Matching NLO calculations and parton showers.

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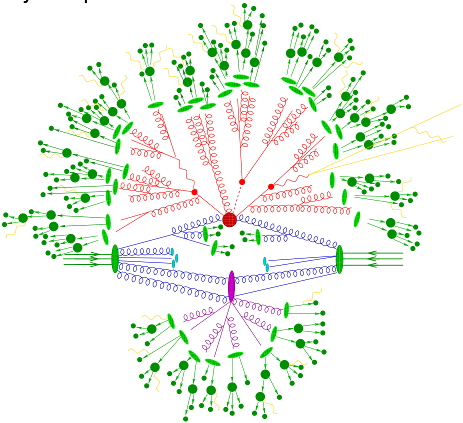
Introduction

High Energy Physics studies scattering and production of elementary constituents: leptons, quarks, gauge and higgs bosons. Hadronic collisions can be well summarized by this picture:

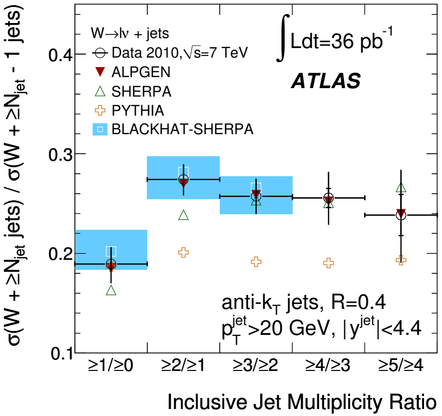


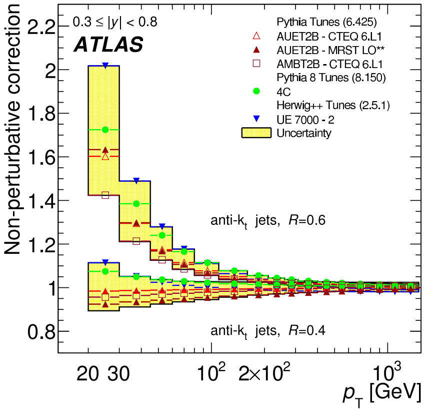
- Parton model - Beam of partons
- Radiation off incoming partons (ISR)
- Primary hard scattering ($\mu \approx Q \gg \Lambda_{QCD}$)
- Radiation off outgoing partons (FSR) ($Q > \mu > \Lambda_{QCD}$)
- Hadronization and heavy hadrons decays ($\mu \approx \Lambda_{QCD}$)
- Multiple Particle Interactions - Underlying Event

We want theoretical frameworks able to describe all these stages as accurately as possible, starting from QCD, EW or BSM hard scatterings and dressing them with QCD effects.

Approaches to QCD calculations

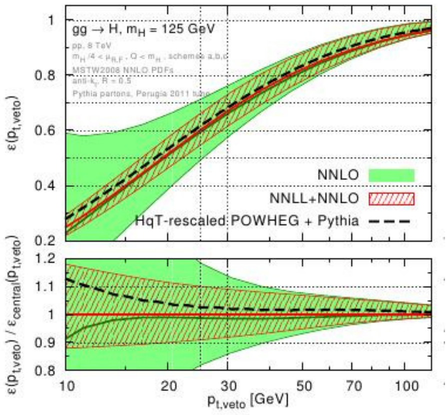
- Fixed Order :
  - Give accurate prediction for inclusive observables
  - Does not model well exclusive final states.

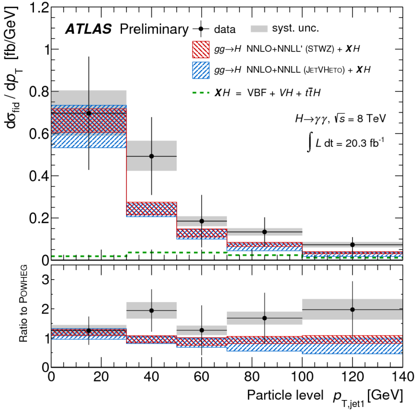




Approaches to QCD calculations

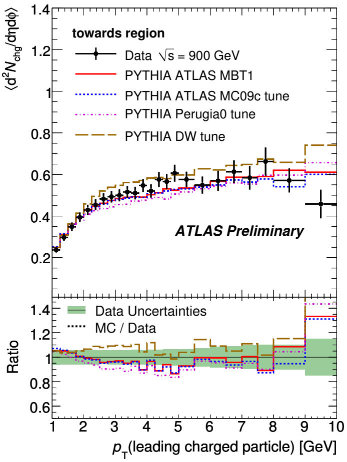
- Resummation:
  - Gives predictions for observables in exclusive limits, by resumming contribution enhanced by large logarithms at all orders.
  - If factorization holds, can be used to model exclusive final states, with more reliable theoretical errors.

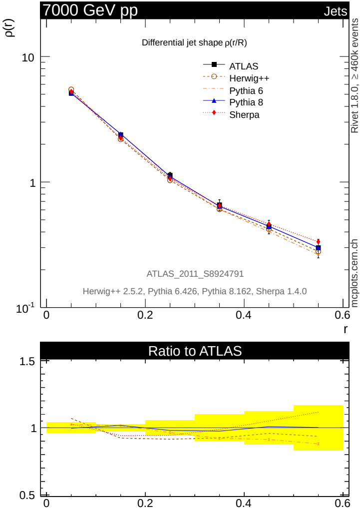




Approaches to QCD calculations

- Parton Showers:
  - Same goal as resummation, but in a observable independent approach.
  - Due to the approximations involved, usually fewer logarithmic terms can actually be resummed.





Directions to improve event generators

✓ A K factor = $\frac{\sigma_{NLO}}{\sigma_{LO}}$ correction only improves inclusive quantities

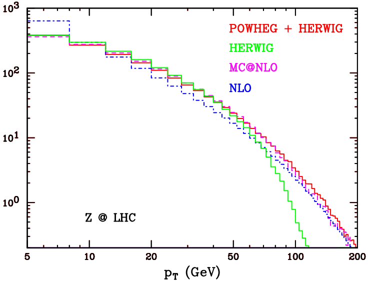
✓ Including further real emissions (ME+PS) may also accomodate shapes:

- ⇒ MEPS only has LO normalization
- ⇒ A matching prescription to avoid double-counting of radiation must be defined
- ⇒ Large uncertainty under scale variations due to the lack of virtual corrections
  $\alpha_S^n(f\mu) \approx \alpha_S^n(\mu)(1 - b_0\alpha_S(\mu)\log(f^2))^n \approx \alpha_S^n(\mu)(1 \pm n\alpha_S(\mu))$

✓ Use full NLO calculation as "hard subprocess" for the SMC ⇒ NLO+PS

Many ideas to avoid double-counting, but two general method perform this merging for hadronic collisions fully tested

- MC@NLO [Frixione & Webber,JHEP 0206:029,2002]
- POWHEG [Nason,JHEP 0411:040,2004]
  [Frixione, Nason & Oleari, JHEP 0711:070,2007]



MC@NLO can now also be interfaced with PYTHIA and HERWIG++ showers.
POWHEG method adopted also in HERWIG++ and SHERPA programs.

