Understanding Jets with Effective Field Theories.

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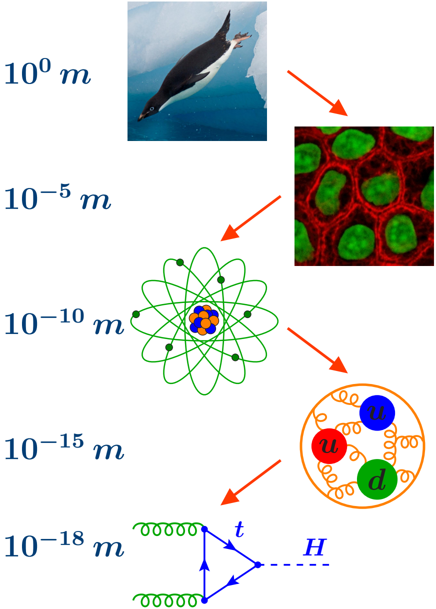
DESY Physics Seminar
February 24, 2015

Outline

1. Introduction
2. Jets in e^+e^-
3. Higgs With and Without Jets
4. Jet Mass and Soft Effects

Introduction.

Effective Theory.



Effective description

- Focus on the relevant physics
- Use the actual, relevant degrees of freedom to describe what happens at a given length or energy scale

Efficient description

- Ignore boundary conditions at larger scales
  - we call that “power expansion”
- Sum over irrelevant degrees of freedom at smaller scales
  - we call that “integrating out”

Defining Feature of a Jet.

This is a jet

Defining Feature of a Jet.

This is a jet

This is not a jet

Defining Feature of a Jet.

This is a jet	This is not a jet
	
	

Defining Feature of a Jet.

This is a jet

$p_{\|} \gg p_{\perp}$

This is not a jet

$p_{\|} \sim p_{\perp}$

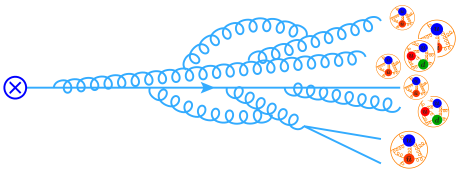
$p_{\|}$: total momentum along direction of flight

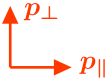
$p_{\perp}$: intrinsic transverse momentum

Jets of Hadrons.

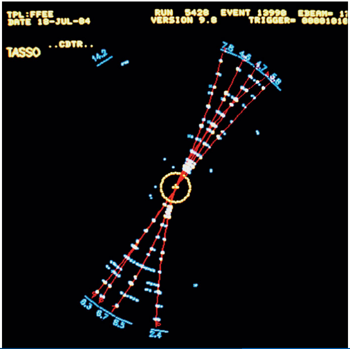
QCD doesn't let us observe quarks and gluons directly, only jets of hadrons

$p_\parallel \gg p_\perp$





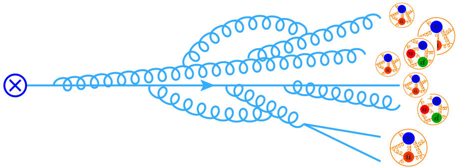
These are 2 jets

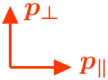


This are not 2 but 3 jets

QCD doesn't let us observe quarks and gluons directly, only jets of hadrons

$p_\parallel \gg p_\perp$





These are 2 jets

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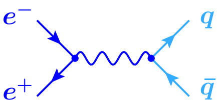
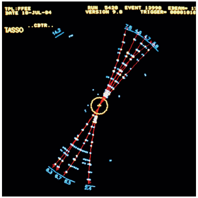
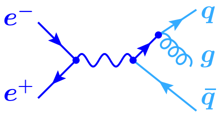


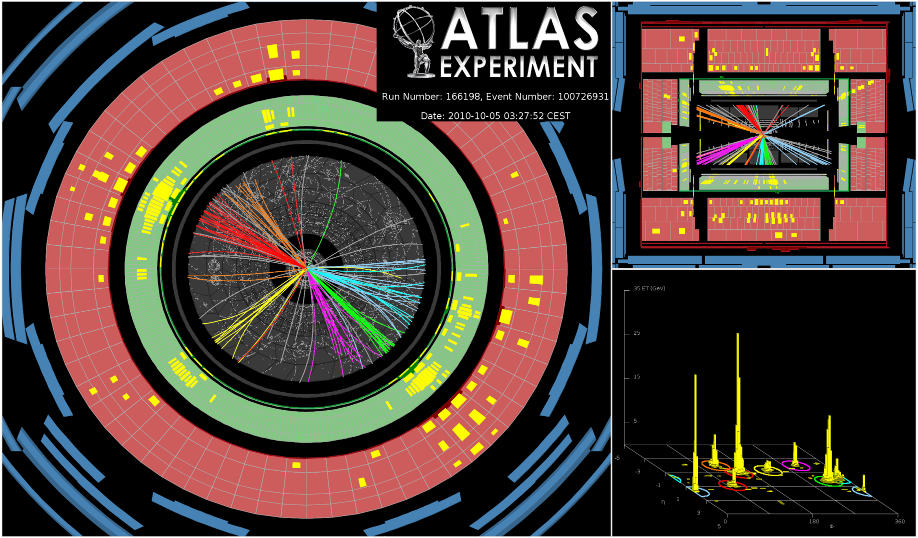




Jets can still tell us the QCD final state of the hard interaction process

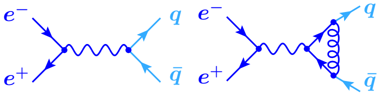
$\Rightarrow$ 36 years ago: Discovery of the gluon

Jets are Ubiquitous.



Effective Theory for Jet Processes.

$\mu_H \sim Q$



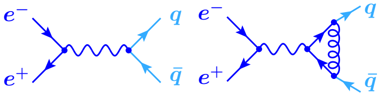
Hard interaction process

$$Q = E_J + |\vec{p}_J| \qquad \simeq p_{\|}$$

- For the total cross section, Q is the only relevant scale

Effective Theory for Jet Processes.

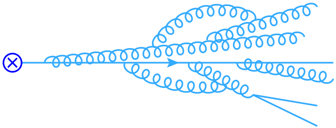
$\mu_H \sim Q$



Hard interaction process

$$Q = E_J + |\vec{p}_J| \qquad \simeq p_{\|}$$

$\mu_J \sim m_J$



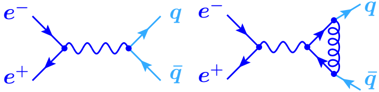
Collinear emissions (perturbative)

$$m_J^2 = E_J^2 - |\vec{p}_J|^2 \qquad \simeq p_\perp^2$$

- By asking more detailed questions, like the number and size of jets, the jets are resolved, which introduces sensitivity to additional scales

Effective Theory for Jet Processes.

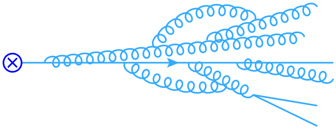
$\mu_H \sim Q$



Hard interaction process

$$Q = E_J + |\vec{p}_J| \qquad \simeq p_\parallel$$

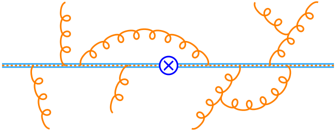
$\mu_J \sim m_J$



Collinear emissions (perturbative)

$$m_J^2 = E_J^2 - |\vec{p}_J|^2 \qquad \simeq p_\perp^2$$

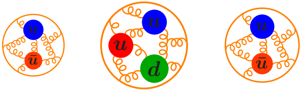
$\mu_S \sim \frac{m_J^2}{Q}$



Soft emissions (perturbative)

$$\frac{m_J^2}{Q} = E_J - |\vec{p}_J| \qquad \simeq \frac{p_\perp^2}{p_\parallel}$$

$\mu_\Lambda \sim \Lambda_{\mathrm{QCD}}$



Hadronization (nonperturbative)

$\Rightarrow$ Physical picture is well-known (e.g. the basis of all Monte Carlo generators)

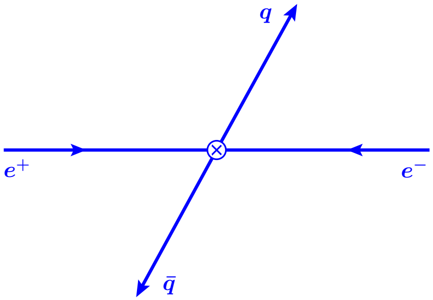
Effective Field Theory for Jets.

