University of Zurich[UZH]

Pseudo Observables in Higgs Physics

[status report & future plans]

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- Introduction [*Why PO?*]
- PO in Higgs decays
- PO in Higgs EW production
- PO vs. EFT, parameter counting & symmetry limits
- Tools & Work in Progress
- Conclusions

Introduction [*Why PO?*]

The Higgs-PO are a natural generalization (*in my opinion the only natural...*) of the "kappa-formalism"

$$\sigma(in \to h+X) \times BR(h \to fin\ ) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{in}{}^2\, \kappa_{fin}{}^2}{\kappa_h{}^2} \sigma_{SM} \times BR_{SM}$$

Main virtues of the κ's:

- Clean SM limit [best up-to-date TH predictions recovered for $\kappa_i \to 1$]
- Well-defined both on TH and EXP sides
- (*almost*) Model independent

Main problem:

- Loss of information on possible NP effects modifying the kinematical distributions

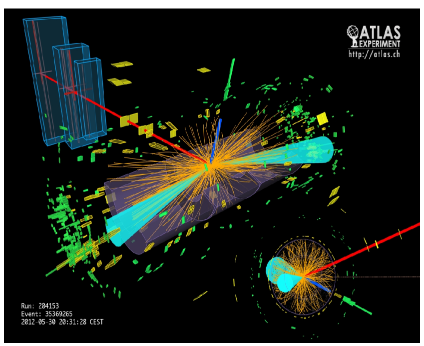
$\rightarrow$ When aiming at high precision, in observables with non-trivial kinematics, we need a larger set of "pseudo-observables"

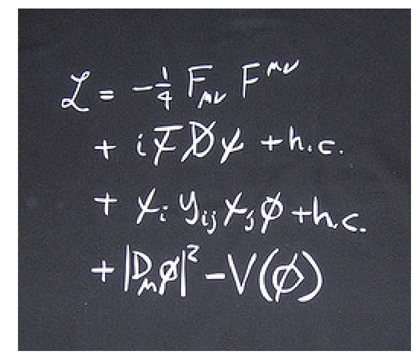
The "old" κ's are nothing but a subset of the Higgs PO

Introduction [*Why PO?*]

- The goal of the PO is to provide a general encoding of the exp. results in terms of a limited number of “simplified” (idealized) observables of easy th. interpretation [*old idea - heavily used and developed at LEP times*]

- The experimental determination of an appropriate set of PO will “help” and not “replace” any explicit NP approach to Higgs physics (*including the EFT*)





Experimental data — Pseudo Observables — Lagrangian parameters

> The PO can be computed in terms of Lagrangian parameters in any specific th. framework (SM, SM-EFT, SUSY, ...)

Introduction [*Why PO?*]

- The goal of the PO is to provide a general encoding of the exp. results in terms of a limited number of "simplified" (idealized) observables of easy th. interpretation [*old idea - heavily used and developed at LEP times*]

- The experimental determination of an appropriate set of PO will "help" and not "replace" any explicit NP approach to Higgs physics (*including the EFT*)

↓

- The PO should be defined from kinematical properties of on-shell processes (*no problems of renormalization, scale dependence,…*)

- The theory corrections applied to extract them should be universally accepted as "NP-free" (*soft QCD and QED radiation*)

Introduction [*Why PO?*]

Some people ask the following question:
Why do we need to measure PO, given we can go to a "more fundamental level" and directly extract the Wilson coefficients of the EFT from data?

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Answer (I):

What is "more fundamental"?

A) The combination $[c_W(\mu)+c_{HW}(\mu)+\tan(\theta_W)(c_B(\mu)+c_{HW}(\mu))]$,

-defined assuming a linear realization of the EWSB & employing the SILH basis for the EFT Lagrangian

-extracted computing amplitudes at LO in the EFT expansion, setting the renormalization scale μ=1 TeV (and assuming that at that scale NLO-EW effects are negligible)

B) The partial width $\Gamma(h \to W_L W_L)$

<u>Introduction</u> [*Why PO?*]

Some people ask the following question:
Why do we need to measure PO, given we can go to a <u>"more fundamental level"</u> and directly extract the Wilson coefficients of the EFT from data?

Answer (II):

There is no reason to consider Wilson coefficients and, more generally, Lagrangian parameters "more fundamental" than on-shell physical amplitudes (or the elements of the *S* matrix). Actually it is the opposite.

Lagrangians are noting but tools...

Extracting their parameters requires a series of additional assumptions, that we may change in the future with more data and/or better understanding of the underlying (BSM) physics theory.

...the "physics" is in the scattering amplitudes, hence in the PO.

Introduction

There are two main categories of PO:

A) "Ideal observables"

M_W, $\Gamma(Z \to ll)$, …

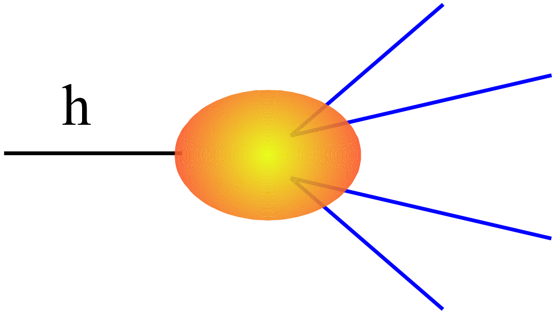
M_h, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to 4\mu)$, …
but also $d\sigma(pp \to hZ)/dm_{hZ}$ ...

B) "Effective on-shell couplings"

g_Z^f, g_W^f, ...

- Both categories are useful
(*there is redundancy having both, but that's not an issue...*).
- For B) one can write an effective Feynman rule, not to be used beyond tree-level (its just a practical way to re-write, *and code in existing tools,* an on-shell amplitude).

PO in Higgs decays



PO in Higgs decays

Multi-body modes
e.g. $h \to 4\ell$, $\ell\ell\gamma$, ...

