Combining higher-order resummation, multiple NLO calculations and parton showers in GENEVA.

GENEVA

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LBNL & UC Berkeley

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Moriond QCD and High Energy Interactions

arXiv:1211.7049 SA, C. Bauer, C. Berggren, A. Hornig, F. Tackmann, C. Vermilion, J. Walsh, S. Zuberi

BERKELEY LAB Lawrence Berkeley National Laboratory
Emmy Noether-Programm Deutsche Forschungsgemeinschaft DFG

What is GENEVA ?

GENEVA is a framework to combine

- Fully Exclusive NLO Calculations NLO_N, NLO_{N+1}, $\ldots$
- Higher-order Resummation $\text{LL}_{\mathcal{O}}$, $\text{NLL}_{\mathcal{O}}$, $\text{NLL'}_{\mathcal{O}}$, $\text{NNLL}_{\mathcal{O}}$ $\ldots$
- Parton Showering and Hadronization   Pythia8, Herwig++, $\ldots$

GENEVA goal is to

Give a coherent description at the **Next-to-Lowest perturbative accuracy** in both fixed-order perturbation theory and logarithmic resummation and combine it with parton shower and hadronization.

What is the Next-to-Lowest perturbative accuracy ?

- Consider jet-resolution parameter $\mathcal{T}$, e.g. p_{T}^{N+1} for $N+1$ jets.

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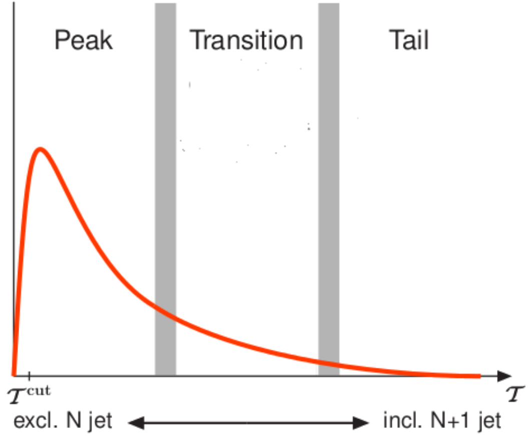

- To which accuracy we want to predict its spectrum?

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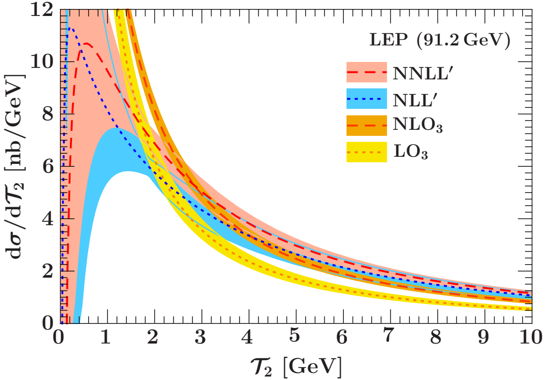

- *"Peak"* $\mathcal{T} \ll Q$ resummation region : expansion in $\alpha_{\mathrm{S}} L^2 \sim 1$, with $L = \log(\frac{\mathcal{T}}{Q})$ and Q hard scale such that $\alpha_{\mathrm{S}}(\alpha_{\mathrm{S}}^n L^{2n}) \approx \alpha_{\mathrm{S}}$
- Fixed-order diverges and its scales variation underestimates uncertainties.

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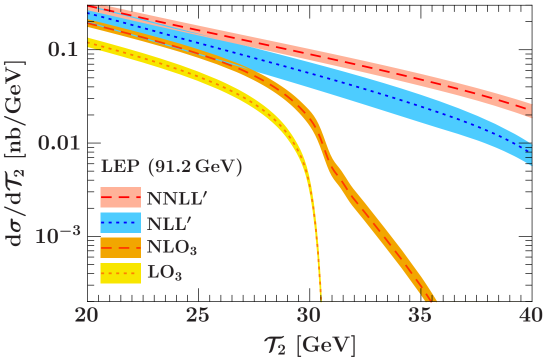

- *"Tail"* $\mathcal{T} \sim Q$ fixed-order region : fixed-order expansion in α_S is valid.
- Resummation gives wrong predictions.
- Higher fixed-order scales variation reliably estimates uncertainties.

