Status of Jet Physics

…actually more an introduction to SCET

André H. Hoang

University of Vienna

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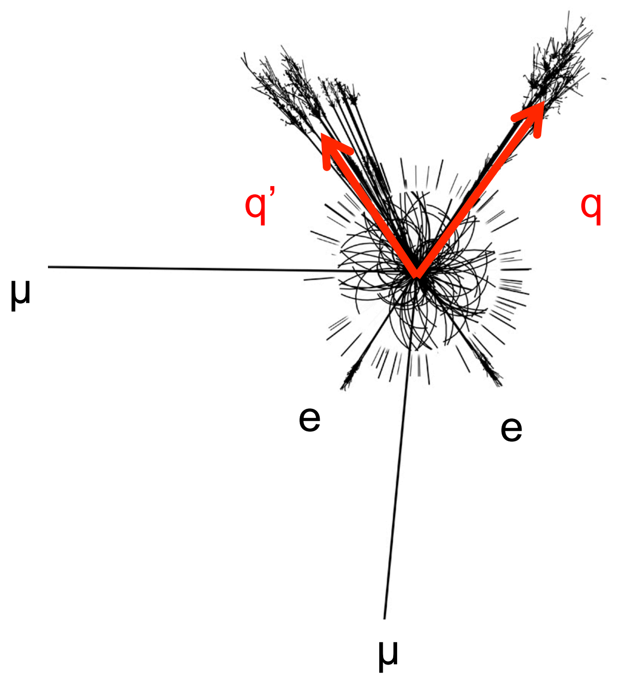
Outline

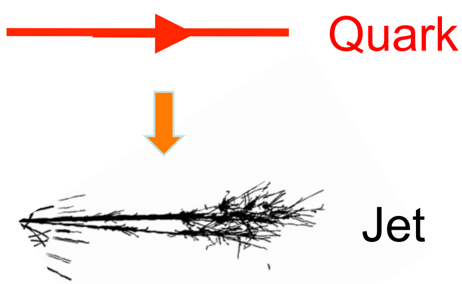
- Introduction
- Jet theory from separation of quantum modes
- Soft-Collinear Effective Theory (SCET)
- Anatomy of the SCET method
- Applications
- Extensions of the basic SCET setup

Jets

- Jet: cluster of energetic hadrons leaving tracks and energy deposits in the detectors.

- Most common object arising in high energy collisions and heavy particle decays





Jets

Aim: Precise (conceptual and) quantitative understanding of jet properties in the framework of QCD.

In order to achieve:

- Disentangle details of physics of the underlying hard reactions (QCD, Higgs, decays of new physics particles, …)
- Test our understanding of QCD and our tools to describe it quantitatively

Characteristics of jets:

- Represent very rich dynamical objects
- Can behave like unambiguous "particles" or quantum objects, that are defined by the measurement prescription, depending on what question we ask.
- Contain perturbative physics are different energy scales as well as non-perturbative effects. Portion depends on which observables we consider.

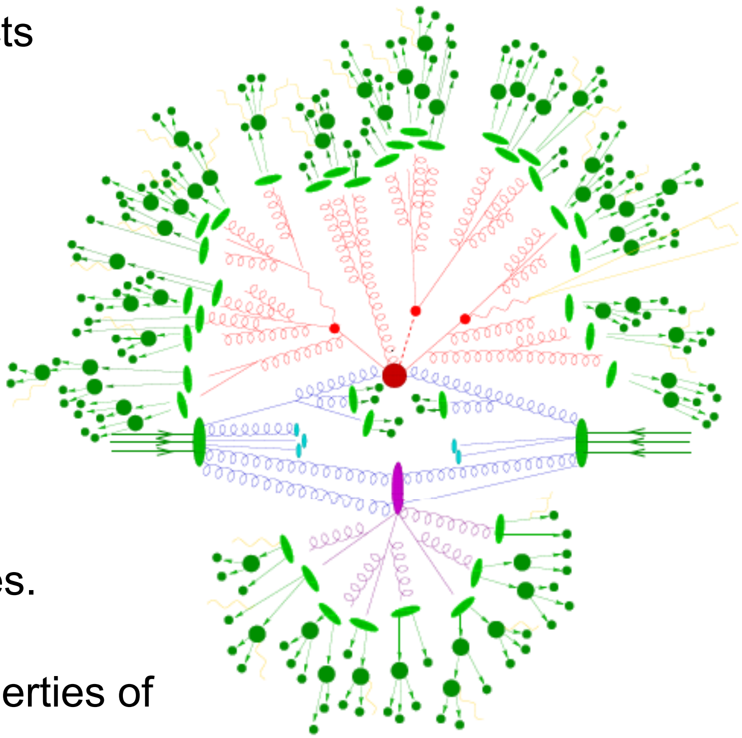
Previous Talks

Monte-Carlo event generators:

Marek Schönherr

→ Separation/factorization of dynamical effects from different energy scales.

- Hard interactions
- Parton evolution to higher multiplicities
- Hadronization
- Secondary interactions



→ The workhorse for all experimental analyses.

- Full description of all aspects down to all properties of the individual final state hadrons
- Extremely versatile

Previous Talks

Applications:

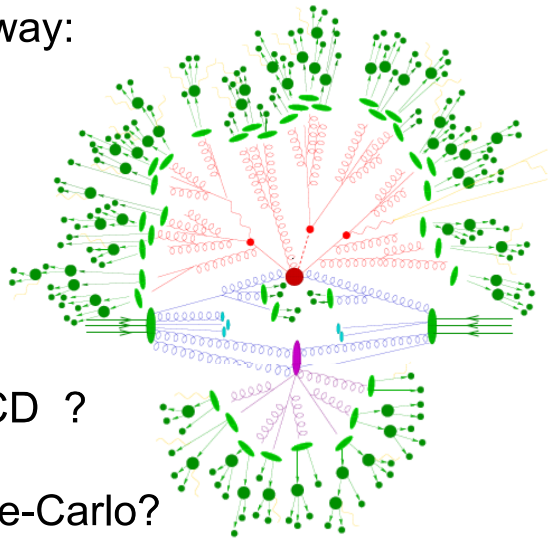
- V+jet production: tests of MCs with NLO hard MEs — Vieri Candelise
  important for assigning precision in BSM searches
- High-p_T jet measurements: α_s and PDF determinations — Nuno Anjos
- Jets as tools to learn about diffraction — Grzegori Gach
- Jets in SUSY searches — Sascha Caron
- Jets in DM decays — Henso Abreu
- Jets in heavy ion collisions — Thomas Trainor

Previous Talks

Active areas or research to improve Monte Carlos:

- N^kLO (k=1,2) partonic calculations — Adam Kardos
- Merging of parton shower and NLO partonic calculations — Marek Schönherr
- Improvements/examinations of parton showers — Stefan Kluth
- Test of models for secondary interactions (e.g. UE) — Wei Yang Wang

→ Brickwall problems that cannot be addressed in that way:



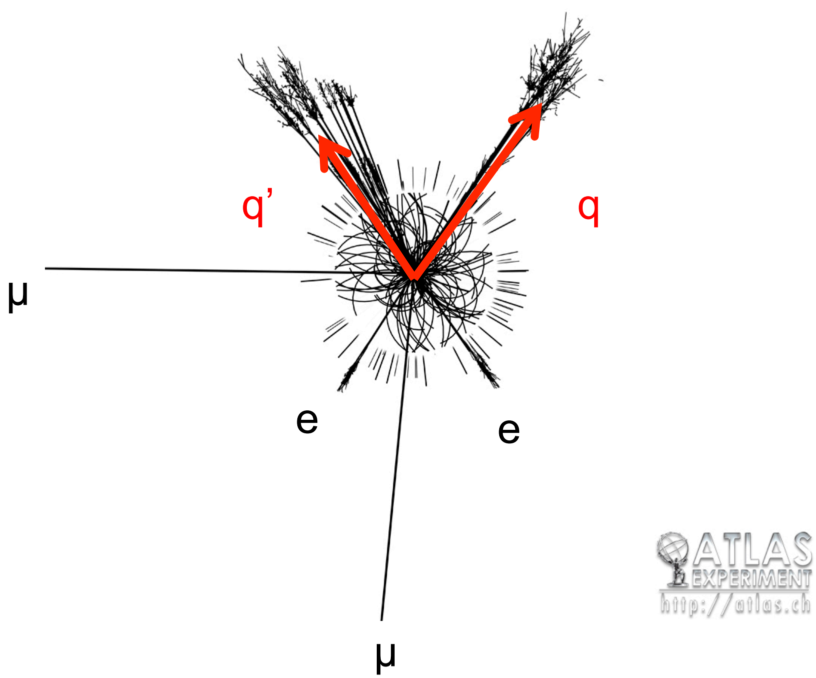
- Parton showers do not have more than LL precision
- Strong model component (hadronization, UE model,…)
- Limited theoretical precision for many subtle aspects
- What is the theory precision of tuning?
- Monte-Carlo: more model OR more first principles QCD ?

