QCD and collider physics IV: Calculation methods, NLO, PS and all that

H. Jung (DESY)

- Announcements
- Monte Carlo techniqes ...
- NLO calculations
- all order calcualtions
  - collinear/kt-factorised
- matching of PS and fixed parton calculations
  - CKKM
  - MC@NLO
- The end

http://www-h1.desy.de/~jung/qcd_collider_physics_sose_2007

Lectures on Higgs and SUSY

- Next lectures:
  Higgs and Supersymmetry: LHC phenomenology by P. Zerwas
  - Mo 25.6. 11:00
  - Do 28.6. 11:00
  - Mo 2.7. 11:00
  - Do 5.7. 11:00
  - Mo 9.7. 11:00
  - Do 12.7. 11:00
- lectures start at 11:00 in sem 2

top production x-section

- x-section NLO calc:

	TeVatron	LHC
$\sigma(pp \to t\bar{t})$	~ 7 pb	~ 830 pb
$gg \to t\bar{t}$	15 %	90 %
$q\bar{q} \to t\bar{t}$	85 %	10 %

- x-section PYTHIA calc:

		$q\bar{q} \to t\bar{t}$ [mb]	$gg \to t\bar{t}$ [mb]	tot
LHC	pp	$6.5 \cdot 10^{-8}$	$3.9 \cdot 10^{-7}$	0.45 nb
LHC	$p\bar{p}$	$8.2 \cdot 10^{-8}$	$3.9 \cdot 10^{-7}$	0.47 nb
TeVatron	pp	$7.2 \cdot 10^{-10}$	$2.7 \cdot 10^{-10}$	0.99 pb
TeVatron	$p\bar{p}$	$4.8 \cdot 10^{-9}$	$2.7 \cdot 10^{-10}$	5.1 pb

Monte Carlo techniques for calculating complicated integrals

Monte Carlo technique

- **Law of large numbers**

$$\frac{1}{N}\sum_{i=1}^{N} f(u_i) \to \frac{1}{b-a}\int_a^b f(u)du$$

  MC estimate converges to true integral

- **Central limit theorem**

  MC estimate is asymptotically normally distributed
  it approaches a Gaussian density

$$\sigma = \frac{\sqrt{V[f]}}{\sqrt{N}} \sim \frac{1}{\sqrt{N}}$$

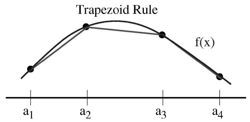
  with effective variance *V(f)*
  decrease σ: reduce *V(f)* or increase *N*

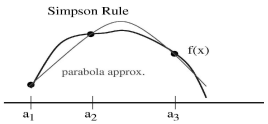
- advantages for n-dimensional integral ...
  i.e. phase space integrals *2* → *n* processes
  is where other approaches tend to fail

Integration: Monte Carlo versus others

One dimensional quadrature

$$I = \int f(x)dx = \sum_{i=1}^{n} w_i f(x_i)$$





- Monte Carlo: Hit & Miss
  w =1 and x_i chosen randomly
- Trapezoidal Rule:
  approximate integral in sub-interval
  by area of trapezoid below (above) curve
- Simpson quadrature
  approximate by parabola
- Gauss quadrature
  approximate by higher order polynomial

method	err (1d)	error
MC	$n^{-1/2}$	$n^{-1/2}$
Trapez	n^{-2}	$n^{-2/d}$
Simpson	n^{-4}	$n^{-4/d}$
Gauss	n^{-2m+1}	$n^{-(2m-1)/d}$

MC method: advantage of hit & miss

- integration ☛ weighting events
  large fluctuations from large weights
  weights also to errors applied
  difficult to apply further
  hadronisation
- real events all have weight = 1 !!!
- Hit & Miss method:

MC for function $f(x)$:
get random number:
$R1$ in $(0,1)$ and $R2$ in $(0,1)$
calculate $x = R1$
reject event if: $f_x < f_{max}\, R2$

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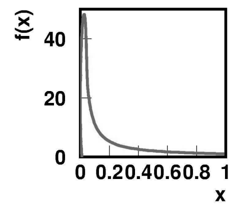

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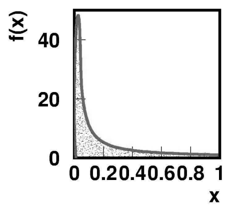

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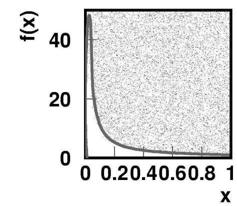

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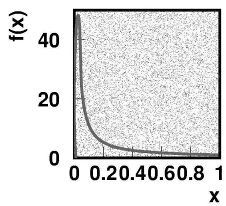

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> get random number:
> $R1$ in $(0,1)$ and $R2$ in $(0,1)$
> calculate $x = R1$
> reject event if: $f_x < f_{max}\, R2$

- BUT: Hit & Miss method inefficient for peaked $f(x)$

MC method: do even better ...

