EW radiation at a very high energy μ collider

Trento, LFC 2022

Lorenzo Ricci

EPFL

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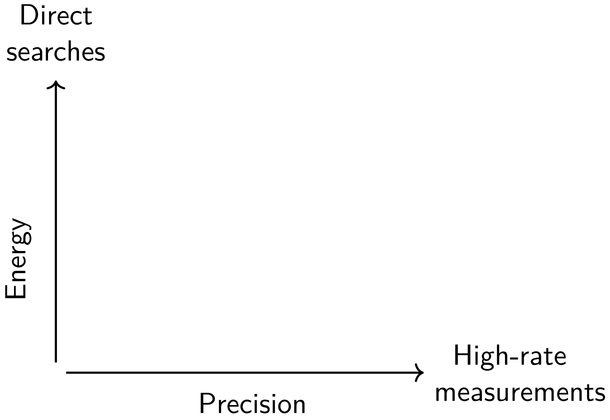
Based on:

[Chen, Glioti, Rattazzi, LR, Wulzer (2022)]

Introduction

A very high energy ($\sim$10 TeV) μ collider is
a dream machine for new physics searches.
It provides three investigation strategies at once.



See Nadia's talk

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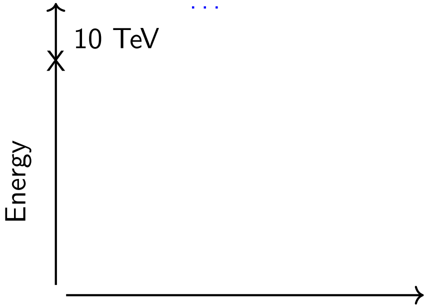
Direct searches

Pair production
WIMP
VBF ($2 \to 1$)
...

[2009.11287] [2205.04486]
[1807.04743] [2005.10289]
...



High-rate measurements

Precision

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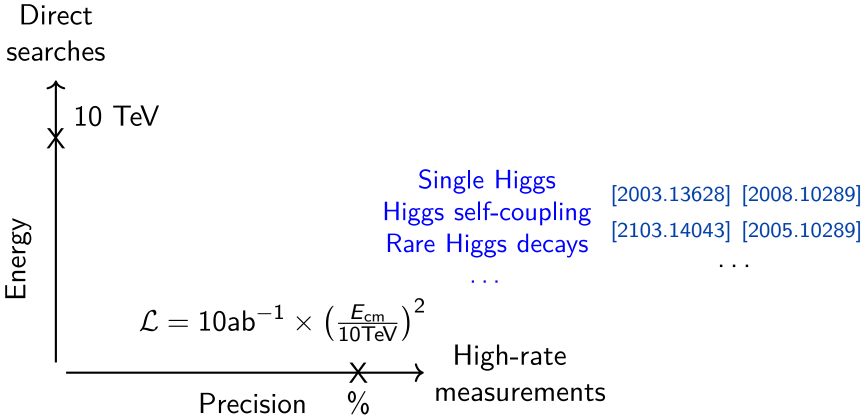

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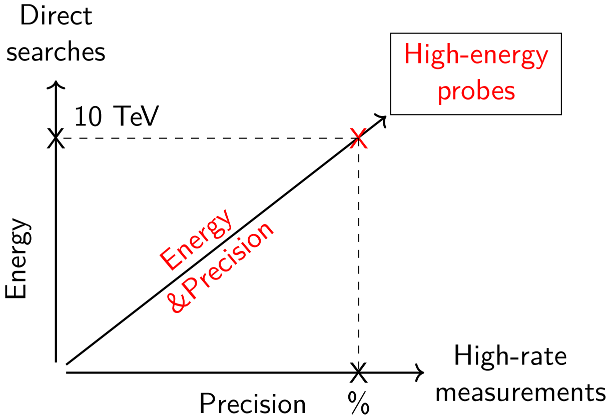

Diboson
Difermion [2012.11555]
EFT [2202.10509]
...

