SCET+PS Discussion Session

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Resummation and Parton Showers
Durham, July 15-17, 2013

The Plan

- Introduction (very brief)
- 3 important/interesting issues I'd like to bring up:
  - Transition between pure resummation (PS) and pure fixed order (ME)
  - Accuracy when resumming one thing and looking at another
  - Double-counting and separation between soft+collinear radiation and soft MPI
- Please feel free to raise more

This is meant as a discussion session, so please discuss ...

Disclaimer:

Nothing here is really SCET specific, so I'm going to think more of a "Higher-order Resummation + PS/MC" discussion

1-page Introduction to SCET

SCET is the effective field theory of QCD in the soft and collinear limit

[Bauer, Fleming, Pirjol, Stewart (+Rothstein; Beneke, Chapovsky, Diehl, Feldmann)]

Advantages of effective-field theory setup

- Power counting and expansion in soft and collinear limits manifest at the Lagrangian level
- Clean separation of different relevant energy scales

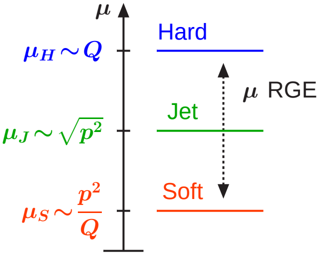
⇒ Logarithms can be resummed using standard RGE methods

- → Can go to higher order in a systematic way
  (“only” need to know higher-order matching and anomalous dimensions)
- → Systematic control of perturbative uncertainties
  (evaluation through variations of matching/resummation scales)

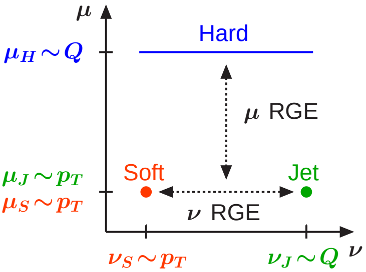
⇒ “Nonsingular” corrections to recover full QCD are formal power corrections and can be added systematically

Two Basic RGE Setups

“SCET-I”: p^2-like (actually p^+-like)



“SCET-II”: p_T-like



Appropriate setup depends on kinematics of the observable in question

- At e^+e^- some bias toward p^2-like (many event shapes are)
  $\longrightarrow$ notable exception: jet broadening
- At LHC some bias toward p_T-like
  $\longrightarrow$ notable exceptions: jet mass and dijet inv. mass

Two Basic RGE Setups

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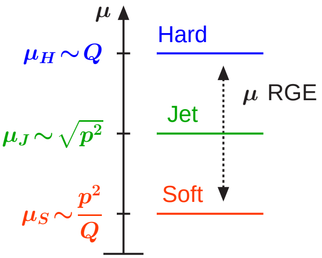

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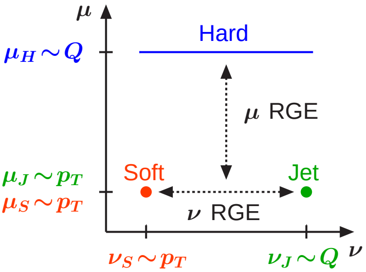


Relation to parton-shower evolution at (N)LL

- p^2-ordered: $U_{\rm PS}(Q, \sqrt{p^2}) = U_H(Q, \sqrt{p^2}) \times U_S(p^2/Q, \sqrt{p^2})$
- p_T-ordered: $U_{\rm PS}(Q, p_T) = U_H(Q, p_T)$

  (Rapidity ν RGE becomes relevant at NNLL, which is why a p_T-ordered shower has a chance to be NLL correct at leading color)

Transition Region

Singular vs. Nonsingular

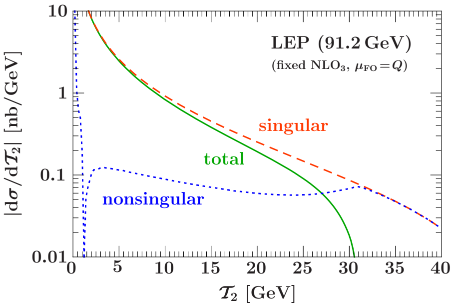
Differential spectrum in some IR-sensitive variable τ has all-order structure (e.g. $\tau = \mathcal{T}_2/Q = 1 - T$)

