Parton shower issues and ideas in VBS

Alexander Karlberg

LHC EW WG General Meeting

12th July 2024

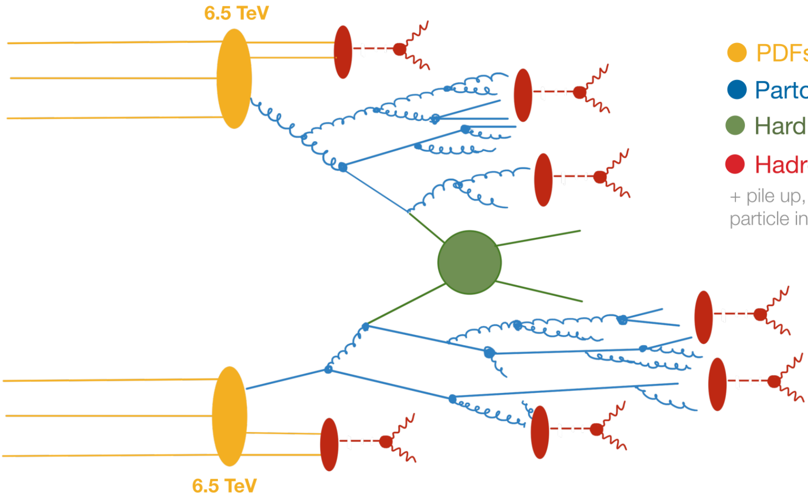
Parton shower issues...

...and ideas in VBS

Alexander Karlberg

LHC EW WG General Meeting

Anatomy of an LHC collision



- PDFs / beam remnants
- Parton shower $\mathcal{O}(1-100)$ **GeV**
- Hard scattering $\mathcal{O}(0.1-1)$ **TeV**
- Hadronisation $\mathcal{O}(1)$ **GeV**

+ pile up, underlying event, multiple-particle interactions (MPI)…

courtesy M. van Beekveld

The ubiquitous Parton Shower

Pythia 8

An introduction to PYTHIA 8.2 #1

Torbjörn Sjöstrand (Lund U., Dept. Theor. Phys.), Stefan Ask (Cambridge U.), Jesper R. Christiansen (Lund U., Dept. Theor. Phys.), Richard Corke (Lund U., Dept. Theor. Phys.), Nishita Desai (U. Heidelberg, ITP) et al. (Oct 11, 2014)

Published in: *Comput.Phys.Commun.* 191 (2015) 159-177 • e-Print: 1410.3012 [hep-ph]

pdf links DOI cite 4,050 citations

Herwig 7

Herwig++ Physics and Manual #1

M. Bahr (Karlsruhe U., ITP), S. Gieseke (Karlsruhe U., ITP), M.A. Gigg (Durham U., IPPP), D. Grellscheid (Durham U., IPPP), K. Hamilton (Louvain U.) et al. (Mar, 2008)

Published in: *Eur.Phys.J.C* 58 (2008) 639-707 • e-Print: 0803.0883 [hep-ph]

pdf links DOI cite 2,644 citations

Sherpa

Event generation with SHERPA 1.1 #1

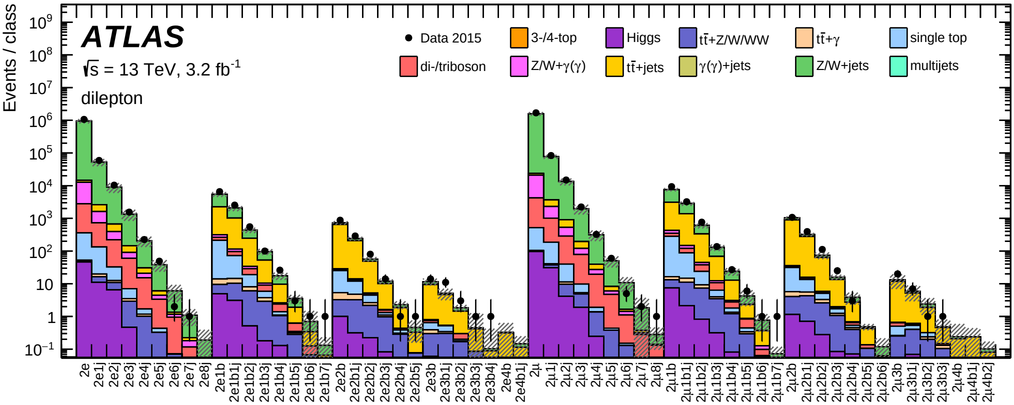
T. Gleisberg (SLAC), Stefan. Hoeche (Zurich U.), F. Krauss (Durham U., IPPP), M. Schonherr (Dresden, Tech. U.), S. Schumann (Edinburgh U.) et al. (Nov, 2008)

Published in: *JHEP* 02 (2009) 007 • e-Print: 0811.4622 [hep-ph]

pdf links DOI cite 3,386 citations

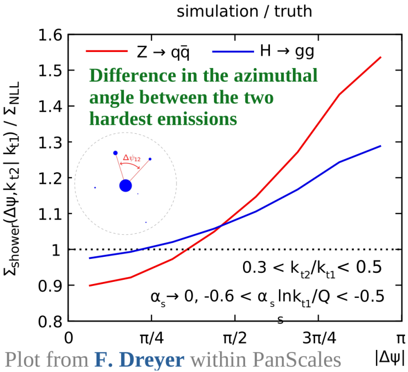
Parton Showers enter one way or another in almost 95% of all ATLAS and CMS analyses. Collider physics would not be the same without them.

The ubiquitous Parton Shower

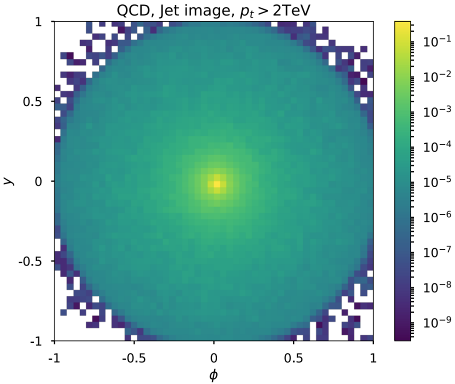


ATLAS [1807.07447]

Machine learning and jet sub-structure



Plot from **F. Dreyer** within PanScales



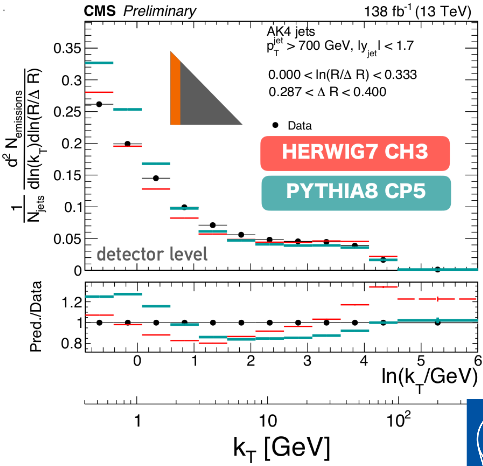
de Oliveira, Kagan, Mackey, Nachmann, Schwartzman [1511.05190]

Machine learning might learn un-physical "features" from MC → can significantly impact the potential of new physics searches.