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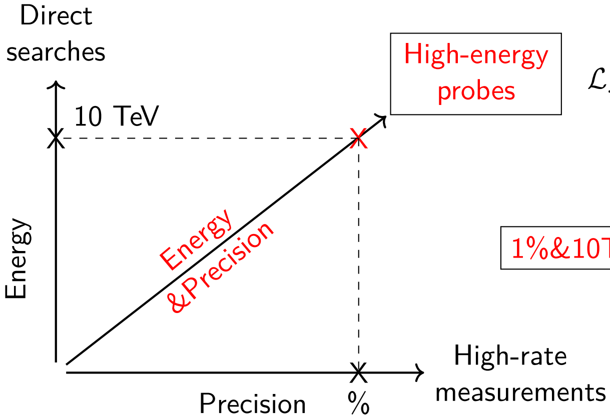

$$\mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} \sim \frac{E^2}{\Lambda^2}$$

$1\%\&10\text{TeV} \Rightarrow \Lambda \sim 100\text{TeV}$

Introduction

$$\boxed{E_{\text{cm}} \sim 10\,\text{TeV} \gg m_W \sim 100\,\text{GeV} \Longrightarrow \text{lots of EW radiation!}}$$

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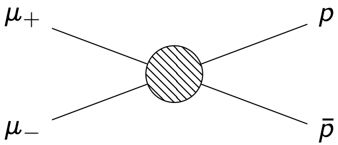
- The 1% accuracy goal requires proper control of the radiative corrections → resummations

$C_{\mu_L} = \frac{3}{4}$
$C_W = 2$
$\dots$



$p = u, d, W, \dots$

Sudakov DL	$E_{\text{cm}} = 10\text{TeV}$	$E_{\text{cm}} = 30\text{TeV}$
$\sum_i C_i \frac{\alpha_w}{4\pi} \log^2\left(\frac{E^2_{\text{cm}}}{m^2_W}\right)$	~ 0.25	~ 0.4

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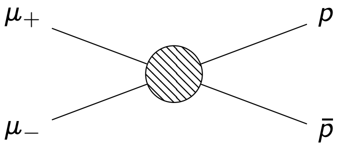

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Sudakov DL persist also in inclusive observables (i.e. BN violation)

[Ciafaloni,Ciafaloni,Comelli (2000)]

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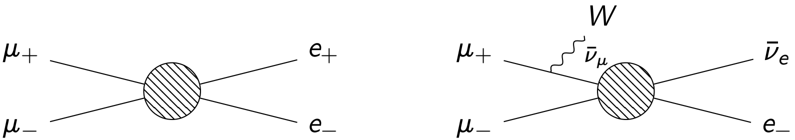
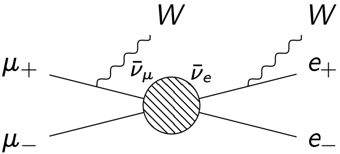
- The 1% accuracy goal requires proper control of the radiative corrections $\rightarrow$ resummations

- The pattern of EW radiation depends on short distance new physics





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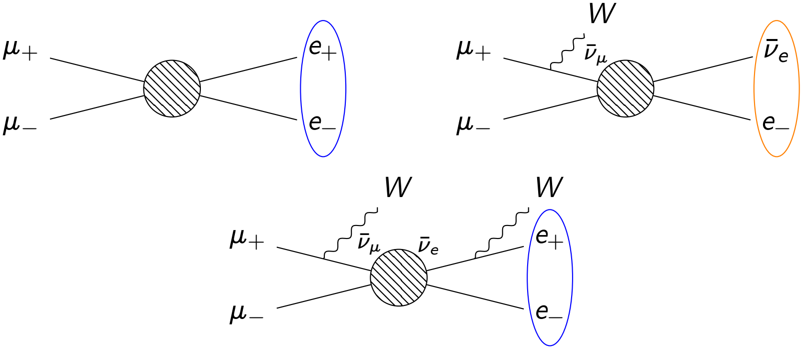

