EFT for soft drop double differential distribution

University of Manchester, Oct 2020

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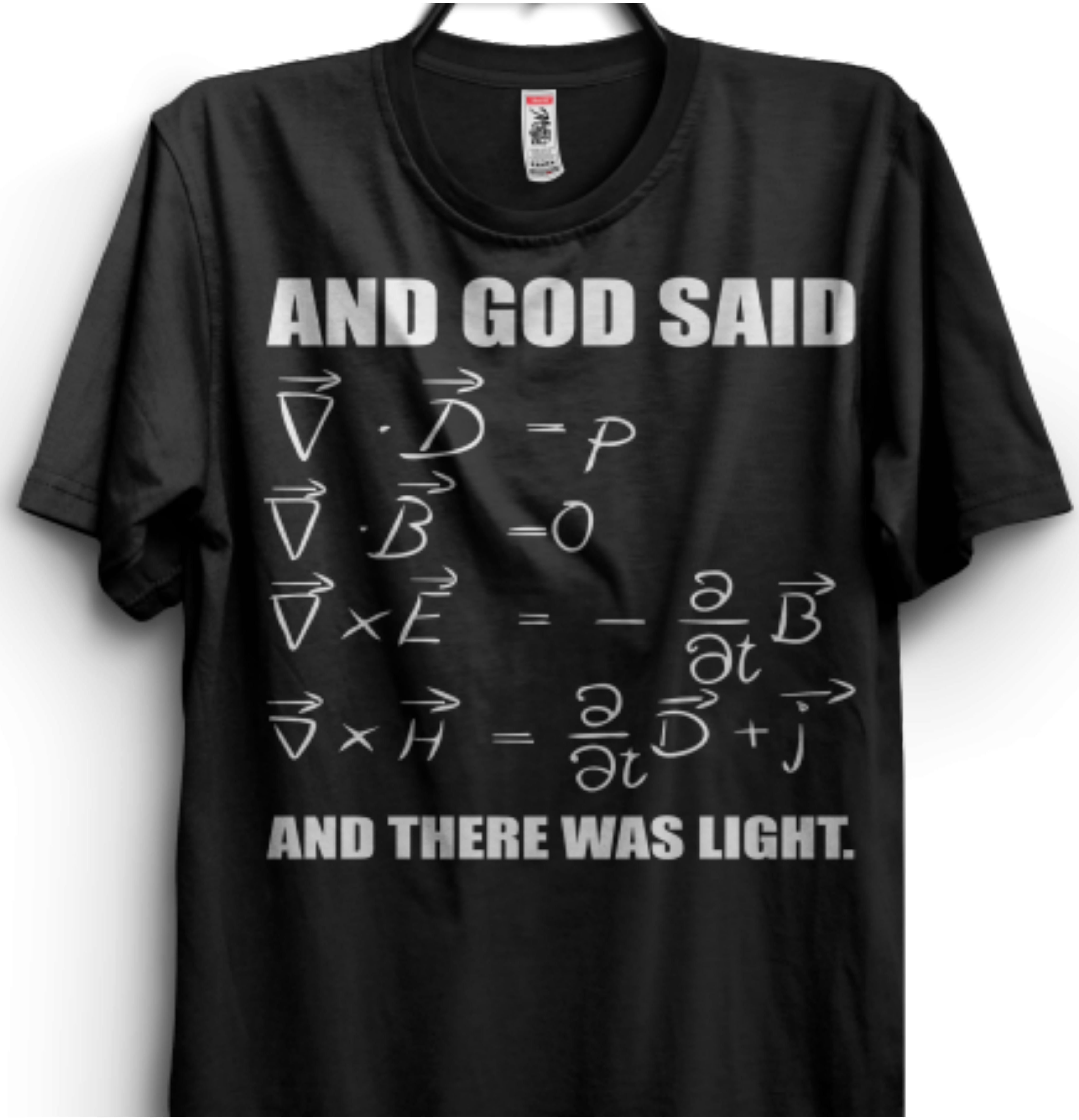
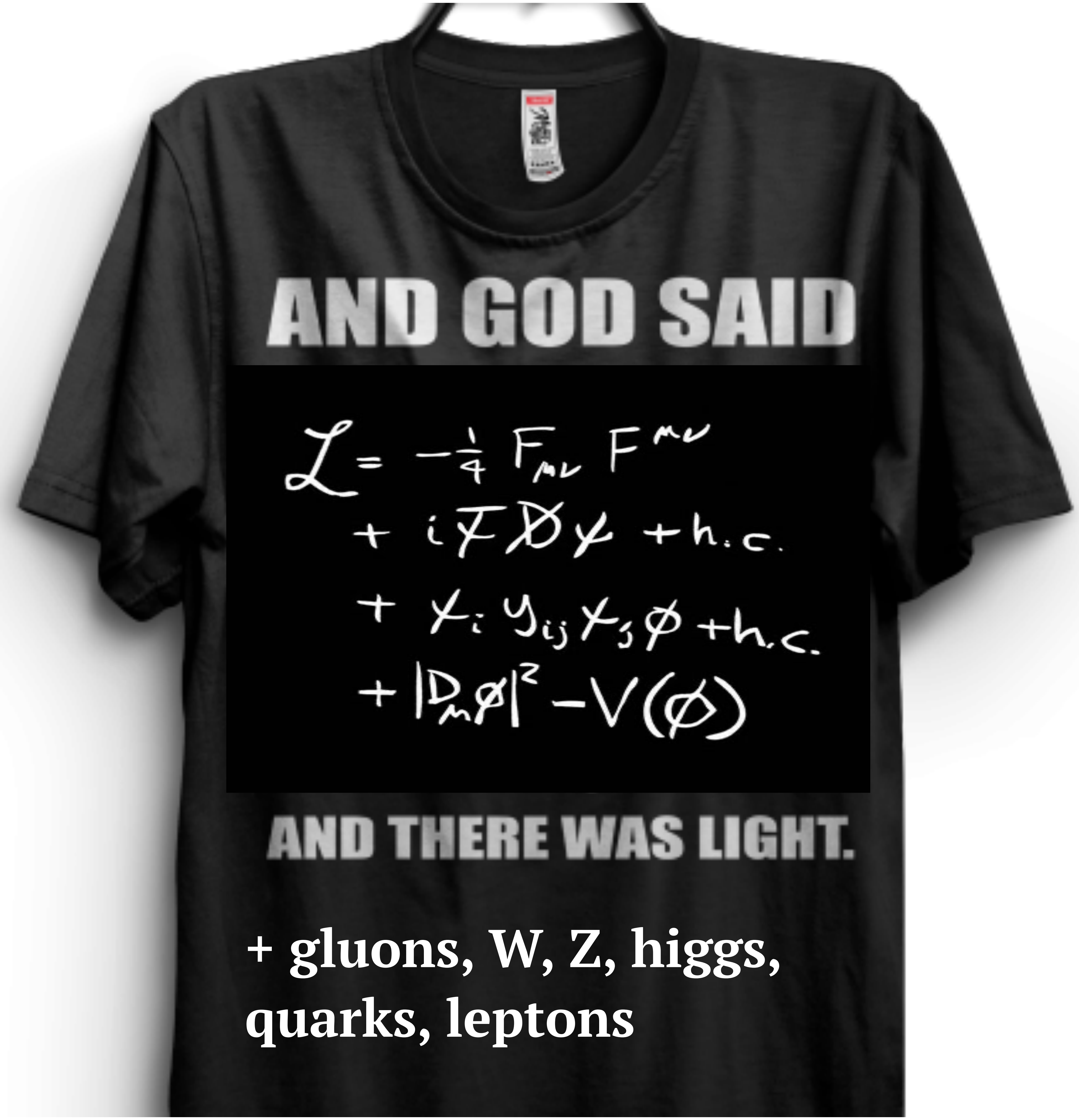
In collaboration with Iain Stewart, Varun Vaidya, Lorenzo Zoppi

Genesis 1:3 + 19th century physics



Genesis 1:3 + 20th century physics



+ gluons, W, Z, higgs, quarks, leptons

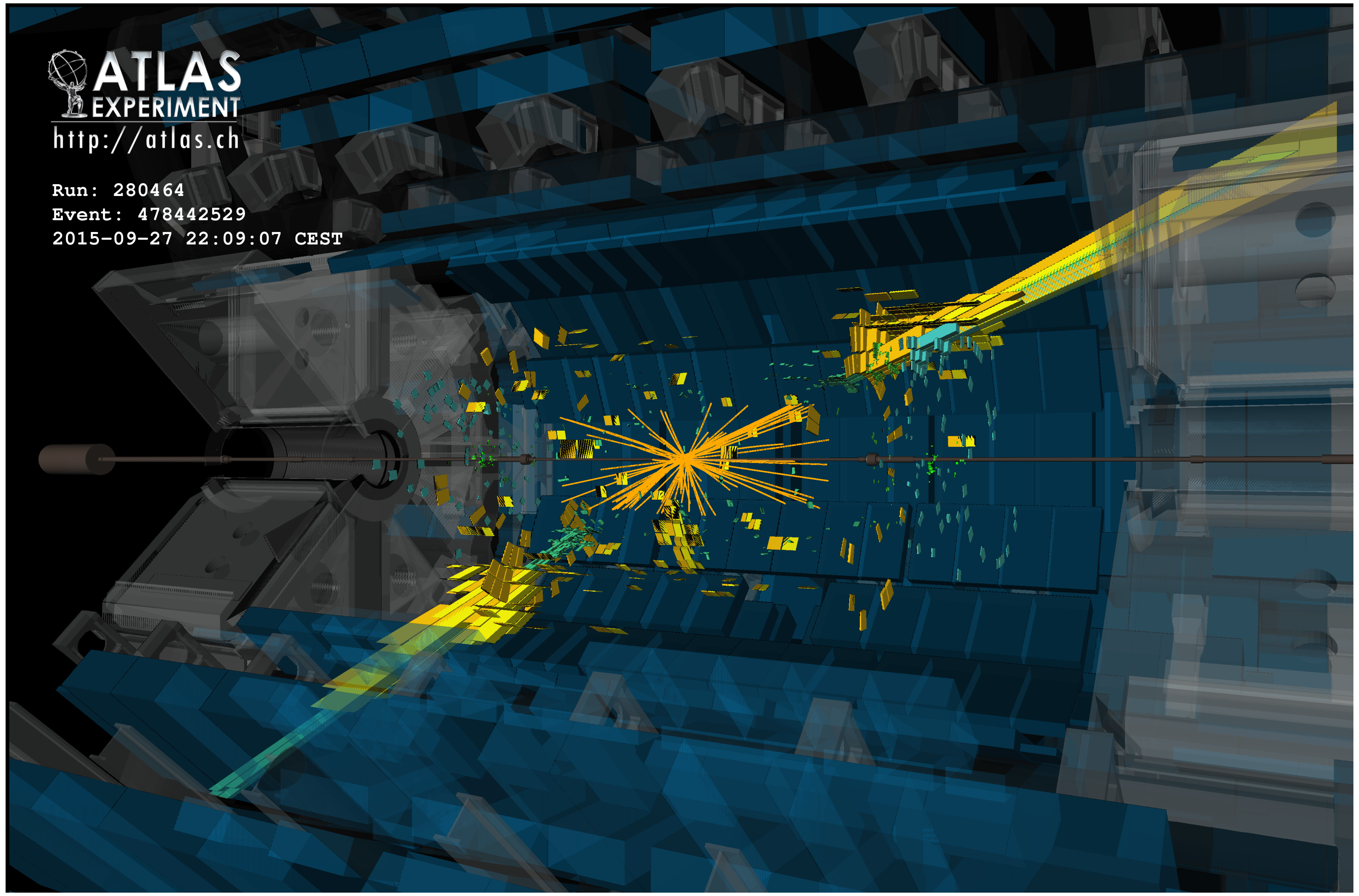
Genesis 1:3 + 21st century physics

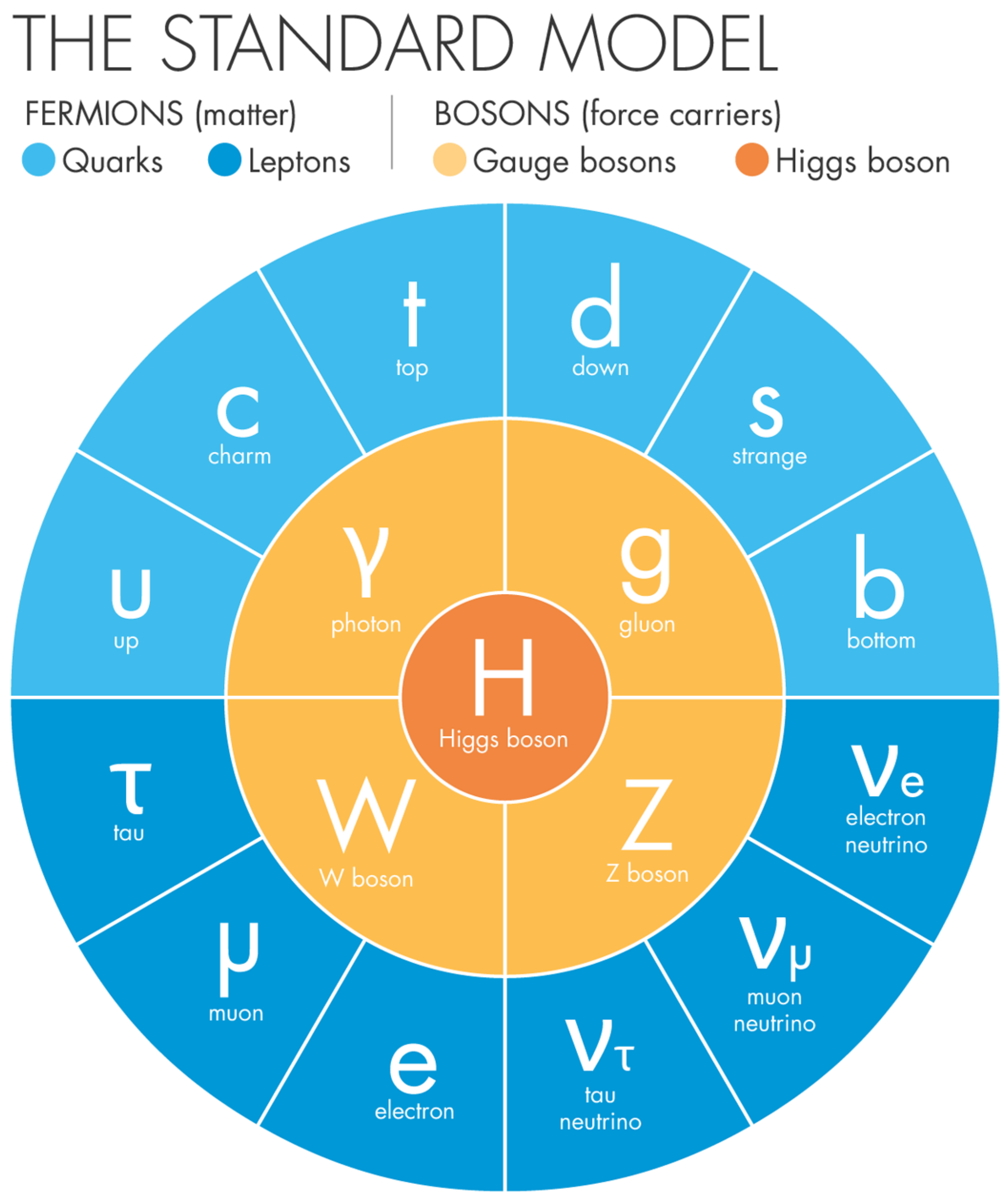
Jets for new physics

Standard Model has 26 free parameters

... whose origin is yet unexplained

So let's try to understand jets!



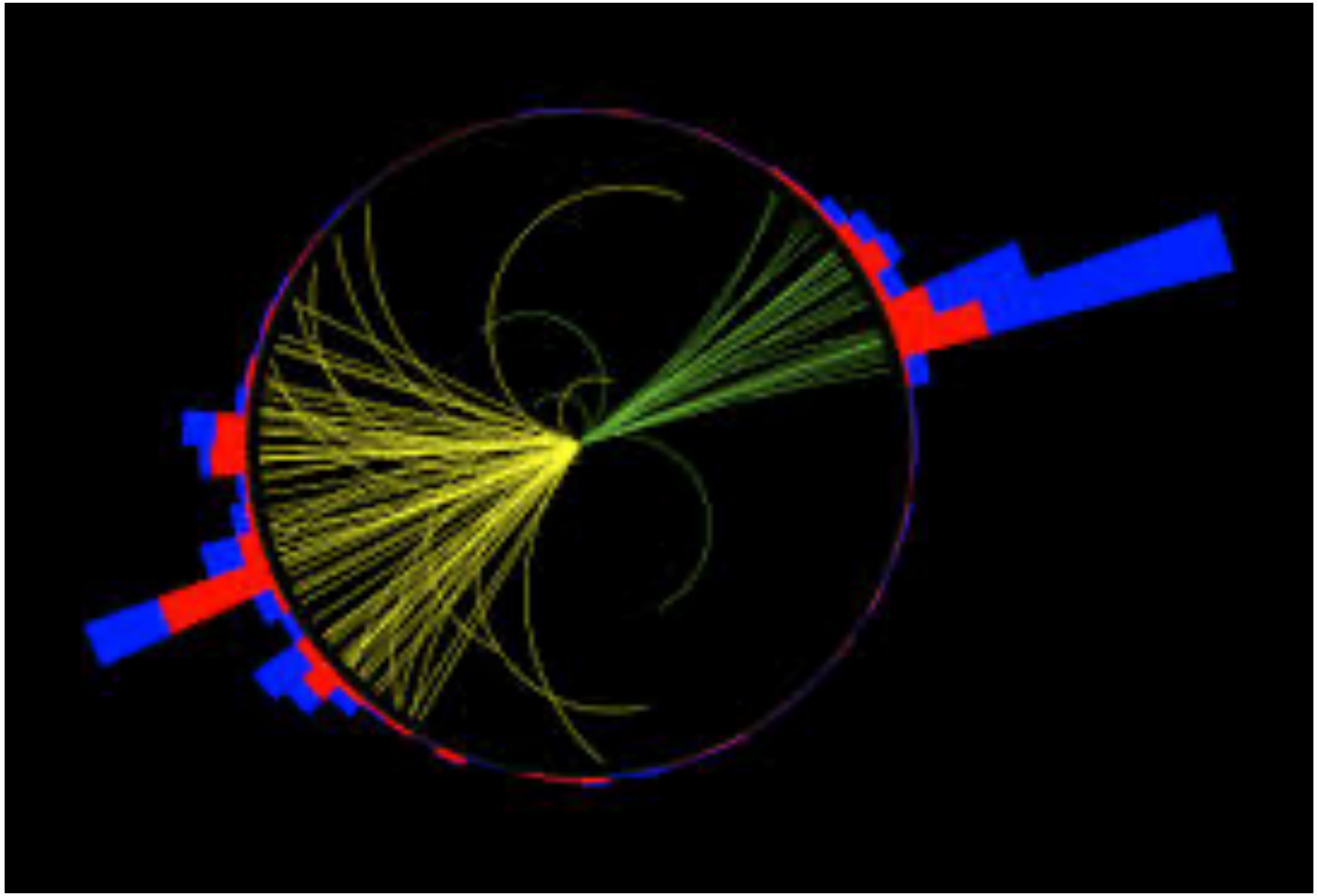


Jets are ubiquitous in collider physics and play a huge role in both new physics searches as well as precision measurements

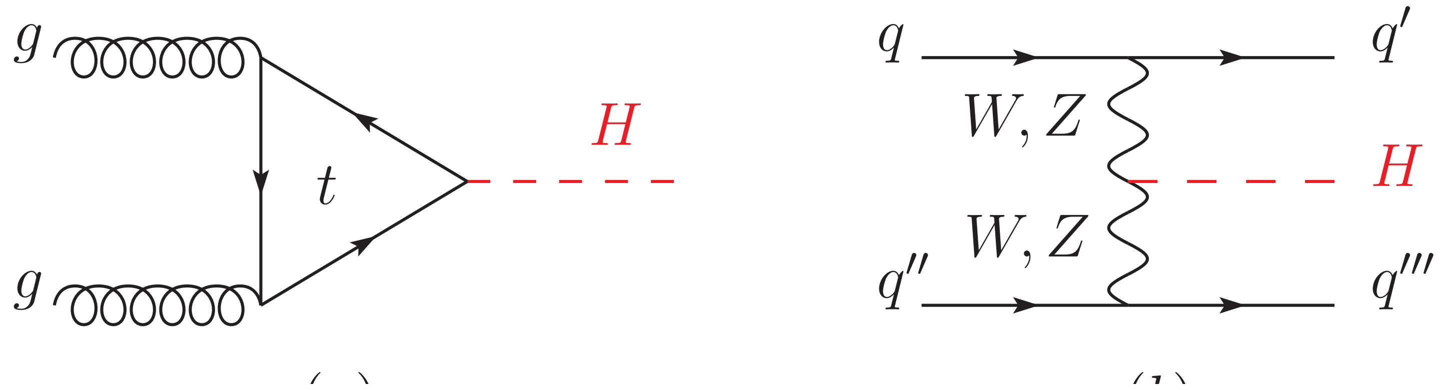
- Why jets?
- Theory overview
- New results

What are jets?

Jets are collimated sprays of radiation emanating from an energetic particle and are a manifestation of how charges in quantum field theory are transported through a collision process

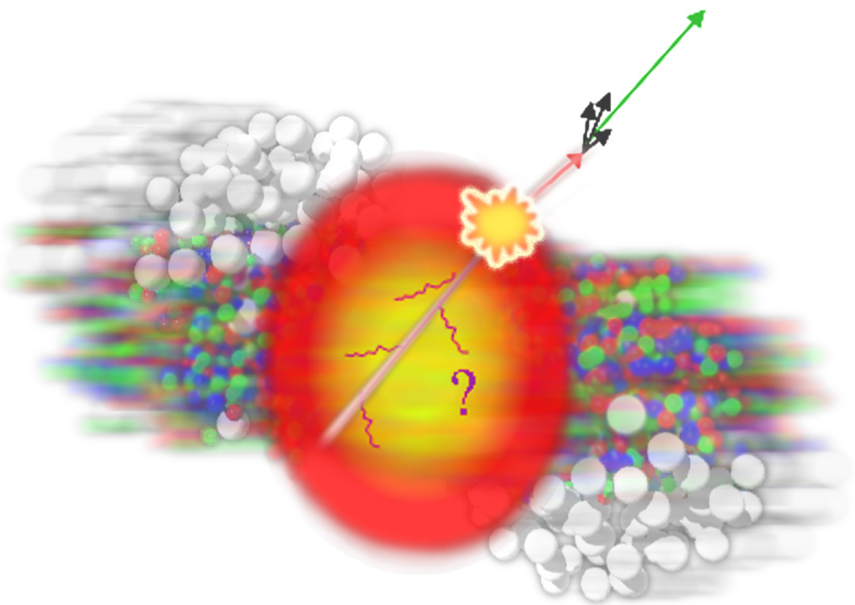


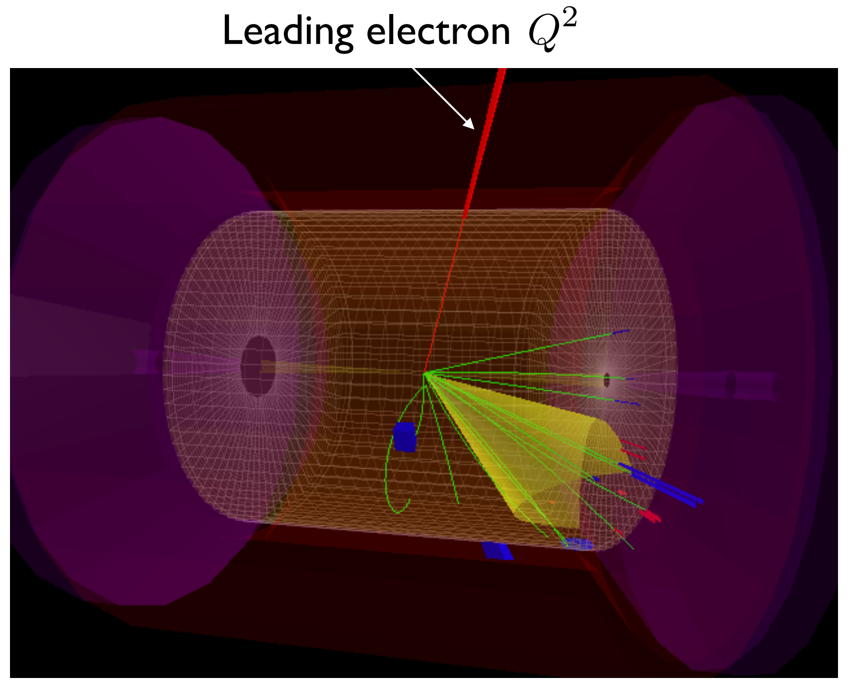
Why Jets?

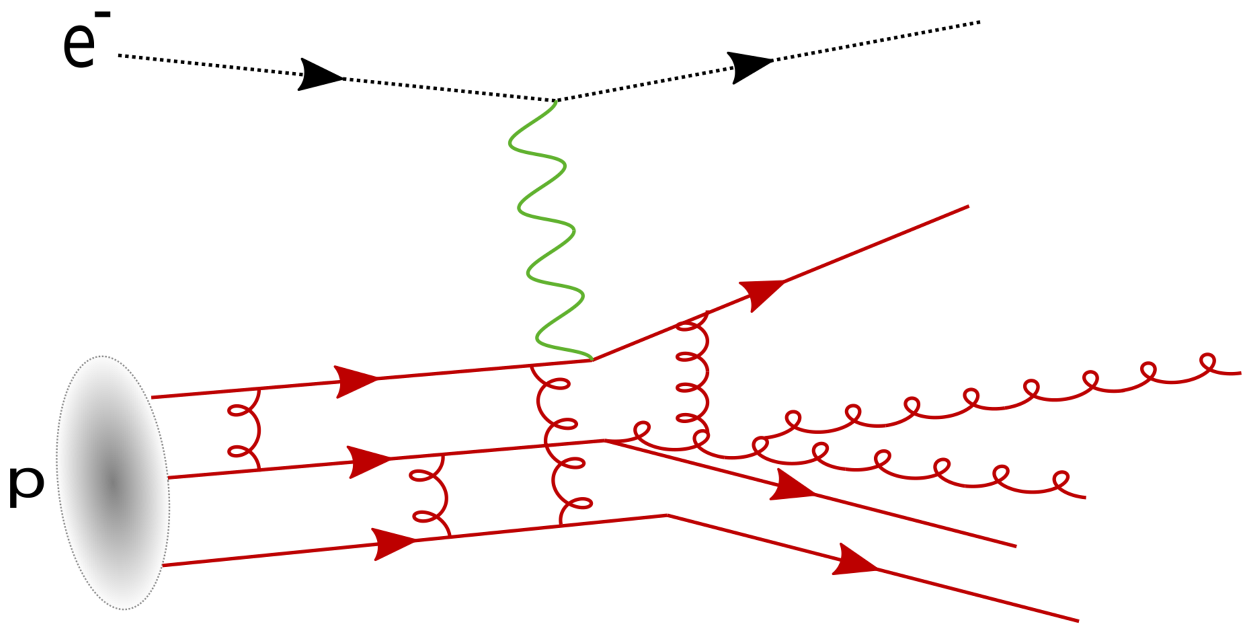


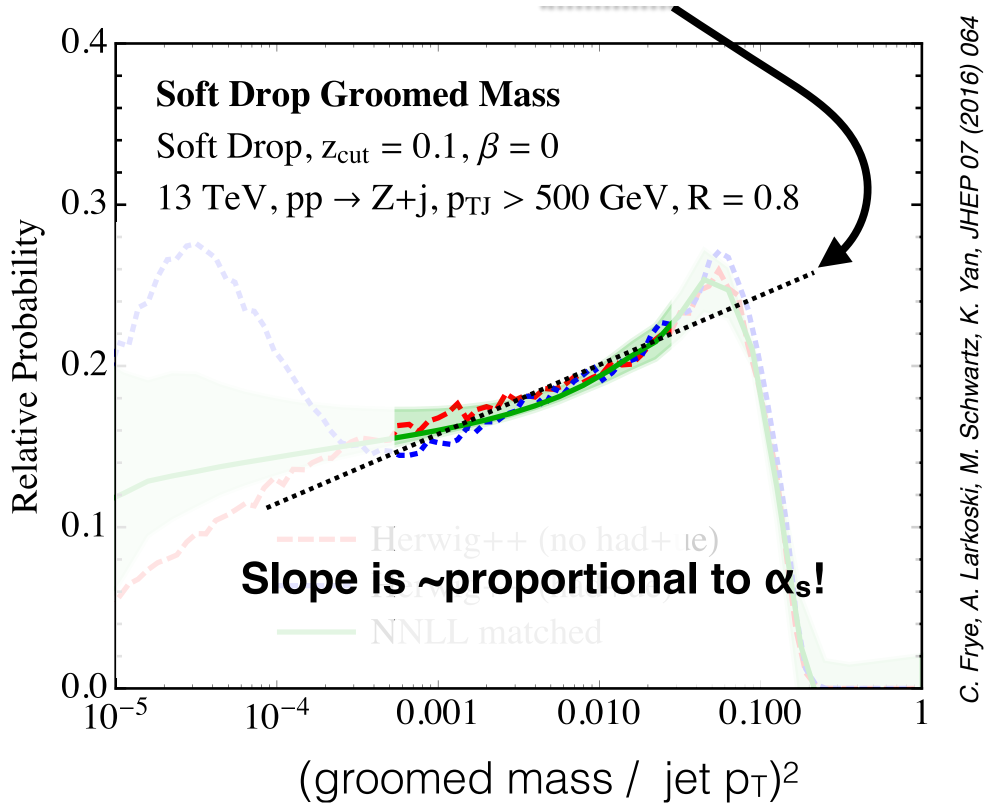
Jets are relevant for a variety of collider physics studies

- Higgs production via gluon fusion
- Physics at the upcoming Electron Ion Collider
- Decays of boosted electroweak bosons
- Precision studies: α_s and top mass
- Jet substructure as a probe of QCD medium
- Heavy flavor, fragmentation process in jets
- Jets for TMD physics
- New physics searches with signatures and backgrounds

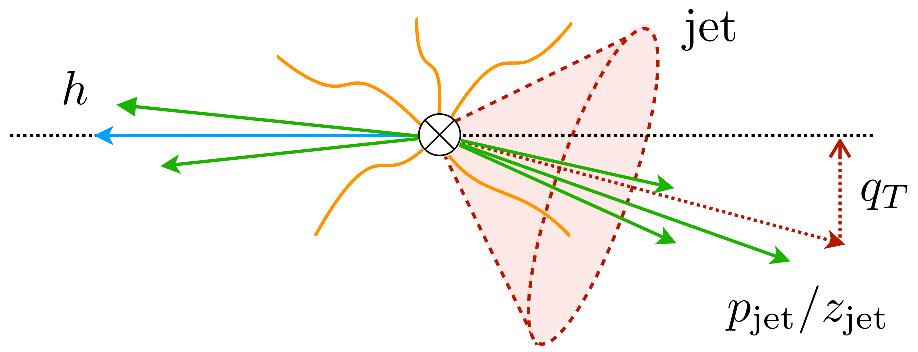




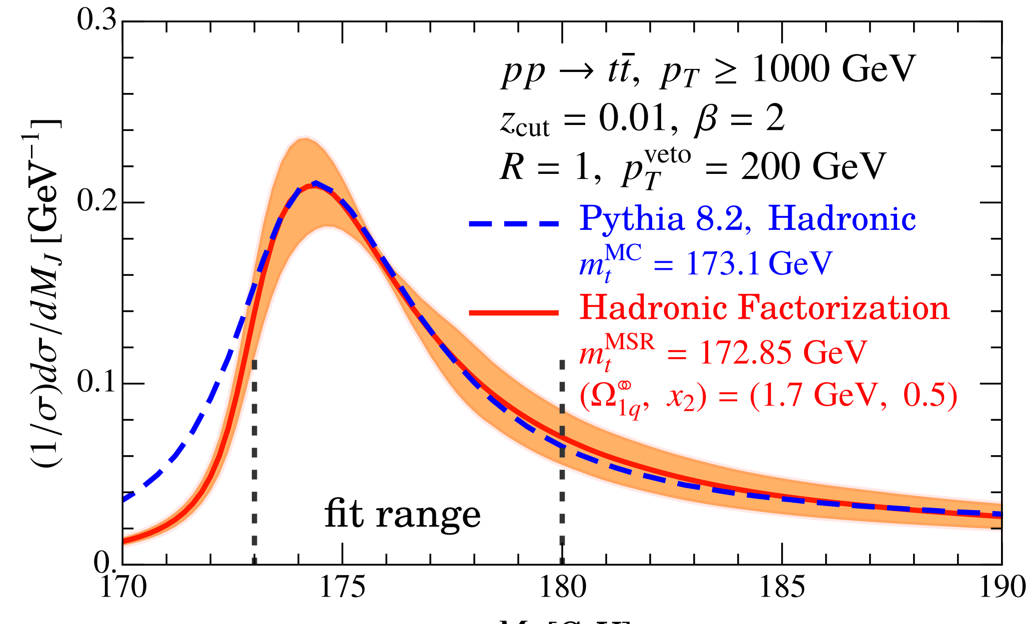




Hoang, AP, Mantry, Stewart



Gutierrez-Reyes tal 1907.05896

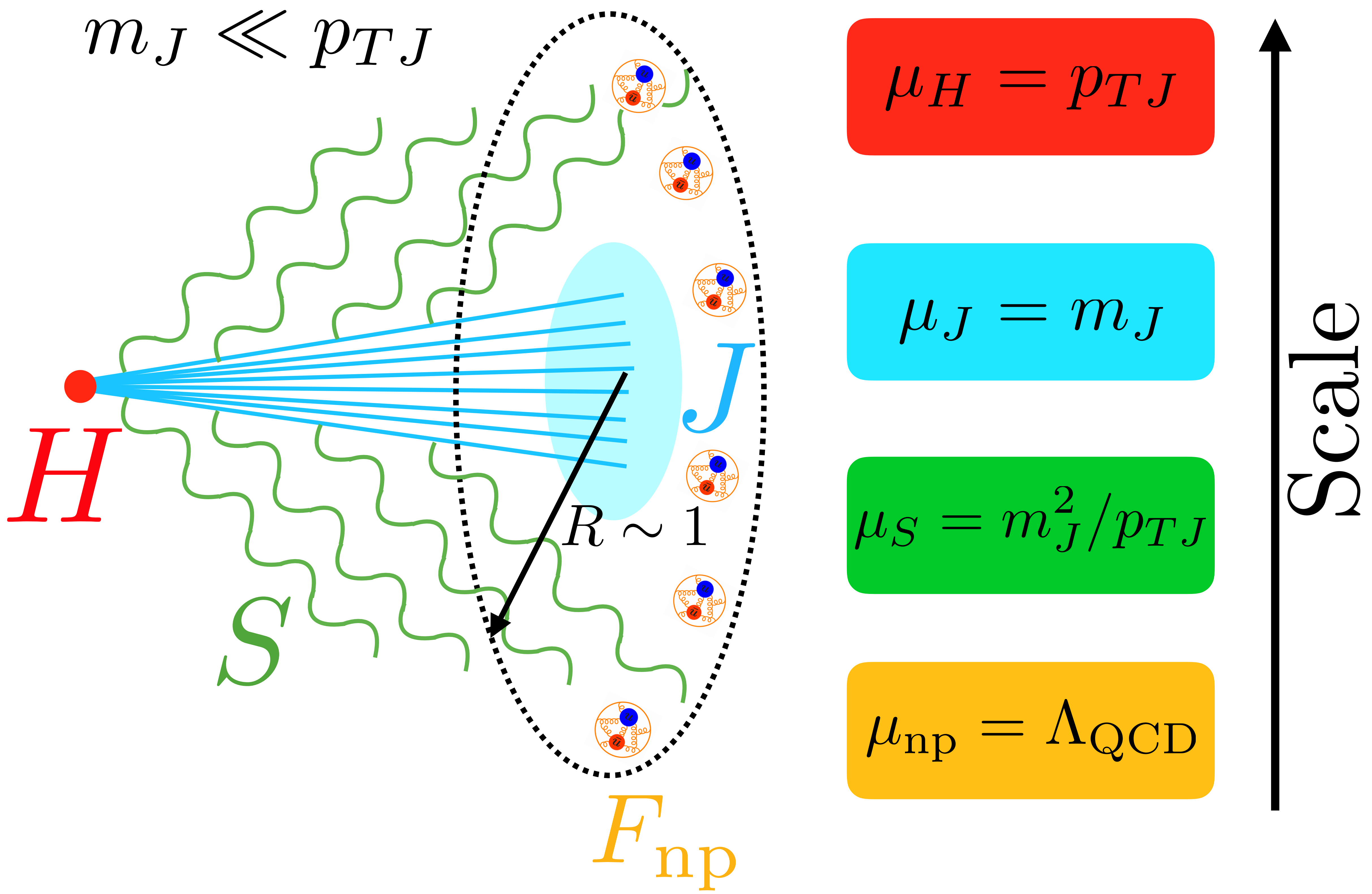


Jet physics is rich!