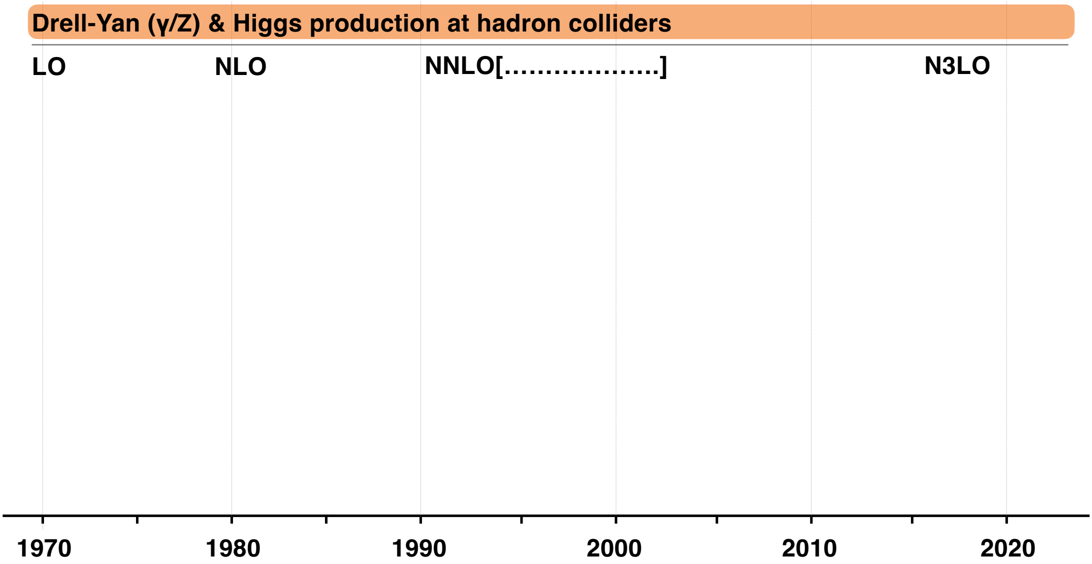
Lund Plane measurements

- Despite common showers doing an amazing job at the LHC, there are still places where big differences are seen
- In particular as we zoom into very differential phase space regions of jets, these differences can easily reach $10-30\%$
- The region shown here is particularly sensitive to soft emissions
- This is a region where some of the developments discussed later are relevant
- See also CMS [2312.16343]

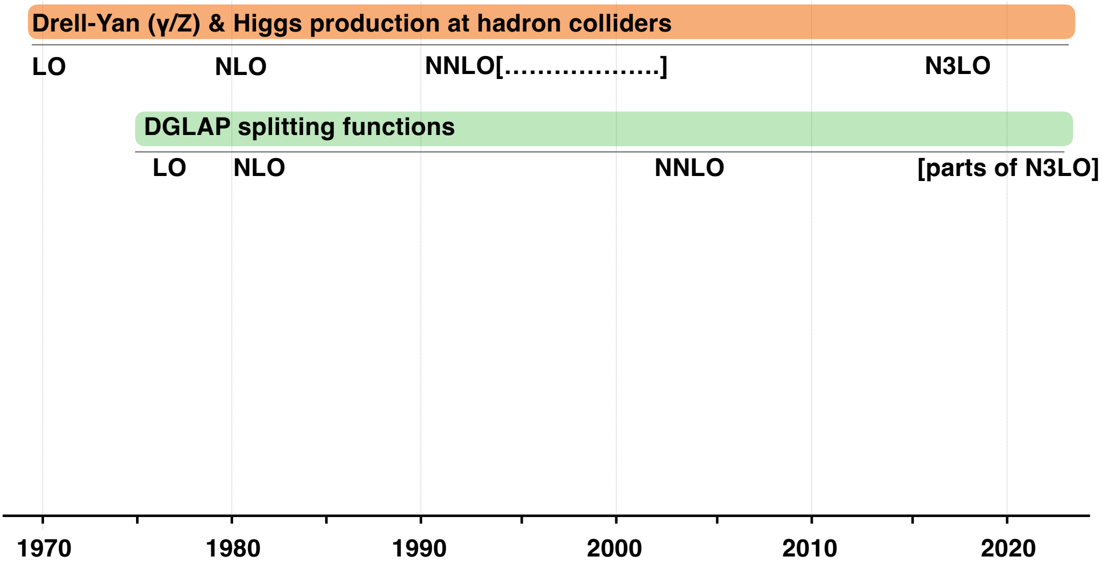
Lund Plane
(Recent CMS results; also ATLAS & ALICE)



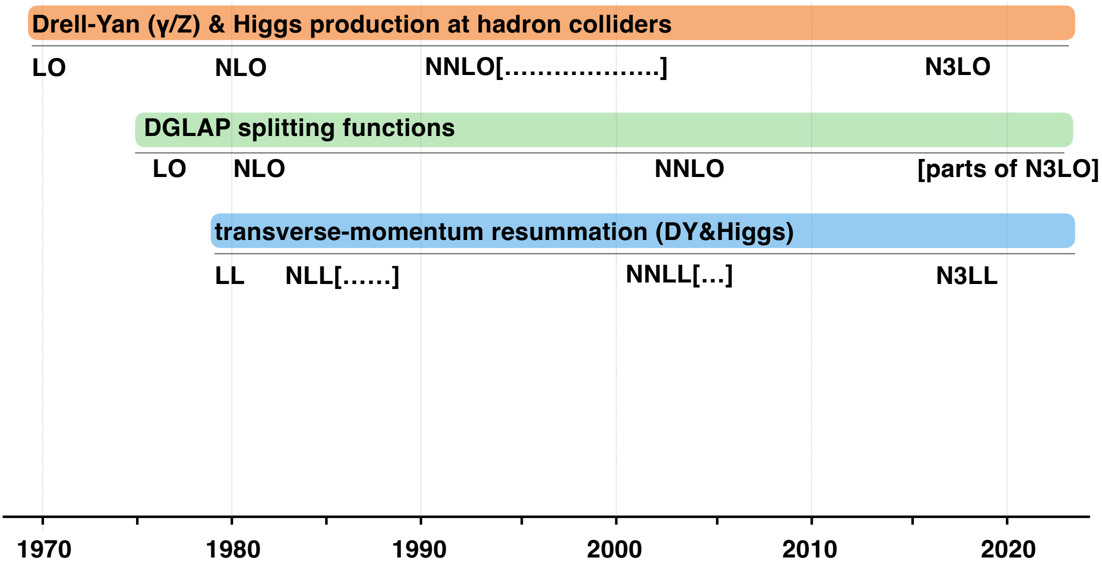
selected collider-QCD accuracy milestones



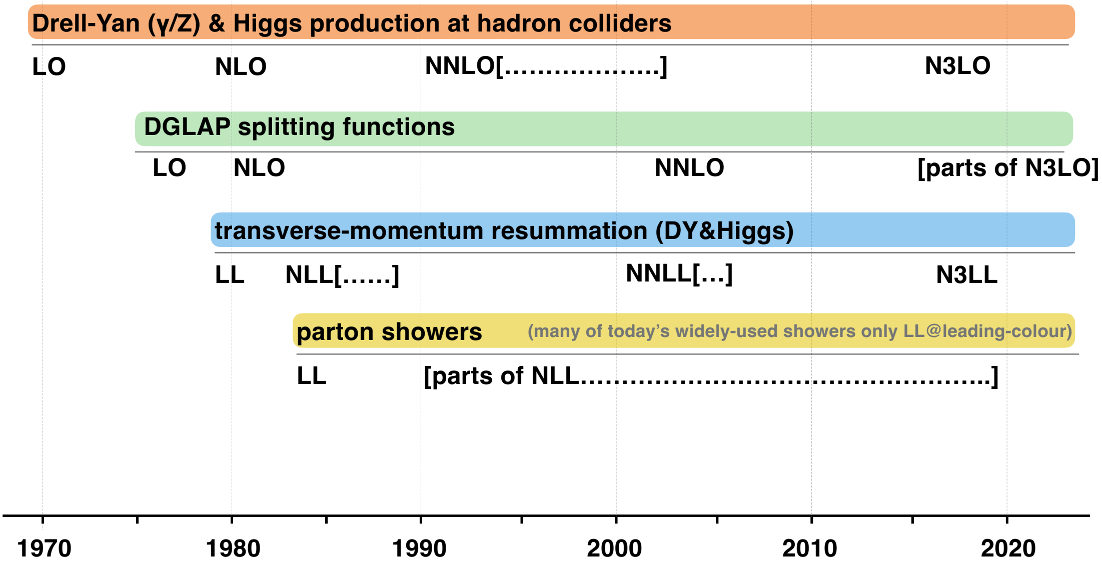
selected collider-QCD accuracy milestones