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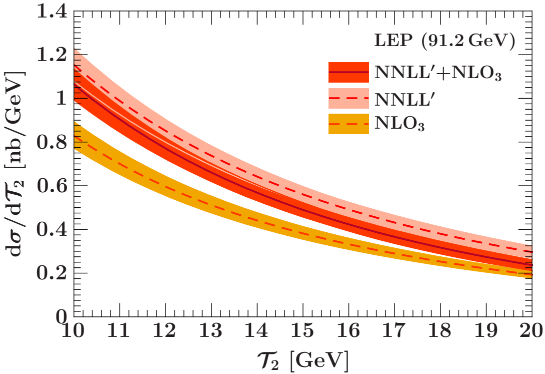

- Transition region requires accurate interplay of *“peak”* and *“tail”* descriptions
  - Interesting physics often in this region, e.g. $\boldsymbol{p}_\mathbf{T}$-jet $\sim$ 25 GeV in $gg \to H$
  - Theoretically challenging. Matched result gives best estimate of theory unc.

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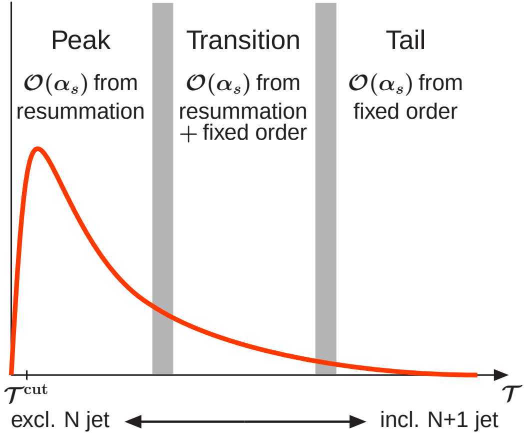

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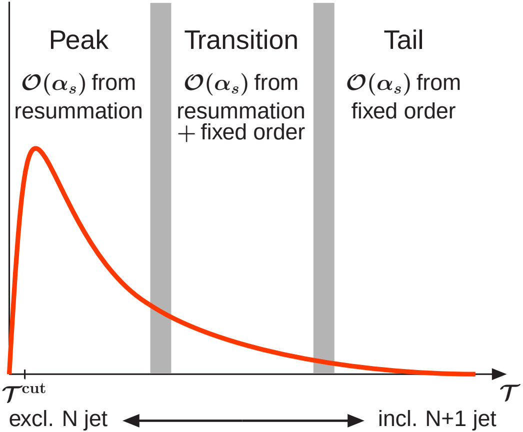

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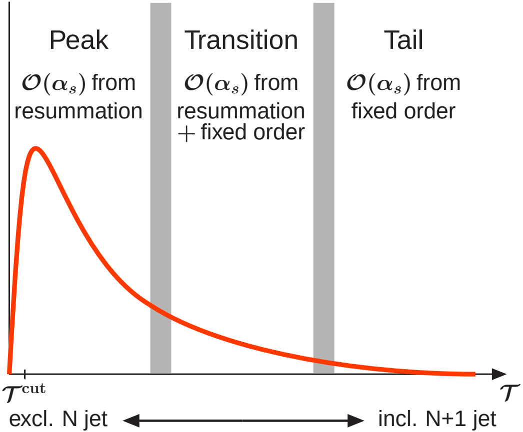

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(* see backup slides)

Problems in merging NLO Shower Monte Carlo samples

- When merging NLO_N and NLO_{N+1} samples separated by a $\mathcal{T}_{\text{cut}}$ cut, the unphysical dependence manifests itself in σ^{tot} as $\log(\mathcal{T}_{\text{cut}}/Q)$.

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GENEVA aims higher:

- We are not just merging two separate NLO+PS calculations
- We are performing a single resummed calculation which naturally incorporates the information from both N and N+1 parton NLO calculations.

GENEVA Master Formula

arXiv:1211.7049

- Introduce an unphysical infrared regulator $\mathcal{T}^{\mathrm{cut}}$ and separate inclusive and exclusive regions: $\mathcal{T}^{\mathrm{cut}}$ dependence drops out to the order we are working.

$$\sigma_{\geq N} = \int \mathrm{d}\Phi_N \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}^{\mathrm{cut}}) + \int \mathrm{d}\Phi_{N+1} \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) \, \theta(\mathcal{T} > \mathcal{T}^{\mathrm{cut}})$$

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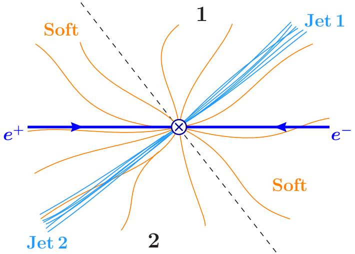
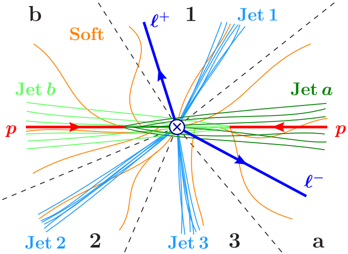
New frontier in either direction ...

