

# Recent developments in Sherpa

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on behalf of the Sherpa collaboration

SLAC National Accelerator Laboratory

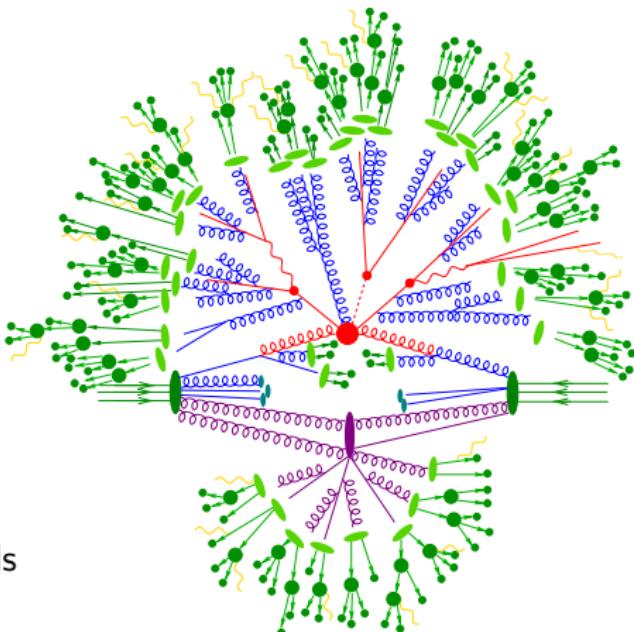
LoopFest XV

Buffalo, 08/16/2016

# Overview

[Gleisberg,Krauss,Schönherr,Schumann,Siegert,Winter,SH] arXiv:0811.4622  
[Bothmann,Krauss,Kuttimalai,Li,Schönherr,Schulz,Schumann,Siegert,Zapp,SH] soon

- ▶ Matrix Element generators  
AMEGIC++ (SM)  
and Comix (SM, BSM)
- ▶ Parton shower based on  
Catani-Seymour subtraction  
and new dipole-like shower
- ▶ Multiple interaction model  
à la Pythia (non-interleaved)
- ▶ In-house cluster hadronization  
and interface to PYTHIA string  
fragmentation (cross-checks!)
- ▶ Built-in hadron decay package  
 $\approx 400$  hadrons,  $\approx 2500$  channels
- ▶ Photon emission generator  
based on YFS formalism

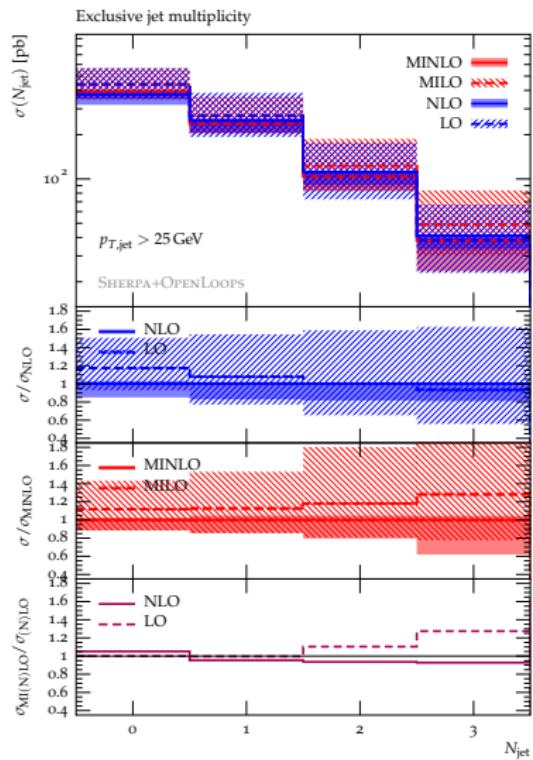


# NLO QCD calculations – $t\bar{t}+3$ jets

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[Maierhöfer,Moretti,Pozzorini,Siegert,SH] arXiv:1607.06934

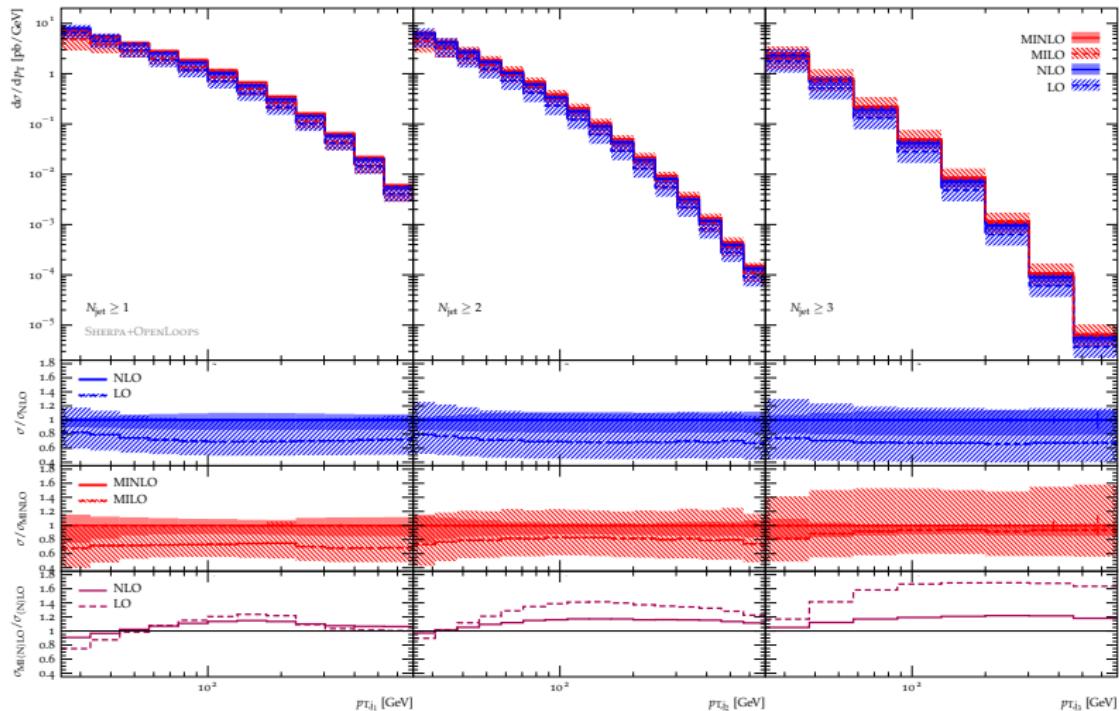
- ▶ First computation of  $t\bar{t}+3$  jets at NLO / MINLO accuracy
- ▶ Sherpa NLO MC framework using Comix [Gleisberg,SH] arXiv:0808.3674 combined with OpenLoops [Cascioli,Maierhöfer,Pozzorini] arXiv:1111.5206
- ▶ Public results in NTuple format à la [BlackHat collaboration] arXiv:1310.7439 for easy analysis & recycling available at NERSC (login req'd)
- ▶ Scale dependence studied using  $H_{T,m} = \sum m_\perp$  and MINLO [Hamilton,Nason,Zanderighi] arXiv:1206.3572 extended to massive partons