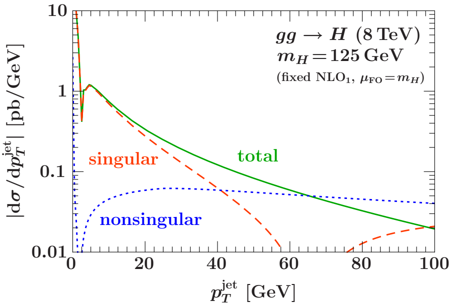
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \sum_k \alpha_s^k \Big\{ c_{k,-1}\delta(\tau) + \sum_{n=0}^{2k-1} c_{kn} \Big[\frac{\ln^n \tau}{\tau}\Big]_+ \quad + \quad f_k^{\mathrm{nons}}(\tau) \Big\}$$

$$\sigma(\tau^{\mathrm{cut}}) = \sum_k \alpha_s^k \Big\{ \underbrace{c_{k,-1} + \sum_{n=0}^{2k-1} c_{kn} \frac{\ln^{n+1}\tau^{\mathrm{cut}}}{n+1}}_{\text{singular}} \quad + \quad \underbrace{F_k^{\mathrm{nons}}(\tau^{\mathrm{cut}})}_{\text{nonsingular}} \Big\}$$

- singular: large logs which are resummed
  - constant $c_{k,-1}$ belongs to singular
- nonsingular: treated in fixed order
  - $f_k^{\mathrm{nons}}(\tau)$ has only integrable divergences
  - $F_k^{\mathrm{nons}}(\tau^{\mathrm{cut}} \to 0) \to 0$

Perturbative Regions



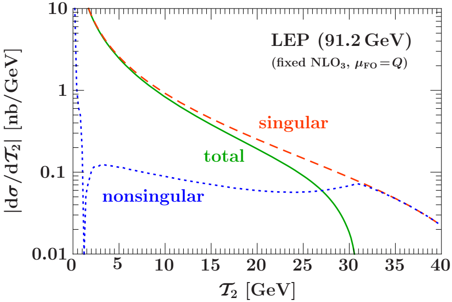


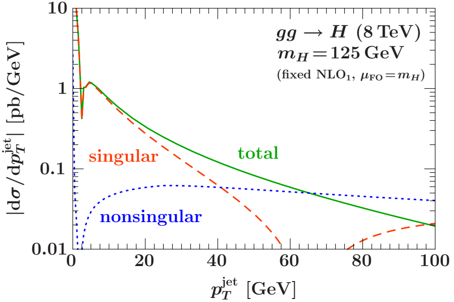
Resummation Resummation

Resummation region

- Singular dominate and must be resummed, nonsingular are power-suppressed
- Fixed-order by itself becomes meaningless here

Perturbative Regions



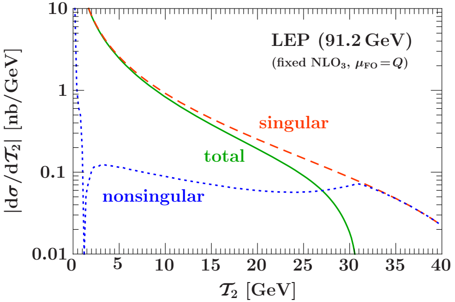


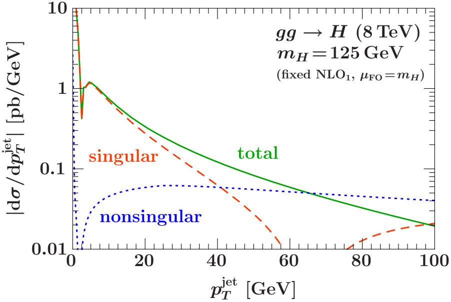
Resummation Fixed Order Resummation Fixed Order

Fixed-order region

- Important large cancellations between singular and nonsingular (their distinction is unphysical here)
- Resummation becomes meaningless here and *must be* turned off (otherwise cancellations are spoiled)

Perturbative Regions





Resummation | Transition | Fixed Order

Resummation | Transition | Fixed Order

Transition region

- Often experimentally the most relevant while theoretically the most subtle
- Most accurate description requires both resummation and fixed order and a consistent combination

$\longrightarrow$ So in some sense this is where ME+PS is really needed

Perturbative Regions

What are the boundaries between different regions?

