The Energy **and** Accuracy Frontier

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EWPT at Hadron Colliders

The LHC precision program is still under construction

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But its key elements are already clear enough

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2) Exploit Low-/High-energy interplay:

EFT

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

Low-energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\rm EW}^2/\Lambda^2$

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

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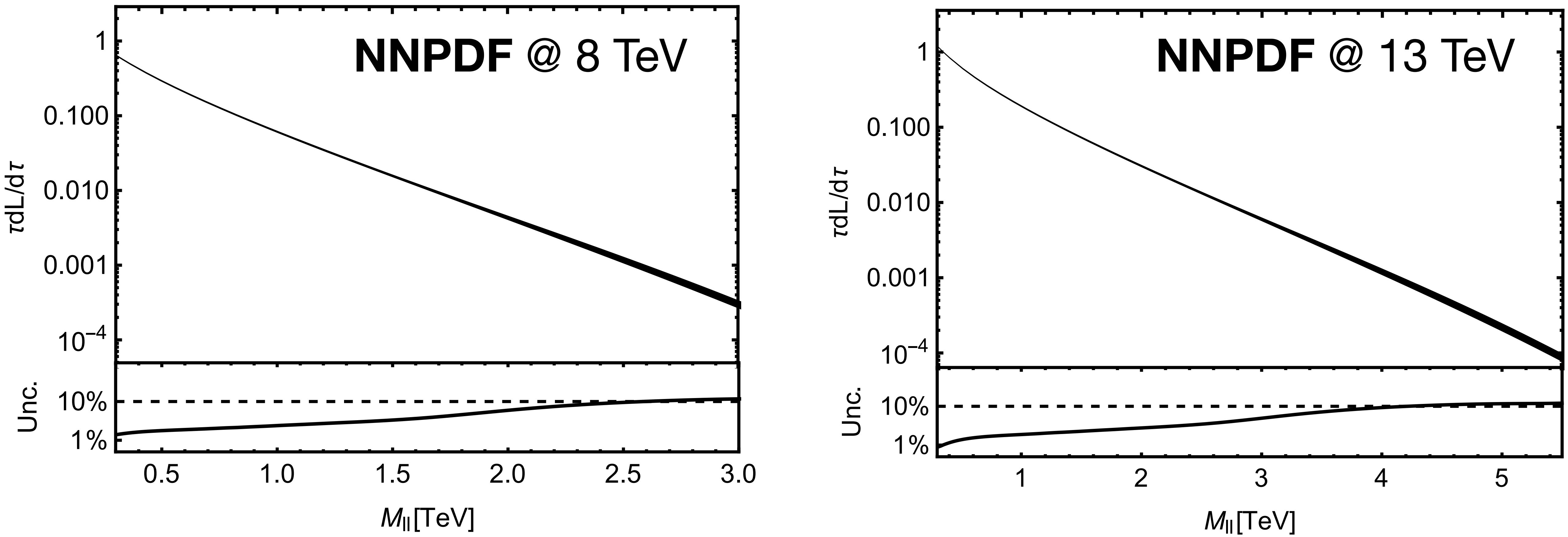
EWPT at Hadron Colliders



Factor ~10 improvement in multi-TeV cross-section. Possible to explore higher energies. Non-trivial interplay with luminosity determines final reach.

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EWPT at Hadron Colliders

The LHC precision

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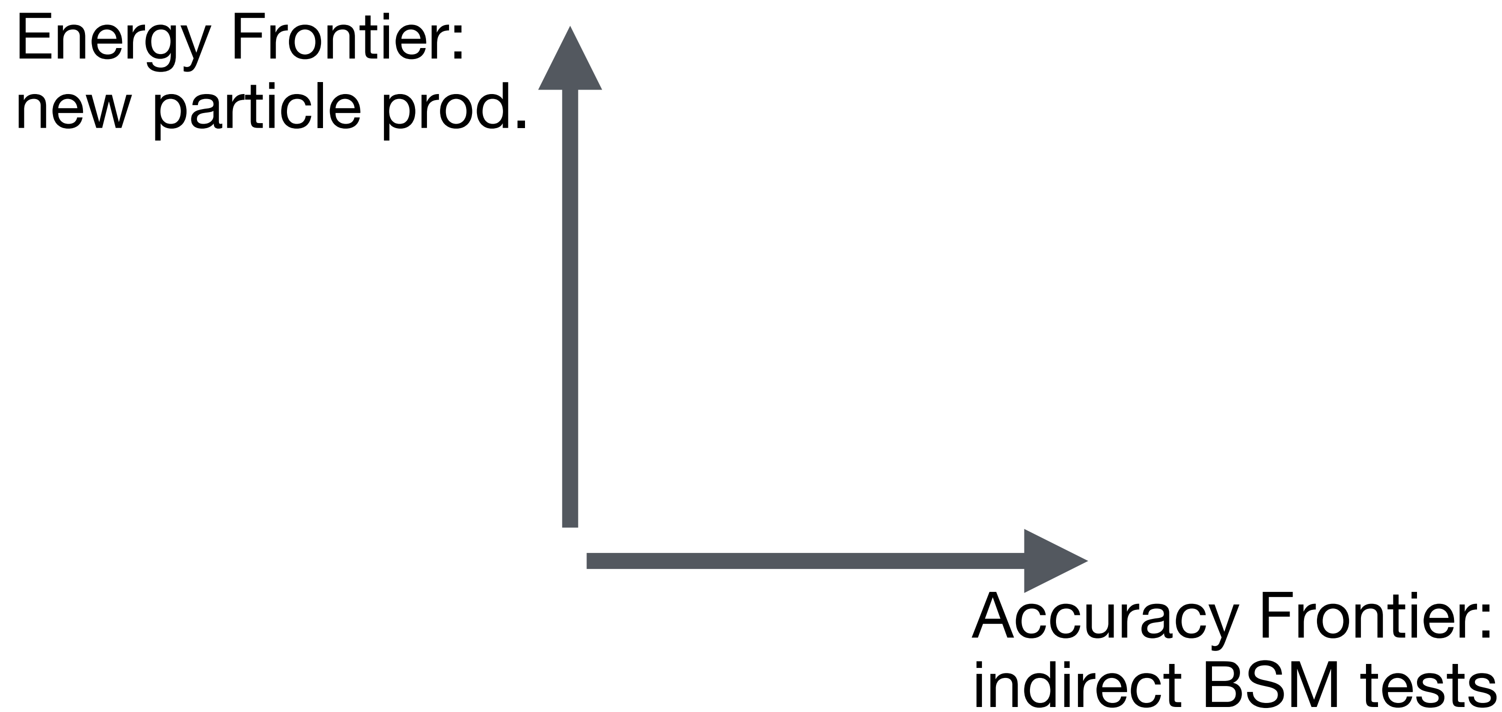
The Energy and Accuracy Frontier



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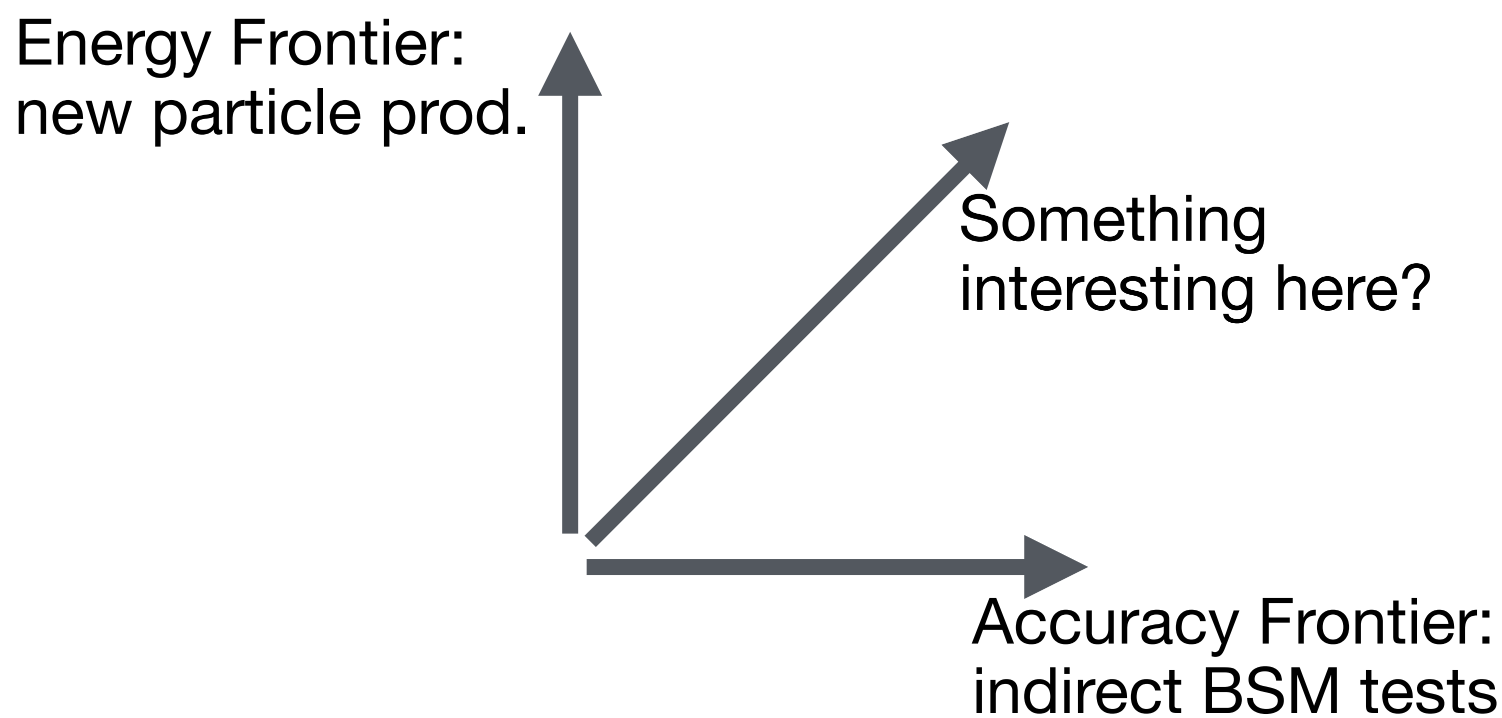

Substantial progress possible at run-2/3 and HL-LHC

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Energy and Accuracy Frontier

The Accuracy and Energy of **LEP** set a **benchmark**

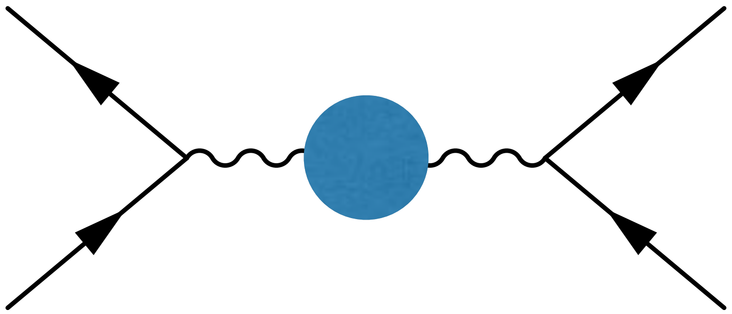
$$1‰ \; @ \; 100\,\mathrm{GeV} \quad \sim \quad 10\% \; @ \; 1\,\mathrm{TeV}$$

Beyond that threshold, **hadron colliders win, even in processes well measured by LEP!**

Hadron colliders also sensitive to processes where LEP could not tell much. More **complete exploration**

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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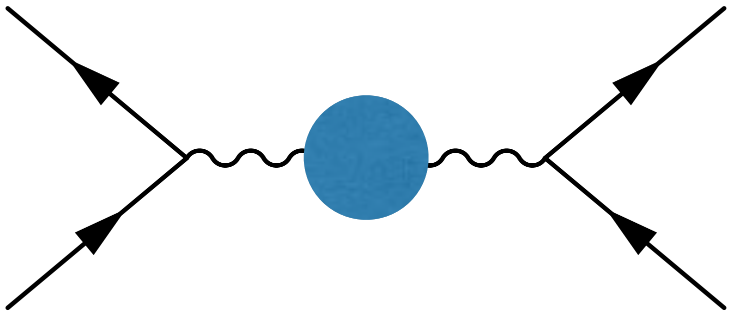

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$\hat{\mathrm{S}}$ and $\hat{\mathrm{T}}$: only affect pole residues, i.e., tot. X-sec.
LHC measurements (%, from syst.) **are not competitive**

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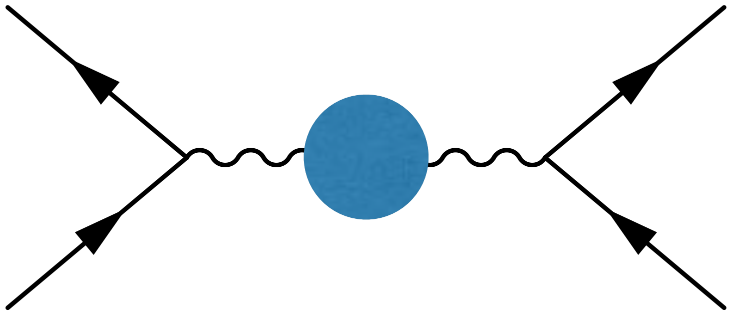

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W and Y: produce constant terms.
quadratically enhanced at high mass. What can LHC do?

Oblique Parameters at the LHC

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

Ingredients for the program to work:

Accurate experimental measurement:

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

$m_{\ell\ell}$ [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

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~ **1 TeV** measured at ~ **10%**

Reach comparable with LEP ?

Oblique Parameters at the LHC

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Ingredients for the program to work:

Accurate experimental measurement: Syst. ~ 2%

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Statistically dominated error

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

Run-2 will surpass LEP ?