NLO+PS: a common view of POWHEG and MC@NLO

- First emission probability

$$d\sigma = \overbrace{\bar{B}_{\text{sing.}}(\Phi_n)}^{\text{NLO}}\, d\Phi_n \overbrace{\left\{\Delta_{\text{sing.}}(t_0) + \Delta_{\text{sing.}}(t)\frac{R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}})}{B(\Phi_n)}\, d\Phi_{\text{rad}}\right\}}^{\text{sum to 1 by unitarity}}$$
$$+ \underbrace{\left[R(\Phi_n,\Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}})\right]}_{\text{NLO}} d\Phi_n\, d\Phi_{\text{rad}}$$

- Normalization : NLO cross section at fixed Born kinematics

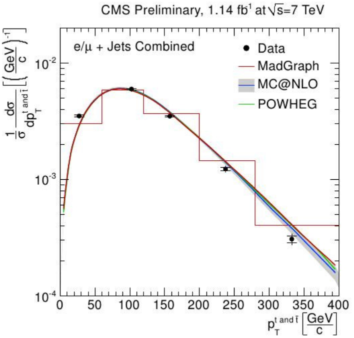
$$\bar{B}_{\text{sing}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}}) - C(\Phi_n,\Phi_{\text{rad}})\right] d\Phi_{\text{rad}}$$

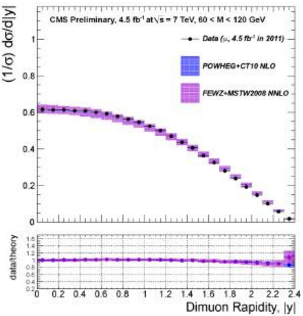
- Sudakov factor:

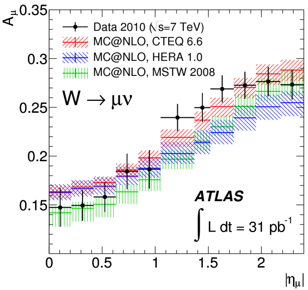
$$\Delta_{\text{sing.}}(t) = \exp\left[-\int d\Phi'_{\text{rad}} \frac{R^{\text{sing.}}(\Phi_n,\Phi'_{\text{rad}})}{B(\Phi_n)}\theta\left(t'-t\right)\right]$$

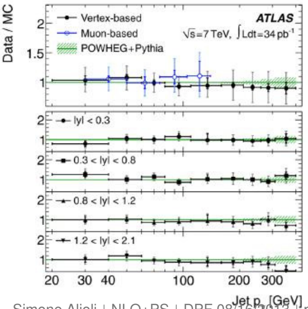
- In POWHEG : $R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}}) = F(\Phi_n,\Phi_{\text{rad}}) \times R(\Phi_n,\Phi_{\text{rad}})$, with $0 \leq F \leq 1$, and $F(\Phi_n,\Phi_{\text{rad}}) \to 1$ in the soft/collinear limit.
- In MC@NLO : $R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}}) = R_{\text{SMC}}(\Phi_n,\Phi^{\text{SMC}}_{\text{rad}})$ is the shower approximation of a real emission

NLO+PS: thoroughly compared and validated with data



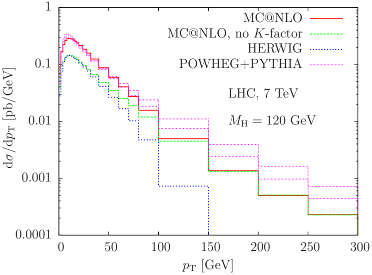


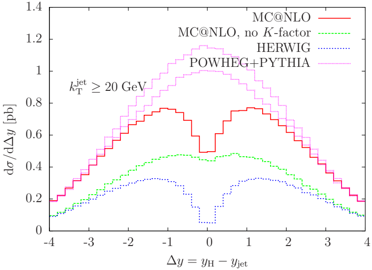




NLO+PS: differences studied and assessed

- Difference arise formally only starting at NNLO. However, they may turn out to be sizeable for some observables





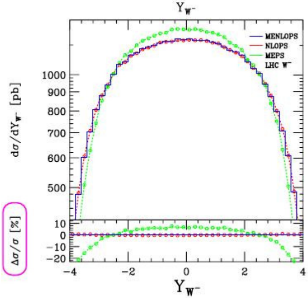
[Nason&Webber arXiv:1202.1251]

1. enhancement by the ratio $\bar{B}(\Phi_n)/B(\Phi_n) \approx 1 + \mathcal{O}(\alpha_s)$
2. different scale choices for different contributions
3. different Sudakov factor $\Delta(p_T)$, which always reduce high-p_T spectrum $\Delta \leq 1$.

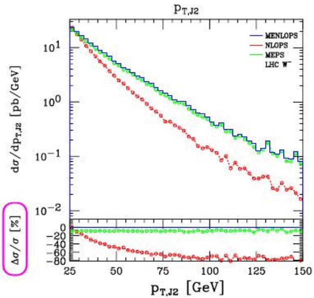
- All major differences found tracked back to 1. or 2. Exponentiation of different $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})$ does not seem to yield large differences since in the $p_T \to 0$ region which dominates the integral, all the $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})$ must be the same.

Directions to improve event generators

✓ MENLOPS: provide ME corrections on top of NLO SMC



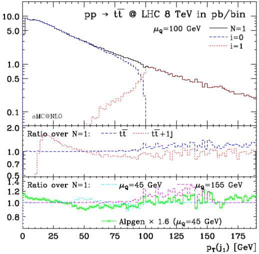
Inclusive observables:
MENLOPS → NLOPS

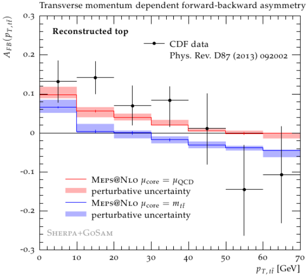


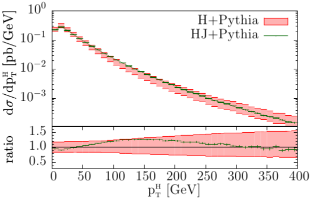
Multi-jet events:
MENLOPS → MEPS

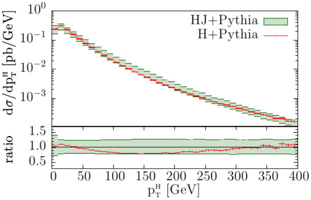
Directions to improve event generators

✓ Merging of NLO+PS samples with different multiplicitities, several recent results: SHERPA,FxFx,UNLOPS,MINLO ...





