GENEVA

CALVIN BERGGREN, UC BERKELEY AND LBL

RESUMMATION AND PARTON SHOWERS WORKSHOP 2013

15 JULY 2013

Simone Alioli, Christian Bauer, CB, Andrew Hornig, Frank Tackmann, Christopher Vermilion, Jonathan Walsh, Saba Zuberi

Ingredients of GENEVA

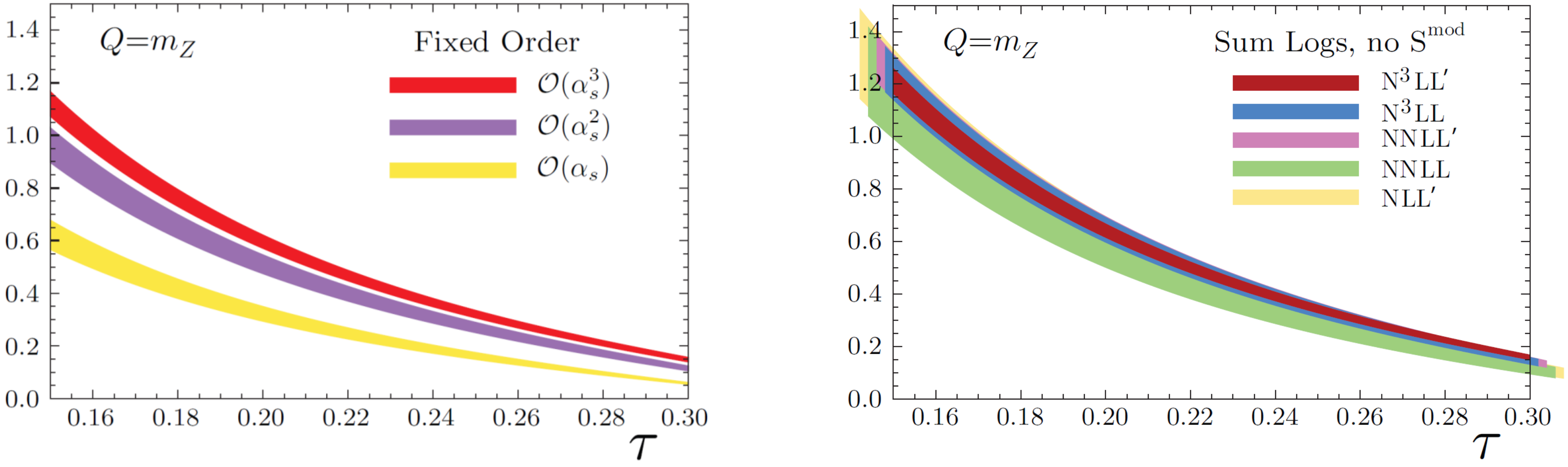
Fully exclusive LO and NLO matrix elements

Higher-order resummation

Parton showering and hadronization

Improved perturbative accuracy in every region of phase space

All ingredients important for many processes

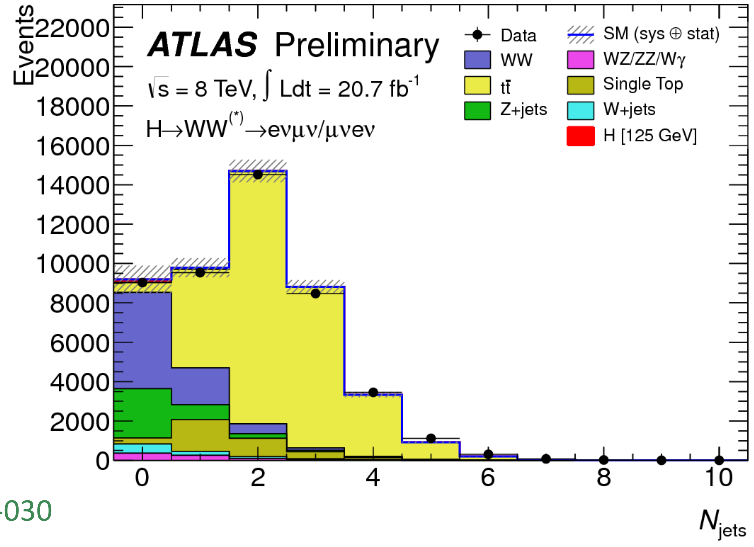


Abbate, Fickinger, Hoang, Mateu, Stewart 1006.3080

Fixed-order calculations alone can show poor convergence

Resummation can significantly improve convergence

All ingredients important for many processes



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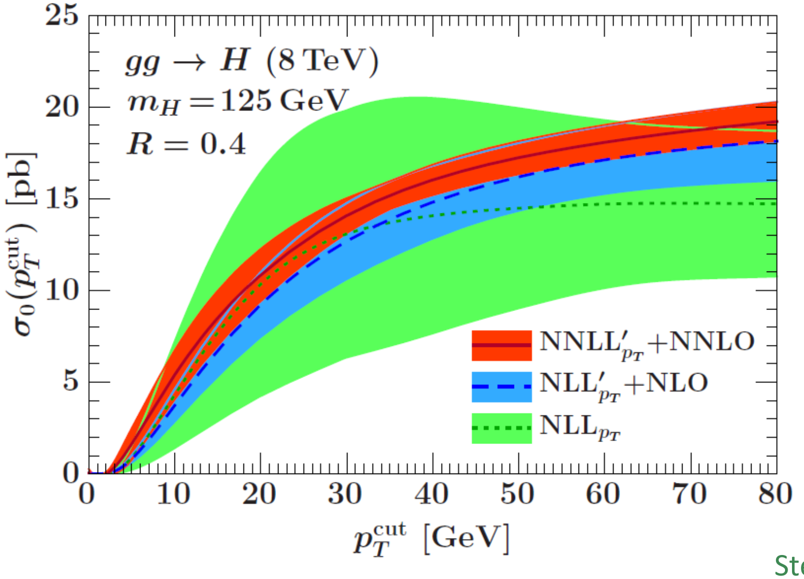


Stewart, Tackmann, Walsh, Zuberi 1307.1808

Many different multiplicities may be important and the backgrounds may be different

Resummation important in exclusive jet bins

Basic Setup

Consider a process with N tree-level partons

Introduce a physical jet resolution variable $\mathcal{T}$ to separate inclusive and exclusive regions in Φ_{N+1} phase space

$\mathcal{T}$ = Dimensionful jet resolution variable

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

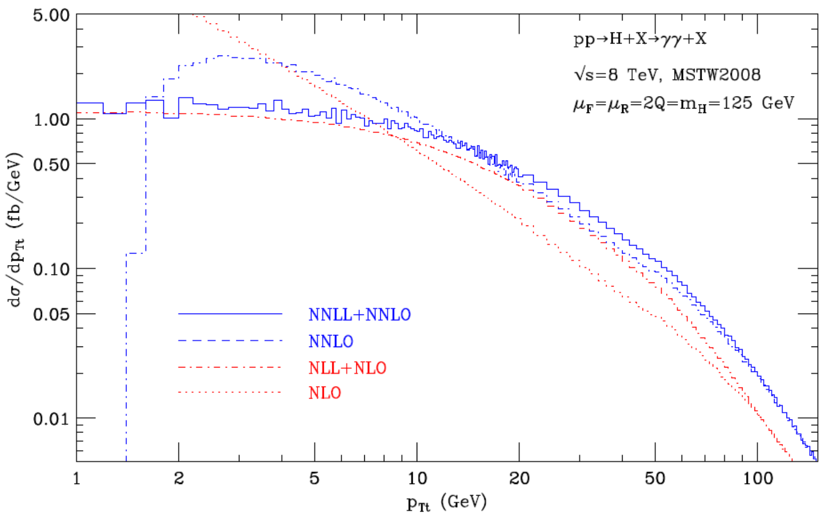
Total (inclusive) N-jet cross section

Exclusive N-jet bin with no emissions above $\mathcal{T}^{\mathrm{cut}}$

Jet resolution spectrum: inclusive (N+1)-jet cross section

Ultimately, $\mathcal{T}^{\mathrm{cut}} \to 0$ (IR cutoff)

