Geneva: Event Generation at NLO

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Outline

- Report on progress towards Event Generation at NLO
- Important Features of Monte Carlos
- Why merging NLO with Resummation is important and challenging
- Current Approaches
- Geneva Approach
- First Results
- Conclusions

Important Features of MC

- Monte Carlos indispensable at colliders

  Goal: Connect most precise theory predictions possible to experiment.

- Key Feature: Monte Carlos are exclusive
  Basic role of event generator: return weight for each point in N-body phase space $\mathrm{d}\sigma/\mathrm{d}\Phi_N$

  - ➡ Can implement arbitrary experimental cuts $\{\eta_{\rm cut}, p_T^{\rm cut}, R\}$
    Major challenge for analytic calculations.

  - ➡ Leading small p_T resummation and large p_T fixed order

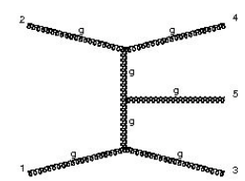
  - ➡ Allows one to be exclusive in jet multiplicities
    Eg. $pp \to H + 0, 1, 2\,\mathrm{jets}$ have different backgrounds and sensitivities

  - ➡ Fully hadronized events

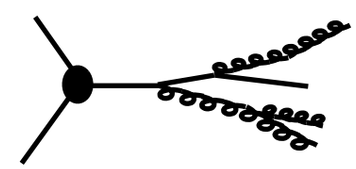
Parts of the Monte Carlo

$$\mathrm{d}\sigma^{MC} = \text{Hard Interaction} \otimes \text{Parton Shower} \otimes \text{Hadronization Underlying Event}$$

- Hard Interaction: Fixed order partonic matrix elements. Legs + Loops.

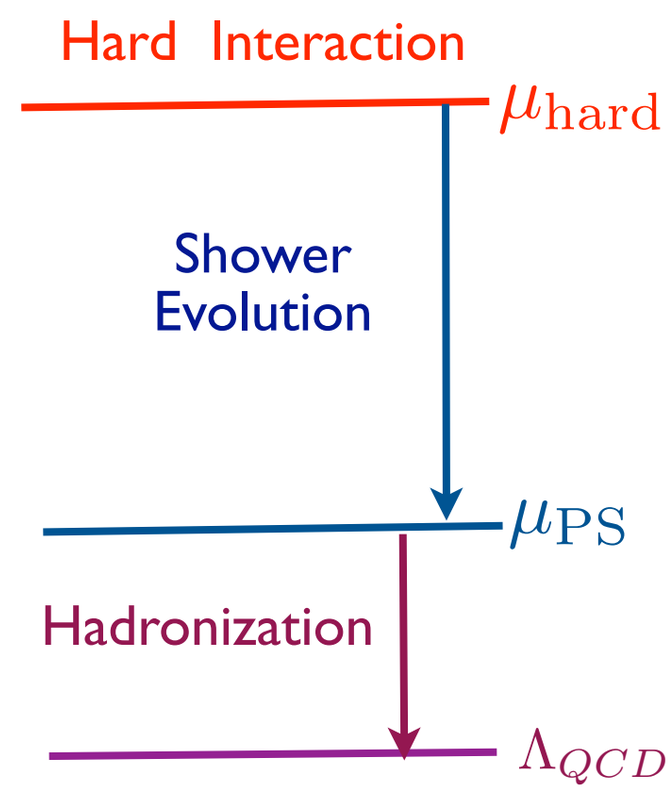


- Parton Shower: Collinear and soft splittings. High Multiplicity final state. Logs $\alpha_s \ln^2 \frac{\mu_{PS}}{\mu_H}$.



$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO Matrix Element	Parton Shower	Parton Shower	Parton Shower

