Simulations in High-Energy Physics

Frank Krauss

Institute for Particle Physics Phenomenology
Durham University

CTEQ school, Pittsburgh, July 2019

INTRODUCTION

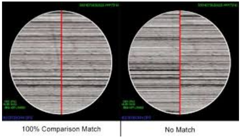
motivation: the quest for precision

- LHC (and particle physics in general) in phase of SM "crash-testing": confirm minutiae of EWSB and gauge structure
- QCD effects often limiting factor: $p_\perp^{W,Z,H}$, $m_{\rm top}$, $g\to Q\bar{Q}$, boosted objects & substructure
- necessary: work on better understanding of parton shower

(based on perturbtion theory: theory-driven with experimental validation)

also: multi-parton interactions, hadronization

(very phenomenological - parially or totally experiment-driven)



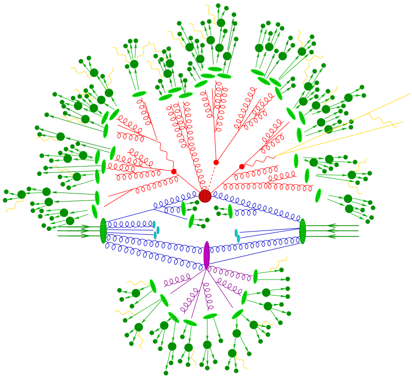
CSI LHC: need precise & accurate tools for precision physics

strategy of event generators

principle: divide et impera

- hard process:
  fixed order perturbation theory

  traditionally: Born-approximation
- bremsstrahlung:
  resummed perturbation theory
- hadronisation:
  phenomenological models
- hadron decays:
  effective theories, data
- "underlying event":
  phenomenological models

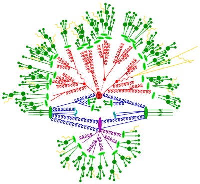


. . . and possible improvements

possible strategies:

- improving the phenomenological models:
  - "tuning" (fitting parameters to data)
  - replacing by better models, based on more physics

  (my hot candidate: "minimum bias" and "underlying event" simulation)



- improving the perturbative description:
  - inclusion of higher order exact matrix elements and correct connection to resummation in the parton shower:

    "NLO-Matching" & "Multijet-Merging"

  - systematic improvement of the parton shower: next-to leading (or higher) logs & colours

aim of the lectures

- review the state of the art in precision simulations

  (celebrate success)
- highlight missing or ambiguous theoretical ingredients

  (acknowledge failure)
- (maybe) suggest some further studies – experiment and theory

  (. . .)

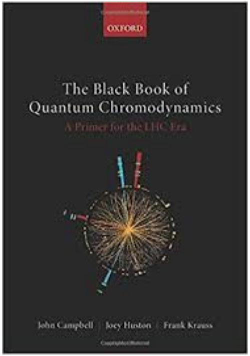
Plan of the Lectures

1. Perturbative QCD
   - Parton Level
   - Parton Showers
2. Precision Simulations
   - Matching
   - Merging
3. Non–Perturbative QCD
   - Hadronization
   - Underlying Event

Shameless promotion:

(as instructed by my co-author J.Huston)

material of lectures covered in

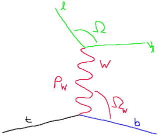


MONTE CARLO FOR PERTURBATIVE QCD

simulating hard processes (signals & backgrounds)

- simple example: $t \to bW^+ \to b\bar{l}\nu_l$:

$$|\mathcal{M}|^2 = \frac{1}{2}\left(\frac{8\pi\alpha}{\sin^2\theta_W}\right)^2 \frac{p_t\cdot p_\nu \;\; p_b\cdot p_l}{(p_W^2-M_W^2)^2+\Gamma_W^2 M_W^2}$$



- phase space integration (5-dim):

$$\Gamma = \frac{1}{2m_t}\frac{1}{128\pi^3}\int \mathrm{d}p_W^2 \frac{\mathrm{d}^2\Omega_W}{4\pi}\frac{\mathrm{d}^2\Omega}{4\pi}\left(1-\frac{p_W^2}{m_t^2}\right)|\mathcal{M}|^2$$

- 5 random numbers $\Longrightarrow$ four-momenta $\Longrightarrow$ "events".
- apply smearing and/or arbitrary cuts.
- Simply histogram any quantity of interest - no new calculation for each observable

calculating matrix elements efficiently

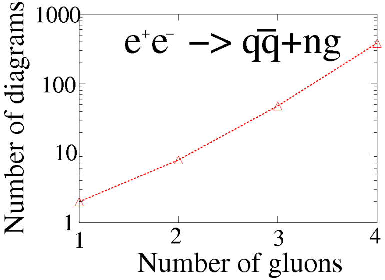
- stating the problem(s):
  - multi-particle final states for signals & backgrounds.
  - need to evaluate $\mathrm{d}\sigma_N$:

$$\int\limits_{\text{cuts}} \left[\prod_{i=1}^{N} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}\right] \delta^4\left(p_1 + p_2 - \sum_i q_i\right) \left|\mathcal{M}_{p_1 p_2 \to N}\right|^2 .$$

  - problem 1: factorial growth of number of amplitudes.
  - problem 2: complicated phase-space structure.
  - solutions: numerical methods.

- example for factorial growth: $e^+e^- \to q\bar{q} + ng$

n	$\#_{\rm diags}$
0	1
1	2
2	8
3	48
4	384



- obvious: traditional textbook methods (squaring, completeness relations, traces) fail
  $\Longrightarrow$ result in proliferation of terms $(\mathcal{M}_i\mathcal{M}_j^*)$
- better ideas of efficient ME calculation:
  $\Longrightarrow$ realise: amplitudes just are complex numbers,
  $\Longrightarrow$ add them before squaring!
- remember: spinors, gamma matrices have explicit form
  could be evaluated numerically (brute force)
  but: Rough method, lack of elegance, CPU-expensive
- can do better with smart basis for spinors (see detour)
- this is still on the base of traditional Feynman diagrams!

phase spacing for professionals

("Amateurs study strategy, professionals study logistics")

- democratic, process-blind integration methods:
  - Rambo/Mambo: Flat & isotropic

    R.Kleiss, W.J.Stirling & S.D.Ellis, Comput. Phys. Commun. **40** (1986) 359;
  - HAAG/Sarge: Follows QCD antenna pattern

    A.van Hameren & C.G.Papadopoulos, Eur. Phys. J. C **25** (2002) 563.
- multi-channelling: each Feynman diagram related to a phase space mapping (= "channel"), optimise their relative weights

  R.Kleiss & R.Pittau, Comput. Phys. Commun. **83** (1994) 141.
- main problem: practical only up to $\mathcal{O}(10\mathrm{k})$ channels.
- some improvement by building phase space mappings recursively: more channels feasible, efficiency drops a bit.

basic idea of multichannel sampling (again):
use a sum of functions $g_i(\vec{x})$ as Jacobean $g(\vec{x})$.

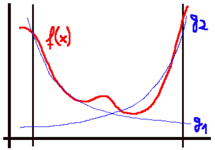
$\Longrightarrow \quad g(\vec{x}) = \sum_{i=1}^{N} \alpha_i g_i(\vec{x})$;

$\Longrightarrow \quad$ condition on weights like stratified sampling;

("combination" of importance & stratified sampling).

algorithm for one iteration:

- select g_i with probability $\alpha_i \to \vec{x}_j$.
- calculate total weight $g(\vec{x}_j)$ and partial weights $g_i(\vec{x}_j)$
- add $f(\vec{x}_j)/g(\vec{x}_j)$ to total result and $f(\vec{x}_j)/g_i(\vec{x}_j)$ to partial (channel-) results.
- after N sampling steps, update a-priori weights.

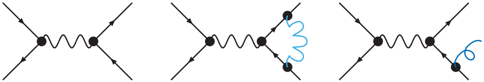


this is the method of choice for parton level event generation!

- quality measure for integration performance: unweighting efficiency
- want to generate events "as in nature".
- basic idea: use hit-or-miss method;
  - generate $\vec{x}$ with integration method,
  - compare actual $f(\vec{x})$ with maximal value during sampling $\Longrightarrow$ "Unweighted events".
- comments:
  - unweighting efficiency, $w_{\rm eff} = \langle f(\vec{x}_j)/f_{\rm max}\rangle$ = number of trials for each event.
  - expect $\log_{10} w_{\rm eff} \approx 3-5$ for good integration of multi-particle final states at tree-level.
  - maybe acceptable to use $f_{\rm max,eff} = Kf_{\rm max}$ with $K < 1$.
    problem: what to do with events where $f(\vec{x}_j)/f_{\rm max,eff} > 1$?
    answer: Add $\mathrm{int}[f(\vec{x}_j)/f_{\rm max,eff}] = k$ events and perform hit-or-miss on $f(\vec{x}_j)/f_{\rm max,eff} - k$.

including higher order corrections

- obtained from adding diagrams with additional:
  loops (virtual corrections) or
  legs (real corrections)



- effect: reducing the dependence on μ_R & μ_F
  NLO allows for meaningful estimate of uncertainties
- additional difficulties when going NLO:
  ultraviolet divergences in virtual correction
  infrared divergences in real and virtual correction

  enforce

  UV regularisation & renormalisation
  IR regularisation & cancellation

(Kinoshita–Lee–Nauenberg–Theorem)

structure of NLO calculations

$$d\sigma = \overbrace{d\Phi_{\mathcal{B}}\mathcal{B}_N(\Phi_{\mathcal{B}})}^{\text{Born term}} + \overbrace{d\Phi_{\mathcal{B}}\mathcal{V}_N(\Phi_{\mathcal{B}})}^{\substack{\text{virtual correction}\\ \text{(renormalized)}}} + \overbrace{d\Phi_{\mathcal{R}}\mathcal{R}_N(\Phi_{\mathcal{R}})}^{\text{real correction}}$$

$$= \underbrace{d\Phi_{\mathcal{B}}\left(\mathcal{B}_N + \mathcal{V}_N + \mathcal{I}_N^{(\mathcal{S})}\right) + d\Phi_{\mathcal{R}}\left(\mathcal{R}_N - \mathcal{S}_N\right)}_{\text{after adding a zero: } \mathcal{I}_N^{(\mathcal{S})} = \int d\Phi_{\mathcal{R}/\mathcal{B}}\mathcal{S}_N}$$

- phase space factorisation assumed here $(\Phi_{\mathcal{R}} = \Phi_{\mathcal{B}} \otimes \Phi_1)$

$$\int \mathrm{d}\Phi_1 \mathcal{S}_N(\Phi_{\mathcal{B}} \otimes \Phi_1) = \mathcal{I}_N^{(\mathcal{S})}(\Phi_{\mathcal{B}})$$

- process independent, universal subtraction kernels

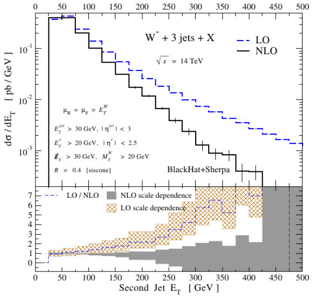
$$\begin{aligned}
\mathcal{S}_N(\Phi_{\mathcal{B}} \otimes \Phi_1) &= \mathcal{B}_N(\Phi_{\mathcal{B}}) \otimes \mathcal{S}_1(\Phi_{\mathcal{B}} \otimes \Phi_1) \\
\mathcal{I}_N^{(\mathcal{S})}(\Phi_{\mathcal{B}} \otimes \Phi_1) &= \mathcal{B}_N(\Phi_{\mathcal{B}}) \otimes \mathcal{I}_1^{(\mathcal{S})}(\Phi_{\mathcal{B}}),
\end{aligned}$$

and invertible phase space mapping (e.g. Catani-Seymour)

$$\Phi_{\mathcal{R}} \longleftrightarrow \Phi_{\mathcal{B}} \otimes \Phi_1$$

aside: choices . . .

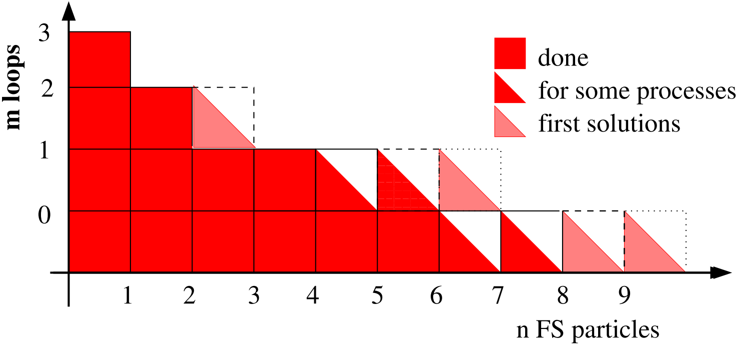
- common lore: NLO calculations reduce scale uncertainties
- this is, in general, true. however:
  unphysical scale choices will yield unphysical results



- more ways of botching it at higher orders

availability of exact calculations (hadron colliders)

- fixed order matrix elements ("parton level") are exact to a given perturbative order. (and often quite a pain!)
- important to understand limitations:
  only tree-level and one-loop level fully automated, beyond: prototyping



a simple analogy

- school book example:
  radiactive decay of isotopes with half-life $\tau = 1/\Gamma$

$$\begin{aligned}\mathcal{N}(t) &= \mathcal{N}(0)\exp\left[-t/\tau\right] = \mathcal{N}(0)\exp\left[-\Gamma t\right]\\ &= \mathcal{N}(0)\exp\left[-\int_0^t \mathrm{d}t'\Gamma(t')\right] = \mathcal{N}(0)\underbrace{\Delta(t,\,0)}_{\text{Sudakov form factor}}\end{aligned}$$

- Sudakov form factor = "survival" probability
- decay probability for individual isotope at given time t

$$\frac{\mathrm{d}\mathcal{P}_{\rm decay}(t)}{\mathrm{d}t} = \overbrace{\Gamma(t)}^{\text{decays at } t}\;\underbrace{\Delta(t,\,0)}_{\text{didn't decay before}} = -\frac{\mathrm{d}\mathcal{P}_{\rm no\,decay}(t)}{\mathrm{d}t}$$

the pattern of QCD radiation

- a detour: Altarelli-Parisi equation
- AP describes the scaling behaviour of the parton distribution function

(which depends on Bjorken-parameter and scale Q^2)

$$\frac{\mathrm{d}q(x,\,Q^2)}{\mathrm{d}\ln Q^2} = \int\limits_x^1 \frac{\mathrm{d}y}{y}\left[\alpha_s(Q^2)P_q(x/y)\right]q(y,Q^2)$$

- term in square brackets determines the probability that the parton emits another parton at scale Q^2 and Bjorken-parameter y

(after the splitting, $x \to yx + (1-y)x$.)

