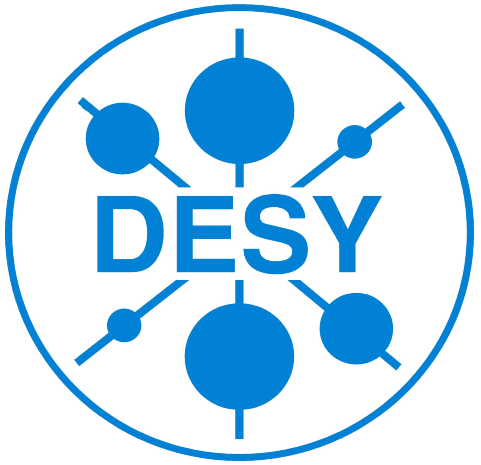
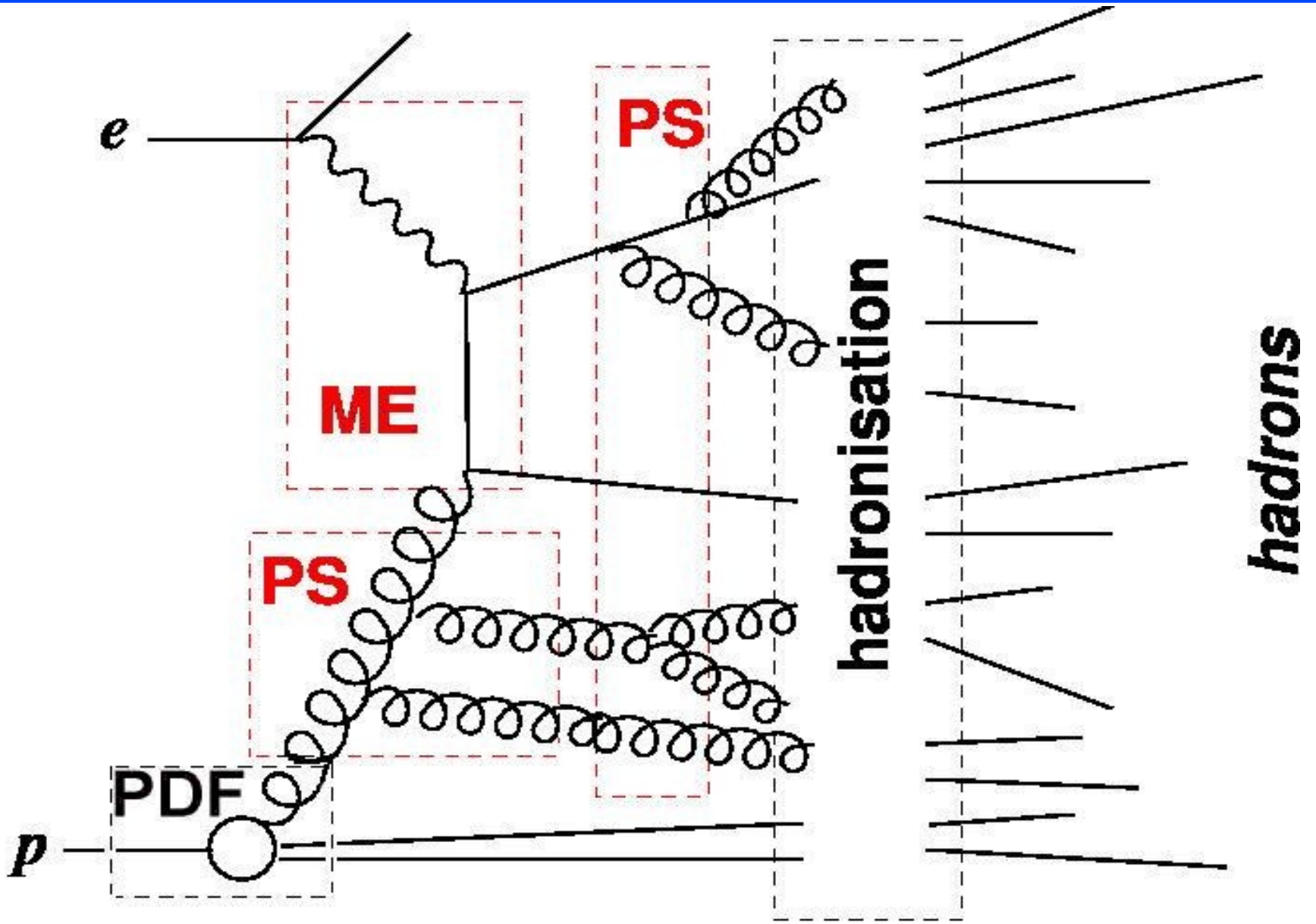


