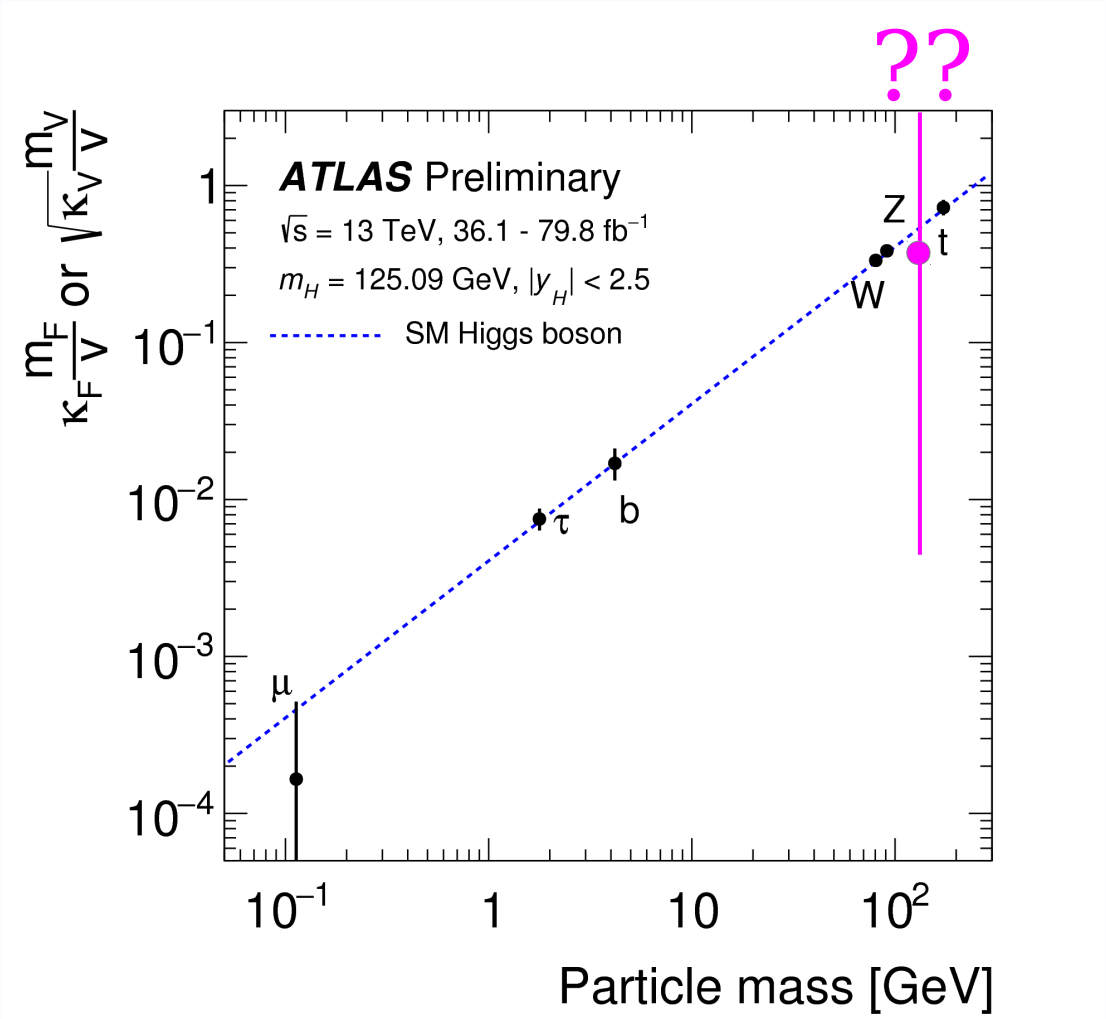
Higgs Couplings and High-Energy Amplitudes

Brian Henning

Université de Genève

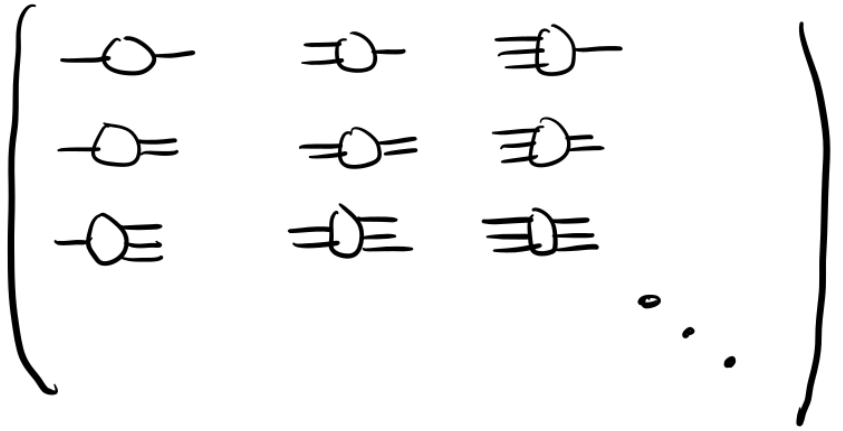
KITP Precision Workshop 2021 Discussion



Deviations in *any* of h couplings leads to unitarity violation

S-matrix and unitarity

The S matrix is unitary

$S =$ 

$$U = \begin{pmatrix} \cdots & a & \cdots \\ & b & \\ & c & \\ & \vdots & \end{pmatrix}$$

