Energy and Accuracy, and DiBosons

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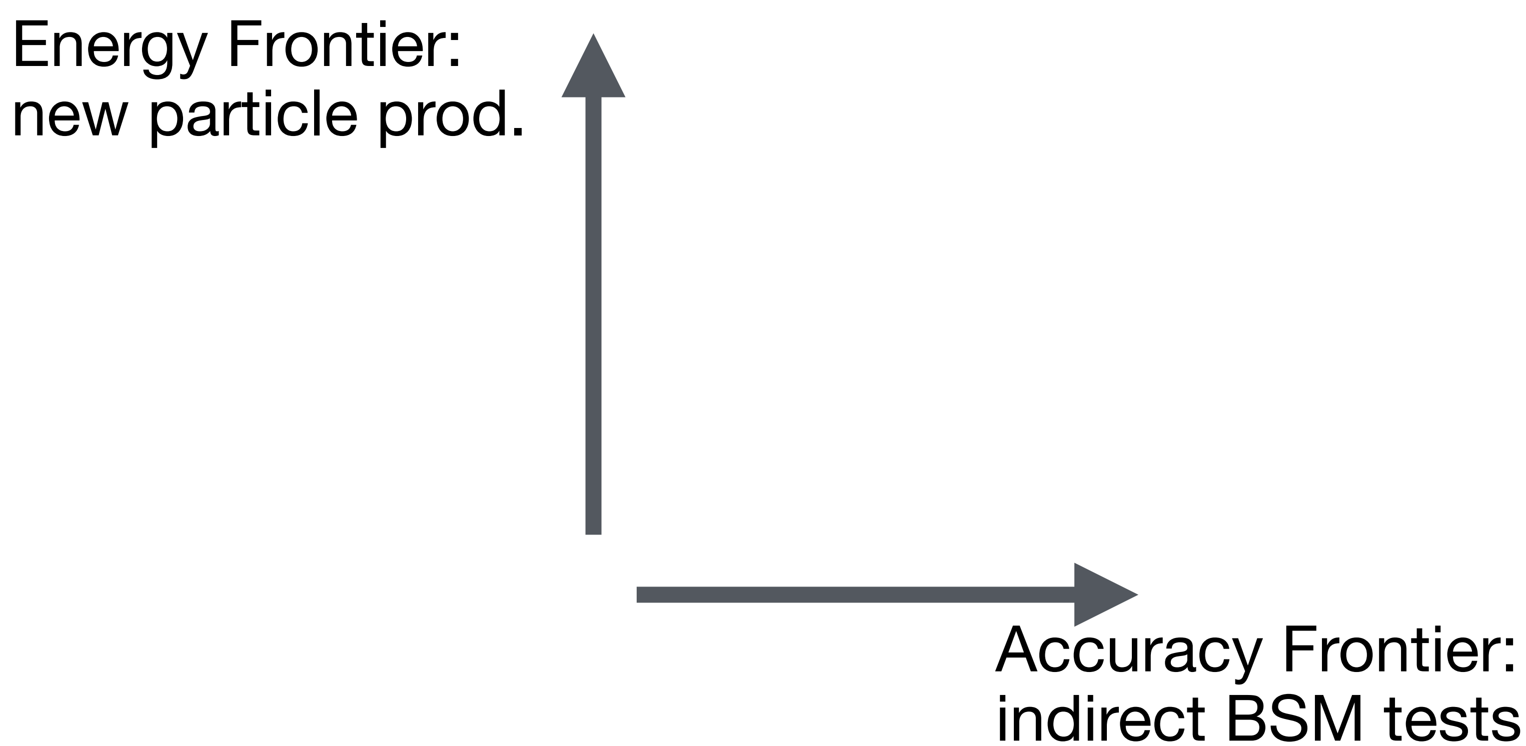
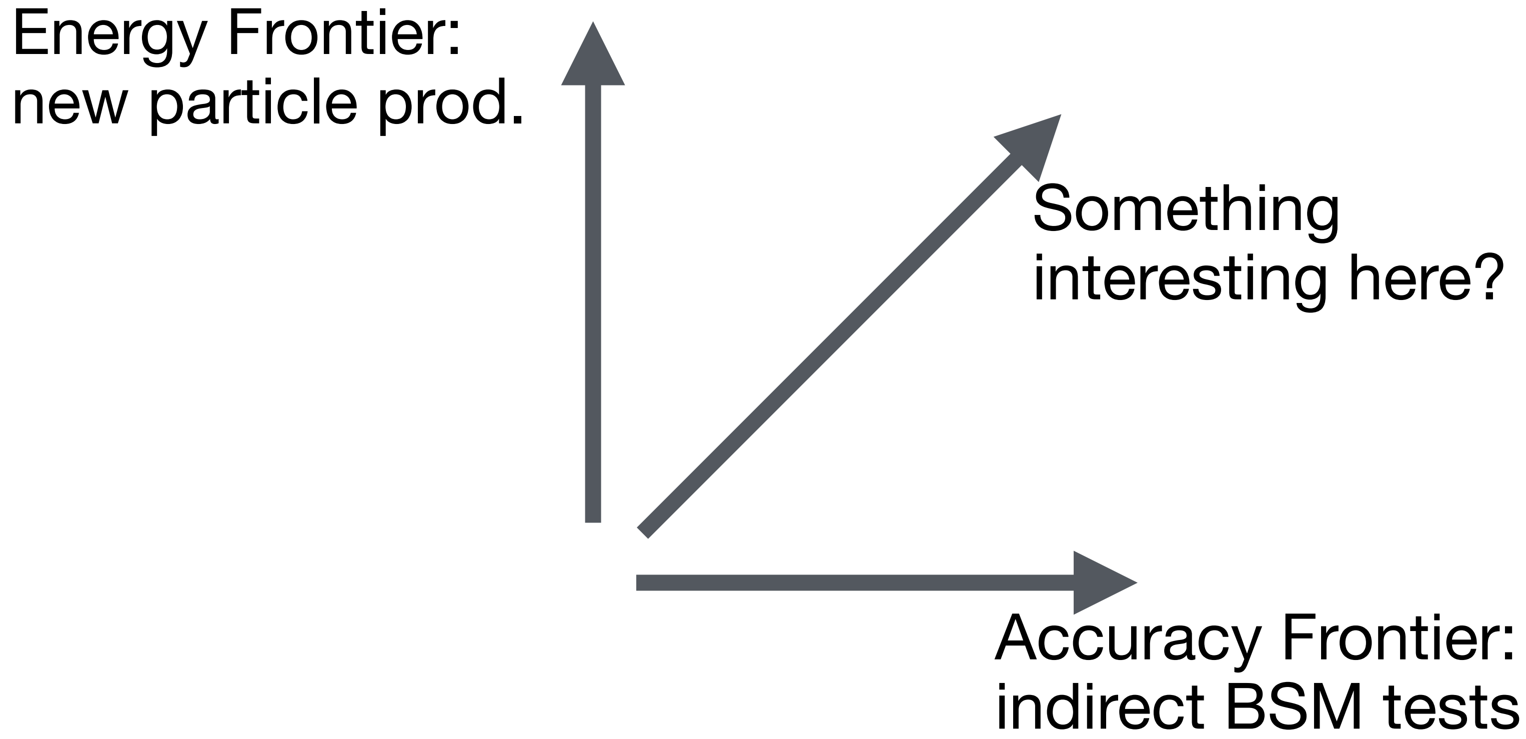
Energy and Accuracy Frontier

Energy Frontier:
new particle prod.