There is more to extract from data other than the κ_i

Two-body (on-shell) decays
[*no polarization properties of the final state accessible*]
e.g. $h \to \gamma\gamma$, $\mu\mu$, $\tau\tau$, bb

The κ_i $(\leftrightarrow\Gamma_i)$ *is all what one can extract from data*

[+ *one more parameter if the polarization is accessible*]

PO in Higgs decays

Multi-body modes
e.g. $h \to 4\ell,\ \ell\ell\gamma,\ \ldots$

$\downarrow$

Form factors $\to f_i(s)$ [E.g.: $s = m^2_{\ell\ell}$]

$\downarrow$

Two-body (on-shell) decays
[*no polarization properties of the final state accessible*]
e.g. $h \to \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

$\downarrow$

$\kappa_i\ (\leftrightarrow \Gamma_i)$

Gonzales-Alonso *et al.* 1412.6038

Momentum expansion of the *f.f.* around leading poles

$$\text{E.g.: } f_i^{SM+NP} = \frac{\kappa_i}{s - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon_i}{m_Z^2} + O(s/m_Z^4)$$

- No need to specify any detail about the EFT, but for the absence of light new particles $\to$ momentum expansion very well justified by the Higgs kinematic
- The $\{\kappa_i, \epsilon_i\}$ thus defined are well-defined PO $\to$ systematic inclusion of higher-order QED and QCD (soft) corrections possible (and necessary...)

PO in Higgs decays [e.g.: $h \rightarrow 4l$]

"Dressing" with QED radiation

↓

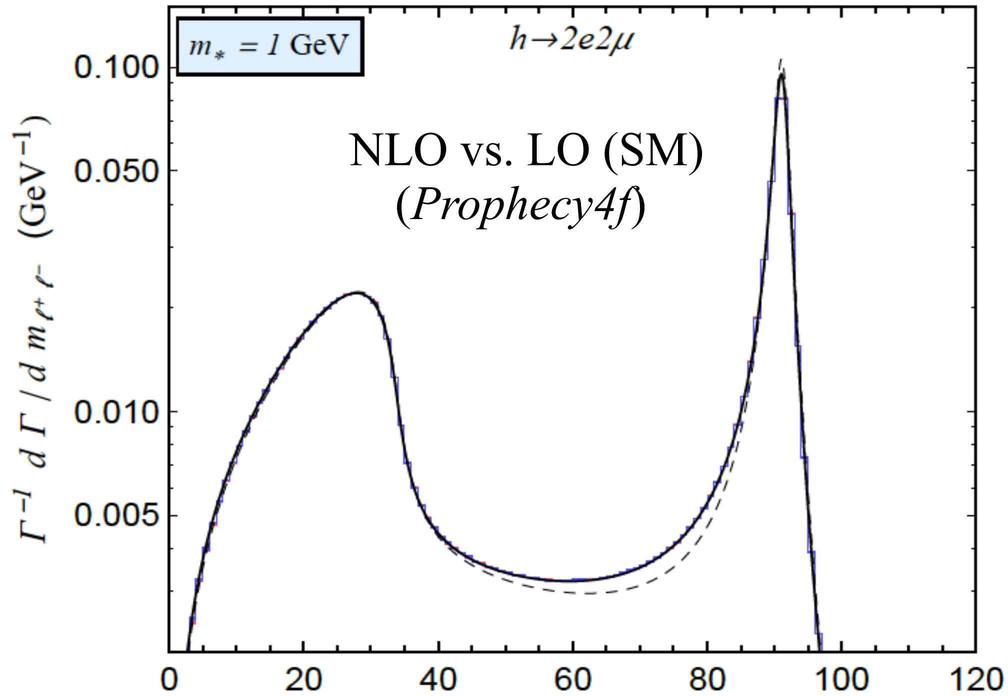
excellent description of NLO SM

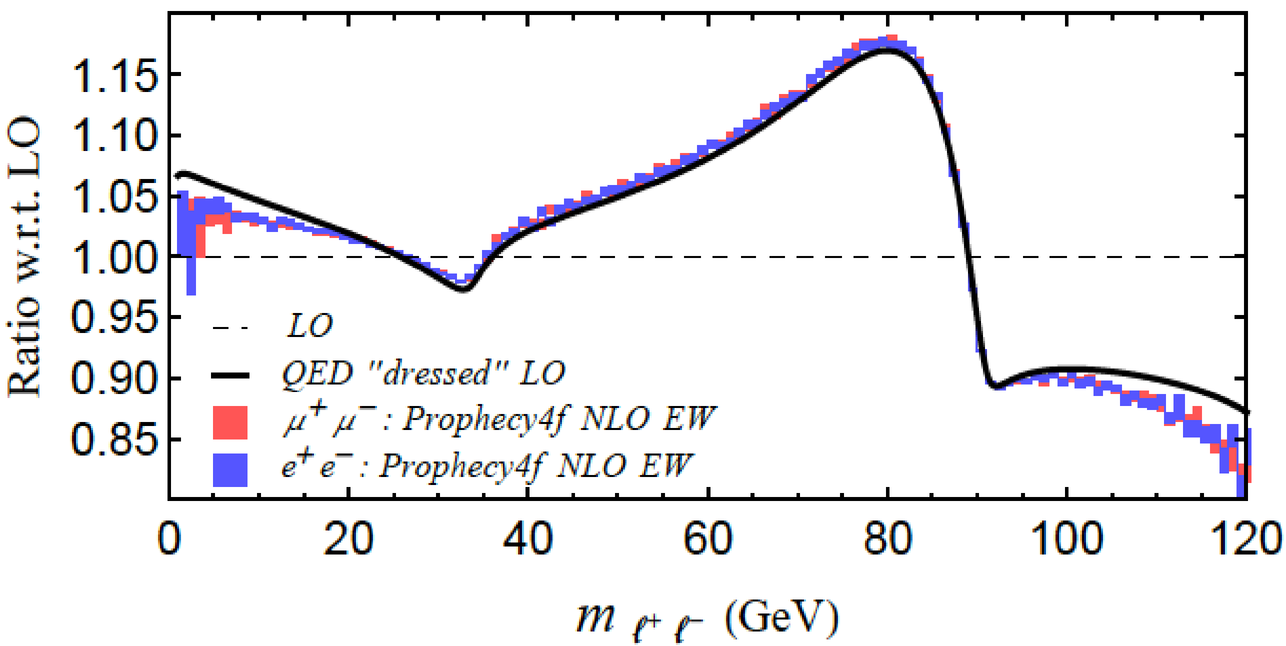
(*when setting PO to SM values*)

↓

tool able to describe

(*general*) NP beyond LO





Bordone *et al.* 1507.02555

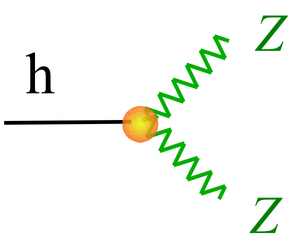
PO in Higgs decays

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

→ PO note in YR4

$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times$$
$$\left[\left(\kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} \right) g^{\alpha\beta} + \right.$$
$$+ \left(\epsilon_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{q_1 \cdot q_2 \; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$
$$\left. + \left(\epsilon_{ZZ}^{CP} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{CP} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{CP} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