- driving term: Splitting function $P_q(x)$
  important property: universal, process independent

splitting kernels

- first implementations used DGLAP splitting kernels:

$$\mathcal{K}_{ijk}(\Phi_1) = \frac{\mathrm{d}t\mathrm{d}\phi}{t}\,\frac{\alpha_S(\mu)}{2\pi}\,\hat{P}_{\{ij\}\to ij}(z)$$

with colour factors C and $\hat{P}_{\{ij\}\to ij}$ given by

$$\begin{aligned}
P_{q\to qg}(z) &= C_F\left[\frac{2}{1-z}-(1+z)\right]\\
P_{q\to gq}(z) &= C_F\left[\frac{1+(1-z)^2}{z}\right]\\
P_{g\to q\bar{q}}(z) &= T_R\left[z^2+(1-z)^2\right]\\
P_{g\to gg}(z) &= C_A\left[\frac{2}{1-z}+\frac{2}{z}-2(z^2-z+2)\right]
\end{aligned}$$

- refinements of splitting kernels: Catani-Seymour subtraction kernels or symmetrised eikonal kernels, both including recoil factor (see later)

rederiving the splitting functions (pedestrianized)

- differential cross section for gluon emission in $e^+e^- \to$ jets

$$\frac{\mathrm{d}\sigma_{ee\to 3j}}{\mathrm{d}x_1\mathrm{d}x_2} = \sigma_{ee\to 2j}\frac{C_F\alpha_s}{\pi}\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)}$$

singular for $x_{1,2} \to 1$.

- rewrite with opening angle θ_{qg} and gluon energy fraction $x_3 = 2E_g/E_{\mathrm{c.m.}}$:

$$\frac{\mathrm{d}\sigma_{ee\to 3j}}{\mathrm{d}\cos\theta_{qg}\mathrm{d}x_3} = \sigma_{ee\to 2j}\frac{C_F\alpha_s}{\pi}\left[\frac{2}{\sin^2\theta_{qg}}\frac{1+(1-x_3)^2}{x_3} - x_3\right]$$

singular for $x_3 \to 0$ ("soft"), $\sin\theta_{qg} \to 0$ ("collinear").

- re-express collinear singularities

$$\frac{2\mathrm{d}\cos\theta_{qg}}{\sin^2\theta_{qg}} = \frac{\mathrm{d}\cos\theta_{qg}}{1-\cos\theta_{qg}} + \frac{\mathrm{d}\cos\theta_{qg}}{1+\cos\theta_{qg}}$$
$$= \frac{\mathrm{d}\cos\theta_{qg}}{1-\cos\theta_{qg}} + \frac{\mathrm{d}\cos\theta_{\bar{q}g}}{1-\cos\theta_{\bar{q}g}} \approx \frac{\mathrm{d}\theta^2_{qg}}{\theta^2_{qg}} + \frac{\mathrm{d}\theta^2_{\bar{q}g}}{\theta^2_{\bar{q}g}}$$

- independent evolution of two jets (q and $\bar{q}$)

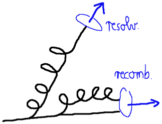
$$\mathrm{d}\sigma_{ee\to 3j} \approx \sigma_{ee\to 2j} \sum_{j\in\{q,\bar{q}\}} \frac{C_F\alpha_s}{2\pi} \frac{\mathrm{d}\theta^2_{jg}}{\theta^2_{jg}} P(z)\,,$$

- note: same form for any $t \propto \theta^2$:
- transverse momentum $k_\perp^2 \approx z^2(1-z)^2E^2\theta^2$
- invariant mass $q^2 \approx z(1-z)E^2\theta^2$

$$\frac{\mathrm{d}\theta^2}{\theta^2} \approx \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \approx \frac{\mathrm{d}q^2}{q^2}$$

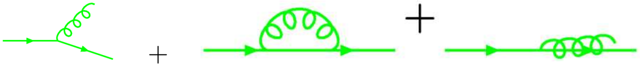
- parametrisation-independent observation: (logarithmically) divergent expression for $t \to 0$.
- practical solution: cut-off Q_0^2.
  $\Longrightarrow$ divergence will manifest itself as $\log Q_0^2$.
- similar for $P(z)$: divergence for $z \to 0$ cured by cut-off.

- what is a parton?
  collinear pair/soft parton recombine!
- introduce resolution criterion $k_\perp > Q_0$.



- combine virtual contributions with unresolvable emissions:
  cancels infrared divergences $\Longrightarrow$ finite at $\mathcal{O}(\alpha_s)$

  (Kinoshita-Lee-Nauenberg, Bloch-Nordsieck theorems)
- unitarity: probabilities add up to one
  $\mathcal{P}(\text{resolved}) + \mathcal{P}(\text{unresolved}) = 1.$



$=1.$

- the Sudakov form factor, once more
- differential probability for emission between q^2 and $q^2 + \mathrm{d}q^2$:

$$\mathrm{d}\mathcal{P} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}q^2}{q^2}\int\limits_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z P(z) =: \mathrm{d}q^2\,\Gamma(q^2)$$

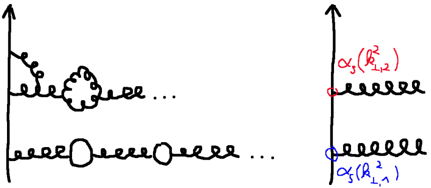
- from radioactive example: evolution equation for Δ

$$-\frac{\mathrm{d}\Delta(Q^2,\, q^2)}{\mathrm{d}q^2} = \Delta(Q^2,\, q^2)\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}q^2} = \Delta(Q^2,\, q^2)\Gamma(q^2)$$

$$\Longrightarrow\ \Delta(Q^2,\, q^2) = \exp\left[-\int\limits_{q^2}^{Q^2}\mathrm{d}k^2\Gamma(k^2)\right]$$

quantum improvements: running coupling

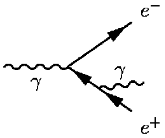
- improvement: inclusion of various quantum effects
- trivial: effect of summing up higher orders (loops) $\alpha_s \to \alpha_s(k_\perp^2)$



- much faster parton proliferation, especially for small $k_\perp^2$.
- avoid Landau pole: $k_\perp^2 > Q_0^2 \gg \Lambda^2_{\rm QCD} \Longrightarrow Q_0^2 =$ physical parameter.

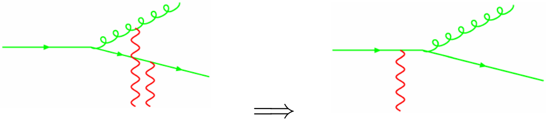
quantum improvements: ordering

- consider two subsequent emissions and effect of interference: leads to (calculable) cancellations in parts of phase space
- QM considerations:
    - assume splittings $\gamma \to e^+e^-$ with θ_{ee} and $e^- \to e^-\gamma$ at θ, with photon momentum k
    - energy imbalance at vertex: $k_\perp^\gamma \sim k_\parallel \theta$, hence $\Delta E \sim k_\perp^2/k_\parallel \sim k_\parallel \theta^2$.
    - formation time for photon emission: $\Delta t \sim 1/\Delta E \sim k_\parallel/k_\perp^2 \sim 1/(k_\parallel \theta^2)$.
    - ee-separation: $\Delta b \sim \theta_{ee}\Delta t$
    - must be larger than transverse wavelength of photon: $\theta_{ee}/(k_\parallel \theta^2) > 1/k_\perp = 1/(k_\parallel \theta)$
    - thus: $\theta_{ee} > \theta$ must be satisfied for photon to form



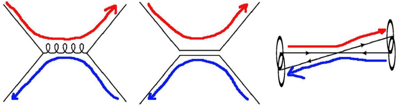
- angular ordering (or similar) as manifestation of quantum coherence

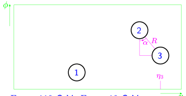
- QCD: all quanta are colured
- pictorial solution

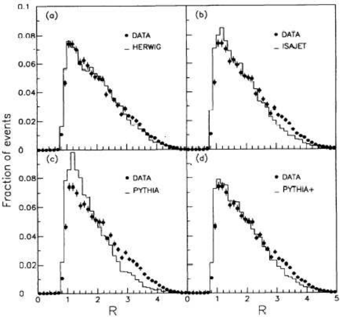


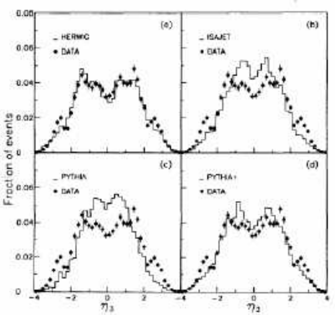
gluons at large angle from combined colour charge!

- experimental manifestation:
  ΔR of 2$^{\rm nd}$ & 3$^{\rm rd}$ jet in multi-jet events in pp-collisions









parton showers, compact notation

- Sudakov form factor (**no-decay** probability)

$$\Delta_{ij,k}^{(\mathcal{K})}(t, t_0) = \exp\left[-\int\limits_{t_0}^{t} \frac{\mathrm{d}t}{t} \frac{\alpha_s}{2\pi} \int \mathrm{d}z \frac{\mathrm{d}\phi}{2\pi} \underbrace{\mathcal{K}_{ij,k}(t,\, z,\, \phi)}_{\text{splitting kernel for } (ij)\to ij \text{ (spectator } k)} \right]$$

splitting kernel for $(ij) \to ij$ (spectator k)

- evolution parameter t defined by kinematics

generalised angle (HERWIG ++) or transverse momentum (PYTHIA, SHERPA)

- will replace $\frac{\mathrm{d}t}{t}\mathrm{d}z\frac{\mathrm{d}\phi}{2\pi} \longrightarrow \mathrm{d}\Phi_1$
- scale choice for strong coupling: $\alpha_s(k_\perp^2)$ — resums classes of higher logarithms
- regularisation through cut-off t_0

- "compound" splitting kernels $\mathcal{K}_n$ and Sudakov form factors $\Delta_n^{(\mathcal{K})}$ for emission off n-particle final state:

$$\mathcal{K}_n(\Phi_1) = \frac{\alpha_s}{2\pi} \sum_{\text{all }\{ij,k\}} \mathcal{K}_{ij,k}(\Phi_{ij,k})\,, \quad \Delta_n^{(\mathcal{K})}(t, t_0) = \exp\left[-\int\limits_{t_0}^{t} \mathrm{d}\Phi_1\, \mathcal{K}_n(\Phi_1)\right]$$

- consider first emission only off Born configuration

$$\mathrm{d}\sigma_B = \mathrm{d}\Phi_N\, \mathcal{B}_N(\Phi_N) \cdot \underbrace{\left\{\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \left[\mathcal{K}_N(\Phi_1)\Delta_N^{(\mathcal{K})}(\mu_N^2, t(\Phi_1))\right]\right\}}_{\text{integrates to unity} \longrightarrow \text{“unitarity” of parton shower}}$$

- further emissions by recursion with $Q^2 = t$ of previous emission

the link to resummation

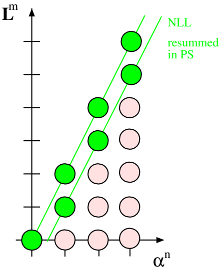
- origin of observables such as $p_\perp^{W,z,H}$:
  (multiple) initial state parton emissions, boson "kicked" out by recoil
- resum emissions with Sudakov form factor
- build Sudakov form factor from "parton splitting kernels", in Q_T resummation:

$$\Delta(Q^2,\, Q_0^2) = \exp\left[-\int\limits_{Q_0^2}^{Q^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\left(A(k_\perp^2)\log\frac{Q^2}{k_\perp^2} + B(k_\perp^2)\right)\right]$$

  both A and B have expansion in α_S
- various schemes available: Q_T, SCET, etc.

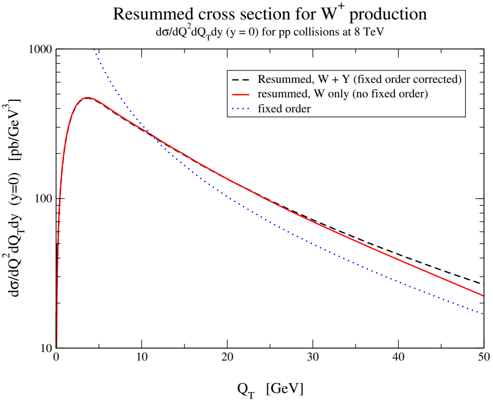
- analyse structure of emissions above
- logarithmic accuracy in $\log \frac{\mu_N}{k_\perp}$ (a la CSS)
  possibly up to next-to leading log,
  - if evolution parameter $\sim$ transverse momentum,
  - if argument in α_s is $\propto\ k_\perp$ of splitting,
  - if $K_{ij,k} \to$ terms $A_{1,2}$ and B_1 upon integration

    (OK, if soft gluon correction is included, and if $K_{ij,k} \to$ AP splitting kernels)



- in CSS $k_\perp$ typically is the transverse momentum of produced system, in parton shower of course related to the cumulative effect of explicit multiple emissions
- resummation scale $\mu_N \approx \mu_F$ given by (Born) kinematics –
  simple for cases like $q\bar{q}' \to V$, $gg \to H$, ...
  tricky for more complicated cases

- example result: interplay of fixed order and resummation



- note: parton shower will act similar to Q_T resummation

currently best realisation:

- evolution and splitting parameter $((ij) + k \to i + j + k)$:

$$\kappa^2_{j,ik} = \frac{4(p_i p_j)(p_j p_k)}{Q^4} \quad \text{and} \quad z_j = \frac{2(p_j p_k)}{Q^2} \, .$$

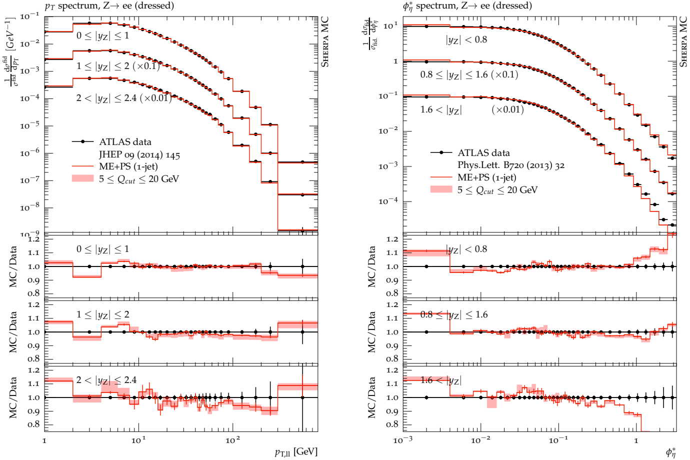
- splitting functions including IR regularisation

(a la Curci, Furmanski & Petronzio, Nucl.Phys. B175 (1980) 27-92)

$$\begin{aligned}
P^{(0)}_{qq}(z,\kappa^2) &= 2C_F \left[\frac{1-z}{(1-z)^2+\kappa^2} - \frac{1+z}{2}\right] \, , \\
P^{(0)}_{qg}(z,\kappa^2) &= 2C_F \left[\frac{z}{z^2+\kappa^2} - \frac{2-z}{2}\right] \, , \\
P^{s(0)}_{gg}(z,\kappa^2) &= 2C_A \left[\frac{1-z}{(1-z)^2+\kappa^2} - 1 + \frac{z(1-z)}{2}\right] \, , \\
P^{(0)}_{gq}(z,\kappa^2) &= T_R \left[z^2 + (1-z)^2\right]
\end{aligned}$$