MC@NLO
Combining NLO-calculations and Parton Showers at HERA

DPG 7/3-08

Tobias Toll, H1
advised by Hannes Jung and Stefano Frixione

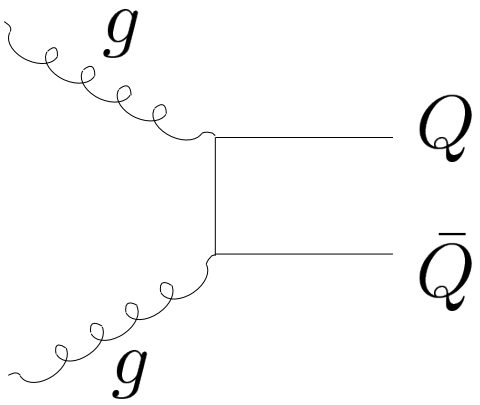
Overview Monte Carlo $ep \to e + X$

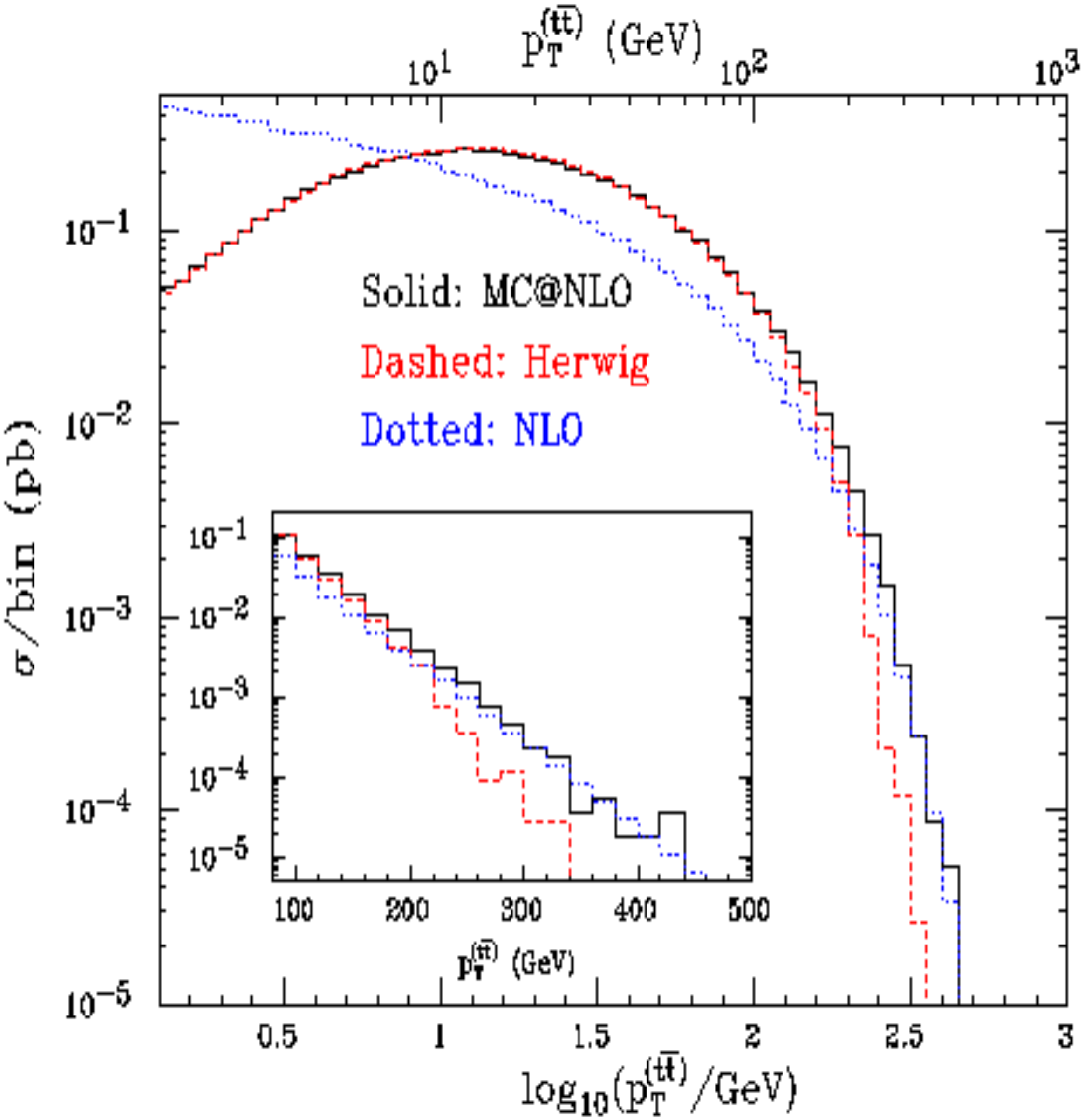


What is an MC@NLO?

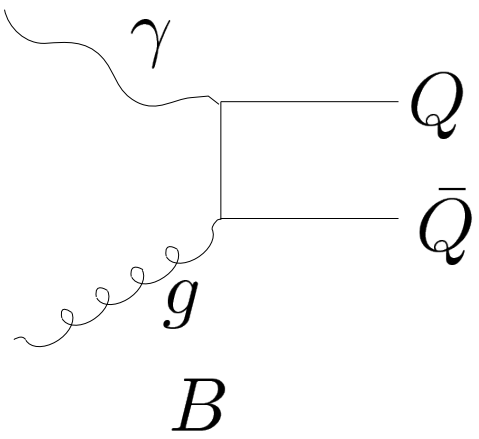
- NLO calculation of ME for heavy quark production (BGF)
- Parton Showers and Hadronisation from MC
- Matching the NLO ME with the PS
- The result is unweighted events
- Here the HERWIG MC is used and the NLO calculations are taken from FMNR.

Why MC@NLO?

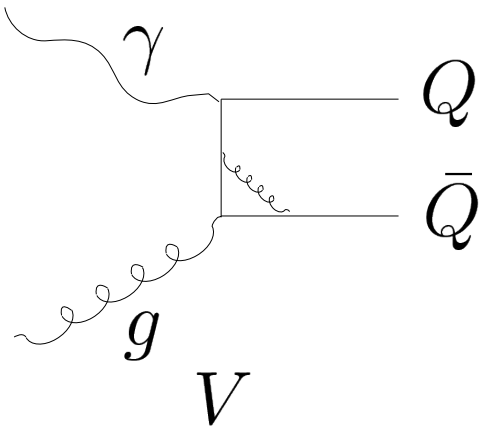

g
Q
$\bar{Q}$
g


$p_T^{(t\bar{t})}$ (GeV)
10^1
10^2
10^3