- Hadronization/ UE: Model non-perturbative physics. Partons to hadrons



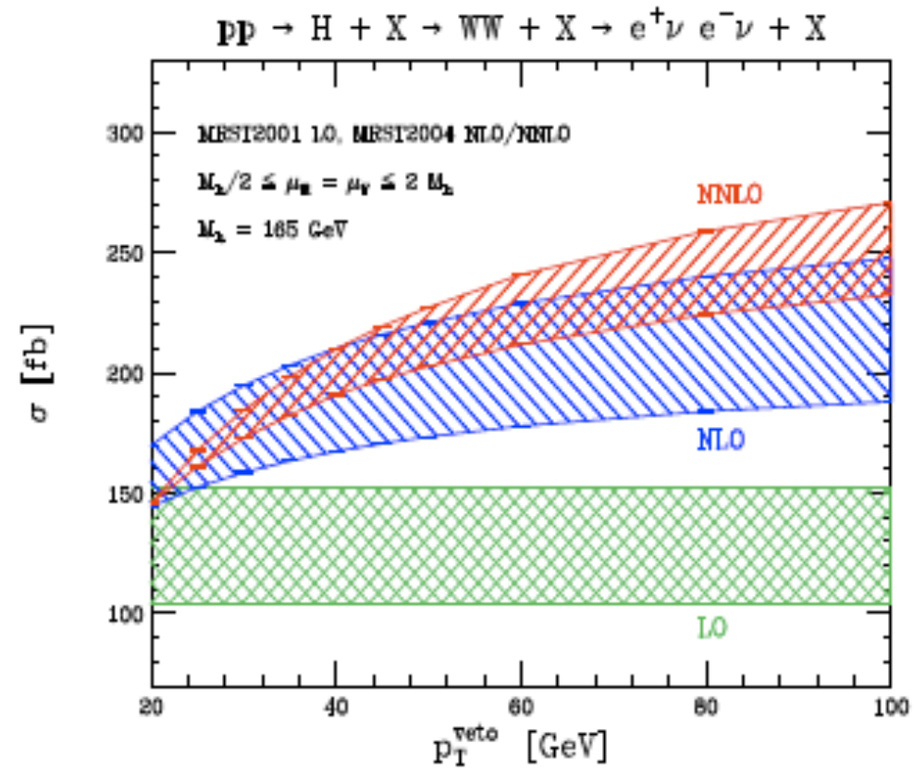
Combining Fixed Order and Resummation

Anastasiou, Dissertori, Stockli (2007)

- Example $pp \to H \to WW \to \ell\nu\ell\nu$:
  Large fixed order corrections. Vary with p_T^{cut}

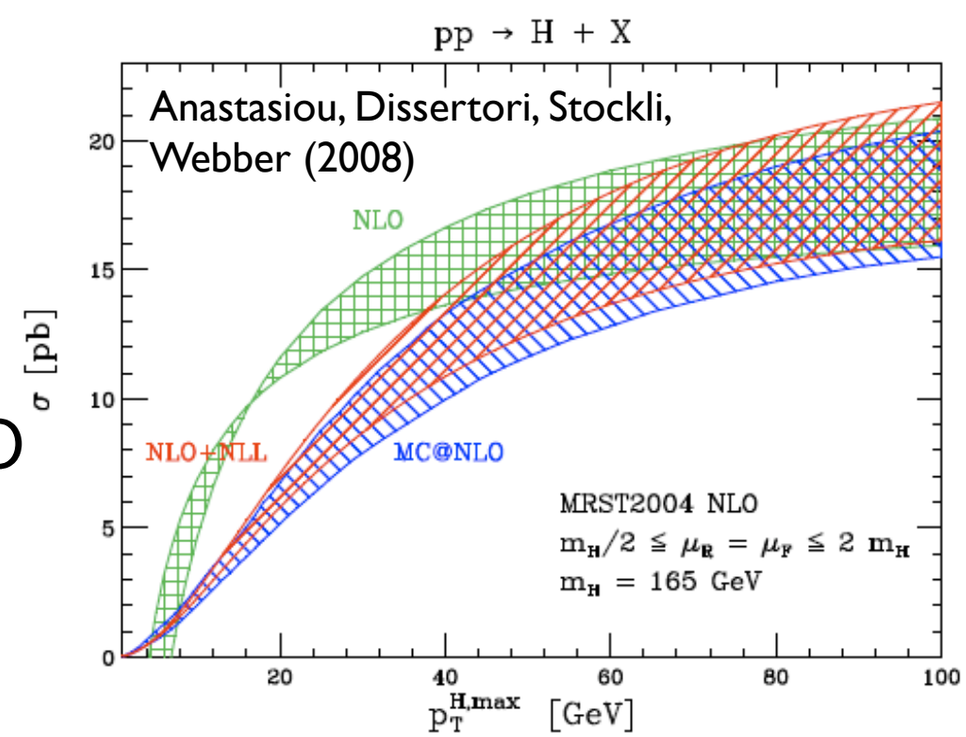
- FO α_s **expansion** describe large p_T^{cut} region
  Unreliable at small p_T^{cut}

- Need $\alpha_s \ln \frac{p_T^{\rm cut}}{m_H}$ resummation (parton shower)



- Combine Hard Matrix Element NLO with Resummation (parton shower)

- Goal of Geneva:
  Combine different jet multiplicities all at NLO with resummation

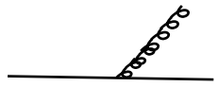


Challenge : Fixed Order and Parton Shower

At LO:

$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO Matrix Element	Parton Shower	Parton Shower	Parton Shower

- Beyond LO: **N-body Phase Space $\neq$ N-parton Phase Space**

IR finite NLO =  $d\Phi_n$ +  $d\Phi_{n+1}$

➡ Make each weight well defined.

- Both Parton Shower and NLO ME include real emission corrections
  FO: exact n+1 body, PS collinear/soft limit.

