Combining Higher-Order Resummation with Fully Exclusive NLO Calculations and Hadronization in GENEVA

GENEVA, 1211.7049

Jonathan Walsh, UC Berkeley

SCET X, Duke University
March 16, 2013

The GENEVA Collaboration:
Simone Alioli, Christian Bauer, Calvin Berggren, Andrew Hornig,
Frank Tackmann, Christopher Vermilion, JW, and Saba Zuberi

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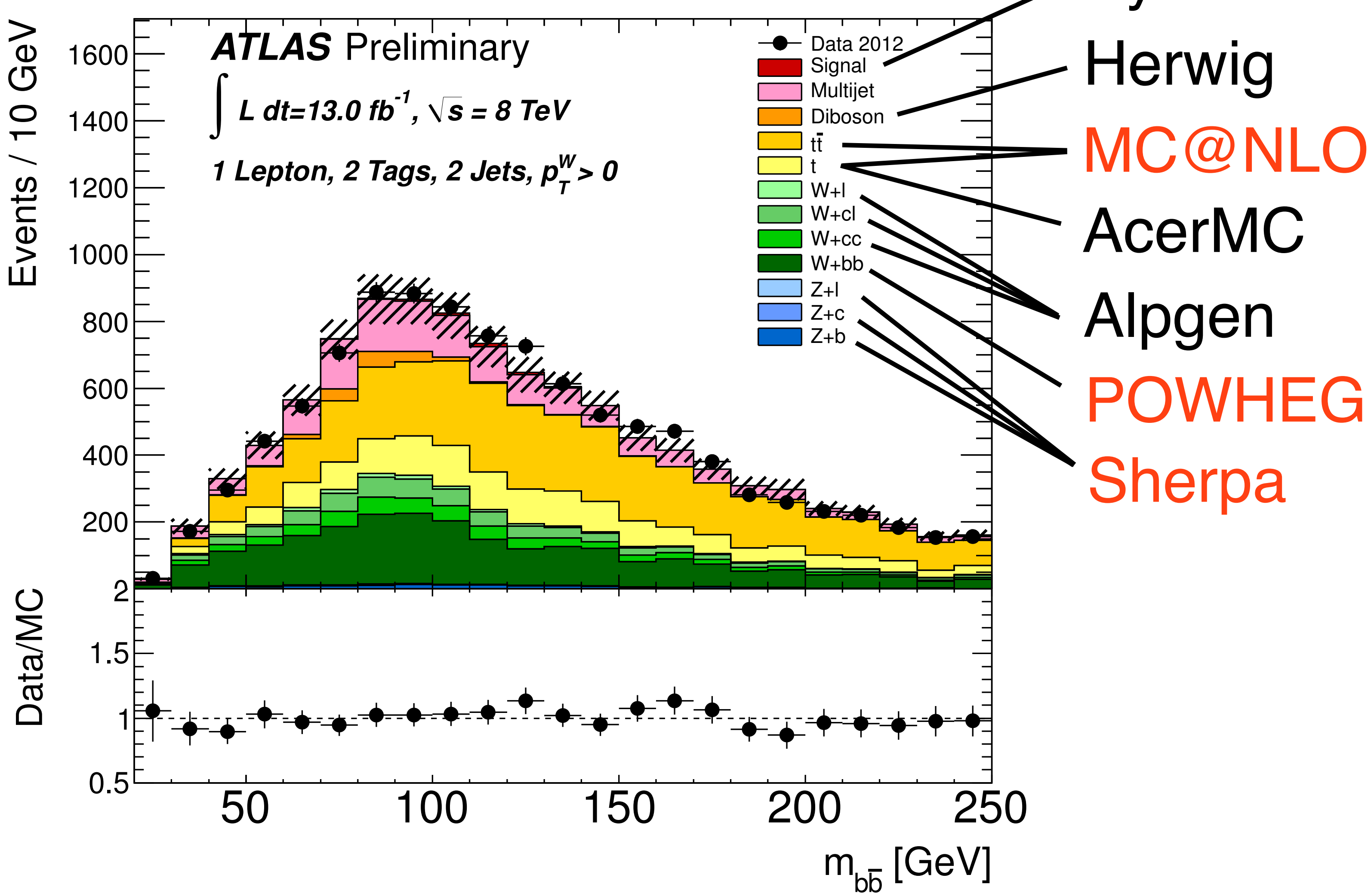
Nicolas

Zia

Precision Calculations + Monte Carlo Generators

$$pp \to Vh \to \ell\nu + b\bar{b}$$

ATLAS-CONF-2012-161

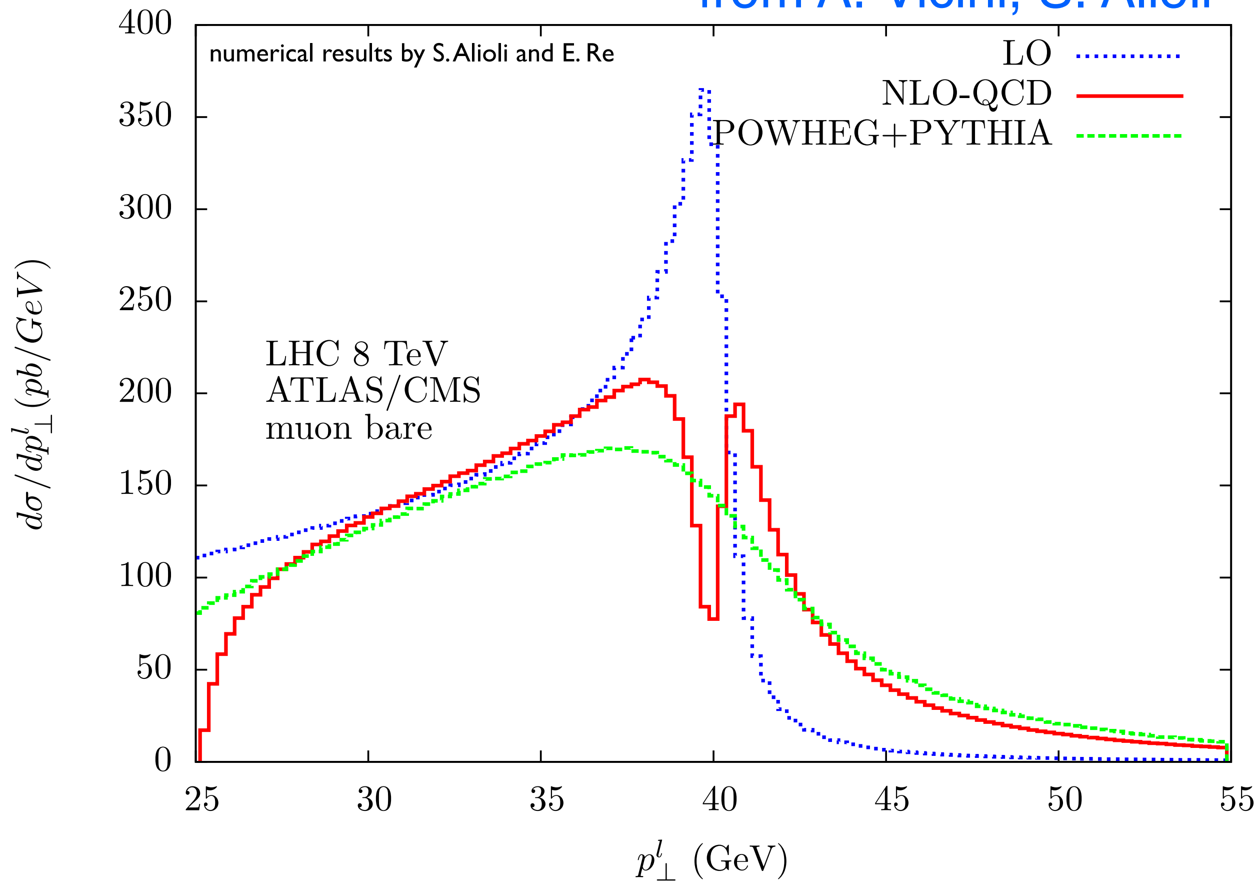


Monte Carlo generators are often the only appropriate tool to understand data, ***even when precision is required***

Precision Calculations + Monte Carlo Generators

But modern Monte Carlos are fundamentally
built from precision calculations

from A. Vicini, S. Alioli



NLO + resummation needed for an
accurate description of a simple observable

Outline

The GENEVA Framework

Comparison to LEP Data

Applications for the LHC

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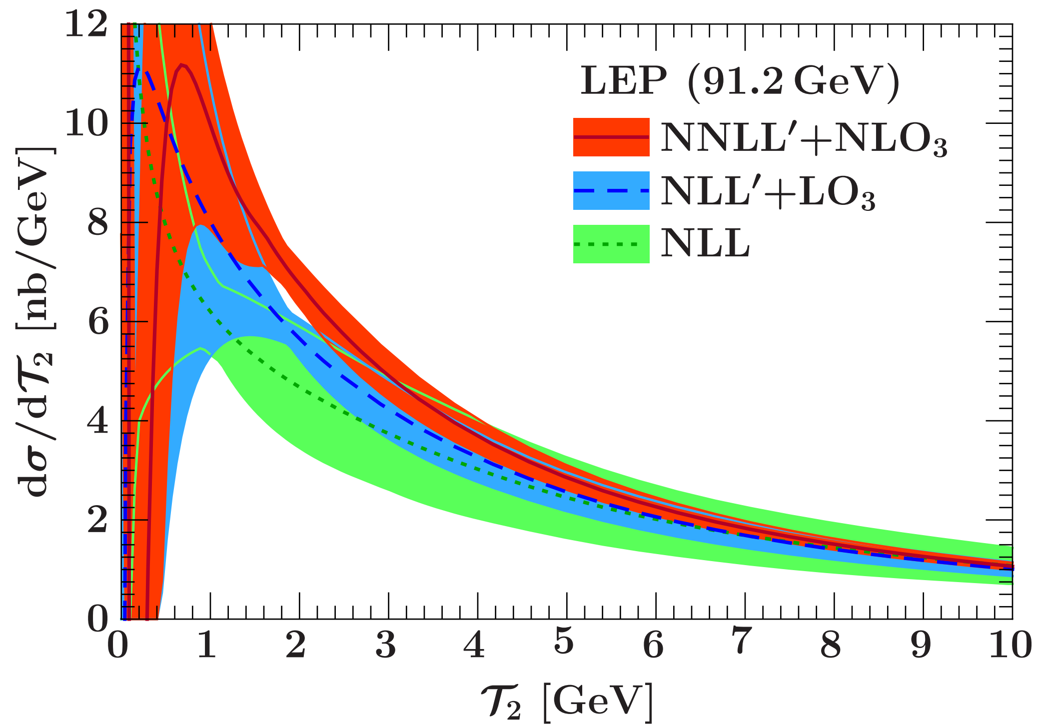
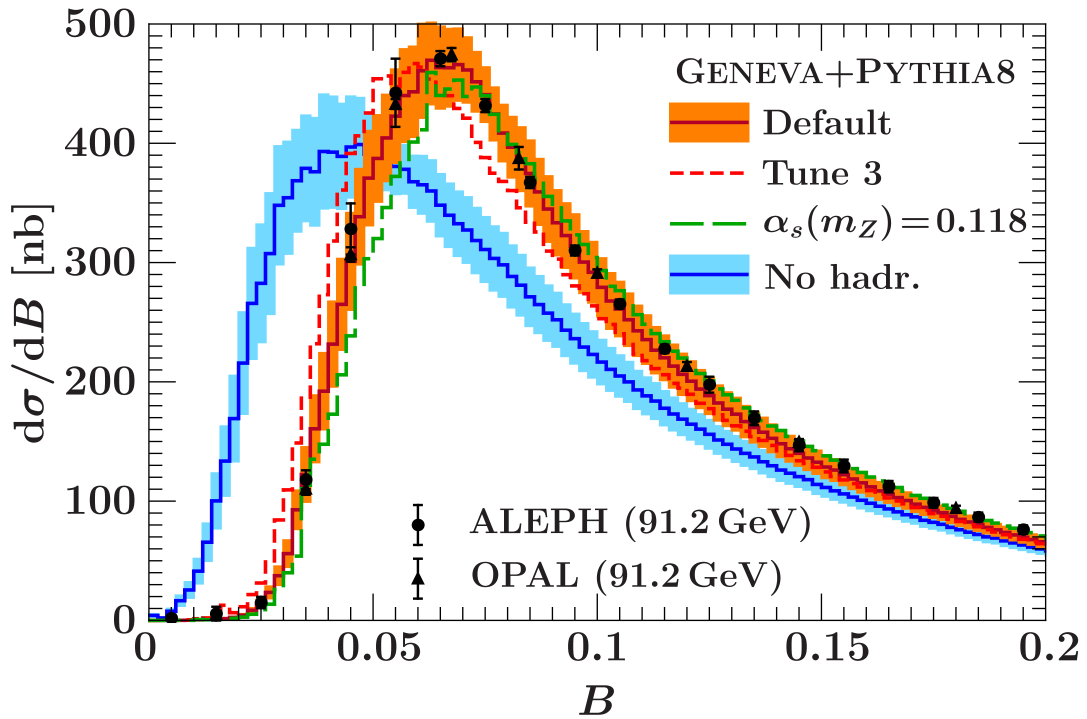
Comparison to LEP Data

