Parton showers and matching (review?)

SM@LHC

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Swedish Research Council

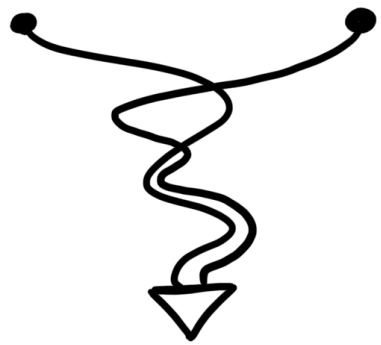
Core concepts

Fixed-order calculation

- well-defined power counting ≈ independent of kinematics
- quantum interference
- fails to describe free asymptotic (aka. Faddeev Kulish, coherent, Wilson line) states

Parton shower

- well-defined multiplicity counting, kinematics-dependent
- logarithmic order counting for *some* observables
- aims at modeling asymptotic states differentially



Matching: Consistent event-by-event combination of both

Why? Produce improved calculations, learn more about differential aspects of (IR) renormalization.

Core concepts

Questions for a matching/merging method

1) What is the "shower accuracy"? And is it preserved?
2) What is the fixed-order-dominated region? And is it retained?

Opinion: One should strive to answer 1) better than a simple "keep LL accuracy". Aim for a self-consistent showered calculation.

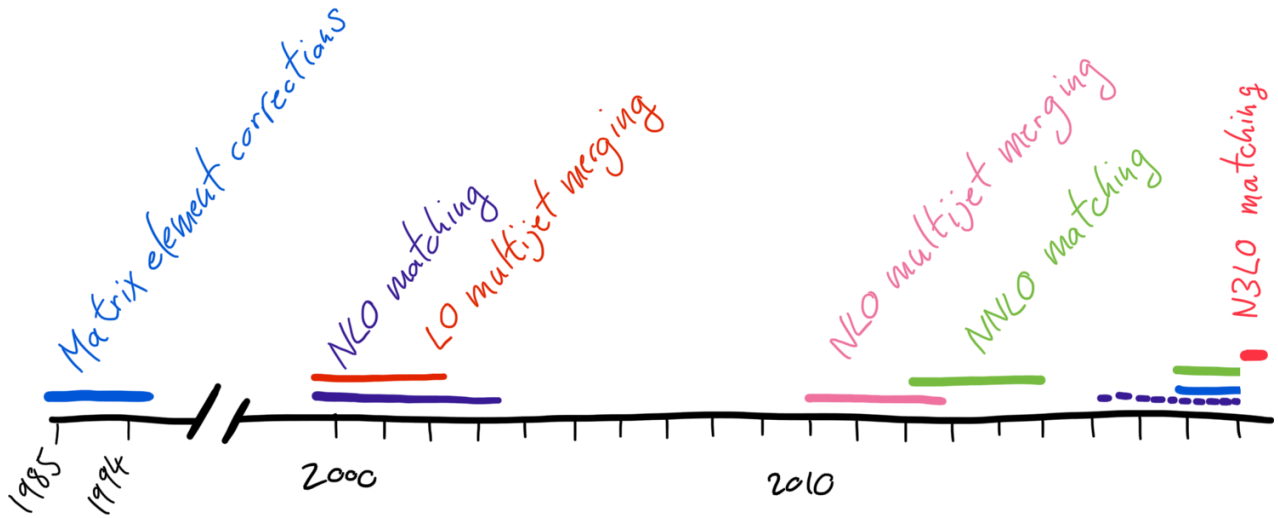
e.g. from `arXiv:2106.03206`: *"The all-order factors of the parton-shower should be reproduced exactly, such that no measurement could distinguish the parton-shower and the matched prediction if all fixed-order cross section were calculated using the same approximations employed to derive parton-shower splitting kernels."*

Core concepts

More opinions:

- We should be critical of using auxiliary jet algorithms
  – since the PS does not use such tricks
- We should be critical of employing approximated versions of showers
  – since PS would not be used that way
- We should use the PS to produce PS resummation
  – if the PS is not good enough, then work on PS.

