# $e^+e^-$ in Pythia 8

## ECFA Higgs Factories: 1st Topical Meeting on Generators 2021

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# Outline

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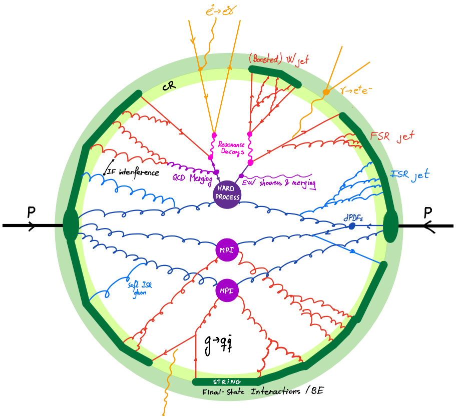
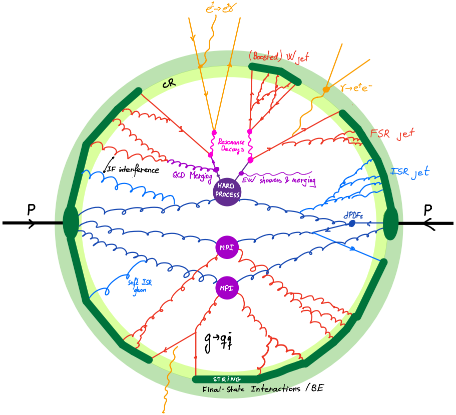
1. PYTHIA 8 basics
2. Hadronization
3. $\gamma\gamma$ collisions
4. Precision studies
5. LHE interface
6. Summary & Outlook




[figure by P. Skands]

## (subset of) Physics covered in 8.3

- Different beam combinations: ee, $\gamma\gamma$, ep, $\gamma$p, pp, p$A$, $AA$, DM
- Hard scattering: native LO, NLO+PS with aMC@NLO and POWHEG-BOX
- Parton showers: Default, DIRE, VINCIA
- Multiparton interactions (MPIs): Interleaved with shower evolution
- Soft physics: Diffraction, Elastic, Hadronic (re-)scattering
- Hadronization: String fragmentation, Color reconnection, Ropes & shoving




[figure by P. Skands]

# Pythia Collaboration

- Christian Bierlich (Lund University)
- Nishita Desai (TIFR, Mumbai)
- Leif Gellersen (Lund University)
- Ilkka Helenius (University of Jyväskylä)
- Philip Ilten (University of Cincinnati)
- Leif Lönnblad (Lund University)
- Stephen Mrenna (Fermilab)
- Stefan Prestel (Lund University)
- Christian Preuss (ETH Zurich)
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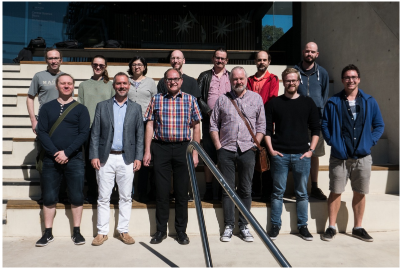
- Peter Skands (Monash University)
- Marius Utheim (University of Jyväskylä)
- Rob Verheyen (University College London)



[Pythia meeting in Monash 2019]

# PYTHIA Collaboration

| | |
|---|---|
| • Christian Bierlich | (Lund University) |
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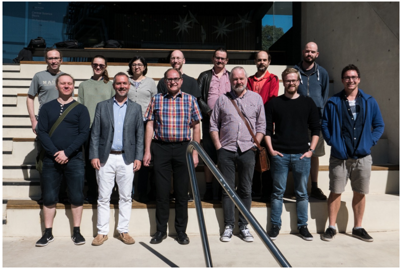


[Pythia meeting in Monash 2019]

- Spokesperson
- Codemaster
- Webmaster

`https://pythia.org`

`authors@pythia.org`

# Hadronization

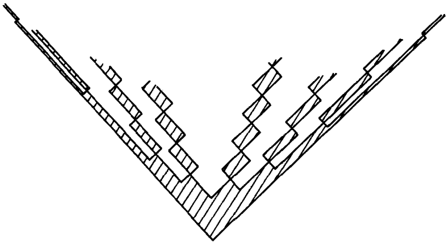
# Hadronization in PYTHIA

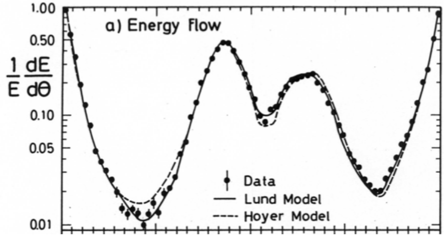
## The Lund string model

- Colour string between q and $\bar{q}$, linear string potential $V(r) \propto \kappa r$
- String breaking with symmetric fragmentation function

$$f(z) \propto \frac{(1-z)^a}{z} \exp(-b m_T^2)$$

- Strings taken non-interacting $\Rightarrow$ Universal fragmentation
- First experimental support from 3-jet events in Petra
- Still main constraints from LEP