Solid: MC@NLO
Dashed: Herwig
Dotted: NLO
σ/bin (pb)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.5
1
1.5
2
2.5
3
$\log_{10}(p_T^{(t\bar{t})}/\mathrm{GeV})$
100
200
300
400
500

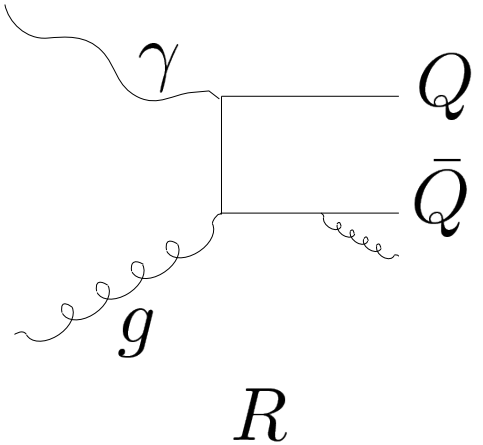
Next to Leading Order MEs for BGF



B



V



R

- Amplitudes for Born and Virtual Corrections interfere:

$$|A_m|^2 = B^*B + (B^*V + V^*B) + V^*V$$
$$\propto \alpha_s \qquad \propto \alpha_s^2 \qquad \propto \alpha_s^4$$

$$|A_{m+1}|^2 = R^*R$$
$$\propto \alpha_s^2$$

NLO calculation

$$\sigma = \int_{m+1} \left(\mathrm{d}\sigma^{\mathrm{Real}}\right) + \int_{m} \left(\mathrm{d}\sigma^{\mathrm{Born}} + \mathrm{d}\sigma^{\mathrm{Virtual}}\right)$$

