Towards new MC(QCD+EW) for W/Z production at LHC

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CAMTOPH-Krakow project

- People involved:

  K. Golec-Biernat*, A. van Hameren, S. Jadach*, M. Jeżabek, G. Nanava, W. Płaczek*, E. Richter-Wąs, M. Skrzypek*, P. Sawicki, P. Stephens, Z. Wąs*

- Papers* on QCD MC evolution and new parton shower MCs: hep-ph/0312355, NP Proc. 135:138(04), hep-ph/0504205, hep-ph/0509178, hep-ph/0504263, hep-ph/0603031, NP Proc. 157:241(06), more in preparation.

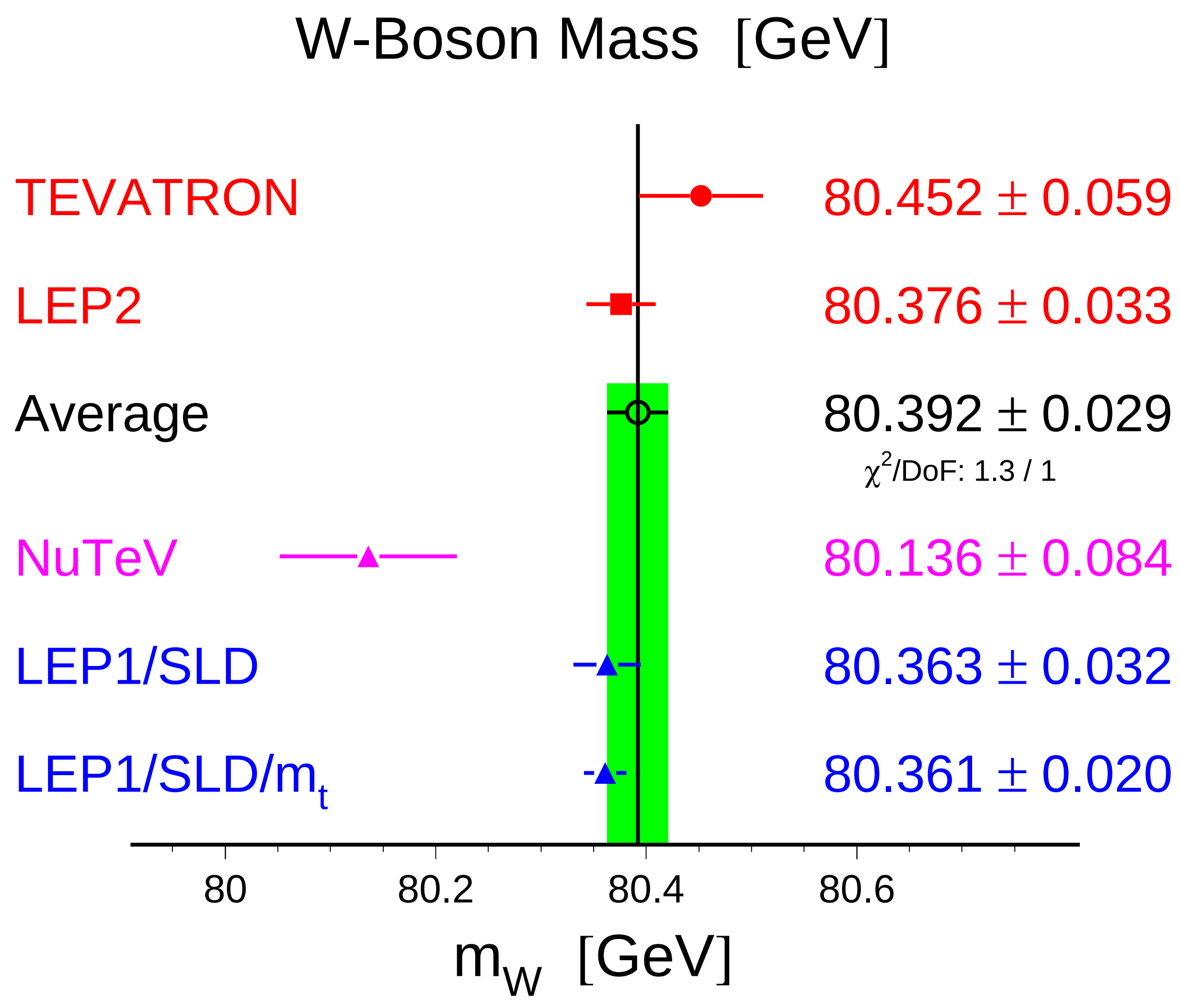
- EW corrections to be taken from SANC group (Dubna)

- Other LHC related MC projects at IFJ-PAN: TAUOLA, PHOTOS, WINHAC.

Motivation

- Experiments at Large Hadron Collider will offer good quality very high statistics data (millions of events) on the production of the W and Z bosons.
- It will be highly nontrivial task to exploit these data fully in order to measure very precisely mass of W, anomalous couplings, parton luminosities, find signals of the presence of new physics at multi-TeV scales.
- For this purpose one needs a new class of the Monte Carlo tools which incorporate high quality, beyond-the-leading-order QCD, QED and Electroweak calculations, which do not exists yet.
- I shall describe new method of MC modeling of QCD evolution and parton shower Monte Carlo, which will hopefully lead us to a new brave world of the combined QCD$\otimes$EW Monte Carlo calculations for LHC.

W mass measurement, direct and indirect, summer 2006



Expectations for EW observables at LHC

NOW $\longrightarrow$ LHC:

δM_W:	33MeV $\longrightarrow$ 15MeV $\longrightarrow$ 5MeV ?!	$(d\sigma/dM_T^l)$
$\Delta\kappa_\gamma, \Delta\lambda_\gamma$:	$1 \cdot 10^{-2} \longrightarrow 3 \cdot 10^{-3}$	$(pp \to VV)$
$\delta \sin^2_{\text{eff}}$:	$17 \cdot 10^{-5} \longrightarrow 15 \cdot 10^{-5}$	$(pp \to Z)$
δM_t:	5GeV $\longrightarrow$ 1GeV	$(ljjb)$

- M_W increasingly important player in the SM precision tests
- Anomalous vector boson couplings constrained factor 10 better
- EW mixing angle measured as precisely as in LEP (??!!)
- Parton luminosities to be measured with 1% precision

Desired specs of TOOLS for EW observables at LHC

Observable∈process	EW	QED	QCD	MC type
$M_W \in$ W,Z	Impr. Born	$\mathcal{O}(\alpha)_{\rm exp}$ FSR!	pdf(x,pT), NLO?	events!
Anom. coupl.∈ VV	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha)$	NLO! NNLO?	events!
$\sin^2\theta_{EW} \in$ Z	$\mathcal{O}(\alpha, \alpha^2_{Sud.})$	$\mathcal{O}(\alpha)_{\rm exp}$ FSR!	NLO	events!
Parton $\mathcal{L} \in$ W,Z	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha)_{\rm exp}$ FSR?	NLO! NNLO?	events?

! $\equiv$ mandatory,

? $\equiv$ to be checked...

Minimum requirement: QCD NLO and Electrowek $\mathcal{O}(\alpha)_{\rm exp}$

None of the existing TOOLS fulfill the above specifications

Where are we? Where do we go?

