Soft drop groomed jet substructure observables

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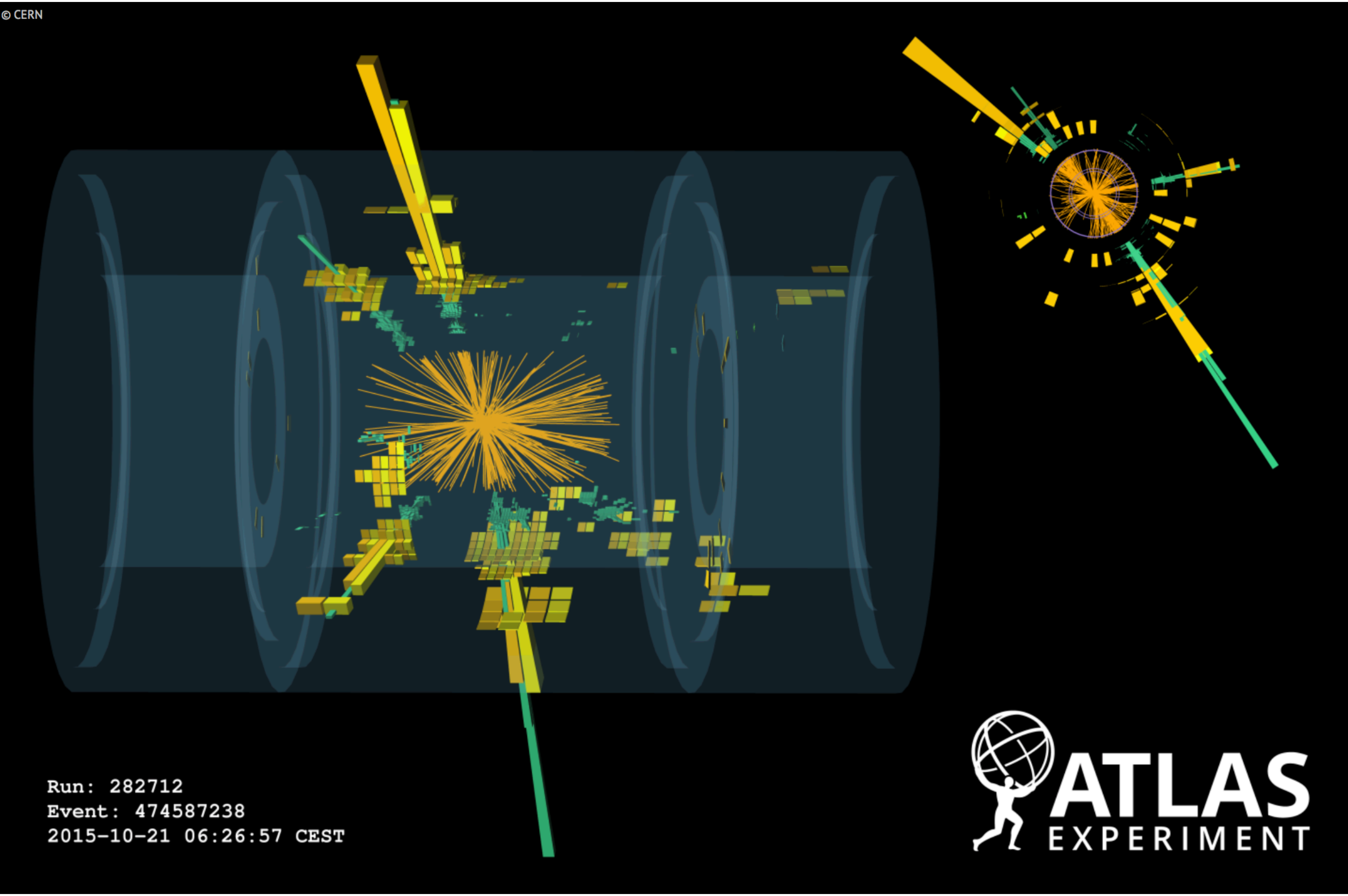
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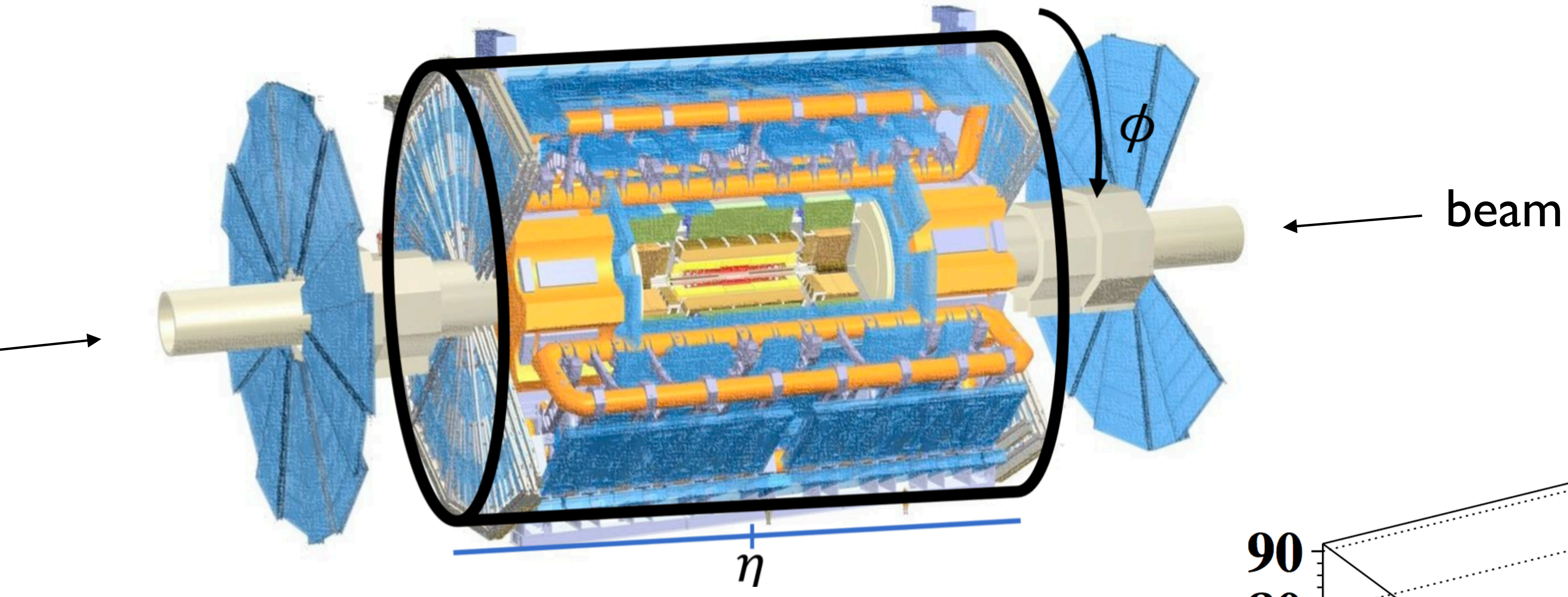
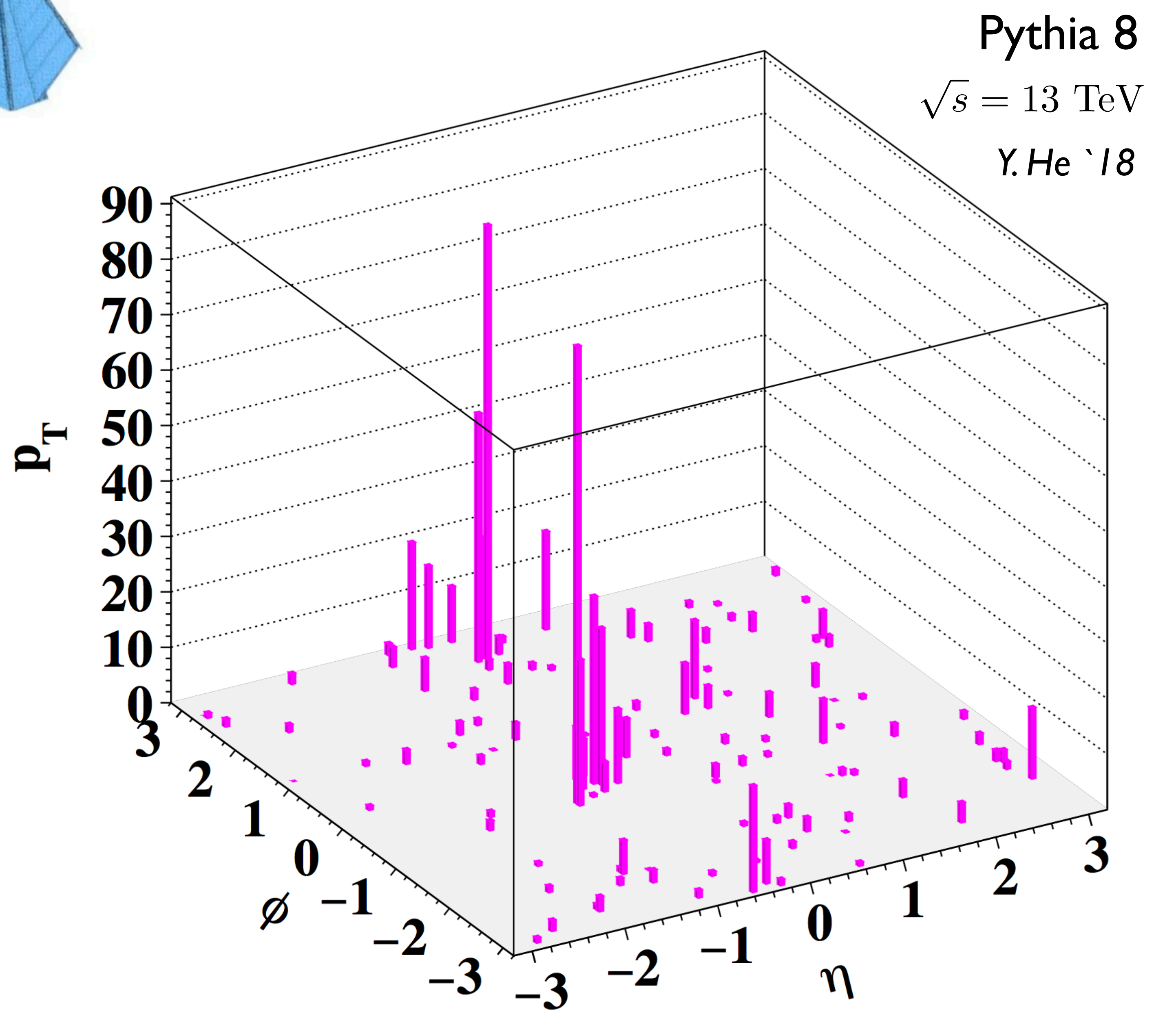
ATLAS
EXPERIMENT

Jets at the LHC

ATLAS detector





- Azimuthal angle ϕ
- Pseudorapidity $\eta = -\ln\tan\theta/2$

Jets at the LHC

- Pioneering work *Sterman, Weinberg `77*
- Jet algorithm, e.g. anti-k_T *Cacciari, Salam, Soyez `08*

Define a distance between all particles

$$d_{ij} = \min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right) \frac{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

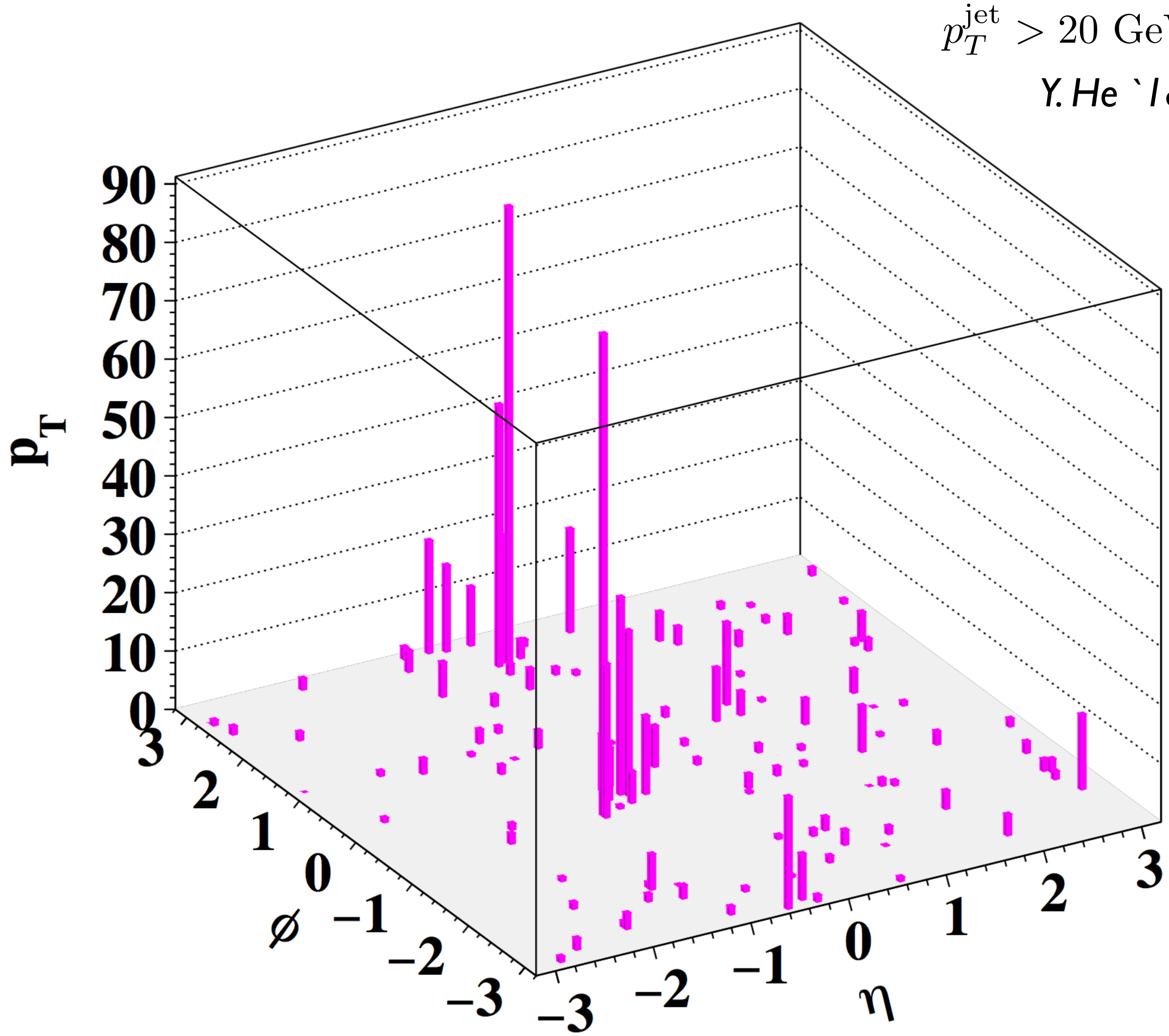
and recursively merge the particles with the smallest distance

Pythia 8, FastJet

$R = 0.4 \quad \sqrt{s} = 13$ TeV

$p_T^{\text{jet}} > 20$ GeV

Y. He `18



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$\longrightarrow$ R is the radius of the jet

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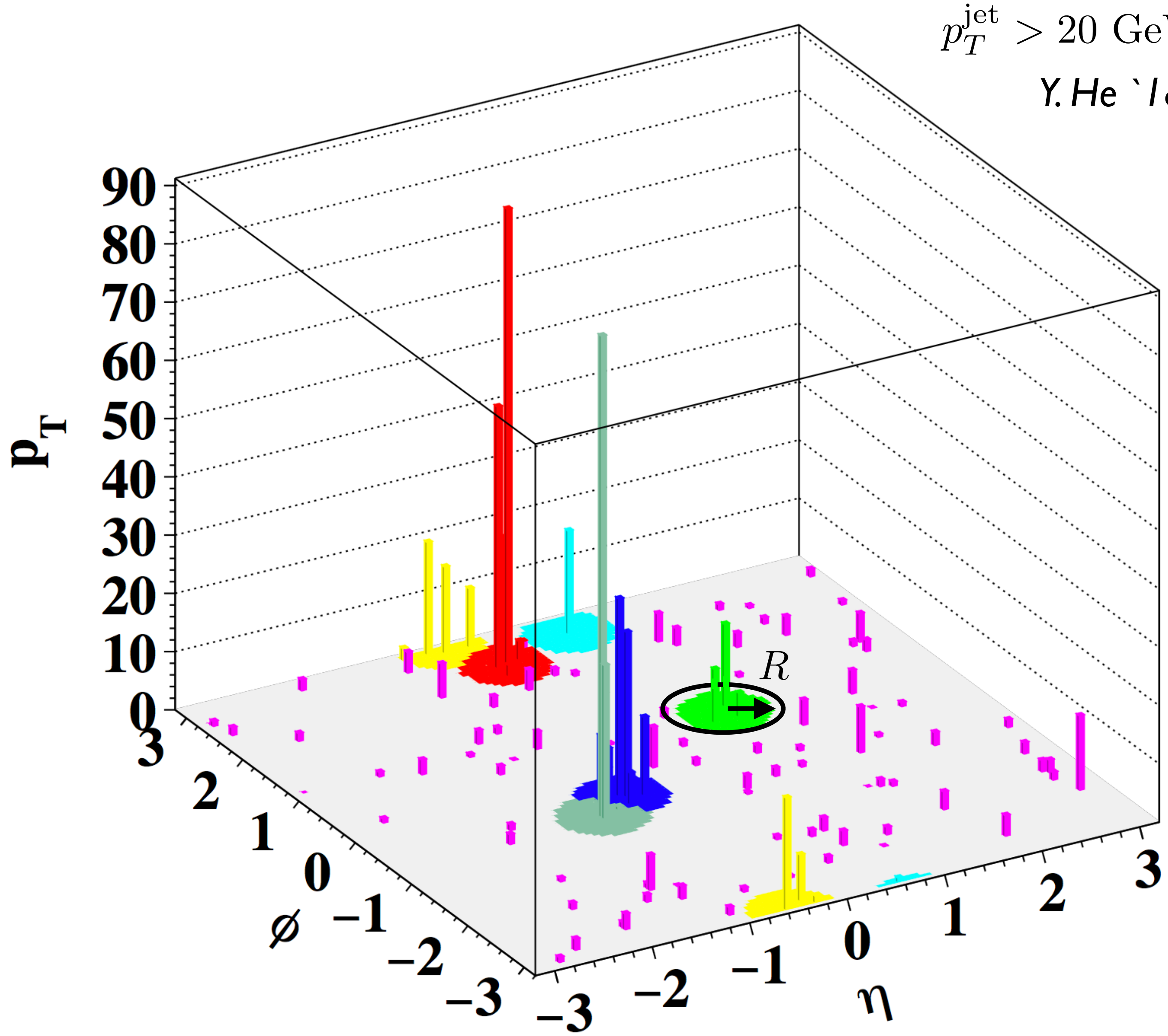
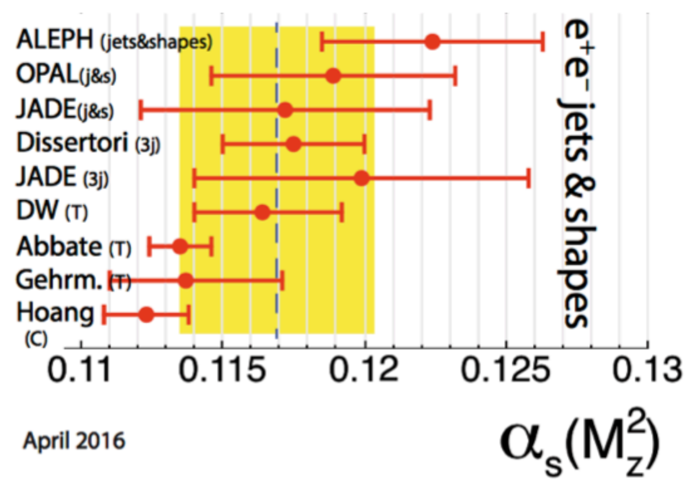


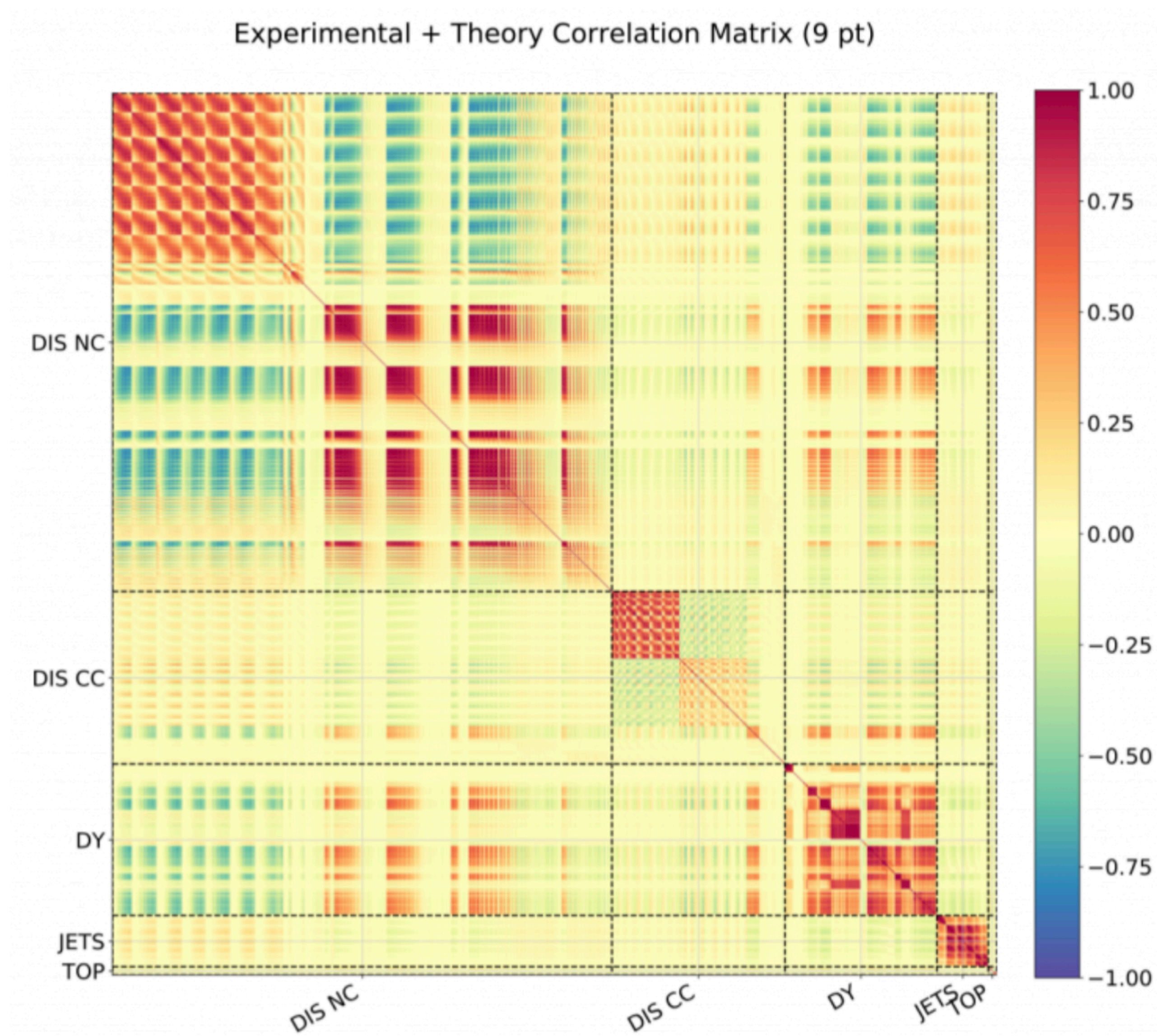
High precision jet physics at the LHC

- Test of the standard model and in particular QCD
- Constrain non-perturbative quantities

  e.g. PDFs and the QCD strong coupling constant α_s
- Tuning of Monte Carlo simulations



