Collider physics II:
Jets

Two aspects of new developments

- Better QCD jet.
  - Smarter jet algorithm.
  - Noise suppression with jet grooming.
- Jet substructure.
  - Boosted top.
  - Higgs.

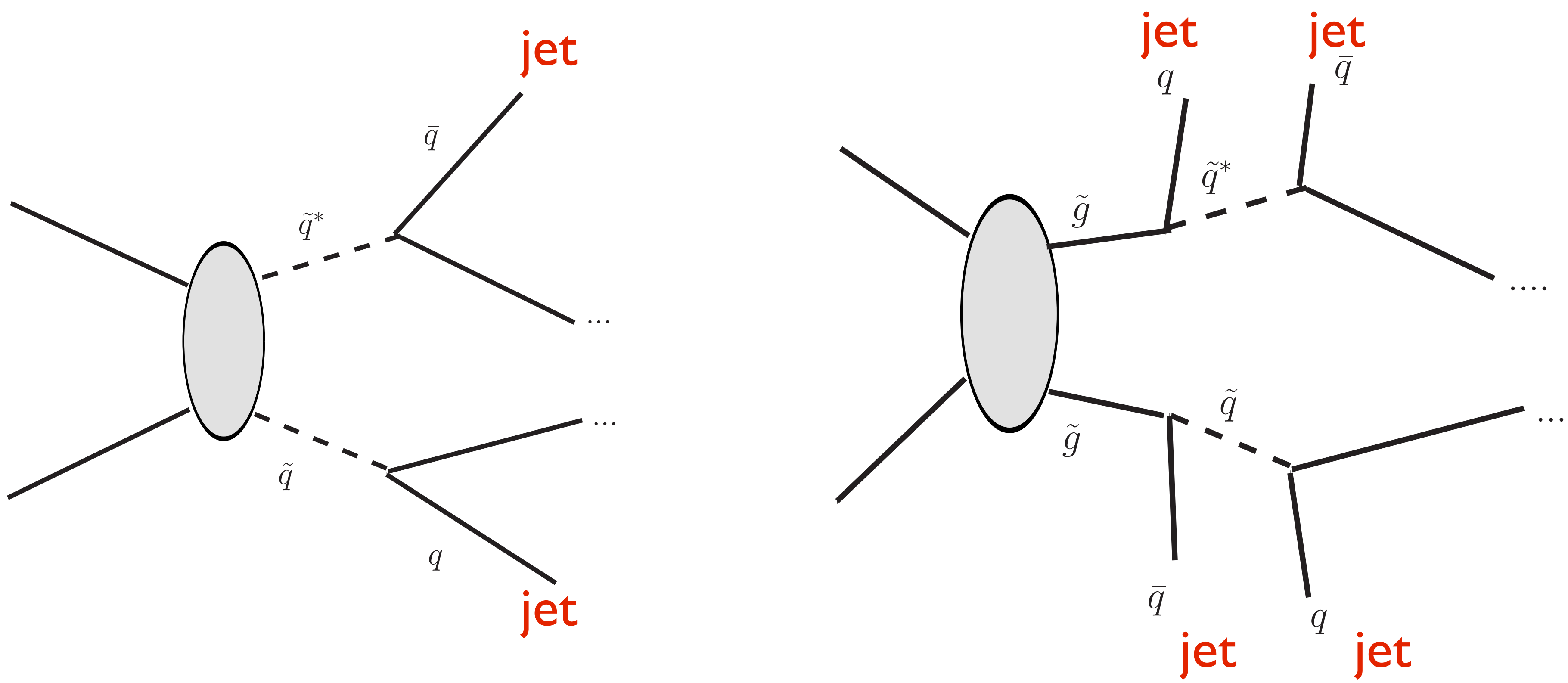
Boston Jet Workshop:
http://jets.physics.harvard.edu/workshop/Main.html
Northwest Terascale workshop
http://www.physics.uoregon.edu/~soper/Jets2011/talks.html
Boost 2011, May, 23-27, Princeton.
http://boost2011.org
Boost 2012, July, 23-27, Valencia, Spain.
http://ific.uv.es/boost2012/

Want to play with it?

- Parton level Signal and background:
  - Madgraph, Alpgen, ...
- ME+PS matching, UE, Pileup:
  - Pythia, Herwig, Sherpa, ...
- Some detector effect, in particular, granularity 0.1x0.1
  - PGS, Delphes, "by hand".
- Jet tools.
  - Fastjet. http://www.lpthe.jussieu.fr/~salam/fastjet/
  - SpartyJet http://projects.hepforge.org/spartyjet/

The importance of jets:

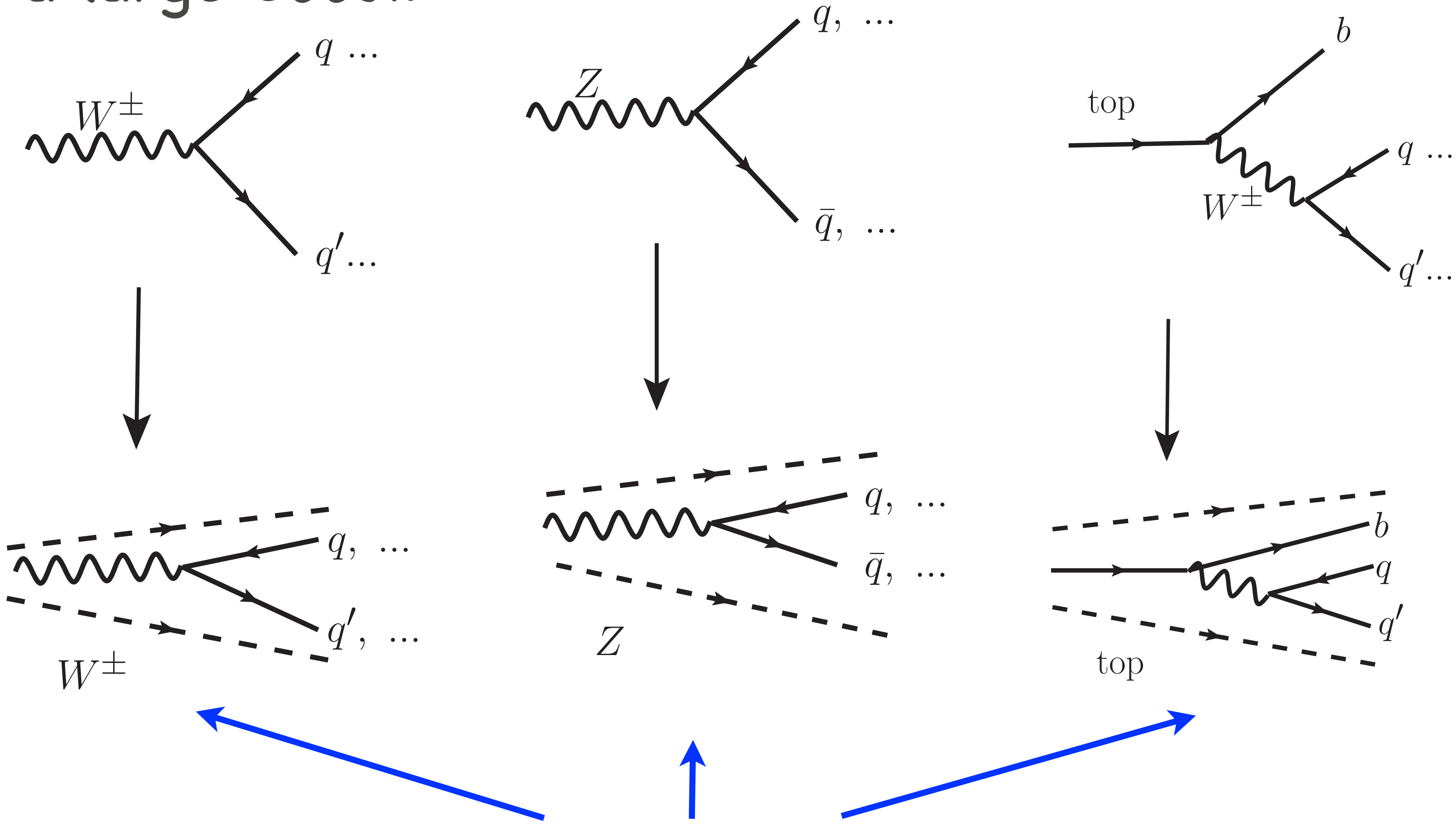
- "Everywhere" at hadron colliders. $p\ p$, or, $p\bar{p}$ initial state.
- Present in (almost) all new physics signals.
  - Many of them only have hadronic channels.



Jet look likes

- When produced at TeV-scale energies, they have a large boost.

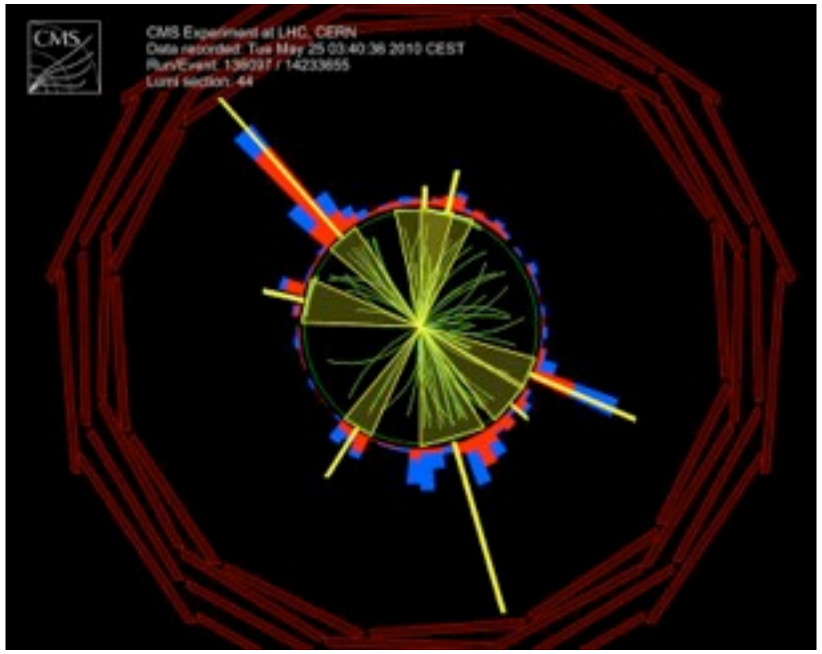
boost

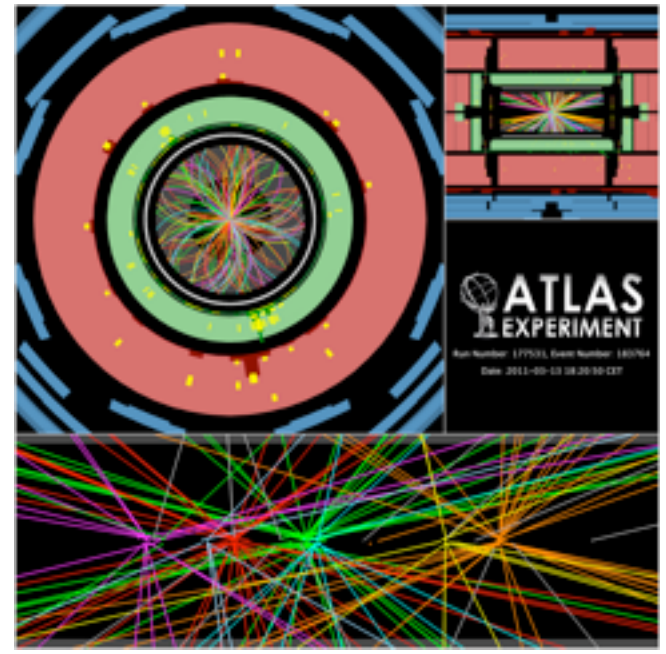


Jets with substructure.

Challenge: distinguishing them from QCD jets (q and g).

Need new jet tools for the LHC.

