NLO merging:
overview and recent developments

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LO+PS (standard Generators like Herwig, Pythia, Sherpa)

LO merging

CKKW(-L) MLM

MEPS ULOPS

NLO matching

MC@NLO POWHEG

NLO merging

MEPS@NLO

GENEVA
See talk by S. Alioli

FxFx UNLOPS Herwig7.1

See talk by S. Alioli for:

UNNLOPS NNLOPS

LO+PS

How to describe exclusive/differential observables?

QCD

$f_a(x)$

$d\sigma/d\vec{x}$

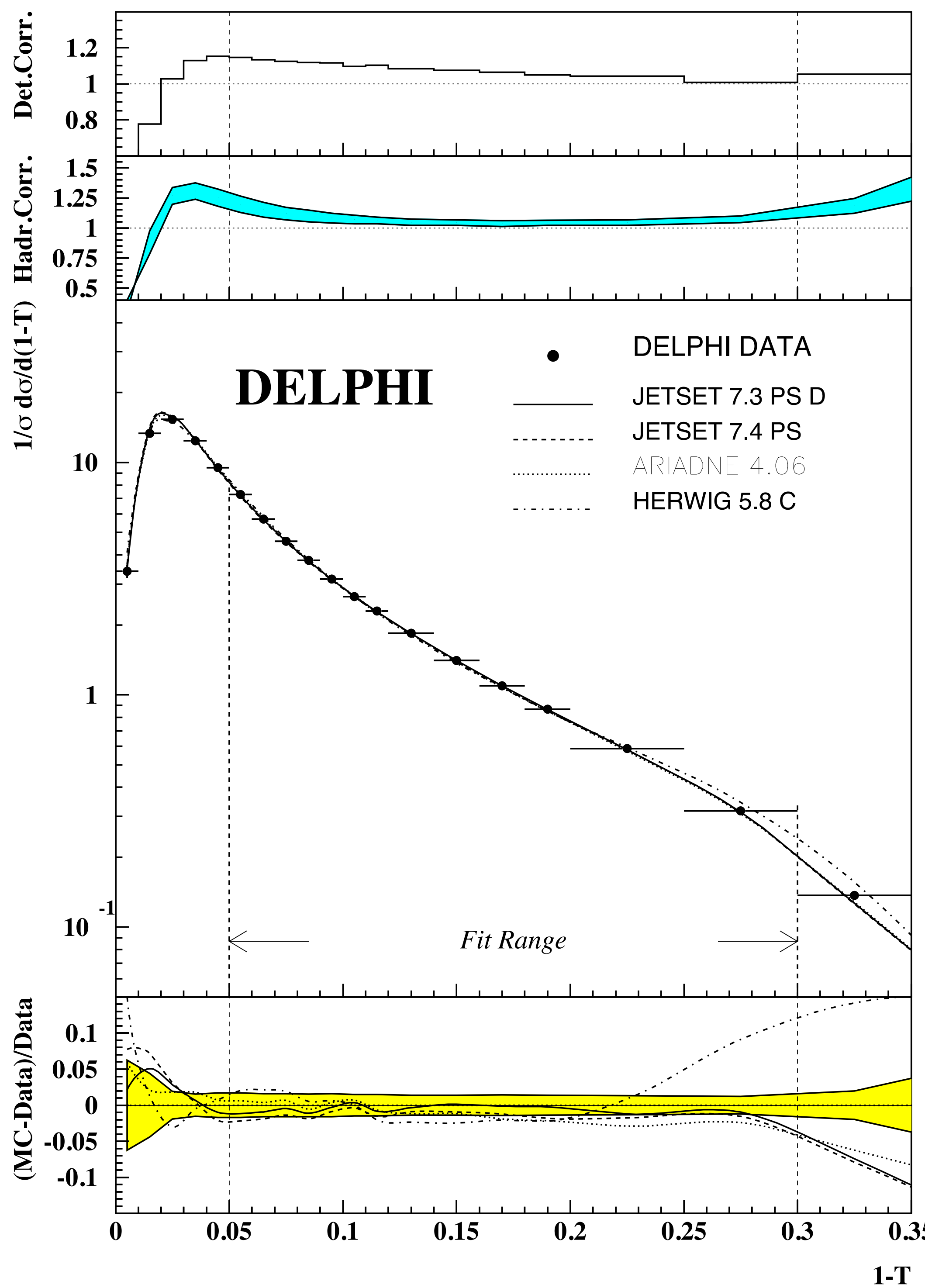
QED

α_s

$PS[\phi_i(Q)]$ Parton Shower

$$\Delta_\mu^Q = e^{-\int \sum_j P_j(z)\theta_j d\phi_{n+1}}$$

emission/no emission



Eur.Phys.J. C14 (2000) 557-584

Motivation

Event generators try to describe data in a full simulation.
So starting from hard processes to the hadronisation and decays.

Parton showers are needed to get to high multiplicities and describe fully exclusive observables.

Approximation breaks for large angle or hard emissions.

Merging of LO predictions helps to correct for these emission but are still LO.