What is the meaning of the QCD parameters in the Monte-Carlo?

$$\alpha_s \,,\ m_{\rm top} \,,\ \ldots$$

→ We also have to go different ways, and describe jets with first principles QCD.

Jets from Mode Separation



$$E_{\text{jet}} \gg m_{\text{jet}} \gg E_{\text{soft particles}}$$

- Jet as multi-scale quantum system
- Separate quantum modes that live in separated areas of phase space
- Different quark and gluon fields for each separated sector in phase space
- Lagrangian formulation

Effective Field Theory Approach

Soft-Collinear-Effective Theory (SCET)

→ 15 years ago: EFT approach invented to describe jets in B decays, for which EFTs are the only known theory approach

→ Until 5 years ago: EFT approach only reproduced many collider physics results already known before from the classic pQCD approach to jets.

→ Today: EFT approach addresses problems not addressed before …

Basic idea of mode separation

→ First developed for single jet problems in B-physics.

Bauer, Fleming, Pirjol, Stewart
2000-2001

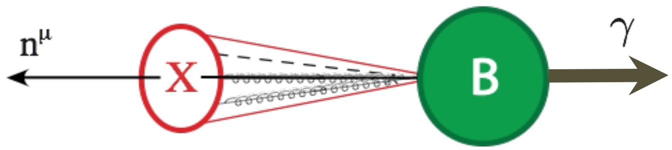
$B \to X_s \gamma$

$E_\gamma \to E_\gamma^{\max}$

jet invariant mass

$m_X^2 \ll Q^2$

$Q = m_b$



We talk about a jet if: $m_X^2 \lesssim Q\Lambda_{\rm QCD}$

Light-cone coordinates: $n^\mu = (1,0,0,-1)$ $\qquad \bar{n}^\mu = (1,0,0,1)$

$$p^\mu = p^+\frac{\bar{n}^\mu}{2} + p^-\frac{n^\mu}{2} + p_\perp = (p^+, p^-, p_\perp)$$

$$p^+ = n.p = p_0 + p_3$$
$$p^- = \bar{n}.p = p_0 - p_3$$

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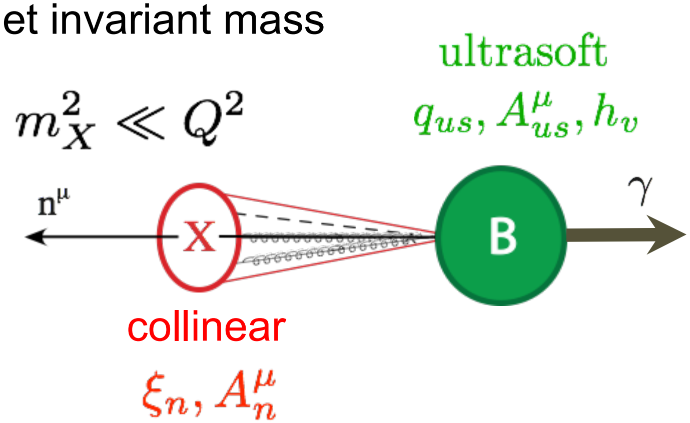


$Q = m_b$

SCET 1 → Separation of modes: $Q^2 \gg m_X^2 \gg \frac{m_X^4}{Q^2} \gtrsim \Lambda_{\rm QCD}^2$

$m_X^2 \sim Q\,\Lambda$

$\lambda = \sqrt{\frac{\Lambda}{Q}}$

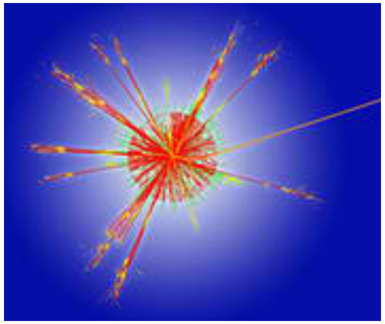
modes	$p^\mu = (+,-,\perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
usoft	$Q(\lambda^2, \lambda^2, \lambda^2)$	$Q^2\lambda^4$	$q_{us},\ A_{us}^\mu$

Jets from Mode Separation

Soft-Collinear Effective Theory:

→ Doing jet physics using the concept of mode and scale separation at the Lagrangian and operator level

- Feynman rules
- systematic power counting



→ Lagrangian level access to jet physics problems.

→ IR-log resummation (soft+collinear) through UV-renormalization.

→ Approach to access power corrections and subleading twist terms, double counting issues at operator level.

→ Leads to results theoretically equivalent to classic pQCD wherever dedicated results have been derived in both approaches.

Differences in the way how results are implemented in applications (subleading).

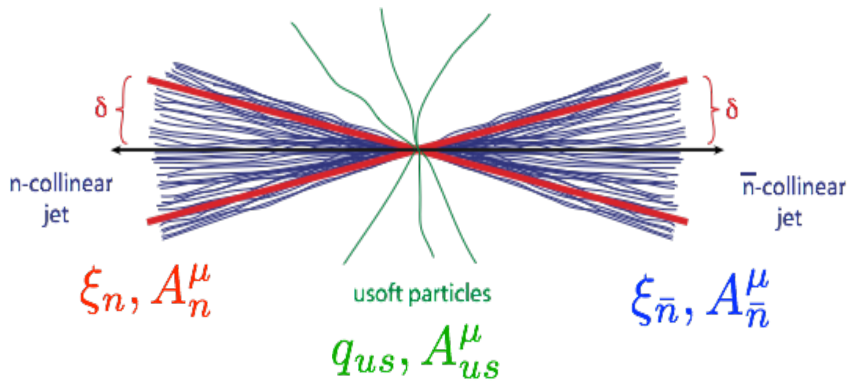
Some problems appear harder / easier in either approach.

Effective Lagrangian

Consider simple example: $e^+e^- \rightarrow 2\,\mathrm{jets}$

(massless quarks)

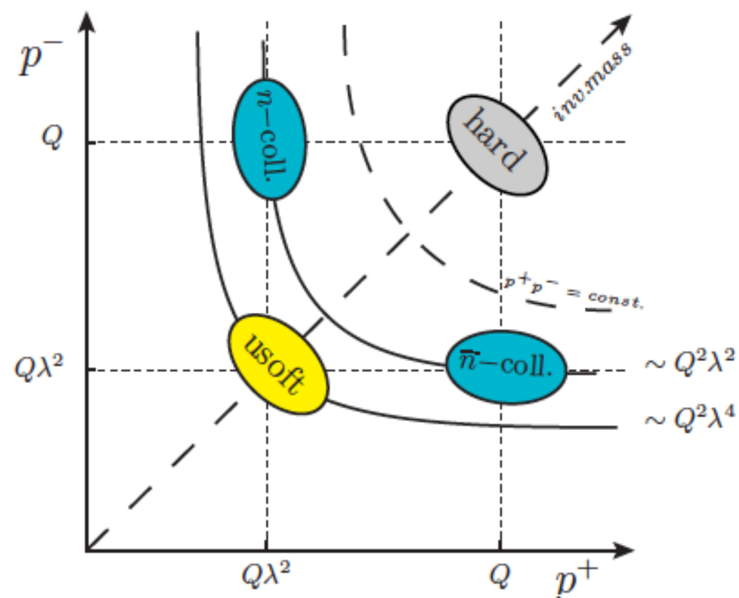
$Q = E_{\mathrm{cm}}$



SCET 1

$m_X^2 \sim Q\,\Lambda$

$\lambda = \sqrt{\frac{\Lambda}{Q}}$



The physical measurement fixed the relevant setup of the quantum modes !