- Importance sampling

> MC for function f(x)
> approximate $f(x) \sim g(x)$
> with $g(x) > f(x)$ simple and integrable
> generate x according to $g(x)$:
>
> $$\int_{x_{min}}^{x} g(x')dx' = R1 \int_{x_{min}}^{x_{max}} g(x')dx'$$
>
> example: $f(x) = 1/x^{0.7}$
>
> $$g(x) = 1/x$$
>
> $$x = x_{min} \cdot \left(\frac{x_{max}}{x_{min}}\right)^{R1}$$
>
> reject event if: $f(x) < g(x)\, R2$

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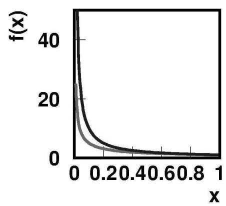

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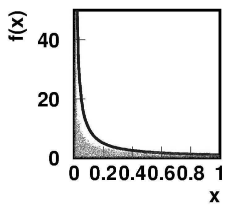

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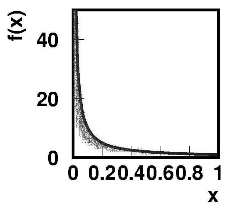

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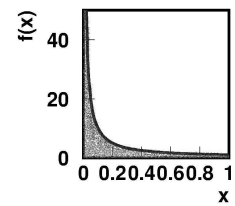


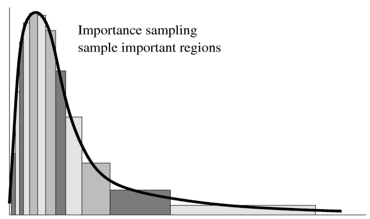
- WOW !!! very efficient even for peaked f(x)

Importance Sampling

- MC calculations most efficient for small weight fluctuations:
  $f(x)dx \to f(x)\, dG(x)/g(x)$
- chose point according to g(x) instead of uniformly
- f is divided by $g(x) = dG(x)/dx$
- generate x according to:

$$R \int_a^b g(x')dx' = \int_a^x g(x')dx'$$

- relevant variance is now $V(f/g)$:
  small if $g(x) \sim f(x)$
- how-to get $g(x)$
  (1) $g(x)$ is probability: $g(x) > 0$ and $\int dG(x) = 1$
  (2) integral $\int dG(x)$ is known analytically
  (3) $G(x)$ can be inverted (solved for x)
  (4) $f(x)/g(x)$ is nearly constant, so that $V(f/g)$ is small compared to $V(f)$



NLO calculations

NLO calculations: principles

Frixione,Webber
hep-ph/0204244

$$\sigma_{ab} = \sigma_{ab}^{LO} + \sigma_{ab}^{NLO}$$
$$\sigma_{ab}^{LO} = \int_m d\sigma^{\text{Born}}$$
$$\sigma_{ab}^{NLO} = \int_m d\sigma^{\text{Virtual}} + \int_{m+1} d\sigma^{\text{Real}}$$

$$\sigma = \int_m d\sigma^{\text{Born}} + \int_m d\sigma^{\text{Virtual}} + \int_{m+1} d\sigma^{\text{Real}}$$

- Virtual (1-loop) corrections:
  - UV ,IR, collinear
- UV corrections handled by renormalisation procedure
- soft/collinear singularities do not cancel within $d\sigma^V$, only with appropriate quantities from $d\sigma^R$

- infrared safe quantities F^m
- ➔ adding any number of soft and collinear partons to F^m should not change the result:

$$F^{m+1} \to F^m$$

Regularization schemes

R. Field, Appl. of pQCD, p 42

- Massive Gluon (MG) scheme:
  - give gluon fictitious mass, which then is removed
  - ➔ regulate UV divergency by: $\frac{1}{k^2} \to \frac{1}{k^2}\frac{L}{L-k^2}$
  - ➔ regulate IR divergency by: $\frac{1}{k^2} \to \int_{m_g^2}^{L} \frac{dl}{k^2 - l^2}$
- Dimensional Regularization (DR) scheme:
  - calculate in N=4-2 ε rather than in 4 dimensions
  - add real and virtual corrections
  - set N=4

Estimate of scale dependence

- variations of scale will lead to corrections of $\mathcal{O}(\alpha_s^4)$for $\mathcal{O}(\alpha_s^3)$calculation:

$$\mu^2 \frac{d\sigma}{d\mu^2} = \mathcal{O}(\alpha_s^4)$$

- use renormalisation group equation for α_s

$$\mu^2 \frac{d}{d\mu_R^2}\alpha_s(\mu_R^2) = -b_0\alpha_s^2 + \cdots$$

- and lowest order DGLAP equations:

$$\mu^2 \frac{d}{d\mu_F^2} f_i(x,\mu_F^2) = \frac{\alpha_s(\mu_F)}{2\pi}\sum_k \int_x^1 \frac{dz}{z} P_{ik}^{(0)}(z) f_k(\frac{x}{z},\mu_F^2) + \cdots$$

