Geneva: Event Generation at NLO

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INT Sept 27, 2011

Outline

- Report on progress towards Event Generation at NLO
- What do event generators do - working parts
- Why merging NLO with Resummation is important and challenging
- Geneva Approach
    - SCET
    - First Results
    - Next Steps
- Conclusions

What do Event Generators Do?

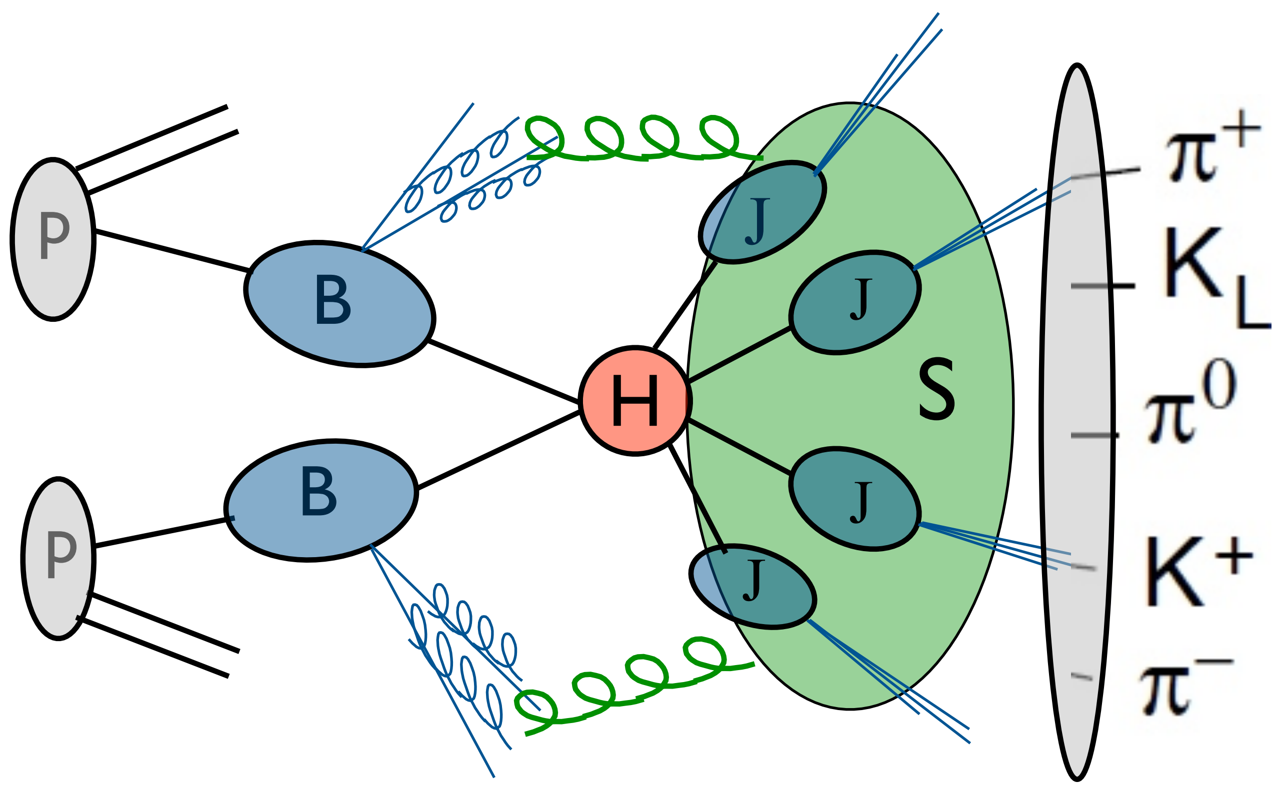
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \int \mathrm{d}\Phi_n \, \underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_n}}\delta\left(\mathcal{O} - \hat{\mathcal{O}}(\Phi_n)\right)$$

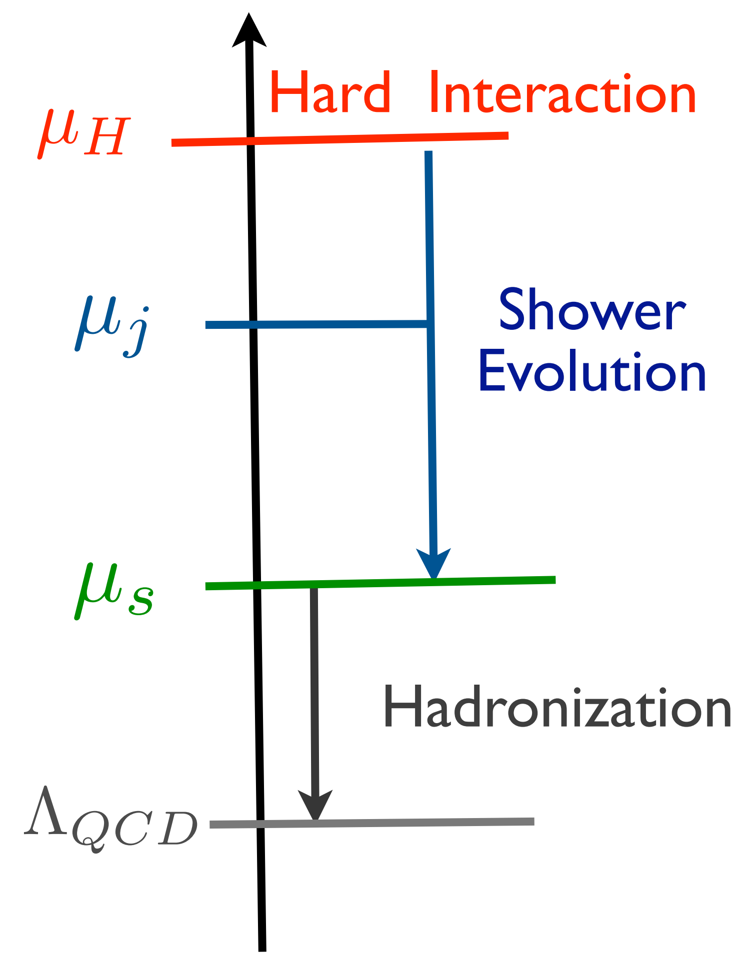
Basic role: return weight for each point in N-body phase space

- Address many of the challenges in connecting theoretical calculations to experimental searches:
    - High multiplicity final states
    - Complicated final state cuts $\{\eta_{\rm cut},\, p_T^{\rm cut},\, R\}$
    - Hadronic final states
    - Tune models of underlying event and pile-up

Parts of the Monte Carlo

- Monte Carlo is built on the idea of factorization





$d\sigma^{MC} =$ Hard Interaction $\otimes$ Collinear Evolution $\otimes$ Soft Radiation $\otimes$ PDFs Hadronization Underlying Event

Parts of the Monte Carlo

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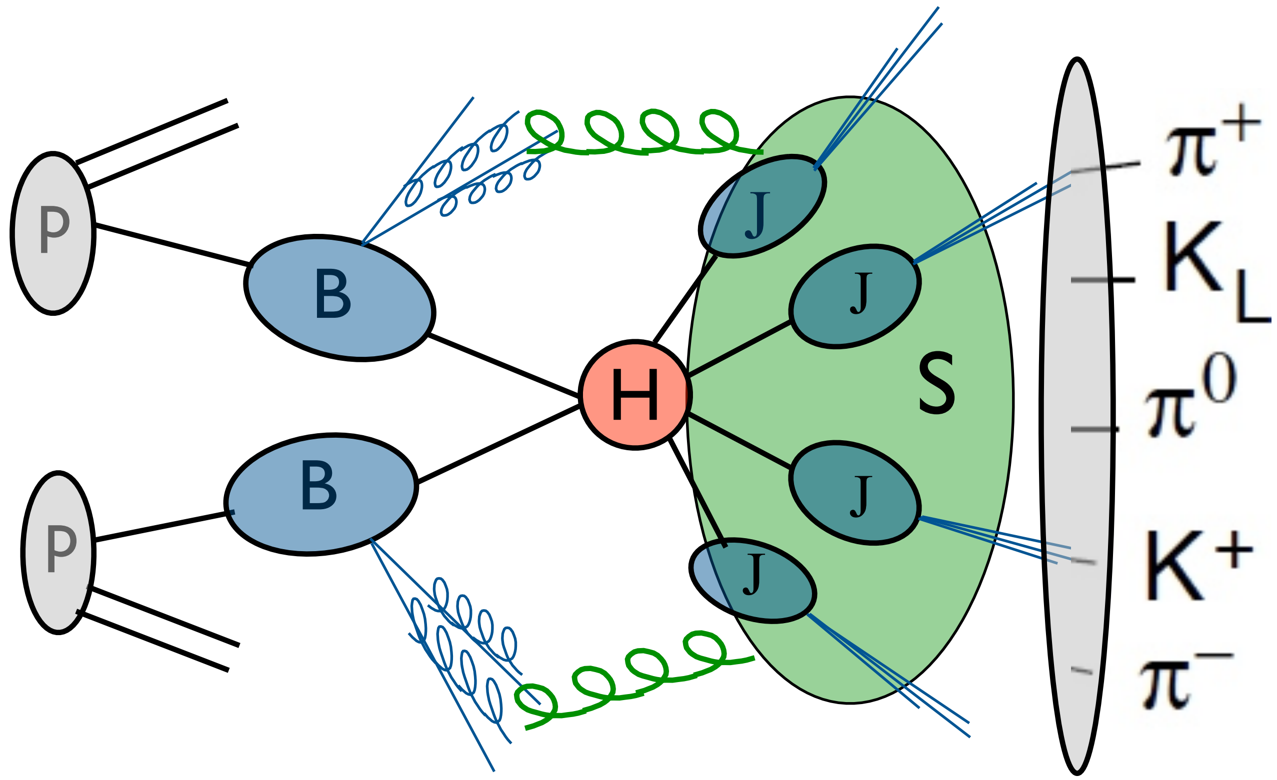
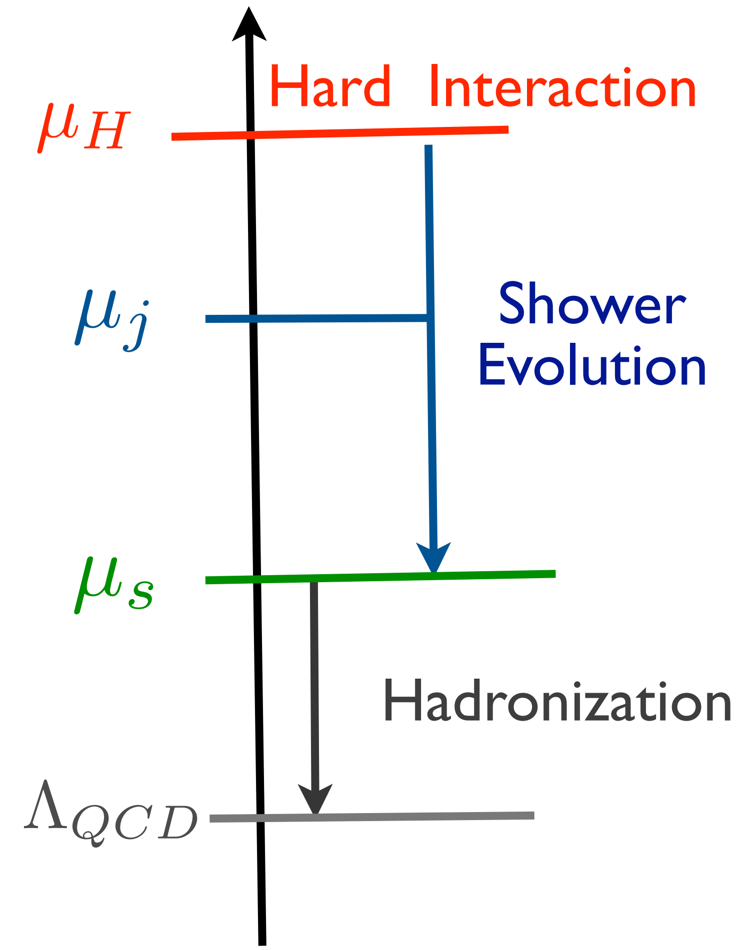




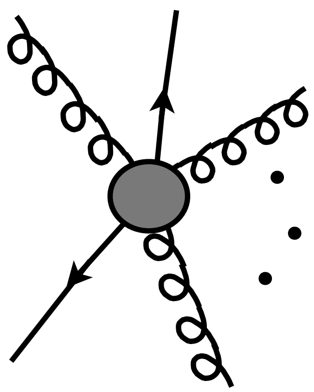
$$d\sigma^{MC} = \text{Hard Interaction} \otimes \boxed{\text{Collinear Evolution} \otimes \text{Soft Radiation}} \otimes \begin{matrix}\text{PDFs} \\ \text{Hadronization} \\ \text{Underlying Event}\end{matrix}$$

Parton Shower Evolution

Parts of the Monte Carlo

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

- Hard Interaction: Fixed order partonic matrix elements.
    - Challenge of perturbative corrections many final states
    - Many developments in calculation techniques



Automization of NLO has seen much progress:

Blackhat, Rocket, MadLoop, GOLEM and more...

