Monte Carlo simulations for processes with massive quarks in the initial state @ NLO

Davide Napoletano, IPPP-Durham University

17/04/2015, HiggsTools meeting, Freiburg

Outline

1. b quarks at LHC
   - 4F vs 5F scheme
2. Monte-Carlo simulations
   - Fixed-Order
   - Parton shower
   - Multi-jet merging
3. Some numerical results
   - Comparing 4F and 5F scheme
4. Towards a 5F-Improved scheme
5. Conclusions

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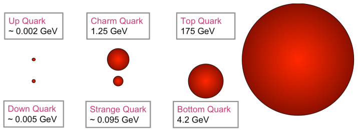
Introduction



$\Lambda_{QCD} \sim 250$ MeV,
A quark Q is **heavy** $\Leftrightarrow m_Q \gg \Lambda_{QCD}$.

$m_u, m_d, m_s \ll \Lambda_{QCD} \Rightarrow$ light quarks

$m_c > \Lambda_{QCD}$ but not by much!

- b quark only quark such that

$$\Lambda_{QCD} \ll m \ll M(m_W, m_Z, m_H, m_t)$$

- b phenomenology crucially important at the LCH, from flavour physics, to Higgs characterisation and measurements and as window to New Physics.
- From a theoretical viewpoint we need better control on this kind of processes which appear as both BSM signals and SM irreducible backgrounds.
- Important examples: H and Z associated production.

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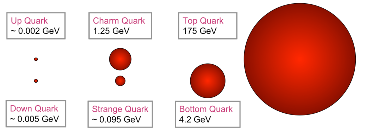

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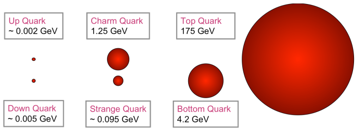

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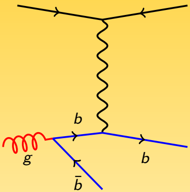
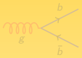
$g \to b\bar{b}$ splitting!

Main production mode: $g \to b\bar{b}$, but $\sigma \propto \alpha_S(\eta^2)\log(\eta^2/m_b^2)$, so when $m_b^2/\eta^2 \to 0$:



$\Longrightarrow \quad \alpha_S \log \frac{\eta^2}{m_b^2} \times$



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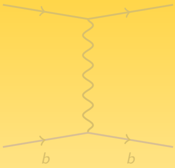

$$\lim_{m_b^2/\eta^2 \to 0} f_g \otimes \hat{\sigma}_{Xg \to b\bar{b}Y} = \underbrace{\alpha_S \log \frac{\eta^2}{m_b^2} P_{qg} \otimes f_g}_{=\tilde{b}(x,\mu^2)} \sigma_{Xb \to Y}$$

DGLAP equations:

$$\Longrightarrow \quad b(x,\mu^2) = \alpha_S \log \frac{\eta^2}{m_b^2} \left(P_{qg} \otimes f_g\right)(x,\mu^2) + \mathcal{O}(\alpha_S^2)$$

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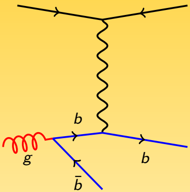

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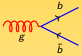

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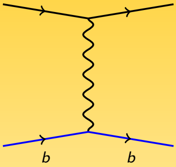

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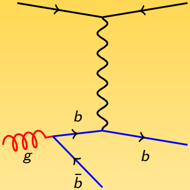

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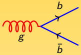

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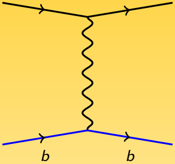

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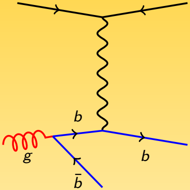

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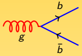

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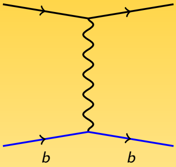

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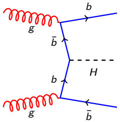
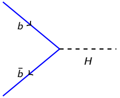
4F versus 5F scheme

4F scheme



- × Doesn't re-sum possibly large logs, but it does have them explicitly
- × Higher orders are computationally more difficult
- ✓ Mass effects present at any order
- ✓ MC@NLO no problem

5F scheme



- ✓ Stabler predictions, re-summation of IS large logs into b-PDF
- ✓ Higher order easily accessible
- × p_T of b and mass effects are pushed to higher orders
- × Implementation in MC depends on the $g \to b\bar{b}$ splitting implemented

