Vector Boson Fusion – approaching the (yet) unknown

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Southern Methodist University – February 2008
Higgs searches at the LHC

Higgs production via vector boson fusion (VBF):
- VBF beyond tree level
- the gluon fusion background
- interference effects

weak boson scattering in VBF
- theoretical concepts & techniques
- phenomenological results

summary & conclusions
Standard Model (SM): couplings and parameters strongly constrained

only free parameter: $M_H$
(not yet measured)

still: theory & experiment impose variety of bounds on Higgs mass

theory: perturbative, well-behaved SM up to high energy

$\mathcal{130} \lesssim M_H \lesssim 180$ GeV

experiment: direct and indirect searches (assuming SM to be correct)

$\mathcal{114} \lesssim M_H \lesssim 182$ GeV
the next steps

- detect Higgs boson and determine $M_H$
- investigate properties of the "Higgs boson" carefully

  determination of couplings, charge, spin, CP quantum numbers necessary to reveal SM, SUSY, or something completely different?

  full, quantitative understanding of most promising search channels required from experiment and theory
Barbara Jäger, February 2008

Higgs production @ hadron colliders

M. Spira (2007)

$\sigma(pp\rightarrow H+X)\ [pb]$
$\sqrt{s} = 14 \text{ TeV}$
$M_t = 174 \text{ GeV}$
CTEQ6M

- gluon fusion (GF)
- $t\bar{t}$ fusion
- $W, Z$ bremsstrahlung
- vector boson fusion (VBF)
uncertainties at the LHC

expected statistical & systematic errors on $\sigma \cdot B$:

**Rainwater et al. (2002)**

$x$ QCD/PDF uncertainties:
- VBF: $\lesssim 5\%$ at NLO
- GF: $\lesssim 10\%$ scale uncertainty (NNLO + resummation effects)
  $\sim 4\%$–$7\%$ PDF uncertainty

$x$ luminosity/acceptance uncertainties: $\sim 5\%$

$$\Delta \sigma_{H}/\sigma_{H} (\%)$$

$$M_{H} \text{ [GeV]}$$

$$\mathcal{L} = 200 \text{ fb}^{-1}$$
take a closer look at vector boson fusion
Higgs production in VBF

scattered quarks
→ two forward tagging jets
(energetic; $p_T > 20$ GeV)

Higgs decay products
typically between tagging jets

little jet activity in central rapidity region
(colorless $V$ exchange → gluon radiation suppressed)
NLO QCD corrections
moderate and
teoretically well under control
(order 10% or less)

inclusive cross section:
Han, Valencia, Willenbrock (1992)
distributions:
Figy, Oleari, Zeppenfeld (2003)
Berger, Campbell (2004)
Ciccolini, Denner, Dittmaier (2007):
NLO EW corrections to inclusive cross sections and distributions

NLO EW corrections non-negligible, modify $K$ factors and distort distributions by up to 10%
higher orders of QCD in VBF


gauge invariant, finite sub-class of virtual
two-loop QCD corrections to $pp \rightarrow Hjj$ via VBF

important due to large gluon luminosity at LHC?

$$gg \rightarrow q\bar{q}H, \ q\bar{q} \rightarrow ggH,$$
$$qg \rightarrow qgH, \ \bar{q}g \rightarrow \bar{q}gH$$

minimal set of cuts: $\sigma_{\text{gluon}}^{2-\text{loop}} \sim 2 \%$ of $\sigma_{\text{VBF}}^{\text{LO}}$

VBF cuts: relative suppression by additional order of magnitude
VBF can be faked by double real corrections to $gg \rightarrow H$ ("gluon fusion")

complete LO calculation (including pentagons):
Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

NLO QCD calculation in $m_t \rightarrow \infty$ limit:
Campbell, Ellis, Zanderighi (2006)

need to understand phenomenology of both processes to distinguish between them
apply **cuts** to enhance either VBF or gluon fusion (GF) (crucial for measurement of $HVV$, $Htt$, $Hgg$ couplings)