- renormalisation/factorisation scale given by $\mu^2 = \kappa^2 Q^2$
- combine gluon splitting from two splitting functions with different spectators $k \to$ accounts for different colour flows

example: achievable precision of shower alone in DY



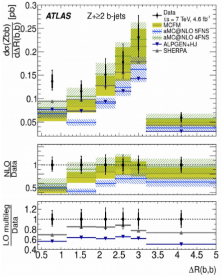
massive quarks are tricky

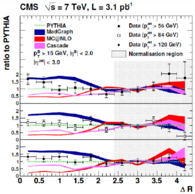
- parton showers geared towards collinear & soft emissions of gluons (double log structure)
- $g \to q\bar{q}$ only collinear, beyond "shower-approximation" $\longrightarrow$ no soft gluon
- old measurements at of inclusive $g \to b\bar{b}$ and $g \to c\bar{c}$ rate
- fix this at LHC for modern showers

(important for $t\bar{t}b\bar{b}$)

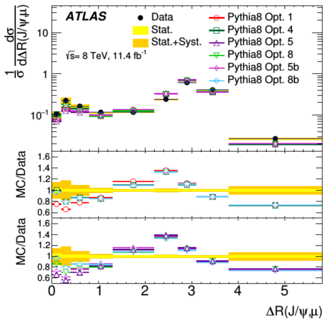
- questions: kernel, scale in α_s

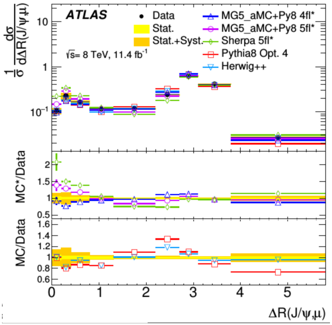
(example: $k_\perp$ vs. m_{bb})





- ATLAS measurement in $b\bar{b}$ production
- use decay products in $B \to J/\Psi(\mu\mu) + X$ and $B \to \mu + X$
- use muons as proxies, most obvious observable $\Delta R(J\Psi, \mu)$





massive quarks are tricky - encore

- heavy quarks also problematic in initial state:
  no PDF support for $Q^2 \leq m_Q^2 \longrightarrow$ quarks stop showering
- possible solutions:
  - naive: ignore and leave for beam remnants (SHERPA)
  - better: enforce splitting in region around m_Q^2 (PYTHIA)
    $\longrightarrow$ effectively produces collinear Q and gluon in IS
- will need to check effect on precision obsevables: $p_\perp^{(W)}/p_\perp^{(Z)}$

another systematic uncertainty

- parton showers are approximations, based on leading colour, leading logarithmic accuracy, spin-averaged
- parametric accuracy by comparing Sudakov form factors:

$$\Delta = \exp\left\{-\int \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\left[A\log\frac{k_\perp^2}{Q^2}+B\right]\right\}\,,$$

  where A and B can be expanded in $\alpha_s(k_\perp^2)$
- showers usually include terms $A_{1,2}$ and B_1 (NLL)
- A_2 realised by pre-factor multiplying scale $\mu_R \simeq k_\perp$

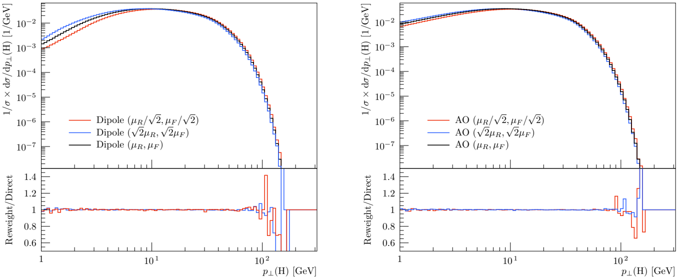
(CMW rescaling: Catani, Marchesini, Webber, Nucl Phys B,349 635)

- fixed-order precision necessitates to consistently assess uncertainties from parton showers (quite often just used as black box)
- maybe improve by including higher orders?

event generation (on-the-fly scale variations)

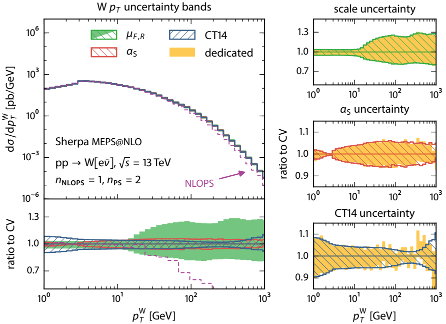
- basic idea: want to vary scales to assess uncertainties
- simple reweighting in matrix elements straightforward
- reweighting in parton shower more cumbersome
  - shower is probabilistic, concept of weight somewhat alien
  - introduce relative weight
  - evaluate (trial-)emission by (trial-)emission

implementation in HERWIG7

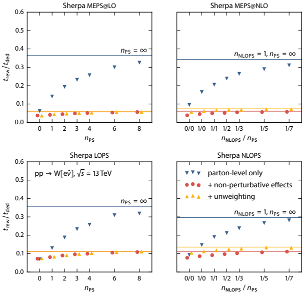


weight variation for W+jets with MEPS@NLO

- uncertainties in $p_\perp^W$



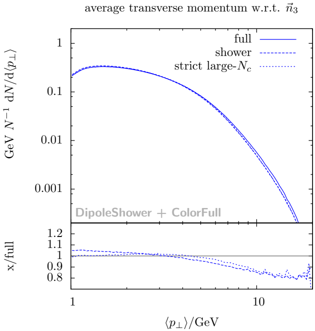
- CPU budget



going beyond leading colour

- start including next-to leading colour

(first attempts by Platzer & Sjodahl; Nagy & Soper)



- also included in 1st emission in SHERPA's MC@NLO

including NLO splitting kernels

(Hoeche, FK & Prestel, 1705.00982, and Hoeche & Prestel, 1705.00742)

- expand splitting kernels as

$$P(z,\,\kappa^2) \;=\; P^{(0)}(z,\,\kappa^2) + \frac{\alpha_s}{2\pi}\,P^{(1)}(z,\,\kappa^2)$$

- aim: reproduce DGLAP evolution at NLO

  include all NLO splitting kernels

- three categories of terms in $P^{(1)}$:
  - cusp (universal soft-enhanced correction) (already included in original showers)
  - corrections to $1 \to 2$
  - new flavour structures (e.g. $q \to q'$), identified as $1 \to 3$
- new paradigm: two independent implementations

subtle symmetry factors

- observations for LO PS in final state:
    - only $P^{(0)}_{qq}$ used but not $P^{(0)}_{qg}$
    - $P^{(0)}_{gg}$ comes with "symmetry factor" 1/2
- challenge this way of implementing symmetry through:

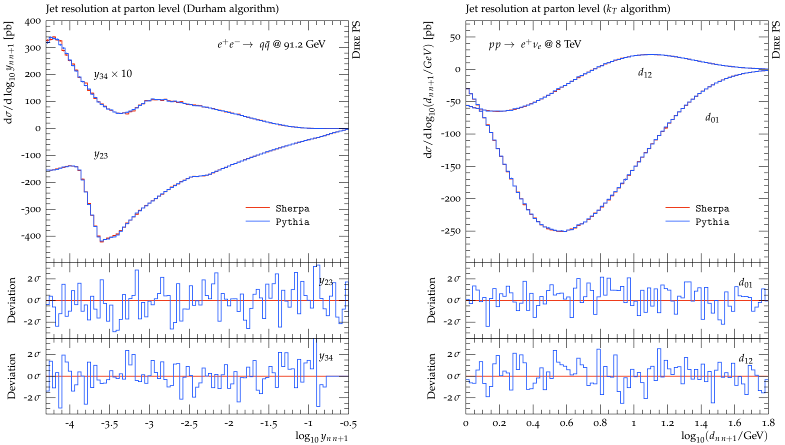
(Jadach & Skrzypek, hep-ph/0312355)

$$\sum_{i=q,g}\int\limits_0^{1-\epsilon}\mathrm{d}z\,z\,P^{(0)}_{qi}(z) = \int\limits_\epsilon^{1-\epsilon}\mathrm{d}z\,P^{(0)}_{qq}(z)+\mathcal{O}(\epsilon)$$

$$\sum_{i=q,g}\int\limits_0^{1-\epsilon}\mathrm{d}z\,z\,P^{(0)}_{gi}(z) = \int\limits_\epsilon^{1-\epsilon}\mathrm{d}z\,\left[\frac{1}{2}P^{(0)}_{gg}(z)+n_f P^{(0)}_{gq}(z)\right]+\mathcal{O}(\epsilon)$$

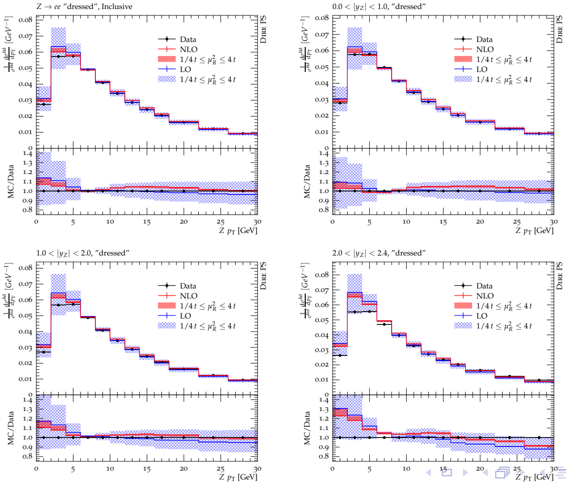
- net effect: replace symmetry factors by parton marker z

validation of $1 \to 3$ splittings



physical results: DY at LHC

(untuned showers vs. 7 TeV ATLAS data, optimistic scale variations)



leading colour differential two-loop soft corrections

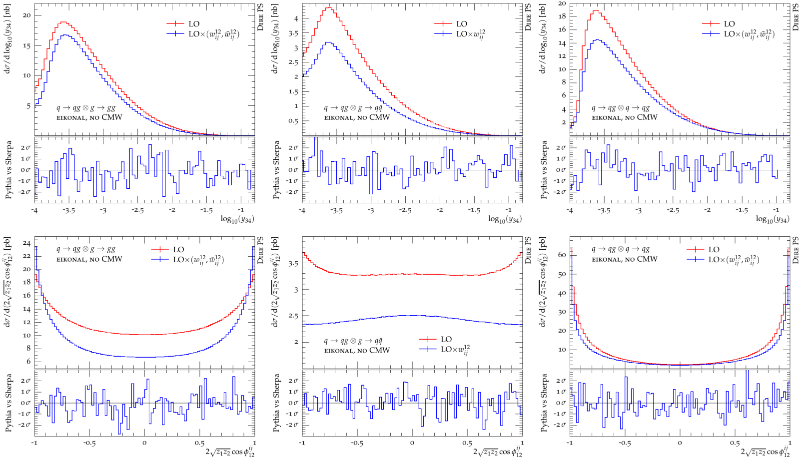
(Dulat, Hoeche & Prestel, 1805.03757)

- analyse two-emission soft contribution and compare with iterated single emissions
- subtract double-counted terms and endpoint contributions
- capture residual effect by reweighting original parton shower, with
  - accounting for finite recoil
  - including first $1/N_c$ corrections

    (another way to solve "problem" in Dasgupta et al., 1805.09327)
  - incorporating spin correlations

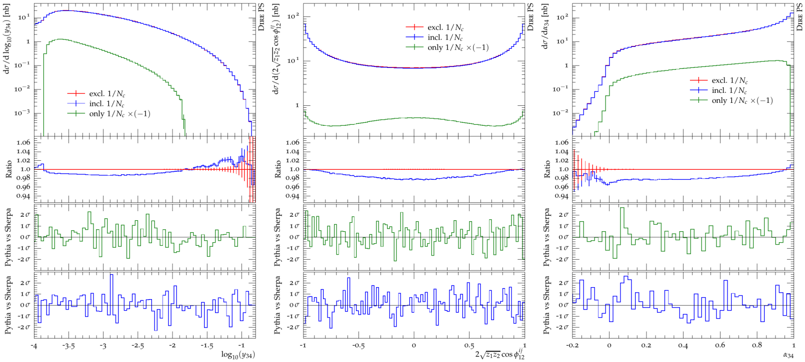
reweighting

$q \to qg \otimes g \to gg$ $q \to qg \otimes g \to q\bar{q}$ $q \to qg \otimes q \to qg$



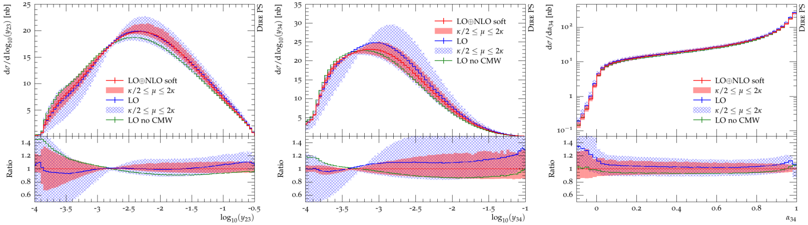
including $1/N_c$ effects

- capturing the difference of $C_F - C_A/2$ in assigning the correct emitter in the admixture of soft and collinear limits



scale uncertainties

- varying κ in the soft-enhanced terms, including NLO explicit corrections



PRECISION MONTE CARLO

- remember structure of NLO calculation for N-body production

$$\begin{aligned} \mathrm{d}\sigma &= \mathrm{d}\Phi_{\mathcal{B}}\mathcal{B}_N(\Phi_{\mathcal{B}}) + \mathrm{d}\Phi_{\mathcal{B}}\mathcal{V}_N(\Phi_{\mathcal{B}}) + \mathrm{d}\Phi_{\mathcal{R}}\mathcal{R}_N(\Phi_{\mathcal{R}}) \\ &= \mathrm{d}\Phi_{\mathcal{B}}\left(\mathcal{B}_N + \mathcal{V}_N + \mathcal{I}_N^{(\mathcal{S})}\right) + \mathrm{d}\Phi_{\mathcal{R}}\left(\mathcal{R}_N - \mathcal{S}_N\right) \end{aligned}$$

- phase space factorisation assumed here ($\Phi_{\mathcal{R}} = \Phi_{\mathcal{B}} \otimes \Phi_1$)

$$\int \mathrm{d}\Phi_1 \mathcal{S}_N(\Phi_{\mathcal{B}} \otimes \Phi_1) = \mathcal{I}_N^{(\mathcal{S})}(\Phi_{\mathcal{B}})$$

