pQCD predictions for the LHC

Tools for multijet phenomenology

Steffen Schumann

II. Physikalisches Institut, Universität Göttingen

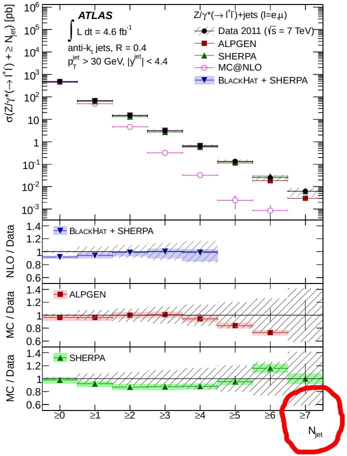
LHC Days in Split

02/10/14

pQCD challenges at the LHC

ATLAS $Z(\to e^+e^-/\mu^+\mu^-)$+jets analysis [JHEP **1307** (2013) 032]

inclusive jet rates



- large jet multiplicities
- wide range of kinematics/scales
  - hard Z associated with jets [requires FO calculations]
  - high-p_T jets associated by Z [expect large logarithmic corrections]

$\rightsquigarrow$ high-multiplicity FO calculations

$\rightsquigarrow$ parton-shower resummation important

$\rightsquigarrow$ combining different jet-multi final states

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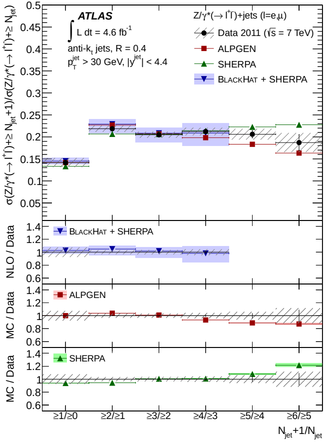

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$\rightsquigarrow$ combining different jet-multi final states

$\rightsquigarrow$ interesting patterns in xsec ratios

Outline

- **NLO QCD predictions** — the new standard
- **ME+PS matching** — towards automation at NLO
- **Applications** — scaling patterns, jet-rate extrapolation

How to address an LHC measurement with pQCD?

the partonic cross section

$$\frac{d\sigma}{dX} \propto \sum_{ab,n} \int \mathrm{d}x_a \mathrm{d}x_b \mathrm{d}\Phi_n(p_1,\ldots,p_n)\; f_a(x_a,\mu_F^2) f_b(x_b,\mu_F^2)\, |\mathcal{M}_{ab\to n}|^2\; \rho_n(p_1,\ldots,p_n)$$

- Φ_n is the n-particle phase space, $f_{a,b}$ the proton PDFs
- $\mathcal{M}_{2\to n}$ invariant matrix element [approx. for large n]
- measurement function ρ_n projects out observable

$$\rho_n = \begin{cases} 1 & : \text{ total cross section} \\ \delta(X - \chi_n(p_1,\ldots,p_n)) & : \text{ differential cross section} \end{cases}$$

$\rightsquigarrow$ implements acceptance cuts, observable definition

$\rightsquigarrow$ evaluated in fixed-order perturbation theory [hard process]

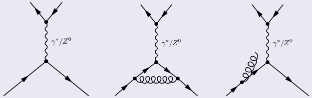
$\rightsquigarrow$ semi-classical approximations for large n [parton shower, resummation]

$\rightsquigarrow$ model parton–hadron transition, remnant interactions [hadronization, underlying event]

Hard Processes at Next-to-Leading Order QCD

Anatomy of NLO QCD calculations [in dim. regularization $d = 4 - 2\epsilon$]

$$\sigma_{2\to n}^{NLO} = \int_n \mathrm{d}^{(4)}\sigma^B + \int_n \mathrm{d}^{(d)}\sigma^V + \int_{n+1} \mathrm{d}^{(d)}\sigma^R$$



- (UV renormalized) virtual-corrections $\sigma^V \rightsquigarrow$ IR divergent
- real-emission $\sigma^R \rightsquigarrow$ IR divergent

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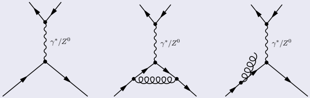