For a unitary matrix, the elements are bounded

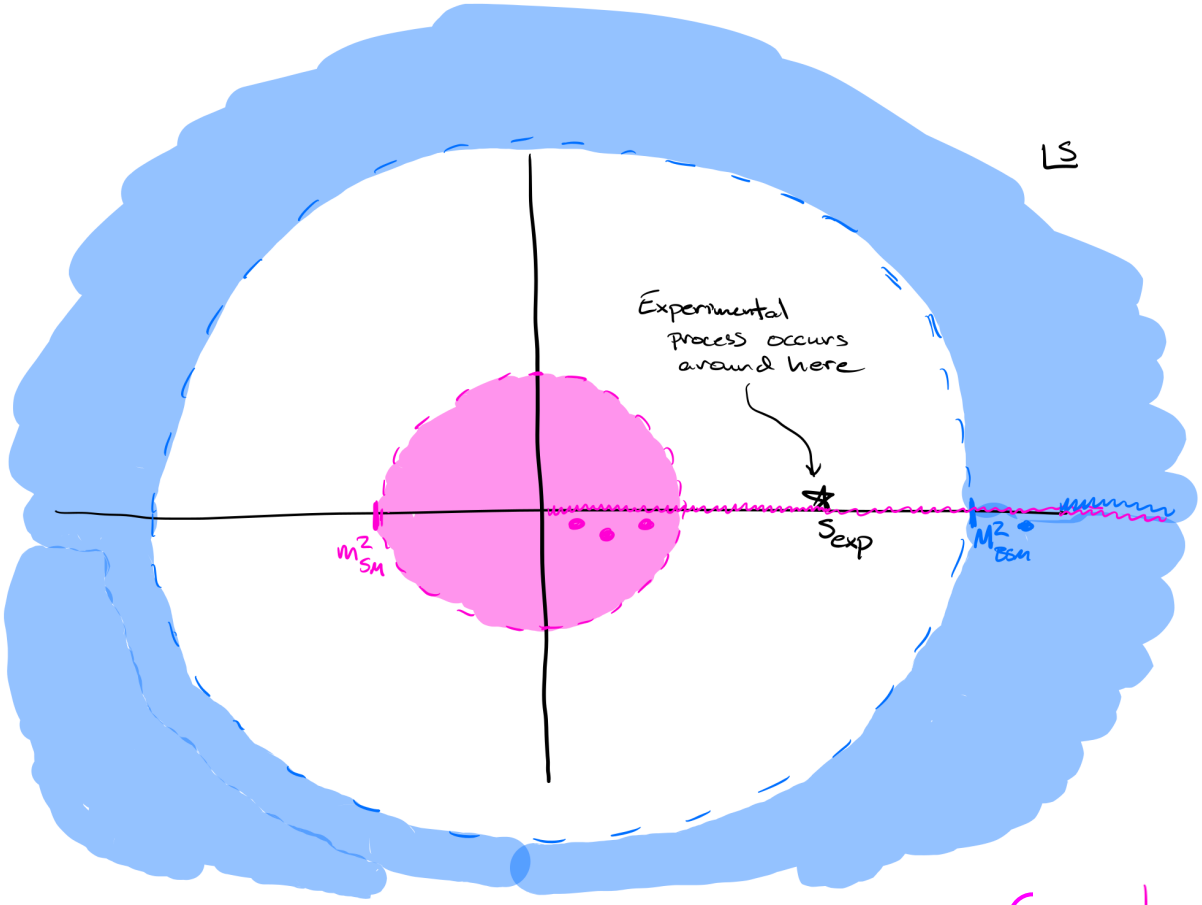
$$U^\dagger U = 1 \Rightarrow |a|^2 + |b|^2 + \cdots = 1$$

$$\Rightarrow |a| \leq 1, \; |b| \leq 1, \; \cdots$$

$$|S_{\alpha\beta}| \leq 1$$

*see Chang's talk for precise formulation

A pedestrian viewpoint



Can expand amplitude around the experimental energy

Energy "falling"
(+ non-analytic in s)

$$\frac{1}{s-m^2_{SM}} \simeq \frac{1}{s} + \frac{1}{s^2} m^2_{SM} + \cdots$$

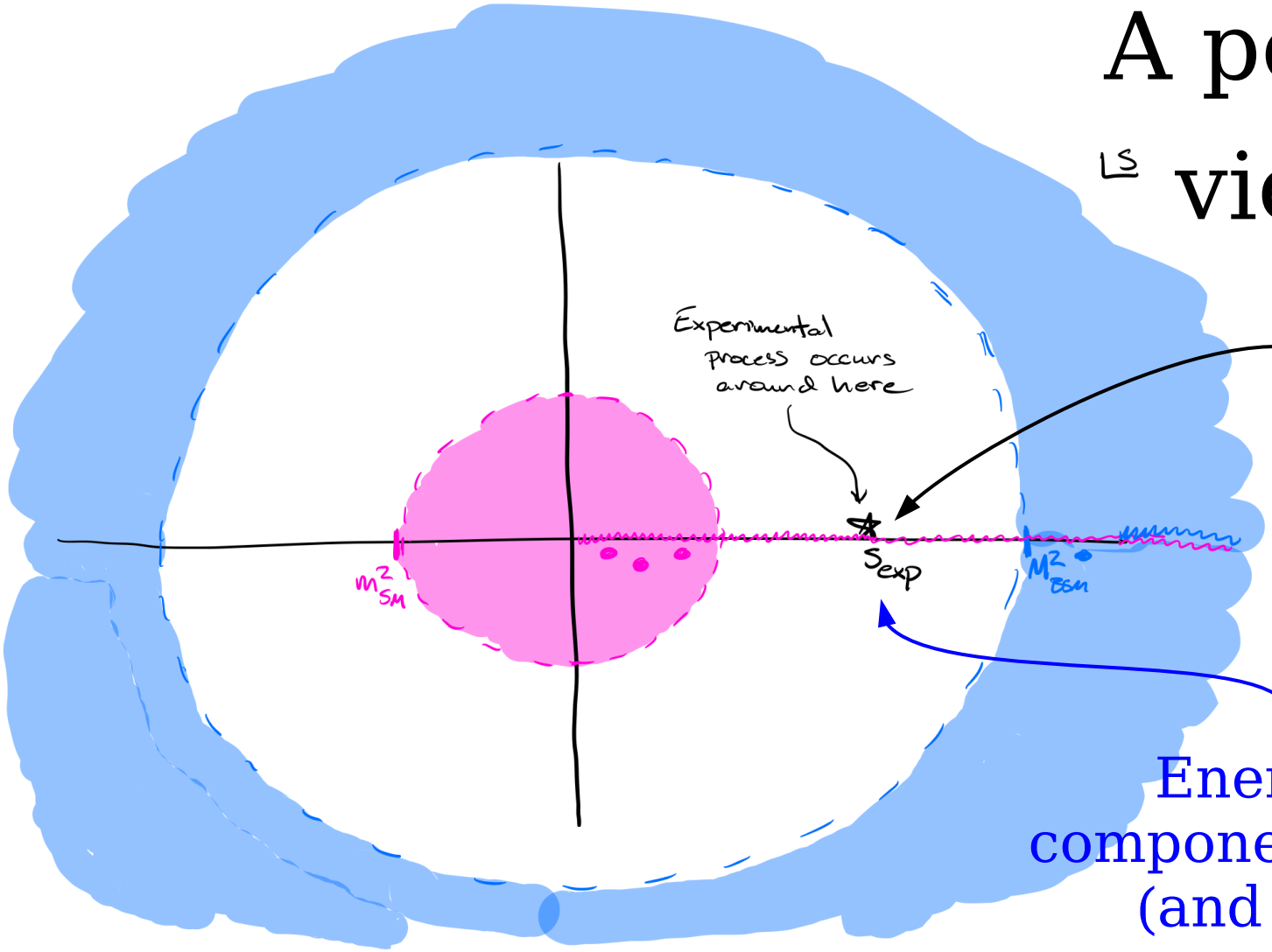
$$\log(s-4m^2_{SM}) \simeq \log s + \sum' \left(m^2_{SM}/s\right)^{\#}$$

