Physics at the LHC
(and other hadron colliders)

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Technicalities

- Lecture: Thursday 11:00-12:30
- Start lecture online
- Can discuss if we go to in-person later
- All info at https://indico.desy.de/event/31576/

Exercises (Evgeniya Cheremushkina):
  - Start with some classroom-problems
  - Later seminars on LHC papers

If anyone needs a final exam we can do an oral exam in the end

Evgeniya will discuss the exercises after this lecture

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Please send me your e-mail address that I can set up a mailing list
Plan

1) Introduction
2) Physics basics
3) Detectors
4) How to do an analysis?
5) QCD
6) Electroweak
7) Top-Quarks
8) Higgs
9) EFT fits
10) Flavour
11) Supersymmetry
12) Dark Matter
13) Other searches
14) Heavy Ions
15) Future of collider physics
Introduction
Why do we need LHC

- The Standard Model of particle physics is well established

- It basically describes all data from hep experiments
- Nevertheless there are lots of open problems in particle physics and cosmology
Open problems in (particle-)physics

- Hierarchy problem: Why is the Higgs mass so much lighter than the Planck mass (\(10^{19}\) GeV)?
- Dark matter: In the universe there is 5x more dark matter than baryonic matter. What does it consist of?
- Dark energy: The universe consists of 75% dark energy. What is this?
- Why is there only matter in the universe and no anti-matter?
- Do forces unify at high energy?
- Can one quantise gravity?
- Why are there exactly 3 families?
- How is the electroweak symmetry broken? (Is the Higgs elementary?)
Colliders

For many of these problems high energy colliders may help to find the answers

Possible roads to pursue:
- high energy to produce new particles (E=mc²)
- high event rate (luminosity) to get high precision and see new physics in loop effects

Why colliders:
- centre of mass energy for fixed target (target mass m): \( \sqrt{s} = \sqrt{2Em} \)
- centre of mass energy for colliders: \( \sqrt{s} = 2E \)
- for fixed target in general only baryonic targets are possible
Principle of a collider

- Injection beam 1
- Injection beam 2
- Deflection (dipole)
- Focussing (quadrupole)
- Acceleration

Detector
Which particles to collide?

- In most cases want to collide particles with anti-particles to have maximum energy for effects to study (protons contain anti-quarks!)
- Particles must be electrically charged to accelerate and guide them.
- Particles must be stable (enough) to collect and accelerate them and hold them in collision.

Leptons (electrons):
- Elementary particles → initial state known, all energy available
- No strong interactions → little background

Protons:
- Composite particles → initial state unknown, only part of the energy available
- Strong interactions → large backgrounds, however also some more processes available to study and in most cases larger signal cross sections.
Which energy can we reach?

Deflection in a magnetic field: \( F = qv \times B \quad q = e \)

\[ B = \frac{p}{eR} \quad B[\text{T}] = p[\text{GeV}] \cdot 3.336 \text{m}/R \]

e.g. LHC: \( p = 7 \text{ TeV}, \ R = 2804 \text{ m} \Rightarrow B = 8.33 \text{T} \) feasible with superc. Nb magnets

Synchrotron radiation:
- accelerated charged particles radiate
- radiation in a homogeneous B-field: \( P = \frac{2}{3} \frac{e^2}{R^2} \left( \frac{E}{m} \right)^4 \)
- loss/turn
  \[ \Delta E = \frac{4\pi}{3} \frac{e^2}{R} \left( \frac{E}{m} \right)^4 \]

  e.g. LEP2(electrons): \( p = 100 \text{ GeV}, \ R = 2800 \text{ m} \Rightarrow \Delta E = 2 \text{ GeV} \)
- if I want to reach 1 TeV in the same ring with electrons: \( \Delta E = 20 \text{ TeV}! \)
- protons with 7 TeV in this ring: \( \Delta E = 3 \text{ keV} \)
# High energy colliders

