Monte Carlo School 2015
13-17 April 2015
DESY, Hamburg

Exercise 3 - Introduction

- Schedule:
  - Tuesday - Exercise 1:
    - Random numbers
    - MC method
    - MC integration
  - Wednesday - Exercise 2:
    - Sudakov form factor
    - MC solution of evolution equation
  - Thursday - Exercise 3
    - Calculation & simulation of Higgs production
    - Using MC solution of evolution equation → calculation of pt spectrum of Higgs at LHC

Original References...

PHYSICS REPORTS (Review Section of Physics Letters) 58, No. 5 (1980) 269–395. North-Holland Publishing Company

HARD PROCESSES IN QUANTUM CHROMODYNAMICS

Yu.L. DOKSHITZER, D.I. DYAKONOV and S.I. TROYAN

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Received 28 May 1979

Nuclear Physics B154 (1979) 427–440

SMALL TRANSVERSE MOMENTUM DISTRIBUTIONS IN HARD PROCESSES

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Received 8 February 1979

All order resummation - kinematics

Ellis, Fleishon,Stirling, PRD 24,1386 (1981)

- impose kinematic constraints ... delta function for k_t

$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim \prod_{i=1}^{N}\left[\int d^2k_{ti}dx_i M^{(N)}\right]\delta\left(\sum \vec{k}_{ti} + \vec{p}_t\right)$$

- **with for soft gluons** $M^{(N)} \sim \prod \frac{\alpha_s}{k_{ti}^2}$

➔ in limit of strong ordering:

$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim \prod_{i=1}^{N}\left[\int \frac{d^2k_{ti}}{k_{ti}^2}\log\frac{s}{k_{ti}^2}\right]\delta\left(\sum \vec{k}_{ti} + \vec{p}_t\right)$$

$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim p_t^2 \log\frac{s}{p_t^2}\int\frac{d^2k_{t,N-1}}{k_{t,N-1}^2}\log\frac{s}{k_{t,N-1}^2}\int\frac{d^2k_{t,N-2}}{k_{t,N-2}^2}\log\frac{s}{k_{t,N-2}^2}\cdots$$

All order resummation

- Iterative procedure:

$$\frac{d\sigma^{(1)}}{dp_t^2} \simeq \frac{1}{p_t^2}\log\frac{s}{p_t^2} = A$$

$$\frac{d\sigma^{(2)}}{dp_t^2} \simeq A\int\frac{d^2k_t}{k_t^2}\log\frac{s}{k_t^2} = A\frac{1}{2}\log^2\frac{s}{k_t^2}$$

$$\frac{d\sigma^{(3)}}{dp_t^2} \simeq \int\frac{d^2k_t}{k_t^2}\log\frac{s}{k_t^2}\frac{d\sigma^{(2)}}{dp_t^2} = A\frac{1}{2}\int\frac{d^2k_t}{k_t^2}\log^3\frac{s}{k_t^2} = A\frac{1}{2}\left(\frac{1}{2}\log^2\frac{s}{k_t^2}\right)^2$$

$$\frac{d\sigma^{(4)}}{dp_t^2} \simeq \int\frac{d^2k_t}{k_t^2}\log\frac{s}{k_t^2}\frac{d\sigma^{(3)}}{dp_t^2} = A\frac{1}{2}\frac{1}{4}\int\frac{d^2k_t}{k_t^2}\log^5\frac{s}{k_t^2} = A\frac{1}{2}\frac{1}{3}\left(\frac{1}{2}\log^2\frac{s}{k_t^2}\right)^3$$

$$\frac{d\sigma^{(N)}}{dp_t^2} \simeq A\frac{1}{(N-1)!}\left(\frac{1}{2}\log^2\frac{s}{k_t^2}\right)^{N-1}$$

- x-section for up to N gluons:

$$\frac{d\sigma}{dp_t^2} = \sum_i\frac{d\sigma^{(i)}}{dp_t^2} \simeq A\sum_i\frac{1}{(i-1)!}\left(\frac{1}{2}\log^2\frac{s}{p_t^2}\right)^{i-1}$$