$$\frac{1}{s-M^2} \simeq -\frac{1}{M^2}\left(1 + \frac{s}{M^2} + \frac{s^2}{M^4} + \cdots\right)$$

$$\log(s-4M^2) \simeq \log(M^2) + \sum' \left(s/M^2\right)^{\#}$$

Energy "growing"
(~polynomial in s)

A pedestrian LS viewpoint



The SM makes a definite prediction here

Energy "growing" components systematically (and transparently) captured by EFT

$$\mathcal{L} = \sum_i \frac{c_i}{\Lambda^{\Delta_i - 4}} \mathcal{O}_i \longrightarrow \mathcal{A}_{\mathcal{O}_i}(E \to \infty) \sim \left(\frac{E}{\Lambda}\right)^{\Delta_i - 4}$$

A pedestrian viewpoint: part II

goldstones = longitudinals

$$|H|^2 \sim (v+h)^2 + \vec{\phi}^2$$

ops that modify HC will induce processes with longitudinal vectors

HC: $|H|^2 \mathcal{O}_{\rm SM} \supset vh\mathcal{O}_{\rm SM}$

HwH: $|H|^2 \mathcal{O}_{\rm SM} \supset \vec{\phi}^2\mathcal{O}_{\rm SM}$

"Higgs without Higgs"

$$\frac{\mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

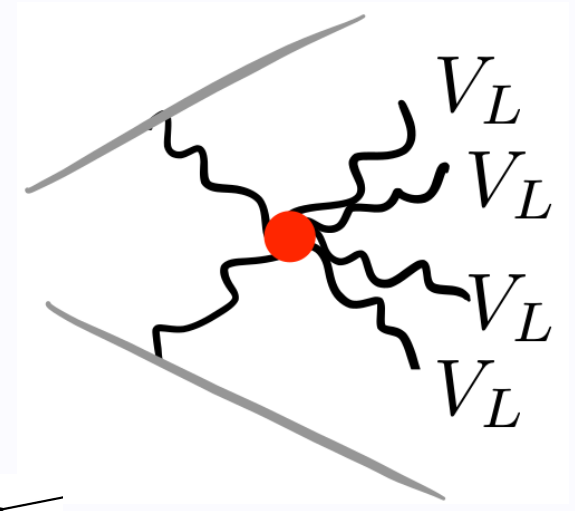
Example: $|H|^6$

$$|H|^6 \supset v^3 h^3 \longleftarrow \text{trilinear}$$

$$|H|^6 \supset v h \phi^4 + \phi^6$$

$V_L V_L \to V_L V_L V_L V_L$

$V_L V_L \to V_L V_L h$



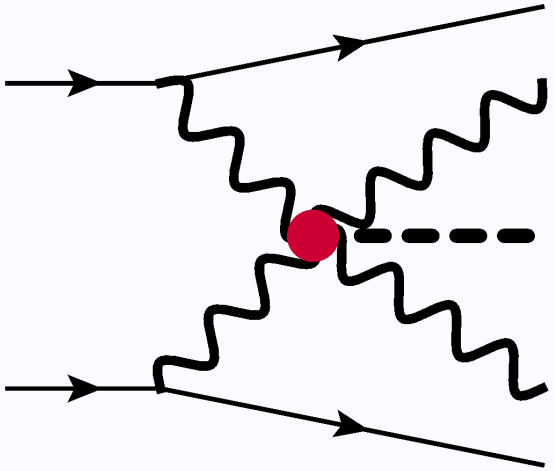
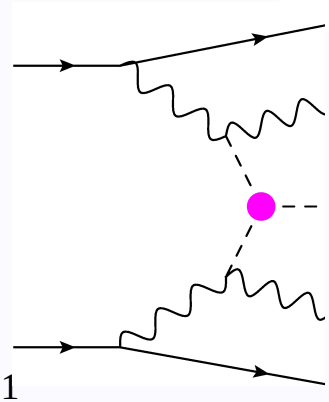
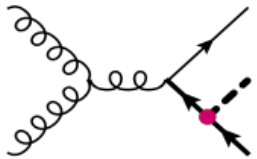
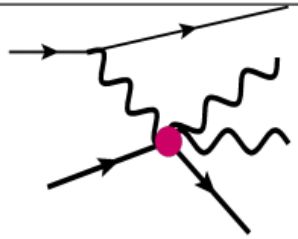
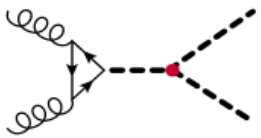
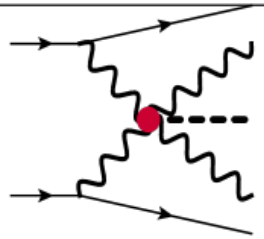
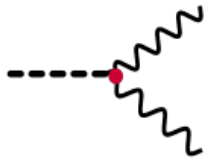
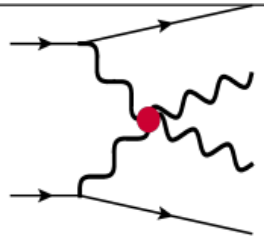
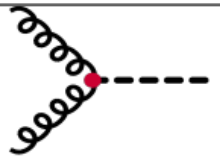
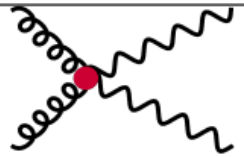


