Monte Carlo Tools

[Aspen 2012 Winter Conference]

Jan Winter [a]

– CERN –

➡ ***Try to cover ...***

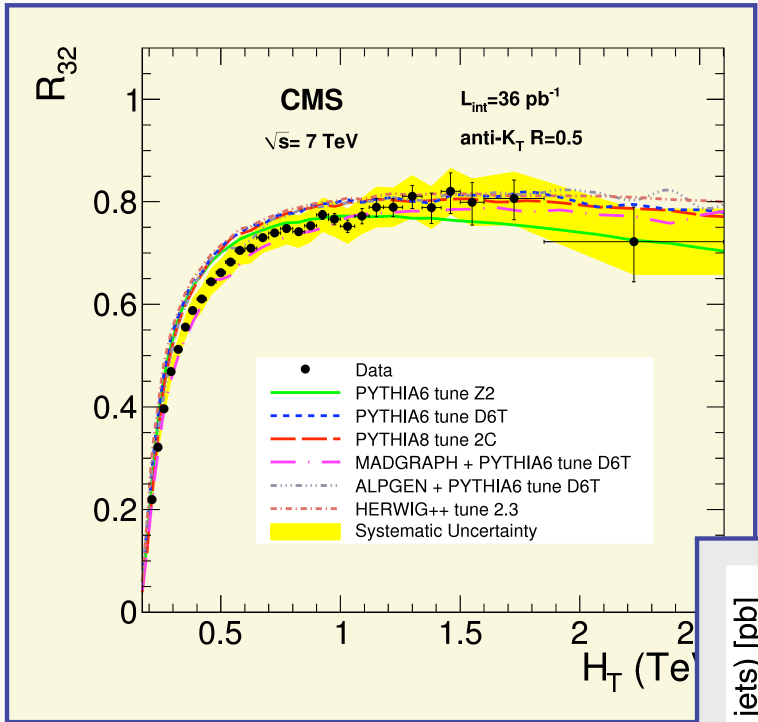
- *recent developments ...*
  ... by talking about selected topics.
- *Focus is on how to combine MEs and PSs ...*
- *... in various ways.*

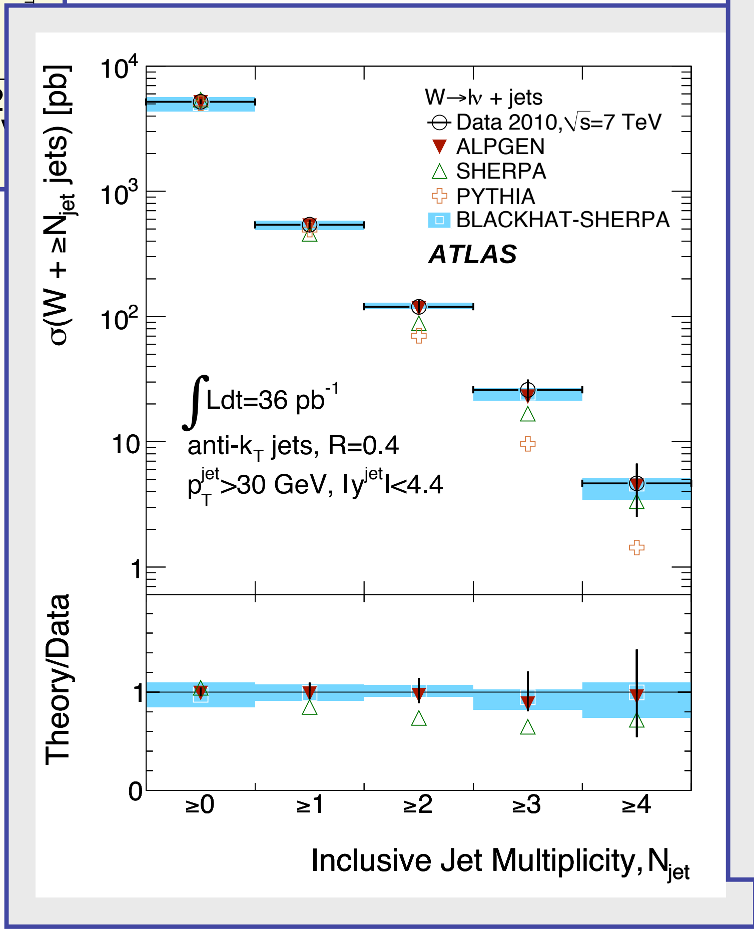
http://www.sherpa-mc.de/

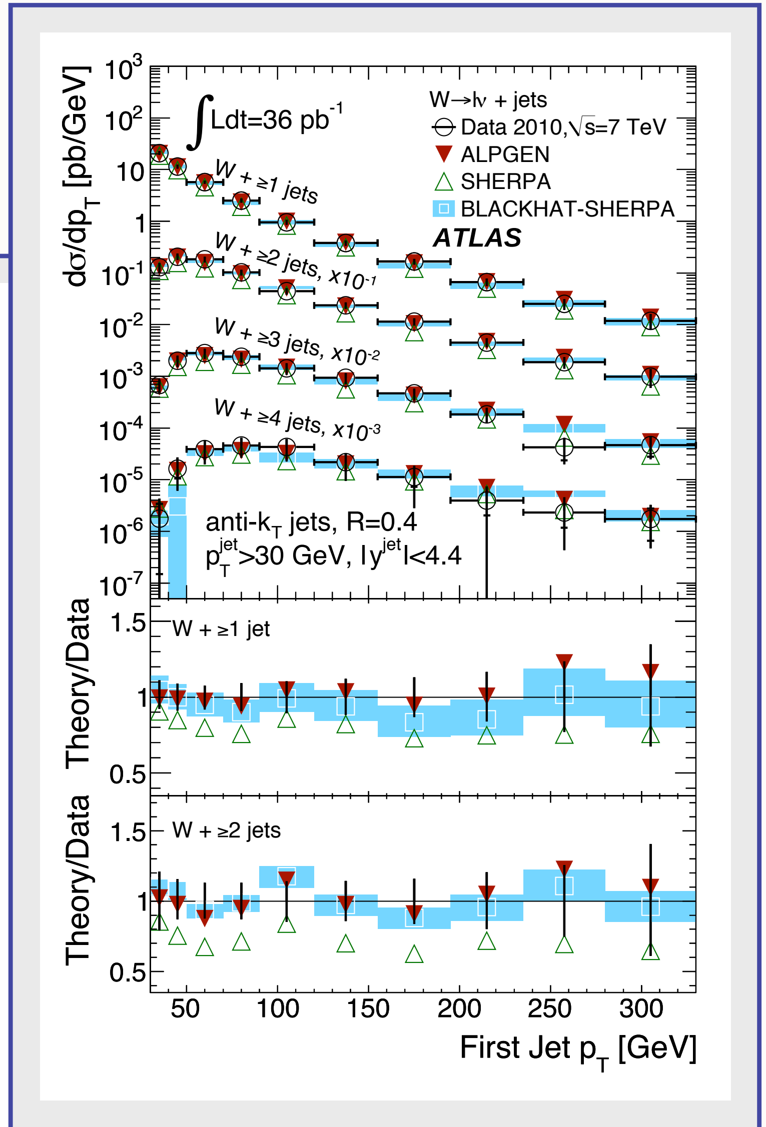
[a] Sherpa authors: S. Höche, H. Hoeth, F. Krauss, M. Schönherr, F. Siegert, S. Schumann, J. Winter and K. Zapp

Monte Carlo tools at work

- ATLAS: W+jets with 36/pb [ARXIV:1201.1276]







- CMS: Ratio of 3-jet to 2-jet xsec as function of H_T

[ARXIV:1106.0647]

various Monte Carlo predictions compared to data.

Monte Carlo event generation

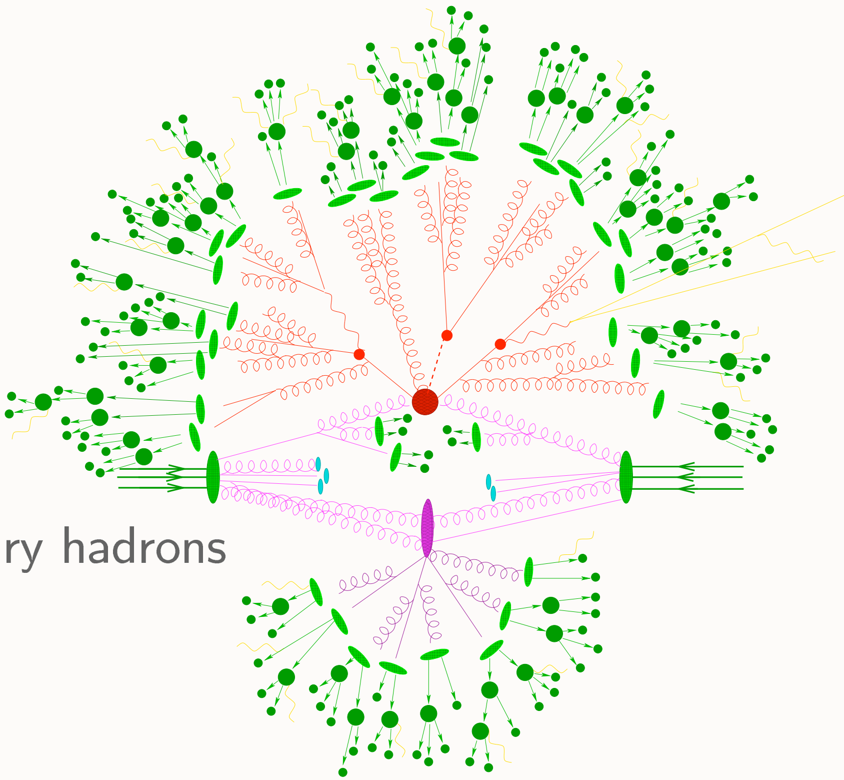
Event generators used to model the multi-hadron final states of high-energy particle collisions.
Factorization approach: divide jet simulation into different phases – use Monte Carlo methods.