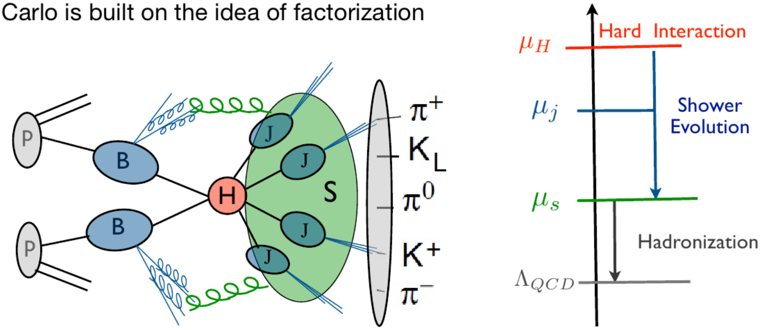


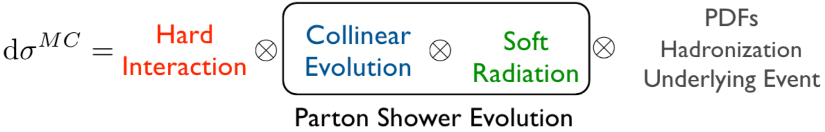


Need to be careful in choosing merging scale (or resumming its dependency to an high-enough order) not to spoil NLO accuracy!

A tangential direction: including higher order resummation.

- Monte Carlo is built on the idea of factorization

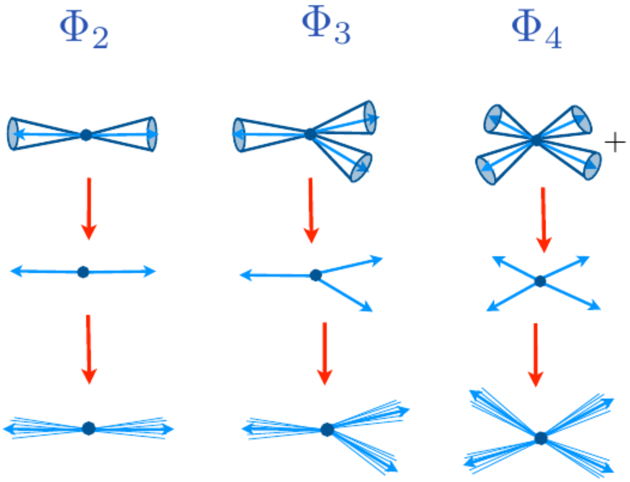




- Replace parton-shower evolution with higher order logarithmic resummation from μ_H to $\mu_{\mathbf{B}}, \mu_{\mathbf{J}}, \mu_S$.

A proposed solution : the GENEVA approach

- Define and calculate Jet Cross Section at NLO
- Assign weights to parton level kinematics (based on resummation)
- Shower to fill in the jets



GENEVA

GENEVA is a framework to combine

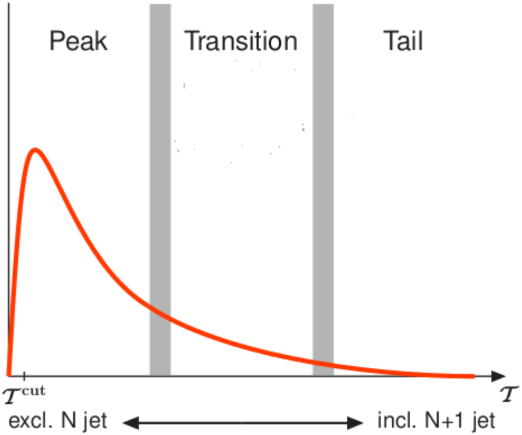
- Fully Exclusive NLO Calculations $\quad$ NLO_N, NLO_{N+1}, ...
- Higher-order Resummation $\quad$ $\text{LL}_\mathcal{O}$, $\text{NLL}_\mathcal{O}$, $\text{NLL'}_\mathcal{O}$, $\text{NNLL}_\mathcal{O}$ ...
- Parton Showering and Hadronization $\quad$ Pythia8, Herwig++, ...

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.



- To which accuracy we want to predict its spectrum?

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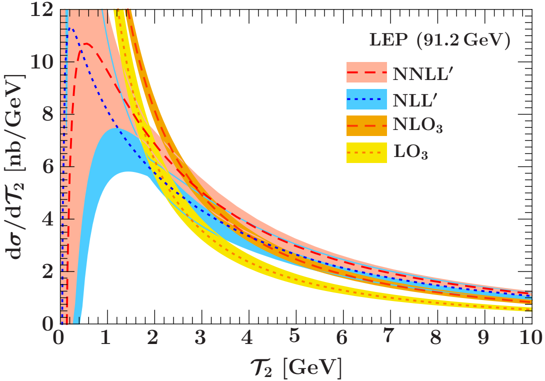

- *"Peak"* $\mathcal{T} \ll Q$ resummation region : expansion in $\alpha_{\mathrm{S}} L^2 \sim 1$, with $L = \log(\frac{\mathcal{T}}{Q})$ and Q hard scale such that $\alpha_{\mathrm{S}}(\alpha_{\mathrm{S}}^n L^{2n}) \approx \alpha_{\mathrm{S}}$
- Fixed-order diverges and its scales variation underestimates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

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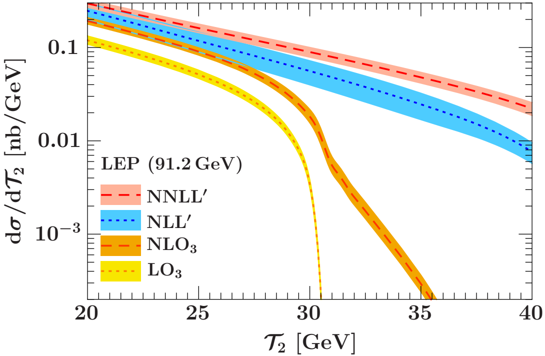

- *"Tail"* $\mathcal{T} \sim Q$ fixed-order region : fixed-order expansion in α_S is valid.
- Resummation gives wrong predictions.
- Higher fixed-order scales variation reliably estimates uncertainties.