"double Z-pole"



$$\boxed{\Gamma(h \to Z_L Z_L)} \equiv \frac{\Gamma(h \to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.209\ |\kappa_{ZZ}|^2\ \text{MeV}$$

$$\boxed{\Gamma(h \to Z_T Z_T)} \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.0189\ |\epsilon_{ZZ}|^2\ \text{MeV}$$

$$\boxed{\Gamma^{\text{CPV}}(h \to Z_T Z_T)} \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}^{CP}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.00799\ |\epsilon_{ZZ}^{CP}|^2\ \text{MeV}$$

PO in Higgs decays

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

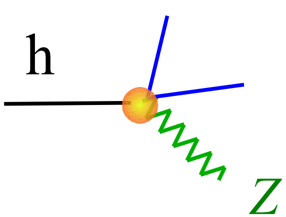
→ PO note in YR4

$$\Bigg[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} +$$

$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\, g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +$$

$$+\left(\epsilon_{ZZ}^{CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\Bigg]$$

"single Z-pole"



$$\boxed{\Gamma(h\to Z\ell^+\ell^-)} = 0.0366\,|\epsilon_{Ze}|^2\ \text{MeV}$$

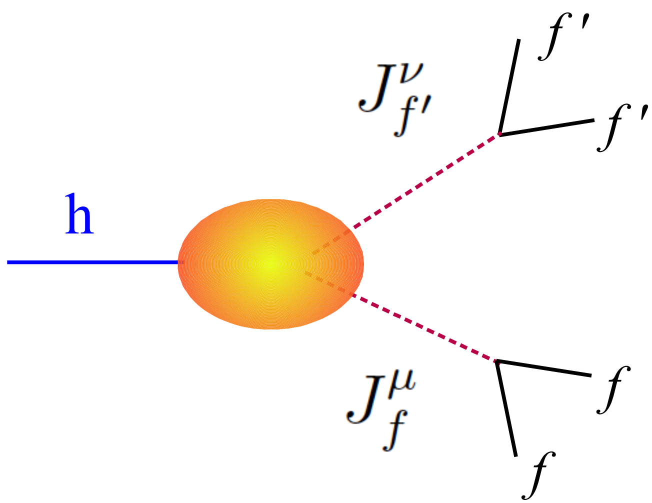
PO in Higgs decays

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

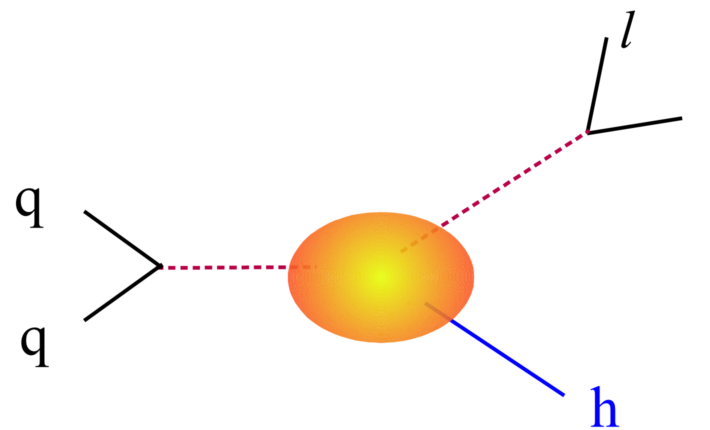
PO	Physical PO	Relation to the eff. coupl.
$\kappa_f,\ \lambda_f^{\mathrm{CP}}$	$\Gamma(h \to f\bar{f})$	$= \Gamma(h \to f\bar{f})^{(\mathrm{SM})}[(\kappa_f)^2 + (\lambda_f^{\mathrm{CP}})^2]$
$\kappa_{\gamma\gamma},\ \lambda_{\gamma\gamma}^{\mathrm{CP}}$	$\Gamma(h \to \gamma\gamma)$	$= \Gamma(h \to \gamma\gamma)^{(\mathrm{SM})}[(\kappa_{\gamma\gamma})^2 + (\lambda_{\gamma\gamma}^{\mathrm{CP}})^2]$
$\kappa_{Z\gamma},\ \lambda_{Z\gamma}^{\mathrm{CP}}$	$\Gamma(h \to Z\gamma)$	$= \Gamma(h \to Z\gamma)^{(\mathrm{SM})}[(\kappa_{Z\gamma})^2 + (\lambda_{Z\gamma}^{\mathrm{CP}})^2]$
κ_{ZZ}	$\Gamma(h \to Z_L Z_L)$	$= (0.209\ \mathrm{MeV}) \times \lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h \to Z_T Z_T)$	$= (1.9 \times 10^{-2}\ \mathrm{MeV}) \times \lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h \to Z_T Z_T)$	$= (8.0 \times 10^{-3}\ \mathrm{MeV}) \times \lvert\epsilon_{ZZ}^{\mathrm{CP}}\rvert^2$
ϵ_{Zf}	$\Gamma(h \to Z f\bar{f})$	$= (3.7 \times 10^{-2}\ \mathrm{MeV}) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h \to W_L W_L)$	$= (0.84\ \mathrm{MeV}) \times \lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h \to W_T W_T)$	$= (0.16\ \mathrm{MeV}) \times \lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h \to W_T W_T)$	$= (6.8 \times 10^{-2}\ \mathrm{MeV}) \times \lvert\epsilon_{WW}^{\mathrm{CP}}\rvert^2$
ϵ_{Wf}	$\Gamma(h \to W f\bar{f}')$	$= (0.14\ \mathrm{MeV}) \times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$

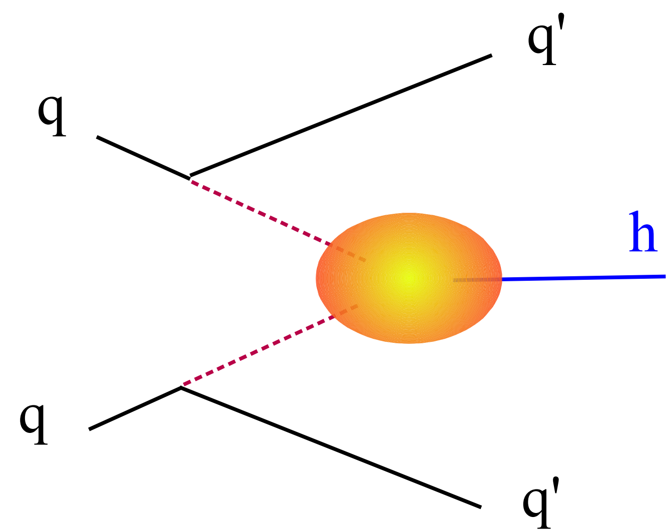
→ PO note in YR4

PO in Higgs EW production



vs.