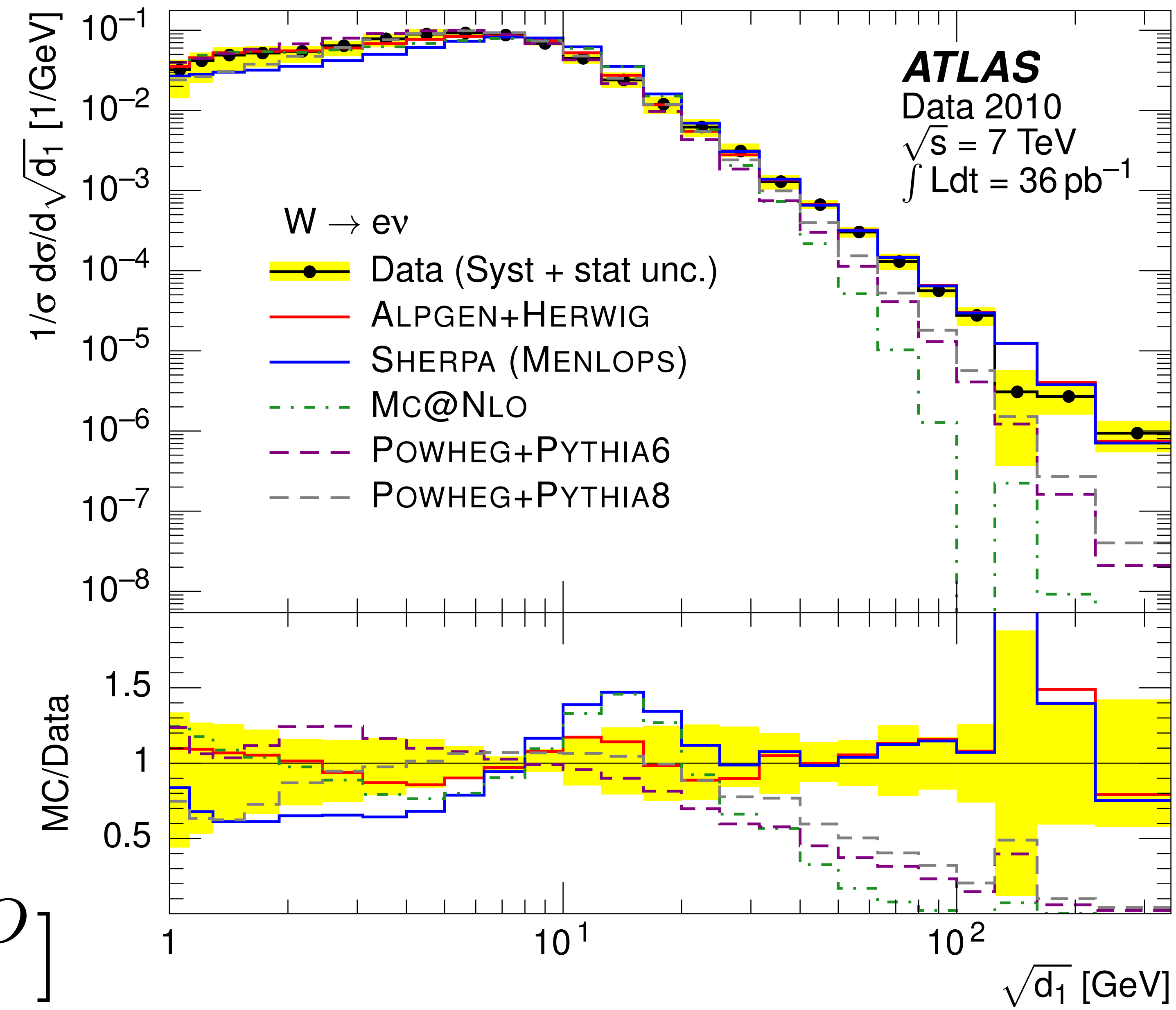
Aim: Full simulation with NLO corrections for inclusive cross section and hard emissions.

NLO matching

MC@NLO (& POWHEG)

Solving the double counting problem by subtraction.

Expand the shower to $\mathcal{O}(\alpha_S)$ in emissions and no emissions.

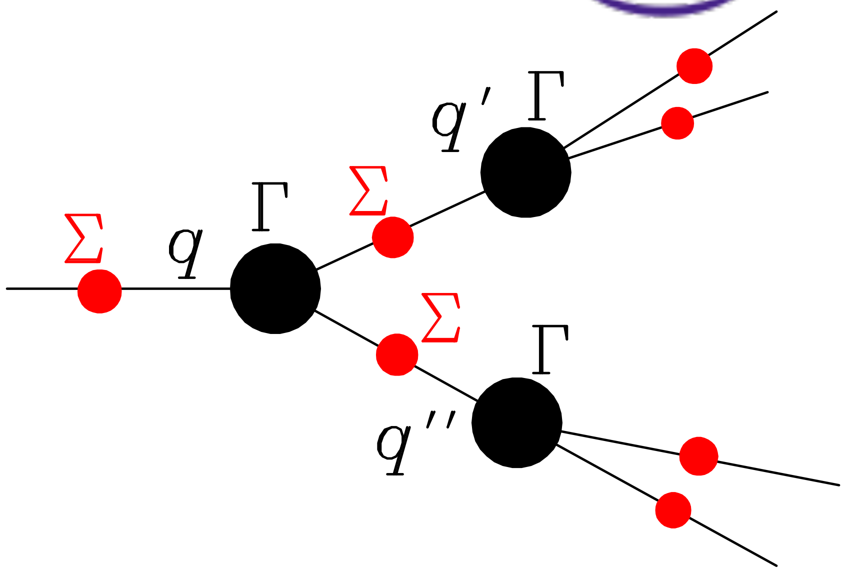


$$PS[d\sigma^{matched}] = PS_0[d\sigma^{LO}]$$
$$+ PS_0[d\sigma^{V} + \int d\phi_1 P(z) d\sigma^{LO}]$$
$$+ PS_1[d\sigma^{R} - d\phi_1 P(z) d\sigma^{LO}]$$

Eur. Phys. J. C, 73 5 (2013) 2432

LO merging

CKKW(-L) (& MLM)



(picture from MiNLO, see next slide)

Merging several exclusive LO cross sections needs:

1. Find a shower history for different multiplicities.
2. Reweight with no emission probabilities for intermediate scales between the emissions and from last scale to shower cutoff (except highest mult.) .
3. Reweight the emissions with appropriate running couplings.

$$\Gamma_q(q,Q) = \frac{2C_F}{\pi}\frac{\alpha_S(q)}{q}\left(\ln\frac{Q}{q}-\frac{3}{4}\right)$$

$$\Gamma_g(q,Q) = \frac{2C_A}{\pi}\frac{\alpha_S(q)}{q}\left(\ln\frac{Q}{q}-\frac{11}{12}\right)$$