$\alpha_s(Mz)= 0.1169 \pm 0.0034$



NNPDF `19

High precision jet physics at the LHC

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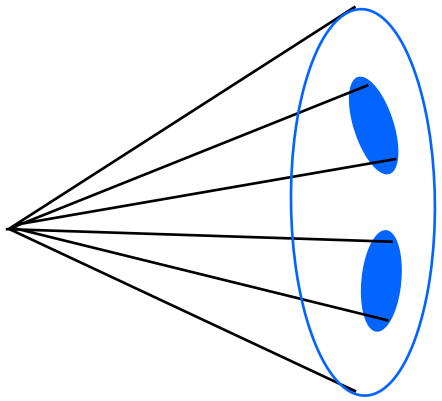
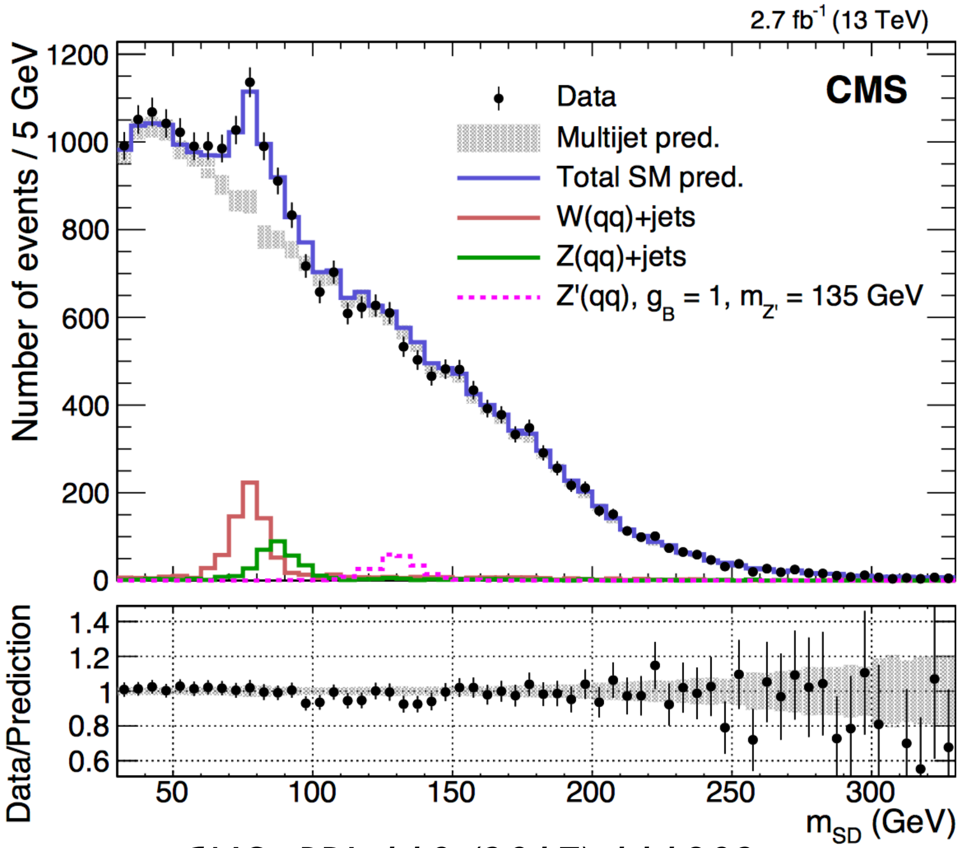
- Search for physics beyond the standard model

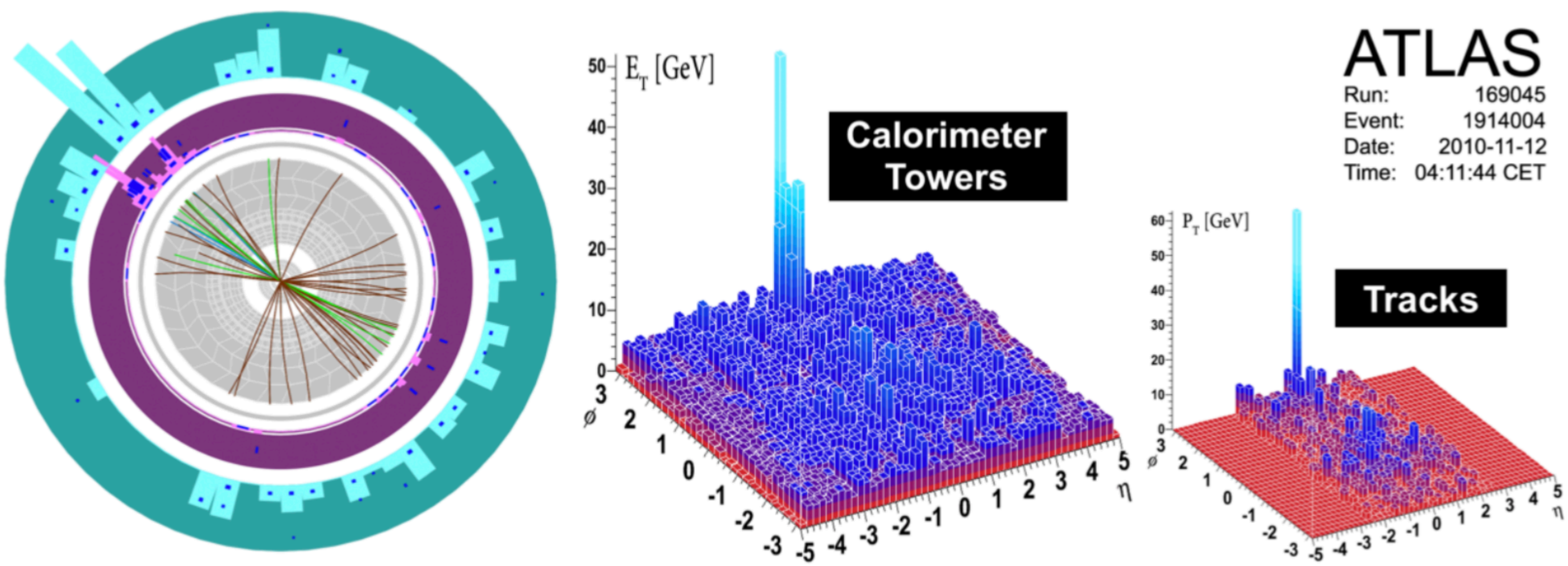




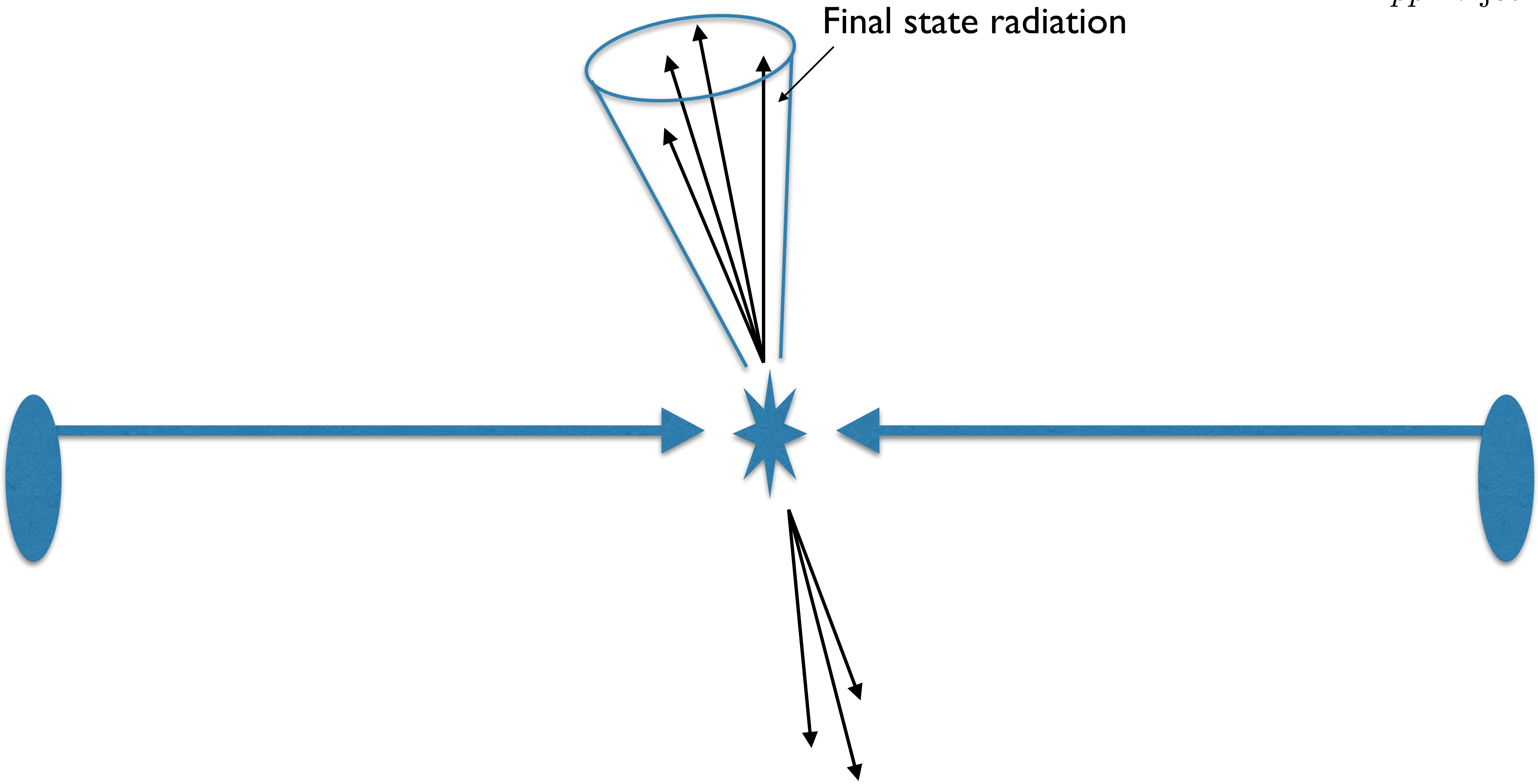
CMS, PRL 119 (2017) 111802

High precision jet physics at the LHC

- Test of the standard model and in particular QCD
- Constrain non-perturbative quantities
  e.g. PDFs and the QCD strong coupling constant α_s
- Tuning of Monte Carlo simulations
- Search for physics beyond the standard model
- Probe of the QGP in heavy-ion collisions



$pp \to \text{jet} + X$



adapted from M. Schwartz `17

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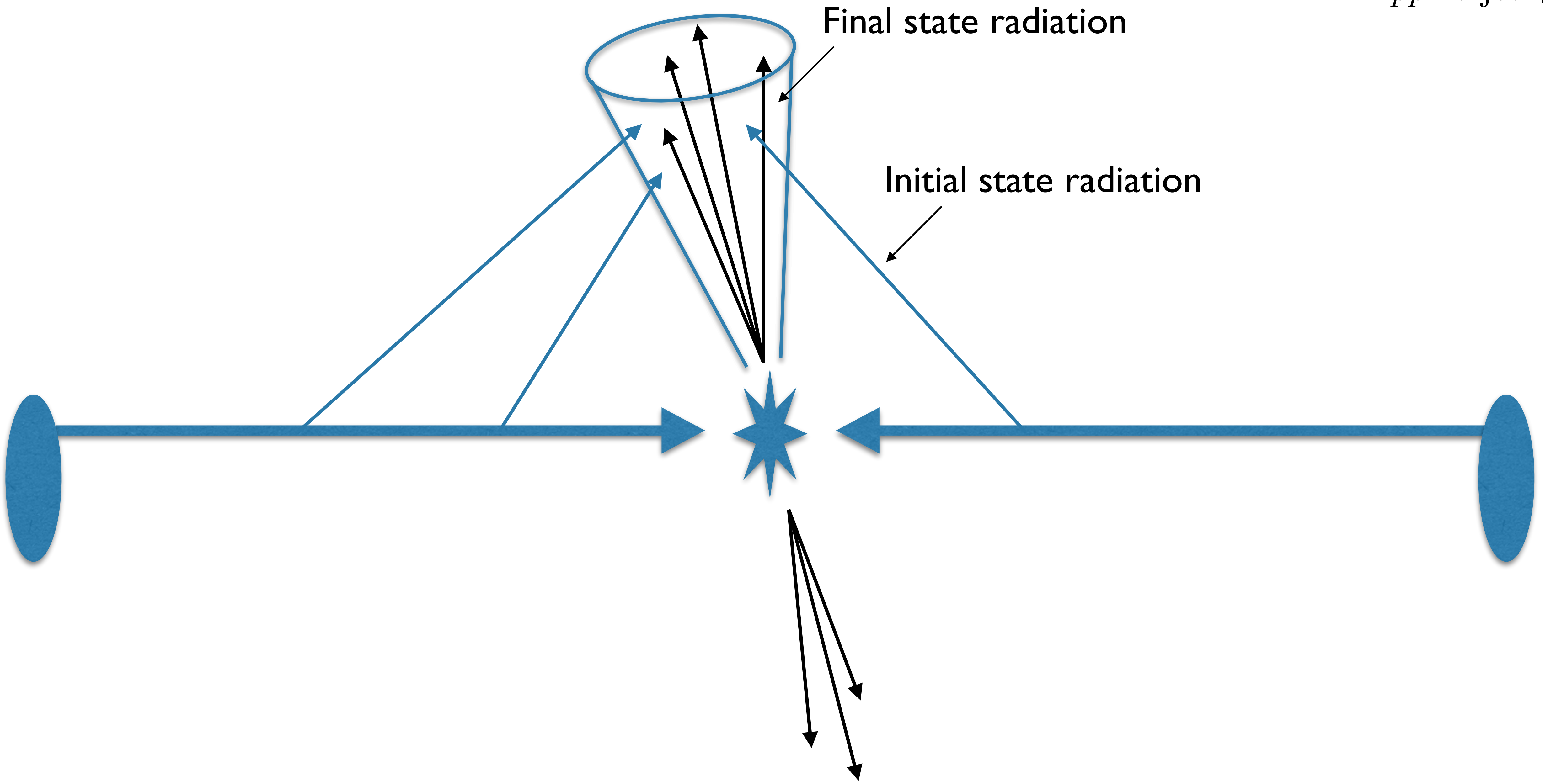

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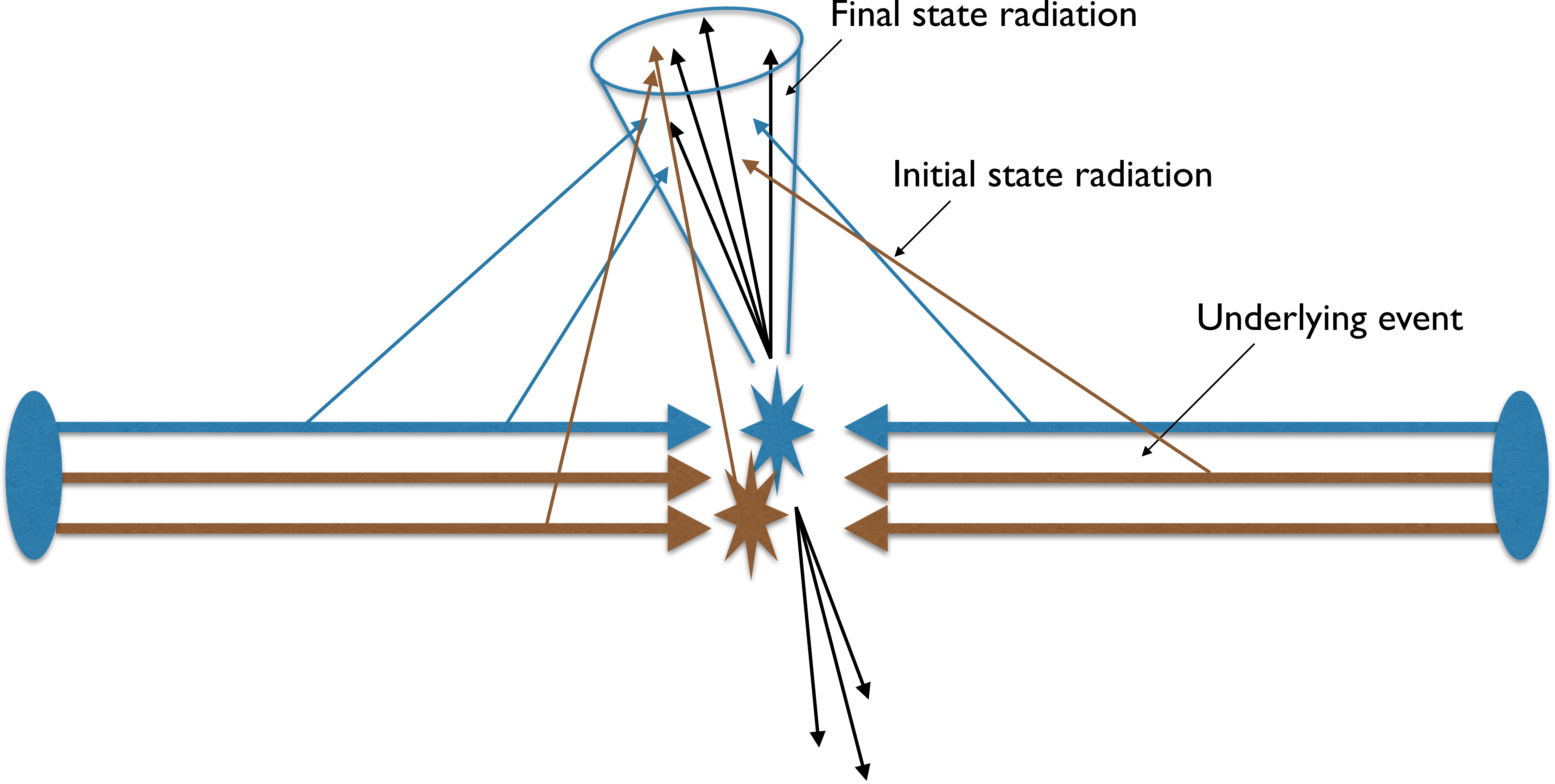

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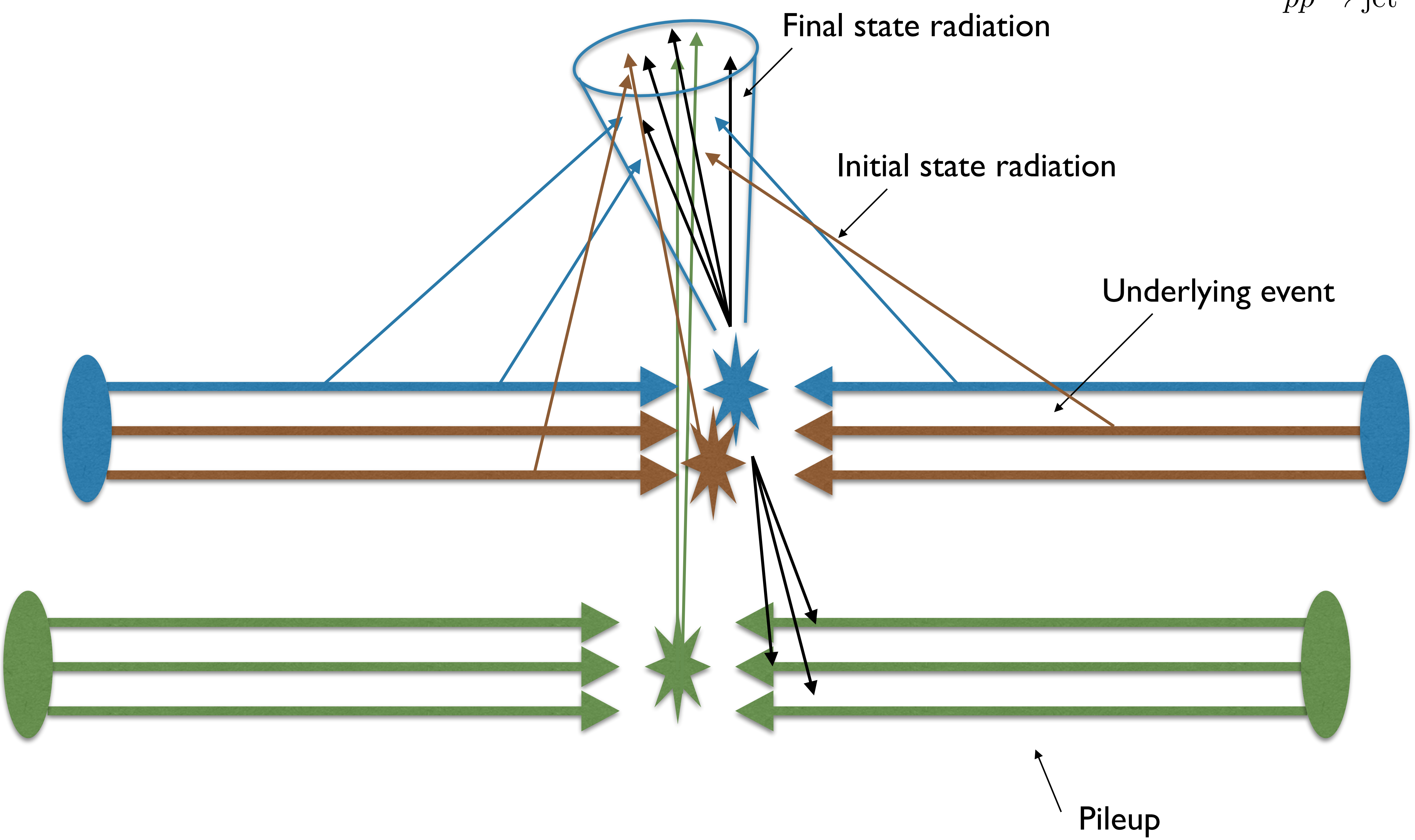