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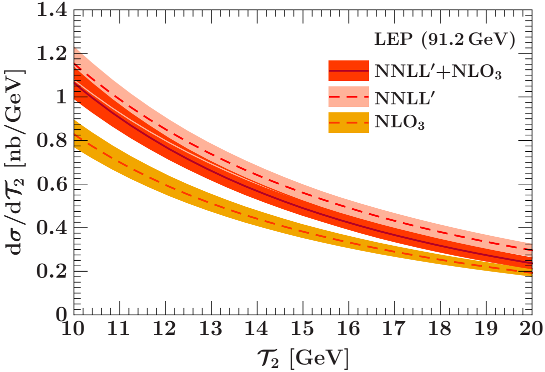

- Transition region requires accurate interplay of *"peak"* and *"tail"* descriptions
  - Interesting physics often in this region, e.g. $\boldsymbol{p_{\mathrm{T}}}$-jet $\sim$ 25 GeV in $gg \to H$
  - Theoretically challenging. Matched result gives best estimate of theory unc.

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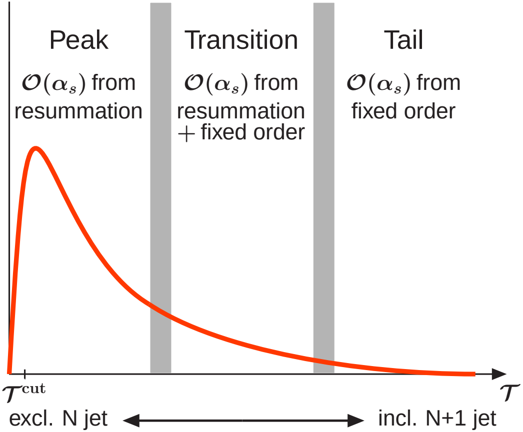

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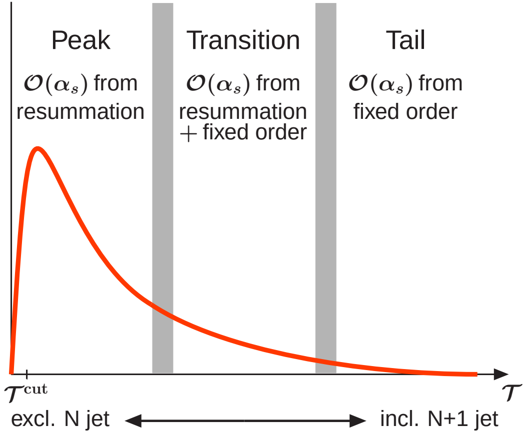

- Lowest pert. accuracy everywhere requires $\mathrm{NLL}_{\mathcal{T}}$ + LO_{N+1} $\sim$ CKKW, MLM

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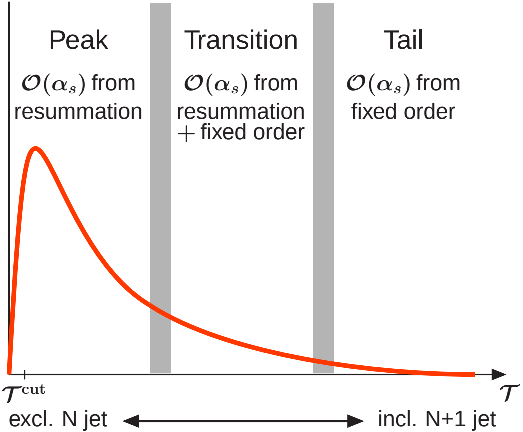

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(* see backup slides)

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 $L \equiv \log(\mathcal{T}_{\text{cut}}/Q)$.

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In GENEVA

- 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 $\mathcal{T}^{\rm cut}$ and separate inclusive and exclusive regions: $\mathcal{T}^{\rm cut}$ dependence drops out to the order we are working.

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

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- Cumulant: $\mathcal{T}$ integral over exclusive N-jets bin up to $\mathcal{T}^{\rm cut}$

$$\frac{d\sigma}{d\Phi_N}(\mathcal{T}^{\rm cut}) = \frac{d\sigma^{\rm resum}}{d\Phi_N}(\mathcal{T}^{\rm cut}) + \left[\frac{d\sigma^{\rm FO}}{d\Phi_N}(\mathcal{T}^{\rm cut}) - \frac{d\sigma^{\rm resum}}{d\Phi_N}(\mathcal{T}^{\rm cut}) \Big|_{\rm FO} \right]$$

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- Spectrum: $\mathcal{T}$ distribution of inclusive $N+1$-jets sample above $\mathcal{T}^{\rm cut}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) = \frac{\mathrm{d}\sigma^{\rm FO}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) \left[\frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N \mathrm{d}\mathcal{T}} \Big/ \frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N\, \mathrm{d}\mathcal{T}}\bigg|_{\rm FO}\right]$$

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- Spectrum: $\mathcal{T}$ distribution of inclusive $N+1$-jets sample above $\mathcal{T}^{\rm cut}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) = \frac{\mathrm{d}\sigma^{\rm FO}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}) \left[\frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N \mathrm{d}\mathcal{T}} \Big/ \frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N \, \mathrm{d}\mathcal{T}} \Big|_{\rm FO} \right]$$

- Correctly reproduces the expected limits for $\mathcal{T} \to 0$ and $\mathcal{T} \sim Q$.

GENEVA Master Formula

arXiv:1211.7049

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

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

- Cumulant: $\mathcal{T}$ integral over exclusive N-jets bin up to $\mathcal{T}^{\rm cut}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}^{\rm cut}) = \frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\rm cut}) + \left[\frac{\mathrm{d}\sigma^{\rm FO}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\rm cut}) - \frac{\mathrm{d}\sigma^{\rm resum}}{\mathrm{d}\Phi_N}(\mathcal{T}^{\rm cut})\Big|_{\rm FO}\right]$$

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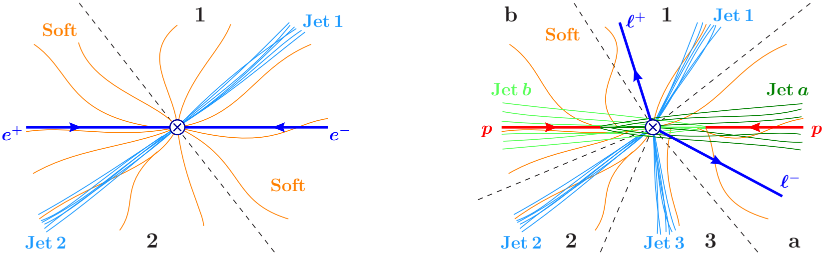
- Correctly reproduces the expected limits for $\mathcal{T} \to 0$ and $\mathcal{T} \sim Q$.

