.5\%$)

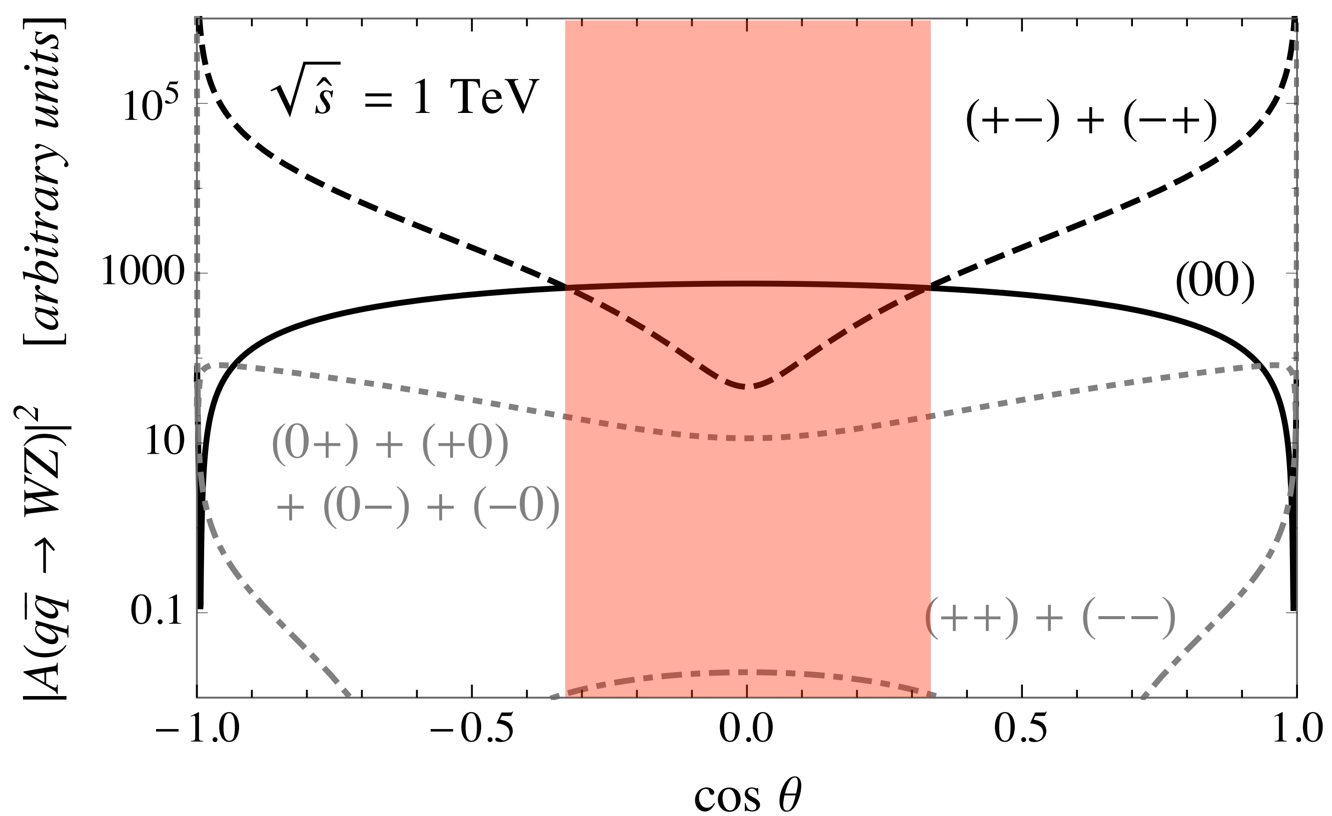
Extracting the longitudinal channel

Transverse amplitudes vanish for (nearly) central scattering

[Baur, Han, Ohnemus '94]

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

- 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}
$\lvert\cos\theta\rvert < 0.5 \quad \sqrt{\hat{s}} > 300$ GeV	630 fb	230 fb	37%
$\lvert\cos\theta\rvert < 0.5 \quad \sqrt{\hat{s}} > 500$ GeV	80 fb	34 fb	42%