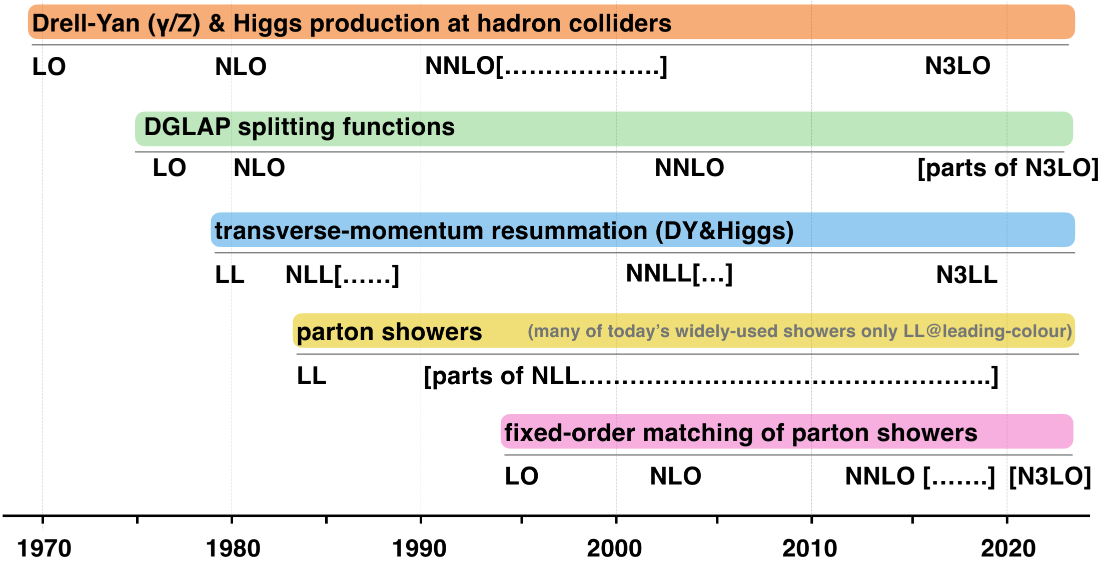
selected collider-QCD accuracy milestones



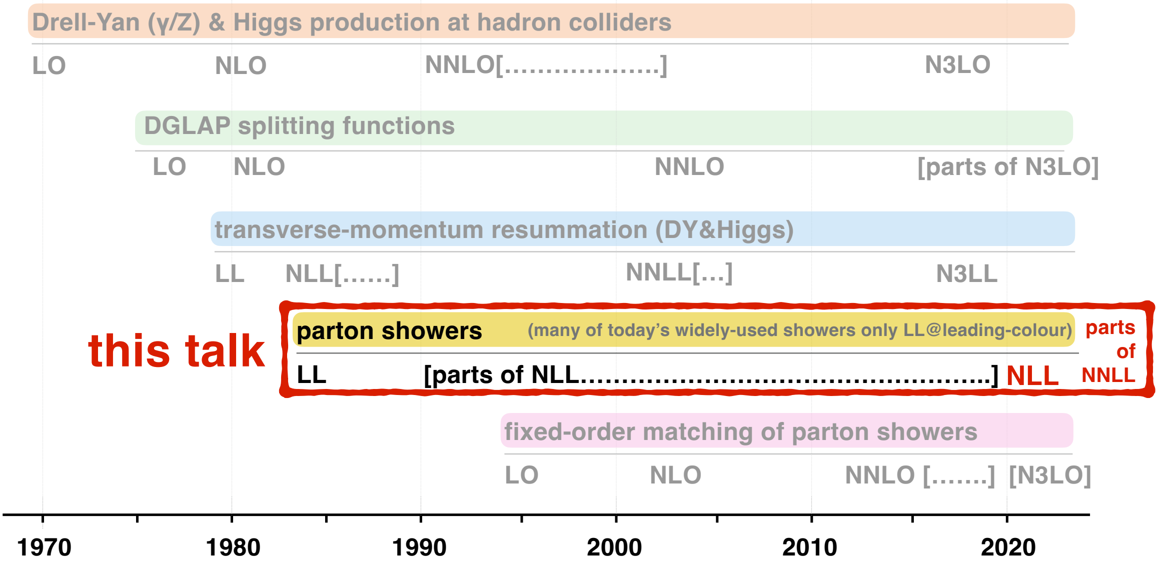
selected collider-QCD accuracy milestones



selected collider-QCD accuracy milestones



selected collider-QCD accuracy milestones



Why are we talking about logarithmic accuracy?

Parton showers evolve hard states $Q \sim \sqrt{\hat{s}}$ down to the hadronization scale $\Lambda \sim 1$ GeV

This evolution generates logarithms of the form $L \sim \ln \frac{Q}{\Lambda} \gg 1$, $(g_X(\alpha_s L) \sim \alpha_s L)$

$$\Sigma(\mathcal{O} < e^{-L}) = \exp\left[-L g_{LL}(\alpha_s L) + g_{NLL}(\alpha_s L) + \alpha_s g_{NNLL}(\alpha_s L) + \ldots\right]$$

	$Q = M_Z$	$Q = 1$ TeV	
$\lvert L g_{LL}\rvert \sim \alpha_s L^2$	2	4	
$\lvert g_{NLL}\rvert \sim \alpha_s L$	0.5	0.6	$\leftarrow \mathcal{O}(100\%)$
$\lvert \alpha_s g_{NNLL}\rvert \sim \alpha_s^2 L$	0.06	0.05	$\leftarrow \mathcal{O}(10\%)$

NNLL crucial for percent-level accuracy!

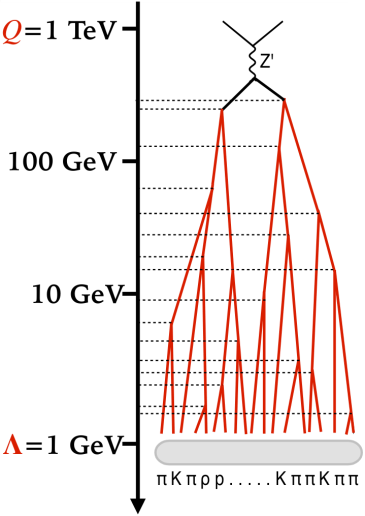


Figure by S. Ferrario Ravasio

Current status of parton showers

- Most widely-used event generators at the LHC, Pythia, Herwig, and Sherpa all limited to LL (some exceptions, cf. Bewick, Ferrario Ravasio, Richardson, Seymour [1904.11866])
- Significant progress in improving the hard matrix elements with NNLO matching and NLO multi-jet merging, but the logarithmic accuracy still limited to LL

→ concerted effort in taking parton showers from LL→NLL in the last couple of years

- Achieved by PanScales [1805.09327], [2002.11114], [2011.10054], [2103.16526], [2111.01161], [2205.02237], [2207.09467], [2305.08645], [2312.13275], ALARIC Herren, Höche, Krauss, Reichelt, Schoenherr [2208.06057], [2404.14360], APOLLO Preuss [2403.19452], DEDUCTOR Nagy, Soper [2011.04773], and Forshaw-Holguin-Plätzer [2003.06400]

Recent significant steps towards general NNLL (focus of this talk)

Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]

NLL showers in a nutshell

Matrix element condition:

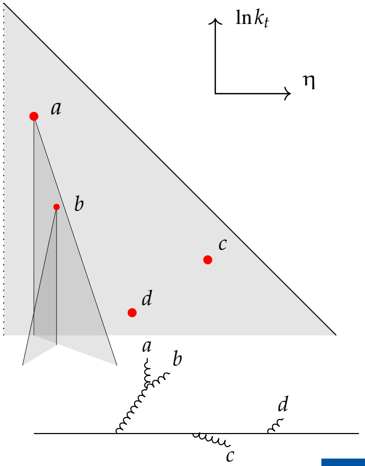
- correctly reproduce n-parton tree-level matrix element for arbitrary configurations, so long as all emissions well separated in the Lund diagram Dasgupta, Dreyer, Hamilton, Monni, Salam [1805.09327]
- Supplement with 2-loop running coupling in the CMW scheme

Resummation condition: reproduce standard NLL results

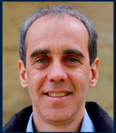
- global event shapes
- non-global observables
- fragmentation functions
- multiplicities
- …

⇒ shower design should respect absence of cross-talk between disparate angles and energies (QCD factorisation).