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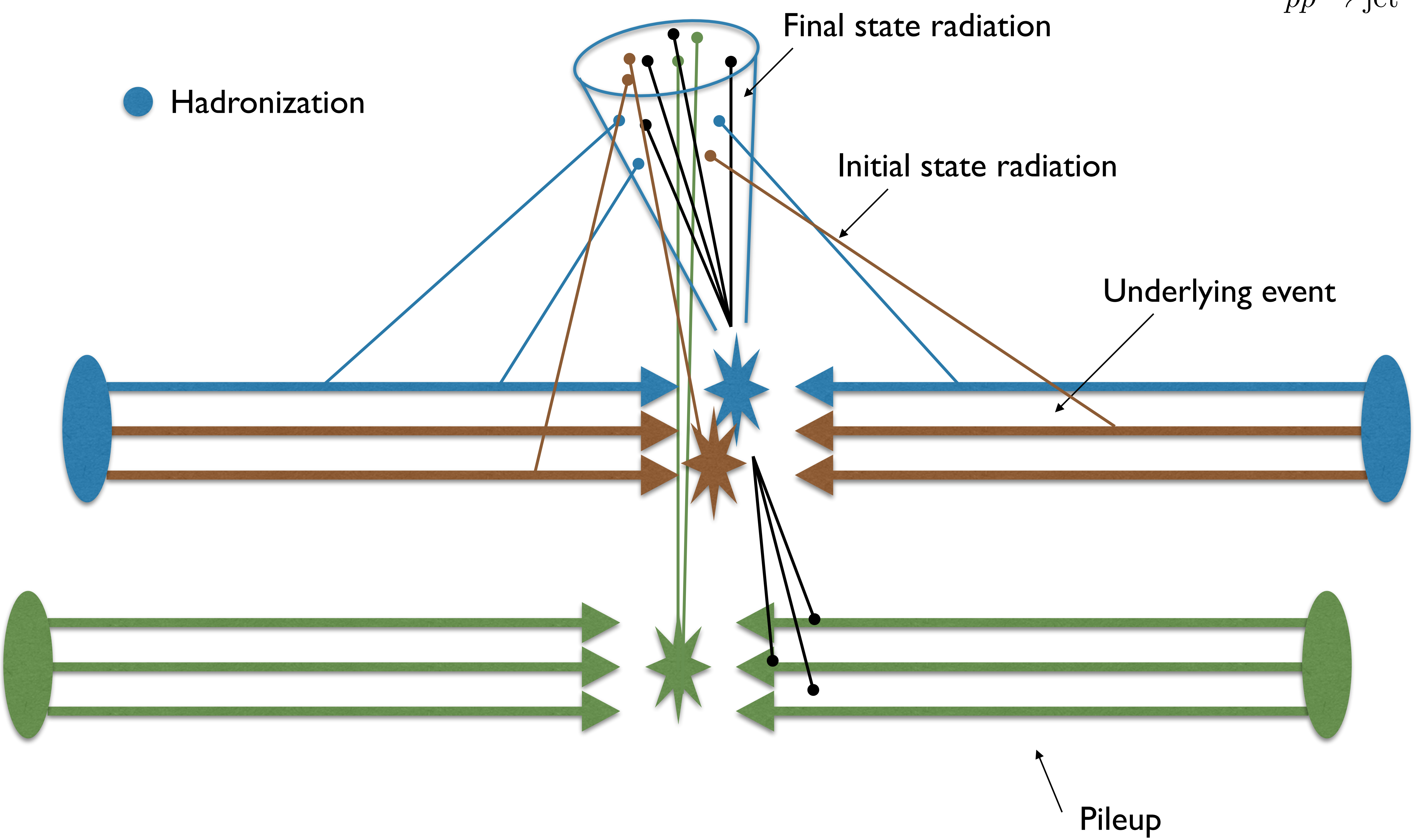

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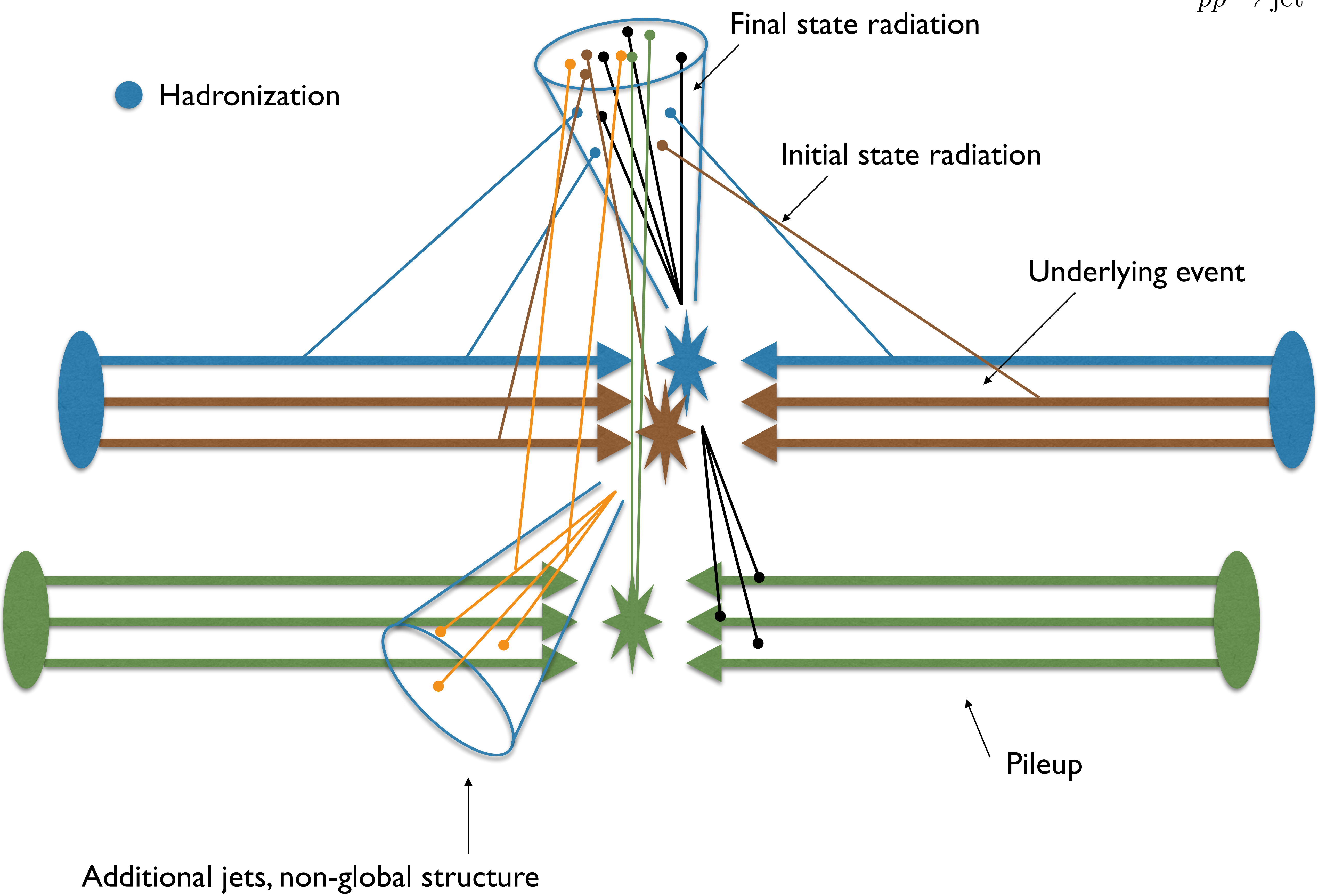

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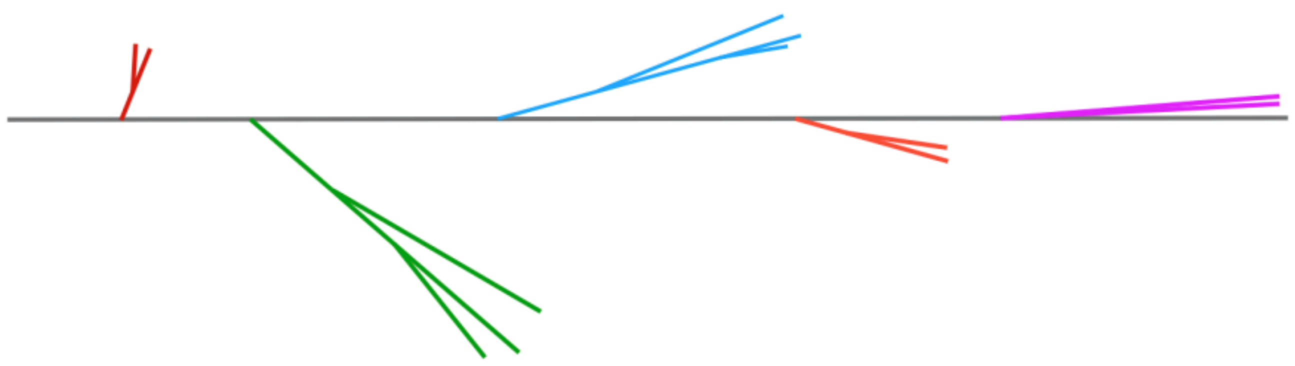
Outline

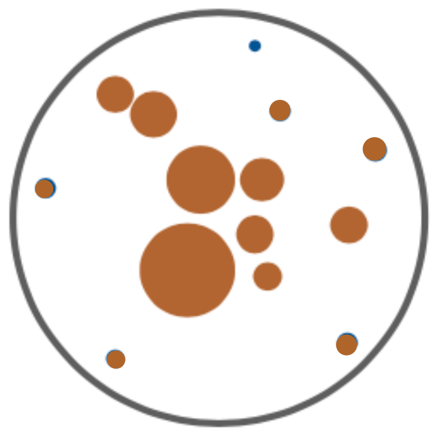
- Introduction
- Soft drop grooming
- The jet radius after grooming
- Other observables
- Conclusions

Soft drop grooming

Dasgupta, Fregoso, Marzani, Salam `13
Larkoski, Marzani, Soyez, Thaler `14

- Systematically remove soft wide-angle radiation in the jet
- Recluster jet with the C/A algorithm $d_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$





Angular ordered clustering tree

See also: Krohn, Thaler, Wang `10, Ellis, Vermilion, Walsh `10

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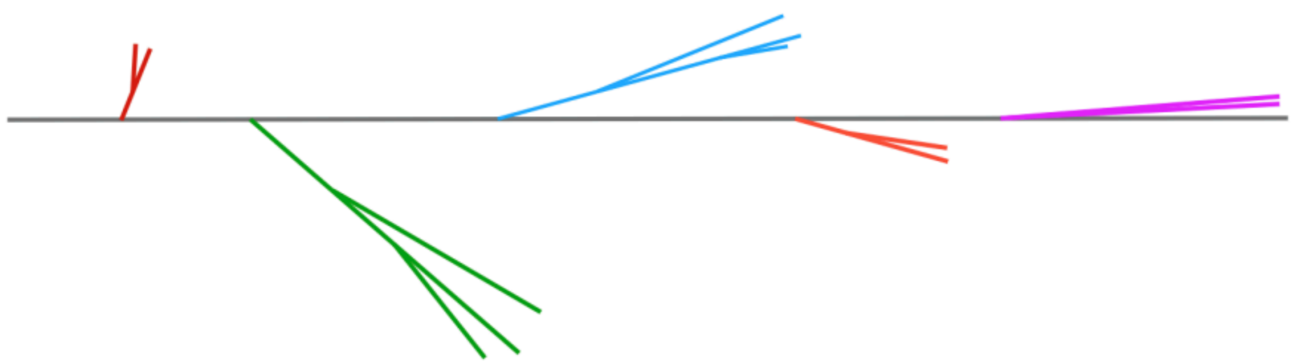

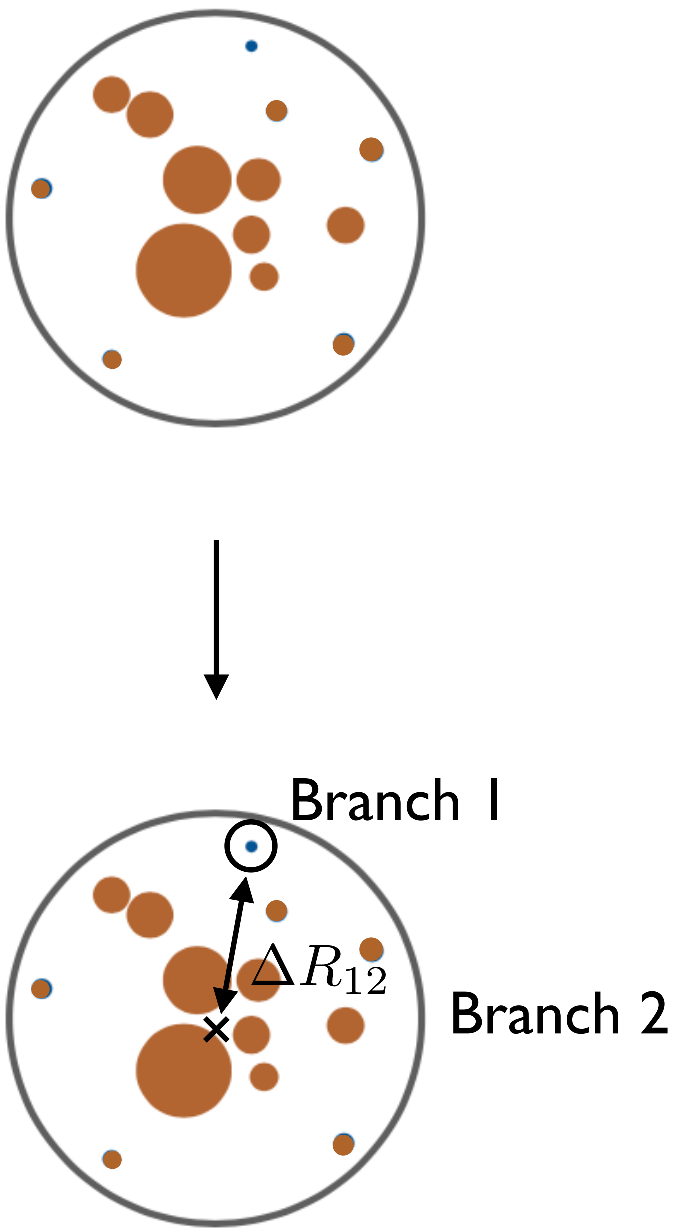

- Recursively decluster jet and check the criterion

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R} \right)^{\beta}$$

$$\Delta R_{12}^2 = \Delta \eta^2 + \Delta \eta^2$$

See also: Krohn, Thaler, Wang `10, Ellis, Vermilion, Walsh `10

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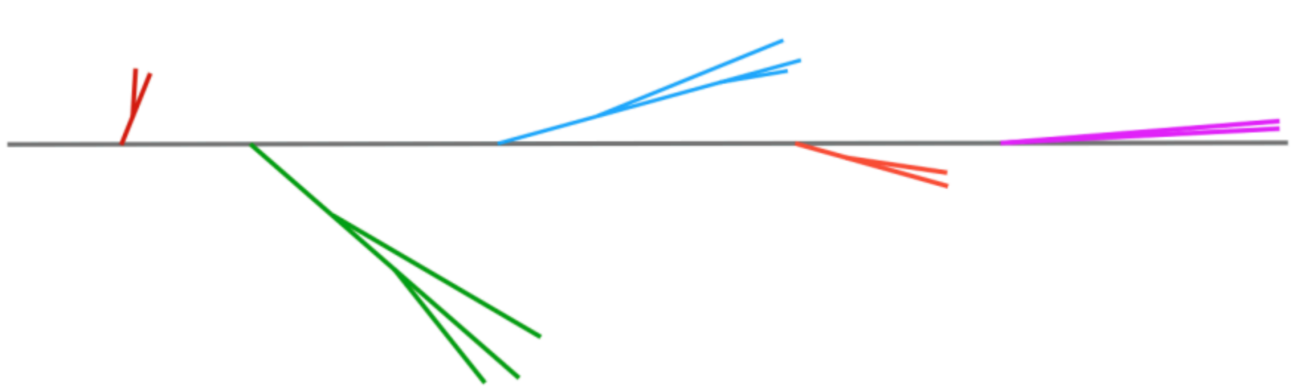

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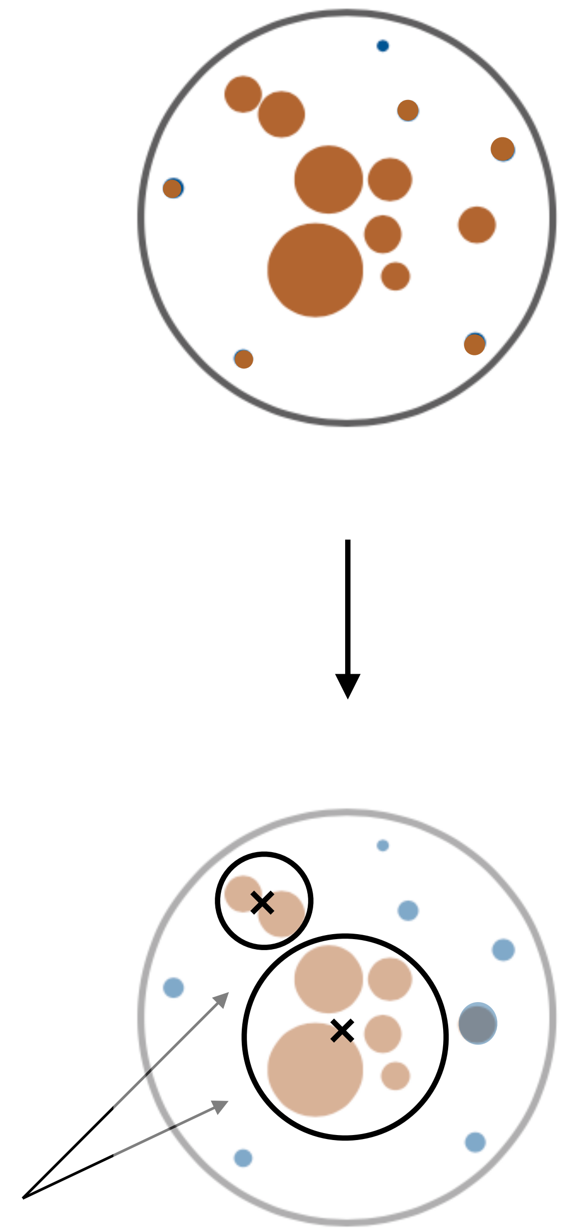


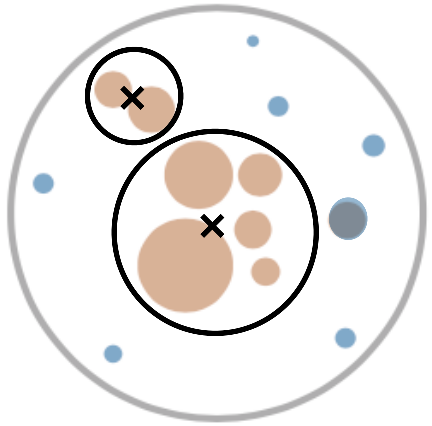
Particles in the groomed jet

See also: Krohn, Thaler, Wang `10, Ellis, Vermilion, Walsh `10

Jet substructure observables with soft drop

- Can ask different questions about the groomed jet such as

  - Groomed radius $R_g = \Delta R_{12} = \theta_g R$
  - Momentum sharing fraction $z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}$
  - Displacement of the jet axis $\theta_{\mathrm{st,gr}}$
  - The jet energy drop due to grooming Δ_E

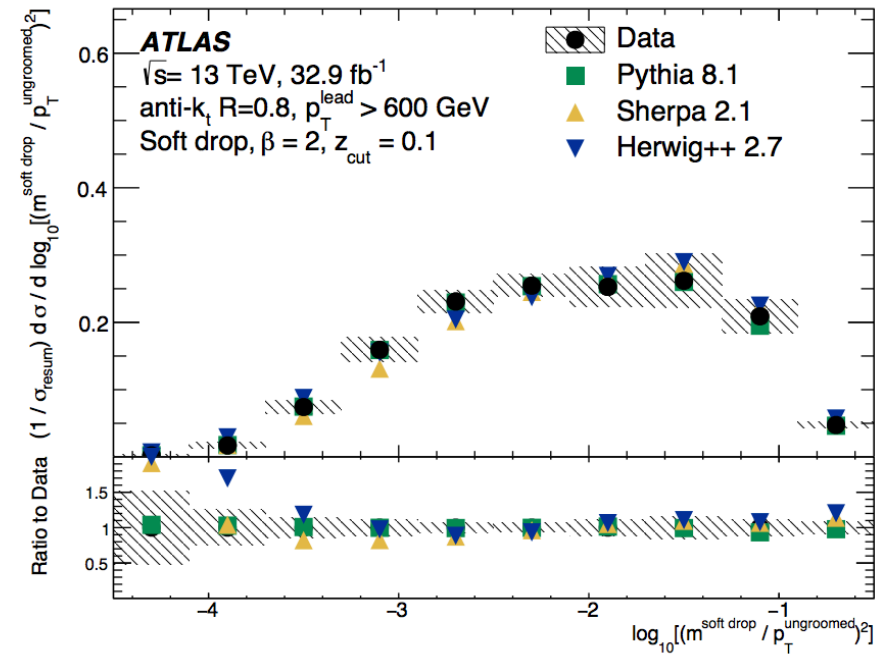


  - Soft drop jet mass
  - Angularities or energy-energy correlation functions

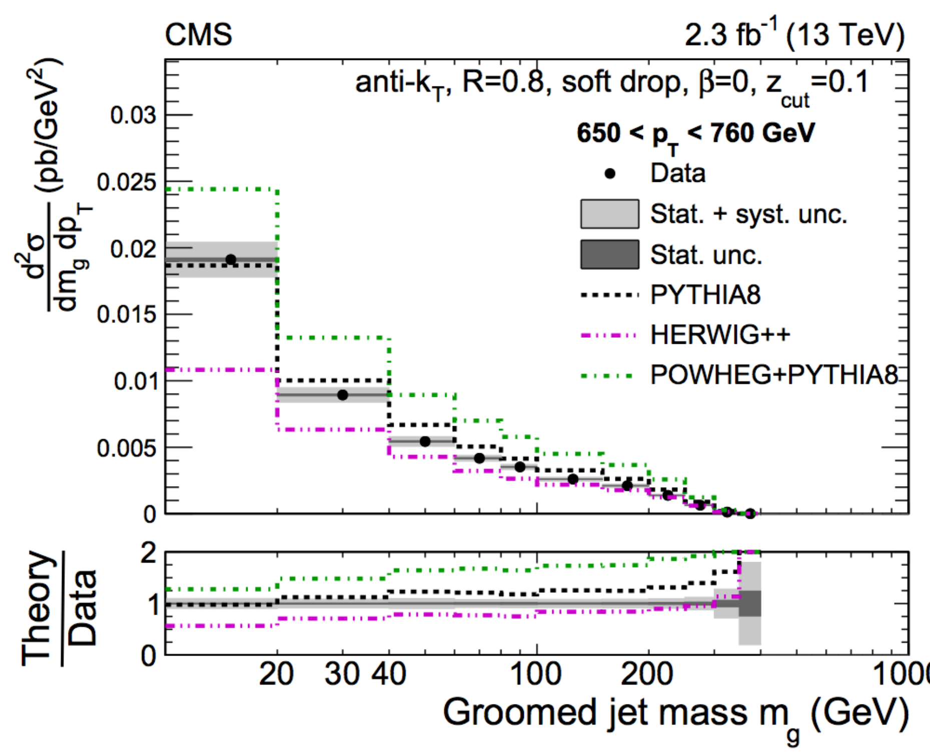
- These observables have interesting properties and turn out to be calculable in pQCD

The jet mass after soft drop grooming

- Jet mass $m_J^2 = \left(\sum_{i\in J} p_i\right)^2$
- Reduced sensitivity to NP effects
- Resummation of logarithms in $m_J/p_T,\ R,\ z_{\rm cut}$



