Electroweak Production of 1, 2, 3, ... electroweak bosons

Marc Riembau
Université de Genève

CLICdp, August 2019

Based on
1812.09299, with **B. Henning**, **D. Lombardo** and **F. Riva**
19xx.xxxxxx, with **G. Durieux** and **M. Montull**
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Davide's talk!

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i.e., it is possible to write down a consistent, renormalizable Lagrangian given its matter content, and it is unique

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Changing any of its relation among couplings must spoil this uniqueness, and induce a pathological behaviour in some process

New phenomena must enter before QFT breakdown at some scale, and SM deformations are classified by an EFT

If you are a detector, without knowledge of EFT, Lagrangians, SM, etc, how do you know that what is going on inside you is given by a complete theory?

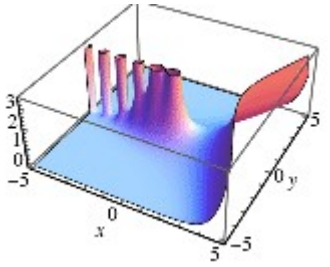
Necessary condition: Given a QFT, Locality and unitarity imply the Froissart bound on large energy behaviour of any 2→2 process:

$$\sigma(s) \leq s \log s$$

Violation of this bound tells you that your formulation is not complete and you are about to discover new states!

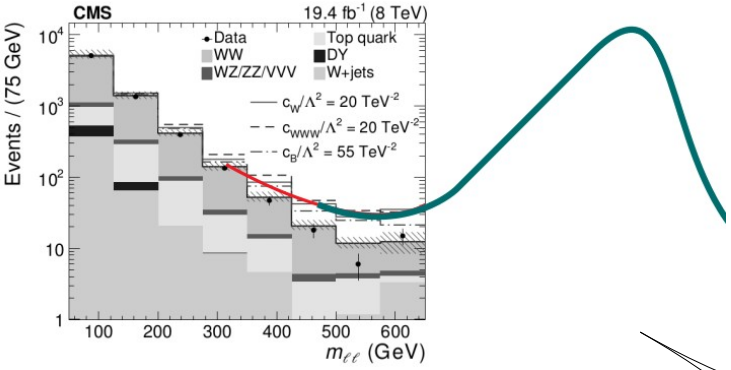
Many way to understand the same Truth

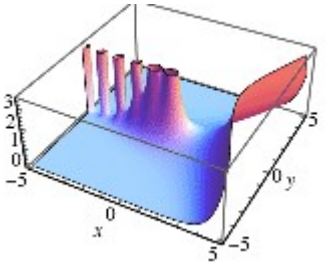
You have more singularities in the complex s-plane



Pathological high energy behaviour

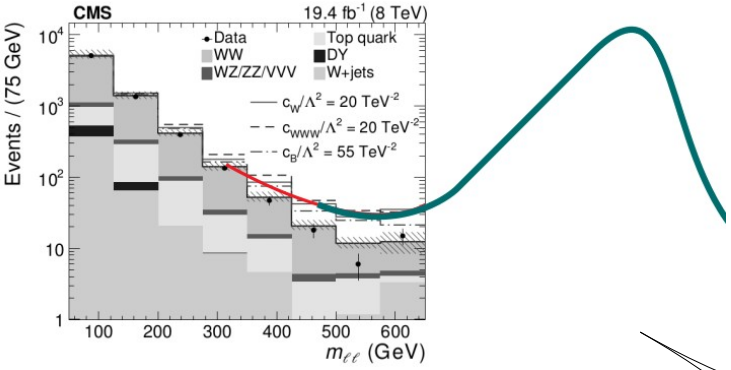
You have more states in your theory

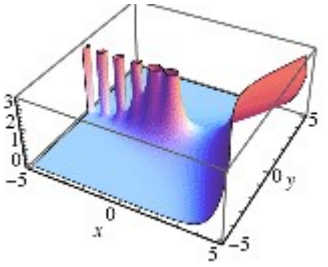




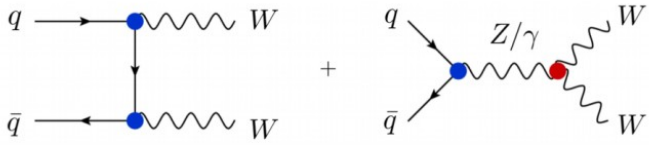
Pathological high energy behaviour

Modification of couplings spoil the cancellation



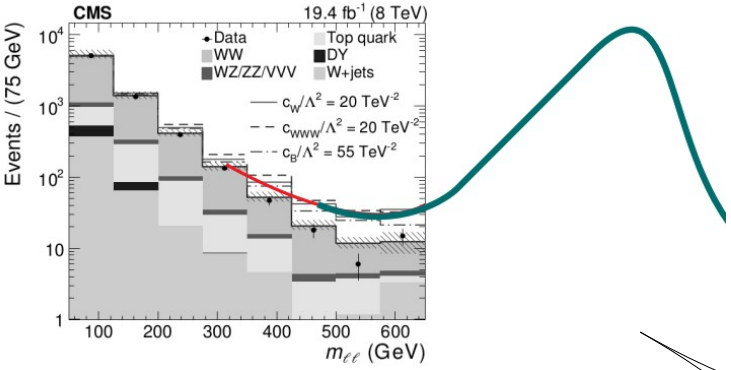


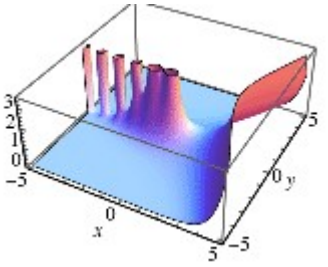
Pathological high energy behaviour



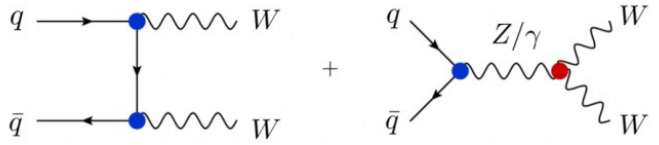
$$\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_t = -i\frac{e^2 \sin\theta}{2m_W^2} s \left(Q_q + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q) - \frac{T_q^3}{s_W^2} \right)$$

Your fields do not form a Lie algebra!