Energy and Accuracy Frontier

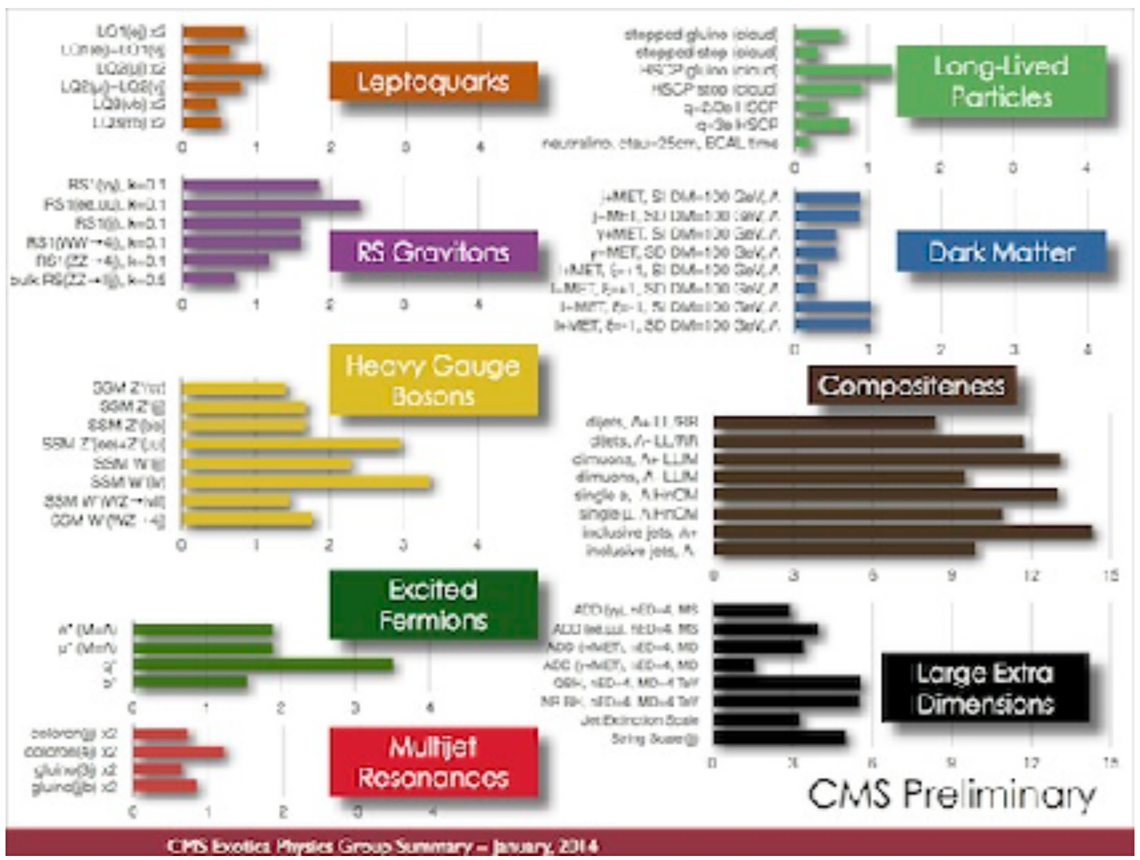


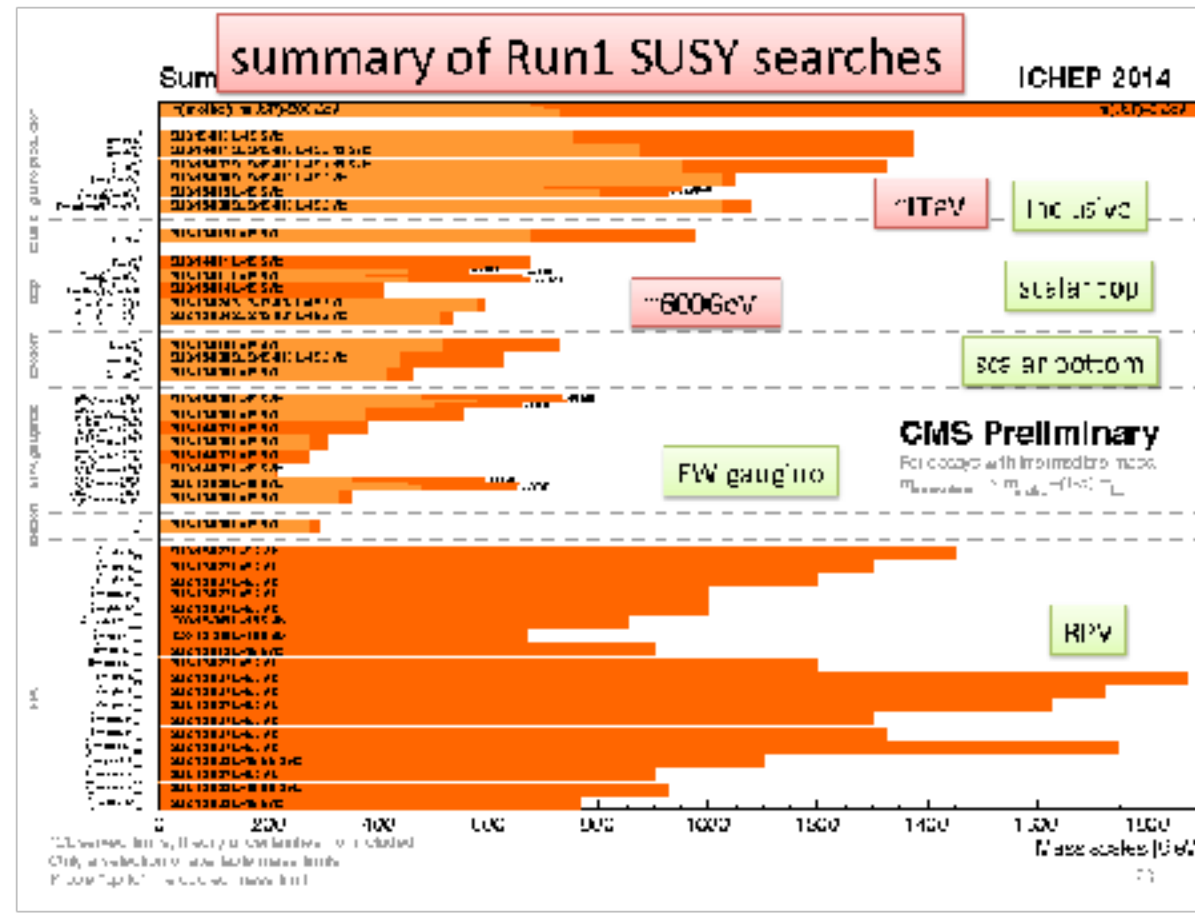
Energy and Accuracy Frontier



Energy Frontier @ LHC: Direct Searches

The simplest and most common way to use LHC data …





… and the best one to make quick progresses at run-2

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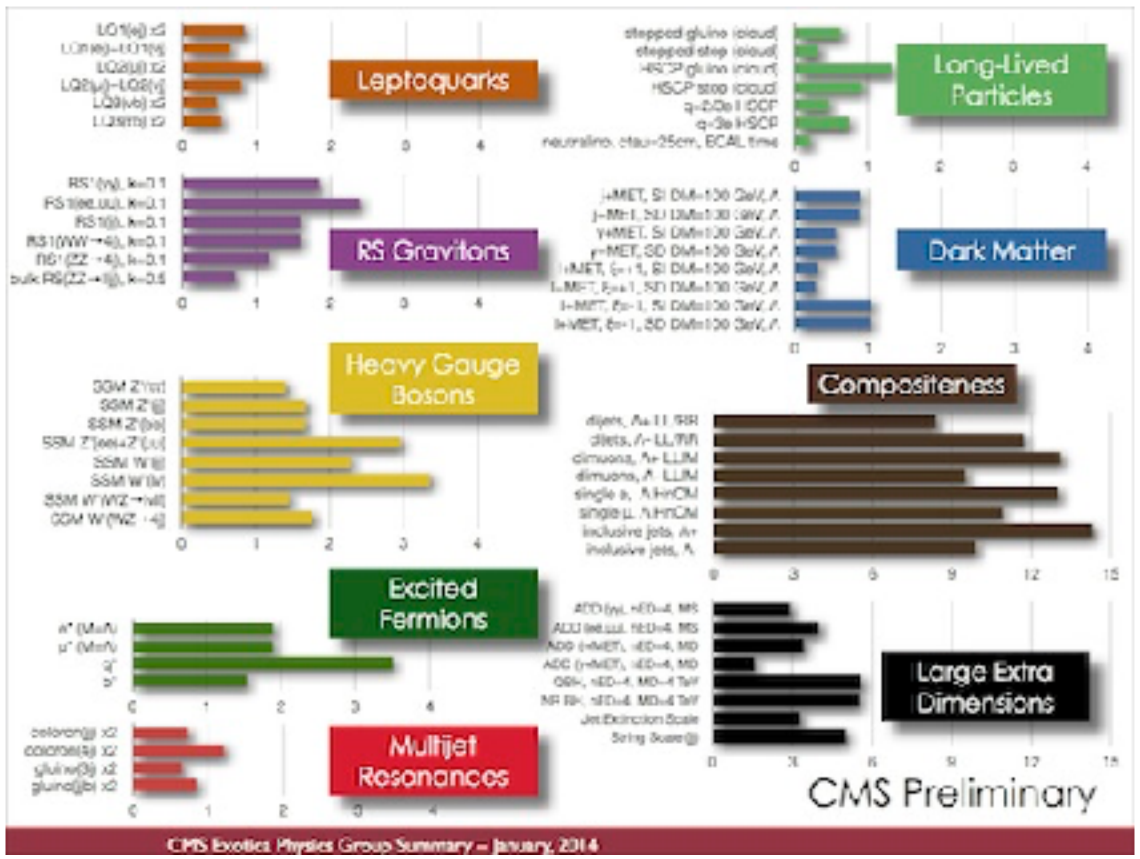
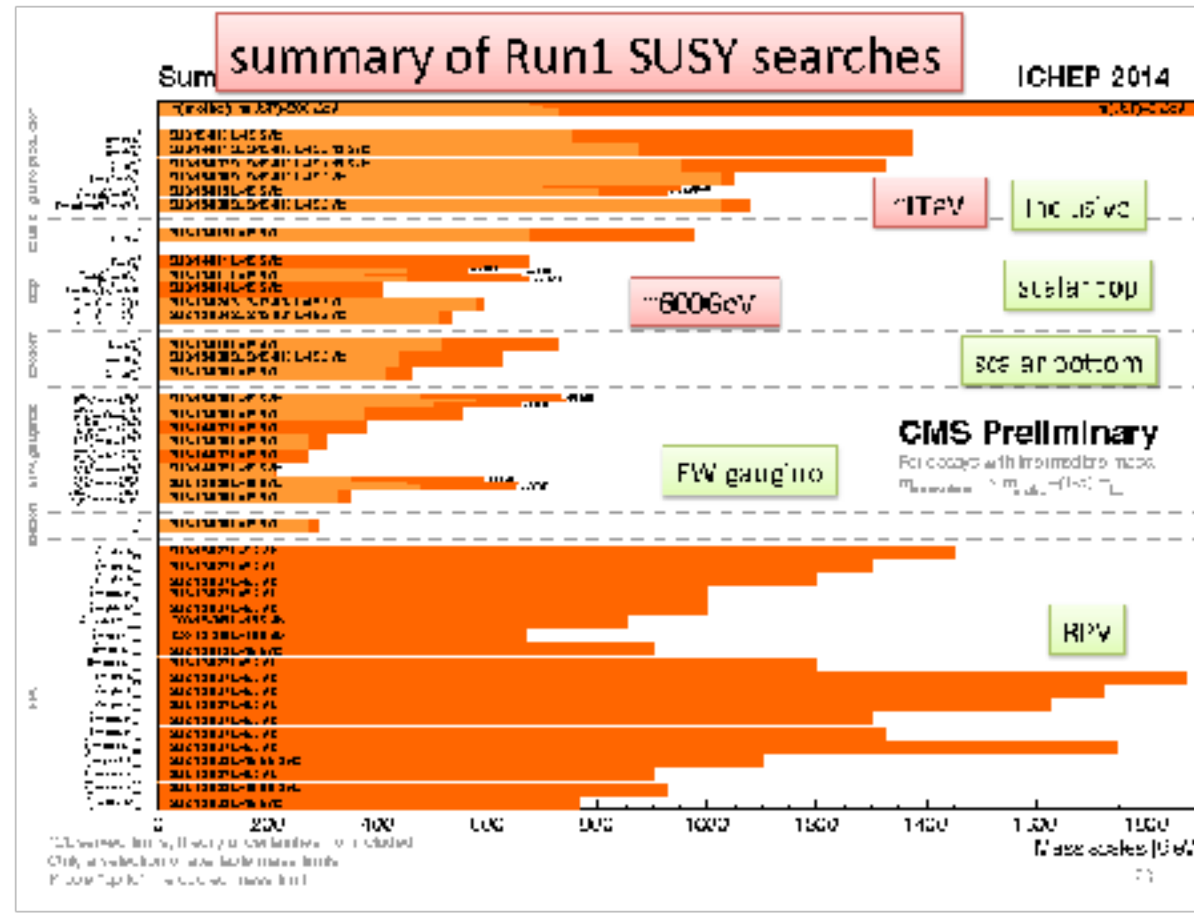




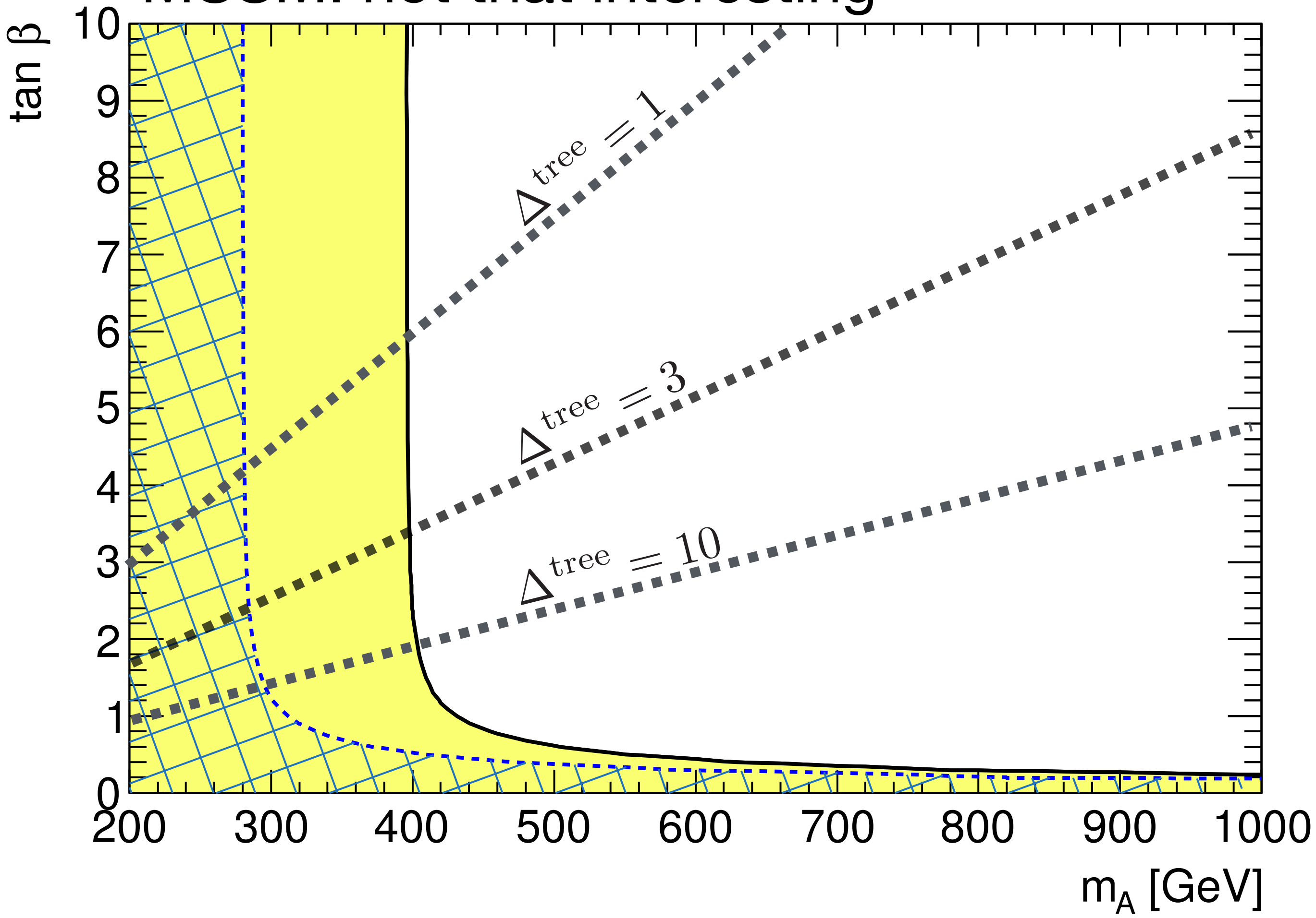
… and the best one to make quick progresses at run-2

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

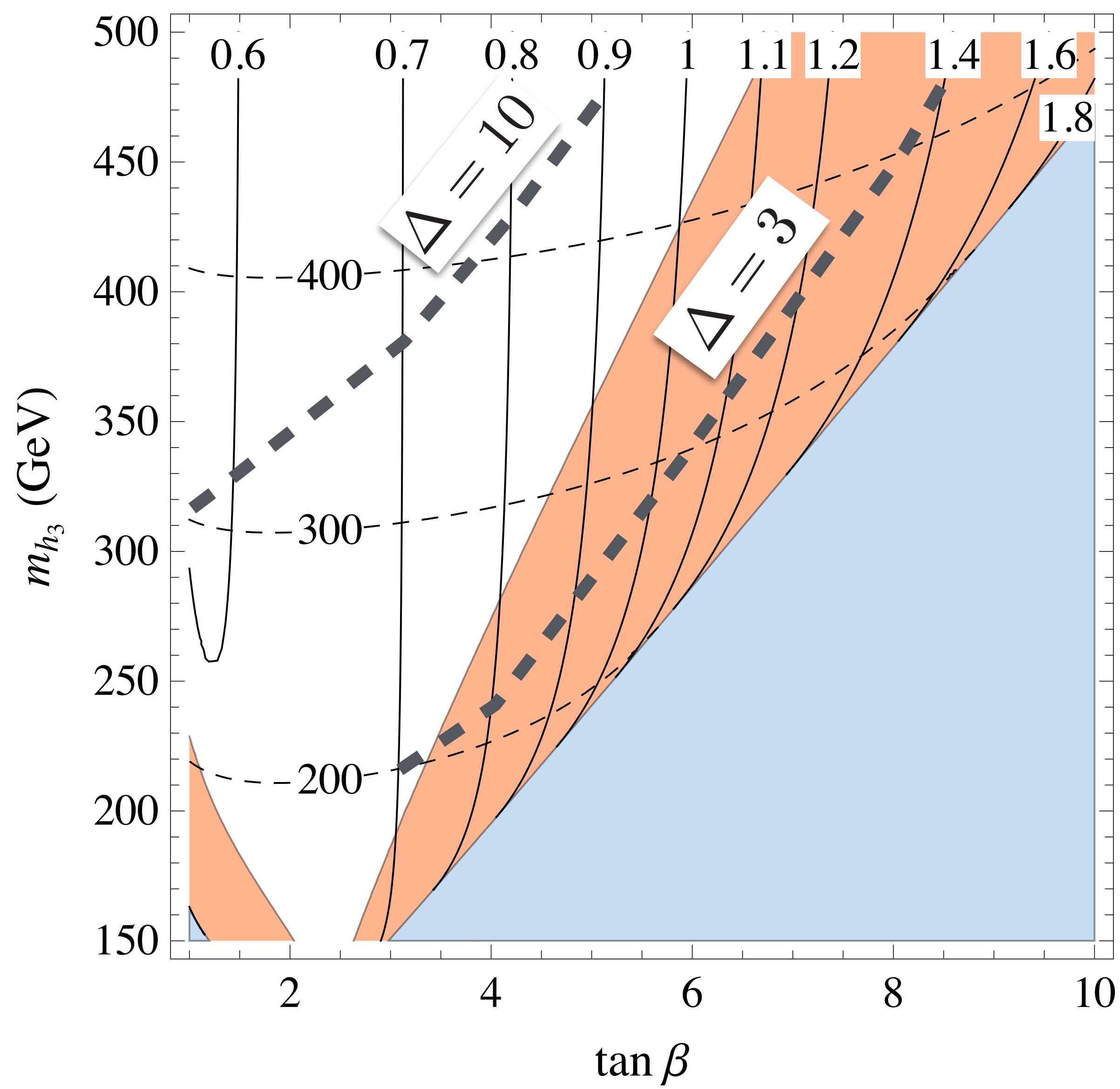
Accuracy Frontier @ LHC: Higgs

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

MSSM: not that interesting



NMSSM: better



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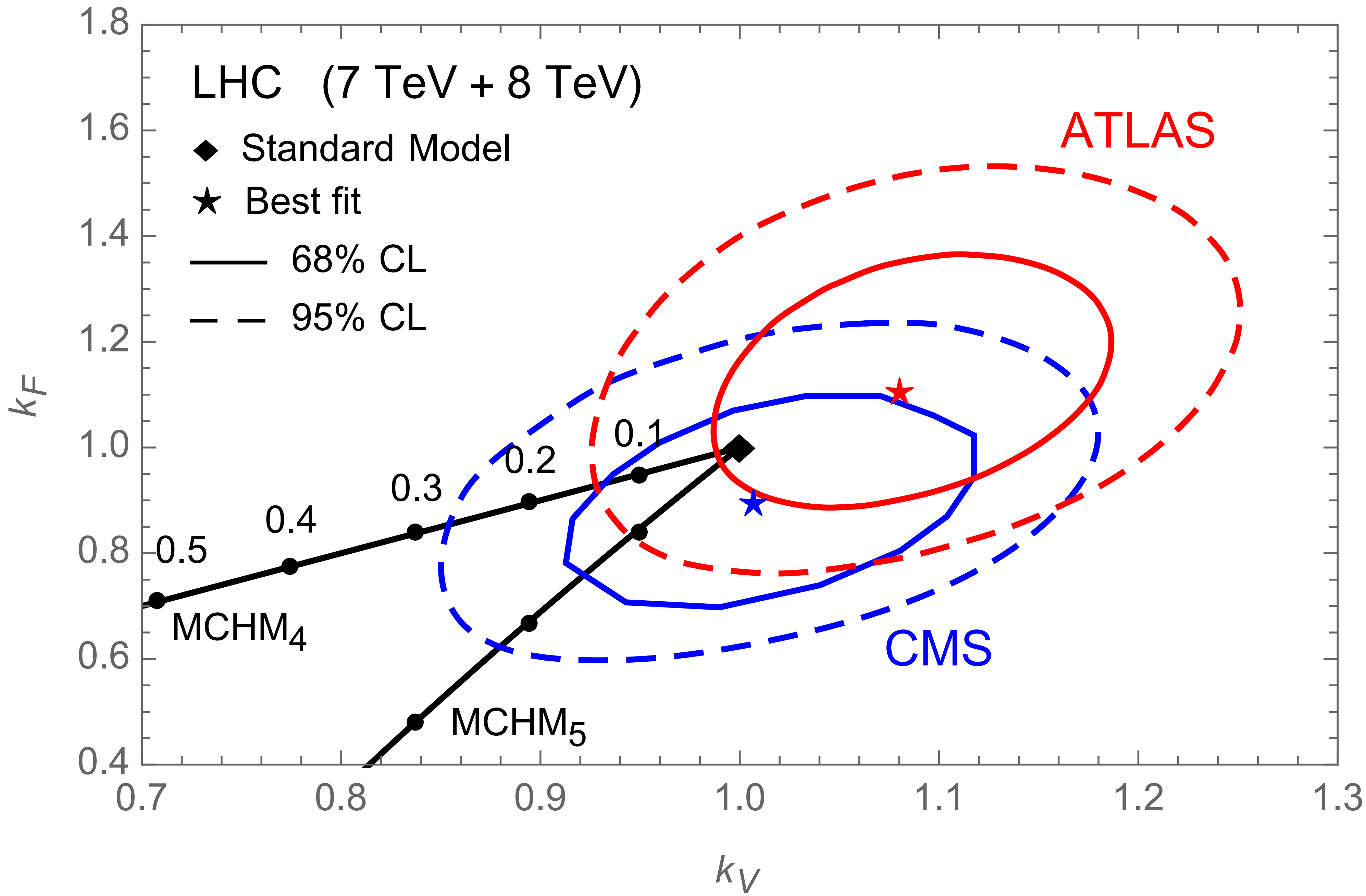