- Can't say for sure, there are no strict boundaries
  - $\longrightarrow$ Even more relevant to have a consistent combination of both limits
    (And it won't matter as much anymore once the result is valid everywhere)
- Can get a good idea by looking at relative size of singular vs. nonsingular

What does "consistent" combination require in practice?

- Be correct in either limit and reasonable (= smooth) in the middle

  Resummation region:
  Include higher-orders through resummed pert. theory

  Fixed-order region:
  Enforce fixed-order pert. theory by turning off resummation

Resummation + Fixed Order

Default conventions:

	Fixed-order corrections		Resummation input		
	H,J,S	nonsingular	$\gamma_{H,J,S}$	$\Gamma_{\rm cusp}$	β
NLL	$\mathcal{O}(1)$	-	1-loop	2-loop	2-loop
NLL′+LO$_3$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	1-loop	2-loop	2-loop
NNLL′+NLO$_3$	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$	2-loop	3-loop	3-loop

$$\mathrm{d}\sigma^{\rm FO}(\mu_{\rm FO}) = \underbrace{\mathrm{d}\sigma^{\rm sing}(\mu_{\rm FO})} + \mathrm{d}\sigma^{\rm nons}(\mu_{\rm FO})$$

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\rm resum'}(\mu_S, \mu_J, \mu_H) + \mathrm{d}\sigma^{\rm nons}(\mu_{\rm FO})$$

N^{k}LL′ fully contains $\mathcal{O}(\alpha_s^k)$ singular (via α_s^k hard, jet, soft functions)

$\Rightarrow$ $\mathrm{d}\sigma^{\rm resum'}(\mu_S = \mu_J = \mu_H = \mu_{\rm FO}) = \mathrm{d}\sigma^{\rm sing}(\mu_{\rm FO})$ exactly

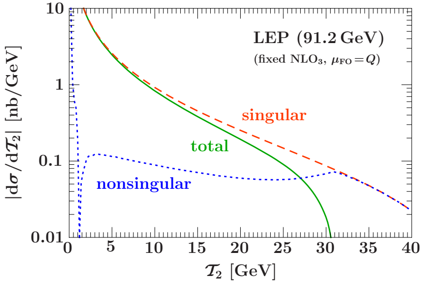
(Formally, α_s^k matching contributes at N^{k+1}LL, so NNLL+LO$_3$ and N^{3}LL+NLO$_3$ are also ok)

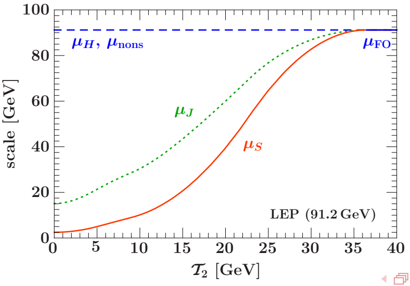
Profile Scales

- Resummation region:
  Logs are resummed using canonical scales:
  $$\mu_H = Q$$
  $$\mu_J = \sqrt{\mu_S \mu_H}$$
  $$\mu_S = \mathcal{T}_2$$
  $+\mathrm{d}\sigma^{\mathrm{nons}}$ adds a power correction

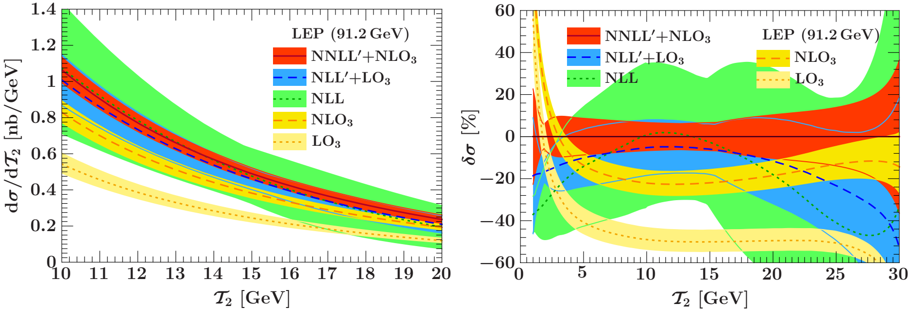
- FO region:
  Resummation turned off by taking
  $$\mu_S, \mu_J, \mu_H \to \mu_{\mathrm{FO}}$$
  $$\Rightarrow \mathrm{d}\sigma \to \mathrm{d}\sigma^{\mathrm{FO}}(\mu_{\mathrm{FO}})$$

