TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

QCD predictions and hadronic final states

Frank Siegert

DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 27, Dallas

TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

QCD precision predictions and hadronic final states

Frank Siegert

DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 27, Dallas

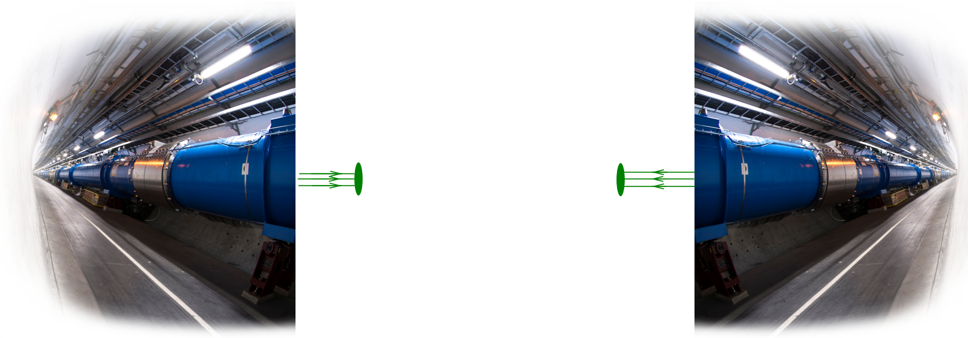
TECHNISCHE
UNIVERSITÄT
DRESDEN

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

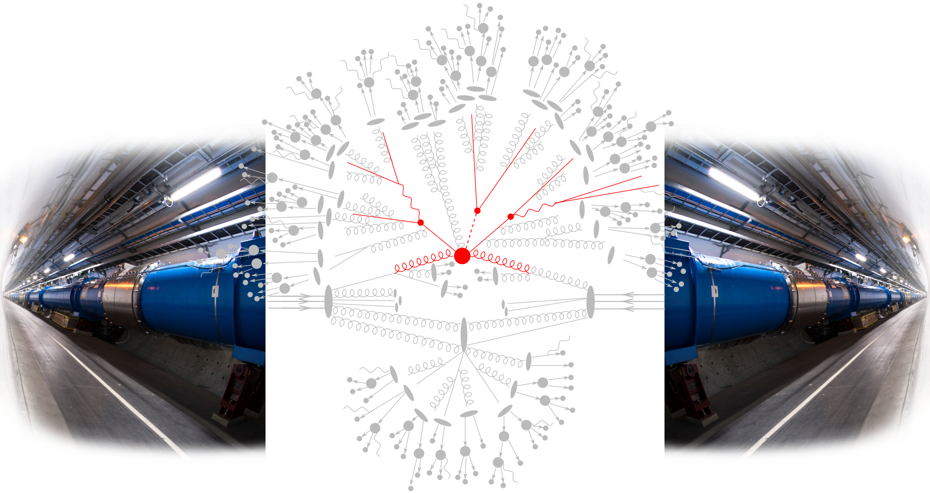
QCD precision predictions despite hadronic final states

Frank Siegert

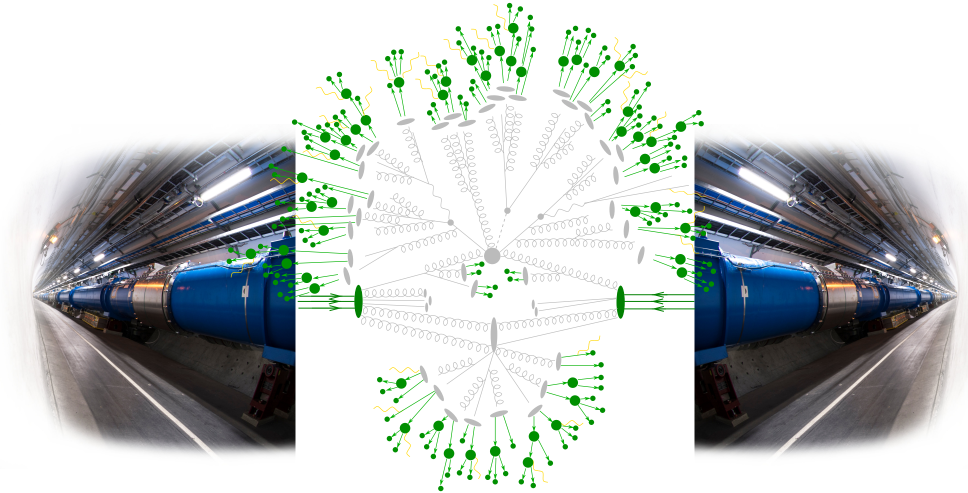
DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 27, Dallas