The radiation inside a jet is predominantly soft and collinear

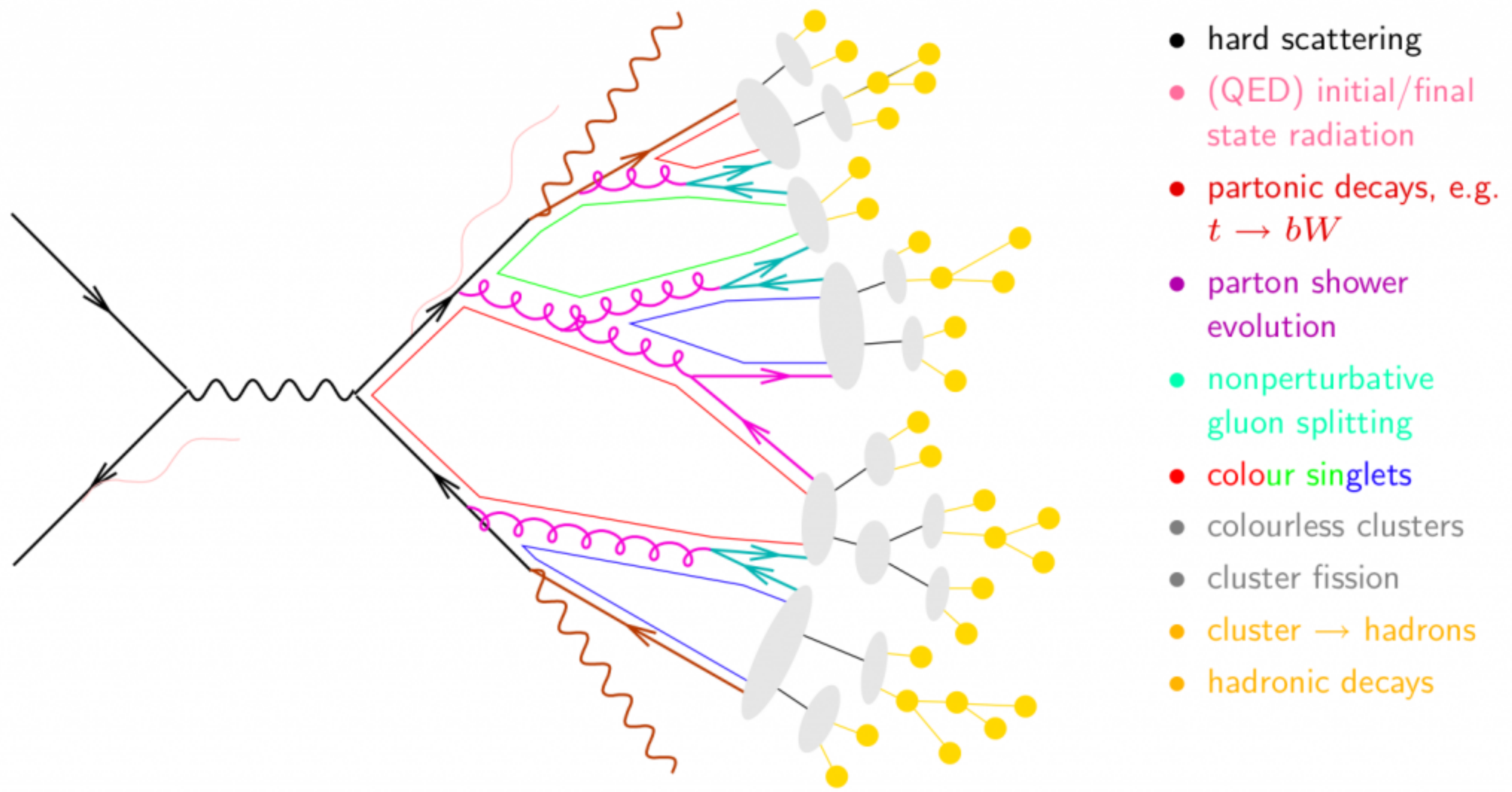
This is tied to the fundamental behavior of QCD in IR

Studying jets involves disentangling physics at different scales.



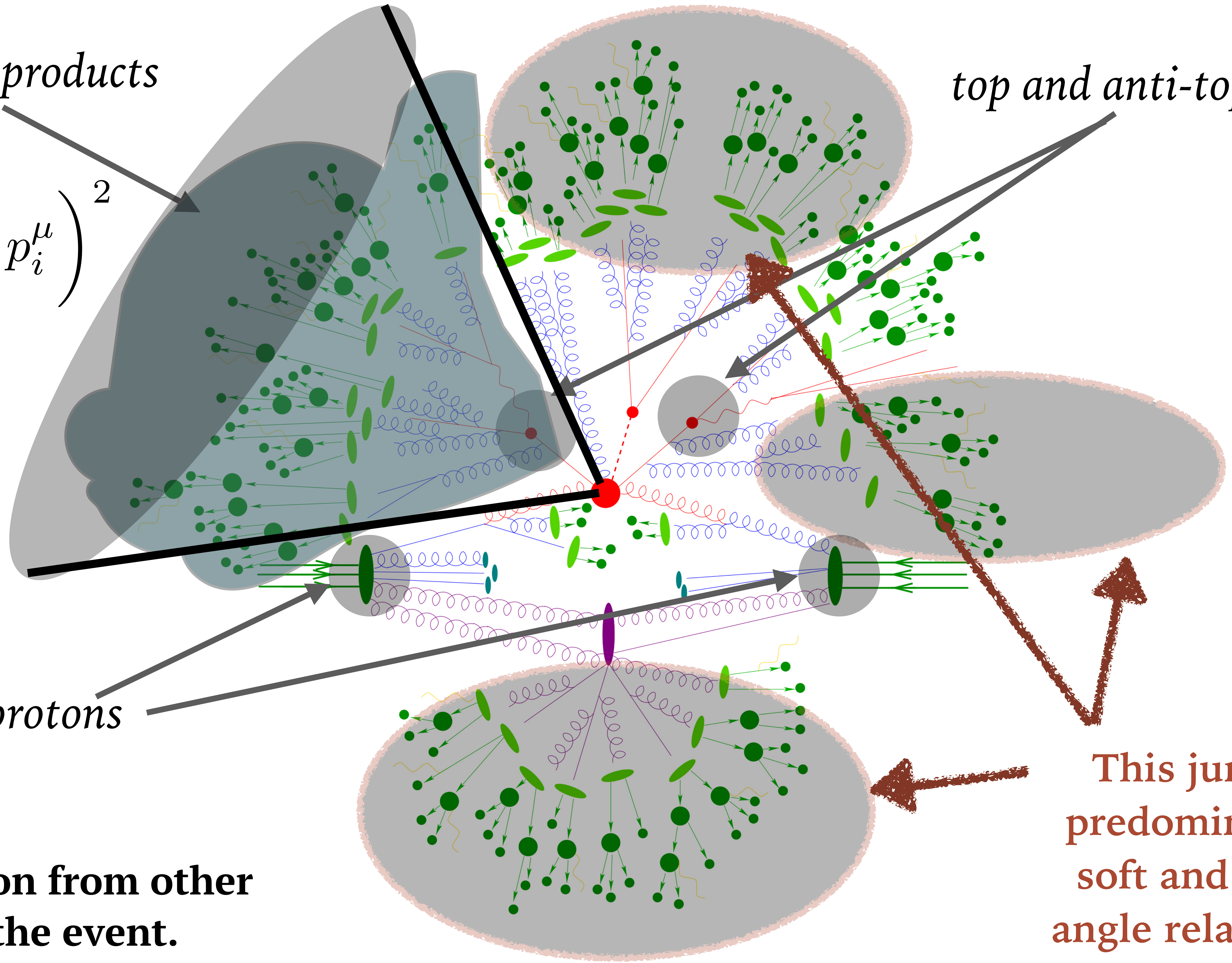
Monte Carlo Simulations

Parton shower Monte Carlos can be improved through jet substructure studies



But there are challenges

$$M_J^2 = \left(\sum_{i \in \text{jet}} p_i^\mu \right)^2$$



Contamination from other processes in the event.

This junk is predominantly soft and wide angle relative to the jet axis

F. Krauss. (Sherpa Collaboration), “Sketch of a tth event”. Available at https: // www.opensciencegrid.org/wp-content/uploads/2014/05/event.jpg

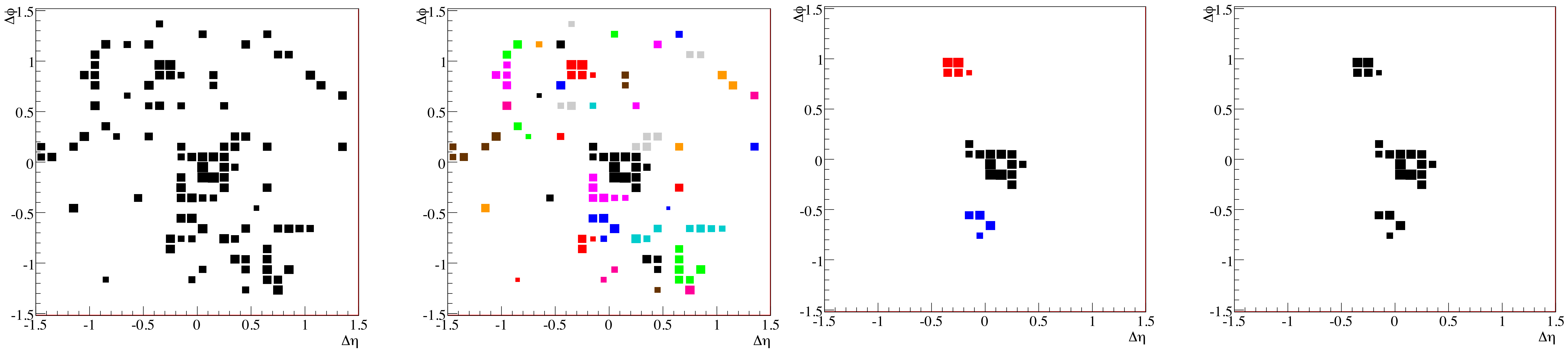
Jet Grooming

Jet grooming selectively removes radiation that includes contamination from the UE and pile up.

Some notable examples:

- Mass Drop Tagger: Butterworth, Davison, Rubin, Salam, 2008
- Ellis, Vermillion, Walsh, 2009, 2010
- Pruning: Trimming: Krohn, Thaler, Wang, 2010
- Modified Mass Drop: Dasgupta, Fregoso, Marzani, Salam 2013
- Soft Drop: Larkoski, Marzani, Soyez, Thaler 2014

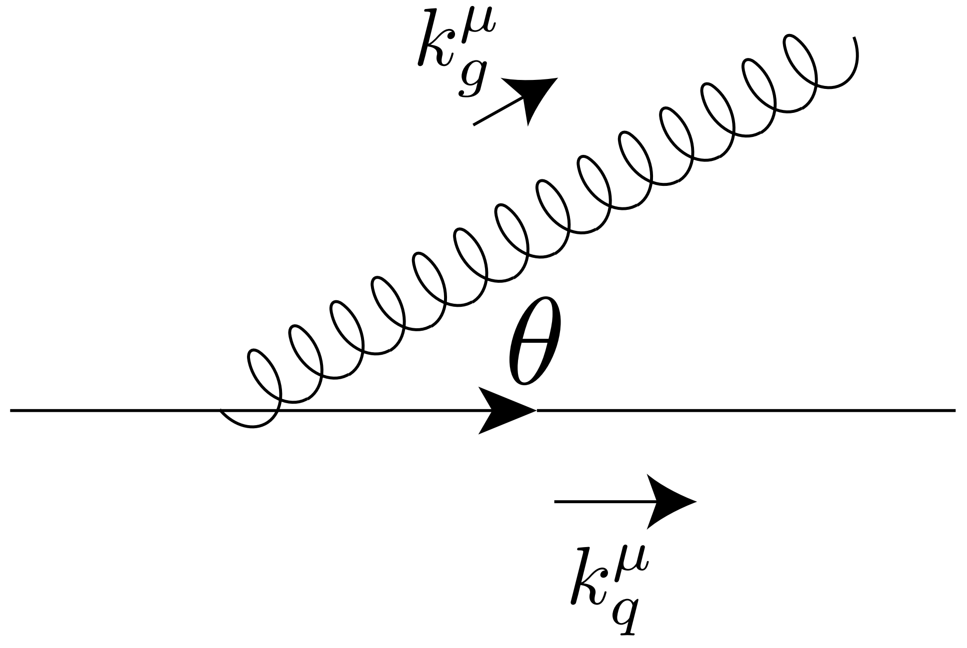
Trimming (2010):



Krohn, Thaler, Wang, 2010

- Why jets?
- Theory overview
- New results

Jet Mass



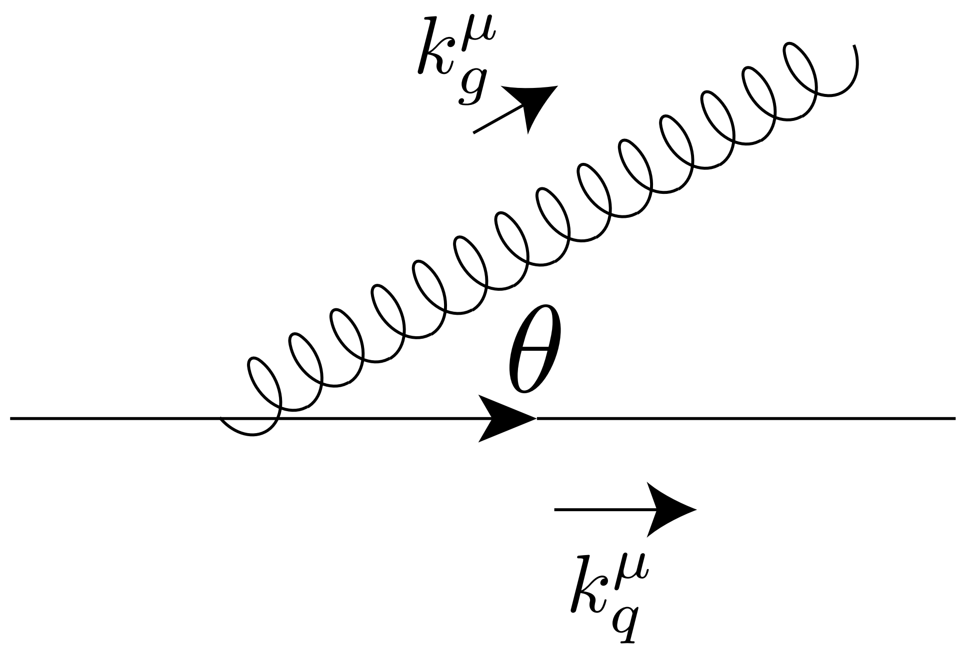
Consider jet mass of a qg pair:

$$m_J^2 = 2E_qE_g(1-\cos\theta) \simeq E_J^2 z\theta^2 \qquad z = \frac{E_g}{E_q+E_q} = \frac{E_g}{E_J}$$

$$\text{Splitting Probability} \equiv P\Big(z_g \in [z, z+dz], \theta_g \in [\theta, \theta+d\theta]\Big) = p(z,\theta)dzd\theta$$

See Unorthodox review on QCD by A. Larkoski 2017,20

Jet Mass



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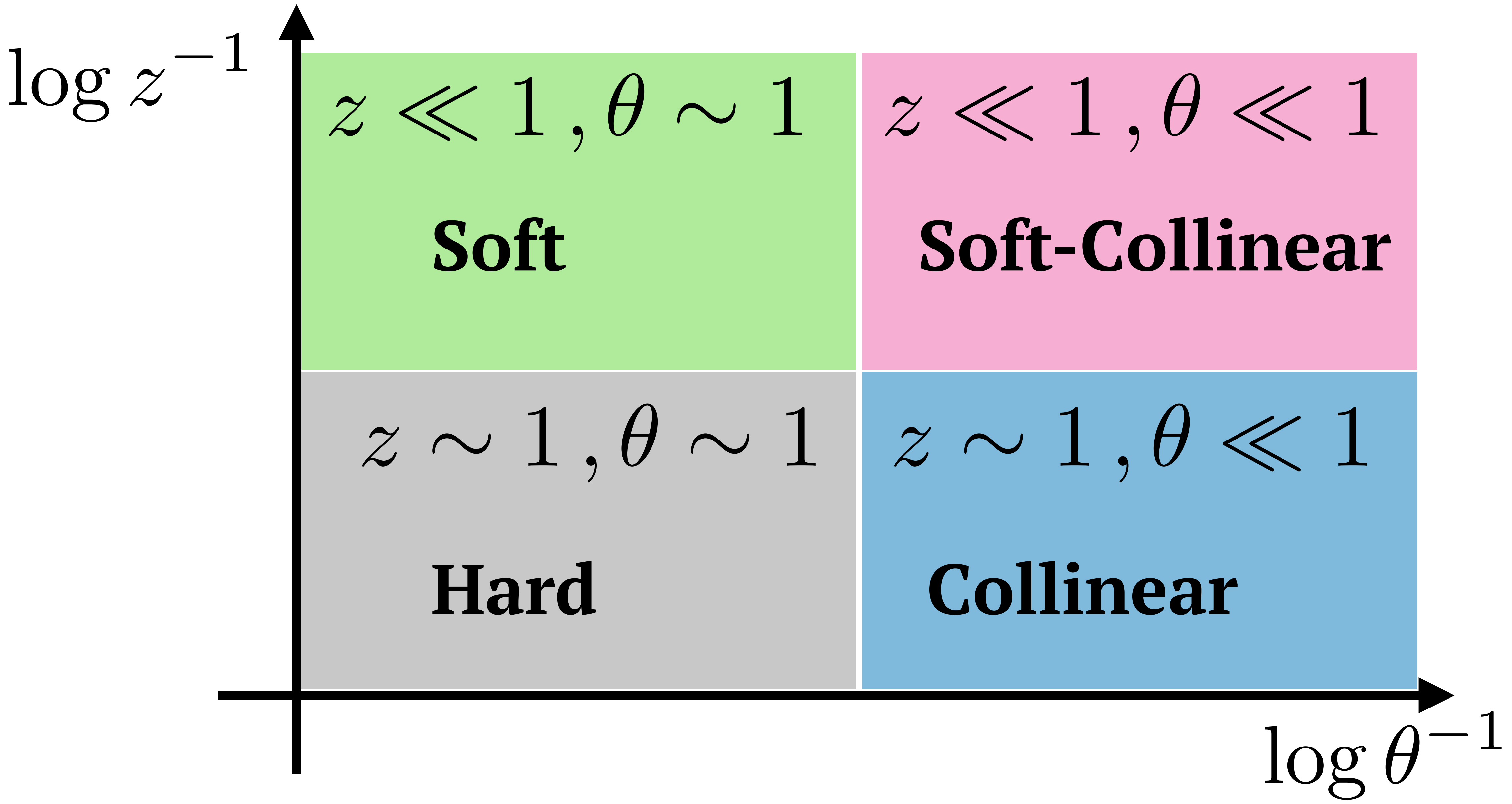
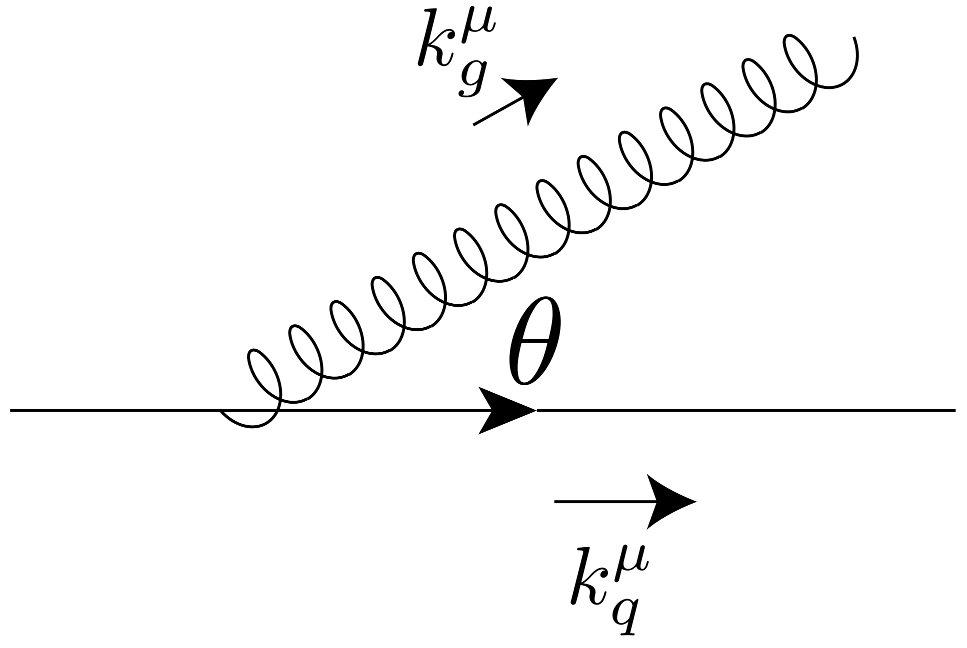
$$p(z,\theta)dzd\theta \simeq \frac{2\alpha_s C_F}{\pi}\frac{dz}{z}\frac{d\theta}{\theta}$$
$$= \frac{2\alpha_s C_F}{\pi} d(\log z^{-1}) d(\log\theta^{-1})$$

Uniform probability in the Lund plane



Jet Mass



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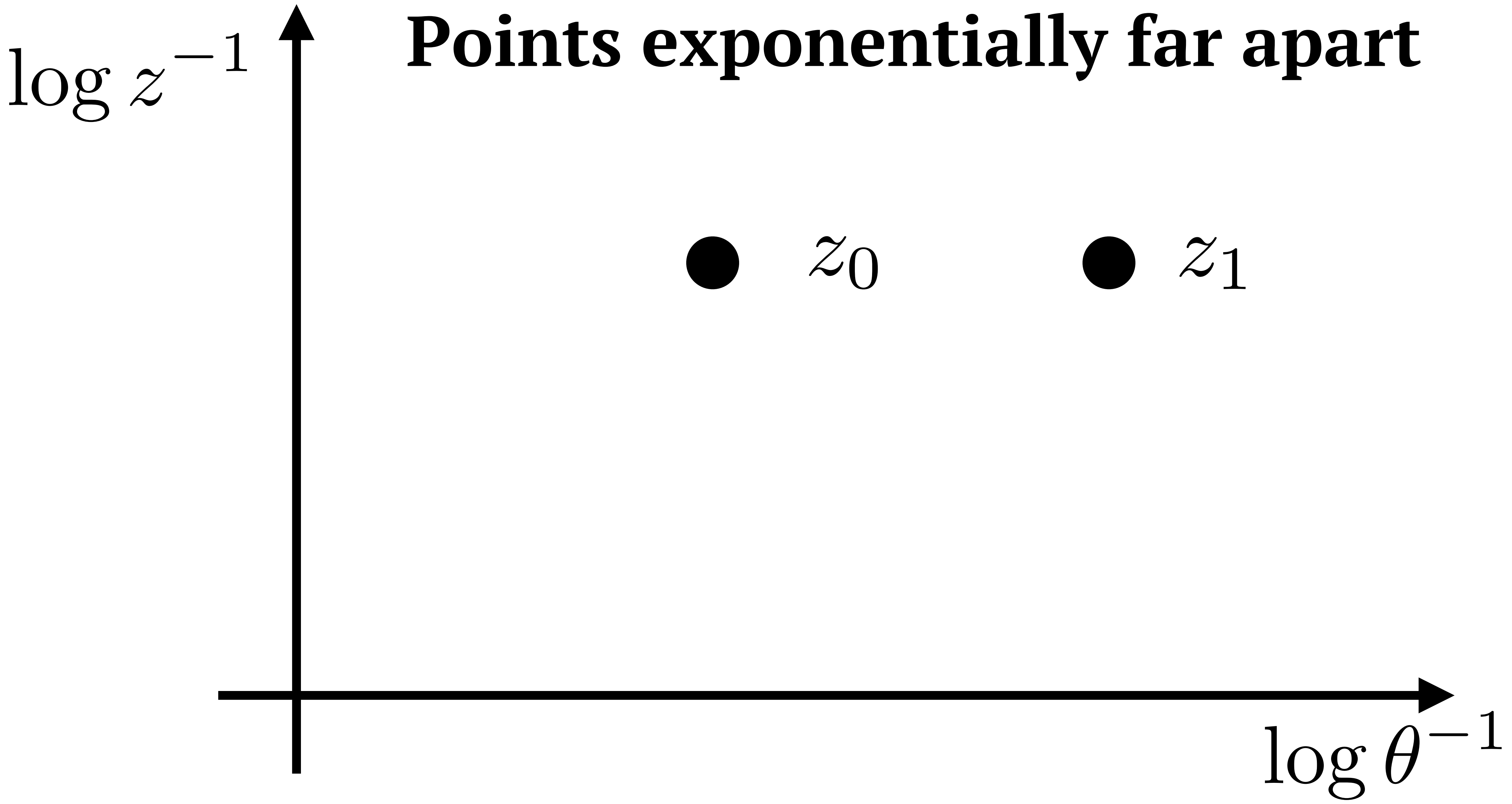
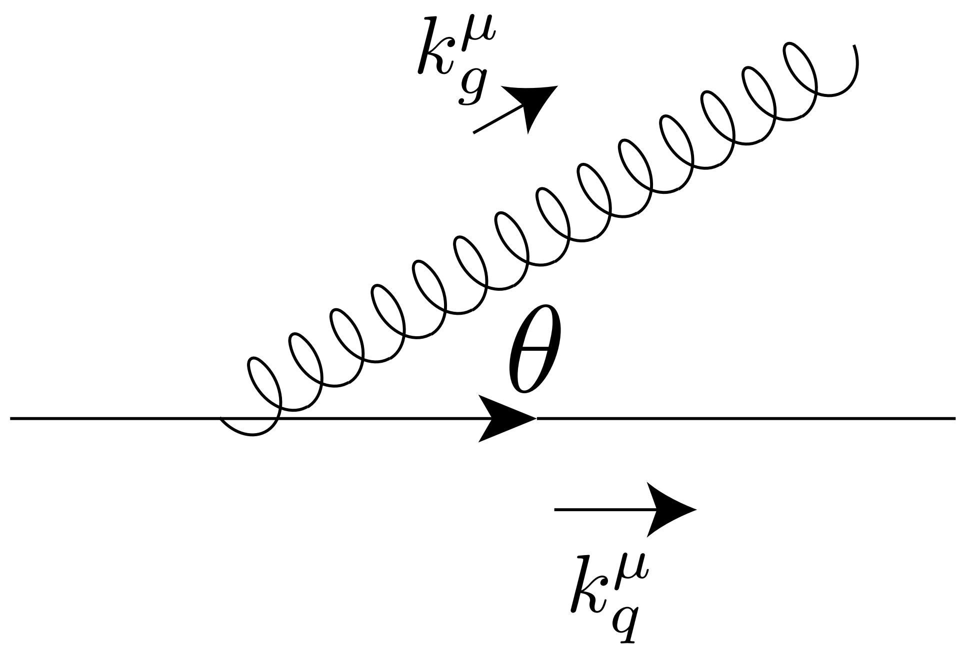


$$\ln z_1^{-1} = \Delta + \ln z_0^{-1} \Rightarrow z_1 = e^{-\Delta}z_0$$

Jet Mass Distribution



$$\log\left(\frac{m_J^2}{E_J^2}\right) = -\log(z^{-1}) - 2\log(\theta^{-1})$$

Uniform Probability density: $p = \dfrac{2\alpha_s C_F}{\pi}$

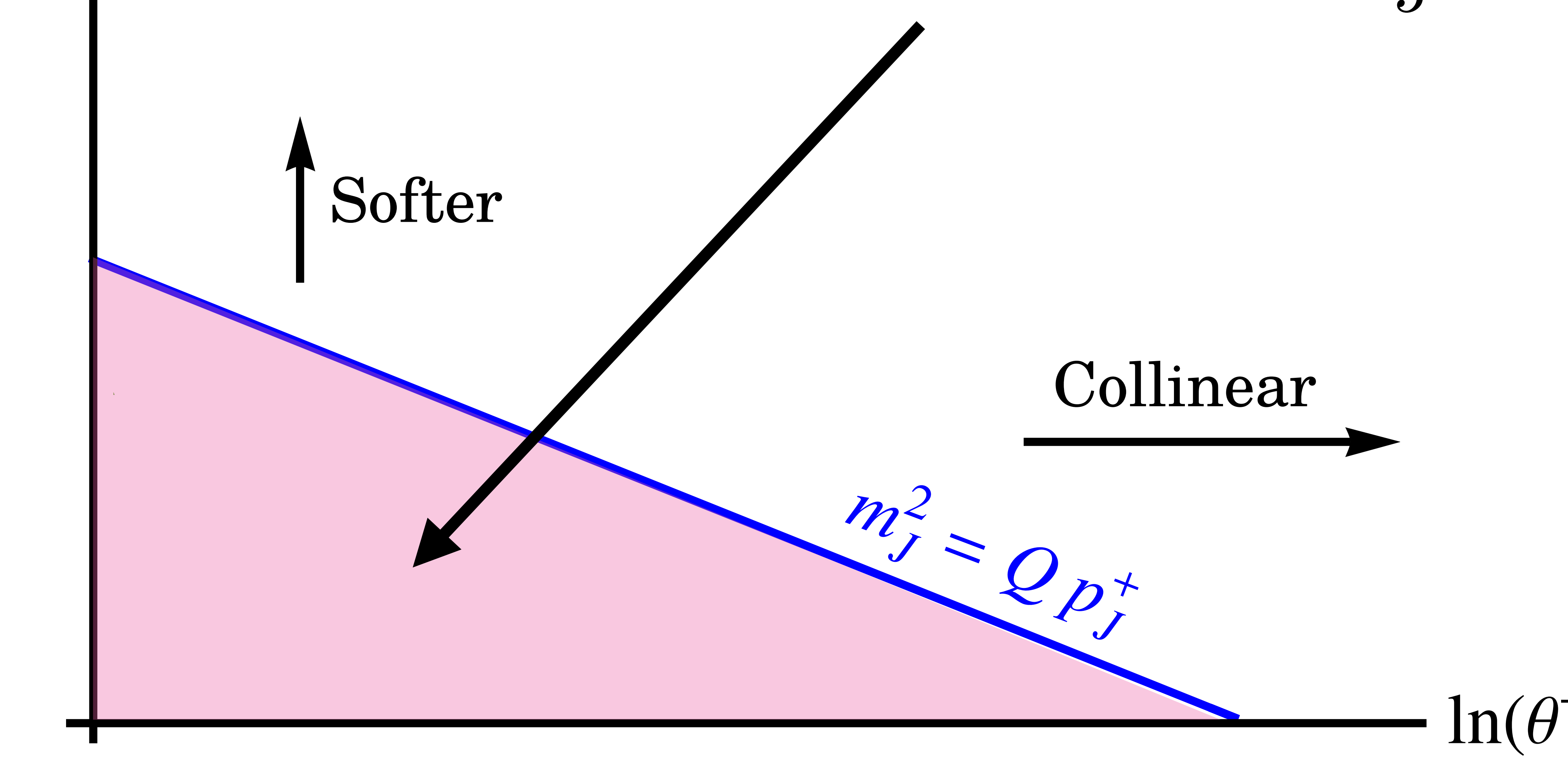
Poisson distribution:

$$P\left(x < \frac{m_J^2}{E_J^2}\right) = \exp\left[-\,\text{area} \times p\right]$$

$$= \exp\left[-\frac{\alpha_s C_F}{2\pi}\log^2\left(\frac{m_J^2}{E_J^2}\right)\right]$$

$$\frac{d\sigma}{d(m_J^2/E_J^2)} = -\frac{\alpha_s C_F}{\pi}\frac{\log\left(\frac{m_J^2}{E_J^2}\right)}{m_J^2/E_J^2} e^{-\frac{\alpha_s C_F}{2\pi}\log^2\left(\frac{m_J^2}{E_J^2}\right)}$$

$$\text{forbidden area} = \frac{1}{4}\log^2\left(\frac{m_J^2}{E_J^2}\right)$$



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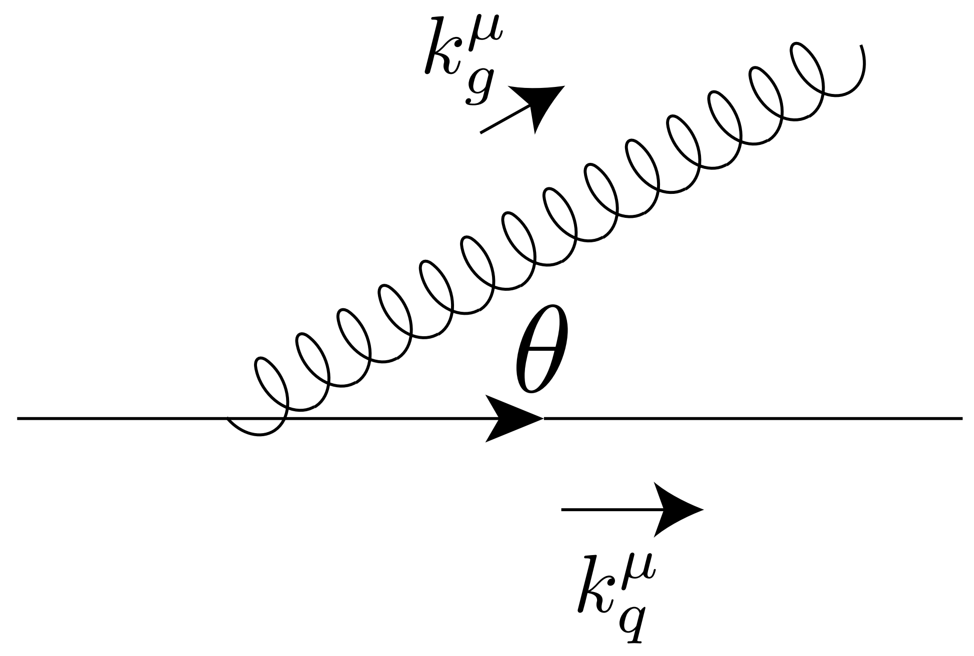

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$$1 - T \simeq \frac{m_J^2}{E_J^2}$$

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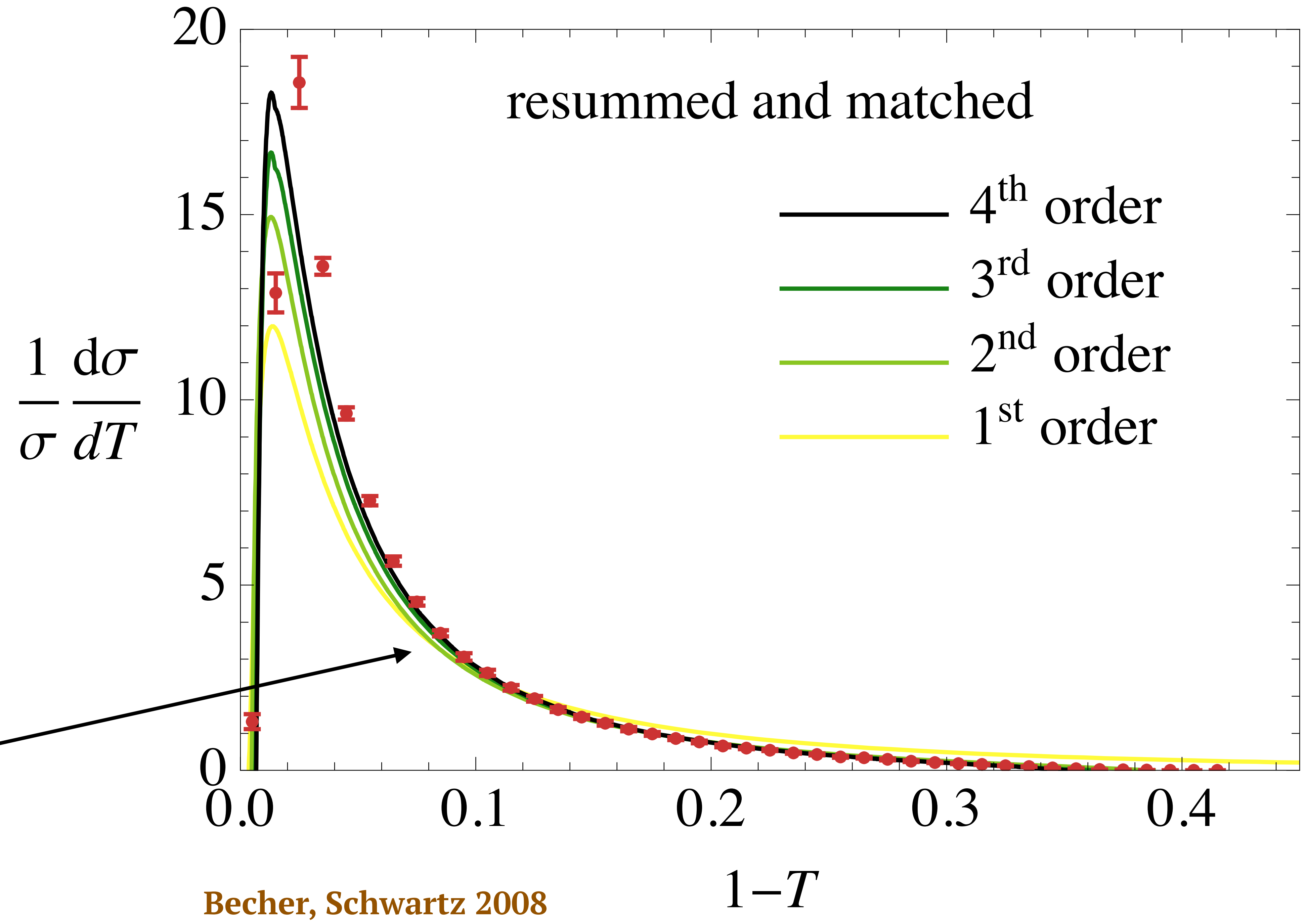


Becher, Schwartz 2008

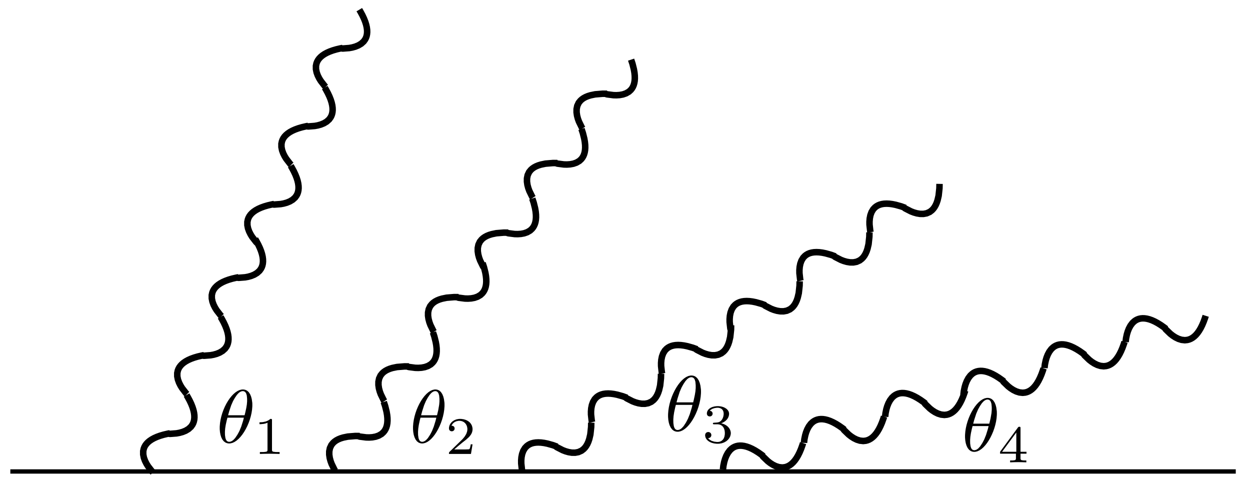
A good approximation

Double Logarithmic Approximation

$$P\left(x < \frac{m_J^2}{E_J^2}\right) = \exp\left[-\frac{\alpha_s C_F}{2\pi}\log^2\left(\frac{m_J^2}{E_J^2}\right)\right] = \sum_{n=0}^{\infty}\frac{1}{n!}\left(\frac{\alpha_s C_F}{2\pi}\right)^n \log^{2n}\left(\frac{m_J^2}{E_J^2}\right)$$

Note that for small jet masses: $\alpha * L^2 \sim 1$

$$m_{J,1}^2 \gg m_{J,2}^2 \gg \ldots \qquad m_{J,i}^2 = E_J^2 z_i \theta_i^2$$



Leading logarithmic expansion can also be obtained by considering a chain of emissions strongly ordered in their contribution to the jet mass