ATLAS, PRL 121 (2018) 092001



CMS, JHEP 1811 (2018) 113

The Lund diagram for the jet mass

- Leading-logarithmic accuracy

$$\int \frac{\mathrm{d}z}{z}\frac{\mathrm{d}\theta}{\theta}$$

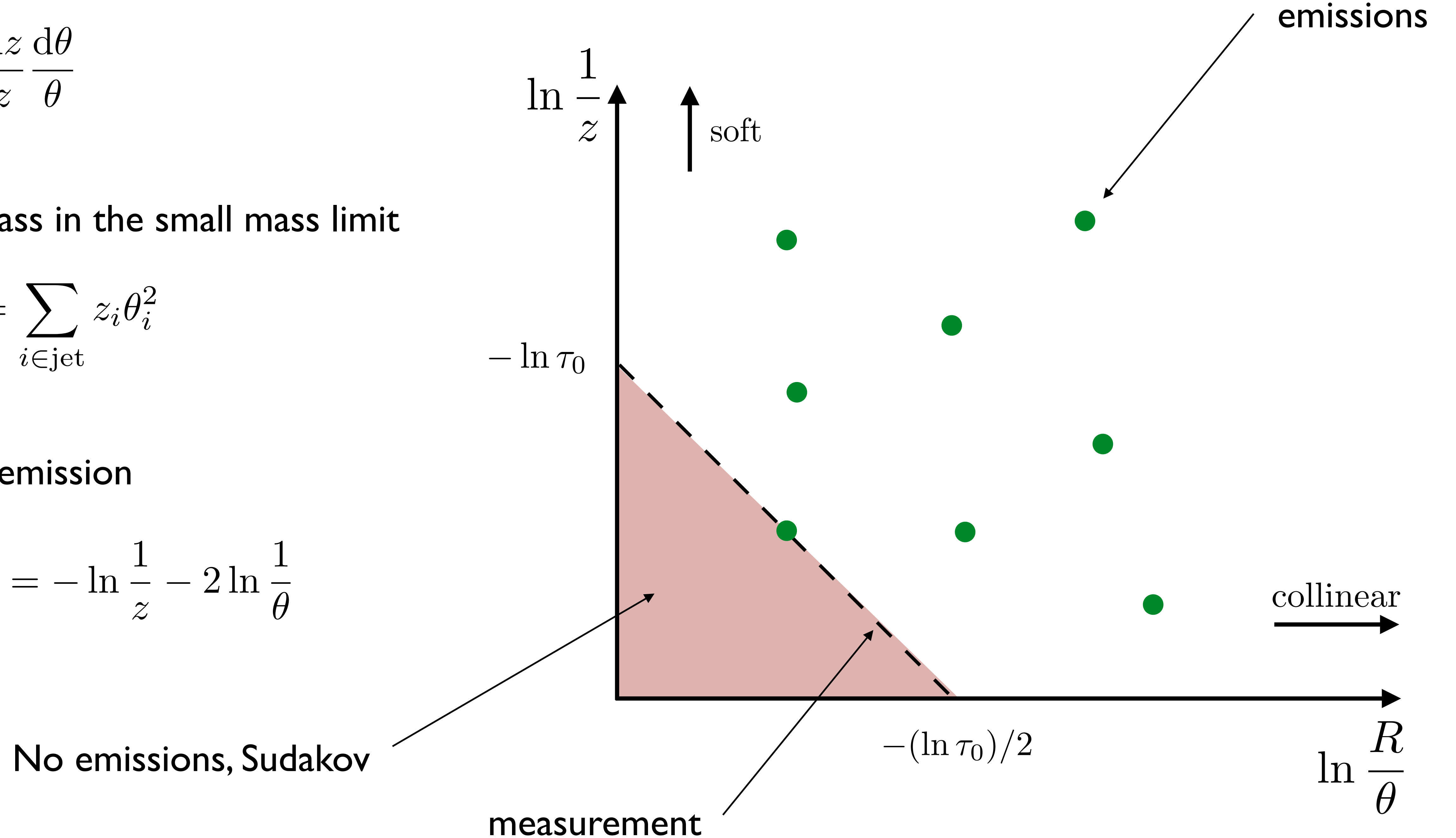
- Jet mass in the small mass limit

$$\tau_0 = \sum_{i \in \text{jet}} z_i \theta_i^2$$

- One emission

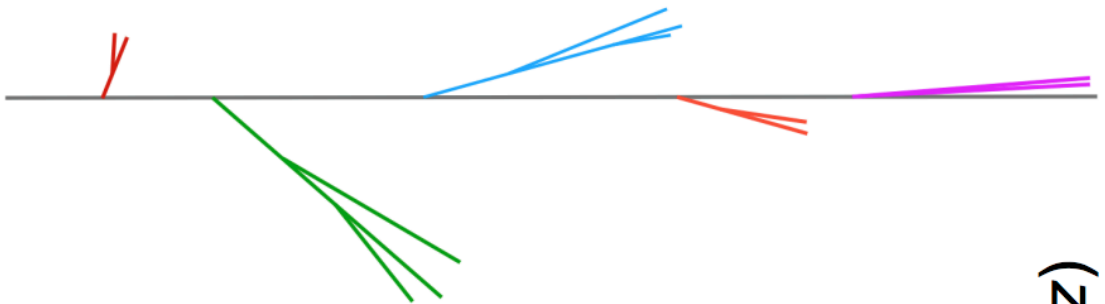
$$\ln \tau_0 = -\ln\frac{1}{z} - 2\ln\frac{1}{\theta}$$

$\tau_0 = m_J^2/p_T^2$

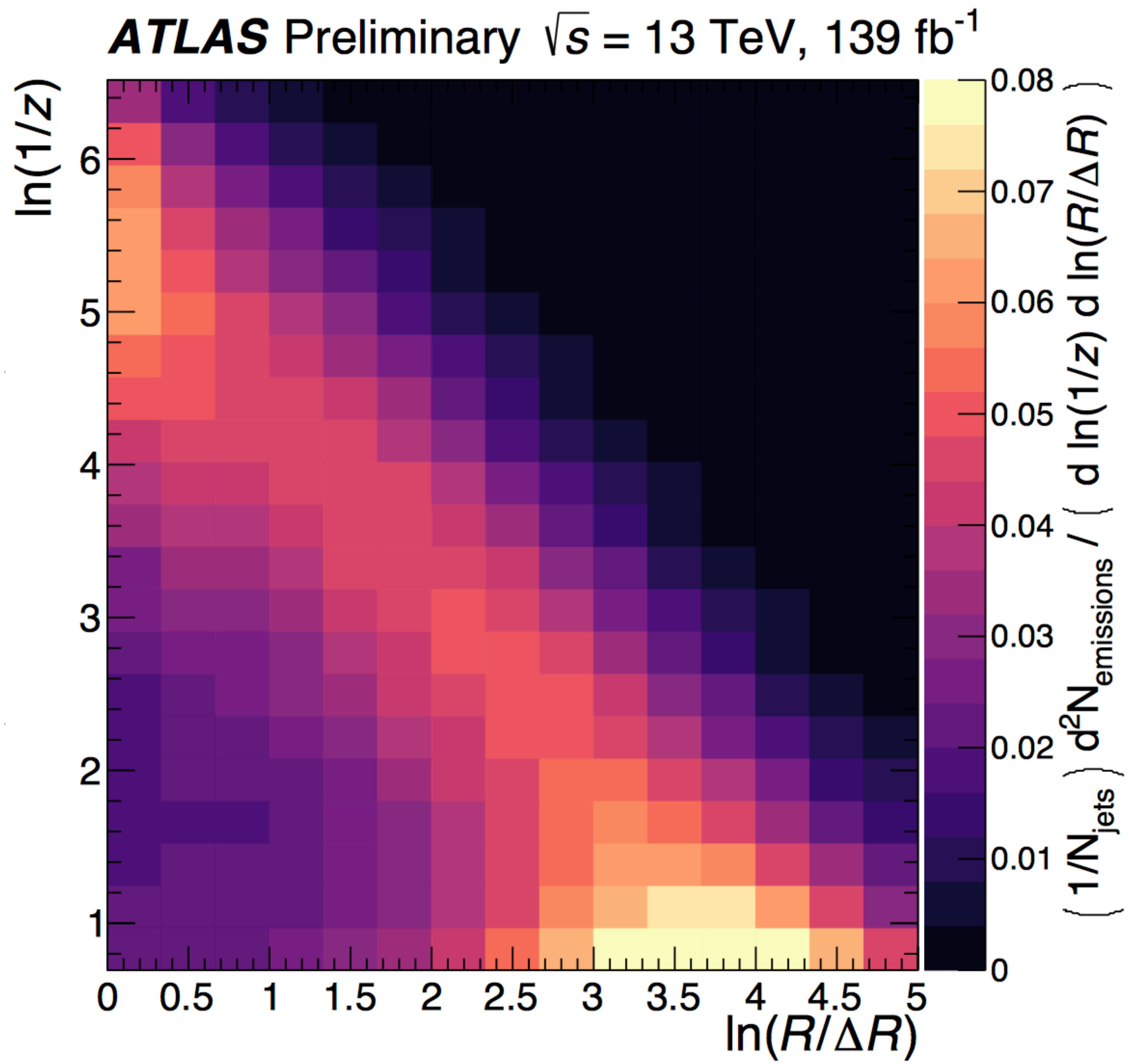


The Lund plane

Andersson, Gustafson, Lönnblad, Pettersson `89
Dreyer, Salam, Soyez `18
ATLAS-CONF-2019-035



Recursive declustering
following the harder branch



Lund diagram for the jet mass

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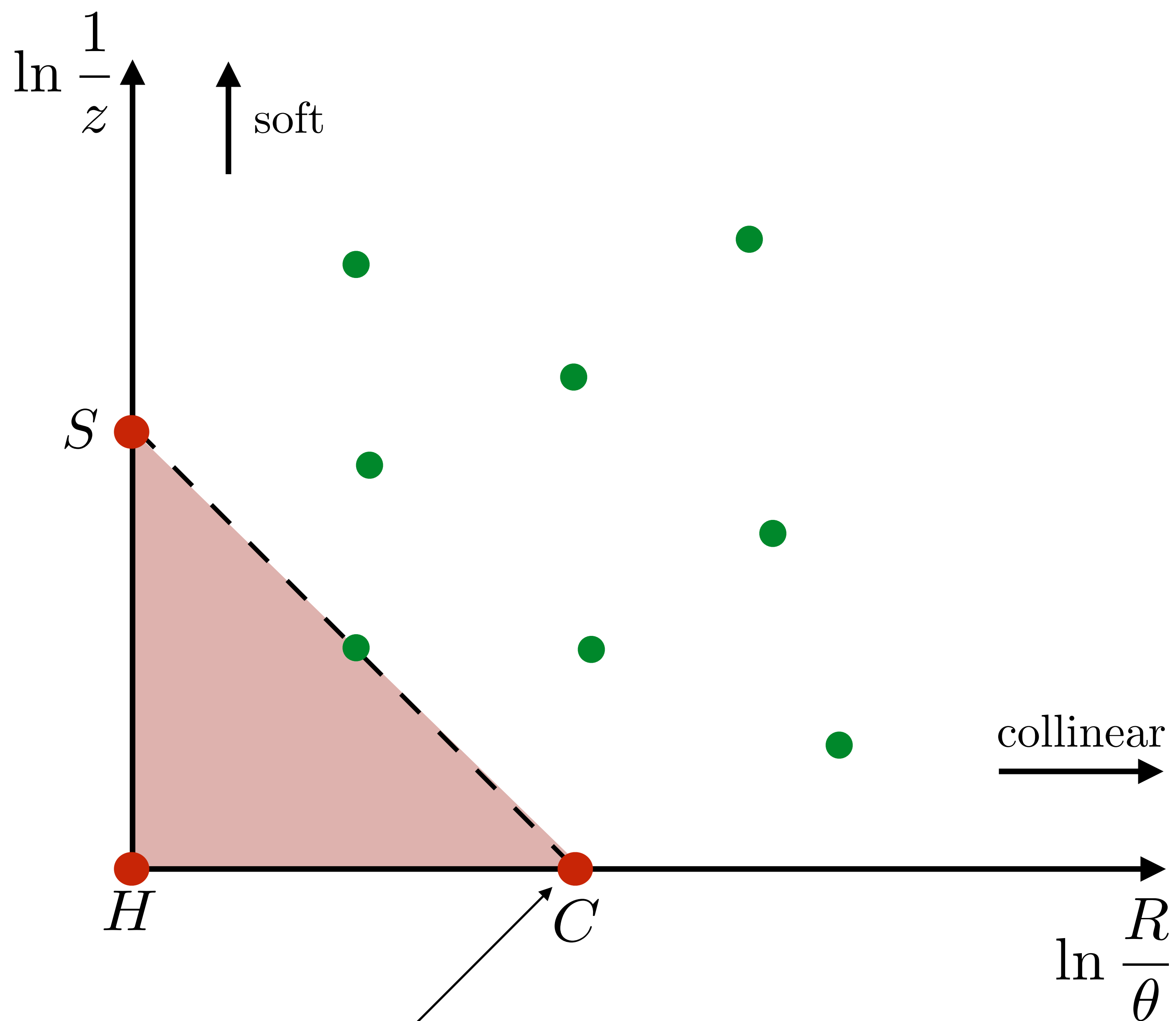
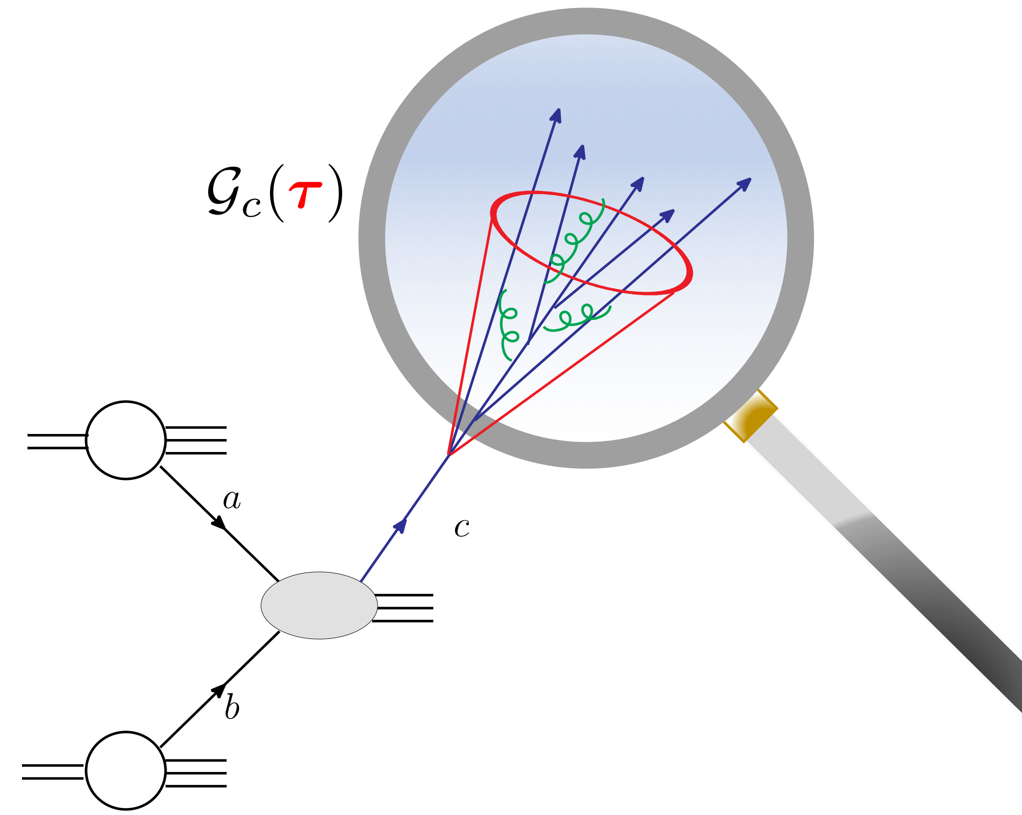


SCET modes relevant for the factorization to resum logarithms of τ_0

The jet mass - factorization

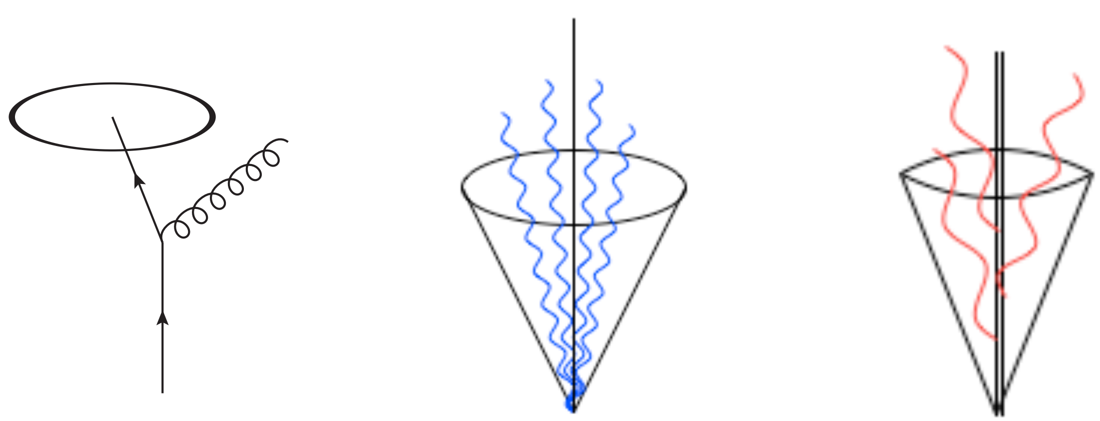
- Jet production in proton-proton collisions

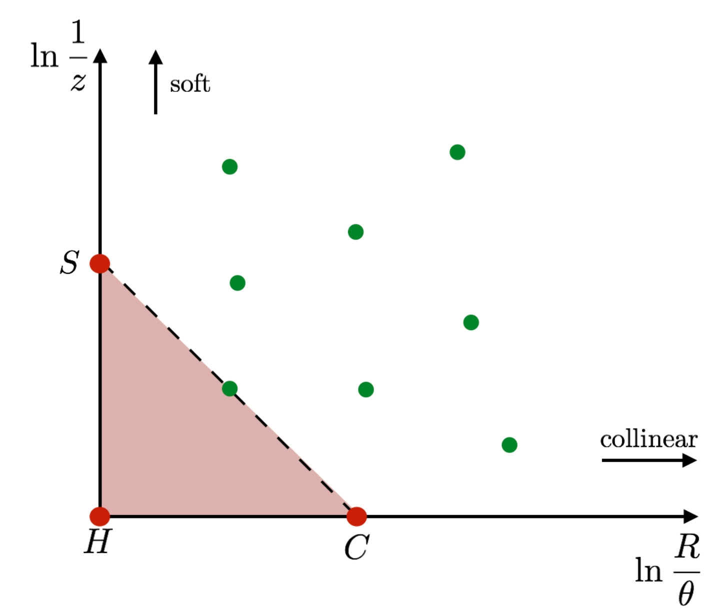


$$\frac{d\sigma^{pp\to(\text{jet}\,\boldsymbol{\tau})X}}{dp_T d\eta \boldsymbol{d\tau}} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c(\boldsymbol{\tau})$$

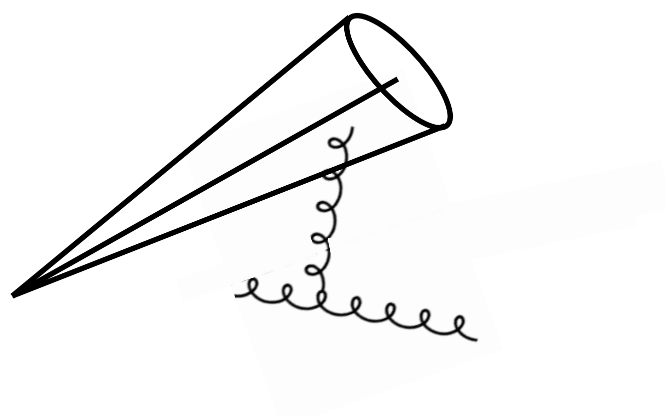
- Refactorization of the jet function

$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_i \mathcal{H}_{i\to j}(z, p_T R, \mu)\, C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu)$$