Oblique Parameters at the LHC

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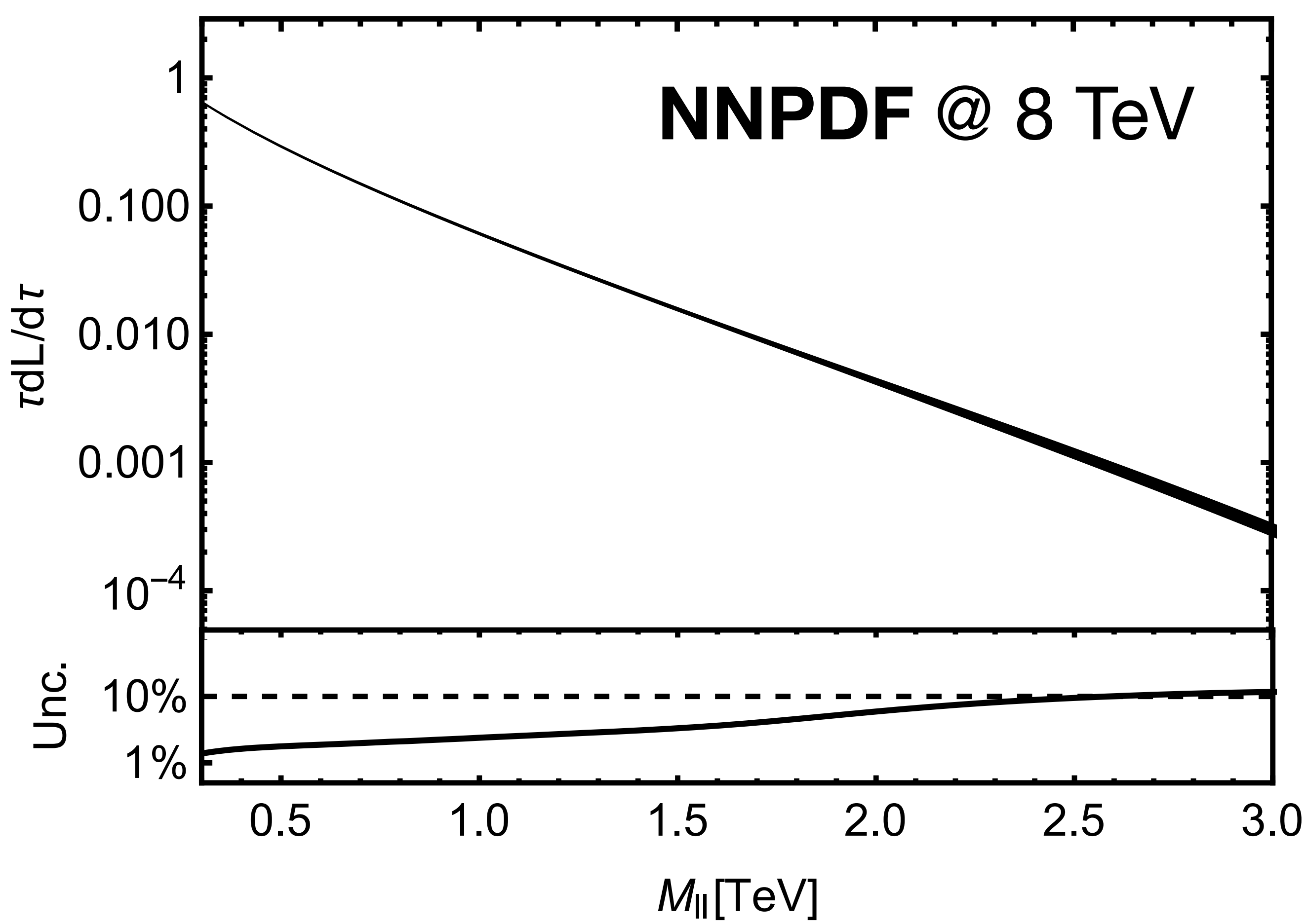
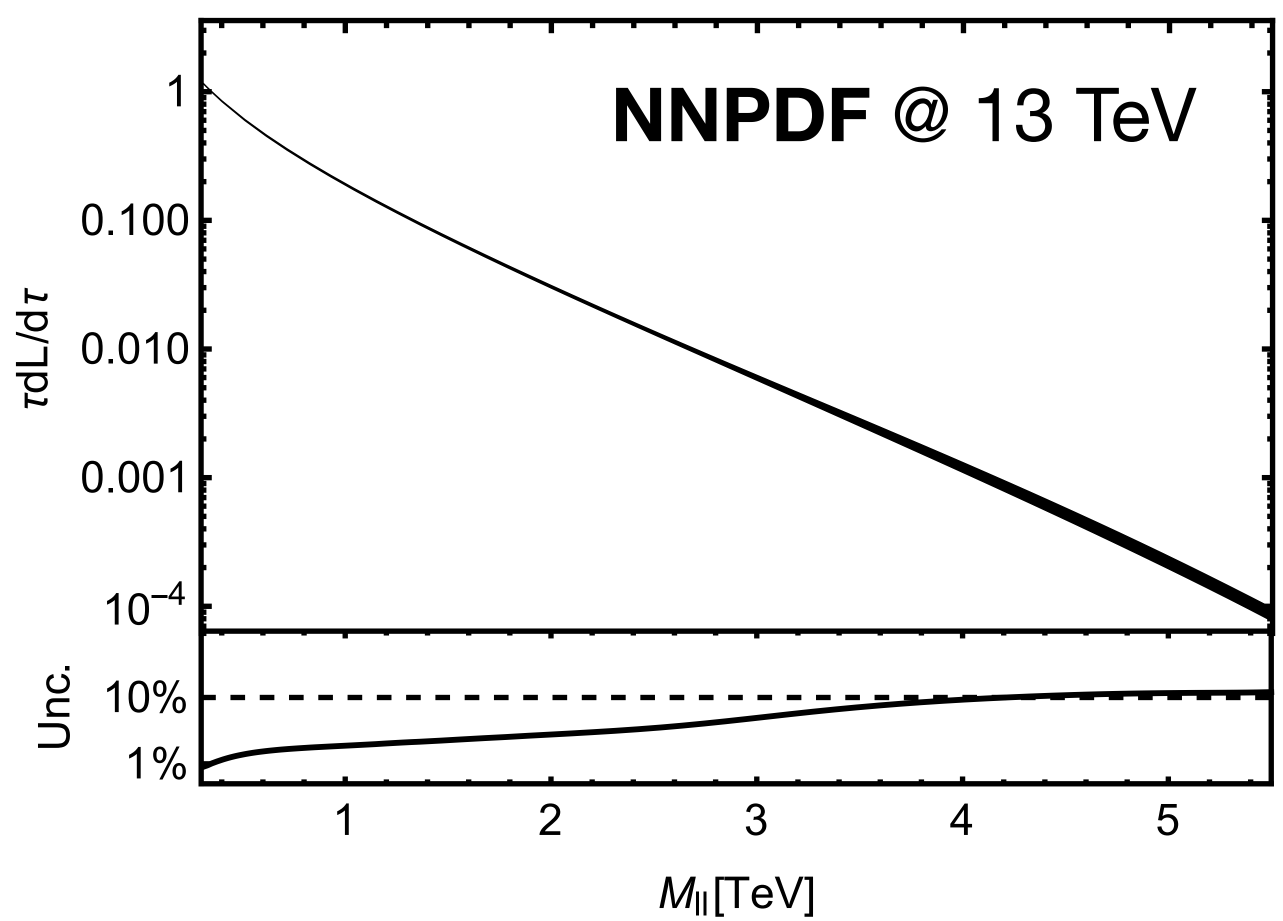
Theory errors well under control:

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





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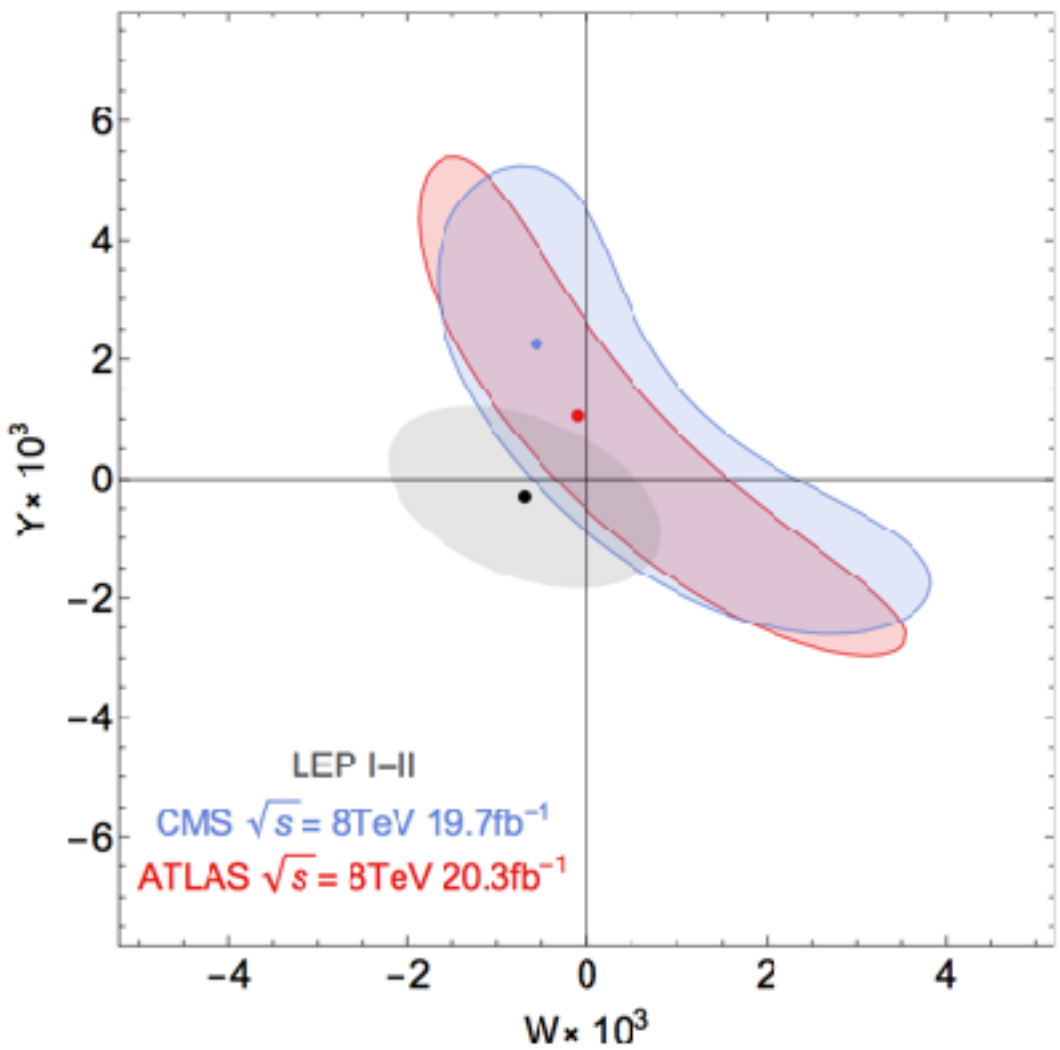
Theory errors well under control:

- q-qbar PDF error < 10% below 3 (4) TeV @ run-1 (run-2)
- NNLO QCD (FEWZ): < 1 % scale variation
- NLO EW known and under control
- photon PDF uncertainty safely small [Manohar,Nason,Salam,Zanderighi, 2016]

Oblique Parameters at the LHC

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



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

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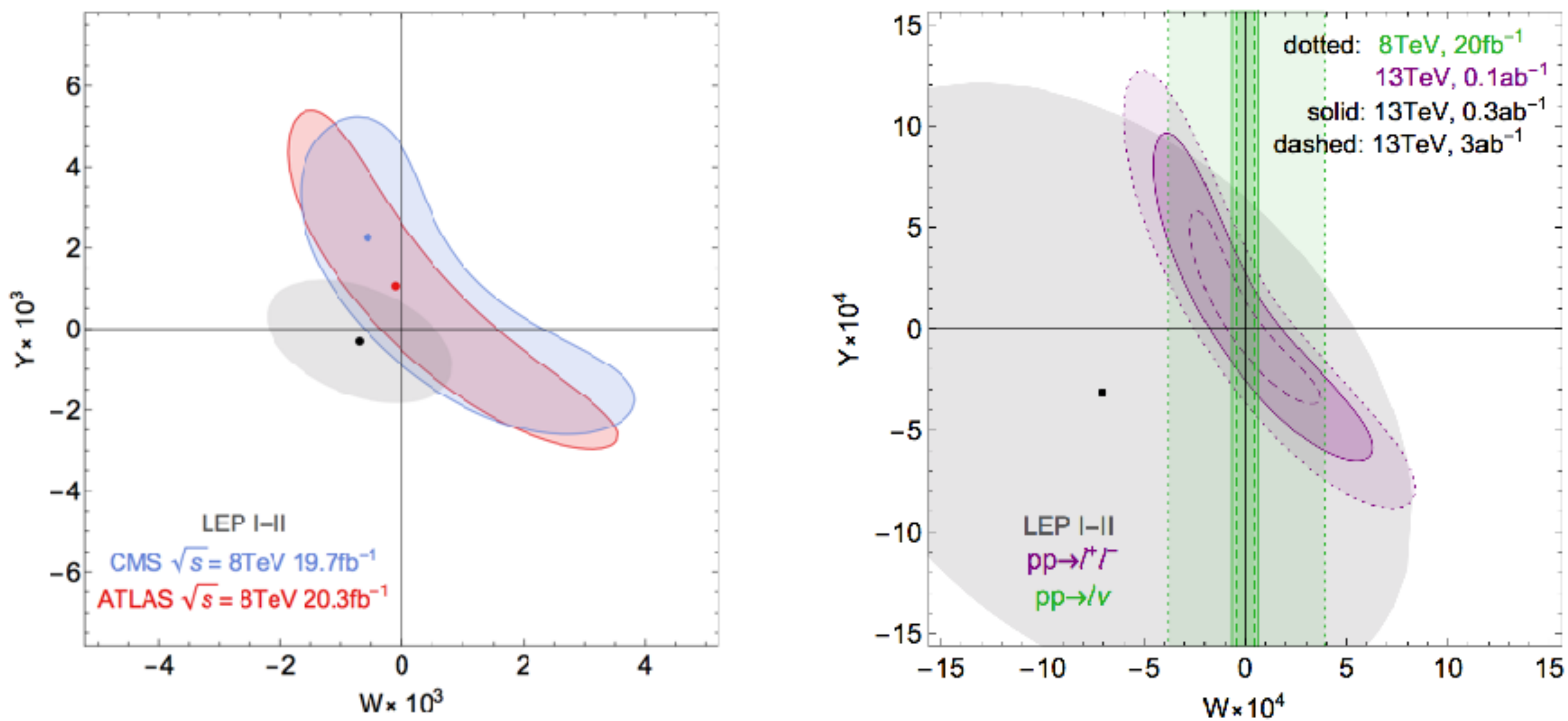

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Charged DY @ **run-1 would surpass LEP**

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

Oblique Parameters at the LHC

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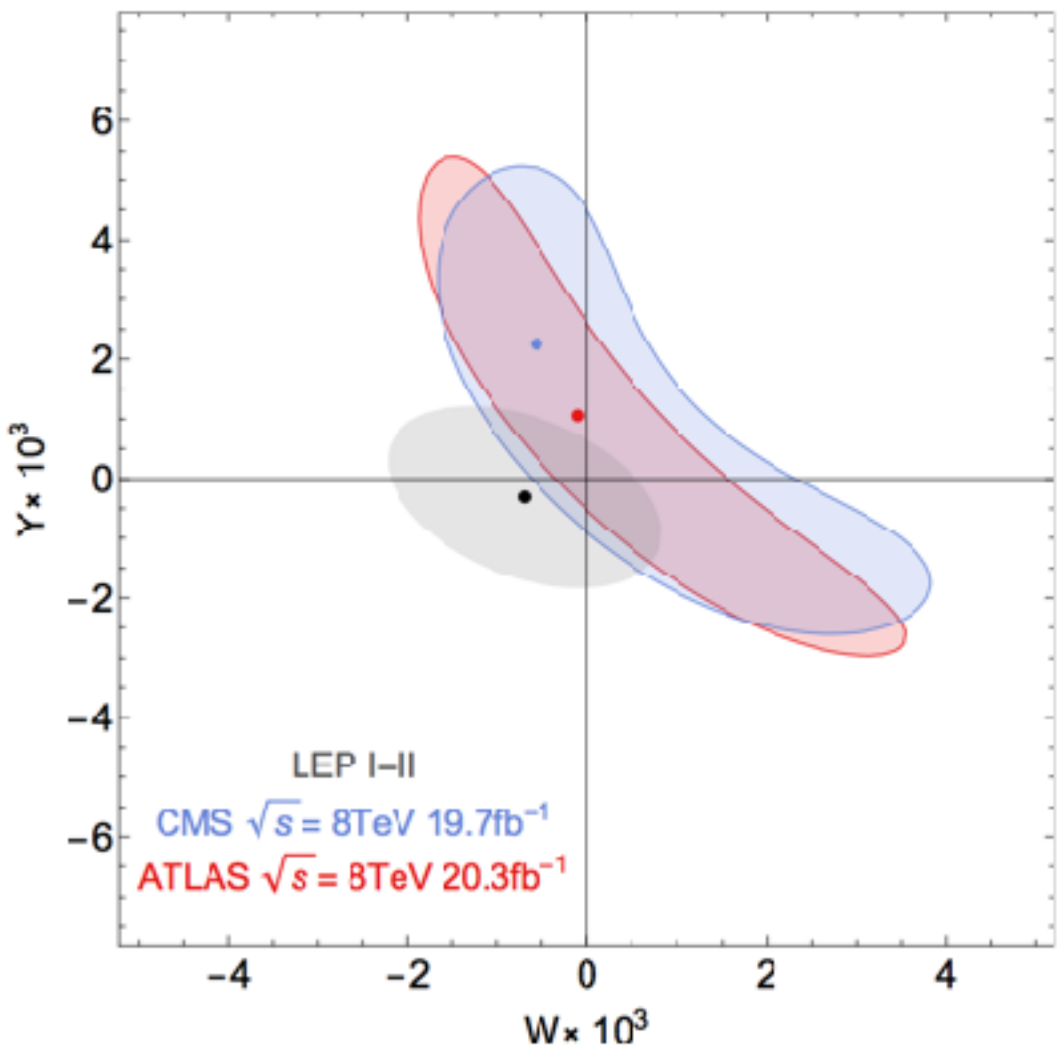

