Pseudo Observables in EW Higgs production



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Future of VBF measurements Durham, 22th September 2016

Run-II Higgs Precision Era

- Run-I Higgs legacy:
 - \checkmark discovery of the Higgs!
 - \checkmark all measured rates and BRs are in very good agreement with SM
- Run-II Higgs prospects:

 - The precision probe of the Higgs sector so far, from direct searches: \Rightarrow as long as direct BSM searches indicate no clear signal: $\Lambda_{NP} \gg m_h$
 - search and parametrize smooth deviations from the SM
 - has to be done in the most general (and below of etical premisions did governa.)

Search for smooth deviations from the SM

(SM)EFT?

- In an EFT analysis further assumptions are needed: • dynamical assumptions ($H \in doublet$?)
- basis choice
- fix order in perturbation theory
- flavour assumptions

- dynamical assumptions (e.g. if Higgs \in doublet)
- a basis has to be specified
- fix order in perturbation theory
- flavor assumptions

...still: EFT approach is of course very powerful!

•



Scale of New Physics is high

How to parametrize smooth deviations from the SM in the **most general** and **theoretically unbiased** way?



Experimental Observables

Raw data on tape, reconstructed events fiducial cross sections, ... parameters

Gauge structure, couplings, running masses, Wilson coefficients, ...

How to parametrize smooth deviations from the SM in the **most general** and **theoretically unbiased** way?





Z=-4 Fre FMV tiupy + h.c. + Ψi yij Yi¢+ L. c. $+ D_{\phi} \phi l^2 - V(\phi)$

Experimental Observables

Raw data on tape, reconstructed events fiducial cross sections, ... Pseudo Observables

Pole masses, decay width, kappas, form factors, ...

Lagrangian parameters

Gauge structure, couplings, running masses, Wilson coefficients, ...

pioneered in the context of Z-pole PO [Bardin, Grunewald, Passarino, '99]

How to parametrize smooth deviations from the SM in the **most general** and **theoretically unbiased** way?



Kappas



Figure 19: Results of fits for the generic model 2 (see text): the results indicated by a full box are obtained for

Pseudo Observables in FW Higgs production 19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)

Jon deal with the fit results indicated by a full circle represent a benchmark model where the total Higgs boson decay width is not modified with respect to the SM. The hatched area indicates regions that are outside the defined parameter boundaries. The inner and outer bars

goal: encode **all experimental information** on a **certain physical process** in a **few parameters** with a **well-defined theoretical interpretation**







also for the production. Jonas M. Lindert

Higgs production via vector boson fusion (VBF) receives contribution both from neut and charged-current channels. Also, depending on the specific partonic process, th could be two different ways to construct the two currents, and these two terms interf ch other SFore rample, for out with one has interforence bouween fig neutral and charge PO for VB current. In this case it is clear that one should sum the two amplitudes with the pro-I) Decompose amplitude into flavour structures allowed by Lorentz symmetry $(q_1, q_2) = 1.42$ fm $Ref^2[q_1]$. Here q_2 is start with the neutron of the start of the star describes CP-violating interactions if the Higg? is assumed to be a CP-even state. The tansar structures to which we call that the bar of the form factor (nuccessing) as the provident of the pr neutral currents: tid (D_{2}) (p.) h(k) teamber parameterized by a compling with the transverse part while f_{2p} and f_{2p} are defined and f_{2p} and $f_$ $\mathcal{A}_{n.c}(q_i(p_1)q_j(p_2) \to q_i(p_3)q_j(p_4)h(k)))$ $h \operatorname{charb}_{c}(\operatorname{dephyse})$ $d_{\mathbf{x}}(p_3)(u_i(p_4)h_i(k)) dan des parametrizactiby with the longitudinal part of the current, as in the second seco$ $\mathcal{T}_{n.c.}^{\mu\nu}(q_1, q_2) = \left| F_L^{q_i q_j}(q_1^2, q_2^2) g^{\mu\nu} + F_T^{q_i q_j}(q_1^2) g^{\mu\nu} + F_T^{q_i q_j}(q_1^2) g^{\mu\nu} + F_T^{q_i q_j}(q_1^2) g^{\mu\nu} + F_T^{q_j q_j}(q_1^2) g^{\mu$ $\begin{array}{c} d_k(p_3)u_l(p_4)h(k) \text{ can be parametrized by} \\ \text{where (also)in=this_L case}, \mathcal{H}_{2,c}^{jkl}(q_1^{\mu\nu}, q_2) \text{ is the same appearing in the Charged q_2^2} \\ \varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma} \\ \text{where (also)in=this_L case}, \mathcal{H}_{2,c}^{jkl}(q_1^{\mu\nu}, q_2) \text{ is the same appearing in the Charged q_2^2} \\ \end{array}$ $\mathcal{T}_{c.c.}^{\mu\nu}(q_1, q_2) = \begin{bmatrix} G_L^{ijkl}(q_1^2, q_2^2)g^{\mu\nu} + G_T^{ijkl}(q_1^2, q_2^2)g^{\mu\nu} +$ charged currents: $\mathcal{A}_{c.c}(u_i(p_1)d_j(p_2) \to d_k(p_3)u_l(p_4)h(k)) =$ Tany six aligitate and a set of the set of t for sees strop and a fermanting a construction of the second state of the second in this comment of the sector -+try measure these form the tactor state as a councies of the state o site changed by between the power that he Jonas M. Handelie and a set of the second of Pseudo Observables in EW Higgs production