Accuracy Frontier @ LHC: Higgs

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

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

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

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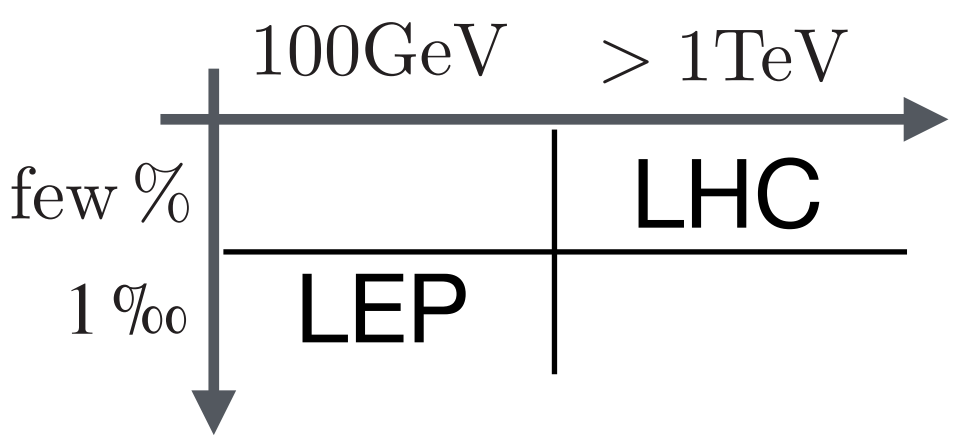
$$1‰ \ @\ 100\,\mathrm{GeV} \ \sim\ 10\% \ @\ 1\,\mathrm{TeV}$$

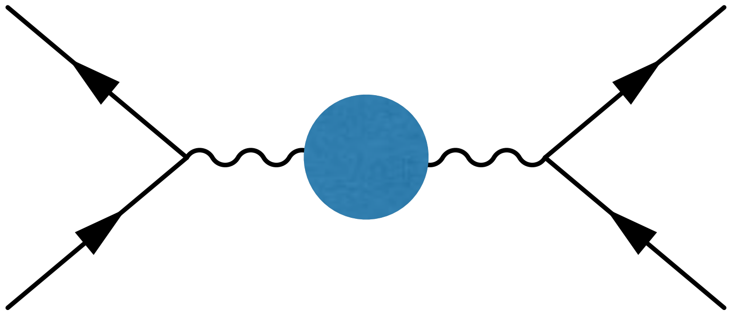


LHC better than LEP on some EWPT par.?

Plus of course probing 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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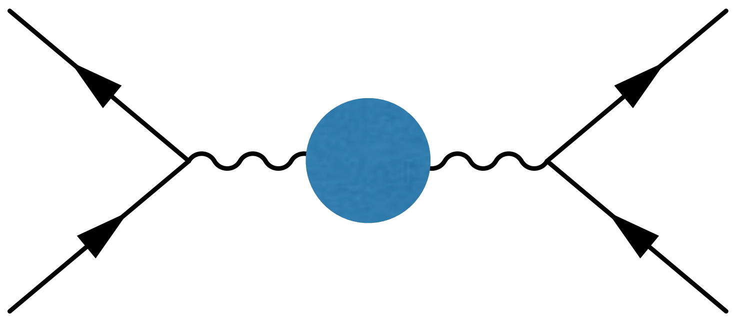

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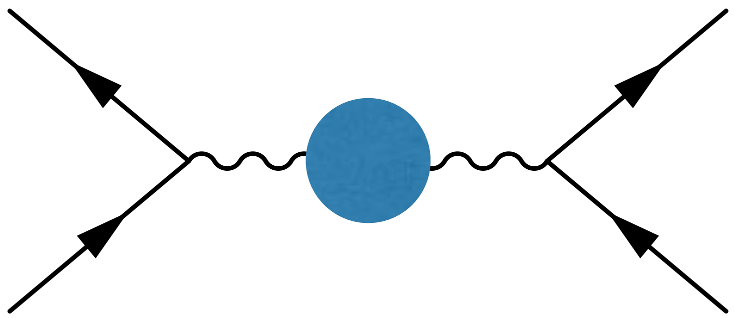

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W and Y: produce constant terms.
quadratically enhanced at high mass. What can LHC do?

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%

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

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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

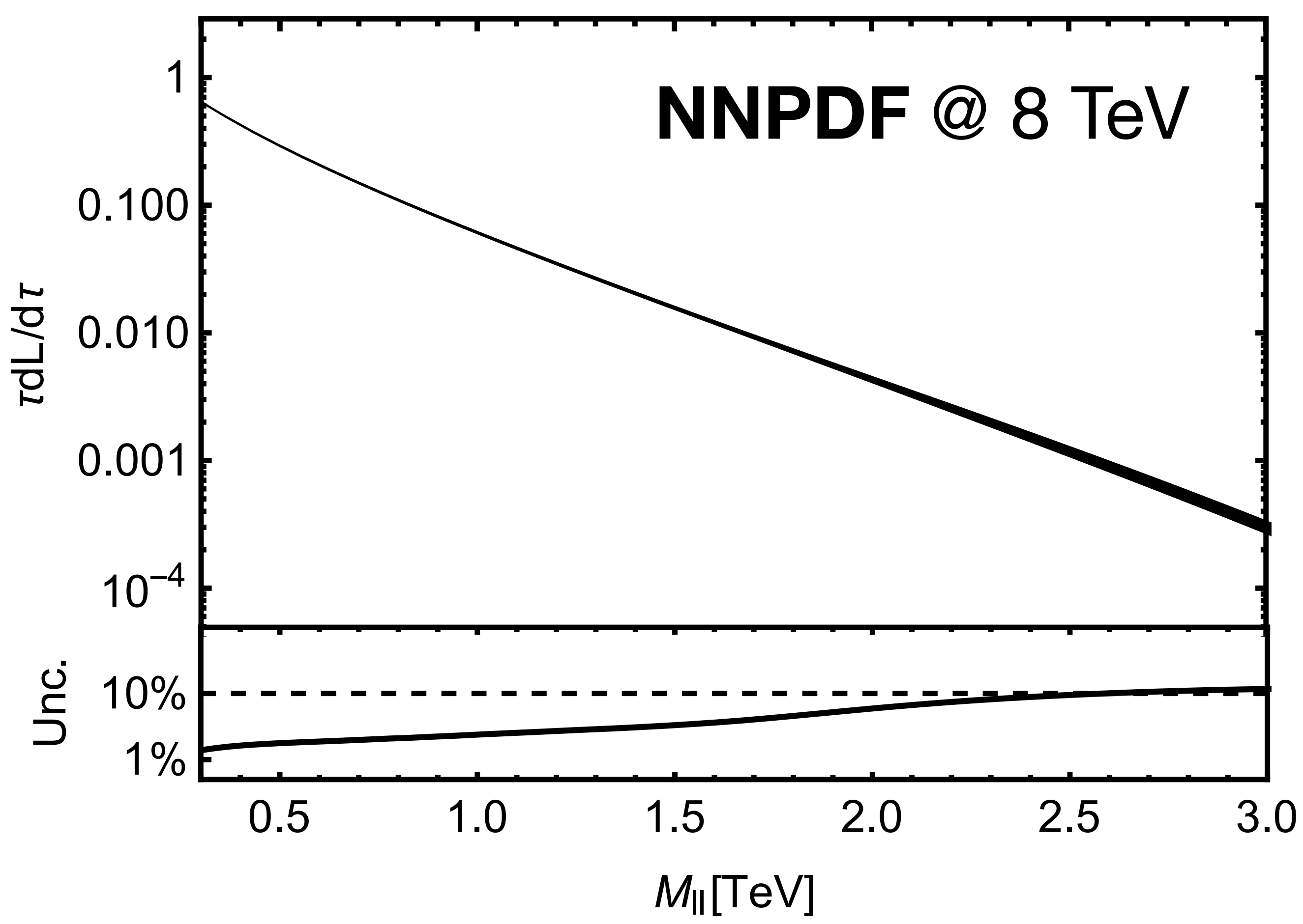
[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

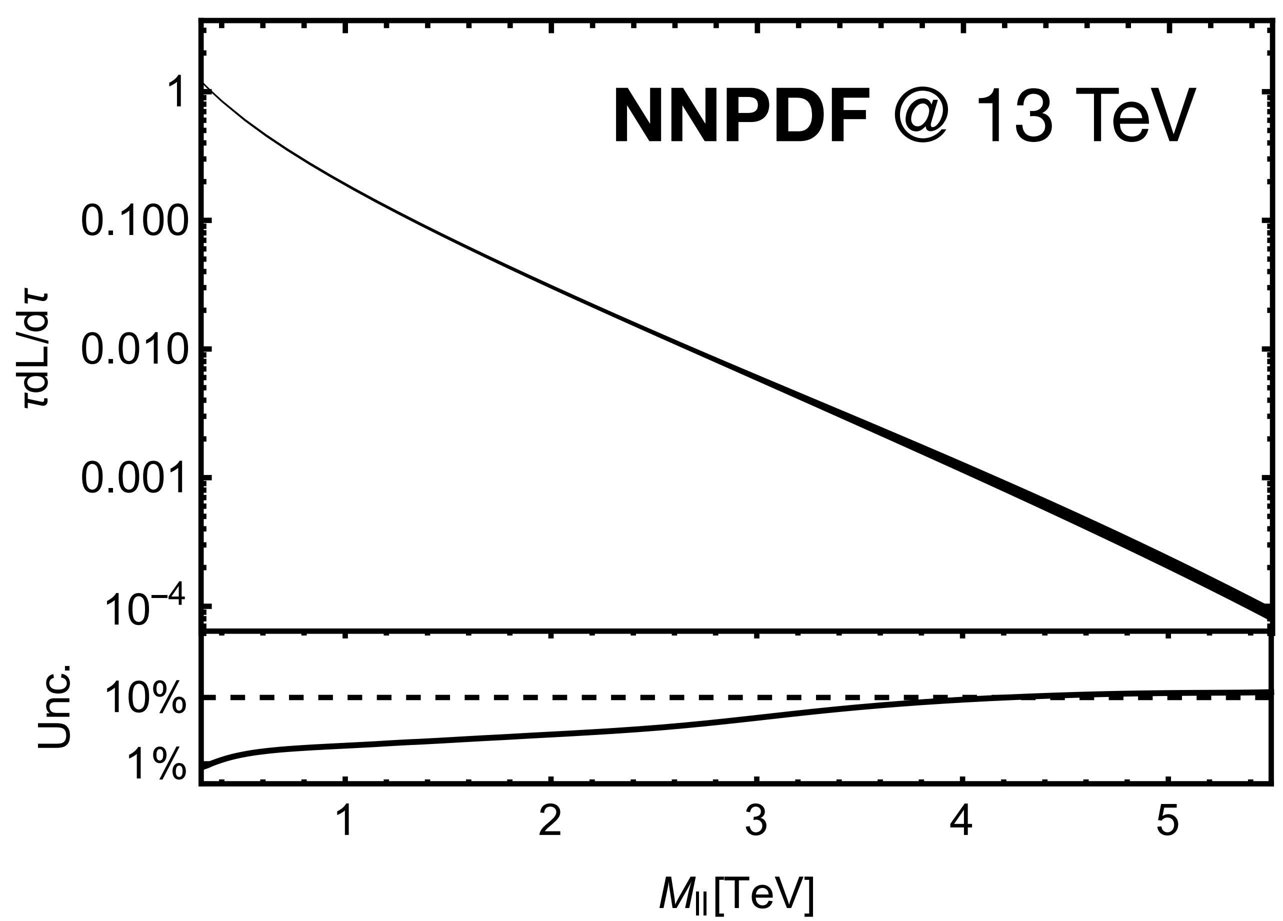
Ingredients for the program to work:

Accurate experimental measurement: Syst. ~ 2%

Theory errors well under control:

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





Oblique Parameters at the LHC

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

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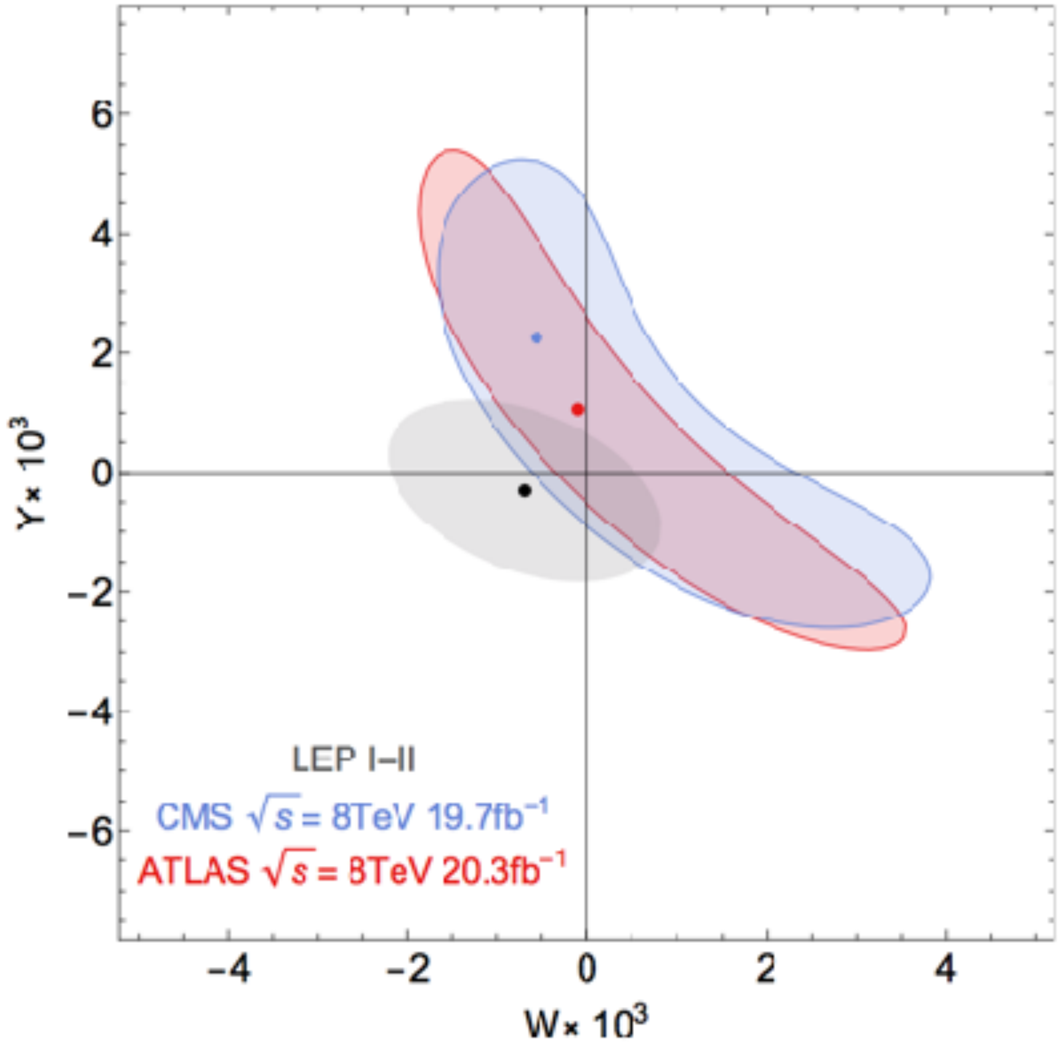
Theory errors well under control:

- 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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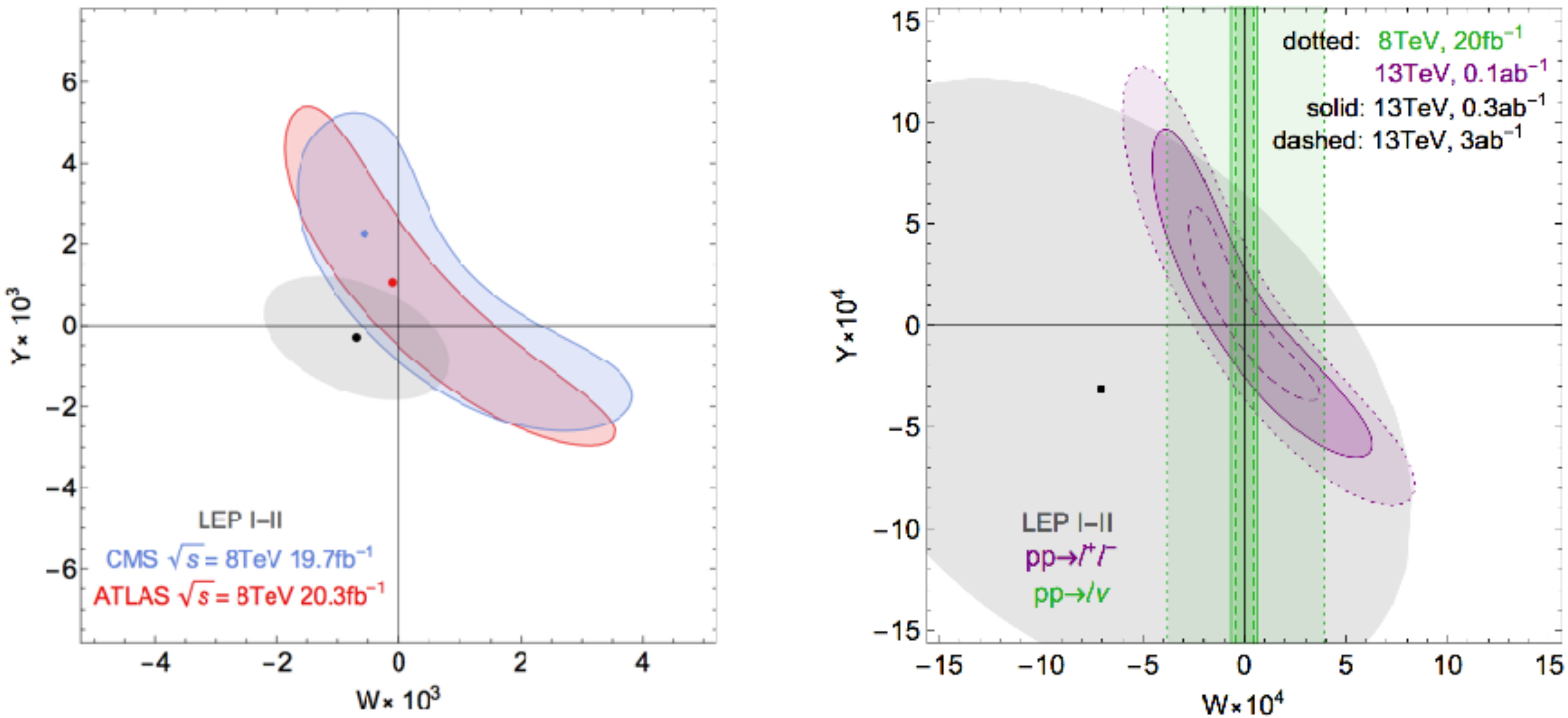

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Charged DY @ **run-1 would surpass LEP**

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

Oblique Parameters at the LHC

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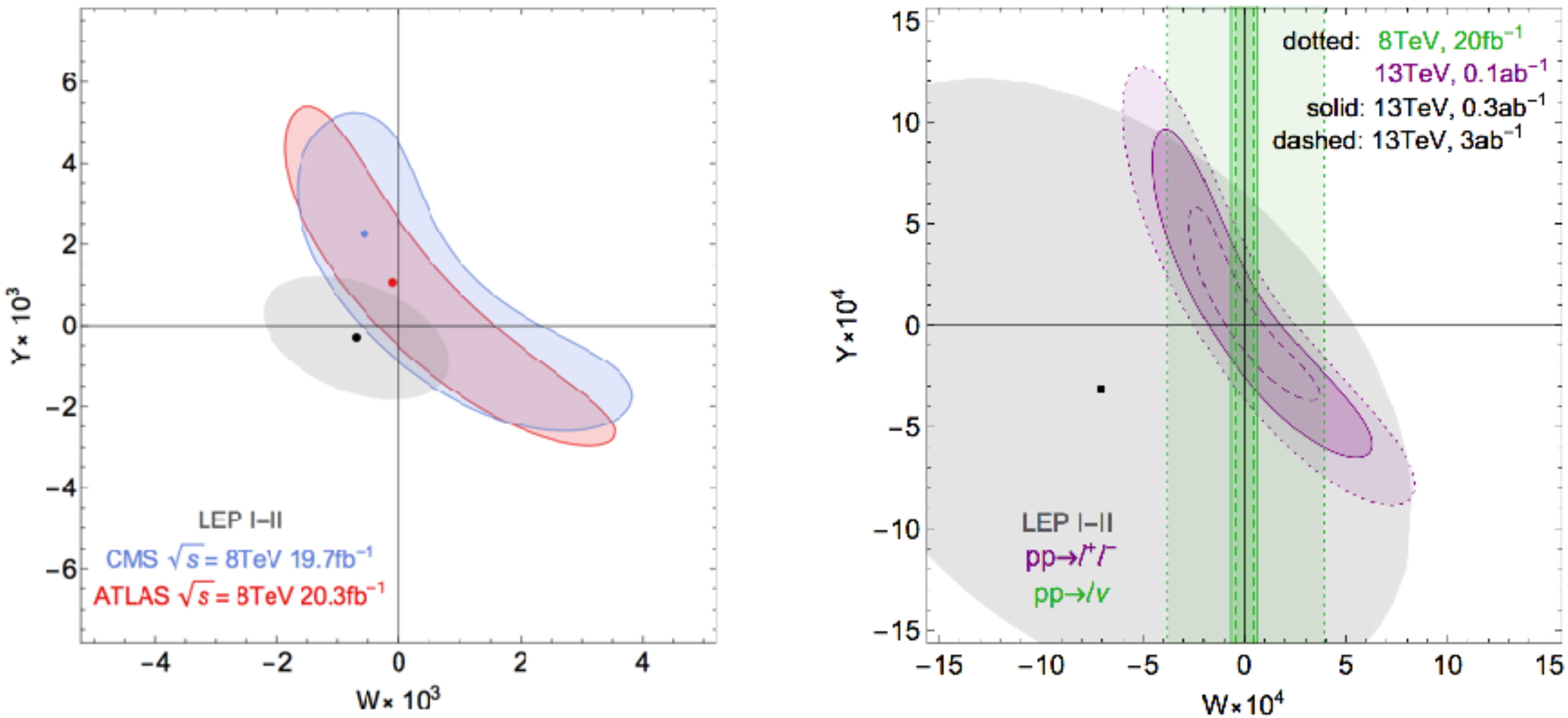

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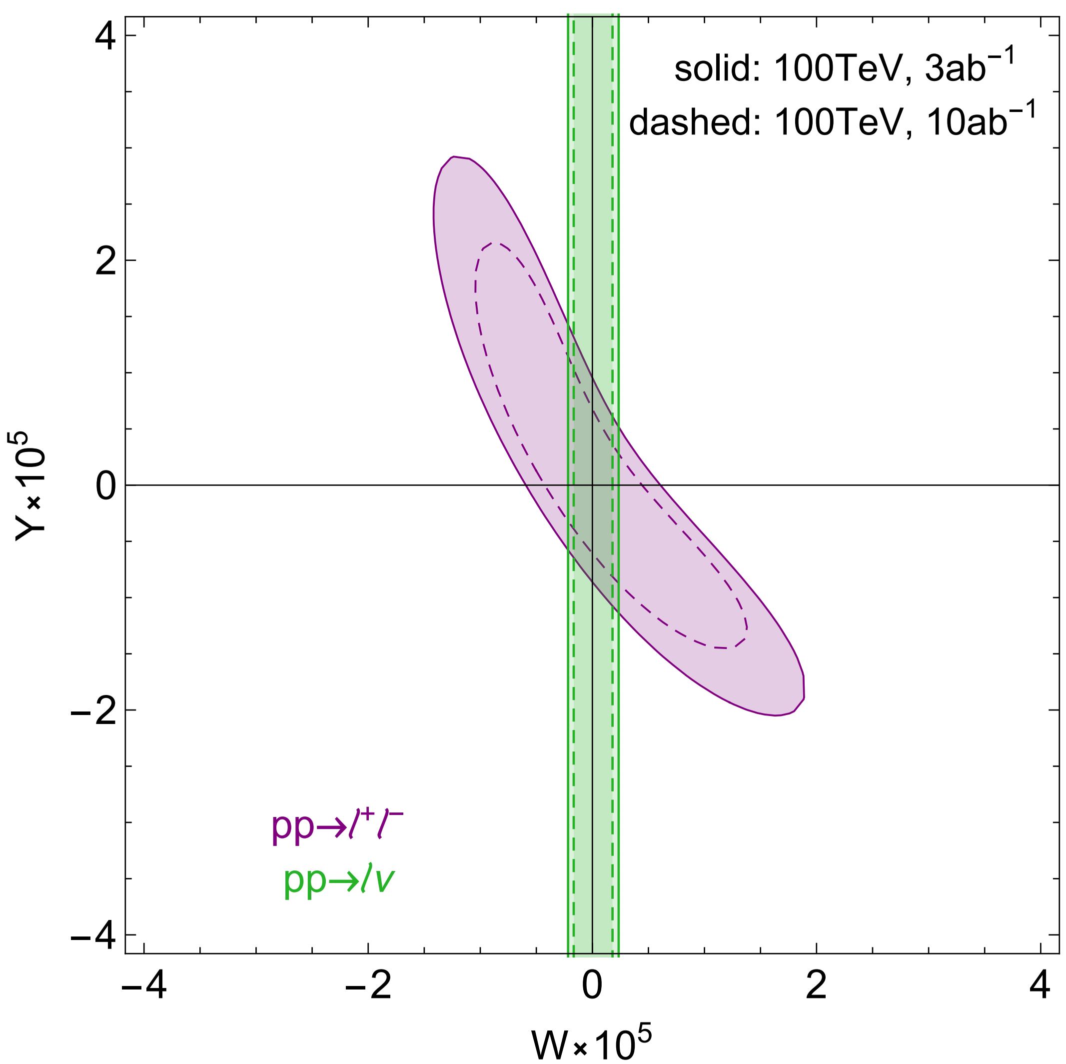

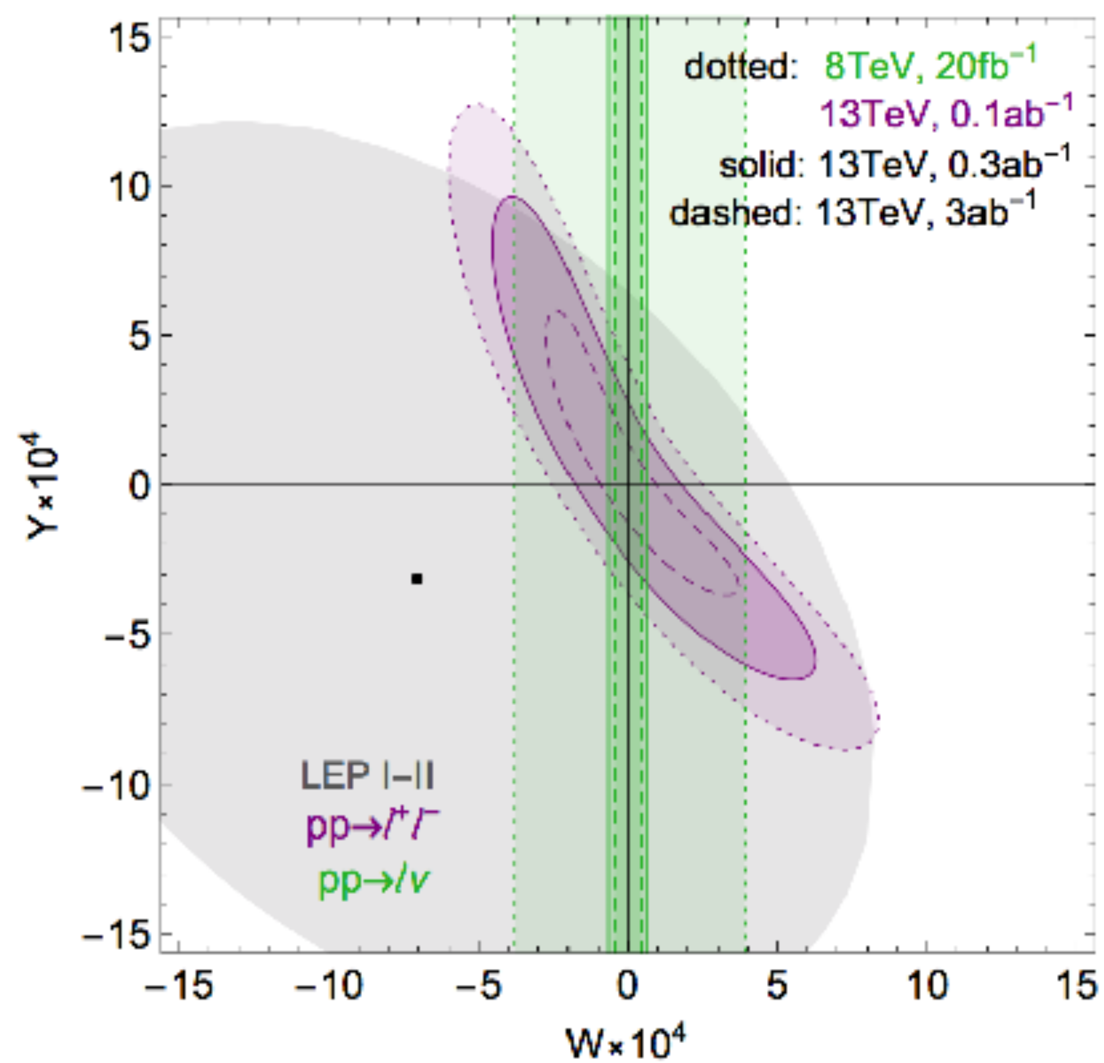

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Raising **energy better** than raising **lumi** (part.lumi boost)