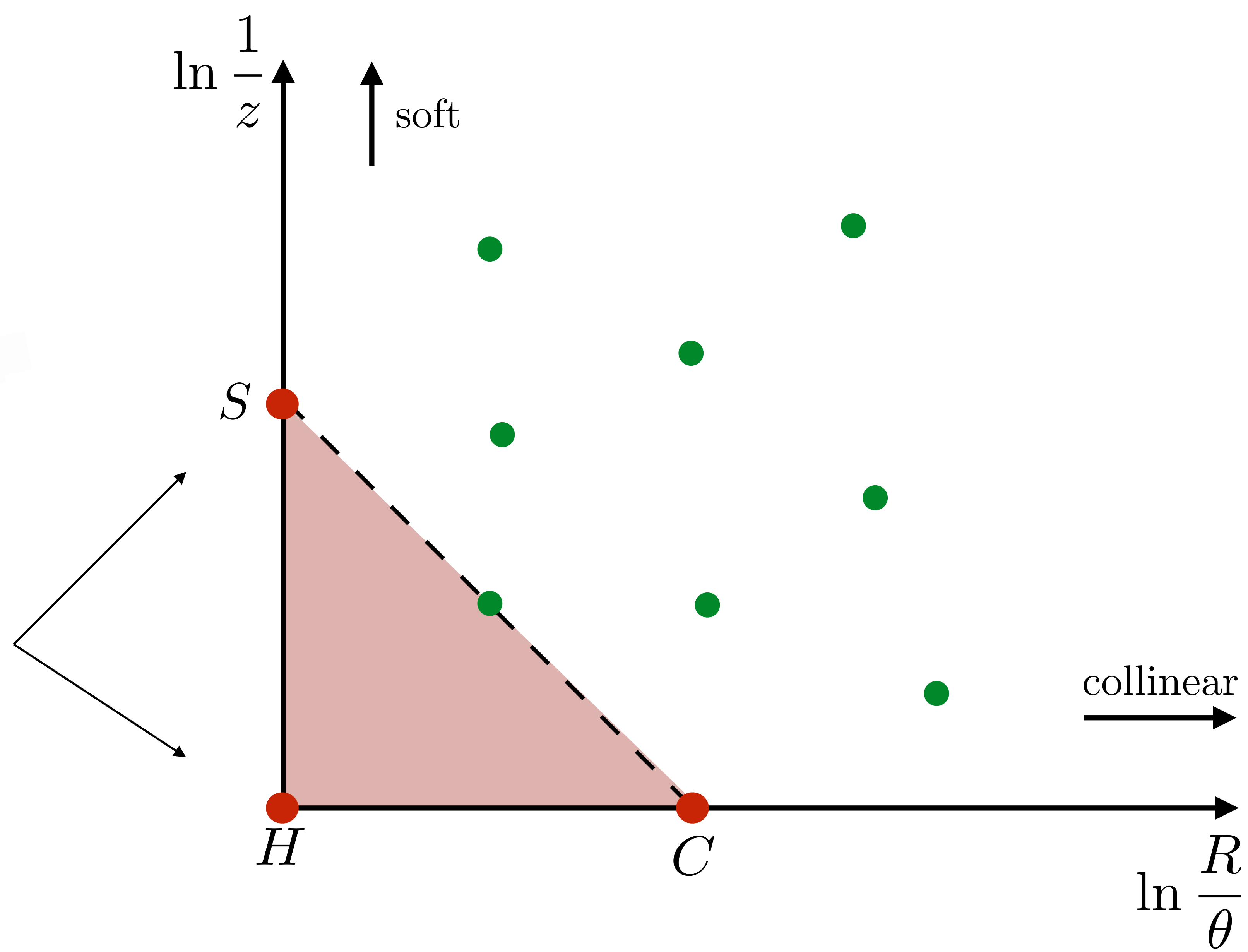


Lund diagram for the jet mass



Non-global logarithms, correlation of the in- and out-of-jet region

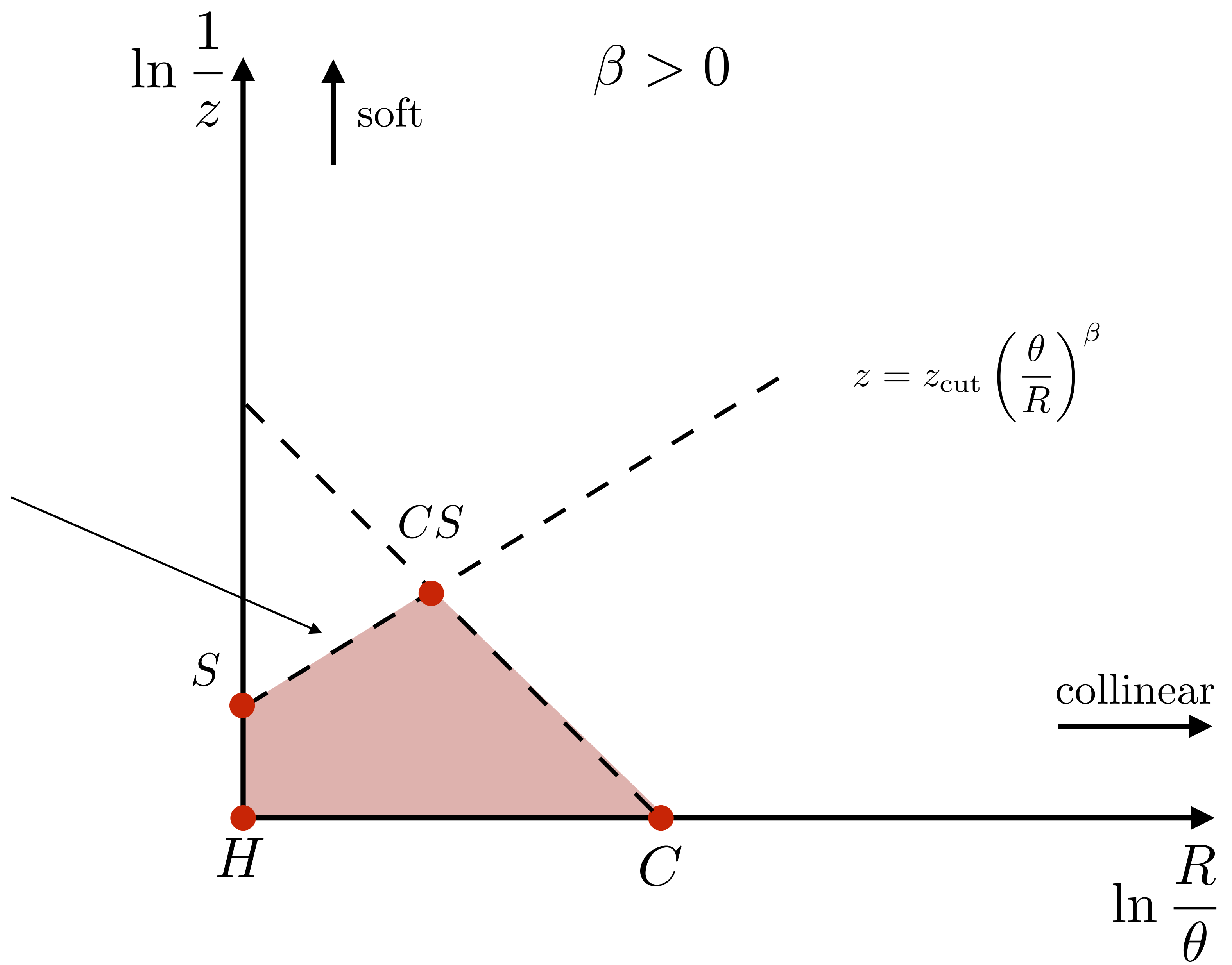
$\alpha_s^n \ln^n(\tau/R^2) \qquad n \geq 2$



Lund diagram for the jet mass

- Soft drop grooming condition

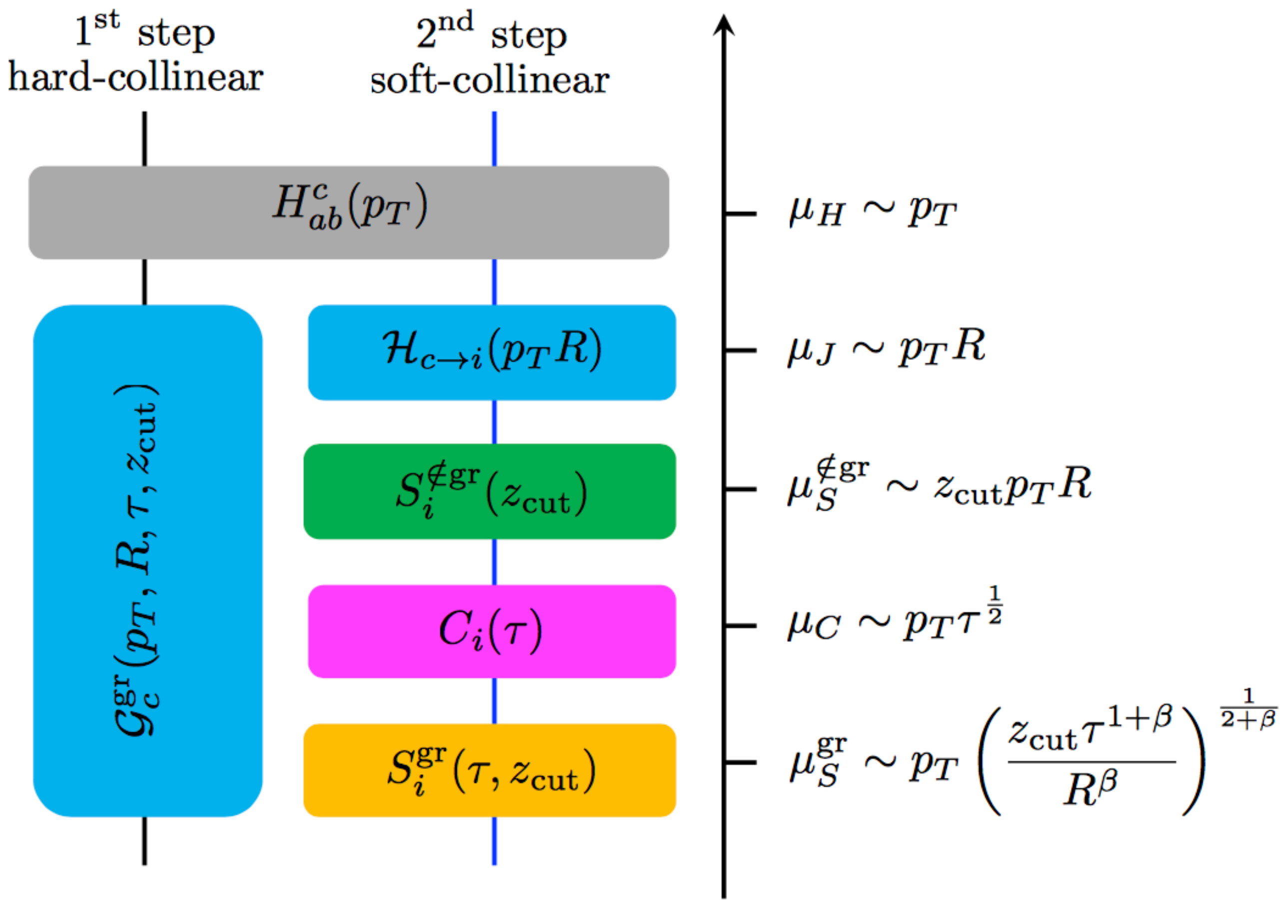
$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

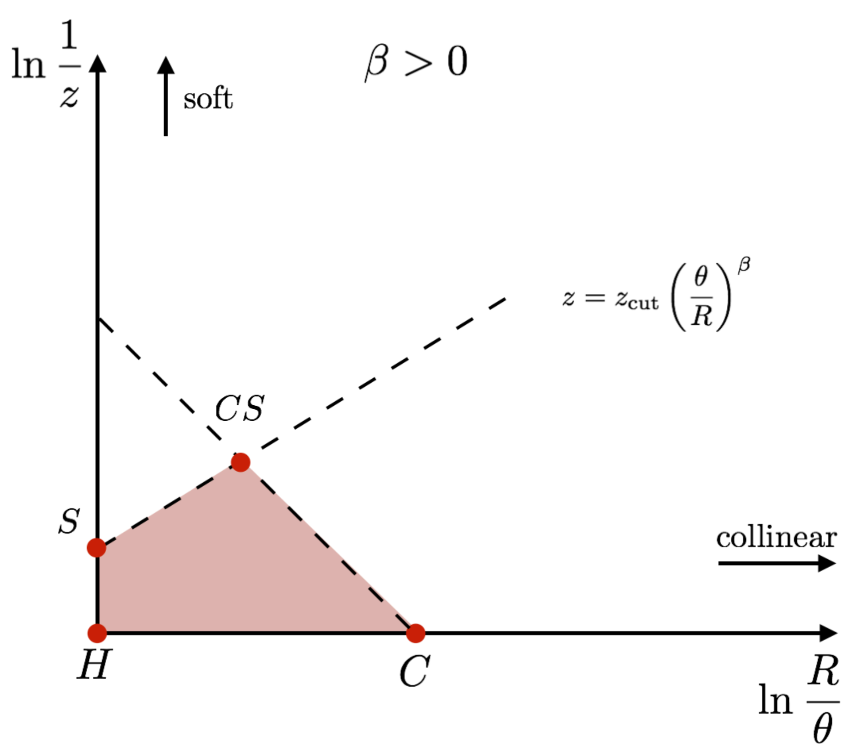


The soft drop jet mass - factorization

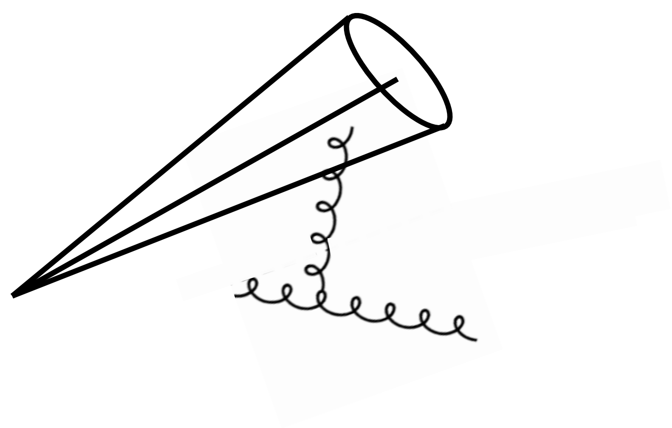
- Same quark/gluon fractions as before
- The groomed jet mass $R \ll 1,\ \tau_{\rm gr}/R^2 \ll z_{\rm cut} \ll 1$

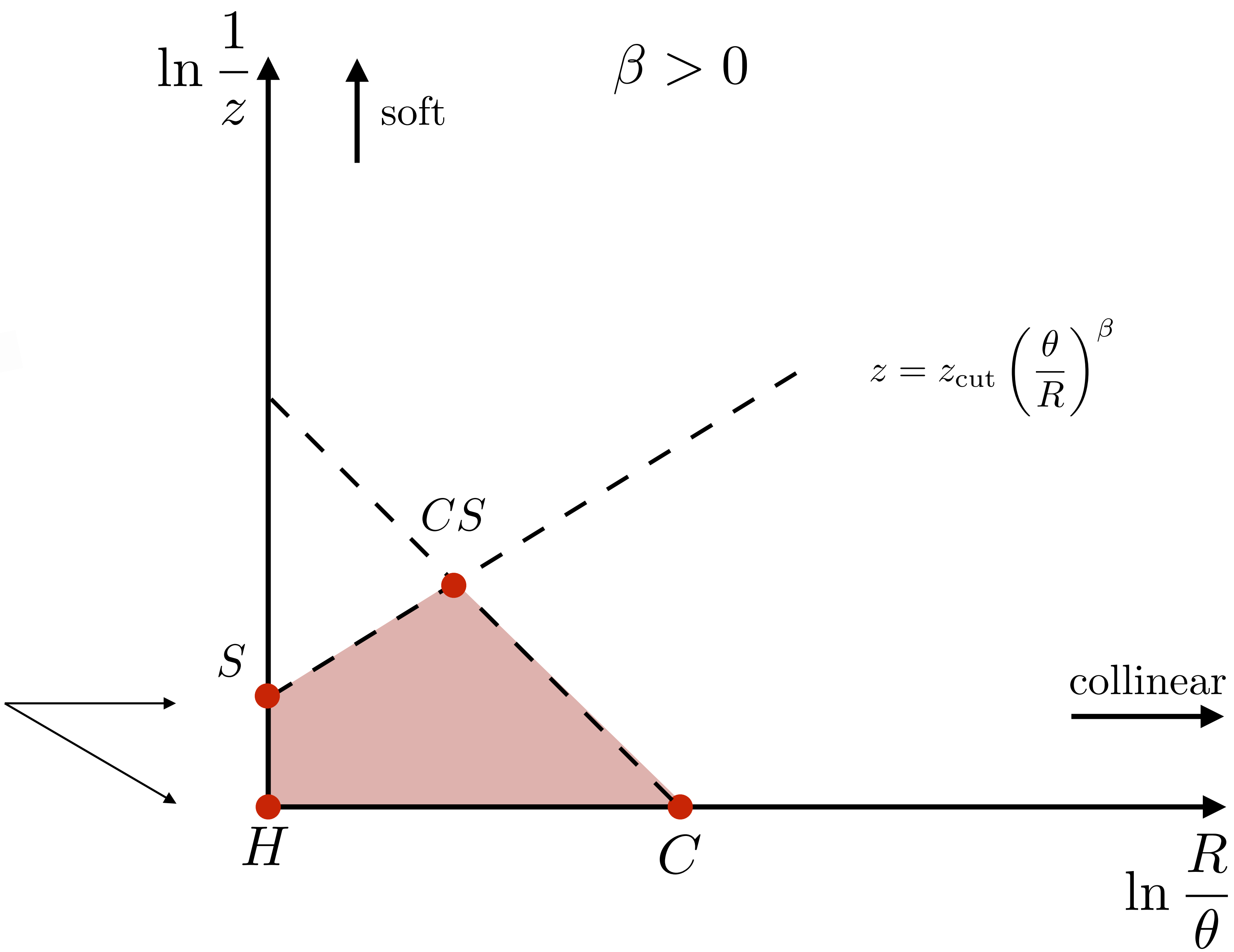
$$\mathcal{G}_i^{\rm gr}(z, p_T R, \tau_{\rm gr}, z_{\rm cut}, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu)\, S_j^{\notin \rm gr}(z_{\rm cut} p_T R, \beta, \mu)\, C_j(\tau_{\rm gr}, p_T, \mu) \otimes S_j^{\rm gr}(\tau_{\rm gr}, p_T, R, z_{\rm cut}, \mu)$$





Lund diagram for the jet mass

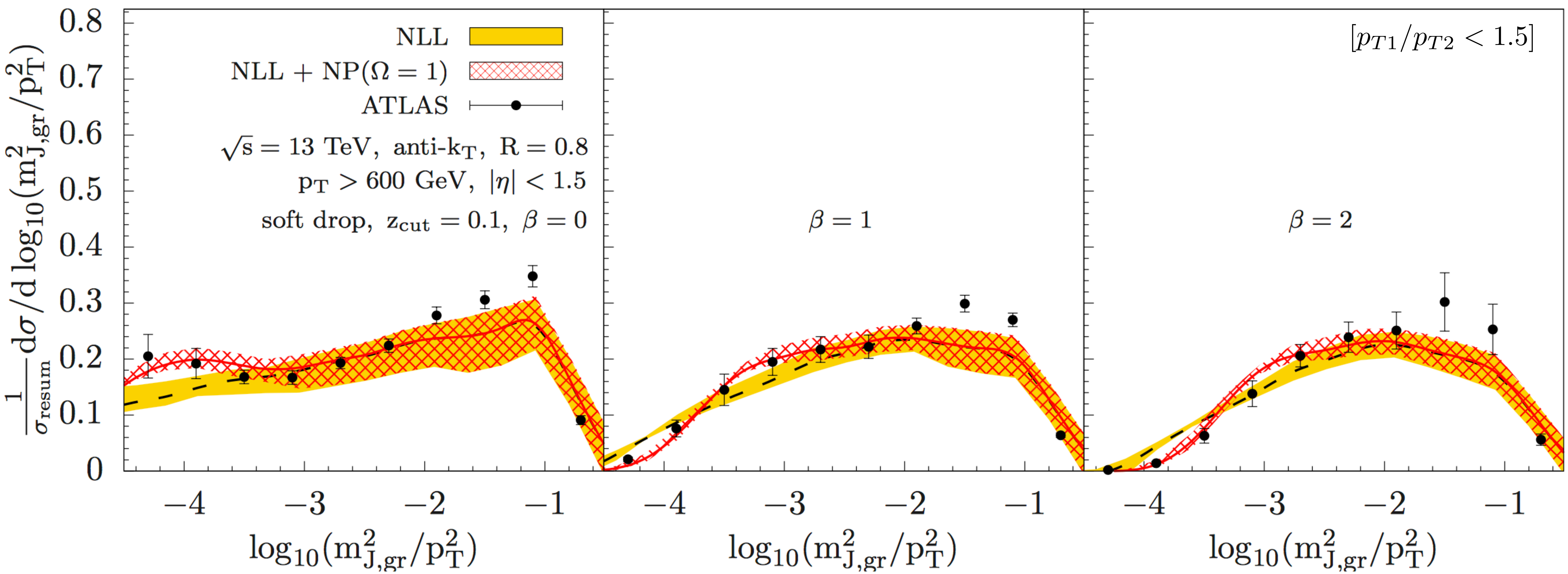




Non-global logarithms, correlation of the in- and out-of-jet region

$\alpha_s^n \ln^n z_{\text{cut}} \qquad n \geq 2$

The soft drop groomed jet mass



ATLAS, PRL 121 (2018) 092001

- Extraction of the QCD strong coupling constant

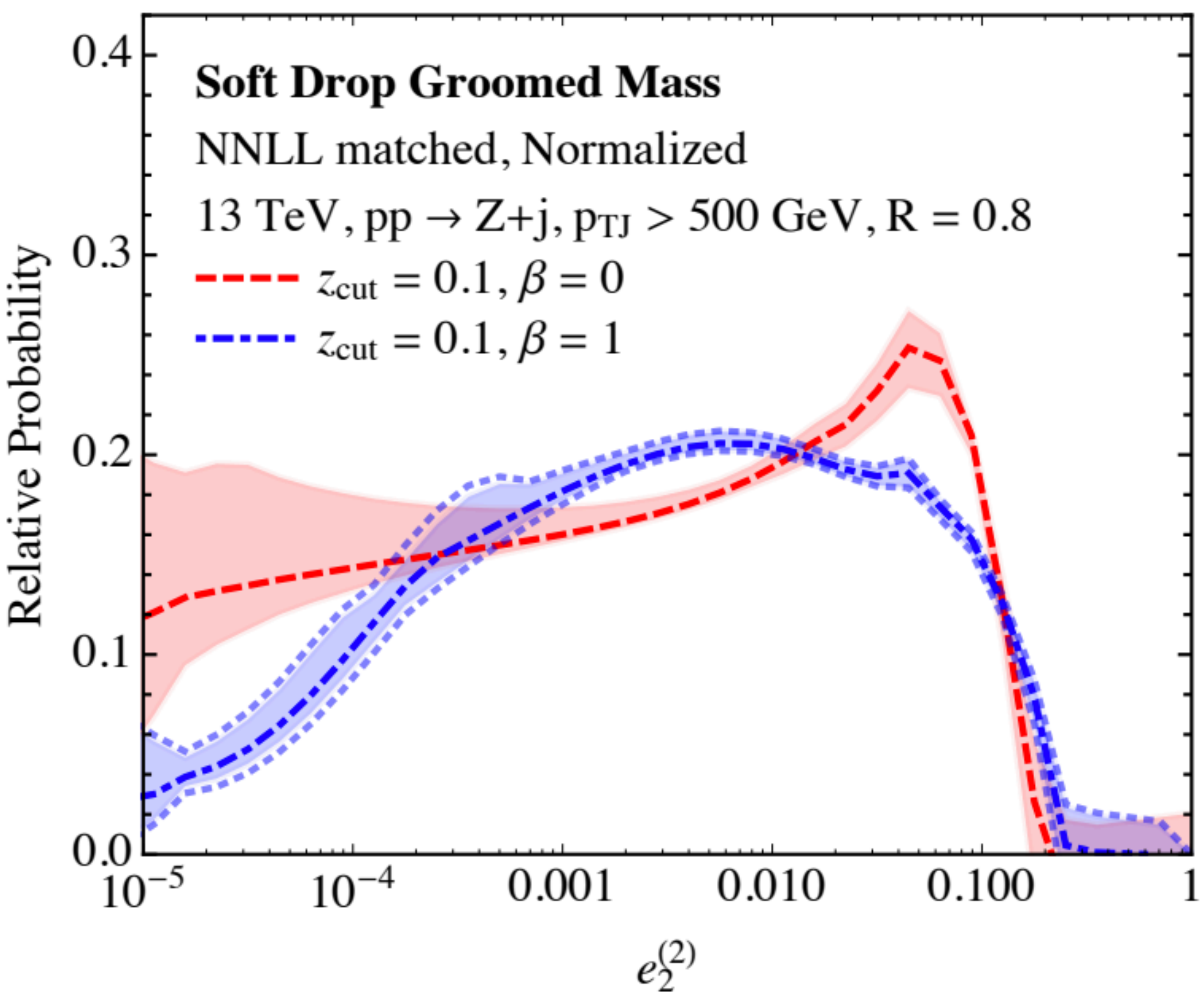
  Les Houches `17

- Theory calculations at NLL/NNLL *Frye, Larkoski, Schwartz, Yan `16, Marzani, Schunk, Soyez `17, `18 Kang, Lee, Liu, FR `17*