Divergent Divergent

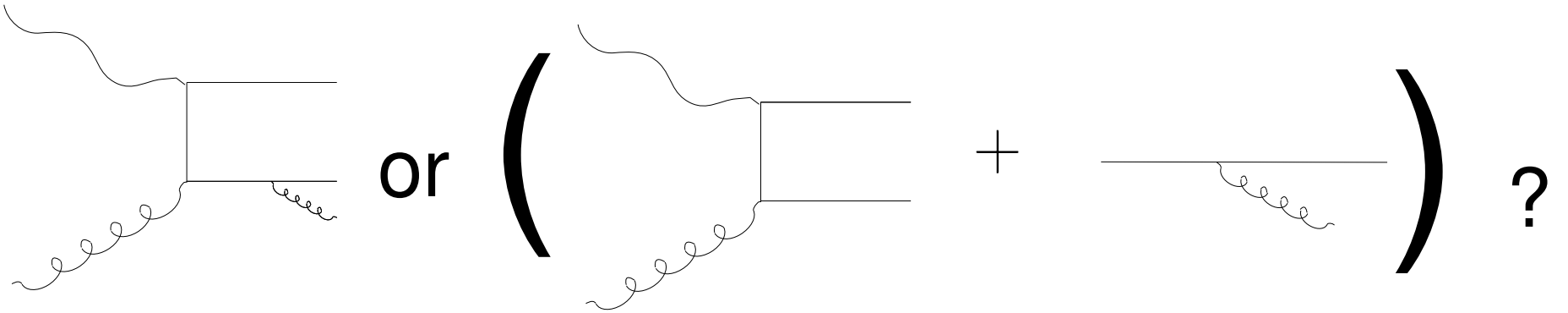
NLO calculation Subtraction

$$\sigma = \int_{m+1} \left(\mathrm{d}\sigma^{\mathrm{Real}} - \mathrm{d}\sigma^{\mathrm{subtr}}_{m+1} \right) + \int_{m} \left(\mathrm{d}\sigma^{\mathrm{Born}} + \mathrm{d}\sigma^{\mathrm{Virtual}} + \mathrm{d}\sigma^{\mathrm{subtr}}_{m} \right)$$

Event

Counter Event

MC@NLO: Double Counting



MC@NLO: Modified Subtraction

$$\sigma = \int_{m+1} \left(\mathrm{d}\sigma^{\mathrm{Real}} - \mathrm{d}\sigma_{MC} \right) +$$

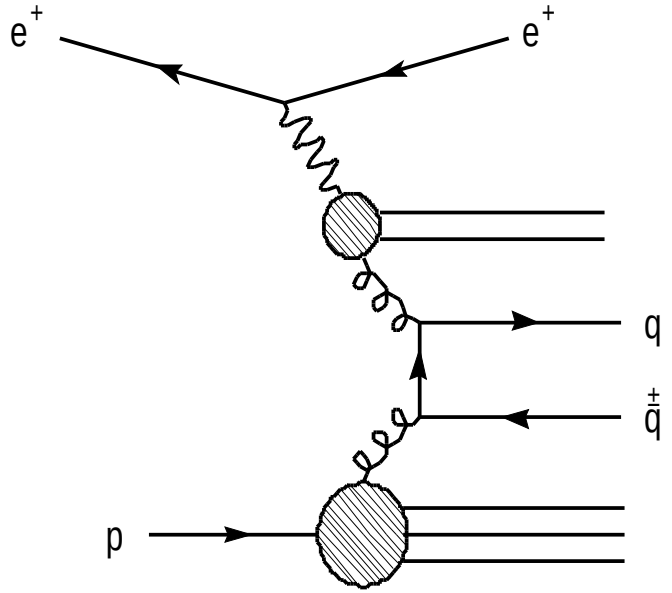
$$+ \int_{m} \left(\mathrm{d}\sigma^{\mathrm{Born}} + \mathrm{d}\sigma^{\mathrm{Virtual}} + \mathrm{d}\sigma_{MC} \right)$$