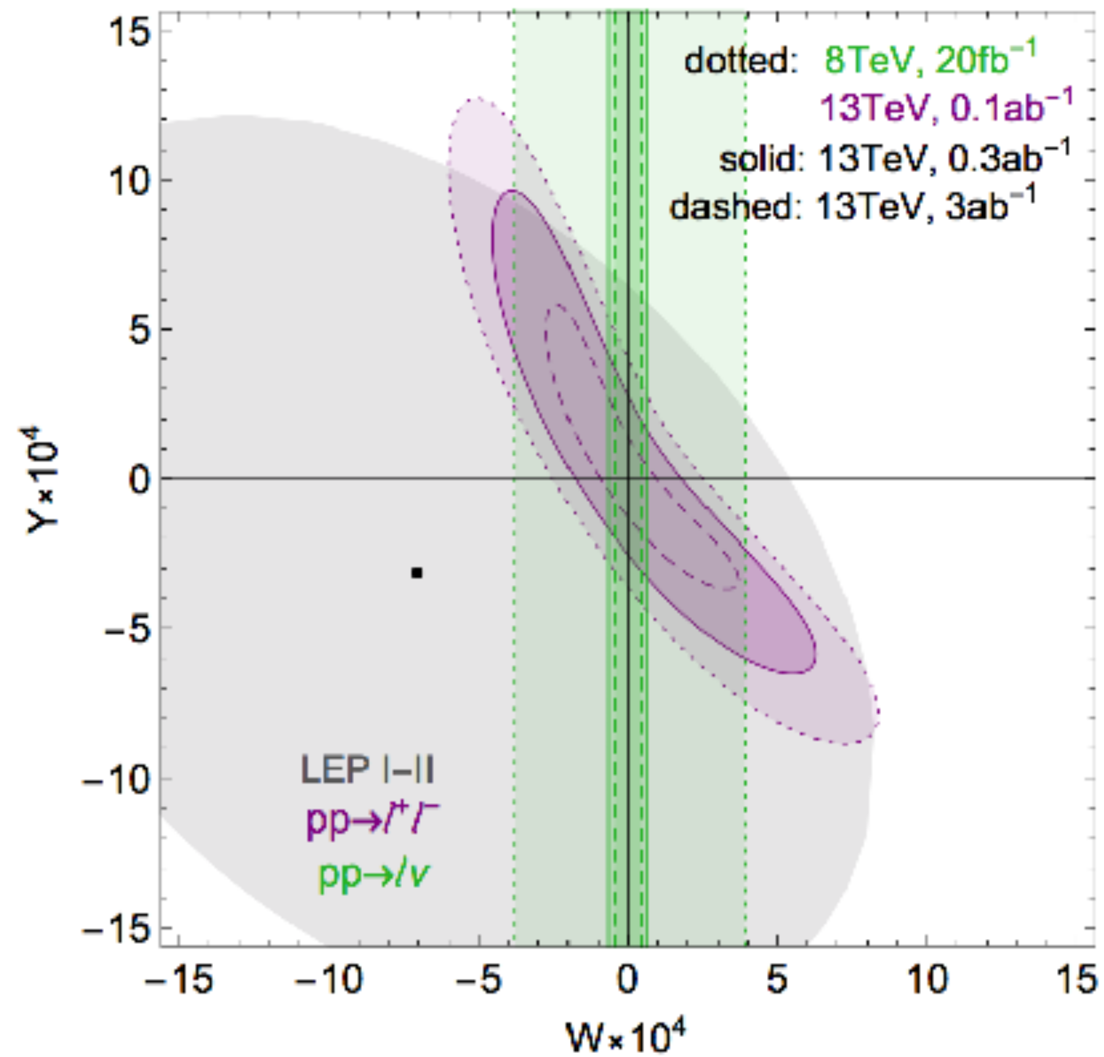

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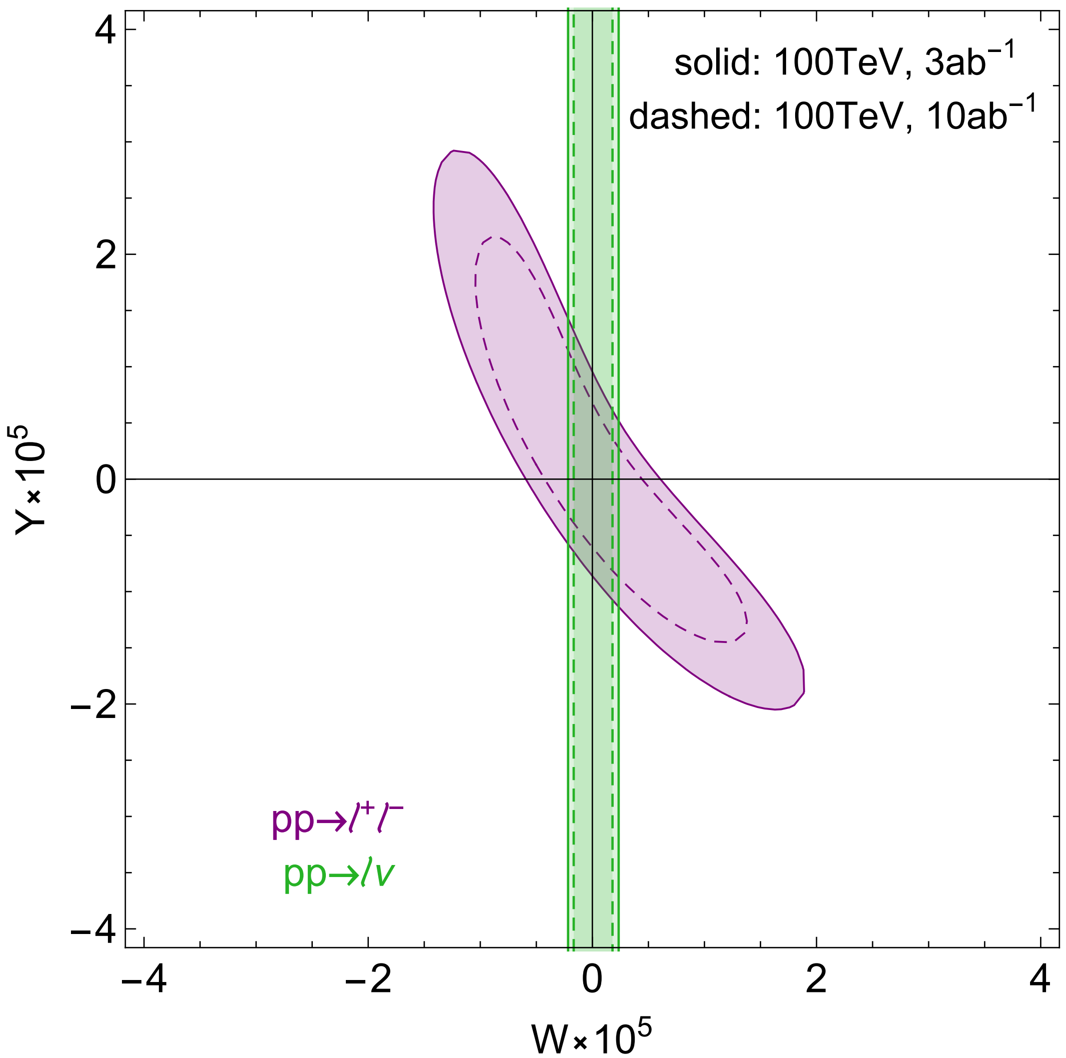

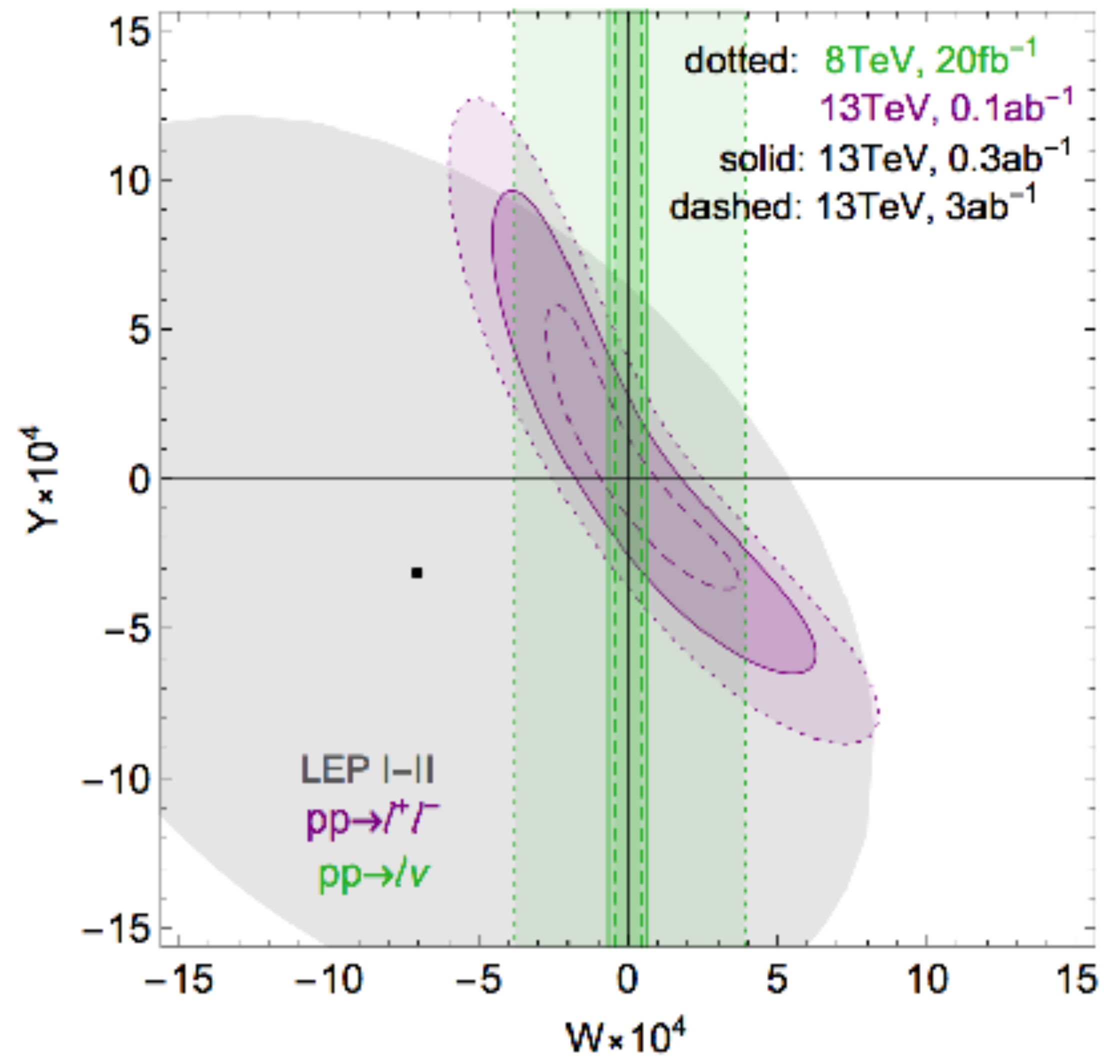

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Raising **energy better** than raising **lumi** (part.lumi boost)

Oblique Parameters at the LHC

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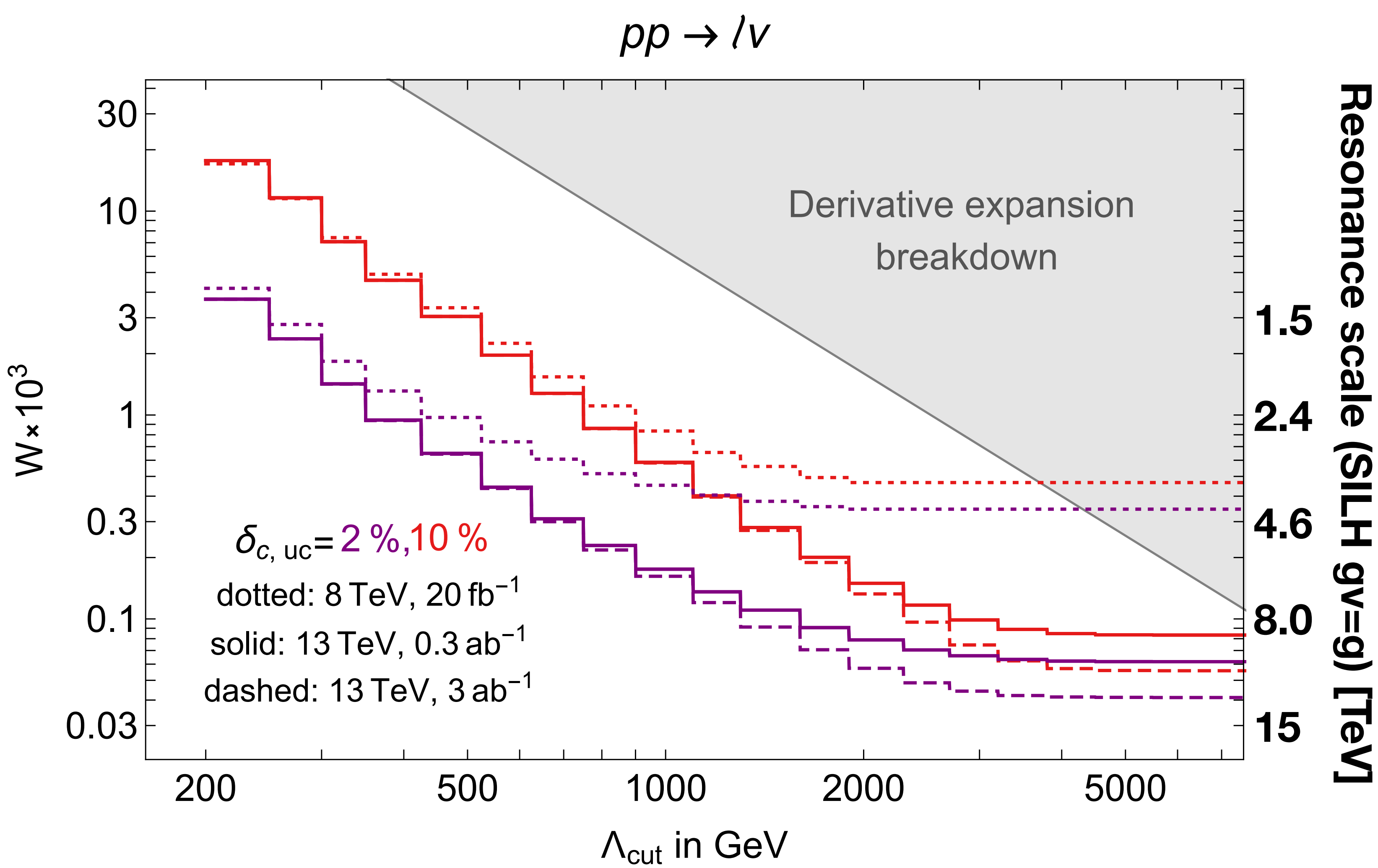
Basic Sanity Check: Limit from scales (2-3 TeV) well below cutoff



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.

Longitudinal DiBosons

[Franceschini, Panico, Pomarol, Riva, AW, to appear]

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

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

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Some un-suppressed operators: $\sim 1/m_*^2$ (SILH-basis coefficient)

SILH basis	Warsaw basis
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_L^{(3)} = (\bar{Q}_L\sigma^a\gamma^\mu Q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$ $\mathcal{O}_L = (\bar{Q}_L\gamma^\mu Q_L)(iH^\dagger\overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$ $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\mathcal{O}_R^u = (\bar{u}_R\gamma^\mu u_R)(iH^\dagger\overleftrightarrow{D}_\mu H)$ $\mathcal{O}_R^d = (\bar{d}_R\gamma^\mu d_R)(iH^\dagger\overleftrightarrow{D}_\mu H)$

SILH basis ⟷ Warsaw basis

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$\Downarrow$

Growing-with-energy longitudinal diboson and boson plus Higgs prod.

