MiNLO

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Outline

- MiNLO
	- **▶ Case for next-to-leading order calculations**
	- **▶ Renormalization and factorization scales**
	- **▶ Motivations for MiNLO**
	- MiNLO example
	- Applications
	- MiNLO*′*

Case for next-to-leading order calculations

- Help looking for / setting limits on SUSY tending the energy frontier into uncharted territory, in
- LO Z / γ * + 4 jets + X \circ Take \widetilde{gg} productⁿ \rightarrow 4 jets + MET and so product plys inter $\widetilde{\sigma}\widetilde{\sigma}$
- \blacksquare Main bkg $Z+4$ jets $[4$ jet = $4 \alpha s's$] especially the containing data containing dat σ ividili brg $2+4$ jets t 4 jet = 4 α s s j

 \overline{a} o We prefer to know this bkg at NLO ρ distribution is the solid (black) histogram and the LO predictions are shown as dashed (blue) lines. The thin process in the search for supersymmetry, and the search for supersymmetry, and the search of the

Case for next-to-leading order calculations

- Precision Higgs physics \circ
- $\overline{}$ $pp \rightarrow t\bar{t}H$ probes top Yukawa at tree level \circ
- $\overline{}$ $\overline{}$ Has significant irreducible background from $pp \rightarrow t\bar{t}bb$ \circ

\circ We prefer to know this bkg at NLO Γ invariant-mass distribution of the bb pair: absolute LO and NLO predictions (left) and NLO predictions (left

reduced to a common set of so-called standard matrix elements. In the set of so-called standard matrix elements. In the set of so-called standard standard standard matrix elements. In the so-called standard standard matrix the sums over physical helicities are strongly boosted. The strongly boosted integrals are related. The relationship integrals are related. The relationship integrals are related. The relationship integrals are related. Th t bevilacqua, Czakon, Fapadopodios, Fittau, Worek PRL 103 (2009)] [Bevilacqua, Czakon, Papadopoulos, Pittau, Worek JHEP 0909 (2009)] [Bredenstein, Denner, Dittmaier, Pozzorini PRL 103 (2009)]

Case for next-to-leading order calculations

Recent years have seen amazing progress in NLO calculatⁿs: \circ

- Increasing complexity brings increasing powers of $\alpha s(\mu)$ \circ
- More emphasis on choosing μ 's carefully \circ

ʻGood scales' commonly considered to be so retrospectively on \circ seeing higher order corrⁿs and residual scale sensitivity are small

ʻBad scales' commonly declared on finding large higher order corrns & \circ res. scale sensitivity : typically diagnosed as large unphysical scale logs

Q1: are large higher order corrⁿs all down to large μ R /F logs? targe nigher order corres all

 $\mathbf{5.2.1\textcolor{black}{\bullet}}$ Big higher order corrⁿs can have real physical origins: new prodⁿ \circ We begin by considering the MINLO in fig. 2 we show the MINLO is well as well channels, big colour factors, large gluon flux, I.R. logs ...

Adjusting scale to make corrⁿs / sensitivity small can effectively 'eat' unrelated physics in scale choice \blacksquare raceale to make corree (consitivity small can offectively 'eat' was defined to make your organisation, the Hollow can encountry one al
I $\overline{}$ can effectively $\overline{\mathfrak{c}}$ punges cools
g scale to make corrⁿs / sensitivity s
d physics in scale choice \vdots ite
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In single/few scale processes it's harder to make a bad scale choice \circ

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In single/few scale processes it's harder to make a bad scale choice \circ

In procs with more jets, i.e. more scales, it's hard to know what to do \circ

- BSM background: $W+3$ jets [3 jets = 3 $\alpha s's$] \circ
- BlackHat paper points out physical distⁿs can go -ve for $\mu_R = \mu_F = E_{T,W}$ \circ

