Welcome!
Welcome

• Summer student projects will be completely online
  • has big advantages
    • many more students could participate
    • equal access for everybody, provided internet works and allow access
DESY summer-students 2021

24 Countries out of 193 countries of the United Nations and 2 countries that are non-member observer states: the Holy See and the State of Palestine.

Summerstudent program organized by: Olaf Behnke, Gernot Meier
Welcome

- Summerstudent projects will be completely online
  - has big advantages
    - many more students could participate
    - equal access for everybody, provided internet works and allow access

- We decided to accept everybody who applied, no selection is made.
  - on purpose, because
    - we want to give everybody a chance
    - we want to bring people from different regions together

- This means, we have:
  - 24 students in B8
  - 2 students in B9
  - 2 students in B10


Topics

• B8: New QCD predictions for ep deep inelastic scattering and comparison with measurements (Hannes Jung, Qun Wang)

  Investigation of ep measurements in the QCD field and comparison with theoretical predictions. We will start with measurements from HERA experiments and implement the measurements into computer codes (Rivet) for comparison with Monte Carlo (MC) event generators. We will learn, how MC generators work and will study different features in detail.

• B9: MC4TMD - determination of Transverse Momentum Dependent parton densities with Monte Carlo event generators (Sara Taheri Monfared, H.Jung)

  We will study Monte Carlo event generators and calculate transverse momentum distributions for the interacting partons after initial and final state parton shower, and provide them in form of transverse momentum dependent (TMD) parton distributions. We will use Pythia and Herwig (and perhaps Sherpa) MC event generators.

• B10: POWHEG and PartonBranching TransverseMomentumDependent parton densities (Armando Bermudez Martinez, Luis Ignacio Estevez Banos)

  We will study the NLO Monte Carlo event generator POWHEG and merge the NLO calculation with transverse momentum dependent (TMD) parton distributions and the TMD parton shower. We will compare these new calculations with recent measurements obtained at the LHC.
CMS QCD summer-students 2021

- B8
- B9
- B10
Program

- We will learn about QCD and Monte Carlo event generators
- We learn how to analyze events generated from Monte Carlo event generators to make predictions
  - We will use Rivet for analyzing Monte Carlo events

Today:
- Intro to QCD and Monte Carlo event generators
- Intro to Rivet
The detectors
The detectors

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g. Pion)
- Light Green: Neutral Hadron (e.g. Neutron)
- Blue Dashed: Photon

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Transverse slice through CMS
What is this?
Events at HERA ...

\[ \sqrt{s} \sim 318 \text{ GeV} \]

\[ x \sim 7 \times 10^{-5} \text{ at } Q^2 = 4 \text{ GeV}^2 \]
From experiment to measurement

- take data
- run MC generator
- detector simulation
- Compare measurement with simulation

Uppppps ...... all measurements rely on proper MC generators and MC simulation !!!!
From experiment to measurement

- take data
- run MC generator
- detector simulation

define visible $x$ - section in kinematic variables

$$\frac{d\sigma_{\text{data}}^{\text{had}}}{dx} = \frac{d\sigma_{\text{data}}^{\text{det}}}{dx} C_{\text{corr}} \text{ with } C_{\text{corr}} = \frac{d\sigma_{\text{MC}}^{\text{had}}}{dx} \frac{d\sigma_{\text{MC}}^{\text{det}}}{dx}$$

visible $x$-section on hadron level

Uppppps ...... all measurements rely on proper MC generators and MC simulation !!!!!
How can processes be calculated?

- Monte Carlo method
  - refers to any procedure that makes use of random numbers
  - uses probability statistics to solve the problem
- Monte Carlo methods are used in:
  - Simulation of natural phenomena
  - Simulation of experimental apparatus
  - Numerical analysis
The easy case: $e^+e^- \rightarrow X$

- use $e^+e^- \rightarrow \mu^+\mu^-$
- $e^+e^- \rightarrow q\bar{q} \rightarrow$ hadrons
- cross
- and for quarks

In QED:

$\sigma(e^+e^- \rightarrow l^+l^-) = \frac{4\pi\alpha^2}{3s}$

$\sigma(e^+e^- \rightarrow q\bar{q}) = 3\frac{4\pi\alpha^2}{3s}e_q^2$

⇒ but quarks carry color and fractional charge ！！！！!
Monte Carlo method

- Monte Carlo method
  - refers to any procedure that makes use of random numbers
  - uses probability statistics to solve the problem
- Monte Carlo methods are used in:
  - Simulation of natural phenomena
  - Simulation of experimental apparatus
  - Numerical analysis
- Random Numbers
  - one of them is 3
  - No such thing as a single random number
  - A sequence of random numbers is a set of numbers that have nothing to do with the other numbers in a sequence
Random Numbers

• In a uniform distribution of random numbers in $[0,1]$ every number has the same chance of showing up

• Note that 0.000000001 is just as likely as 0.5

To obtain random numbers:

• Use some chaotic system like roulette, lotto, 6-49, ...

