Precision Jet Physics for pp and e^-p Collisions

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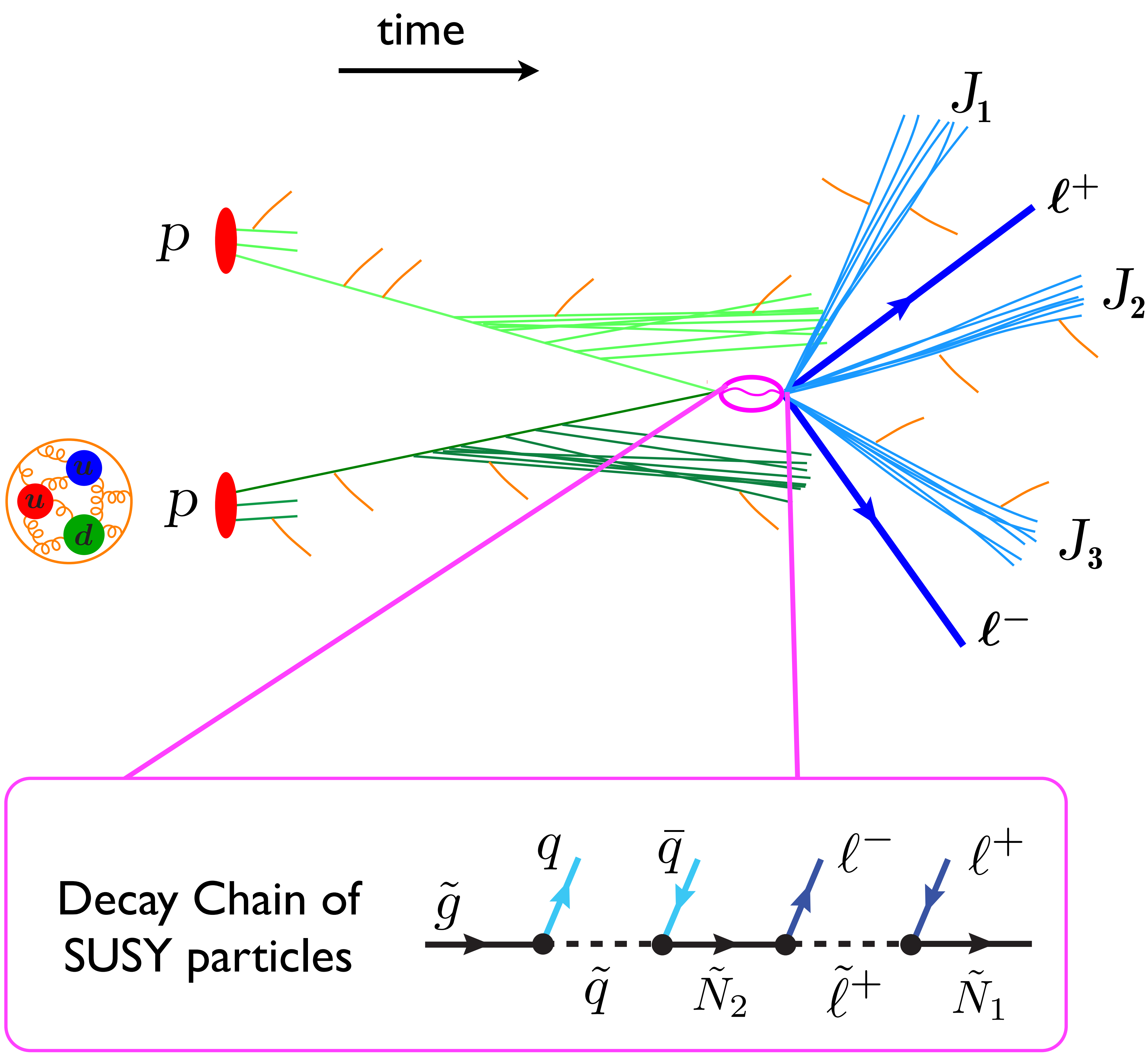
DESY Seminar, March 2013

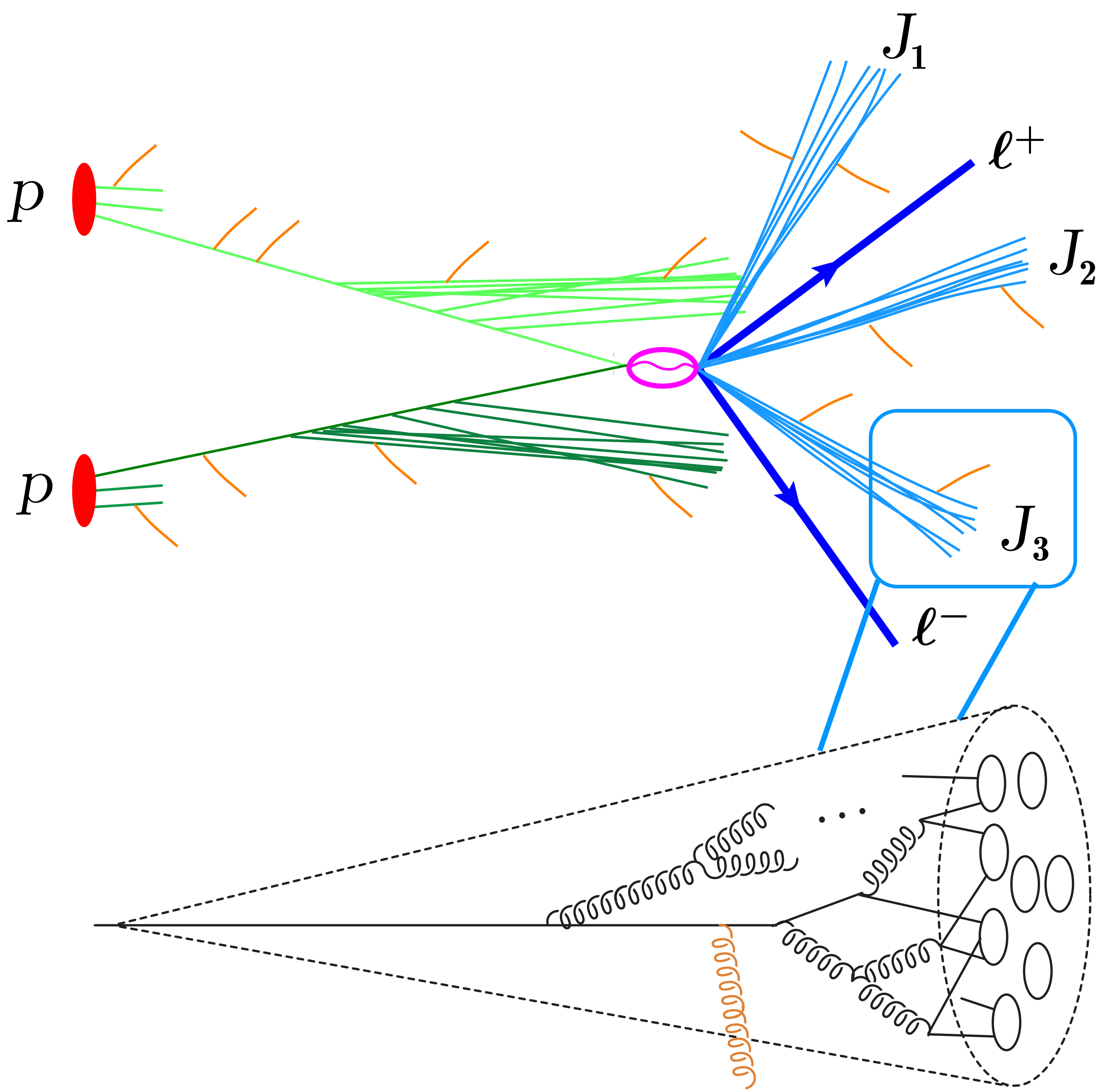
NNLL Jet mass in pp: T. Jouttenus, IS, F. Tackmann, W. Waalewijn arXiv:1302.0846
NNLL Jets in e^-p & recoil: C.Lee, D.Kang, IS arXiv:1303.xxxx (soon)
Operator Analysis of Power corrections: V. Mateu, IS, J. Thaler arXiv:1301.4555

Events with a Hard Interaction:



Search for New Heavy Particles at short distances

Events with a Hard Interaction:



Quarks and Gluons Form Jets

Outline:

- Motivations for Precision Jet Physics
  - $e^+e^- \to \text{jets}$, $\alpha_s(m_Z)$
  - $e^-p \to \text{jets}$
  - $pp \to L + \text{jets}$ & $pp \to L(\to \text{jets}) + X$
- Event Shapes for N-jets: N-jettiness & N-subjettiness
- 2 Next-to-Next-to-Leading Log examples

  Jet Technology (factorization, NNLL summation, hadronization, ...)

  - $pp \to H + 1\,\text{jet}$ Jet mass spectrum
  - $e^-p \to 2\ \text{jets}$ DIS, jet axis & initial state radiation
- Hadronization corrections & Universality

Jets in e^+e^- collisions

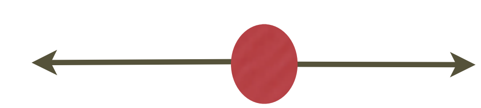
High Precision from event shapes

Moch, Vermaseren, Vogt
Gehrmann et al. & Weinzierl
Becher, Schwartz; Chien, Schwartz
Abbate, Fickinger, Hoang, Mateu, IS
Kolobrubetz, Hoang, Mateu, IS (in prep)

- Fixed order calculations to $\mathcal{O}(\alpha_s^3)$
- \+ Resummation to N^{3}LL for thrust, HJM, C-parameter
- $+\ \frac{\Omega_1}{Q\tau}$ power correction + renormalon subtractions, R-RGE + full treatment of {peak, tail, multijet} + ... + global fit, various Q's

2 jets

$$\tau \to 0$$
$$C \to 0$$



- Thrust $\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i\,|}$
- C-parameter $C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2(\theta_{ij})}{(\sum_i |\vec{p}_i|)^2}$

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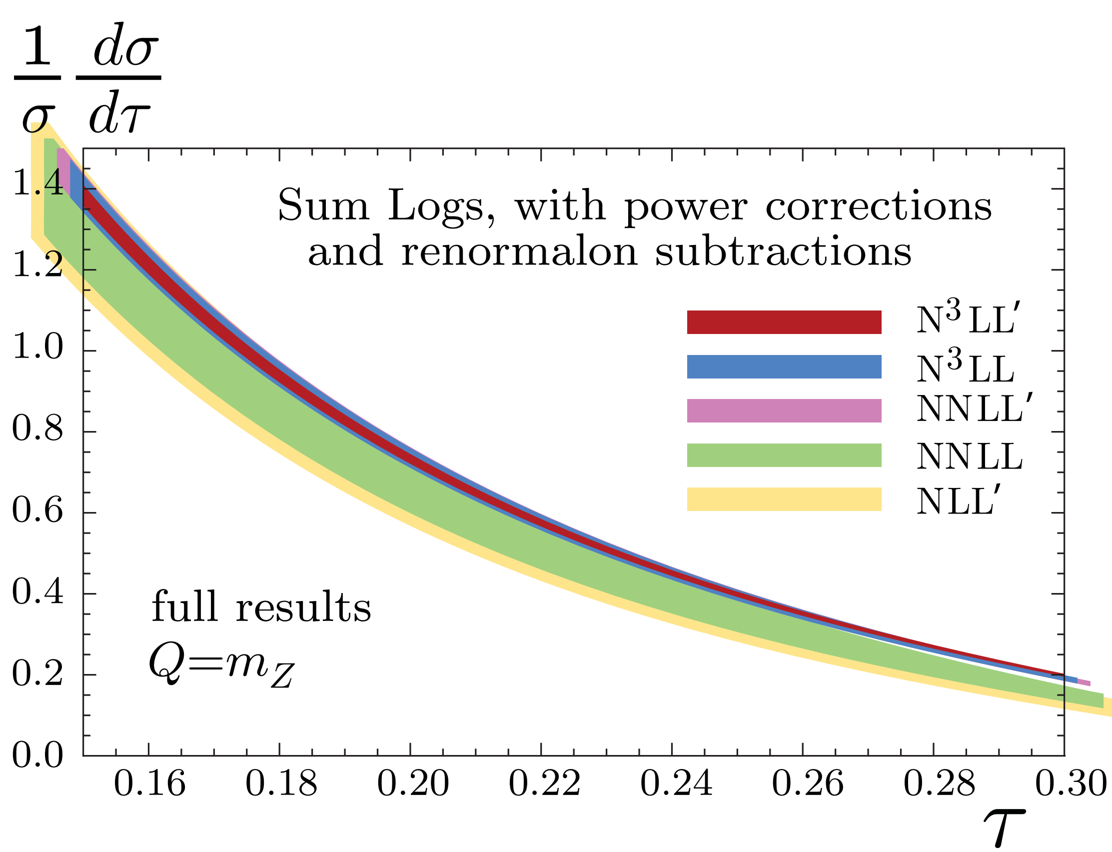
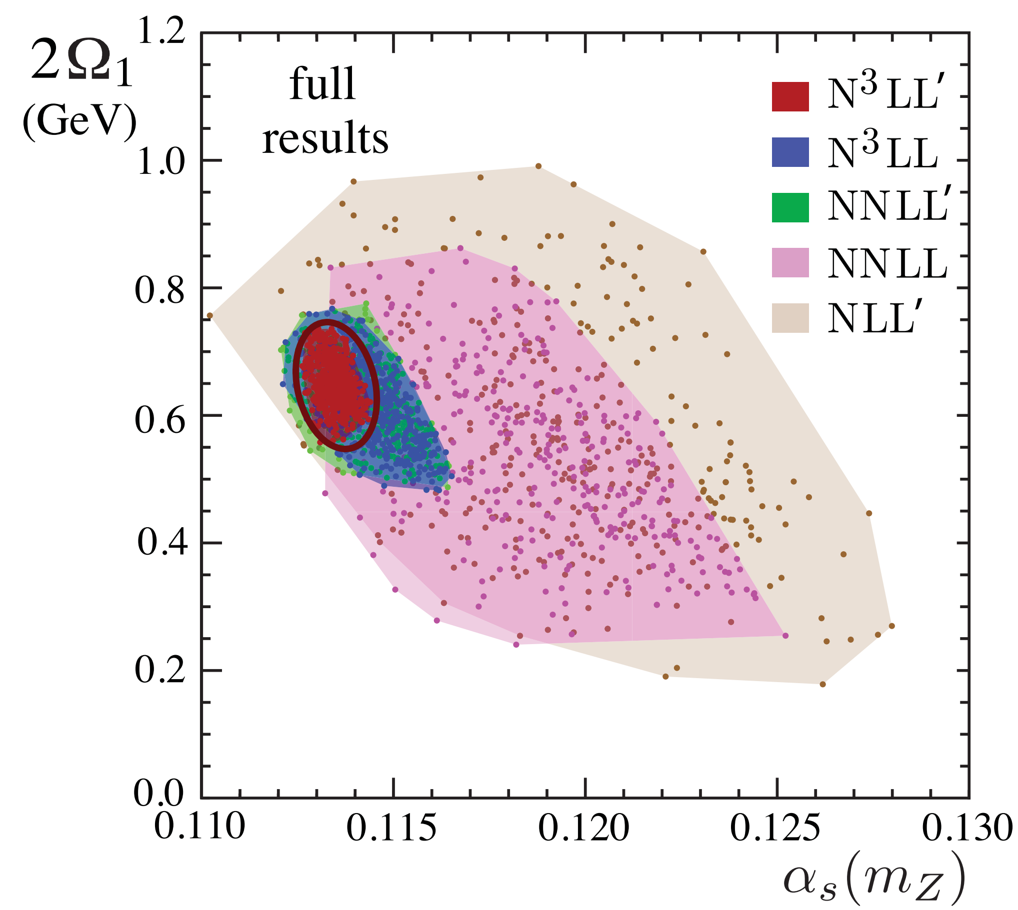
thrust tail



2 parameter fit



Large Logs

log summation

$L = \ln \tau$

$\alpha_s L \sim 1$

$\alpha_s \ll 1$

	LO	NLO	NNLO	N^{3}LO		
$\int_0^\tau d\tau \, \frac{d\sigma}{d\tau} =$	1	$+ \alpha_s L^2$	$+ \alpha_s^2 L^4$	$+ \alpha_s^3 L^6$	$+ \ldots$	LL
		$+ \alpha_s L$	$+ \alpha_s^2 L^3$	$+ \alpha_s^3 L^5$	$+ \ldots$	NLL
		$+ \alpha_s$	$+ \alpha_s^2 L^2$	$+ \alpha_s^3 L^4$	$+ \ldots$	NNLL
			$+ \alpha_s^2 L$	$+ \alpha_s^3 L^3$	$+ \ldots$	
			$+ \alpha_s^2$	$+ \alpha_s^3 L^2$	$+ \ldots$	N^{3}LL
				$+ \alpha_s^3 L$	$+ \ldots$	
				$+ \alpha_s^3$	$+ \ldots$	
				$\ddots$		

N^{3}LL$'$ enhances fixed order terms

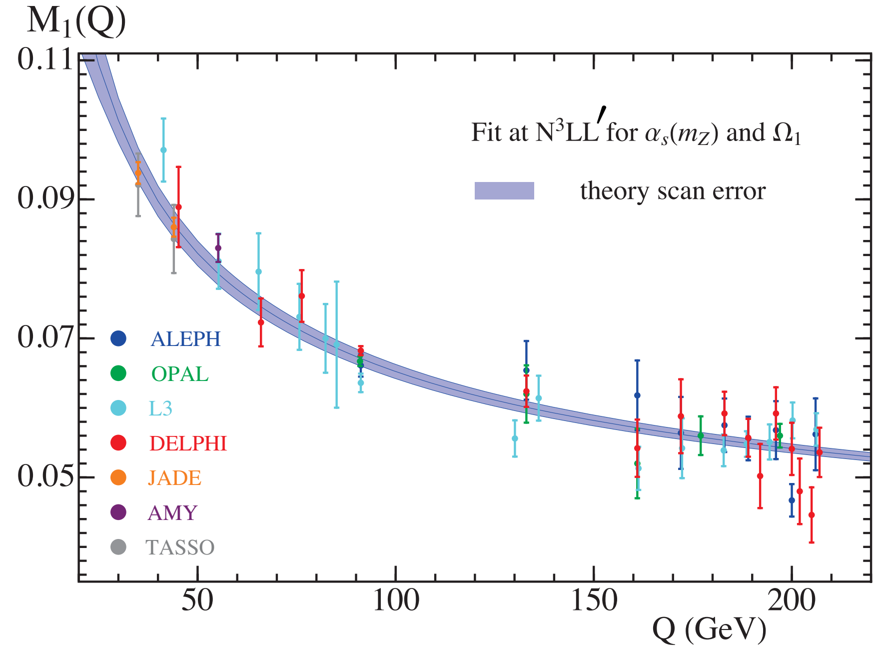
small print: its really

$$\ln \frac{d\sigma}{dy} = \sum_k (\alpha_s \ln)^k \ln + (\alpha_s \ln)^k + \alpha_s (\alpha_s \ln)^k + \alpha_s^2 (\alpha_s \ln)^k + \ldots$$

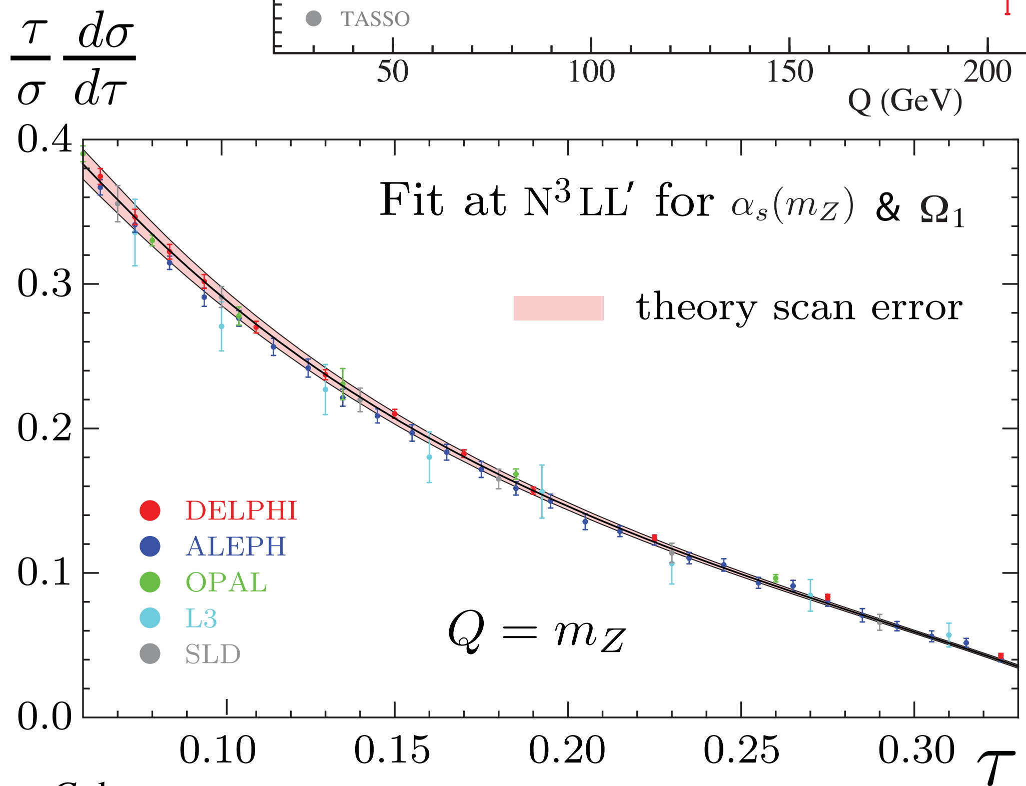
LL NLL NNLL N^{3}LL

Global Fits

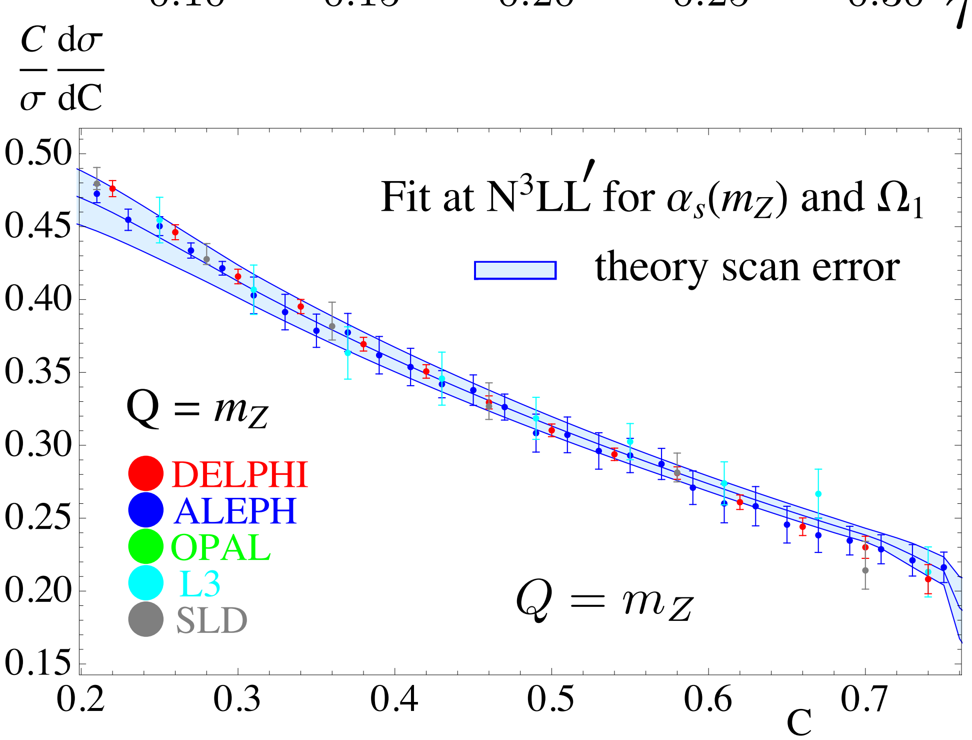
thrust moment

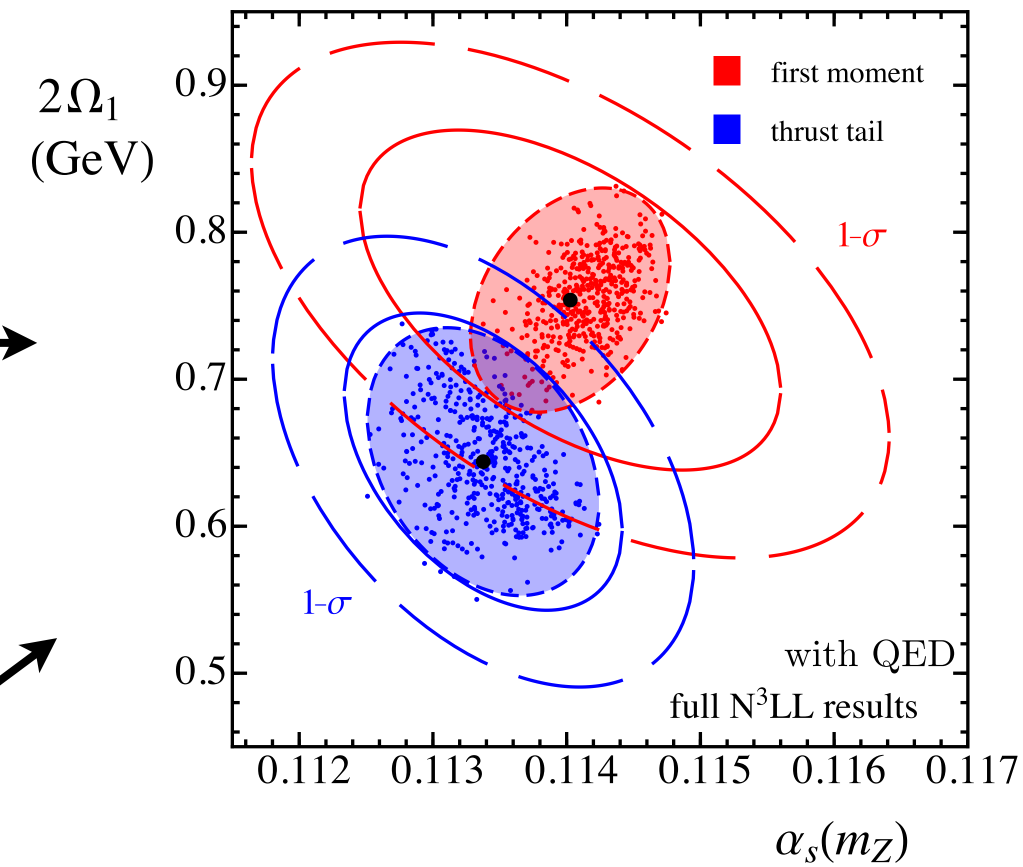


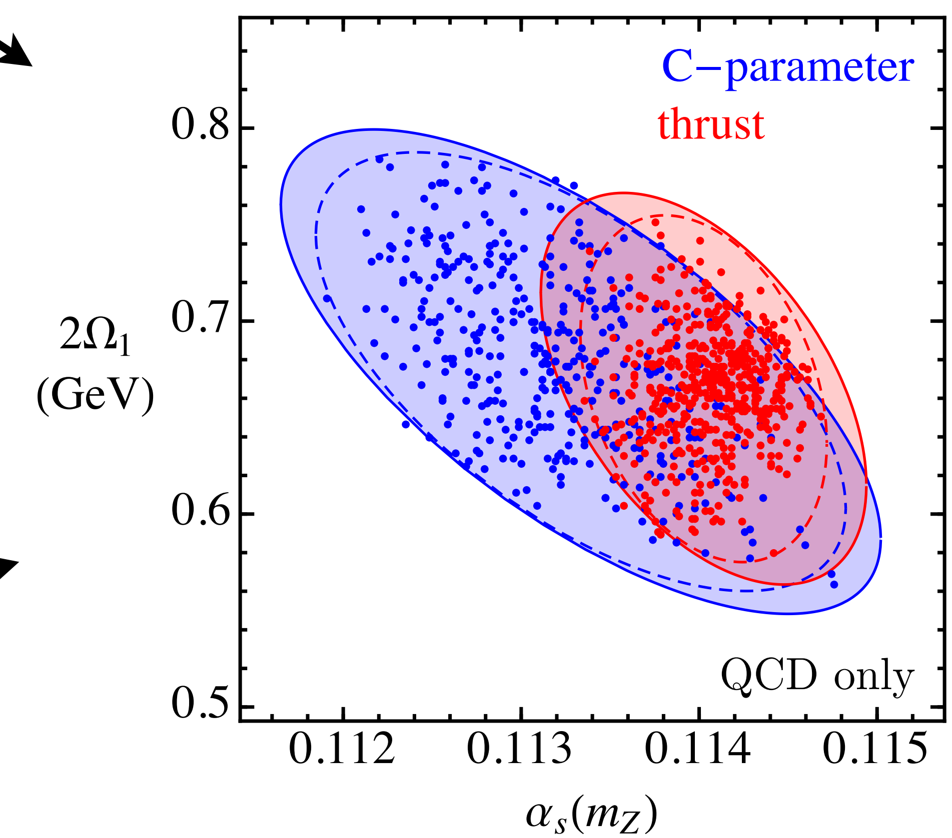
thrust tail



C-param

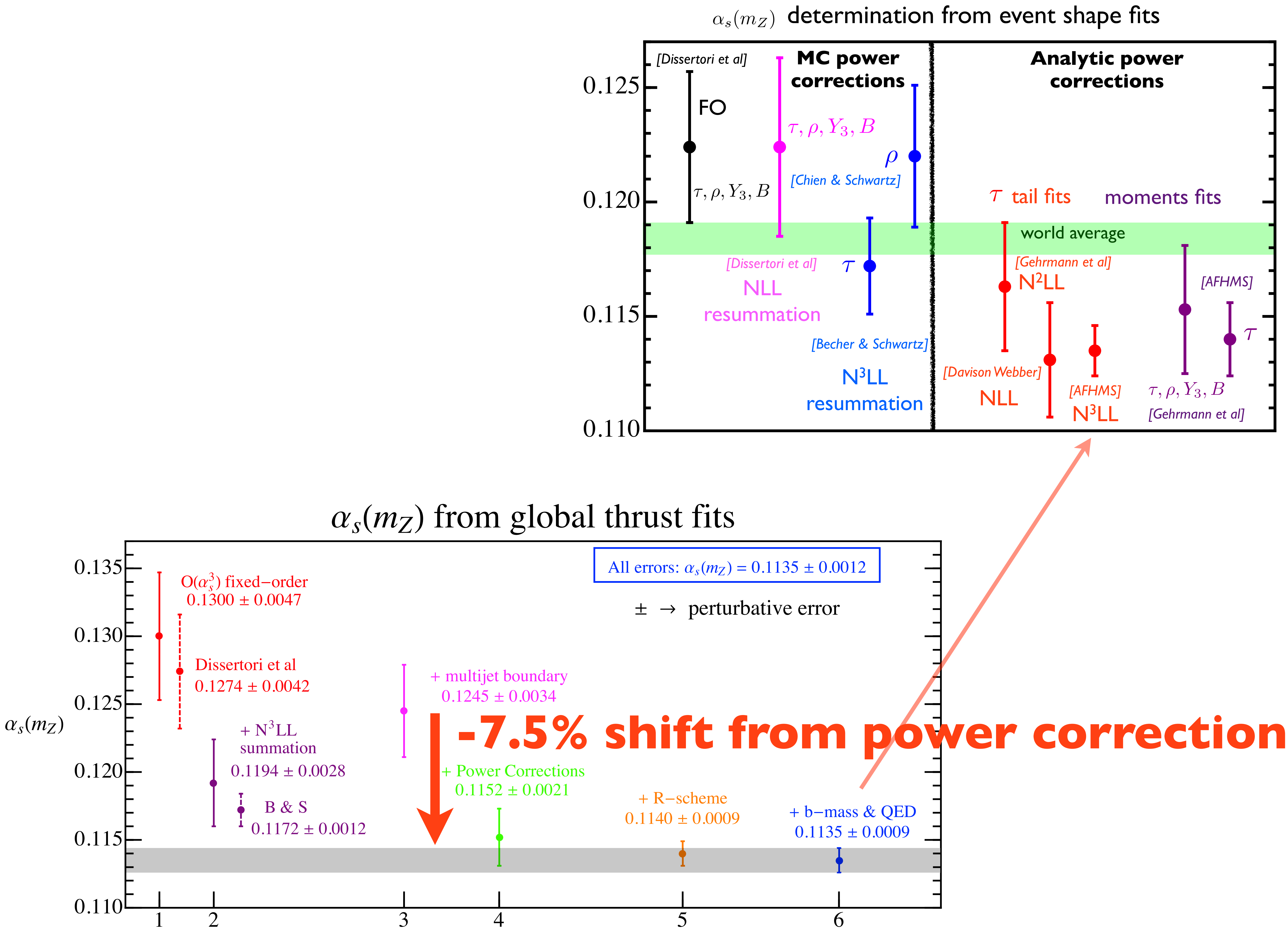






universality? $\Omega_1^C \leftrightarrow \Omega_1^\tau$

Only consider analysis with 3-loop input



Nonperturbative corrections

$$S_e(\ell) = \langle 0 | \overline{Y}^{\dagger}_{\bar{n}} Y^{\dagger}_{n} \delta(\ell - Q\hat{e}) Y_n \overline{Y}_{\bar{n}} | 0 \rangle$$

$$= \int dk \; \hat{S}_e(\ell - k) \; F_e(k)$$

perturbative — Shape function

For $e \gg \frac{\Lambda_{\rm QCD}}{Q}$

Shape function can be expanded

$$F_e(k) \simeq \delta(k) - \Omega_1 \delta'(k)$$

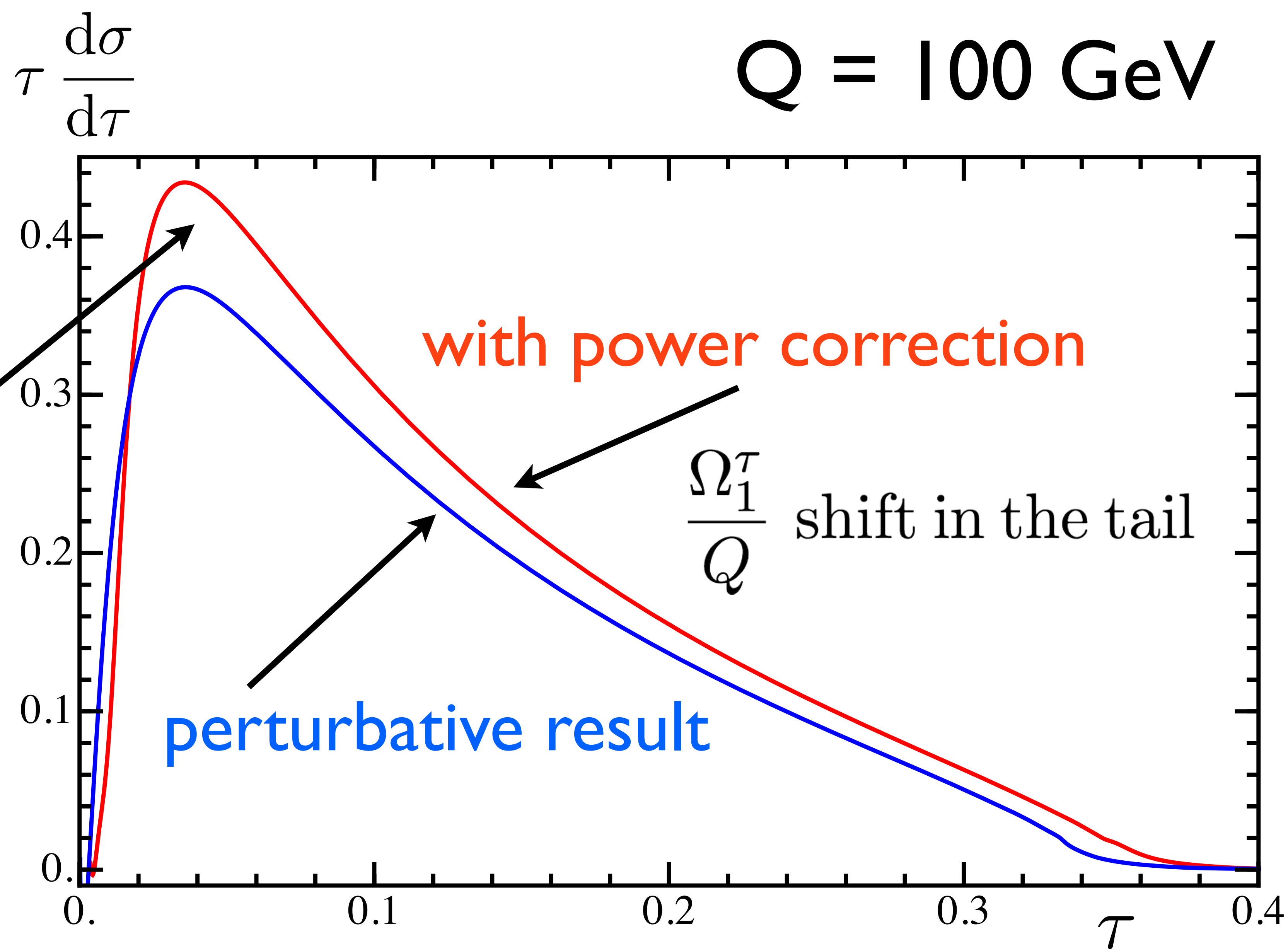
$$\Omega_1 = \langle 0 | \overline{Y}^{\dagger}_{\bar{n}} Y^{\dagger}_{n} Q\hat{e} Y_n \overline{Y}_{\bar{n}} | 0 \rangle$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}e} = \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e} - \frac{\Omega_1}{Q}\frac{\mathrm{d}}{\mathrm{d}e}\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e} \simeq \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e}\left(e - \frac{\Omega_1}{Q}\right) + \mathcal{O}\left[\left(\frac{\Lambda_{\rm QCD}}{Q\,e}\right)^2\right]$$

Leading nonperturbative correction in the tail is a shift of the distribution

Power correction for Thrust

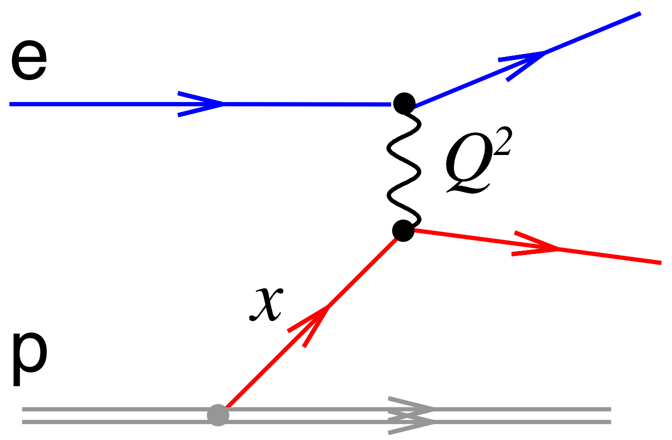
Power corrections in the peak are more complicated than a shift



The main effect of the power correction is a shift of the distribution to the right proportional to 1/Q.