➔ to obtain:

$$\frac{d\sigma}{dE_t} = \left[\alpha_s^2(\mu_R)\sigma_0 + \alpha_s^3(\mu_R)(\sigma_1 + 2b_0 \log\frac{\mu_R}{E_T}\sigma_0 - 2P_{qq}\log\frac{\mu_F}{E_T}\sigma_0)\right] \otimes f_q(\mu_F) \otimes f_{\bar{q}}(\mu_F)$$

Scale dependence

Campbell, Huston Stirling
Rep.Prog.Phys 70 (2007) 89

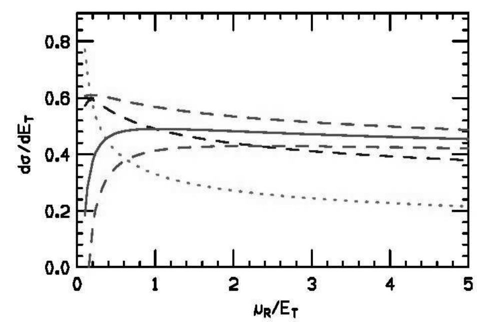


Figure 16. The single jet inclusive distribution at $E_T = 100$ GeV, appropriate for Run I of the Tevatron. Theoretical predictions are shown at LO (dotted magenta), NLO (dashed blue) and NNLO (red). Since the full NNLO calculation is not complete, three plausible possibilities are shown.

NLO toy model

Frixione,Webber
hep-ph/0204244

- Use a simple toy model to illustrate behavior of real and virtual contributions:

$$\begin{aligned}\left(\frac{d\sigma}{dx}\right)_{born} &= B\delta(x)\\ \left(\frac{d\sigma}{dx}\right)_{virtual} &= a\left(\frac{B}{2\epsilon}+V)\delta(x)\right)\\ \left(\frac{d\sigma}{dx}\right)_{real} &= a\frac{R(x)}{x}\\ \lim_{x\to 0} R(x) &= B\end{aligned}$$

- task of NLO is to compute:

$$\langle O\rangle = \lim_{\epsilon\to 0}\int_0^1 dx\, x^{-2\epsilon} O(x)\left[\left(\frac{d\sigma}{dx}\right)_b + \left(\frac{d\sigma}{dx}\right)_v + \left(\frac{d\sigma}{dx}\right)_r\right]$$

Factorisation of soft/collinear radiation

Bassetto, Ciafaloni, Marchesini, Phys Rep 100(1983) 201
Dokshitzer, Khoze, Mueller, Troian Basics of pQCD (1991)
Ellis, Stirling, Webber QCD and Collider physics, p164

General Form with singular part **V**

$$|M_{m+1}|^2 \to |M_m|^2 \otimes \text{V}$$

Collinear factorisation:

- Investigations of multi parton radiation leads to (at small t):

$$|M_{n+1}|^2 \sim \frac{4g^2}{t} P_{ab}\,|M_n|^2$$

➔ and (at small t)

$$d\sigma_{n+1} = d\sigma_n \frac{dt}{t} dz \frac{\alpha_s}{2\pi} P_{ab}$$

➔ depends on helicity structure (splitting functions)

Soft factorisation (small x) (Bassetto et al)

- multiple soft gluon emissions with $|q_1| \ll |q_2| \ll |q_3| \cdots \ll |q_n|$

$$d\sigma(q_1,...,q_n) = \prod_{i=1}^{n} \frac{\alpha_s dz_i^2 d\xi_i}{\pi z_i^2 \xi_i} d\sigma_{jet}$$

Bassetto et al Phys Rep 100(1983) 201 eq. 3.35

➔ with $\xi_i = \frac{1}{2}\theta_{i\,jet}$

➔ depends on color structure (coherence, angular ordering, etc)

Applications for initial and final state radiation, universal, factorisation

Phase Space slicing

- task is to comute

Frixione,Webber hep-ph/0204244

$$\langle O \rangle = \lim_{\epsilon \to 0} \int_0^1 dx\, x^{-2\epsilon} O(x) \left[\left(\frac{d\sigma}{dx}\right)_b + \left(\frac{d\sigma}{dx}\right)_v + \left(\frac{d\sigma}{dx}\right)_r \right]$$

- we have:

$$\begin{aligned} \langle O \rangle_r &= \int_0^1 dx\, x^{-2\epsilon} O(x) \left(\frac{d\sigma}{dx}\right)_r \\ &= \int_0^\delta dx\, x^{-2\epsilon} O(x) \left(\frac{d\sigma}{dx}\right)_r + \int_\delta^1 dx\, x^{-2\epsilon} O(x) \left(\frac{d\sigma}{dx}\right)_r \\ &= O(0) \cdot R(0) \left(\frac{1}{-2\epsilon} + \log \delta \right) + a \cdot \int_\delta^1 dx\, O(x) \frac{R(x)}{x} \end{aligned}$$

- use also:

$$\left(\frac{d\sigma}{dx}\right)_v = a \left(\frac{B}{2\epsilon} + V \right) \delta(x)$$