$$\Gamma_f(q) = \frac{N_f}{3\pi}\frac{\alpha_S(q)}{q} ,$$

$$R_2(Q_1,Q) = [\Delta_q(Q_1,Q)]^2 ,$$

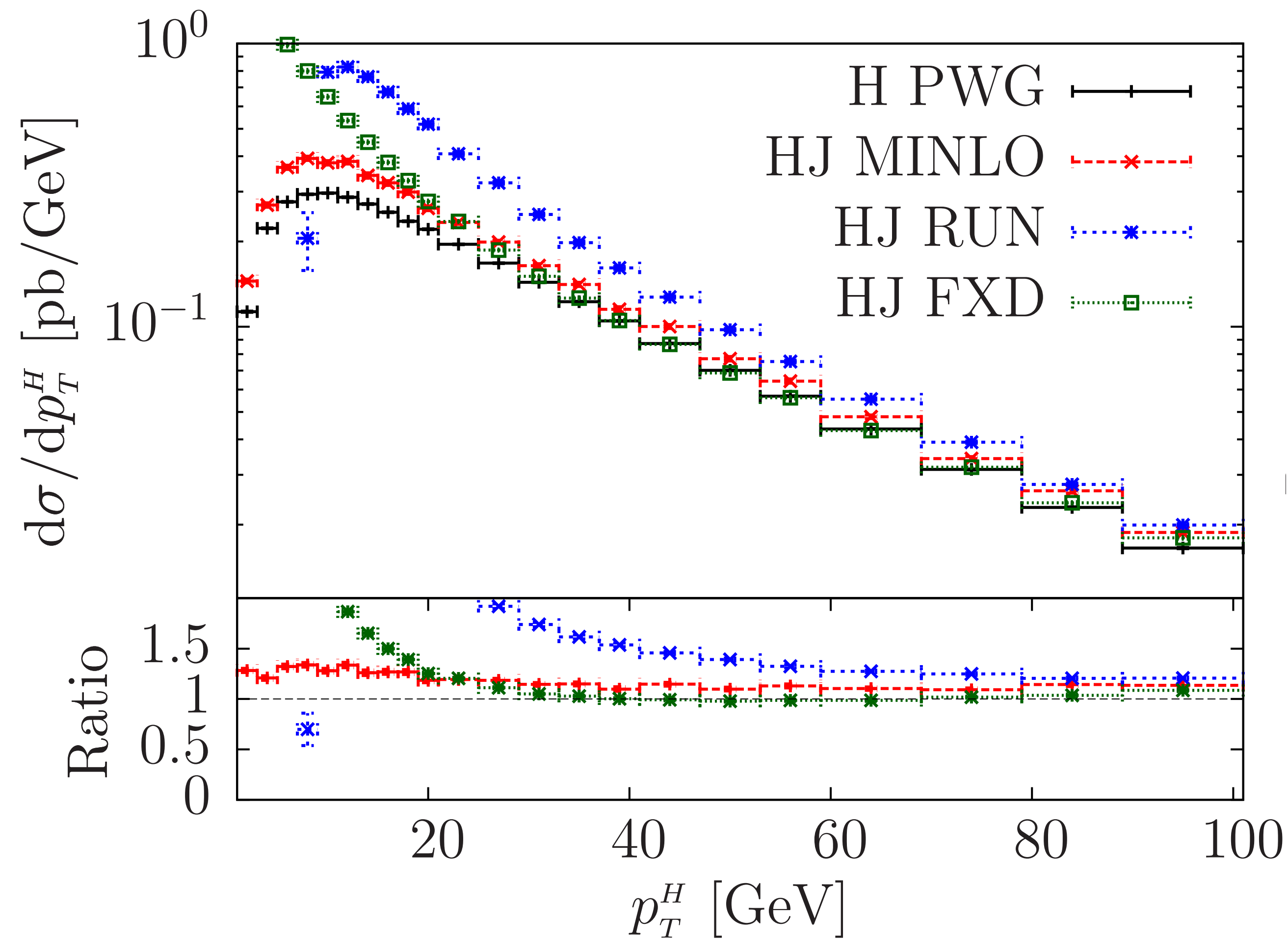
$$R_3(Q_1,Q) = 2\,[\Delta_q(Q_1,Q)]^2\int_{Q_1}^{Q} dq\,\Gamma_q(q,Q)\Delta_g(Q_1,q)$$

Catani,Krauss,Kuhn,Webber, JHEP 0111 (2001) 063

MiNLO (Multi-scale improved NLO)

Combining fixed order NLO for e.g. H+jet with ideas of LO merging/resummation.

Reweight with (analytic) shower history.



$$\bar{B} = \alpha_S^2\left(M_H^2\right)\alpha_S\left(q_T^2\right)\Delta_g^2\left(M_H, q_T\right)\left[B\left(1 - 2\Delta_g^{(1)}\left(M_H, q_T\right)\right) + V + \int d\Phi_{\rm rad}\, R\right]$$

weighted with Sudakov suppression (e.g. Higgs):

$$F = \alpha_S^2(M_H)\alpha_S(p_T)\left\{\exp\left[-\frac{C_A}{\pi b_0}\left\{\log\frac{\log\frac{Q^2}{\Lambda^2}}{\log\frac{Q_0^2}{\Lambda^2}}\left(\frac{1}{2}\log\frac{Q^2}{\Lambda^2} - \frac{\pi b_0}{C_A}\right) - \frac{1}{2}\log\frac{Q^2}{Q_0^2}\right\}\right]\right\}^2$$

Hamilton, Nason, Zanderighi, JHEP 1210 (2012) 155

NLO merging

Same problems as matching and LO merging (combined).

Idea: Use LO merging and expand to $\mathcal{O}(\alpha_S)$
as it was done in the matching.

Lowest multiplicity basically behaves as in NLO matching??

$$PS[d\sigma^{merged}] = PS_0^V[d\sigma^0\Delta_\mu^0] + PS_1^V[d\sigma^1\Delta_1^0\Delta_\mu^1] + PS_2[d\sigma^2\Delta_1^0\Delta_2^1\Delta_\mu^1]$$

The expanded version constructs
the subtraction expression as in NLO matching

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$$\Delta_\mu^0 = 1 - \int d\phi_1 P(z) + \mathcal{O}(\alpha_S^2)$$

$$PS[d\sigma^{matched}] = PS_0[d\sigma^{LO}] + PS_0[d\sigma^V + \int d\phi_1 P(z) d\sigma^{LO}] + PS_1[d\sigma^R - d\phi_1 P(z) d\sigma^{LO}]$$

$$d\sigma^1 = d\sigma^R + \mathcal{O}(\alpha_S^2)$$

NLO merging

Same problems as matching and LO merging (combined).

Idea: Use LO merging and expand to $\mathcal{O}(\alpha_S)$
as it was done in the matching.

Weight in LO merging:

$$B_1 \, \Delta_1^0 \, \theta_{ME} = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta_{q_1}^0 \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_{ME}$$

