PYTHIA from 2017 to 2021: an overview

For the PYTHIA collaboration
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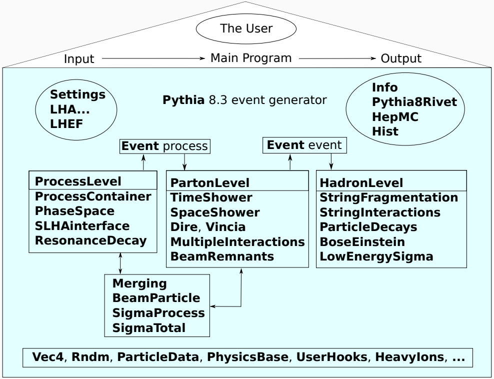
Lund University

Dec 7th 2021, 23rd MCnet Meeting, Manchester

PYTHIA: General purpose Monte Carlo

- General purpose MCEG for pp **and much more.**
- **Versatility** as a guiding principle.



- Historically JETSET + LO ME and parton shower.
- Past 4 years: extensions to many collision systems, new showers, shower uncertainties, many new soft physics models...

This talk

- Broad rather than deep overview.
- Not just developments on the physics side.

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PYTHIA 8.223, Jan 5 2017

- 10 authors (33% in Lund).
- Torbjörn Sjöstrand carrying most tasks and responsibilities.
- Recent physics focus: M&M.
- Mostly caught up with PYTHIA6, some new physics scope.

1. Physics developments.
2. Technical developments.
3. Organisatorial developments.
4. PYTHIA & the future.

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PYTHIA 8.306, Jun 28, 2021

- 13 authors (38% in Lund).
- More distributed leadership structure.
- Recent physics focus: Soft QCD models & two new showers.
- Many benefits over PYTHIA6.

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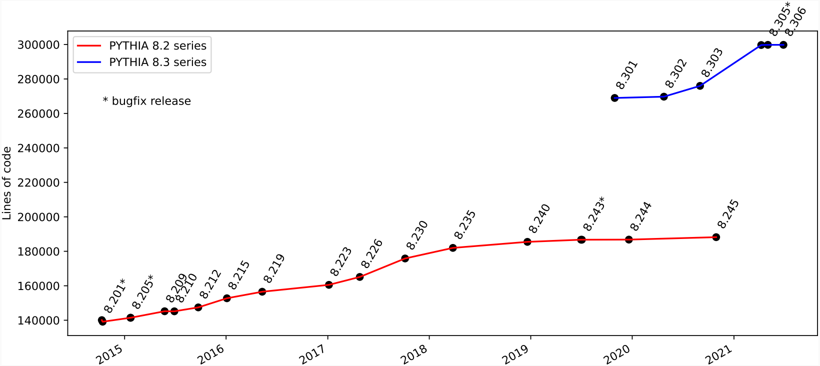

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2. Technical developments.
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Main physics developments, 8.223 $\rightarrow$ 8.306

Not a complete list, but an overview of main physics extensions.
Most with published code, some only paper.

- Cross sections and diffraction:
  1. Cross section calculations.
  2. Diffraction with γ-beams & UPCs.

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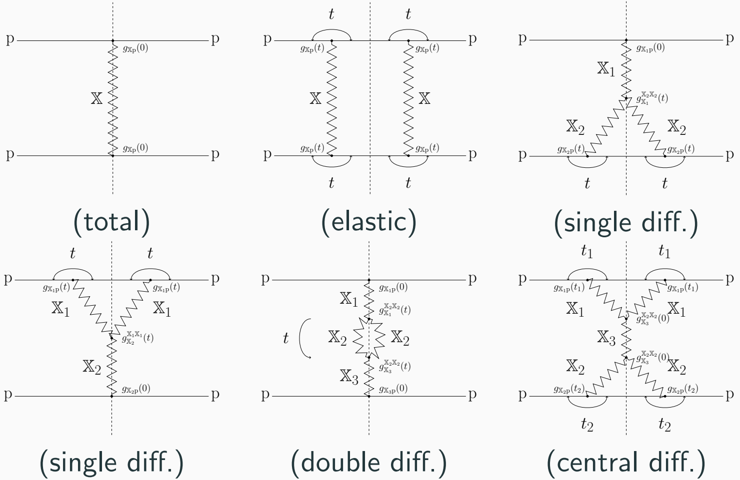
And many, many more smaller updates, fixes, convenience implementations etc.
Apologies to those not mentioned.

