Monte Carlo Generators (2)

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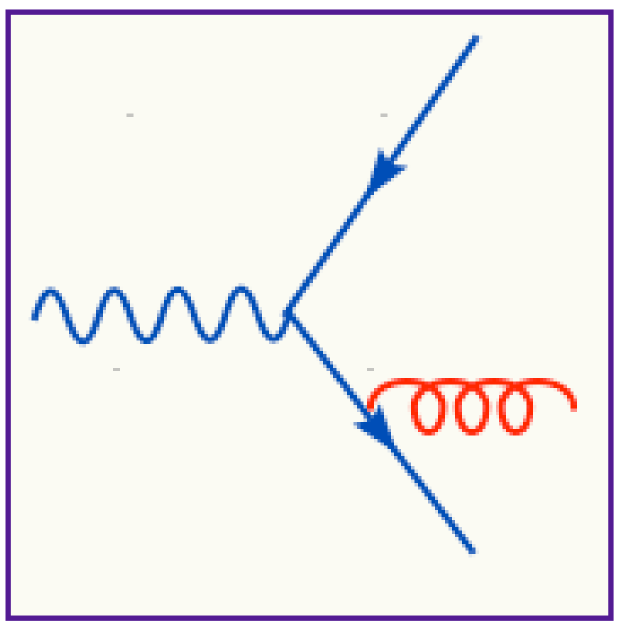
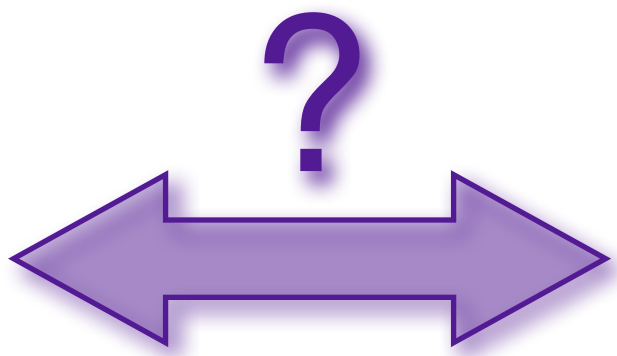
NLO summary

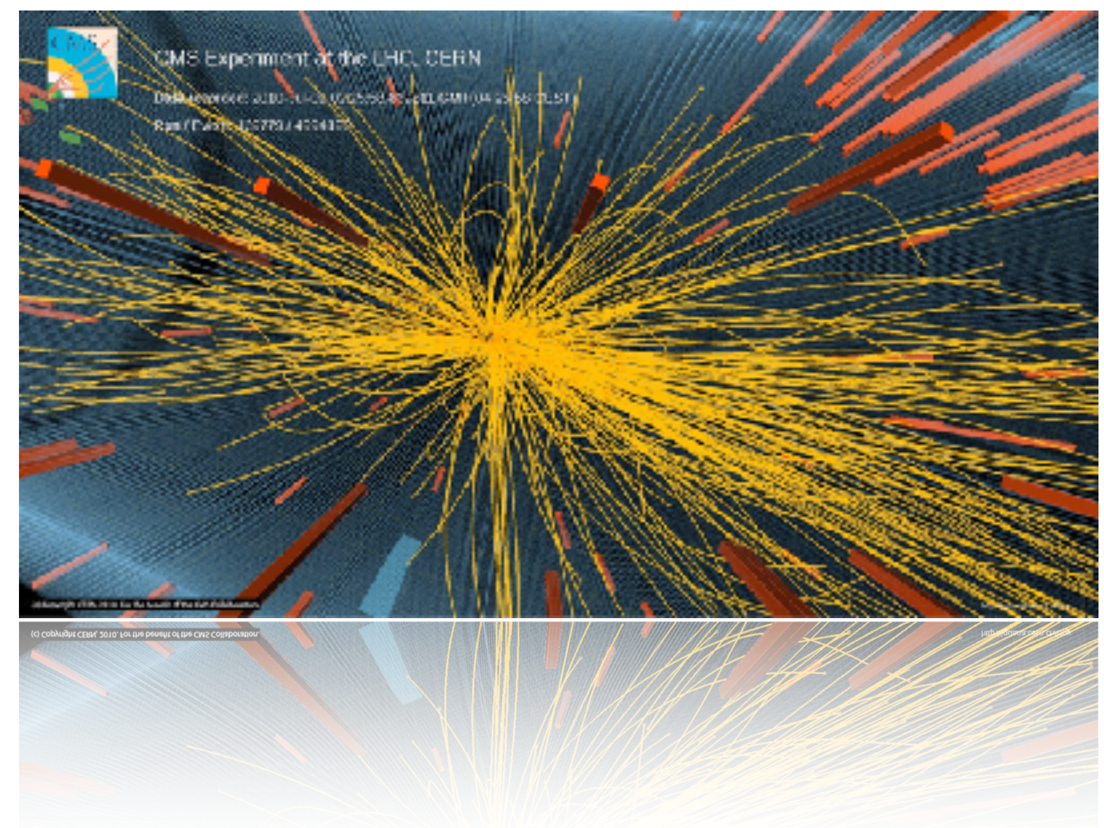
- Monte Carlo Basics
- NLO corrections (at fixed order, i.e., no parton shower)
  - Both the virtual and real-emission corrections are IR divergent, but their sum is finite: We can use a subtraction methods to factor the divergences in the real-emission phase-space integration and cancel them explicitly against the terms in the virtual corrections
  - This generates events and counter events with slightly different kinematics. This means we cannot generate unweighed events (integrals are not bounded), but we can fill plots with weighted events: MC integrator (not an MC event generator)
  - When making plots or applying cuts, use only IR safe observables with finite resolution
- NNLO is very similar, but at least a couple of orders of magnitude more intricate: double loop integrals, and a rather more involved IR structure.

Parton Shower

Exclusive observables



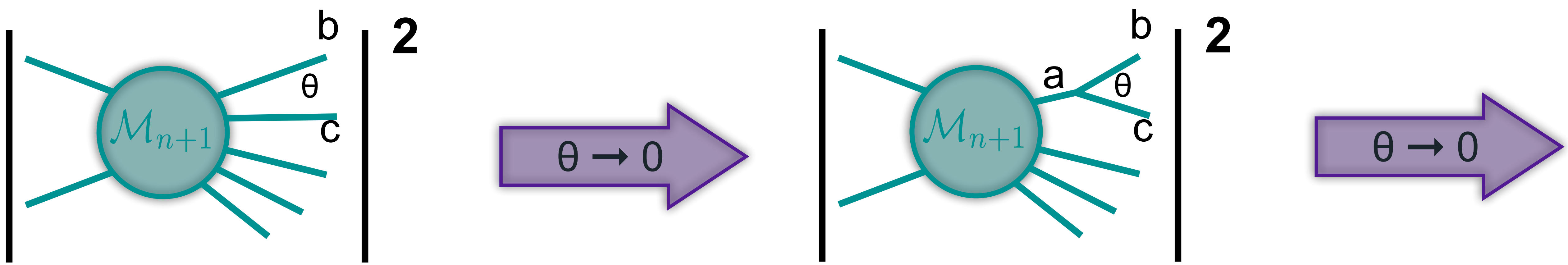




Exclusive observables

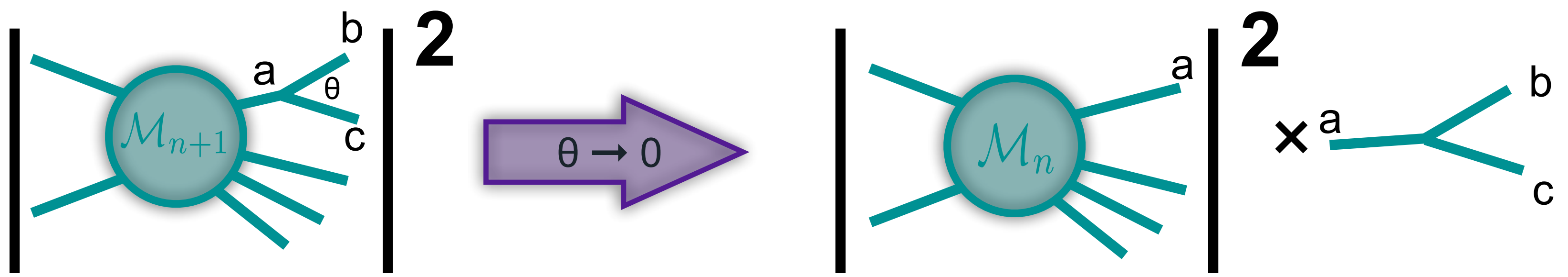
- Very exclusive observables are poorly described in perturbation theory.
  - One could take the conservative attitude of considering only perturbatively well-behaved observables. But one would miss an extremely rich variety of observables which may play important roles in experimental analyses.
- If fixed-order perturbation theory breaks down for an observable, this does NOT mean that observable is useless/unimportant: it is just that one is not using the right tools to describe it.
- It is better to try and find a way to reorganise the computation in order to take into account emissions close to the singular regions of the phase space, to all orders in perturbation theory.
  - This can be done in a systematic way: "resummation"!

Collinear factorisation



- Consider a process for which too particles are separated by a small angle θ
- In the limit of θ → 0 the contribution is coming from a single parent particle going on shell: therefore its branching is related to time scales which are very long with respect to the hard subprocess
- The inclusion of such a branching cannot change the picture set up by the hard process: the whole emission process must be writable in this limit as the simpler one times a branching probability

Collinear factorisation



- The process factorises in the collinear limit. This procedure it universal

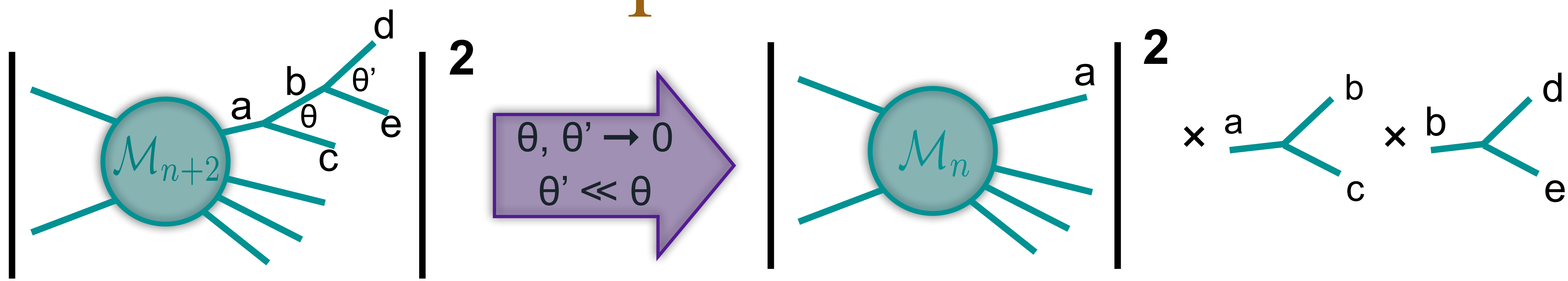
$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \simeq |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

- Notice that what has been roughly called 'branching probability' is actually a singular factor, so one will need to make sense of this definition.
- At the leading contribution to the (n+1)-body cross section the Altarelli-Parisi splitting kernels are defined as:

$$P_{g\to qq}(z) = T_R\left[z^2 + (1-z)^2\right], \qquad P_{g\to gg}(z) = C_A\left[z(1-z) + \frac{z}{1-z} + \frac{1-z}{z}\right],$$

$$P_{q\to qg}(z) = C_F\left[\frac{1+z^2}{1-z}\right], \qquad P_{q\to gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right].$$

Multiple emissions



- The dominant contribution comes from the region where the subsequently emitted partons satisfy the strong ordering requirement: $\theta \gg \theta' \gg \theta''$...

