QCD for the LHC

Alexander Karlberg
Rudolf Peierls Centre for Theoretical Physics, University of Oxford
Aknowledgments: E. Re and P. Monni

UNIVERSITY OF OXFORD

Nordic Winter School on Cosmology and Particle Physics, 5 January 2015

Outline

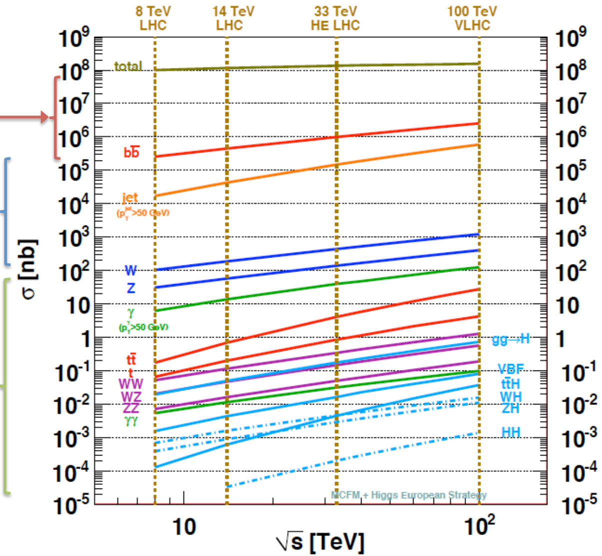
- What?
  - QCD phenomenology
- Why?
  - Benchmarking: Precision
  - Discovery: Higgs, BSM
  - QCD interesting on it's own
- How?
  - Pertubative calculations (LO, NLO, NNLO)
  - Resummation (LL, NLL, NNLL)
  - Numerical tools: `MadGraph`, `SHERPA`, `HERWIG`, `PYTHIA`, `MCFM`, `POWHEG-BOX`, `MC@NLO` (and many more)
- Examlpes
  - DY-NNLOPS

Impact of QCD at the LHC

Soft QCD

Hard QCD

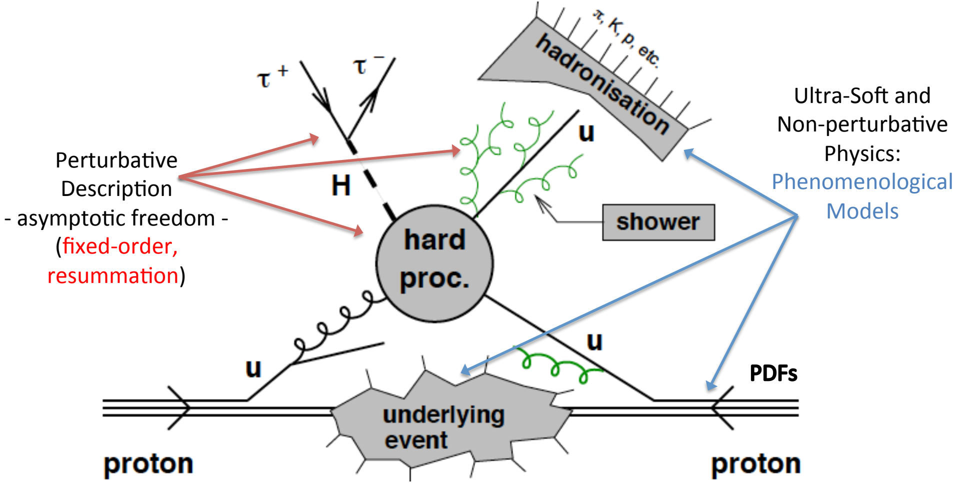
Hard QCD/EW



Dynamics dominated by QCD.
We need to understand it in order to decipher complex events.

European Strategy Report

What goes on in a collision



Credit: G.P.Salam

Role of QCD : benchmarking

- Understanding QCD dynamics relevant for a collider experiment to run:
  - Precise simulation/measurement of benchmark processes (e.g. Drell-Yan) necessary to test and calibrate the machine
  - Test tools for theory predictions: precise assessment of theory uncertainties
  - Tuning of Phenomenological models for Underlying Events, Pile Up, Multi-Particle Interactions, Hadronisation...
  - Accurate tests of the Standard Model and precise measurement of its parameters

Role of QCD : discovering

- Precise predictions for New-Physics signals and relative Background processes

- Understanding behaviour of QCD radiation and process kinematics to improve experimental sensitivity

    - Design of new observables less sensitive to soft physics – use of jet algorithms as a key to "read" events

e.g. anti-kt algorithm [Cacciari, Salam, Soyez]

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}$$

$$[\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j^2)]$$

$$d_{iB} = \frac{1}{p_{ti}^2}$$

Standard recombination algorithm for LHC analyses.

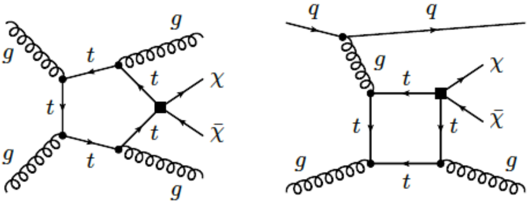
Role of QCD : discovering

- Precise predictions for New-Physics signals and relative Background processes

- Understanding behaviour of QCD radiation and process kinematics to improve experimental sensitivity

  - Background reduction and enhancement of new physics

e.g. Dark matter + dijet events [Haisch, Hibbs, Re]

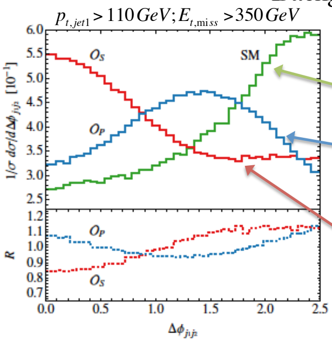


Role of QCD : discovering

- Precise predictions for New-Physics signals and relative Background processes

- Understanding behaviour of QCD radiation and process kinematics to improve experimental sensitivity

  - Background reduction and enhancement of new physics



e.g. Dark matter + dijet events [Haisch, Hibbs, Re]

$Z(\nu\bar{\nu}) + 2j$

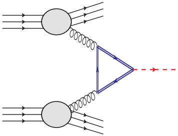
$$\mathcal{O}_P = \frac{m_t}{\Lambda_P^3}\,\bar{t}\gamma_5 t\,\bar{\chi}\gamma_5\chi$$

$$\mathcal{O}_S = \frac{m_t}{\Lambda_S^3}\,\bar{t}t\,\bar{\chi}\chi$$

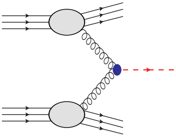
e.g. azimuthal correlation between the two jets

perturbative QCD: fixed order

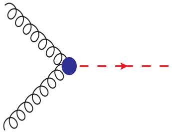
- Higgs production as guiding example



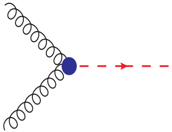
- Higgs production as guiding example
  - will assume a ggH pointlike interaction
    (EFT is known to reproduce full result within 1%)



- Higgs production as guiding example
  - will assume a ggH pointlike interaction (EFT is known to reproduce full result within 1%)
  - will also neglect the (fundamental) role played by PDFs



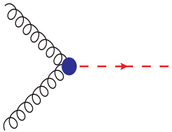
- Higgs production as guiding example
  - will assume a ggH pointlike interaction
    (EFT is known to reproduce full result within 1%)
  - will also neglect the (fundamental) role played by PDFs



- this is the *leading-order* (LO) contribution to Higgs production at the LHC
  - LO is by definition an approximation: does it work well ?