# NLO QCD calculations – $t\bar{t}+3$ jets

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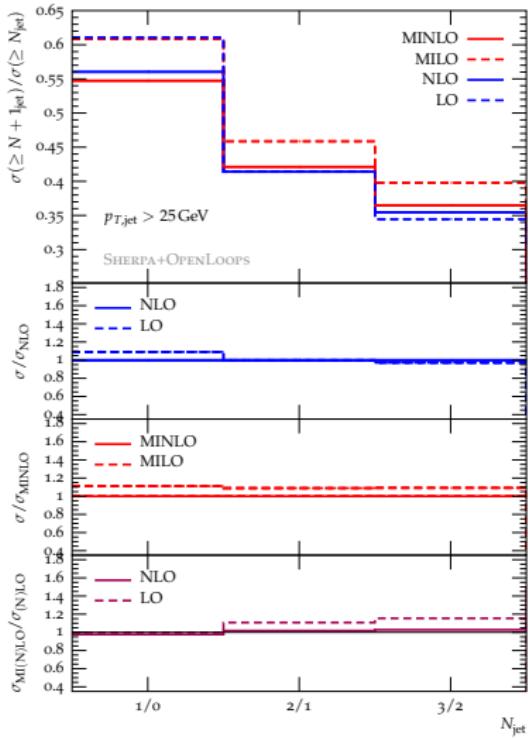
- Inclusive jet- $p_T$  spectra

# NLO QCD calculations – $t\bar{t}+3$ jets

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[Maierhöfer, Moretti, Pozzorini, Siegert, SH] arXiv:1607.06934

- ▶ No staircase scaling up to 3 jets  
→ similar to  $V +$  multi-jets  
[BlackHat collaboration] arXiv:1412.4775
- ▶ Attributed to suppression of important partonic channels  
→ quark–gluon turns on in  $t\bar{t} + 1j$   
quark–quark truly active in  $t\bar{t} + 2j$   
(gluon initial state strongly favored at LO due to parton luminosity and  $t$ -channel enhancement)
- ▶ Tests of staircase scaling ultimately requires  $t\bar{t} + 4/3$ -jet and  $t\bar{t} + 5/4$ -jet ratio

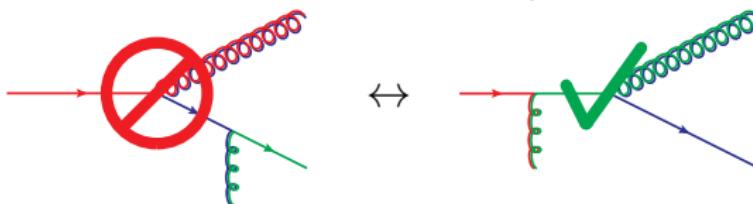


# Color coherence and the color dipole picture

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[Marchesini,Webber] NPB310(1988)461

- ▶ Individual color charges inside a color dipole cannot be resolved by gluons of wavelength larger than the dipole size  
→ emission off combined mother parton instead



- ▶ Net effect is destructive interference outside cone with opening angle defined by emitting color dipole  
→ Soft anomalous dimension halved due to reduced phase space
- ▶ Formerly implemented by angular ordering / angular veto
- ▶ Alternative description in terms of color dipoles

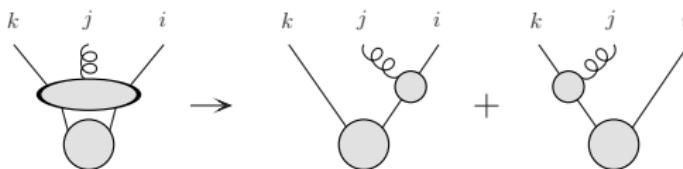
[Gustafsson,Pettersson] NPB306(1988)746, [Kharraziha,Lönnblad] hep-ph/9709424  
[Winter,Krauss] arXiv:0712.3913

# The midpoint between dipole and parton showers

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- ▶ Angular ordered / vetoed parton shower does not fill full phase space  
Dipole shower lacks parton interpretation → prefer alternative to both
- ▶ Can preserve parton picture by partial fractioning soft eikonal  
↔ soft enhanced part of splitting function [Catani,Seymour] hep-ph/9605323

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j} \frac{p_i p_k}{(p_i + p_k)p_j} + \frac{1}{p_k p_j} \frac{p_i p_k}{(p_i + p_k)p_j}$$



- ▶ “Spectator”-dependent kernels, singular in soft-collinear region only  
→ capture dominant coherence effects (3-parton correlations)

$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2 + \kappa^2} \quad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

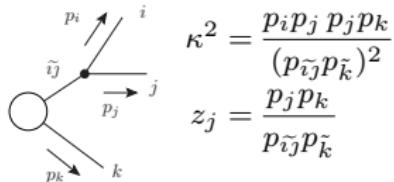
- ▶ For correct soft evolution, ordering variable must be identical at both “dipole ends” (→ recover soft eikonal at integrand level)

# The midpoint between dipole and parton showers

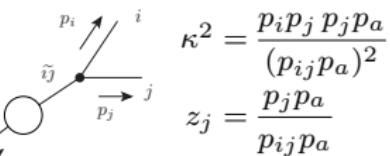
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Choose parametrization such that soft term is  $\frac{1-z}{(1-z)^2 + \kappa^2}$  in all dipole types

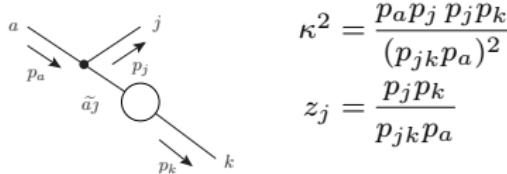
(1) FF



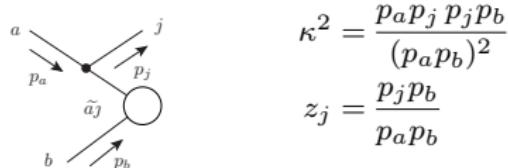
(2) FI



(3) IF



(4) II



Preserve collinear anomalous dimensions & sum rules  $\rightarrow$  splitting functions fixed

$$P_{qq}(z, \kappa^2) = 2 C_F \left[ \left( \frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ - \frac{1+z}{2} \right] + \gamma_q \delta(1-z)$$