Effective Lagrangian

Collinear Lagrangian:

$$\chi_{n_i} = \frac{\bar{n}_i n_i}{4}\psi$$ small

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\, i\not{D}\, \psi \qquad \psi = \xi_{n_i} + \chi_{\bar{n}_i}$$

$$\xi_{n_i} = \frac{n_i \bar{n}_i}{4}\psi$$ large

$$\mathcal{L}_{c,n} = \bar{\xi}_n \left(in.D_{us} + i\not{D}_{c,\perp} \frac{1}{i\bar{n}.D_c} i\not{D}_{c,\perp} \right) \frac{\bar{n}}{2} \xi_n$$

$$iD^\mu_{us} = i\partial^\mu + gA^\mu_{us}$$

"Integrate out small component"

"Foldy-Woulthuysen-Tani transformation"

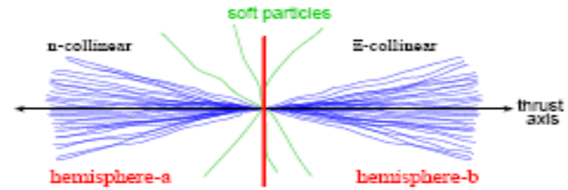
Effective Lagrangian: (leading in λ)

similar to QCD Lagrangian

$$\mathcal{L}_{\mathrm{SCET}} = \sum_{\text{jets } i} \mathcal{L}_{c,n_i}(\xi_{n_i}, A^\mu_{n_i}) + \mathcal{L}_s(q_{us}, A^\mu_{us})$$

Effective Lagrangian

Effective jet currents: (dijet production in e^+e



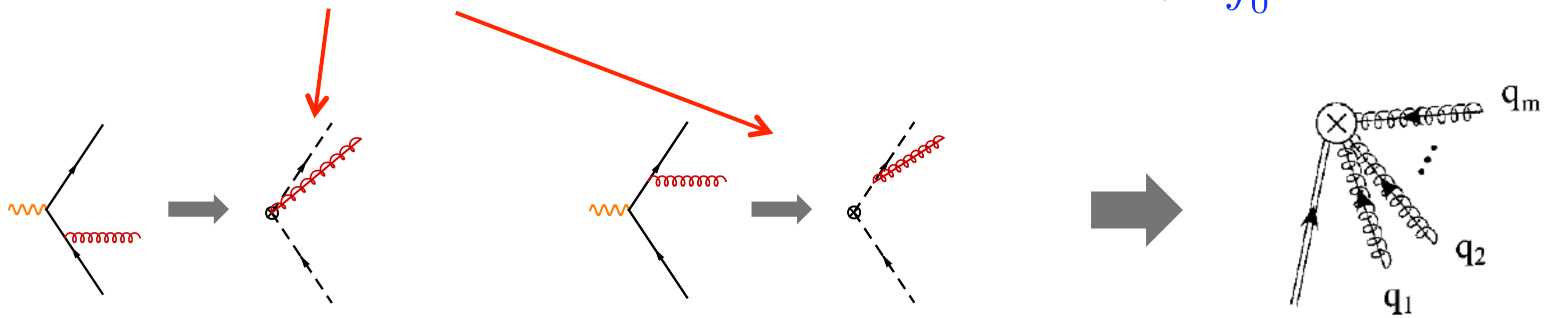
$$\mathcal{J}^\mu(\omega,\bar{\omega}) = \bar{\chi}_{n,\omega}(0)\Gamma^\mu\,\chi_{\bar{n},\bar{\omega}}(0)$$

jet field

$$\chi_{n,\omega}(0) = (W^\dagger\xi_n)(0)$$

n-collinear Wilson line

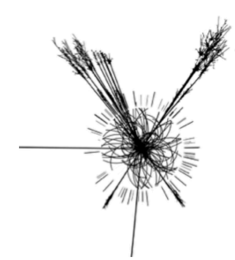
$$W_n(0) = P\exp\left(ig\int_0^\infty \mathrm{d}s\,\bar{n}.A_n(s\bar{n})\right)$$



Jet fields are gauge invariant under collinear gauge transformations.

Complete gauge invariance in connection with all soft processes.

Explains the existence of jets + soft radiation between jets!



Factorization at Operator Level

Factorization:

$$\mathcal{L}_{c,n} = \bar{\xi}_n \, in.D_{us} \, \frac{\bar{n}}{2} \, \xi_n$$

ultrasoft Wilson line

Soft field redefinition:
soft-collinear decoupling

$$\xi_n \to Y_n \, \xi_n , \qquad A_n^\mu \to Y_n A_n^\mu Y_n^\dagger$$

$$Y_n(x) = \bar{\mathrm{P}} \exp\Big(- ig \int_0^\infty \mathrm{d}s \, n.A_{us}(ns + x) \Big)$$

$$\mathcal{L}_{c,n} = \bar{\xi}_n \, in.\partial_{us} \, \frac{\bar{n}}{2} \, \xi_n$$

$$|X\rangle \longrightarrow |X_n \, X_{\bar{n}} \, X_{\mathrm{us}}\rangle = |X_n\rangle \otimes |X_{\bar{n}}\rangle \otimes |X_{\mathrm{us}}\rangle$$

$$\mathcal{J}^\mu(\omega, \bar{\omega}) \to \bar{\chi}_{n,\omega}(0) Y_n^\dagger Y_{\bar{n}} \, \Gamma^\mu \, \chi_{\bar{n},\bar{\omega}}(0)$$

soft-collinear decoupling
at the operator level

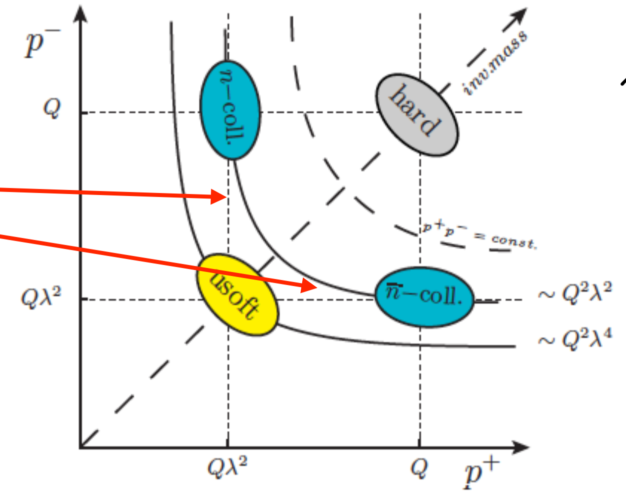
Anatomy of SCET Predictions

Singular Cross section (SCET 1)

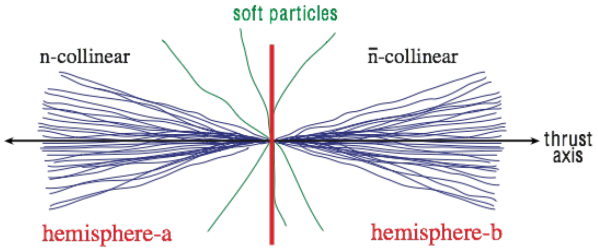
Korchemsky, Sterman; Bauer etal.
Fleming, Mantry, Stewart, AHH
Schwartz

$$\left(\frac{d\sigma}{d\tau}\right)^{\text{sing}}_{\text{part}} \sim \sigma_0\, H(Q,\mu_Q) U_H(Q,\mu_Q,\mu_s) \int d\ell d\ell'\, U_J(Q\tau - \ell - \ell', \mu_Q, \mu_s)\, J_T(Q\ell', \mu_j)\, S_T(\ell - \Delta, \mu_s)$$

Convolution



$\lambda \sim \tau$



Anatomy of SCET Predictions

Matrix element terms (fixed-order)

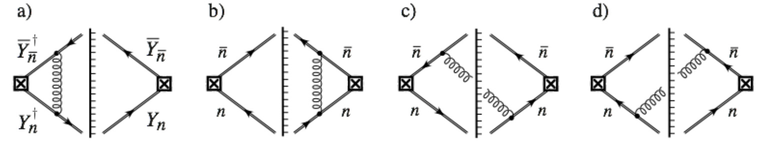
$$\left(\frac{d\sigma}{d\tau}\right)^{\rm sing}_{\rm part} \sim \sigma_0\, H(Q,\mu_Q)\, U_H(Q,\mu_Q,\mu_s) \int d\ell d\ell'\, U_J(Q\tau-\ell-\ell',\mu_Q,\mu_s)\, J_T(Q\ell',\mu_j)\, S_T(\ell-\Delta,\mu_s)$$

Hard function

Each factor gauge invariant !