- MonteCarlo's perspective: increases SMC resummation while including multiple NLO.
- Resummation's perspective: takes the resummation of $\mathcal{T}$ and produces fully differential results.

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.
- $\mathcal{T}_N < \mathcal{T}_N^{\rm cut}$ acts as jet-veto, e.g. CJV $\mathcal{T}_0 = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k\} < \mathcal{T}_0^{\rm cut}$

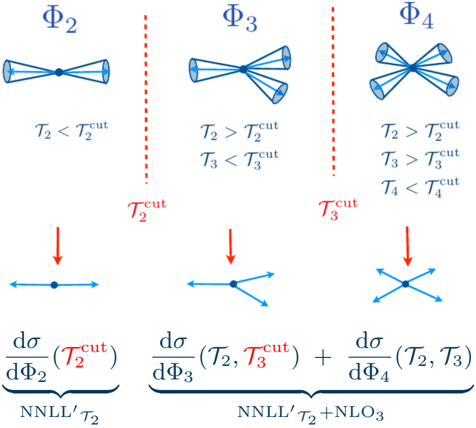
First application: $e^+e^- \to$ jets

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

- Use 2- and 3-jettiness.

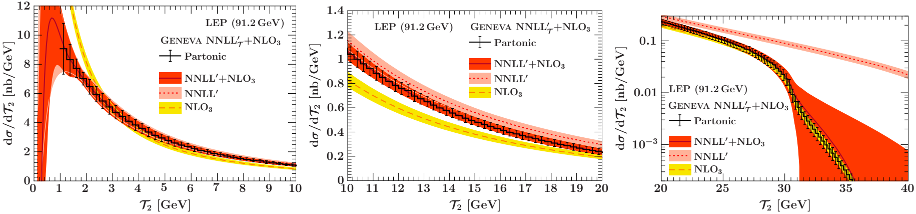
$$\mathcal{T}_2 = E_{\rm cm}\left(1 - \max_{\hat{n}} \frac{\sum_k |\hat{n}\cdot\vec{p}_k|}{\sum_k |\vec{p}_k|}\right) = E_{\rm cm}(1-T)$$

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



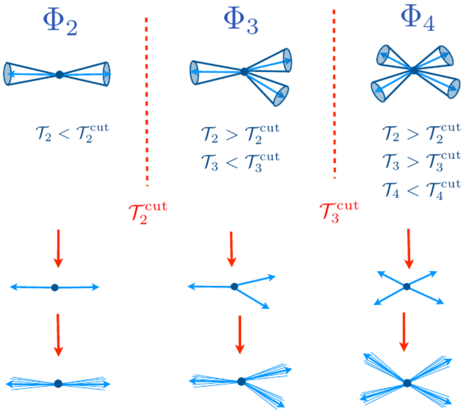
Resummation of $\mathcal{T}_2$

- 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. $\bigoplus$ 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 $\mathcal{T}_2^{\rm cut} = 1$ GeV above
  - Scale uncertainties agree across most of the spectrum, differences after kinematic 3-body endpoint consequence of different matching procedure (multiplicative vs. additive).

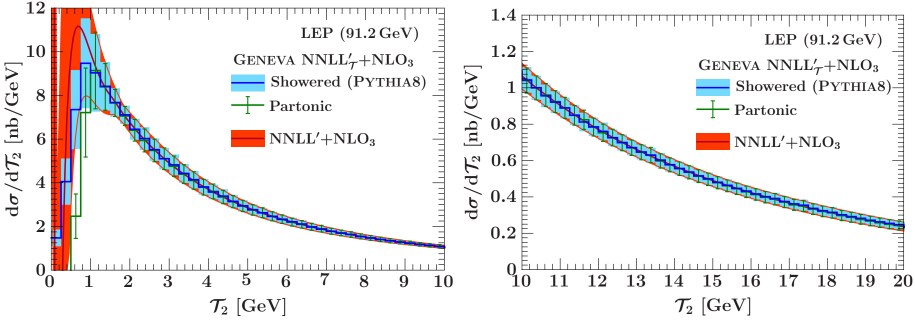
Interface with the parton shower



- The shower must not be allowed to spoil NNLL'$_{\mathcal{T}}$ accuracy of GENEVA, but only used to fill out jets.
- Internal shower machinery not changed.

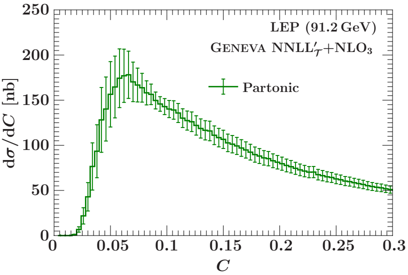
Interface with the parton shower

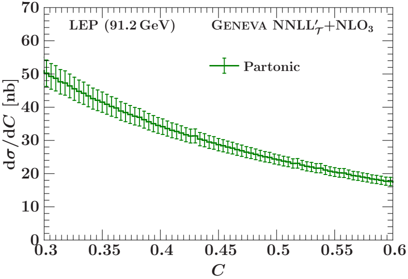
- $\mathcal{T}_2$ spectrum for 3 and 4-parton events constrained by higher-order resummation. Only $\Delta\mathcal{T}_2 < \mathcal{T}_2^{\rm cut}(1+\epsilon)$ allowed. Also, 2-parton events must remain in 2-jets bin.
- Similarly for $\mathcal{T}_3(\Phi_4)$ spectrum and 3-jets bin. Proxy for $\mathcal{T}$-ordered PS.
- Shower unconstrained in the far tail, since only LO_4 there.