- *Perturbative Phases:* [parton jets]

- ***Hard process/interaction (hard jet production)***
  exact matrix elements $|\mathcal{M}|^2$
- ***QCD bremsstrahlung (soft/coll multiple emissions)***
  initial- and final-state parton showering
- ***Multiple/Secondary interactions***
  modelling the underlying event

- *Non-perturbative Phases:* [jet confinement – particle jets]

- ***Hadronization***
  phenomenological models to convert partons into primary hadrons
- ***Hadron decays***
  phase-space or effective models to decay unstable into stable hadrons as observed in detectors



→ predictions at hadron level – comparable to experimental data if corrected for detector effects

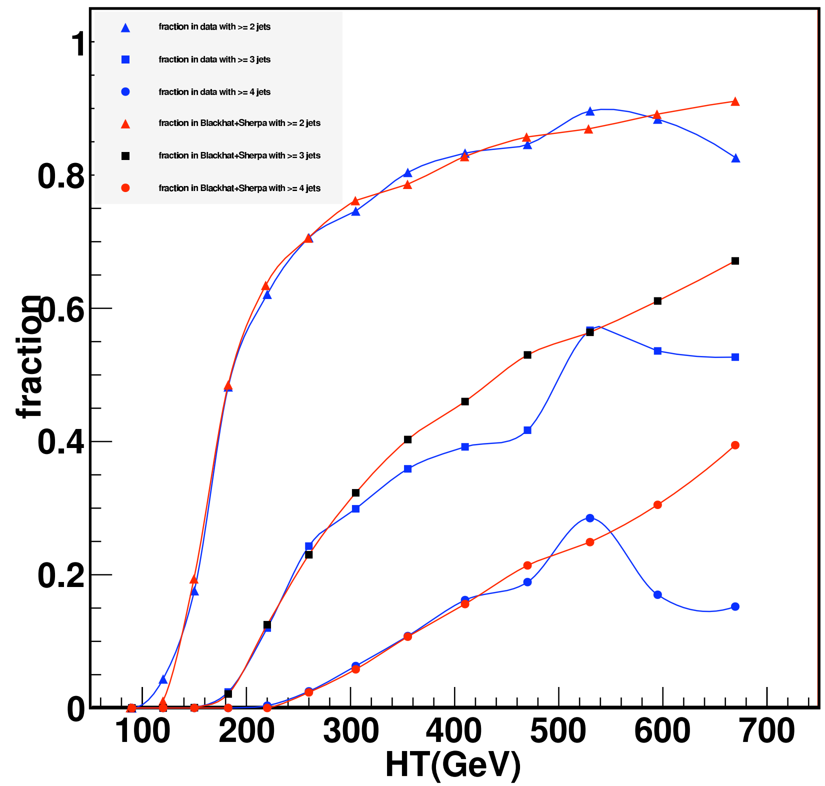
HT distribution in recent ATLAS measurement

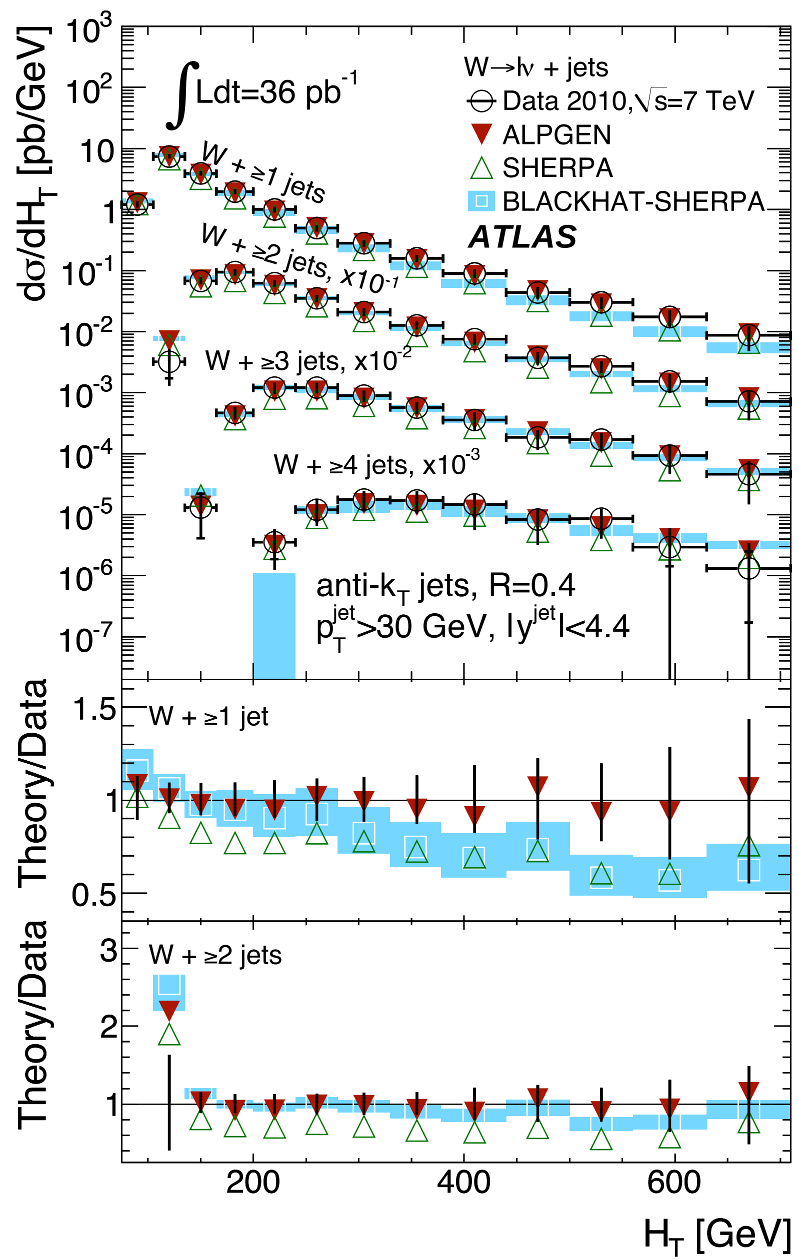
[ATLAS COLLABORATION (GEORGES AAD ET AL.), ARXIV:1201.1276 [HEP-EX]]

➡ ***HT ... scalar pT sum of jets, lepton and MET,***

- in different inclusive $W + n$-jet bins.
- particularly problematic, large H_T area for $W + 1$-jet.
- below, inclusive xsec ratios as funtion of H_T.

THX TO JOEY HUSTON





HT distribution in recent ATLAS measurement

[ATLAS Collaboration (Georges Aad et al.), arXiv:1201.1276 [hep-ex]]

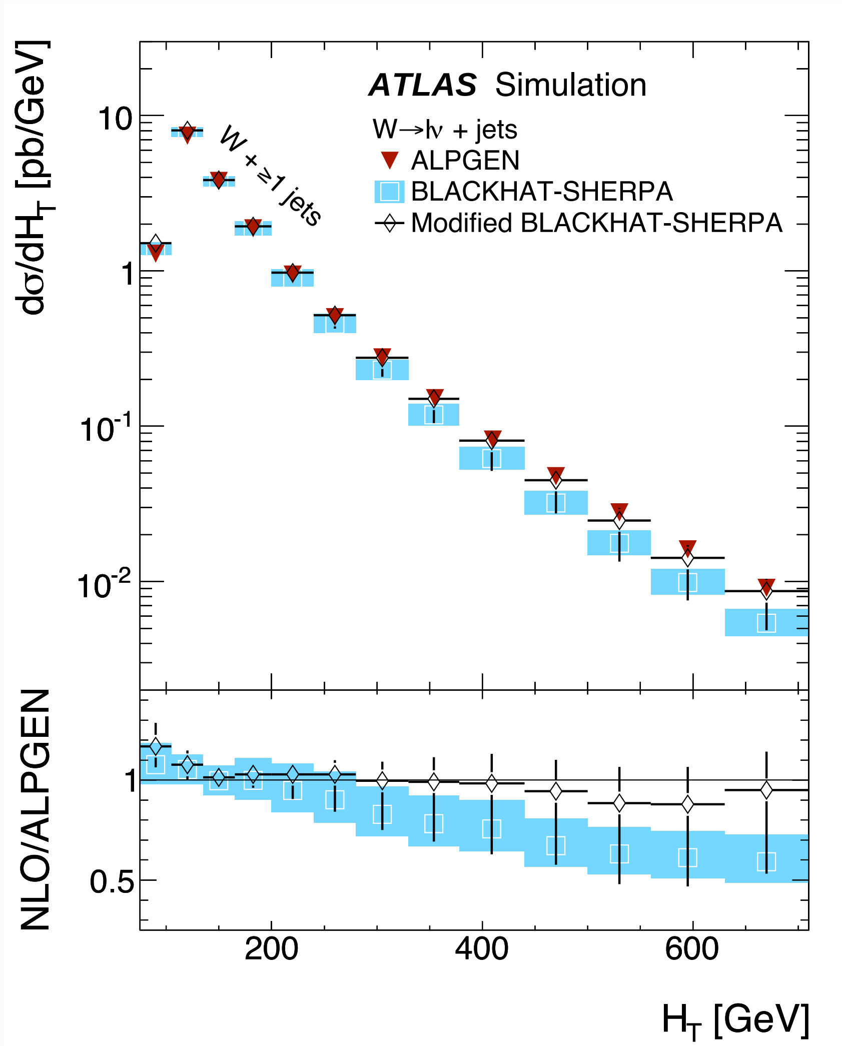
➡ ***HT ... scalar pT sum of jets, lepton and MET in inclusive W+1-jet bin.***

- Alpgen gives fantastic agreement, use as reference.
- Sherpa's problem here: default scale & PDF choices not optimal.
- BlackHat+Sherpa's problem: $W+1$-jet NLO calculation is not valid in this high H_T region.