- Complete MC tools for EW+QCD precision ($\sim 1\%$) predictions for LHC still not available. Partial solutions close to specs.
- Progress in recent years for “semi-inclusive” QCD observables, NLLO PDFs, NLLO distributions, matching NLO with parton shower, etc.
- More effort needed to implement QCD+QED predictions in form of the high quality exclusive MC tools (MC events), creating system of “numerical benchmarks”, better evaluation/estimation of theoretical errors, etc.

We focus on the QCD initial state radiation (ISR) for the purpose of W/Z production at LHC, believing that:

Combining resummed (exponentiated) calculations with fixed order (NLO/NNLO) is the most effective method of improving precision of perturbative QCD predictions.

Contrary to MC@NLO we start by trying to improve parton shower MC formulation, before adding NLO corrections.

Single hadron QCD Evolution in Cracow using MC, 2005/06

- Towards high quality MC for QCD ISR (+EW) in the W/Z production at LHC. DIS in the scope.
- Main emphasis on **CMC**= **C**onstrained **M**onte **C**arlo
- **MMC**s = **M**arkovian**M**onte **C**arlos developed for testing MMCs.
- MMC programs implement presently:
  - DGLAP LL/NLL (xchecked with QCDnum16 and APCHEB to within 0.2%),
  - CCFM-like $\alpha_S(q(1-z))$, $\epsilon_{IR} = q_0/q$, with Q-G transitions.
  - CCFM all-loop, $\alpha_S(k^T)$, $k^T > \lambda$, with Q-G transitions.
- **CMC**s feature presently:
  - DGLAP LL (xchecked with MMC and QCDnum16), Q-G transitions.
  - CCFM-like $\alpha_S(q(1-z))$, $\epsilon_{IR} = q_0/q$, Q-G trans., tested with MMC
  - CCFM all-loop, $\alpha_S(k^T)$, $k^T > \lambda$, agrees with MMC, without Q-G transitions yet (coming soon).

QCD ISR: Double evolution in rapidity – June 06

Emitted particle 4-moms in lightcone $\pm$ variables and rapidities:

$$k_i = (k_i^+, k_i^-, \vec{k}_{Ti}), \quad \vec{k}_{Ti}^2 = k_i^+ k_i^-, \quad e^{2\eta_i} = \xi_i = \frac{k_i^-}{k_i^+} = \frac{\vec{k}_{Ti}^2}{s k_i^{+2}}$$

Parametrization of the“eikonal phase space element”:

$$\frac{d^3 k_i}{2k_i^0} \frac{1}{k_i^- k_i^+} = \frac{d\xi_i dk_i^+ d\varphi_i}{\xi_i k_i^+}$$

The IR boundary on k_i^T (alternatively on $x_{i-1} k_i^T$):

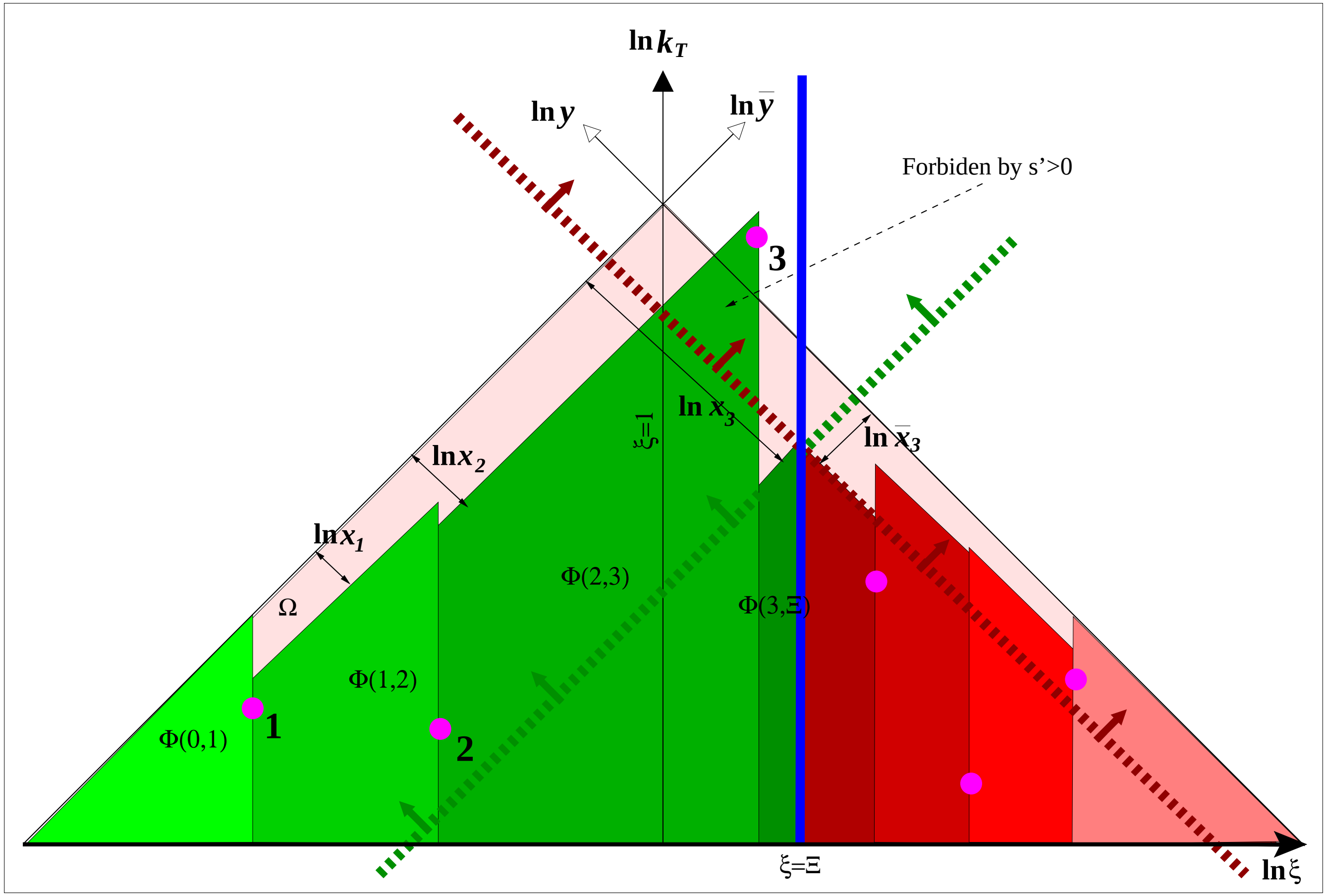
$$k_{Ti}^2 = k_i^+ k_i^- = k_i^{+2} \xi_i > \lambda^2, \quad k_i^+ = p_0^+ (1 - z_i) x_{i-1} > \frac{\lambda}{\sqrt{\xi_i}},$$

We chose rapidity as the evolution time (CCFM)

It is: $q_i = p_0^+ \sqrt{\xi_i}$, where $p_0 = (p_0^+, 0, 0, 0)$ is the primary emitter.

(Also $q_i =$ maximum k_T of the next emission.)