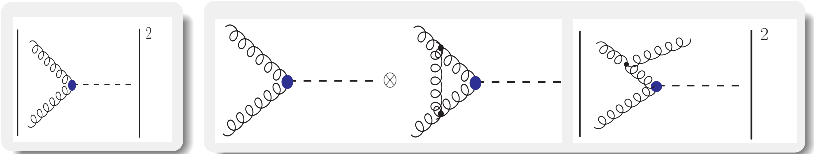
- Higds production as guiding example

- Higgs production as guiding example
  - will assume a ggH pointlike interaction (EFT is known to reproduce full result within 1%)
  - will also neglect the (fundamental) role played by PDFs



- this is the *leading-order* (LO) contribution to Higgs production at the LHC
  - LO is by definition an approximation: does it work well ?
- to addredss this issue, and in general to increase the precision of our computations, we need to improve on the LO approximation, including formally subleading terms
  - general structure of perturbative corrections:

$$\sigma = \alpha_S^2\, \sigma_{LO} + \alpha_S^3\, \sigma_{NLO} + \ldots$$



  - from NLO onwards, we need to renormalize (and absorb collinear singularities from ISR into PDFs). This is a systematic and well-defined procedure. However, the price to pay is that we introduce artifical scales (renormalization and factorization scales). Their exact choice is an ambiguity, although some choices are clearly better than others...

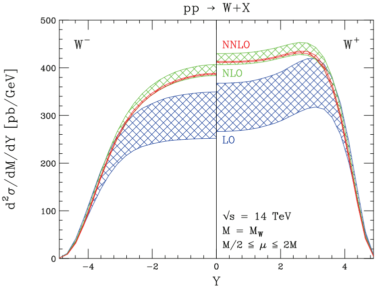
perturbative QCD: convergence of fixed order expansion

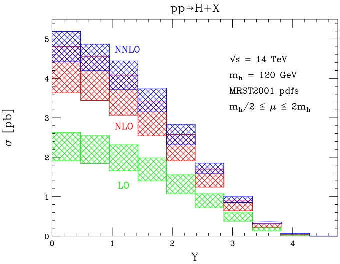
- "working well" means that (at each order) corrections are of order α_S ($\sim$ 10%), and results (seem to) become stable (as shown *e.g.* by bands)

- does the perturbative expansion show good convergence properties?

- "working well" means that (at each order) corrections are of order α_S ($\sim$ 10%), and results (seem to) become stable (as shown *e.g.* by bands)

- does the perturbative expansion show good convergence properties?

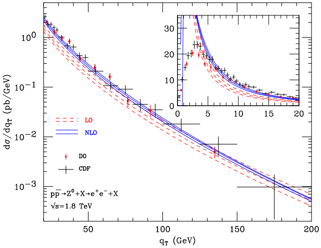


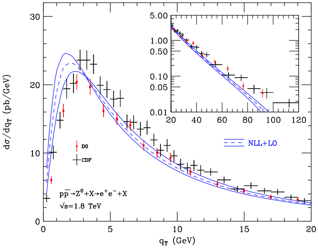


perturbative QCD: convergence of fixed order expansion

- “working well” means that (at each order) corrections are of order α_S ($\sim$ 10%), and results (seem to) become stable (as shown *e.g.* by bands)

- does the perturbative expansion show good convergence properties?

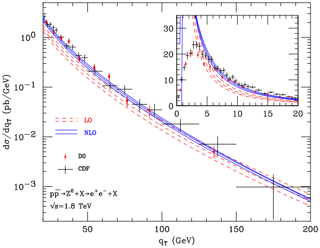


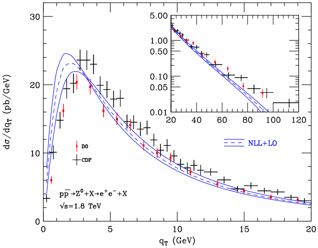


perturbative QCD: convergence of fixed order expansion

- "working well" means that (at each order) corrections are of order α_S ($\sim$ 10%), and results (seem to) become stable (as shown *e.g.* by bands)

\- does the perturbative expansion show good convergence properties?





- clearly a power expansion in the strong coupling is not always a good approximation. As shown by above examples, this depends on the observable we are intersted in, and, to some extent, to the particular process we are considering.

extra emissions: a closer look

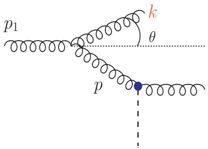
We want to understand why a power expansion sometimes can fail, and how we can “fix” it. To do this, we need to look into the structure of multileg (QCD) squared amplitudes and their integration over phase space.

- the rapidity distribution gives an hint that when one doesn’t ask questions about the “details” of radiation and integrate over it (technically when the observable is *inclusive over QCD emissions*), a fixed-order expansion works well

extra emissions: a closer look

We want to understand why a power expansion sometimes can fail, and how we can "fix" it. To do this, we need to look into the structure of multileg (QCD) squared amplitudes and their integration over phase space.

- the rapidity distribution gives an hint that when one doesn't ask questions about the "details" of radiation and integrate over it (technically when the observable is *inclusive* over QCD emissions), a fixed-order expansion works well
- single emission and singularities:

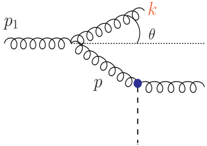


- $p_1 = (E; \vec{0}, E)$, $k = (E_k; \vec{k}_T, \sqrt{E_k^2 - |\vec{k}_T|^2})$
  - can also write $k_T^2 = E_k^2(1 - \cos^2\theta)$
- $p^2 = -2EE_k(1 - \cos\theta)$
  - propagator goes on-shell if $E_k \to 0$ and/or $\theta \to 0$
  - singularities in soft and/or collinear limit

extra emissions: a closer look

We want to understand why a power expansion sometimes can fail, and how we can “fix” it. To do this, we need to look into the structure of multileg (QCD) squared amplitudes and their integration over phase space.

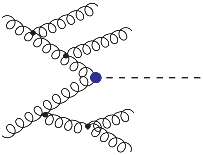
- the rapidity distribution gives an hint that when one doesn’t ask questions about the “details” of radiation and integrate over it (technically when the observable is *inclusive* over QCD emissions), a fixed-order expansion works well
- single emission and singularities:



- $p_1 = (E;\vec{0},E)$, $k = (E_k;\vec{k}_T,\sqrt{E_k^2 - |\vec{k}_T|^2})$
  - can also write $k_T^2 = E_k^2(1-\cos^2\theta)$
- $p^2 = -2EE_k(1-\cos\theta)$
  - propagator goes on-shell if $E_k \to 0$ and/or $\theta \to 0$
  - singularities in soft and/or collinear limit

- multiple emissions:

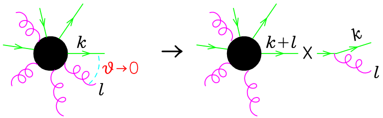
for an emission at a given k_T, the more natural choice for the α_S argument is $\alpha_S(k_T)$
$\Rightarrow$ dominant contributions come from phase space regions where there are 'lots' of soft-collinear emissions (internal propagator on-shell + coupling “large”).