Sensitivity to new physics

Good sensitivity to new physics: $$\frac{c_L^{(3)}}{(1\ \mathrm{TeV})^2}(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\overline{q}_L\sigma^a\gamma^\mu q_L)$$

13 TeV ($|\cos\theta| < 0.5$)	$\sqrt{\hat{s}} > 300$ GeV			$\sqrt{\hat{s}} > 500$ GeV		
	σ_{LL}	σ_{LL}/σ_{tot}	$\delta\sigma_{tot}$	σ_{LL}	σ_{LL}/σ_{tot}	$\delta\sigma_{tot}$
SM	230 fb	37%		34 fb	42%	
$c_L^{(3)} = 0.05$	290 fb	43%	6%	46 fb	52%	10%
$c_L^{(3)} = 0.5$	470 fb	61%	24%	92 fb	82%	40%

In progress:

- realistic analysis
  - find sensitive observables/distributions (c.o.m. reconstruction?)
  - systematics (detector effects, …)
- comparison with existing bounds

Azimuthal correlation

The $W\gamma$ process

in progress w/ Franceschini, Pomarol, Riva, Wulzer

"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

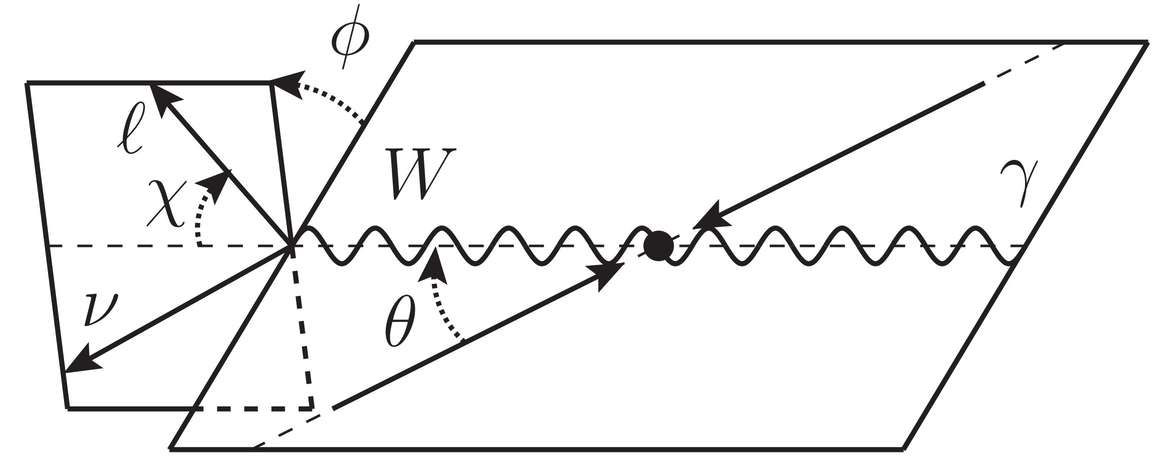
A simple process to explore interference is $W\gamma$ production

Polarized **production**:

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

Polarized W **decay**:

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



- azimuthal phase depending on W polarization

Wγ production: the amplitude

Total amplitude:

$$|\mathcal{A}_{tot}|^2 \sim (1+c_\chi)^2|\mathcal{A}_{(+\pm)}|^2 + (1-c_\chi)^2|\mathcal{A}_{(-\pm)}|^2 + 2s_\chi^2|\mathcal{A}_{(0\pm)}|^2$$