Rapidity – log(kT) plane: Multiple emission in 2 hemispheres



Using twice CMC for single evolution (`with the strict maximum rapidity phase space limit`) we cover smoothly the entire phase space of the emitted gluons **without any gaps or overlaps**.

The boundary blue line in rapidity should coincide with rapidity of the W/Z boson. Its actual position is unimportant for the soft gluon distributions.

Factorisation formula for QCD ISR parton shower Monte Carlo

$$
\sigma = \int_0^1 \frac{dx}{x}\frac{d\bar{x}}{\bar{x}} \sum_{f\bar{f}f_0\bar{f}_0} \int dx_0 \int d\bar{x}_0 \tilde{D}_{f_0}(t_\lambda, x_0)\, \tilde{D}_{\bar{f}_0}(t_\lambda, \bar{x}_0)
\times \mathcal{U}_{ff_0}(t_F, x|t_\lambda, x_0)\, \mathcal{U}_{\bar{f}\bar{f}_0}(t_B, \bar{x}|t_\lambda, \bar{x}_0)\, \theta_{\hat{s}>0}\, \sigma^{\rm Born}_{f\bar{f}}(\hat{s}),
$$

- $\tilde{D}_f(t,x) = xD_f(t,x)$ is PDF for f= parton type (quark gluon)
- $K = \sum_F k_i$ and $\bar{K} = \sum_B \bar{k}_i$ are total 4-momenta of emited gluons in the F/B hemispheres
- $\hat{s} = (q_0 + \bar{q}_0 - K - \bar{K})^2 = (px_0 + \bar{p}\bar{x}_0 - K - \bar{K})^2$!!!
- $q_0 = x_0 q$, $\bar{q}_0 = \bar{x}_0 \bar{q}$ are 4-momenta of primordial partons at scale $q_0 = \lambda \simeq$ 1GeV
- $\mathcal{U}_{ff_0}(t_F, x|t_\lambda, x_0)$ is fully exclusive evolution operator, see next slides.
- $t_F(x,\bar{x}) = \ln\sqrt{s} + \eta^*(x,\bar{x})$ and $t_B(x,\bar{x}) = \ln\sqrt{s} - \eta^*(x,\bar{x})$
- Where $\eta^\star(x,\bar{x}) = \frac{1}{2}\ln\frac{x}{\bar{x}}$ is rapidity boundary between F/B hemispheres.

DGLAP/CCFM Evolution equation and its solution

$$
\begin{aligned}
\partial_t D_k(t,x) &= \sum_j \int_x^1 du \mathcal{K}_{kj}(t,x,u) D_j(t,u)\,, \\
\mathcal{K}_{kj}(t,x,u) &= = \frac{\alpha_S(k^T(t,x,u))}{\pi} \frac{1}{u} P_{kj}\left(t, \frac{x}{u}\right) \\
&= -\mathcal{K}^v_{kk}(t,u)\delta_{kj}\delta_{x=u} + \mathcal{K}^\theta_{kj}(t,x,u)\theta_{u \geqslant x + \lambda e^{-t}}
\end{aligned}
$$

where $k^T(t,x,u) = (u-x)e^t$ and $P_{ij}(t,z)$ are LL DGLAP kernels.

The solution

$$
\tilde{D}_f(t,x) = x D_f(t,x) = \sum_{f_0} \int_x^1 dx_0\, \mathcal{U}_{f f_0}(t, x | t_0, x_0) \tilde{D}_{f_0}(t_0, x_0)\,,
$$

in terms of the evolution operator $\mathcal{U}$ and initial condition at t_0.

Evolution operator

The evolution operator is **the time-ordered exponential** in the combined space of f and x (we use $y_i \equiv x_i - x_{i-1}$)

$$\begin{aligned}
\mathcal{U}_{f f_0}(t, x|t_0, x_0) &= e^{-\Phi_f(t,t_0|x)} \delta_{x_0-x} \delta_{f f_0} + \\
&+ \sum_{n=1}^{\infty} \sum_{f_0, f_1 \dots, f_{n-1}} \left[\prod_{i=1}^{n} \int_{t_0}^{t} dt_i \theta_{t_i > t_{i-1}} \int_{\lambda e^{-t_i}}^{x_0 - x} dy_i \right] e^{-\Phi_f(t,t_n|x)} \\
&\times \left[\prod_{i=1}^{n} \frac{x_i}{x_{i-1}} \mathcal{K}^{\theta}_{f_i f_{i-1}}(t_i, x_i|x_{i-1}) e^{-\Phi_{f_{i-1}}(t_i,t_{i-1}|x_{i-1})} \right] \delta_{x_0 - x = \sum y_j}
\end{aligned}$$

It obeys Chapman-Kolmogorov-Smoluchowski-Einstein identity

$$\sum_{f'} \int dx'\, \mathcal{U}_{f f'}(t, x|t', x') \mathcal{U}_{f' f_0}(t', x'|t_0, x_0) = \mathcal{U}_{f f_0}(t, x|t_0, x_0)$$

and normalization rules:

$$\sum_{f} \int dx\, \mathcal{U}_{f f_0}(t, x|t_0, x_0) = 1, \qquad \mathcal{U}_{f f_0}(t, x|t, x_0) = \delta_{x_0 - x} \delta_{f f_0}.$$

Sudakov formfactor $\Phi_f(t_{i+1}, t_i|x) = \int_{t_{i-1}}^{t_i} dt\, \mathcal{K}^{v}_{f f}(t, x)$ enters as usual.

Simple relation to unintegrated PDF

uPDF is defined in a natural way, by inserting into evolution operator an extra δ-function defining total accumulated transverse momentum of the emitter parton:

$$\begin{aligned}\mathcal{U}_{f f_0}(t,x,\vec{k}^T|t_\lambda,x_0,\vec{0}) &= \sum_{n=0}^{\infty}\frac{1}{n!}\sum_{f_0,f_1\dots,f_{n-1}}\left[\int\prod_{i=1}^{n}\frac{dk_i^+\,dk_i^-\,d\varphi_i}{k_i^+k_i^-}\theta_{\eta_i>\eta^\star}\right]\\ &\times\; w^n_{f_0\dots,f_n}(t,x;t_0,x_0|k_1^\mu,\dots,k_n^\mu)\delta_{(x_0-x)p^+=\sum k_j^+}\delta_{\vec{k}^T=\sum_i\vec{k}_i^T},\\ \tilde{D}_f(t,x,\vec{q}^T) &= \sum_{f_0}\int_x^1 dx_0\,\mathcal{U}_{f f_0}(t,x,\vec{q}^T|t_0,x_0,\vec{0})\tilde{D}_{f_0}(t_0,x_0)\end{aligned}$$