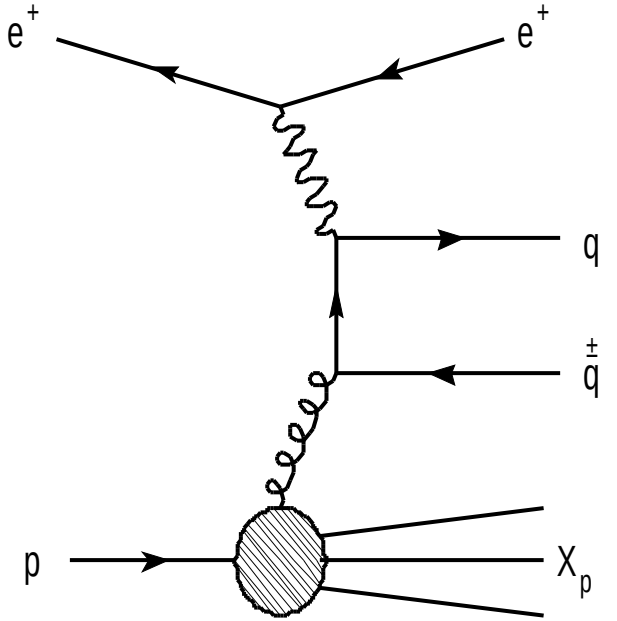
With the addition and subtraction of the PS emission both integrals become finite!!!

Some can still be negative counter events.

MC-subtraction terms for ep-scattering

- In ep-scattering two parts have to be considered separately:
  - the hadronic (resolved)
  - the direct interaction





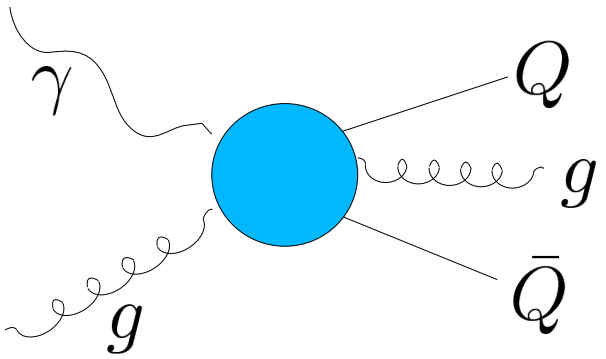
- Hadronic Case is not completely new
- For direct case MC subtraction terms need to be calculated

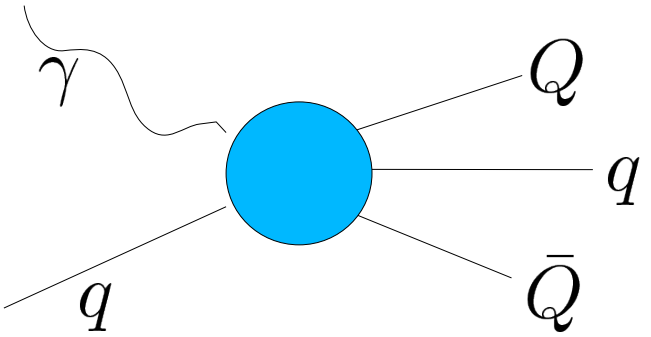
Calculation of direct MC-subtr. terms

- The MC subtraction terms for HERWIG all have the same general structure:

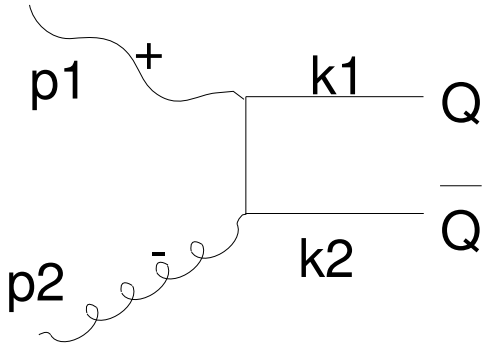
$$\sigma_{\mathrm{MC}} = \sigma_{\mathrm{Born}}^{(s,t,u)} \times P_{\mathrm{A.P.}}(z) \times \{\mathrm{PhaseSpace}, \mathrm{couplings}, \mathrm{PS} - \mathrm{regions\ etc.}\}$$