Double Logarithmic Approximation

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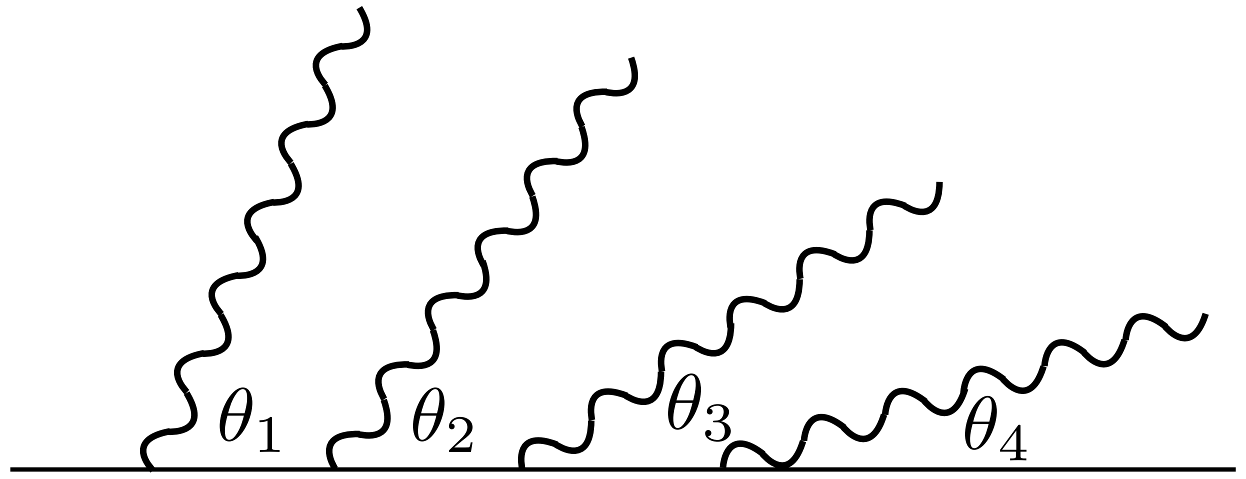

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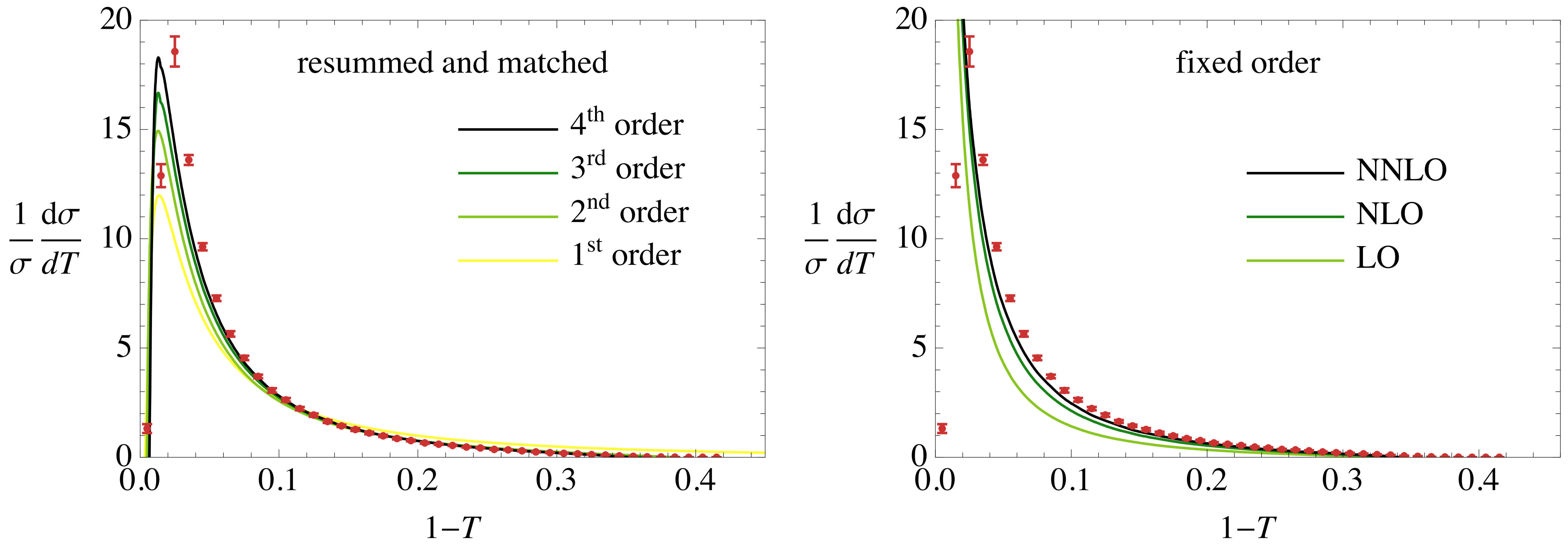
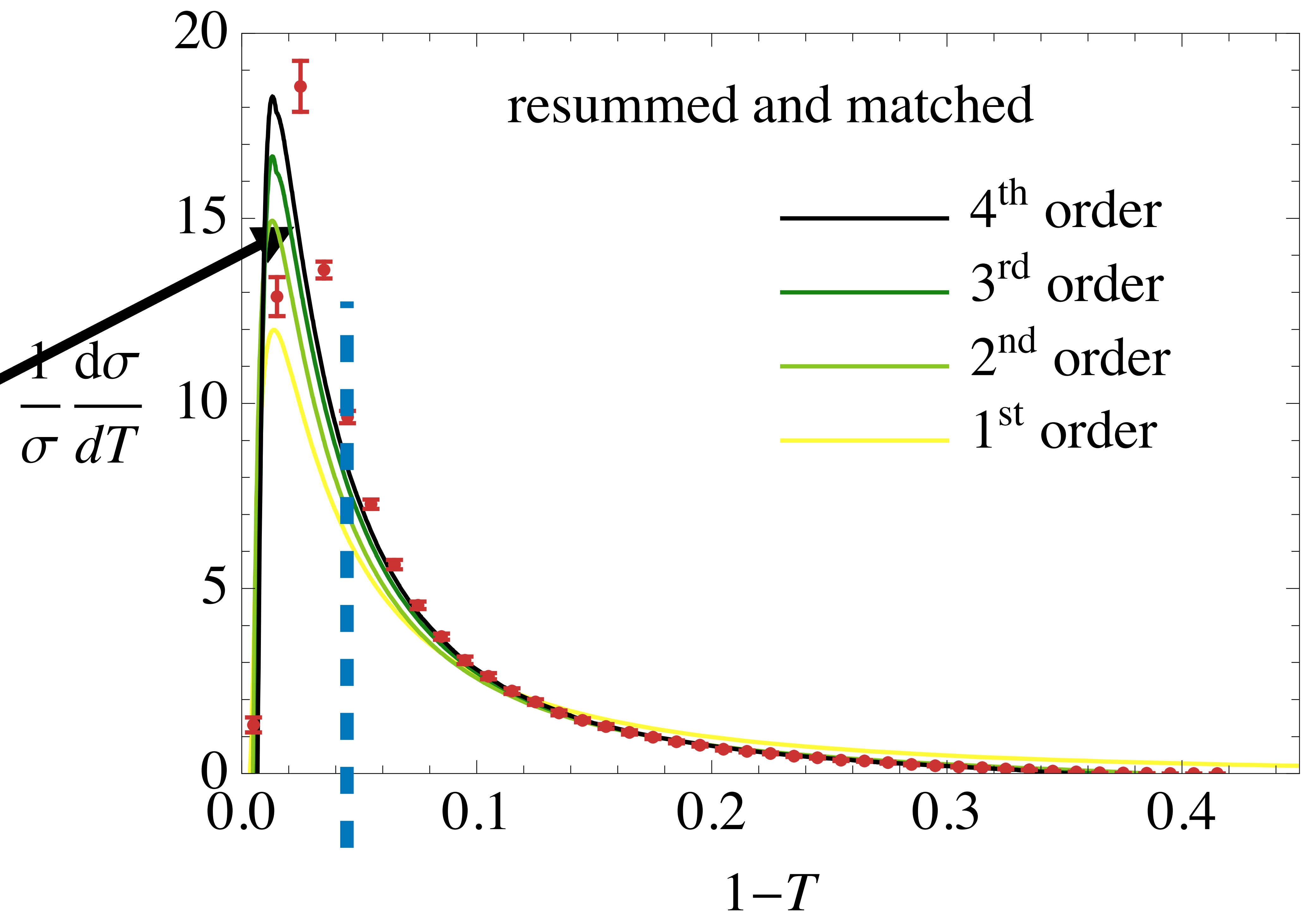


Individual terms in expansion diverge for small jet masses

Hadronization corrections



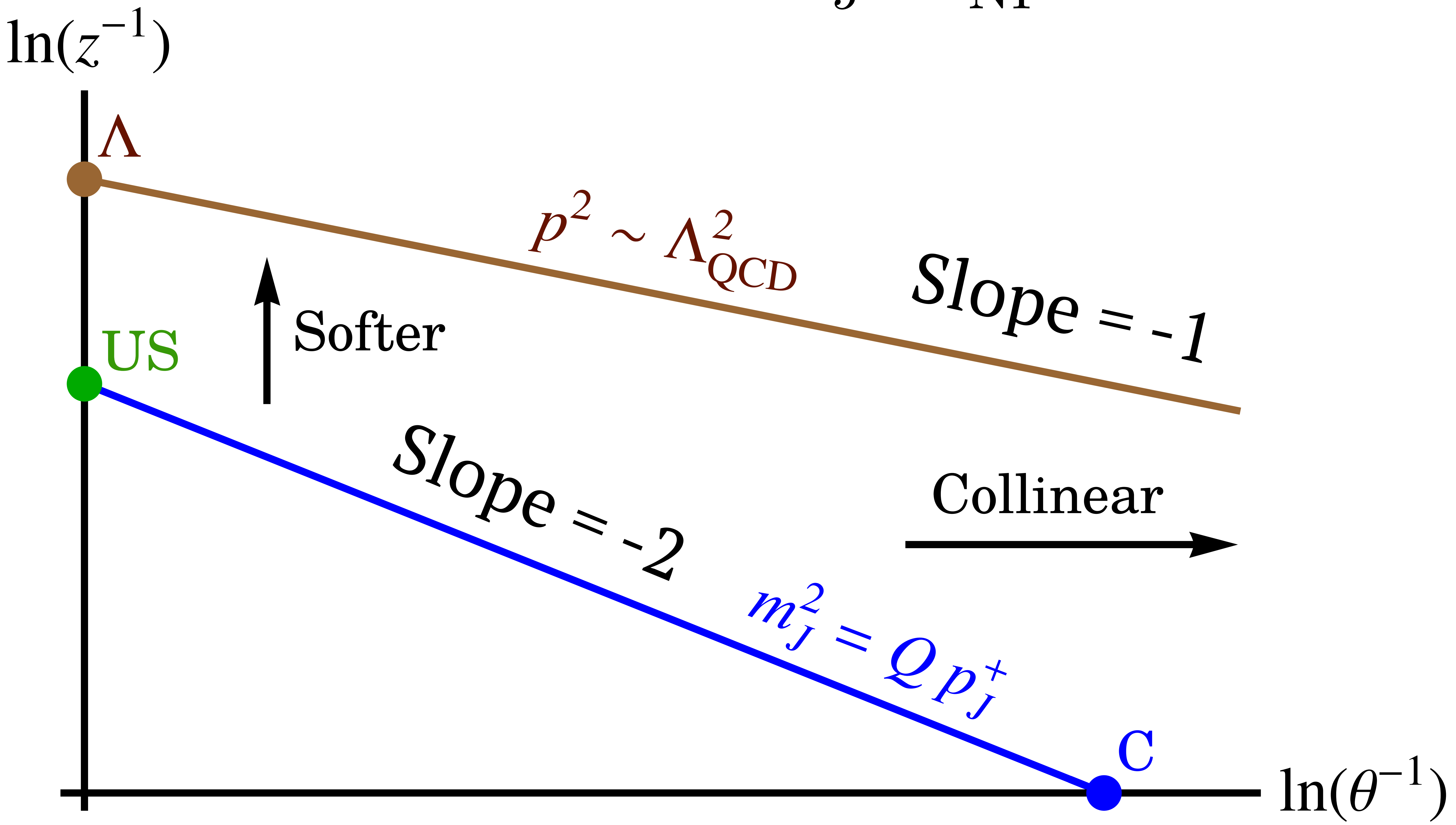
Inaccurate prediction for low jet masses

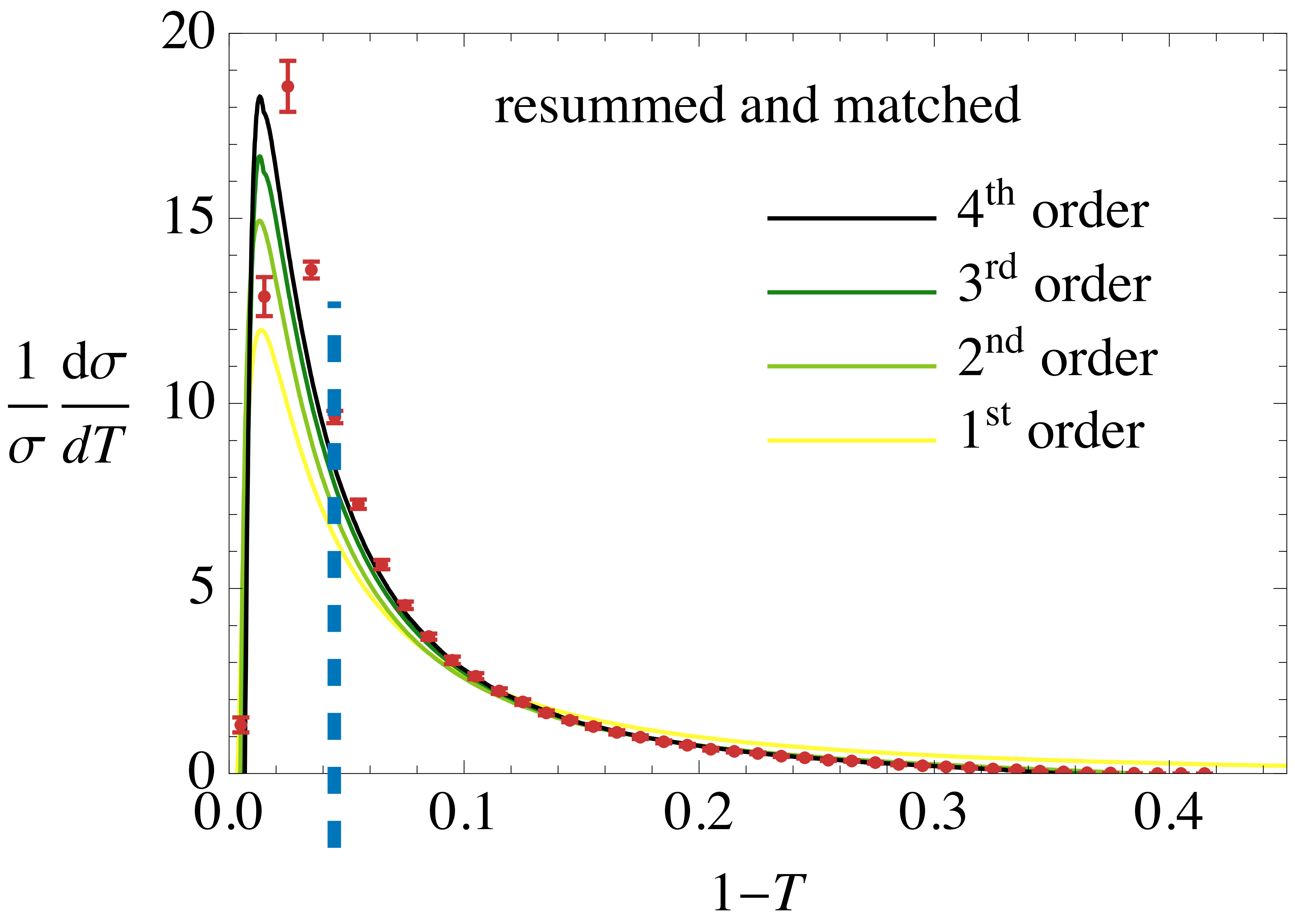
Hadronization corrections

Condition that an emission is nonperturbative:

$$p_{\rm NP}^2 = (E_J z_{\rm NP} \theta_{\rm NP})^2 \sim \Lambda_{\rm QCD}^2$$

$$z_{\rm NP} = \frac{\Lambda_{\rm QCD}}{E_J} \frac{1}{\theta_{\rm NP}}$$





See [Lee, Sterman hep-ph/0603066; Dokshitzer, Lucenti, Marchesini and Salam hep-ph/9707532; Dasgupta, Salam hep-ph/0312283]

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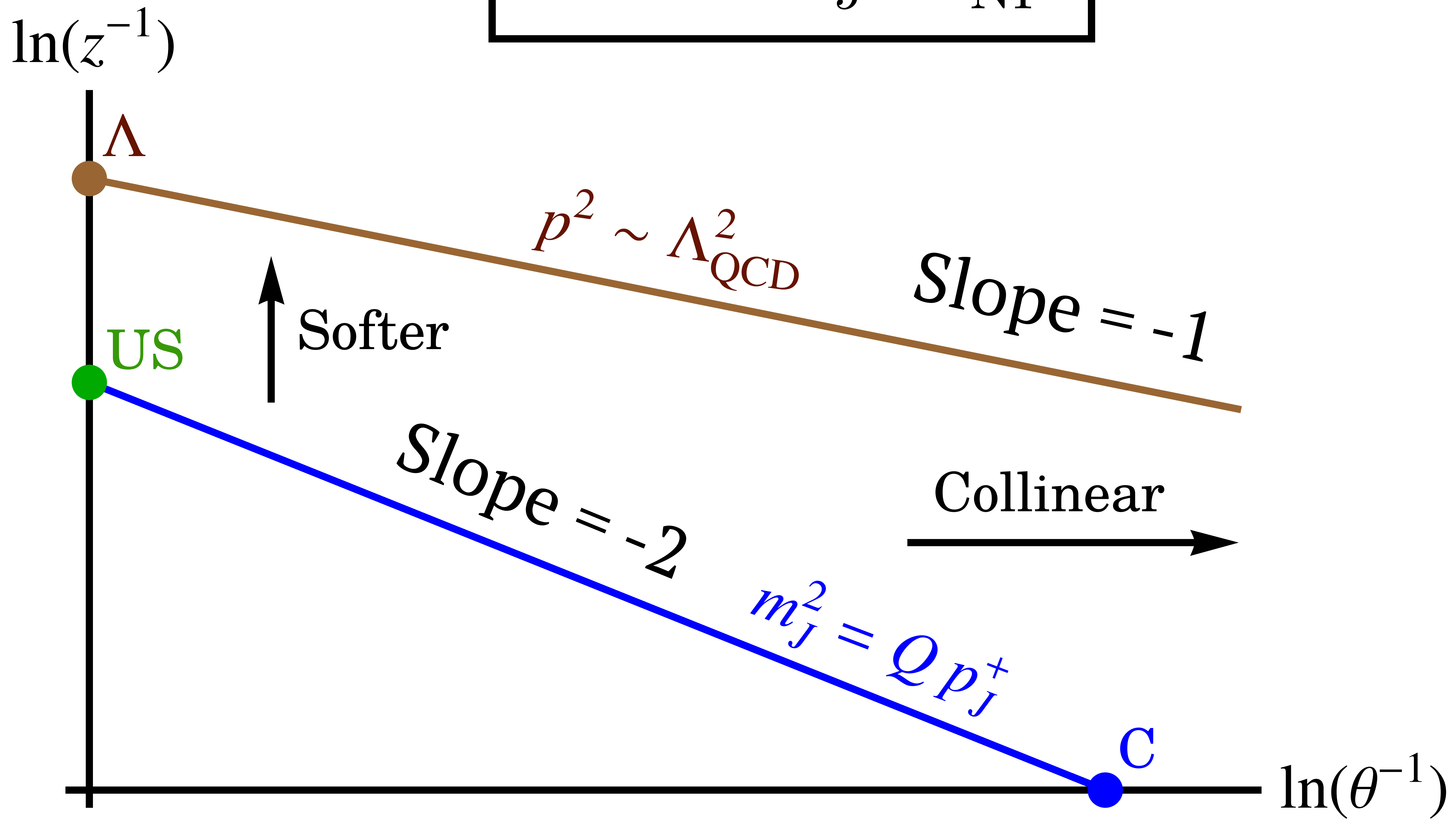

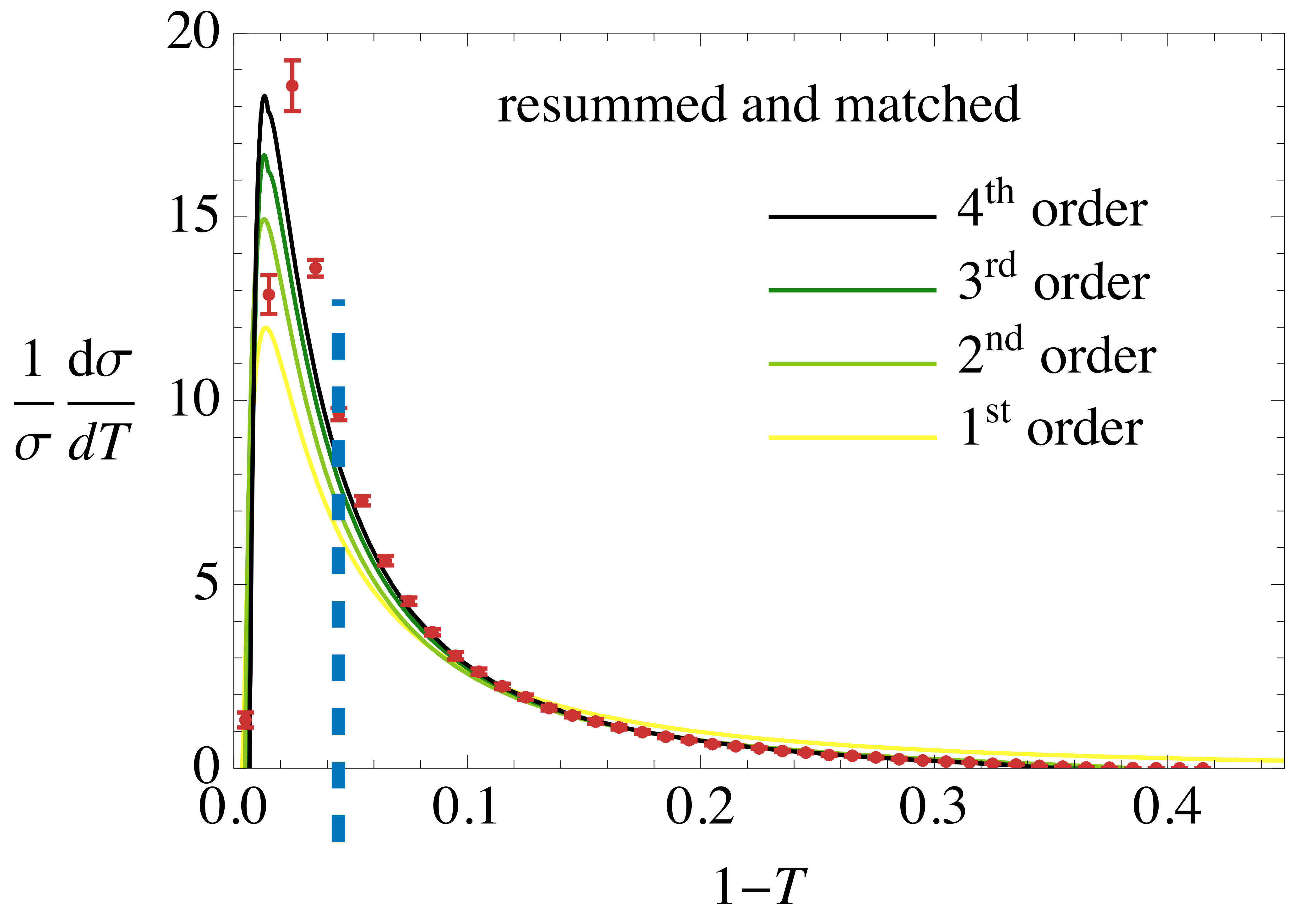

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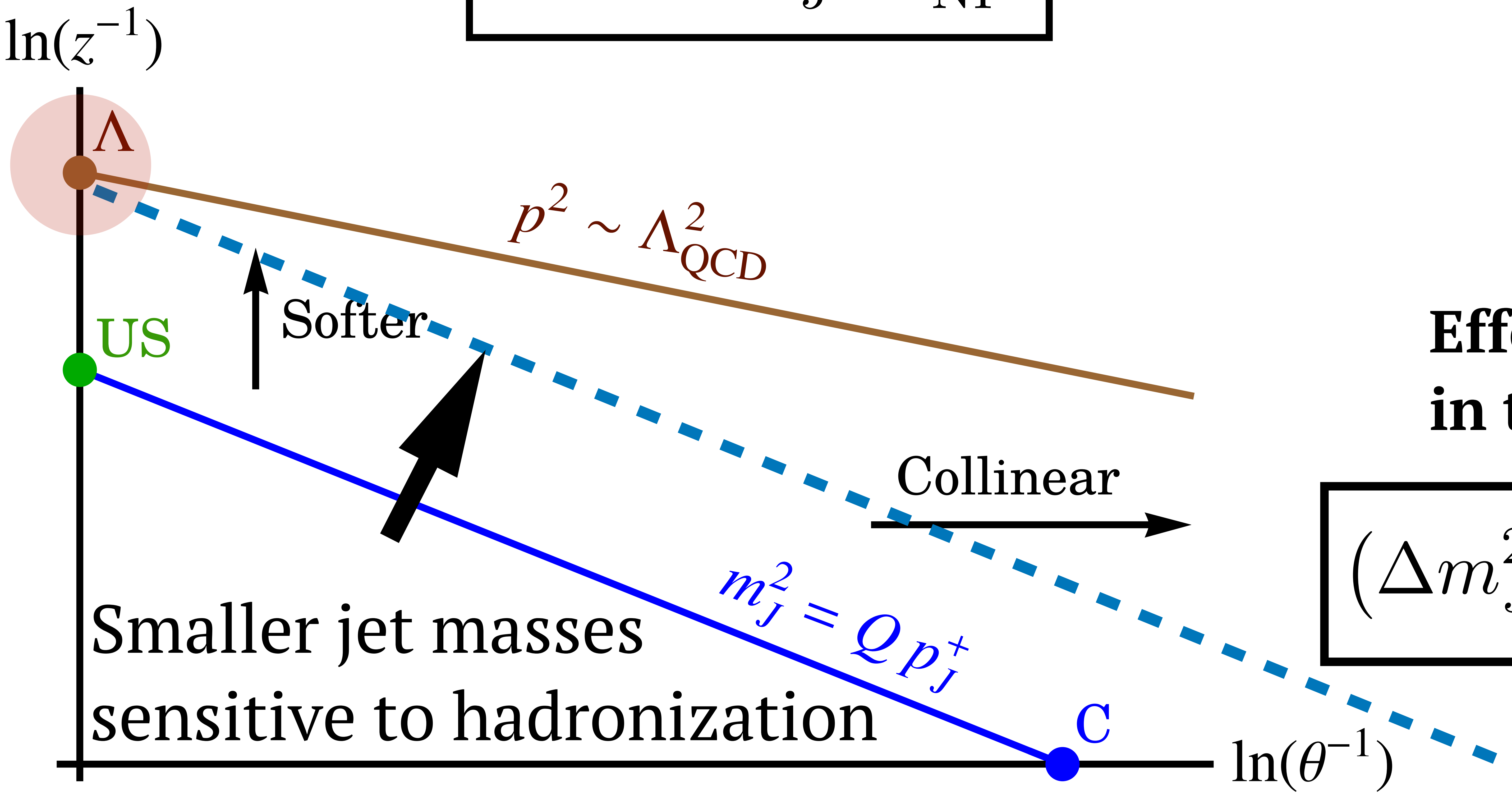
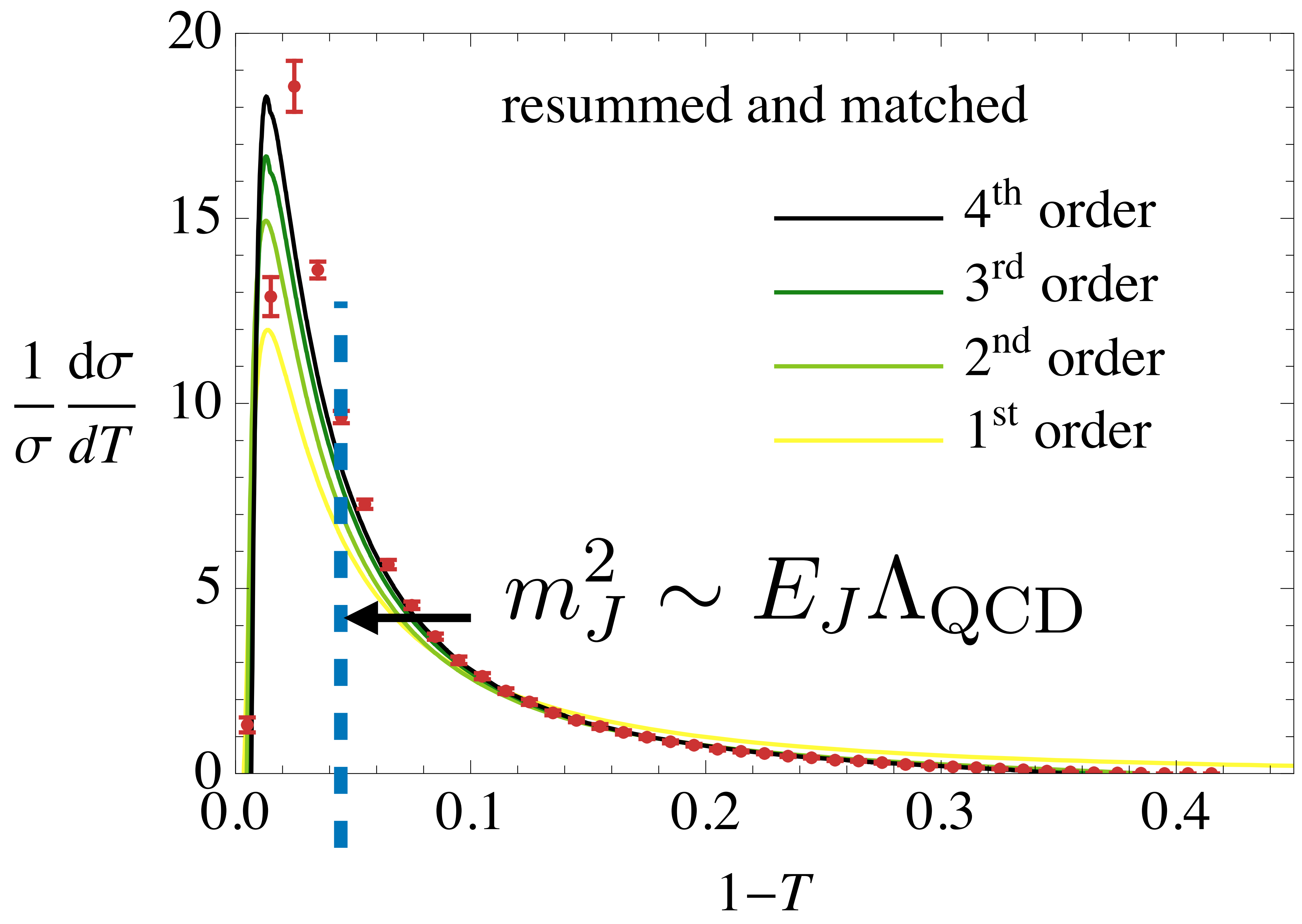


Smaller jet masses sensitive to hadronization



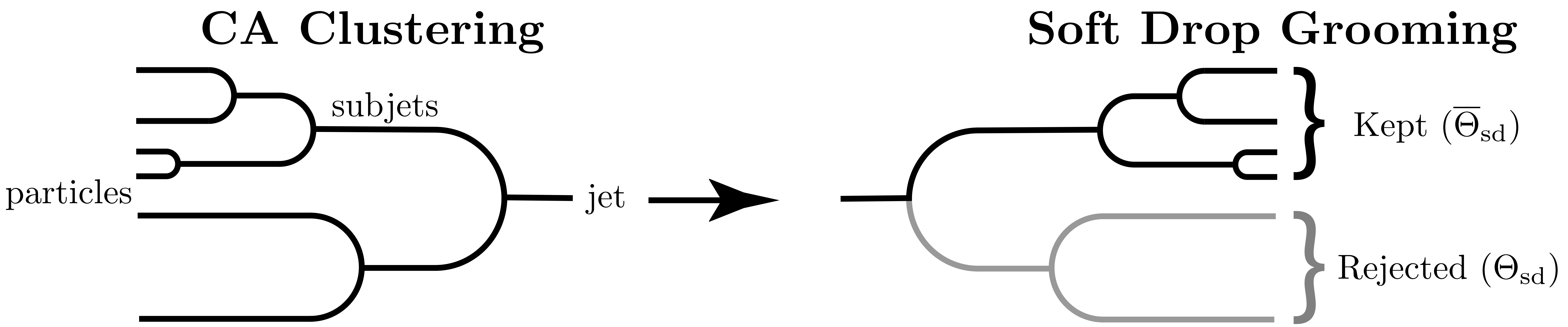
Effect of hadronization is seen in the wide angle emissions

$$(\Delta m_J^2)_{\rm NP} = E_J^2 z_{\rm NP}\theta_{\rm NP}^2 \sim E_J\Lambda_{\rm QCD}\theta_{\rm NP}$$

See [Lee, Sterman hep-ph/0603066; Dokshitzer, Lucenti, Marchesini and Salam hep-ph/9707532; Dasgupta, Salam hep-ph/0312283]

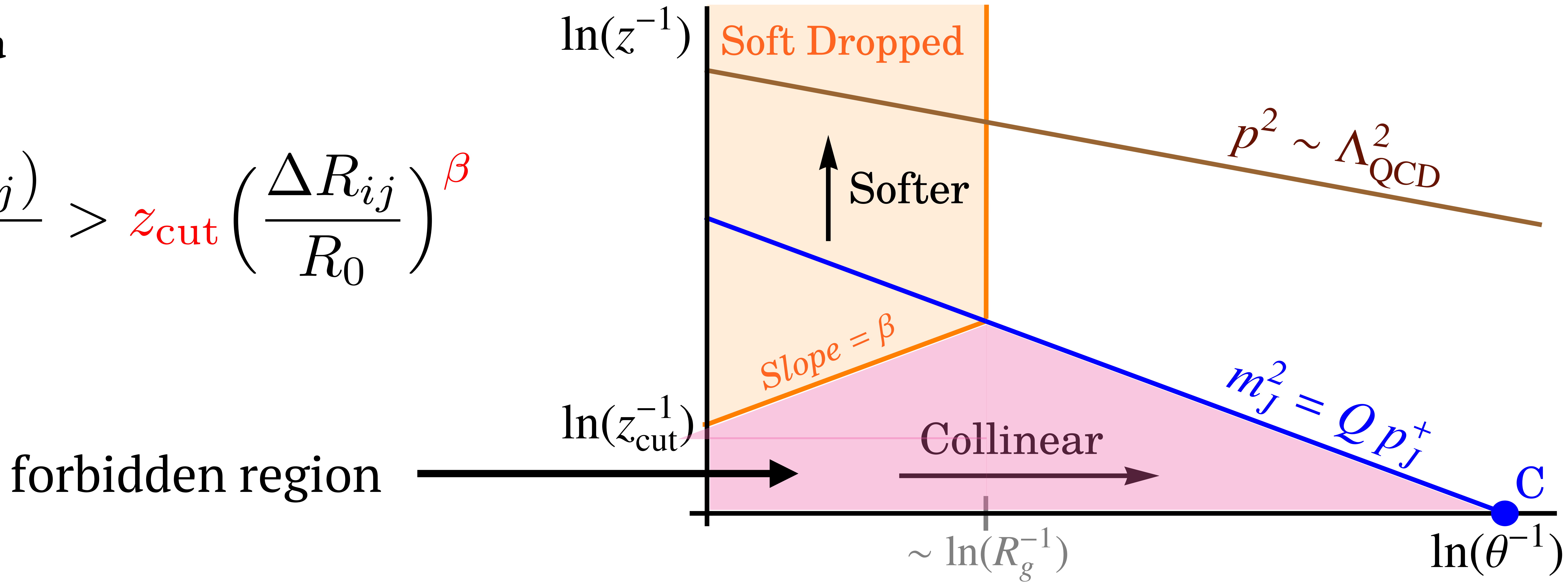
Soft Drop Grooming

Larkoski, Marzani, Soyez, Thaler 2014

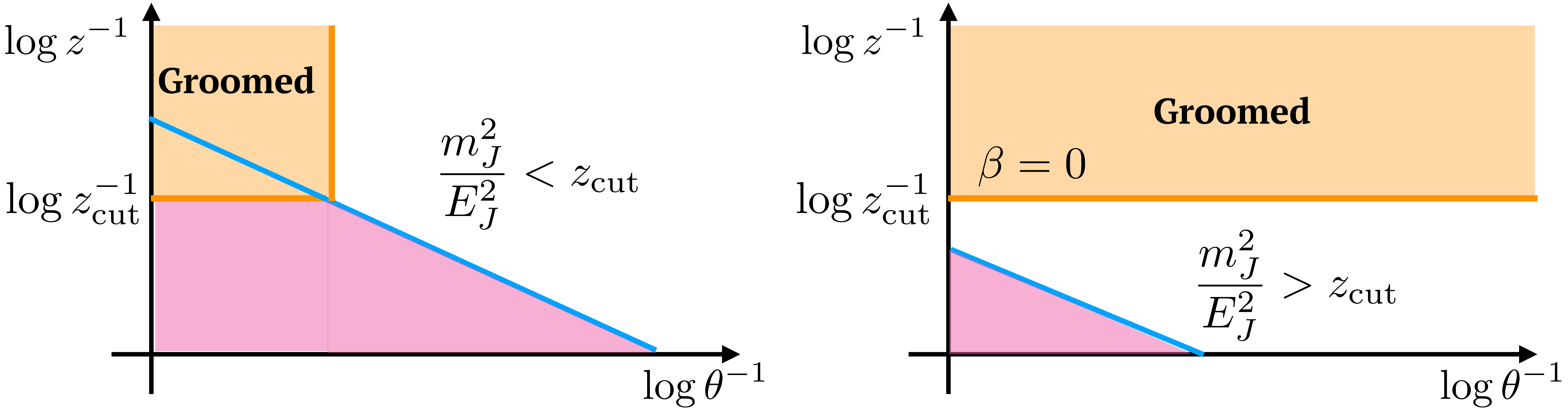


Soft Drop criteria

$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$



mMDT (β = 0)



