QCD and SM Working Group

Les Houches, 6/6/2003

Activities at and after the workshop

In Les Houches, we have been revising some of the current research topics in QCD, which will likely have an impact on Tevatron Run II and LHC physics programs

Some of the issues we discussed:

- Monte Carlos (with many hard legs, with NLO corrections, underlying events, background simulations)
- Higher-order computations (through analytic and/or numerical techniques)
- Resummations and small-x, BFKL physics
- Heavy-flavour physics (production)
- Photon physics
- Les Houches accords #1 and #2

Our aim: get new results for the proceedings, some due to collaborations started here; write a state-of-the-art review on tools and techniques commonly used by experimentalists and theorists

Resummation

Talks by

- Grazzini: Threshold, k_T resummation for Higgs production
- Magnea: Exponentiation of constants in Drell-Yan
- Cacciari: Dressed-gluon exponentiation and the b-quark fragmentation function

Resummation = organization of large logarithms in perturbative expansions:

$$\sigma = a(L)\alpha_S^n + b(L)\alpha_S^{n+1} + \ldots \quad \Rightarrow \quad a(L) \sim L^{2n} \quad \text{as} \quad L \to \infty$$

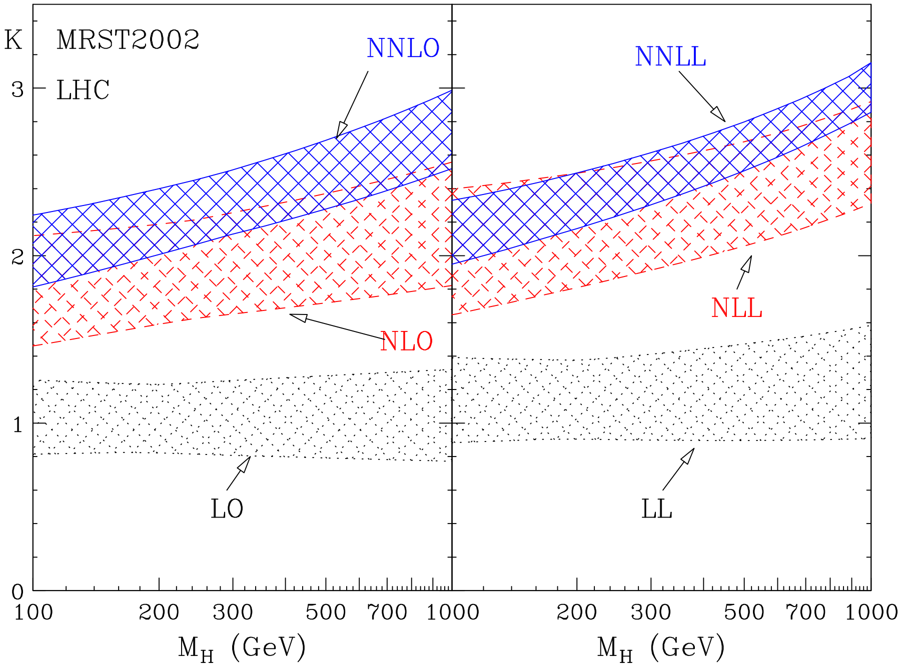
Perturbative expansion is spoiled $(\alpha_S L \sim 1)$, so reorganize it:

$$\sigma = \exp\left(\underbrace{\underbrace{L g_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots \right) \underbrace{C(\alpha_s)}_{constants} \; + \; \text{suppressed terms}$$