- This principle is violated by most standard dipole-showers, due to the way the recoil is distributed after an emission. First observed by Andersson, Gustafson, Sjogren '92
- For full NLL one also needs to include spin-correlations and sub-leading colour corrections



Oxford



Gavin Salam

Jack Helliwell

Silvia Zanoli

NIKHEF

Melissa van Beekveld

Manchester

Mrinal Dasgupta

UCL

Keith Hamilton

Monash

Basem El-Menoufi

Ludo Scyboz

IPhT

Gregory Soyez

CERN

AK

Silvia Ferrario Ravasio

Pier Monni

Alba Soto-Ontoso

PanScales current members

A project to bring logarithmic understanding and accuracy to parton showers

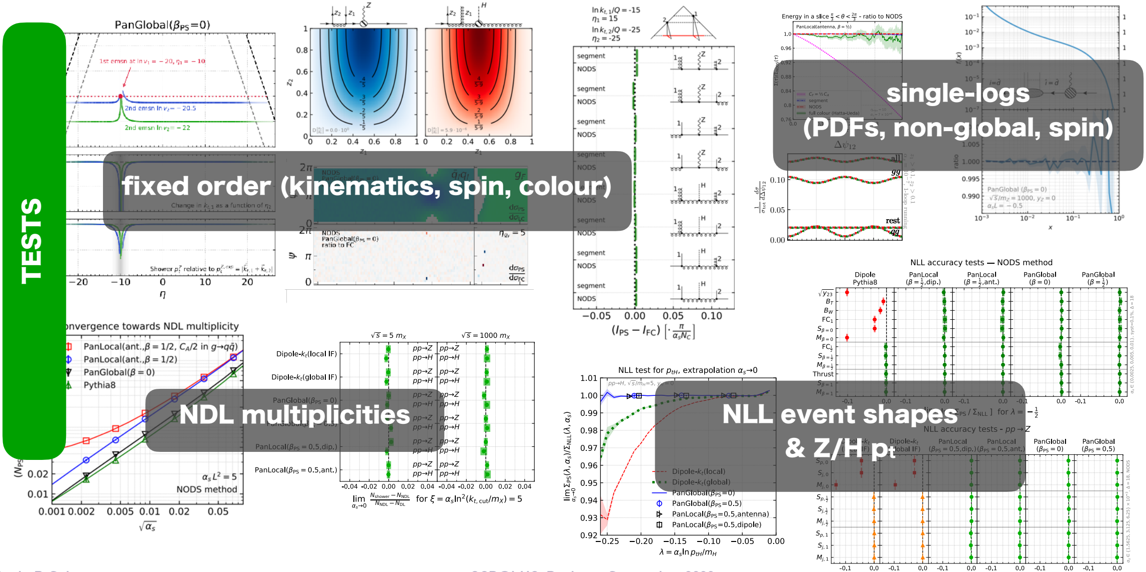
PanLocal	PanGlobal	Colour	Spin
$k_t\sqrt{\theta}$ ordered	k_t or $k_t\sqrt{\theta}$ ordered	nested ordered double soft (NODS)	for correct azimuthal structure in collinear and soft→collinear
Recoil ⊥: local +: local −: local	**Recoil** ⊥: global +: local −: local	Designed to ensure LL are full colour (also gets many NLL at full colour)	[Collins-Knowles extended to soft sector]
Dipole partition event CoM	**Dipole partition** event CoM		

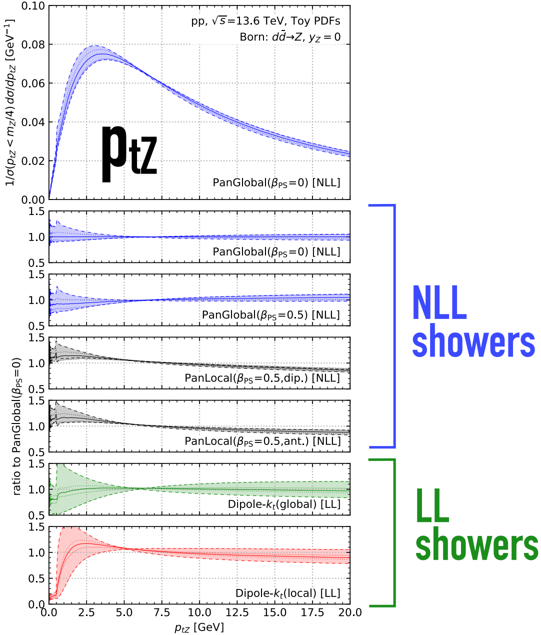
e^+e^-: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]; *pp* (w/spin+colour): van Beekveld, Ferrario Ravasio, Salam, Soto-Ontoso, Soyez, Verheyen [2205.02237]; + *pp* tests: eid. + Hamilton [2207.09467]; DIS+VBF: van Beekveld, Ferrario Ravasio [2305.08645]

Hamilton, Medves, Salam, Scyboz, Soyez [2011.10054]

AK, Salam, Scyboz, Verheyen [2103.16526], eid. + Hamilton [2111.01161]

a selection of the logarithmic accuracy tests



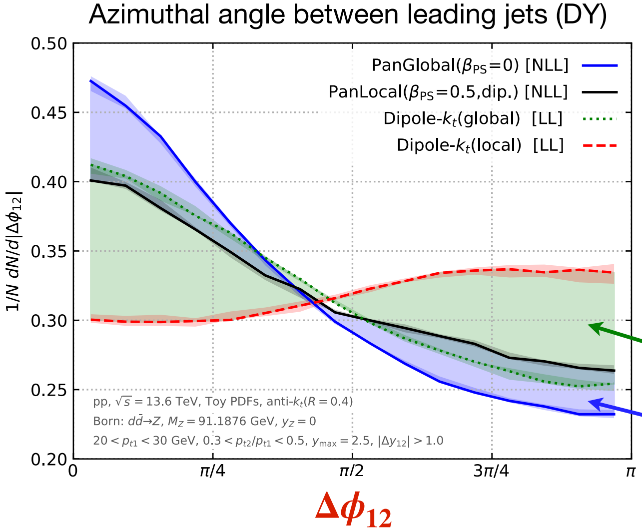


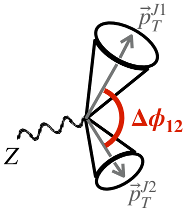
for inclusive quantities like p_{tZ}, advantage of NLL shower is partly in reduction of uncertainties

van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467

COMMISSIONING

$m_{\ell\ell} = m_Z$





for more exclusive quantities, also see clear shape differences in going to NLL

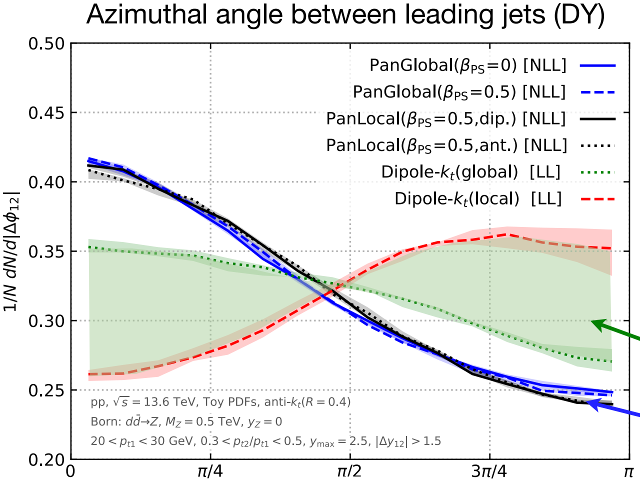
LL showers

NLL showers

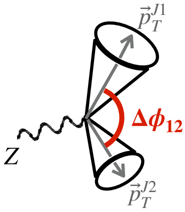
van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467

$m_{\ell\ell} = 500\,\mathrm{GeV}$

COMMISSIONING



$\Delta\phi_{12}$



for more exclusive quantities, also see clear shape differences in going to NLL

especially at larger scales

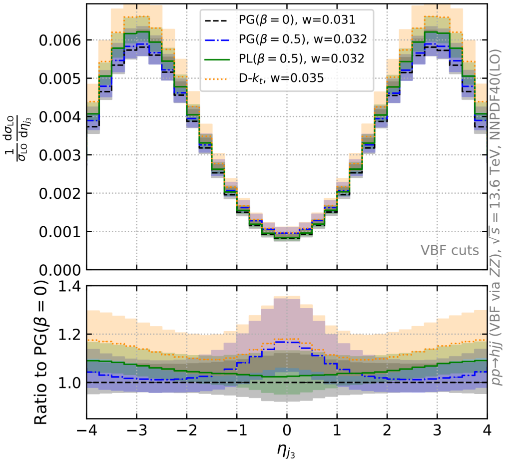
LL showers

NLL showers

van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467

van Beekveld, Ferrario Ravasio [2305.08645]

What about VBF/VBS?



- PanScales showers in principle ready for VBS, but not implemented
- In particular, no matching for these processes implemented yet (but we are working towards VBF)
- Our implementation conserves the vector boson momentum in DIS like scattering → may facilitate projection-to-Born type matching for VBF
- Here shown the third jet pseudo-rapidity, η_{j_3}, with correct central-jet behaviour and moderate uncertainty band reduction going from LL (yellow) → NLL (black, green, blue).