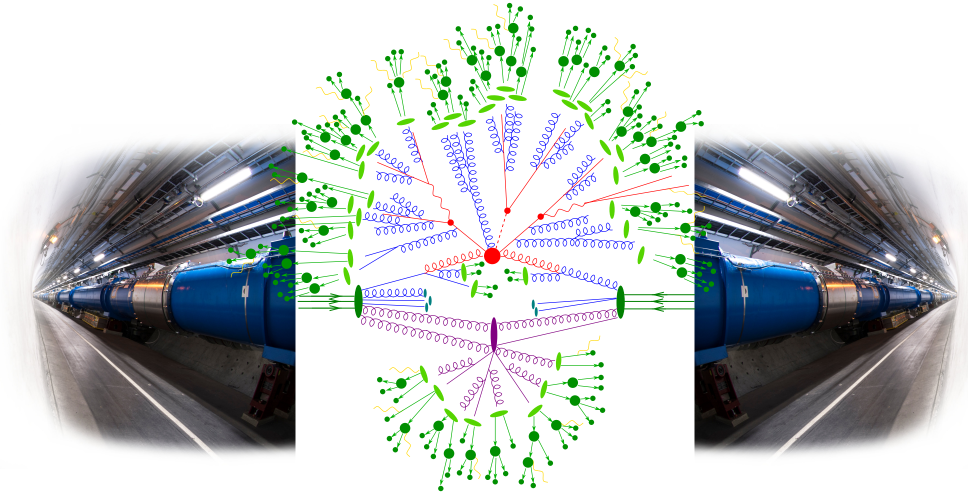
Precision vs. Hadronic Final States



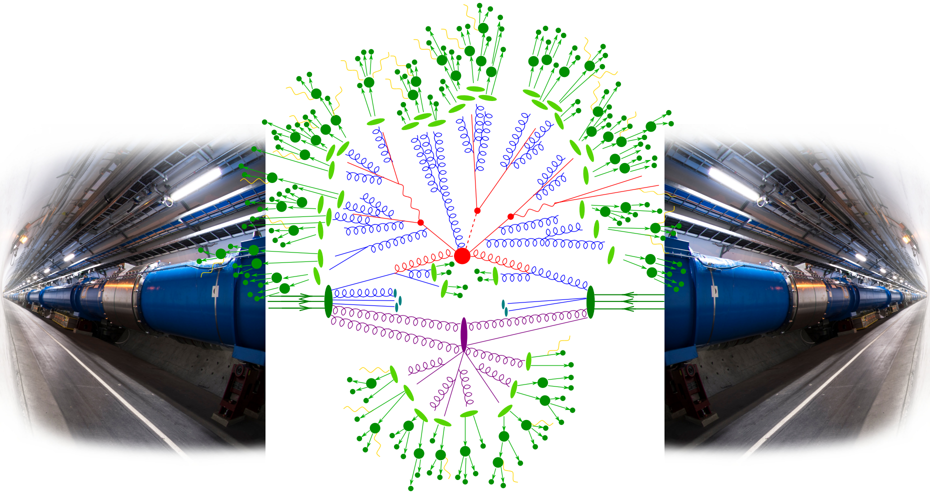
Precision vs. Hadronic Final States



Precision vs. Hadronic Final States



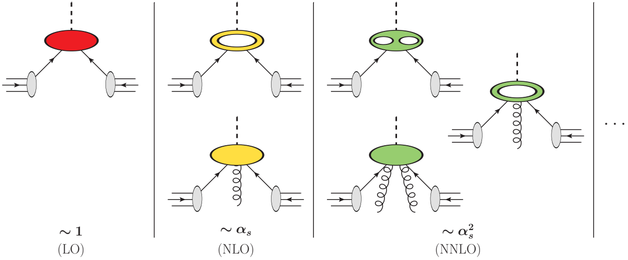
Precision vs. Hadronic Final States



Vision: bring progress in higher order calculations and resummation to the hadron level.