For sufficiently poor choices [of scales] large logs can appear in some distributions, \circ U samerently poor enorees for searcs, large logs can appear in some alsents invalidating even an NLO prediction — BlackHat collaboration BlackHat collaboration $\frac{1}{2}$ in prediction $\frac{1}{2}$

- α_S^n $\log^n \frac{\mu_P^2}{\Omega^2}$ Residual scale dependence of NLO calcⁿs goes as $\sim \alpha_S^n \log^n \frac{\mu_R^2}{Q^2}$ [n≥2] al scale dependence of NLO calcⁿs goes as $\sim \ \alpha_{\rm S}^n \ \log^n \frac{\mu_R}{\widehat{\Omega}^2} \qquad \,$ [n>2 *R* \circ *Q*²
- But often have situations were NNLO etc corrⁿs go as $\sim \alpha_S^n \log^{2n} \frac{Q^2}{n^2}$ [n≥2] $\sim \alpha_S^n \log^2$ *p*2 *T* Ω^2

T

isonable to worry about single log terms bevond NLO & not also ggH generator (H PWG), the HJ-MINLO result (HJ MINLO), the HJ default *µ*^F = *µ*^R = *p^H* RUN), and H_J with an and H_J with *zucakov* double logs? sc n_O beyond)peyonc
I onable to worry about single log ter
bout IR Sudakov double logs? .
a a Is it reasonable to worry about single log terms beyond NLO & not also $\prod_{i=1}^n$ worry about IR Sudakov double logs? \circ

MiNLO: Multi-scale improved Next-to-leading Order

Nason, Zanderighi, KH

- In a nutshell: \circ
	- Determine the parton shower branching history associated with the \circ kinematic configns in the NLO events in the x-secn integrals.
	- Take **all-orders rad corrⁿs** that the shower would associate to such \circ configns, as in CKKW*, and **match** them with the exact NLO corrns
- Addressing questions / objections of last few slides: \circ
	- A1: small/moderate NLO corrns/scale sensitivity isn't a consideration
	- A2: PS have natural uniquely defined scale setting for multi-scale probs \circ
	- A3: PS resum large IR double logs as well as single scale logs
- Catani, Krauss, Kuhn, Webber \circ

Ask how a parton shower would have generated this event:

μμμ

μ

:

H

:

:
:

- Emissions strongly ordered in hardness factorise from one another
- In PS each branching is like its own simple process with own scale
- Evaluating each $\alpha s(\mu)$ associated to a branching vertex at branching's own pt sums large class of higher order corrⁿs

extra coupling constant ratios:

 α s(q2) α s(μ)

extra coupling constant ratios:

 α s(q2) α s(q1) α s(μ) α s(μ)

resolvable radⁿ [q>q2] : Sudakov form factors

associated with ratios of self-energies [ratios of self-energies in this cartoon]

factors are also needed to account for any external legs

produced above q2 evolving down to q2

Parton shower also effectively sets the factorisation scale for such a configuration to the scale beneath which all activity is integrated out, q2 …

$$
\frac{10}{d\sigma_{H_{33}}} = \frac{dx_1 dx_2 d\Phi_{H_{33}} f_{h_1}(x_1,\mu_F) f_{h_2}(x_2,\mu_F) \frac{1}{2\hat{s}} M(\Phi_{H_{33}},\mu_A)}{L_0 \text{ terms}} = O(\alpha_s^4)
$$
\n
$$
\frac{P.S.}{d\sigma_{H_{33}}} = \frac{10}{d}x_1 dx_2 d\Phi_{H_{33}} f_{h_1}(x_1,\mu_F) f_{h_2}(x_2,\mu_F) \frac{1}{2\hat{s}} M^{\text{PS}}(\Phi_{H_{33}})
$$
\n
$$
\times \frac{\alpha_s(q_2)}{\alpha_s(\mu)} \cdot \frac{\alpha_s(q_1)}{\alpha_s(\mu)} \cdot \frac{\alpha_s^2(q_m)}{\alpha_s^2(\mu)}
$$
\n
$$
\times \frac{\Delta_g(q_m; q_2)}{\Delta_g(q_2; q_2)} \cdot \dots \cdot \frac{\Delta_g(q_1; q_2)}{\Delta_g(q_2; q_2)} \cdot \frac{\Delta_g(q_1; q_2)}{\Delta_g(q
$$