At NLO:

$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO +Virtual	Real / PS	Parton Shower	Parton Shower

➡ Avoid Double Counting

Current Approaches: Fixed Order $\otimes$ Parton Shower

*touch on just a few

- MC@NLO/ POWHEG (NLO for single jet multiplicity) $\otimes$ (LL Parton Shower)

➡ Divergences: Define Subtraction $\mathrm{d}\Phi_n \left[V_n + \int \mathrm{d}\Phi_{n+1|n} S \right] + \mathrm{d}\Phi_{n+1} \left[R_{n+1} - S \right]$

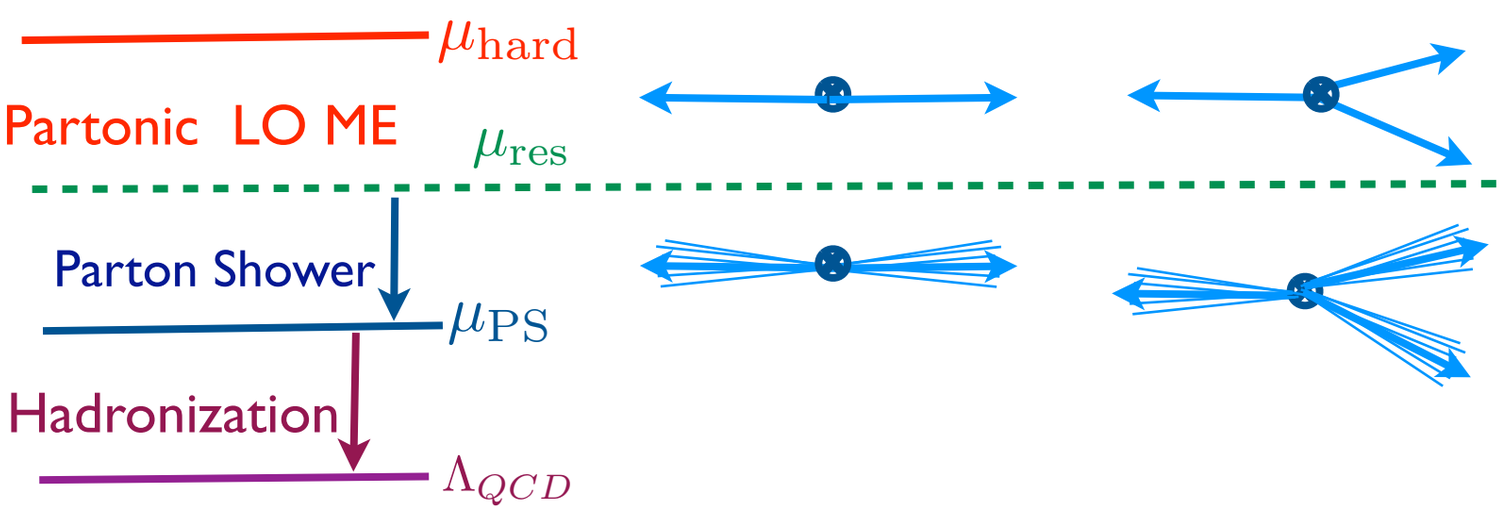
Maps N-Body Phase Space to N-Parton Phase Space

[Frixione, Webber; Nason; Frixione, Nason, Oleari]

➡ Double Counting: Modify 1st emission of parton shower. **Inclusive** jet observable at NLO

- Multi-jets at LO (LO for **all** jet multiplicities) $\otimes$ (LL Parton Shower)

[Catani, Krauss, Kuhn, Webber; Lönnblad; Mangano]



Hard matrix element combined with Sudakov to cancel $\mu_{\rm res}$ dependence.

[Bauer, Tackmann, Thaler; Hamilton, Nason; Hoche, Krauss, Schonherr, Siegert]

➡ MENLOPS (NLO single jet + LO rest jet multiplicities) $\otimes$ (LL Parton Shower)