[JADE: Phys.Lett.B 101 (1981) 129-134]

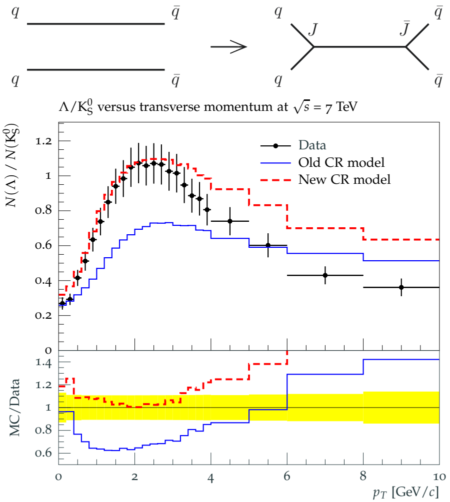
# Universality breaking in hadronic collisions

## Colour reconnection (CR)

- Initial colour configuration from PS splittings (large $N_C$)
- Possible to find a preferred (string-length minimizing) configuration by altering the colour connections

## Available Pythia models

- MPI-based scheme (default)
- QCD-based scheme
  - Baryon production enhanced by junction-style reconnection




[Christiansen, Skands: JHEP 1508 (2015) 003]

## Rope hadronization

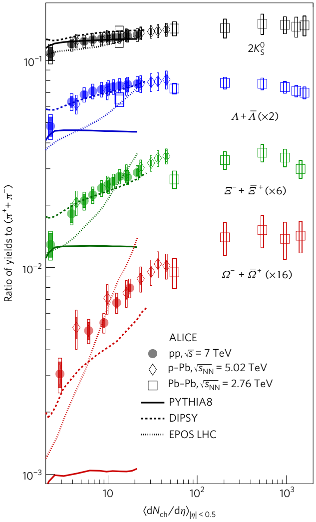
[Bierlich, Gustafson, Lönnblad, Tarasov: JHEP 03 (2015) 148]

- Introduce a finite width for the colour field
  - Strings → Ropes
- Overlapping strings enhance string tension in high-multiplicity collisions
  - Strangeness and baryon enhancement
- Rope hadronization implemented into PYTHIA 8

## String shoving

[Bierlich, Gustafson, Lönnblad: PLB 779 (2018) 58]

- Repulsion between overlapping strings produce long-range correlations (the ridge effect)




[ALICE Nature Phys. 13 (2017) 535-539]

## Wish list for hadronization studies

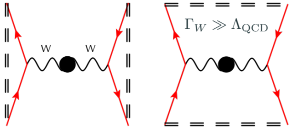
- Identified hadrons with $\Delta|p| \lesssim \Lambda_{\mathrm{QCD}}$

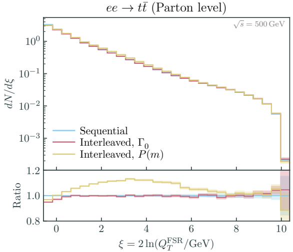
  $\Rightarrow$ Clean constraints for hadronization models, including promptly decaying ones

- High statistics for ee $\to WW$

  $\Rightarrow$ Clean environment to study CR effects, no-CR scenario excluded at 99.5% in LEP II [Phys.Rept. 532 (2013) 119], see also a study for Higgs decays [Christiansen , Sjöstrand: EPJC 75 (2015) 9, 441]

  $\Rightarrow$ Interleaved resonance decays with parton shower, implemented in VINCIA [Brooks, Skands, Verheyen: arXiv:2108.10786]




[arXiv:2108.10786]

# $\gamma\gamma$ collisions

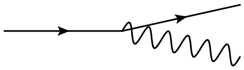
# $\gamma\gamma$ collisions

- High-energy charged leptons radiate photons, approx. flux given by EPA:

$$f_\gamma^l(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{1+(1-y)^2}{y}\frac{1}{Q^2}$$

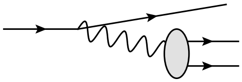
where $y$ the light-cone fraction of the photon wrt. lepton momentum and $Q^2$ photon virtuality $\Rightarrow$ $\gamma\gamma$ collisions