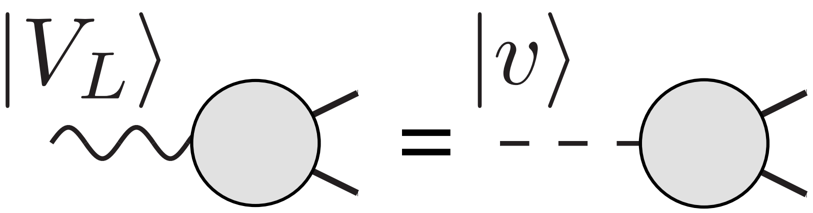
Valid channels for **energy and accuracy frontier exploration ?**

Longitudinal DiBosons

[Franceschini, Panico, Pomarol, Riva, AW, to appear]

G_{SM} restoration implies **relations** among H and V_L high-energy production

Equivalence Theorem makes such relations evident: [see also AW, 2014]



$+\ O(m_W/E)$

$$|\Phi\rangle_i = \begin{bmatrix} |w^+\rangle \\ \frac{1}{\sqrt{2}}(|h\rangle - |z\rangle) \end{bmatrix}_i \in \mathbf{2_{1/2}}$$

V_L and H in **same multiplet:** V_L V_L and V_L H contain **same information**

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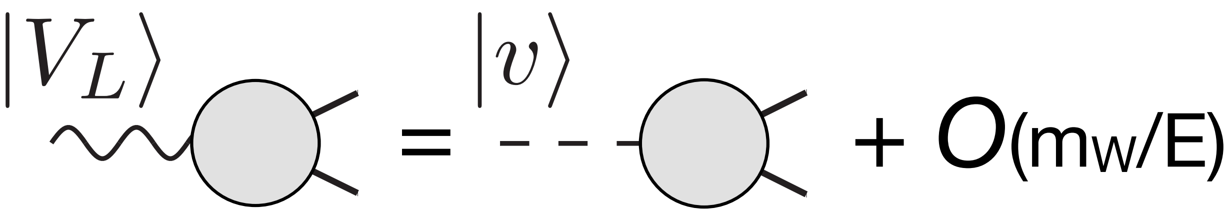

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E^2-enhanced BSM in $q\overline{q} \to \Phi\Phi'$ only sensitive to **4 H.E. Primaries**
[under reasonable assumptions]

$$\delta\mathcal{A}\left(q'_{\pm}\overline{q}_{\mp} \to \Phi\Phi'\right) = f^{\Phi\Phi'}_{q'_{\pm}\overline{q}_{\mp}}(s)\sin\theta = 4A^{\Phi\Phi'}_{q'_{\pm}\overline{q}_{\mp}}\frac{s}{\Lambda^2}\sin\theta + O(s^2/\Lambda^4) \qquad \mathbf{\Lambda \equiv 1\ TeV}$$

$$A^{W^+W^-}_{u_+\overline{u}_-} = A^{Zh}_{u_+\overline{u}_-} = a_u\,, \qquad A^{W^+W^-}_{d_+\overline{d}_-} = A^{Zh}_{d_+\overline{d}_-} = a_d\,,$$

$$A^{W^+W^-}_{u_-\overline{u}_+} = A^{Zh}_{d_-\overline{d}_+} = a_q^{(1)} + a_q^{(3)}\,, \qquad A^{W^+W^-}_{d_-\overline{d}_+} = A^{Zh}_{u_-\overline{u}_+} = a_q^{(1)} - a_q^{(3)}$$

$$A^{hW^+}_{u_+\overline{d}_-} = A^{ZW^+}_{u_+\overline{d}_-} = A^{hW^-}_{d_+\overline{u}_-} = -A^{ZW^-}_{d_+\overline{u}_-} = \sqrt{2}a_q^{(3)}$$

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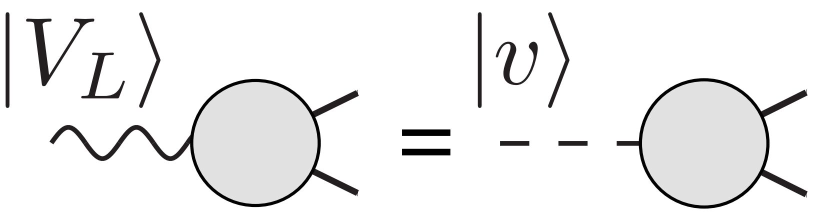

$+ O(m_W/E)$

$$|\Phi\rangle_i = \begin{bmatrix} |w^+\rangle \\ \frac{1}{\sqrt{2}}(|h\rangle - |z\rangle) \end{bmatrix}_i \in \mathbf{2_{1/2}}$$

V_L and H in **same multiplet:** V_L V_L and V_L H contain **same information**

E^2-enhanced BSM in $q\bar{q} \to \Phi\Phi'$ only sensitive to **4 H.E. Primaries**
[under reasonable assumptions]

$$\delta\mathcal{A}\left(q'_\pm \bar{q}_\mp \to \Phi\Phi'\right) = f^{\Phi\Phi'}_{q'_\pm \bar{q}_\mp}(s)\sin\theta = 4A^{\Phi\Phi'}_{q'_\pm \bar{q}_\mp}\frac{s}{\Lambda^2}\sin\theta + O(s^2/\Lambda^4)$$

$$\mathbf{\Lambda \equiv 1\ TeV}$$

$$A^{W^+W^-}_{u_+\bar{u}_-} = A^{Zh}_{u_+\bar{u}_-} = a_u\,, \qquad A^{W^+W^-}_{d_+\bar{d}_-} = A^{Zh}_{d_+\bar{d}_-} = a_d\,,$$

$$A^{W^+W^-}_{u_-\bar{u}_+} = A^{Zh}_{d_-\bar{d}_+} = a_q^{(1)} + a_q^{(3)}\,, \qquad A^{W^+W^-}_{d_-\bar{d}_+} = A^{Zh}_{u_-\bar{u}_+} = a_q^{(1)} - a_q^{(3)}$$

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Simple map to Warsaw basis

$$a_u = c_R^u\,, \quad a_d = c_R^d$$

$$c_L^{(1)} = a_q^{(1)}\,, \quad c_L^{(3)} = a_q^{(3)}$$

Longitudinal DiBosons

[Franceschini, Panico, Pomarol, Riva, AW, to appear]

G$_{SM}$ restoration implies **relations** among H and V$_L$ high-energy production

Amplitude	High-energy primaries	Deviations from SM couplings
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2\Lambda^2}{4m_W^2}\left[c_{\theta_W}(\boldsymbol{\delta g^Z_{uL}} - \boldsymbol{\delta g^Z_{dL}})/g - c^2_{\theta_W}\boldsymbol{\delta g^Z_1}\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_L t^2_{\theta_W}\boldsymbol{\delta\kappa_\gamma} + T_Z^{u_L}\boldsymbol{\delta g^Z_1} + c_{\theta_W}\boldsymbol{\delta g^Z_{dL}}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_L t^2_{\theta_W}\boldsymbol{\delta\kappa_\gamma} + T_Z^{d_L}\boldsymbol{\delta g^Z_1} + c_{\theta_W}\boldsymbol{\delta g^Z_{uL}}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_{f_R} t^2_{\theta_W}\boldsymbol{\delta\kappa_\gamma} + T_Z^{f_R}\boldsymbol{\delta g^Z_1} + c_{\theta_W}\boldsymbol{\delta g^Z_{fR}}/g\right]$

$$\delta\mathcal{A}\left(q'_\pm \bar{q}_\mp \to \Phi\Phi'\right) = f^{\Phi\Phi'}_{q'_\pm\bar{q}_\mp}(s)\sin\theta = 4A^{\Phi\Phi'}_{q'_\pm\bar{q}_\mp}\frac{s}{\Lambda^2}\sin\theta + O(s^2/\Lambda^4)$$

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Longitudinal DiBosons

[Franceschini, Panico, Pomarol, Riva, AW, to appear]

Naive estimate of the reach (on one benchmark operator)
Leading order, high PT, no systematics, no detector

Channel	Bound without bkg.	Bound with bkg.	
Wh	$[-0.0096, 0.0096]$	$[-0.036, 0.031]$	→ Top/bb Higgs fakes
Zh	$[-0.030, 0.028]$	–	→ Maybe promising [for $a^{(1)}$]
WW	$[-0.012, 0.011]$	$[-0.044, 0.037]$	→ Swamped by V_T production
WZ	$[-0.013, 0.012]$	$[-0.023, 0.021]$	→ Less V_T background

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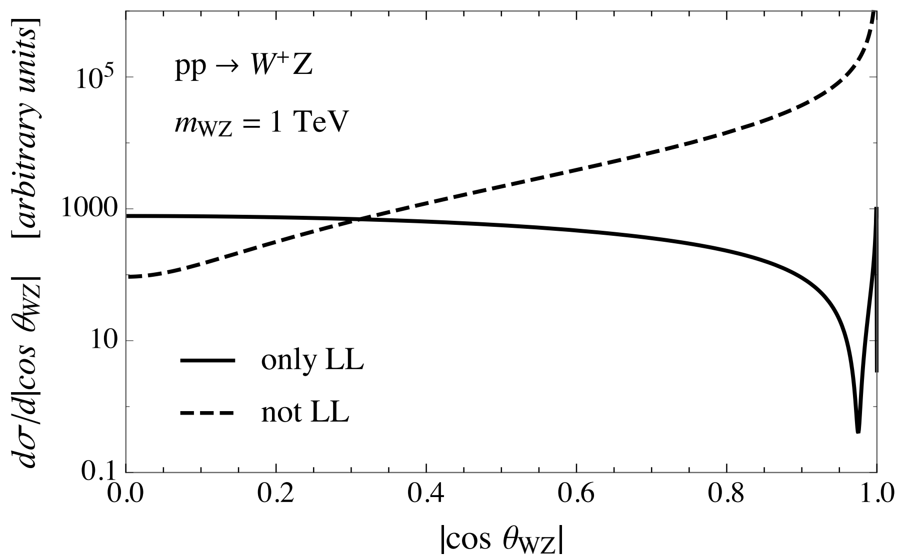
Summary:

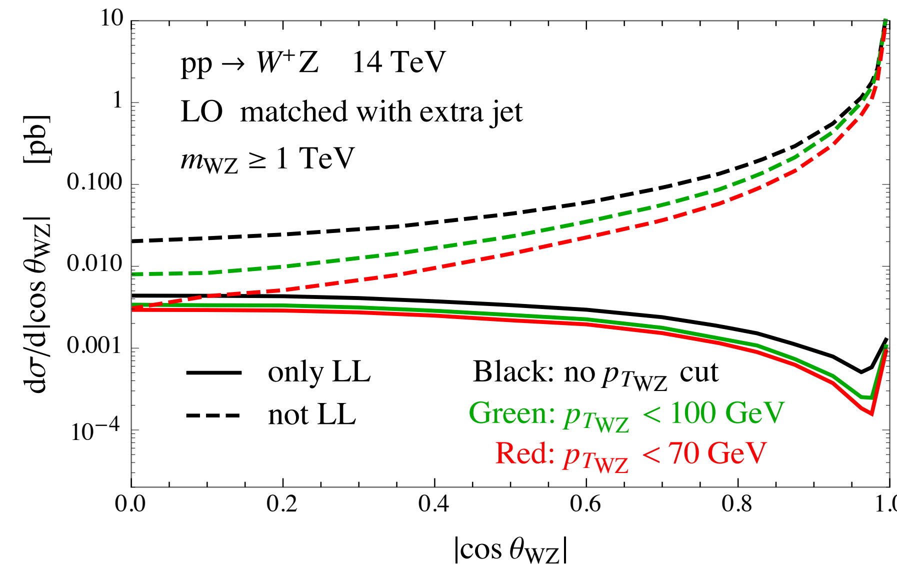
Channel	Challenge
$WW \quad WZ$	**V_T Background**
$WH \quad ZH$	**Needs Boosted Higgs**

Leptonic WZ

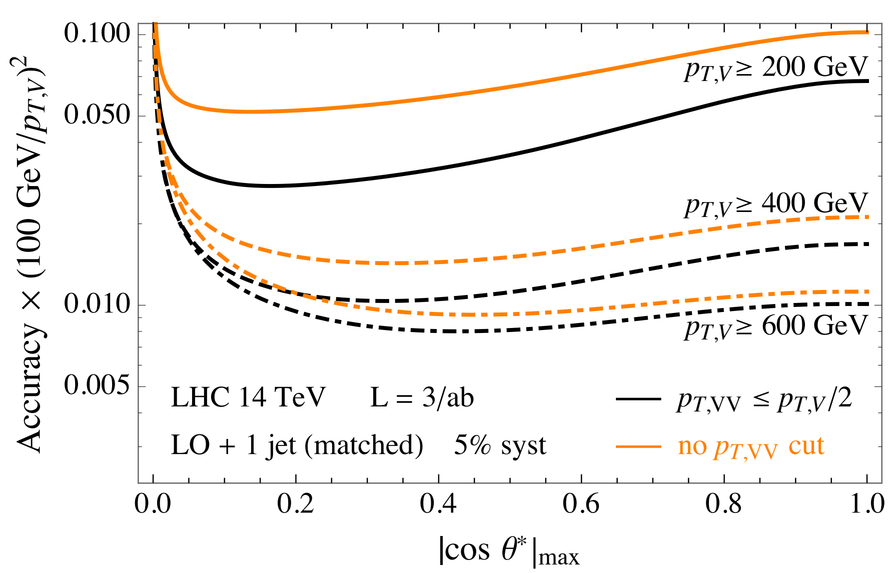
[Franceschini, Panico, Pomarol, Riva, AW, to appear]

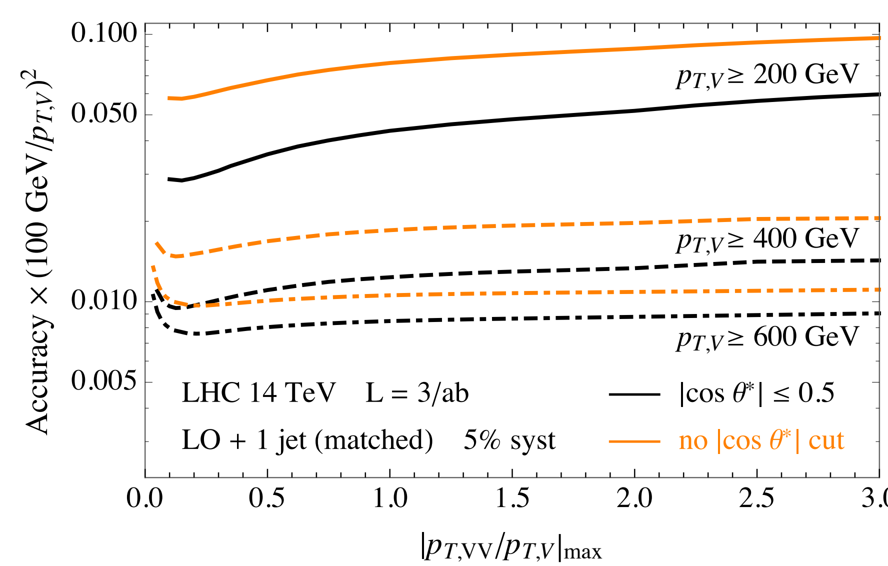
Exploit (~accidental) ~vanishing transverse amplitude at $\theta = \pi/2$