$L = \ln(?)$. Argument differs per observable

Threshold resummation for Higgs production (Grazzini), $L = \ln N, N \to \infty$

Results at the LHC

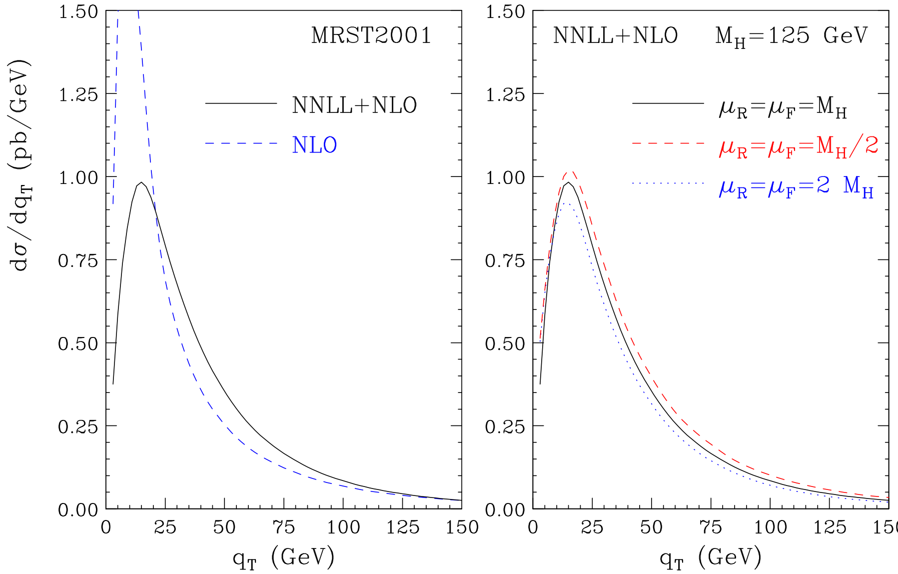


- Resummed result matched to corresponding fixed order
- K-factors defined with respect to $\sigma^{LO}(\mu_F = \mu_R = M_H)$
  - with $\mu_{F(R)} = \chi_{F(R)} M_H$ and $1/2 \leq \chi_{F(R)} \leq 2$
  - but $1/2 \leq \chi_F/\chi_R \leq 2$
- For a light Higgs:
  - NNLL effect about +6% with respect to NNLO
  - Scale uncertanty at NNLL of about ±8%

Find:

- $\sigma(gg \to H)_{m_t \to \infty}$ now known with 4 N's (NNLO-NNLL)
- Scale uncertainties reduced, perturbation theory well-behaved
- At the Tevatron:
  $\mathrm{NLL + NLO = NLO}\ (1 + 30\%)$
  $\mathrm{NNLL{+}NNLO = NNLO}\ (1{+}16\%)$
- At the LHC:
  $\mathrm{NLL + NLO = NLO}\ (1 + 20\%)$
  $\mathrm{NNLL + NNLO = NNLO}\ (1 + 9\%)$

Q_T resummation for Higgs production (Grazzini), $L = \ln(M_H/Q_T)$



The NLO result diverges to $-\infty$ as $q_T \to 0$ (unphysical peak)

The q_T distribution is slightly harder than at NLL+LO ($\langle q_T \rangle \sim 39$ GeV)

The effect of the coefficient $A^{(3)}$ is negligible whereas the coefficient $\mathcal{H}^{(2)}$ increases the cross section by about 20%

The scale dependence is reduced with respect to NLL+LO: It varies from $\pm 10\%$ at the peak to $\pm 20\%$ at $q_T \sim 100$ GeV

A modified b-space (CSS) resummation formula has been used, with $\log(M_H^2 b^2/b_0^2) \to \log(1 + M_H^2 b^2/b_0^2)$. This is motivated by e^+e^- event shapes

Find:

- $d\sigma(gg \to H)/dq_T$ known to NNLL
- spectrum slightly harder than NLL
- result well-matched to NLO, and normalized

Plan for write-up: comparing spectrum with MC predictions

Resummation of constants in Drell-Yan (Magnea), $L = \ln N + \pi^2 N^0$

Partonic Drell-Yan cross section can be computed in different ϕ schemes

$$\hat{\sigma}(N, Q^2) = \frac{\sigma(N, Q^2)}{(\phi_S(N, Q^2))^2}$$

with $S = \overline{\mathrm{MS}}$ or DIS. By *factorization* of $\hat{\sigma}$ near threshold (N large), it follows that

$$\hat{\sigma} = \exp\left[F(\alpha_s, \ln N)\right] C(\alpha_s) + \mathcal{O}\left(\frac{\ln^k N}{N}\right)$$

