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RECENT DEVELOPMENTS IN MONTE CARLO EVENT GENERATORS

LHCP 2024 Boston, June 7 2024

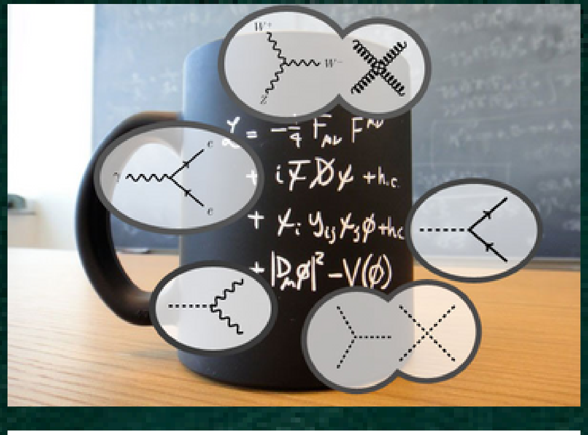
MONTE-CARLO EVENTGENERATORS

... are essential for all branches of HEP:

- Collider experiments
- Neutrino physics ...

... provide fully realistic SM & BSM predictions usable by experiments to

- design analyses & detectors
- predict backgrounds
- unfold detector effects
- compare with theory predictions



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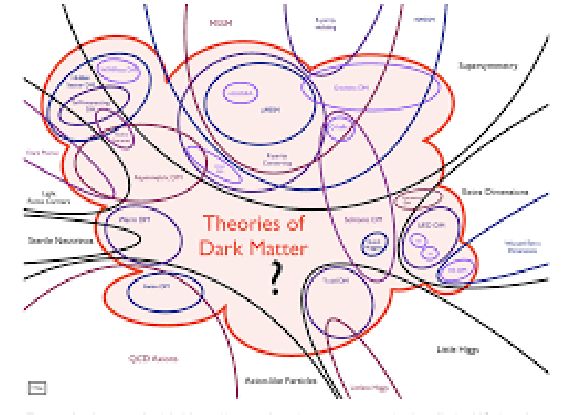

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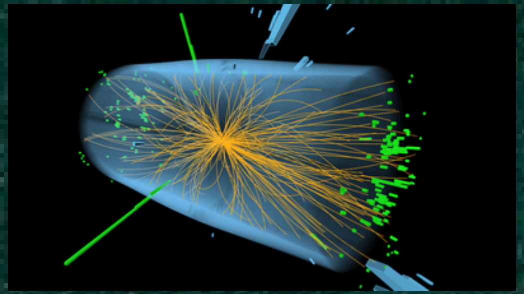

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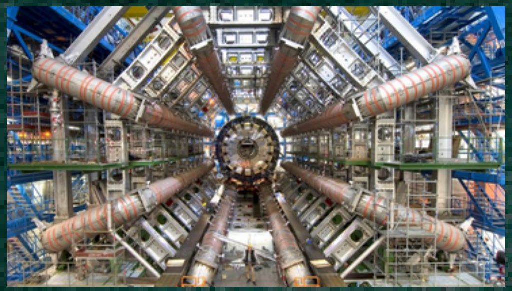

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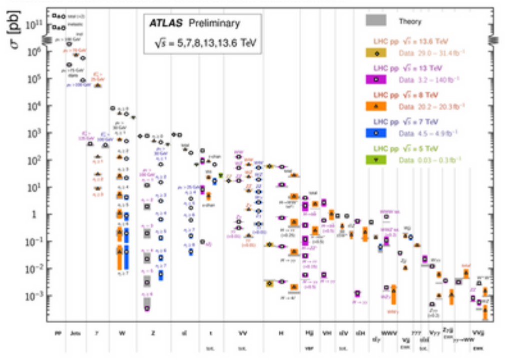


[5]

Here: focus on most common event generators for LHC physics

MONTE-CARLO EVENTGENERATORS

Factorization of QCD

$$\sigma_{p_1 p_2 \to X} = \sum_{i,j \in \{q,g\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \underbrace{f_{p_1,i}(x_1, \mu_F^2) f_{p_2,j}(x_2, \mu_F^2)}_{\text{long distance}} \underbrace{\hat{\sigma}_{ij \to X}(x_1 x_2, \mu_F^2)}_{\text{short distance}}$$

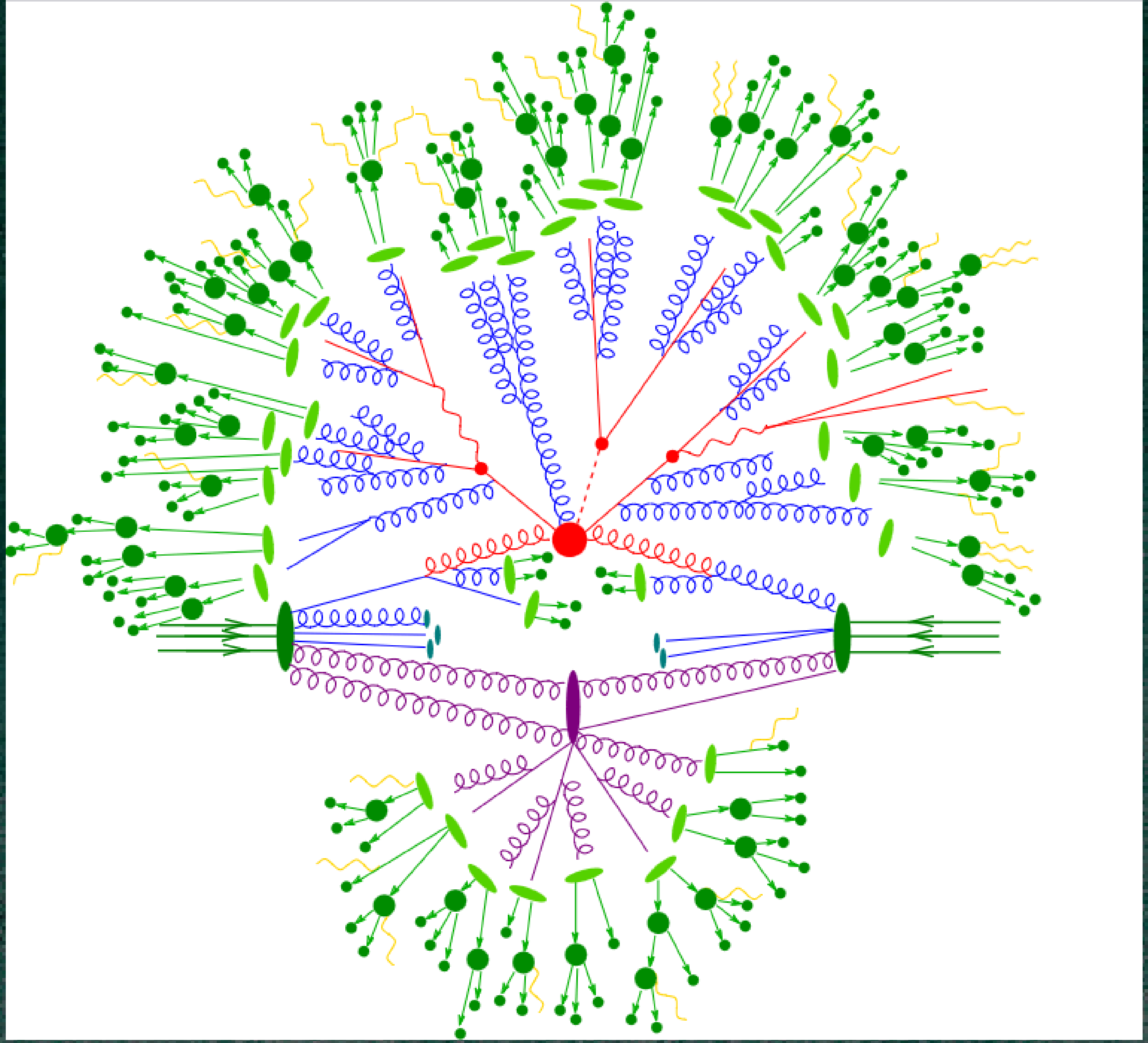
Modular structure of event generators

Short distance interactions

- Hard process
- Parton shower
- QED radiation

Long distance interactions

- Hadronization
- Hadron decays
- Multiple interactions



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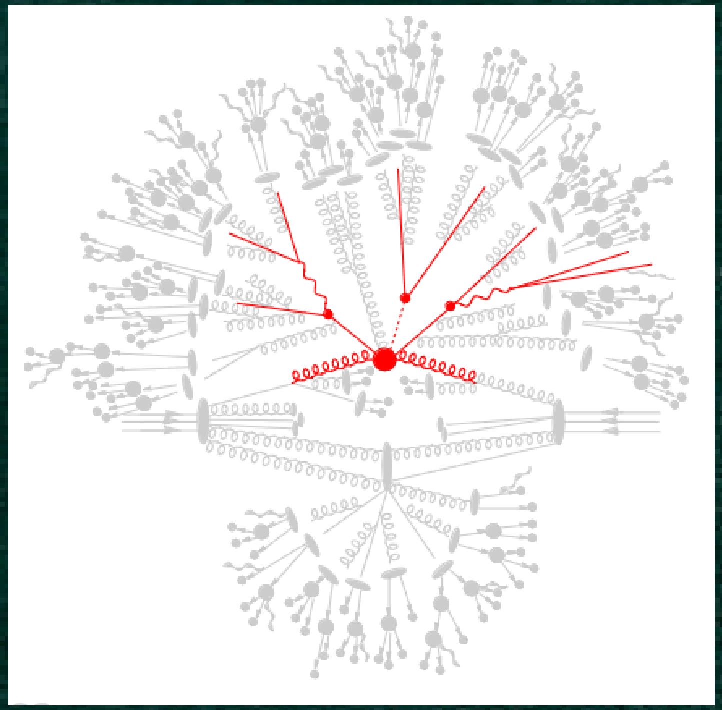
HARD PROCESS