Pathological high energy behaviour



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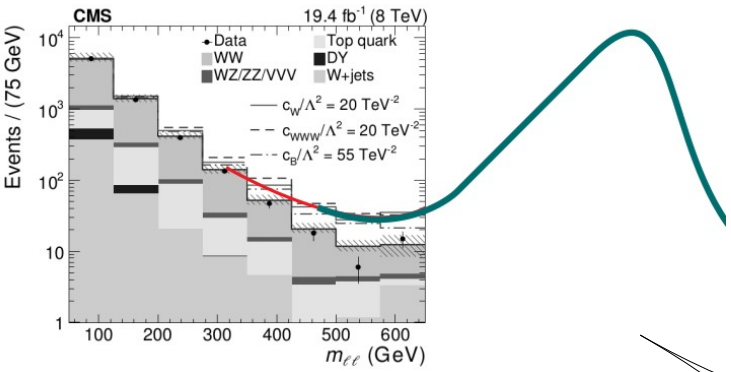
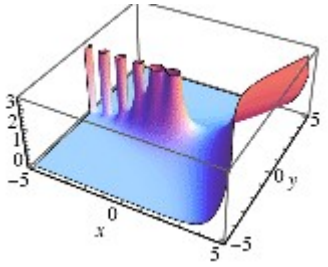
$$i\mathcal{A}(q_i^-\bar{q}_j^+ V^A V^B) = -i\frac{\langle 2|\not{p}_3 - \not{p}_4|1]}{2m_V^2}\left(\sum_{F_I}(g_L^{iF_IA}g_L^{jF_IB} - g_L^{jF_IA}g_L^{iF_IB}) - i\sum_{V_I} f^{V_I34}g_L^{ijV_I}\right)$$

$$[T^A, T^B] \neq f^{ABC}T^C$$

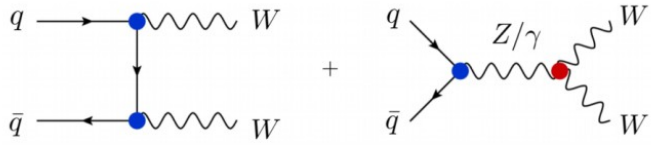
Heavy states generate higher dimension operators





Pathological high energy behaviour

$$(\bar{q}\gamma_\mu q)(H^\dagger \overleftrightarrow{D}_\mu H),$$



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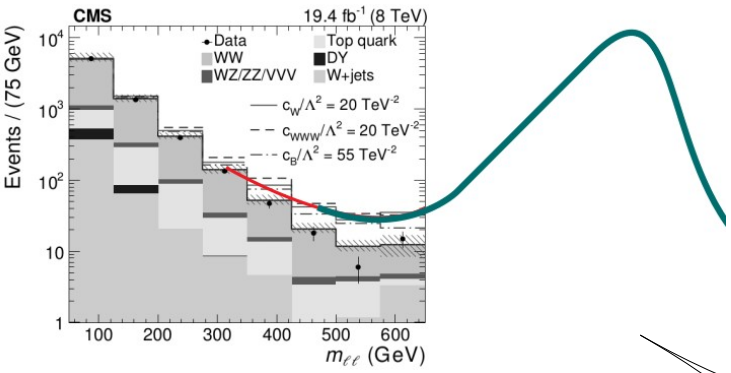
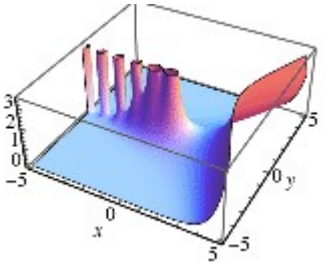
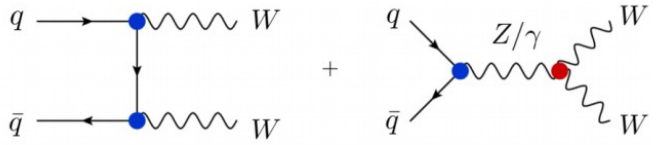




What CLIC is specially useful for!

$$(\bar{q}\gamma_\mu q)(H^\dagger \overleftrightarrow{D}_\mu H),$$



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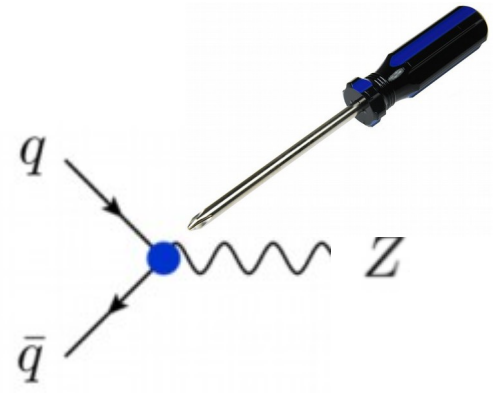
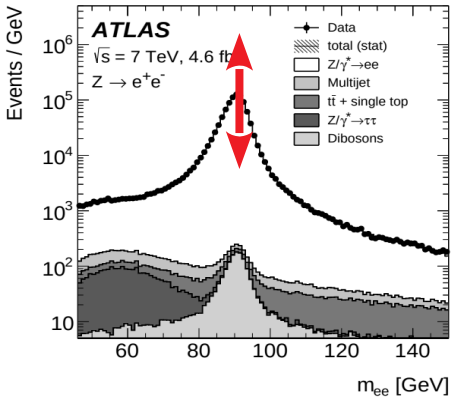
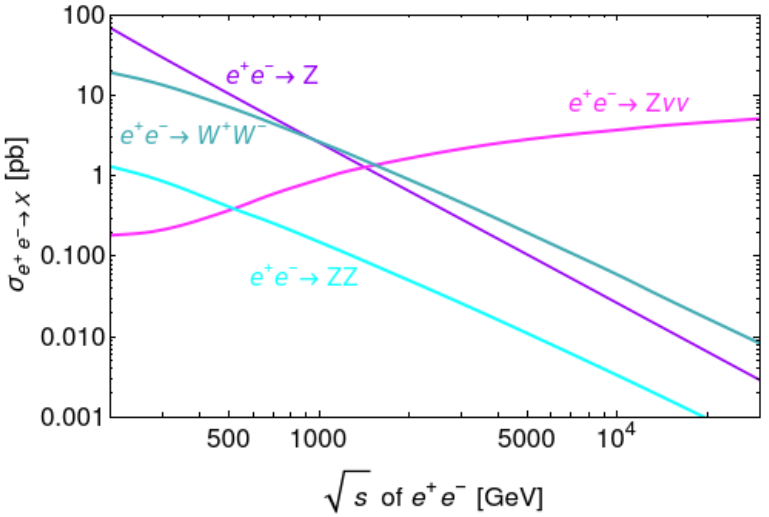
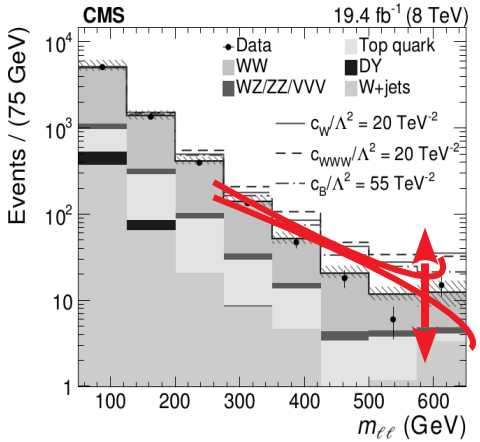
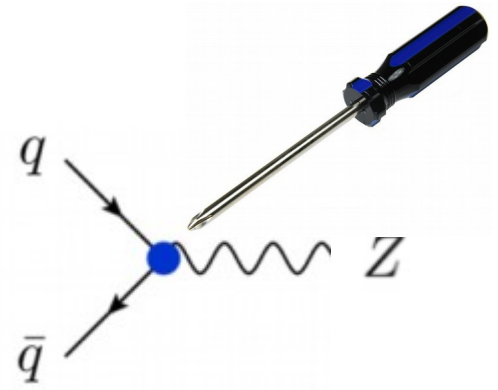
Electroweak Production of 1 electroweak bosons