- process independent subtraction kernels

$$\begin{aligned} \mathcal{S}_N(\Phi_{\mathcal{B}} \otimes \Phi_1) &= \mathcal{B}_N(\Phi_{\mathcal{B}}) \otimes \mathcal{S}_1(\Phi_{\mathcal{B}} \otimes \Phi_1) \\ \mathcal{I}_N^{(\mathcal{S})}(\Phi_{\mathcal{B}} \otimes \Phi_1) &= \mathcal{B}_N(\Phi_{\mathcal{B}}) \otimes \mathcal{I}_1^{(\mathcal{S})}(\Phi_{\mathcal{B}}) \end{aligned}$$

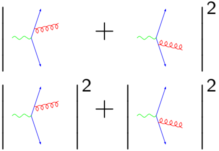
with universal $\mathcal{S}_1(\Phi_{\mathcal{B}} \otimes \Phi_1)$ and $\mathcal{I}_1^{(\mathcal{S})}(\Phi_{\mathcal{B}})$

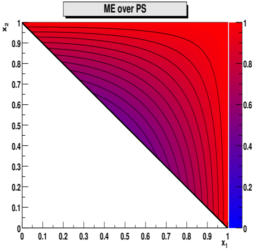
matrix element corrections

- parton shower ignores interferences typically present in matrix elements
- pictorially

ME :

PS :





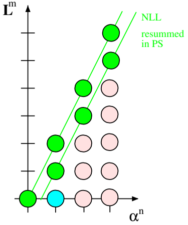
- form many processes $\mathcal{R}_N < \mathcal{B}_N \times \mathcal{K}_N$
- typical processes: $q\bar{q}' \to V$, $e^-e^+ \to q\bar{q}$, $t \to bW$
- practical implementation: shower with usual algorithm, but reject first/hardest emissions with probability $\mathcal{P} = \mathcal{R}_N/(\mathcal{B}_N \times \mathcal{K}_N)$

- analyse **first** emission, given by

$$d\sigma_B = d\Phi_N \, \mathcal{B}_N(\Phi_N) \cdot \underbrace{\left\{ \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2, t_0) + \int\limits_{t_0}^{\mu_N^2} d\Phi_1 \left[\frac{\mathcal{R}_N(\Phi_N \times \Phi_1)}{\mathcal{B}_N(\Phi_N)} \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2, t(\Phi_1)) \right] \right\}}_{\text{once more: integrates to unity} \longrightarrow \text{"unitarity" of parton shower}}$$

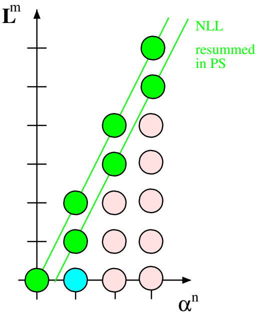
- radiation given by $\mathcal{R}_N$ (correct at $\mathcal{O}(\alpha_s)$)

  (but modified by logs of higher order in α_s from $\Delta_N^{(\mathcal{R}/\mathcal{B})}$)
- emission phase space constrained by μ_N
- also known as "soft ME correction"
  hard ME correction fills missing phase space
- used for "power shower":
  $\mu_N \to E_{pp}$ and apply ME correction



NLO matching: Basic idea

- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- adjust ("match") terms:
  - cross section at NLO accuracy &
    correct hardest emission in PS to exactly
    reproduce ME at order α_s
    ($\mathcal{R}$-part of the NLO calculation)
    (this is relatively trivial)
  - maintain (N)LL-accuracy of parton shower
    (this is not so simple to see)



PowHeg

- reminder: $\mathcal{K}_{ij,k}$ reproduces process-independent behaviour of $\mathcal{R}_N/\mathcal{B}_N$ in soft/collinear regions of phase space

$$\mathrm{d}\Phi_1\,\frac{\mathcal{R}_N(\Phi_{N+1})}{\mathcal{B}_N(\Phi_N)}\;\xrightarrow{\text{IR}}\;\mathrm{d}\Phi_1\,\frac{\alpha_s}{2\pi}\,\mathcal{K}_{ij,k}(\Phi_1)$$

- define modified Sudakov form factor (as in ME correction)

$$\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,t_0)=\exp\left[-\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\frac{\mathcal{R}_N(\Phi_{N+1})}{\mathcal{B}_N(\Phi_N)}\right]\,,$$

- assumes factorisation of phase space: $\Phi_{N+1}=\Phi_N\otimes\Phi_1$
- typically will adjust scale of α_s to parton shower scale

- define local K-factors
- start from Born configuration Φ_N with NLO weight:

("local K-factor")

$$\begin{aligned} d\sigma_N^{(\mathrm{NLO})} &= d\Phi_N\,\bar{\mathcal{B}}(\Phi_N) \\ &= d\Phi_N \left\{ \mathcal{B}_N(\Phi_N) + \underbrace{\mathcal{V}_N(\Phi_N) + \mathcal{B}_N(\Phi_N)\otimes\mathcal{S}}_{\tilde{\mathcal{V}}_N(\Phi_N)} \right. \\ &\quad \left. + \int d\Phi_1 \left[\mathcal{R}_N(\Phi_N\otimes\Phi_1) - \mathcal{B}_N(\Phi_N)\otimes d\mathcal{S}(\Phi_1)\right] \right\} \end{aligned}$$

- by construction: exactly reproduce cross section at NLO accuracy
- note: second term vanishes if $\mathcal{R}_N \equiv \mathcal{B}_N \otimes d\mathcal{S}$

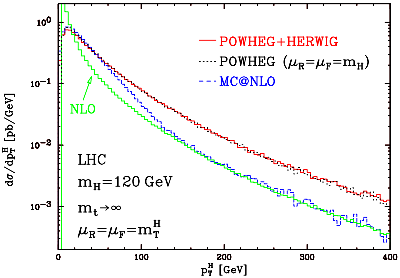
(relevant for MC@NLO)

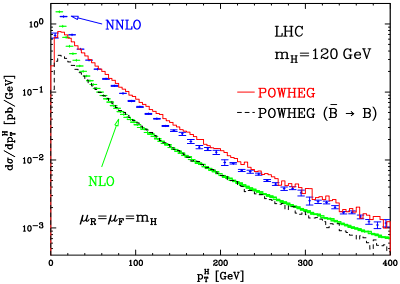
- analyse accuracy of radiation pattern
- generate emissions with $\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, t_0)$:

$$\mathrm{d}\sigma_N^{(\mathrm{NLO})} = \mathrm{d}\Phi_N\, \bar{\mathcal{B}}(\Phi_N)$$
$$\times \underbrace{\left\{ \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \frac{\mathcal{R}_N(\Phi_N \otimes \Phi_1)}{\mathcal{B}_N(\Phi_N)} \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, k_\perp^2(\Phi_1)) \right\}}_{\text{integrating to yield 1 - “unitarity of parton shower”}}$$

- radiation pattern like in ME correction
- pitfall, again: choice of upper scale μ_N^2 (this is vanilla PowHeg!)
- apart from logs: which configurations enhanced by local K-factor

(K-factor for inclusive production of X adequate for $X+$ jet at large $p_\perp$?)

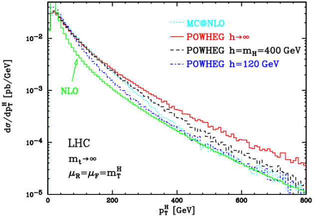




- large enhancement at high $p_{T,h}$
- can be traced back to large NLO correction
- fortunately, NNLO correction is also large $\to\sim$ agreement

- improving PowHeg
- split real-emission ME as

$$\mathcal{R} = \mathcal{R}\left(\underbrace{\frac{h^2}{p_\perp^2 + h^2}}_{\mathcal{R}^{(S)}} + \underbrace{\frac{p_\perp^2}{p_\perp^2 + h^2}}_{\mathcal{R}^{(F)}}\right)$$



- can "tune" h to mimick NNLO - or other (resummation) result
  - differential event rate up to first emission

$$\mathrm{d}\sigma = \mathrm{d}\Phi_B \bar{\mathcal{B}}^{(\mathrm{R}^{(\mathrm{S})})}\left[\Delta^{(\mathcal{R}^{(S)}/\mathcal{B})}(s,\, t_0) + \int\limits_{t_0}^{s} \mathrm{d}\Phi_1 \frac{\mathcal{R}^{(S)}}{\mathcal{B}} \Delta^{(\mathcal{R}^{(S)}/\mathcal{B})}(s,\, k_\perp^2)\right]$$
$$+\mathrm{d}\Phi_R\, \mathcal{R}^{(F)}(\Phi_R)$$

MC@NLO

- MC@NLO paradigm: divide $\mathcal{R}_N$ in soft ("S") and hard ("H") part:

$$\mathcal{R}_N = \mathcal{R}_N^{(S)} + \mathcal{R}_N^{(H)} = \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}_1 + \mathcal{H}_N$$

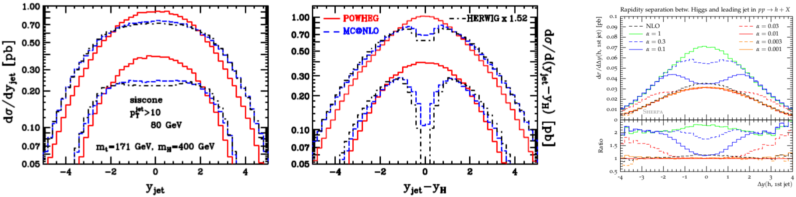
- identify subtraction terms and shower kernels $\mathrm{d}\mathcal{S}_1 \equiv \sum_{\{ij,k\}} \mathcal{K}_{ij,k}$

(modify $\mathcal{K}$ in 1st emission to account for colour)

$$\mathrm{d}\sigma_N = \mathrm{d}\Phi_N \underbrace{\tilde{\mathcal{B}}_N(\Phi_N)}_{\mathcal{B}+\tilde{\mathcal{V}}} \left[\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \, \mathcal{K}_{ij,k}(\Phi_1) \, \Delta_N^{(\mathcal{K})}(\mu_N^2, k_\perp^2) \right]$$
$$+ \mathrm{d}\Phi_{N+1} \, \mathcal{H}_N$$

- effect: only resummed parts modified with local K-factor

- phase space effects: shower vs. fixed order



- problem: impact of subtraction terms on local K-factor (filling of phase space by parton shower)
- studied in case of $gg \to H$ above
- proper filling of available phase space by parton shower paramount

NNLOPS in the MINLO approach: merging without Q_J

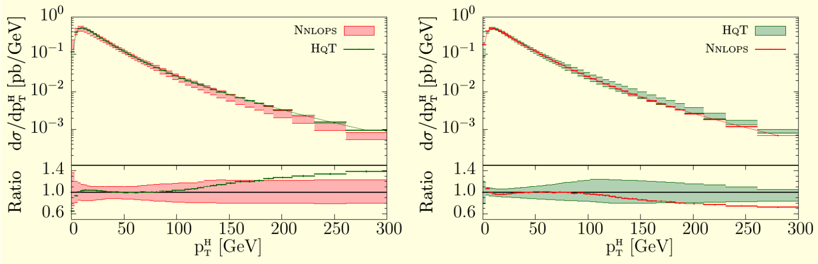
(K.Hamilton, P.Nason, C.Oleari & G.Zanderighi, JHEP 1305 (2013) 082)

- based on POWHEG + shower from PYTHIA or HERWIG
- up to today only for singlet S production, gives NNLO + PS
- basic idea:
  - use S+jet in POWHEG
  - push jet cut to parton shower IR cutoff
  - apply analytical NNLL Sudakov rejection weight for intrinsic line in Born configuration

    (kills divergent behaviour at order α_S)
  - don't forget double-counted terms
  - reweight to NNLO fixed order

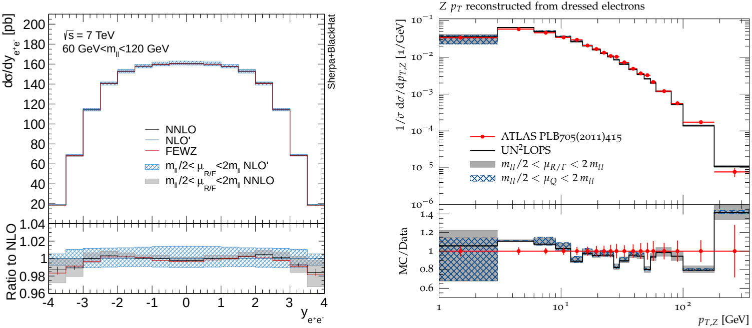
NNLOPS for H production

(K.Hamilton, P.Nason, E.Re & G.Zanderighi, JHEP 1310 (2013) 222)



NNLOPS for Z production: UNNLOPS

S. Hoche, Y. Li, & S. Prestel, Phys.Rev.D90 & D91



- also available for H production

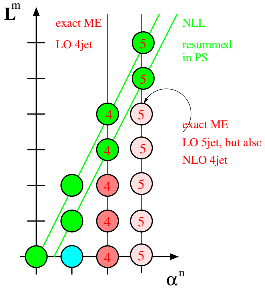
NNLOPS: shortcomings/limitations

- MINLO relies on knowledge of B_2 terms from analytic resummation
  $\longrightarrow$ to date only known for colour singlet production
- MINLO relies on reweighting with full NNLO result
  $\longrightarrow$ one parameter for H (y_H), more complicated for Z, ...

- UNNLOPS relies on integrating single- and double emission to low scales and combination of unresolved with virtual emissions
  $\longrightarrow$ potential efficiency issues, need NNLO subtraction
- UNNLOPS puts unresolved & virtuals in “zero-emission” bin
  $\longrightarrow$ no parton showering for virtuals (?)

multijet merging: basic idea

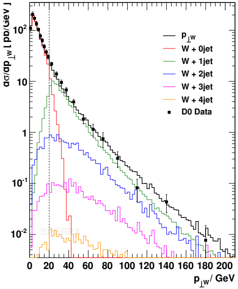
- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- combine ("merge") both:
  result: "towers" of MEs with increasing number of jets evolved with PS
  - multijet cross sections at Born accuracy
  - maintain (N)LL accuracy of parton shower



- separate regions of jet production and jet evolution with jet measure Q_J

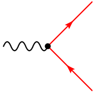
  ("truncated showering" if not identical with evolution parameter)

- matrix elements populate hard regime
- parton showers populate soft domain

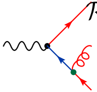


why it works: jet rates with the parton shower

- consider jet production in $e^+e^- \to$ hadrons
  Durham jet definition: relative transverse momentum $k_\perp > Q_J$
- fixed order: one factor α_S and up to $\log^2 \frac{E_{\rm c.m.}}{Q_J}$ per jet
- use Sudakov form factor for resummation &
  replace approximate fixed order by exact expression:



$$\mathcal{R}_2(Q_J) = \left[\Delta_q(E^2_{\rm c.m.},\, Q^2_J)\right]^2$$



$$\mathcal{R}_3(Q_J) = 2\Delta_q(E^2_{\rm c.m.},\, Q^2_J) \int\limits_{Q^2_J}^{E^2_{\rm c.m.}} \frac{{\rm d}k^2_\perp}{k^2_\perp} \left[\frac{\alpha_s(k^2_\perp)}{2\pi}{\rm d}z\mathcal{K}_q(k^2_\perp, z) \right.$$
$$\left. \times\Delta_q(E^2_{\rm c.m.},\, k^2_\perp)\Delta_q(k^2_\perp,\, Q^2_J)\Delta_g(k^2_\perp,\, Q^2_J)\right]$$

multijet merging at LO

- expression for first emission

$$\begin{aligned}\mathrm{d}\sigma \quad = \quad & \mathrm{d}\Phi_N\,\mathcal{B}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,\,t_0)\right.\\ & \left.+\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,\,t_{N+1})\Theta(Q_J-Q_{N+1})\right]\\ & +\mathrm{d}\Phi_{N+1}\,\mathcal{B}_{N+1}\,\Delta_N^{(\mathcal{K})}(\mu_{N+1}^2,\,t_{N+1})\Theta(Q_{N+1}-Q_J)\end{aligned}$$

- note: $N+1$-contribution includes also $N+2$, $N+3$, ...