Suppress real NLO by upper cut on total WZ P_T





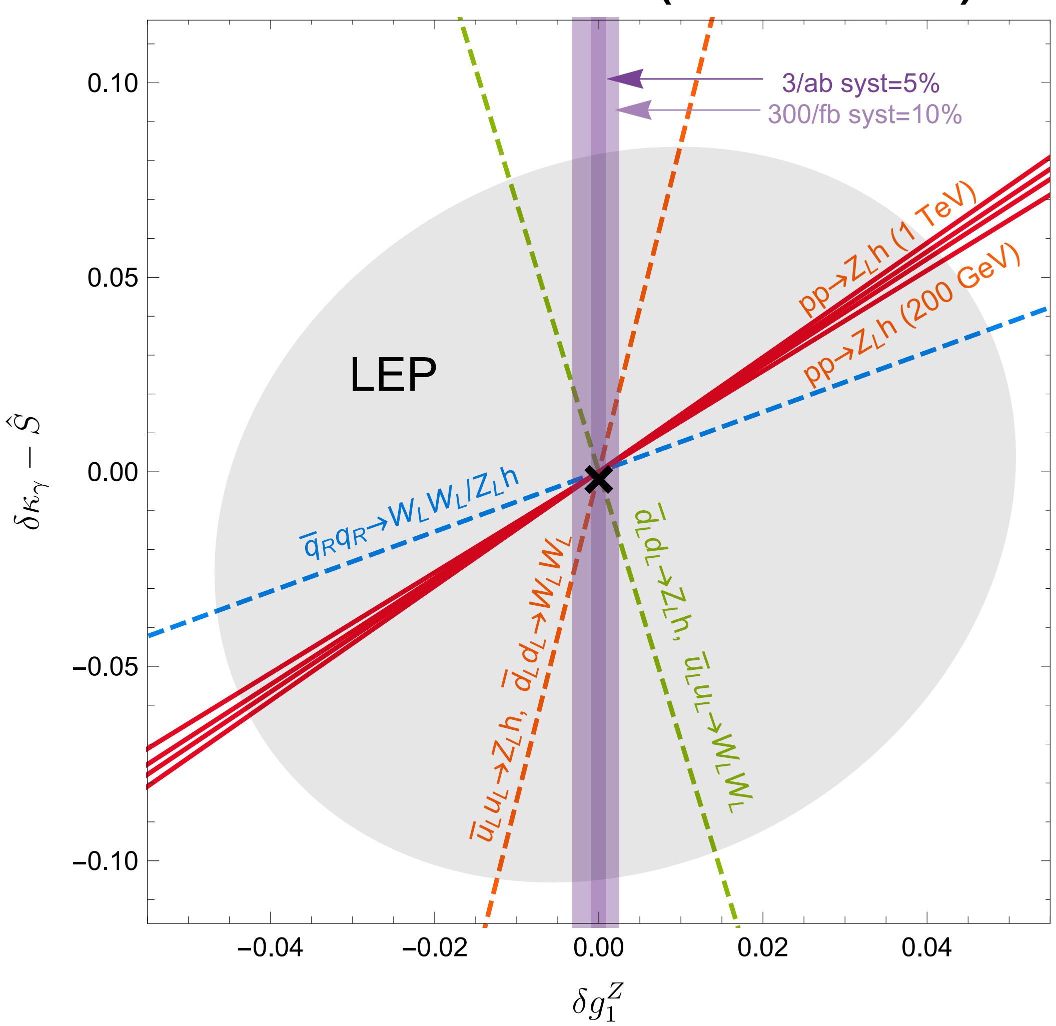
Limits from fit to P_T distribution in fiducial regions (cuts improve sens.)

Leptonic WZ

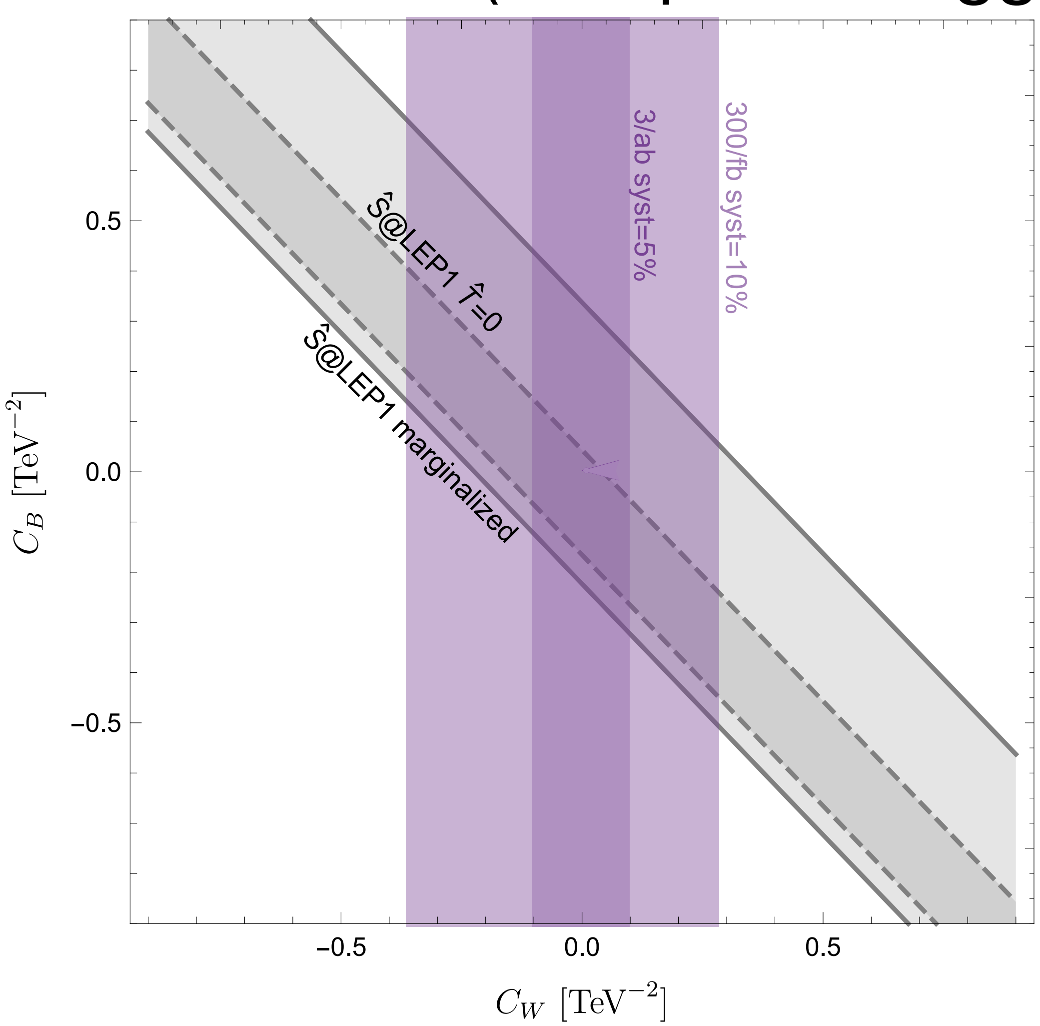
[Franceschini, Panico, Pomarol, Riva, AW, to appear]

Results: [MG@NLO, assumed 10%/5% syst., found <5% NLO scale unc.]

LHC vs LEP (Univ. Th.)



LHC vs LEP (Composite Higgs)



Imposing strong W/Y bounds

$$a_q^{(3)} = -\frac{g^2\Lambda^2}{4m_W^2}\left(c_{\theta_W}^2\delta g_1^Z + \cancel{W}\right)$$

$$a_q^{(1)} = \frac{g^2\Lambda^2}{12m_W^2}t_{\theta_W}^2\left(\widehat{S} - \delta\kappa_\gamma + c_{\theta_W}^2\delta g_1^Z - \cancel{Y}\right)$$

Power-counting + loop suppression

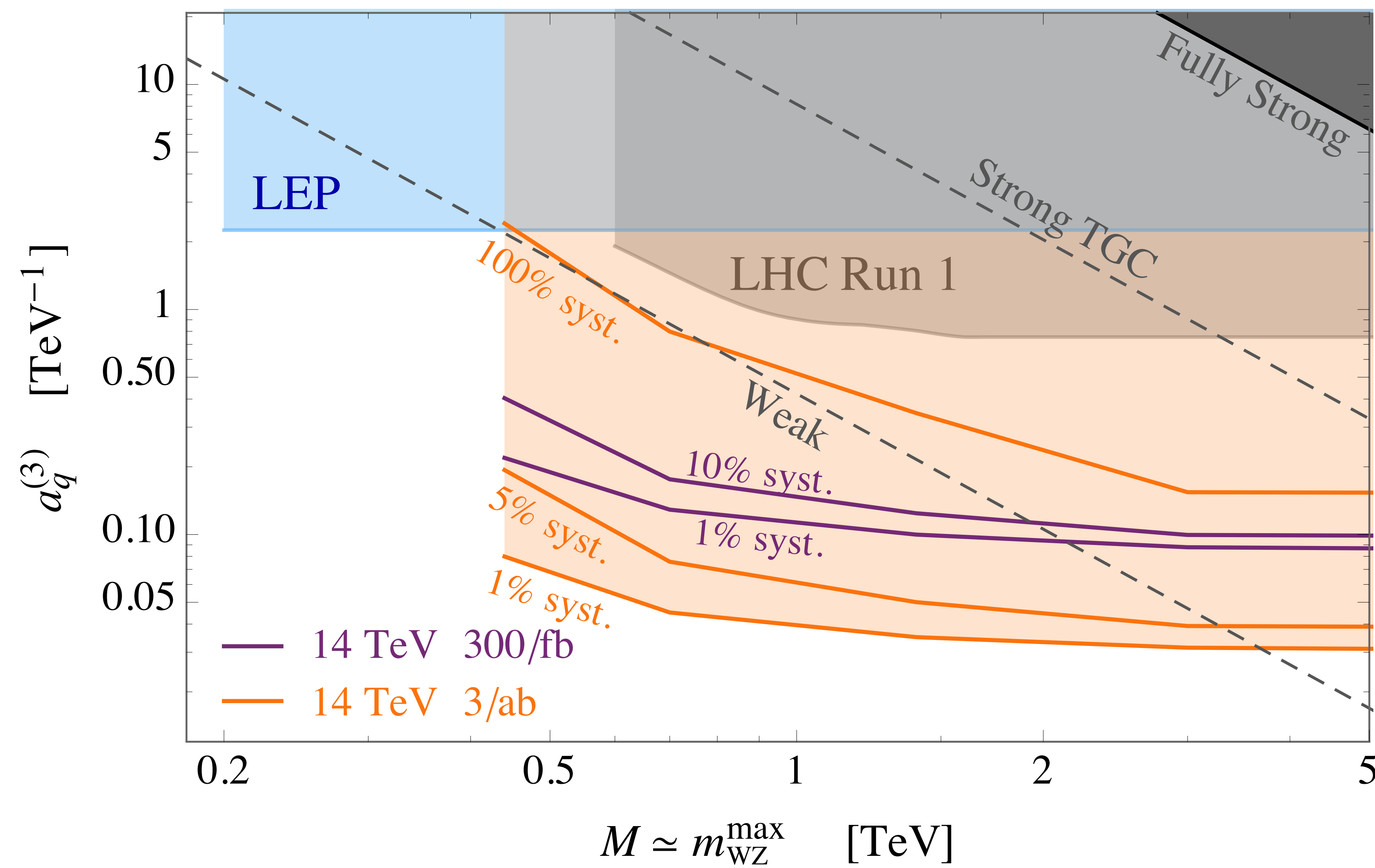
$$a_q^{(3)} = \frac{g^2}{4}(c_W + \cancel{c_{HW}} - \cancel{c_{2W}})$$

$$\widehat{S} = (c_W + c_B)\frac{m_W^2}{\Lambda^2}$$

Leptonic WZ

[Franceschini, Panico, Pomarol, Riva, AW, to appear]

The **most important plot:** reach now extends to reasonable theories!



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Strongly-coupled quarks
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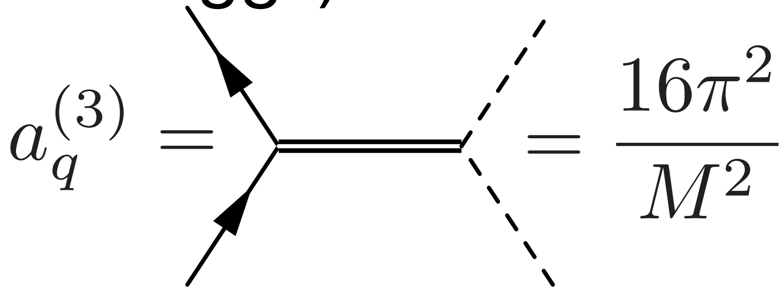

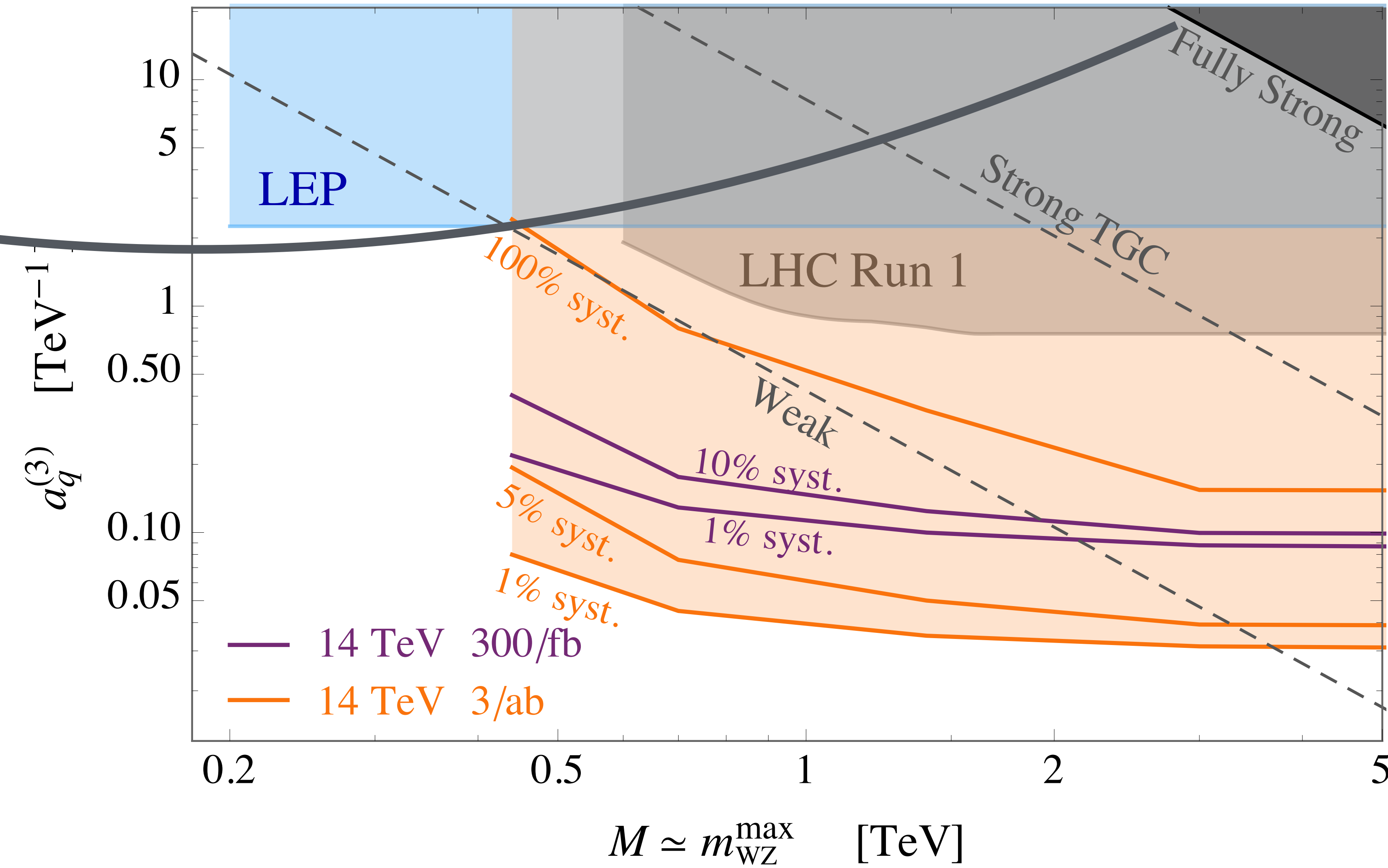

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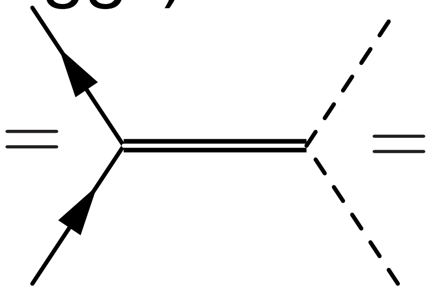