diagram in unitary gauge



Processes considered

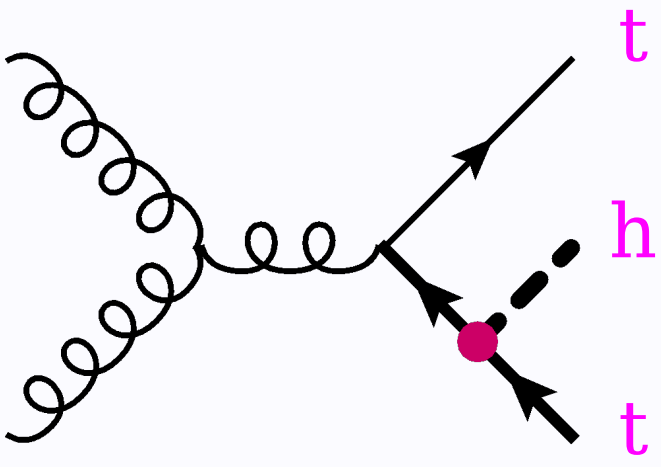
		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

BH, Lombardo, Riembau, Riva 1812.09299

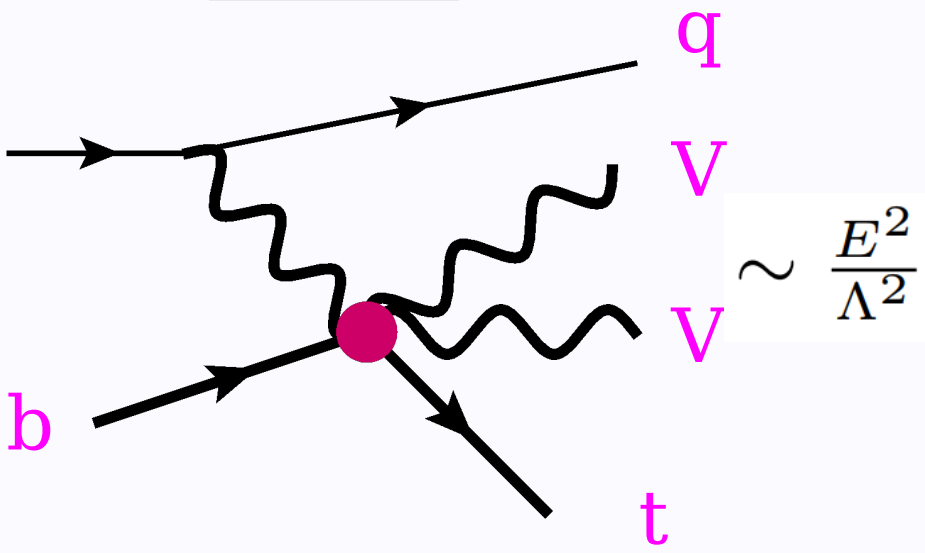
$$\mathcal{L} \supset \frac{c_t}{\Lambda^2} y_t |H|^2 \bar{q}_L H t_R$$

$\phi^+\phi^-$ $\qquad$ $b_L\phi^+ t_R$

HC



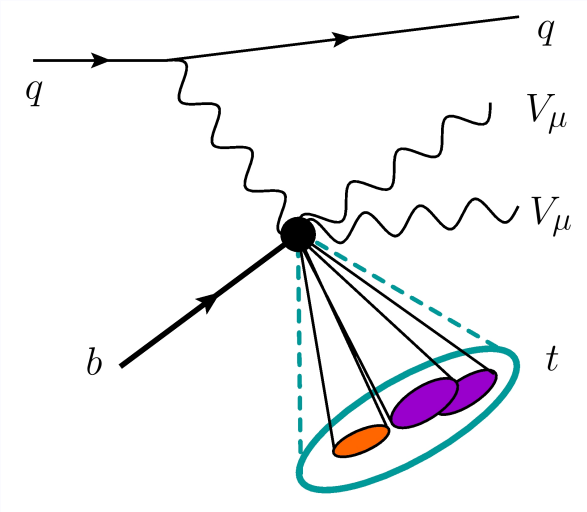
HwH



$$\sim \frac{E^2}{\Lambda^2}$$

(lower production threshold)

signal topology



look for single boosted top + forward jet, then just count leptons

≥2L: small background

events @ HL-LHC

Process	0ℓ	1ℓ	$\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$3\ell(4\ell)$
$W^\pm W^\mp$	3449/567	1724/283	216/35	-	-
$W^\pm W^\pm$	2850/398	1425/199	-	178/25	-
$W^\pm Z$	3860/632	965/158	273/45	-	68/11
ZZ	2484/364	-	351/49	-	(12/2)