Soft-collinear effective theory (SCET) is the systematic implementation of this physical picture at the Lagrangian level as an effective field theory of QCD

$$\sigma = H(Q)$$

μ_H All hard interactions are integrated out

- Hard function H



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$$\sigma = H(Q) \times (J_1\, J_2)(m_J^2)$$

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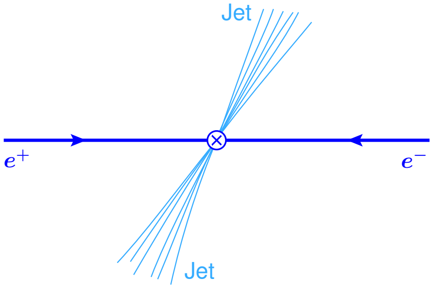
μ_J Collinear emissions described by collinear jet fields

- Jet functions J



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$$\sigma = H(Q) \times (J_1 J_2)(m_J^2) \otimes S(m_J^2/Q)$$

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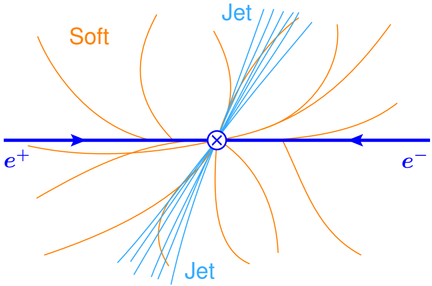
μ_S Soft emissions described by soft Wilson lines

- Soft function S



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$$\sigma = H(Q) \times (J_1 J_2)(m_J^2) \otimes S(m_J^2/Q) \otimes F$$

μ_H All hard interactions are integrated out

- Hard function H

μ_J Collinear emissions described by collinear jet fields

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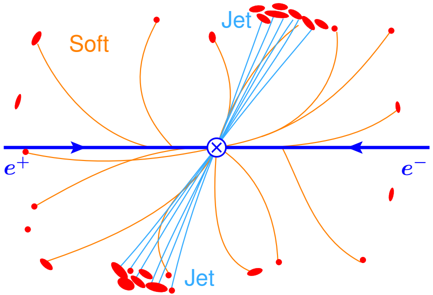
μ_S Soft emissions described by soft Wilson lines

- Soft function S

μ_Λ Hadronization is encoded in nonperturbative matrix elements

- Nonpert. soft function F



Resummation of Large Logarithms.

$\sigma(Q, m_J)$ contains logarithms $L \equiv \ln \frac{m_J}{Q} \sim \ln \frac{\mu_J}{\mu_H} \sim \ln \frac{\mu_S}{\mu_J}$

$$
\begin{aligned}
\sigma = 1 & \\
&+ \alpha_s L^2 + \alpha_s L + \alpha_s + \alpha_s \mathcal{O}(\tfrac{m_J}{Q}) && \text{NLO} \\
&+ \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2 + \alpha_s^2 \mathcal{O}(\tfrac{m_J}{Q}) && \text{NNLO} \\
&+ \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \alpha_s^3 L + \alpha_s^3 + \cdots && \text{N}^3\text{LO} \\
&+ \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \ddots
\end{aligned}
$$

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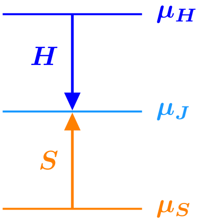
$$
\begin{array}{lllllllllll}
\sigma = 1 & & & & & & & & & & \\
+\alpha_s L^2 & + \alpha_s L & + \alpha_s & & & & & & & + \alpha_s \mathcal{O}(\frac{m_J}{Q}) & \text{NLO} \\
+\alpha_s^2 L^4 & + \alpha_s^2 L^3 & + \alpha_s^2 L^2 & + \alpha_s^2 L & + \alpha_s^2 & & & & & + \alpha_s^2 \mathcal{O}(\frac{m_J}{Q}) & \text{NNLO} \\
+\alpha_s^3 L^6 & + \alpha_s^3 L^5 & + \alpha_s^3 L^4 & + \alpha_s^3 L^3 & + \alpha_s^3 L^2 & + \alpha_s^3 L & + \alpha_s^3 & + & & \cdots & \text{N}^3\text{LO} \\
+ \vdots & + \vdots & + \vdots & + \vdots & + \vdots & + \vdots & + \vdots & + & & \ddots & \\
\text{LL} & \text{NLL} & \text{NLL}' & \text{NNLL} & \text{NNLL}' & \text{N}^3\text{LL} & & & & &
\end{array}
$$

In the EFT limit $m_J \ll Q$, logarithmic terms $\alpha_s^n L^m$ are the dominant perturbative corrections

- Are resummed to all orders by RGE running in SCET
  - Can obtain precise predictions by carrying out resummation to higher orders
  - Different resummation scales provide systematic handles on perturbative uncertainties



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$$\begin{aligned}
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\end{aligned}$$

LL NLL NLL′ NNLL NNLL′ N^{3}LL

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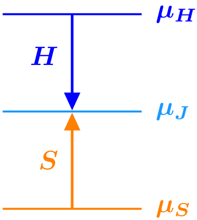

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$$\sigma = 1$$

$$+\alpha_s L^2 + \alpha_s L + \alpha_s \qquad + \alpha_s \mathcal{O}\Big(\frac{m_J}{Q}\Big) \qquad \text{NLO}$$

$$+\alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2 \qquad + \alpha_s^2 \mathcal{O}\Big(\frac{m_J}{Q}\Big) \qquad \text{NNLO}$$

$$+\alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \alpha_s^3 L + \alpha_s^3 + \cdots \qquad \text{N}^3\text{LO}$$

$$+ \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \ddots$$

$$\text{LL} \quad \text{NLL} \quad \text{NLL}' \quad \text{NNLL} \quad \text{NNLL}' \quad \text{N}^3\text{LL}$$

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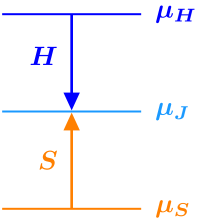
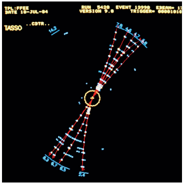
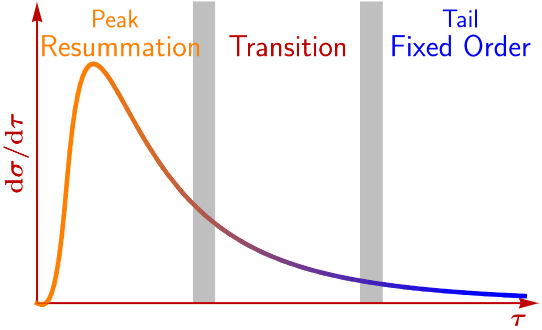


Jets in e^+e^-.

2 jets





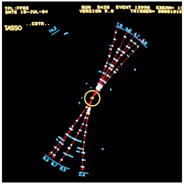
≥ 3 jets

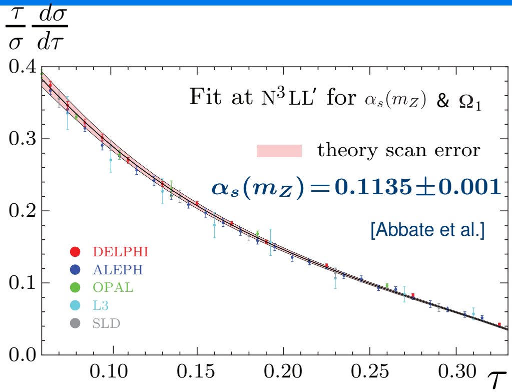
Thrust event shape τ determines "2-jettiness" $\mathcal{T}_2$ of an event

$$\Rightarrow \qquad m_J^2 \simeq Q \times \mathcal{T}_2 = Q^2 \times \tau \qquad\qquad (\tau = \mathcal{T}_2/Q)$$

Thrust Spectrum.