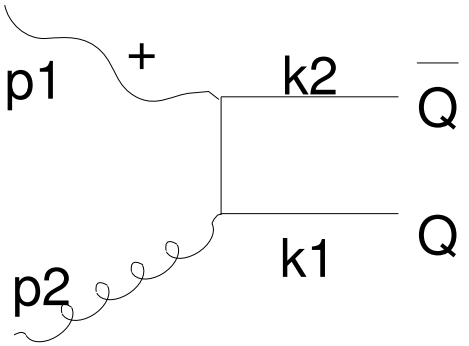
- Two main processes at Born level for direct case:
  - Photon-Gluon scattering
  - Photon-Quark/Antiquark scattering





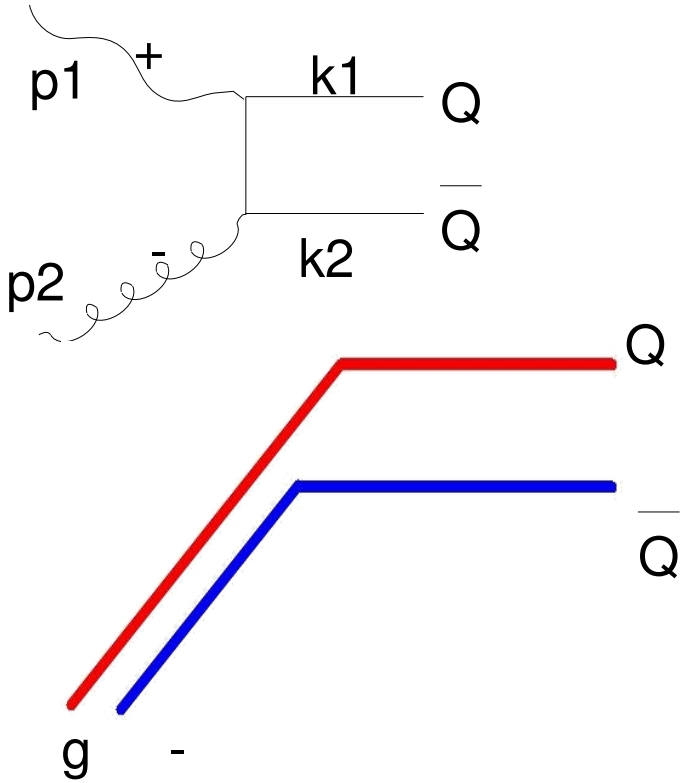
MC subtraction terms γg-scattering

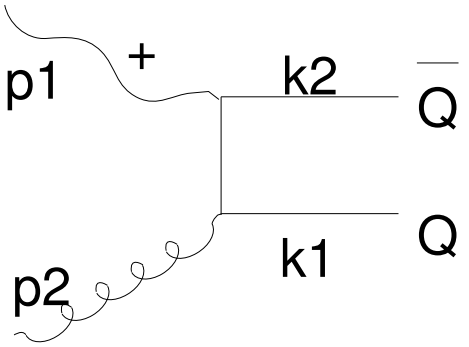




- Two diagrams at Born level
- Emissions possible from "–" leg and from outgoing legs (no QCD-emission from photon)

MC subtraction terms γg-scattering





Initial state radiation:

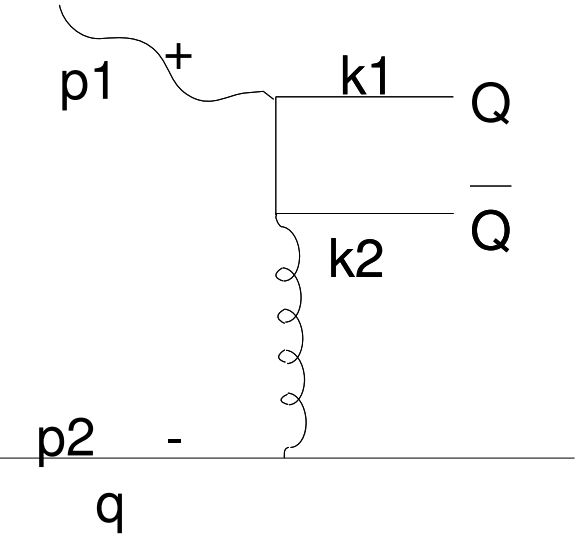
"-" leg: $d\sigma_{\gamma g}\left[\frac{1}{2}t+\frac{1}{2}u\right]\cdot P_{gg}$