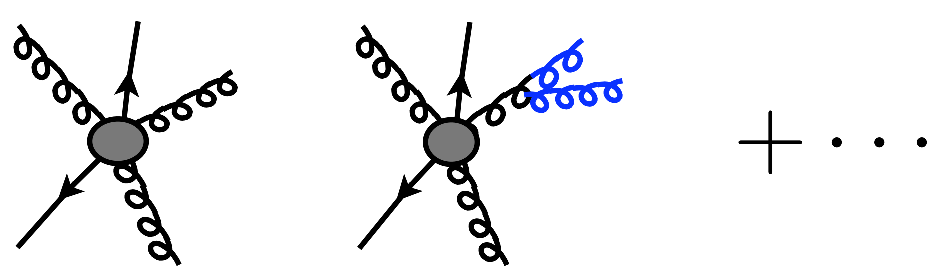
Processes like pp -> W + 4 jets at NLO [Berger,Bern,Dixon,Febres-Cordero,Gleisberg,Forde,Ita,Kosower,Maitre], [Diana,Ozeren,SH]

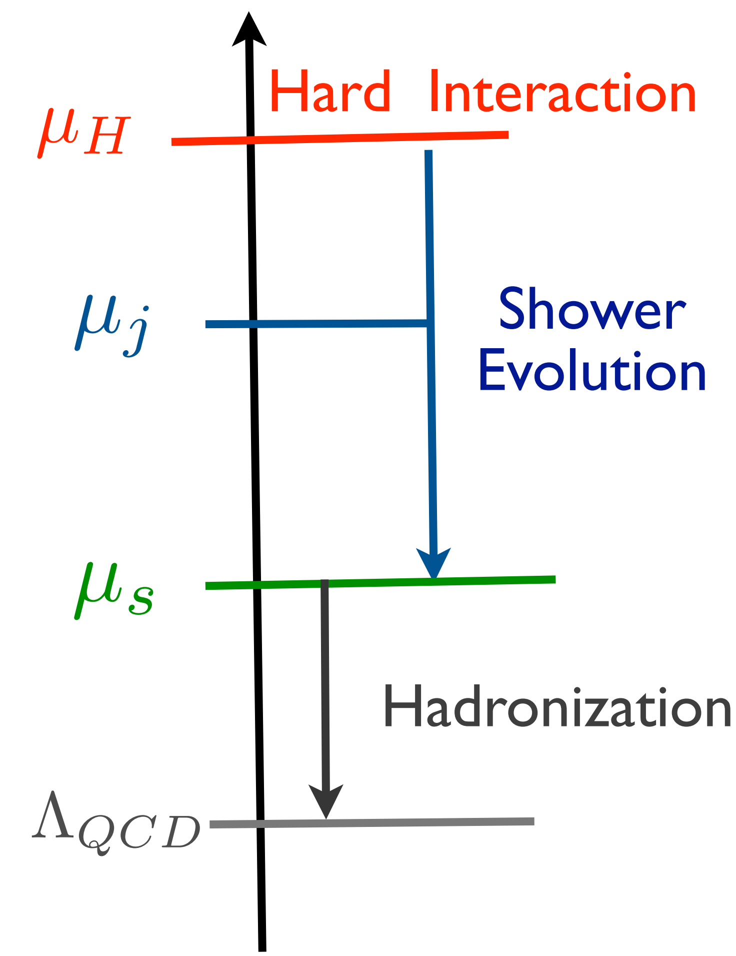
✴ See Zvi Bern's talk

Parts of the Monte Carlo

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

- Parton Shower: Collinear and soft splittings added to hard partons fills out phase space.
  - Sums leading double logs $\alpha_s \ln^2 \frac{\mu_S}{\mu_H}$





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

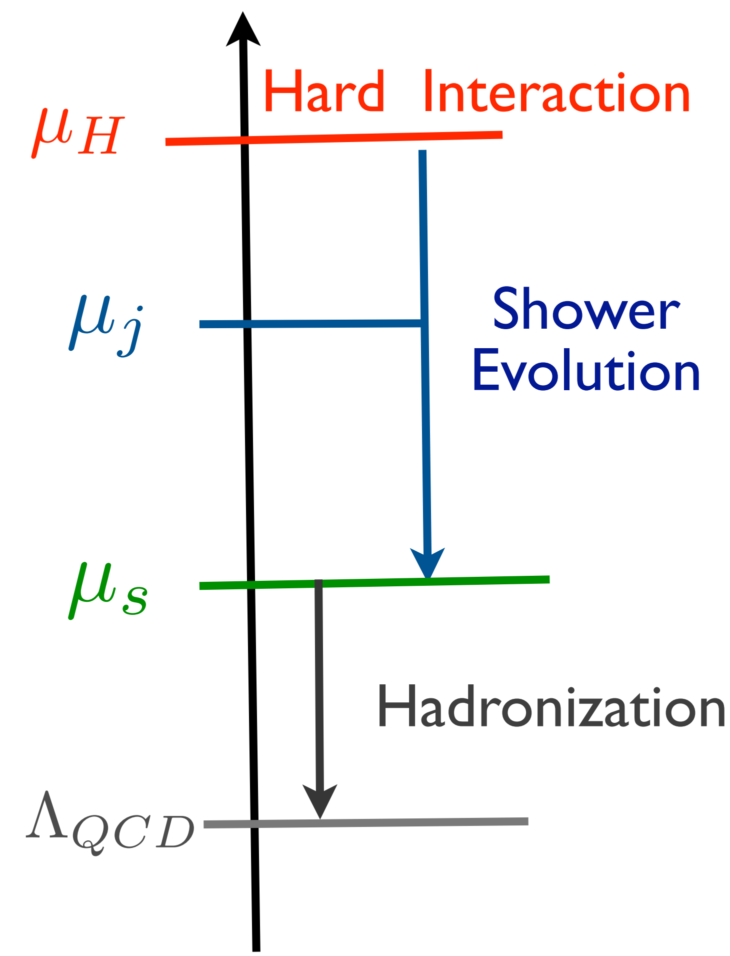
$1\,\mathrm{LO} \otimes$ Parton Shower

Parts of the Monte Carlo

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

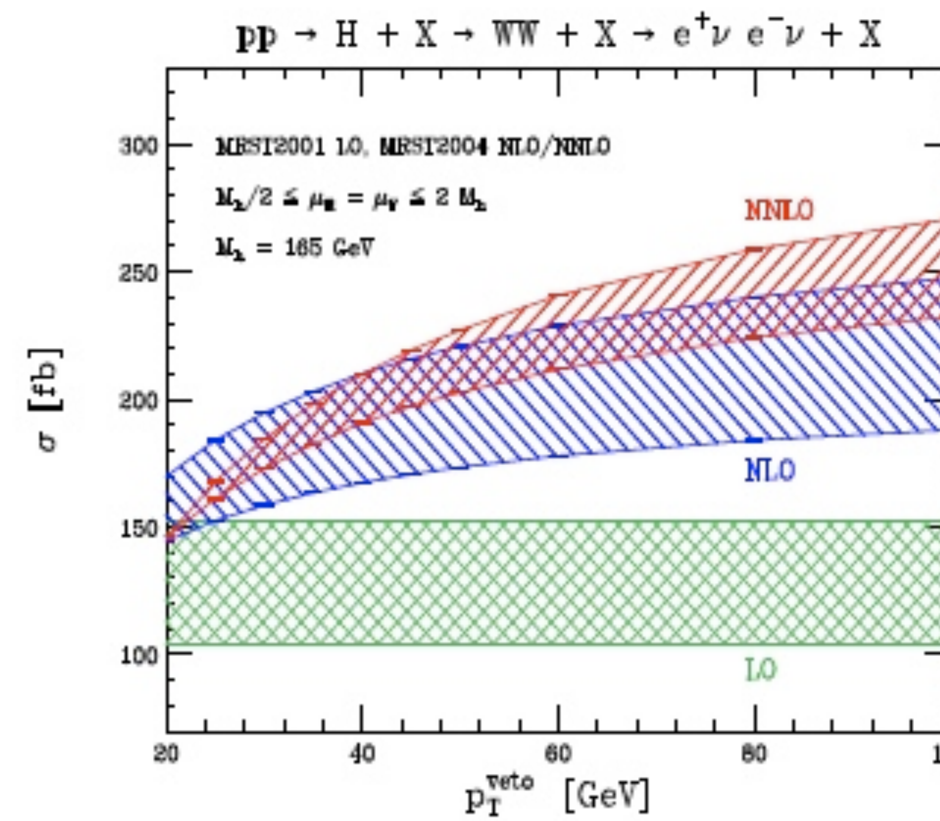
$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO Matrix Element	Parton Shower	Parton Shower	Parton Shower

I will focus on Fixed Order $\otimes$ Parton Shower



Combing FO and Resummation is Important

Anastasiou, Dissertori, Stockli (2007)



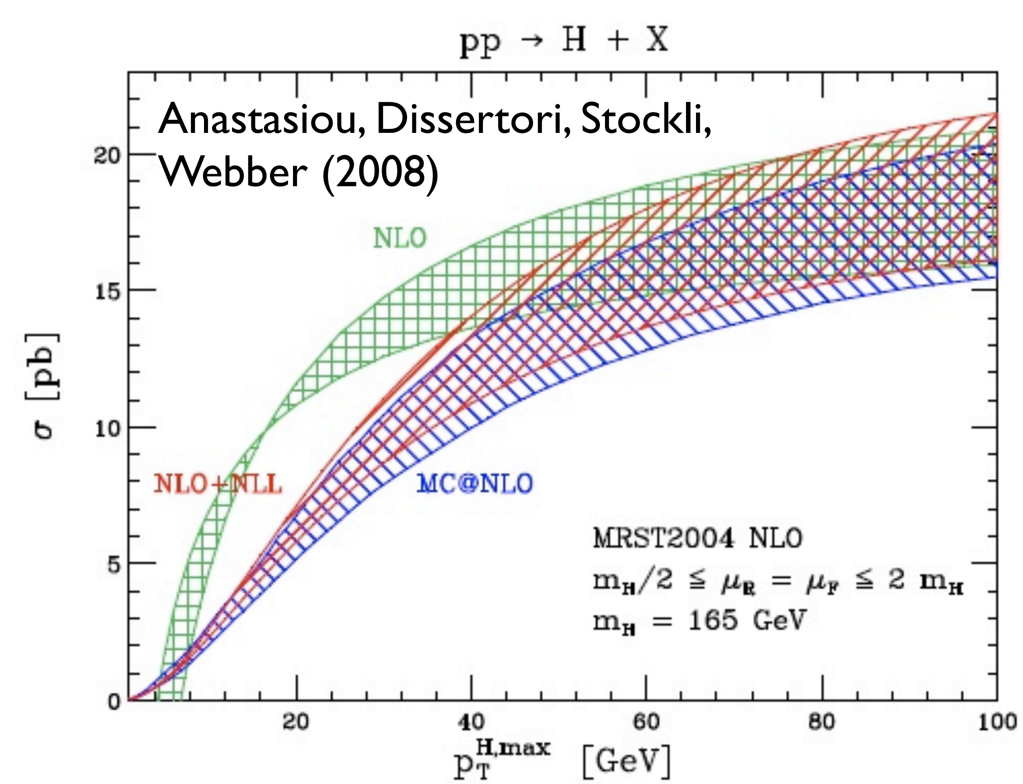
- Example $pp \to H \to WW \to \ell\nu\ell\nu$:

- **Going to NLO is important**
  Large fixed order corrections. Vary with p_T^{cut}