$p_T^t > 250$ GeV / $p_T^t > 500$ GeV

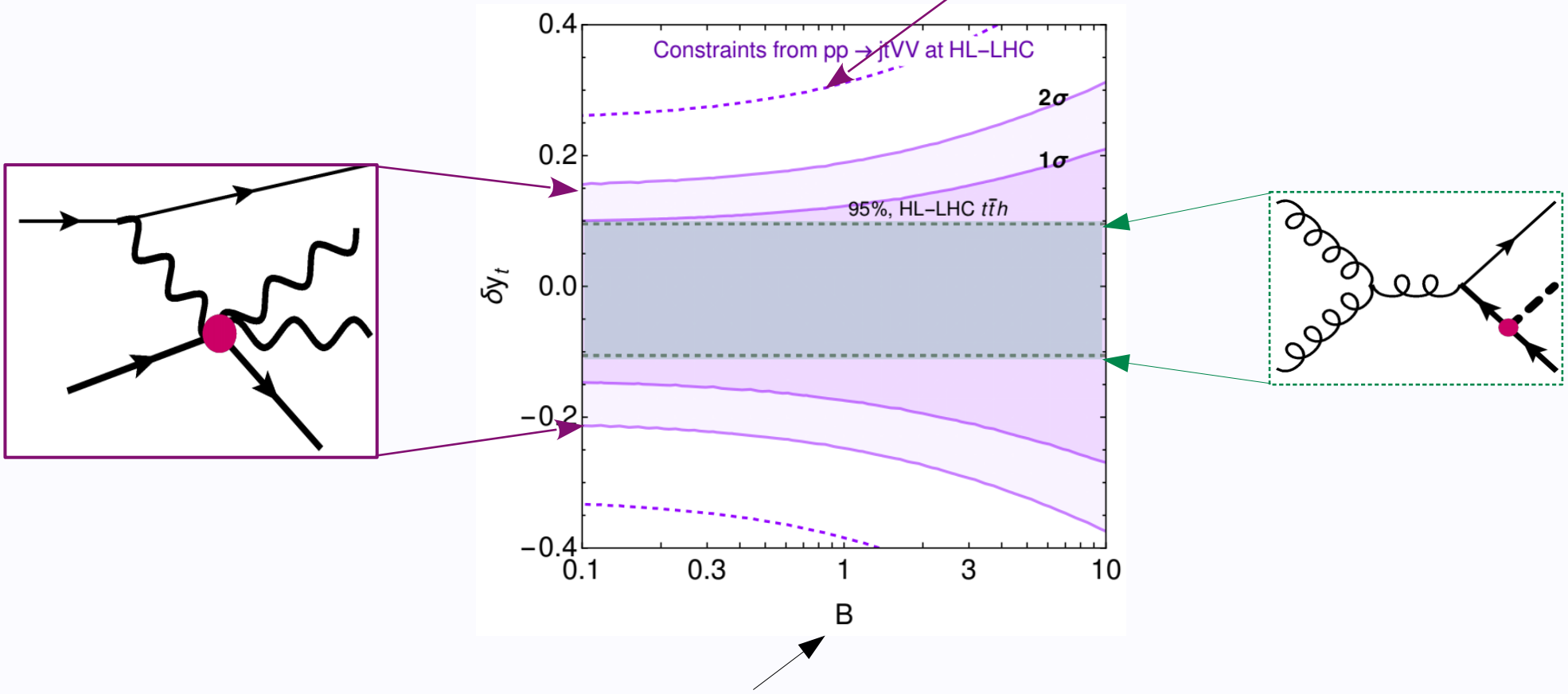
Main bkg: $ttjj \to tW\boxed{bj}j$

$\sim W$

large background, but manageable

Top Yukawa

>2 leptons only



we parametrize background with **B x signal**

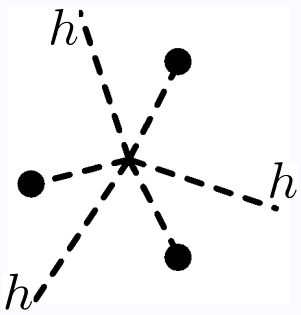
Competitive with on-shell Higgs measurements

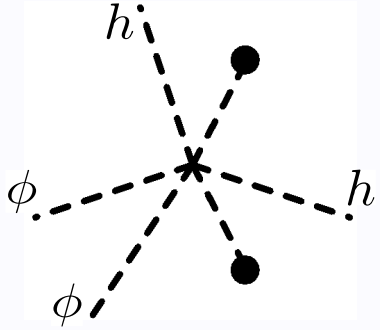
Further improvements:

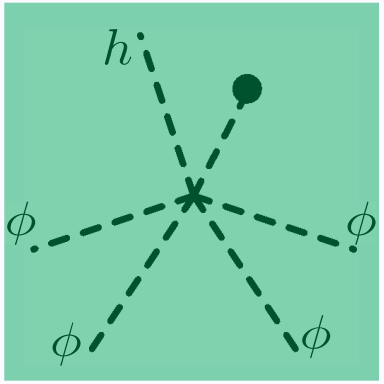
background characterization, especially for hadronic,
differential information, larger E^2,
get rid of transverse polarizations

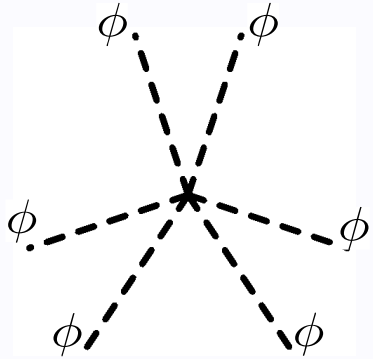
Higgs self-coupling

$$\frac{1}{\Lambda^2}|H|^6 \supset \frac{1}{\Lambda^2}(v^3h^3 + 3v^2h^2\phi^2 + 3vh\phi^4 + \phi^6 + \ldots) \qquad \frac{\mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \frac{vE}{\Lambda^2}$$