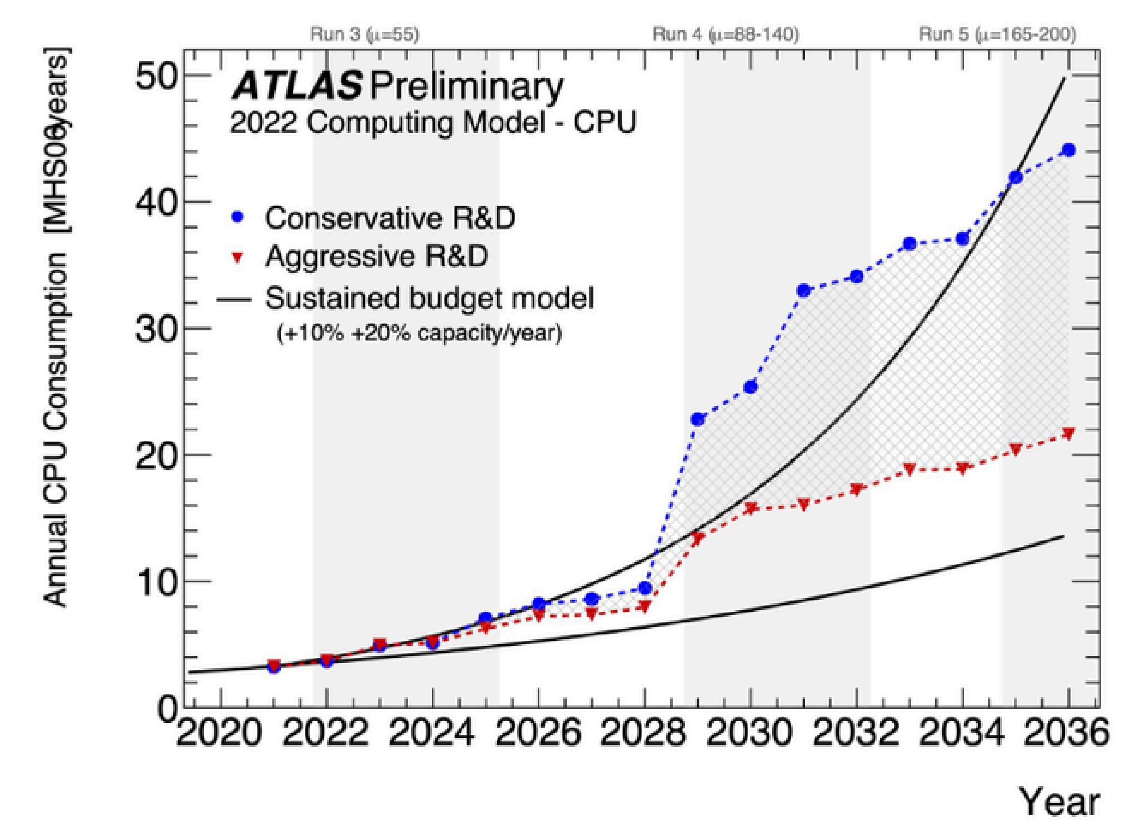


State of the art

- Automated NLO QCD & approximate NLO EW

Current challenges

- Precision
- Speed / Efficiency



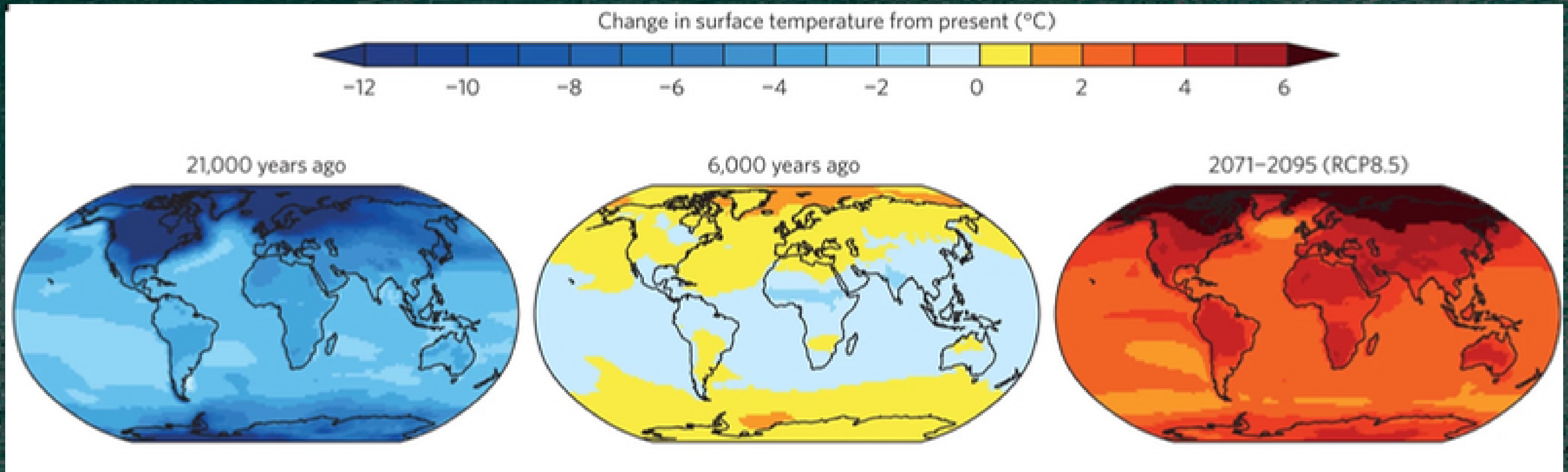
CERN-LHCC-2022-005

Impact beyond particle physics

Fully differential NNLO matching

N3LO matching

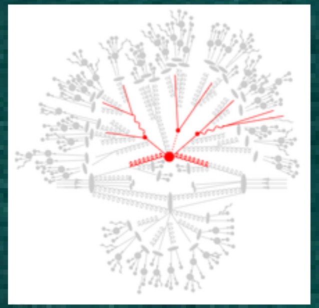
Polarized XS



https://climateknowledgeportal.worldbank.org/overview

POLARIZED CROSS SECTIONS FOR VECTOR BOSON PRODUCTION

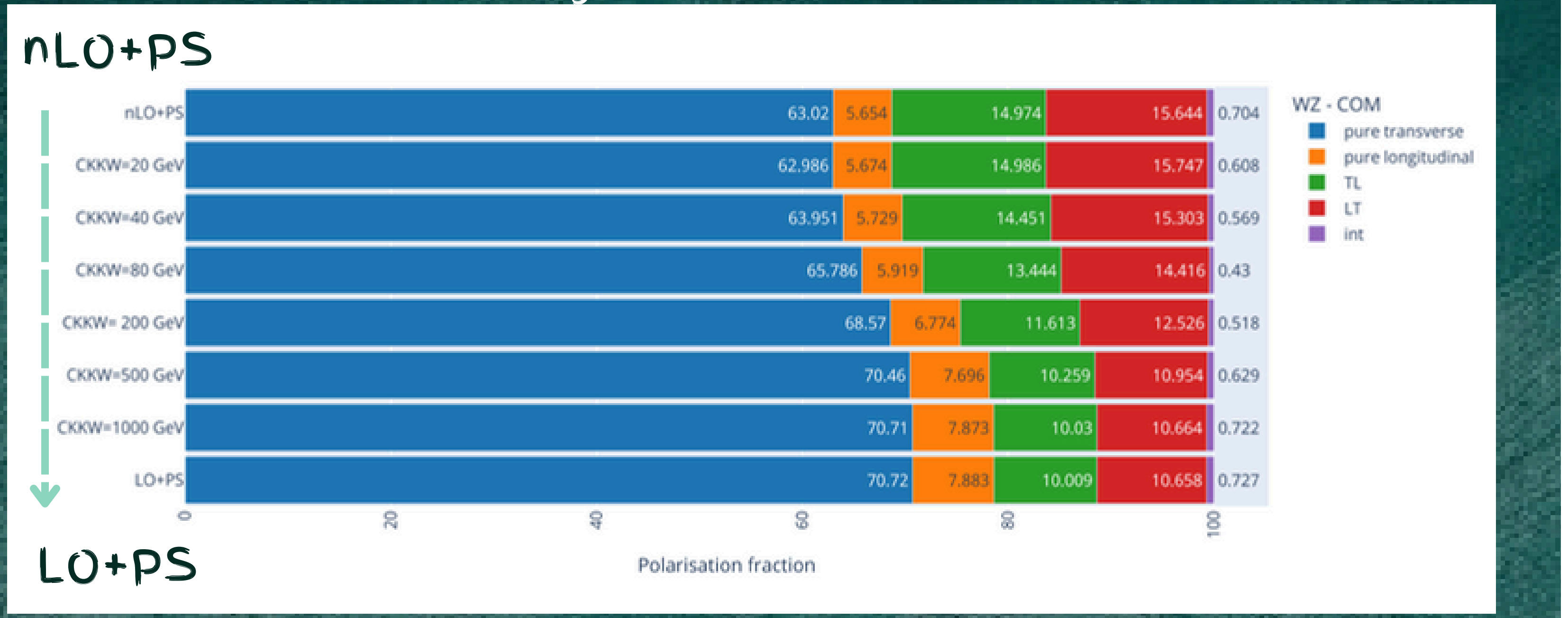




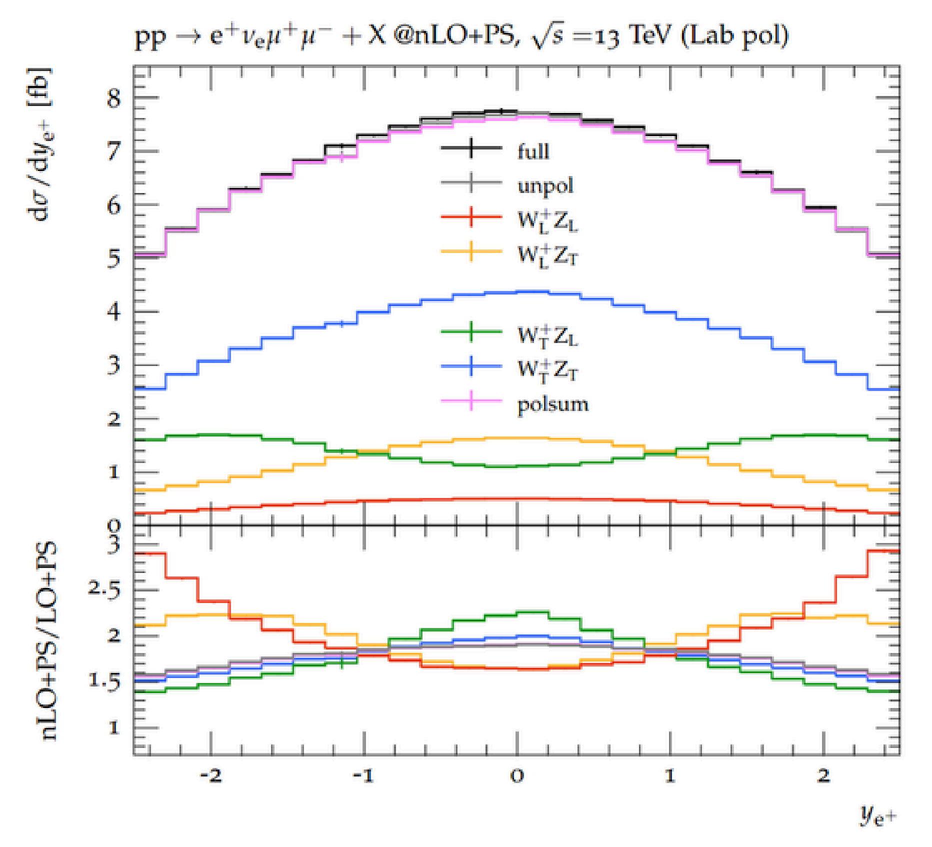
More details?
MH Fri 11:36 AM

- Probe for the electroweak gauge sector & electroweak symmetry breaking
- Measurement strategy: fully exclusive polarized XS from MC as fitting templates
- Established generators: PHANTOM & MadGraph5 @LO+PS [A. Ballestrero et al. 2008, 2017] [D. Buarque Franzosi et al. 2020, M. Javurkova et al. 2024]
- **NEW:** Extension of SHERPA & POWHEG:
  - SHERPA: nLO+PS for arbitrary VB production processes [MH, M. Schönherr & F. Siegert 2023]
  - POWHEG: NLO+PS for inclusive diboson production [G. Pelliccioli & G. Zanderighi 2023]

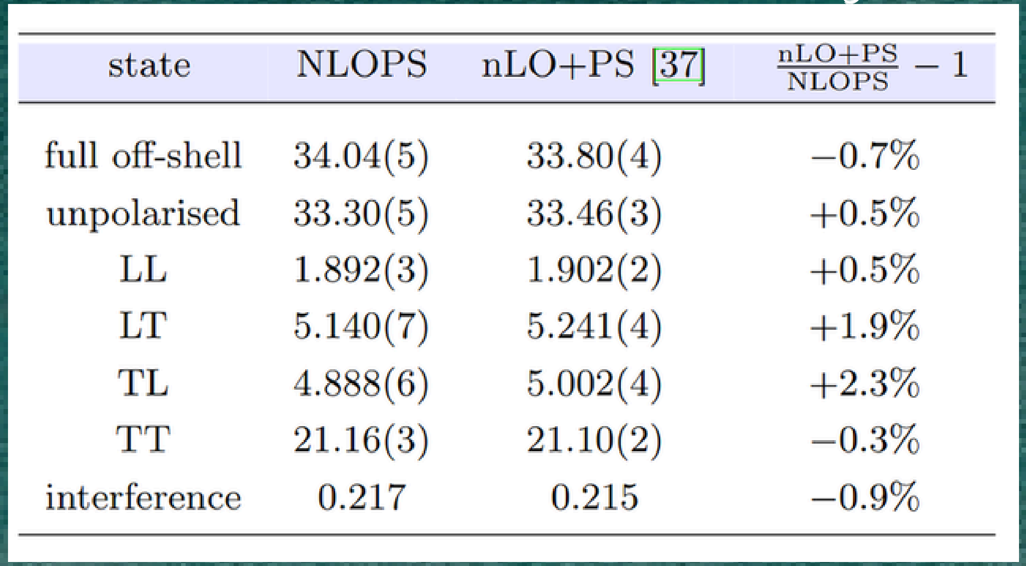
[MH, M. Schönherr & F. Siegert 2023]



WZ production



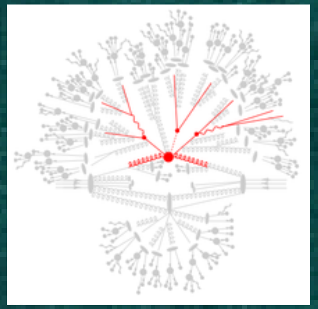
[G. Pelliccioli & G. Zanderighi 2023]



state	NLOPS	nLO+PS [37]	$\frac{\text{nLO+PS}}{\text{NLOPS}} - 1$
full off-shell	34.04(5)	33.80(4)	−0.7%
unpolarised	33.30(5)	33.46(3)	+0.5%
LL	1.892(3)	1.902(2)	+0.5%
LT	5.140(7)	5.241(4)	+1.9%
TL	4.888(6)	5.002(4)	+2.3%
TT	21.16(3)	21.10(2)	−0.3%
interference	0.217	0.215	−0.9%

NLO QCD polarization effects strongly dominated by real corrections!

SIMPLER ALGORITHMS FOR MATRIX ELEMENT GENERATION

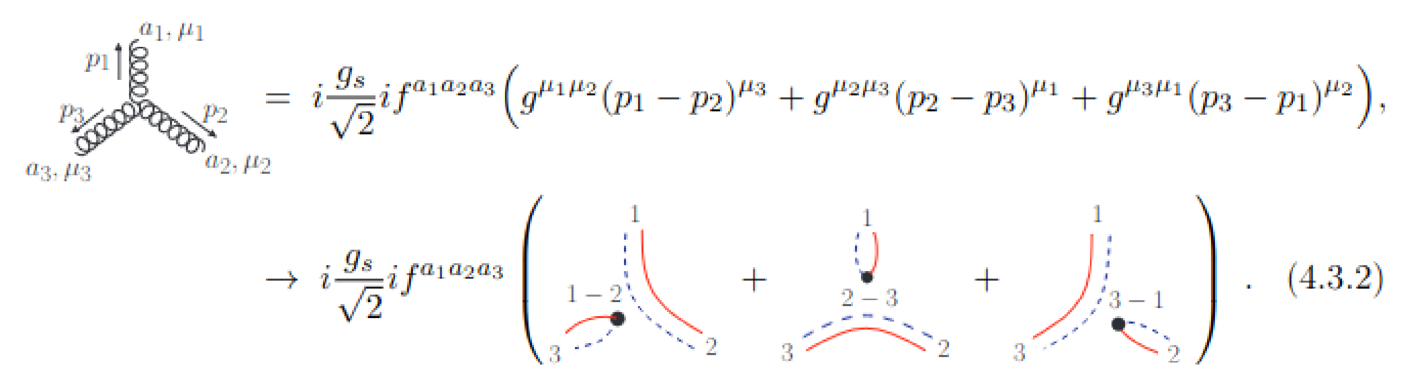


Chirality flow formalism

- Introduced in [A. Lifson, C. Reuschle & M. Sjodahl 2020], [J. Alnefjord et al. 2020]

→ Lorentz structure analogue to color flow picture

→ Recently extended to one-loop calculations
[A. Lifson, S. Plätzer & M. Sjodahl 2023]

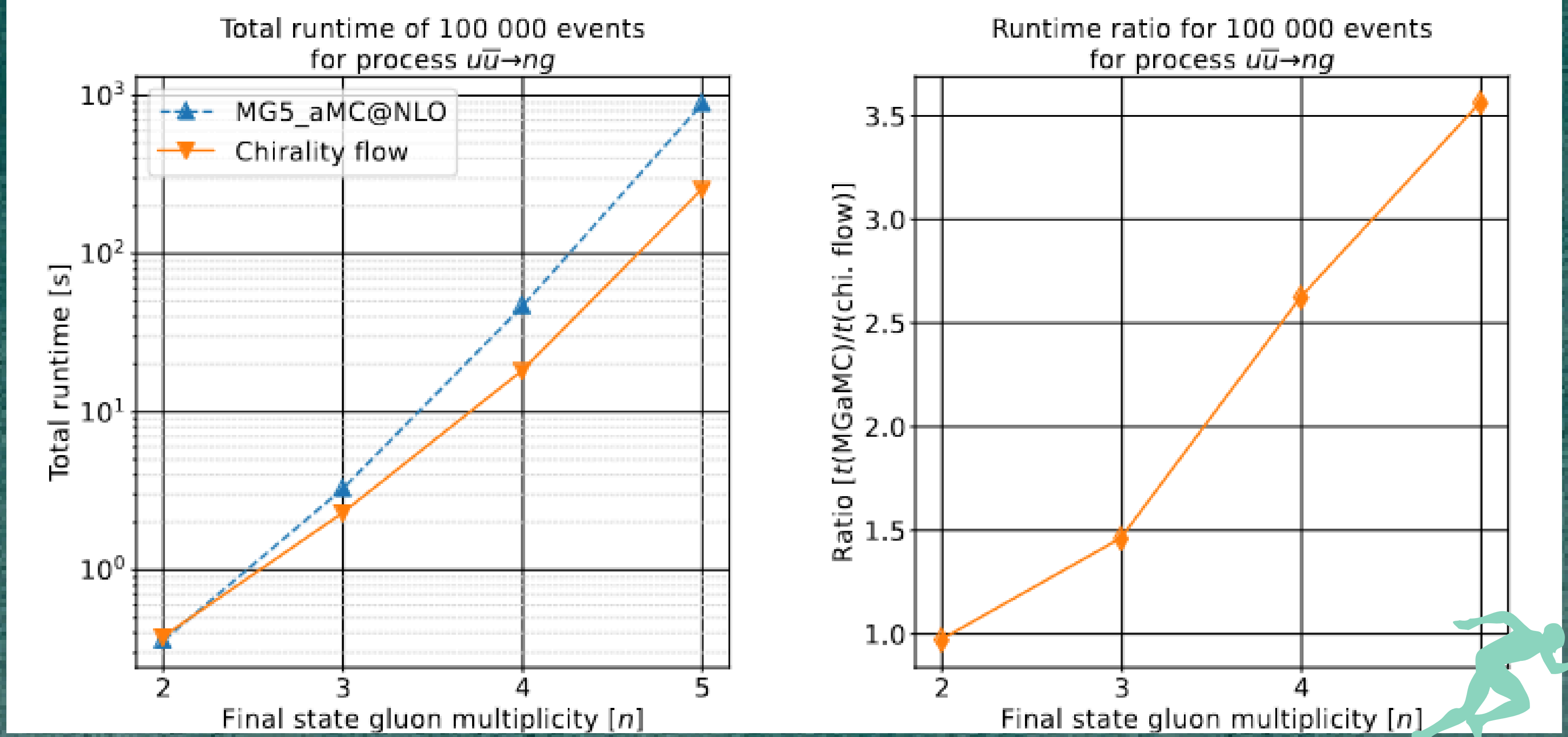


$$= i\frac{g_s}{\sqrt{2}} i f^{a_1 a_2 a_3}\left(g^{\mu_1\mu_2}(p_1-p_2)^{\mu_3} + g^{\mu_2\mu_3}(p_2-p_3)^{\mu_1} + g^{\mu_3\mu_1}(p_3-p_1)^{\mu_2}\right),$$

$$\to i\frac{g_s}{\sqrt{2}} i f^{a_1 a_2 a_3}\left(\quad + \quad + \quad \right). \quad (4.3.2)$$

$$\sigma^{\mu,\dot{\alpha}\beta}\bar{\sigma}_{\mu,\alpha\dot{\beta}} = 2\delta^{\dot{\alpha}}{}_{\dot{\beta}}\delta_{\alpha}{}^{\beta}$$

- Proof-of-concept in MadGraph5@NLO for QED: improvement up to factor 10 in $e^+e^- \to n\gamma$
[A. Lifson, M. Sjodahl & Z. Wettersten 2022]
- Most recent: implementation for QCD
[E. Boman et al. 2023]
- Performance improvements due to:
  - simplified Lorentz structures
  - gauge based Feynman/chirality-flow diagram removal due to clever choice of reference momenta / spin axes



EVENTGENERATION ON MODERN ARCHITECTURES

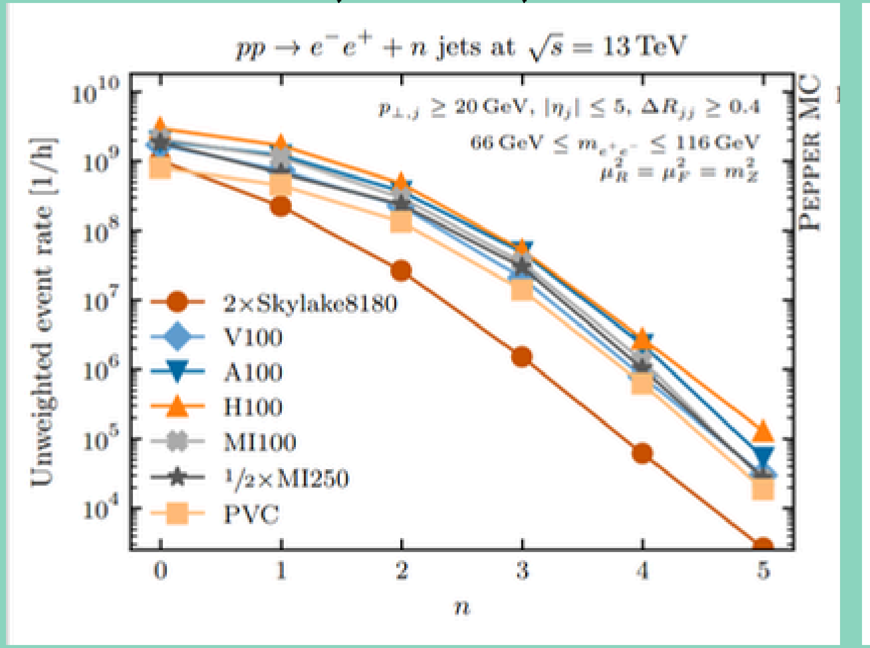
- Current event generation codes written for traditional CPU+RAM model
- Computing architectures designed for data parallelism increasingly standard in data centers
- Improvements of at least one order of magnitude expected [E. Bothmann et al. 2021]

PEPPER

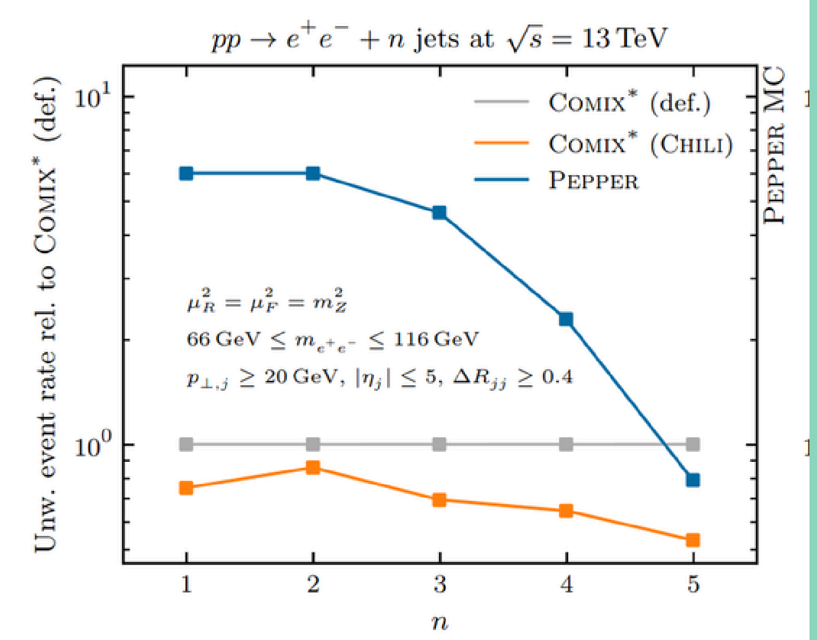
[E. Bothmann et al. 2023]