- Modified BlackHat+Sherpa is attempt to combine various $W+n$-jet NLO calculations $(n=1,\ldots,4)$ avoiding double counting of contributions:

  $\Rightarrow$ n-jet prediction only describes n-jet events
  $\Rightarrow$ $n+1$-jets allowed for highest multiplicity

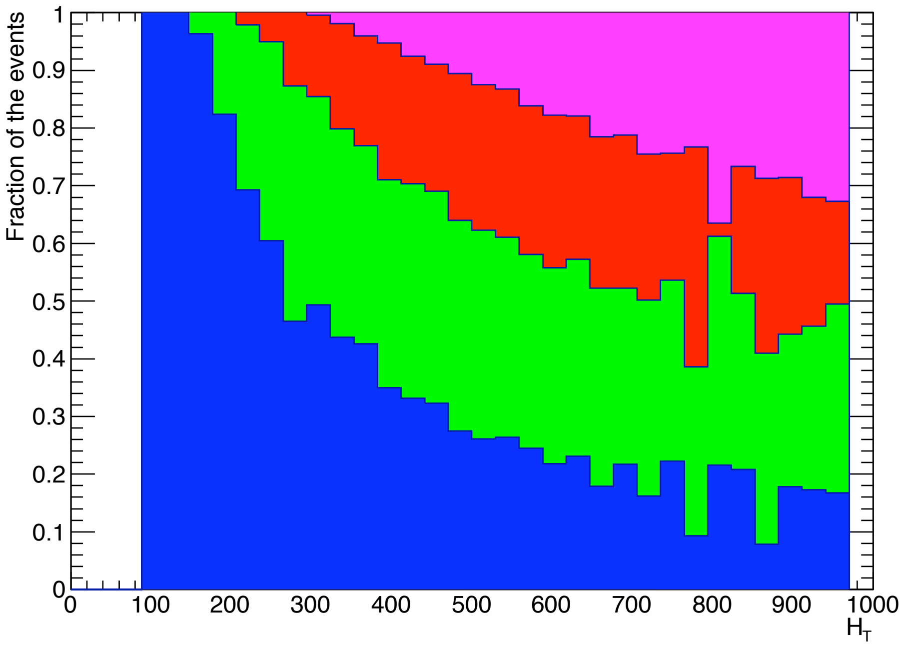
$$\sigma^{\rm tot} \equiv \sigma_m^{\rm inc} = \sum_{n=m}^{M-1} \sigma_n^{\rm exc} + \sigma_M^{\rm inc} \,.$$



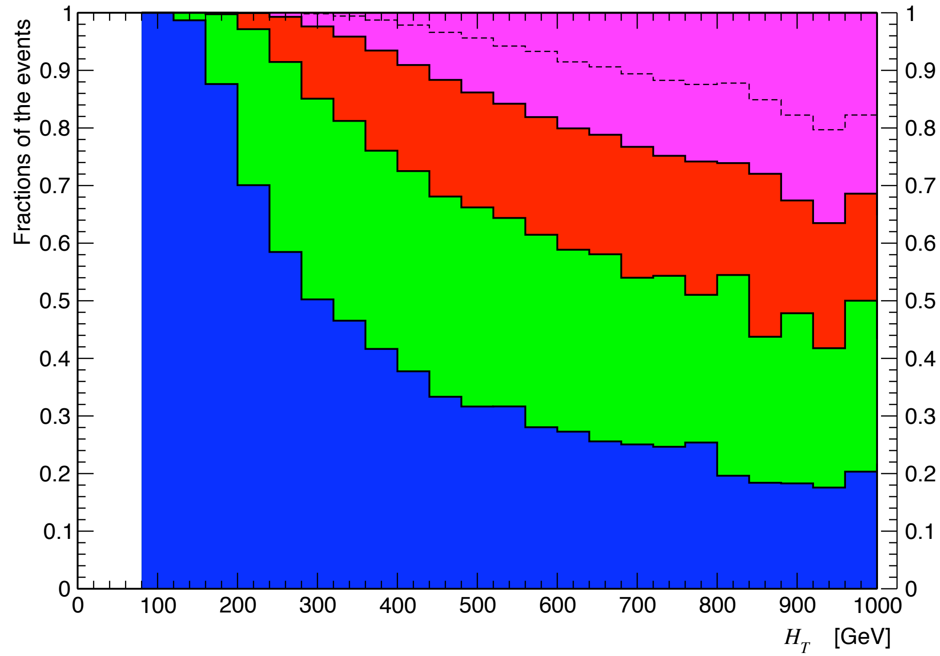
W production in association with at least 2 jets

[ANDERSEN, MAÎTRE, SMILLIE, WINTER; LES HOUCHES 2011 PROCEEDINGS]

- studying the significance of multi-jet contributions in description of various observables
- colour code: $W + 2, 3, 4, 5$ jets, last bin inclusive; $\langle N \rangle = (\sum_{2,3,4} i\, n_i^{\rm exc} + 5\, n_5^{\rm inc})/n_2^{\rm inc}$
- relative multiplicity fractions and average number of jets $\langle N \rangle$ as functions of H_T and $H_{T,2}$
- fraction of $W+ \geq 4$ jets as large as 50% for large H_T, amplified in $\langle N \rangle(H_T)$
- composition of inclusive $W + 2$ jet predictions remarkably similar in all cases



BlackHat+Sherpa NLO exclusive sums



Sherpa ME+PS merging up to 5 jets

W production in association with at least 2 jets

[Andersen, Maître, Smillie, Winter; Les Houches 2011 proceedings]

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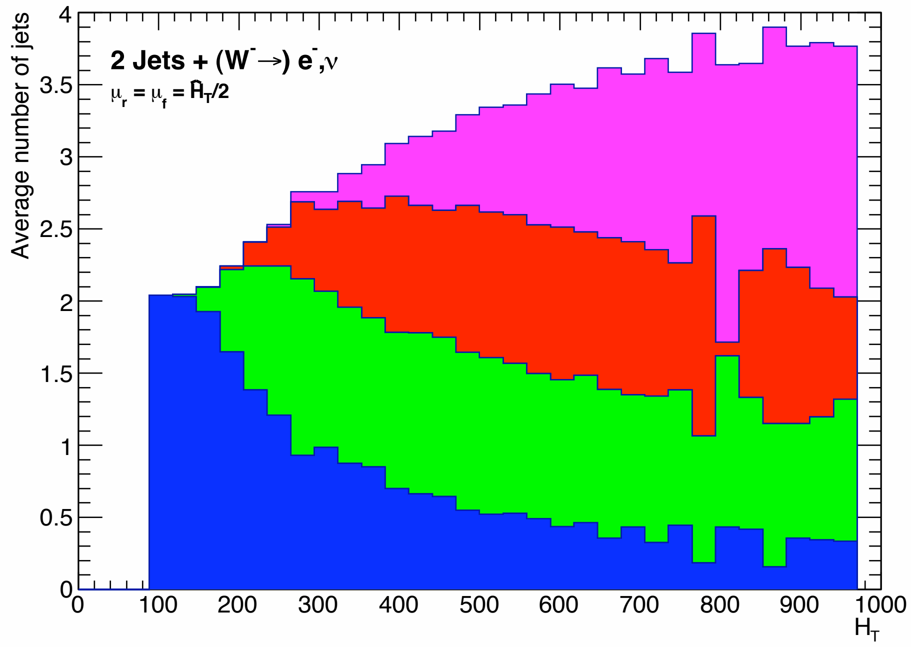

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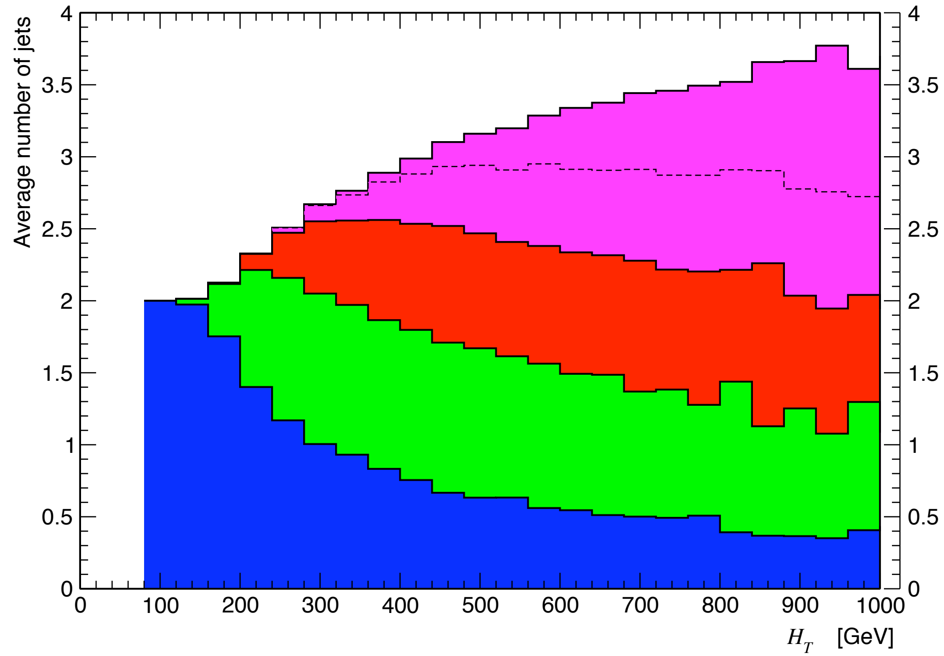

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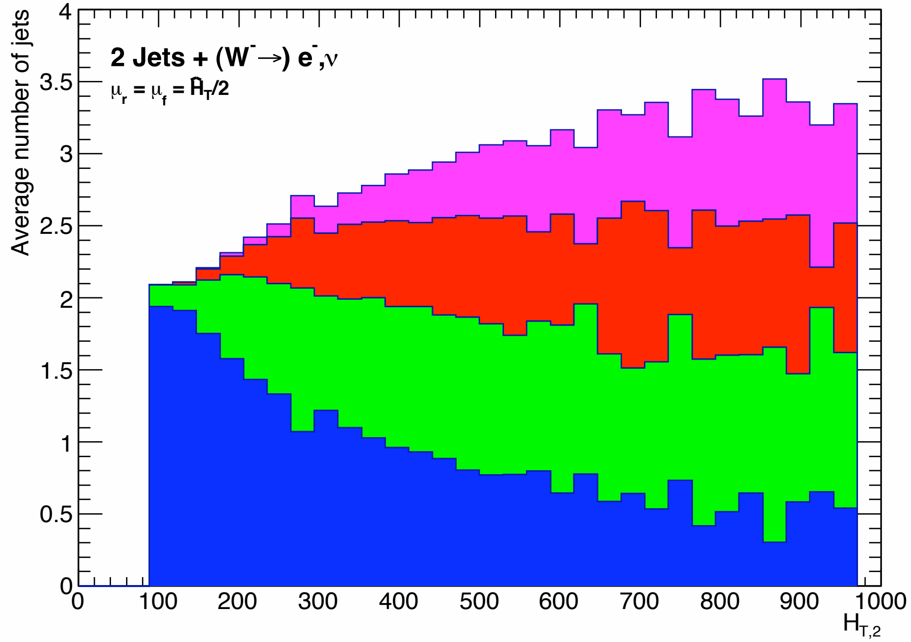