Direct photons



- Point-like initiator of the hard process, “PDF” given by the flux

Resolved photons



- Low $Q^2$ Photon may fluctuate into a hadronic state $\Rightarrow$ MPIs
- PDFs for partonic structure

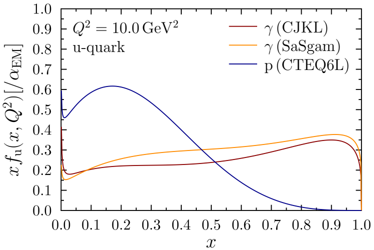
# Resolved photons

## PDFs for for resolved photons

- DGLAP evolution contain term for $\gamma \to q\bar{q}$

$$\frac{\partial f_i^{\gamma}(x,Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{em}}}{2\pi} e_i^2 P_{i\gamma}(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{\mathrm{d}z}{z} P_{ij}(z) f_j(x/z, Q^2)$$

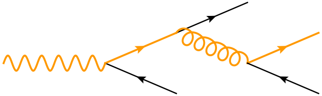
- Convolute PDFs with the flux, save $(y, Q^2)$




## Initial state shower for resolved photons

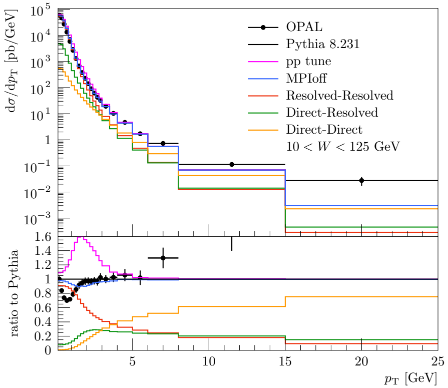
- The $\gamma \to q\bar{q}$ splitting can collapse photon to unresolved state during evolution

$$\mathrm{d}\mathcal{P}_{a\leftarrow b} = \frac{\mathrm{d}Q^2}{Q^2} \frac{\alpha_s}{2\pi} \frac{x' f_a^{\gamma}(x',Q^2)}{x f_b^{\gamma}(x,Q^2)} P_{a\to bc}(z)\,\mathrm{d}z + \frac{\mathrm{d}Q^2}{Q^2} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{e_b^2\, P_{\gamma\to bc}(x)}{f_b^{\gamma}(x,Q^2)}$$



- MPIs allowed above the scale of such splitting (interleaved PS and MPIs)

# Comparison to LEP $\gamma\gamma$ data




[OPAL: Phys. Lett. B651 (2007) 92-101]

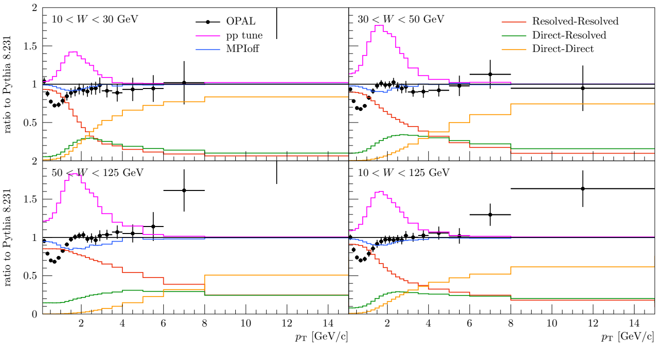
## OPAL data for charged-hadron $d\sigma/dp_T$

- Data taken with $\sqrt{s_{ee}} = 161$ and 172 GeV
- Based on anti-tagging of beam leptons $\Rightarrow$ (quasi-)real photons

## PYTHIA results

- Contributions from resolved (low-$p_T$) and direct photons (high-$p_T$)
- Sensitivity to MPIs at ≈few GeV

# Invariant mass dependence




[OPAL: Phys. Lett. B651 (2007) 92-101]

Can use OPAL data to constrain MPI parameters

- $W$ = invariant mass of $\gamma\gamma$ system
- Larger contribution from resolved processes with higher $W$, also more MPIs
- Fit energy dependence of MPI regulator $p_{T,0}$

- Fitted result set as default in PYTHIA 8 for $\gamma\gamma$

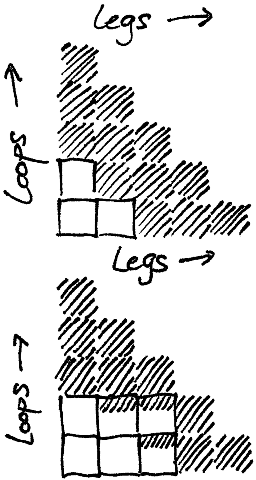
$$p_{T0}^{\gamma\gamma}(\sqrt{s}) = 1.567\text{ GeV} + 0.419 \cdot \log\left[\sqrt{s}/100\text{ GeV}\right]$$