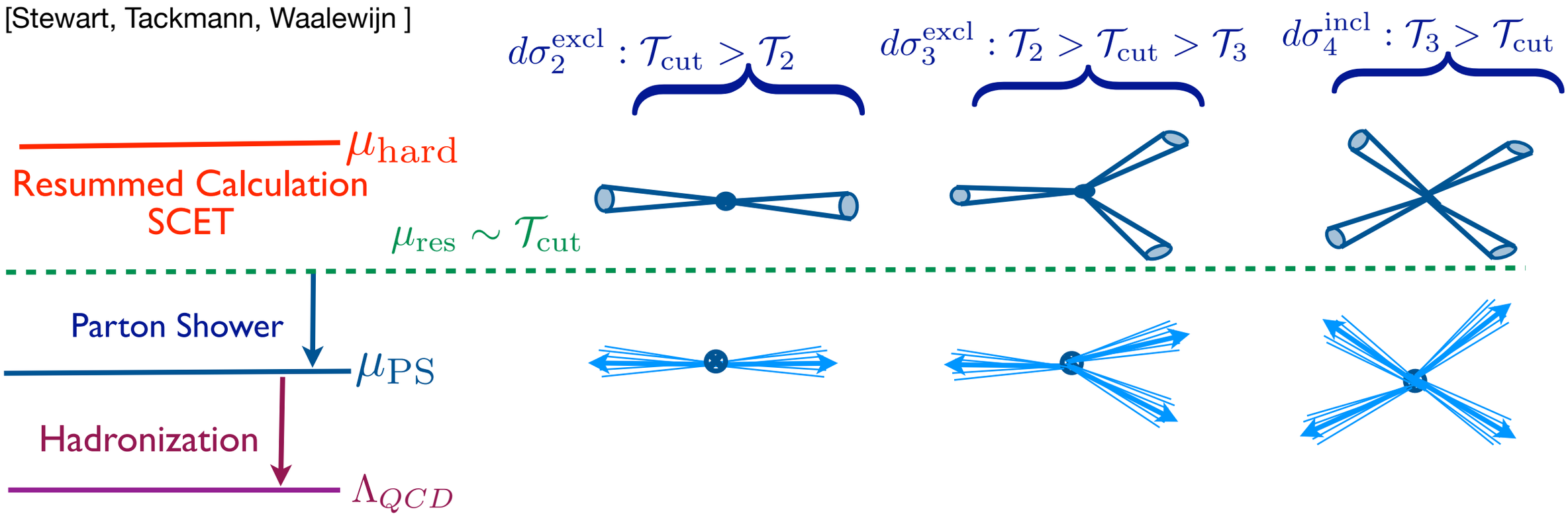
The Geneva Approach

- **Goal:** Exclusive jet multiplicities all at NLO + resummation $pp \to H/W + 0, 1, 2\,\mathrm{jets}$
  Start with $e^+e^- \to 2, 3, 4\,\mathrm{jets}$.
  Naively 4 jets NLO would require 2 jet to N^{3}LO to be IR finite.
  Geneva: relevant pieces obtained from resummation

➡ Divergences: **Map N-jet Phase Space to N-body Phase Space**

➡ **Divide Phase Space :** Resolution variable, N-jettiness $\mathcal{T}_N$. Vetos > N jets. Well defined for any number of partonic final states.

[Stewart, Tackmann, Waalewijn]



Systematic Improvement of MC Using EFT

- For given N-jet 

[Bauer, Fleming, Luke, Pirjol, Stewart]

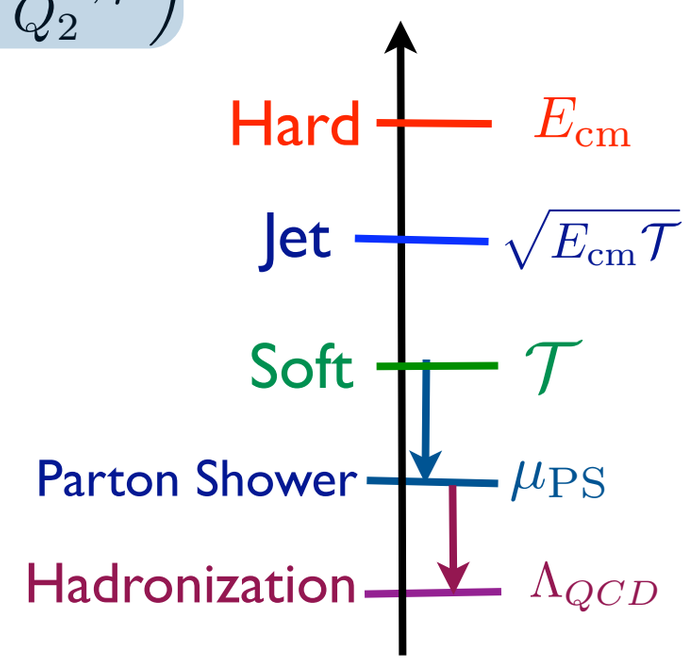
- **Small** $\mathcal{T}_2$: Soft Collinear Effective Theory - framework to calculate resummed QCD distributions.

  Systematically include: α_s^n matching and resum renormalization group $\alpha_s^n \ln^m(\mathcal{T}/Q)/\mathcal{T}$

$$\frac{\mathrm{d}\sigma_2^s}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}} = \frac{\mathrm{d}\sigma_B}{\mathrm{d}\Omega} H_2(E_{\mathrm{cm}}^2,\mu) \int \mathrm{d}s_1 \mathrm{d}s_2\, J_1(s_1,\mu)\, J_2(s_2,\mu)\, S_2\left(\mathcal{T} - \frac{s_1}{Q_1} - \frac{s_2}{Q_2}, \mu\right)$$

