Herwig, QCD and the Higgs boson

Bryan Webber

UNIVERSITY OF CAMBRIDGE

- Before the Standard Model
- QCD and me
- History of Herwig
- Usage of parton shower event generators
- PSEGs and Higgs
- Ongoing/future developments

Before the SM

- I was an experimentalist!
- $K^- p \to \bar{K}^0 n\,,\ \bar{K}^0/K^0 \to \pi^{\pm} l^{\mp} \nu$ in HBC at Berkeley Bevatron

PHYSICAL REVIEW D VOLUME 3, NUMBER 1 1 JANUARY 1971

Experimental Test of the $\Delta S = \Delta Q$ Rule in Leptonic Decays of Neutral K Mesons*

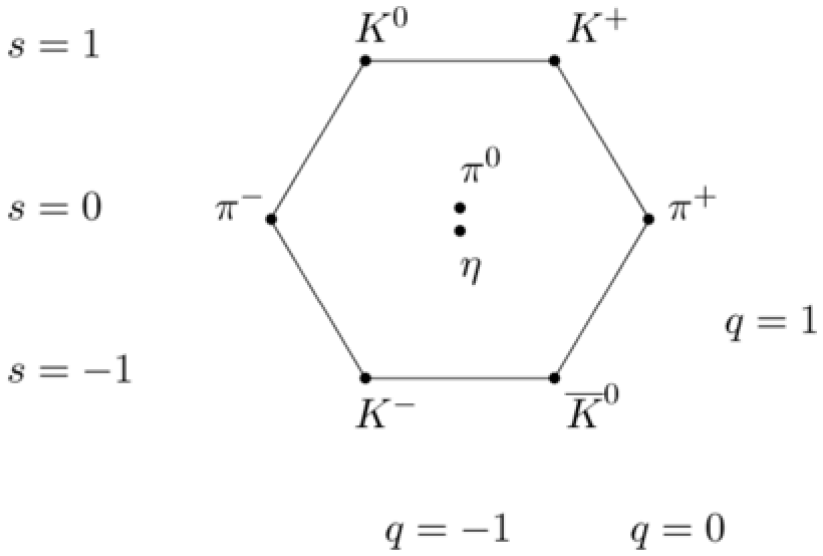
BRYAN R. WEBBER, FRANK T. SOLMITZ, FRANK S. CRAWFORD, JR., AND MARGARET ALSTON-GARNJOST
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
(Received 17 August 1970)

PHYSICAL REVIEW D VOLUME 1, NUMBER 7 1 APRIL 1970

Experimental Search for CP-Violating Decay $K_S \to \pi^+\pi^-\pi^0$†

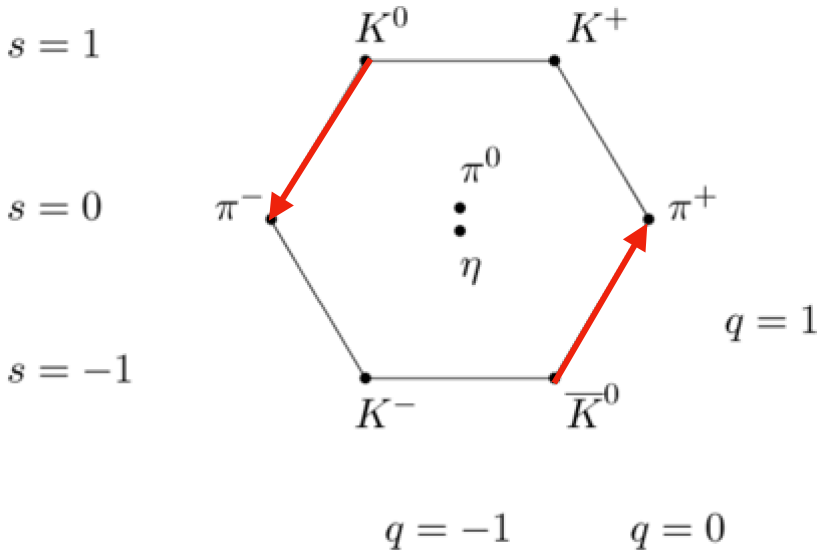
BRYAN R. WEBBER, FRANK T. SOLMITZ, FRANK S. CRAWFORD, JR., AND MARGARET ALSTON-GARNJOST
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
(Received 15 December 1969)

Before the SM



- ΔS=ΔQ, Feynman & Gell-Mann 1958
- Eightfold Way, Gell-Mann 1961

Before the SM



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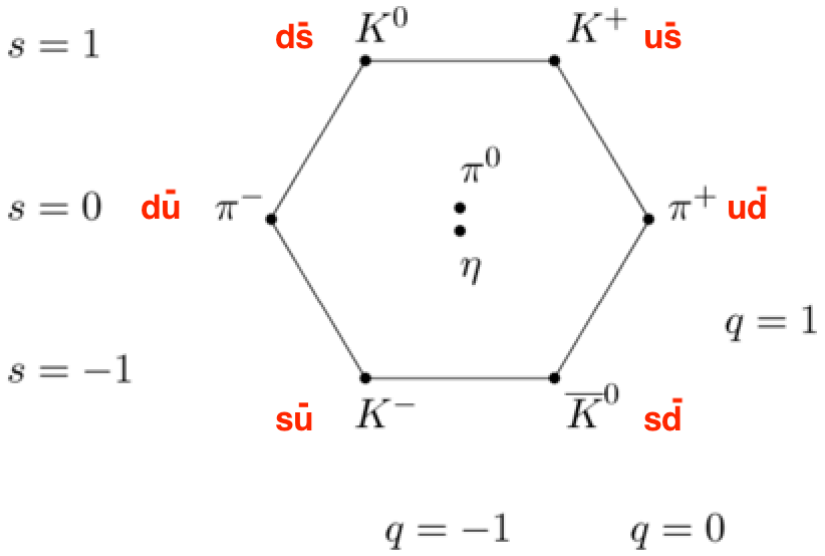
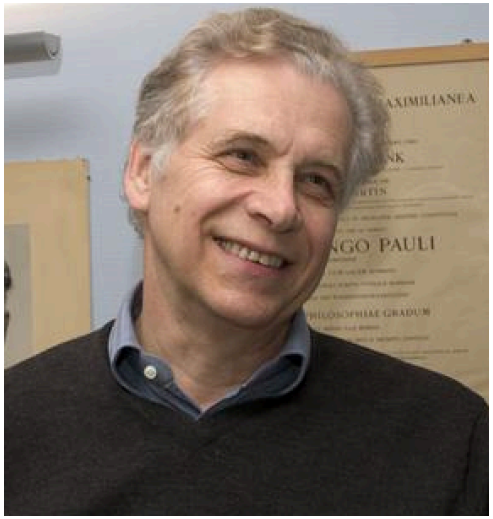


- ΔS=ΔQ, Feynman & Gell-Mann 1958
- Eightfold Way, Gell-Mann 1961
- Quarks, Gell-Mann & Zweig 1963
- CP Violation, Fitch & Cronin, 1964
- DIS, SLAC-MIT 1968

1969

1969



1969

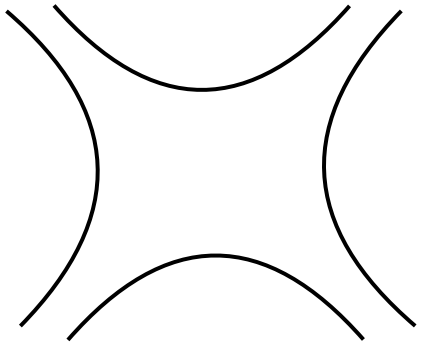
IL NUOVO CIMENTO Vol.. LVII A, N. 1 1º Settembre 1968

Construction of a Crossing-Simmetric, Regge-Behaved Amplitude for Linearly Rising Trajectories.

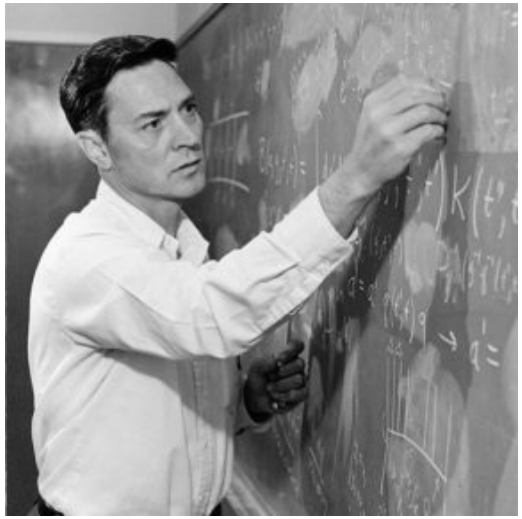
G. VENEZIANO (*)
CERN - Geneva

(ricevuto il 29 Luglio 1968)

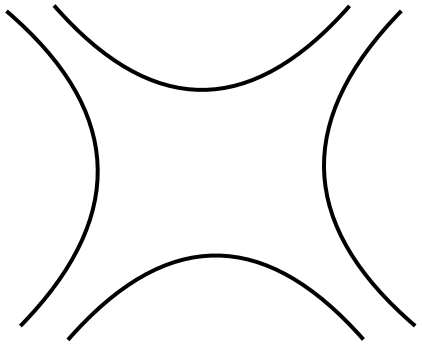
- Veneziano Berkeley seminar
  - "Dual resonance model" → string theory



1969



- Veneziano Berkeley seminar
  - "Dual resonance model" → string theory
- PhD thesis defence
- Chew postdoc offer



