# Pythia 8: Physics and usage

Saariselkä Midsummer School 2024

Ilkka Helenius

June 28, 2024

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Research Council of Finland

Centre of Excellence in Quark Matter

# Outline

Lecture 1:

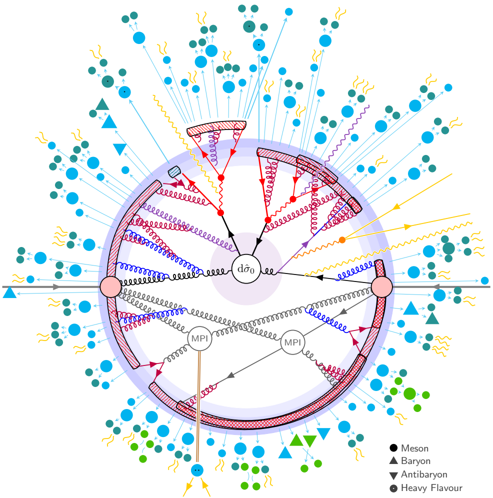
- History of Pythia
- Monte Carlo techniques
- Hard-process sampling

Lecture 2:

- Multiparton interactions
- Parton showers

Lecture 3:

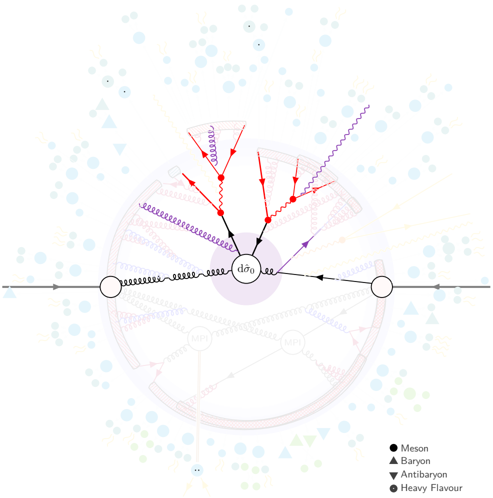
- Hadronization
- Beam configurations




[figure by P. Skands]

# Outline

Lecture 2:

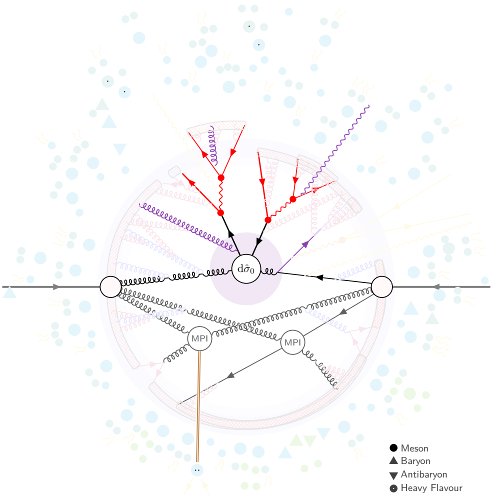



[figure by P. Skands]

# Outline

## Lecture 2:

- Multiparton interactions

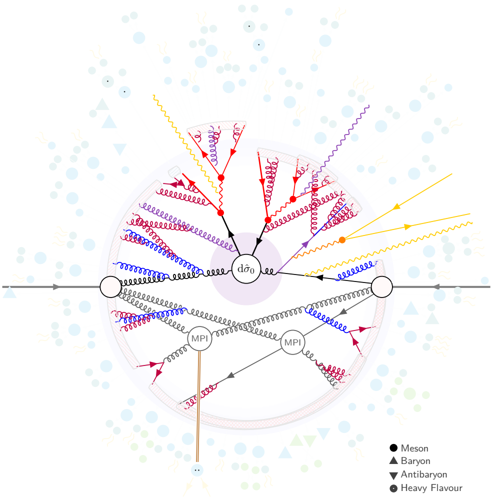



[figure by P. Skands]

# Outline

Lecture 2:

- Multiparton interactions
- Parton showers




[figure by P. Skands]