PO in Higgs EW production

The same Green Function controlling $h \to 4f$ decays is accessible also in $pp \to hV$ and $pp \to h$ via VBF, i.e. the two leading EW-type Higgs production processes (*N.B.: this follows from "plain QFT" no need to invoke any EFT...*)

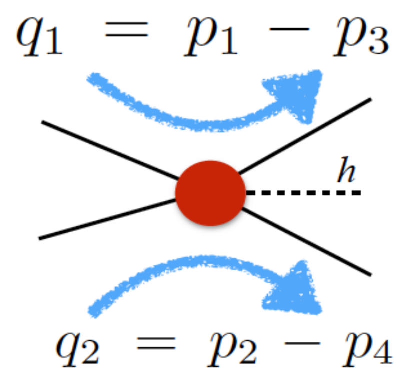
$$\langle 0|\mathcal{T}\left\{ J_f^{\mu}(x), J_{f'}^{\nu}(y), h(0) \right\}|0\rangle$$

Same approach as in $h \to 4f$ (and, to some extent, same PO) but for three important differences:

Greljo et al. 1512.06135

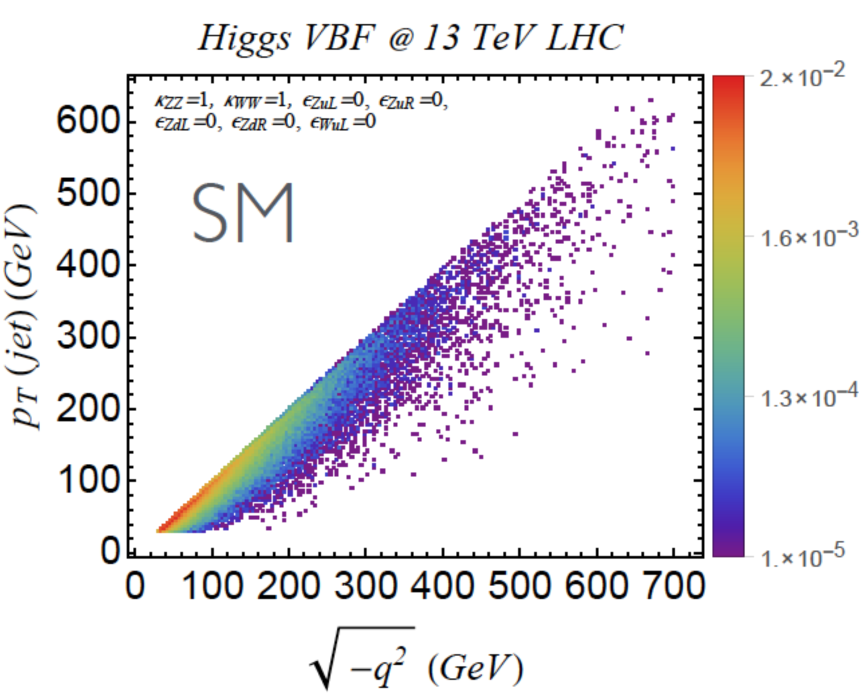
- different flavor composition ($q \leftrightarrow \ell$) $\to$ new param. associated to the physical PO $\Gamma(h \to Zqq)$ & $\Gamma(h \to Wud)$ — trivial
- large impact of (facotrizable) QCD corrections — conceptually easy
- different kinematical regime: momentum exp. not always justified (*large momentum transfer*) — delicate point

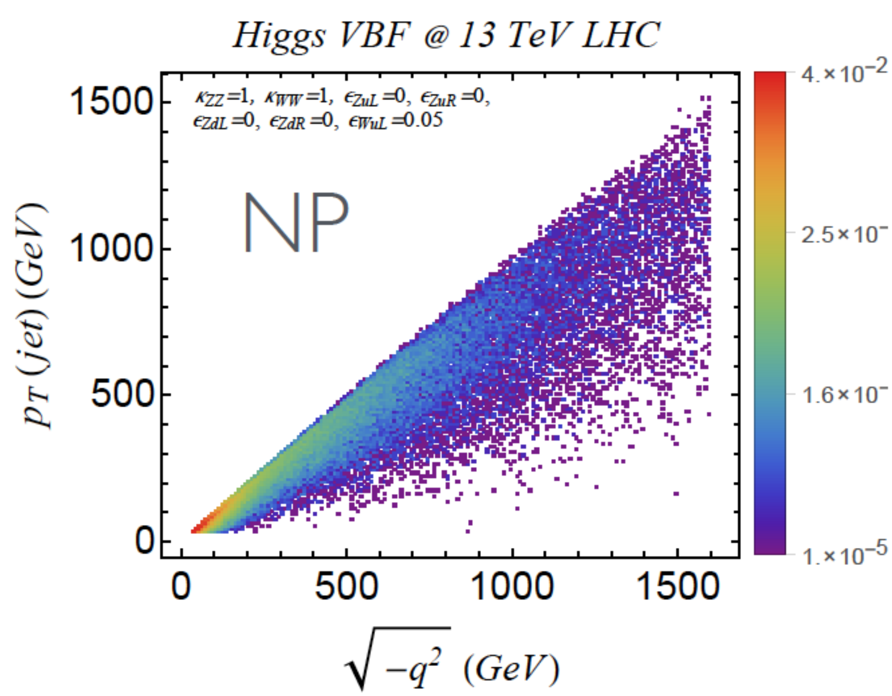
PO in VBF [*slides by J. Lindert*]



Practical problem:

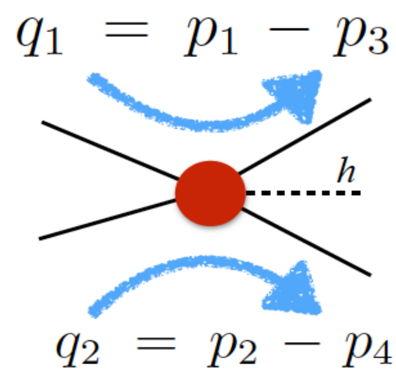
- $F_X(q_1^2, q_2^2)$, $G_X(q_1^2, q_2^2)$ not directly measurable
- not even q_1^2, q_2^2 measurable (in particular not in H→WW)
- construct proxy:





$$\Rightarrow \quad q_i^2 \approx -p_{\mathrm{T,i}}^2$$ (for Higgs produced near threshold)