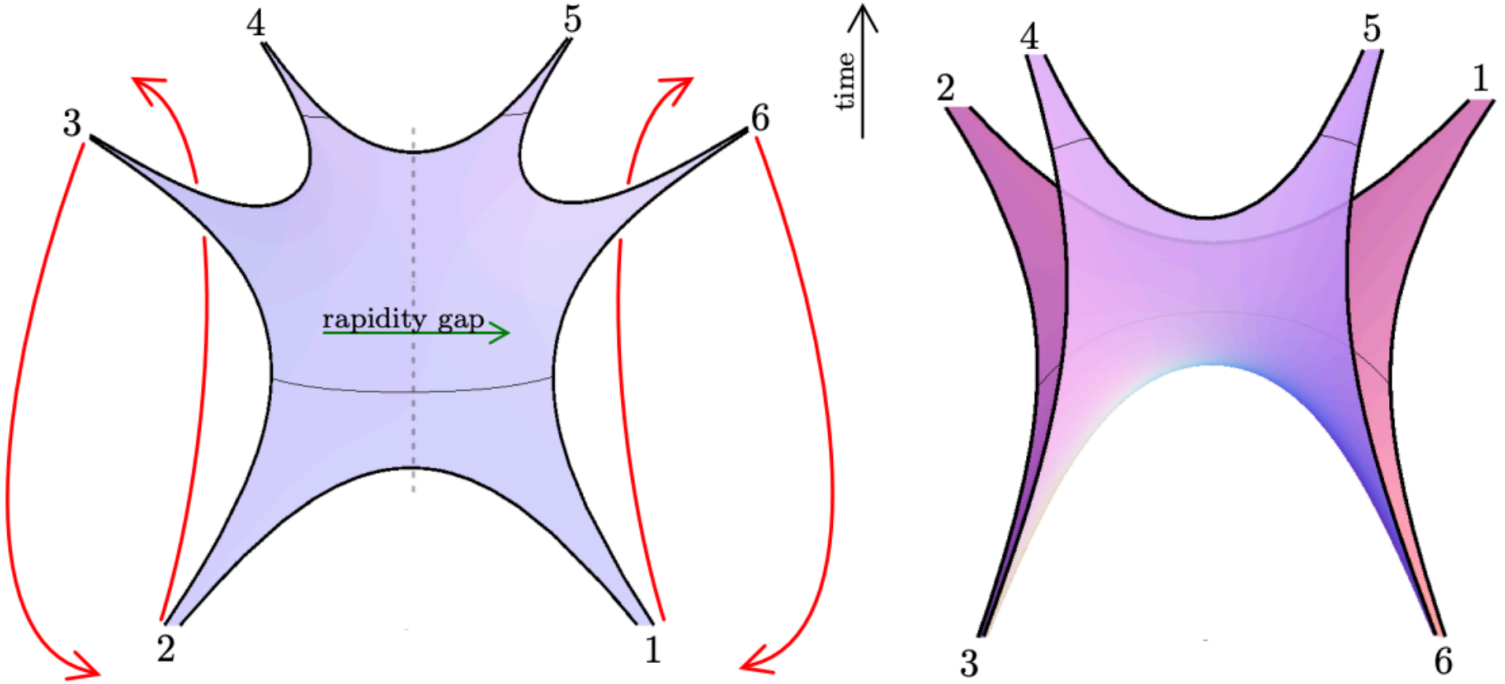
A NEW REGGE TRAJECTORY IN THE DUAL RESONANCE MODEL☆

P. HOYER and N.A. TÖRNQVIST[1]
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

and

B.R. WEBBER[2]
Cavendish Laboratory, University of Cambridge, Cambridge, England

Received 7 January 1976



Basso, Caron-Huot, Sever JHEP 01(2015)027

QCD and me

- Asymptotic freedom: Gross & Wilczek, Politzer, 1973
  - Jets: CERN ISR 1973, SLAC SPEAR 1975
- QCD jets: Sterman & Weinberg, 1977
- Leningrad lectures 'samizdat': Dokshitzer, Diakonov & Troian, 1978 (Phys Rep 1980)

Jet Broadening

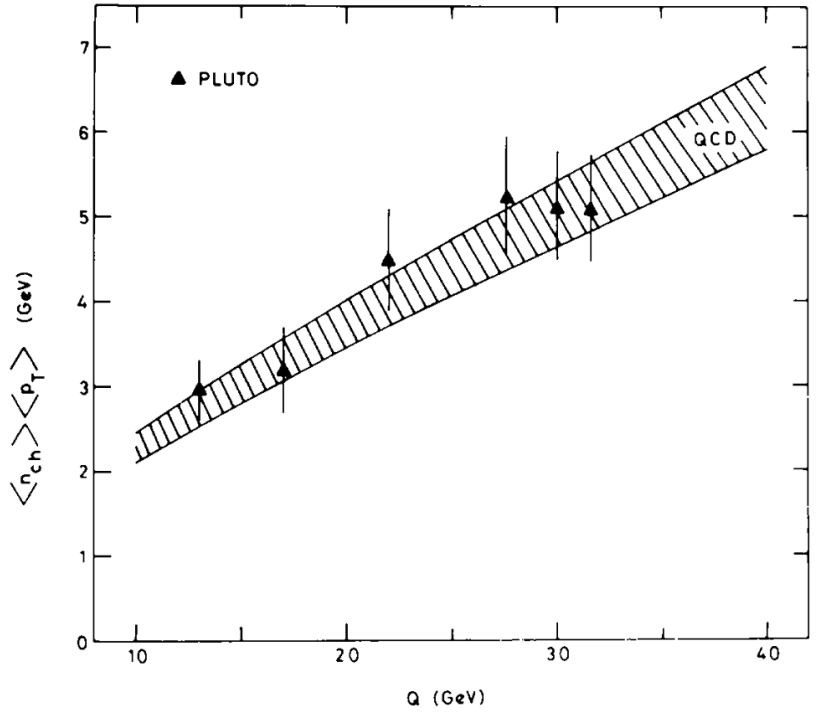
TRANSVERSE MOMENTUM MOMENTS OF HADRON DISTRIBUTIONS IN QCD JETS*

P.E.L. RAKOW and B.R. WEBBER

Cavendish Laboratory, Cambridge, England

NPB 191 (1981) 63

$$\left\langle \sum_{\text{all}} |\underline{p}_{\text{T}}| \right\rangle = \langle n_{\text{tot}} \rangle \langle p_{\text{T}} \rangle = 1.29 \alpha_s(Q^2) Q + O(\alpha_s^2 Q)$$



QCD JET BROADENING IN HADRON-HADRON COLLISIONS

R. K. Ellis
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois, 60510, U.S.A.
and
B. R. Webber
Cavendish Laboratory, University of Cambridge,
Madingley Road, Cambridge CB3 0HE, U.K.

(Proc. Snowmass 1986)

Jet broadening measures in e^+e^- annihilation

S. Catani [a,1], G. Turnock [b] and B.R. Webber [a,2]

[a] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*
[b] *Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3*

PLB 295 (1992) 269

QCD and me

- Asymptotic freedom: Gross & Wilczek, Politzer, 1973
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- Preconfinement: Amati & Veneziano, 1979
- Angular ordering: Bassetto, Ciafaloni, Marchesini & Mueller, 1982

SIMULATION OF QCD JETS INCLUDING SOFT GLUON INTERFERENCE

G. MARCHESINI

Istituto di Fisica dell'Università di Parma
and
INFN, Sezione di Milano, Italy

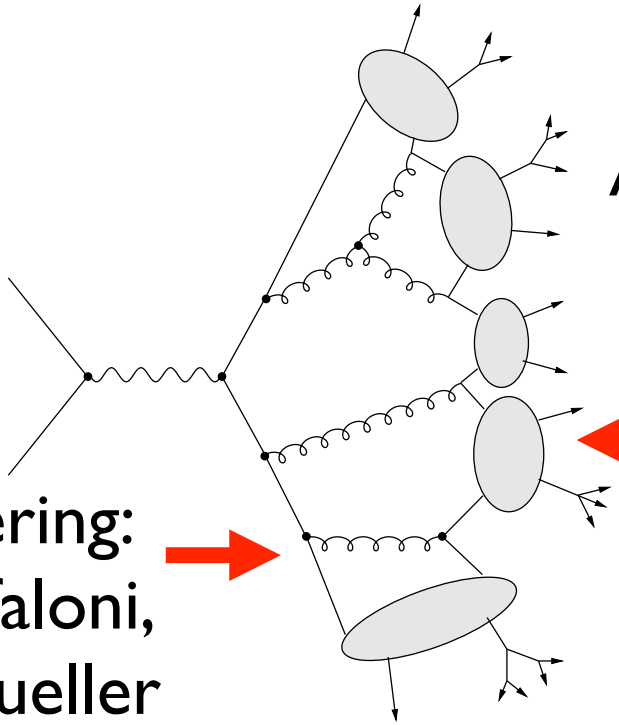
B.R. WEBBER*

CERN, Geneva, Switzerland

Received 21 March 1983
(Revised 14 December 1983)