Basic problem

- no exact solution to QCD, only perturbative series in α_s



- predictions at hadron level: confinement at "resolution" scale $\Lambda \sim 1$ GeV

→ finite remainders of infrared divergences:

logarithms of $\frac{\mu^2_{\text{hard}}}{\Lambda^2}$ with each $\mathcal{O}(\alpha_s)$

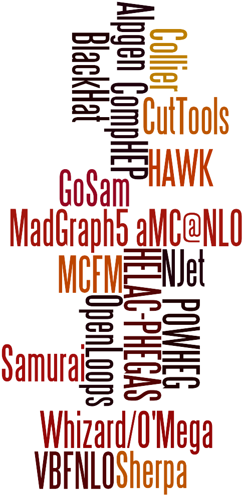
can become large and spoil convergence of perturbative series

⇒ Need to resum the series to all orders
- Problem: We are not smart enough for that.
- Workaround: Resum only the logarithmically enhanced terms in the series

→ Parton Showers!

Event generation programs

Parton level generators



Parton shower and hadronisation programs

In production:

- Herwig++
- Pythia
- Sherpa

Interesting new approaches for showers:

- dipole-antenna showers (Vincia, Adicic/Ants)
- "analytic" showers (Geneva, Whizard)
- Deductor
- ...

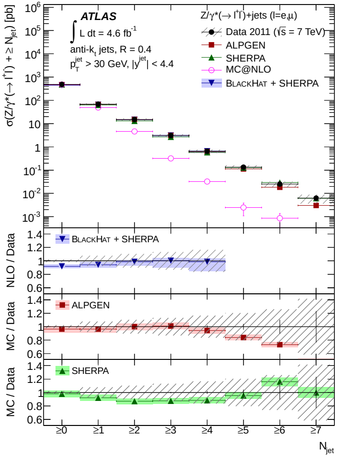
HERE: focus on fixed-order improvements in QCD parton shower event generators

SEE ALSO:
⇝ parton-level review
Frank Petriello, Mon 17:10
⇝ EW corrections
Jia Zhou, Tue 17:00

Multi-jet production

- high multi-jet production rates at LHC
  ⇝ **talks by Kwan (Tue 8:55), Perry (Wed 18:00), Schwanenberger (Wed 9:45)**
- important backgrounds for BSM searches
- even data-driven background estimation relies on good simulation of shapes between control and signal region
- in some cases precision measurements very sensitive to simulation of multi-jet production (Z polarization, ϕ^*)
- "naive" inclusive NLO accuracy at best status quo, often not sufficient

→ precision predictions for multi-jet processes are one of the current frontiers for event generators



Problem:

Combination of higher-order matrix elements and parton shower evolution

Todo list

- avoid double counting of higher order corrections
  $\rightarrow$ preserve fixed-order accuracy of MEs in combined sample
- preserve logarithmic accuracy in the parton shower resummation

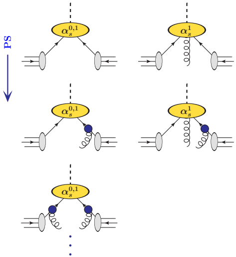
Todo list

- avoid double counting of higher order corrections
  $\rightarrow$ preserve fixed-order accuracy of MEs in combined sample
- preserve logarithmic accuracy in the parton shower resummation

Two long established approaches

- NLO matrix elements matched with parton shower emissions

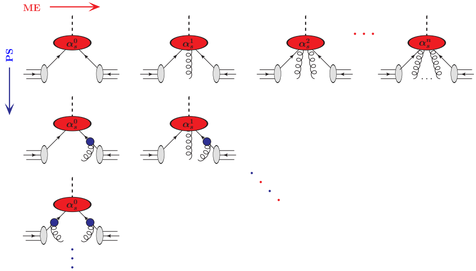
(NLO+PS matching)



e.g. MC@NLO, Powheg

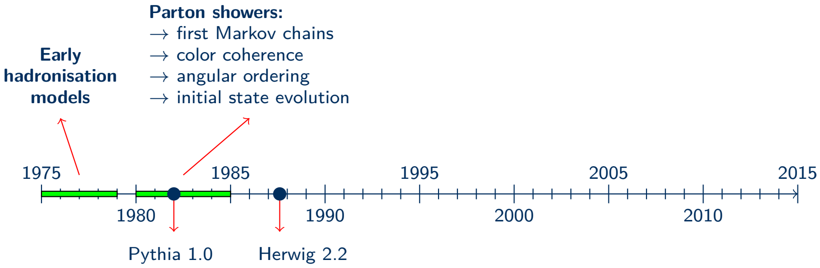
- Merging tree-level multi-jet matrix elements with parton showering into one inclusive sample