<table>
<thead>
<tr>
<th>Lepton collider</th>
<th>Beam particles</th>
<th>CM energy</th>
<th>Location</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEAR</td>
<td>e+e−</td>
<td>3-5 GeV</td>
<td>SLAC</td>
<td>1972-1990</td>
</tr>
<tr>
<td>DORIS</td>
<td>e+e−</td>
<td>3-10 GeV</td>
<td>DESY</td>
<td>1974-1993</td>
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<tr>
<td>CESR</td>
<td>e+e−</td>
<td>9-12 GeV</td>
<td>Cornell</td>
<td>1979-2002</td>
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<tr>
<td>PETRA</td>
<td>e+e−</td>
<td>&lt; 35 GeV</td>
<td>DESY</td>
<td>1978-1986</td>
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<tr>
<td>PEP</td>
<td>e+e−</td>
<td>&lt; 35 GeV</td>
<td>SLAC</td>
<td>1980-1990</td>
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<tr>
<td>LEP</td>
<td>e+e−</td>
<td>200 GeV</td>
<td>CERN</td>
<td>1989-2000</td>
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<tr>
<td>PEP/KEKB</td>
<td>e+e−</td>
<td>10.6 GeV</td>
<td>SLAC/KEK</td>
<td>1999-2010</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>e+e−</td>
<td>10.6 GeV</td>
<td>KEK</td>
<td>2018-27(?)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Hadron collider</th>
<th>Beam particles</th>
<th>CM energy</th>
<th>Location</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR</td>
<td>pp</td>
<td>62 GeV</td>
<td>CERN</td>
<td>1971-1984</td>
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<tr>
<td>Tevatron</td>
<td>p̅p</td>
<td>1.96 TeV</td>
<td>Fermilab</td>
<td>1987-2011</td>
</tr>
<tr>
<td>LHC</td>
<td>pp</td>
<td>13 TeV</td>
<td>CERN</td>
<td>2009-2024</td>
</tr>
<tr>
<td>LHC upgrade</td>
<td>pp</td>
<td>14 TeV</td>
<td>CERN</td>
<td>&gt; 2028</td>
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</table>

<table>
<thead>
<tr>
<th>Lepton-hadron collider</th>
<th>Beam particle</th>
<th>CM energy</th>
<th>Location</th>
<th>Years</th>
</tr>
</thead>
</table>
Hadron Colliders

- Fermilab
  - 1987 - 2009
  - Tevatron PbarP
  - 1.8 - 1.96 TeV
  - CDF, DØ

- CERN
  - 1981 - 1990
  - SPPS PbarP
  - 0.6 TeV
  - UA1, UA2

- CERN
  - 2007 - 2020
  - LHC PP
  - 14 TeV
  - ATLAS, CMS, ALICE, LHC-B
Livingston Plot
Hadron colliders: which particles?

- To produce new particles most efficiently want to collide particles with anti-particles
- Textbook: (anti-)protons consist of 3 (anti-)quarks
- However at high energy quarks radiate gluons and gluons split into quark-antiquark pairs
- The higher the energy the more symmetric a proton becomes
top-ant-top cross section vs energy
pp vs pp collisions

- Protons: very easy to get
- Anti-protons: don’t exist in nature
  - shoot proton beam on target
  - collect few anti-protons that are produced
  - store them and cool them
    (Nobel Prize van der Meer 1984)
  - severely limits the luminosity of a machine
- Build pp-colliders at low energies (SppS, Tevatron)
  - At high energies (LHC) can do the same physics with much higher luminosity using pp
Luminosity

Number of events for a given process: \( \frac{dN}{dt} = \sigma \cdot \mathcal{L} \)
- \( \sigma \): cross section → physics
- \( \mathcal{L} \): luminosity → collider parameter
- descriptive: \( \int \mathcal{L} dt = N_1 N_2 / \text{area} \times \text{frequency} \times \text{time} \)

Luminosity unit \( 1 / (\text{area} \times \text{time}) \)

“Typical” luminosities of modern colliders: \( \mathcal{L} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
Luminosity and machine physics

The luminosity is given by: \[ \mathcal{L} = f_c N_b \frac{N^+ N^-}{4\pi \sigma_x \sigma_y} = f_c N_b \frac{N^+ N^-}{4\pi \sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}} \]