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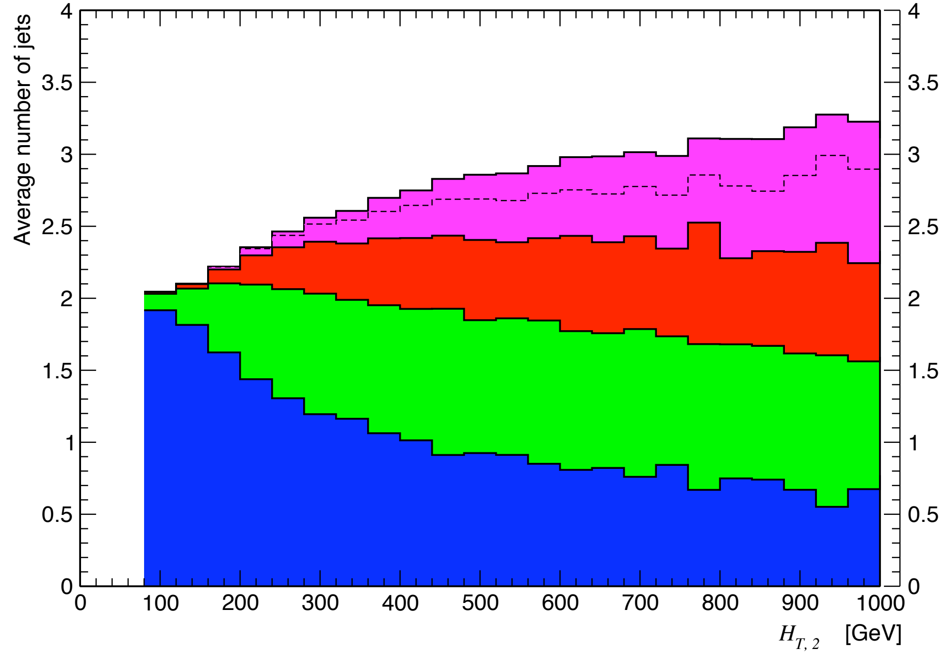


Sherpa ME+PS merging up to 5 jets

(Automated) Matrix-elements frontier

[SLIDE FROM STEFAN HÖCHE]

Cutting edge: Automating multi-leg NLO calculations

$$d\sigma^{NLO} = d\Phi_B\,(B+V) + d\Phi_R\,R = d\Phi_B\,\left[(B+V+I) + d\Phi_{R|B}\,(R-S)\right]$$

S - subtraction term constructed such that IR singularities in R are removed

I - integrated subtraction term locally compensates $S \to 0 \stackrel{!}{=} I - \int d\Phi_{(1)}\, S$

S and I universal and "easy" to automate, V tedious

$\Rightarrow$ Two pieces combined using the Binoth Les Houches accord CPC181(2010)1612

- One-Loop-Engine $\to$ virtual piece
  BlackHat, GOLEM, HELAC, MADLOOP, MCFM, NLOJET++, Rocket, Samurai, ...
- MC $\to$ Born, real emission, subtraction and phase space
  SHERPA, HELAC, MADDIPOLE, MADFKS, ...

Example: W+4 jets with BlackHat [Berger et al.] PRL 106(2011)092001

no. jets	W^- LO	W^- NLO	W^+/W^- LO	W^+/W^- NLO	$W^- n/(n-1)$ LO	$W^- n/(n-1)$ NLO
0	$1614.0(0.5)^{+208.5}_{-235.2}$	$2077(2)^{+40}_{-31}$	1.656(0.001)	1.580(0.004)	—	—
1	$264.4(0.2)^{+22.6}_{-21.4}$	$331(1)^{+15}_{-12}$	1.507(0.002)	1.498(0.009)	$0.1638(0.0001)^{+0.044}_{-0.031}$	0.159(0.001)
2	$73.14(0.09)^{+20.81}_{-14.92}$	$78.1(0.5)^{+1.5}_{-4.1}$	1.596(0.003)	1.57(0.02)	$0.2766(0.0004)^{+0.051}_{-0.037}$	0.236(0.002)
3	$17.22(0.03)^{+8.07}_{-4.95}$	$16.9(0.1)^{+0.2}_{-1.3}$	1.694(0.005)	1.66(0.02)	$0.2354(0.0005)^{+0.034}_{-0.025}$	0.216(0.002)
4	$3.81(0.01)^{+2.44}_{-1.34}$	$3.55(0.04)^{+0.08}_{-0.30}$	1.812(0.001)	1.73(0.03)	$0.2212(0.0004)^{+0.026}_{-0.020}$	0.210(0.003)

Multi-jet predictions @ LO+LL and beyond

Traditional approach: parton showers describe additional jet activity. There are limitations:

- semi-classical picture; quantum interferences and correlations only approximate
- lack of high-energetic large-angle emissions (LO+LL)
- shower seeds are (QCD) LO processes only, and evolution proceeds in large N_C limit
- uncertainties hard to assess & not so small; compensate for missing PT by non-PT tuning?

Possible improvements:

- first few hardest emissions given by tree-level MEs ➡ improved LO+LL predictions

  [called (tree-level/LO) ME+PS merging – CKKW, CKKW-L, MLM, ME&TS – No NLO xsecs!]

- use NLO QCD core processes and match to parton showers ➡ NLO+LL predictions

  [called NLO+PS matching – MC@NLO, POWHEG – Full NLO xsecs!]

- MENLOPS ➡ originally combination of POWHEG and ME+PS

  [nowadays, core: NLO+PS & additional multiplicities: ME+PS]

Systematic embedding of higher-order QCD corrections in multi-purpose Monte Carlos like Herwig, Pythia or Sherpa. (enormous progress in last 10 years with two effects)

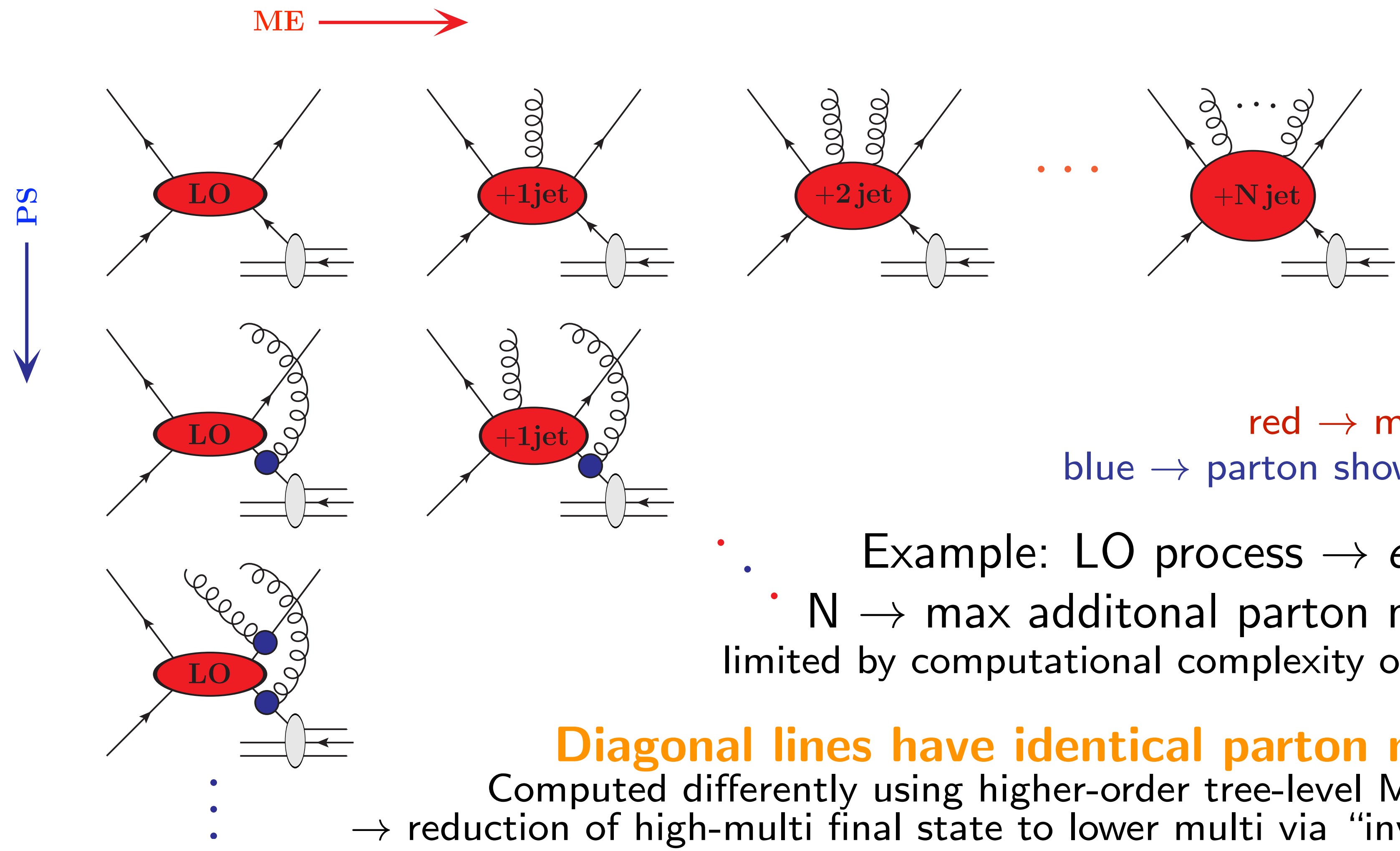
$\Rightarrow$ qualitatively better description of QCD jet data at all colliders (LEP, Hera, Tevatron, LHC)

$\Rightarrow$ improved handling and understanding of systematic uncertainties

(LO) Matrix-element + parton-shower merging

- combine PS pros (resumming soft emissions) + ME pros (hard emissions, quantum interferences, correlations)

⇒ Fully populate emission's phase space with either ME or PS – avoid dead regions.
⇒ ME and PS describe the same final state – remove double counting.



red → matrix element
blue → parton shower branching

Example: LO process → $e^{\pm}q \to e^{\pm}q$
N → max additonal parton multi in ME
limited by computational complexity of the problem

Diagonal lines have identical parton multiplicity
Computed differently using higher-order tree-level ME or/and PS
→ reduction of high-multi final state to lower multi via "inverse" shower

Tree-level ME+PS merging

Merging procedures have main steps in common:

(1) calculate n-jet cross sections: use jet criteria to define/regularize the MEs,

(2) generate hard-parton samples with ME kinematics and $P \propto n$-jet/total xsecs,

(3) accept/reject jet configurations based on their (further) PS evolution,

(4) find suitable starting conditions for the parton showering and veto unwanted jets.