(no Sudakov suppression below t_{n+1}, see further slides for iterated expression)

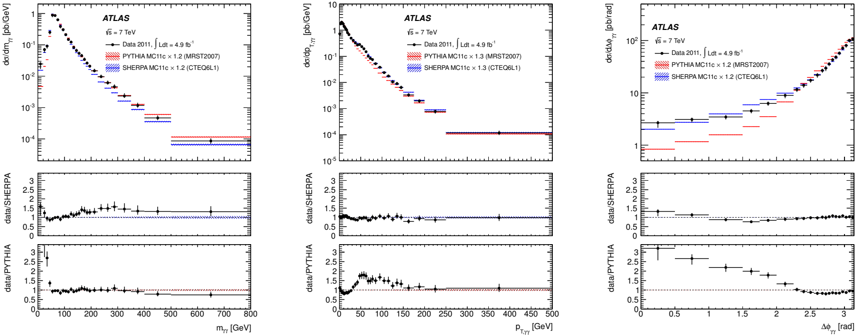
- potential occurence of different shower start scales: $\mu_{N,N+1,\dots}$
- "unitarity violation" in square bracket: $\mathcal{B}_N\mathcal{K}_N \longrightarrow \mathcal{B}_{N+1}$

(cured with UMEPS formalism, L. Lonnblad & S. Prestel, JHEP 1302 (2013) 094 & S. Platzer, arXiv:1211.5467 [hep-ph] & arXiv:1307.0774 [hep-ph])

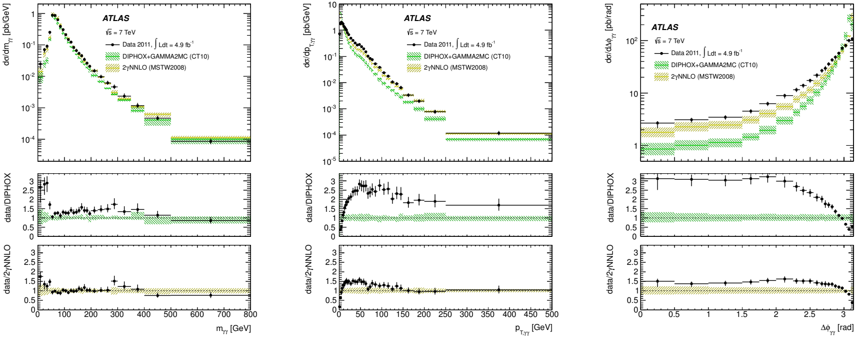
$$
\begin{aligned}
d\sigma \;=\; \sum_{n=N}^{n_{\max}-1} \Bigg\{ d\Phi_n\, \mathcal{B}_n\, & \overbrace{\left[\prod_{j=N}^{n-1} \Theta(Q_{j+1}-Q_J)\right]}^{(n-N)\text{ extra jets}} \overbrace{\left[\prod_{j=N}^{n-1} \Delta_j^{(\mathcal{K})}(t_j,\, t_{j+1})\right]}^{\text{no emissions off internal lines}} \\
& \times \Bigg[\underbrace{\Delta_n^{(\mathcal{K})}(t_n, t_0)}_{\text{no emission}} + \underbrace{\int_{t_0}^{t_n} d\Phi_1\, \mathcal{K}_n \Delta_n^{(\mathcal{K})}(t_n, t_{n+1}) \Theta(Q_J - Q_{n+1})}_{\text{next emission no jet \& below last ME emission}} \Bigg] \\
+ d\Phi_{n_{\max}}\, \mathcal{B}_{n_{\max}} & \left[\prod_{j=N}^{n_{\max}-1} \Theta(Q_{j+1}-Q_J)\right] \left[\prod_{j=N}^{n_{\max}-1} \Delta_j^{(\mathcal{K})}(t_j,\, t_{j+1})\right] \\
& \times \Bigg[\Delta_{n_{\max}}^{(\mathcal{K})}(t_{n_{\max}}, t_0) + \int_{t_0}^{t_{n_{\max}}} d\Phi_1\, \mathcal{K}_{n_{\max}} \Delta_{n_{\max}}^{(\mathcal{K})}(t_{n_{\max}}, t_{n_{\max}+1}) \Bigg]
\end{aligned}
$$

di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

(arXiv:1211.1913 [hep-ex])



aside: Comparison with higher order calculations



multijet-merging at NLO: MEPS@NLO

- basic idea like at LO: towers of MEs with increasing jet multi (but this time at NLO)
- combine them into one sample, remove overlap/double-counting

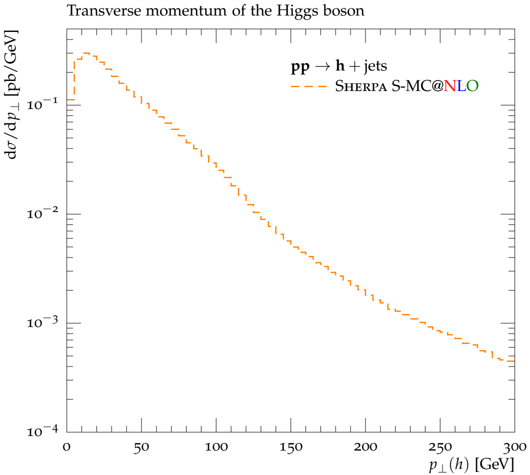
maintain NLO and (N)LL accuracy of ME and PS

- this effectively translates into a merging of MC@NLO simulations and can be further supplemented with LO simulations for even higher final state multiplicities

first emission(s), once more

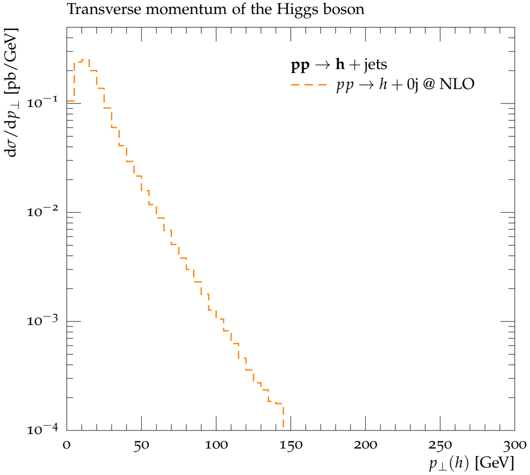
$$
\begin{aligned}
\mathrm{d}\sigma \;=\;& \mathrm{d}\Phi_N\,\tilde{\mathcal{B}}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0)+\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\right]\\
&+\mathrm{d}\Phi_{N+1}\,\mathcal{H}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\\
&+\mathrm{d}\Phi_{N+1}\,\tilde{\mathcal{B}}_{N+1}\left(1+\frac{\mathcal{B}_{N+1}}{\tilde{\mathcal{B}}_{N+1}}\int\limits_{t_{N+1}}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\right)\Theta(Q_{N+1}-Q_J)\\
&\cdot\left[\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_0)+\int\limits_{t_0}^{t_{N+1}}\mathrm{d}\Phi_1\,\mathcal{K}_{N+1}\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_{N+2})\right]\\
&+\mathrm{d}\Phi_{N+2}\,\mathcal{H}_{N+1}\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_{N+2})\Theta(Q_{N+1}-Q_J)+\dots
\end{aligned}
$$

$p_\perp^H$ in MEPS@NLO



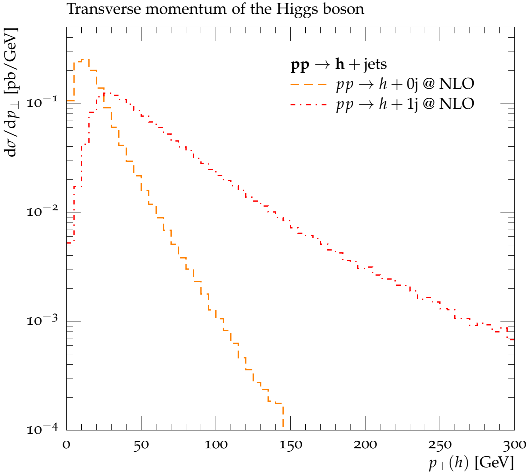
- first emission by MC@NLO

$p_\perp^H$ in MEPS@NLO



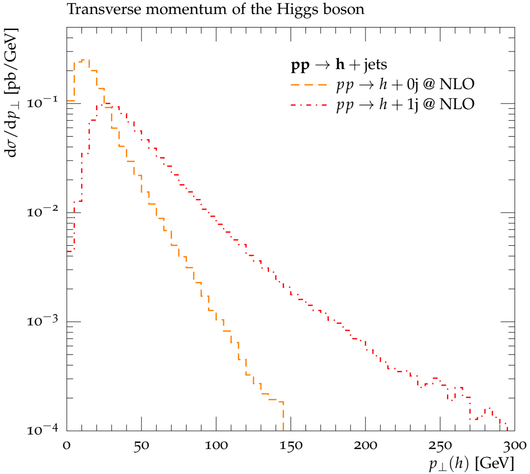
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$

$p_\perp^H$ in MEPS@NLO



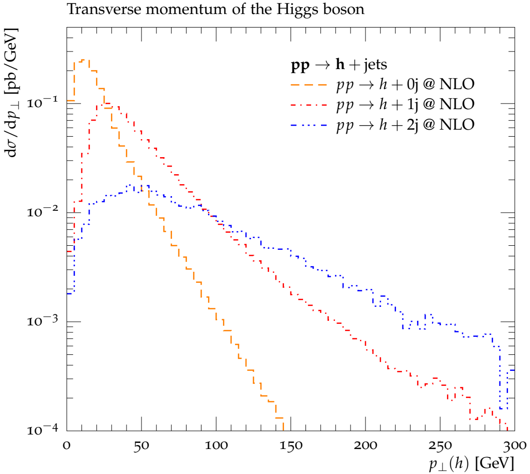
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$

$p_\perp^H$ in MEPS@NLO



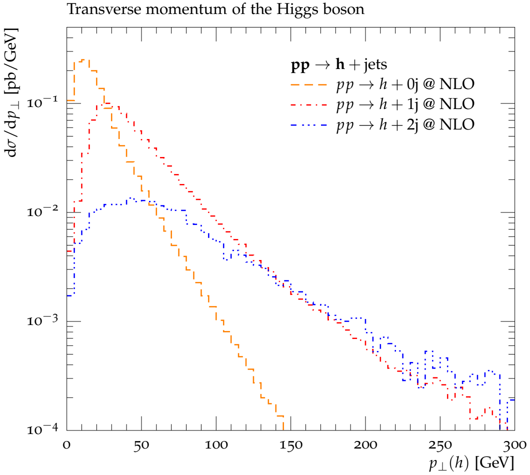
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



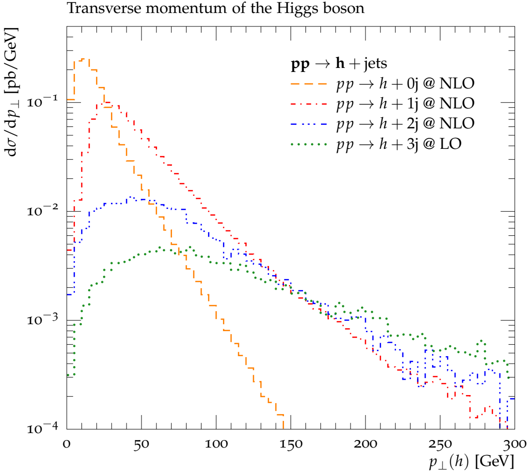
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h+$jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h+$jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



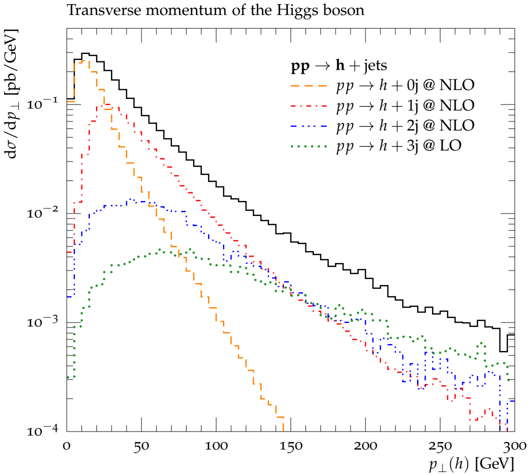
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate

$p_\perp^H$ in MEPS@NLO



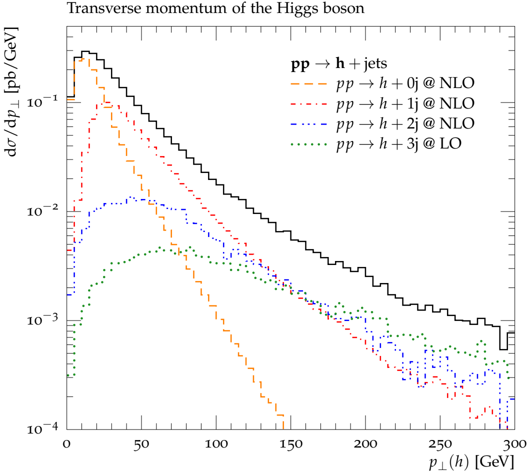
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate

$p_\perp^H$ in MEPS@NLO



- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h+$ jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h+$ jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h+$ 2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions

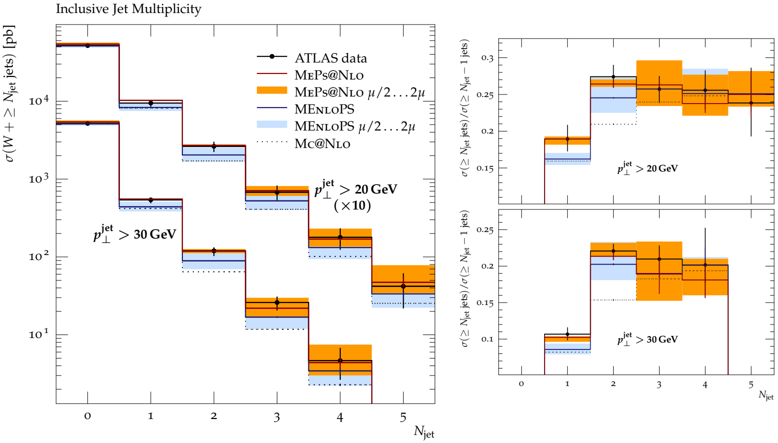
$p_\perp^H$ in MEPS@NLO



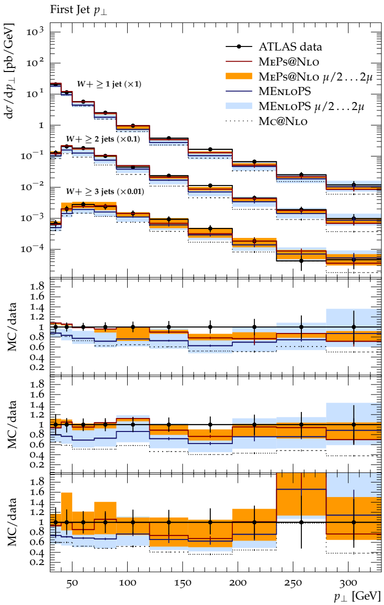
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h+$jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h+$jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

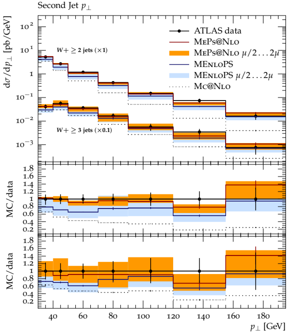
example: MEPS@NLO for W+jets

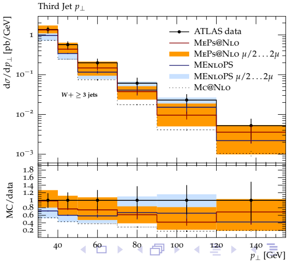
(up to two jets @ NLO, from BLACKHAT, see arXiv: 1207.5031 [hep-ex])



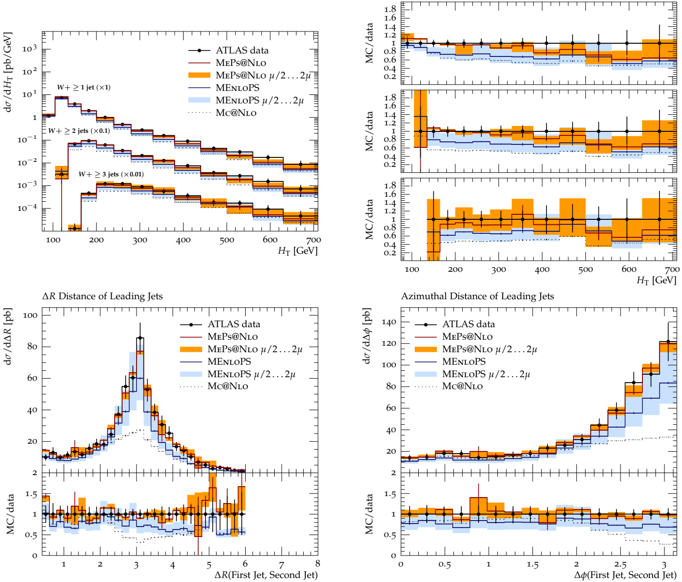
Multijet merging at NLO







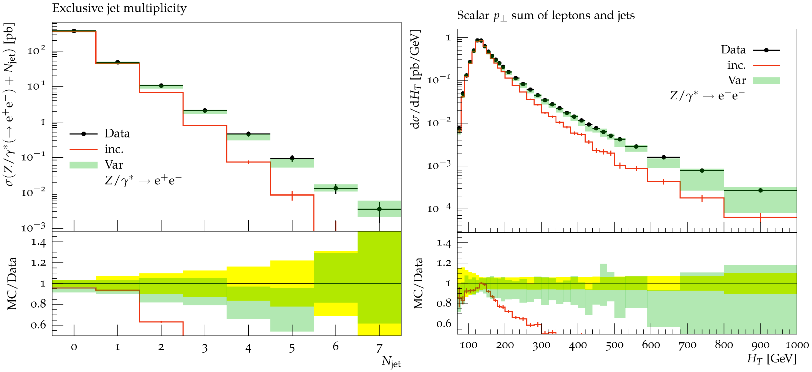
Multijet merging at NLO



FxFx: validation in Z+jets

(Data from ATLAS, 1304.7098, aMC@NLO_MADGRAPH with HERWIG++)

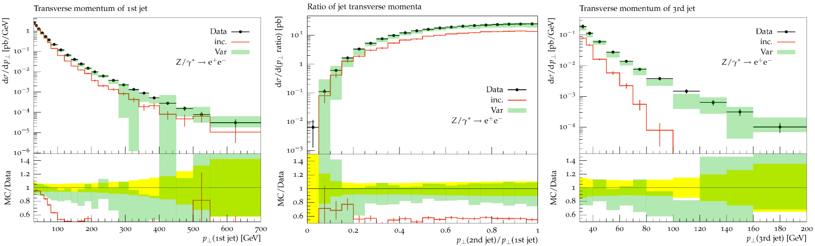
(green: 0, 1, 2 jets + uncertainty band from scale and PDF variations, red: MC@NLO)



FxFx: validation in Z+jets

(Data from ATLAS, 1304.7098, aMC@NLO _MADGRAPH with HERWIG++)

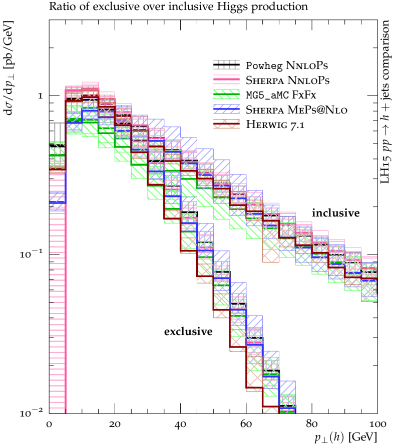
(green: 0, 1, 2 jets + uncertainty band from scale and PDF variations, red: MC@NLO)

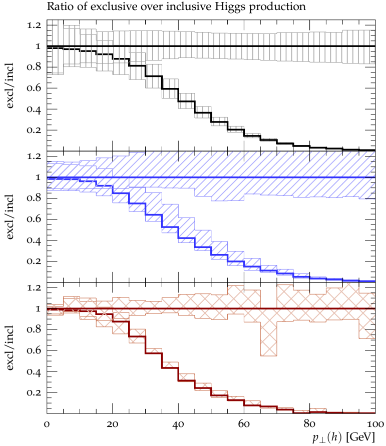


differences between MEPs@NLO, UNLOPs & FxFx

	FxFx	MEPs@NLO	UNLOPs
ME	all internal aMC@NLO _MADGRAPH	$\mathcal{V}$ external COMIX or AMEGIC++ $\mathcal{V}$ from OPENLOOPS, BLACKHAT, MJET, ...	all external
shower	external HERWIG or PYTHIA	intrinsic	intrinsic PYTHIA
Δ_N $\Theta(Q_J)$	analytical a-posteriori	from PS per emission	from PS per emission
Q_J-range	relatively high (but changed)	$>$ Sudakov regime $\approx$ 10%	$\approx$ Sudakov regime $\approx$ 10%

Higgs-$p_\perp$: exclusive over inclusive rate





- $\approx 20\%$ of Higgs with $p_\perp = 60$ GeV are not accompanied by a jet

motivation: the size of EW corrections

- EW corrections sizeable $\mathcal{O}(10\%)$ at large scales: must include them!
- but: more painful to calculate
- need EW showering & possibly corresponding PDFs

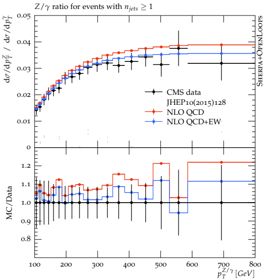
(somewhat in its infancy: chiral couplings)

- example: $Z\gamma$ vs. p_T (right plot)

(handle on $p_\perp^Z$ in $Z \to \nu\bar{\nu}$)

(Kallweit, Lindert, Pozzorini, Schoenherr for LH'15)

- difference due to EW charge of Z
- no real correction (real V emission)
- improved description of $Z \to \ell\ell$



inclusion of electroweak corrections in simulation

- incorporate approximate electroweak corrections in MEPS@NLO
  1. using electroweak Sudakov factors

$$\tilde{\mathrm{B}}_n(\Phi_n) \;\approx\; \tilde{\mathrm{B}}_n(\Phi_n)\,\Delta_{\mathrm{EW}}(\Phi_n)$$

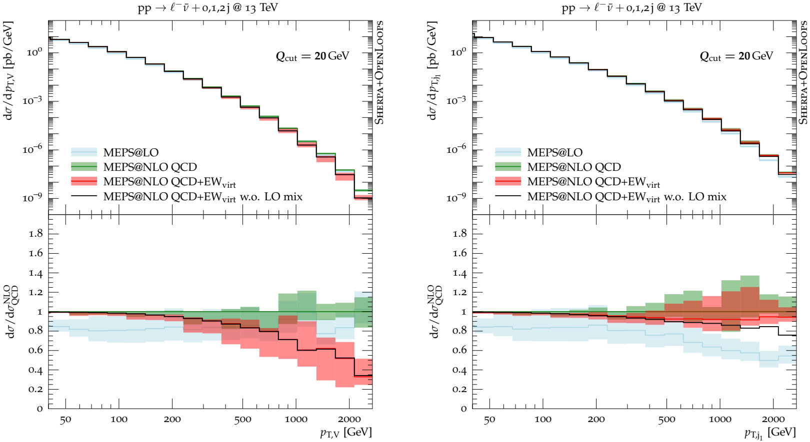
  2. using virtual corrections and approx. integrated real corrections

$$\tilde{\mathrm{B}}_n(\Phi_n) \;\approx\; \tilde{\mathrm{B}}_n(\Phi_n)+\mathrm{V}_{n,\mathrm{EW}}(\Phi_n)+\mathrm{I}_{n,\mathrm{EW}}(\Phi_n)+\mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD$\oplus$EW matching and merging
  $\to$ validated at fixed order, found to be reliable,
  difference $\lesssim 5\%$ for observables not driven by real radiation

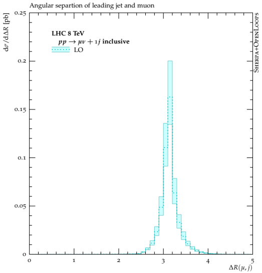
results: $pp \to \ell^- \bar{\nu} + \text{jets}$

(Kallweit, Lindert, Maierhöfer, Pozzorini, Schoenherr JHEP04(2016)021)



⇒ particle level events including dominant EW corrections

NLO EW predictions for $\Delta R(\mu, j_1)$

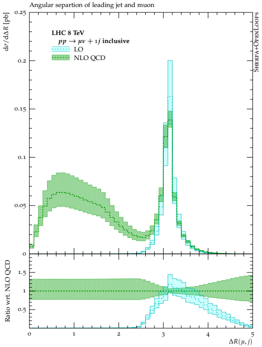


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$

NLO EW predictions for $\Delta R(\mu, j_1)$

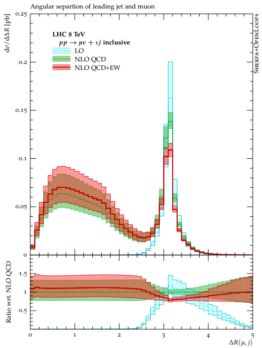


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS

NLO EW predictions for $\Delta R(\mu, j_1)$

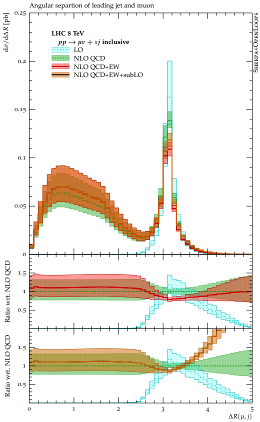


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS

NLO EW predictions for $\Delta R(\mu, j_1)$

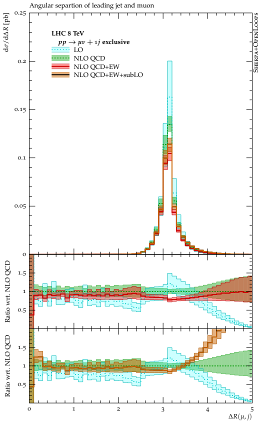


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR

NLO EW predictions for $\Delta R(\mu, j_1)$

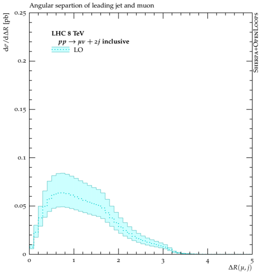


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\text{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100\,\text{GeV}$

NLO EW predictions for $\Delta R(\mu, j_1)$

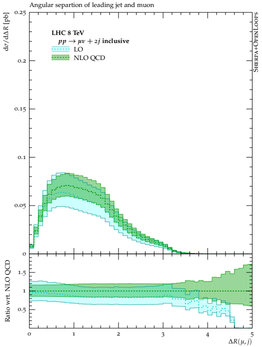


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV

NLO EW predictions for $\Delta R(\mu, j_1)$

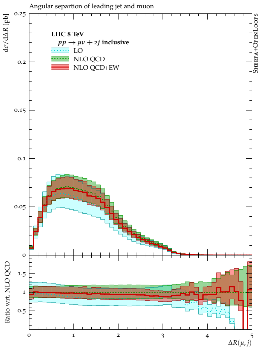


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\text{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV
- pos. NLO QCD, $\sim$ flat

NLO EW predictions for $\Delta R(\mu, j_1)$

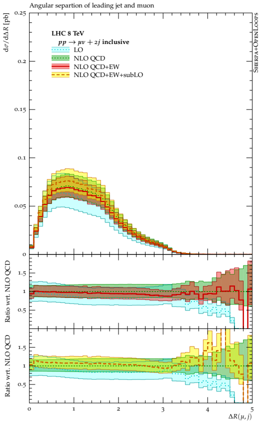


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV
- pos. NLO QCD, neg. NLO EW, $\sim$ flat

NLO EW predictions for $\Delta R(\mu, j_1)$

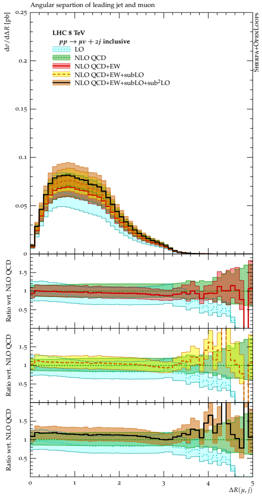


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV
- pos. NLO QCD, neg. NLO EW, $\sim$ flat
- sub-leading Born contribs positive