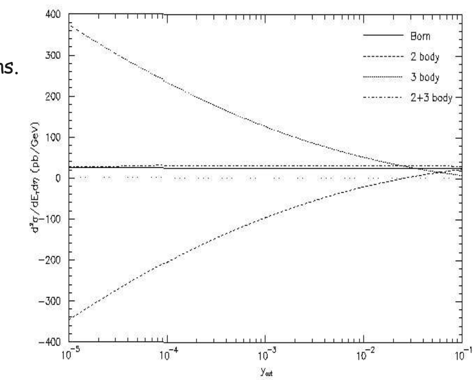
- to obtain:

$$\langle O \rangle_{slice}^{NLO} = BO(0) + a \left[O(0) \left(B \log \delta + V \right) + \int_\delta^1 dx\, O(x) \frac{R(x)}{x} \right] + \mathcal{O}(\delta)$$

Phase Space Slicing

Klasen, Kleinwort, Kramer hep-ph/9712256

- define parameter y_{cut} to separate soft + virtual from finite real emissions.
- each contribution shows sensitivity
- but sum of all contributions is independent of y_{cut}



Subtraction method

- task is to comute

Frixione,Webber
hep-ph/0204244

$$\langle O \rangle = \lim_{\epsilon \to 0} \int_0^1 dx\, x^{-2\epsilon} O(x) \left[\left(\frac{d\sigma}{dx} \right)_b + \left(\frac{d\sigma}{dx} \right)_v + \left(\frac{d\sigma}{dx} \right)_r \right]$$

- we have:

$$\begin{aligned} \langle O \rangle_r &= \int_0^1 dx\, x^{-2\epsilon} O(x) \left(\frac{d\sigma}{dx} \right)_r \\ &= \int_0^1 dx \frac{x^{-2\epsilon}}{x} a \left(O(x) R(x) + BO(0) - BO(0) \right) \\ &= -a \frac{B}{2\epsilon} O(0) + a \int_0^1 \frac{dx}{x} \left(O(x) R(x) - BO(0) \right) \end{aligned}$$

- use also:

$$\left(\frac{d\sigma}{dx} \right)_v = a \left(\frac{B}{2\epsilon} + V \right) \delta(x)$$

- to obtain:

$$\langle O \rangle_{sub}^{NLO} = \int_\delta^1 dx \left[O(x) \frac{aR(x)}{x} + O(0) \left(B + aV - \frac{aB}{x} \right) \right]$$

NLO programs: MCFM

MCFM overview — John Campbell and R.K. Ellis

- Parton level cross-sections predicted to NLO in α_S

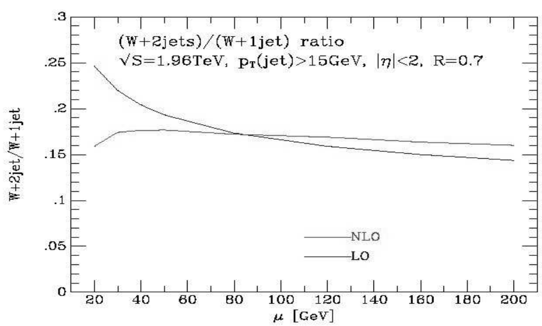
$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm + \gamma$	$p\bar{p} \to W^\pm/Z + H$
$p\bar{p} \to W^\pm + g^\star (\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^\pm/Z + 1$ jet	$p\bar{p} \to W^\pm/Z + 2$ jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H + 1$ jet
$p\bar{p}(VV) \to H + 2$ jets	$pp \to t + X$
$pp \to t + W$	

- ⊕ less sensitivity to μ_R, μ_F, rates are better normalized, fully differential distributions.
- ⊖ low particle multiplicity (no showering), no hadronization, hard to model detector effects

NLO programs: MCFM II

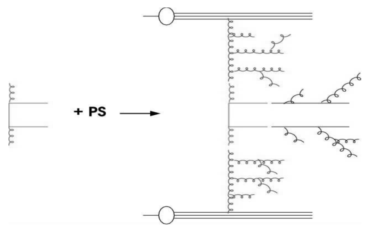
MCFM:examples

- $(W+2\text{ jet})/(W+1\text{ jet})$



All order approaches

All order approach: ME & parton evolution



- use LO matrix elements
  - for light quarks, cutoffs are needed
- apply initial and final state parton showers (**PS**)
  - matching of cutoff in ME with parton showers
- apply hadronisation
- obtain cross sections fully differential in any observable
- **BUT:**
  - only in LO (attempts to include NLO: Collins et al, MC@NLO, etc)

All Orders Resummation

- differential form: $t\frac{\partial}{\partial t}f(x,t) = \int \frac{dz}{z}\frac{\alpha_s}{2\pi}P_+(z)\, f\left(\frac{x}{z},t\right)$
- differential form using f/Δ_s with

$$\Delta_s(t) = \exp\left(-\int_x^{z_{max}} dz \int_{t_0}^{t} \frac{\alpha_s}{2\pi}\frac{dt'}{t'}\tilde{P}_2(z)\right) \quad \text{with} \quad \tilde{P}_2 \sim \frac{1}{1-z}$$

$$t\frac{\partial}{\partial t}\frac{f(x,t)}{\Delta_s(t)} = \int \frac{dz}{z}\frac{\alpha_s}{2\pi}\frac{\tilde{P}(z)}{\Delta_s(t)}\, f\left(\frac{x}{z},t\right)$$