- Parallelized LO parton-level event generator in C++
- Color-summed Berends-Giele recursion, CHILI phase-space integration method [E. Bothmann et al. 2023]
- CUDA/kokkos for GPU portability, CPU parallization via MPI

parallel performance



single-thread CPU performance



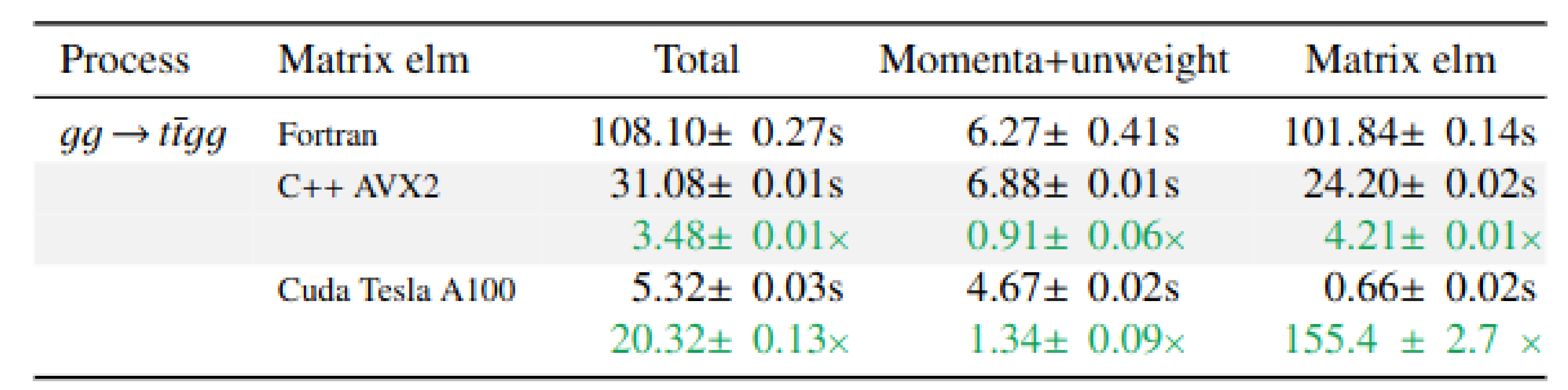
Madgraph5_aMC@NLO on GPUs

[A.Valassi et al. 2023; S. Hageböck et al. 2023; Z. Wettersten et al. 2023]

- madgraph4gpu plugin: LO C++ MadGraph based on helicity amplitudes on GPUs & SIMDs

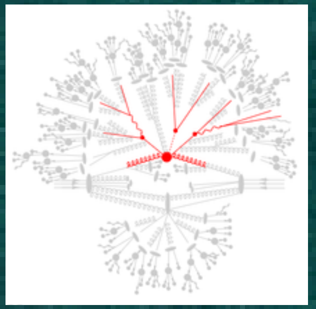
-> GPU: ME-calculation, event re- & unweighting

- Code generator for CUDA, SYCL output & for vectorized code using AVX2 extension for SIMDs



Process	Matrix elm	Total	Momenta+unweight	Matrix elm
$gg \to t\bar{t}gg$	Fortran	108.10± 0.27s	6.27± 0.41s	101.84± 0.14s
	C++ AVX2	31.08± 0.01s	6.88± 0.01s	24.20± 0.02s
		3.48± 0.01×	0.91± 0.06×	4.21± 0.01×
	Cuda Tesla A100	5.32± 0.03s	4.67± 0.02s	0.66± 0.02s
		20.32± 0.13×	1.34± 0.09×	155.4 ± 2.7 ×

ML-ASSISTED EVENTGENERATION



Improving phase space sampling and unweighting efficiency

- Problem: - VEGAS decreasing performance for complex final states / higher orders
  - bad unweighting efficiency
- Idea: ML for faster importance sampling & improved unweighting efficiency
- Much interest in last years: Generative Adversarial Networks, Normalizing & autoregressive Flows …

[J. Bendavid 2017, M.D. Klimek & M. Perelstein 2020, C. Gao et al. 2020, S. Pina-Otey et al. 2020, B. Stienen & R. Verheyen 2020, M. Backes et al. 2020, E. Bothmann et al. 2021, …]

Surrogate unweighting in SHERPA

[K. Danzinger et al. 2021]
[T. Janßen et al. 2023]

- KERAS DNN for dipol model

$$|\mathcal{M}_{n+1}|^2 \simeq \sum_{\{ijk\}} C_{ijk} D_{ijk}$$

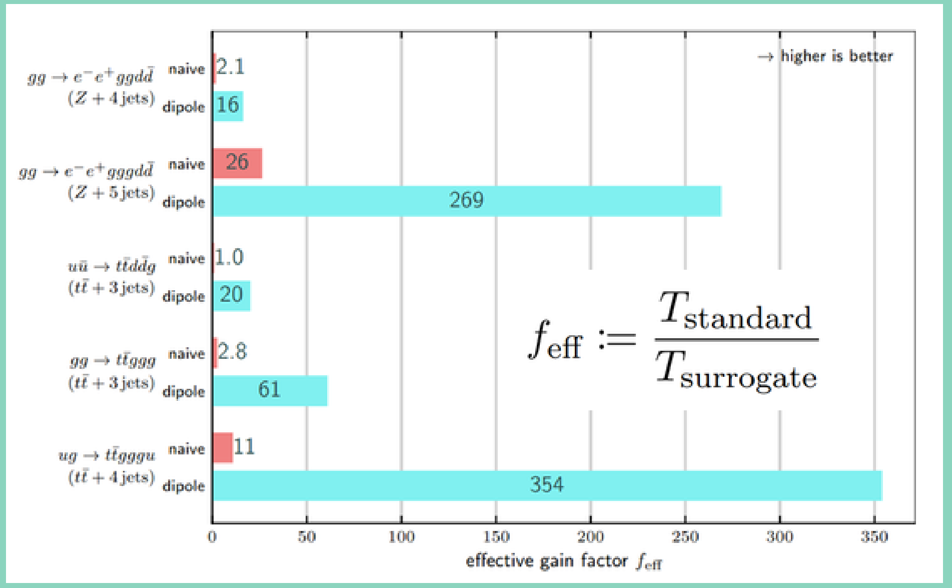
pre-defined dipols

coefficients learned during integration

- Two-step unweighting:

1. based on fast ME surrogate prediction from Onnx model
2. based on exact ME, when event is kept

-> exact distributions retained



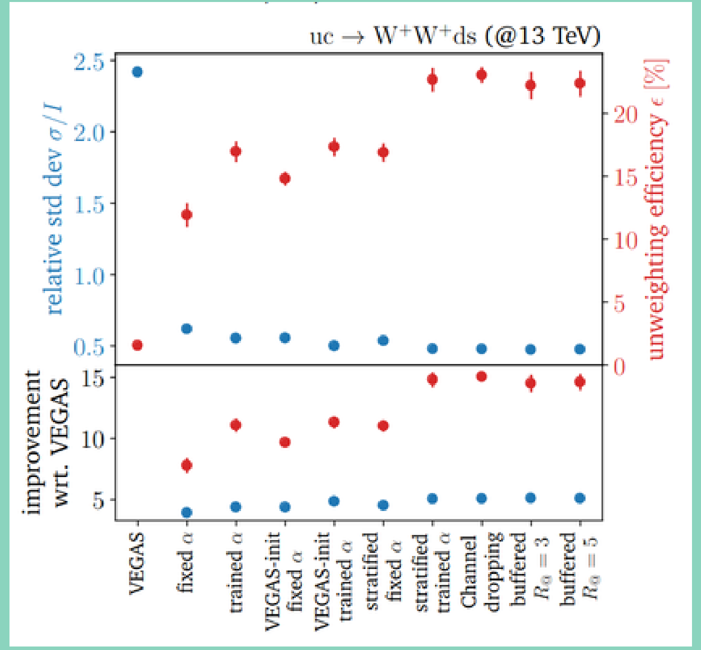
MadNIS [T. Heimel et al. 2022, 2023]

Neural importance sampling

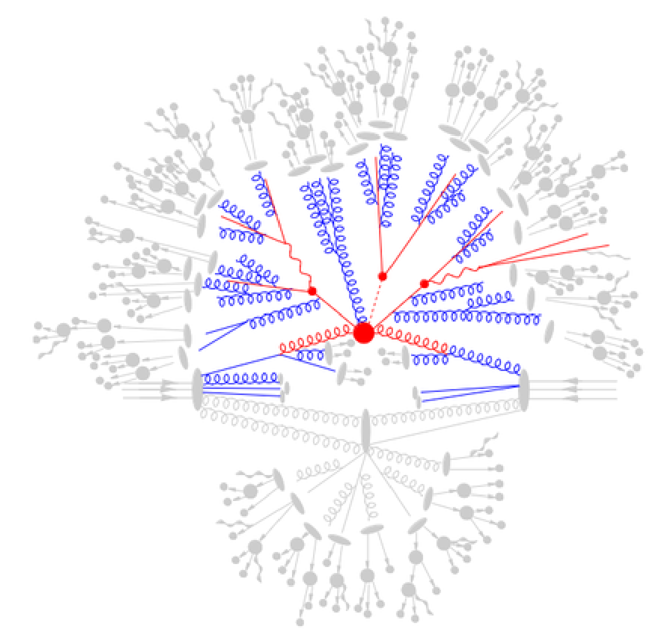
$$I = \sum_i \left\langle \alpha_i(x) \frac{f(x)}{g_i(x)} \right\rangle_{x\sim g_i(x)}$$

channel weights learned by regression NN

phase space mapping with Normalizing flows



PARTON SHOWERS

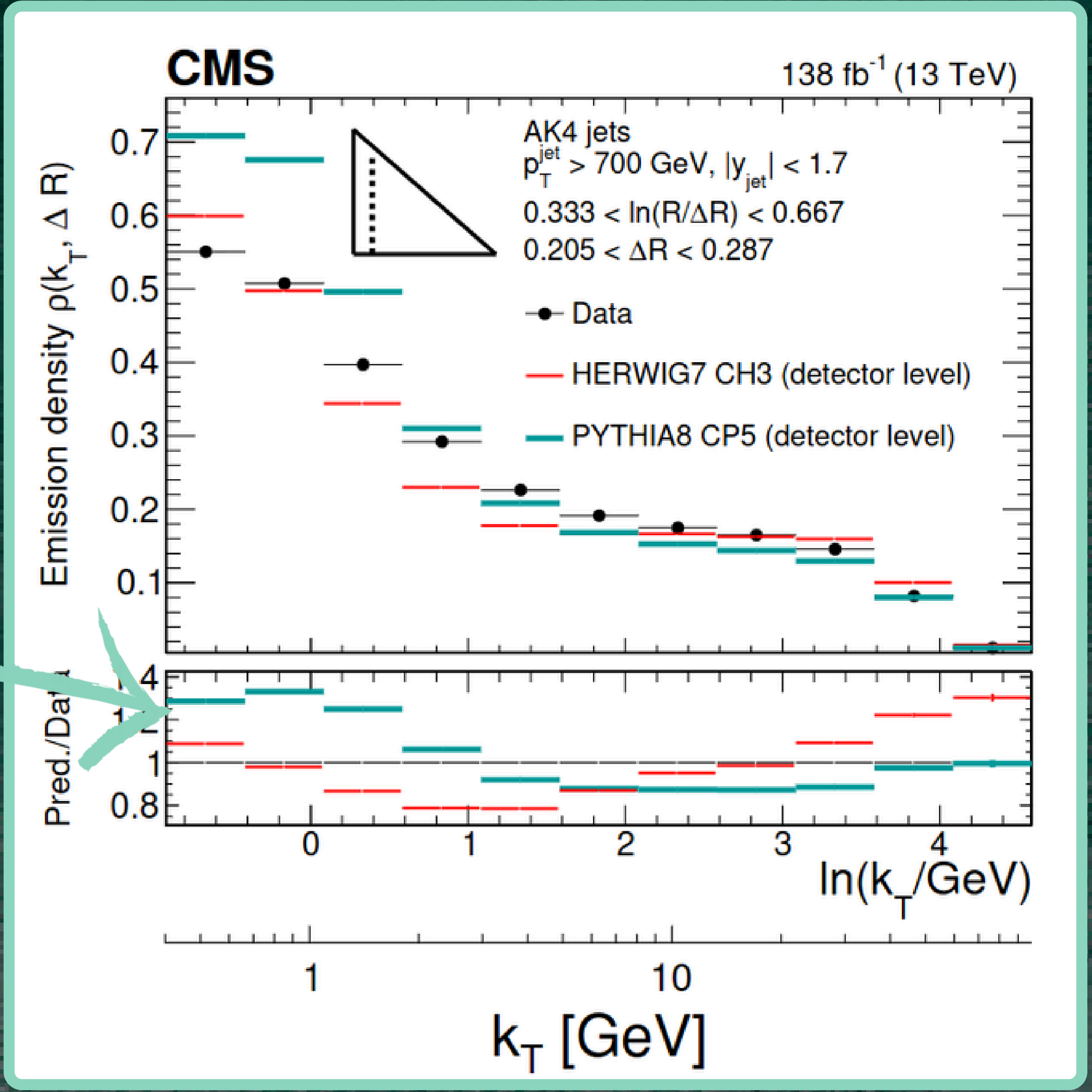


State of the art

- LL accurate shower @ leading color
- Different types:
  - dipole/antenna showers e.g. in SHERPA (default CS, Dire), HERWIG 7, PYTHIA 8 (default CS, Vincia, Dire)
  - angular-ordered shower in HERWIG 7

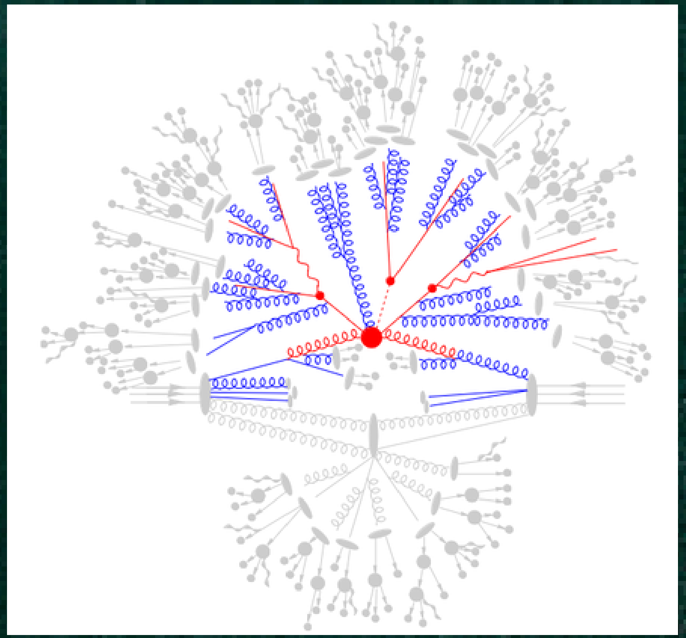
Good enough?

- Good description of many observables
- Other observables with significant discrepancies between data & shower models / shower models it selves
- Influences many analyses e.g. via jet energy scale calibration



[CMS-SMP-22-007]

PARTON SHOWERS



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Current challenges

- Improve underlying approximations:
    - NLL & NNLL accuracy
    - NLO showers
    - beyond leading color
    - NLL accurate NLO, NNLO & N3LO matching
    - quantum interference effects, spin correlations
    - new approaches: quantum computers, amplitude evolution ...
- Faster algorithms

FERMILAB-PUB-24-0178-T, IPPP/24/20, MCNET-24-07

The Alaric parton shower for hadron colliders

Stefan Höche,[1] Frank Krauss,[2] and Daniel Reichelt[2]

[1] *Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA*
[2] *Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*

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A partitioned dipole-antenna shower with improved transverse recoil

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Christian T Preuss

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ABSTRACT: The implementation of a new final-state parton-shower algorithm in the PYTHIA event generator is described. The shower algorithm, dubbed APOLLO, combines central aspects of the VINCIA antenna shower with the global transverse-recoil scheme of the ALARIC framework in order to achieve formal consistency with next-to-leading logarithmic (NLL) resummation. The shower algorithm is constructed in such a way that it facilitates a straightforward combination with fixed-order calculations. As an explicit proof of concept, a general scheme for matrix-element corrections (MECs) and two separate multiplicative next-to-leading order (NLO) matching schemes are outlined. It is argued that both matching schemes retain the logarithmic accuracy of the shower. The improved modelling of radiation is examined by contrasting the new algorithm with existing leading-logarithmic parton showers in PYTHIA.

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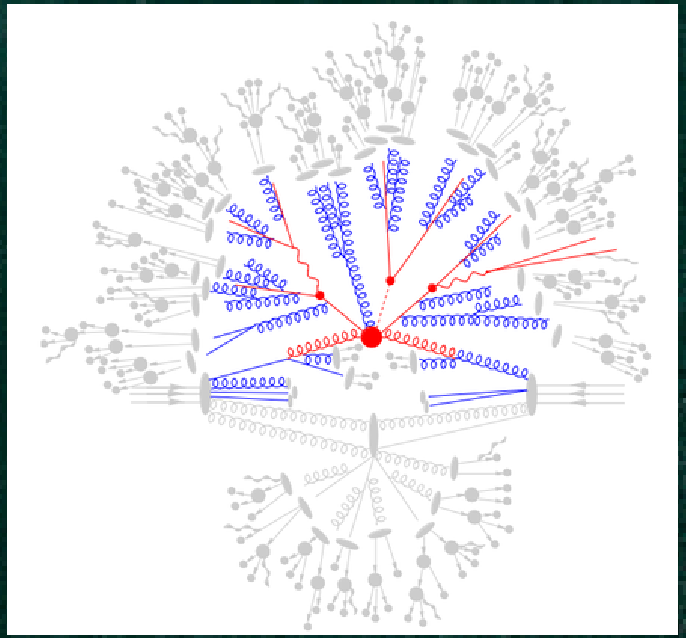

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ALARIC

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APOLLO

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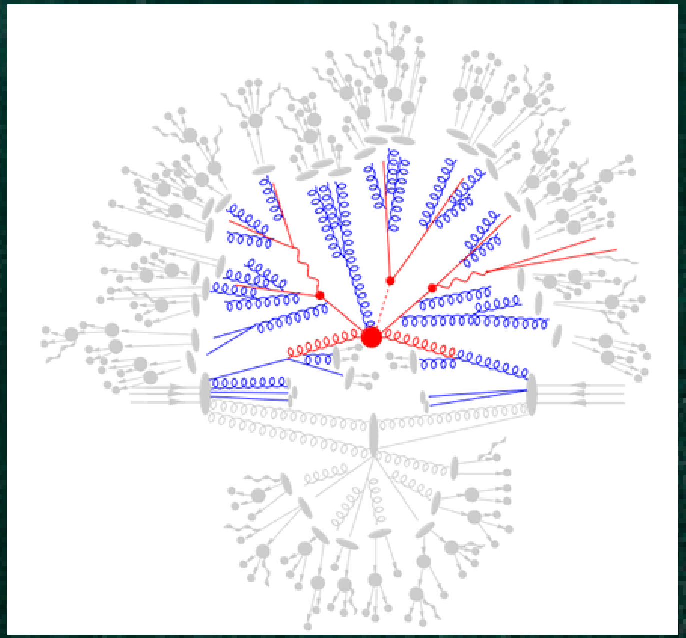