- we are still in “weak coupling” regime, *i.e.* $\alpha_S \lesssim 1$

origin of logs I

- collinear factorization (a factorization formula holds for soft non-collinear emissions too):



$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \to \left(|\mathcal{M}_n|^2 d\Phi_n\right) \frac{\alpha_S}{2\pi} \frac{d\theta^2}{\theta^2} P(z) dz \frac{d\varphi}{2\pi} \qquad P(z) \simeq C_A \frac{2}{1-z} \qquad z = \frac{k_0}{k_0 + \ell_0}$$

- assume we want to know the x-section for $k_T < \bar{k}_T$ ("jet veto"): the integration over the real emission phase space is now restricted !

$$\sigma(k_T < \bar{k}_T) = \sigma_{LO} + \frac{\alpha_S}{2\pi}\left(\int R\, d\Phi_r\, \Theta(\bar{k}_T - k_T) + V\right)$$

- For our purposes, we can assume that the soft/collinear approximation works well for $\theta < 1$ and $E < M$:

$$\sigma(k_T < \bar{k}_T) \simeq \sigma_{LO} + \frac{\alpha_S}{2\pi}\left[\text{reg}_{V+R} + B \cdot 2\, C_A \int_0^M \frac{dE}{E} \int_0^1 \frac{d\theta^2}{\theta^2} \left(\Theta(\bar{k}_T - k_T) - 1\right)\right]$$

$$\simeq \sigma_{LO}\left(1 - C_A \frac{\alpha_S}{\pi} \int_0^M \frac{dE}{E} \int_0^1 \frac{d\theta^2}{\theta^2} \Theta(k_T - \bar{k}_T)\right)$$

$$= \sigma_{LO}\left(1 - C_A \frac{\alpha_S}{\pi} \log^2(M/\bar{k}_T)\right)$$

where we have used $k_T^2 = E^2\theta^2$

origin of logs II

$$\sigma(k_{\rm T} < \bar{k}_{\rm T}) \simeq \sigma_{LO} \left(1 - C_A \frac{\alpha_{\rm S}}{\pi} \log^2(M/\bar{k}_{\rm T})\right)$$

- observe the presence of $\alpha_{\rm S} \log^2(M/\bar{k}_{\rm T})$!
- the dominant contribution in presence of 2 uncorrelated emissions of similar hardness gives
$$\sim \sigma_{LO} \frac{1}{2} \left(\frac{\alpha_{\rm S}}{\pi}\right)^2 \log^4(M/\bar{k}_{\rm T})$$
- $\alpha_{\rm S} L^2$ and $(\alpha_{\rm S} L^2)^2$ are of the same order if $\alpha_{\rm S} L^2 \simeq 1$!
  - when this is the case (*i.e.* when scales are very different), a perturbative expansion in powers of $\alpha_{\rm S}$ fails
  - need to reorganize perturbation theory, summing logs
  - $\alpha_{\rm S} L^2 \simeq 1$ defines where resummation important
- from the above simplified example, we have learned that:
  - large logs can spoil perturbation theory
  - they typically appear when there is an hierarchy of scales in the problem
  - a hierarchy can be introduced when looking at particular observables rather than integrating over them
  - $\alpha_{\rm S} L^2$ are called LL; there are also subleading terms, NLL, NNLL, etc.
  - when logs are large, they need to be resummed

Fixed order, resummation, MC programs

QCD for LHC phenomenology:

1. compute the above effects, as accurately as possible
2. make theoretical predictions available to the EXP community

---

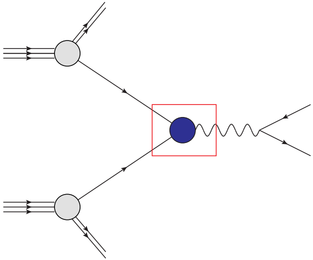
- fixed order computations:
  - work well for inclusive observables, and/or when jets are widely separated
  - NLO is now automated, NNLO is the frontier
- resummation:
  - when observables are inclusive enough, it can be done with analytic or seminumerical methods
  - there are different classes of logs that can be resummed (and several approaches to do that): NNLL is the frontier for LHC pheno
- Monte Carlo programs:
  - they are used in almost all experimental analyses
  - they allow to obtain predictions for generic observables, since they simulate events as they would occurr in real collisions
  - parton shower algorithms allow to perform resummation in an observable-independent way, but they are formally less accurate than dedicated resummation: (N)LL

Part of the recent development in these fields is to incorporate as much information as possible in multipurpose tools.

Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

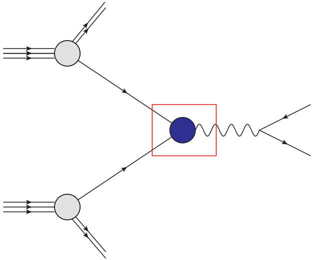
$$d\sigma_{\mathrm{SMC}} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \Big\{ \qquad \Big\}$$



Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

$$d\sigma_{\mathrm{SMC}} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \left\{ \Delta(t_{\max}, t_0) \right\}$$

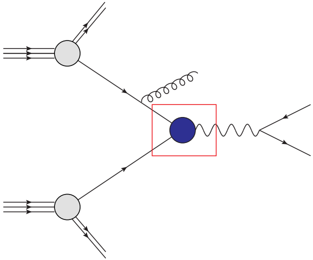


$$\Delta(t_{\max}, t) = \exp\left\{ -\int_t^{t_{\max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

$$d\sigma_{\rm SMC} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \left\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \quad \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\ \frac{1}{t} P(z)\ d\Phi_r} \right\}$$

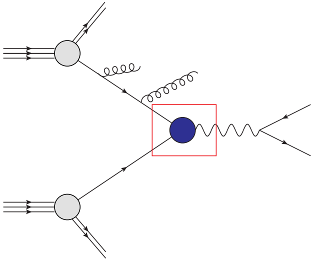


$$\Delta(t_{\rm max}, t) = \exp\left\{ - \int_t^{t_{\rm max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

$$d\sigma_{\rm SMC} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \Big\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\,\frac{1}{t}P(z)\,d\Phi_r} \underbrace{\{\Delta(t, t_0) + \Delta(t, t')d\mathcal{P}_{\rm emis}(t')\}}_{t'<t} \Big\}$$

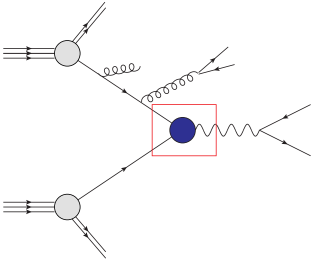


$$\Delta(t_{\rm max}, t) = \exp\left\{ - \int_t^{t_{\rm max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

$$d\sigma_{\rm SMC} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \left\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\ \frac{1}{t} P(z)\ d\Phi_r} \underbrace{\{\Delta(t, t_0) + \Delta(t, t') d\mathcal{P}_{\rm emis}(t')\}}_{t'<t} \right\}$$