Hard Function: NLO matrix elements

Jet and Soft functions: Collinear and soft limit

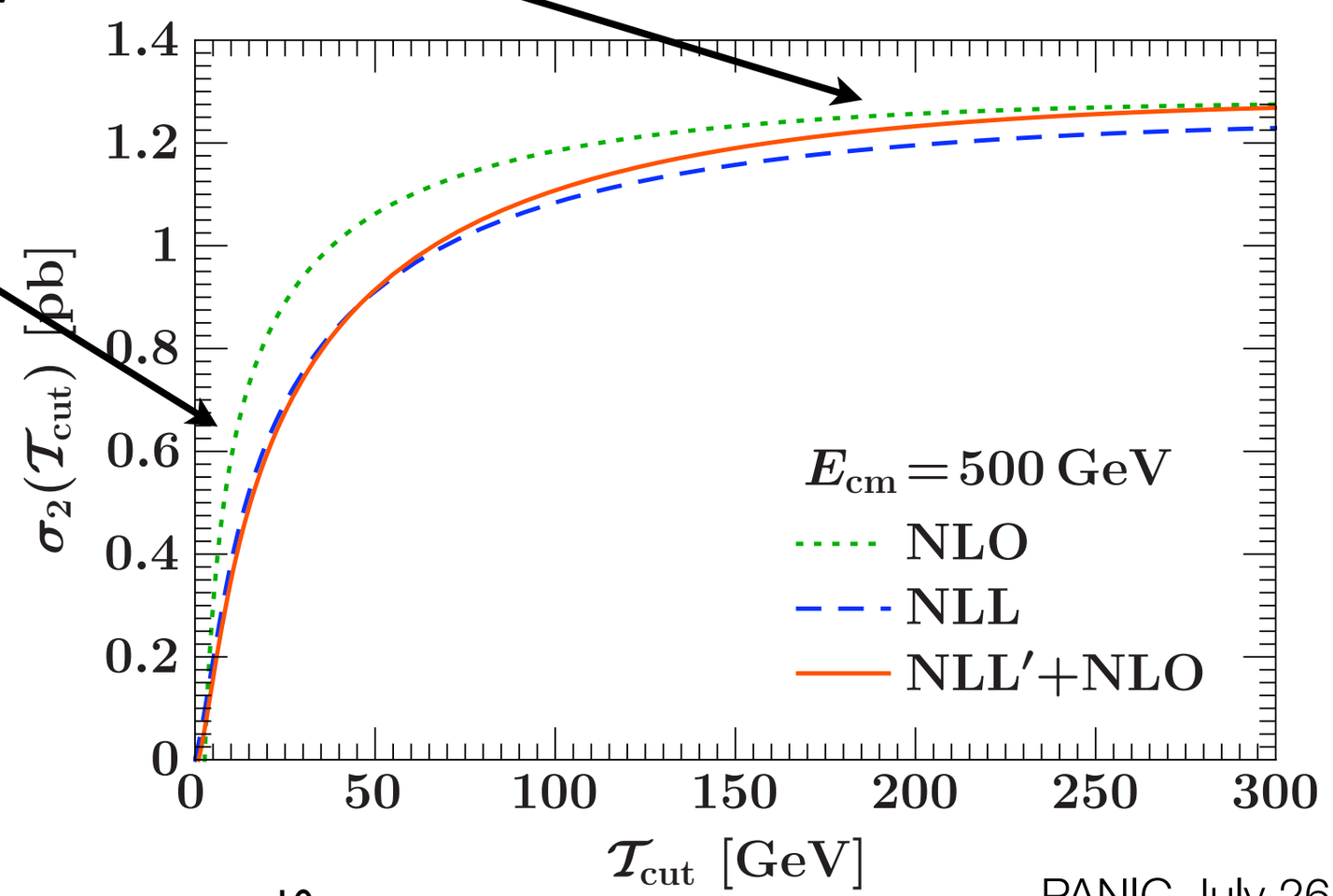


Systematic Improvement of MC Using EFT

- Combine with large $\mathcal{T}_2$ in 2-jet bin

$$\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}} = \underbrace{\frac{\mathrm{d}\sigma_2^s}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}}}_{\text{Resummed}} + \left[\underbrace{\frac{\mathrm{d}\sigma_2^{\mathrm{QCD}}}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}} - \frac{\mathrm{d}\sigma_2^s}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}}\Big|_{\mathrm{exp}}}_{\text{Non-singular NLO}}\right]$$

NLL'= NLO FO+ $\alpha_s^n L^{2n-1}$



Combining Higher Jet Multiplicities

- Focus on 2-jet NLL+NLO, 3 jet LO (MC@NLO/POWHEG equivalent)

- Distribute events according to:

2-body events

3-body events

$$\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}}) = \int_0^{\mathcal{T}_{\mathrm{cut}}} \mathrm{d}\mathcal{T}_2 \frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}_2} + \frac{\mathrm{d}\sigma_{\geq 3}}{\mathrm{d}\Phi_3} = \left(\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega_2\,\mathrm{d}\mathcal{T}_2} \Big/ \frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega_2\,\mathrm{d}\,\mathcal{T}_2}\Big|_{\mathrm{exp}} \right) \frac{\mathrm{d}\sigma^{\mathrm{FO}}_{\geq 3}}{\mathrm{d}\Phi_3}\theta(\mathcal{T}_2 > \mathcal{T}_{\mathrm{cut}})$$