State-of-the-art



The current status is well-described in the whitepaper `arXiv:2203.11110`:
Three main NNLO+PS avenues capable of handling LHC:

Direct-QCD resummation-based

methods as part of POWHEGBOX + PYTHIA (NNLOPS, MINNLOPS).

SCET resummation-based

methods using τ and $q_\perp$ resolution implemented in GENEVA + PYTHIA.

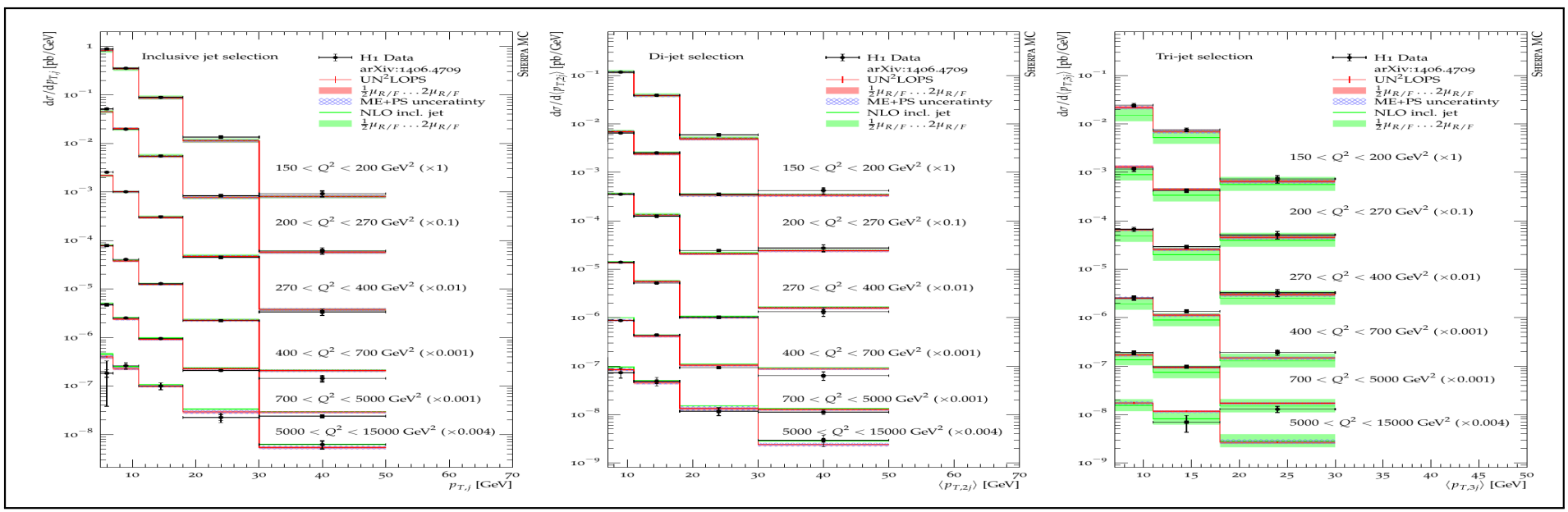
Shower-unitarity based

method using $q_\perp$ subtraction implemented in SHERPA (UN^{2}LOPS)