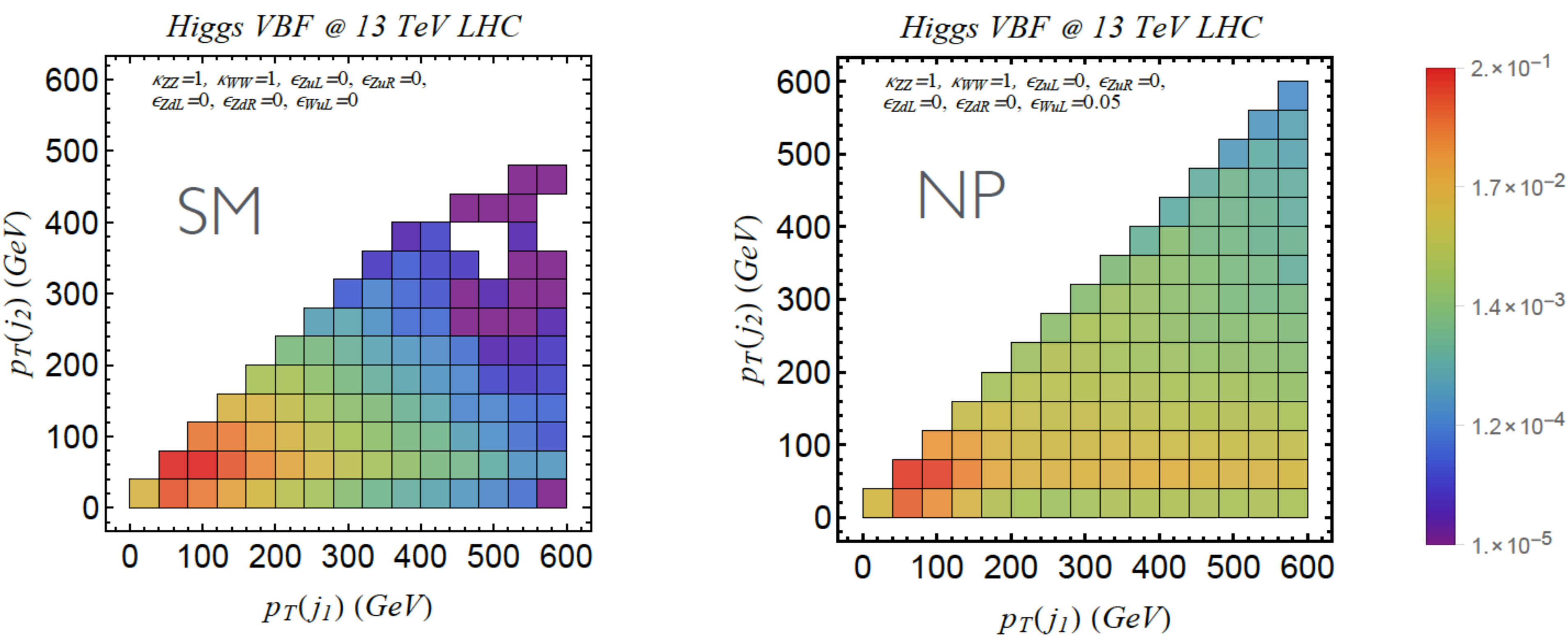
▶ PO in VBF [slides by J. Lindert]



- Crucial measurement:
  double differential cross section in jet pT's
  (order by pT and/or $\Delta\eta_{ij}$)

$$\boxed{\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T,j_1}}\mathrm{d}p_{\mathrm{T,j_2}}}}$$

- allows for extraction/fit of PO! $F(q_1^2, q_2^2) \rightarrow \tilde{F}(p_{T1}^2, p_{T2}^2)$



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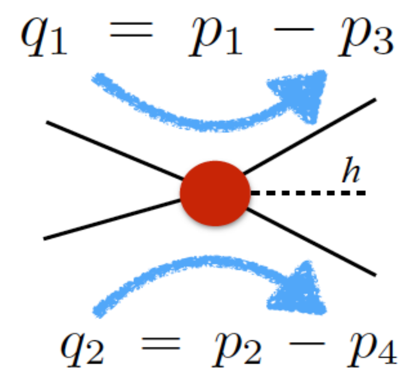

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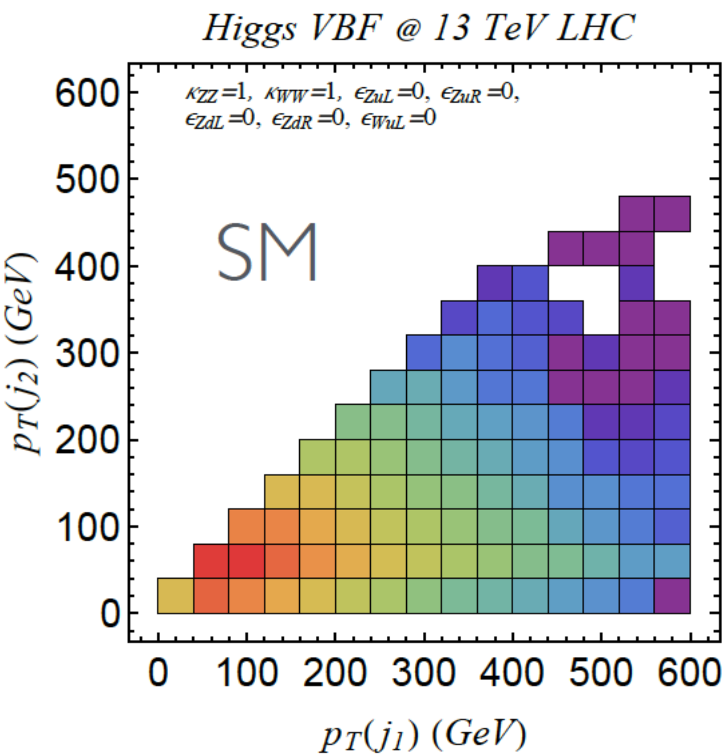


General procedure:

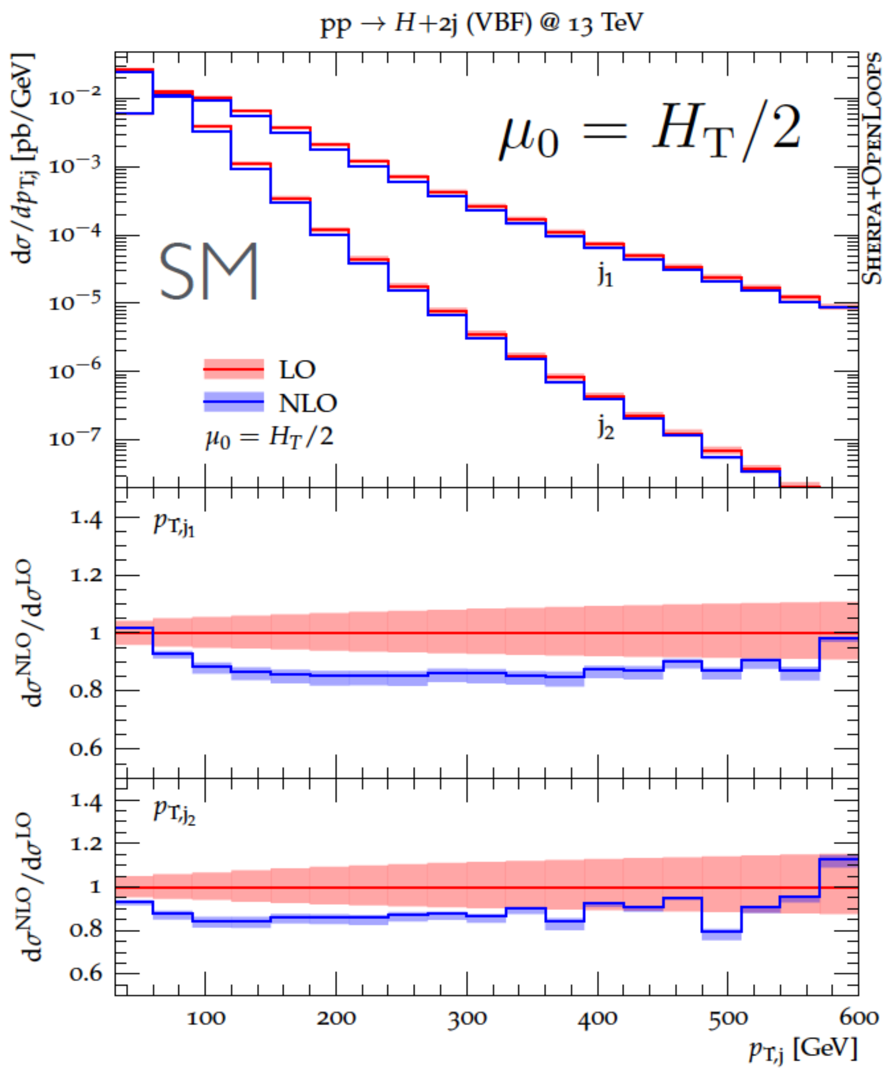
- Measure the PO setting close to the threshold region, setting a cut on the "dangerous" kinematical variable [→ a-posteriori data-driven check of the validity of the momentum expansion ↔ definition of threshold region]
- Report the cross-section as a function of the kinematical variable in the high-momentum region [→ natural link/merging with template cross-section]

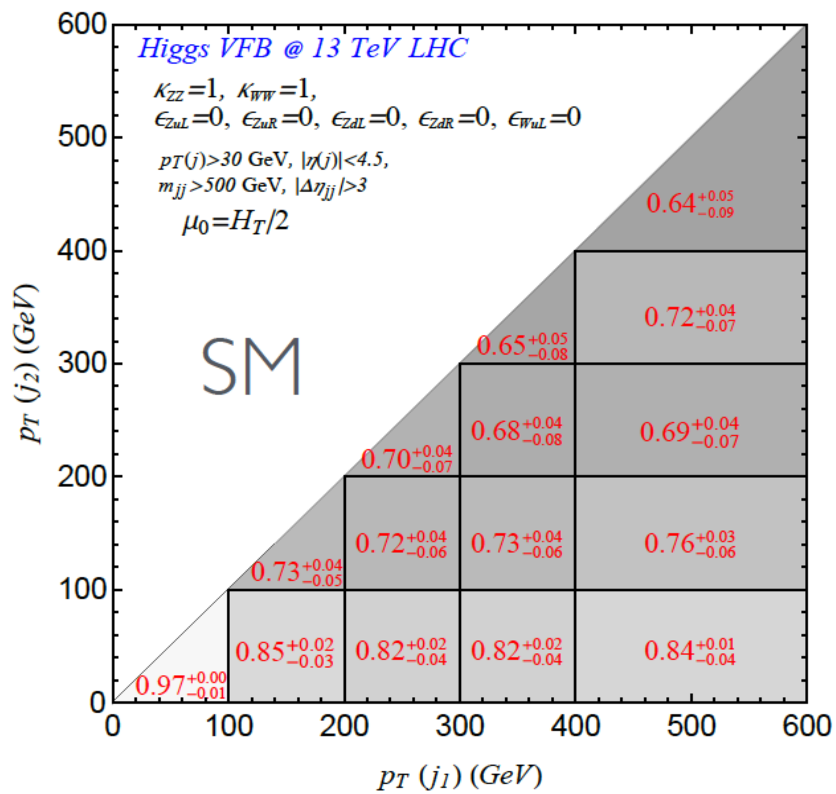
▶ PO in VBF [*slides by J. Lindert*]

NLO QCD corrections

$$p_{\mathrm{T,j_{1,2}}} > 30\ \mathrm{GeV}, \quad |\eta_{\mathrm{j_{1,2}}}| < 4.5, \quad \text{and} \quad m_{\mathrm{j_1 j_2}} > 500\ \mathrm{GeV}$$