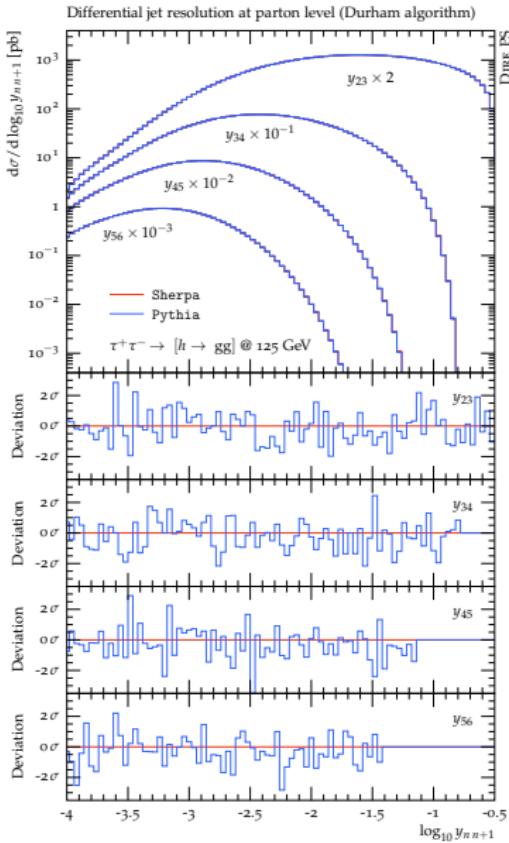
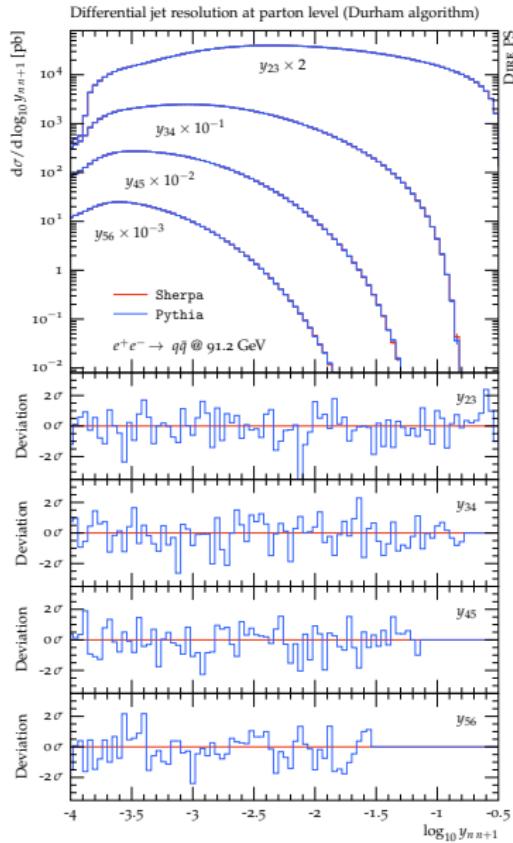
$$P_{gg}(z, \kappa^2) = 2 C_A \left[ \left( \frac{1-z}{(1-z)^2 + \kappa^2} \right)_+ + \frac{z}{z^2 + \kappa^2} - 2 + z(1-z) \right] + \gamma_g \delta(1-z)$$

$$P_{qg}(z, \kappa^2) = 2 C_F \left[ \frac{z}{z^2 + \kappa^2} - \frac{2-z}{2} \right]$$

$$P_{gq}(z, \kappa^2) = T_R \left[ z^2 + (1-z)^2 \right]$$

# The midpoint between dipole and parton showers

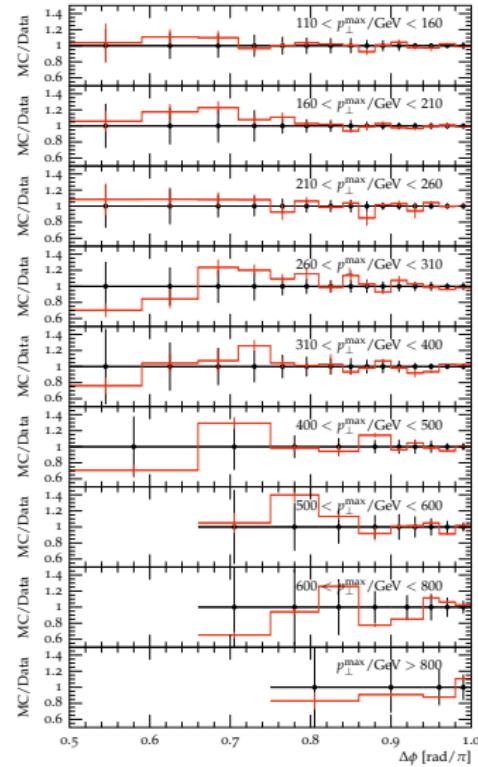
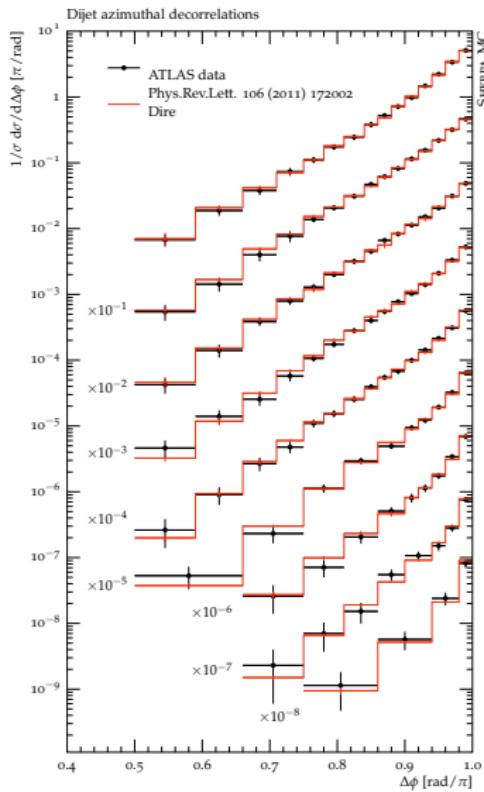
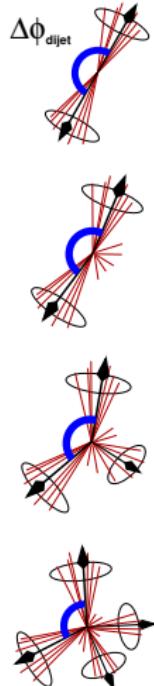
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# Predictions for the LHC