• Use a process, inherently random, like radioactive decay

• Tables of a few million truly random numbers exist ..... (.....until a few years ago.....)

**BUT** not enough for most applications

→ .... we have true random number generators ...
Generating distributions

• Brute Force or Hit & Miss method
  • use this if there is no easy way to find a analytic integrable function
  • find \( c \leq \max f(x) \)
  • reject if \( f(x_i) \leq u_j \cdot c \)
  • accept if \( f(x_i) \geq u_j \cdot c \)
Generating distributions: Hit & Miss

**MC for function f(x):**
- get random number: R1 in (0,1) and R2 in (0,1)
- calculate $x = R1$
- reject event if: $f_x < f_{\text{max}} \times R2$
MC for function $f(x)$:
get random number:
R1 in $(0,1)$ and R2 in $(0,1)$
calculate $x = R1$
reject event if: $f_x < f_{\text{max}}$ R2
Generating distributions: Hit & Miss

**MC for function $f(x)$:**
get random number:
R1 in (0,1) and R2 in (0,1)
calculate $x = R1$
reject event if: $f_x < f_{max} \cdot R2$

Works always:
→ but can be very inefficient
Constructing a MC for $e^+e^-\rightarrow\mu^+\mu^-$

- process: $e^+e^-\rightarrow\mu^+\mu^-$
  \[
  \frac{d\sigma}{d\cos\theta d\phi} = \frac{\alpha_{em}^2}{4s} \left(1 + \cos^2\theta\right)
  \]

- goal: generate 4-momenta of $\mu$'s, need cm energy $s$, $\cos\theta$, $\phi$

random number $R1(0,1)$: $\phi = 2\pi R1$
random number $R2(0,1)$: $\cos\theta = -1 + 2R2$

for every $R1$, $R2$ use weight with $\frac{d\sigma}{d\cos\theta d\phi}$

after $10^6$ events
Example event: $e^+e^- \rightarrow \mu^+ \mu^-$

- example from PYTHIA: Event listing

<table>
<thead>
<tr>
<th>particle/jet</th>
<th>KS</th>
<th>KF</th>
<th>orig</th>
<th>p_x</th>
<th>p_y</th>
<th>p_z</th>
<th>E</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 le+</td>
<td>21</td>
<td>-11</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>30.000</td>
<td>30.000</td>
<td>0.001</td>
</tr>
<tr>
<td>2 le-</td>
<td>21</td>
<td>11</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>-30.000</td>
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<td>3 le+</td>
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<td>4 le-</td>
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<td>0.000</td>
</tr>
<tr>
<td>5 le+</td>
<td>21</td>
<td>-11</td>
<td>3</td>
<td>0.143</td>
<td>0.040</td>
<td>26.460</td>
<td>26.460</td>
<td>0.000</td>
</tr>
<tr>
<td>6 le-</td>
<td>21</td>
<td>11</td>
<td>4</td>
<td>0.000</td>
<td>0.000</td>
<td>-29.998</td>
<td>29.998</td>
<td>0.000</td>
</tr>
<tr>
<td>7 lZ0t</td>
<td>21</td>
<td>23</td>
<td>0</td>
<td>0.143</td>
<td>0.040</td>
<td>-3.539</td>
<td>56.458</td>
<td>56.347</td>
</tr>
<tr>
<td>8 Imu-</td>
<td>21</td>
<td>13</td>
<td>7</td>
<td>-9.510</td>
<td>1.741</td>
<td>24.722</td>
<td>26.546</td>
<td>0.106</td>
</tr>
<tr>
<td>9 Imu+</td>
<td>21</td>
<td>-13</td>
<td>7</td>
<td>9.653</td>
<td>-1.700</td>
<td>-28.261</td>
<td>29.913</td>
<td>0.106</td>
</tr>
<tr>
<td>10 (Z0)</td>
<td>11</td>
<td>23</td>
<td>7</td>
<td>0.143</td>
<td>0.040</td>
<td>-3.539</td>
<td>56.458</td>
<td>56.347</td>
</tr>
<tr>
<td>11 gamma</td>
<td>1</td>
<td>22</td>
<td>3</td>
<td>-0.143</td>
<td>-0.040</td>
<td>3.539</td>
<td>3.542</td>
<td>0.000</td>
</tr>
<tr>
<td>12 mu-</td>
<td>1</td>
<td>13</td>
<td>8</td>
<td>-9.510</td>
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<td>0.106</td>
</tr>
</tbody>
</table>

sum: 0.00 0.000 0.000 0.000 60.000 60.000

- technicalities/advantages
  - can work in any frame
  - Lorentz-boost 4-vectors back and forth
  - can calculate any kinematic variable
  - history of event process
Transition from Quarks to Hadrons