no interference

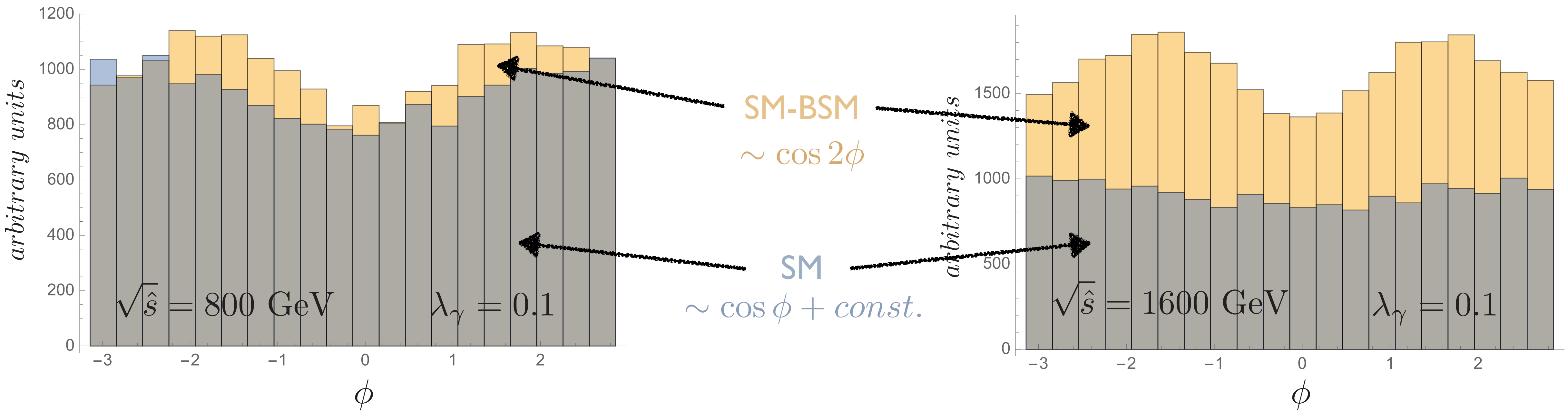
$$-2s_\chi^2\,\mathrm{Re}[\mathcal{A}_{(+\pm)}\mathcal{A}^*_{(-\pm)}e^{2i\phi}]$$
$$-2\sqrt{2}(1+c_\chi)s_\chi\,\mathrm{Re}[\mathcal{A}_{(+\pm)}\mathcal{A}^*_{(0\pm)}e^{i\phi}]$$
$$+2\sqrt{2}(1-c_\chi)s_\chi\,\mathrm{Re}[\mathcal{A}_{(-\pm)}\mathcal{A}^*_{(0\pm)}e^{-i\phi}]$$

interference: **azimuthal correlations**

→ interference terms lead to non-trivial dependence on ϕ

Wγ production: TGC corrections

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



In progress:

- ✦ extraction of bounds on TGC's
- ✦ application to other processes (eg. WZ)?