(Multi-jet merging)

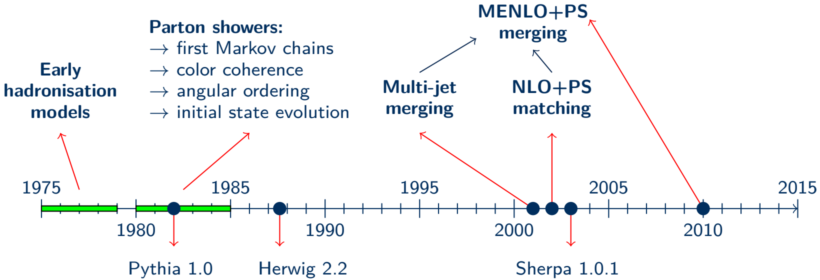


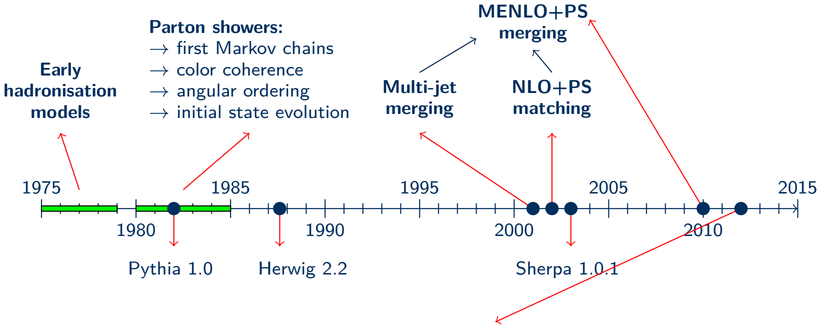
e.g. CKKW(-L), MLM, UMEPS

Shower generators over the years



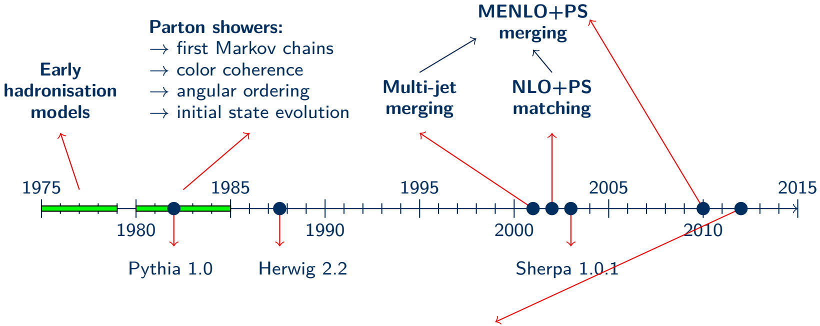
Shower generators over the years





2012 – Year of the Higgs

Shower generators over the years



2012 – Year of ~~the Higgs~~ multi-jet merging at NLO

Many algorithmic developments . . .

- Lavesson, Lönnblad (2008)
- Höche, Krauss, Schönherr, FS (2012)
- Frederix, Frixione (2012)
- Plätzer (2012)
- Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi (2012)
- Lönnblad, Prestel (2012) ⇝ talk Tue 8:30
- Hamilton, Nason, Oleari, Zanderighi (2012)

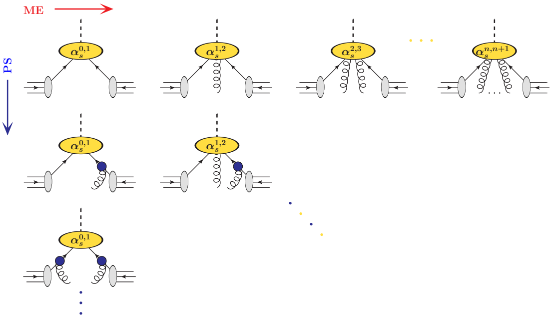
. . . and applications

- $p\bar{p} \to t\bar{t} + 0, 1$ jets Höche et al. (2013)
- $pp \to 4\ell + 0, 1$ jets Cascioli et al. (2013)
- $pp \to H + 0, 1, 2$ jets Höche et al. (2014)
- $pp \to t\bar{t} + 0, 1, 2$ jets Höche et al. (2014)
- $pp \to VVV + 0, 1$ jets Höche et al. (2014)
- $pp \to H/W + 0, 1, 2$ jets, $pp \to t\bar{t}/ZZ + 0, 1$ jets Alwall et al. (2014)
- $pp \to H + 0, 1$ jets Buschmann et al. (2014)

