The Monte Carlo Event Generator

AcerMC version 3.2 - Status report

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http://cern.ch/Borut.Kersevan/AcerMC.Welcome.html

- **New processess:** Current status

- **AcerMC goes (part) NLO :** t-channel single top production, associated $Z^0\,b$ production and tWb production, done with Ian Hinchliffe

Main Goal: Provide implementations of select physics processes for ATLAS/LHC environment.

Design Requirements:

- Compact (*all-in-one*) tool with reasonable user interface
- Extensibility ⇒ **modular design**
- Exact **LO** matrix elements ⇒ **MADGRAPH/HELAS**
- Full phase space coverage
- High generation efficiency ⇒ **native phase space algorithm**
- Use of standard libraries ⇒ **CERNLIB,LHAPDF**.
- Interface to ↗ **PYTHIA 6.3** / ↘ **HERWIG 6.5** for ISR/FSR/hadronisation
- Use **current versions** of **PYTHIA** and **HERWIG**
- **Event record** dump/read ⇒ **LesHouches format**

Currently implemented processes:

Process	Description
1	$gg \to t\bar{t}b\bar{b}$
2	$q\bar{q} \to t\bar{t}b\bar{b}$
3	$q\bar{q} \to W(\to f\bar{f})b\bar{b}$
4	$q\bar{q} \to W(\to f\bar{f})t\bar{t}$
5	$gg \to Z/\gamma^*(\to f\bar{f})b\bar{b}$
6	$q\bar{q} \to Z/\gamma^*(\to f\bar{f})b\bar{b}$
7	$gg \to Z/\gamma^*(\to f\bar{f}, \nu\nu)t\bar{t}$
8	$q\bar{q} \to Z/\gamma^*(\to f\bar{f}, \nu\nu)t\bar{t}$
9	$gg \to (Z/W/\gamma^* \to)t\bar{t}b\bar{b}$
10	$q\bar{q} \to (Z/W/\gamma^* \to)t\bar{t}b\bar{b}$
11	$gg \to (t\bar{t} \to)f\bar{f}bf\bar{f}b$
12	$q\bar{q} \to (t\bar{t} \to)f\bar{f}bf\bar{f}b$
13	$gg \to (WWb\bar{b} \to)f\bar{f}f\bar{f}b\bar{b}$
14	$q\bar{q} \to (WWb\bar{b} \to)f\bar{f}bf\bar{f}b\bar{b}$
15	$gg \to t\bar{t}t\bar{t}$
16	$q\bar{q} \to t\bar{t}t\bar{t}$
17	$qb \oplus qg \to qt \oplus b \to qbf\bar{f} \oplus b$ (100+101)
18	$bb \oplus bg \to Z^0 \oplus b \to f\bar{f} \oplus b$ (96+97)
19	$qq \to tb \to bf\bar{f}b$
20	$gb \oplus gg \to (WWb \oplus \bar{b} \to)f\bar{f}f\bar{f}b \oplus \bar{b}$ (13+105)
21	$gb \to tW \to bf\bar{f}f\bar{f}$
22	$qq \to Z^{0\prime} \to t\bar{t} \to b\bar{b}f\bar{f}f\bar{f}$

'Control' processes:

Process	Description
91	$q\bar{q} \to Z/\gamma^* \to f\bar{f}$
92	$gg \to t\bar{t}$
93	$q\bar{q} \to t\bar{t}$
94	$q\bar{q} \to W \to f\bar{f}$
95	$gg \to (t\bar{t} \to)WbW\bar{b}$
96	$bb \to Z^0 \to f\bar{f}$
97	$bg \to Z^0b \to f\bar{f}b$
98	$qb \to qt$
99	$gg \to qtb$
100	$qb \to qt \to qbf\bar{f}$
101	$gg \to qtb \to qbf\bar{f}b$
102	$qb \to qt \to qbW$
103	$qb \oplus qg \to qt \oplus b$ (98+99)
104	$gb \to tW \to tf\bar{f}$
105	$gb \to tW \to bf\bar{f}f\bar{f}$ (equal to 21)
106	$gg \to (tWb \to)tf\bar{f}b$
107	$gg \to (tWb \to)f\bar{f}f\bar{f}b \oplus b$

- The new single top processes
- The $(A + B)$ denote PS+ME matched processes.

Details on the AcerMC 3.x Monte-Carlo generator

- A Monte-Carlo generator of background processes for searches at **ATLAS/LHC**.
- Matrix elements coded by **MADGRAPH/HELAS**
- Phase space sampling done by native **AcerMC** routines:

  ⊕ Each channel topology constructed from the t-type and s-type modules and sampling functions described in this talk. The event topologies derived from modified **MADGRAPH/HELAS** code.