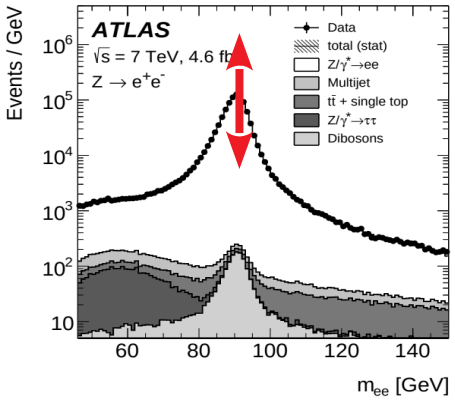

q
Z
q̄


ATLAS
√s = 7 TeV, 4.6 fb
Z → e+e-
Data
total (stat)
Z/γ*→ee
Multijet
tt̄ + single top
Z/γ*→ττ
Dibosons
Events / GeV
mee [GeV]


e+e- → Z
e+e- → W+W-
e+e- → Zνν
e+e- → ZZ
σe+e-→X [pb]
√s of e+e- [GeV]


CMS
19.4 fb-1 (8 TeV)
Data
Top quark
WW
DY
WZ/ZZ/VVV
W+jets
cW/Λ2 = 20 TeV-2
cWWW/Λ2 = 20 TeV-2
cB/Λ2 = 55 TeV-2
Events / (75 GeV)
mℓℓ (GeV)


q
Z
$\bar{q}$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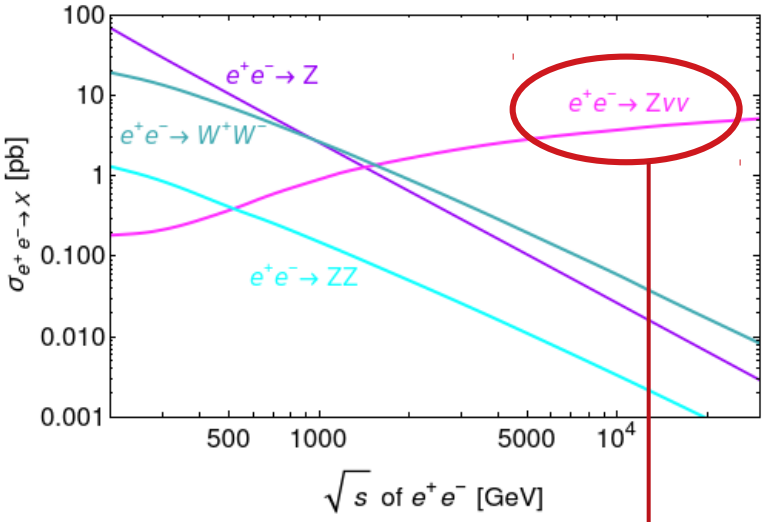
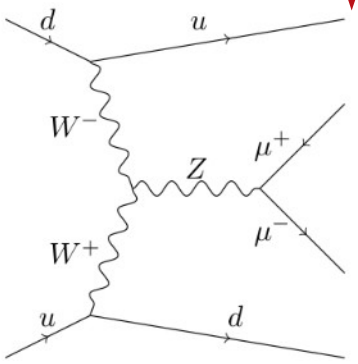
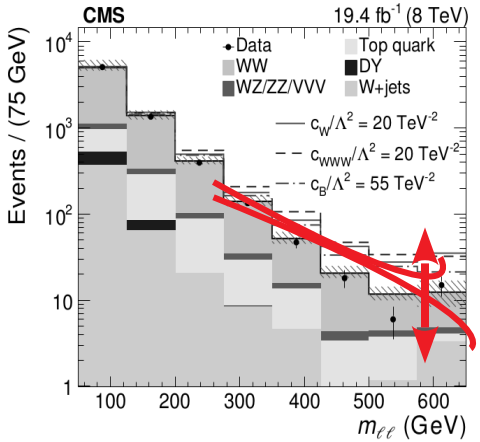

e+e- → Z
e+e- → W+W-
e+e- → ZZ
e+e- → Zνν
σe+e-→X [pb]
√s of e+e- [GeV]