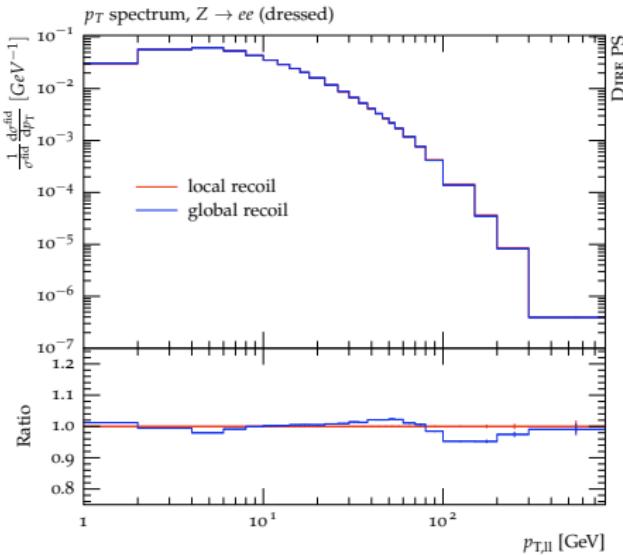
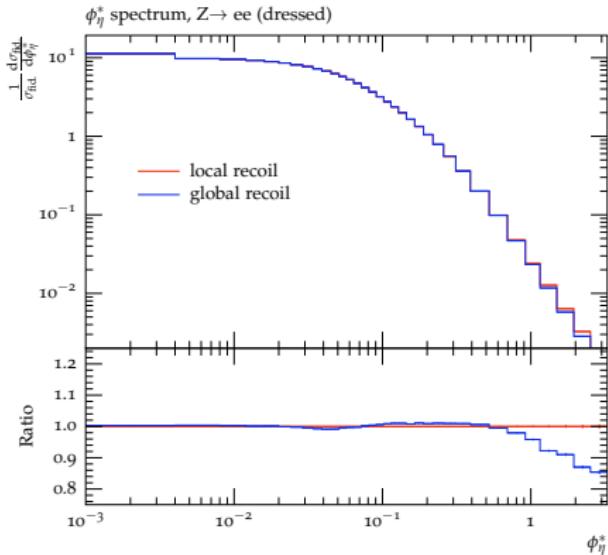
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[Prestel,SH] arXiv:1506.05057



# Kinematics mapping in IF dipoles

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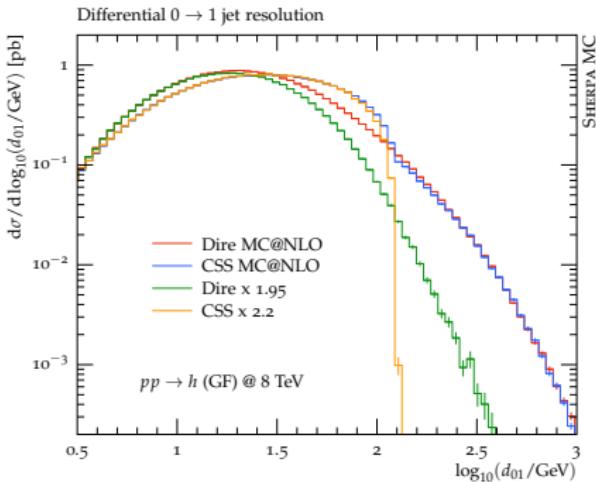


- ▶ Two mapping schemes for IF dipoles  $\rightarrow$  local [[Catani,Seymour](#)] [hep-ph/9605323](#) and global [[Plätzer,Gieseke](#)] [arXiv:0909.5593](#), [[Schumann,Siegert,SH](#)] [arXiv:0912.3501](#)
- ▶ Negligible impact on  $q_T$ -spectrum in low- $q_T$  range  
(spectrum dominated by singlet evolution at LHC energies)

# Extension to a subtraction method and MC@NLO

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- ▶ Can view new shower model as modification of CS subtraction
- ▶ Counterterms computed and implemented in Sherpa
- ▶ Sherpa MC@NLO based on exponentiation of CS dipole subtraction terms  
[Krauss,Siegert,Schönherr,SH]  
arXiv:1111.1220, arXiv:1208.2815
- ▶ Dire modified CS subtraction automatically available for MC@NLO matching
- ▶ Interesting differences due to evolution variables and kernels

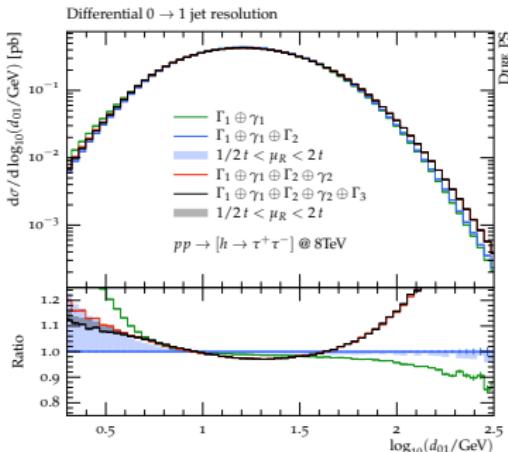
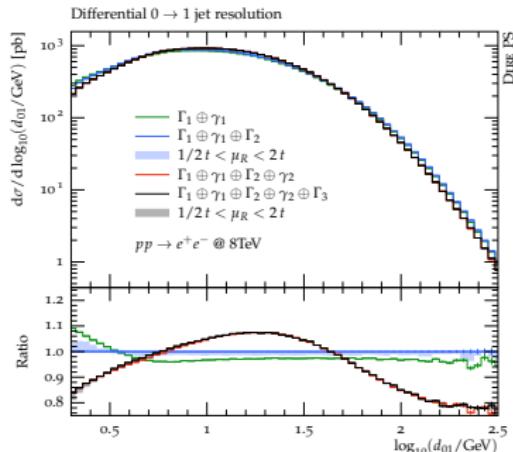