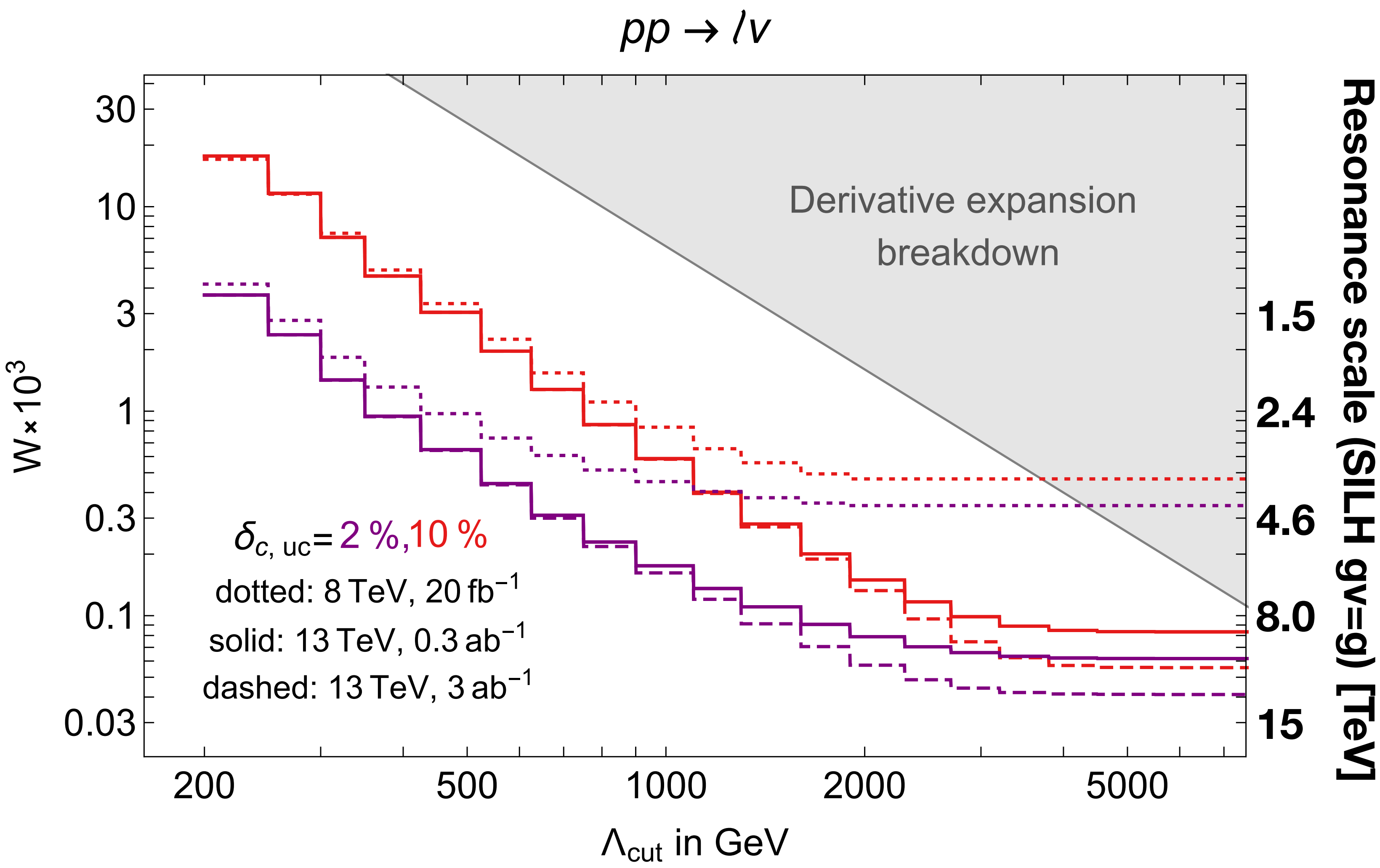
Oblique Parameters at the LHC

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

EFT Validity Check: Limit from scales (2-3 TeV) well below cutoff

$$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$$

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



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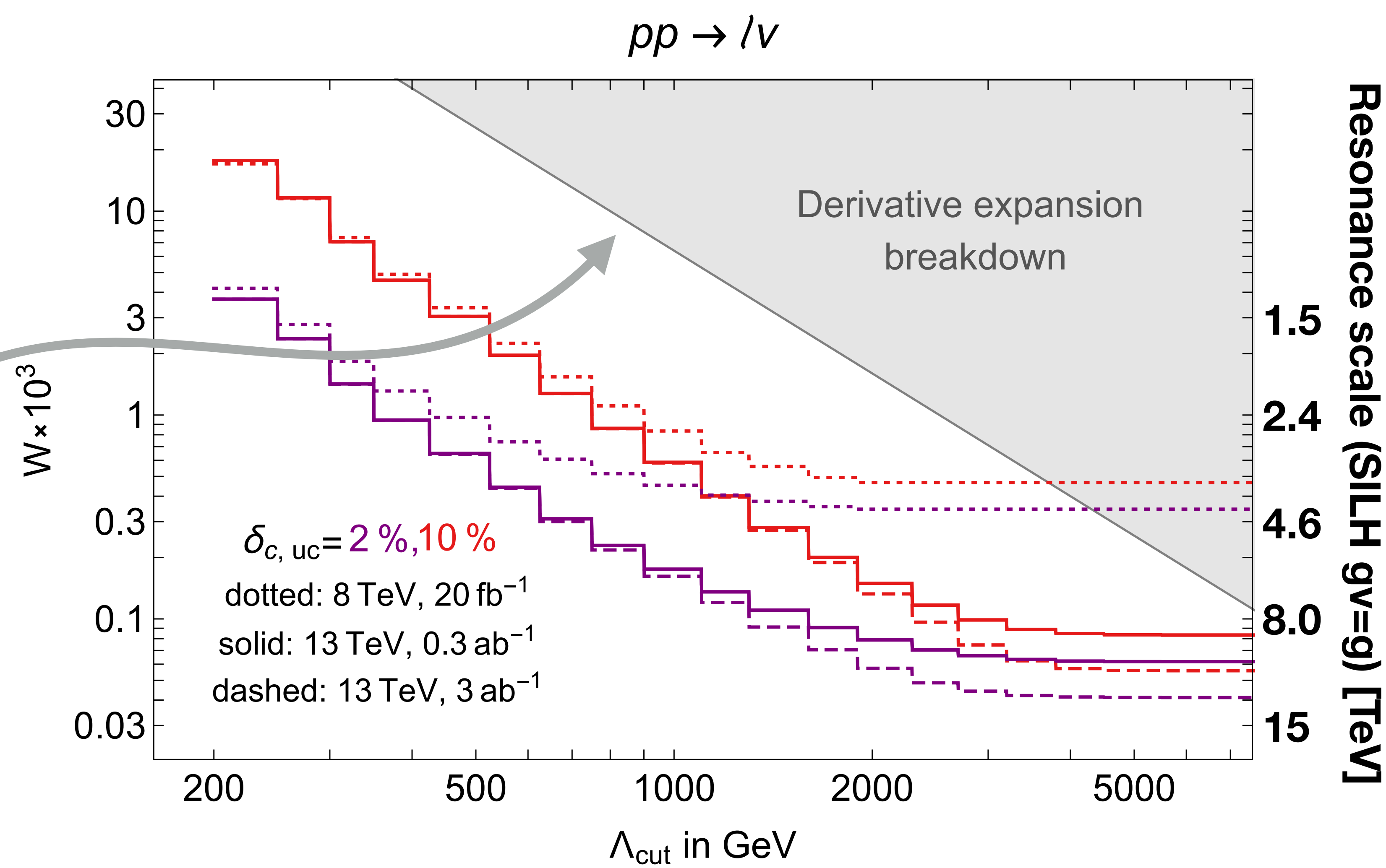
far from pert.unit. break



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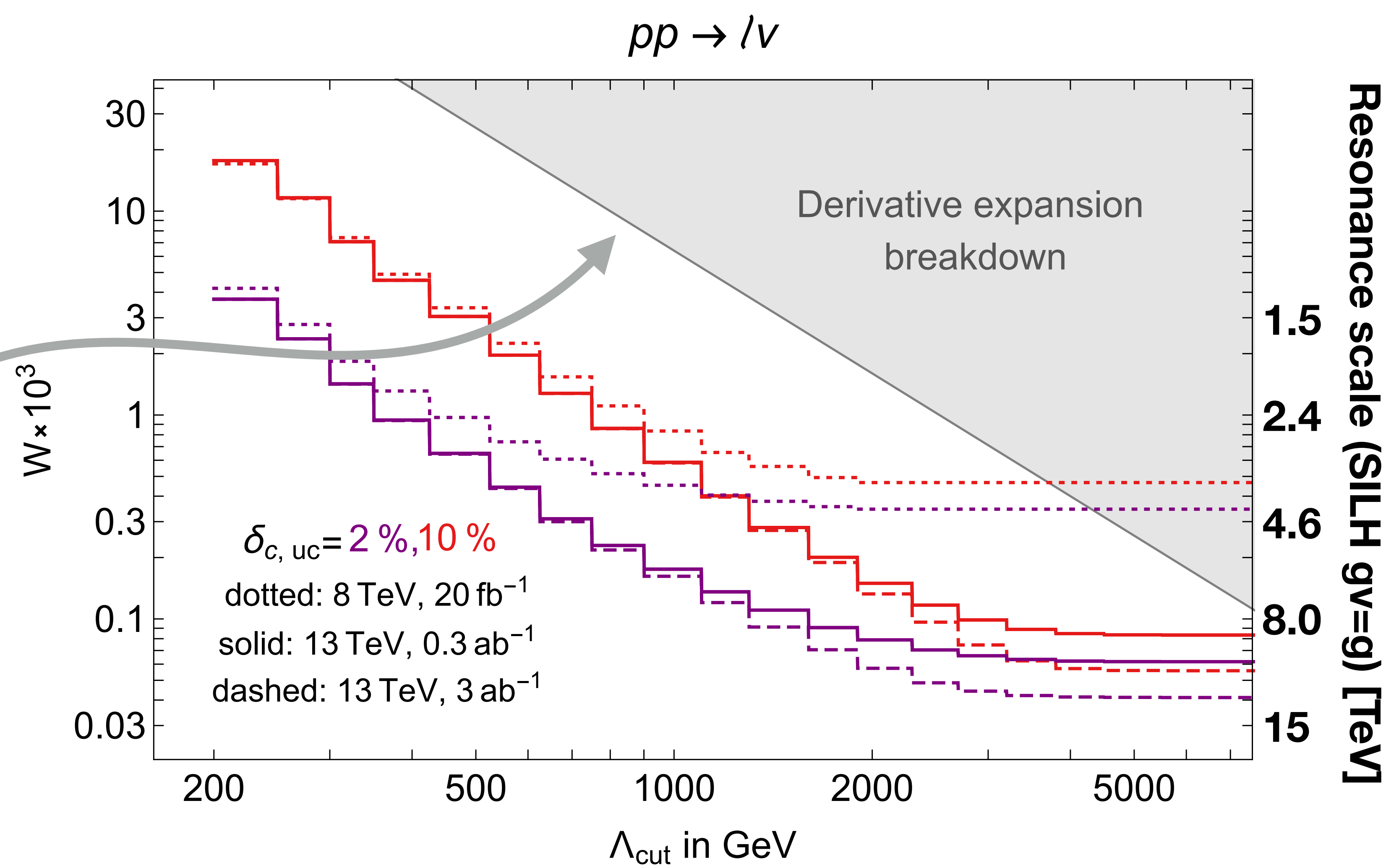

Mass limit competitive or stronger than direct searches for small-coupling SILH realisation or for W-compositeness "remedios" power-counting

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)

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

SILH basis

$\longleftrightarrow$

$$\mathcal{O}_L^{(3)} = (\bar{Q}_L\sigma^a\gamma^\mu Q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}_L = (\bar{Q}_L\gamma^\mu Q_L)(iH^\dagger\overleftrightarrow{D}_\mu H)$$
$$\mathcal{O}_R^u = (\bar{u}_R\gamma^\mu u_R)(iH^\dagger\overleftrightarrow{D}_\mu H)$$
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Warsaw basis

Longitudinal DiBosons

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Warsaw basis

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

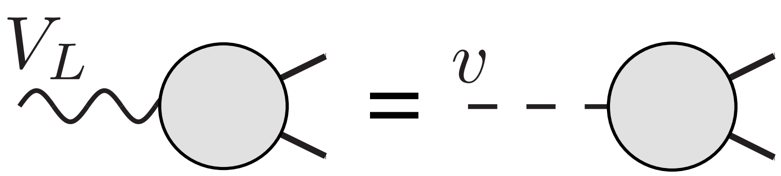
Valid channels for **energy and accuracy frontier exploration ?**

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**

Longitudinal DiBosons

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

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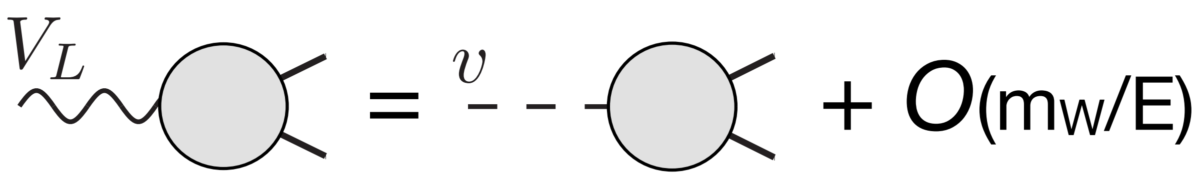

