Jets and Jet Shapes in SCET

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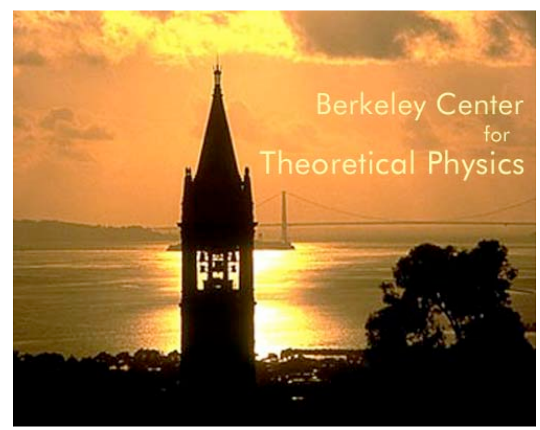
and Berkeley Center for Theoretical Physics

Santa Fe 2010 Meeting
July 6, 2010



Jets as Signals of and Backgrounds to New Physics

- **Signal: New Physics** with strong interactions decay into **Jets**
  - e.g. Squark and Gluino Decays
- **Backgrounds**: Standard Model is very good at producing jets copiously!
- **Probing inside jets** yields more clues to the origin of jets, identifying underlying hard interaction
- **Important Standard Model applications**
  - test of understanding of perturbative vs. nonperturbative QCD
  - precision extractions of strong coupling constant from jet structure

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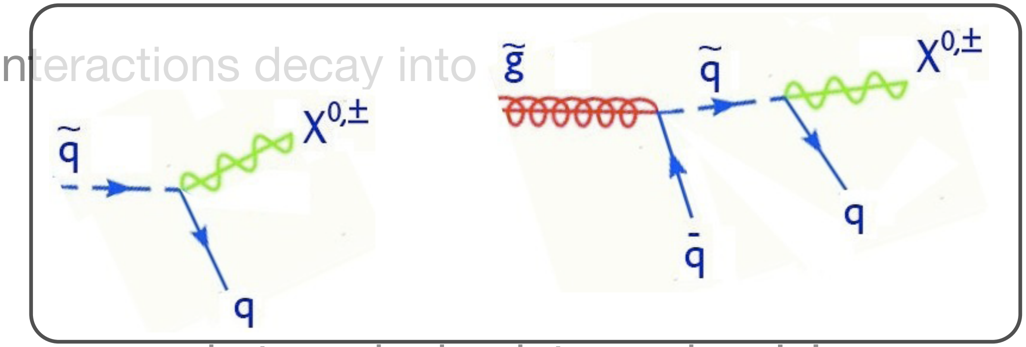

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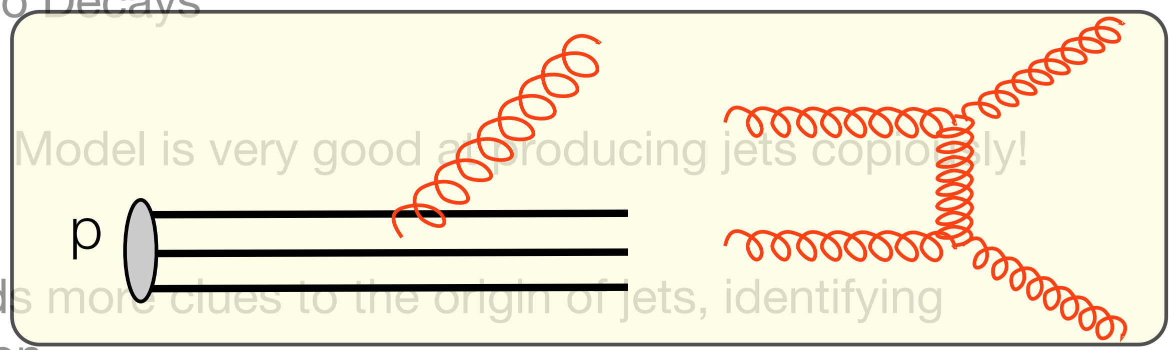

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Challenges in Predicting Jet Observables

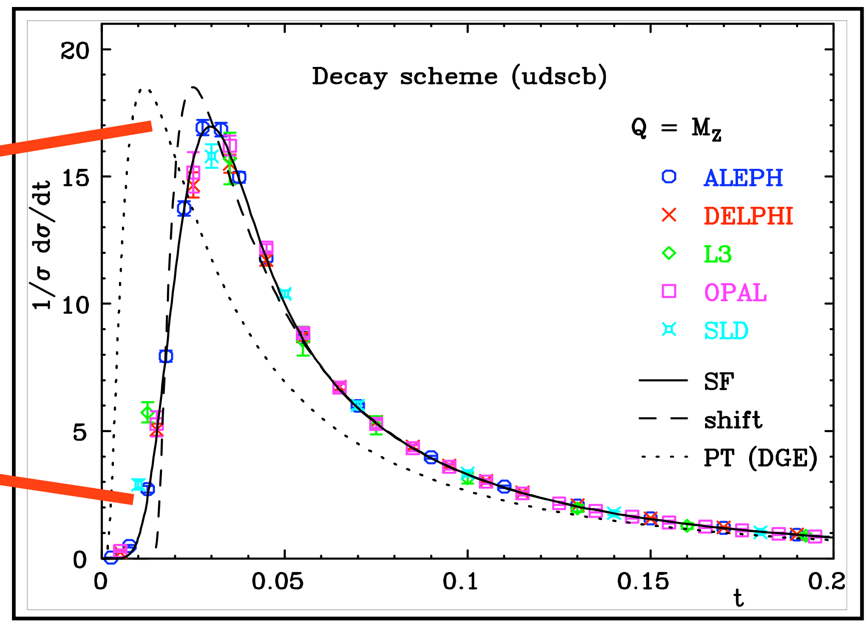
- Example: Two-Jet Event Shapes
  - Thrust: $$T = \frac{1}{Q}\max_{\hat{t}}\sum_i |\hat{t}\cdot\mathbf{p}_i|$$

    Farhi (1977)

- Distribution of events in $\tau = 1\text{-}T$:

$\frac{1}{\tau Q}$ power corrections due to nonperturbative soft radiation

fixed-order PT blows up, large logarithms must be resummed to obtain physical behavior $\alpha_s^m \frac{\ln^n \tau}{\tau}$



Gardi, Rathsman (2002)

Theoretical Tools to Tackle Jet Physics

Tasks 	**Tools** 

Disentangling Perturbative and Nonperturbative Physics	• Factorization
	  • Power counting
	  • Separation of Scales

Resumming Large Logarithms in Perturbation Series	• Renormalization Group Evolution • QCD IR → EFT UV
Predictive Descriptions of Nonperturbative Effects	• Universal Soft Matrix Elements • e.g. PDFs, soft shape functions

Plan of the Talk

- A Theory Toolbox to Probe Jets: Soft-Collinear Effective Theory
  - Tools for Factorization: Power Counting and Soft-Collinear Decoupling
  - Tools for Resummation: the Renormalization Group
  - Tools for Hadronization: Universal Soft Model Functions

- Precision Predictions of Jet Observables
  - Event Shapes in e^+e^-: probing strong coupling and hadronization
  - Quark and Gluon Jet Shapes in e^+e^-
  - Towards Event Shapes and Jet Shapes in Hadron Collisions

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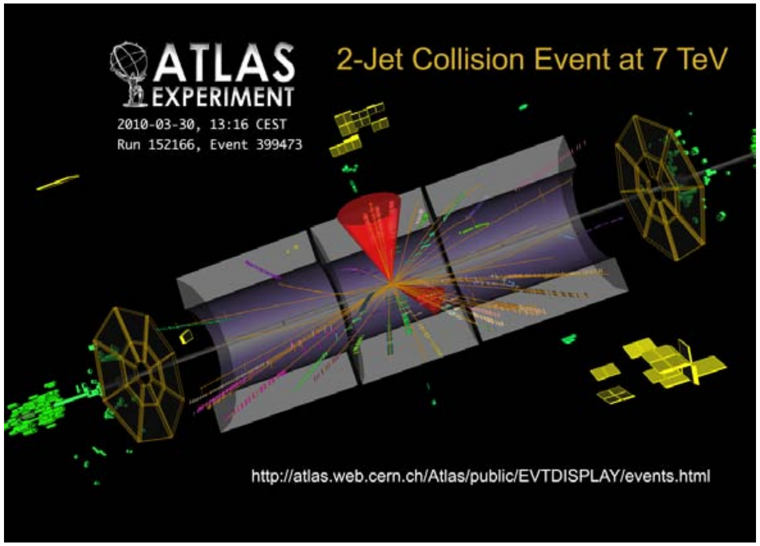
Factorization of Jet Cross Sections

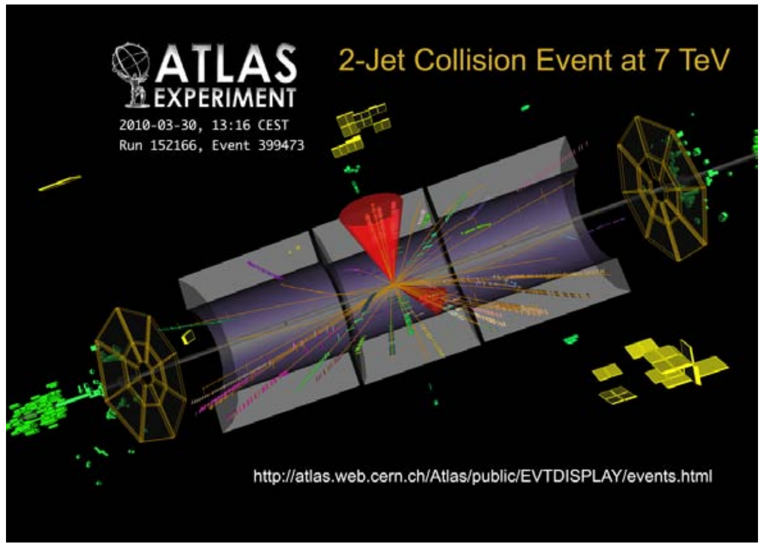
Collins, Soper, Sterman



Factorization of Jet Cross Sections

Collins, Soper, Sterman

Separate into physics at disparate time scales



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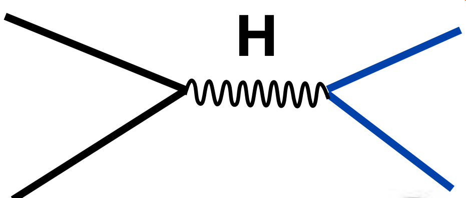

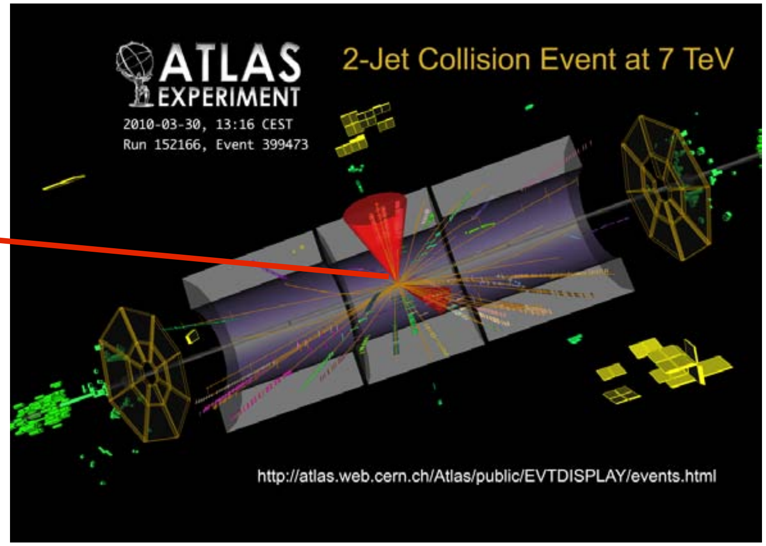

Partonic hard scattering cross section

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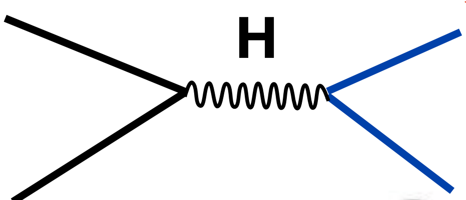

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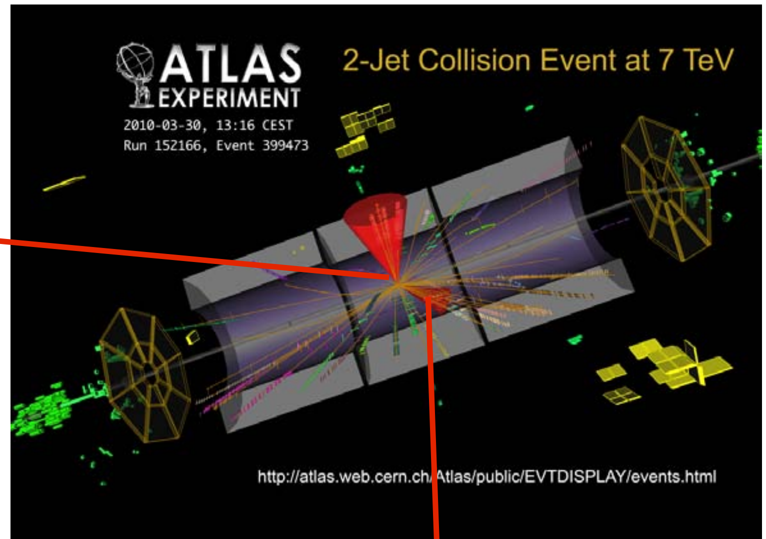

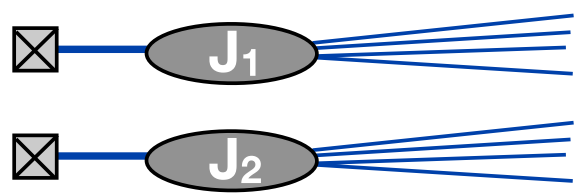

Collinear branching and showering
(cf. parton shower)

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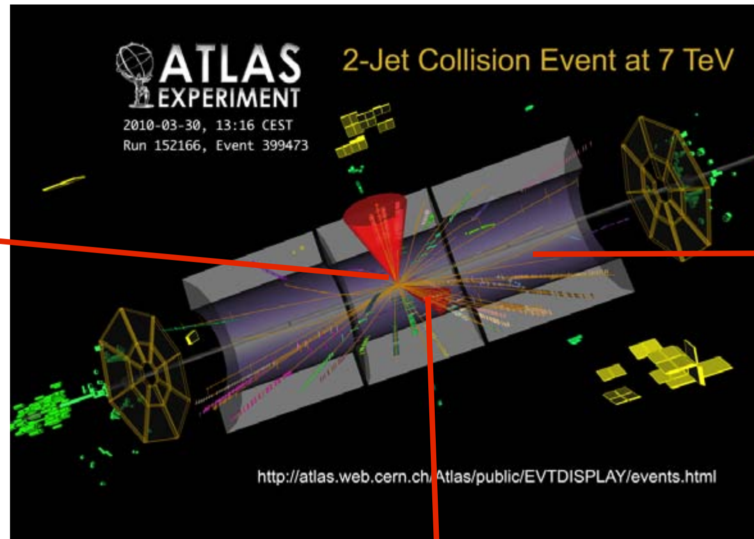

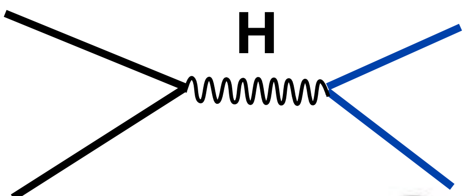

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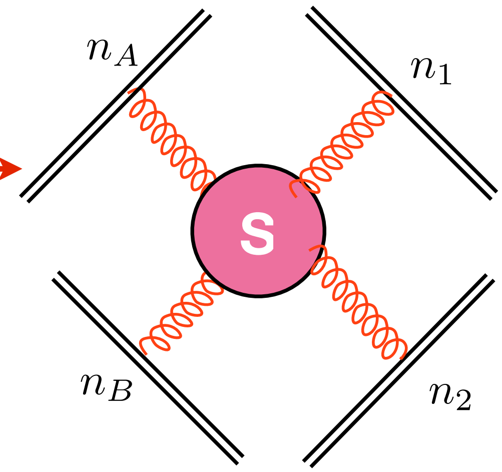
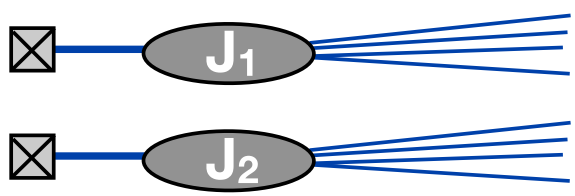


Soft radiation, color exchange *(hadronization)*



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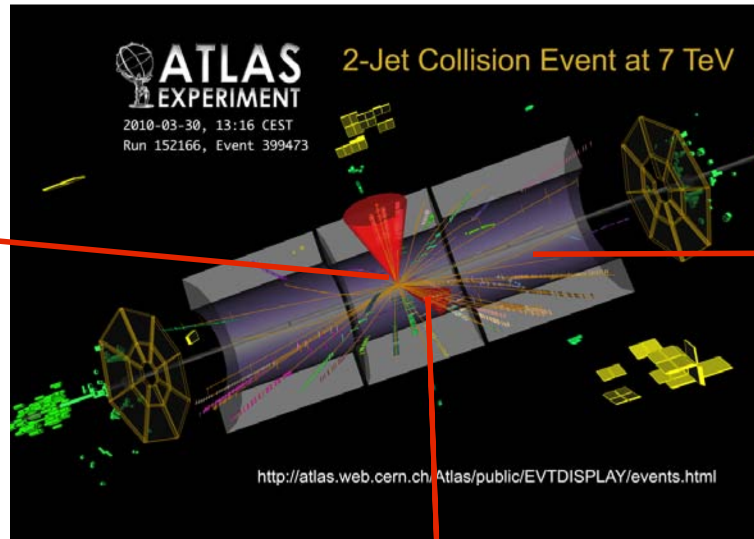

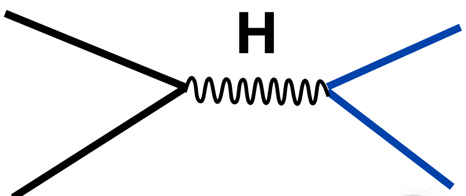

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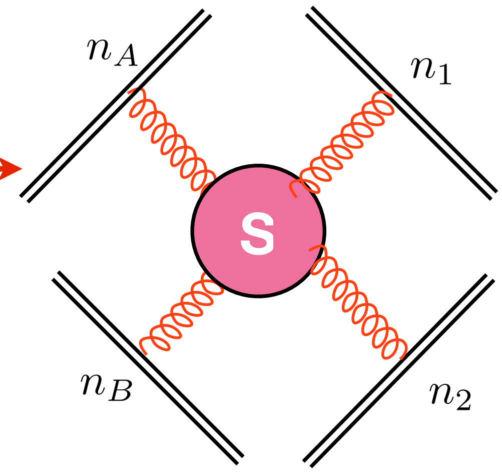