- Transition region:
  Profiles for μ_S, μ_J provide smooth transition between both limits
  $\Rightarrow$ Ambiguity is a scale uncertainty





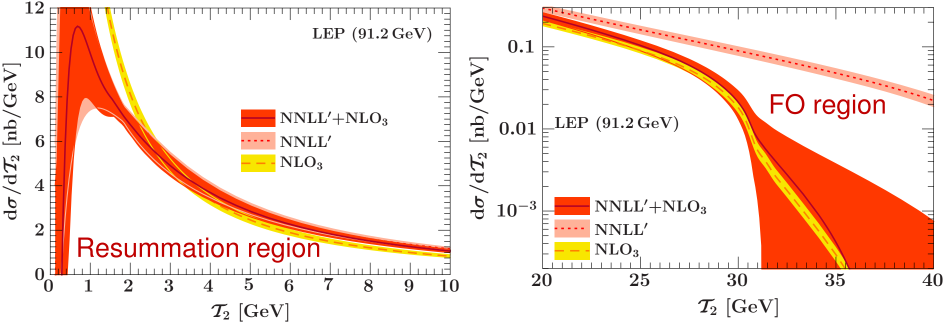
Example: Thrust in e^+e^-



- Fixed order does not converge well for spectrum (well-known)
- Uncertainties in resummed from $\Delta_{\text{total}} = \Delta_{\text{FO}} \oplus \Delta_{\text{resum}}$ where
  - Δ_{FO} from overall μ_{FO} factor 2 variation
  - Δ_{resum} from μ_S, μ_J profile scale variations

$\Rightarrow$ Even N^{3}LL′+NNLO$_3$ is known and within the N^{2}LL′+NLO$_3$ uncertainties, so in the following I'll use the latter as the correct result to compare to

Example: Thrust in e^+e^-



pure NNLL′ ⟵ matched NNLL′+NLO$_3$ ⟶ pure NLO$_3$

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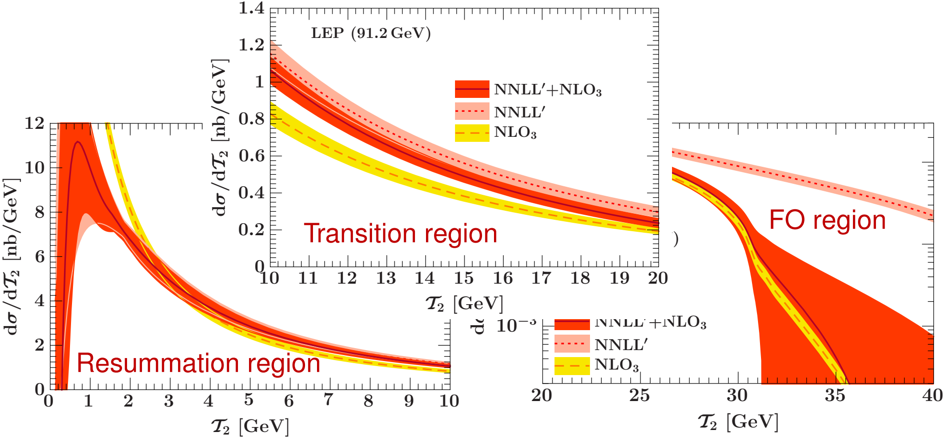


pure NNLL′ ⟵ matched NNLL′+NLO$_3$ ⟶ pure NLO$_3$

In transition region

- Neither pure NNLL′ nor pure NLO$_3$ alone give NLO-accurate result

Relation to ME+PS Merging

In usual ME+PS matching/merging, resummation and FO do not match up in the same way, since PS is only (N)LL$_{(\sigma)}$

"Additive" merging (a la MC@NLO)

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{resum}} + \left[\mathrm{d}\sigma^{\mathrm{FO}} - \mathrm{d}\sigma^{\mathrm{resum}}\Big|_{\mathrm{FOexpanded}}\right]$$