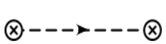
Soft function

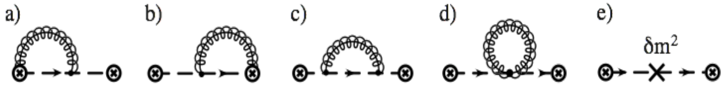
$$S_{\rm hemi}(\ell^+,\ell^-,\mu) = \frac{1}{N_c}\sum_{X_s} \delta(\ell^+ - k_s^{+a})\delta(\ell^- - k_s^{-b}) \langle 0|\overline{Y}_{\bar n}\, Y_n(0)|X_s\rangle\langle X_s|Y_n^\dagger\, \overline{Y}_{\bar n}^\dagger(0)|0\rangle$$

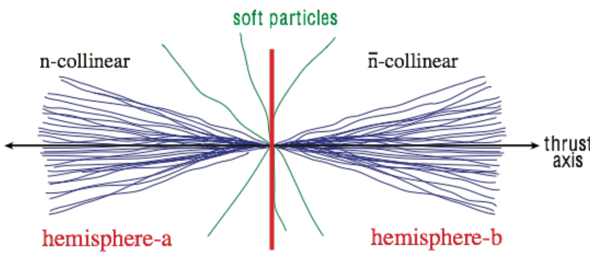


Jet function

$$J_n(Qr_n^+,\mu) = \frac{-1}{8\pi N_c Q}\, {\rm Disc} \int d^4x\, e^{ir_n\cdot x}\, \langle 0|{\rm T}\, \bar\chi_{n,Q}(0)\, \bar{n}\!\!\!/\, \chi_n(x)|0\rangle$$







Anatomy of SCET Predictions

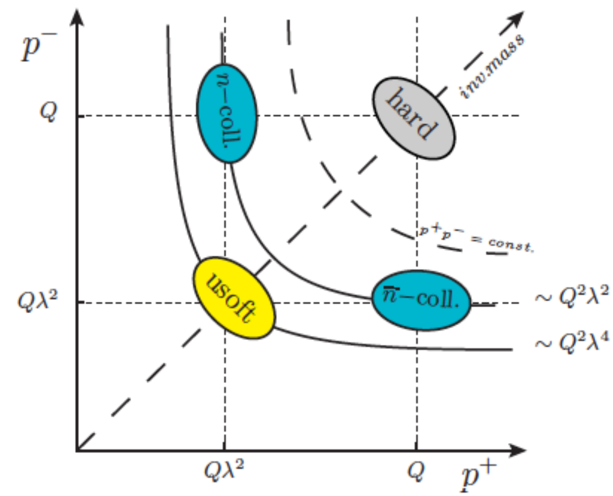
Summation of large logarithms (RG-summation, SCET 1)

$$\left(\frac{d\sigma}{d\tau}\right)^{\text{sing}}_{\text{part}} \sim \sigma_0\, H(Q,\mu_Q) U_H(Q,\mu_Q,\mu_s) \int d\ell d\ell'\, U_J(Q\tau-\ell-\ell',\mu_Q,\mu_s)\, J_T(Q\ell',\mu_j)\, S_T(\ell-\Delta,\mu_s)$$

2-jet production current

$$\mu\frac{d}{d\mu}H_Q(Q,\mu) = \gamma_{H_Q}(Q,\mu)\, H_Q(Q,\mu)$$

$$\gamma_{H_Q}(Q,\mu) = \Gamma_{H_Q}[\alpha_s]\ln\left(\frac{\mu^2}{Q^2}\right) + \gamma_{H_Q}[\alpha_s]$$



$\lambda \sim \tau$

NNNLL summations possible!

More powerful, but less general than CEASAR/ARES!

→Heather McAslan

Jet function evolution

$$\mu\frac{d}{d\mu}J(y,\mu) = \gamma_J(y,\mu)\, J(y,\mu) = \left[2\Gamma^{\text{cusp}}(\alpha_s)\ln(iy\mu^2 e^{\gamma_E}) + \gamma_J(\alpha_s)\right] J(y,\mu)$$

Anatomy of SCET Predictions

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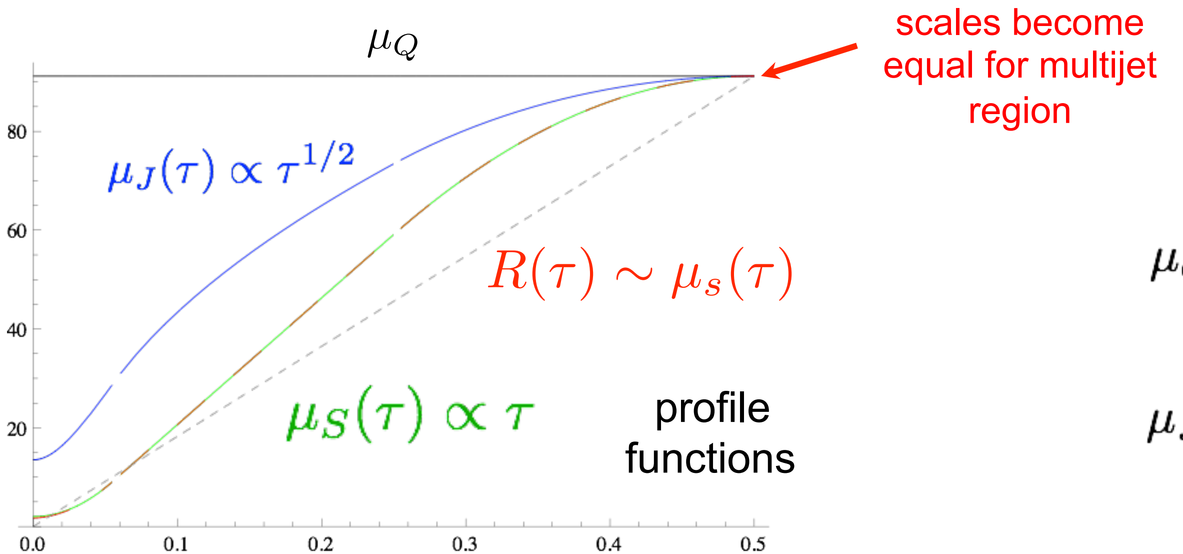
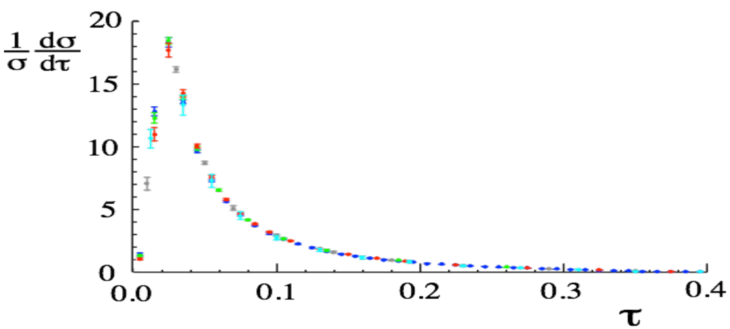
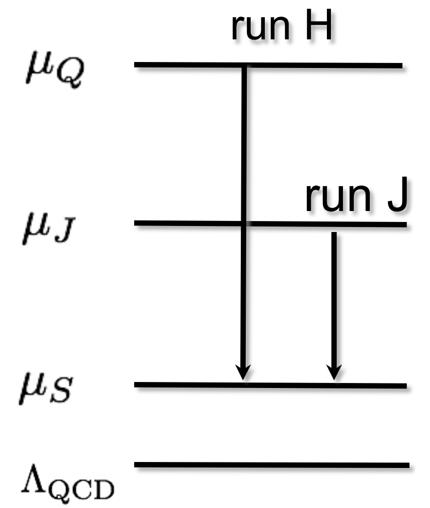
$$\left(\frac{d\sigma}{d\tau}\right)^{\text{sing}}_{\text{part}} \sim \sigma_0\, H(Q,\mu_Q) U_H(Q,\mu_Q,\mu_s) \int d\ell d\ell'\, U_J(Q\tau-\ell-\ell',\mu_Q,\mu_s)\, J_T(Q\ell',\mu_j)\, S_T(\ell-\Delta,\mu_s)$$