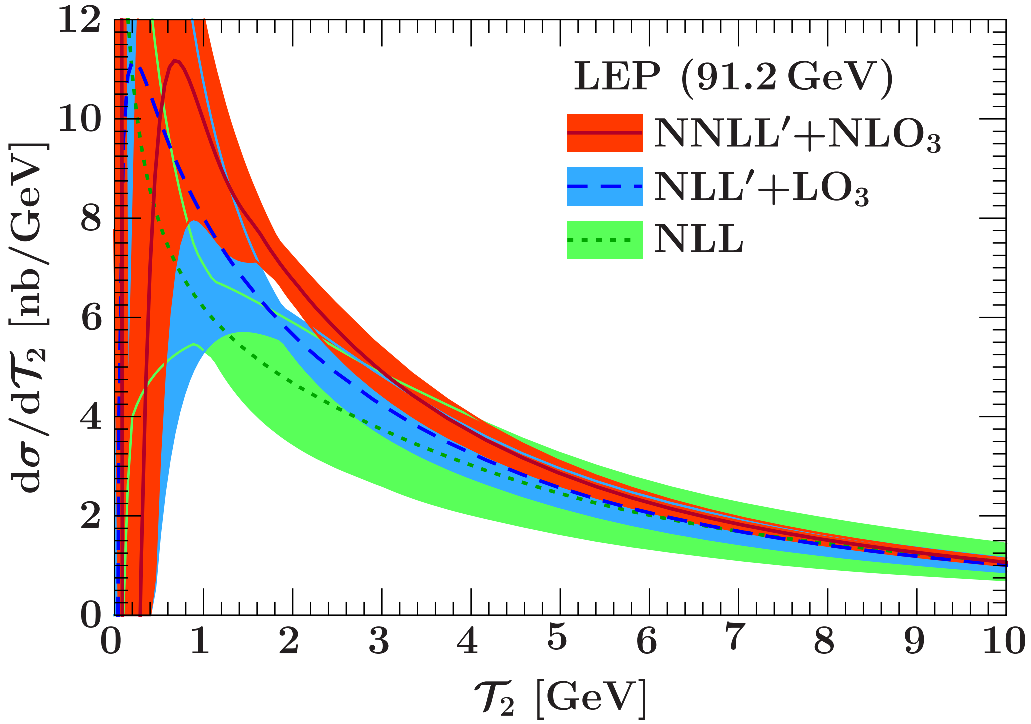
Applications for the LHC





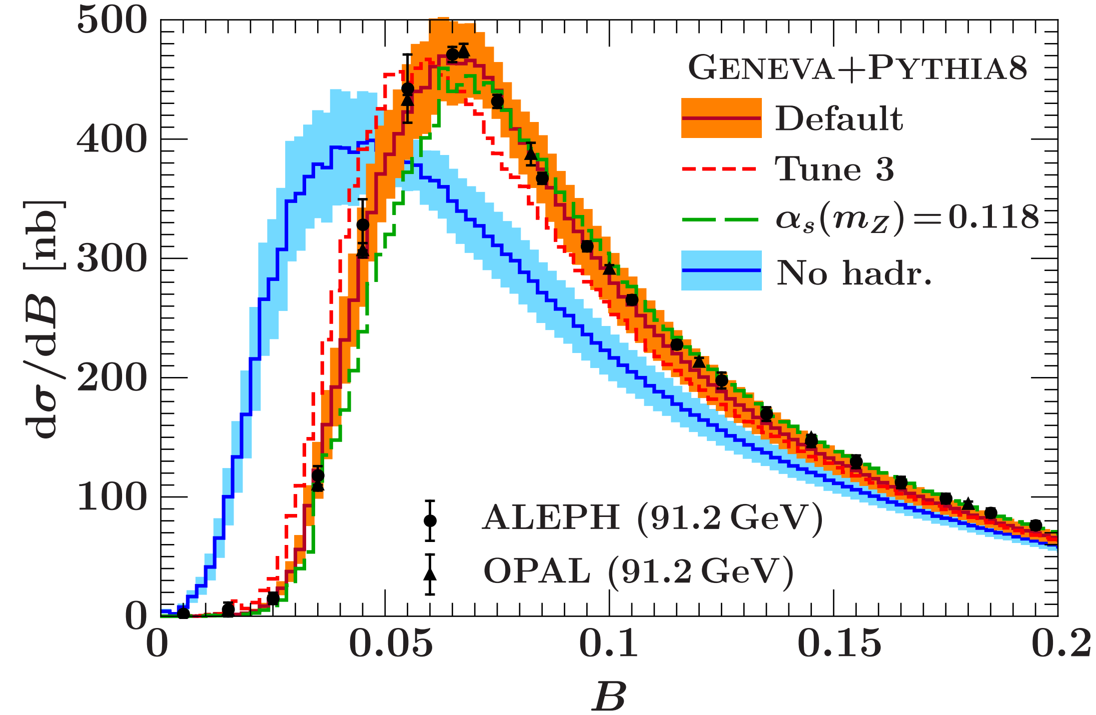
The GENEVA Monte Carlo in a Nutshell

analytic thrust resummation



high accuracy prediction
of a single observable

Monte Carlo hadronized events

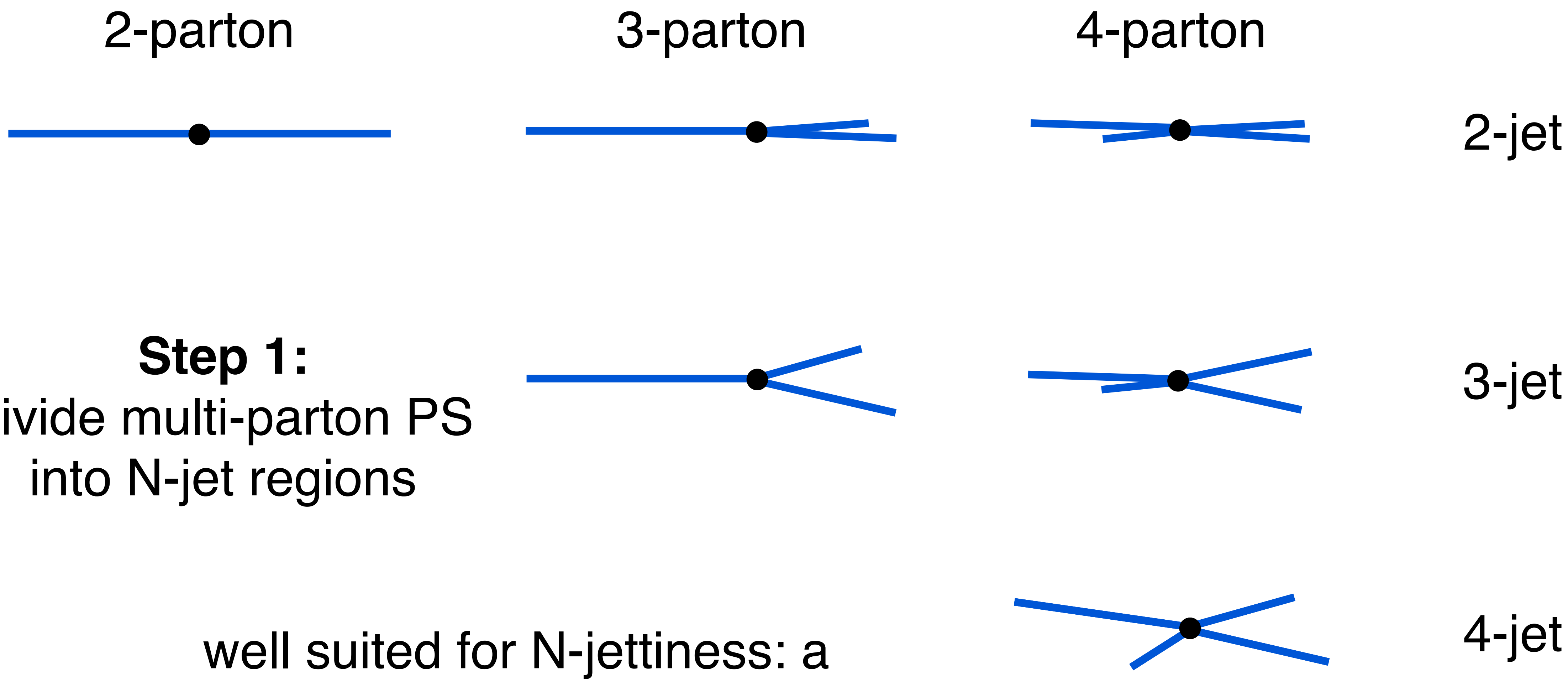


reasonably accurate prediction
of a broad palette of observables

need:

- fully exclusive fixed order calculations
- high order resummation of jet resolution parameter
- matching between jet multiplicities
- parton shower to fill out jets
- hadronization/MPI model for nonperturbative corrections

The GENEVA Monte Carlo in a Nutshell



Step 1:
divide multi-parton PS
into N-jet regions

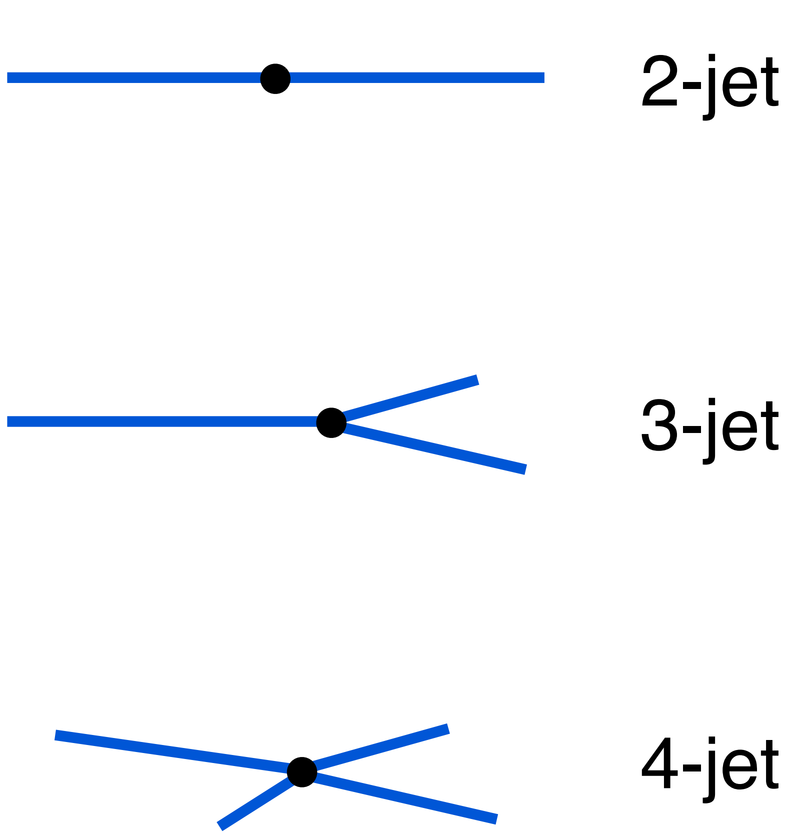
well suited for N-jettiness: a
physical jet resolution parameter

$$
\begin{aligned}
\mathcal{T}_2 < \mathcal{T}_2^{\rm cut} &\;:\; \text{2-jet exclusive} \;:\; \Phi_2 \\
\mathcal{T}_2 > \mathcal{T}_2^{\rm cut} \text{ and } \mathcal{T}_3 < \mathcal{T}_3^{\rm cut} &\;:\; \text{3-jet exclusive} \;:\; \Phi_3 \\
\mathcal{T}_2 > \mathcal{T}_2^{\rm cut} \text{ and } \mathcal{T}_3 > \mathcal{T}_3^{\rm cut} &\;:\; \text{4-jet inclusive} \;:\; \Phi_4
\end{aligned}
$$

A N-jet PS point is
represented by a
N-parton event

Stewart, Tackmann, Waalewijn 1004.2489

The GENEVA Monte Carlo in a Nutshell

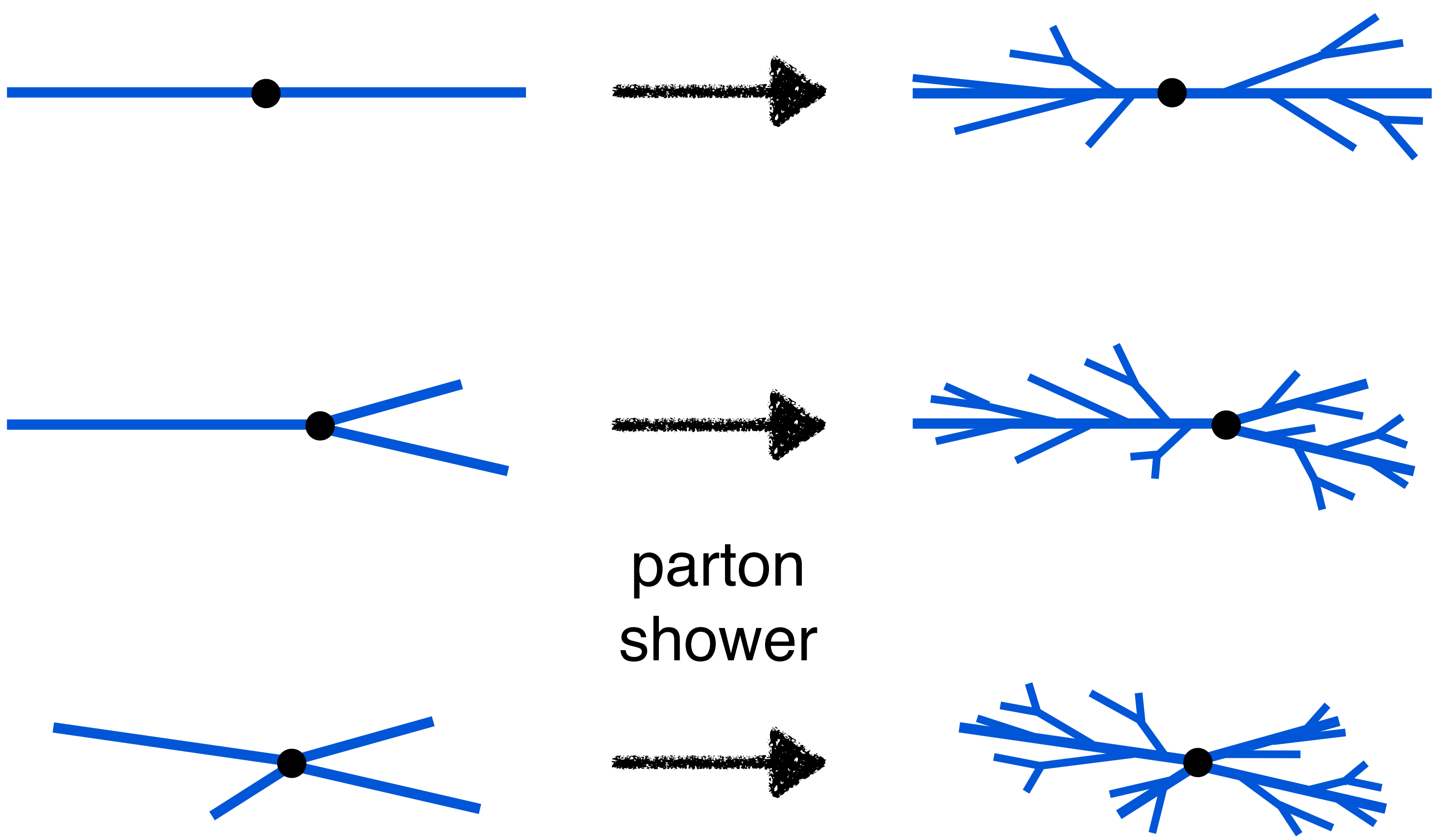


Step 2:
assign each N-jet PS point a fully differential weight

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}$$

We use an N-jettiness factorization theorem to compute the weight

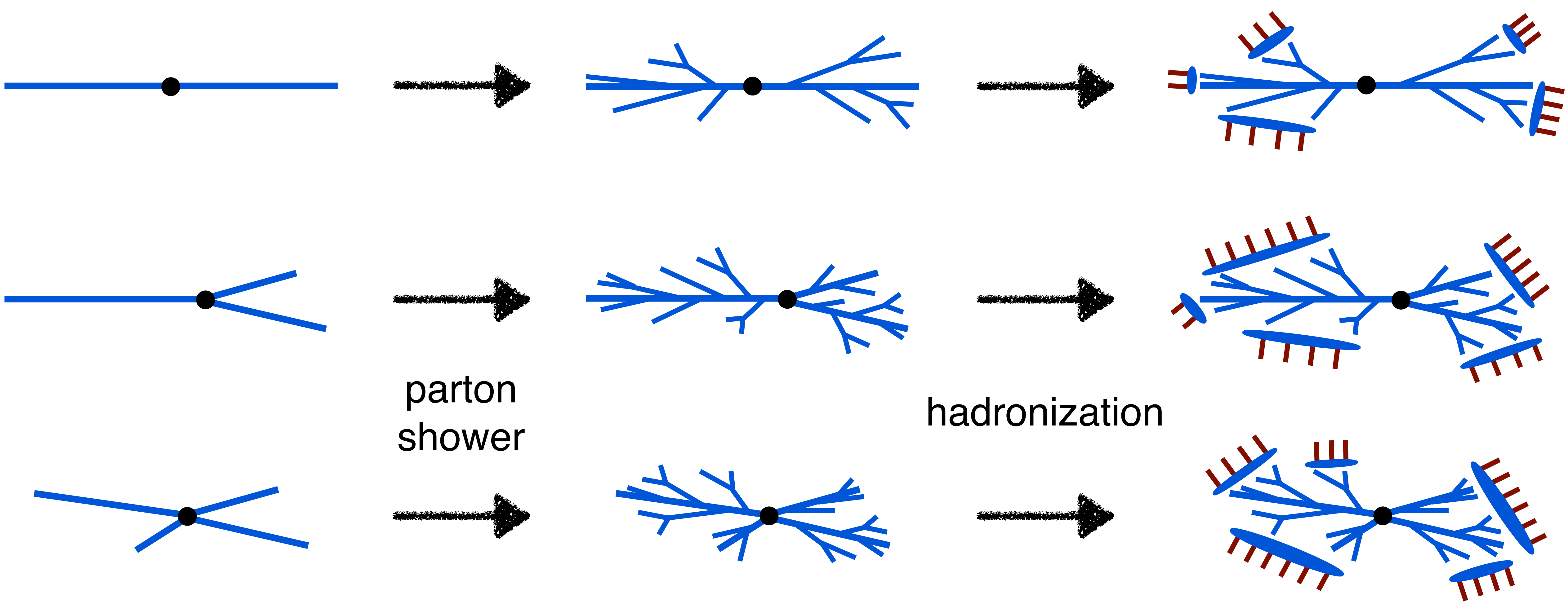
The GENEVA Monte Carlo in a Nutshell



Step 3:
shower each event
to “fill out” the jets

the shower is restricted
based on N-jettiness

The GENEVA Monte Carlo in a Nutshell



Step 4:
hadronize the events

Fully Exclusive Cross Sections in GENEVA

thrust spectrum

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_2 \mathrm{d}\mathcal{T}} = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2 \mathrm{d}\mathcal{T}} + \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_2 \mathrm{d}\mathcal{T}} - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2 \mathrm{d}\mathcal{T}}\bigg|_{\mathrm{exp}}$$