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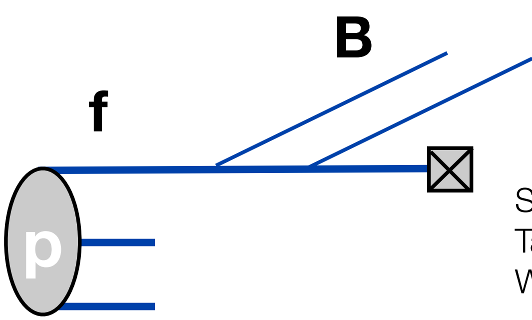
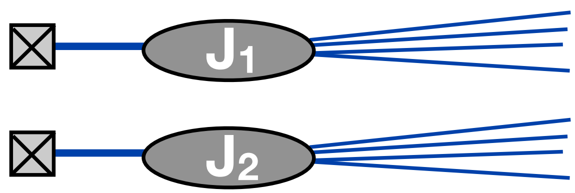


Stewart, Tackmann, Waalewijn

PDFs + beam functions (ISR)



Collinear branching and showering *(cf. parton shower)*

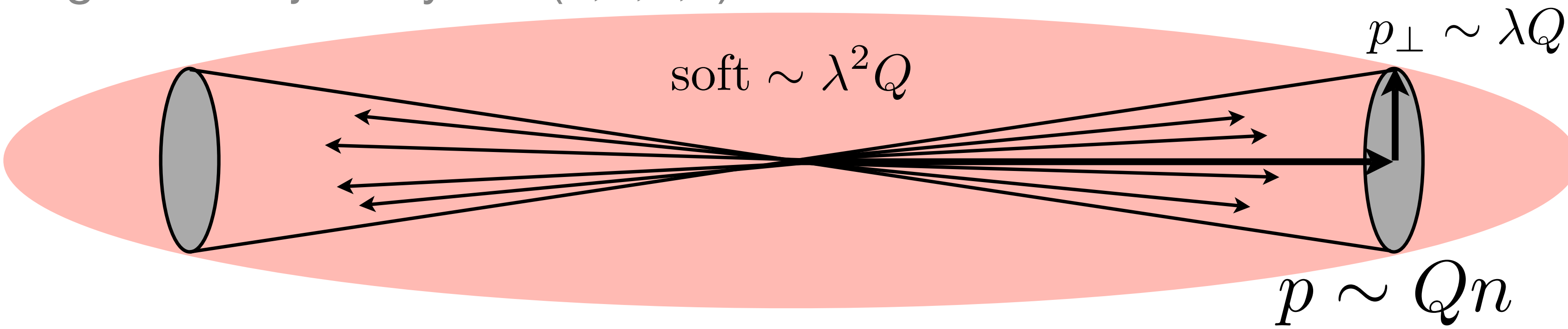
Effective Field Theory

- Use degrees of freedom relevant at the energy or distance scales at which one is working
- Expand full theory quantities in powers of small parameters, ratios of disparate scales
- **Effective theory often possesses enhanced symmetries or simplifications not immediately evident in full theory**
- **Renormalization group evolution between scales resums large logarithms in perturbative series**

Soft-Collinear Effective Theory

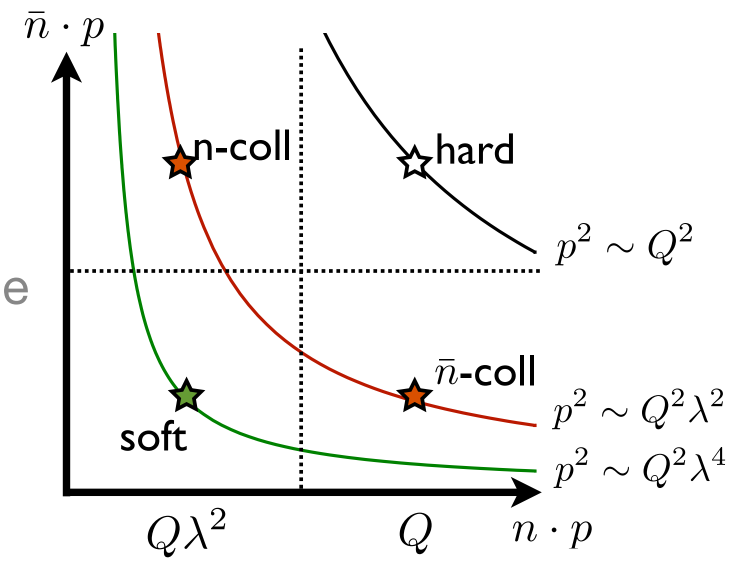
Bauer, Fleming, Luke, Pirjol, Stewart (2000, 2001)

- Effective field theory for small momentum fluctuations about lightlike trajectory *n* = (1,0,0,1)



- In momentum space:

integrate out modes of large virtuality one at a time



A Brief and Biased History of SCET

2000 2001 2003 2005

2006 2007 2008 2009 2010

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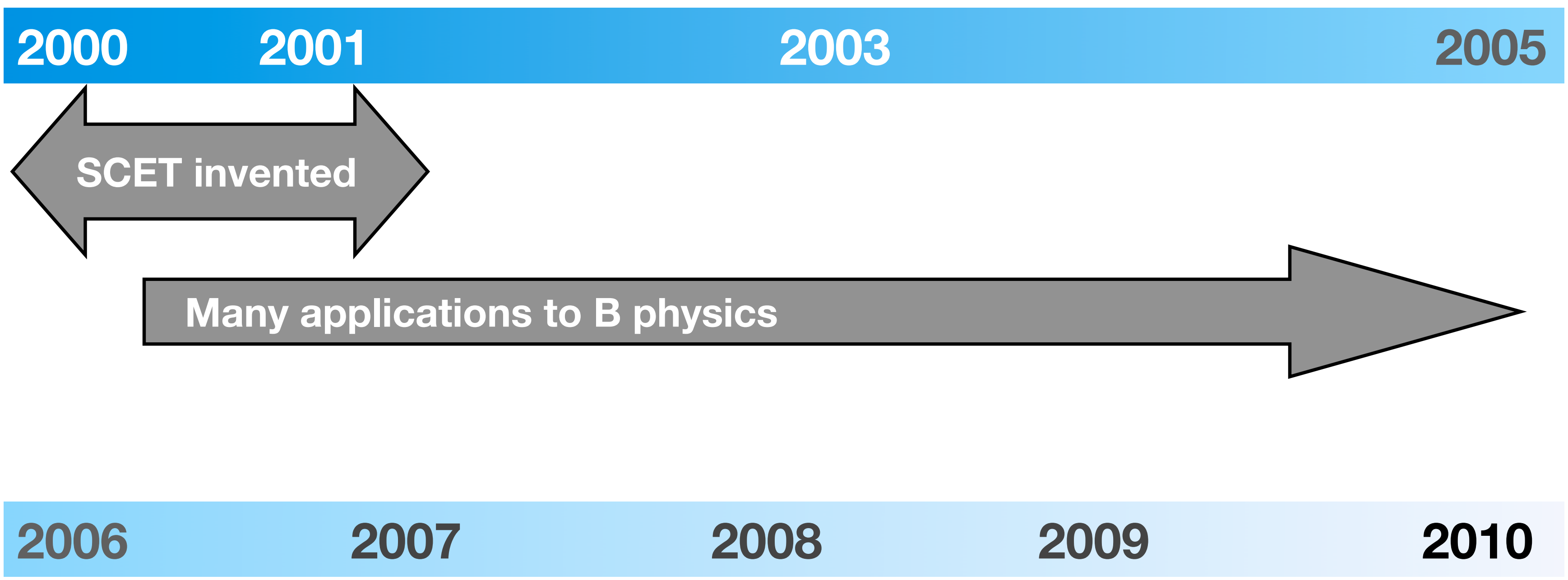

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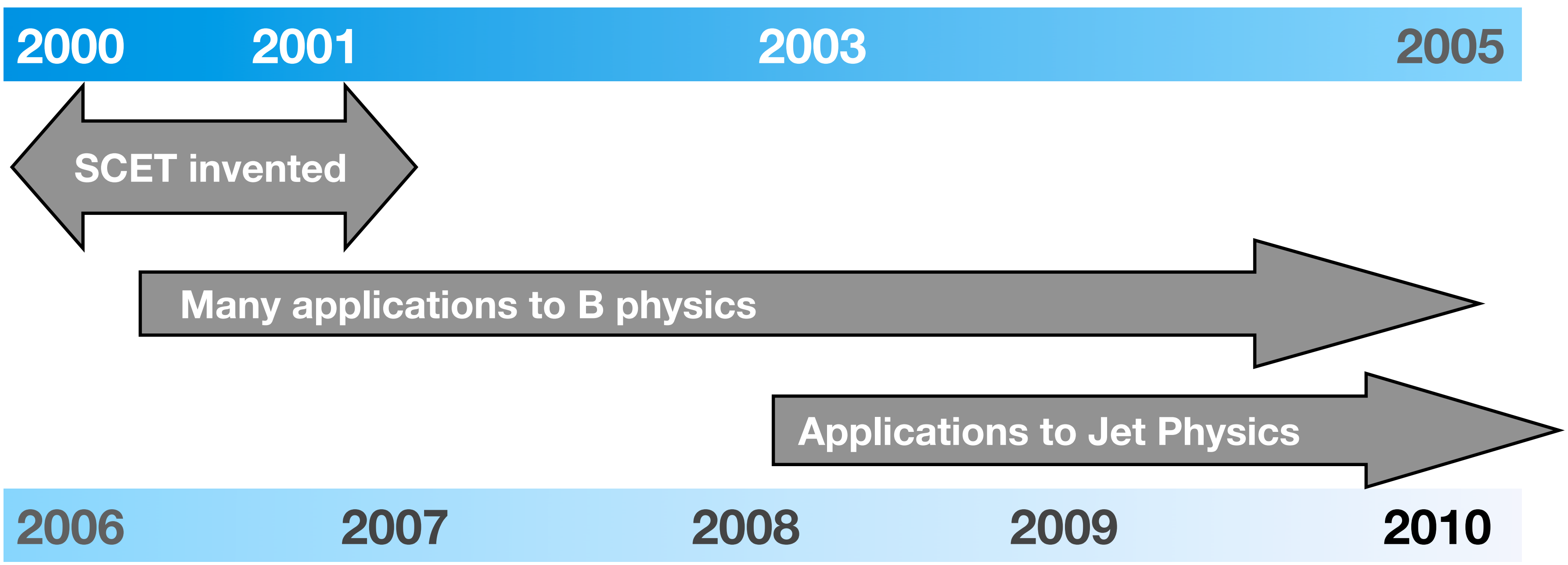

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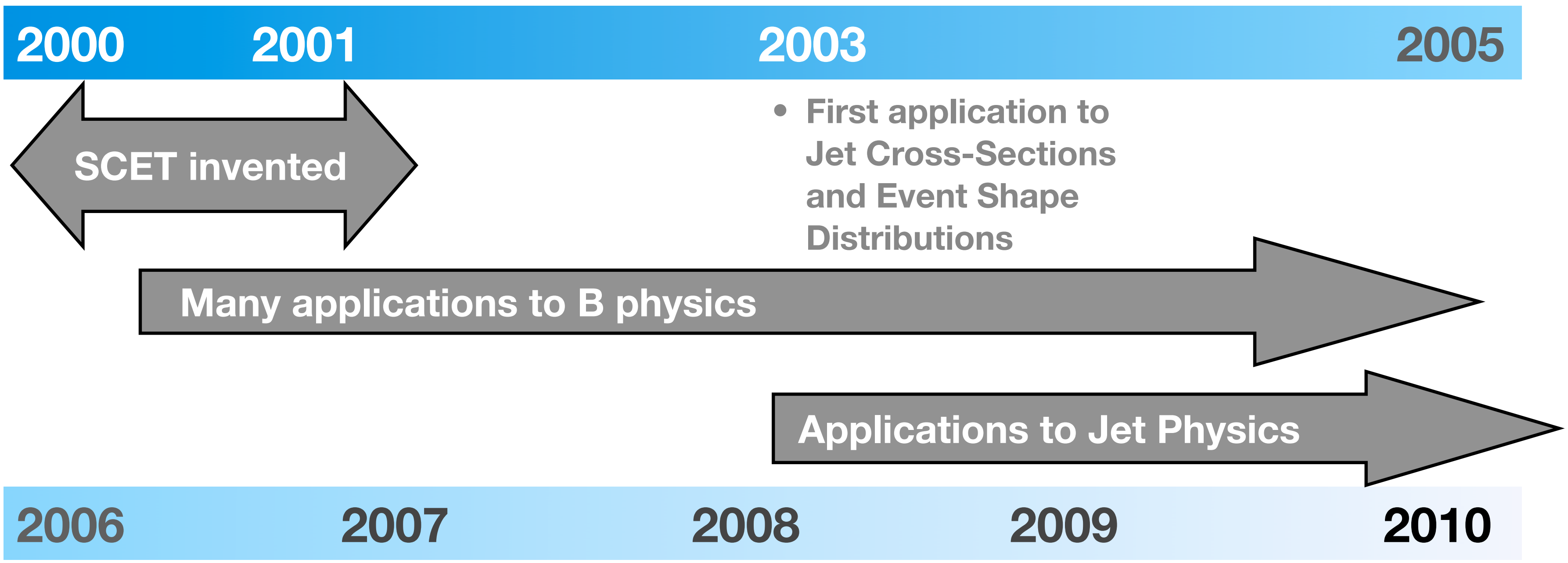

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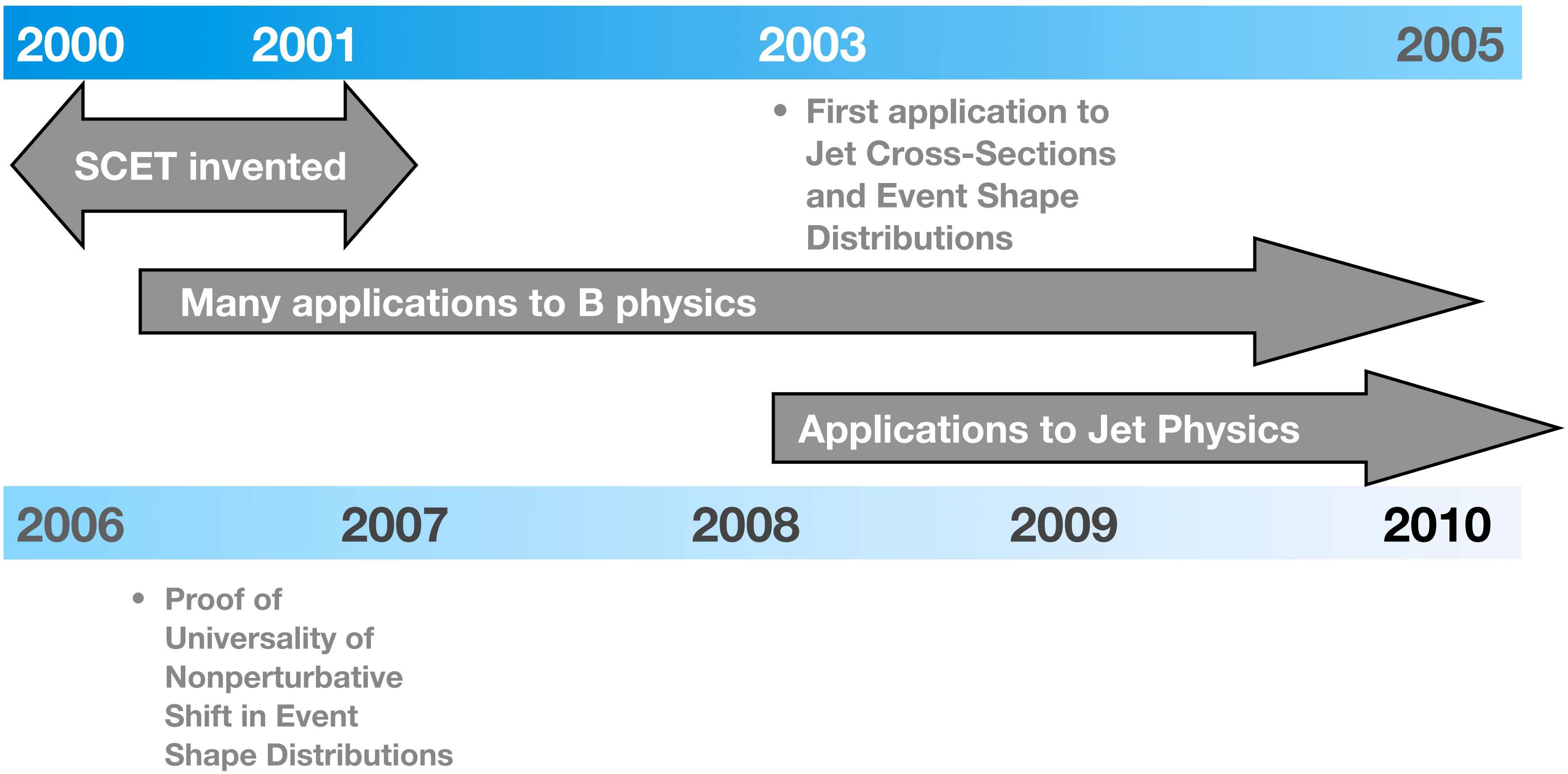