Different methods use different techniques in dealing with (1), (3) and (4):

- CKKW, for example: (1) employ k_T-jet measure; (3) reweight MEs through α_s and analytical Sudakov form factors; (4) evolve each ME parton using k_T cluster scales & veto emissions above $Q_{\rm jet}$

Examples for ME+PS merging Monte Carlos:

- Alpgen – MLM; interfaced to Pythia or Herwig [MANGANO ET AL.]
- MadGraph – MLM, cone or k_T jets; interfaced to Pythia [MALTONI ET AL.]
- Sherpa – CKKW, ME&TS from vs1.2; truly interconnected with PSs [KRAUSS ET AL.]
- Herwig++ – modified CKKW, i.e. truncated showers [RICHARDSON ET AL.]
- Ariadne/Pythia8 – CKKW-L; combination with interleaved showers [LÖNNBLAD ET AL.]

- By and large predictions agree [HEP-PH/0602031, EPJC53(2008)473, PHYS.REPT.504(2011)145]

Tree-level ME+PS merging

Merg

(1) calculate n-jet cro

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Different* methods use *diffe

- CKKW, for example:
  through α_s and analytica
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- Alpgen – ML
- MadGraph –
- Sherpa – CK
- Herwig++ –
- Ariadne/Pyth

- By and large predictions

CKKW

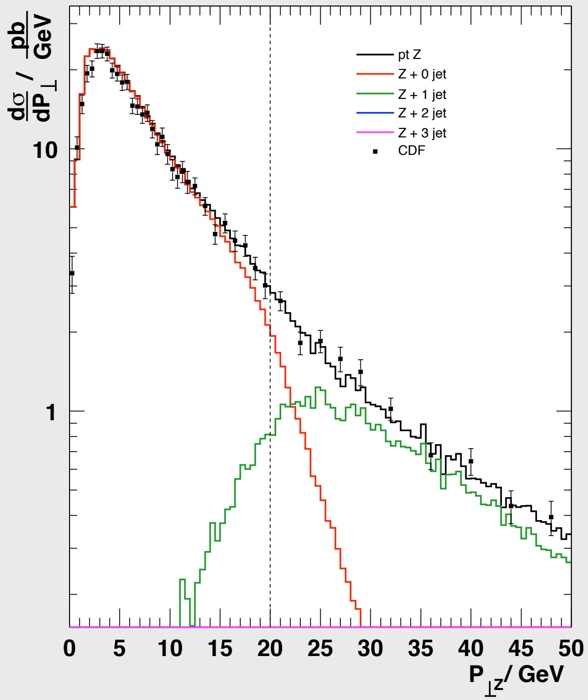
[Catani, Krauss, Kuhn, Webber, JHEP 11 (2001) 063]

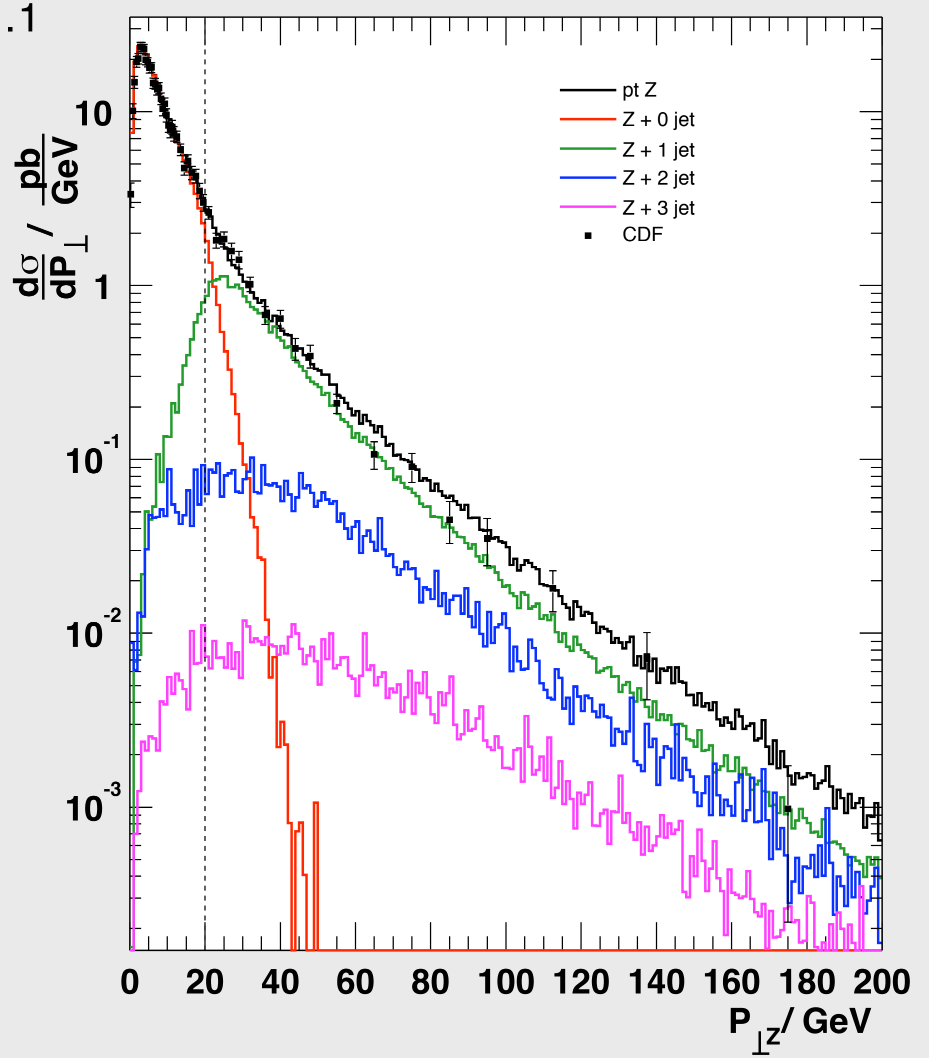
[Krauss, JHEP 08 (2002) 015]

⇒ in Sherpa vs1.0 and vs1.1

e.g. Z + jets @ 1.8 TeV

- AMEGIC + APACIC
- constant K-factor
- intrinsic k_T-smearing of order 1 GeV





Krauss et al. PRD 70 (2004) 114009

Systematic uncertainties of ME+PS predictions

related to ME+PS merging

- Q_{cut} – magnitude of phase-space separation cut [cancels to log-accuracy of shower]
- $N_{\text{ME}}^{\max}$ – maximum number of jets from hard tree-level MEs
- [choice of internal jet separation measure]

related to pQCD :: dynamical and local scale choices

- scale uncertainties from MEs [renormalization and factorization scale settings]
- scale uncertainties from PSs [coupling and PDF scale settings]

related to pQCD–npQCD transition

- parton-shower IR cut-off / intrinsic transverse momentum [tuned @ LEP & low-p_T DY pair production]
- PDFs plus $\alpha_s(M_Z)$ taken from the fit [enter globally, affect ME and PS]

related to npQCD [phenomenological universal models need be tuned to data]

- hadronization parameters [PROFESSOR tune against LEP data]
- underlying event parameters [PROFESSOR tune mainly against LHC data]

Les Houches 2011:

Step-by-step systematics study.

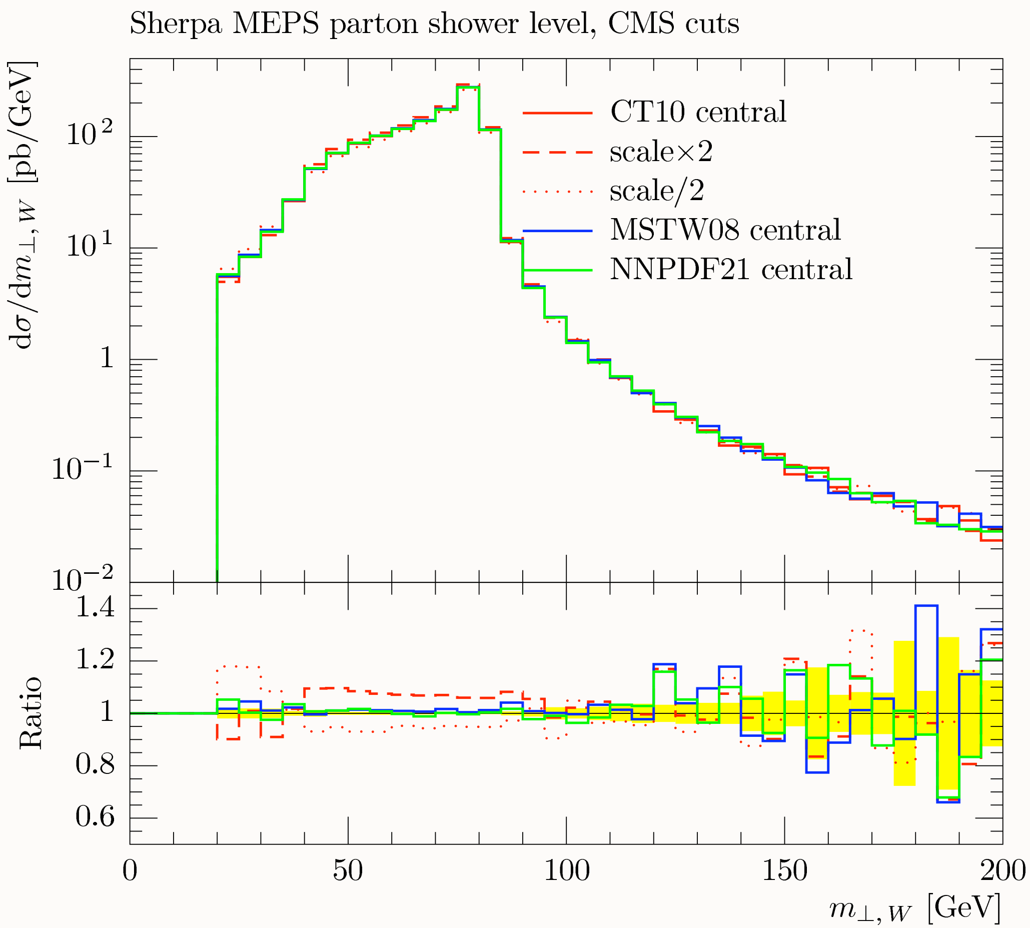
Estimate and understand uncertainties related to each source.