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Dipole subtraction method [Catani, Seymour Nucl. Phys. B **485** (1997) 291]

$$\sigma^{NLO}_{2\to n} = \int_n \left[\mathrm{d}^{(4)}\sigma^B + \int_{\mathrm{loop}} \mathrm{d}^{(d)}\sigma^{\mathrm{V}} + \int_1 \mathrm{d}^{(d)}\sigma^{\mathrm{A}}\right]_{\epsilon=0} + \int_{n+1}\left[\mathrm{d}^{(4)}\sigma^{\mathrm{R}} - \mathrm{d}^{(4)}\sigma^{\mathrm{A}}\right]$$

- subtraction terms yield local approximation for the real emission process
- describe the amplitude in the soft & collinear limits [$1/\epsilon$ and $1/\epsilon^2$ poles]

$$\int_{n+1} \mathrm{d}^{(d)}\sigma^{\mathrm{A}} = \sum_{\mathrm{dipoles}} \int_n \mathrm{d}^{(d)}\sigma^{\mathrm{B}} \otimes \int_1 \mathrm{d}^{(d)} V_{\mathrm{dipole}}$$

spin- & color correlations $\longleftrightarrow$ $\hookrightarrow$ universal dipole terms

Hard Processes at Next-to-Leading Order QCD

The emerging picture: a fully differential NLO calculation

$$\sigma^{NLO}_{2\to n} = \int_{n+1}\left[\mathrm{d}^{(4)}\sigma^{\mathrm{R}} - \mathrm{d}^{(4)}\sigma^{\mathrm{A}}\right] + \int_{n}\left[\mathrm{d}^{(4)}\sigma^{B} + \int_{\mathrm{loop}} \mathrm{d}^{(d)}\sigma^{\mathrm{V}} + \int_{1} \mathrm{d}^{(d)}\sigma^{\mathrm{A}}\right]_{\epsilon=0}$$

Monte-Carlo codes

- all the tree-level bits
- subtraction of singularities
- efficient phase-space integration

One-Loop codes

- Loop amplitudes, *i.e.* $2\Re(\mathcal{A}_V\mathcal{A}_B^\dagger)$
- Loop integration

$\leadsto$ $1/\epsilon$, $1/\epsilon^2$ coefficients & finite terms

some recent NLO calculations:

2009 $W+3$jets, $t\bar{t}+1$jet

2010 $W+4$jets, $Z+3$jets

2011 $Z+4$jets, $t\bar{t}+2$jets, 4jets

2012 $\gamma+3$jets

2013 $W+5$jets, 5jets

2014 $\gamma\gamma+3$jets

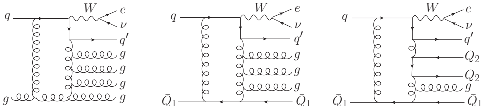
OL tools & names:

- BlackHat: Bern et al.
- HelacNLO: Bevilacqua et al.
- OpenLoops: Pozzorini et al.
- GoSam: Cullen et al.
- NJET: Biedermann et al.
- MadLoops: Hirschi et al.

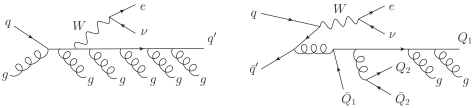
NLO QCD predictions: $W + 5$jets

$W + 5$j @ NLO: The challenge

- one-loop corrections



- real emission corrections



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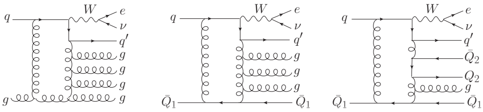

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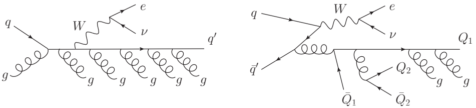


first calculation completed recently

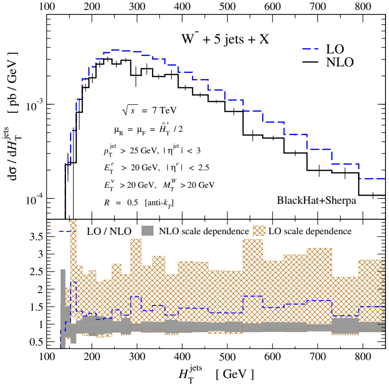
- BLACKHAT+SHERPA: Bern et al. [Phys. Rev. D **88** (2013) 1, 014025]
  - BLACKHAT: on-shell methods for one-loop amplitudes [arXiv:0808.0941]
  - SHERPA: dipole subtraction, real-emission, phase space, stearing
  - ↪ fully differential partonic event generator with NLO accuracy