ia vector-boson fusion. Extracting the kinematical structure of Eqector boson fusion (VBF) receives contribution both from neut v us both to determine the effective coupling of $h^{nd}o^{challged}$ such that the second determine the specific partonic process, the could be two different ways to construct the two currents, and these two terms interferences investigate possible couplings of to new macrosceles that is the former of the former of the specific partonic process, the second determined double-pole structure in Eq. (7), what the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic process. The former of the specific partonic process is a process of the specific partonic p with one or no poles. We perform a momentum expansion around the provide the provided poles of the case of the c s with one or no poles. $\frac{F_X(q_1^e_2)^* q_2^\mu}{P_W(q_1^2) P_W(q_2^2)_V} = \sum_{\substack{\downarrow}} \frac{(\epsilon_{We_L})^{(\text{const})_{2V}}}{(q_1^2 m_W^2 m_W^2)^2 (q_2^2 q_2^2)} \frac{\epsilon_{W\mu_L}}{m_V^2} \frac{(const)_W}{(q_2^2 m_W^2)^2 (q_2^2 q_2^2)} \frac{\epsilon_{W\mu_L}}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{\epsilon_{W\mu_L}}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{\epsilon_{W\mu_L}}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)^2 (q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_2^2)} \frac{(const)_W}{(q_2^2 q_$ (9) $\frac{2^{\mu}t_{T}}{\mu}$ transverse parture hild F_{C} gipplellappagesspartphier and si $\begin{aligned} & F_L^{e\mu}(q_1^2,q_2^2) = \kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2 g_Z^e g_Z^\mu)} + \frac{\epsilon_{Ze}}{q_g^2 g_Z^2} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2 g_Z^e g_Z^\mu)} + \frac{\epsilon_{Ze}}{q_g^2 g_Z^2} \frac{g_Z^e g_Z^\mu}{P_Z(q_2^2) P_Z(q_2^2 g_Z^e g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2) P_Z(q_2^2) P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2) P_Z(q_2^2) P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2) P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2) P_Z(q_2^2) P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2) P_Z(q_2^2) P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2) P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_2^2 g_Z^\mu)} + \frac{\epsilon_{Ze}}{P_Z(q_$ The mexicity the ones appearing in the ones appearing in the ones appearing in the Type mexicity the ones appearing in the Type mexicity the ones appearing in the Type mexicity of the ones appearing in the Type mexicity of the ones appearing in the the type of the ones appearing in the ones appeared in the ones appe $\delta \epsilon_X = \epsilon_X - \epsilon_X^{\mathrm{SM}}$ for voerststroppia ad a farmanting the formation of the second states of the polase the stoke this of the stoke the second states are the second states ar 3) Define PO from the residues on the poles such that SML corresponds to the total of onlendepoled different in the states of the $\frac{(\text{const})_{2V}}{\frac{m^2}{V}(q_2^2 - m^2)}$ (const ndozical vesteten en leiten en leite Pseudo Observables in EW Higgs production