- As it turns out a lot of it has already been done in the '60 (!) by K. Kajantie and E. Byckling.

  ➔E. Byckling and K. Kajantie, Nucl. Phys. **B9** (1969) 568.

  ⊕ **multi-channel approach**

  ➔J.Hilgart, R. Kleiss, F. Le Dibider, Comp. Phys. Comm. **75** (1993) 191.

  ➔F. A. Berends, C. G. Papadopoulos and R. Pittau, hep-ph/0011031.

  ⊕ additional **ac-VEGAS** smoothing

- `ac−VEGAS` Cell splitting in view of maximal weight reduction based on function:

$$< F >_{\mathrm{cell}} = \left(\Delta_{\mathrm{cell}} \cdot \mathrm{wt}^{\mathrm{max}}_{\mathrm{cell}}\right) \cdot \left\{1 - \frac{<\mathrm{wt}_{\mathrm{cell}}>}{\mathrm{wt}^{\mathrm{max}}_{\mathrm{cell}}}\right\}$$

- `ac−VEGAS` logic in this respect analogous to FOAM:

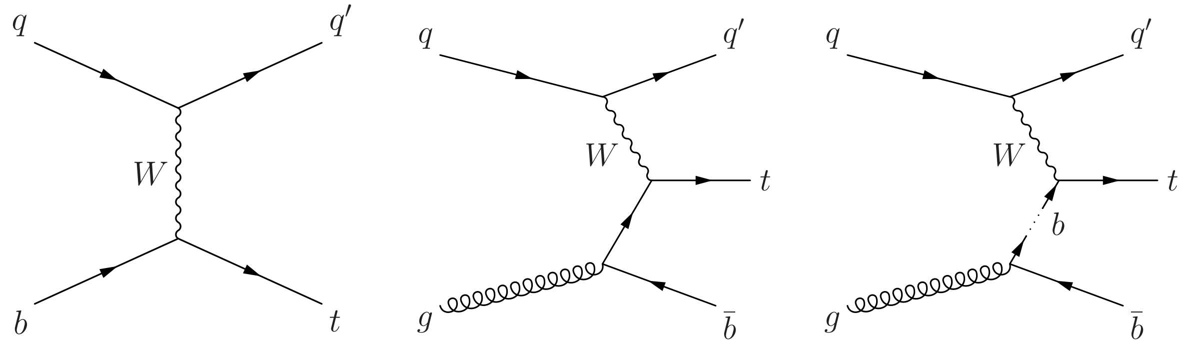
  ➔S. Jadach, Comput. Phys. Commun. **130** (2000) 244.

Factorisation theorem: The factorisation theorem in hadron-hadron (proton-proton) collisions is usually formulated within the following expression:

$$|\mathcal{M}_{AB\to X}|^2 = \sum_{a,b} f_{a/A} \otimes H_{ab\to X} \otimes f_{b/B} = \sum_{a,b} \int \frac{d\xi_a}{\xi_a} \int \frac{d\xi_b}{\xi_b} f_{a/A}(\xi_a, \mu_F)\, f_{b/B}(\xi_b, \mu_F)\, H_{ab\to X}(\xi_a, \xi_b, \mu_F \ldots),$$

where $H_{ab\to X}$ is the the hard ('short time') part of the squared amplitude and the soft contributions are absorbed into the parton distribution functions $\mathrm{f}_{\mathrm{i/I}}(\xi_{\mathrm{i}}, \mu_{\mathrm{F}})$ with μ_{F} being the (factorization) scale at which the two parts were separated.

The 'double counting' problem



- There is of course some ambiguity in the choice of the 'hard' matrix element: At which order in α_s should it be?
- There is in principle some phase space overlap of the two approaches, which results in double-counting.
- The problem becomes obvious when using full NLO calculations. . .

In order to solve this one has to go back to basics. . .

The solution to the double counting problem is simple in principle...

- What is often forgotten is that the hard amplitude squared $H_{ab\to X}$ (or hence derived 'hard' cross-section $\sigma^{\rm hard}_{ab\to X}(\hat{s},\mu_F)$) are not just the direct results of perturbative calculations (using e.g. Feynman diagrams), one still has to isolate and remove the soft contributions!
- In case of ISR the 'soft' contributions are the collinear/mass singularities.
- The rest of the singular behaviour (UV and IR) is removed by the renormalisation procedures.

- In practice one thus has to take the collinear limit of a certain process/event using suitable kinematic transforms and construct the appropriate subtraction term corresponding to the equivalent ISR event.
- Hard to do in practice!
- In our method we use the approach developed by Collins *et. al.* in a series of papers.
- The approach has been shown to reproduce the $\overline{MS}$ Compton part of the NLO Drell-Yan.