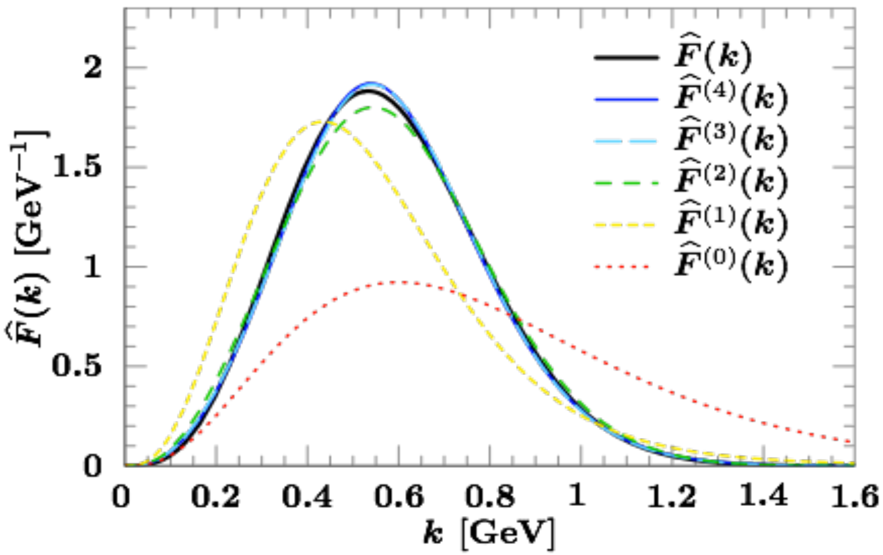
Anatomy of SCET Predictions

Combination for hadron level prediction

$$\left(\frac{d\sigma}{d\tau}\right) = \int d\ell \left[\left(\frac{d\sigma}{d\tau}\right)^{\text{sing}}_{\text{part}} \left(\tau - \frac{\ell}{Q}\right) + \left(\frac{d\sigma}{d\tau}\right)^{\text{nonsing}}_{\text{part}} \left(\tau - \frac{\ell}{Q}\right) \right] S^{\text{mod}}(\ell)$$

Fixed-order minus terms already resummed

Soft matrix element model function



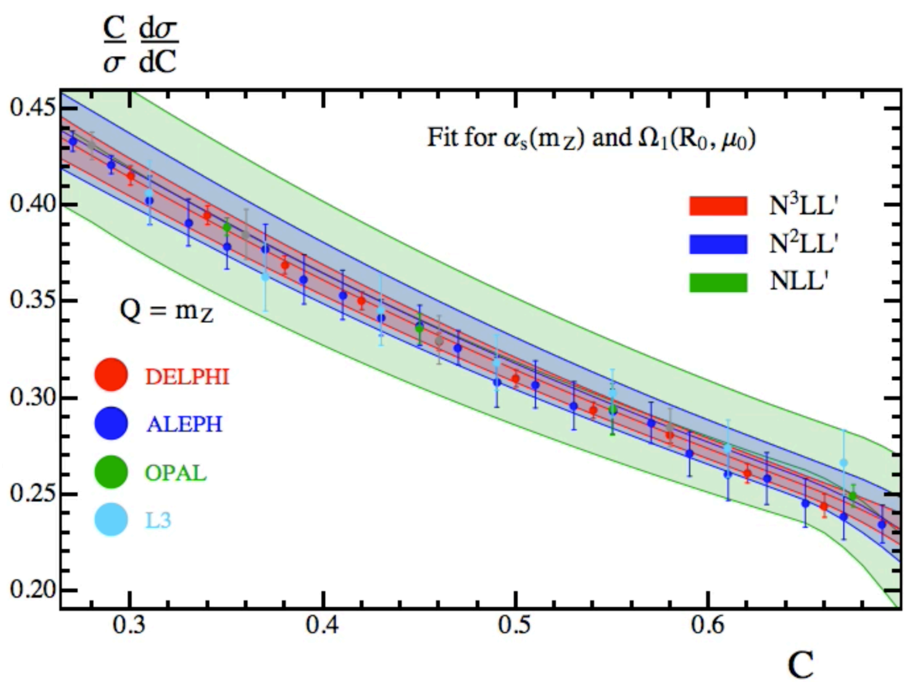
Application of SCET 1

- Can be applied to global jet shape variables, not sensitive to transverse momenta: e.g. e^+e^- eventshapes

Thrust $$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

C-parameter $$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$

- Analyses at NNNLL + O(α^2) fixed order using tail data (all available Q>25 GeV)



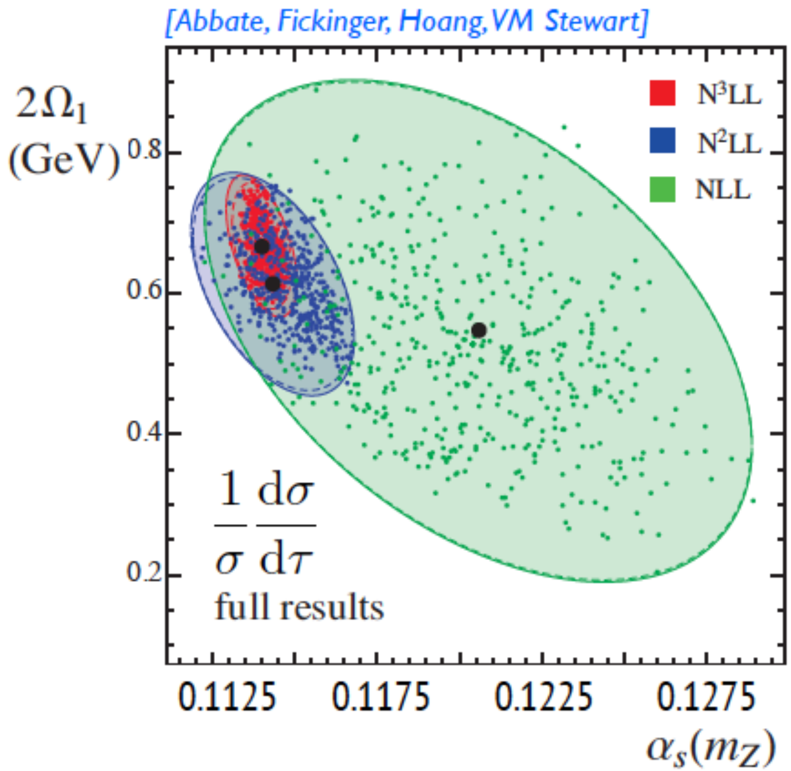
Becher, Schwartz (partonic resummation)

