Pythia 8: Physics and usage

Saariselkä Midsummer School 2024

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Centre of Excellence in Quark Matter

Outline

Lecture 1:

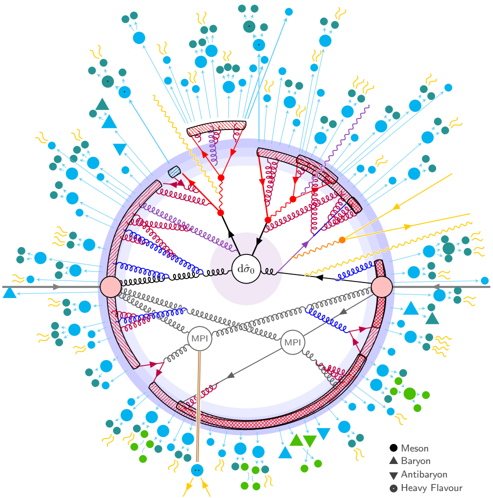
- History of Pythia
- Monte Carlo techniques
- Hard-process sampling

Lecture 2:

- Multiparton interactions
- Parton showers

Lecture 3:

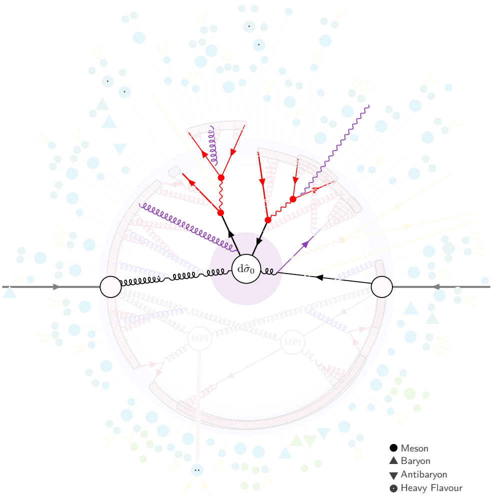
- Hadronization
- Beam configurations



[figure by P. Skands]

Outline

Lecture 2:



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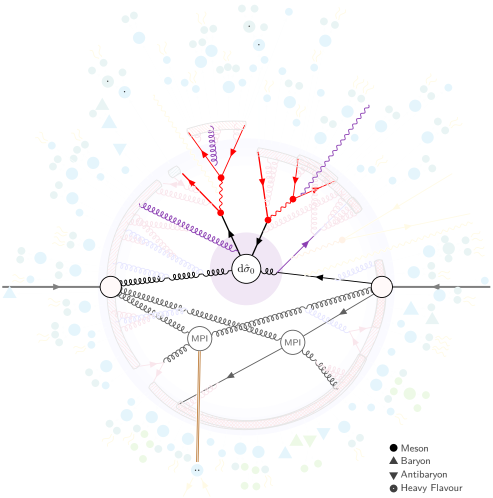
Lecture 2:

- Multiparton interactions



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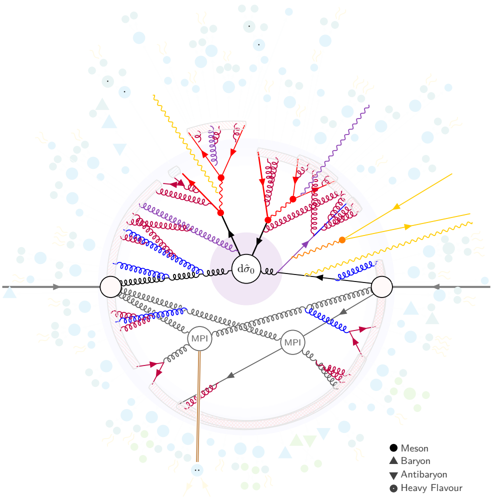
Lecture 2:

- Multiparton interactions
- Parton showers



[figure by P. Skands]

Multiparton interactions

Multiparton interactions (MPIs)

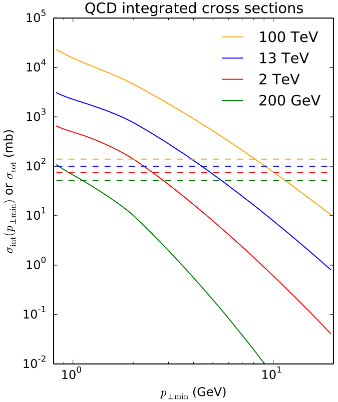
- Integrated cross section for QCD $2 \to 2$ processes

$$\sigma_{\text{int}}(p_{\text{T,min}}) = \int_{p_{\text{T,min}}}^{\sqrt{s}/2} \mathrm{d}p_{\text{T}} \frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}p_{\text{T}}^2}$$