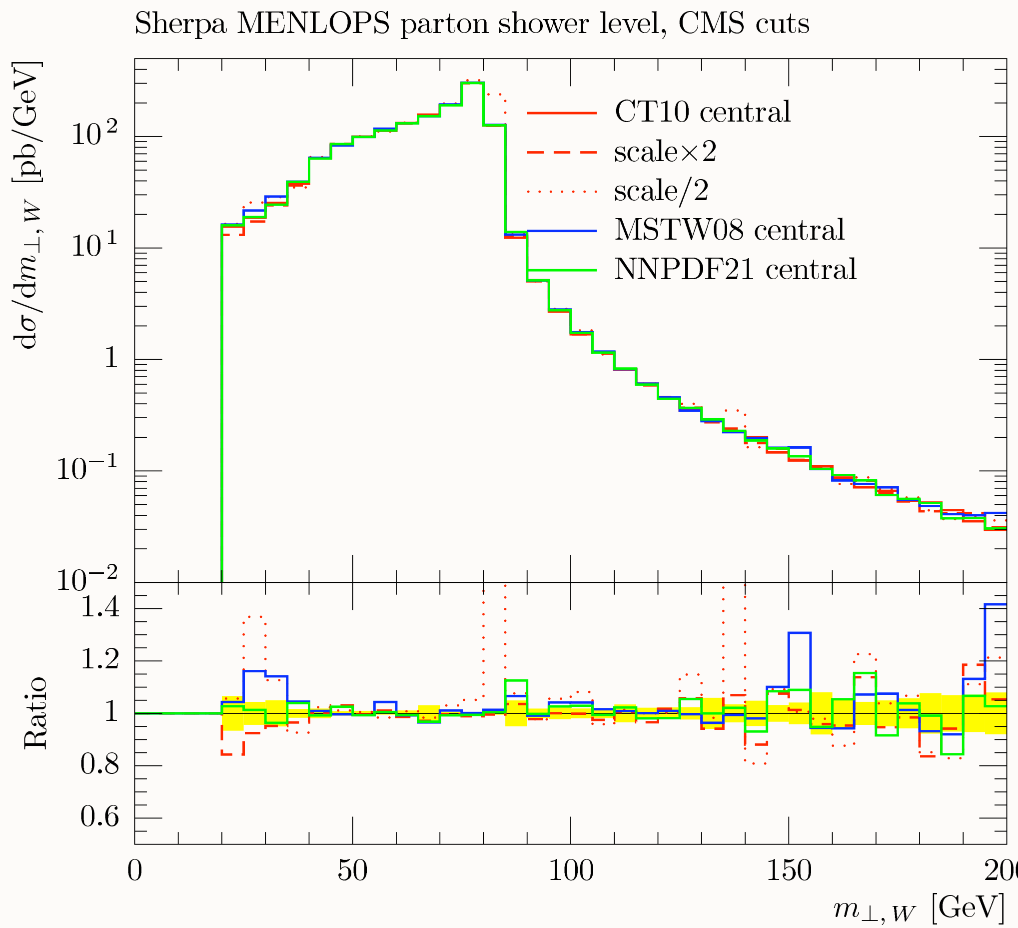
Step-by-step systematics study

[Alioli et al. Les Houches 2011 proceedings]

➡ ***Example: transverse mass of W boson in Sherpa using ME+PS and MEnloPS.***

- factorization and renormalization scale variations affecting ME and PS domain
- MEnloPS has smaller scale uncertainties due to NLO accuracy of core process
- PDF uncertainties estimated by comparing different PDF sets



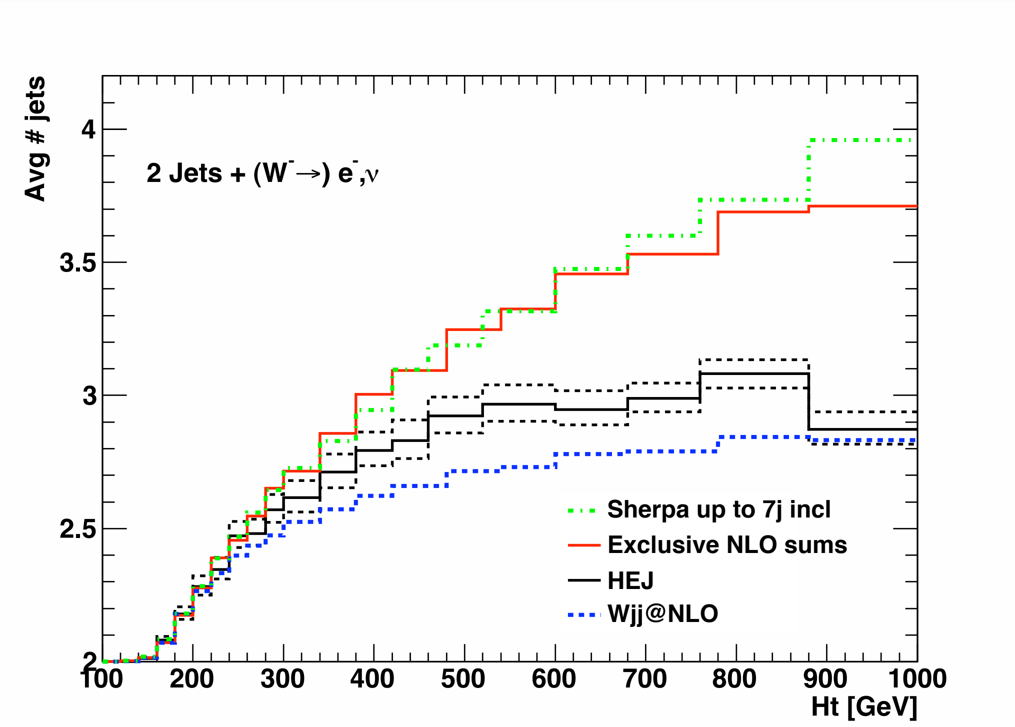


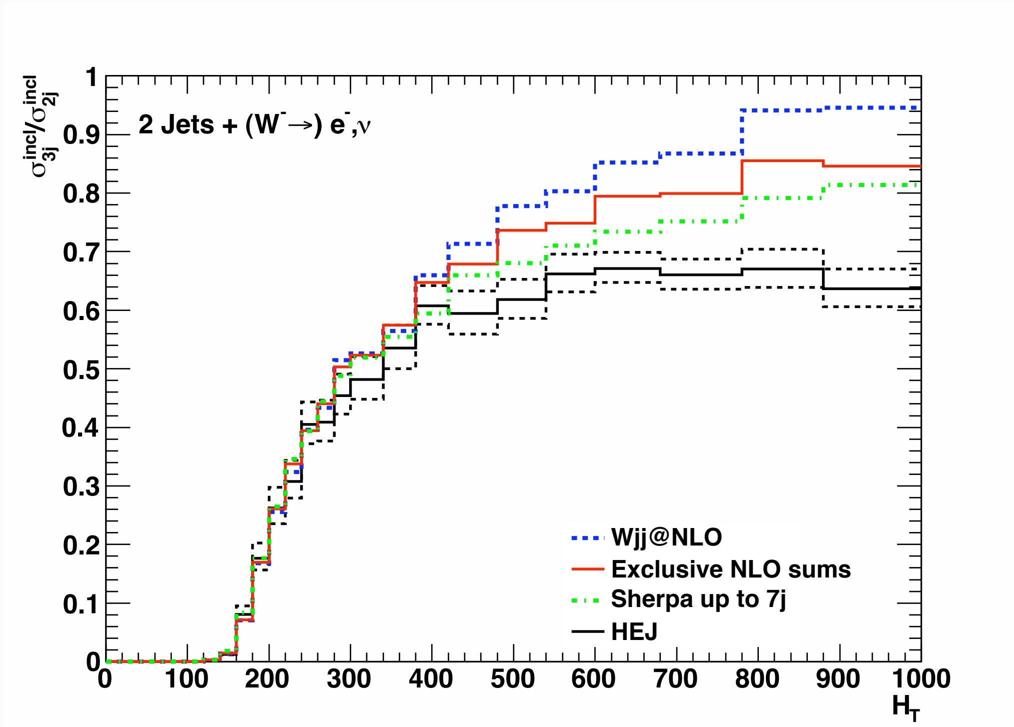
Once more, W bosons in association with at least 2 jets

[ANDERSEN, MAÎTRE, SMILLIE, WINTER; LES HOUCHES 2011 PROCEEDINGS]

➡ ***Average number of jets and ratio of 3-jet to 2-jet rate as a function of HT.***

- including the predictions of HEJ (High Energy Jets, an all-order resummation of wide-angle radiation) [ANDERSEN, SMILLIE]
- and of the $W + 2$ jets BlackHat+Sherpa calculation.
- More data will allow to discriminate the approaches.
- Again, NLO exclusive sums and Sherpa ME+PS look rather similar.





NLO exclusive sums versus ME+PS

➡ ***Decompose total cross section based on exclusive and inclusive jet bins.***

$$\sigma^{\rm tot} \equiv \sigma_m^{\rm inc} = \sum_{n=m}^{M-1} \sigma_n^{\rm exc} + \sigma_M^{\rm inc}$$

- NLO exclusive sums: each jet bin at NLO accuracy, i.e. $\mathcal{O}(\alpha_s^{n+1})$
- terms are hence summed at different orders of α_s and there is no detailed treatment of jet vetoing $\Rightarrow$ exclusive sums introduce artefacts
- for example, scale dependence of exclusive sums is not under good control

- ME+PS: each jet bin at least at LL (soft/collinear) accuracy improved by LO n-jet effects
- terms are summed at the same (infinite) order of α_s and jet vetoing is LL accurate

  $\Rightarrow$ Similarity likely due to inclusion of same set of tree-level MEs and unresolved $\mathcal{O}(\alpha_s)$ corrections (encoded in Sudakov form factors)