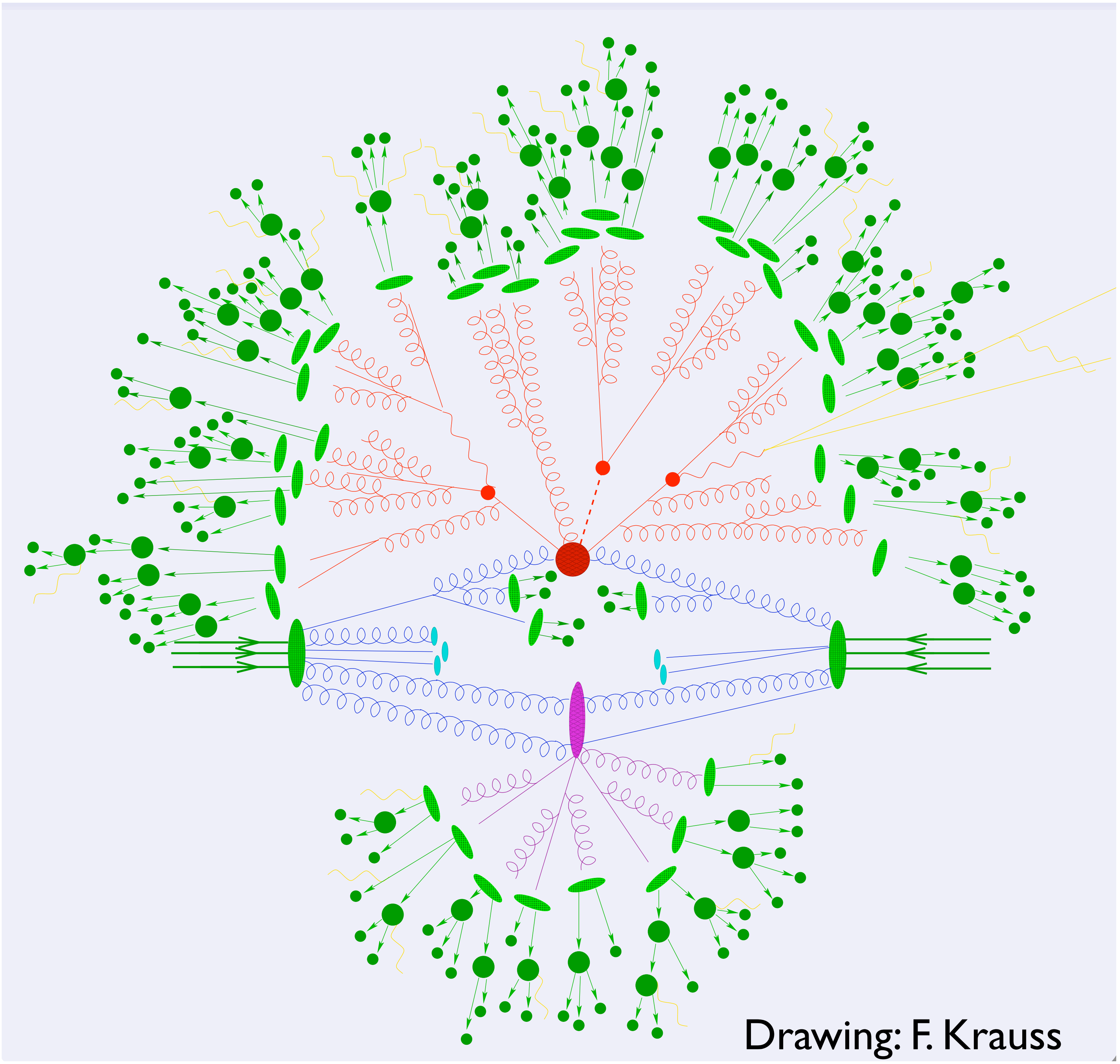




- More energetic, bigger, jet at the LHC.
  - LHC jet: 50 GeV - several TeV
  - Tevatron jet: 50 - 100s GeV

- Much higher "noise" level at the LHC.
  - LHC: 10-100 GeV / rapidity
  - Tevatron: 2-10 GeV / rapidity

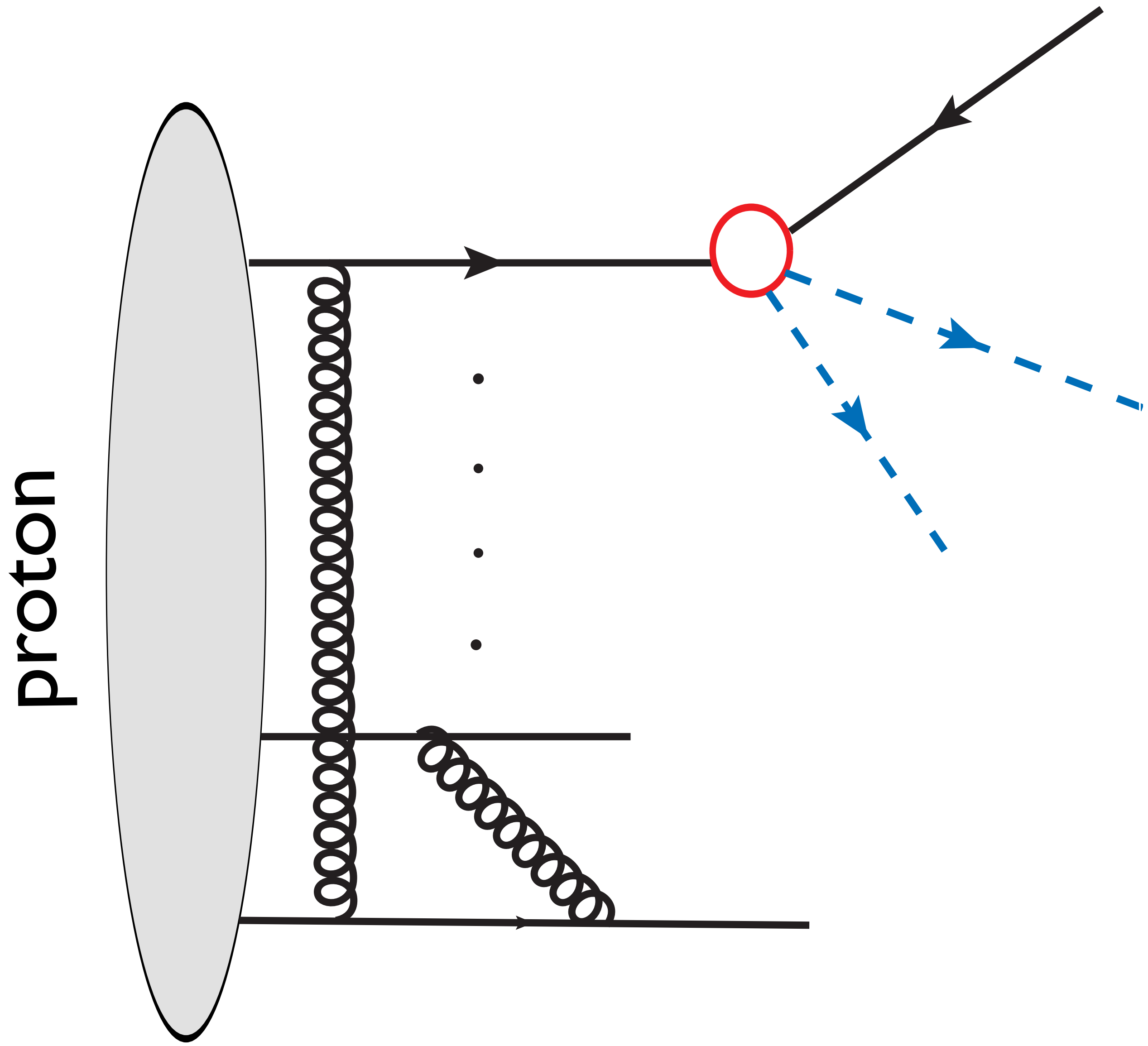
Hadron collision



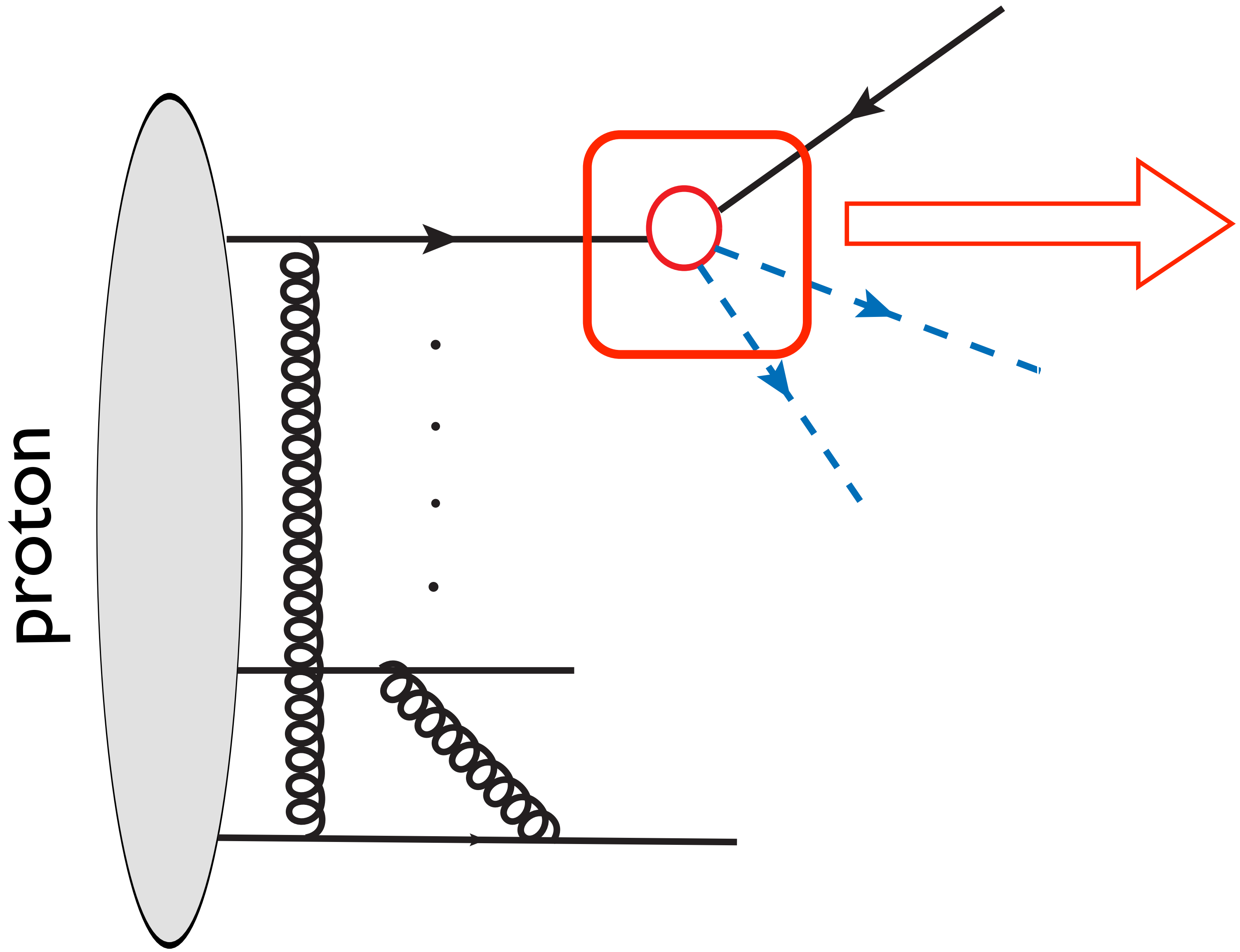
Why can we calculate at all?

- Perturbatively, we can only calculate with quark and gluon in hard collisions.
- Factorization.
- IRC safety, need proper choice of observable.
  - Soft or collinear radiation should not be able to induce "large" changes in the observable.
  - Otherwise, we cannot compare calculation with observables.