NLO QCD calculations: $W + 5$jets

BlackHat+Sherpa: 7 TeV LHC predictions [Phys. Rev. D **88** (2013) 1, 014025]

- consider anti-k_t jets with $p_T^{\rm jet} > 25$ GeV & R=0.5

process	W^- – LO	W^- – NLO	W^+ – LO	W^+ – NLO
xsec [pb]	$1.076(0.003)^{+0.985}_{-0.480}$	$0.77(0.02)^{+0.07}_{-0.19}$	$2.005(0.006)^{+1.815}_{-0.888}$	$1.45(0.04)^{+0.12}_{-0.34}$



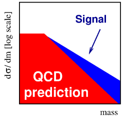
central scale

$$\mu_R = \mu_F = \mu = \hat{H}'_T/2$$

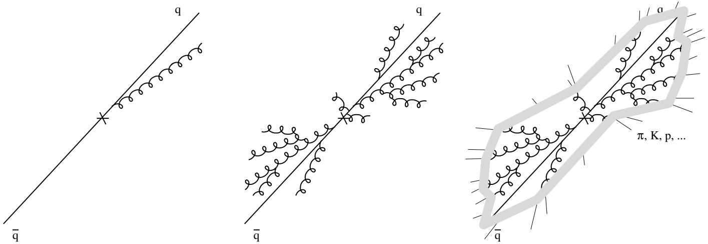
$$\hat{H}'_T \equiv \sum_i p^{\rm jet}_{T,i} + \sqrt{M_W^2 + p^2_{T,W}}$$

scale variations

$$\mu/2, \mu/\sqrt{2}, \mu, \sqrt{2}\mu, 2\mu$$



The QCD Parton Shower picture



- construct explicitely the initial- & final-state partons history/fate
- successive branching of incoming and outgoing legs

  $\rightsquigarrow$ exclusive partonic final states with $\mathcal{P}_{\text{tot}} = \mathcal{P}_{\text{hard}} \cdot \mathcal{P}_{\text{IS}} \cdot \mathcal{P}_{\text{FS}}$
- evolve parton ensemble from high- to low scale $\mathcal{O}(1\text{GeV}^2)$

  $\rightsquigarrow$ link the hard process to universal hadronization models
- model intra-jet energy flows: jets become multi-parton objects

Matching exact matrix elements with parton showers

The art of combining matrix elements with parton showers

- model few hardest emissions by exact matrix elements
- account for subsequent splittings, i.e. soft and/or collinear emissions
- avoid any double counting or dead regions of emission phase space
- preserve fixed-order & logarithmic precision of the calculation
- ground-breaking work:
  - multileg tree-level matching: Catani et al. JHEP **0111** (2001) 063
  - NLO + Parton Shower: Frixione, Webber JHEP **0206** (2002) 029

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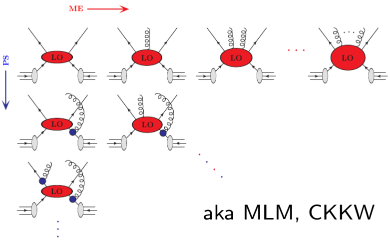
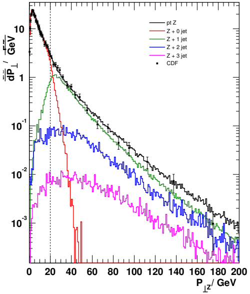
MEPS@LO



aka MLM, CKKW

Drell-Yan p_T @ CDF



[Krauss et al. Phys. Rev. D **70** (2004) 114009]

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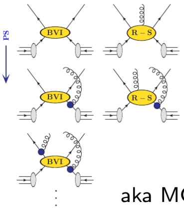
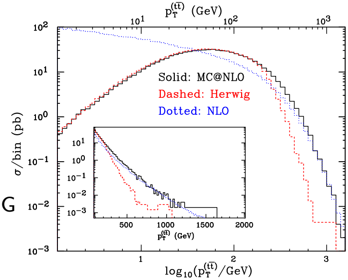
MC@NLO



aka MC@NLO, POWHEG

Top-pair p_T @ 14 TeV



[Frixione et al. JHEP **0308** (2003) 007]