uPDF and PDF are related by construction in a simple and elegant way

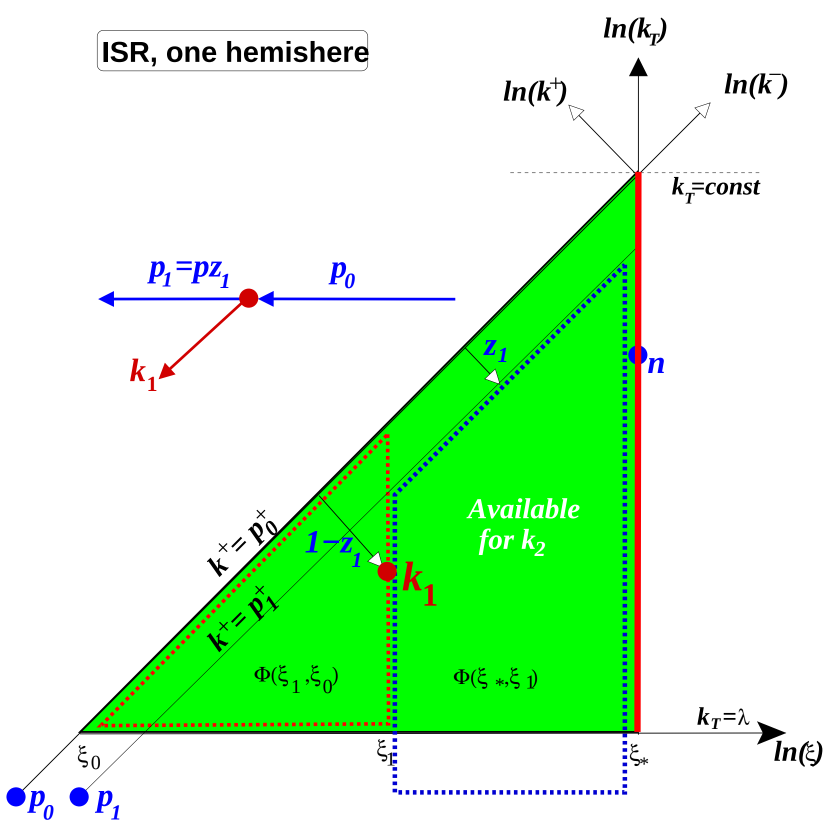
$$\tilde{D}_f(t,x)=\int d^2\vec{q}^T\,\tilde{D}_f(t,x,\vec{q}^T),$$

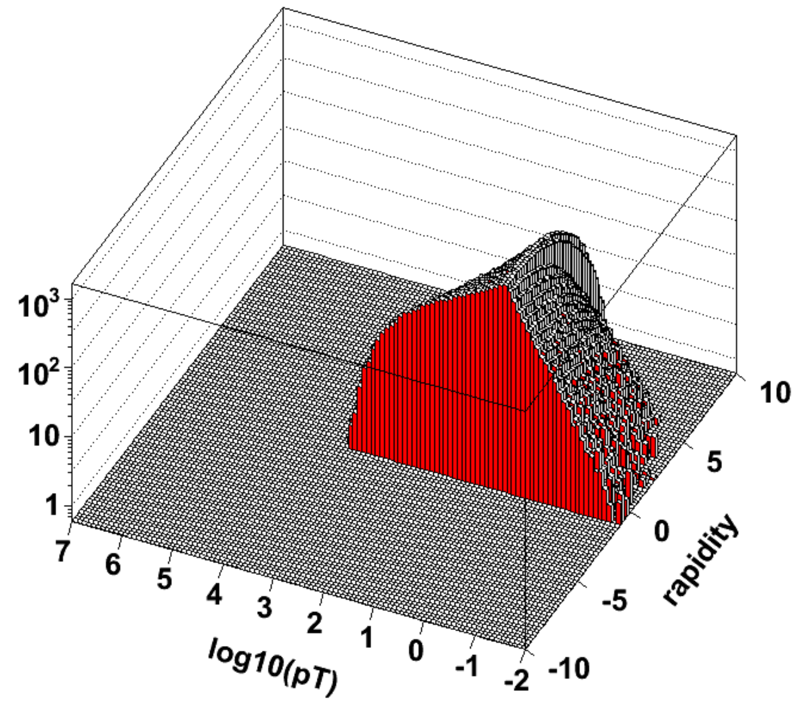
(the so called strong factorization scheme).
The above uPDF obeys evolution equation of its own

$$\partial_t D_k(t,x,\vec{q}^T) = \sum_j\int_x^1 du\int d^2k^T\mathcal{K}_{kj}(t,x,u)D_j\left(t,u,\vec{q}^T-\vec{k}^T\right)\delta_{|\vec{k}^T|=(u-x)e^t}.$$

Of course, fully exclusive MC model of $\mathcal{U}$ does better job than any inclusive uPDF!

Intermediate step CMC (June 05), $Q(1-z)$ instead of k^T





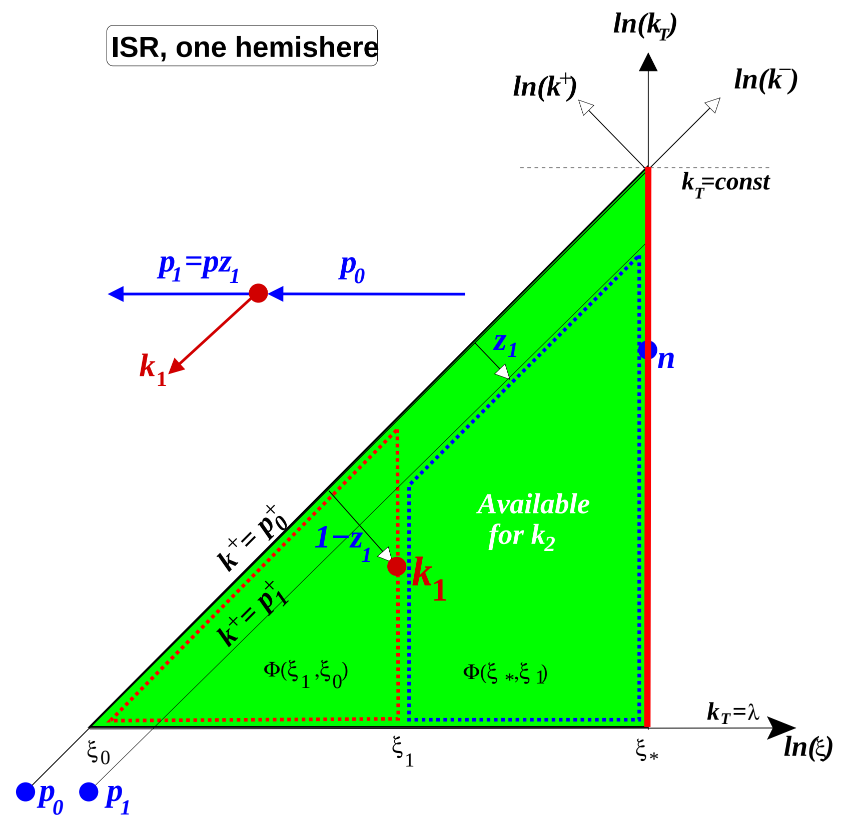
IR boundary in CMC (CCFM-like)