EARWIG

- Electron Annihilation Reactions With Interfering Gluons



QCD coherence

Angular ordering:
Bassetto, Ciafaloni,
Marchesini, Mueller

Preconfinement:
Amati & Veneziano

Cluster model:
Wolfram

+ Backward evolution:
Sjöstrand

HERWIG

- Hadron Emission Reactions With Interfering Gluons

MONTE CARLO SIMULATION OF GENERAL HARD PROCESSES WITH COHERENT QCD RADIATION*

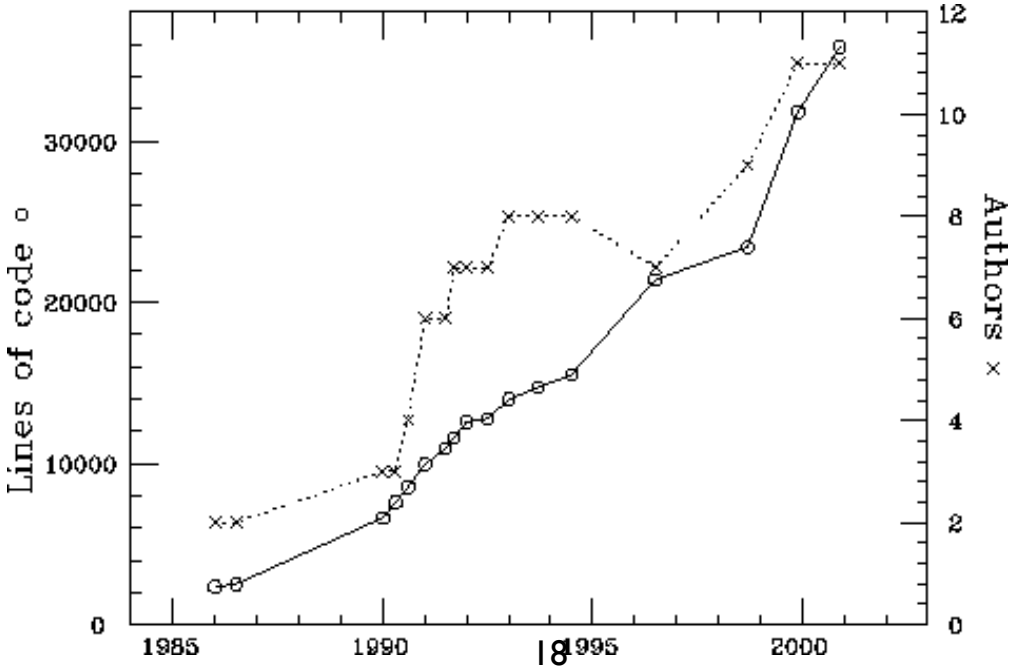
G MARCHESINI

Dipartimento di Fisica, Università di Parma, INFN, Gruppo Collegato di Parma, Italy

B R WEBBER

Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Received 8 February 1988



Preprint typeset in JHEP style. - HYPER VERSION

Cavendish-HEP-99/03
CERN-TH/2000-284
RAL-TR-2000-048

HERWIG 6.5: an event generator for Hadron Emission Reactions With Interfering Gluons (including supersymmetric processes)*

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E-mail: corcella@mppmu.mpg.de

Ian G. Knowles
Department of Physics and Astronomy, University of Edinburgh, UK
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Kosuke Odagiri
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Bryan R. Webber
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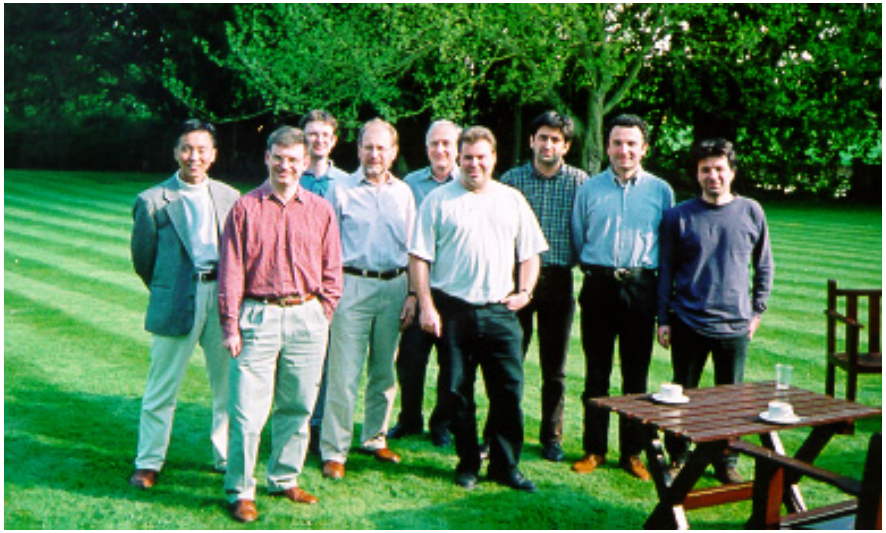
E-mail: webber@hep.phy.cam.ac.uk



HERWIG++/7

Eur. Phys. J. C
DOI 10.1140/epjc/s10052-008-0798-9

THE EUROPEAN PHYSICAL JOURNAL C

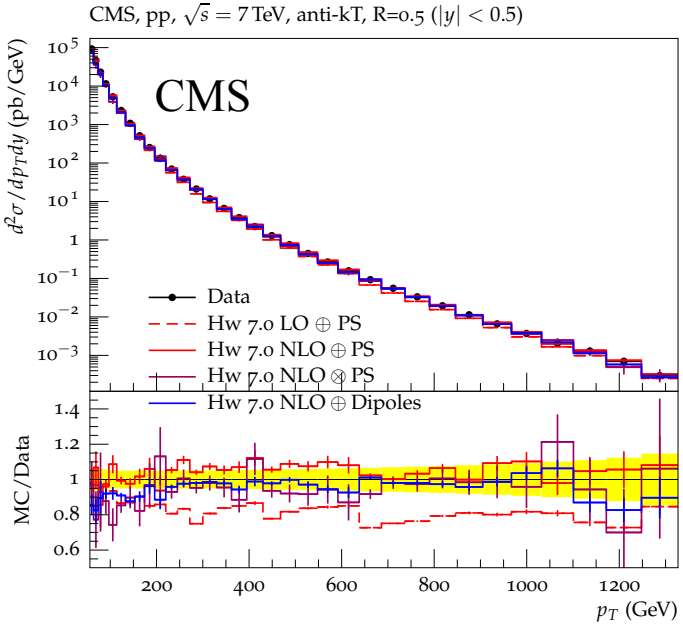
Special Article - Tools for Experiment and Theory

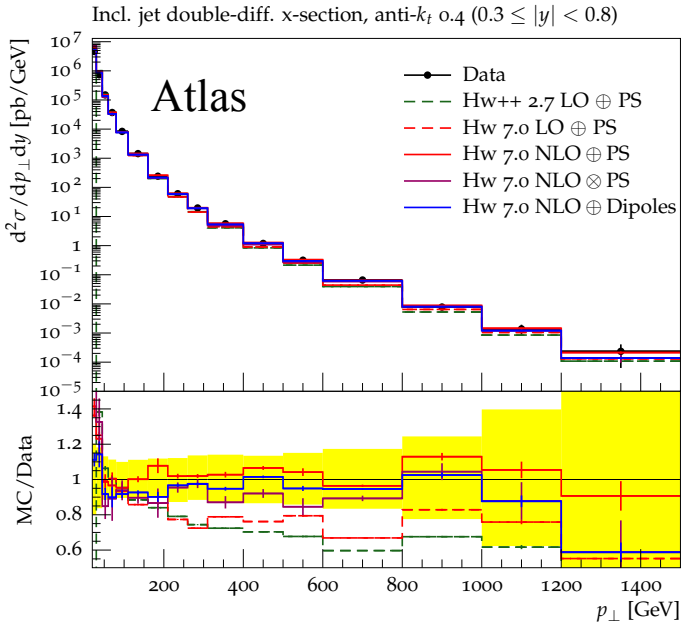
Herwig++ physics and manual

Manuel Bähr[1], Stefan Gieseke[1], Martyn A. Gigg[2], David Grellscheid[2], Keith Hamilton[3], Oluseyi Latunde-Dada[4], Simon Plätzer[1], Peter Richardson[2,5,a], Michael H. Seymour[5,6], Alexander Sherstnev[4], Bryan R. Webber[4]

[1]Institut für Theoretische Physik, Universität Karlsruhe, Karlsruhe, Germany
[2]IPPP, Department of Physics, Durham University, Durham, UK
[3]Centre for Particle Physics and Phenomenology, Université Catholique de Louvain, Louvain-la-Neuve, Belgium
[4]Cavendish Laboratory, University of Cambridge, Cambridge, UK
[5]Physics Department, CERN, Geneva, Switzerland
[6]School of Physics and Astronomy, University of Manchester, Manchester, UK

Received: 1 September 2008





HERWIG 7

- The project is now in good hands:

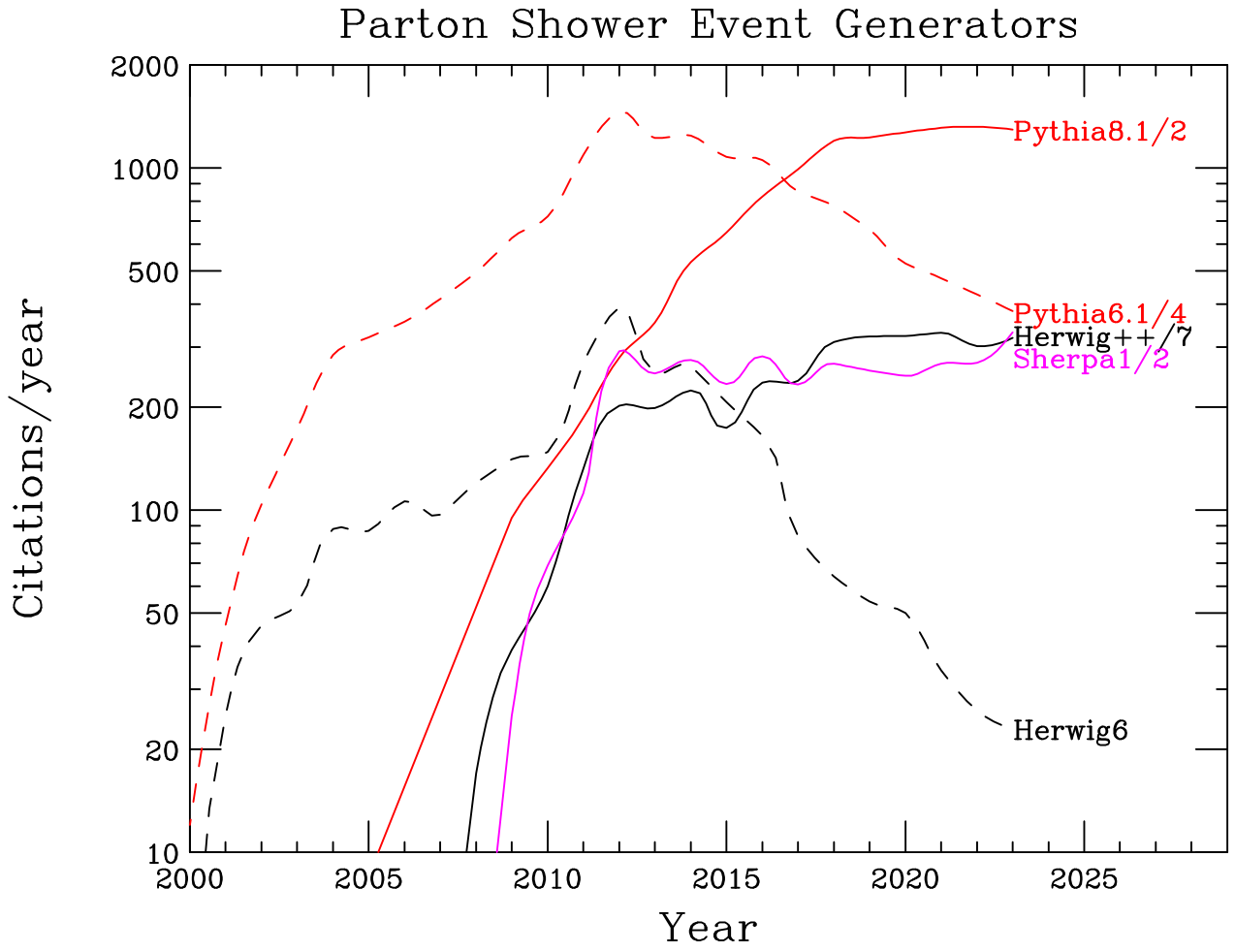
Mike Seymour
Manchester

Peter Richardson
Durham

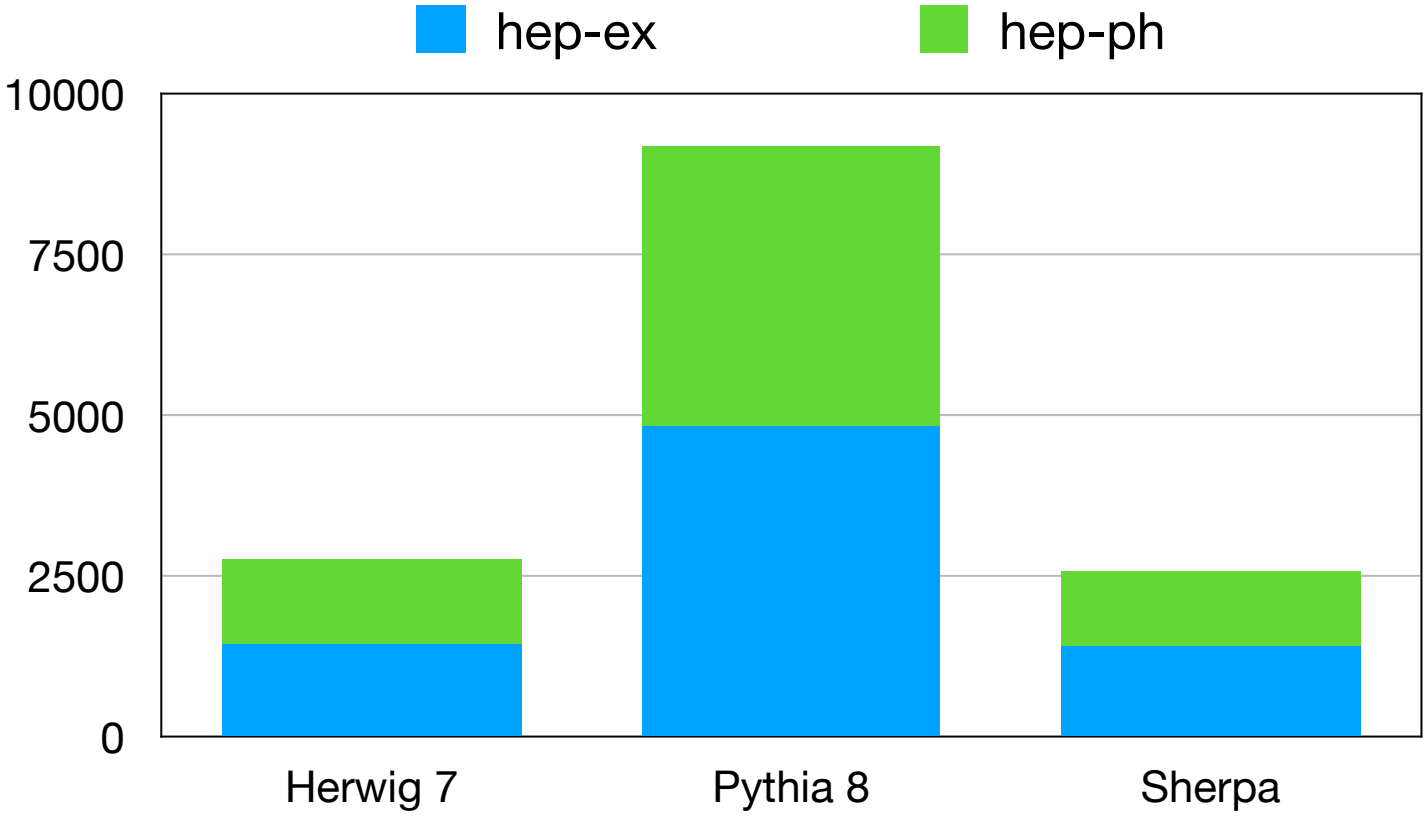
Simon Plätzer
Vienna

Stefan Gieseke
Karlsruhe

Usage of Parton Shower Event Generators

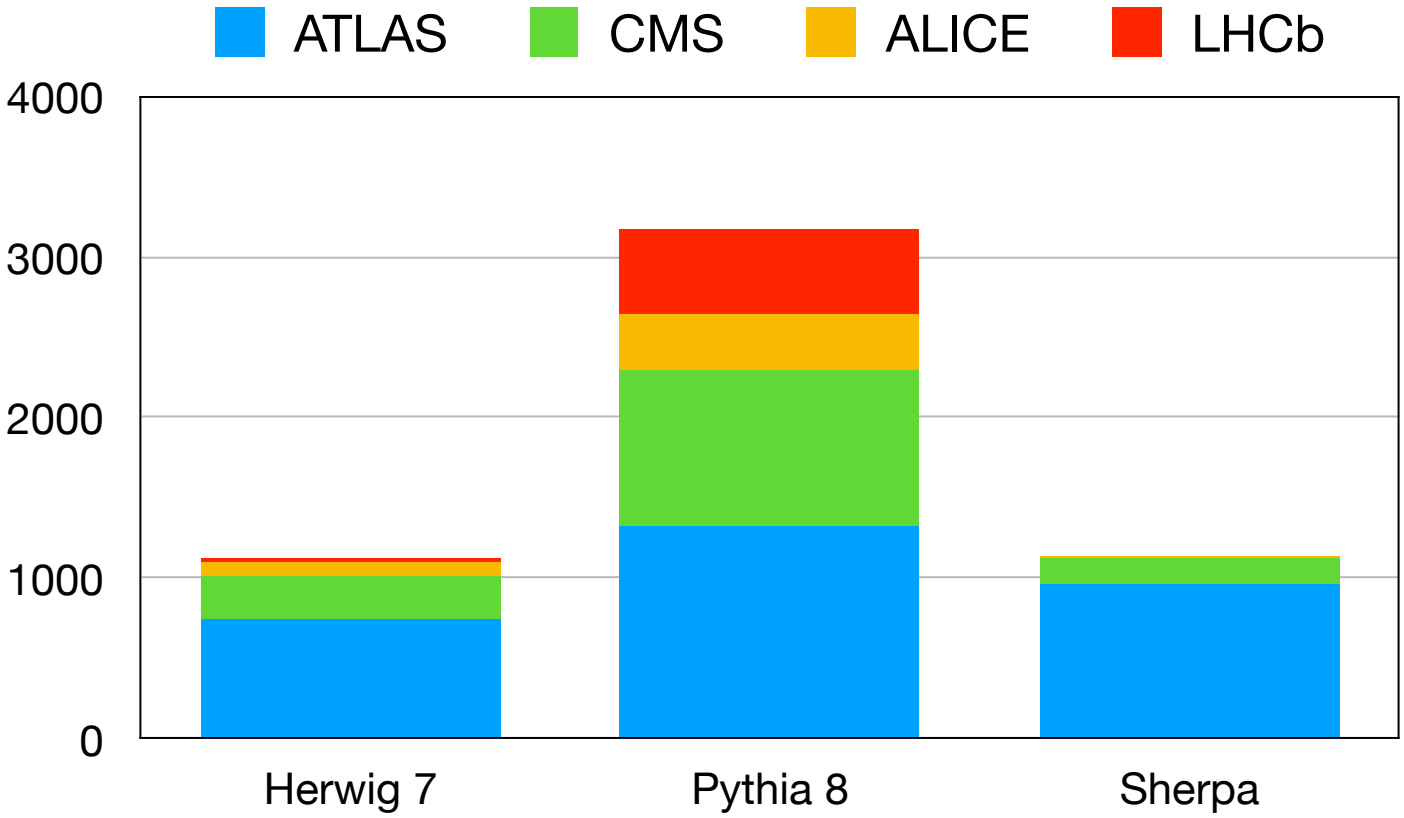

Parton Shower Event Generators
Citations/year
Year
2000
1000
500
200
100
50
20
10
2000
2005
2010
2015
2020
2025
Pythia8.1/2
Pythia6.1/4
Herwig++/7
Sherpa1/2
Herwig6

Citations: ex vs ph



- Equal use for expt and pheno!