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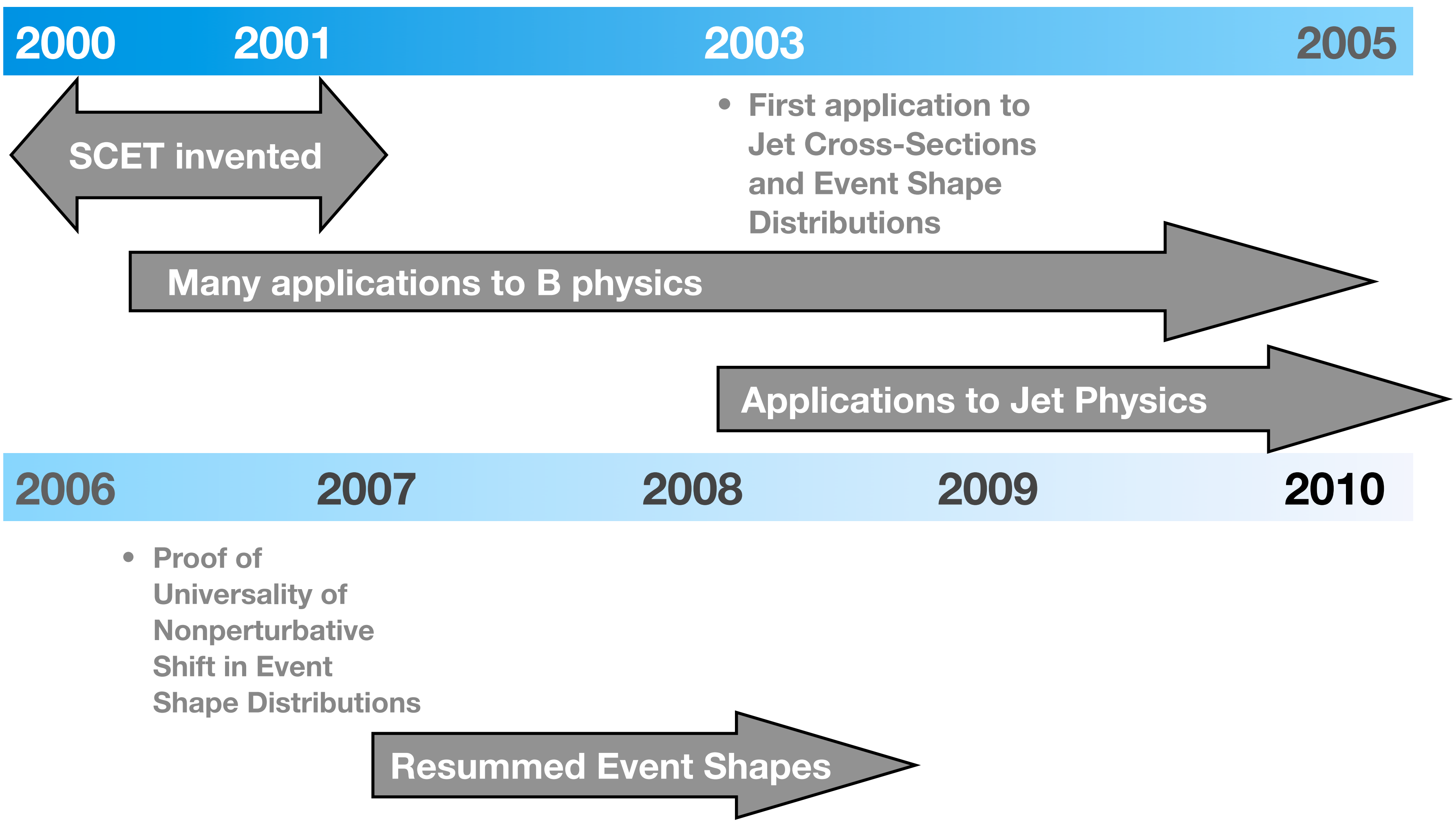

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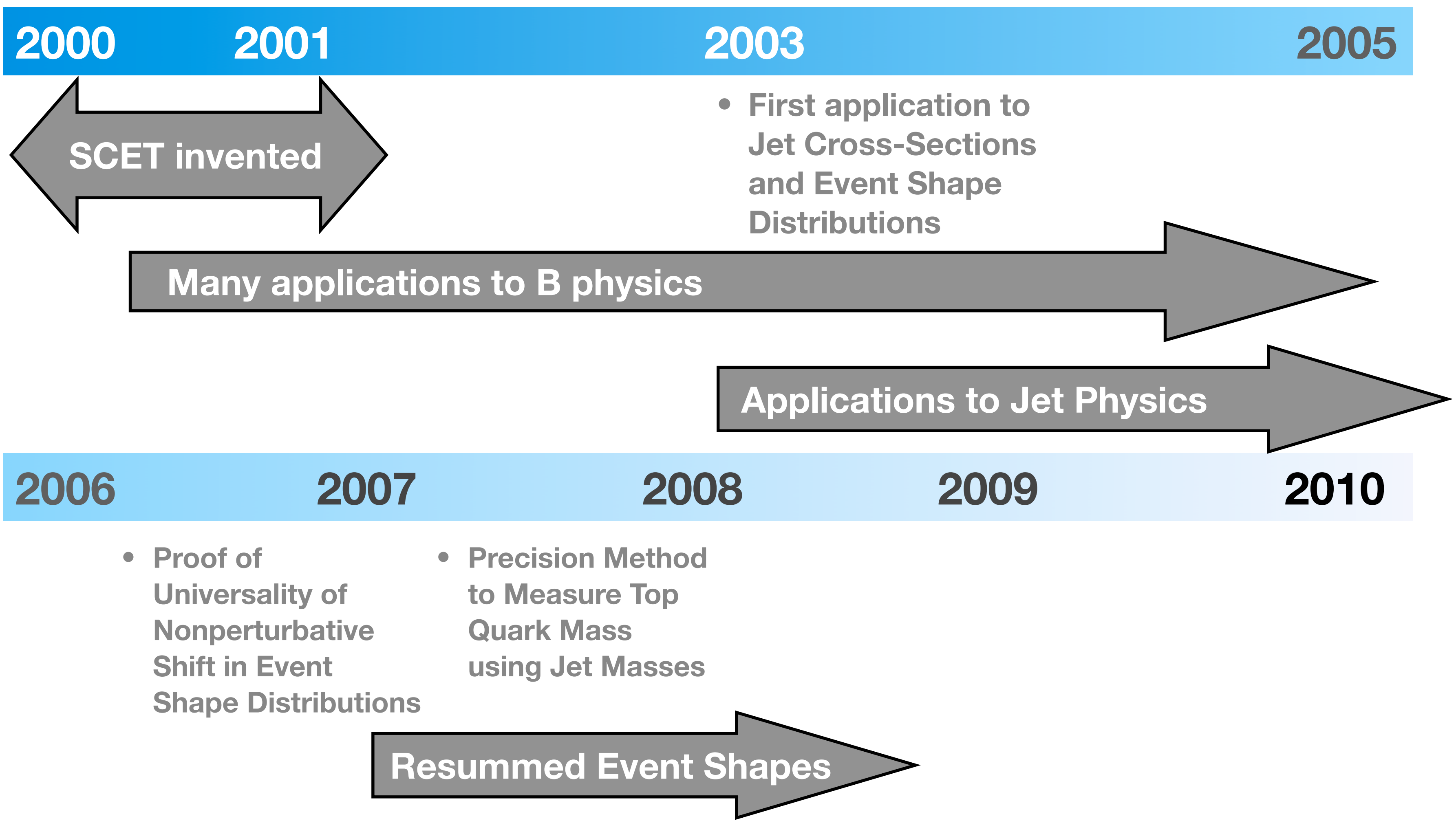

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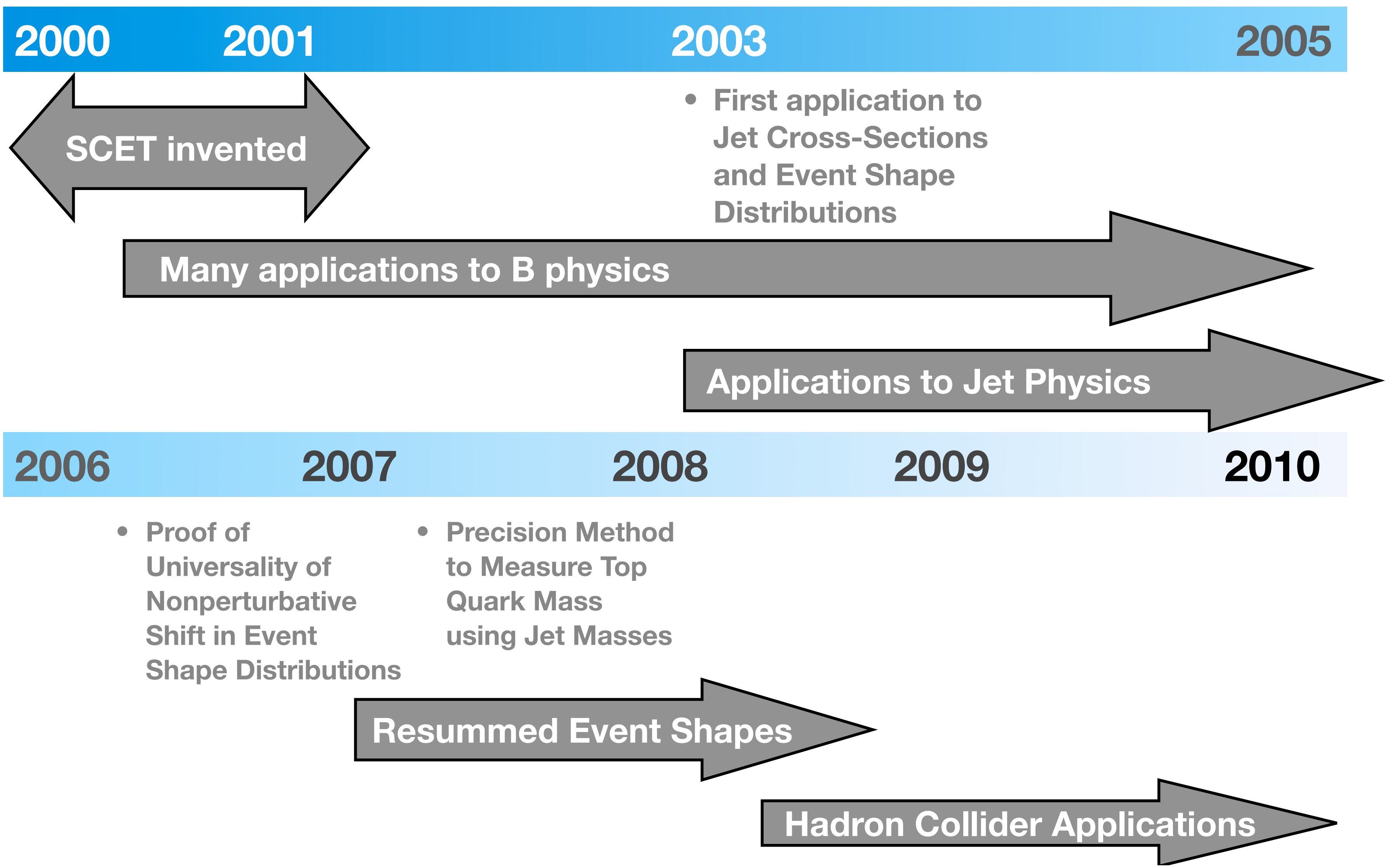

A Brief and Biased History of SCET

2000 **2001** **2003** **2005**

SCET invented

- First application to Jet Cross-Sections and Event Shape Distributions

Many applications to B physics

Applications to Jet Physics

2006 **2007** **2008** **2009** **2010**

- Proof of Universality of Nonperturbative Shift in Event Shape Distributions
- Precision Method to Measure Top Quark Mass using Jet Masses
- Initiation of development of a SCET-inspired Event Generator (GenEvA)

Resummed Event Shapes

Hadron Collider Applications

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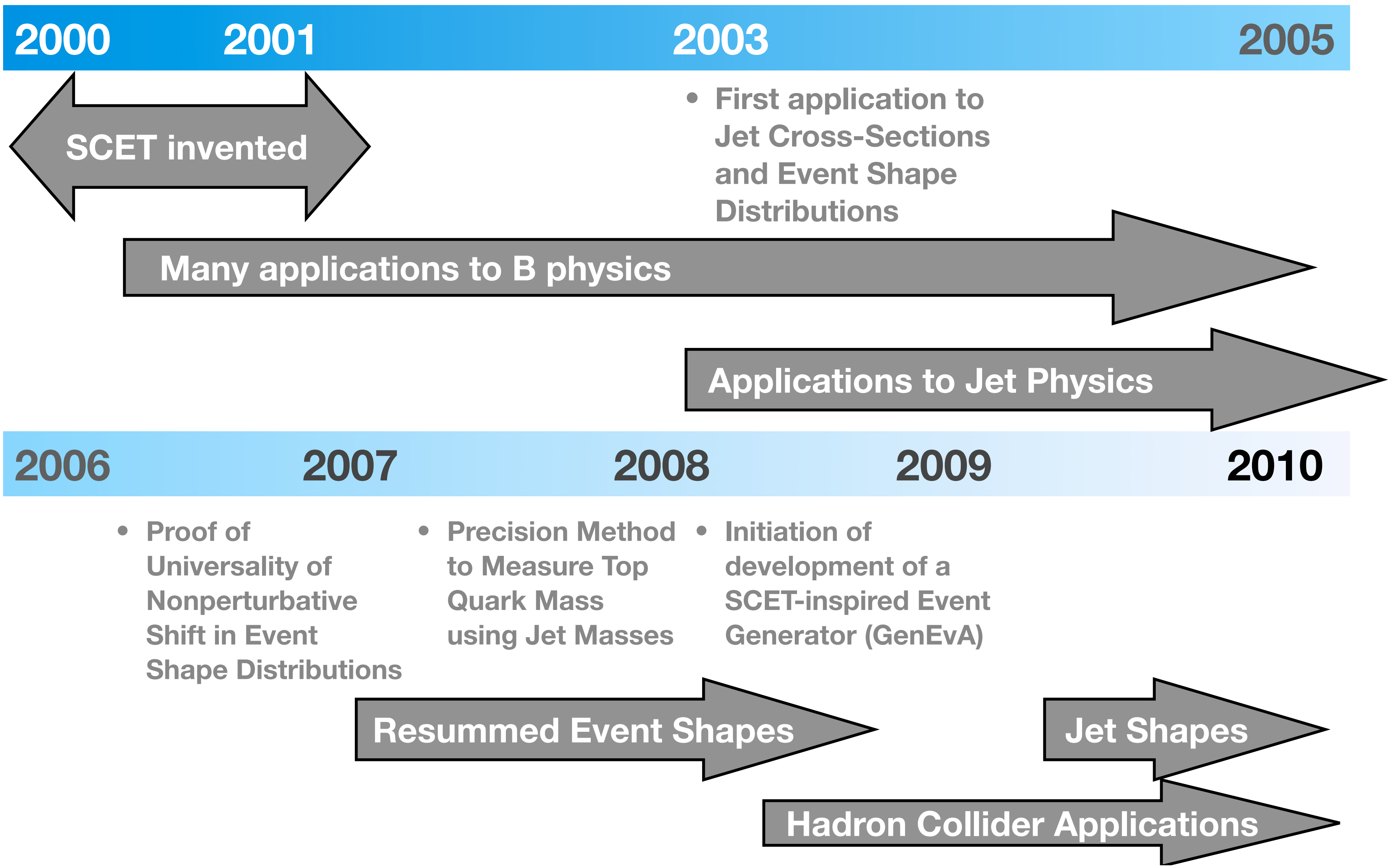

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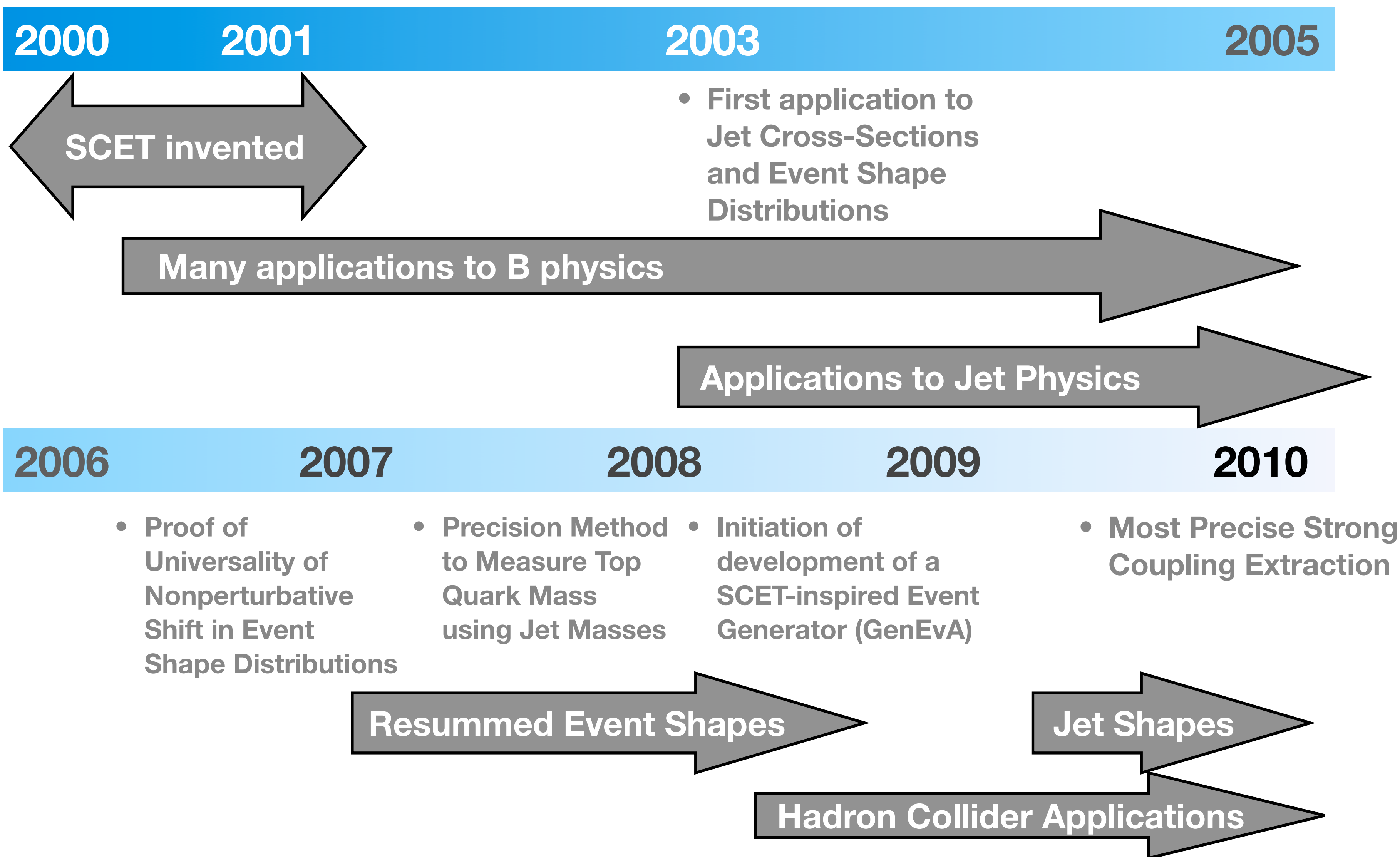

A Brief and Biased History of SCET

2000 **2001** **2003** **2005**

- SCET invented (2000–2001)
- Many applications to B physics
- 2003:
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- Proof of Universality of Nonperturbative Shift in Event Shape Distributions
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- Initiation of development of a SCET-inspired Event Generator (GenEvA)
- Most Precise Strong Coupling Extraction
- Jets in Dense QCD Media