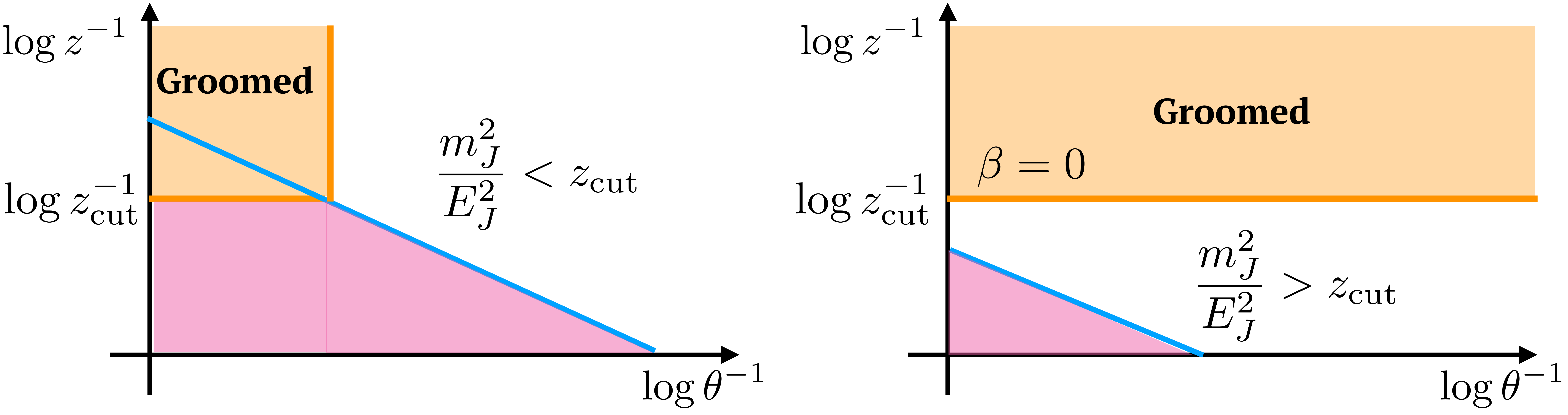
$$\log\left(\frac{m_J^2}{E_J^2}\right) = -\log(z^{-1}) - 2\log(\theta^{-1})$$

forbidden area:

$$\Theta\left(z_{\rm cut} - \frac{m_J^2}{E_J^2}\right)\left[-\frac{1}{2}\log^2 z_{\rm cut} + \log z_{\rm cut}\log\left(\frac{m_J^2}{E_J^2}\right)\right]$$

$$+\,\Theta\left(\frac{m_J^2}{E_J^2} - z_{\rm cut}\right)\frac{1}{2}\log^2\left(\frac{m_J^2}{E_J^2}\right)$$

mMDT (β = 0)



Leading Log cross section:

$$\frac{d\sigma}{d\log(m_J^2/E_J^2)} = \Theta\left(z_{\rm cut} - \frac{m_J^2}{E_J^2}\right)\left[\frac{\alpha_s C_F}{\pi}\log z_{\rm cut}^{-1} e^{-\frac{1}{2}\log^2 z_{\rm cut} + \log z_{\rm cut}\log\left(\frac{m_J^2}{E_J^2}\right)}\right]$$
$$+\,\Theta\left(\frac{m_J^2}{E_J^2} - z_{\rm cut}\right)\left[-\frac{\alpha_s C_F}{\pi}\log\left(\frac{m_J^2}{E_J^2}\right)e^{-\frac{\alpha_s C_F}{2\pi}\log^2\left(\frac{m_J^2}{E_J^2}\right)}\right]$$

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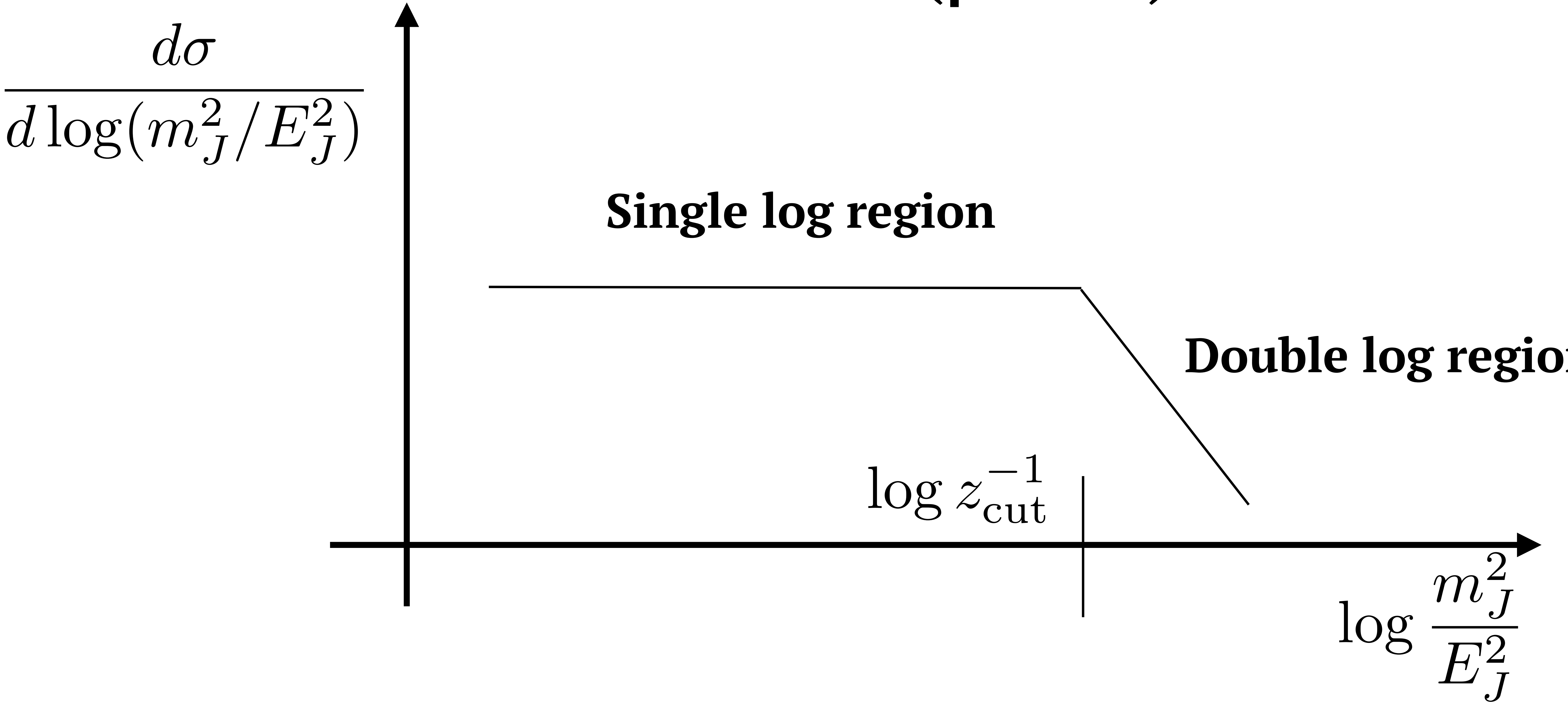

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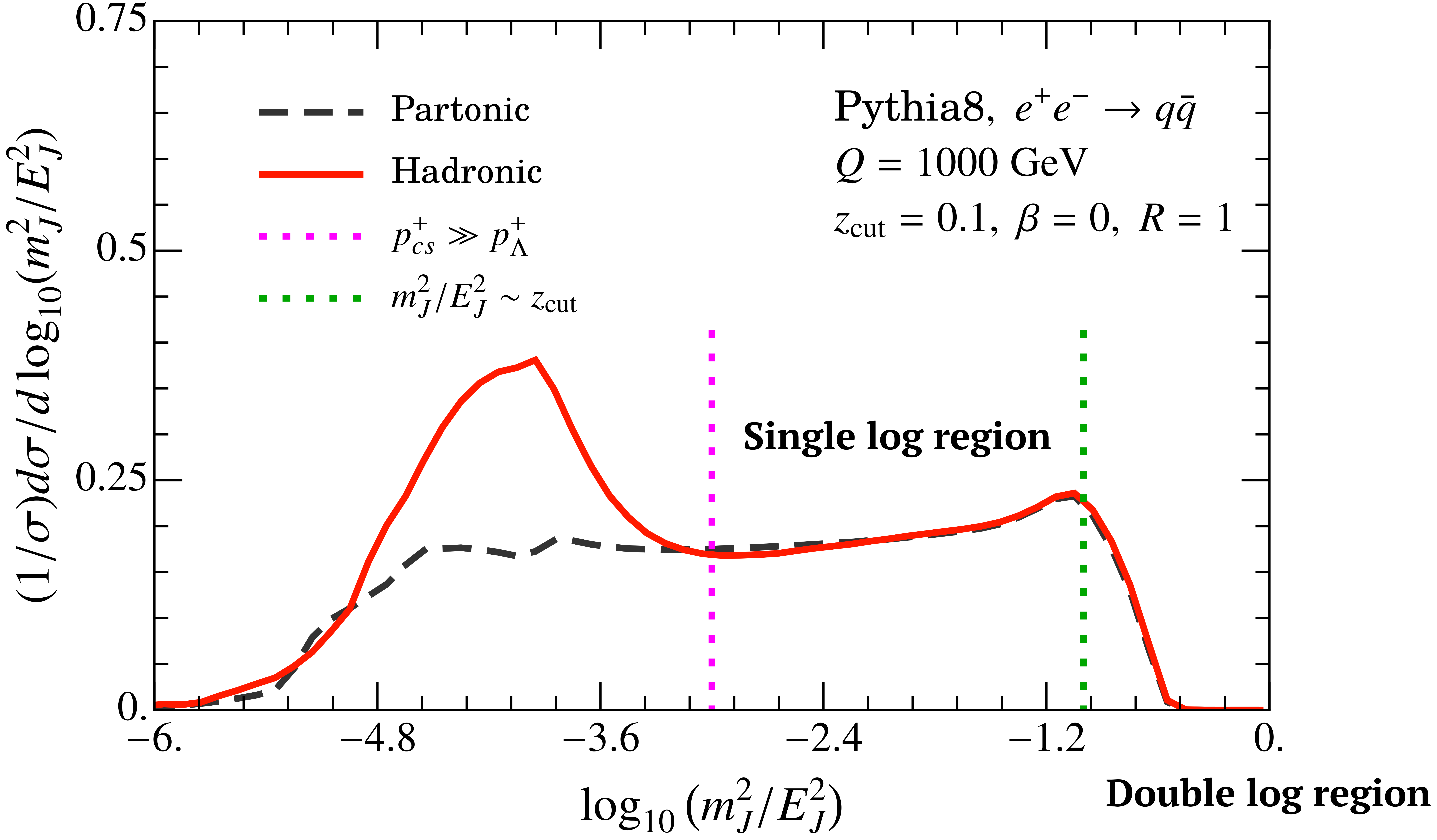
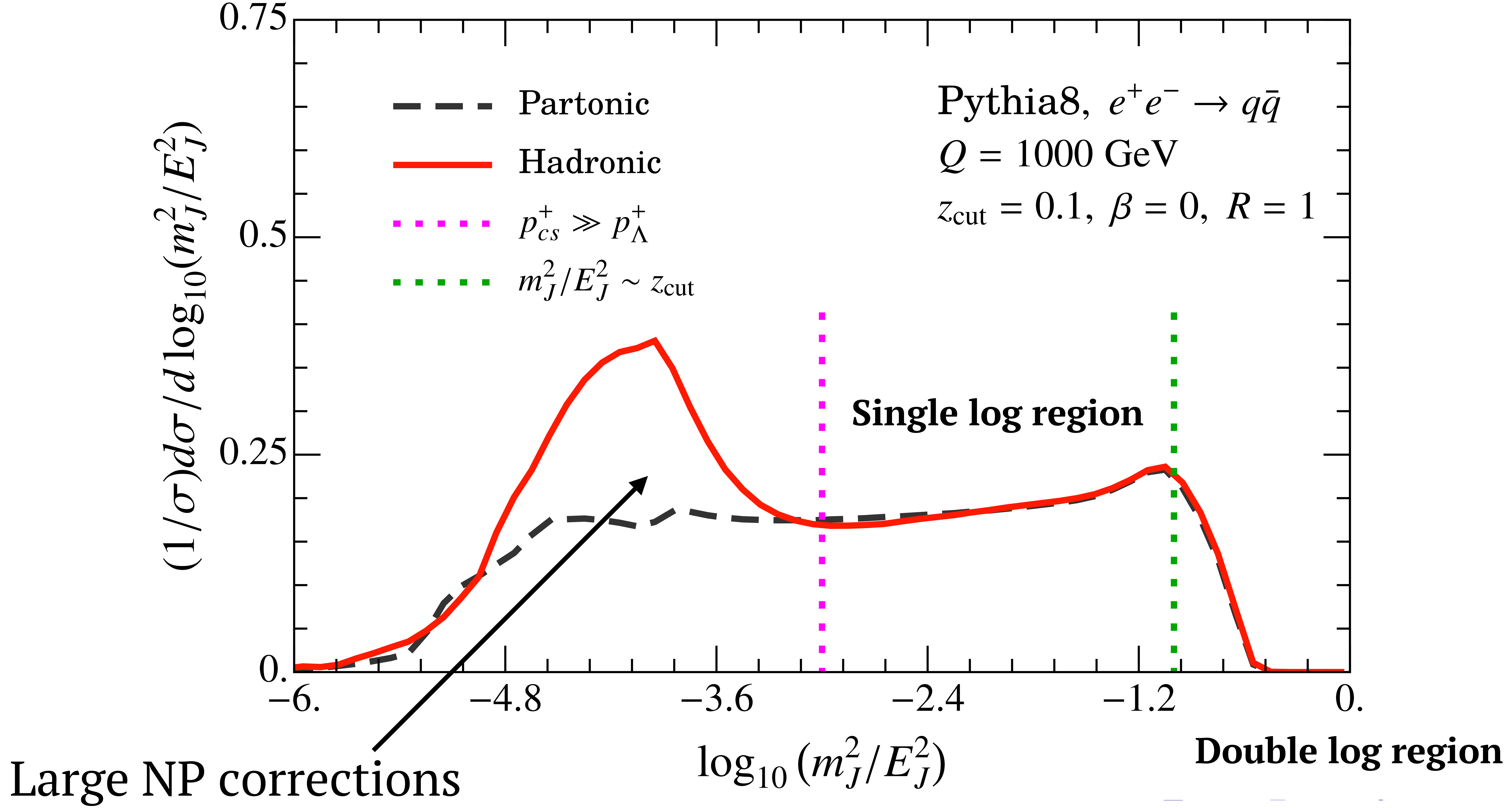


0.75
0.5
0.25
0.
−6.
−4.8
−3.6
−2.4
−1.2
0.
Partonic
Hadronic
$p^+_{cs} \gg p^+_\Lambda$
$m_J^2/E_J^2 \sim z_{\rm cut}$
Pythia8, $e^+e^- \to q\bar{q}$
Q = 1000 GeV
$z_{\rm cut}$ = 0.1, β = 0, R = 1
Single log region
$(1/\sigma)d\sigma/d\log_{10}(m_J^2/E_J^2)$
$\log_{10}(m_J^2/E_J^2)$
Double log region

mMDT (β = 0)

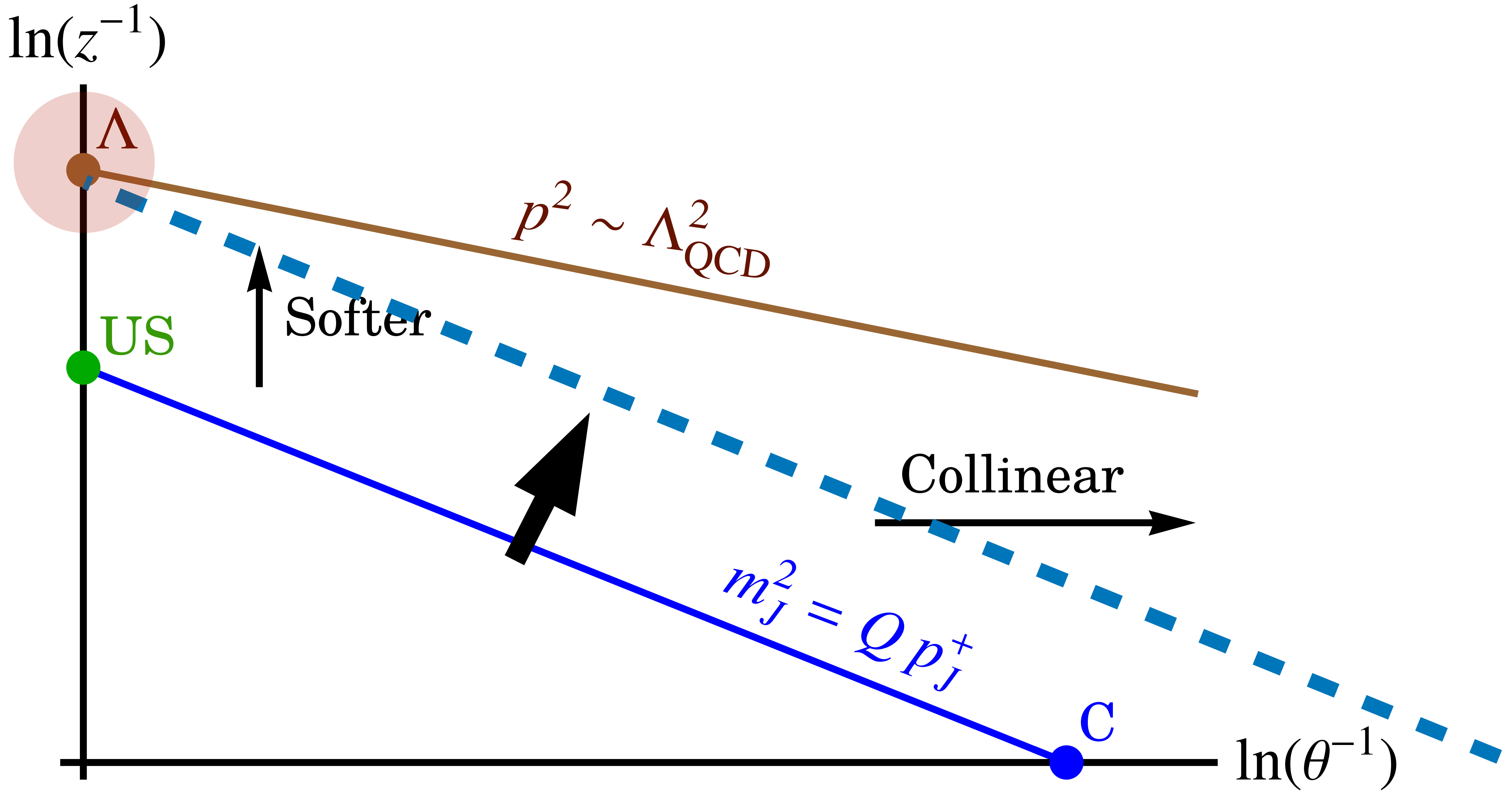


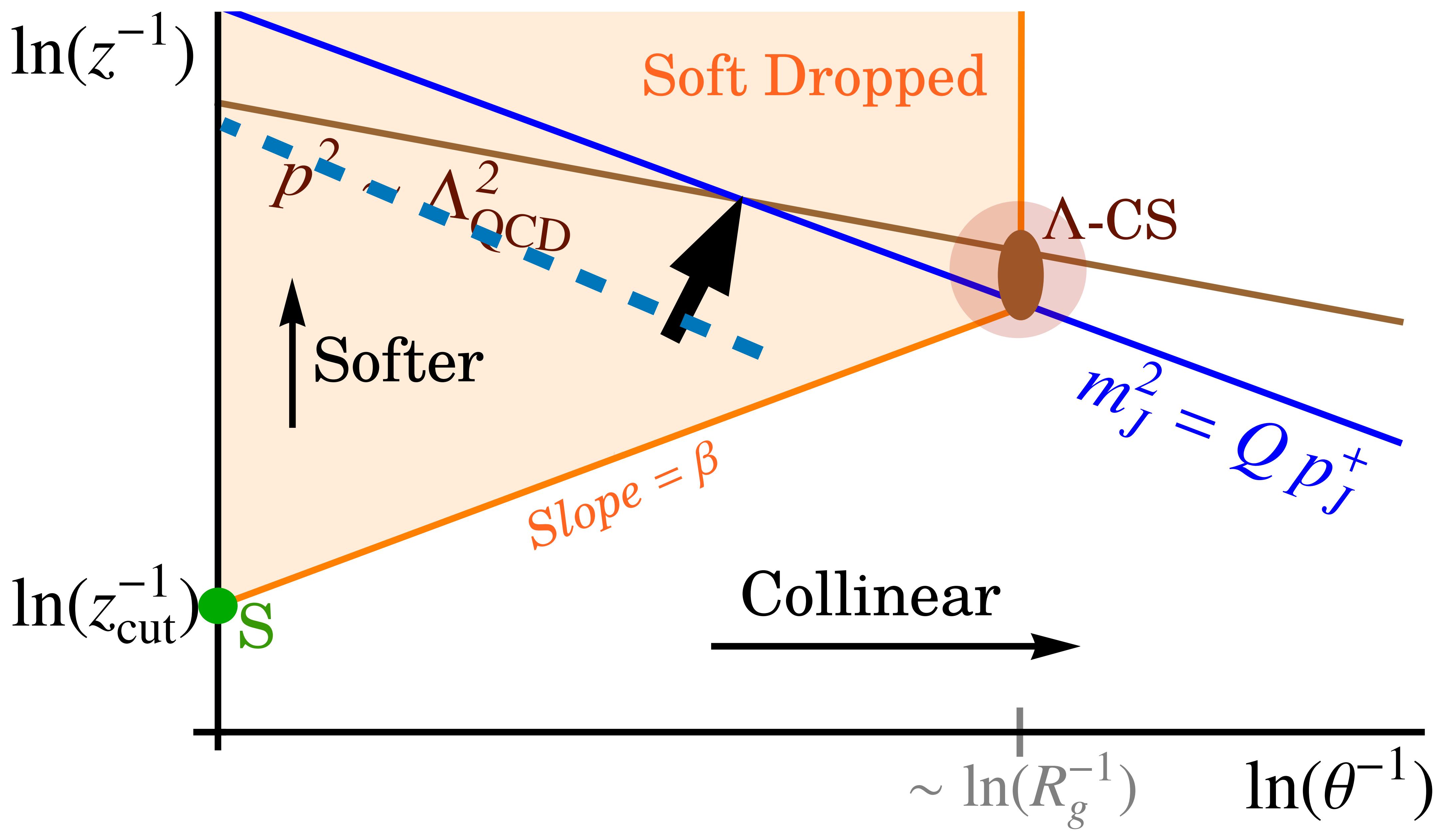
0.75
0.5
0.25
0.
−6.
−4.8
−3.6
−2.4
−1.2
0.
$(1/\sigma)d\sigma/d\log_{10}(m_J^2/E_J^2)$
$\log_{10}(m_J^2/E_J^2)$
Partonic
Hadronic
$p_{cs}^+ \gg p_\Lambda^+$
$m_J^2/E_J^2 \sim z_{\rm cut}$
Pythia8, $e^+e^- \to q\bar{q}$
Q = 1000 GeV
$z_{\rm cut} = 0.1,\ \beta = 0,\ R = 1$
Single log region
Double log region
Large NP corrections

NP region of Groomed Jet mass

Dasgupta, Fregoso, Marzani, Salam 2013
Marzani, Schunk, Soyez 2018
Frye, Larkoski, Schwartz, Yan 2016

The large NP corrections are pushed to yet smaller jet masses





[Hoang, AP, Mantry, Stewart 2019]

Plain jet mass NP region:

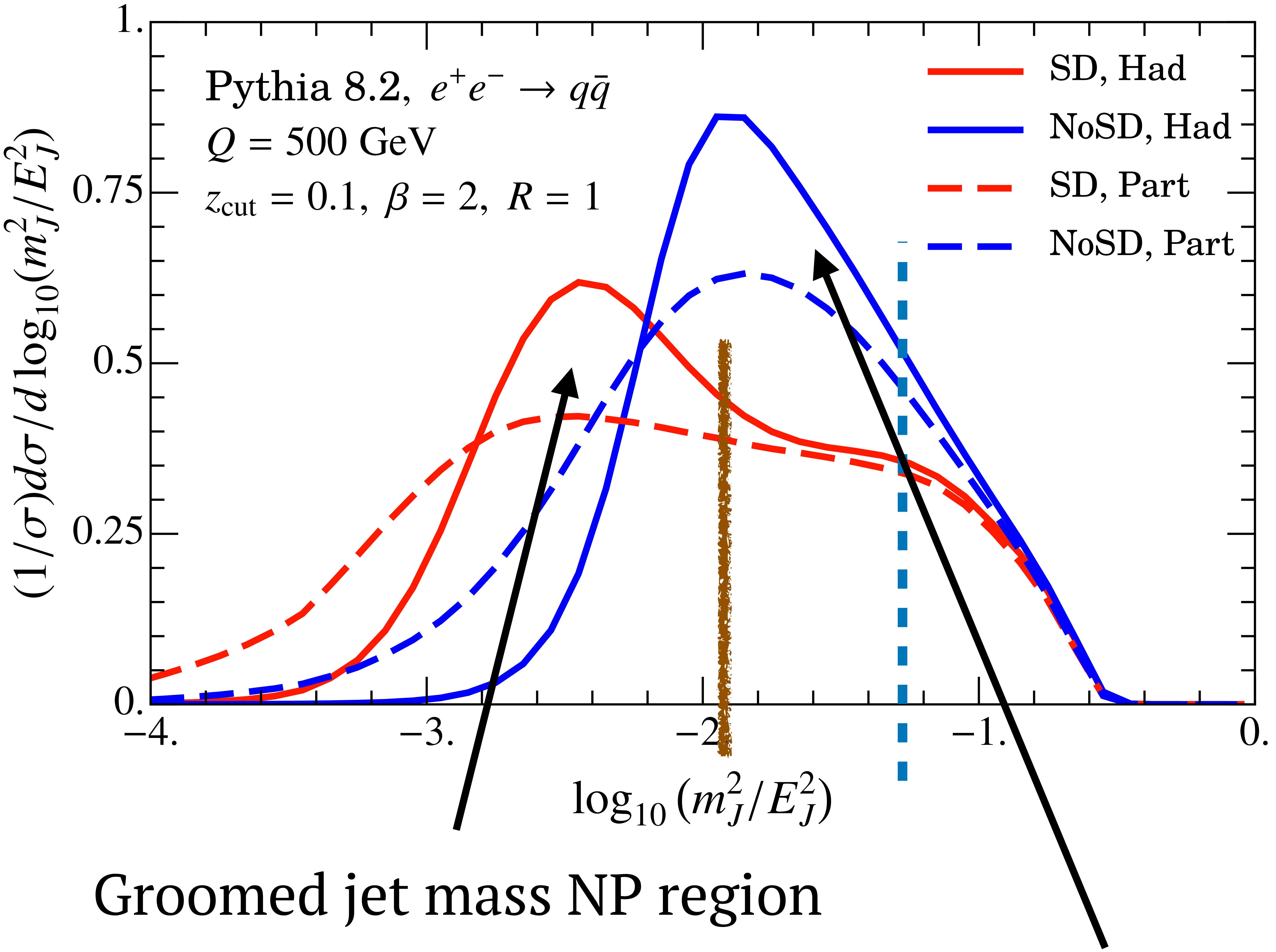
$$m_J^2 \sim E_J \Lambda_{\rm QCD}$$

Groomed jet mass NP region:

$$m_J^2 \sim E_J \Lambda_{\rm QCD} \left(\frac{\Lambda_{\rm QCD}}{E_J z_{\rm cut}} \right)^{\frac{1}{1+\beta}}$$

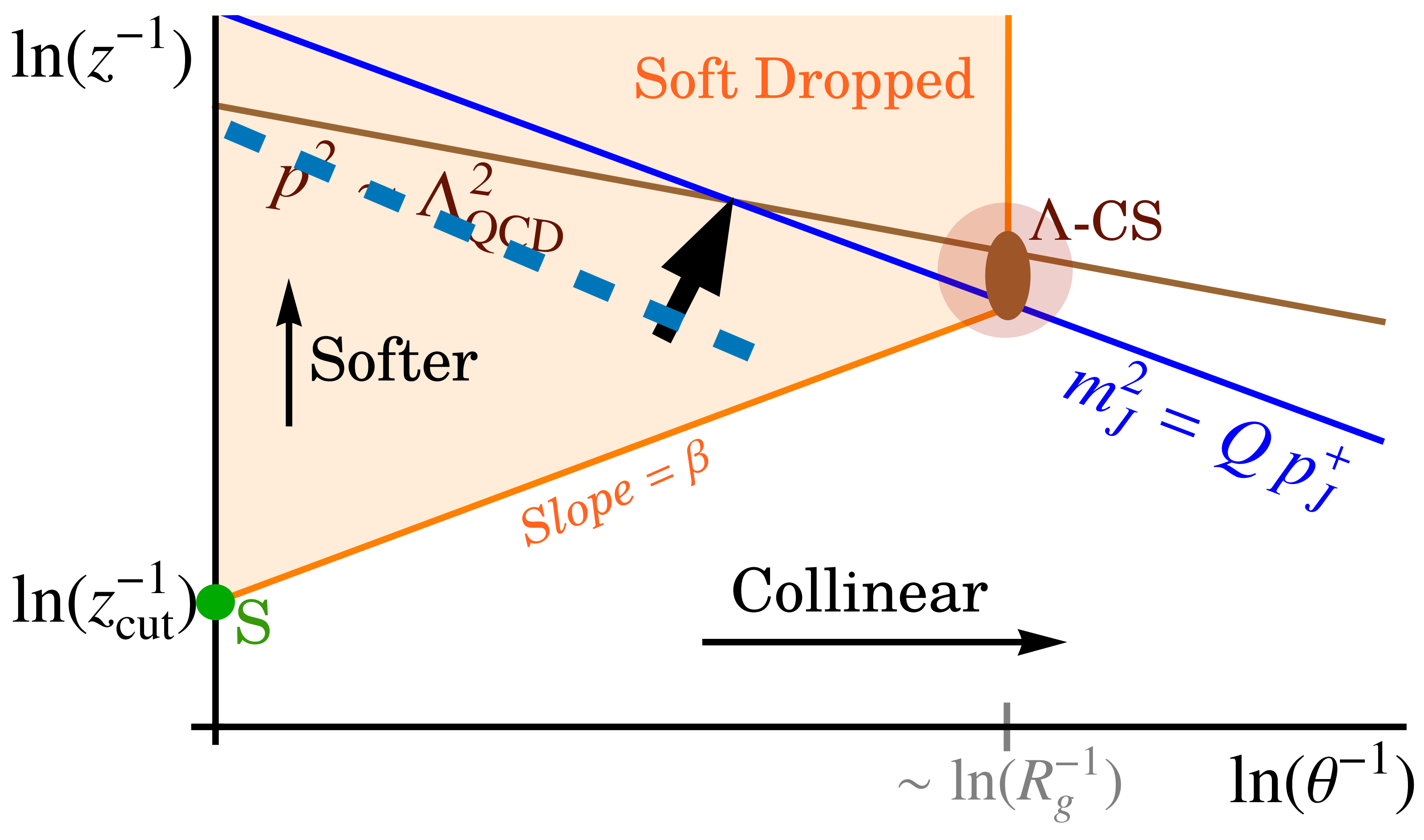
NP region of Groomed Jet mass

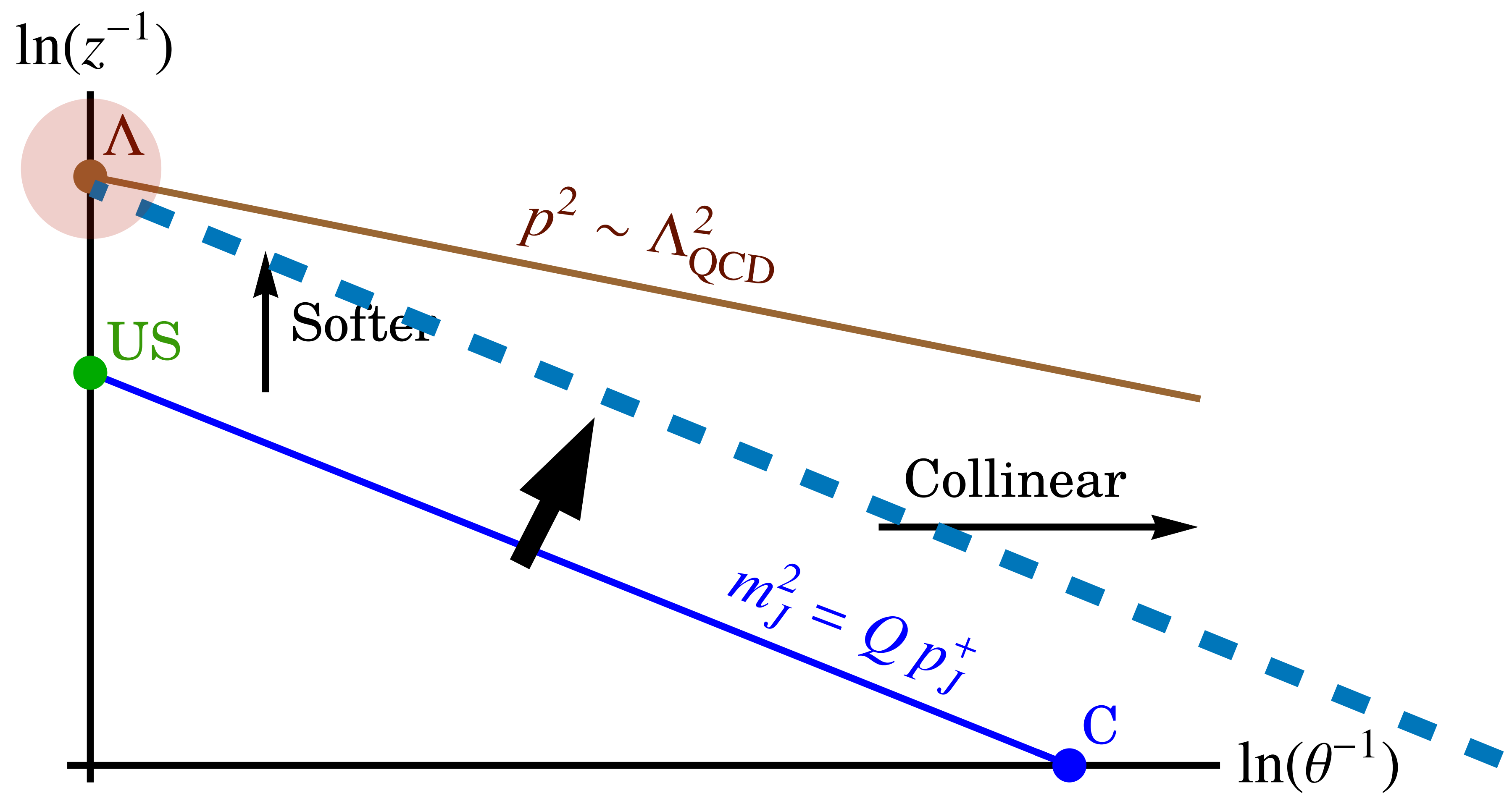
The large NP corrections are pushed to yet smaller jet masses