$$
\frac{d\sigma_{H_{33}}^{LO}}{d\sigma_{H_{33}}^{LO}} = \frac{d\chi_4 d\chi_2 d\Phi_{H_{33}} f_{\mu_4}(x_1,\mu_F) f_{\mu_1}(x_2,\mu_F) \frac{1}{2\hat{s}} M(\Phi_{H_{33}},\mu_A)}{LO terms = O(\alpha_s^4)}
$$
\n
$$
\frac{d\sigma_{H_{33}}^{P.S.}}{d\chi_4 d\chi_2 d\Phi_{H_{33}} f_{\mu_4}(x_1,\mu_F) f_{\mu_1}(x_2,\mu_F) \frac{1}{2\hat{s}} M^S(\Phi_{H_{33}})}
$$
\n
$$
\times \frac{\alpha_s(q_2)}{\alpha_s(q_1)} \cdot \frac{\alpha_s(q_1)}{\alpha_s(q_1)} \cdot \frac{\alpha_s^2(q_m)}{\alpha_s^2(q_2)}
$$
\n
$$
\times \frac{\Delta_g(q_m; q_2)}{\Delta_g(q_2; q_2)} \cdot \frac{\Delta_g(q_1; q_2)}{\Delta_g(q_2; q_2)} = \frac{\frac{P.S.}{d\chi_{J3}}}{\left[\frac{P.S.}{d\chi_{J3}}\right]_{LO}}
$$
\n
$$
\times \frac{f(x_1, q_2)}{f(x_1, \mu_F)} \cdot \frac{f(x_2, q_2)}{f(x_2, \mu_F)}
$$

 -0 $\sqrt{2}$ $\sigma_{H_{3,1}} = dx_1 dx_2 d\Phi_{H_{3,1}} f_{h_1}(x_1,\mu_F) f_{h_2}(x_2,\mu_F) - \frac{1}{2\hat{s}} M(\Phi_{H_{3,1}}\mu_R)$) P.S. . \overline{A} l σ_{H} $0
\n153
\n α
\n $\alpha$$ l σ_{H_3} × \cdot . 5 . $d\sigma_{H_{\rm JJ}}$ $\overline{}$ C = $d\sigma$ 15. . $x \Delta_g(q_m; q_2) \ldots \Delta_g(q_1; q_2)$ $\Delta_{g}(q_2; q_2)$ $\Delta_{g}(q_2; q_2)$ α s(q2) α s(q1) α s(q_m) α s(μ) α s(μ) α s(μ) 2 $\cdot \frac{\alpha s(q_1)}{\alpha s(q_1)} \cdot \frac{\alpha s_1}{2}$ $f(x_1,q_2)$ $f(x_2,q_2)$ $f(x_1, q_2)$. $f(x_2, q_2)$
 $f(x_1, \mu_F)$ $f(x_2, \mu_F)$

Example: H+2 jets MiNLO at next-to-leading order

• To extend from LO 'MiLO' example to NLO apply the same all orders shower corrⁿs to the conventional NLO HJJ computation

And subtract a term to render the expansion in α s unchanged to NLO \circ

- Application: H+T jet MiNLO at next-to-leadin \sim considering the MINLO improved HJ calculation. In fig. 2 we show the transverse \sim \mathcal{L} Application: H+1 jet MiNLO at next-to-leading order