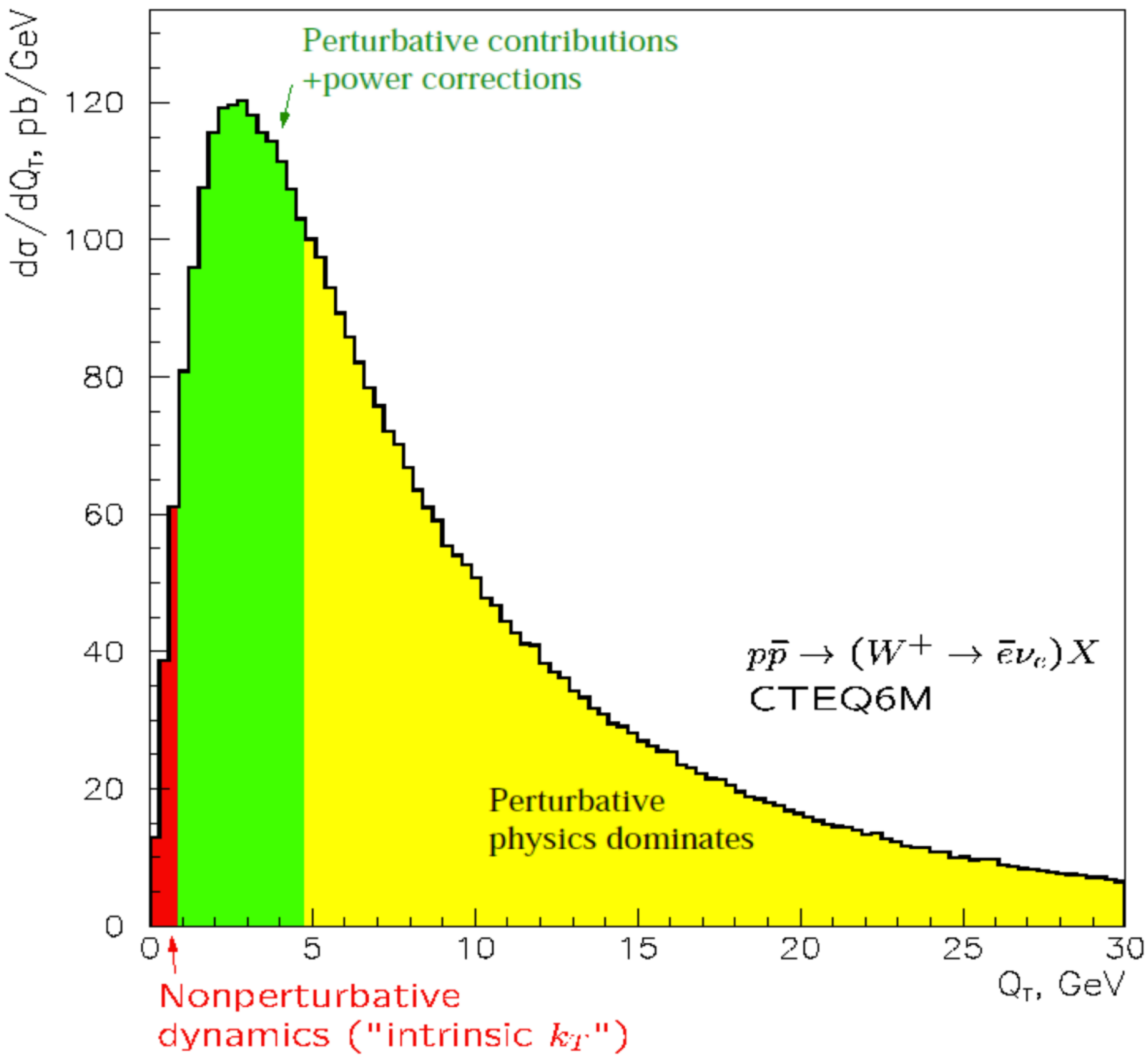
$$\simeq A\exp\left[\frac{1}{2}\log^2\frac{s}{p_t^2}\right]$$