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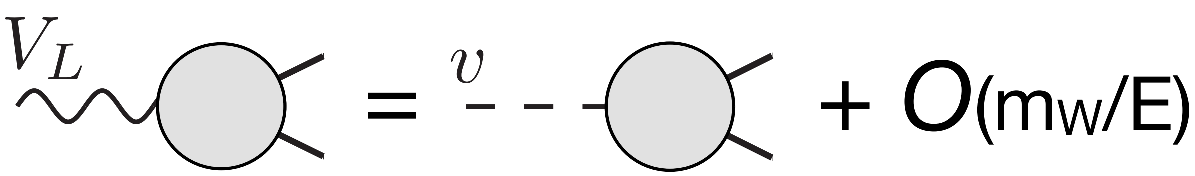

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Simple map to Warsaw basis

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

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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	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_{f_R} t^2_{\theta_W}\boldsymbol{\delta\kappa_\gamma} + T_Z^{f_R}\boldsymbol{\delta g^Z_1} + c_{\theta_W}\boldsymbol{\delta g^Z_{fR}}/g\right]$

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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	bounds no bkg.	bounds with bkg.	
$W_l H_h$	$[-0.024, 0.024]$	$[-0.089, 0.078]$	→ Top/bb Higgs fakes
$Z_l H_h$	$[-0.074, 0.070]$	–	→ Maybe promising [for $a^{(1)}$]
$W_l W_l$	$[-0.029, 0.028]$	$[-0.11, 0.093]$	→ Swamped by V_T production
$W_l Z_l$	$[-0.032, 0.031]$	$[-0.057, 0.052]$	→ Less V_T background

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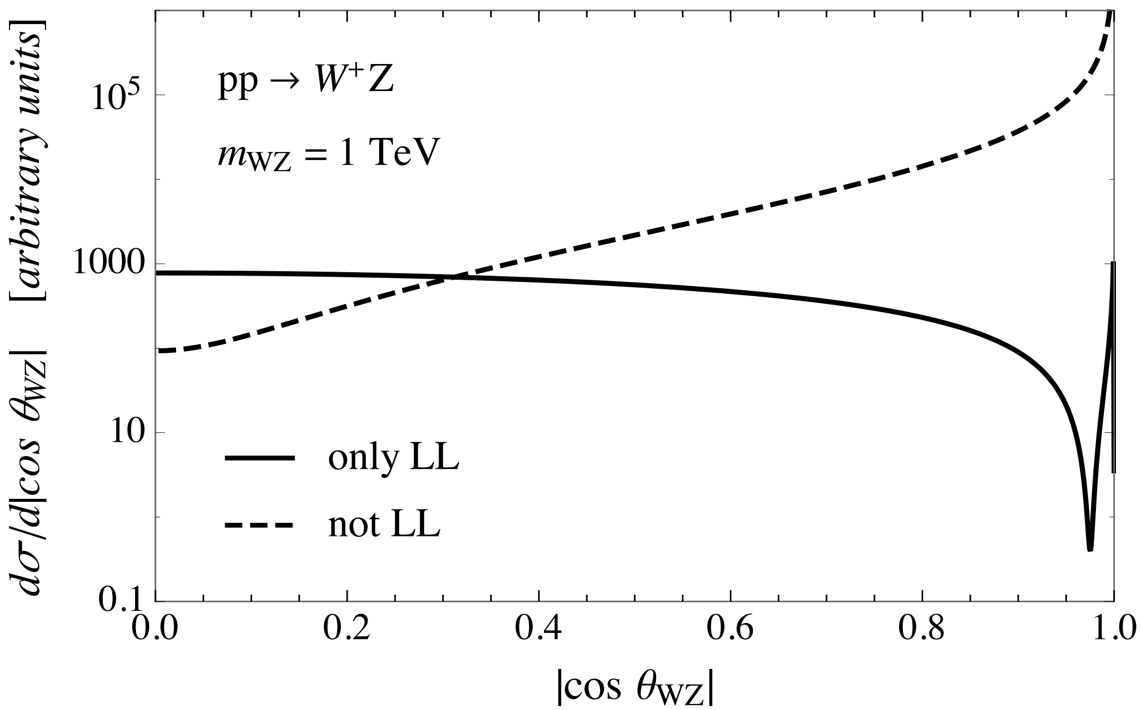
Summary:

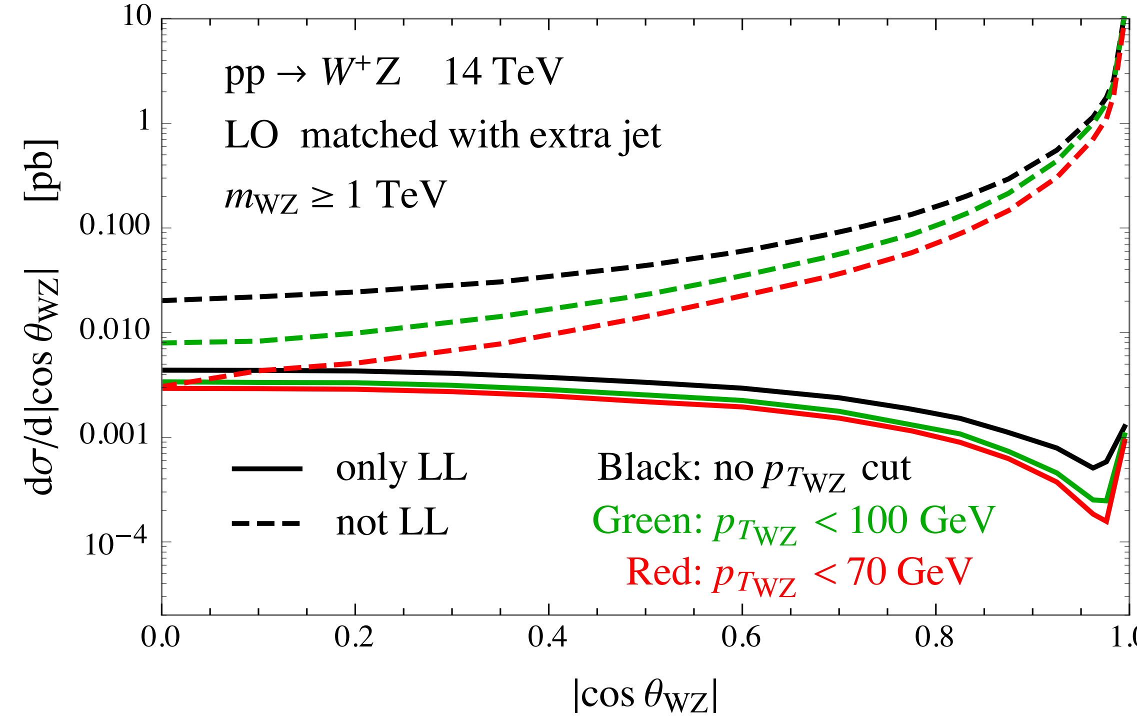
Channel	Challenge
$WW \quad WZ$	**V_T Background**
$WH \quad ZH$	**Needs Boosted Higgs**

Leptonic WZ

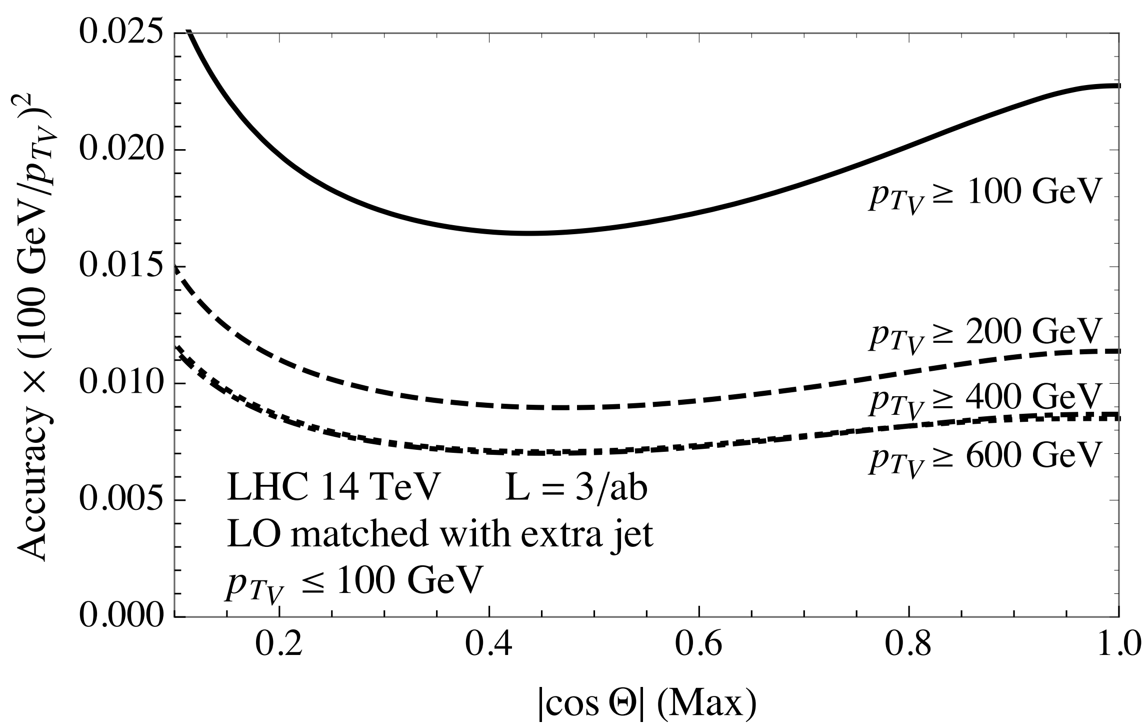
[Franceschini, Panico, Pomarol, Riva, AW, to appear]

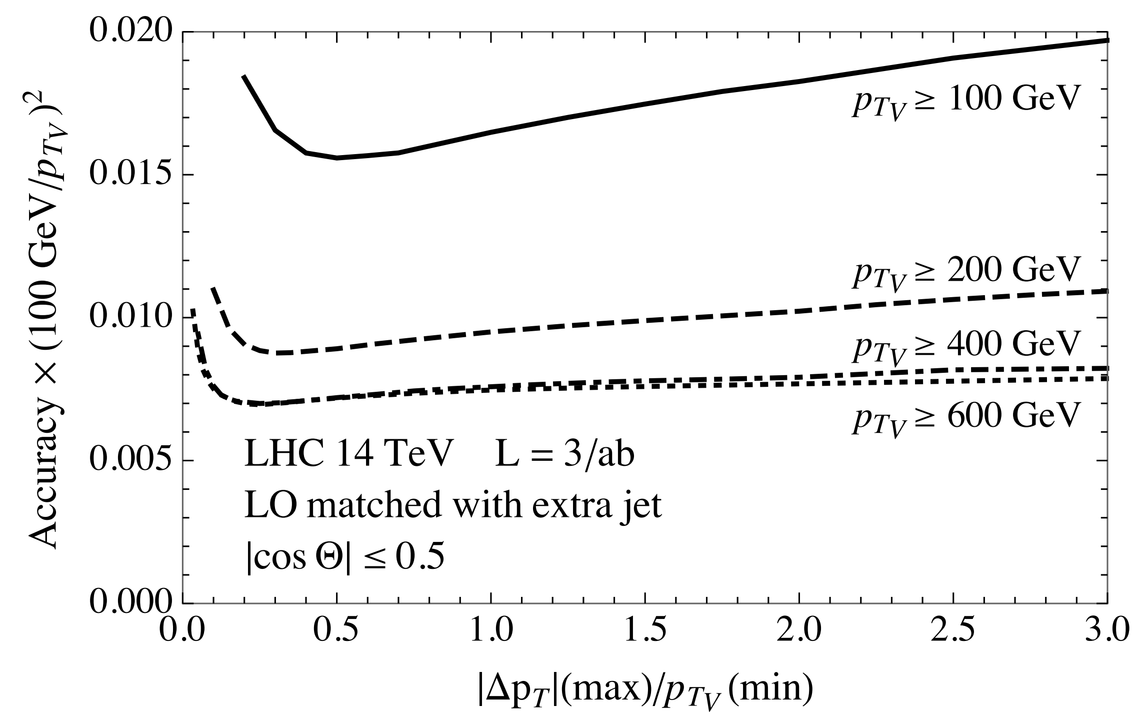
Exploit (~accidental) ~vanishing transverse amplitude at $\theta = \pi/2$