Regions of Phase Space

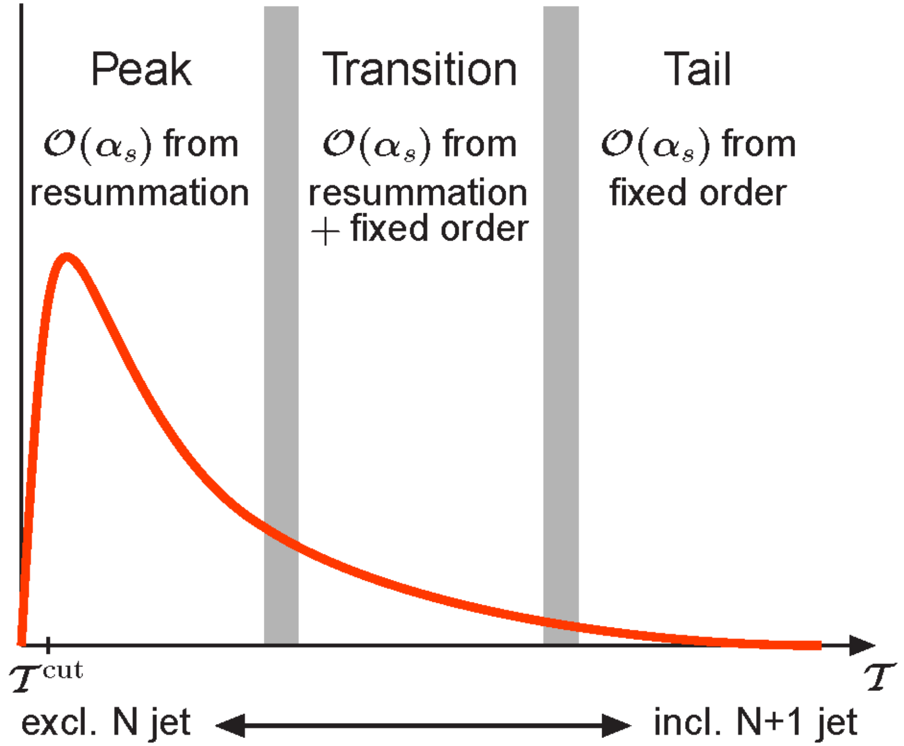


De Florian, Ferrera, Grazzini, Tommasini 1203.6321

Generic observables have multiple important regions of phase space

Peak region contains large logarithms

Regions of Phase Space

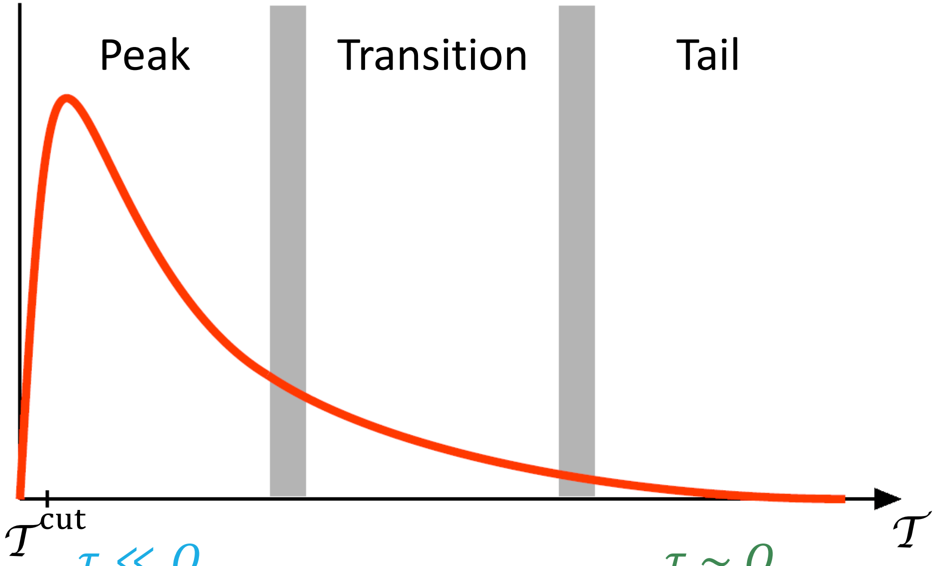


Generic observables have multiple important regions of phase space

Peak region contains large logarithms

Perturbative Accuracy

Lowest perturbative accuracy everywhere requires NLL + $\mathrm{LO}_{\mathrm{N+1}}$ (CKKW, MLM)



$\tau \ll Q$
N narrow jets

$\tau \sim Q$
$\geq$ N jets

Notation:
$\tau = \mathcal{T}/Q$
$L = \ln \tau$

Pert Accuracy	Resummation ($\alpha_s L^2 \sim 1$)	Fixed Order
LO	$\mathrm{NLL}_\sigma \sim \alpha_s/\tau\,(\alpha_s L^2)^n$	$\mathrm{LO}_{\mathrm{N+1}} \sim \alpha_s$

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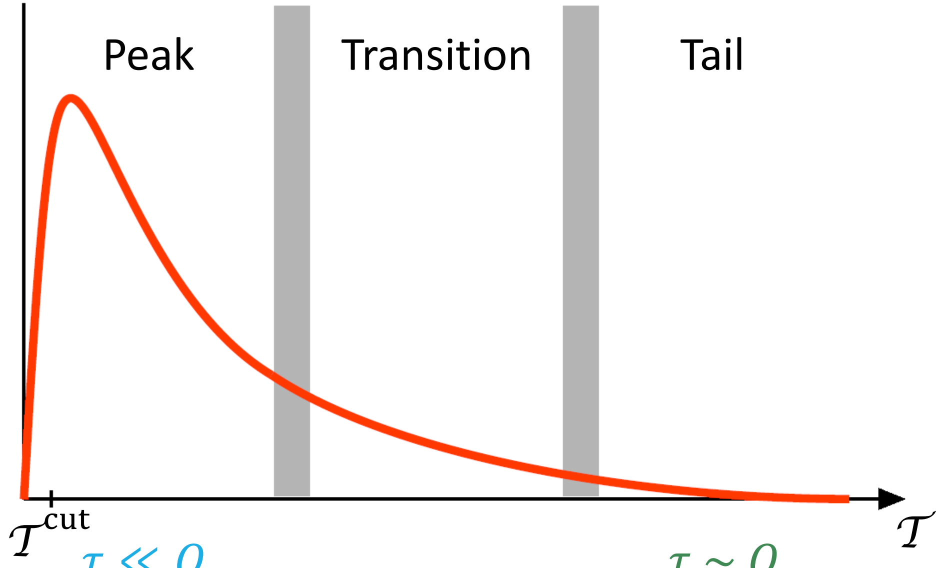