# Multiparton interactions

# Multiparton interactions (MPIs)

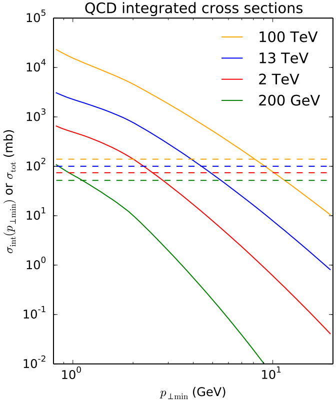
- Integrated cross section for QCD $2 \to 2$ processes

$$\sigma_{\text{int}}(p_{\text{T,min}}) = \int_{p_{\text{T,min}}}^{\sqrt{s}/2} \mathrm{d}p_{\text{T}} \frac{\mathrm{d}\sigma^{2\to2}}{\mathrm{d}p_{\text{T}}^2}$$

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

$$\frac{\mathrm{d}\sigma^{2\to2}}{\mathrm{d}p_{\text{T}}^2} \propto \frac{\alpha_{\text{s}}(p_{\text{T}}^2)}{p_{\text{T}}^4} \to \frac{\alpha_{\text{s}}(p_{\text{T0}}^2 + p_{\text{T}}^2)}{(p_{\text{T0}}^2 + p_{\text{T}}^2)^2}$$

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



# Multiparton interactions (MPIs)

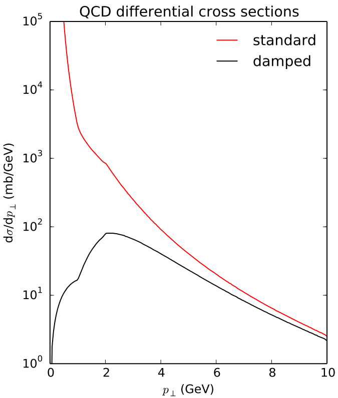
- Now a finite QCD cross section

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

$\sigma_{\text{nd}}(\sqrt{s})$ 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 $p_{\text{T}}$
   - Energy conservation by rescaling PDFs
   - Sudakov factor to account for the $p_{\text{T}}$-ordering




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

# Multiparton interactions (MPIs)

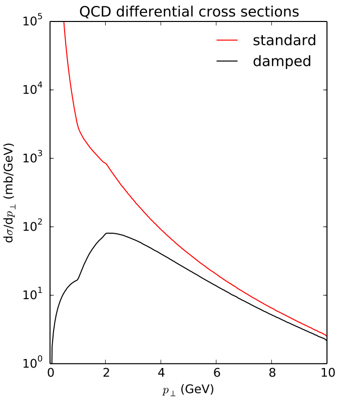
- Now a finite QCD cross section

$$\sigma_{\text{int}}(p_{T,0}) = \int_0^{\sqrt{s}/2} \mathrm{d}p_T \frac{\mathrm{d}\sigma^{2\to2}(p_{T,0})}{\mathrm{d}p_T^2}$$

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

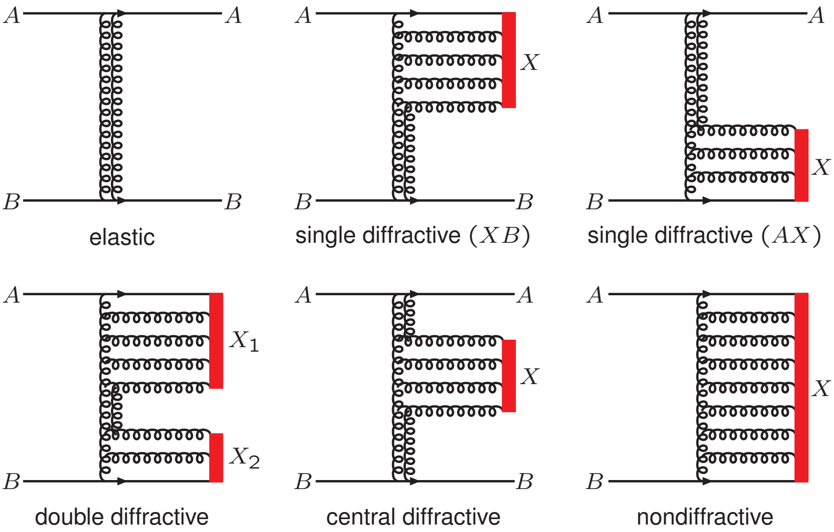
- Number of interactions: $\langle n\rangle = \sigma_{\text{int}}(p_{T,0})/\sigma_{\text{nd}}$