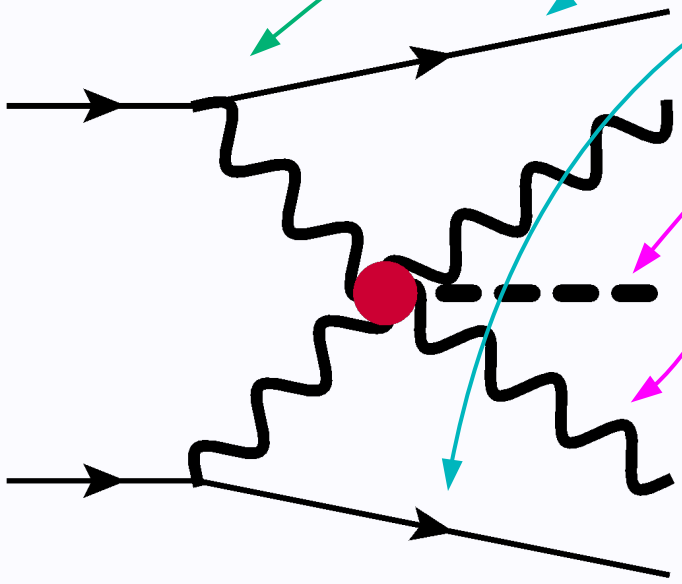








at collider



VBF topology

VVh final states

$W^\pm W^\pm h$

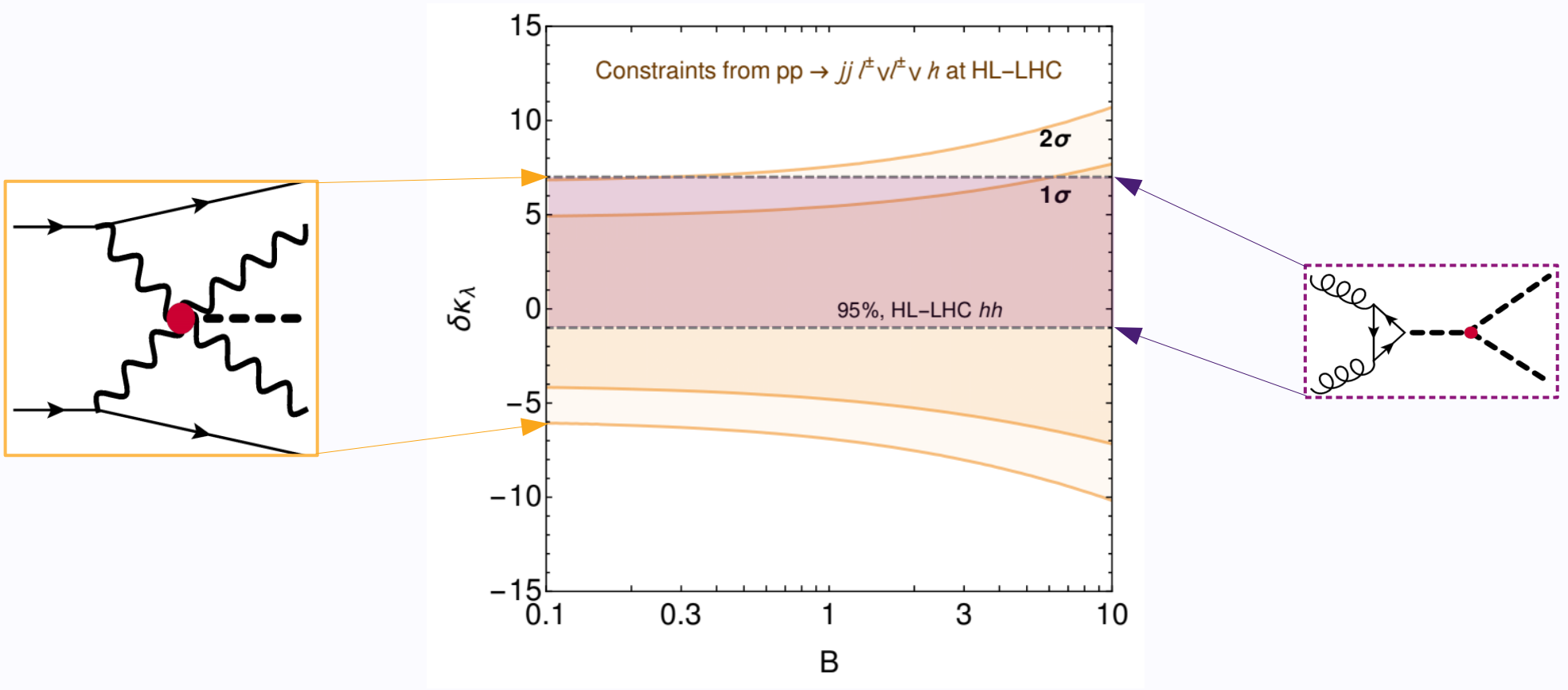
$W^\pm W^\mp h$

$W^\pm Z\, h$

$Z\, Z\, h$

same sign di-leptons

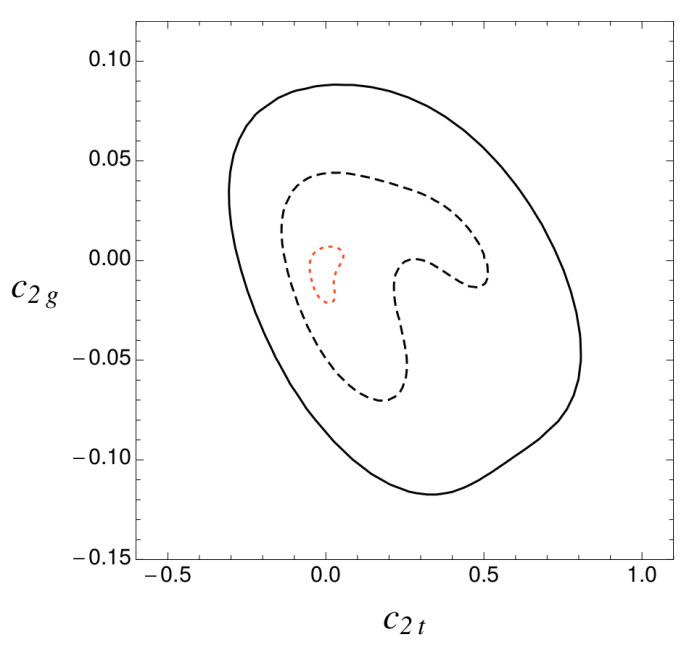
Higgs self-coupling



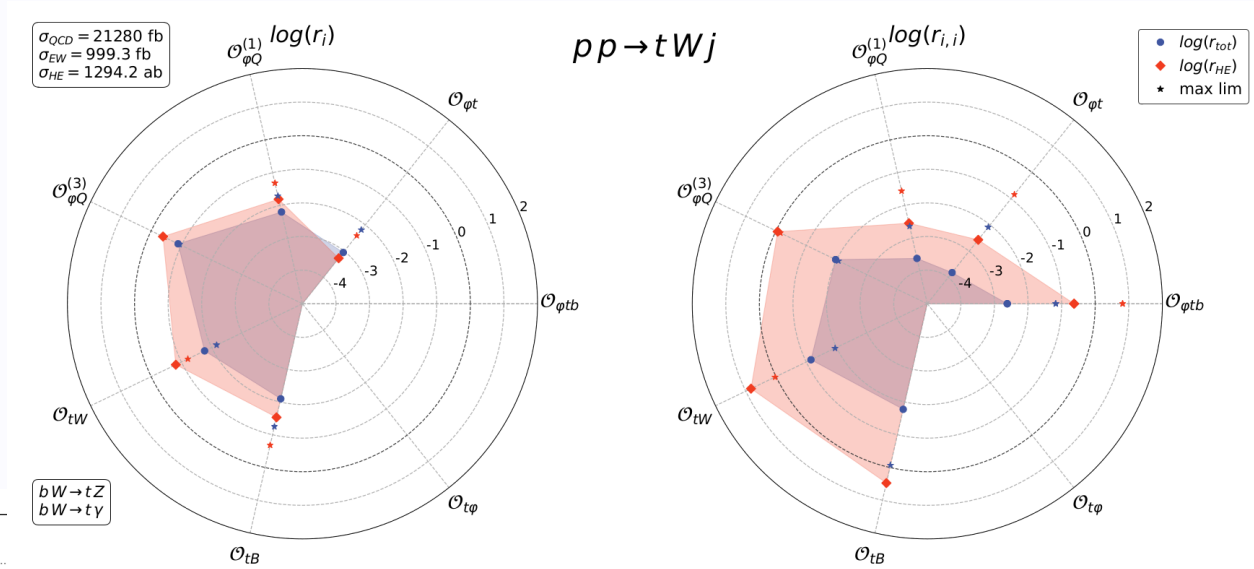
- 50-ish events in the SM
- Irreducible background negligible