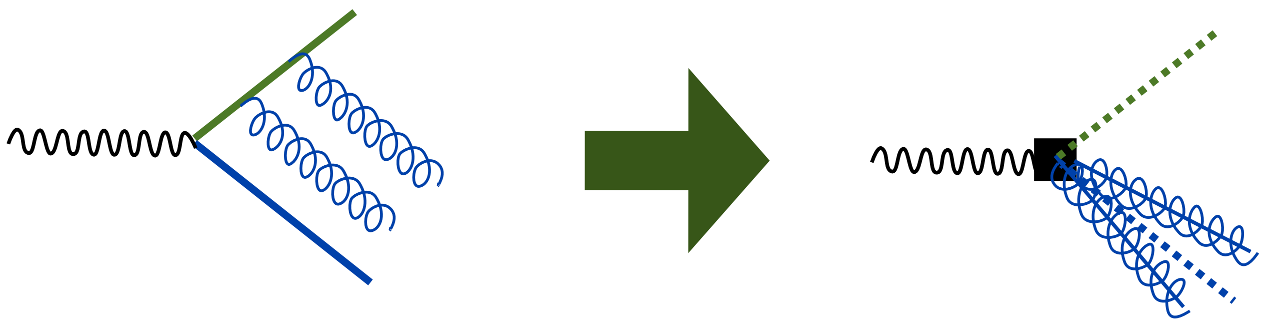
Resummed Event Shapes

Jet Shapes

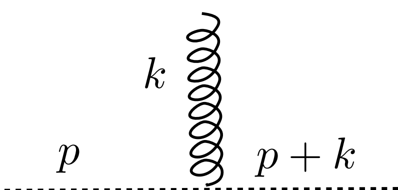
Hadron Collider Applications

Going from QCD to SCET

- Integrate out hard fluctuations, e.g. when jets in other directions emit particles into the n-collinear jet



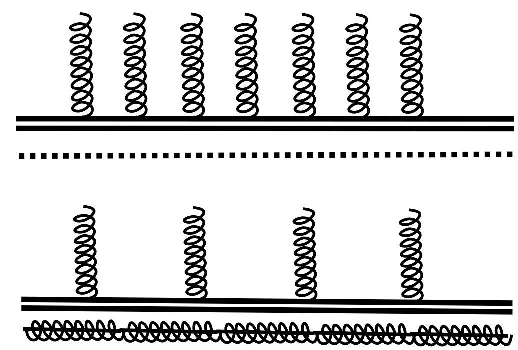
- Take eikonal limit of soft gluon attachments to collinear particles:



$$= -ig n^\mu T^A \frac{\not{n}}{2}$$

$$\frac{i(\not{p} + \not{k})}{(p+k)^2 + i\epsilon} \longrightarrow \frac{i}{n \cdot k + i\epsilon} \frac{\not{n}}{2}$$

soft gluons "see" only direction and color of jet



$$Y_n(z) = P \exp \left[ig \int_0^\infty ds \, n \cdot A_s(ns + z) \right]$$

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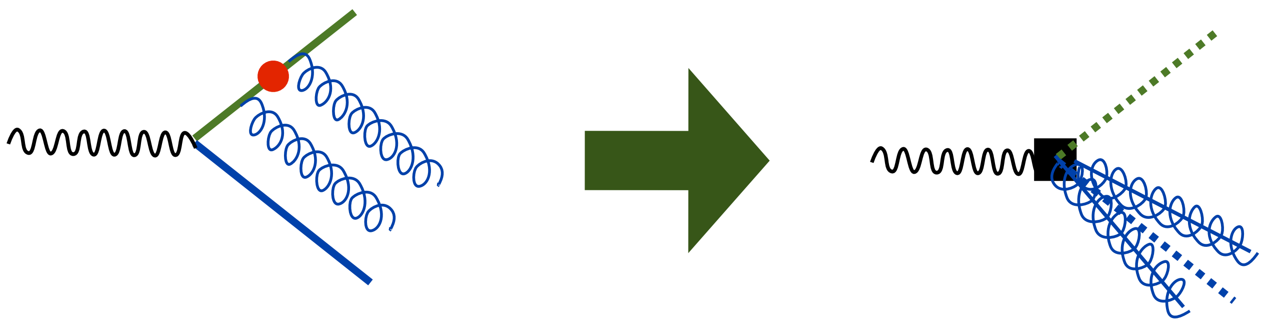

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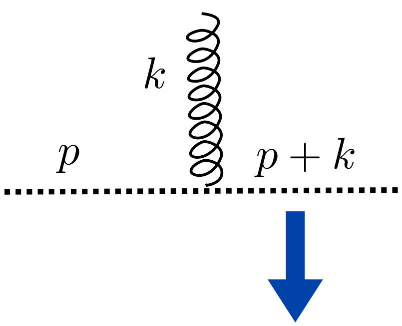

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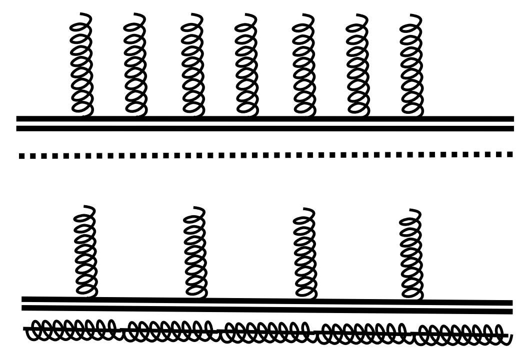

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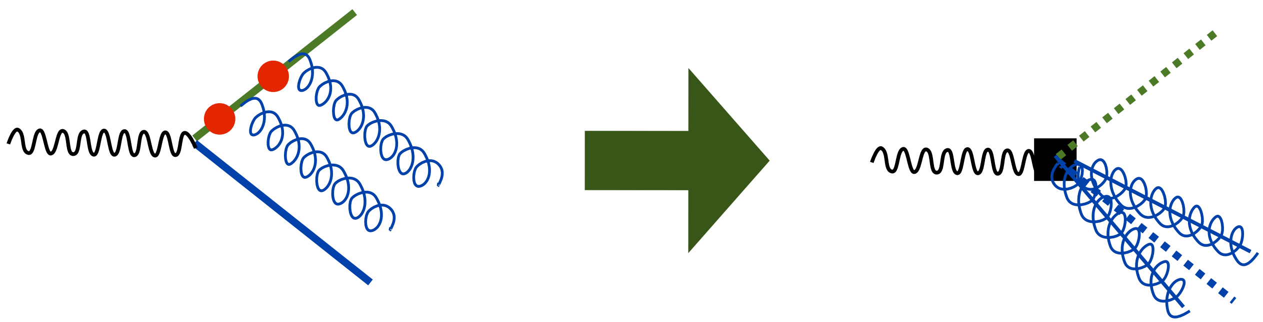

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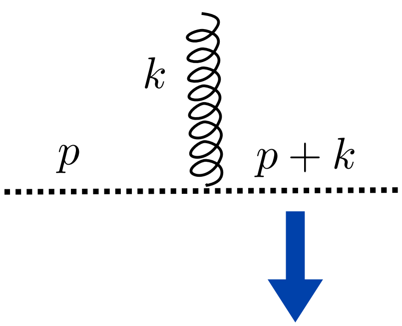

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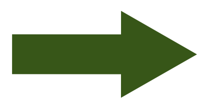

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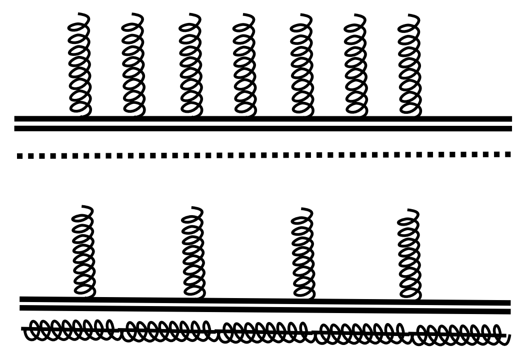

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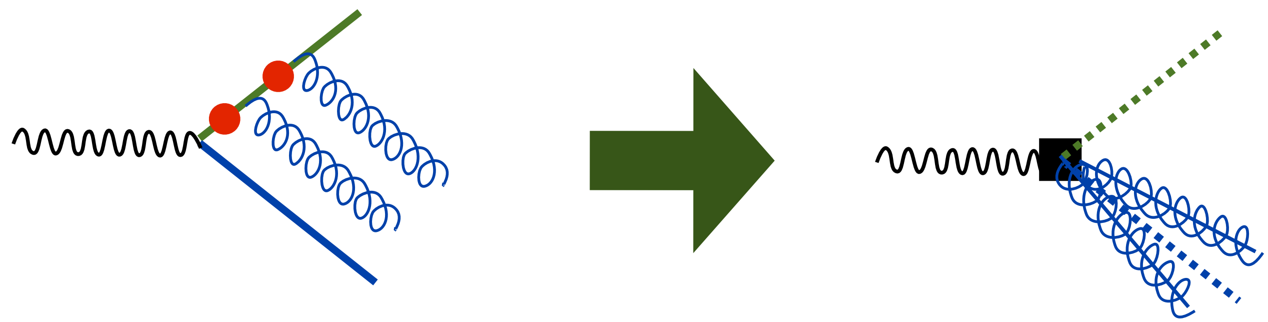

decouples different collinear directions

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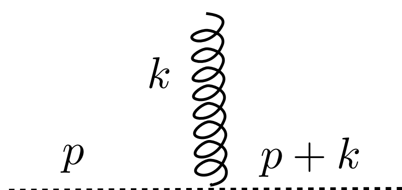

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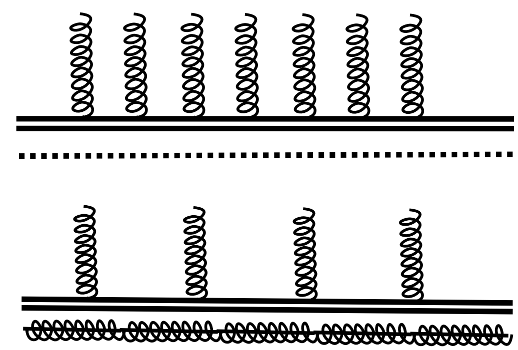

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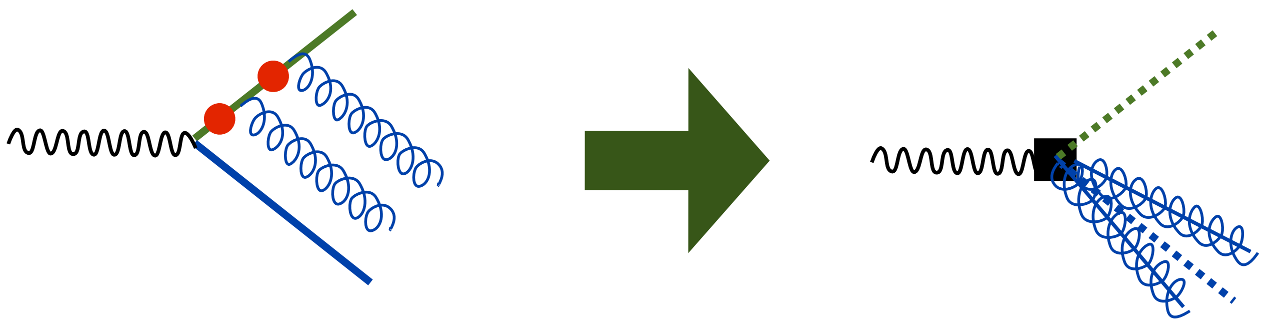

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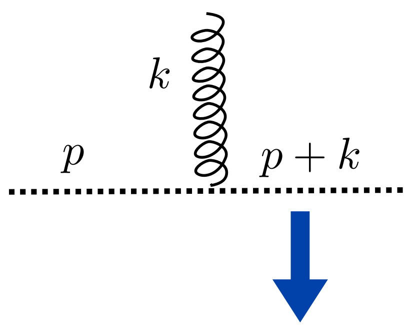

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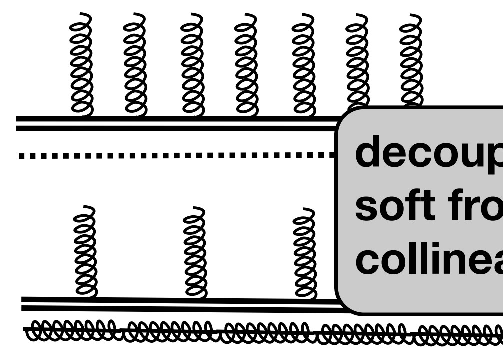


decouples soft from collinear

$$Y_n(z) = P\exp\left[ig\int_0^\infty ds\, n\cdot A_s(ns+z)\right]$$

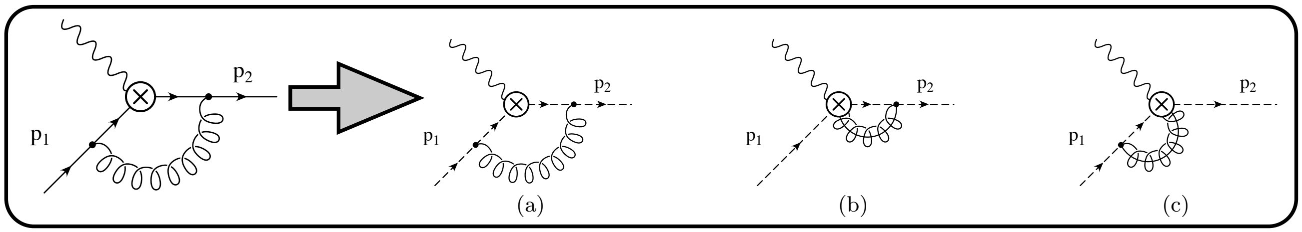
Factorization of Event Shape Distributions

Bauer, Fleming,
CL, Sterman

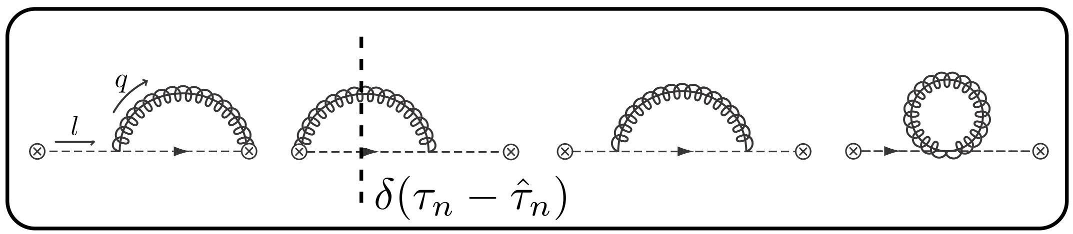
- Convolution of hard, jet, and soft functions:

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = H(Q,\mu)\int d\tau_n d\tau_{\bar{n}} J_n(\tau_n;\mu) J_{\bar{n}}(\tau_{\bar{n}};\mu) S(\tau - \tau_n - \tau_{\bar{n}};\mu)$$

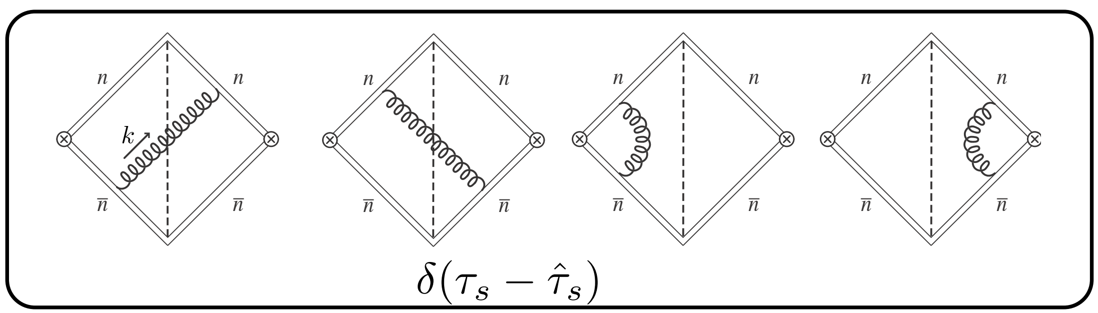
- Hard Function



- Jet Function



- Soft Function



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Large Logarithms in Distributions

- Thrust distribution contains divergent terms $\alpha_s^n \frac{\ln^m \tau}{\tau}$
- or, in integrated distribution $\alpha_s^n \ln^{m+1} \tau$

$$R(\tau) = \int d\tau \frac{1}{\sigma_0} \frac{d\sigma}{d\tau}$$

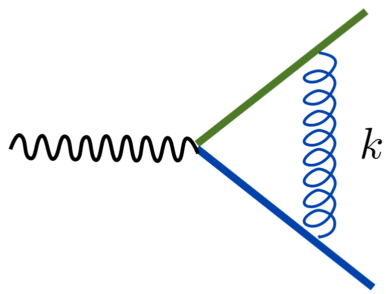
- Resum all terms up to a given order of accuracy

$$\begin{aligned} \ln R(\tau) \sim \quad & \alpha_s (\ln^2 \tau + \ln \tau) \\ & + \alpha_s^2 (\ln^3 \tau + \ln^2 \tau + \ln \tau + \cdots) \\ & + \alpha_s^3 (\ln^4 \tau + \ln^3 \tau + \ln^2 \tau + \ln \tau + \cdots) \\ & + \cdots \end{aligned}$$

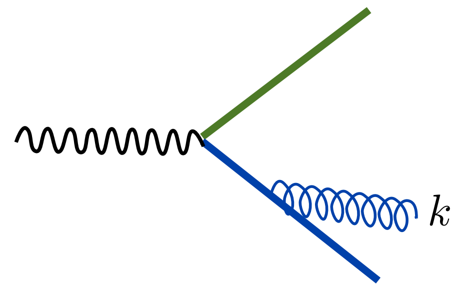
LL NLL NNLL

Where Do Logs Come from?