State-of-the-art: UN^{2}LOPS

Unitarized N^{2}LO+PS in SHERPA

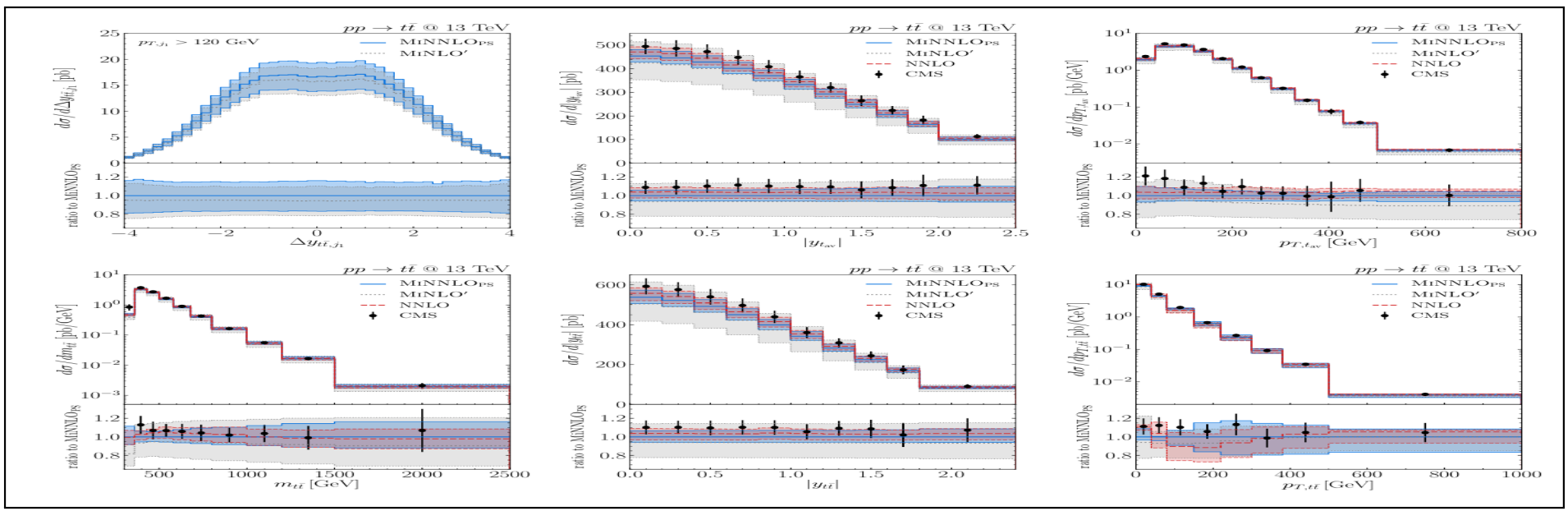
- Requires hand-crafted NNLO calculation
- Resummation purely supplied by shower
- 3 processes & not actively pursued (last paper `arXiv:1809.04192`)
- not obvious if unitarization introduces a "projection bias"



State-of-the-art: MINNLO$_{PS}$

dQCD resummation-based NNLO+PS in POWHEGBOX (+ PYTHIA)

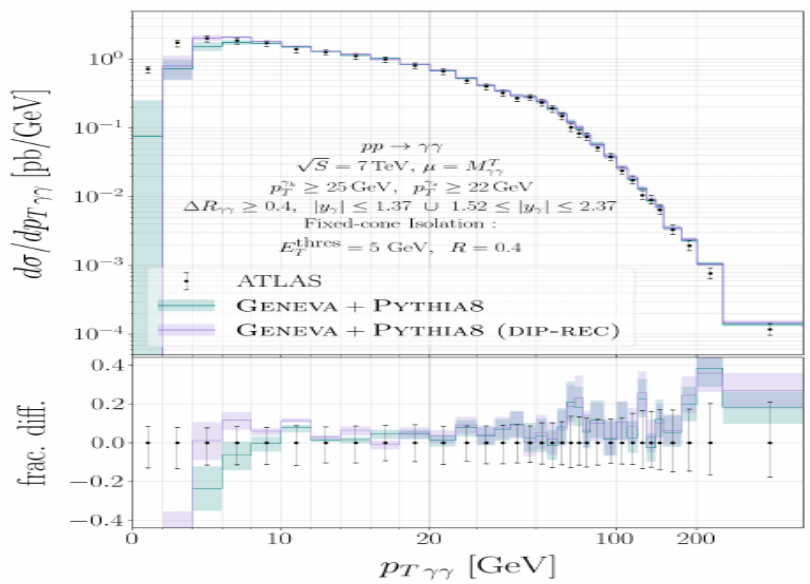
- Employs ingredients of NNLL $q_\perp$ resummation
- NNLOPS and MINNLO$_{PS}$. MINNLO$_{PS}$ employs hand-crafted NNLO
- see `arXiv:2203.07240` for excellent summary
- in principle requires "truncated showering" when using PYTHIA.