- For resum = (N)NLL′ and FO = (N)LO$_3$ the term in brackets precisely gives $\mathrm{d}\sigma^{\mathrm{nons}}$

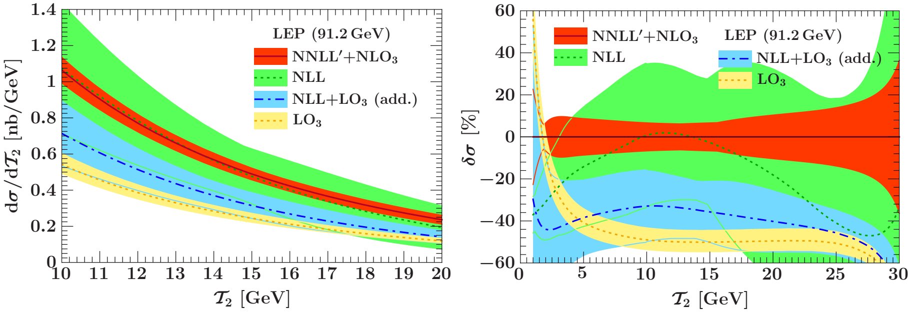
"Multiplicative" (a la CKKW, POWHEG)

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{resum}} \times \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\sigma^{\mathrm{resum}}\Big|_{\mathrm{FOexpanded}}}$$

(Obviously there are many differences to MC implementations:
Different Sudakovs, profiles vs. canonical scales, evolution/resummation variables etc. ...
Nevertheless, regarding the resummation and FO pert. accuracy these are equivalent.)

Merging NLL and LO_3

Using additive merging of NLL and LO_3

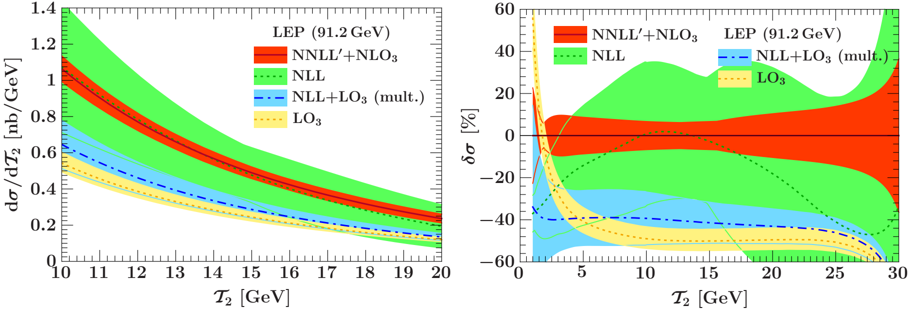


- Expanding the resummed and correcting it to LO_3 pushes the result toward LO_3: That's precisely as one should expected

⇒ However: Central value gets worse while the scale uncertainties shrink (uncertainties would be even smaller without profile scale variations)

Merging NLL and LO_3

Using multiplicative merging of NLL and LO_3



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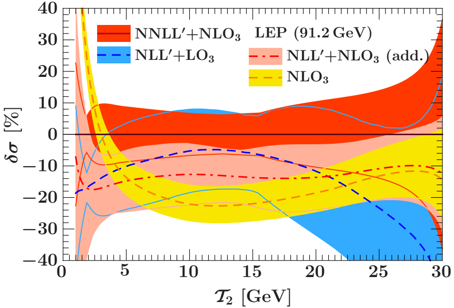
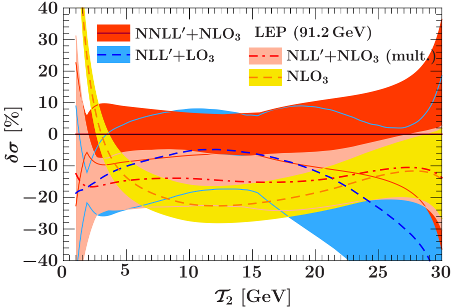
NLO$_3$ Merging

Merging NLL′+LO$_3$ with NLO$_3$

Additive



Multiplicative



- Improvement seen in the pure FO limit, but as soon as we are in the transition region the result is again worse than lower order (and fully consistent) NLL′+LO$_3$ result
- This is likely optimistic already since MC@NLO / POWHEG don't have full NLL′+LO$_3$ (Possibly MiNLO might, but not sure ...)