Another issue are the particle/parton masses:

- Another problem is the treatment of masses in the factorisation theorem:
  - The partons are generally treated as massless.
  - This becomes a problem in case of gluon splitting to heavy partons like b or c quarks.
  - The partons in the final state need to have masses to accurately describe the observable jet kinematics.
  - If the incoming partons are massless the matrix element is not strictly conforming to the Standard model and/or gauge invariance.
- Back to basics again...to see that the factorisation theorem is actually derived using the light-cone coordinates $p^{\mu} = (p^{+}, \vec{p}^{T}, p^{-})$ where $\mathrm{p}^{\pm} = \frac{1}{\sqrt{2}}(\mathrm{p}^{0} \pm \mathrm{p}^{3})$, which can incorporate particle massess.
- A series of ACOT papers (M. A. G. Aivazis, J. C. Collins, F. I. Olness and W. K. Tung) solved this issue for DIS, we adapted it to the proton-proton collisions.

The final result is thus a prescription for the combination of ISR and pQCD calculations in case of massive colliding partons. For experimental needs this has been incorporated into a full Monte-Carlo generation procedure.

AcerMC goes (part) NLO:

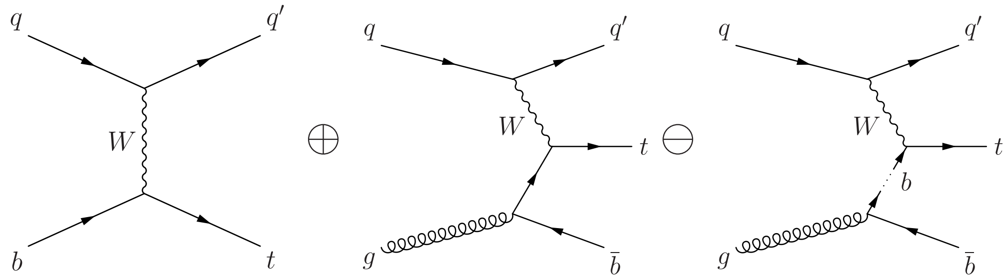
- AcerMC now incorporates **ISR and ME matching** for $g \to b\bar{b}$ splitting, using the (modified) procedure developed by Collins *et. al.* (several papers).
- the procedure has been shown to **reproduce the 'collinear' part of the NLO results** in $\overline{\text{MS}}$ calculations for Drell-Yan production in the massless limit.
- A paper on the implemented procedure is submitted to JHEP (hep-ph/0603068).

Implementation:

- The ISR 'showering' involving $g \to b\bar{b}$ has been implemented inside AcerMC.
- This algorithm is used to evolve a process from $bX \to Y$ to $gX \to Y \oplus b$.
- This process is combined with the corresponding 'NLO' process $gX \to Y + b$ and the double counting terms are calculated and removed = subtracted.
- As the result a fraction of events has negative (=-1) weights!
- This procedure has been implemented for the:
  - t-channel single top production.
  - Associated $Z^0 b$ production.
  - $b\bar{b}WW$ production which involves the ('evolved') tWb single top production.

t-channel single top production:

- The t-channel process is the combined production of the $qb \to qt$ and $qg \to qtb$ W-exchange processes.
- One needs to remove the double counting between the ISR $g \to b\bar{b}$ splitting and the next-order α_S process $qg \to qtb$.
- In fact the t-channel single top production involves the full matrix element including top decays.
- The procedure similar to what is done in MC@NLO but we use different prescription (Collins *et. al.* and massive b-quarks.