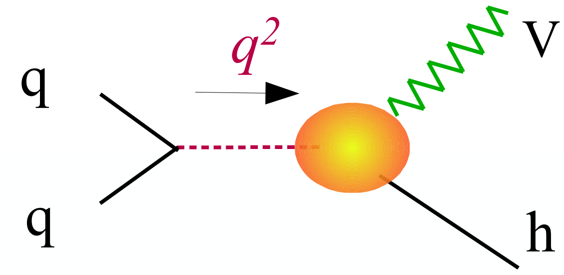
$$\Delta\eta_{j_1 j_2} > 3$$





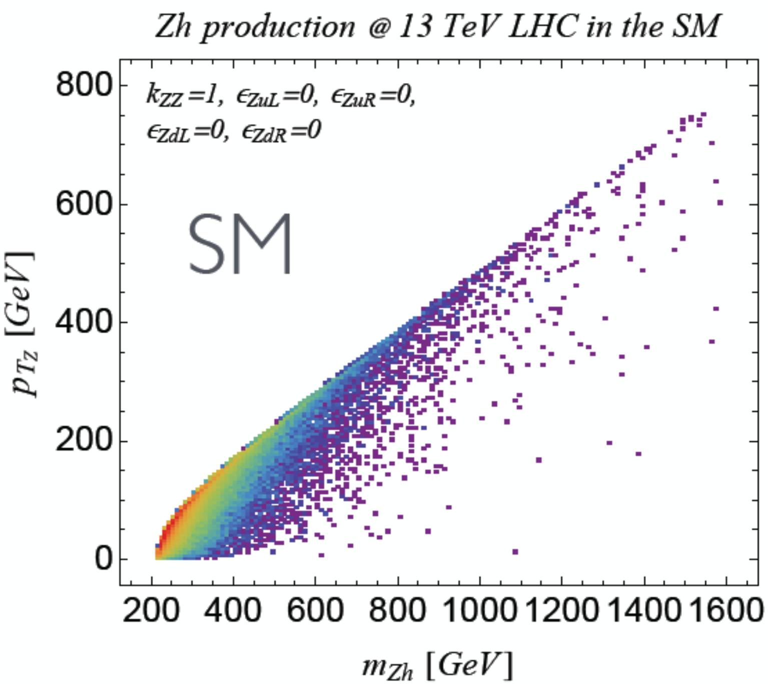
- NLO QCD corrections: max ~15-35%
- NNLO ~10% shape effects
- NLO EW ~10-15% shape effects

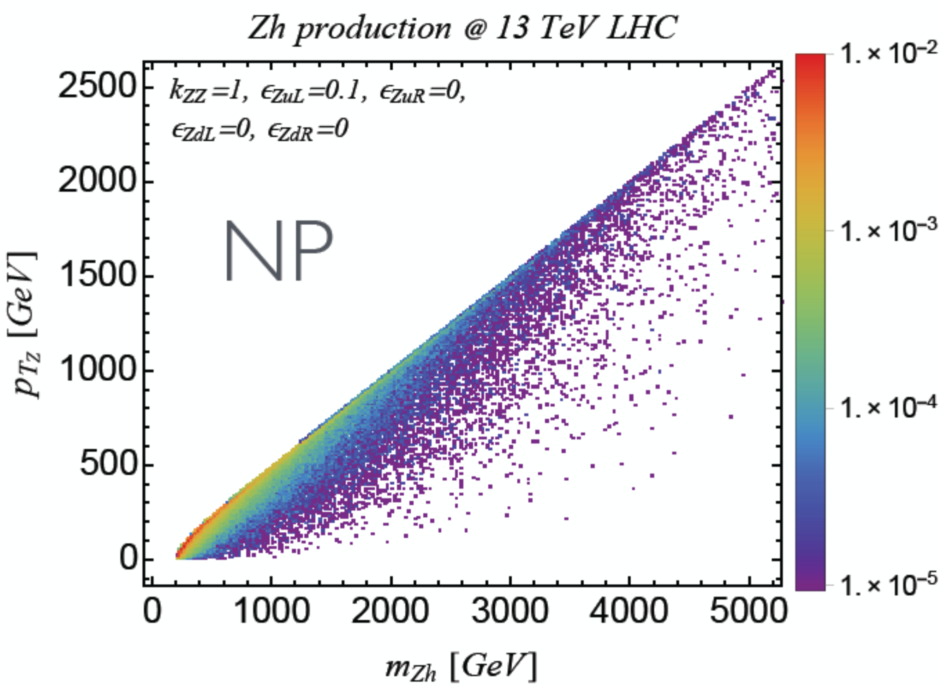
PO in VH [slides by J. Lindert]



Practical problem:

- process governed by $q^2 = m^2_{Vh}$
- not measurable in all decay modes (V=W or H→WW)