# Towards higher logarithmic accuracy

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[Krauss,Prestel,SH,...] in preparation

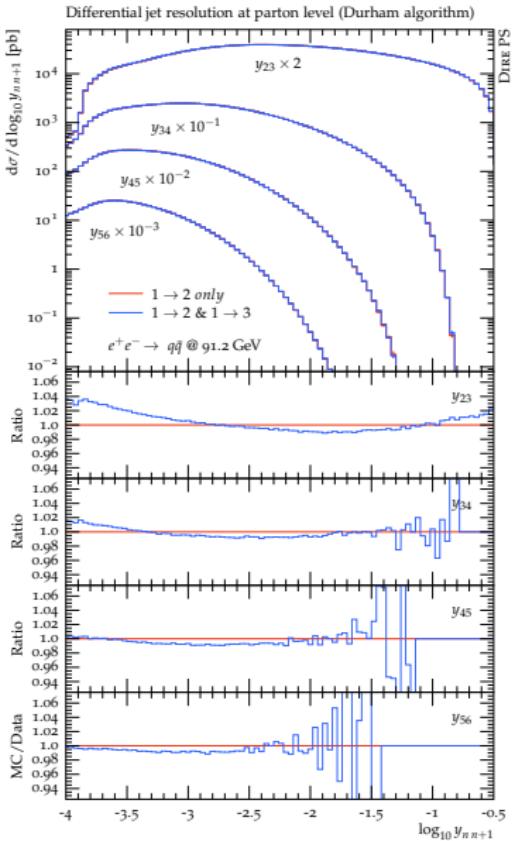
- Big drawback of parton showers is lack of higher-order kernels
- Start improving with spacelike NLO kernels  
[Curci,Furmanski,Petronzio] NPB175(1980)27, PLB97(1980)437
- 2-loop cusp term subtracted & combined with LO soft contribution  
(similar to CMW rescaling [Catani,Marchesini,Webber] NPB349(1991)635)
- Implemented using weighting algorithms [Schumann,Siegert,SH] arXiv:0912.3501



# Towards higher logarithmic accuracy

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- ▶ New topology at NLO from  $q \rightarrow \bar{q}$  and  $q \rightarrow q'$  splittings
- ▶ Generic  $1 \rightarrow 3$  process in parton shower  
 $2 \rightarrow 4$  process in dipole(-like) shower
- ▶ First branching treated as soft gluon radiation, second as collinear splitting (to match diagrammatic structure)
- ▶ FF & FI splittings complete and cross-checked (Pythia vs. Sherpa)
- ▶ II dipoles technically working to be validated, IF in the works



# Parton-shower uncertainty estimates

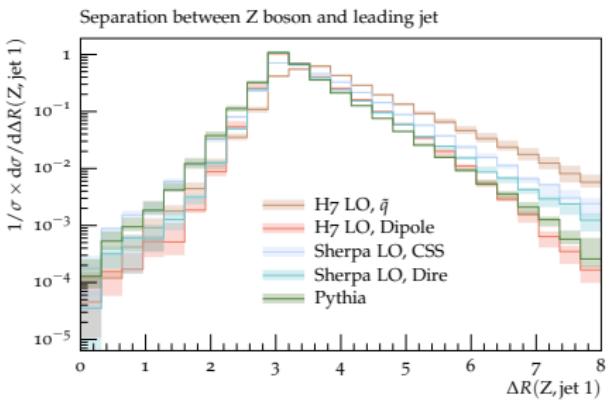
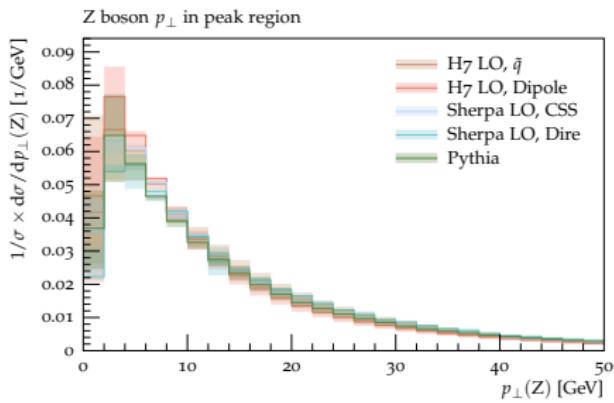
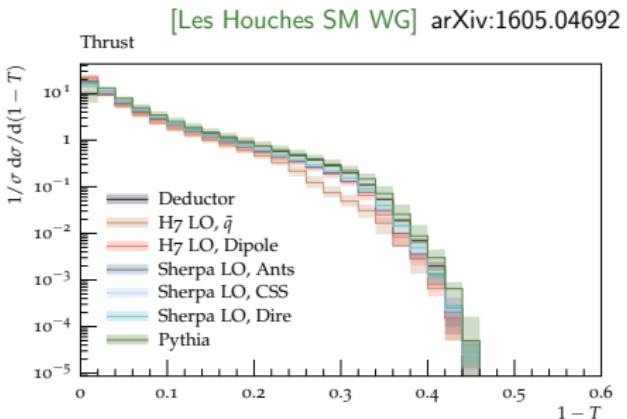
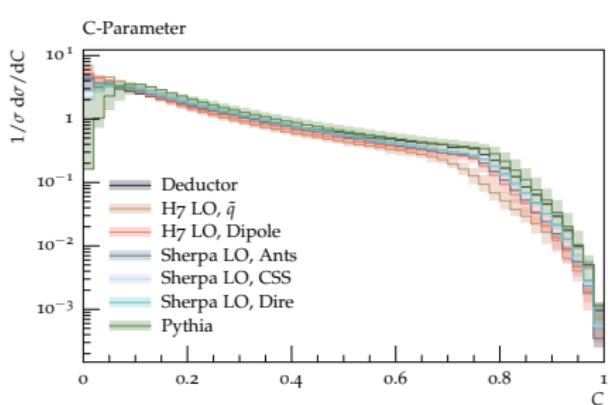
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[Les Houches SM WG] arXiv:1605.04692