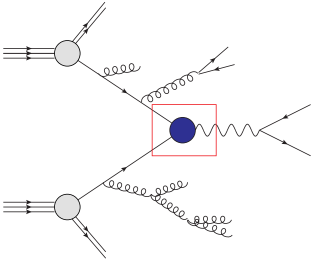


$$\Delta(t_{\rm max}, t) = \exp\left\{ - \int_t^{t_{\rm max}} d\Phi_r' \ \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

$$d\sigma_{\rm SMC} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \left\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\,\frac{1}{t} P(z)\, d\Phi_r} \underbrace{\{\Delta(t, t_0) + \Delta(t, t') d\mathcal{P}_{\rm emis}(t')\}}_{t'<t} \right\}$$

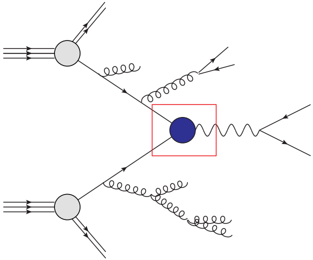


$$\Delta(t_{\rm max}, t) = \exp\left\{ -\int_t^{t_{\rm max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers

- parton shower: algorithm to resum (some classes of) collinear/soft logs in a "fully-exclusive" way.
- based on description of multiple soft-collinear real and virtual radiative corrections using a probabilistic language

$$d\sigma_{\rm SMC} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \Big\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\ \frac{1}{t} P(z)\ d\Phi_r} \underbrace{\{\Delta(t, t_0) + \Delta(t, t') d\mathcal{P}_{\rm emis}(t')\}}_{t'<t} \Big\}$$

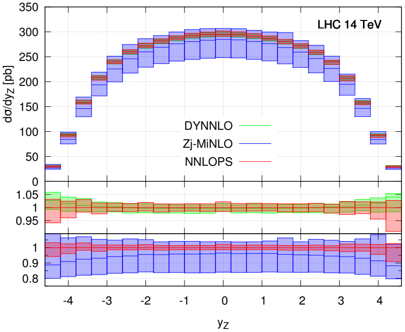


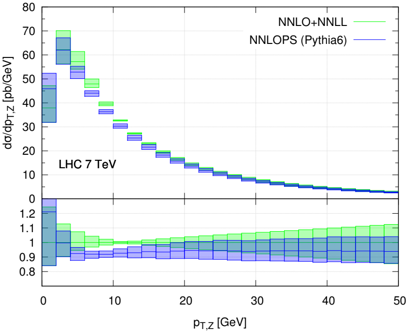
$$\Delta(t_{\rm max}, t) = \exp\left\{ -\int_t^{t_{\rm max}} d\Phi'_r \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

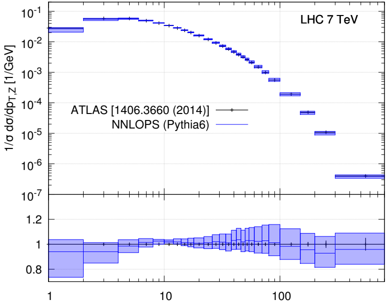
This is "LOPS"

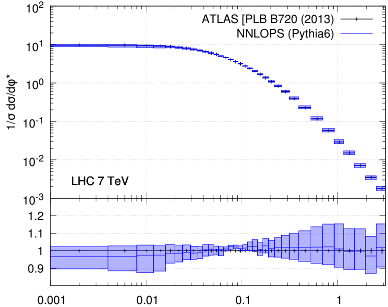
- A parton shower changes shapes, not the overall normalization, which stays LO (*unitarity*)
- LL resummation is included in Sudakov form factors: easy to see that probability of having arbitrarily collinear emission becomes 0, instead of ∞

Results - 1407.2940









Conclusions

- The LHC is a jet factory
- High precision paramount for benchmarking of the Standard Model
  - But also for discovering new physics (DM+jj, Jet Veto, ...)
- Fixed order calculations work very well for inclusive quantitites
- To fully describe exclusive quantities resummation of logs is necessary
  - NNLL is state-of-the-art
- LO, LOPS, NLO and NLOPS have been around for a long time
  - NNLO is now the frontier $\rightarrow$ NNLOPS is on its way

Ok, that's nice...but perhaps it isn't clear enough?...

Parton showers

Ok, that's nice...but perhaps it isn't clear enough?...

This is what MC programs produce:

- fully exclusive simulation: momenta of all outgoing leptons and hadrons:

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY
31	NU_E	12	1	29	22	0	0	60.53	37.24	-1185.0	1187.1
32	E+	-11	1	30	22	0	0	-22.80	2.59	-232.4	233.6
148	K+	321	1	109	9	0	0	-1.66	1.26	1.3	2.5
151	PI0	111	1	111	9	0	0	-0.01	0.05	11.4	11.4
152	PI+	211	1	111	9	0	0	-0.19	-0.13	2.0	2.0
153	PI-	-211	1	112	9	0	0	0.84	-1.07	1626.0	1626.0
154	K+	321	1	112	9	0	0	0.48	-0.63	945.7	945.7
155	PI0	111	1	113	9	0	0	-0.37	-1.16	64.8	64.8
156	PI-	-211	1	113	9	0	0	-0.20	-0.02	3.1	3.1
158	PI0	111	1	114	9	0	0	-0.17	-0.11	0.2	0.3
159	PI0	111	1	115	18	0	0	0.18	-0.74	-267.8	267.8
160	PI-	-211	1	115	18	0	0	-0.21	-0.13	-259.4	259.4
161	N	2112	1	116	23	0	0	-8.45	-27.55	-394.6	395.7
162	NBAR	-2112	1	116	23	0	0	-2.49	-11.05	-154.0	154.4
163	PI0	111	1	117	23	0	0	-0.45	-2.04	-26.6	26.6
164	PI0	111	1	117	23	0	0	0.00	-3.70	-56.0	56.1
167	K+	321	1	119	23	0	0	-0.40	-0.19	-8.1	8.1
186	PBAR	-2212	1	130	9	0	0	0.10	0.17	-0.3	1.0

- At some level, this enters in almost all experimental analyses.
  $\hookrightarrow$ The more precise we are, the smaller the impact of uncertainties on measured quantities

- parton showers are only LO+LL: clearly including NLO corrections would be a big improvement. There are 2 methods to achieve this consistently:

NLO+Parton Showers

- parton showers are only LO+LL: clearly including NLO corrections would be a big improvement. There are 2 methods to achieve this consistently:
- the POWHEG method:
  1. do these replacement

$$B(\Phi_n) \Rightarrow \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})\, d\Phi_r\right]$$

$$\Delta(t_{\mathrm{m}}, t) \Rightarrow \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\frac{\alpha_s}{2\pi}\int \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)}\theta(k'_{\mathrm{T}} - k_{\mathrm{T}})\, d\Phi'_r\right\}$$

  2. POWHEG "master formula" for the hardest emission:

$$d\sigma_{\mathrm{POW}} = d\Phi_n\ \bar{B}(\Phi_n)\left\{\Delta(\Phi_n; k_{\mathrm{T}}^{\min}) + \Delta(\Phi_n; k_{\mathrm{T}})\frac{\alpha_s}{2\pi}\frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r\right\}$$

[+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting]

  3. properties:
     - inclusive observables: @NLO
     - first hard emission: full tree level ME
     - (N)LL resummation of collinear/soft logs