Emittance (\(\varepsilon\)): Invariant phase space volume (~constant in pp colliders)

The \(\beta\) function:
- if the beam is undisturbed the bunches would blow up
  \(\rightarrow\) needs to be focussed by a magnetic lattice \(\rightarrow\) \(x(s) = \sqrt{\varepsilon \beta(s)} \cos(\mu(s) + \phi)\)
- beam size rms: \(\sigma(s) = \sqrt{\varepsilon \beta(s)}\)
- beam divergence \(\theta(s) = \sqrt{\varepsilon / \beta(s)}\)
- \(\beta^*\) is the minimum of the \(\beta\) function given by the strength of the focussing magnets
How to measure the luminosity

- Reference reaction (reaction with well known cross section)
  \[ \int \mathcal{L} dt = \frac{N_{\text{ref}}}{\sigma_{\text{ref}}} \]
  - use Bhabha scattering in $e^+e^-$
  - can be extremely precise (0.1% at LEP)

- From beam parameters
  - for Gaussian beams:
    \[ \mathcal{L} = f_c N_b \frac{N^+ N^-}{4\pi \sigma_x \sigma_y} \]
  - need to know all beam parameters from special measurements

- Hybrid (LHC)
  - measure beam parameters and reference cross section in special runs
  - use reference cross section to measure luminosity in normal running
Luminosity measurement at LHC

1\textsuperscript{st} step: measure luminosity in specialised run (few bunches, low bunch charge)

\[ \mathcal{L} = f_c N_b \frac{N^+ N^-}{4\pi \sigma_x \sigma_y} \]

- revolution frequency and number of bunches is known exactly
- bunch charges can be measured precisely from induction in BPMs
- challenge: measurement of beam size:
  - scan beams against each other (van der Meer scans)
  - needs detailed understanding of beam shape, x-y correlations, beam-beam effects…
  - LHC achieved already precision around 1%
2\textsuperscript{nd} step: define reference cross section

Need large cross section: inelastic pp scattering

However cross section is too large: \(~50\) events/bunch cross section with \(~100\) tracks/event

Take special detector that measures track rate in a very small phase space region and define counting rate in this detector as reference cross section

Reference cross section is then obtained from maximum count rate

\[
\sigma_{\text{vis}} = \mu_{\text{vis}} \max \frac{4\pi \sigma x \sigma y}{N + N^-}
\]
Luminosity measurement at LHC (iii)

3rd step: extrapolate to high luminosity

- In principle can use this directly at high luminosity taking non linearity into account.
- Luminosity for a given bunch: \( P_{\text{hit}} = 1 - e^{-\mu_{\text{vis}}} \)
  \[ L_b = \frac{\mu_{\text{vis}} f_r}{\sigma_{\text{vis}}} \]
- Then need to add over bunches
- For time stability use other detectors that work only at high luminosity
- In total achieve preliminary luminosity uncertainty of 1.7% for run 2 in ATLAS
## Preliminary luminosity error in ATLAS

<table>
<thead>
<tr>
<th>Data sample</th>
<th>2015+16</th>
<th>2017</th>
<th>2018</th>
<th>Comb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity (fb(^{-1}))</td>
<td>36.2</td>
<td>44.3</td>
<td>58.5</td>
<td>139.0</td>
</tr>
<tr>
<td>Total uncertainty (fb(^{-1}))</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