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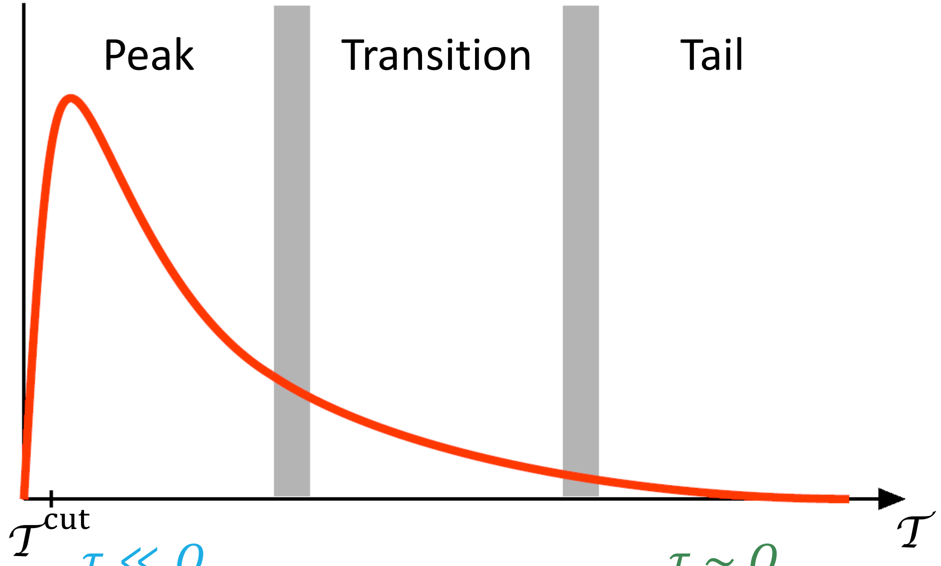
NLO		$\mathrm{NLO}_{\mathrm{N+1}} \sim \alpha_s^2$

Perturbative Accuracy

Lowest perturbative accuracy everywhere requires NLL + $\mathrm{LO}_{\mathrm{N+1}}$ (CKKW, MLM)

Next-to-Lowest perturbative accuracy everywhere requires NNLL+$\mathrm{NLO}_{\mathrm{N+1}}$



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NLO	$\mathrm{NNLL}_\sigma \sim \alpha_s^2/\tau\,(\alpha_s L^2)^n$	$\mathrm{NLO}_{\mathrm{N+1}} \sim \alpha_s^2$

Perturbative Accuracy

Order counting $\alpha_s L^2 \sim 1$ gives towers of logarithms (Notation: $\tau = \mathcal{T}/Q$, $L = \ln\tau$, $L_\mathrm{cut} = \ln\tau^\mathrm{cut}$)

$$
\begin{array}{cccccccccccc}
 & & & \mathrm{LL}_\sigma & & \mathrm{NLL}_\sigma & & \mathrm{NLL'}_\sigma & & \mathrm{NNLL}_\sigma & & \\
\dfrac{\sigma(\tau^\mathrm{cut})}{\sigma_B} & = & & 1 & & & & & & & & \mathrm{LO_N} \\
 & + & \alpha_s[& \frac{c_{11}}{2}L_\mathrm{cut}^2 & + & c_{10}L_\mathrm{cut} & + & c_{1,-1} & + & & F_1(\tau_{cut})] & \mathrm{NLO_N} \\
 & + & \alpha_s^2[& \vdots & + & \vdots & + & \vdots & + & \vdots & & \\
 & & & & & & & & & & & \\
\dfrac{1}{\sigma_B}\dfrac{d\sigma}{d\tau} & = & \alpha_s/\tau[& c_{11}L & + & c_{10} & + & & & & \tau f_1(\tau)] & \mathrm{LO_{N+1}} \\
 & + & \alpha_s^2/\tau[& c_{23}L^3 & + & c_{22}L^2 & + & c_{21}L & + & c_{20} & + \; \tau f_2(\tau)] & \mathrm{NLO_{N+1}} \\
 & + & \alpha_s^3/\tau[& \vdots & + & \vdots & + & \vdots & + & \vdots & &
\end{array}
$$

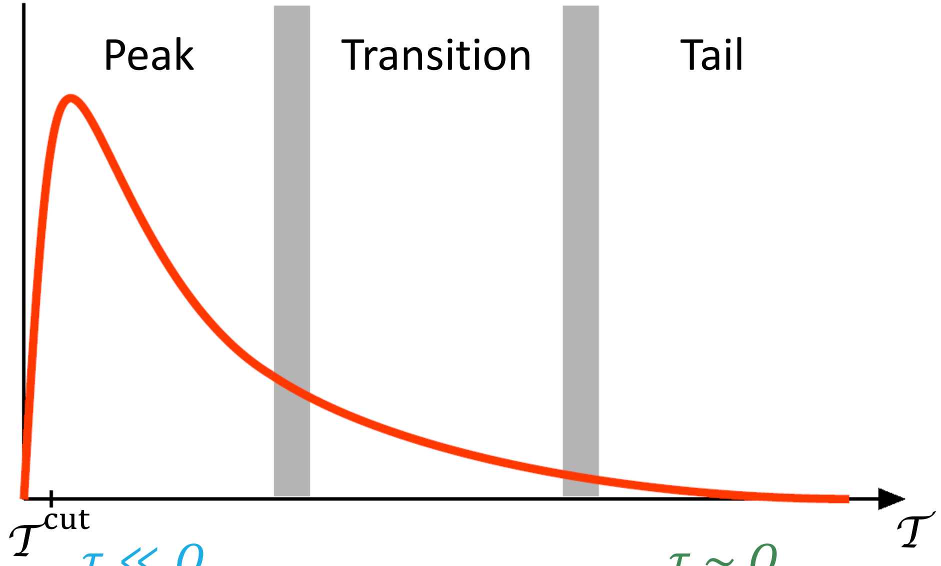
Perturbative Accuracy

In transition region, it is not obvious which corrections will be more important → should include both

- Consider $gg \to H$ with p_T roughly between 20 and 40 GeV

Using resummation provides reliable uncertainties

- Uncertainties come from theory calculation as opposed to some variation of the parton shower



Notation:
$\tau = \mathcal{T}/Q$
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$\tau \ll Q$ N narrow jets ⟷ $\tau \sim Q$ $\geq$ N jets

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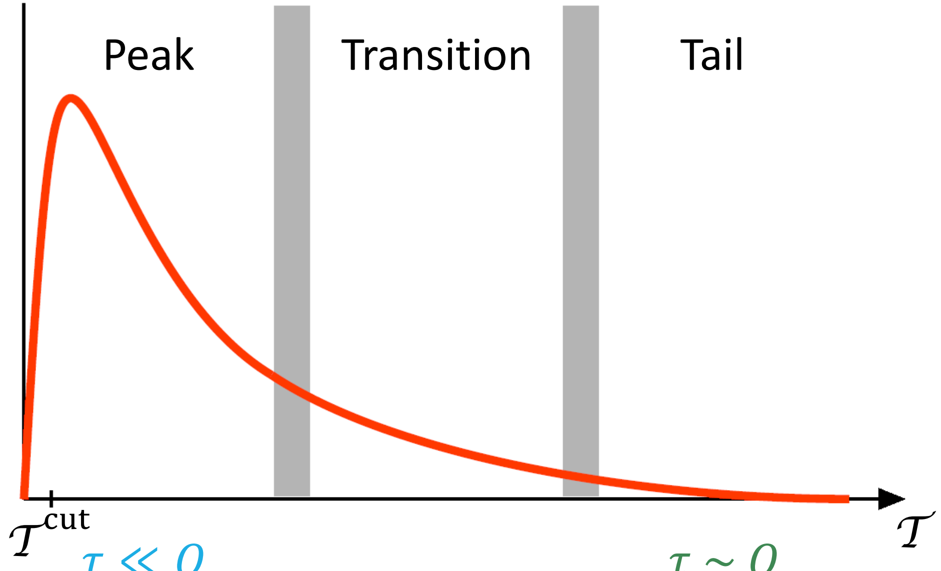
NLO	$\mathrm{NNLL}_\sigma \sim \alpha_s^2/\tau\,(\alpha_s L^2)^n$	$\mathrm{NLO}_{\mathrm{N+1}} \sim \alpha_s^2$