2 jets





$\geq$ 3 jets

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$$\Rightarrow \qquad m_J^2 \simeq Q \times \mathcal{T}_2 = Q^2 \times \tau \qquad\qquad (\tau = \mathcal{T}_2/Q)$$

- Has been resummed in SCET to N^{3}LL′+N^{3}LO
  - Global fit to e^+e^- data yields precision determination of $\alpha_s(m_Z)$ together with nonperturbative hadronization parameter Ω_1

$\Rightarrow$ Want to make use of the same high precision in Monte Carlo generators

GENEVA Monte Carlo Framework

GENEVA combines 3 ingredients

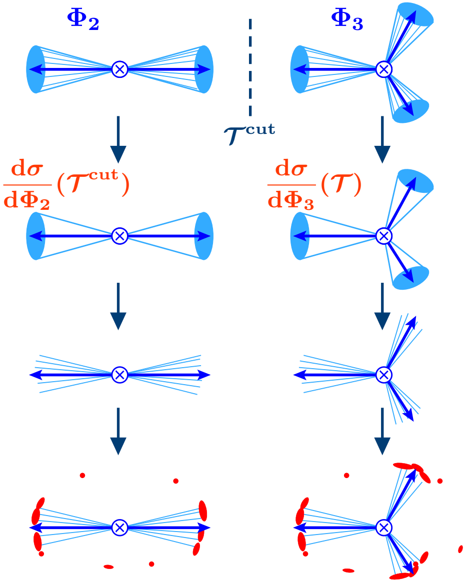
1. Higher-order resummation (NNLL′)
   - Use SCET framework for resummation
     (Requires nontrivial extension to multi-differential cross sections)
2. Fully differential fixed-order calculations
   - Developed a systematic framework to go to NNLO
3. Parton showering and hadronization to “fill out” jets
   - Can be provided by standard SMCs Pythia8, Herwig++
     (with some modifications)

⇒ Result will be a fully exclusive NNLO+NNLL′+PS MC generator
(including systematic theory uncertainties)

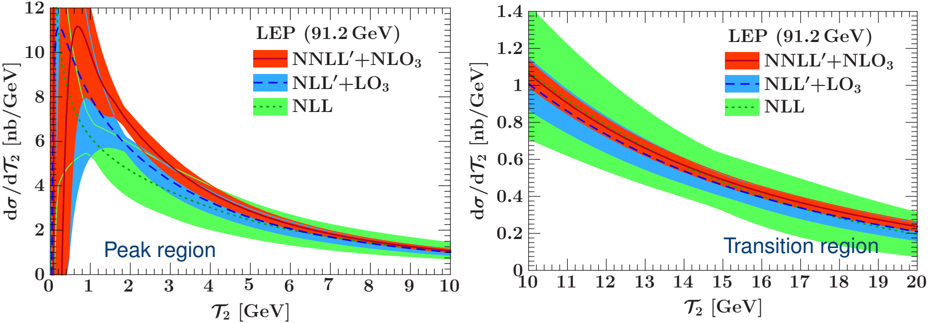
- Proof-of-concept implementation exists for e^+e^-
- $pp \to Z$+jets version is mostly complete and being validated

GENEVA in a Nut Shell.

1. Divide phase space into jet multiplicities using jet resolution variable $\mathcal{T}_N$ (e.g. N-jettiness)
2. Compute resummed $\mathcal{T}_N$ cross sections at NNLL$'_2$+NNLO$_2$, NLL$'_3$+NLO$_3$, ...
3. Let Pythia8 shower fill out jets with radiation
4. Pythia8 hadronization



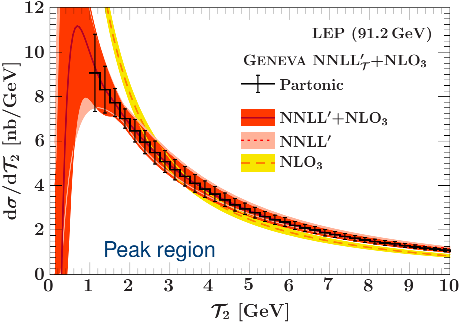
Results for $\mathcal{T}_2$.

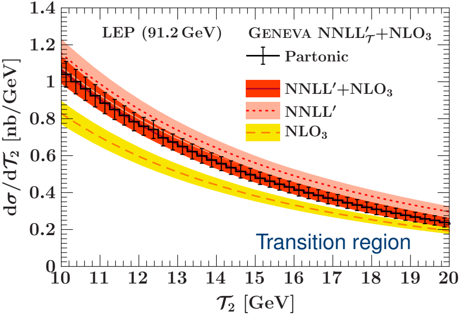


$$\frac{d\sigma}{d\mathcal{T}_2} = H(Q) \times (J\,J)(Q\mathcal{T}_2) \otimes S(\mathcal{T}_2)$$

- Higher-order resummation significantly improves precision

Results for $\mathcal{T}_2$.





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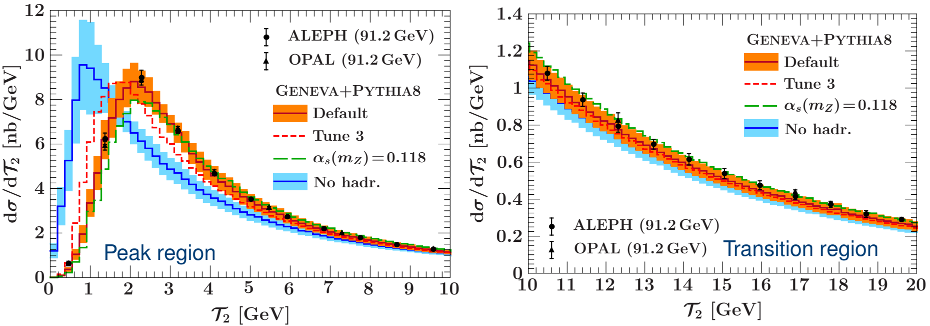
- GENEVA is constructed to exactly reproduce the analytic NNLL$'$+NLO$_3$ result of its resolution variable (here $\mathcal{T}_2$) including pert. uncertainties

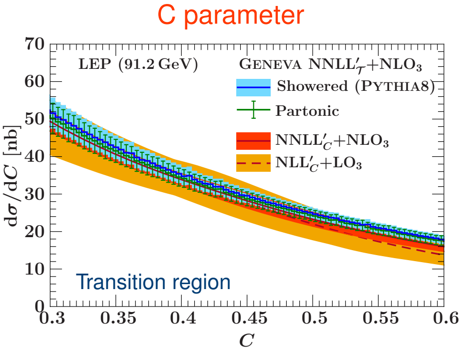
Results for $\mathcal{T}_2$.

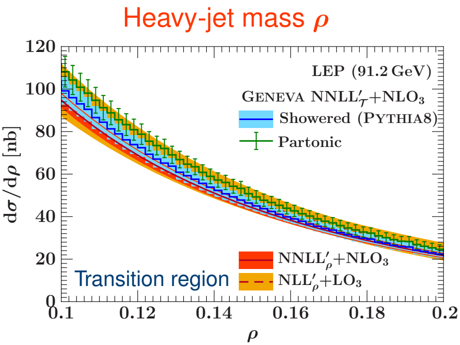


$$\frac{d\sigma}{d\mathcal{T}_2} = H(Q) \times (J\,J)(Q\mathcal{T}_2) \otimes S(\mathcal{T}_2) \otimes F$$

- Higher-order resummation significantly improves precision
- GENEVA is constructed to exactly reproduce the analytic NNLL$'$+NLO$_3$ result of its resolution variable (here $\mathcal{T}_2$) including pert. uncertainties
- Pythia8 hadronization effect behaves as expected from field theory
  - Excellent agreement with data using $\alpha_s(m_Z)$ from N^{3}LL$'$ thrust fits

Results for Other 2-Jet Observables.