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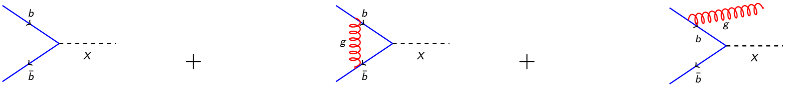
Computing NLO observables

To compute a NLO observable we need:

$$\mathrm{d}\sigma = \mathrm{d}\Phi_{\mathcal{B}} \left[\mathcal{B}(\Phi_{\mathcal{B}}) + \mathcal{V}(\Phi_{\mathcal{B}}) \right] + \mathrm{d}\Phi_{\mathcal{B}+1} \mathcal{R}(\Phi_{\mathcal{B}+1})$$



- $\mathcal{V}(\Phi_{\mathcal{B}})$ and $\int \mathrm{d}\Phi_{\mathcal{B}+1}\, \mathcal{R}(\Phi_{\mathcal{B}+1})$ are separately soft (and collinear) divergent in $4d$
- $\int \mathrm{d}\Phi_{\mathcal{B}}\, \mathcal{V}(\Phi_{\mathcal{B}}) + \int \mathrm{d}\Phi_{\mathcal{B}+1}\, \mathcal{R}(\Phi_{\mathcal{B}+1})$ is finite!
- Need method to render the integrand finite for MC integration!
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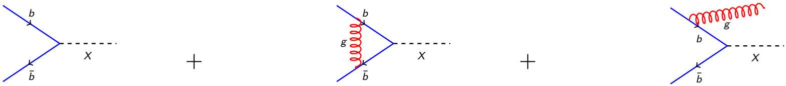

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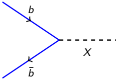

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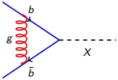

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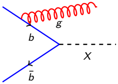

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CS-Dipoles

Exploit universal structure of **soft-** and **collinear- singularities** $\Rightarrow$ in these limits:

$$|\mathcal{M}(\{p_n\},p_k)|^2 \sim \sum_{ijk} \mathcal{D}_{ijk} = \mathcal{S}$$

$$\mathcal{D}_{ijk} \propto V_{ij,k}(\{p_n\},p_k) \otimes |\mathcal{M}(\{\tilde{p}_n\})|^2$$

If we also use this to factorise the PS $\Rightarrow \mathrm{d}\Phi_{\mathcal{B}+1} = \mathrm{d}\tilde{\Phi}_{\mathcal{B}} \otimes \mathrm{d}\Phi_1$ we can write:

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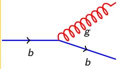

$$\Rightarrow \quad d\sigma \propto \sigma_0 \int_{Q_0^2}^{Q^2} \frac{dt}{t} \propto \alpha_S \log \frac{Q^2}{Q_0^2}$$

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$\Rightarrow$ Many sub-sequential emissions, with $t_1 > t_2 > \cdots > t_n$

Sudakov Form-Factor exponentiate these logs (DGLAP equations):

$$\Delta(Q_0^2, Q^2) = \exp\left[-\int_{Q_0^2}^{Q^2} \frac{dt}{t} \int dz \alpha_S(t(z)) P_{ab}(z)\right] \sim \exp\left[-C_F \alpha_S \log^2 \frac{Q^2}{Q_0^2}\right]$$

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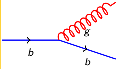

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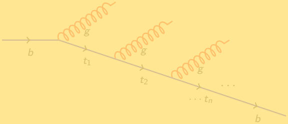

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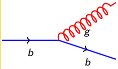

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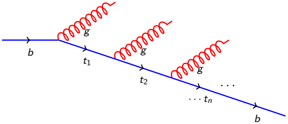

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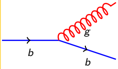

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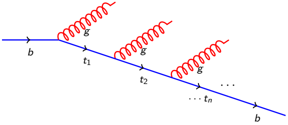

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Matching to the Fixed Order

Leading-Order

At LO, we start with the $\mathcal{B}$ cross section:

$$\mathrm{d}\sigma^{(\mathrm{Born})} = \mathrm{d}\Phi_{\mathcal{B}}\mathcal{B}(\Phi_{\mathcal{B}}) \underbrace{\left\{ \Delta(Q_0^2, Q^2) + \int_{Q^2}^{Q_0^2} \mathrm{d}\Phi_1 \left[\mathcal{K}(\Phi_1)\Delta\left(Q_0^2, t(\Phi_1)\right)\right]\right\}}_{\text{Unitarity of the PS}}$$