Merging Multiple NLO Calculations

Including $\mathrm{NLO}_{\mathrm{N+1}}$ at small $\mathcal{T}$ only meaningful together with higher-order resummation

We see multi-NLO as a byproduct of resummation



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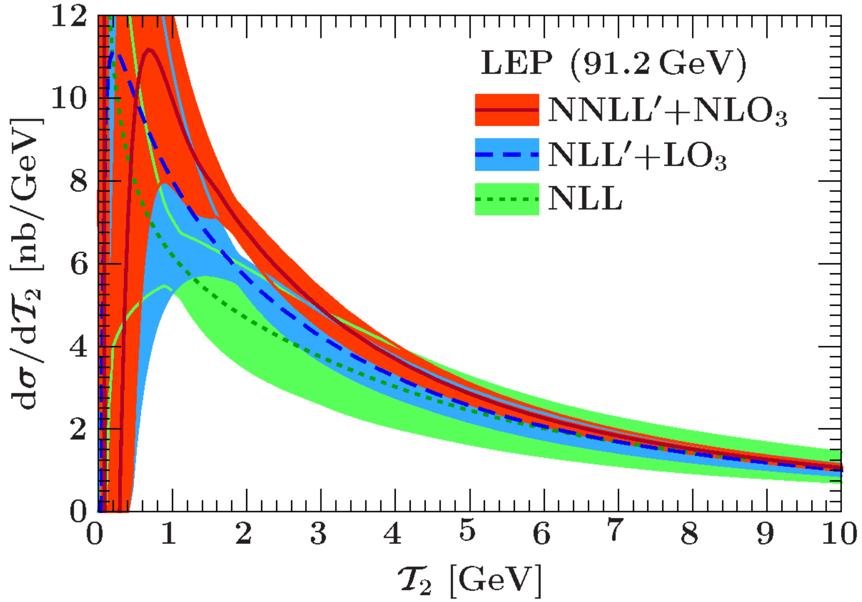
The Goal of GENEVA

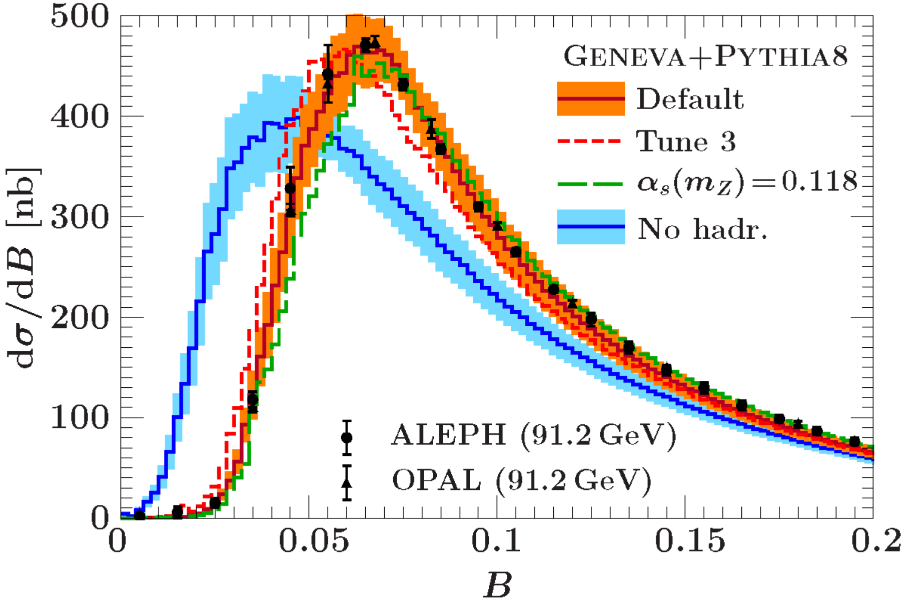
Analytic Thrust Resummation



High-accuracy prediction of a jet resolution variable including uncertainties

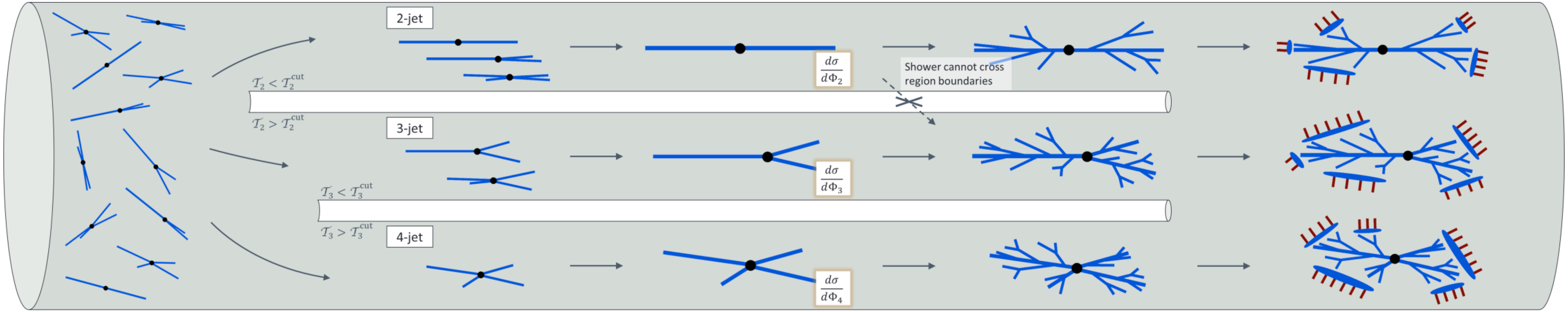
?

Monte Carlo Hadronized Events



Reasonably accurate prediction of a broad palette of observables

The process of GENEVA



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

N-jet Weights

$$\frac{d\sigma}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}}) + \left[\frac{d\sigma^{\mathrm{NLO}}}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}}) - \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}})\Big|_{\mathrm{NLO}}\right]$$

$$\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2) = \left[\frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2} \Big/ \frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2}\Big|_{\mathrm{NLO}}\right] \frac{d\sigma^{\mathrm{NLO}}}{d\Phi_3}$$

$$\frac{d\sigma}{d\Phi_4} = \frac{d\sigma^{\mathrm{LO}}}{d\Phi_4}$$

N-jet Weights

cumulant

$$\frac{d\sigma}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right) = \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right) + \left[\frac{d\sigma^{\mathrm{NLO}}}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right) - \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right)\Big|_{\mathrm{NLO}}\right]$$

Exclusive 2-jet bin uses the cumulant of the $\mathcal{T}_2$ spectrum, which includes the NLO fixed order

$$\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2) = \left[\frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2} \Big/ \frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2}\Big|_{\mathrm{NLO}}\right] \frac{d\sigma^{\mathrm{NLO}}}{d\Phi_3}$$

$$\frac{d\sigma}{d\Phi_4} = \frac{d\sigma^{\mathrm{LO}}}{d\Phi_4}$$

N-jet Weights

$$\frac{d\sigma}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right) = \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right) + \left[\frac{d\sigma^{\mathrm{NLO}}}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right) - \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}\left(\mathcal{T}_2^{\mathrm{cut}}\right)\Big|_{\mathrm{NLO}}\right]$$

In the tail, the terms in the brackets cancel, leaving the high-order NLO term.