Suppress real NLO by upper cut on total WZ P_T



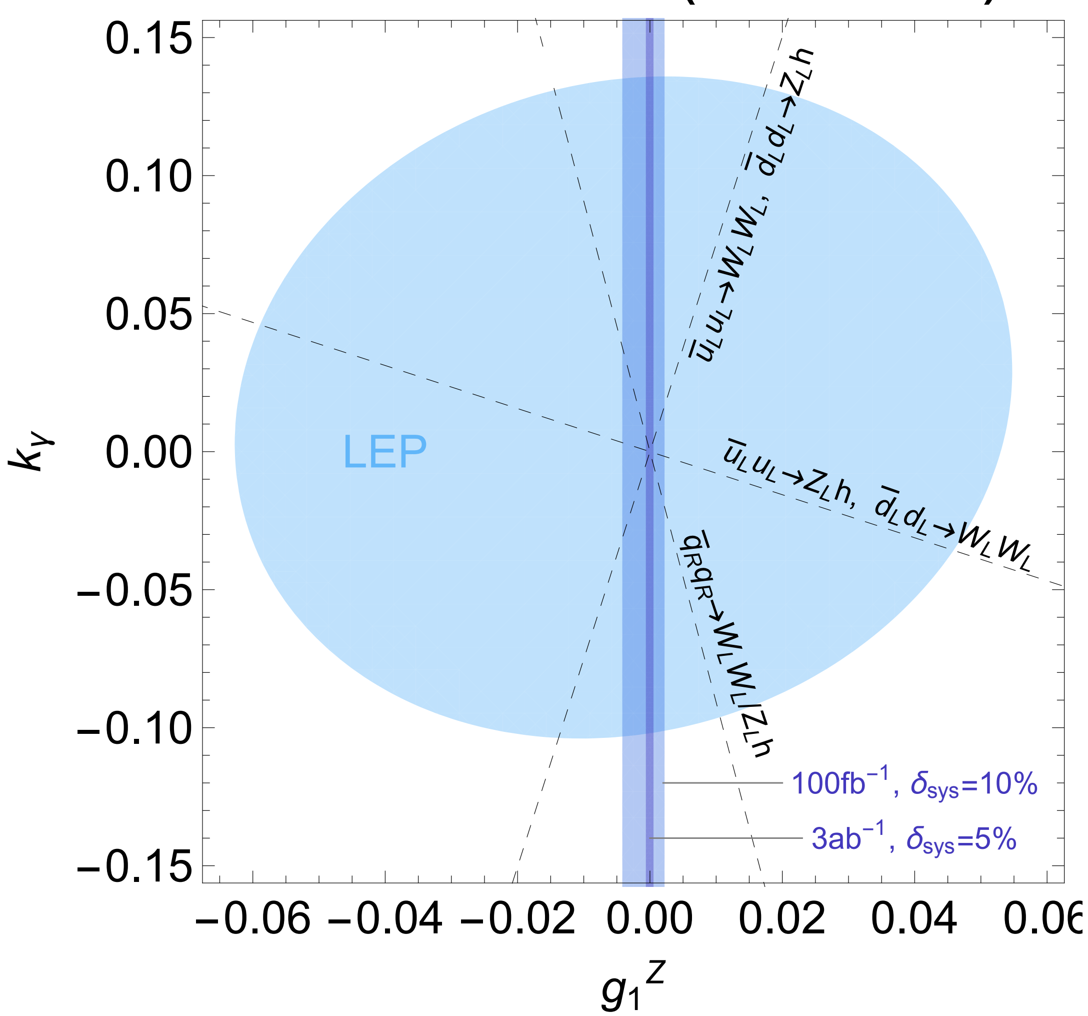


Leptonic WZ

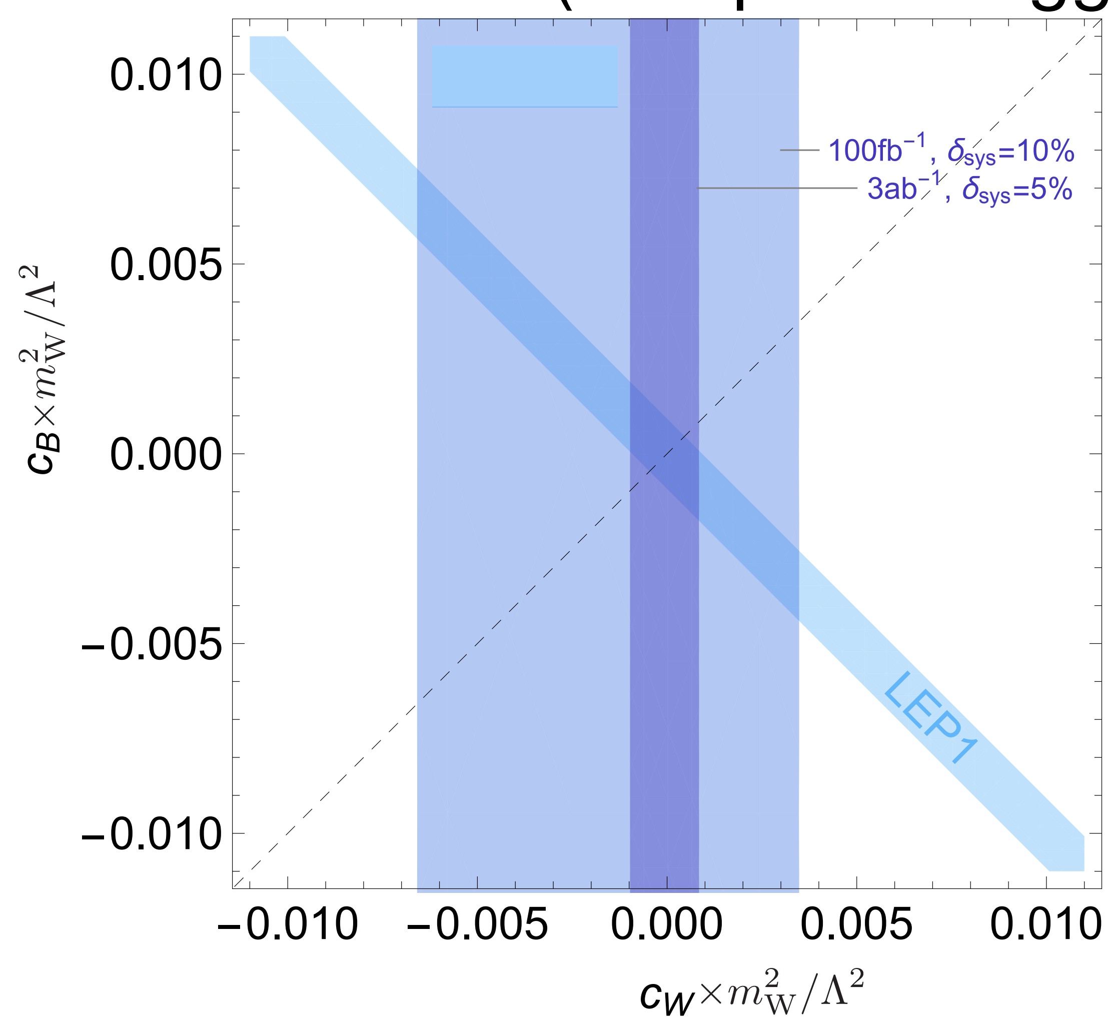
[Franceschini, Panico, Pomarol, Riva, AW, to appear]

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/S bounds

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

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

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

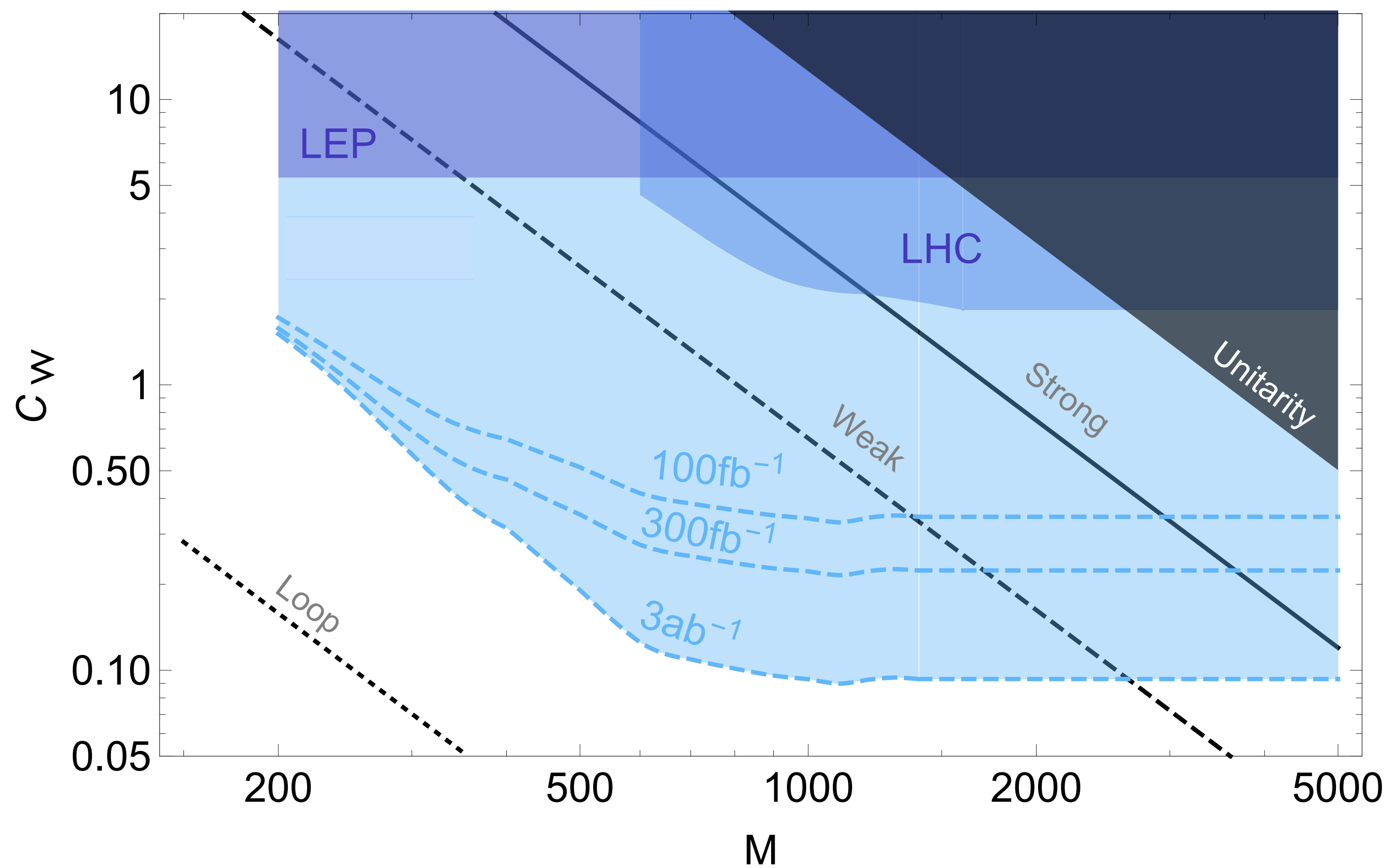
[Franceschini, Panico, Pomarol, Riva, AW, to appear]

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

$$\frac{c_{\rm W}}{\Lambda^2} g_{\rm W} (iH^\dagger \tau^a \overleftrightarrow{D}_\mu) D^\nu W^a_{\mu\nu}$$

$$=$$

$$\frac{g_{\rm UV}}{M^2} (iH^\dagger \tau^a \overleftrightarrow{D}_\mu) D^\nu W^a_{\mu\nu}$$



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$$||$$

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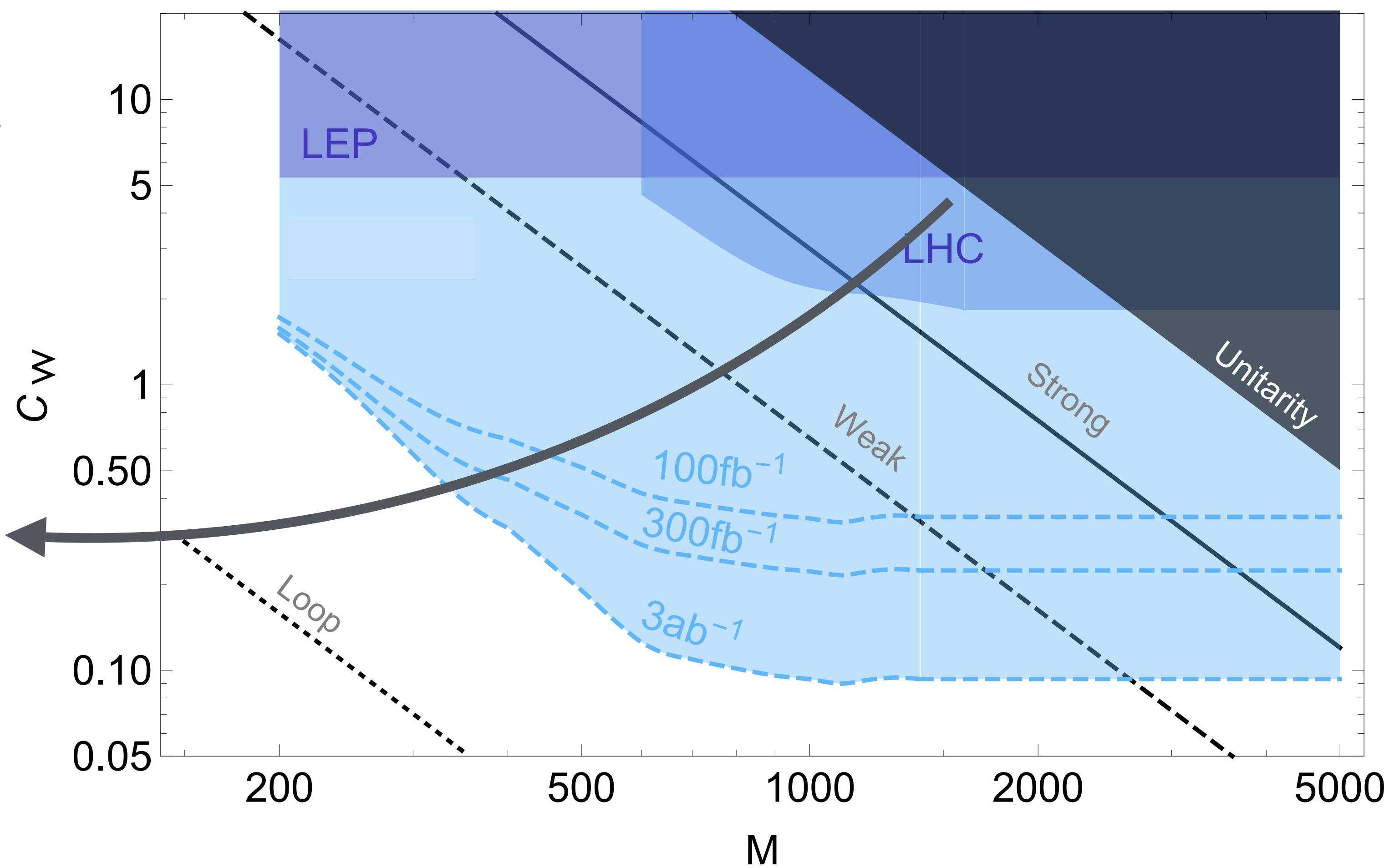
Unit. breakdown: $g_{UV} = 4\pi$



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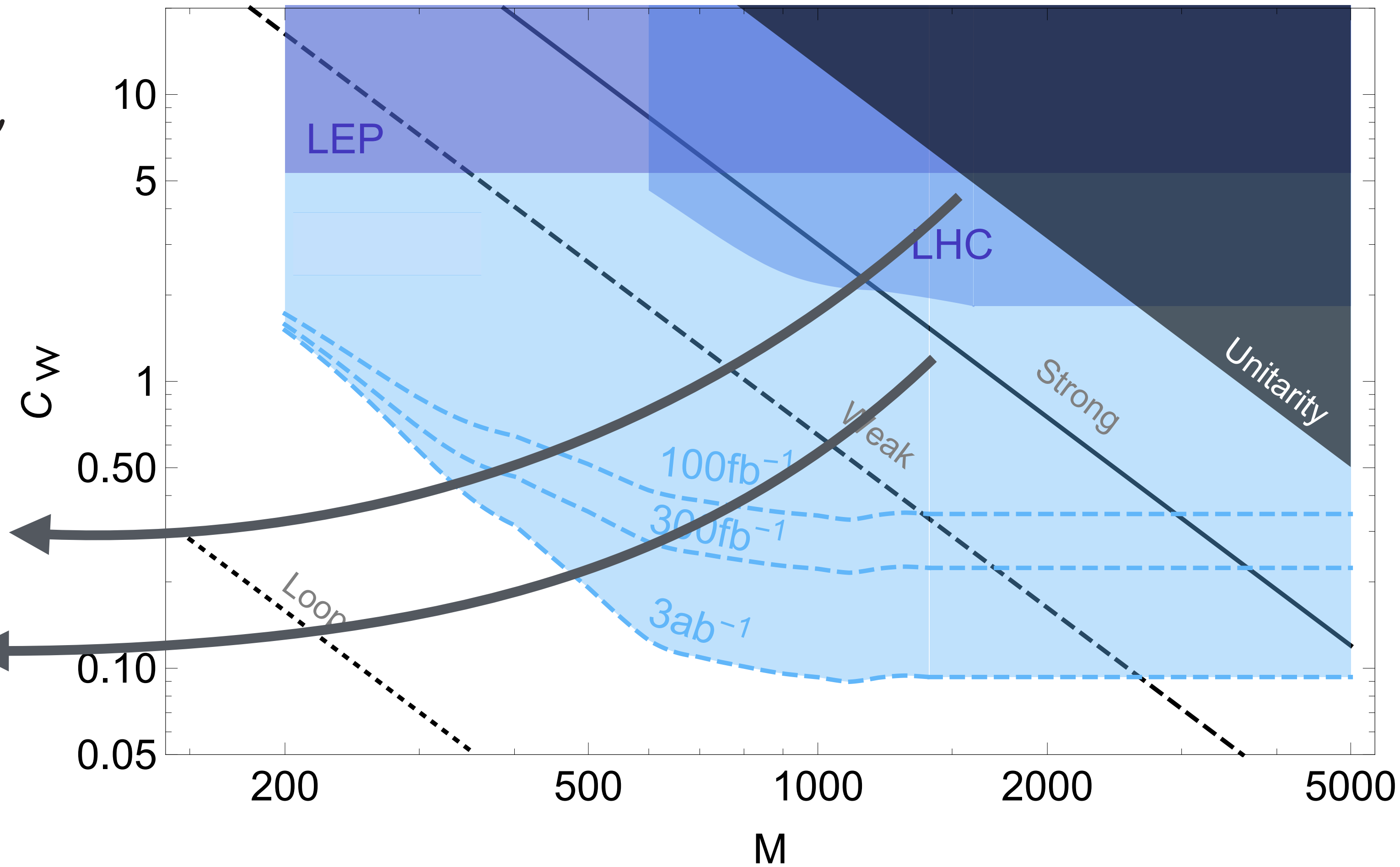