- σ_{int} exceeds σ_{tot} when p_{T}^2 small
  $\Rightarrow$ Multiple partonic interactions per event
- Partonic cross section diverges at $p_{\text{T}} \to 0$
  $\Rightarrow$ Introduce a screening parameter p_{T0}

$$\frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}p_{\text{T}}^2} \propto \frac{\alpha_s(p_{\text{T}}^2)}{p_{\text{T}}^4} \to \frac{\alpha_s(p_{\text{T0}}^2 + p_{\text{T}}^2)}{(p_{\text{T0}}^2 + p_{\text{T}}^2)^2}$$

- Energy-dependent parametrization:
  $p_{\text{T0}}(\sqrt{s}) = p_{\text{T0}}^{\text{ref}}(\sqrt{s}/\sqrt{s_{\text{ref}}})^{\alpha}$



Multiparton interactions (MPIs)

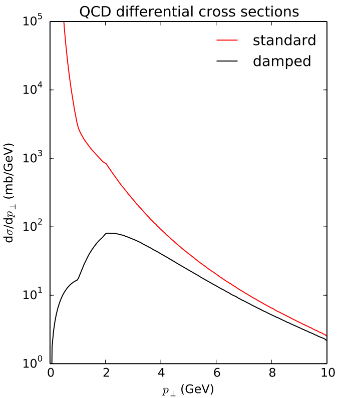
- Now a finite QCD cross section

$$\sigma_{\text{int}}(p_{\text{T},0}) = \int_0^{\sqrt{s}/2} \mathrm{d}p_{\text{T}} \frac{\mathrm{d}\sigma^{2\to 2}(p_{\text{T},0})}{\mathrm{d}p_{\text{T}}^2}$$

$\sigma_{\text{nd}}(\sqrt{s})$ is the non-diffractive cross section

- Number of interactions: $\langle n \rangle = \sigma_{\text{int}}(p_{\text{T},0})/\sigma_{\text{nd}}$

1. Sample *n* independent interactions
2. Order interactions in p_{T}
   - Energy conservation by rescaling PDFs
   - Sudakov factor to account for the p_{T}-ordering



$$\mathcal{P}_{\text{MPI}}(p_{\text{T}}) = \frac{1}{\sigma_{\text{nd}}(\sqrt{s})} \frac{\mathrm{d}\sigma^{2\to 2}(p_{\text{T},0})}{\mathrm{d}p_{\text{T}}^2} \exp\left[-\int_{p_{\text{T}}}^{p_{\text{T,max}}} \mathrm{d}p_{\text{T}}'^2 \frac{1}{\sigma_{\text{nd}}(\sqrt{s})} \frac{\mathrm{d}\sigma^{2\to 2}(p_{\text{T},0})}{\mathrm{d}p_{\text{T}}'^2} \right]$$

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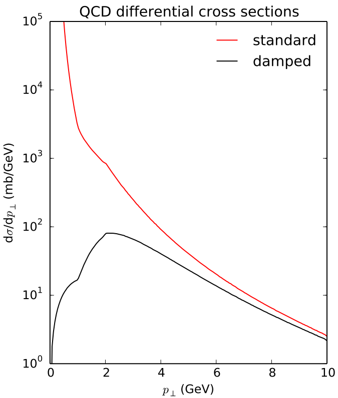
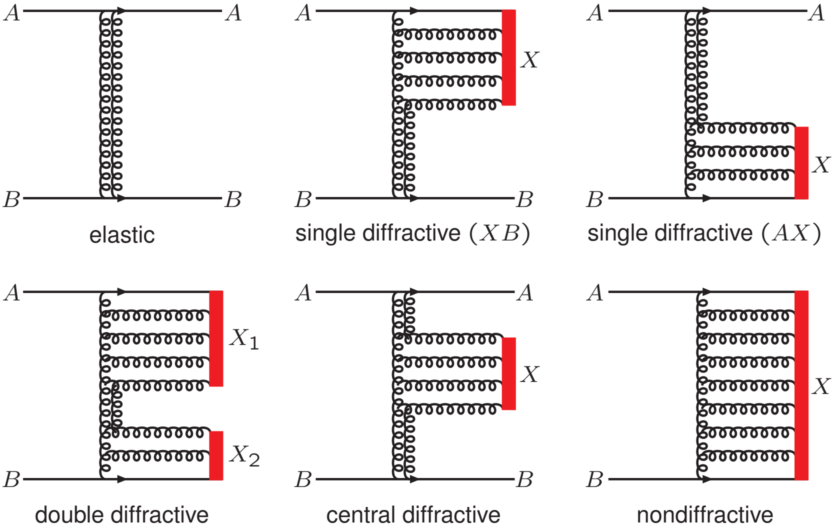
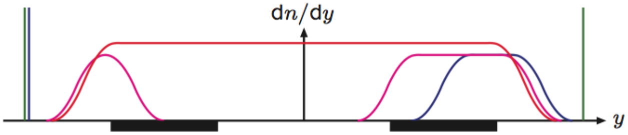


