TMD fragmentation in jets

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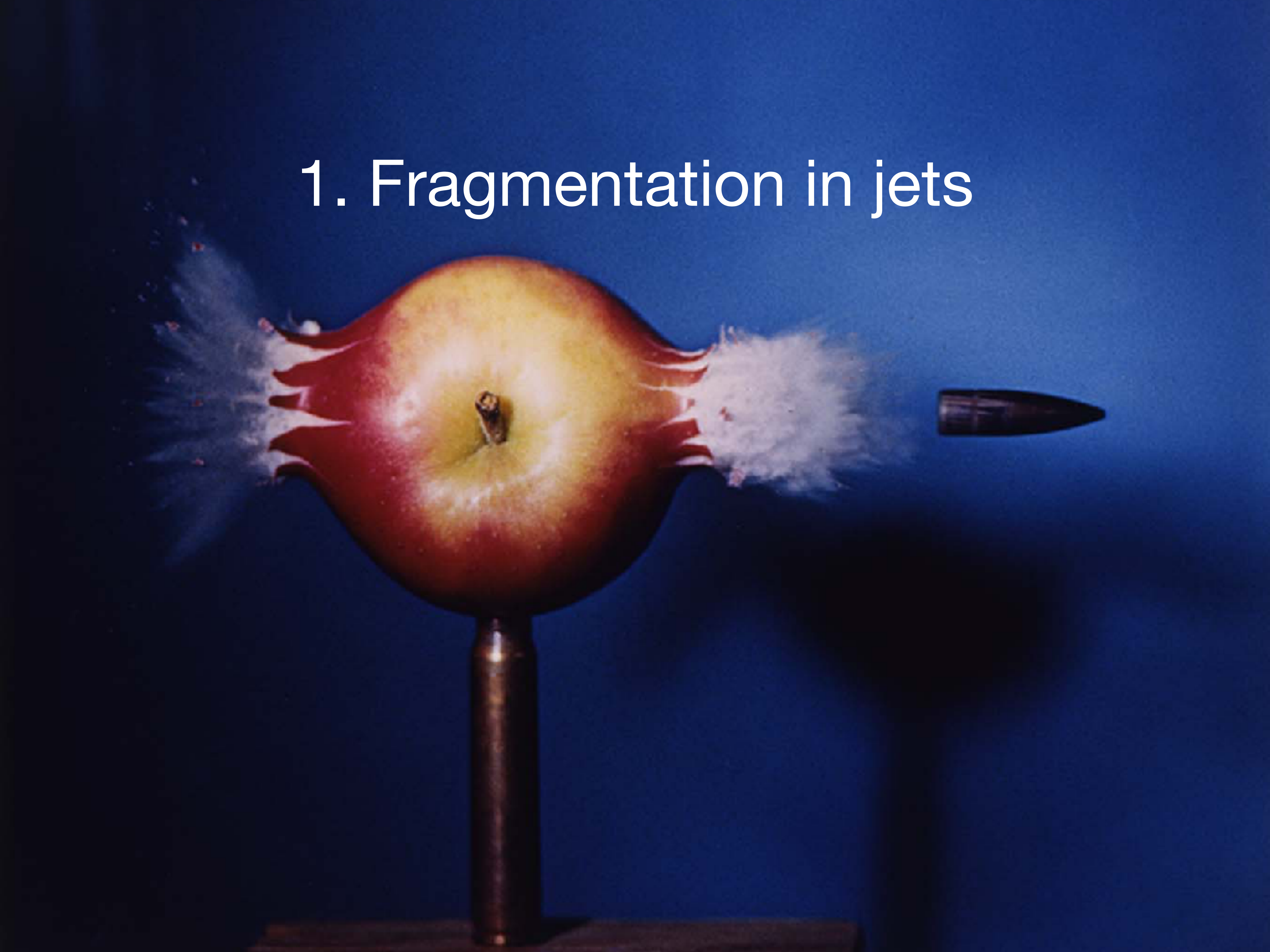
Outline

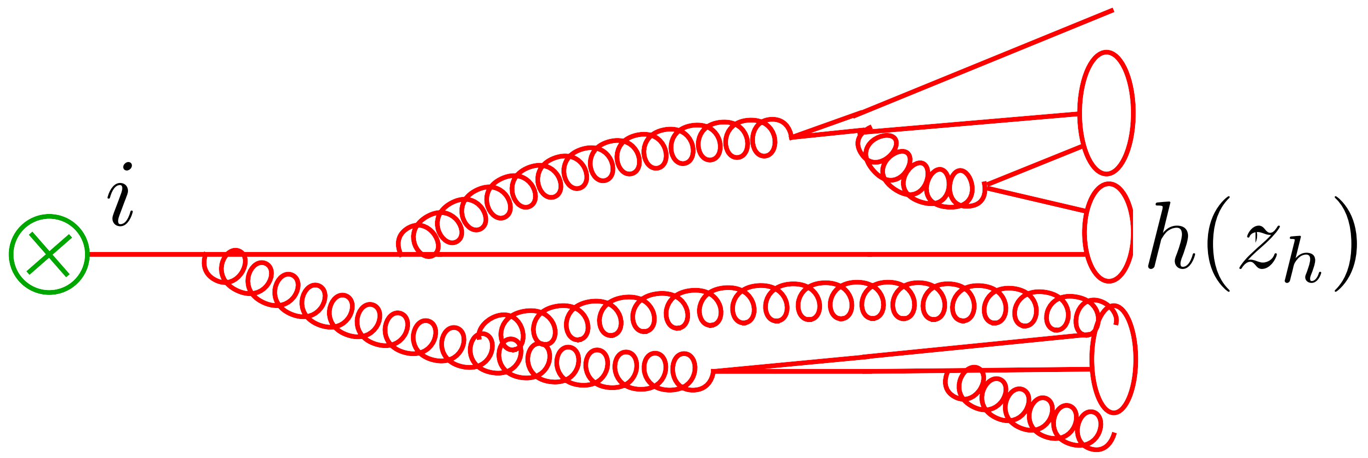
1. Fragmentation in jets
2. TMD fragmentation in jets
3. First results
4. Conclusions and outlook

In collaboration with D. Neill and I. Scimemi

1. Fragmentation in jets



Introduction: What is fragmentation?



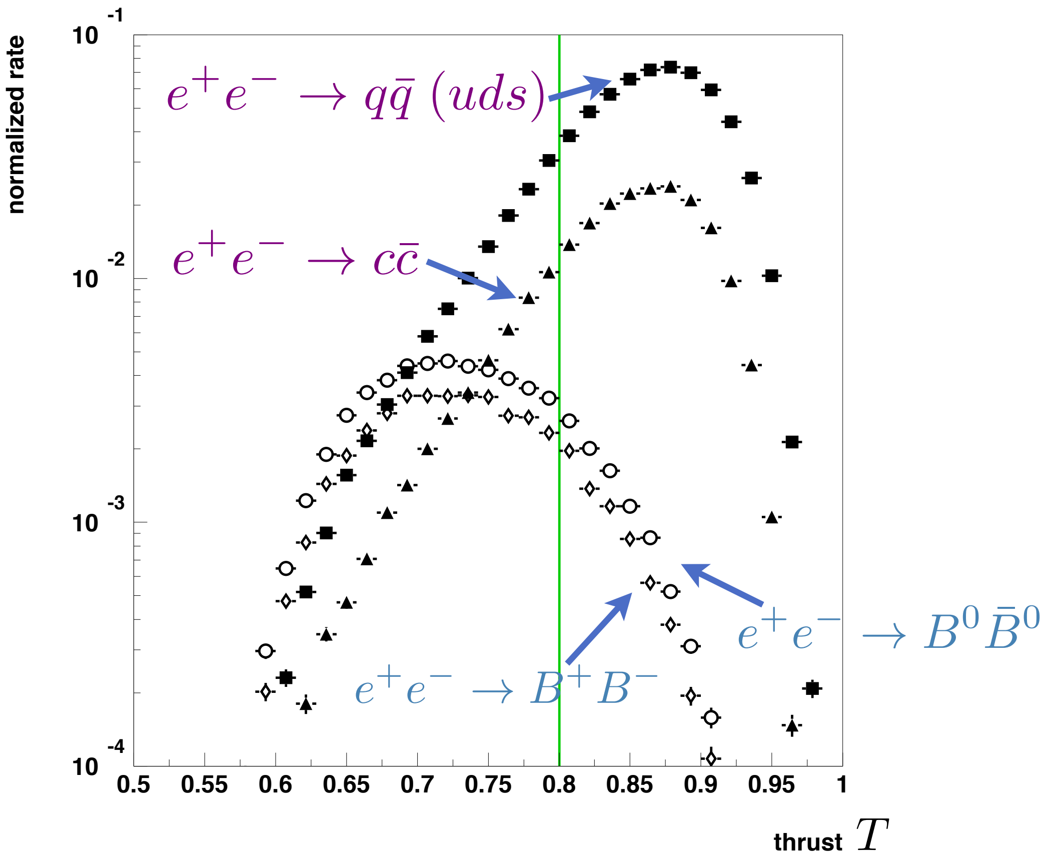
- Parton *i*=*q*, *g* radiates and hadronizes → produces hadron *h*
- Described by fragmentation function $D_{i\to h}(z_h, \mu)$ [Collins, Soper]
- E.g. $e^+e^- \to hX$

$$\frac{d\sigma}{dz_h} = \sigma_0 \sum_i \int_{z_h}^1 \frac{dz}{z}\, \hat{\sigma}_i(z, Q, \mu)\, D_{i\to h}\left(\frac{z_h}{z}, \mu\right)$$

[Collins, Soper, Sterman]