Φ_2: hard kinematics

But we want to be fully differential in N-body PS

Fully Exclusive Cross Sections in GENEVA

thrust spectrum

$$\frac{d\sigma}{d\Phi_2 d\mathcal{T}} = \frac{d\sigma^{\text{resum}}}{d\Phi_2 d\mathcal{T}} + \frac{d\sigma^{\text{FO}}}{d\Phi_2 d\mathcal{T}} - \frac{d\sigma^{\text{resum}}}{d\Phi_2 d\mathcal{T}}\bigg|_{\text{exp}}$$

cancel in singular limit

cancel in nonsingular limit

multiplicative matching

$$\frac{d\sigma}{d\Phi_2 d\mathcal{T}} = \left[\frac{d\sigma^{\text{FO}}}{d\Phi_2 d\mathcal{T}} \bigg/ \frac{d\sigma^{\text{resum}}}{d\Phi_2 d\mathcal{T}}\bigg|_{\text{FO}}\right] \frac{d\sigma^{\text{resum}}}{d\Phi_2 d\mathcal{T}}$$

alternative to additive matching

Fully Exclusive Cross Sections in GENEVA

thrust spectrum

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}} = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}} + \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}} - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}}\bigg|_{\mathrm{exp}}$$

cancel in singular limit

cancel in nonsingular limit

multiplicative matching

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_3} = \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_3} \bigg/ \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}}\bigg|_{\mathrm{FO}}\right] \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}}$$

fully differential 3-body PS

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

GENEVA Master Formula

$$\frac{\mathrm{d}\sigma^{\mathrm{incl}}}{\mathrm{d}\Phi_2} = \underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}})}_{\text{cumulant}} + \int \underbrace{\frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2}\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_3}(\mathcal{T})\theta(\mathcal{T} > \mathcal{T}_{\mathrm{cut}})}_{\text{spectrum}}$$

cumulant
exclusive 2-jet bin

spectrum
inclusive 3-jet bin

GENEVA Master Formula

$$\frac{d\sigma^{\text{incl}}}{d\Phi_2} = \frac{d\sigma}{d\Phi_2}(\mathcal{T}_{\text{cut}}) + \int \frac{d\Phi_3}{d\Phi_2}\underbrace{\frac{d\sigma}{d\Phi_3}(\mathcal{T})\theta(\mathcal{T} > \mathcal{T}_{\text{cut}})}$$

cumulant
exclusive 2-jet bin

spectrum
inclusive 3-jet bin

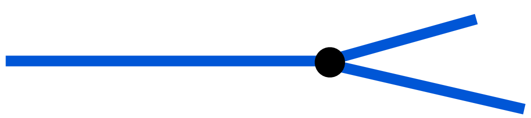
$$\frac{d\sigma}{d\Phi_2}(\mathcal{T}_{\text{cut}}) = \frac{d\sigma^{\text{resum}}}{d\Phi_2}(\mathcal{T}_{\text{cut}}) + \left[\frac{d\sigma^{\text{FO}}}{d\Phi_2}(\mathcal{T}_{\text{cut}}) - \frac{d\sigma^{\text{resum}}}{d\Phi_2}(\mathcal{T}_{\text{cut}})\bigg|_{\text{FO}}\right]$$

$$\frac{d\sigma}{d\Phi_3}(\mathcal{T}) = \frac{d\sigma^{\text{FO}}}{d\Phi_3}\left[\frac{d\sigma^{\text{resum}}}{d\Phi_2 d\mathcal{T}} \bigg/ \frac{d\sigma^{\text{resum}}}{d\Phi_2 d\mathcal{T}}\bigg|_{\text{FO}}\right]$$

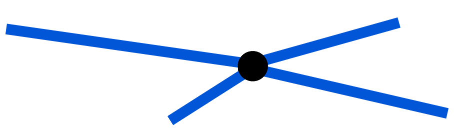
can calculate the N-jet FO cross section to NLO: NLO_N

N-jet Weights from the Master Formula

2-jet
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}}) + \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}}) - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}})\bigg|_{\mathrm{FO}}\right]$$



3-jet
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_3}(\mathcal{T}) = \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_3}\left[\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}} \bigg/ \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_2\mathrm{d}\mathcal{T}}\bigg|_{\mathrm{FO}}\right]$$



4-jet
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_4}(\mathcal{T}) = \frac{\mathrm{d}\sigma^{\mathrm{LO}}}{\mathrm{d}\Phi_4}$$

Iterating To More Jet Multiplicities: Future Possibilities

$$\frac{d\sigma^{\rm incl}}{d\Phi_2} = \frac{d\sigma}{d\Phi_2}(\mathcal{T}_2^{\rm cut}) + \int \frac{d\Phi_3}{d\Phi_2}\frac{d\sigma}{d\Phi_3}(\mathcal{T}_2)\theta(\mathcal{T}_2 > \mathcal{T}_2^{\rm cut})$$

$$\frac{d\sigma^{\rm incl}}{d\Phi_3} = \frac{d\sigma}{d\Phi_3}(\mathcal{T}_3^{\rm cut}) + \int \frac{d\Phi_4}{d\Phi_3}\frac{d\sigma}{d\Phi_3}(\mathcal{T}_3)\theta(\mathcal{T}_3 > \mathcal{T}_3^{\rm cut})$$

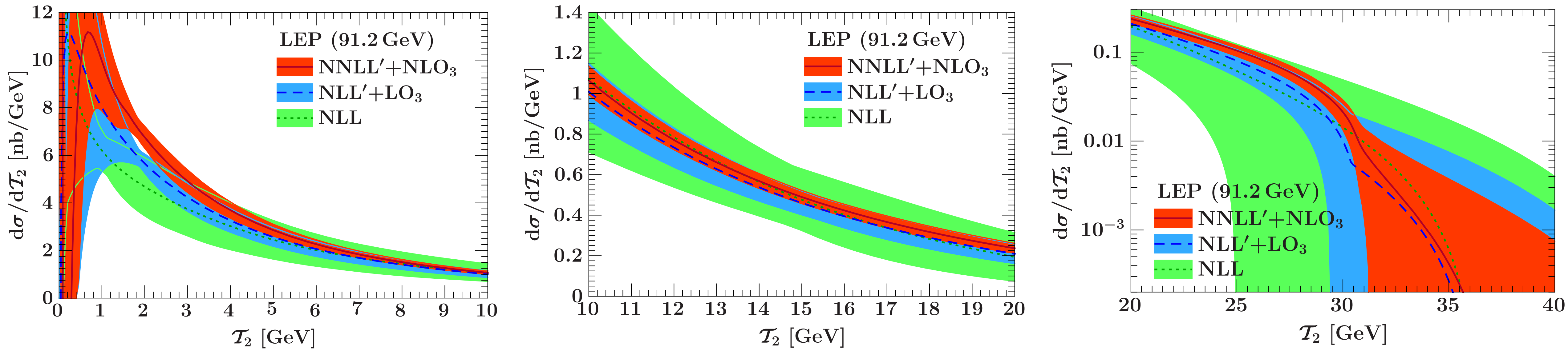
matching several jet multiplicities at NLO, with simultaneous resummation of N-jettiness for multiple N

$$\vdots$$

$$\frac{d\sigma^{\rm incl}}{d\Phi_{N_{\rm max}}} = \frac{d\sigma^{\rm LO}}{d\Phi_{N_{\rm max}}}$$

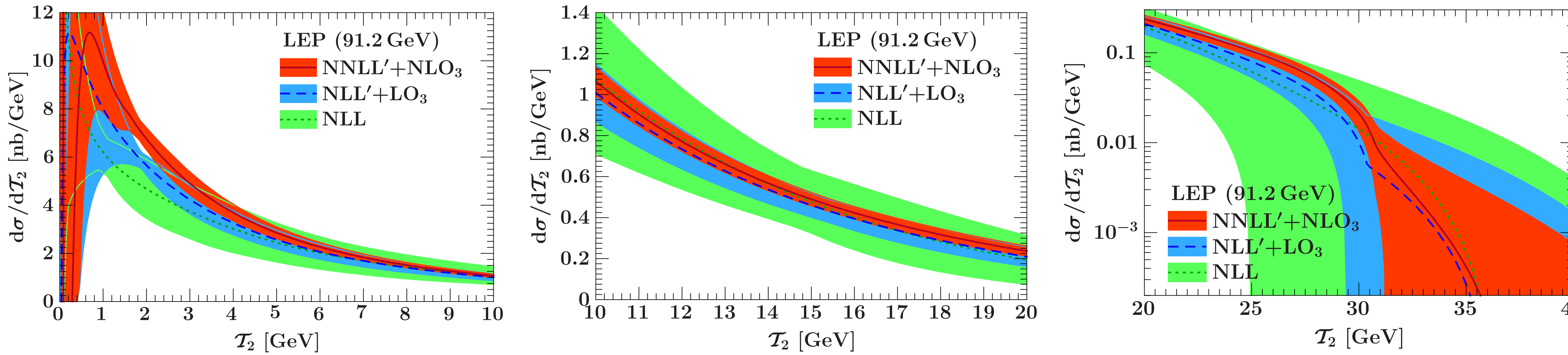
where $$\frac{d\sigma}{d\Phi_{N+1}} = \frac{d\sigma^{\rm incl}}{d\Phi_{N+1}}\left[\frac{d\sigma^{\rm resum}}{d\Phi_N d\mathcal{T}_N} \Big/ \frac{d\sigma^{\rm resum}}{d\Phi_N d\mathcal{T}_N}\bigg|_{\rm FO}\right]$$

GENEVA Reproduces Thrust Distribution

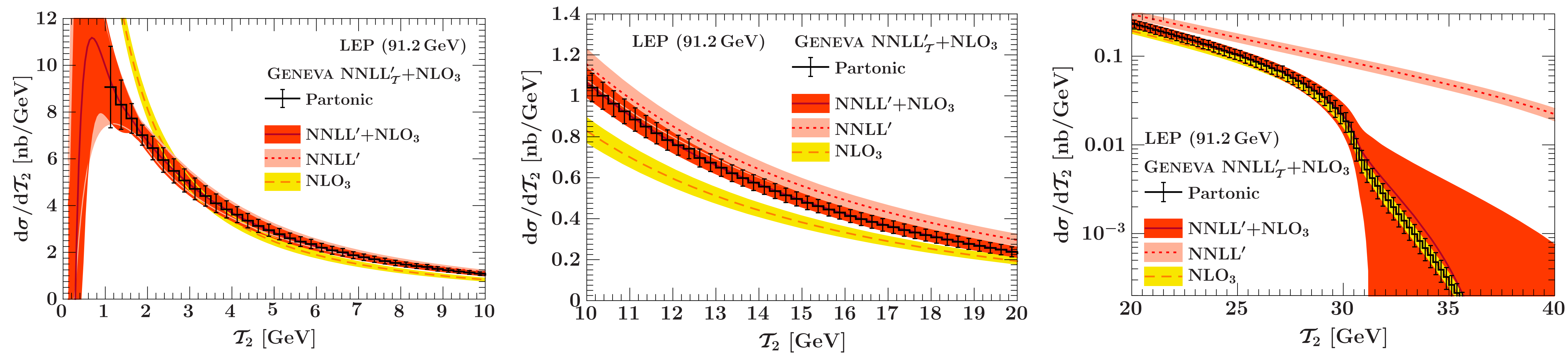


analytic calculation of thrust distribution using the usual nonsingular matching formula

GENEVA Reproduces Thrust Distribution

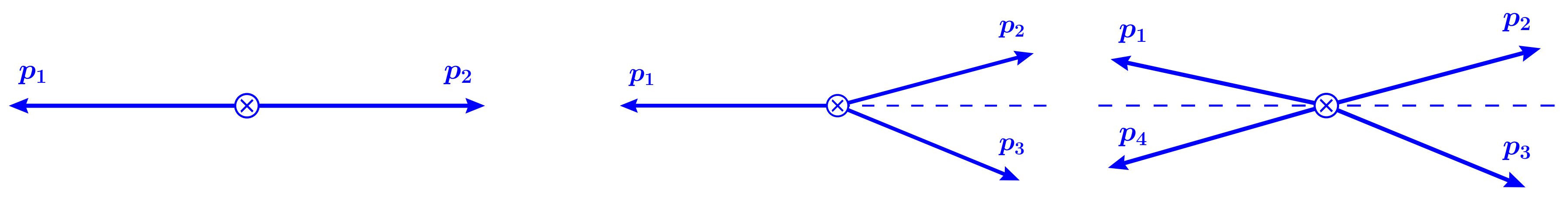


analytic calculation of thrust distribution using the usual nonsingular matching formula



☑ **Step 2**: onto parton shower and hadronization

Matching onto the Parton Shower



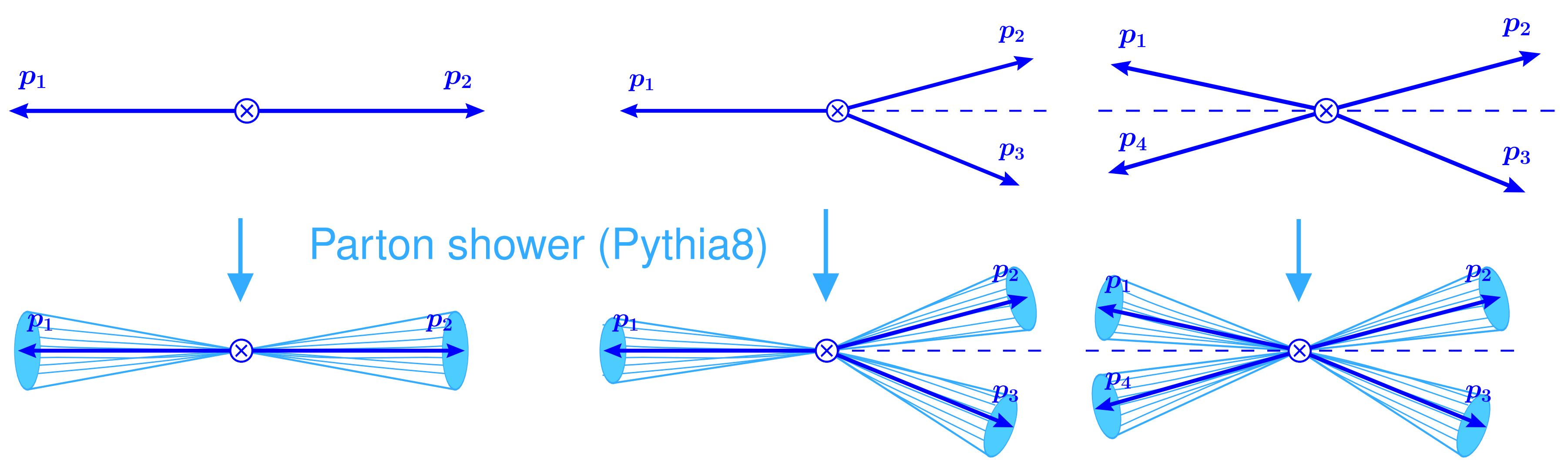
So far, we have assigned a weight to events that does two important things:

- Resums logs of the 2/3 jet resolution scale to NNLL′
- Has the 2 and 3 jet events calculated to NLO accuracy

But our events still only have 2, 3, or 4 partons
→ *We need the parton shower to fill out our jets*

We will see the important effect of showering on other observables

Matching onto the Parton Shower

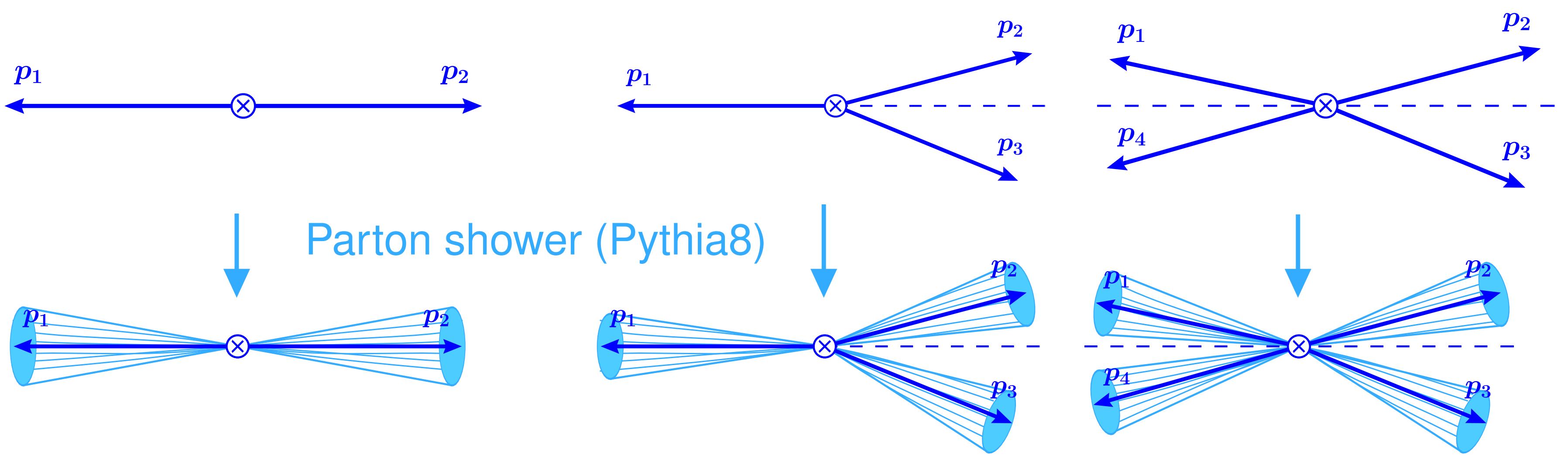


Use the Pythia8 parton shower routine, *with modifications*

How do we want to limit Pythia's shower?

- We want to preserve the accuracy of our thrust distribution calculation
- We want 2/3 jet partonic events in GENEVA to shower into 2/3 jet events
- We want the 4 jet events to shower inclusively

Matching onto the Parton Shower

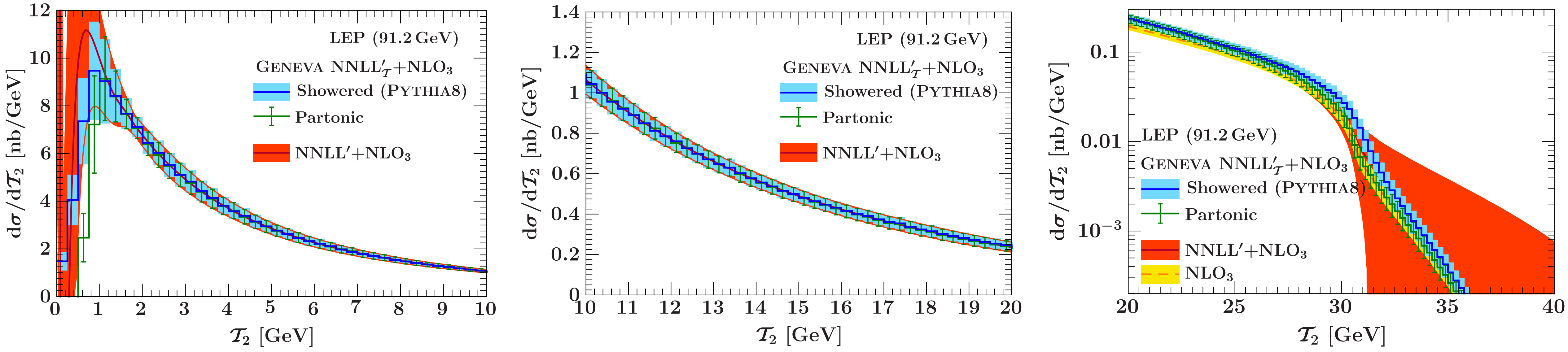


Use the Pythia8 parton shower routine, *with modifications*

How do we want to limit Pythia’s shower?

- We want to preserve the accuracy of our thrust distribution calculation
  - $\left| \mathcal{T}_{\text{GENEVA+PY}} / \mathcal{T}_{\text{GENEVA}} - 1 \right| < \lambda_N$
- We want 2/3 jet partonic events in GENEVA to shower into 2/3 jet events
  - We want to preserve the hard kinematics of the jets
- We want the 4 jet events to shower inclusively
  - Multijet tail of distributions only filled out by shower; need to match to higher order LO matrix elements

Results on Thrust Distribution



as advertised, showering does not change the thrust distribution

☑ **Step 3**: next is to add hadronization

Hadronization

Pythia
shower

Pythia is tuned to match
a palette of observables

This tuning effectively replaces
higher order corrections

Pythia
hadronization

Hadronization

what we want
from GENEVA

Pythia
shower

partonic
GENEVA

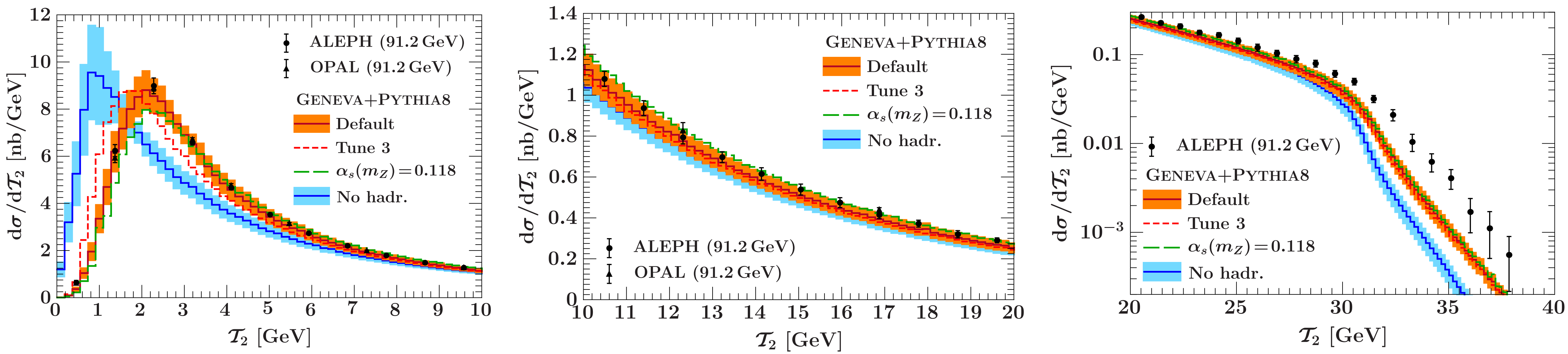
In GENEVA we match our
showered results directly onto
Pythia8's hadronization model

parton shower constrained,
hadronization unconstrained

Pythia
hadronization

Tuning of Pythia8 for
GENEVA is ***necessary***
for a more robust
comparison to data

Results on Thrust Distribution



☑ **Step 4**: excellent agreement with LEP data in peak and transition regions (tail region requires higher multiplicity matrix elements)

Compare GENEVA with two e^+e^- Pythia tunes (“tune 1”) and (“tune 3”) and two values of $\alpha_s(M_Z)$ (0.1135, 0.118)

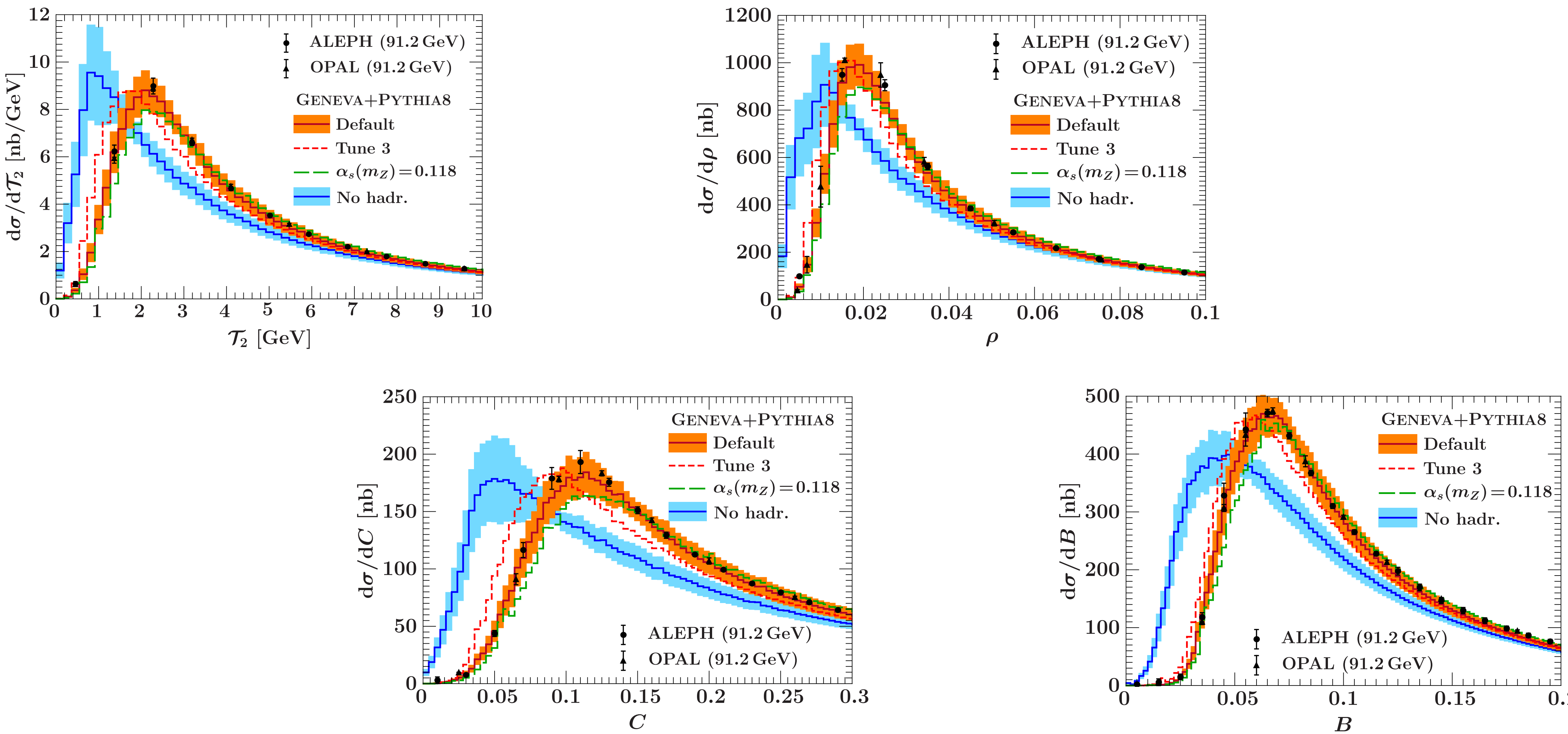
Find that for thrust, “tune 1” with α_s = 0.1135 works best (use as our default)
Also show “tune 3” with α_s = 0.1135 and “tune 1” with α_s = 0.118

Outline

The GENEVA Framework

Comparison to LEP Data

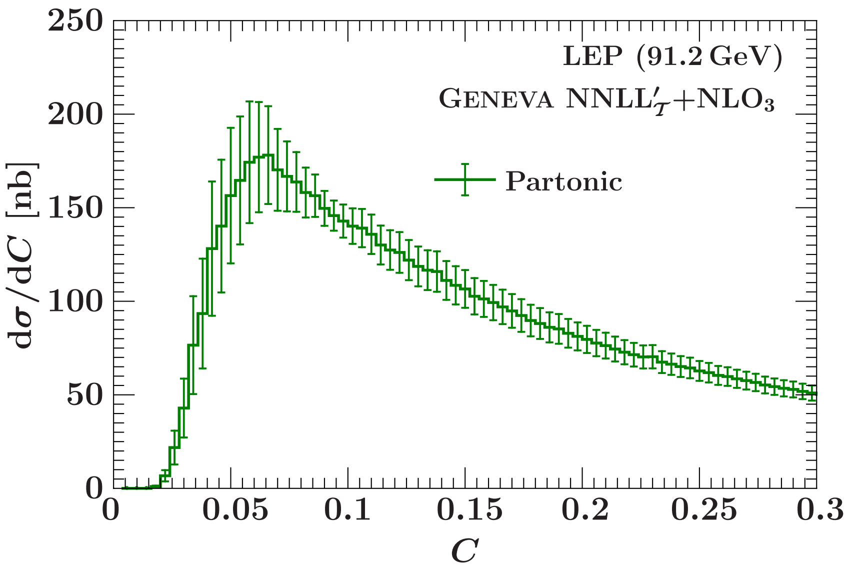
Applications for the LHC

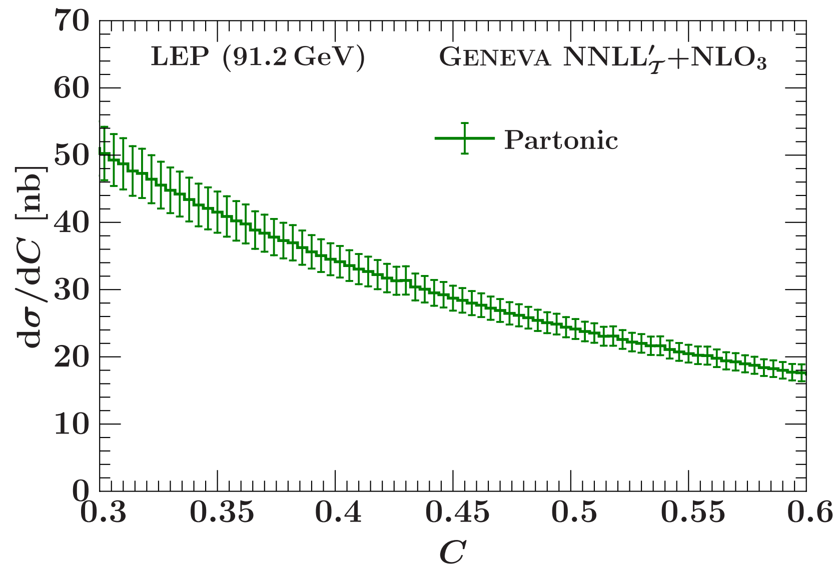


Other 2-jet Event Shapes

- C-parameter
  - Log structure essentially the same as thrust, with different nonsingular terms, power corrections, and nonperturbative effects
- Heavy Jet Mass
  - Log structure a different projection of dijet mass distribution
- Jet Broadening
  - $\mathrm{SCET_{II}}$ observable, tests the ability of GENEVA to describe other observables with different log series
- GENEVA is making a *prediction* for these observables: important to validate against their known resummation