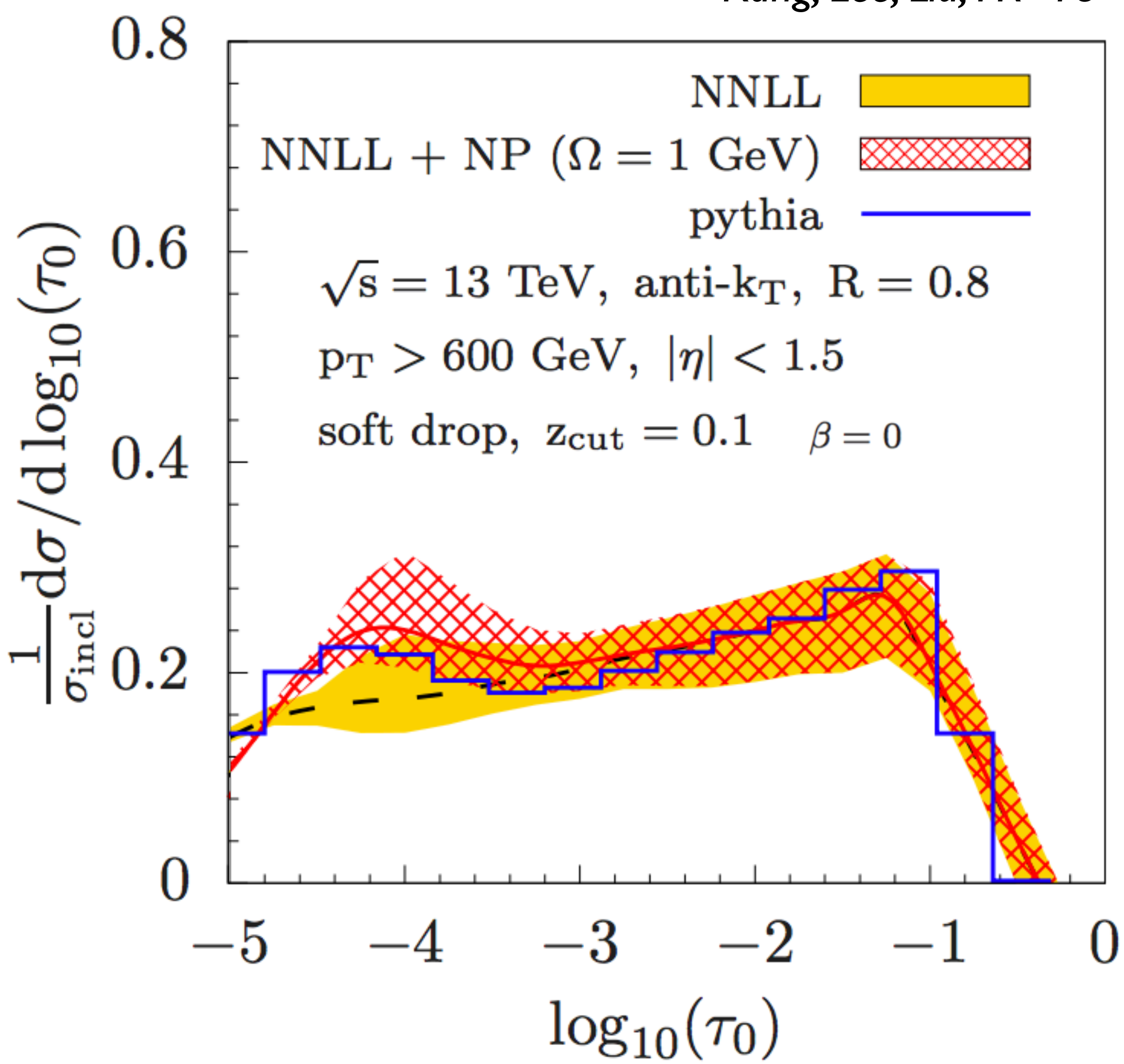
- Non-perturbative effects *Hoang, Mantry, Pathak, Stewart `19*

The groomed jet mass at NNLL

Frye, Larkoski, Schwartz, Yan `16



Kang, Lee, Liu, FR `18



$$e_2^{(2)} = \tau_0 = m_J^2/p_T^2$$

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- The jet radius after grooming
- Other observables
- Conclusions

The soft drop groomed jet radius

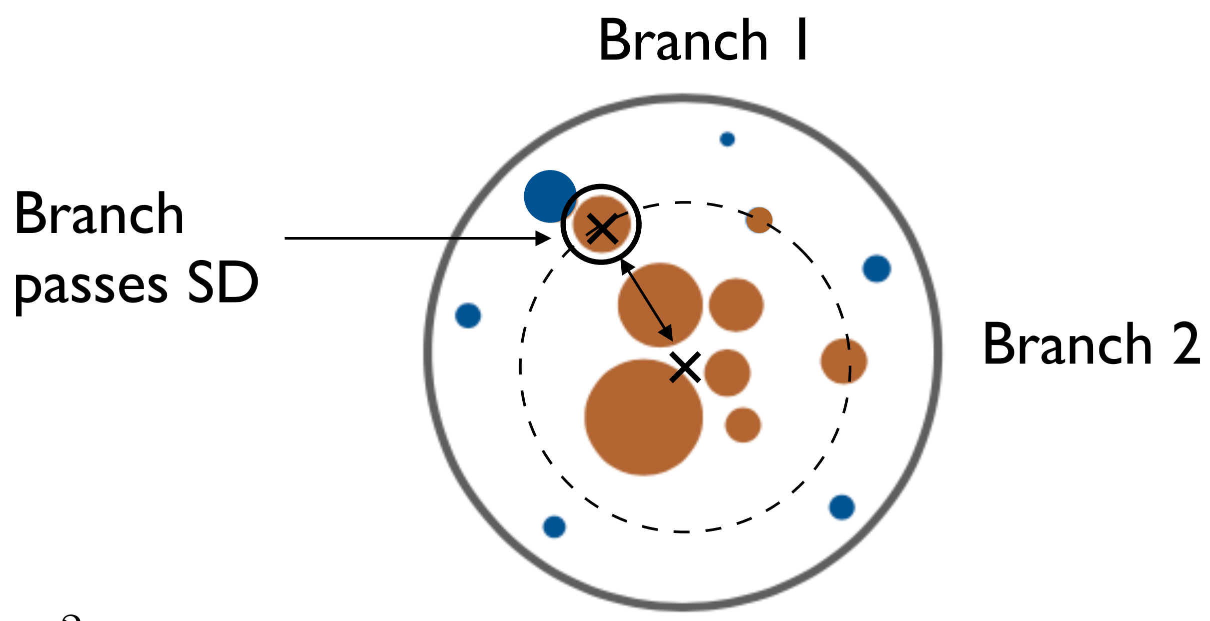
Larkoski, Marzani, Soyez, Thaler `14
Kang, Lee, Liu, Neill, FR `19

- Groomed radius $\theta_g = \frac{\Delta R_{12}}{R} = \frac{R_g}{R}$

$$\Delta R_{12} = R_g = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

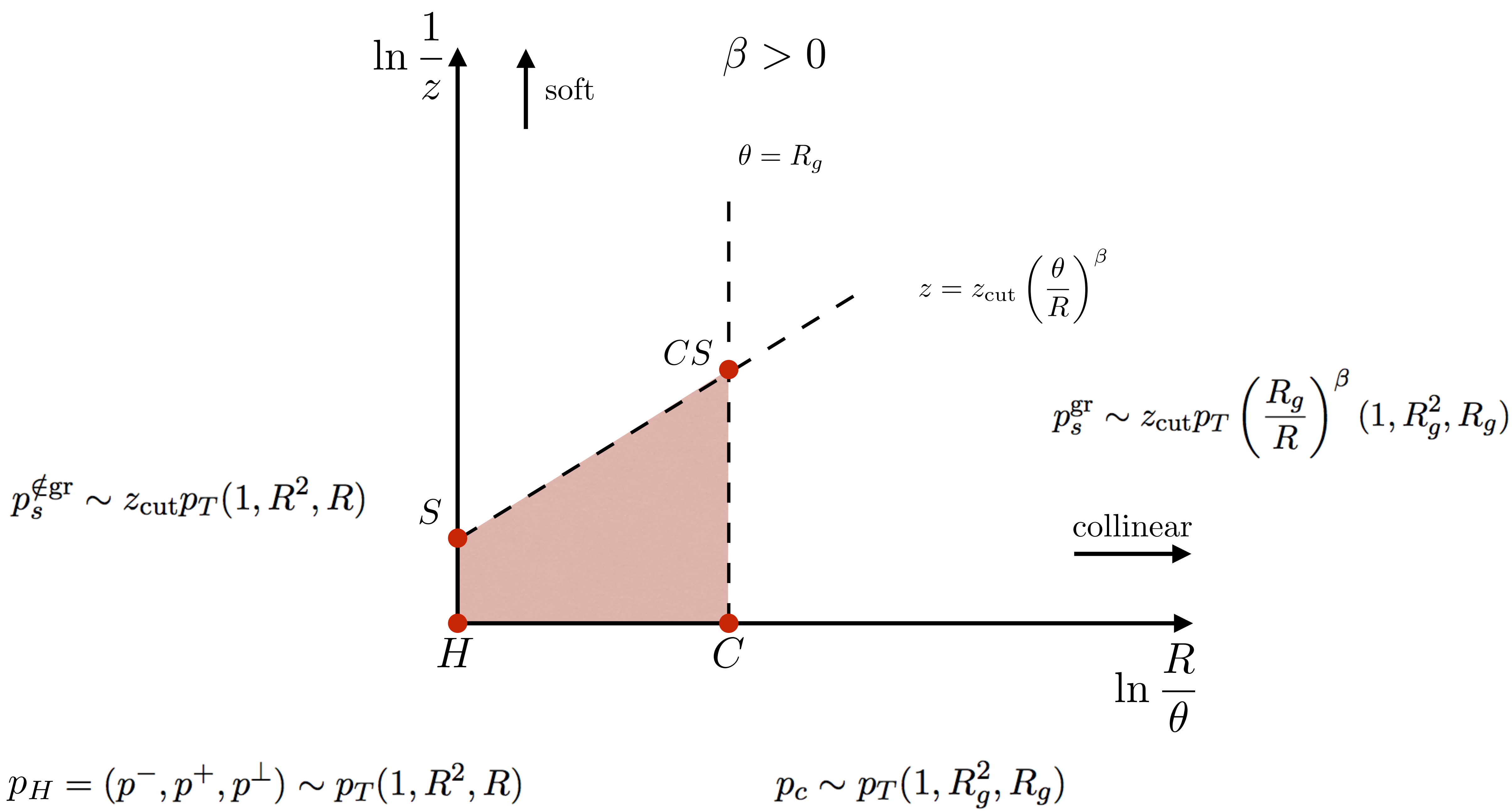
$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R}\right)^\beta$$

- Groomed radius $\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\,\mathrm{d}p_T\,\mathrm{d}\theta_g}$



- Key observable to characterize SD groomed jet
- Related to the active area of the groomed jet $\sim \pi R_g^2$
- Used to calculate Sudakov safe observables

Lund diagram for the groomed jet radius R_g



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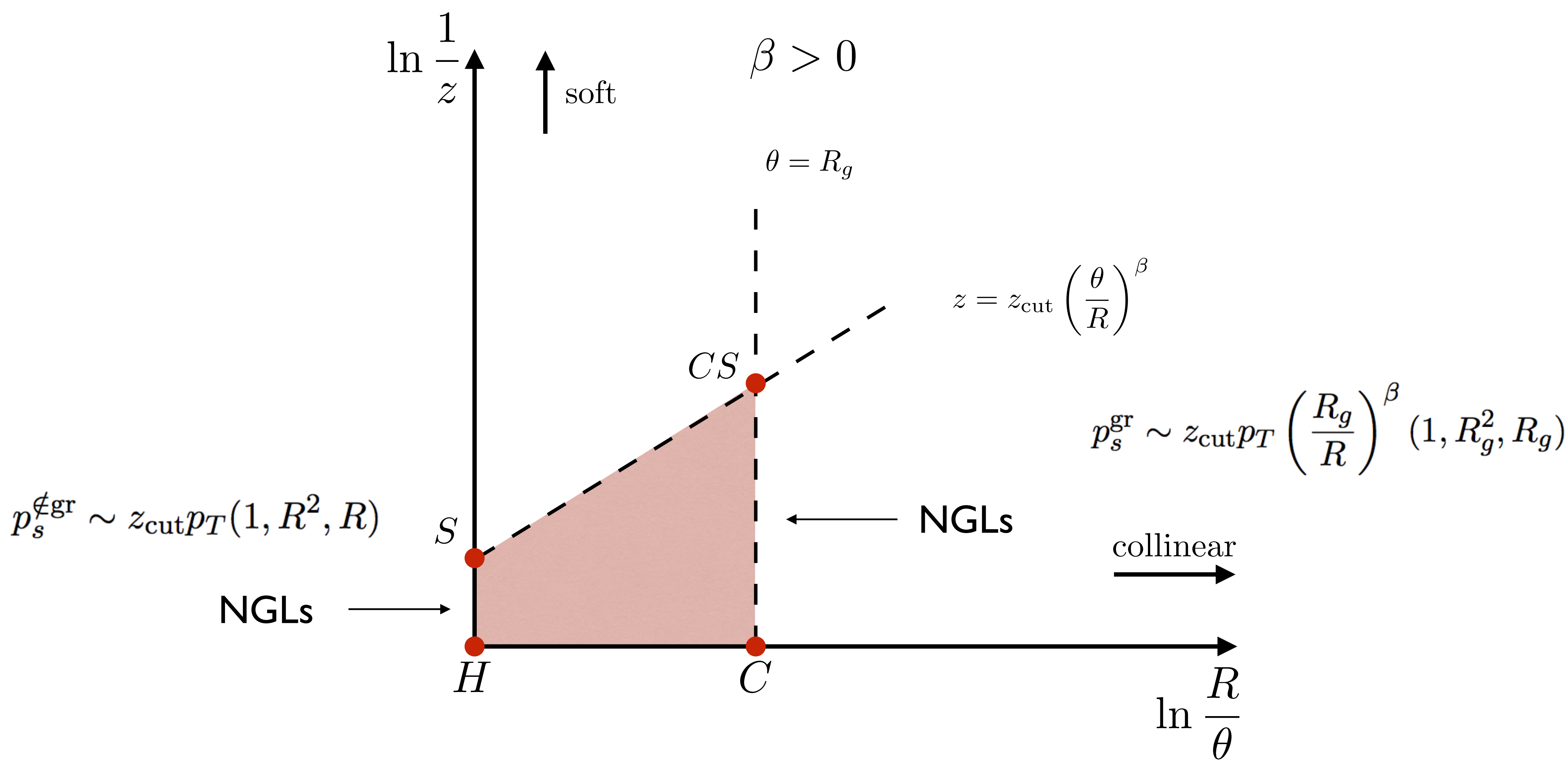


$$= (p^-, p^+, p^\perp) \sim p_T(1, R^2, R)$$

$$p_c \sim p_T(1, R_g^2, R_g)$$

The groomed radius - factorization

- Cumulative cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\,\mathrm{d}p_T\,\mathrm{d}\theta_g} = \frac{\mathrm{d}}{\mathrm{d}\theta_g}\frac{\mathrm{d}\Sigma(\theta_g)}{\mathrm{d}\eta\,\mathrm{d}p_T}$$

- Relevant scales

$$\mu_H \sim p_T R$$

$$\mu_{S\notin\mathrm{gr}} \sim z_{\mathrm{cut}} p_T R$$

$$\mu_C \sim \theta_g p_T R$$

$$\mu_{S\in\mathrm{gr}} \sim z_{\mathrm{cut}} \theta_g^{1+\beta} p_T R$$

- Refactorization of the jet function

$$\mathcal{G}_c\left(z, \theta_g, p_T R, \mu; z_{\mathrm{cut}}, \beta\right) = \sum_{i=q,\bar{q},g} \sum_n \mathcal{H}^n_{c\to i}\left(z, p_T R, \mu\right) \otimes_\Omega S^{\notin\mathrm{gr}}_{i,n}\left(z_{\mathrm{cut}} p_T R, \mu; \beta\right)$$

$$\times \sum_m C^m_i\left(\theta_g p_T R, \mu\right) \otimes_\Omega S^{\in\mathrm{gr}}_{i,m}\left(z_{\mathrm{cut}} \theta_g^{1+\beta} p_T R, \mu; \beta\right)$$

The groomed radius - factorization

- Cumulative cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\,\mathrm{d}p_T\,\mathrm{d}\theta_g} = \frac{\mathrm{d}}{\mathrm{d}\theta_g}\frac{\mathrm{d}\Sigma(\theta_g)}{\mathrm{d}\eta\,\mathrm{d}p_T}$$

- Refactorization of the jet function

$$\mathcal{G}_c\left(z,\theta_g,p_T R,\mu;z_{\rm cut},\beta\right) = \sum_{i=q,\bar{q},g}\sum_n \mathcal{H}^n_{c\to i}\left(z,p_T R,\mu\right)\otimes_\Omega S^{\notin \rm gr}_{i,n}\left(z_{\rm cut}p_T R,\mu;\beta\right)$$

← as before

$$\times\sum_m C_i^m\left(\theta_g p_T R,\mu\right)\otimes_\Omega S^{\in \rm gr}_{i,m}\left(z_{\rm cut}\theta_g^{1+\beta}p_T R,\mu;\beta\right)$$

At NLL′ $\langle C_i\left(\theta_g p_T R,\mu\right)\rangle\langle S_i^{\in\rm gr}\left(z_{\rm cut}\theta_g^{1+\beta}p_T R,\mu;\beta\right)\rangle\times\mathcal{S}^{\rm C/A}_{i,\rm NGL}\left(t,\theta_g\right)\;\mathcal{A}^{\rm C/A}_{i,\rm Abel}\left(t,\theta_g\right)$

Non-global and Abelian clustering logarithms

The groomed radius - factorization

- Refactorization of the jet function

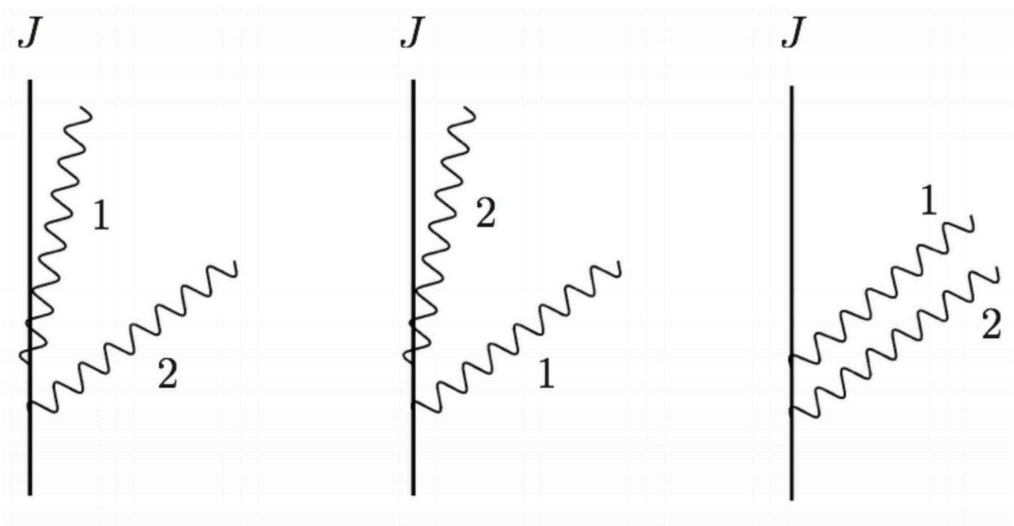
$$\mathcal{G}_c\left(z,\theta_g,p_T R,\mu;z_{\rm cut},\beta\right) = \sum_{i=q,\bar{q},g}\sum_n \mathcal{H}^n_{c\to i}\left(z,p_T R,\mu\right)\otimes_\Omega S^{\notin {\rm gr}}_{i,n}\left(z_{\rm cut}p_T R,\mu;\beta\right)$$
$$\times\sum_m C^m_i\left(\theta_g p_T R,\mu\right)\otimes_\Omega S^{\in {\rm gr}}_{i,m}\left(z_{\rm cut}\theta_g^{1+\beta}p_T R,\mu;\beta\right)$$

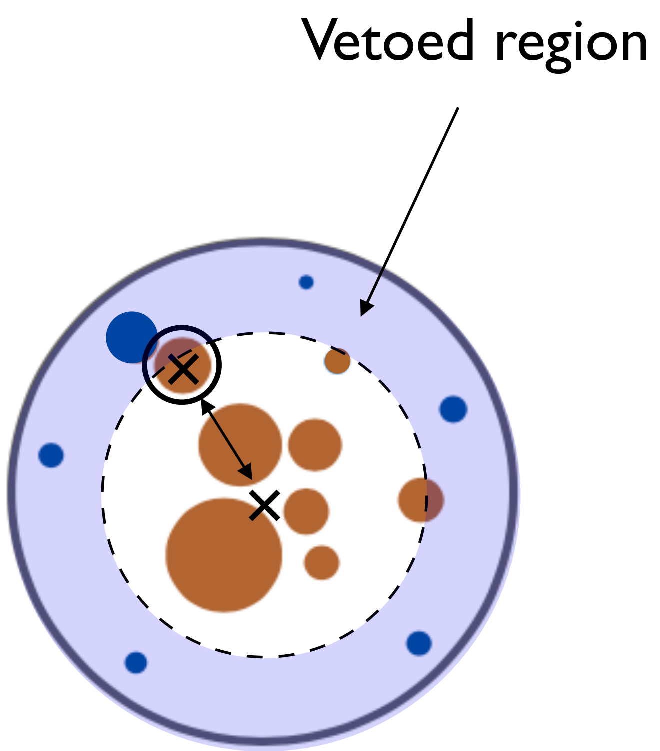
- Based on equivalence to the jet veto case

Emissions outside the groomed jet are vetoed with $z_{\rm cut}\theta_g^\beta p_T$