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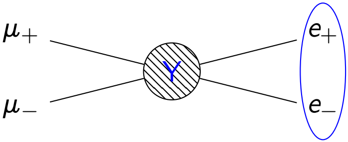
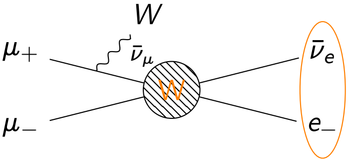
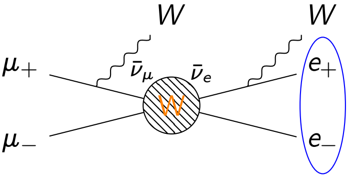




W

Y



The "hard" initial/-final states are not enough to characterize the hard process.

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We need accurate predictions for the right (BSM motivated) observables

e.g. "fully-inclusive" XS are not enough to characterize new physics

$$(\mu\mu \rightarrow ee + X) + (\mu\mu \rightarrow \nu_e e + X) + (\mu\mu \rightarrow \nu_e \nu_e + X)$$

Exclusive and (Semi-)Inclusive XS

$$\mu_+ \mu_- \longrightarrow p\bar{p} + X$$

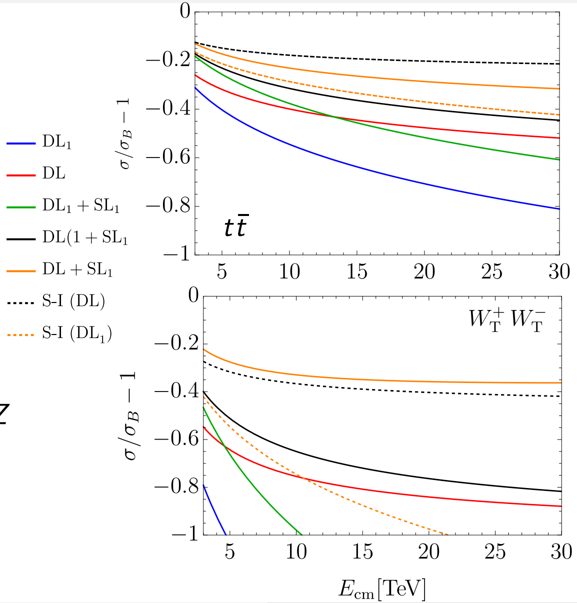
$p\bar{p} =$ difermion or diboson

Exclusive: $X = \gamma$

- DL (All order double log) [Fadin, Lipatov, Martin, Melles (99)]
- SL_1 (1-Loop single log) [Denner, Pozzorini (00)]

Semi-inclusive: $X = \gamma, W_\pm, Z$

- DL (All order double log)



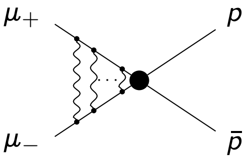
Exclusive XS

	3 TeV			10 TeV			30 TeV		
	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$	DL	$e^{\mathrm{DL}}-1$	$\mathrm{SL}(\frac{\pi}{2})$
$\ell_L \to \ell'_L$	-0.46	-0.37	0.25	-0.82	-0.56	0.33	-1.23	-0.71	0.41
$\ell_L \to q_L$	-0.44	-0.36	0.25	-0.78	-0.54	0.34	-1.18	-0.69	0.42
$\ell_L \to e_R$	-0.32	-0.27	0.13	-0.56	-0.43	0.17	-0.85	-0.57	0.21
$\ell_L \to u_R$	-0.27	-0.24	0.11	-0.48	-0.38	0.15	-0.72	-0.51	0.18
$\ell_L \to d_R$	-0.24	-0.21	0.10	-0.43	-0.35	0.13	-0.64	-0.47	0.16
$\ell_R \to \ell'_L$	-0.32	-0.27	0.13	-0.56	-0.43	0.17	-0.85	-0.57	0.21
$\ell_R \to q_L$	-0.30	-0.26	0.12	-0.53	-0.41	0.16	-0.79	-0.55	0.21
$\ell_R \to \ell'_R$	-0.17	-0.16	0.07	-0.30	-0.26	0.09	-0.46	-0.37	0.12
$\ell_R \to u_R$	-0.12	-0.12	0.05	-0.22	-0.20	0.07	-0.33	-0.28	0.08
$\ell_R \to d_R$	-0.09	-0.09	0.04	-0.17	-0.16	0.05	-0.25	-0.22	0.06