- use concept of local parton-hadron duality

\[
\frac{d\sigma}{d \cos \theta d\phi} = \frac{\alpha_{em}^2}{4s} \left( 1 + \cos^2 \theta \right)
\]

linear confinement potential: \( V(r) \sim -1/r + \kappa r \)
with \( \kappa \sim 1 \) GeV/fm
qq connected via color flux tube of transverse size of hadrons (~1 fm)
color tube: uniform along its length \( \rightarrow \) linearly rising potential

\( \rightarrow \text{Lund string fragmentation} \)
Models for jet evolution

- **Parton Showering**
  - Color field of Lund string interpreted in terms of gluons
  - successive parton radiation, with splitting function
  - ordering introduced explicitly:
    - virtuality, pt or angular ordered
  - need to take care of recoil
  - implemented in JETSET/PYTHIA/HERWIG
The fun with ep scattering

- Deep Inelastic Scattering is a incoherent sum of $e^+ q \rightarrow e + q$
- only 50% of p momentum carried by quarks
- need a large gluon component
- partonic part convoluted with parton density function $f_i(x)$

$$\sigma(e^+ p \rightarrow e^+ X) = \sum_i f_i(x) \sigma(e^+ q_i \rightarrow e^+ q_i)$$
The fun with ep scattering

- Deep Inelastic Scattering is an incoherent sum of $e^+ q \rightarrow e + q$
- Only 50% of p momentum carried by quarks
- Need a large gluon component
- Partonic part convoluted with parton density function
- BUT we know, PDF depends on resolution scale

$$\sigma(e^+ p \rightarrow e^+ X) = \sum_i f_i(x, Q^2) \sigma(e^+ q_i \rightarrow e^+ q_i)$$
$F_2(x,Q^2)$: DGLAP evolution equation

- QPM: $F_2$ is independent of $Q^2$

- $Q^2$ dependence of structure function: Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

$F_2 = OPM + QCDC + BGF$

$\Rightarrow$ Test of theory: $Q^2$ evolution of $F_2(x,Q^2)$ !!!!!
From Naïve $F_2$ picture to QCD ...

From Halzen & Martin: Quarks & Leptons, p201

if the proton is

then $F_2(x)$ is

if the proton is

then $F_2(x)$ is

valence

sea

small x
Lepton Hadron scattering

- Deep Inelastic Scattering is a incoherent sum of

\[ \sigma(e^+ p \to e^+ X) = \sum_i f_i(x, Q^2) \sigma(e^+ q_i \to e^+ q_i) \]

- only 50% of p momentum carried by quarks
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Lepton Hadron scattering

- Deep Inelastic Scattering is a incoherent sum of \( e^+ q \rightarrow e + q \)

\[
\sigma(e^+ p \rightarrow e^+ X) = \sum_i f_i(x, Q^2) \sigma(e^+ q_i \rightarrow e^+ q_i)
\]

- only 50 % of p momentum carried by quarks
- need a large gluon component

H1 and ZEUS preliminary
Inelastic Scattering: main results

- $F_2$ scaling at large $x$
- $\sim$ 50% gluons
- $F_2$ rise at small $x$
  - How can rising $F_2$ be understood?
  - Does rise continue forever?
  - What limits $F_2$?
And ....

What about pp?
Rotating the diagrams

\[ \sigma(e^+ e^- \rightarrow q\bar{q}) = 3 \frac{4\pi \alpha^2}{3s} e_q^2 \]

\[ \sigma(q\bar{q} \rightarrow l^+ l^-) = \frac{4\pi \alpha^2}{3 \times 3s} e_q^2 \]
The full mass spectrum

Measurement of the full $\mu^+\mu^-$ mass spectrum at LHC

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 3.1$ pb$^{-1}$
Calculating higher order contributions

\[
d\sigma(q + \bar{q} \rightarrow l^+ + l^-) = d\sigma(q + \bar{q} \rightarrow \gamma^* + g) \times \frac{1}{Q^4} \times d\sigma(\gamma^* \rightarrow l^+ + l^-)
\]

For example:

\[
\frac{d^2\sigma(q + \bar{q} \rightarrow g + l^+ + l^-)}{dM^2dp_t^2} = \frac{d^2\sigma(q + \bar{q} \rightarrow \gamma^* + g)}{dM^2dp_t^2} \times \frac{\alpha}{3\pi M^2}
\]
How to obtain a finite $x$-section?