Also C, however, is a pure exponential (both in $\overline{\mathrm{MS}}$ and in DIS)

$$C(\alpha_s) = \exp(G(\alpha_s)), \quad G \simeq \alpha_s \pi^2 + \ldots$$

Benefits and outlook for write-up

- New relations between real and virtual parts of F $\longrightarrow$ NNN..LO
- Gateway to $\ln^k N/N$ resummation $\longrightarrow$ Higgs
- Estimates for higher orders
- One particle-inclusive QCD cross sections currently studied

Dressed gluon exponentiation (DGE) for b-quark fragmentation (Cacciari), $L = \ln N$

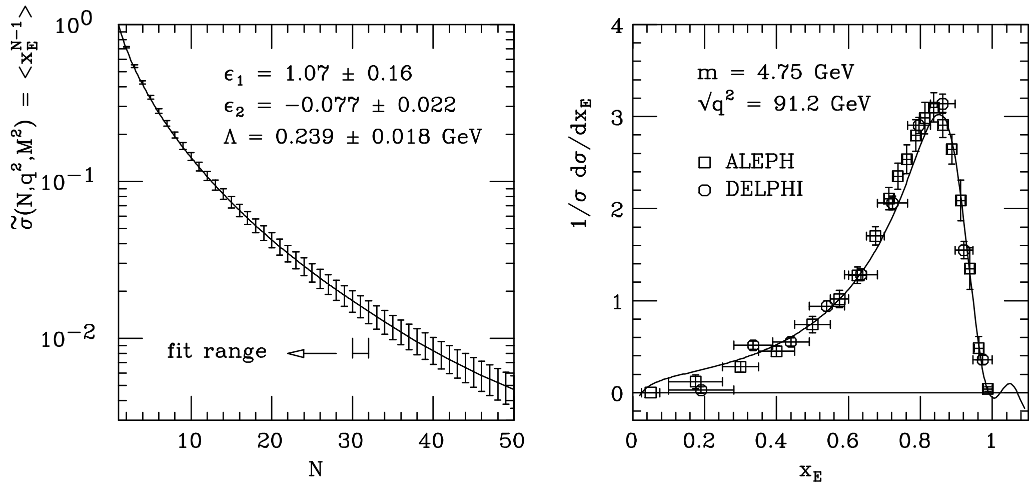
For process $e^+e^- \to B(b) + X$

$$\frac{1}{\sigma}\frac{d\sigma}{dx_E} = \int dN (x_E)^{-N} \sigma(N, \alpha_s, Q, m) \otimes D^{np}(N, \Lambda, m), \quad x_E = E_B/E_{\mathrm{beam}}$$

For D^{np} one usually uses Peterson form, or Kartvelishvili et al. But can infer it in terms of power corrections, using DGE. Result with fit to ALEPH data (in N space):

$$D^{np}(N, \Lambda, m) = \exp\left[-\epsilon_1 \left(\frac{(N-1)\Lambda}{m}\right) - \epsilon_2 \left(\frac{(N-1)\Lambda}{m}\right)^2\right]$$

$$\epsilon_1 = 1.07 \pm 0.16, \quad \epsilon_2 = -0.077 \pm 0.022, \quad \alpha_S(M_Z) = 0.118 \pm 0.003$$

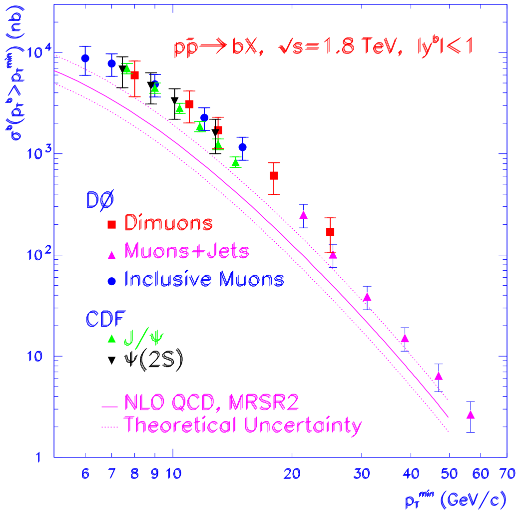


Usable (with care!) for other b-production processes. Possible to fit m?