Single Log are within the perturbative control but resummation is needed to reach the % accuracy.

Exclusive XS at DL

$$\mu_+ \, \mu_- \quad \longrightarrow \quad p\bar{p} \;+\; X(\gamma)_{p_T < m_W}$$



$$\mathcal{M}_{n\text{-loop}} \;\simeq\; \mathcal{M}_B \;\times\; \underbrace{\left(\# \frac{\alpha}{4\pi} \log^2\left(\frac{E^2}{m_W^2}\right)\right)^n}_{(\gtrsim 1)^n}$$

$$\mathcal{M}_{n\text{-loop}} \sim \mathcal{M}_B$$

We cannot compute the amplitude in a perturbative expansion

$$\mathcal{M}_{\text{full}} = \mathcal{M}_B + \mathcal{M}_{1\text{-loop}} + \ldots = ?$$

Exclusive XS at DL

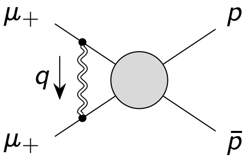
$$\mu_+ \mu_- \quad \longrightarrow \quad p\bar{p} \; + \; X(\gamma)_{p_T < m_W}$$

InfraRed Evolution Equation: [Fadin, Lipatov, Martin, Melles (99)]

we can introduce an unphysical IR cut-off λ and compute the derivative of $\mathcal{M}_{\text{full}}(\lambda)$

$$\mathcal{M}_{\text{full}} \longrightarrow \mathcal{M}_{\text{full}}(\lambda) \qquad\qquad \lambda < \frac{(k_i \cdot q)(k_j \cdot q)}{k_i \cdot k_j}$$

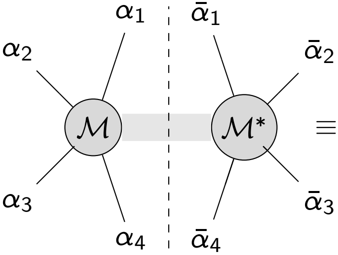
$$\mathcal{K} \sim \alpha$$



$$\begin{cases} \frac{d\mathcal{M}_{\text{full}}(\lambda)}{d\log^2(\lambda)} = -\mathcal{K}\mathcal{M}_{\text{full}}(\lambda) \\ \mathcal{M}_{\text{full}}(\lambda = m_W^2) = \mathcal{M}_{\text{full}} \end{cases}$$

Semi-inclusive XS at DL

$$\mu_+ \mu_- \quad \longrightarrow \quad p\bar{p} \; + \; X(\gamma, W_\pm, Z)$$



$\equiv \mathcal{D}_\lambda^{\alpha\bar{\alpha}}$

$\alpha = \alpha_1 \ldots \alpha_n \longrightarrow SU(2)$ indices

for instance $\alpha_1 = \bar{\nu}_\mu$ or μ_+

$\longrightarrow \lambda$ is an IR cut-off on both real and virtual radiation

$$\mathcal{D}_\lambda^{\alpha\bar{\alpha}} \equiv \mathcal{M}^{\alpha}_{\text{full}}(\lambda)(\mathcal{M}^{\bar{\alpha}}_{\text{full}}(\lambda))^* + \sum_{N=1}^{\infty} \int \mathrm{dPh}^{\mathcal{H}}_{N,\lambda} \sum_{\rho_1 \ldots \rho_N} \mathcal{M}^{\alpha;\rho}_{\text{full}}(\lambda)(\mathcal{M}^{\bar{\alpha};\rho}_{\text{full}}(\lambda))^*$$