  $\Rightarrow$ ME+PS is LO exclusive sums combined at LL accuracy

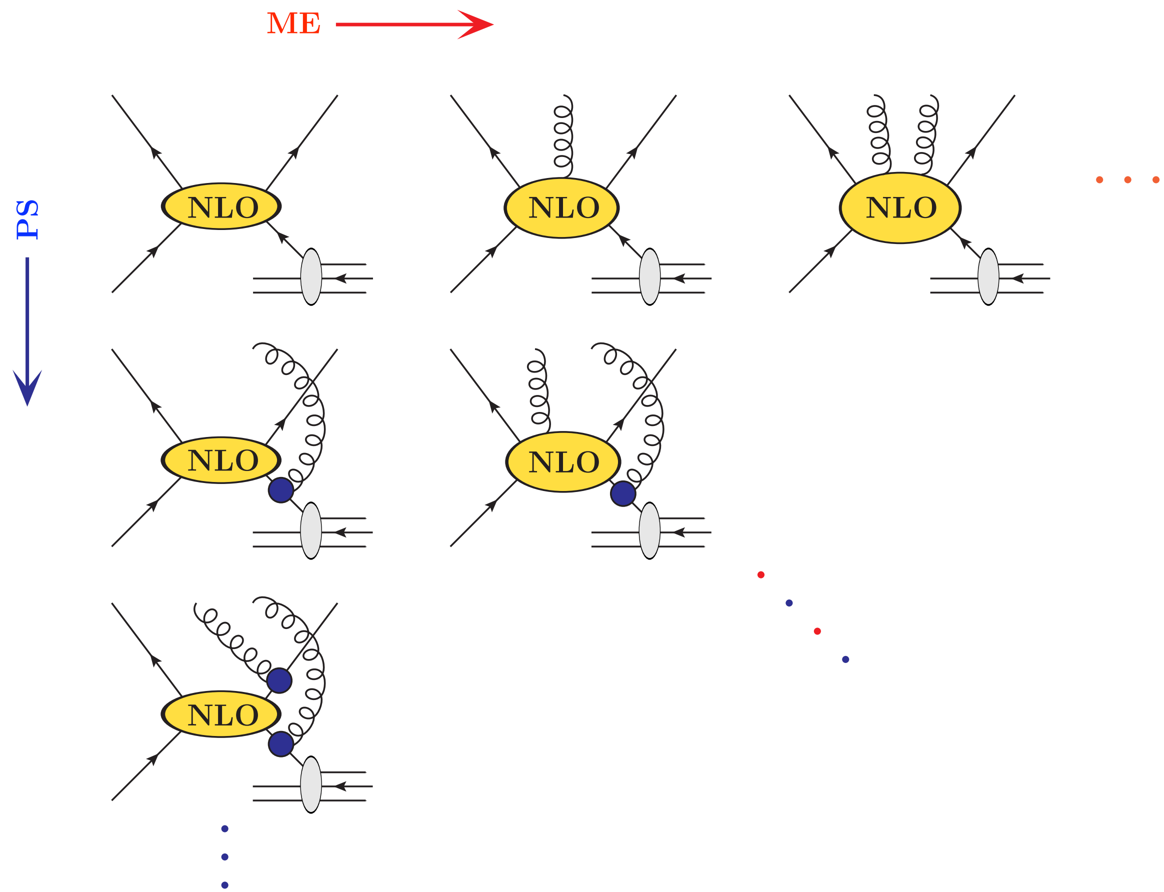
- Way to go: bring all terms in NLO exclusive sum to same order of strong coupling

  $\Rightarrow$ include (approx.) x-loop corrections to all terms but highest, e.g. by using LoopSim [Rubin, Salam, Sapeta, JHEP1009(2010)084]

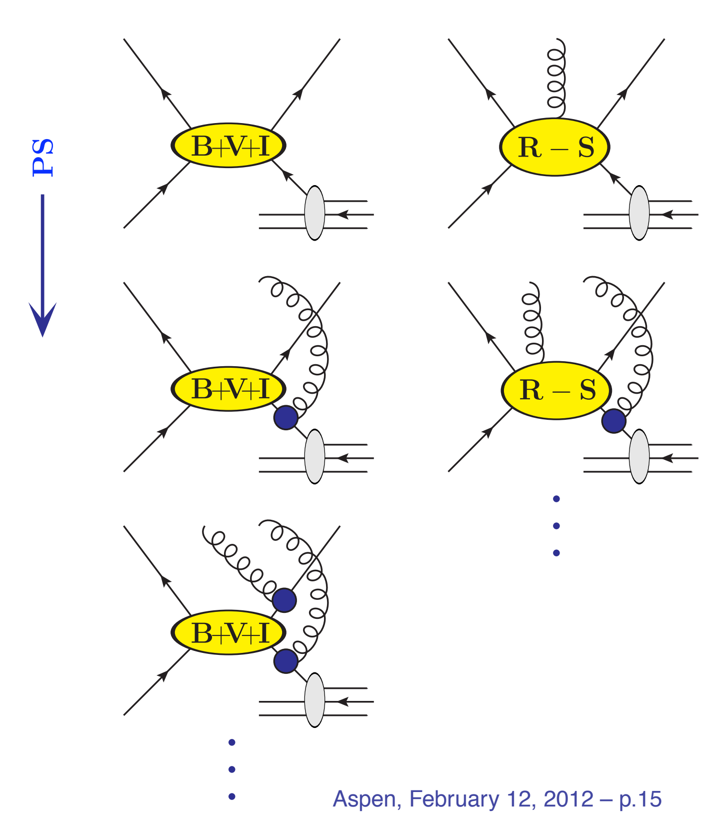
  $\Rightarrow$ do ME+PS trick at NLO ➡ construction zone

Future goal

ME+PS merging with multiple NLO processes



- First, NLO+PS matching needs to be under full control.
- The NLO challenge: B, V, I and S terms kinematically different from R.

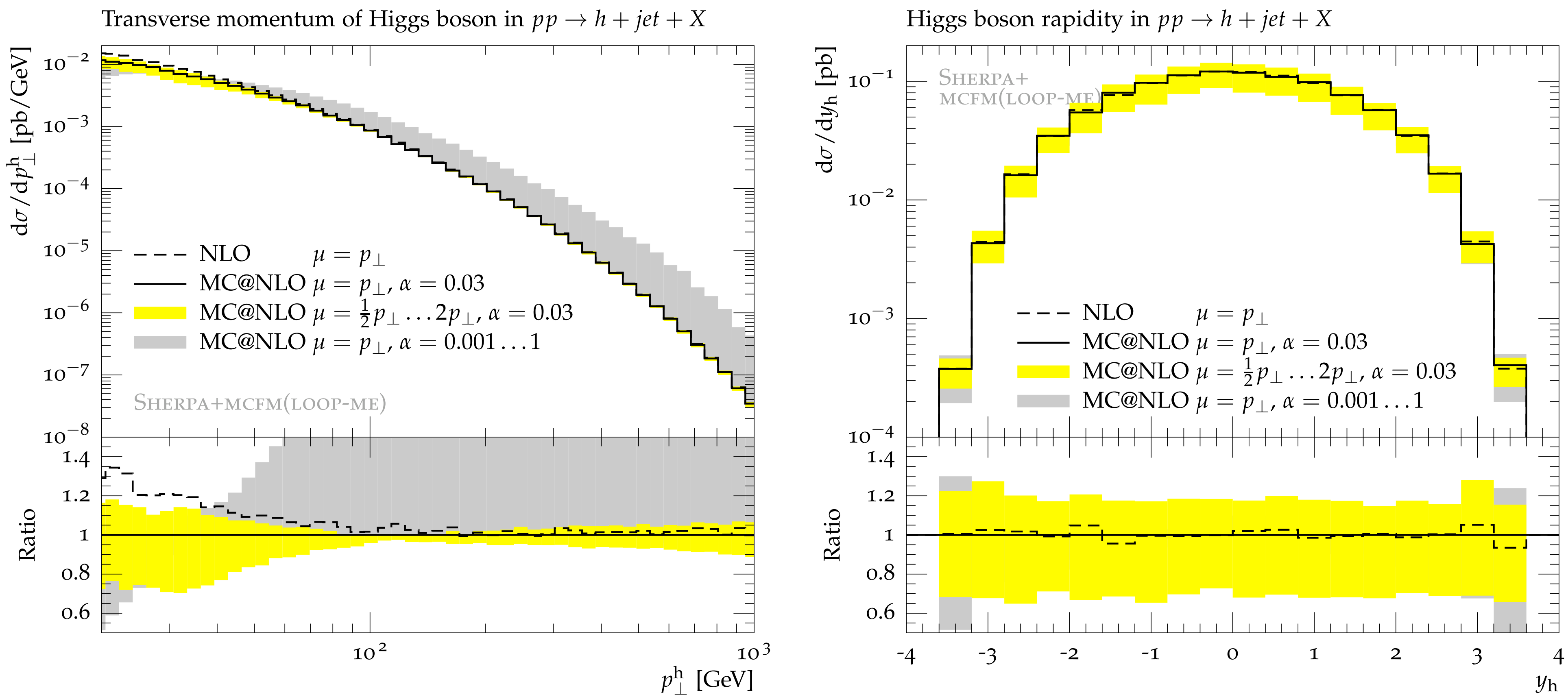


NLO+PS matching

- match PS to NLO preserving good features of both approaches
  (Sudakov suppression at small p_T, multiple soft/coll emissions)
  (NLO rate, high-p_T shape, reduced scale dependence)
- matching is smooth, no phase-space separation cut, final states are ready to be hadronized
- ***MC@NLO:*** http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/
  [Frixione, Webber; ...]
- ***aMC@NLO:*** automation of MC@NLO $\equiv$ MadFKS + MadLoop [JHEP1105(2011)044] + automation of MC subtraction terms
  [Frederix, Frixione, Torielli (+ Hirschi, Garzelli, Maltoni, Pittau)] ($W/Zb\bar{b}$ [arXiv:1106.6019], Wjj [arXiv:1110.5502])
- ***POWHEG:*** http://powhegbox.mib.infn.it
  [Alioli, Hamilton, Nason, Oleari, Re] (Vj/dijets [JHEP1101/4(2011)095/81], $Wb\bar{b}$ [arXiv:1105.4488])
  (POWHEG in Herwig/++ [Richardson et al.] automated in Matchbox [Plätzer et al.])
- ***MEnloPS:*** combine POWHEG and ME+PS via phase-space slicing
  [Hamilton, Nason, JHEP 06 (2010) 039]
  (ME+PS rescaled to correct inclusive norm by global cut-dependent K-factor.)
  (Non-unitarity of ME+PS is no problem as long as is smaller than NLO effects.)