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



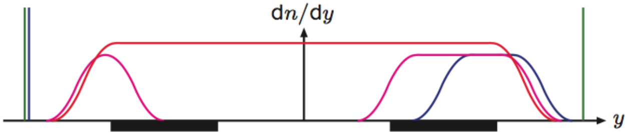

$$\mathcal{P}_{\text{MPI}}(p_T) = \frac{1}{\sigma_{\text{nd}}(\sqrt{s})}\frac{\mathrm{d}\sigma^{2\to2}(p_{T,0})}{\mathrm{d}p_T^2}\exp\left[-\int_{p_T}^{p_{T,\max}} \mathrm{d}p_T'^2 \frac{1}{\sigma_{\text{nd}}(\sqrt{s})}\frac{\mathrm{d}\sigma^{2\to2}(p_{T,0})}{\mathrm{d}p_T'^2}\right]$$

# 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)

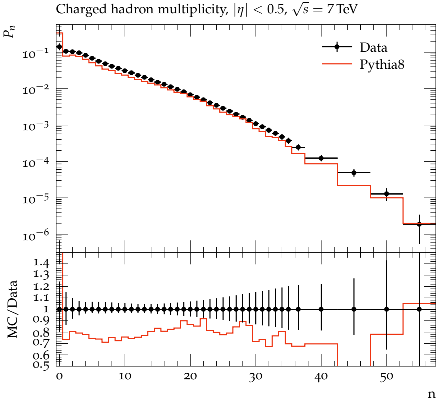
# Exercise III: Charged-particle multiplicities

## 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

# Exercise III: Charged-particle multiplicities

## Exercise IIIb:

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

```
MultipartonInteractions:
   pT0Ref = 2.28
```

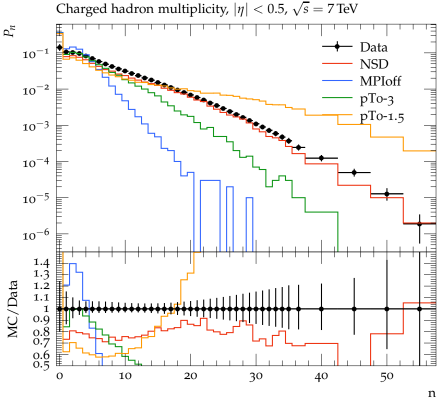
   - Run with `pythia8-main93`

2. Turn off MPIs completely with

```
PartonLevel:MPI=off
```

   - Run with `pythia8-main93`

- Compare results



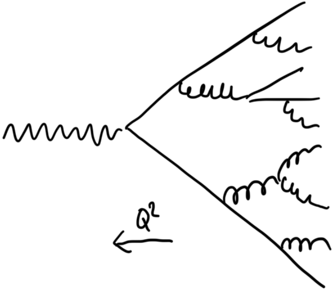

[CMS: JHEP 01 (2011) 079]

# 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

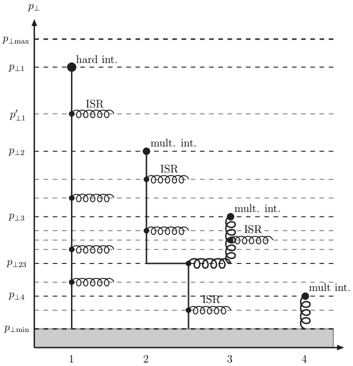
- Probability for something to happen at given $p_T$

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

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]