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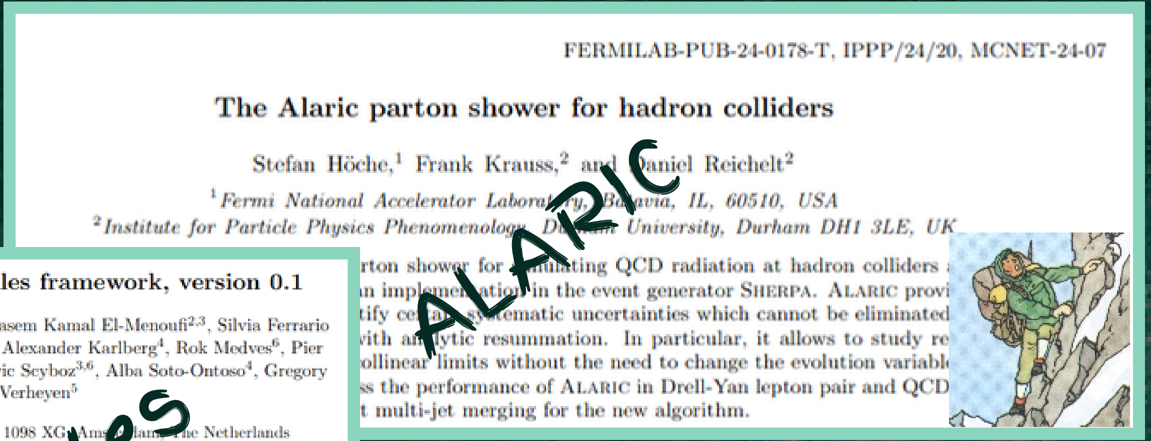

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Melissa van Beekveld[1], Mrinal Dasgupta[2], Basem Kamal El-Menoufi[2,3], Silvia Ferrario Ravasio[4], Keith Hamilton[5], Jack Helliwell[6], Alexander Karlberg[4], Rok Medves[6], Pier Francesco Monni[4], Gavin P. Salam[6,7], Ludovic Scyboz[3,6], Alba Soto-Ontoso[4], Gregory Soyez[8], Rob Verheyen[5]

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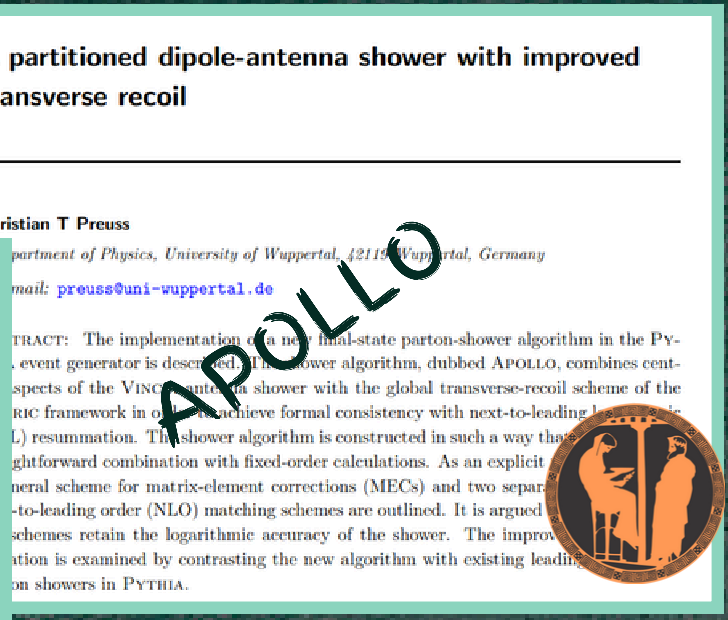
silvia.ferrario.ravasio@cern.ch, keith.hamilton@ucl.ac.uk, jack.helliwell@physics.ox.ac.uk,



A partitioned dipole-antenna shower with improved transverse recoil

Christian T Preuss

partment of Physics, University of Wuppertal, 42119 Wuppertal, Germany

mail: preuss@uni-wuppertal.de

TRACT: The implementation of a new final-state parton-shower algorithm in the PY-
event generator is described. The shower algorithm, dubbed APOLLO, combines cent-
spects of the VINCIA antenna shower with the global transverse-recoil scheme of the
RIC framework in order to achieve formal consistency with next-to-leading
L) resummation. The shower algorithm is constructed in such a way tha
ghtforward combination with fixed-order calculations. As an explicit
neral scheme for matrix-element corrections (MECs) and two separ
-to-leading order (NLO) matching schemes are outlined. It is argued
schemes retain the logarithmic accuracy of the shower. The improv
ation is examined by contrasting the new algorithm with existing leadin
on showers in PYTHIA.

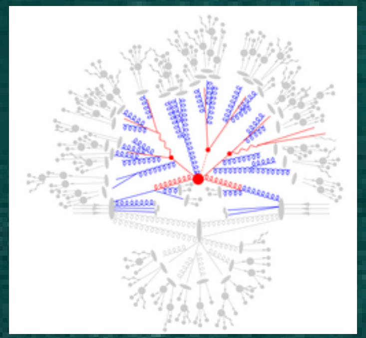
Further NLL showers

Deductor
[Z. Nagy & D. E. Soper 2020]

Manchester-Vienna
[J. R. Forshaw, J. Holguin & S. Plätzer 2020]

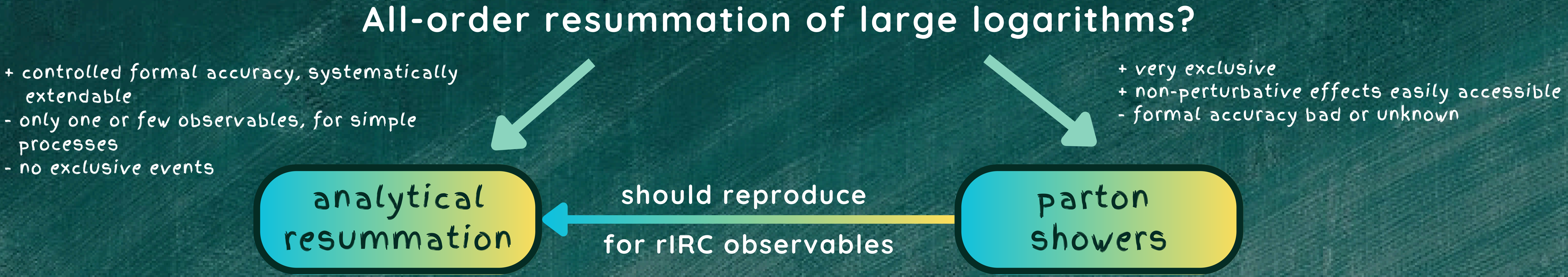
Herwig 7 (angular ordered shower)
[G. Bewick et al. 2019, 2021]

LOGARITHMIC ACCURACY IN PARTON SHOWERS



- Parton showers connect hard-process high-energy scales O(TeV) & hadronization regimes O(1GeV)

→ During evolution large logarithms $L = \log Q/\Lambda$ appear [A. Banfi, G.P. Salam & G. Zanderighi 2005]



All-order resummation of large logarithms?

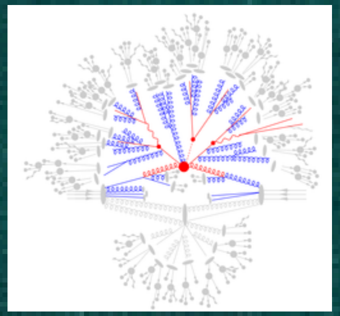
+ controlled formal accuracy, systematically extendable
- only one or few observables, for simple processes
- no exclusive events

+ very exclusive
+ non-perturbative effects easily accessible
- formal accuracy bad or unknown

- Criteria for NLL accurate parton showers @ leading color [M. Dasgupta et al. 2018, 2020]
    - standard dipole showers only LL accurate [M. Dasgupta et al. 2018]
    - main problem: kinematic mapping

ALARIC

A Logarithmically Accurate Resummation In C++
[F. Herren et al. 2022]



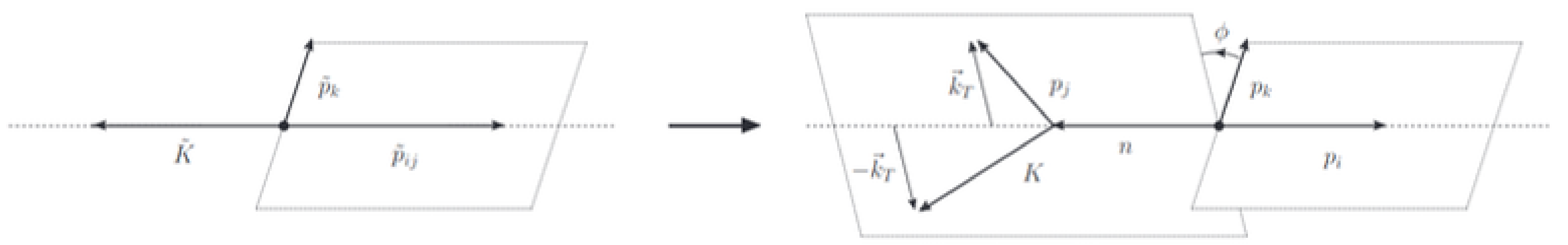
- Shower based on Catani-Seymour dipols
- Partial fractioning of eikonal [S. Catani & M. H. Seymour 1997]

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} = \frac{1}{E_j^2} \frac{1-\cos\theta_{ik}}{(1-\cos\theta_{ij})(1-\cos\theta_{jk})} \equiv \frac{W_{ik,j}}{E_j^2}$$

→ positive definite splitting with full phase space coverage

$$W_{ik,j} = \bar{W}^i_{ik,j} + \bar{W}^k_{ki,j}\,, \qquad \text{where} \qquad \bar{W}^i_{ik,j} = \frac{1-\cos\theta_{ik}}{(1-\cos\theta_{ij})(2-\cos\theta_{ij}-\cos\theta_{jk})}$$

- New global recoil scheme
  - *analytical* proof of NLL accuracy

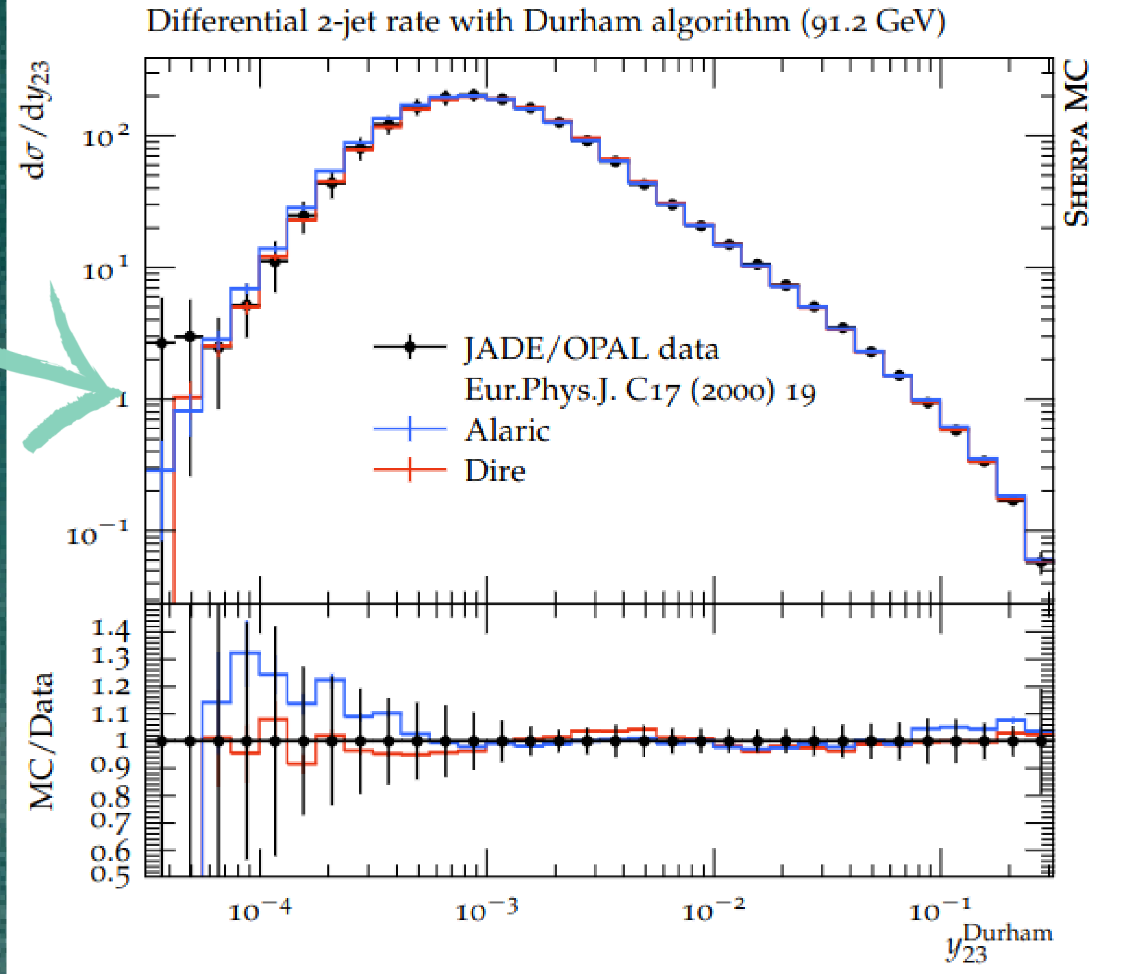


- Evolution variable

ISR $t^{(n)} = 2E_j^2\,(1-\cos\theta_j^{\,i}) = v\,(1-z)\,2\tilde{p}_i\tilde{K}$

FSR $t^{(K)} = 2E_j^2\,(1-\cos\theta_j^{\,i}) = \dfrac{v}{1-v}\,(1-z)\,2\tilde{p}_i\tilde{K}$

- Inclusion of
  - massive quark effects [B. Assi & S. Höche 2023]
  - initial state radiation & LO multi-jet merging [S. Höche, F. Krauss & D. Reichelt 2024]



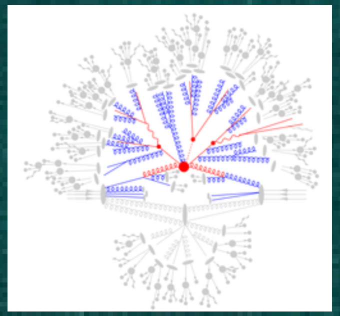
Next steps to become "competitive" for LHC

- Spin correlations
- Sub-leading color effects
- Implementation of NLO matching, merging
- Matching to light-flavor PDFs
- Beyond: NLO splitting kernels, Alaric@NNLL

APOLLO

Antenna Partitioning Overcomes Logarithmically Limiting Obstacles

[C. T. Preuss 2024]



- Antenna shower VINCIA with global recoil scheme from ALARIC
- Partitioned dipole antenna functions

$$P_{\mathrm{qg}}(p_i,p_j,p_k;n_j) = \frac{1}{s_{ij}}\left[\frac{2s_{ik}(p_in_j)}{s_{jk}(p_in_j)+s_{ij}(p_kn_j)} + \frac{s_{jk}}{s_{ijk}}\right],$$

$$P_{\mathrm{gg}}(p_i,p_j,p_k;n_j) = \frac{1}{s_{ij}}\left[\frac{2s_{ik}(p_in_j)}{s_{jk}(p_in_j)+s_{ij}(p_kn_j)} + \frac{s_{jk}s_{ik}}{s_{ijk}^2}\right]$$

Auxiliary vector n chosen in spirit of ALARIC construction

$$n_j^\mu = K^\mu + p_j^\mu$$

$$K^\mu = -\sum_{k\in\mathrm{FS}} p_k^\mu = \sum_{k\in\mathrm{IS}} p_k^\mu$$

Differences to ALARIC

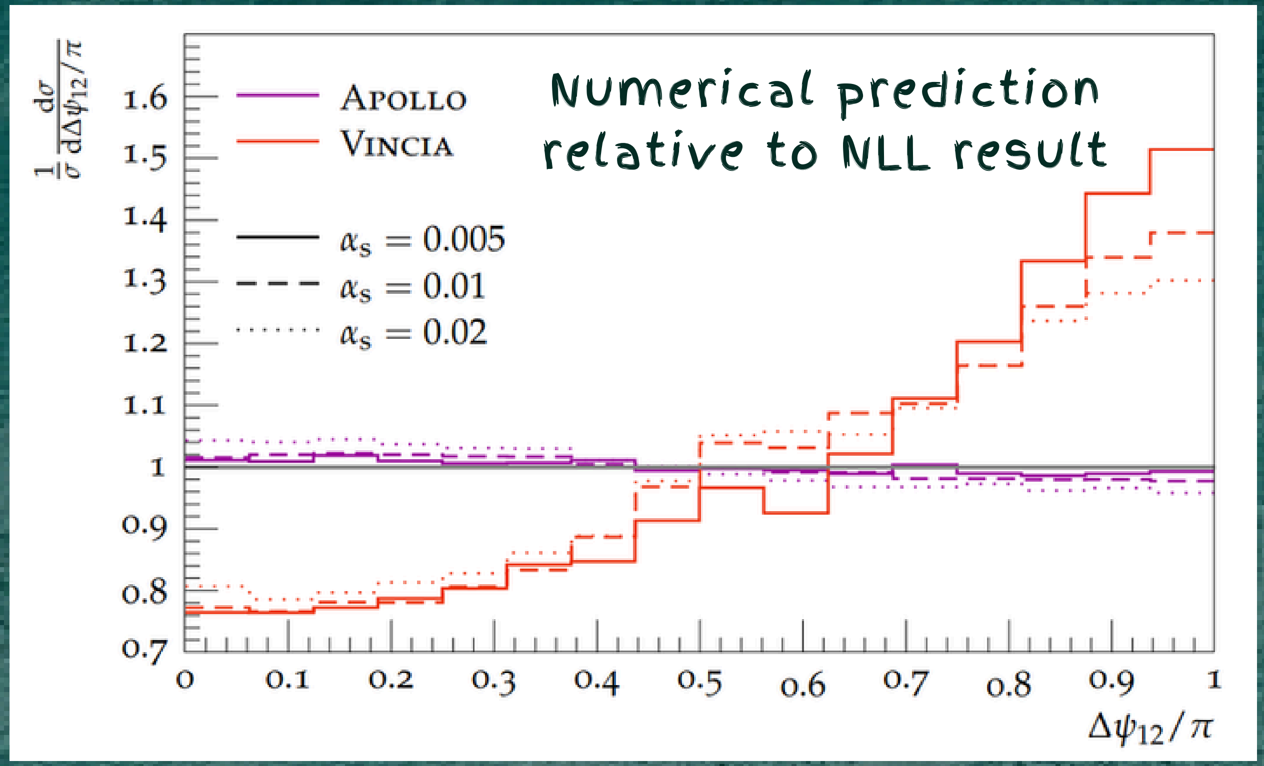
- Modelling of purely collinear parts of the branching kernels
- Evolution variable