Jets in e⁻p

DIS with jets



Strong Coupling

C. Glasman, in the Proceedings of the Workshop on Precision Measurements of α_s [1110.0016]

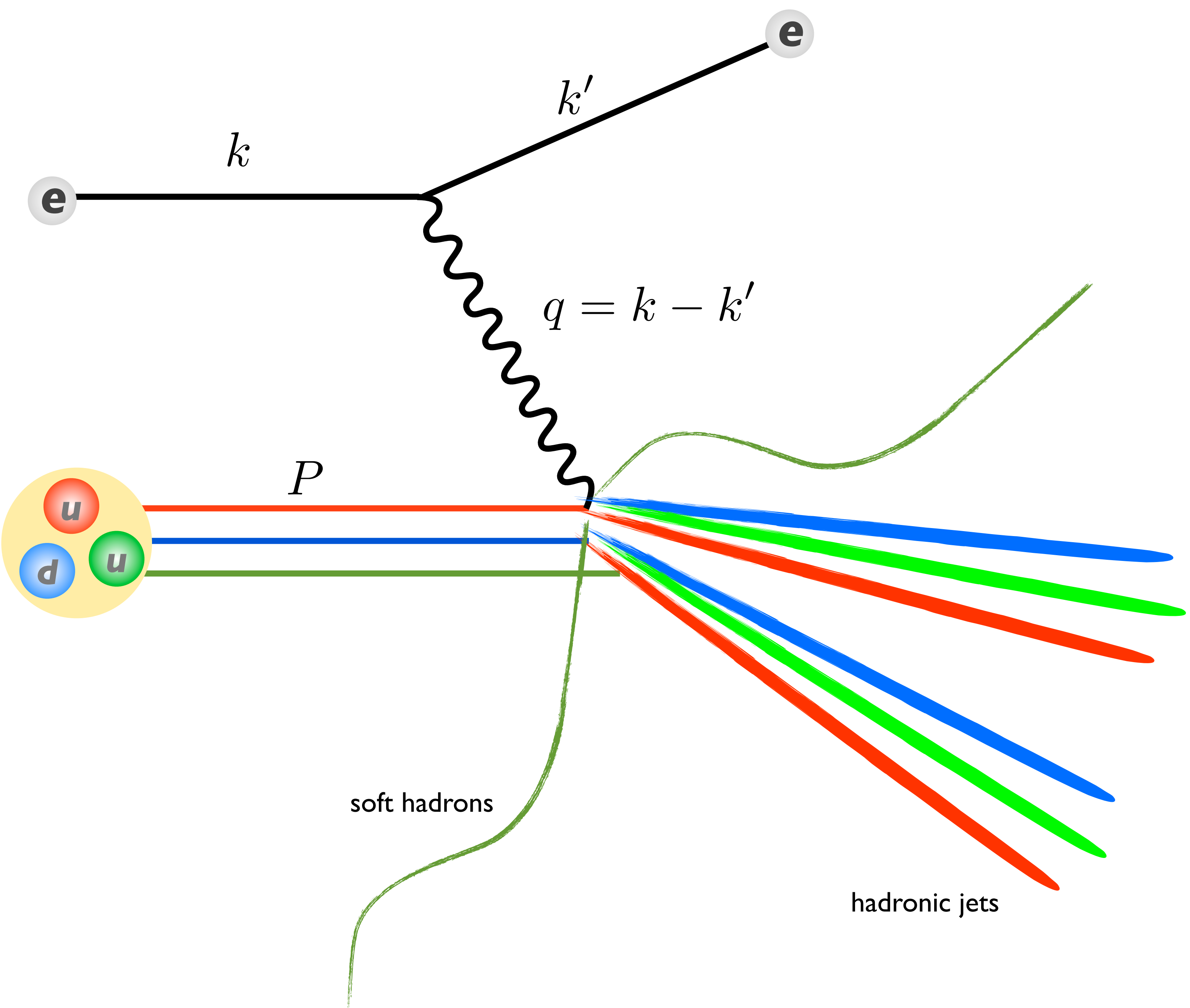
Process	Collab.	Value	Exp.	Th.	Total	(%)
(1) Inc. jets at low Q^2	H1	0.1180	0.0018	$^{+0.0124}_{-0.0093}$	$^{+0.0125}_{-0.0095}$	$^{+10.6}_{-8.1}$
(2) Dijets at low Q^2	H1	0.1155	0.0018	$^{+0.0124}_{-0.0093}$	$^{+0.0125}_{-0.0095}$	$^{+10.8}_{-8.2}$
(3) Trijets at low Q^2	H1	0.1170	0.0017	$^{+0.0091}_{-0.0073}$	$^{+0.0093}_{-0.0075}$	$^{+7.9}_{-6.4}$
(4) Combined low Q^2	H1	0.1160	0.0014	$^{+0.0094}_{-0.0079}$	$^{+0.0095}_{-0.0080}$	$^{+8.2}_{-6.9}$
(5) Trijet/dijet at low Q^2	H1	0.1215	0.0032	$^{+0.0067}_{-0.0059}$	$^{+0.0074}_{-0.0067}$	$^{+6.1}_{-5.5}$
(6) Inc. jets at medium Q^2	H1	0.1195	0.0010	$^{+0.0052}_{-0.0040}$	$^{+0.0053}_{-0.0041}$	$^{+4.4}_{-3.4}$
(7) Dijets at medium Q^2	H1	0.1155	0.0009	$^{+0.0045}_{-0.0035}$	$^{+0.0046}_{-0.0036}$	$^{+4.0}_{-3.1}$
(8) Trijets at medium Q^2	H1	0.1172	0.0013	$^{+0.0053}_{-0.0032}$	$^{+0.0055}_{-0.0035}$	$^{+4.7}_{-3.0}$
(9) Combined medium Q^2	H1	0.1168	0.0007	$^{+0.0049}_{-0.0034}$	$^{+0.0049}_{-0.0035}$	$^{+4.2}_{-3.0}$
(10) Inc. jets at high Q^2 (anti-k_T)	ZEUS	0.1188	$^{+0.0036}_{-0.0035}$	$^{+0.0022}_{-0.0022}$	$^{+0.0042}_{-0.0041}$	$^{+3.5}_{-3.5}$
(11) Inc. jets at high Q^2 (SIScone)	ZEUS	0.1186	$^{+0.0036}_{-0.0035}$	$^{+0.0025}_{-0.0025}$	$^{+0.0044}_{-0.0043}$	$^{+3.7}_{-3.6}$
(12) Inc. jets at high Q^2 (k_T; HERA I)	ZEUS	0.1207	$^{+0.0038}_{-0.0036}$	$^{+0.0022}_{-0.0023}$	$^{+0.0044}_{-0.0043}$	$^{+3.6}_{-3.6}$
(13) Inc. jets at high Q^2 (k_T; HERA II)	ZEUS	0.1208	$^{+0.0037}_{-0.0032}$	$^{+0.0022}_{-0.0022}$	$^{+0.0043}_{-0.0039}$	$^{+3.6}_{-3.2}$
(14) Inc. jets in γp (anti-k_T)	ZEUS	0.1200	$^{+0.0024}_{-0.0023}$	$^{+0.0043}_{-0.0032}$	$^{+0.0049}_{-0.0039}$	$^{+4.1}_{-3.3}$
(15) Inc. jets in γp (SIScone)	ZEUS	0.1199	$^{+0.0022}_{-0.0022}$	$^{+0.0047}_{-0.0042}$	$^{+0.0052}_{-0.0047}$	$^{+4.3}_{-3.9}$
(16) Inc. jets in γp (k_T)	ZEUS	0.1208	$^{+0.0024}_{-0.0023}$	$^{+0.0044}_{-0.0033}$	$^{+0.0050}_{-0.0040}$	$^{+4.1}_{-3.3}$
(17) Jet shape	ZEUS	0.1176	$^{+0.0013}_{-0.0028}$	$^{+0.0091}_{-0.0072}$	$^{+0.0092}_{-0.0077}$	$^{+7.8}_{-6.5}$
(18) Subjet multiplicity	ZEUS	0.1187	$^{+0.0029}_{-0.0019}$	$^{+0.0093}_{-0.0076}$	$^{+0.0097}_{-0.0078}$	$^{+8.2}_{-6.6}$
HERA average 2004		0.1186	±0.0011	±0.0050	±0.0051	±4.3
HERA average 2007		0.1198	±0.0019	±0.0026	±0.0032	±2.7

Table 1: Values of $\alpha_s(M_Z)$ extracted from jet observables at HERA together with their uncertainties (rows 1 to 18). The 2004 [10] and 2007 [11] HERA averages are shown in the last two rows.

Extractions from (exclusive) jet cross sections:
uncertainty dominated by theory

Improve to level of e^+e^-?

DIS Kinematics



$s = (k + P)^2$ squared center-of-mass energy

$Q^2 = -q^2$ momentum transfer

$x = \frac{Q^2}{2P \cdot q}$ Björken scaling variable

$y = \frac{P \cdot q}{P \cdot k}$ lepton energy loss in proton rest frame

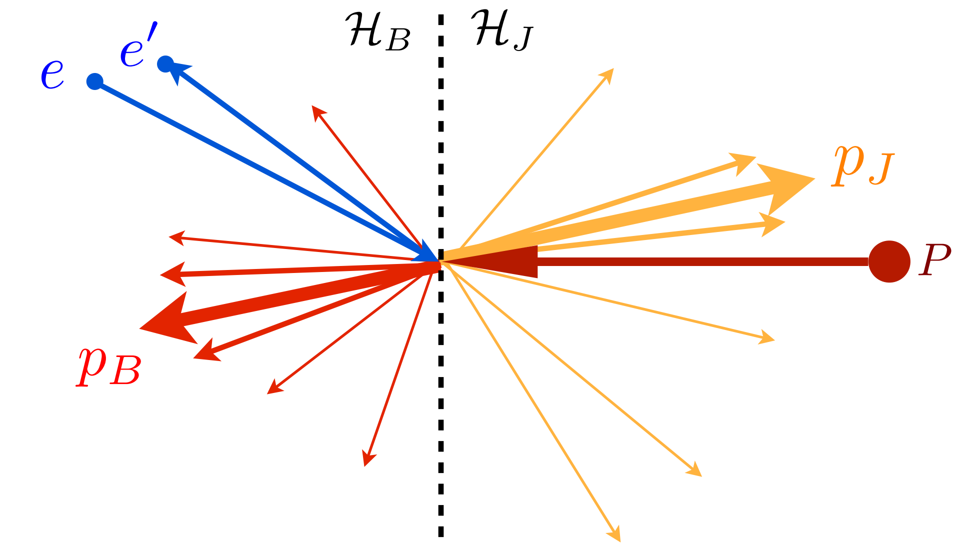
$Q^2 = xys$

DIS event shapes

Breit frame: $q^\mu = (0,0,0,Q)$

DIS thrust (review by Dasgupta & Salam '03)

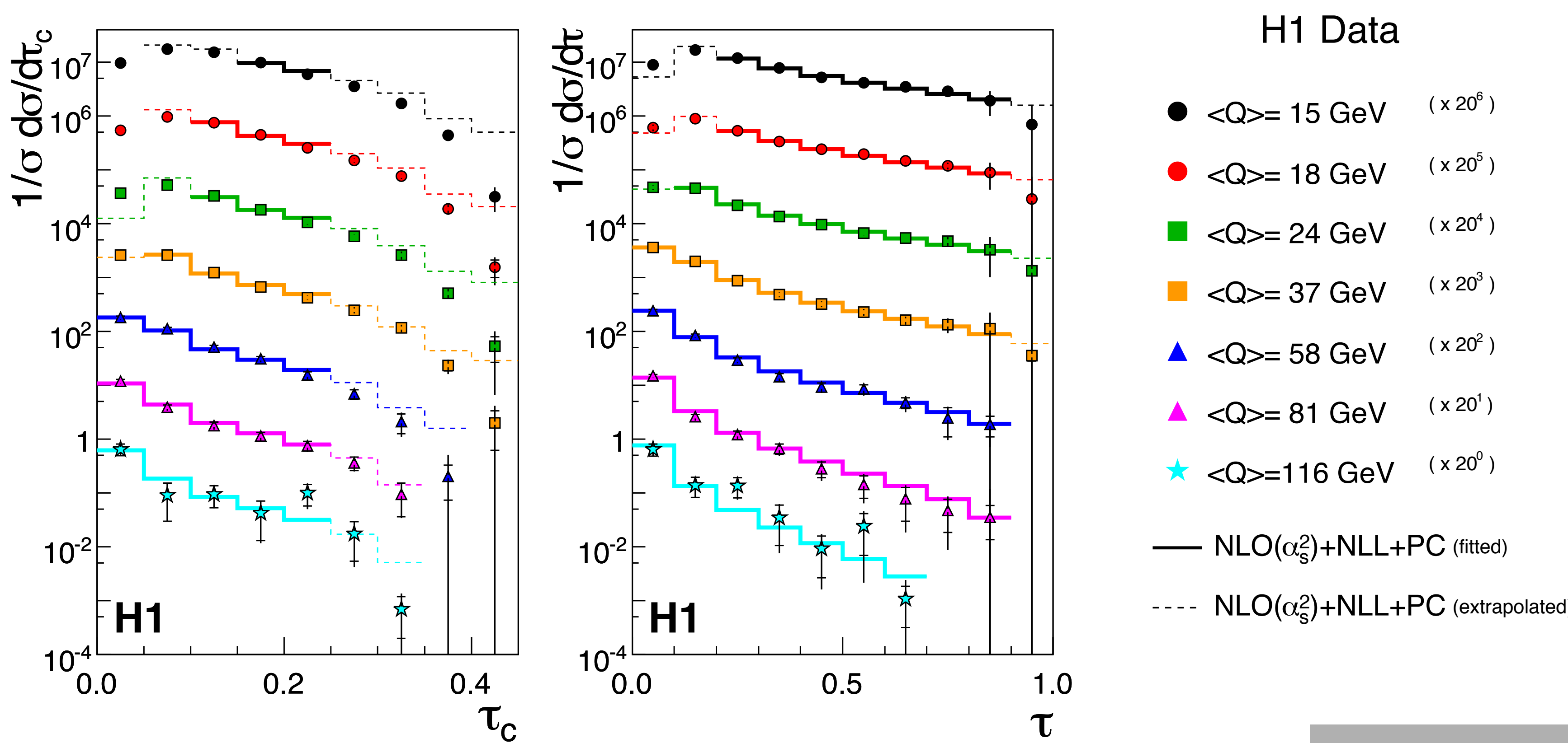
$$\tau_{nQ} = 1 - \frac{2}{Q} \sum_{i\in\mathcal{H}_J} |\vec{p}_i \cdot \vec{n}|$$

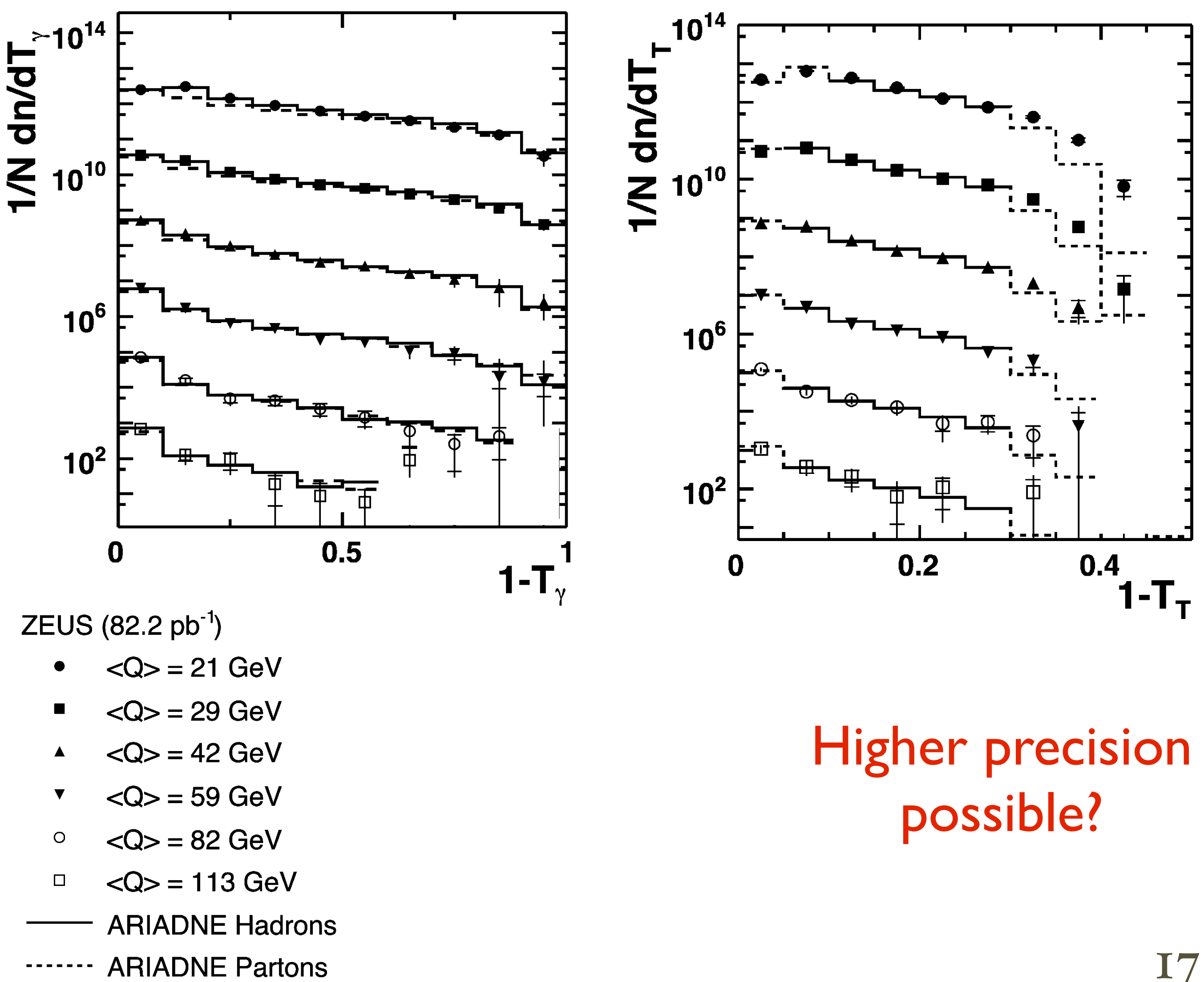


different versions:

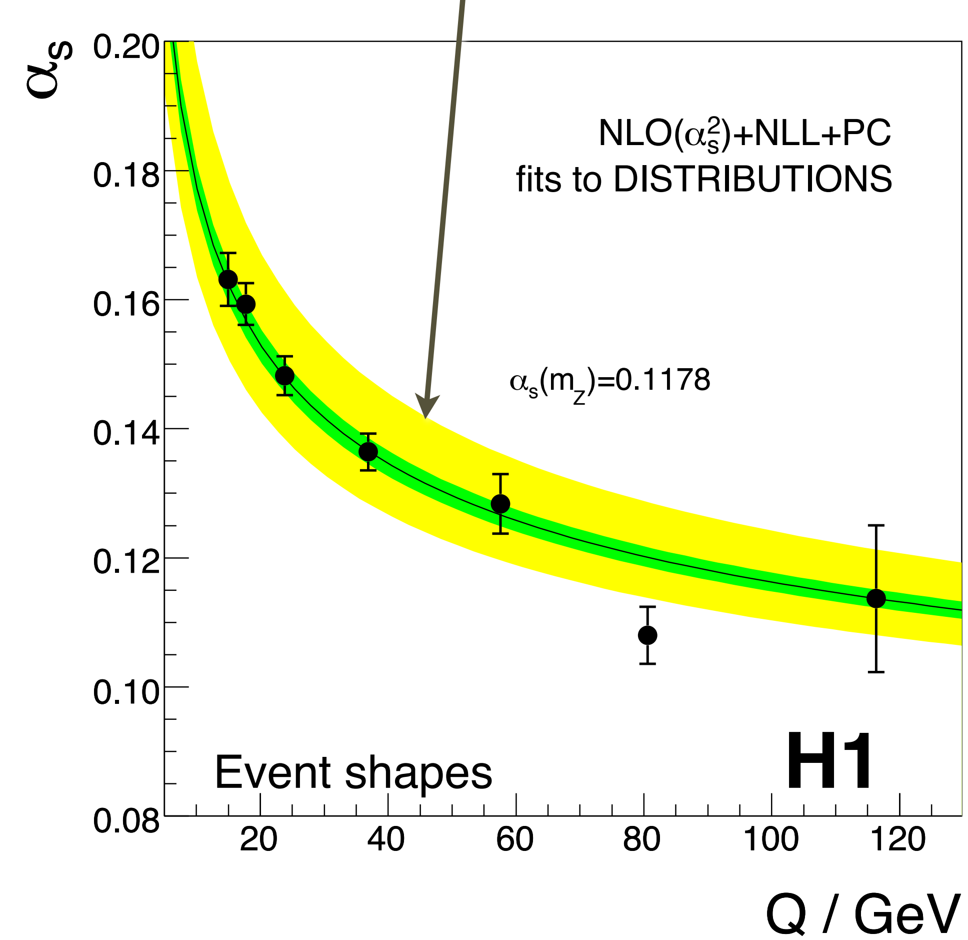
- $\frac{Q}{2} \to \sum_{i\in\mathcal{H}_J} E_i$
- $\vec{n} = \hat{z}$ fixed to photon/weak boson's axis τ
- vary $\vec{n}$ to minimize τ_{nQ} τ_C

calculations to NLO & NLL Dasgupta, Salam, ...





perturbative uncertainty



Higher precision possible?

Jet Bins for pp

$pp \longrightarrow H + N\text{-jets}$

Jet Bin Motivations

- Enhance new physics signals that like to produce jets

- $W + 0, 1, 2, 3, \ldots \text{jets}$ Background for new physics searches

  $Z + 0, 1, 2, 3, \ldots \text{jets}$ Test QCD calculations

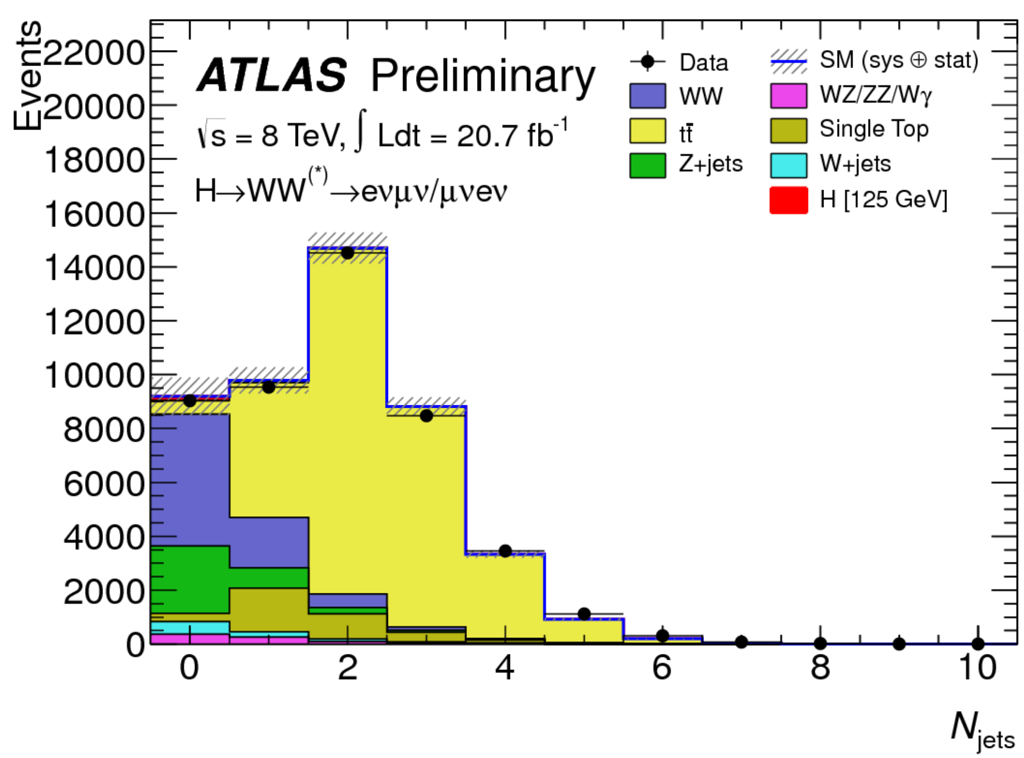
- Analyses where backgrounds vary with the number of jets

  Use jet bins to maximize sensitivity

  $H + 0, 1, 2, \ldots \text{jets}$

  $W/Z + \gamma + 0\text{jets}$

eg. large top background in $H \to WW$



Jet Bins are important for coupling analyses

$H \to WW \to \ell\ell\nu\nu$

$H \to WW \to \ell\nu q'\bar{q}$

- 0–jets
- 1–jet
- 2–jets (VBF)

$H \to \tau\tau$

- 0–jets
- 1–jet
- 2–jets (VBF)

$H \to \gamma\gamma$

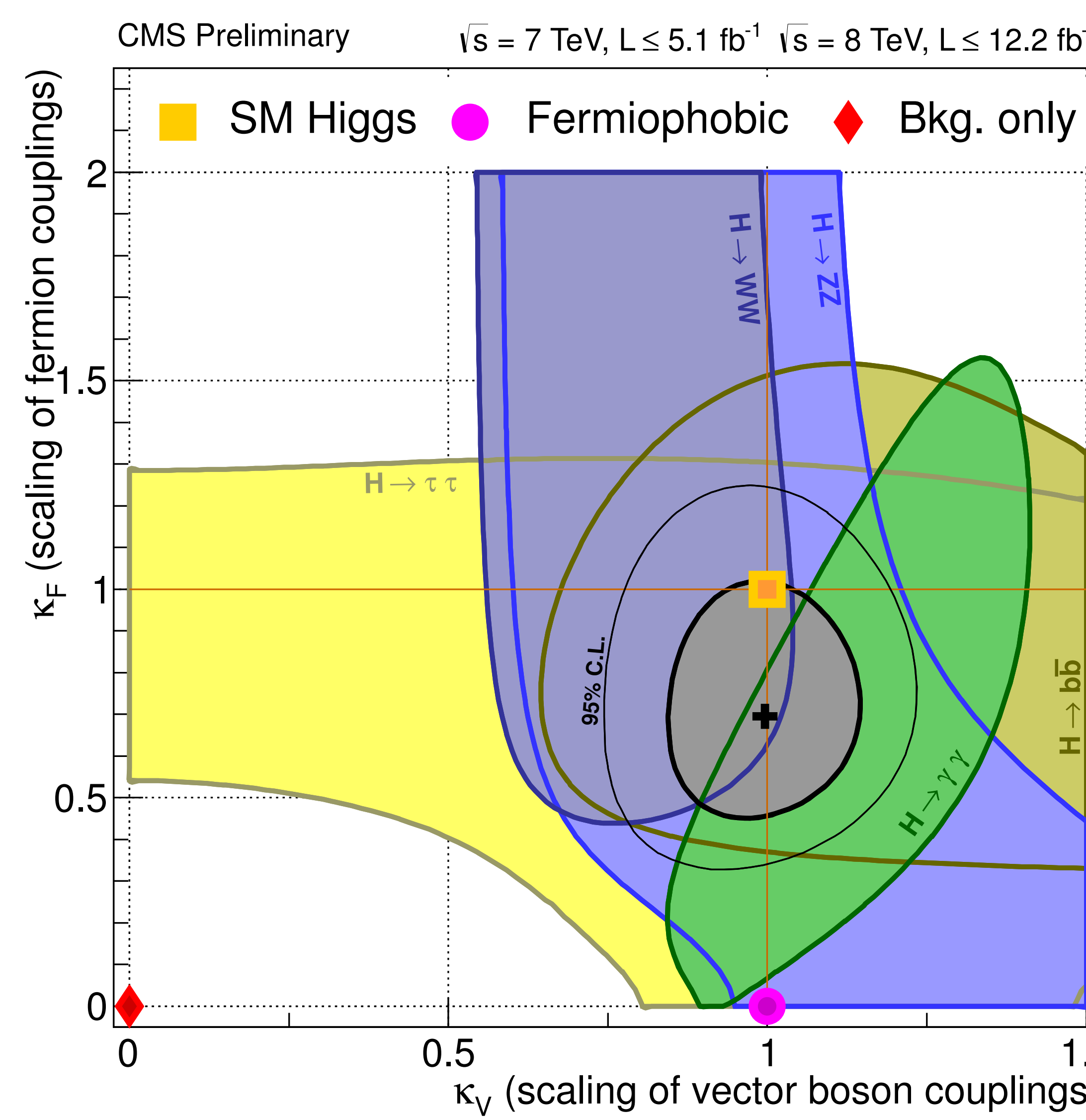
$H \to ZZ$

- inclusive
- 2–jets (VBF)

First step: fit for common scaling factor for vector and fermionic Higgs couplings

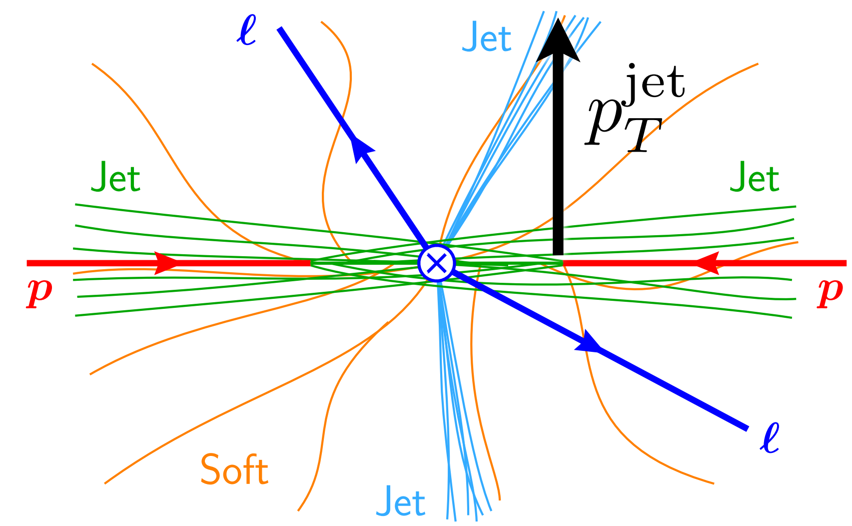
$$H \to \tau\tau, b\bar{b} \qquad H \to WW$$

involve exclusive jet bins



Jet veto gives double logs

veto >N jets $\quad p_T^{\text{jet}} \le p_T^{\text{cut}}$



$$L = \ln \frac{p_T^{\text{cut}}}{m_H}$$

	LO	NLO	NNLO		
$\sigma_{\text{0-jet}} =$	1	$+\ \alpha_s L^2$	$+\ \alpha_s^2 L^4$	$+\ \alpha_s^3 L^6$	$+ \ldots$ LL
		$+\ \alpha_s L$	$+\ \alpha_s^2 L^3$	$+\ \alpha_s^3 L^5$	$+ \ldots$ NLL
		$+\ \alpha_s n_1(p_T^{\text{cut}})$	$+\ \alpha_s^2 L^2$	$+\ \alpha_s^3 L^4$	$+ \ldots$
			$+\ \alpha_s^2 L$	$+\ \alpha_s^3 L^3$	$+ \ldots$ NNLL
			$+\ \alpha_s^2 n_2(p_T^{\text{cut}})$	$+\ \alpha_s^3 L^2$	$+ \ldots$
				$+\ \alpha_s^3 L$	$+ \ldots$
				$+\ \alpha_s^3$	$+ \ldots$

$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$$
$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

NNLO Fixed Order:

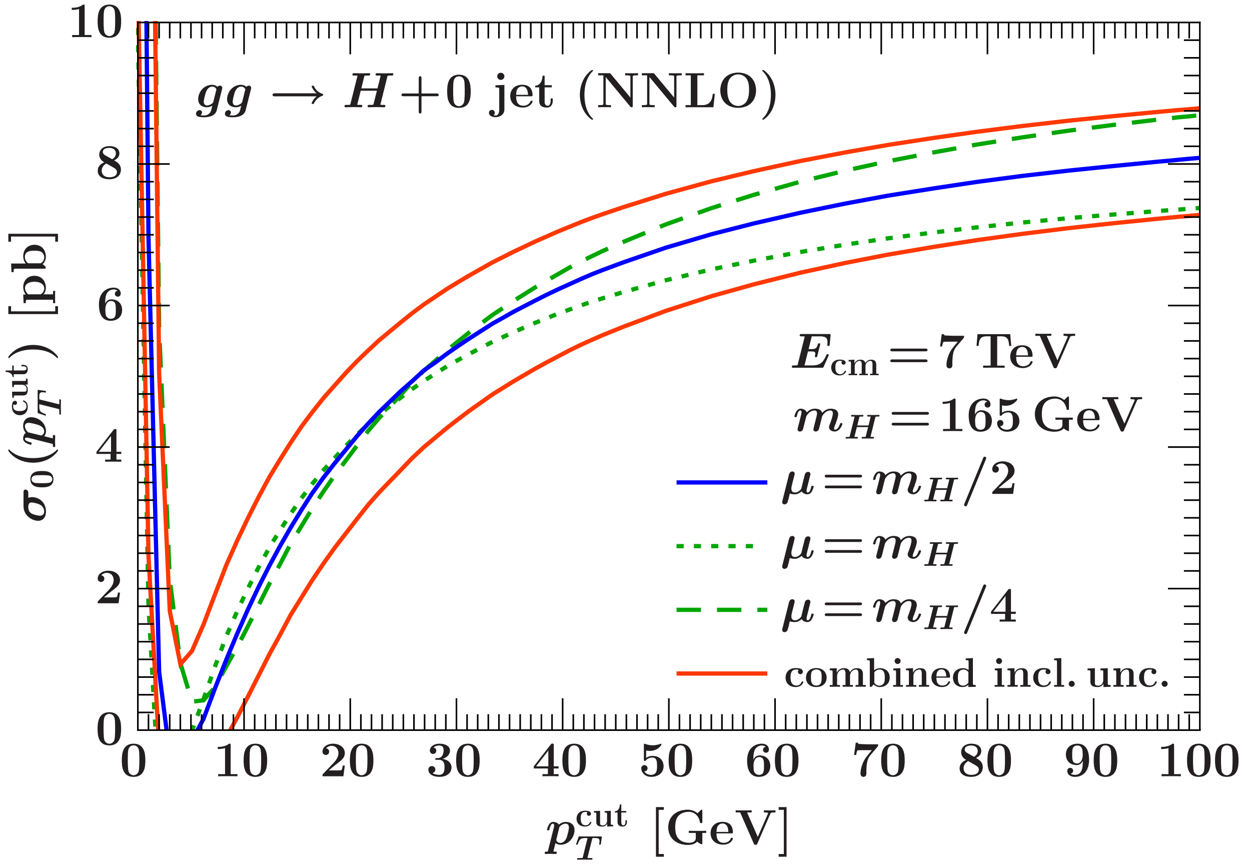
FEHiP, HNNLO, MCFM

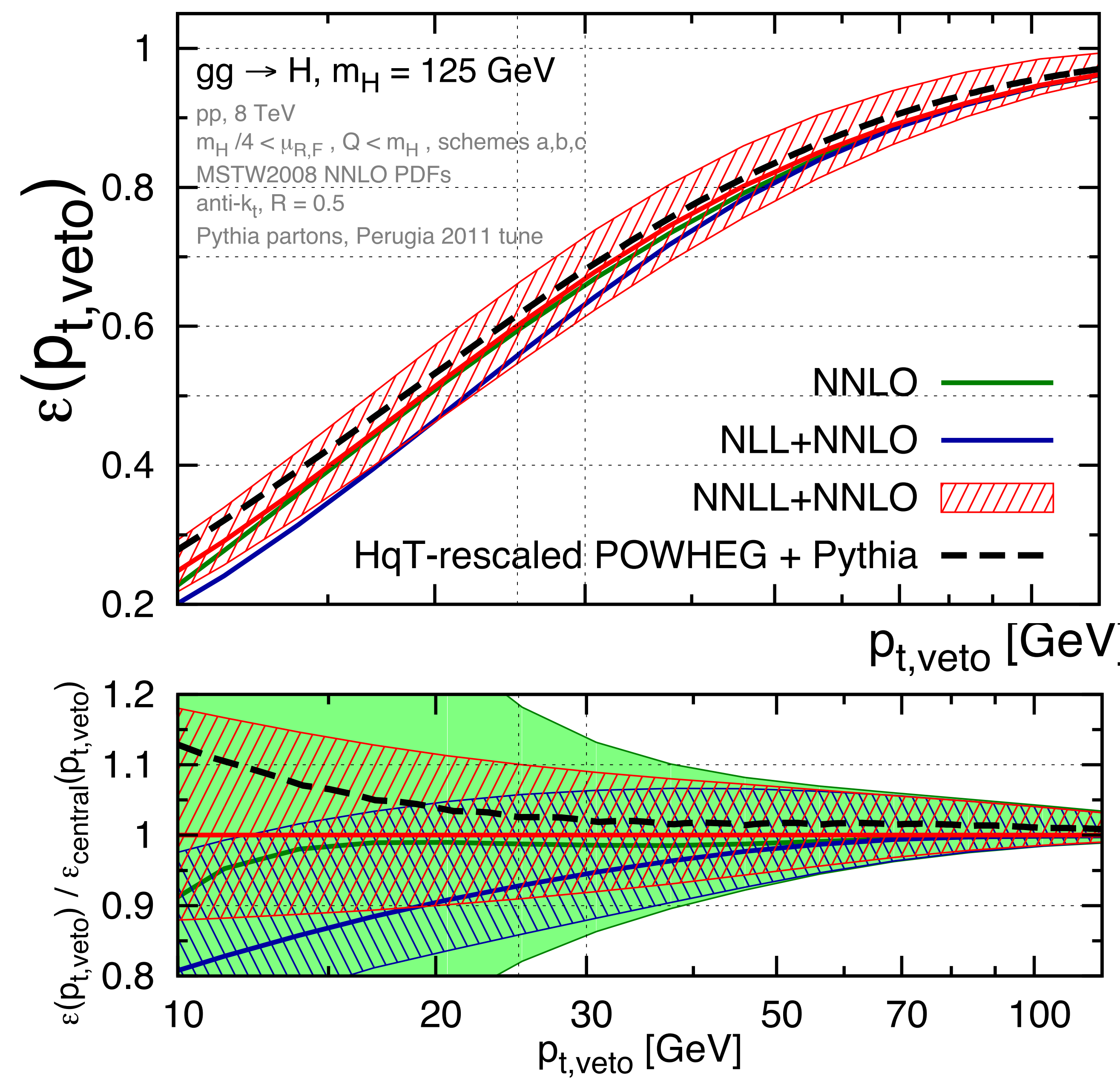
Uncertainty procedure: IS, Tackmann

Resummation of Veto Logs

Banfi, Monni, Salam, Zanderighi

Becher, Neubert; Tackmann, Walsh, Zuberi



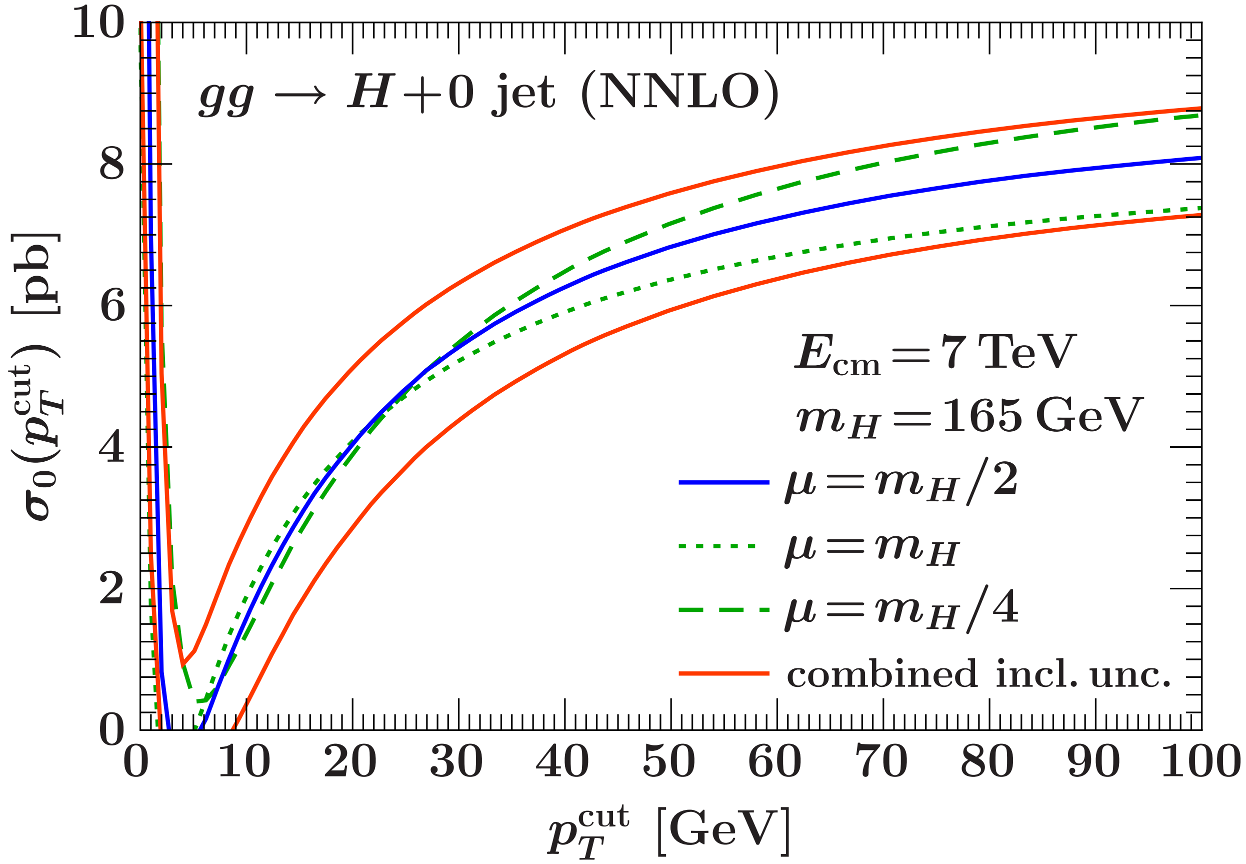


$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$$
$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