⋮

Basic idea

- NLO accuracy for multiple jet bins in inclusive simulation

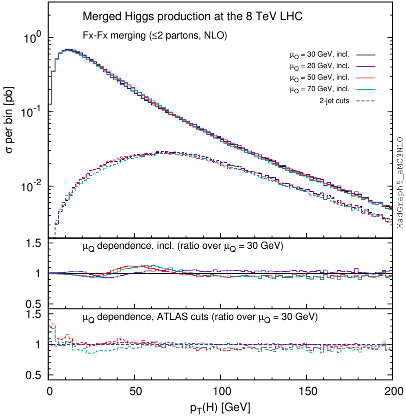


- continuation from tree-level multi-jet merging:
  - phase space slicing to separate ME and parton shower contributions
  - showering on multi-parton final states, leading to Sudakov shape/vetoes

  ⇒ jet production with exact matrix elements, intrajet evolution with parton shower
- replace individual LO+PS with NLO+PS simulations in each multiplicity
- adjust Sudakov to take existing emission into account

Example: $pp \to H + 0, 1, 2j$@NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro (2014)



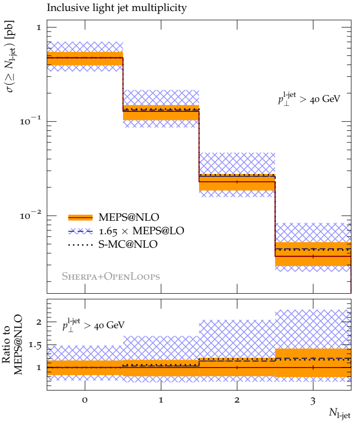
- Higgs production in gluon-fusion with up to 2 jets at NLO accuracy
- merging cut variation to assess systematic uncertainties
- debate about reasonable choice of merging cut value:
  - too large: loss of NLO accuracy in hard regions
  - too low: sensitivity to resummation uncertainties

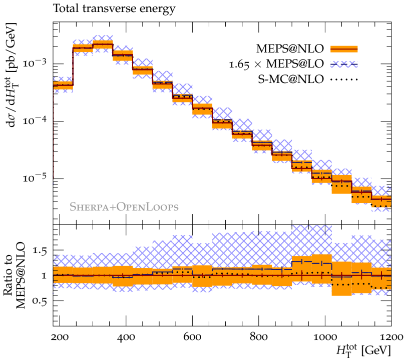
$\to$ reasonable range for systematic uncertainty?

Example: $pp \to t\bar{t} + 0, 1, 2j$@NLO

Höche, Krauss, Maierhöfer, Pozzorini, Schönherr, FS (2014)

- ME+PS@NLO simulation for $t\bar{t} + 0, 1, 2$jets@NLO



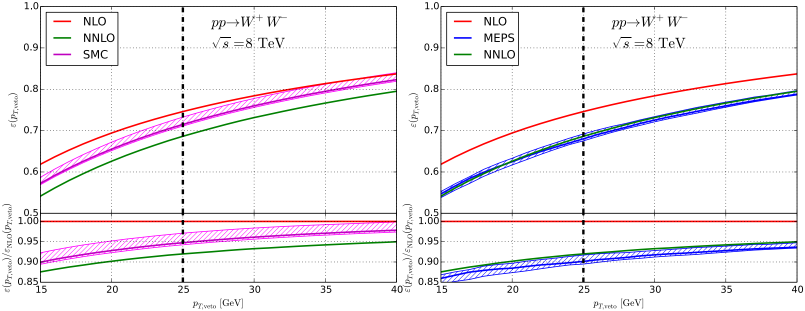


- comparison with LO multi-jet merging
- perturbative uncertainties reduced in particular in $+0, 1, 2$-jet bins
- BSM search region $H_T^{\text{tot}} > 500$ GeV significantly improved

Relevance for non-jet processes?