N-Jettiness as jet-resolution variable

- Use N-jettiness as resolution parameter. Global physical observable with straightforward definitions for hadronic colliders, in terms of beams $q_{a,b}$ and jet-directions q_j

$$\mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_1 \cdot p_k, \ldots, q_N \cdot p_k\} \Rightarrow \mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$





- N-jettiness has good factorization properties, IR safe and resummable at all orders. Resummation known at NNLL for any N [Stewart et al. 1004.2489, 1102.4344]
- $\mathcal{T}_N \to 0$ for N pencil-like jets, $\mathcal{T}_N \gg 0$ spherical limit.
- $\mathcal{T}_N < \mathcal{T}_N^{\mathrm{cut}}$ acts as jet-veto, e.g. CJV $\mathcal{T}_0 = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k\} < \mathcal{T}_0^{\mathrm{cut}}$

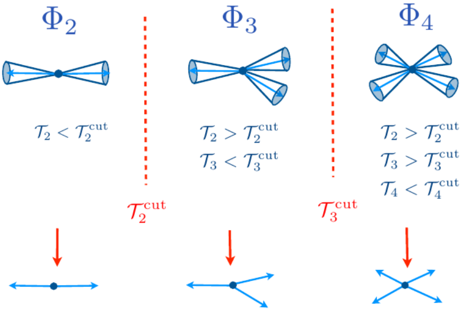
First application: $e^+e^- \to$ jets

- ✓ Simpler process to test our construction.
- ✓ Thrust spectrum known to $N^3LL'_{\mathcal{T}}$+ $NNLO_3$.
- ✓ Several 2-jet shapes known to $NNLL_{\mathcal{O}}$+$NNLO_3$.
- ✓ LEP data available for validation.

- Use 2- and 3-jettiness.

$$\mathcal{T}_2 = E_{\rm cm}\left(1 - \max_{\hat{n}} \frac{\sum_k |\hat{n}\cdot\vec{p}_k|}{\sum_k |\vec{p}_k|}\right) = E_{\rm cm}(1-T)$$

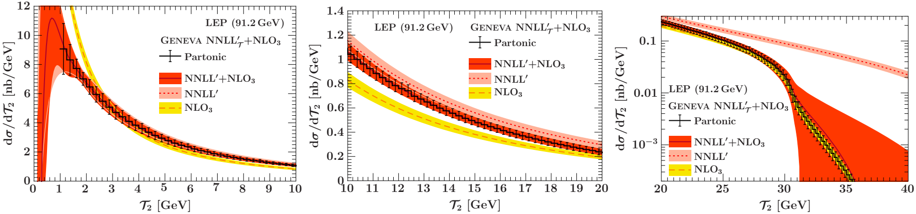
- Opportunely partitioning the phase-space
- Perturbatively calculating NLO/Resumm. jet-cross sections.



$$\underbrace{\frac{d\sigma}{d\Phi_2}(\mathcal{T}_2^{\rm cut})}_{NNLL'_{\mathcal{T}_2}} \quad \underbrace{\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2, \mathcal{T}_3^{\rm cut}) + \frac{d\sigma}{d\Phi_4}(\mathcal{T}_2, \mathcal{T}_3)}_{NNLL'_{\mathcal{T}_2}+NLO_3}$$

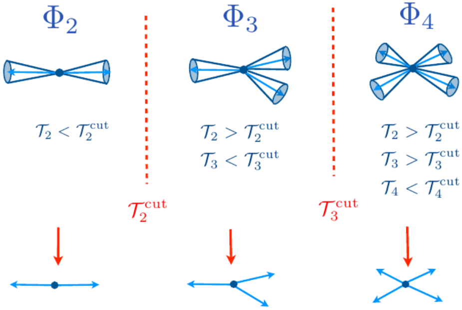
Resummation of $\mathcal{T}_2$

- GENEVA precisely reproduces full NNLL'+NLO3 analytic result : simply getting out what we put in!