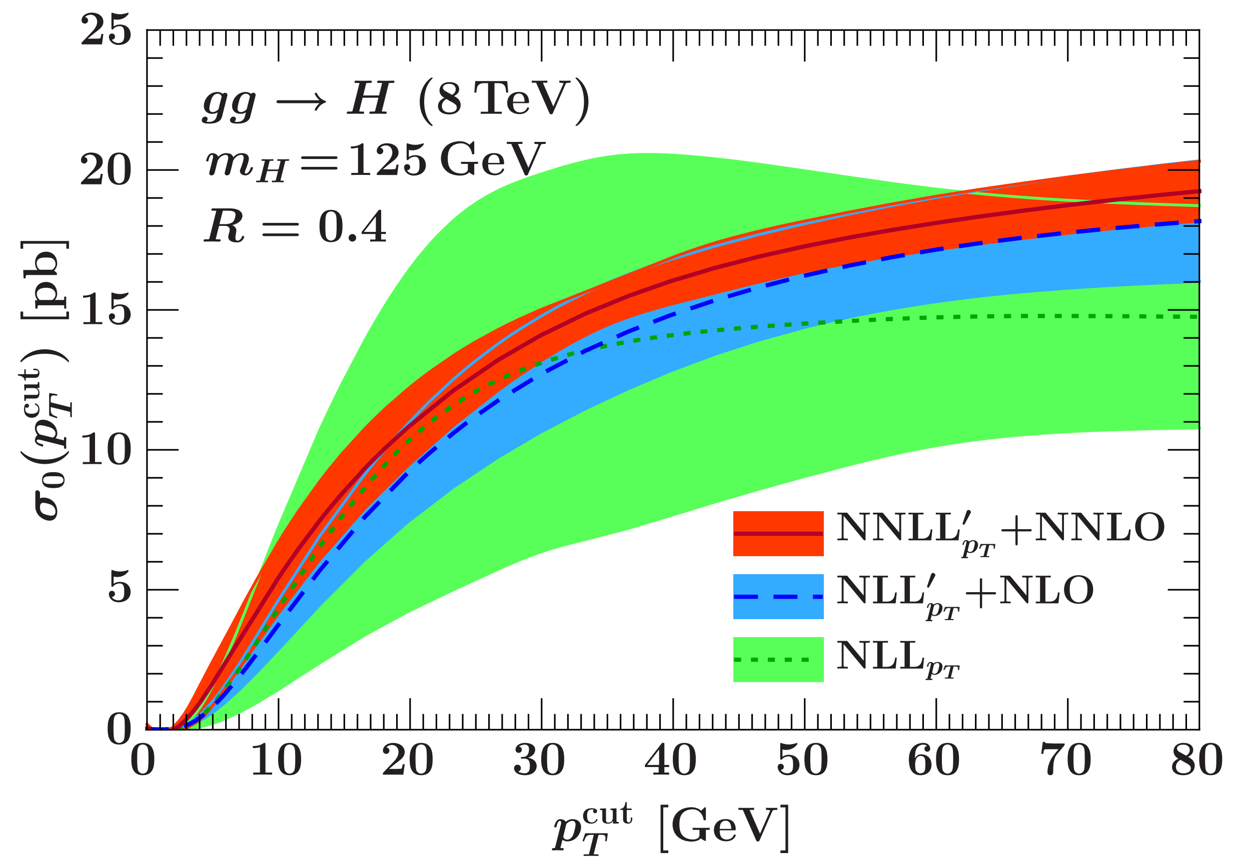
Resummation of Veto Logs

NNLO Fixed Order: FeHIP, HNNLO

Uncertainty procedure: IS, Tackmann



IS, Tackmann, Walsh, Zuberi (in prep)

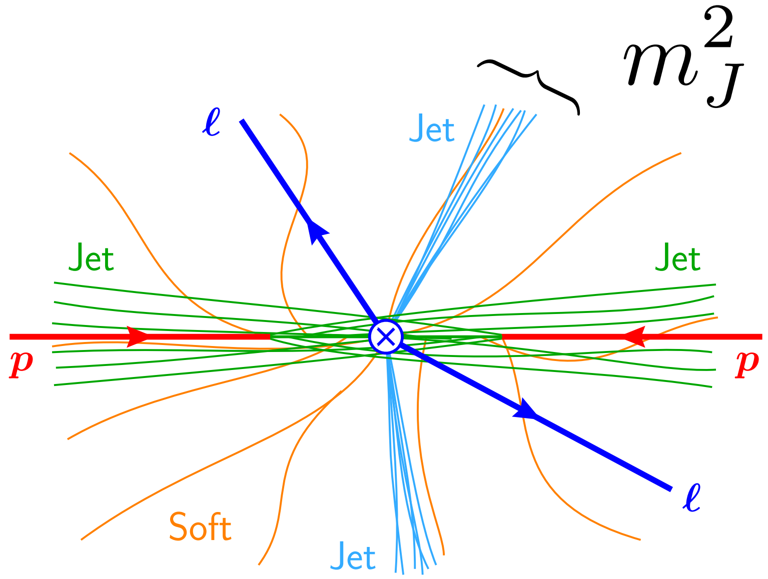


Resummation of Veto Logs

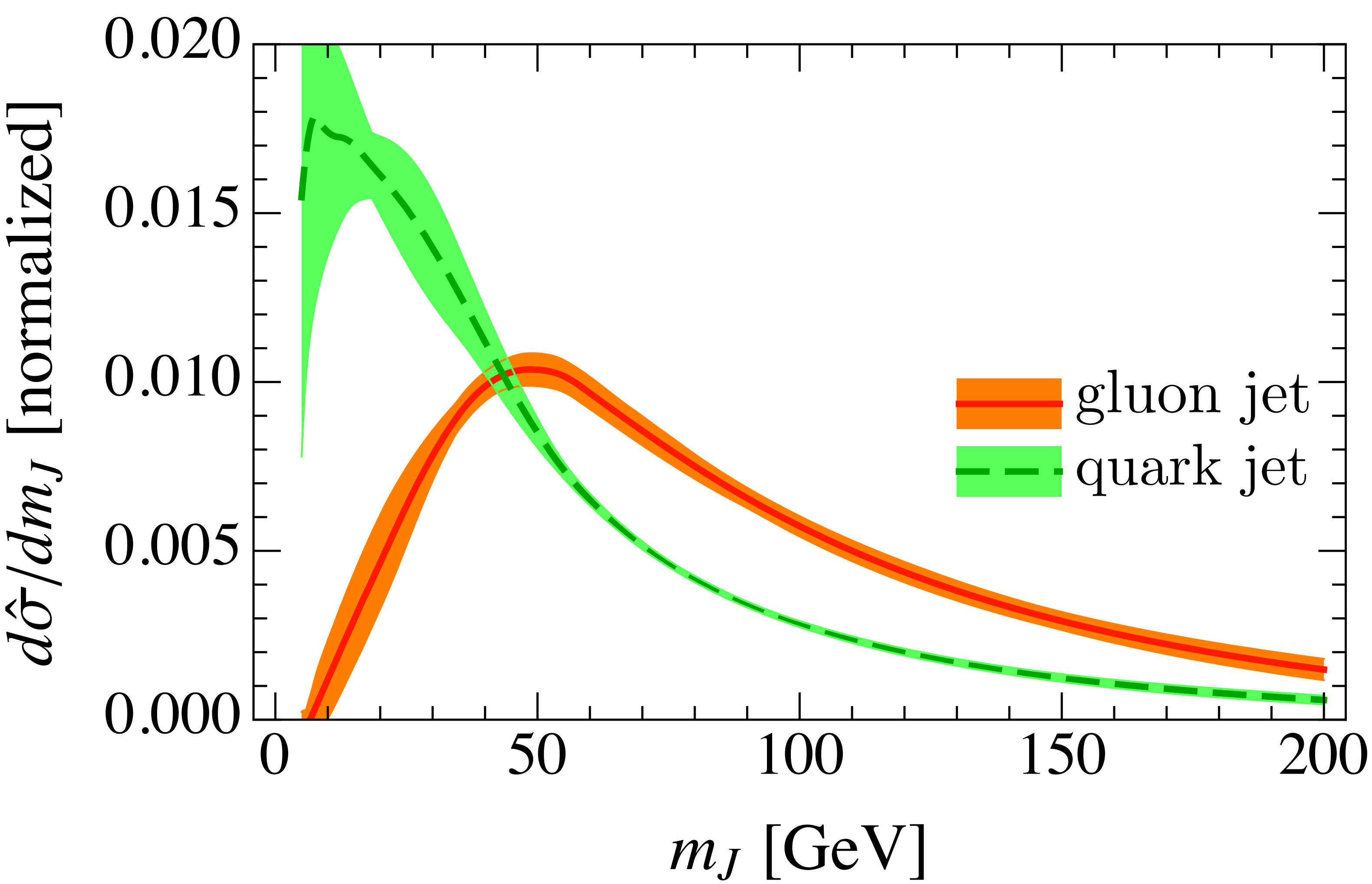
Jet Substructure

Jet Substructure

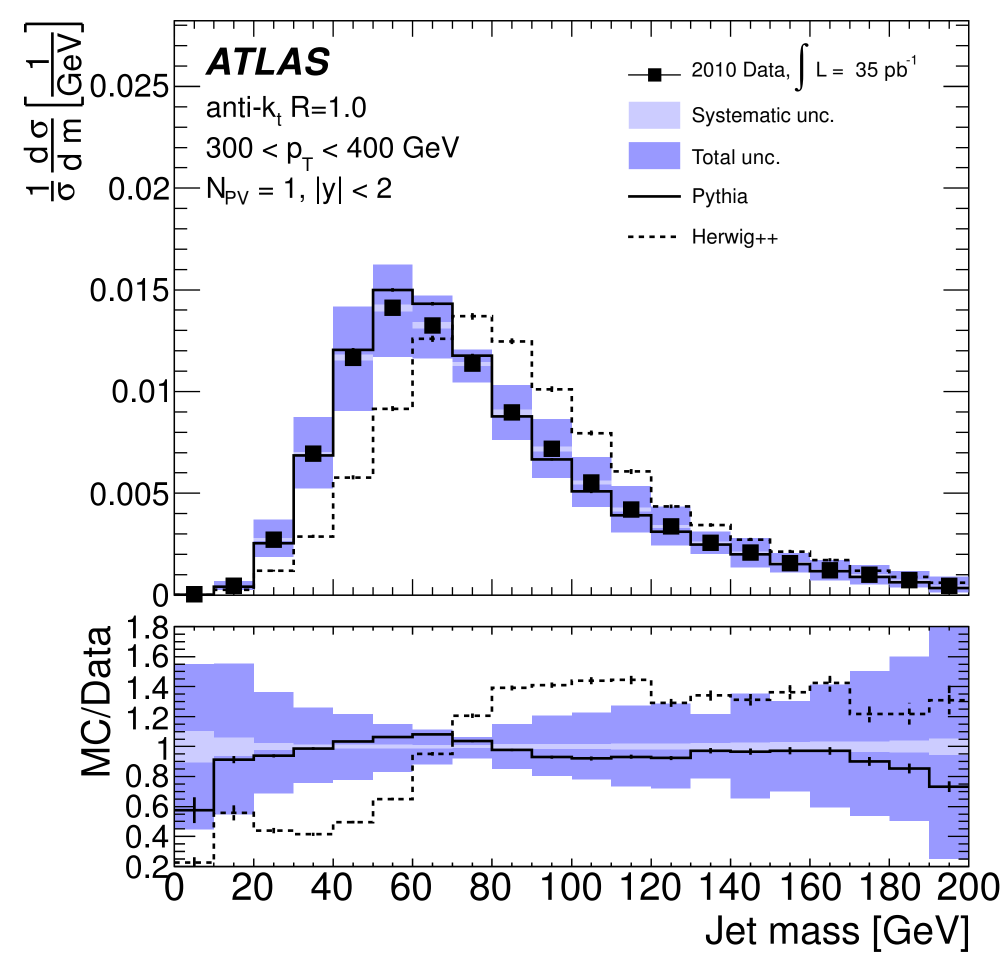
- Distinguish quark jets from gluon jets by radiation pattern



Jet Mass: $$m_J^2 = \Big(\sum_{i \in J} p_i^\mu\Big)^2$$



inclusive jet sample

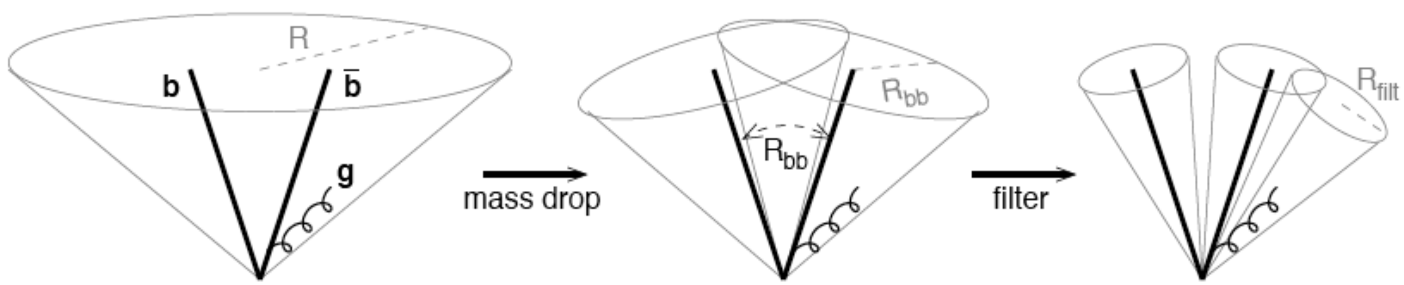


Jet Substructure

- Distinguish quark jets from gluon jets by radiation pattern
- Distinguish heavy boosted objects from QCD

boosted

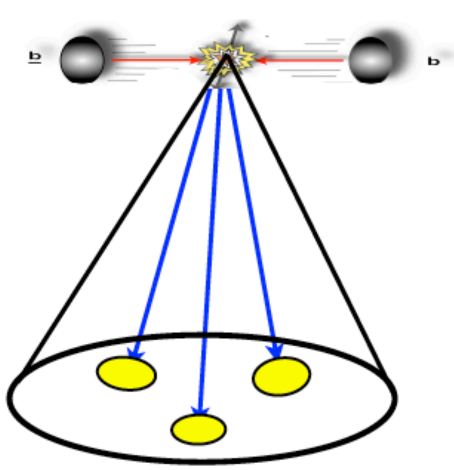
$H \to b\bar{b}$



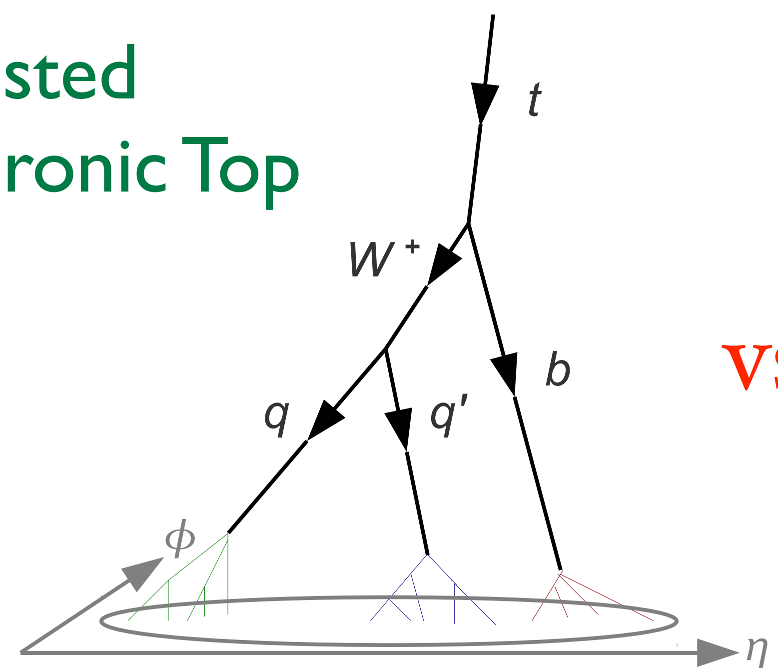
BDRS Method

[Butterworth, Davison, Rubin, Salam]

top tagging

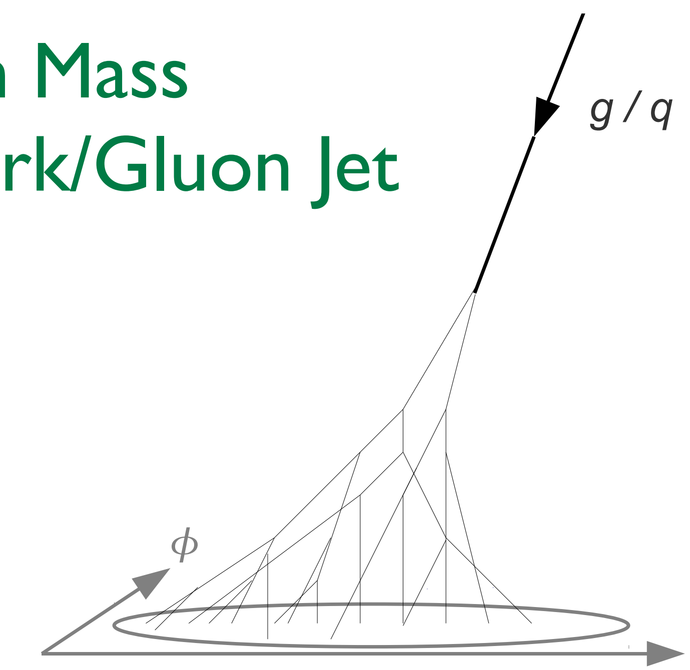


Boosted Hadronic Top



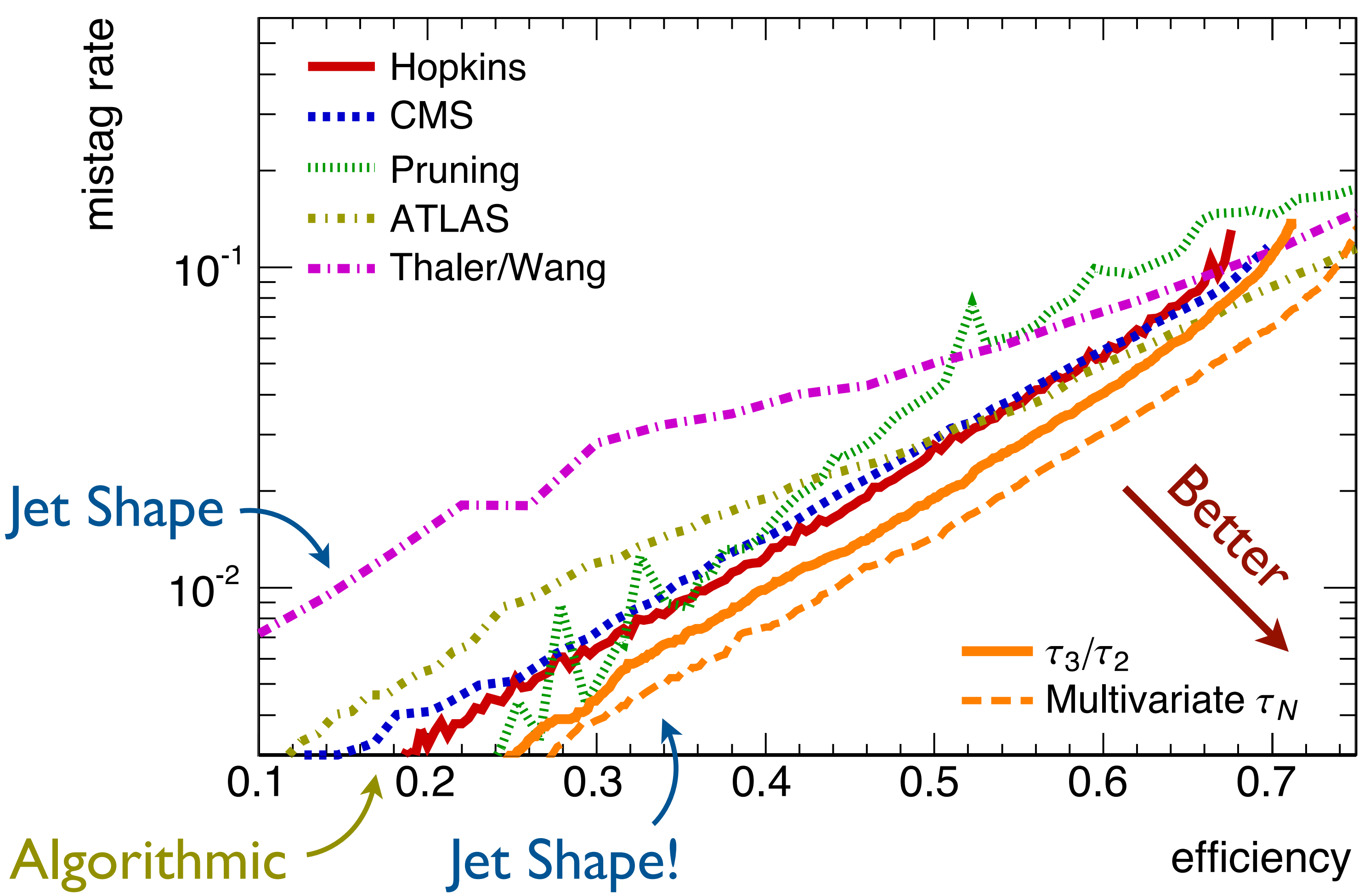
vs.

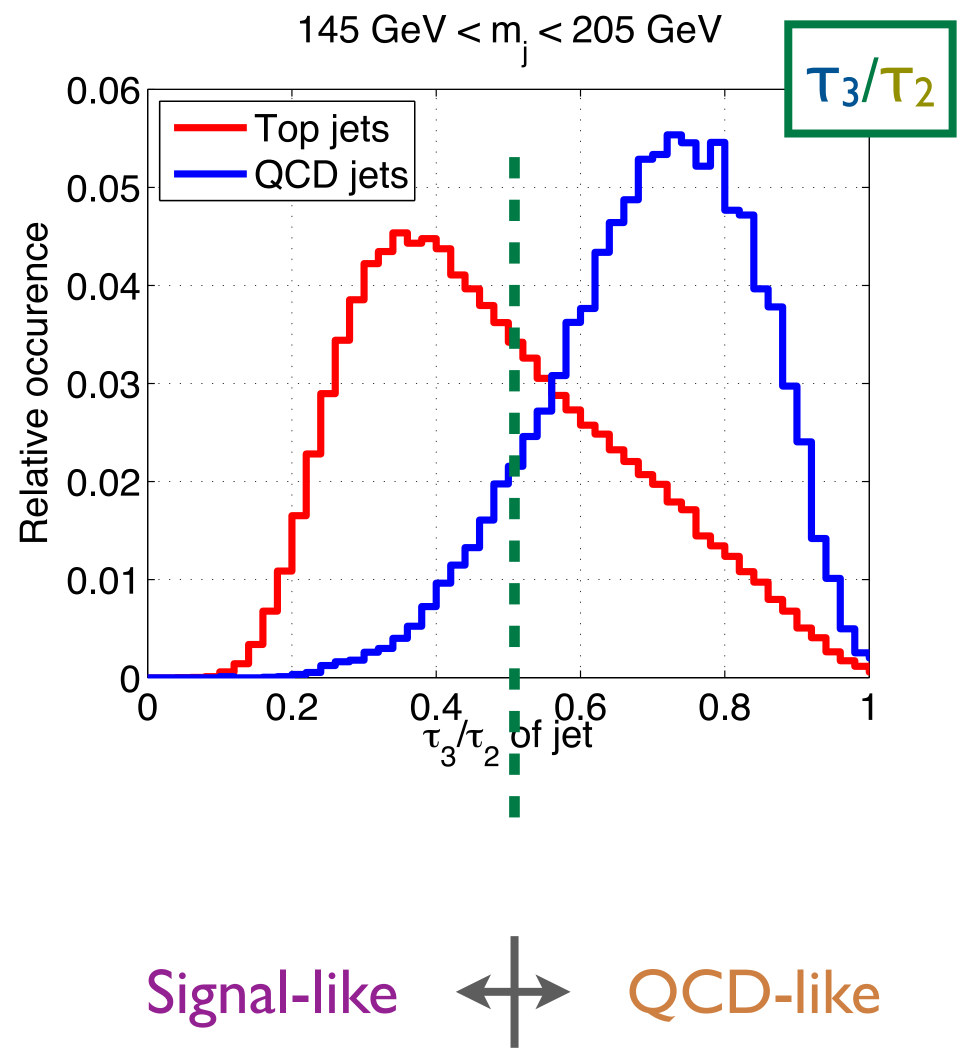
High Mass Quark/Gluon Jet



Top Tagging

one-dimensional cut using jet shapes: τ_3/τ_2 Thaler, Van Tilburg





500 GeV < p_T < 600 GeV

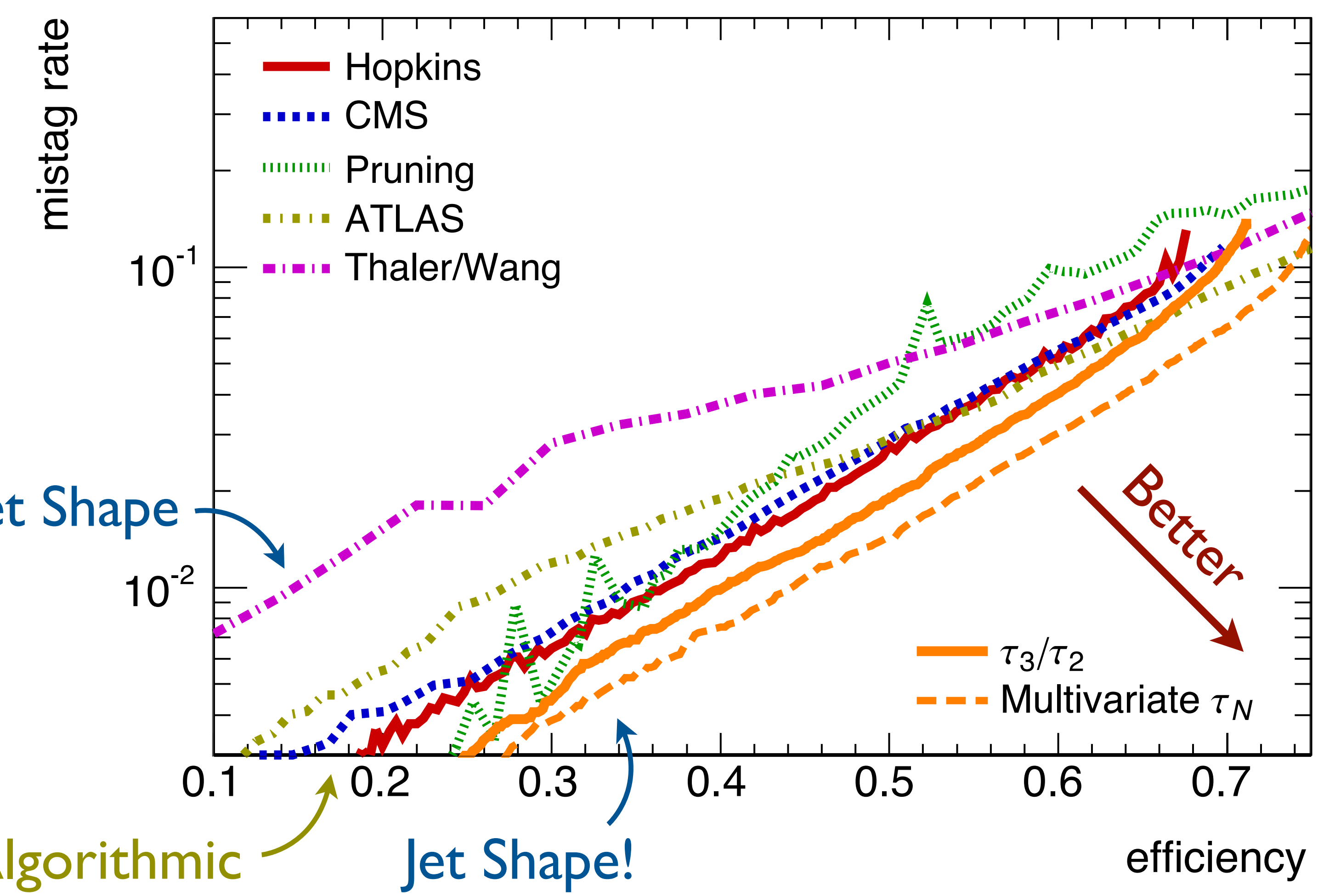
fixed 160 GeV < m_{jet} < 240 GeV cut

dashed = Fisher Discriminant

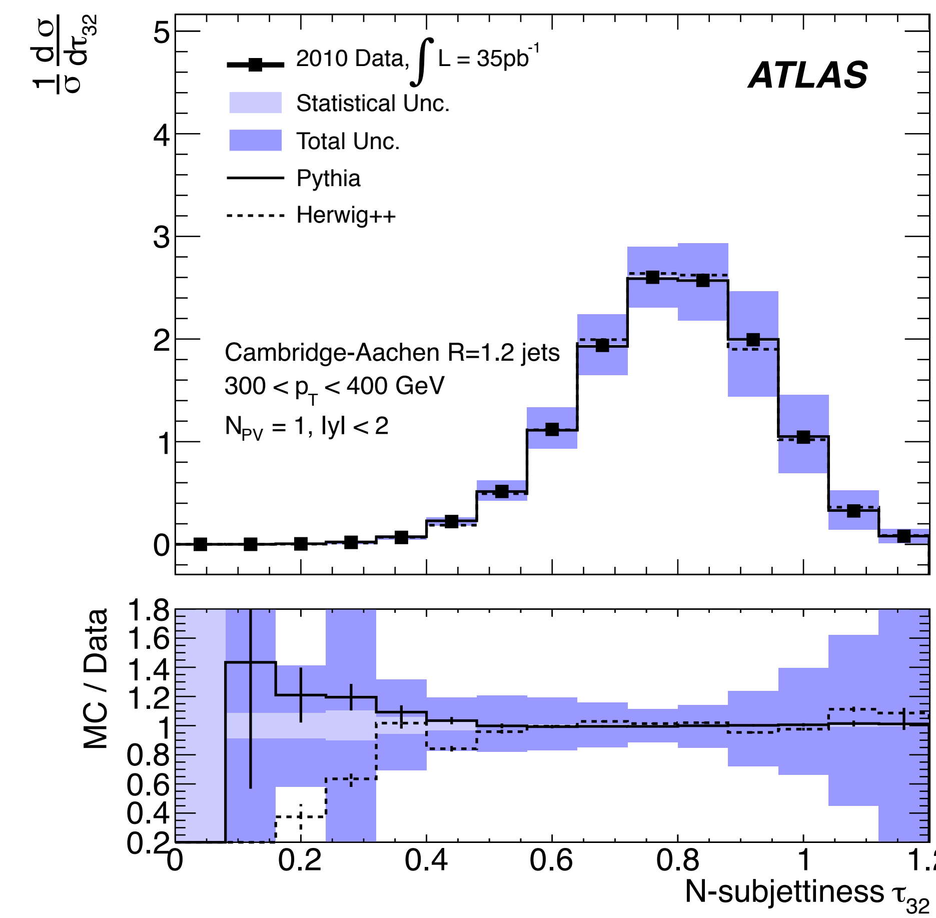
Flexible cut to adjust signal acceptance vs. background rejection

Top Tagging

one-dimensional cut using jet shapes: τ_3/τ_2 Thaler, Van Tilburg



background measurement



Signal-like ↔ QCD-like

500 GeV < p_T < 600 GeV

fixed 160 GeV < m_{jet} < 240 GeV cut

dashed = Fisher Discriminant

N-Jettiness Event Shape $\mathcal{T}_N$

IS, Tackmann, Waalewijn

# of jets: $\leq$ N $\qquad$ $>$ N

$\mathcal{T}_N$: 0 $\qquad$ 1

N-Subjettiness Event Shape τ_N

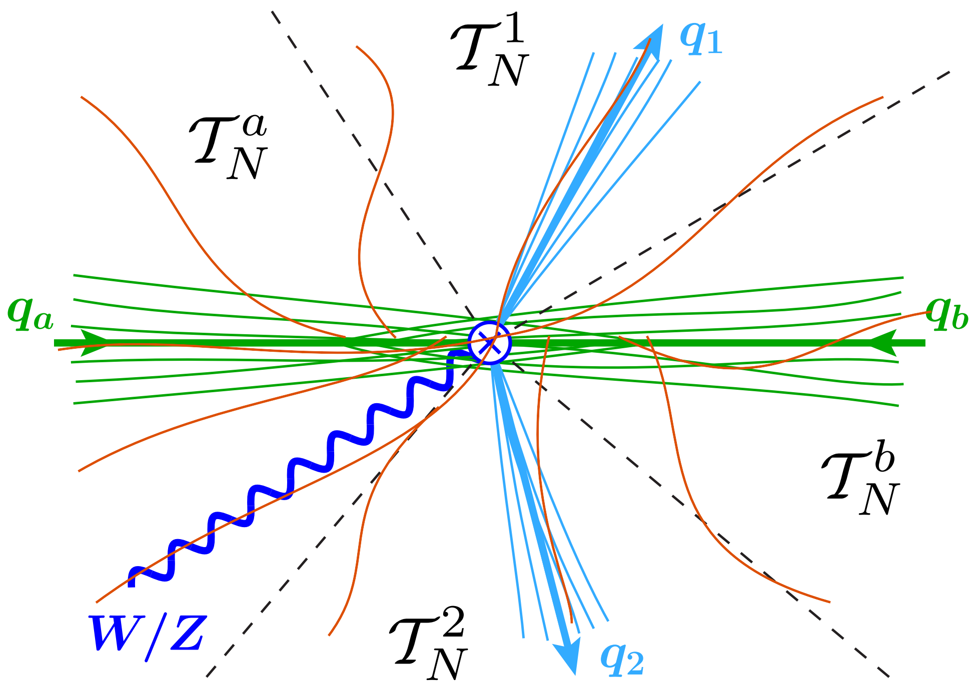
Thaler, Van Tilburg

# of subjets: $\leq$ N $\qquad$ $>$ N

τ_N : 0 $\qquad$ 1

N-Jettiness

$$\mathcal{T}_N = \sum_k \min\left\{\frac{2q_a\cdot p_k}{Q_a}, \frac{2q_b\cdot p_k}{Q_b}, \frac{2q_1\cdot p_k}{Q_1}, \ldots, \frac{2q_N\cdot p_k}{Q_N}\right\}$$



align q_i^μs with jets

use anti-kT axis from inclusive N-jet sample

or

find axis by minimizing $\mathcal{T}_N$

$$q_i^\mu = E_i(1, \hat{n}_i)$$

$$q_a^\mu = \frac{1}{2} x_a\, E_{\rm cm}(1, \hat{z})\,,$$

- Compares distance of particle k to beams and jets
- Q_j determine the jet measure
- particles assigned to jet and beam regions

$$\mathcal{T}_N = \mathcal{T}_N^a + \mathcal{T}_N^b + \mathcal{T}_N^1 + \cdots + \mathcal{T}_N^N$$

- Applies to $pp \to \text{jets},\ pp \to H + \text{jets},\ \ldots$
- Related to Jet Masses: $m_J^2 = Q_i \mathcal{T}_N^i$

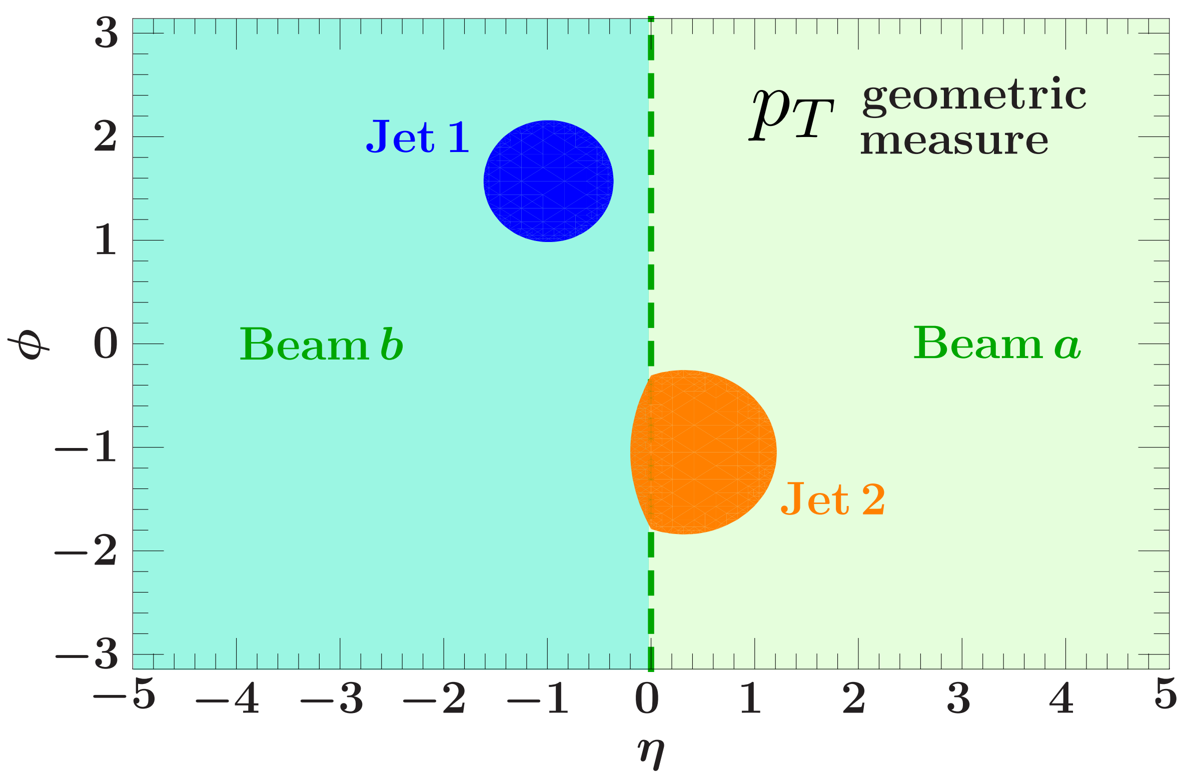
- Factorization Friendly

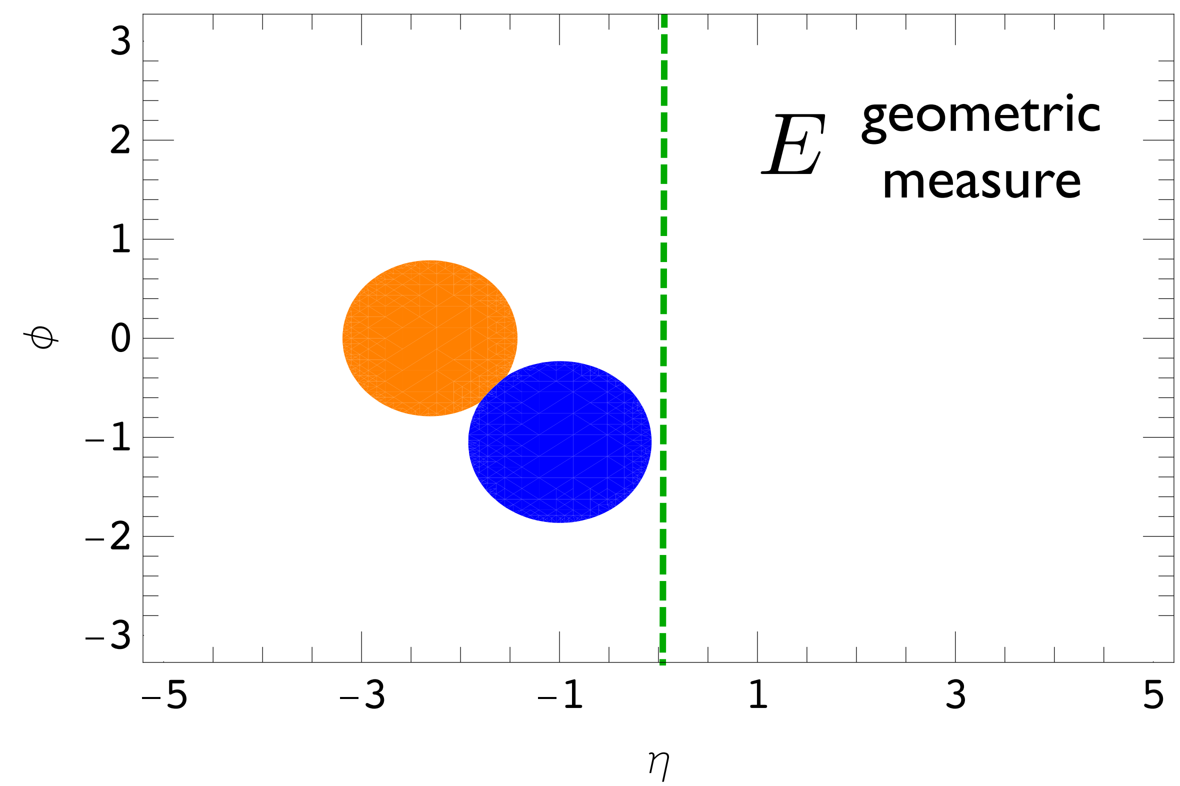
$$\frac{d\sigma}{d\mathcal{T}_N^a \cdots d\mathcal{T}_N^N}$$