- **Resummation is important**

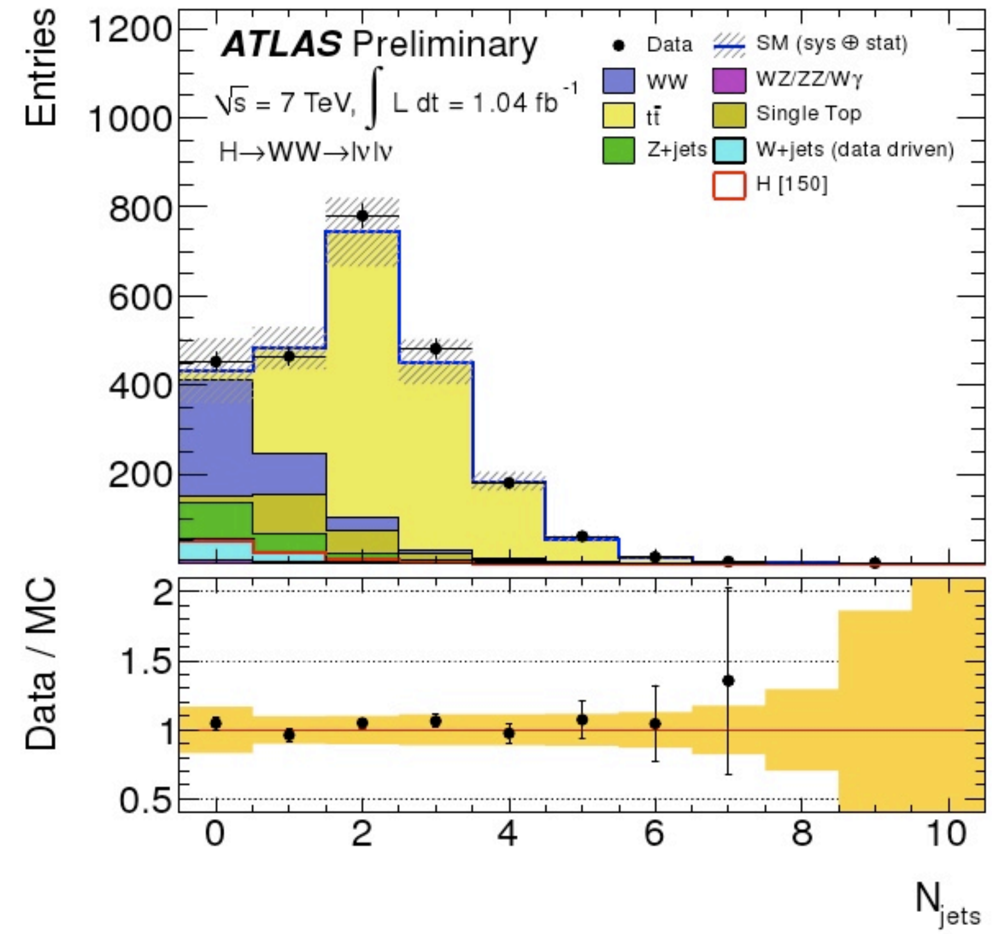
- FO α_s expansion describe large p_T^{cut} region
  Unreliable at small p_T^{cut}

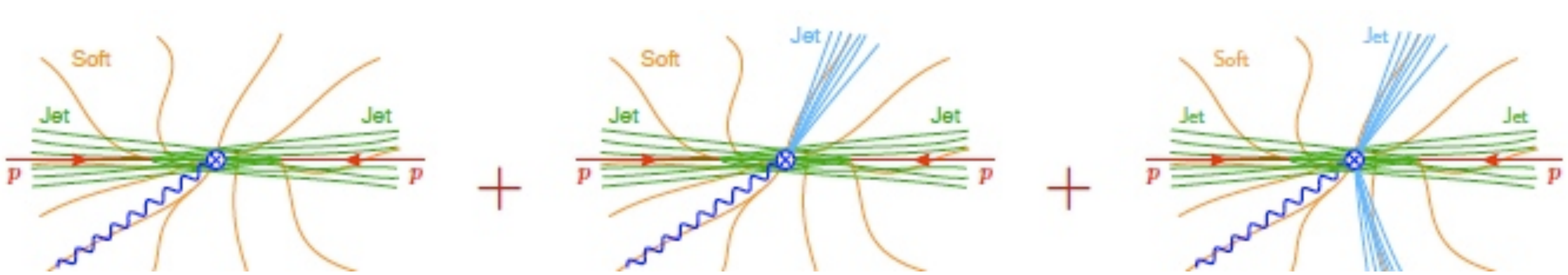
  Large logs of $\alpha_s \ln \frac{p_T^{\rm cut}}{m_H}$



Combing FO and Resummation is Important

- Often interested in exclusive jet samples
- For example $pp \to H + 0\,,1\,,2\,\mathrm{jets}$
  Backgrounds depend on jet multiplicity.
- Want exclusive jet multiplicities all at NLO with resummation



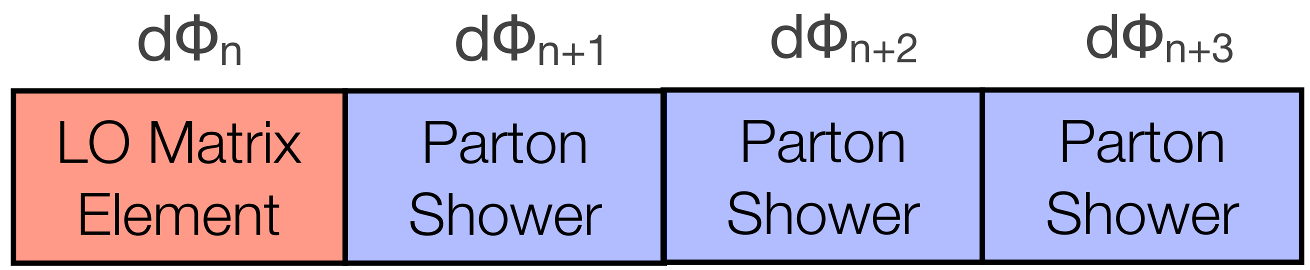


$\mathrm{d}\sigma_{0\,jet}$ $\mathrm{d}\sigma_{1\,jet}$ $\mathrm{d}\sigma_{2\,jet}$

*Image from Frank Tackmann

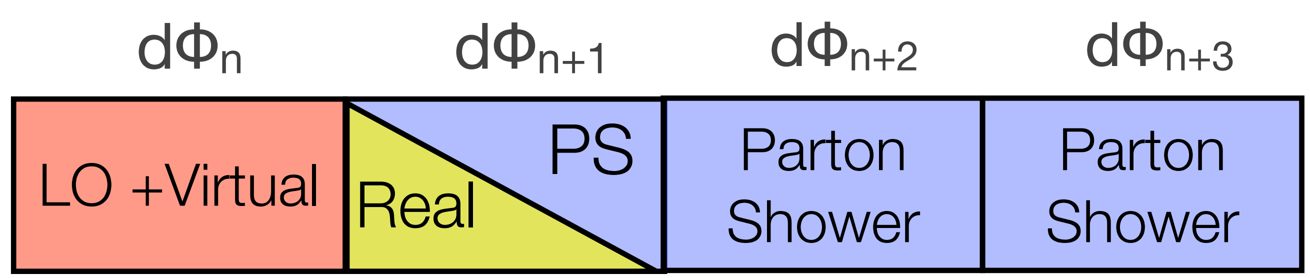
Challenge : Fixed Order and Parton Shower

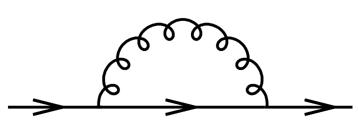
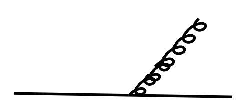
n-jet sample at LO:



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

n-jet sample at NLO:

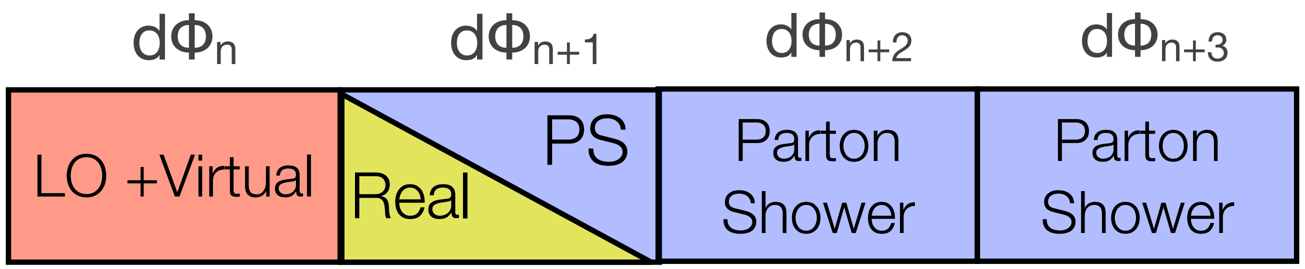


-  $d\Phi_n$ +  $d\Phi_{n+1}$ = IR finite NLO

- FO ME requires cancellation in singular limit. Collinear/soft limit described by parton shower

Challenge : Fixed Order and Parton Shower

n-jet sample at NLO:



- Challenge: ➡ Make each $d\Phi_n$ weight well-defined

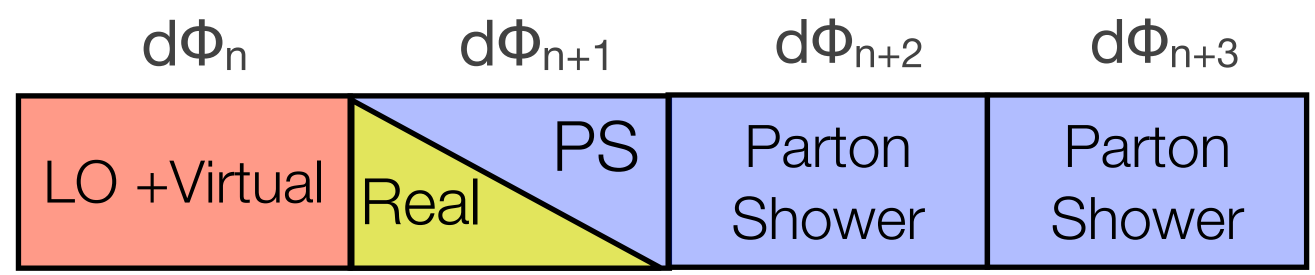
  ➡ Avoid double-counting

- Broadly speaking, two approaches on the market:

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

Challenge : Fixed Order and Parton Shower

n-jet sample at NLO:



- Challenge:
  - ➡ Make each $d\Phi_n$ weight well-defined
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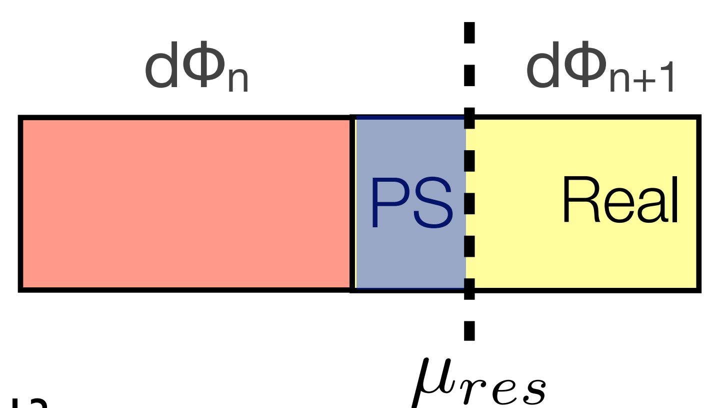
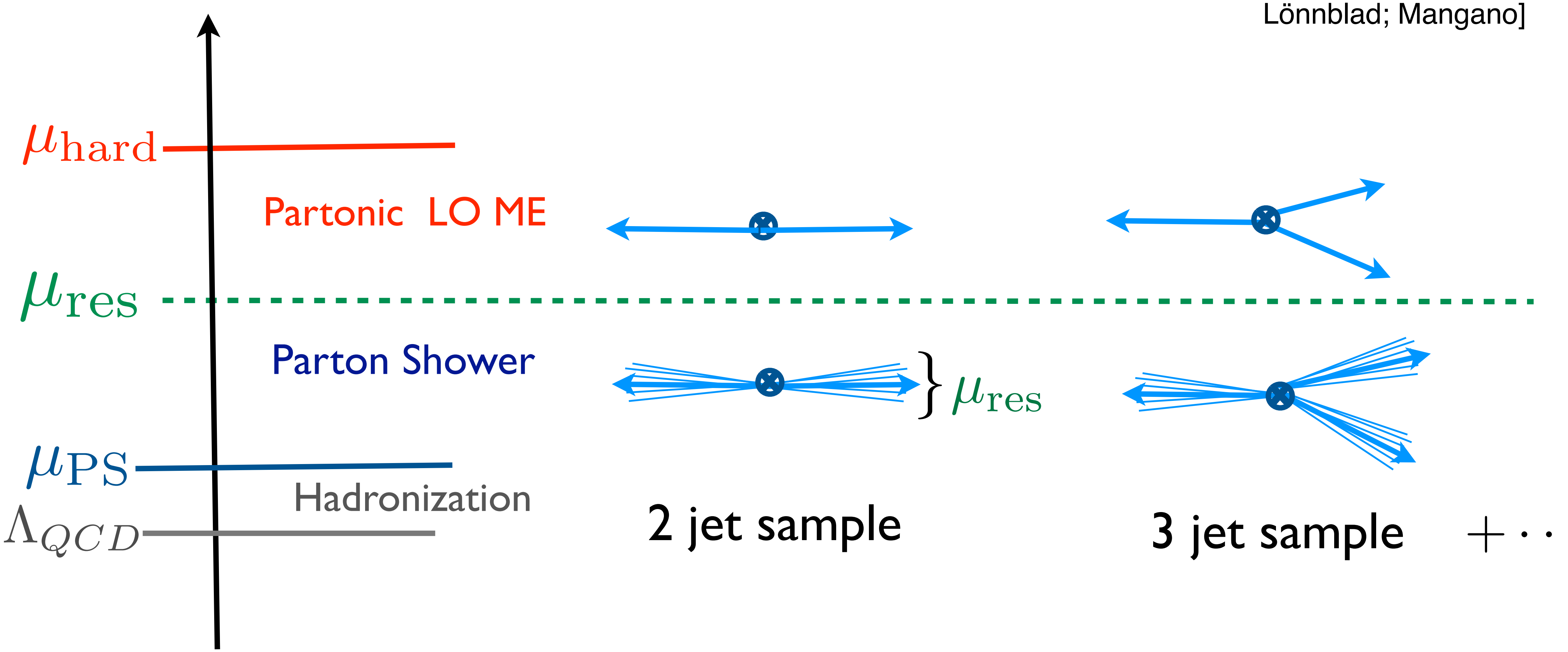
- Broadly speaking, two approaches on the market:
  - Subtraction $$d\Phi_n \left[V_n + \int d\Phi_{n+1|n} S \right] + d\Phi_{n+1} \left[R_{n+1} - S \right]$$
  - Phase space separation