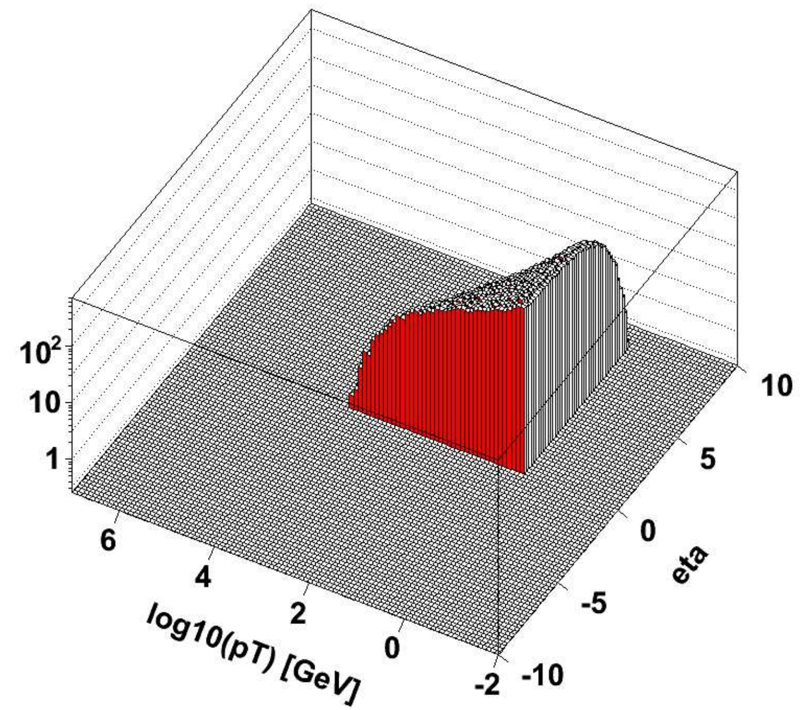
was $1 - z_i > \frac{\lambda}{p_0^+ \sqrt{\xi_i}}$ instead of $k_i^T > \lambda$.

Spurious $k_i^T < \lambda$ gluons and simplified $\alpha_S(Q(1-z))$.

Blue line defines phase space of the 2nd emission.

New! CMC compatible with all-loop CCFM





Full $\alpha(p^T) = \alpha(e^t x(1-z)/z)$ dependence!

No gluons below $p^T = p^T_{\min} = 1 GeV$

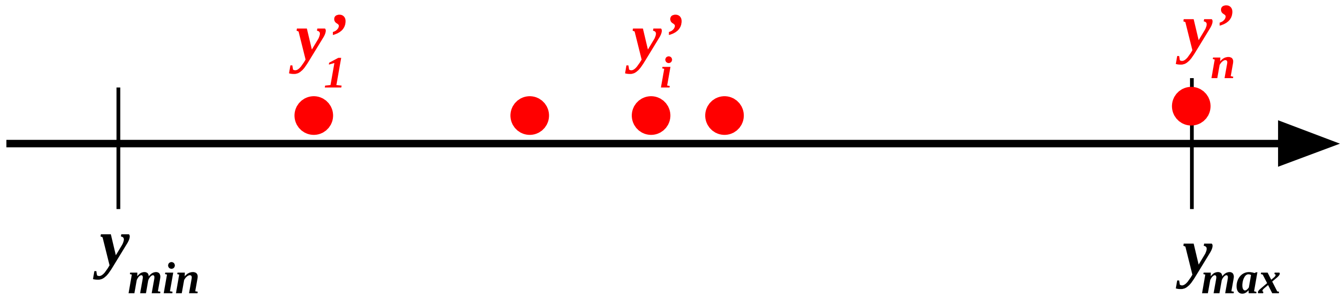
NB. Integration domains for Sudakov ffactors $\Phi_f(\xi|\xi_1, x)$ and $\Phi_f(\xi_1|\xi_0, x_0)$ are triangle and trapezoid in the 1-gluon distr.:

$$\tilde{D}_f(\xi, x)_{n=1} = \int_{\xi_0}^{\xi} \frac{d\xi_1}{\xi_1} \int_{\lambda/\sqrt{\xi_1}}^{p_0^+} \frac{dk_1^+}{k_1^+} \int \frac{d\varphi_1}{2\pi} e^{-\Phi_f(\xi|\xi_1,x)} \tilde{\mathbf{P}}_{ff}(k_1, z_1) e^{-\Phi_f(\xi_1|\xi_0,x_0)} \delta_{x=z_1}$$

CMC in a nutshell

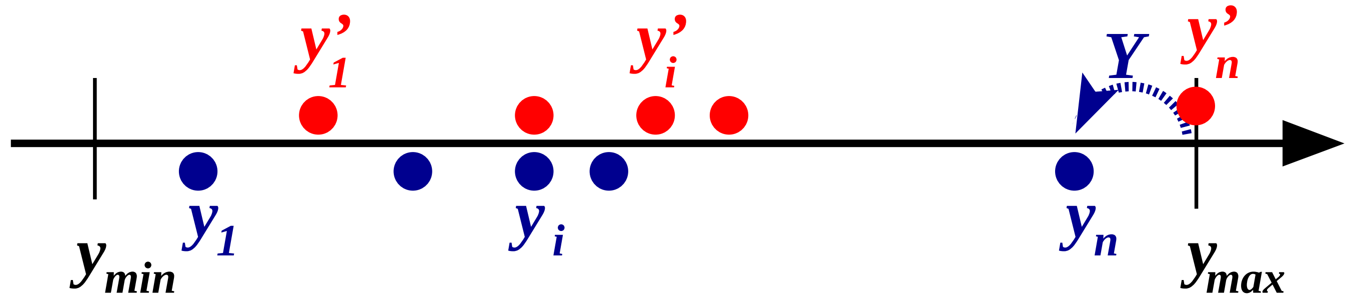
- **Mapping of evolution time $t_i \to s_i$ and $u_i = x_i - x_{i-1} \to y_i$, such that Jacobian eliminates completely the (simplified) kernel $zP_{ff}(z,t)$.**
- **Ordering in $s_i(t_i, y_i)$ temporarily removed (compensated by $1/n!$)**
- **The constraint $\delta(x - \sum u_i)$ is eliminated/fulfilled by means of the parallel shift $y_i \to y_i - Y$.**
- **Quark-Gluon transitions modeled with "brute force" method with help of general purpose MC simulator FOAM.**
- **Appropriate correcting MC weights applied at the end.**
- **For more details see my talks in previous HERA-LHC and other places, http://jadach.web.cern.ch/jadach/ and http://arxiv.org/abs/hep-ph/0504263**
- **Such algorithm is now implemented in CMC (and tested with MMC) for all-loop CCFM (unpublished), including quark-gluon transitions.**

Linear shift: $y_i' \to y_i = y_i' - Y$



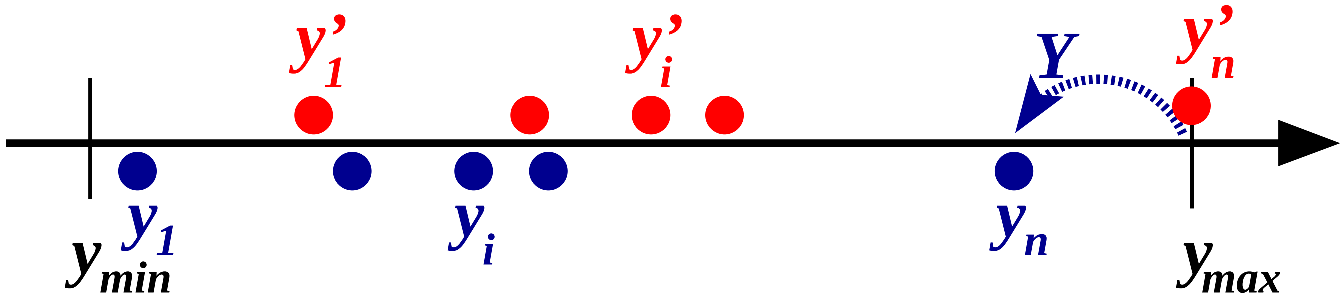
- Begin with y_i' such that one of them $y_n \equiv y_{\rm max}$