history weight

also needs to be expanded up to $\mathcal{O}(\alpha_S)$

MEPS@NLO

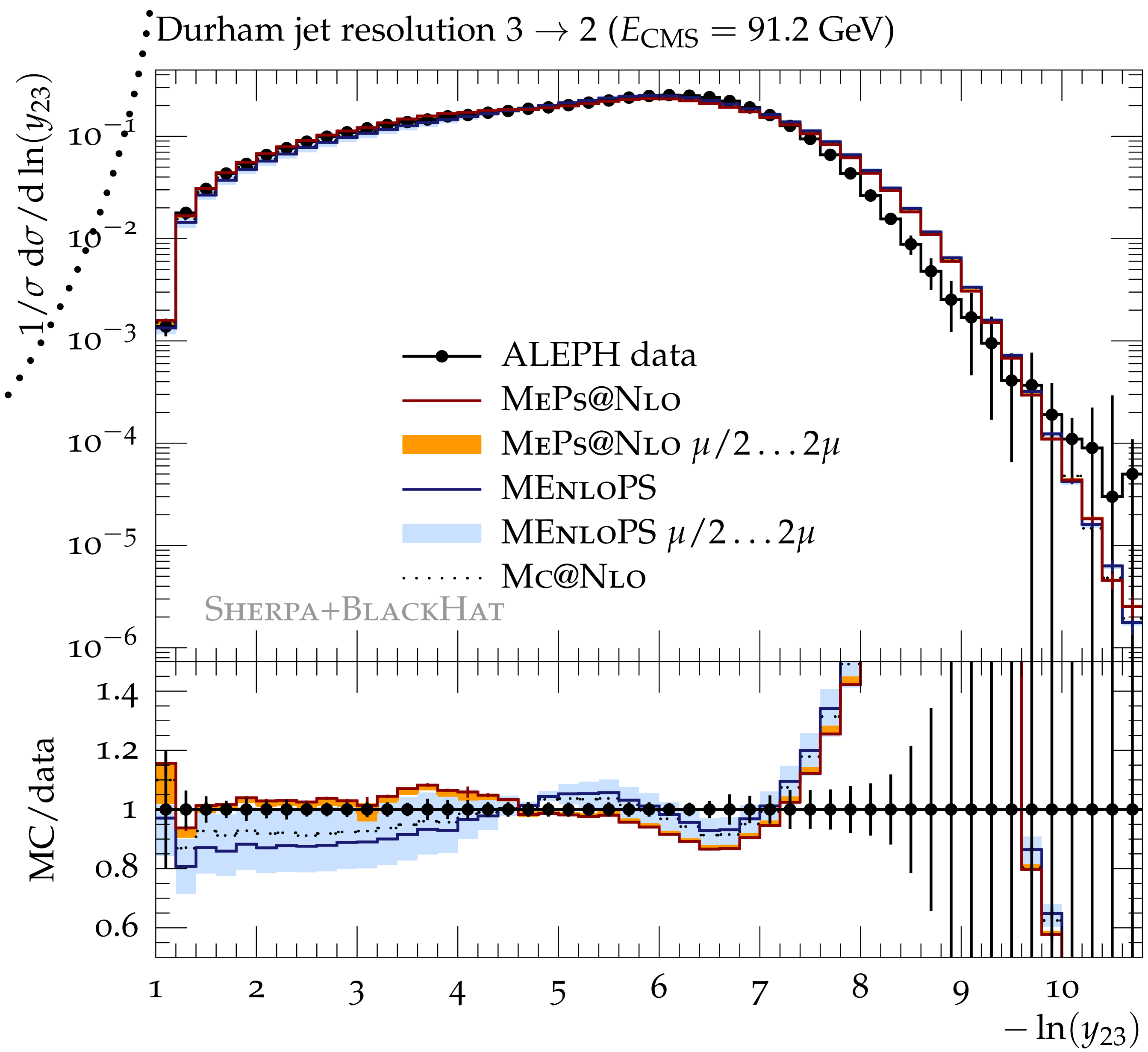
$$B_1 \, \Delta_1^0 \, \theta_{ME} = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta_{q_1}^0 \, \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \, \frac{f_0(Q_f)}{f_0(q_1)} \, \frac{f_1(q_1)}{f_1(Q_f)} \, \theta_{ME}$$

$$\alpha_s(\tilde{\mu}_R^2)^n \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\beta_0 \sum_{i=1}^{n} \log \frac{\mu_i^2}{\tilde{\mu}_R^2}\right)$$

Expanding (naturally) produces expressions used in the MiNLO ansatz.

$$\bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}\left(1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1 \, \mathrm{K}_n\right)$$

In addition one needs to expand the intermediate Sudakov factors.