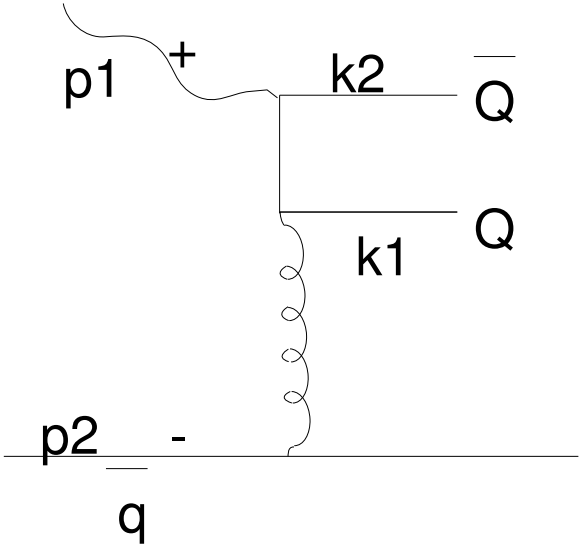
Final state radiation:

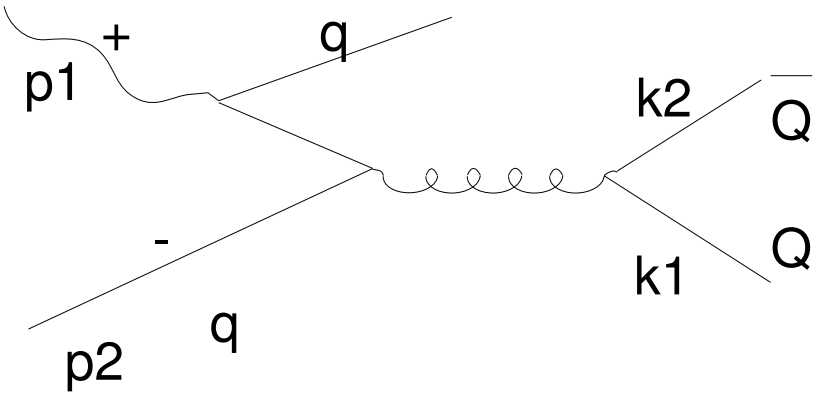
"Q" leg: $d\sigma_{\gamma g}\left[u\right]\cdot P_{qq}$