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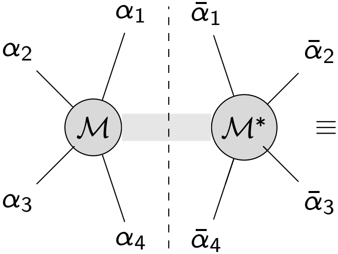

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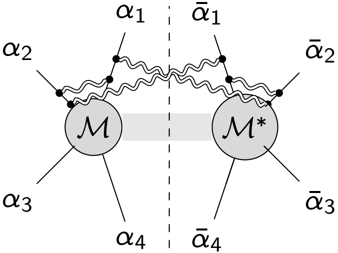
λ is an IR cut-off on all the real and virtual radiation



The IR evolution is not diagonal in the "$SU(2)$ color" space

$$\begin{cases} \dfrac{d\mathcal{D}_\lambda^{\alpha\bar{\alpha}}}{d\log^2(\lambda)} = -\mathcal{K}_{\beta\bar{\beta}}^{\alpha\bar{\alpha}}\, \mathcal{D}_\lambda^{\beta\bar{\beta}} \\ d\sigma_{\text{inc}} = \mathcal{D}_{m_W^2}^{\alpha\bar{\alpha}} \Big|_{\alpha_1 = \bar{\alpha}_1 = \mu_+, \ldots} \end{cases}$$

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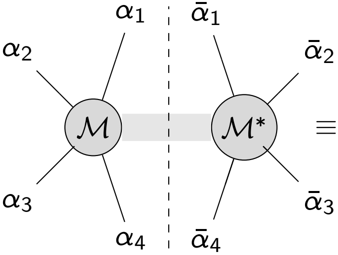

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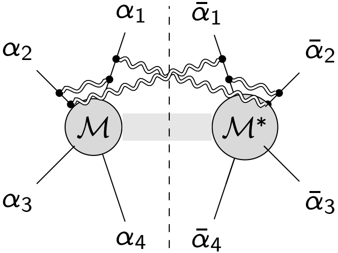

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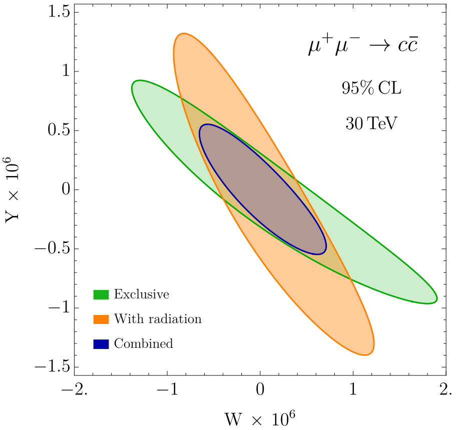
$$\sum_{\alpha=\bar{\alpha}} \mathcal{K}_{\beta\bar{\beta}}^{\alpha\bar{\alpha}} = 0$$

Sensitivity projections: W&Y operators

$$O_{2W} = J_W J_W,\ O_{2W} = J_Y J_Y$$

$$J_W^{\mu a} = \sum_f \bar{f} \tau^a \gamma^\mu f \quad J_Y^\mu = \sum_f Y_f \bar{f} \gamma^\mu f$$

Semi-inclusive and exclusive XS (with the same hard states) probe different directions on the W&Y plane