d
u
W−
Z
μ+
μ−
W+
u
d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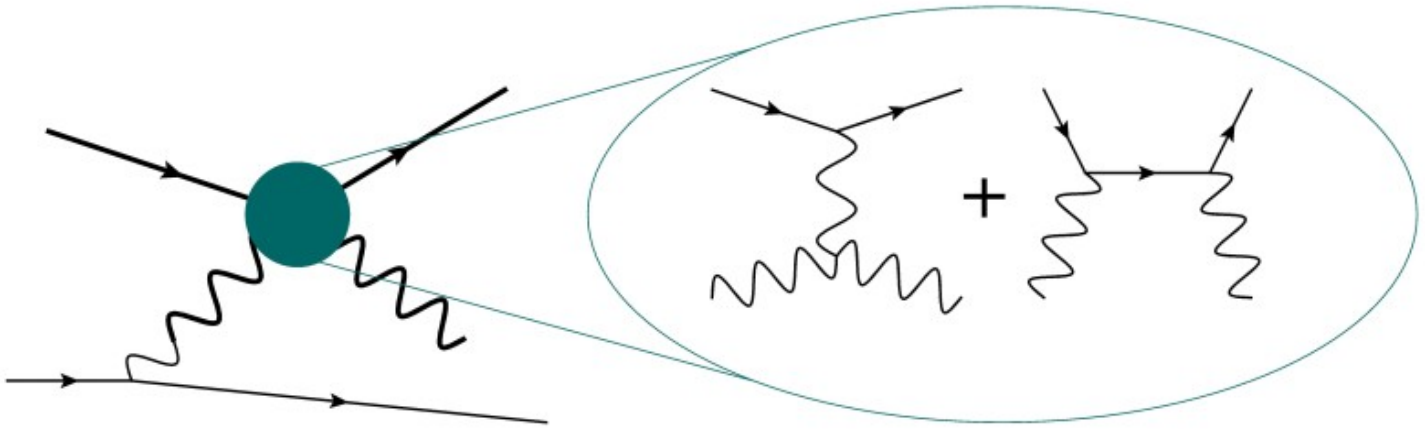
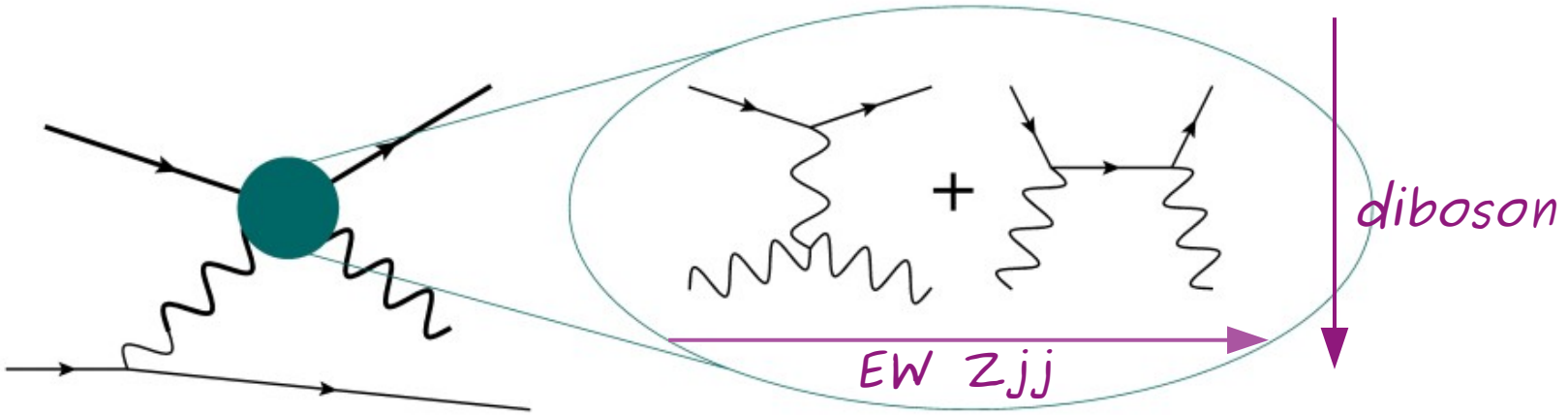
Events / (75 GeV)
mℓℓ (GeV)

G. Durieux, M. Montull, MR, in progress

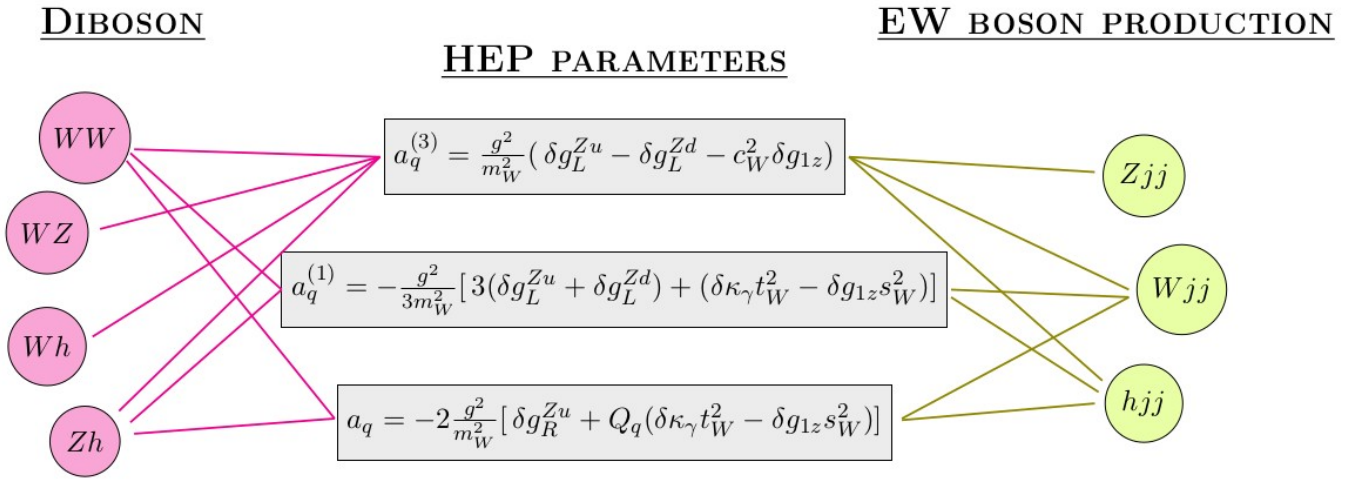


The process has two scales: a soft scale and a hard scale

G. Durieux, M. Montull, MR, in progress

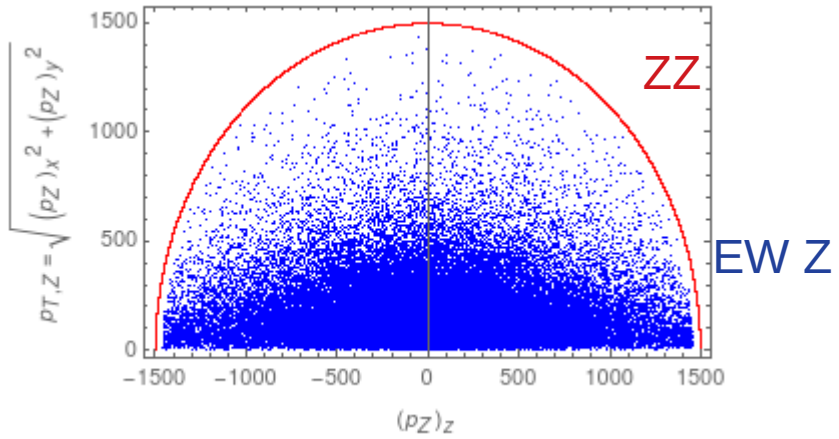


The process has two scales: a soft scale and a hard scale
So it factorizes as a soft radiation times *t-channel diboson*



G. Durieux, M. Montull, MR, in progress

Basically no background from ZZ(Z>νν) since it is 2 body
This is modified by ISR and beam energy spread