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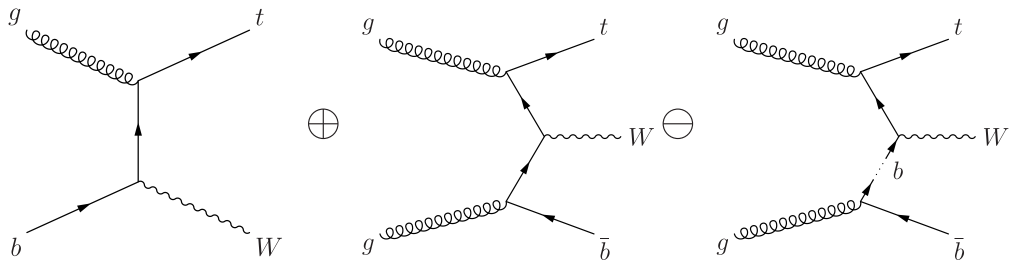
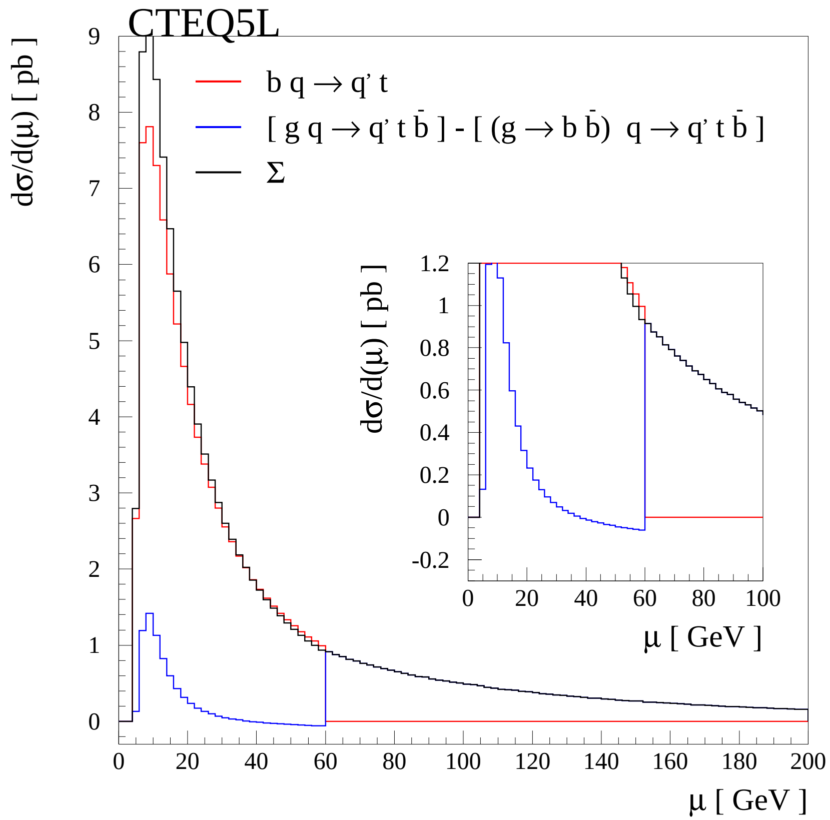
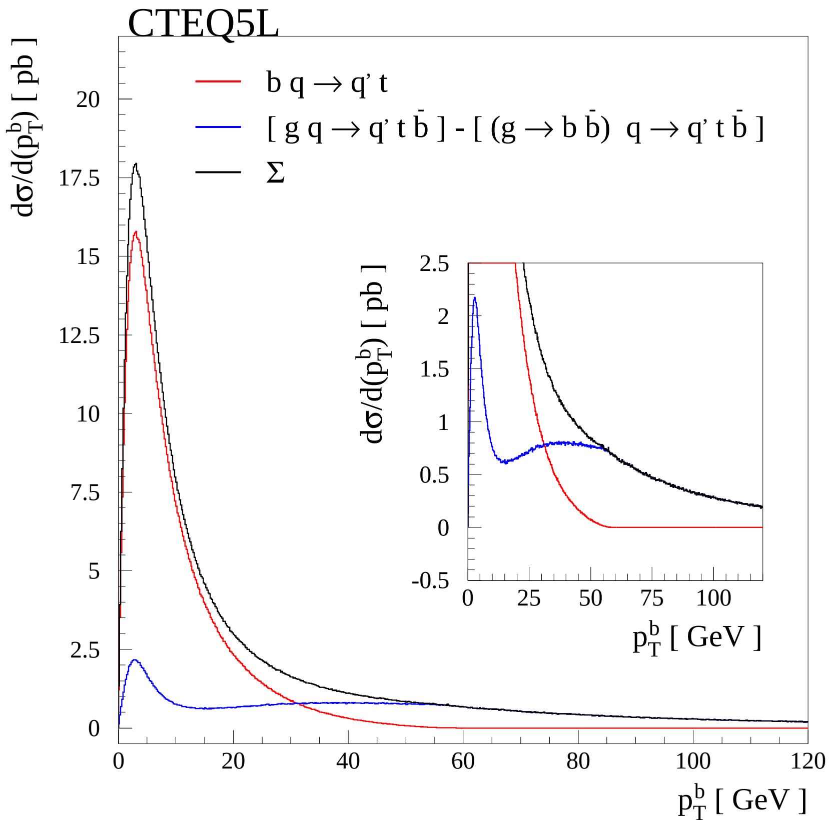
tW-channel single top production: Similar case, it double counts the tWb diagrams.