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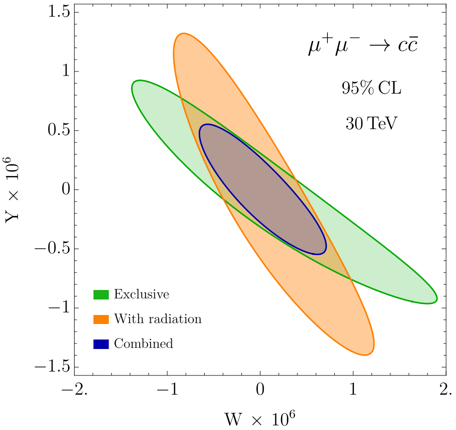
$$\sigma_{\text{exc}}^{\mu_L^+\mu_L^-\to c_L\bar{c}_L} \propto \sigma_B^{\mu_L^+\mu_L^-\to c_L\bar{c}_L}$$

$$\sigma_{\text{inc}}^{\mu_L^+\mu_L^-\to c_L\bar{c}_L} \propto \sigma_B^{\mu_L^+\mu_L^-\to c_L\bar{c}_L} + \#\sigma_B^{\mu_L^+\nu_\mu\to c_L\bar{s}_L}$$

Different dependence on W and Y



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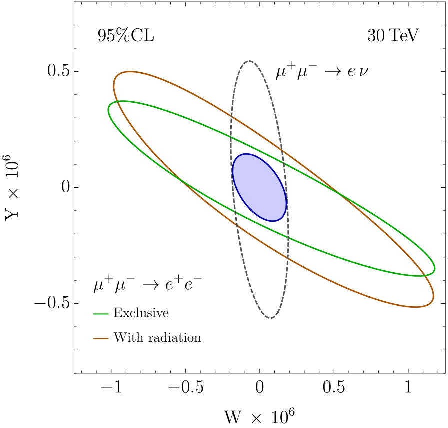
Semi-inclusive and exclusive XS (with the same hard states) probe different directions on the W&Y plane

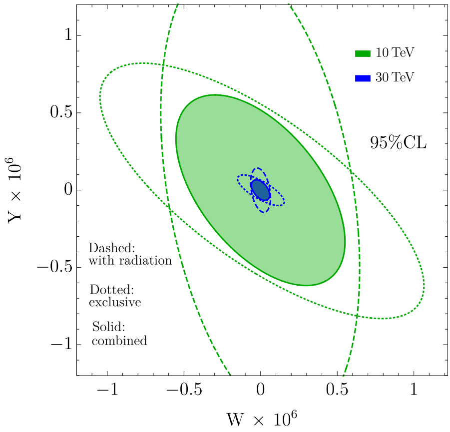
"Charged" processess are as important as the "neutral" ones



Sensitivity projections: W&Y operators

There is still advantage to combine semi-inclusive and exclusive XS when we put together all the many channels

Process	N (Ex)	N (S-I)	Eff.
$e^+ e^-$	6794	9088	100%
$e\nu_e$	—	2305	100%
$\mu^+ \mu^-$	206402	254388	100%
$\mu\,\nu_\mu$	—	93010	100%
$\tau^+ \tau^-$	6794	9088	25%
$\tau\nu_\tau$	—	2305	50%
jj (Nt)	19205	25725	100%
jj (Ch)	—	5653	100%
$c\,\bar{c}$	9656	12775	25%
cj	—	5653	50%
$b\,\bar{b}$	4573	6273	64%
$t\,\bar{t}$	9771	11891	5%
$b\,t$	—	5713	57%



Sensitivity projections: W&Y operators

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	Exclusive-only [95% CL]			Combined [95% CL]		
	$W\times10^7$	$Y\times10^7$	$\rho_{W,Y}$	$W\times10^7$	$Y\times10^7$	$\rho_{W,Y}$
3 TeV	$[-53, 53]$	$[-48, 48]$	-0.72	$[-41, 41]$	$[-46, 46]$	-0.60
10 TeV	$[-5.71, 5.71]$	$[-4.47, 4.47]$	-0.74	$[-3.71, 3.71]$	$[-4.16, 4.16]$	-0.54
14 TeV	$[-3.11, 3.11]$	$[-2.31, 2.31]$	-0.74	$[-1.90, 1.90]$	$[-2.13, 2.13]$	-0.52
30 TeV	$[-0.80, 0.80]$	$[-0.52, 0.52]$	-0.75	$[-0.42, 0.42]$	$[-0.47, 0.47]$	-0.48