- integral form

$$f(x,t) = f(x,t_0)\Delta_s(t) + \int \frac{dz}{z}\int \frac{dt'}{t'}\cdot\frac{\Delta_s(t)}{\Delta_s(t')}\tilde{P}(z) f\left(\frac{x}{z},t'\right)$$

no – branching probability from t_0 to t

All Order resummed evolution

$$f(x,t) = f(x,t_0)\Delta_s(t) + \int \frac{dz}{z} \int \frac{dt'}{t'} \cdot \frac{\Delta_s(t)}{\Delta_s(t')} \tilde{P}(z) f\left(\frac{x}{z}, t'\right)$$

- solve integral equation via iteration:

from t' to t w/o branching | branching at t' | from t_0 to t' w/o branching

$$f_0(x,t) = f(x,t_0)\Delta(t)$$

$$f_1(x,t) = f(x,t_0)\Delta(t) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \tilde{P}(z) f(x/z, t_0)\Delta(t')$$

$$= f(x,t_0)\Delta(t) + \log\frac{t}{t_0} A \otimes \Delta(t) f(x/z, t_0)$$

$$f_2(x,t) = f(x,t_0)\Delta(t) + \log\frac{t}{t_0} A \otimes \Delta(t) f(x/z, t_0) + \frac{1}{2}\log^2\frac{t}{t_0} A \otimes A \otimes \Delta(t) f(x/z, t_0)$$

$$f(x,t) = \lim_{n\to\infty} f_n(x,t) = \lim_{n\to\infty} \sum_n \frac{1}{n!} \log^n\left(\frac{t}{t_0}\right) A^n \otimes \Delta(t) f(x/z, t_0)$$

DGLAP re-sums $\log t$ **to all orders !!!!!!!!!!!!!!!!**

Parton Showers from evolution eq.

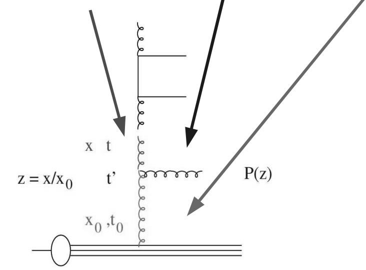
$$f(x,t) = f(x,t_0)\Delta_s(t) + \int \frac{dz}{z} \int \frac{dt'}{t'} \cdot \frac{\Delta_s(t)}{\Delta_s(t')} \tilde{P}(z) f\left(\frac{x}{z}, t'\right)$$

- solve integral equation via explicit iteration:

from t' to t w/o branching | branching at t' | from t_0 to t' w/o branching

$$f_0(x,t) = f(x,t_0)\Delta(t)$$

$$f_1(x,t) = f(x,t_0)\Delta(t) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \tilde{P}(z) f(x/z, t_0)\Delta(t')$$



Recall: W p_t resummation to all orders

- pt spectrum for W/Z production

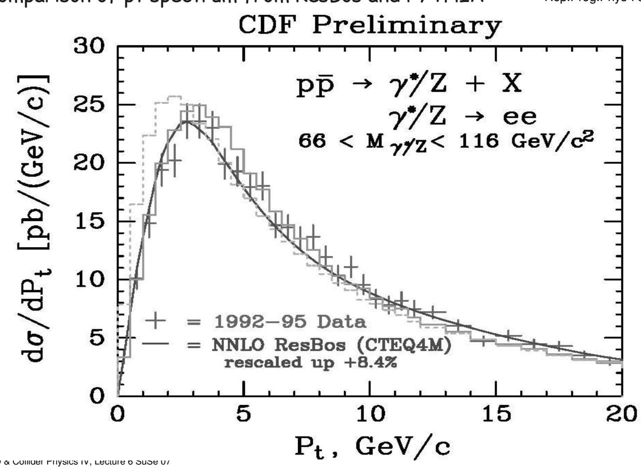
$$\frac{d\sigma}{dM^2 dy dp_t^2} = \left(\frac{d\sigma}{dM^2 dy}\right)_{Born} \left(\frac{1}{p_t^2}\frac{4\alpha_s}{3\pi}\log s/p_t^2\right) \exp\left(-\frac{2\alpha_s}{3\pi}\log^2 s/p_t^2\right)$$

➔ Sudakov form factor appears
➔ expresses resummation of leading double logs
➔ exponential cancels singularity at pt -> 0
➔ **Probability to produce massive lepton pair (or Z_0, W etc) without additional soft gluon radiation is ZERO**