Groomed jet mass NP region

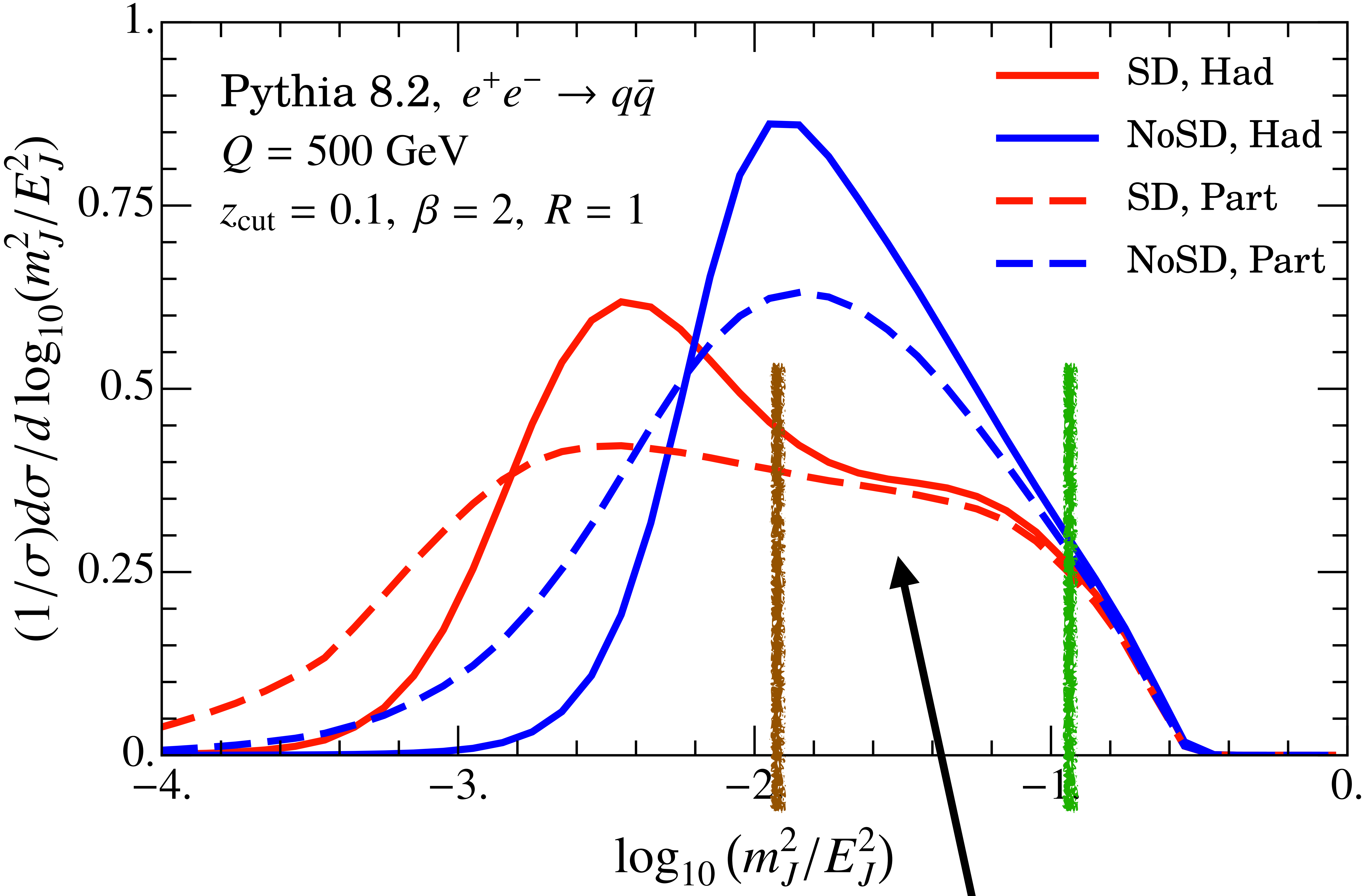
Plain jet mass NP region

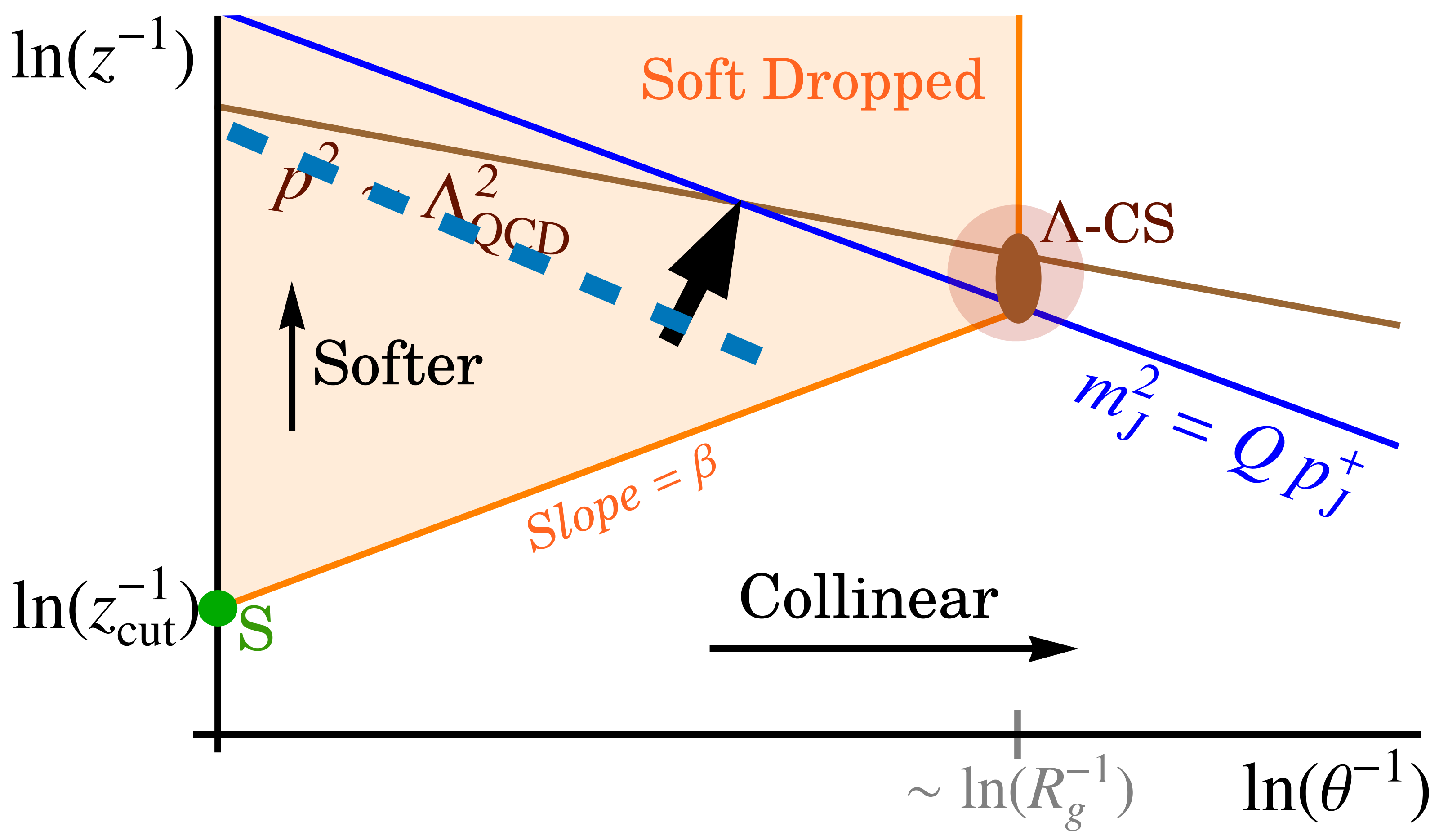


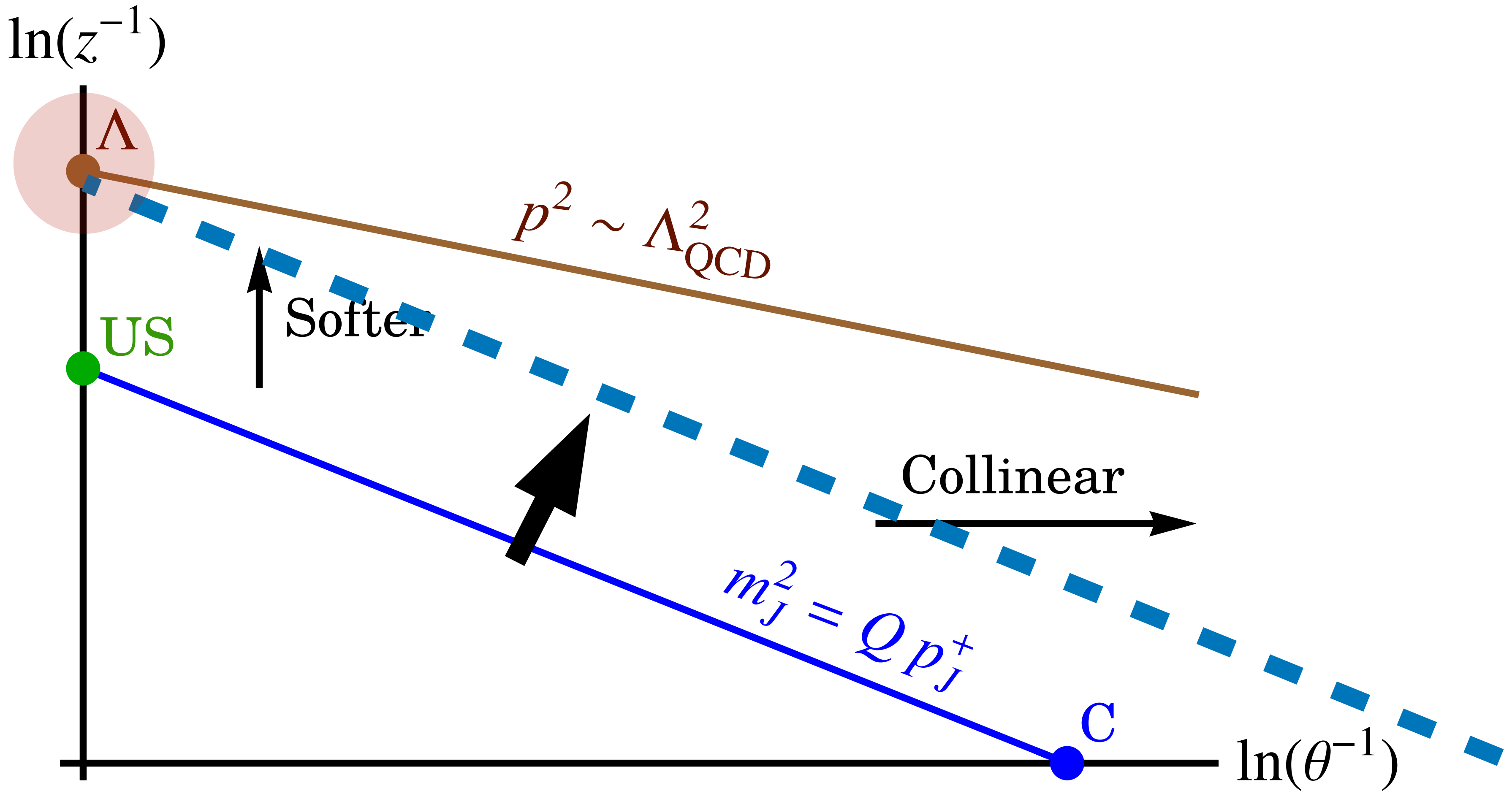


NP region of Groomed Jet mass

The large NP corrections are pushed to yet smaller jet masses

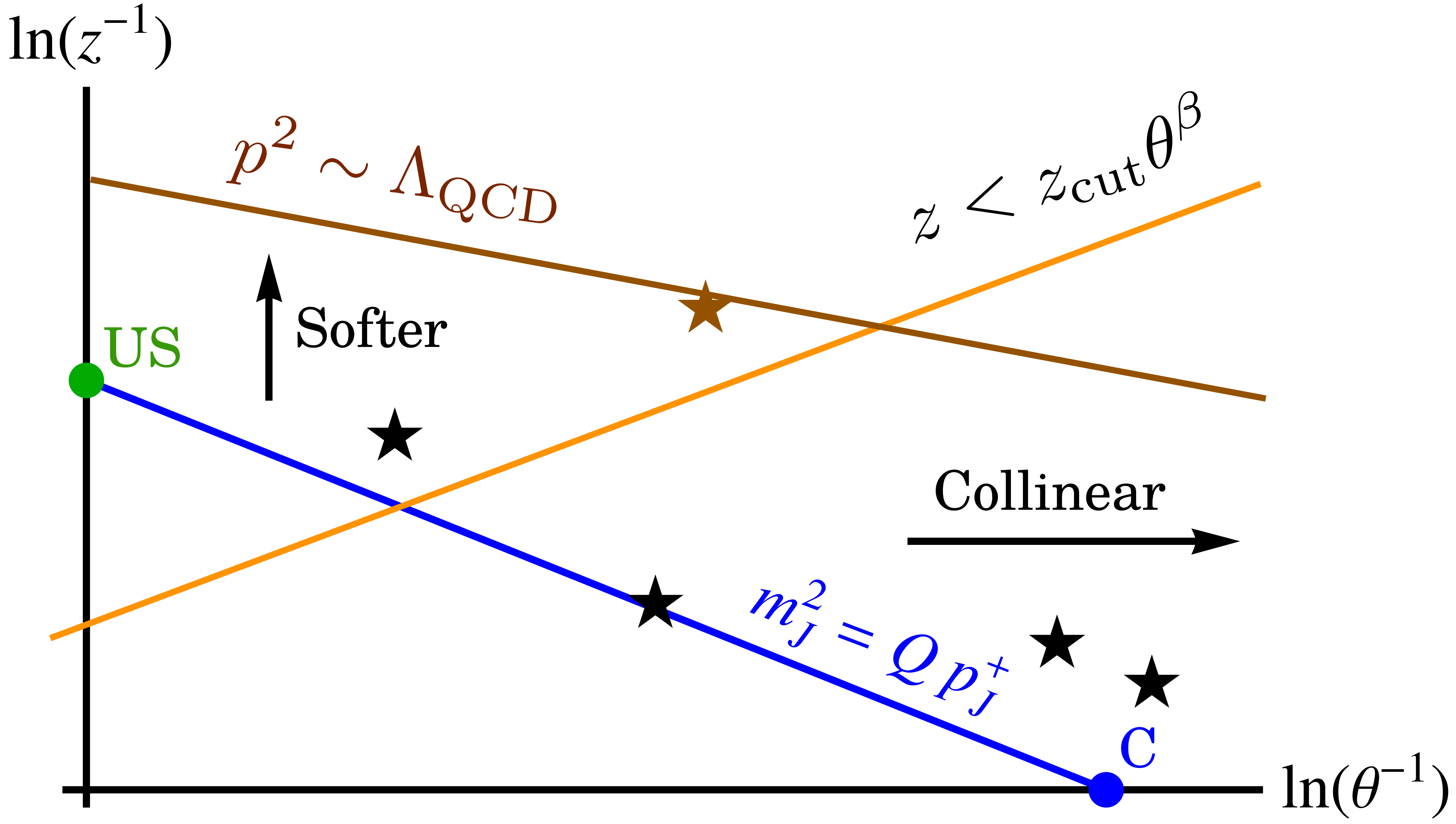






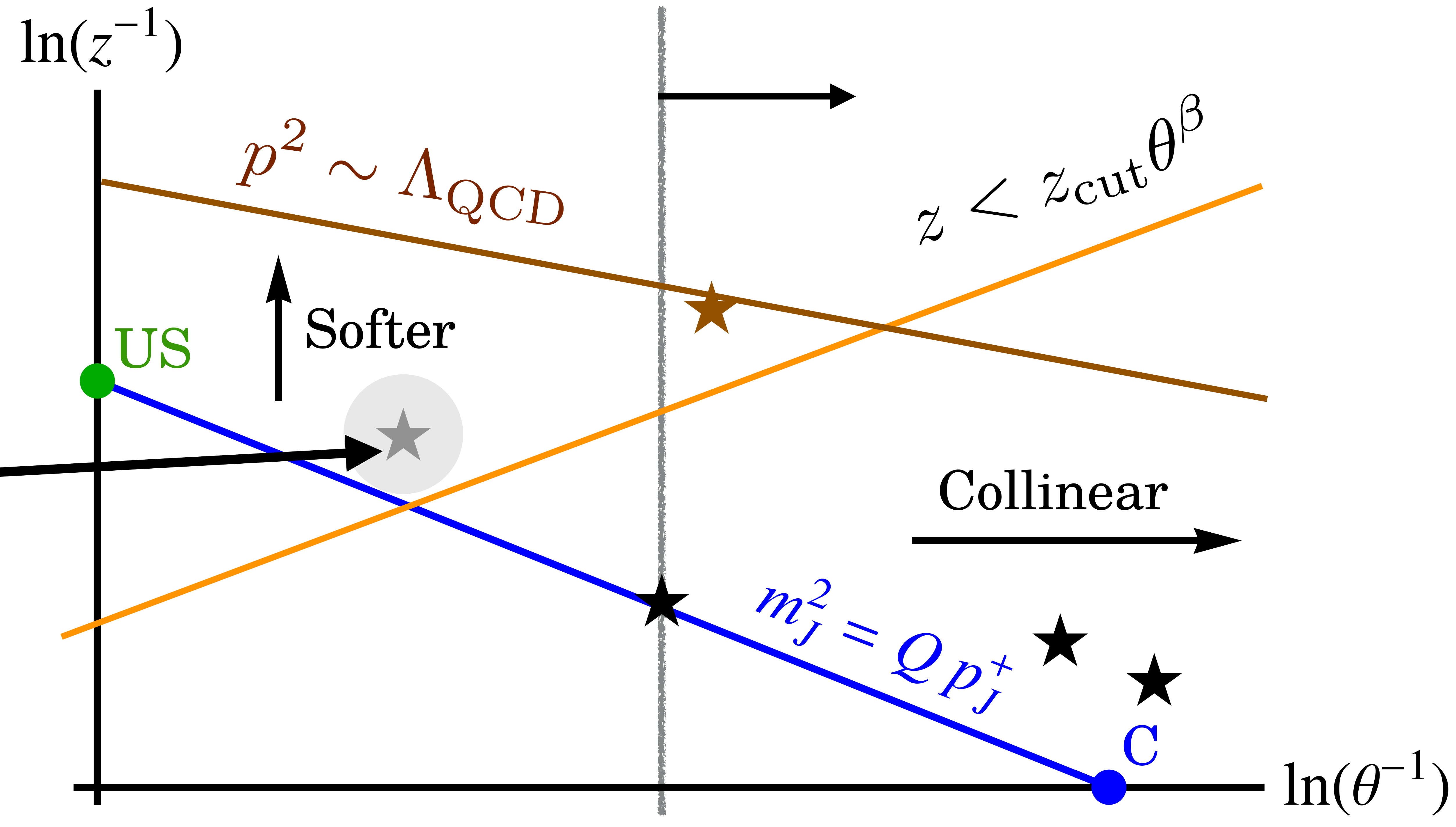
In this talk we will focus on the groomed resummation region

NP Corrections in the Resummation region

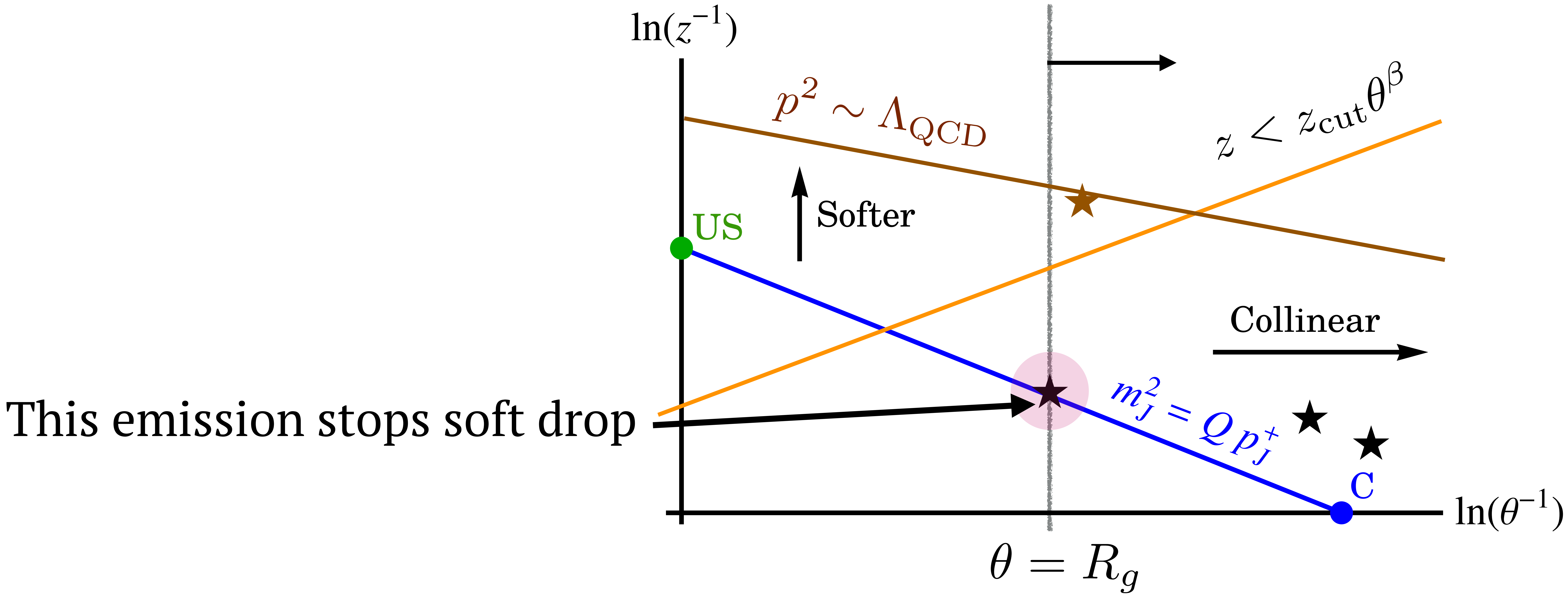


NP Corrections in the Resummation region

This emission is groomed away

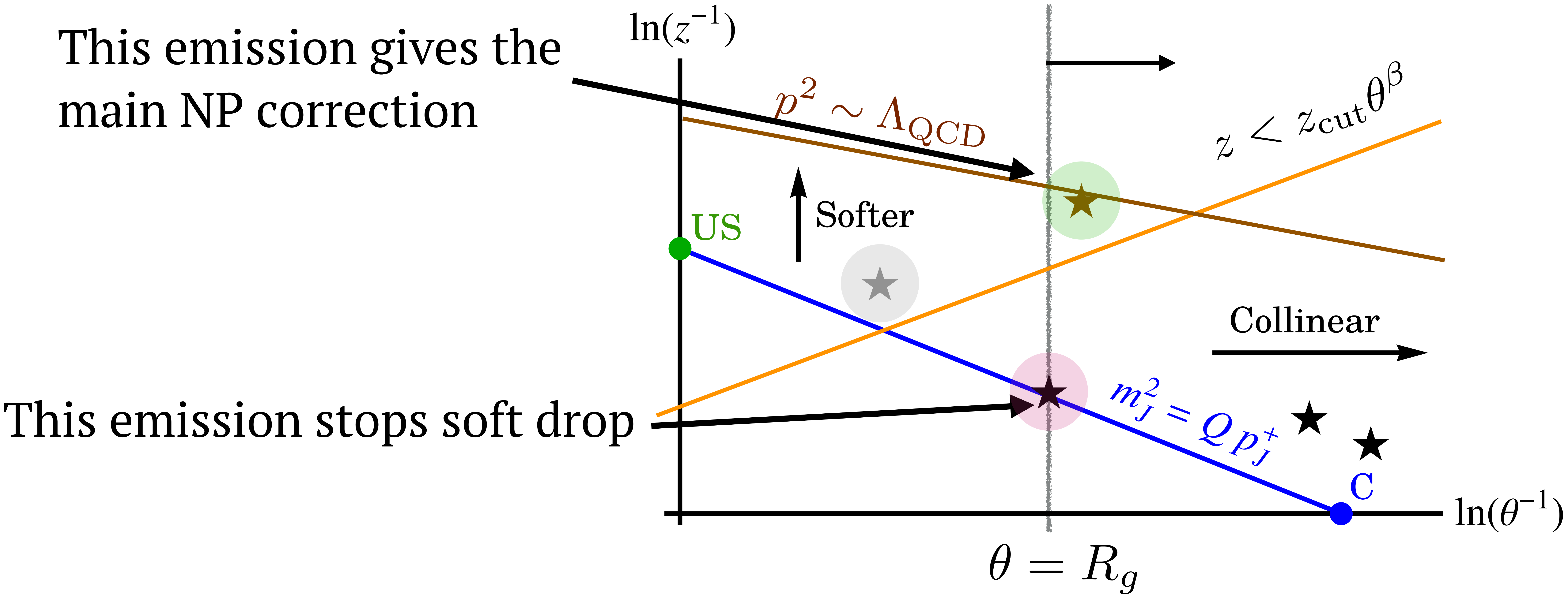


NP Corrections in the Resummation region



- The soft drop stopping emission sets the **groomed jet radius $\mathbf{R_g}$**

NP Corrections in the Resummation region



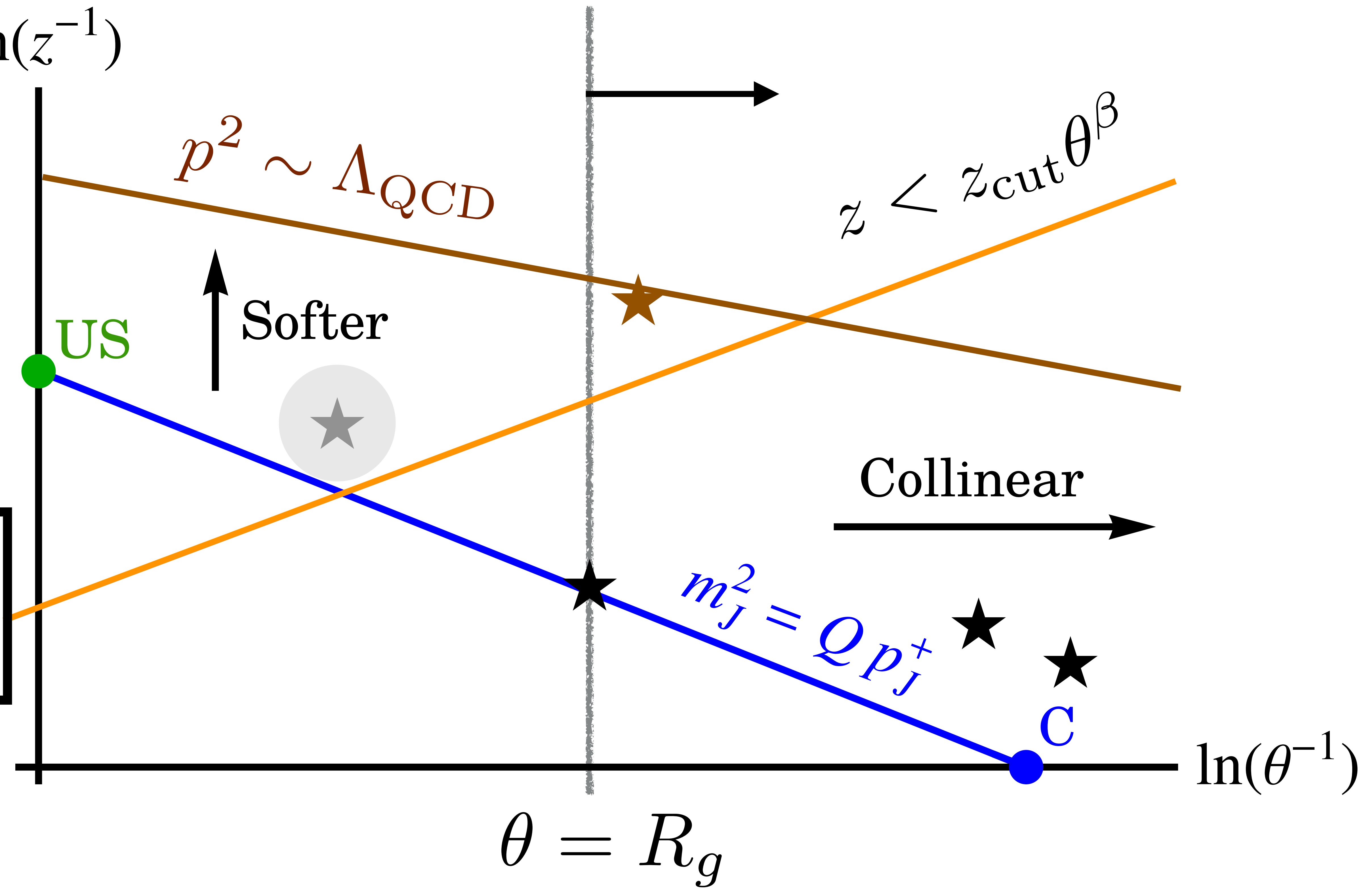
- The soft drop stopping emission sets the **groomed jet radius R_g**
- The leading NP correction comes from emissions at R_g

NP Corrections in the Resummation region

Let us recall our boxed equations:

$$z_{\rm NP} = \frac{\Lambda_{\rm QCD}}{E_J}\frac{1}{\theta_{\rm NP}}$$

$$\left(\Delta m_J^2\right)_{\rm NP} = E_J^2 z_{\rm NP}\theta_{\rm NP}^2 \sim E_J \Lambda_{\rm QCD}\theta_{\rm NP}$$



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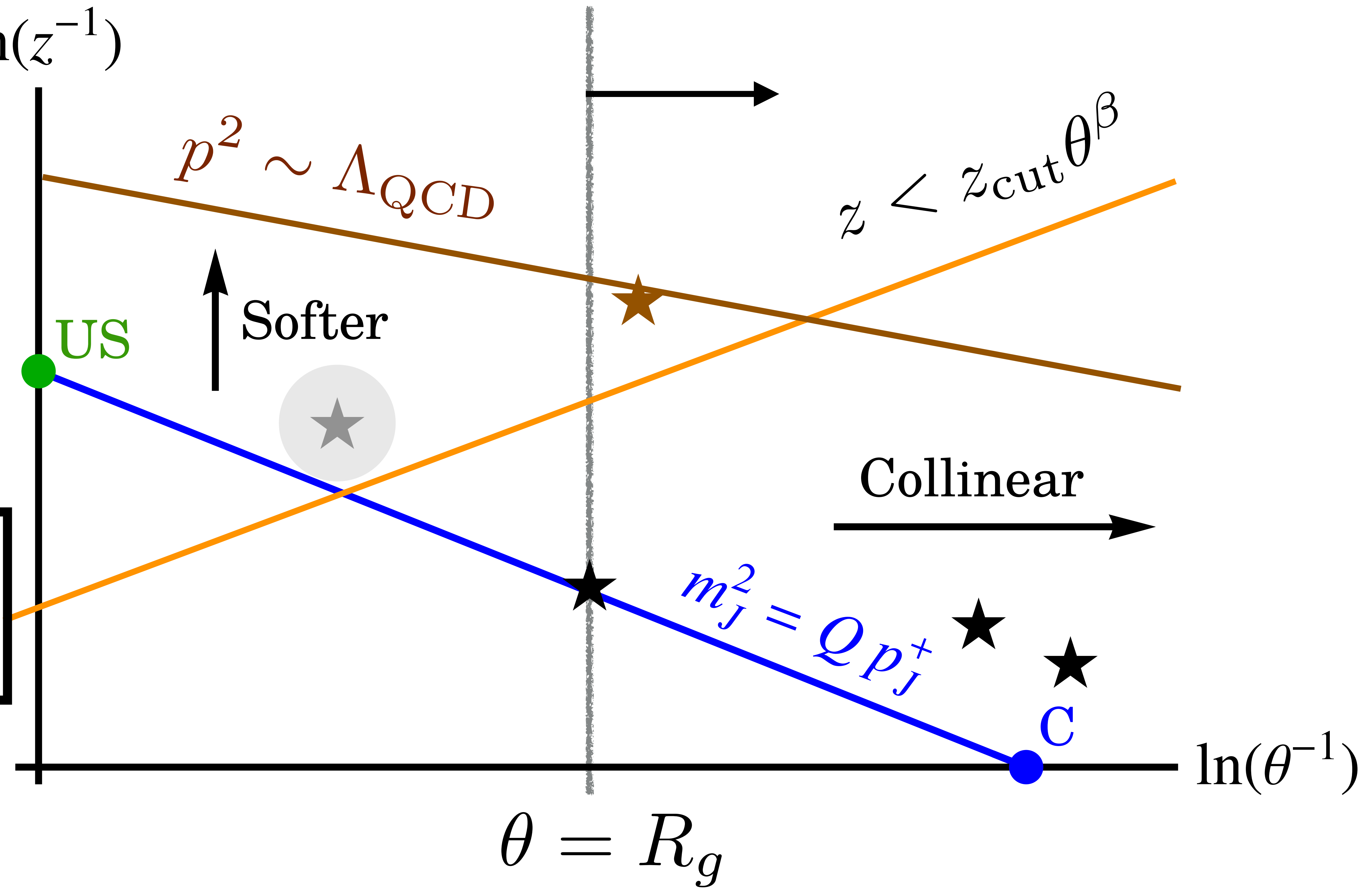


Shift in the groomed jet mass:

$$\left(\Delta m_J^2\right)_{\rm NP} \sim E_J \Lambda_{\rm QCD} R_g$$

The shift in the jet mass is proportional to R_g

Boundary Correction

We have yet another correction in groomed jet mass due to Hadronization

A *barely passing* subjet looses energy and fails

A *barely failing* subjet gains energy and passes

This correction is important at the soft drop threshold:

Changes in energy: $$\Delta z_{\mathrm{NP}} = \frac{\Lambda_{\mathrm{QCD}}}{E_J}\frac{1}{\theta_{\mathrm{NP}}} \sim \frac{\Lambda_{\mathrm{QCD}}}{E_J}\frac{1}{R_g}$$

The boundary correction is inversely proportional to R_g

Both corrections matter

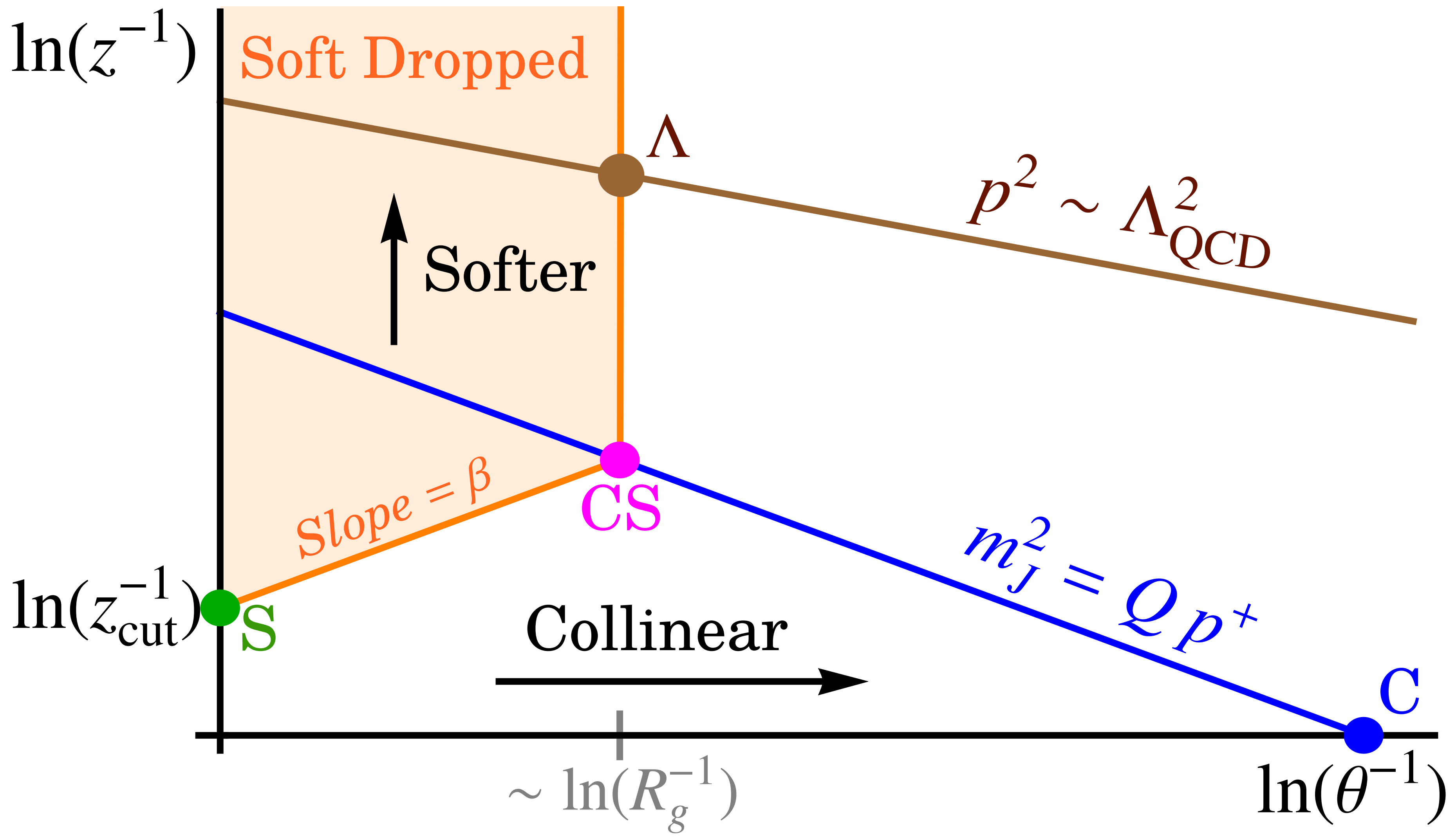
Shift in the groomed jet mass: $\left(\Delta m_J^2\right)_{\text{NP}} \sim E_J \Lambda_{\text{QCD}} R_g$

Changes in energy: $\Delta z_{\text{NP}} = \frac{\Lambda_{\text{QCD}}}{E_J} \frac{1}{\theta_{\text{NP}}} \sim \frac{\Lambda_{\text{QCD}}}{E_J} \frac{1}{R_g}$

Contribution of the stopping subjet: $(m_J^2)_{cs} = E_J^2 z_{cs} R_g^2$

Relative corrections are of the same order:

$$\frac{\Delta z_{\text{NP}}}{z_{cs}} \sim \frac{\left(\Delta m_J^2\right)_{\text{NP}}}{(m_J^2)_{cs}} \sim \frac{\Lambda_{\text{QCD}}}{E_J z_{cs}} \frac{1}{R_g}$$



NP corrections in the resummation region

[Hoang, AP, Mantry, Stewart 2019]

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\circ\!\!\circ}\,\frac{d}{dm_J^2}\bigg(C_1^\kappa(m_J^2,Q,\tilde z_{\rm cut},\beta,R)\,\frac{d\hat\sigma_\kappa}{dm_J^2}\bigg) + \frac{Q\Upsilon_1^\kappa(\beta)}{m_J^2}\,C_2^\kappa(m_J^2,Q,\ \tilde z_{\rm cut},\beta,R)\,\frac{d\hat\sigma_\kappa}{dm_J^2}$$

Shift correction **Boundary correction**

$$\Upsilon_1^\kappa(\beta) = \Upsilon_{1,0}^\kappa + \beta\,\Upsilon_{1,1}^\kappa$$

The coefficients C_1 and C_2 are perturbatively calculable and are related to moments of R_g

$$C_1^\kappa(m_J^2) \sim \left\langle \frac{\theta_{cs}(m_J^2)}{2} \right\rangle\,, \qquad C_2^\kappa(m_J^2) \sim \left\langle \frac{2}{\theta_{cs}(m_J^2)}\,\frac{m_J^2}{Q^2}\,\delta\big(z_{cs} - \tilde z_{\rm cut}\theta_{cs}^\beta\big) \right\rangle\,.$$

$$\big(\Delta m_J^2\big)_{\rm NP} \sim E_J\Lambda_{\rm QCD}R_g \qquad\qquad \Delta z_{\rm NP} \sim \frac{\Lambda_{\rm QCD}}{E_J}\frac{1}{R_g}$$

NP corrections in the resummation region

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\infty}\,\frac{d}{dm_J^2}\bigg(C_1^\kappa(m_J^2, Q, \tilde z_{\rm cut}, \beta, R)\,\frac{d\hat\sigma_\kappa}{dm_J^2}\bigg) + \frac{Q\Upsilon_1^\kappa(\beta)}{m_J^2}\,C_2^\kappa(m_J^2, Q,\ \tilde z_{\rm cut}, \beta, R)\,\frac{d\hat\sigma_\kappa}{dm_J^2}$$