$= \frac{16\pi^2}{M^2}$

Weakly-coupled quarks, **strongly coupled gauge**

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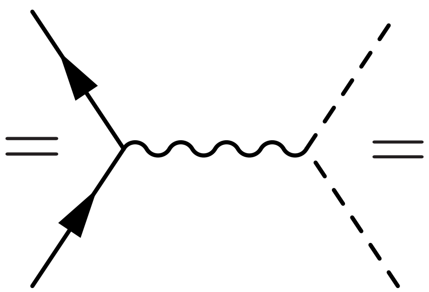
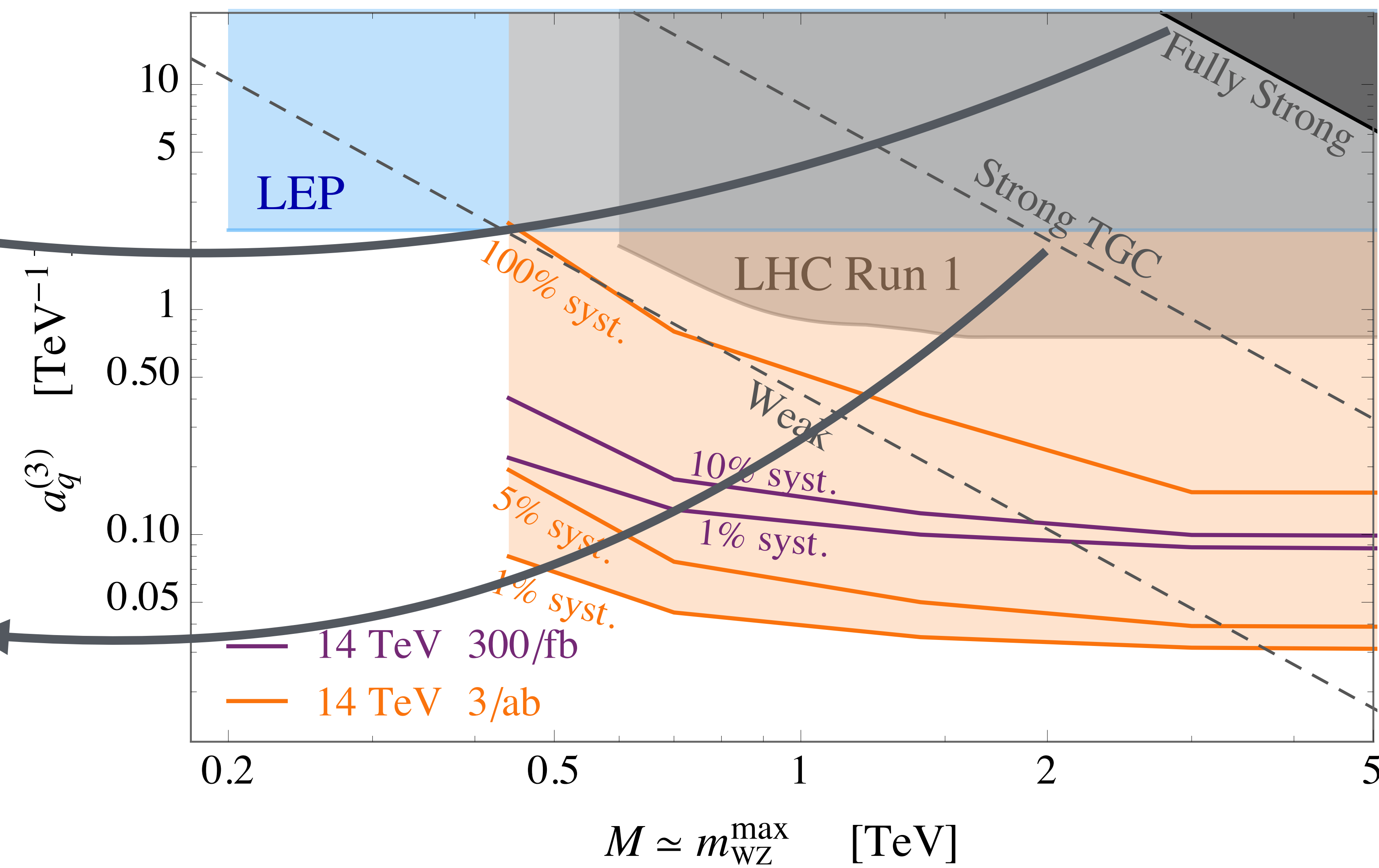


$= \frac{4\pi\, g_W}{M^2}$



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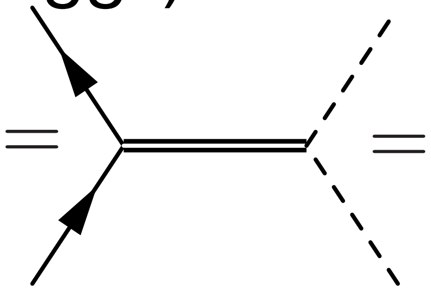
$a_q^{(3)} =$  $= \dfrac{16\pi^2}{M^2}$

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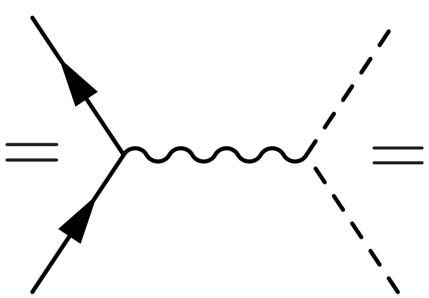
$a_q^{(3)} =$  $= \dfrac{4\pi\, g_W}{M^2}$

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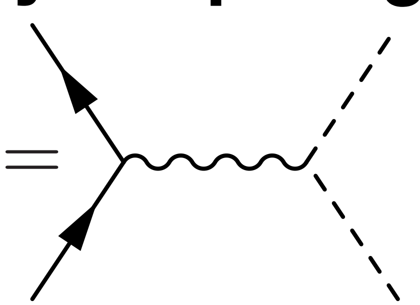
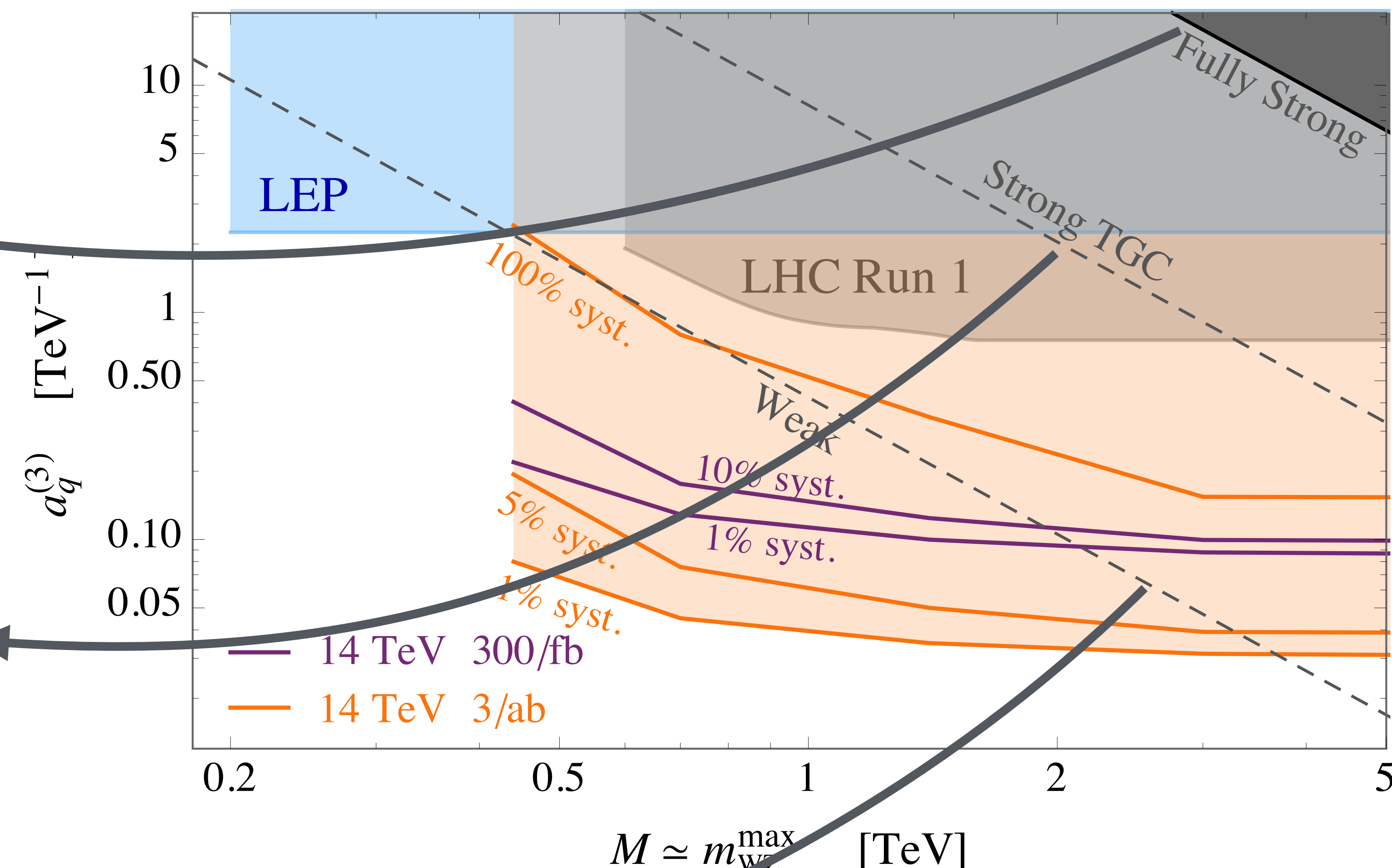
$a_q^{(3)} =$  $= \dfrac{g_W^2}{M^2}$



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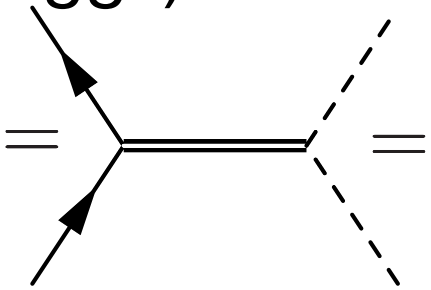
$a_q^{(3)} =$  $= \dfrac{16\pi^2}{M^2}$

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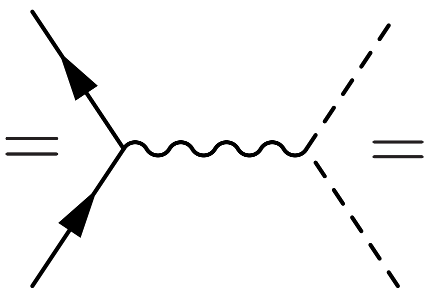
$a_q^{(3)} =$  $= \dfrac{4\pi\, g_W}{M^2}$

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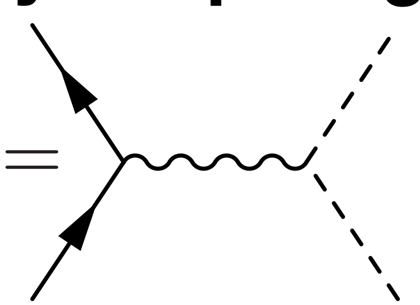
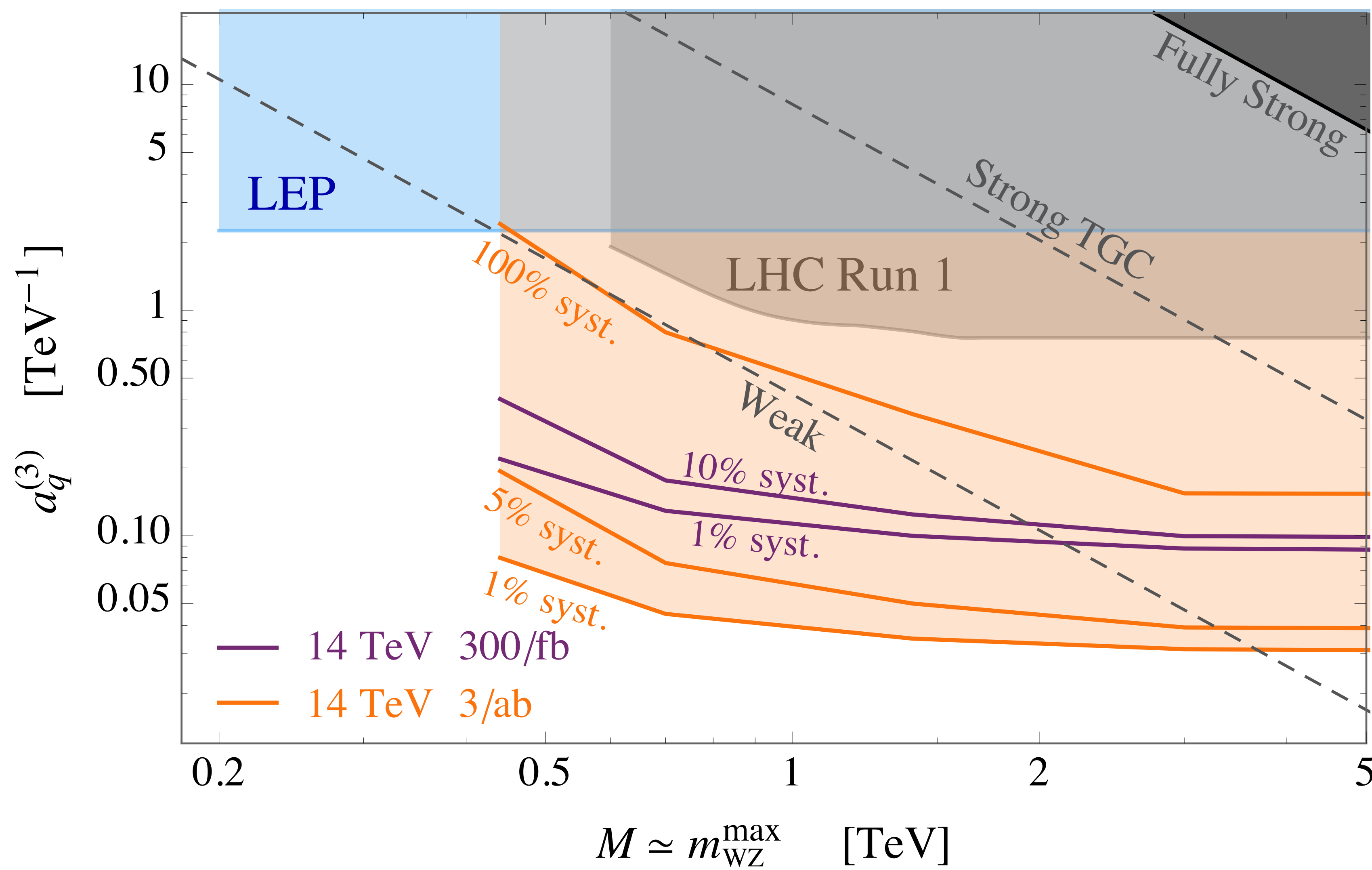
$a_q^{(3)} =$  $= \dfrac{g_W^2}{M^2}$