Cross section calculations (CB, Rasmussen & Sjöstrand: 1804.10373, 1907.12871)

- Old SaS default appended with several other models.
- Regge based parametrizations, includes LHC related updates.
- Alternative Mueller-dipole based → EIC & substructure.



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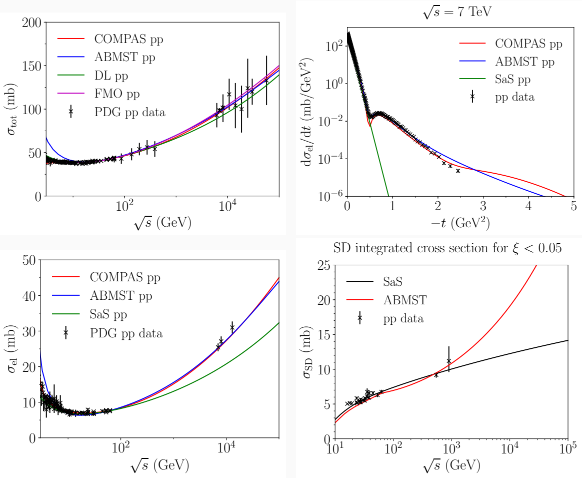

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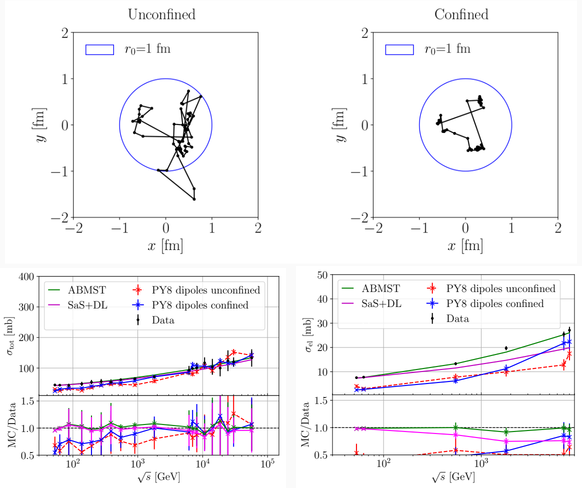
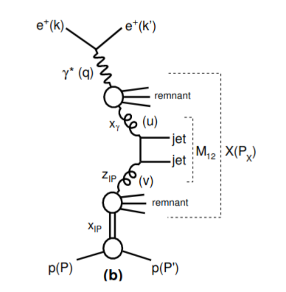
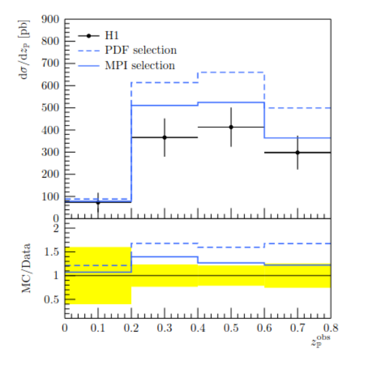


Hard and soft diffraction with γ-beams (Helenius & Rasmussen: 1901.05261)

- Important processes for DIS-type systems. Factorization breaking at HERA.
- Using MPIs to "fill the gap" of diffractive systems. Reject events where MPIs shroud the diffractive signature.





- Framework can also do UPCs!

VINCIA (Brooks, Preuss, Skands & Verheyen: 1907.08980, 2002.04393, 2003.00702, 2008.09468)

- Fully incorporated new shower, based on antenna formalism.

◇ Interleaved evolution for ISR, FSR & coloured resonances.

◇ Fully coherent soft interference for QED.

◇ Includes module for electroweak shower (see also 2108.10786).

◇ Technical: "sector" shower makes HO corrections easier.

◇ Dedicated CKKW-L merging in VINCIA, exploiting power of sector showers.

◇ NNLO matching in the pipeline (2108.07133).