- Infrared divergences in **virtual** loop graphs canceled by soft and collinear divergences in **real** emission diagrams integrated over all phase space:

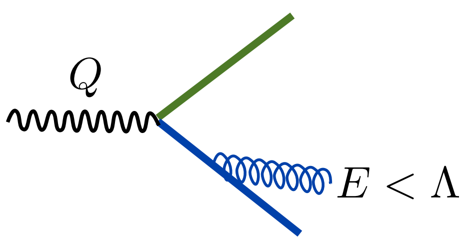


$$\int d\Pi_2 \int d^4k \Rightarrow \frac{A}{\epsilon_{\mathrm{IR}}}$$

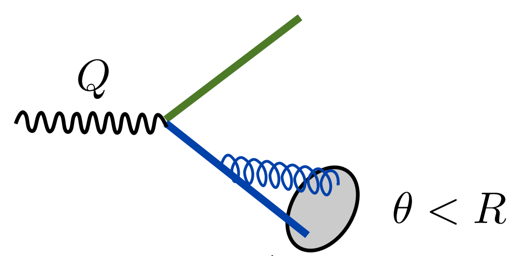


$$\int d\Pi_3 \Rightarrow -\frac{A}{\epsilon_{\mathrm{IR}}}$$

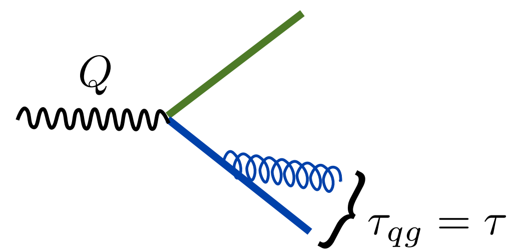
- Restrictions on real emission phase space leave the cancellation **incomplete** and generate **large logarithms:**



$$\int_{E<\Lambda} d\Pi_3 \Rightarrow -\frac{A}{\epsilon_{\mathrm{IR}}} + \ln\frac{\Lambda}{Q}$$



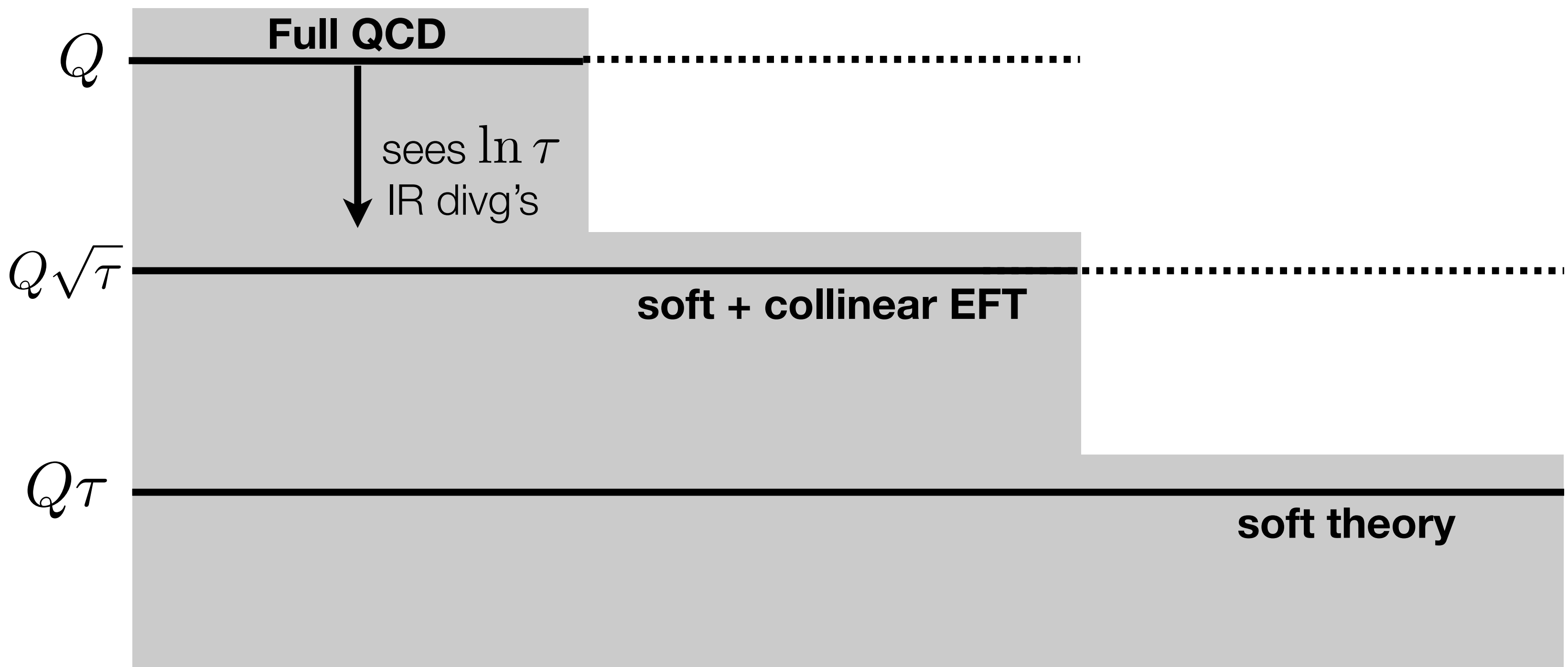
$$\int_{\theta<R} d\Pi_3 \Rightarrow -\frac{A}{\epsilon_{\mathrm{IR}}} + \ln\tan\frac{R}{2}$$



$$\int d\Pi_3 \delta(\tau_{qg} - \tau) \Rightarrow -\frac{A}{\epsilon_{\mathrm{IR}}} + \ln\tau$$

IR Resummation from UV Evolution

- IR divergences in the full theory are converted to UV divergences in the effective theory, e.g. for thrust distribution:



- Logs can now be resummed using renormalization group evolution with the factorization scale μ

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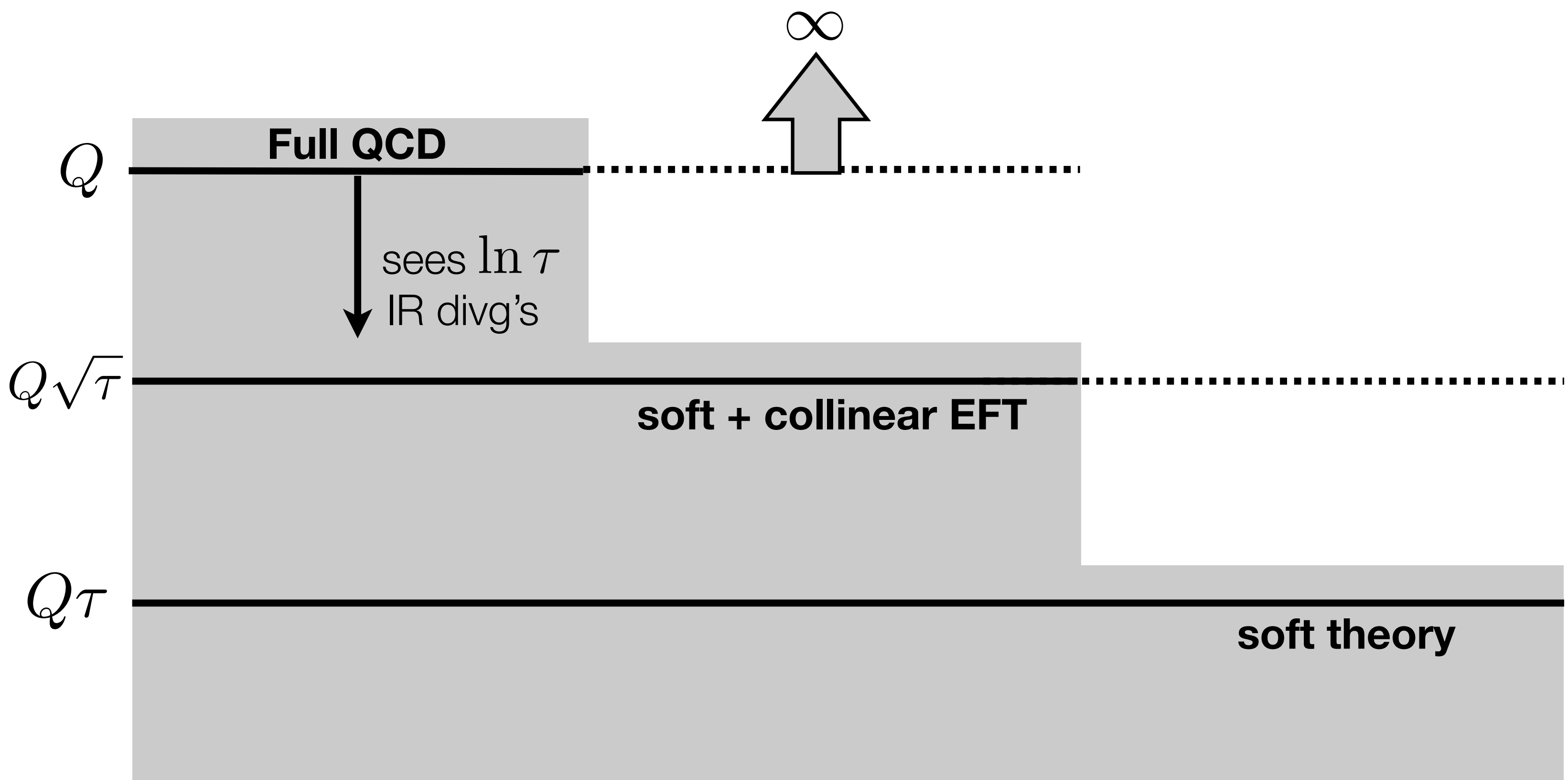

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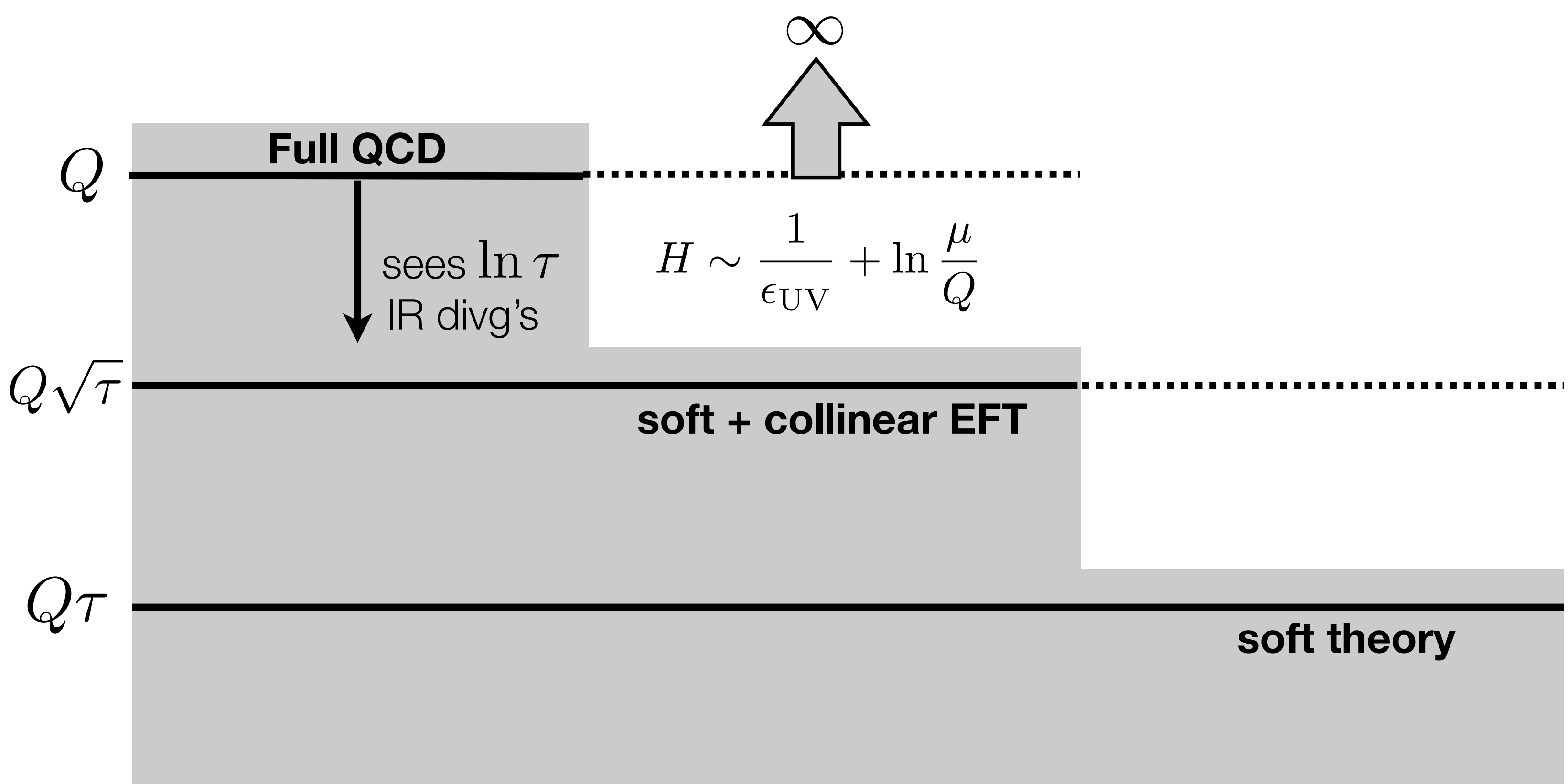

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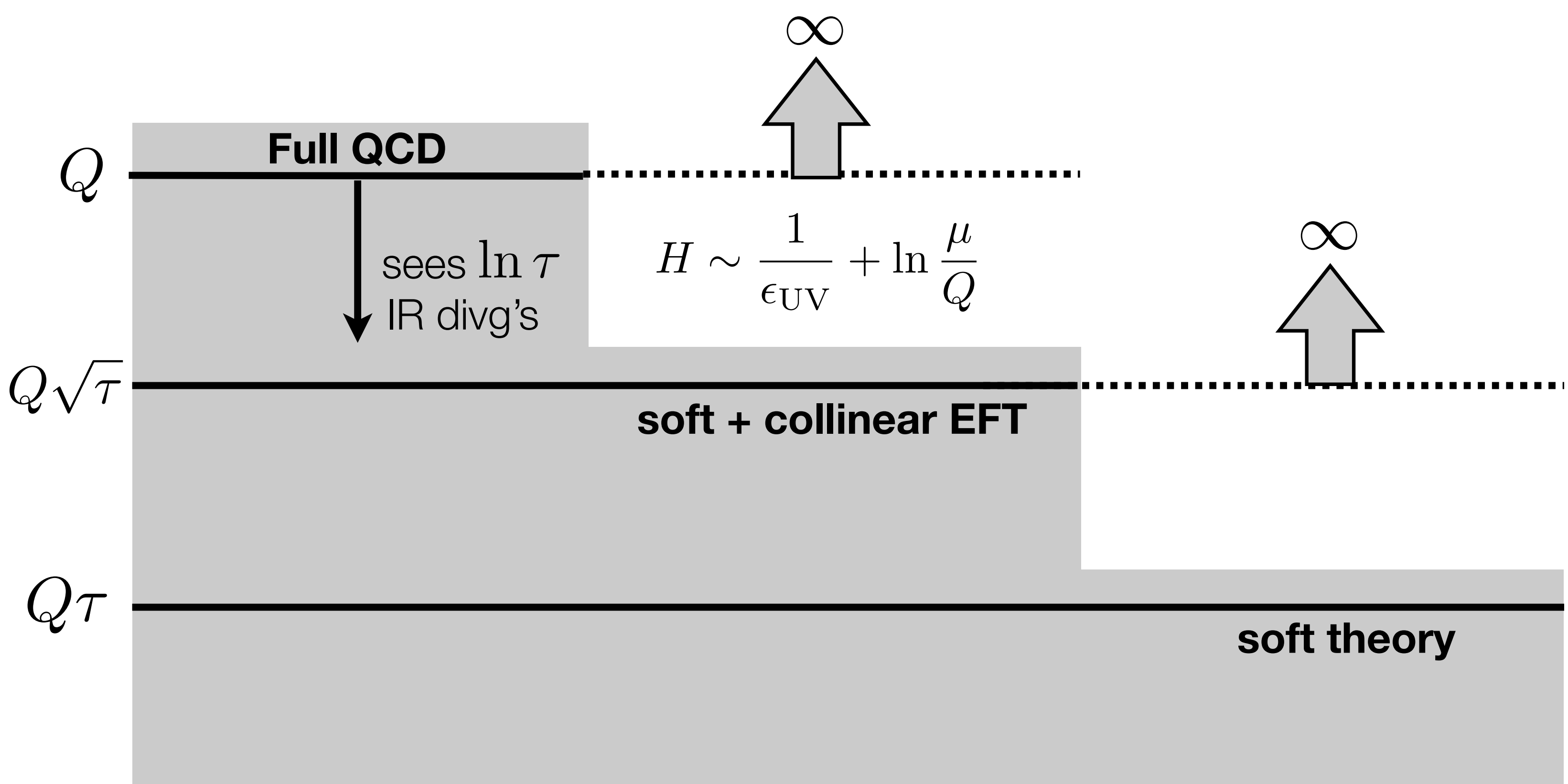

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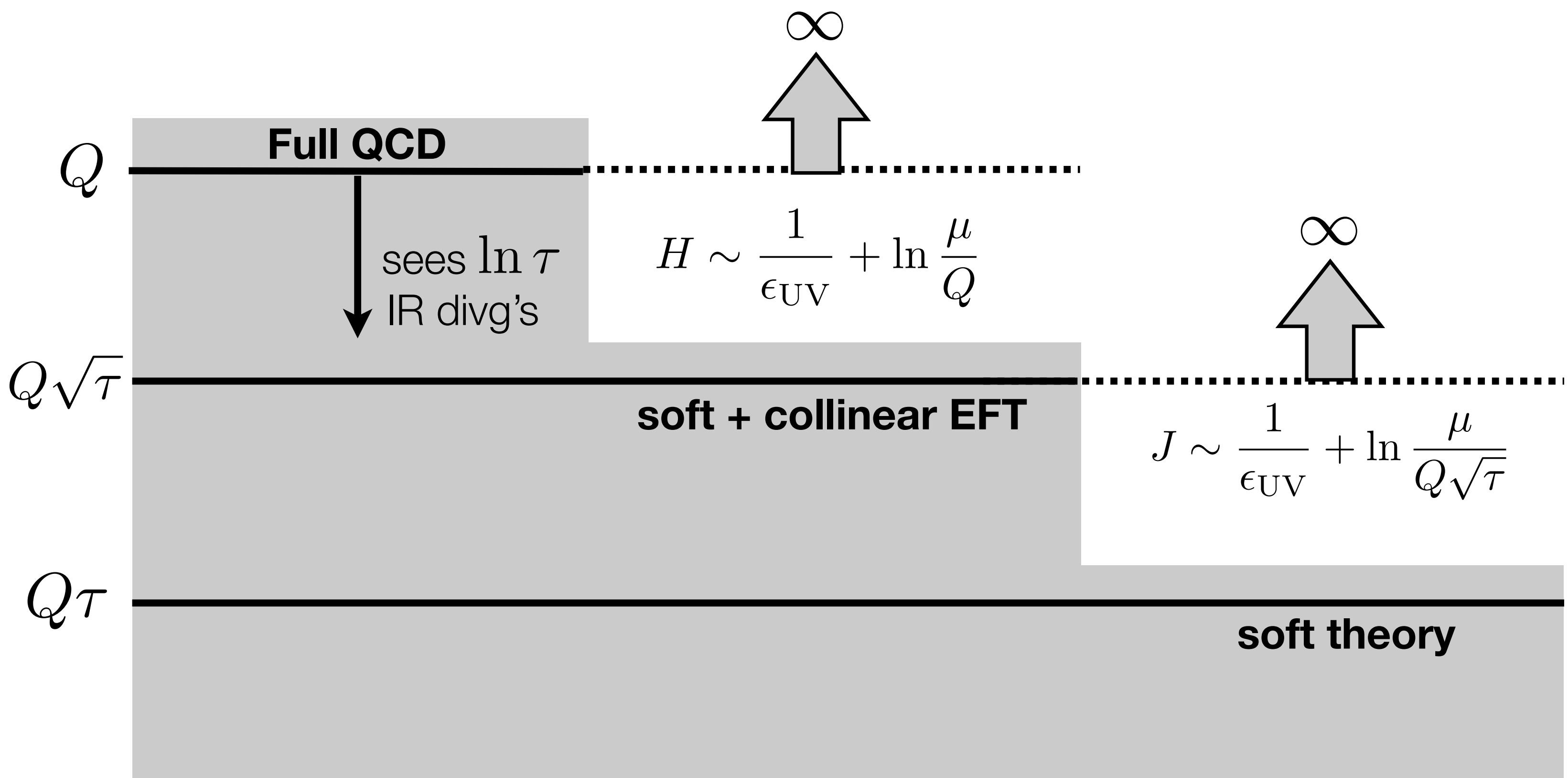