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**

- proof of principle: W and Y from di-lepton DY

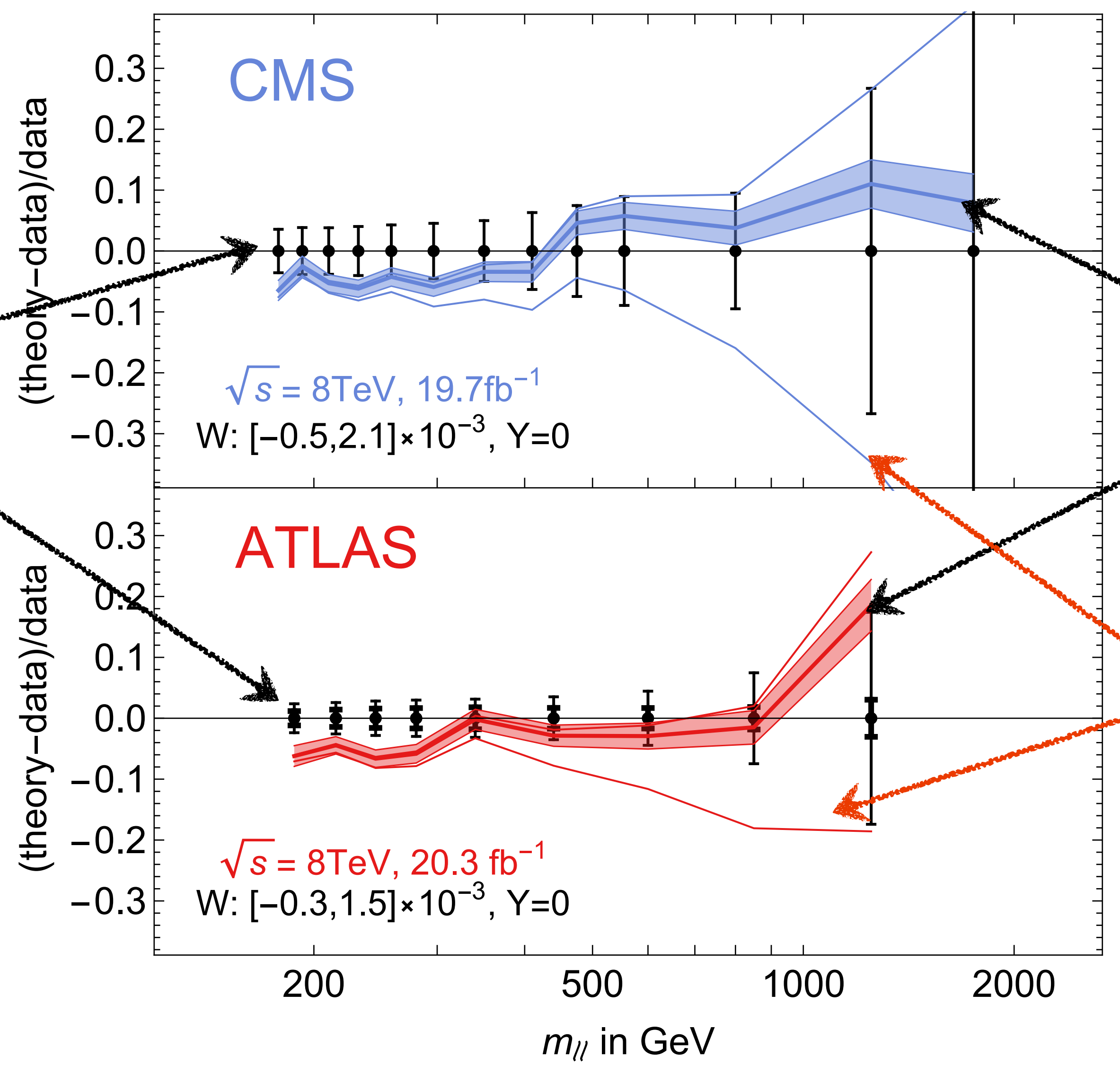
Many more channels to explore (eg. di-boson production)

Backup

The SM prediction

The SM predictions are in excellent agreement with the data

statistical uncertainty



SM prediction w/ pdf and scale variation error

shift due to W and Y in the 95% CL region

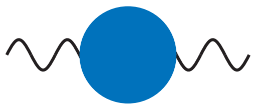
✦ Deviations for W, Y ~ 10^{-3} clearly visible

Validity of the EFT description

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

form factor picture

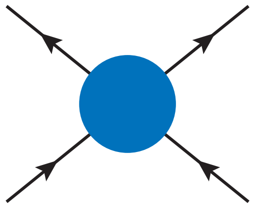
$$-\frac{W}{4m_{\rm W}^2}(D_\rho W^a_{\mu\nu})^2 \qquad -\frac{Y}{4m_{\rm W}^2}(\partial_\rho B_{\mu\nu})^2$$



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

contact interactions picture

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



new physics directly coupled to SM
fermions with "universal" couplings

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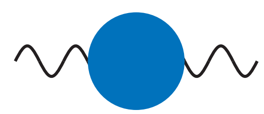

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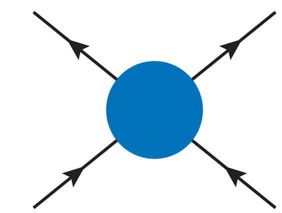

new physics directly coupled to SM
fermions with "universal" couplings

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

Comparison with future colliders

Bounds on W and Y at different colliders

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

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