- Comments:
  - Error bars are always theory uncertainties, obtained via scales variation. (resumm. unc. $\oplus$ FO unc.). Statistical uncertainties negligible and not shown.
  - Reliable estimation of perturbative theoretical uncertainties on event-by-event basis is one of GENEVA's guiding principle.
  - GENEVA $\mathcal{T}_2^{\mathrm{cut}} = 1$ GeV above
  - Scale uncertainties agree across most of the spectrum, differences after kinematic 3-body endpoint consequence of different matching procedure (multiplicative vs. additive).

Interface with the parton shower



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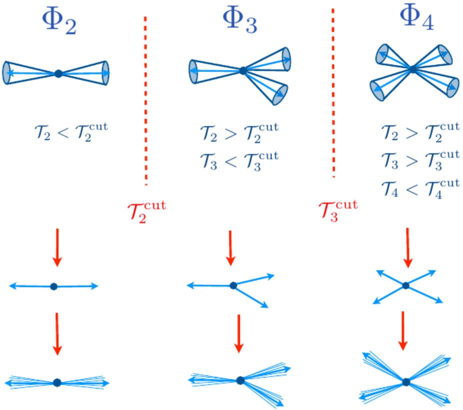

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- Similarly for $\mathcal{T}_3(\Phi_4)$ spectrum and 3-jets bin. Proxy for $\mathcal{T}$-ordered PS.
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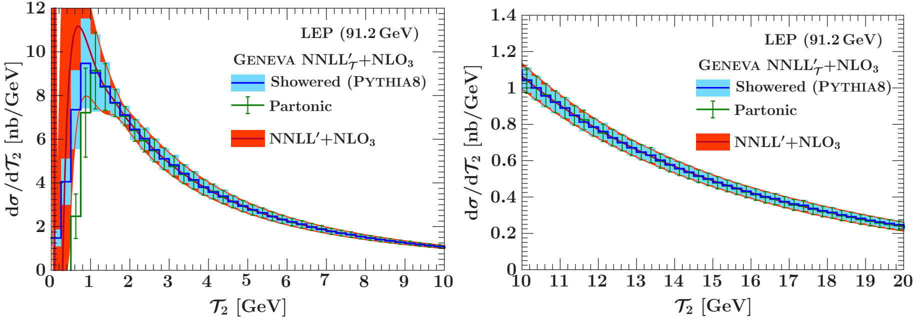

Predictive power for other observables

- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}$. Naively, (N)LL is expected.
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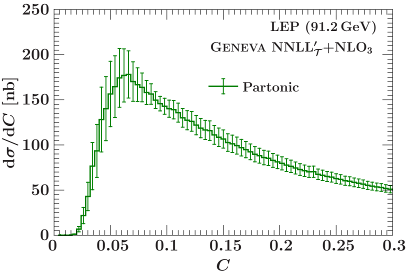
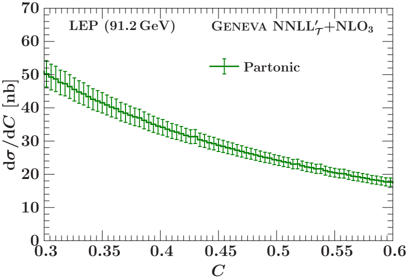
- C-parameter – perturbative structure very similar to $\mathcal{T}_2$





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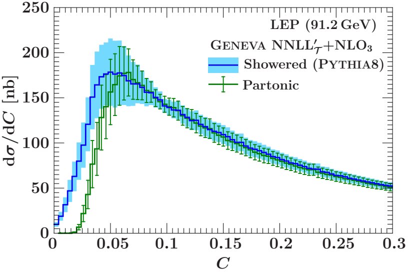

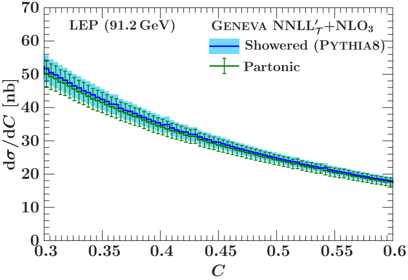

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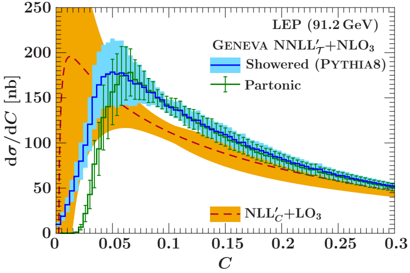