Analytic structure beyond NLL

Taking an event shape, $\mathcal{O}$, to be less than some value $e^{-|L|}$ we have at NNLL (focusing for now on e^+e^- only)

$$\Sigma(\mathcal{O} < e^{-|L|}) = (1 + \alpha_s C_1 + \ldots) \exp\left[\frac{1}{\alpha_s} g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right] \quad (1)$$

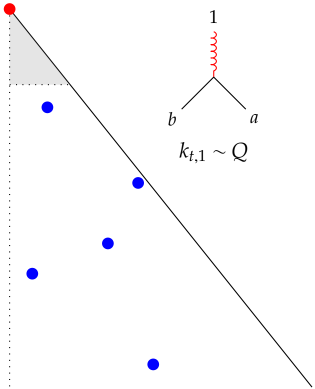
where g_1 accounts for LL terms, g_2 for NLL terms, and g_3 and C_1 for NNLL terms[1].
NB: Shower generates spurious higher order terms $\rightarrow$ need to correct for this

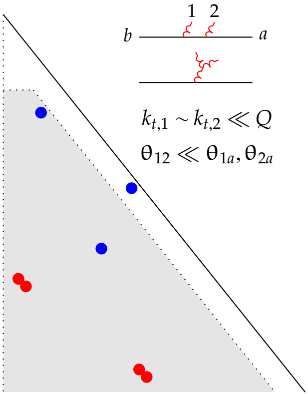
$$\Sigma(\mathcal{O} < e^{-|L|}) = (1 + \alpha_s \tilde{C}_1 + \ldots) \exp\left[\frac{1}{\alpha_s} g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s \tilde{g}_3(\alpha_s L) + \ldots\right] \quad (2)$$

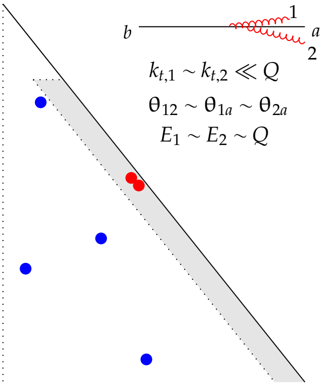
Two developments needed beyond NLL: 1) what are the necessary analytic ingredients from resummation and 2) how do we compensate the NNLL terms already present in the shower?

[1] In the language of q_T resummation A_1 is responsible for LL terms, A_2 and B_1 for NLL terms and A_3 and B_2 for NNLL terms (together with the hard coefficient function $C_1(z)$).

Lund plane picture







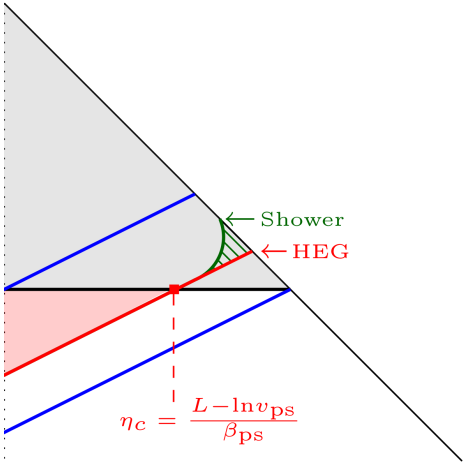
hard matching $\rightarrow$
α_S correct for first emission

double-soft $\rightarrow$
get any pair of soft commen- -surate energy/angle right

triple-collinear $\rightarrow$
account for genuine $2 \rightarrow 4$ collinear splittings

Hamilton, AK, Salam, Scyboz, Verheyen [2301.09645]

Match without breaking NLL



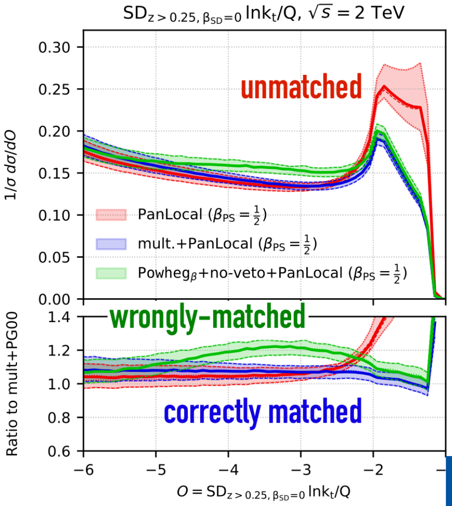
- Exploration of two-body decays $\gamma \to q\bar{q}$ and $h \to gg$ @ NLO
- For additive-style matching (such as MC@NLO, KrkNLO, and MAcNLOPS) log accuracy easy to maintain.
- For POWHEG style matchings (including MiNNLO and GENEVA) log accuracy is more subtle to maintain.
- Main concern related to kinematic mismatch between shower and hardest emission generator (in general they are only guaranteed to agree in the soft-collinear region). This issue has been studied in the past Corke, Sjöstrand [1003.2384] but logarithmic understanding is new.
- NB: Also issue with mismatch in partioning function

Hamilton, AK, Salam, Scyboz, Verheyen [2301.09645]

Phenomenological impact

- Contour mismatch by area $\alpha\Delta$ leads to breaking of NLL and exponentiation
- Correct matching on the other hand augments the shower from NLL to NLL+NNDL for event shapes.
- Impact of NLL breaking terms vary - for SoftDrop they have a big impact due to the single-logarithmic nature of the observable. In particular the breaking manifests as terms with super-leading logs

$$\partial_L \Sigma_{\mathrm{SD}}(L) = \bar{\alpha} c\, e^{\bar{\alpha} c L - \bar{\alpha}\Delta} - 2\bar{\alpha} L e^{-\bar{\alpha} L^2}\left(1 - e^{-\bar{\alpha}\Delta}\right)$$



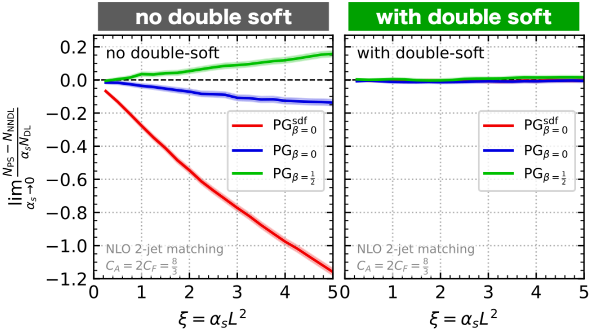
Ferrario Ravasio, Hamilton, AK, Salam, Scyboz, Soyez [2307.11142]

Include double-soft real emissions

- NLO matching is a necessary ingredient for going beyond NLL, but to some extent NLO matching is a solved problem
- Until recently the inclusion of double-soft emissions in an NLL shower was still an open question
- To get them right we must ensure that any pair of soft emissions with commensurate energy and angles should be produced with the correct ME
- Any additional soft radiation off that pair must also come with the correct ME
- In addition must get the single-soft emission rate right at NLO (CMW-scheme)
- This should achieve NNDL accuracy for multiplicities, i.e. terms $\alpha_s^n L^{2n}$, $\alpha_s^n L^{2n-1}$ and $\alpha_s^n L^{2n-2}$
- and next-to-single-log (NSL) accuracy for non-global logarithms, for instance the energy in a rapidity slice, $\alpha_s^n L^n$ and $\alpha_s^n L^{n-1}$ (albeit only at leading-N_C for now)

Ferrario Ravasio, Hamilton, AK, Salam, Scyboz, Soyez [2307.11142]

Lund Multiplicities at NNDL ($\alpha_s^n L^{2n-2}$)

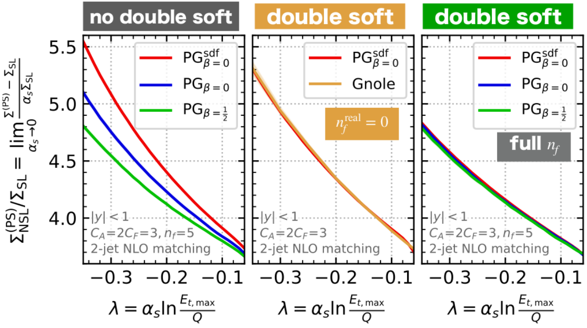


$$\lim_{\alpha_S \to 0} \frac{N_{(PS)} - N_{NNDL}}{\alpha_S N_{DL}} \Bigg|_{\text{fixed } \alpha_S L^2}$$

- Reference NNDL analytic result from Medves, Soto-Ontoso, Soyez [2205.02861]
- We take $\alpha_S \to 0$ limit to isolate NNDL terms. This is significantly more challenging than at NDL due to presence of $1/\alpha_S$ in denominator.
- Showers without double-soft corrections show clear differences from reference (and each other).
- Adding the double-soft corrections brings NNDL agreement.