Factorization: intuition



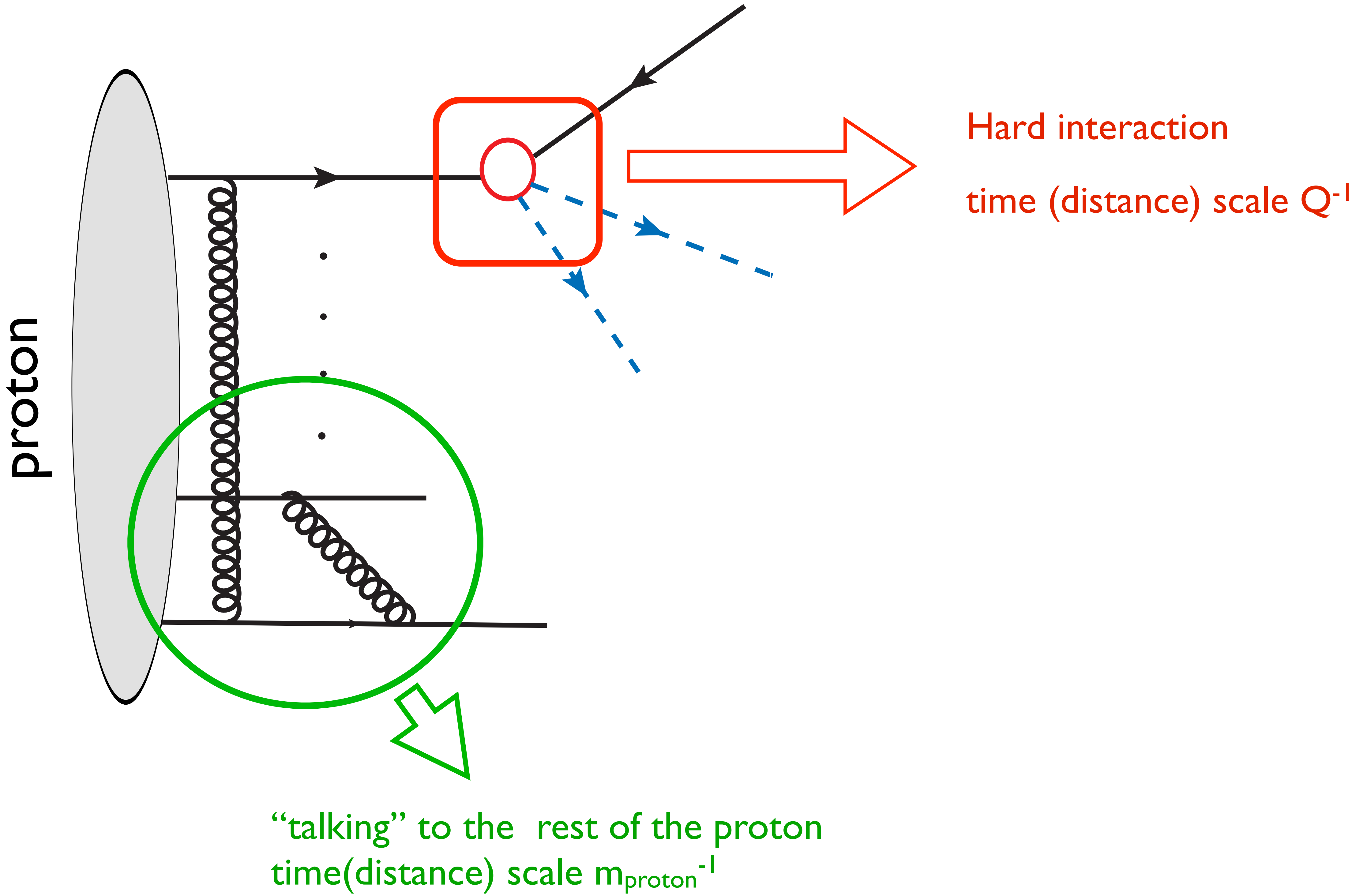
Factorization: intuition



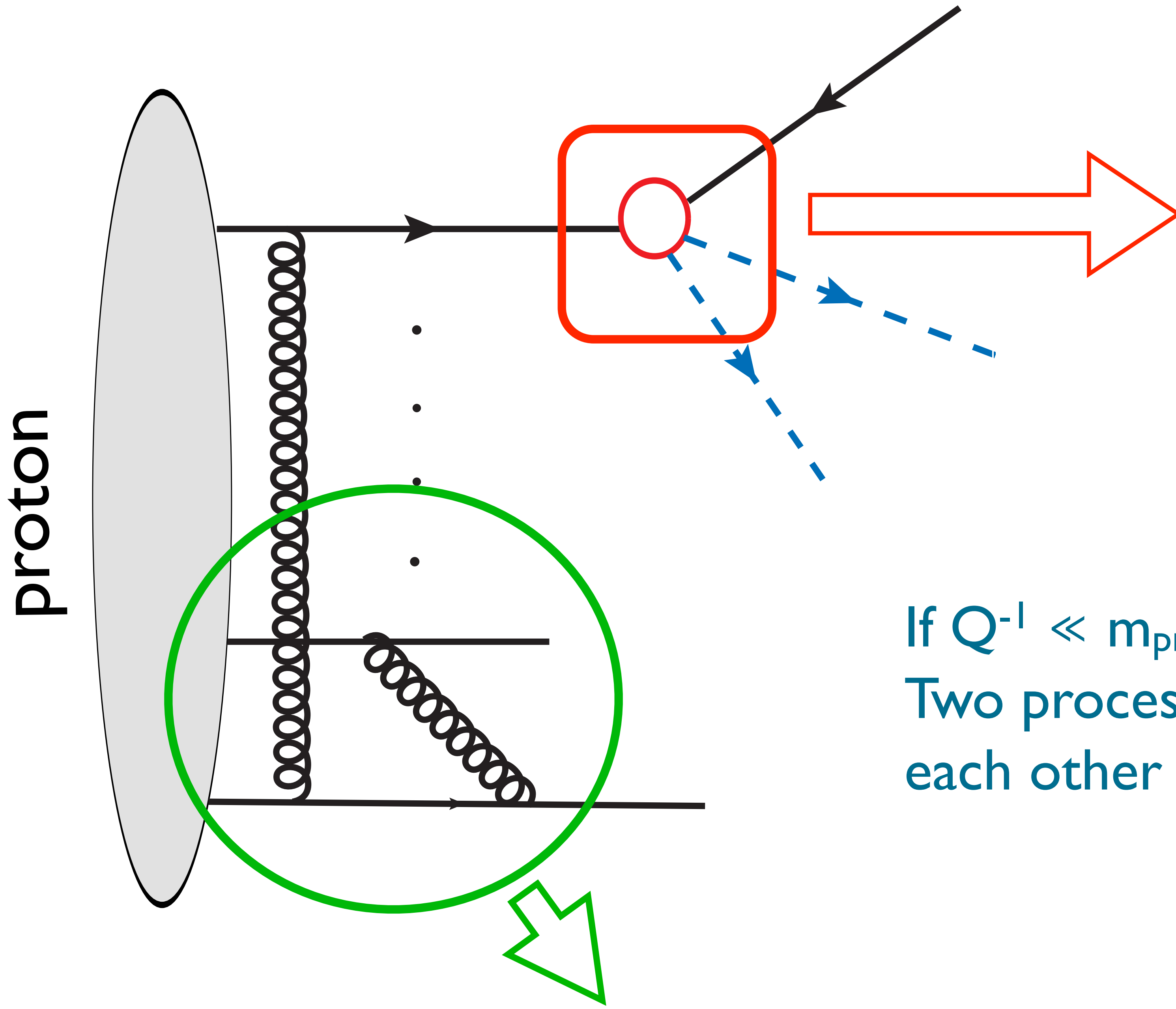
Hard interaction

time (distance) scale Q^{-1}

Factorization: intuition



Factorization: intuition



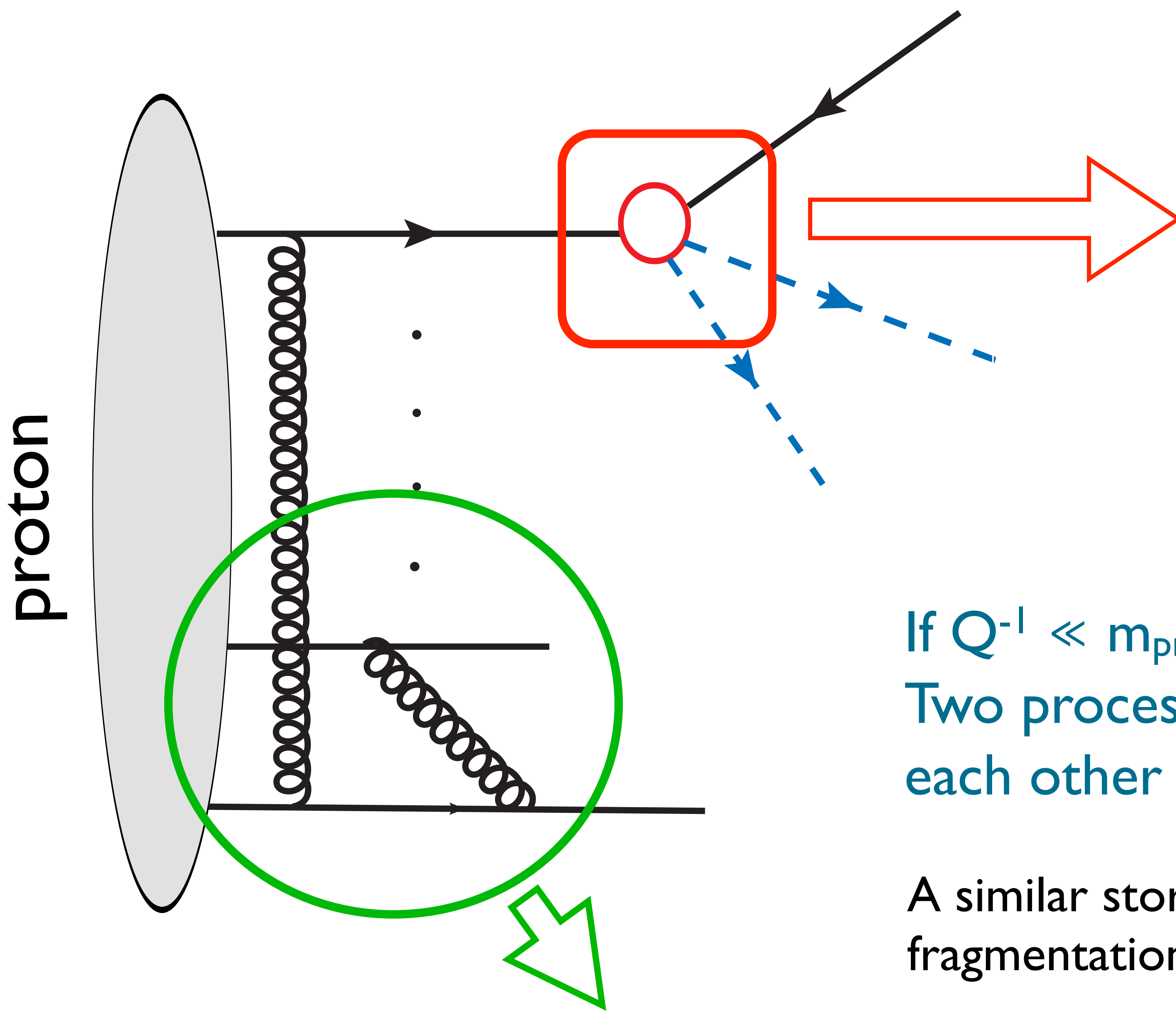
Hard interaction

time (distance) scale Q^{-1}

If $Q^{-1} \ll m_{proton}^{-1}$ (hard interaction)
Two processes should not affect each other → Factorization!

"talking" to the rest of the proton
time(distance) scale m_{proton}^{-1}

Factorization: intuition



Hard interaction

time (distance) scale Q^{-1}

If $Q^{-1} \ll m_{proton}^{-1}$ (hard interaction)
Two processes should not affect each other → Factorization!

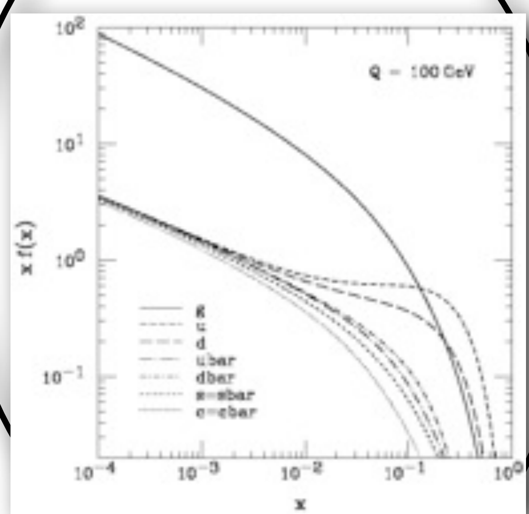
A similar story for final states
fragmentation, q,g⇒ hadrons (pion, K...)

“talking” to the rest of the proton
time(distance) scale m_{proton}^{-1}

Factorization

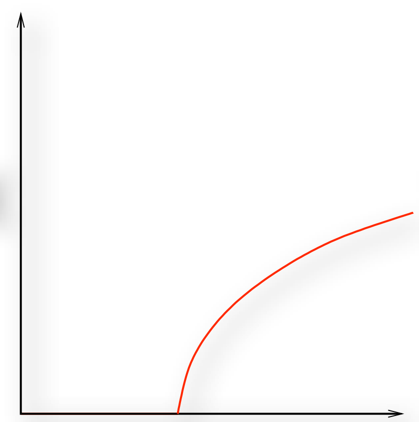
- Schematics of production at hadron colliders.

$$\int \left(\quad \right)^2$$



Parton densities

$\times$



Threshold

$\times$?