Shift correction **Boundary correction**

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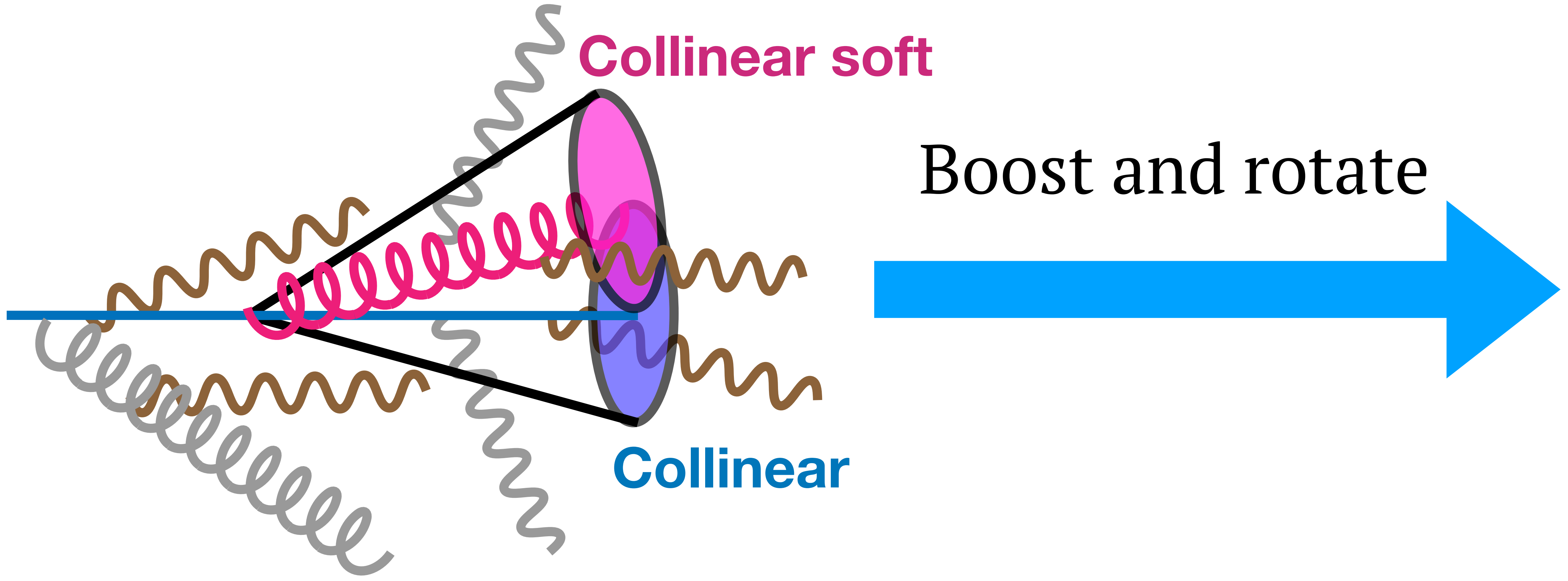
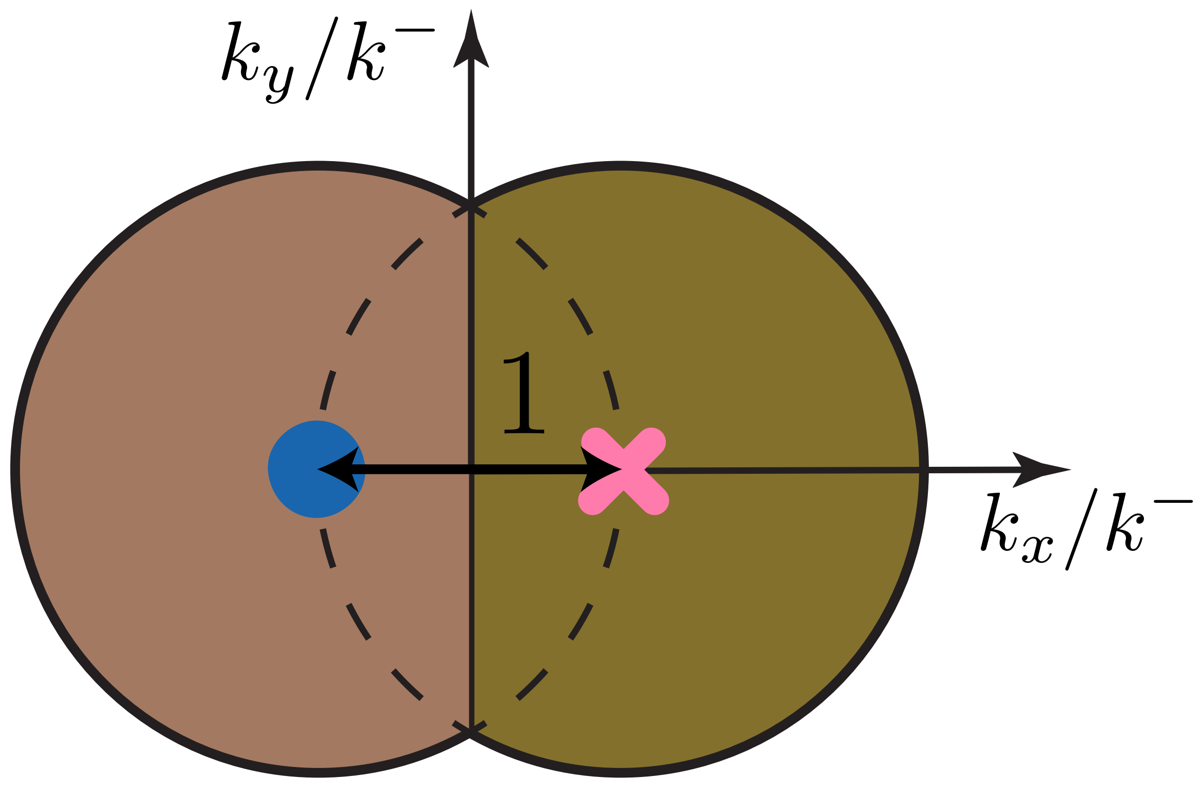
The 3 Nonperturbative parameters are **universal** and do not depend on anything but the NP scale (and whether we have a q or g jet):

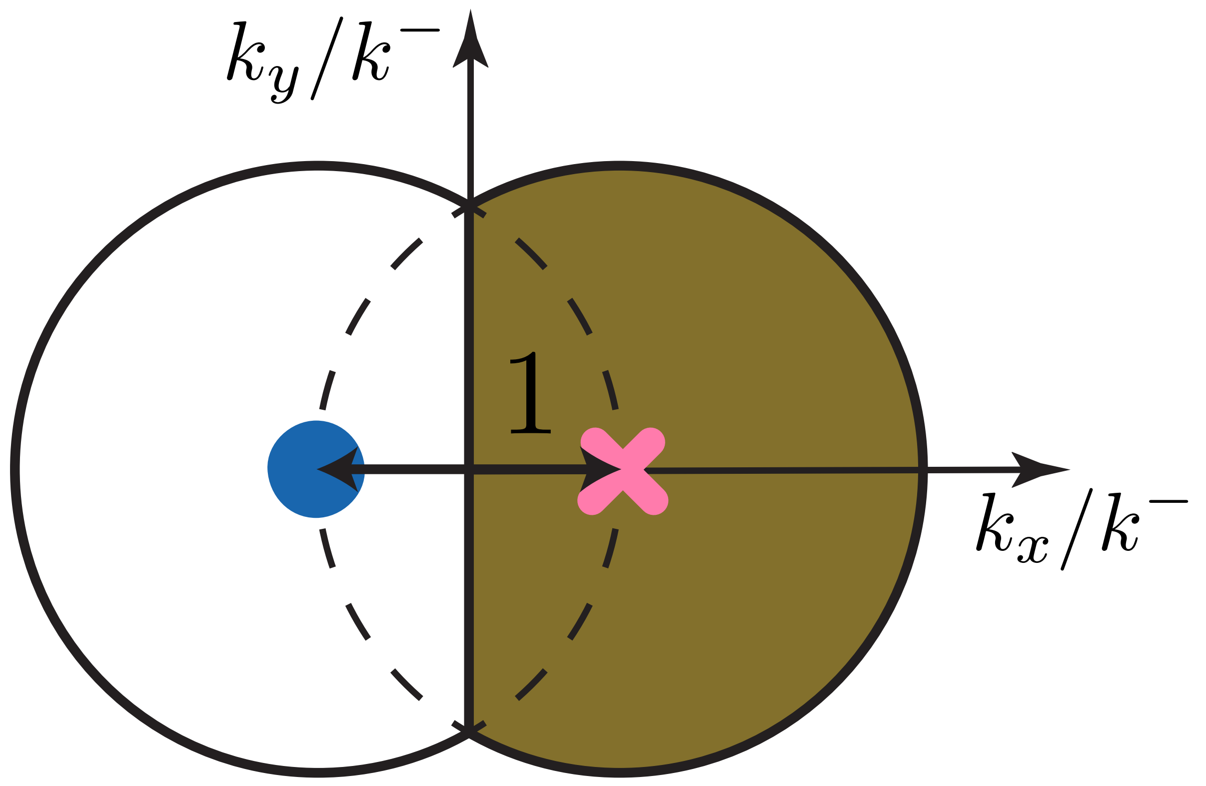
$$\Omega_{1\kappa}^{\infty} \sim \Upsilon_{1,0}^\kappa \sim \Upsilon_{1,1}^\kappa \sim \Lambda_{\rm QCD}$$

Universality of the NP corrections

By applying a boost related to the momentum of the stopping emission and an azimuthal rotation we show that a **universal geometry** emerges at LL accuracy:







The k coordinates are momentum of the NP emissions in the boosted frame:

$$q_i^+ = \frac{\theta_{cs}}{2}\,k_i^+ = \sqrt{\frac{p_{cs}^+}{p_{cs}^-}}\,k_i^+, \qquad q_i^- = \frac{2}{\theta_{cs}}\,k_i^- = \sqrt{\frac{p_{cs}^-}{p_{cs}^+}}\,k_i^-\,, \qquad q_{i\perp} = k_{i\perp}\,, \qquad \phi_{q_i} = \phi_{k_i} + \phi_{cs}$$

Universality of the NP corrections

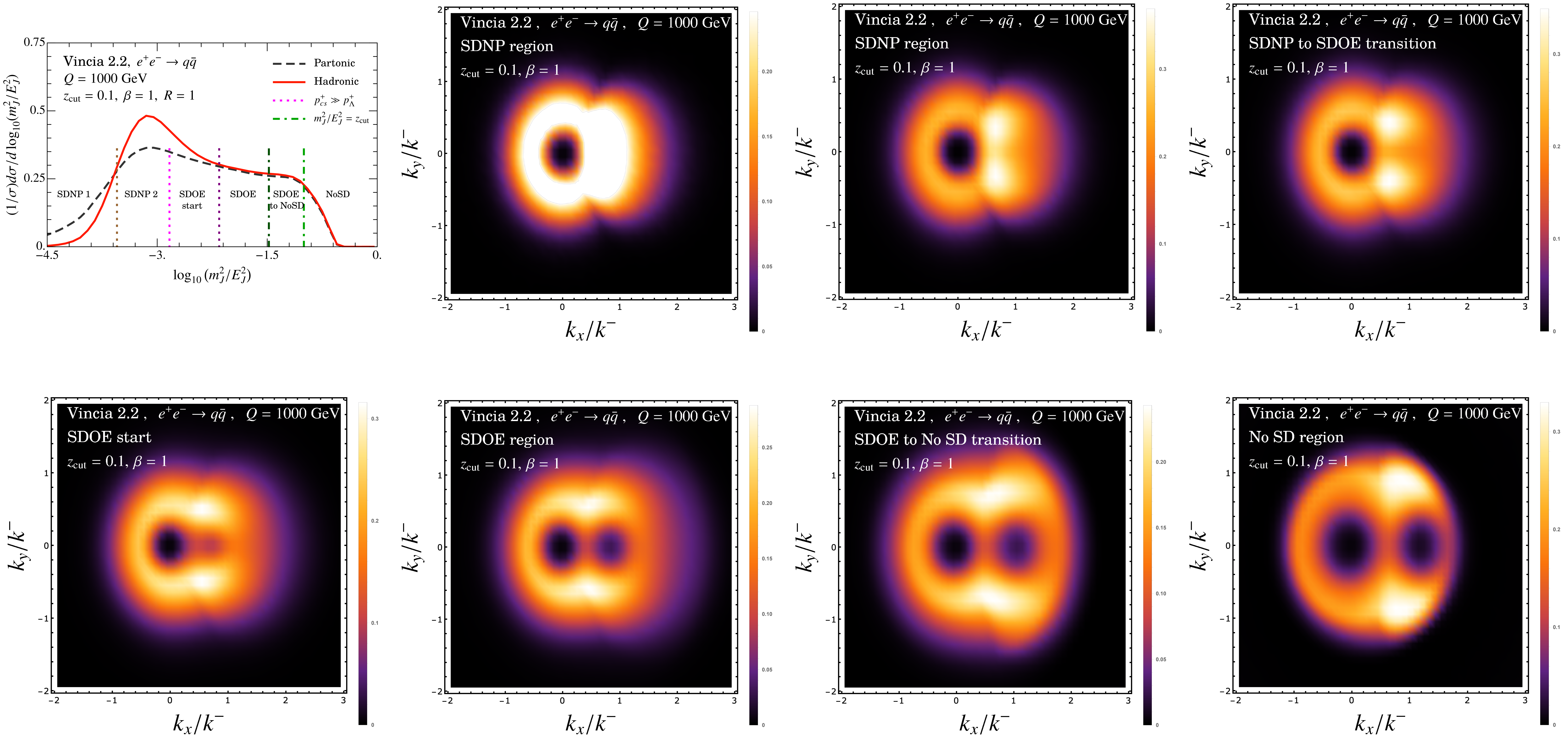
By applying a boost related to the momentum of the stopping emission and an azimuthal rotation we show that a **universal geometry** emerges at LL accuracy:

In the boosted frame the **catchment area of NP particles** is independent of R_g

$$\Omega^{\circledcirc}_{1\kappa} \equiv \int \frac{d^d k}{(2\pi)^d}\, k^+\, \overline{\Theta}^{\circledcirc}_{\rm NP}\left(\frac{k_\perp}{k^-},\, 1,\, \phi_k\right) \tilde{F}_\kappa(k^\mu)$$

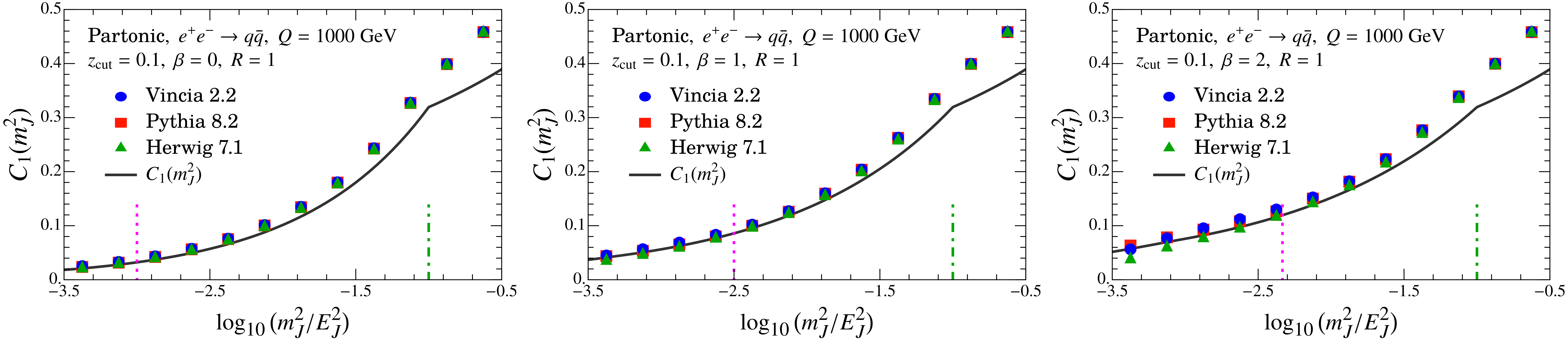
Visualizing distribution of NP emissions

The expected geometry emerges in the resummation region

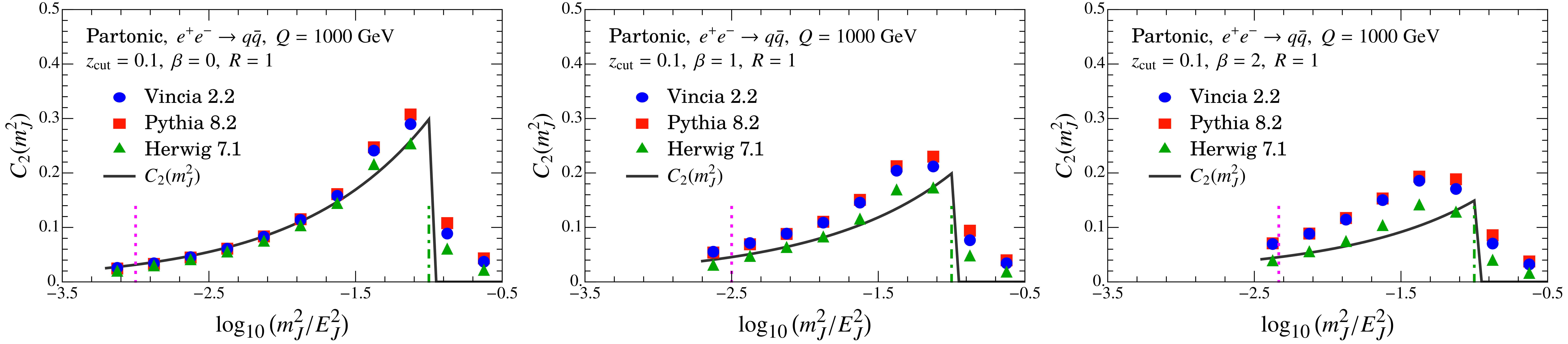


Shift and Boundary Wilson Coefficients

Coefficient for shift correction:

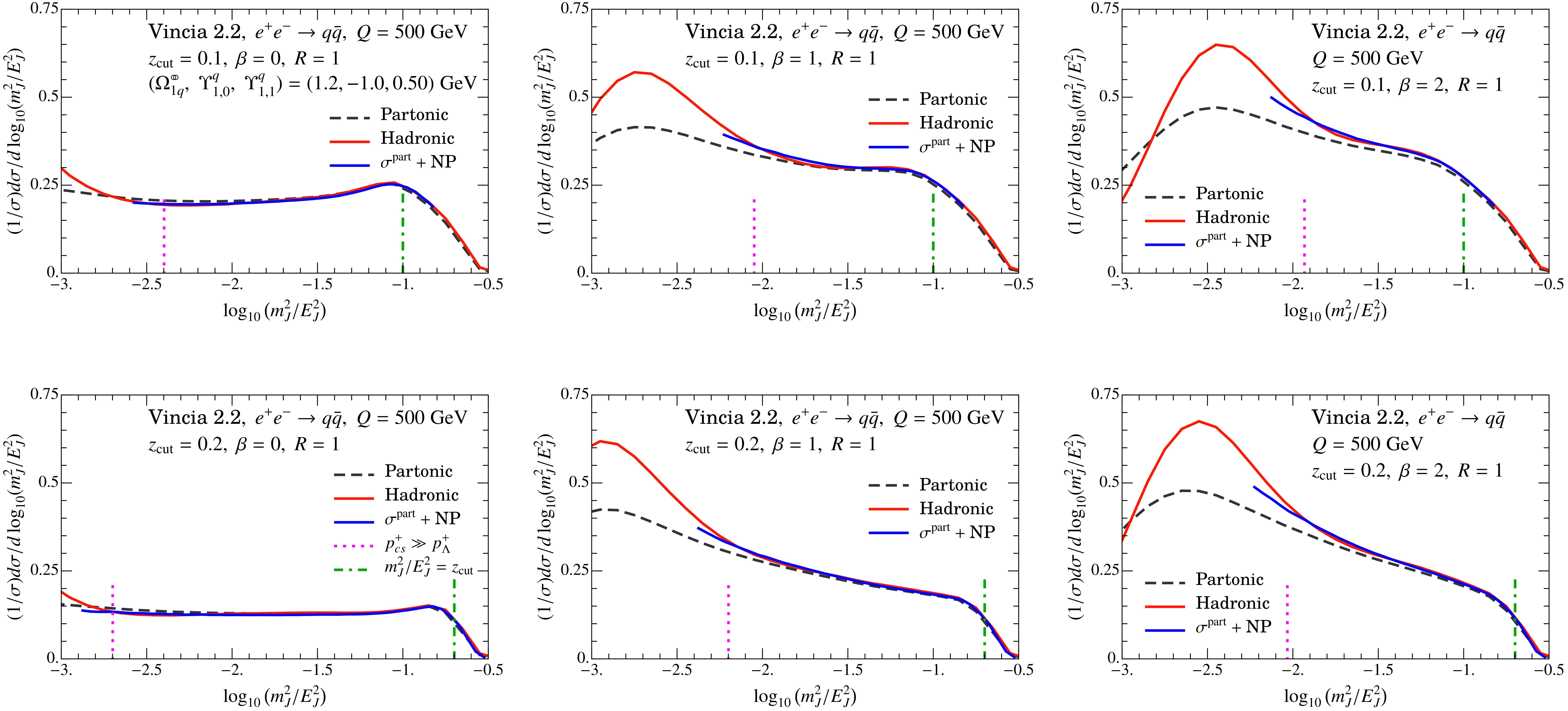


Coefficient for boundary correction:



Testing with Monte Carlo Hadronization models

3 NP parameters fit well an entire grid of jet mass distributions for various Q, zcut, β



Recap

- We can get a lot of milage out of a simple Leading log analysis
- Groomed jet mass receives NP corrections at much smaller jet masses (compared to plain jet mass)
- Two main NP corrections in the resummation region: Shift and Boundary
  - Involves perturbatively calculable coefficients
  - 3 Universal NP parameters

So what’s next?

- Why jets?
- Theory overview
- New results

NP corrections in the resummation region

We had derived the NP factorization in the strong ordering (LL) limit

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma^\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\varpi}\,\frac{d}{dm_J^2}\bigg(C_1^\kappa(m_J^2, Q, z_{\rm cut}, \beta, R)\,\frac{d\hat\sigma^\kappa}{dm_J^2}\bigg)$$

$$+\,\frac{Q\big(\Upsilon_{1,0}^\kappa + \beta\,\Upsilon_{1,1}^\kappa\big)}{m_J^2}\,C_2^\kappa(m_J^2, Q,\; z_{\rm cut}, \beta, R)\,\frac{d\hat\sigma^\kappa}{dm_J^2} + \ldots$$

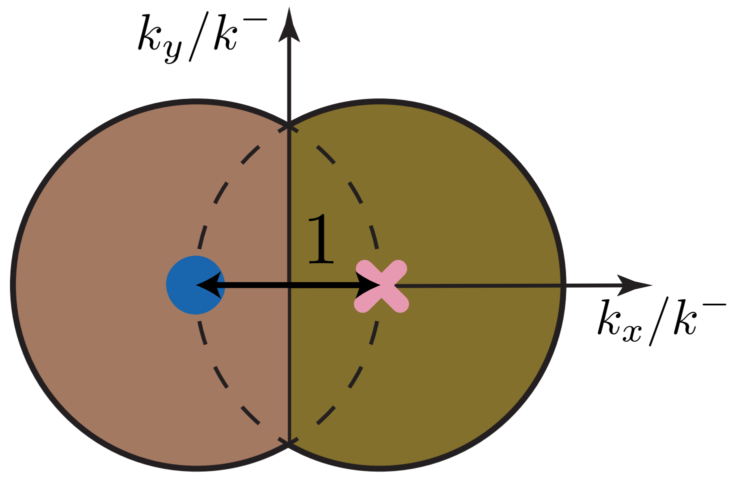
NP corrections in the resummation region

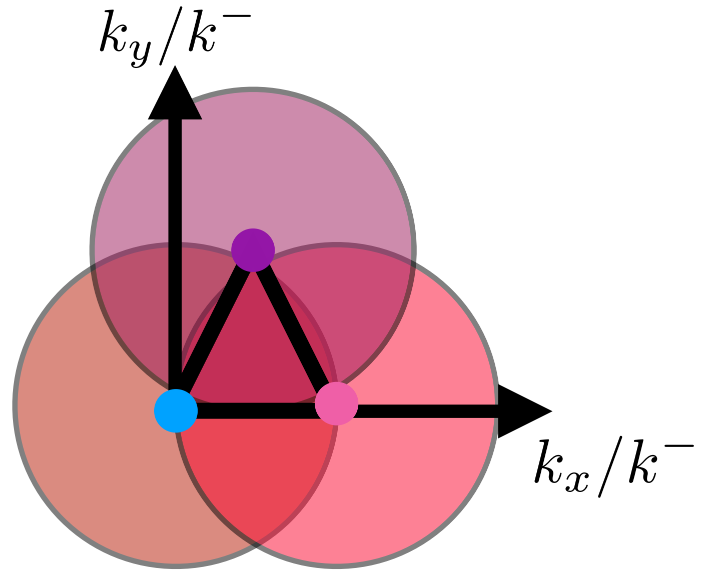
We had derived the NP factorization in the strong ordering (LL) limit

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma^\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\circledcirc}\,\frac{d}{dm_J^2}\bigg(C_1^\kappa(m_J^2, Q, z_{\rm cut}, \beta, R)\,\frac{d\hat\sigma^\kappa}{dm_J^2}\bigg)$$

$$+\,\frac{Q\big(\Upsilon_{1,0}^\kappa + \beta\,\Upsilon_{1,1}^\kappa\big)}{m_J^2}\,C_2^\kappa(m_J^2, Q,\, z_{\rm cut}, \beta, R)\,\frac{d\hat\sigma^\kappa}{dm_J^2} + \ldots$$

We expect:

NP corrections = $C_i(m_J^2)\times$ 

$+\;(\ldots)\otimes$ 

$+\;\cdots$

LL, NLL, …

LL

NLL

While a higher order NP factorization is lacking we can still improve the LL perturbative predictions of C_1 and C_2

Higher order resummation of C1 and C2

[AP, Stewart, Vaidya, Zoppi]

Consider inclusive jet measurement: $$\frac{d\sigma^{\rm had}}{dm_J^2} = \sum_{\kappa=q,g} N_\kappa(\Phi_J, R, z_{\rm cut}, \beta)\frac{d\sigma_\kappa^{\rm had}}{dm_J^2}$$

Calculate these moments starting from the double differential cross section:

$$M_1^\kappa(m_J^2) \equiv \Big(\frac{d\hat\sigma^\kappa}{dm_J^2}\Big)^{-1}\int d\theta_g \frac{\theta_g}{2}\frac{d^2\hat\sigma^\kappa}{dm_J^2 d\theta_g}\,,$$

$$M_{-1}^{\kappa\circledcirc}(m_J^2) \equiv \Big(N_\kappa(\Phi_J, R, z_{\rm cut}, \beta)\frac{d\hat\sigma^\kappa}{dm_J^2}\Big)^{-1}\int d\theta_g \frac{m_J^2}{Q^2}\frac{2}{\theta_g}\frac{d}{d\varepsilon}\Big[N_\kappa(\Phi_J, R, z_{\rm cut}, \beta, \varepsilon)\frac{d^2\hat\sigma^\kappa(\varepsilon)}{dm_J^2 d\theta_g}\Big]\Big|_{\varepsilon\to 0}$$

By calculating Next-to-leading-log double differential cross section we can improve C1 and C2 predictions

$$C_1 \simeq M_1^\kappa \text{ and } C_2 \simeq M_{-1}^{\kappa\circledcirc}$$

To probe the effects at the boundary of soft drop we can shift the constraint slightly and expand

$$\overline{\Theta}_{\rm sd} = \Theta(z - z_{\rm cut}\theta_g^\beta) \to \overline{\Theta}_{\rm sd}(\varepsilon) = \Theta(z - z_{\rm cut}\theta_g^\beta + \varepsilon)$$

Higher order resummation

We only looked at the LL cross section, but there are more terms suppressed by powers of α_s

Log of dσ:

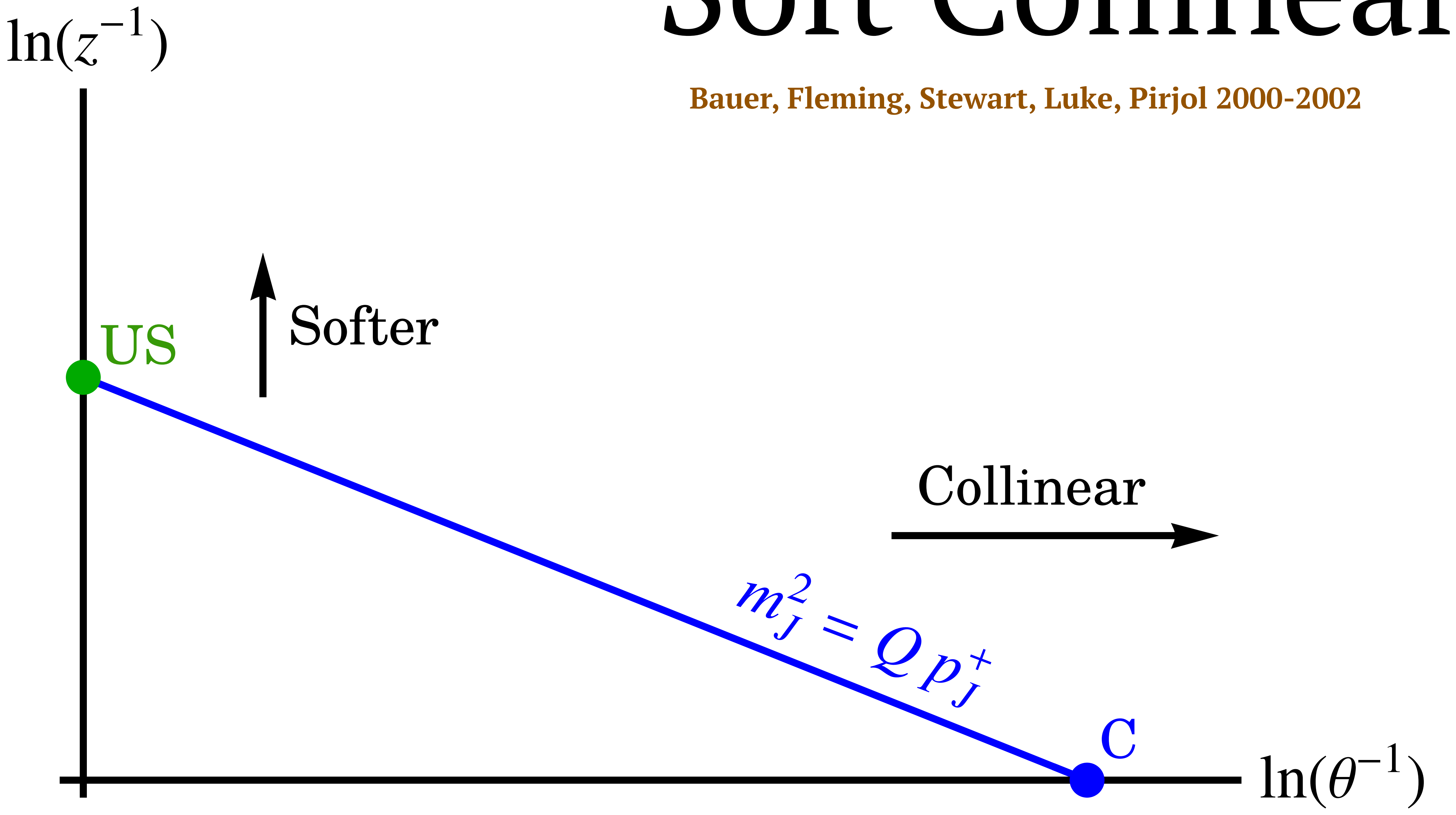
$$\ln\left[\frac{\mathrm{d}\tilde{\sigma}_s}{\mathrm{d}y}\right] \sim \left[L\sum_{k=1}^{\infty}(\alpha_s L)^k\right]_{\mathrm{LL}} + \left[\sum_{k=1}^{\infty}(\alpha_s L)^k\right]_{\mathrm{NLL}} + \left[\alpha_s\sum_{k=0}^{\infty}(\alpha_s L)^k\right]_{\mathrm{NNLL}} + \left[\alpha_s^2\sum_{k=0}^{\infty}(\alpha_s L)^k\right]_{\mathrm{N^3LL}}$$

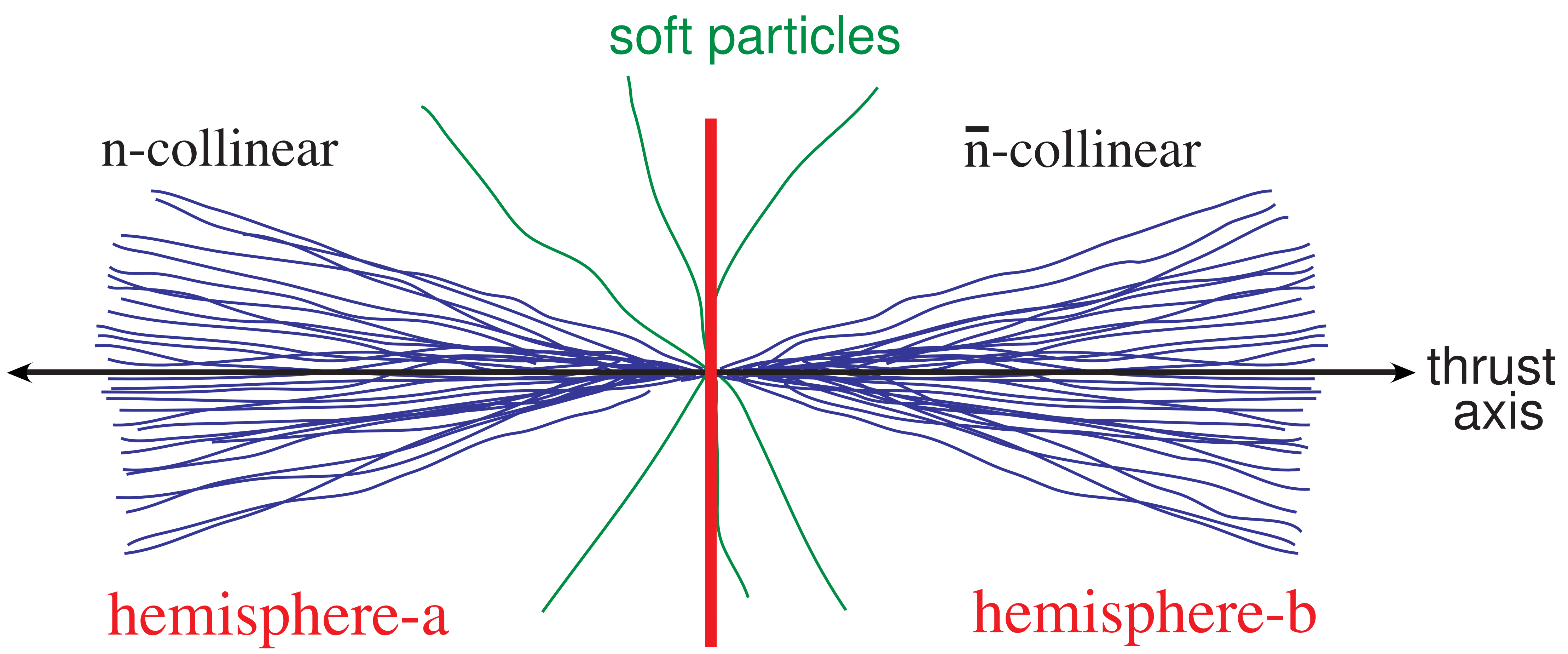
Improving logarithmic accuracy is a challenging task and various tools have been developed over the last 4 decades.

- Start from an ordered chain of emissions and start including corrections there (running coupling, relaxing strong ordering, correlated emissions, …) Catani et al. Nucl.Phys. B407 (1993) 3-42], see also [Luisoni Marzani, 1505.0408]
- Use effective field theory methods to resum towers of logarithms

Soft Collinear Effective Theory

Bauer, Fleming, Stewart, Luke, Pirjol 2000-2002



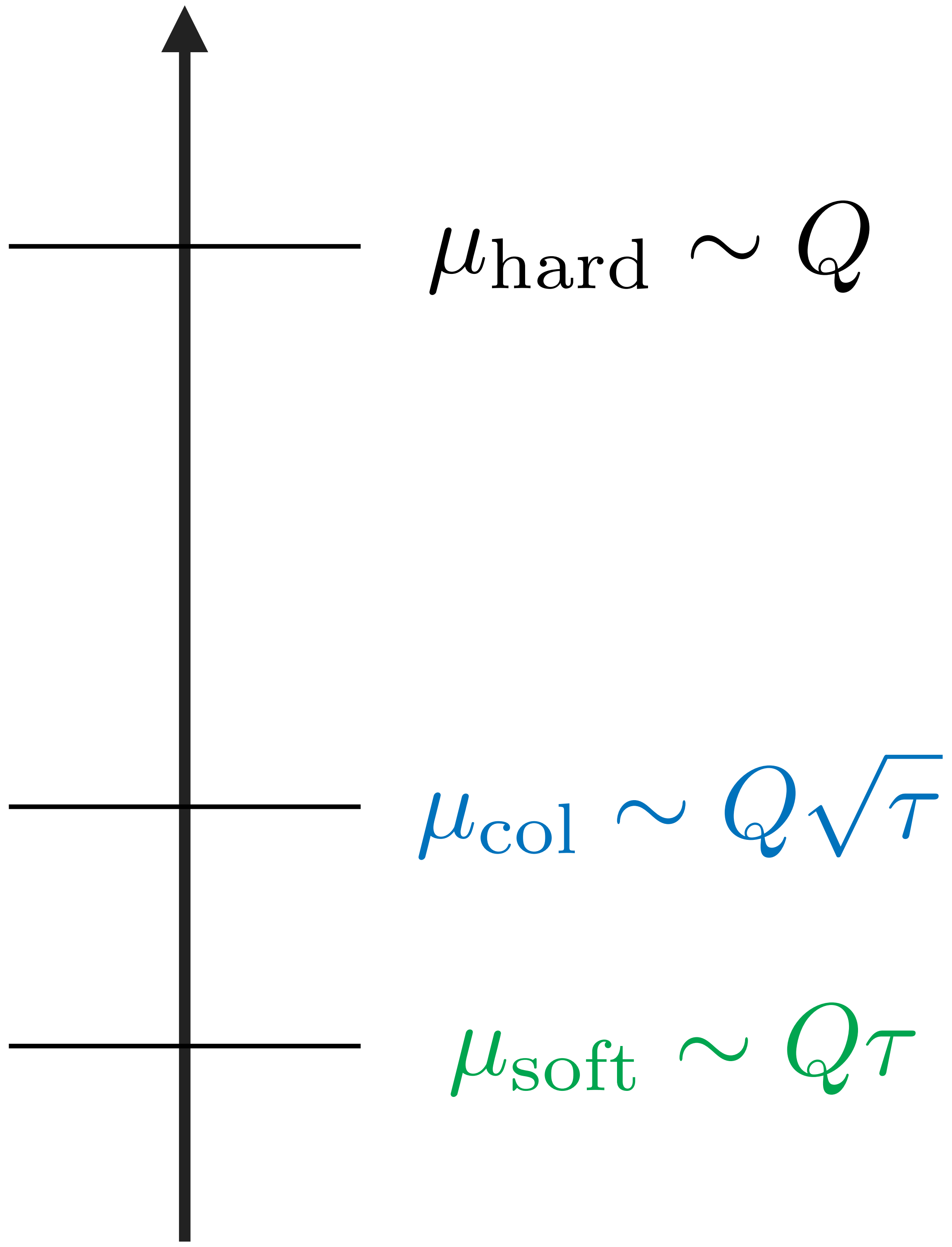


In the region of small τ (or jet mass) the contributions from the soft and collinear particles factorize

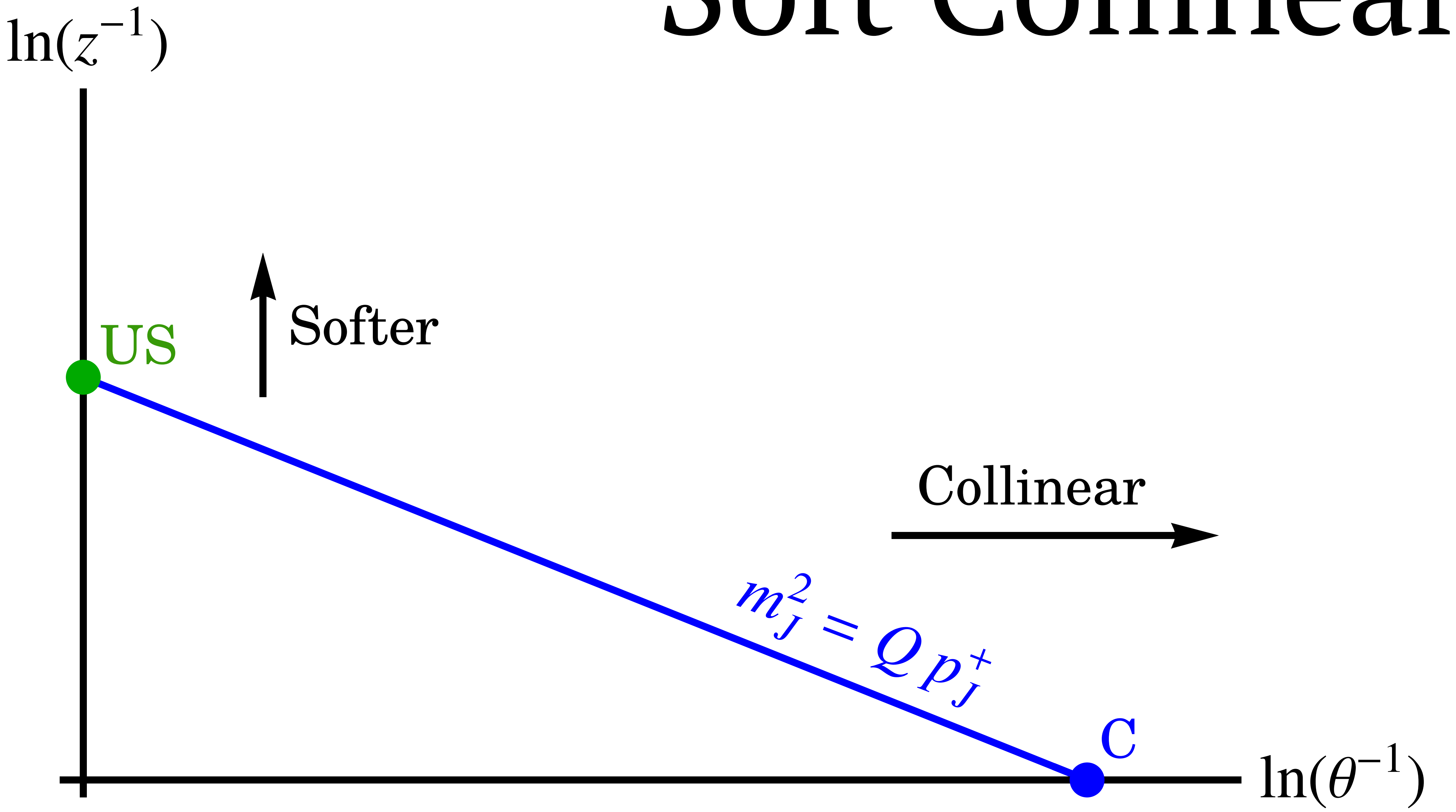
$$\tau \sim \frac{m_J^2}{E_J^2} \sim z\theta^2$$