- Figure 2: Transverse momentum spectrum of the Higgs boson, computed with the POWHEG BOX ggH generator (H PWG), the HJ-MINLO result (HJ MINLO), the HJ default *µ*^F = *µ*^R = *p^H* F_{per} Resummation matched to NI \bigcap inclusive $\sigma\sigma \rightarrow H$ yseen $\left[$ = 1 in ratios 1 gg and the Hotel matches to the Historic $\frac{1}{20}$ and $\frac{1}{20}$ \circ Resummation matched to NLO inclusive gg \rightarrow H xsecⁿ [\equiv 1 in ratios] $\frac{1}{\sqrt{2}}$ \overline{r} $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ xs ve Resummation matched to NLO inclusive $gg \rightarrow H xsec^n$ [\equiv 1 in ratios]
- \circ HJ RUN: NLO H + 1 jet with $\mu_R = \mu_F = p_{T,H}$ $g = \mu_F = \text{D}T_H$ $\begin{aligned} \n\text{all} \n\end{aligned}$ \mathbb{R} HJ RUN: NLO H + 1 jet with $\mu_R = \mu_F = p_{T,H}$
- H_1 FYO, NLO H_1 is the nutth the nutth the NLO game of the NLO game H_2 central values in dication the combined renormalization scale uncertainty. Results in the combined values of the combined values o $N_{\rm H}$ respect to the NLO galaxy minimizing simulation with the band either side of the band either central values indication in the combined renormalization and $\mu_R - \mu_F - i \nu_H$ RUN), and HJ with *µ*^F = *µ*^R = *M^H* (HJ FXD). The right panel shows the ratio of each of the $N_{\text{L}} - \mu + -\text{IVI}$ RUN), and HJ with *µ*^F = *µ*^R = *M^H* (HJ FXD). The right panel shows the ratio of each of the $\mu_{\rm R} = \mu_{\rm F} - m_{\rm H}$ respect to the NLO simulation with the band either side of the band either s HJ FXD: NLO H + 1 jet with $\mu_R = \mu_F = M_H$
- ∘ HJ-MiNLO_{Ratio} conventional NLO H + 1 jet at high p⊤ n
P $=$
association α \overline{H} $\overline{1}$ Ratio $HJ-MiNLO_{R₁}$ conventional NLO H + 1 jet at high pt
- \mathcal{L} at low produce at \mathcal{L} TeV and a Higgs mass of 120 \circ HJ-MiNLO \rightarrow resummation result at low pt calculation. HJ-MiNLO → resummation result at low pT
- multijet $\frac{1}{2}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{k}$ $\ddot{}$ HJ-M**iN#O** → sensible scale unc. band [doesn't shrink as p $\tau \rightarrow 0$] \circ

*j*1*j*²

Events are classified according to the number of jets, as defined above. Application: Z+2 jet MiNLO ⊕ Pythia vs ATLAS

Table 3. Cuts for *Z* production in association with jets.

- \sim 1 oft, improves \sim 0 NUO st gives even prodicta for \sim 0 iot evital α of β is strong two-inclusive two-jet events. Left: improves $Z + 2$ NLO s.t. gives even predictⁿ for ≥ 0 jet evts!
	- Right: NLO accuracy retained $[&$ improved] for ≥ 2 jet events \circ
- 5.2 *Z* production data $\frac{1}{2}$ sum of the ATI AS W jets, data In all cases one expects a non-negligible contribution from the MPI in the MPI in the M Equally nice improvement & agreement for ATLAS W+jets data

In the second compare the output of our compare the output of our products of our \mathcal{L}_{sum} ref. [12]. The parameters used in the same as in the same as in section 3.1. The set of same as in section 5.1 [Campbell, Ellis, Nason, Zanderighi]

minlo

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MiNLO' for H+1-jet consideration that merger more smoothly with smoothly with smaller more smaller multiplicity. It is possible to concern the MINLO method includes \mathcal{L} construction that merger more smoothly with smoothly with smaller more smaller multiplicity. VINLO' for H+1-jet $\overline{}$ section $\overline{}$ and $\overline{}$ and $\overline{}$ we will consider two such examples.