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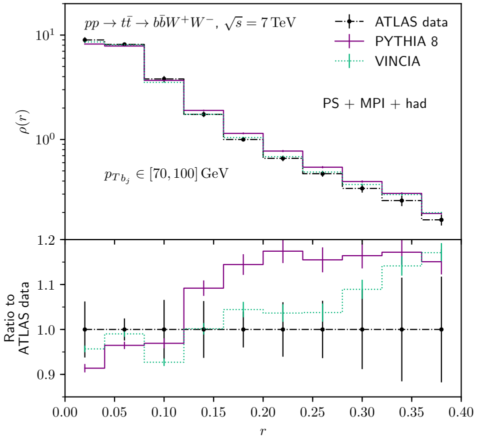

- QCD: Vincias more narrow jet profile favoured by data
- b-jet profile in $t\bar{t}$ production.

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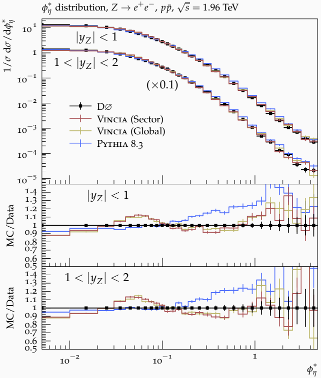

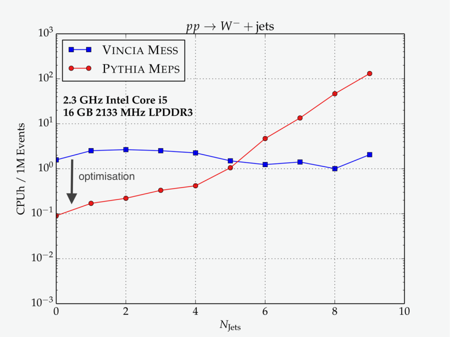

- ISR sector shower: Drell-Yan leptons opening angle.
- Performance: VINCIA shower slow (oversampling) but sector merging faster (linear vs. factorial) due to limited histories.

DIRE (Gellersen, Höche & Prestel: 1506.05057, 2109.09706)

- Fully incorporated new shower, based on dipole formalism + collinear enhancements.

◇ QCD and QED shower with automatic uncertainties.

◇ Includes higher order corrections to kernels.

◇ Focus on making merging easy, also for the user.

◇ Option for Dark Matter emissions in shower.

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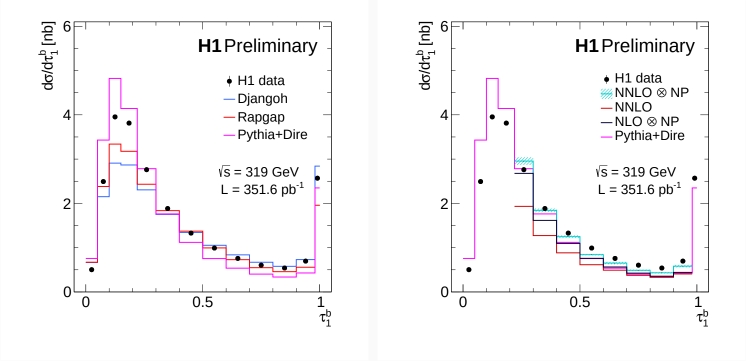
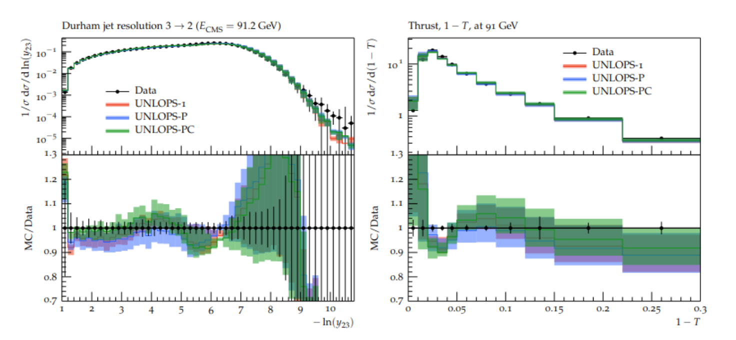


(Figure credit: H1/Johannes Hessler)

- Well used (massive PR campaign) for $ep \to$ EIC.
- Here 1-jettiness event shape in new H1 analysis (2111.11364.)