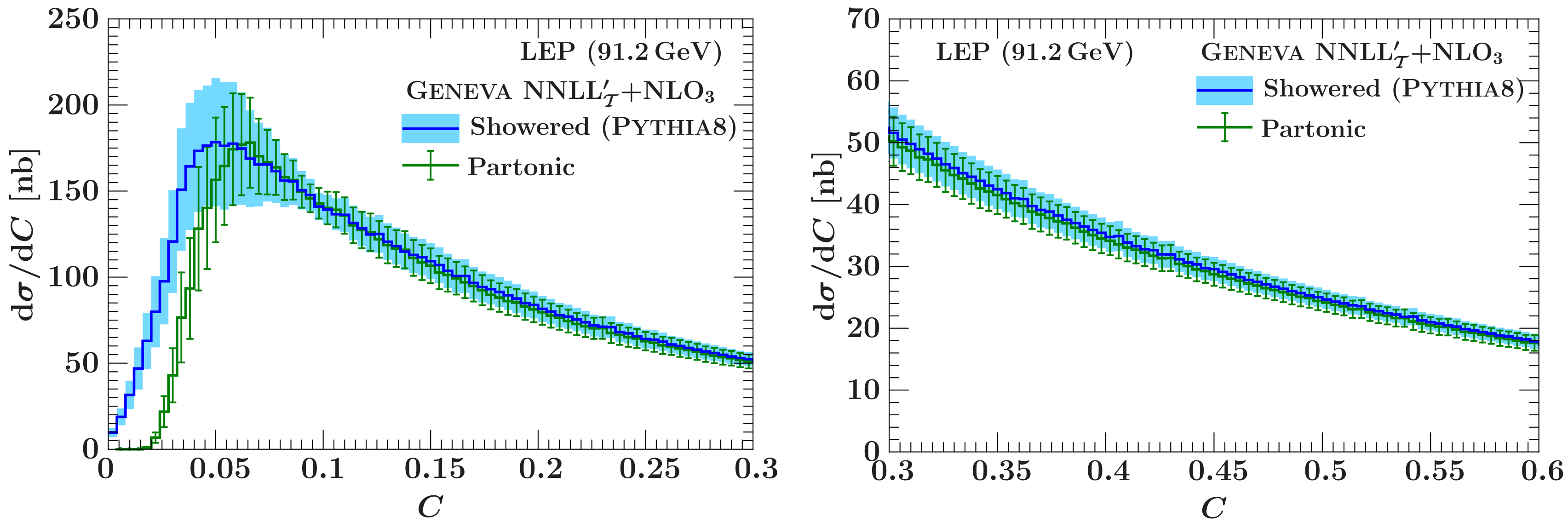
Parton Shower: C-parameter





partonic GENEVA

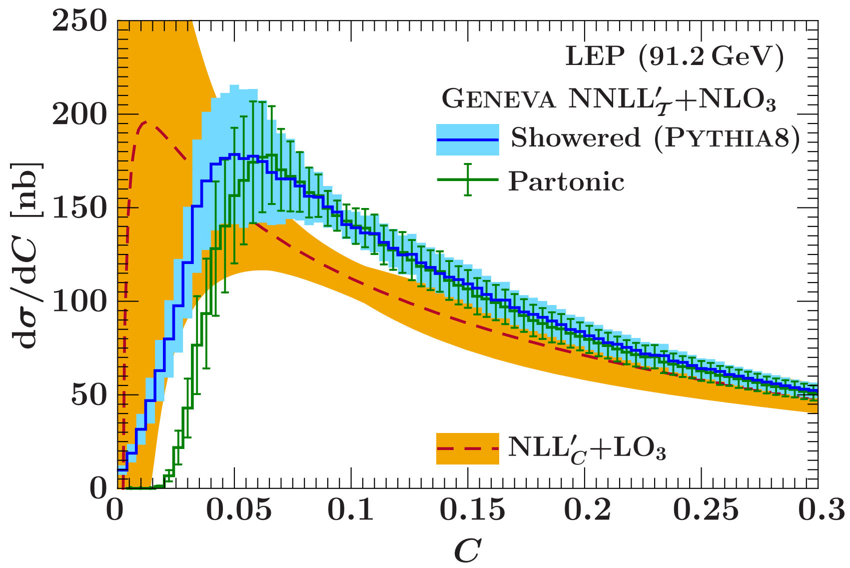
Parton Shower: C-parameter

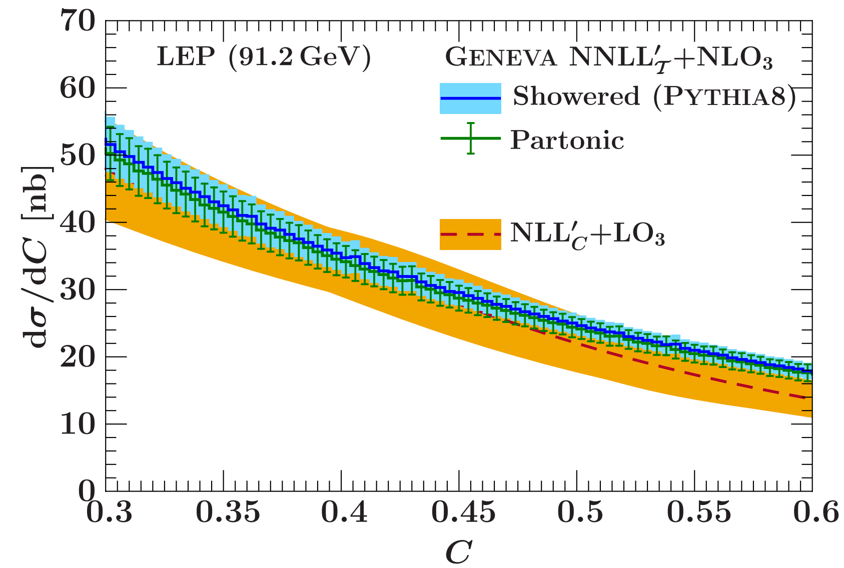


showered GENEVA

The parton shower does not significantly change the *C* spectrum and fills out the 2-jet region

Parton Shower: C-parameter

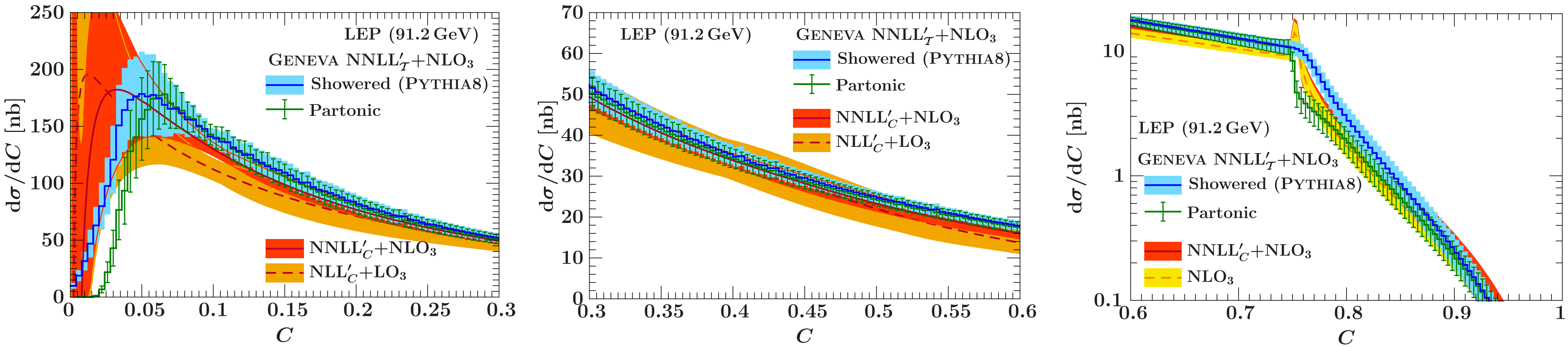




showered GENEVA vs. NLL′ + LO3 analytic resummation

The parton shower does not significantly change the *C* spectrum and fills out the 2-jet region

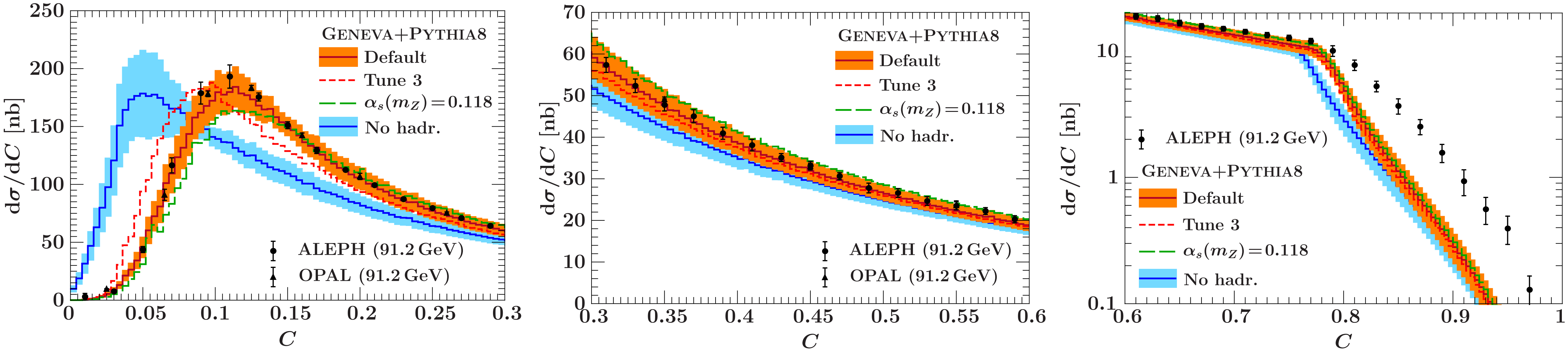
Parton Shower: C-parameter



The parton shower does not significantly change the *C* spectrum and fills out the 2-jet region

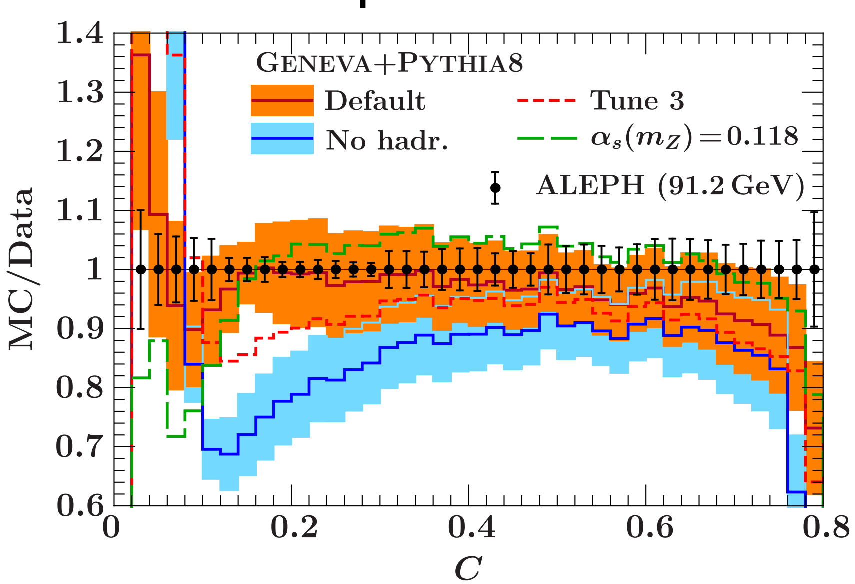
Solid agreement between analytic NNLL′ resummation and the GENEVA prediction

LEP Comparison: C-parameter

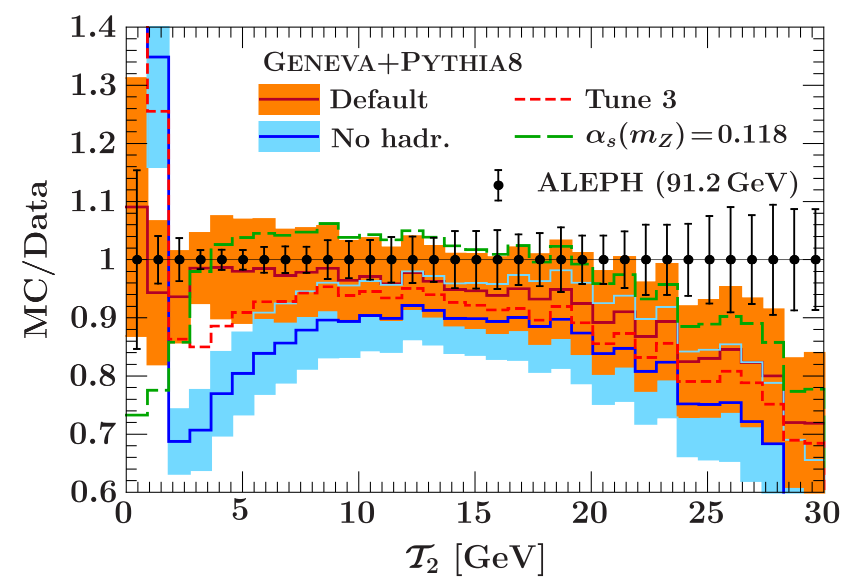


The default tune + α_s = 0.1135 gives as good of an agreement as thrust

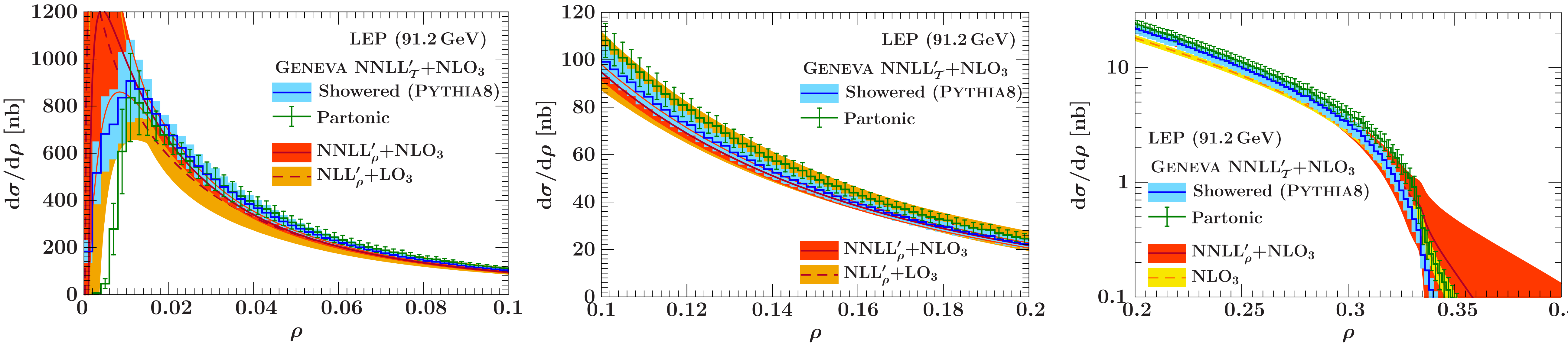
C parameter



thrust

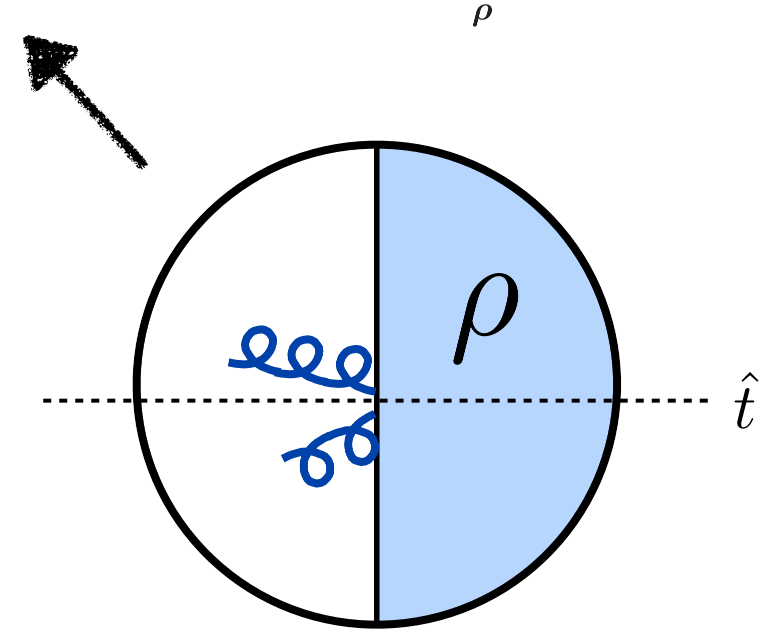


Parton Shower: Heavy Jet Mass



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = \int \mathrm{d}m_1^2 \mathrm{d}m_2^2 \frac{\mathrm{d}\sigma}{\mathrm{d}m_1^2 \mathrm{d}m_2^2} \delta(\rho - \max(m_1^2, m_2^2)/Q^2)$$