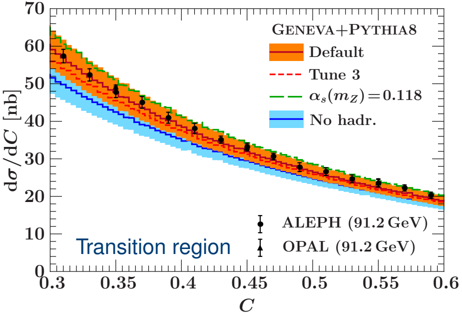




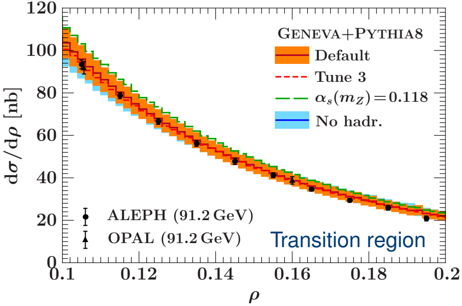
- After showering, high precision of built-in $\mathcal{T}_2$ resummation also improves other 2-jet event shape observables
  - close to the respective exact NNLL$'_C$ and NNLL$'_\rho$ results

Results for Other 2-Jet Observables.

C parameter



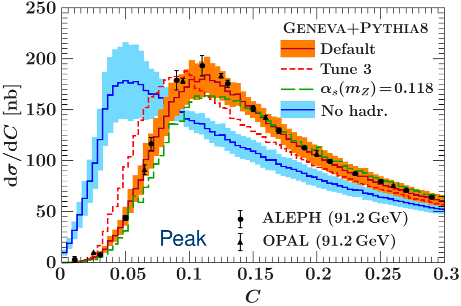
Heavy-jet mass ρ



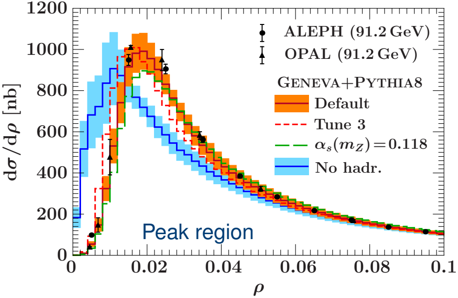
- After showering, high precision of built-in $\mathcal{T}_2$ resummation also improves other 2-jet event shape observables
  - close to the respective exact NNLL$'_C$ and NNLL$'_\rho$ results
- Data is well described using the same α_s and hadronization tune
  - Confirms that e^+e^- data implies low α_s value
  - Low α_s was also confirmed recently by explicit N^{3}LL$'$ fits to C parameter [Hoang, Kolodrubetz, Mateu, Stewart]

Results for Other 2-Jet Observables.

C parameter



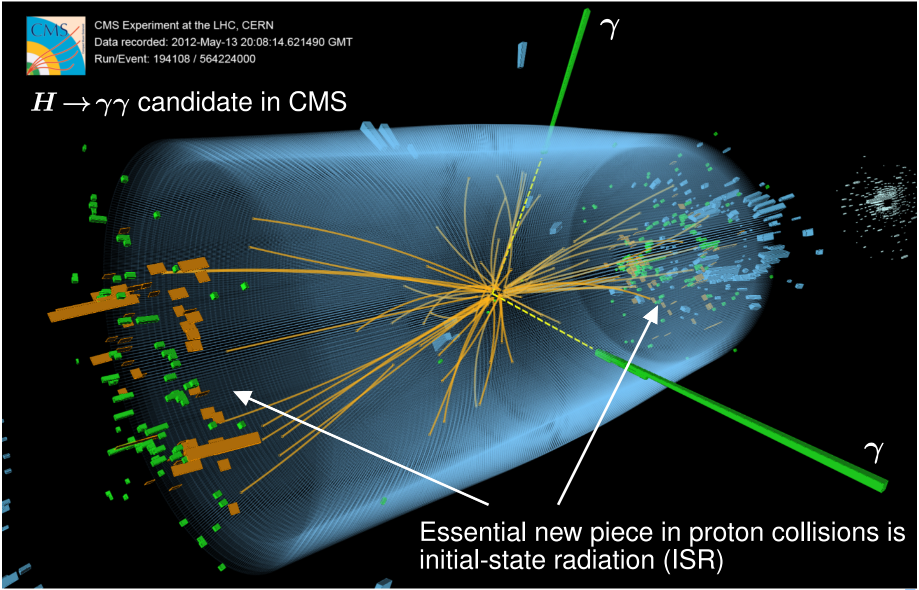
Heavy-jet mass ρ



- After showering, high precision of built-in $\mathcal{T}_2$ resummation also improves other 2-jet event shape observables
  - close to the respective exact NNLL'_C and NNLL'_ρ results
- Data is well described using the same α_s and hadronization tune
  - Confirms that e^+e^- data implies low α_s value
  - Low α_s was also confirmed recently by explicit $\mathrm{N^3LL}'$ fits to C parameter [Hoang, Kolodrubetz, Mateu, Stewart]

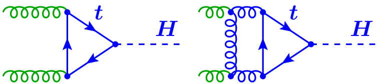
Higgs With and Without Jets.

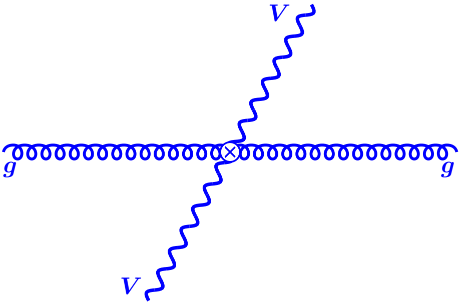
Hadronic Collisions.



Physical Picture with ISR.

μ_H





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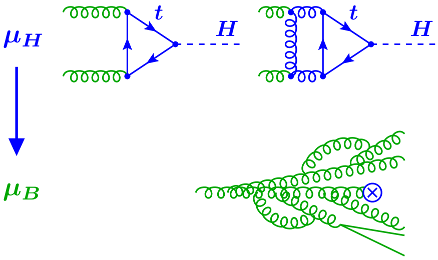

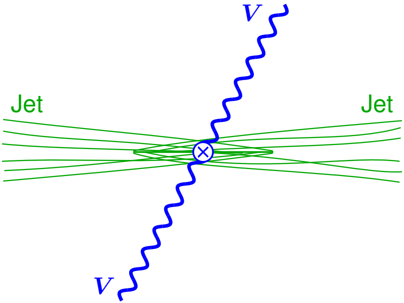

Initial-state analog of jet functions are beam functions [Stewart, FT, Waalewijn '09]

- Correspond to a more differential parton distribution
- Have been computed to NNLO for several observables [Luebbert, Gehrmann, Yang; Gaunt, Stahlhofen, FT]
  - e.g. necessary for pp GENEVA

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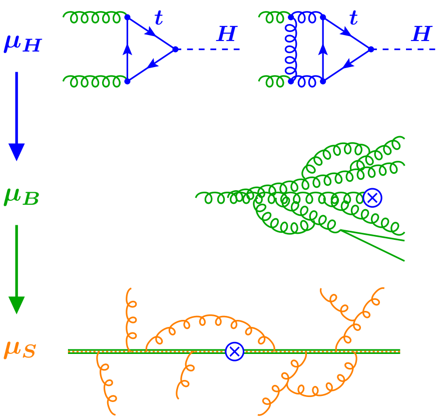

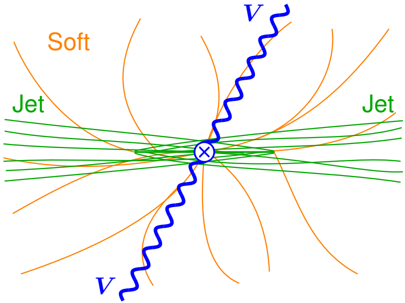

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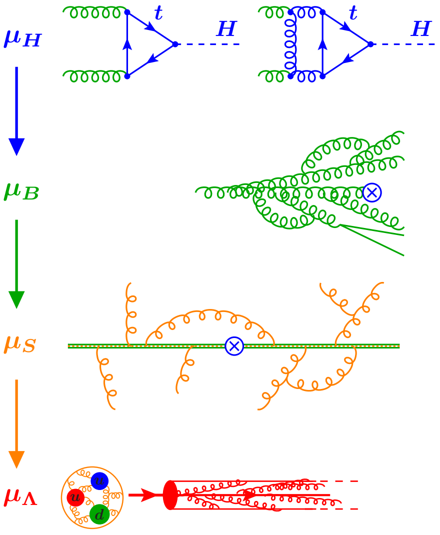
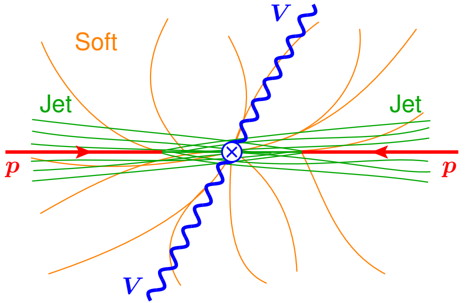


(+ Hadronization)



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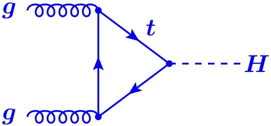
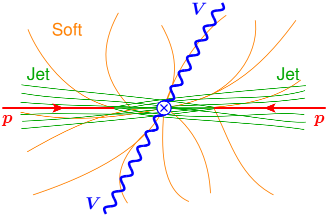
  - e.g. necessary for pp GENEVA

Higgs Production.