- ▶ Renormalization scale choice in parton showers
  - ▶  $k_T$  [Amati,Bassetto,Ciafaloni,Marchesini,Veneziano] NPB173(1980)429
  - ▶ CMW rescaling [Catani,Marchesini,Webber] NPB349(1991)635
  - ▶ plus additional factor to be tuned to data ( $\approx 1$ )
- ▶ Scale variations typically not considered  
First attempt during LesHouches '15
- ▶ Participating projects
  - ▶ Deductor [Nagy,Soper] arXiv:1401.6364
  - ▶ Herwig [Bellm,Plätzer,Richardson,Siódmok,Webster] arXiv:1605.08256
    - ▶  $\tilde{q}$ -shower [Gieseke,Stephens,Webber] hep-ph/0310083
    - ▶ Dipole shower [Plätzer,Gieseke] arXiv:0909.5593
  - ▶ Pythia [Mrenna,Skands] arXiv:1605.08352
  - ▶ Sherpa [Bothmann,Schönherr,Schumann] arXiv:1606.08753
    - ▶ Ants [Krauss,Zapp] in preparation
    - ▶ CSS [Schumann,Krauss] arXiv:0709.1027
    - ▶ Dire [Prestel,SH] arXiv:1506.05057

# Parton-shower uncertainty estimates

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## Explicit variations

- ▶ Can be done for any scale or PDF dependence
- ▶ Functional form can be changed
- ▶ Separate runs with changed input

## On-the-fly variations

- ▶ Can be done for  $\mu_{R/F}$  and PDF dependence of matrix elements
- ▶ Functional form of scale can currently not be changed
- ▶ Full syntax cf. Manual, simplified syntax:

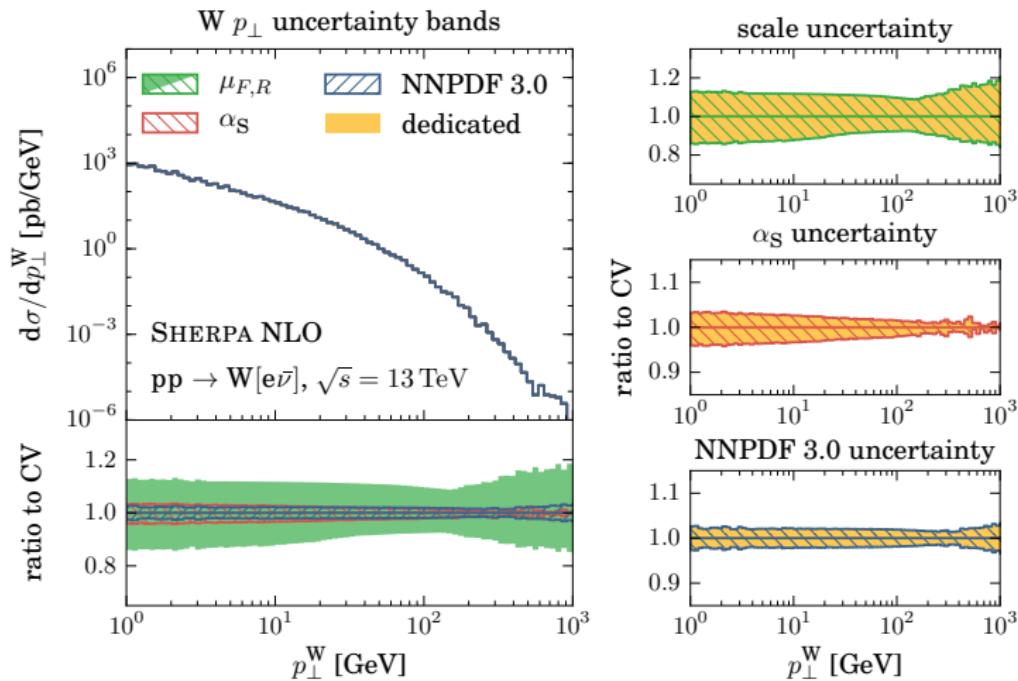
```
VARIATIONS 0.25,0.25 4.,4.;  
VARIATIONS NNPDF30_nnlo_as_0118[all];
```

- ▶ Stored in HepMC::WeightContainer  
using LH naming convention [[LesHouches SM WG](#)] arXiv:1405.1067

# Uncertainty estimates – NLO

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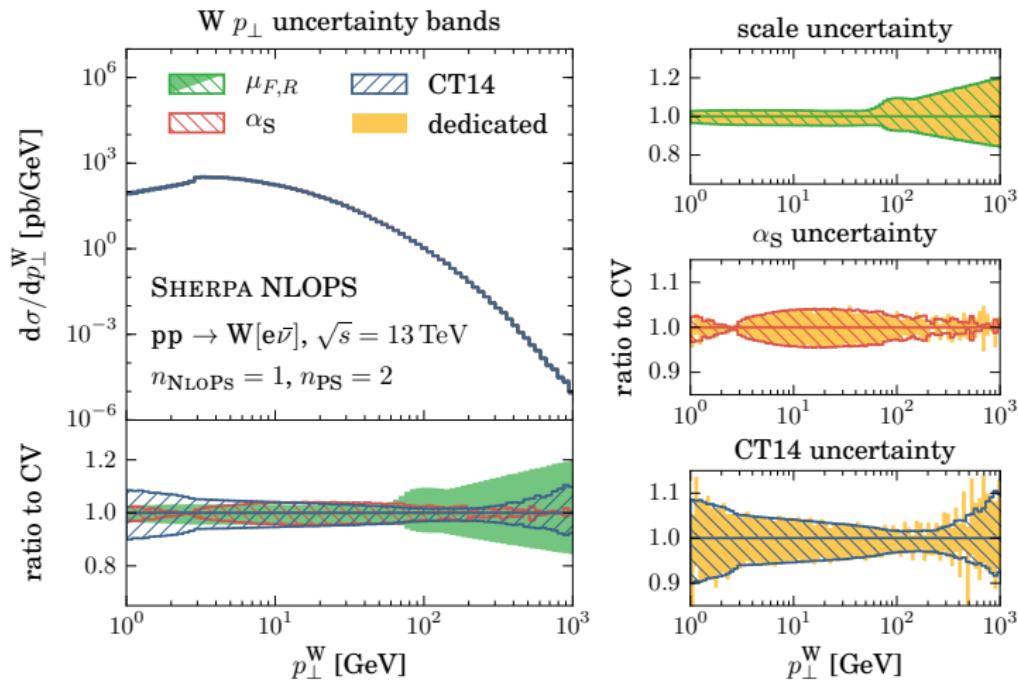
[Bothmann,Schönherr,Schumann] arXiv:1606.08753