Recall: Monte Carlo vrs ResBos

- Comparison of pt spectrum from ResBos and PYTHIA

Campbell, Huston Stirling
Rep.Prog.Phys 70 (2007) 89

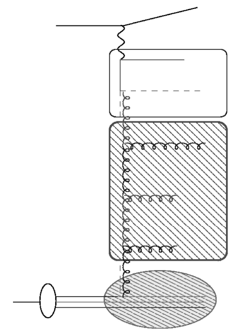


All order MCEGs

- colliner factorisation (DGLAP) based:
  - PYTHIA
    - Q^2 or p_t^2 ordered parton showers
    - Lund string fragmentation
    - ep, pp, γ p processes included
  - HERWIG
    - angular ordered parton showers
    - Cluster fragmentation
    - ep, pp, γ p processes included
- kt-factorisation (CCFM based)
  - CASCADE
    - angular ordered parton showers
    - Lund string fragmentation
    - ep, pp, γ p processes included
  - LDCMC
    - angular ordered parton showers
    - Lund string fragmentation

CASCADE – C$_{\text{atani}}$C$_{\text{iafaloni}}$F$_{\text{iorani}}$M$_{\text{archesini}}$ evolution

CCFM (all loops)
- angular ordering
- non – Sudakov Δ_{ns}

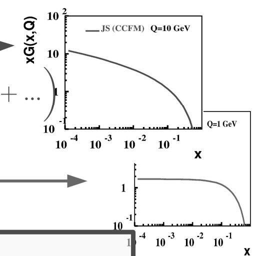


BGF matrix element off shell

evolution of parton cascade:

$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z}\Delta_{ns} + ... \right)$$

initial distribution ~ flat



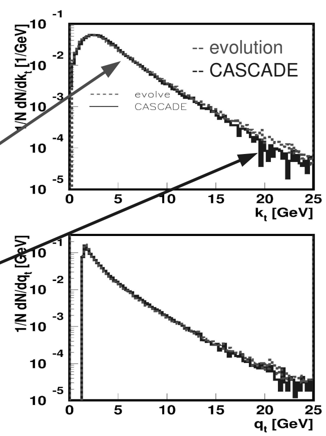
$$\sigma(ep \to e'q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$$

$$\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$$

CASCADE MC generator

- DGLAP or CCFM
- ➔ only inclusive predictions
- ➔ no information on emitted partons
- CCFM treats explicitly
  partons emitted during cascade
  color coherence
  energy momentum conservation

- best to implement in MC generator
- ➔ compare evolution and parton shower
- need unintegrated parton densities



CACADE MC event generator II

- Processes included (gluon induced)

$$\gamma g^* \to q\bar{q},\ \gamma^* g^* \to Q\bar{Q},\ \gamma g^* \to J/\psi g$$

$$g^* g^* \to q\bar{q},\ g^* g^* \to Q\bar{Q},\ g^* g^* \to h$$

- initial state parton shower, backward evolution, according to CCFM
- final state PS
- p-remnant treatment
- Hadronization
- ➔ full PYTHIA final state PS & remnant treatment included
  - ➔ applicable for $t\bar{t}$ -production

using LHA interface to
PYTHIA/HERWIG
for
- final state PS
- p-remnant
- hadronization

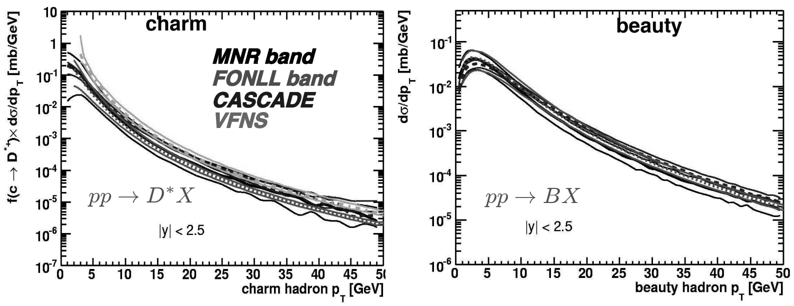
CASCADE* for *ep* and *pp

Heavy Quarks at the LHC

from HERA-LHC workshop proceedings: hep-ph/061012-061013 page 411

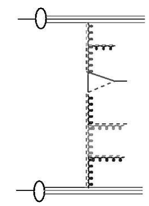
Benchmarks at hadron level in central region

MNR (massive NLO) - FONLL (matched NLL) - **CASCADE (uPDF)** - VFNS



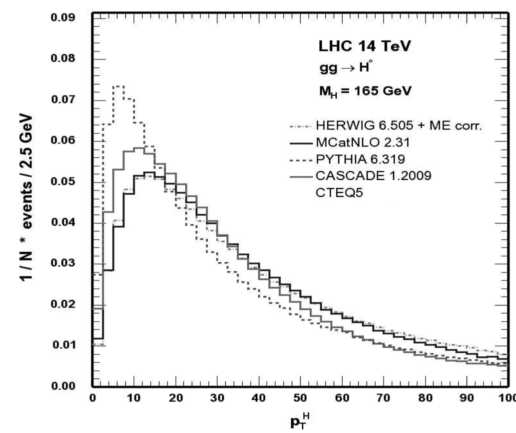
- **CASCADE** agrees well with **MNR** and FONLL for charm and beauty.
  VFNS is larger for charm at small p_t ... !!!
  All agree reasonably well ... success