Soft QCD processes



[figure by T. Sjöstrand]

Particle production in minimum bias collisions



[figure by T. Sjöstrand]

- Diffractive processes relevant at large rapidities
- Non-diffractive at mid-rapidities

Soft-QCD non-diffractive processes

- Need to sample QCD processes without any phase-space cuts
  - Standard cross section diverges when $p_{\mathrm{T}} \to 0$

  $\Rightarrow$ Use the regulated cross sections from the MPI framework
  - Contain the same QCD sub-processes as hard QCD event class

    $\Rightarrow$ Could also be used for jet production (with inifinte statistics)

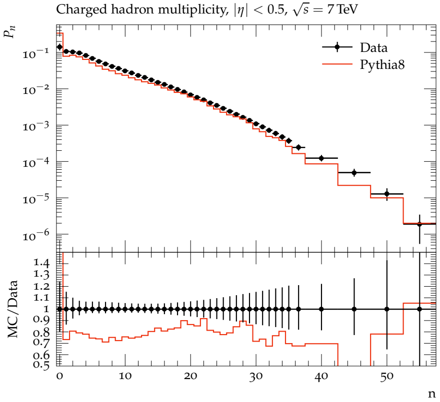
Exercise III: Charged-particle multiplicities

CMS analysis: CMS_2011_S8884919

- Number of charged particles in p+p collisions at 7 TeV
- Non-single-diffractive (NSD) events

Exercise IIIa:

- Go to Pythia online manual https://pythia.org//latest-manual/Welcome.html
- Find how to enable processes for the NSD trigger (Process Selection -> Soft QCD Processes)
- Make a `.cmnd` file and run with `pythia8-main93`



[CMS: JHEP 01 (2011) 079]

Exercise III: Charged-particle multiplicities

Exercise IIIb:

1. Vary $p_{T,0}^{ref}$ parameter

```
MultipartonInteractions:
   pT0Ref = 2.28
```

   - Run with `pythia8-main93`

2. Turn off MPIs completely with

```
PartonLevel:MPI=off
```

   - Run with `pythia8-main93`

- Compare results

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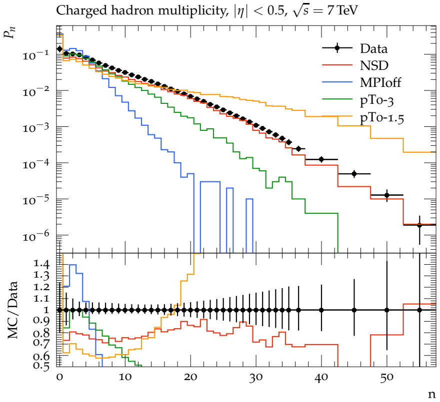


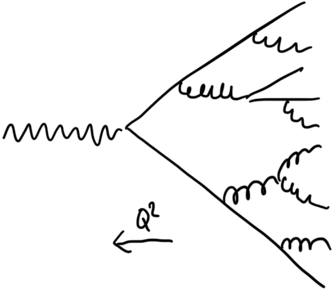
[CMS: JHEP 01 (2011) 079]

Parton showers

Final state radiation

- Splitting probabilities from DGLAP

$$d\mathcal{P}_{a\to bc} = \frac{dQ^2}{Q^2}\frac{\alpha_s}{2\pi}P_{a\to bc}(z)\,dz$$