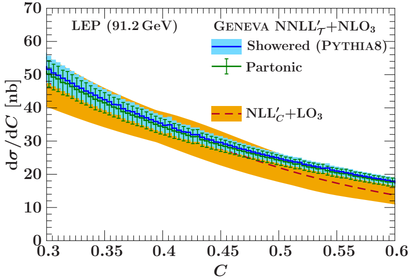

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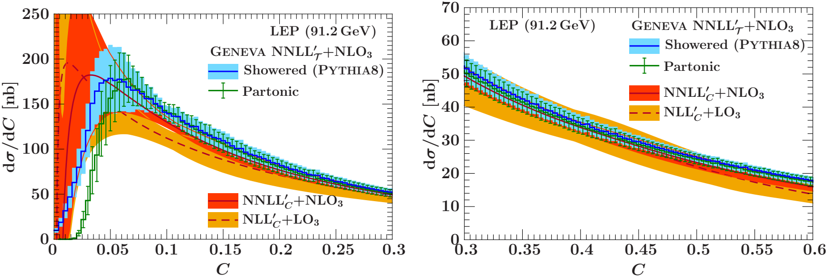
- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}$. Naively, (N)LL is expected.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?

- C-parameter – perturbative structure very similar to $\mathcal{T}_2$



- Good agreement in central values and scale uncertainties envelopes at NNLL, also for observables with a very different resummation structure.
- NNLL resummation allows to push $\mathcal{T}_2^{\mathrm{cut}}$ to very small values, effectively replacing the shower evolution.

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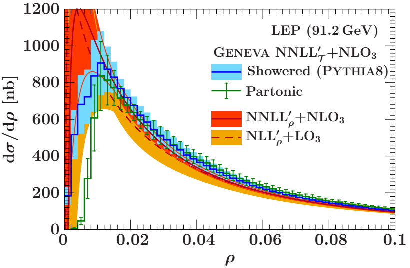
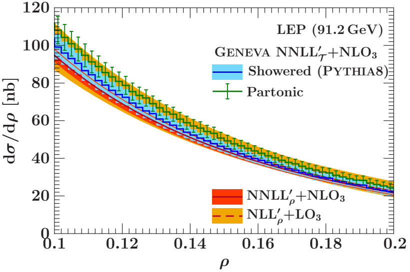
- Heavy jet mass – perturbative structure partially related to $\mathcal{T}_2$





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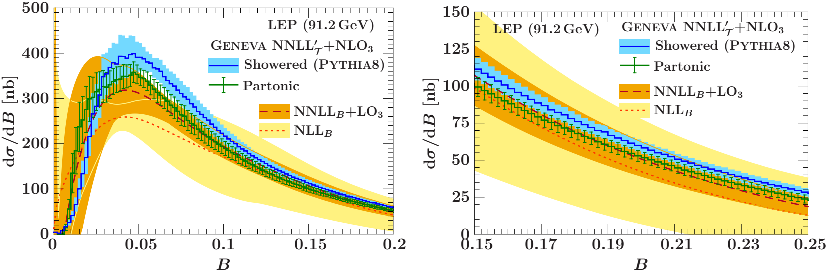
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?
- Jet Broadening – perturbative structure completely different from $\mathcal{T}_2$



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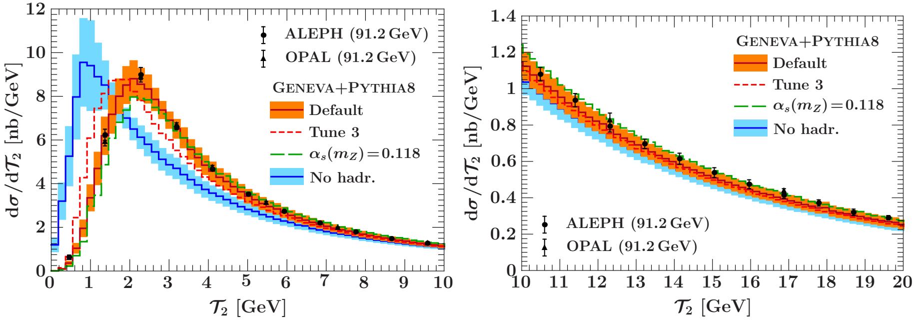
Hadronization and comparison with LEP data.