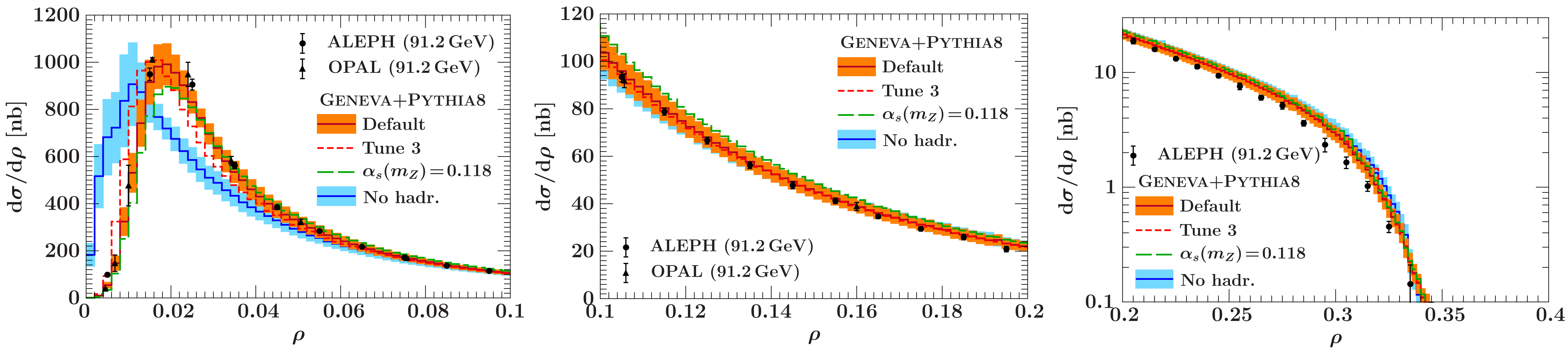
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \int \mathrm{d}m_1^2 \mathrm{d}m_2^2 \frac{\mathrm{d}\sigma}{\mathrm{d}m_1^2 \mathrm{d}m_2^2} \delta(\tau - (m_1^2 + m_2^2)/Q^2)$$



The GENEVA + Pythia prediction agrees better than partonic GENEVA with the analytic NNLL′ result (as it should)

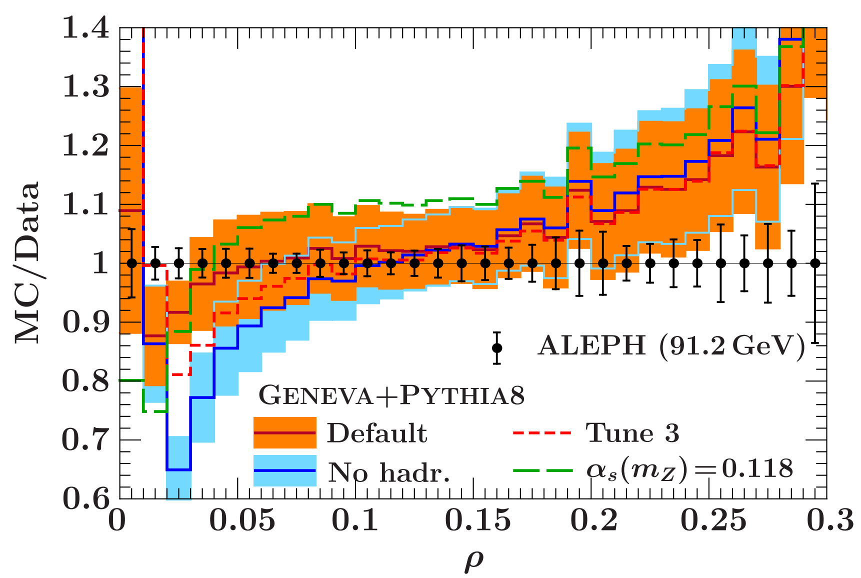
“backshowering” into light hemisphere

LEP Comparison: Heavy Jet Mass



fast transition into the tail region

again the default tune performs better than larger α_s or tune 3

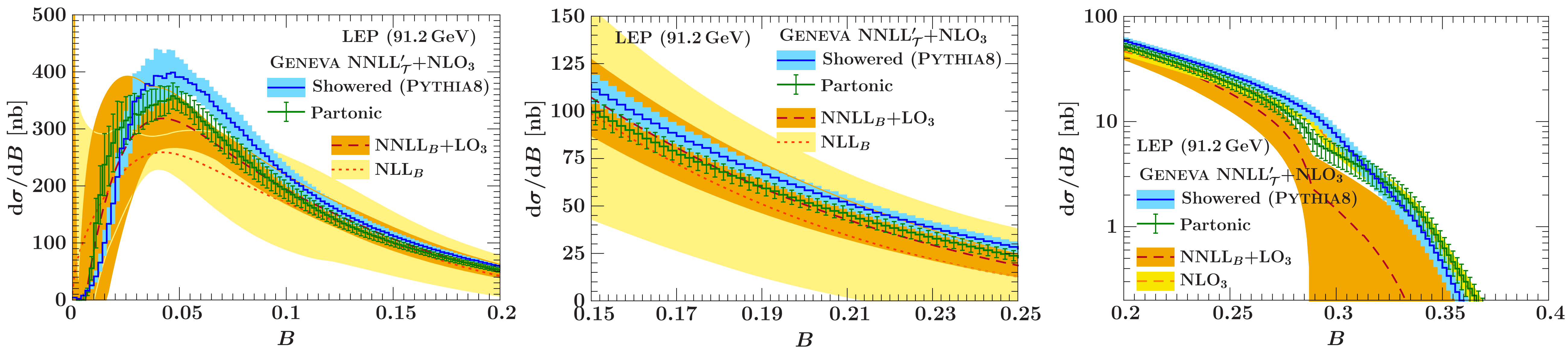


the need for matching out to high jet multiplicity is apparent

even matching to 5 jets at LO will improve the tail region

Parton Shower: Jet Broadening

Becher, Bell
1210.0580



Pythia changes the spectrum from partonic GENEVA due to the lack of correlation with thrust

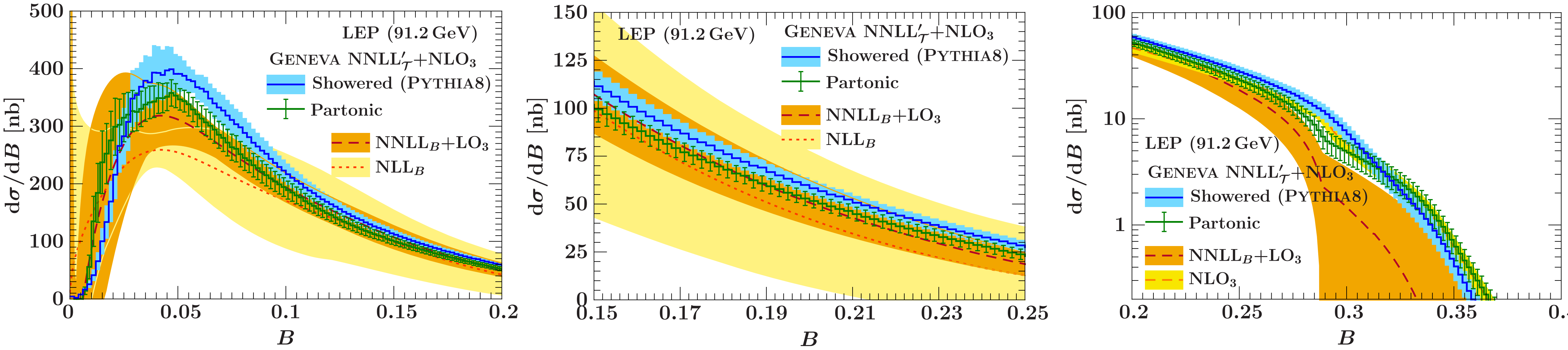
GENEVA showered result closer to the NNLL than NLL resummation for jet broadening

SCET$_{II}$: $$\frac{d\sigma}{dB} = \frac{\alpha_s C_F}{2\pi}\left(\frac{-8\ln B - 6}{B}\right) + \dots$$

SCET$_I$: $$\frac{d\sigma}{d\tau} = \frac{\alpha_s C_F}{2\pi}\left(\frac{-4\ln \tau - 3}{\tau}\right) + \dots$$

interesting to ask how accurately GENEVA is describing uncorrelated observables

Interlude on Uncertainties



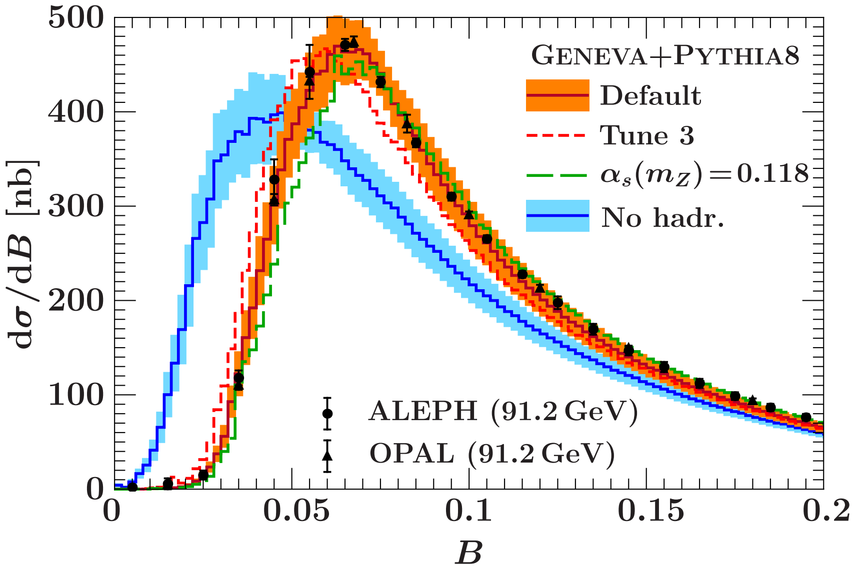
GENEVA provides FO and scale variation uncertainties event-by-event

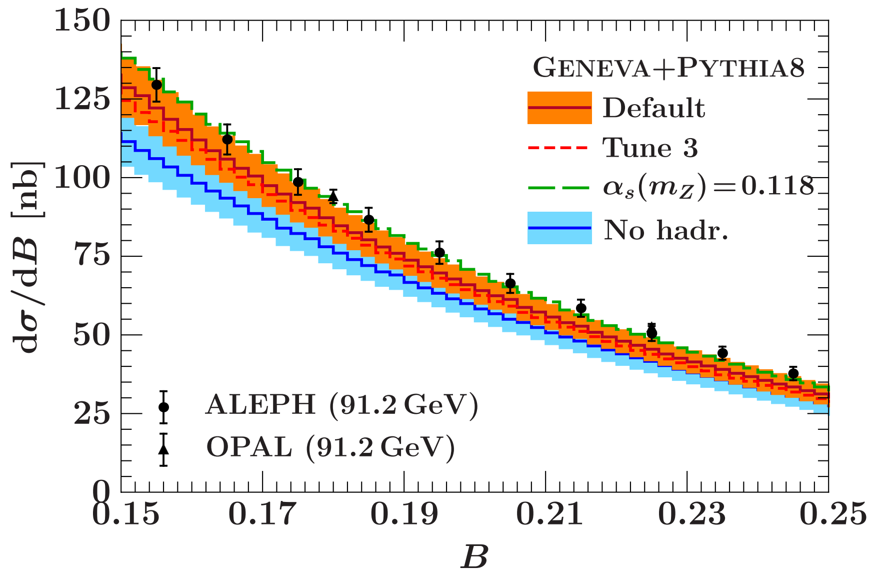
We do not (yet) give uncertainties associated with Pythia

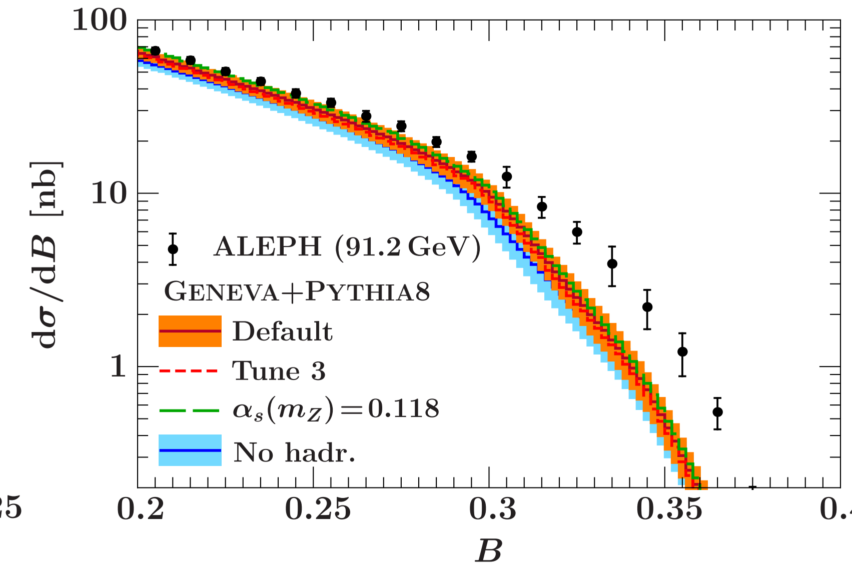
A reasonable proxy for parton shower uncertainties could be the spread between partonic and showered GENEVA