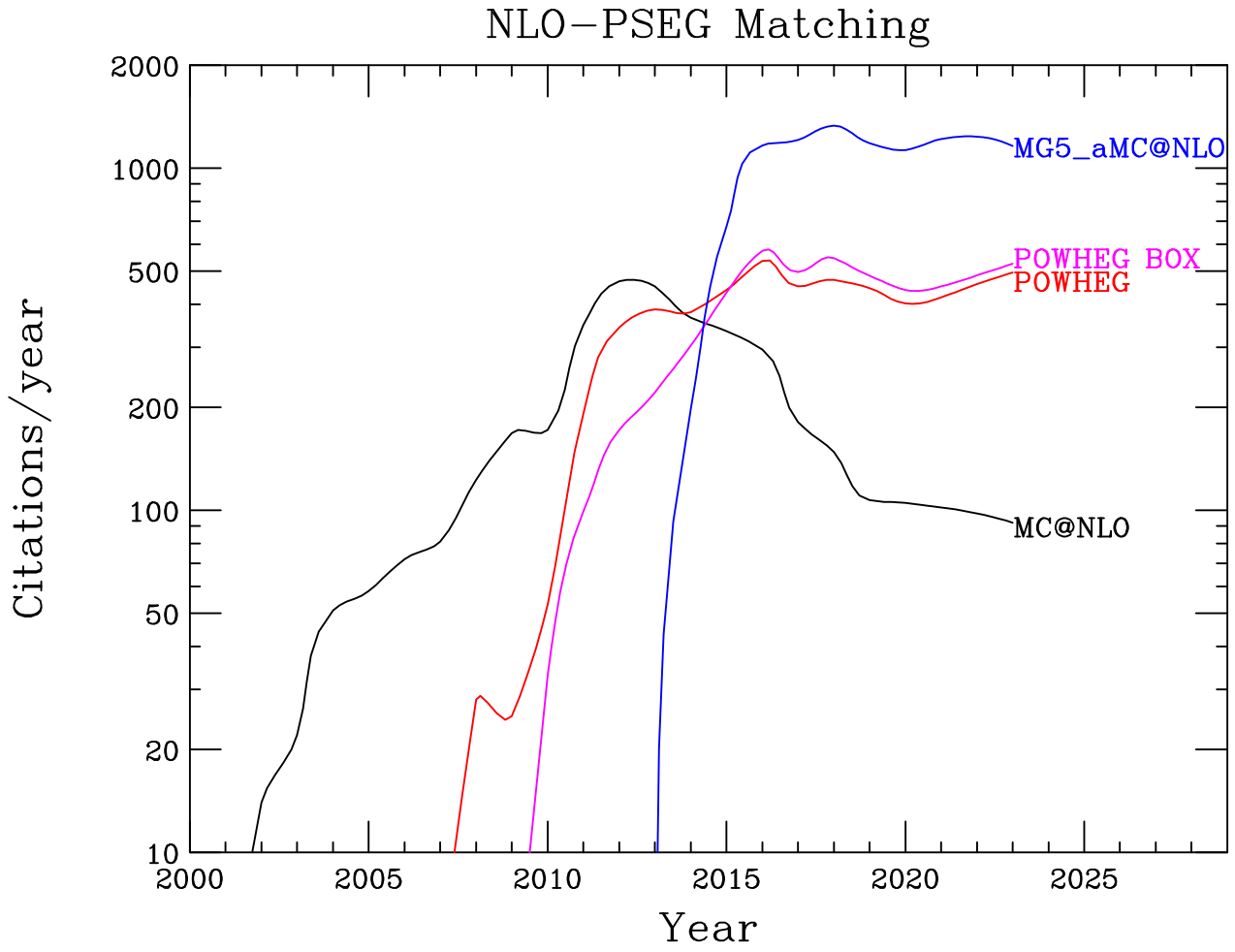
Citations: LHC expts



- ATLAS uses all three
- CMS mostly Pythia
- ALICE, LHCb almost exclusively Pythia

NLO-PSEG Matching

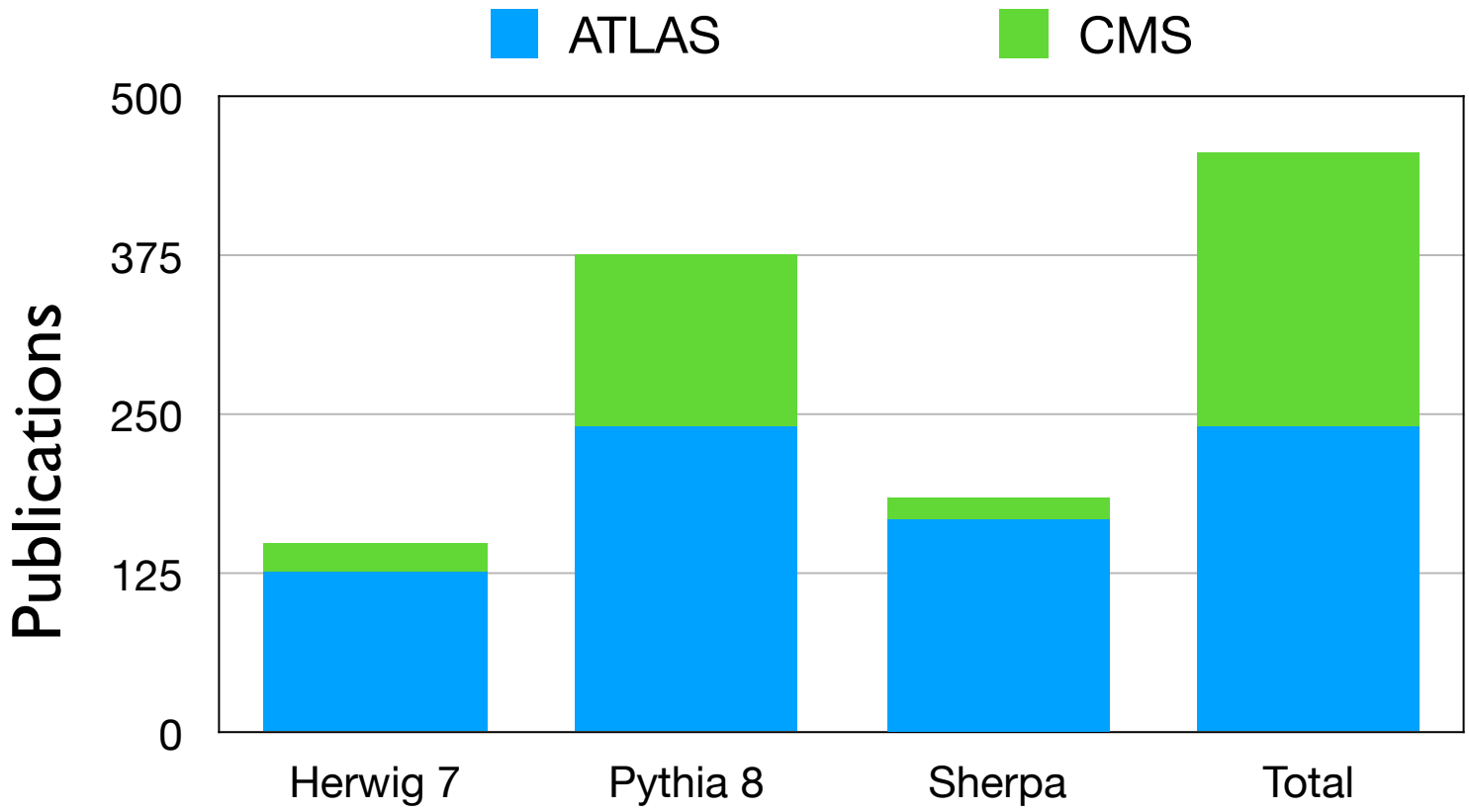
- MC@NLO: Frixione & BW, 2002
  - Modify NLO subtractions
- POWHEG: Nason, 2004; Frixione, Nason & Oleari, 2007
  - Modify hardest shower emission



- POWHEG BOX: Alioli, Nason, Oleari & Re, 2010
- MadGraph5_aMC@NLO: Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli & Zaro,

PSEGs and Higgs

Citations: LHC Higgs



- ATLAS cites Pythia + 1 or 2 others
- CMS cites mainly Pythia or none (i.e. MG5_aMC and/or POWHEG BOX)