matrix elements

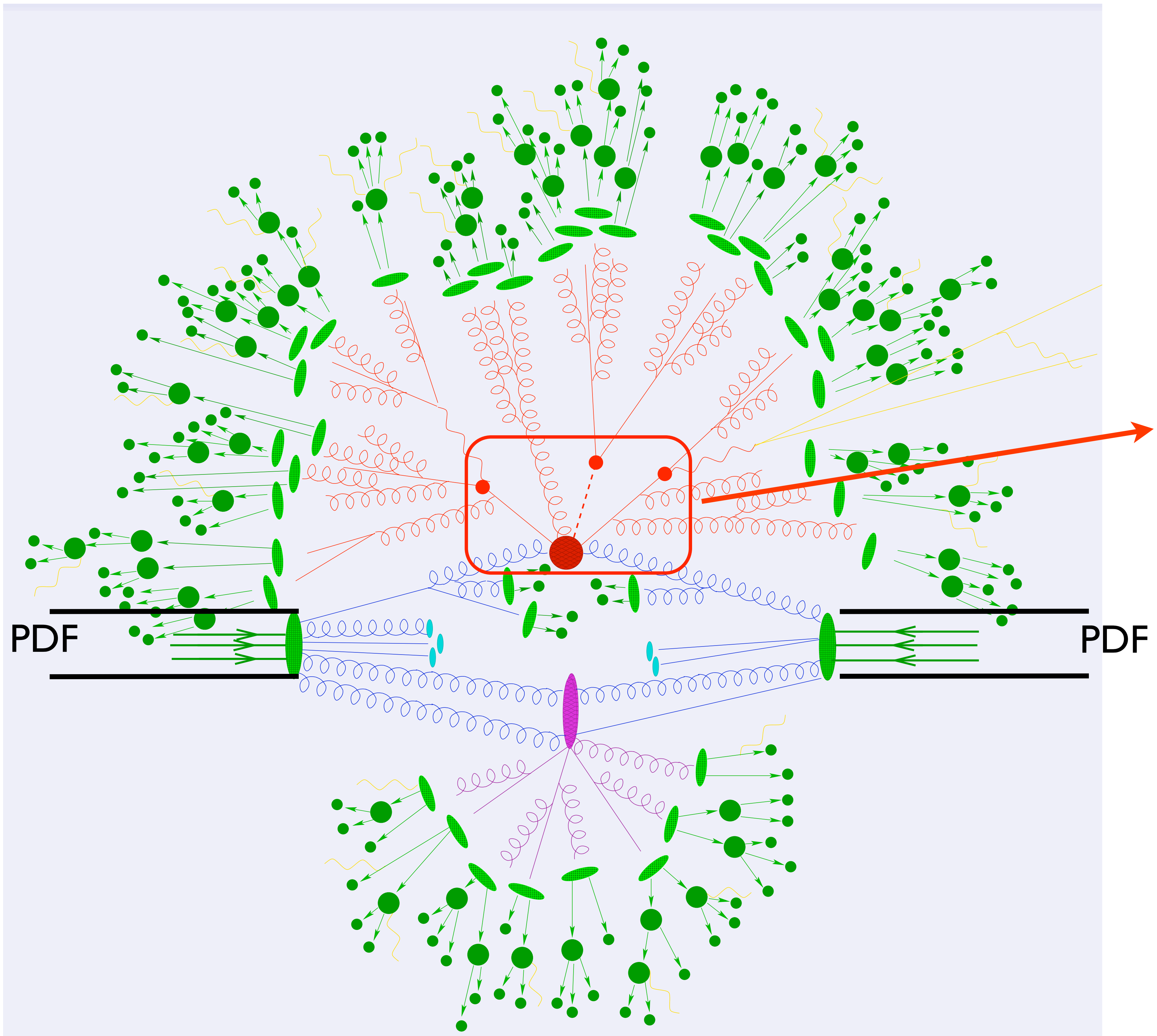
$\times$ phase-space

$$a + b \rightarrow \ldots$$

$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}$$

Partonic cross section

Hadron collision.



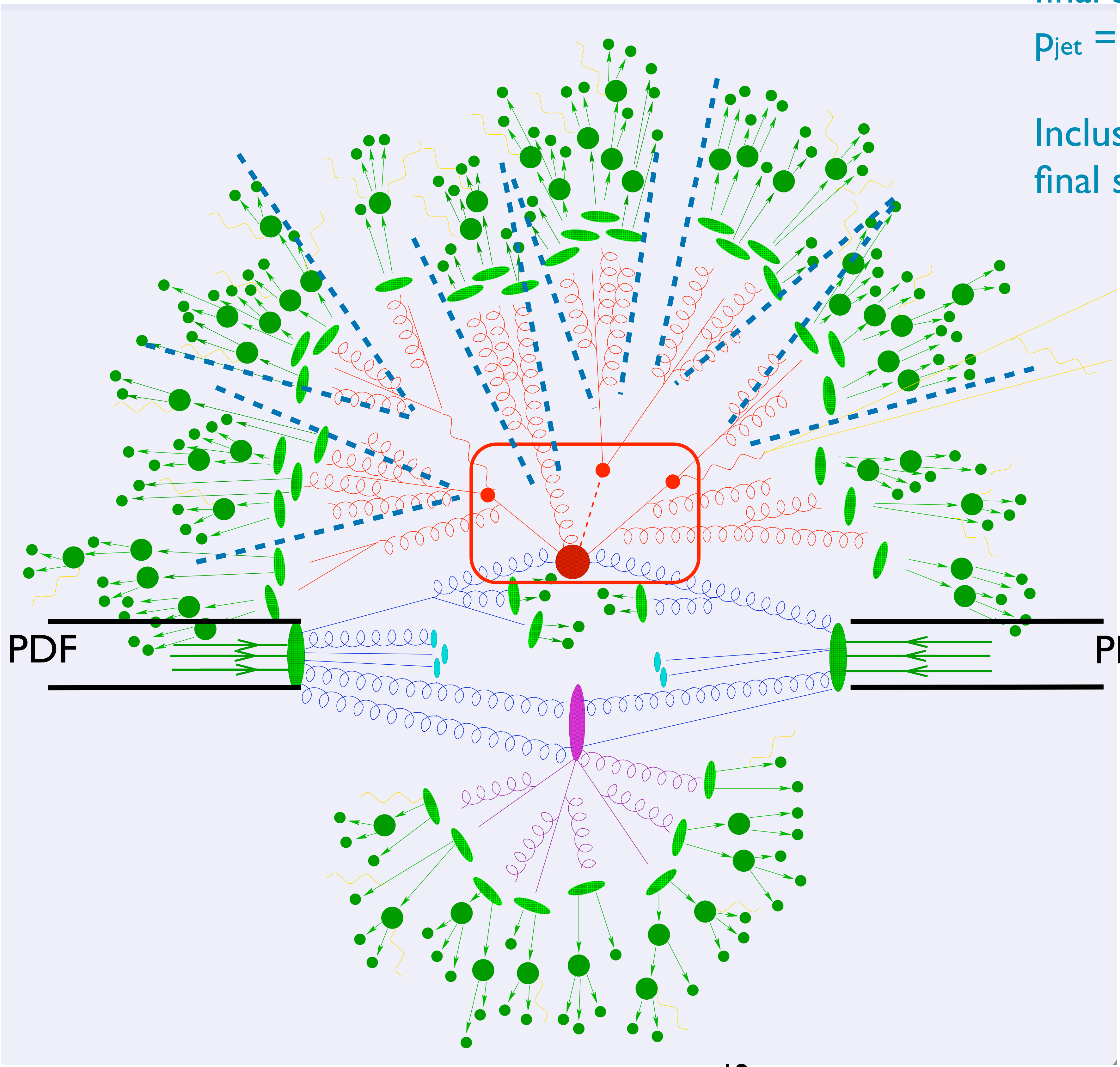
Hard interaction, gg⇒ g h t tbar

⇒h t tbar decay

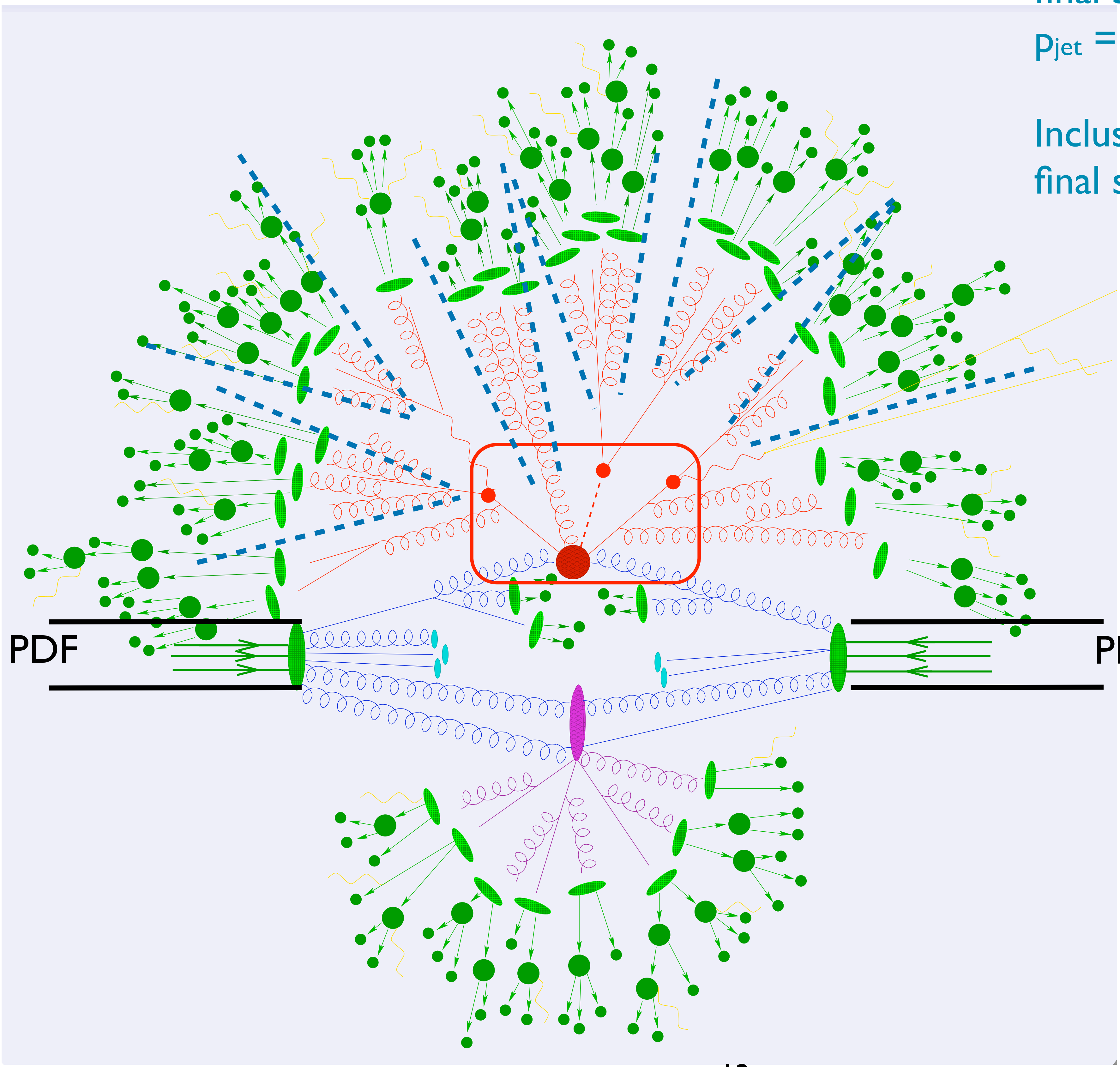
Hadron collision

Clusters of hadronic energy
final state object: jet
$p_{jet} = \Sigma$ p of constituents

Inclusive: independent of
final states, just energy



Hadron collision

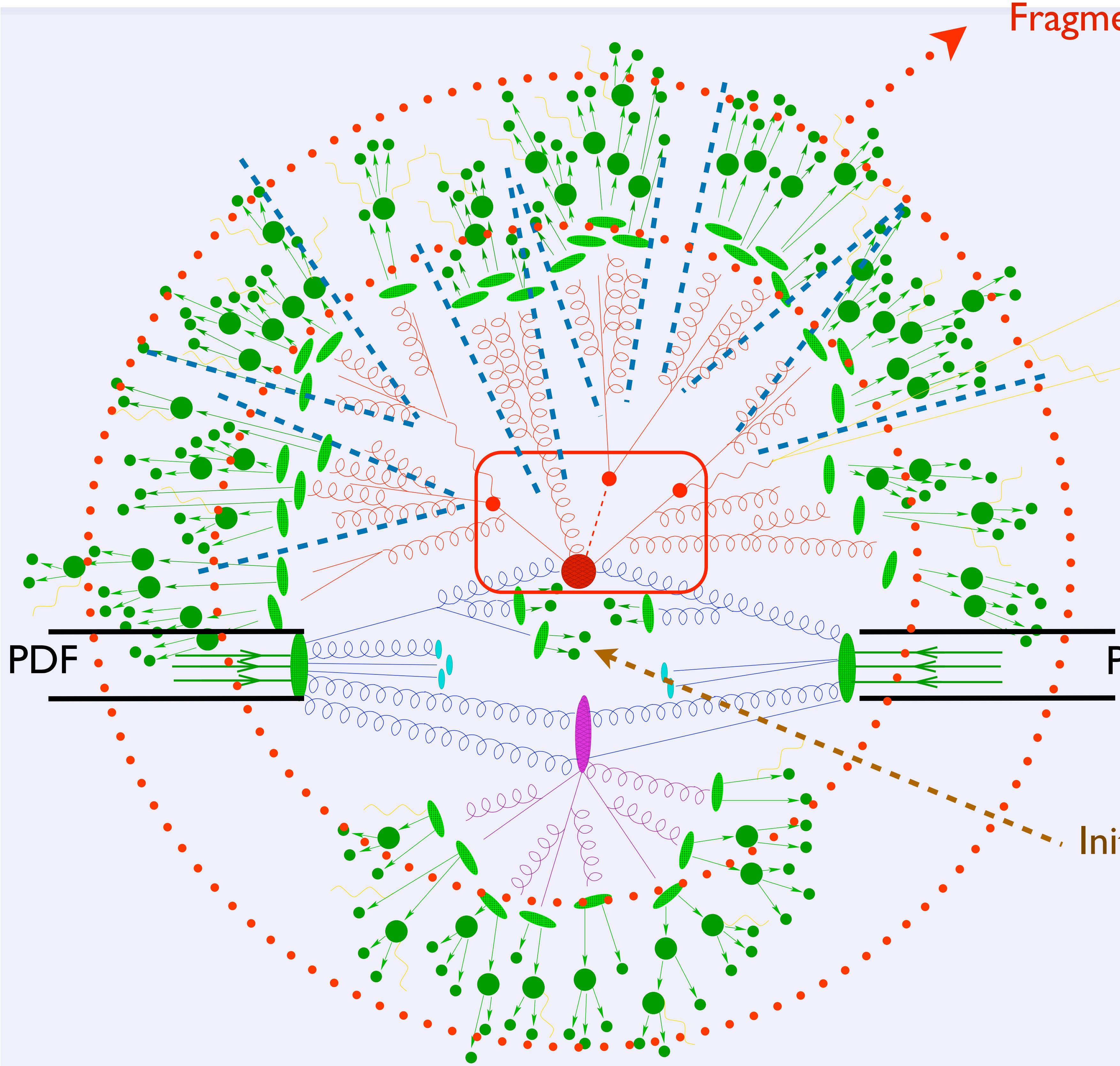


Clusters of hadronic energy
final state object: jet
$p_{jet} = \Sigma$ p of constituents