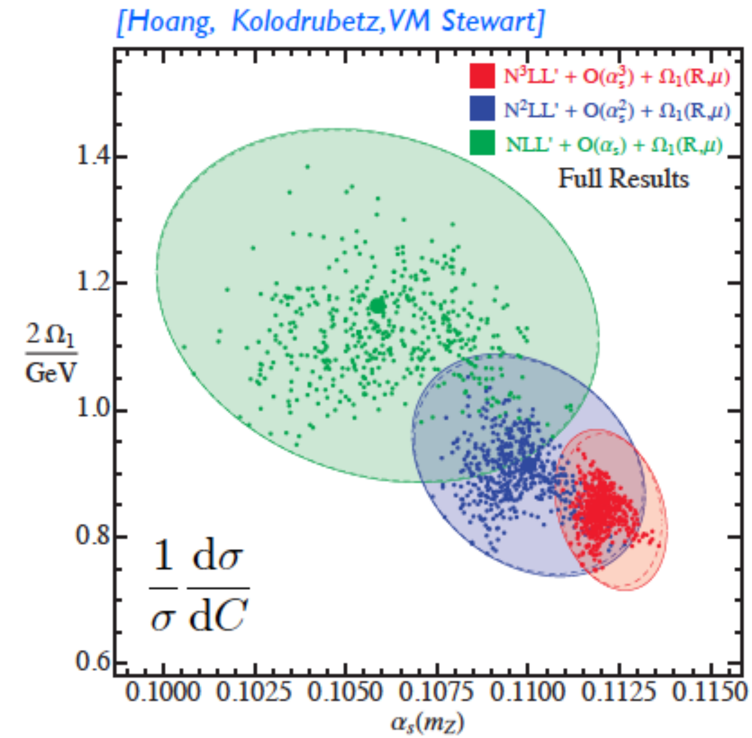
Full analysis incl. nonpert. effects:

Abbate, Fickinger, AHH, Mateu, Stewart (thrust)

AHH, Kolodrubetz, Mateu, Stewart (C-para)

Strong Coupling Determination





$\alpha_s(M_Z) = 0.1135 \pm 0.001$

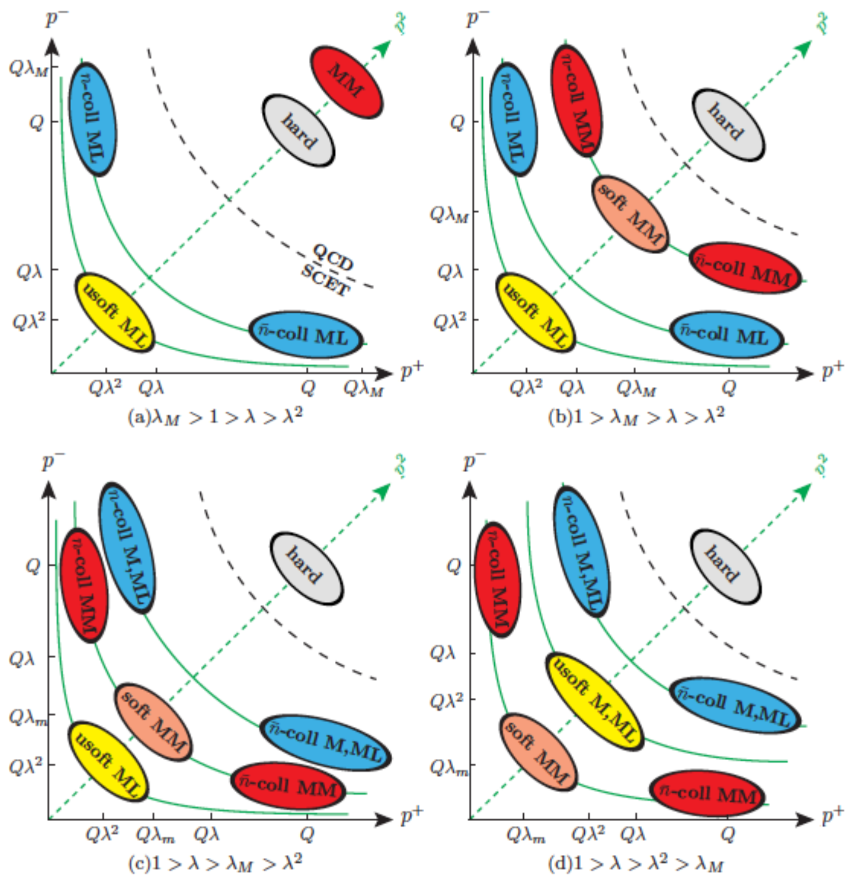
→ Strong coupling from jets smaller than world average (basically lattice).

Further Developments (small selection)

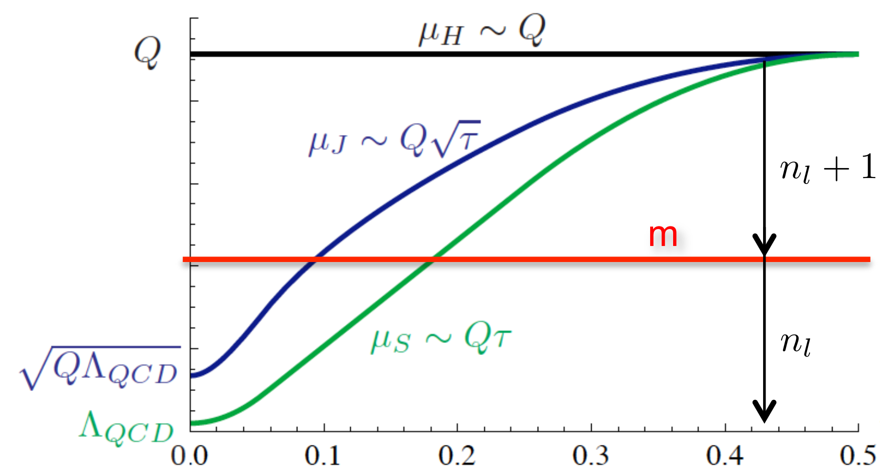
Extension of massless SCET-1 to massive quarks: Pietrulewicz, AHH, Jemos, Mateu

Variable Flavor Number scheme for final state jets (can be combined with PDF)

For arbitrary masses and full log resummation in any kinematic regime.



"profile functions"



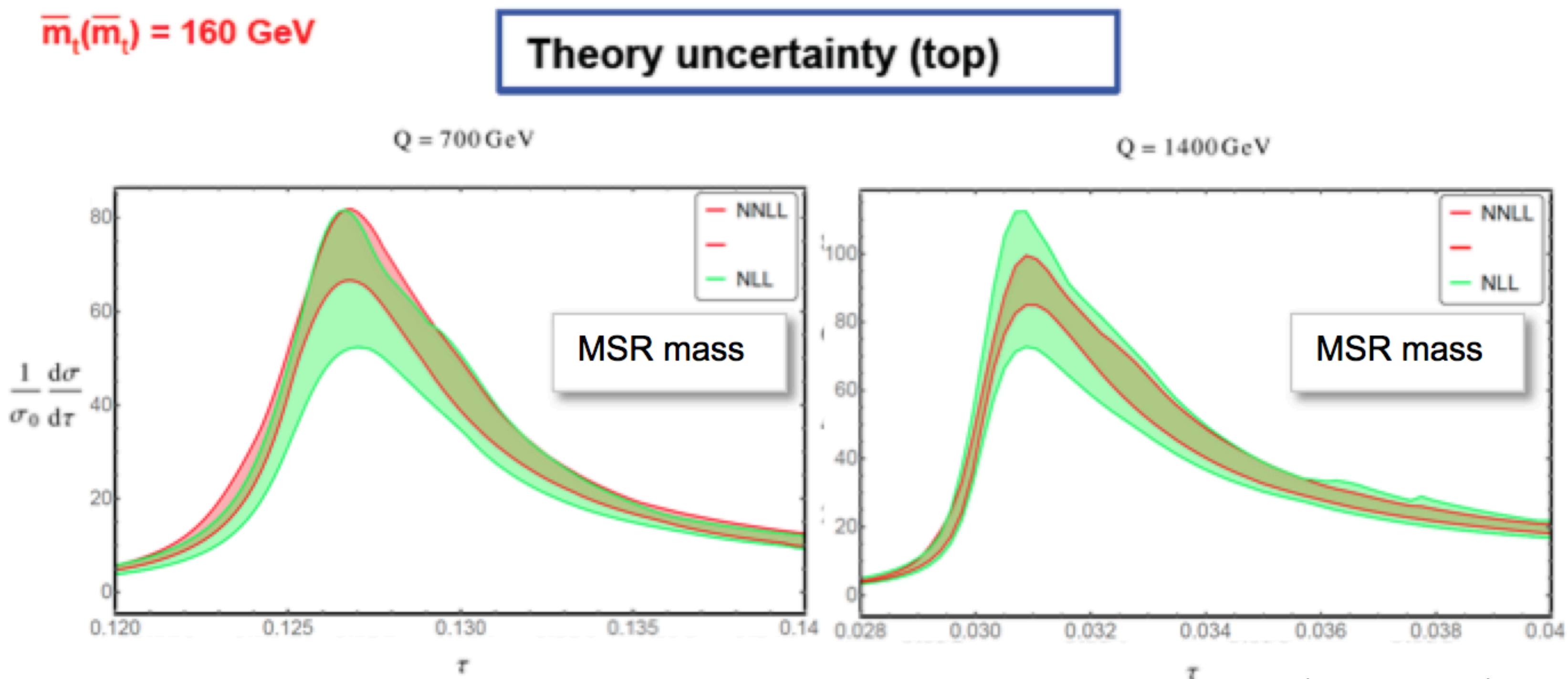
"profile functions"