Current Approaches: Fixed Order $\otimes$ Parton Shower

- Leading Order ME for all jet multiplicities $\otimes$ Parton Shower

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



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

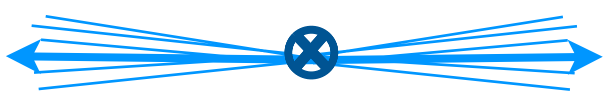
Current Approaches: Fixed Order ⊗ Parton Shower

- NLO for single jet multiplicity ⊗ LL Parton Shower   MC@NLO/ POWHEG

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

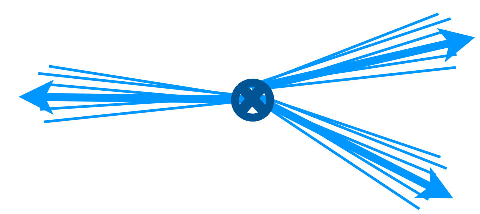
➡ Divergences in $d\Phi_n$ at NLO:

Define Subtraction function $S(\Phi_n)$ $$\int d^d k\, S(k) = \frac{A_{QCD}}{\epsilon^2} + \frac{B_{QCD}}{\epsilon} + C'$$



$$d\Phi_2 \left[V_n + \int d\Phi_{3|2} S \right] + d\Phi_3 \left[R_3 - S \right]$$

2 jet sample at NLO



$$d\Phi_3\, R_3$$

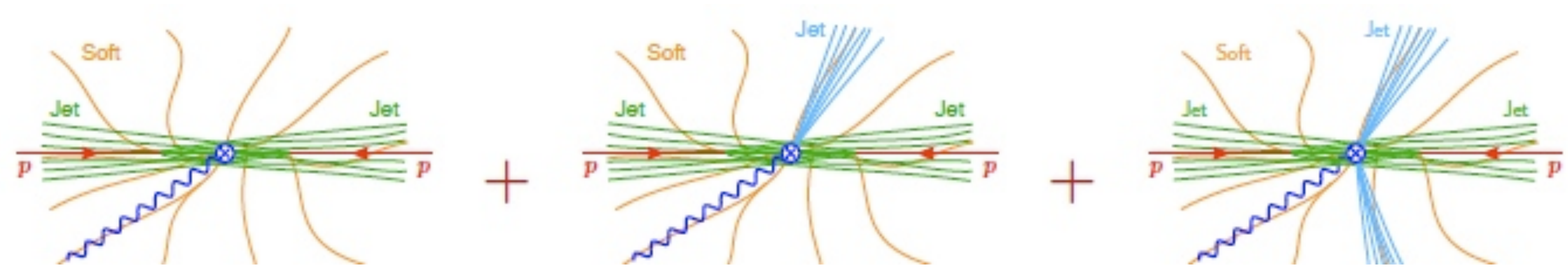
3 jet sample at LO

- Maintain map from N-Parton Phase Space to N-Body Phase Space

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

Current Approaches: Fixed Order $\otimes$ Parton Shower

*Image from Frank Tackmann



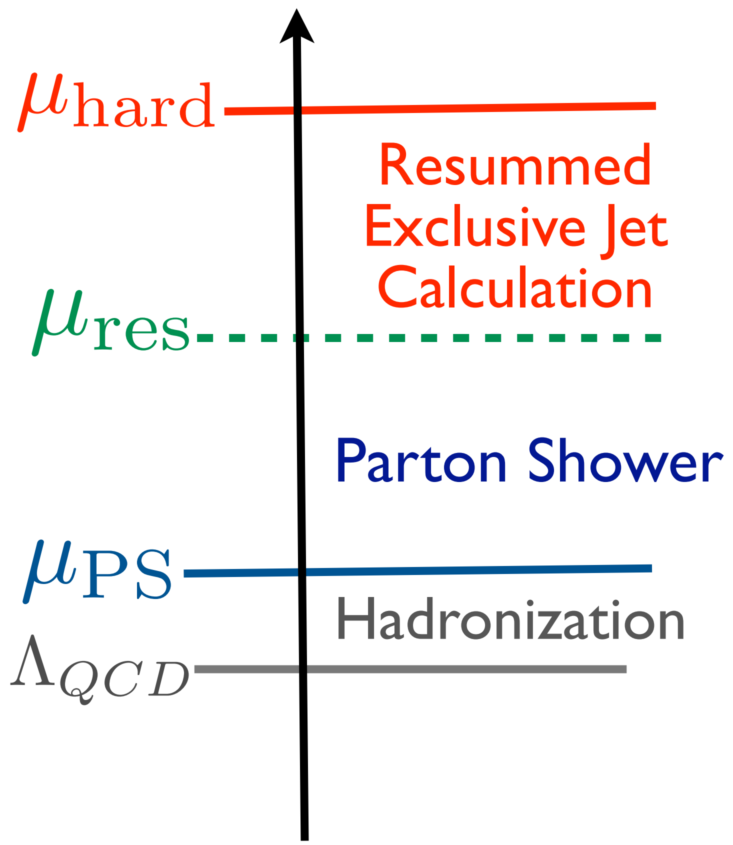
	$\mathrm{d}\sigma_{0\,jet}$	$\mathrm{d}\sigma_{1\,jet}$	$\mathrm{d}\sigma_{2\,jet}$
• CKKW/MLM	LOxPS	LOxPS	LOxPS
• POWHEG MC@NLO	NLOxPS	LOxPS	
• MENLOPS Genva 0.1	NLOxPS	LOxPS	LOxPS [Bauer, Tackmann, Thaler; Hamilton, Nason; Hoche, Krauss, Schonherr, Siegert]
• **Goal Geneva**	NLOxPS	NLOxPS	NLOxPS

The Geneva Approach

- Goal: Exclusive jet multiplicities all at NLO + resummation

  $pp \to H/W + 0, 1, 2\,\text{jets}.$ Start with $e^+e^- \to 2, 3, 4\,\text{jets}\,.$

➡ Divergences in $d\Phi_n$ at NLO:
MC theory input: Exclusive jet cross-sections
Map N-jet Phase Space to N-body Phase Space



➡ Avoid Double Counting with Parton Shower:
Phase space separation μ_{res}

Resummed calculation to cancel dependence

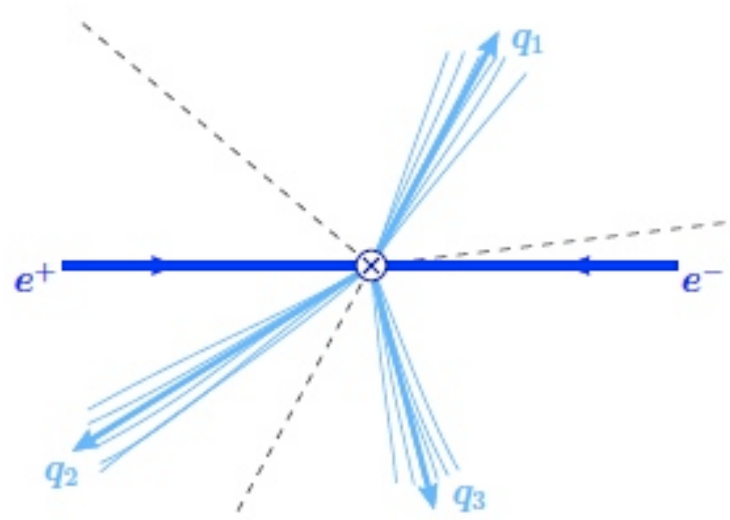
➡ Divide Phase Space in to N-jet samples using resolution variable, N-jettiness.

N-jettiness

- Use N-jettiness to divide into exclusive-jet regions.

[Stewart, Tackmann, Waalewijn;Jouttenus, Stewart, Tackmann, Waalewijn]

- Quantifies distance of particles from jet directions q_i



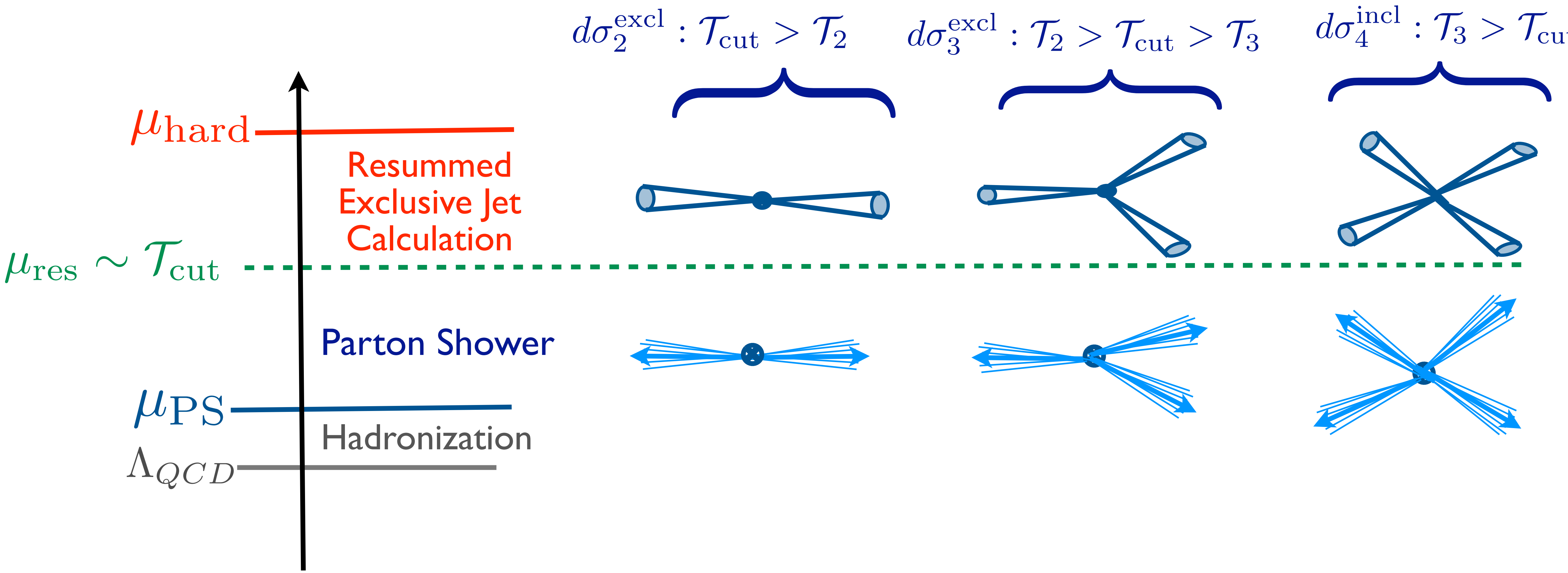
$$\mathcal{T}_N = \sum_k \min_i \{2\hat{q}_i \cdot p_k\}$$

- Each final state particle is assigned to a region.