The effect of radiation grows with the energy and mostly affects the reach on W

Sensitivity projections: $\mathcal{O}_W \& \mathcal{O}_B$ operators

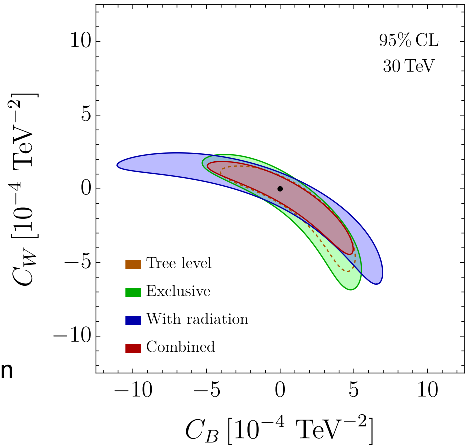
Are semi-inclusive and exclusive observables enough?

$$O_W = ig(H^\dagger \tau^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$$

$$O_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

In the $C_W \& C_B$ plane there is an accidental flat direction for $C_W \simeq -C_B$

The combination of semi-inclusive and exclusive final states is not enought to constrain the flat direction



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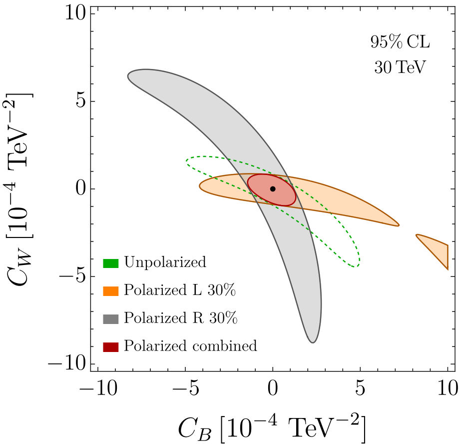
The flat direction disappears when we polarize the beams



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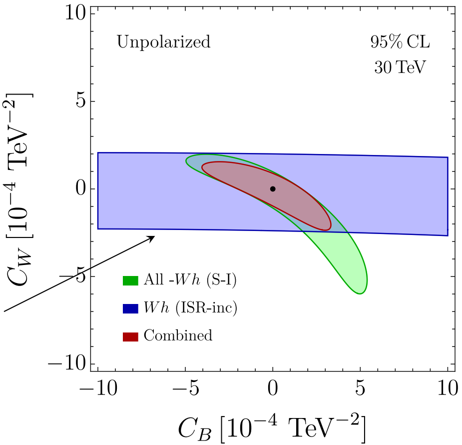
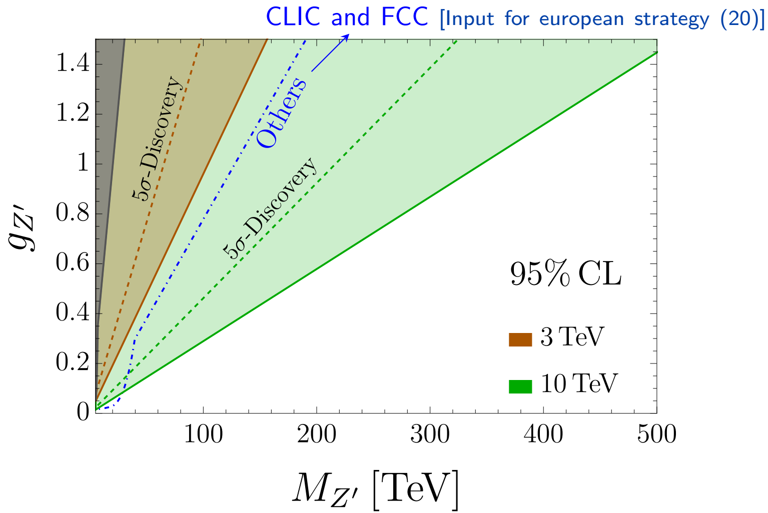
In the $C_W \& C_B$ plane there is an accidental flat direction for $C_W \simeq -C_B$

Less inclusive final states mimic the effects of polarization and seem to resolve the flat direction but we have no consistent (resummed) prediction for them.