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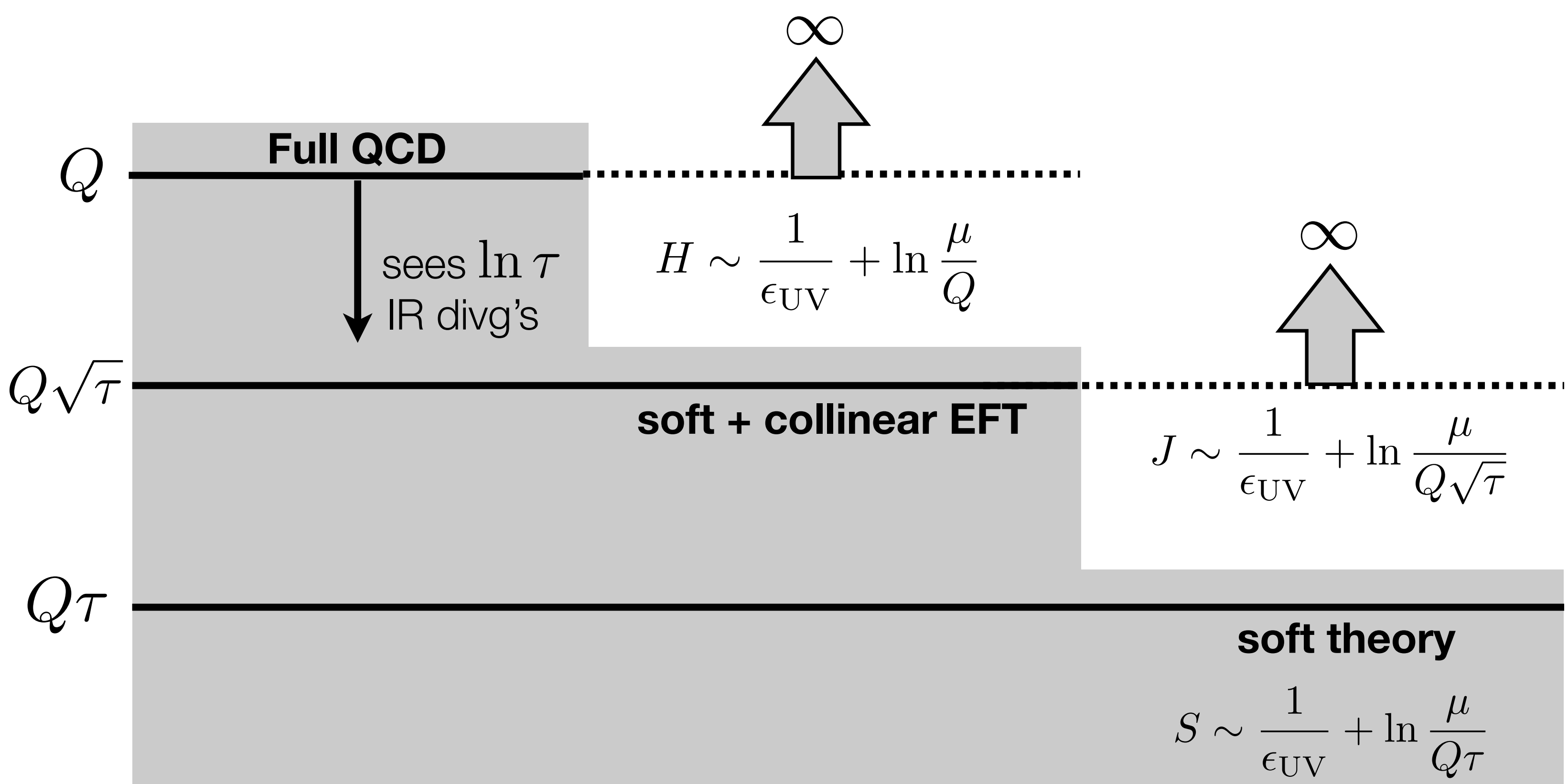

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Universal Soft Power Corrections

- Soft power corrections shift mean values of event shapes

conjecture from single soft gluon emission: Dokshitzer, Webber (1995, 1997)

$$\langle e \rangle = \langle e \rangle_{\rm PT} + c_e \frac{\mathcal{A}}{Q}$$

c_e observable dependent, calculable coefficient

$\mathcal{A}$ universal nonperturbative parameter

- Stronger version: simple shift of full distribution

$$\frac{d\sigma}{de}(e) = \frac{d\sigma}{de}\left(e - c_e \frac{\mathcal{A}}{Q}\right)\bigg|_{\rm PT}$$

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- In general, use NP soft shape function to smear out perturbative distribution, with universal information for first moment

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Abbate, Fickinger, Hoang, Mateu, Stewart

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In general not true

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Angularities: a general class of event shapes

- Generalization of thrust:

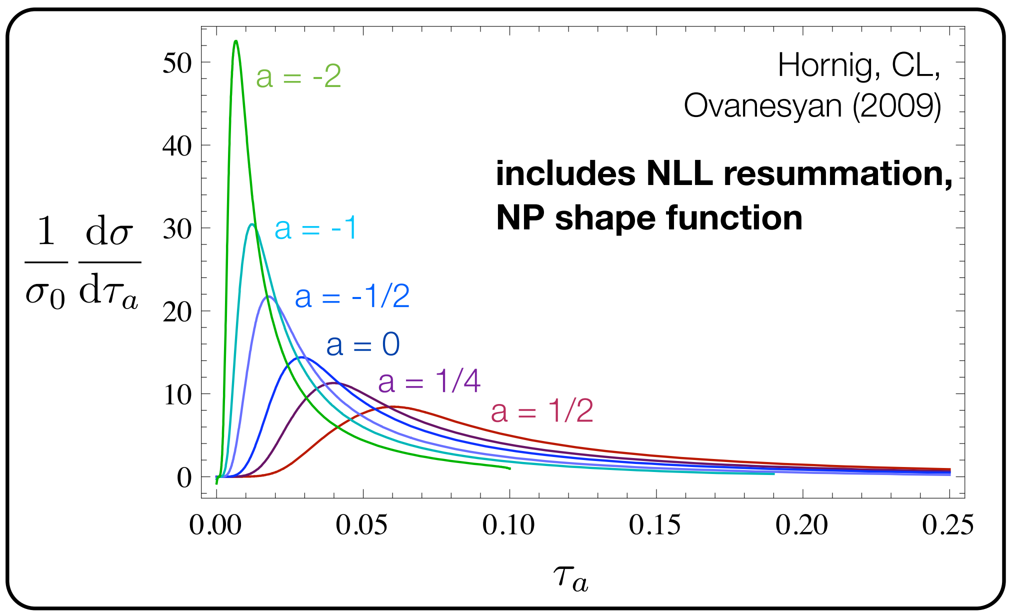
Berger, Kucs, Sterman

$$\tau_a = \frac{1}{Q}\sum_i E_i(\sin\theta_i)^a(1-|\cos\theta_i|)^{1-a} = \frac{1}{Q}\sum_i |\mathbf{p}_i^T| e^{-|\eta_i|(1-a)}$$

a = 0 thrust
a = 1 broadening

infrared safety: $-\infty < a < 2$
factorizability: $-\infty < a < 1$

Peak region dominated by narrower jets for large *a*, wider jets for small *a*



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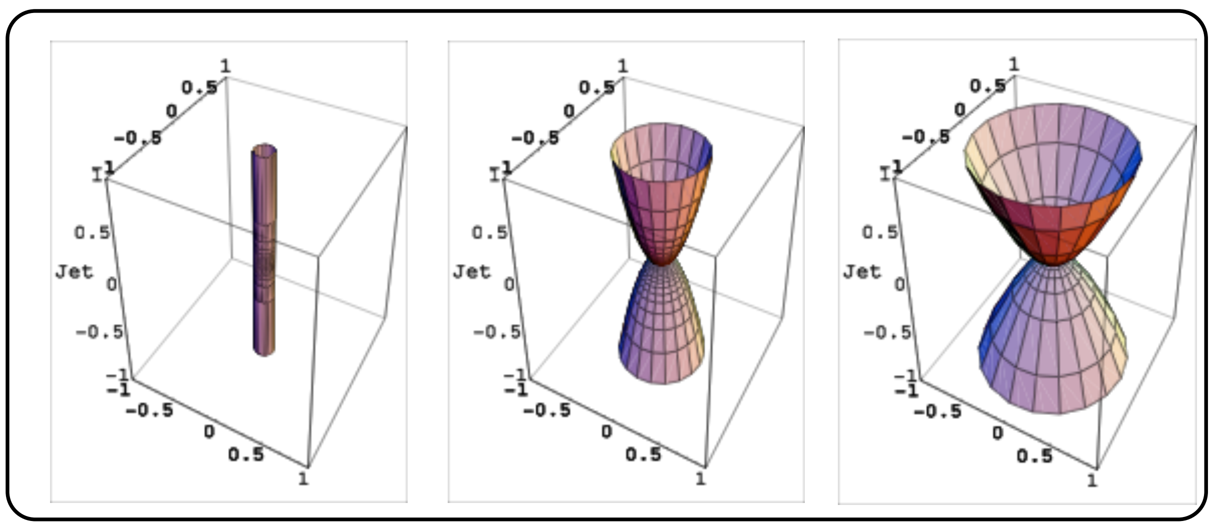
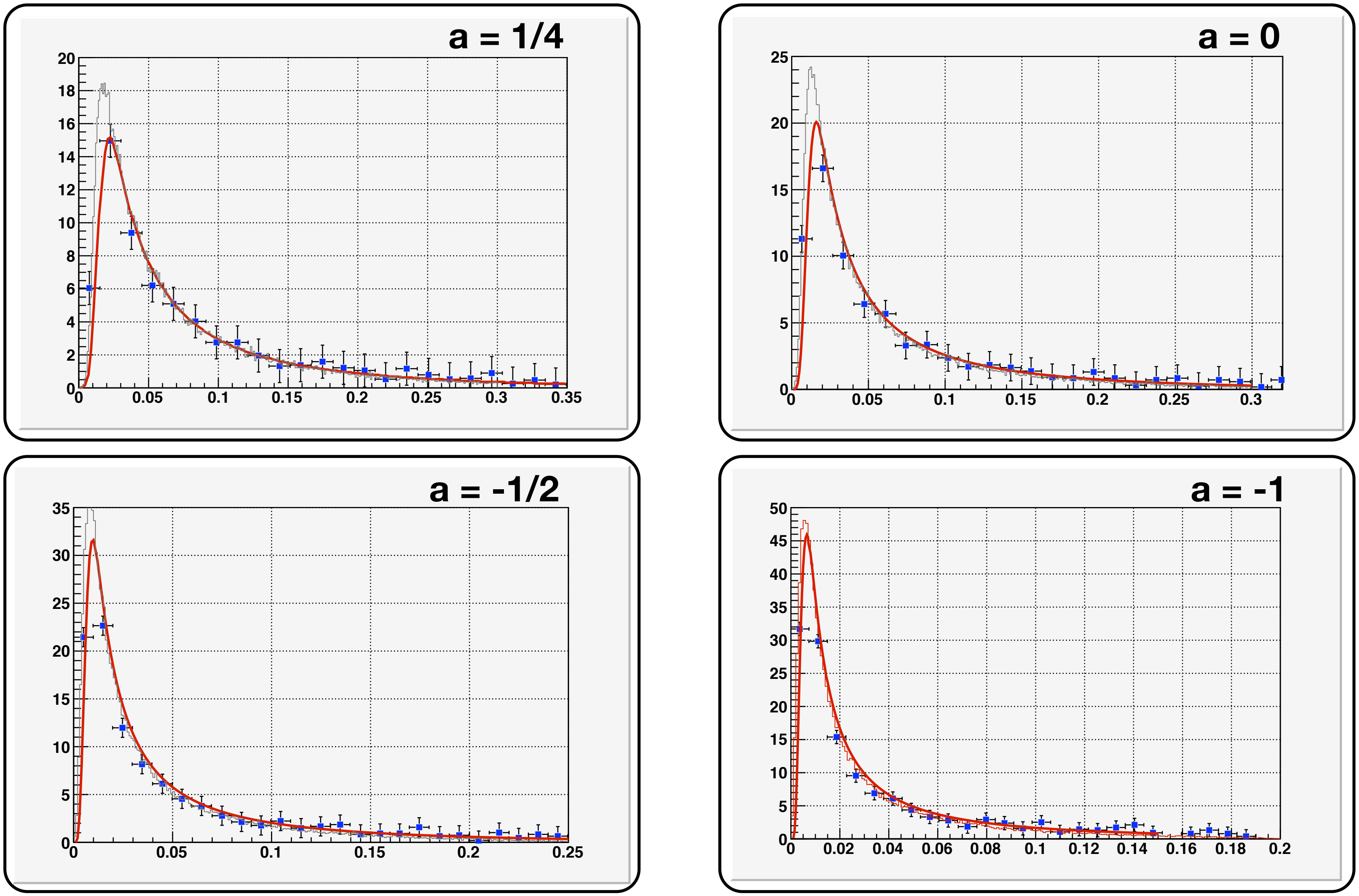


a = 1 a = 0 a = -1

Angularity Distributions at ***Q = 197 GeV***:

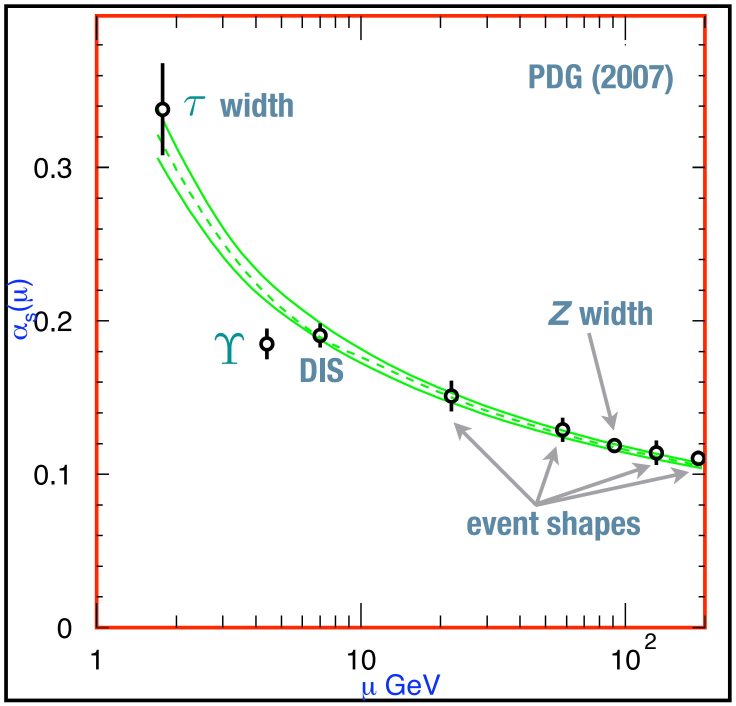
NLL Theory vs. Experiment (and PYTHIA8)

Th: Hornig, CL, Ovanesyan
Ex: P. Jindal (LEP), PhD Thesis



Precision extractions of strong coupling

$$\alpha_s(M_Z) = 0.1176 \pm 0.0020 \text{ (PDG)}$$



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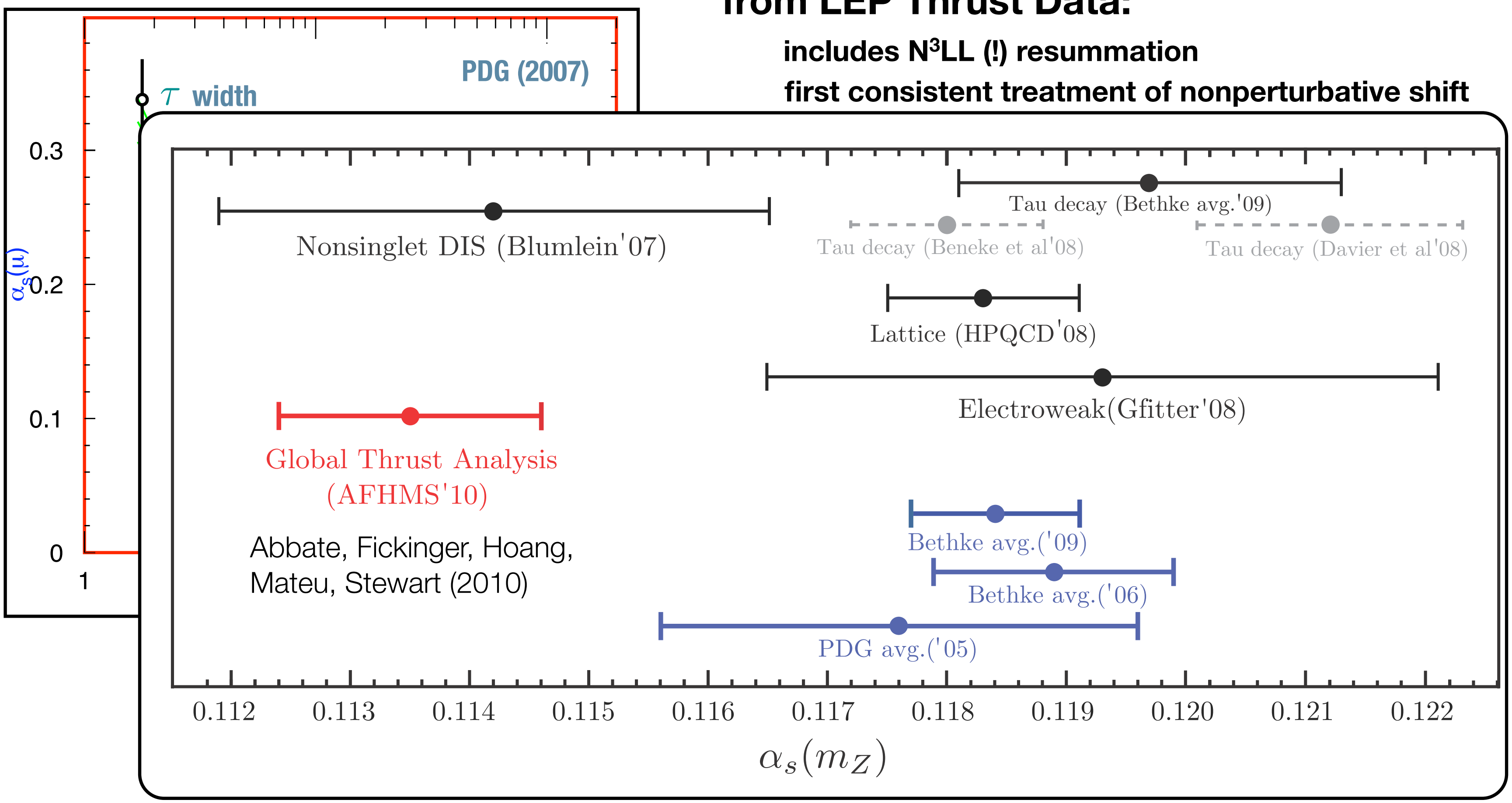
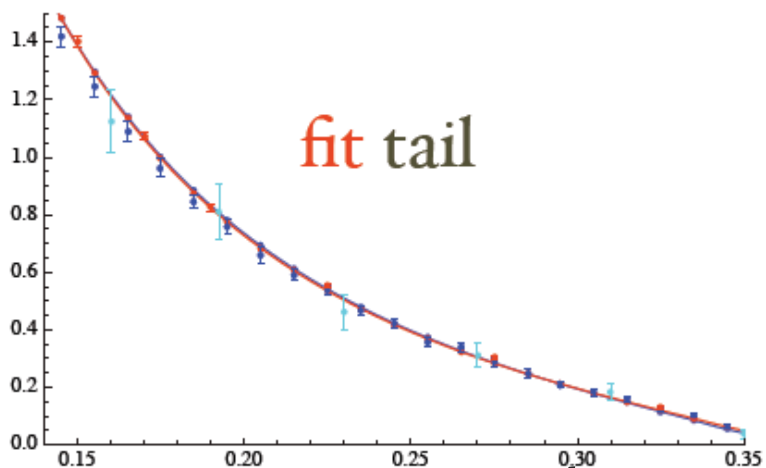
New SCET-based Extraction from LEP Thrust Data:

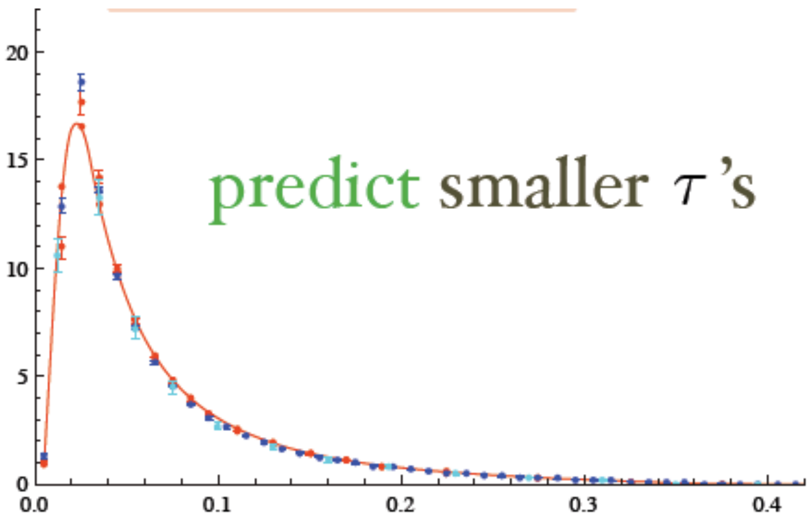
- **includes N^{3}LL (!) resummation**
- **first consistent treatment of nonperturbative shift**

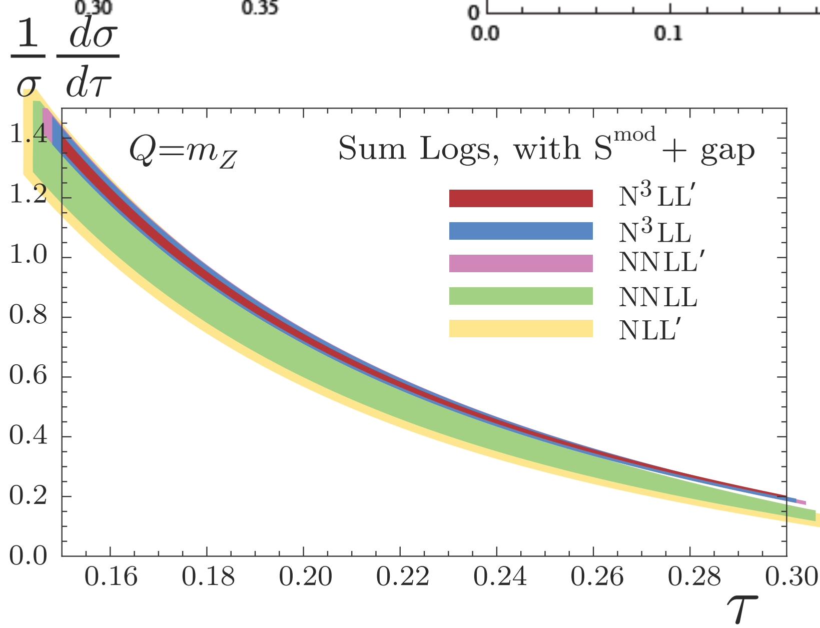


$$\alpha_s(M_Z) = 0.1135 \pm (0.0002)_{\text{exp}} \pm (0.0005)_{\text{hadr}} \pm (0.0009)_{\text{pert}}$$

Precision extractions of strong coupling







Abbate, Fickinger, Hoang, Mateu, Stewart (2010)

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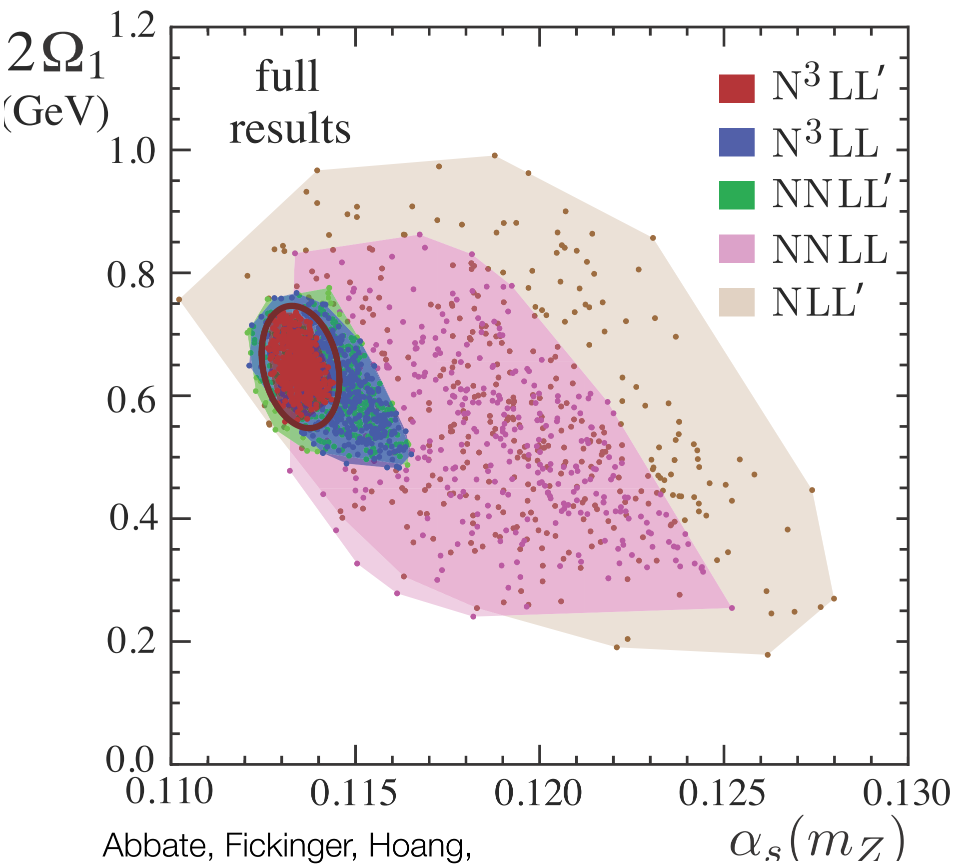
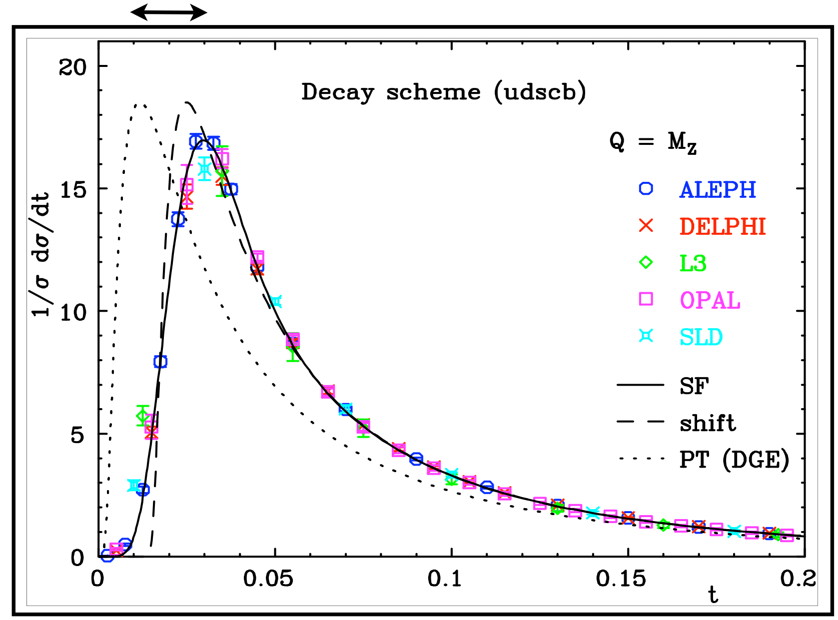


Abbate, Fickinger, Hoang, Mateu, Stewart (2010)

$\sim \Omega_1/Q$



$$\overline{\Omega}_1 \equiv \frac{1}{2N_c}\langle 0|\mathrm{tr}\ \overline{Y}_{\bar{n}}(0)Y_n(0)\ i\partial_\tau\ Y_n^\dagger(0)\overline{Y}_{\bar{n}}^\dagger(0)|0\rangle \qquad (\overline{MS})$$

$$i\partial_\tau \equiv \theta(i\bar{n}\cdot\partial - in\cdot\partial)\ in\cdot\partial + \theta(in\cdot\partial - i\bar{n}\cdot\partial)\ i\bar{n}\cdot\partial$$

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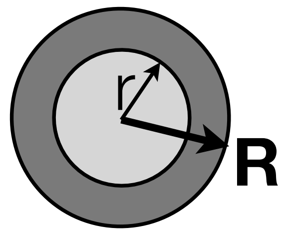
Strategies to Probe Jet Substructure

- **“Jet Grooming”:** Filtering, Trimming, Pruning...
  - well-suited for implementation in Monte Carlo or expt.

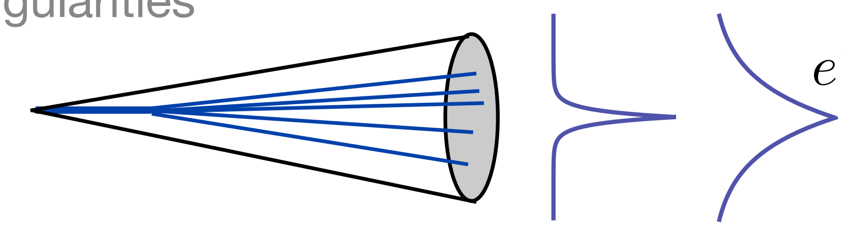
Butterworth, Davison, Rubin, Salam; Thaler, Wang; Ellis, Vermilion, Walsh; Kaplan, Rehermann, Schwartz, Tweedie; Plehn, Salam, Spannowsky; Kribs, Martin, Roy, Spannowsky; ...

- **Jet Shapes**
  - “The” Jet Shape $\Psi(r/R)$



Ellis, Kunzst, Soper; CDF

  - Angularities



$$e^{-|\eta|(1-a)}$$

$$\tau_a(\text{jet}) = \frac{1}{2E_{\text{jet}}} \sum_{i \in \text{jet}} |\mathbf{p}_i^T| e^{-|\eta_i|(1-a)}$$

Berger, Kucs, Sterman

Almeida, Lee, Perez, Sterman, Sung, Virzi

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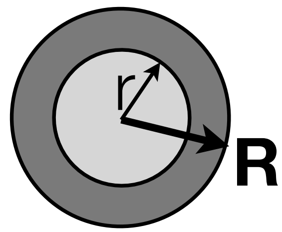

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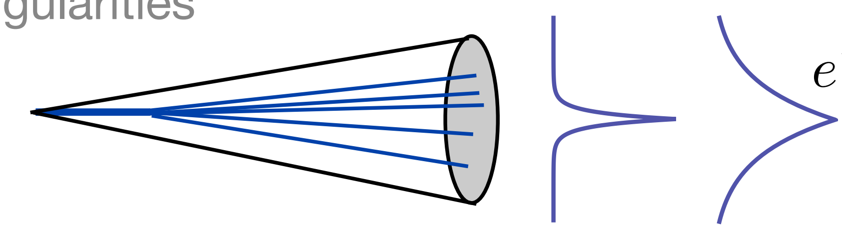

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$$\tau_a(\text{jet}) = \frac{1}{2E_{\text{jet}}} \sum_{i\in\text{jet}} |\mathbf{p}_i^T| e^{-|\eta_i|(1-a)}$$

Well suited for analytical calculations

From Event Shapes to Jet Shapes

- Modify notion of event shape to the “jet shape” of a single jet:

$$\tau_a(\text{jet}) = \frac{1}{2E_{\text{jet}}} \sum_{i\in\text{jet}} |\mathbf{p}_i^T| e^{-|\eta_i|(1-a)}$$

(theoretical convenience)

- Requires specification of jet definition (algorithm)

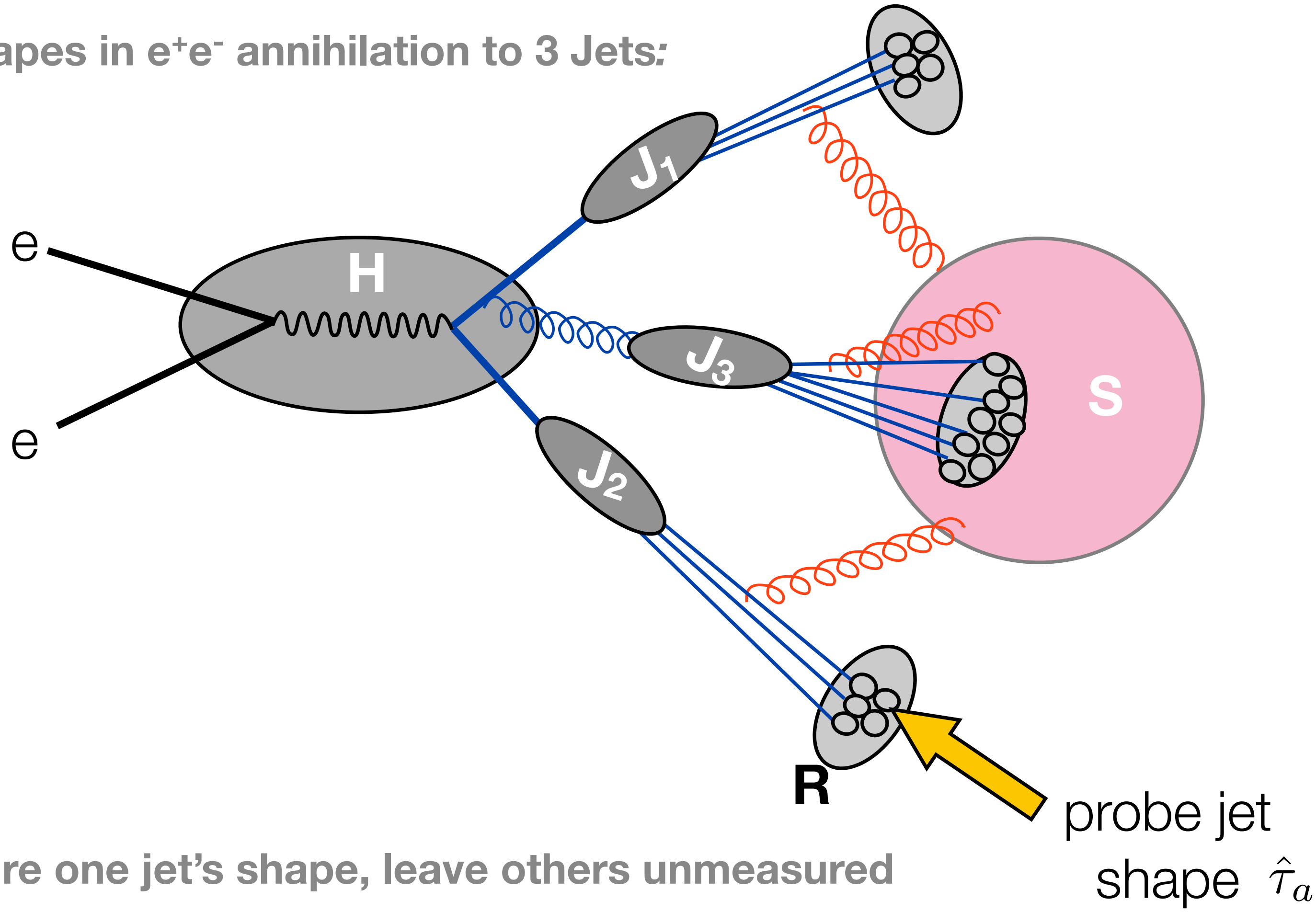
- Transverse momentum and rapidity with respect to jet axis, identified by algorithm

- Requires new formulation of factorization theorem, new calculation of hard, jet, and soft functions

Ellis, Hornig, CL, Vermilion, Walsh (2009, 2010)