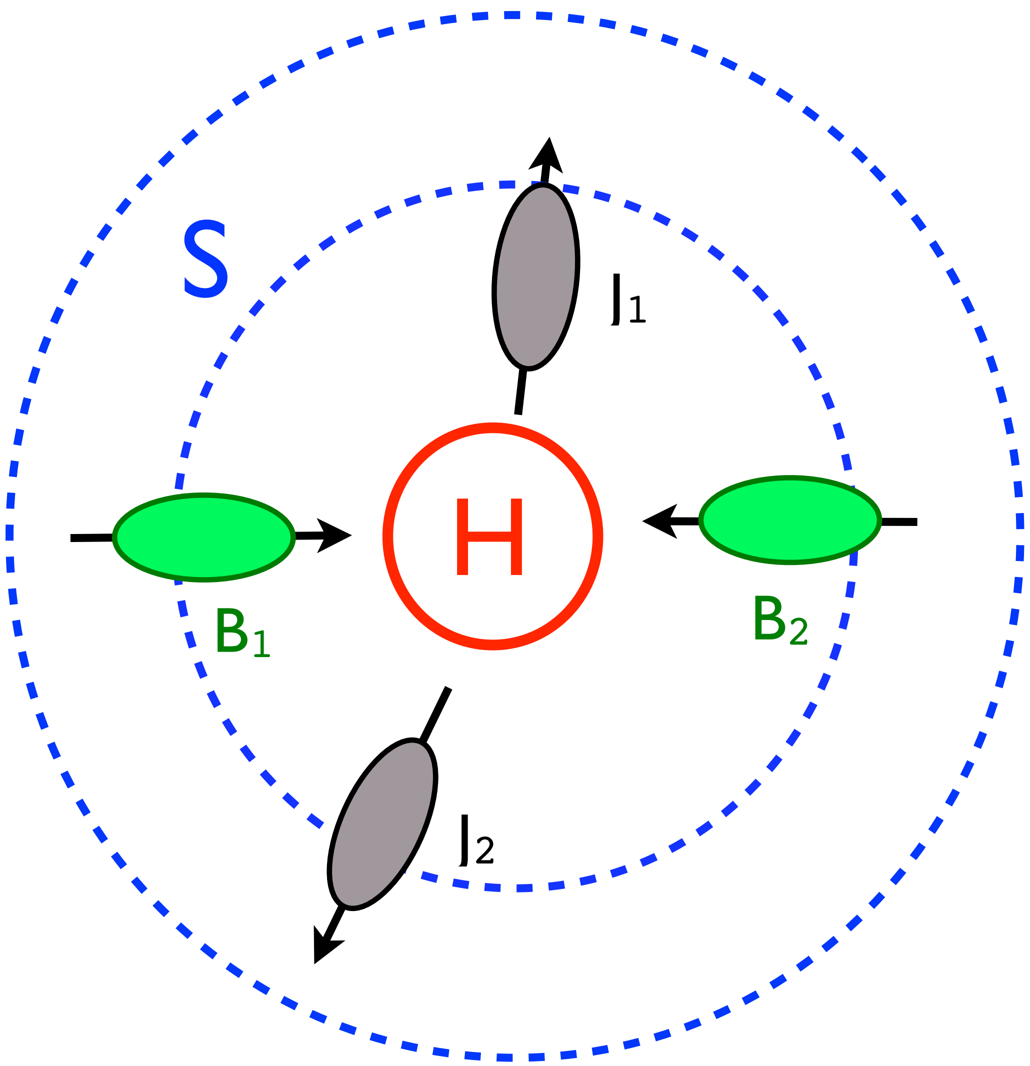
Inclusive: independent of
final states, just energy

Very important:
need $p_{jet} \approx p_{parton}$
Can use parton level
calculation to predict
jet properties

Hadron collision



Factorization



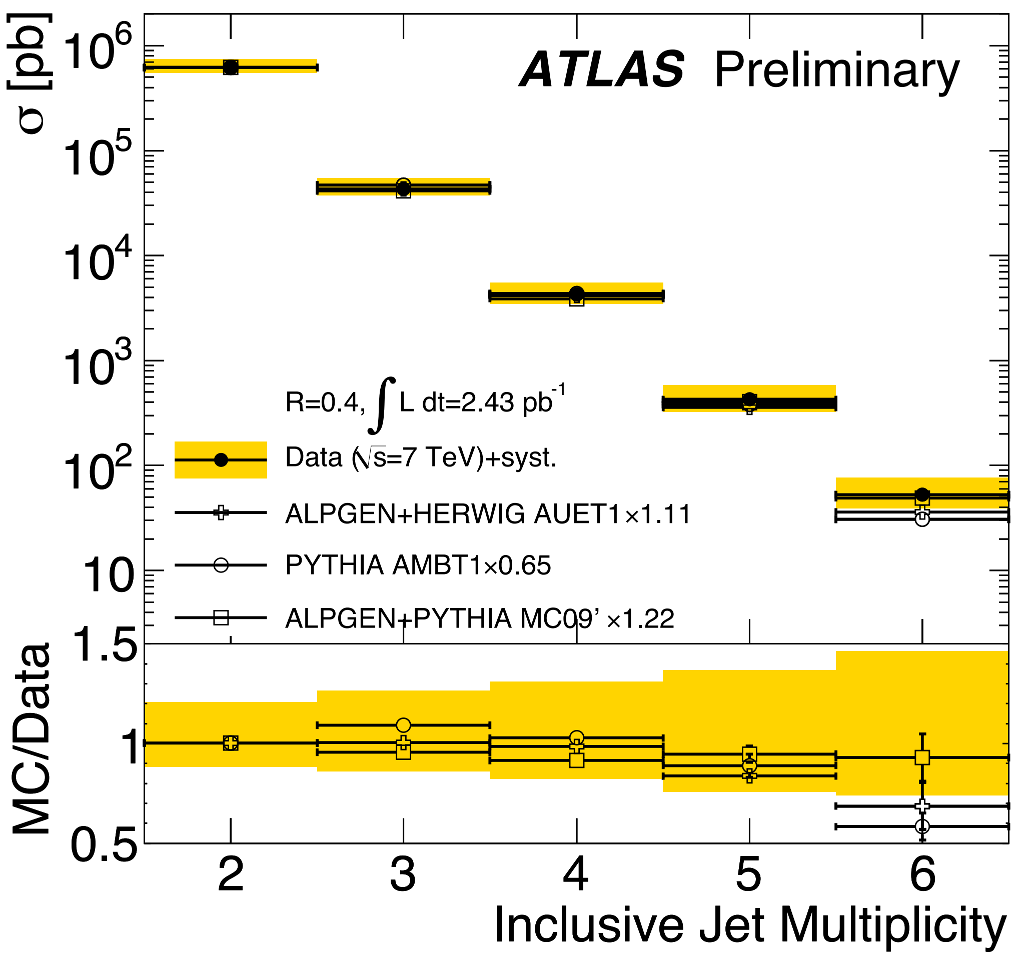
$$\sigma = B_1 \otimes B_2 \otimes H \otimes J_1 \otimes J_2 \otimes S$$

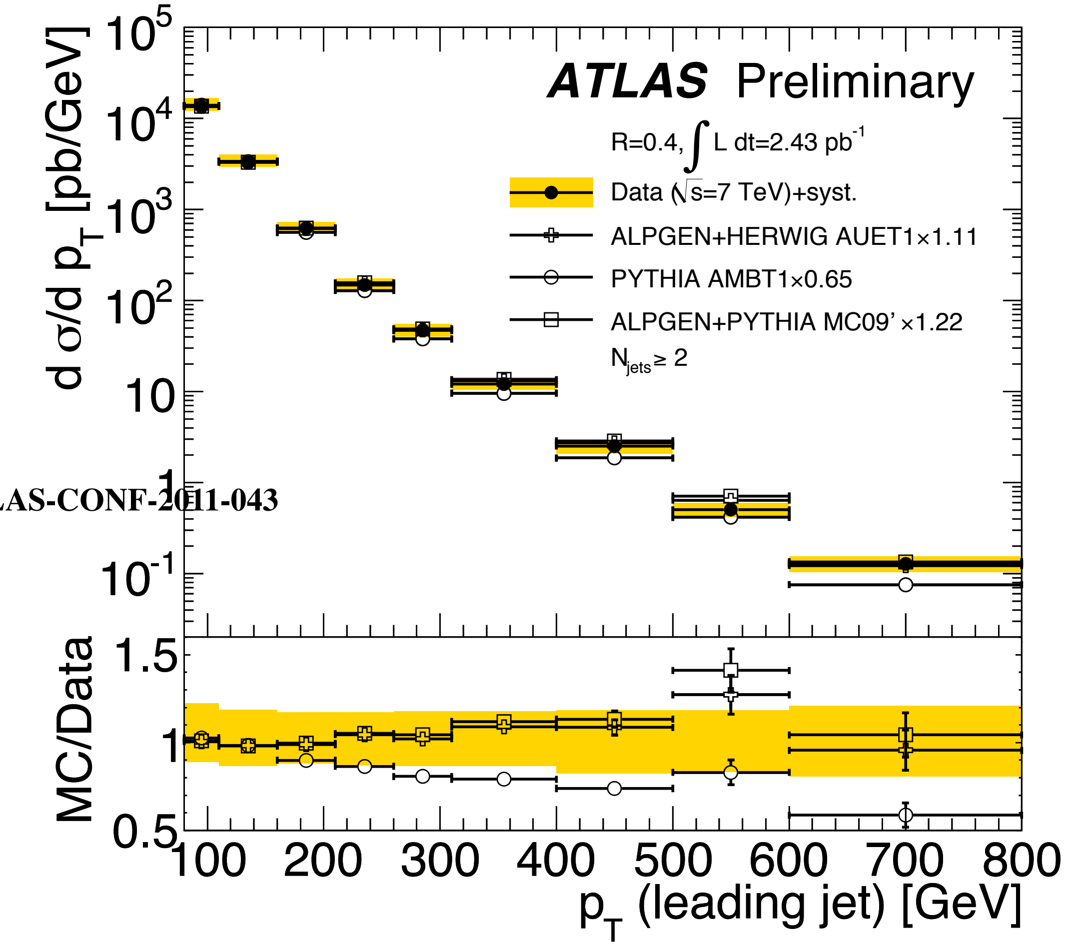
$$B_1 = dx_1\, f(x_1),\; B_2 = dx_2\, f(x_2).$$

$$\hat{\sigma} = H \otimes J_1 \otimes J_2 \otimes S$$

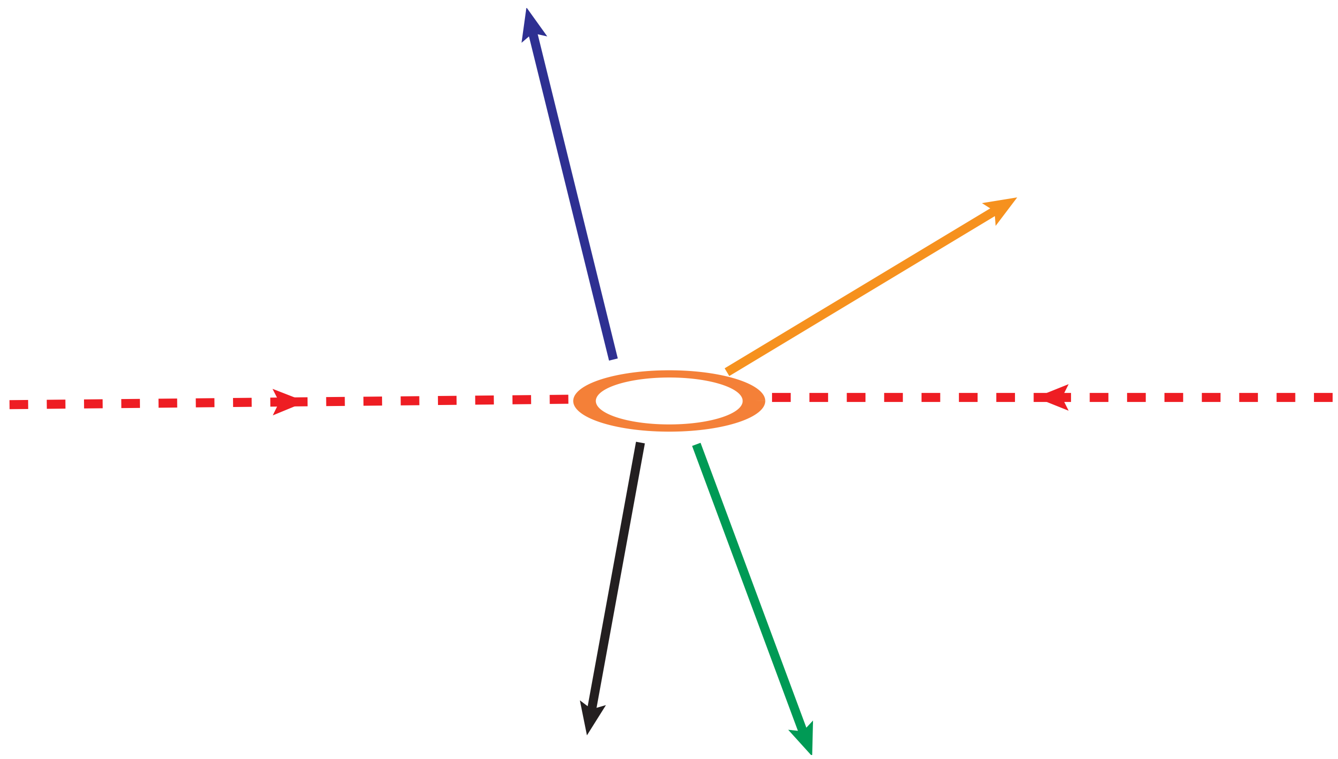
Well tested.