- 2-jettiness $= E_{\rm cm}(1-T)$



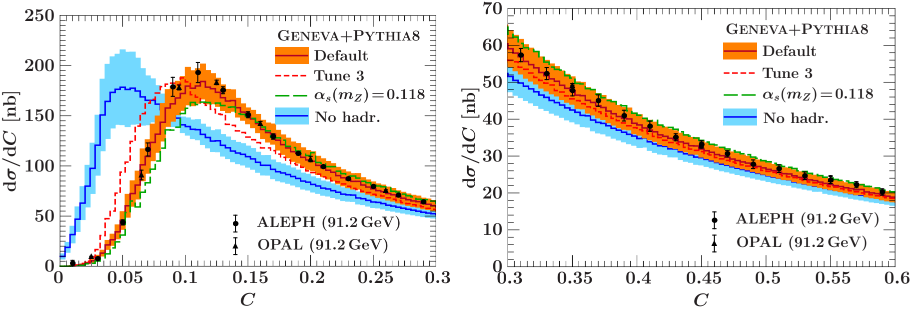
- Hadronization (non-perturbative effect) is unconstrained.
- No ad-hoc tune, default Pythia8 Tune1 with $\alpha_{\rm s}(mZ) = \mathbf{0.1135}$ from τ fits.

[Abbate et al. 1006.3080]

- Large shift due to hadronization, $\mathcal{O}(1)$, in the peak.
- Power suppressed effect elsewhere, as expected.

Hadronization and comparison with LEP data.

- C-parameter



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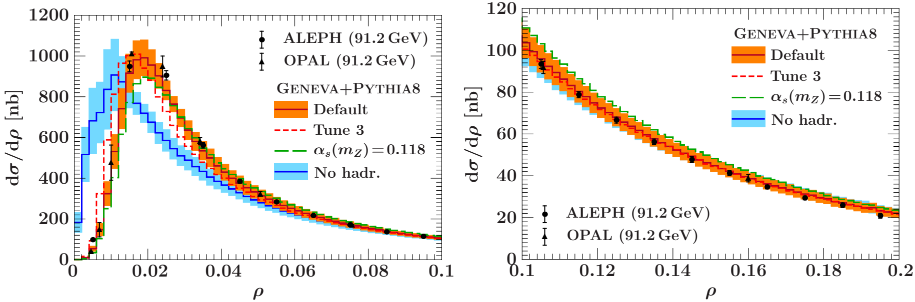

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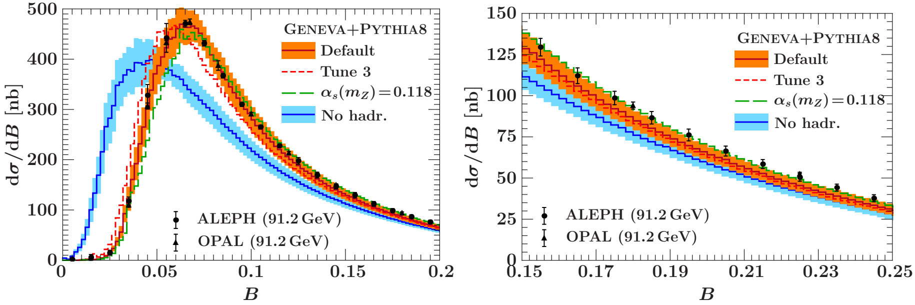

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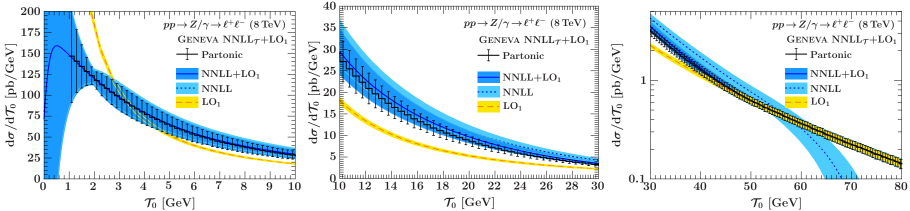
Hadronic collisions: $pp \to V$ + jets

- Ingredients for hadronic collisions:
  - Beam Thrust $\mathcal{T}_0$ is the resolution parameter. ✓
  - Resummation of beam-thrust to NNLL ✓
  - NLO calculations for $pp \to V + 0, 1$-jets ✓
  - Interface with Pythia8 shower and MPI without changing $\mathcal{T}_0$ ✓



Ongoing work:

- Validating NNLL' resummation, combination with NLO_0 + NLO_1 and addition of Pythia8 shower.
- Comparisons with LHC data.

Conclusions and outlook

GENEVA provides a framework for combining higher-order resummation with multiple NLO calculations and shower/hadronization.