In the peak, the terms involving NLO cancel, leaving the high-order resummed term.

$$\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2) = \left[\frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2} \Big/ \frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2}\Big|_{\mathrm{NLO}}\right] \frac{d\sigma^{\mathrm{NLO}}}{d\Phi_3}$$

Fully differential 3-body PS

$$\frac{d\sigma}{d\Phi_4} = \frac{d\sigma^{\mathrm{LO}}}{d\Phi_4}$$

3-jet bin uses fully differential NLO fixed order improved by the resummed $\mathcal{T}_2$ spectrum

$\frac{d\sigma^{\mathrm{FO}}}{d\Phi_3}$ projects onto $\frac{d\sigma^{\mathrm{FO}}}{d\Phi_2 d\mathcal{T}_2}$

N-jet Weights

$$\frac{d\sigma}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}}) + \left[\frac{d\sigma^{\mathrm{NLO}}}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}}) - \frac{d\sigma^{\mathrm{cum}}}{d\Phi_2}(\mathcal{T}_2^{\mathrm{cut}})\Big|_{\mathrm{NLO}}\right]$$

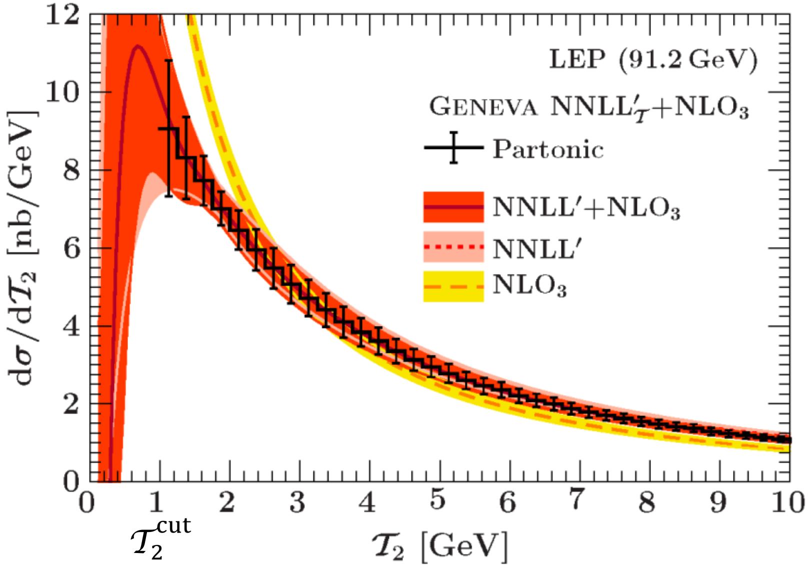
$$\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2) = \left[\frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2} \Big/ \frac{d\sigma^{\mathrm{resum}}}{d\Phi_2 d\mathcal{T}_2}\Big|_{\mathrm{NLO}}\right]\frac{d\sigma^{\mathrm{NLO}}}{d\Phi_3}$$

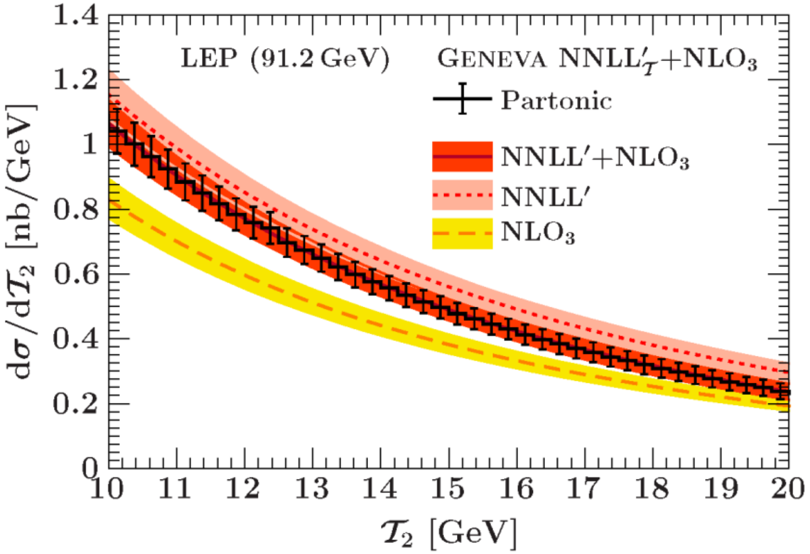
$$\frac{d\sigma}{d\Phi_4} = \frac{d\sigma^{\mathrm{LO}}}{d\Phi_4}$$