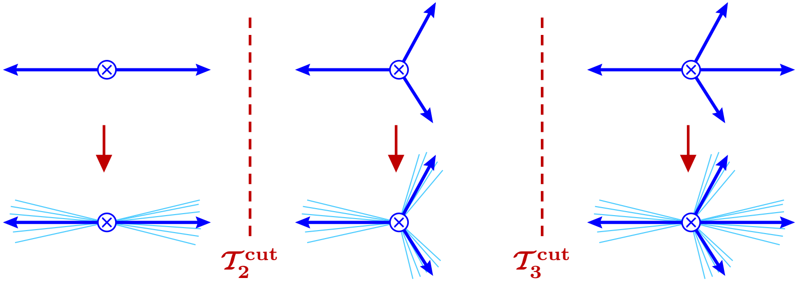
Comments ...

... to instigate discussion ;-)

- Are we really sure that by doing all this merging, matching, mixing of higher fixed-order corrections that we're not shooting ourselves in the foot?
- Shouldn't adding higher fixed orders (keeping everything else as accurate as before) always improve the pert. accuracy?
    - Not necessarily, one can only take this for granted in the region of phase space where fixed-order pert. theory provides the proper organization of the perturbative series
    - In other regions (certainly in the resummation region and maybe also in the transition) at the very minimum one should at least check (which I wouldn't really know how to do without having a consistent combination of resummed and FO pert. theory and having at least two orders to check convergence etc.)

Other Observables

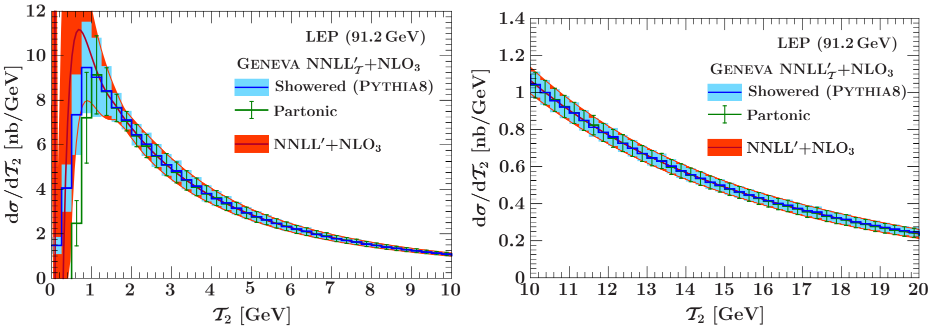
Attaching the Parton Shower in GENEVA



Partonic events represent resummed jet cross sections. Since the parton shower generates perturbative emissions it should

- only fill jets with radiation below $\mathcal{T} < \mathcal{T}^{\mathrm{cut}}$
- not change resummed jet cross sections
  - Requires the shower to not change the jet kinematics, in particular $\mathcal{T}_2$, of an event (up to small power corrections)
  - Currently done by repeatedly running Pythia8 shower on the same event. Clearly, there should be a smarter more efficient way ...

2-Jettiness $\mathcal{T}_2 = Q(1 - T)$



- For $\mathcal{T}_2$ we get out what we put in by construction
- Shower fills out $\mathcal{T}_2 < \mathcal{T}_2^{\rm cut} \simeq 1\,\mathrm{GeV}$ ("no-emission" bin)
  (here shape is Pythia while normalization is still NNLL$'$+NLO$_3$)

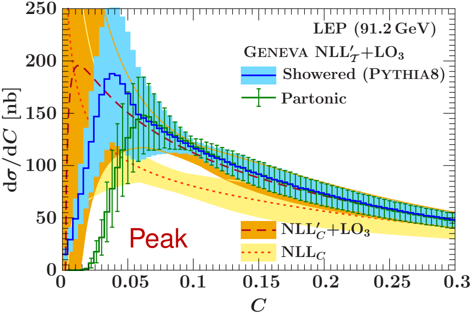
Interesting Question: What's the formal accuracy for other observables?