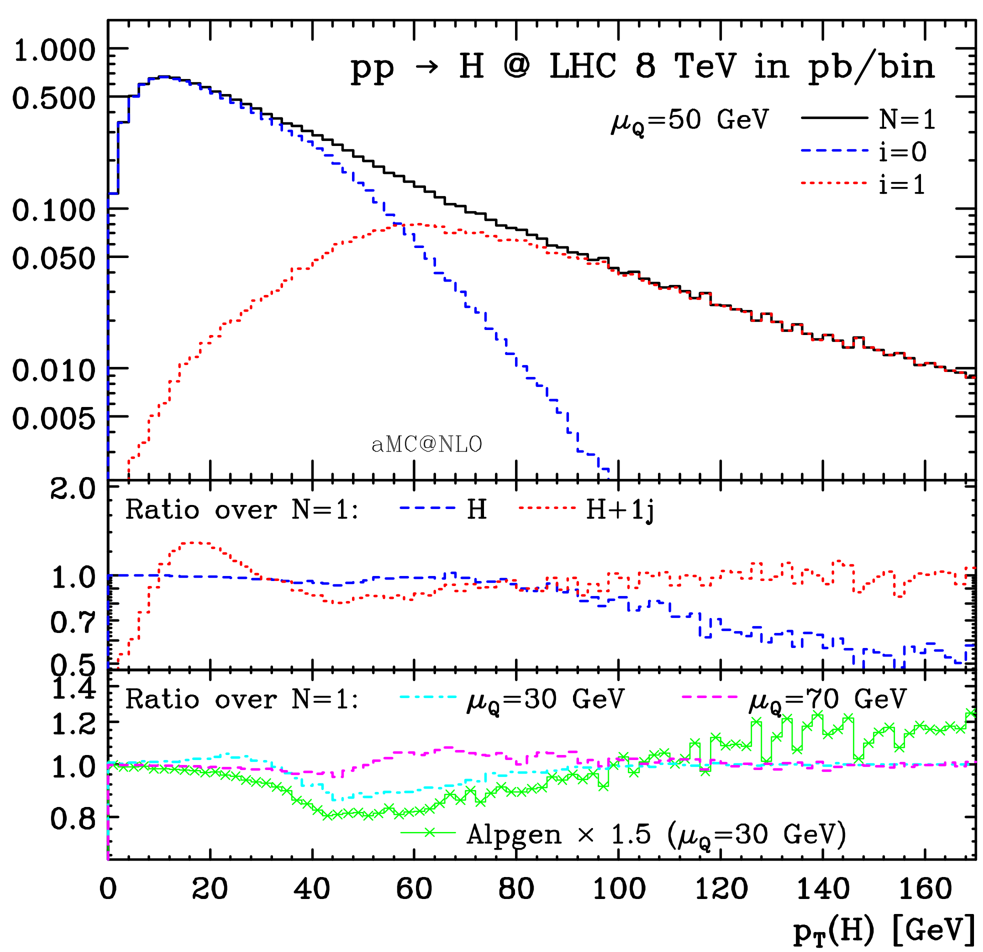


Gehrmann, Höche, Krauss, Schönherr, Sieger JHEP 1301 (2013) 144

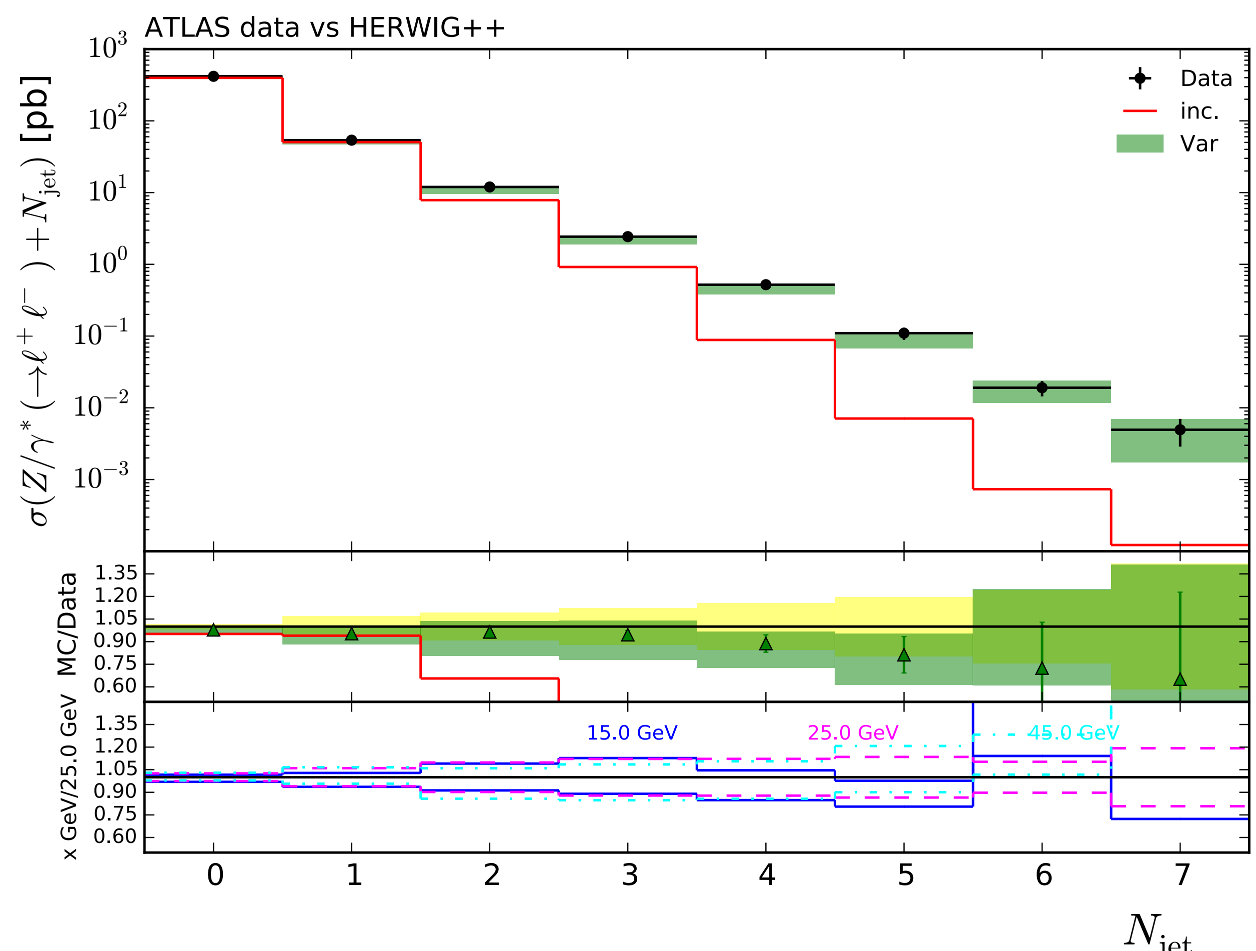
FxFx

Staging multiple MC@NLO expressions
with phase space restrictions on emissions.

Analytical Sudakov suppression, MiNLO-like scale choice
and introduction of a smooth transition function
between shower and ME region



Frederix, Frixione JHEP12(2012)061



Fx Fx+Papaefstathiou, Prestel,
Torrielli JHEP 1602 (2016) 131

Unitarised Merging

The „subtract-what-you-add“-method of merging NLO.

Inspired by the LoopSim method for nNLO

Rubin, Salam, Sapeta JHEP 1009 (2010) 084

Major Difference to other merging schemes:

$$B_n \Delta_n^0 \Delta_\mu^n \to B_n \Delta_n^0 - \int_\mu^{q_n} B_{n+1} \Delta_{n+1}^0$$

Less influence on inclusive observables.

UNLOPS:

$$\frac{x_{i-1}^{\pm} f_{i-1}^{\pm}(x_{i-1}^{\pm}, \rho_{i-1})}{x_{i-1}^{\pm} f_{i-1}^{\pm}(x_{i-1}^{\pm}, \rho_i)} = 1 + \frac{\alpha_s(\mu_R)}{2\pi} \ln\left\{\frac{\rho_{i-1}}{\rho_i}\right\} \int_{x_{i-1}^{\pm}}^{1} \frac{dy}{y} \frac{x_{i-1}^{\pm} \widehat{f}_{i-1}^{\pm}(\frac{x_{i-1}^{\pm}}{y}, \mu_F)}{x_{i-1}^{\pm} f_{i-1}^{\pm}(x_{i-1}^{\pm}, \mu_F)} + \mathcal{O}(\alpha_s^2(\mu_R))$$