Hadronization uncertainties are more delicate, and would require proper tuning of hadronization parameters

LEP Comparison: Jet Broadening

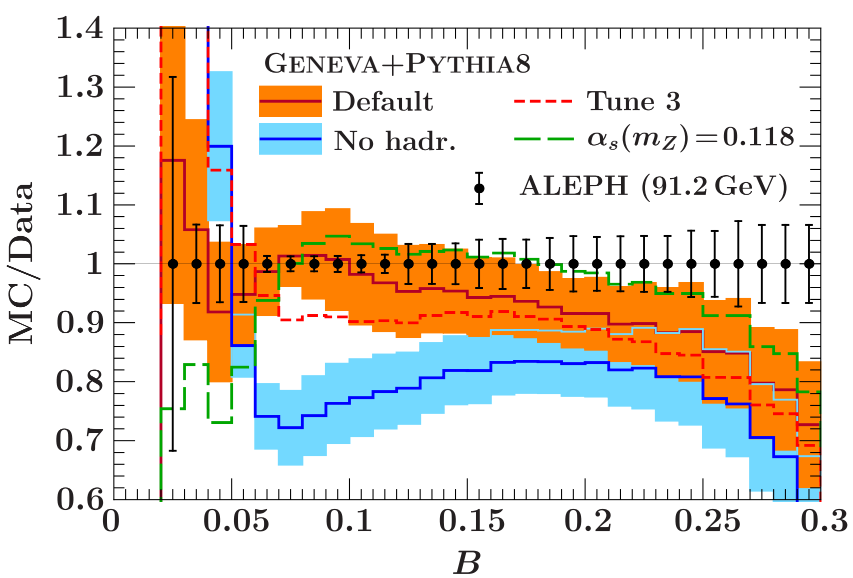




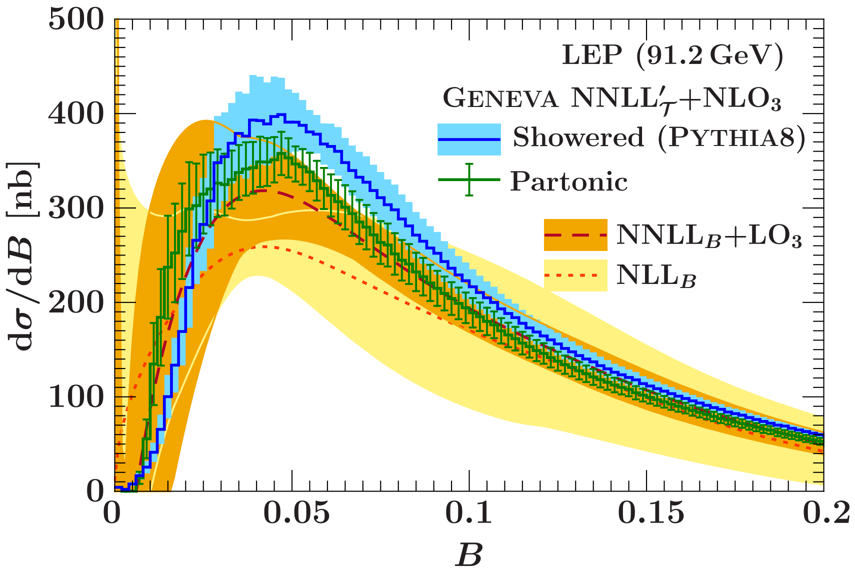


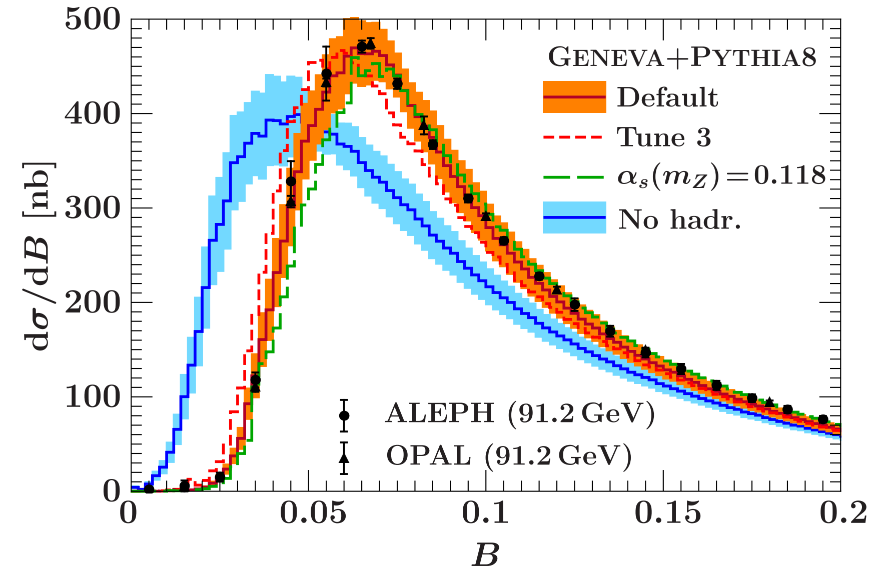
good agreement with data
through peak/early transition

multijet corrections
in the tail region

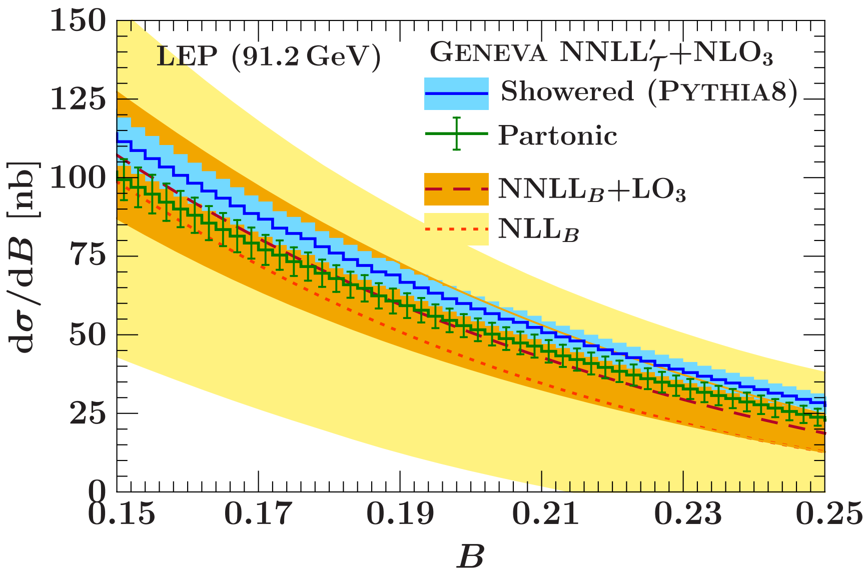


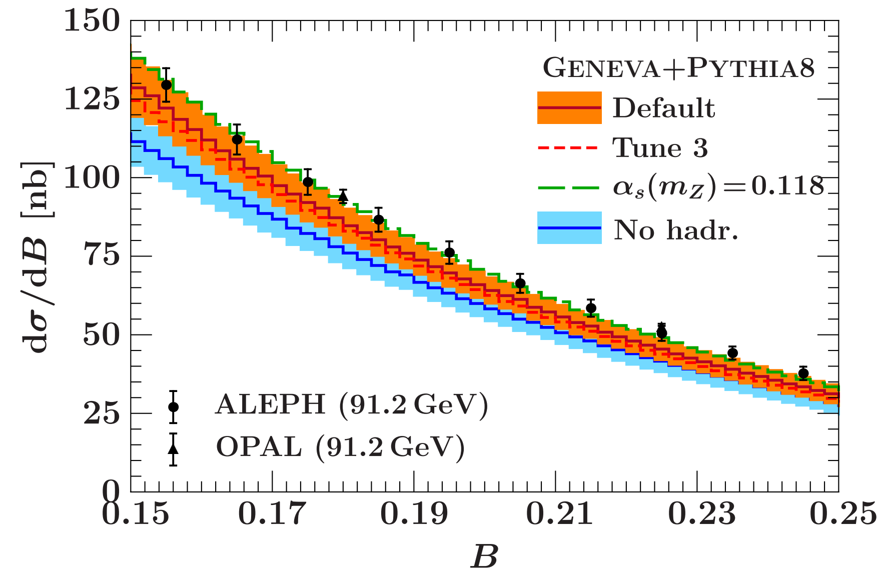
Jet Broadening: GENEVA Prediction





Showered agrees with analytic resummation, hadronized agrees with data



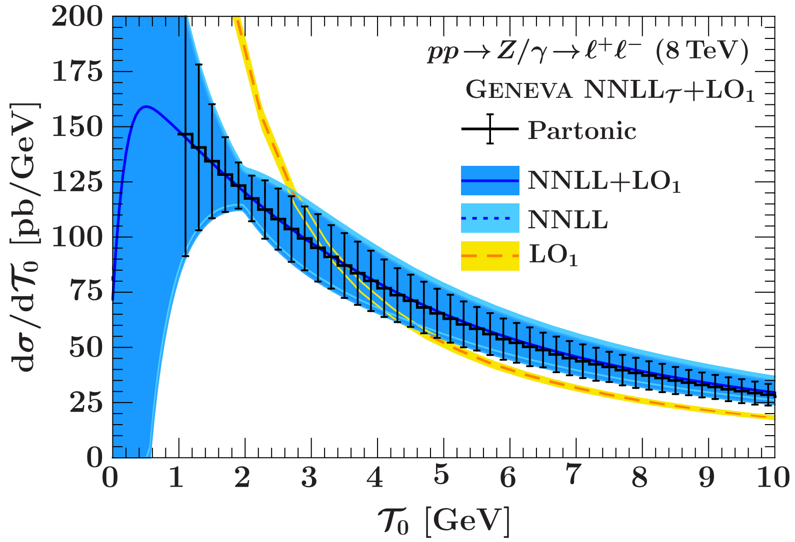


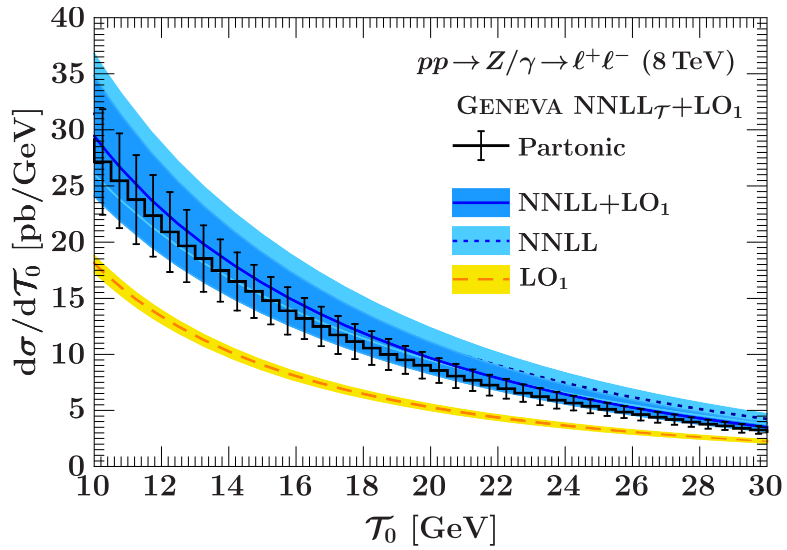
Outline

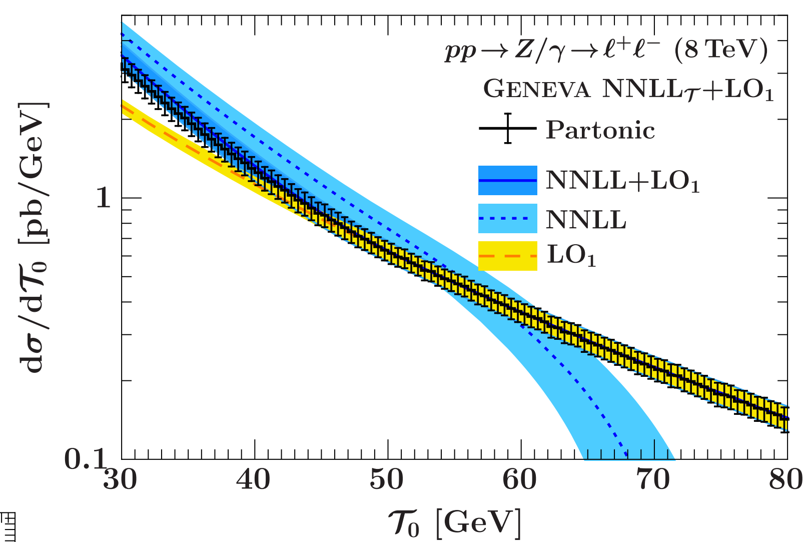
The GENEVA Framework

Comparison to LEP Data

Applications for the LHC







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

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

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

From e^+e^- to pp Collisions

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

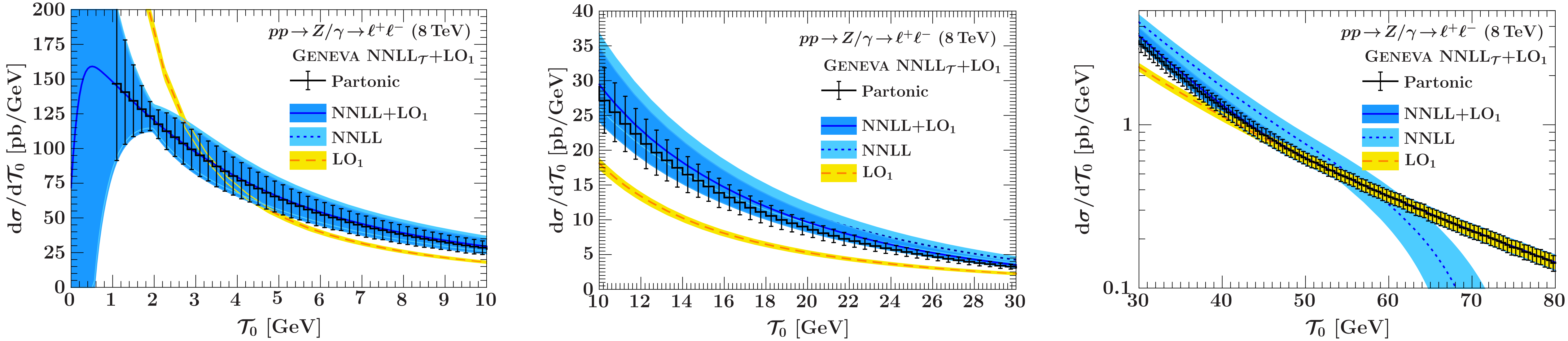
master formula: $$\frac{\mathrm{d}\sigma^{\mathrm{incl}}}{\mathrm{d}\Phi_0} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \int \frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0}\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_1}(\mathcal{T}_0)\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

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

Initial LHC Plots: Drell-Yan Production

partonic GENEVA, NNLL + LO_1



agrees with resummation in the peak

agrees with FO in the tail

Drell-Yan is a good test process - lots of physics, lots of data

W + jets, Higgs production, top production are next steps

Road to Improvements for pp Collisions

- ☐ Improve resummation accuracy to NNLL′
- ☐ Improve FO accuracy to NLO_1
- ☐ Add parton shower, hadronization, MPI
- ☐ Combine and test against DY studies at the LHC, Tevatron
- ☐ Add other processes

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We are in the process of validating the combination