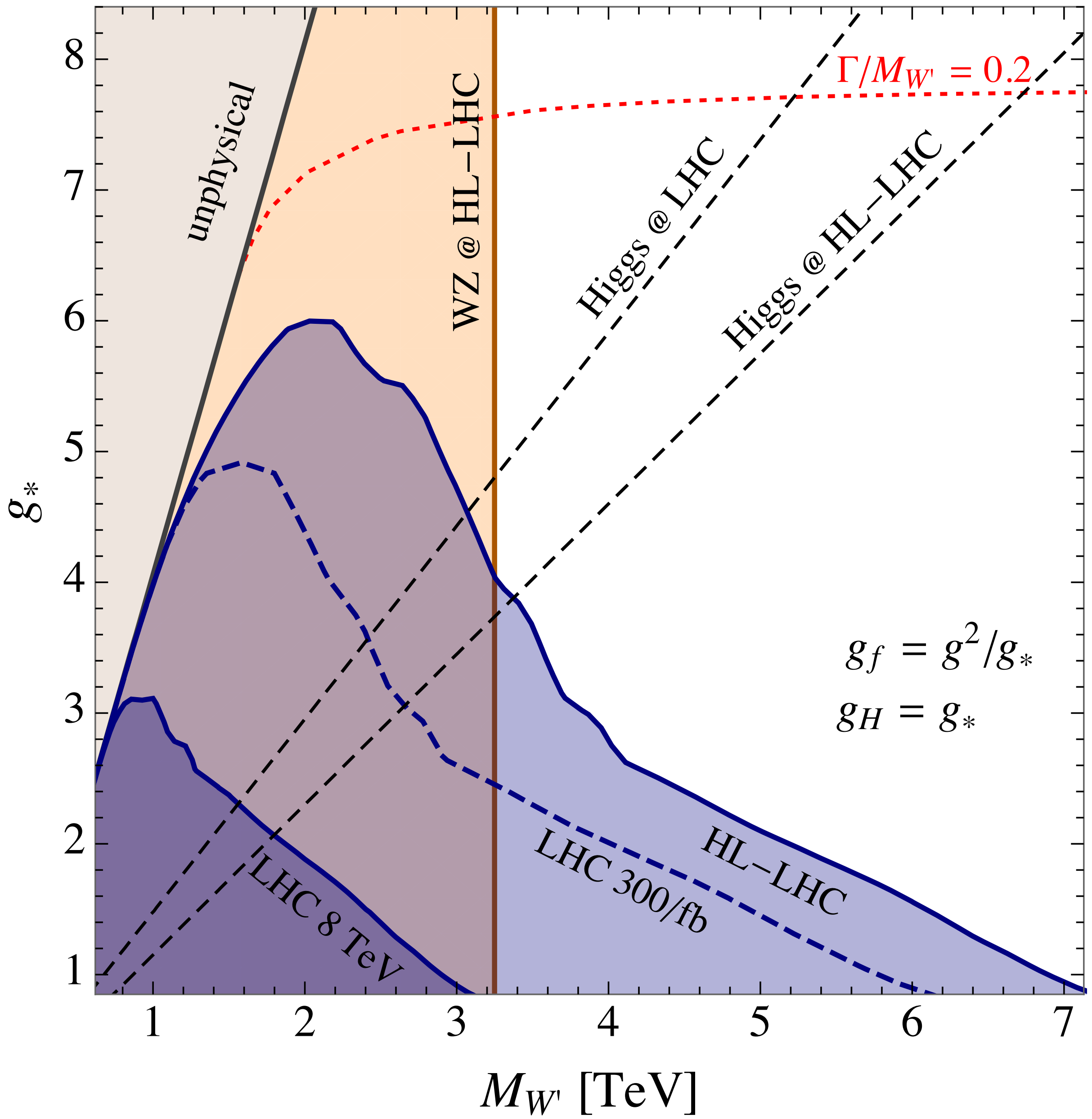


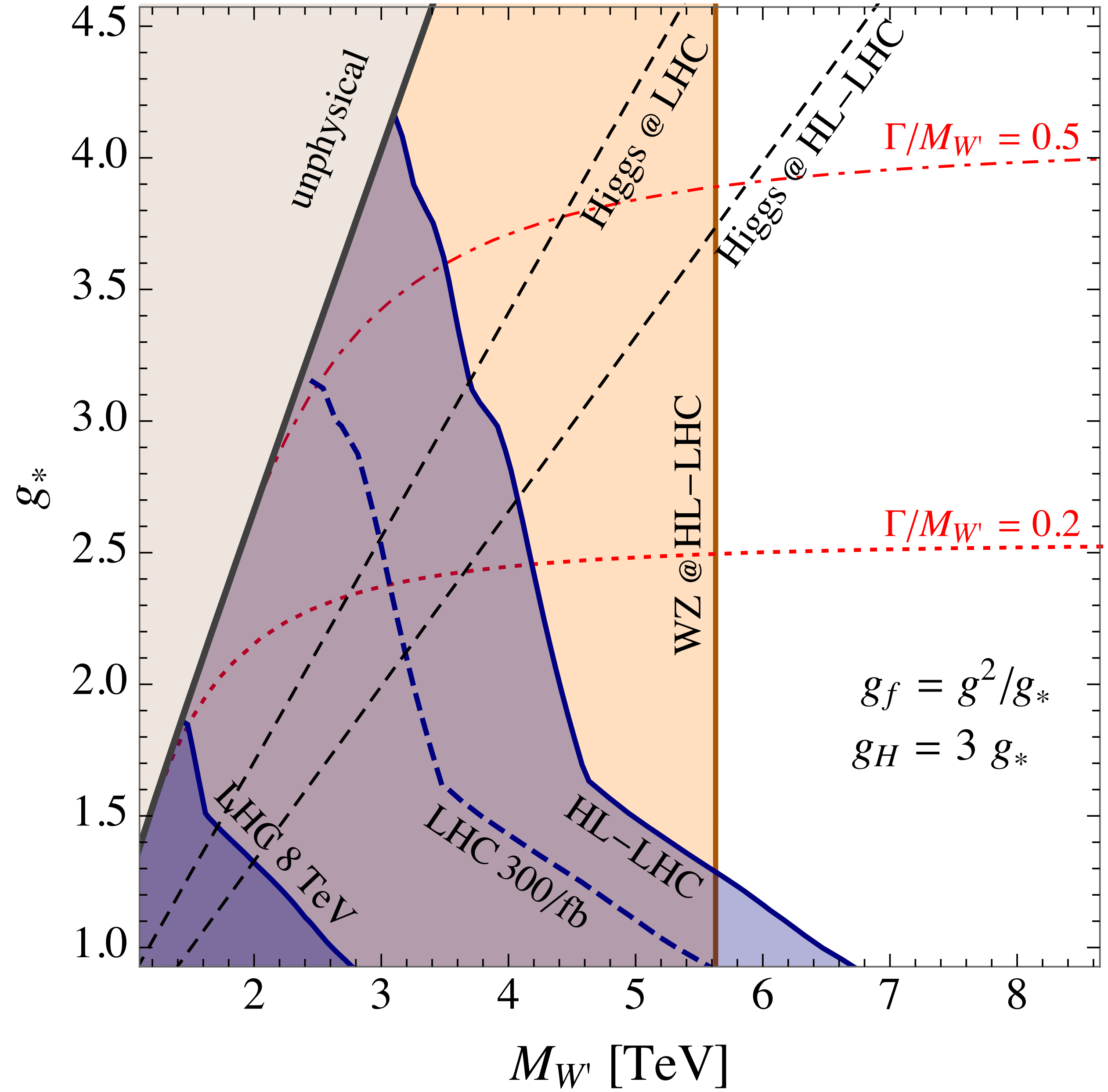
Unlike run-1, we will surpass LEP for theories where quarks and gauge fields are elementary! (Higgs can be composite)

Leptonic WZ

[Franceschini, Panico, Pomarol, Riva, AW, to appear]

Indirect reach on **Composite Heavy Vector Triplets:**





Transverse DiBosons

[Panico, Riva, AW, 2017]

Sensitive to transverse **aTGC** operators, e.g.

$$\mathcal{O}_{3W} = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}\,, \quad \mathcal{O}_{3\widetilde{W}} = \epsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

Challenging, because of **non-interference:**

[Azatov, Contino, Machado, Riva, 2016]

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
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$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

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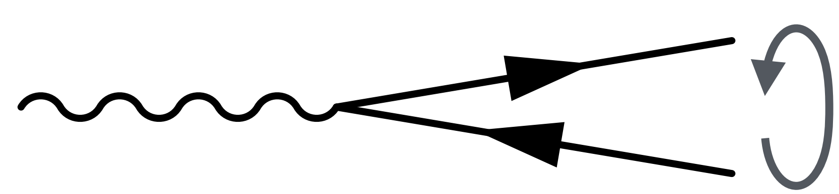
Solution is **Interference Resurrection:**

V decay products **are not** in an ang. mom. (V-helicity) eigenstates.
Linear (entangled) superposition of eigenstates.

Different V helicites **interference cancels** only in quantities that are **inclusive over the azimuthal decay angle**



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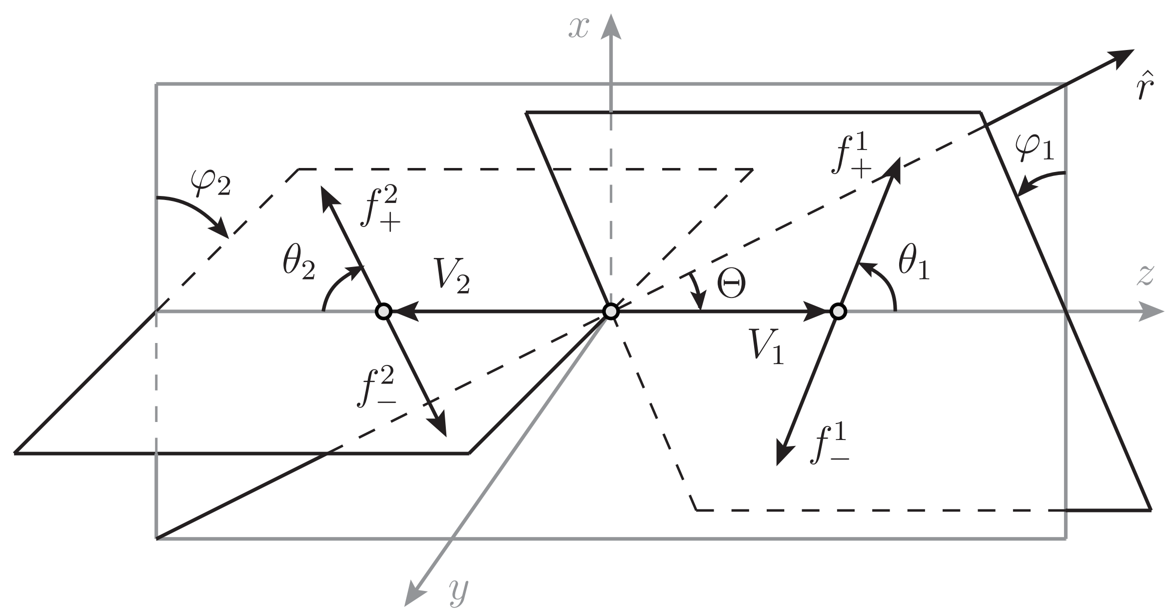

Simplest case is **Wγ**: $\text{“Interference”} \propto \sin\theta \cos 2\varphi$

Compulsory to measure φ. Measuring θ would help, Θ as well

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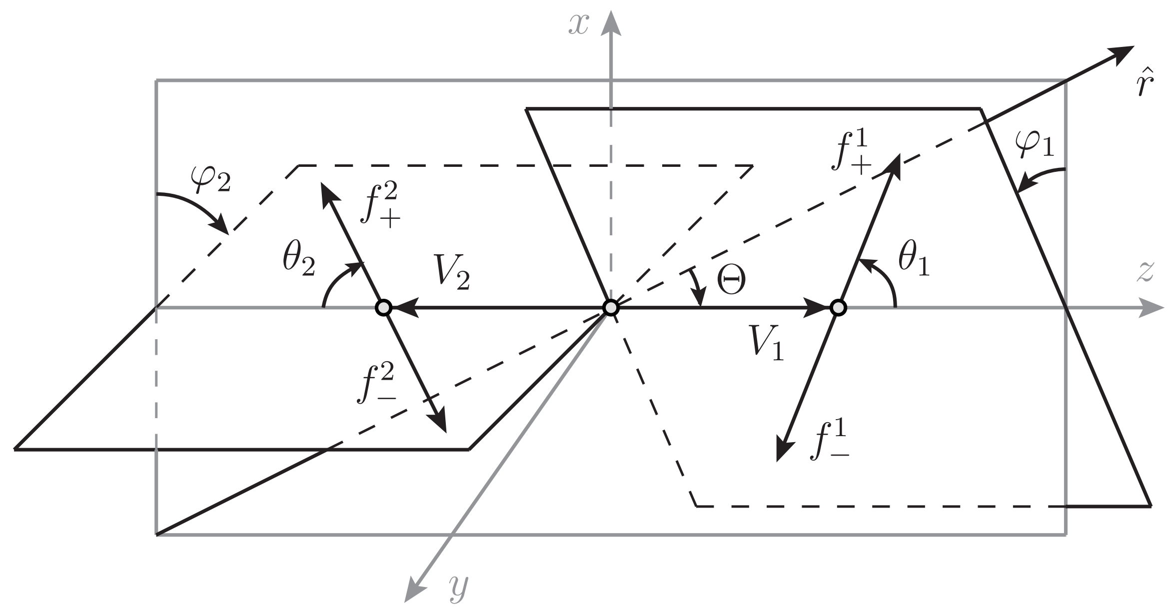

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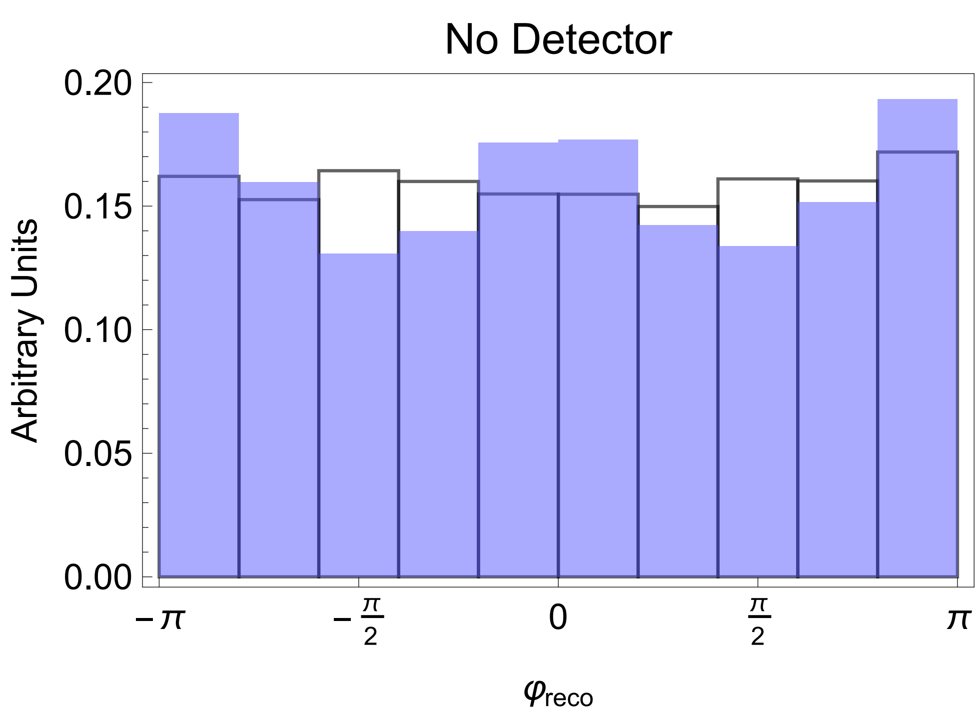