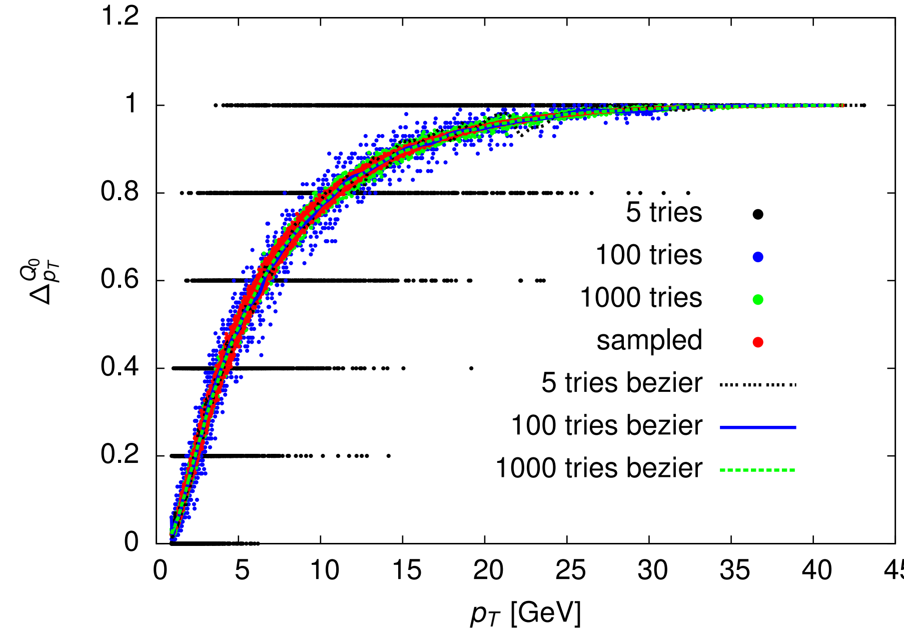
Plätzer JHEP 1308 (2013) 114

Lonnblad, Prestel JHEP 1302 (2013) 094

Herwig NLO Merging

(JB, Plätzer, Gieseke)

Based on developments in Herwig7 and publicly available in Herwig 7.1.

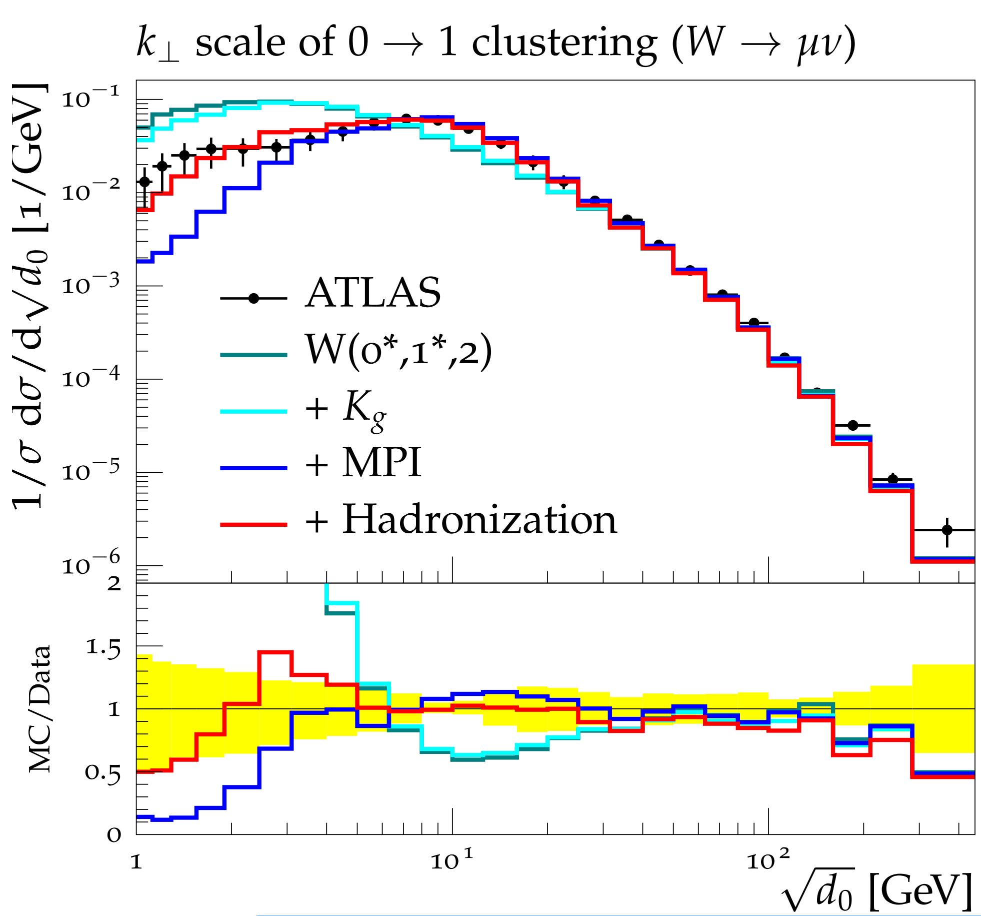


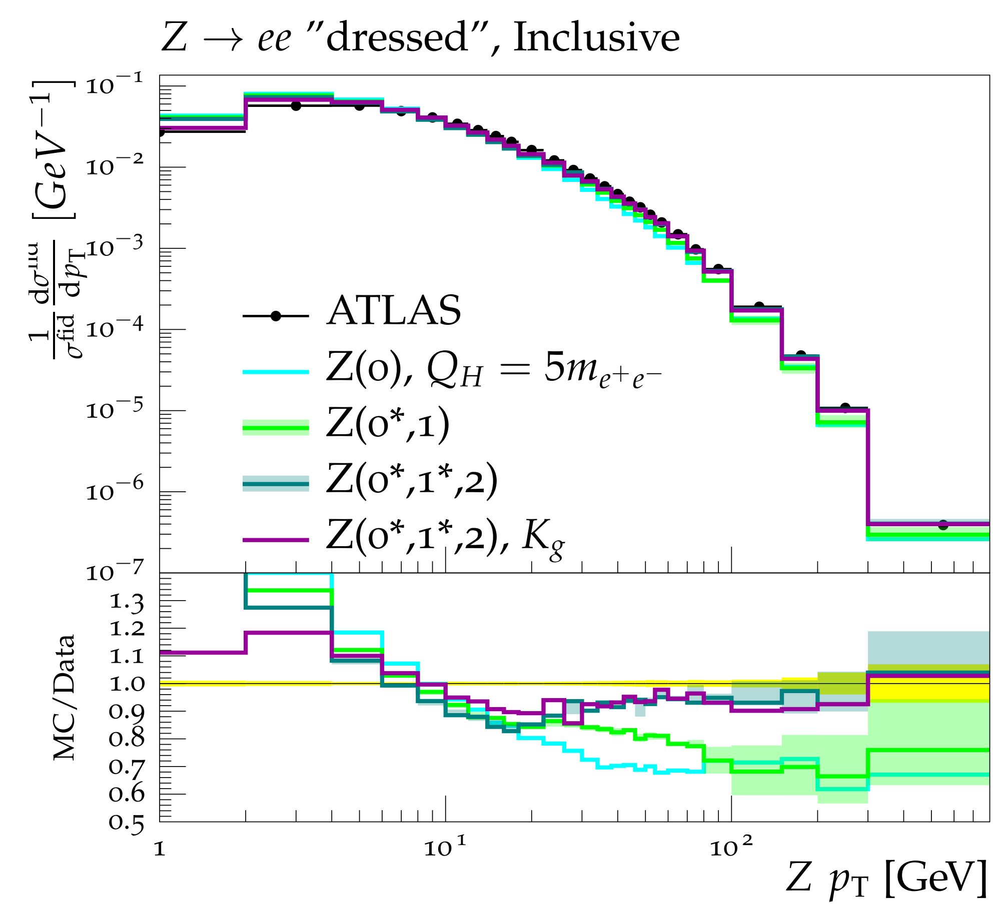
$(\bar{V}_1 + IPK_1 - (\partial^1_{\alpha_s}\Delta^0_1)B_1)\theta^1_{ME}$	$\int(B_2 - D_2)\theta^2_{ME}\theta^1_{ME}$	$\int(P_2B_1 - D_2)\not\theta^2_{ME}\theta^1_{ME}$
	$(B_2\ominus - P_2B_1)\not\theta^2_{ME}\theta^1_{ME}$	