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.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?
- C-parameter – perturbative structure very similar to $\mathcal{T}_2$





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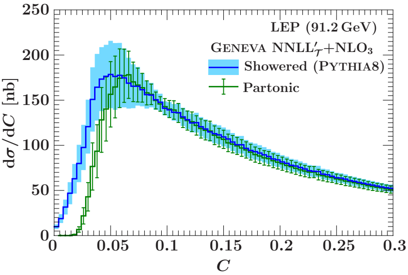

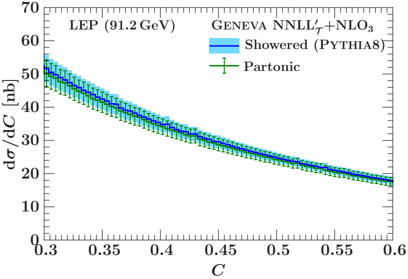

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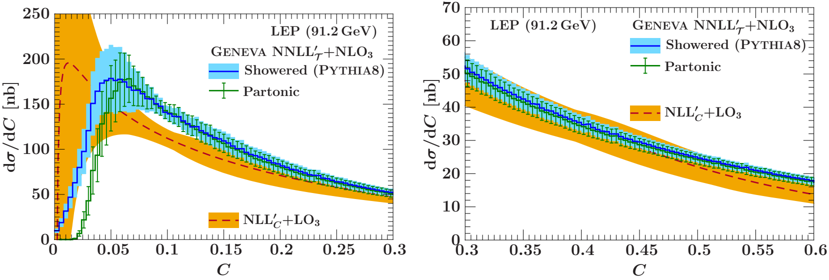

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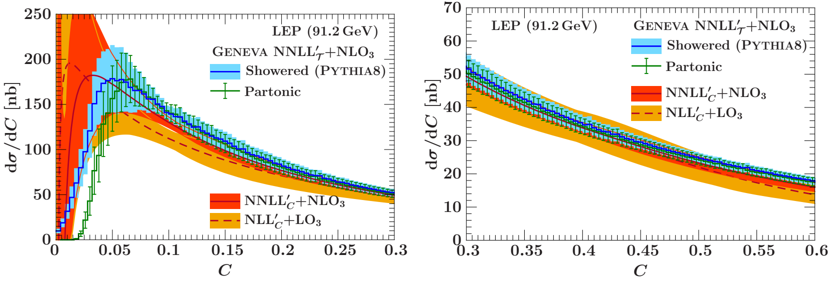
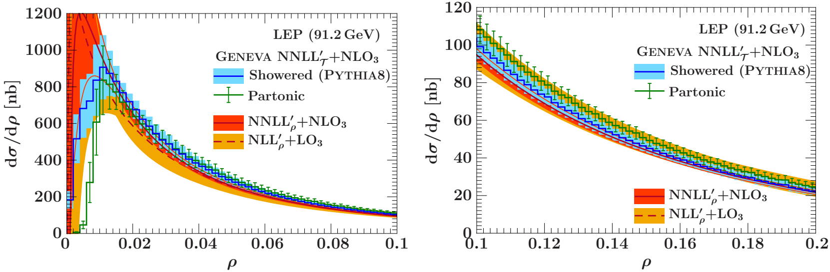


- Good agreement in central values and scale uncertainties envelopes at NNLL, also for observables with a very different resummation structure.
- NNLL resummation allows to push $\mathcal{T}_2^{\rm cut}$ to very small values, effectively replacing the shower evolution.

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.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?

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



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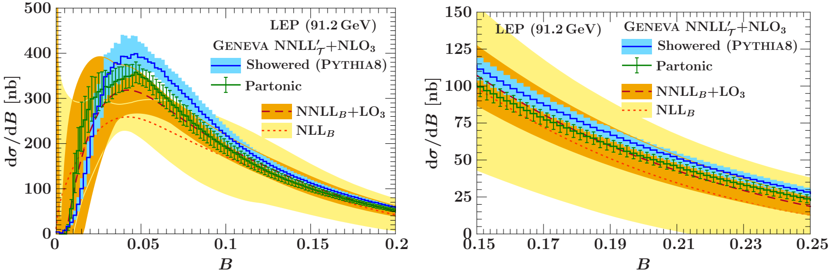
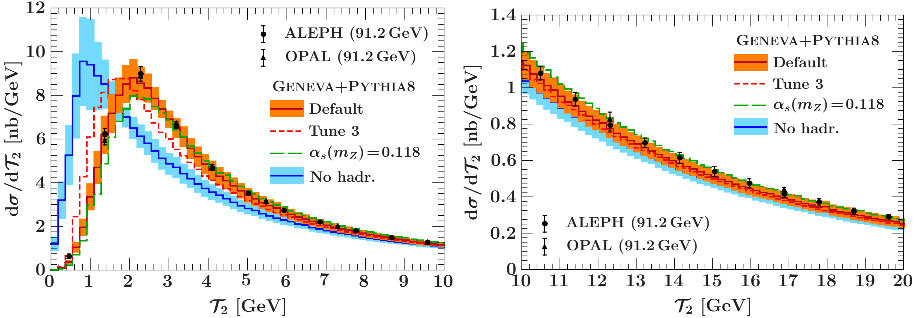
- After showering we are formally limited by shower resummation for generic observables $\mathcal{O} \neq \mathcal{T}$. Naively, (N)LL is expected.
- What is the perturbative accuracy we obtain for other $\mathcal{O}$?
- Jet Broadening – perturbative structure completely different from $\mathcal{T}_2$



- 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 $\mathcal{T}_2^{\rm cut}$ to very small values, effectively replacing the shower evolution.

Hadronization and comparison with LEP data.

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



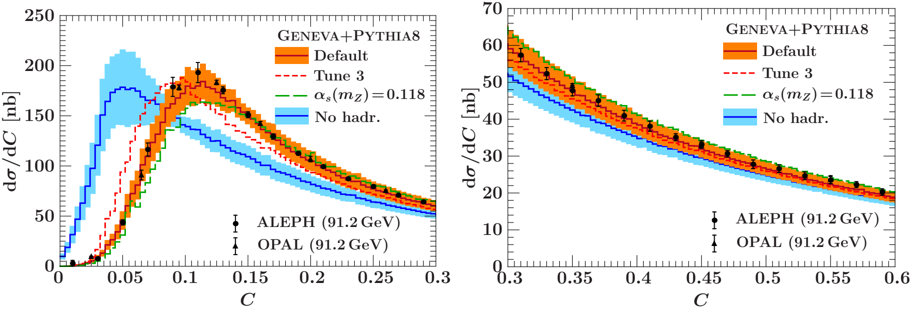
- Hadronization (non-perturbative effect) is unconstrained.
- No ad-hoc tune, default Pythia8 Tune1 with $\alpha_{\rm s}(mZ) = \mathbf{0.1135}$ from τ fits.