Higgs production



$gg \to \text{Higgs} \to W^+W^- \to l^+\bar{\nu}l^-\nu$

from G. Davatz, HERA – LHC workshop hep-ph/0601012, hep-ph/0601013



Merging parton showers and fixed order

CataniKraussKuhnWebber approach

Catani,Krauss,Kuhn,Webber
hep-ph/0109231

- Sudakov form factors

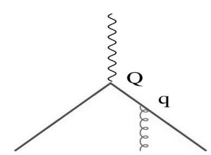
$$\Delta(Q_1, Q) = \exp\left(-\int_{Q_1}^{Q} dq \Gamma(q, Q)\right)$$

- integrated branching probabilities

$$\Gamma_q(q, Q) = \frac{2C_F}{\pi}\frac{\alpha_s(q)}{q}\left(\ln\frac{Q}{q} - \frac{3}{4}\right)$$

$$\Gamma_g(q, Q) = \frac{2C_A}{\pi}\frac{\alpha_s(q)}{q}\left(\ln\frac{Q}{q} - \frac{11}{12}\right)$$

- calculate multijet rate with Sudakov form factors (no-branching probs)



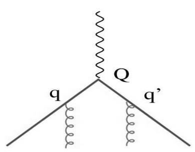
$$\Delta_q(Q_1, Q)\frac{\Delta_q(Q_1, Q)}{\Delta_q(Q_1, \tilde{q})}\Gamma_q(q, Q)\Delta_q(Q_1, \tilde{q})\Delta_g(Q_1, q) = \Gamma_q(q, Q)F_{q\bar{q}g}(Q_1, Q; q)$$

$$F_{q\bar{q}g}(Q_1, Q; q) = \left[\Delta_q(Q_1, Q)\right]^2 \Delta_g(Q_1, q)$$

$C_{atani}K_{rauss}K_{uhn}W_{ebber}$ approach

Catani,Krauss,Kuhn,Webber
hep-ph/0109231

- calculate multijet rate with Sudakov form factors (no-branching probs)



$$\frac{\Delta_q(Q_1,Q)}{\Delta_q(Q_1,\tilde{q})}\Gamma_q(q,Q)\Delta_q(Q_1,\tilde{q})\Delta_g(Q_1,q)$$
$$\cdot\frac{\Delta_q(Q_1,Q)}{\Delta_q(Q_1,\tilde{q'})}\Gamma_q(q',Q)\Delta_q(Q_1,\tilde{q'})\Delta_g(Q_1,q') =$$
$$\Gamma_q(q,Q)\Gamma_q(q',Q)F_{q\bar{q}gg}(Q_1,Q;q,q')$$

$$F_{q\bar{q}g}(Q_1,Q;q,q') = \left[\Delta_q(Q_1,Q)\right]^2\Delta_g(Q_1,q)\Delta_g(Q_1,q')$$

$C_{atani}K_{rauss}K_{uhn}W_{ebber}$ approach

- Comparison of fixed order calculation with CKKW

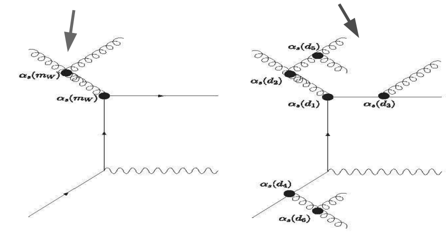


Figure 26. In the NLO formalism, the same scale, proportional to the hardness of the process, is used for each QCD vertex. For the case of the $W+$ 2 jet diagram shown above to the left, a scale related to the mass of the W boson, or to the average transverse momentum of the produced jets, is typically used. The figure to the right shows the results of a simulation using the CKKW formalism. Branchings occur at the vertices with resolution parameters d_i, where $d_1 > d_2 \gg d_{ini} > d_3 > d_4 > d_5 > d_6$. Branchings at the vertices 1–2 are produced with matrix element information while the branchings at vertices 3–6 are produced by the parton shower.

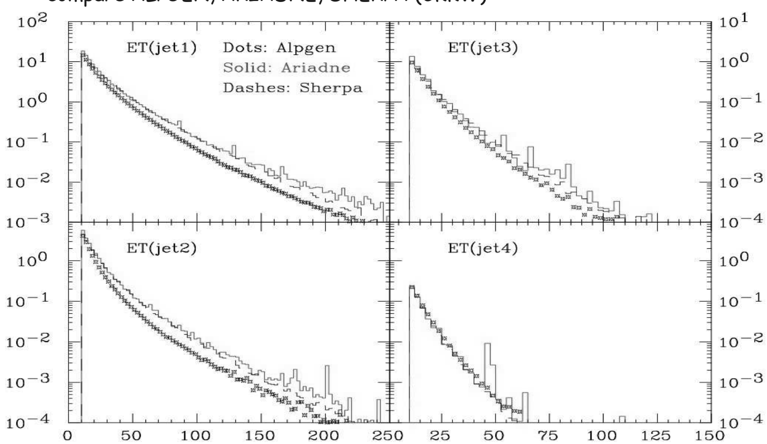
- separation of PS (< k_{t0}) and ME(>k_{t0}) region by k_t measure:

$$k_\perp^{(ij)2} = 2\min\left(p_t^{(i)},p_t^{(j)}\right)^2\left[\cosh\left(\eta^{(i)}-\eta^{(j)}\right)-\cos\left(\phi^{(i)}-\phi^{(j)}\right)\right]$$

- reweight Matrix elements with Sudakov form factors and alphas:
  - ➔ to take into account terms that would appear in a shower evolution ..