Linear shift: $y_i' \to y_i = y_i' - Y$



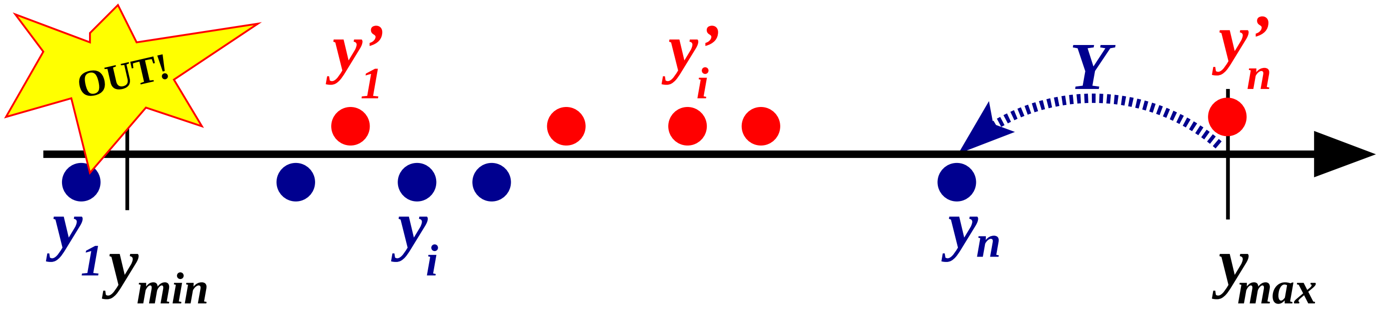
- Begin with y_i' such that one of them $y_n \equiv y_{\max}$
- Shift $y_i' \to y_i$ by Y, where Y solves constraint condition $x = \sum u_i = x$

Linear shift: $y_i' \to y_i \;= y_i' - Y(y_1', y_2', ..., y_n')$



- Begin with y_i' such that one of them $y_n \equiv y_{\max}$
- Shift $y_i' \to y_i$ by Y, where Y solves constraint condition $x = \sum u_i = x$
- Y is therefore complicated function of all y_i'

Linear shift: $y_i' \to y_i \; = y_i' - Y(y_1', y_2', ..., y_n')$



- Begin with y_i' such that one of them $y_n \equiv y_{\max}$
- Shift $y_i' \to y_i$ by Y, where Y solves constraint condition $x = \sum u_i = x$
- Y is therefore complicated function of all y_i'
- Sometimes the smallest y_i' is shifted OUT of the phase space, below IR the limit $y_{\min}$. Such an event gets MC weight $w = 0$

HERA-LHC June 06: Joining smoothly two evolutions of 2 hemispheres

IMPORTANT PROBLEM to be solved:

In the existing CMC for single evolution the constraint is on the $\sum_F p_i^+$ of all gluons in the forward hemisphere and separately on the $\sum_B p_i^-$ in the backward one.

In reality we need the constraint on the effective mass $\hat{s}$ of the W/Z boson involving also $\sum_F p_i^-$, $\sum_B p_i^+$ and all transverse momenta.

$$\sigma = \int_0^1 \frac{dx}{x}\frac{d\overline{x}}{\overline{x}} \sum_{f\bar{f}f_0\bar{f}_0} \int_0^1 d\hat{x}\; \sigma^{\rm Born}_{f\bar{f}}(s\hat{x}) \int dx_0 \int d\bar{x}_0 \tilde{D}_{f_0}(t_\lambda, x_0)\, \tilde{D}_{\bar{f}_0}(t_\lambda, \bar{x}_0)$$

$$\times \quad \mathcal{U}_{ff_0}(t_F, x|t_\lambda, x_0)\, \mathcal{U}_{\bar{f}\bar{f}_0}(t_B, \bar{x}|t_\lambda, \bar{x}_0)\; \theta_{\hat{s}>0}\; \delta_{\hat{x}=\hat{s}/s}$$

Can we impose in the MC constraint on $\hat{s}$, which is a nontrivial function of 4-momenta of ALL emitted partons? Yes we can!

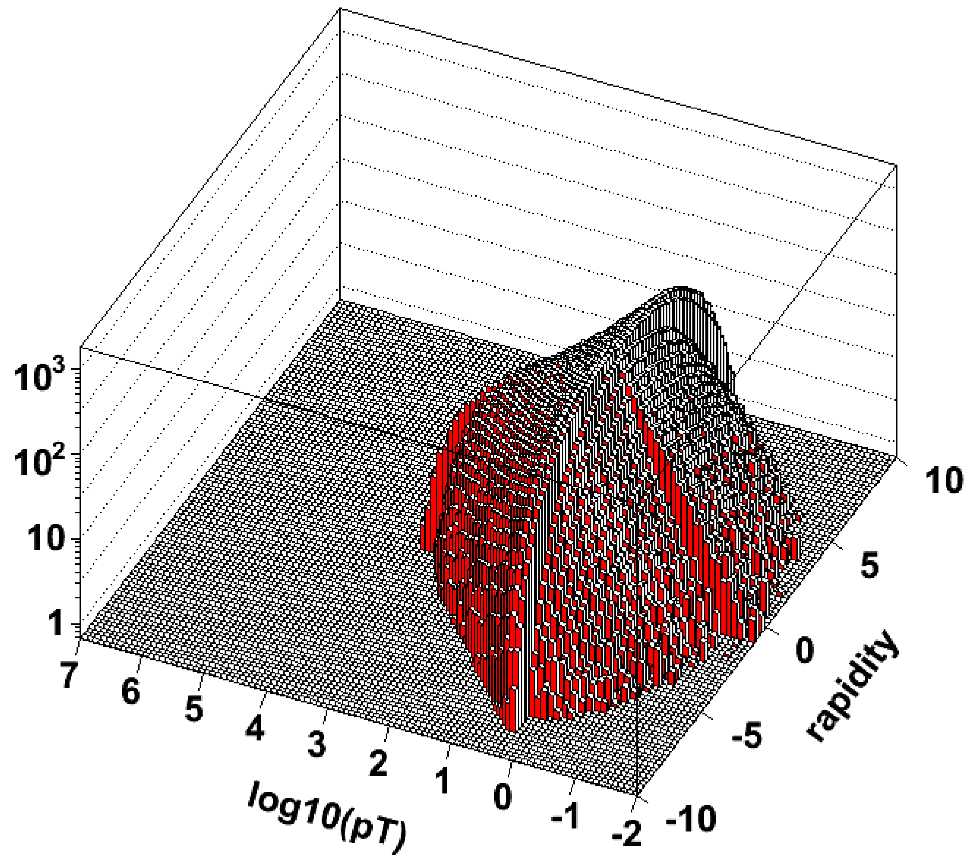
Can we impose constraint on $\hat{s}$?