Ferrario Ravasio, Hamilton, AK, Salam, Scyboz, Soyez [2307.11142]

Energy in a slice at NSL ($\alpha_s^n L^{n-1}$)

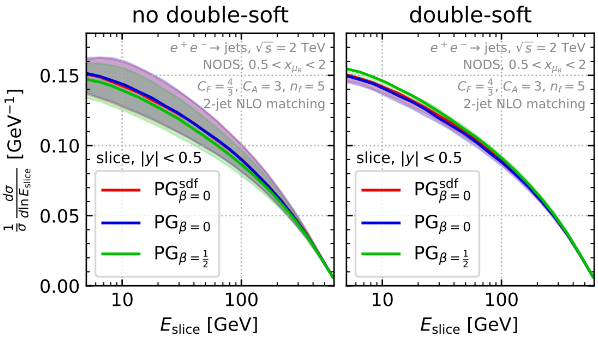


$$\lim_{\alpha_S \to 0} \frac{\Sigma^{(PS)} - \Sigma_{SL}}{\alpha_S}\Bigg|_{\text{fixed } \alpha_S L}$$

- Reference NSL from Gnole Banfi, Dreyer, Monni [2111.02413] (see also Becher, Schalch, Xu [2307.02283]).
- We did this test semi-blind: only compared to Gnole after we had agreement between the three PanGlobal variants.
- We have NSL agreement with Gnole (using $n_f^{\text{real}} = 0$) and agreement between all showers with full-n_f dependence (first calculation of this kind as a by-product!)

Ferrario Ravasio, Hamilton, AK, Salam, Scyboz, Soyez [2307.11142]

What about pheno?



- We studied energy flow between two hard (1 TeV) jets as a preliminary pheno case
- The three PanGlobal variants are remarkably close without double-soft corrections, but have large uncertainties
- With double-soft corrections we see a small shift in central values but a significant reduction in uncertainties.

Compute triple-collinear ingredients

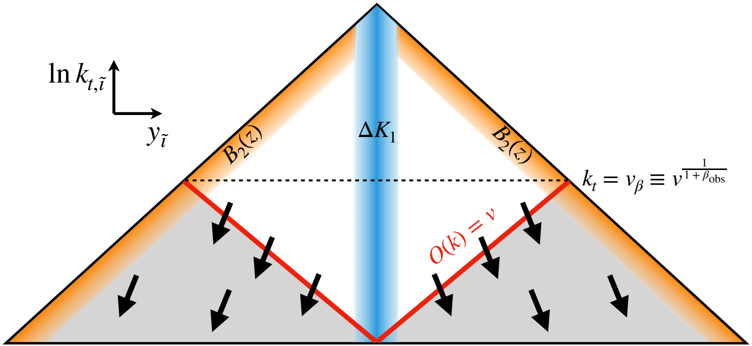
- Double-soft corrections are not by themselves enough to reach NNLL accuracy for event shapes. We also need triple-collinear ingredients (cf. Dasgupta, El-Menoufi [2109.07496], eid. + van Beekveld, Helliwell, Monni [2307.15734], eid. + AK [2402.05170] for work in this direction)
- However, it turns out that with the inclusion of real double-soft emissions, only the Sudakov form factor needs to be modified to reach NNLL for event shapes, i.e. we do not need the fullly differential triple-collinear structure
- Taking

$$\alpha_{\text{eff}} = \alpha_s \left[1 + \frac{\alpha_s}{2\pi}\left(K_1 + \Delta K_1(y) + B_2(z)\right) + \frac{\alpha_s^2}{4\pi^2} K_2\right]$$

there are two pieces missing - B_2 which is of triple-collinear origin [2109.07496], [2307.15734] and K_2 (A_3) which is known Banfi, El-Menoufi, Monni [1807.11487], Catani, De Florian, Grazzini [1904.10365]

- NB: NLL showers generate spurious $\tilde{B}_2$ and $\tilde{K}_2$ $\to$ must be compensated

An intuitive picture



Imagine an emission, $\tilde{1}$, sitting anywhere right at the observable boundary (red line). The key observation is that whenever the shower splits $\tilde{1} \to 12$, the kinematic variables $(y_{12}, k_{t,12}, z_{12})$ of the resulting pair, do not agree with that of the parent $(y_{\tilde{1}}, k_{t,\tilde{1}}, z_{\tilde{1}})$. Since the Sudakov was computed assuming conserved kinematics of $\tilde{1}$, and the observable is computed with the actual kinematics of (12), we have generated a mismatch. We can compute these drifts!

Relation between shower and resummation ingredients

It is fairly straightforward to see that at NNLL we only depend on ΔK_1 and B_2 through their respective integrals

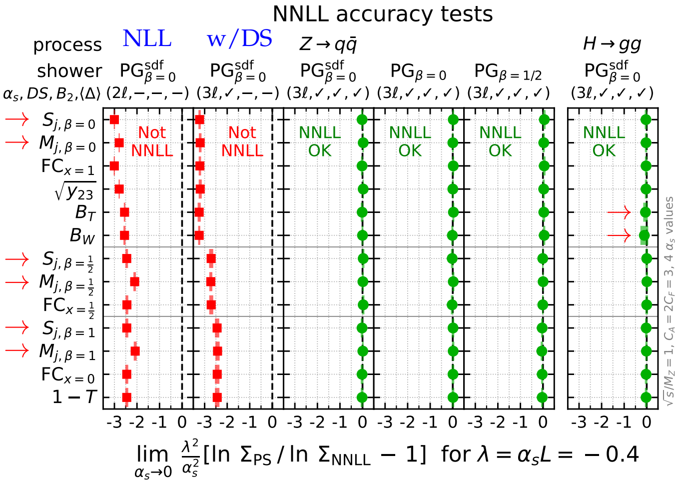
$$\Delta K_1^{\text{int}} \equiv \int_{-\infty}^{\infty} dy\, \Delta K_1(y)\,,\; B_2^{\text{int}} \equiv \int_0^1 dz \frac{P_{gq}(z)}{2C_F} B_2(z).$$

These (and K_2) can be related to the drifts in y ($\langle \Delta_y \rangle$), $\ln z$ ($\langle \Delta_{\ln z} \rangle$), and $\ln k_t$ ($\langle \Delta_{\ln k_t} \rangle$) and analytical resummation through

$$\Delta K_1^{\text{int,PS}} = 2\langle \Delta_y \rangle, \quad B_2^{\text{int,PS}} = B_2^{\text{int,NLO}} - \langle \Delta_{\ln z} \rangle, \quad K_2^{\text{PS}} = K_2^{\text{resum}} - 4\beta_0 \langle \Delta_{\ln k_t} \rangle.$$

Using these relations and taking $B_2^{\text{int,NLO}}$ from [2109.07496], [2307.15734] and K_2^{resum} from [1807.11487] one can prove that our showers are NNLL accurate for event-shape observables.

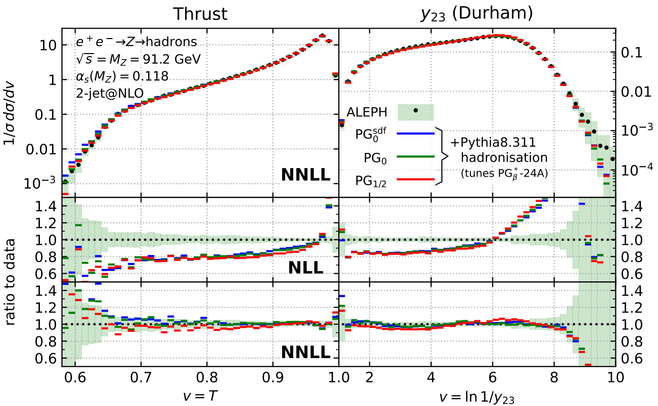
Are we there yet?