*Klämke, Zeppenfeld (2007)*
can VBF × GF interference pollute the clean VBF signature?

tree-level interference possible only for

- neutral current graphs (no charged current interference)
- identical quark contributions with $t \leftrightarrow u$ crossing
  (kinematically suppressed)

☞ completely negligible
additional gluon → VBF×GF interference for $qq' \rightarrow qq'H$

Andersen, Smillie (2006):

“...the size of the one-loop interference should be comparable to the size of the one-loop NLO corrections to the WBF and the GF processes...”
$pp \rightarrow Hjj$ via VBF x GF beyond tree level

**Andersen et al. (2007) & Bredenstein, Hagiwara, B. J. (2008):**
explicit loop calculation reveals **strong cancelation effects**

<table>
<thead>
<tr>
<th>initial state</th>
<th>interaction</th>
<th>isospin</th>
<th>$\sigma_{\text{cuts}}^{\text{int}}$ [ab]</th>
<th>$\sigma_{\text{WBF}}^{\text{cuts}}$ [fb]</th>
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<tbody>
<tr>
<td>$qq$</td>
<td>NC</td>
<td>+ + or - -</td>
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<td>72.3</td>
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<td>+ - or - +</td>
<td>-49.8</td>
<td>70.8</td>
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<tr>
<td></td>
<td>CC</td>
<td>+ - or - +</td>
<td>-</td>
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<tr>
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<td>+ - or - +</td>
<td>-3.1</td>
<td>39.3</td>
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<tr>
<td>sum</td>
<td>NC+CC</td>
<td>all</td>
<td>1.5</td>
<td>896.9</td>
</tr>
</tbody>
</table>
cancelations lead to unexpected shapes of distributions but: $\sigma_{\text{int}}$ tiny $\rightarrow$ no effect on VBF signal
open issues:

✘ is the pattern found in VBF \times GF characteristic for loop-induced QCD \times EW interference contributions?

✘ worthwhile considering other (even simpler) processes . . .
Higgs signal in VBF

- $pp \to Hjj$ via VBF under excellent control
- QCD & EW NLO corrections at 10% level
- dominant NNLO QCD corrections small
- interference with GF $Hjj$ production negligible

but: establishing a signal for the Higgs boson in VBF requires also calculation of large background contributions

precise predictions needed to match statistical accuracy of LHC
EW $VVjj$ production

$pp \rightarrow VV + jj$ via VBF

similar characteristics to Higgs signal process

background rejection difficult
VBF induced $qq \rightarrow VVqq$

contains weak boson scattering

$V_L V_L \rightarrow V_L V_L$

very sensitive to mechanism of electroweak symmetry breaking:

light Higgs boson? $M_H$?
strong EWSB?
$W^+_L W^-_L \rightarrow W^+_L W^-_L$ with $\epsilon^\mu_L \sim \frac{\sqrt{s}}{M_W}$

$\mathcal{M} = \begin{array}{c}
\text{growth violates unitarity} \rightarrow \text{need:} \\
\end{array}$

Higgs with $M_H \lesssim 1$ TeV or new physics at TeV scale
1984  $qq \to qqVV$ within the “Effective W Approximation”
1986  full $qq \to qqVV$ without $V$ decay
1990  $qq \to qqVV$ with $V$ decay in narrow width approximation
1993  application to strongly interacting gauge boson systems
        SSC canceled → focus redirected towards LHC
2005  PHASE – LO event generator for six-fermion processes
2006  vbfnlo – NLO QCD event generator for VBF processes,
        including $qqVV$ with full lepton correlations
need stable, fast & flexible Monte Carlo program allowing for
  • computation of various jet observables at NLO-QCD accuracy
  • straightforward implementation of cuts


major challenges:
  • multi-parton process: \(2 \rightarrow 4\) for \(qq \rightarrow qq \, VV\);
    \(2 \rightarrow 6\) for \(qq \rightarrow qq \, \ell^+\ell^-\nu_\ell\bar{\nu}_\ell\)
    or \(qq \rightarrow qq \, \ell^+\ell^-\ell^+\ell^-\)
  • full consideration of finite width effects
  • numerically stable treatment of pentagon contributions
Outline of the calculation

\[ d\hat{\sigma}_{ab\rightarrow 4\ell+jjX} \sim \sum |\mathcal{M}|^2_{ab\rightarrow 4\ell+cd(e)} \mathcal{F}_{\text{jet}} \ dP S_f \]