80

- $\overline{}$ • MiNLO matches fully differential NLO to LL [NLL_σ] resummation
- 5.2 Higgs boson production 5.2 Higgs boson production 5.2.1 Higgs boson production in association with one jet · MiNLO finite in all ph.space: no need of gen. cuts

^T (HJ

the

Sudakov

 \Box generation what's MiNH \bigcap accuracy for inclusive quantities? RUN), and HJ with *µ*^F = *µ*^R = *M^H* (HJ FXD). The right panel shows the ratio of each of the \Box generation w hat's M ^{INII}O accuracy for inclusive quantities² Question: what's MiNLO accuracy for inclusive quantities? Figure 2: Transverse momentum spectrum of the Higgs boson, computed with the POWHEG BOX Figure 2: Transverse momentum spectrum of the Higgs boson, computed with the POWHEG BOX tit
— $\frac{1}{\sqrt{2}}$ $\frac{1}{1}$ in $\overline{}$ icl Question: what's MiNLO accuracy for inclusive quantities?

d^F μ known analytically to high accuracy *i i*^{*l*}*i***^{***l***}***ii<i>i<i>i<i>i<i><i>i******<i>i<i>i* H+1-jet spectrum known analytically to high accuracy \circ ^ˆ *^Q*² $\overline{}$

↵¯*i*

(*a) pous pour am*
lours to determin *n* accuracy
i NLO for H+0-je $A + \Box$ (A) is \vdots A **P** $\overline{\Omega}$ Allows to determine Sudakov s.t. H+1-jet is NLO for H+0-jet **k**c \circ *p*2 T *nⁱ*

^S*Aⁱ , B* (↵S) = ^X

i

↵¯*i*

^S*Bⁱ ,*

i

$$
\boxed{\begin{aligned}\n\text{MINLO} &\rightarrow \text{MINLO'} \\
\Delta(Q, p_{\text{T}}) &\rightarrow \Delta'(Q, p_{\text{T}}) = \Delta(Q, p_{\text{T}}) \delta \Delta(Q, p_{\text{T}}) \\
\delta \Delta(Q, p_{\text{T}}) & = \exp\left[\int_0^L dL' \bar{\alpha}_{\text{s}}^2 (p_{\text{T}}') \left[\tilde{R}_{21} L' + \tilde{R}_{20} - \bar{\beta}_0 \mathcal{H}_1\right]\right] \\
\frac{d\sigma'_{\text{M}}}{d\Phi} & = \int_L \frac{d\sigma'_{\text{R}}}{d\Phi dL} + \int_L \frac{d\sigma_{\text{F}}}{d\Phi dL} = \frac{d\sigma_{\text{NLO}}}{d\Phi}\n\end{aligned}}
$$

ˆ *d^M* $\frac{1}{\sqrt{2}}$,
H+1-iet MiNLO*′* simultaneously NLO for H & H+1-jet prodn N for H δ \circ $($ *ddL*

MiNLO for H+1-jet *′* [Nason, Oleari, Zanderighi, KH]

• Higgs rapidity

- Conventional NLO H prodn: red \circ • **125 Gev, Letter and Marshall** and the second method of $\frac{1}{2}$.
- MiNLO*′* H+1-jet+parton shower: green • WIINLO' H+1-jet+parton shower: green
	- $f_{\rm A}$ $f_{\rm 2}$ Agree with each other ~ to within the line thickness*′* \circ
- Conventional scale setting in complex processes subject to large \circ ambiguities, and lacking physical justifications
- MiNLO is a physically well motivated scale setting for processes with \circ jets: identifies all important scales, treats all coherently
- MiNLO taken up by independent groups: applied in complex \circ processes, used in new NLO merging schemes [e.g. FxFx]
- MiNLO' = NLO x NLO calcⁿs w.o. merging scales
- MiNLO' extended to (N)NLO x NLO x NLO accuracy in H+2 jets \circ

MiNLO pgs. 394 - 398

Thank you Paolo