$$t = (1-z)s_{ij} = z(1-z)2\tilde{p}_{ij}\tilde{K}$$

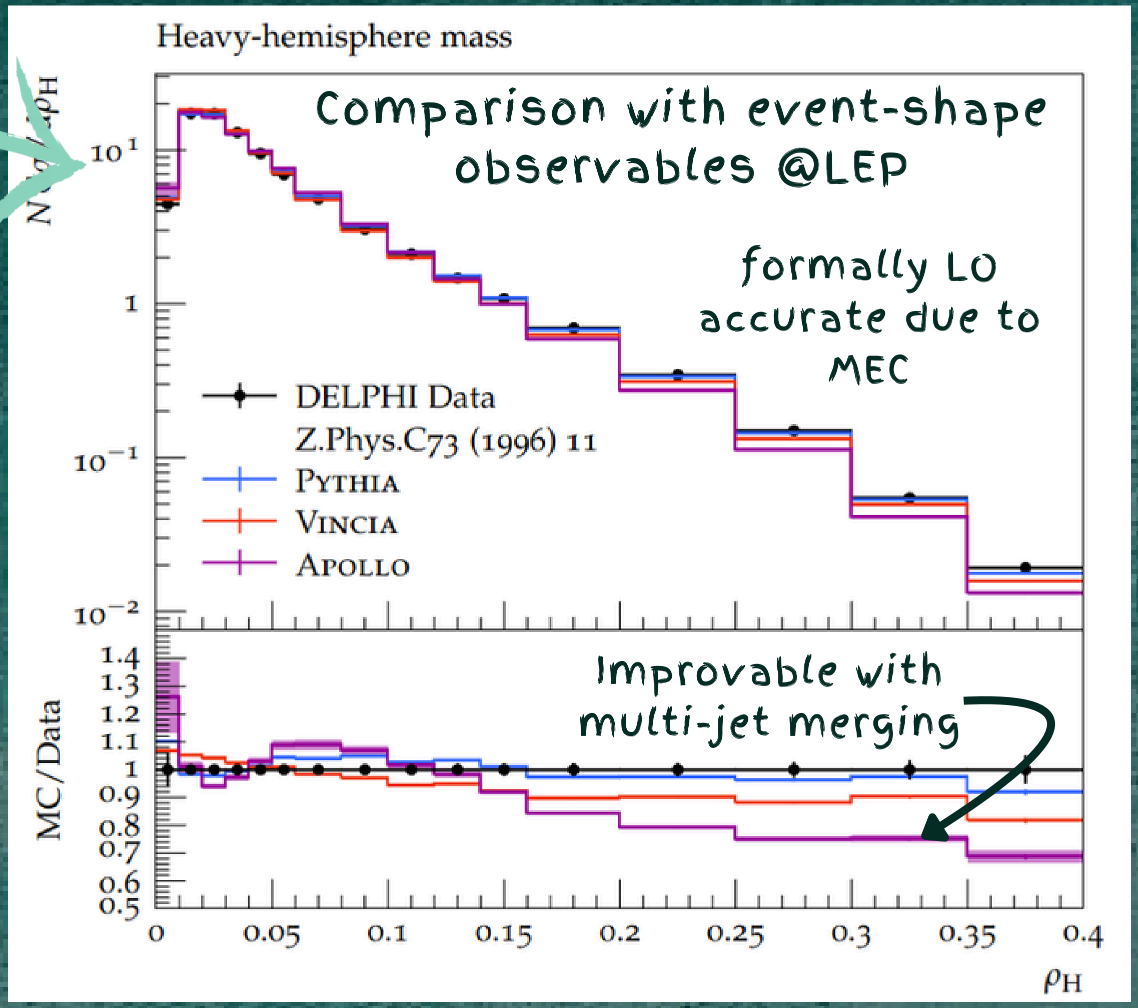
- Matrix element corrections in PS implemented
- Two multiplicative NLO matching schemes developed

Next steps to become "competitive" for LHC

- Massive quark effects
- Initial state radiation
- Spin correlations
- Subleading color effects
- Multi-jet merging



Numerical prediction relative to NLL result



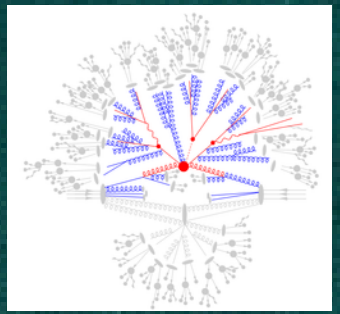
Comparison with event-shape observables @LEP

formally LO accurate due to MEC

Improvable with multi-jet merging

PANSCALES SHOWERS

$$v = \frac{k_t}{\rho} e^{-\beta_{\mathrm{PS}}|\bar{\eta}|}\,, \qquad \rho = \left(\frac{s_{\tilde{\imath}} s_{\tilde{\jmath}}}{Q^2 s_{\tilde{\imath}\tilde{\jmath}}}\right)^{\frac{\beta_{\mathrm{PS}}}{2}}$$



[M. van Beekveld et al. 2022]

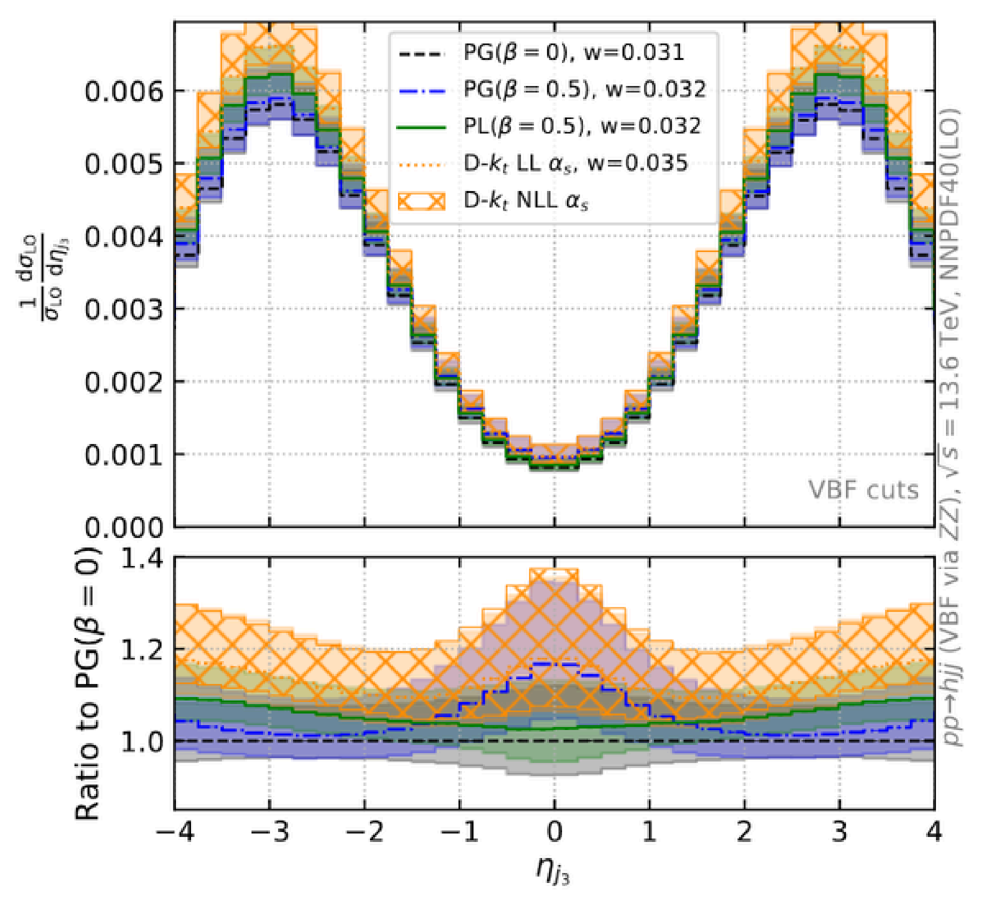
Hadron collider PanGlobal showers

- Antenna showers
- Evolution observable v: $0 \leq \beta_{PS} < 1$
- Recoil ||: conserved locally
- Recoil ⊥: conserved globally

Hadron collider PanLocal showers

- Antenna & dipole showers
- Evolution observable v: $0 < \beta_{PS} < 1$
- Dipole-local recoil
    - dipole variant: emitter takes transverse recoil
    - antenna: transverse recoil shared by emitter & spectator

[M. van Beekveld & S. Ferrario Ravasio 2023]



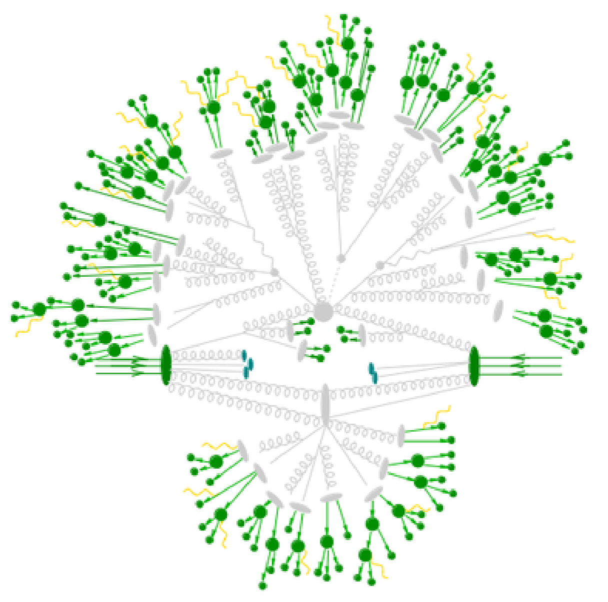
VBF: pp->hjj

- Included:
    - sub-leading color effects [K. Hamilton et al. 2020, M. van Beekveld et al. 2022]
    - soft & collinear spin correlations [A. Karlberg et al. 2021, K. Hamilton et al. 2021, M. van Beekveld et al. 2022]
    - first steps towards matching & NNLL accuracy [K. Hamilton et al. 2023] [M. van Beekveld et al. 2024] [S. Ferrario Ravasio et al. 2023]
- Published in PANSCALES framework [M. van Beekveld et al. 2023]
    - interface to PYTHIA 8
    - tests of logarithmic accuracy
    - opportunity to implement & test own showers

Next steps to become “competitive” for LHC

- massive quark effects
- higher-order matching

HADRONIZATION MODELLING



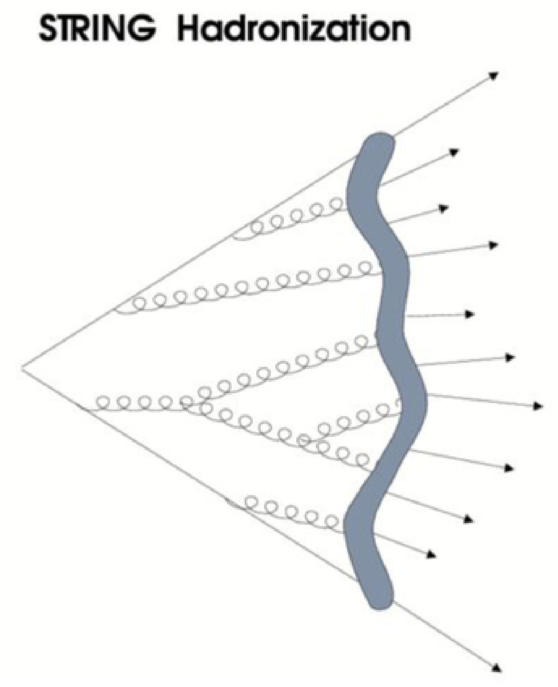
State of the art

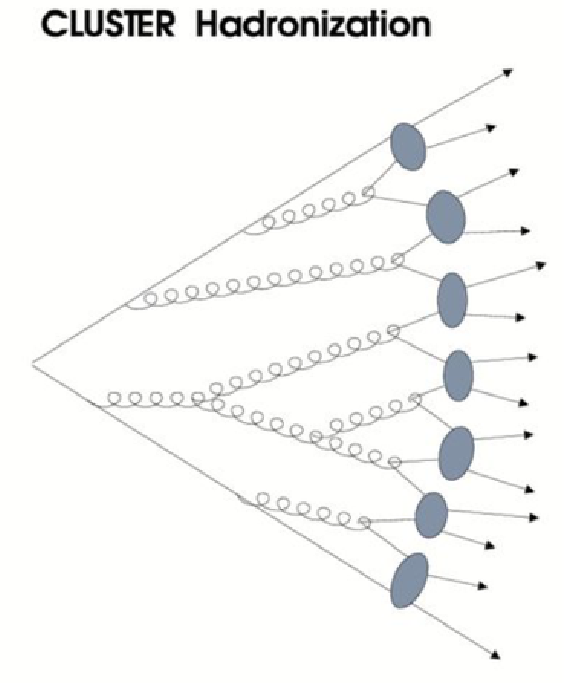
- Actual connection from "pure theory" to measurable quantities
- No derivation from first principles

⟶ Based on phenomenological models

⟶ Model parameters need to be tuned on data

- Common models
    - cluster hadronization: SHERPA, HERWIG 7
    - string fragmentation: PYTHIA 8





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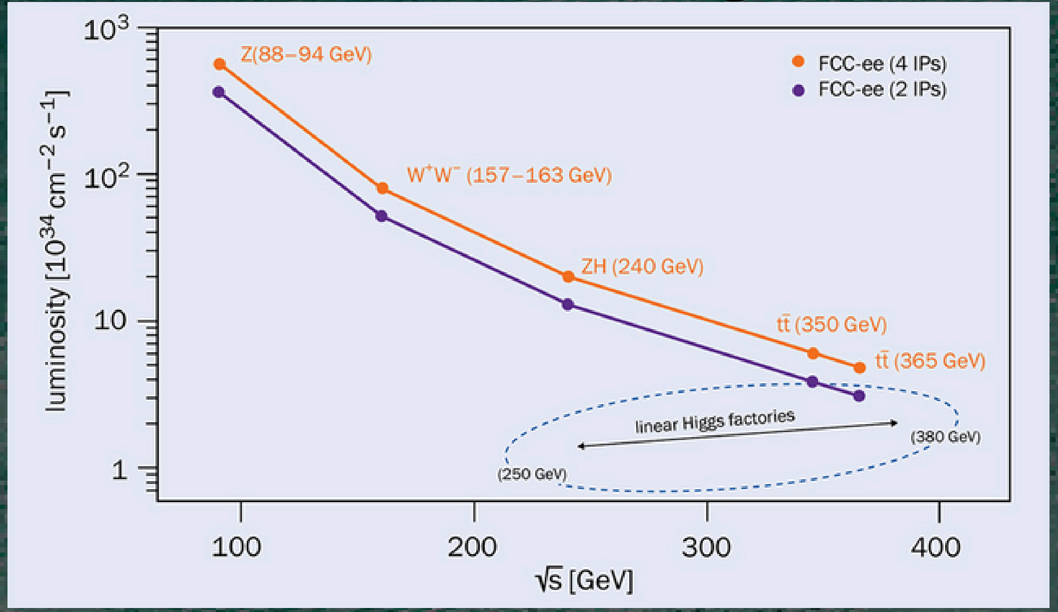
Why important?

- Many perturbative improvements: soft physics likely become limitation for more & more LHC measurements

e.g. [M. Johnson & D. Maitre 2017] , [M. Freytsis et al. 2018], [S. Argyropoulos & T. Sjöstrand 2014]

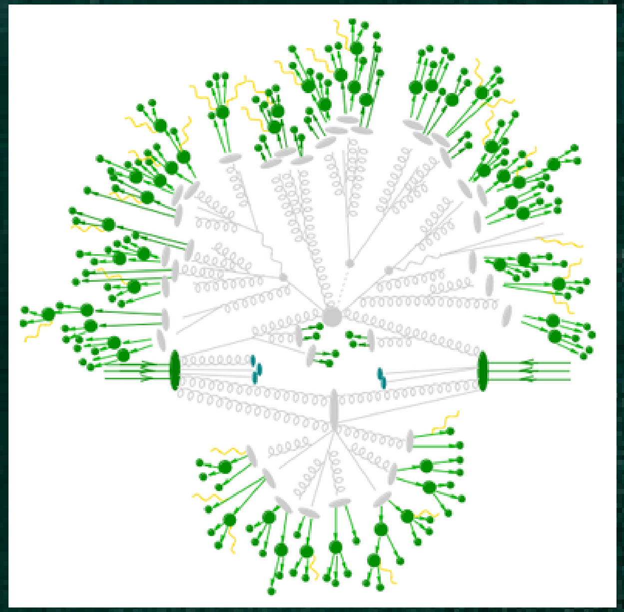
- High expected luminosity at FCC-ee @ Z-pole

⟶ predictions surely limited by non-perturbative effects



https://cerncourier.com/a/fcc-the-physics-case/

HADRONIZATION MODELLING



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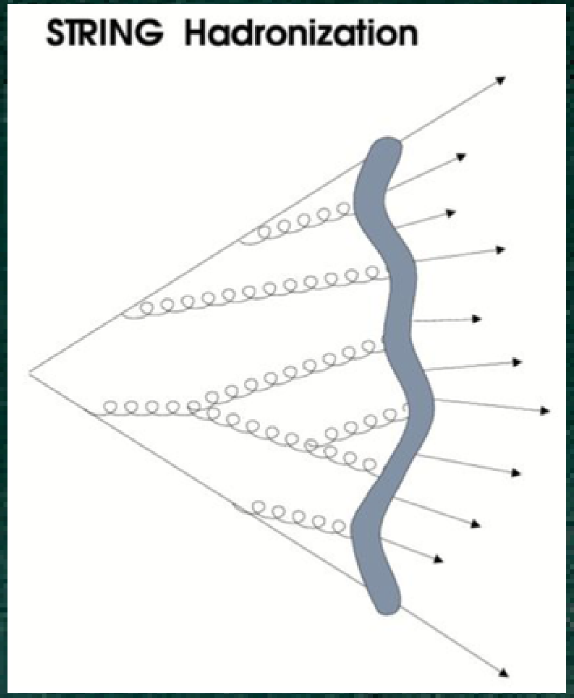