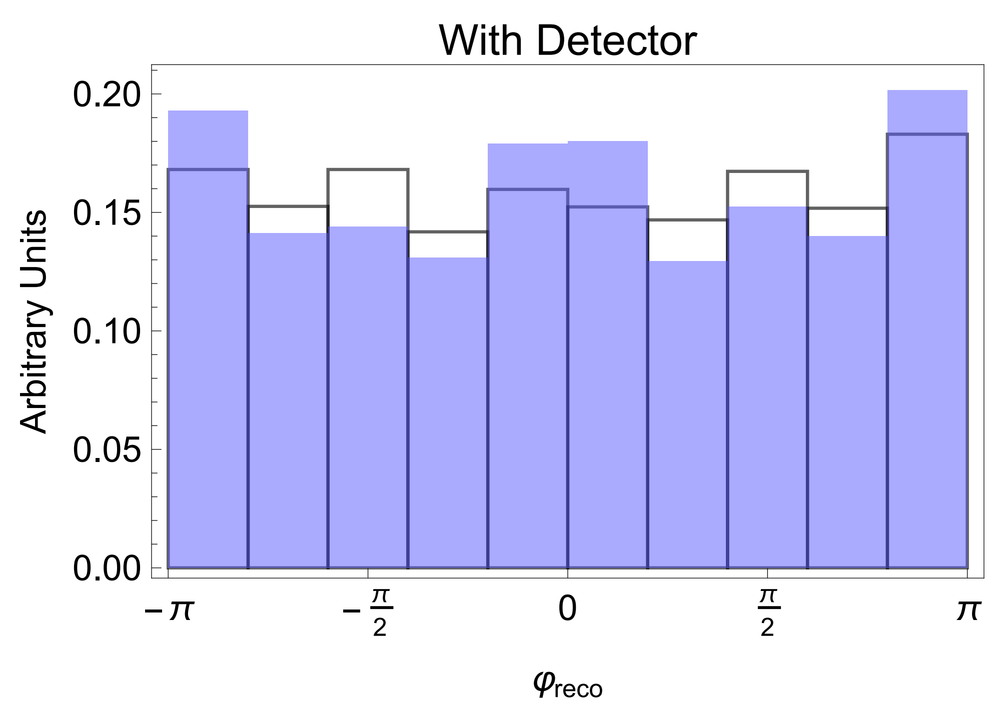

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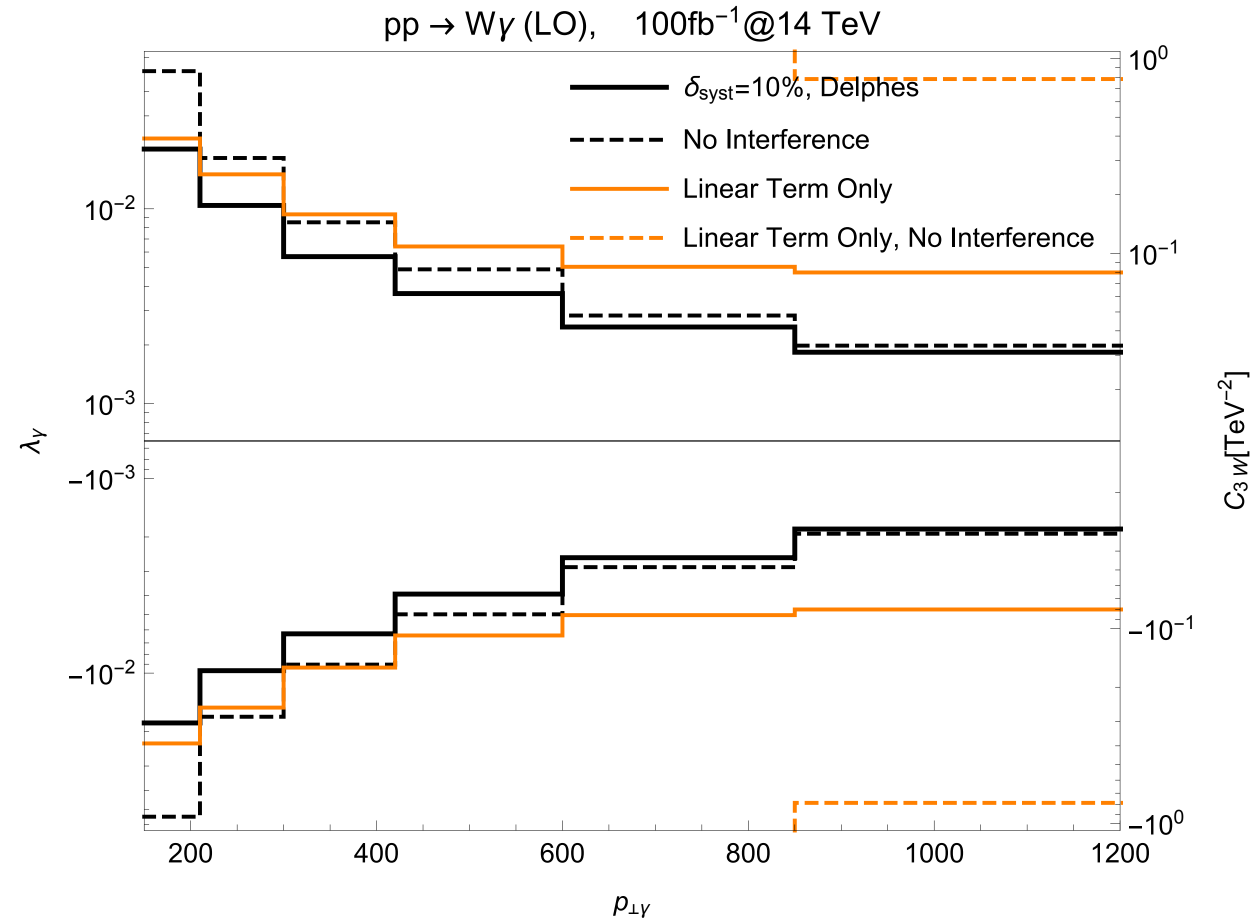

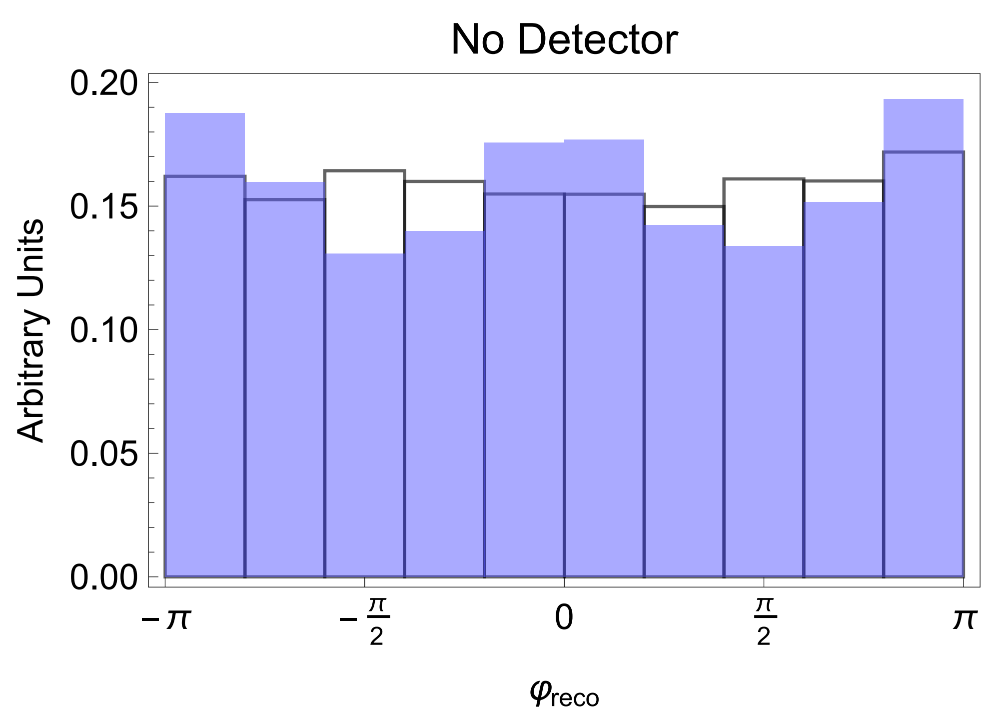

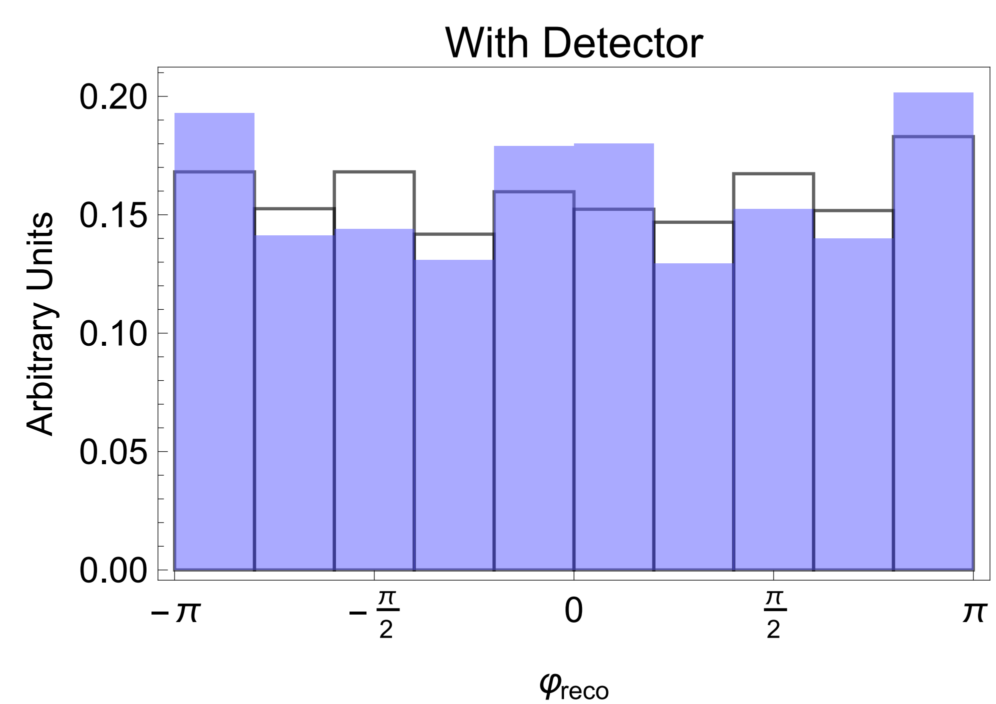

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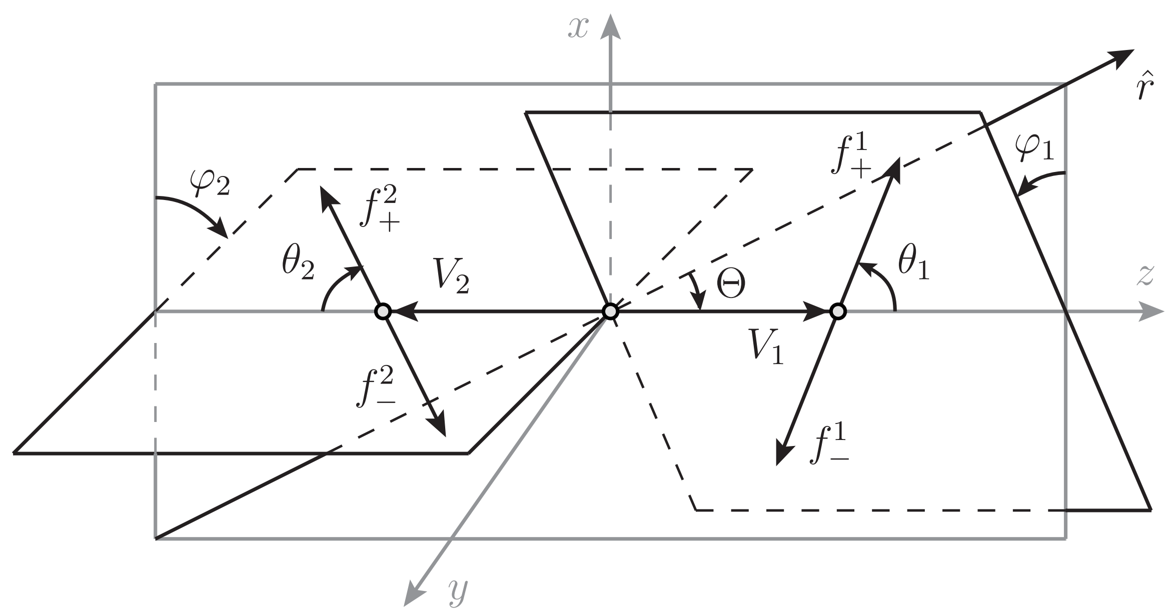

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Next to simplest case is **WZ**: [see also Azatov, Elias-Miro, Reyimuaji,Venturini, 2017]

Maximal information from 2 azimuthal angles, plus one polar, plus …

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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  We do **truly** (valid EFT) **beat LEP TGC** with tomorrow's data

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- Can we do more?
  EWPT@LHC is a **cross-community** endeavour. BSM must play pivotal role.

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  Sensitive to other, **non-g_*-suppressed**, EFT operators
  We do **truly** (valid EFT) **beat LEP TGC** with tomorrow's data

- **Can we do more?**

  EWPT@LHC is a **cross-community** endeavour. BSM must play pivotal role.

  All diboson channels should be studied to constrain all the **4 HEPs.**

  Extension to **transverse** dibosons, through **Interference Resurrection.**

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

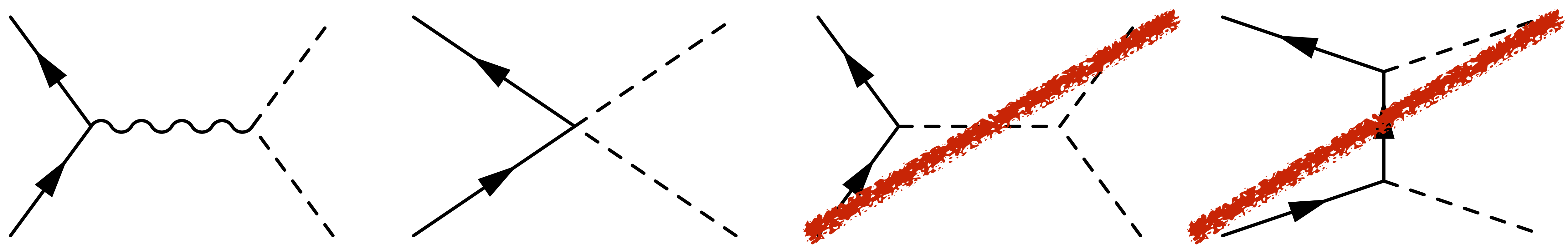
- **VV/VH play major role in energy and accuracy exploration**
  Sensitive to other, **non-g_*-suppressed**, EFT operators
  We do **truly** (valid EFT) **beat LEP TGC** with tomorrow's data

- **Can we do more?**
  EWPT@LHC is a **cross-community** endeavour. BSM must play pivotal role.
  All diboson channels should be studied to constrain all the **4 HEPs.**
  Extension to **transverse** dibosons, through **Interference Resurrection.**
  Dream: **Resurrect WW scattering?**

Backup

Assumptions behind primaries dominance:

1) Anomalous Hqq negligibly small:



2) d=6 interactions only: [implies purely J=1 partial wave amplitude]

$$\delta\mathcal{A}\left(q'_{\pm}\overline{q}_{\mp} \to \Phi\Phi'\right) = f^{\Phi\Phi'}_{q'_{\pm}\overline{q}_{\mp}}(s)\sin\theta = 4A^{\Phi\Phi'}_{q'_{\pm}\overline{q}_{\mp}}\frac{s}{\Lambda^2}\sin\theta + O(s^2/\Lambda^4)$$

All the rest is derived from G_{SM} symmetry

Backup

Neutrino Reconstruction