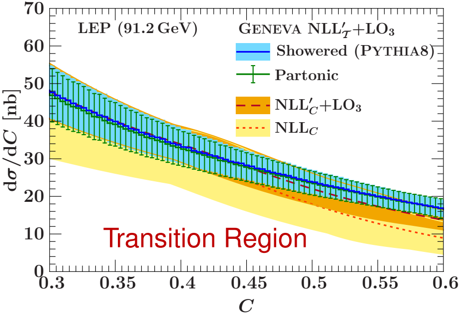
- So far we validate numerically against analytic resummed results

C Parameter

C parameter

- Logarithmic structure closely related to $\mathcal{T}_2$
  (differs in soft contributions, more extended resummation and transition regions)





- “No-emission” bin in $\mathcal{T}_2$ is more spread out now
- Putting in NLL′$_{\mathcal{T}}$+LO$_3$ we essentially get out analytic NLL′$_C$+LO$_3$ for both central value and uncertainties

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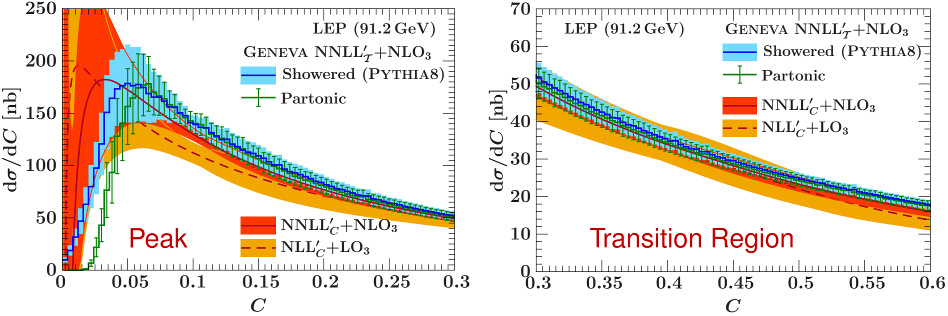

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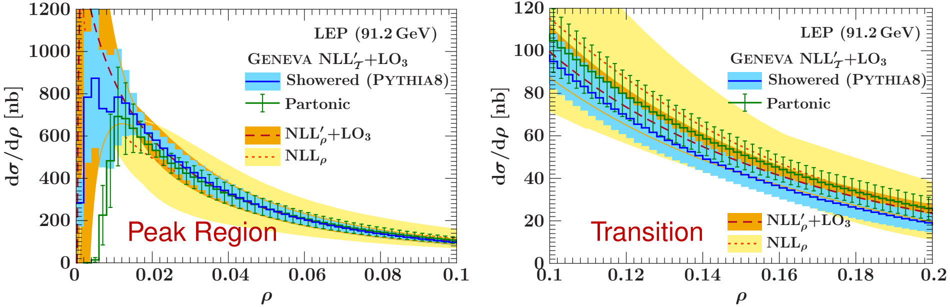
Heavy-Jet Mass

Heavy Jet Mass ρ

- Less related to $\mathcal{T}_2$
  (different projection of di-hemisphere mass distribution, max instead of sum)



- Expect higher-order corrections to shift spectrum to left due to back radiation into the other hemisphere

  $\Rightarrow$ Precisely what the showering "below" $\mathcal{T}_2$ does and which helps getting again close agreement with analytic NLL$'_C$+LO$_3$

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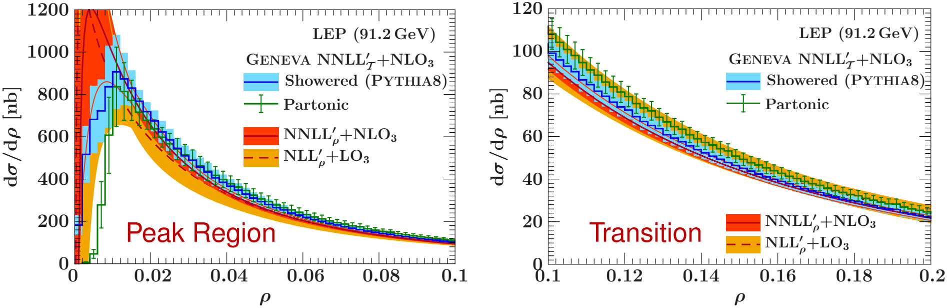