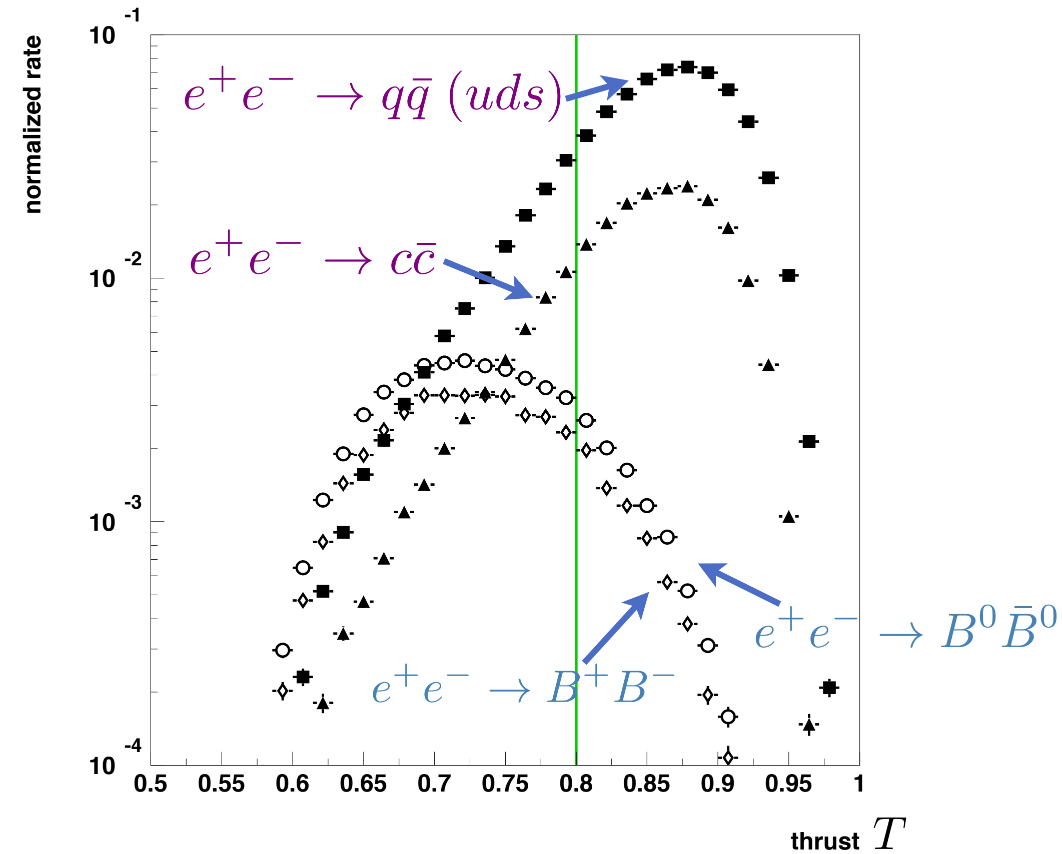
Case study: Fragmentation with a cut on thrust

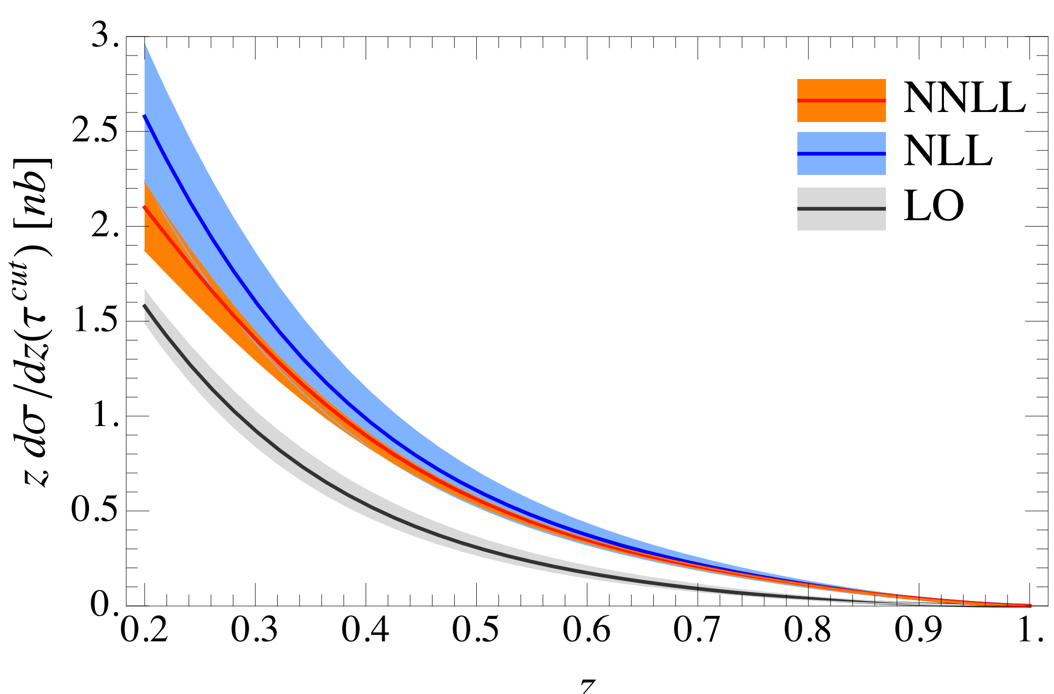
- Motivation: study light-quark fragmentation at Belle
- Dominant *b*-quark contribution in on-resonance data removed by cut on thrust *T*>0.8

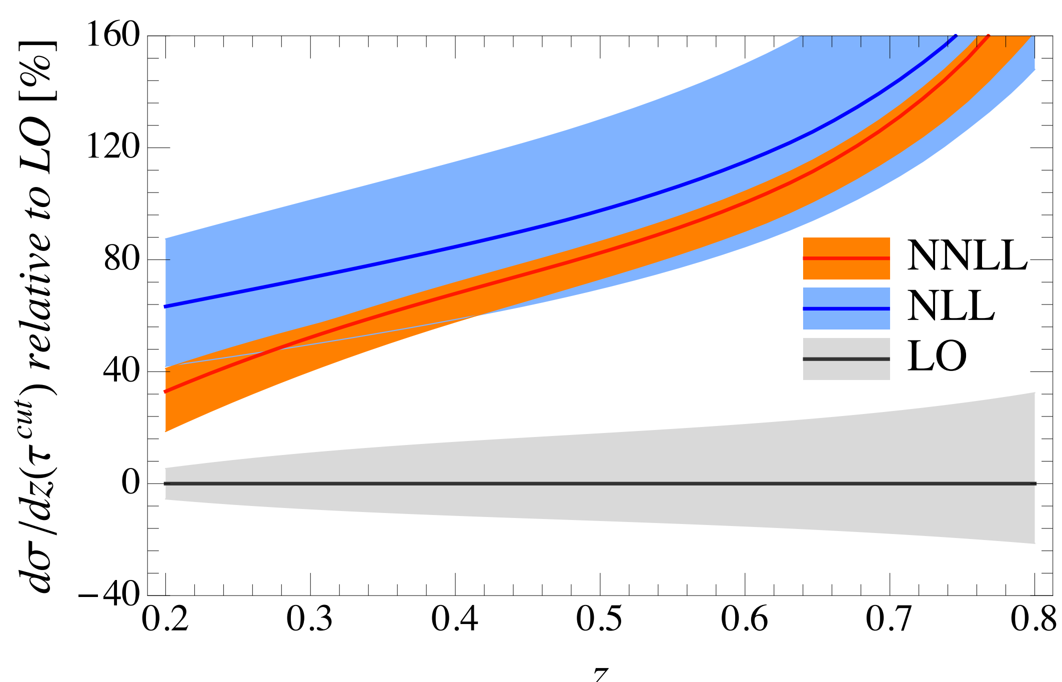


Case study: Fragmentation with a cut on thrust

- Motivation: study light-quark fragmentation at Belle
- Dominant *b*-quark contribution in on-resonance data removed by cut on thrust *T*>0.8
- Thrust cut modifies **shape** of fragmentation spectrum

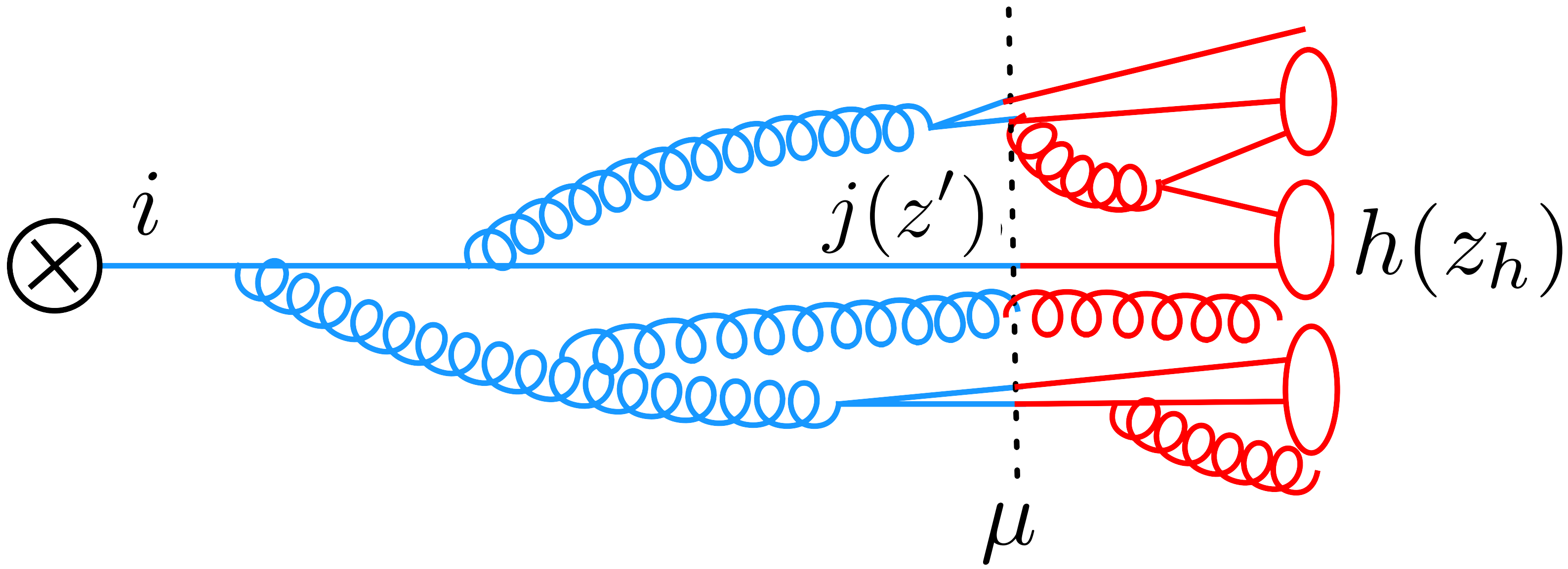






[Jain, Procura, WW]