### Uncertainty contributions (%):

<table>
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<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DCCT calibration(^{†})</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>FBCT bunch-by-bunch fractions</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Ghost-charge correction(^{*})</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Satellite correction(^{†})</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Scan curve fit model(^{†})</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>Orbit-drift correction</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Beam position jitter(^{†})</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
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<tr>
<td>Beam-beam effects(^{*})</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
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<tr>
<td>Emittance growth correction(^{*})</td>
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<td>0.2</td>
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<tr>
<td>Non-factorization effects(^{*})</td>
<td>0.4</td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
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<tr>
<td>Length-scale calibration</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>ID length scale(^{*})</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Bunch-by-bunch $\sigma_{\text{vis}}$ consistency</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Scan-to-scan reproducibility</td>
<td>0.5</td>
<td>1.2</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Reference specific luminosity</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Subtotal for absolute vdm calibration</td>
<td>1.1</td>
<td>1.5</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>Calibration transfer(^{†})</td>
<td>1.6</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
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<tr>
<td>Afterglow and beam-halo subtraction(^{*})</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Long-term stability</td>
<td>0.7</td>
<td>1.3</td>
<td>0.8</td>
<td>0.6</td>
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<tr>
<td>Tracking efficiency time-dependence</td>
<td>0.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
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<tr>
<td>Total uncertainty (%)</td>
<td>2.1</td>
<td>2.4</td>
<td>2.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>
The LHC
The LHC

- pp collider at CERN (also heavy ions, mainly PbPb)
- Circumference: 27km
- Number of dipole magnets: 1232
- Design field B=8.3T
- Number of bunches: 2800 → bunch spacing 25ns
- Bunch charge at beginning of fill: $1.2 \cdot 10^{11}$ protons/bunch
- Design centre of mass energy: $\sqrt{s}=14$ TeV
- Design peak luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
- Total stored energy is 360 MJ per beam (This corresponds to a British aircraft carrier at 12 knots or a luxury car at 2000 km/h)
- However the energy of two colliding protons corresponds to the energy of two colliding mosquitoes
The LHC magnets

- For $\sqrt{s}=14$ in a 27km tunnel need B-field of 8.3T
- Possible with superconducting Nb magnets cooled with superfluid He at T=1.9K
- Challenge: have to keep huge forces inside magnets under control
- This also means that the magnets need “training quenches” before they reach their design field
- If they didn’t run for a while they tend to “forget”
- That’s why the LHC runs now only with 13 TeV
- After installation a full string needs to be powered and cooled down again after one magnet quenches
Cross Section of LHC Dipole
The 15-m long LHC cryodipole
Detailed layout of the LHC

- Beams circulate separate beam-pipes and cross in the interaction region.
- They cross with a small crossing angle to avoid parasitic collisions.
- The two high-luminosity experiments (ATLAS & CMS) are opposite to each other to get a symmetric configuration.
- In IP 4 there is a superconducting RF section to accelerate the beam and to compensate the small synchrotron radiation losses.
The accelerator complex

- The protons get pre-accelerated mainly in the old accelerators of CERN.
- They start as $H^+$ ions in a Linac, get stripped and continue through a series of circular accelerators.
- They are injected into the LHC at 450 GeV and are then accelerated to their final energy.

<table>
<thead>
<tr>
<th>Kinetic energy of a proton (K)</th>
<th>Speed (%c)</th>
<th>Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MeV</td>
<td>31.4</td>
<td>Linac 2</td>
</tr>
<tr>
<td>1.4 GeV</td>
<td>91.6</td>
<td>PS Booster</td>
</tr>
<tr>
<td>25 GeV</td>
<td>99.93</td>
<td>PS</td>
</tr>
<tr>
<td>450 GeV</td>
<td>99.9998</td>
<td>SPS</td>
</tr>
<tr>
<td>7 TeV</td>
<td>99.999991</td>
<td>LHC</td>
</tr>
</tbody>
</table>

Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c$^2$. 
LHC luminosity considerations

Luminosity: \( \mathcal{L} = f_c N_b \frac{N^+ N^-}{4\pi \sqrt{\varepsilon_x \beta^* \varepsilon_y \beta^*}} F \) (F delusion from crossing angle)

If \( \beta^* \) too small beam at final focus gets too large
- beam doesn’t fit through machine aperture
- need to increase crossing angle to avoid parasitic collisions → lower luminosity
- optimal \( \beta^* \): 25cm
Crossing angle dilution