Transverse Momentum of W/Z and Higgs

Fred Olness, CTEQ summerschool 2003

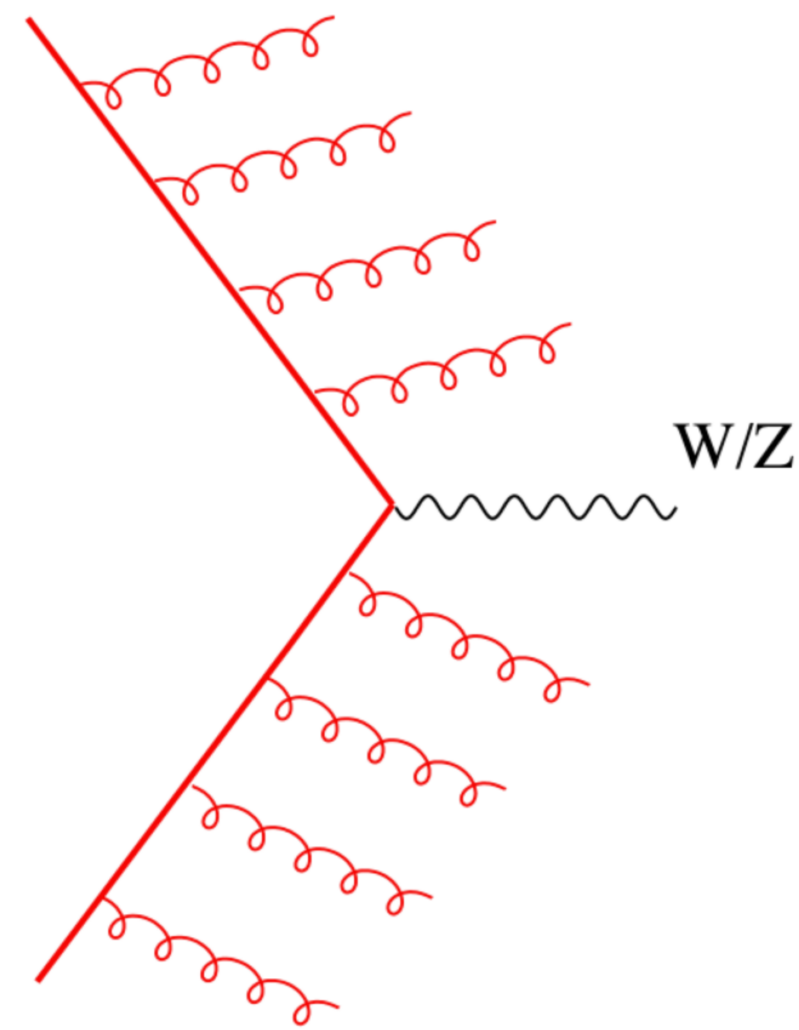
The complete P_T spectrum for the W boson