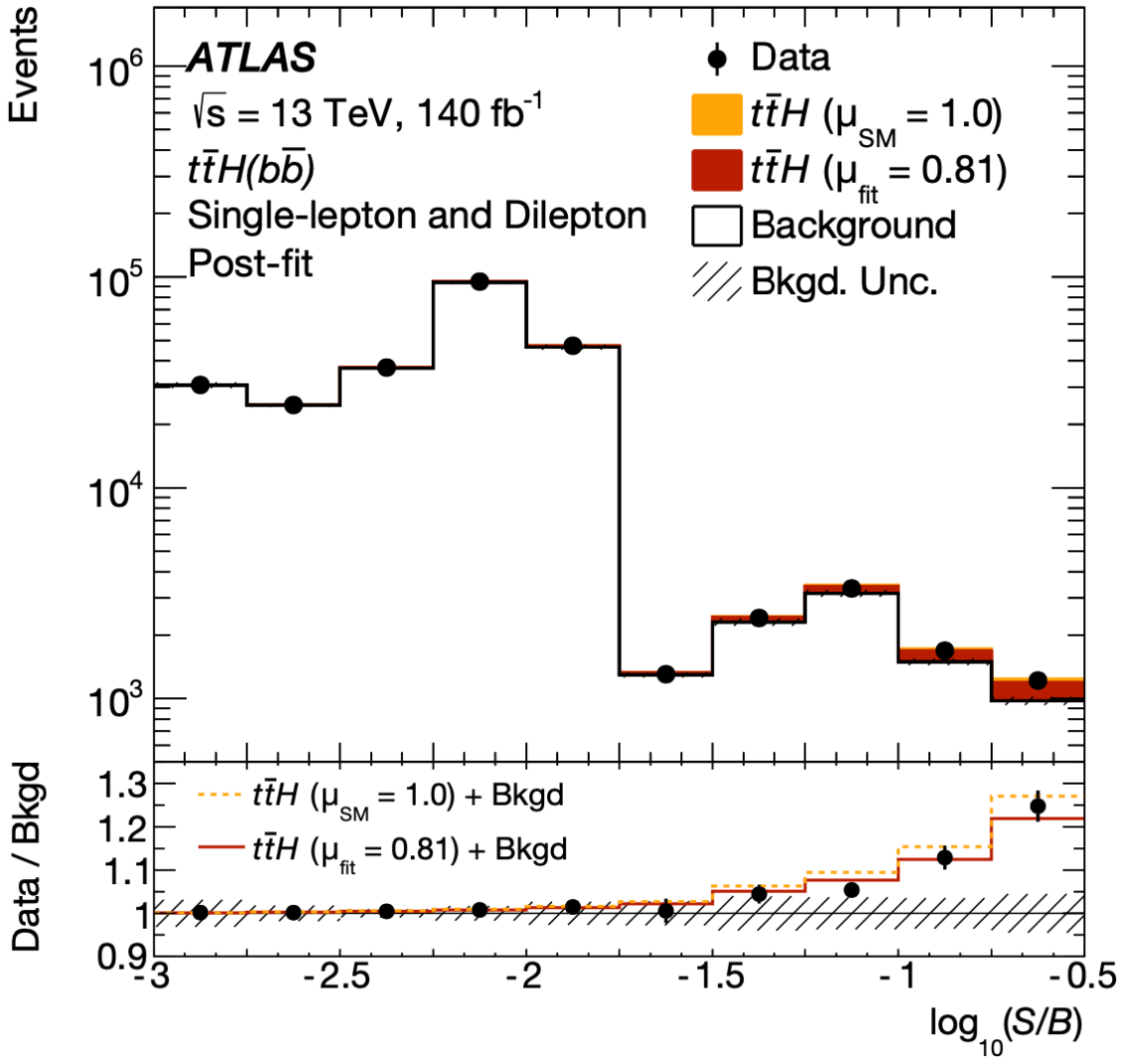
Measurement of the associated production of a top-antitop-quark pair and a Higgs boson decaying into a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC

CERN-EP-2024-194

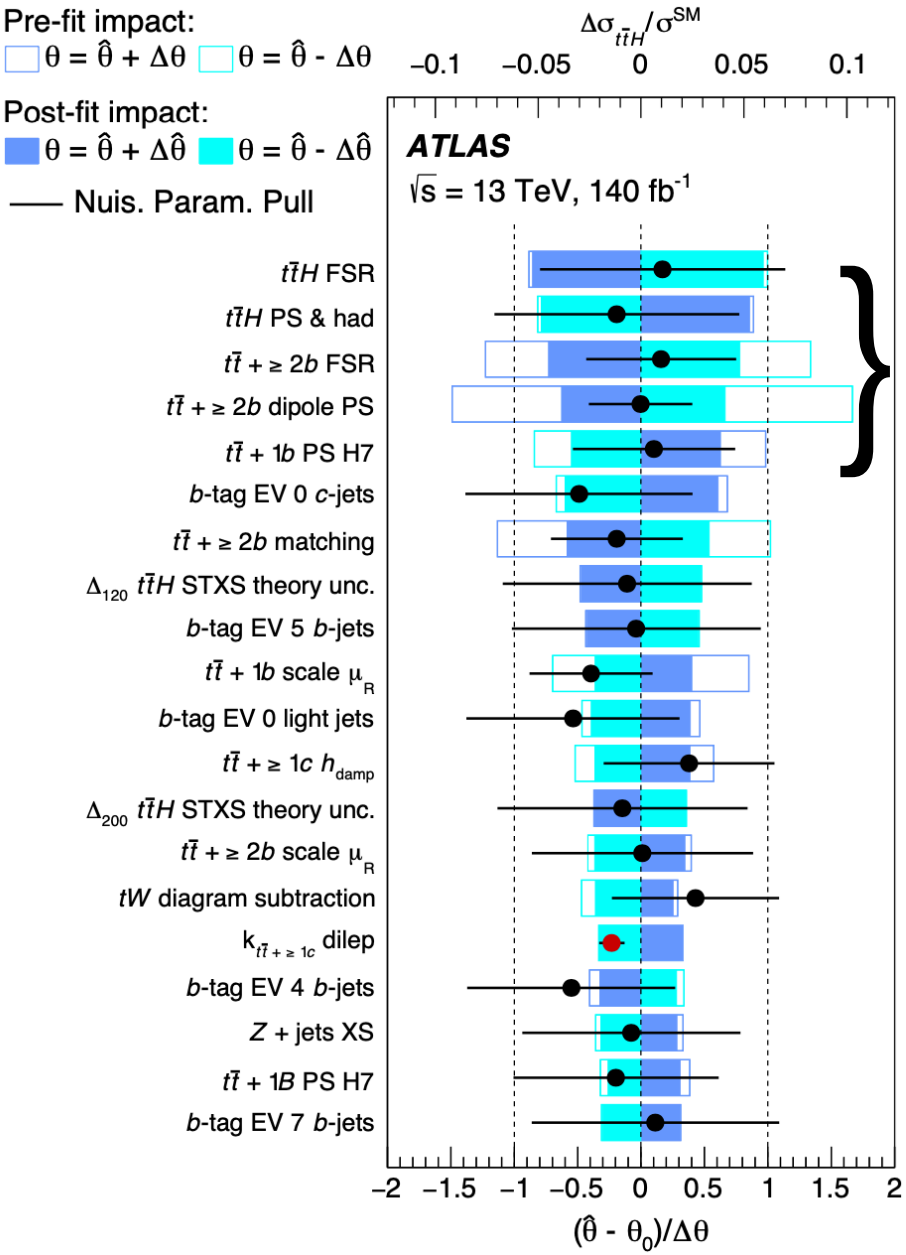
All samples generated with PowhegBox [34–37] and MadGraph5_aMC@NLO [38] were interfaced to Pythia8 [39] to simulate the parton shower (PS), fragmentation, and underlying event with the A14 tune [40] and the NNPDF2.3lo [41] parton distribution function (PDF) set. Some alternative samples use the Herwig7 [42, 43] PS model with the H7UE set of tuned parameters [43] and the MMHT2014LO PDF set [44].

To assess the uncertainties associated with the PS, hadronisation and underlying event, the nominal $t\bar{t}H$ sample is compared with the alternative Powheg+Herwig7 sample,

The modelling uncertainty in the $t\bar{t}Z$ background is evaluated by comparing the nominal MadGraph5_aMC@NLO+Pythia8 sample with the sample where Pythia8 is replaced by Herwig7 to simulate the PS and hadronisation.



The measurement is dominated by the systematic uncertainties arising from the $t\bar{t}H$ signal modelling followed by the $t\bar{t}$ + jets background modelling.



PSEG systematics dominant

Differential cross-section measurements of Higgs boson production in the $H \to \tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

CERN-EP-2024-198

Several sources of theoretical uncertainty in the signal are considered. For all production modes, uncertainties are considered for the PDF and α_s, the parton shower and hadronization model, and missing higher orders in the matrix element calculation. The effects of PDF and α_s uncertainties were estimated from the PDF4LHC15NLO set of eigenvectors. The impact of using a different parton shower and hadronization model is evaluated by comparing the nominal sample with an event sample generated using HERWIG 7 [118] instead of PYTHIA 8. The impact of using a different matrix element generator for the signal sample is evaluated by comparing the nominal signal sample with an alternative sample generated with MADGRAPH5_AMC@NLO [119] instead of POWHEG BOX, while keeping the same parton shower model.