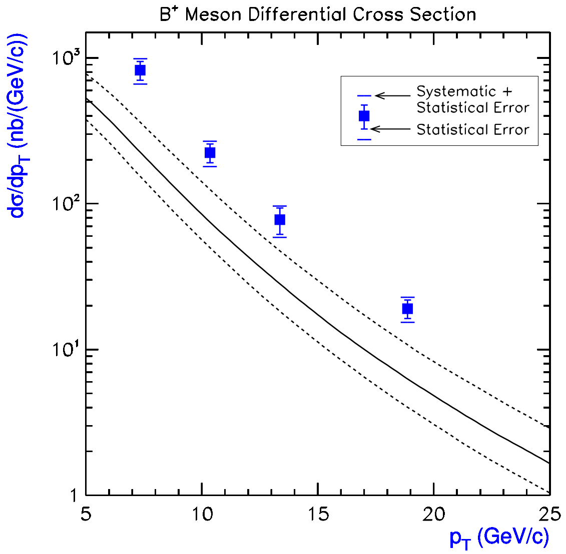
Plans: release b-fragmentation function including power corrections as public package.

The former bottom excess (Cacciari)

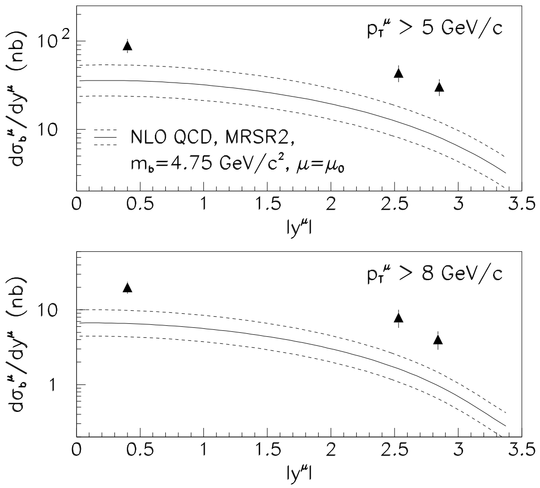
b @ CDF/D0



B @ CDF



μ from B @ D0



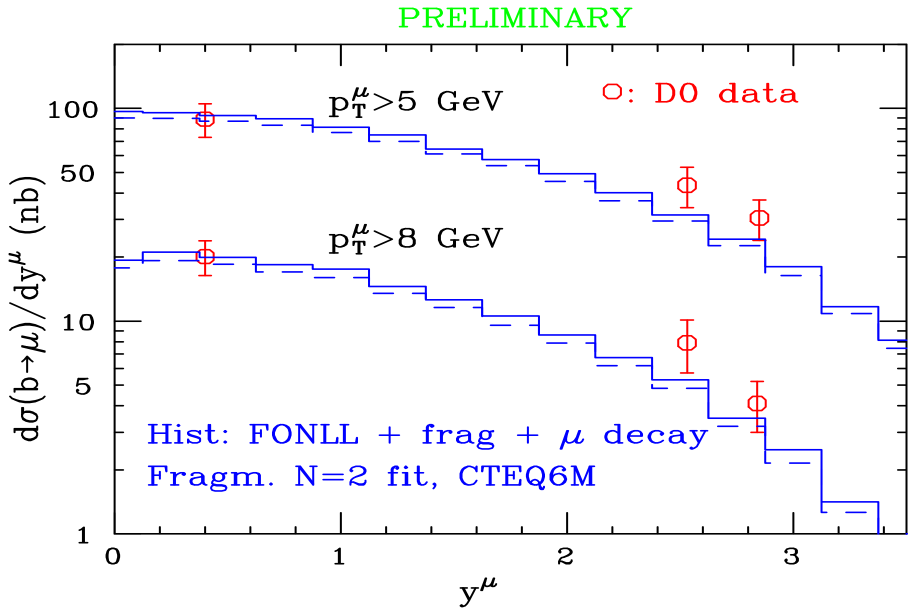
Theoretical predictions for B mesons contain non-perturbative information. The same is true for measurements, if presented in terms of b quark variables