Various Jet definitions:

division into jet and beam regions fully specified by kinematics

$$\mathcal{T}_N = \sum_k \min\left\{ \frac{2q_a \cdot p_k}{Q_a}, \frac{2q_b \cdot p_k}{Q_b}, \frac{2q_1 \cdot p_k}{Q_1}, \ldots, \frac{2q_N \cdot p_k}{Q_N} \right\}$$





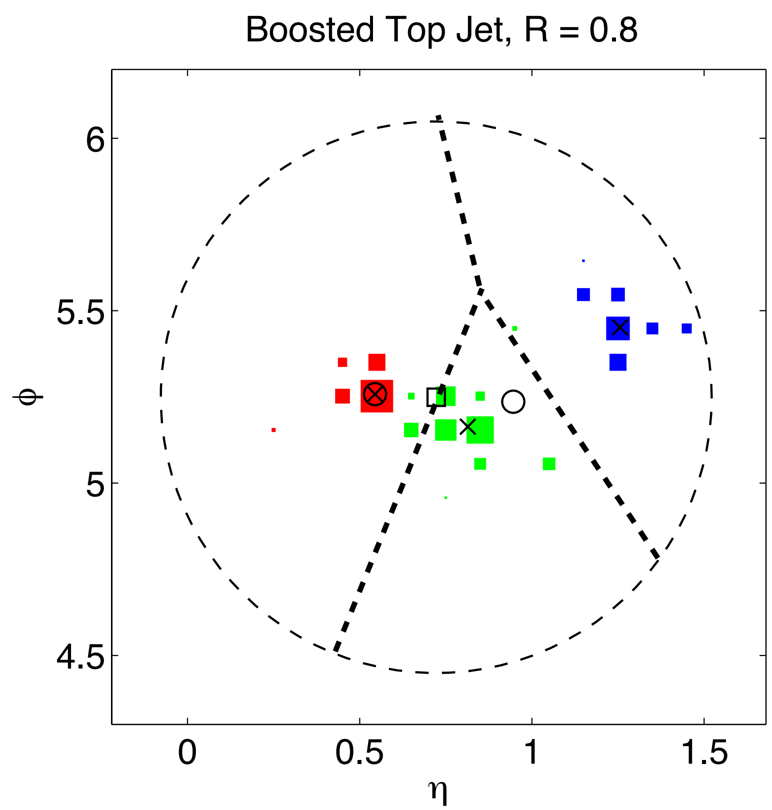
$$Q_a = x_a E_{\rm cm}$$
$$Q_b = x_b E_{\rm cm}$$
$$Q_i = |\vec{p}_T^{\,\text{jet } i}|$$

$$Q_a = x_a E_{\rm cm}$$
$$Q_b = x_b E_{\rm cm}$$
$$Q_i = E_{\rm jet}^i$$

circular jets (default)

N-Subjettiness

$$\tau_N = \frac{1}{d_0} \sum_{k \in \text{jet}} p_{T,k} \min\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}$$

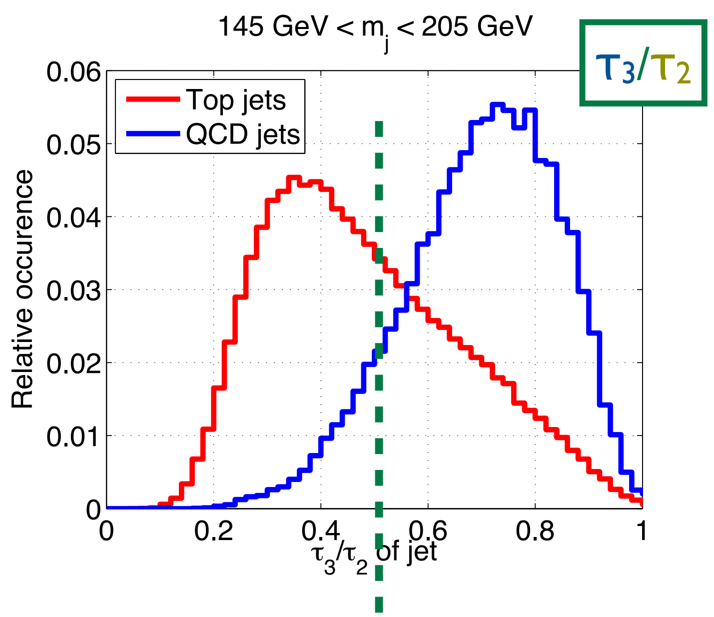


τ_3/τ_2: Boosted Tops

Ratio is quasi-boost invariant

available as fastjet plugin

Fast implementation by generalized k-means clustering



Jet Mass in pp collisions

. Jouttenus, IS, F. Tackmann, W. Waalewijn arXiv:1302.0846

Why Compute the Jet Mass Spectrum? $d\sigma/dm_J$

- Benchmark for our ability to compute jet-substructure at LHC
- Test MC

Address Dependence on:

- Kinematics: $p_T^{\rm jet}\,,\ \ \eta^{\rm jet},\ldots$
- Hard process: $pp\to 2\ {\rm jets}\,,\ pp\to H+{\rm jet}\,,\ pp\to Z+{\rm jet}\,,\ pp\to\gamma+{\rm jet}$

  - ISR - gluon vs. quark jets - color flow - incl. vs excl. jets

- Jet algorithm/grouping - anti-kT, CA, kT, N-jettiness jets, ...
- Jet size: R
- Order of the calculation: $\rm NNLL/NLL/LL$ (theory uncertainty)
- Non-global logs
- Underlying event
- pileup
- Hadronization
- trimming/filtering/pruning

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✓ • Order of the calculation: $\mathrm{NNLL/NLL/LL}$ (theory uncertainty)

✓ • Non-global logs • Underlying event • pileup

✓ • Hadronization • trimming/filtering/pruning

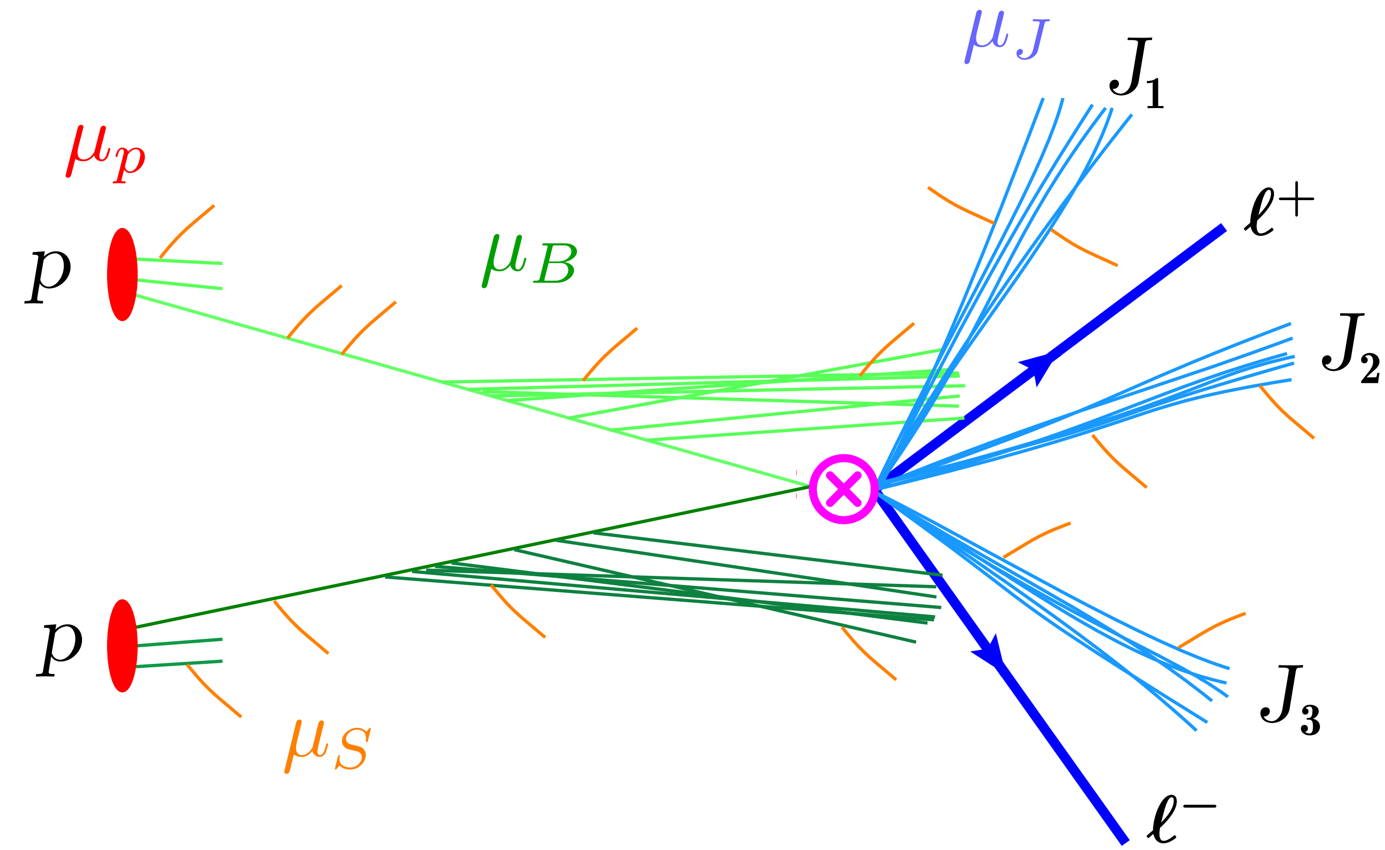
✓ = address in this talk

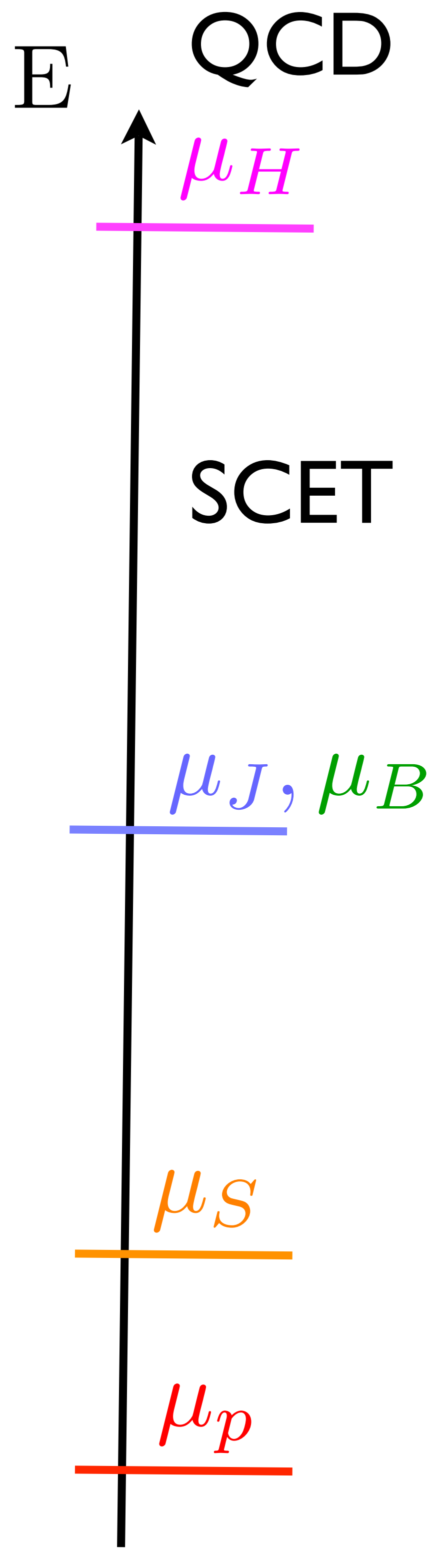
Exclusive Jet Event with Hard Interaction:

$p_T^{\rm jet} \sim 300\,{\rm GeV}$

$m_{\rm jet} \sim 50\,{\rm GeV}$

$$m_{\rm jet}^2 = \Big(\sum_{i\in J} p_i^\mu\Big)^2$$





N-jet Factorization:

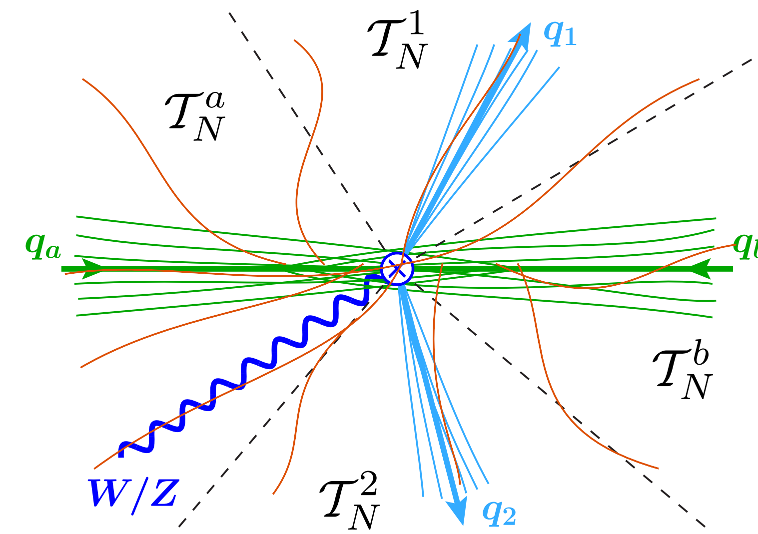
$$d\sigma = \text{PDFs} \otimes \text{ISR} \otimes \text{hard interactions} \otimes \text{FSR} \otimes \text{soft radiation}$$

$$\mathbf{d\sigma} = f_{a,b} \otimes \mathcal{I}_{a,b} \otimes H \otimes \prod_i J_i \otimes S$$

$\Lambda_{\rm QCD}$ $\quad \mu_B \quad \mu_H \quad \mu_J \quad \mu_S$

well known that jet mass gives sensitivity to a soft scale: $\mu_S = \dfrac{\mu_J^2}{\mu_H} \sim \dfrac{m_J^2}{\mu_H}$

N-Jettiness Factorization Formula



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_N^a\,\mathrm{d}\mathcal{T}_N^b\cdots\mathrm{d}\mathcal{T}_N^N} = \int \mathrm{d}x_a \mathrm{d}x_b \int \mathrm{d}(\text{phase space})$$

$$\times \sum_\kappa \int \mathrm{d}t_a\, B_{\kappa_a}(t_a, x_a) \int \mathrm{d}t_b\, B_{\kappa_b}(t_b, x_b) \prod_{J=1}^{N} \int \mathrm{d}s_J\, J_{\kappa_J}(s_J)$$

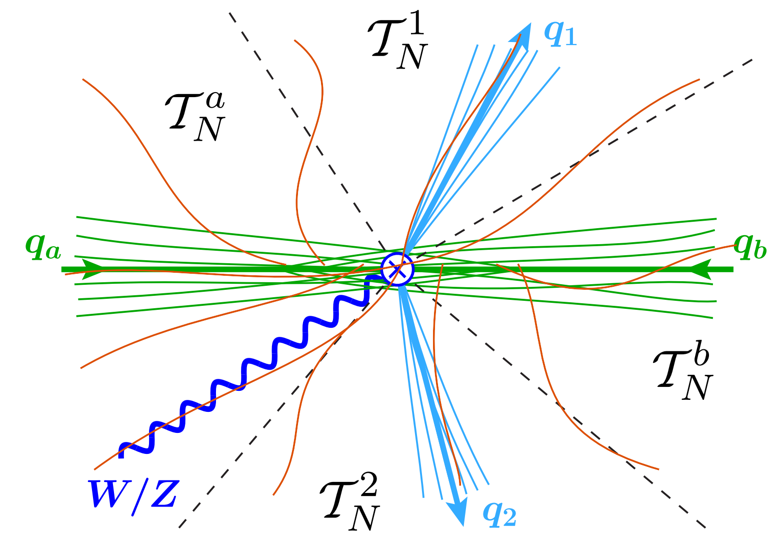
$$\times\ \mathrm{tr}\left[H_N^\kappa(\{q_i\cdot q_j\}, x_{a,b})\, \widehat{S}_N^\kappa\left(\mathcal{T}_N^a - \frac{t_a}{Q_a}, \mathcal{T}_N^b - \frac{t_b}{Q_b}, \mathcal{T}_N^1 - \frac{s_1}{Q_1}, \ldots, \mathcal{T}_N^N - \frac{s_N}{Q_N}, \{\hat{q}_i\cdot\hat{q}_j\}\right)\right]$$

$$\hat{q}_i^\mu = \frac{q_i^\mu}{Q_i}$$

$$B_\kappa(t,x) = \sum_i \int_x^1 d\xi\, \mathcal{I}_{\kappa i}(t, x/\xi) f_i(\xi)$$

pdfs

N-Jettiness Factorization Formula



$$\frac{d\sigma}{d\mathcal{T}_N^a\, d\mathcal{T}_N^b \cdots d\mathcal{T}_N^N} = \int dx_a dx_b \int \underline{d(\text{phase space})}$$

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$$\times\, \mathrm{tr}\Big[H_N^\kappa(\underline{\{q_i \cdot q_j\}}, x_{a,b})\, \widehat{S}_N^\kappa\Big(\mathcal{T}_N^a - \frac{t_a}{Q_a}, \mathcal{T}_N^b - \frac{t_b}{Q_b}, \mathcal{T}_N^1 - \frac{s_1}{Q_1}, \ldots, \mathcal{T}_N^N - \frac{s_N}{Q_N}, \underline{\{\hat{q}_i \cdot \hat{q}_j\}}\Big)\Big]$$

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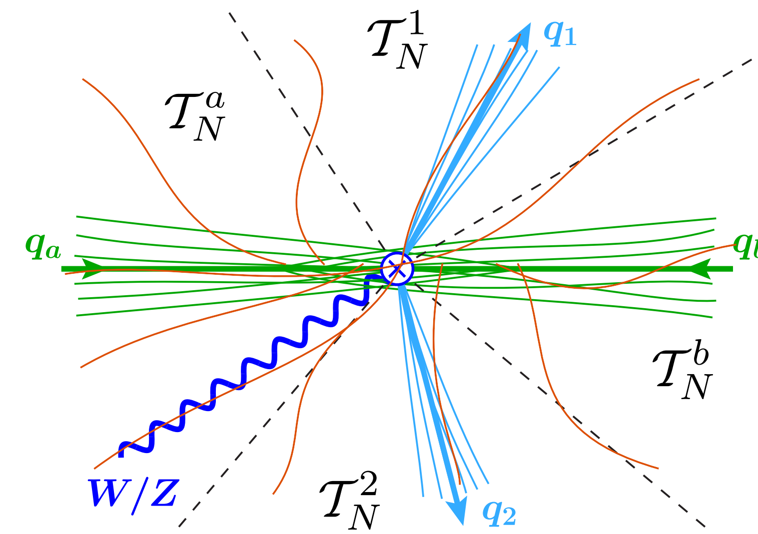
Kinematics

N-Jettiness Factorization Formula



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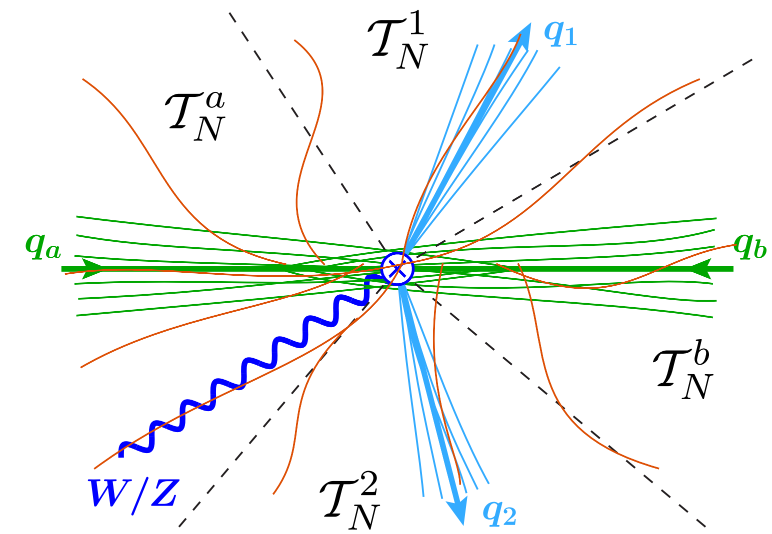
$$B_\kappa(t,x) = \sum_i \int_x^1 d\xi\, \mathcal{I}_{\kappa i}(t, x/\xi) f_i(\xi)$$ pdfs

κ = gluons vs. quarks

Kinematics

N-Jettiness Factorization Formula



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color

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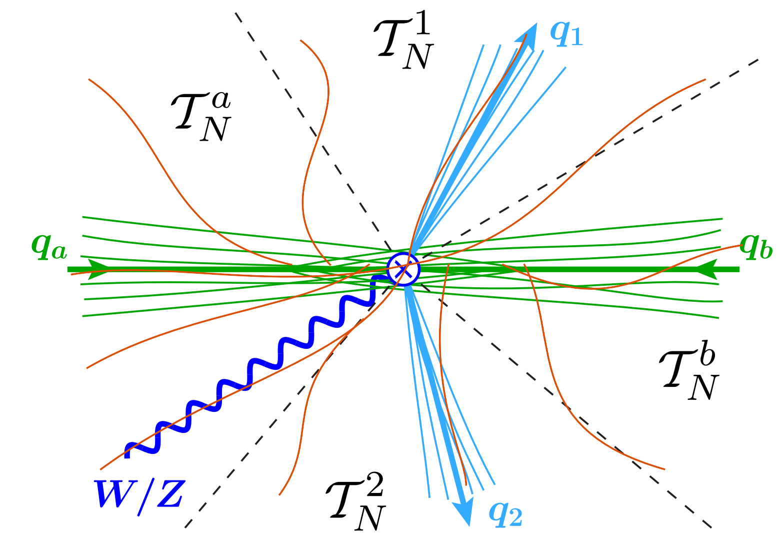
Kinematics

N-Jettiness Factorization Formula



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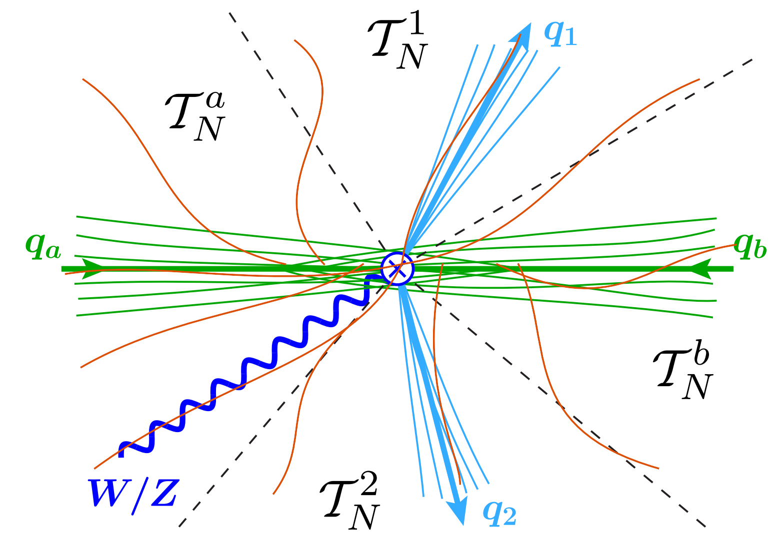
Hard process

κ = gluons vs. quarks

Kinematics

N-Jettiness Factorization Formula



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color

jet mass

$$\hat{q}_i^{\mu} = \frac{q_i^{\mu}}{Q_i}$$

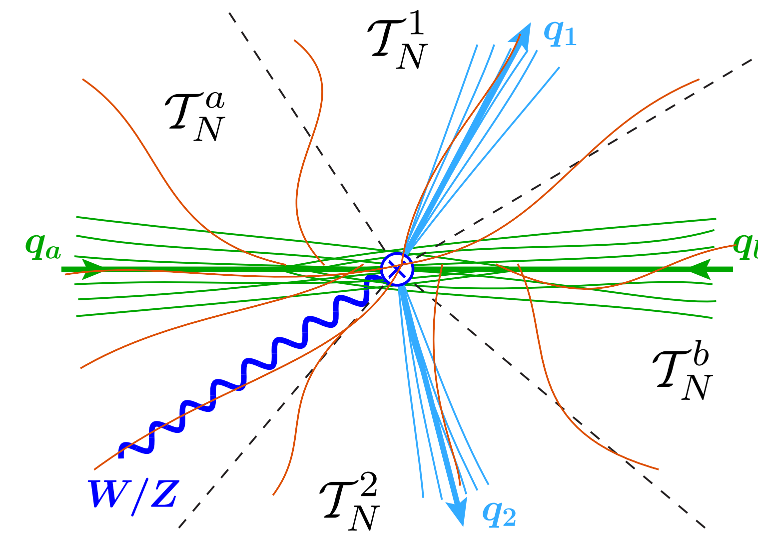
$$B_\kappa(t, x) = \sum_i \int_x^1 d\xi\, \mathcal{I}_{\kappa i}(t, x/\xi) f_i(\xi)$$ pdfs

Hard process

κ = gluons vs. quarks

Kinematics

N-Jettiness Factorization Formula



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color

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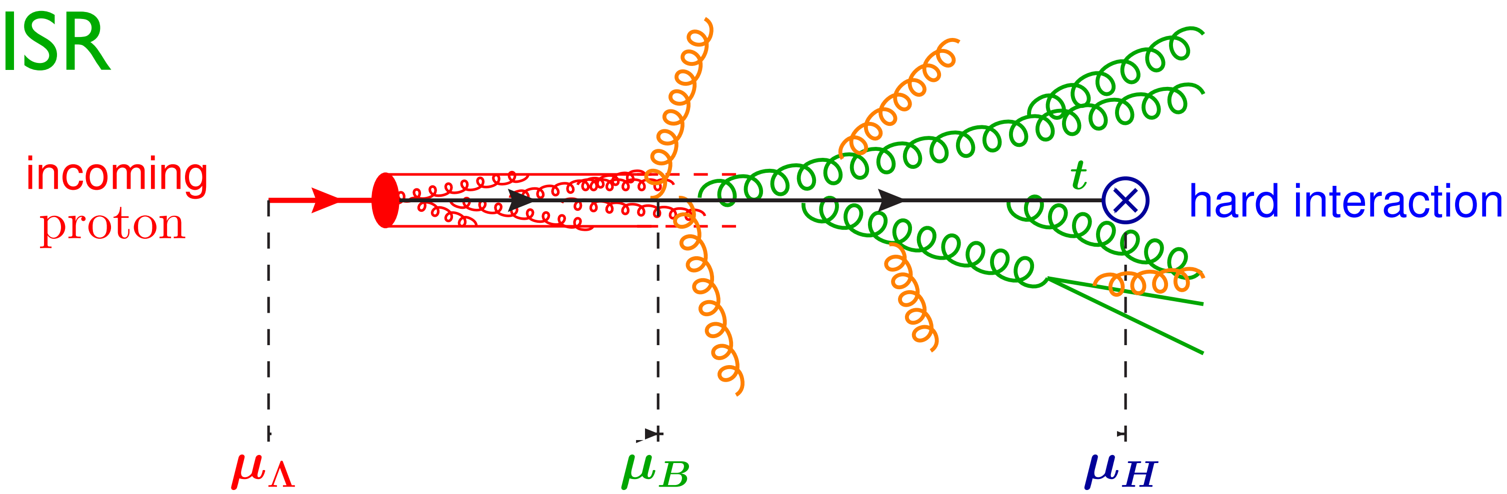
pdfs

Hard process

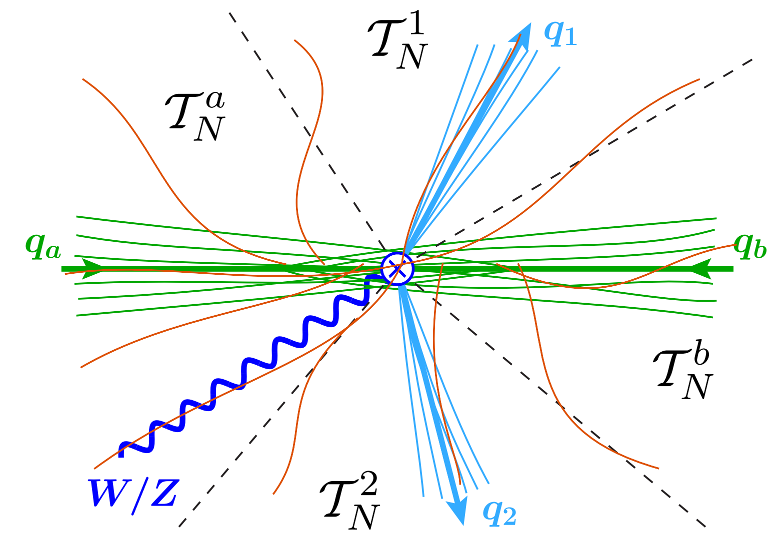
ISR



κ = gluons vs. quarks

Kinematics

N-Jettiness Factorization Formula



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pdfs

Hard process

ISR

Jet algorithm

Jet size R

Non-global logs

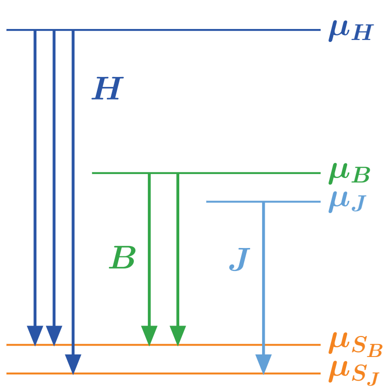
Hadronization

κ = gluons vs. quarks

Kinematics

NNLL/NLL/LL

theory uncertainty: $\mu_H,\ \mu_B,\ \mu_J,\ \mu_S$



Consider 1-jettiness for $pp \to H + 1\text{-jet}$

one exclusive jet

T. Jouttenus, IS, F. Tackmann, W. Waalewijn arXiv:1302.0846

NNLL

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}m_J}(m_J^{\rm cut}, \mathcal{T}^{\rm cut}) \equiv \frac{1}{\sigma(m_J^{\rm cut}, \mathcal{T}^{\rm cut})} \frac{\mathrm{d}\sigma(\mathcal{T}^{\rm cut})}{\mathrm{d}m_J}$$

normalized

cut on beam radiation

not normalized

$$\int_0^{m_J^{\rm cut}} dm_J \, \frac{d\widehat{\sigma}}{dm_J} = 1$$

kinematic variables:

$m_J^2 = \text{jet-mass}$

$\mathcal{T}_{a,b} \leq \mathcal{T}^{\rm cut}$

$p_T^J = \text{jet } p_T$

$\eta^J = \text{jet rapidity}$

$Y = \text{event rapidity}$

include $gg \to gH\,,\ qg \to qH\,,\ \bar{q}g \to \bar{q}H\,,\ q\bar{q} \to gH$

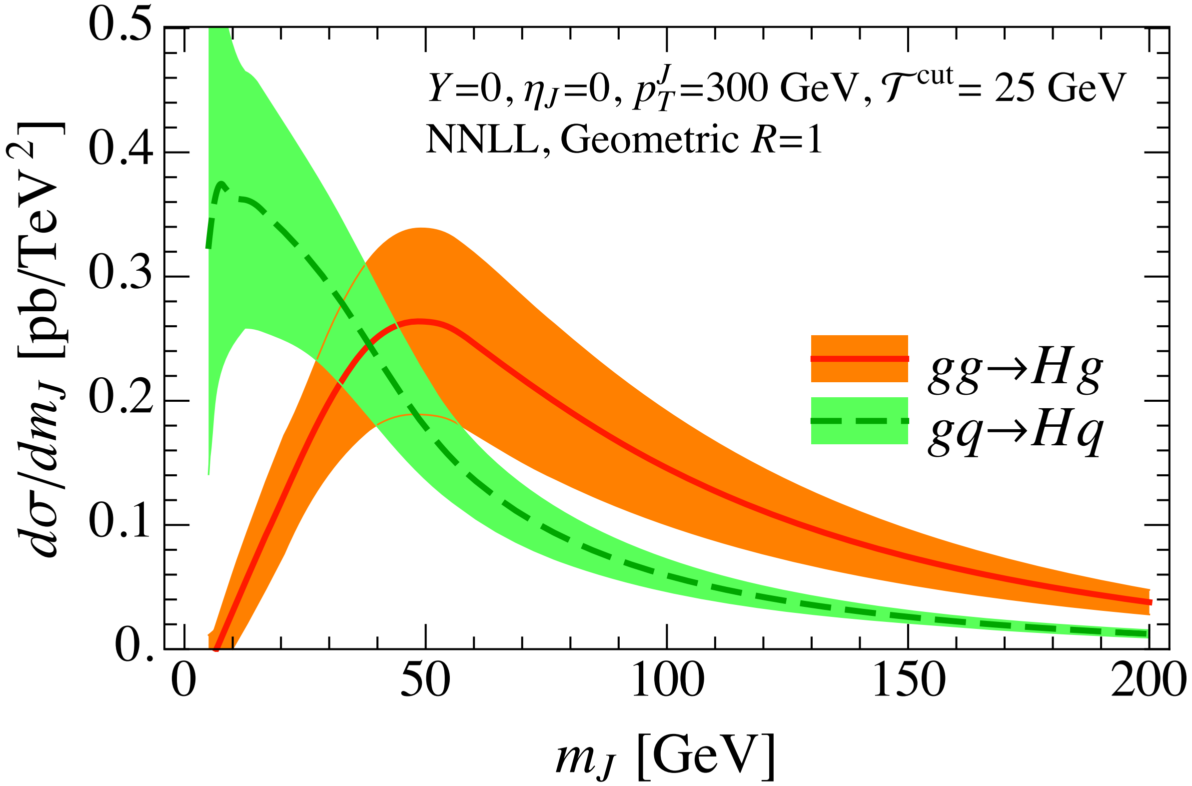
pick $m_H = 125\,\text{GeV}$, MSTW pdfs, $\alpha_s(m_Z)$

use NLO Hard Fn's:

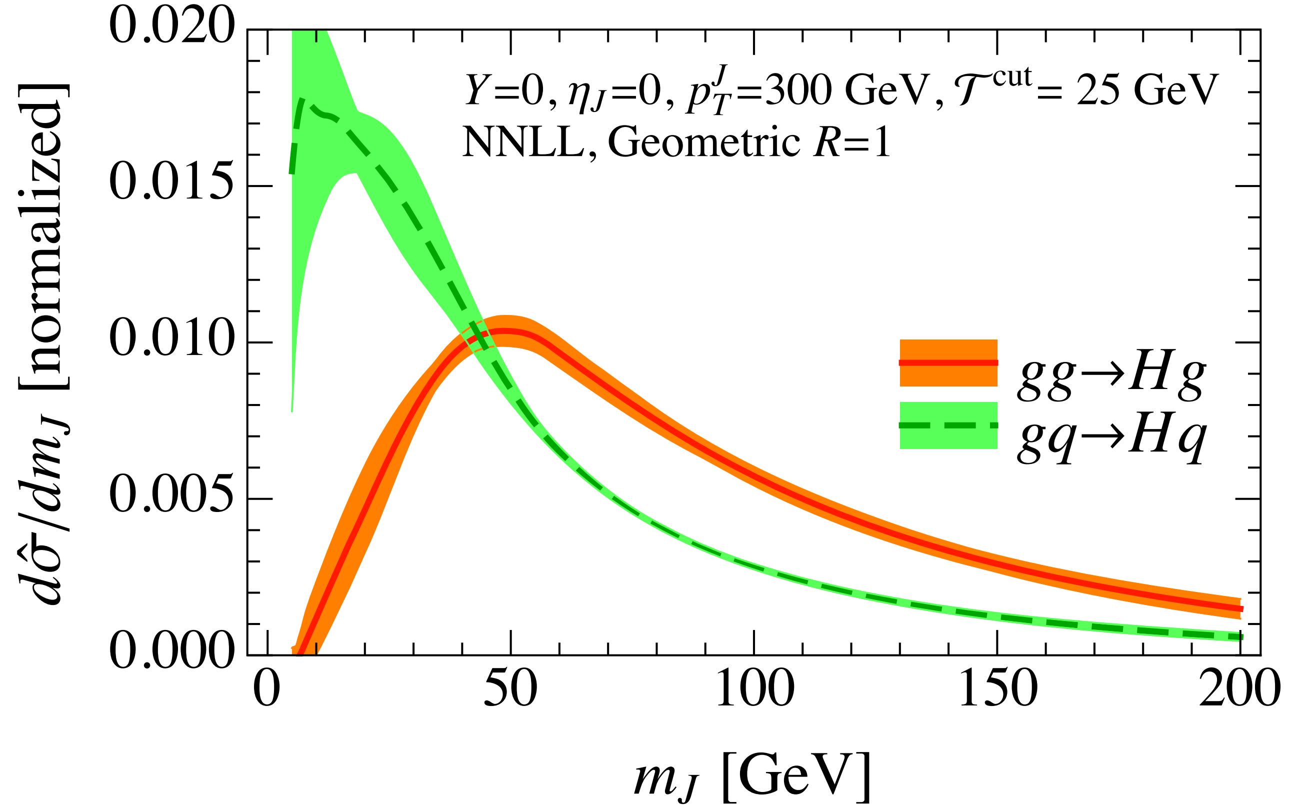
C.Schmidt (2007)