$\mathcal{O}(\alpha_s)$ expansion of parton shower weights

cuts on multiple emissions

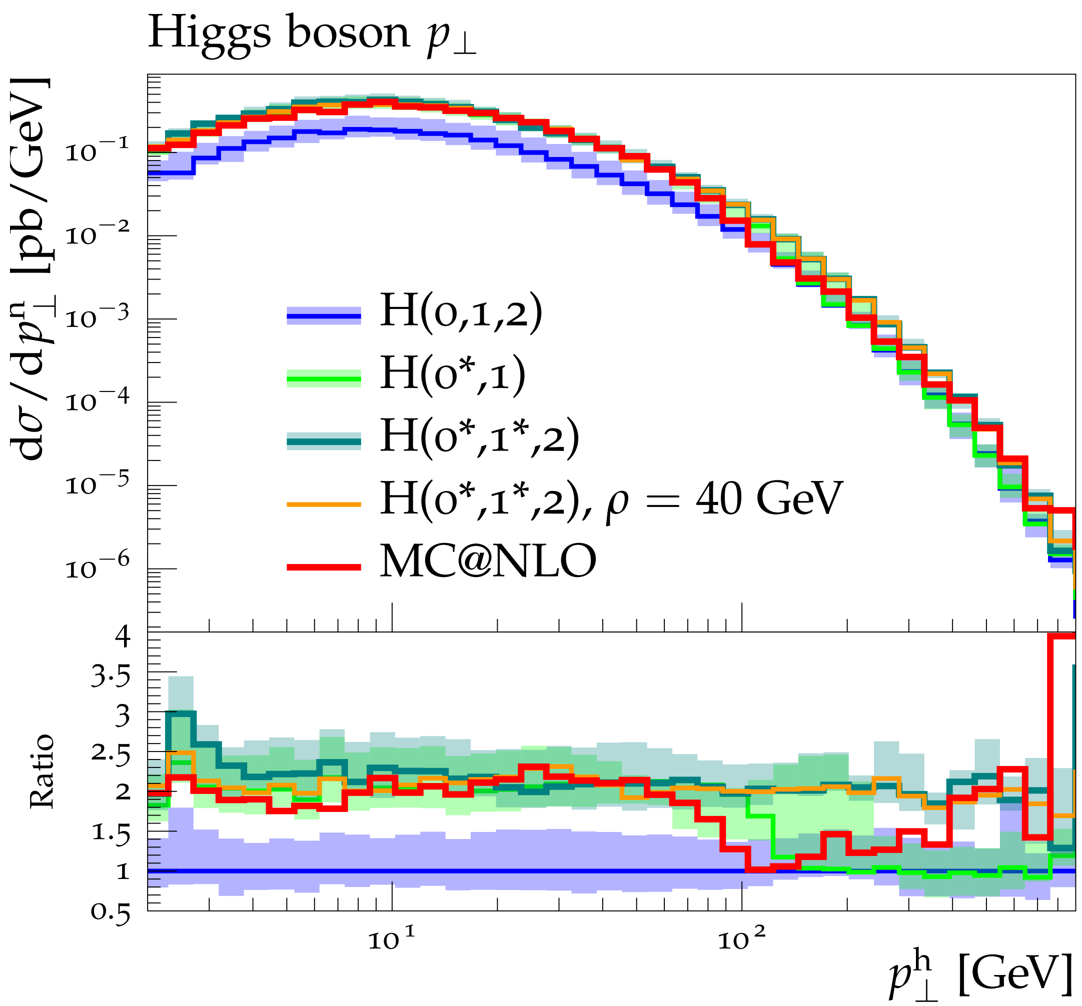
MC@NLO-like contributions below the merging scale





Data from ATLAS, Eur. Phys. J. C73 (2013) 2432 and ATLAS Collaboration, JHEP 1409 (2014) 145