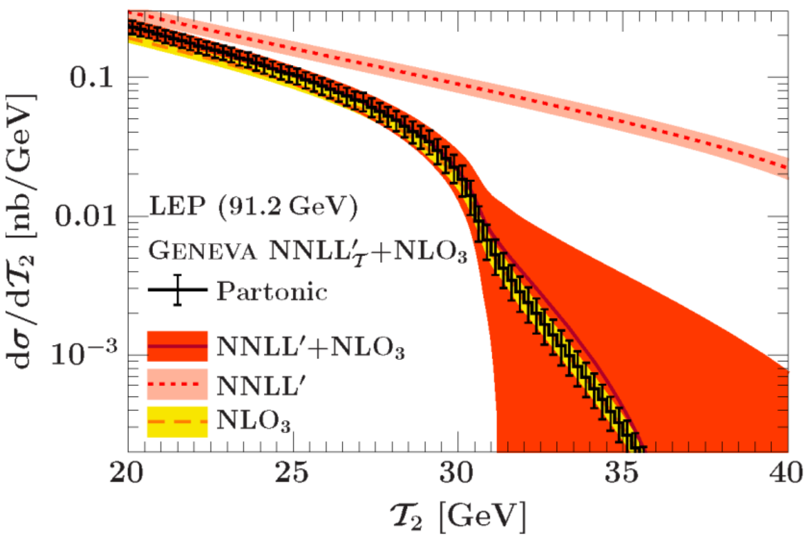
In this talk, last bin is LO

Process can be iterated to include more results at LO or NLO

Parton-Level Results

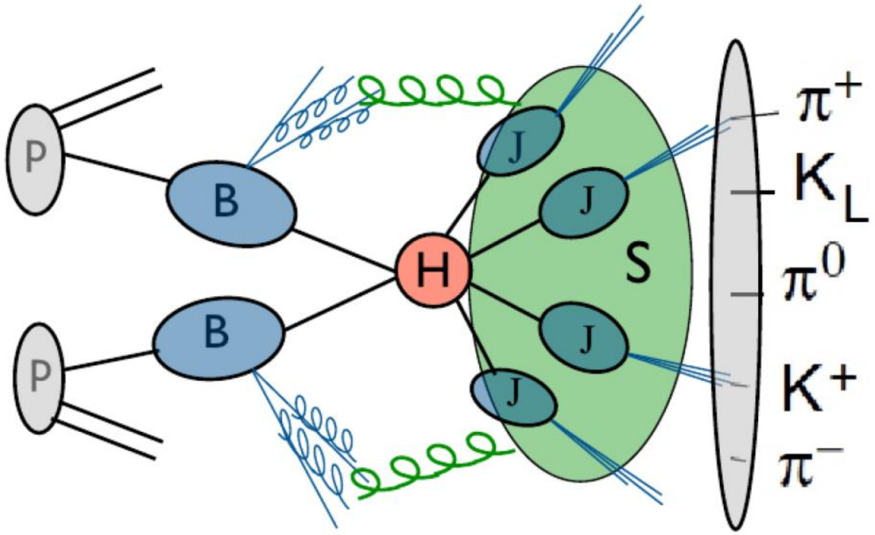






Adding the Shower

Division of Responsibility

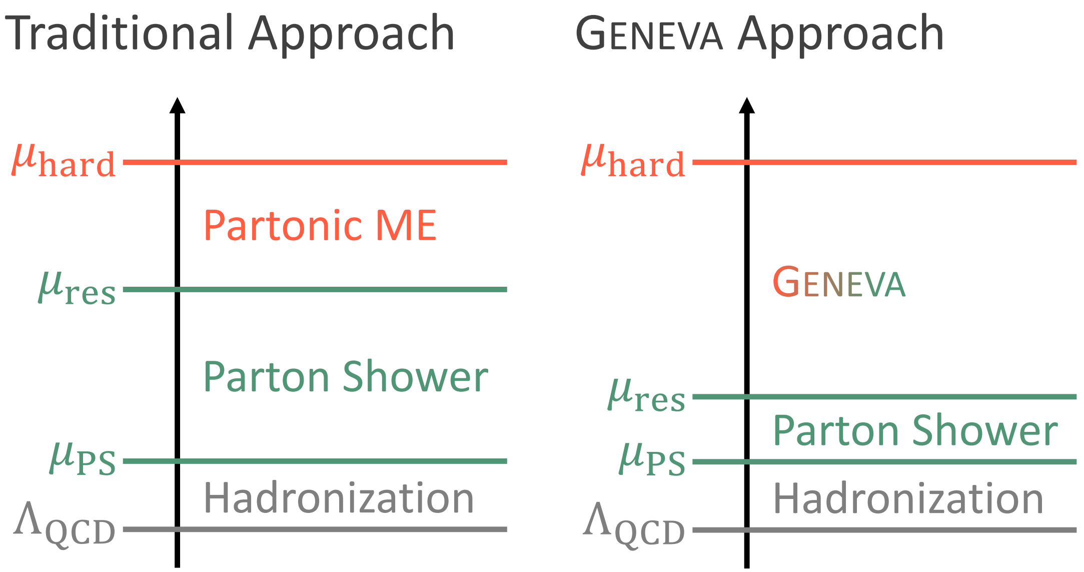


$$d\sigma^{\mathrm{MC}} = \boxed{\text{Hard Interaction}} \otimes \boxed{\text{Collinear Evolution} \otimes \text{Soft Radiation}} \otimes \begin{matrix}\text{PDFs}\\ \text{Hadronization}\\ \text{Underlying Event}\end{matrix}$$

Matrix Elements

Parton Shower Evolution

Division of Responsibility

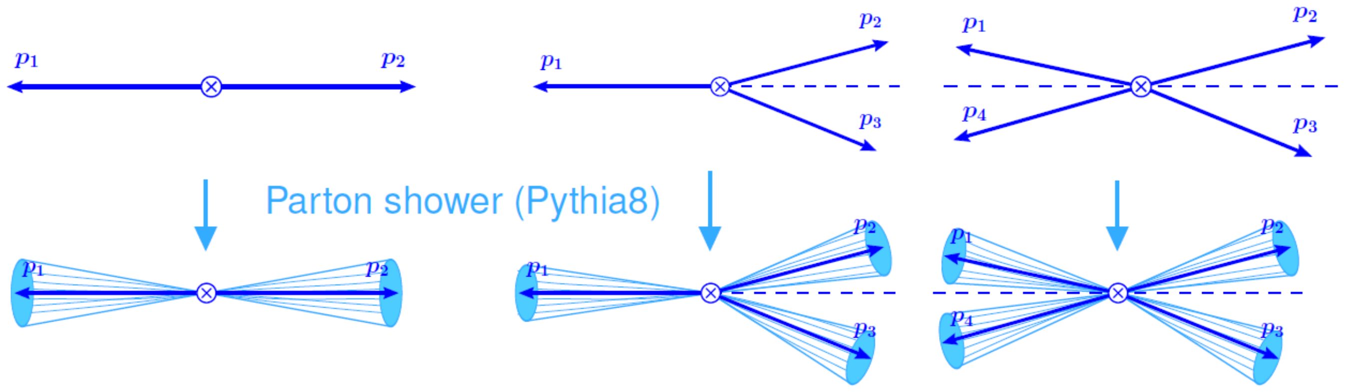


GENEVA seeks to replace portions of the parton shower with resummed calculations

We would like to “break apart” the parton shower and replace those pieces for which calculations exist

- Investigating other effects such as MPI
- Ultimately, GENEVA will require a new tune of the shower

Adding the Shower



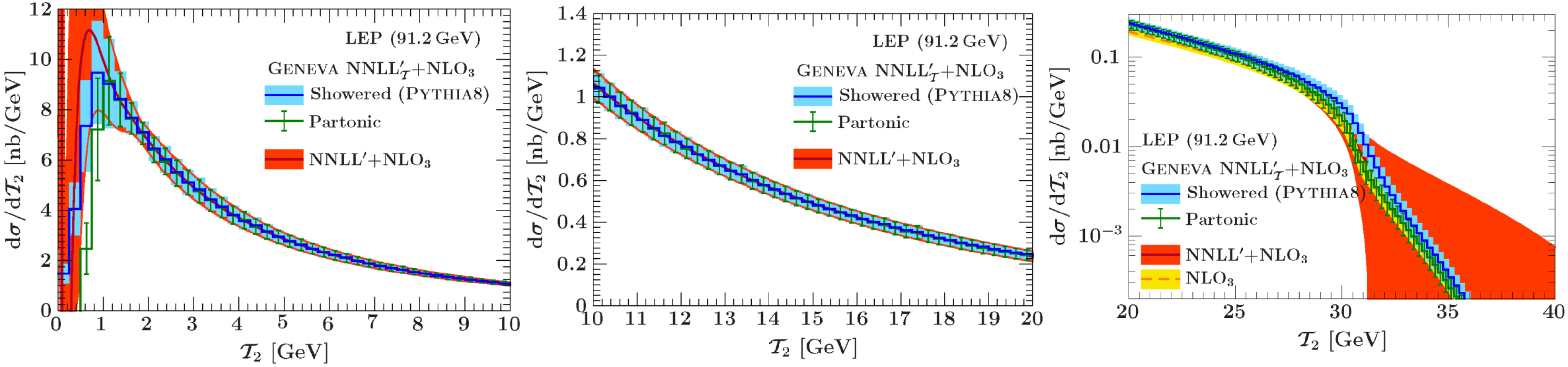
Require showered event to not change the value of $\mathcal{T}$ to within a power correction

$$\frac{\mathcal{T}_{\mathrm{GENEVA+PY}} - \mathcal{T}_{\mathrm{GENEVA}}}{\mathcal{T}_{\mathrm{GENEVA}}} < \lambda$$

Exclusive N-jet events do not cross jet boundaries, while the highest multiplicity bin showers inclusively