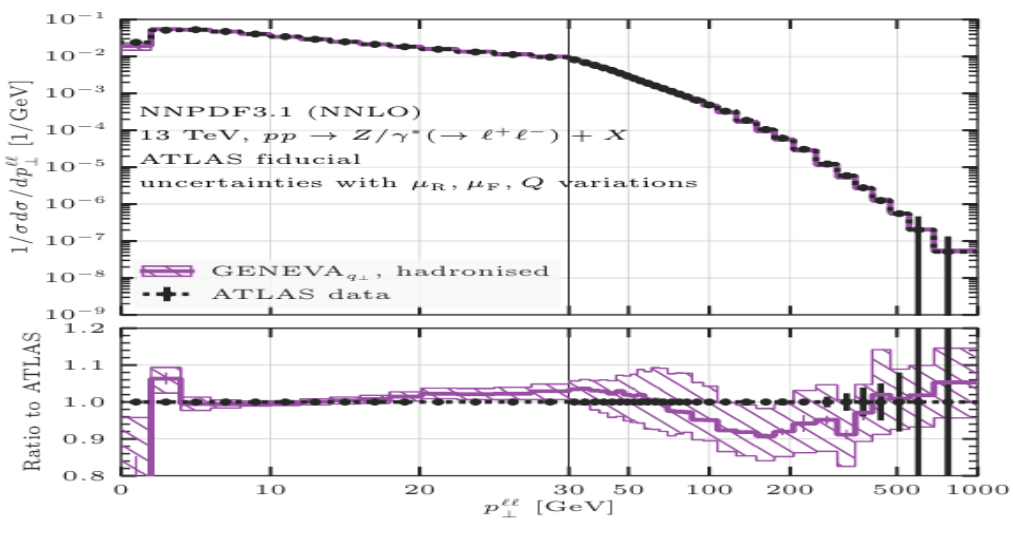


State-of-the-art: GENEVA

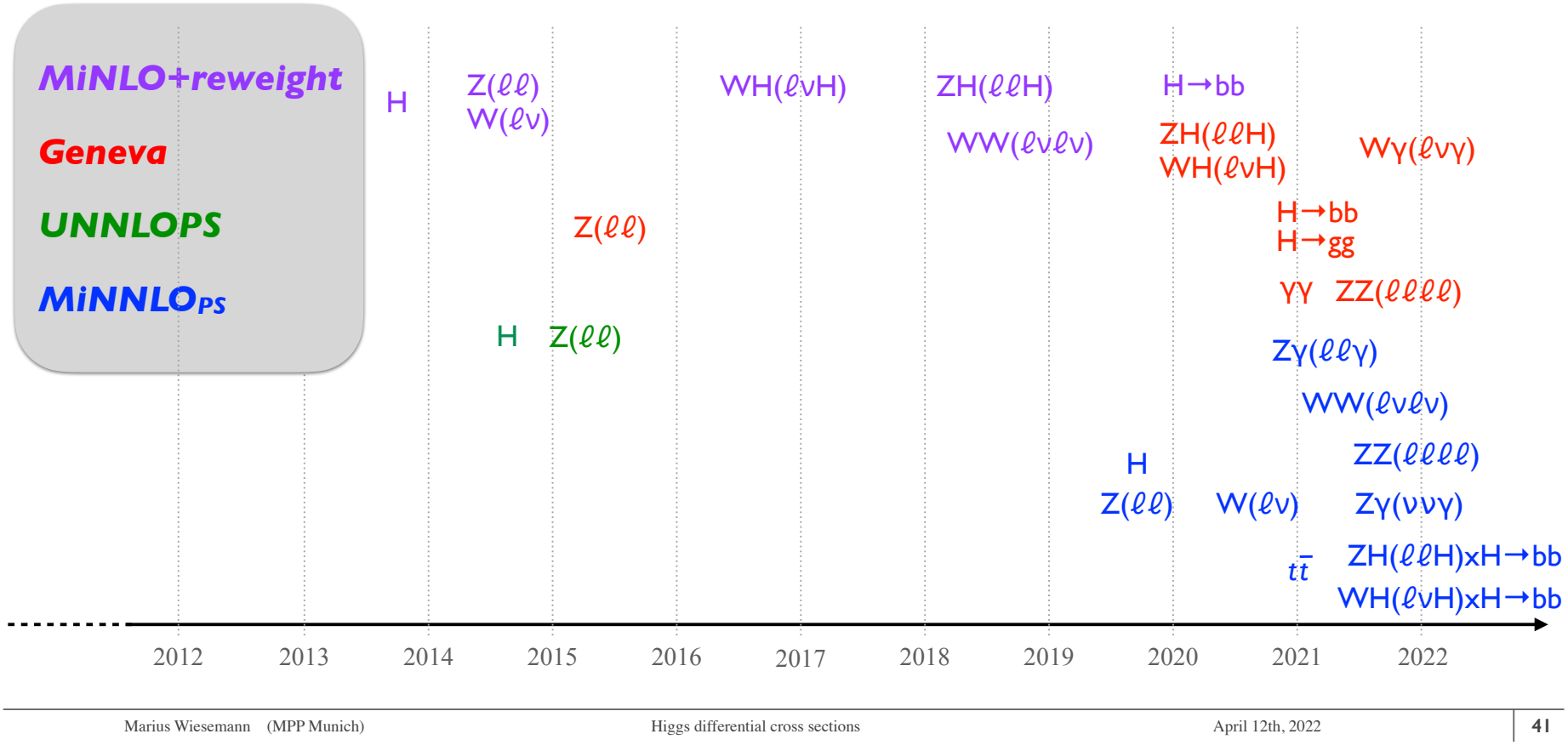
SCET resummation-based in GENEVA (+ PYTHIA)

- Employs ingredients of NNLL τ_0 or N^{3}LL dQCD $q_\perp$ resummation. Requires hand-crafted NNLO calculation
- Impact of multiparton interactions also studied.
- see `arXiv:2203.11110` for recent summary
- additional *global* shower vetoes required