mode	$p^\mu = (+, -, \perp)$	p^2
n-coll MM	$Q(\lambda_m^2, 1, \lambda_m)$	m^2
soft MM	$Q(\lambda_m, \lambda_m, \lambda_m)$	m^2

Further Developments (small selection)

→ Upcoming: Measurement of MC top quark mass from NNLL + $O(\alpha_s)$ calculation from eventshapes (2-jettiness)

Butenschön, Dehnadi, AHH, Mateu, Stewart



(preliminary)

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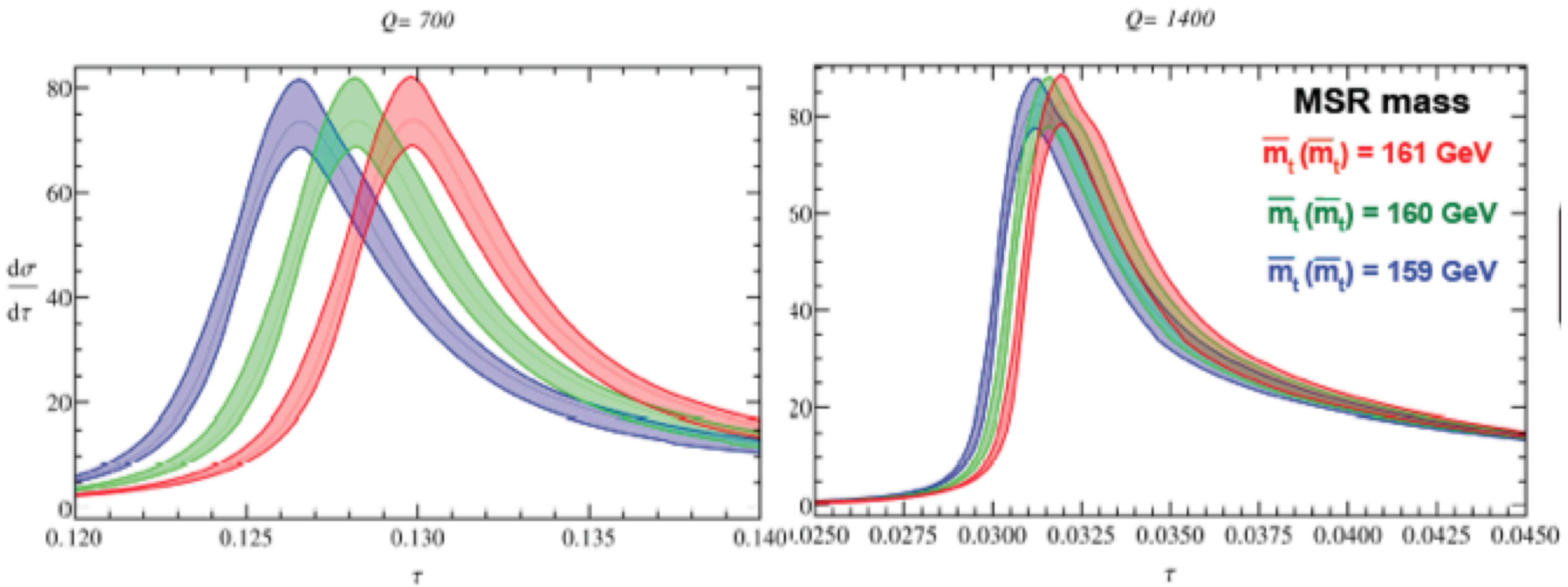


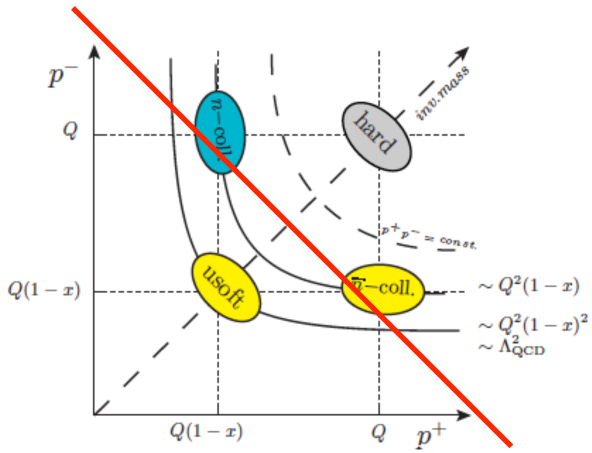
(preliminary)

Further Developments (small selection)

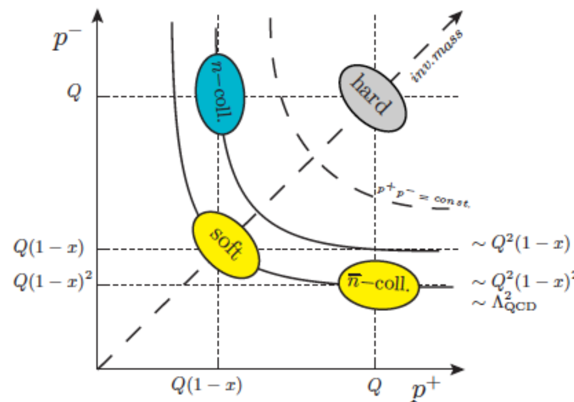
→ **Different types of SCET (examples)**

Actually all different EFTs, but they are all part of to the SCET method.

For example: DIS for x → 1 AHH, Pietrulewicz, Samitz

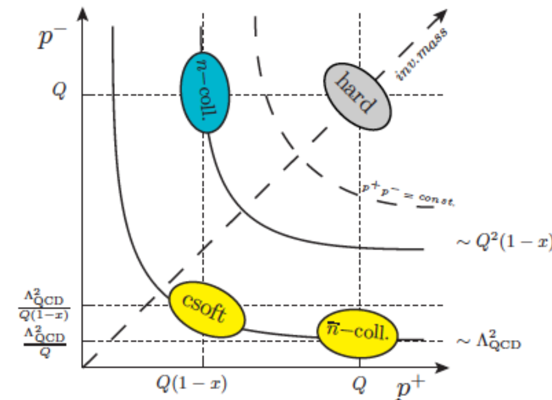


SCET 1



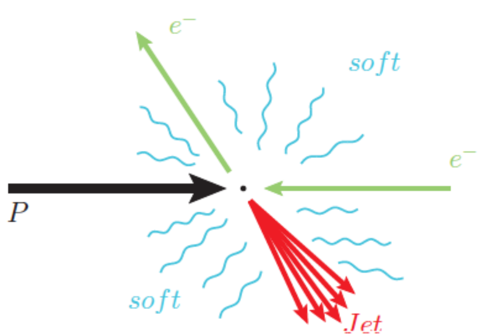
SCET 2+

$$Q \gg Q\sqrt{1-x} \sim \Lambda_{\mathrm{QCD}}$$



SCET 2

$$Q \gg Q\sqrt{1-x} \gg \Lambda_{\mathrm{QCD}}$$



Fixes flaws in previous factorization proofs by Becher, Neubert and Fleming, Zang.