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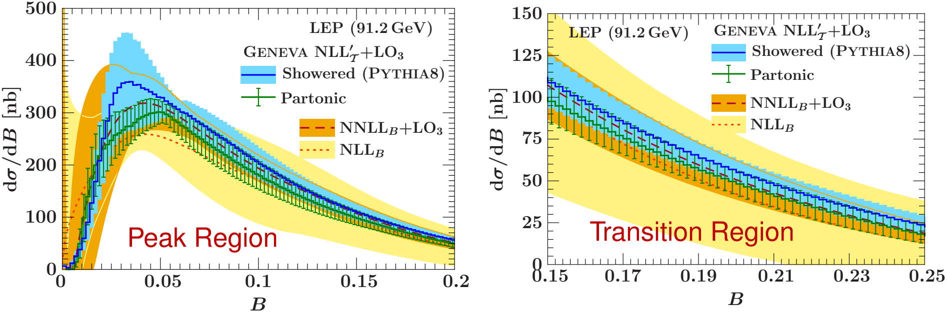
Jet Broadening

Jet Broadening B

- Very different log structure from $\mathcal{T}_2$ (p_T-like)



- Spectrum gets shifted by showering below $\mathcal{T}_2$ (consider including size of shift as additional uncertainty)
  - Remarkably close to NNLL+LO$_3$ (highest known analytic order)

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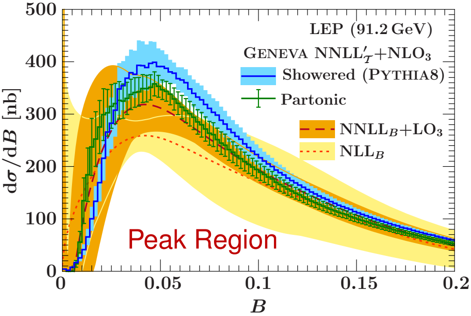

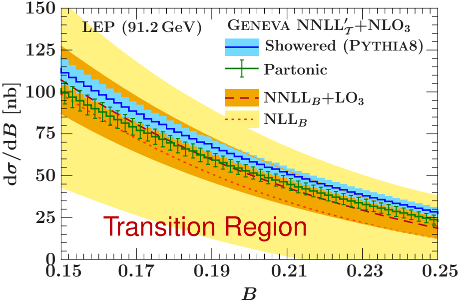

- Spectrum gets shifted by showering below $\mathcal{T}_2$
  (consider including size of shift as additional uncertainty)
  - Remarkably close to NNLL+LO$_3$ (highest known analytic order)
  - If I were to be provocative I'd say that GENEVA's NNLL$'_{\mathcal{T}}$+NLO$_3$ is the current best prediction for B

Food for Thought

Formal accuracy for other observables cannot be the same as that for $\mathcal{T}_2$

- Numerically, we clearly are getting very close
- We are "squeezing" from various directions
  - NNLL′ resummation in $\mathcal{T}_2$: Improves the distribution of events in the IR-sensitive region and everybody gets their logs from that same region
  - NLO_3 is fully exclusive: So it is right (up to the usual power corrections) for other observables, and since the integrated cross section is exactly the same there cannot be leftover fixed-order logs in other spectra either
  - Showering below $\mathcal{T}_2$: The fully exclusive nature of the shower is certainly helping to "transfer" the accuracy from $\mathcal{T}_2$

⇒ Closely related question: What is the actual formal accuracy of various showers for these (and other) observables (beyond "NLLish")?

MPI and Double Counting

MPI and Double Counting

I have only one slide and a lot of questions here:

- In practice, we can “just” let the MC add additional partonic interactions to model the UE

  (basically what everybody does at the moment and which is very unsatisfying)

- We barely know how to factorize/treat hard double parton scattering, do we have any idea about the perturbative/factorized QCD description of soft MPI?
  - What is the relevant scale? Is it perturbative or nonperturbative?
  - What is the factorization/separation between MPI and soft/collinear ISR?

- Do we know what we are doing when merging ME+PS/MPI (i.e. beyond doing ME+PS merging for a parton collider)?
  - Could the sizable soft MPI effects in the MC partly be fixing short-comings of the ISR shower (like wide-angle soft radiation between incoming and outgoing Wilson lines)?
  - If so, we would be ignoring nontrivial double counting between ME and MPI