The real background: the signal is in the production of the longitudinal modes, while pure SM produces only longitudinals.
Can be disentangled using angular asymmetries

Preliminary results show that the reach is similar to diboson

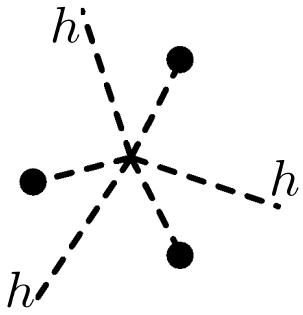
Electroweak Production of 3 electroweak bosons

B. Henning, D. Lombardo, MR, F. Riva, 1812.09299

B. Henning, D. Lombardo, MR, F. Riva, 19xx.xxxxx

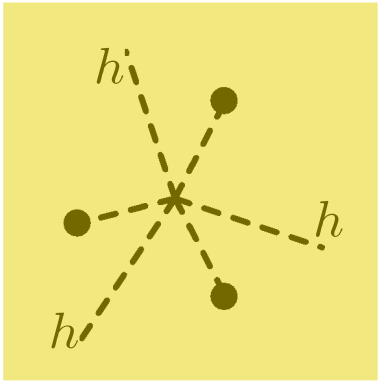
Higgs self-coupling

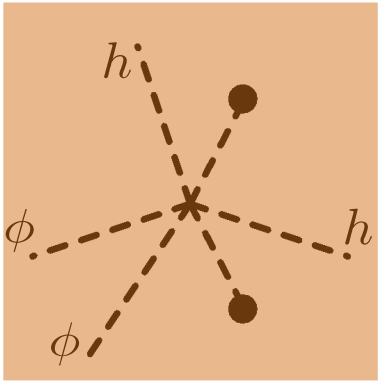
$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 \qquad)$$

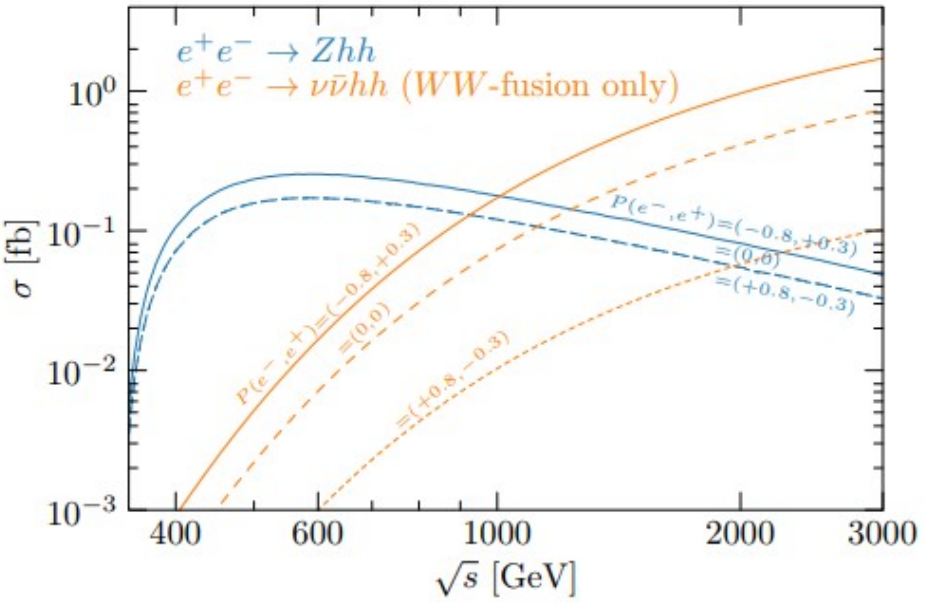


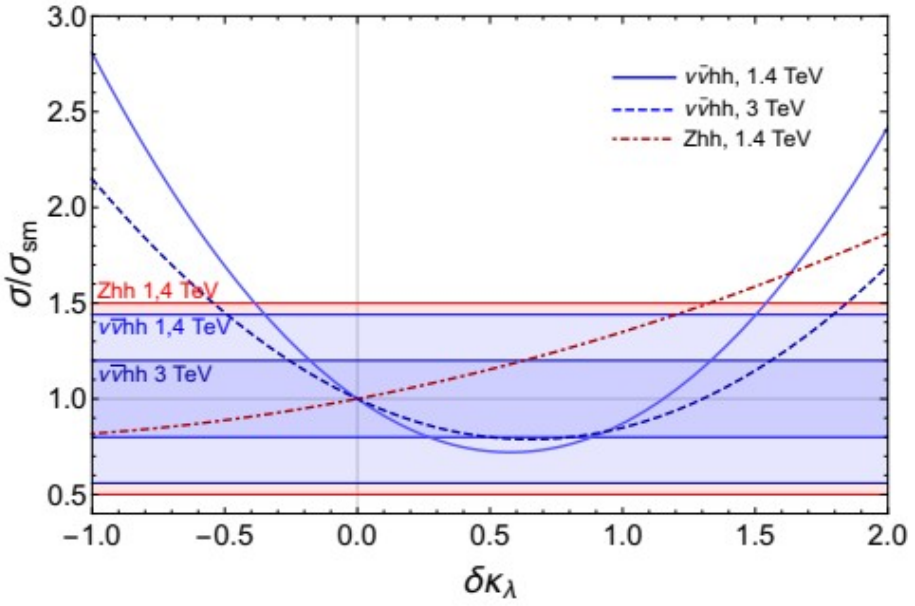
Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 + 3v^2h^2\phi^2 \quad)$$