  For the rate for multiple emission we get

$$\sigma_{n+k} \propto \alpha_S^k \int_{Q_0^2}^{Q^2} \frac{dt}{t} \int_{Q_0^2}^{t} \frac{dt'}{t'} \cdots \int_{Q_0^2}^{t^{(k-2)}} \frac{dt^{(k-1)}}{t^{(k-1)}} \propto \sigma_n \left(\frac{\alpha_S}{2\pi}\right)^k \log^k(Q^2/Q_0^2)$$

  where Q is a typical hard scale and Q_0 is a small infrared cutoff that separates perturbative from non perturbative regimes.

- Each power of α_s comes with a logarithm. The logarithm can easily be large, and therefore we see a breakdown of perturbation theory

Absence of interference

- The collinear factorisation picture gives a branching sequence for a given leg starting from the hard subprocess all the way down to the non-perturbative region.
- Suppose you want to describe two such histories from two different legs:
  - these two legs are treated in a completely uncorrelated way. And even within the same history, subsequent emissions are uncorrelated.
- The collinear picture completely misses the possible interference effects between the various legs
  - the extreme simplicity comes with the price of quantum inaccuracy.
- **Smart choices improve upon this: soft enhancement (which is purely an interference contribution) can be included. For this, the evolution variable must be related to the angle of the emission**
- Nevertheless, the collinear picture captures the leading contributions: it gives an excellent description of an arbitrary number of (collinear) emissions:
  - it is a “resummed computation” and
  - it bridges the gap between fixed-order perturbation theory and the non-perturbative hadronisation.

Emission probability & Sudakov form factor

- The differential probability for the branching $a \longrightarrow bc$ between scales t and t+dt knowing that no emission occurred before:

$$dp(t) = \sum_{bc} \frac{dt}{t} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

- The probability that a parton does NOT split between the scales t and t+dt is given by 1-dp(t)

- Probability that particle a does not emit between scales Q^2 and t

$$\Delta(Q^2, t) = \prod_k \left[1 - \sum_{bc} \frac{dt_k}{t_k} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] =$$

$$\exp\left[-\sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] = \exp\left[-\int_t^{Q^2} dp(t')\right]$$

$\Delta(Q^2,t)$ is the Sudakov form factor

Parton shower

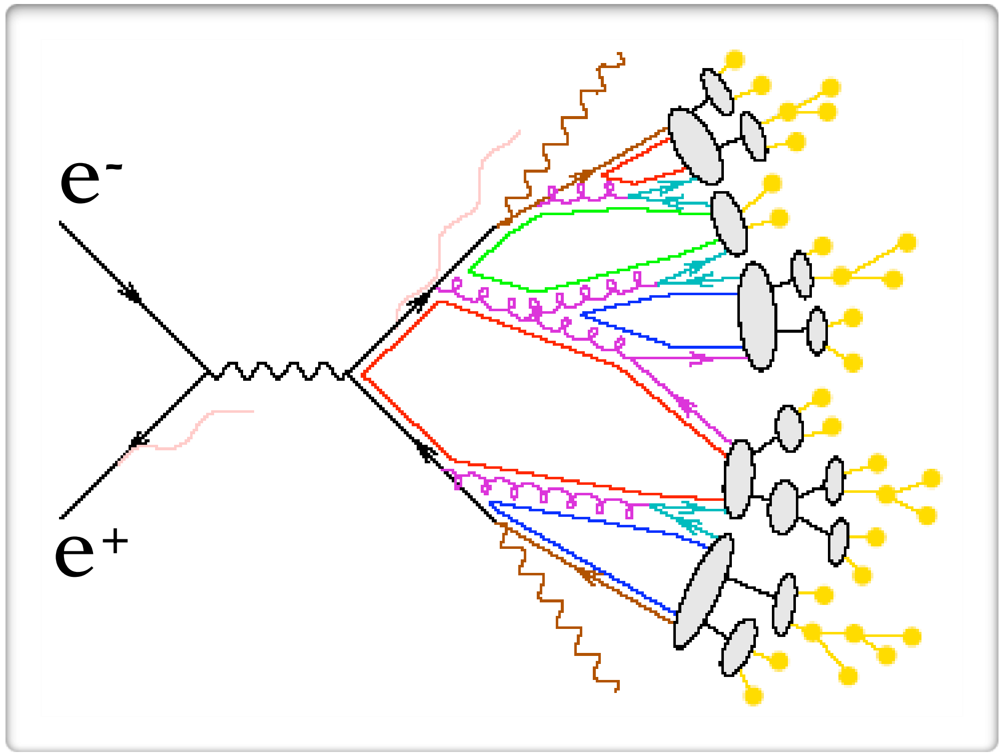
- The Sudakov form factor is the heart of the parton shower. It gives the probability that a parton does not branch between two scales
  *Initial state shower also requires PDF contributions
- Using this no-emission probability one can generate the branching tree of a parton
- Define dP_k as the probability for k ordered splittings from leg a at given scales

$$
\begin{aligned}
dP_1(t_1) &= \Delta(Q^2, t_1)\ dp(t_1)\Delta(t_1, Q_0^2), \\
dP_2(t_1, t_2) &= \Delta(Q^2, t_1)\ dp(t_1)\ \Delta(t_1, t_2)\ dp(t_2)\ \Delta(t_2, Q_0^2)\Theta(t_1 - t_2), \\
\ldots &= \ldots \\
dP_k(t_1, \ldots, t_k) &= \Delta(Q^2, Q_0^2) \prod_{l=1}^{k} dp(t_l)\Theta(t_{l-1} - t_l)
\end{aligned}
$$

- Q_0^2 is the hadronisation scale (~1 GeV^2). Below this scale we do not trust the perturbative description for parton splitting anymore
- This is what is implemented in a parton shower, taking the scales for the splitting t_i randomly (but weighted according to the no-emission probability)

Hadronisation

- The shower stops if all partons are characterised by a scale at the IR cut-off: $Q_0 \sim 1$ GeV
- Physically, we observe hadrons, not (coloured) partons
- We need a non-perturbative model in passing from partons to colourless hadrons
- There are various models, with tuneable parameters, based on physical and phenomenological considerations



Improving Parton Showers

Improving MC's: the hard region

- Parton shower MC programs are only correct in the soft-collinear region. Hard radiation cannot be described correctly
- There are two ways to improve a Parton Shower Monte Carlo event generator with matrix elements:
  - ME+PS merging: include matrix elements with more final state partons to describe hard, well-separated radiation better
  - NLO+PS matching: include full NLO corrections to the matrix elements to reduce theoretical uncertainties in the matrix elements. The real-emission matrix elements will describe the hard radiation

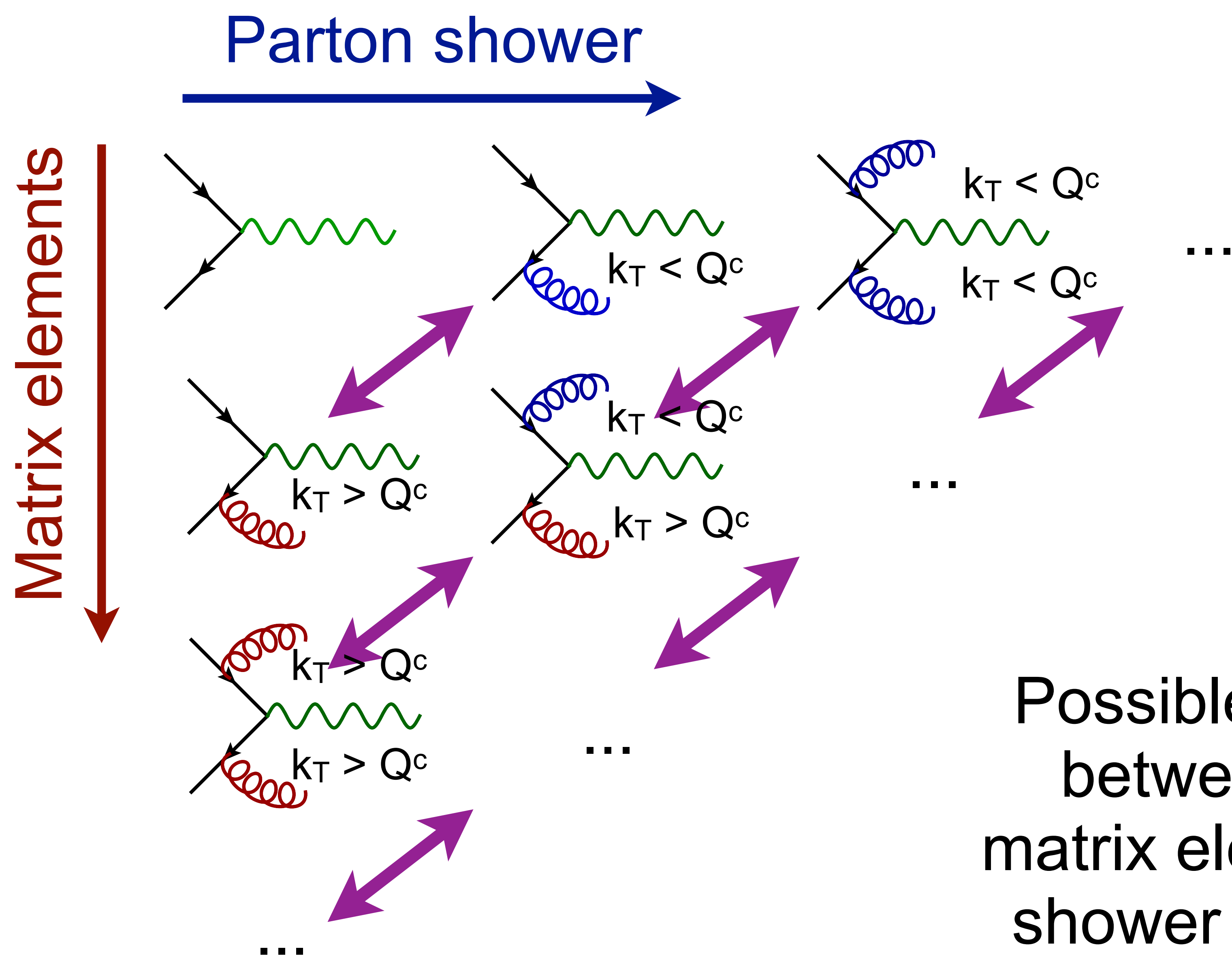
Matrix elements vs. Parton showers

ME	Shower MC
1. Fixed order calculation	1. Resums logs to all orders
2. Computationally expensive	2. Computationally cheap
3. Limited number of particles	3. No limit on particle multiplicity
4. Valid when partons are hard and well separated	4. Valid when partons are collinear and/or soft
5. Quantum interference correct	5. Partial interference through angular ordering
6. Needed for multi-jet description	6. Needed for hadronisation

Approaches are complementary: merge them!