- $\mathcal{T}_N \to 0$: N pencil-like jets. $\mathcal{T}_N \to Q$: More than N-jets

- Vetoes > N jets. Well defined for any number of partonic final states.

Geneva Approach

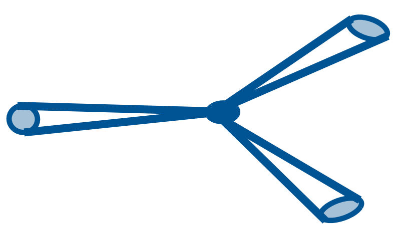


- Choose $\mathcal{T}_{cut}$ to be small. Narrow jets.
- Parton Shower fills up region below $\mathcal{T}_{cut}$
- Integrate up to get other observables to LL

Resumed Exclusive Jet Cross-Section

- Use Soft Collinear Effective Theory to calculate $\frac{d\sigma}{d\mathcal{T}_N}\Big|$

  [Bauer, Fleming, Luke, Pirjol, Stewart]



- In the limit of small $\mathcal{T}_N$ SCET provides framework to calculate resummed QCD distributions

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

Soft Collinear Effective Theory

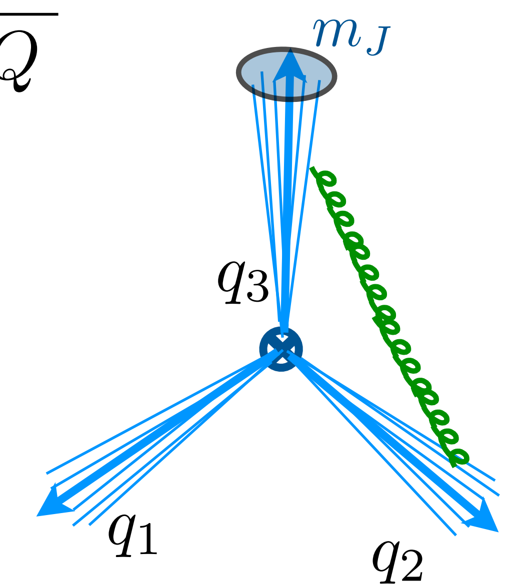
Bauer, Fleming, Luke, 2000

Bauer, Fleming, Pirjol, Stewart 2001

- Construct expansion: large energy, small invariant mass $\lambda \sim \sqrt{\frac{\mathcal{T}_N}{Q}}$

$$q^\mu = q^+ \frac{\bar{n}^\mu}{2} + q^- \frac{n^\mu}{2} + q_\perp^\mu \qquad n = (1, \vec{n}) \qquad \bar{n} = (1, -\vec{n})$$

$$(\bar{n} \cdot q, n \cdot q, q^\perp)$$

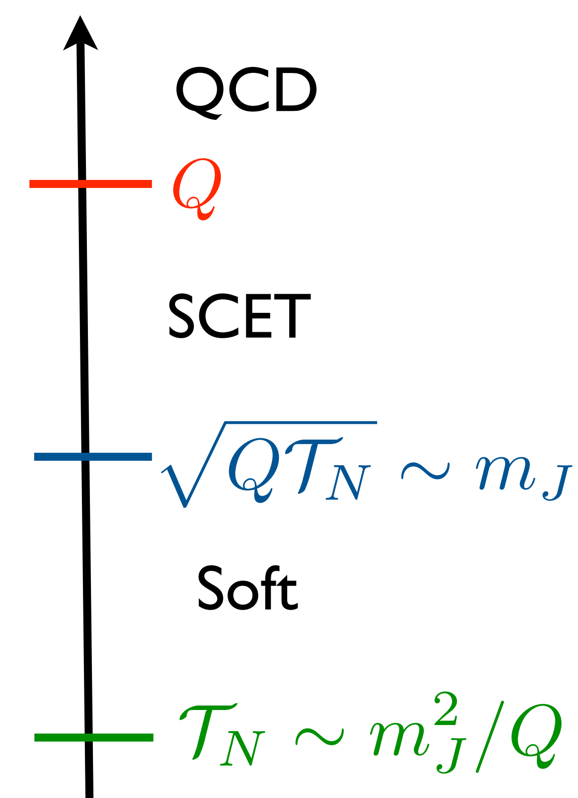


- Collinears in each jet direction.

$$p_c \sim Q(1, \lambda^2, \lambda) \qquad p_c^2 \sim \lambda^2 Q^2 \sim \mathcal{T}_N Q$$

- Soft radiation between jets, without changing their virtuality

$$p_s \sim Q(\lambda^2, \lambda^2, \lambda^2) \qquad p_s^2 \sim \lambda^4 Q^2 \sim \ {}^2_N$$

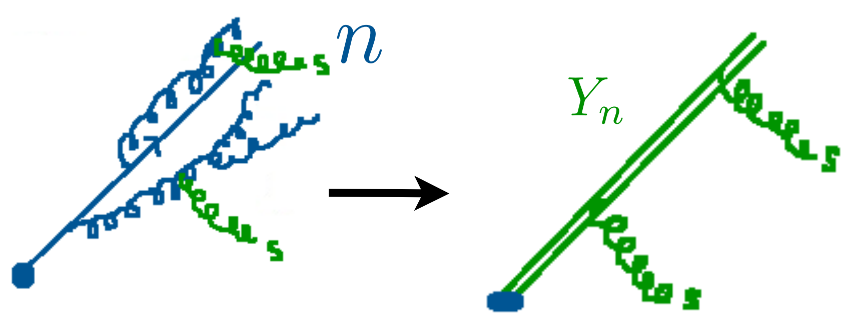


SCET: An Overview

- Modes with different scaling are different fields in SCET.

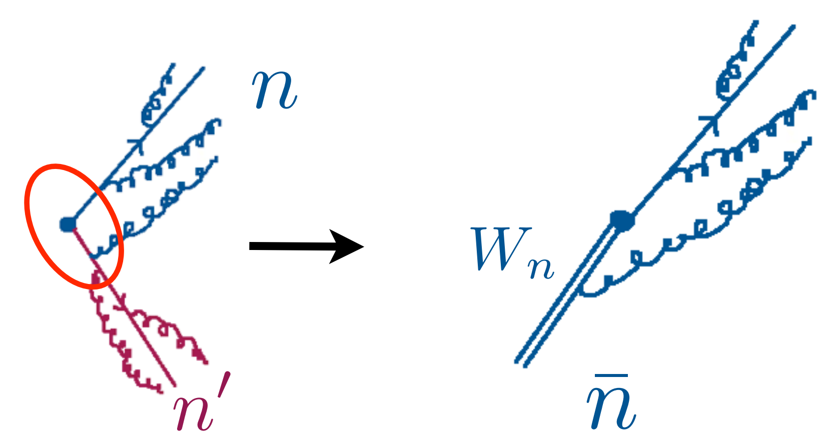
- Interactions are simple, consequence of scaling.

➡ Soft only sees color and direction



$$Y_n = P exp\left(ig\int_{-\infty}^{x} \mathrm{d}s\, n\cdot A_s(sn)\right)$$

➡ Collinears see other jet directions colour source moving in $\bar{n}$ -direction.



- BPS Field redefinition $\mathcal{L}_{SCET} = \mathcal{L}_s + \sum_i \mathcal{L}_{c_i}$ (Bauer, Pirjol, Stewart)

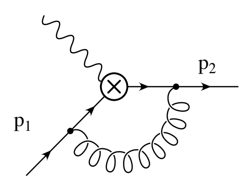
- Operators built from Jet field $\chi_n = W_n^\dagger \xi_n$ and couples to soft through Y_n

Calculating in SCET

- Factorization shown for N-jettiness for general N [Stewart, Tackmann, Waalewijn]

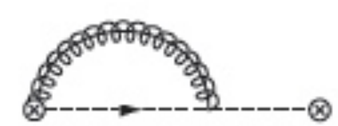
$$\frac{d\sigma_N}{d\mathcal{T}_N} = H_N(Q) \prod_i J_i(\sqrt{Q\mathcal{T}_N}) \otimes S_N(\mathcal{T}_N) \qquad \mathcal{T}_N \ll 1$$

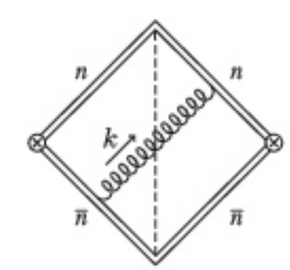
- Separately calculate α_s^n corrections to each piece.

- **Hard Function:** QCD 

$\longrightarrow$ $C_N \langle \mathcal{O}_N \rangle$

  Virtual correction of QCD. Independent of observable Use known NLO result

- **Jet Function** $J_n(\mathcal{T}_N) \sim \langle \chi_n \, \widehat{\mathcal{M}}(\mathcal{T}_N^c) \, \bar{\chi}_n \rangle$ 

- **Soft Function:**. $S(\mathcal{T}_N) \sim \langle Y_j^\dagger Y_i \, \widehat{\mathcal{M}}(\mathcal{T}_N) Y_i^\dagger Y_j \rangle$ 

$\mathcal{M}$

observable dependent

Calculating in SCET

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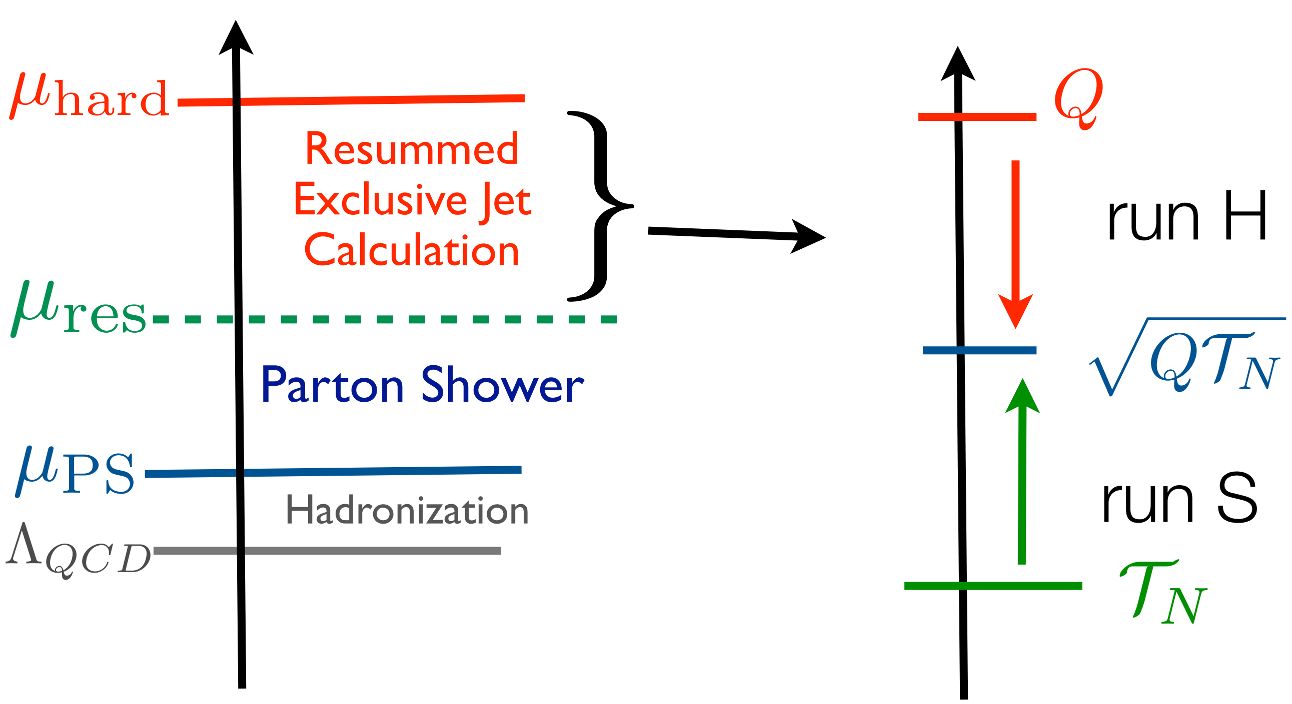
$$\frac{d\sigma_N}{d\mathcal{T}_N} = H_N(Q) \prod_i J_i(\sqrt{Q\mathcal{T}_N}) \otimes S_N(\mathcal{T}_N) \qquad \mathcal{T}_N \ll 1$$