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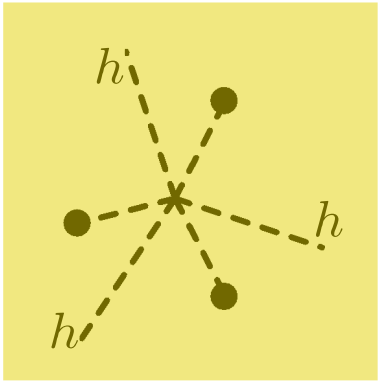
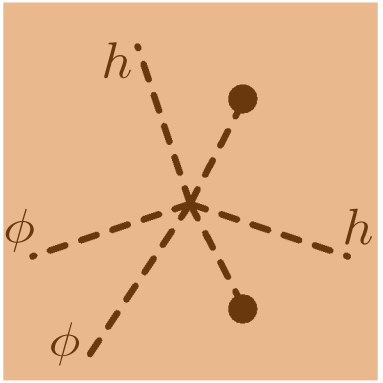
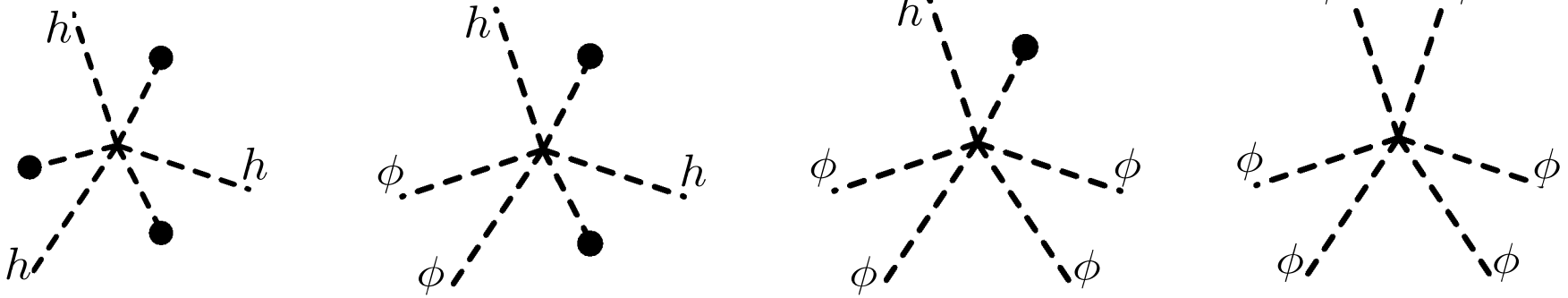




	$\Delta\chi^2 = 1$	$\Delta\chi^2 = 4$
CLIC Stage 2	$[-0.22,\ 0.48]$	$[-0.40,\ 1.05]$
CLIC Stage 3	$[-0.13,\ 0.16] \cup [1.13,\ 1.42]$	$[-0.24,\ 0.42] \cup [0.87,\ 1.53]$
CLIC Stage 2+3	$[-0.12,\ 0.14]$	$[-0.21,\ 0.35]$
5 bins in $\nu\bar{\nu}hh$	$[-0.11,\ 0.13]$	$[-0.21,\ 0.29]$

Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(\, v^3h^3 + 3v^2h^2\phi^2 + 3vh\phi^4 + \phi^6 + \ldots)$$



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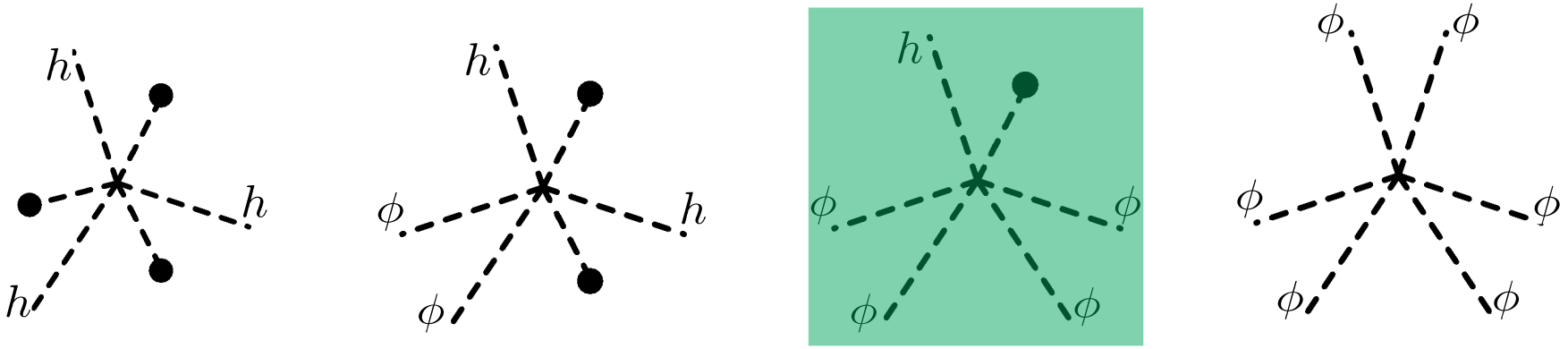


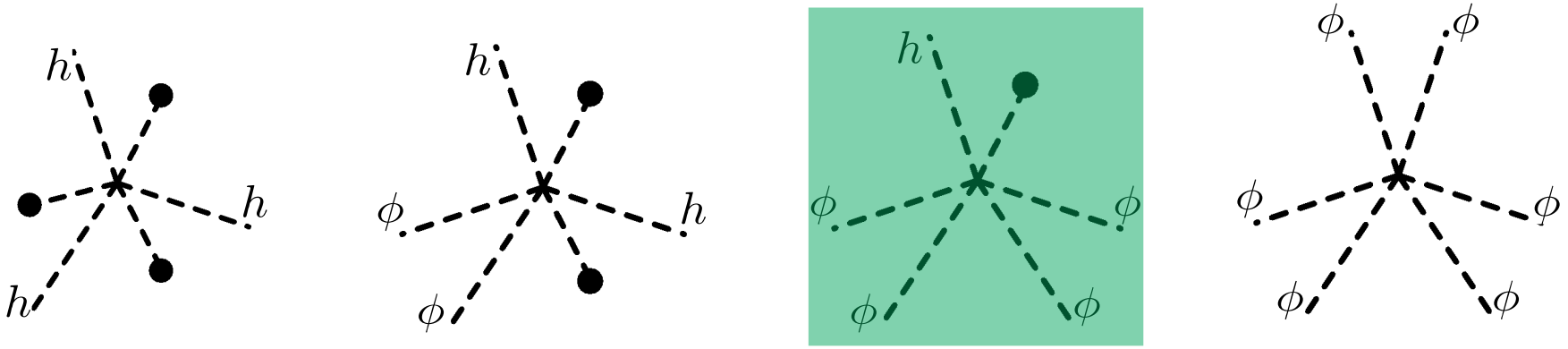
$$\frac{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)}{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)_{SM}} \sim \frac{c_6 v/\Lambda^2}{v/E^2} \sim c_6\frac{E^2}{\Lambda^2}$$