Kinematic distributions for t-channel single top :

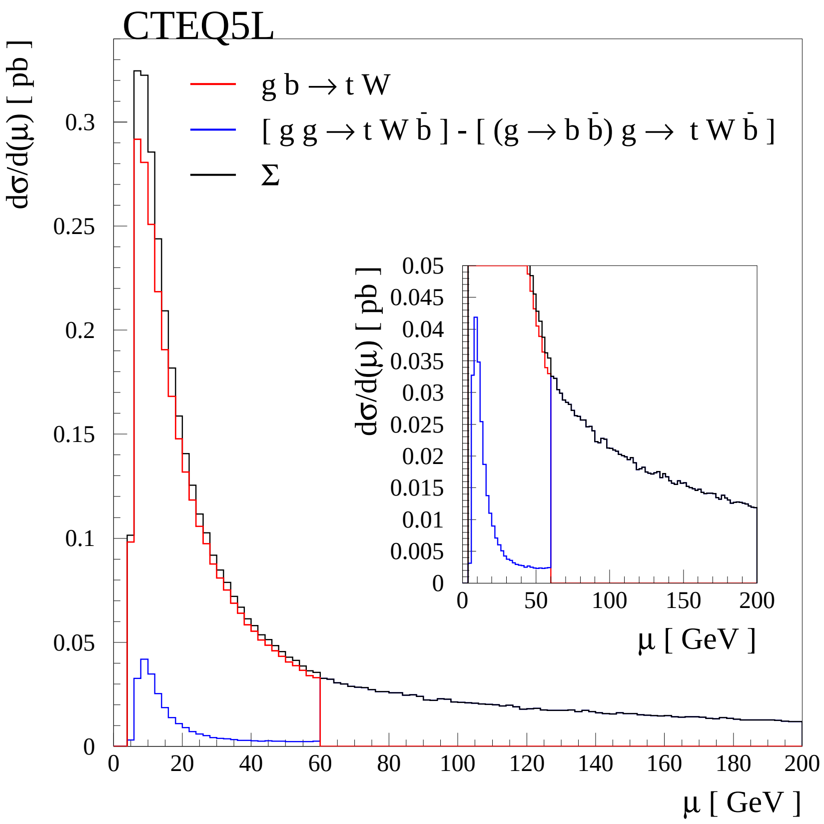
- Note that a smooth continuation in the b-quark virtuality is achieved.
- The p_T distribution a result of non-trivial contributions - matching on p_T alone (often used in approximations) seems not to be the right way to do it.

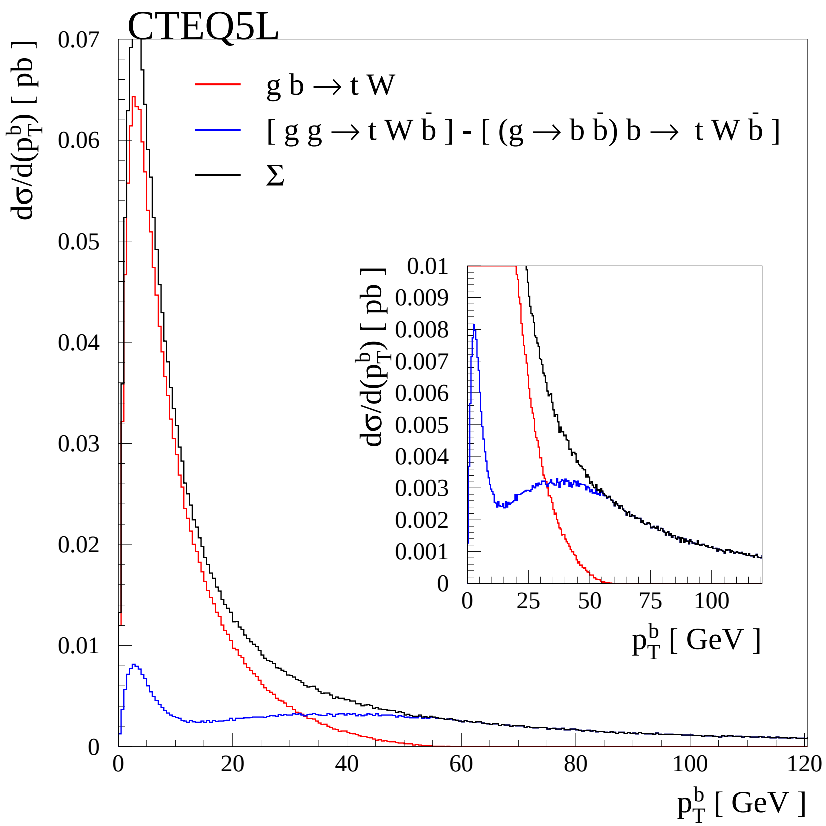




Kinematic distributions for tW-channel single top:

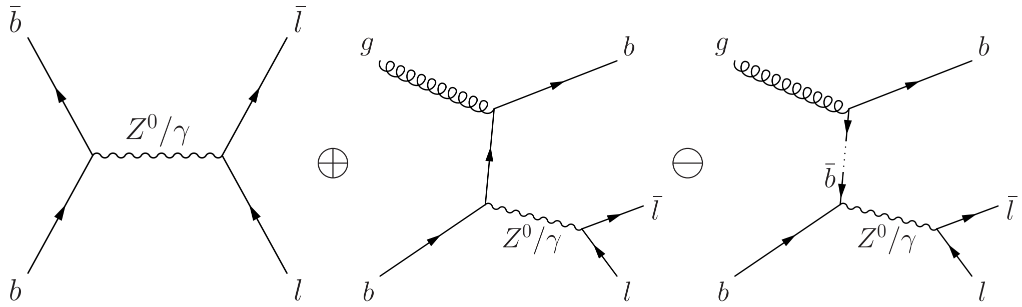
- Note that a smooth continuation in the b-quark virtuality is again achieved.
- The p_T distribution again a result of non-trivial contributions.
- The plots serve as a cross-check; in AcerMC process 20 the procedure is applied to the $WWb\bar{b}$ $(2 \to 6)$ process 13 which includes the tWb intermediate states among its 31 diagrams.





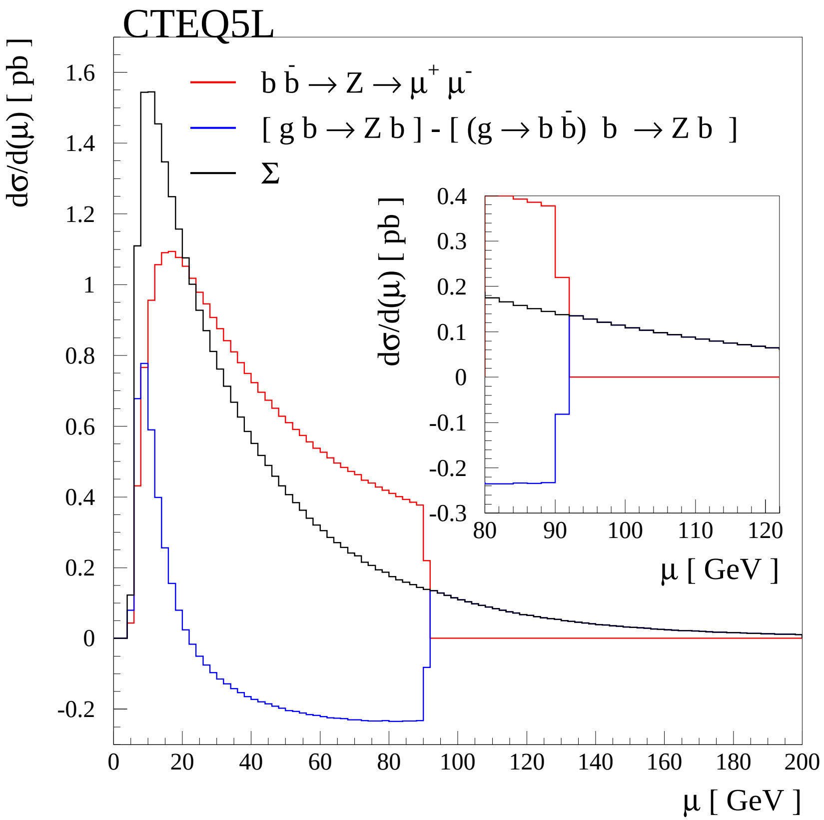
Associated $Z^0\,b$ production:

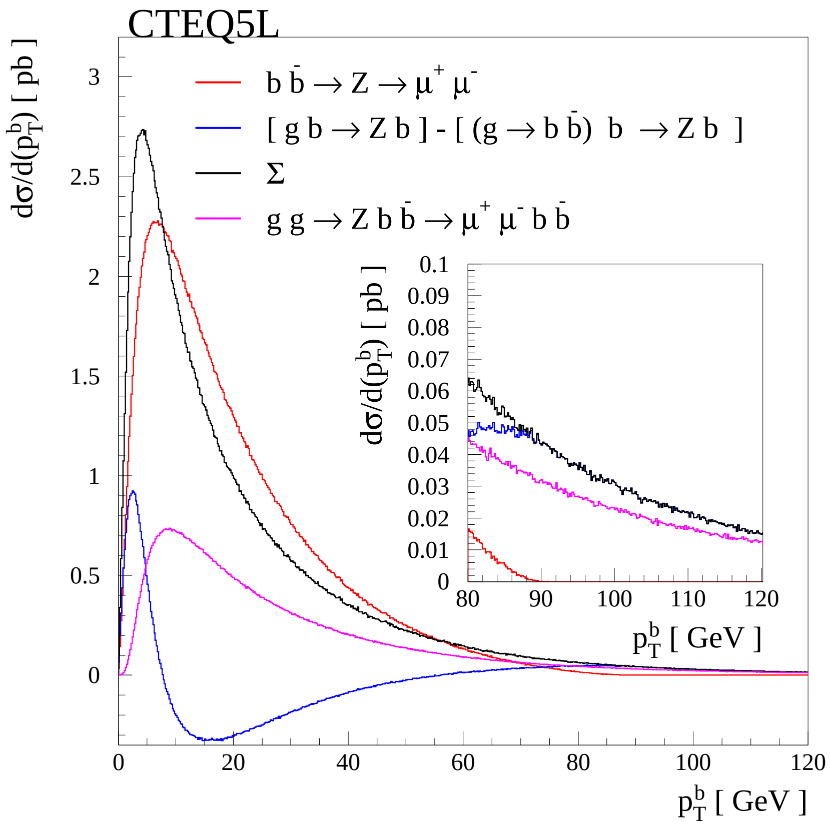
- The associated $Z^0\,b$ production is a combination of the processes $b\bar{b} \to Z$ and $gb \to Zb$.
- Again, double counting due to ISR has to be removed.
- In this case both incoming b-quarks are subject to ISR. The one with the highest induced virtuality is subtracted.



Kinematic distributions for Associated $Z^0\,b$ production:

- Note that a smooth continuation in the b-quark virtuality is again achieved.
- The p_T distribution again a result of non-trivial contributions.





Conclusions:

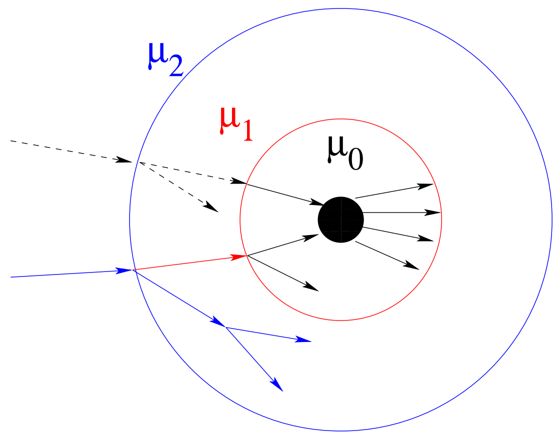
- The described procedure has been shown to work...
- For details please consult hep-ph/0603068.
- In case one wants to check this in practice: The complete **AcerMC** manual available from:

  `http://cern.ch/Borut.Kersevan/AcerMC.Welcome.html`

- **AcerMC** code is available from the same URL.

BACKUP

Unresolving the partons: DGLAP evolution:



- By virtue of the DGLAP evolution equations one can 'unresolve' the incoming partons by decreasing the 'resolution' scale μ_F:

$$\frac{d}{d\ln\mu_F^2} f_{i/I}(z,\mu_F) = \frac{\alpha_s(\mu_F)}{2\pi} \sum_j \int_z^1 \frac{d\xi}{\xi} P_{j\to i}(\frac{z}{\xi}, \alpha_s(\mu_F))\, f_{j/I}(\xi,\mu_F).$$

- In order to obtain the probability for sequential branchings the Sudakov exponent is derived from the DGLAP evolution equations:

$$S_a = \exp\left\{ -\int_{\mu^2}^{\mu_0^2} \frac{d\mu'^2}{\mu'^2} \frac{\alpha_s(\mu'^2)}{2\pi} \times \sum_c \int_{\xi_c}^1 \frac{dz}{z} P_{a\to c}(z) \frac{f_{a/I}(\frac{\xi_c}{z},\mu'^2)}{f_{c/I}(\xi_c,\mu'^2)} \right\}.$$

How does Sudakov showering work in practice?

- The Sudakov exponent gives the branching probabilities for sequential evolution of the incoming partons.
- At each step the evolving parton is pushed off-shell $m^2 = -\mu^2 = \hat{t}$.
- The new 'incoming parton' is assumed to be on-shell again, carrying the new momentum fraction of the parent hadron and the spectator is added.
- There is some freedom of choosing the quantities that are preserved in this kinematic transform:
  - One can preserve the invariant mass $\hat{s}$ of the subsytem or its rapidity y etc...
- The branching stops when a lower limit is reached - usually some kinematic limit and/or limit of the perturbative method.
- Effects like e.g. colour coherence have to be imposed 'by hand', e.g. by requiring additional ordering in the branchings.
- The result of this procedure is commonly known as the initial state radiation (ISR).