The full P_T spectrum for the W-boson showing the different theoretical regions



Monte Carlo approach

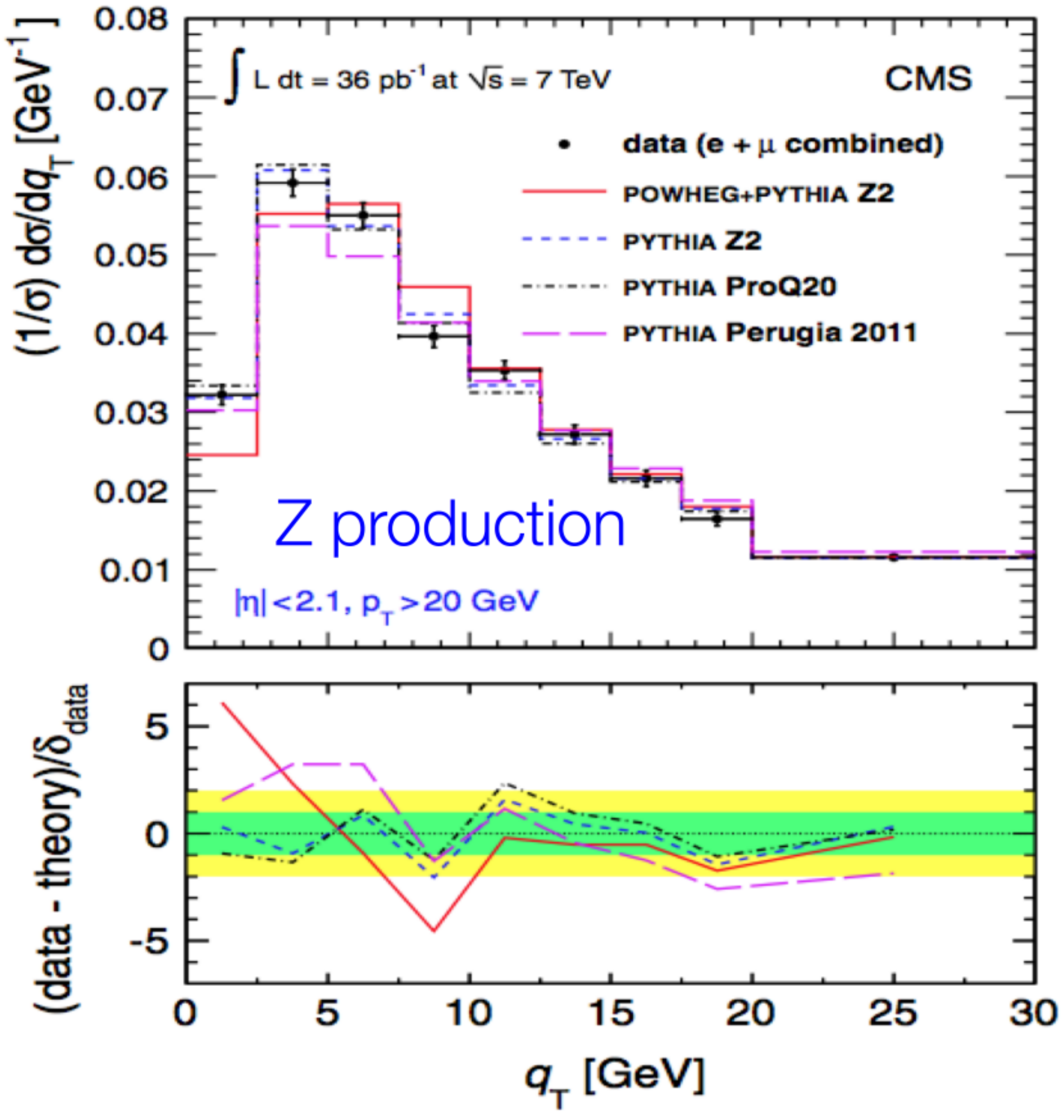
- simulate explicitly parton radiation with evolution of parton densities
- advantage to include properly energy momentum conservation in each step
- perform resummation numerically
- will be done in exercise !!!