Difficulty: avoid double counting, ensure smooth distributions

Possible double counting

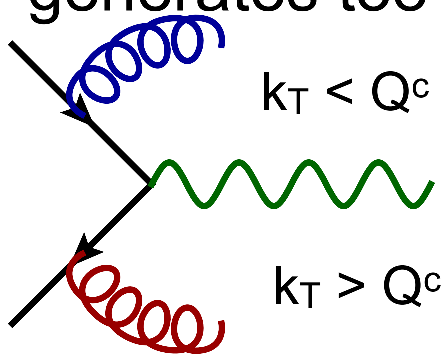


Possible double counting between partons from matrix elements and parton shower easily avoided by applying a cut in phase space

Merging ME with PS

CKKW (2004) and MLM (2004)

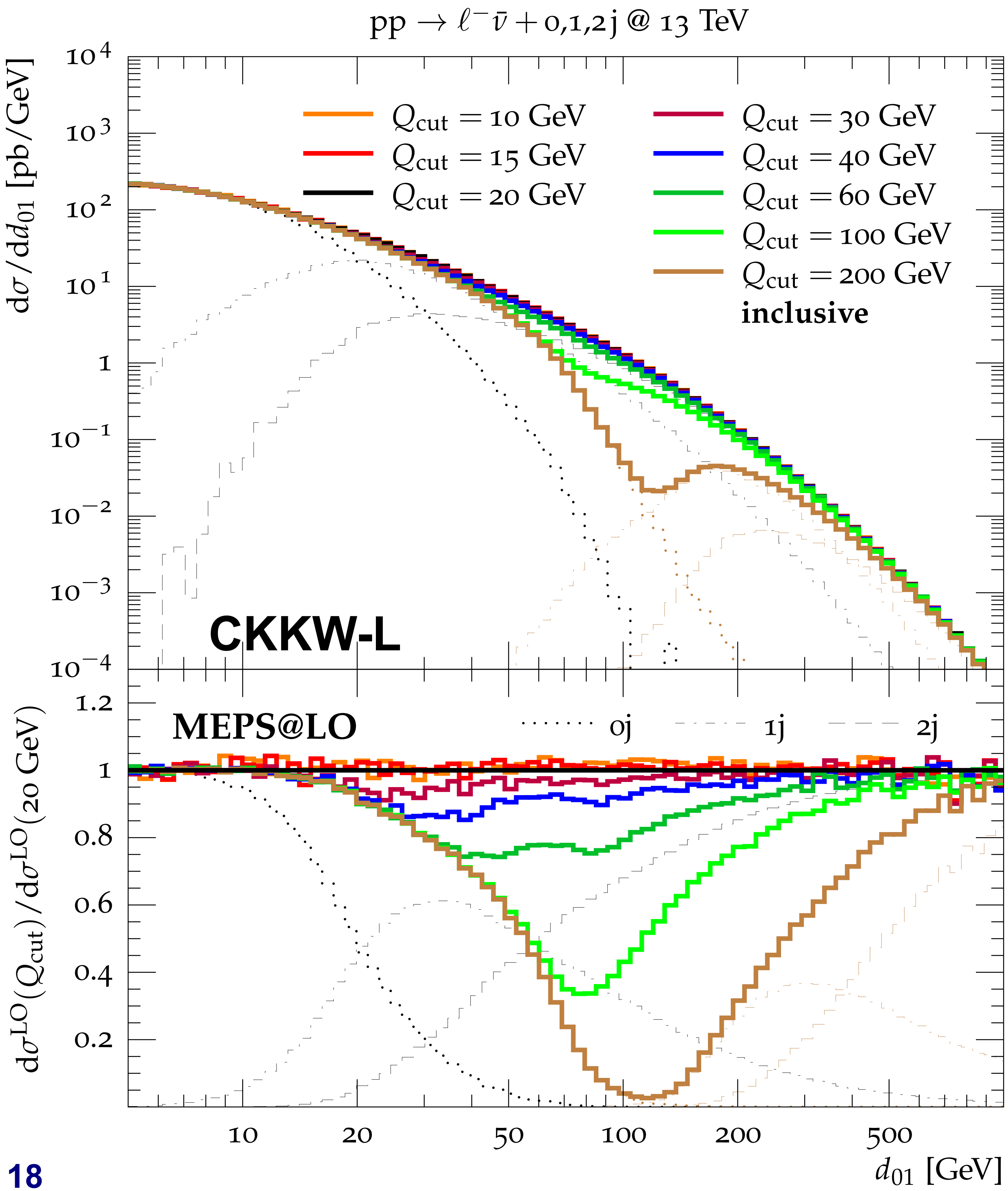
- At LO this has been solved ~15 years ago: use tree-level matrix elements of various multiplicities to generate hard radiation, and the parton shower for the collinear and soft
- Double counting no problem: we simply throw events away when the matrix-element partons are too soft, or when the parton shower generates too hard radiation



- Applying the matrix-element cut is easy: during phase-space integration, we only generate events with partons above the matching scale
- For the cut on the shower, there are two methods. Throwing events away after showering is not very efficient, although it is working ("MLM method")
- Instead we can also multiply the Born matrix elements by suitable product of Sudakov factors (i.e. the no-emission probabilities) $\Delta(Q^{max}, Q^c)$ and start the shower at the scale Q^c ("CKKW method").
- For a given multiplicity we have

$$\sigma_{n,\mathrm{excl}}^{\mathrm{LO}} = B_n \Theta(k_{T,n} - Q^c) \Delta_n(Q_{\mathrm{max}}, Q^c)$$

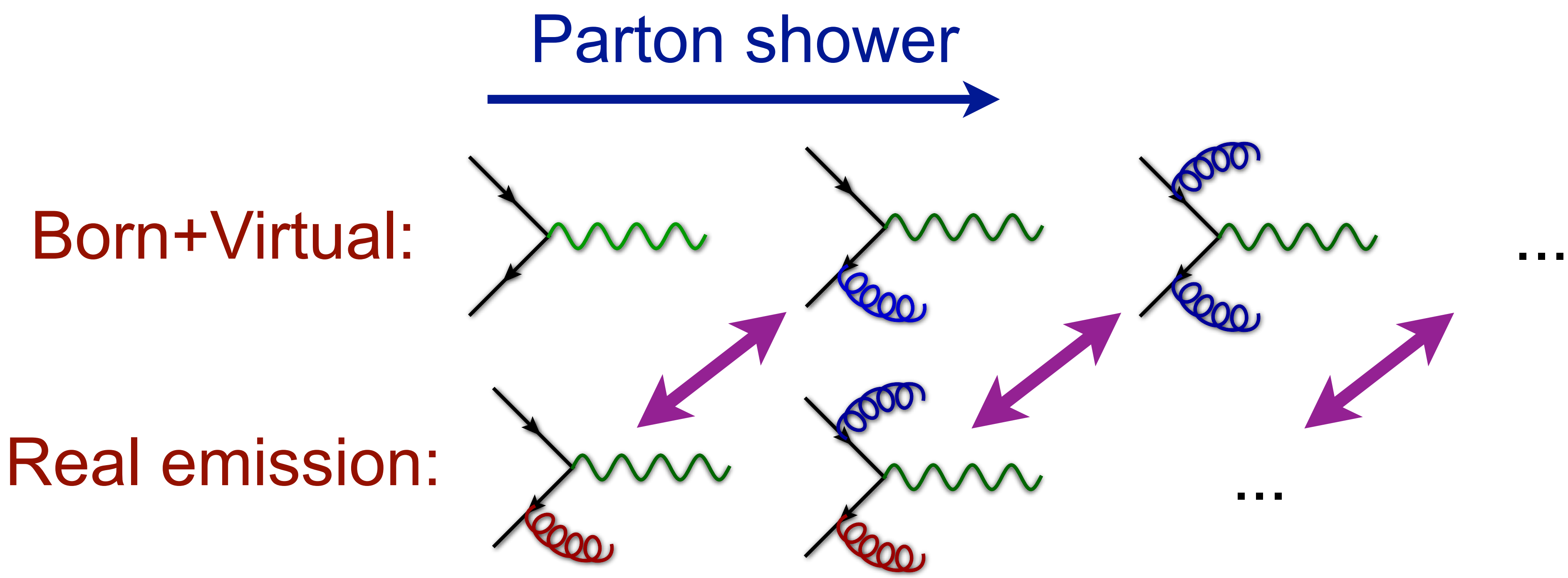
Matching results



- W+jets production: diff. jet rate for 0➞1 transition (~ p_T of hardest jet)
- Small dependence on the merging scale for small values, ~10%
  - When taken too large, the parton shower cannot fill the region all the way up to the merging scale anymore, leading to large deficits

[Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr 2016]