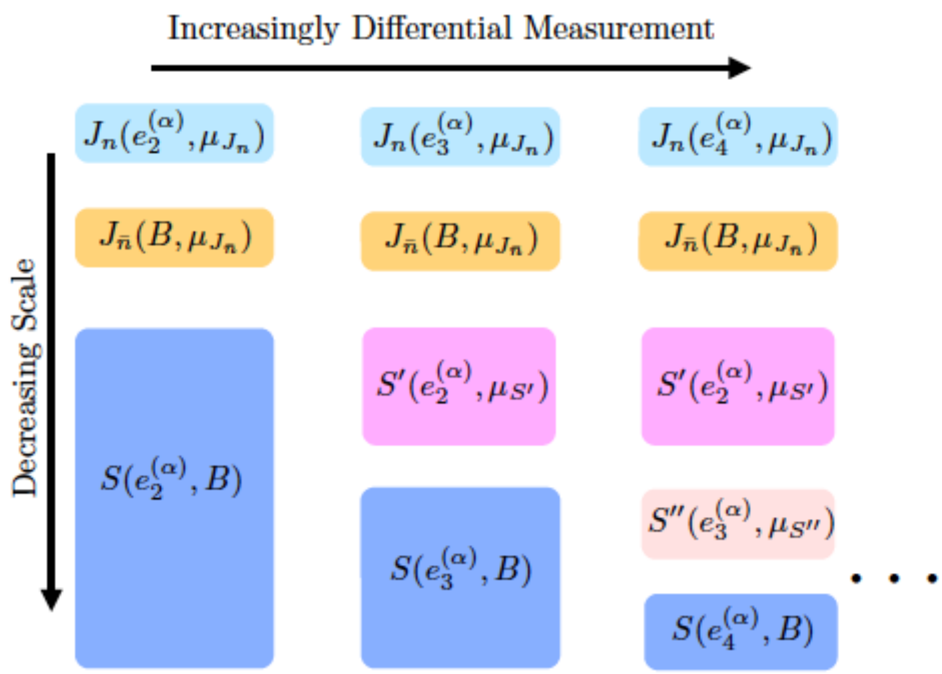
Further Developments (small selection)

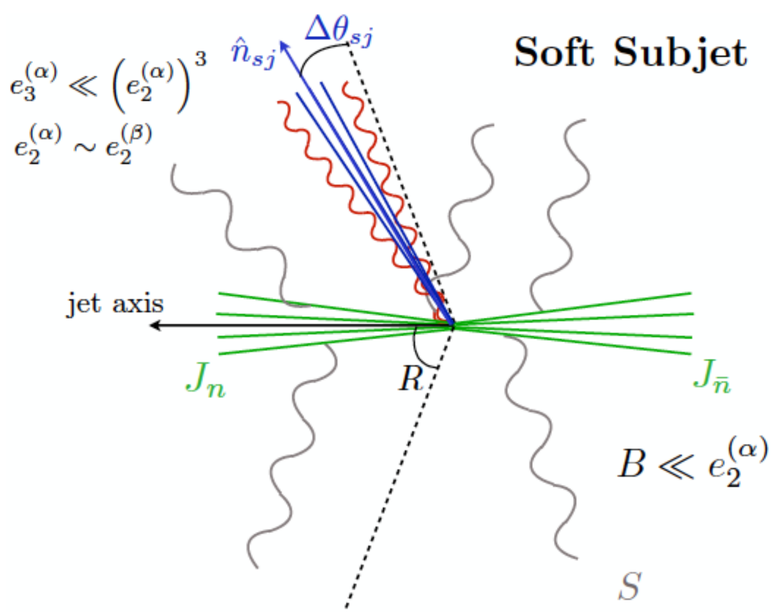
Larkoski, Moult, Neill

Summation of non-global logarithms (NGLs)

NGLs arise in non-global jet observables (only radiation in limited regions included)

Add more and more measurements to resolve increasing number of soft subjets located at the jet boundary, where the NGLs are generated. Resummation of NGL by usual RG methods.





Further Developments (small selection)

Summation of non-global logarithms (NGLs) Larkoski, Moult, Neill

NGLs arise in non-global jet observables (only radiation in limited regions included)

Problem is actually a jet substructure problem which is also an active subject in the SCET community.

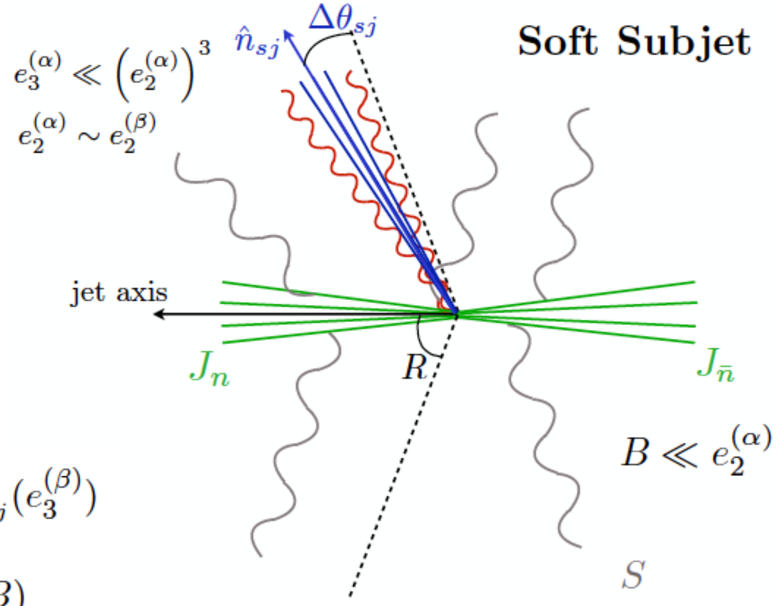
$$\frac{d\sigma}{dAdB} = H_{n\bar{n}} J_n(A) \otimes J_{\bar{n}}(B) \otimes S_{n\bar{n}}(A,B)$$

Observable wanted

marginalize

$$\frac{d\sigma}{de_2^{(\alpha)} de_2^{(\beta)} de_3^{(\beta)} dB} = H_{n\bar{n}} H_{n\bar{n}}^{sj}(e_2^{(\alpha)}, e_2^{(\beta)}) J_{n_{sj}}(e_3^{(\beta)}) \otimes S_{n_{sj}\bar{n}_{sj}}(e_3^{(\beta)}) \otimes S_{n\bar{n}n_{sj}}(e_3^{(\beta)}; B) \otimes J_n(e_3^{(\beta)}) \otimes J_{\bar{n}}(B)$$

Sum logs here



Conclusions

- Monte-Carlo event generator description of jets is and will be the working horse of jet physics
- Versatility of the MCs represents a brickwall for the conceptual/theoretical precision of parton showers beyond LO/LL order
- Soft-Collinear Effective Theory: aimed at making internal dynamics of jets accessible to pQCD and factorization in a systematically improvable matter
- Lagrangian formulation of SCET is its strength (e.g. bookkeeping, all log summtion related to renormalization and RG-evolution)
- Crucial aspect of SCET: finding the relevant quantum modes for a particular measurement → factorization → calculations (FO+logs)
- SCET allows for high precision computations
- SCET allows for very complicated mode setups to solve previously hard problems

Conclusion


Q
Quality
C
Cost
D
Delivery
4
QCDの改善が必要じゃないかしら?


QCD
Quality, Cost & Delivery


High Quality
Q
Customer Satisfaction
D
C
Precise Delivery
Reasonable Cost


Quality
Cost
Delivery