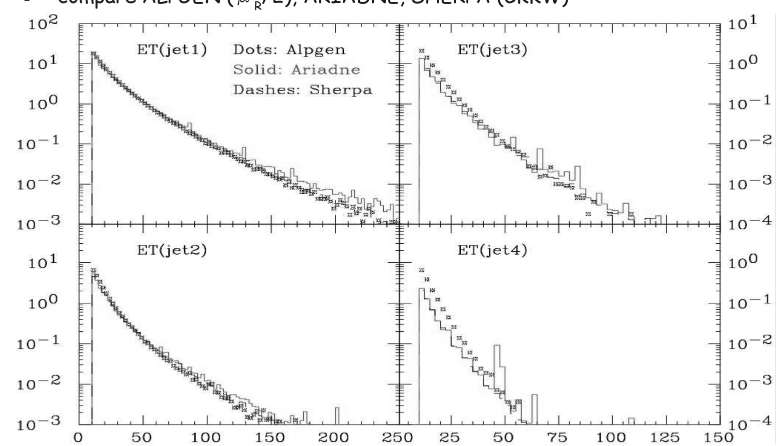
Comparison of approaches

- compare ALPGEN, ARIADNE, SHERPA (CKKW)



Comparison of approaches

- compare ALPGEN ($\mu_R/2$), ARIADNE, SHERPA (CKKW)

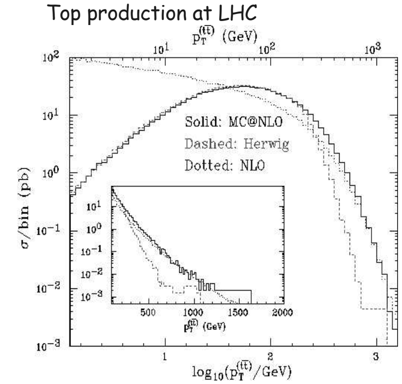


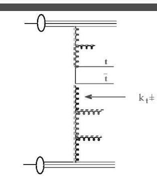
Merging NLO calculations with parton showers

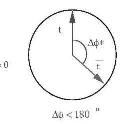
Parton Showers versus fixed NLO

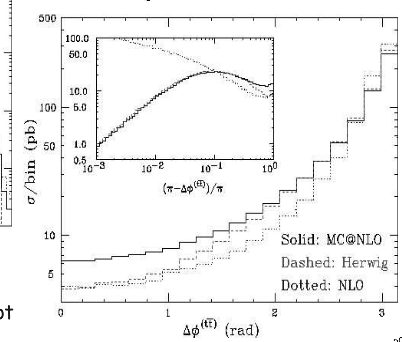
- MC@NLO Frixione, Nason, Webber hep-ph/0305252

  Top production at LHC



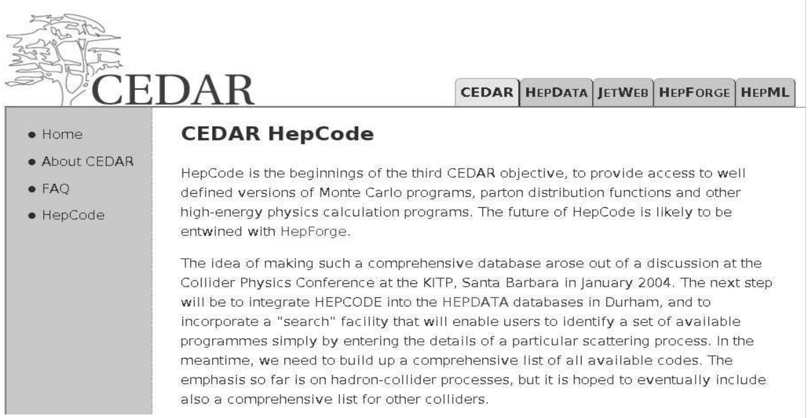






- ✔ advantage of PS at small pt and phi
- ✔ advantage of fixed order at large pt

Available programs - HEPCODE



HEPCODE database (http://www.cedar.ac.uk/hepcode/)

The end

- NLO calculations best for x-section in certain kinematic regions
- LO tree level calcs supplemented with parton showers are necessary for multi-jet or multi-parton final states

- There is nothing like "Simply the best ... "

QCD

is still a very interesting field..... and many new things are still to be discovered ....