- →: New analytic results, not available in literature van Beekveld, Buonocore, El-Menoufi, Ferrario Ravasio, Monni, Soto-Ontoso, Soyez [in preparation]
- With no NNLL improvements, the coefficient of NNLL difference is significant, $\mathcal{O}(2-3)$, indicating importance of getting NNLL right
- With the inclusion of double-soft, observables with the same β_{obs} align but do still not agree with the analytics
- After inclusion of shifts and B_2 and K_2 we have perfect agreement

PanScales [2406.02661]

Not far now...



Long-standing tension between LEP data and Pythia8 unless using an anomalously large value of $\alpha_S(M_Z) = 0.137$ Skands, Carrazza, Rojo [1404.5630] (also present for PanScales showers)

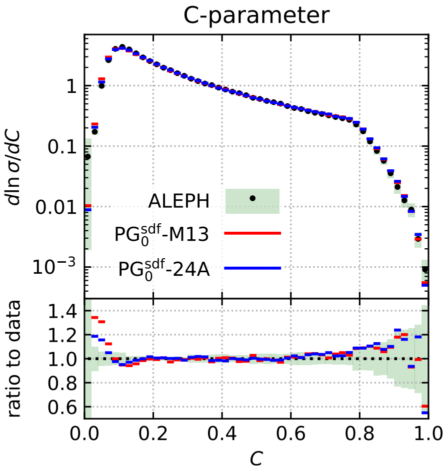
Inclusion of NNLL brings large corrections with respect to NLL

Agreement with data achieved without anomalously large value of α_S

Beware: no 3j@NLO which is known to be relevant in the hard regions

Residual uncertainties still need to be worked out

What about tuning?



Improved agreement with data across a large range of event shapes

Tuning here still rough

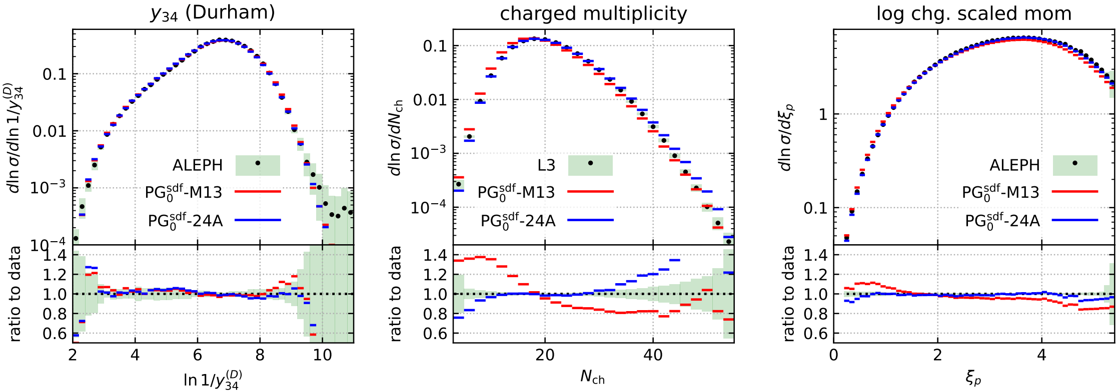
→ We start from the Monash tune (see ref. above) but fix $\alpha_S(M_Z) = 0.118$ (M13)

For our NLL showers this is the tune we use

For the NNLL showers we tune a number of parameters in the string model semi-automatically (24A)

Full tuning exercise still to be done!

What about tuning?



Impact of tune very minor on infrared safe observables, even those that are only NLL accurate

Impact on unsafe observables much larger, bringing good agreement with ALEPH data.

Parton Shower outlook

- As the experiments at the LHC record more and more data, it will become increasingly more important to improve on the accuracy of event generators
- NLL accurate showers have now been established by several groups
- Reduced and reliable uncertainties one of the main advantages of having controlled logarithmic accuracy

→ Major steps towards general NNLL accuracy recently taken!

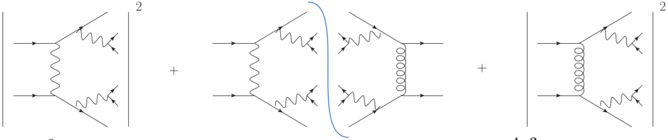
- With these corrections we have reached NNDL accuracy for multiplicity and NSL accuracy for non-global observables and NNLL for event shapes
- Not fully studied, but uncertainties certainly reduced compared to NLL
- The associated NNLL code has been made public in a the 0.2 release of the PanScales code
- Work ongoing for hadron-collisions. Will bring improved logarithmic accuracy to observables like colour-singlet p_T and (central) jet veto

And now for something completely different...

VBSCAN [1803.07943]

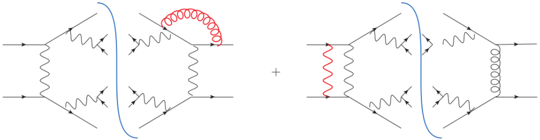
Defining the VBS process

LO: α^6, $\alpha^5\alpha_s$ and $\alpha^4\alpha_s^2$



α^6 : signal $\alpha^5\alpha_s$: interference $\alpha^4\alpha_s^2$: QCD background

NLO QCD: $\alpha^6\alpha_s$ (not the end of the story, `arXiv:1708.00268`)

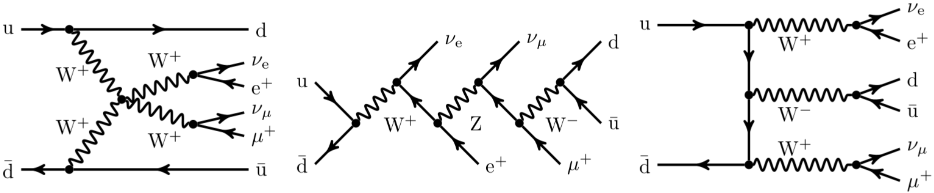


$\alpha^6\alpha_s$: QCD correction of the signal α^6 $\alpha^6\alpha_s$: EW correction of the interference $\alpha^5\alpha_s$

Figure: M. Zaro

VBSCAN [1803.07943]

Defining the VBS process



At LO the VBS approximation consists of keeping

all t/u-channel diagrams at $\mathcal{O}(\alpha^6)$

and discarding all

s-channel diagrams

$\mathcal{O}(\alpha^5\alpha_s)$ and $\mathcal{O}(\alpha^4\alpha_s^2)$

interference between t/u/s-channel

At NLO there are many various degrees of approximations available. Usually calculations using t/u-channel only and including only QCD corrections to the signal are said to be in the VBS approximation. [See also talk by A. Denner]

VBSCAN [1803.07943]

Defining the VBS process

CODE	$\mathcal{O}(\alpha^6)$ s,t,u	$\mathcal{O}(\alpha^6)$ interf.	Non-res.	NLO	NF QCD	EW corr. to $\mathcal{O}(\alpha_s\alpha^5)$
BONSAY	t/u	No	Yes, virt. No	Yes	No	No
POWHEG	t/u	No	Yes	Yes	No	No
MG5_AMC	Yes	Yes	Yes	Yes	No virt.	No
MOCANLO+RECOLA	Yes	Yes	Yes	Yes	Yes	Yes
PHANTOM	Yes	Yes	Yes	No	-	-
VBFNLO	Yes	No	Yes	Yes	No	No
WHIZARD	Yes	Yes	Yes	No	-	-

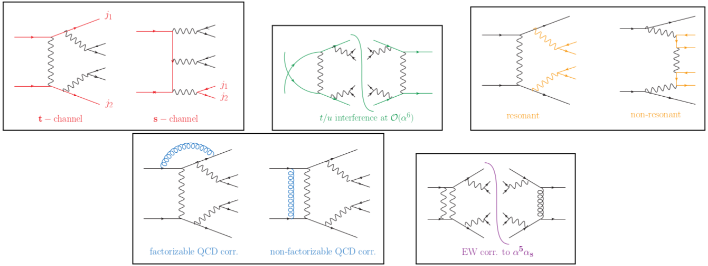
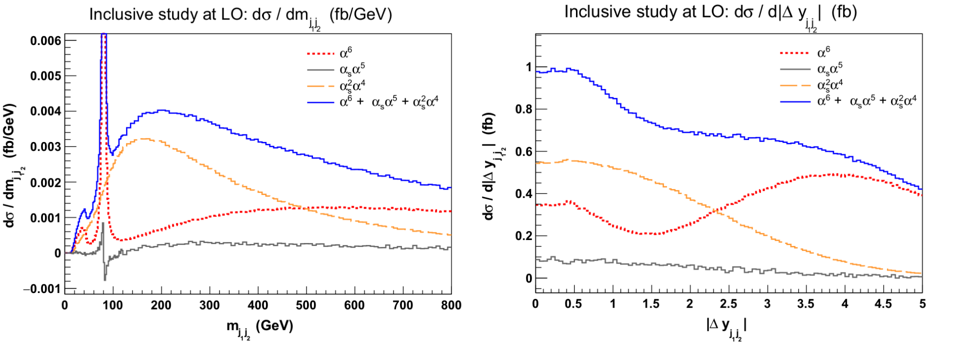