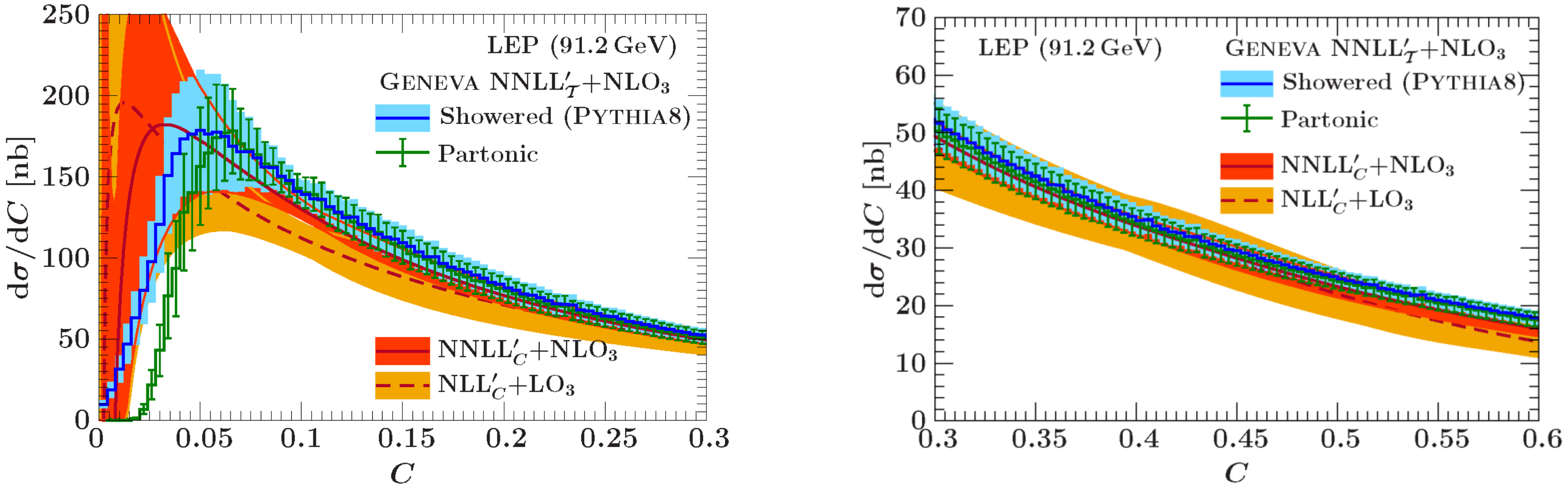
Internal shower kinematics not changed

Showered Results



Results for C-parameter

Different observable but similar log structure to thrust



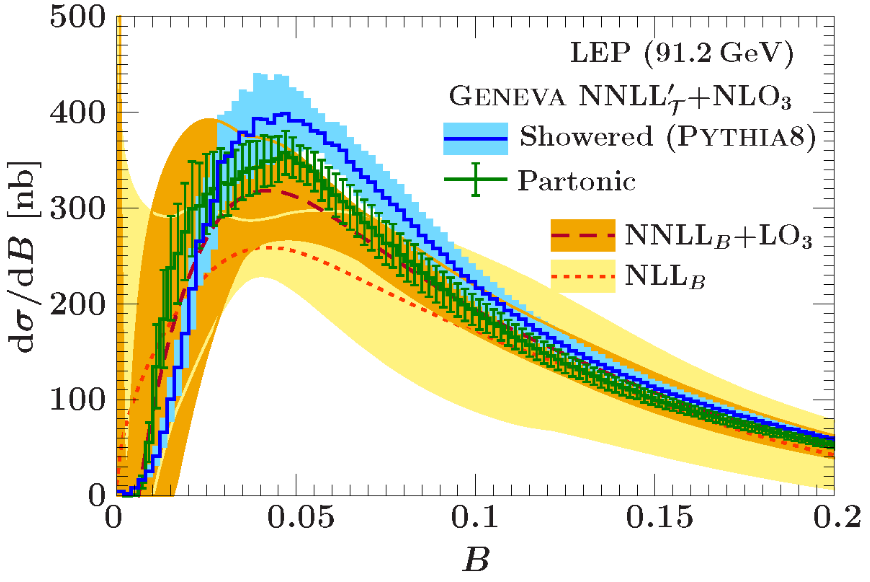
See SCET+PS session tomorrow for more discussion

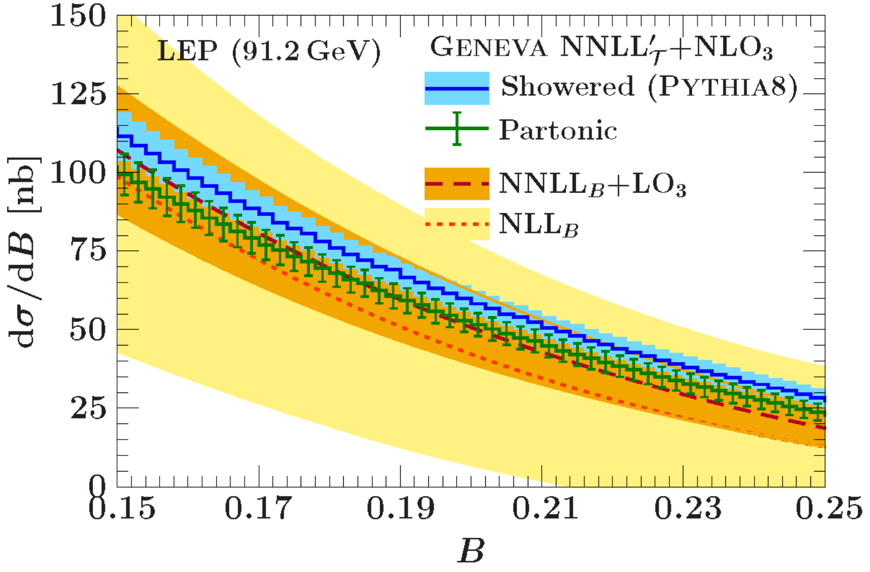
Spectrum at very small C filled out by shower

Remarkably close to NNLL′ analytic result – both central value and uncertainties

Results for Jet Broadening

Highly orthogonal observable to thrust – p_T-like





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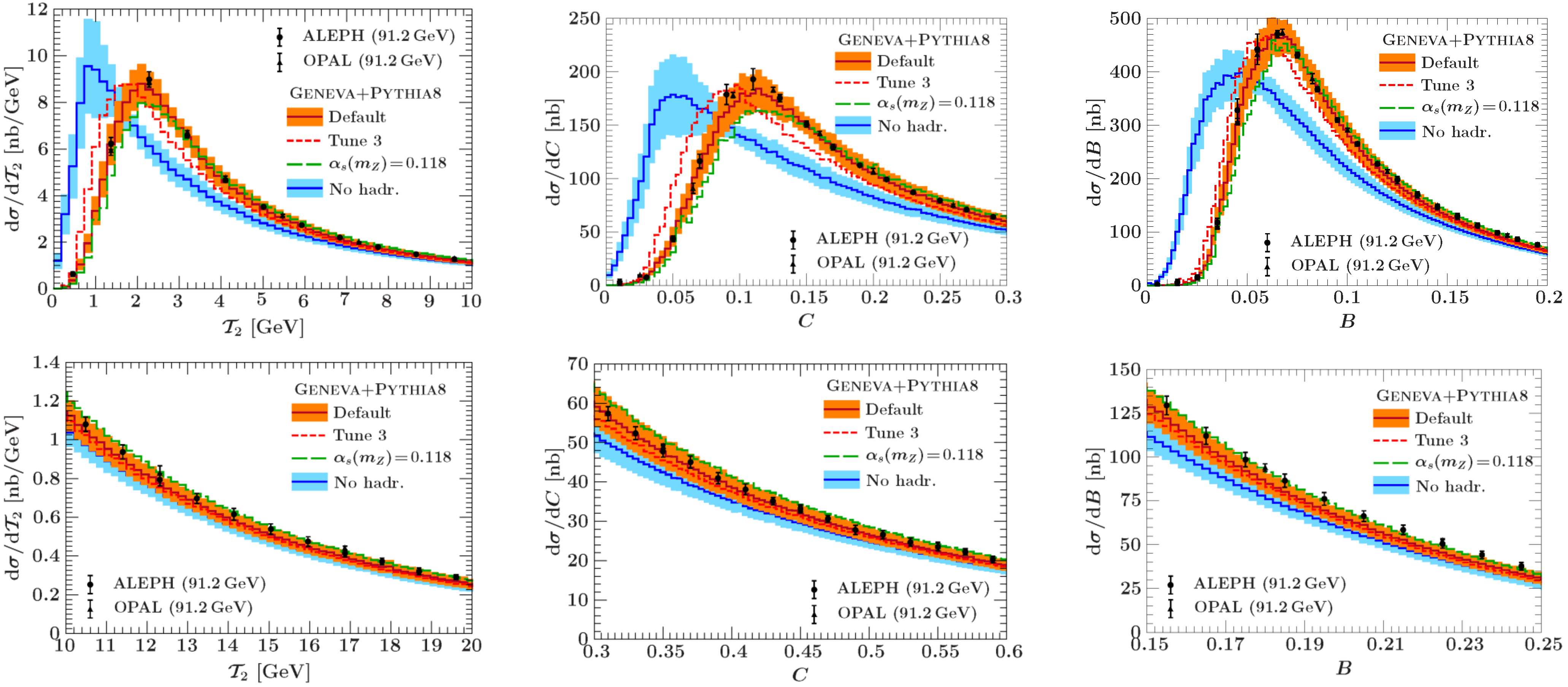
Spectrum filled out by shower