- Iterative structure, emissions ordered in Q^2
- Use Sudakov factor to account for the ordering (A parton can only branch if it had not already branched)

$$d\mathcal{P}_{a\to bc} = \frac{dQ^2}{Q^2}\frac{\alpha_s}{2\pi}P_{a\to bc}(z)\,dz\,\exp\left[-\sum_{b,c}\int_{Q^2}^{Q^2_{max}}\frac{dQ'^2}{Q'^2}\int dz'\frac{\alpha_s}{2\pi}P_{a\to bc}(z')\right]$$

- Several options for the ordering variable, different phase-space mapping
  $\Rightarrow$ Pythia uses $p_T = z(1-z)Q^2$

Initial state radiation

- Start from a highly-virtual parton participating to the hard scattering
- Backwards evolution, trace back splittings that have occurred before the hard interactions ($\sim$ undo DGLAP evolution of the PDFs)
- Need to consider conditional probability for the splitting

$$d\mathcal{P}_{a\leftarrow b} = \frac{df_b}{f_b} = \frac{x' f_a(x', Q^2)}{x f_b(x, Q^2)} \frac{dQ^2}{Q^2} \frac{\alpha_s}{2\pi} P_{a\to bc}(z)\, dz \quad (x' = x/z)$$

- Similarly need a Sudakov factor to account for the non-emission probability
- Evolution variable in Pythia: $p_T = (1 - z)Q^2$

Parton-level evolution

Common evolution scale (p_T) for FSR, ISR and MPIs

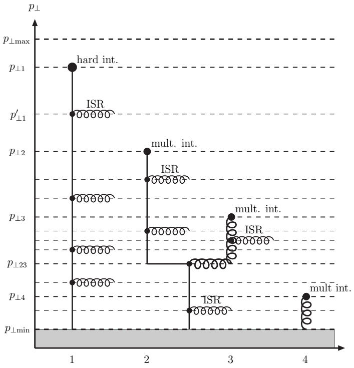
- Probability for something to happen at given p_T

$$\frac{d\mathcal{P}}{dp_T} = \left(\frac{d\mathcal{P}_{MPI}}{dp_T} + \sum \frac{d\mathcal{P}_{ISR}}{dp_T} + \sum \frac{d\mathcal{P}_{FSR}}{dp_T}\right) \times \exp\left[-\int_{p_T}^{p_T^{max}} dp'_T \left(\frac{d\mathcal{P}_{MPI}}{dp'_T} + \sum \frac{d\mathcal{P}_{ISR}}{dp'_T} + \sum \frac{d\mathcal{P}_{FSR}}{dp'_T}\right)\right]$$

where $\exp[\ldots]$ is a Sudakov factor (probability that nothing else has happened before p_T)

Simultaneous partonic evolution

1. Start the evolution from the hard-process scale
2. Sample p_T for each $\mathcal{P}_i$, pick one with highest p_T
3. Continue until $p_{Tmin} \sim \Lambda_{QCD}$ reached



[T. Sjöstrand, P. Skands: EPJC 39 (2005) 129-154]

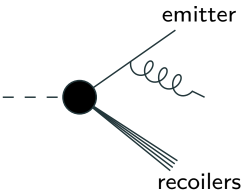
Parton shower options in Pythia: The Simple Shower

The default parton shower implementation

[T. Sjöstrand, P. Skands, EPJC 39 (2005) 129-154]

- The only one available until 8.3 release
- Improved Leading-Log (LL) approximation
- Recoil distributed to the whole final state
- Applicable to photoproduction

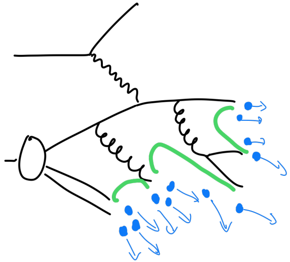
DGLAP



`DipoleRecoil` variant

[B. Cabouat, T. Sjöstrand, EPJC 78 (2018 no.3, 226)]

- Restrict recoil to the emitting dipole instead of the whole final state
- Can be applied processes like DIS or Vector-Boson fusion



Parton shower options in Pythia: Vincia and Dire

Vincia antenna shower `PartonShowers:model = 2`

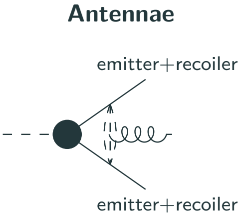
[H. Brooks, C. T. Preuss, P. Skands, JHEP 07 (2020) 032]