# Uncertainty estimates – NLO+PS

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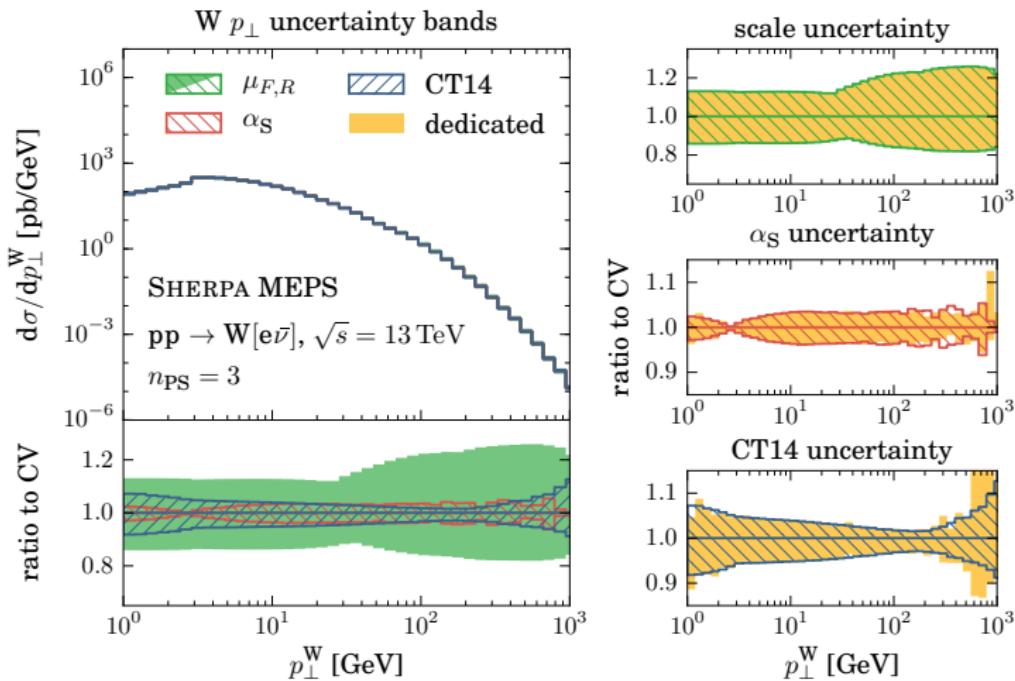
[Bothmann,Schönherr,Schumann] arXiv:1606.08753



# Uncertainty estimates – ME+PS

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[Bothmann,Schönherr,Schumann] arXiv:1606.08753



Extension of Sherpa's capabilities:

- ▶ Dipole-like parton shower (DiRe)
- ▶ On-the-fly scale variations, (N)LO(+PS) & MEPS(@NLO)
- ▶ Electroweak corrections ↗ M. Schönherr's talk
- ▶ MINLO method for massless and massive partons

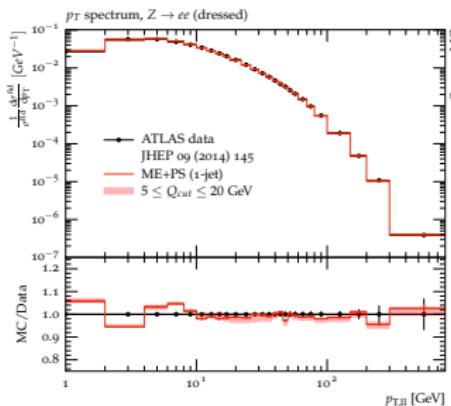
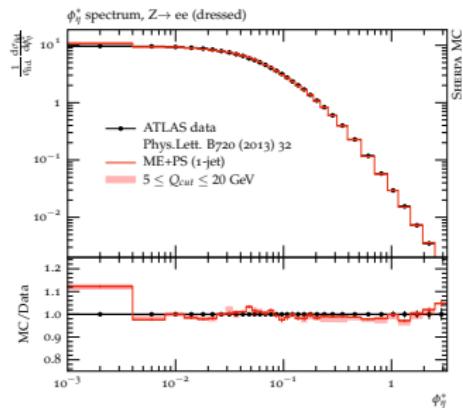
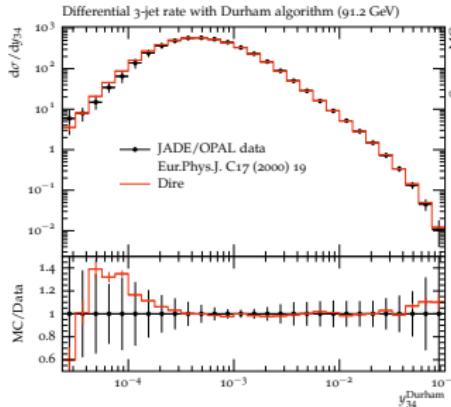
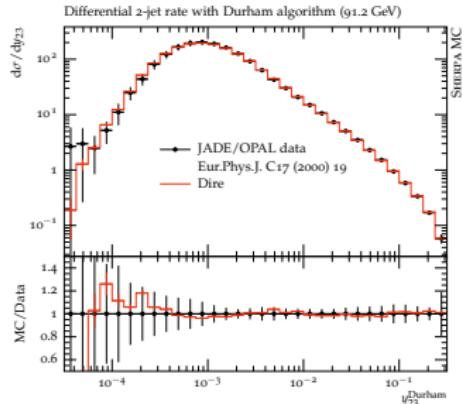
Near-term goals:

- ▶ Complete implementation of NLO kernels in DiRe
- ▶ Comparison of PS with analytic resummation  
↗ [Gerwick,Marzani,Schumann,SH] arXiv:1411.7325
- ▶ Assessment of overall uncertainty in UN<sup>2</sup>LOPS  
when using shower with NLO splitting functions  
↗ [Li,Prestel,SH] arXiv:1405.3607

# The midpoint between dipole and parton showers

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[Prestel,SH] arXiv:1506.05057



# Negative “probabilities” in parton showers

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- ▶ Problem in sub-leading corrections (NLO, sub-leading color) usually in negative weights → no-emission probability *locally* exceeds unity
- ▶ Recall standard parton shower:  $\Delta(t, t') = \exp\{F(t) - F(t')\}$   
Exact MC solution  $t = F^{-1}[F(t') + \log R]$ ,  $R$  – random number  
But don't want to compute  $F(t) = -\int_t d\bar{t} f(\bar{t})$ , as  $f(t) = \sum_b \int dz \frac{\alpha_s}{2\pi t} P_{ab}(t, z)$

## Solution in veto algorithm (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
- ▶ Generate points according to  $g(t)$  and accept with  $f(t)/g(t)$

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### Probability for one acceptance