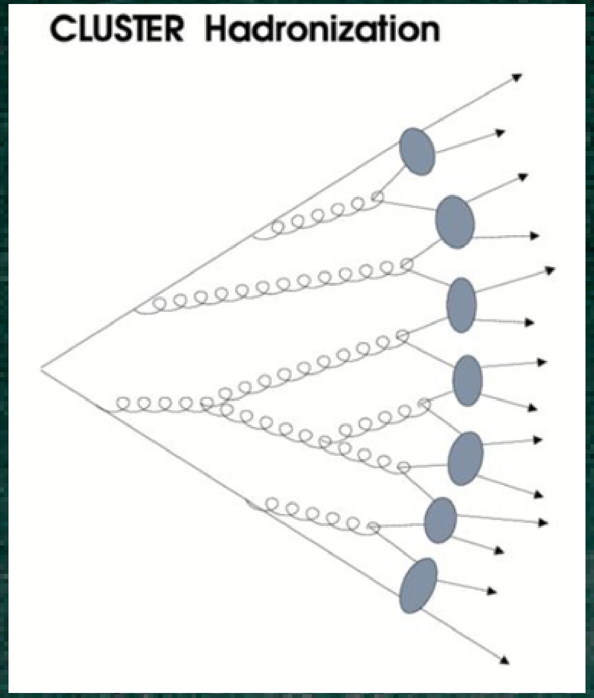

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Current challenges

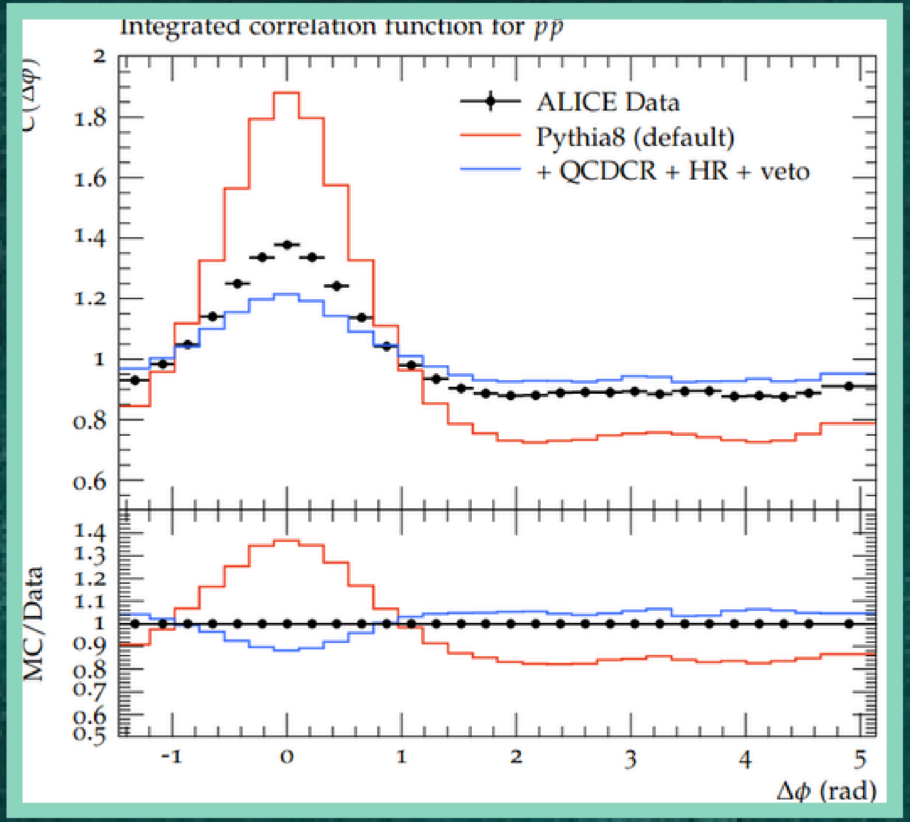
- Improve existing string & cluster models
- Add / better understand new effects: colour reconnection, hadron spin, hadron rescattering, Bose-Einstein effects, rope hadronization …
- Alternative models / application of ML methods
- Better tuning on more data (more than LEP)

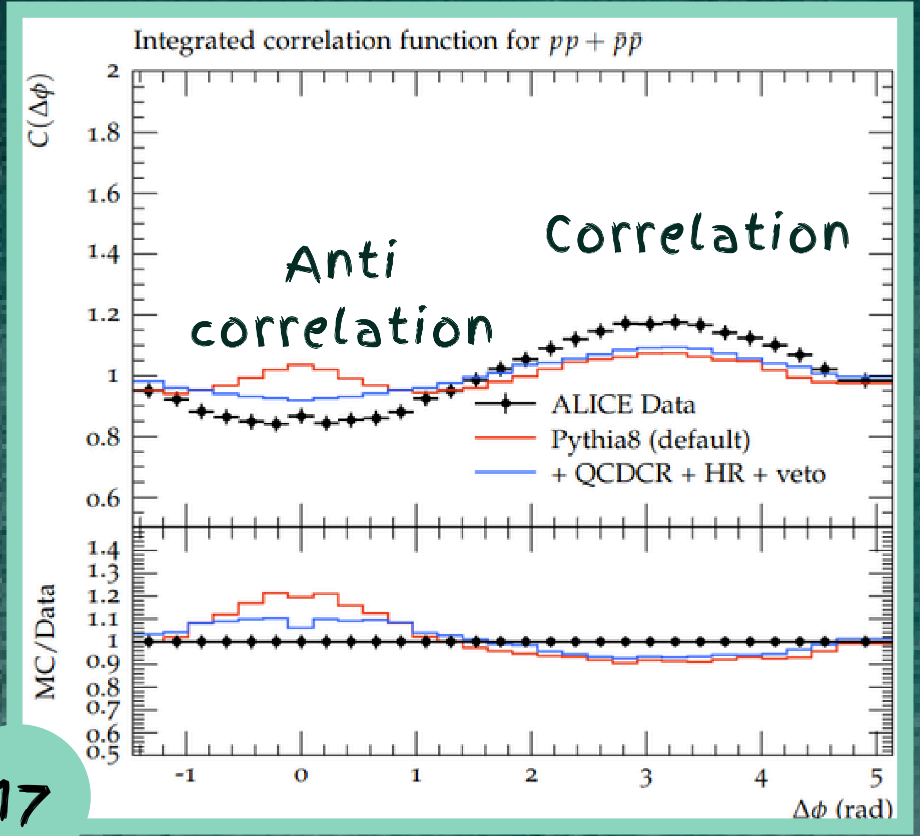
Better measure-ments!

More discussions also: J. Altmann Wed 11:18 AM & A.Beraudo Wed 2:18 PM

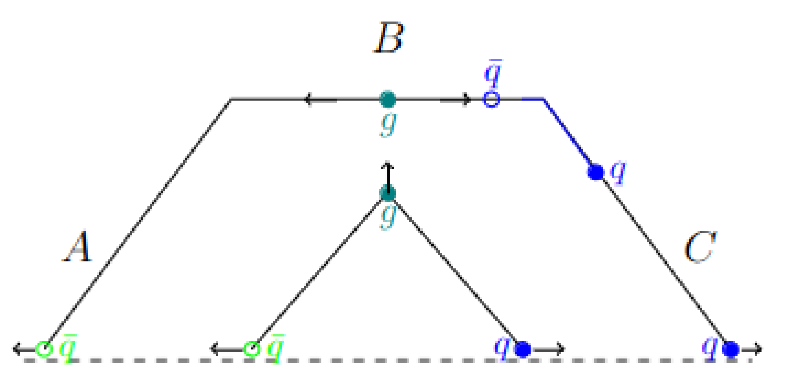
BARYON CORRELATIONS

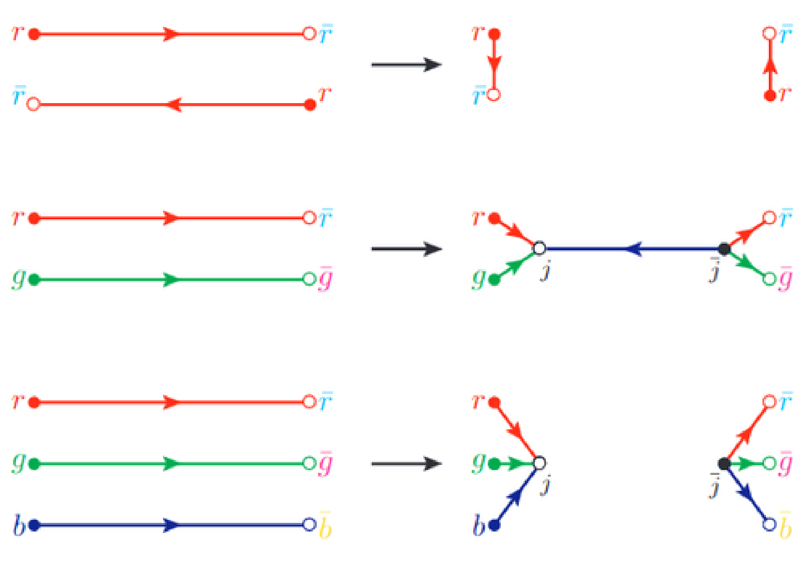
[L. Lönnblad & H. Shah 2023]





- Baryon correlations badly modeled in pp collisions
  (e+e- / meson correlation in pp 👍)
- QCDCR model for color reconnection
  - additional baryon production mechanism, but less correlation
  - improvement for opposite-sign pairs
- Hadronic rescattering & toy model for suppression of baryon production close to gluon kinks
  - improves modelling for same-sign pairs
  - aggravates model for opposite-sign pairs



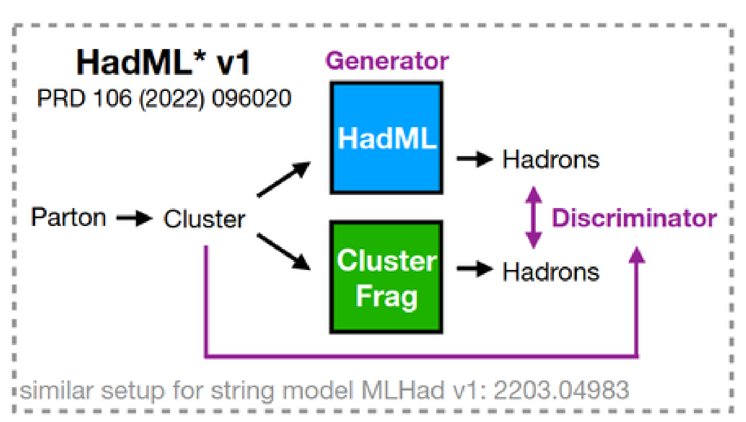


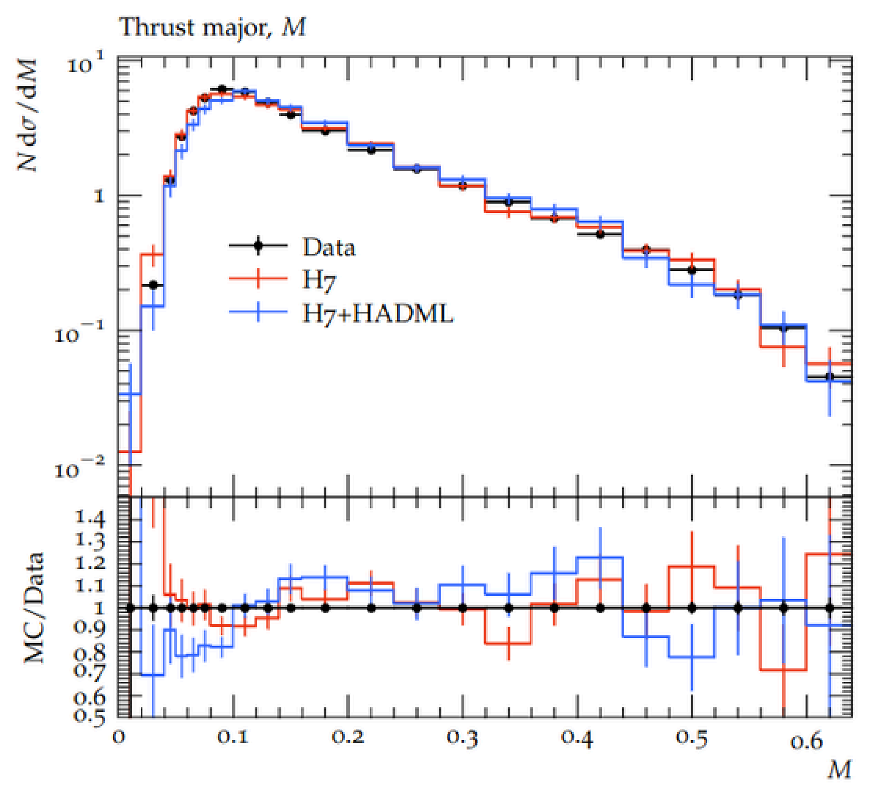
Newer ALICE measurements: M. van Leeuwen Mon 9:30 AM

HERWIG progress:
[Talk by S. Kiebacher at QCD@LHC 2023]

ML FOR HADRONIZATION

- Proof-of-principle studies: parts of cluster- / string fragmentation replaced with ML models
    - HERWIG: cluster decay by Generative Adversarial Network (GAN) model [A. Ghosh et al. 2022]
    - PYTHIA 8: string break by Conditional sliced-Wasserstein autoencoders [P. Ilten et al. 2022]





⟶ Training access to cluster/string-hadron assignments

- More recently: GAN model fitted on observable features [J. Chan et al. 2023]
    - currently restricted on clusters created from pre-confined partons, pions in FS

    ⟶ Inclusion of hadron flavor in HadML v1 [J. Chan et al. 2023]

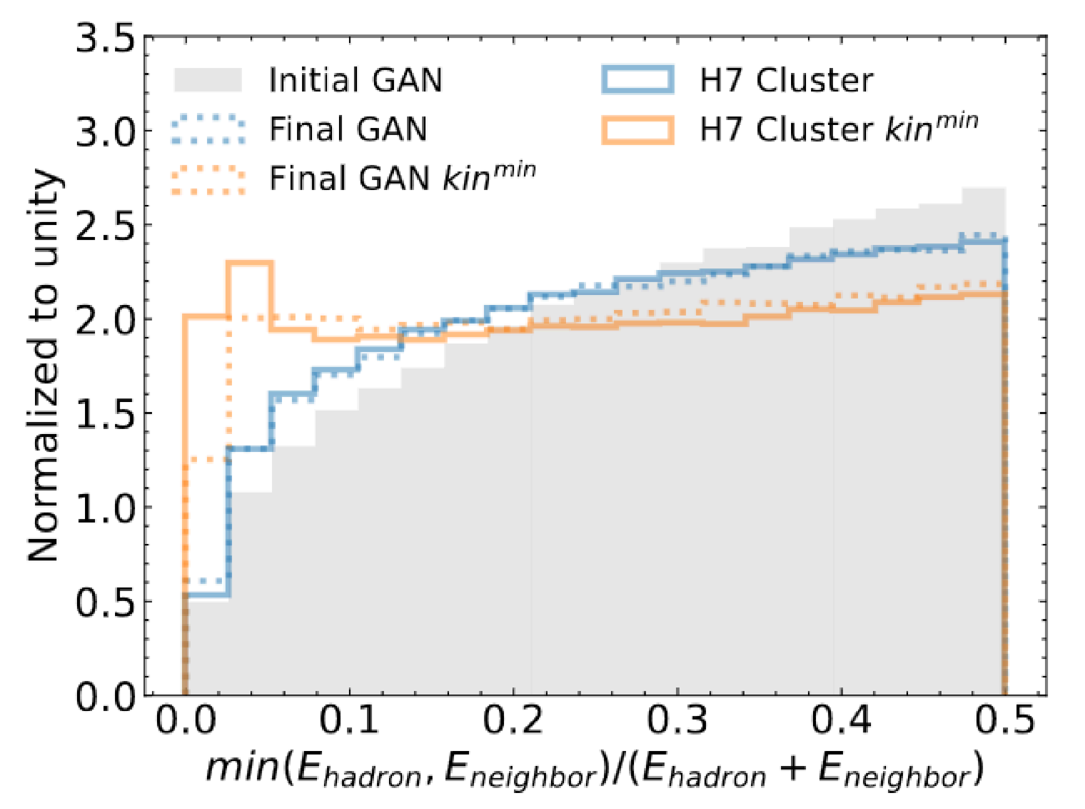
    - permutation invariance

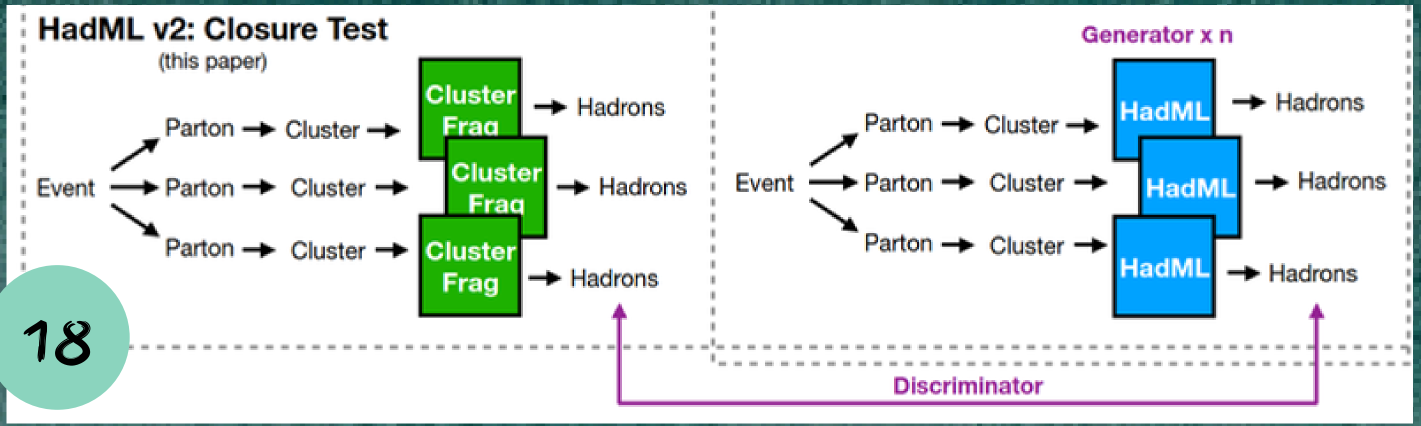
$$D_E(x) = F\left(\frac{1}{n}\sum_{i=1}^{n}\Phi\left(h_i, \omega_{D_\Phi}\right), \omega_F\right)$$