Figure: M. Zaro

VBSCAN [1803.07943]

LO contributions



Plots for ssWW, but results generalise to other VBS processes

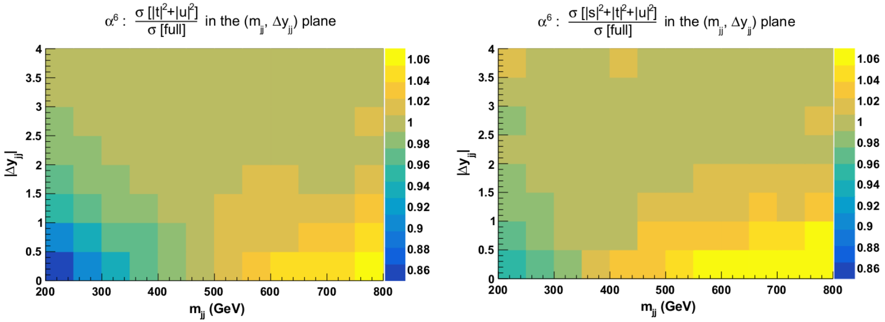
EW signal tends to dominate at large Δy_{jj} and m_{jj}

EW/QCD interference in general very small

At LO it looks as if the EW and QCD modes can be separated at the %-level

VBSCAN [1803.07943]

VBS approximation



Large discrepancies between full and VBS approximated calculations

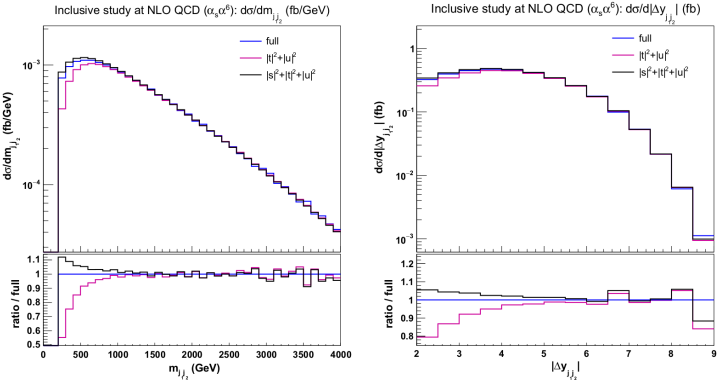
This discrepancy disappears when applying suitable cuts in Δy_{jj} and m_{jj}

Adding the s-channel after cuts make little to no difference

At LO this leads to the erroneous conclusion that under tight VBS cuts the signal is defined at the %-level by the VBS approximation alone

VBSCAN [1803.07943]

NLO contributions



With NLO corrections → VBS approximation breaks down at the $\mathcal{O}(10\%)$-level even with moderate cuts

Separation between EW signal and QCD background breaks down at the same level

Jäger, AK, Reinhardt [2403.12192]

Semi-leptonic decays

- Recent work in the POWHEG-BOX on semi-leptonic (and fully hadronic) decays in $WZjj$ (also available for W^+W^-jj Jäger, Zanderighi [1301.1695] and $ZZjj$ eaed. + AK [1312.3252])
- Studied impact of retaining full spin correlations and off-shell effects compared to decaying with e.g. MadSpin, as was done in some analysis, cf. ATLAS [1905.07714] and CMS [1905.07445]
- Also studied impact of NLO-QCD and parton shower in semi-leptonic and fully hadronic decay modes
- Implemented dim-6 EFT operators (not discussed here)
- See also recent very comprehensive fixed-order study of semi-leptonic decays in Denner, Lombardi, Schwan [2406.12301]

Jäger, AK, Reinhardt [2403.12192]

Off-shell effects

We study pp collisions at $\sqrt{s} = 13$ TeV with typical VBS cuts

$$p_{T,j}^{\text{tag}} > 30 \text{ GeV}, \qquad |y_j^{\text{tag}}| < 4.5, \qquad m_{jj}^{\text{tag}} > 500 \text{ GeV}$$

and further more require the tag jets to be in opposite hemispheres with a large rapidity separation

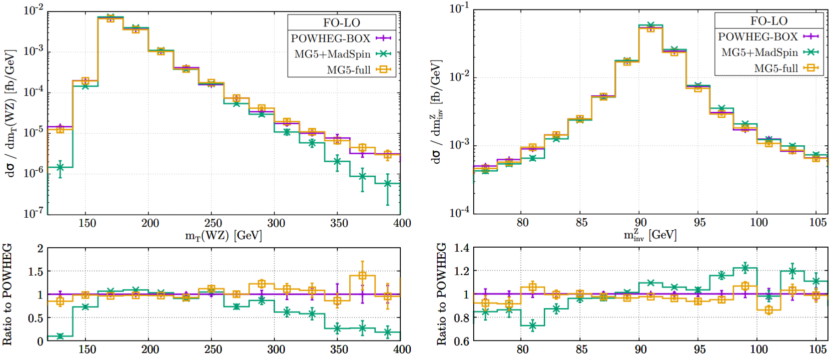
$$y_{j_1}^{\text{tag}} \cdot y_{j_2}^{\text{tag}} < 0, \qquad |y_{j_1}^{\text{tag}} - y_{j_2}^{\text{tag}}| > 5$$

We compare our `POWHEG` (VBS approximation) implementation against predictions obtained with `MadGraph5_aMC@NLO` in two modes, for the leptonic decay mode $\nu_e e^+ \mu^- \mu^+ jj$ at LO:

1. Full off-shell computation (`MG5-full`)
2. On-shell calculation with bosons decayed by `MadSpin` (`MG5+MadSpin`)

Jäger, AK, Reinhardt [2403.12192]

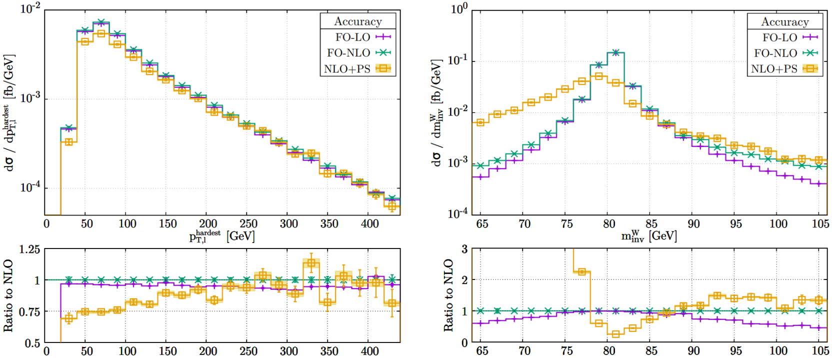
Off-shell effects in $\nu_e e^+ \mu^- \mu^+ jj$



- Clear impact of full off-shell calculation away from on-shell peak compared to on-shell calculation
- Very good agreement between VBS approximation and full calculation

Jäger, AK, Reinhardt [2403.12192]

Parton shower effects in $W(jj)Z(\mu^-\mu^+)jj$



Huge impact of Parton Shower due to smearing of m_W^{dec}. Here we require two jets close to m_W satisfying

$$p_{T,j_1}^{\mathrm{dec}} > 40\ \mathrm{GeV}, \qquad p_{T,j_2}^{\mathrm{dec}} > 30\ \mathrm{GeV}$$

VBSCAN [1803.07943]

Best practices

- NLO+PS predictions available for all processes (in VBS approximation) in most generators. Use them.
- Combine with NLO-EW whenever possible through k-factors or dedicated generators (cf. Chiesa, Denner, Lang, Pellen [1906.01863])
- VBS approximation typically good enough, unless cuts become too inclusive.
- Not possible to separate VBS signal from QCD-induced background beyond LO. Better to measure both rather than trying to subtract the background.
- Until Parton Showers with robust uncertainties become available (i.e. NNLL accurate showers) best practice is to compare two or more generators
- Impact of soft QCD and non-perturbative effects not discussed here, but also of importance (cf. Bittrich et al. [2110.01623])