NLO+PS: sources of double counting

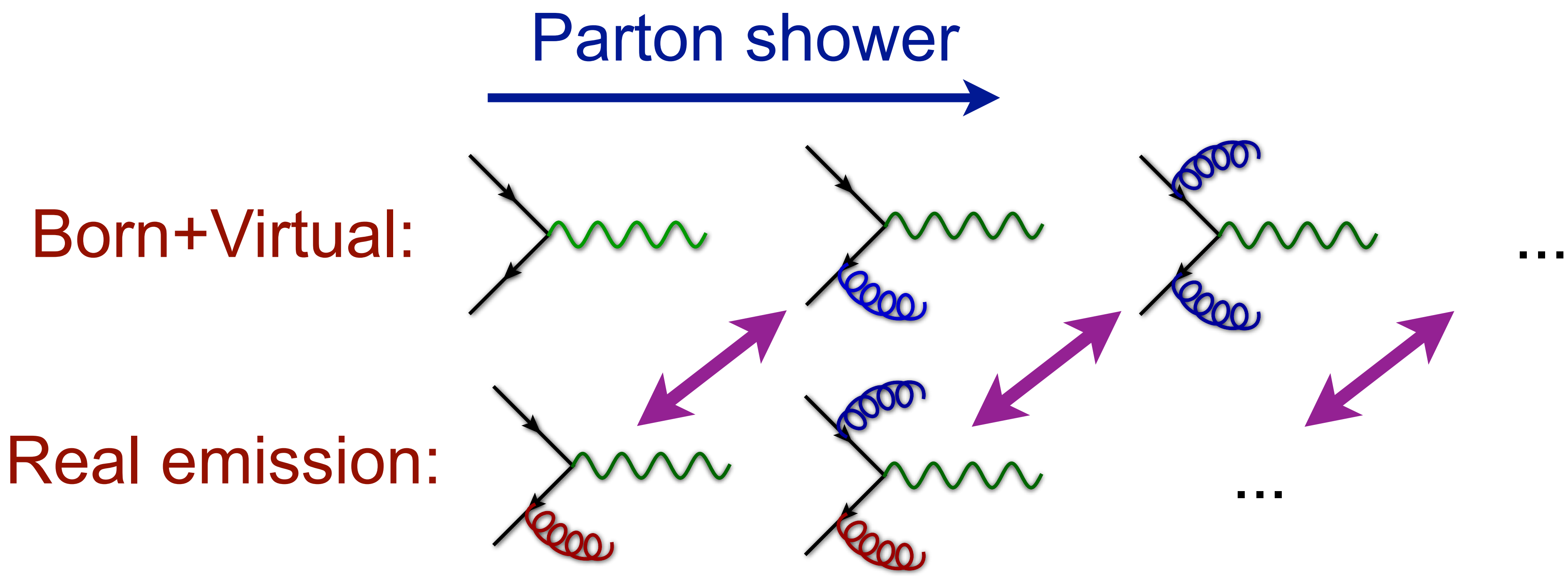


- There is double counting between the real emission matrix elements and the parton shower: the extra radiation can come from the matrix elements or the parton shower
- There is also an overlap between the virtual corrections and the Sudakov suppression in the zero-emission probability
- We have to integrate the real emission over the **complete** phase-space of the one particle that can go soft or collinear to obtain the infra-red poles that will cancel against the virtual corrections
- We can NOT use the same merging procedure as used at LO (MLM or CKKW): requiring that all partons should produce separate jets is not infrared safe

Avoiding double counting

- There are two widely methods to circumvent this double counting
  - MC@NLO (Frixione & Webber)
  - POWHEG (Nason)

MC@NLO procedure



- Double counting is explicitly removed by including the “shower subtraction terms”

$$\frac{d\sigma_{\rm NLOwPS}}{dO} = \left[d\Phi_m \left(B + \int_{\rm loop} V + \int d\Phi_1 MC \right) \right] I_{\rm MC}^{(m)}(O)$$

$$+ \left[d\Phi_{m+1} (R - MC) \right] I_{\rm MC}^{(m+1)}(O)$$

Negative weights

$$\frac{d\sigma_{\text{NLOwPS}}}{dO} = \left[d\Phi_m \left(B + \int_{\text{loop}} V + \int d\Phi_1 MC \right) \right] I_{\text{MC}}^{(m)}(O) + \left[d\Phi_{m+1} (R - MC) \right] I_{\text{MC}}^{(m+1)}(O)$$

- We generate events for the two terms between the square brackets (S- and H-events) separately
- There is no guarantee that these contributions are separately positive (even though predictions for infra-red safe observables should always be positive!)
- Therefore, when we do event unweighting we can only unweight the events **up to a sign**. These signs should be taken into account when doing a physics analysis (i.e. making plots etc.)
- The events are only physical when they are showered

Powheg

- Rescale the Born to "NLO" and modify the Sudakov factor for the first emission:

$$d\sigma_{\text{POWHEG}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} R \right] \left[\tilde{\Delta}(Q^2, Q_0^2) + \tilde{\Delta}(Q^2, t) \; d\Phi_{(+1)} \frac{R}{B} \right]$$

$$\tilde{\Delta}(Q^2, Q_0^2) = \exp\left[-\int_{Q_0^2}^{Q^2} d\Phi_{(+1)} \frac{R}{B} \right]$$

- The term in the square brackets integrates to one (integrated over the extra parton phase-space between scales Q_0^2 and Q^2)
(this can also be understood as unitarity of the shower below scale t)
POWHEG cross section is normalised to the NLO

- Expand up to the first-emission level:

$$d\sigma_{\text{POWHEG}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} R \right] \left[1 - \int d\Phi_{(+1)} \frac{R}{B} + d\Phi_{(+1)} \frac{R}{B} \right] = d\sigma_{\text{NLO}}$$

so double counting is avoided

- Its structure is identical an ordinary shower, with normalisation rescaled by a global K-factor and a different Sudakov for the first emission: no negative weights are involved.

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NLO+PS

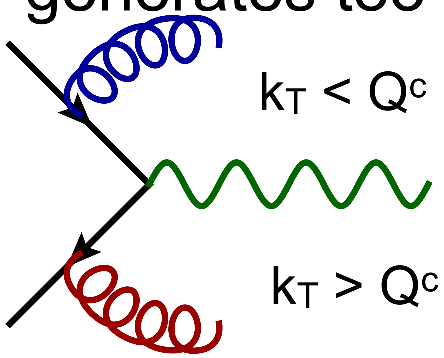
- Advantages:
  - Total cross section and differential distributions related to the hard process are NLO accurate
  - Reduced renormalisation and factorisation scale uncertainties
  - Shower to include multiple emissions; there are models for hadronisation and underlying event
    - Fully exclusive description of the event
- Disadvantages
  - Other observables (e.g., "multi-jet") are only LO accurate, or only generated by the shower

Merging ME+PS at NLO accuracy

Merging ME with PS

CKKW (2004) and MLM (2004)

- At LO this has been solved ~10 years ago: use tree-level matrix elements of various multiplicities to generate hard radiation, and the parton shower for the collinear and soft
- Double counting no problem: we simply throw events away when the matrix-element partons are too soft, or when the parton shower generates too hard radiation
- Applying the matrix-element cut is easy: during phase-space integration, we only generate events with partons above the matching scale



- For the cut on the shower, there are two methods. Throwing events away after showering is not very efficient, although it is working ("MLM method")
- Instead we can also multiply the Born matrix elements by suitable product of Sudakov factors (i.e. the no-emission probabilities) $\Delta(Q^{max}, Q^c)$ and start the shower at the scale Q^c ("CKKW method").
- For a given multiplicity we have

$$\sigma^{\mathrm{LO}}_{n,\mathrm{excl}} = B_n \Theta(k_{T,n} - Q^c)\Delta_n(Q_{\mathrm{max}}, Q^c)$$

Merging at NLO

- To make a LO prediction exclusive in the number of jets, we need to multiply it by a Sudakov damping factor; this is CKKW method:

$$\sigma^{\rm LO}_{n,\rm excl} = B_n \Theta(k_{T,n} - Q^c)\Delta_n(Q_{\rm max}, Q^c)$$

  This makes the prediction exclusive at leading logarithmic accuracy

- Similarly we can make an NLO prediction exclusive at leading logarithm

$$\sigma^{\rm NLO}_{n,\rm excl,\ LL} = \left\{ B_n + V_n + \int d\Phi_1\, R_{n+1} \right\} \Theta(k_{T,n} - Q^c)\Delta_n(Q_{\rm max}, Q^c)$$

- We can improve here and use the real-emission matrix elements instead of just the Sudakov:

$$\sigma^{\rm NLO}_{n,\rm excl,\ LL} = \left\{ B_n + V_n + \int_0^{Q^c} d\Phi_1\, R_{n+1} - B_n \Delta_n^{(1)}(Q_{\rm max}, Q^c) \right\}$$

$$\Theta(k_{T,n} - Q^c)\Delta_n(Q_{\rm max}, Q^c)$$

Exclusive MC@NLO: FxFx merging and MEPS@NLO

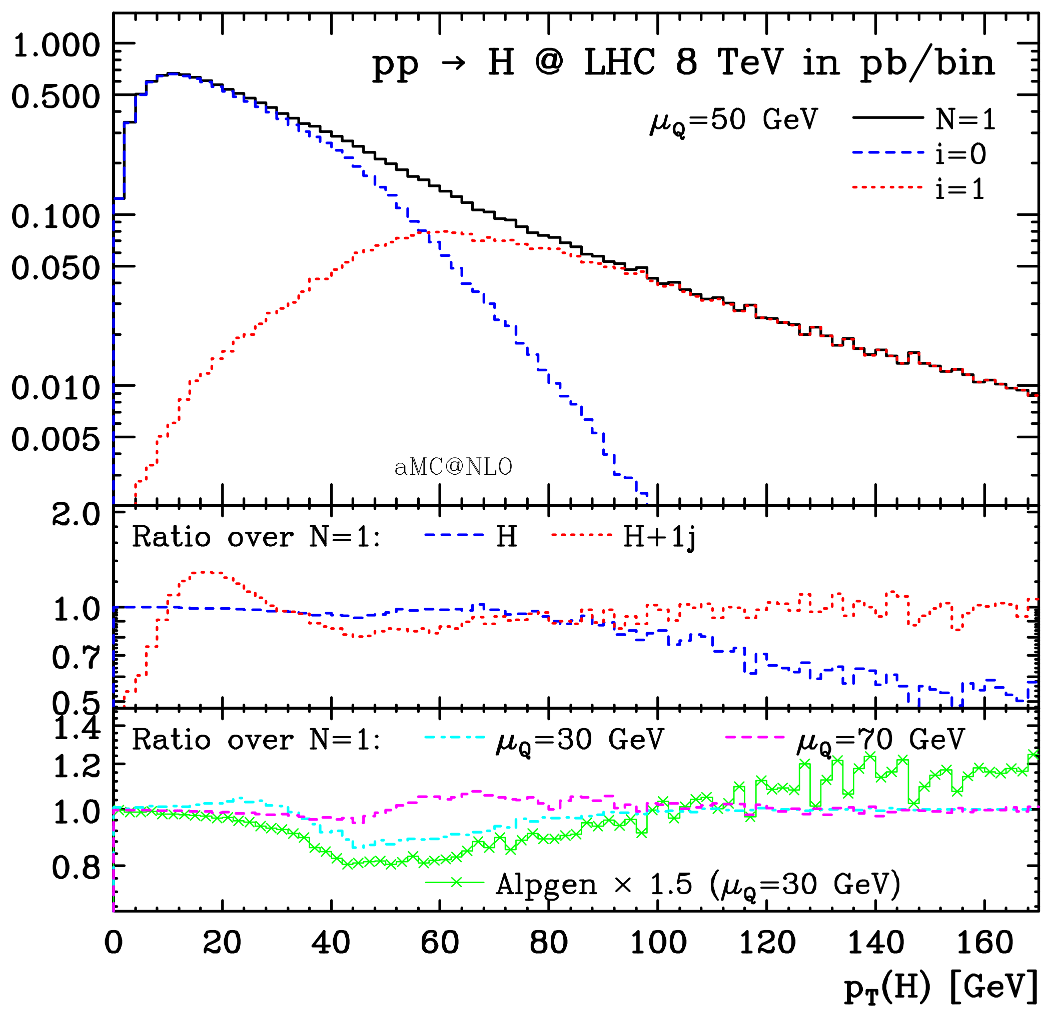
- Converting the NLO exclusive predictions in the number of jets to the MC@NLO event generation is straight-forward:

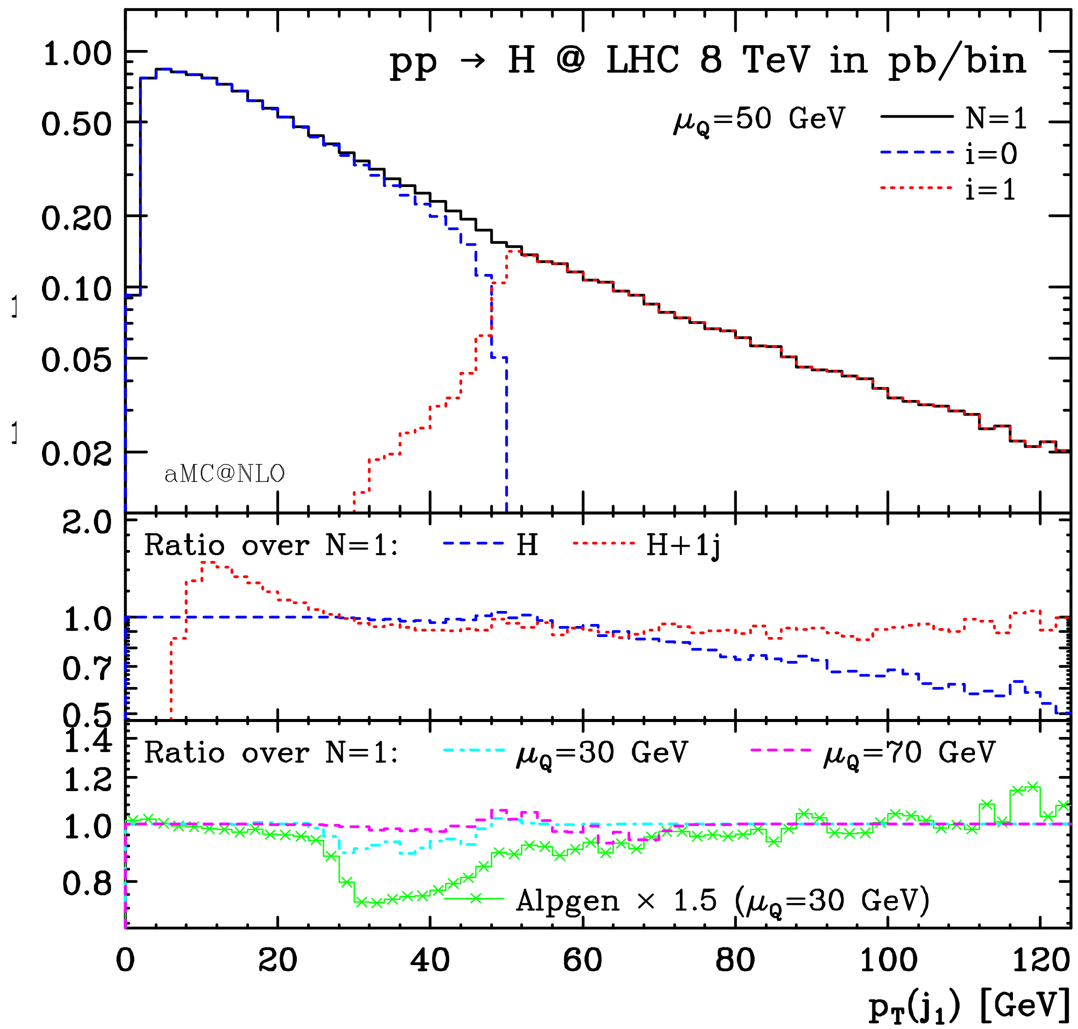
$$\mathbb{S}\text{-events:} \qquad \left\{ B_n + V_n + \int_0^{Q^c} d\Phi_1 \, \mathrm{MC} - B_n \Delta_n^{(1)}(Q_{\max}, Q^c) \right\} \Theta(k_{T,n}^B - Q^c) \Delta_n(Q_{\max}^B, Q^c)$$

$$\mathbb{H}\text{-events:} \qquad \left\{ R_{n+1} \Theta(k_{T,n}^R - Q^c) - \mathrm{MC} \, \Theta(k_{T,n}^B - Q^c) \right\} \Theta(Q^c - k_{T,n+1}^R) \Delta_n(Q_{\max}^R, Q^c)$$

FxFx merging: Higgs boson production

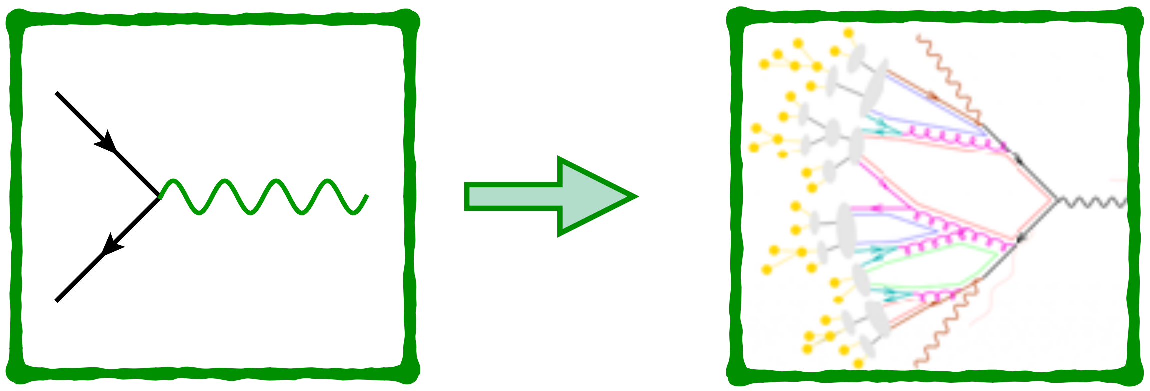
[RF and Frixione]

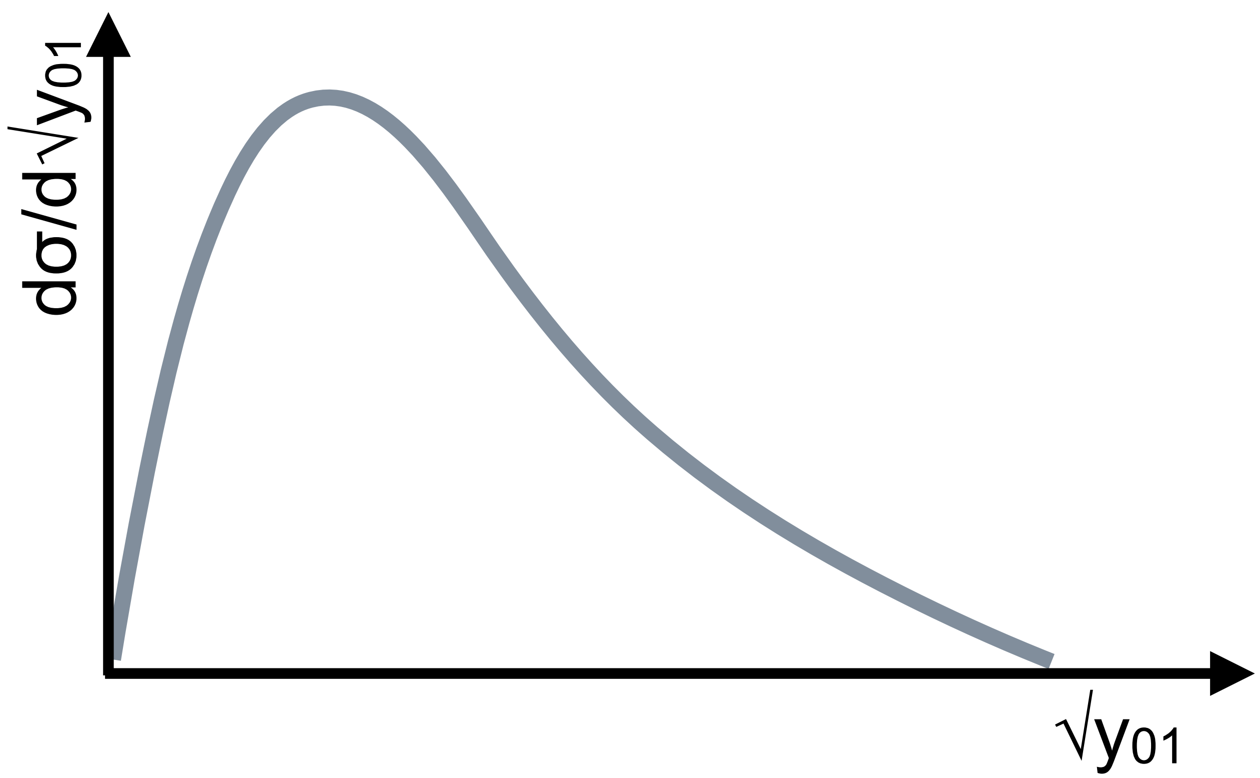




- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with H+0j at MC@NLO and H+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale

NLO+PS V



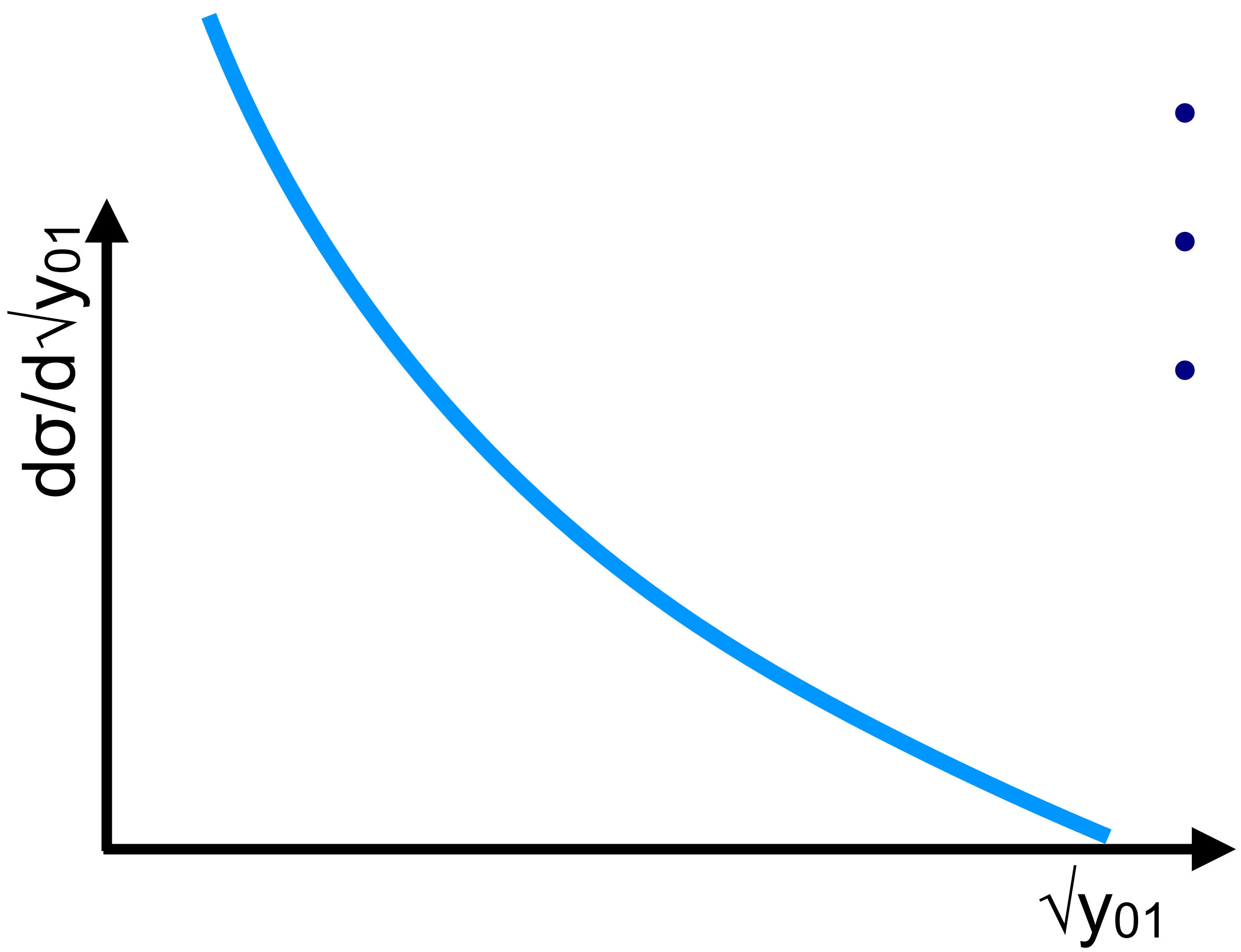


- To get a physical shape at low p_T need to resum radiation at all orders
- Can either be done analytically, or with a **parton shower**
- Parton shower also includes hadronisation and other non-factorisable corrections
- Most used methods are MC@NLO and POWHEG

Physical curve	**Yes**
Tail	**LO**
Integral	**NLO**
Extendible to multi-jet	**Yes**

MC@NLO: [Frixione, Webber (2002)]
POWHEG: [Nason (2004)]

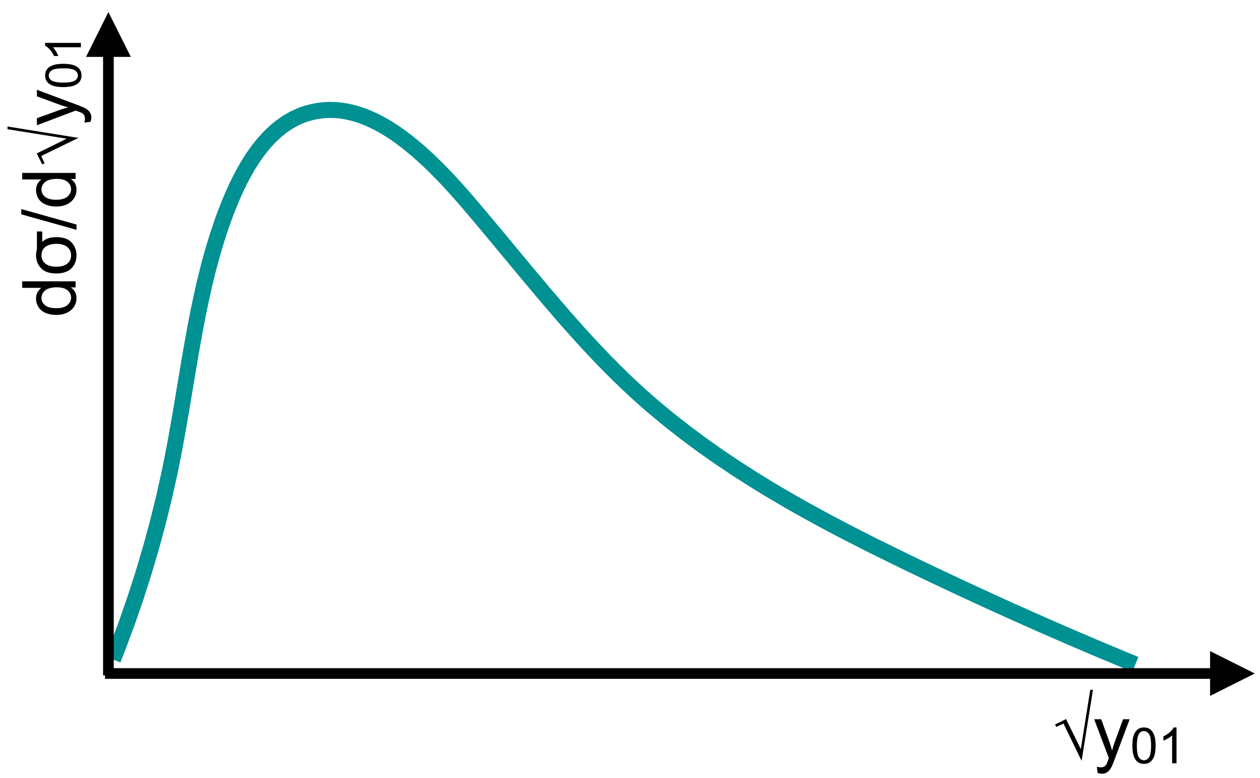
NLO(+PS) V+1 jet



- Distribution diverges at small p_T
- Have to put a generation cut
- Parton shower can easily be added, but this does not solve the low-p_T problem

Physical curve	**Only at high-p_T**
Tail	**NLO**
Integral	**∞**
Extendible to multi-jet	**Yes**

Minlo V+1jet



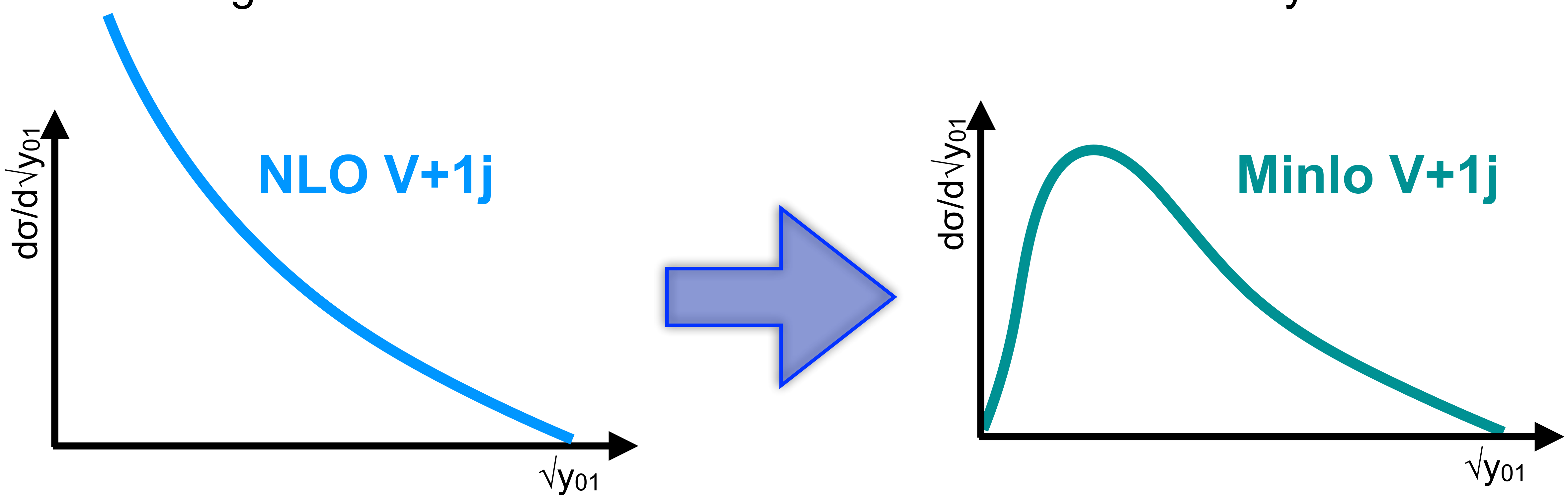
[Hamilton, Nason, Zanderighi (2012)]

- Include suitable Sudakov Form factors in the NLO V+1j predictions
- Distributions is NLO accurate
- Integral is not NLO accurate: the difference starts at $O(\alpha_s^{3/2})$
- Parton shower can easily be attached

Physical curve	**Yes**
Tail	**NLO**
Integral	**LO+**
Extendible to multi-jet	**Yes**