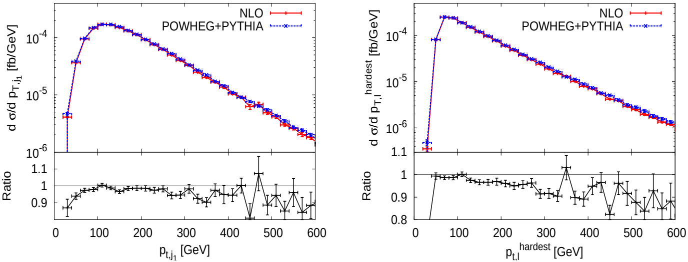
- NLOPS has become the standard for LHC searches (at least for SM processes)

POWHEG: an example

- Here we study VBF production $pp \to ZZjj$ [Jäger,AK,Zanderighi, 1312.3252]
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$, $|\eta_{j_1} - \eta_{j_2}| > 4.0$
  - $\eta_{j,min} < \eta_l < \eta_{j,max}$
  - $M_{jj} > 600\ GeV$
- Process important as Higgs background (and for BSM - anomalous couplings implemented)
- NLO corrections can be of order $\sim 20\%$
- NLO calculation based on VBFNLO. PYTHIA 6 used to shower (Perugia 0 tune)

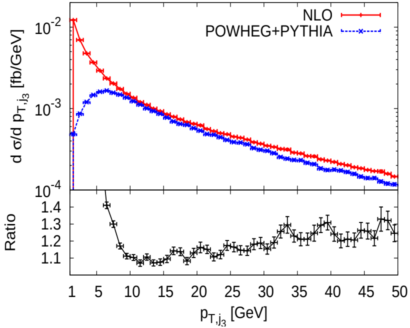
POWHEG: an example

- Here we study VBF production $pp \to ZZjj$ [Jäger,AK,Zanderighi, 1312.3252]
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$, $|\eta_{j_1} - \eta_{j_2}| > 4.0$
  - $\eta_{j,min} < \eta_l < \eta_{j,max}$
  - $M_{jj} > 600\ GeV$
- Process important as Higgs background (and for BSM - anomalous couplings implemented)
- NLO corrections can be of order $\sim 20\%$
- NLO calculation based on VBFNLO. PYTHIA 6 used to shower (Perugia 0 tune)
- Hard objects only modified slightly by PS
- Soft objects substantially modified by PS



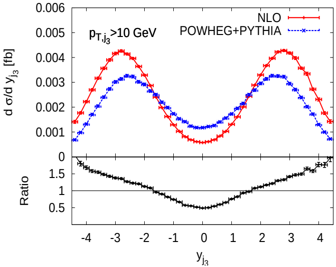
POWHEG: an example

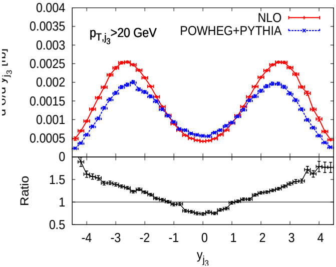
- Here we study VBF production $pp \to ZZjj$ [Jäger,AK,Zanderighi, 1312.3252]
  - $\eta_{j_1} \cdot \eta_{j_2} < 0, |\eta_{j_1} - \eta_{j_2}| > 4.0$
  - $\eta_{j,min} < \eta_l < \eta_{j,max}$
  - $M_{jj} > 600\ GeV$
- Process important as Higgs background (and for BSM - anomalous couplings implemented)
- NLO corrections can be of order $\sim 20\%$
- NLO calculation based on VBFNLO. PYTHIA 6 used to shower (Perugia 0 tune)
- Hard objects only modified slightly by PS
- Soft objects substantially modified by PS



POWHEG: an example

- Here we study VBF production $pp \to ZZjj$ [Jäger,AK,Zanderighi, 1312.3252]
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$, $|\eta_{j_1} - \eta_{j_2}| > 4.0$
  - $\eta_{j,min} < \eta_l < \eta_{j,max}$
  - $M_{jj} > 600\ GeV$
- Process important as Higgs background (and for BSM - anomalous couplings implemented)
- NLO corrections can be of order $\sim 20\%$
- NLO calculation based on VBFNLO. PYTHIA 6 used to shower (Perugia 0 tune)
- Hard objects only modified slightly by PS
- Soft objects substantially modified by PS





NNLO+PS

- NNLO computations are the current frontier ($t\bar{t}$, dijet, $H + j$ performed in 2012-13)
- for some processes (Drell-Yan, Higgs via gluon-fusion) NNLO corrections have been known already for a while...

Can we match NNLO with parton showers?

At least for simple processes, this is possible, and we are working on it...

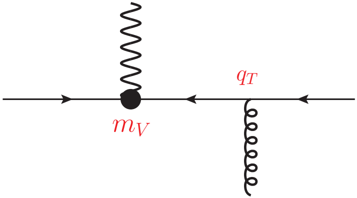
1. V+j @ NLO, V+jj @ LO ⇒ use V+j @ NLOPS (POWHEG)

$$d\sigma_{\rm POWHEG} = d\Phi_n\, \bar{B}_{\rm NLO}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\rm T}^{\rm min}) + \Delta(\Phi_n; k_{\rm T}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \right\}$$

1. V+j @ NLO, V+jj @ LO $\Rightarrow$ use V+j @ NLOPS (POWHEG)

$$d\sigma_{\mathrm{POWHEG}} = d\Phi_n\, \bar{B}_{\mathrm{NLO}}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\mathrm{T}}^{\min}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \right\}$$

$$\bar{B}_{\mathrm{NLO}}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n = \alpha_{\mathrm{S}}(\mu_R) \Big[B + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} V(\mu_R) + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} \int d\Phi_{\mathrm{r}} R \Big]\, d\mathbf{\Phi}_n$$

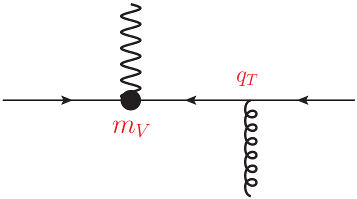


V+j is a 2-scales problem ($\rightarrow$ choice of μ not unique)

1. V+j @ NLO, V+jj @ LO $\Rightarrow$ use V+j @ NLOPS (POWHEG)

$$d\sigma_{\rm POWHEG} = d\Phi_n\, \bar{B}_{\rm NLO}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\rm T}^{\rm min}) + \Delta(\Phi_n; k_{\rm T}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \right\}$$

$$\bar{B}_{\rm NLO}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n = \alpha_{\rm S}(\mu_R) \Big[B + \alpha_{\rm S}^{\rm (NLO)} V(\mu_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R \Big]\, d\mathbf{\Phi}_n$$



V+j is a 2-scales problem ($\rightarrow$ choice of μ not unique)

☞ want to reach NNLO accuracy for *e.g.* y_V, *i.e.* when fully inclusive over QCD radiation

- need to allow the 1st jet to become unresolved
- the above approach needs to be modified: as it stands, $\bar{B}_{\rm NLO}(\Phi_n)$ is not finite when $q_T \rightarrow 0$!

2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

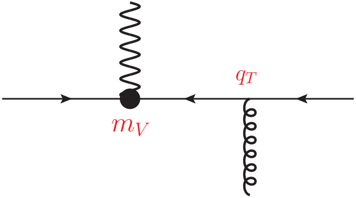
- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:
  - for all PS points, build the “more-likely” shower history that would have produced it (can be done by clustering kinematics with k_T-algo)
  - correct original NLO including α_S couplings evaluated at nodal scales and Sudakov FFs
  - make sure that NLO accuracy is not spoiled !