- N collinear-soft emissions $\mathcal{M}_N = \prod_i^N \mathcal{M}_1(J_i)$

- Example of two emissions

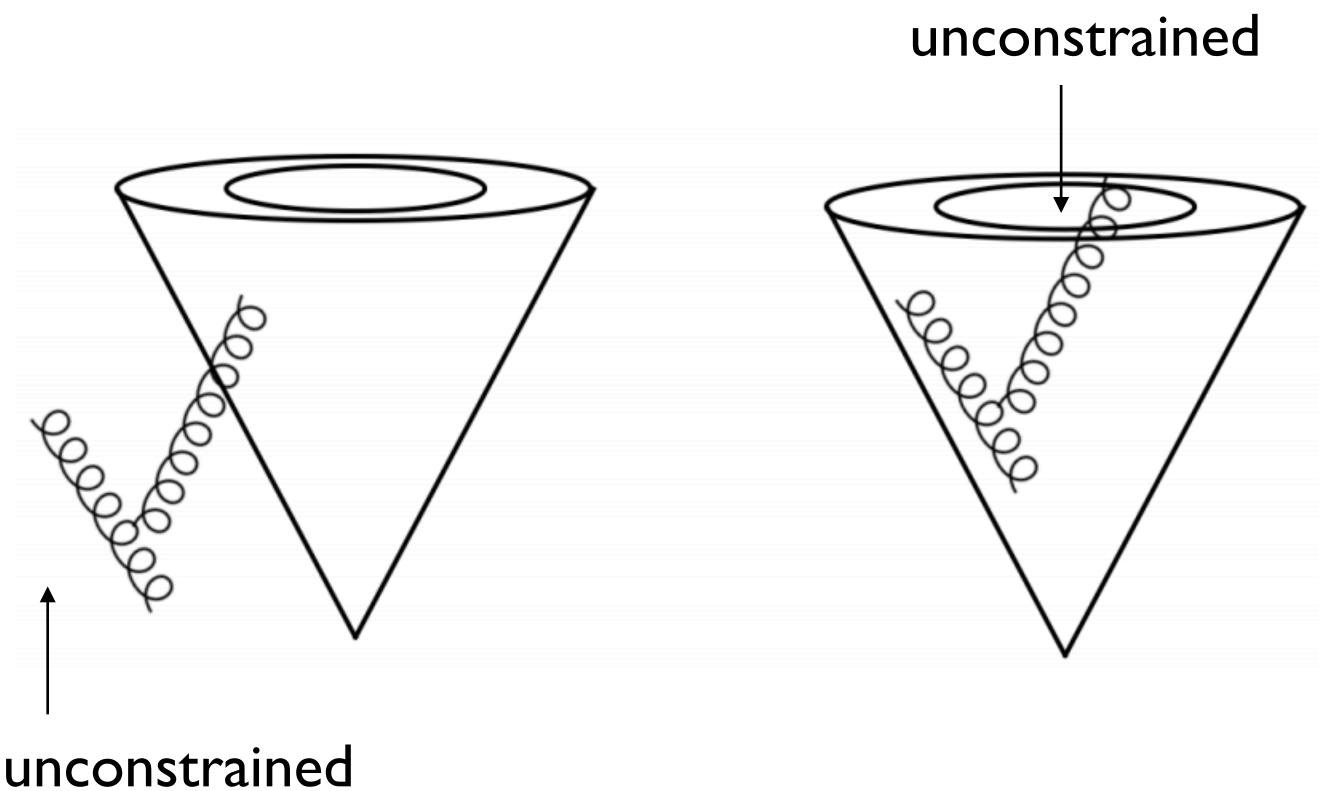


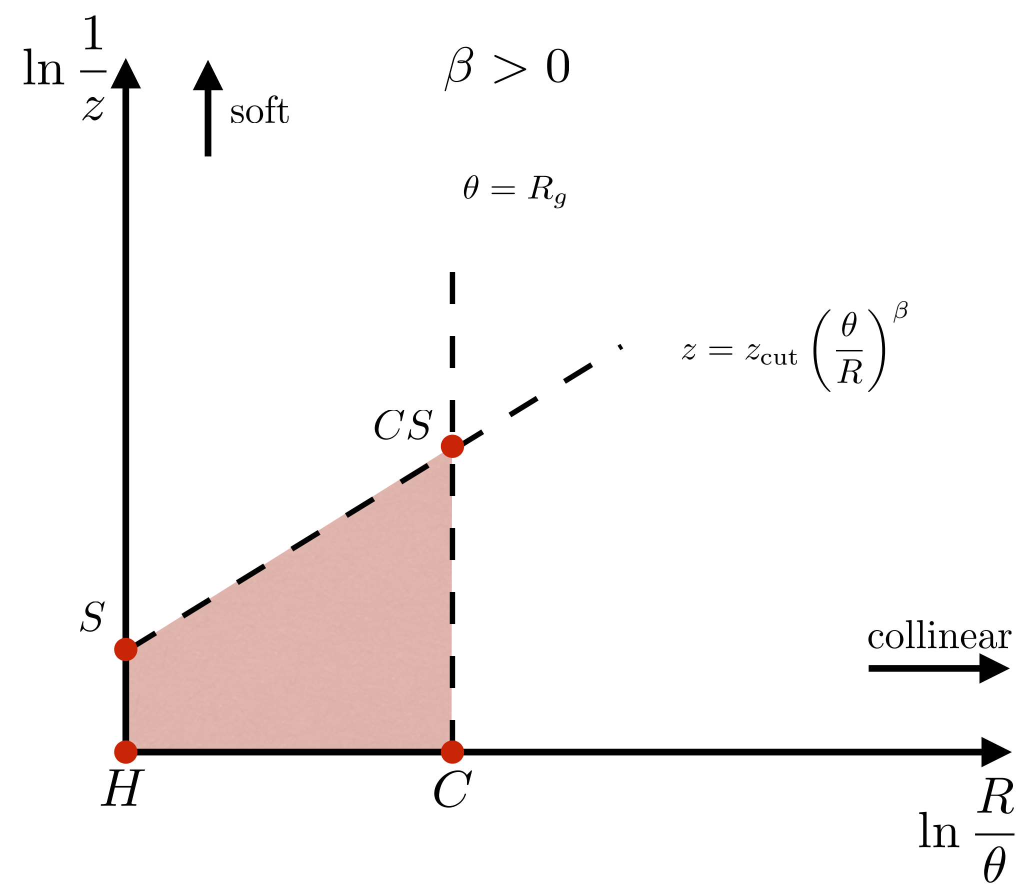


Non-global logarithms

- Two types of NGLs

  Dasgupta, Salam `01



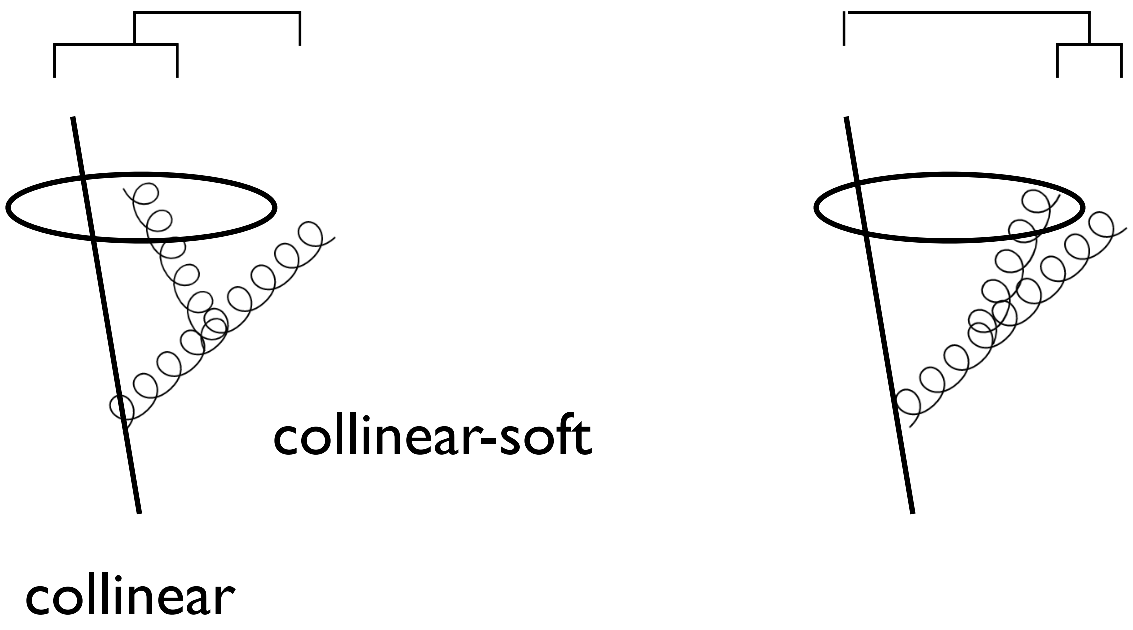


$\alpha_s^n \ln^n(z_{\rm cut})$ $\alpha_s^n \ln^n(z_{\rm cut}\theta_g^\beta)$

Non-global and Abelian clustering logarithms

- NGLs with C/A clustering

Dasgupta, Salam `01
Appelby, Seymour `02
Delenda, Appelby, Dasgupta, Banfi `06
Delenda, Khelifa-Kerfa `12
Kelley, Walsh, Zuberi `12
Neill `18
…



Non-global and Abelian clustering logarithms

- NGLs with C/A clustering

Dasgupta, Salam `01
Appelby, Seymour `02
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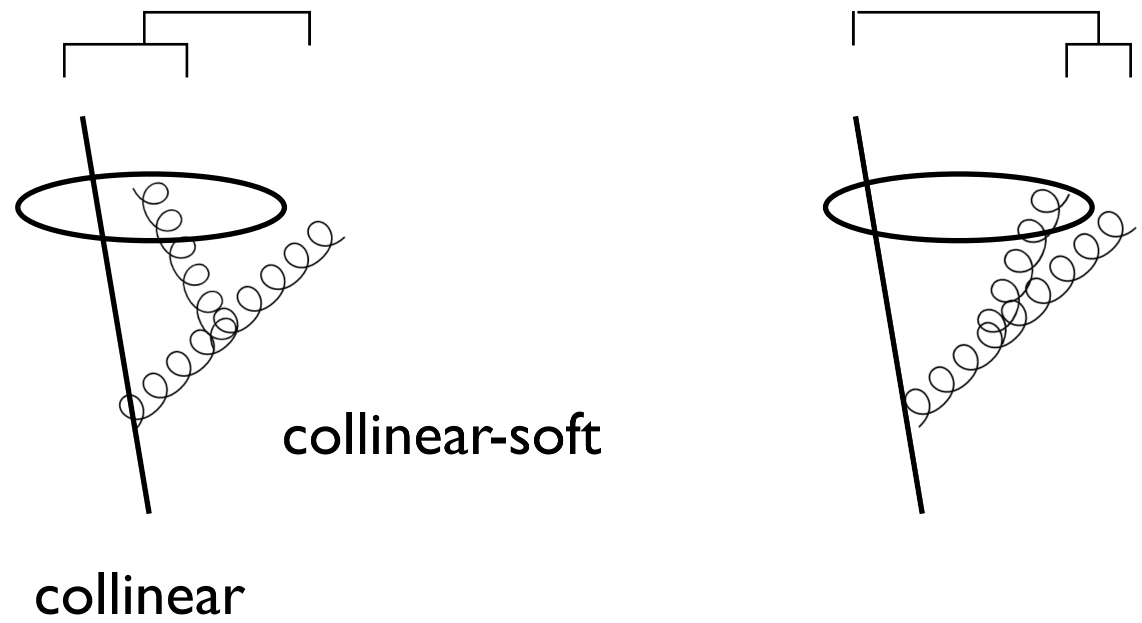
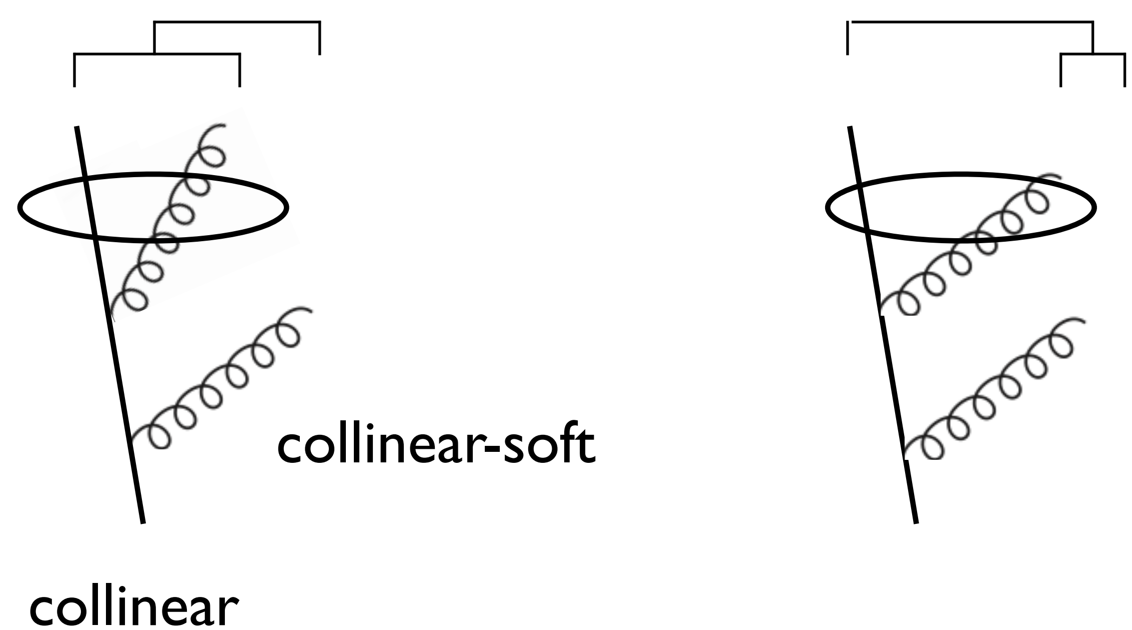
…



- Abelian C/A clustering



Non-global and Abelian clustering logarithms

- NGLs with C/A clustering

  Dasgupta, Salam `01
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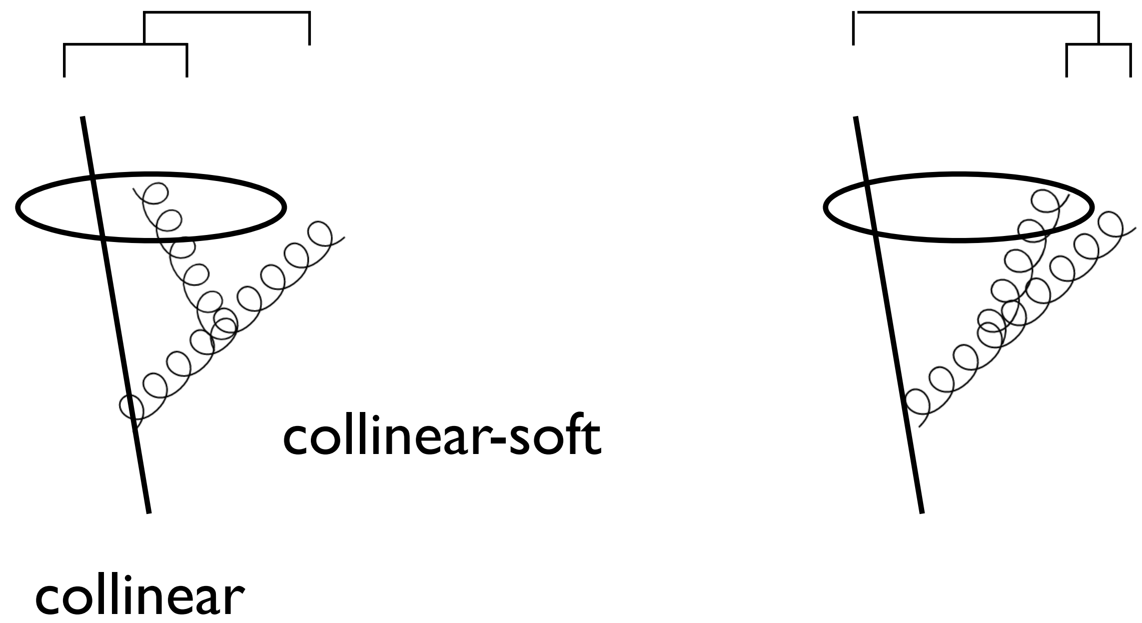
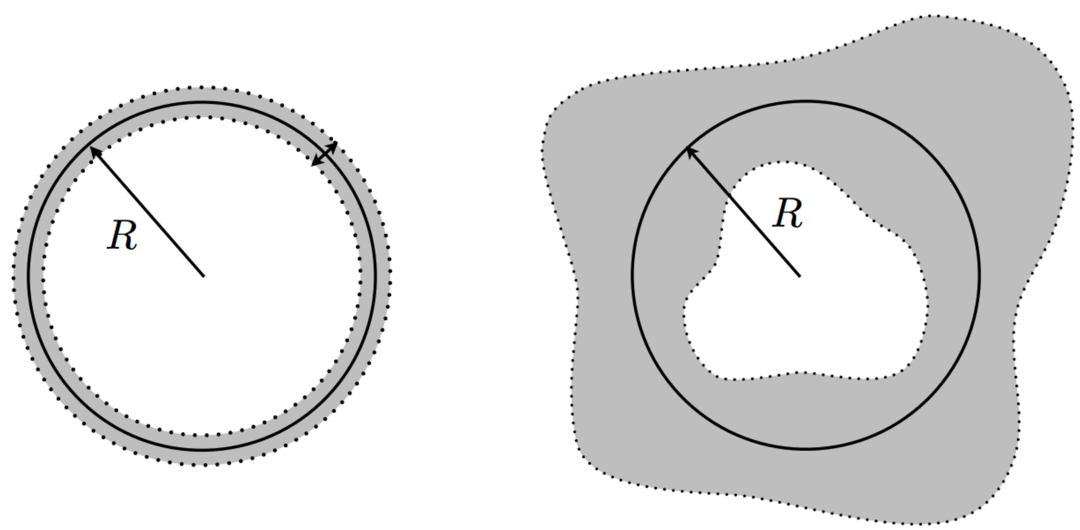




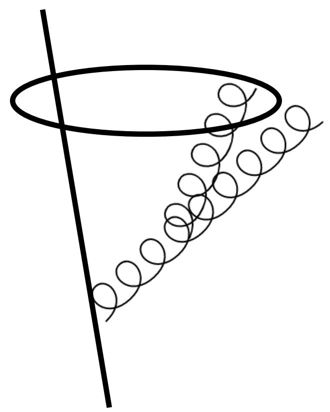
(a) anti-k_T (b) C/A or k_T

Kelley, Walsh, Zuberi `12

Non-global logarithms with C/A clustering effects

- Fixed order without clustering

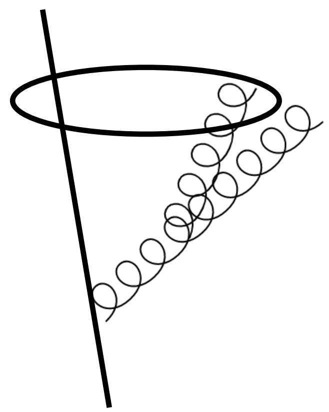
$$
\begin{aligned}
\mathcal{S}_{i,\mathrm{NGL}}(L,\theta_g) =& 1 - C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} \int_{1\in J} \mathrm{d}c_1 \frac{\mathrm{d}\phi_1}{2\pi} \int_{2\notin J} \mathrm{d}c_2 \frac{\mathrm{d}\phi_2}{2\pi} \\
& \times \Theta(x_1 - x_2)\, \Theta(x_2 - z_{\mathrm{cut}}\theta_g^\beta)\, \frac{\cos\phi_2}{(1 - c_1 c_2 - s_1 s_2 \cos\phi_2)\, s_1 s_2} \\
& \approx 1 - C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{\pi^2}{3} \ln^2(z_{\mathrm{cut}}\theta_g^\beta)
\end{aligned}
$$



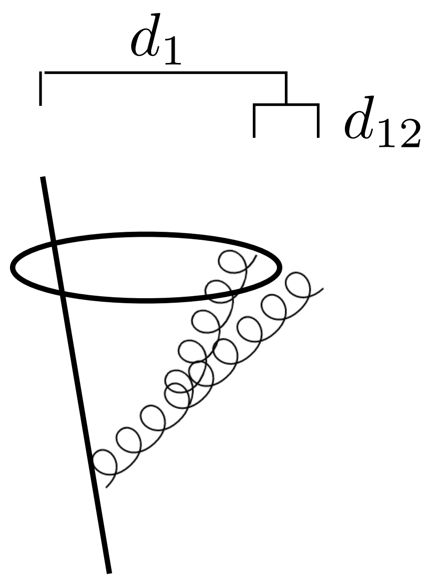
Non-global logarithms with C/A clustering effects

- Fixed order without clustering

$$\mathcal{S}_{i,\mathrm{NGL}}(L,\theta_g) = 1 - C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} \int_{1\in J} \mathrm{d}c_1 \frac{\mathrm{d}\phi_1}{2\pi} \int_{2\notin J} \mathrm{d}c_2 \frac{\mathrm{d}\phi_2}{2\pi}$$
$$\times\, \Theta(x_1 - x_2)\, \Theta(x_2 - z_{\mathrm{cut}}\theta_g^\beta)\, \frac{\cos\phi_2}{(1 - c_1 c_2 - s_1 s_2 \cos\phi_2)\, s_1 s_2}$$
$$\approx 1 - C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{\pi^2}{3} \ln^2(z_{\mathrm{cut}}\theta_g^\beta)$$



- With C/A clustering include $\Theta(d_{12} - d_1)$

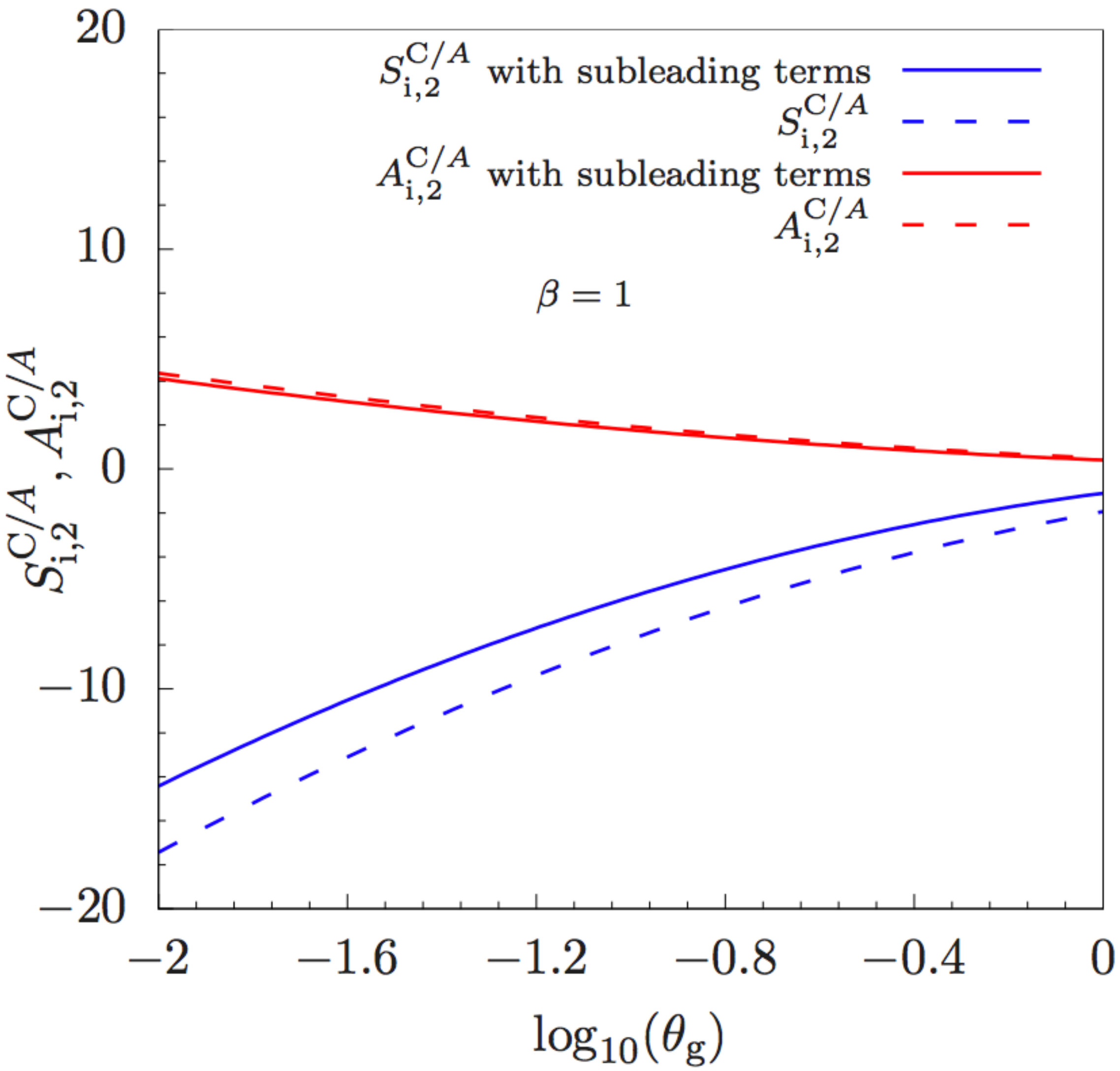


$$\mathcal{S}_{i,\mathrm{NGL}}(L,\theta_g) \approx 1 - C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{\pi^2}{3} \ln^2(z_{\mathrm{cut}}\theta_g^\beta) \times \frac{4}{9} + \mathcal{O}(\theta_g)$$