[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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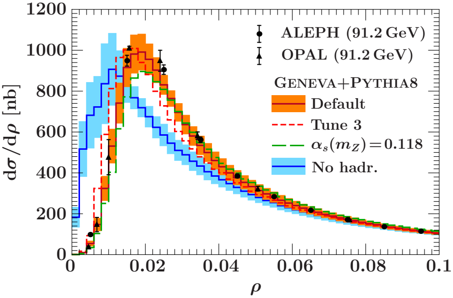
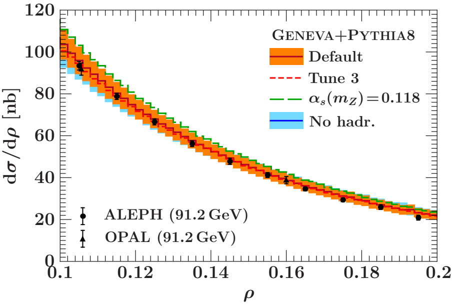
- Heavy jet mass





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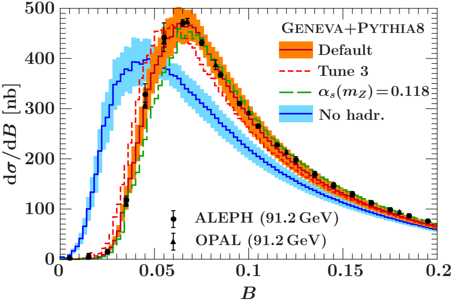
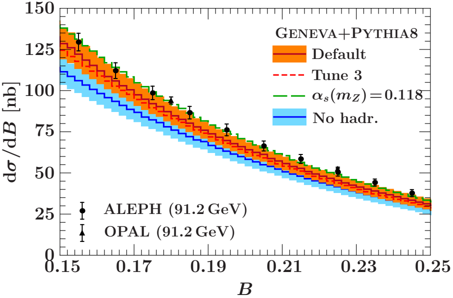
Hadronization and comparison with LEP data.

- Jet Broadening





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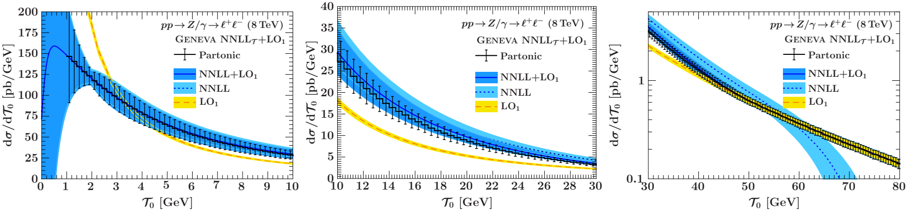
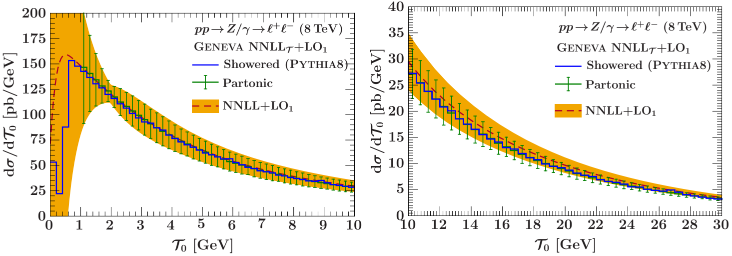
Hadronic collisions: $pp \to V$ + jets

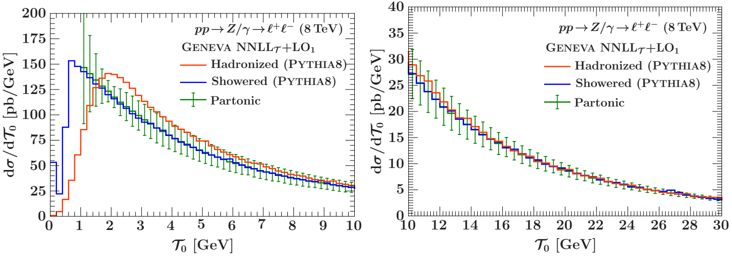
- Ingredients for hadronic collisions:
  - Beam Thrust $\mathcal{T}_0$ is the resolution parameter. ✓
  - Resummation of beam-thrust to NNLL' ✓
  - NLO calculations for $pp \to V + 0, 1$-jets ✓
  - Interface with Pythia8 shower and MPI ✓



Hadronic collisions: $pp \to V$ + jets

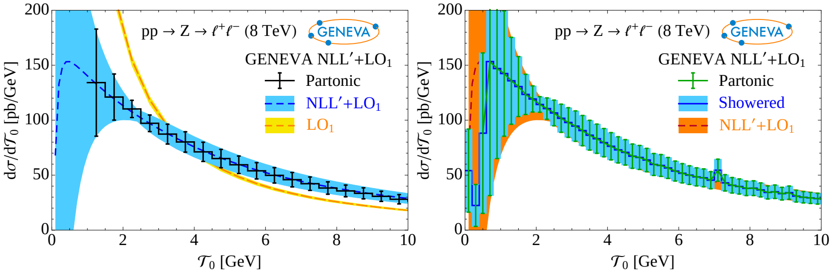


- From showered to hadronized events there's no further constraint.



- A separate tuning of GENEVA+PYTHIA8 is foreseeable for a more robust comparison with data.

Hadronic collisions: $pp \to V$ + jets



Ongoing work:

- Optimization of NNLL' resummation, combination with $\mathbf{NLO_0}$ + $\mathbf{NLO_1}$ and addition of Pythia8 shower with MPI.
- Predictions for observables other than beam-thrust and comparison with LHC data.

Conclusions

- Precision measurements require precise predictions and reliable uncertainties.
- Tools are available and routinely used by LHC experiments for NLO+PS.
- First steps towards improving resummation accuracy and merging NLO calculations are ongoing work.
- Going beyond NLL is crucial to obtain a consistent NLO description everywhere (including merging multiple fixed NLOs)

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

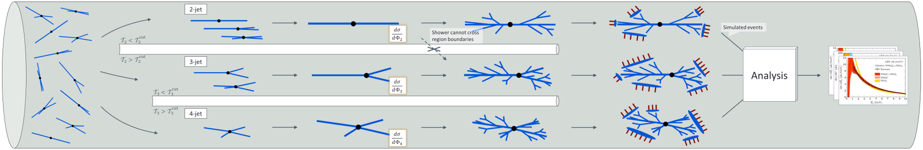
- Uses a physics observable, N-jettiness, factorizable and whose resummation is known to NNLL as jet resolution parameter.

- 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.

Thank you for your attention!