NLO EW predictions for $\Delta R(\mu, j_1)$

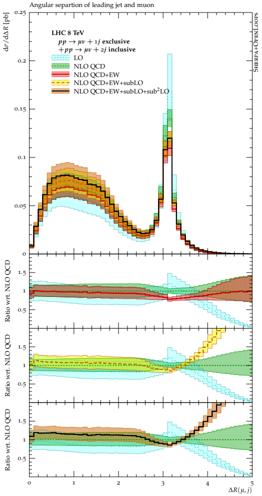


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\text{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV
- pos. NLO QCD, neg. NLO EW, $\sim$ flat
- sub-leading Born contribs positive
- sub^{2}leading Born (diboson etc) conts. pos.
  $\to$ possible double counting with BG

NLO EW predictions for $\Delta R(\mu, j_1)$

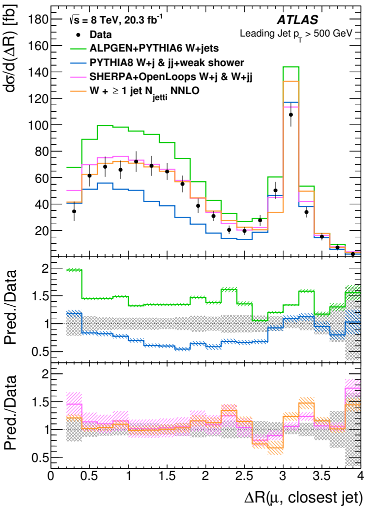


measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV
- pos. NLO QCD, neg. NLO EW, $\sim$ flat
- sub-leading Born contribs positive
- sub^{2}leading Born (diboson etc) conts. pos.
  $\to$ possible double counting with BG
- merge using exclusive sums

NLO EW predictions for $\Delta R(\mu, j_1)$

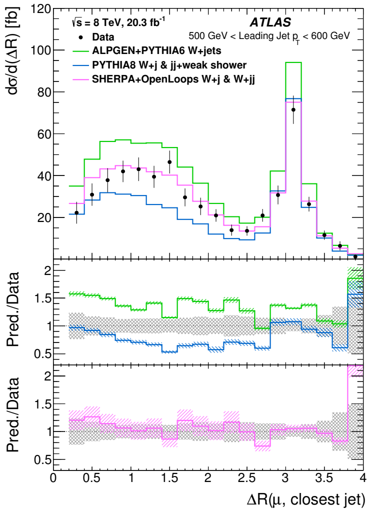


data comparison

(M. Wu ICHEP'16, ATLAS arXiv:1609.07045)

- ALPGEN+PYTHIA
  $pp \to W +$ jets MLM merged
  (Mangano et.al., JHEP07(2003)001)
- PYTHIA 8
  $pp \to Wj$ + QCD shower
  $pp \to jj$ + QCD+EW shower
  (Christiansen, Prestel, EPJC76(2016)39)
- SHERPA+OPENLOOPS
  NLO QCD+EW+subLO
  $pp \to Wj/Wjj$ excl. sum
  (Kallweit, Lindert, Maierhöfer,)
  (Pozzorini, Schoenherr, JHEP04(2016)021)
- NNLO QCD $pp \to Wj$
  (Boughezal, Liu, Petriello, arXiv:1602.06965)

NLO EW predictions for $\Delta R(\mu, j_1)$

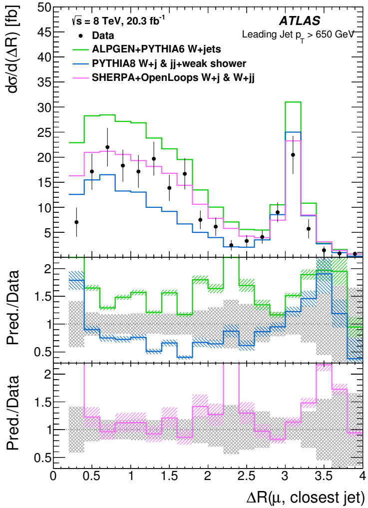


data comparison

(M. Wu ICHEP'16, ATLAS arXiv:1609.07045)

- ALPGEN+PYTHIA
  $pp \to W +$ jets MLM merged
  (Mangano et.al., JHEP07(2003)001)
- PYTHIA 8
  $pp \to Wj$ + QCD shower
  $pp \to jj$ + QCD+EW shower
  (Christiansen, Prestel, EPJC76(2016)39)
- SHERPA+OPENLOOPS
  NLO QCD+EW+subLO
  $pp \to Wj/Wjj$ excl. sum
  (Kallweit, Lindert, Maierhöfer,)
  (Pozzorini, Schoenherr, JHEP04(2016)021)
- NNLO QCD $pp \to Wj$
  (Boughezal, Liu, Petriello, arXiv:1602.06965)

NLO EW predictions for $\Delta R(\mu, j_1)$



data comparison
(M. Wu ICHEP'16, ATLAS arXiv:1609.07045)

- ALPGEN+PYTHIA
  $pp \to W +$ jets MLM merged
  (Mangano et.al., JHEP07(2003)001)
- PYTHIA 8
  $pp \to Wj$ + QCD shower
  $pp \to jj$ + QCD+EW shower
  (Christiansen, Prestel, EPJC76(2016)39)
- SHERPA+OPENLOOPS
  NLO QCD+EW+subLO
  $pp \to Wj/Wjj$ excl. sum
  (Kallweit, Lindert, Maierhöfer,)
  (Pozzorini, Schoenherr, JHEP04(2016)021)
- NNLO QCD $pp \to Wj$
  (Boughezal, Liu, Petriello, arXiv:1602.06965)

SIMULATING SOFT QCD

QCD radiation, once more

- remember QCD emission pattern

$$\mathrm{d}w^{q\to qg} = \frac{\alpha_s(k_\perp^2)}{2\pi}\,C_F\,\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\,\frac{\mathrm{d}\omega}{\omega}\,\left[1+\left(1-\frac{\omega}{E}\right)\right]\,.$$

- spectrum cut-off at small transverse momenta and energies by onset of hadronization, at scales $R \approx 1\,\mathrm{fm}/\Lambda_{\mathrm{QCD}}$
- two (extreme) classes of emissions: gluons and gluers determined by relation of formation and hadronization times

- gluers formed at times R, with momenta $k_\parallel \sim k_\perp \sim \omega \gtrsim 1/R$
- assuming that hadrons follow partons,

$$\mathrm{d}N_{\text{(hadrons)}} \sim \int\limits_{k_\perp > 1/R}^{Q} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \frac{C_F\, \alpha_s(k_\perp^2)}{2\pi} \left[1 + \left(1 - \frac{\omega}{E}\right)\right] \frac{\mathrm{d}\omega}{\omega}$$

$$\sim \frac{C_F \alpha_s(1/R^2)}{\pi} \log(Q^2 R^2) \frac{\mathrm{d}\omega}{\omega}$$

or - relating their energyn with that of the gluers -

$$\mathrm{d}N_{\text{(hadrons)}}/\mathrm{d}\log\epsilon = \text{const.}\,,$$

a plateau in log of energy (or in rapidity)

- impact of additional radiation
- new partons must separate before they can hadronize independently
- therefore, one more time

$$
\begin{aligned}
t^{\rm form} &\sim \frac{k_\parallel}{k_\perp^2} \\
t^{\rm sep} &\sim R\theta \sim t^{\rm form}\,(Rk_\perp) \\
t^{\rm had} &\sim k_\parallel R^2 \sim t^{\rm form}\,(Rk_\perp)^2\,.
\end{aligned}
$$

- for gluers $Rk_\perp \approx 1$: all times the same
- naively; new & more hadrons following new partons
- but: colour coherence
  primary and secondary partons not separated enough in

$$1/R \lesssim \omega_{\rm (hadron)} \lesssim 1/(R\theta)$$

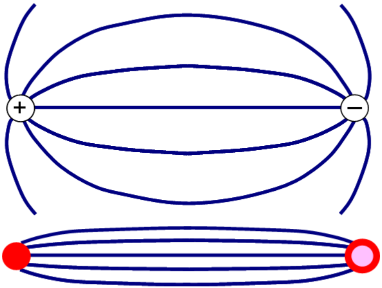
  and therefore no independent radiation

hadronisation: General thoughts

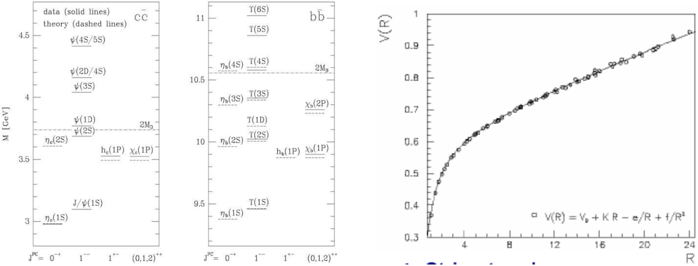
- confinement the striking feature of low–scale sotrng interactions
- transition from partons to their bound states, the hadrons
- the Meissner effect in QCD

QED:

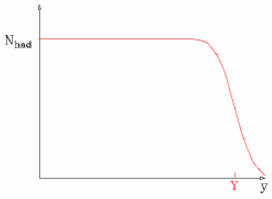
QCD:

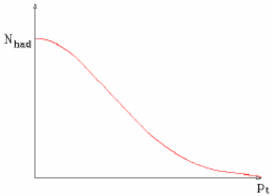


- linear QCD potential in Quarkonia – like a string



- combine some experimental facts into a naive parameterisation
- in $e^+e^- \to$ hadrons: exponentially decreasing $p_\perp$, flat plateau in y for hadrons





- try "smearing": $\rho(p_\perp^2) \sim \exp(-p_\perp^2/\sigma^2)$

- use parameterisation to "guesstimate" hadronisation effects:

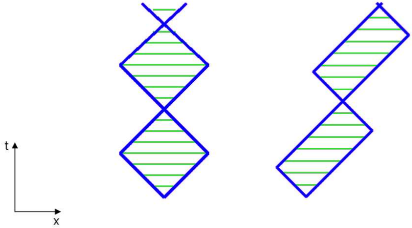
$$
\begin{aligned}
E &= \int_0^Y \mathrm{d}y\mathrm{d}p_\perp^2\,\rho(p_\perp^2)p_\perp \cosh y = \lambda \sinh Y \\
P &= \int_0^Y \mathrm{d}y\mathrm{d}p_\perp^2\,\rho(p_\perp^2)p_\perp \sinh y = \lambda(\cosh Y - 1) \approx E - \lambda \\
\lambda &= \int \mathrm{d}p_\perp^2\,\rho(p_\perp^2)p_\perp = \langle p_\perp \rangle \,.
\end{aligned}
$$

- estimate $\lambda \sim 1/R_{\rm had} \approx m_{\rm had}$, with $m_{\rm had}$ 0.1-1 GeV.
- effect: jet acquire non-perturbative mass $\sim 2\lambda E$ ($\mathcal{O}(10\mathrm{GeV})$ for jets with energy $\mathcal{O}(100\mathrm{GeV})$).

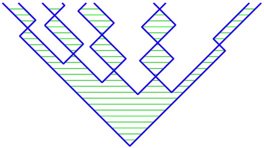
- similar parametrization underlying Feynman-Field model for independent fragmentation
- recursively fragment $q \to q' +$ had, where
  - transverse momentum from (fitted) Gaussian;
  - longitudinal momentum arbitrary (hence from measurements);
  - flavour from symmetry arguments + measurements.
- problems: frame dependent, “last quark”, infrared safety, no direct link to perturbation theory, ...

string model

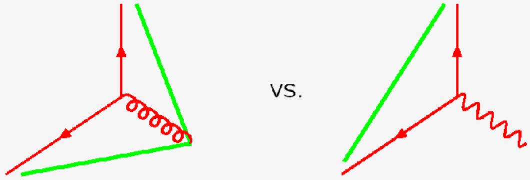
- a simple model of mesons: yoyo strings
  - light quarks ($m_q = 0$) connected by string, form a meson
  - area law: $m^2_{\rm had} \propto$ area of string motion
  - L=0 mesons only have 'yo-yo' modes:



- turn this into hadronisation model $e^+e^- \to q\bar{q}$ as test case
- ignore gluon radiation: $q\bar{q}$ move away from each other, act as point-like source of string
- intense chromomagnetic field within string:
  more $q\bar{q}$ pairs created by tunnelling and string break-up
- analogy with QED (Schwinger mechanism):
  $\mathrm{d}\mathcal{P} \sim \mathrm{d}x\mathrm{d}t\,\exp\left(-\pi m_q^2/\kappa\right)$, $\kappa =$ "string tension".



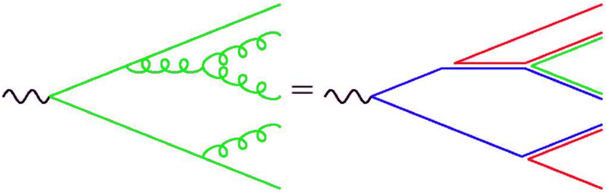
- string model = well motivated model, constraints on fragmentation (Lorentz-invariance, left-right symmetry, ...)
- how to deal with gluons?
- interpret them as kinks on the string $\Longrightarrow$ the string effect



- infrared-safe, advantage: smooth matching with PS.

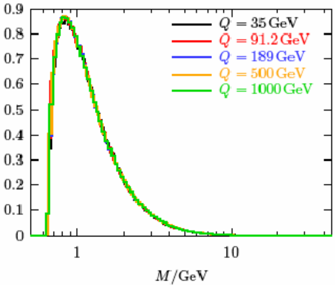
cluster model

- underlying idea: preconfinement/LPHD
  - typically, neighbouring colours will end in same hadron
  - hadron flows follow parton flows $\longrightarrow$ don't produce any hadrons at places where you don't have partons
  - works well in large–N_c limit with planar graphs
- follow evolution of colour in parton showers



- paradigm of cluster model: clusters as continuum of hadron resonances
- trace colour through shower in $N_c \to \infty$ limit
- force decay of gluons into $q\bar{q}$ or $\bar{d}d$ pairs, form colour singlets from neighbouring colours, usually close in phase space
- mass of singlets: peaked at low scales $\approx Q_0^2$
- decay heavy clusters into lighter ones or into hadrons (here, many improvements to ensure leading hadron spectrum hard enough, overall effect: cluster model becomes more string-like)
- if light enough, clusters will decay into hadrons
- naively: spin information washed out, decay determined through phase space only $\to$ heavy hadrons suppressed (baryon/strangeness suppression)

- self–similarity of parton shower will end with roughly the same **local** distribution of partons, with roughly the same invairant mass for colour singlets
- adjacent pairs colour connected, form colourless (white) clusters.
- clusters ("≈ excited hadrons) decay into hadrons



practicalities

- practicalities of hadronisation models: parameters
  - kinematics of string or cluster decay: 2-5 parameters
  - must "pop" quark or diquark flavours in string or cluster decay — cannot be completely democratic or driven by masses alone
    $\longrightarrow$ suppression factors for strangeness, diquarks 2-10 parameters
  - transition to hadrons, cannot be democratic over multiplets
    $\longrightarrow$ adjustment factors for vectors/tensors etc. 2-6 parameters
- tuned to LEP data, overall agreement satisfying
- validity for hadron data not quite clear

  (beam remnant fragmentation not in LEP.)
- there are some issues with inclusive strangeness/baryon production

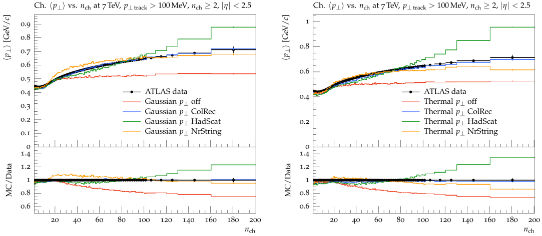
colour reconnections and friends

(Fischer, Sjostrand, 1610:09818)

Collective flow observed in pp at LHC. Partly unexpected.
New mechanisms required; could also (partly) replace CR.