Discriminator

Hadron kinematics

Deep Set





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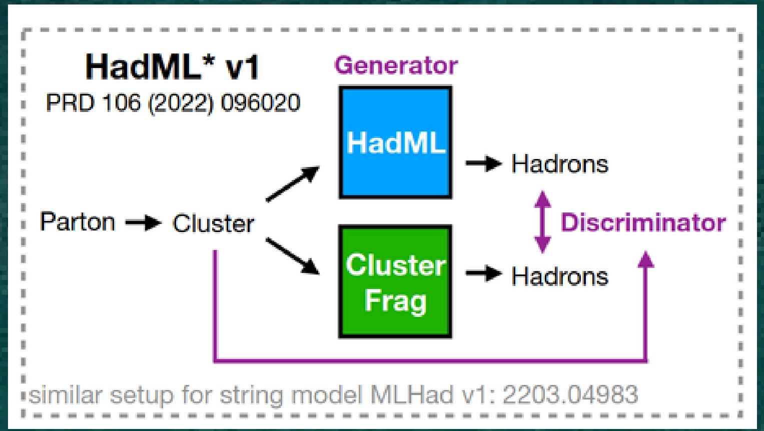
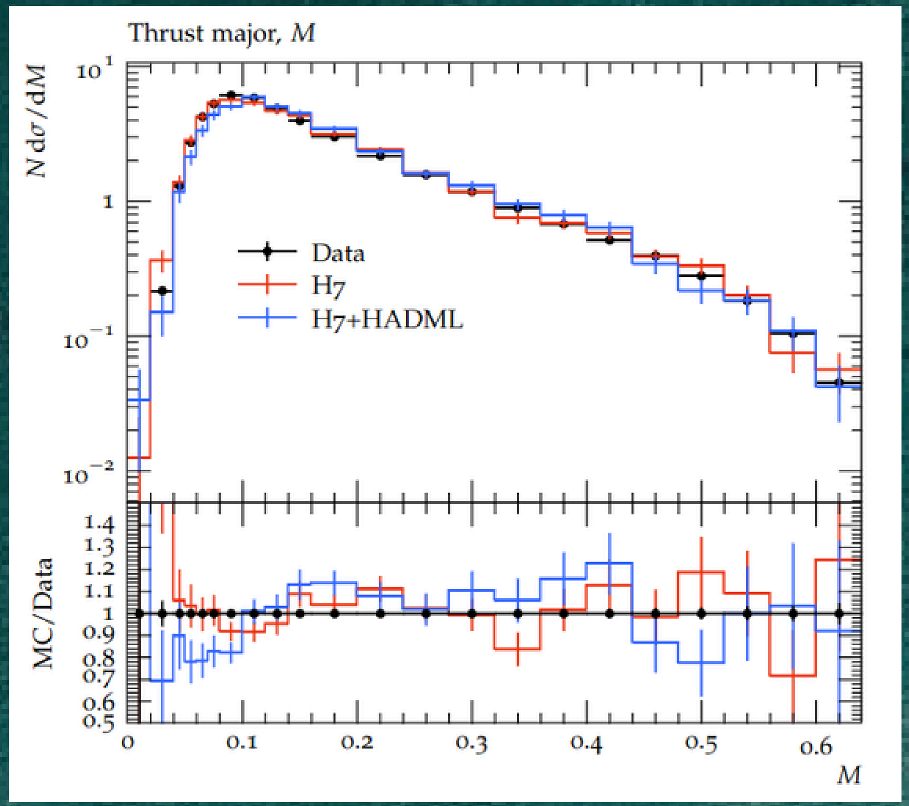

HadML* v1
PRD 106 (2022) 096020

similar setup for string model MLHad v1: 2203.04983



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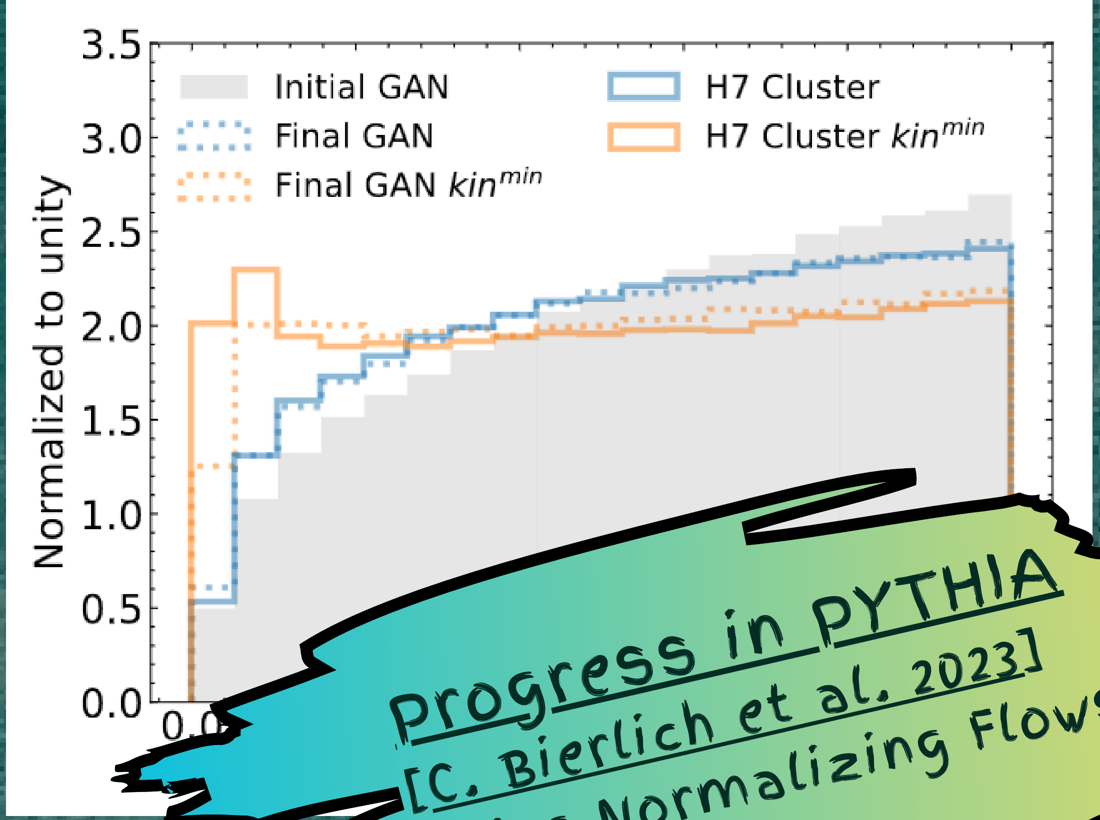
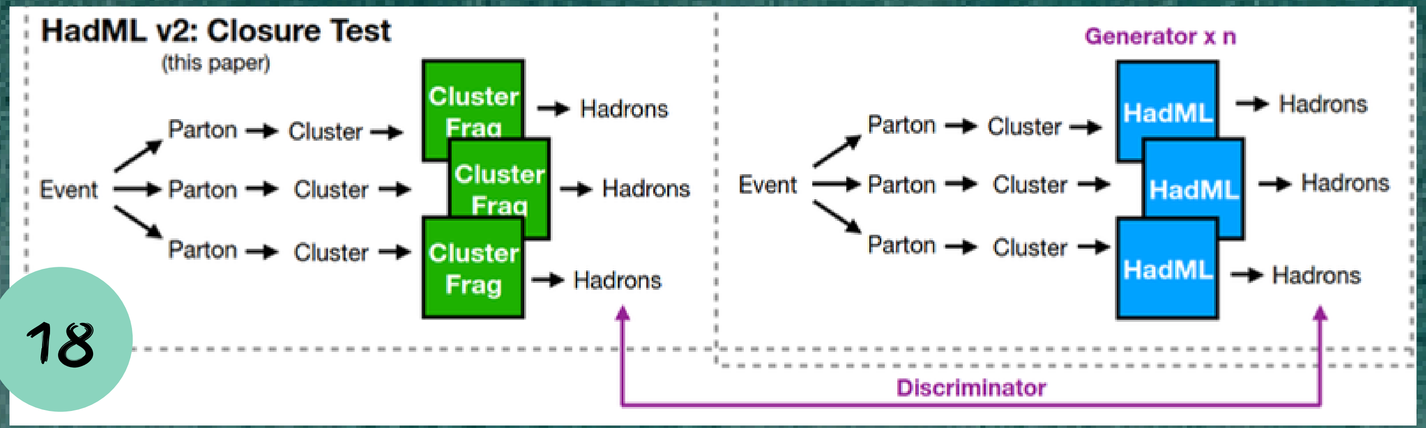


Progress in PYTHIA
[C. Bierlich et al. 2023]
using Normalizing Flows


HadML v2: Closure Test
(this paper)

CONCLUSION

A lot of ONGOING WORK in ALL PARTS of

to reach

& 

NEEDs of the HL-LHC & beyond!

More details?
Snowmass 2021 Event Generators report

Learn more & get involved:
Website
MCnet

CONCLUSION

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to reach

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Thank you for your attention!

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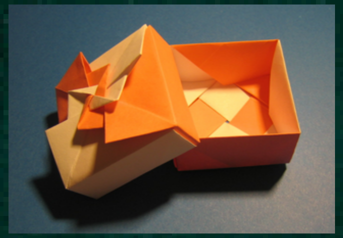
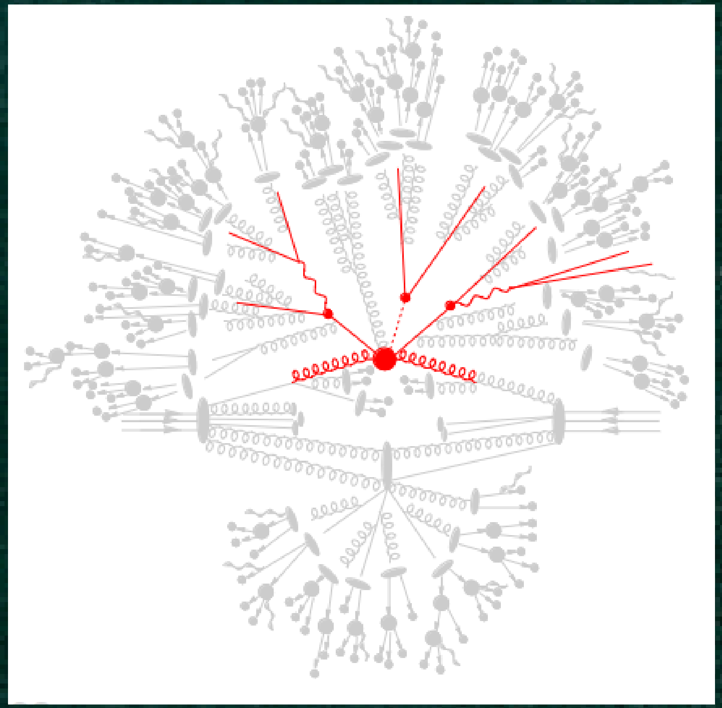
HARD PROCESS

MADGRAPH5 aMC@NLO





State of the art

- Automated NLO QCD & approximate NLO EW

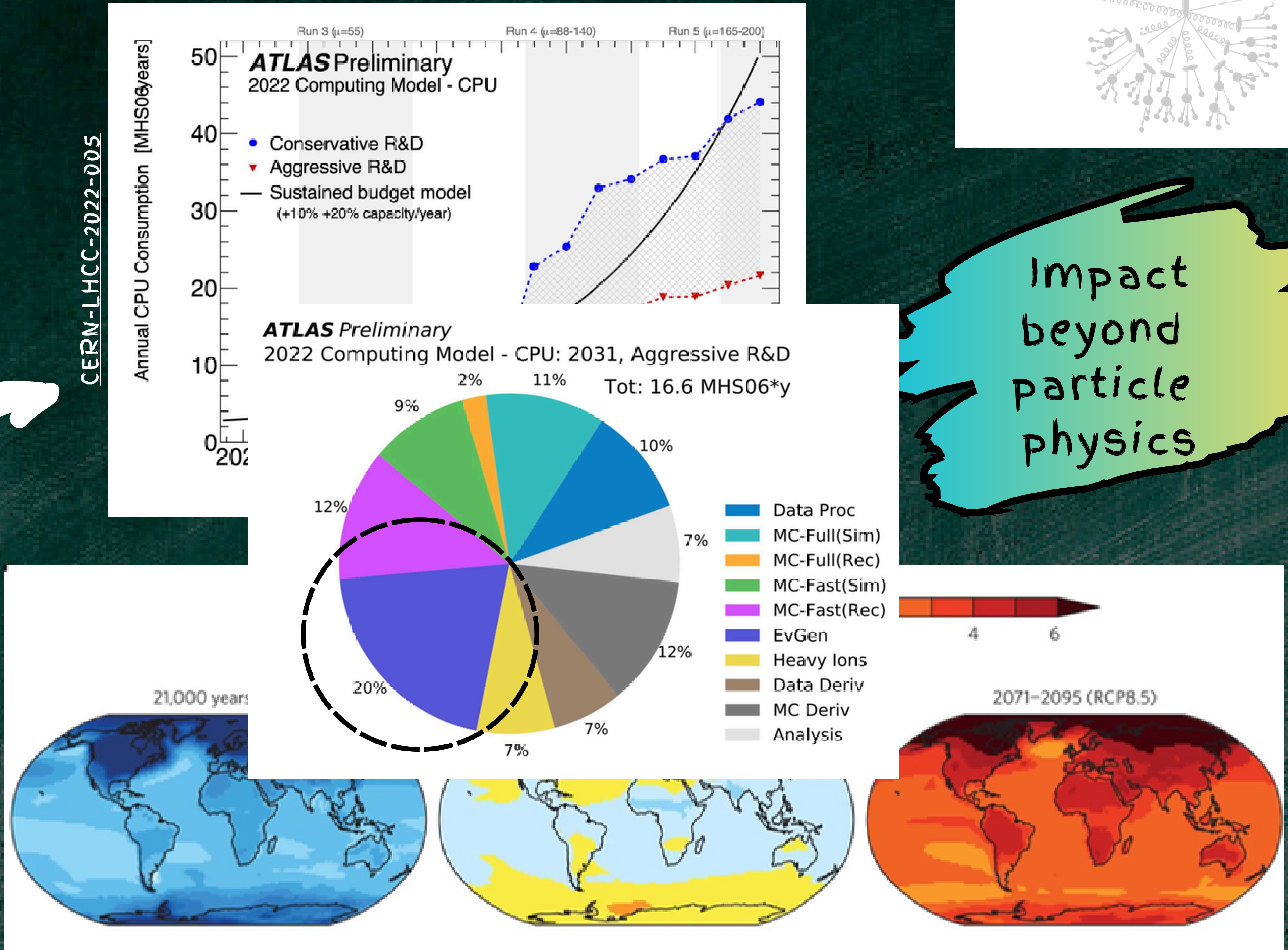
Current challenges

- Precision
- Speed / Efficiency

Fully differential NNLO matching

N3LO matching

Polarized XS

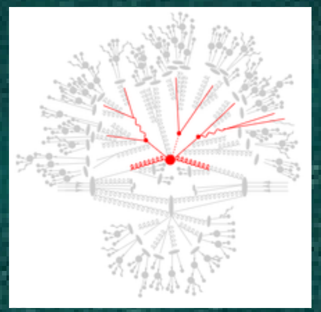


CERN-LHCC-2022-005

Impact beyond particle physics

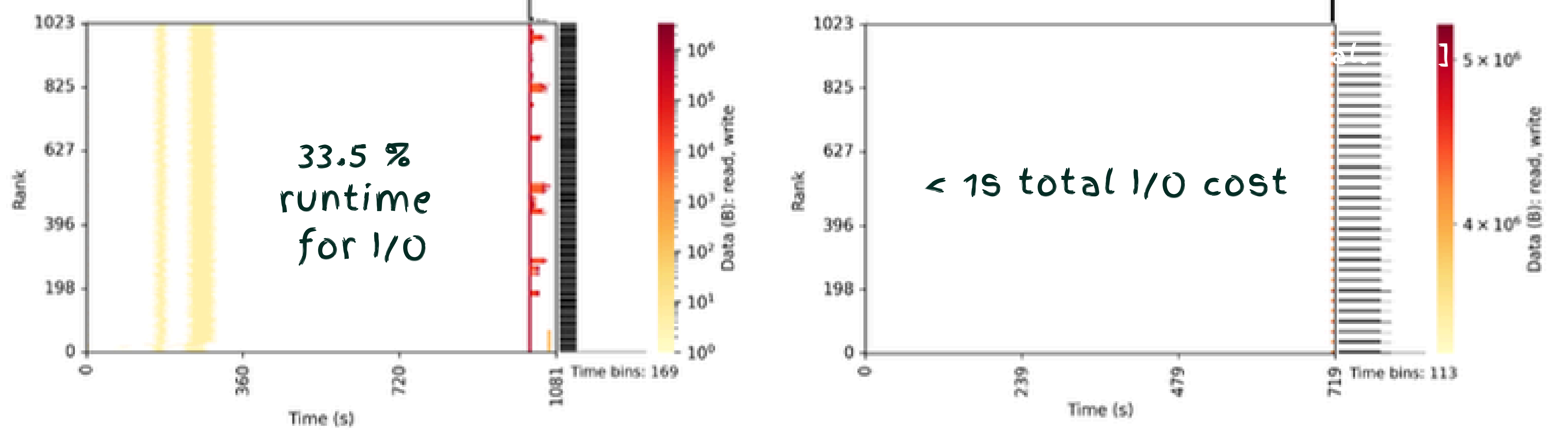
https://climateknowledgeportal.worldbank.org/overview

“SIMPLE” OPTIMIZATIONS CAN HELP MUCH



Improved new event format [E.Bothmann et al. 2023]

- New event format LHEH5
    - allow for scalability of event production over many MPI ranks
    - optimize, extend to NLO QCD new format proposed in [S.Höche, S.Prestel & H.Schulz 2019]
- Large performance improvements:
    - consolidation of HDF5 data sets
    - collective I/O
    - stat calls to master rank limited



33.5 % runtime for I/O

< 1s total I/O cost

Darshan graphs for Sherpa during parton level H+3j @LO QCD on 1024 MPI ranks

(a) POSIX operations before optimization

(b) POSIX operations after optimization

LHEH5 event format

LHE-like data format based on HDF5-HighFive

- LHE information collected in HDF5 data sets
- Established LHEF: based on XML
    - flexible for new features, but challenge for I/O operations at scale
- HDF5: database-kind computing model
    - rigid, but efficient in parallel workflows