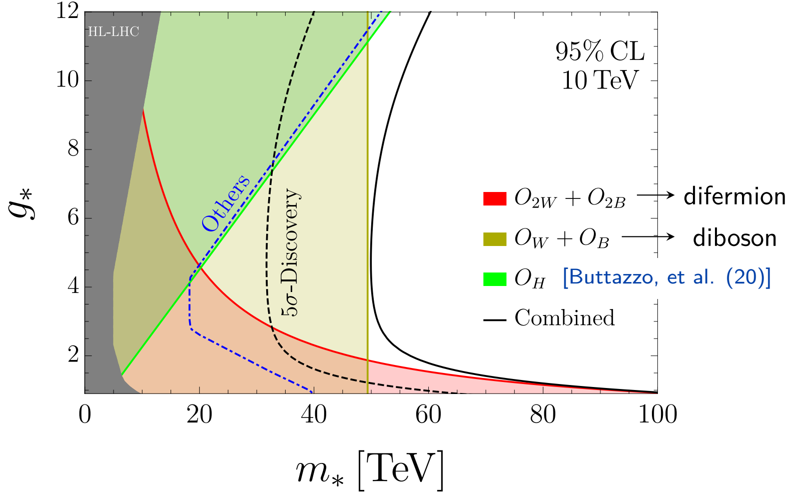
We need more control on more observables!

Sensitivity projections: a simple universal Z'



10 TeV μ collider can generically test 100+ TeV new physics

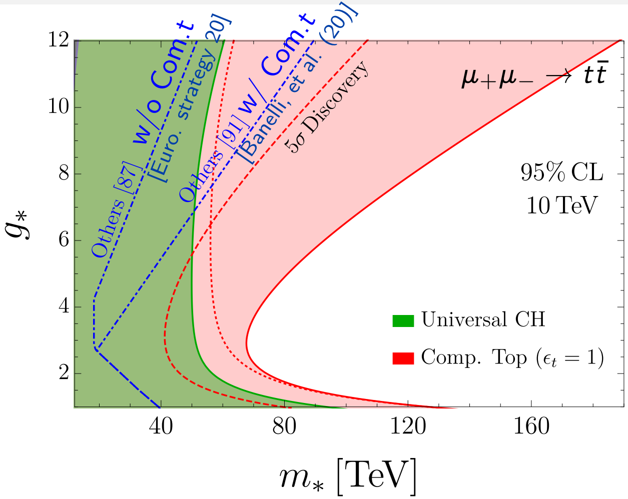
Sensitivity projections: Composite Higgs



Indirect effects of a finite Higgs size are enhanced by the energy

A 10TeV μ collider can rule out an extremely high compositeness scale m_*

Sensitivity projections: Composite Higgs



High-energy ditop production is particularly sensitive to composite top.

The same processes can be used to discover or characterize new physics!

Conclusions and outlook

- 10 TeV μ collider with 1% accuracy can test 100+ TeV new physics
- Consistent predictions require proper control of the radiative corrections $\Rightarrow$ Resummations
  - SCET is most likely the right "tool" to go beyond DL toward the 1% accuracy [Manohar, Waalewijn (18)]. EW PDF/Showering is a related subject [Bauer, Webber (17); Han, Xie, Tweedie (16);...]
  - IR effects in QFT are interesting per se. The μ collider offers extra motivation to study this problem in a novel (and completely perturbative) framework.
- Heavy new physics modify the pattern of EW radiation: we can learn BSM by looking at the SM radiation
  - More observables beyond the semi-inclusive and the exclusive ones offer additional information on new physics. Can we control them?
  - This non trivial BSM/SM interplay offers a new playground for phenomenologists

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Thank you!