$\mathcal{K}(\Phi_1) = \int \mathrm{d}z \alpha_S\left(t(z)\right) P_{ab}(z)$

- Note that $\mathcal{R}(\Phi_{\mathcal{B}} \otimes \Phi_1) \leq \mathcal{B}(\Phi_{\mathcal{B}}) \otimes \mathcal{K}(\Phi_1)$
- introduce $\tilde{\mathcal{K}}(\Phi_1) = \mathcal{R}(\Phi_{\mathcal{B}} \otimes \Phi_1)/\mathcal{B}(\Phi_{\mathcal{B}})$ thus:

$$\mathrm{d}\sigma^{(\mathrm{Born})} = \mathrm{d}\Phi_{\mathcal{B}}\mathcal{B} \left\{ \tilde{\Delta}(Q_0^2, Q^2) + \int_{Q^2}^{Q_0^2} \mathrm{d}\Phi_1 \left[\tilde{\mathcal{K}}(\Phi_1)\tilde{\Delta}\left(Q_0^2, t(\Phi_1)\right)\right]\right\}$$

$$\tilde{\Delta}(Q_0^2, Q^2) = \exp\left[- \int_{Q_0^2}^{Q^2} \mathrm{d}\Phi_1 \tilde{\mathcal{K}}(\Phi_1)\right]$$

Matching to the Fixed Order

Leading-Order

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$$\mathrm{d}\sigma^{(\mathrm{Born})} = \mathrm{d}\Phi_{\mathcal{B}}\mathcal{B}(\Phi_{\mathcal{B}}) \underbrace{\left\{ \Delta(Q_0^2, Q^2) + \int_{Q^2}^{Q_0^2} \mathrm{d}\Phi_1 \left[\mathcal{K}(\Phi_1)\Delta\left(Q_0^2, t(\Phi_1)\right)\right] \right\}}_{\text{Unitarity of the PS}}$$

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Matching to the FO (NLO)

Going MC@NLO

Can we do even better? First recall Catani-Seymour:

- $\Rightarrow$ Identify the shower kernels with the CS dipoles:

$$\mathcal{S}(\Phi_\mathcal{B} \otimes \Phi_1) = \sum_{ijk} \mathcal{B}(\Phi_\mathcal{B}) \otimes V_{ijk}(\Phi_1) = \mathcal{B}(\Phi_\mathcal{B}) \otimes \mathcal{K}(\Phi_1)$$

- In this way we get

$$d\sigma^{\text{MC@NLO}} = d\,\Phi_\mathcal{B}\widetilde{\mathcal{B}}\left\{\Delta(Q_0^2, Q^2) + \int_{Q^2}^{Q_0^2} d\Phi_1 \mathcal{K}(\Phi_1)\Delta\left(Q_0^2, t(\Phi_1)\right)\right\} + d\Phi_{\mathcal{B}+1}\mathcal{H}(\Phi_{\mathcal{B}+1})$$

where

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LO-Merging

Basic idea

- PS $\Rightarrow$ re-sums logs in **soft- collinear-region** $\rightarrow$ jet evolution
- ME exact at any give order and description of **hard region** $\rightarrow$ jet production
- Separate jet production from jet evolution with jet measure Q_J
- ME populate **hard region**
- PS populate **soft- collinear-region**

$$\mathrm{d}\sigma = \mathrm{d}\Phi_N \mathcal{B}_N \left\{ \Delta_N(\mu_N^2, t_0) + \int_{t_0}^{\mu_N^2} \mathrm{d}\Phi_{N+1} \left[\mathcal{K}_N \Delta_N \left(\mu_N^2, t_{N+1}\right) \right] \Theta(Q_J - Q_{N+1}) \right\}$$

$$+ \quad \mathrm{d}\Phi_{N+1} \mathcal{B}_{N+1} \Delta_N \left(\mu_{N+1}, t_{N+1}\right) \Theta(Q_J - Q_{N+1})$$