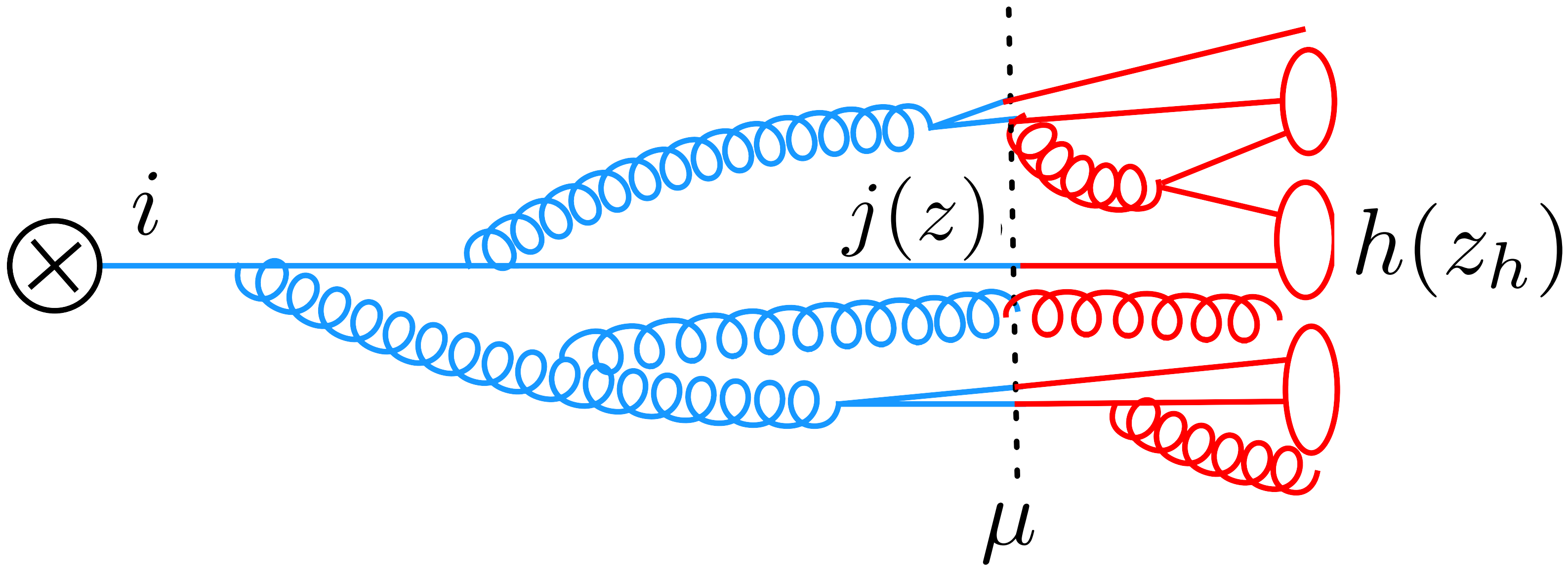
Key ingredient: Fragmenting jet function



$$\mathcal{G}_{i\to h}(s, z_h, \mu)$$

- Collinear radiation contributes s to thrust **and** produces hadron

Key ingredient: Fragmenting jet function



$$\mathcal{G}_{i\to h}(s, z_h, \mu) = \sum_j \int_{z_h}^1 \frac{dz}{z} \mathcal{J}_{ij}(s, z, \mu) D_{j\to h}\left(\frac{z_h}{z}, \mu\right)$$

[Procura, Stewart; Jain, Procura, WW]

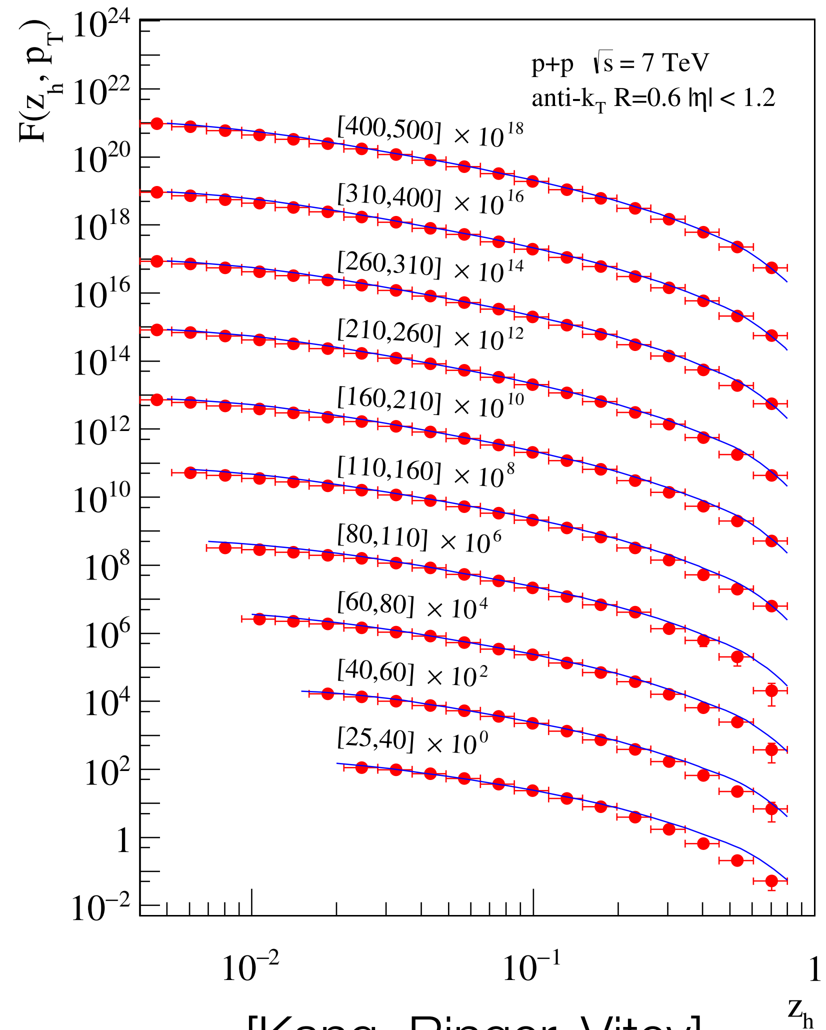
- Collinear radiation contributes s to thrust **and** produces hadron
- OPE in $\Lambda_{\mathrm{QCD}}^2/s$ with perturbatively calculable coefficients

$$\mathcal{J}_{ij}(s, z, \mu) = \delta_{ij}\delta(s)\delta(1-z) + \mathcal{O}(\alpha_s)$$

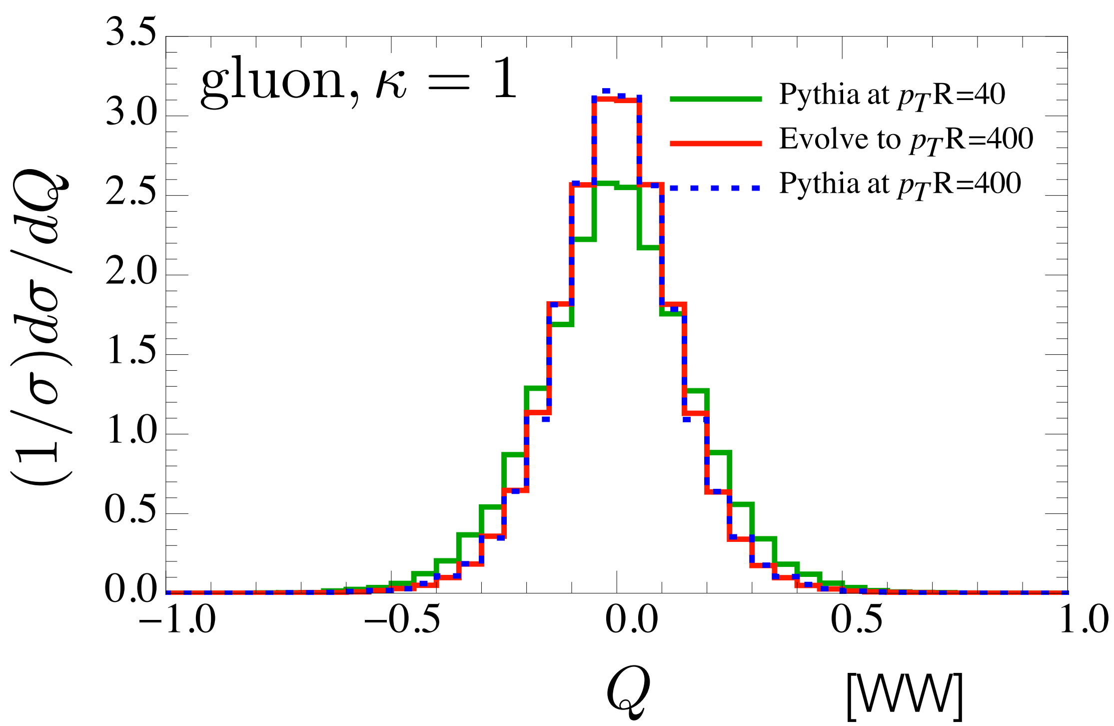
- Fragmentation function probed at $\mu \sim \sqrt{s} \ll Q$

Developments

- Hemisphere jets [Procura, Stewart; Liu; Jain, Procura, WW; Bauer, Mereghetti; Ritzmann, WW]
- Exclusive jet production [Procura, WW; Chien, Kang, Ringer, Vitev, Xing; Baumgart, Leibovich, Mehen, Rothstein; Bain, Dai, Hornig, Leibovich, Makris, Mehen]
- Inclusive jet production [Kaufmann, Mukherjee, Vogelsang; Dai, Kim, Leibovich; Kang, Ringer, Vitev]
- Jet charge [Krohn, Schwartz, Lin, WW; WW]