- Uses a physics observable, N-jettiness, factorizable and whose resummation is known to NNLL as jet resolution parameter.
- Going beyond NLL is crucial to obtain a consistent NLO description everywhere (including merging multiple fixed NLOs)
- Comparison with LEP 2-jets event shape data shows excellent agreement.
- Currently validating results against TeV and LHC data for V+0,1 jets production.

Next steps:

- Adding more jets, e.g. $pp \to V + 0, 1, 2$ and validation with LHC.
- Obvious goal is $gg \to H + 0, 1, 2$ jets.
- Pre-release code next summer. Let us know if you are interested in being an “early adopter”.
- Interface to other SMC: HERWIG++, SHERPA . . .
- Specific tuning of GENEVA + SMC.

Thank you for your attention!

BACKUP

Perturbative accuracy

- Lowest perturbative accuracy $L = \log(\tau)$, LL NLL NLL' NNLL

$$\frac{1}{\sigma_B}\frac{d\sigma}{d\tau}\bigg|_{\tau>0} = \overbrace{\frac{\alpha_s}{\tau}\left[L\, f_0(\alpha_s L^2) + f_1(\alpha_s L^2) + \tau f_1^{\rm nons}(\tau)\right]}^{LO_{N+1}}$$

$$\frac{1}{\sigma_B}\sigma(\tau^{\rm cut}) = \underbrace{1}_{LO_N} + \underbrace{\alpha_s\left[L_{\rm cut}^2\, F_0(\alpha_s L_{\rm cut}^2) + L_{\rm cut}\, F_1(\alpha_s L_{\rm cut}^2)\right]}_{NLO_N}$$

- Next-to-Lowest perturbative accuracy

$$\frac{1}{\sigma_B}\frac{d\sigma}{d\tau}\bigg|_{\tau>0} = \overbrace{\frac{\alpha_s}{\tau}\left[L\, f_0(\alpha_s L^2) + f_1(\alpha_s L^2) + \tau f_1^{\rm nons}(\tau)\right]}^{LO_{N+1}}$$
$$+ \underbrace{\frac{\alpha_s^2}{\tau}\left[L\, f_2(\alpha_s L^2) + f_3(\alpha_s L^2) + \tau f_2^{\rm nons}(\tau)\right]}_{NLO_{N+1}}$$

$$\frac{1}{\sigma_B}\sigma(\tau^{\rm cut}) = \overbrace{1}^{LO_N} + \overbrace{\alpha_s\left[L_{\rm cut}^2\, F_0(\alpha_s L_{\rm cut}^2) + L_{\rm cut}\, F_1(\alpha_s L_{\rm cut}^2)\right]}^{NLO_N}$$
$$+ \underbrace{\alpha_s\left[c_{1,-1} + F_1^{\rm nons}(\tau^{\rm cut})\right] + \alpha_s^2\left[L_{\rm cut}^2\, F_2(\alpha_s L_{\rm cut}^2) + L_{\rm cut}\, F_3(\alpha_s L_{\rm cut}^2)\right]}_{NLO_{N+1}}$$

Notation and ingredients

- Accuracy of fixed and resummation orders

notation	inclusive N-jet fixed order	inclusive N-jet accuracy	exclusive N-jet log. order	exclusive N-jet accuracy	inclusive $(N+1)$-jet fixed order	inclusive $(N+1)$-jet accuracy
LL$_{\mathcal{T}}$+LO$_{N+1}$	LO$_N$	~ 1	LL	$\sim \alpha_s^{-1/2}$	LO$_{N+1}$	~ 1
NLL$_{\mathcal{T}}$	LO$_N$	~ 1	NLL	~ 1	-	-
NLL$_{\mathcal{T}}$+LO$_{N+1}$	LO$_N$	~ 1	NLL	~ 1	LO$_{N+1}$	~ 1
NLL$'_{\mathcal{T}}$+LO$_{N+1}$	NLO$_N$	$\sim \alpha_s$	NLL$'$	$\sim \alpha_s^{1/2}$	LO$_{N+1}$	~ 1
NNLL$_{\mathcal{T}}$+NLO$_{N+1}$	NLO$_N$	$\sim \alpha_s$	NNLL	$\sim \alpha_s$	NLO$_{N+1}$	$\sim \alpha_s$
NNLL$'_{\mathcal{T}}$+NLO$_{N+1}$	NLO$_N$	$\sim \alpha_s$	NNLL$'$	$\sim \alpha_s^{3/2}$	NLO$_{N+1}$	$\sim \alpha_s$