$\sim 2/3$ of Higgs bosons are produced mostly at rest (i.e. low p_T)

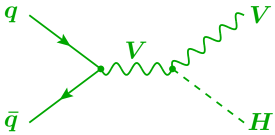
0 jets



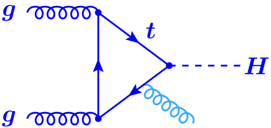


$\sim 1/3$ of Higgs bosons have sizeable p_T

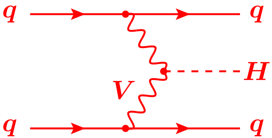
0 jets



1 jet

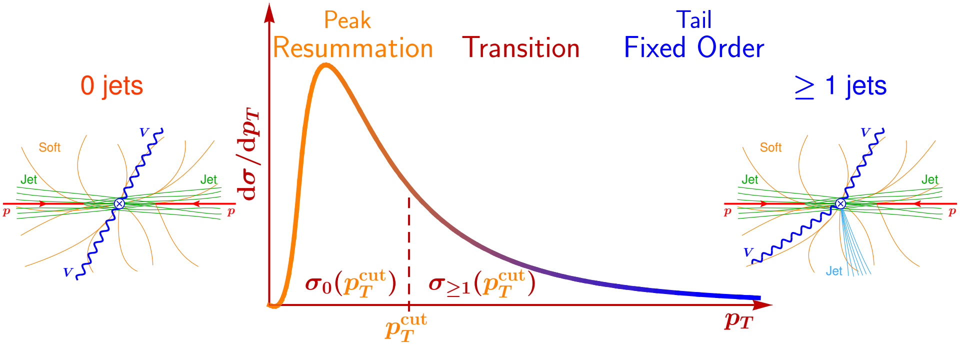


2 jets



- Number of jets in the final state distinguishes different processes
  - Essential for measuring Higgs couplings
  - Also important to separate different backgrounds, e.g. in $H \to WW$

$p_T^{\rm jet}$ Spectrum.



$p_T^{\rm jet}$ spectrum of leading jet determines "0-jettiness" of an event

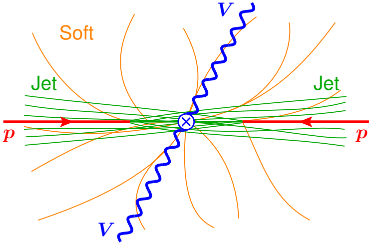
- Basic idea analogous to thrust, but also some important differences:
  - Constraints p_T rather than virtuality of emissions
  - Based on jets of radius R (local clustering of emissions) rather than global sum of emissions (e.g. 0-jettiness/beam-thrust event shape)
- Resummation is known up to NNLL$'$+NNLO
  [Banfi, Monni, Salam, Zanderighi; Becher, Neubert, Rothen; FT, Walsh, Zuberi]

Resummation for $p_T^{\rm jet}$

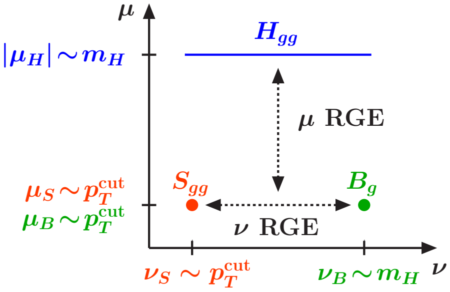
0-jet cross section in SCET for $p_T^{\rm jet} < p_T^{\rm cut}$

(valid for $R^2 \ll 1$ and $p_T^{\rm cut} \ll m_H$)

$$\sigma_0(p_T^{\rm cut}) = H_{gg}(m_H) \times [B_g(m_H, p_T^{\rm cut}, R)]^2 \times S_{gg}(p_T^{\rm cut}, R)$$



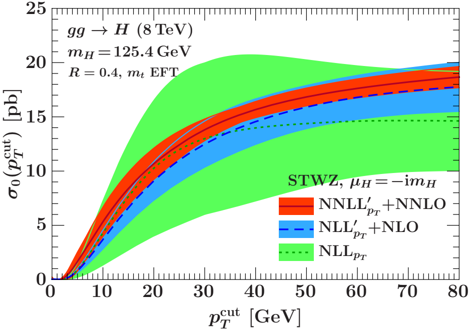
RGE running now happens in 2 dimensions: virtuality μ and rapidity ν



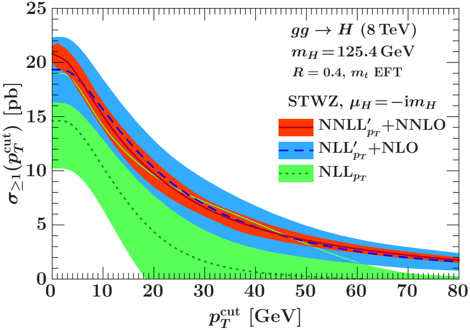
$$2\ln^2\frac{p_T^{\rm cut}}{m_H} = 2\ln^2\frac{m_H}{\mu} + 4\ln\frac{p_T^{\rm cut}}{\mu}\ln\frac{\nu}{m_H} + 2\ln\frac{p_T^{\rm cut}}{\mu}\ln\frac{\mu\, p_T^{\rm cut}}{\nu^2}$$

Results for Higgs + 0-jet Bin.

0 jets: $\sigma_0(p_T^{cut})$



≥1 jets: $\sigma_{\geq 1}(p_T^{cut})$

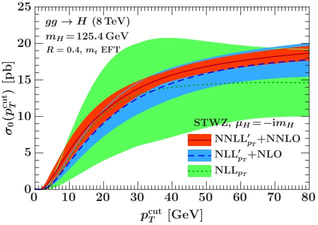


[Stewart, FT, Walsh, Zuberi]

- Resummation yields much improved precision: small uncertainties and good convergence
  - Most precise predictions to date
  - Jet clustering uncertainties are not included but appear to be under control [Alioli, Walsh; Dasgupta et al.]
  - PDF+α_s uncertainties are not shown (become relevant now)

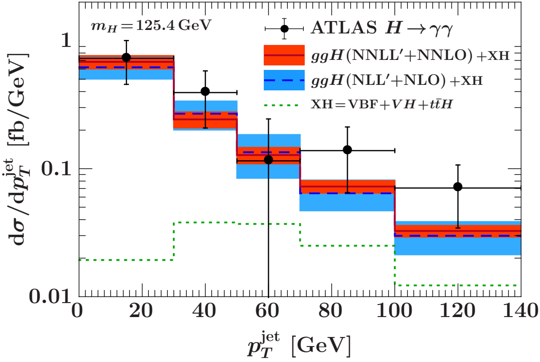
Comparison with Higgs Differential Measurements.

$\sigma_0(p_T^{\rm jet} \leq p_T^{\rm cut})$



$\Rightarrow$

$d\sigma/dp_T^{\rm jet}$

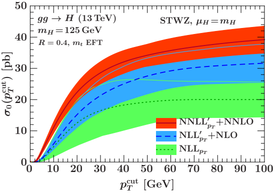


Can compare directly to $p_T^{\rm jet}$ spectrum measured by ATLAS in $H \to \gamma\gamma$
[ATLAS, JHEP 09 (2014) 112]

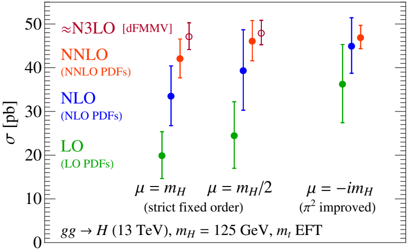
- Multiply by $\mathrm{BR}(H \to \gamma\gamma)$
- Include photon acceptance (essentially $p_T^{\rm jet}$ independent)
- Also add 5% branching ratio and and 8% PDF+α_s uncertainties

Inclusive Cross Section.