NNLL′ + NLO_1 + Pythia

Conclusions

- Precision physics is going to play a large role in Higgs measurements and BSM physics at the LHC
    - Higgs property measurements improved through more accurate calculations
    - More challenging new physics searches require higher precision background estimation
- GENEVA combines the high accuracy from the calculation of single observables with the flexibility of a Monte Carlo
    - Excellent agreement with LEP data for a variety of observables
    - Look for more pp results in the next several months
    - Initial code release planned this summer

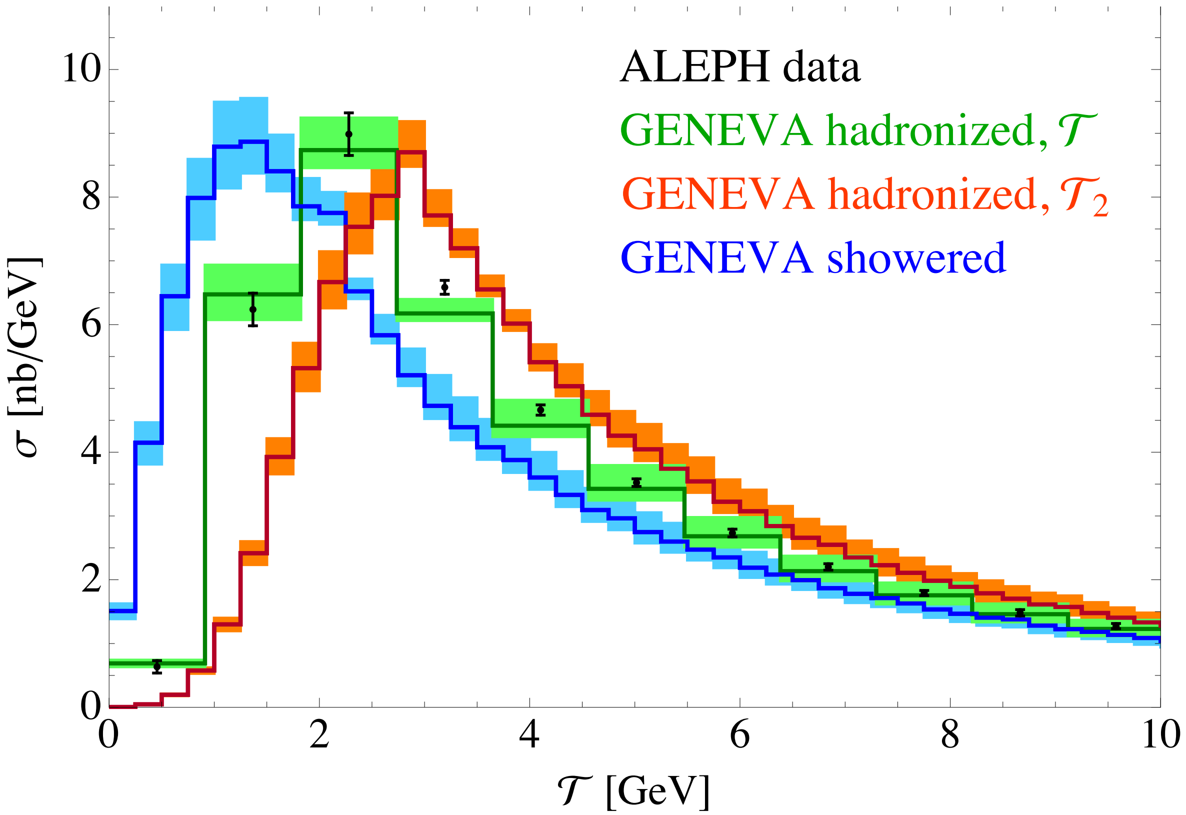
Extra Slides

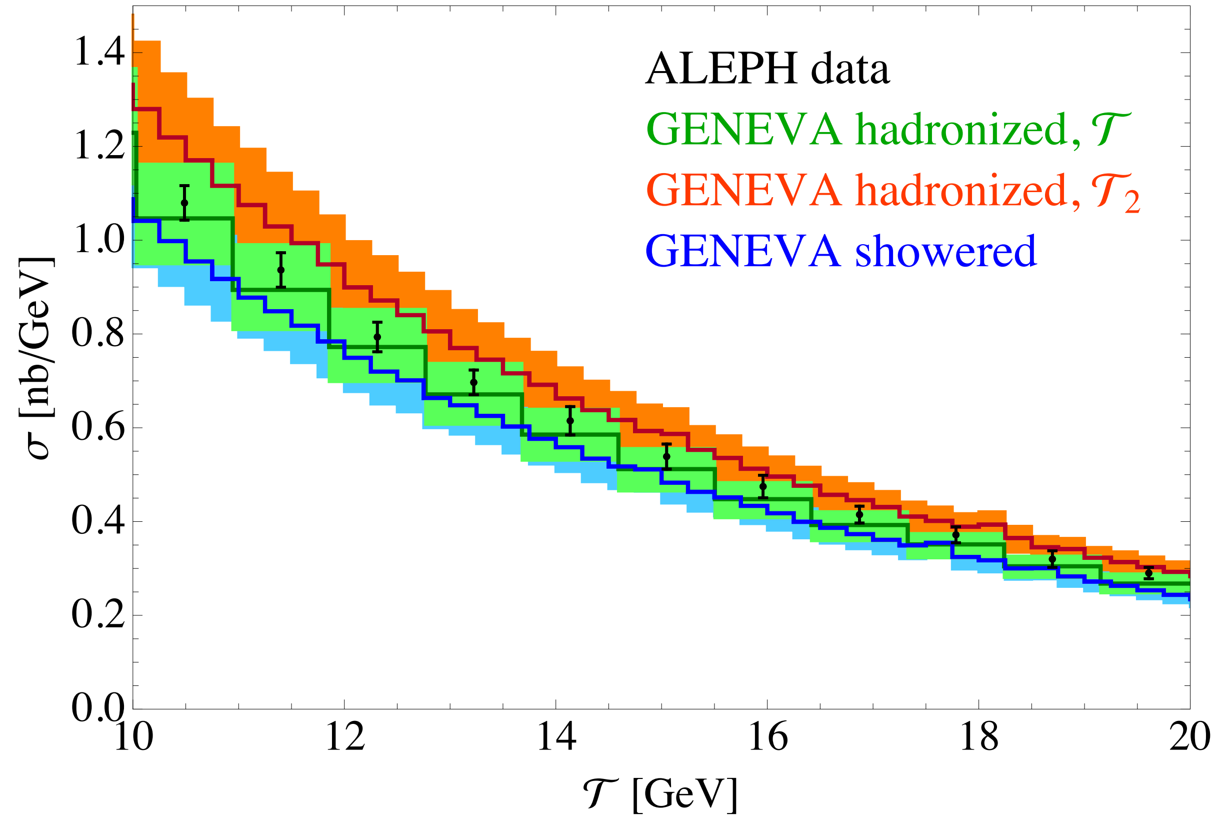
Power Corrections from Hadron Masses

power corrections for thrust, 2-jettiness differ: $\Omega_1^{\mathcal{T}_2} = 2\Omega_1^{\mathcal{T}}$

Mateu, Stewart, Thaler 1209.3781

Observe an 1 scaling with thrust and 2-jettiness that agrees with MST





Fixed Order Calculation

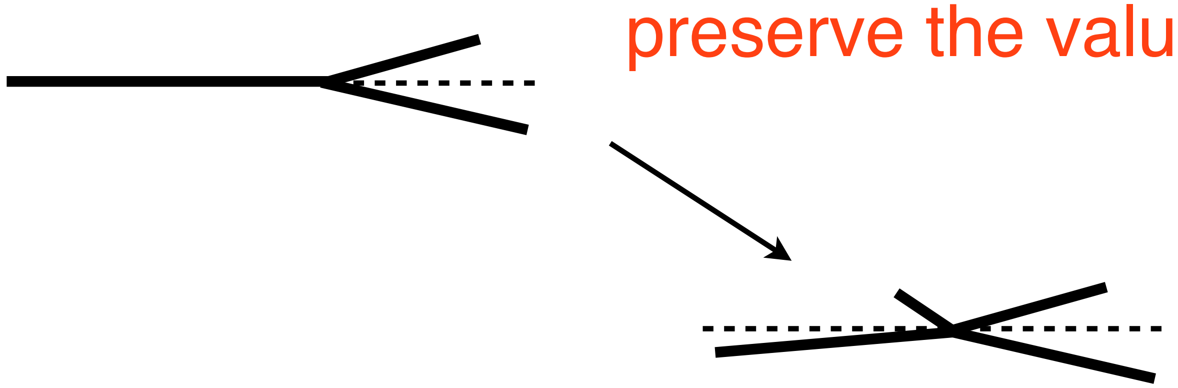
Born virtual real emission

$$\frac{d\sigma^{\mathrm{NLO}}}{d\Phi_3}(\mathcal{T}) = B_3(\Phi_3,\mathcal{T}) + V_3(\Phi_3,\mathcal{T}) + \int \frac{d\Phi_4}{d\Phi_3} B_4(\Phi_4)\delta[\mathcal{T}(\Phi_4(\Phi_3)) - \mathcal{T}(\Phi_3)]$$

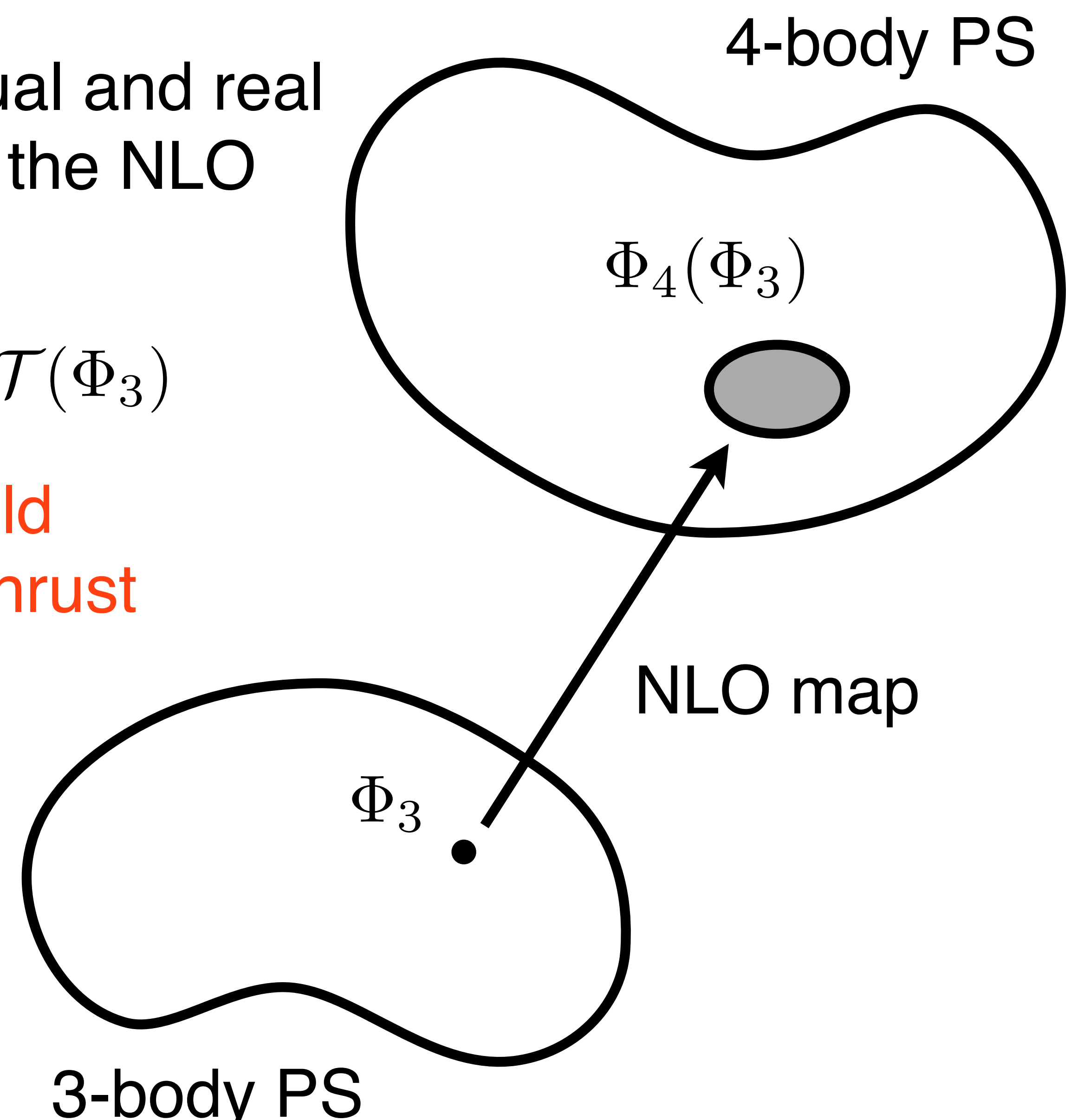
We use FKS subtractions to render the virtual and real emission calculations finite and calculate the NLO

need $\mathcal{T}(\Phi_4(\Phi_3)) = \mathcal{T}(\Phi_3)$

real emissions should preserve the value of thrust



We have designed a PS map that does this



Resummation in a Monte Carlo vs. Direct Calculation

matching formula for the spectrum:

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

our usual formula for the resummation:

$$\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0} = \sum_\kappa H_0^\kappa(\Phi_0) \int \mathrm{d}Y\, B_a^\kappa(Y, \mathcal{T}_0) \otimes B_b^\kappa(Y, \mathcal{T}_0) \otimes S(\mathcal{T}_0)$$

each part of the matching formula is a sum over contributions from separate parton channels

$$\{u\bar{u},\, d\bar{d},\, c\bar{c},\, s\bar{s},\, b\bar{b}\} \to \ell^+\ell^-$$

events are generated in individual flavor channels

Resummation in a Monte Carlo vs. Direct Calculation

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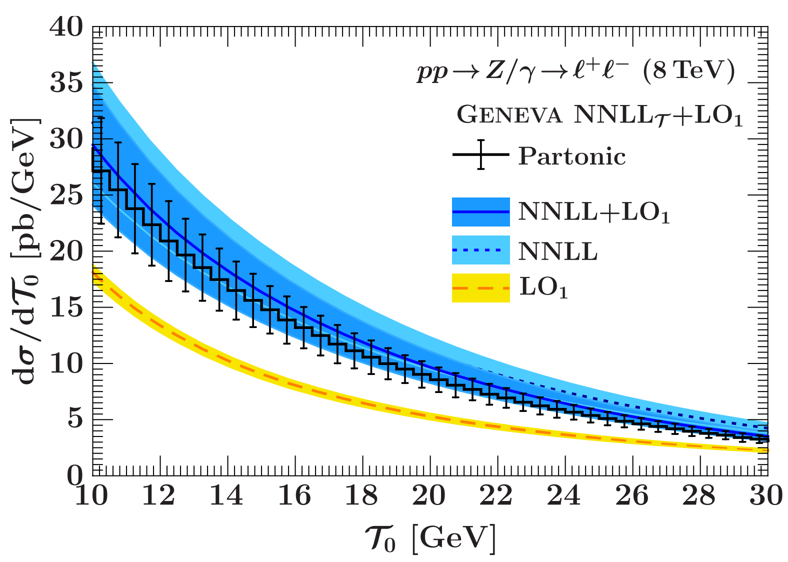
events are generated in individual flavor channels

Resummation in a Monte Carlo vs. Direct Calculation

In GENEVA we pull the sum over parton channels out:

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

The difference is small but noticeable:



Both matching formulas are equally valid, as they correctly interpolate in the singular/nonsingular limits