2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

$$\bar{B}_{\mathrm{NLO}} = \alpha_{\mathrm{S}}(\mu_R)\Big[B + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} V(\mu_R) + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} \int d\Phi_{\mathrm{r}} R\Big]$$



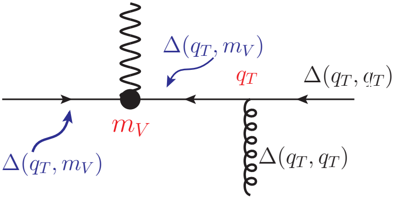
2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

$$\bar{B}_{\rm NLO} = \alpha_{\rm S}(\mu_R)\Big[B + \alpha_{\rm S}^{\rm (NLO)} V(\mu_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R\Big]$$

$$\bar{B}_{\rm MiNLO} = \alpha_{\rm S}(q_T)\Delta_q^2(q_T, m_V)\Big[B\left(1 - 2\Delta_q^{(1)}(q_T, m_V)\right) + \alpha_{\rm S}^{\rm (NLO)} V(\bar{\mu}_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm r} R\Big]$$



- $\bar{\mu}_R = q_T$
- $\log \Delta_{\rm f}(q_T, m_V) = -\int_{q_T^2}^{m_V^2} \frac{dq^2}{q^2} \frac{\alpha_{\rm S}(q^2)}{2\pi}\left[A_f \log \frac{m_V^2}{q^2} + B_f\right]$
- $\Delta_{\rm f}^{(1)}(q_T, m_V) = -\frac{\alpha_{\rm S}^{\rm (NLO)}}{2\pi}\left[\frac{1}{2} A_{1,{\rm f}} \log^2 \frac{m_V^2}{q_T^2} + B_{1,{\rm f}} \log \frac{m_V^2}{q_T^2}\right]$
- $\mu_F = q_T$

MiNLO

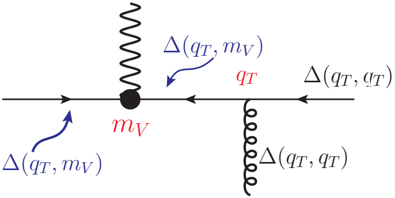
2. integrate over phase space regions where V is produced with arbitrarily soft/collinear jet (i.e. finite results when integrating over all q_T spectrum)

MiNLO: Multiscale Improved NLO [Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation (where hierarchy among scales can spoil accuracy since resummation of logs is missing)
- how: correct weights of different NLO terms with CKKW-inspired approach:

$$\bar{B}_{\rm NLO} = \alpha_{\rm S}(\mu_R)\Big[B + \alpha_{\rm S}^{(\rm NLO)} V(\mu_R) + \alpha_{\rm S}^{(\rm NLO)} \int d\Phi_{\rm r} R\Big]$$

$$\bar{B}_{\rm MiNLO} = \alpha_{\rm S}(q_T)\Delta_q^2(q_T, m_V)\Big[B\left(1 - 2\Delta_q^{(1)}(q_T, m_V)\right) + \alpha_{\rm S}^{(\rm NLO)} V(\bar{\mu}_R) + \alpha_{\rm S}^{(\rm NLO)} \int d\Phi_{\rm r} R\Big]$$



☞ Sudakov FF included on V+j Born kinematics

- VJ-MiNLO yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\rm MiNLO}$ ideal to extend validity of V+j POWHEG

- after further relatively minor changes, VJ-MiNLO differential cross section $(d\sigma/dy)_{\mathrm{VJ-MiNLO}}$ is NLO accurate

$$W(y) = \frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{VJ-MiNLO}}} = \frac{c_0 + c_1\alpha_{\mathrm{S}} + c_2\alpha_{\mathrm{S}}^2}{c_0 + c_1\alpha_{\mathrm{S}} + d_2\alpha_{\mathrm{S}}^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_{\mathrm{S}}^2 + \mathcal{O}(\alpha_{\mathrm{S}}^3)$$

- thus, reweighting each event with this factor, we get NNLO+PS
  - obvious for y_V, by construction
  - α_{S}^2 accuracy of VJ-MiNLO in 1-jet region not spoiled, because $W(y) = 1 + \mathcal{O}(\alpha_{\mathrm{S}}^2)$

NNLO+PS

- after further relatively minor changes, VJ−MiNLO differential cross section $(d\sigma/dy)_{\mathrm{VJ-MiNLO}}$ is NLO accurate

$$W(y) = \frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{VJ-MiNLO}}} = \frac{c_0 + c_1\alpha_S + c_2\alpha_S^2}{c_0 + c_1\alpha_S + d_2\alpha_S^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_S^2 + \mathcal{O}(\alpha_S^3)$$

- thus, reweighting each event with this factor, we get NNLO+PS
  - obvious for y_V, by construction
  - α_S^2 accuracy of VJ−MiNLO in 1-jet region not spoiled, because $W(y) = 1 + \mathcal{O}(\alpha_S^2)$

---

* Variants for W are possible:

$$W(y, p_T) = h(p_T)\frac{\int d\sigma_A^{\mathrm{NNLO}}\delta(y - y(\mathbf{\Phi}))}{\int d\sigma_A^{\mathrm{MiNLO}}\delta(y - y(\mathbf{\Phi}))} + (1 - h(p_T))$$

$$d\sigma_A = d\sigma\ h(p_T), \qquad d\sigma_B = d\sigma\ (1 - h(p_T)), \qquad h = \frac{(\beta m_H)^2}{(\beta m_H)^2 + p_T^2}$$

* $h(p_T)$ controls where the NNLO/NLO K-factor is spread
* β cannot be too small, otherwise resummation spoiled

- For Higgs production the reweighting can be performed as-is

[Hamilton,Nason,Re,Zanderighi, 1309.0017]

- Drell-Yan has more complicated Born kinematics : $W(y, p_T) \to W(\{\Phi_i\}, p_T)$
  - $\{\Phi_i\} = (y, M_{ll}, \theta_l)$

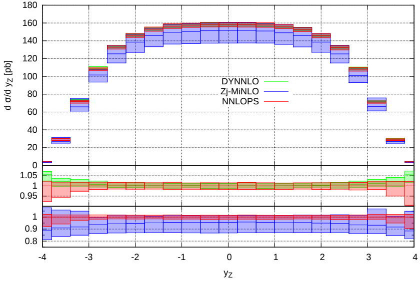
Inputs for the following plots:

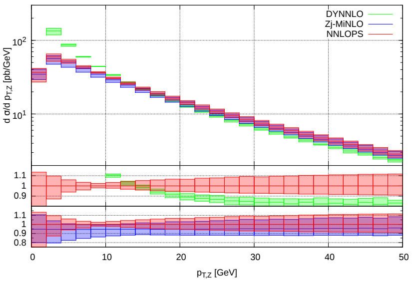
- results are for 7 TeV LHC
- scale choices: NNLO input with $\mu = m_V$, VJ-MiNLO "core scale" m_V (other powers are at q_T)
- PDF: everywhere MSTW2008 NNLO
- NNLO always from DYNNLO
- 20M events reweighted at the LH level
- plots after k_{T}-ordered PYTHIA 8 shower with hadronisation and MPI effects

[AK,Re,Zanderighi, work in progress]

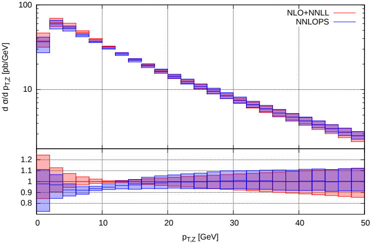
DY-NNLOPS

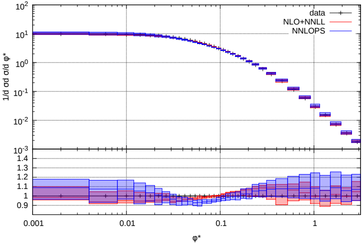
- 21 scalevariations: $\mu_R = K_r M_V$, $\mu_F = K_F M_V$, $K_R, K_F \in \{0.5, 1.0, 2.0\}$ with $\frac{1}{2} \leq \frac{K_R}{K_F} \leq 2$ in `VJ-MiNLO` and $K_R = K_F$ in `DYNNLO`
- Profile function: $\beta = 1$ and p_T of hardest jet.
- Good agreement with `DYNNLO` for inclusive quantities and improvement over `ZJ-MiNLO` for exclusive quantities.