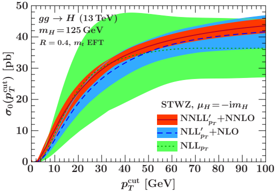
$\mu_H = m_H$



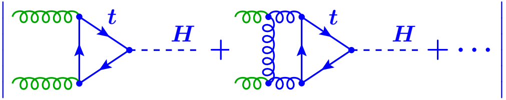
$\sigma_{\rm total}$ (13 TeV)



$\mu_H = -im_H$



$H_{gg}(m_H) = \Big|$



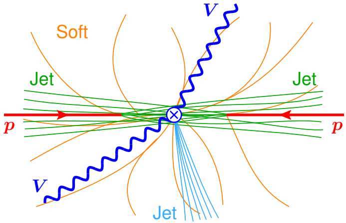
$\Big|^2 \supset \alpha_s^n \ln^m \frac{-m_H^2 - i0}{\mu_H^2}$

Imaginary scale $\mu_H = -im_H$ resums large $\ln^2(-1) = -\pi^2$ terms in H_{gg}
(π^2 resummation [Parisi, Sterman, Magnea; Ahrens et al.])

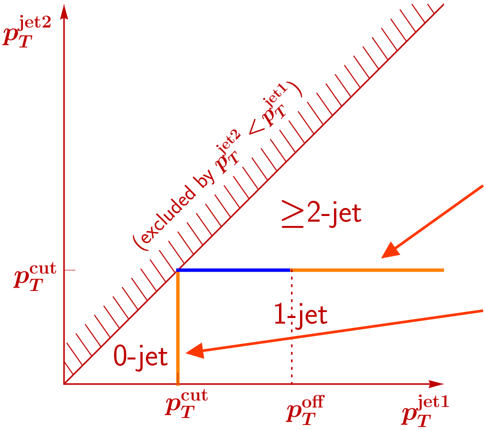
- Improvement in 0-jet region carries over to total inclusive cross section
- π^2-improved NNLO cross section consistent with approximate N^{3}LO estimates [e.g. de Florian, Mazzitelli, Moch, Vogt]

Resummation for Higgs + 1-jet Bin.

[Boughezal, Liu, Petriello, FT, Walsh]



1-jet bin adds another scale dimension:



$p_T^{\rm jet2}$ resummation at NLL′+NLO

[Liu, Petriello]

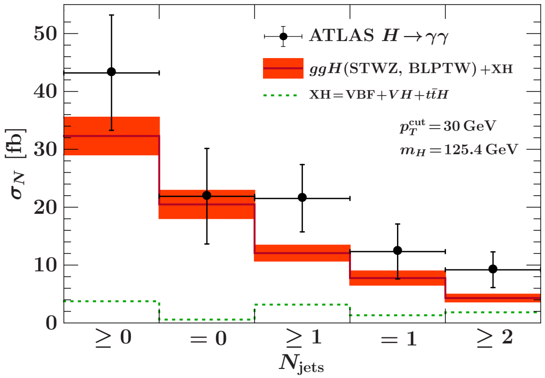
($p_T^{\rm jet1} > p_T^{\rm off}$ treated in fixed order)

$p_T^{\rm jet1}$ resummation at NNLL′+NNLO

(for $p_T^{\rm jet1} < p_T^{\rm off}$ with $p_T^{\rm jet2}$ treated at fixed order)

- Important consistency check: results must be insensitive to $p_T^{\rm off}$
- Provides first combination of resummed 0-jet and 1-jet bins

Cross Section in Jet Bins.



Putting everything together we can compare with measured cross sections as a function of the number of jets

- Same corrections applied as for p_T^{jet} spectrum
- VBF $+VH + t\bar{t}H$ contributions as given by ATLAS measurement (come from Monte Carlo normalized to available (N)NLO results)

New Rapidity-Dependent Jet Binning.

[Gangal, Stahlhofen, FT]

Generalize p_T^{jet} by defining

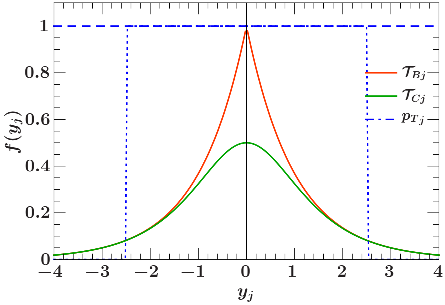
$$\mathcal{T}_{fj} = p_{Tj}\, f(y_j)$$

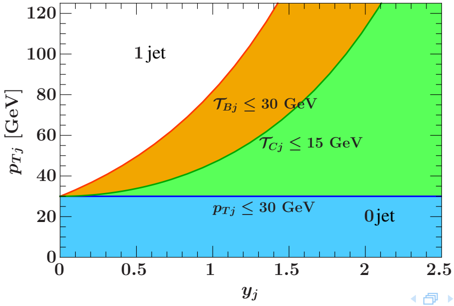
$$\mathcal{T}_f^{\mathrm{jet}} = \max_{j \in J(R)} \mathcal{T}_{fj}$$

- Can choose different rapidity weighting functions such that $\mathcal{T}_f^{\mathrm{jet}}$
  - can be resummed
  - is insensitive to forward rapidities
- Count jets according to $\mathcal{T}_{fj}$

0 jets: $\sigma_0(\mathcal{T}_f^{\mathrm{jet}} < \mathcal{T}^{\mathrm{cut}})$

≥ 1 jets: $\sigma_{\geq 1}(\mathcal{T}_f^{\mathrm{jet}} > \mathcal{T}^{\mathrm{cut}})$

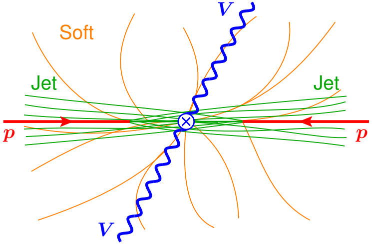




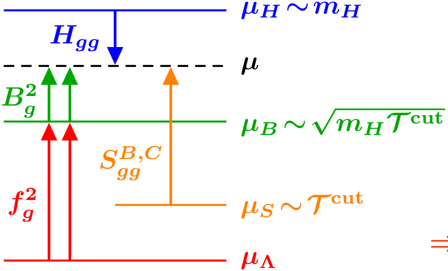
0-jet cross section in SCET for $\mathcal{T}_{B,C}^{\rm jet} < \mathcal{T}^{\rm cut}$

(valid for $R^2 \ll 1$ and $\mathcal{T}^{\rm cut} \ll m_H$)

$$\sigma_0(\mathcal{T}^{\rm cut}) = H_{gg}(m_H) \times [B_g(m_H \mathcal{T}^{\rm cut}, R)]^2 \times S_{gg}^{B,C}(\mathcal{T}^{\rm cut}, R)$$



RGE running is now thrust-like and only involves virtuality

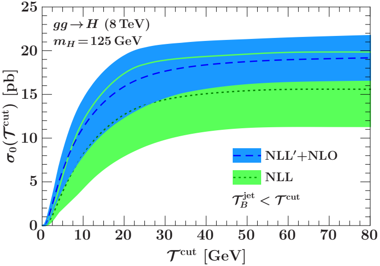


$$\ln^2 \frac{\mathcal{T}^{\rm cut}}{m_H} = 2 \ln^2 \frac{m_H}{\mu} - \ln^2 \frac{m_H \mathcal{T}^{\rm cut}}{\mu^2} + 2 \ln^2 \frac{\mathcal{T}^{\rm cut}}{\mu}$$

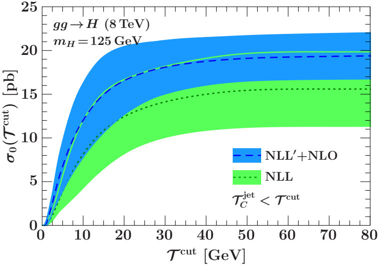
$\Rightarrow$ Complementary to $p_T^{\rm jet}$ also from theory perspective

First Results for $\mathcal{T}_B^{\rm jet}$ and $\mathcal{T}_C^{\rm jet}$.