- Use renormalization group to run each component to a common scale RG arranges terms to all orders in log counting. Makes series more convergent

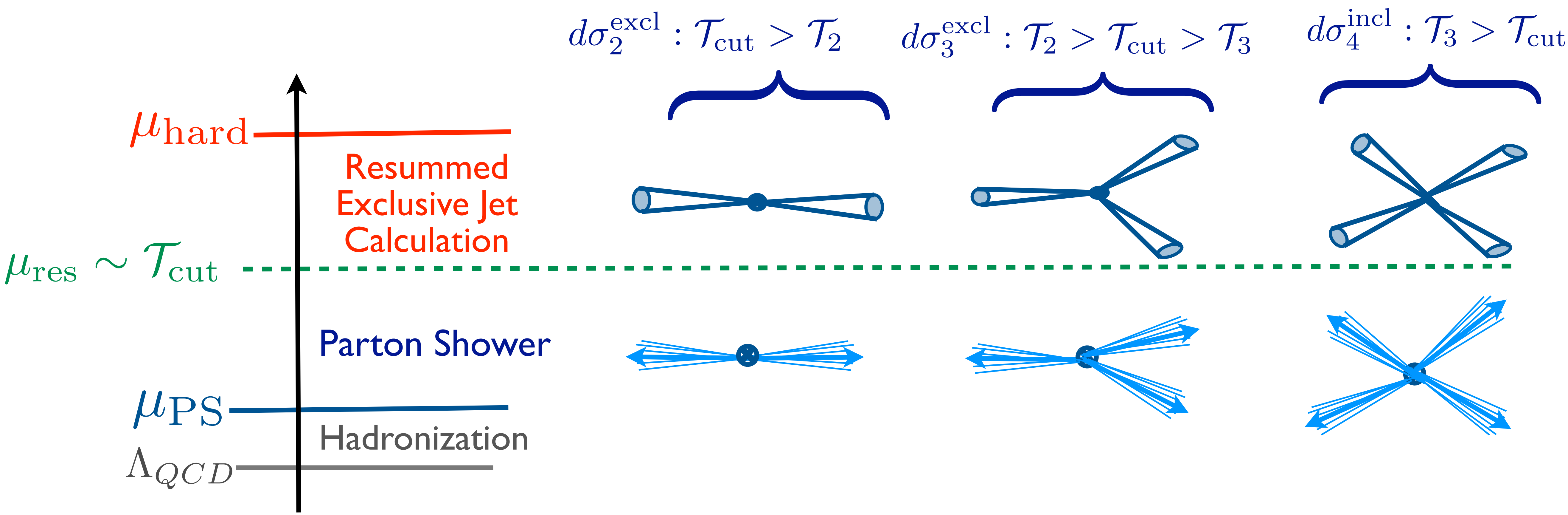
$$F(\mu) = \exp\left(\int_{\mu_F}^{\mu} \frac{d\mu'}{\mu'} \gamma_F(\mu')\right) F(\mu_F) \equiv \Pi_F(\mu_F, \mu) F(\mu_F)$$



$$\sigma_2(\mathcal{T}_{\rm cut}) = \int_0^{\mathcal{T}_{\rm cut}} {\rm d}\mathcal{T}_2 \frac{{\rm d}\sigma}{{\rm d}\mathcal{T}_2}$$

➡ Resummed to NNLL

Recall what we are after....



- Focus on exclusive 2 jet and inclusive 3 jets for now. Divide samples with cut on $\mathcal{T}_2$.
- Generate 2 body PS weights $\mathrm{d}\sigma_2(\mathcal{T}_{\rm cut})$ at NLO $\mathcal{O}(\alpha_s)$ and resummed.

  3 body PS weights $\mathrm{d}\sigma_{\geq 3}(\mathcal{T}_2 > \mathcal{T}_{cut})$ at NLO $\mathcal{O}(\alpha^2)$. Combine to $\mathrm{d}\sigma_2$ inclusive NLO.
- Naively 3 jets NLO would require 2 jet to N^{2}LO to be IR finite.

  Geneva: Relevant pieces obtained from resummation

Perturbative Accuracy

- For resumed 2-jet exclusive rate combine $\mathcal{O}(\alpha_s)$ and leading log (LL)

$$\alpha L^2 \sim 1 \qquad\qquad L \sim \ln \frac{\mathcal{T}_{cut}}{Q}$$

$$\sigma \sim 1$$

NLO 2-jet $+\ \alpha_s L^2 + \alpha_s L + \alpha_s$

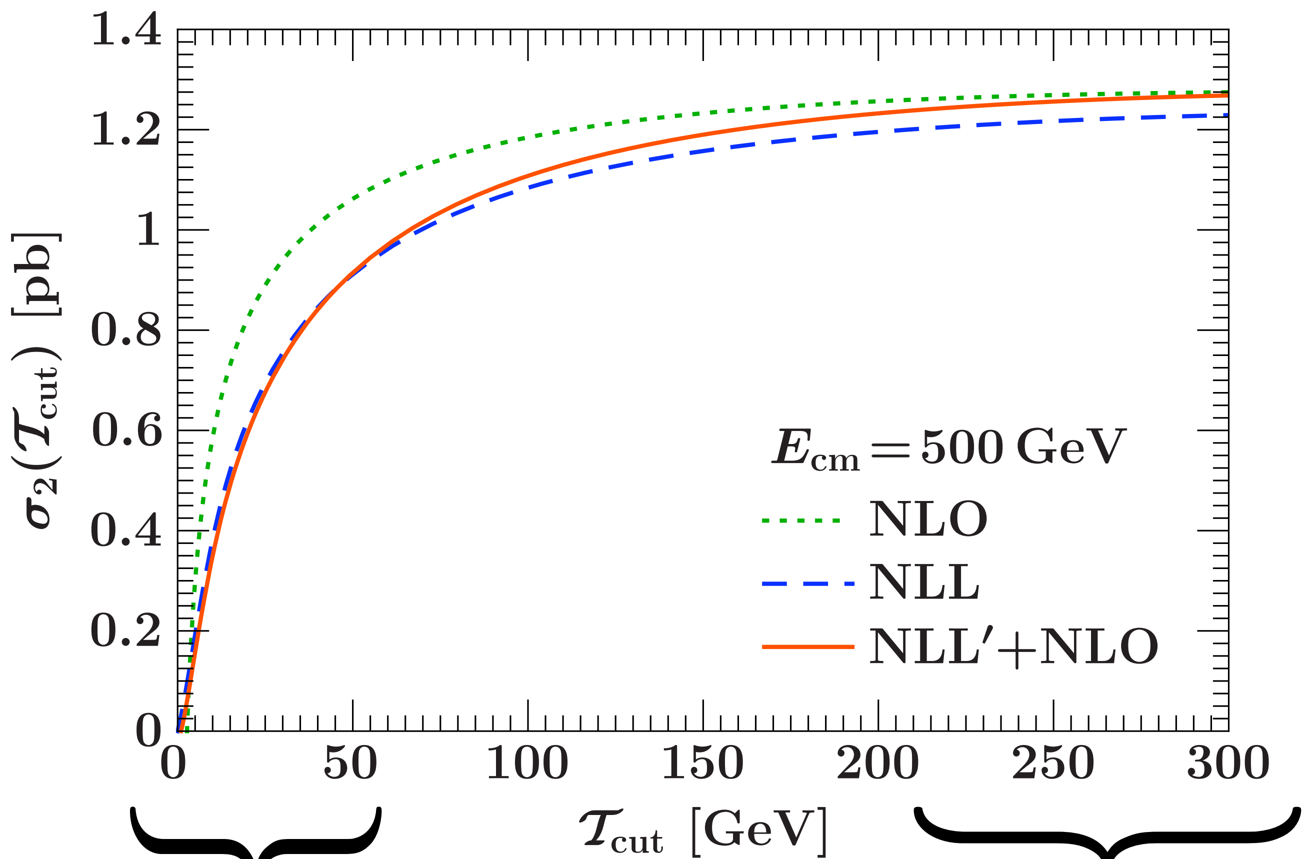
NNLO 2-jet/ NLO 3-jet $+\ \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2$

LL $\quad NLL$

- Consistent counting requires all $\alpha_s^n L^{2n-2} \sim \alpha_s$ to be resummed. NLL'$_D$

Combining Jet Multiplicities

- Combine on 2-jet NLL'+NLO, 3 jet NLO
- Need to properly interpolate between $\mathrm{d}\sigma_2(\mathcal{T}_{\mathrm{cut}})$ at NLO and resummed 3 body PS weights $\mathrm{d}\sigma_{\geq 3}(\mathcal{T}_2 > \mathcal{T}_{cut})$ at NLO

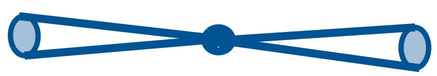


2-jet ResummedSCET
NLL'= NLO FO+ $\alpha_s^n L^{2n-2}$

More than 2-jets region.
Non-singular NLO

Combining Jet Multiplicities

- Combine on 2-jet NLL'+NLO, 3 jet NLO
- Distribute events according to:



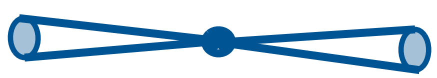
2-body events

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

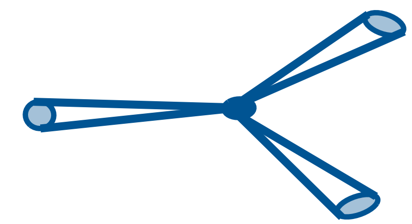
Constant $\mathcal{T}_2$ dependence for 2-body events

Combining Jet Multiplicities

- Combine on 2-jet NLL'+NLO, 3 jet NLO
- Distribute events according to:



2-body events



3-body events

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

Has full Φ_3 dependence

Resummed to $\alpha_s^n L^{2n-2}$

Expanded to $\mathcal{O}(\alpha_s^2)$

Full FO contribution at NLO

Combining Jet Multiplicities

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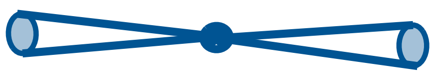
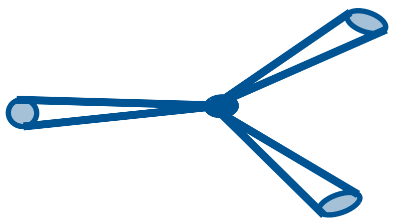
- Distribute events according to:



2-body events



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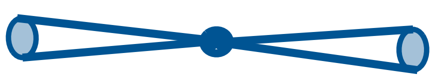
Large $\mathcal{T}_2$:

Resummation starts to turn off.

Ratio starts at $\mathcal{O}(\alpha_s^3)$

Combining Jet Multiplicities

- Combine on 2-jet NLL'+NLO, 3 jet NLO
- Distribute events according to:



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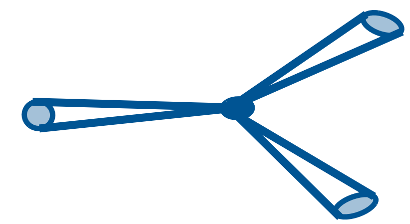