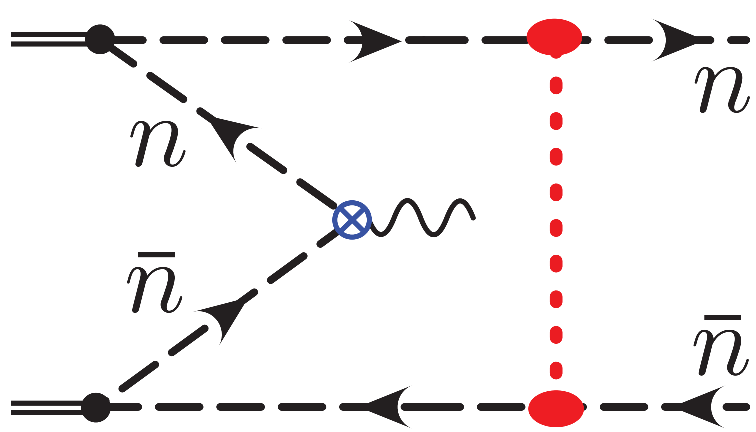
[Kang, Ringer, Vitev]



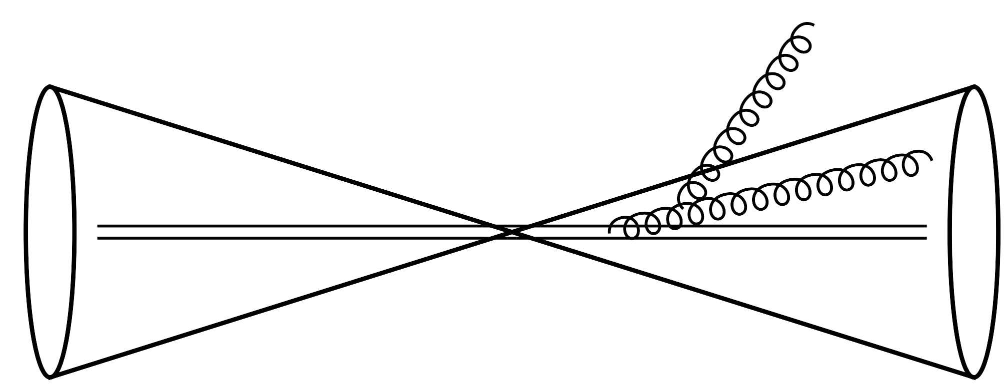
[WW]

Challenges

- x Event shapes: susceptible to spectator-spectator interactions (Glaubers) in *pp* collisions [Gaunt; Zeng; Rothstein, Stewart]
- x Exclusive jet production: non-global logarithms from different restrictions in regions of phase-space [Dasgupta, Salam, …]
- ✓ Inclusive jet production: insensitive to soft radiation