- Background from ttjj with lepton misidentification under control
- Backgorund from fake leptons is potentially the dominant one. We parametrize it with **#back = B x #signal**.
- Rough cut-and-count analysis—from just a single channel—gives competitive results with double higgs production

E-growing opportunities in many channels

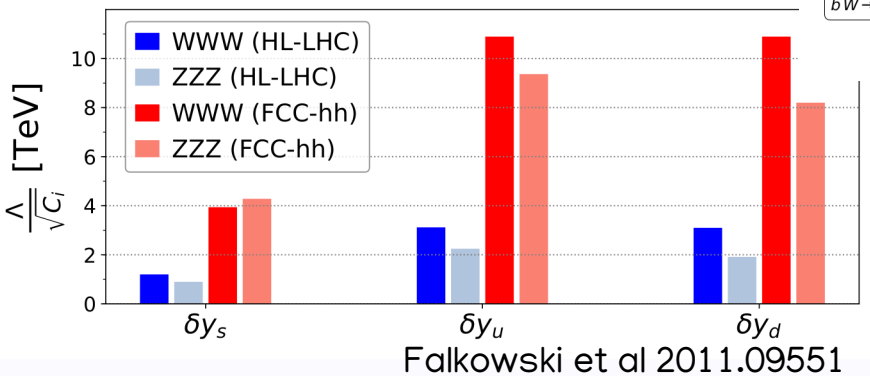
hh, VV, Vh, tV, th, VVV, ...