Quark and Gluon Jets

Not Normalized

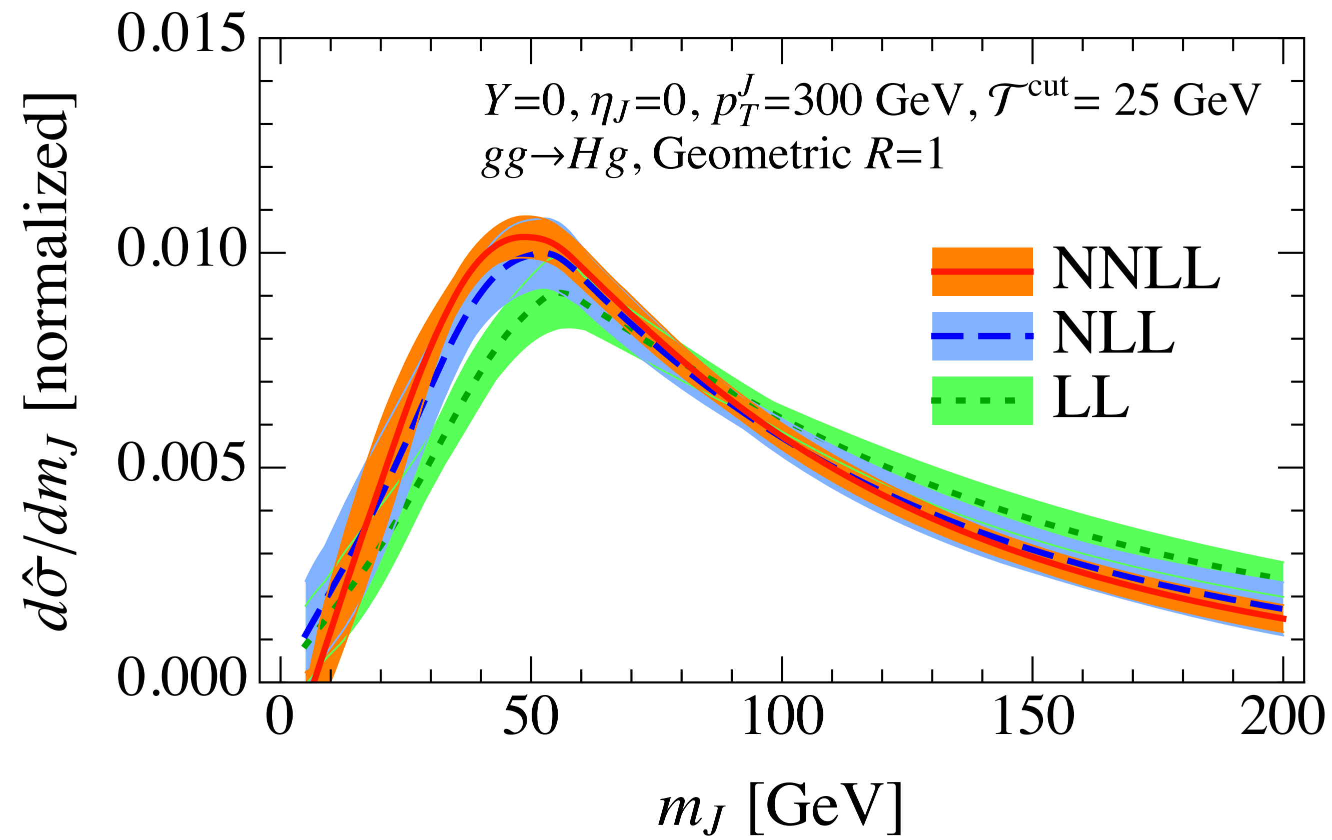


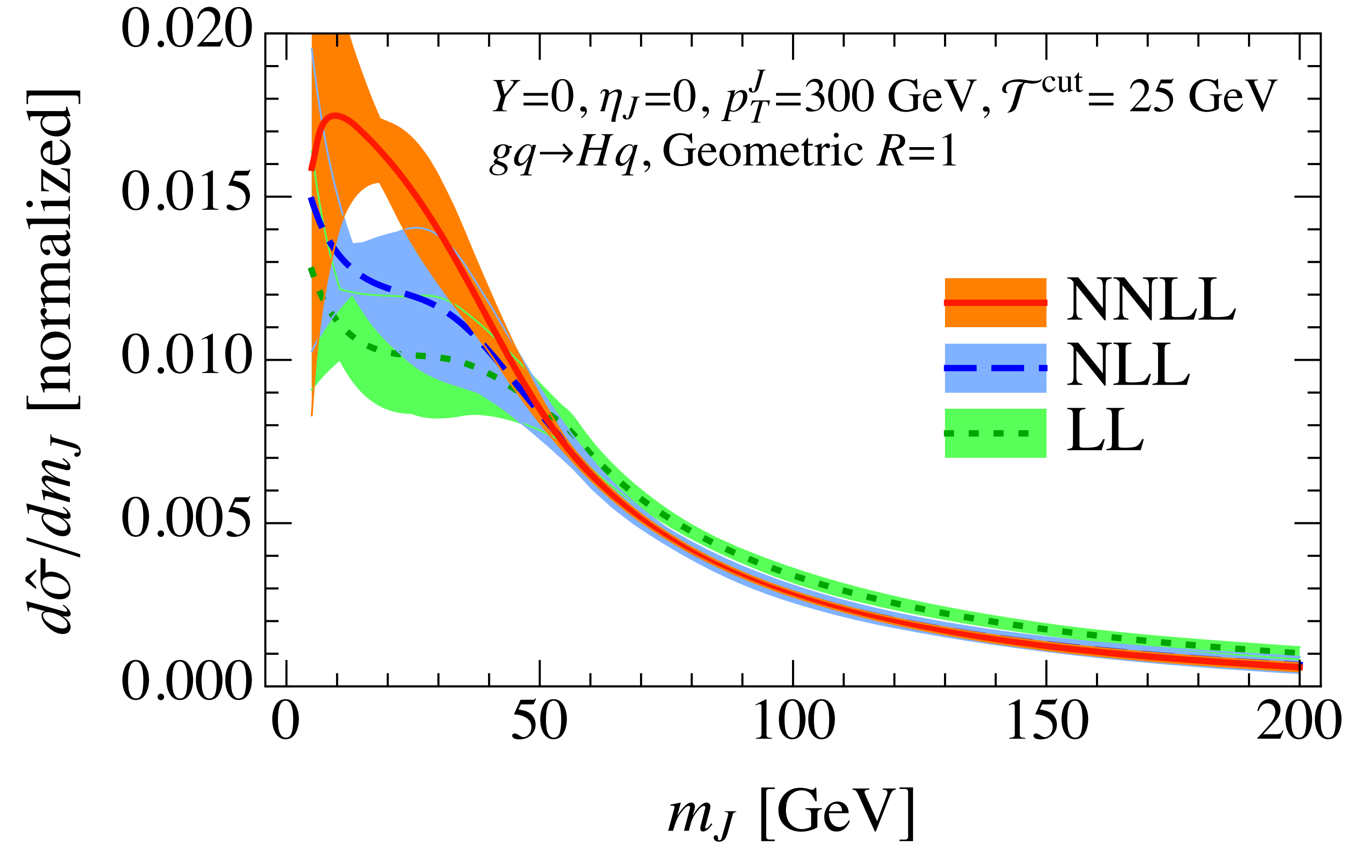
Normalized



Normalized

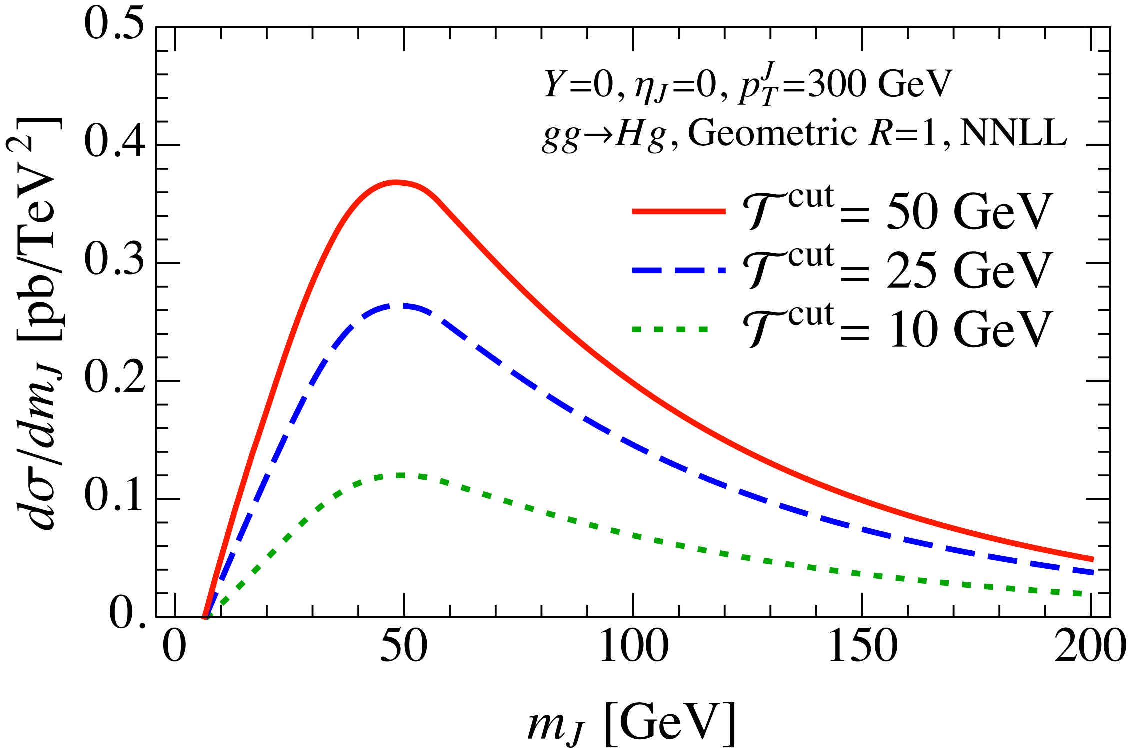
Order by Order Convergence



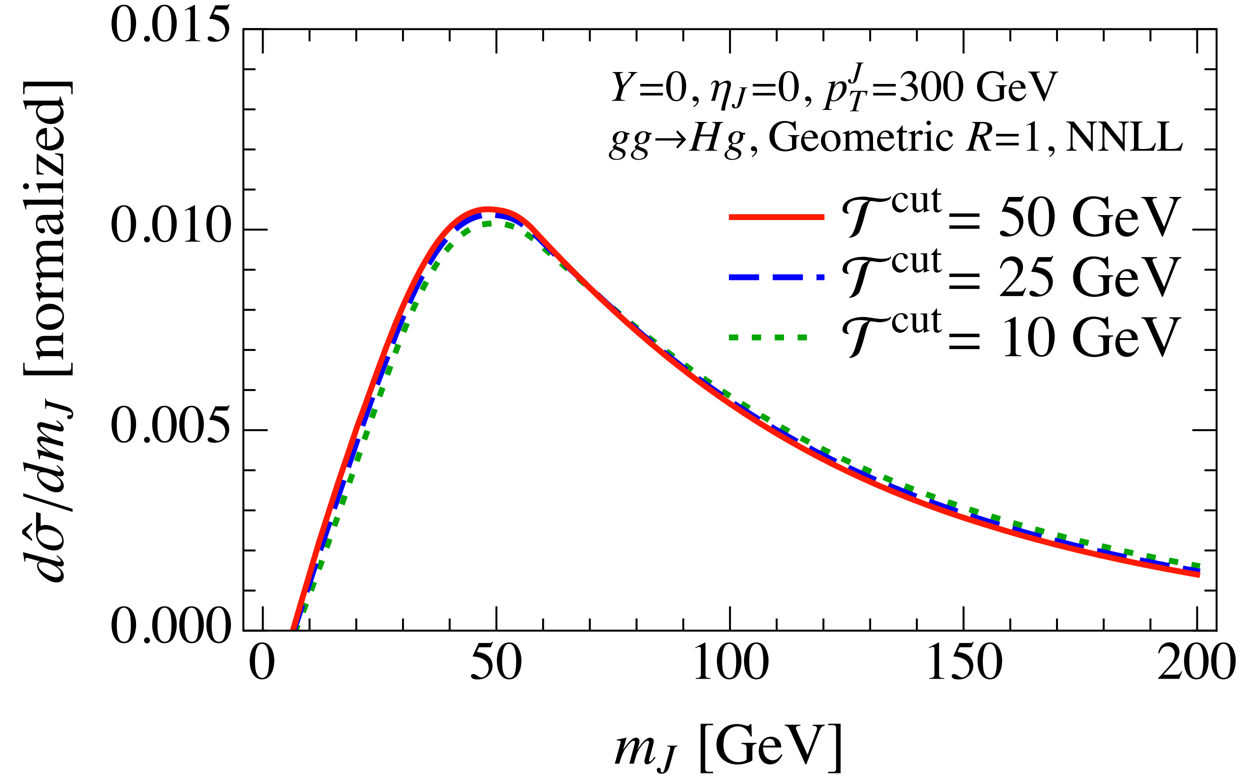


Effect of the Beam Cut

Not Normalized



Normalized

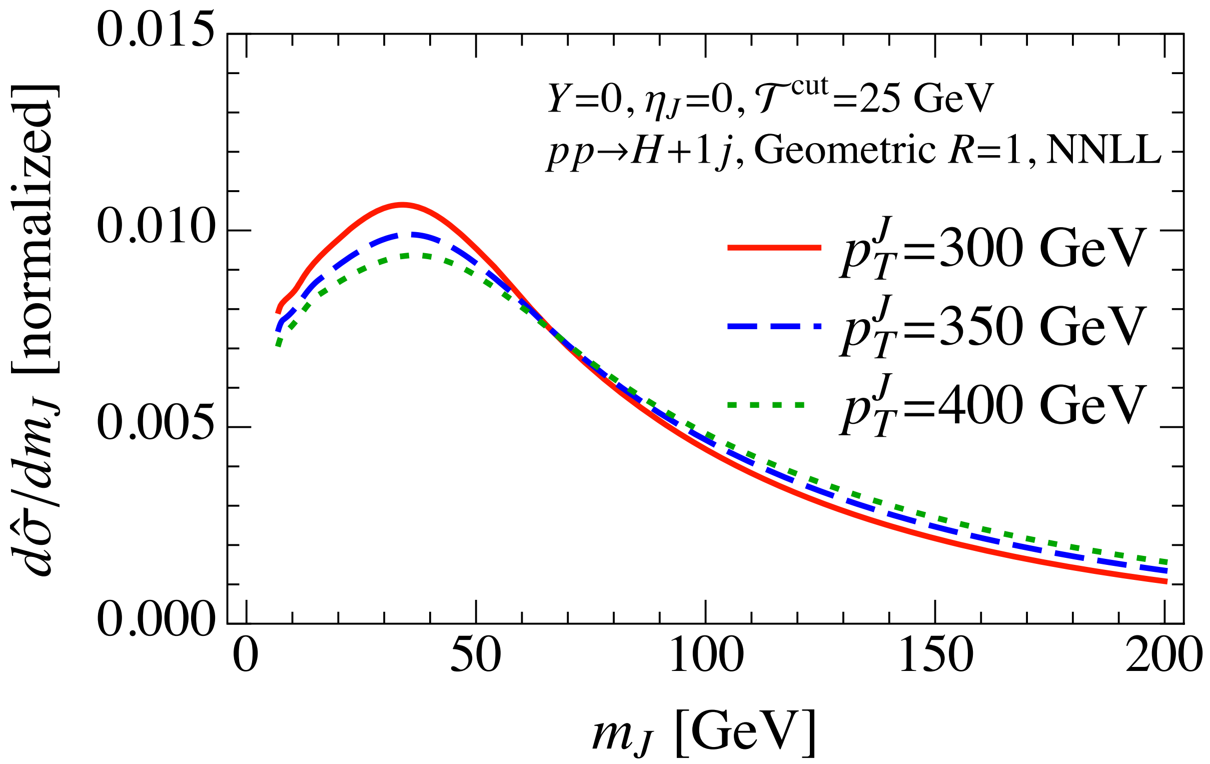


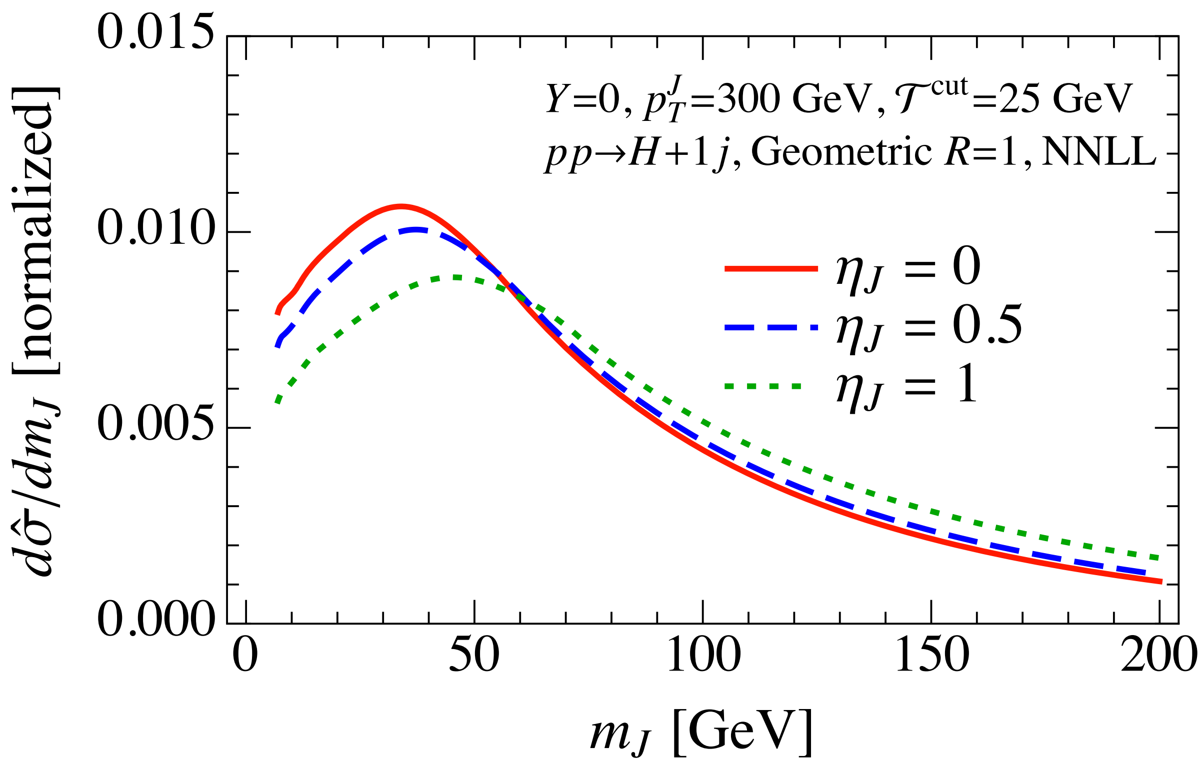
Jet Kinematic Variables:

Normalized

$$m_J^{\rm peak} \propto \sqrt{p_T^J}$$

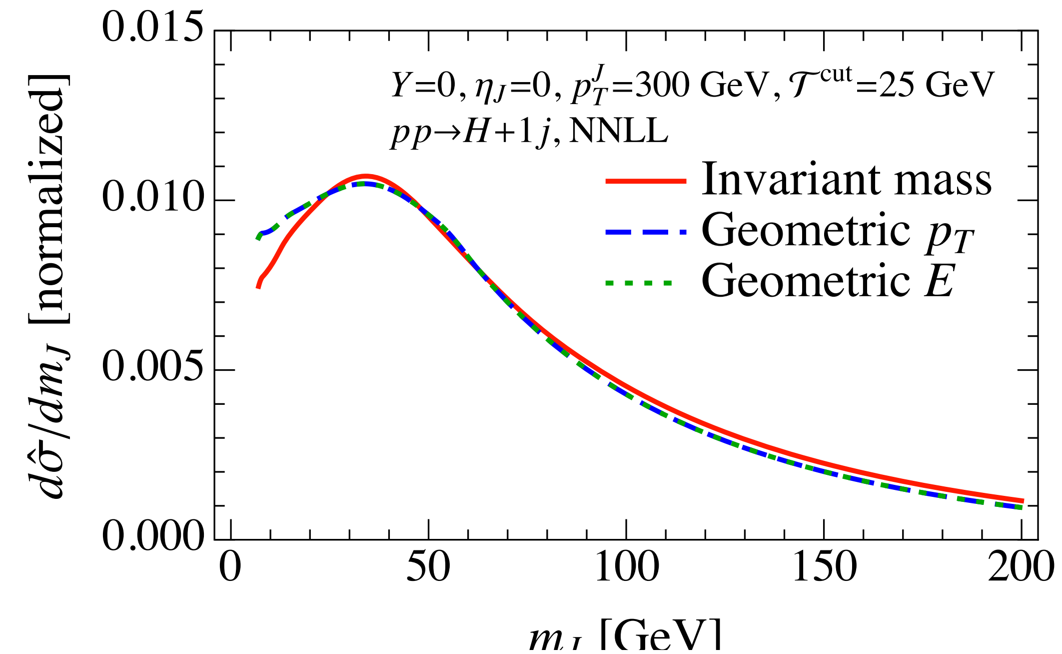
but also gains more quark jets

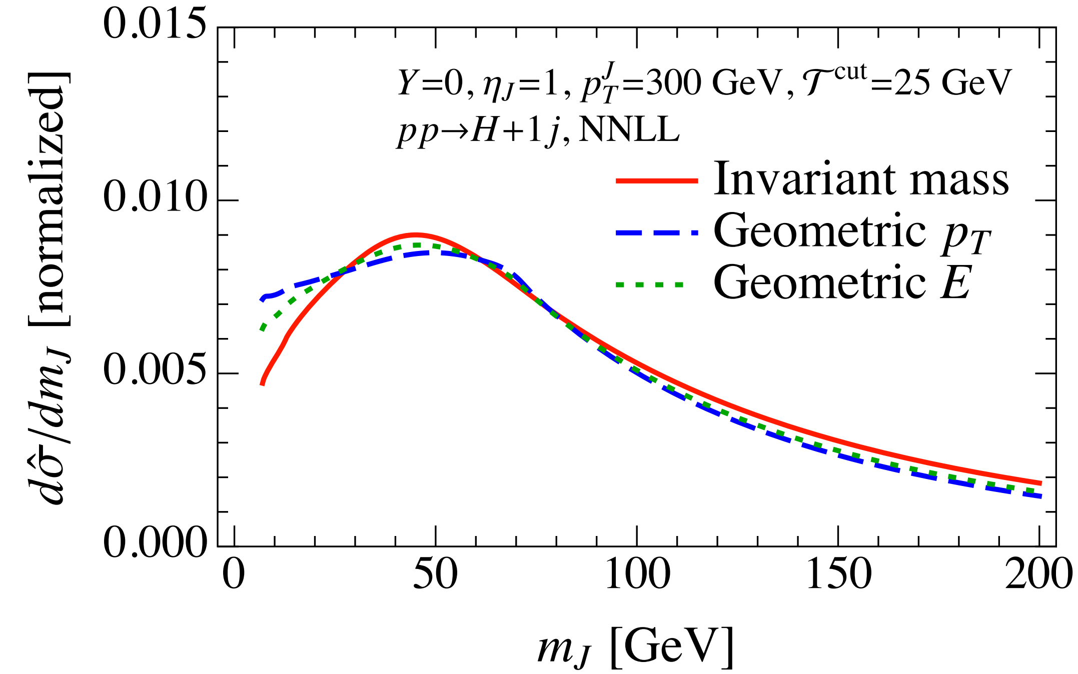




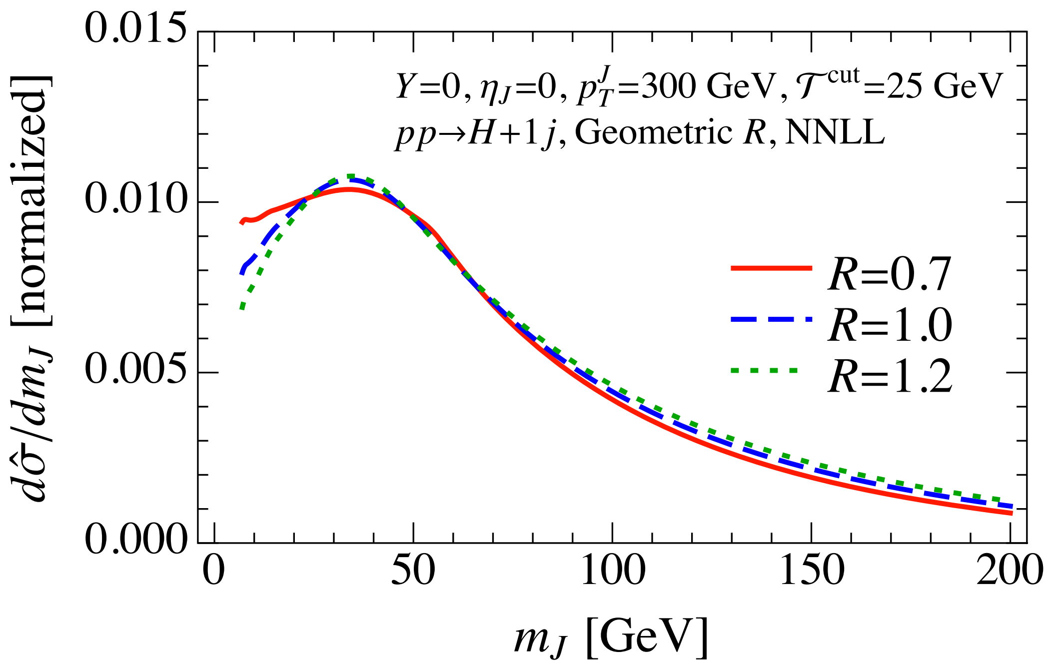
Dependence on the Jet Algorithm

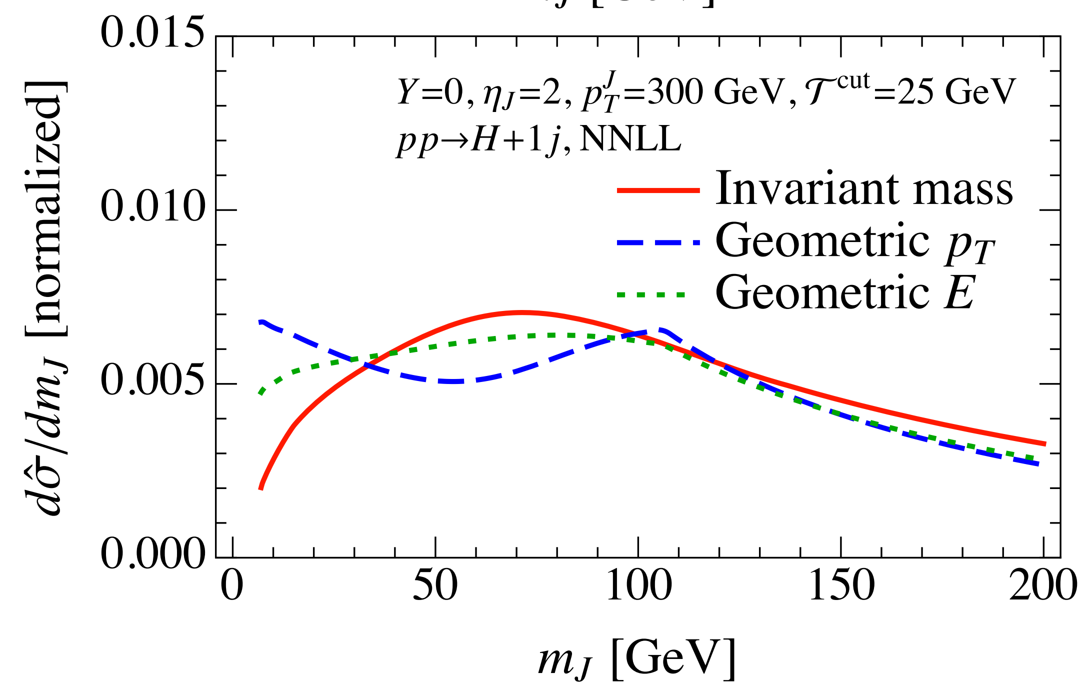
invariant mass
vs
geometric pT
vs
geometric E



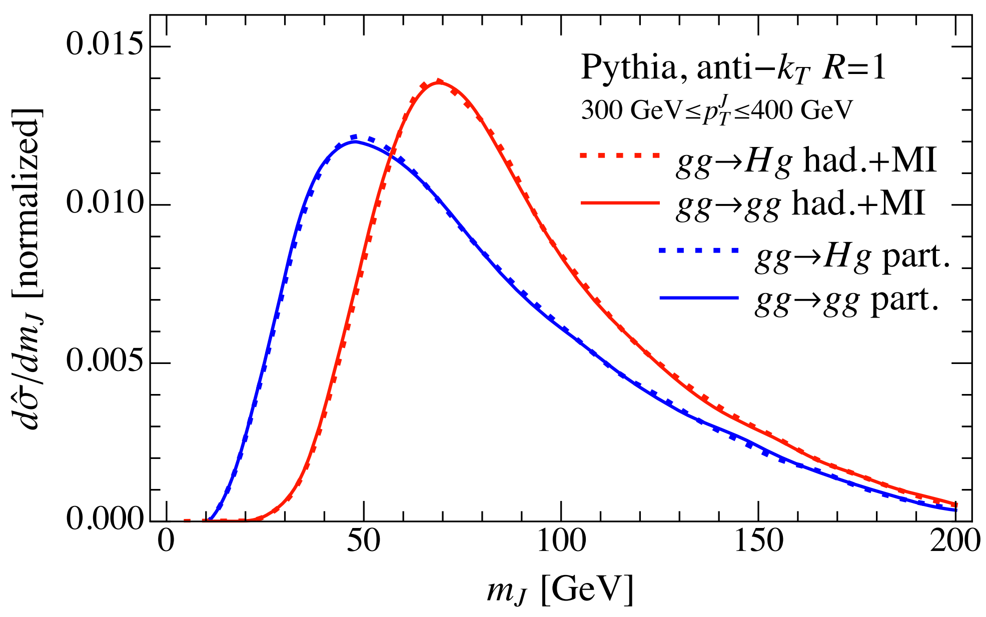


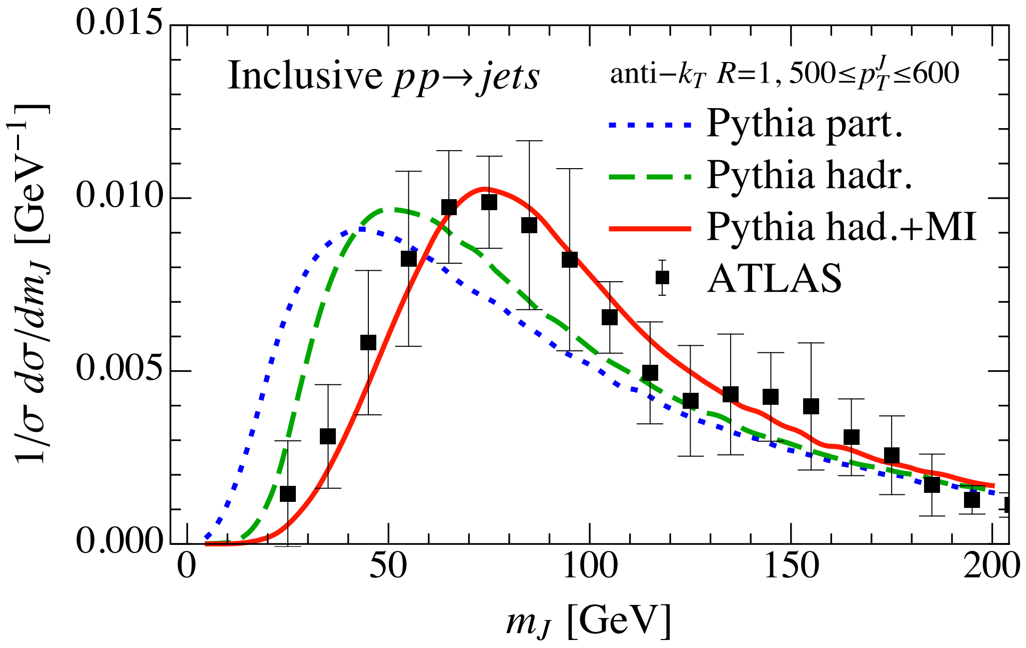
Jet Size R



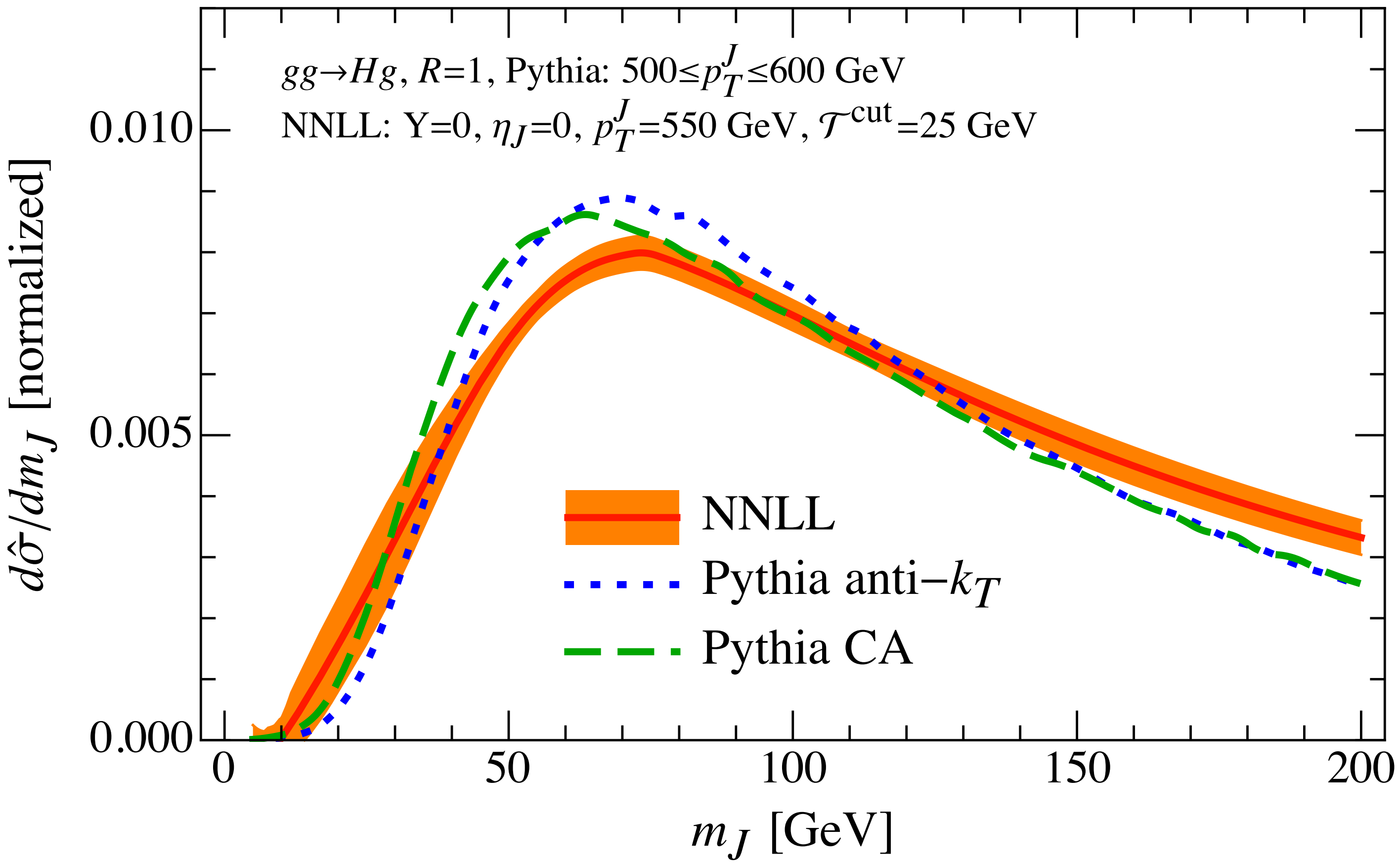


Comparisons to Monte Carlo (Pythia 8)

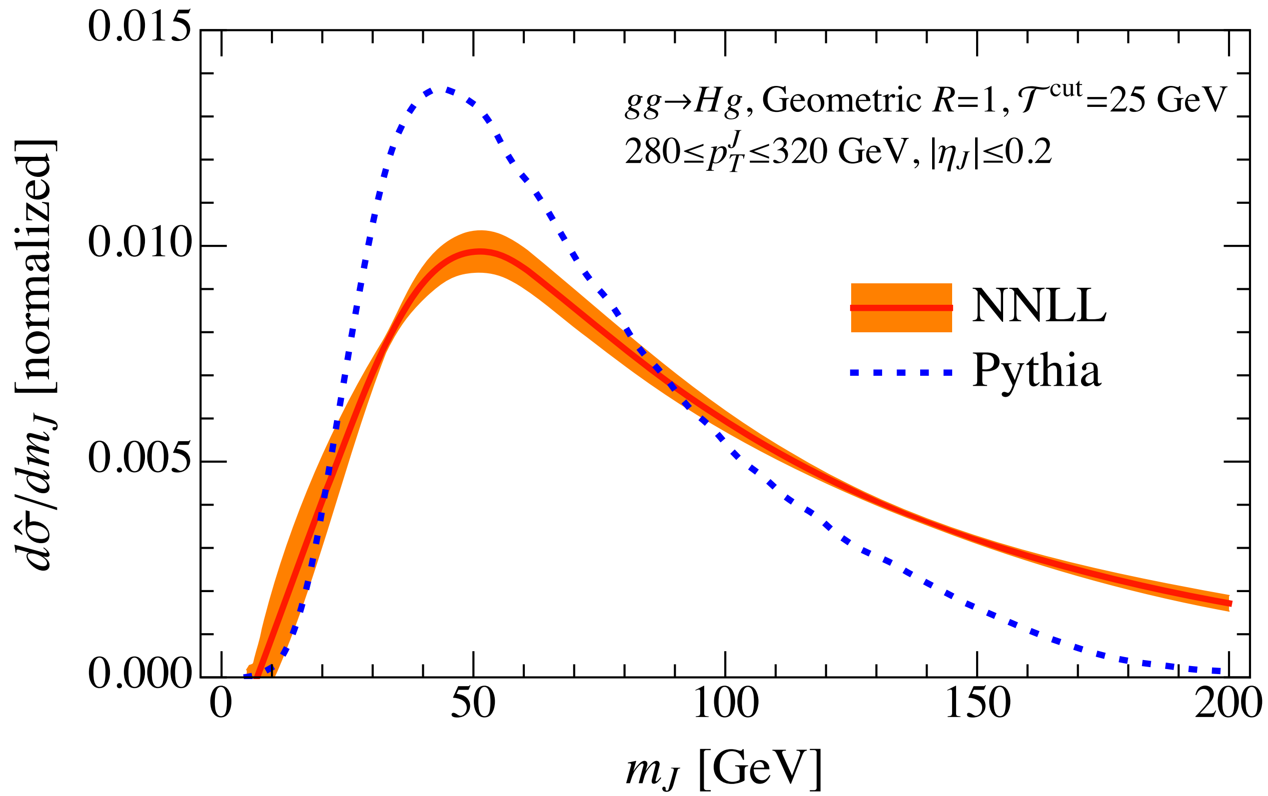




larger pT, same m^{cut}



smaller pT



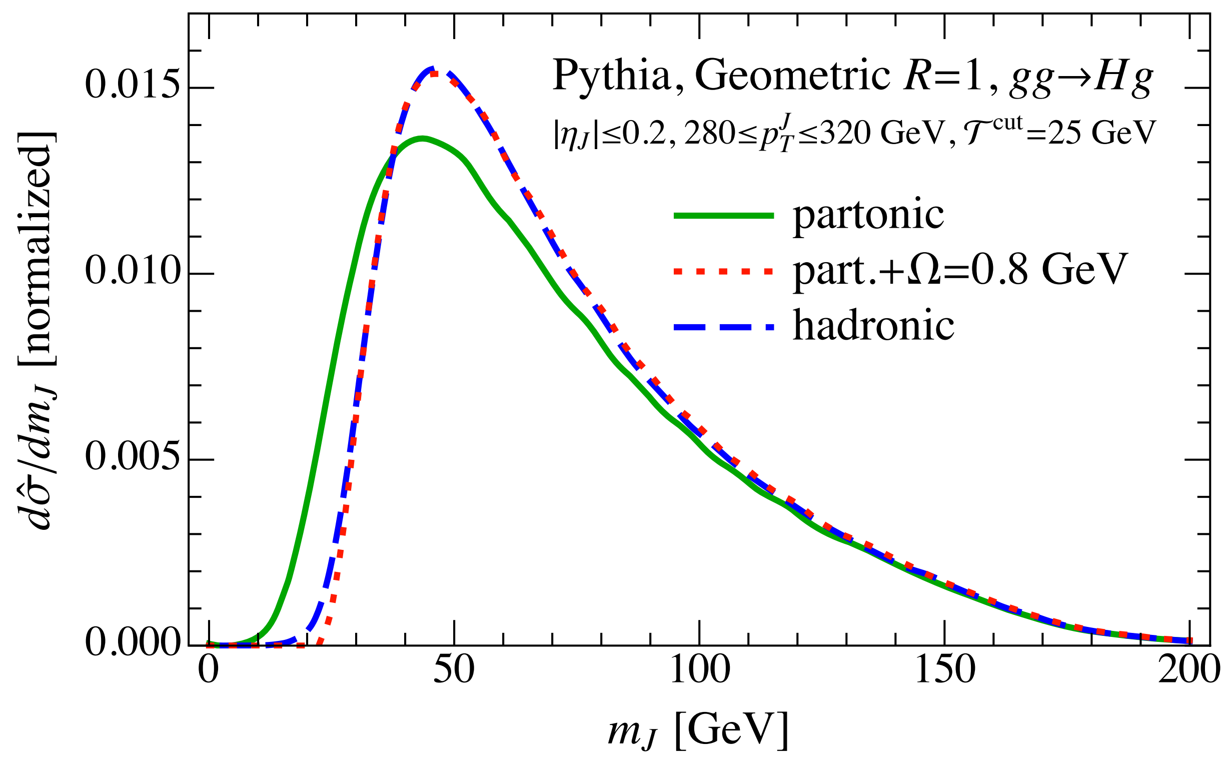
Power Corrections / Hadronization Effects

(Pythia 8 partonic → hadronization is a simple shift)

shift is:

$$m_J^2 \to m_J^2 - Q_J \Omega$$

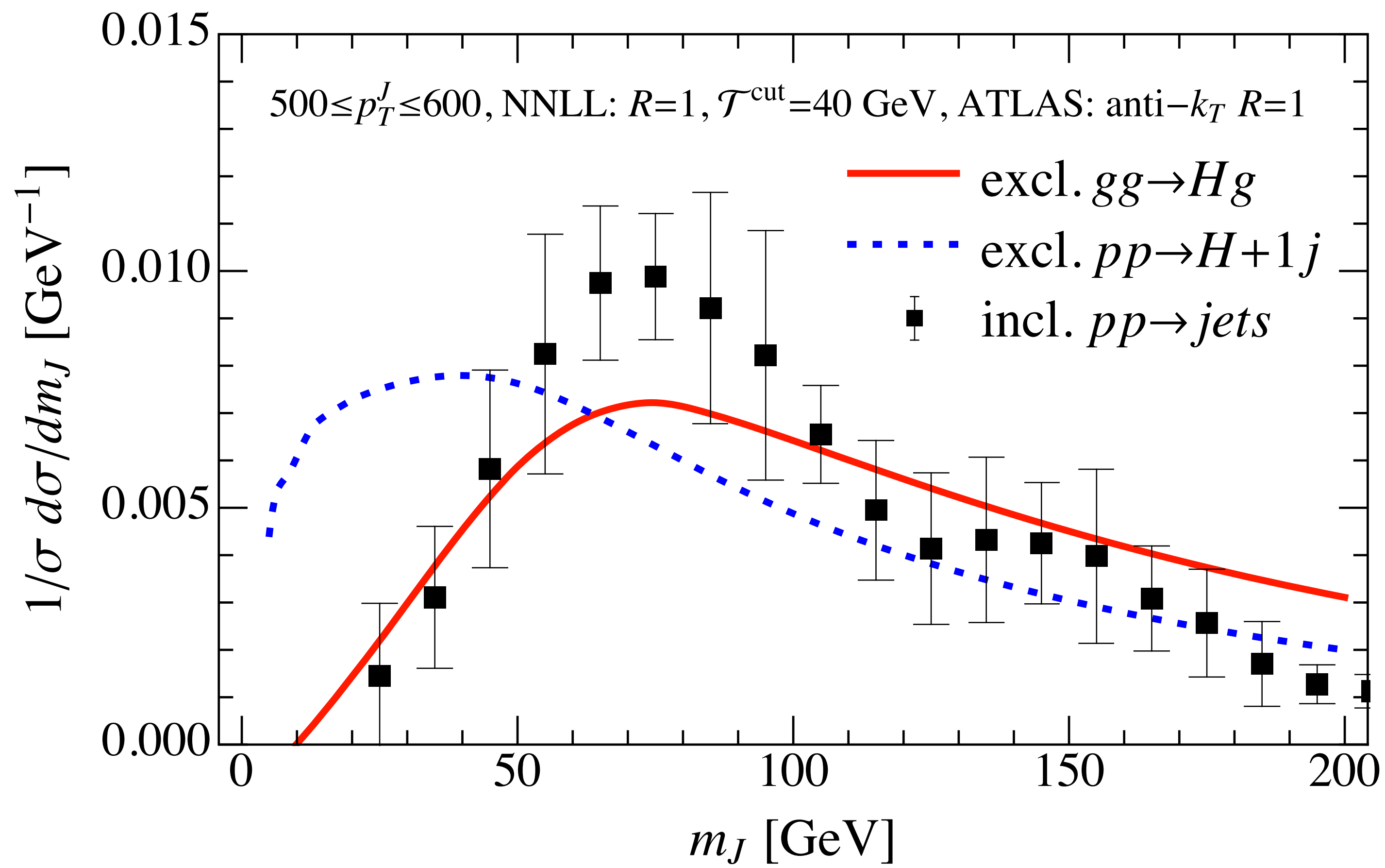
$$\Omega \sim \Lambda_{\rm QCD}$$



Of course it is also tempting to compare to the ATLAS inclusive jet data

This is only meaningful at the level that their jet mass results are gluon dominated and process independent
(please read this apples to oranges comparison carefully)

- underlying event pushes to right
- quark channels push to left



Jets in $e^{-}p$

Using 1-Jettiness to Measure 2 Jets in DIS in 3 Ways

C.Lee, D.Kang, IS arXiv:1303.xxxx (soon)

$$\tau_1 = \frac{2}{Q^2} \sum_i \min\{q_B \cdot p_i, q_J \cdot p_i\}$$

How shall we pick q_B and q_J?