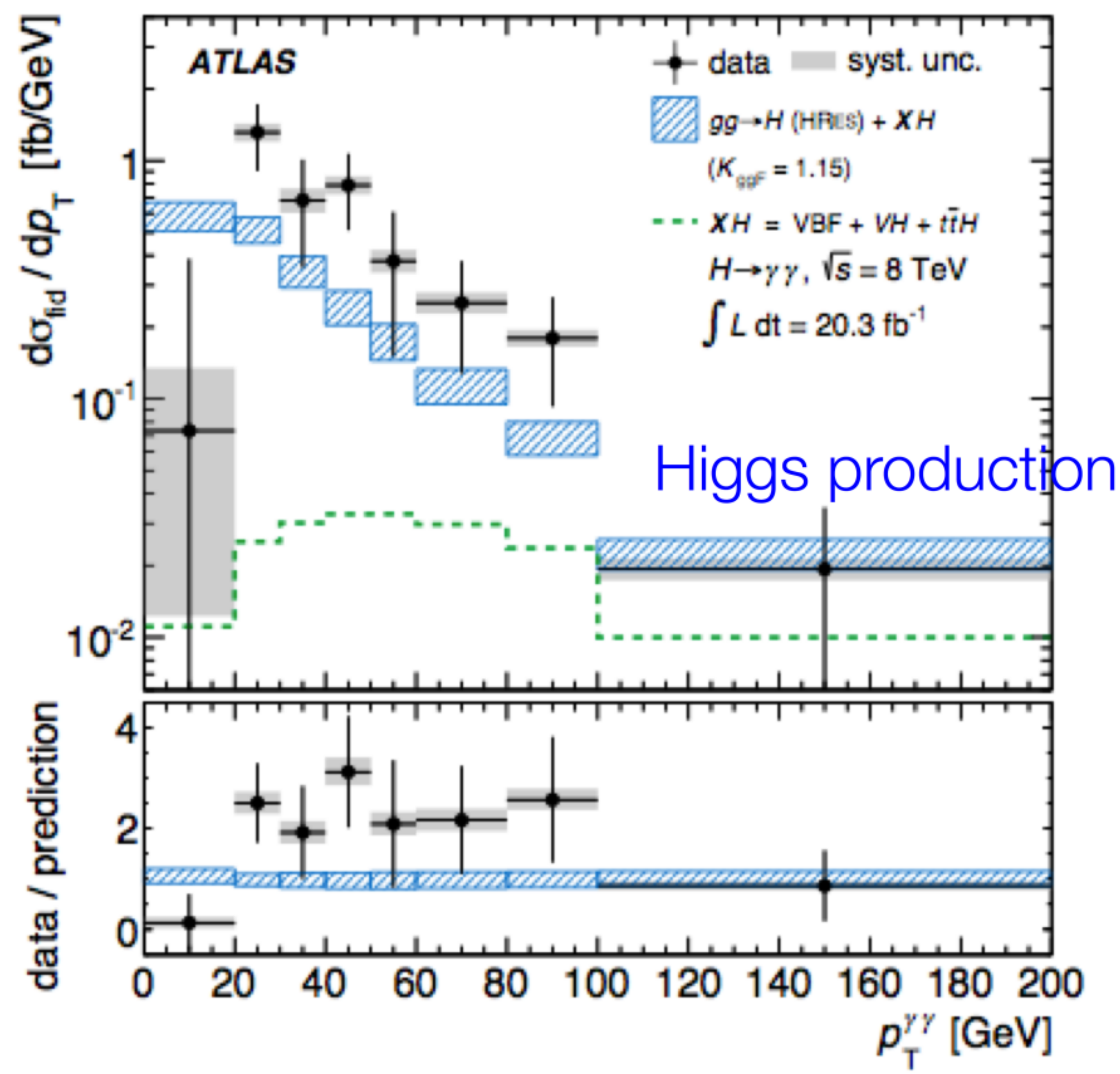
Transverse Momentum of Z and Higgs

CMS Coll. Measurement of the Rapidity and Transverse Momentum Distributions of Z Bosons in pp Collisions at√s = 7 TeV. Phys.Rev., D85:032002, 2012.

CMS Coll., PRD 85, 032002 (2012)



Differential cross sections of the higgs boson measured in the diphoton decay channel using 8 TeV pp collisions. ATLAS arXiv 1407.4222



Q_t - Resummation

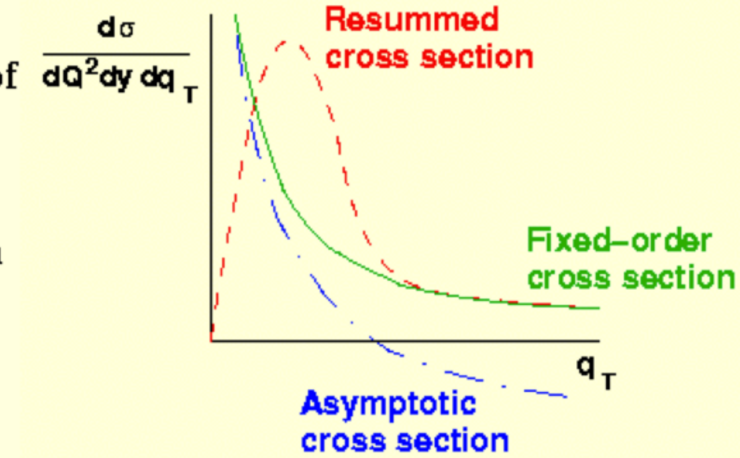
RESUMMED TRANSVERSE MOMENTUM DISTRIBUTIONS

go directly to the plotter

On this website, you can plot transverse momentum distributions for cross sections of several particle reactions. Currently, the following processes are implemented (p corresponds both to protons and antiprotons):

- Massive vector boson production: $pp \to W^{\pm}X$, $pp \to Z^0 X$
- Photon pair production: $pp \to \gamma\gamma X$
- Z-boson pair production: $pp \to Z^0 Z^0 X$
- SM Higgs boson production $pp \to H^0 X$

The output figure shows distributions $d\sigma/dQ^2 dy dq_T$ for the production of *on-shell* particles (or pairs of *on-shell* particles in the case of the $\gamma\gamma$ and ZZ production) with specified invariant mass Q, rapidity y and transverse momentum q_T in the lab frame (the center-of-mass frame of the hadron beams). You can plot resummed, fixed-order and asymptotic cross sections. For a short explanation of these quantities, visit **this page** (for a detailed explanation see, for instance, a paper by J.C. Collins, D.E. Soper and G. Sterman in Nucl. *Phys. B250, 199 (1985)*).