Can we impose constraint on $\hat{s}$ which is nontrivial function of all emitted 4-momenta?
Example solution based on rescaling of 4-momenta (June 06):
Replace complicated constraint on $\hat{s}$ with a simplified one.
Total control on the overall normalization corrected rigorously with help of special compensating MC weight W_{MC}.

$$\delta\left(sx - (p_{0F} + p_{0B} - K_F - K_B)^2\right) \quad \longrightarrow \quad \delta(sx - s_0 \hat{Z}_F \hat{Z}_B)\, W_{MC}$$

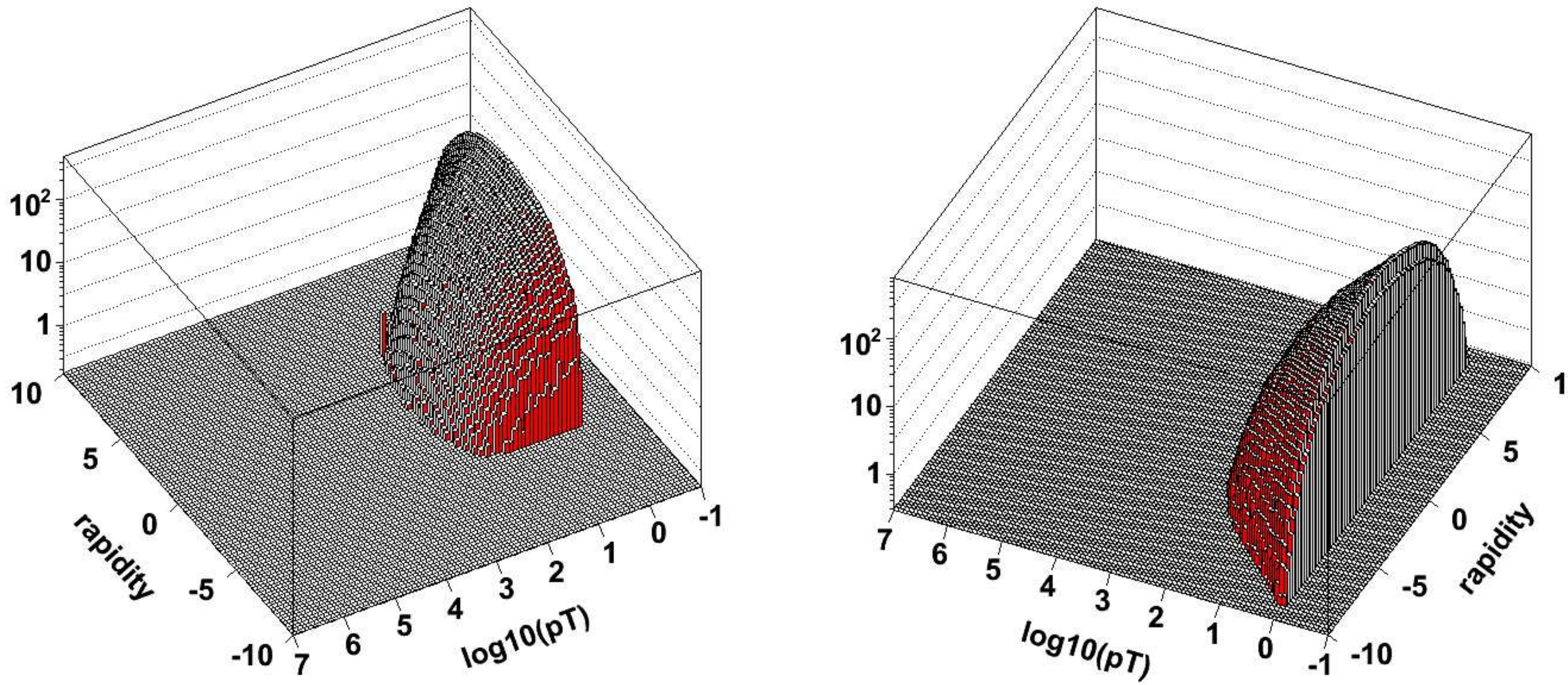
where $K_F = \sum_F k_{iF}$ and $K_B = \sum_B k_{iB}$ are total momenta of emitted partons in the F/B hemispheres
and $\hat{Z}_F = 1 - \sum_F x_i^+$, $\hat{Z}_B = 1 - \sum_B x_i^-$ are total lightcone variables restricted to a single F/B hemisphere.
More details in my HERA-LHC talk, June 2006.

June-July 06: Two simplified CMCs glued together



- Full coverage of 2 hemispheres, no overlap, no gaps :-)
- Visible gluons below k^T_{min}=1GeV (temporarily) and discontinuities due to $\alpha_S(Q(1-z))$:-(
- No L-R symmetry because rapitity of W is fixed at non-zero value (for this exercise) :-(

NEW!!! 2 hemispheres: Matched rapidity and minimum kT,



Joining 2 hemispheres – looks OK, more tests required.

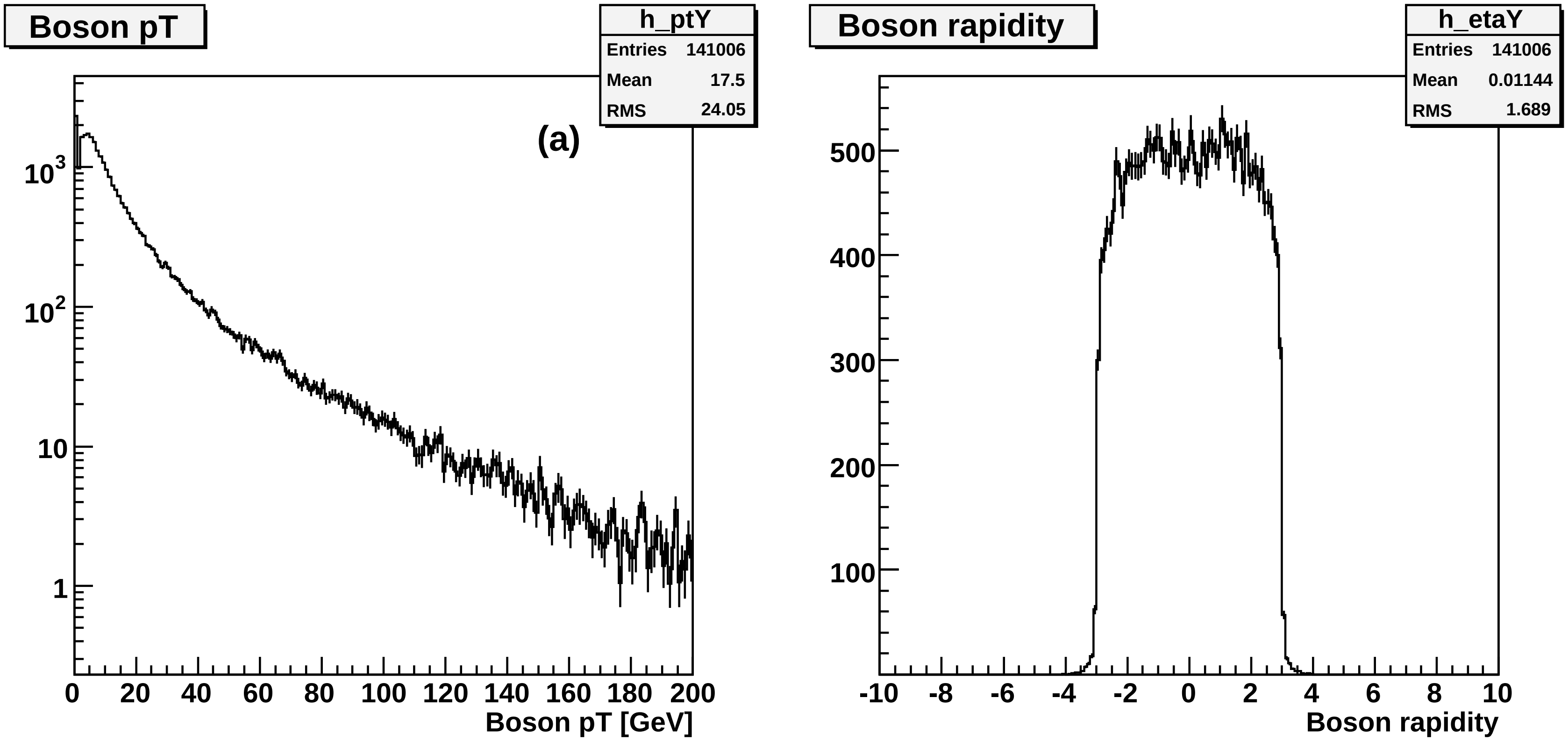
Full $\alpha(p^T) = \alpha(e^t x(1-z)/z)$ dependence!