Automated shower variations (Gellersen & Prestel: 2001.10476)

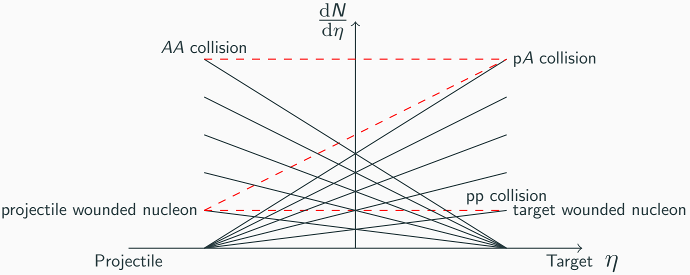
- Adding to previous PDF variation, one can now perform automatic renormalization scale variation in the CKKW-L, UMEPS, NL-3 and UNLOPS merging schemes.
- Completely unified weights scheme in progress, but difficult.



- Automating these tasks potentially improves users' error estimation significantly! Lots of potential and interest.

Angantyr (CB, Gustafson, Lönnblad & Shah: 1806.10820)

- Framework for full heavy ion collisions.
  - ◇ Glauber calculation decides which nucleons hit each other.
  - ◇ PYTHIA pp, pn & nn events stacked on top of each other.
  - ◇ A clean slate for adding collective effects, no QGP.



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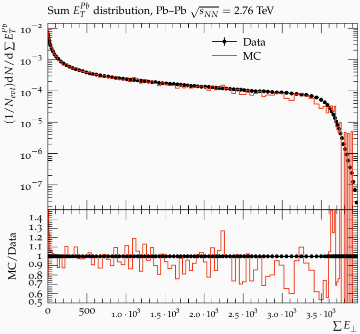
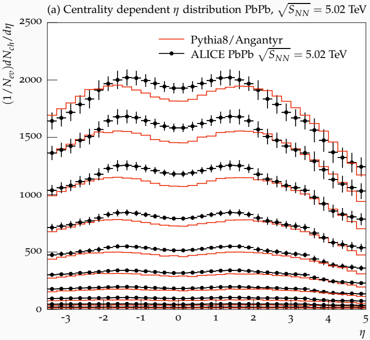
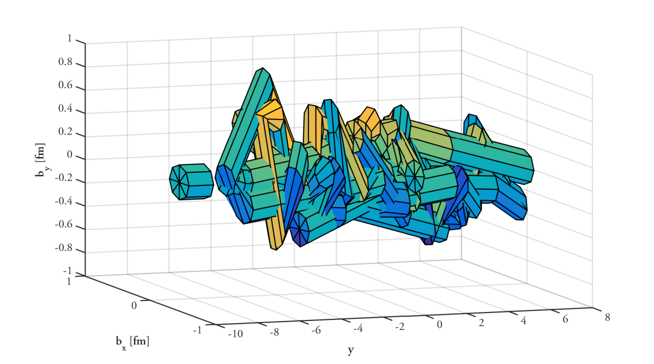




- Just specify your nuclear beams and run!

String interactions (CB, Chakraborty, Gustafson & Lönnblad: 1710.09725, 1807.05271, 1901.07447)

- Extending Lund strings' abilities: interactions between strings.
  - ◇ **String shoving** generates flow.
  - ◇ **Rope hadronization** increases strangeness and baryons.



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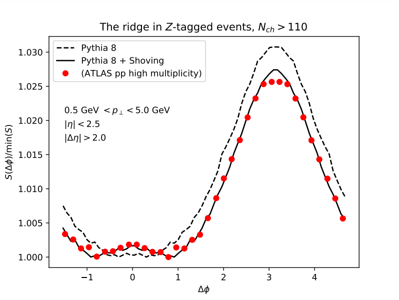
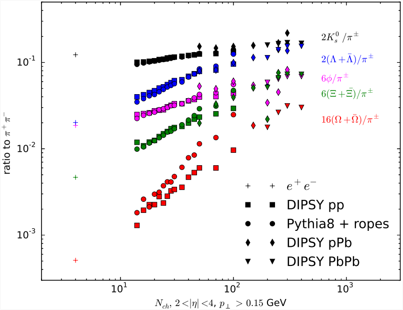
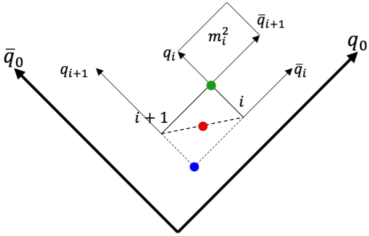




- Intended as an alternative to QGP models.
- Extensions to AA ongoing (2010.07595).