NNLO+PS timeline

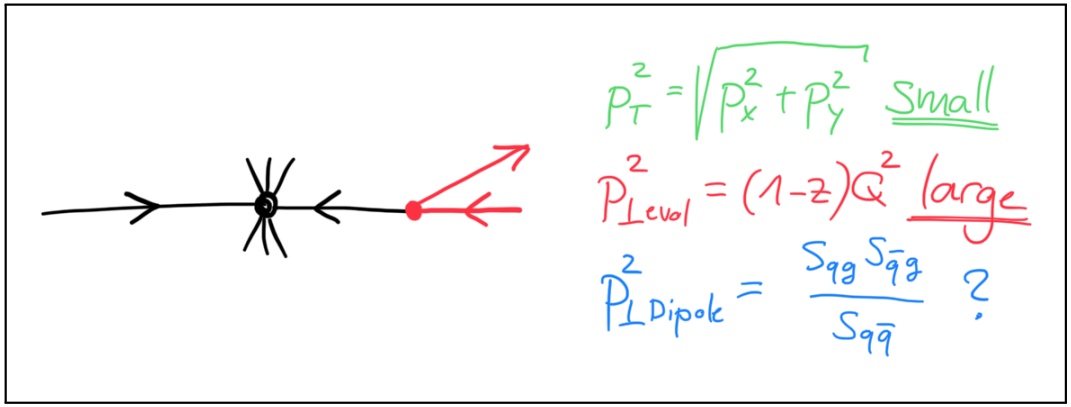


Taken from Marius Wiesemann's talk, SM@LHC 2022

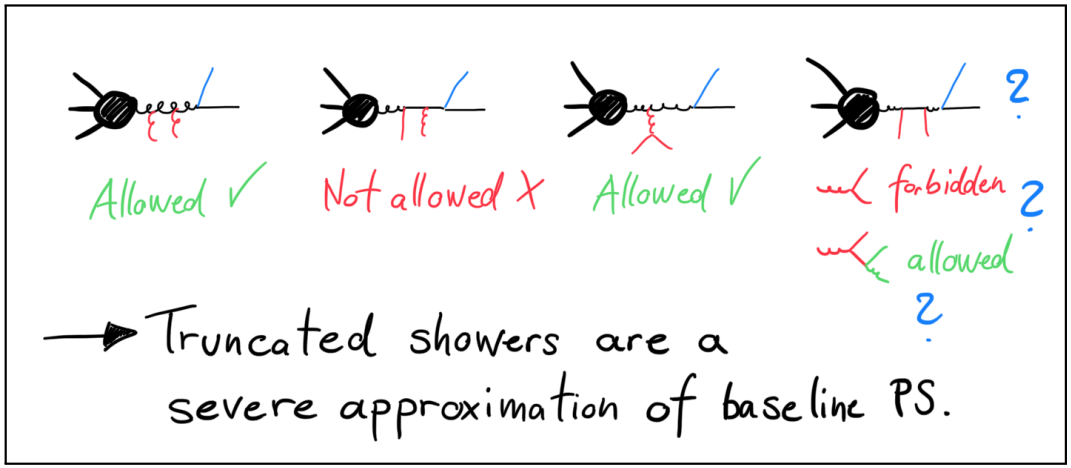
State-of-the-art: Opportunities

If PS sequence is divided between two codes with different ordering variables, then *"[..] it does not seem possible to implement the soft radiation of a collinear bunch of partons without truncated showers."* (`arXiv:hep-ph/0409146`)

No two "transverse momenta" are the same!

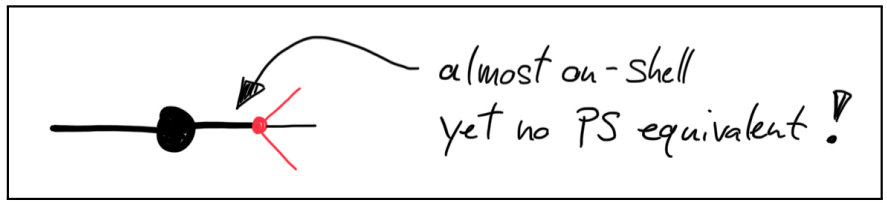


Truncated PS mandatory, but impossible in PYTHIA.
(cf. S. Höche, MCnet school 2017)

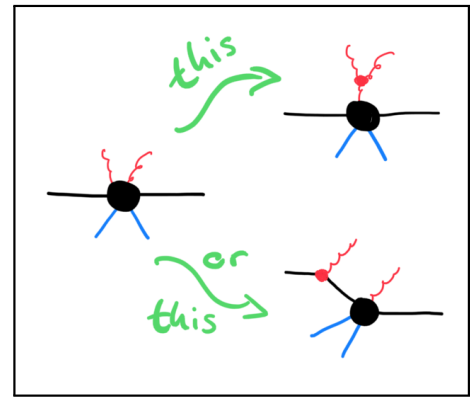


State-of-the-art: Opportunities

Missing higher orders in showers, i.e. no fully differential[†] matching; missing local PS counterterms



Non-unique association *radiative event* $\leftrightarrow$ *underlying Born* leads to projection/mapping bias[‡]



$\Rightarrow$ Still ample opportunities to improve.