- Calculation of \(|\mathcal{M}|^2\) at \(\mathcal{O}(\alpha^6)\) (LO) and \(\mathcal{O}(\alpha^6\alpha_s)\) (NLO QCD)
  - Dimensional reduction \((d = 4 - 2\varepsilon)\)
  - \(\overline{\text{MS}}\)-renormalization

- Handling of infrared singularities by Catani & Seymour’s dipole subtraction approach
  (need real emission & virtual contributions and counterterms)

- Phase space integration and convolution with PDFs with Monte Carlo techniques in 4 dimensions
need to compute numerical value for

\[ |\mathcal{M}_B|^2 = \left| \sum \text{diagrams} \right|^2 \]

at each generated phase space point in 4 dim (finite)

\[ \ldots \text{depending on leptonic final state: up to 580 diagrams} \]

essential: organize calculation economically

\[ \downarrow \]

- employ amplitude techniques to evaluate \( \mathcal{M} \) first (numerically) for specific helicities of external particles, then square
- avoid multiple evaluation of recurring building blocks
develop modular structure with leptonic tensors . . .

\[ J_{\text{up}}^\mu \quad T_{\mu\nu} \quad J_{\text{low}}^\nu \]

= \quad + \quad + \quad \cdots

. . . and evaluate each building block only once per phase space point (related sub-diagrams, various flavor combinations, crossed processes . . .)

such recycling is used to a very small extent by automatized programs like MadGraph/MadEvent
nice extra: implementation of new interactions in bosonic sector rather straightforward, e.g.


C. Englert, diploma thesis: “Spin-1 resonances in vector boson fusion in warped Higgsless models”, Karlsruhe 2007
employ MadGraph for computing first reference result
but: repeated calculation of similar diagrams makes code extremely slow
(1 ÷ 2 months CPU time on a 3 GHz Linux PC for $\Delta \sigma / \sigma \approx 0.2\%$
for $WW$ and even more in $ZZ$-case)

high statistics needed especially for kinematic distributions

pre-calculate leptonic tensors

$\Rightarrow$ gain speed-up of factor 70 for real emission code

valuable check: comparison to result obtained with MadGraph
the next-to-leading order:

- real emission
- subtraction terms
- virtual corrections
needed: numerical value for up to 2892 diagrams ($ZZjj$ case)

$$|M_R|^2 = \begin{vmatrix} \text{Diagram 1} & \text{Diagram 2} & \ldots \end{vmatrix}^2$$

at each generated phase space point in 4 dimensions

→ apply same techniques as at LO

😊 the major challenge: large number of diagrams (without optimization code extremely slow!)

😊 the solution: apply speed-up tricks developed at LO (here even more effective)

still: MadGraph extensively used for debugging and cross checks
real emission contributions

\[ |\mathcal{M}_R|^2 = \begin{vmatrix} \text{diagram 1} & + & \text{diagram 2} & + \cdots \end{vmatrix}^2 \]

complication: real emission contribution diverges as unobserved parton becomes soft or collinear

- analytic calculation: divergencies canceled directly by respective singularities in virtual contributions
- numerical approach: apply subtraction formalism (phase space slicing, dipole subtraction, \ldots)
- divergencies are absorbed by auxiliary counterterms
needed: \[ \sigma^{NLO} \equiv \int d\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_{m} d\sigma^V \]

\text{IR divergent} \quad \Leftrightarrow \quad \text{regularize in } d = 4 - 2\varepsilon \text{ dim}

introduce \textbf{local counterterm} \[ d\sigma^A \] with same singularity structure as \[ d\sigma^R \]:

\[ \sigma^{NLO} = \int_{m+1} \left[ d\sigma^R - d\sigma^A \right] + \int_{m+1} d\sigma^A + \int_{m} d\sigma^V \]