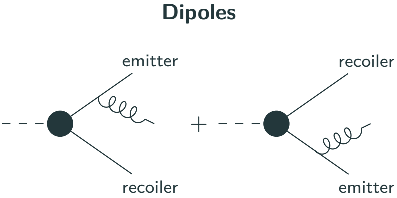
- QCD, QED, EW, interleaved with MPIs
- Interleaved resonance decays
- Iterated LO matrix-element corrections
- Efficient multi-jet merging with sectors

Dire in Pythia `PartonShowers:model = 3`

[S. Höche, S. Prestel, EPJC 75 (2015) no.9, 461]

- QCD, QED, $\sim$ EW and dark photons
- Correct soft-gluon interference at lowest order
- Inclusive NLO corrections to collinear splittings
- Recoil given to the non-emitting side of the dipole





[figures by C. Preuss]

ATLAS analysis: ATLAS_2011_S9131140

- Transverse momentum of Z-boson
  $\Rightarrow$ LO calculation: $p_T^Z = 0$
- Reconstructed from lepton pair

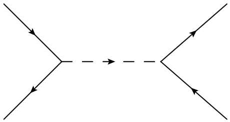
Exercise IVa:

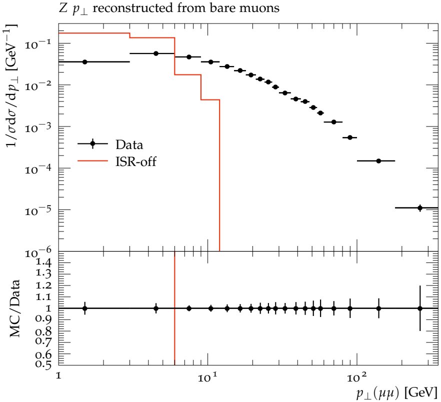
1. Enable Z production and turn off ISR

```
WeakSingleBoson:ffbar2gmZ = on
PartonLevel:ISR=off
```

   - Run and compare to data

2. Turn ISR on
   - Compare to data and result with ISR





[ATLAS: PLB 705 (2011) 415-434]

Exercise IV: Z-boson p_T

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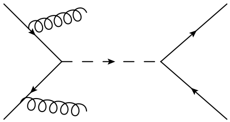

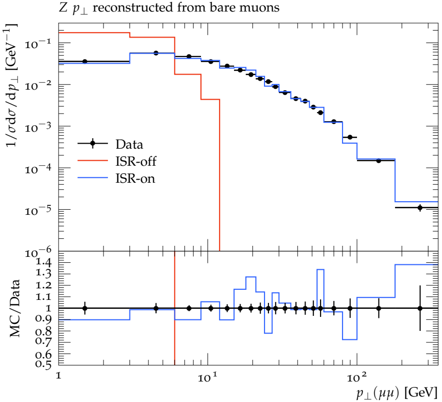

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Exercise IV: Z-boson p_T

Exercise IVb:

- Generate events $\mathcal{O}(10k)$ with all three parton-shower models,
  Default (Simple), Vincia and Dire

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PartonShowers:model=1,2,3
```

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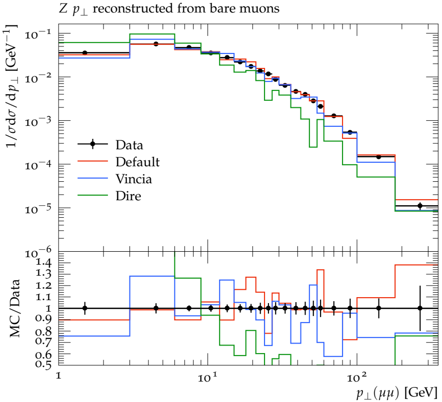

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Results with 100k events

Bonus exercise

Number of MPIs

- Study the online manual how to extract number of MPIs from the event information
- Calculate the average number of MPIs in non-diffractive (min. bias) events and in events with a Z boson

$\Rightarrow$ Are these the same?

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⇒ Are these the same?

- Pedestal effect: Harder processes with smaller impact parameter
  ⇒ More MPIs and larger $\langle n_{\mathrm{ch}} \rangle$