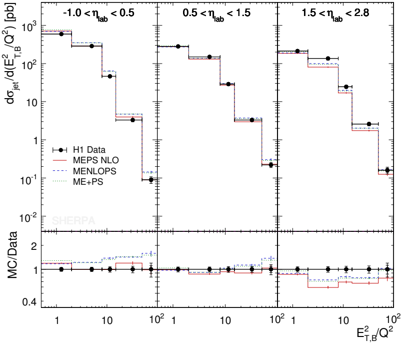
Grazzini, Kallweit, Moretti, Pozzorini, Rathlev (in progress)

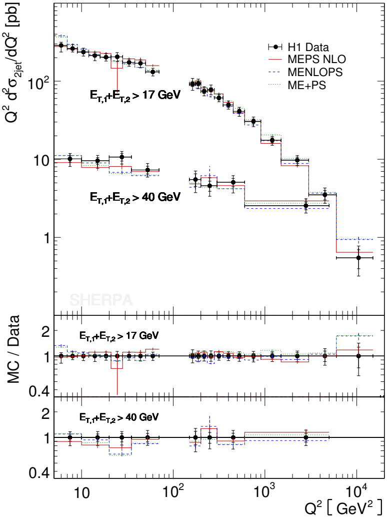
- jet vetoes important tool for background suppression, e.g. in $H \to WW$ vs. $t\bar{t}$
- recently: differential calculation of $pp \to W^+W^-$ at NNLO
- interesting comparison to shower predictions for jet veto efficiencies:
  - S-MC@NLO is Sherpa with NLO+PS matching
  - ME+PS@NLO is Sherpa with multi-jet merging for $pp \to W^+W^- + 0, 1j$@NLO



Example: DIS with ME+PS@NLO

World Premiere

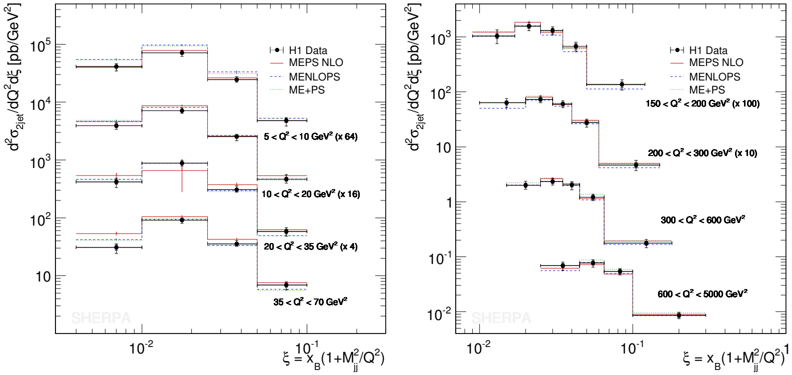




- continuation from tree-level merging
  Carli, Gehrmann, Höche (2009)
  Höche (private comm.)
- special in DIS: kinematics with low factorisation scale but hard jets
  $\Rightarrow$ related to boosted $pp \to Z+$jets
- notoriously difficult for parton showers!