PO counting

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV		
$ \begin{array}{c} h \rightarrow \gamma \gamma, 2e\gamma, 2\mu \gamma \\ 4e, 4\mu, 2e2\mu \end{array} $	$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$\boldsymbol{\varepsilon}_{Z\mu_L}, \boldsymbol{\varepsilon}_{Z\mu_R}$	$arepsilon_{ZZ}^{CP}, \delta_{Z\gamma}^{CP}, \delta_{\gamma\gamma}^{CP}$		
$h \rightarrow 2e2v, 2\mu 2v, ev\mu v$	$ \begin{array}{c} \kappa_{WW}, \varepsilon_{WW} \\ \varepsilon_{Zv_e}, \operatorname{Re}(\varepsilon_{We_L}) \end{array} $	$\varepsilon_{Z\nu_{\mu}}, \operatorname{Re}(\varepsilon_{W\mu_{L}})$ Im(a)	$\varepsilon_{WW}^{CP}, \operatorname{Im}(\varepsilon_{We_L})$ $\varepsilon_{W\mu_L})$		

Higgs (EW) decay amplitudes

Higgs (EW) production amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
VBF neutral curr. and Zh	$\begin{bmatrix} \kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \varepsilon_{ZZ} \end{bmatrix}$ $\varepsilon_{Zu_L}, \varepsilon_{Zu_R}, \varepsilon_{Zd_L}, \varepsilon_{Zd_R}$	$egin{aligned} oldsymbol{\mathcal{E}}_{Zc_L}, oldsymbol{\mathcal{E}}_{Zc_R} \ oldsymbol{\mathcal{E}}_{Zs_L}, oldsymbol{\mathcal{E}}_{Zs_R} \end{aligned}$	$\left[\left[\varepsilon_{ZZ}^{CP}, \delta_{Z\gamma}^{CP}, \delta_{\gamma\gamma}^{CP} \right] \right]$
VBF charged curr. and <i>Wh</i>	$\begin{bmatrix} \kappa_{WW}, \varepsilon_{WW} \end{bmatrix}$ Re(ε_{Wu_L})	$Re(\mathcal{E}_{Wc_L})$	$[\varepsilon_{WW}^{CP}], \operatorname{Im}(\varepsilon_{Wu_L})$ $m(\varepsilon_{Wc_L})$

[...]: present both in production and decays.

- → Flavor-independent PO probed in $h \rightarrow 4f$
- ➡ in EW production focus on quark contact terms

Matching PO to effective couplings

• at LO there is a direct correspondence between PO and these effective couplings

$$\begin{aligned} \mathcal{L}^{eff} &= \kappa_{ZZ} \frac{m_Z^2}{v} Z_{\mu} Z^{\mu} h + \kappa_{WW} \frac{2m_W^2}{v} W_{\mu}^+ W^{-\mu} h + \\ &- \frac{\epsilon_{\gamma\gamma}}{2} \frac{h}{v} A_{\mu\nu} A^{\mu\nu} - \epsilon_{Z\gamma} \frac{h}{v} Z_{\mu\nu} A^{\mu\nu} - \frac{\epsilon_{ZZ}}{2} \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu} - \epsilon_{WW} \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu} + \\ &- \frac{\tilde{\epsilon}_{\gamma\gamma}}{2} \frac{h}{v} A_{\mu\nu} \tilde{A}^{\mu\nu} - \tilde{\epsilon}_{Z\gamma} \frac{h}{v} Z_{\mu\nu} \tilde{A}^{\mu\nu} - \frac{\tilde{\epsilon}_{ZZ}}{2} \frac{h}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \tilde{\epsilon}_{WW} \frac{h}{v} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} + \\ &+ \sum_{f} \epsilon_{Zf^{ij}} \frac{2h}{v} Z_{\mu} \bar{f}^i \gamma^{\mu} f^j + \\ &+ \epsilon_{We^{ij}} \frac{2h}{v} W_{\mu}^+ \bar{\nu}_{e^i L} \gamma^{\mu} e_L^j + \epsilon_{Wu_L^i} d_L^j \frac{2h}{v} W_{\mu}^+ \bar{u}_L^i \gamma^{\mu} d_L^j + \epsilon_{Wu_R^i} d_R^j \frac{2h}{v} W_{\mu}^+ \bar{u}_R^i \gamma^{\mu} d_R^j + h.c. \end{aligned}$$