- Crossing angle is needed to avoid parasitic bunch crossings
- However crossing leads to non optimal overlap of bunches
- LHC settings lead to ~40% loss
- Half crossing angle: 120-150 mrad
- Beam sizes:
  - Transverse: ~15μm in both directions due to beam parameters
  - Longitudinal: ~7cm
- Length of luminous region: ~5cm (reduction from crossing angle)
Radiation from inelastic interaction heats up the final focus magnets → limits luminosity to around $2 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$

Pileup (see later) limits the luminosity for ATLAS and CMS to about the same value
Typical LHC run cycle

- Fill LHC
- Accelerate beams
- Bring beams into collision and optimise luminosity
- Take data until luminosity decays to some value (typically 1/3)
- Dump beam
- Cycle magnets to eliminate hysteresis
Operation in Run 3

- In Run 3 the bunch charge can be almost doubled.
- This leads to a theoretical maximal luminosity around $5 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$.
- The luminosity will be turned down to $2 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ increasing $\beta^*$.
- $\beta^*$ will then gradually be decreased down to 25cm to keep the luminosity at its maximum value.
- This will lead to fills with ~12h constant luminosity.
Experimental problem: pile-up

- The total inelastic cross section at the LHC is 80mb
- Under normal running conditions this leads to 25 pile-up events each bunch crossing for a luminosity of $10^{34}$cm$^{-2}$s$^{-1}$
- This results in ~1600 charged particles in the detector
- For charged particles the tracks can still mostly be separated from the z-positions of the vertices
- For neutral particles pile-up can only be subtracted on a statistical basis
ATLAS event with 25 pile-up vertices
Cross sections at the LHC

- Huge signal cross sections:
  - 150 W → eν/s
  - 15 Z → e⁺e⁻/s
  - 8 t̅t̅/s
  - 0.5 Higgs/s
  - 0.03 SUSY particles/s

- However also huge backgrounds
  - e.g. 50000 jet events/s with Eₜ>100GeV

- Numbers are for L=10^{34} cm⁻²s⁻¹
- Trigger rate is around 1 kHz
- Triggering is a challenge!
The LHC timeline

- First discussions on the project: 1984
- Constructed in the LEP tunnel since 2001
- End 2008: First beam in the machine, severe accident in a connection between magnets
- Late 2009: first collisions at $\sqrt{s} = 0.8$ TeV
- 2010-2012: Collisions at $\sqrt{s} = 7/8$ TeV (Higgs discovery!)
- 2013/14: LS1: Final repair of interconnects to reach 14 TeV
- 2015-2018: Run 2 at 13 TeV with $\sim 140$fb$^{-1}$/experiment
- 2019-2021: LS2 with first detector and machine upgrades for the high-lumi phase
- 2022-2024(?): Run 3 at 13.6(?) TeV with $\sim 200$fb$^{-1}$/experiment
- 2025-2026(?): LS3 with final detector and machine upgrades for the HL-LHC
- 2027(?)-2040(???) Run4+ with $L \sim 5 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$ and 3ab$^{-1}$/experiment
The Tevatron at Fermilab

- Proton-Antiproton collider at Fermilab near Chicago
- Superconducting ring 6.5km circumference
- \( \sqrt{s} = 1.96 \) TeV
- At this energy \( pp \) is still advantageous:
  - more \( q\bar{q} \) interactions at high mass
  - however complicated infrastructure to collect and cool antiprotons
  - can lead to significant breaks after beam loss
- Two experiments: CDF and D0
- Two main runs: Run 1, Run 2
Tevatron Run 1 (1990-1996)

- Main injector in the same tunnel as Tevatron (running through a whole in D0)
- D0 was non-magnetic detector
- Relatively low luminosity (0.125 fb$^{-1}$/experiment)
- Top-quark discovery
Tevatron Run 2 (2001-2011)

- New main injector ring that could also recycle anti-protons
- New magnet in D0
- 36 bunches with 396 ns separation
- Peak luminosity: $4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$
  - peak pile-up 10 events/bunch crossing
- Total luminosity
  $\sim 10 \text{ fb}^{-1}/\text{experiment}$
- Important contributions to
  B-physics, top-physics, W-mass