$\sigma_0(\mathcal{T}_B^{\rm jet} < \mathcal{T}^{\rm cut})$



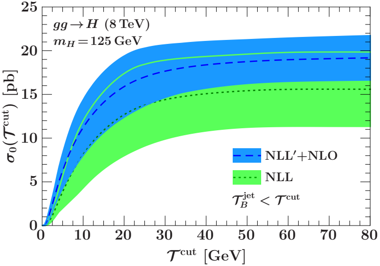
$\sigma_0(\mathcal{T}_C^{\rm jet} < \mathcal{T}^{\rm cut})$



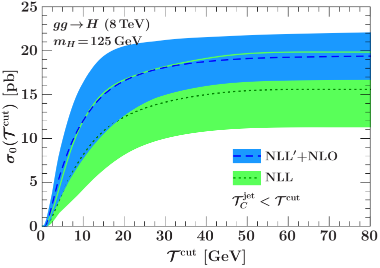
- NNLL′+NNLO is work in progress
  - Expect significant reduction in theory uncertainties (to similar level as $p_T^{\rm jet}$)

First Results for $\mathcal{T}_B^{\rm jet}$ and $\mathcal{T}_C^{\rm jet}$.

$\sigma_0(\mathcal{T}_B^{\rm jet} < \mathcal{T}^{\rm cut})$



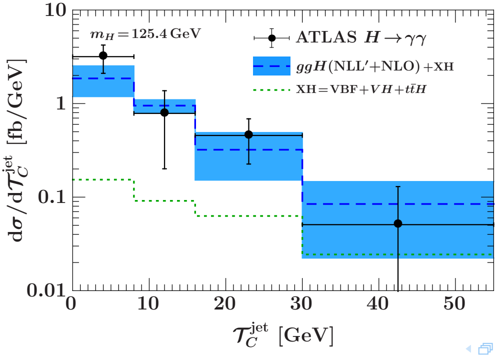
$\sigma_0(\mathcal{T}_C^{\rm jet} < \mathcal{T}^{\rm cut})$



- NNLL′+NNLO is work in progress
  - Expect significant reduction in theory uncertainties (to similar level as $p_T^{\rm jet}$)
- Compare to $\mathcal{T}_C^{\rm jet}$ spectrum measured in $H \to \gamma\gamma$

$\Rightarrow$

$d\sigma/d\mathcal{T}_C^{\rm jet}$



Jet Mass and Soft Effects.

Jet Mass Spectrum.

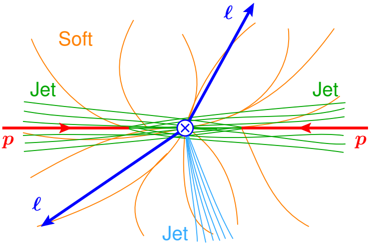
[Stewart, FT, Waalewijn]

Use 1-jet bin to look in detail at the jet itself

- Consider 3 hard processes κ:

  $qg \to Zq, \quad q\bar{q} \to Zg, \quad gg \to Hg$

- Require signal jet with $p_T^J \geq 200\,\mathrm{GeV}$
- Veto additional jets with $p_T^J > 50\,\mathrm{GeV}$



Jet mass spectrum in SCET

(for $m_J \ll p_T^J$, without MPI)

$$\frac{\mathrm{d}\sigma_\kappa}{\mathrm{d}m_J^2} = H_\kappa(p_T^J, y_J) \times B^2(\mathrm{veto}) \times J_{q,g}(m_J^2) \otimes S_\kappa(m_J^2/(2p_T^J))$$

Jet Mass Spectrum.

[Stewart, FT, Waalewijn]

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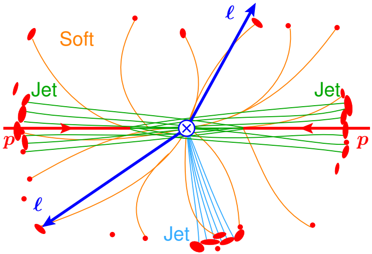


Jet mass spectrum in SCET including hadronization

(for $m_J \ll p_T^J$, without MPI)

$$\frac{\mathrm{d}\sigma_\kappa}{\mathrm{d}m_J^2} = H_\kappa(p_T^J, y_J) \times B^2(\mathrm{veto}) \times J_{q,g}(m_J^2) \otimes S_\kappa(m_J^2/(2p_T^J)) \otimes F_\kappa$$

Jet Mass Spectrum.

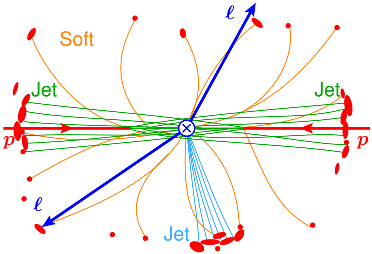
[Stewart, FT, Waalewijn]

Use 1-jet bin to look in detail at the jet itself

- Consider 3 hard processes κ:

  $qg \to Zq, \quad q\bar{q} \to Zg, \quad gg \to Hg$

- Require signal jet with $p_T^J \geq 200\,\mathrm{GeV}$
- Veto additional jets with $p_T^J > 50\,\mathrm{GeV}$



Jet mass spectrum in SCET including hadronization

(for $m_J \ll p_T^J$, without MPI)

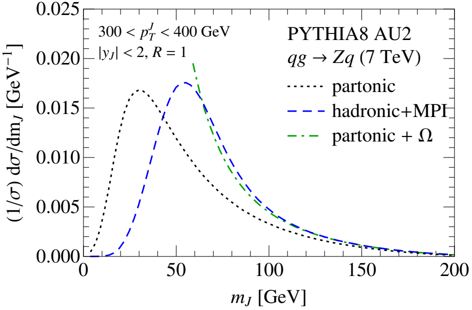
$$\frac{1}{\sigma_\kappa}\frac{\mathrm{d}\sigma_\kappa}{\mathrm{d}m_J^2} = H_\kappa(p_T^J, y_J) \times B^2(\mathrm{veto}) \times J_{q,g}(m_J^2) \otimes S_\kappa(m_J^2/(2p_T^J)) \otimes F_\kappa$$

- Dependence on hard kinematics and jet-veto effect essentially drops out for *normalized* jet mass spectrum

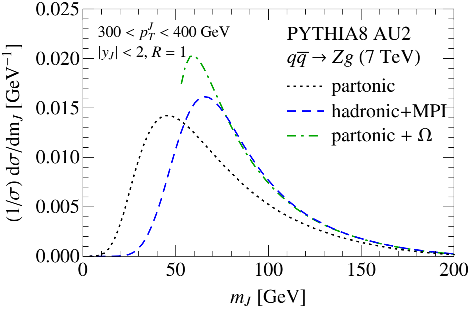
$\Rightarrow$ Can study and predict properties of soft and nonperturbative effects

Jet Mass Spectrum in Pythia8.

$qg \to Zq$: quark jet



$q\bar{q} \to Zg$: gluon jet



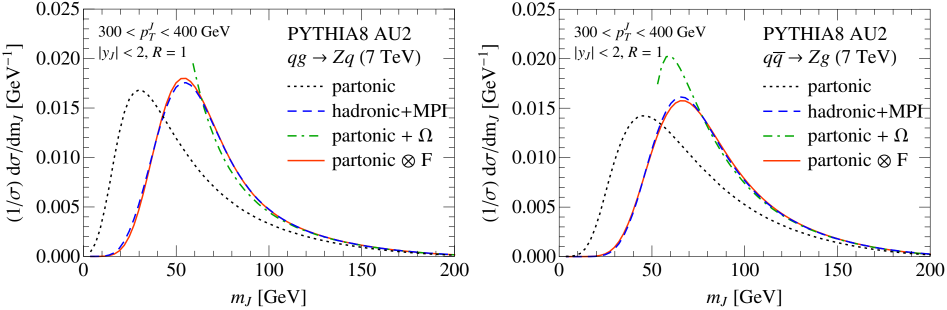
Predict hadronization to behave qualitatively as for thrust in e^+e^-

- $m_J^2/p_T^J \gg \Lambda_{\mathrm{QCD}}$: jet mass shifted by 1st moment $\Omega_k = \int \mathrm{d}k\, k\, F_\kappa(k)$

$$m_J^2 = (m_J^2)^{\mathrm{pert}} + 2p_T^J\,\Omega_\kappa$$

Jet Mass Spectrum in Pythia8.