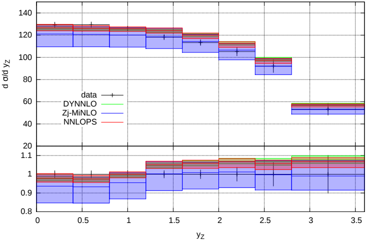


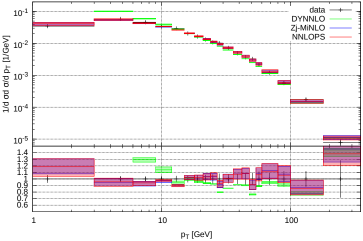
- 21 scalevariations: $\mu_R = K_r M_V$, $\mu_F = K_F M_V$, $K_R, K_F \in \{0.5, 1.0, 2.0\}$ with $\frac{1}{2} \le \frac{K_R}{K_F} \le 2$ in `VJ-MiNLO` and $K_R = K_F$ in `DYNNLO`
- Profile function: $\beta = 1$ and p_T of hardest jet.
- Good agreement with `DYNNLO` for inclusive quantities and improvement over `ZJ-MiNLO` for exclusive quantities.
- Compares well with NNLL resummed results

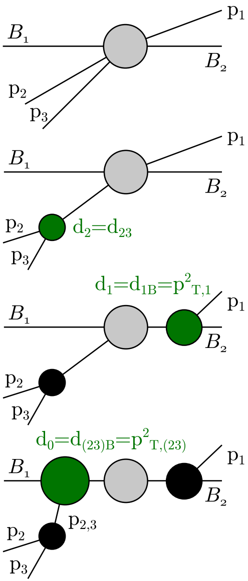




- 21 scalevariations: $\mu_R = K_r M_V$, $\mu_F = K_F M_V$, $K_R, K_F \in \{0.5, 1.0, 2.0\}$ with $\frac{1}{2} \leq \frac{K_R}{K_F} \leq 2$ in `VJ-MiNLO` and $K_R = K_F$ in `DYNNLO`
- Profile function: $\beta = 1$ and p_T of hardest jet.
- Good agreement with `DYNNLO` for inclusive quantities and improvement over `ZJ-MiNLO` for exclusive quantities.
- Compares well with NNLL resummed results







[ATLAS, 1302.1415]

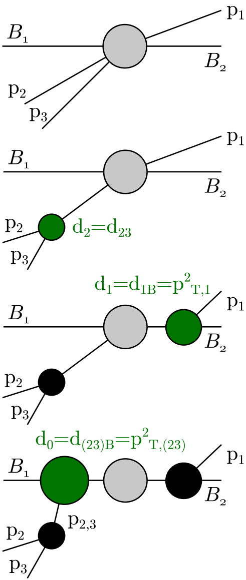
- Splitting scale $\sqrt{d_i}$ gives the scale at which exactly i jets are found ($\sqrt{d_0}$ always p_T of hardest jet) in an event
- Very sensitive to PS but d_0 and d_1 governed by fixed-order at high scales
- Very good test of resummation and matching/merging procedure
- Here data shown for $W \to l\nu$

$$d_{ij} = min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i^2 + \phi_j^2)$$

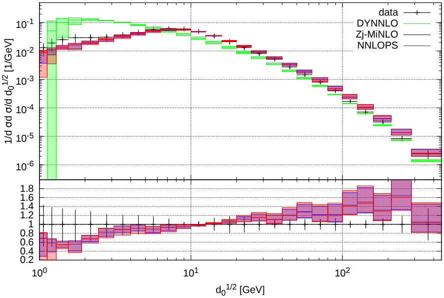
$$d_{iB} = p_{Ti}^2$$

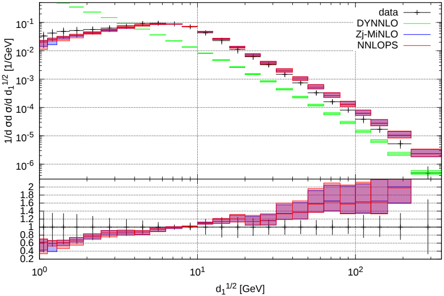
$$\sqrt{d_i} = min(d_{ij}, d_{iB})$$

DY-NNLOPS

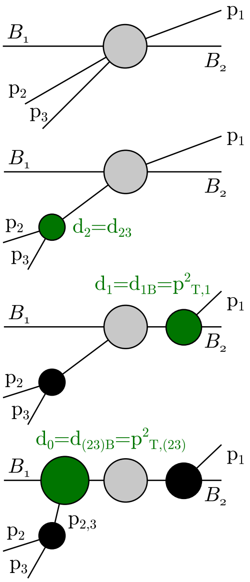


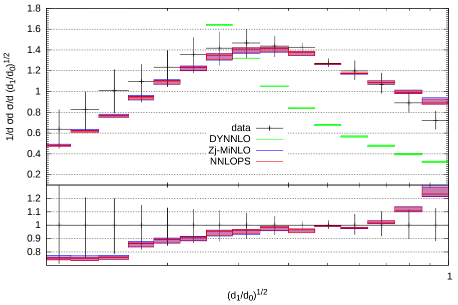
[ATLAS, 1302.1415]





DY-NNLOPS





[ATLAS, 1302.1415]

Jet bins in H→WW channel

- A cut in transverse momentum of 25-30 GeV does not lead to dramatically large Sudakov logarithms, so a fixed-order prediction can be reliable

$$\Sigma_{0j}(p_{t,veto}) = 1 - 6\frac{\alpha_s}{\pi}\ln^2\frac{m_H}{p_{t,veto}} + \ldots$$

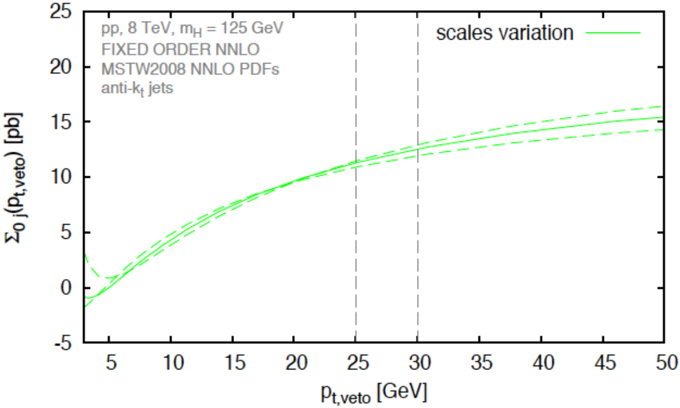
- Nevertheless, Sudakov logarithms cancel against large K factor when one performs renormalization scale variation to estimate the uncertainties. This makes the fixed-order scale uncertainty unreliable and the theory error cannot be assessed precisely