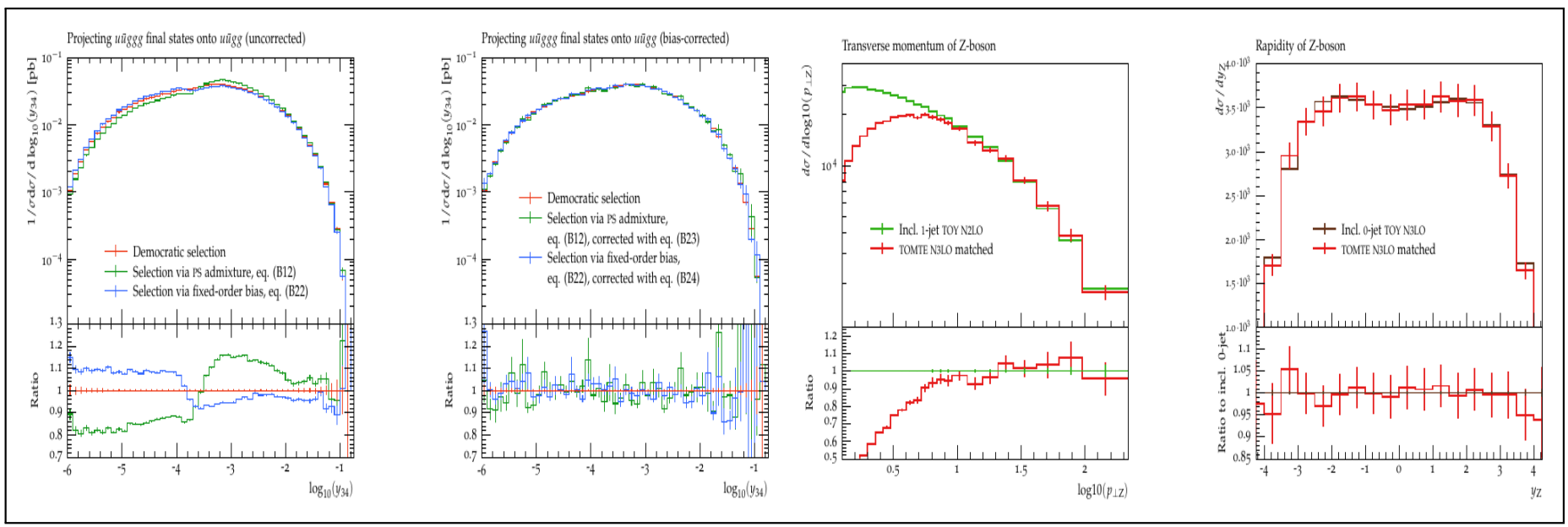
[†] no separation of multiplicities with parameters other than PS cut-off. All states required for calculation have a fully differential representation that can be corrected numerically by matching or improving PS.

[‡] cf. arXiv:0801.4026 and arXiv:2106.03206, or arXiv:1506.02660

Recent developments: N3LO+PS

…recently became possible (TOMTE, `arXiv:2106.03206`, `arXiv:2202.01082`)

- Projection bias (e.g. for V+j @ NNLO) addressed. Allows consistent combination of N3LO and showers.
- Proof-of-principle code using Pythia+Dire+Apfel available.
- Not fully differential, treatment of non-PS states subject to choices.