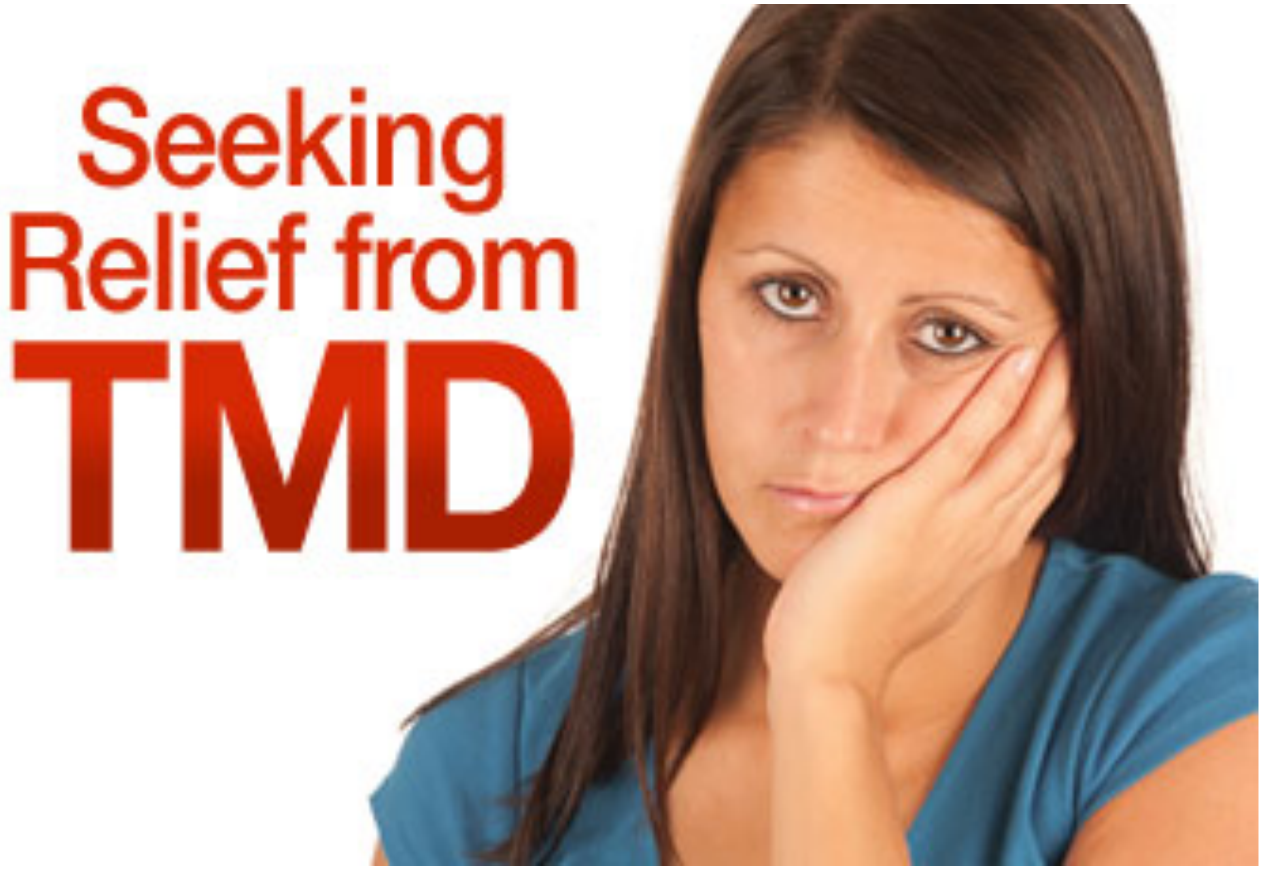


Glauber exchange

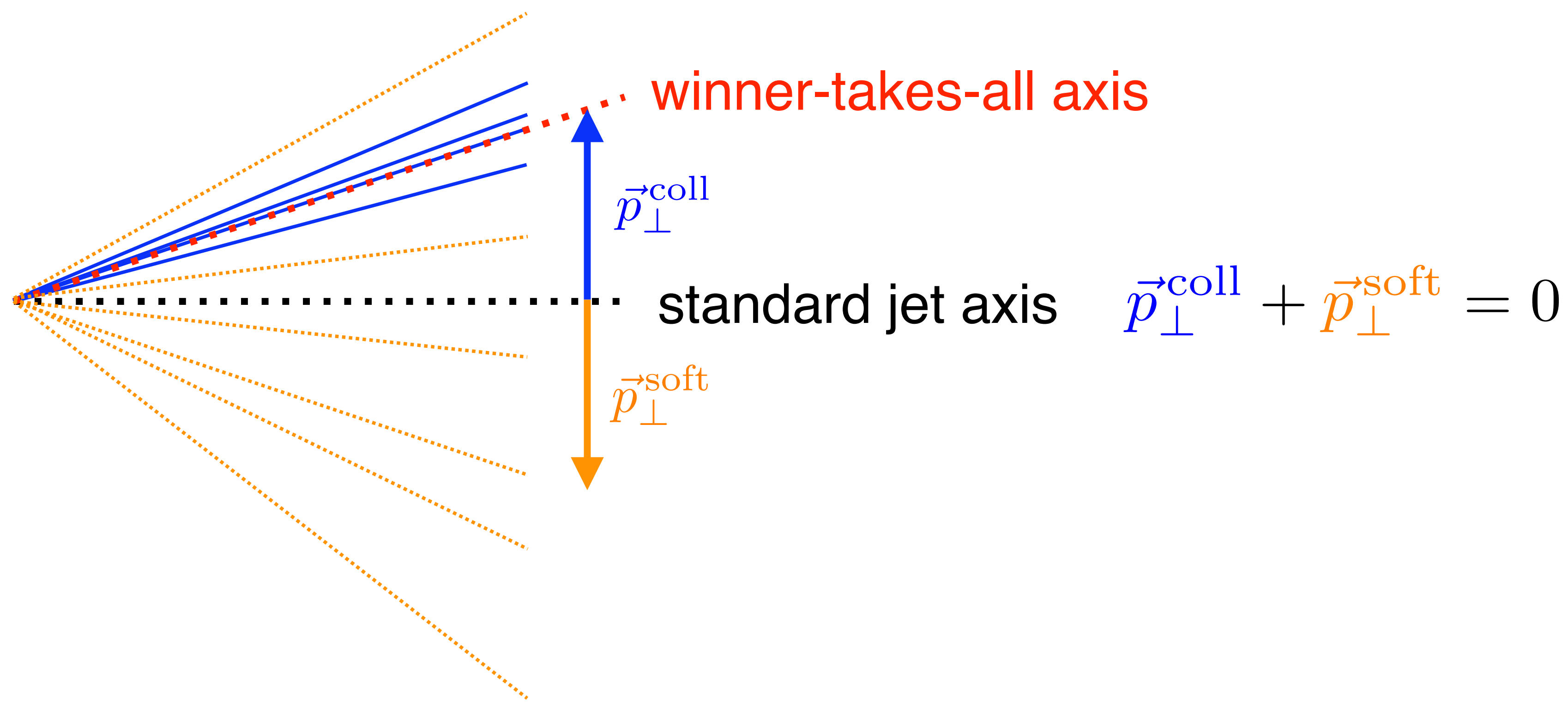


Soft emission giving rise to non-global logarithm

2. TMD fragmentation in jets



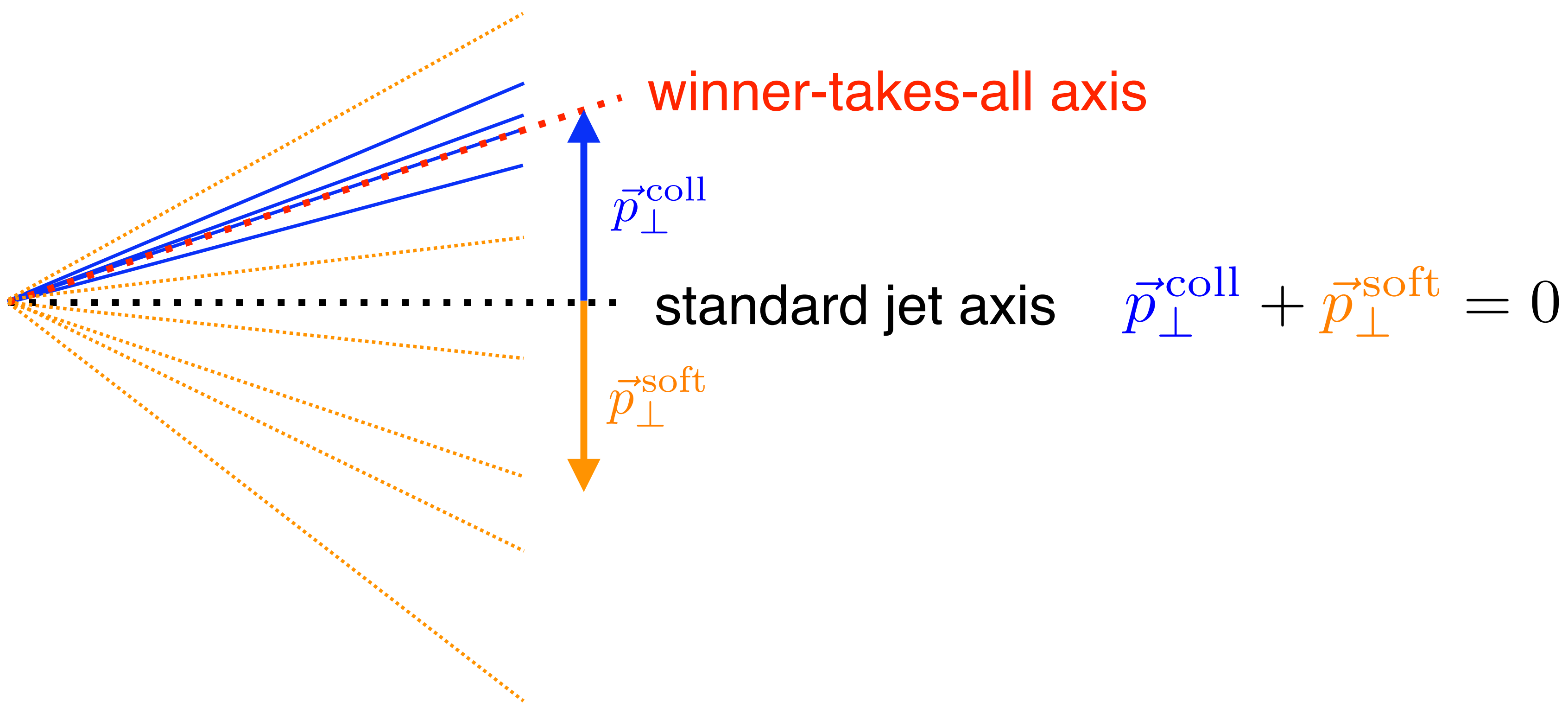
Removing soft recoil



- Fragmentation in inclusive jet production is purely collinear
- TMD measurement introduces soft sensitivity through axis

✓Choose a recoil free axis, *e.g.* winner-takes-all [Larkoski, Neill, Thaler]

Winner-takes-all axis



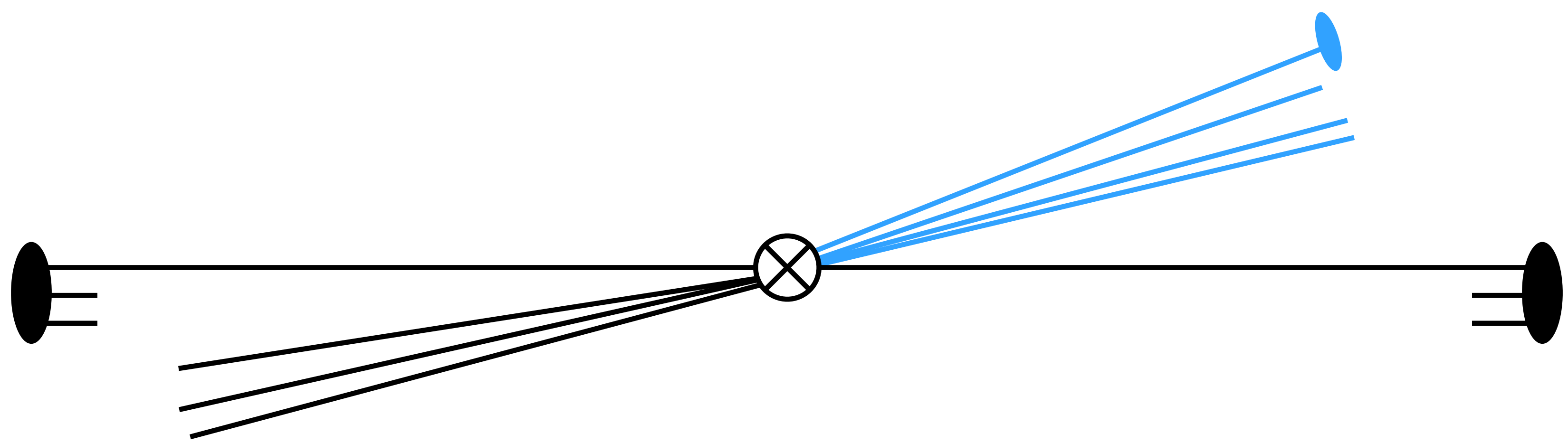
- Run jet algorithm with following recombination scheme

$$E_r = E_1 + E_2$$

$$\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } E_1 > E_2 \\ \hat{n}_2 & \text{if } E_2 > E_1 \end{cases}$$

- Axis tracks energetic radiation, along direction of a particle

Factorization of the jet



- Factor hard scattering from jet production for jet radius $R \ll 1$

$$\frac{d\sigma_h}{dp_T\, d\eta\, d\vec{p}^{\,2}_{h\perp}\, dz_h} = \sum_i \int \frac{dx}{x}\, \hat{\sigma}_i\Big(\frac{p_T}{x}, \eta, \mu\Big)\, \mathcal{G}_{i\to h}(x, p_T R, \vec{p}^{\,2}_{h\perp}, z_h, \mu)$$

  - Transverse momentum p_T and rapidity η of jet

✓$\mathcal{G}$ is **universal** because measurement is purely collinear, *i.e.* same for *ee*, *ep* and *pp* and independent of other jets

Factorization of TMD fragmentation

- For $r \equiv |\vec{p}_{h\perp}|/p_T \ll R$ factor jet from TMD fragmentation

$$\mathcal{G}_{i\to h}(x, p_T R, \vec{p}_{h\perp}^{\,2}, z_h, \mu) = \sum_k \int \frac{dz}{z} B_{ik}(x, p_T R, z, \mu)\, D_{k\to h}\Big(\frac{\vec{p}_{h\perp}^{\,2}}{z^2}, \frac{z_h}{z}, \mu\Big)$$

  - B and D describe emissions at angular scales R and r

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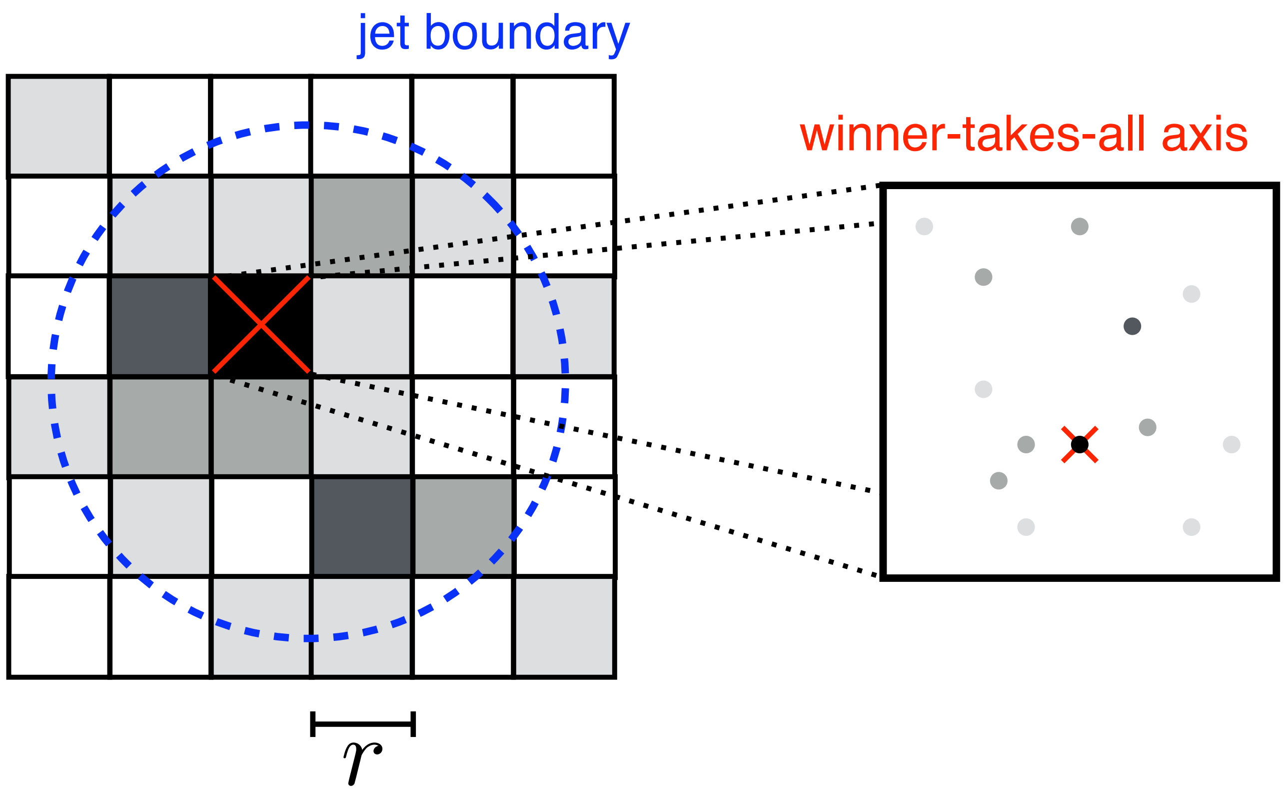
Factorization of the measurement:

- B identifies pixel of size r containing axis
- D determines axis in pixel

✓ Ok for Cambridge/Aachen with winner-takes-all axis



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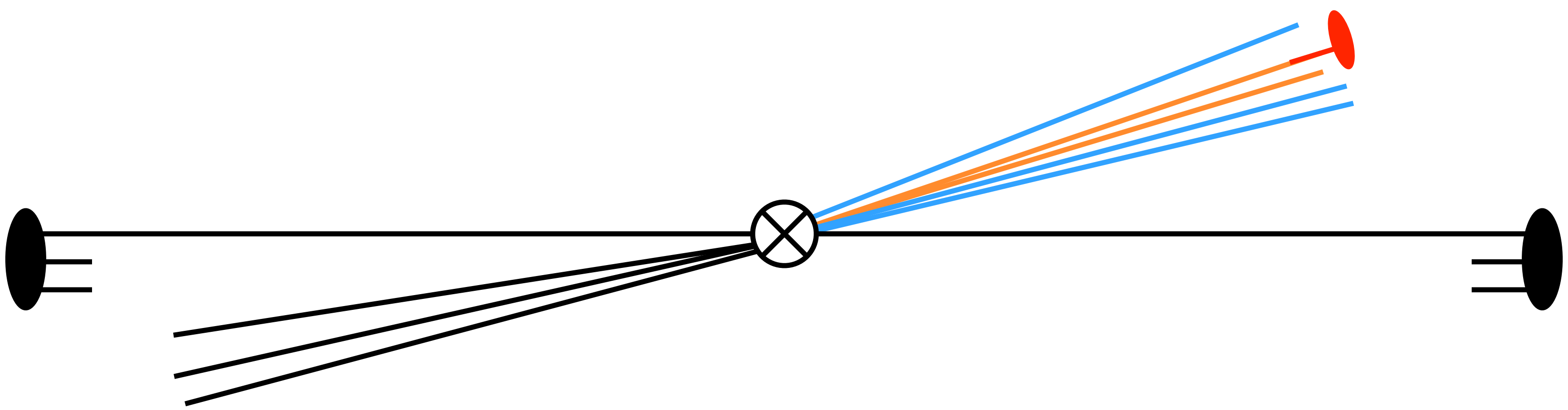
  - *B* and *D* describe emissions at angular scales *R* and *r*

Factorization of the amplitude:

✓ Winner-takes-all axis guarantees that *B* produces **one** energetic parton near axis (not true for standard axis)

- Hadron must fragment from this to be $1/\vec{p}_{h\perp}^{\,2}$ enhanced

Factorization of fragmentation



- For perturbative $|\vec{p}_{h\perp}| \gg \Lambda_{QCD}$

$$D_i^k(\vec{p}^{\,2}_{h\perp}, z_h, \mu) = \sum_k \int \frac{dz}{z}\, C_{ik}\Big(\frac{\vec{p}^{\,2}_{h\perp}}{z^2}, \frac{z_h}{z}, \mu\Big)\, D_{k\to h}(z, \mu)$$

Evolution and resummation

$$\frac{d\sigma_h}{dp_T\, d\eta\, d\vec{p}_{h\perp}^{\,2}\, dz_h} = \hat{\sigma}(p_T, \eta) \otimes B(p_T R) \otimes C(\vec{p}_{h\perp}^{\,2}) \otimes D(\Lambda_{\mathrm{QCD}})$$

TMD fragmentation $D(\vec{p}_{h\perp}^{\,2})$ $= C(\vec{p}_{h\perp}^{\,2}) \otimes D(\Lambda_{\mathrm{QCD}})$

Jet boundary: $B(p_T R)$

$\mathcal{J}(p_T R, \vec{p}_{h\perp}^{\,2}) = B(p_T R) \otimes C(\vec{p}_{h\perp}^{\,2})$

$\mathcal{G}(p_T R, \vec{p}_{h\perp}^{\,2}) = B(p_T R) \otimes C(\vec{p}_{h\perp}^{\,2}) \otimes D(\Lambda_{\mathrm{QCD}})$

- Factorization separates physics at disparate scales

Evolution and resummation

TMD fragmentation $D(\vec{p}_{h\perp}^{\,2})$

Jet boundary

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$\mathcal{J}(p_T R, \vec{p}_{h\perp}^{\,2})$

$\mathcal{G}(p_T R, \vec{p}_{h\perp}^{\,2})$

- Factorization separates physics at disparate scales
- Logarithms are resummed by renormalization group evolution

3. First results

Matching coefficients for $p_T R \sim \vec{p}_{h\perp}^{\,2}$

- We calculated all matching coefficients at next-to-leading order

$$
\begin{aligned}
\mathcal{J}_{qq}(x, p_T R, \vec{p}_{h\perp}^{\,2}, z) &= \delta(\vec{p}_{h\perp}^{\,2})\,\delta(x-1)\,\delta(z-1) \\
&\quad + \frac{\alpha_s C_F}{2\pi}\left[\frac{1}{\mu^2}\frac{1}{(\vec{p}_{h\perp}^{\,2}/\mu^2)}_{+}\delta(x-1)\,\theta\Big(\frac{1}{2} \geq z \geq \frac{|\vec{p}_{h\perp}|}{p_T R}\Big)\frac{1+z^2}{1-z}\right. \\
&\quad \left. + \delta(\vec{p}_{h\perp}^{\,2})(\dots)\right] + \mathcal{O}(\alpha_s^2)
\end{aligned}
$$

- At this order only two partons and winner-takes-all axis along most energetic one, so $\vec{p}_{h\perp} = 0$ for $z > 1/2$

- No rapidity divergences

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&+ \delta(\vec{p}_{h\perp}^{\,2})(\dots)\bigg] + \mathcal{O}(\alpha_s^2)
\end{aligned}
$$

- At this order only two partons and winner-takes-all axis along most energetic one, so $\vec{p}_{h\perp} = 0$ for $z > 1/2$
- No rapidity divergences
- Interplay between jet boundary and TMD measurement (more complicated at higher orders)

Matching coefficients for $p_T R \gg \vec{p}_{h\perp}^{\,2}$

- Jet boundary restriction and TMD measurement factorize

$$B_{qq}(x, p_T R, z, \mu) = \delta(x-1)\,\delta(z-1) + \frac{\alpha_s C_F}{2\pi}\bigg\{ -\ln\frac{p_T^2 R^2}{\mu^2}\bigg[\frac{1+x^2}{(1-x)}_+ \delta(z-1) - \delta(x-1)\,\theta\Big(z \geq \frac{1}{2}\Big)\,\frac{1+z^2}{(1-z)}_+\bigg] + \dots\bigg\}$$

$$C_{qq}(\vec{p}_{h\perp}^{\,2}, z) = \delta(\vec{p}_{h\perp}^{\,2})\,\delta(1-z) + \frac{\alpha_s C_F}{2\pi}\bigg[\frac{1}{\mu^2}\,\frac{1}{(\vec{p}_{h\perp}^{\,2}/\mu^2)}_+ \theta\Big(\frac{1}{2} \geq z\Big)\,\frac{1+z^2}{1-z} + \delta(\vec{p}_{h\perp}^{\,2})(\dots)\bigg]$$

- *B* describes parton along axis and thus vanishes for $z < 1/2$

Matching coefficients for $p_T R \gg \vec{p}_{h\perp}^{\,2}$

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$$C_{qq}(\vec{p}_{h\perp}^{\,2}, z) = \delta(\vec{p}_{h\perp}^{\,2})\,\delta(1-z) + \frac{\alpha_s C_F}{2\pi}\biggl[\frac{1}{\mu^2}\frac{1}{(\vec{p}_{h\perp}^{\,2}/\mu^2)}_+\theta\Bigl(\frac{1}{2} \geq z\Bigr)\frac{1+z^2}{1-z} + \delta(\vec{p}_{h\perp}^{\,2})(\dots)\biggr]$$

- *B* describes parton along axis and thus vanishes for $z < 1/2$
- Between *B* and *C* the DGLAP evolution in *z* is modified