"$\overline{\text{Q}}$" leg: $d\sigma_{\gamma g}\left[t\right]\cdot P_{qq}$

MC subtraction terms γq-scattering

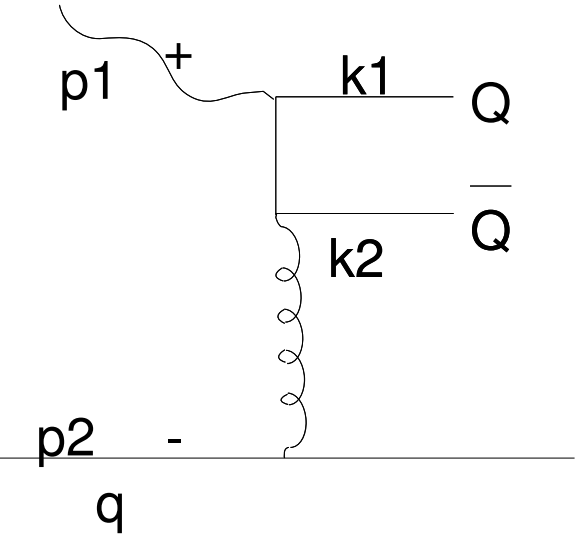


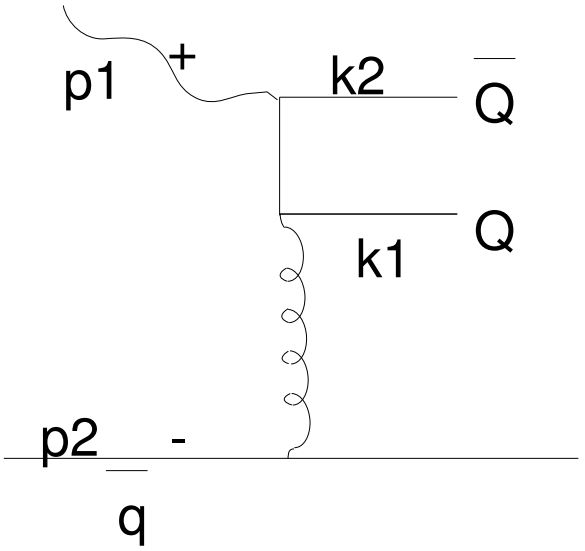


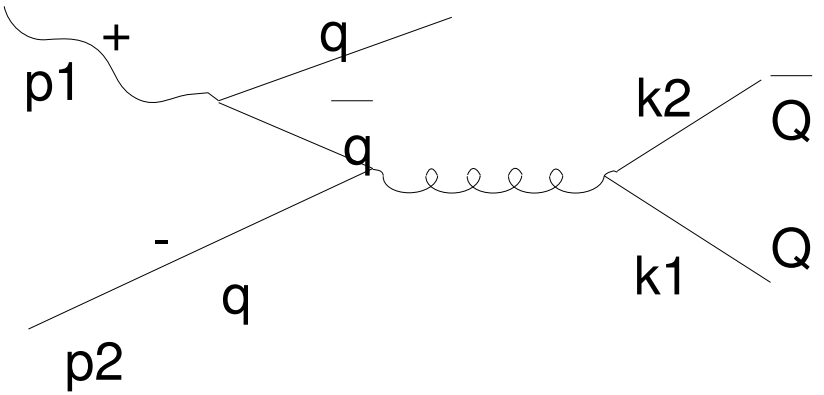


- In the first two diagrams only radiation from the "–" leg. Born is photon-gluon.
- In the third diagram only radiation from "+" leg. Here electromagnetic "splitting function" has to be used. Born is quark-antiquark

MC subtraction terms γq-scattering







"-" leg: $d\sigma_{\gamma g}\left[\frac{1}{2}t+\frac{1}{2}u\right]\cdot P_{gq}$

"+" leg: $d\sigma_{\bar{q}q}\left[u\right]\cdot P_{\gamma\to q\bar{q}}$

$$P_{\gamma\to q\bar{q}}=\frac{T_f}{N_C}\cdot P_{qg}$$

Internal Test of MC-terms

$$\frac{MC_{\text{subtr.}}(\cos\theta \to -1)}{MC_{\text{subtr.}}(\cos\theta = -1)}$$

**** Collinear- limit	**** Soft limit
0.911385659	1.0209289
0.963471603	0.999248357
0.988041227	0.999897717
0.996217561	0.999989494
0.998803796	0.999998902
0.9999995	1.00000232
0.99999995	1.00000023
0.999999995	1.00000002

Test of Divergency Cancellation

$$\frac{MC_{\text{subtr.}}(\cos\theta \to -1)}{ME_{2\to 3}(\cos\theta = -1)}$$

$$\frac{MC_{\text{subtr.}}(x \to 0)}{ME_{2\to 3}(x = 0)}$$

**** Collinear- limit

0.974061006
1.004122
1.00254968
1.00093199
1.00030953
0.999999501
0.99999995
0.999999995

**** Soft limit

1.00412524
0.998628304
0.999845295
0.999984345
0.99995661
0.999996662
0.999999666
0.999999967

This is the important test!!

Test of total rates - direct

- Comparison of NLO-rates between MC@NLO and FMNR. When implementation is correct these should be equal.
- This is a test of Double Counting cancellation!!

- Charm production [mb]

	Total Rate	Ratio
MC@NLO	0.8448 +/- .003	1.003 +/- 0.005
FMNR	0.8423 +/- .003	

- Beauty production [pb]

	Total Rate	Ratio
MC@NLO	5199 +/-30	0.997 +/- 0.006
FMNR	5215 +/-10	

Summary and Outlook

- When combining NLO ME and Parton showers there is a problem with double counting.
- In MC@NLO this problem is solved with process dependent MC Subtraction Terms. These terms also cancel the divergencies in the NLO calculation.
- I have successfully constructed and tested MC Subtraction Terms for Heavy Quark production in eP collisions, both for divergencies and doublecounting!

- The program is finished, apart from a HERWIG routine, which will be written by Brian Webber next week.
- MC@NLO for HERA will be ready by then and, when tested, ready for use in your analyses!!!