Active field, e.g. N. Fischer & TS, arXiv:1610:09818 [hep-ph]:

- Thermal $exp(-p_\perp/T) \to exp(-m_\perp/T)$ hadronic spectrum.
- Close-packed strings $\Rightarrow$ increased string κ or T.
- Dense hadronic gas $\Rightarrow$ hadronic rescattering.

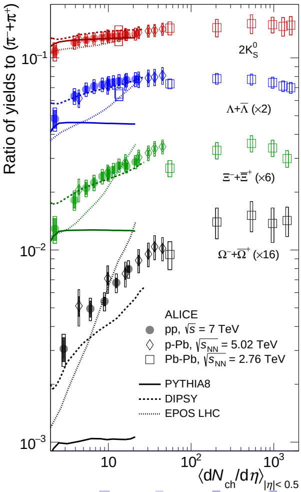


(slide stolen from Torbjorn Sjostrand)

strange strangeness

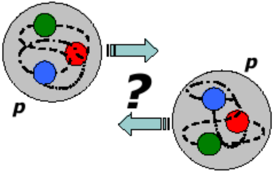
(ALICE collaboration)

- universality of hadronisation assumed
- parameters tuned to LEP data
  in particular: strangeness suppression
- for strangeness: flat ratios
  but data do not reproduce this
- looks like $SU(3)$ restoration
  not observed for protons
- needs to be investigated



multiple parton scattering

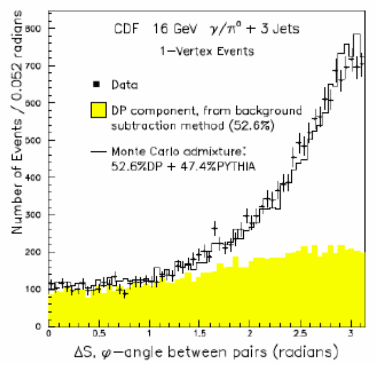
- hadrons = extended objects!
- no guarantee for one scattering only.
- running of α_S
  $\Longrightarrow$ preference for soft scattering.



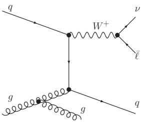
- first experimental evidence for double–parton scattering: events with $\gamma + 3$ jets:
  - cone jets, $R = 0.7$, $E_T > 5$ GeV; $|\eta_j| < 1.3$;
  - "clean sample": two softest jets with $E_T < 7$ GeV;
- cross section for DPS

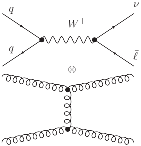
$$\sigma_{\rm DPS} = \frac{\sigma_{\gamma j}\sigma_{jj}}{\sigma_{\rm eff}}$$

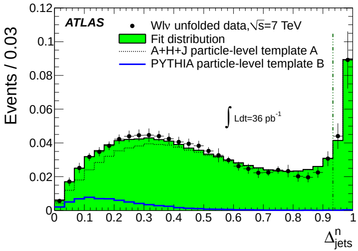
$\sigma_{\rm eff} \approx 14 \pm 4$ mb.

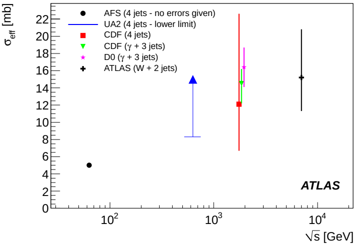


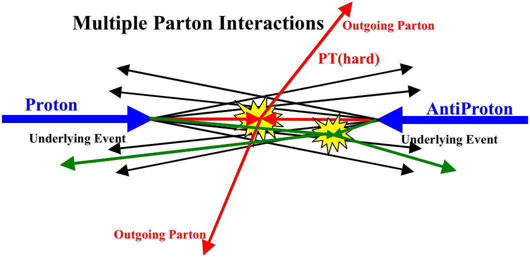
- more measurements, also at LHC
- ATLAS results from $W + 2$ jets











but: how to define the underlying event?

1. everything apart from the hard interaction, but including IS showers, FS showers, remnant hadronisation.
2. remnant-remnant interactions, soft and/or hard.
3. lesson: hard to define

- origin of MPS: parton–parton scattering cross section exceeds hadron–hadron total cross section

$$\sigma_{\rm hard}(p_{\perp,{\rm min}}) = \int\limits_{p^2_{\perp,{\rm min}}}^{s/4} {\rm d}p_\perp^2 \frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} > \sigma_{pp,{\rm total}}$$

  for low $p_{\perp,{\rm min}}$

- remember

$$\frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} = \int\limits_0^1 {\rm d}x_1{\rm d}x_2 f(x_1,\, q^2) f(x_2,\, q^2)\, \frac{{\rm d}\hat\sigma_{2\to 2}}{{\rm d}p_\perp^2}$$

- $\langle \sigma_{\rm hard}(p_{\perp,{\rm min}})/\sigma_{pp,{\rm total}}\rangle \geq 1$
- depends strongly on cut-off $p_{\perp,{\rm min}}$ (energy-dependent)!

modelling the underlying event

- take the old PYTHIA model as example:
  - start with hard interaction, at scale $Q^2_{\rm hard}$.
  - select a new scale $p_\perp^2$ from

$$\exp\left[-\frac{1}{\sigma_{\rm norm}}\int\limits_{p_\perp^2}^{Q^2_{\rm hard}} {\rm d}p_\perp{}'^2\frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp'^2}\right]$$

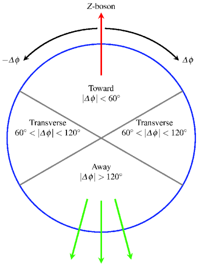
  with constraint $p_\perp^2 > p^2_{\perp,\rm min}$
  - rescale proton momentum ("proton-parton = proton with reduced energy").
  - repeat until no more allowed $2\to 2$ scatter

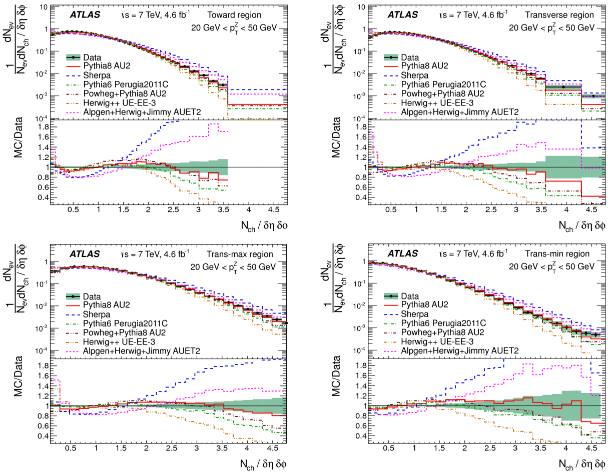
modelling the underlying event

- possible refinements:
  - may add impact-parameter dependence $\longrightarrow$ more fluctuations
  - add parton showers to UE
  - "regularisation" to dampen sharp dependence on $p_{\perp,\mathrm{min}}$: replace $1/\hat{t}$ in MEs by $1/(t+t_0)$, also in α_s.
  - treat intrinsic $k_\perp$ of partons ($\to$ parameter)
  - model proton remnants ($\to$ parameter)

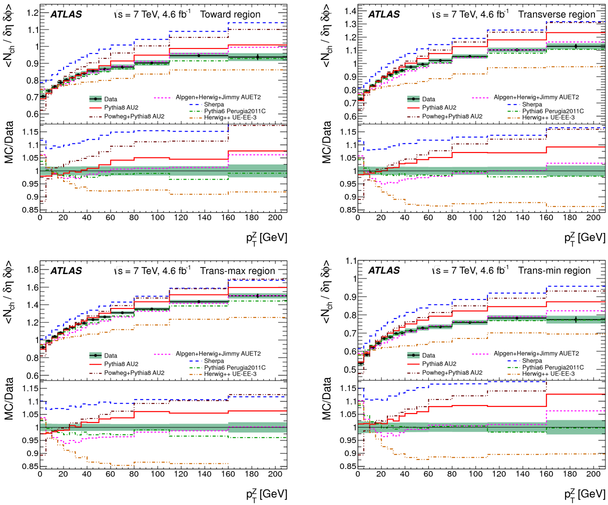
some results for MPS in Z production

- observables sensitive to MPS
- classical analysis: transverse regions in QCD/jet events
- idea: find the hardest system, orient event into regions:
  - toward region along system
  - away region back-to-back
  - transverse regions
- typically each in 120°

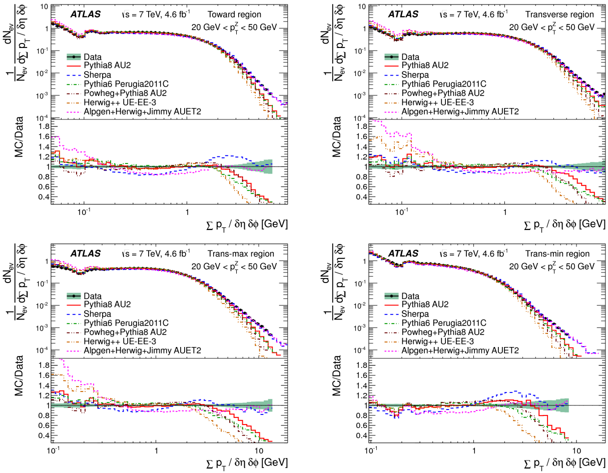



ATLAS
√s = 7 TeV, 4.6 fb⁻¹
Toward region
Transverse region
Trans-max region
Trans-min region
20 GeV < p_T^Z < 50 GeV
Data
Pythia8 AU2
Sherpa
Pythia6 Perugia2011C
Powheg+Pythia8 AU2
Herwig++ UE-EE-3
Alpgen+Herwig+Jimmy AUET2
MC/Data
N_ch / δη δφ
1/N_ev dN_ev/dN_ch / δη δφ

Some results in Z production



Some results in Z production



- see some data comparison in Minimum Bias
- practicalities of underlying event models: parameters
  - profile in impact parameter space — 2-3 parameters
  - IR cut-off at reference energy, its energy evolution, dampening paramter and normalisation cross section — 4 parameters
  - treating colour connections to rest of event — 2-5 parameters
- tuned to LHC data, overall agreement satisfying
- energy extrapolation not exactly perfect, plus other process categories such as diffraction etc..

SUMMARY

Summary of fixed order

- NLO (QCD) "revolution" consolidated:
    - lots of routinely used tools for large FS multis (4 and more)
    - incorporation in MC tools done, need comparisons, critical appraisals and a learning curve in their phenomenological use
    - to improve: description of loop–induced processes
- amazing success in NNLO (QCD) calculations:
    - emergence of first round of $2 \to 2$ calculations
    - next revolution imminent (with question marks)
    - first MC tools for simple processes ($gg \to H$, DY), more to be learnt by comparison etc. (see above)
- first N^{3}LO calculation in $gg \to H$, more to come (?)
- attention turning to NLO (EW)
    - first benchmarks with new methods (V+3j)
    - calculational setup tricky
    - need maybe faster approximation for high-scales (EW Sudakovs)

Limitations of fixed order

- practical limitations/questions to be overcome:
  - dealing with IR divergences at NNLO: slicing vs. subtracting

    (I'm not sure we have THE solution yet)
  - how far can we push NNLO? are NLO automated results stable enough for NNLO at higher multiplicity?
  - users of codes: higher orders tricky $\rightarrow$ training needed

    (MC = black box attitude problematic - a new brand of pheno/experimenters needed?)
- limitations of perturbative expansion:
  - breakdown of factorisation at HO (Seymour et al.)
  - higher-twist: compare $(\alpha_s/\pi)^n$ with $\Lambda_{\rm QCD}/M_Z$
- limitations in analytic resummation: process- and observable-dependent
  - first attempts at automation (CAESAR and some others) – checks/cross-comparison necessary
- showering needs to be improved (for NNLO the "natural" accuracy is NNLL)

Summary for event generation

- Systematic improvement of event generators by including higher orders has been at the core of QCD theory and developments in the past decade:
  - multijet merging (“CKKW”, “MLM”)
  - NLO matching (“MC@NLO”, “POWHEG”)
  - MENLOPS NLO matching & merging
  - MEPS@NLO (“SHERPA”, “UNLOPS”, “MINLO”, “FxFx”)

- multijet merging an important tool for many relevant signals and backgrounds - pioneering phase at LO & NLO over
- complete automation of NLO calculations done
  $\longrightarrow$ must benefit from it!

(it's the precision and trustworthy & systematic uncertainty estimates!)

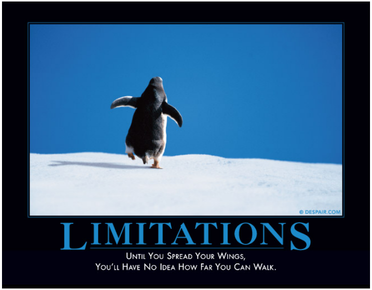
Vision

- we have constructed lots of tools for precision physics at LHC
  but we did not cross-validate them careful enough (yet)
  but we did not compare their theoretical foundations (yet)
- we also need unglamorous improvements:
  - systematically check advanced scale-setting schemes (MINLO)
  - automatic (re-)weighting for PDFs & scales (ME: ✓, PS: -)
  - scale compensation in PS is simple (implement and check)
  - PDFs: to date based on FO vs. data — will we have to move to resummed/parton showered?

(reminder: LO^* was not a big hit, though)

- . . . and maybe we will have to go to the "dirty" corners:
  higher-twist, underlying event, hadronization, . . .

(many of those driven by experiment)


© DESPAIR.COM
LIMITATIONS
Until You Spread Your Wings,
You'll Have No Idea How Far You Can Walk.