Minlo

- The Minlo approach can be summarised as follows:
  - Renormalisation and factorisation scale setting, a la CKKW
  - Together with matching to the Sudakov form factor, $\exp\left[-R\left(v\right)\right]$
    - Matching requires to subtract the O(alpha_s) expansion of the Sudakov form factor times the Born to prevent double counting with the NLO corrections
  - NLO accuracy of V+1j observables is not hampered by the scale setting and inclusion of the form factor: differences are beyond NLO



Minlo decomposed

$$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$$

Resummed cross section. (Almost) identical to known LL/NNLL$_\sigma$ results

Logarithmically enhanced terms for y->0 that are not captured by dσ_R

Finite terms in the limit y->0 (coming from real emission corrections)

Resummed cross section

$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$

[Banfi, Salam, Zanderighi (2005); Dokshitzer, Diakonov, Troian (1980)]

$$\frac{d\sigma_{\mathcal{R}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi}\left[1 + \bar{\alpha}_S\left(\mu_R^2\right)\mathcal{H}_1\left(\mu_R^2\right)\right]\frac{d}{dL}\left[\exp\left[-R\left(v\right)\right]\mathcal{L}\left(\{x_\ell\},\mu_F,v\right)\right]$$

LO cross section

(Hard) virtual contributions

Sudakov form factor

Luminosity factor

$L = \log(1/v) = \log(Q^2/y)$

- Well-known formula; used e.g. in the Caesar approach
- Sudakov form factor exp[R] not identical to what's (originally) used in Minlo. But Minlo approach can be improved to incorporate these terms (not relevant when colour is trivial)
- Written as **total derivative**: straight-forward to show that this is NLO correct in phase-space Φ up to $d\sigma_F$ after integration over *L* and expanding in α_S
- However, not NLO correct in the dΦdL phase space (i.e., tail is not NLO correct)

Accuracy of Minlo

$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$

- Explicit derivation, using the general form of the differential NLO V+1j cross sections in the small y limit,

$$\frac{d\sigma_{\mathcal{S}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \sum_{n=1}^{2} \sum_{m=0}^{2n-1} H_{nm} \bar{\alpha}_{\mathrm{S}}^{n} \left(\mu_{R}^{2}\right) L^{m}$$

gives

$$\frac{d\sigma_{\mathcal{MR}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \exp\left[-R\left(v\right)\right] \prod_{\ell=1}^{n_i} \frac{q^{(\ell)}\left(x_\ell, \mu_F^2 v\right)}{q^{(\ell)}\left(x_\ell, \mu_F^2\right)} \left[\bar{\alpha}_{\mathrm{S}}^{2}\left(K_R^2 y\right) \left[\widetilde{R}_{21}\, L + \widetilde{R}_{20}\right] + \bar{\alpha}_{s}^{3}\left(K_R^2 y\right) L^2\, \widetilde{R}_{32}\right]$$

Only non-zero when exp[R] and Minlo Sudakov exponent are different, or when exp[R] is not NNLL$_\sigma$ accurate.

Unknown coefficient!

Known coefficient

Minlo accuracy for (inclusive) 0-jet observables

$$\frac{d\sigma_{\mathcal{MR}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \exp\left[-R(v)\right] \prod_{\ell=1}^{n_i} \frac{q^{(\ell)}\left(x_\ell, \mu_F^2 v\right)}{q^{(\ell)}\left(x_\ell, \mu_F^2\right)} \left[\bar{\alpha}_S^2\left(K_R^2 y\right)\left[\widetilde{R}_{21} L + \widetilde{R}_{20}\right] + \bar{\alpha}_s^3\left(K_R^2 y\right) L^2 \widetilde{R}_{32}\right]$$

- After integration over the logarithm L (taking R_{21}=0, which is okay for the processes considered here) this results into terms of

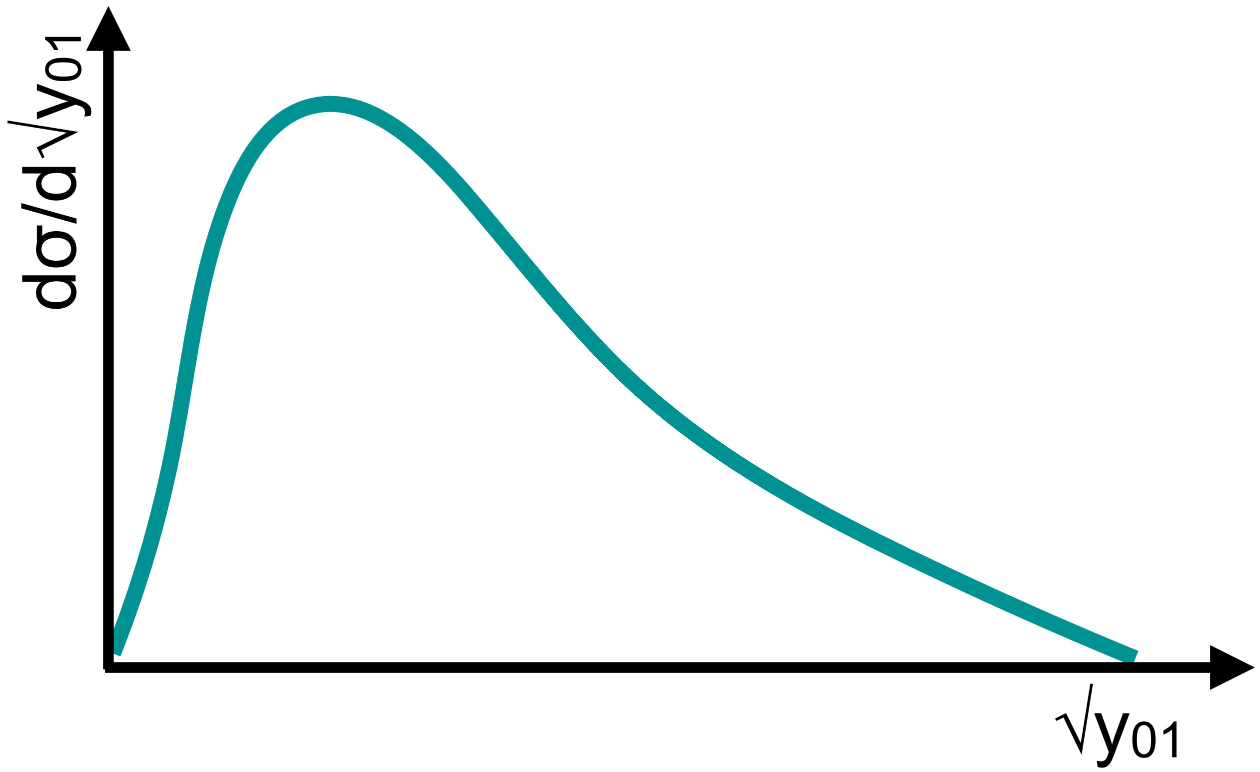
$$\int dL' \frac{d\sigma_{\mathcal{MR}}}{d\Phi dL'} = -\frac{d\sigma_0}{d\Phi}\left[\widetilde{R}_{20} - \bar{\beta}_0 \mathcal{H}_1\left(\mu_R^2\right)\right] \sqrt{\frac{\pi}{2}} \frac{1}{\left|2G_{12}\right|^{1/2}} \bar{\alpha}_S^{3/2}\left(1 + \mathcal{O}\left(\sqrt{\bar{\alpha}_S}\right)\right)$$

- Hence, diff. NLO-0jet cross section not correct with NLO-1jet Minlo

[Hamilton, Nason, Oleari, Zanderighi (2012); RF, Hamilton (2015)]

$$\int_{\Lambda^2}^{Q^2} \frac{dq_T^2}{q_T^2} \log^m \frac{Q^2}{q_T^2}\, \alpha_S^n\left(q_T^2\right) \exp \mathcal{S}\left(Q, q_T\right) \approx \left[\alpha_S\left(Q^2\right)\right]^{n - \frac{m+1}{2}}$$

Minlo V+1jet

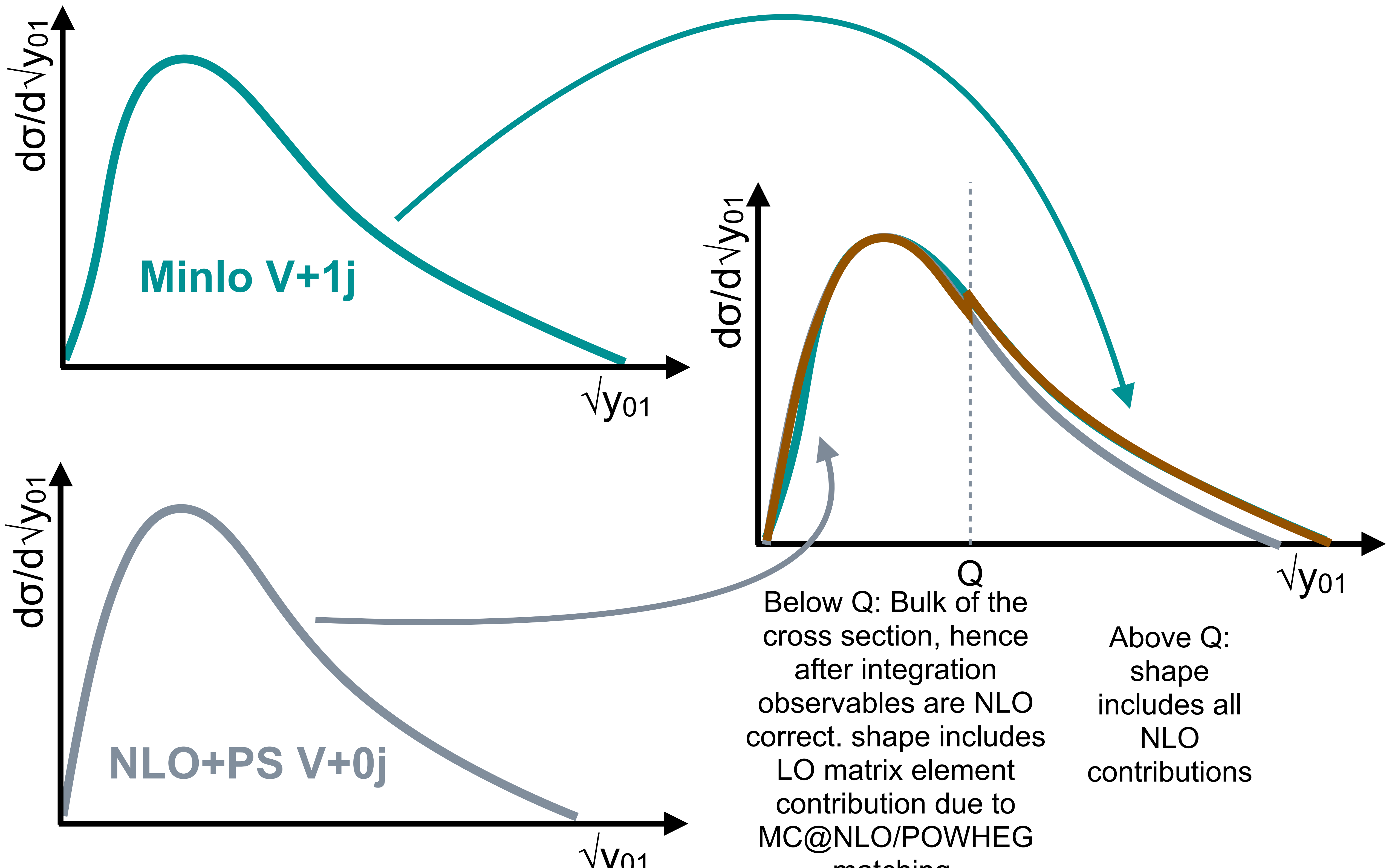


[Hamilton, Nason, Zanderighi (2012)]