# Precision studies

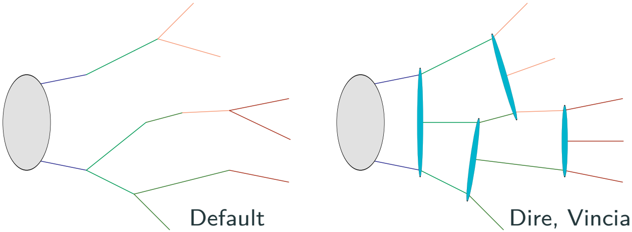
# Precision in parton showers

## Matching Fixed-order and parton showers

- Native Pythia: LO fixed order $\otimes$ LL resummation from parton shower (PS)
- Current standard for most of the processes is NLO matched to PS
  - In Pythia the NLO hard processes typically provided with LHE files (aMC@NLO and Powheg-Box)
  - Also Matrix-element (ME) corrections for the first splitting



# New native PS options in PYTHIA 8.3




## VINCIA

[Fischer, Prestel, Ritzmann, Skands: EPJC 11 (2016) 589]

- Coherent evolution (antenna pattern)
- Iterated LO ME corrections
- QCD, QED and EW (all splittings), interleaved resonance decays

## DIRE

[Höche, Prestel: EPJC 75 (2015) 9, 461]

- Coherent evolution, split into collinear regions
- NLO corrections for the evolution, ME corrections
- QCD, QED, ∼EW, dark photons

# Future improvements

## Proof of concept NNLO+PS in VINCIA

[Campbell, Höche, Li, Preuss, Skands: arXiv:2108.07133]

- Focus on $e^+e^- \to Z \to$ two jets
- Possible to adapt formalism also to more complicated final states but require more effort
- Publicly available $\sim$ 1-2 years

## N3LO+PS with TOMTE[1] method

[1]Third Order Mathced Transition Events

[Prestel: arXiv:2106.03206]

- Currently in proof-of-concept state
- Tested for $e^+e^- \to$ jets
- Part of DIRE, unclear if a PYTHIA implementation will follow

# Interfacing

# Interfacing ME and general-purpose generators

## Les Houches event files (LHEF)

- Provide Parton-level ME generator based hard processes as a set of four-momenta in `<event>...</event>` blocks
- Beam and relevant generator settings provided in `<header>...</header>`
- Can also include optional event information, such as PDF or scale variations

## PYTHIA 8.3 interface

- Can read and write LHEF v1 and v3 formats
- Handles any number of xml tags (such as <event>, e.g. for NLO matching)
- Has handled `#pdf` tags from the beginning for PDF uncertainties
- Now handles also Madgraph scale variations consistently, shower variations correctly propagated into HepMC (`main89.cc`)
- Possible to read in two hard processes in the same event

# Interfacing ME and general-purpose generators

## Possible extensions in LHEF

- Standard for separate shower starting scale setting for resonance decays, currently some "private agreements" between POWHEG and PYTHIA
- Separation of photons emitted by bremsstrahlung and beamstrahlung (relevant especially for linear $e^+e^-$ colliders)

$\Rightarrow$ $p_\mathrm{T}$ kicks can be large for the former but negligible for the latter

- Store intermediate $\gamma$ kinematics for resolved photons (though currently not many ME generators available)

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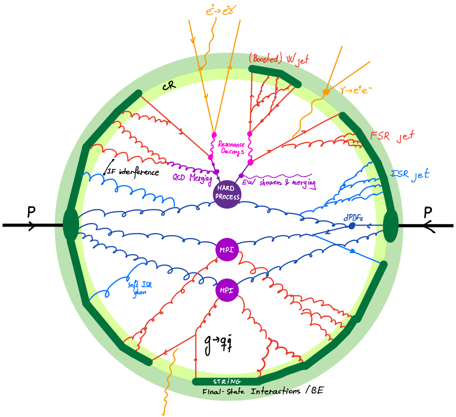
What else?

## PYTHIA 8.3

- Extensions to string hadronization
- Collision with (quasi-)real photons
- New shower models with improved precision
- Generic LHEF (v1 and v3) interface

## Upcoming features

- A new parallelization framework for multithreading
- Further improvements in matching precision




[figure by P. Skands]