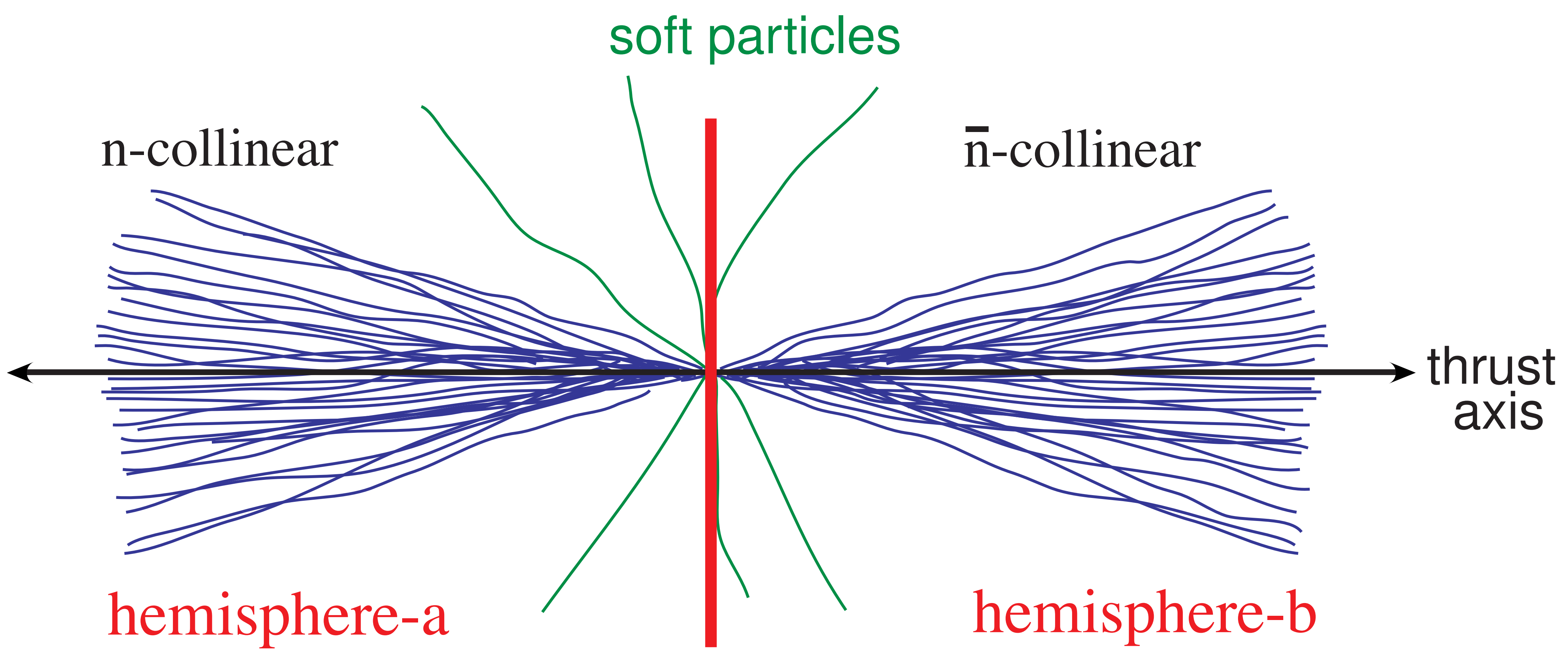
$$E_{\rm soft} \sim Q\tau,\ \theta_{\rm soft} \sim 1$$

$$E_{\rm col} \sim Q,\ \theta_{\rm col} \sim \sqrt{\tau}$$



Soft Collinear Effective Theory

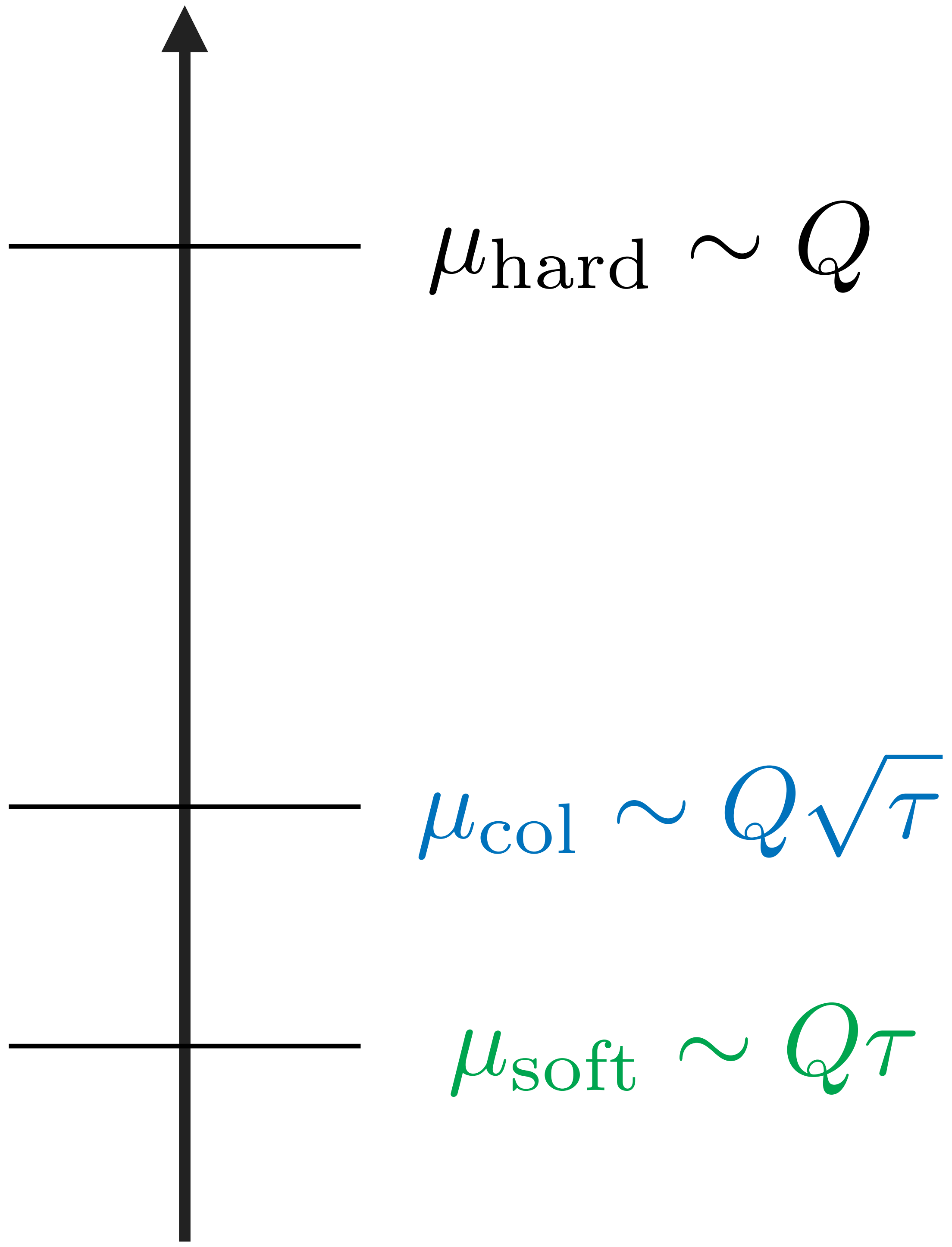




For a fairly large class of observables rigorous factorization theories can be proved:

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = H(Q^2,\mu)\int dp_L^2\, dp_R^2\, dk\, J(p_L^2,\mu)\, J(p_R^2,\mu)\, S_T(k,\mu)\, \delta\left(\tau - \frac{p_L^2+p_R^2}{Q^2} - \frac{k}{Q}\right)$$

This formula is composed of matrix elements calculated with modes at one specific energy

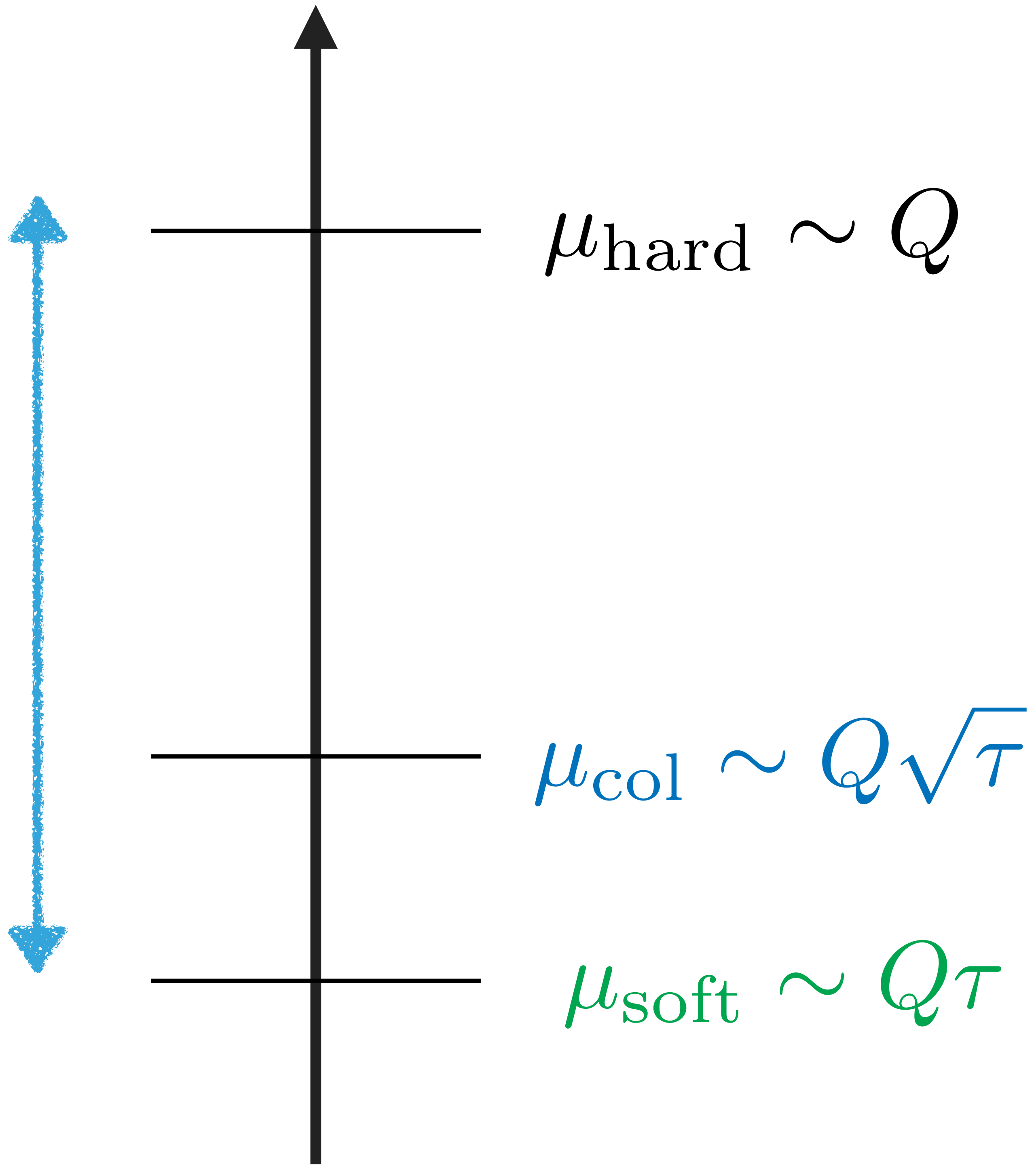


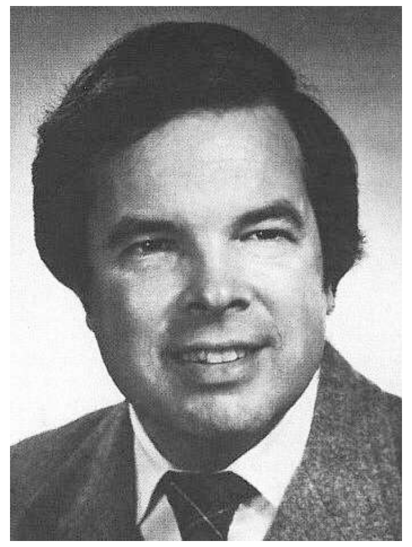
Renormalization group evolution

Effective Field theory methods employ renormalization group methods to resum logs

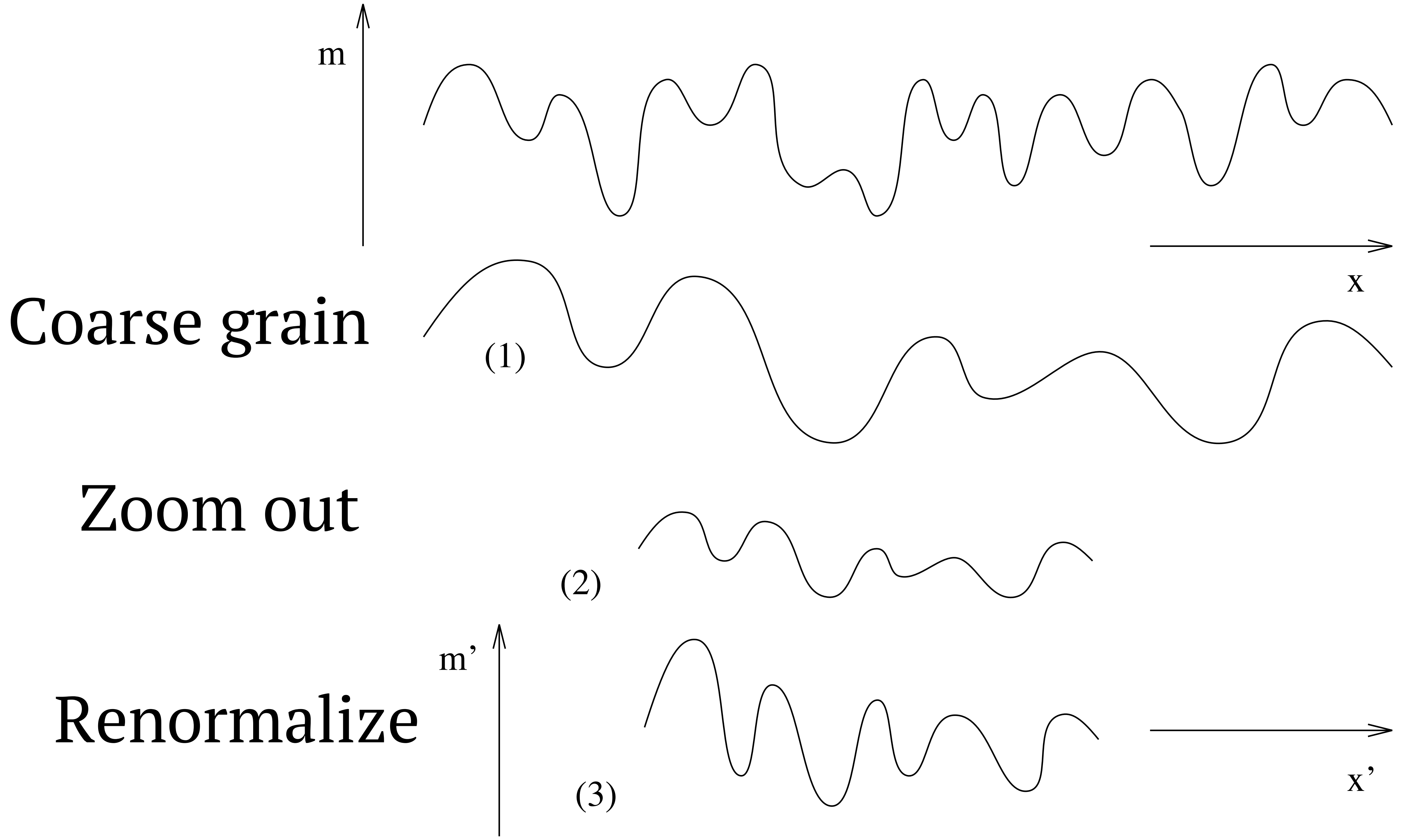
Different matrix elements describe physics at widely separated energy scales

Connect physics at these scales by RG running





Kenneth G. Wilson



Kadanoff's renormalization procedure

[Taken from Ben Simons lecture notes, University of Cambridge]

Renormalization group evolution

Effective Field theory methods employ renormalization group methods to resum logs

RGE for the hard function:
$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \log\big[H_Q(Q,\mu)\big] = \Gamma_{H_Q}[\alpha_s] \log\left(\frac{\mu}{Q}\right) + \gamma_{H_Q}[\alpha_s]$$

$$\Gamma_{H_Q}[\alpha_s] = -4\frac{\alpha_s C_F}{\pi} + \dots$$

LL solution: $H_Q(Q,\mu) = H_Q(Q,Q)\exp\left[-\frac{\alpha_s(Q)C_F}{2\pi}\log\left(\frac{\mu^2}{Q^2}\right) + \dots\right]$

Compare this with our previous LL estimate with fixed coupling:

$$P\left(x < \frac{m_J^2}{E_J^2}\right) = \exp\left[-\frac{\alpha_s C_F}{2\pi}\log^2\left(\frac{m_J^2}{E_J^2}\right)\right]$$

The mJ dependent logs are provided by the combination of the jet and the soft function.

EFT modes for groomed jet mass

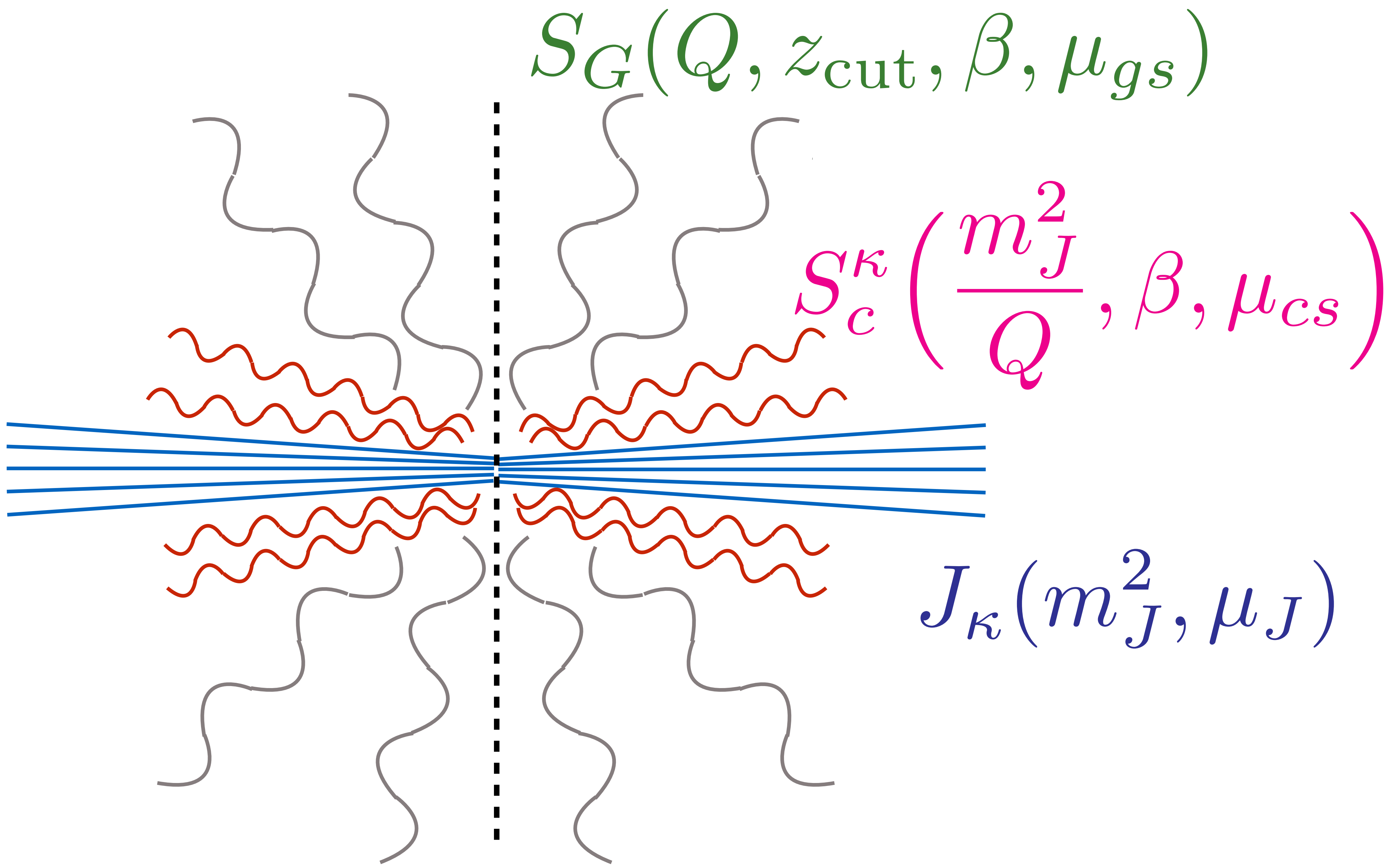
Factorization formula for groomed jet mass

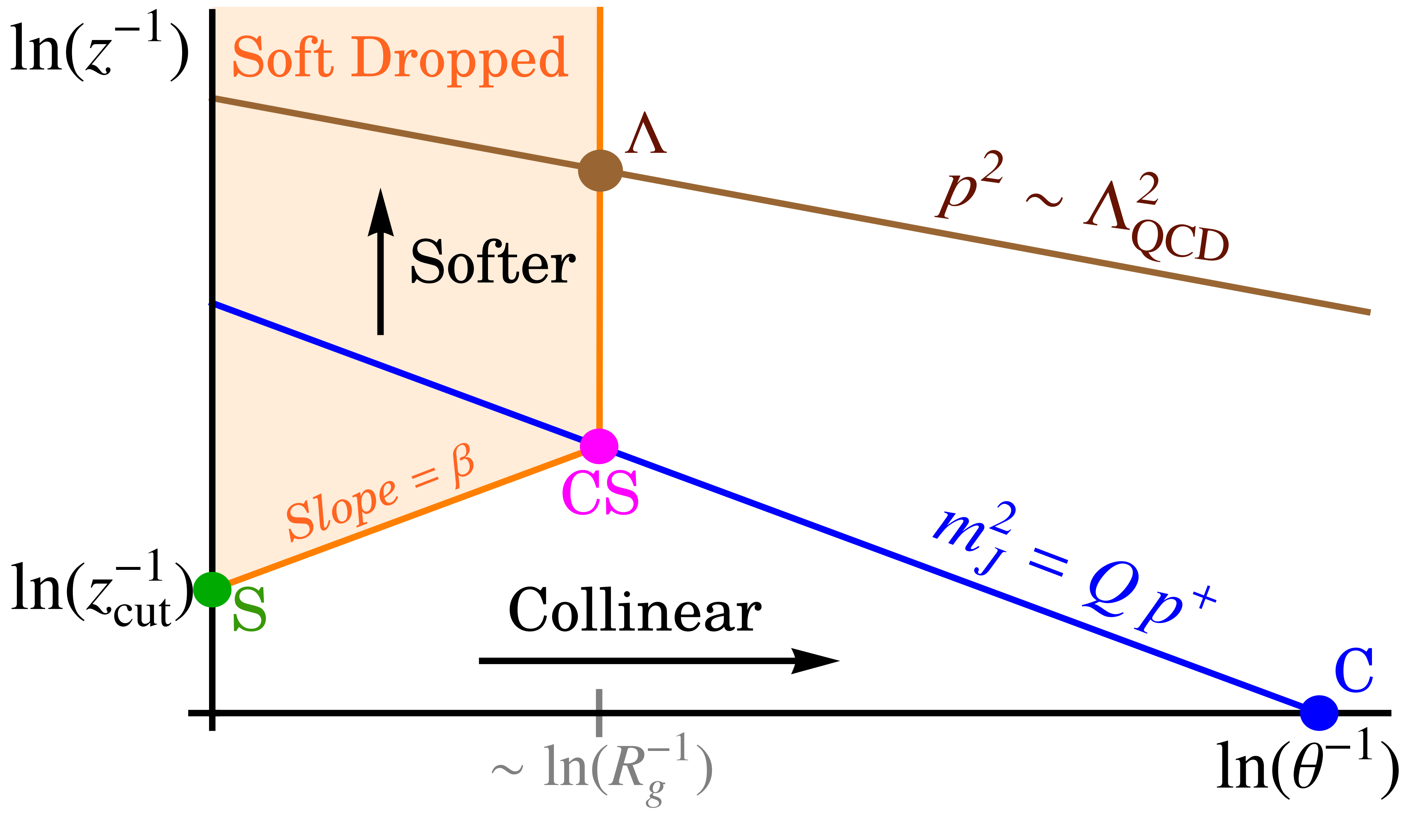
Frye, Larkoski, Schwartz, Yan 2016

$$\frac{d\hat{\sigma}}{dm_J^2 d\Phi_J} = \sum_{\kappa=q,g} N_\kappa(\Phi_J, R, z_{\rm cut}, \beta, \mu_h, \mu_{gs})\, U_{S_G}(Q_{\rm cut}, \mu_{gs}, \mu_{cs})\, Q_{\rm cut}^{\frac{1}{1+\beta}} \int d\ell^+ ds\, J_\kappa\big(m_J^2 - s,\, \mu_J\big)$$

$$\times\, U_J(s - Q\ell^+, \mu_J, \mu_{cs})\, S_c^\kappa\Big[\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu_{cs}\Big]\,,$$

Distinguish groomed vs. kept soft radiation:





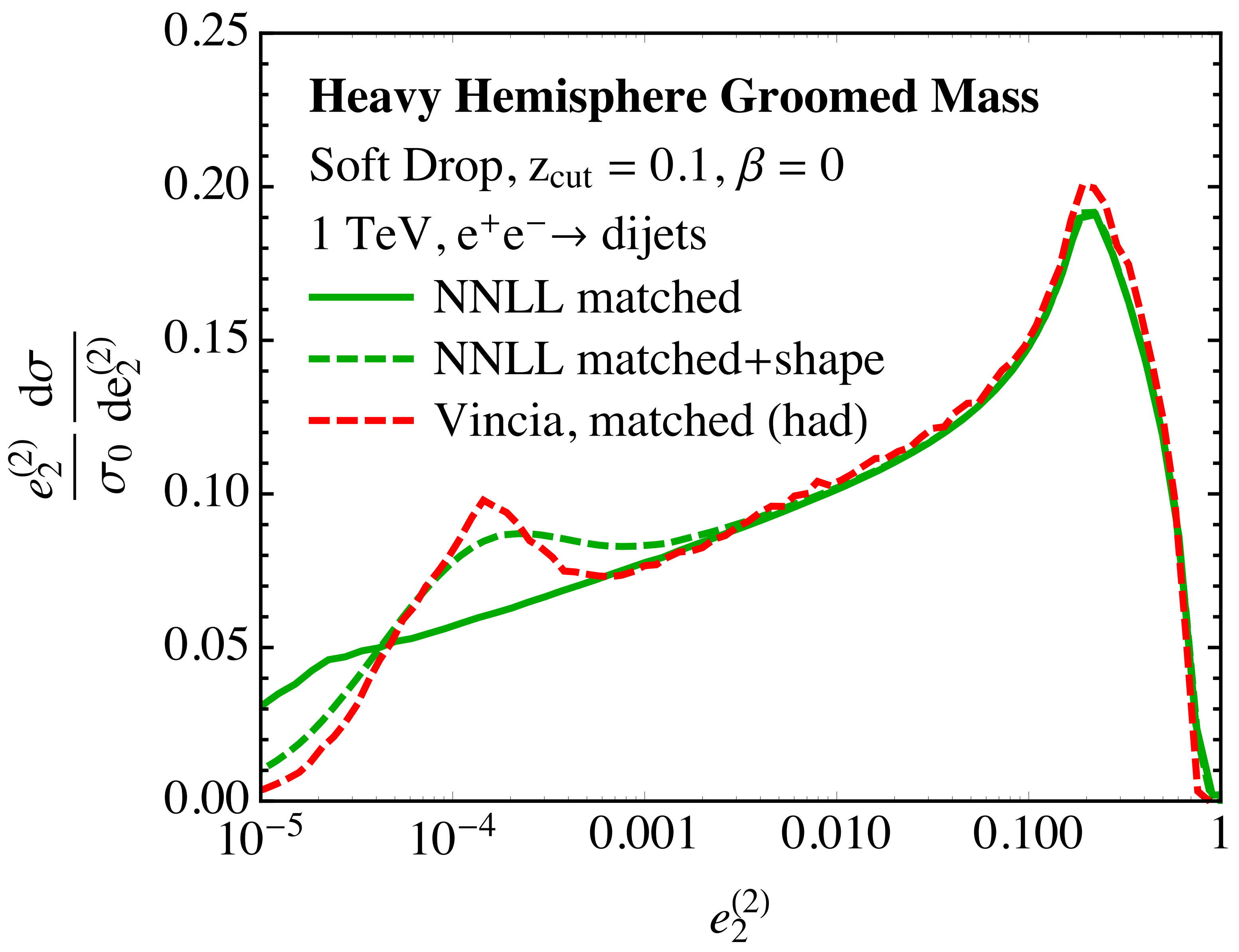
EFT modes for groomed jet mass

Factorization formula for groomed jet mass

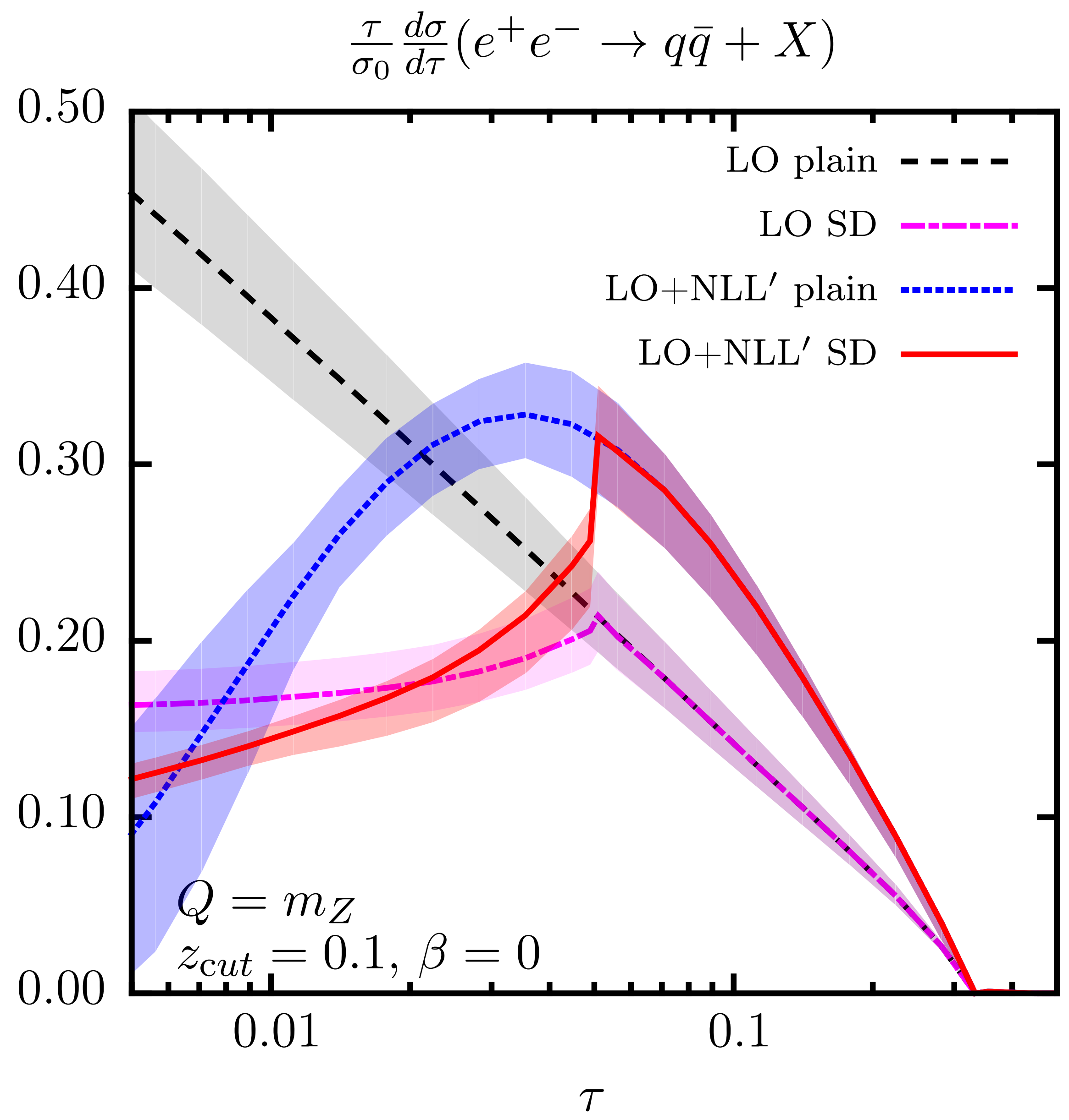
$$\frac{d\hat{\sigma}}{dm_J^2 d\Phi_J} = \sum_{\kappa=q,g} N_\kappa(\Phi_J, R, z_{\rm cut}, \beta, \mu_h, \mu_{gs})\, U_{S_G}(Q_{\rm cut}, \mu_{gs}, \mu_{cs})\, Q_{\rm cut}^{\frac{1}{1+\beta}} \int d\ell^+ ds\, J_\kappa(m_J^2 - s, \mu_J)$$
$$\times\, U_J(s - Q\ell^+, \mu_J, \mu_{cs})\, S_c^\kappa\left[\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu_{cs}\right],$$

N(N)LL resummation for soft drop observables:

Frye, Larkoski, Schwartz, Yan 2016



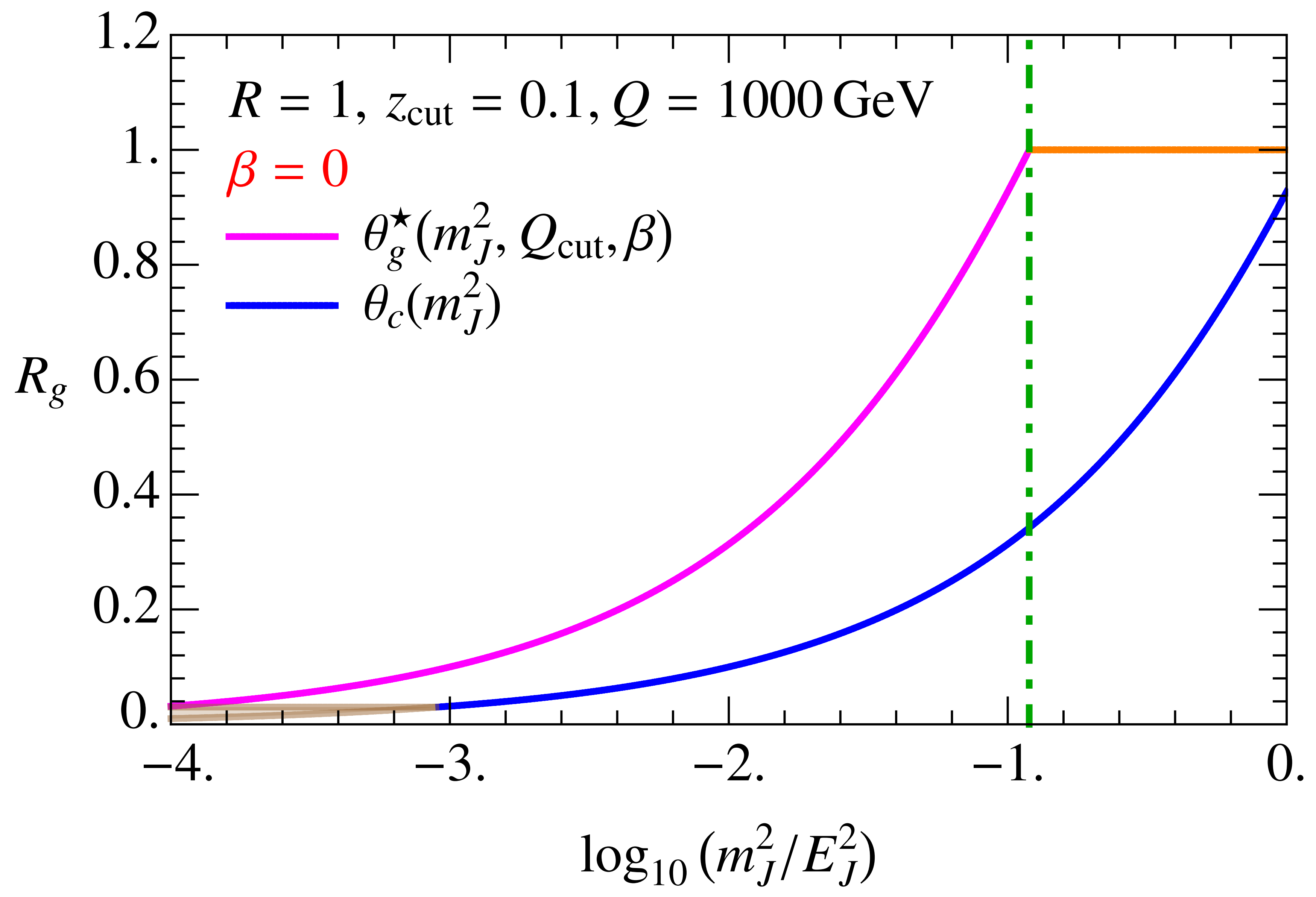
Baron et al. 1803.04719

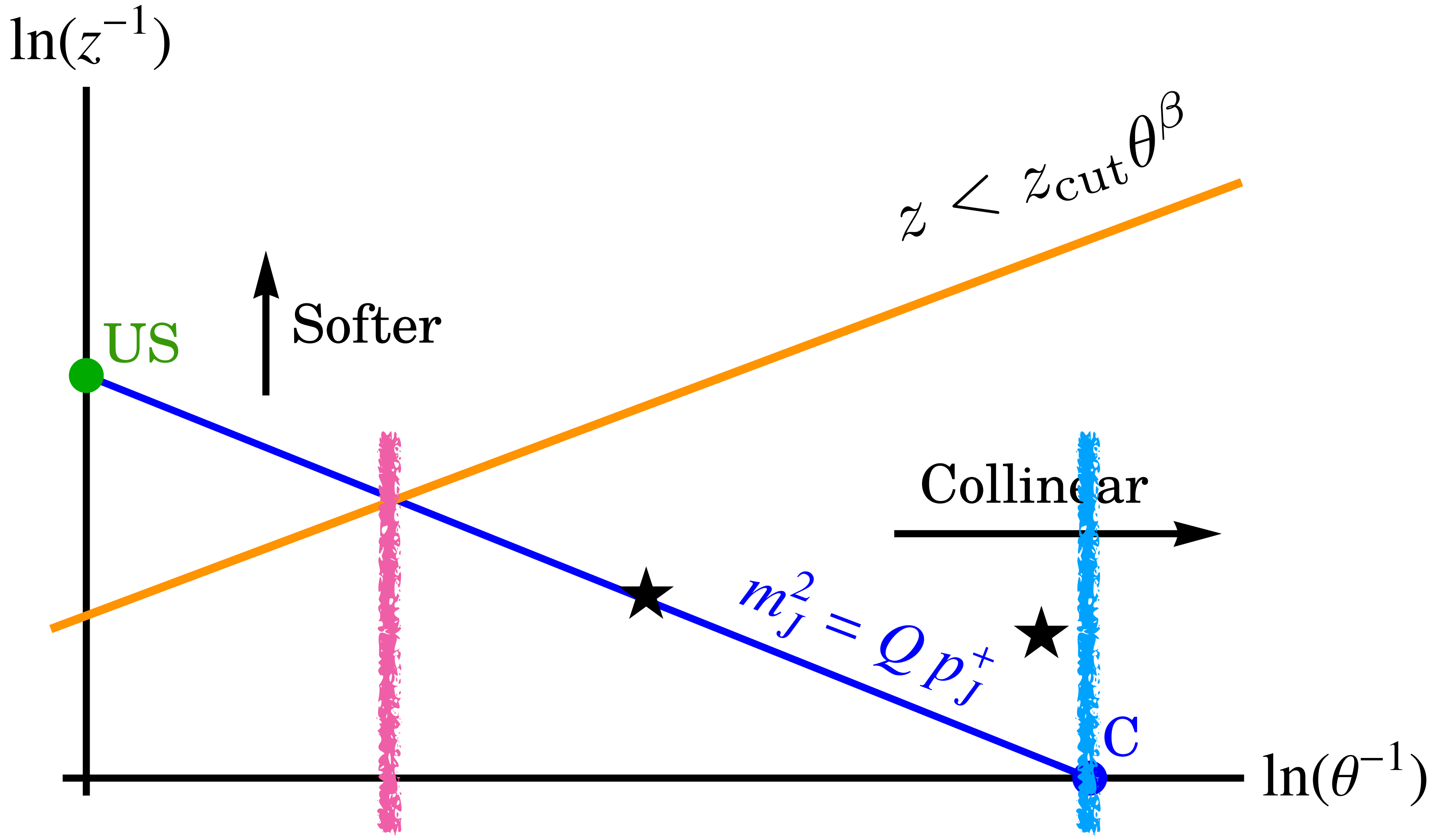


See also Larkoski, Moult, Neill 2017; Lee, Shrivastava, Vaidya 2019; Kang, Lee, Liu, Ringer 2018, 2019; Anderle et. al. 2007.10355