ATLAS-CONF-2011-043, 7 TeV, 2.43 pb^{-1}





Why is it hard?



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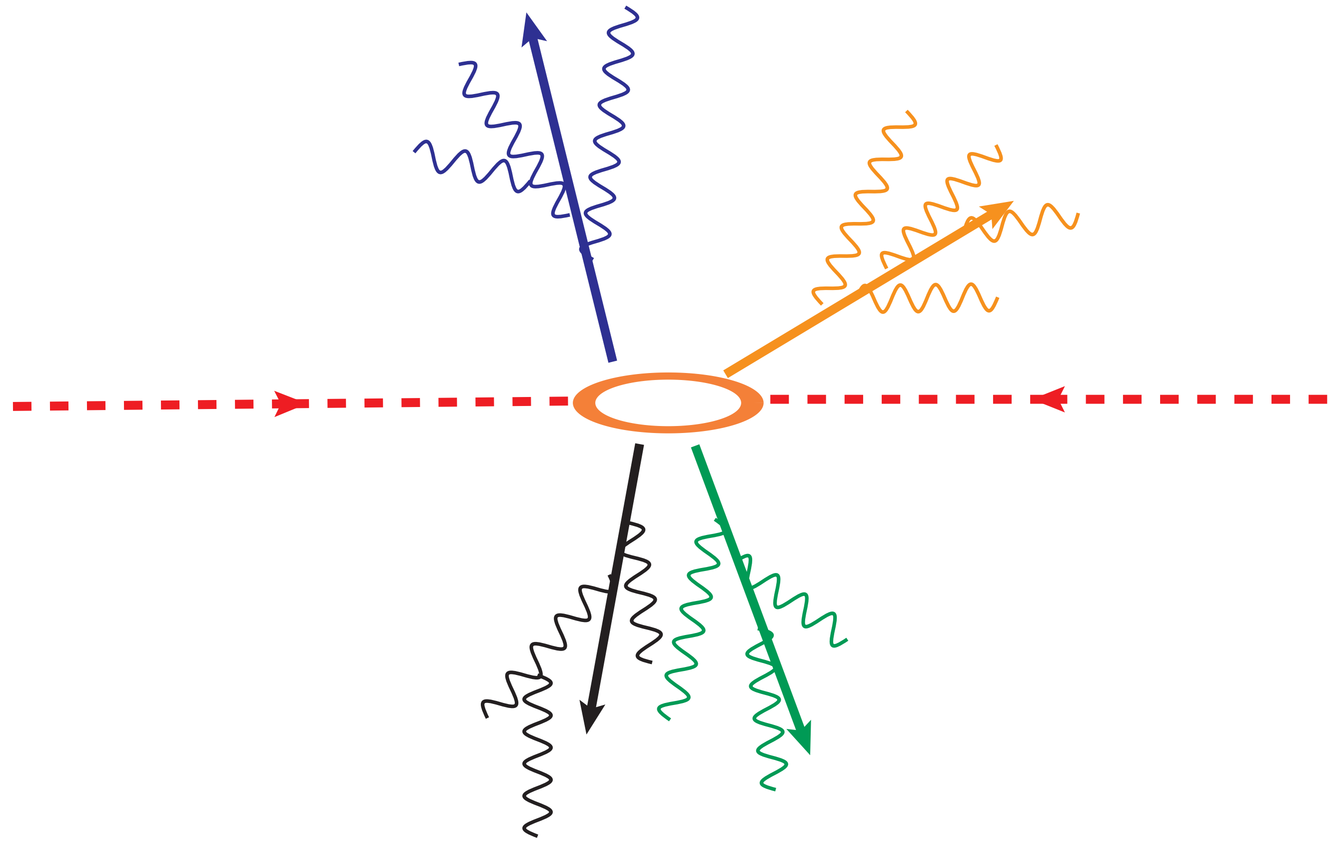

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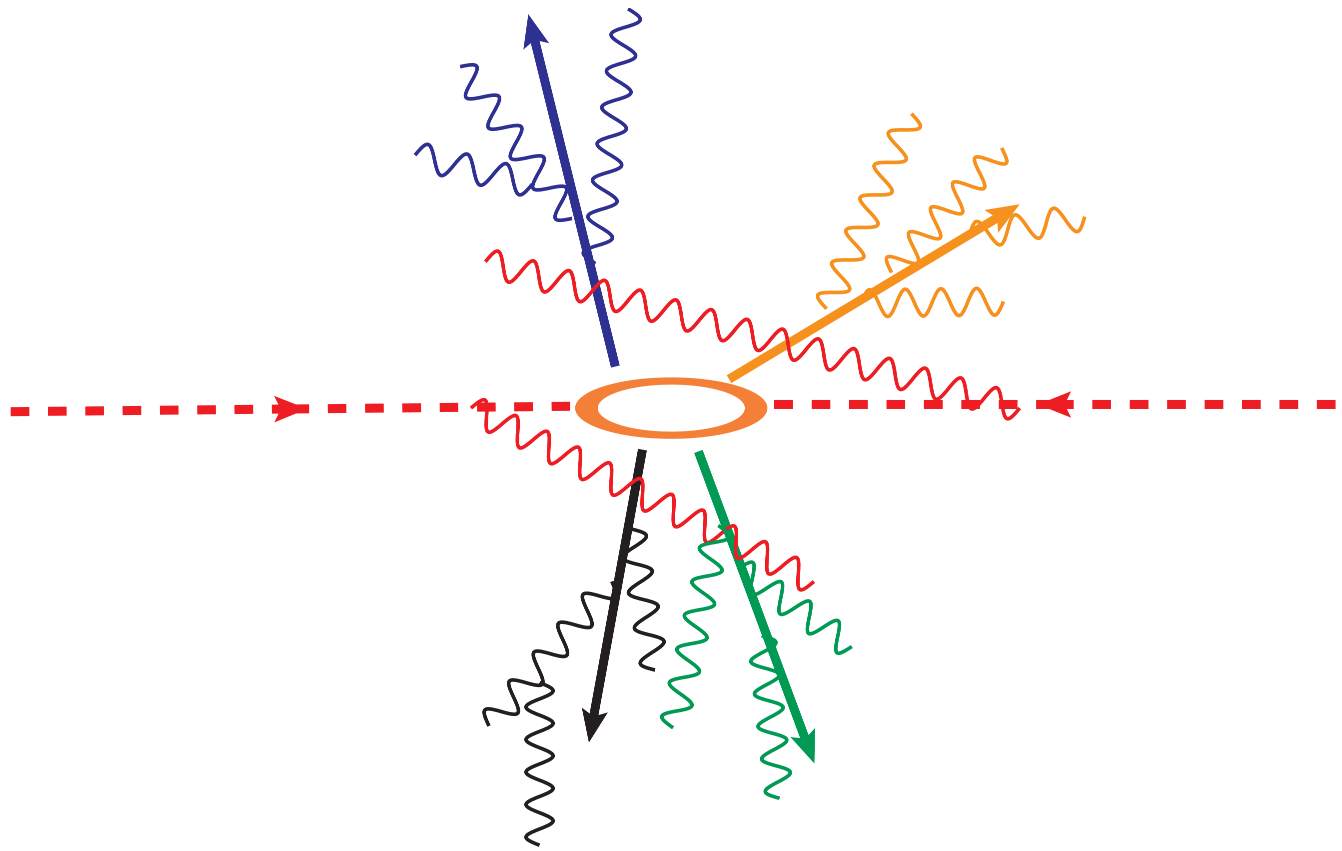

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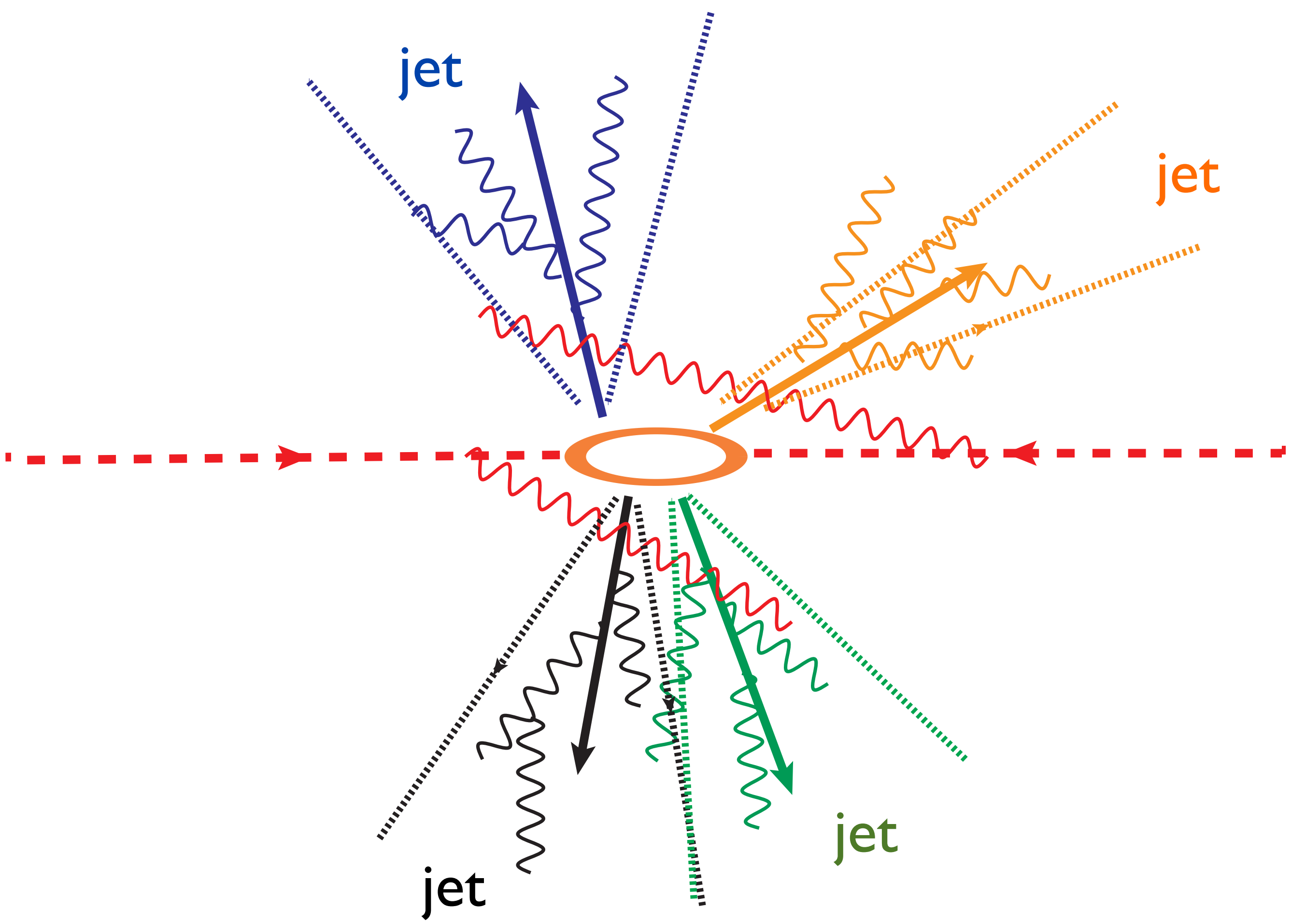