- Perturbative ingredients for resummation

	Fixed-order corrections singular	Fixed-order corrections nonsingular	Resummation input γ_x	Resummation input $\Gamma_{\rm cusp}$	Resummation input β
LL	LO$_N$	-	-	1-loop	1-loop
NLL	LO$_N$	-	1-loop	2-loop	2-loop
NLL$'$	NLO$_N$	-	1-loop	2-loop	2-loop
NLL$'$+LO$_{N+1}$	NLO$_N$	LO$_{N+1}$	1-loop	2-loop	2-loop
NNLL+LO$_{N+1}$	NLO$_N$	LO$_{N+1}$	2-loop	3-loop	3-loop
NNLL$'$	NNLO$_N$	-	2-loop	3-loop	3-loop
NNLL$'$+NLO$_{N+1}$	NNLO$_N$	NLO$_{N+1}$	2-loop	3-loop	3-loop

Iterating the Geneva method to higher multiplicities

- Geneva approach can be iterated to merge several multiplicities at NLO
- Separation of cumulant and spectrum

$$\frac{d\sigma_{\rm incl}}{d\Phi_N} = \frac{d\sigma}{d\Phi_N}(\mathcal{T}_N^{\rm cut}) + \int \frac{d\Phi_{N+1}}{d\Phi_N}\,\frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T}_N)\,\theta(\mathcal{T}_N > \mathcal{T}_N^{\rm cut})\,,$$

$$\frac{d\sigma_{\rm incl}}{d\Phi_{N+1}} = \frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T}_{N+1}^{\rm cut}) + \int \frac{d\Phi_{N+2}}{d\Phi_{N+1}}\,\frac{d\sigma}{d\Phi_{N+2}}(\mathcal{T}_{N+1})\,\theta(\mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\rm cut})\,,$$

$$\vdots$$

$$\frac{d\sigma_{\rm incl}}{d\Phi_{N_{\max}}} = \frac{d\sigma}{d\Phi_{N_{\max}}}(\mathcal{T}_{N_{\max}}^{\rm cut} \to \infty)$$

Iterating the Geneva method to higher multiplicities

- Geneva approach can be iterated to merge several multiplicities at NLO
- Resummation factors U replaces shower Sudakovs

$$U_N(\Phi_N, \mathcal{T}_N) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N \mathrm{d}\mathcal{T}_N} \Big/ \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N \mathrm{d}\mathcal{T}_N}\Big|_{\mathrm{FO}}$$

$$\frac{\mathrm{d}\sigma_N^{\mathsf{MC}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}})\,,$$

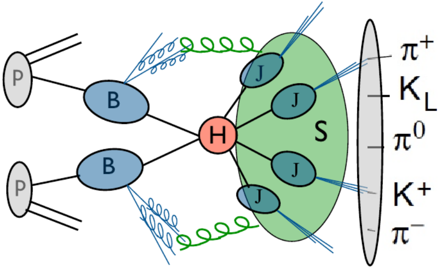
$$\frac{\mathrm{d}\sigma_{N+1}^{\mathsf{MC}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_{N+1}^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_{N+1}^{\mathrm{cut}})\, U_N(\Phi_N, \mathcal{T}_N)\,,$$

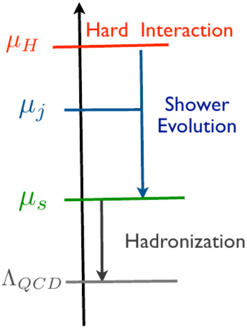
$$\vdots$$

$$\frac{\mathrm{d}\sigma_{\geq N_{\max}}^{\mathsf{MC}}}{\mathrm{d}\Phi_{N_{\max}}} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N_{\max}}}(\mathcal{T}_{N_{\max}}^{\mathrm{cut}} \to \infty)\, U_N(\Phi_N, \mathcal{T}_N)\, U_{N+1}(\Phi_{N+1}, \mathcal{T}_{N+1}) \times \cdots \times U_{N_{\max}-1}(\Phi_{N_{\max}-1}, \mathcal{T}_{N_{\max}-1})$$

Including higher order resummation in Monte Carlo

- Monte Carlo is built on the idea of factorization





$d\sigma^{MC} =$ Hard Interaction $\otimes$ [Collinear Evolution $\otimes$ Soft Radiation] $\otimes$ PDFs, Hadronization, Underlying Event

Parton Shower Evolution

- Replace parton-shower evolution with higher order logarithmic resummation from μ_H to $\mu_{\mathbf{B}}, \mu_{\mathbf{J}}, \mu_S$.