BACKUP

GENEVA pipeline



Divide multi-parton phase space into N-jet regions

Represent with N-parton event

Assign a weight $\frac{d\sigma}{d\Phi_N}$

Shower each event

Hadronize events

Analyze simulated events to produce experimental observables

Perturbative accuracy

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

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

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

- Next-to-Lowest perturbative accuracy

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

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

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
$\mathrm{LL}_{\mathcal{T}}+\mathrm{LO}_{N+1}$	LO_N	~ 1	LL	$\sim \alpha_s^{-1/2}$	LO_{N+1}	~ 1
$\mathrm{NLL}_{\mathcal{T}}$	LO_N	~ 1	NLL	~ 1	-	-
$\mathrm{NLL}_{\mathcal{T}}+\mathrm{LO}_{N+1}$	LO_N	~ 1	NLL	~ 1	LO_{N+1}	~ 1
$\mathrm{NLL}'_{\mathcal{T}}+\mathrm{LO}_{N+1}$	NLO_N	$\sim \alpha_s$	NLL′	$\sim \alpha_s^{1/2}$	LO_{N+1}	~ 1
$\mathrm{NNLL}_{\mathcal{T}}+\mathrm{NLO}_{N+1}$	NLO_N	$\sim \alpha_s$	NNLL	$\sim \alpha_s$	NLO_{N+1}	$\sim \alpha_s$
$\mathrm{NNLL}'_{\mathcal{T}}+\mathrm{NLO}_{N+1}$	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: Γ_{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
$\mathrm{NLL}'+\mathrm{LO}_{N+1}$	NLO_N	LO_{N+1}	1-loop	2-loop	2-loop
$\mathrm{NNLL}+\mathrm{LO}_{N+1}$	NLO_N	LO_{N+1}	2-loop	3-loop	3-loop
NNLL′	NNLO_N	-	2-loop	3-loop	3-loop
$\mathrm{NNLL}'+\mathrm{NLO}_{N+1}$	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

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

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

$$\vdots$$

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

Iterating the Geneva method to higher multiplicities

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

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

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

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

$$\vdots$$

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

Comparison of available tools

Tool	Hard SubProcess	Extra Emissions(s)	Logarithmic Accuracy	Inclusive x-sec
SMC@LO (PYTHIA,HERWIG)	LO	all shower approx.*	(N)LL	LO
CKKW / MLM	LO	LO $1^{\rm st} - k^{\rm th}, k < 6$ + shower approx.	(N)LL	LO
SMC@NLO (POWHEG,MC@NLO)	NLO	LO $1^{\rm st}$ + shower approx.	(N)LL	NLO
MENLOPS (POWHEG,SHERPA CKKW@NLO)	NLO	LO $1^{\rm st} - k^{\rm th}$ or NLO $1^{\rm st}$ + shower approx.	(N)LL	NLO + $\alpha_S^2 L^3$
Geneva	NLO	NLO $1^{\rm st} - k^{\rm th}$	NLL†	NLO + α_S^2 + $\alpha_S^3 L^2$

* LO with ME corrections

() NLL for simple color structures only

† up to $\mathcal{T}_N^{\rm cut}$ + (N)LL PS

NLO accuracy of POWHEG formula (1)

- Use the POWHEG formula

$$d\sigma = \bar{B}(\Phi_n)\ d\Phi_n\ \left\{\Delta(\Phi_n, p_T^{\min}) + \Delta(\Phi_n, k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)}\ \theta(k_T - p_T^{\min})\ d\Phi_{\rm rad}\right\}$$

- to calculate the expectation value of a generic observable $< \mathcal{O} > =$

$$= \int \bar{B}(\Phi_n)\ d\Phi_n \left\{\Delta(\Phi_n, p_T^{\min}) O_n(\Phi_n) + \int_{p_T^{\min}} \Delta(\Phi_n, k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)} O_{n+1}(\Phi_{n+1})\ d\Phi_{\rm rad}\right\}$$

$$= \int \bar{B}(\Phi_n)\ d\Phi_n\ \left\{\left[\Delta(\Phi_n, p_T^{\min}) + \int_{p_T^{\min}} \Delta(\Phi_n, k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)}\ d\Phi_{\rm rad}\right] O_n(\Phi_n)\right.$$

$$\left. + \int_{p_T^{\min}} \Delta(\Phi_n, k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)}\ [O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n)]\ d\Phi_{\rm rad}\right\}$$

- O_n, O_{n+1} are the actual forms of $\mathcal{O}$ in the $n, n+1$-body phase space.
- $\mathcal{O}$ is required to be infrared-safe and to vanish fast enough when two singular regions are approached at the same time

NLO accuracy of POWHEG formula (2)

- Now observe that

$$\int_{p_{\rm T}^{\rm min}} d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, k_{\rm T}) = \int_{p_{\rm T}^{\rm min}}^{\infty} dp'_{\rm T} \int d\Phi_{\rm rad}\ \delta(k_{\rm T} - p'_{\rm T}) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, p'_{\rm T})$$

$$= - \int_{p_{\rm T}^{\rm min}}^{\infty} dp'_{\rm T} \Delta(\Phi_n, p'_{\rm T}) \frac{d}{dp'_{\rm T}} \int_{p_{\rm T}^{\rm min}} d\Phi_{\rm rad}\ \theta(k_{\rm T} - p'_{\rm T}) \frac{R(\Phi_{n+1})}{B(\Phi_n)}$$

$$= \int_{p_{\rm T}^{\rm min}}^{\infty} dp'_{\rm T} \frac{d}{dp'_{\rm T}} \Delta(\Phi_n, p'_{\rm T}) = 1 - \Delta(\Phi_n, p_{\rm T}^{\rm min})$$

- Furthermore we can replace $\bar{B}(\Phi_n) \approx B(\Phi_n)\,(1 + \mathcal{O}(\alpha_{\rm S}))$
- and also $\Delta(\Phi_n, k_{\rm T}) \approx 1 + \mathcal{O}(\alpha_{\rm S})$ since $[O_{n+1} - O_n] \to 0$ at small $k_{\rm T}$'s
- The final result is (up to $p_{\rm T}^{\rm min}$ power-suppressed terms)

$$\begin{aligned} < \mathcal{O} > \quad = & \quad \int d\Phi_n \bar{B}(\Phi_n)\ 1\ O_n(\Phi_n) \\ + & \quad \int 1 \frac{R(\Phi_{n+1})}{1} \left[O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n) \right]\ d\Phi_{\rm rad} + \mathcal{O}(\alpha_{\rm S}) \end{aligned}$$