$$p_{\text{jet}} = \sum_{\text{constituents}} p_i$$

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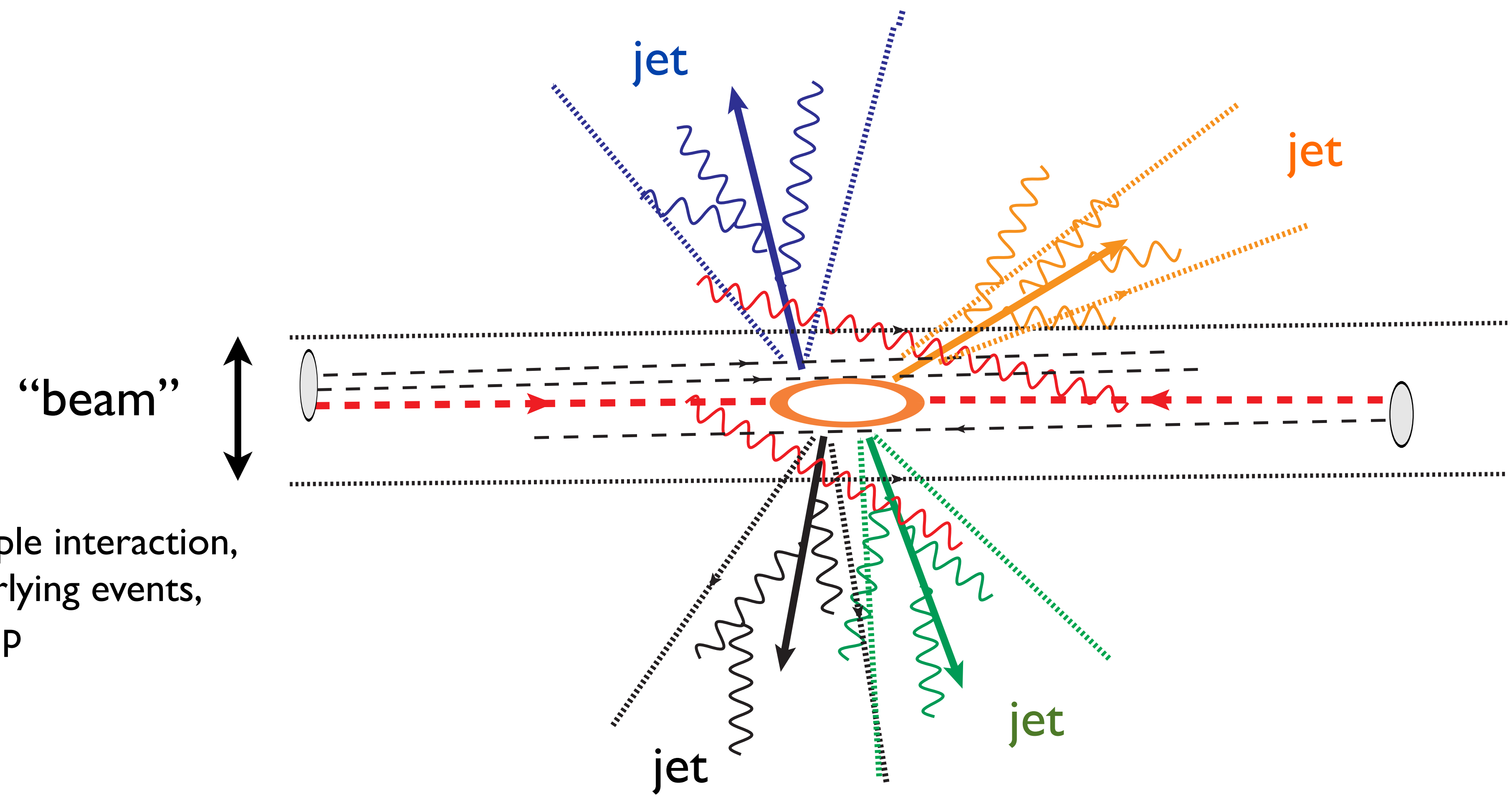

Multiple interaction, underlying events, pile-up

$$p_{\text{jet}} = \sum_{\text{constituents}} p_i$$

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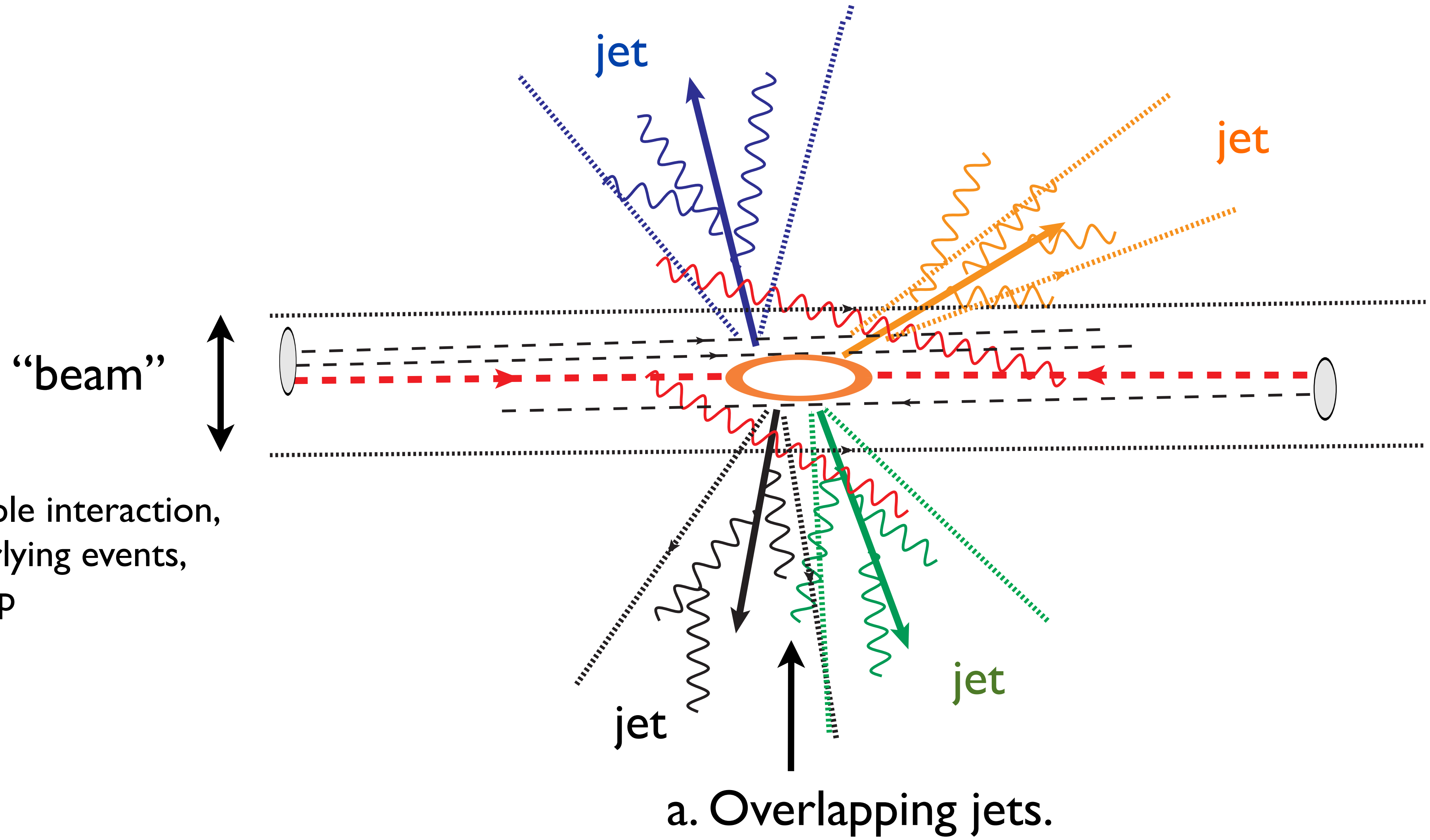

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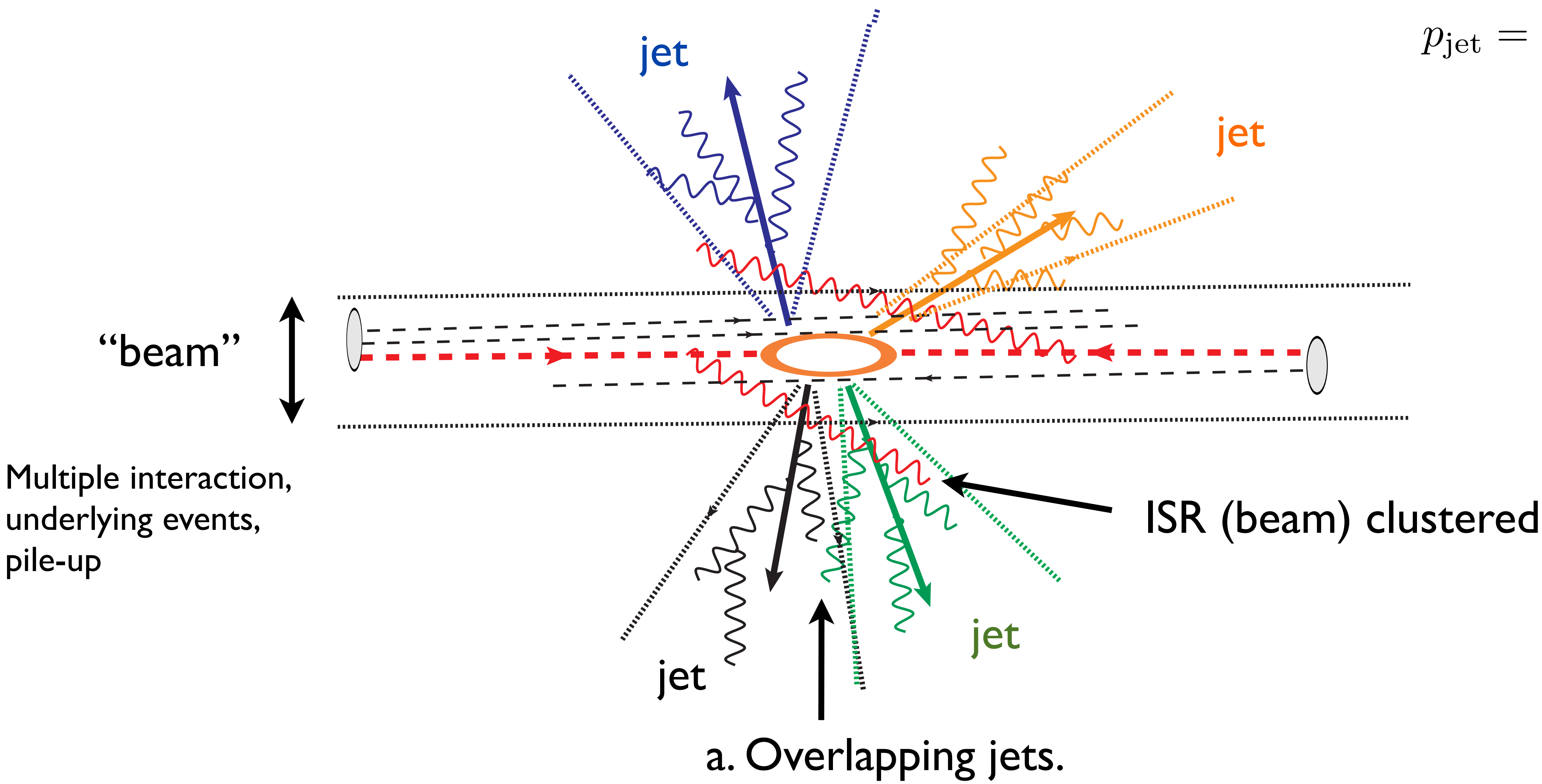

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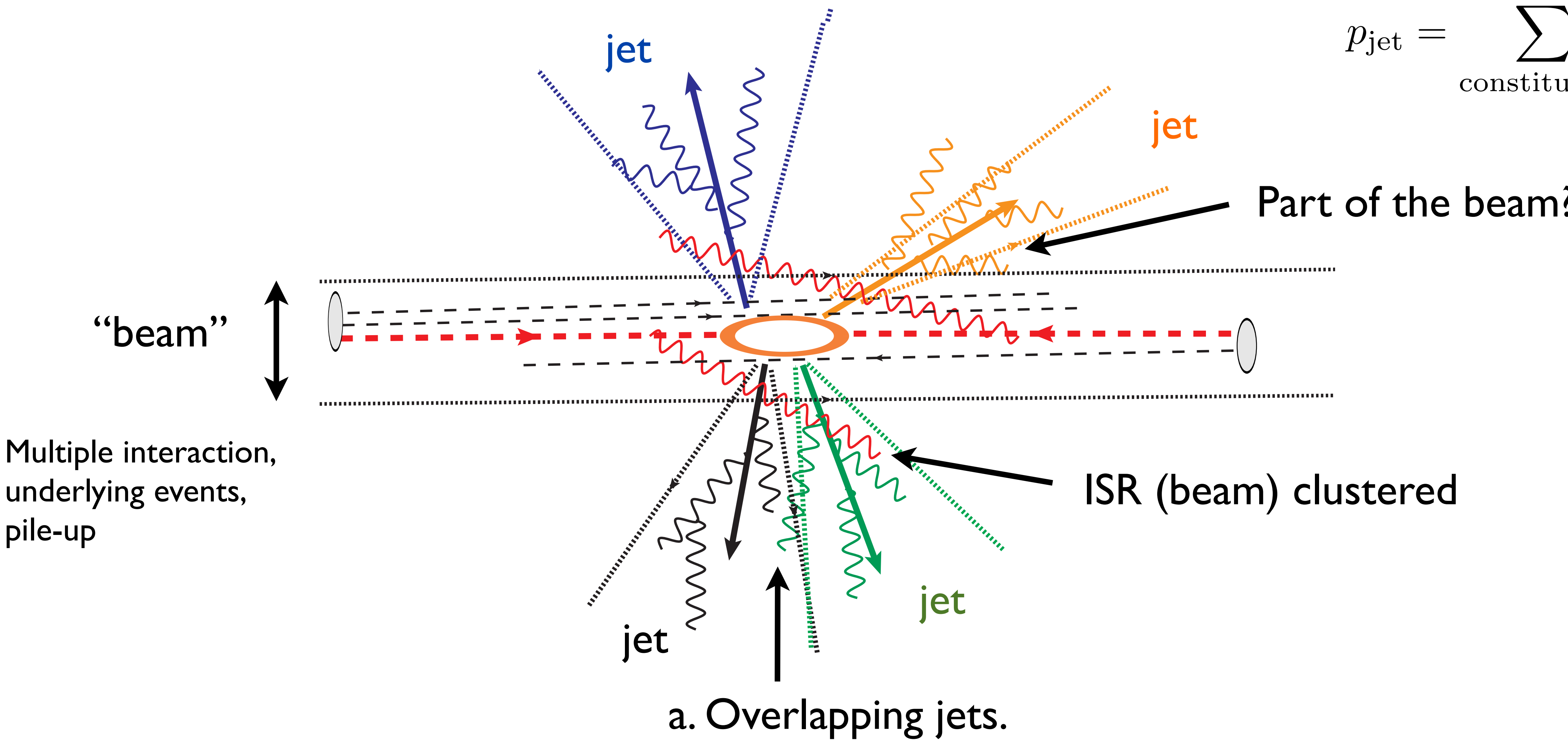