Three choices for DIS 1-jettiness

τ_1^a

$$q_B = xP$$

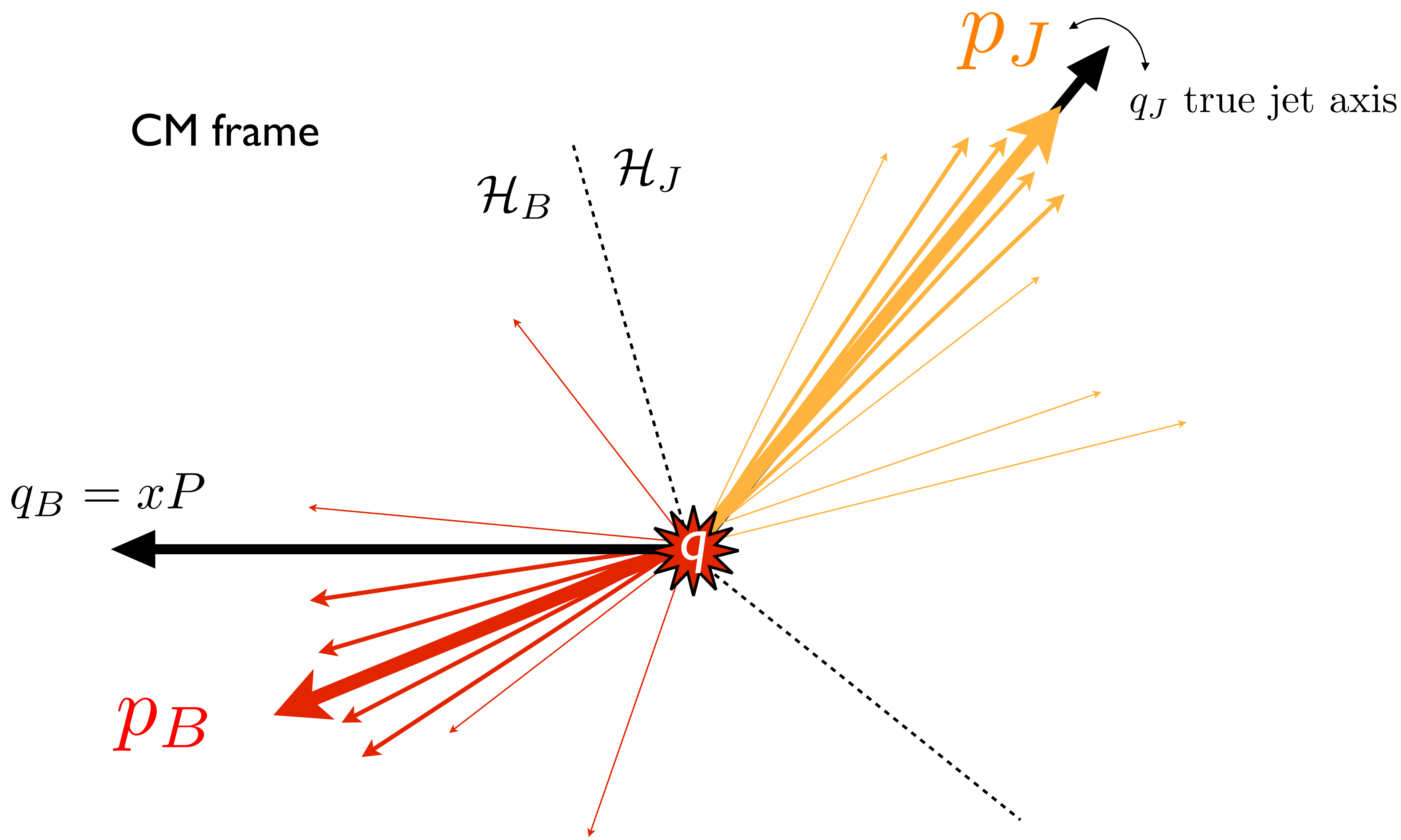
$$q_J = \text{true jet axis}$$

Kang, Mantry, Qiu (2012)

not the same as

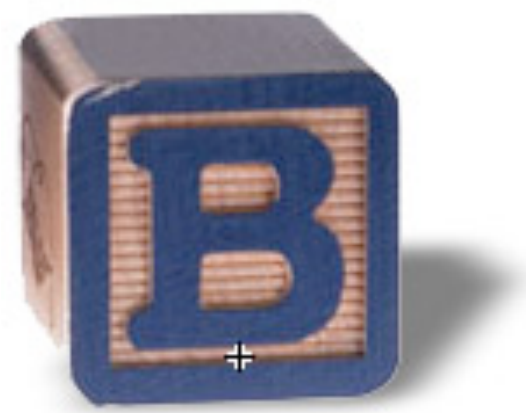
$$\min_{\hat{n}} \tau_{\hat{n}Q}$$

CM frame

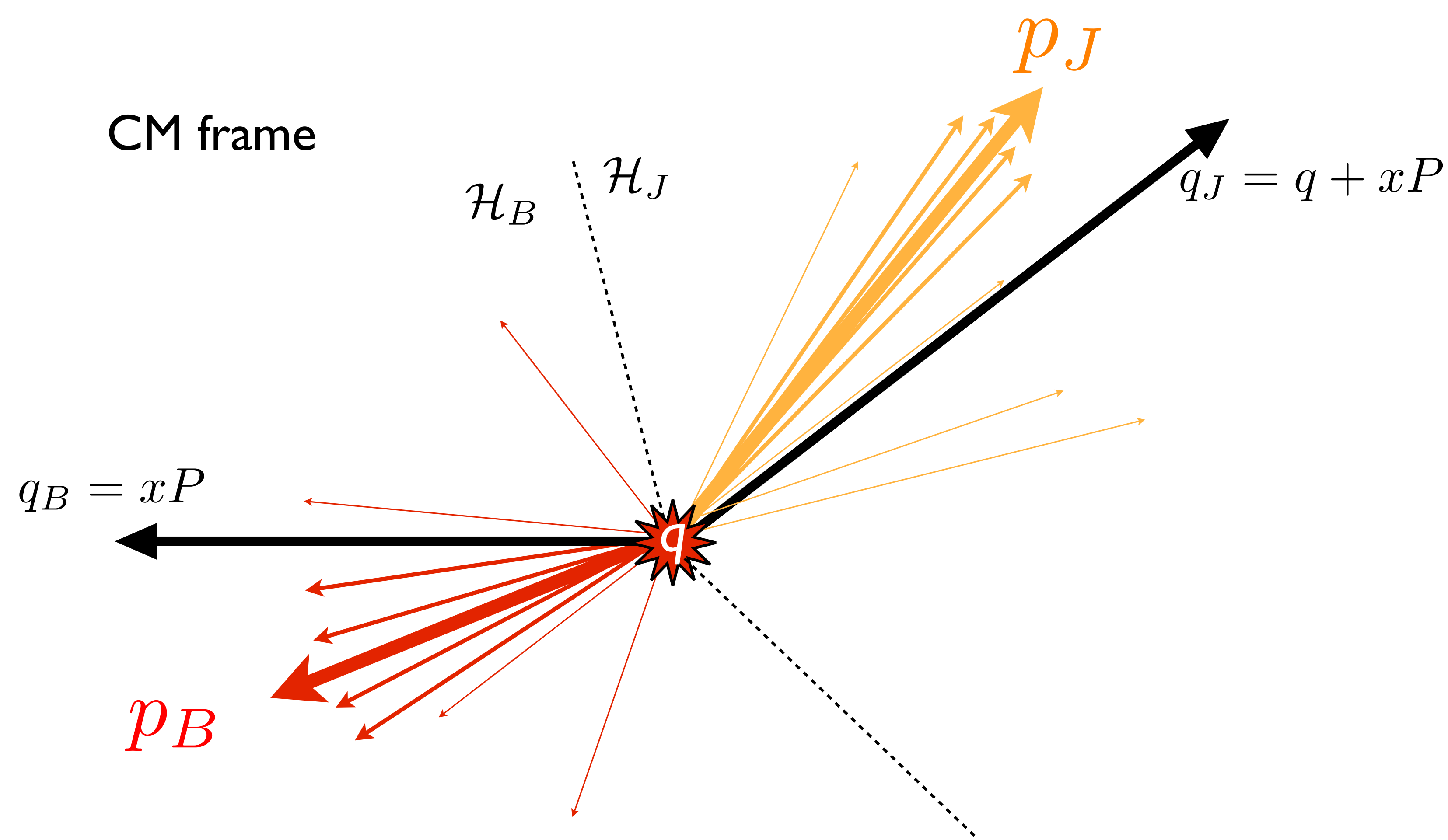


q_J is **A**ligned with the jet momentum, find by jet algorithm or minimization

Three choices for DIS 1-jettiness



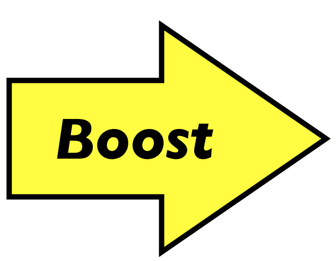
τ_1^b



$$q_B = xP$$
$$q_J = q + xP$$

same as DIS thrust $\tau_{\hat{z}Q}$ of Antonelli, Dasgupta, Salam (1999)

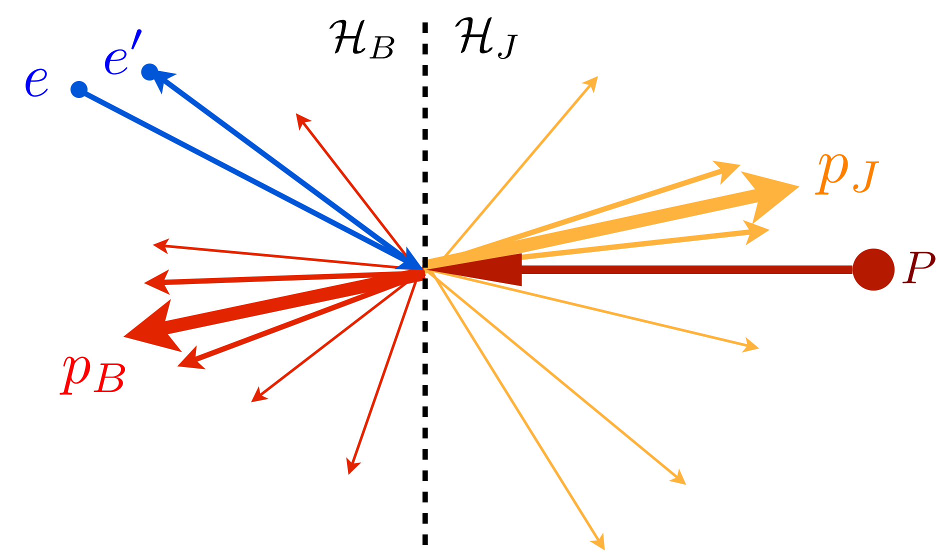
***q*$_J$ no longer aligned with jet, but**
q+*xP* is given only by lepton and proton momenta



Breit frame:

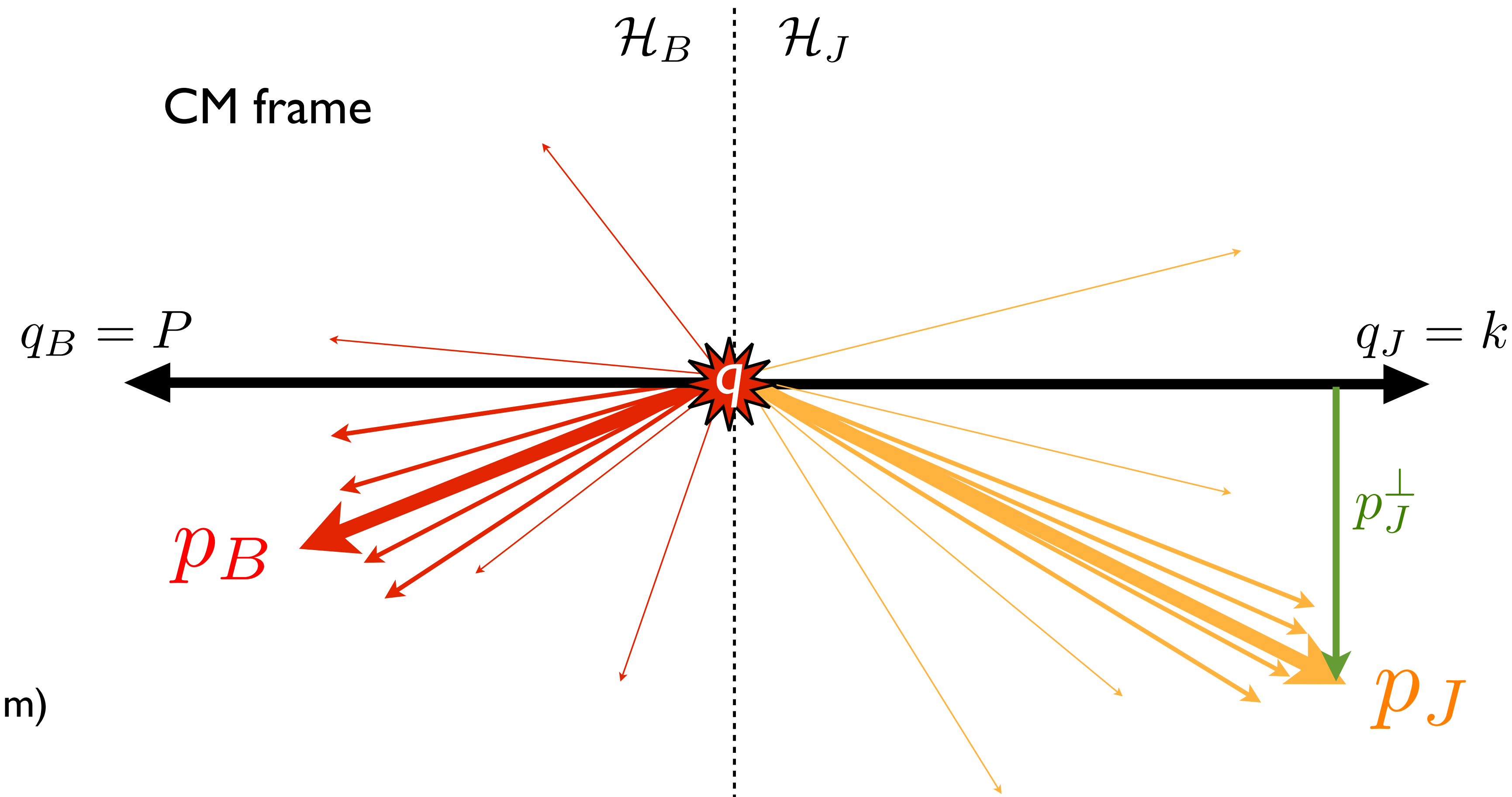
$$q = (0, 0, 0, Q)$$
$$q_B = Q\bar{n}_z \quad q_J = Qn_z$$

1-jettiness regions are hemispheres in Breit frame



Three choices for DIS 1-jettiness

τ_1^c



$$q_B = P$$

$$q_J = k$$

(electron momentum)

measures thrust in back-to-back hemispheres in **C**enter-of-momentum frame

momentum transfer ***q*** itself has a nonzero transverse component:

$$q = y\sqrt{s}\frac{n_z}{2} - xy\sqrt{s}\frac{\bar{n}_z}{2} + \sqrt{1-y}\,Q\hat{n}_\perp$$

seemingly simplest definition: *in practice* hardest to calculate!

Restriction: $p_J^\perp$ has to be small for 1-jettiness τ_1^c to be small $\Rightarrow 1 - y \sim \lambda^2$

Factorization Theorem for 1-Jettiness

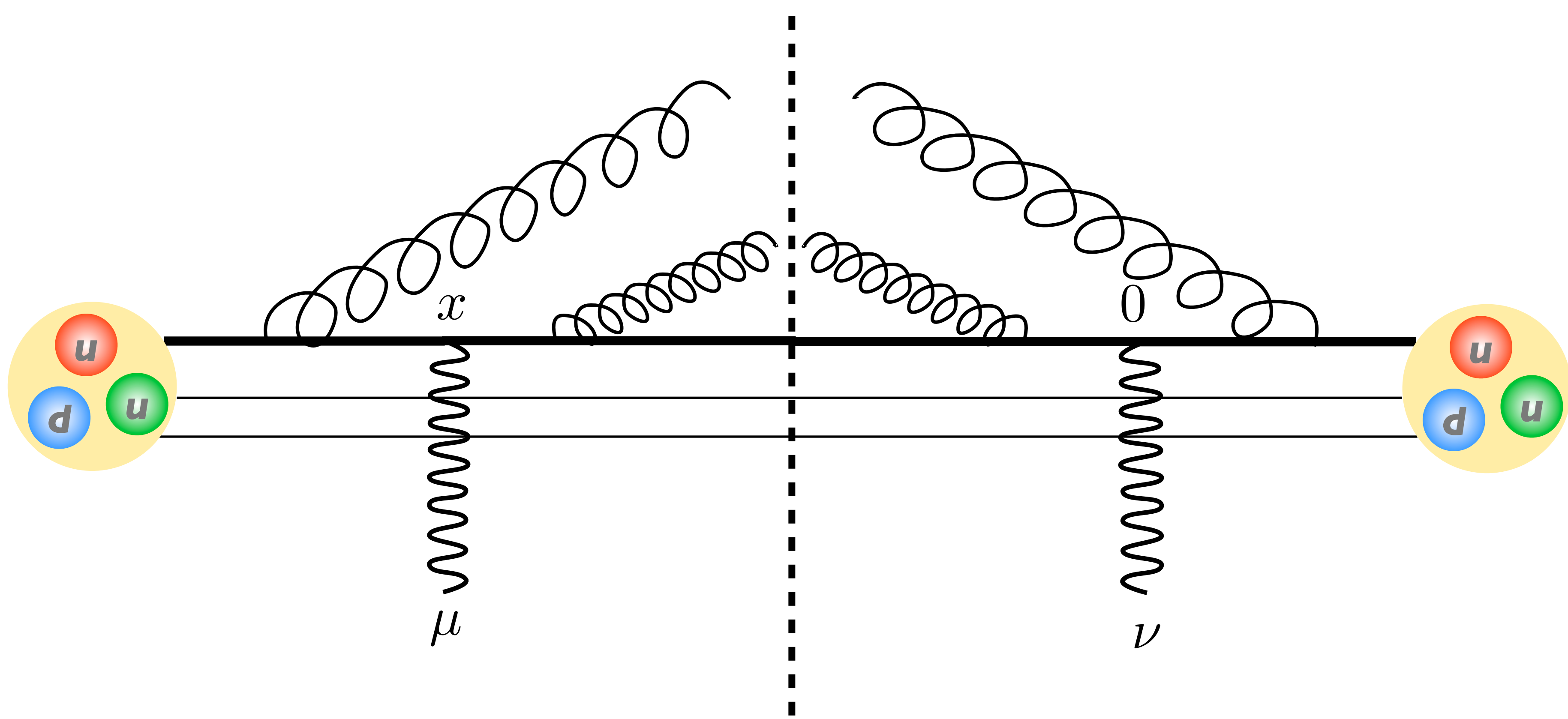
$$\frac{d\sigma(x,Q^2)}{d\tau_1} = L_{\mu\nu}(x,Q^2) W^{\mu\nu}(x,Q^2,\tau_1)$$

leptonic tensor hadronic tensor

Start in QCD:

$$W^{\mu\nu}(x,Q^2,\tau_1) = \int d^4x\, e^{iq\cdot x} \langle P|\bar{q}\gamma^\mu q(x)\delta(\tau_1 - \hat{\tau}_1)\bar{q}\gamma^\nu q(0)|P\rangle$$

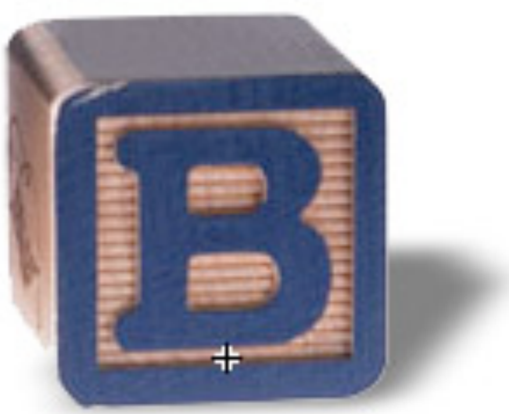
$$\hat{\tau}_1|X\rangle = \tau_1(X)|X\rangle$$



Measure τ_1 of particles crossing the cut

Factorization Theorems for 1-Jettiness

$$\frac{1}{\sigma_0}\frac{d\sigma(x,Q^2)}{d\tau_1^a} = H(Q^2,\mu)\int dt_J dt_B dk_S \delta\Big(\tau_1^a - \frac{t_J}{Q^2} - \frac{t_B}{Q^2} - \frac{k_S}{Q}\Big) \times J_q(t_J,\mu) B_q(t_B,x,\mu) S(k_S,\mu)$$

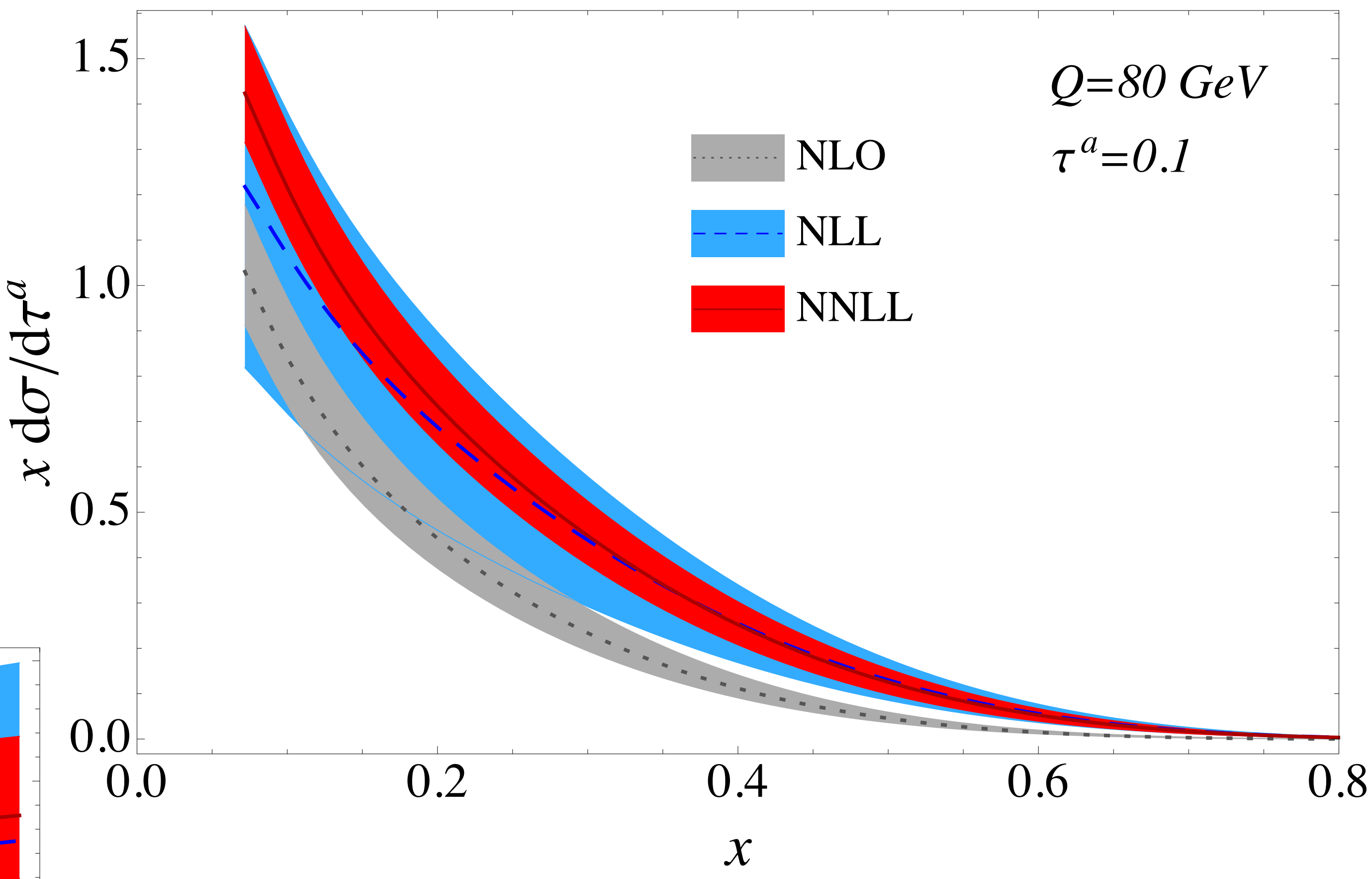


$$\frac{1}{\sigma_0}\frac{d\sigma(x,Q^2)}{d\tau_1^b} = H(Q^2,\mu)\int d^2p_\perp dt_J dt_B dk_S \delta\Big(\tau_1^b - \frac{t_J}{Q^2} - \frac{t_B}{Q^2} - \frac{k_S}{Q}\Big) \times J_q(t_J - \mathbf{p}_\perp^2,\mu) \mathcal{B}_q(t_B,x,\mathbf{p}_\perp^2,\mu) S(k_S,\mu)$$

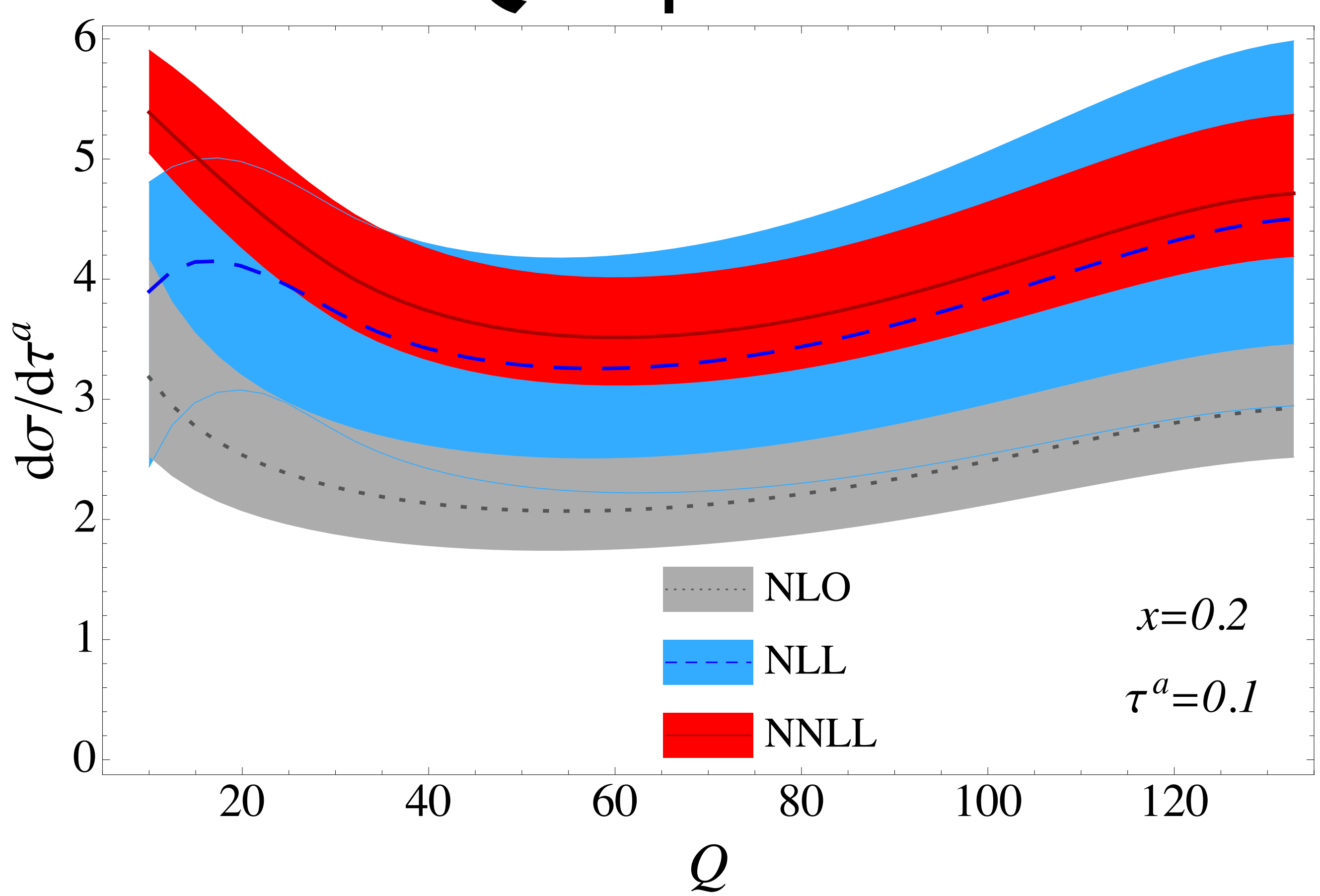
$$\frac{1}{\sigma_0}\frac{d\sigma(x,Q^2)}{d\tau_1^c} = H(Q^2,\mu)\int d^2p_\perp dt_J dt_B dk_S \delta\Big(\tau_1^c - \frac{t_J}{Q^2} - \frac{t_B}{xQ^2} - \frac{k_S}{\sqrt{x}Q}\Big) \times J_q(t_J - (\mathbf{q}_\perp + \mathbf{p}_\perp)^2,\mu) \mathcal{B}_q(t_B,x,\mathbf{p}_\perp^2,\mu) S(k_S,\mu)$$

Predictions for DIS 1-jettiness

x dependence:



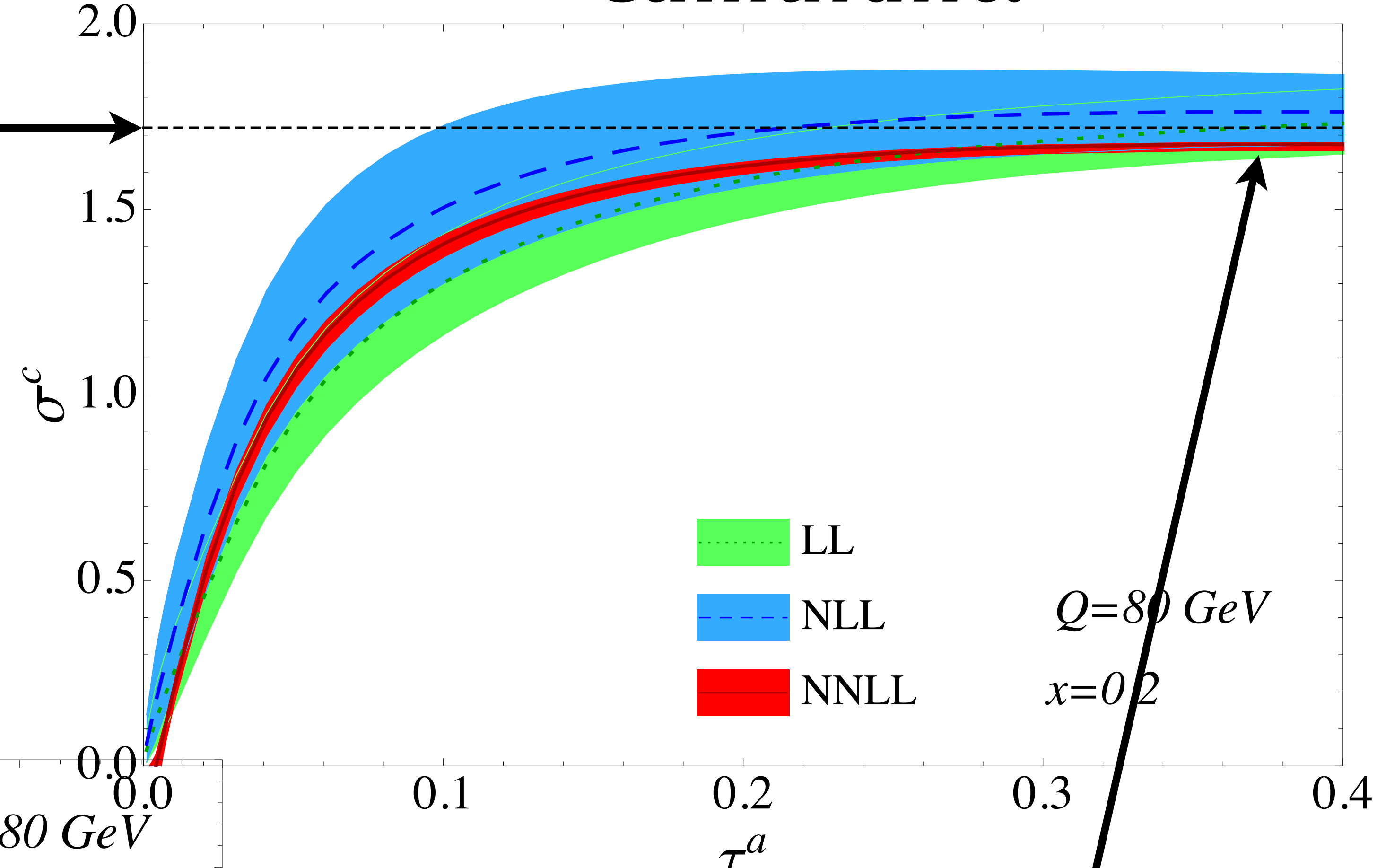
Q dependence:



Predictions for DIS 1-jettiness

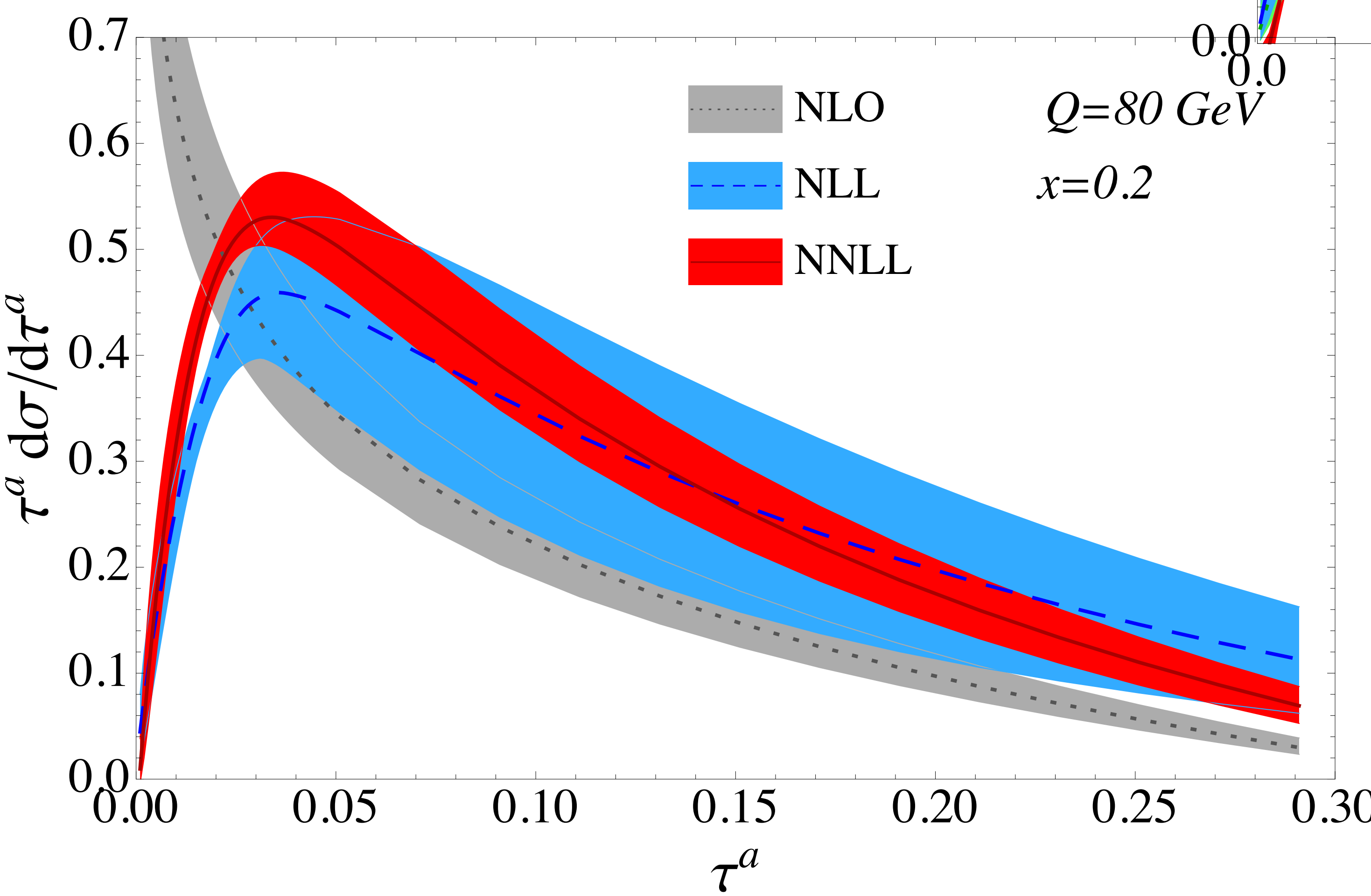
cumulant:

NLO QCD



nonsingular corrections small

differential distribution:

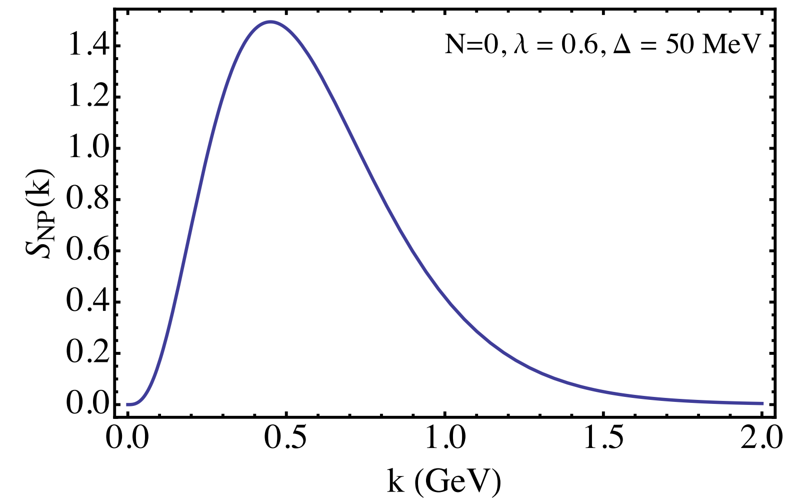


Predictions for DIS 1-jettiness

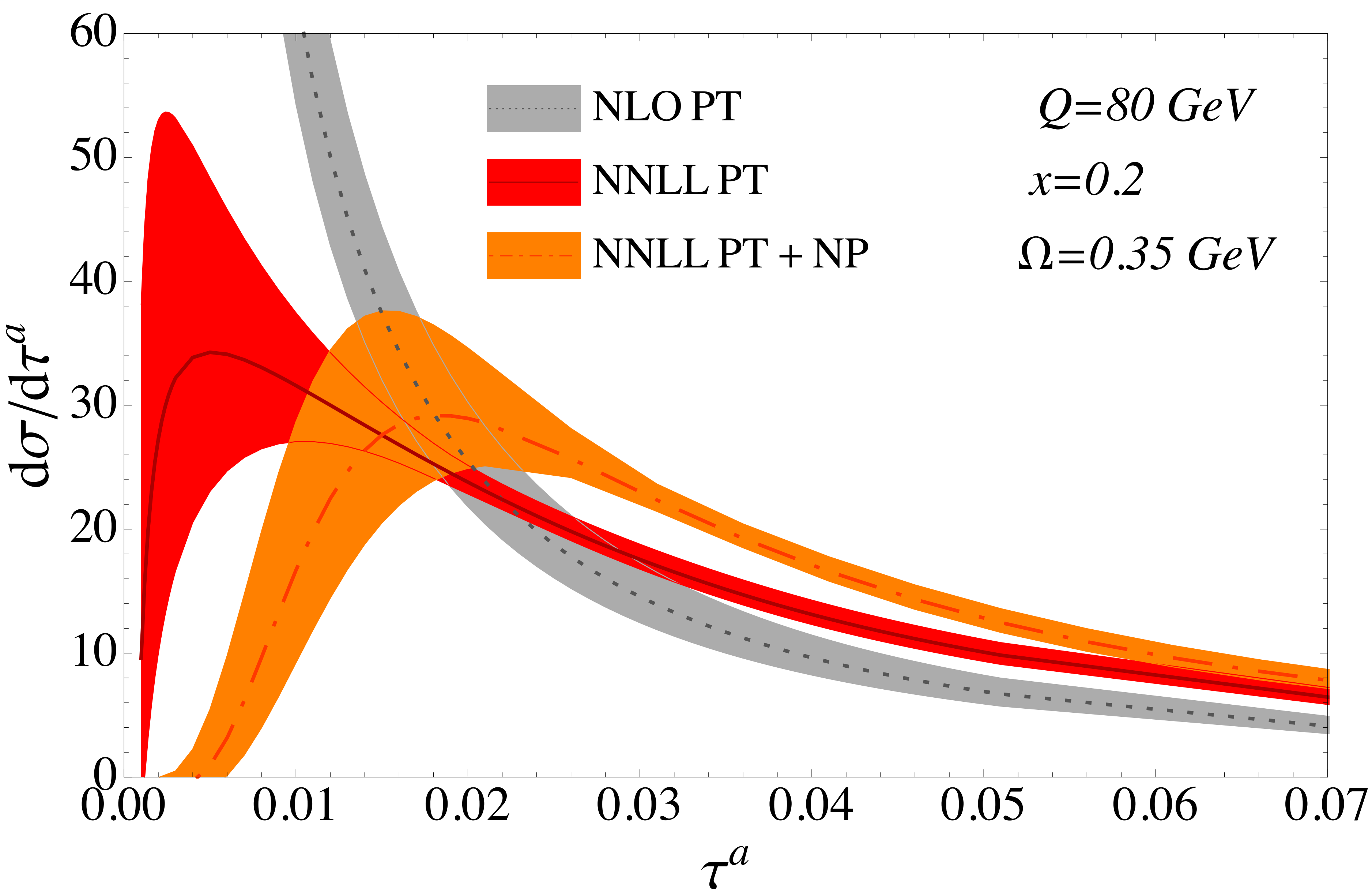
$$S_{NP}(l) = f(l - \Delta)$$

$$f(l) = \frac{1}{\lambda}\sum_{n=0}^{N} c_n f_n\Big(\frac{l}{\lambda}\Big)$$

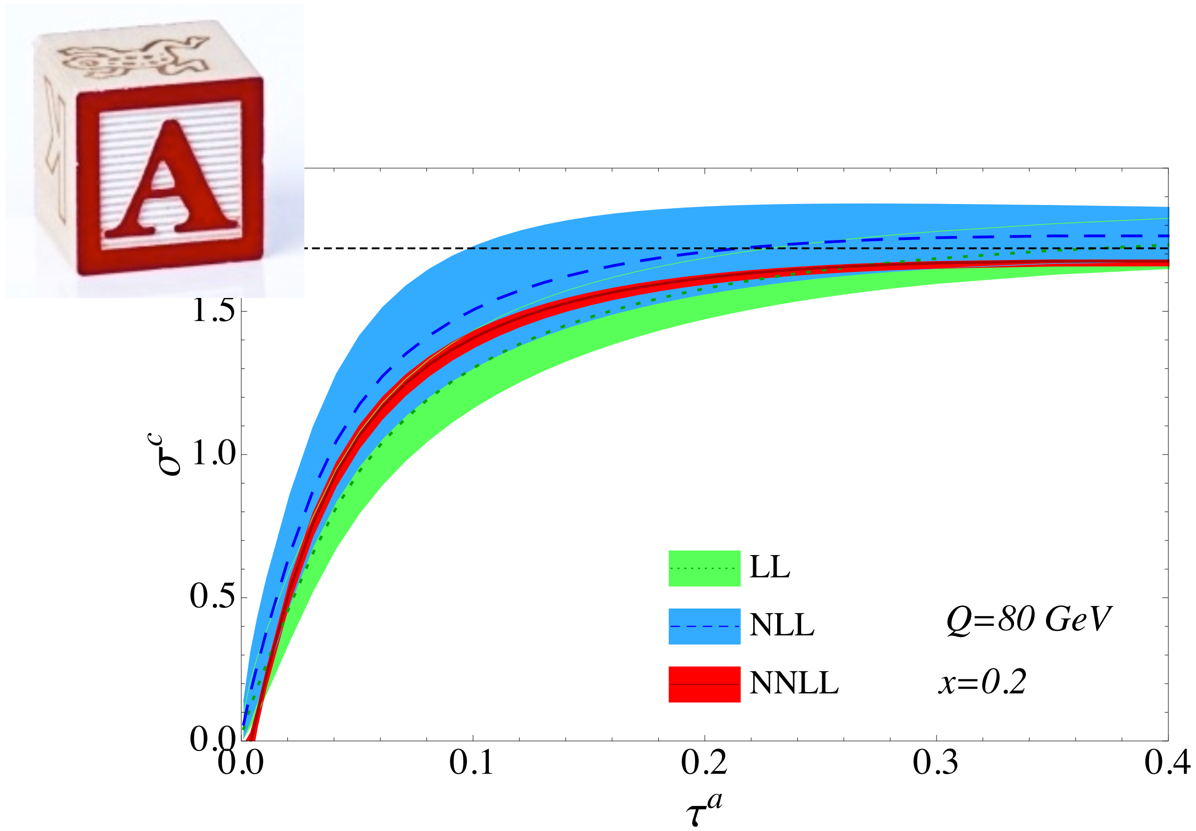
Ligeti, Stewart, Tackmann (2008)

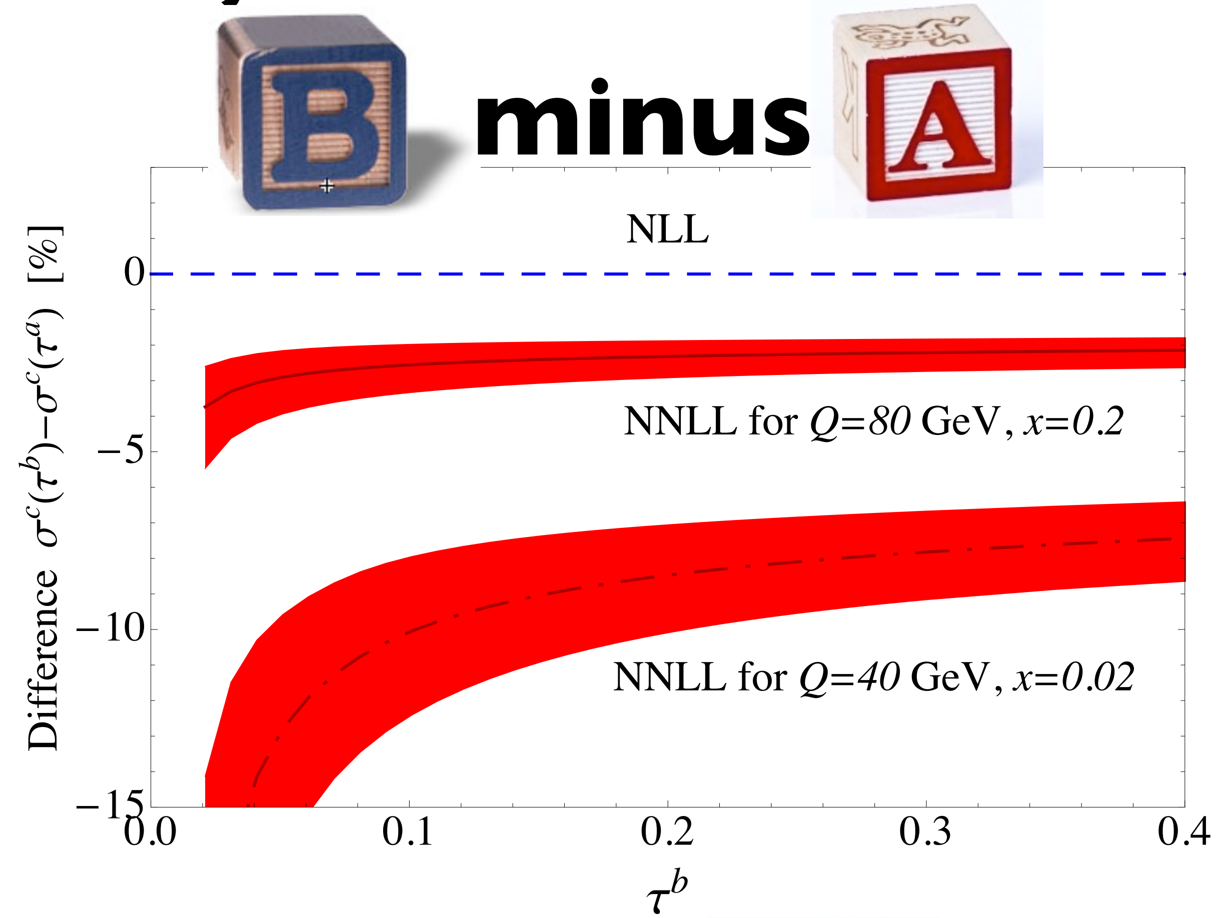


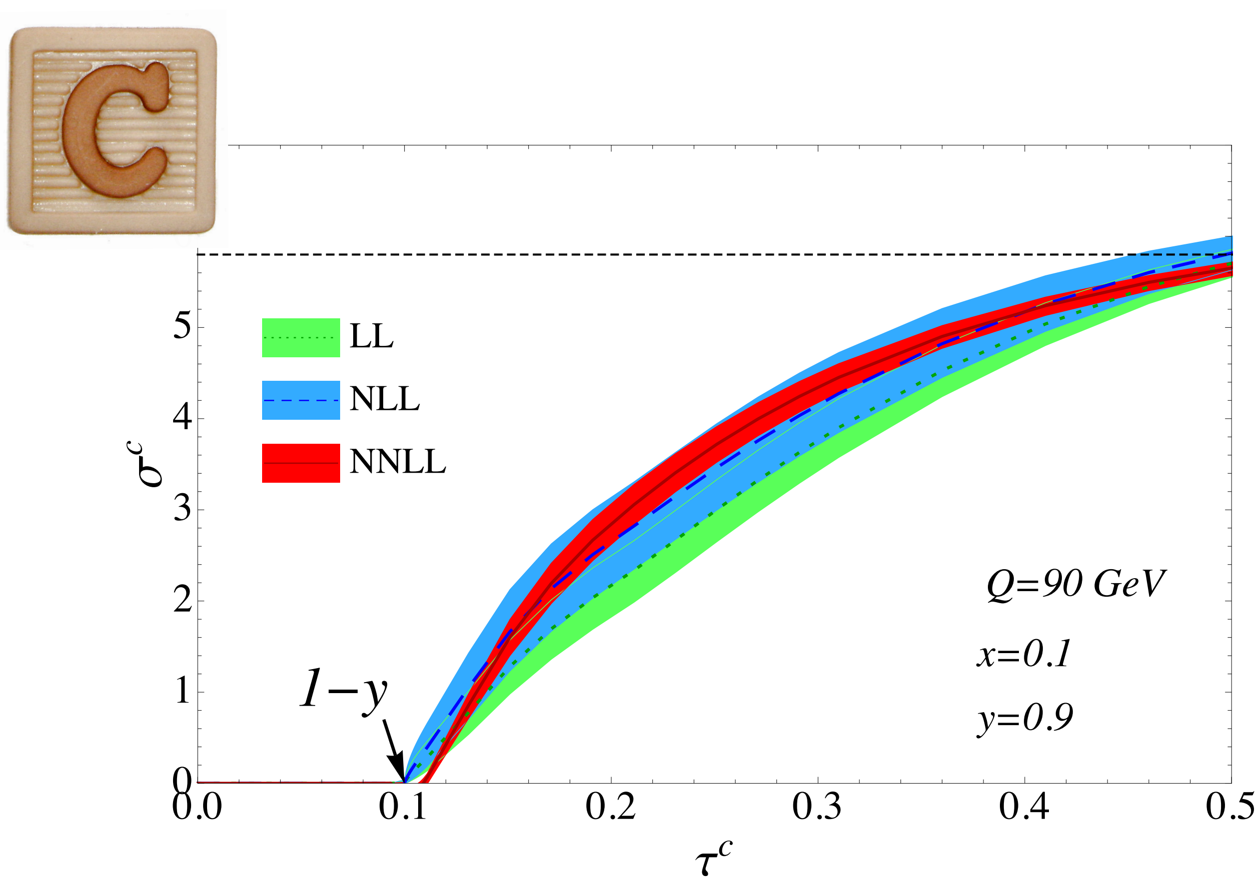
convolution with NP shape function:

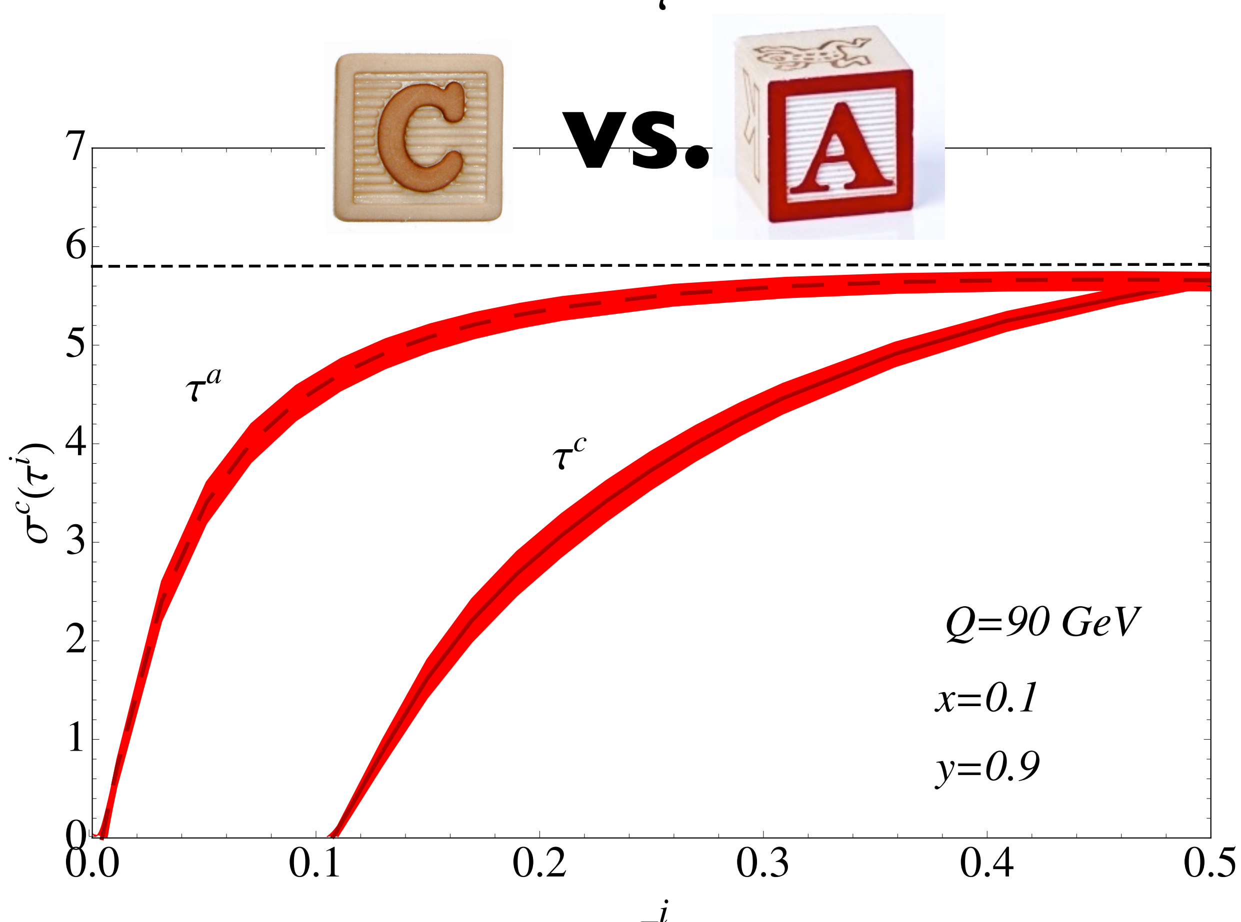


Predictions for DIS 1-jettiness

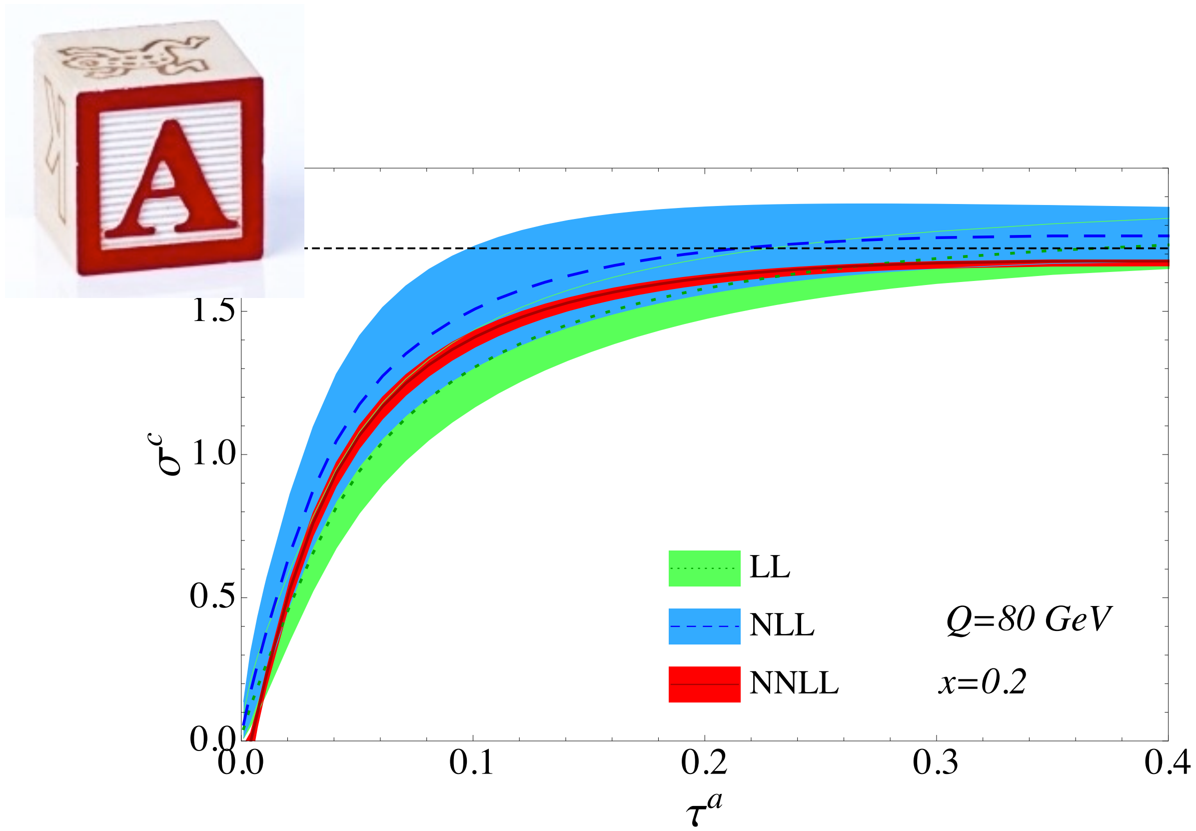


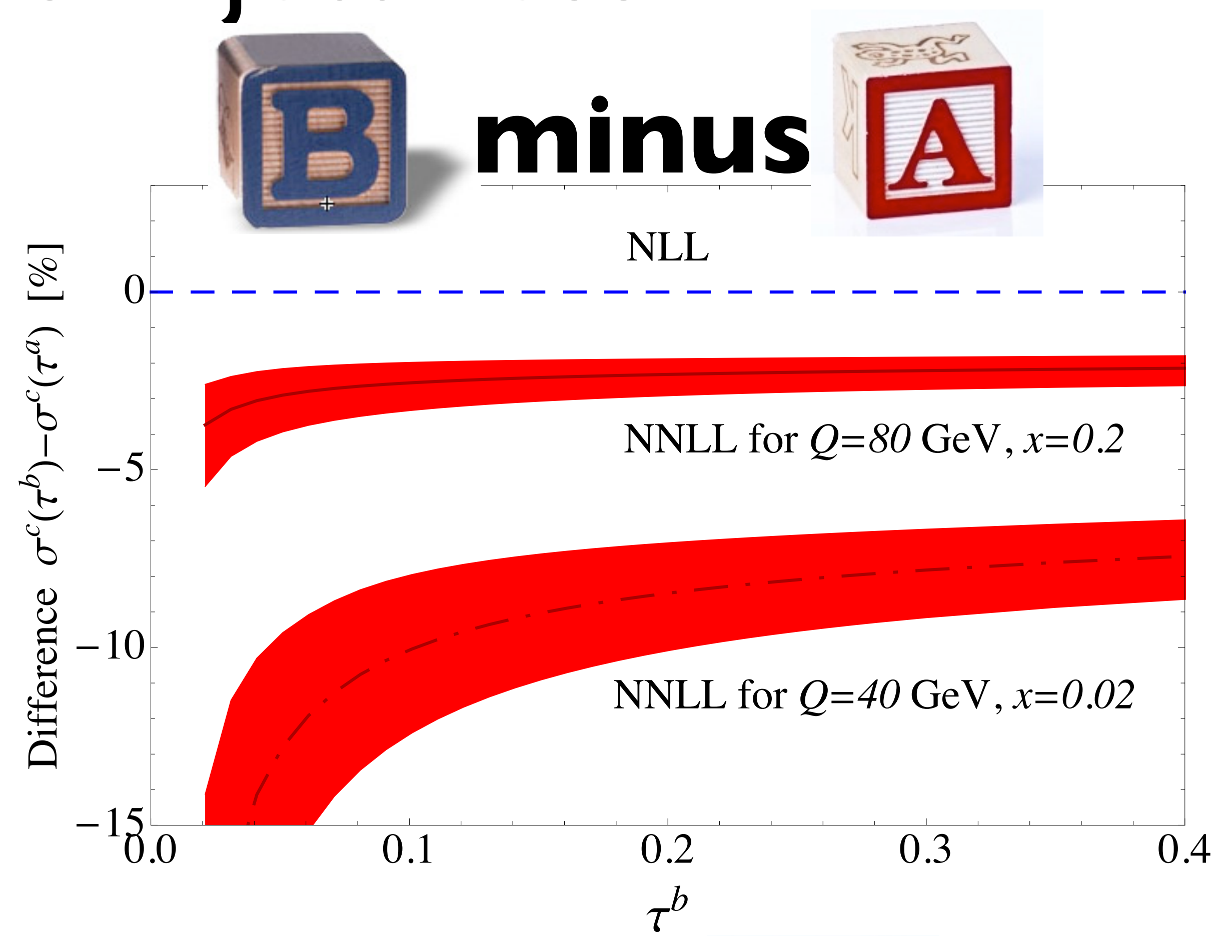


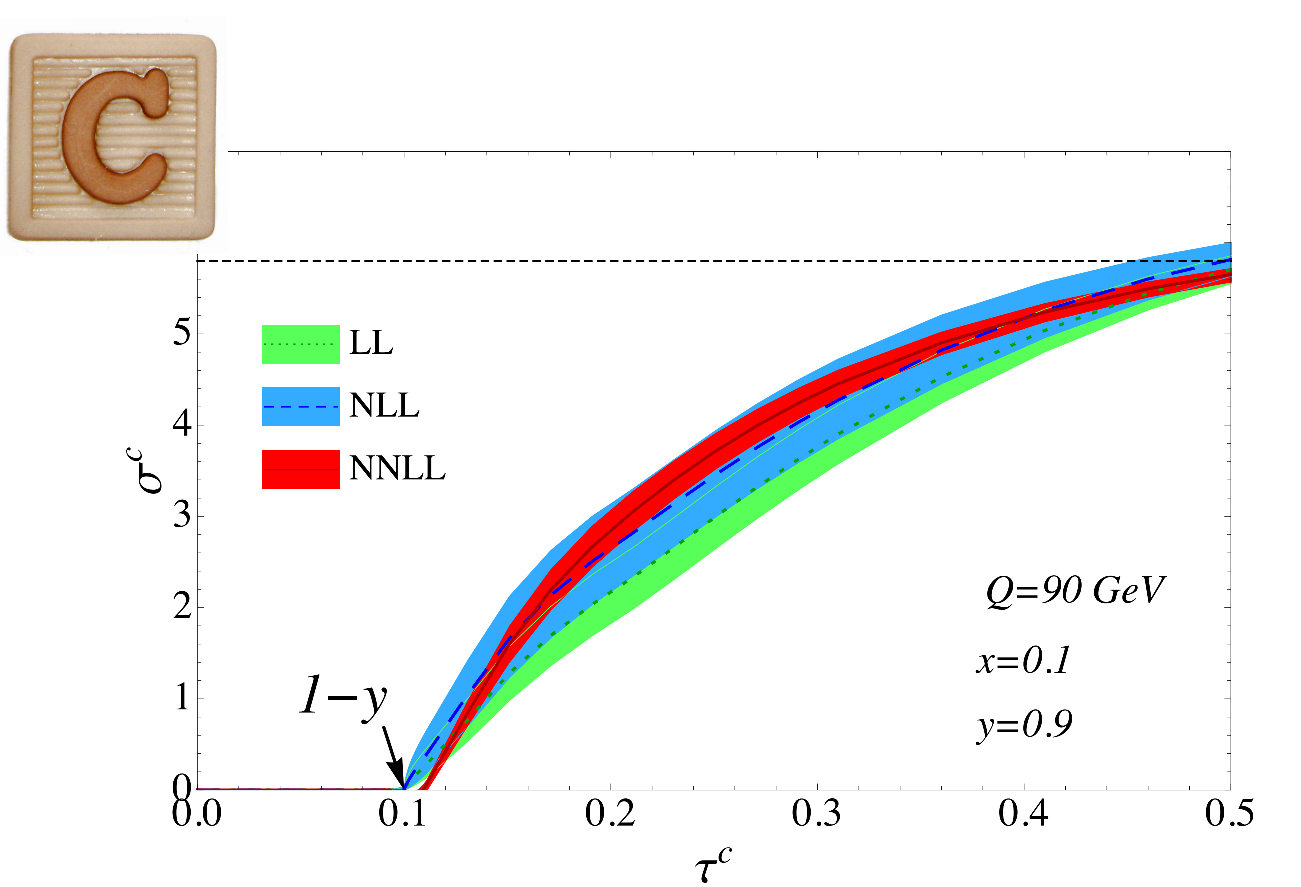


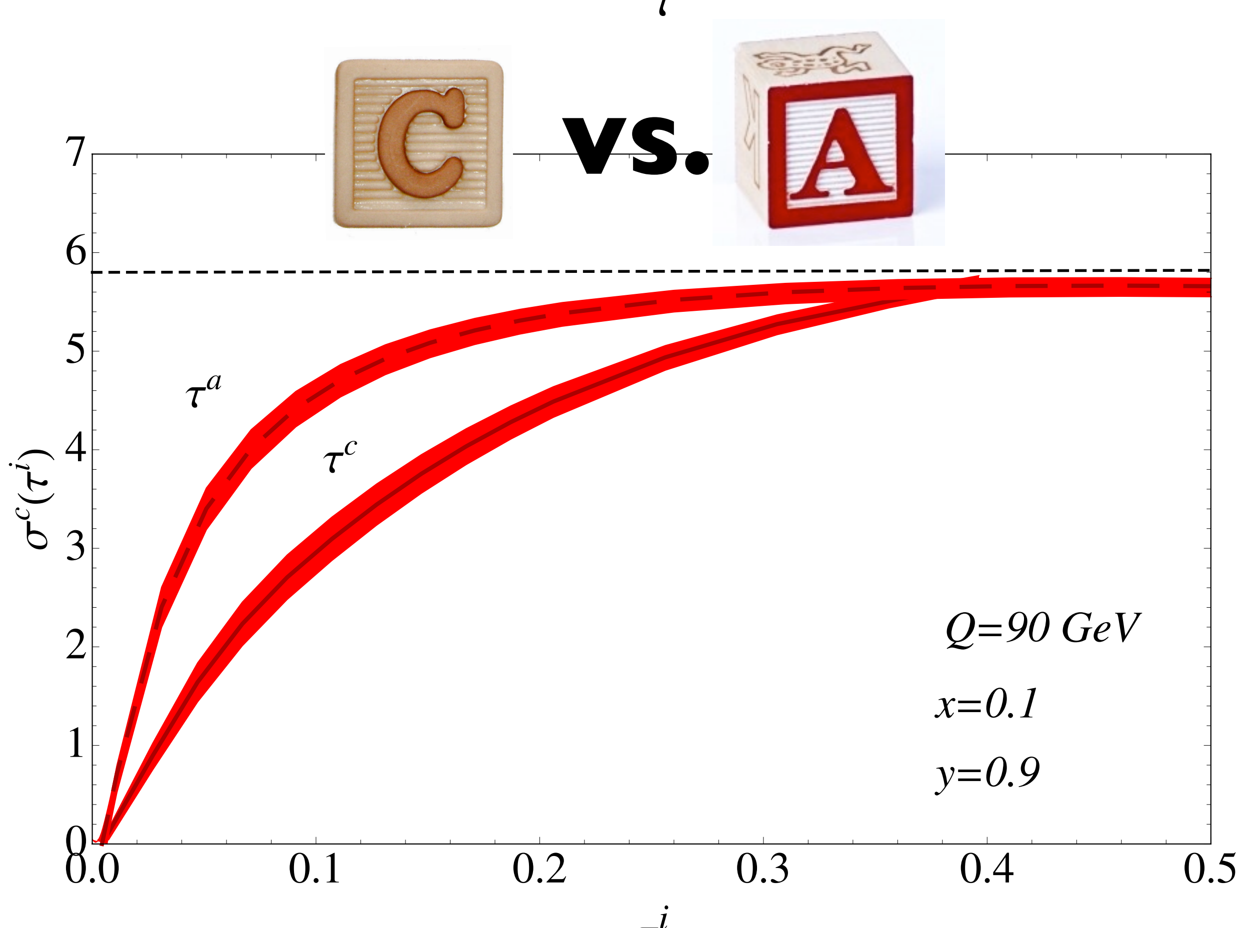


Predictions for DIS 1-jettiness









Power Correction / Hadronization Universality & Hadron Masses

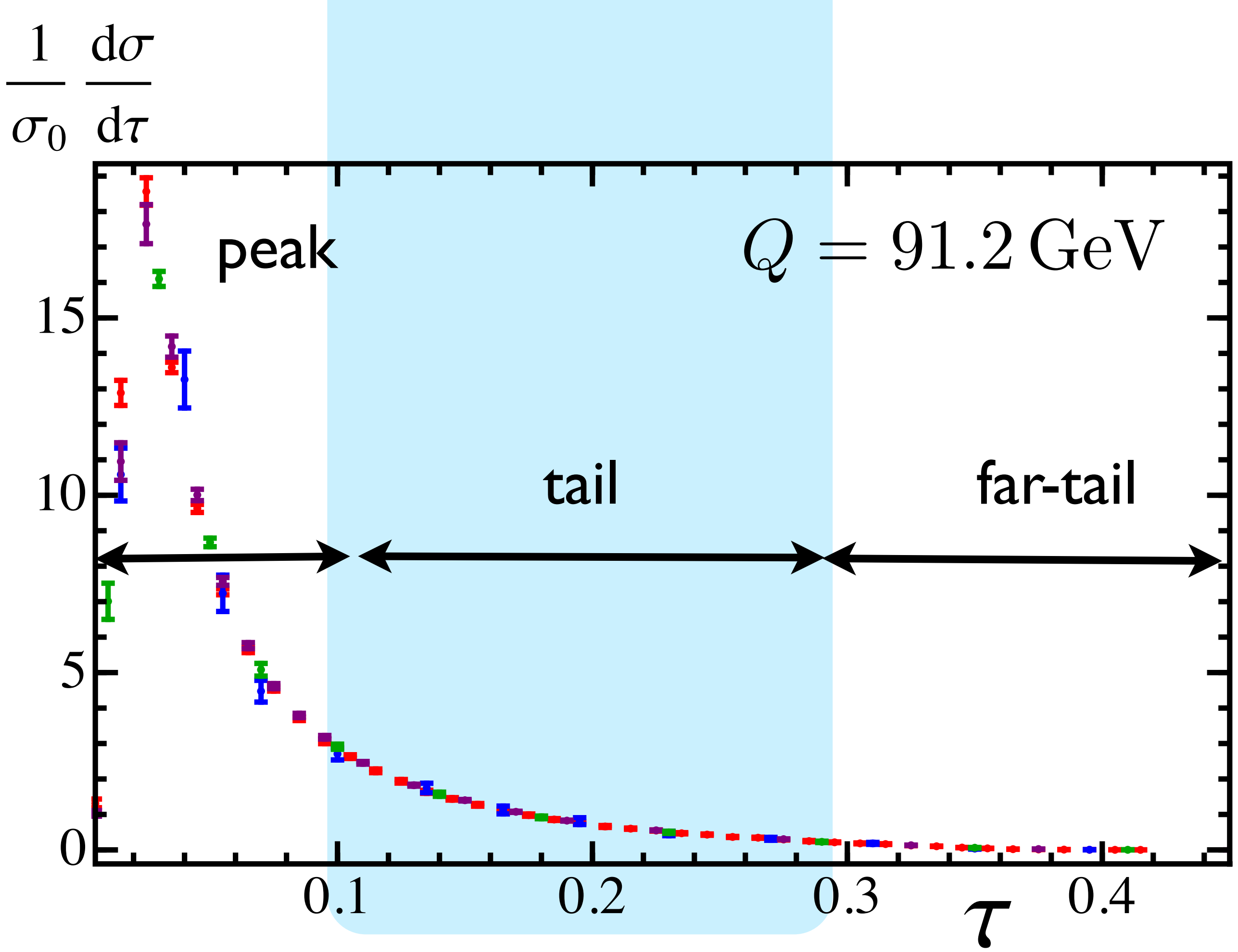
back to e^+e^-

Salam and Wicke; Lee and Sterman;

V. Mateu, IS, J. Thaler arXiv:1301.4555

Event Shapes $e^+e^- \to \text{jets}$

study power corrections and hadron mass effects in tail region, where an OPE is well defined



Dispersive approach

[Dokshitzer & Webber]

Shape Function Approach

$$S_e(\ell) = \int dp\, \hat{S}_e(\ell - p) F_e(p)$$

We will concentrate on event shapes that are not recoil sensitive, They can be written in the dijet limit as: $$e(N) = \frac{1}{Q}\sum_{i\in N} m_i^{\perp} f_e(r_i, y_i)$$

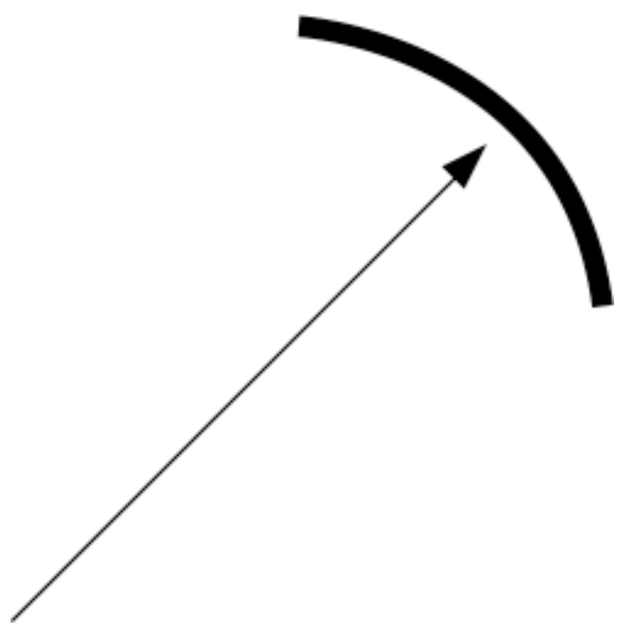
$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$	rapidity	All event shapes can be expressed in terms of these two variables
$r \equiv \frac{p^{\perp}}{m^{\perp}}$	transverse velocity	

$m^{\perp} = \sqrt{p_{\perp}^2 + m^2}$ transverse mass

for $p^{\perp} \sim \Lambda_{\rm QCD}$ can not neglect m

massless limit $r = 1$

Hadron masses and Schemes



What can be measured for a particle in the detector?

Ideally we would like **energy and momentum separately**, but this is not always possible.

If a **particle** is **not identified**, mass is not known, no information on magnitude of momentum.

One can assume all particles are pions ["default" scheme]

Alternatively one can use only energy and directions [E scheme] $|\vec{p}| \to E$

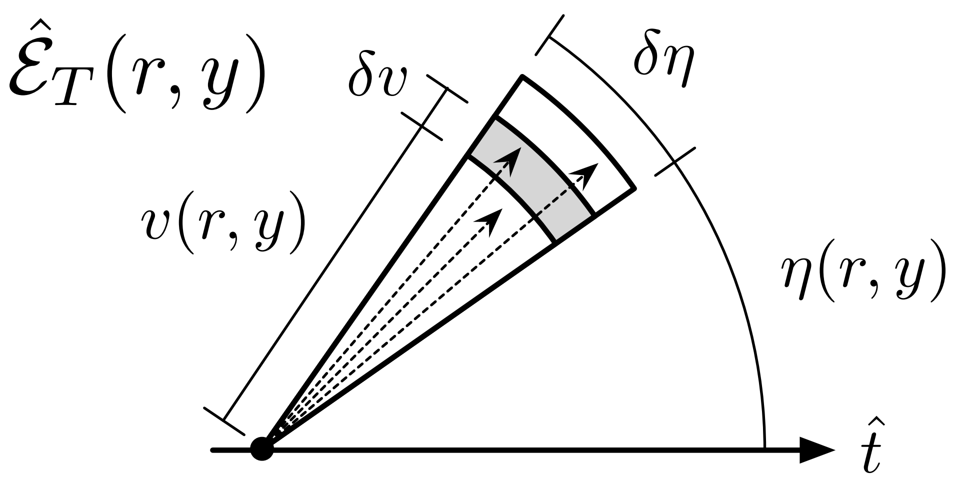
Finally one can use only momenta and directions [P scheme] $E \to |\vec{p}|$

These considerations are irrelevant in perturbation theory, but change the function $f_e(r, y)$, so they have important consequences for power corrections!