No gluons below $p^T = p^T_{\min} = 1GeV$

Fig. left: 1-hemisphere, with W rapidity fixed, emitted gluons.

Fig. right: 2 hemispheres, emitted gluons.

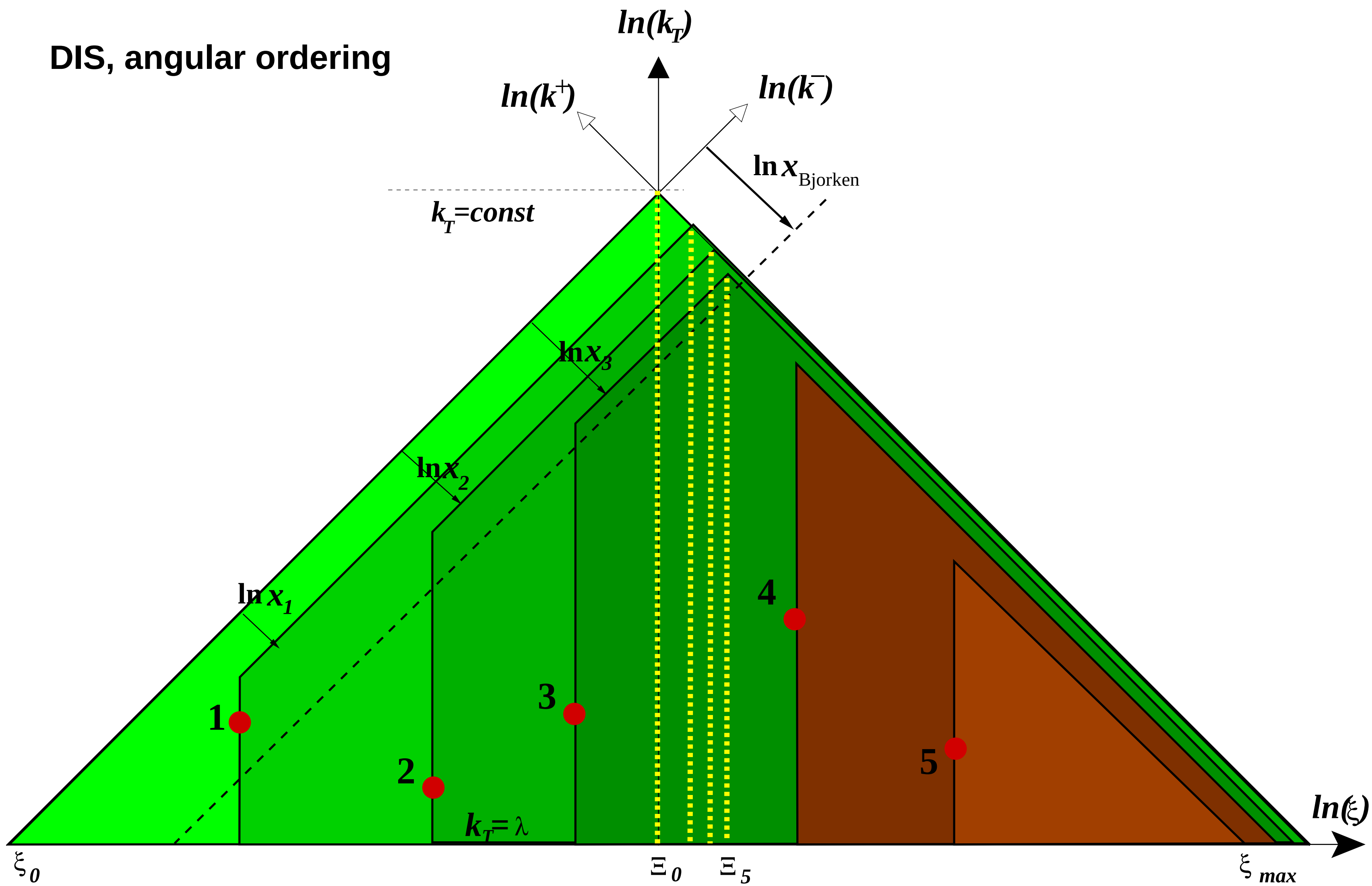
EW boson transverse momentum and rapitity distributions



Transverse momentum and rapidity distribution of the EW boson (mass 100GeV). Matrix element is maximally simplified (only Breit-Wigner). VERY PRELIMINARY!!!

This was shown in June 06. Next round of tests/upgrades soon.

What about MC for DIS?



We plan MC for DIS according scenario schematised above, with angular ordering and coverage of the FSR part of the phase space.

To be done soon, some components needed already for QCD ISR for W/Z@LHC.

Recent developments and plans

Recent activity:

- In progress: 2 single evolutions into one MC for W/Z production at LHC, more and more testing!
- Getting more realistic distributions of W/Z rapidity and kT
- Quark-gluon transitions in CMC and double CMC
- Non-Sudakov formfactor for full CCFM compatibility
- QCD NLO in the hard process (easy?) and evolution (difficult?). See talk by Phil Stephens.

Plans:

- Better EW +QED FSR matrix element, from WINHAC/SANC
- xchecks with uPDFs of CASCADE/SMALLX?
- CMC/MMC for DIS process, fitting F_2
- Establishing relation to k^T-ordering and CSS in b-space