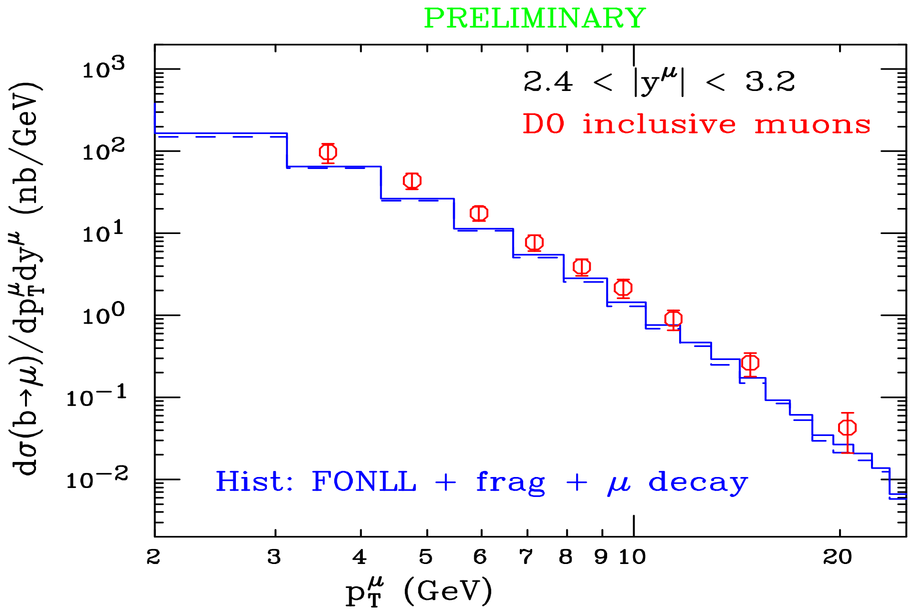
A Peterson et al. FF with $\epsilon = 0.006$ is not necessarily an appropriate choice for describing the hadronization of the b quark into the B mesons

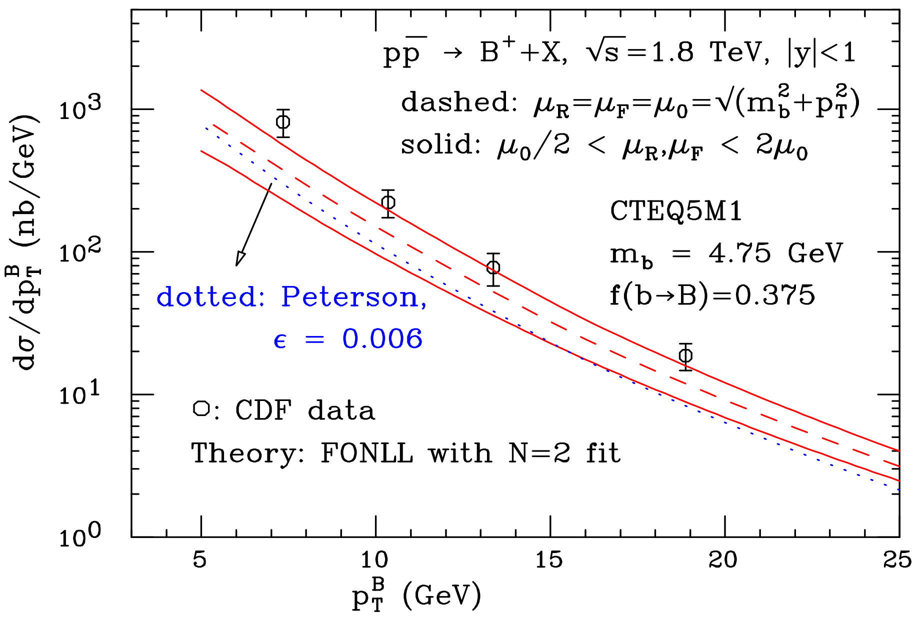
Perturbative and non-perturbative contributions are separately unphysical and must be properly matched

When this doesn't happen, fake discrepancies may appear

New Theoretical Results for B Meson Hadroproduction







The pQCD result is convoluted with a non-perturbative FF describing $b \longrightarrow B$ hadronization fitted in moment space to e^+e^- data. Proper matching and transportation of the relevant information are ensured

$\Longrightarrow$ No relevant discrepancy

Similar results for b-jets, which do not depend on non-perturbative information

NLO calculations of multi-particle/jet production (Binoth)