Constant $\mathcal{T}_2$ dependence for 2-body events

Has full Φ_3 dependence

Large $\mathcal{T}_2$: Resummation starts to turn off.
Ratio starts at $\mathcal{O}(\alpha_s^2)$

Small $\mathcal{T}_2$: Resummation important
Ratio starts at NNLL

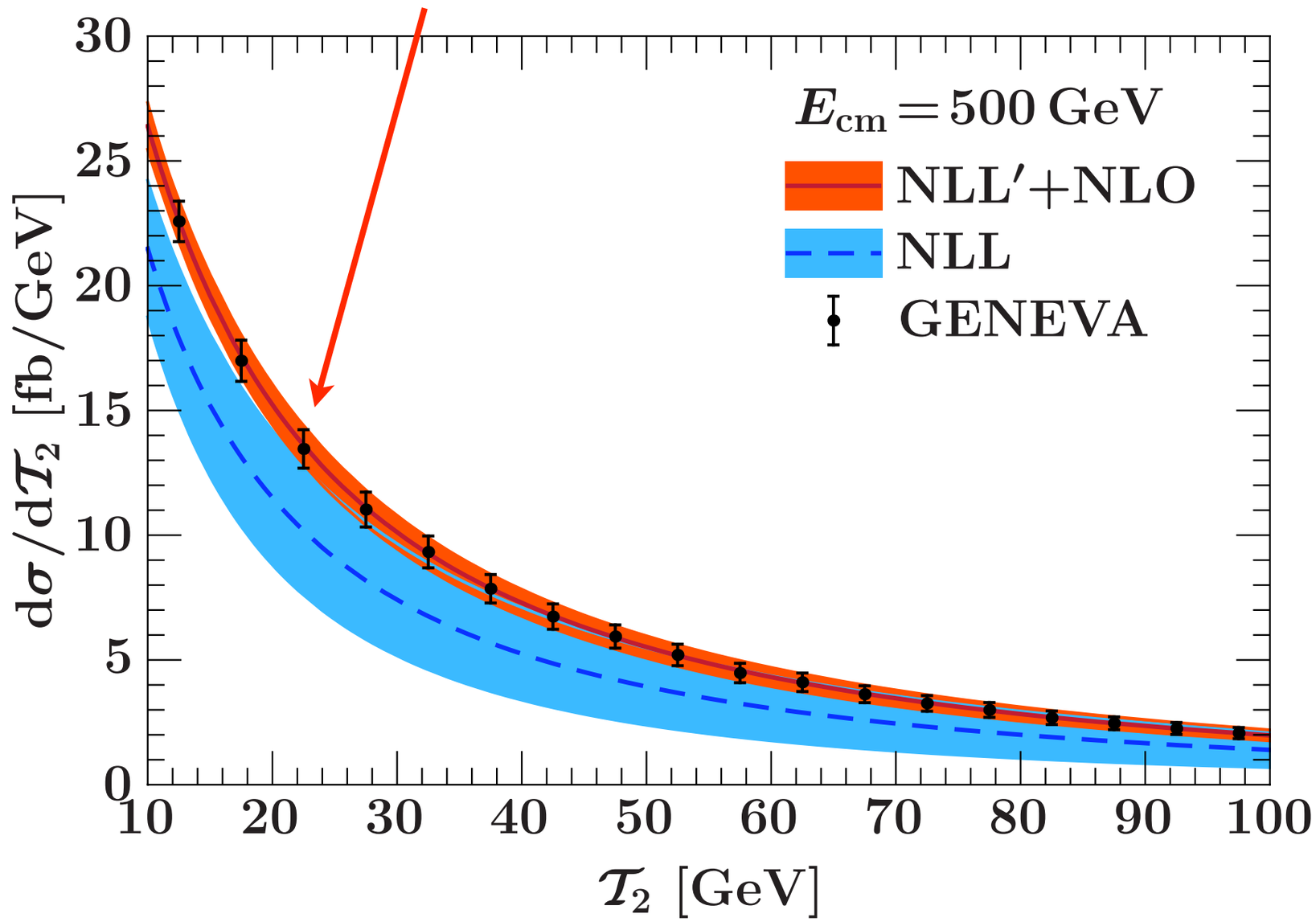
- Now straightforward to extend to 3 jet NLO.

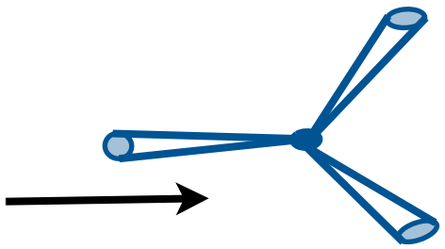
First Results

- Distribute events according to $\frac{\mathrm{d}\sigma_{\geq 3}}{\mathrm{d}\Phi_3}$

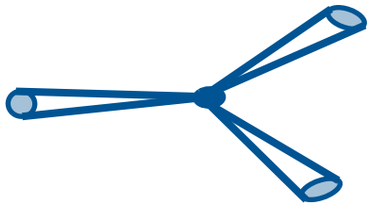
$\mathcal{T}_2 = 2(1-T)$

- Monte Carlo with theory (scale) uncertainties not MC statistics! Exactly matches analytic central value + uncertainty.