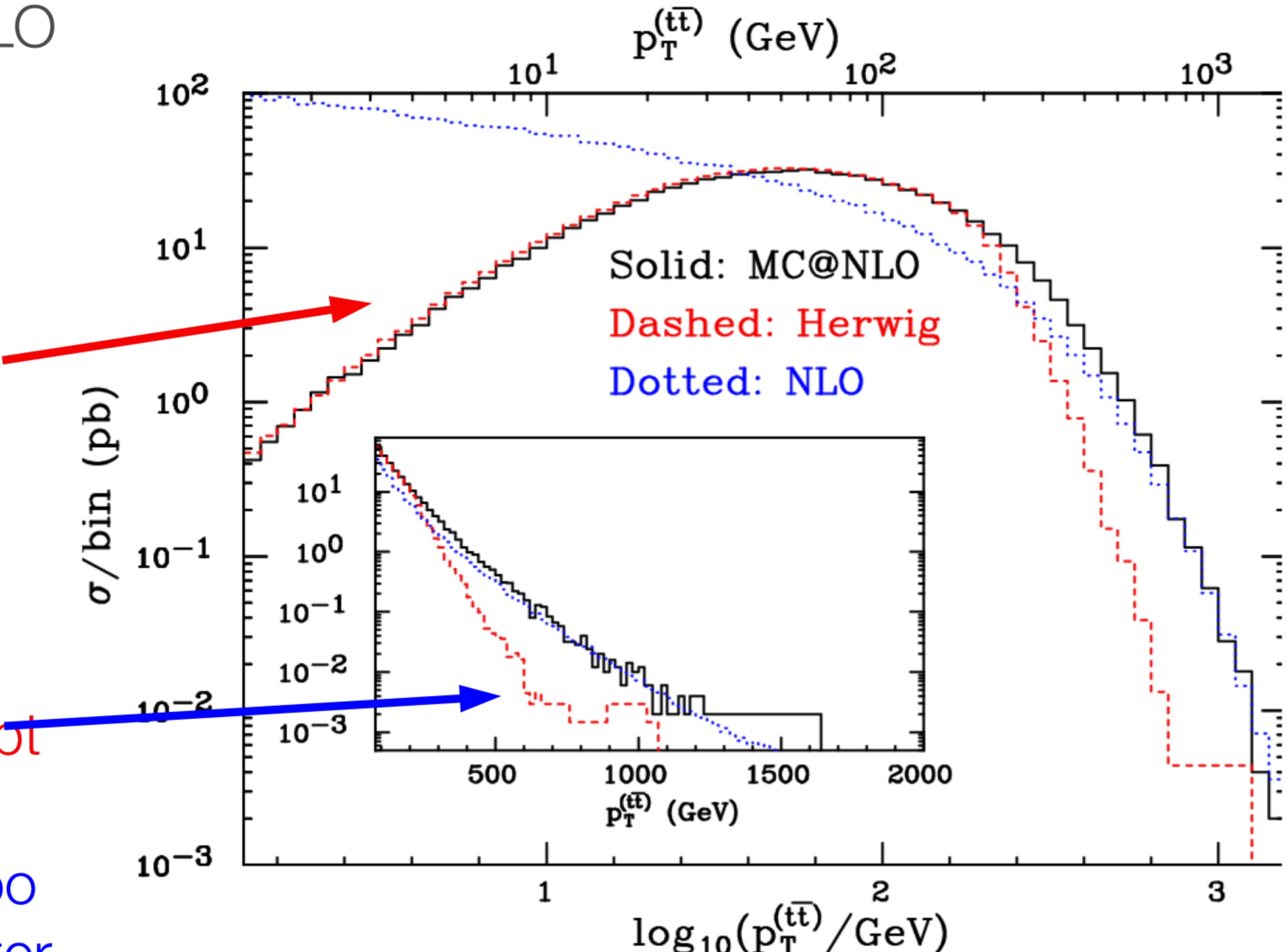


http://hep.pa.msu.edu/wwwlegacy/

Small pt in heavy quark prod.