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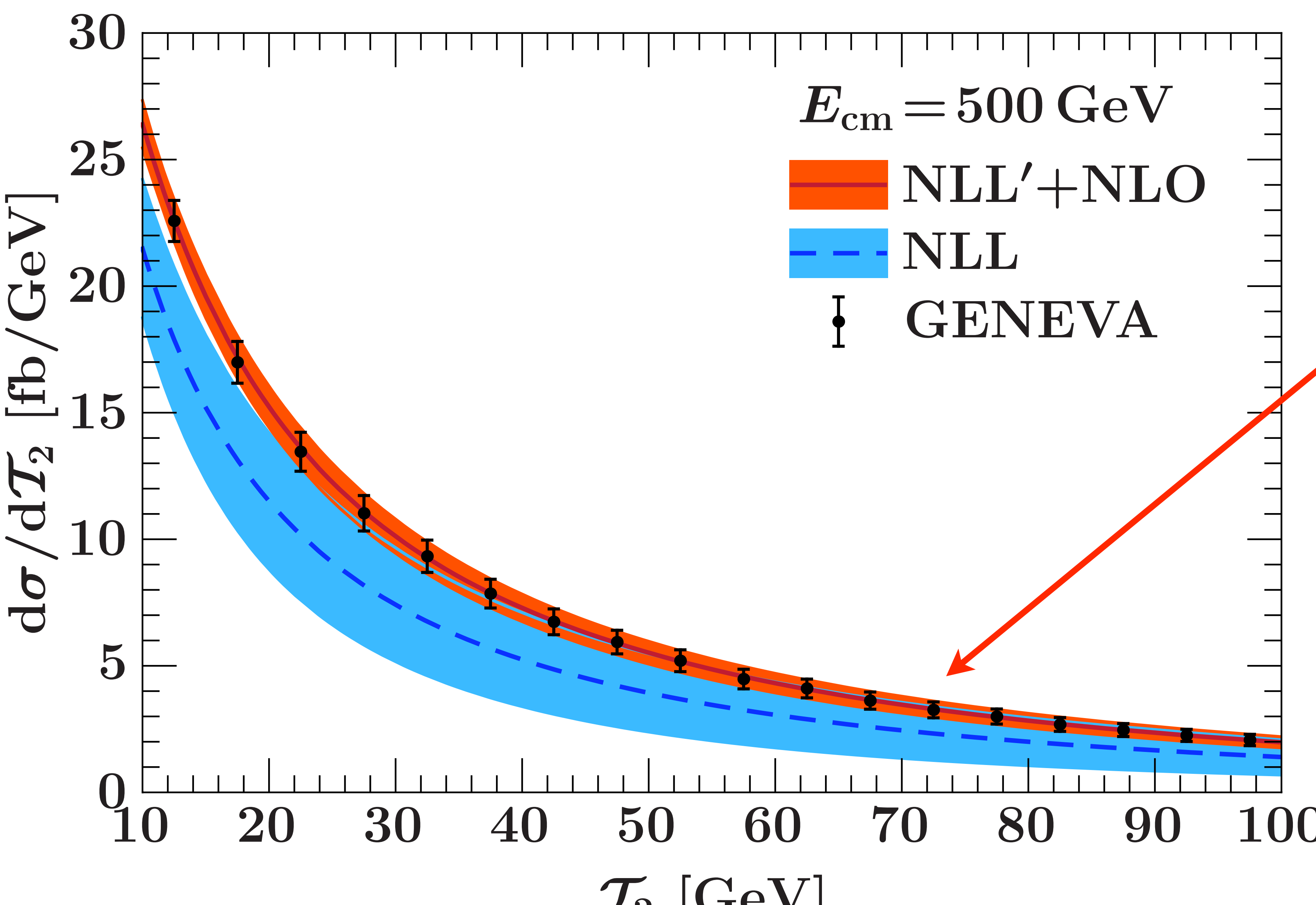
Small $\mathcal{T}_2$:

Resummation important

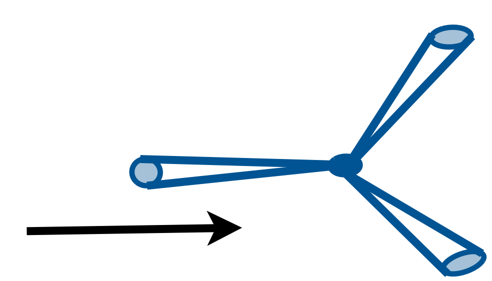
Ratio starts at $\mathcal{O}(\alpha_s^2 L)$ NNLL

First Results: 2 and 3 jets at NLO

- **Previously: 2 jets at NLL+NLO and 3 jets at LO**
- **Now with Geneva have 2 jets at NLL+NLO and 3 jets at NLO**
  Systematically extendable

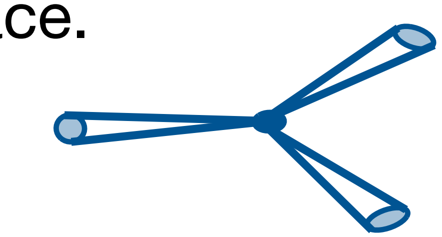


- **Monte Carlo with theory (scale) uncertainties not MC statistics!**



First Results: 2 and 3 jets at NLO

- $\mathcal{T}_2$ was the spectrum we used to distinguish 2 and 3 body Phase Space. Consider variable sensitive to Φ_3 angular dependence.



- Should reproduce shape. $\mathrm{d}\Phi_3 = \mathrm{d}\Phi_2\,\mathrm{d}z\,\mathrm{d}\mathcal{T}_2\,\mathrm{d}\phi$ $\quad z = \dfrac{E_1}{E_1 + E_2}$
  Definition of variables consistent for 3-jets (at any order).

Another variable z

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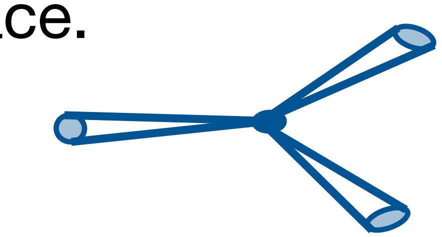

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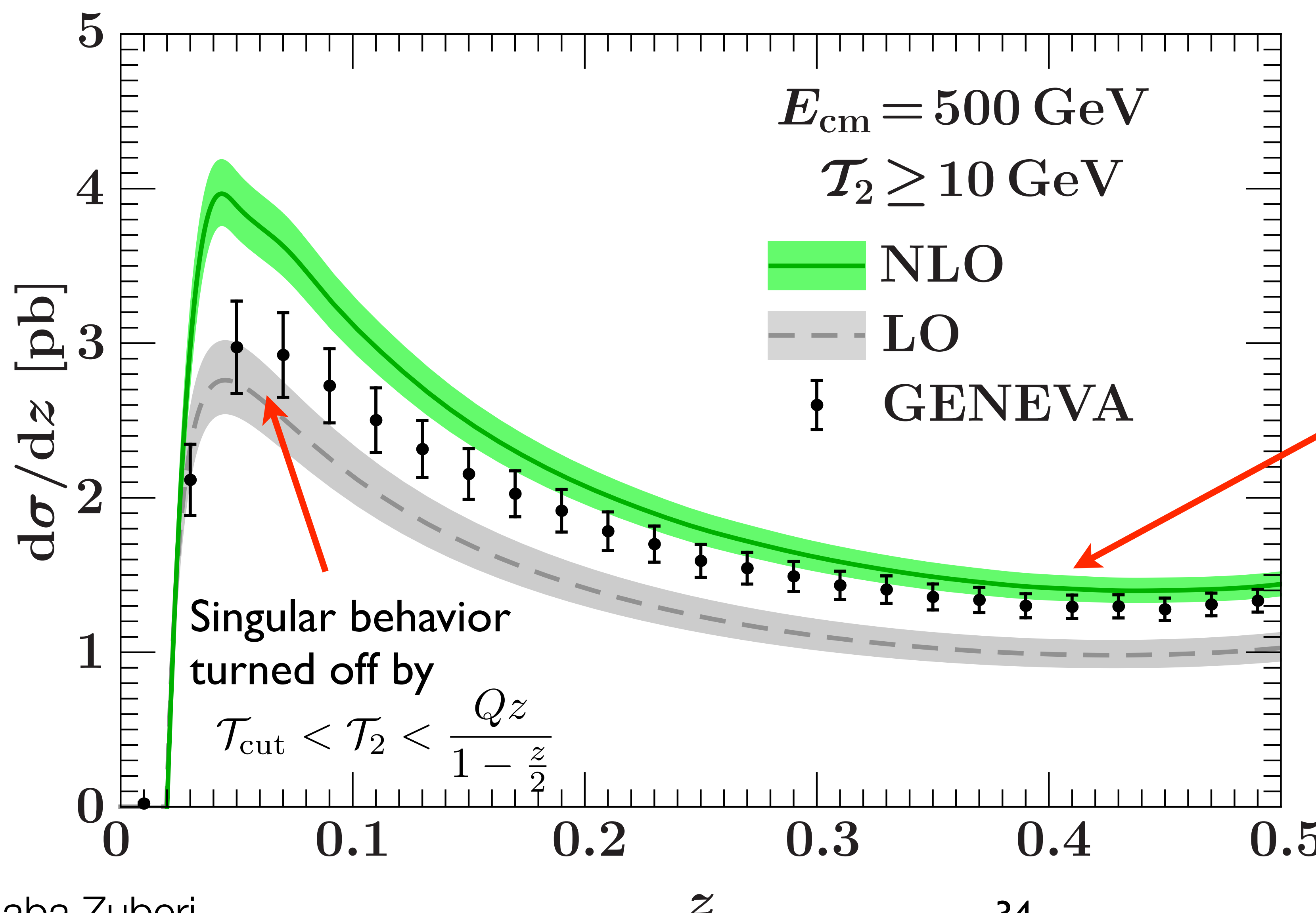

- **2 + 3 jets at NLO**
  3 jet NLO shift ~ α_s^2

- **Theory scale uncertainties**

Other Variables: Angularities

- A non-trivial check: Integrate up events distributed according to N-jettiness to get other observables to LL.
  Check cancellation of cut dependence when combined with parton shower

$$\tau_a(X) = \frac{1}{Q} \sum_i |p_i^T| e^{-\eta_i (1-a)}$$ (Berger, Kucs, Sterman)

2 jet like for $\tau_a \to 0$
Thrust a=0

Consider a = -1

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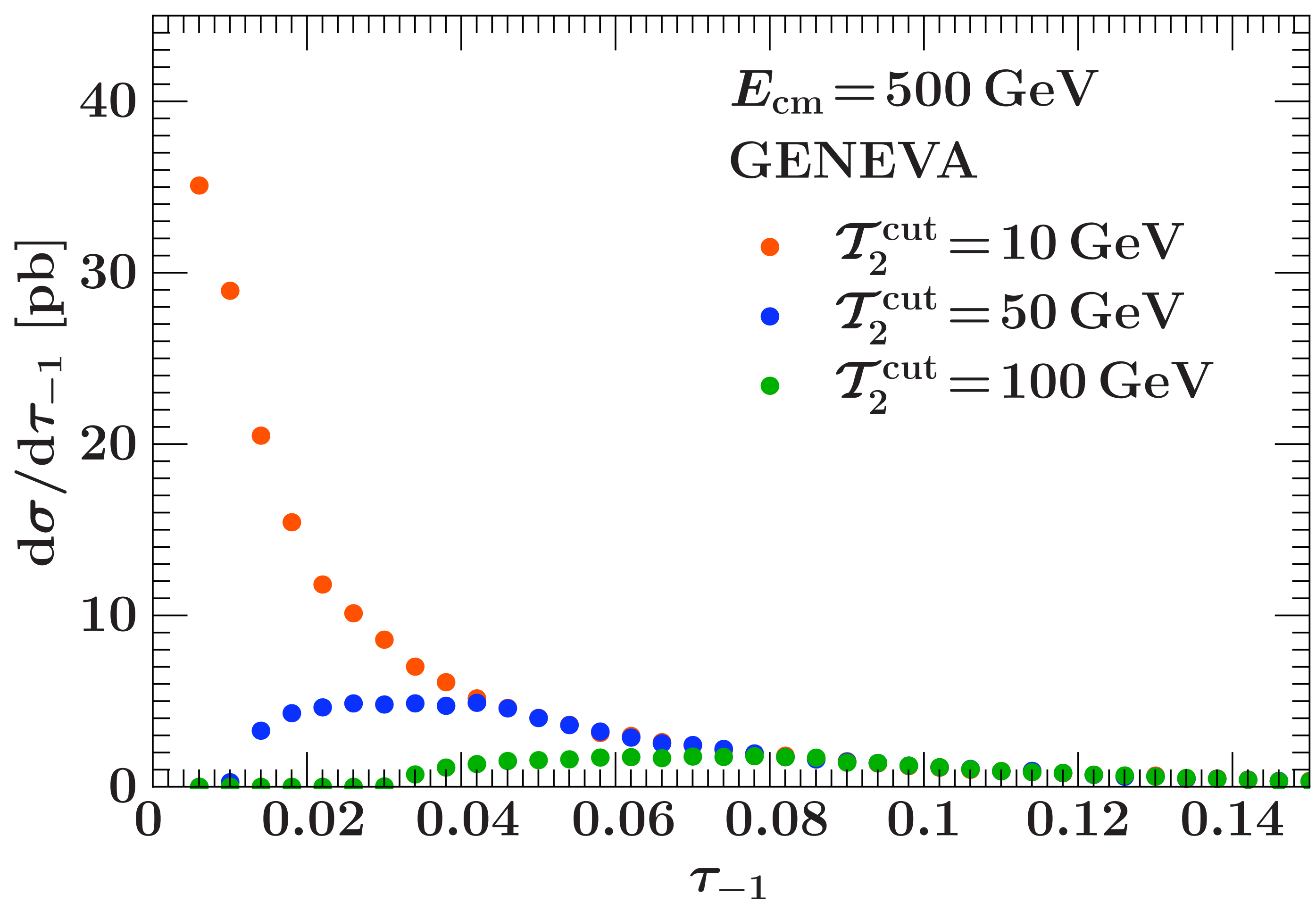