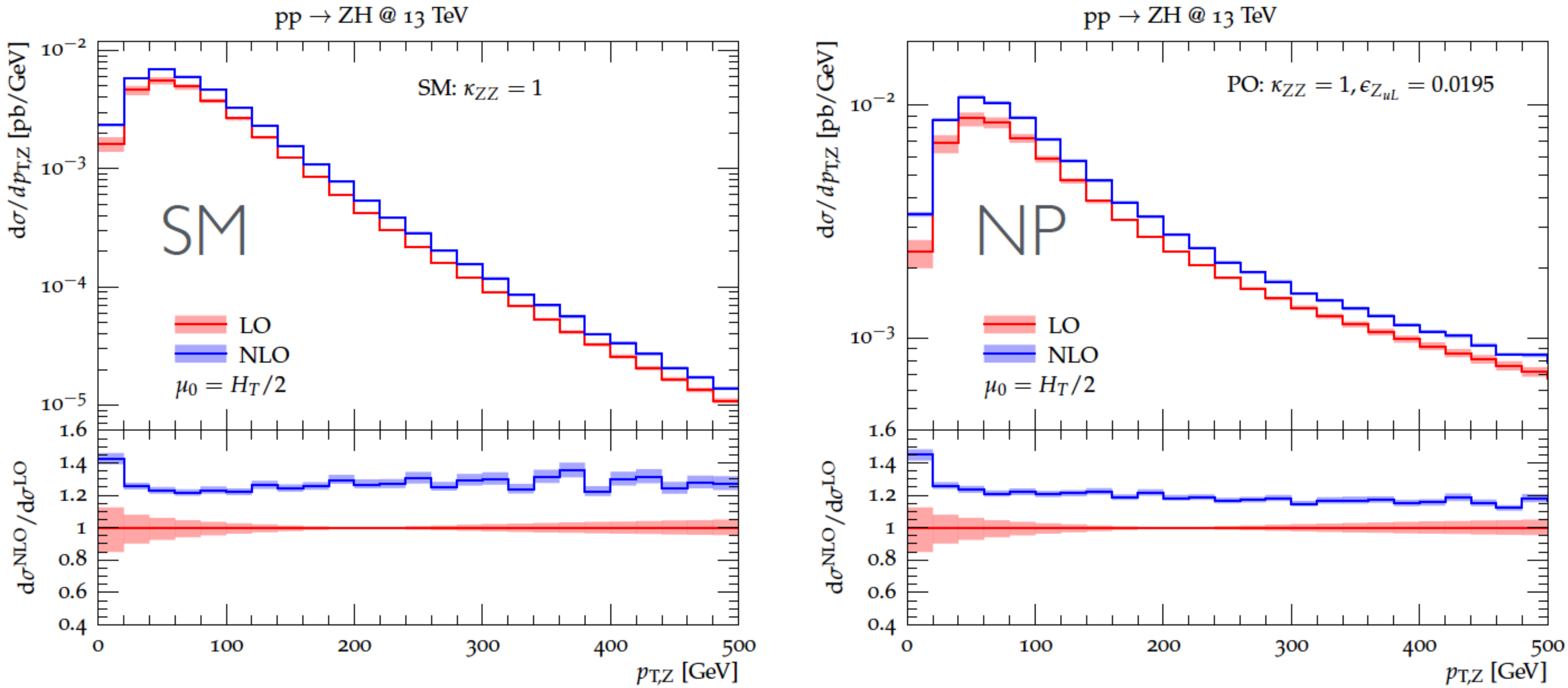


$$m^2_{Vh} \to 4p_T^2 \qquad \text{for} \qquad |p_T| \to \infty$$

▶ PO in VH [slides by J. Lindert]

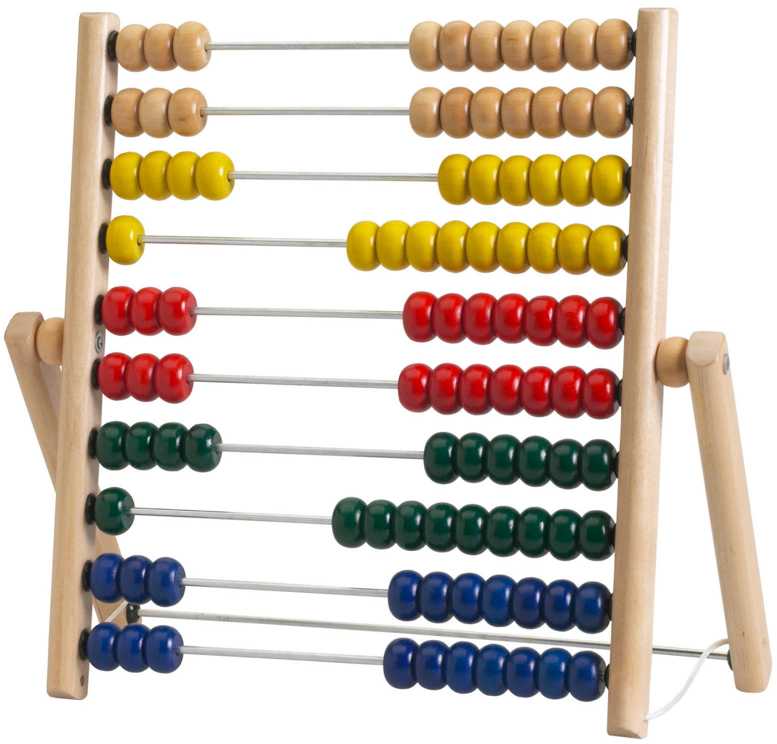
NLO QCD corrections in PO

- process independent implementation of **Higgs PO @ NLO QCD** in Sherpa+OpenLoops
- via Sherpa's UFO functionality (1412.6478)



- NP shapes largely unaffected by QCD corrections
- detailed study @ NLO+PS in preparation

PO vs. EFT, parameter counting & symmetry limits



PO vs. EFT

PO and couplings in EFT Lagrangians are *intimately related but are not the same thing* (on-shell amplitudes vs. Lagrangians parameters) → full complementarity

- The PO are calculable in any EFT approach (*linear, non-linear, LO, NLO...*)
  - In the limit where we work at the tree-level in the EFT there is a simple linear relation between PO and EFT couplings: each PO represent a unique linear combination of couplings of the most general Higgs EFT.
  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)

→ PO note in YR4

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- For Higgs production also the PO involve an expansion in momenta; however, this is different than the operator expansion employed within the EFT
  - To define the PO we expand only on a measurable kinematical variables, this is why the validity of the *expansion can be checked directly by data* (on the same process used to determine the PO)

- In each process the PO are the maximum number of independent observables that can be extracted by that process only → naturally optimized for data analyses

Parameter counting & symmetry limits

Number of independent PO for EW Higgs decays + EW production + Yukawa modes (h → ff):

PO set with maximal symmetry [CP + Lepton Univ]:

	Minimal set:	*Without custodial symm.:*
Prod. & decays	$\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}$	$\kappa_{WW}, \epsilon_{WW}$
EW decays only	$\kappa_{\gamma\gamma}, \epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{We_L}$	$\epsilon_{Z\nu_\mu}$
EW prod. only	$\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$	ϵ_{Wu_L}
	15 (11)	[→ 32 with no symm.]
Yukawa modes	$\kappa_b, \kappa_\tau, \kappa_c, \kappa_\mu$ 4	[→ 8 with no symm.]
	(as in the original κ-formalism)	
gg→h & ttH	κ_g, κ_t 2	[→ 4 with no symm.]

Tools

A first automated public tool (*UFO model* for MG5_aMC@NLO or Sherpa) is now

- fully available for decays (*QED corrections fully accounted by standard shower algorithms, as verified by the comparison with Profecy4f*)
- will soon be available also for EW production, with inclusion of NLO QCD corrections (*work in prog....*)

Universität Zürich[UZH]

HPO

Higgs PO

DESCRIPTION DOWNLOAD CONTACTS

http://www.physik.uzh.ch/data/HiggsPO

Tools & Work in Progress

A first automated public tool (*UFO model* for MG5_aMC@NLO or Sherpa) is now

- fully available for decays (*QED corrections fully accounted by standard shower algorithms, as verified by the comparison with Profecy4f*)

- will soon be available also for EW production, with inclusion of NLO QCD corrections (*work in prog....*)

Beside the activity on the tools (for NLO QCD corrections), more-theoretical on-going (post YR4...) activities includes:

- Inclusion of NLO EW corrections in production (VBF & VH)

- Development of the PO formalism for ttH beyond κ_t (*non-trivial kin. effects*)

- Extraction of EFT couplings @ NLO

Conclusions

- The PO represent a general tool for the exploration of Higgs properties (in view of high-statistics data), with minimum loss of information and minimum theoretical bias → *full complementary to EFT* (and explicit BSM)
- The formalism is now fully developed for Higgs decays and Higgs EW productions [→ *see PO section in YR4*]
- NLO tools are ready for all relevant Higgs decay channels and (almost) ready for EW production (VBF+VH)
- On-going (beyond YR4) activity on NLO EW corrections & ttH.