First Results

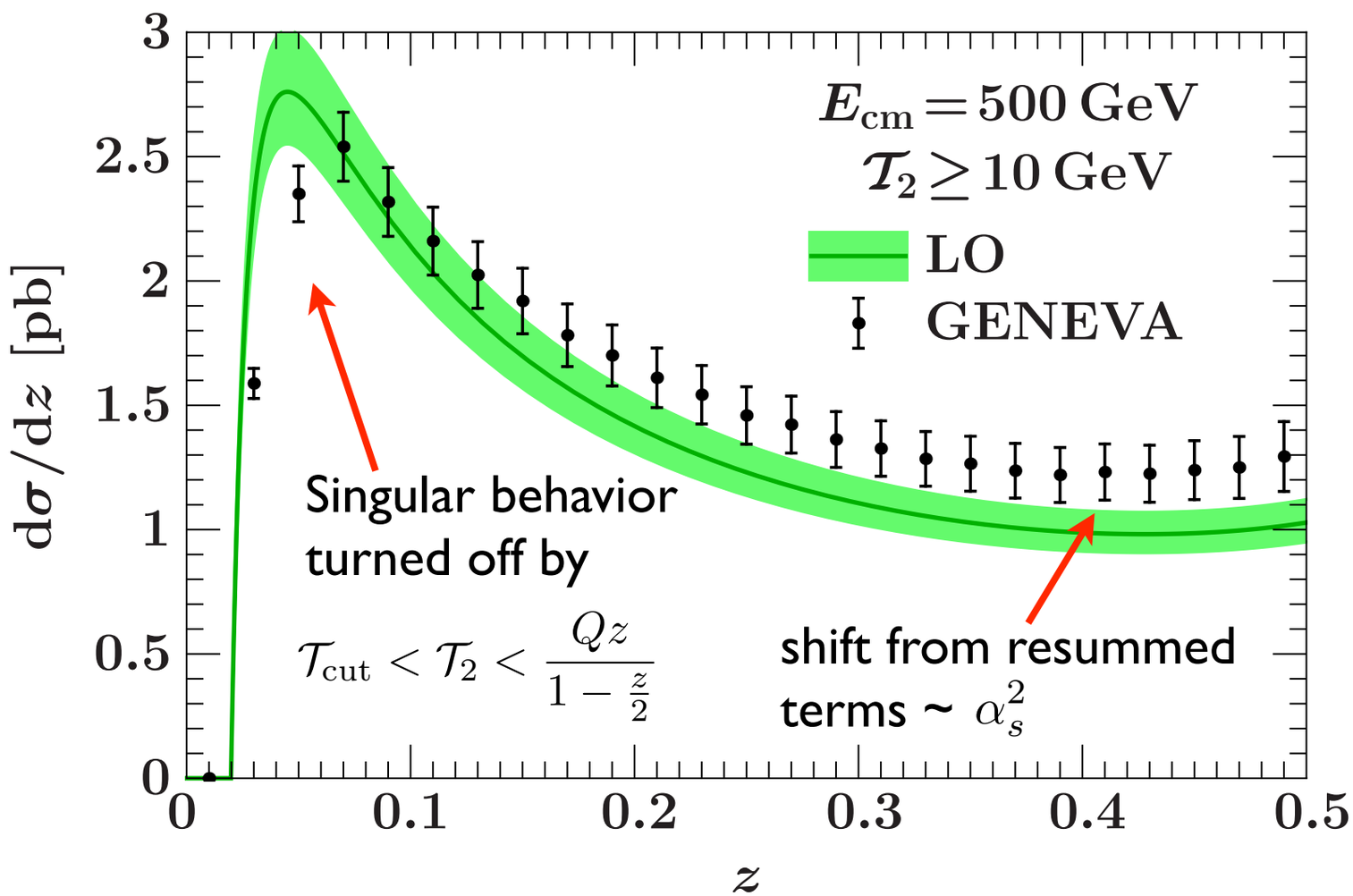


- Consider variable sensitive to Φ_3 angular dependence.

  Using $$\frac{\mathrm{d}\sigma_{\geq 3}}{\mathrm{d}\Phi_3} = \left(\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega_2\,\mathrm{d}\mathcal{T}_2} \Big/ \frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega_2\,\mathrm{d}\,\mathcal{T}_2}\Big|_{\mathrm{exp}} \right) \frac{\mathrm{d}\sigma^{\mathrm{FO}}_{\geq 3}}{\mathrm{d}\Phi_3} \theta(\mathcal{T}_2 > \mathcal{T}_{\mathrm{cut}})$$

- Should reproduce **shape**. $\mathrm{d}\Phi_3 = \mathrm{d}\Phi_2\,\mathrm{d}z\,\mathrm{d}\mathcal{T}_2\,\mathrm{d}\phi$ $\qquad z = \dfrac{E_1}{E_1 + E_2}$

  Definition of variables consistent for 3-jets (at any order).