There are very advanced tools on the market that implement this, most notably **PYTHIA 6.3** or **HERWIG 6.5** . In principle these methods should come close to the NLL precision...

Short derivation of the subtraction terms:

The appropriate subtraction terms can actually be derived from the factorisation theorem itself by using DGLAP at the parton level and doing power counting of α_s:

- The pQCD squared amplitude $|\mathcal{M}_{\mathrm{ab}\to\mathrm{X}}|^2$ involving initial state partons a, b is subject to the same factorization theorem:

$$|\mathcal{M}_{ab\to X}|^2 = \sum_{c,d} f_{c/a} \otimes H_{cd\to X} \otimes f_{d/b},$$

- At zero-th order in α_s:

$$f^{(0)}_{i/j}(\xi) = \delta^i_j \delta(\xi - 1)$$

- and hence:

$$|\mathcal{M}^{(0)}_{ab\to X}|^2 = H^{(0)}_{ab\to X}.$$

Subsequently, at first order in α_s:

$$f_{i/j}(\xi) = f^{(0)}_{i/j}(\xi) + f^{(1)}_{i/j}(\xi) = f^{(0)}_{i/j}(\xi) + \frac{\alpha_s(\mu_F)}{2\pi} P^{(0)}_{j\to i}(\xi) \ln\left(\frac{\mu_F^2}{m^2}\right),$$

- and thus at this order:

$$|\mathcal{M}^{(1)}_{ab\to X}|^2 = H^{(1)}_{ab\to X} + \sum_c f^{(1)}_{c/a} \otimes H^{(0)}_{cb\to X} + \sum_d H^{(0)}_{ad\to X} \otimes f^{(1)}_{d/b},$$

- The last equation can thus be inverted to give:

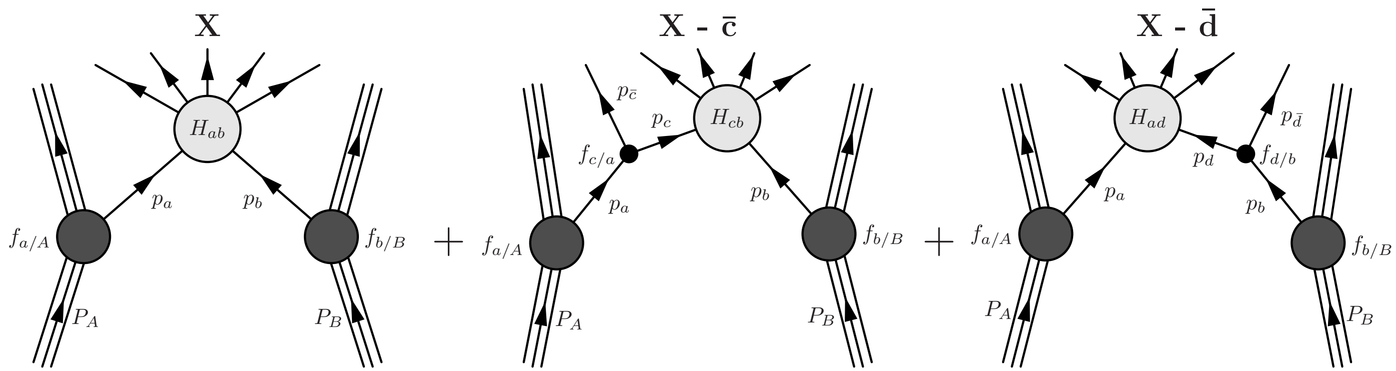
$$H^{(1)}_{ab\to X} = |\mathcal{M}^{(1)}_{ab\to X}|^2 - \sum_c f^{(1)}_{c/a} \otimes |\mathcal{M}^{(0)}_{cb\to X}|^2 - \sum_d |\mathcal{M}^{(0)}_{ad\to X}|^2 \otimes f^{(1)}_{d/b}$$

- Putting it back into the factorisation theorem expression:

$$|\mathcal{M}_{AB\to X}|^2 = |\mathcal{M}^{(0)}_{AB\to X}|^2 + |\mathcal{M}^{(1)}_{AB\to X}|^2 - |\mathcal{M}_{AB\to X}|^2_{\mathrm{s}},$$

- with the subtraction terms given by:

$$|\mathcal{M}_{AB\to X}|^2_{\mathrm{s}} = \sum_{a,b} f_{a/A} \otimes \sum_c f^{(1)}_{c/a} \otimes H^{(0)}_{cb\to X} \otimes f_{b/B} + \sum_{a,b} f_{a/A} \otimes \sum_d H^{(0)}_{ad\to X} \otimes f^{(1)}_{d/b} \otimes f_{b/B}.$$



The kinematic transforms are however far from simple...