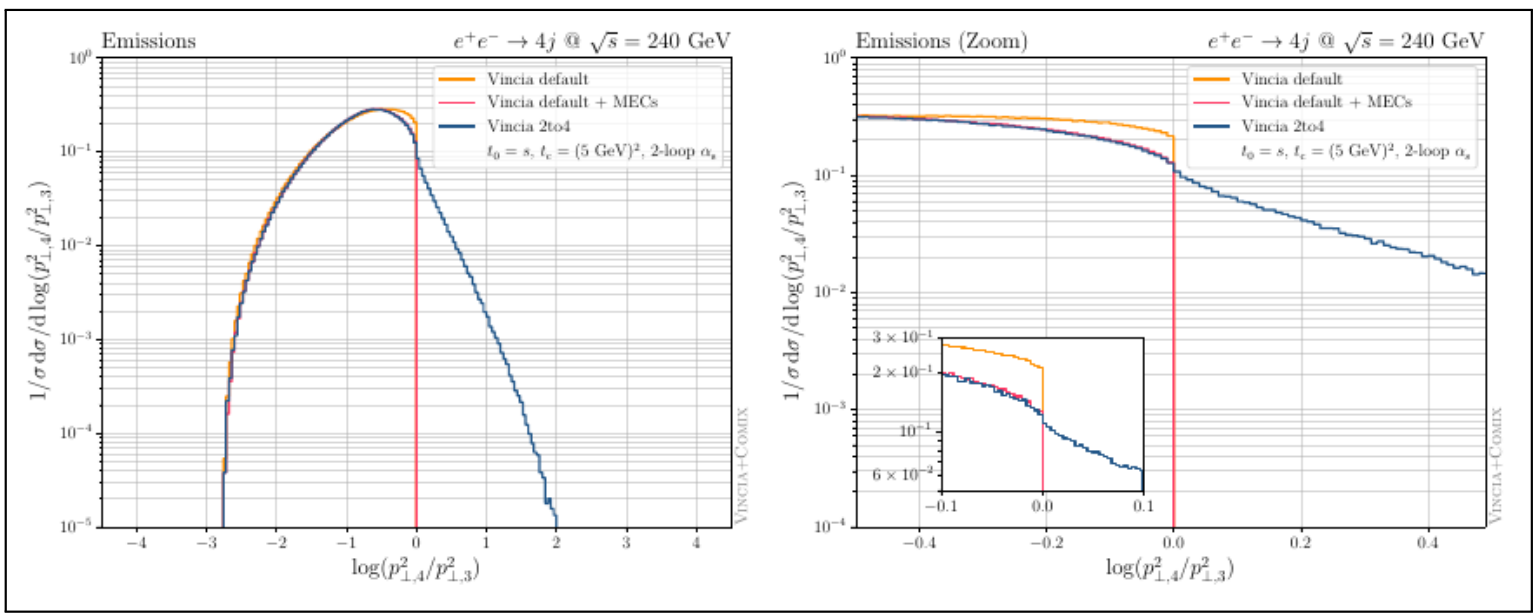
Recent developments: Fully differential NNLO+PS

An extension of the POWHEG philosophy to NNLO requires

1) Born-local NNLO K-factor
2) Hardest-emission spectrum of PS given by NLO result, i.e. with real-virtual and double-real corrections.

...sounds easy, but subtle in practice. arXiv:2108.07133:

- fully differential NNLO+PS by implementing 1st emission of NLO PS
- proof-of-concept worked out for $e^+e^- \to 2j$



Summary

- HL-LHC set to rely on precision calculations
- Matching fixed-order calculations with showers is a mature field.
- Tougher at higher orders; focus shifted to (PS) resummation parts.
- Efficient "production-grade" NNLO+PS codes emerging
- Old problems remain
  ...we should present conclusive evidence that this is acceptable

some honorable mentions should also go to:

- CKKW-L merging with sector showers arXiv:2008.09468
- Constructing matched-shower surrogates using autoencoders arXiv:1807.03685
- Matching high-energy and DGLAP evolution arXiv:1712.00178
- Jet matching with TMD evolution arXiv:2107.01224
- Work towards NLO showers for matching arXiv:1606.00355, arXiv:1705.00742, arXiv:1805.03757, arXiv:2110.05964, arXiv:2112.14454