- Perturbative calculations of $\mathcal{O}(\alpha_s)$, $\mathcal{O}(\alpha_s^2)$ diverge for small $p_t$.
- Virtual corrections are expected to cancel small $p_t$ divergency.

http://hep.pa.msu.edu/wwwlegacy/
What happens at small $p_t$?
Transverse Momentum of W/Z

The complete $P_T$ spectrum for the W boson

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

$pp \rightarrow (W^+ \rightarrow \bar{e}v_e)X$

CTEQ6M

Nonperturbative dynamics ("intrinsic $k_T$")

Perturbative physics dominates

Perturbative contributions + power corrections
The new thing: Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step
- Calculate Transverse Momentum Dependent parton densities


\[ z = \frac{x_a}{x_b} \]

\[ q_{t,c} \rightarrow \mu \]

Hannes Jung, CMS QCD Project Intro, Summerstudent lecture 2021, DESY
Parton Branching approach

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

Hautmann, F. et al, JHEP, 01(), 070
Transverse Momentum of $Z$ - bosons

- Transverse Momentum of $Z$ boson measured at LHC (CMS) compared to prediction from Parton Branching:
  - low $p_T$ region is very well described
  - without further assumptions
  - how can this be?

Jet production in pp

• x-section (i.e. for light and heavy quarks (t\bar{t}) production)

$$\sigma(pp \rightarrow q\bar{q}X) = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} x_1 G(x_1, \bar{q}) x_2 G(x_2, \bar{q}) \times \hat{\sigma}(s, \bar{q})$$

• with gluon densities

$$xG(x, \bar{q})$$

• hard x-section:

$$\frac{d\sigma}{dt} = \frac{1}{64s^2} |M_{ij}|^2$$
Lowest Order Diagrams

\[ qq' \rightarrow qq' \]

\[ qq \rightarrow qq \]

\[ q\bar{q} \rightarrow gg \]

\[ gg \rightarrow gg \]
Color Flow in pp

- quarks carry color
- anti-quarks carry anti-color
- gluons carry color – anti-color
  - connect to color singlet systems
  - watch out $pp$ or $p\bar{p}$

$pp \rightarrow q\bar{q} + X$

http://www.desy.de/~jung/qcd_and_mc_2015
http://www.desy.de/~jung/qcd_and_mc_2015
http://www.desy.de/~jung/qcd_and_mc_2015

Hannes Jung, CMS QCD Project Intro, Summerstudent lecture 2021, , DESY
Jet production at the LHC
Literature

http://www.desy.de/~jung/qcd_and_mc_2015

Hannes Jung, CMS QCD Project  Intro, Summerstudent lecture 2021, , DESY
Rivet

https://rivet.hepforge.org/

Rivet — the particle-physics MC analysis toolkit

The Rivet toolkit (Robust Independent Validation of Experiment and Theory) is a system for validation of Monte Carlo event generators. It provides a large (and ever growing) set of experimental analyses useful for MC generator development, validation, and tuning, as well as a convenient infrastructure for adding your own analyses.

Rivet is the most widespread way by which analysis code from the LHC and other high-energy collider experiments is preserved for comparison to and development of future theory models. It is used by phenomenologists, MC generator developers, and experimentalists on the LHC and other facilities.

Features

- Object-oriented C++ framework for analysis algorithms
- Ever-increasing collection of analyses, more than 900 so far...
- Python interface and suite of user-friendly data handling scripts
- Large collection of generator-independent event analysis tools
- Automatic caching of expensive calculations, for efficiently running many analyses on each event
- Flexible system for fast detector effect simulation in BSM analyses
- Close matching of standard observables to experimental analysis definitions
- Reference data connection to HepData, avoid hard-coding

The Rivet3 paper, including a short user guide, is available at this arXiv link. Up-to-date documentation and tutorials can be found here. The old Rivet user manual is also available on the arXiv (1003.0694 [hep-ph]).

The C++ MC generators Herwig and Sherpa have convenient user interfaces for producing input events for Rivet analysis, as well as built-in Rivet support. Users may find the Sacrifice interface convenient for running Pythia 8, and the AGILe steering package useful for older Fortran generators like PYTHIA6 and HERWIG6.

WANTED: Analysis code

We need your analyses! Preserving analysis logic in a re-runnable, re-interpretable form is a key part of scientific reproducibility and impact at the LHC and other HEP experiments. If you are member of an experimental collaboration, please have a look at our wishlist and help us by providing us with Rivet analyses for your publications. This will also ensure that your measurements get used (and cited)!

Docker containers for Rivet

A fully working and relatively lightweight Rivet container is available with all dependencies necessary for running, building plugins, and plotting. We suggest this to be used in tutorials and for people eager to try out Rivet. A short documentation showing how to use Rivet in three simple steps is given at our Docker instructions.
First steps (for running Rivet with docker)

First

- either get docker installed locally on your computer
  - https://gitlab.com/hepcedar/rivet/-/blob/release-3-1-x/doc/tutorials/docker.md
- or logon to DESY computer (with your DESY account)

First do linux warm-up Linux-Intro

Then follow instructions in Rivet-Intro