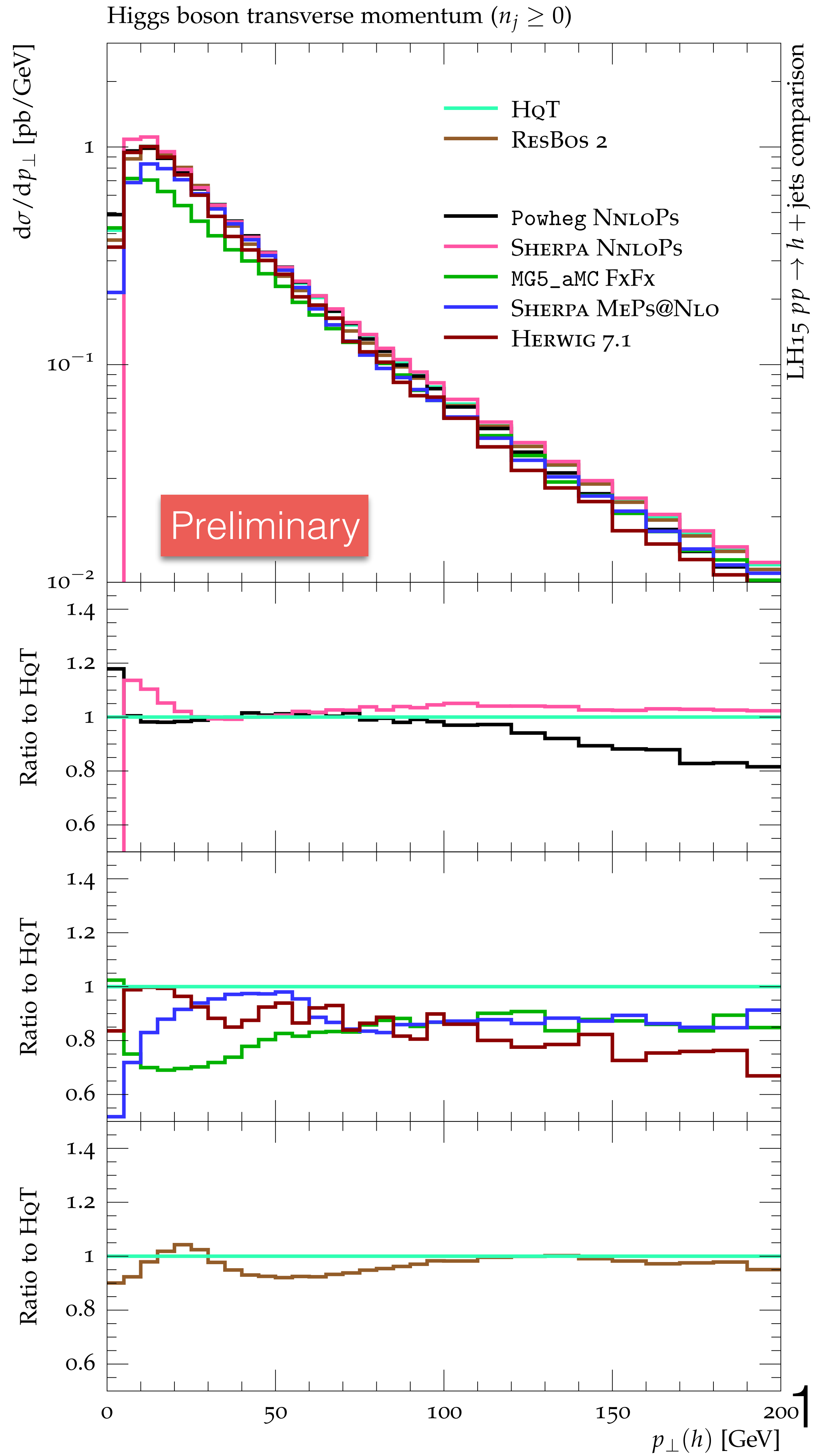
Herwig NLO Merging



MC@NLO and merging 1 NLO agree.

NLO merging of 2 NLO show smooth transition at the merging scale. (remember the large K-factor)

Right: Up to 3 NLO merged.



Herwig NLO Merging

Comment on α_S and scale choice:

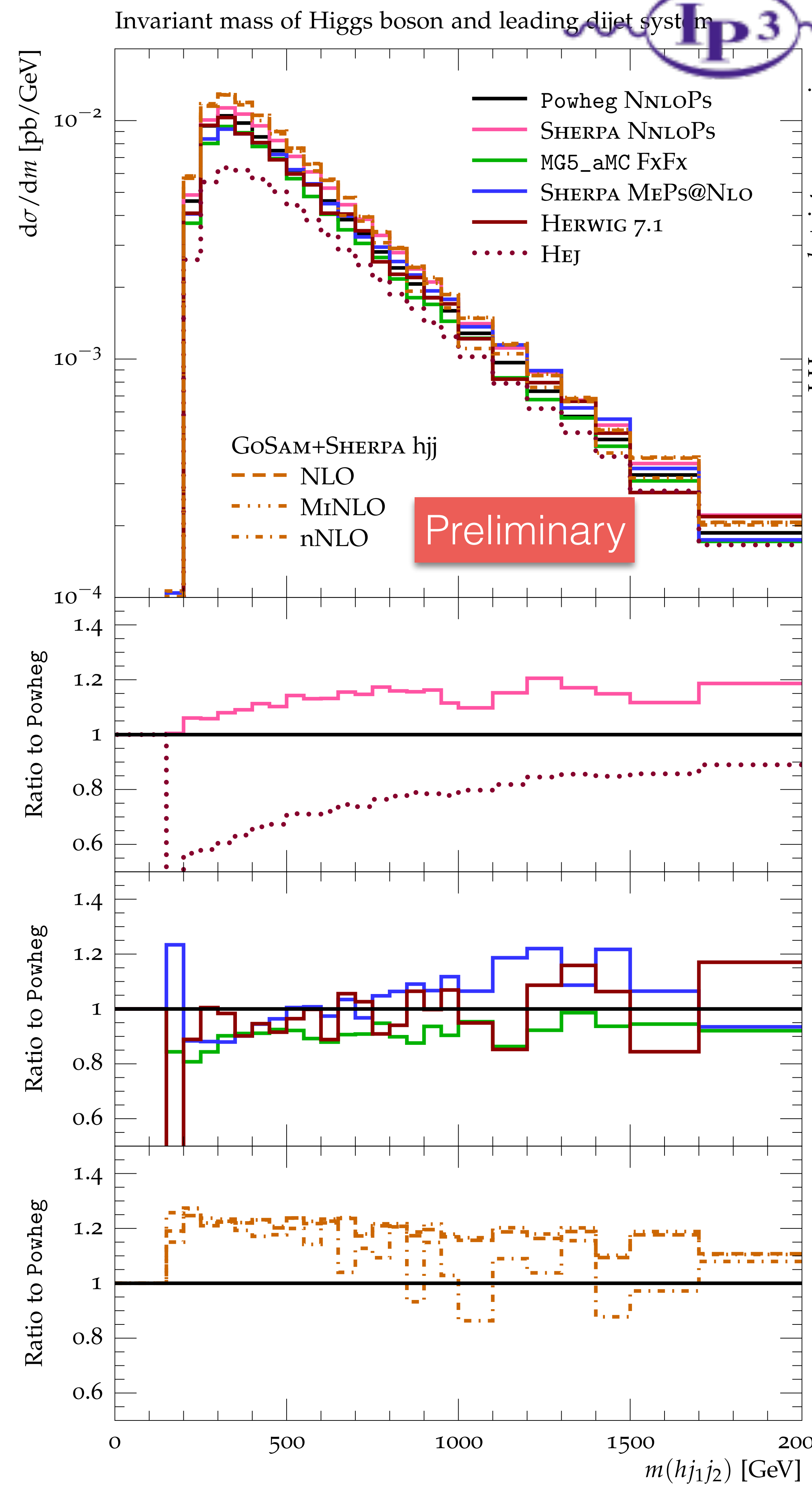
The value of α_S is usually tuned to data.

Motivated by CMW scheme:

$$K_g = \left(\frac{67}{18} - \frac{\pi^2}{6}\right) C_A - \frac{10}{9} T_R n_f$$

Approximates already NLO to first emission.

Need to take this into account to describe data.



Summary

Gave an overview on various merging schemes.

Methods are used but still need to be improved.

The merging should not spoil the NLO accuracy of the inclusive cross section.

Choice of couplings and pdf scales can improve the prediction.