POWHEG and MC@NLO in Sherpa

[SLIDE FROM STEFAN HÖCHE]



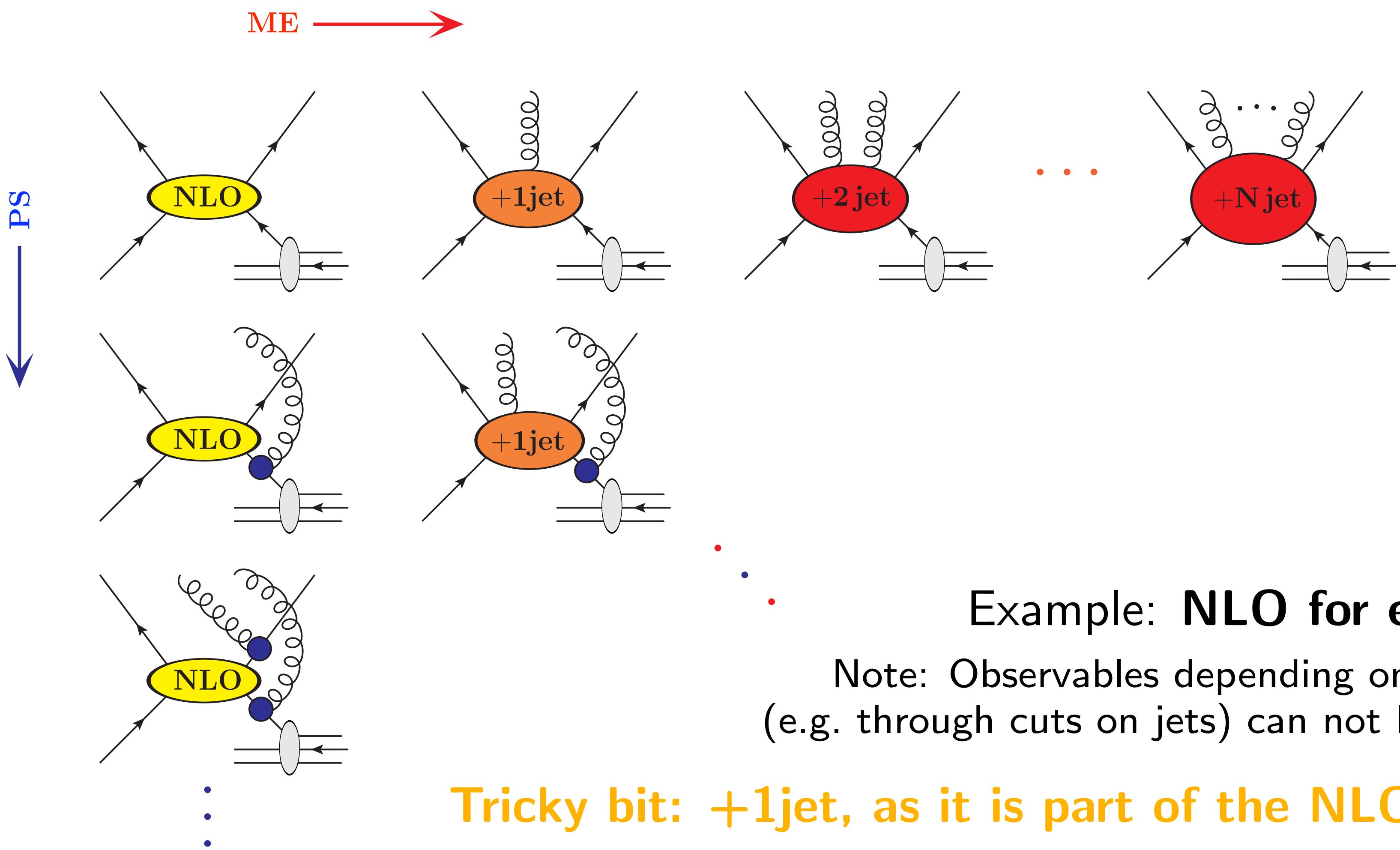
Example process: Higgs-boson plus jet production at the LHC
Assessment of matching uncertainties in POWHEG by varying $\mathrm{D}^{(\mathrm{A})}$

Upper edge of band ⇔ plain POWHEG, lower edge ⇔ MC@NLO
[Krauss,Schönherr,Siegert,SH] arXiv:1111.1220 [hep-ph]

To take home: Resumming small terms can make a big difference
Factorization scales must be respected in the parton shower

MEnloPS

Promoting the simulation to NLO accuracy for the core is currently cutting edge



Example: **NLO for $e^{\pm}q \rightarrow e^{\pm}q$**

Note: Observables depending on higher multi (e.g. through cuts on jets) can not be improved !

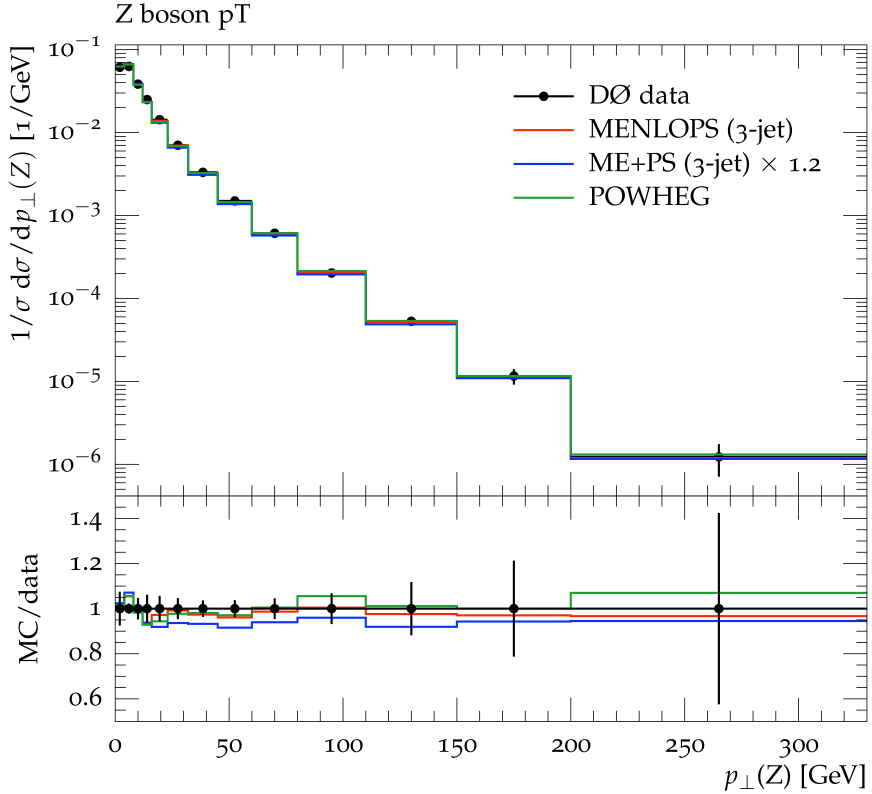
Tricky bit: +1jet, as it is part of the NLO core, too

- Slice POWHEG/MC@NLO phase space in ME+PS style.

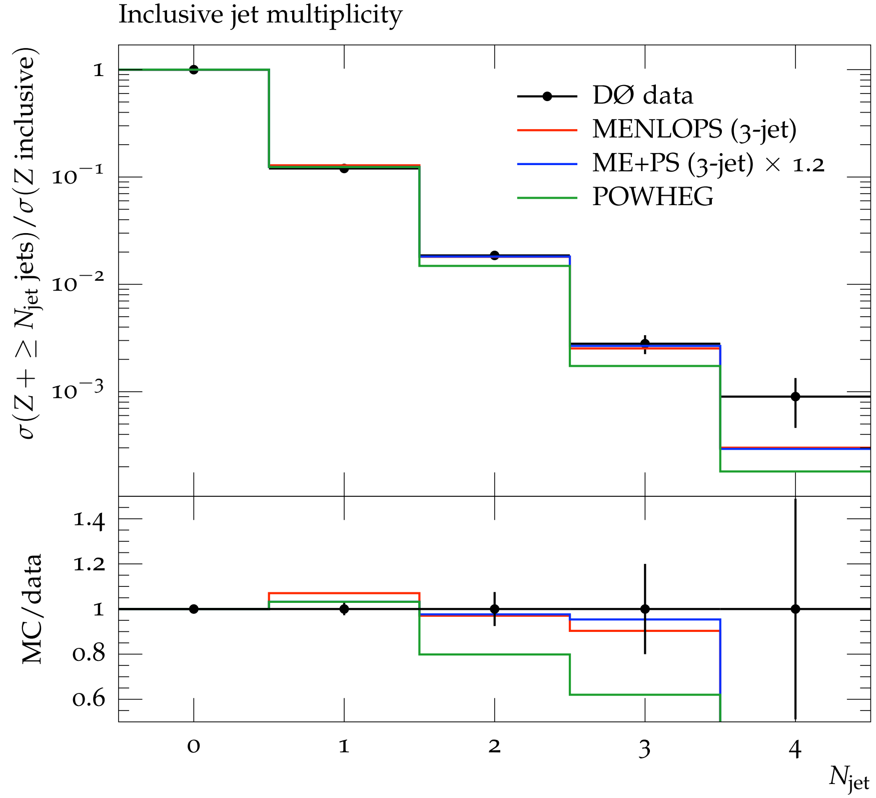
MENLOPS in Sherpa

[HÖCHE, KRAUSS, SCHÖNHERR, SIEGERT, JHEP 08 (2011) 123]

Z-boson p_T [DØ] PLB693(2010)522



Jet multiplicity [DØ] PLB658(2008)112



First Run II measurement using μ's
Data corrected to the particle level

SHERPA prediction: $p\bar{p} \to \ell\ell$@NLO
$\oplus$ $p\bar{p} \to \ell\ell+\{1,2,3\}$-jets@LO

- accuracy inherited from POWHEG/MC@NLO $\Rightarrow$ stable rates for core process
- higher order tree-level MEs via ME+PS $\Rightarrow$ improved multi-jet predictions

Summary

- Higher-order calculations are needed to meet the requirements on the precision of theoretical predictions in the LHC era.
  - Discussed by means of H_T measurements and predictions.
- Big issue is to have a very good understanding of the uncertainties related to our predictions. Necessary to have reliable estimates for S/B ratios and significances.
- Covered topics:
  - Tree-level ME+PS merging.
  - NLO exclusive sums and related problems.
  - NLO+PS matching. (new frontier $Wjjj$ MC@NLO in Sherpa [ARXIV:1201.5882])
  - MENLOPS.
- Lots of subjects uncovered: needed to be selective due to short amount of time; for an extensive review of MC tools, see Phys.Rept.504(2011)145.
- Need for good understanding of how NLO, NLO+PS, ME+PS, MENLOPS and (simple) shower models compare to each other and data.
  - This is crucial for assessing any future reported anomaly.