\text{finite}
\[ \sigma^{NLO} = \int_{m+1} \left[ d\sigma^R - d\sigma^A \right] \bigg|_{\varepsilon=0} + \int_{m} d\sigma^V + \int_{m+1} d\sigma^A \]

integrate over one-parton PS analytically explicitly cancel poles & then set \( \varepsilon \to 0 \)

\[ \sigma^{NLO} = \int_{m+1} \left[ d\sigma^R_{\varepsilon=0} - d\sigma^A_{\varepsilon=0} \right] + \int_{m} d\sigma^V + \int_{1} d\sigma^A \bigg|_{\varepsilon=0} \]
qq' \rightarrow qq'(g)H: upper & lower quark lines “decoupled”

simple singularity structure with counterterms

\[
\frac{8\pi\alpha_s(\mu_r)}{Q^2}C_F \frac{x^2 + z^2}{(1-x)(1-z)} |\mathcal{M}_B(\tilde{p})|^2
\]

and \(\{\tilde{p}_i\} \rightarrow \{p_i\}\) in divergent regions

...continuous interpolation between soft and collinear gluon radiation \((x \text{ and } z \rightarrow 1)\)

analytical integration over soft/collinear phase space gives

\[
|\mathcal{M}_B(p)|^2 F(Q) \left[ \frac{2}{\varepsilon^2} + \frac{3}{\varepsilon} + \text{const.} \right]
\]
virtual contributions

\[ \mathcal{M}_V = \mathcal{M}_B F(Q) \left[ \frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right] + \tilde{\mathcal{M}}_V^{\text{finite}} \]

\( \tilde{\mathcal{M}}_V^{\text{finite}} \) computed with Passarino-Veltman / Denner-Dittmaier reduction
cumbersome: (numerically small) pentagon contributions

combination of real emission, virtuals, and subtraction terms:
poles canceled analytically → finite results
checks

✔ comparison of LO and real emission amplitudes with MadGraph

✔ soft / collinear limits: \( d\sigma^R \rightarrow d\sigma^A \)

✔ QCD gauge invariance of real emission contributions:

\[
\mathcal{M} = \varepsilon^*_\mu(p_g) \mathcal{M}^\mu = \left[ \varepsilon^*_\mu(p_g) + C p_{g,\mu} \right] \mathcal{M}^\mu
\]

✔ EW gauge invariance of virtual contributions

✔ produce independent code for NC amplitudes

✔ comparison of LO result to MadEvent (generic cuts)
methods developed are applicable to processes with different leptonic final states:

× \( pp \rightarrow jj e^+ \nu_e \mu^- \bar{\nu}_\mu \)

(“EW \( W^+ W^- jj \) production”)

× \( pp \rightarrow jj e^+ e^- \mu^+ \mu^- \) and \( pp \rightarrow jj e^+ e^- \nu_\mu \bar{\nu}_\mu \)

(“EW \( ZZ jj \) production”)

× \( pp \rightarrow jj e^+ \nu_e \mu^+ \mu^- \) and \( pp \rightarrow jj e^- \bar{\nu}_e \mu^+ \mu^- \)

(“EW \( W^+ Z jj \) and \( W^- Z jj \) production”)

\( pp \rightarrow VV jj @ LHC \)
developed Monte Carlo program for cross sections and distributions which allow for the implementation of realistic experimental selection cuts

embedded in more general framework for various VBF-type processes

\texttt{vbfnlo}

available from

http://www-itp.physik.uni-karlsruhe.de/\~vbfnloweb/

user options:

- various scale choices and PDF sets
- arbitrary selection cuts
- arbitrary differential distributions at LO and NLO
- anomalous gauge boson couplings for several channels
- differential $K$ factors for all distributions
- weighted / unweighted events and LHA format files

implemented processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \ Hjj$,</td>
<td>$H \rightarrow \gamma\gamma$</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow \mu^+\mu^-$</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow \tau^+\tau^-$</td>
</tr>
<tr>
<td></td>
<td>$H \rightarrow b\bar{b}$</td>
</tr>
<tr>
<td>$pp \rightarrow W^+W^-jj \rightarrow \ell^+\nu\ell'^{-}\bar{\nu}'jj$</td>
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</tr>
<tr>
<td>$pp \rightarrow ZZjj \rightarrow \ell^+\ell^-\ell'^+\ell'^{-}jj$</td>
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<tr>
<td>$pp \rightarrow ZZjj \rightarrow \ell^+\ell^-\nu\bar{\nu}jj$</td>
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<tr>
<td>$pp \rightarrow Wjj \rightarrow \ell^+\nu jj$</td>
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<tr>
<td>$pp \rightarrow Zjj \rightarrow \ell^+\ell^- jj$</td>
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</tr>
<tr>
<td>$pp \rightarrow Zjj \rightarrow \nu\bar{\nu}jj$</td>
<td></td>
</tr>
</tbody>
</table>
with $k_T$ algorithm, CTEQ6 parton distributions, and typical VBF cuts:

| tagging jets | $p_T^j \geq 20$ GeV, $|y_j| \leq 4.5$, $\Delta y_{jj} = |y_{j1} - y_{j2}| > 4$, $(M_{jj} > 600$ GeV) |
|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|              | jets located in opposite hemispheres                                                                                                                                                             |
| charged leptons | $p_{T\ell} \geq 20$ GeV, $|\eta_{\ell}| \leq 2.5$, $\Delta R_{j\ell} \geq 0.4$, $y_{j,min} < \eta_{\ell} < y_{j,max}$                                                                                     |
|              | $M_H = 120$ GeV, $M_{WW,ZZ} > 130$ GeV                                                                                                                                                             |
|              | (for $WW$ and $ZZ$ case: $VV$ continuum only)                                                                                                                                                     |
for judging the reliability of our prediction: estimate theoretical uncertainties associated with it

✗ PDF uncertainties:

Figy, Oleari, Zeppenfeld (2003):
- applied 40 error eigenvector sets of CTEQ6M
- estimated $3.5\%$ uncertainty for VBF type reactions

✗ dependence on unphysical renormalization and factorization scales

$$\mu \frac{d}{d\mu} \sum_{n=0}^{N} \alpha_s^n \sigma^{(n)} = -\mu \frac{d}{d\mu} \sum_{n=N+1}^{\infty} \alpha_s^n \sigma^{(n)}$$

→ scale dependence $\sim$ measure for reliability of perturbative calculation
scale uncertainty: \( pp \rightarrow W^+ Zjj \)

Choose \( \mu_R = \xi \mu_0 \) and \( \mu_F = \xi \mu_0 \) with variable \( \xi \) and set \( \mu_0 = m_V \) or \( \mu_0 = Q \).

LO: no control on scale

NLO QCD: scale dependence strongly reduced
crossed process: $pp \rightarrow WWZ$

*Hankele, Zeppenfeld (2007)*

LO: very mild scale dependence
- LO is $\mathcal{O}(\alpha_s^0)$,
- PDFs probed in regions with small $\mu_f$ dependence

but large QCD corrections with

\[
\frac{\sigma^{NLO}}{\sigma^{LO}} \sim 1.7 \div 2.2
\]
parton-level Monte Carlo program:
can calculate cross sections and kinematic distributions

\[ K(x) = \frac{d\sigma_{NLO}/dx}{d\sigma_{LO}/dx} \]

estimate for importance of NLO contributions:
dynamical $K$-factor

often more interesting than integrated cross sections
simplify separation of signal from backgrounds
$W^+W^- jj$ distributions: $p_T$ of tagging jet

$\mu = M_W$

solid: NLO
dashes: LO

$$K = \frac{d\sigma^{NLO}}{dx} / \frac{d\sigma^{LO}}{dx}$$
\( W^+ W^- jj \) distribution: \( p_T \) of tagging jets