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$\parallel$

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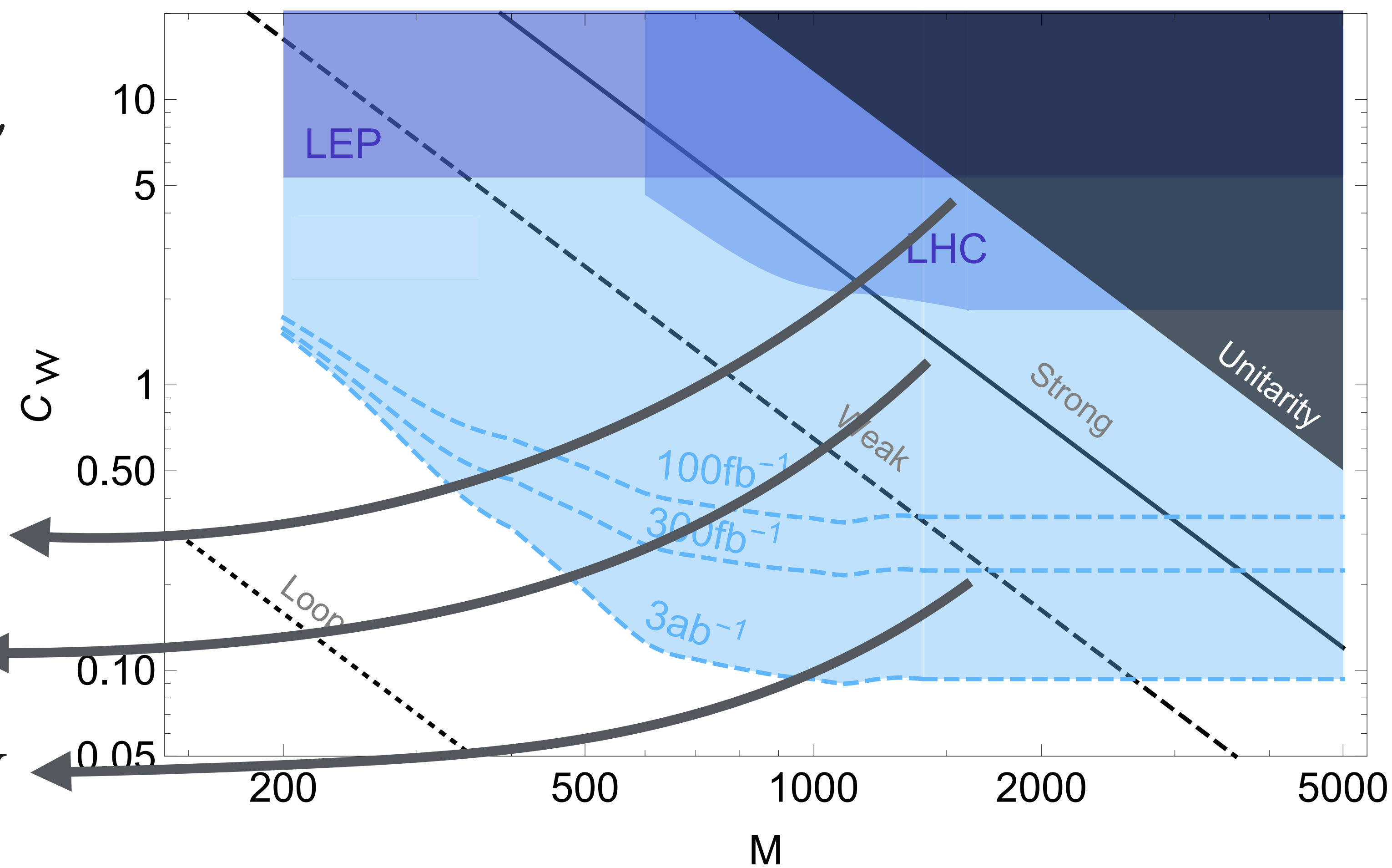
Strong: $g_{UV} = 3$

Weak: $g_{UV} = g_W$



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$$\parallel$$

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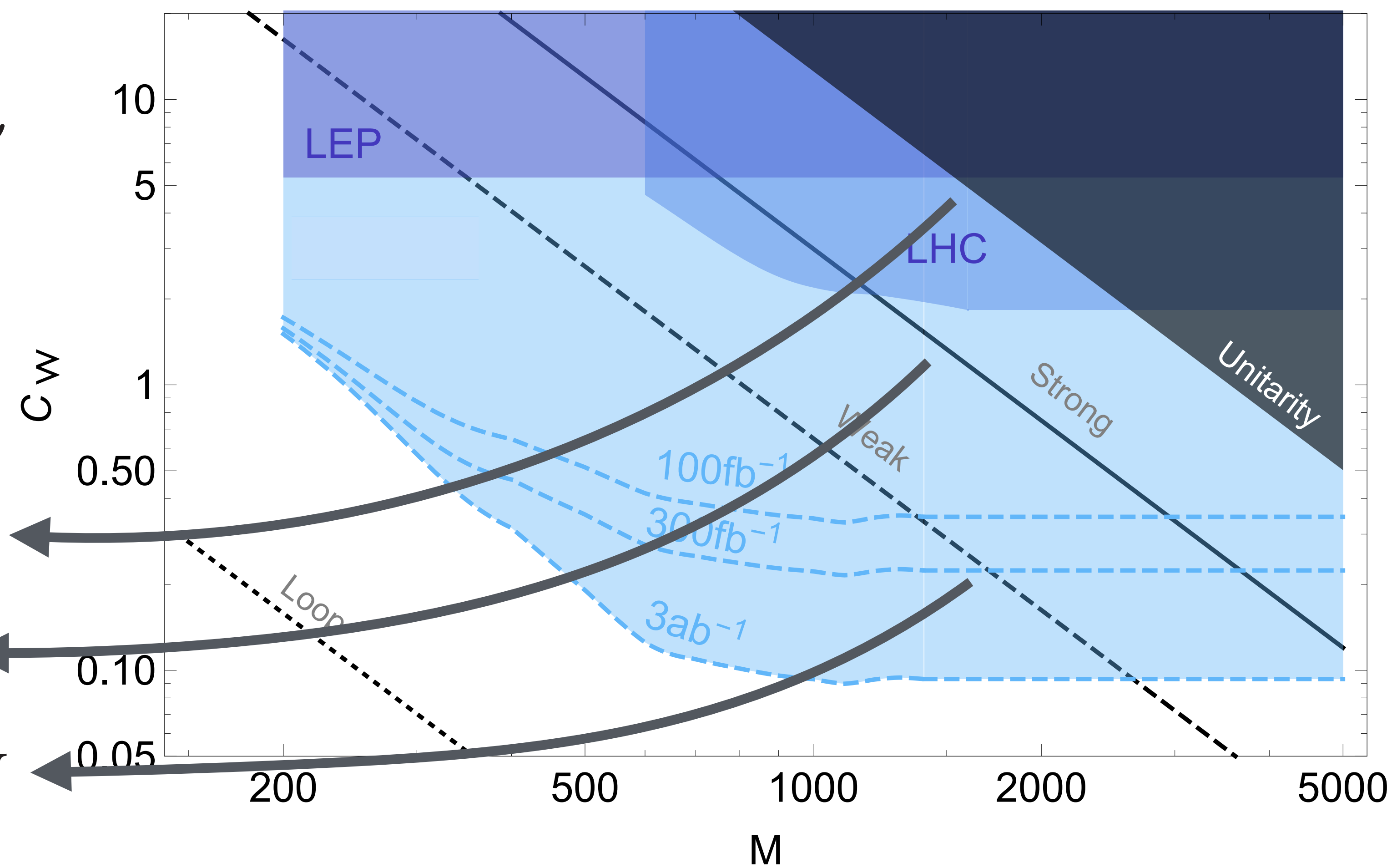
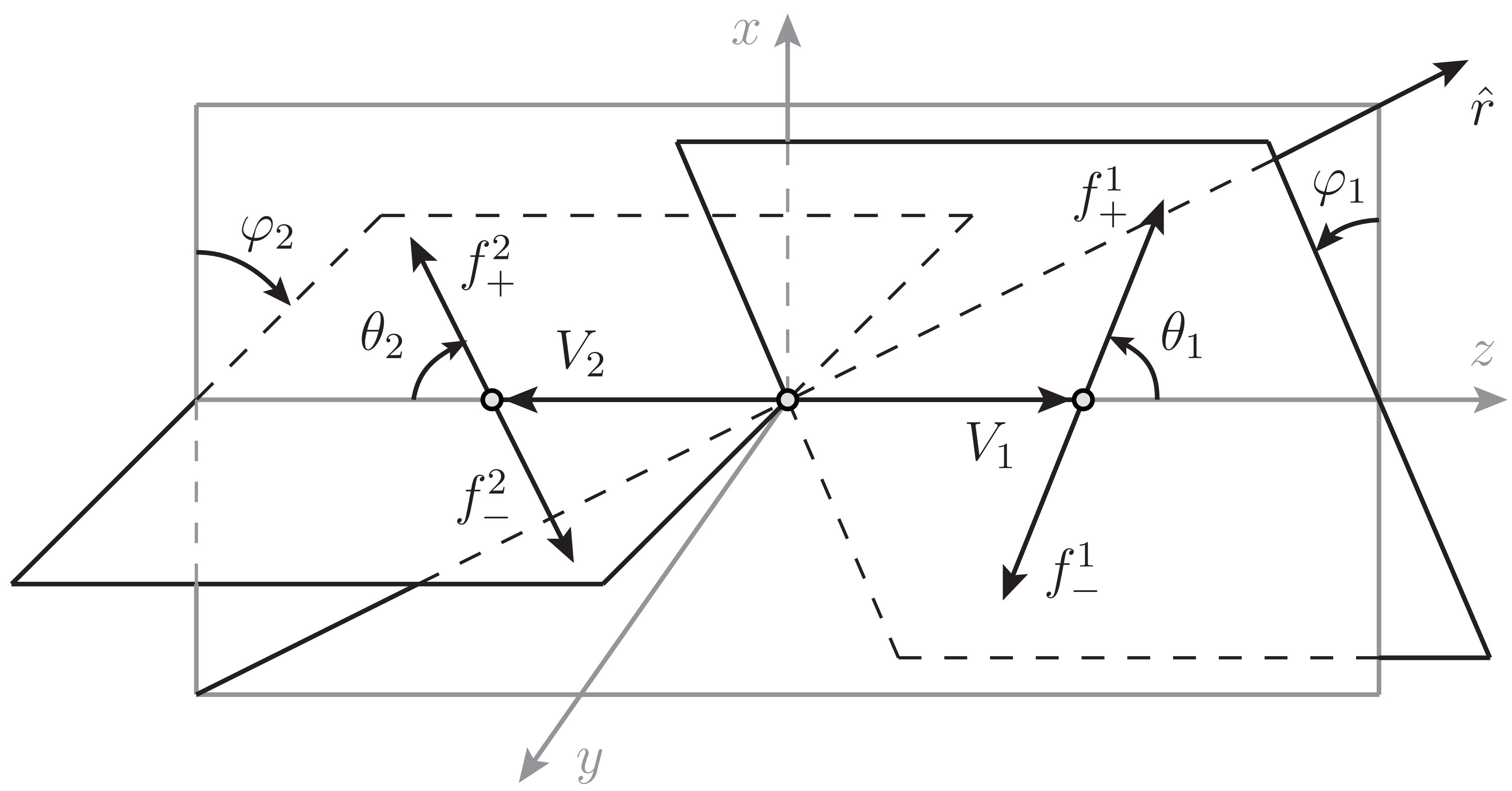


We are sensitive to UV theories where W is elementary !

Transverse DiBoson

[Panico, Riva, AW, arXiv:1708.07823]

Interference Resurrection: see Riva's talk



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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  Sensitive to other, **non-g_*-suppressed**, EFT operators

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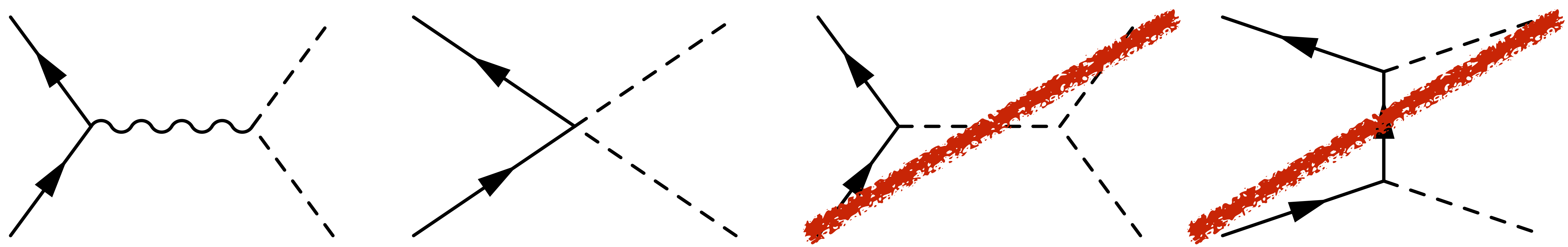
- What next?
  We just started a preliminary investigation of Diboson channels
  Many more (HZ, HW?, some hadronic V?) should be explored
  EXP/SM/BSM cooperation is **essential** for this program

Backup

Assumptions behind primaries dominance:

1) Anomalous Hqq negligibly small:



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

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All the rest is derived from G_{SM} symmetry

Backup

Naive estimate of expected rates [3/ab]

channel		[200, 400]	[400, 600]	[600, 1000]	[1000, 2000]
WH	signal	$3700 + 2700\, c_{HW}$	$570 + 1140\, c_{HW}$	$125 + 560\, c_{HW}$	
	signal substr. [?]	$2230 + 1290\, c_{HW}$	$368 + 670\, c_{HW}$	$108 + 450\, c_{HW}$	
	bkg. substr. [?]	11400	1720	700	
ZH	signal	$600 + 340\, c_{HW}$	$84 + 155\, c_{HW}$	$17 + 71\, c_{HW}$	
WW	signal	$5080 + 2980\, c_{HW}$	$380 + 690\, c_{HW}$	$74 + 310\, c_{HW}$	$5.8 + 64\, c_{HW}$
	bkg.	89500	5500	990	69
WZ	signal	$2970 + 2020\, c_{HW}$	$226 + 485\, c_{HW}$	$46 + 217\, c_{HW}$	$3.7 + 49\, c_{HW}$
	bkg.	10800	600	100	6.0