Frixione et al, hep-ph/035252

- Compare fixed NLO calculation of top production with resummed calculation from Monte Carlo
- Similar effects at small pt are observed: Suppression of xsection at small pt
- At large pt, resummation is too small, NLO is better



Exercise 3

Exercises 3 (16. April 2015)

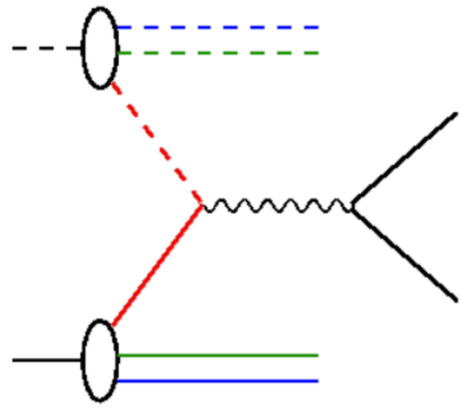
8. Calculate $\sigma(p+p \to h)$ (Higgs production via gluon fusion) in lowest order. Take $\sqrt{s} = 7000$ GeV. Calculate the total cross section, and plot x_1, x_2 and y_h. Require $120 < m_h < 130$ GeV. Plot the transverse momenta of the incoming partons. Use for simplicity parton density of the form $xg(x) = 3(1-x)^5$.
   The Higgs cross section is:
$$\sigma(g+g \to h) = \alpha_s^2 \frac{\sqrt{2}}{\pi} \frac{G_F}{576}$$
   with $G_F = 1.166 \cdot 10^{-5}$ GeV^{-1} and $\alpha_s = 0.1$.
   Use a Breit-Wigner form for the Higgs:
$$P(m) = \frac{1}{2\pi} \frac{\Gamma_h}{(m-m_h)^2 + \Gamma_h^2/4}$$
   with $m_h = 125$ GeV and $\Gamma_h = 0.4$ GeV. Calculate the cross section.
   Include in the calculation a small intrinsic transverse momentum from both of the incoming partons. Assume $h(k_t) = \exp\left(-bk_t^2\right)$. Using $b = 1$ corresponds to a gauss distribution with $\mu = 0$ and $\sigma \sim 0.7$. Plot the transverse momentum k_t and the transverse momentum squared k_t^2 of both incoming partons and the resulting h.
   Write the code in a modular way, such that it can be used for the last exercise.

9. Use the evolved pdf (from previous exercise) to calculate higgs production from above. Set the scale $t = 10000$ GeV^2. Use for simplicity the a gluon density $xg(x) = 3(1-x)^5$ as a starting distribution and use P_{gg}. Calculate the transverse momentum of the incoming partons and calculate the transverse momentum of the Higgs. Plot the x-values of the incoming partons and the transverse momenta.

Rapidities and all that ...

- define rapidity:

$$y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$$



$$y(l^+\, l^-)\ \text{pair} = y(q\bar{q})\ \text{pair}$$

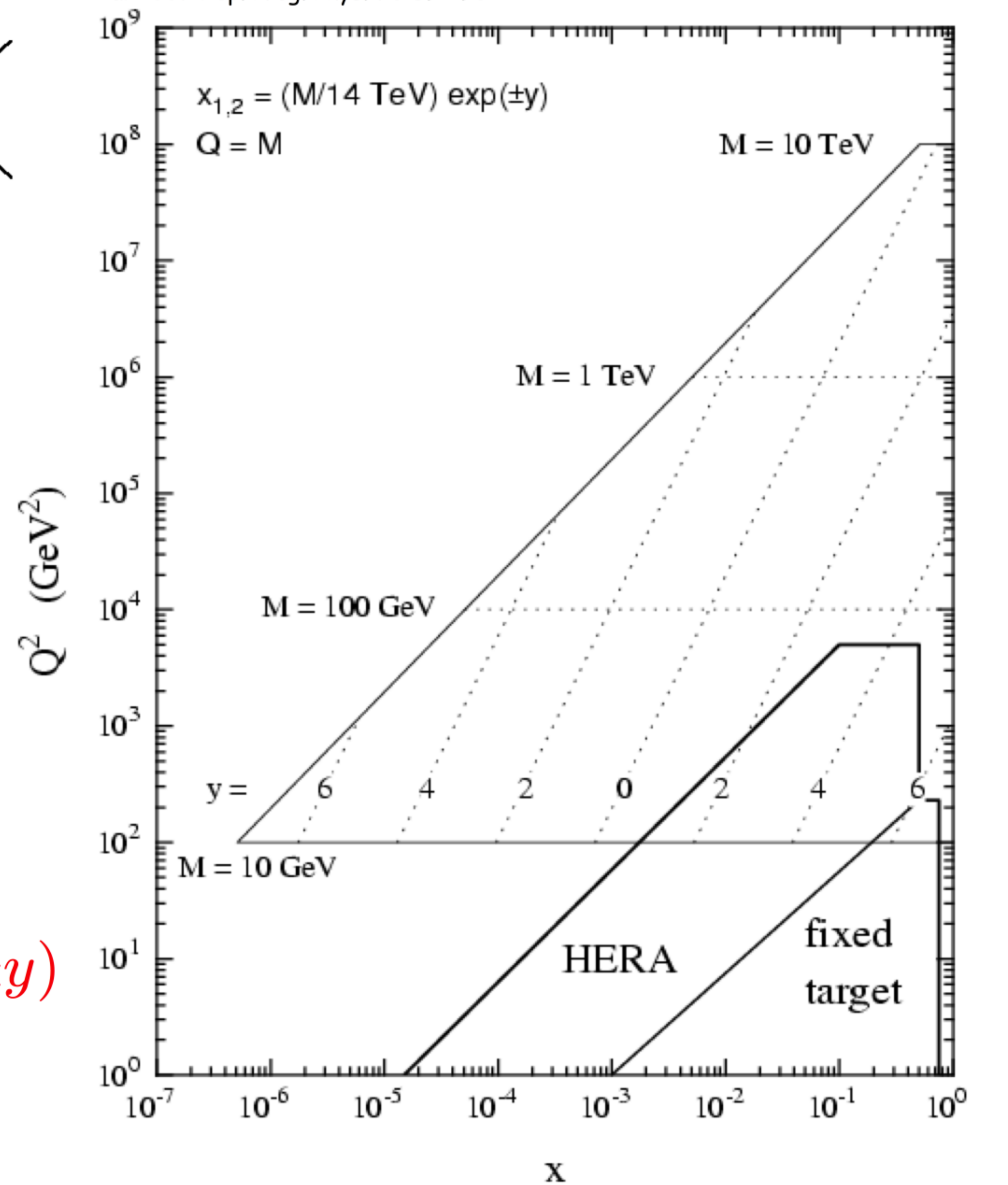
- gives: $y = \frac{1}{2}\log\frac{x_1}{x_2}$

- using: $\tau = \frac{M^2}{s} = x_1 x_2$

- gives:

$$x_{1,2} = \sqrt{\tau}\exp(\pm y) = \frac{M}{\sqrt{s}}\exp(\pm y)$$

Hard interactions of quarks and gluons: a primer for LHC physics J M Campbell et al 2007 Rep. Prog. Phys. 70 89-193



How to get started

- utilities:

```
courselib.h: include headers
ranlxd.h, ranlxd.cc: random number generator ranlux
```

- initialize ROOT (needed for plotting)

```
module avail
module load root/5.34
```

- copy all the templates (be careful, do not to overwrite …)

  cp -rp /afs/desy.de/user/s/school30/public/Exercises .

- compiling and running:

```
cd exercise-1
make -f makefile-example-1
./example-1
```

- templates are provided which include the general structure – you only have to fill the interesting – important parts … good luck

Computing setup

- Connect either to eduroam or to the school network:

  Name: terascale

  WPA/WPA2-PSK: XxPWjNH7

- All will get school accounts for naf:
  - for example: ssh -X school30@naf-school01.desy.de
  - create folder:

    `cd public`
  - copy all templates:

    cp -rp /afs/desy.de/user/s/school30/public/Exercises .

- Writeup, Exercise sheets, templates and solutions at:

  `http://www.desy.de/~jung/mcschool2015/`