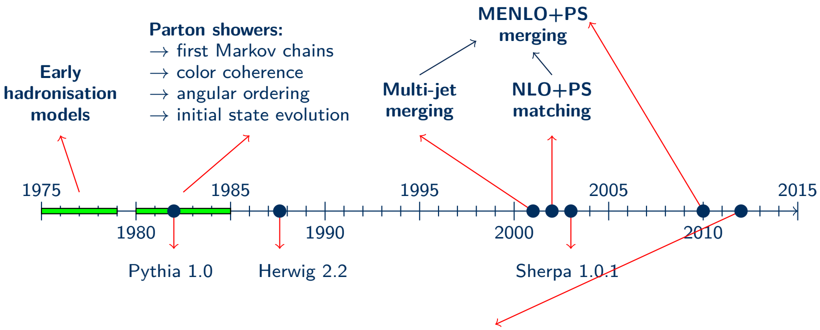
Example: DIS with ME+PS@NLO

World Premiere



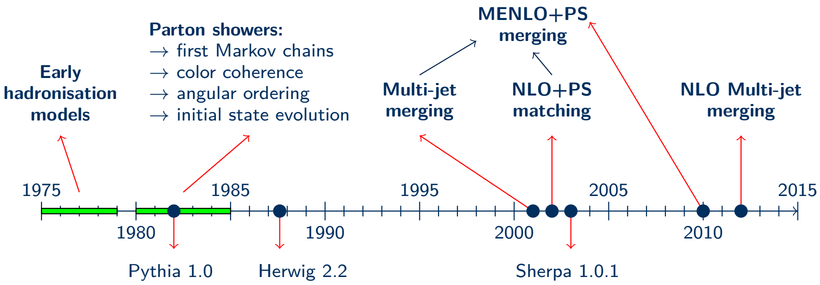
- similarly good description of rescaled momentum fractions
- tree-level merging (at LO or NLO) necessary to describe difficult DIS regions
- NLO accuracy comes "for free" with today's automated merging tools
- same concepts can be applied to charged-current DIS, e.g. at a potential LHeC

Shower generators over the years

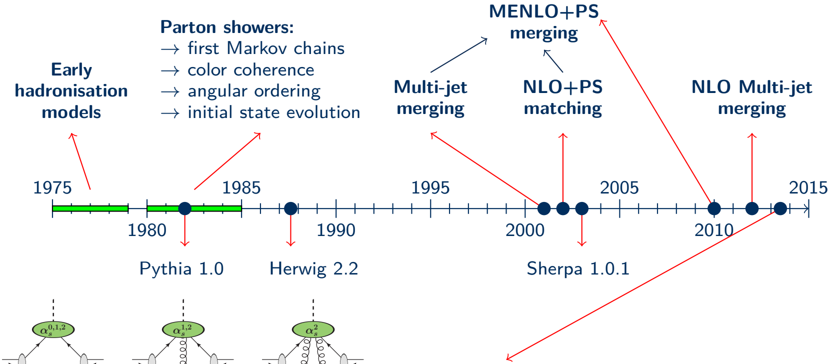


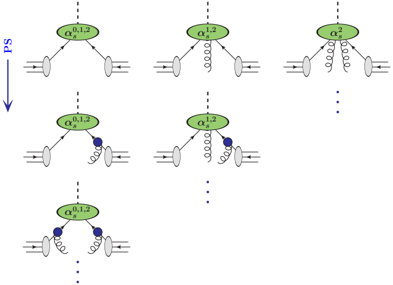
2012 – Year of ~~the Higgs~~ multi-jet merging at NLO

Shower generators over the years



Shower generators over the years





Beyond NLO: Matching NNLO matrix elements and parton showers

Matching NNLO and parton showers

- more accurate inclusive rates for processes with large K-factor or high experimental precision
- two independent approaches on the market:

NNLOPS

Hamilton, Nason, Re, Zanderighi (2013)

- matching scheme based on MiNLO method
  - use $pp \to X + j$ NLO+PS simulation
  - apply scale choice and Sudakov form factor (like in multi-jet merging)

  $\Rightarrow$ finite for $p_\perp^j \to 0$
- reweight with fully-differential $pp \to X$ @ NNLO

UN^{2}LOPS

Höche, Li, Prestel (2014)

- matching scheme based on unitarised merging method Lönnblad, Prestel (2012)
- dedicated NNLO calculation using q_T-cutoff subtraction

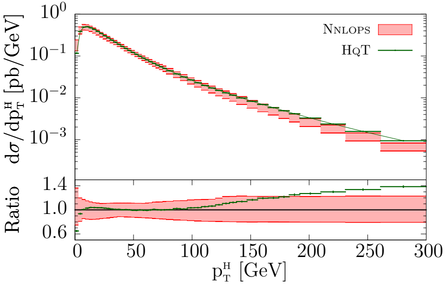
  $\rightsquigarrow$ talk by Stefan Prestel, Tue 8:30

Higgs production in gluon fusion with NNLOPS

- NNLOPS predictions in the large m_t limit

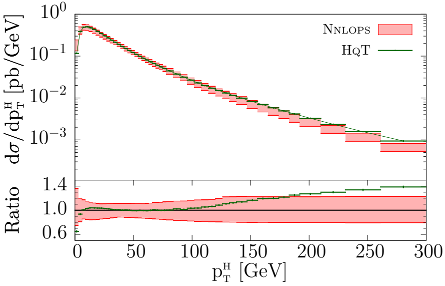
  Hamilton, Nason, Re, Zanderighi (2013)

- comparison against analytical resummation from HqT (NNLL+NLO)