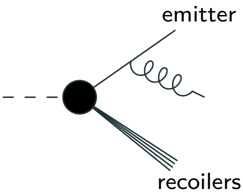
- The only one available until 8.3 release
- Improved Leading-Log (LL) approximation
- Recoil distributed to the whole final state
- Applicable to photoproduction

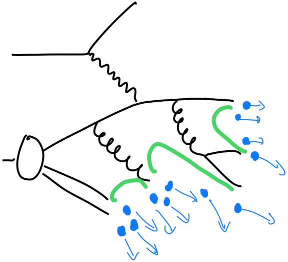
`DipoleRecoil` variant

[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

DGLAP



# 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]

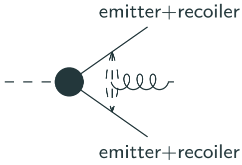
- QCD, QED, EW, interleaved with MPIs
- Interleaved resonance decays
- Iterated LO matrix-element corrections
- Efficient multi-jet merging with sectors

Dire in Pythia `PartonShowers:model = 3`

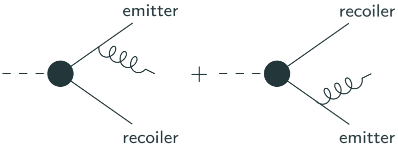
[S. Höche, S. Prestel, EPJC 75 (2015) no.9, 461]

- 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

**Antennae**




**Dipoles**




[figures by C. Preuss]

# Exercise IV: Z-boson $p_T$

ATLAS analysis: ATLAS_2011_S9131140

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

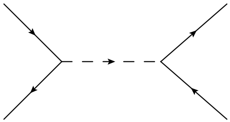
Exercise IVa:

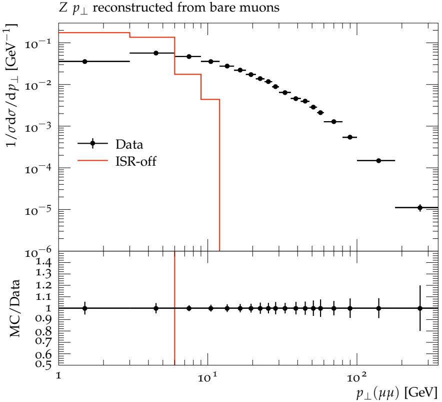
1. Enable Z production and turn off ISR

```
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 $p_T$

ATLAS analysis: ATLAS_2011_S9131140

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

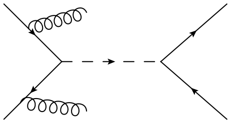
Exercise IVa:

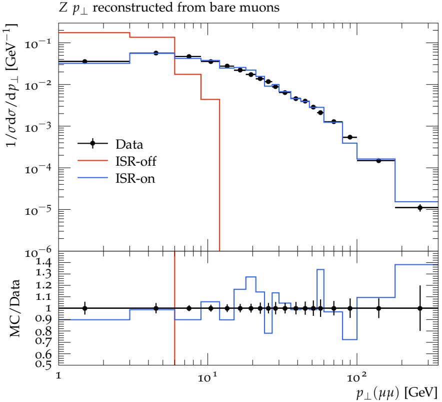
1. Enable Z production and turn off ISR

```
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 $p_T$

Exercise IVb:

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

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

- Run and compare to data

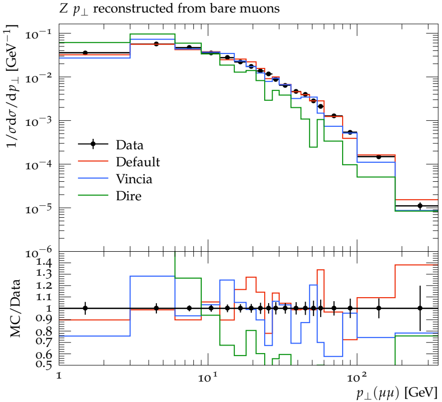
# Exercise IV: Z-boson $p_T$

## Exercise IVb:

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

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

- Run and compare to data




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

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

⇒ Are these the same?

# 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

⇒ Are these the same?

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