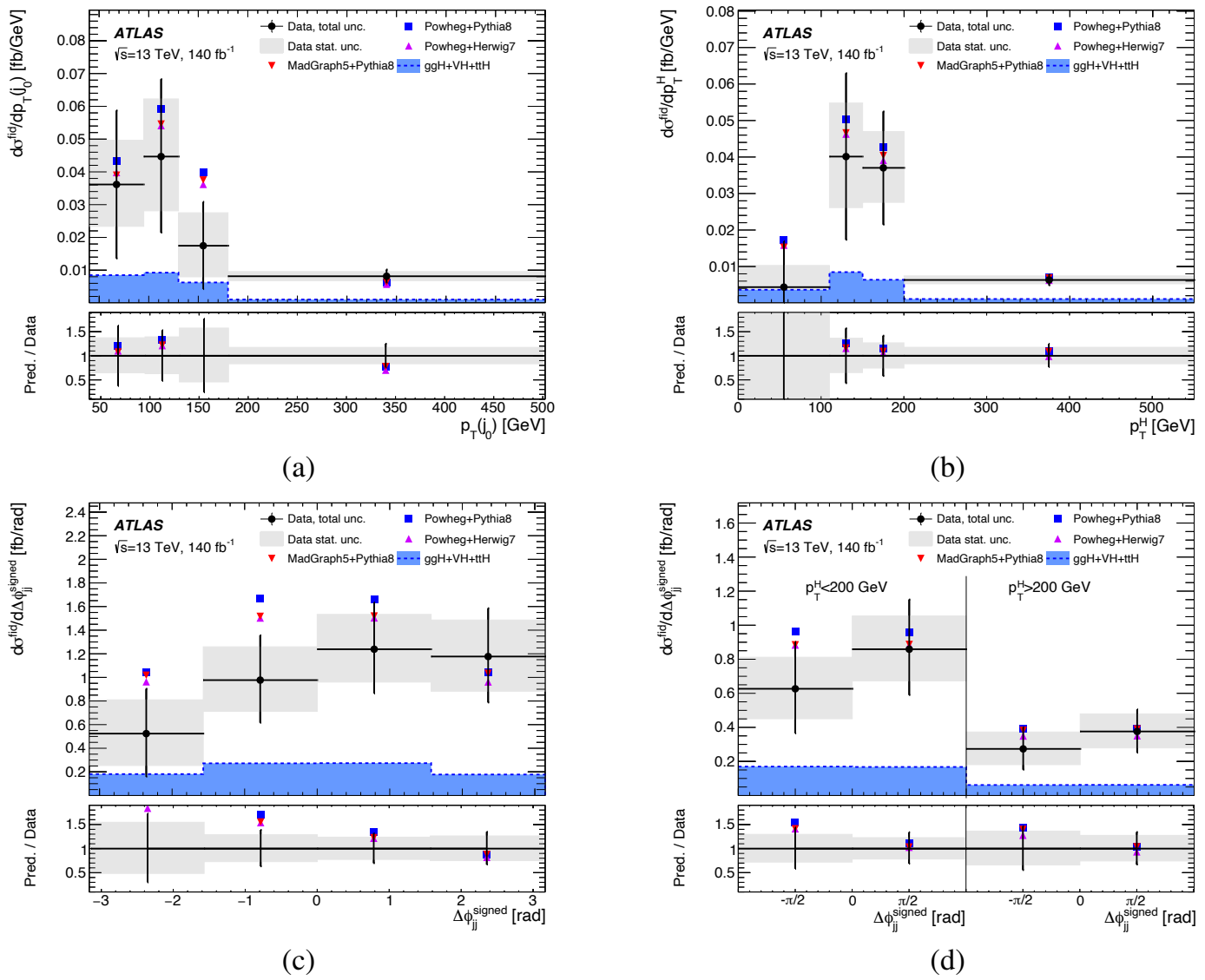


Figure 10: Measured fiducial differential cross-sections for (a) $p_{\mathrm{T}}(j_0)$, (b) $p_{\mathrm{T}}^{\mathrm{H}}$, (c) $\Delta\phi_{jj}^{\mathrm{signed}}$, and (d) $\Delta\phi_{jj}^{\mathrm{signed}}$ vs $p_{\mathrm{T}}^{\mathrm{H}}$. The measurements are compared with particle-level SM predictions from the Powheg+Pythia 8, Powheg+Herwig 7 and MadGraph5_aMC@NLO+Pythia 8 generators for the combined VBF, ggF, VH, and $t\bar{t}H$ Higgs boson production modes. The shaded box around each data point shows the statistical uncertainty, while the total uncertainty is indicated by the error bar. The contribution from the ggF, VH, and $t\bar{t}H$ production modes as predicted by Powheg+Pythia 8 is also shown. The bottom panel shows the ratio of different predictions to the data, with the error bars and shaded bands representing the total and statistical uncertainties of the measurements, respectively.

CERN-EP-2022-027
2023/07/07

Measurements of Higgs boson production in the decay channel with a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

An uncertainty in the parton-shower model of PYTHIA is obtained by varying the scales in the initial- and final-state radiation models; the observed effect typically ranges 1–3%, but can become as large as 10% for gluon fusion production with VBF-like topologies.

Estimating PSEG Uncertainties

- ATLAS: compare Pythia with Herwig
- CMS: vary parameters within Pythia
- Both have their dangers!

Ongoing/Future Developments

- Higher precision showers (initial & final)
- Higher precision matching/merging
- Electroweak showering
- Hadronization

Ongoing/Future Developments

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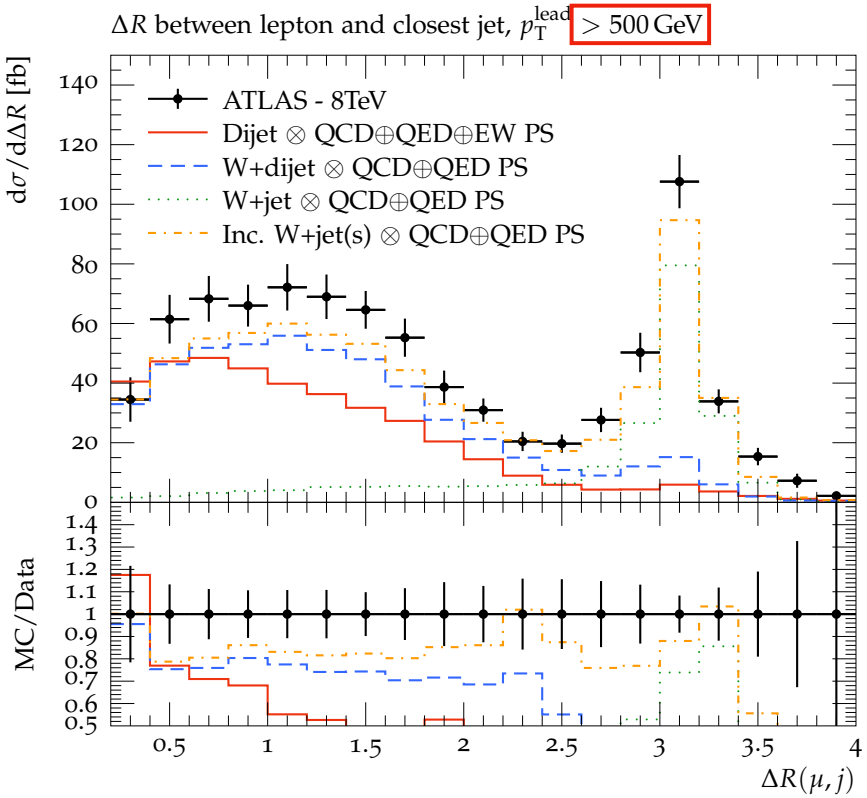
Physics Test

EW Showering

(Thanks to Aidin Masouminia, IPPP)

[Richardson, AM, JHEP 04 (2022) 112]

- The angular distribution of $W^{\pm}$ bosons accompanied with high transverse momentum jets at $\sqrt{s} = 8$ TeV. The data is from ATLAS [arXiv:1609.07045].
- Pure QCD di-jet event showered with EW PS → red solid histograms
- Explicit (prompt) $W^{\pm}$ plus jets → orange dashed-dotted histograms



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[Richardson, AM, JHEP 04 (2022) 112]

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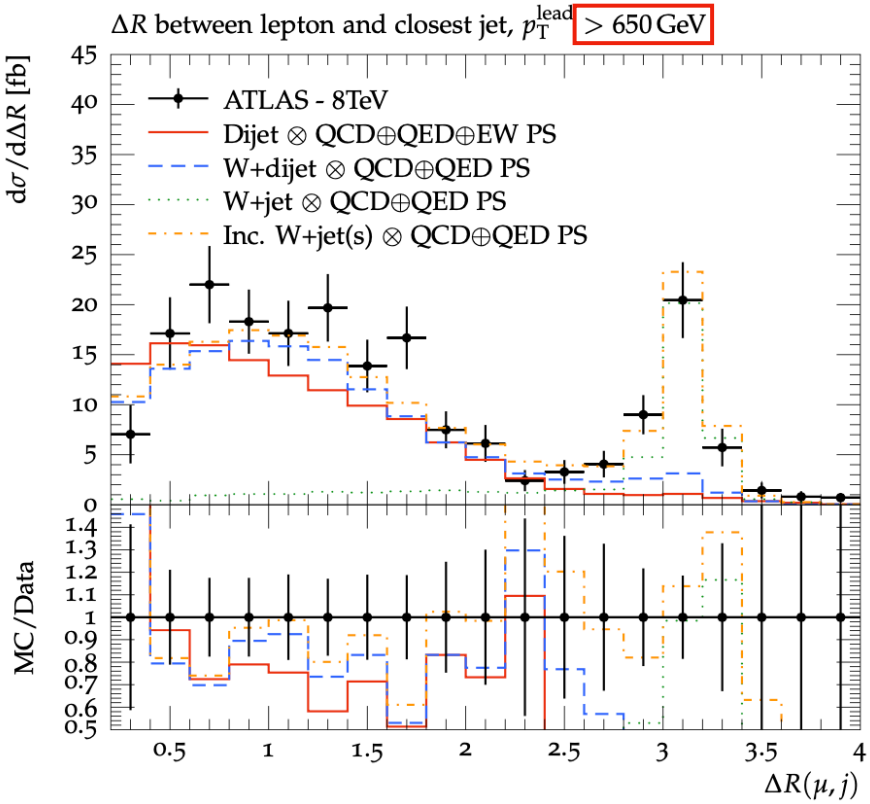