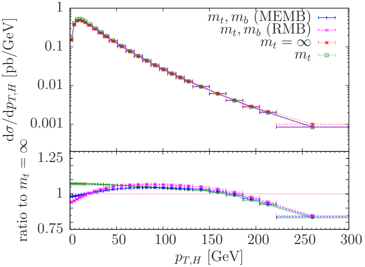


Higgs production in gluon fusion with NNLOPS

- NNLOPS predictions in the large m_t limit
  Hamilton, Nason, Re, Zanderighi (2013)
- comparison against analytical resummation from HqT (NNLL+NLO)



- supplemented with finite quark mass effects at NLO
  Hamilton, Nason, Zanderighi (2015)
- sizable effects of m_t at high and m_b at low $p_\perp^H$



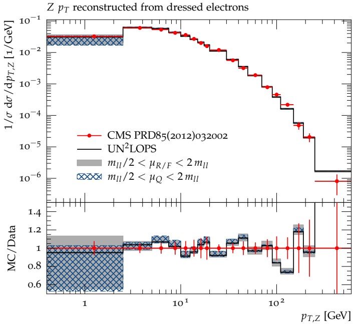
W/Z production with UN^{2}LOPS

⇝ Stefan Prestel, Tue 8:30

- UN^{2}LOPS predictions for vector boson production

Höche, Li, Prestel (2014)

→ comparison with experimental data



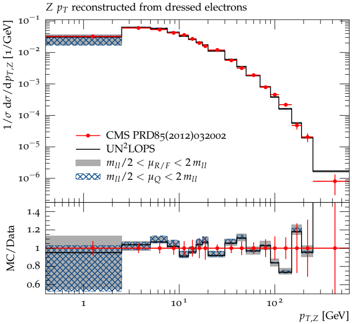
W/Z production with UN^{2}LOPS

⇝ Stefan Prestel, Tue 8:30

- UN^{2}LOPS predictions for vector boson production

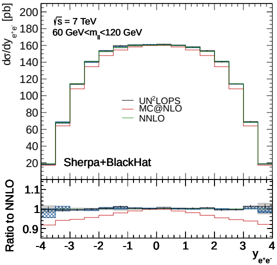
Höche, Li, Prestel (2014)

→ comparison with experimental data



- interesting study of PDF impact in NLO+PS simulations

Höche (Loopfest 2014)



S-MC@NLO with ⟵ NLO PDFs

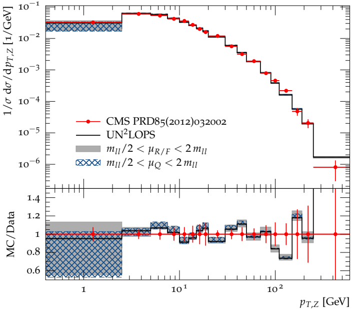
W/Z production with UN^{2}LOPS

⇝ Stefan Prestel, Tue 8:30

- UN^{2}LOPS predictions for vector boson production

  Höche, Li, Prestel (2014)

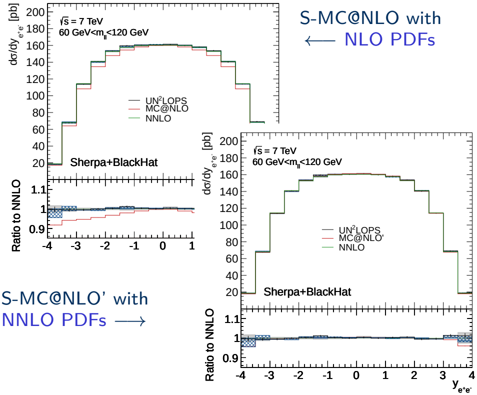
→ comparison with experimental data



- interesting study of PDF impact in NLO+PS simulations

  Höche (Loopfest 2014)

S-MC@NLO with ⟵ NLO PDFs



S-MC@NLO' with NNLO PDFs ⟶

Summary

- parton shower event generators have evolved into precision tools
- realistic simulation of hadronic final state makes them crucial for the LHC physics program
- current state of the art: NLO accuracy for multi-jet final states, NNLO accuracy for simple inclusive processes

Outlook

- perturbative improvements to be applied to more complicated processes
- possibly combination of NNLO+PS and NLO multi-jet merging?
- skipped today:
  - non-perturbative effects
    → no ground breaking developments fruitful yet, mainly tuning of phenomenological models
  - developments on resummation accuracy of parton showers
    → will become important field over the next years