Hadronic rescattering (CB, Ferreres-Solé, Sjöstrand & Utheim: 1808.04619, 2005.05658, 2103.09665)

- Hadrons may scatter again in the final state
- Some effects in pp, very important in ion collisions.
- Requires knowledge of hadron production vertices.
- ...a new framework for Low Energy QCD processes.
- ...with an extensive amount of cross sections!



incoming	rate	incoming	rate	incoming	rate
$\pi+\pi$	12.63	$\mathrm{K}+\mathrm{N}$	0.39	$\eta/\eta'+N$	0.19
$\pi+\rho$	4.59	$\rho+\rho$	0.38	$\pi+\mathrm{B}$	0.18
$\pi+\mathrm{K}$	3.84	$\rho+\mathrm{N}$	0.36	$N+\Delta$	0.16
$\pi+\mathrm{N}$	3.44	$\rho+\omega/\phi$	0.34	$\pi+\Sigma^*$	0.15
$\pi+\omega/\phi$	2.08	$\rho+\eta/\eta'$	0.30	$\rho+\Delta$	0.14
$\pi+\eta/\eta'$	1.80	$\pi+f_0(500)$	0.29	$\eta/\eta'+\omega/\phi$	0.14
$\pi+\mathrm{K}^*$	1.33	$\mathrm{K}+\omega/\phi$	0.27	$\pi+\mathrm{M}$	0.12
$\pi+\Delta$	1.10	$\mathrm{K}+\mathrm{K}$	0.26	$\mathrm{K}+\Delta$	0.11
$\rho+\mathrm{K}$	0.54	$\pi+\Lambda$	0.25	$\mathrm{K}^*+\mathrm{N}$	0.11
$\pi+\Sigma$	0.46	$\omega/\phi+\mathrm{N}$	0.24		
$\mathrm{N}+\mathrm{N}$	0.46	$\mathrm{K}+\eta/\eta'$	0.23		
$\mathrm{K}+\mathrm{K}^*$	0.41	$\rho+\mathrm{K}^*$	0.20	other	1.87

(Rescatterings per 13 TeV ND pp event)

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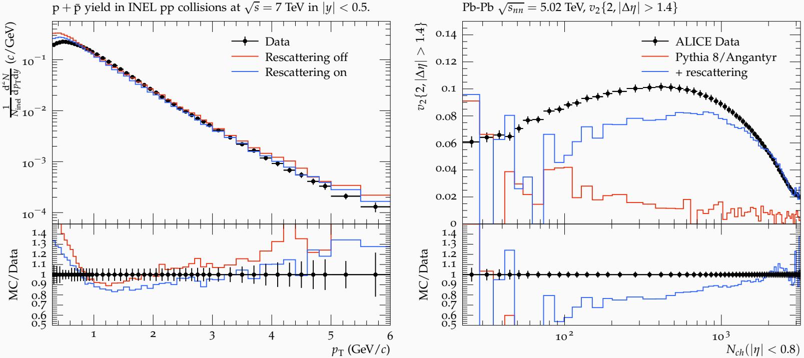
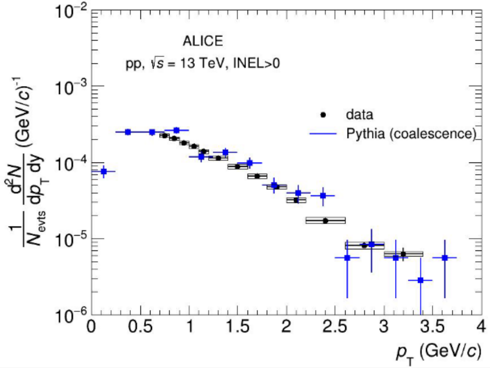


- Inevitable for precision, even in min-bias.
- Low Energy framework very versatile, added bonus!