• can easily be implemented in any Monte Carlo (via publicly available UFO model) ...tested within Sherpa & MadGraph_aMC@NLO

Matching PO to effective couplings

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$$\begin{aligned} \mathcal{L}^{eff} &= \kappa_{ZZ} \frac{m_Z^2}{v} Z_\mu Z^\mu h + \kappa_{WW} \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} h + \\ &- \frac{\epsilon_{\gamma\gamma}}{2} \frac{h}{v} A_{\mu\nu} A^{\mu\nu} - \epsilon_{Z\gamma} \frac{h}{v} Z_{\mu\nu} A^{\mu\nu} - \frac{\epsilon_{ZZ}}{2} \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu} - \epsilon_{WW} \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu} + \\ &- \frac{\tilde{\epsilon}_{\gamma\gamma}}{2} \frac{h}{v} A_{\mu\nu} \tilde{A}^{\mu\nu} - \tilde{\epsilon}_{Z\gamma} \frac{h}{v} Z_{\mu\nu} \tilde{A}^{\mu\nu} - \frac{\tilde{\epsilon}_{ZZ}}{2} \frac{h}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \tilde{\epsilon}_{WW} \frac{h}{v} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} + \\ &+ \sum_{f} \epsilon_{Zf^{ij}} \frac{2h}{v} Z_\mu \bar{f}^i \gamma^\mu f^j + \\ &+ \epsilon_{We^{ij}} \frac{2h}{v} W_\mu^+ \bar{\nu}_{e^i L} \gamma^\mu e_L^j + \epsilon_{Wu_L^i d_L^j} \frac{2h}{v} W_\mu^+ \bar{u}_L^i \gamma^\mu d_L^j + \epsilon_{Wu_R^i d_R^j} \frac{2h}{v} W_\mu^+ \bar{u}_R^i \gamma^\mu d_R^j + h.c. \end{aligned}$$

can easily be implemented in any Monte Carlo (via publicly available UFO model)
 ...tested within Sherpa & MadGraph_aMC@NLO

Practical problem:

- not even q_1^2, q_2^2 measurable
- construct proxy:



- Higgs production via vector boson fusion (VBF) receives contribution both from neut and charged-current channels. Also, depending on the specific partonic process, th could be two different ways to construct the two currents, and these two terms interf Measureme kample, for us a wuh one has interference beren to preut can und triply intenference for isfact ween neutral and charge current. In this case it is clear that one should sum the two amplitudes with the prosymmetrization, $\mathbf{p}_{I_{1}}^{q_{1}} = \frac{\mathbf{p}_{I_{1}}^{q_{1}}}{\mathbf{p}_{I_{1}}^{q_{1}}} = \frac{\mathbf{p}_{I_{1}}^{q_{1}}}{\mathbf{p}_{I_{1}}^{q_{1}}}} = \frac{\mathbf{p}_{I_{1}}^{q_{1}}}{\mathbf{p}_{I_{1}}$ of these structures cathing war amenizer in a sensitif pop. let us start with the neutr current one. The amplitude for the on-shell process $q_i(p_1)q_j(p_2)$ • $F_X(q_1^2, q_2^2)$, $G_X(q_1^2, q_2^2)$ not directly measured by the distribution of the transverse the (B3) by (pe) h(k) team bargarametrized by a compling with the transverse part while F where the off which the stand of the same tensors the stand of the stand of the same tensors the stand of the h charge de un strate the the tribut of and the state of the second strate of the second stra dT(p3) fur(p4) h (to) can be man intrized in with the transverse part, while 5001 C HE CHART STATES contribution to the amplitude for $u_l(p_4)h(k)$ can be parametrized by also in this L case $\mathcal{T}_{2,2}^{\mu}(q_1, p_2)$ is the same $d_{1} 0 0 0 | 1_{2} 0 0 | d_{k}(p_{3}) u_{l}(p_{4}) h(k))$ 1.6×10[−]de $\mathcal{J}_{i}^{\mu\nu}(p_{2})\mathcal{T}_{c.c.}^{\mu\nu}(q_{1},q_{2})$ amptude for the processes with obtainedufre 500 1.3×10^{-1} explicit lorin expansion can be found in cal polo directory propagation of the interm above bries paronte to Ott 500 a 500 to 00 a 1009 500 th 500 stop this
 - paie a state of the second state of the second state of the second secon an statistics and the statistic statistics and the state of the state in this cionaniant to the sector of the sect anstasianstitud avalatic constitute sample tryRb&t [142]). Sudisai Aftar Pafa ab whe See Di OCOL CEOL EST OLOVIA A COLOR STATISTICS I Sudicavia in that the AB nheigesudecavis ishtilat the she bsig2in his souther at the battine of Odenici of a Alvertine compared include in MBiFHigen site kundaget hu hotevelant boloom flogtad refe