- Include suitable Sudakov Form factors in the NLO V+1j predictions
- Distributions is NLO accurate
- Integral is not NLO accurate: the difference starts at $O(\alpha_s^{3/2})$
- Parton shower can easily be attached

Physical curve	**Yes**
Tail	**NLO**
Integral	**LO+**
Extendible to multi-jet	**Yes**

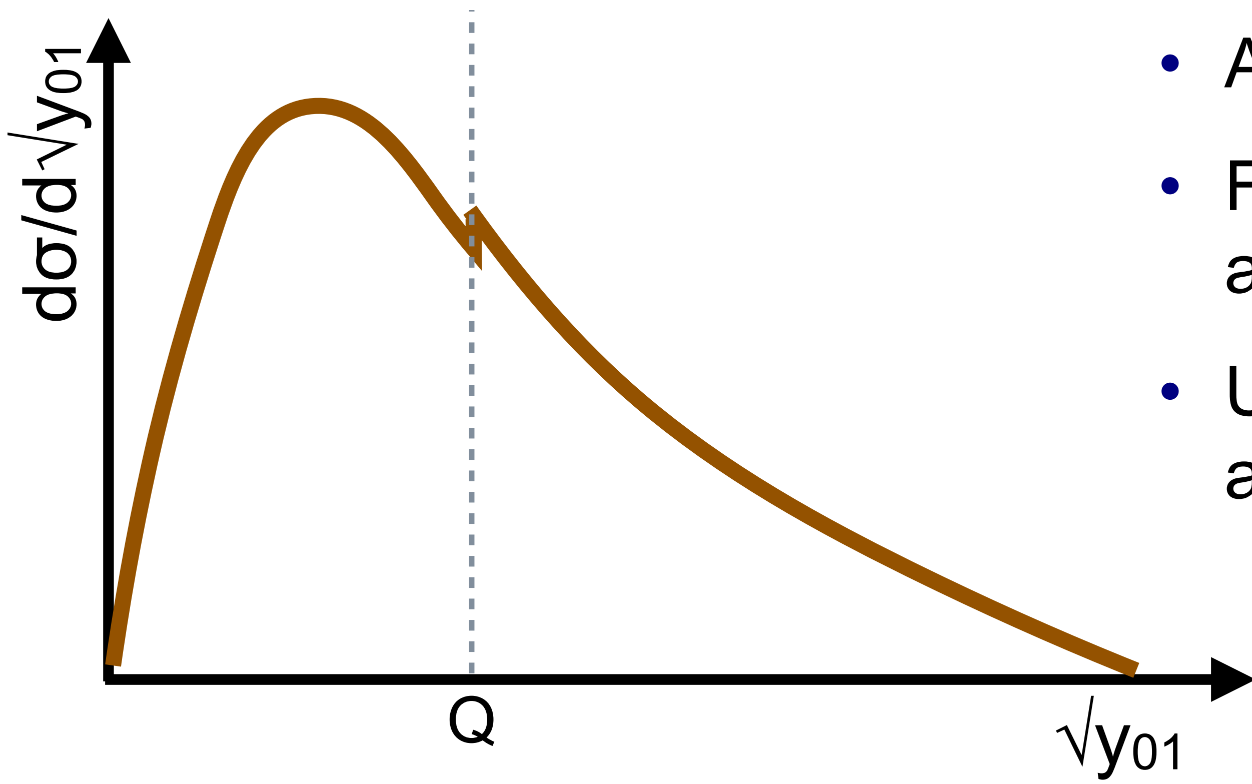
Getting 0-jet observables NLO correct



Below Q: Bulk of the cross section, hence after integration observables are NLO correct. shape includes LO matrix element contribution due to MC@NLO/POWHEG matching.

Above Q: shape includes all NLO contributions

FxFx / Meps@nlo: V & V+1j merging



- Merge NLO+PS for V with Minlo for V+1j, at "merging scale" Q
- Above Q the tail is NLO accurate
- For not-too-small Q, integral is NLO accurate
- Used by ATLAS & CMS for LHC run II analyses

FxFx: [RF, Frixione (2012)]
MEPS@NLO: [Hoeche, Krauss, Schonherr, Siegert; +Gehrmann (2012)]

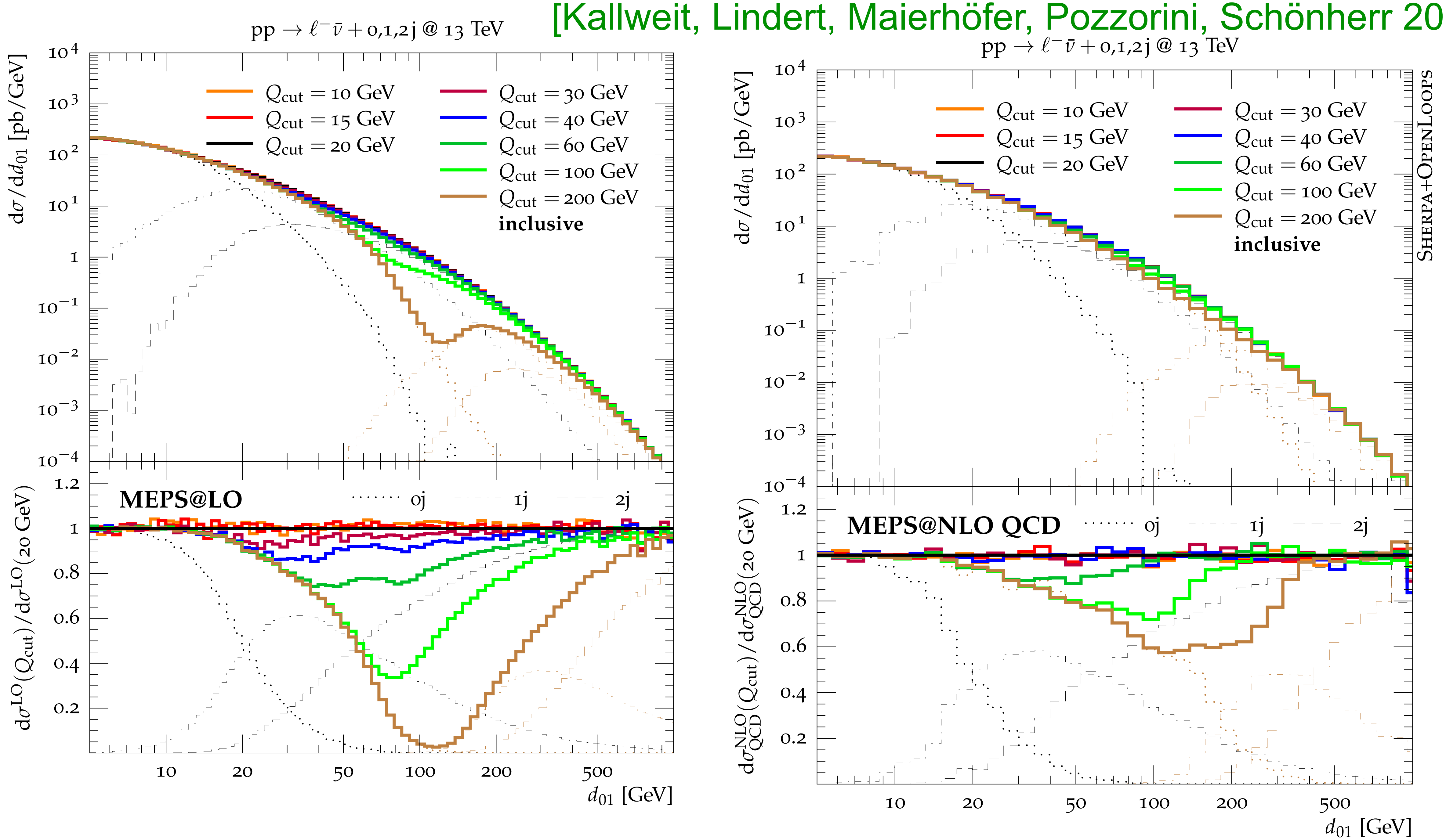
Physical curve	**Yes**
Tail	**NLO**
Integral	**NLO**
Extendible to multi-jet	**Yes**

Differences between FxFx & MEPS@NLO

- Both FxFx and MEPS@NLO merging are based on making MC@NLO calculation for jet-multiplicities *exclusive* in more jets
  - Veto additional radiation; resum dependence on the veto scale (=merging scale)
- Major difference is in the way this exclusivity is applied
  - CKKW-L approach (i.e. Sudakov rejection based on shower kernels)
    - Used in Sherpa's "MEPS@NLO"
    - Using shower kernels prevents for a direct link with Minlo approach (and comparison to analytic resummation and accuracy), but prevents issues with mismatch in k_T and shower ordering values
  - Minlo (CKKW) from hard scale down to the scale of the softest jet not affected by veto; MLM-type rejection from there down to merging scale
    - Used in MadGraph5_aMC@NLO w/ Pythia/Herwig: "FxFx merging"
    - Direct link with Minlo, but MLM-type rejection prevents mismatches in ordering values

Merging scale dependence

[Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr 2016]



- Besides having the benefits from higher-accurate matrix elements, there is also a **smaller merging scale dependence at NLO**

Conclusions

- In the last couple of years the accuracy of event generation has greatly improved, and full automation has been achieved at NLO accuracy
- A lot of freedom in tuning has been replaced by accurate theory descriptions:
  - More predictive power
  - Better control on uncertainties
  - Greater trust in the measurements
- Recent developments for which I have had no time
  - NLO EW corrections and the parton shower
  - Combining NNLO in QCD and the parton shower: MINNLO
  - MC@NLO-Delta: reducing negative weights in MC@NLO