Transverse momentum dependence

- TMD fragmentation matching coefficients C give $1/\vec{p}_{h\perp}^{\,2}$
- Difference between RG evolution above and below C modify

$$1/\vec{p}_{h\perp}^{\,2} \quad \to \quad 1/\vec{p}_{h\perp}^{\,2-\Delta}$$

where Δ follows from anomalous dimensions

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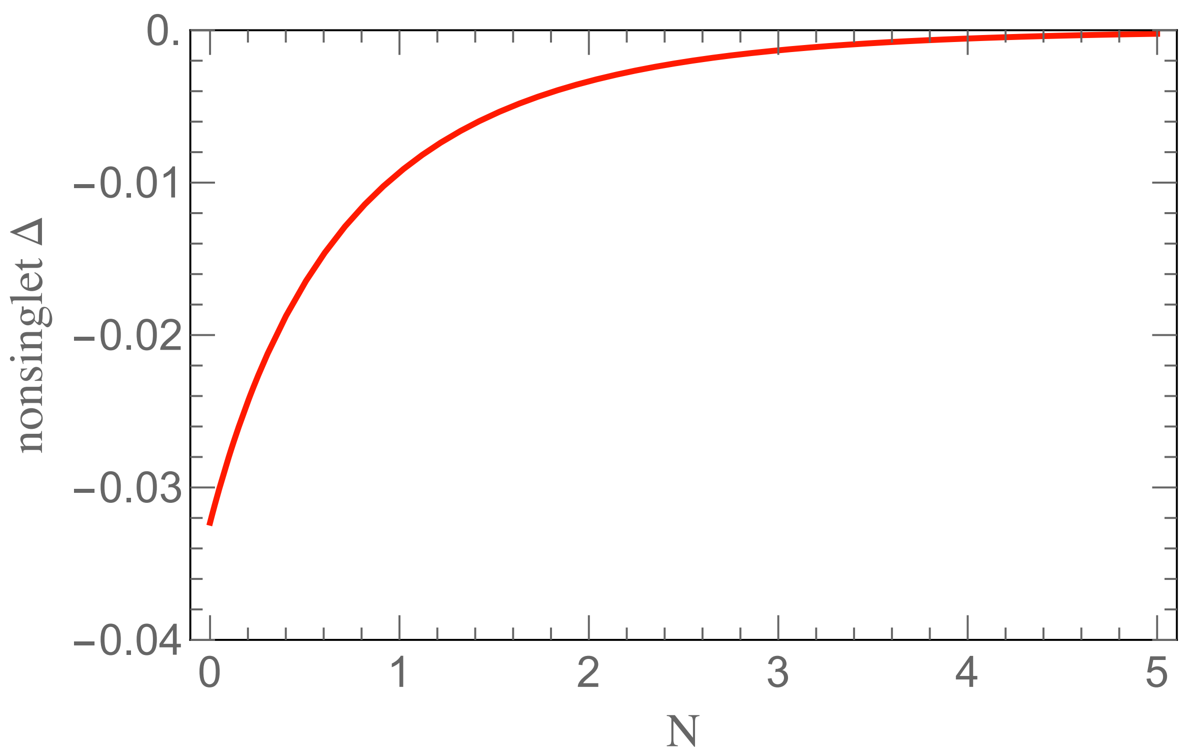
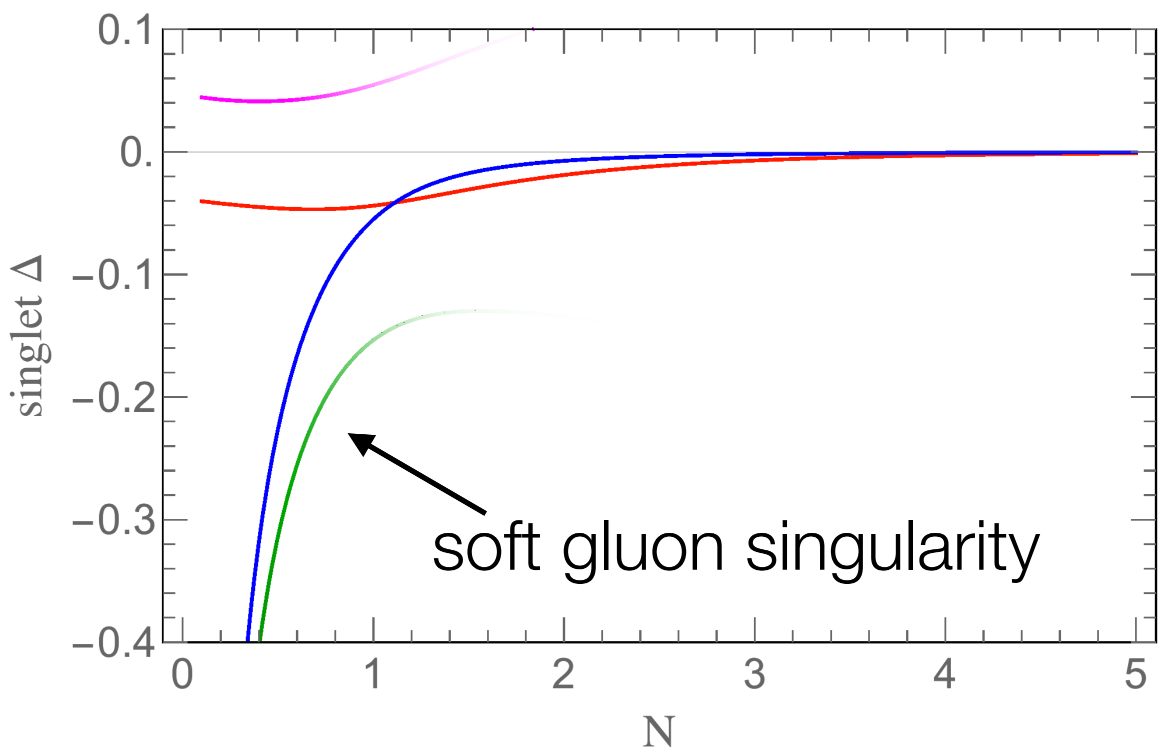
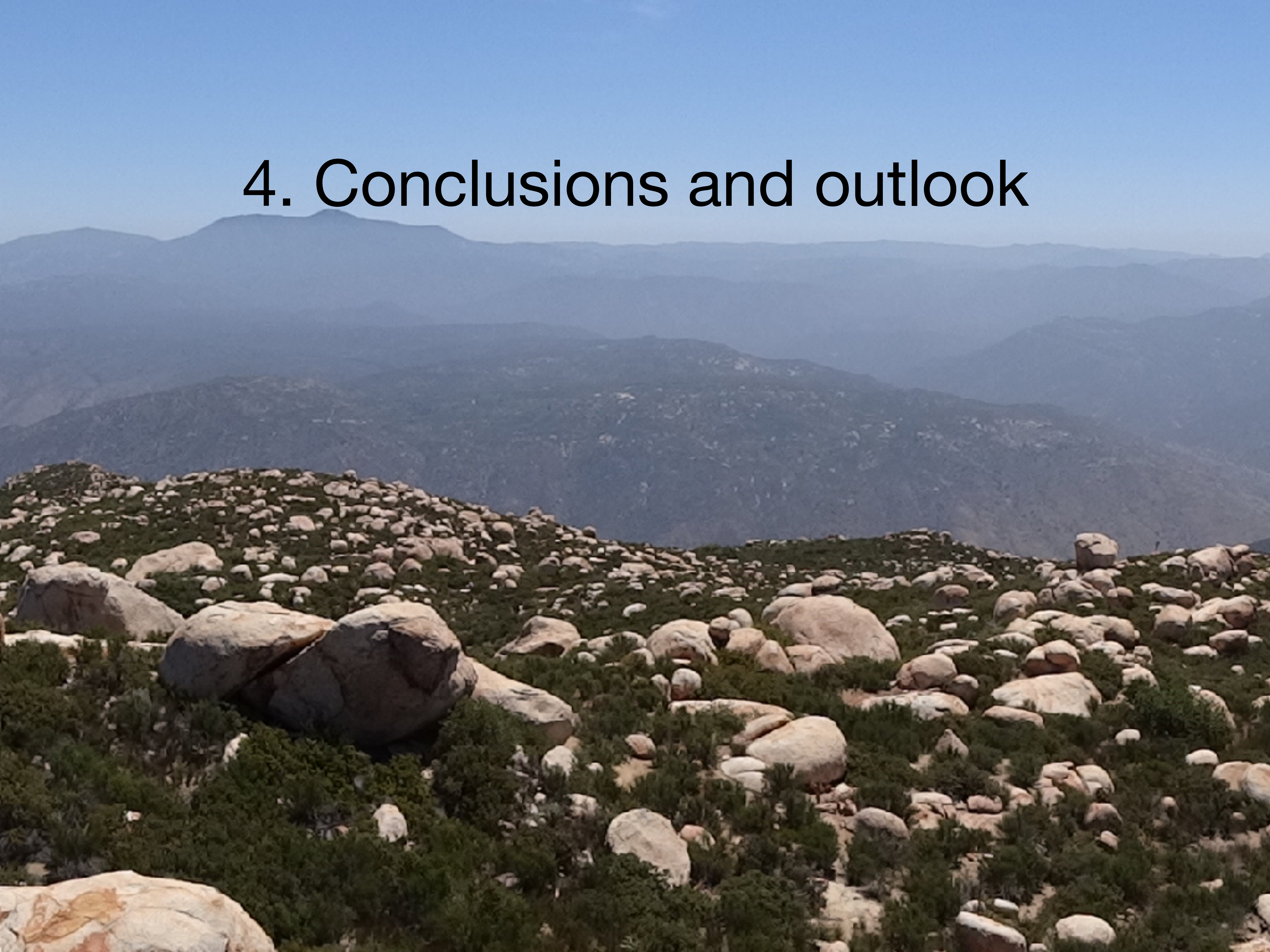
- For *N*-th moment and $\alpha_s = 0.1$ this gives