Pseudo Observables in EW Higgs production

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• NLO EW ~10-15% shape effects

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Measurement of PO in VH

Practical problem:

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



$$m_{Vh}^2 \to 4p_{\rm T}^2$$
 for $|p_{\rm T}| \to \infty$

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NLO QCD corrections in PO

• process independent implementation of Higgs PO @ NLO QCD in Sherpa+OpenLoops



• NP shapes largely unaffected by QCD corrections

detailed study in preparation

As anticipated, a key point to be addressed for a consistent extraction of the PO is e validity of the momentum expansion. ${}^{\epsilon}Z^{u}_{I}$ order to control such expansion, we set an per cut on the $p_{\rm T}$ of the leading with finance of the first sality of the first sector of the rm factors in Eq. (6) only makes sense if the higher order terms in $H_{1,2}^2$ are swith ease 1. We fix: nis requirement leads to the consistency conditioned study: Control the momentum expansion validate.

Consistency condition:
$$\epsilon_{X_f} |q_{\max}^2| \leq m_Z^2 g_X^f$$
,
 $\mu_{WW} = \mu_1$ (20)

here q_{max}^2 is the fargest momentum transfer in the process. A priori we do not know the e of ϵ_{X_f} With approximately approximates uncontain the steriori we n verify by means of Eq. 130 events in all gradies of the there on the solution expansion to a first non-trivial terms. In practice, setting we wat still statistics implied by define a value $\sqrt{-q_{\text{max}}^2}$. Extracting the ϵ_{X_f} for $p_{\text{T},j} < (p_{\text{T},j})^{\text{max}} \approx \sqrt{-q_{\text{max}}^2}$ we can check if Eq. (20) satisfied, WBallyOtfie of the and a states of the states of the states of the struction of the for different values of $(p_{\rm T})^{\rm max}$ optimizing the range according to the results obtained the following exercise we set $(p_{\rm T},j)^{\rm max} = 600$ GeV which, a posteriori, will turn out to a good choice in absence of any sizeable deviations from the SM.³⁰ signal events (SM) In our man all in the laple of heel in the line of the here of the found of the formation of the second of the laple of the line of the formation of the format o VBF taggentiet prosent for accoracy 300 - 400 - 600} GeV. We use the UFO plementat Same Che Che Che Che Canster total rate is retained. events over the relevant PO parameter space in proton-proton collisions at 22 TeV cm energy Here we employ the VRE uppler tiop manter of higher shirin Edicas 7 With here here we all

Match PO to toy model: Z'



and beyond): High Precision Higgs erays perform quadratic fit of PO

HPO vs. SMEFT

- HPO and SMEFT interpretation go hand in hand
- add a given perturbative order HPO can be matched to coefficients of dim-6 of SMEFT



HPO vs. SMEFT

- HPO and SMEFT interpretation go hand in hand
- add a given perturbative order HPO can be matched to coefficients of dim-6 of SMEFT



- Basis and EFT independent
- directly related to physical properties of process at hand
- allows to classify ALL information that can be experimentally obtained from a given process
- defined at all-orders in perturbation theory

- allows to relate *different process classes* with same operators (e.g. ttbar and VBF)
- combined predictions/limits across different classes of processes
- allows for studies of UV completion

Conclusions

- Higgs Pseudo Observables (HPO) offer a framework for model independent parametrisation of NP effects in Higgs decays and Higgs EW production
- based on physical properties of the Green functions
- can easily be matched to specific models
- trivial factorization of soft QCD and QED radiation
- LL+NLL EW effects via redefinition of PO
- can be extended to VBF-V
- FeynRules model for Higgs PO @ LO+PS is publicly available at: http://www.physik.uzh.ch/data/HiggsPO/
 ...can easily be used within Sherpa or MadGraph_aMC@NLO
 ...NLO QCD+PS will follow soon!

Backup slides