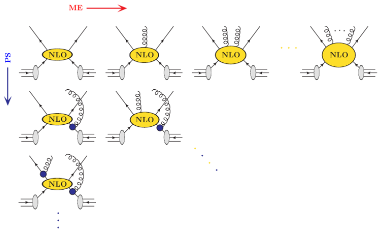
ME+PS: pull the rabbit – merging NLO processes

a new standard emerging – merging at NLO

- combination of NLO processes of varying jet multi, matched with shower
- option to add in higher-multiplicity tree-level matrix elements

$\hookrightarrow$ needs notion of exclusive NLO cross sections, e.g. vetoed showers

MEPS@NLO



available approaches

- merging of MC@NLO-type processes in SHERPA [Höche et al. arXiv:1207.5030]

  $W + 0, 1, 2$ at NLO & $W+ \geq 3$ at LO
- aMC@NLO merging approach [Frederix, Frixione arXiv:1209.6215]

  adding up $W + 0, 1$ MC@NLO processes
- CKKW-L at NLO [Lönnblad, Prestel arXiv:1211.7278]

  merging $W + 0, 1$j at NLO & PYTHIA8
- Merging of POWHEG processes [Hamilton et al. arXiv:1212.4504]

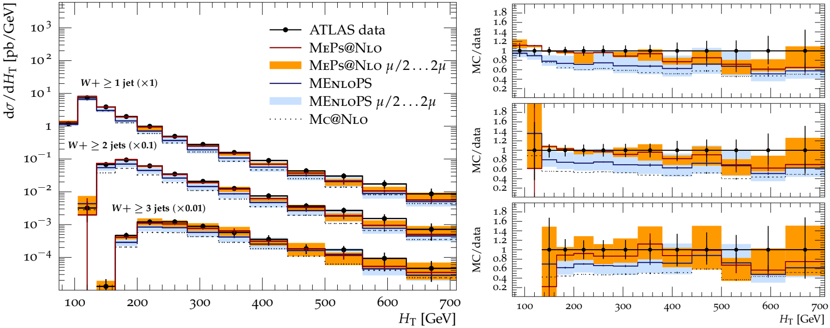
  combine $W/Z + 0, 1$ POWHEG generators

calculational setup MEPS@NLO [Höche et al. JHEP **1304** (2013) 027]

- $W+0,1,2$j at NLO matched MC@NLO style
- $W+3,4$j at LO matched using truncated shower

} on the flight merged into inclusive sample

- CKKW-style scale setting: $\alpha_s(\mu_R^2)^n = \prod_{i=1}^{n} \alpha_s(\mu_i^2)$
- factorization & renormalization scale variations – $\mu/2$ & 2μ



$\hookrightarrow$ largely reduced systematics for merged NLO samples

$\hookrightarrow$ leading-order systematics where dominated by tree-level, i.e. high-H_T

Applications: jet-ratio scaling patterns

consider ratios of successive exclusive jet rates [Gerwick et al. JHEP **1210** (2012) 162]

$$R_{(n+1)/n} = \frac{\sigma_{n+1}^{\mathrm{excl}}}{\sigma_n^{\mathrm{excl}}}$$

- $\rightsquigarrow$ n counting (radiated) jets in addition to the core process
- $\rightsquigarrow$ ratios quite stable against QCD corrections, reduced systematics
- $\rightsquigarrow$ analytically accessible via resummed jet rates [Gerwick et al. JHEP **1304** (2013) 089]

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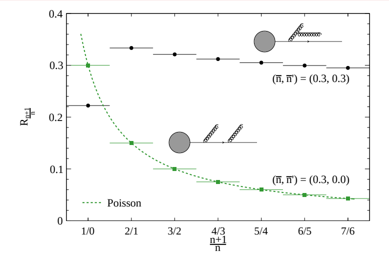
Poisson scaling

defined via $R_{(n+1)/n} \equiv \frac{\bar{n}}{n+1}$

- jet rates given by a Poisson dist. $\sigma_n \sim \frac{\bar{n}^n e^{-\bar{n}}}{n!}$
- independent emission picture
- inclusive ratios more cumbersome
- like soft-photon emission in QED

$\hookrightarrow$ driven by large emission prob.