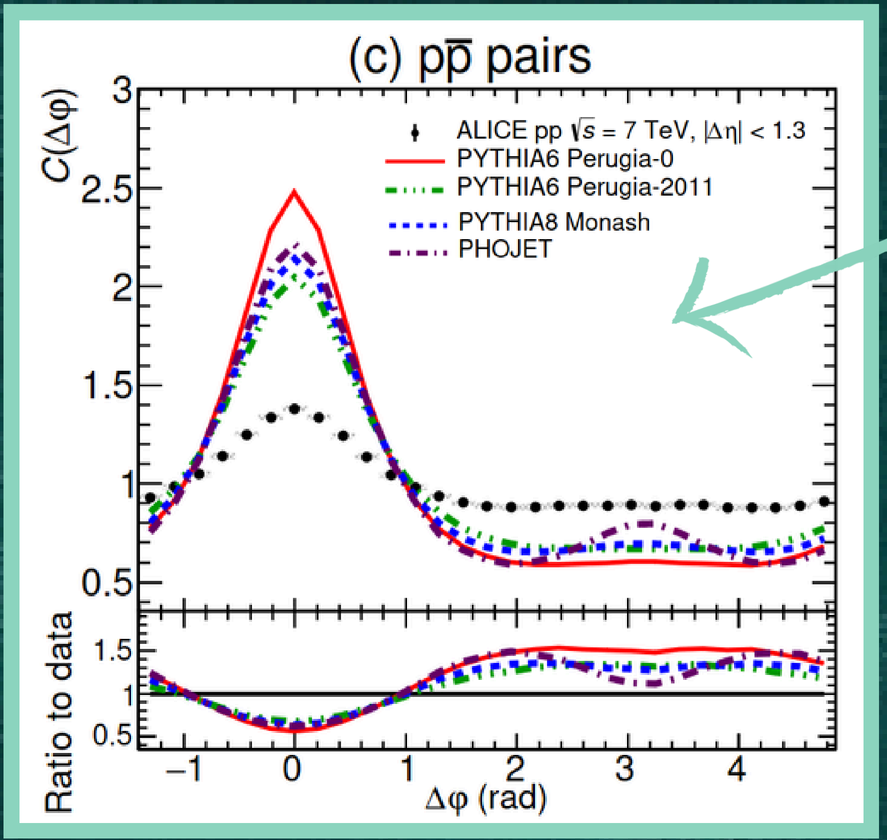
Similar simple optimizations : Faster LHAPDF + simplified pilot runs

~ 40x speed up [E. Bothmann et al. 2022]

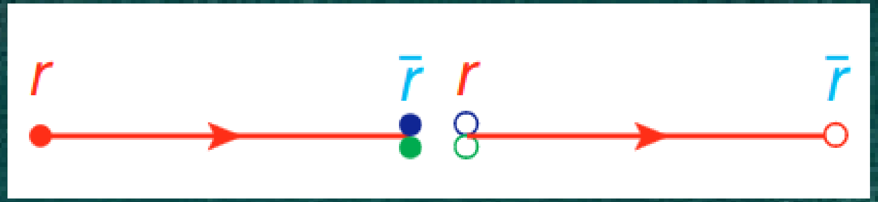
BARYON CORRELATIONS

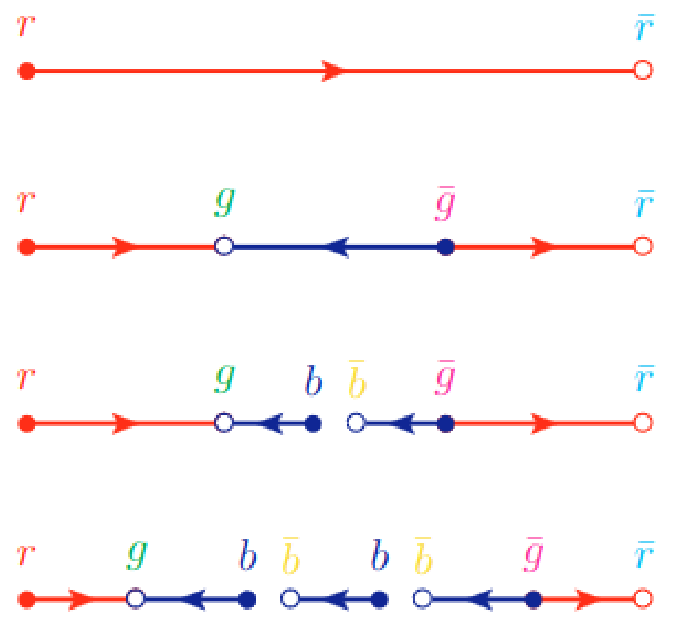
[ALICE CERN-EP-2016-322]

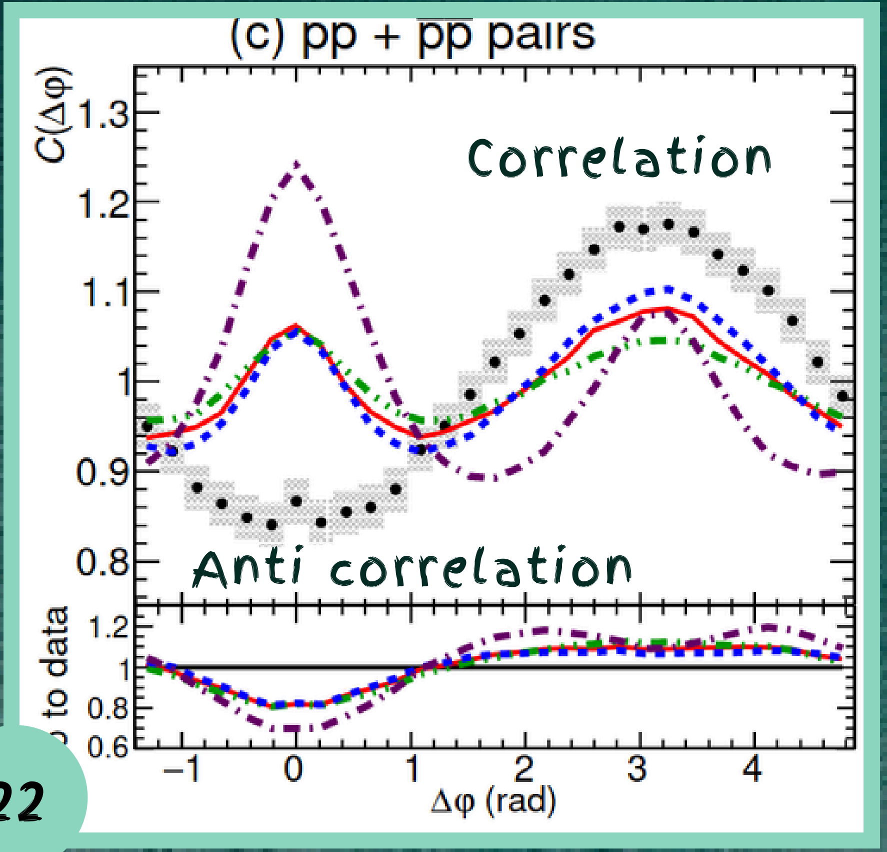
[L. Lönnblad & H. Shah 2023]



- Baryon correlations badly modeled in pp collisions (e+e- / meson correlation in pp 👍)
- Modes of baryon production in string models:
  - diquark model
  - **popcorn model**
- Gluon participation (gluon kink) important for angular correlation

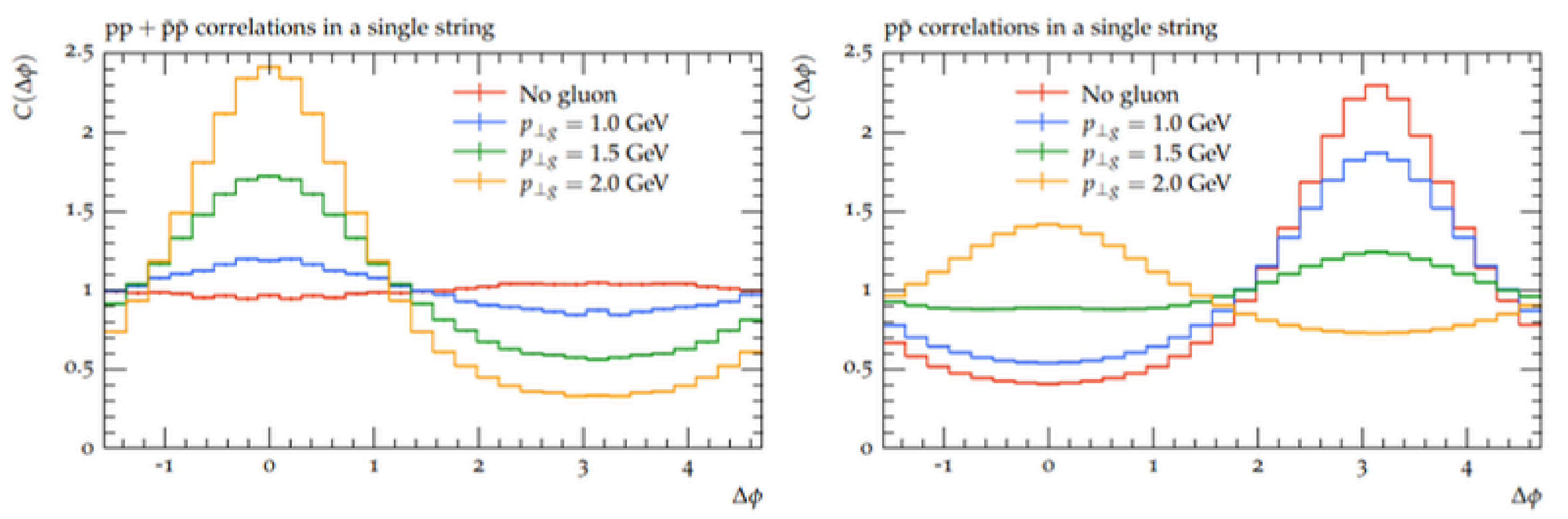


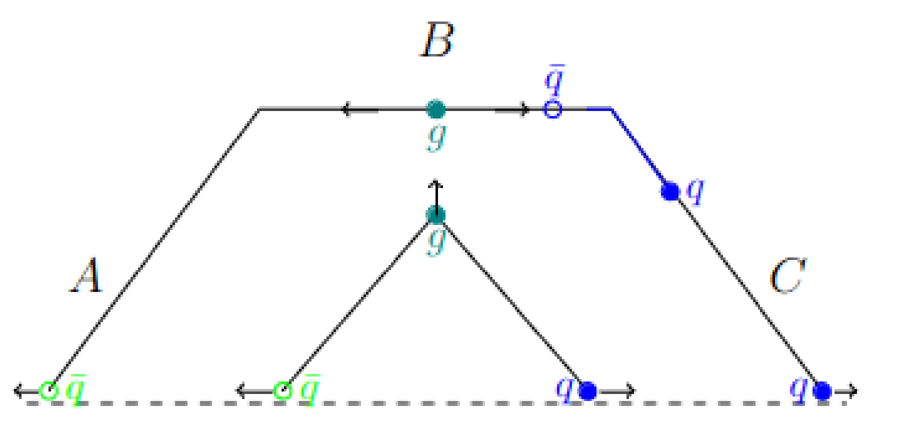




Correlation

Anti correlation

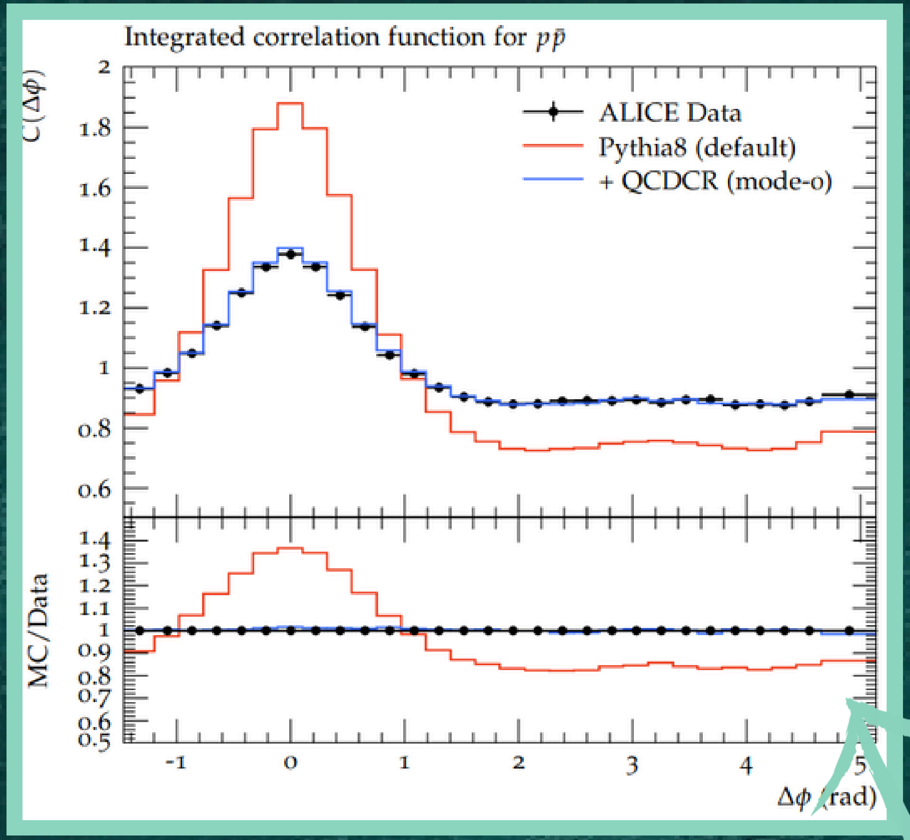


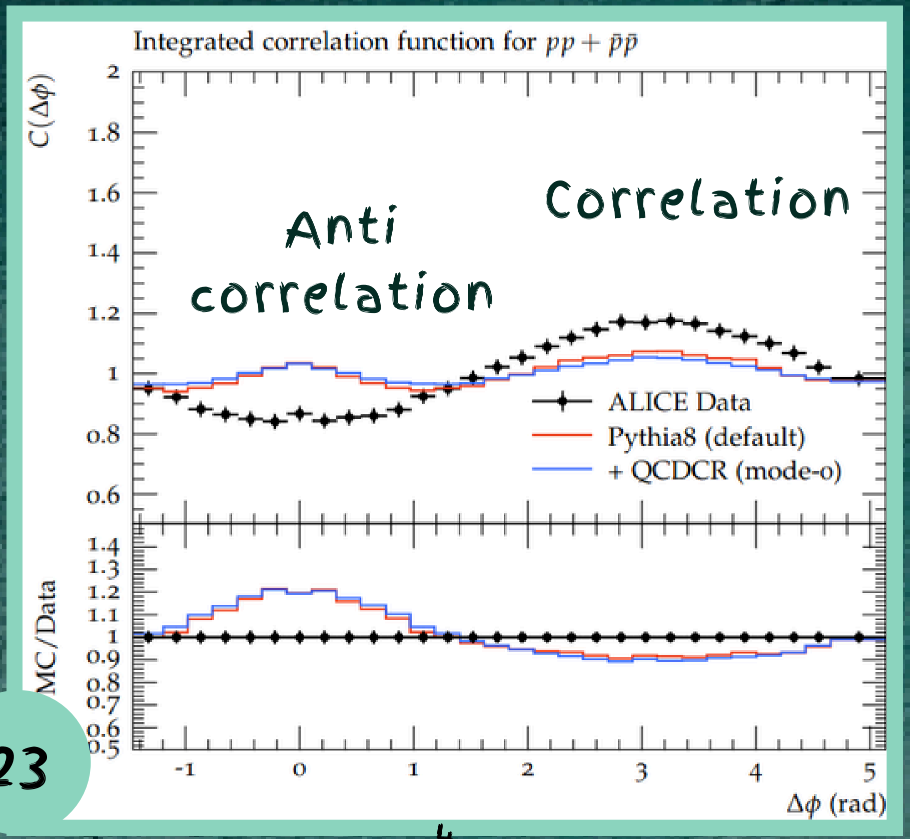


HERWIG progress: [Talk by S. Kiebacher at QCD@LHC 2023]

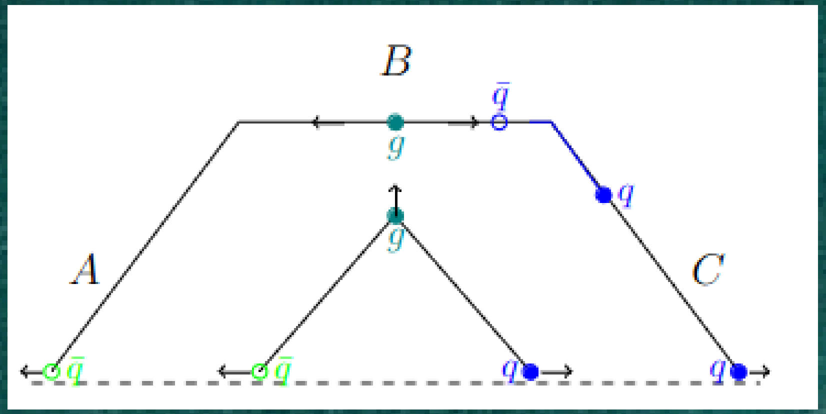
BARYON CORRELATIONS

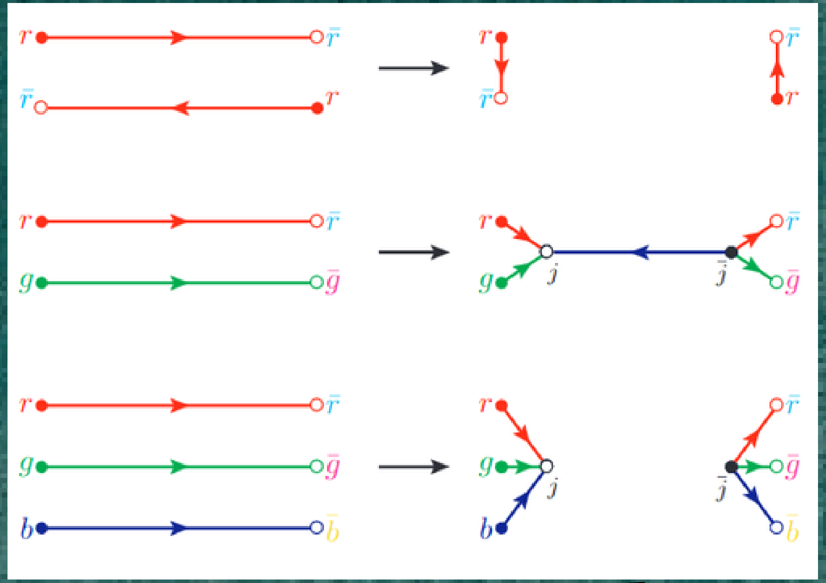
[L. Lönnblad & H. Shah 2023]





- Baryon correlations badly modeled in pp collisions (e+e- / meson correlation in pp 👍)
- Modes of baryon production in string models:
  - diquark model
  - **popcorn model**
- Gluon participation (gluon kink) important for angular correlation
- QCDCR model for color reconnection
  - additional baryon production mechanism, but less correlation
  - improvement for opposite-sign pairs





HERWIG progress:
[Talk by S. Kiebacher at QCD@LHC 2023]