Azatov et al 1502.00539



Maltoni, Mantani, Mimasu 1904.05637



Falkowski et al 2011.09551

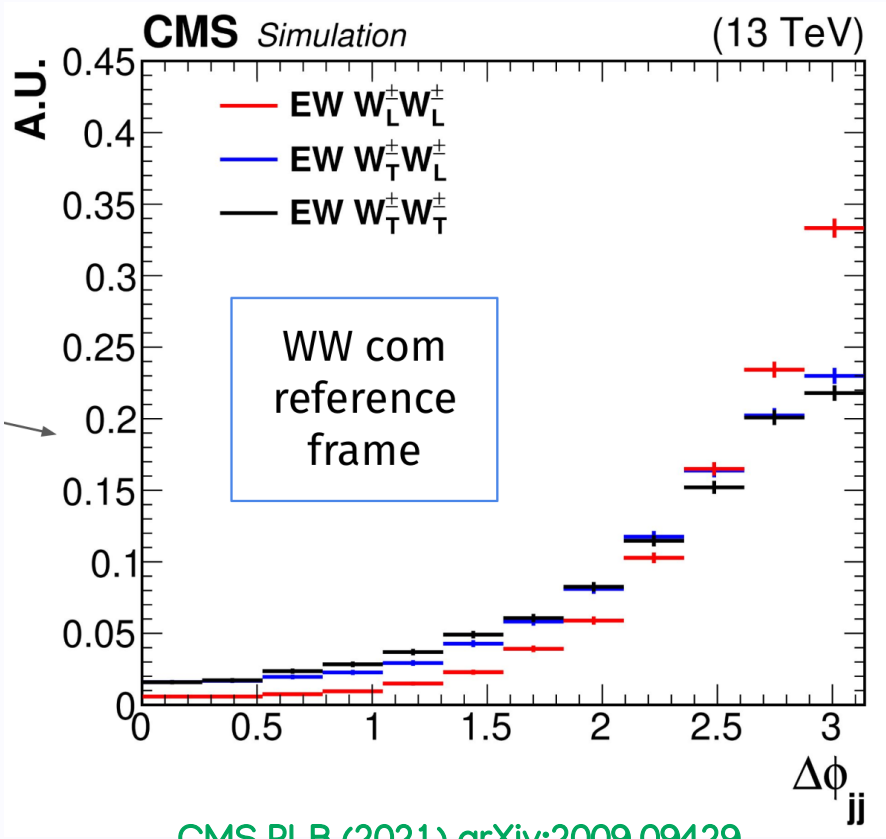
Some questions I have

Accessing longitudinals

Longitudinal polarizations play key role in EW sector

Best processes to look at?

Polarization tagging possibilities?



CMS PLB (2021) arXiv:2009.09429

High Energy. High multiplicity. High opportunities?

2 → n processes offer exciting and challenging experimental opportunities

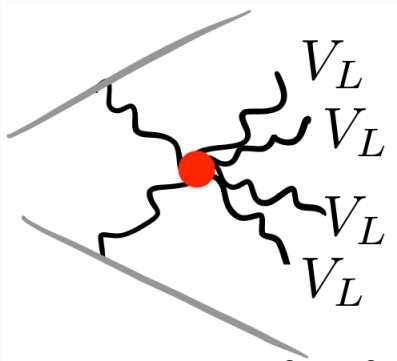
Adding more final state particles decreases cross-section due to phase space

→ what is feasibly measurable at (HL-)LHC? 100 TeV?

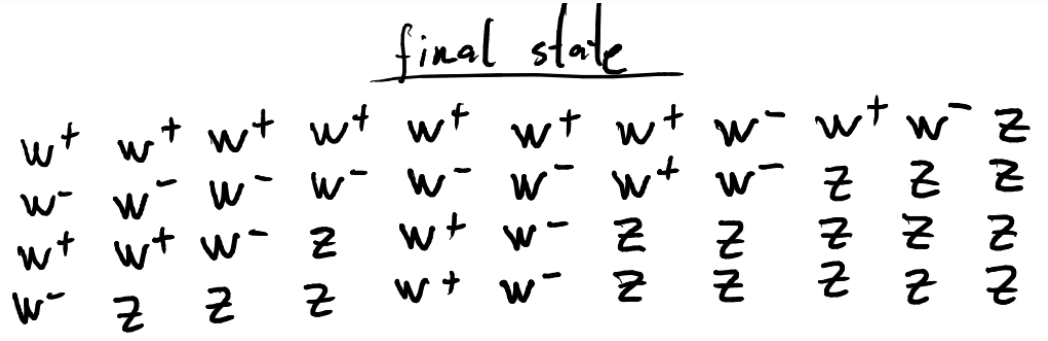
→ to what extent can we access differential information?

→ what are “optimal” differential variables?

→ to what extent can we access hadronic decays of vectors?



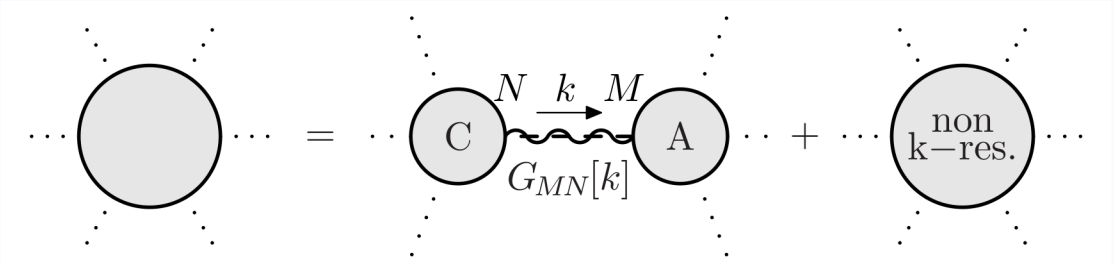
$\delta\mathcal{A}/\mathcal{A} \sim E^2/\Lambda^2$



many channels, but smaller cross-sections

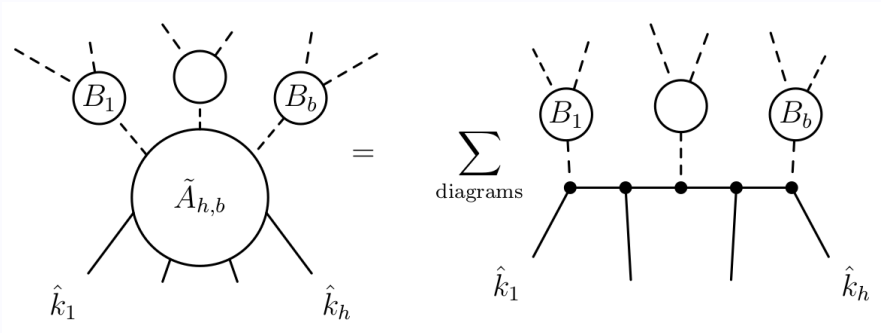
Computing high multiplicity, massive amplitudes

Both analytic and numeric (MC) methods are challenging



Cuomo, Vecchi, Wulzer 1911.12366

- What tools do we have?
- What are worth developing?
- To what extent can experiments employ theory calculations?



Franken & Schwinn 1910.13407

Thank you!