Mass Effects in SCET

$$e(N) = \frac{1}{Q}\sum_{i\in N} m_i^{\perp}\, f_e(r_i, y_i)$$

$$\Omega_1^e = \int \mathrm{d}r\,\mathrm{d}y\, f_e(r,y) \langle\, 0 \,|\, \overline{Y}_{\bar n}^{\dagger} Y_n^{\dagger} \mathcal{E}_T(r,y) Y_n \overline{Y}_{\bar n} \,|\, 0\,\rangle$$



measures momenta of particles with given transverse velocity flowing at a given rapidity

$$\gamma^{\Omega_1(r)} = -\frac{\alpha_s C_A}{\pi}\ln(1-r^2)$$

r-dependent anomalous dimension
no mixing between various r values

Mass Effects in SCET

[VM, I.W. Stewart, J.Thaler]
arXiv: 1209.3781

$$e(N) = \frac{1}{Q}\sum_{i\in N} m_i^\perp\, f_e(r_i, y_i)$$

$$\Omega_1^e = \int \mathrm{d}r\,\mathrm{d}y\, f_e(r,y) \langle\, 0\,|\,\overline{Y}^\dagger_{\bar n} Y^\dagger_n \mathcal{E}_T(r,y) Y_n \overline{Y}_{\bar n}\,|\,0\,\rangle = c_e \int \mathrm{d}r\, g_e(r)\Omega_1(r)$$

Boost invariance requires this term is y-independent

Operator definition of power correction $\Omega_1(r) = \langle\, 0\,|\,\overline{Y}^\dagger_{\bar n} Y^\dagger_n \mathcal{E}_T(r,0) Y_n \overline{Y}_{\bar n}\,|\,0\,\rangle$

Same as for massless computation $c_e = \int_{-\infty}^{\infty} \mathrm{d}y\, f_e(1,y)$

$$g_e(r) = \frac{1}{c_e}\int \mathrm{d}y\, f_e(r,y)$$

encodes all mass effects

each $g_e(r)$ defines a universality class of events with same power correction

Event shapes considered

Thrust

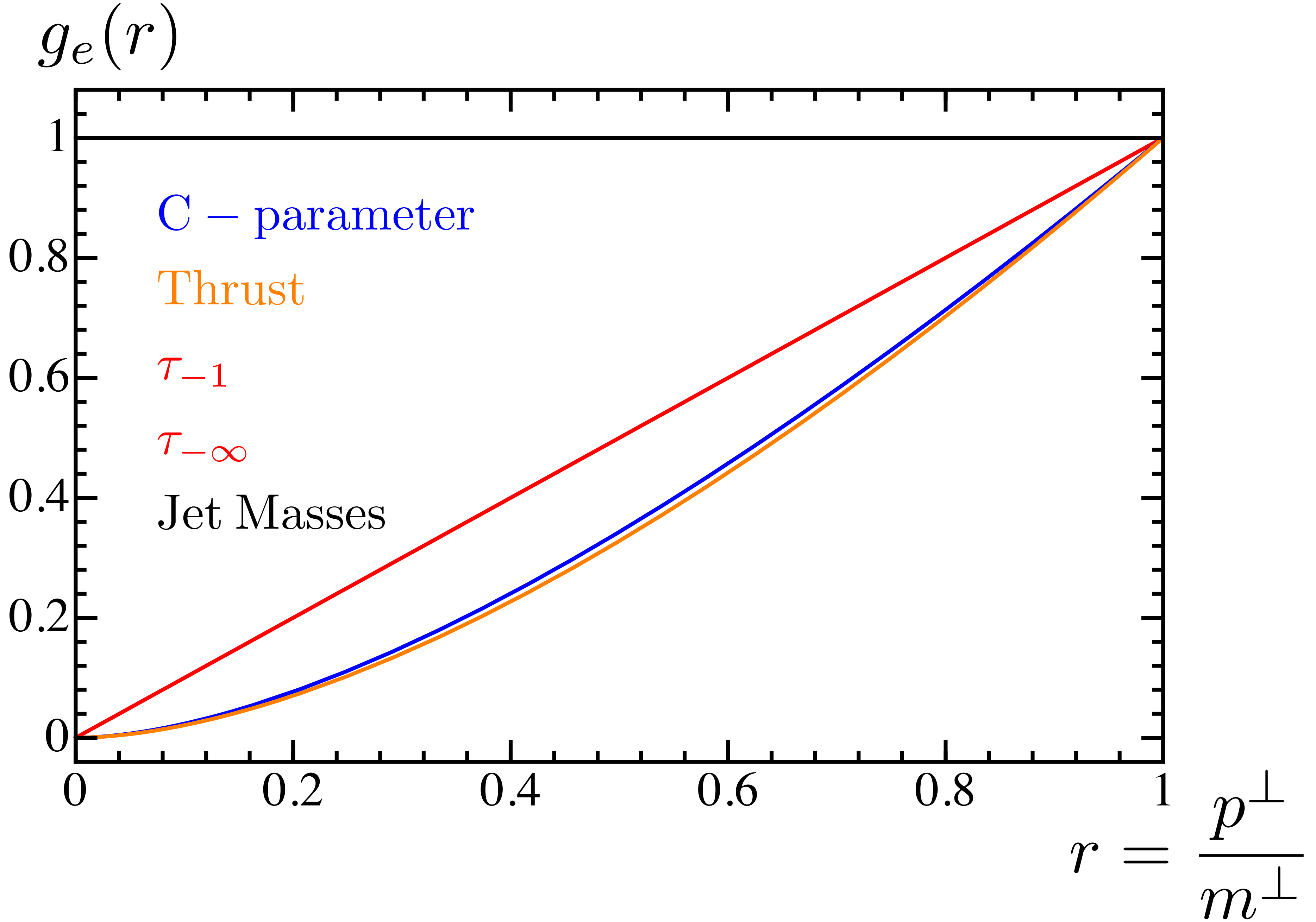
Jet Masses

C-parameter

Angularities

2-Jettiness

mass scheme (default definition)



Same **color** means same **power correction**

C-parameter $\simeq$ Thrust

Event shapes considered

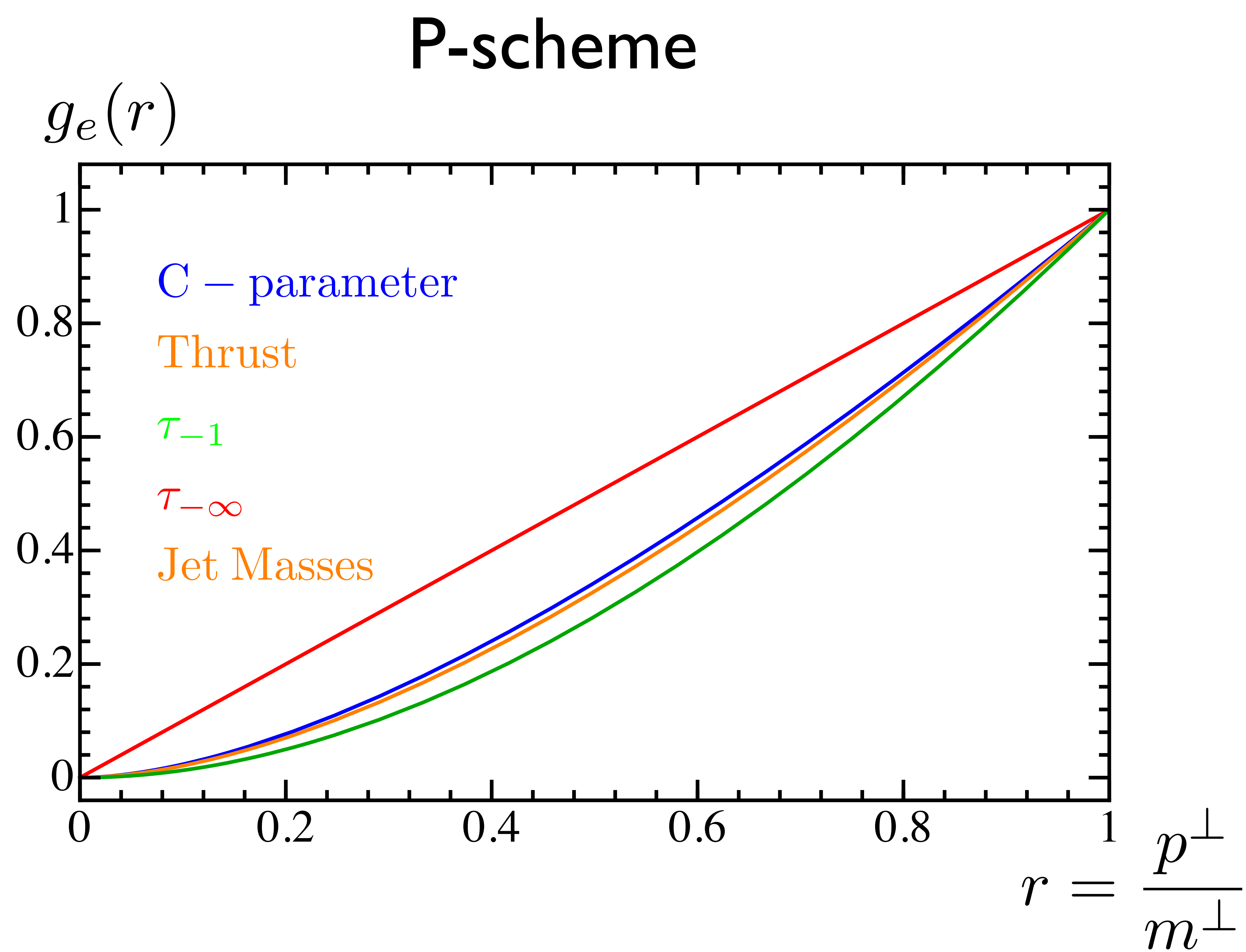
Thrust

Jet Masses

C-parameter

Angularities

2-Jettiness



Scheme changes event shape definition

Event shapes considered

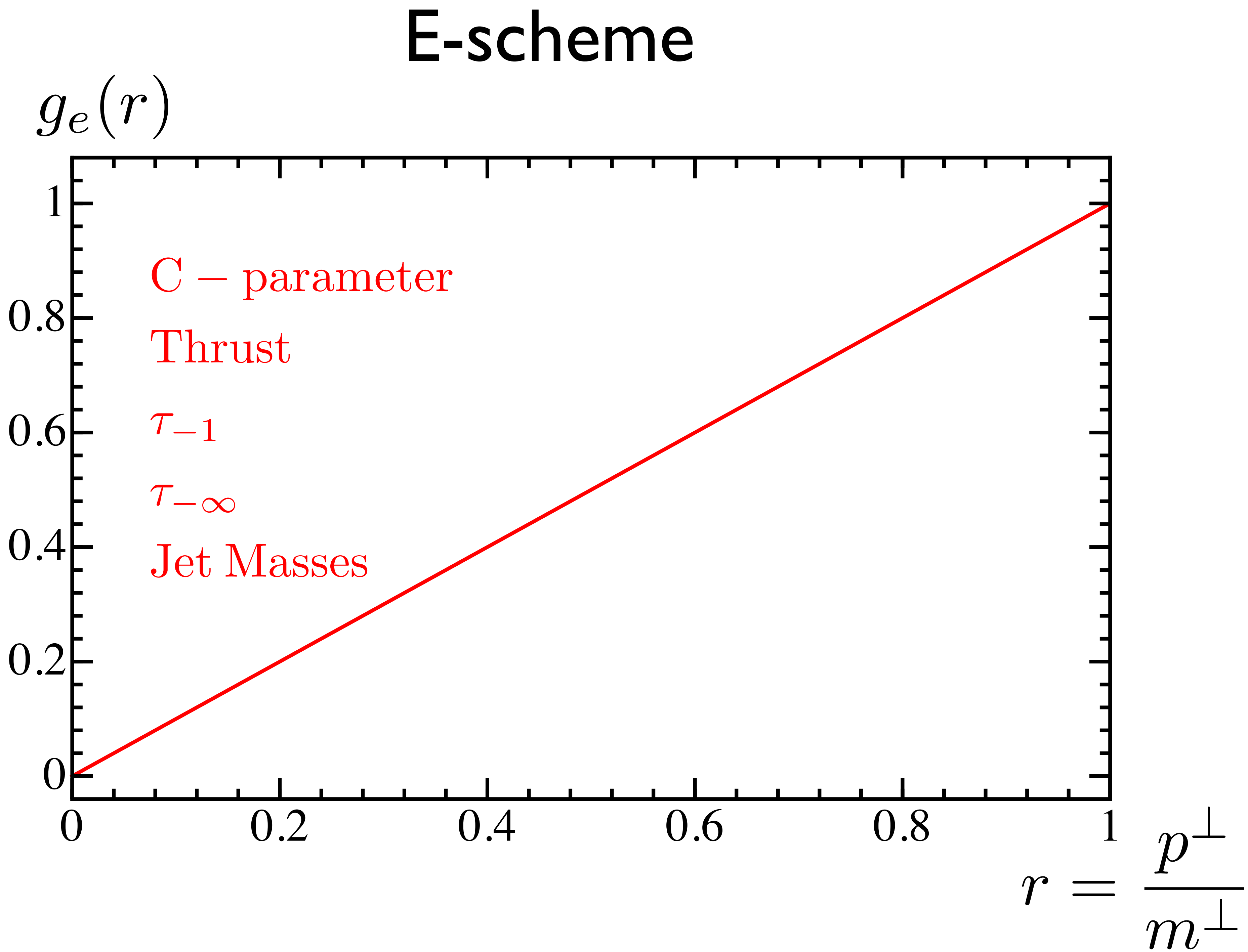
Thrust

Jet Masses

C-parameter

Angularities

2-Jettiness

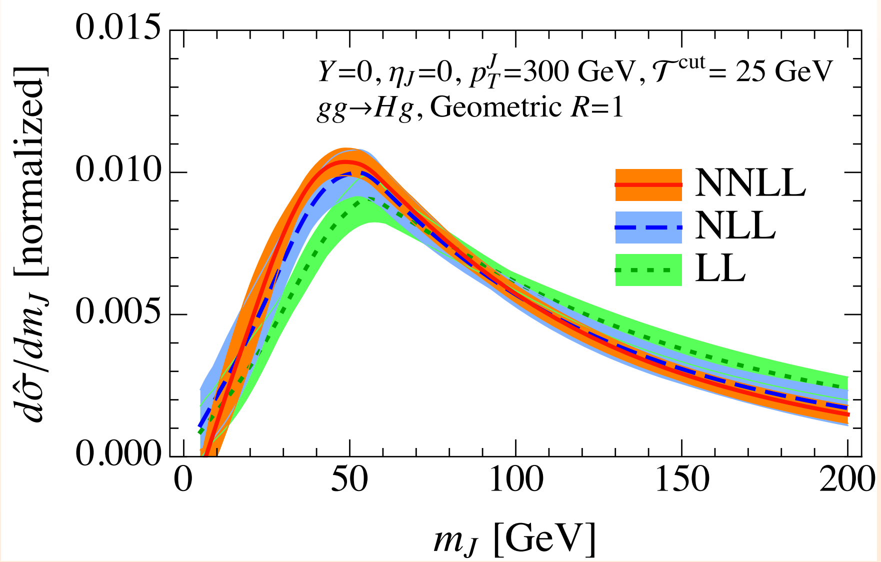


Scheme changes
event shape definition

Summary

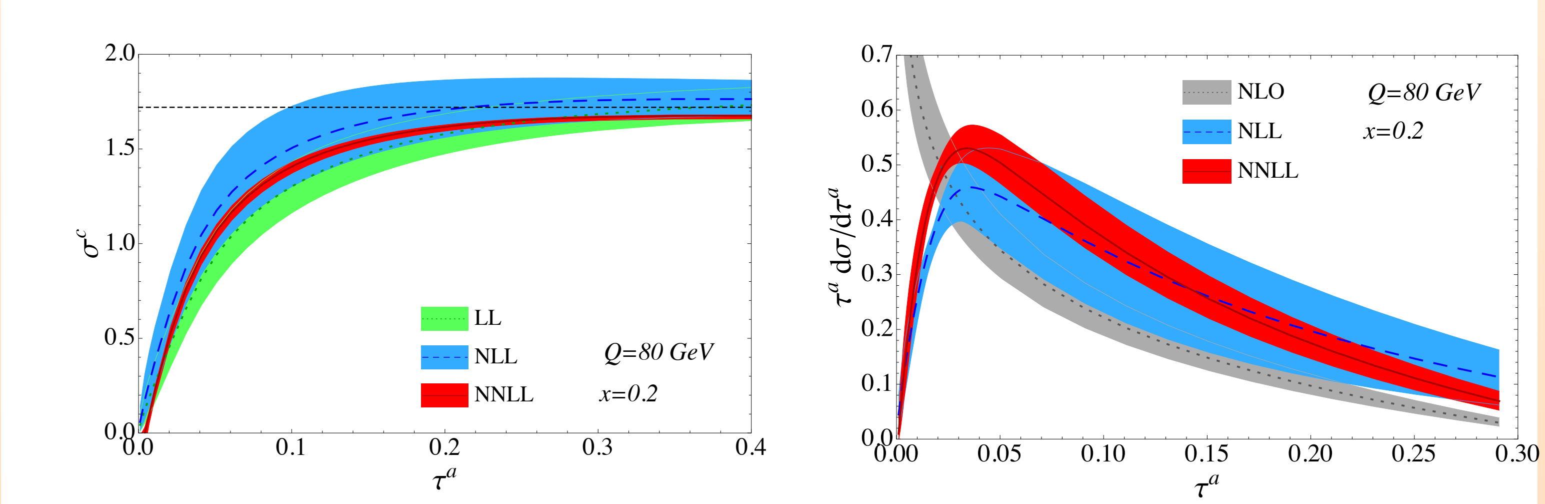
Jet Mass at NNLL for exclusive jets from pp

- NNLL analytic jet mass computations with control over most of the things that influence this spectrum
- N-jettiness ⟶ extend to other processes



Factorization Theorems for DIS event shapes

- Factorization results for 3 DIS event shapes & NNLL predictions



Hadronization/Power Corrections

- $\Omega_1^C \simeq \frac{3\pi}{2}\Omega_1^\tau$
  $\Omega_1^{\rm HJM} \neq 2\,\Omega_1^\tau$
  agrees with data
- anomalous dimension gives extra ln(Q) dependence
- framework can also be applied to pp and e⁻p

Backup Slides

Varying the jet radius:

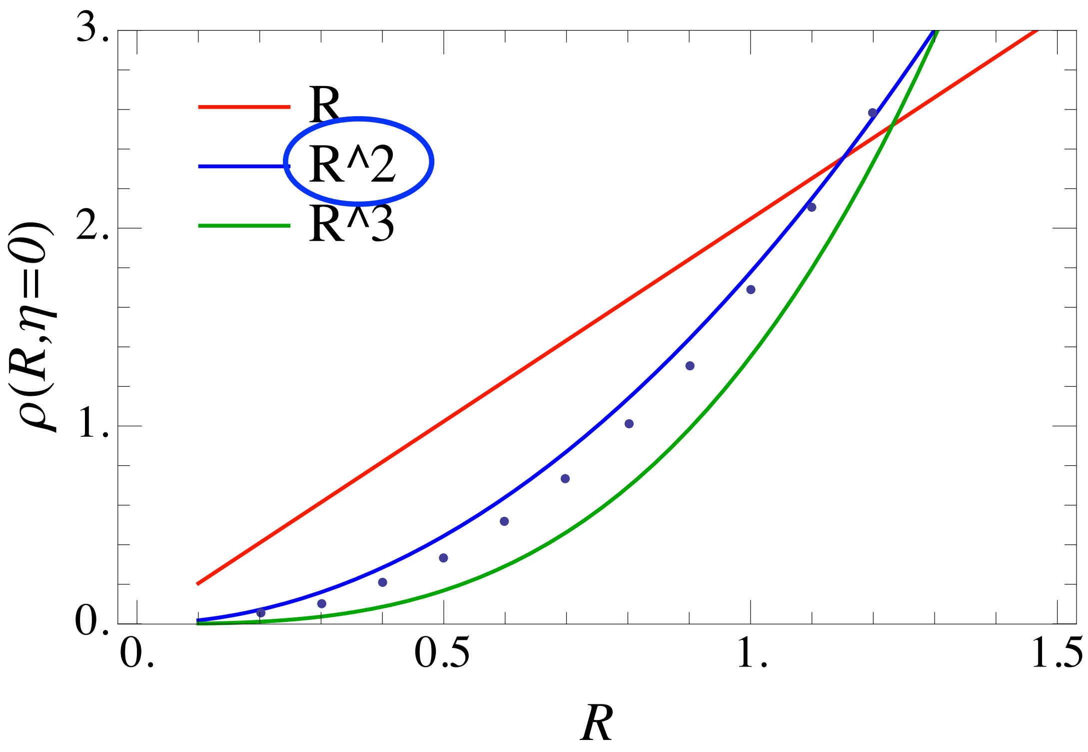
E geometric measure

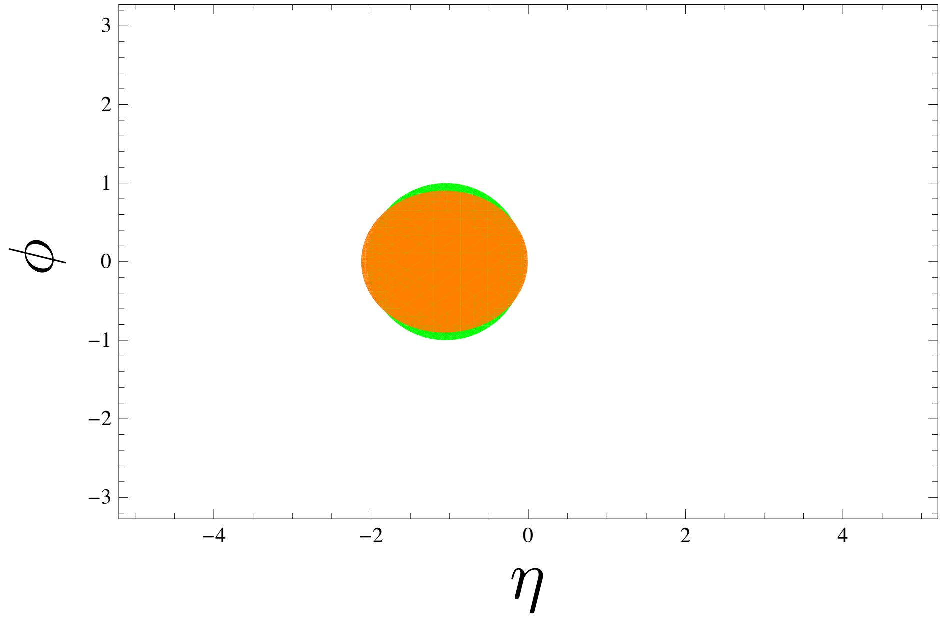
radius = R

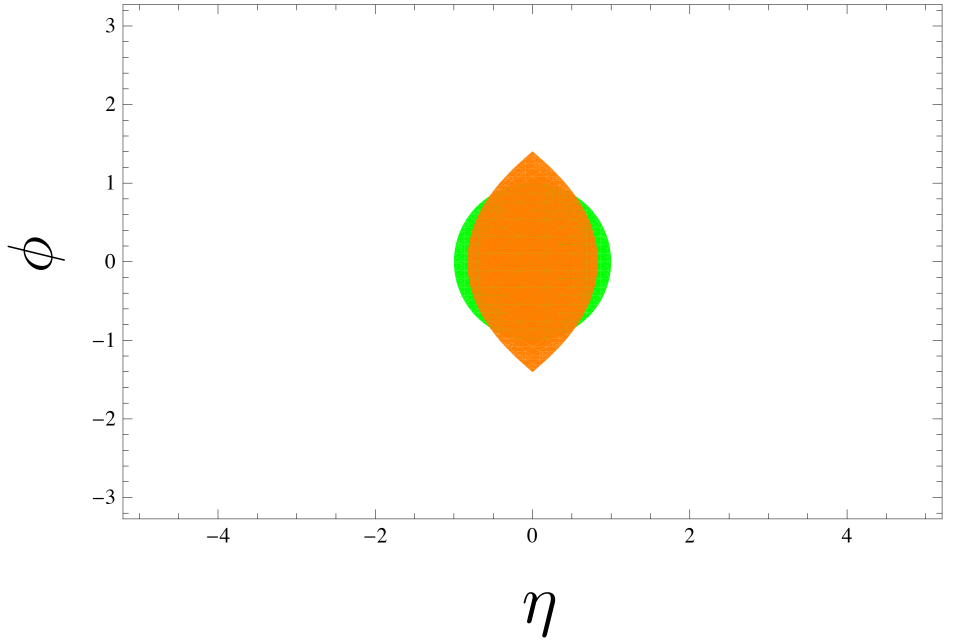
$$Q_i = E^{\,i}_{\text{jet}}\,\rho(R,\eta_{\text{jet}})$$

pick $\rho(R,\eta_{\text{jet}}) \propto R^2$

to match area for cone of radius R





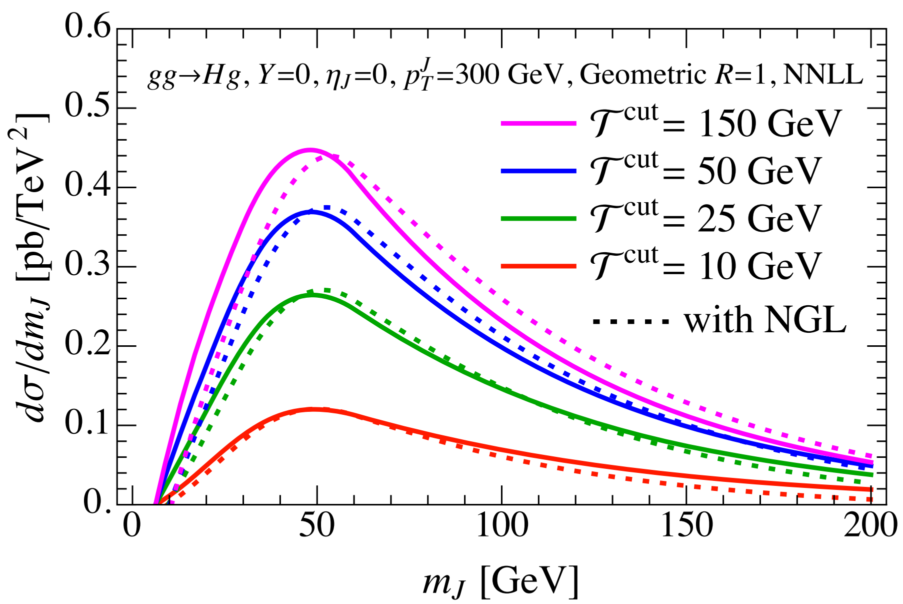


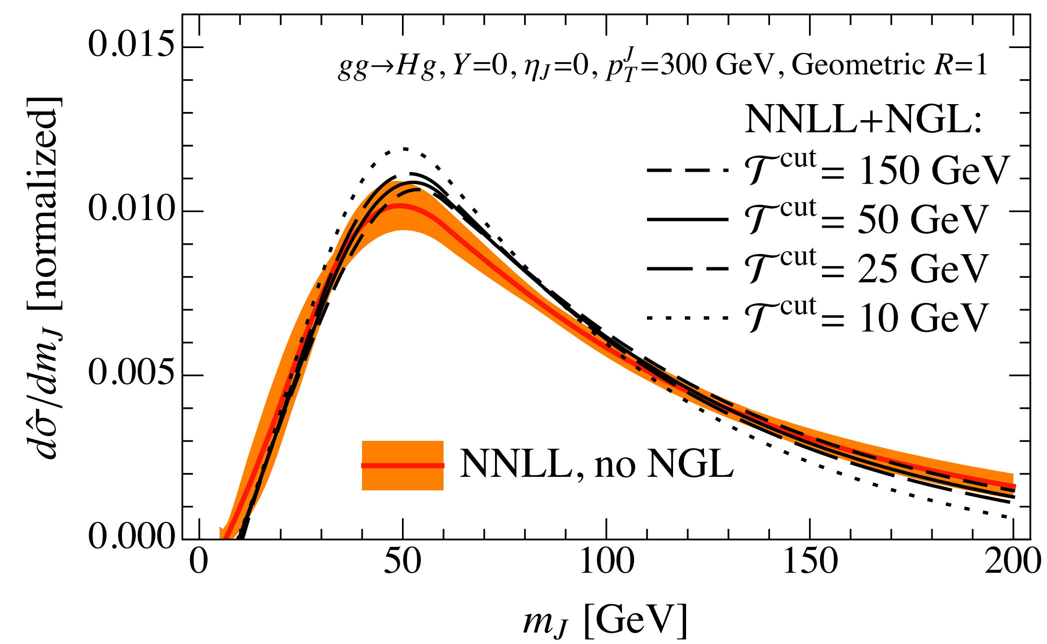
Dasgupta, Salam

Non-global logs: $\alpha_s^2(\mu_S)\ln^2\left(\frac{m_J^{\mathrm{cut}\,2}}{p_T^J \mathcal{T}^{\mathrm{cut}}}\right)$, $\alpha_s^2(\mu_S)\frac{p_T^J \ln(m_J^2/p_T^J \mathcal{T}^{\mathrm{cut}})}{m_J^2}$

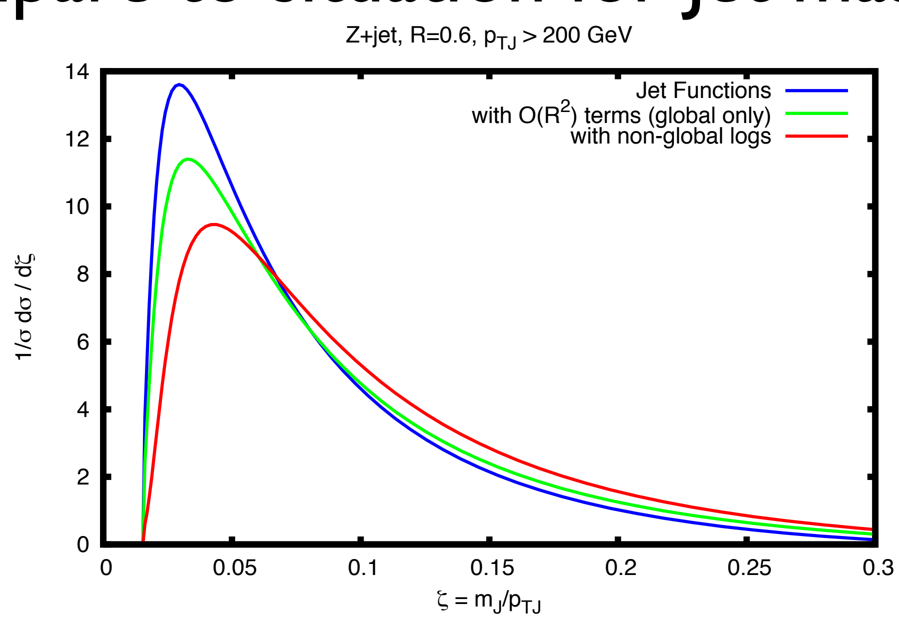
NGLs appear as fixed order corrections in S

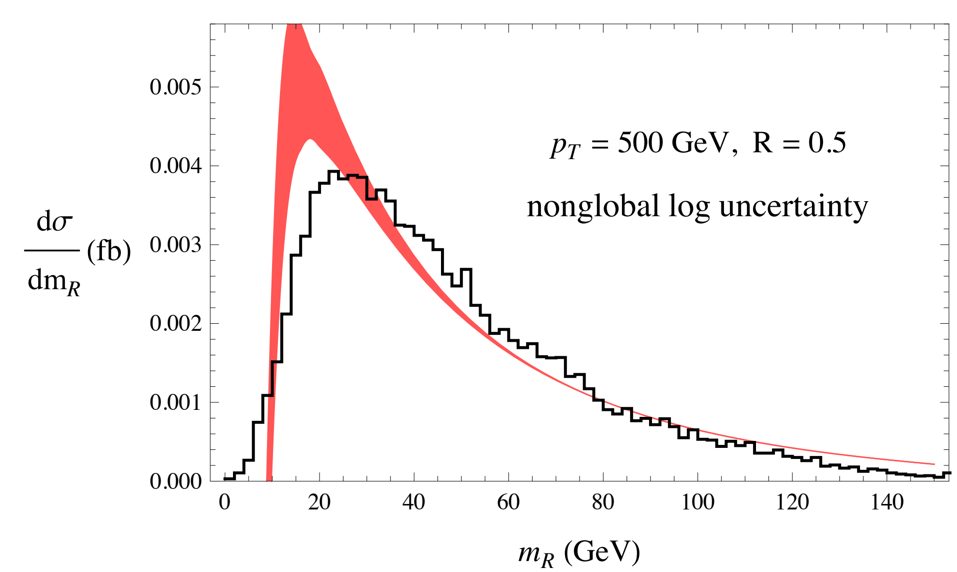
Tempered by our global log summation





Compare to situation for Jet mass spectrum for inclusive jets:





Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky

Chien, Kelley, Schwartz, Zhu

Mass Effects in SCET

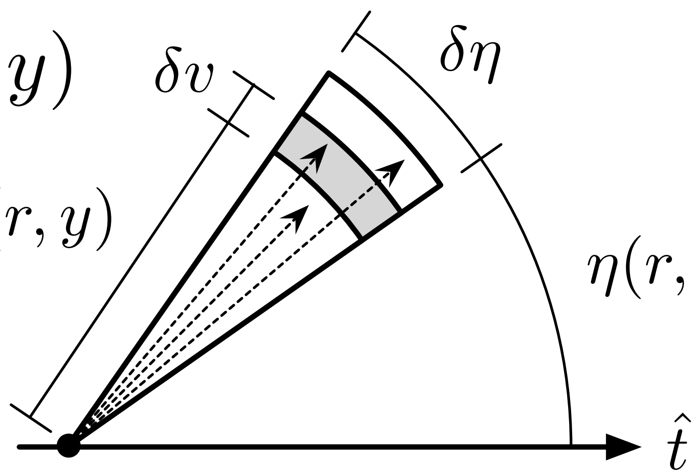
[Mateu, IS, J.Thaler]
arXiv: 1209.3781

$$e(N) = \frac{1}{Q}\sum_{i\in N} m_i^{\perp}\, f_e(r_i, y_i)$$

Transverse velocity operator

$$\mathcal{E}_T(r,y)|\,N\,\rangle = \sum_{i\in N} m_i^{\perp}\delta(r-r_i)\delta(y-y_i)|\,N\,\rangle$$

$\hat{\mathcal{E}}_T(r,y)$



$$v = v(r,y)$$
$$\eta = \eta(r,y)$$

measures momenta of particles with given transverse velocity flowing at a given rapidity

$$\hat{e} = \frac{1}{Q}\int \mathrm{d}y\,\mathrm{d}r\,\mathcal{E}_T(r,y) f_e(r,y)$$

two integrals

$$\mathcal{E}_T(v,\eta) = -\frac{v(1-v^2\tanh^2 y)^{\frac{3}{2}}}{\cosh\eta}\lim_{R\to\infty} R^3\int_0^{2\pi}\mathrm{d}\phi\,\hat{n}_i\,T_{0i}(R, v\,R\,\hat{n})$$

Results and consequences

$$\gamma^{\Omega_1} = -\frac{\alpha_s C_A}{\pi} \log(1-r^2)$$

r-dependent anomalous dimension
no mixing between various r values

RGE solution at NLL

$$\Omega_1(r,\mu) = \Omega_1(r,\mu_0)\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\frac{2\,C_A}{\beta_0}\log(1-r^2)}$$

$$\sim \Omega_1(r,\mu_0)\left[1 - \frac{\alpha_s(\mu_0)C_A}{\pi}\log\left(\frac{\mu}{\mu_0}\right)\log(1-r^2)\right]$$

Expanded out result

Not a resummation formula for Ω_1^e

$$\Omega_1^e(\mu) = \int \mathrm{dr}\, \mathrm{g_e(r)}\, \Omega_1(\mathrm{r},\mu_0)\left(\frac{\alpha_\mathrm{s}(\mu)}{\alpha_\mathrm{s}(\mu_0)}\right)^{\frac{2\,\mathrm{C_A}}{\beta_0}\log(1-\mathrm{r}^2)}$$

Unknown function !

Using expanded out result

$$\Omega_1^e(\mu) = \Omega_1^e(\mu_0) - \frac{\alpha_s(\mu_0)C_A}{\pi}\log\left(\frac{\mu}{\mu_0}\right)\Omega_{\log}^e(\mu_0)$$

$$\Omega_{\log}^e(\mu_0) = \int \mathrm{dr}\,\log(1-\mathrm{r}^2)\,\mathrm{g_e(r)}\,\Omega_1(\mathrm{r},\mu_0)$$

New nonperturbative parameter

Effect of hadron masses

Distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}e} = \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e} - \frac{1}{Q}\left(\Omega_1^{e}(\mu) + \frac{\alpha_s(\mu)}{\pi}\,\Omega_1^{e,\,d}(\mu)\right)\frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}e^2}(e)$$

usual shift

$$+ \frac{\Omega_1^{e,\,\ln}(\mu)}{Q}\,\frac{\alpha_s(\mu)C_A}{\pi}\left\{ \ln\left(\frac{\mu}{eQ}\right)\frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}e^2}(e) - \int_0^{eQ}\frac{\mathrm{d}\ell}{\ell}\left[\frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}e^2}\left(e-\frac{\ell}{Q}\right) - \frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}e^2}(e)\right]\right\},$$

additional term
(not just a shift)

First moment

$$\langle e\rangle = \langle e\rangle_{\mathrm{pert}} + \frac{\Omega_1^{e}(\mu)}{Q} + \frac{\alpha_s(\mu)}{\pi}\,\frac{\Omega_1^{e,\,d}}{Q} + \frac{\Omega_1^{e,\,\ln}(\mu)}{Q}\,\frac{C_A\alpha_s(\mu)}{\pi}$$

usual shift

$$\times\int_0^{e_{\max}}\mathrm{d}e\,\frac{1}{\hat{\sigma}}\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e}(e)\left[\ln\left(\frac{\mu}{Q(e_{\max}-e)}\right) - \frac{e^2}{e_{\max}(e_{\max}-e)}\right]$$

additional term

Comparisons to MC generators

Define generalized angularities, useful to compare to MC

$$\tau_{(n,a)} \equiv \sum_i m_i^{\perp} r_i^n e^{-|y_i|(1-a)} \quad \begin{cases} g_{(n,a)} = r^n \\ c_{(n,a)} = \dfrac{2}{1-a} \end{cases}$$

Comparisons to MC generators

Define generalized angularities, useful to compare to MC

$$\tau_{(n,a)} \equiv \sum_i m_i^{\perp} r_i^n e^{-|y_i|(1-a)} \quad \begin{cases} g_{(n,a)} = r^n \\ c_{(n,a)} = \dfrac{2}{1-a} \end{cases}$$

We study the first moment of the distributions
Taking differences of classes we obtain:

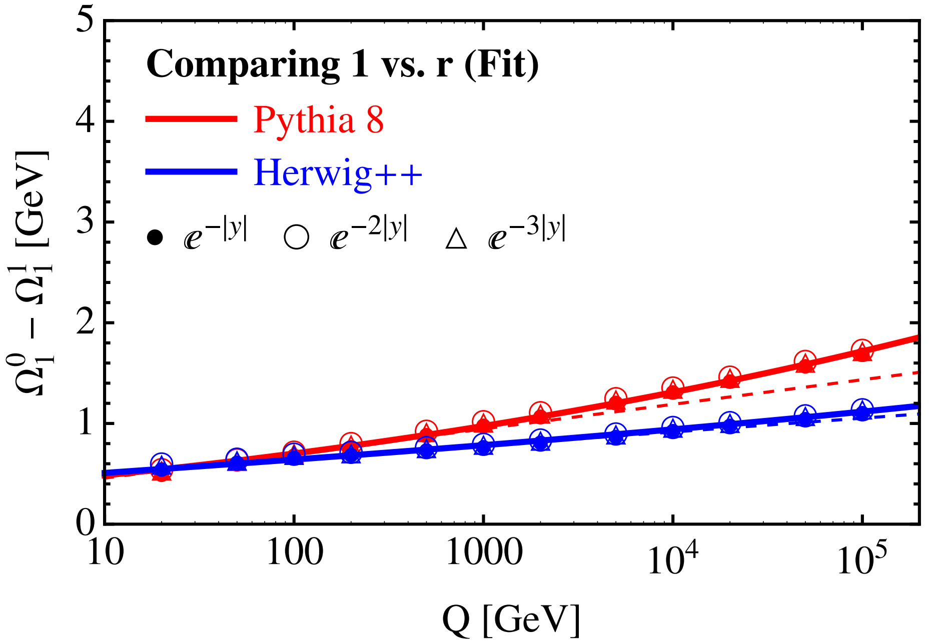
$$\Omega_1^0(\mu_Q) - \Omega_1^n(\mu_Q) = \frac{Q}{c_a}\left(\langle\tau_{(0,a)}\rangle - \langle\tau_{(n,a)}\rangle\right)$$

Perturbative moment is class-independent and vanishes in the difference

Comparisons to MC generators

Define generalized angularities, useful to compare to MC

$$\tau_{(n,a)} \equiv \sum_i m_i^{\perp} r_i^n e^{-|y_i|(1-a)} \begin{cases} g_{(n,a)} = r^n \\ c_{(n,a)} = \dfrac{2}{1-a} \end{cases}$$



resummed expression

expanded out expression

fit function basis $\{1, r, (1-r)^{-\frac{1}{4}}\}$