Reduces the size of the NGL

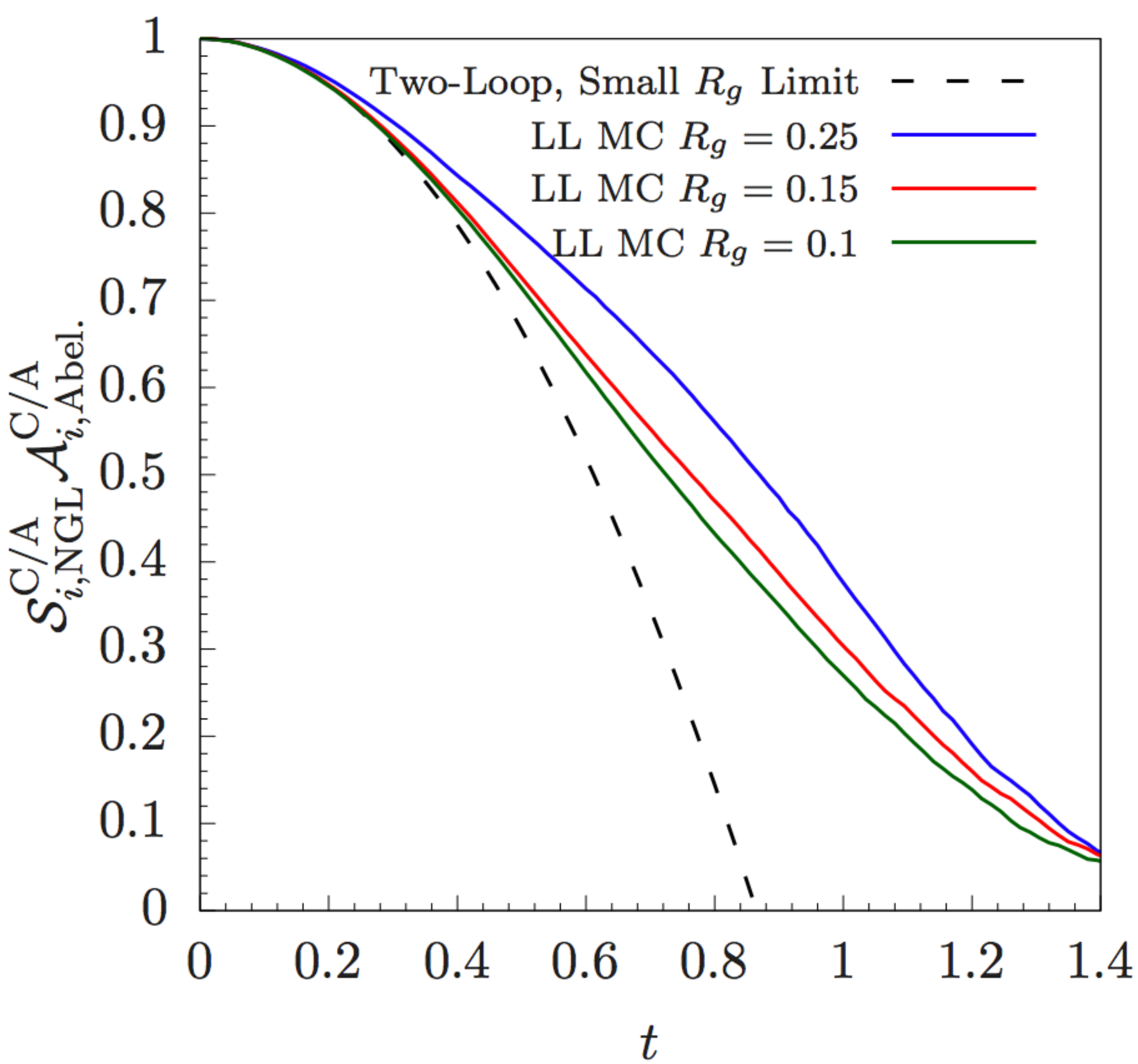
Non-global logarithms with C/A clustering effects

- Size of subleading terms



- Numerical results at LL and large-N_c

$$t = \frac{C_A}{2\pi}\int_{\omega}^{Q}\frac{d\mu}{\mu}\alpha_s(\mu)$$

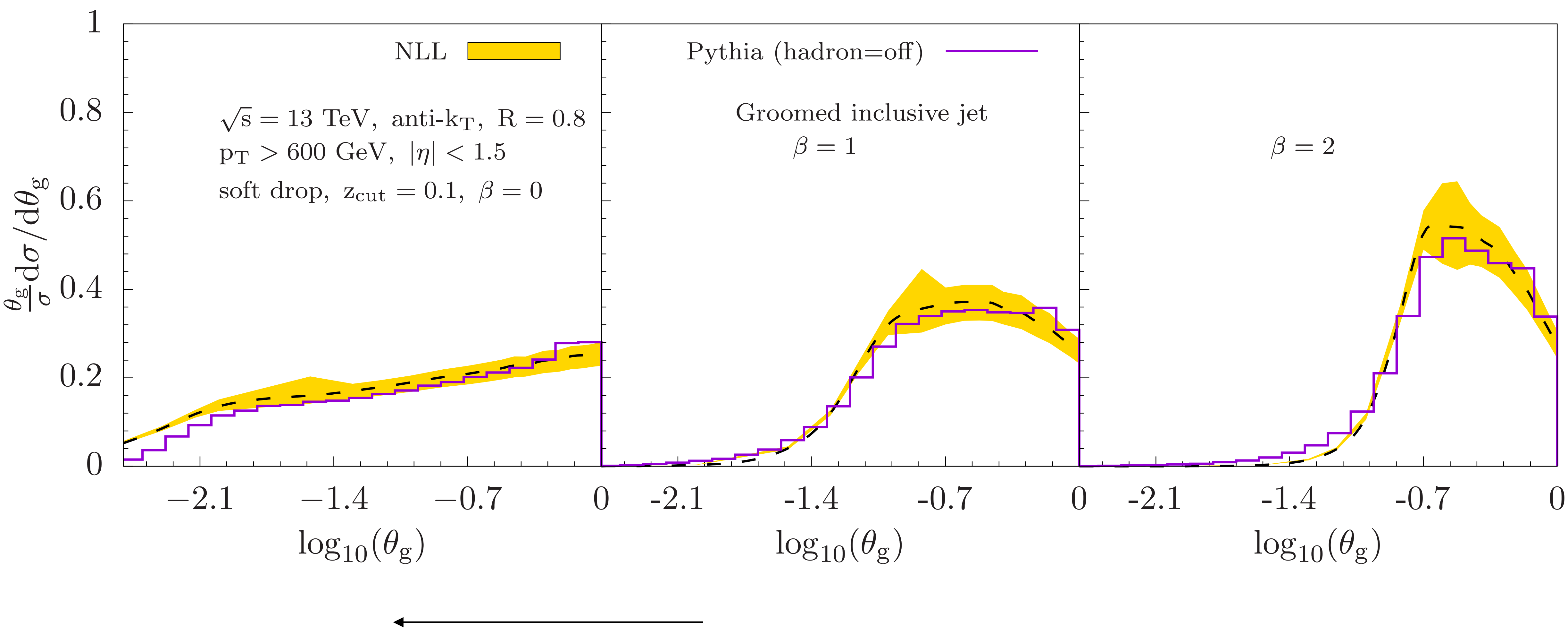


Phenomenological results

Kang, Lee, Liu, Neill, FR `19

- Groomed radius $\theta_g = \frac{\Delta R_{12}}{R} = \frac{R_g}{R}$

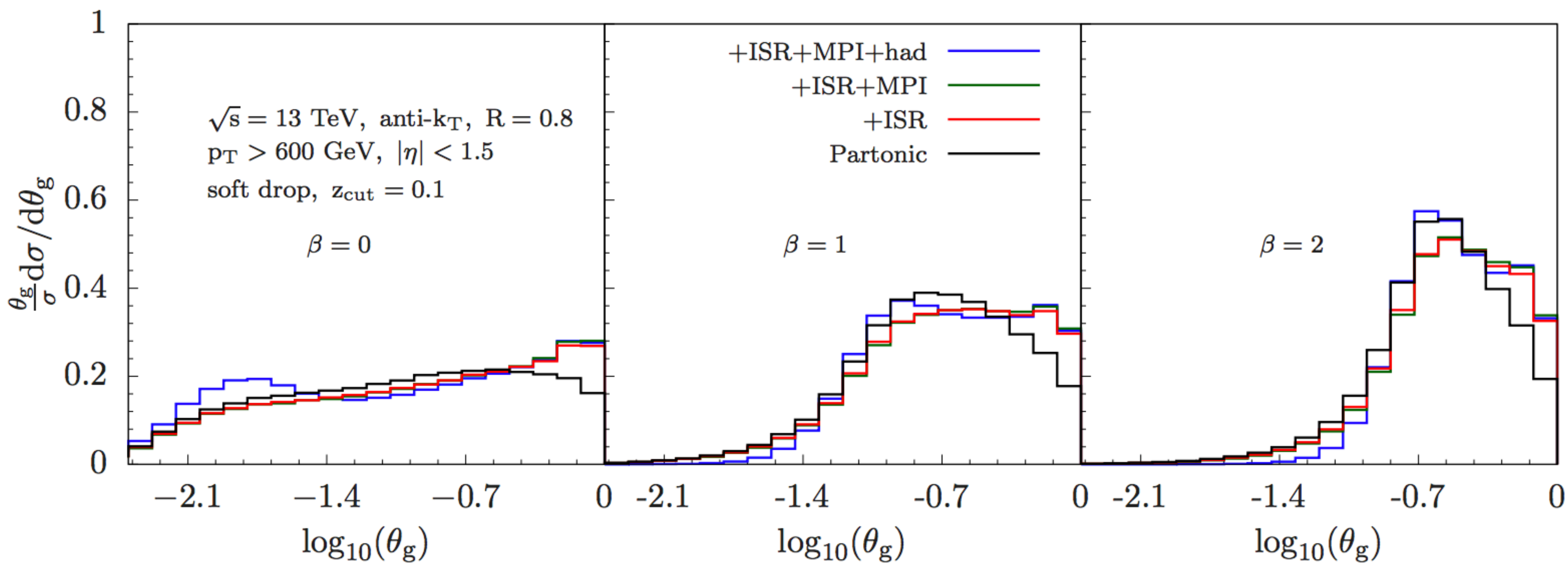
$\theta_g = 1$

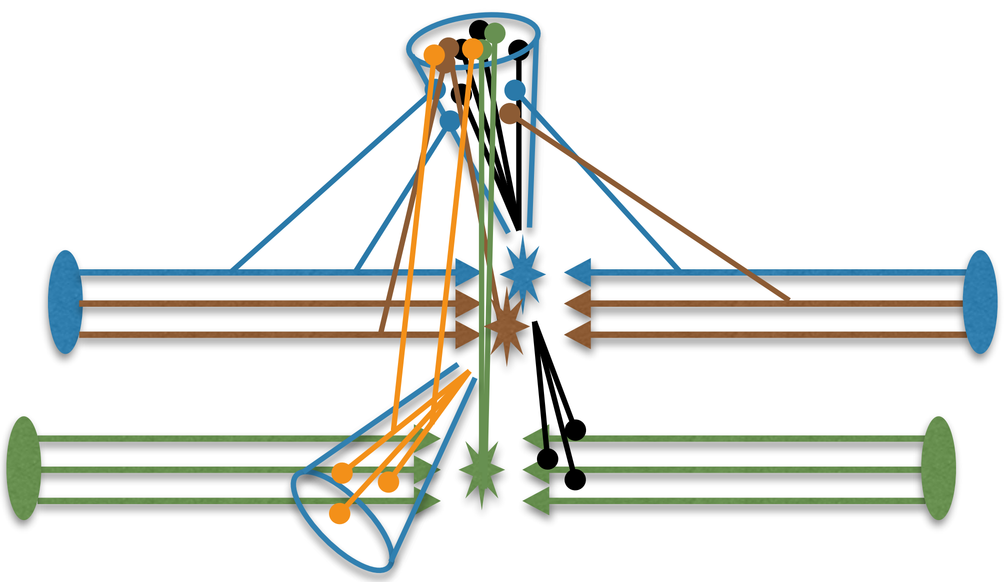


More aggressive grooming

Comparison to Pythia 8

Pythia simulations





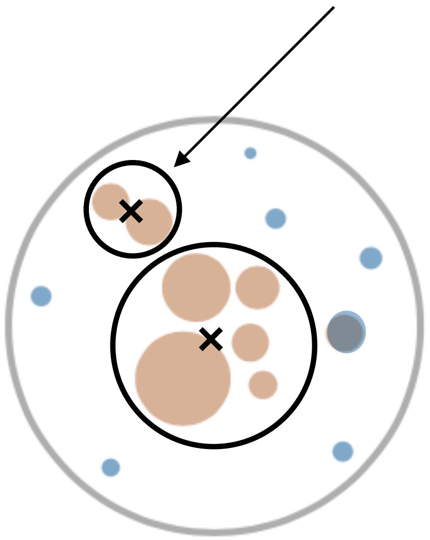
Outline

- Introduction
- Soft drop grooming
- The jet radius after grooming
- Other observables
- Conclusions

The momentum sharing fraction z_g

Larkoski, Marzani, Thaler `15

- Momentum fraction of the softer branch



$$z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}$$

- Can be calculated using the conditional probability

$$p\left(z_g\right) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \int \mathrm{d}\theta_g p\left(\theta_g\right) p\left(z_g|\theta_g\right)$$

Groomed radius cross section now calculated at NLL′

and

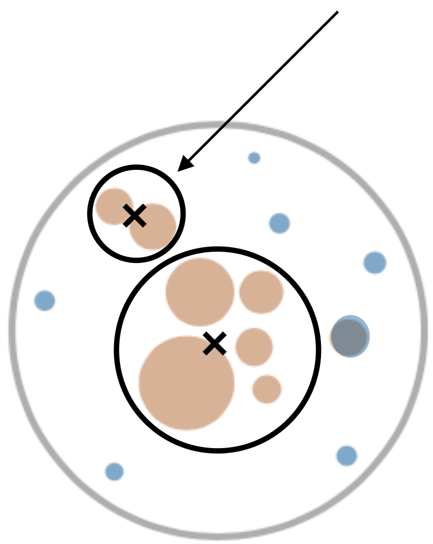
$$p\left(z_g|\theta_g\right) = \frac{\bar{P}_i\left(z_g\right)}{\int_{z_{\mathrm{cut}}\ \theta_g^\beta}^{1/2} \mathrm{d}z \bar{P}_i(z)} \Theta\left(z_g - z_{\mathrm{cut}}\ \theta_g^\beta\right)$$

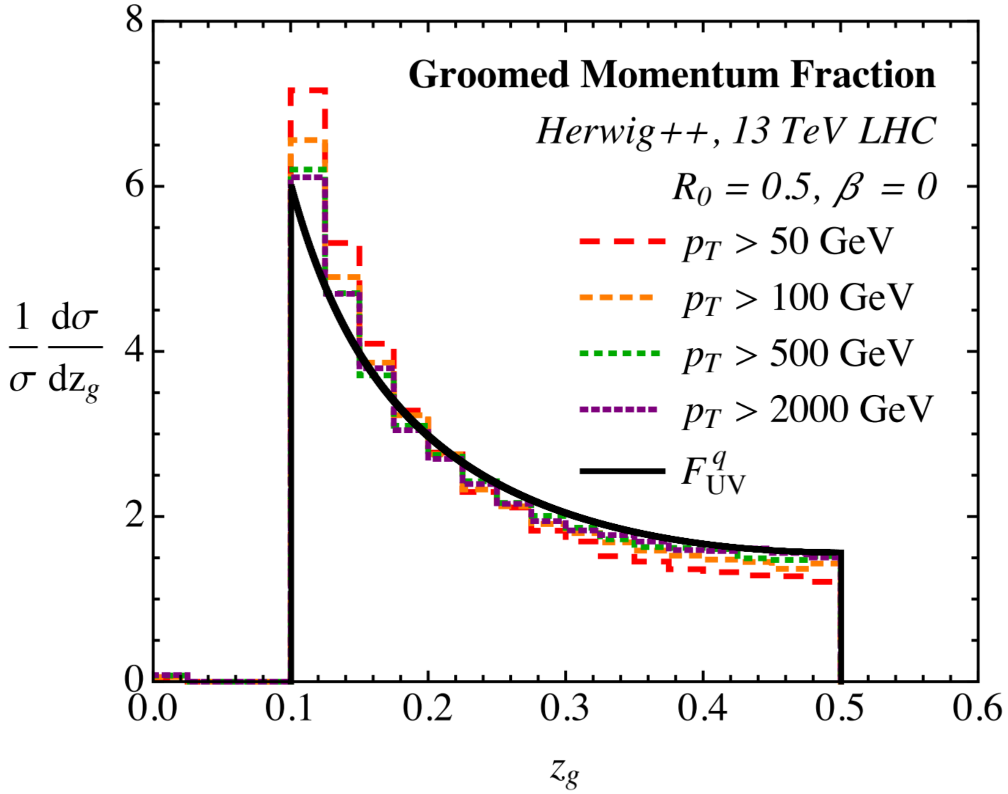
The momentum sharing fraction z_g

Larkoski, Marzani, Thaler `15

- Momentum fraction of the softer branch

$$z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}$$





$$\beta > 0: \quad p(z_g) = \sqrt{\frac{\alpha_s C_i}{\beta}}\, \overline{P}_i(z_g) + \mathcal{O}(\alpha_s)$$

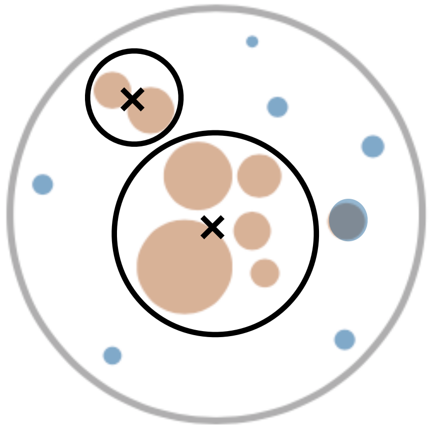
Sudakov safe

$$\beta = 0: \quad p(z_g) = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\, \overline{P}_i(z)}\Theta(z_g - z_{\rm cut})$$

Independent of α_s
QCD splitting function

The momentum sharing fraction z_g

Larkoski, Marzani, Thaler `15



- Momentum fraction of the softer branch

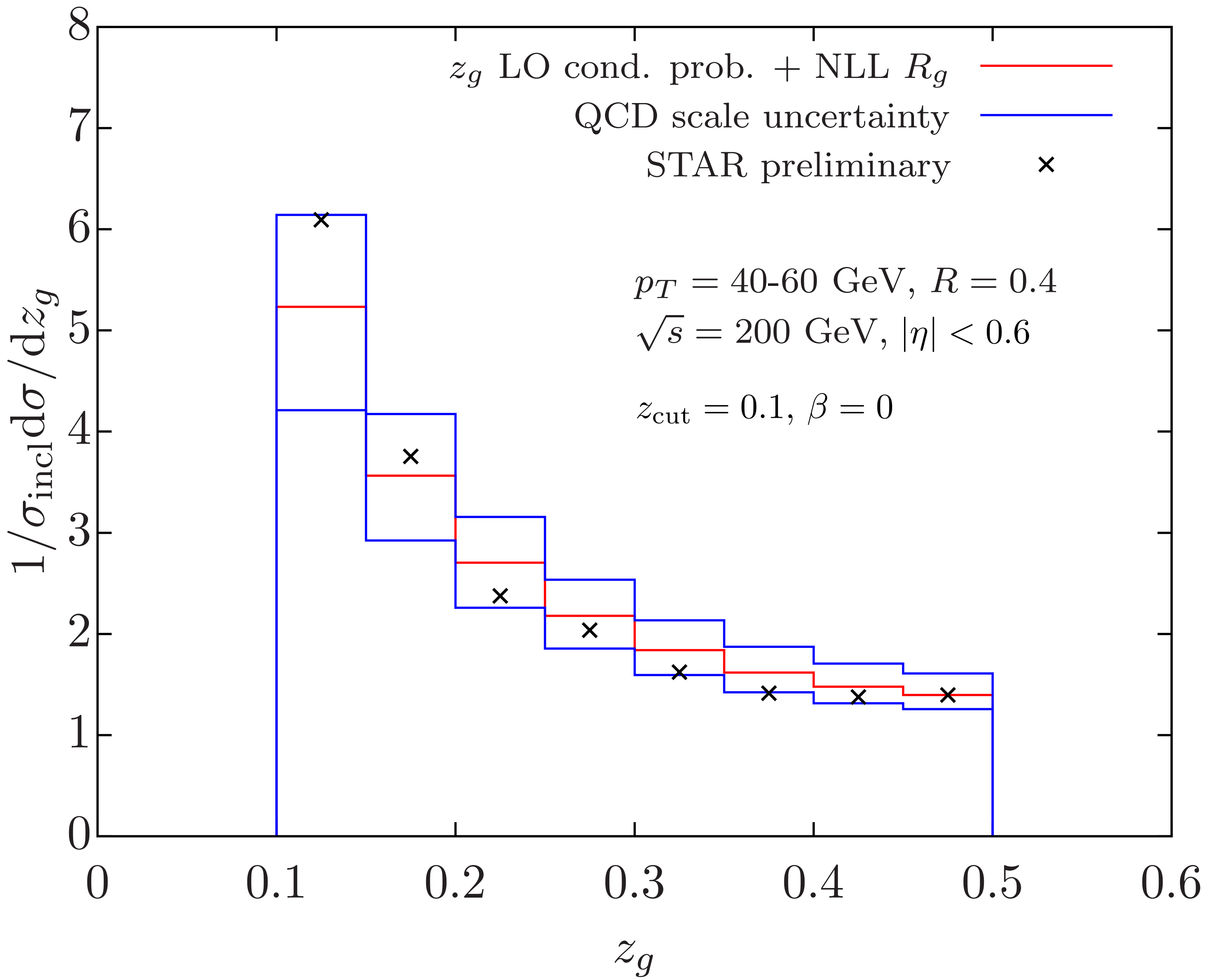
$$z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}$$

- Conditional probability including running coupling effects $\beta = 0$

$$p\left(z_g\right) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \int \mathrm{d}\theta_g p\left(\theta_g\right) p\left(z_g|\theta_g\right)$$

and $$p\left(z_g|\theta_g\right) = \frac{\alpha_s(z_g\theta_g p_T R)\, \bar{P}_i\left(z_g\right)}{\int_{z_{\mathrm{cut}}}^{1/2} \mathrm{d}z\, \alpha_s(z\theta_g p_T R)\, \bar{P}_i(z)} \Theta\left(z_g - z_{\mathrm{cut}}\right)$$

Phenomenological results for RHIC kinematics



More phenomenological results in the future

Outline

- Introduction
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Conclusions

- Jets are important precision probes at the LHC
- Soft drop grooming reduces nonperturbative effects significantly
- Novel observables
- More theoretical results and new data sets coming out soon
- Systematic studies of nonperturbative effects