Including an additional R_g measurement

[AP, Stewart, Vaidya, Zoppi]

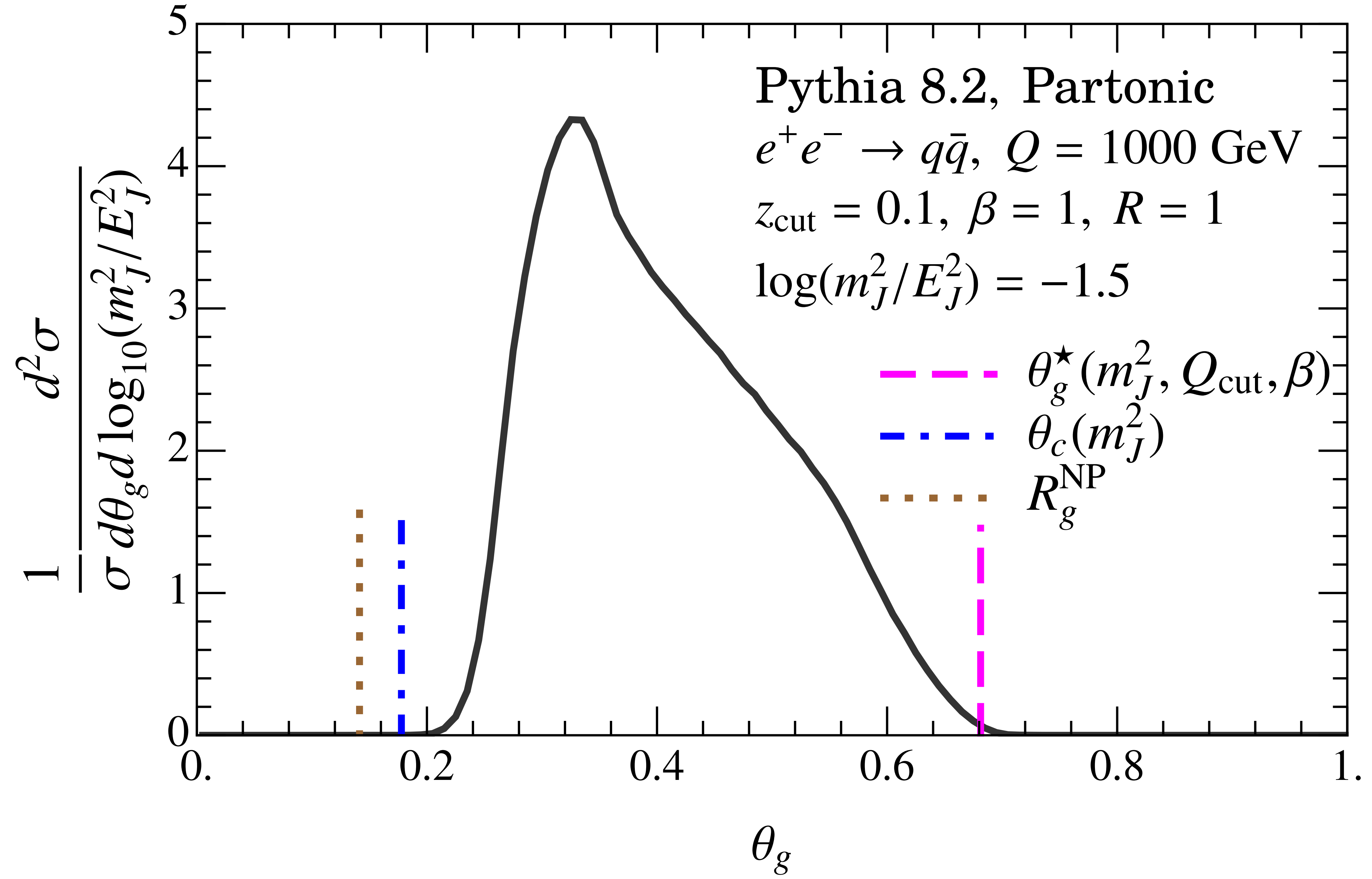




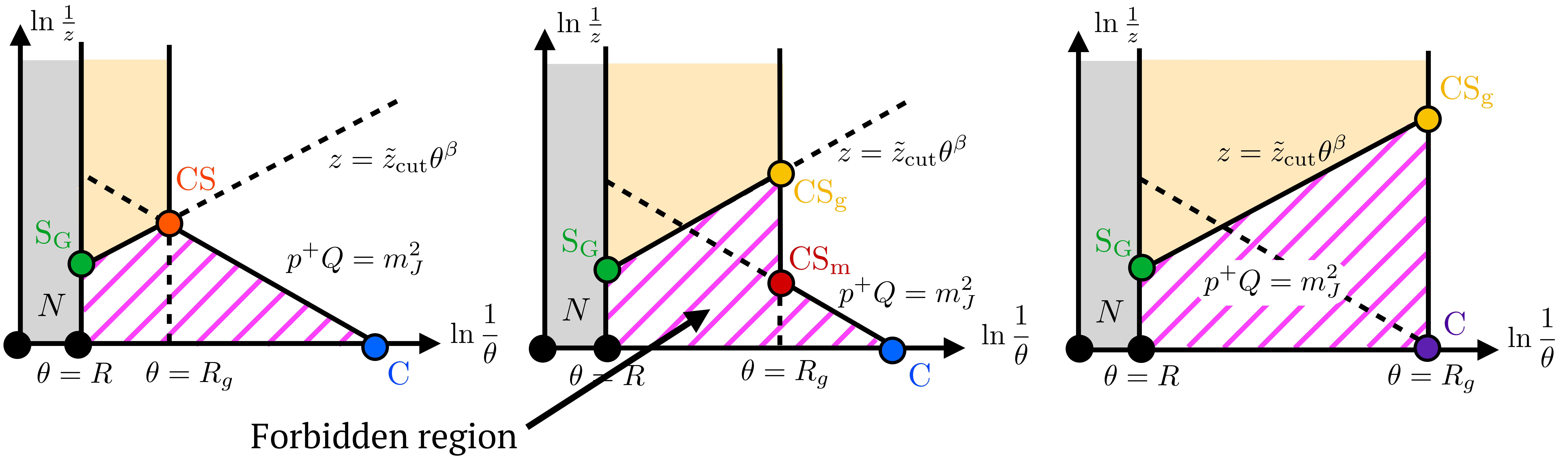
$$\theta_g^\star(m_J^2, Q_{\rm cut}, \beta) < R_g < \theta_c(m_J^2)$$

The groomed jet radius is constrained by the jet mass measurement

$$\theta_c(m_J^2) = \frac{m_J}{E_J}\,, \qquad \theta_g^\star(m_J^2, Q_{\rm cut}, \beta) = 2\Big(\frac{m_J^2}{QQ_{\rm cut}}\Big)^{\frac{1}{2+\beta}}$$

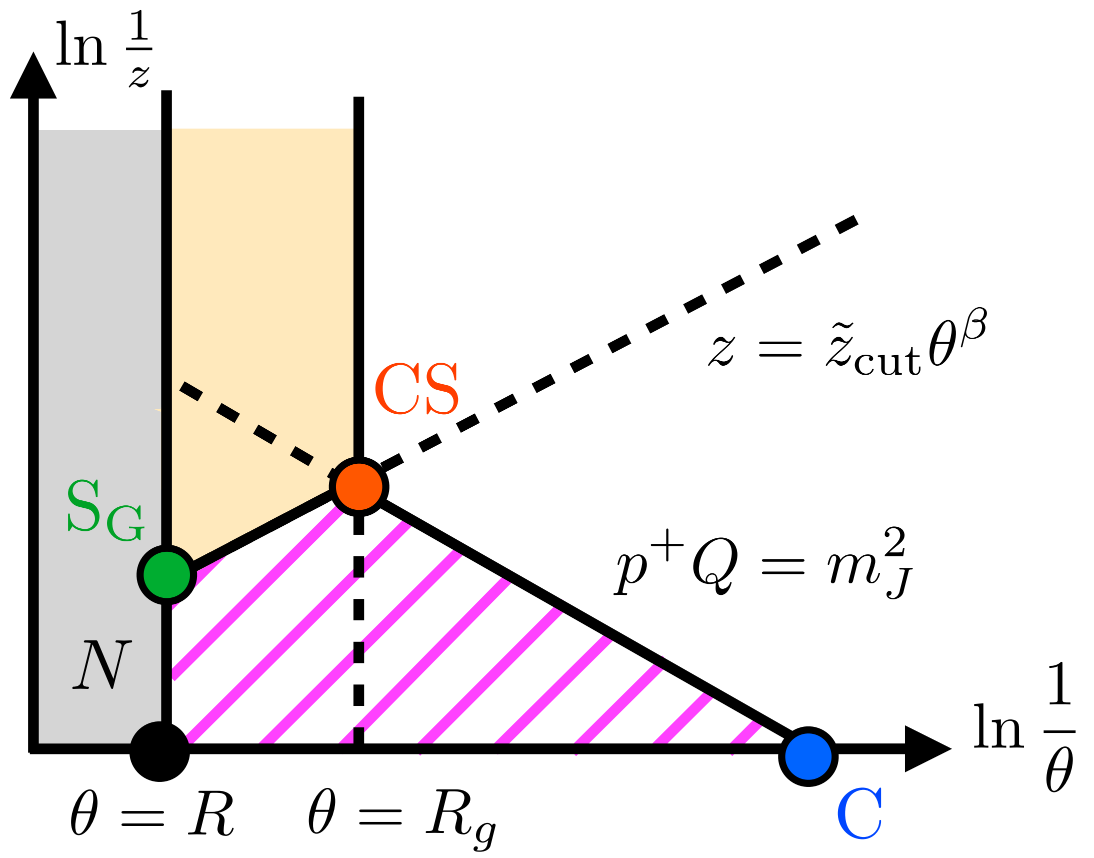


EFT modes for double differential distribution

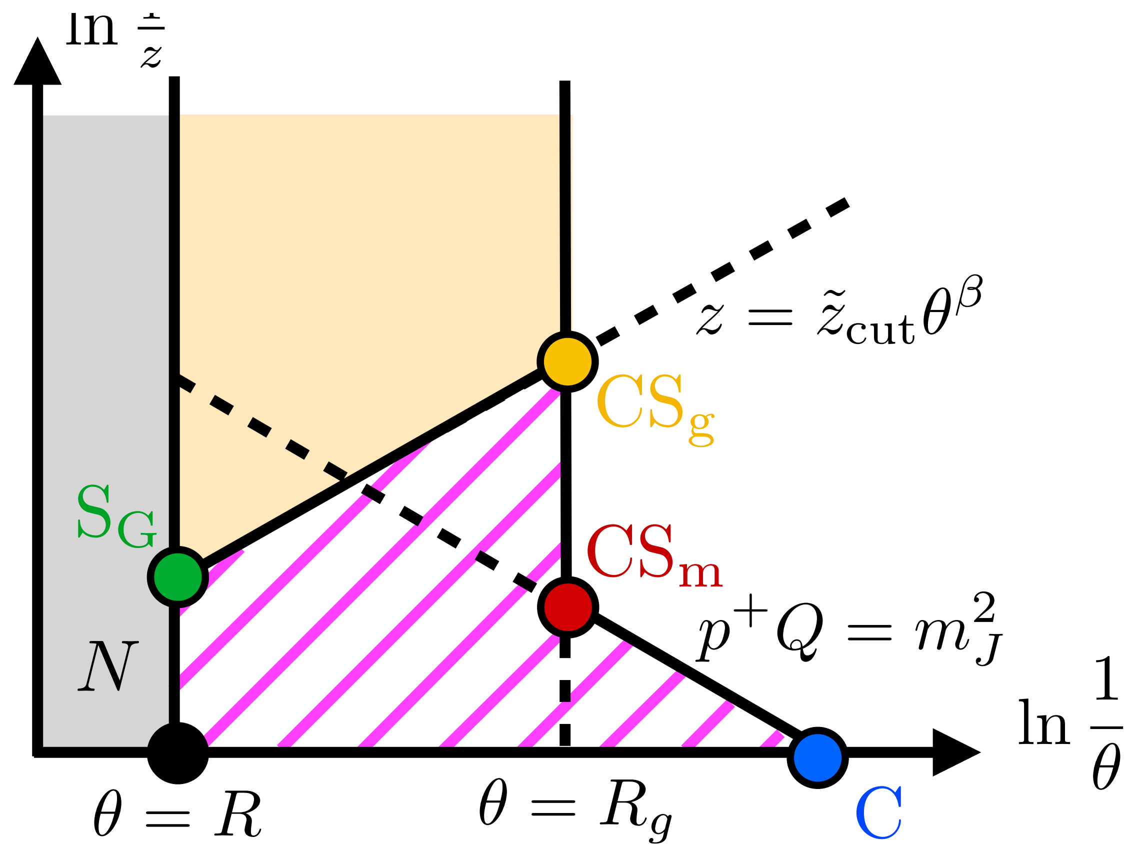


1. Large groomed jet radius: $\theta_c \ll R_g \lesssim \theta_g^\star \ll R$
2. Intermediate groomed jet radius: $\theta_c \ll R_g \ll \theta_g^\star \ll R$
3. Small groomed jet radius: $\theta_c \lesssim R_g \ll \theta_g^\star \ll R$

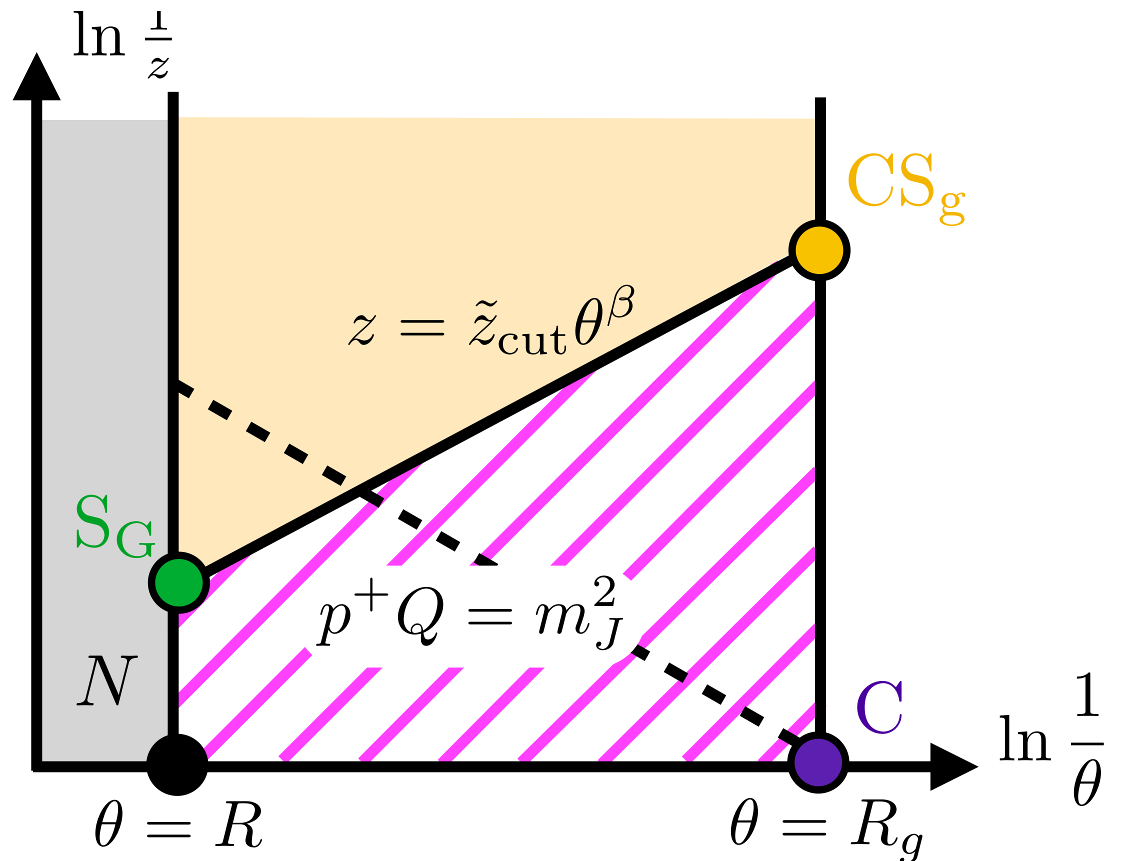
Factorization in the three regimes



$$\frac{d\hat{\Sigma}(R_g)}{dm_J^2} = N_q(\Phi_J, Q, R, \mu)\, S^q(Q_{\rm cut}, R, \beta, \mu)$$
$$\times\; Q_{\rm cut}^{\frac{1}{1+\beta}} \int d\ell^+ J_q(m_J^2 - Q\ell^+, \mu)\, S_c^q\Big[\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, R_g Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big]$$



$$\frac{d\Sigma(R_g)}{dm_J^2 d\Phi_J} = \sum_{\kappa=q,g} N_\kappa(\Phi_J, Q, R, \mu)\, S_G^\kappa(Q_{\rm cut}, R, \beta, \mu)\, S_{c_g}^\kappa\big(R_g Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\big)$$
$$\times \int \frac{d\ell^+}{R_g/2} J_\kappa\big(m_J^2 - Q\ell^+, \mu\big)\, S_{c_m}^\kappa\Big(\frac{\ell^+}{R_g/2}, \mu\Big)\,.$$



$$\frac{d\Sigma(R_g)}{dm_J^2 d\Phi_J} = \frac{1}{(Q\frac{R_g}{2})^2} \sum_{\kappa=q,g} N_\kappa(\Phi_J, Q, R, \mu)\, S_G^\kappa(Q_{\rm cut}, R, \beta, \mu)\, S_{c_g}^\kappa\big(R_g Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\big)\, \mathcal{C}^\kappa\Big[\frac{m_J^2}{Q^2 R_g^2}, QR_g, \mu\Big]$$

Power corrections

Factorization entails expanding in a region where a power counting parameter becomes small.

The three regimes are related unto power corrections:

Connection between the large and intermediate Regime:

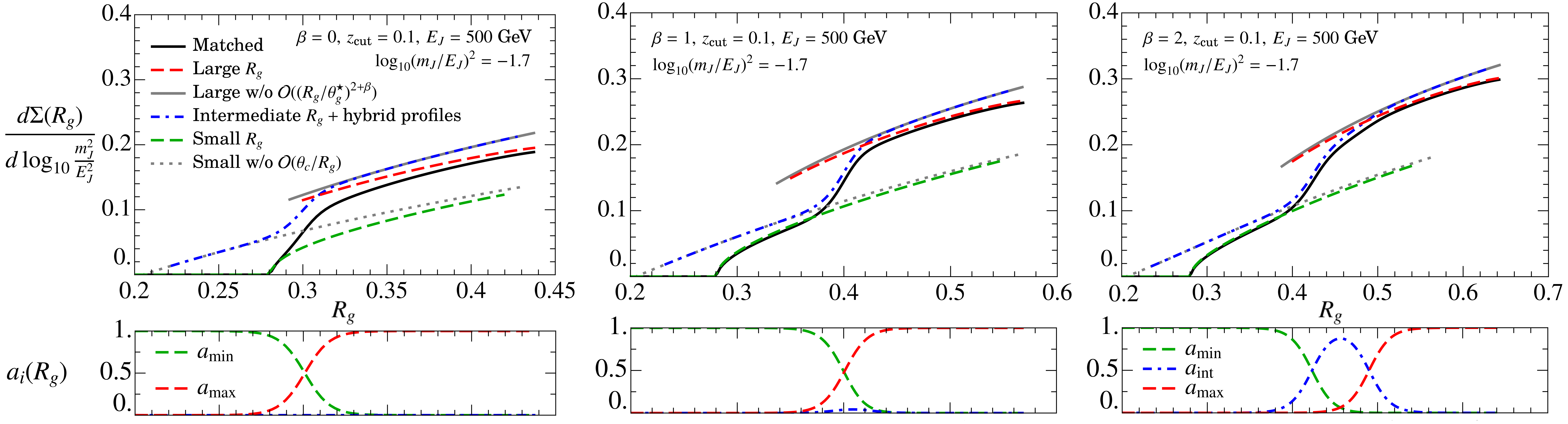
$$S_c^\kappa\Big[\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, R_g Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big] = S_{c_g}^\kappa\big(R_g Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\big)\, S_{c_m}^\kappa\Big(\frac{2\ell^+}{R_g}, \mu\Big)\left[1 + \mathcal{O}\Big(\frac{R_g^{2+\beta} Q_{\rm cut}}{\ell^+}\Big)\right]$$

Connection between small and intermediate regime:

$$\frac{1}{\big(Q\frac{R_g}{2}\big)^2}\mathcal{C}^\kappa\Big[\frac{m_J^2}{Q^2 R_g^2}, QR_g, \mu\Big] = \int \frac{d\ell^+}{R_g/2} J_\kappa\big(m_J^2 - Q\ell^+, \mu\big)\, S_{c_m}^\kappa\Big(\frac{\ell^+}{R_g/2}, \mu\Big)\left[1 + \mathcal{O}\Big(\frac{4m_J^2}{Q^2 R_g^2}\Big)\right]$$

Matched Cross Section

We match the three regimes consistently turning on/off resummation in the three regions:



In practice the intermediate regime is really valid only for β > 1

NLL + NLO results for C_1

By integrating over the matched cumulant we can evaluate a more precise prediction for C1

$$M_1^q(m_J^2) = \left[\int_{\theta_{\min}}^{\theta_{\max}} d\theta_g \, \frac{\theta_g}{2} \left(\frac{d}{dR_g} \frac{d\Sigma^q(R_g)}{dm_J^2 d\Phi_J} \right)_{R_g=\theta_g} \right] \Big/ \int_{\theta_{\min}}^{\theta_{\max}} d\theta_g \left(\frac{d}{dR_g} \frac{d\Sigma^q(R_g)}{dm_J^2 d\Phi_J} \right)_{R_g=\theta_g}$$

We expect M1 ~ C1

MC data agrees better with the improved prediction

Soft drop boundary cross section

We are interested in the “boundary" moment:

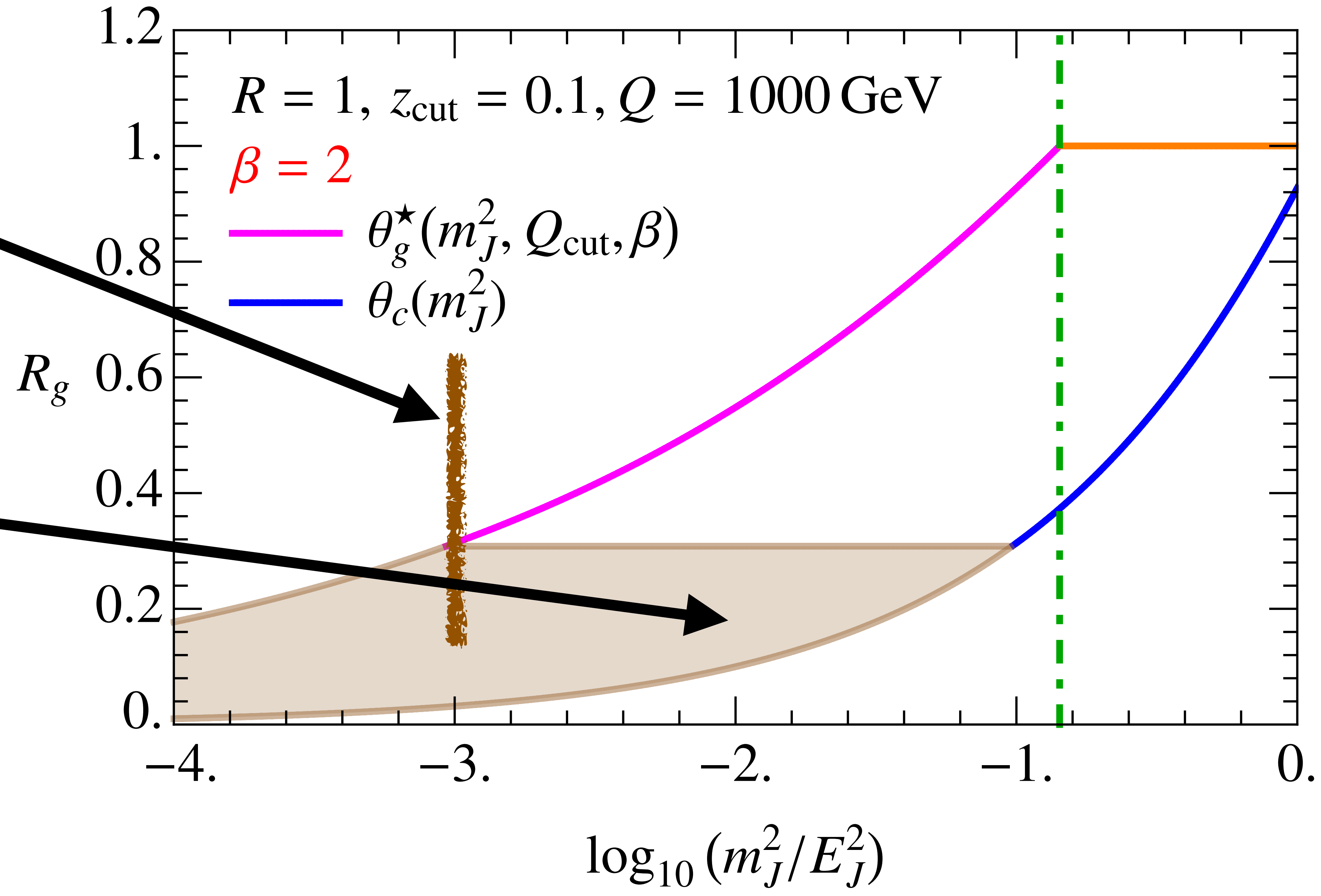
$$M_{-1}^{\kappa \circledcirc}(m_J^2) = \lim_{\varepsilon \to 0} \left(\frac{d\hat{\sigma}^\kappa}{dm_J^2} \right)^{-1} \frac{d}{d\varepsilon} \int d\theta_g \, \frac{m_J^2}{Q^2} \frac{2}{\theta_g} \frac{d^2 \hat{\sigma}^\kappa(\varepsilon)}{dm_J^2 d\theta_g} \, ;$$

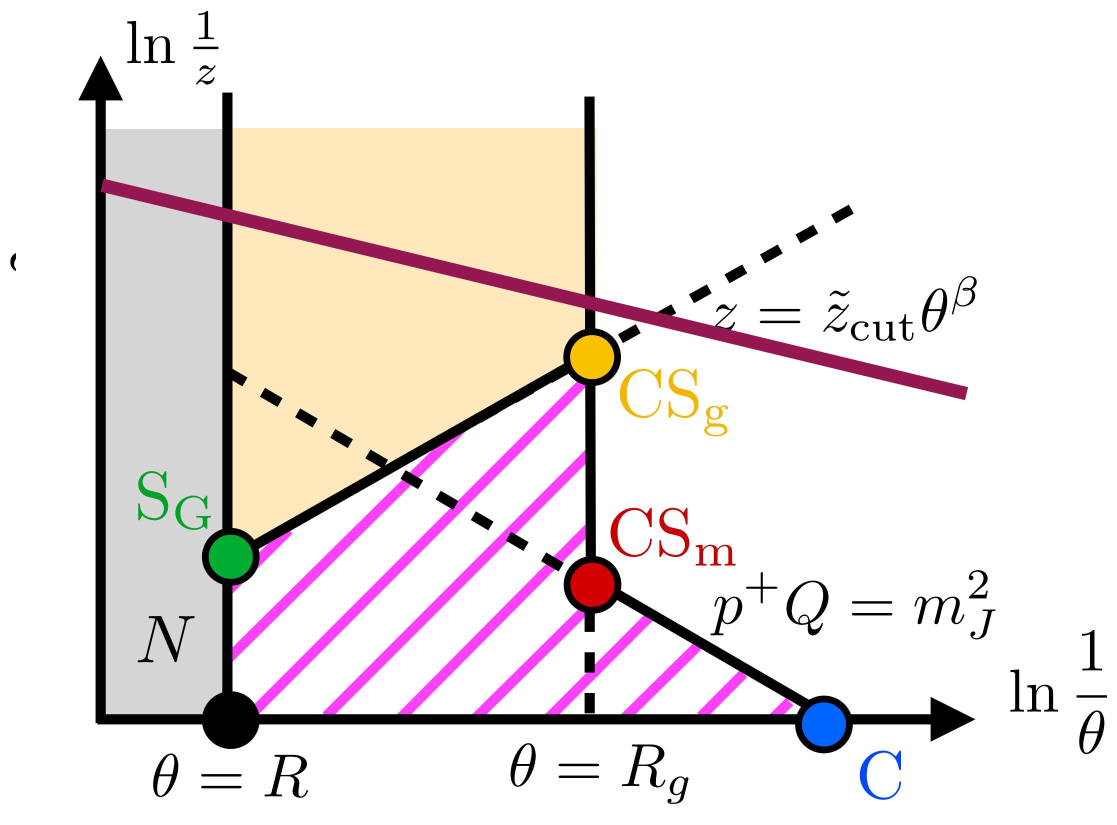
The connection between this moment and C2 is more subtle

We expected NP effects to enter only below these jet masses

Intermediate regime becomes nonperturbative for larger jet masses

Here due to inverse power of Rg intermediate contribution is enhanced





Soft drop boundary cross section

Expand the shifted soft drop constraint and consistently resum

$$\frac{d\Sigma^\kappa(R_g,\overline{\Theta}_{\rm sd}(\varepsilon))}{dm_J^2} = \frac{d\sigma^\kappa\big(\delta_{\beta,0}\gamma_0(\varepsilon,z_{\rm cut})\big)}{dm_J^2} + \frac{d\Sigma^\kappa\big(R_g,\delta_{\beta,0}\gamma_0(\varepsilon,z_{\rm cut})\big)}{dm_J^2} + \frac{Q\varepsilon}{Q_{\rm cut}}\frac{d\Delta\Sigma^\kappa_\varepsilon(R_g)}{dm_J^2} + \mathcal{O}(\varepsilon^2)$$

Additional O(ε) single logs for β = 0

$$S_G^{\kappa[1],{\rm bare}}\big[Q_{\rm cut},R,\beta,\Theta_{\rm sd}(\varepsilon),\mu\big] = S_G^{\kappa[1],{\rm bare}}\big[Q_{\rm cut},R,\beta,\mu\big] + \frac{Q\varepsilon}{Q_{\rm cut}}S_{G,\varepsilon}^{\kappa[1],{\rm bare}}\big[Q_{\rm cut},R,\beta,\mu\big] + \mathcal{O}(\varepsilon^2)$$

$$S_{G,\varepsilon}^{\kappa[1],{\rm bare}}\big[Q_{\rm cut},R,\beta,\mu\big] =$$

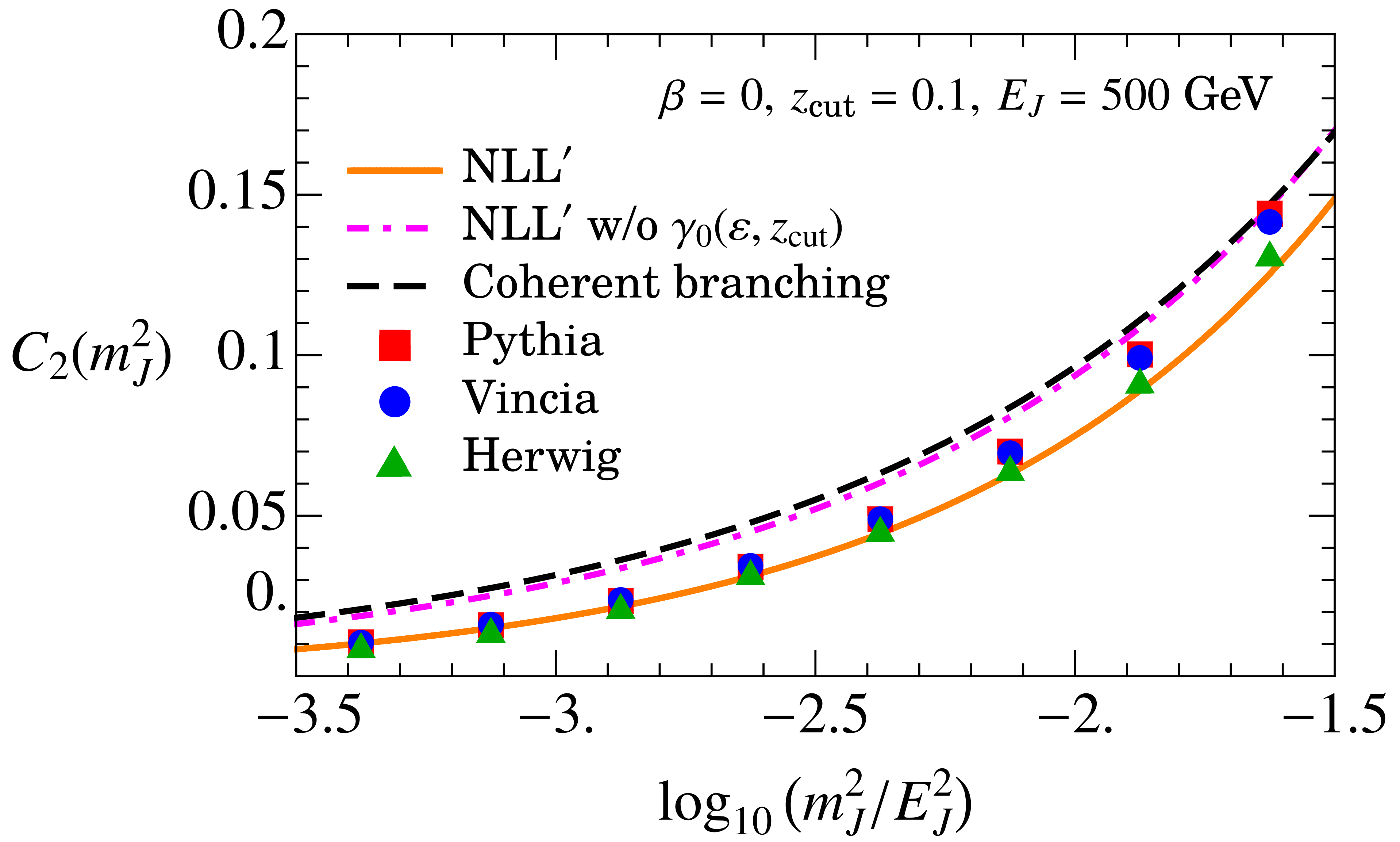
$$(\beta = 0) \qquad = \frac{\alpha_s C_\kappa}{\pi}\left[\frac{1}{\epsilon_{\rm UV}} + 2\log\left(\frac{\mu}{Q_{\rm cut}\tan\frac{R}{2}}\right)\right]$$

$$(\beta > 0) \qquad = \frac{\alpha_s C_\kappa}{\pi}\left[\frac{2}{\beta}\frac{1}{\sin^\beta\left(\frac{R}{2}\right)} + \dots\right],$$

Similar expansion for other soft functions

NLL + NLO results for C_2

- Overall good agreement with MC predictions
- Deviation in large jet masses (we didn't include power corrections there)
- Additional single log resummation in $\beta = 0$ result improves agreement with MC



Summary

- Jet physics plays an important role in the search for new physics
- Interesting nonperturbative effects in groomed jet mass
- Higher order resummation of Wilson coefficients C1 and C2 via double differential distribution
- Future goals to study further the double differential cross section as a tool for some exciting precision physics!

Merci