Aim: Efficient, largely automated calculation of NLO cross sections for

QCD <u>and</u> electroweak processes

wanted: processes like $pp \to 4\,jets$, $e^+e^- \to \nu\bar{\nu}\,WW, \ldots$ at NLO

[T. Binoth, J.Ph. Guillet, G. Heinrich, N. Mahmoudi, N. Kauer, C. Schubert]

New techniques:

- Tensor reduction avoiding Gram determinants
- Organization of amplitudes by analyticity structure
  $\Rightarrow$ isolation of IR divergences possible in a transparent manner
- Calculation of integrals: new approach
  (transition analytical $\to$ numerical at earlier stage)

Project: GOLEM : General One Loop Evaluation of Matrix Elements

possibility: interface with MC@NLO

Achieved so far:

1. Analytic calculation of massless amplitudes

   - 6-point amplitudes (still missing in QCD):
     - $\phi\phi \to \phi\phi\phi\phi$ (Yukawa model) done
     - $\gamma\gamma \to \phi\phi\phi\phi$
       $\mathcal{M}^{++}$ done (compact expression!)
       $\mathcal{M}^{+-}$ progress at this workshop
     - increase complexity of tensor structure gradually ...
   - 5-point amplitudes:
     direct calculation of $g\, g \to \gamma\, \gamma\, g$ finished at this workshop

$$\Gamma^{+++++} = 32 f^{abc} \frac{\mathrm{tr}(F_1^+ F_2^+)\mathrm{tr}(F_3^+ F_4^+ F_5^+)}{s_{34} s_{45} s_{35}}$$

2. Numerical calculation of massive amplitudes (electroweak sector)

   by combining deterministic and Monte Carlo integration methods: numerically stable and fast integration of scalar 6-point and 5-point functions with thresholds in integration region achieved

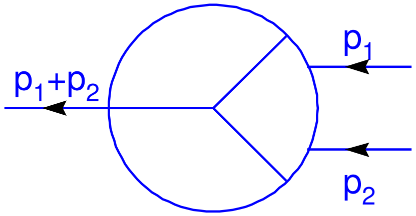
Numerical methods for NNLO (Heinrich)

1. Multi-loop integrals

Automated method ("sector decomposition") to disentangle overlapping divergences in parameter space

Pole coefficients: sums of finite integrals over functions of Feynman parameters and kinematic invariants $\{s_{ij}, m_i\} \rightarrow$ numerical integration

3-loop example (enters e.g. Drell-Yan at N^3LO)



$$G = (-s - i\delta)^{-2-3\epsilon} \left[\frac{0.02778}{\epsilon^6} + \frac{0.2288}{\epsilon^4} - \frac{0.6692}{\epsilon^3} - \frac{0.6152}{\epsilon^2} + \frac{2.005}{\epsilon} + 17.85 \right]$$

Problem for integrals with more than one scale: threshold singularities may hinder stable numerical evaluation $\rightarrow$ stick to Euclidean region – a very good check for very complicated analytical results

Needed: numerical integration routine which can deal with thresholds in multi-dimensional parameter space

2. Phase space integrals

The same problem again: overlapping divergences

The "conventional" procedure is:

A) Find appropriate subtraction terms

B) Integrate subtraction terms analytically in $D = 4 - 2\epsilon$ dimensions (to isolate IR poles from finite remainder)

Idea: isolate overlapping IR poles with generalized sector decomposition algorithm to obtain pole coefficients and finite remainder in terms of finite parameter integrals

$\longrightarrow$ which are integrated numerically (no problems with thresholds)

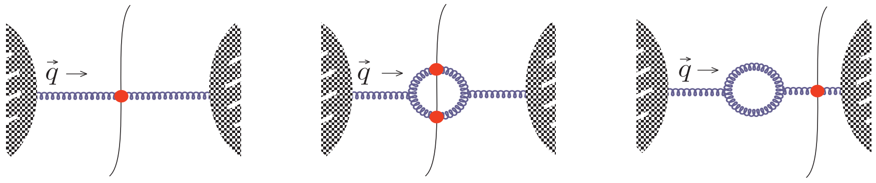
Note: the method can also serve as a check for analytically calculated subtraction terms