Conclusions

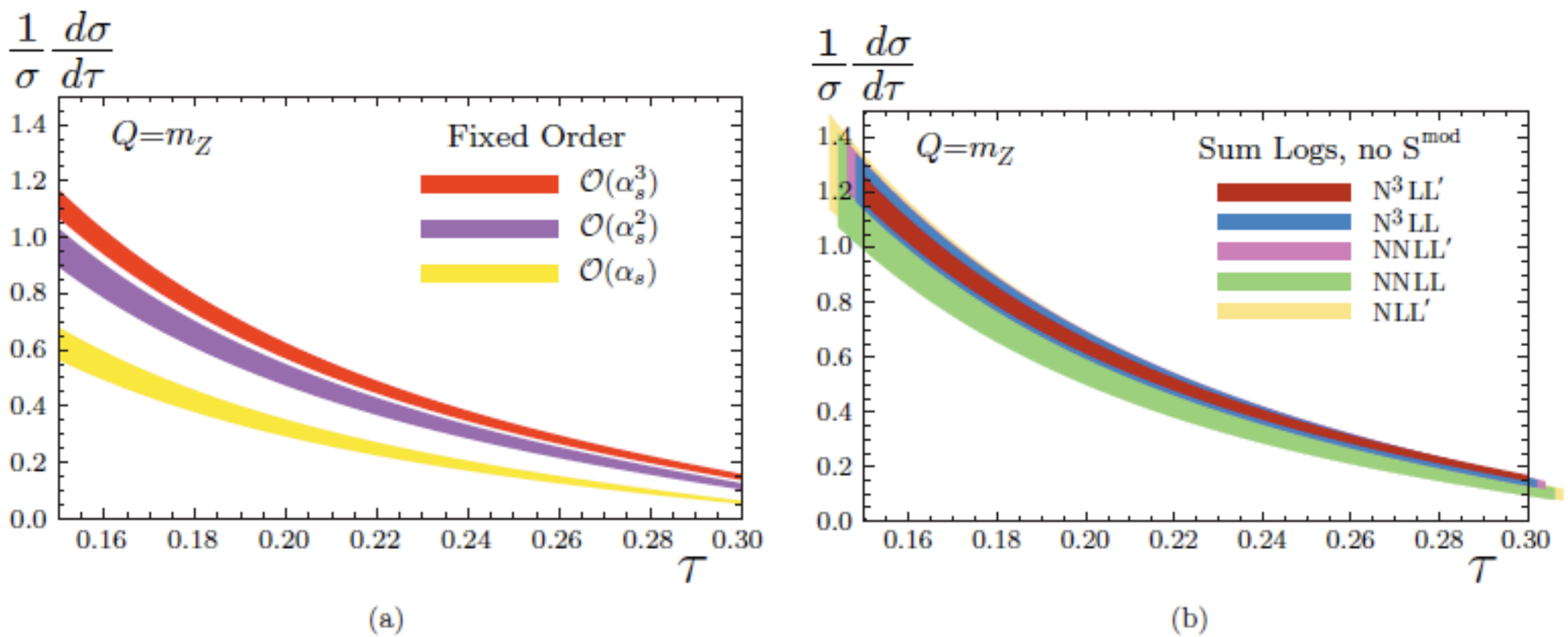
- Want event generators with best possible accuracy to connect theory and experiment
- Goal of Geneva: Combining several jet multiplicities at NLO with resummation/ parton shower
- Method: Use resummed exclusive cross-sections from SCET
- Status: 2 jet NLL'+ NLO and 3 jet LO; 3 jet NLO almost complete.
- Expect $pp \to H + 0, 1\,\mathrm{jets}\,, \quad pp \to W + 0, 1\,\mathrm{jets}$ at NLO soon!

END

Back Up Slides

α_s^2 corrections are Large

- NLL' much larger than α_s contribution



[Abbate, Fickinger, Hoang, Mateu, Stewart]

Perturbative Structure

- Perturbative structure of hard interaction $\otimes$ parton shower

$$L \sim \ln \frac{\mu_{\rm PS}}{\mu_{\rm hard}}$$

$$\begin{aligned}
\sigma \quad \sim \quad & 1 \\
+ \quad & \alpha_s L^2 + \alpha_s L + \alpha_s \qquad NLO \\
+ \quad & \underbrace{\alpha_s^2 L^4}_{LL} + \underbrace{\alpha_s^2 L^3}_{NLL} + \underbrace{\alpha_s^2 L^2 + \alpha_s^2 L}_{N^2LL} + \alpha_s^2 \qquad N^2LO
\end{aligned}$$