statistical toy model



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staircase scaling

defined via $R_{(n+1)/n} \equiv R = \rm const$

$\rightsquigarrow$ $\sigma_n = \sigma_0 R^n$

- excl. & incl. scale the same

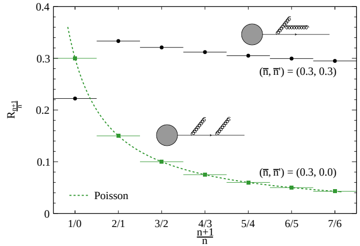
$\rightsquigarrow$ $\frac{\sigma_{n+1}^{\rm incl}}{\sigma_n^{\rm incl}} = \frac{\sigma_{n+1}^{\rm excl}}{\sigma_n^{\rm excl}} = R$

- first mentioned for $W/Z + jets$

[Ellis, Kleiss, Stirling '85 & Berends, Giele, Kuijf '89]

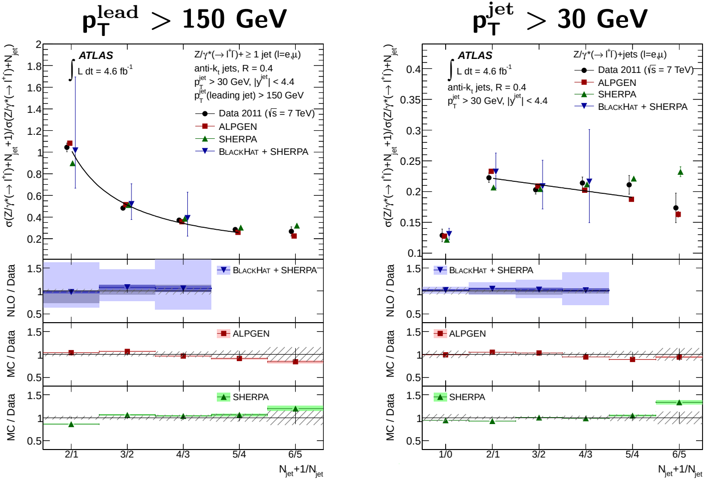
$\hookrightarrow$ induced by democratic jet cuts

statistical toy model



Applications: jet-ratio scaling patterns

ATLAS $Z(\rightarrow e^+e^-/\mu^+\mu^-)$+jets analysis [JHEP **1307** (2013) 032]



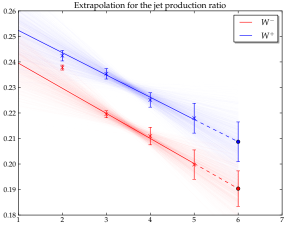
- confirms analytic findings based on resummed jet rates
- PDF/energetic suppression for low-multi bins in democratic selection

[Gerwick et al. JHEP **1210** (2012) 162 & JHEP **1304** (2013) 089]

Applications: jet-rate extrapolation

Predicting $W + 6$j with BLACKHAT+SHERPA

[Bern et al. Phys. Rev. D **88** (2013) 1, 014025 & arXiv:1407.6564]



phenomenological fits motivated by scaling arguments:

$$R^{\mathrm{NLO},\,W^-}_{n/(n-1)} = 0.248 \pm 0.008 - (0.009 \pm 0.002)\,n$$

$$R^{\mathrm{NLO},\,W^+}_{n/(n-1)} = 0.263 \pm 0.009 - (0.009 \pm 0.003)\,n$$

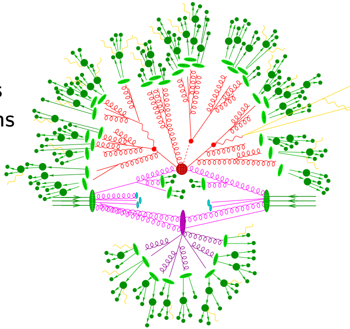
NLO rate estimates

$W^- + 6$ jets : 0.15 ± 0.01 pb & $W^+ + 6$ jets : 0.30 ± 0.03 pb

Summary: pQCD predictions for the LHC

Prepare(d) for the LHC challenge

- precise predictions for the Standard Model
    - multileg tree-level & one-loop matrix elements
    - improved parton-shower & matching algorithms
- invoke models for non-perturbative physics
    - capture main features of low-energy dynamics
    - testable/tunable against experimental data



Current activities

- further improving our Standard Model predictions
    - improving the logarithmic accuracy of shower algorithms
    - matching NLO calculations of varying multiplicity with showers
    - attaching parton showers to NNLO matrix elements
- BSM searches in a QCD environment
    - new analysis techniques, e.g. subjets, event shapes
    - NLO matrix-element and shower matching for signals