$\longrightarrow$ powerful tool to deal with NNLO phase space integrals

Fully numerical NLO and MC+NLO computations (Krämer)

Adding showers to a NLO calculation

- The NLO calculation



$$\mathcal{I}[\text{Born}] + \mathcal{I}[\text{real}] + \mathcal{I}[\text{virtual}] \quad = \quad \int \frac{d\vec{q}}{2|\vec{q}\,|}\, \mathrm{Tr}\Big\{ \not{q}\, R_0 + \int_0^\infty \frac{d\bar{q}^2}{\bar{q}^2} \int_0^1 dx \int_{-\pi}^{\pi} \frac{d\phi}{2\pi} \Big[\mathcal{M}_{g/q}(\bar{q}^2, x, \phi) R(\bar{q}^2, x, \phi) - \frac{\alpha_s}{2\pi}\, \mathcal{P}_{g/q}(\bar{q}^2, x)\, \not{q}\, R_0 \Big] \Big\}.$$

- The parton shower way

$$\mathcal{I}[\text{shower}] \quad = \quad \int \frac{d\vec{q}}{2|\vec{q}\,|}\, \mathrm{Tr}\Big\{ \int_0^\infty \frac{d\bar{q}^2}{\bar{q}^2} \int_0^1 dx \int_{-\pi}^{\pi} \frac{d\phi}{2\pi}\, \mathcal{M}_{g/q}(\bar{q}^2, x, \phi) R(\bar{q}^2, x, \phi) \times \exp\Big(- \int_{\bar{q}^2}^\infty \frac{d\bar{l}^2}{\bar{l}^2} \int_0^1 dz\, \frac{\alpha_s}{2\pi}\, \mathcal{P}_{g/q}(\bar{l}^2, z) \Big) \Big\}.$$

- The connection

$$\mathcal{I}[\text{Born}] + \mathcal{I}[\text{real}] + \mathcal{I}[\text{virtual}] = \mathcal{I}[\text{shower}] \times \big(1 + \mathcal{O}(\alpha_s^2)\big)\,.$$

The Beowulf project (Soper): do everything numerically

At the NLO, this implies the necessity of computing one IR-safe observable at the time (no event generation, no unweighting)

- Works for $e^+e^- \rightarrow 3$ jets at NLO
- Extended to Coulomb gauge
- Current work on matching with showers

The subtraction method at NNLO (Weinzierl)

Contributions at NNLO:

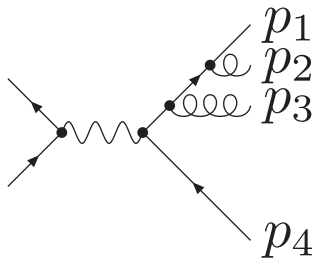
$$\begin{aligned}
d\sigma_{n+2}^{(0)} &= \left({\mathcal{A}_{n+2}^{(0)}}^* \mathcal{A}_{n+2}^{(0)} \right) d\phi_{n+2}, \\
d\sigma_{n+1}^{(1)} &= \left({\mathcal{A}_{n+1}^{(0)}}^* \mathcal{A}_{n+1}^{(1)} + {\mathcal{A}_{n+1}^{(1)}}^* \mathcal{A}_{n+1}^{(0)} \right) d\phi_{n+1}, \\
d\sigma_{n}^{(2)} &= \left({\mathcal{A}_{n}^{(0)}}^* \mathcal{A}_{n}^{(2)} + {\mathcal{A}_{n}^{(2)}}^* \mathcal{A}_{n}^{(0)} + {\mathcal{A}_{n}^{(1)}}^* \mathcal{A}_{n}^{(1)} \right) d\phi_{n},
\end{aligned}$$