Hadronization

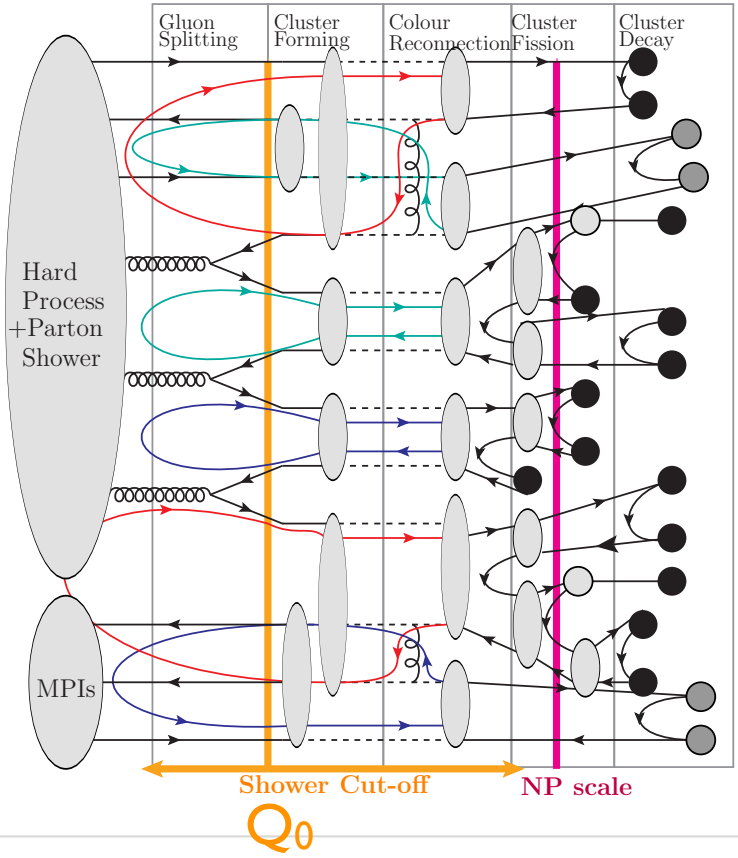
(Thanks to Stefan Kiebacher, KIT)

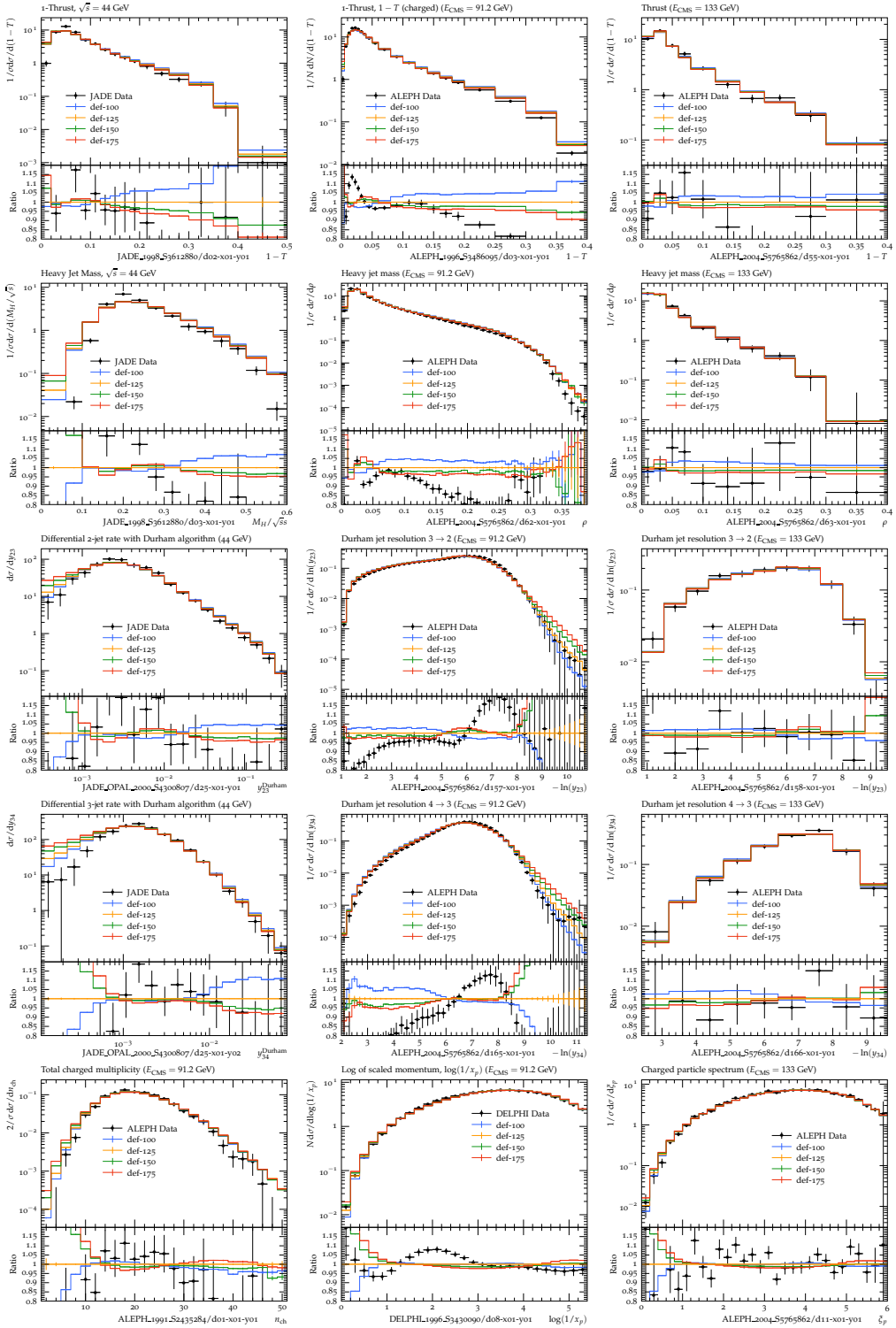
Hadronization From Colour Evolution

Idea of colour evolution picture [Plätzer 2023]:

- **Shower Cut-off** is a factorization scale (see also [Hoang et al. 2024]) Q_0
- Parton shower, Colour Reconnection and Hadronization (Cluster Fission) should be matched
- Final non-perturbative scale (**NP scale**) interfaces to the initial condition

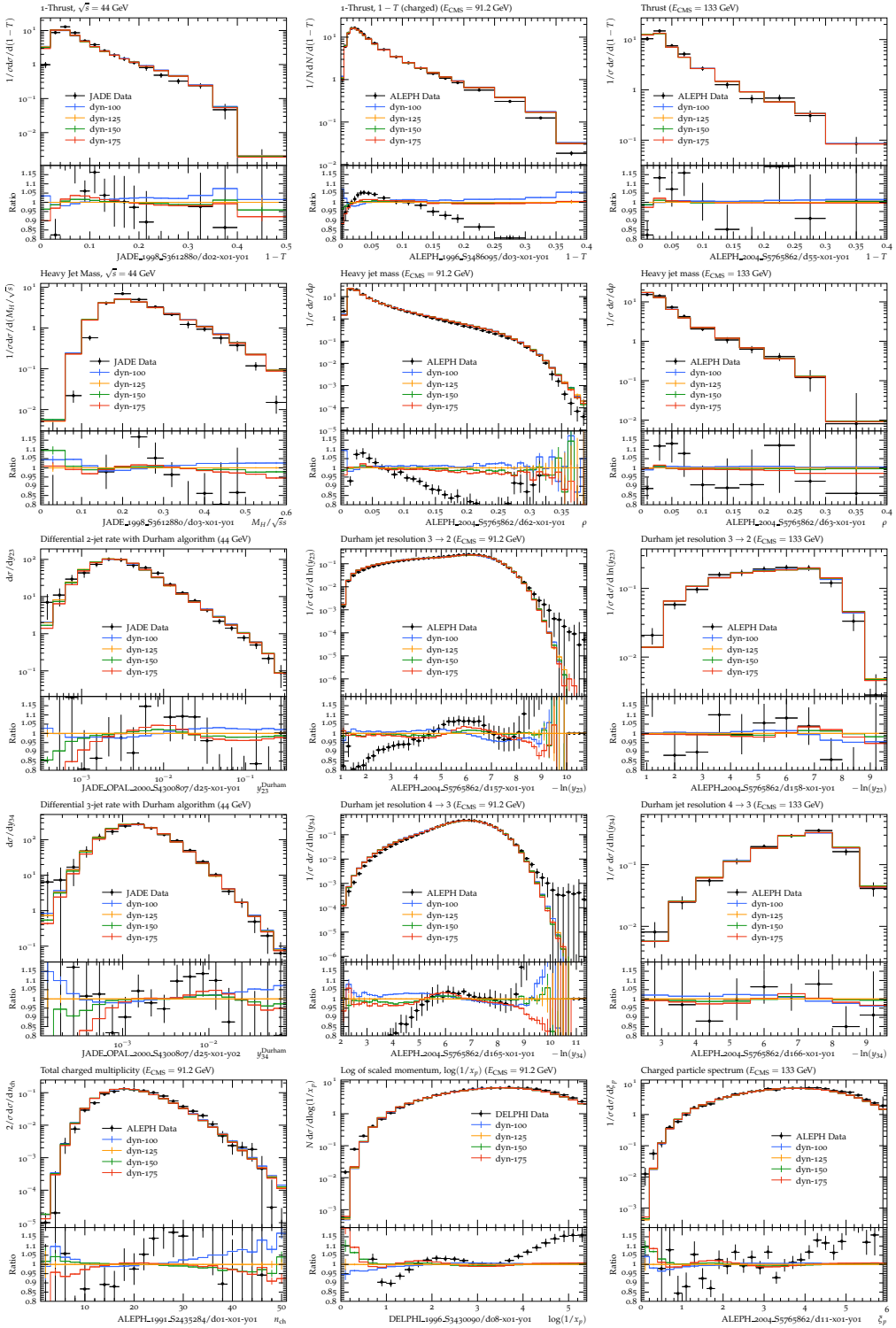
Consequence: Cluster Fission is a perturbative process similar to the parton shower. Only Cluster Decay is non-perturbative (could be obtained from lattice QCD)





- Default hadronization
  - Q_0=1.0 to1.75 GeV

Hoang, Plätzer & Samitz, 2404.09856



- Dynamical hadronization
  - Q_0=1.0 to1.75 GeV

Hoang, Plätzer & Samitz, 2404.09856

Thanks for your attention!