Factorization of Jet Shape Distributions

- **Jet shapes in e^+e^- annihilation to 3 Jets:**

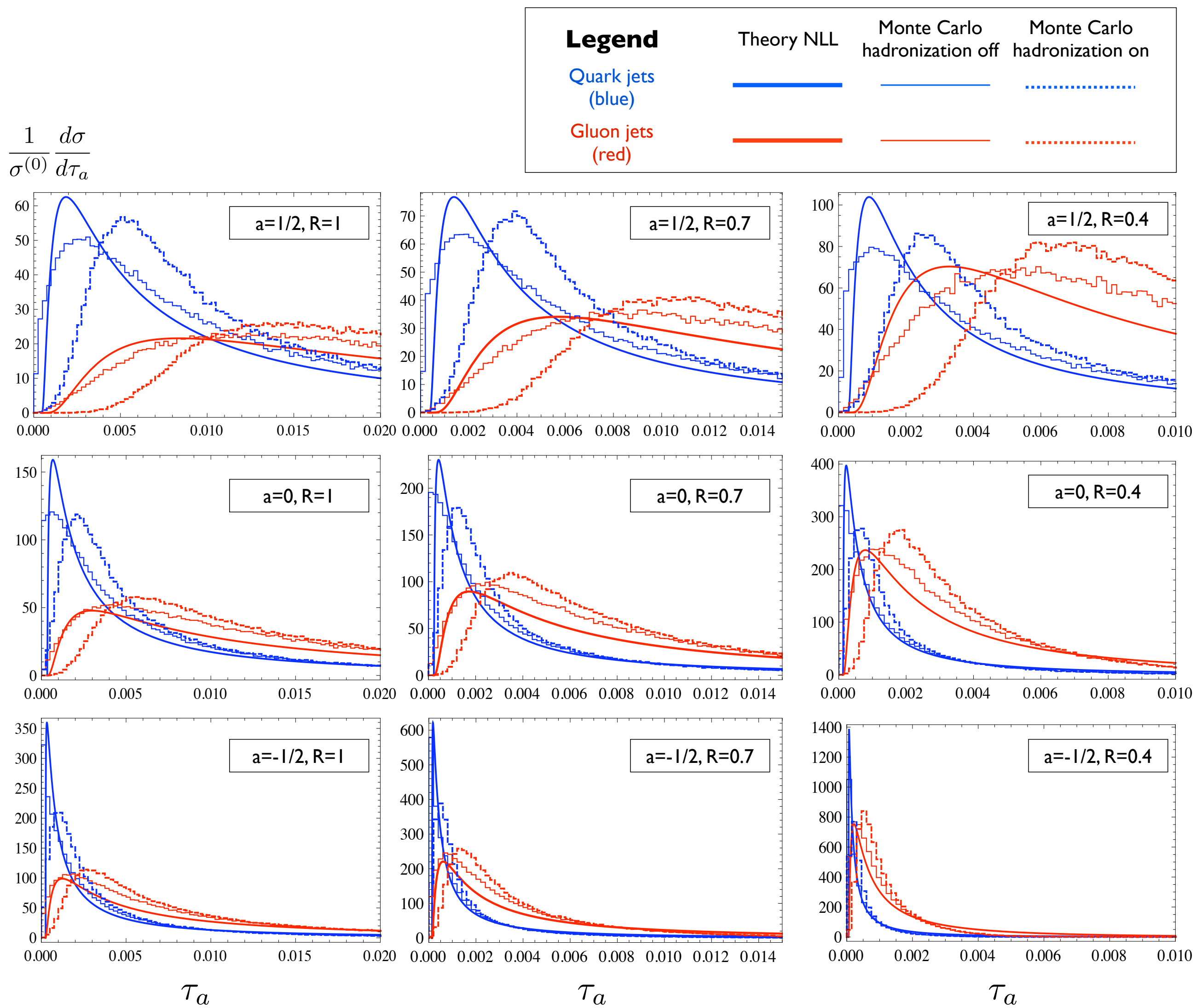


- **Measure one jet's shape, leave others unmeasured**

- **New factorization theorem to account for algorithm dependence (2010)**

Resummed Predictions of Jet Shape Distributions vs. Monte Carlo

Ellis, Hornig, CL, Vermilion, Walsh



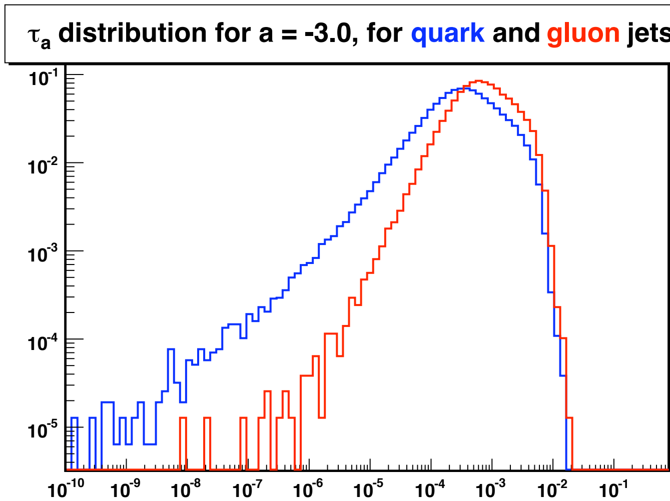
Q = 500 GeV

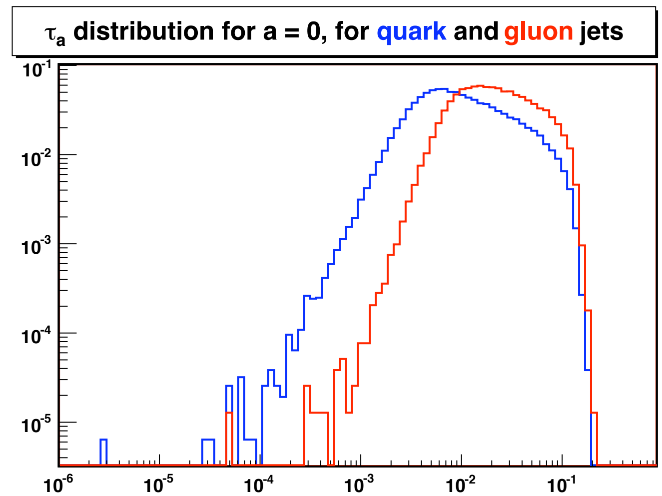
E_J = 150 GeV

Using angularities to distinguish quark and gluon jets

PRELIMINARY

Ellis, Hornig, CL, Vermilion, Walsh



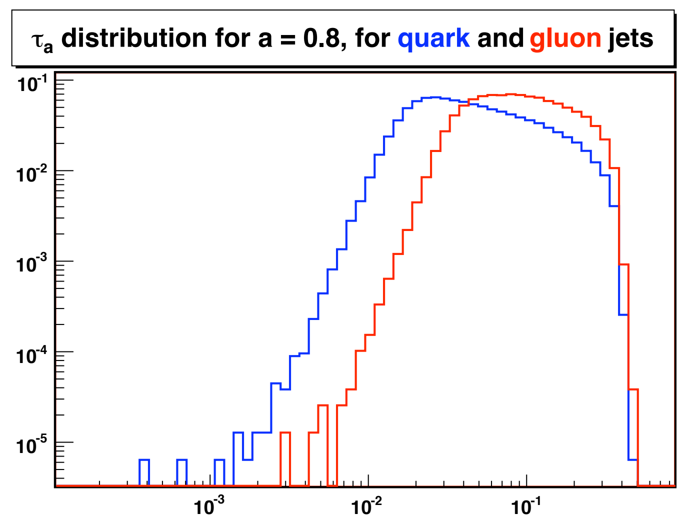


Studied quark v. gluon jets 3 well-separated jets in e^+e^-

cuts exist keeping ~2% of gluon jets and ~20% of quark jets (**10:1** enhancement)

or ~15% of gluons and 8% quarks (**2:1** enhancement).

Expect greater discriminating power in correlated distributions for multiple values of *a*



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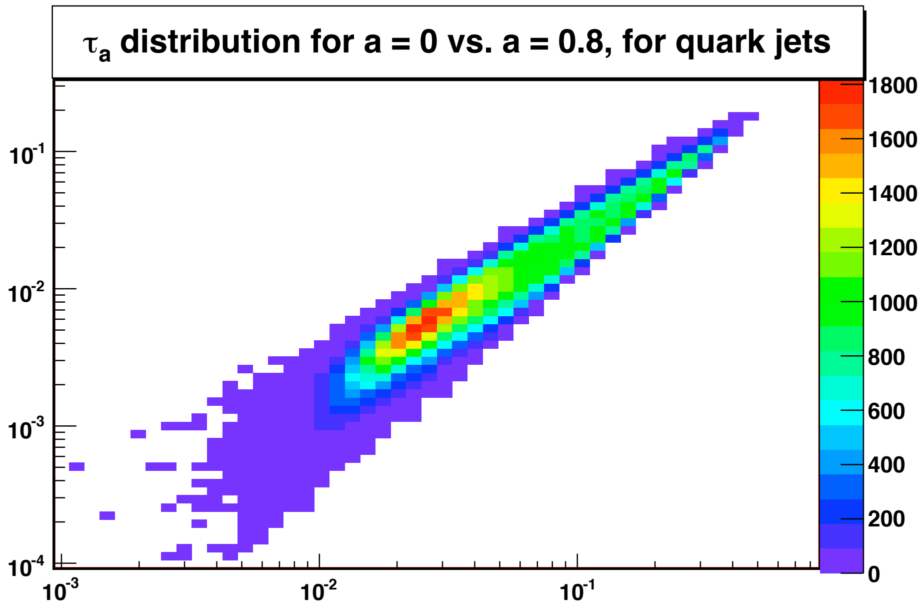

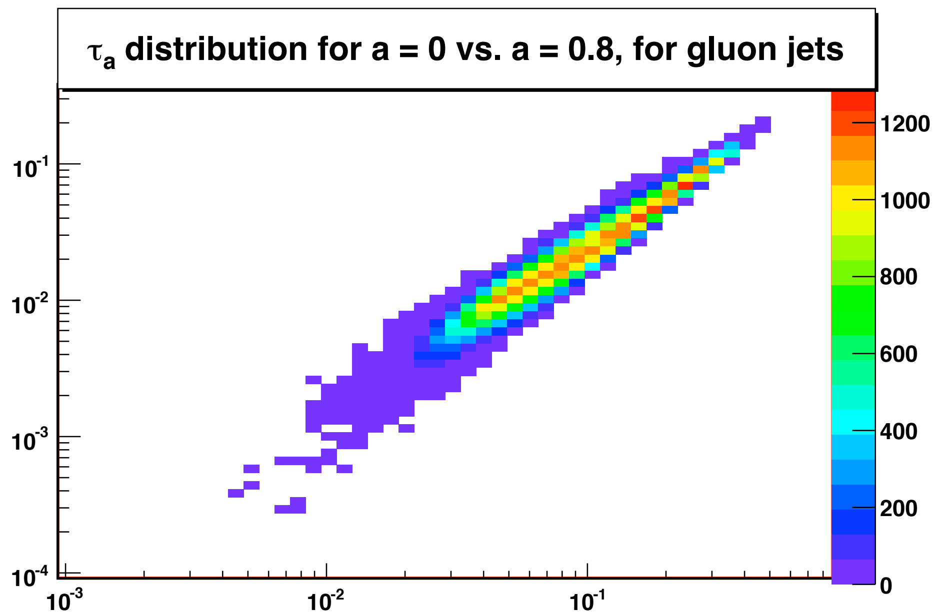

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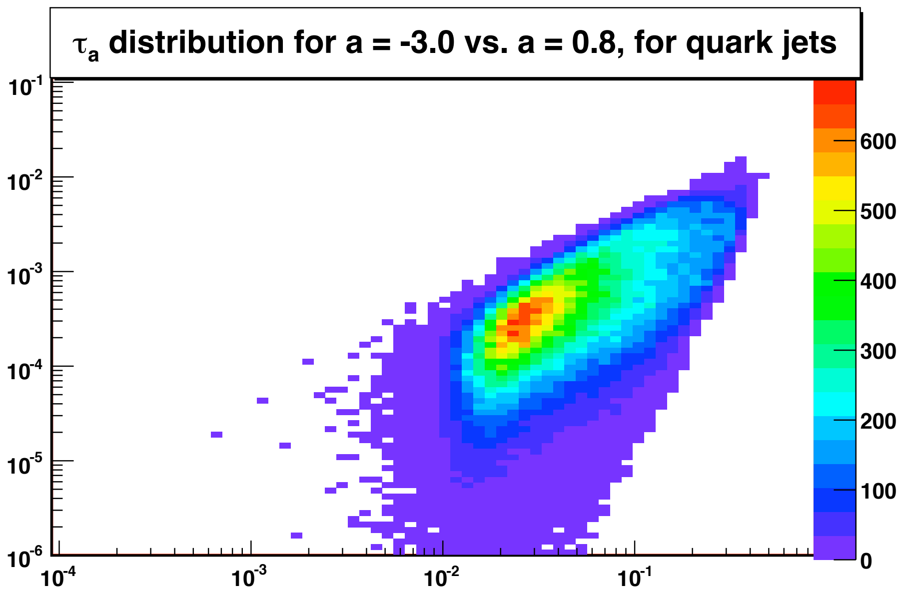
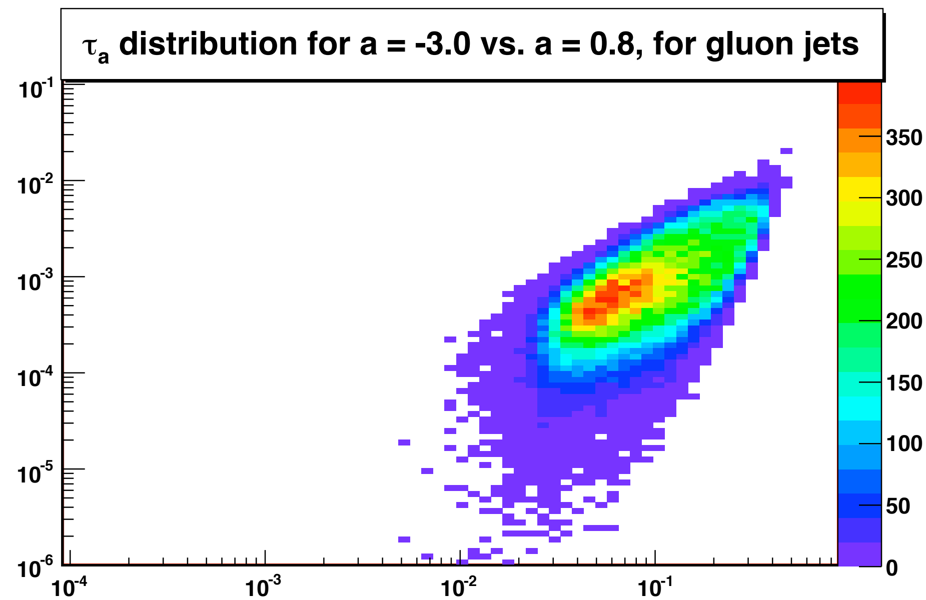
Ellis, Hornig, CL, Vermilion, Walsh





May find more elaborate cuts in these planes with greater distinguishing power than 1-D plots

Suggests use of multivariate analysis of many values of *a* to maximize discriminatory power. (**really preliminary:** factor of **3-4** enhancement over single variable discriminatory power)

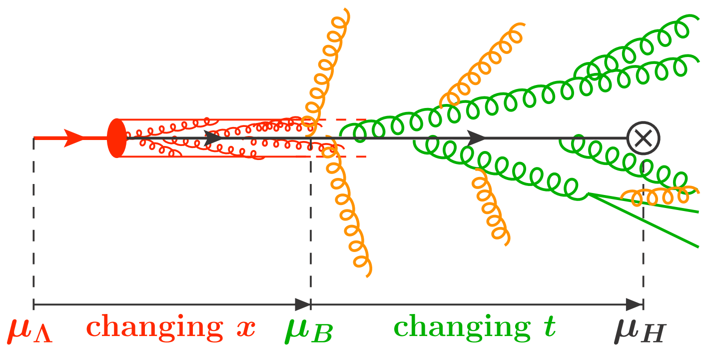
Plan of the Talk

- Motivation: Probing QCD and New Physics with Jet Shapes
- A Theory Toolbox to Probe Jets: Soft-Collinear Effective Theory
  - Tools for Factorization: Power Counting and Soft-Collinear Decoupling
  - Tools for Resummation: the Renormalization Group
  - Tools for Hadronization: Universal Soft Model Functions

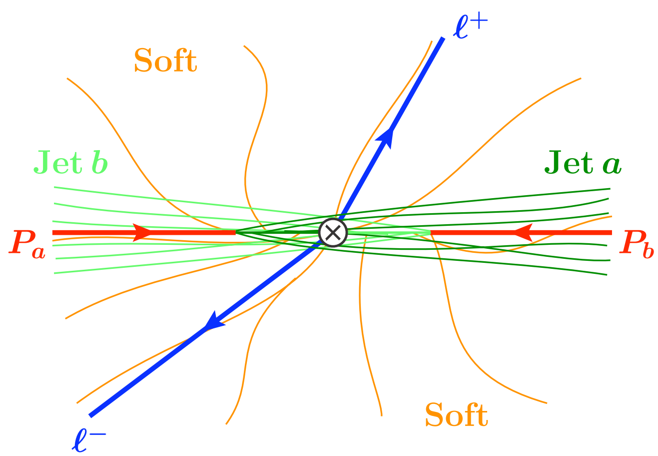
- **Precision Predictions of Jet Observables**
  - Event Shapes in e^+e^-: probing strong coupling and hadronization
  - Quark and Gluon Jet Shapes in e^+e^-
  - ***Towards Event Shapes and Jet Shapes in Hadron Collisions***

Progress in Describing Hadron Collisions

"Beam Functions": PDFs + ISR

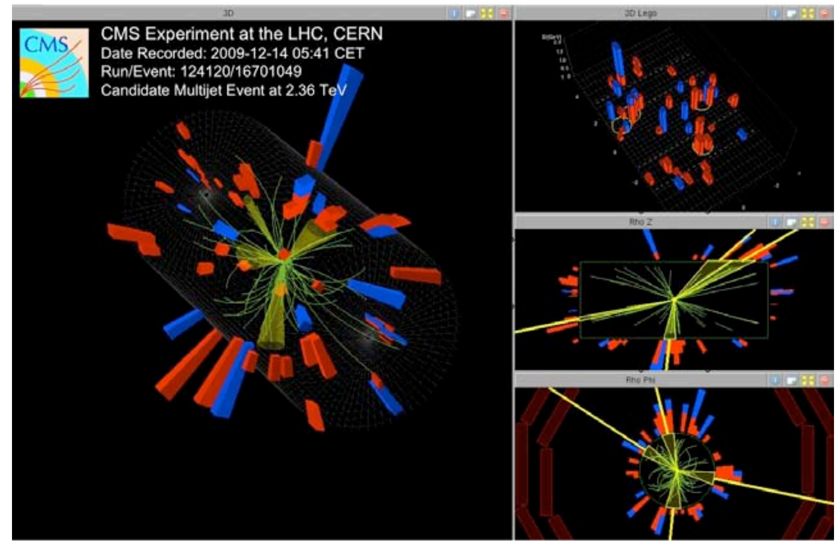


"Beam Thrust" in Drell-Yan



"N-jettiness" hadronic event shape

Stewart, Tackmann, Waalewijn



Top quark pair production

Ahrens, Ferroglia, Neubert, Pecjak, Yang

Higgs production Chiu, Fuhrer, Kelley, Manohar; Ahrens, Becher, Neubert, Yang; Mantry, Petriello

"Dynamical" threshold enhancements from PDF steepness Becher, Neubert, Xu; Bauer, Dunn, Hornig

Jets in Dense QCD Media Idillbi, Majumder; D'Eramo, Liu, Rajagopal

New Tools for Probing Jets at LHC

- **A unified framework** in EFT for **factorization**, **resummation,** and **universal nonperturbative corrections** to jet shape distributions and other jet cross-sections

- **Recent new tools and applications of SCET to jets**
  - first consistent factorization of jet shape distributions with jet algorithms
  - first NLL resummation of jet angularity jet shapes
  - most precise extraction of strong coupling with consistent treatment of NP effects
  - hadronic event shapes, top & Higgs cross-sections at LHC

- **Future directions and challenges**
  - Distinguishing quark, gluon, and other jets using jet shapes and substructure
  - Resumming logarithms induced by phase space cuts from jet algorithms
  - Devising and predicting more observables suitable at LHC
- **2010+: EFT and Jet Shapes will help distinguish SM and New Physics at the LHC**