Deuteron coalescence & molecular states (Ilten & Utheim: 2108.03479)

- Existing model(s): Momentum space recombination of $\mathrm{p} + \mathrm{n}^0, \mathrm{p} + \mathrm{p}, \mathrm{n}^0 + \mathrm{n}^0 \to {}^2\mathrm{H} + X$.
- Cross sections taken from experiments/shape only.

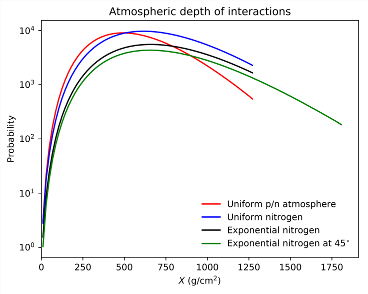


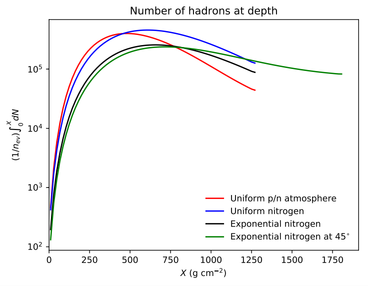
(Figure credit: ALICE/Alberto Caliva, Valentina Zaccolo)

- Extending to space-time in rescattering picture.
- Other molecular states; tetraquarks & pentaquarks.

Extension to cosmic rays (Sjöstrand & Utheim: 2108.03481)

- Building upon updated framework for low energy interactions.
- Proof-of-principle atmospheric cascade, a new playing field.
- Includes simplified model for pA interactions.





- 10^8 GeV initiator proton through atmosphere. Left: number of interactions. Right: hadrons remaining above kinematic threashold.

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- Transition from svn → gitlab.com
  - ◇ More possibilities for collaboration on issues.
  - ◇ Automatic checks (both technical and physics) at commit-level, merge level and release.
  - ◇ Still some manual checks (PVS).
  - ◇ Strong gatekeeper → distributed code checks (with a **codemaster** to oversee).
  - ◇ Main repo private. Have https://pythia.org for code tarballs, historic code (dating back to 1986!) and online manual.
- Technical changes supporting organisatorial changes.

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    - ◇ Major sprints for code and manuscript writing.
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- One such outcome: Git repo with 1h topical tutorials.
  - ◇ Need for consistent and maintained tutorial material for special topics!
  - ◇ Also a chance to try each others' work.
  - ◇ Already used for summer schools, might be extended with video in the future.

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- Communication with experiments.
  - Contact persons for all LHC experiments (and others) are helpful. Pragmatically different in approach.
  - PHENOmenal discussion meetings started (mainly PYTHIA/ALICE, but others also present).

PYTHIA and the future

- Many developments in the pipeline, here just a selection!
- A dedicated PYTHIA 8.3 paper with physics and guides for new users.
  - ◇ Complete replacement of the PYTHIA6 physics manual.
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- Driven by individuals' interests, little common strategy.
    - ◇ Cosmic ray physics, coherent framework for HI physics, eA support, NNLO matching, more electroweak shower options, ...
    - ◇ PYTHIA contrib, better ME interfacing, HPC compatibility, ...
- Active involvement in EIC community.

The PYTHIA collaboration

- CB, Lund, hadronization, HI, ALICE. **webmaster**.
- Nishita Desai, Tata Inst, SUSY, SLHA, BSM.
- Leif Gellersen, Lund, scale uncertainties, matching/merging.
- Ilkka Helenius, Jyväskyla, photoproduction, $\gamma - \gamma$, diffraction. **deputy spokesperson**.
- Philip Ilten, Cincinnati, τ's, onia, LHCb. **codemaster**.
- Leif Lönnblad, Lund, HI, hadronization.
- Stephen Mrenna, Fermilab, SUSY, matching/merging, CMS.
- Stefan Prestel, Lund, matching/merging, DIRE, ATLAS.
- Christian Preuss, Zürich, VINCIA, ext ME, matching/merging.
- Torbjörn Sjöstrand, Lund, SM, parton showers, MPIs, CR, hadronization, core structure.
- Peter Skands, Monash, VINCIA, MPIs, CR, tuning, hadronization. **spokesperson**.
- Marius Utheim, Jyväskyla, hadronic rescattering.
- Rob Verheyen, UCL, weak showers, VINCIA.