$qg \to Zq$: quark jet $\qquad$ $q\bar{q} \to Zg$: gluon jet



Predict hadronization to behave qualitatively as for thrust in e^+e^-

- $m_J^2/p_T^J \gg \Lambda_{\rm QCD}$: jet mass shifted by 1st moment $\Omega_k = \int \mathrm{d}k\, k\, F_\kappa(k)$

$$m_J^2 = (m_J^2)^{\rm pert} + 2p_T^J\, \Omega_\kappa$$

- $m_J^2/p_T^J \sim \Lambda_{\rm QCD}$: partonic spectrum gets convolved with some F_κ

⇒ Remarkably well satisfied by Pythia's hadronization *and also* MPI

First Jet Mass Moment.

Consider the 1st moment of the normalized jet mass spectrum, which tracks the shift in the spectrum

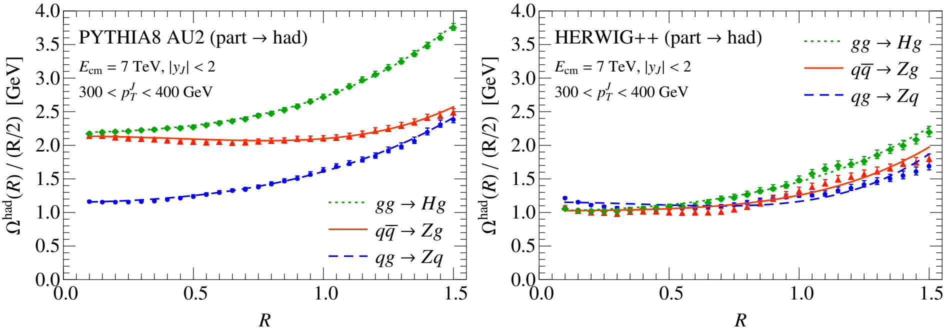
$$M_1 = \frac{1}{\sigma} \int \mathrm{d}m_J^2\, m_J^2\, \frac{\mathrm{d}\sigma}{\mathrm{d}m_J^2}$$

- We can predict the following behaviour

$$\frac{M_1}{2p_T^J} \sim \underbrace{c_2^\kappa(p_T^J, y_J) R^{2-\gamma_\kappa}}_{\text{dominant pert.}} + \underbrace{c_4^\kappa(p_T^J, y_J)\, R^4}_{\text{pert. soft ISR}} + \underbrace{\frac{R}{2}\Omega_{q,g}^{(1)} + \frac{R^3}{8} \cdots}_{\text{hadronization}} + \underbrace{R^4}_{\text{MPI}}$$

- Dependence on jet radius R, partonic channel κ, and p_T^J, y_J allows one to separate physically distinct sources of soft effects
  - Soft ISR interference (part of primary hard collision)
  - Nonperturbative effects (hadronization)
  - Soft multi-parton interactions (underlying event)

$\Rightarrow$ Should try to measure $M_1(R)$, even without measurements we can compare MC models with predictions from field theory



$\Omega_\kappa(R)$ is defined by nonpert. matrix element which we can expand in R

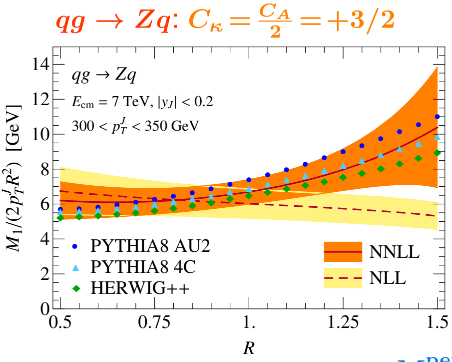
$$\Omega_\kappa(R) = \frac{R}{2}\,\Omega^{(1)}_{q,g} + \frac{R^3}{8}\,\Omega^{(3)}_\kappa + \frac{R^5}{32}\,\Omega^{(5)}_\kappa + \cdots$$

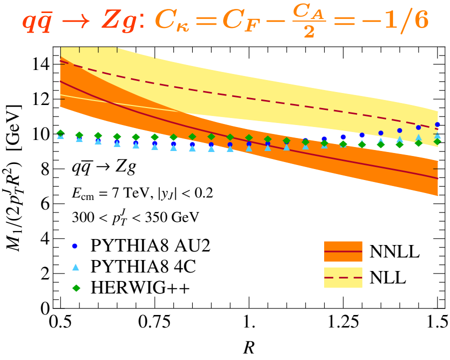
- Leading $\Omega^{(1)}_{q,g}$ is universal for quark and gluon initiated jets
  - Could be measured in 1-jettiness (thrust) in DIS

⇒ Pythia8 and Herwig++ agree with predictions (very well for Pythia8)

- Have very different channel dependence compared to each other

Primary Soft ISR.





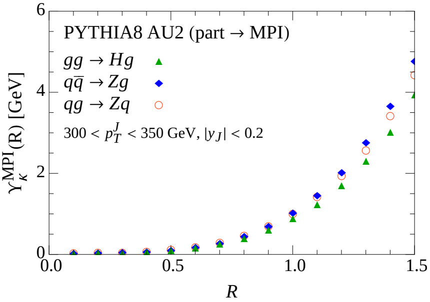
Pert. contributions scale as $\frac{M_{1\,\kappa}^{\text{pert}}}{2p_T^J} \sim p_T^J\, R^{2-\gamma_\kappa} + p_T^J\, \alpha_s C_\kappa\, R^4$

- R^4 contribution due to soft ISR interference (between beam Wilson lines)
  - Enters at $\mathcal{O}(\alpha_s)$ and NNLL, color factor depends on partonic channel
- In MCs soft ISR is modelled as part of parton showering
  - Good agreement for $qg \to Zq$ (not as good for $gg \to Hg$)
  - MCs do not reproduce negative interference effect for $q\bar{q} \to Zg$

Distinguishing Primary Soft ISR and MPI.

MPI also behaves as R^4

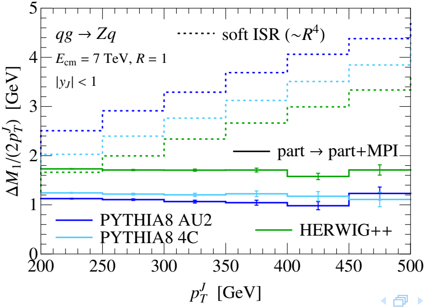
- Like soft ISR, MPI populates jet with constant background of soft particles
- Mostly independent of partonic channel and p_T^J (also as one expects)



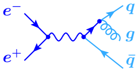
Both MPI and soft ISR behave as soft “underlying event”

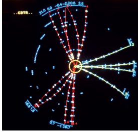
- Different MCs/tunes trade more/less soft ISR for less/more MPI
- Can be distinguished by different p_T^J and channel dependence

$\Rightarrow$ Should measure $M_1(R)$ for different p_T^J and partonic channels

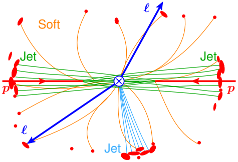


Summary.





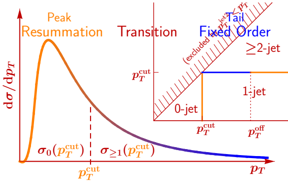
Hadronic jets are our messengers of the hard QCD interaction



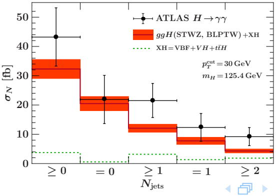
- Jet processes typically involve multiple physical scales

⇒ In such cases, effective field theories are powerful tools to obtain precise theory predictions

⇒ With many scales there are also many aspects that are important and have to fit together
  - Higher fixed orders
  - Resummation of large logarithmic corrections
  - Soft and nonperturbative effects
  - Reliable uncertainty estimates



Other situations with multiple scales I did not talk about



- Heavy quarks
- Hierarchies between jets and in multidifferential cross sections
- Jet substructure and heavy boosted objects