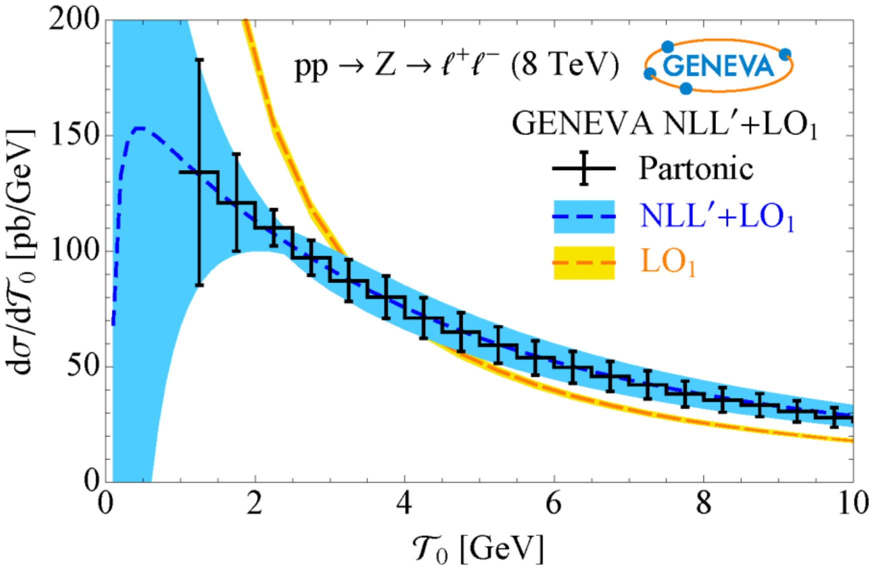
Remarkably close to NNLL analytic result – both central value and uncertainties

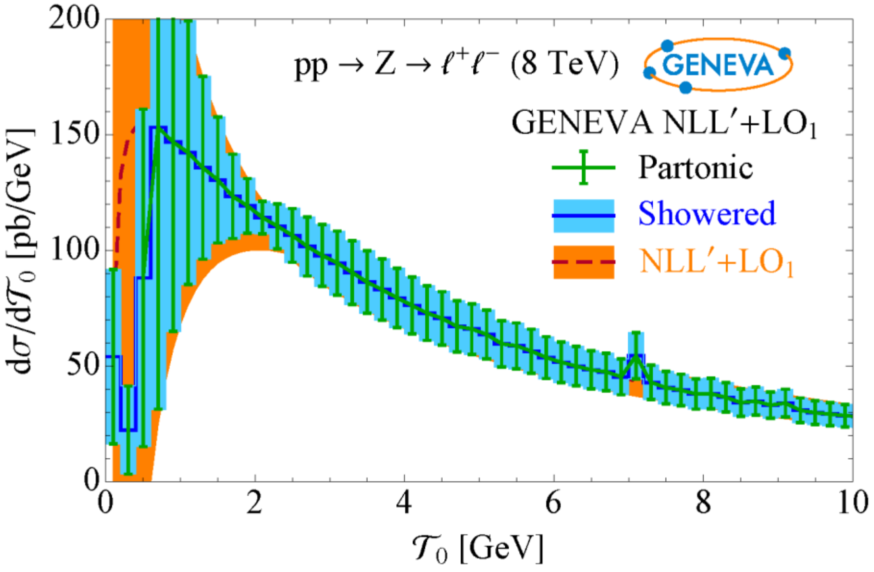
Including hadronization



Going to pp

Currently, Beam Thrust is our jet resolution parameter for $pp \to Z + \text{jets}$





We are in the process of validating the combination of higher-accuracy pieces:

NNLL′ + NLO$_1$ + Pythia

Conclusions

Precision measurements require precise predictions and reliable theory uncertainties

GENEVA is a Monte Carlo capable of systematically increasing perturbative accuracy across all of phase space including the resummation/shower region and capable of merging multiple calculations at NLO

Excellent agreement with LEP data for a variety of 2-jet observables

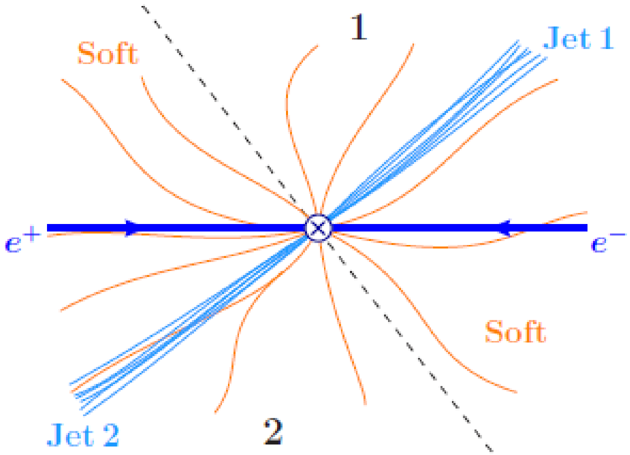
Currently focusing on $pp \to V + 0/1/2$ jets

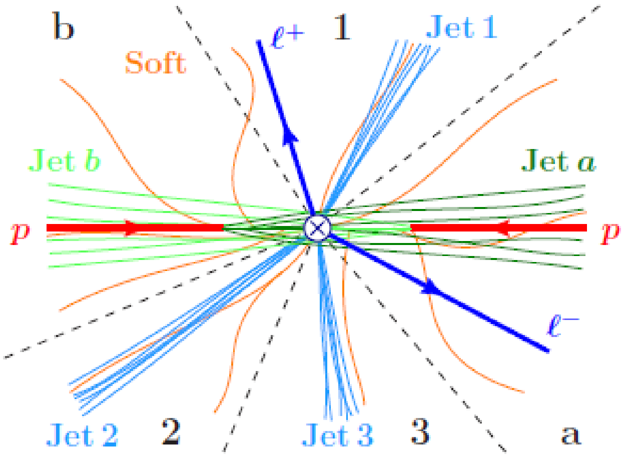
Backup Slides

N-Jettiness

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

From e^+e^- to pp collisions

Can use N-jettiness as in e^+e^- to distinguish jet multiplicities

master formula: $$\frac{\mathrm{d}\sigma^{\mathrm{incl}}}{\mathrm{d}\Phi_0} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \int \frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0}\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_1}(\mathcal{T}_0)\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

The essential perturbative physics translates to pp collisions

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\bigg|_{\mathrm{FO}}\right]$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_1}(\mathcal{T}_0) = \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_1}\left[\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\bigg/\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\bigg|_{\mathrm{FO}}\right]$$

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Initial state radiation provides conceptual, technical challenges

- Resummation involves beam functions, sum over partonic channels
- FO calculations more challenging
- Requires matching GENEVA to an initial state parton shower
- pp collisions require multiple parton interaction (MPI) model