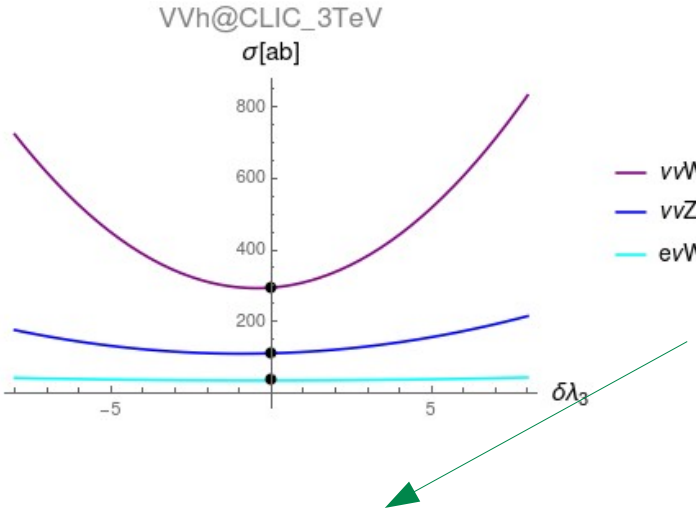
but,

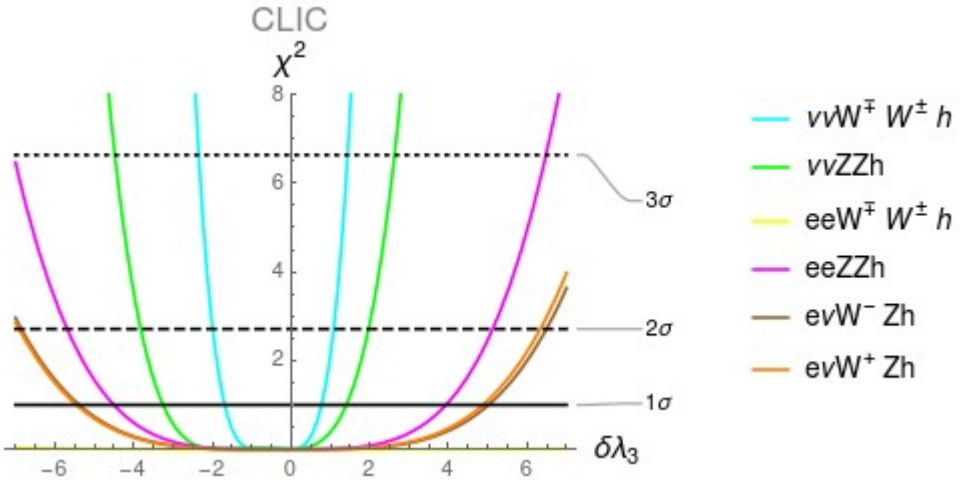
$$\frac{\mathcal{A}(\phi^+\phi^-\phi^+\phi^-h)}{\mathcal{A}(W_T^+W_T^-W_T^+\phi^-h)_{SM}} \sim \frac{c_6 v/\Lambda^2}{p\cdot\epsilon/E^2} \sim c_6\frac{vE}{\Lambda^2}$$

Transverse modes scale as 1/E and become an important background

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 + 3v^2h^2\phi^2 + 3vh\phi^4 + \phi^6 + \ldots)$$





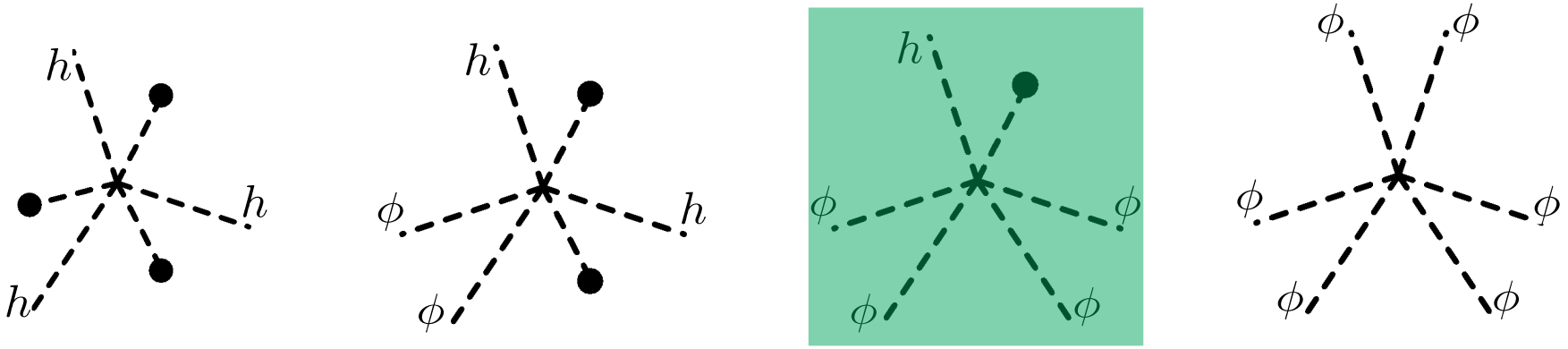


xs are 100's ab

Inclusive cross section only

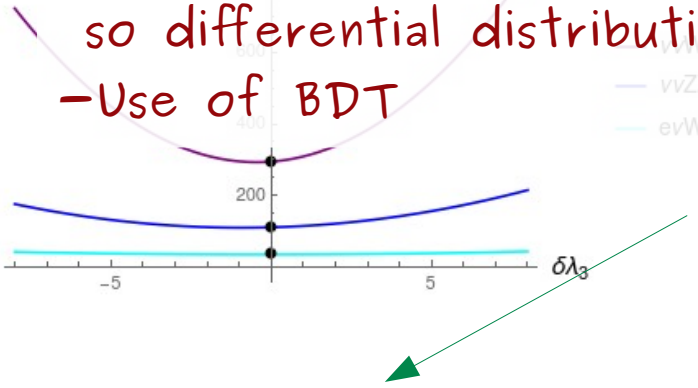
This is a back of the ~~envelope~~ MadGraph estimate

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 + 3v^2h^2\phi^2 + 3vh\phi^4 + \phi^6 + \ldots)$$

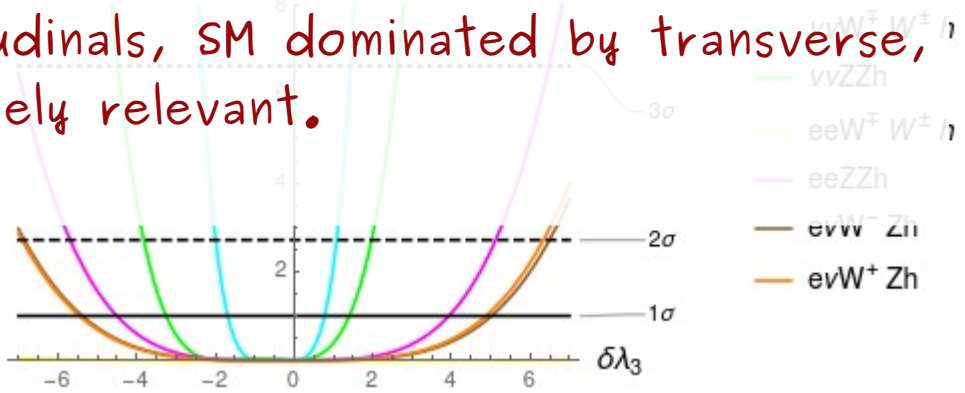


Many things to be done!