- On the one hand K-factor effects can be estimated using a fixed-order expansion, and on the other hand resummation of jet-veto logarithms is needed to keep under control higher-order Sudakov effects and assess the uncertainty reliably

Jet bins in H→WW channel

- Fixed-order prediction (Theory uncertainty: 4.5 % - even more dramatic at 25 GeV)

$e.g.\ R = 0.5, p_{t,veto} = 30\ \mathrm{GeV}$

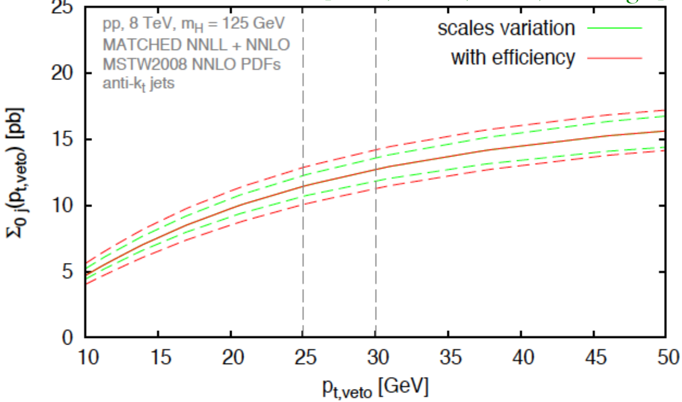


Jet bins in H→WW channel

- Resummed prediction (Theory uncertainty: 9-11 %)

$e.g.\ R = 0.5,\ p_{t,veto} = 30\ \text{GeV}$

[Banfi, Monni, Salam, Zanderighi]



- Sudakov FF from infinitesimal emission probabilities

$$\mathcal{P}_i^{\text{no emiss}}(t \to t') \simeq \prod_{k=1}^{N} (1 - d\mathcal{P}_i^{\text{emiss}}(t_k)) = \prod_{k=1}^{N} \left(1 - \frac{\alpha_S(t_k)}{2\pi} \frac{\delta t}{t_k} \sum_{(jl)} \int P_{i,jl}(z)\, dz\, \frac{d\phi}{2\pi}\right)$$

  This reduces to the Sudakov form factor $\Delta_i(t, t')$ in the continuum limit $N \to +\infty$. We can state that, in Parton Showers, virtual corrections are included in a probabilistic way.

- Choice of the ordering variable affects double-log structure
  - angular ordering is the correct choice
  - exact in `HERWIG`, approximate in other generators
- The use of $\alpha_S = \alpha_S(p_T^2)$, in the radiation scheme, allows to include (part of) the 2-loop splitting kernels
- Nominal accuracy is LL, although it's common believe that in practice it's better.
- For some observables (*e.g.* low-p_T DY) NLL can be achieved.
- Momentum conservation (via reshuffling/recoil) is respected (and this is a NLL effect).

"Improved" MiNLO & NLOPS merging

- accuracy of VJ−MiNLO for inclusive observables carefully investigated

  [Hamilton,Nason,Oleari,Zanderighi, 1212.4504]

- VJ−MiNLO describes inclusive observables at order α_S (relative to inclusive H @ LO)
- to reach genuine NLO when inclusive, "spurious" terms must be of relative order α_S^2, *i.e.*

$$O_{\rm VJ-MiNLO} = O_{\rm V@NLO} + \mathcal{O}(\alpha_S^{b+2}) \qquad (b = 0 \text{ for DY})$$

  if O is inclusive (V@LO $\sim \alpha_S^b$).

- "Original MiNLO" contains ambiguous $\mathcal{O}(\alpha_S^{b+3/2})$ terms.

“Improved” MiNLO & NLOPS merging

- accuracy of `VJ-MiNLO` for inclusive observables carefully investigated
  [Hamilton,Nason,Oleari,Zanderighi, 1212.4504]
- `VJ-MiNLO` describes inclusive observables at order α_S (relative to inclusive H @ LO)
- to reach genuine NLO when inclusive, “spurious” terms must be of relative order α_S^2, *i.e.*

$$O_{\mathrm{VJ-MiNLO}} = O_{\mathrm{V@NLO}} + \mathcal{O}(\alpha_S^{b+2}) \qquad (b = 0 \text{ for DY})$$

if O is inclusive (V@LO $\sim \alpha_S^b$).

- “Original MiNLO” contains ambiguous $\mathcal{O}(\alpha_S^{b+3/2})$ terms.

- Possible to improve `VJ-MiNLO` such that V @ NLO is recovered (NLO$^{(0)}$) , without spoiling NLO accuracy of V+j (NLO$^{(1)}$) .
  - proof based on careful comparisons of `MiNLO` with general resummation formula
  - need to include B_2 in `MiNLO`-Sudakovs
  - need to evaluate $\alpha_S{}^{(\mathrm{NLO})}$ in `VJ-MiNLO` at scale q_T, and $\mu_F = q_T$

Effectively as if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).

Other NLOPS-merging approaches: [Hoeche,Krauss, et al.,1207.5030] [Frederix,Frixione,1209.6215] [Lonnblad,Prestel,1211.7278 - Platzer,1211.5467] [Alioli,Bauer, et al.,1211.7049] [Hartgring,Laenen,Skands, 1303.4974]

"Improved" MiNLO & NLOPS merging II

- Resummation formula

$$\frac{d\sigma}{dq_T^2 dy} = \sigma_0 \frac{d}{dq_T^2}\Big\{[C_{ga}\otimes f_a](x_A, q_T) \times [C_{gb}\otimes f_b](x_B, q_T) \times \exp S(q_T, Q)\Big\} + R_f$$

$$S(q_T, Q) = -2\int_{q_T^2}^{Q^2} \frac{dq^2}{q^2}\frac{\alpha_S(q^2)}{2\pi}\left[A_f \log\frac{Q^2}{q^2} + B_f\right]$$

- If $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$, then upon integration we get NLO$^{(0)}$
- Take derivative, then compare with MiNLO :

$$\sim \sigma_0 \frac{1}{q_T^2}[\alpha_S, \alpha_S^2, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L] \exp S(q_T, Q) + R_f \qquad L = \log(Q^2/q_T^2)$$

- highlighted terms are needed to reach NLO$^{(0)}$:

$$\int^{Q^2} \frac{dq_T^2}{q_T^2} L^m {\alpha_S}^n(q_T) \exp S \sim \left(\alpha_S(Q^2)\right)^{n-(m+1)/2}$$

- if I don't include B_2 in MiNLO Δ_g, I miss a term $(1/q_T^2)\alpha_S^2 B_2 \exp S$
- upon integration, violate NLO$^{(0)}$ by a term of relative $\mathcal{O}(\alpha_S^{3/2})$
- "wrong" scale in $\alpha_S^{(\mathrm{NLO})}$ in MiNLO produces again same error