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Numerical results

Set-up

- SHERPA + OpenLoops, LHC @ 14 TeV

4F

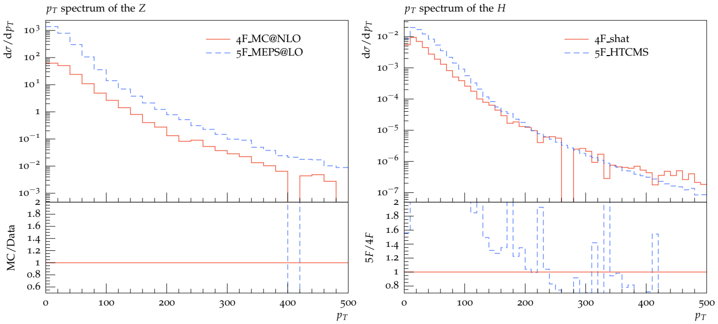
- $pp \to Hb\bar{b}$ @ NLO
- b jets with $p_T > 25$ GeV
- Jet algorithm: anti-k_T, $R = 0.5$
- Parton-level only, for now
- $\mu_{R,F,Q} = \hat{s}$

5F (massive (but LO))

- $pp \to H + 0j + 1j + 2j + 3j$ @ LO
- b jets with $p_T > 25$ GeV
- Jet algorithm: anti-k_T, $R = 0.5$. $Q_J = 20$ GeV
- Parton-level only, for now
- $0j$-$\mu_{R,F,Q} = m_V$, $\mu_{R,F,Q} = \sqrt{\mathrm{H}_T^2 + \sum m_T^2}$ for $j \geq 1$

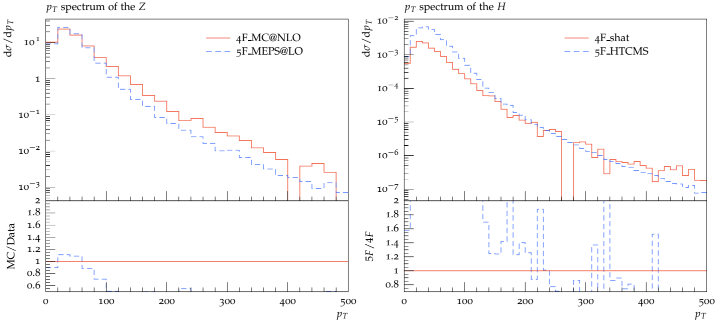
The p_T of the H/Z boson

Looking at the p_T distribution of the H/Z...



The p_T of the H/Z boson

More p_T



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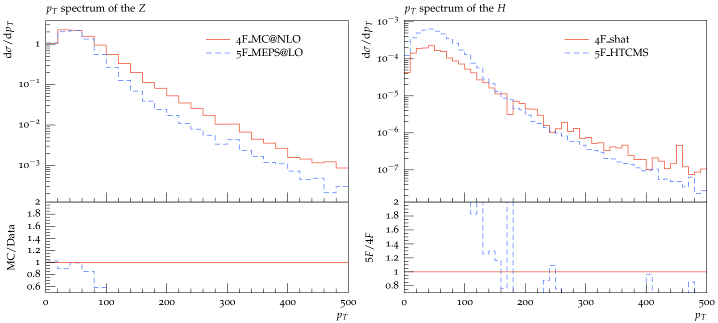

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State of the art

What's there

Many possibilities have been proposed:

- GM-VFNS, ACOT scheme and variants, FONLL and many more...
- Most of them only valid only for DIS
- The others difficult to extend and very much process-dependent

What's going to be there

- Naive improvements: b are massive!
- $\rightarrow$ try to treat b massive everywhere
- In this way we gain process-independence

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What do we need?

Recall that for a fixed order NLO calculation we need

$$d\sigma = d\Phi_{\mathcal{B}}\underbrace{[\mathcal{B}+\mathcal{V}] + d\Phi_{\mathcal{B}+1}\mathcal{R}}_{\text{This we have!}} + \underbrace{\mathrm{d}\Phi_{\mathcal{B}}\mathcal{I} - d\Phi_{\mathcal{B}+1}\mathcal{S}}_{\text{This we need..}}$$

And for a MC@NLO we also need $\mathcal{S}$ for the Sudakov form factor.

- Massive dipoles already computed for a general QCD and EW radiation
- Work in progress for the implementation in SHERPA
- What to do with PDFs?

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- 4F and 5F scheme, both have pro and cons
- Neither is completely satisfactory
- Turning on mass effects in the 5F scheme could to provide a good solution
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