4. Conclusions and outlook

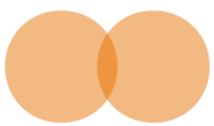


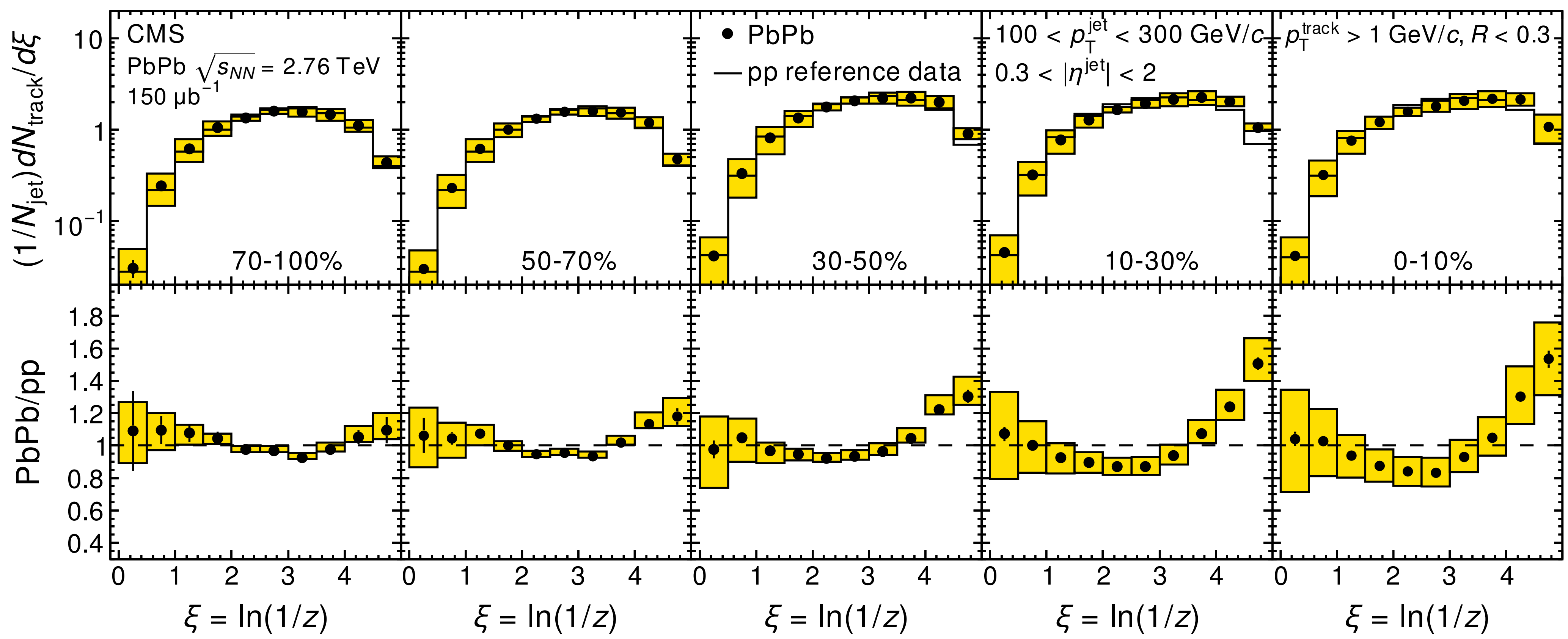
Conclusions and outlook

- TMD fragmentation in a jet with winner-takes-all axis:
  - Purely collinear observable, so universal
  - Jet and TMD fragmentation factorize for Cambridge/Aachen
  - No rapidity divergences
- Applications (work in progress)
  - Extend to spin-dependent fragmentation
  - Medium modification of TMD fragmentation
  - Jet substructure for boosted analyses
  - …

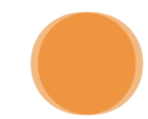
Application: medium modifications

Peripheral collisions





Central collisions



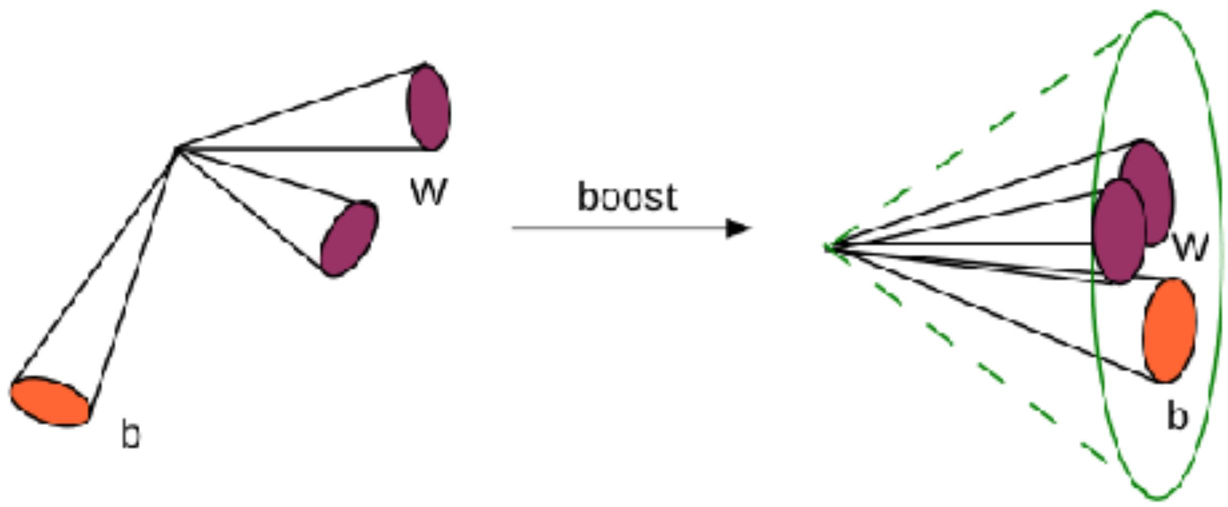
[CMS-HIN-12-013]

- Medium modification of fragmentation function is studied
- Can now be extended to TMD fragmentation

✓Observable must be insensitive to overload of soft "crap"

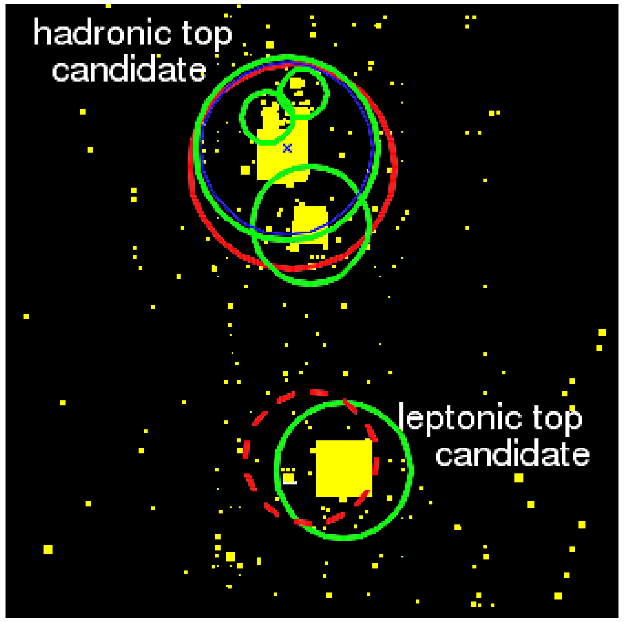
Application: jet substructure

- Jet substructure is key to tag heavy particles at high energies



3 jets

3 subjets



[ATLAS-CONF-2013-052]

- Exploits that subjet splittings differ between *e.g.* top and gluon
- TMD fragmentation can be extended from hadrons to subjets

  ✓Provides direct measure of subjet energies and angle

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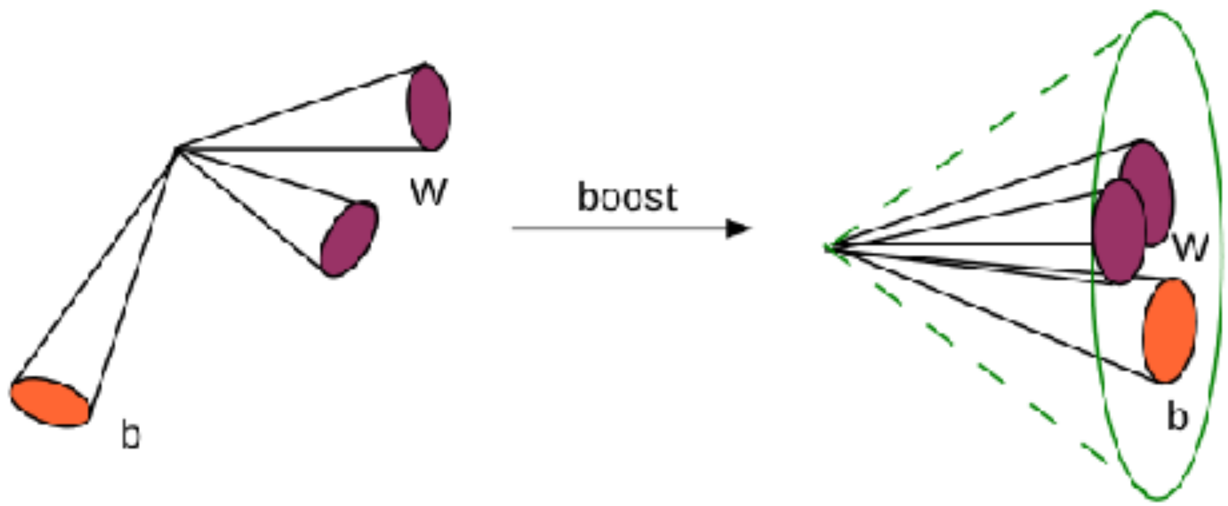
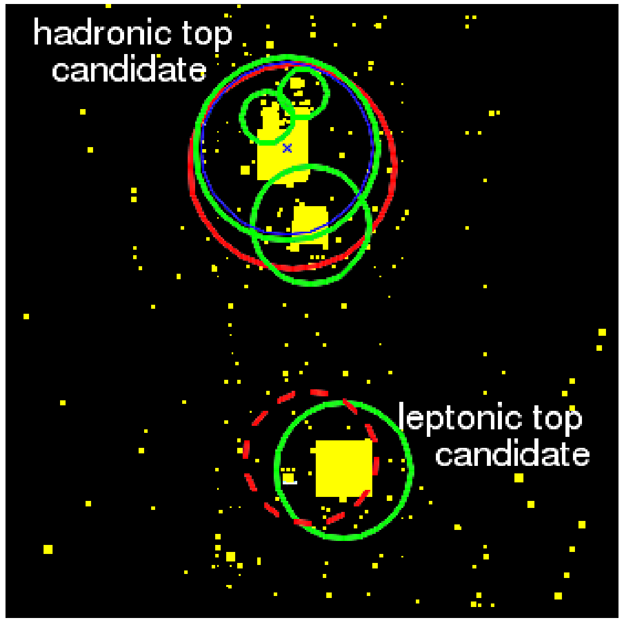


3 jets 3 subjets



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Thank you!