- note: significant change in shape at NLO
- extra gluon in real emission contributions
- quarks which produce tag-jets carry lower transverse momenta

\[
K = \frac{d\sigma^{NLO}/dx}{d\sigma^{LO}/dx}
\]
angular distribution of charged leptons

in $H \rightarrow W^+ W^-$: 
spins anti-correlated

leptons emitted preferentially in same direction

no such correlation, if $W$ bosons 
do not stem from the Higgs

Dittmar, Dreiner (1996)

distribution for EW $W^+ W^-$ production significantly
different from Higgs signal

Rainwater, Zeppenfeld (1999)
in $H \rightarrow W^+ W^-$: spins anti-correlated

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*Dittmar, Dreiner (1996)*

distribution for EW $W^+ W^-$ production significantly different from Higgs signal

![Graph showing angular distribution of charged leptons](image-url)
$pp \to ZZ jj$

- clean final state for $pp \to \ell^+\ell^-\ell'^+\ell'^- jj$
  (all leptons can be detected)

- small branching ratios $Z \to$ leptons:
  \[
  BR(W \to \ell \nu) \sim 10.8\% \\
  BR(Z \to \ell^+\ell^-) \sim 3.3\% \\
  BR(Z \to \nu \bar{\nu}) \sim 6.6\%
  \]

  $\Rightarrow$ cross sections small: $\sigma_{ZZ} \ll \sigma_{WW}$

  work-around: consider $pp \to \ell^+\ell^-\nu\bar{\nu} jj$

  [more difficult to reconstruct from experiment, but larger BR and x-sec]
$M_{VV}$ distribution: $pp \rightarrow \ell^+ \ell^- \ell'^+ \ell'^- jj$

reminder:

\[ M_{ZZ} = \sqrt{(p_{\ell^+} + p_{\ell^-} + p_{\ell'^+} + p_{\ell'^-})^2} \]

- observable very sensitive to light Higgs boson:
  pronounced resonance behavior for $m_H \lesssim 800$ GeV

- for $m_H \sim 1$ TeV: peak diluted ($\Gamma_H \sim 500$ GeV)
  $\rightarrow$ signal distributed over wide range in $M_{ZZ}$
$M_{VV}$ distribution: $pp \rightarrow \ell^+\ell^-\ell'^+\ell'^- jj$

$M_H = 120$ GeV
$M_{ZZ} > 130$ GeV

solid: NLO
dashes: LO

$M_H = 500$ GeV

solid: NLO
dashes: LO

background + signal
... back to $V_L V_L \rightarrow V_L V_L$ ...

can we distinguish signatures of SM type Higgs boson from strong EWSB?


need detailed, up-to-date phenomenological analysis of signal and backgrounds

work in progress

M. Worek, D. Zeppenfeld, B. J.
VBF crucial for understanding mechanism of electroweak symmetry breaking

need to know signal and backgrounds precisely

developed fully flexible parton-level Monte Carlo program with NLO QCD cross sections and distributions for

\[ pp \rightarrow W^+W^- jj \quad \text{and} \quad pp \rightarrow ZZ jj \]
\[ pp \rightarrow W^+Z jj \quad \text{and} \quad pp \rightarrow W^-Z jj \]
(including leptonic decays)

[\text{\textsc{vbfnlo now available from the web}}]
VBF reactions under excellent control perturbatively (moderate $K$-factors and mild scale dependences at NLO)

- shape of some distributions changes noticeably at NLO (e.g. $p_T$ distributions)

...and this implies...
for understanding and interpreting physics at the LHC (and beyond . . . ) it is vital to prepare:

✗ precise predictions for signals and backgrounds, including
  · NLO QCD corrections
  · NLO EW corrections
  · and more: interference effects, resummations, well-constrained PDFs, . . .

✗ cross sections and distributions within realistic acceptance cuts

☞ need to develop flexible precision tools which can be used by experimentalists and intensify communication between theory and experiment
let’s start right away and ... 

... get prepared for the journey towards the unknown