- Establish backgrounds
- Include ISR/beam energy spread
- Most important: signal is in longitudinals, SM dominated by transverse, so differential distributions extremely relevant.
- Use of BDT



xs are 100's ab



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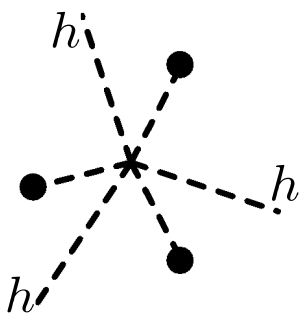
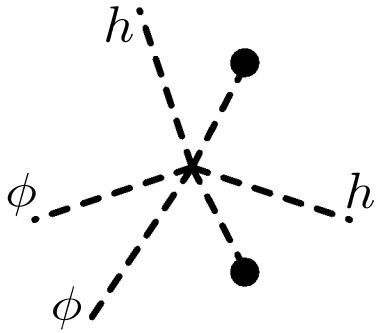
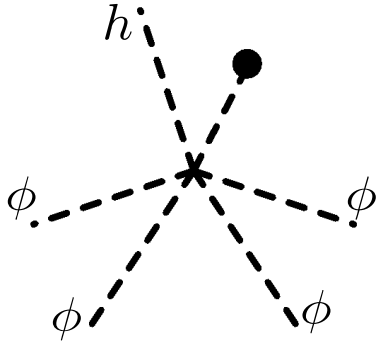
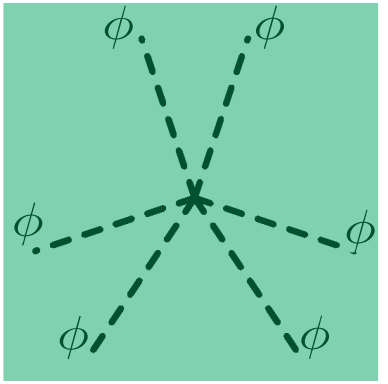


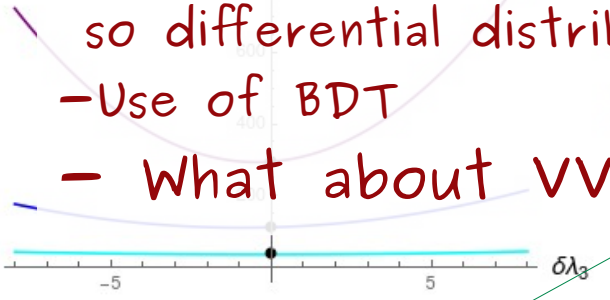




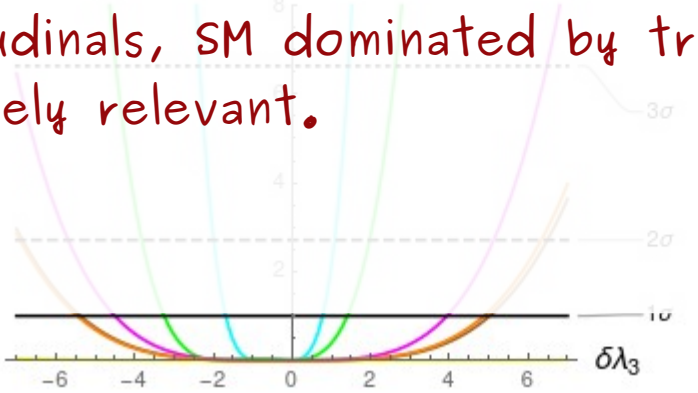


Many things to be done!

- Establish backgrounds
- Include ISR/beam energy spread
- Most important: signal is in longitudinals, SM dominated by transverse, so differential distributions extremely relevant.
- Use of BDT
- What about VVVV?



xs are 100's ab



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...

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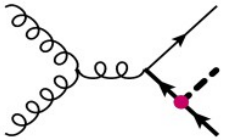
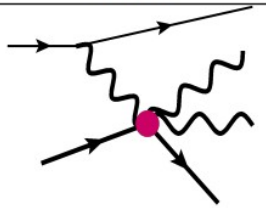
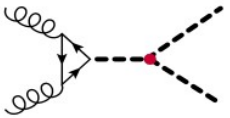
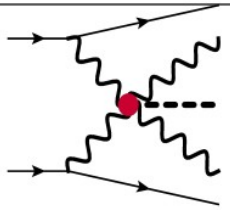
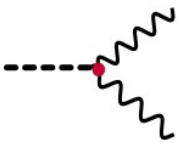
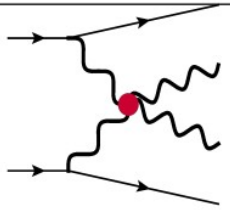
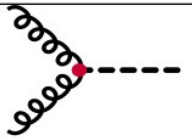
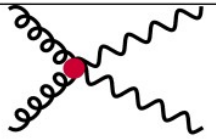
In hadron colliders, there is a complete classification of the high energy process and the corresponent operator it probes

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

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In hadron colliders, there is a complete classification of the high energy process and the corresponent operator it probes

We need the same for lepton colliders!

$\kappa_t : pp \to jt + V_L V_L'$

$(e^+e^- \to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\})$

$\kappa_\lambda : pp \to jjh + V_L V_L', \quad (e^+e^- \to llhV_L V_L')$

$pp \to jj + 4V_L, \quad (e^+e^- \to ll\, 4V_L)$

$\kappa_{\gamma\gamma, Z\gamma} : pp \to jj + V'V, \quad (e^+e^- \to llV'V)$

$\kappa_V : pp \to jj + V_L V_L', \quad (e^+e^- \to llV_L V_L')$

$\kappa_g : pp \to W_L^+ W_L^-, Z_L Z_L, \quad (e^+e^- \to lljj)$

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$\kappa_g : pp \to W_L^+ W_L^-, Z_L Z_L,\ (e^+e^- \to lljj)$

- Is this everything?
- What is the reach for each one?
- Are they competitive?
- Can we suppress the transverse modes?
- What are the NLO xs's?
- What is the effect of beam spread?
- What is the improve of using BDT?

We don't know...
... many things to do!

Conclusions

Deviations from SM couplings are not harmless, they induce Energy growth in some process

This can be used in our favor in very high energy lepton colliders to develop a precision program.

Many physics yet to be studied from both theoretical and experimental sides

Thank you