Adding and subtracting:

$$\begin{aligned}
\langle \mathcal{O} \rangle_n^{NNLO} &= \int \left(\mathcal{O}_{n+2}\, d\sigma_{n+2}^{(0)} - \mathcal{O}_{n+1} \circ d\alpha_{n+1}^{(0,1)} - \mathcal{O}_{n} \circ d\alpha_{n}^{(0,2)} \right) \\
&+ \int \left(\mathcal{O}_{n+1}\, d\sigma_{n+1}^{(1)} + \mathcal{O}_{n+1} \circ d\alpha_{n+1}^{(0,1)} - \mathcal{O}_{n} \circ d\alpha_{n}^{(1,1)} \right) \\
&+ \int \left(\mathcal{O}_{n}\, d\sigma_{n}^{(2)} + \mathcal{O}_{n} \circ d\alpha_{n}^{(0,2)} + \mathcal{O}_{n} \circ d\alpha_{n}^{(1,1)} \right).
\end{aligned}$$

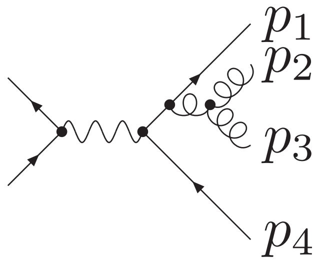
An example involving double unresolved configurations

The leading-colour contributions to $e^+e^- \rightarrow qgg\bar{q}$.



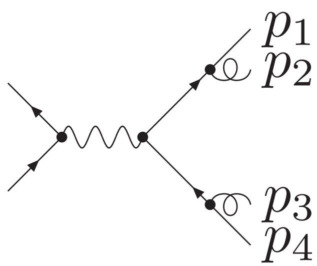
Double unresolved configurations:

- Two pairs of separately collinear particles
- Three particles collinear
- Two particles collinear and a third soft particle
- Two soft particles
- Coplanar degeneracy



Single unresolved configurations:

- Two collinear particles
- One soft particle



The problems: avoid overlapping IR divergences

disentangle double-unresolved and single-unresolved divergences

Outlook

Extension of the subtraction method to NNLO:

- Construction of the subtraction terms

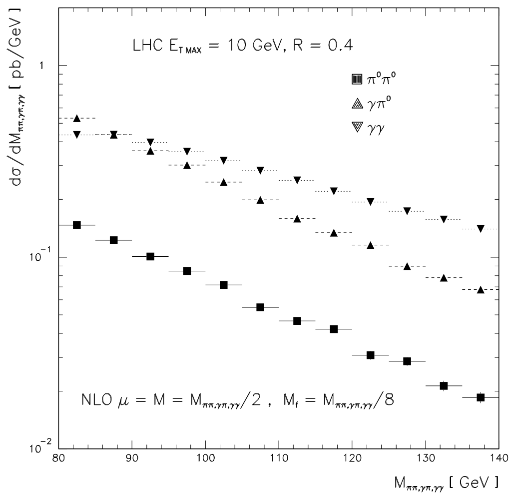
$\longrightarrow$ Subtracted matrix elements can be integrated numerically !

To be done:

- Analytic integration over the unresolved phase space

Diphoton production at the LHC

T. Binoth, J. Ph. Guillet, E. Pilon (DIPHOX), K. Lassila-Perini, A. Nikitenko (CMS), L. Fayard, G. Unal M. Escalier (ATLAS)



- Study of theoretical uncertainties of the full diphoton background to Higgs searches in $H \to \gamma\gamma$ initiated at the workshop
- Detailed comparison of Pythia vs. NLO QCD "DIPHOX" planned

Diphoton+jet production at the LHC (Del Duca)

Process computed at the NLO, and implemented in a MC-like program (parton level) which allows the definition of any acceptance cut

$$\frac{\sigma_{NLO}}{\sigma_{LO}} > 2 \quad \text{with} \quad R_\gamma = 0.4, \qquad \frac{\sigma_{NLO}}{\sigma_{LO}} = 1.3 - 1.6 \quad \text{with} \quad R_\gamma = 1$$

♦ (Joey) Huston, we have a problem: Severe isolation cuts lead to perturbative instability, loose isolation cuts lead to large background. Any way out?

Conclusions

Not yet! Matt and Kirsten will follow

Thanks to Eric, Matt, Kirsten, Thomas, Gudrun, Matteo, Stefan, Lorenzo, for so much help in the preparation of the summary

Improve the food soon (before the cook has an accident)

From the cahier de doleances of the School of Physics, 1984!!!!,

signed by *Almost All Participants*