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\}$$

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**Solution in veto algorithm** (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
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Probability for **one acceptance** with **one rejection**

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \left[ \int_t^{t'} dt_1 \left( 1 - \frac{f(t_1)}{g(t_1)} \right) g(t_1) \exp \left\{ - \int_{t_1}^{t'} d\bar{t} g(\bar{t}) \right\} \right]$$

# Negative “probabilities” in parton showers

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- ▶ Recall standard parton shower:  $\Delta(t, t') = \exp\{F(t) - F(t')\}$   
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But don't want to compute  $F(t) = -\int_t d\bar{t} f(\bar{t})$ , as  $f(t) = \sum_b \int dz \frac{\alpha_s}{2\pi t} P_{ab}(t, z)$

## Solution in veto algorithm (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
- ▶ Generate points according to  $g(t)$  and accept with  $f(t)/g(t)$

### Probability for one acceptance with two rejections

$$\begin{aligned} \frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} & \left[ \int_t^{t'} dt_1 \left( 1 - \frac{f(t_1)}{g(t_1)} \right) g(t_1) \exp \left\{ - \int_{t_1}^{t_2} d\bar{t} g(\bar{t}) \right\} \right] \\ & \times \left[ \int_{t_1}^{t'} dt_2 \left( 1 - \frac{f(t_2)}{g(t_2)} \right) g(t_2) \exp \left\{ - \int_{t_2}^{t'} d\bar{t} g(\bar{t}) \right\} \right] \end{aligned}$$

# Negative “probabilities” in parton showers

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- ▶ Problem in sub-leading corrections (NLO, sub-leading color) usually in negative weights → no-emission probability *locally* exceeds unity
- ▶ Recall standard parton shower:  $\Delta(t, t') = \exp\{F(t) - F(t')\}$   
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**Solution in veto algorithm** (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
- ▶ Generate points according to  $g(t)$  and accept with  $f(t)/g(t)$

Probability for one acceptance with  $n$  rejections

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[ \int_{t_{i-1}}^{t_i} dt_i \left( 1 - \frac{f(t_i)}{g(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

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**Solution in veto algorithm** (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
- ▶ Generate points according to  $g(t)$  and accept with  $f(t)/g(t)$

Probability for one acceptance with  $n$  rejections

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[ \int_{t_{i-1}}^{t'} dt_i \left( 1 - \frac{f(t_i)}{g(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

Disentangle nested integrals:

$$f(t) \exp \left\{ - \int_t^{t'} d\bar{t} g(\bar{t}) \right\} \frac{1}{n!} \left[ \int_t^{t'} d\bar{t} (g(\bar{t}) - f(\bar{t})) \right]^n$$

# Negative “probabilities” in parton showers

SLAC

- ▶ Problem in sub-leading corrections (NLO, sub-leading color) usually in negative weights → no-emission probability *locally* exceeds unity
- ▶ Recall standard parton shower:  $\Delta(t, t') = \exp\{F(t) - F(t')\}$   
Exact MC solution  $t = F^{-1}[F(t') + \log R]$ ,  $R$  – random number  
But don't want to compute  $F(t) = -\int_t d\bar{t} f(\bar{t})$ , as  $f(t) = \sum_b \int dz \frac{\alpha_s}{2\pi t} P_{ab}(t, z)$

**Solution in veto algorithm** (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
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Probability for one acceptance with  $n$  rejections

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[ \int_{t_{i-1}}^{t_i} dt_i \left( 1 - \frac{f(t_i)}{g(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

Disentangle nested integrals and sum over  $n$ :

$$f(t) \exp \left\{ - \int_t^{t'} d\bar{t} g(\bar{t}) \right\} \frac{1}{n!} \left[ \int_t^{t'} d\bar{t} (g(\bar{t}) - f(\bar{t})) \right]^n \rightarrow f(t) \exp \left\{ - \int_t^{t'} d\bar{t} f(\bar{t}) \right\}$$

# Negative “probabilities” in parton showers

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**Solution in veto algorithm** (hit-or-miss for Poisson distributions)

- ▶ Find simple function  $g(t) > f(t)$  with simple integral  $G(t)$
- ▶ Generate points according to  $g(t)$  and accept with  $f(t)/g(t)$

Standard probability for one acceptance with  $n$  rejections

$$\frac{f(t)}{g(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[ \int_{t_{i-1}}^{t'} dt_i \left( 1 - \frac{f(t_i)}{g(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

Split weight into MC and analytic part using auxiliary function  $h(t)$

$$\frac{f(t)}{h(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[ \int_{t_{i-1}}^{t'} dt_i \left( 1 - \frac{f(t_i)}{h(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$

$$w(t, t_1, \dots, t_n) = \frac{h(t)}{g(t)} \prod_{i=1}^n \frac{h(t_i)}{g(t_i)} \frac{g(t_i) - f(t_i)}{h(t_i) - f(t_i)}$$

# Negative “probabilities” in parton showers

SLAC

Weighted veto algorithm

$$\frac{f(t)}{h(t)} g(t) \exp \left\{ - \int_t^{t_1} d\bar{t} g(\bar{t}) \right\} \prod_{i=1}^n \left[ \int_{t_{i-1}}^{t'} dt_i \left( 1 - \frac{f(t_i)}{h(t_i)} \right) g(t_i) \exp \left\{ - \int_{t_i}^{t_{i+1}} d\bar{t} g(\bar{t}) \right\} \right]$$
$$w(t, t_1, \dots, t_n) = \frac{h(t)}{g(t)} \prod_{i=1}^n \frac{h(t_i)}{g(t_i)} \frac{g(t_i) - f(t_i)}{h(t_i) - f(t_i)}$$

Looks trivial, surprisingly it's not: It allows to

- ▶ Include sub-leading color terms in MC@NLO and POWHEG  
[Krauss,Schönherr,Siegert,SH] arXiv:1111.1220
- ▶ Implement higher-order splitting functions in parton showers  
[Catani,Krauss,Prestel,SH] in preparation
- ▶ Use PDFs with negative values in parton showers  
[Prestel,SH] arXiv:1506.05057
- ▶ Enhance branching probabilities in parton showers  
[Schumann,Siegert,SH] arXiv:0912.3501, [Lönnblad] arXiv:1211.7204
- ▶ Reweight parton showers [Bellm,Plätzer,Richardson,Siódmok,Webster] arXiv:1605.08256  
[Mrenna,Skands] arXiv:1605.08352, [Bothmann,Schönherr,Schumann] arXiv:1606.08753