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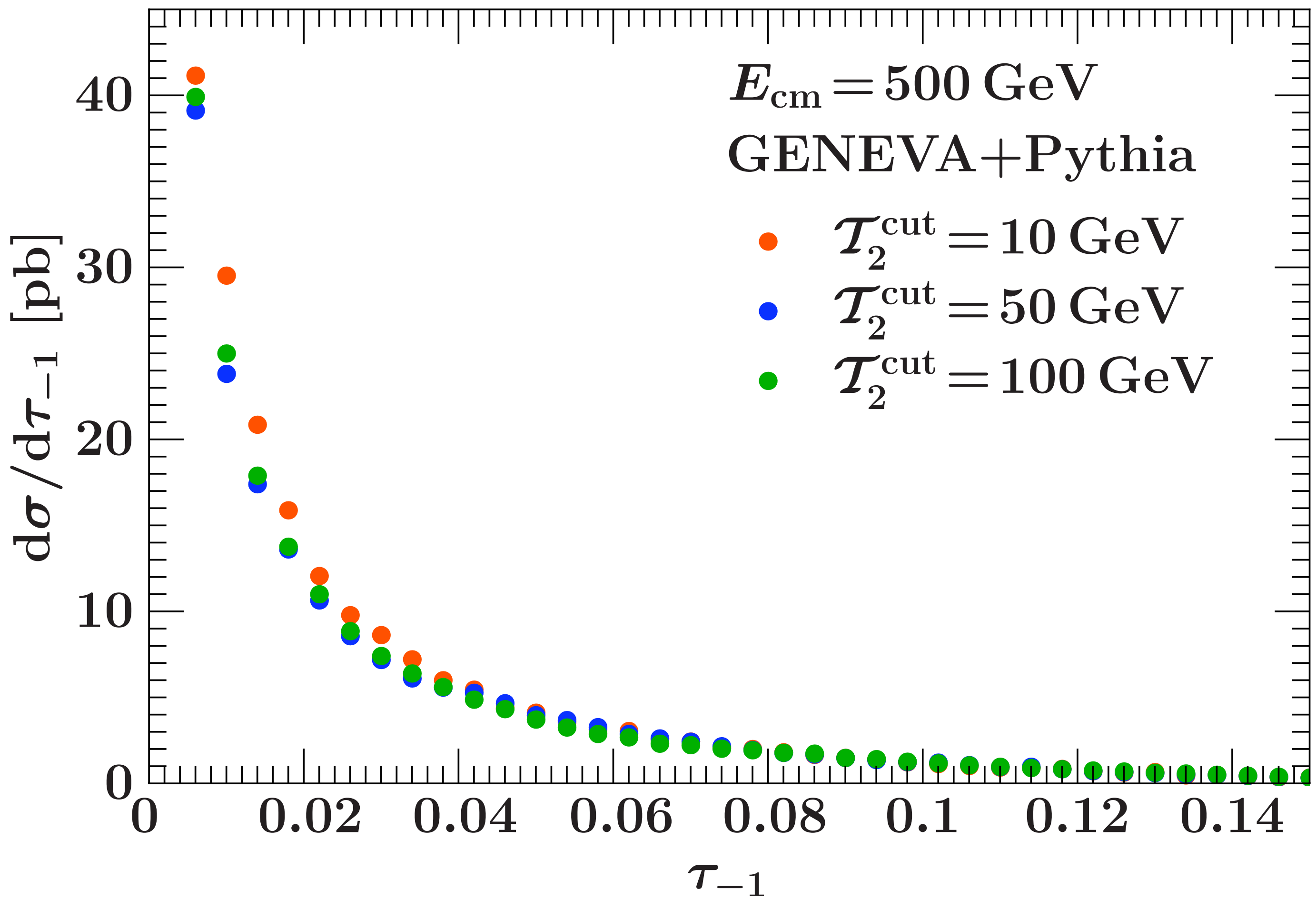
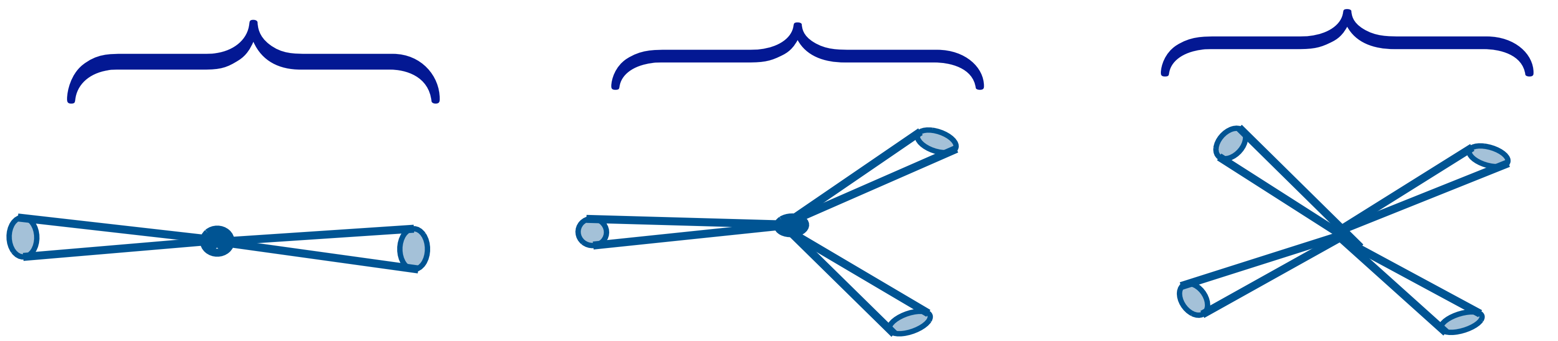


Next Steps for Geneva: Theory Challenges

- **Combine higher jet multiplicities at NLO :**

$d\sigma_2^{\rm excl} : \mathcal{T}_{\rm cut} > \mathcal{T}_2$ $\quad d\sigma_3^{\rm excl} : \mathcal{T}_2 > \mathcal{T}_{\rm cut} > \mathcal{T}_3$ $\quad d\sigma_4^{\rm incl} : \mathcal{T}_3 > \mathcal{T}_{\rm cut}$



This involves summing logs of wider range of kinematic configurations with additional scales $\mathcal{T}_i$.

(Bauer, Tackmann, Walsh, SZ)

✳ See Jon Walsh's talk

- **Soft subtractions:** $S(\mathcal{T}_N) \sim \langle Y_j^\dagger Y_i \widehat{\mathcal{M}}(\mathcal{T}_N) Y_i^\dagger Y_j \rangle = \frac{A_{SCET}}{\epsilon^2} + \frac{B_{SCET}}{\epsilon} + C$

Subtraction function: $\int \mathrm{d}^d k\, Sub(k) = \frac{A_{SCET}}{\epsilon^2} + \frac{B_{SCET}}{\epsilon} + C'$

Algorithm dependence!

(Bauer, Dunn, Hornig; Dunn Hornig)

Conclusions

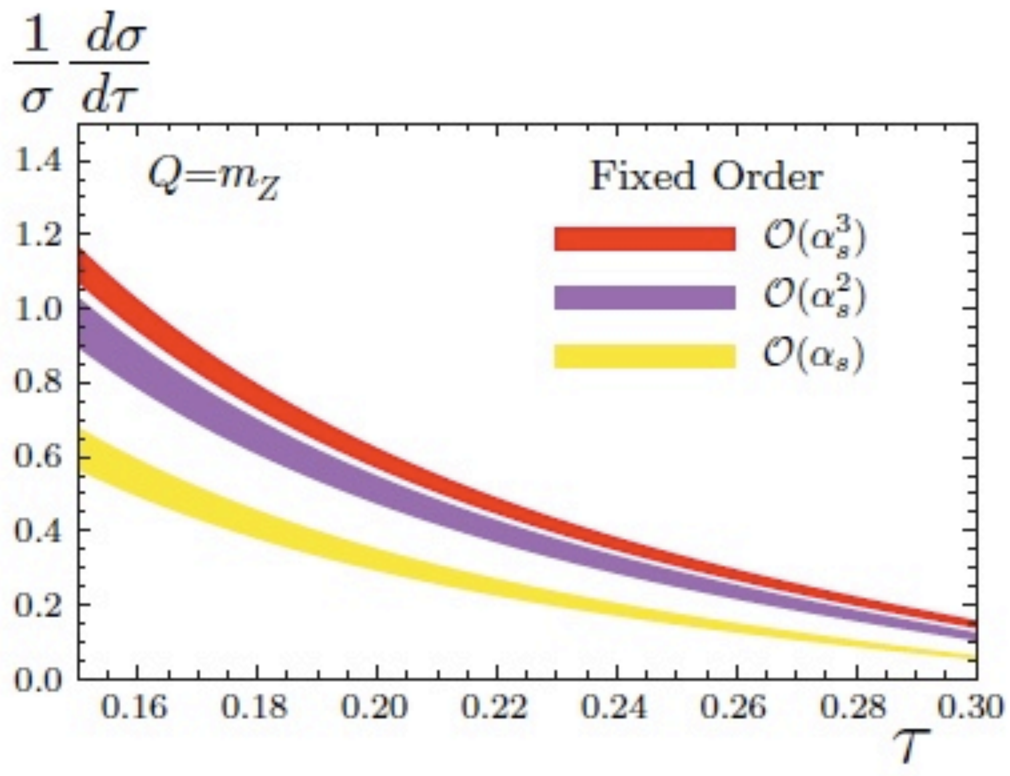
- Want event generators with best possible accuracy to connect theory and experiment
- Goal of Geneva: Combining several jet multiplicities at NLO with resummation/ parton shower
- Method: Use resummed exclusive cross-sections from SCET
- Status: 2 jet NLL'+ NLO and 3 jet NLO
- Coming soon at NLO $pp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

Thank You

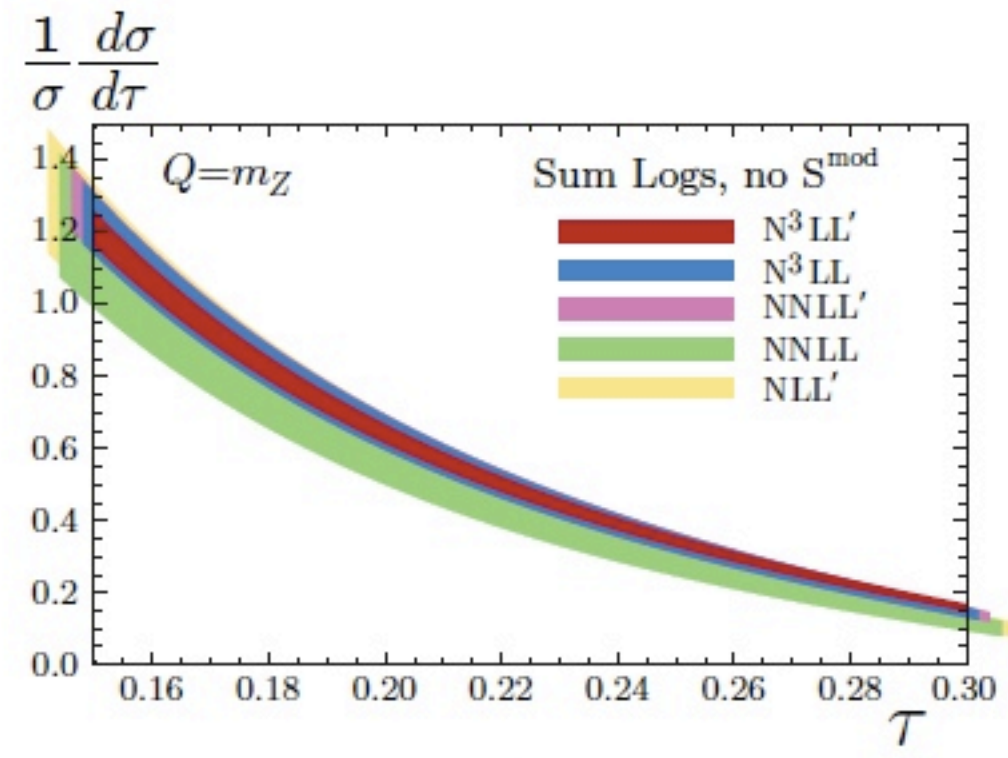
Back Up Slides

α_s^2 corrections are Large

- NLL' much larger than α_s contribution



(a)



(b)

[Abbate, Fickinger, Hoang, Mateu, Stewart]