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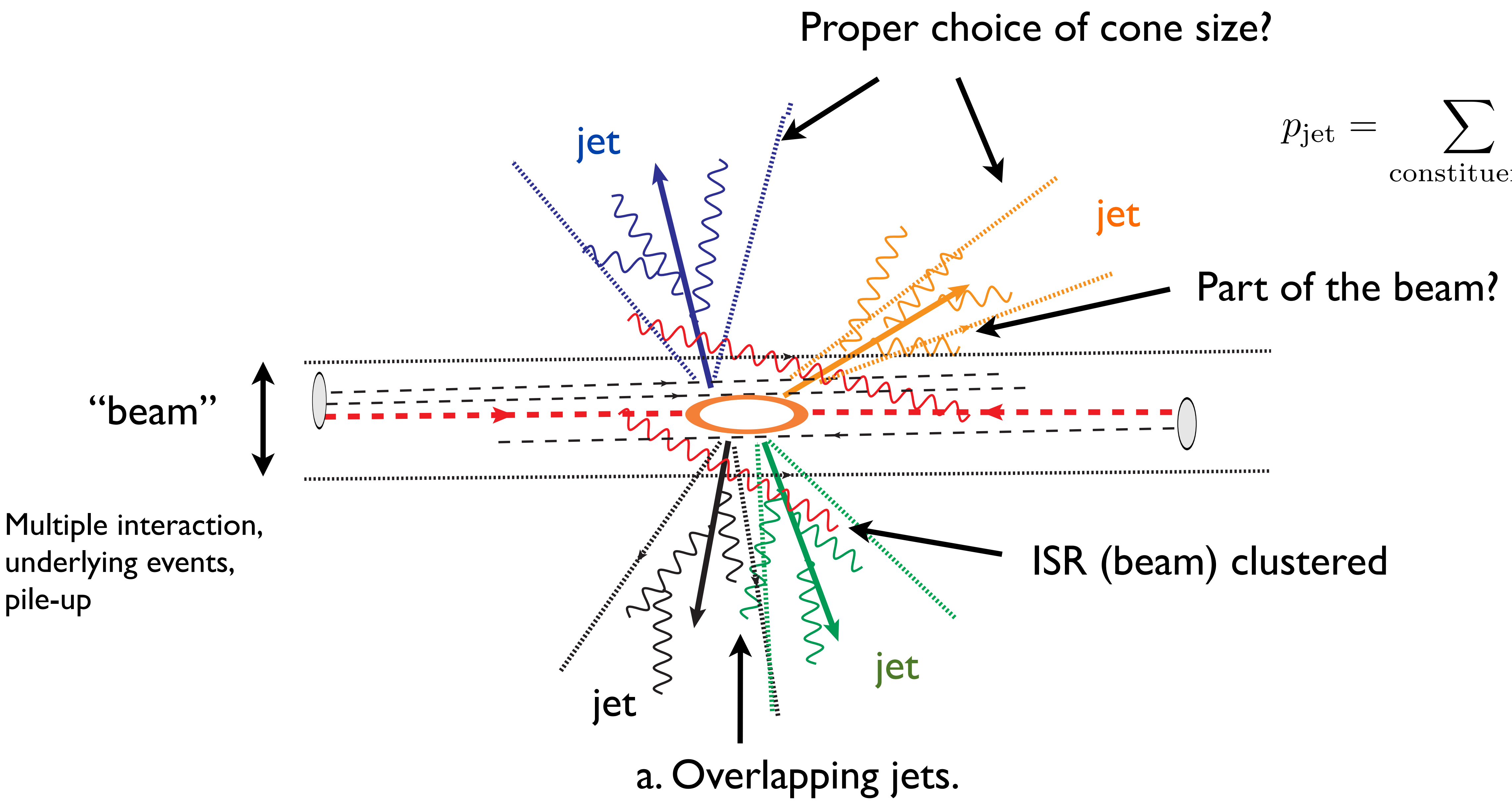

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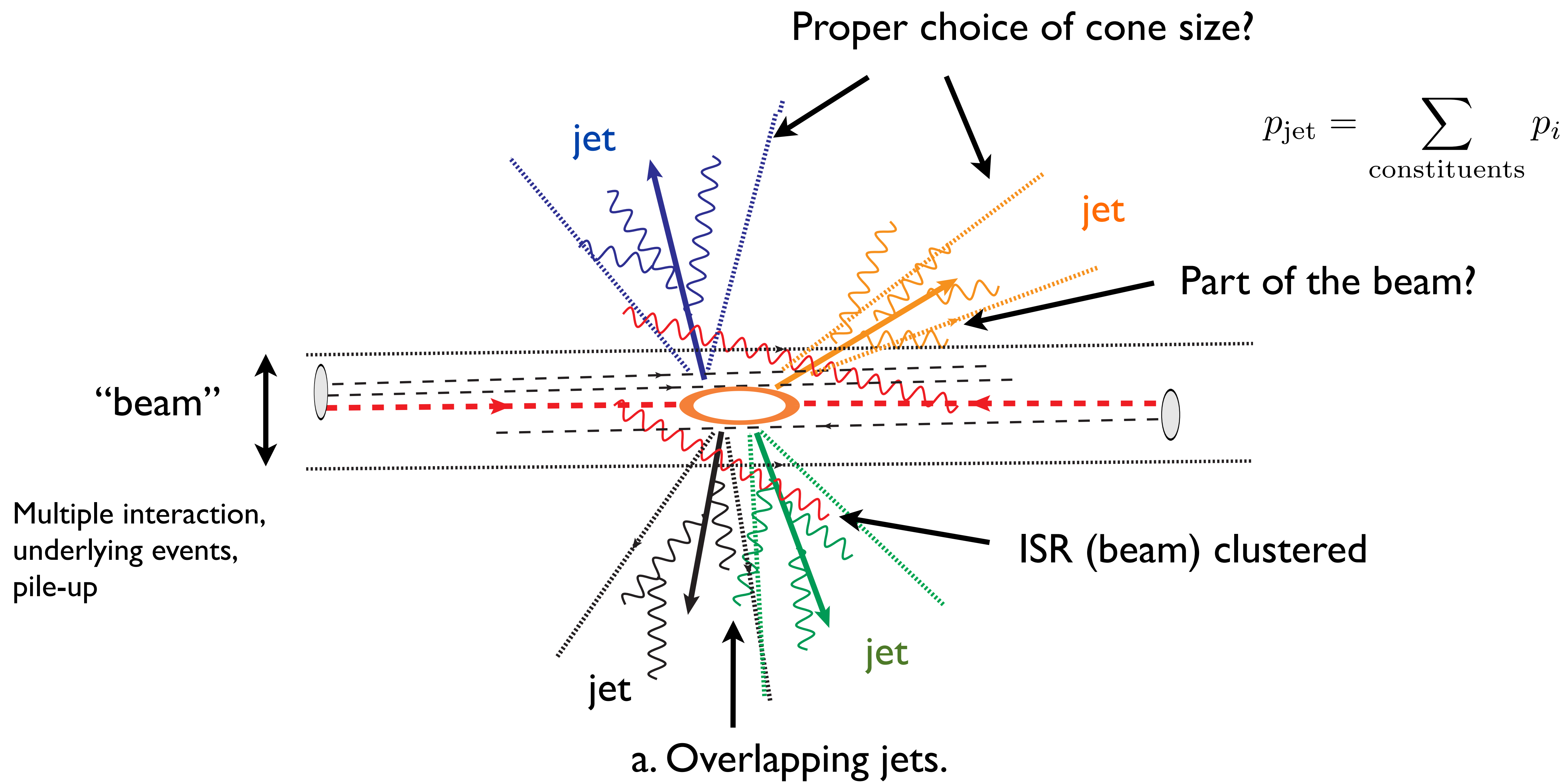
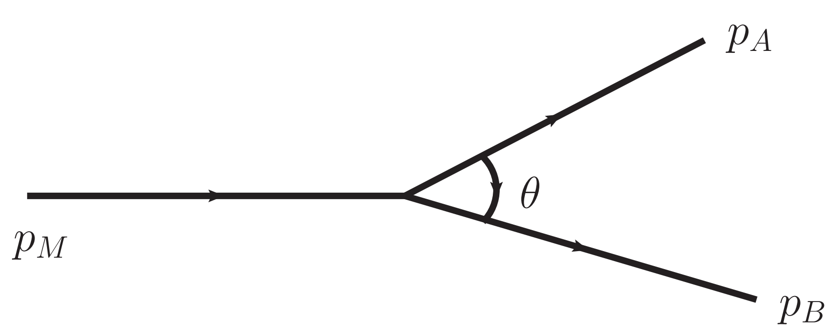


- To best preserve $p_{\text{jet}} \simeq p_{[\text{initial parton}]}$ we would like to:
  - Use "smart" jet shapes.
  - Reduce "noise".

What do jets look like?

Parton splitting, collinear limit



Relevant kinematical variables

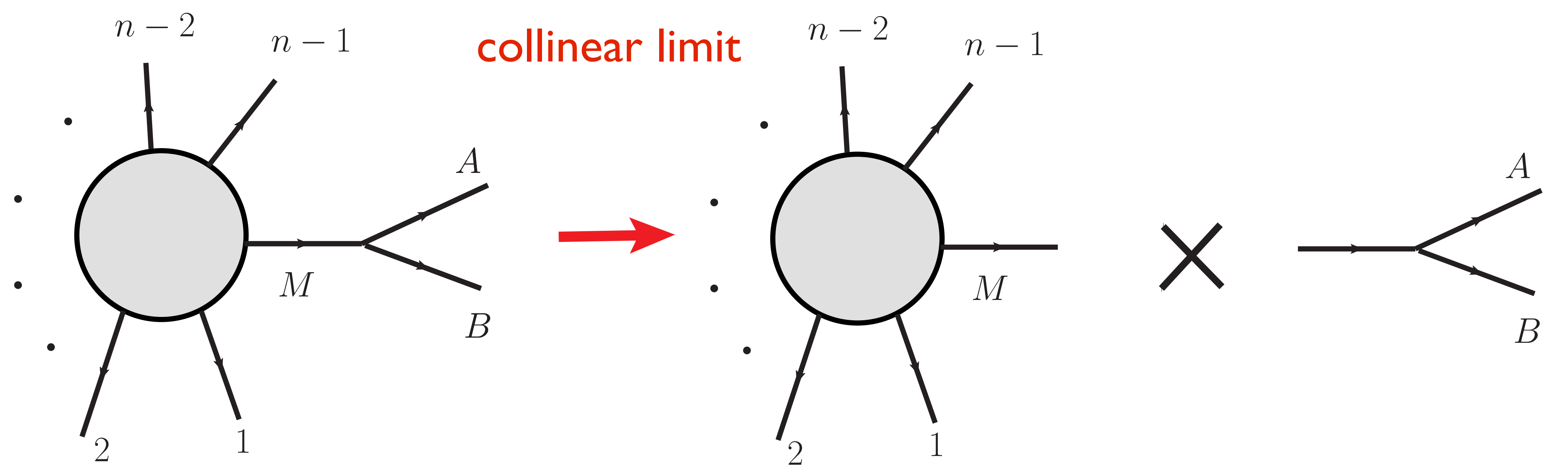
$$t = p_M^2 = (p_A + p_B)^2$$

$$z = \frac{E_A}{E_M}$$

$$\phi$$

The main feature of radiation can be seen by considering the Collinear limit: $\theta \Rightarrow 0$, $t \ll E_M^2$

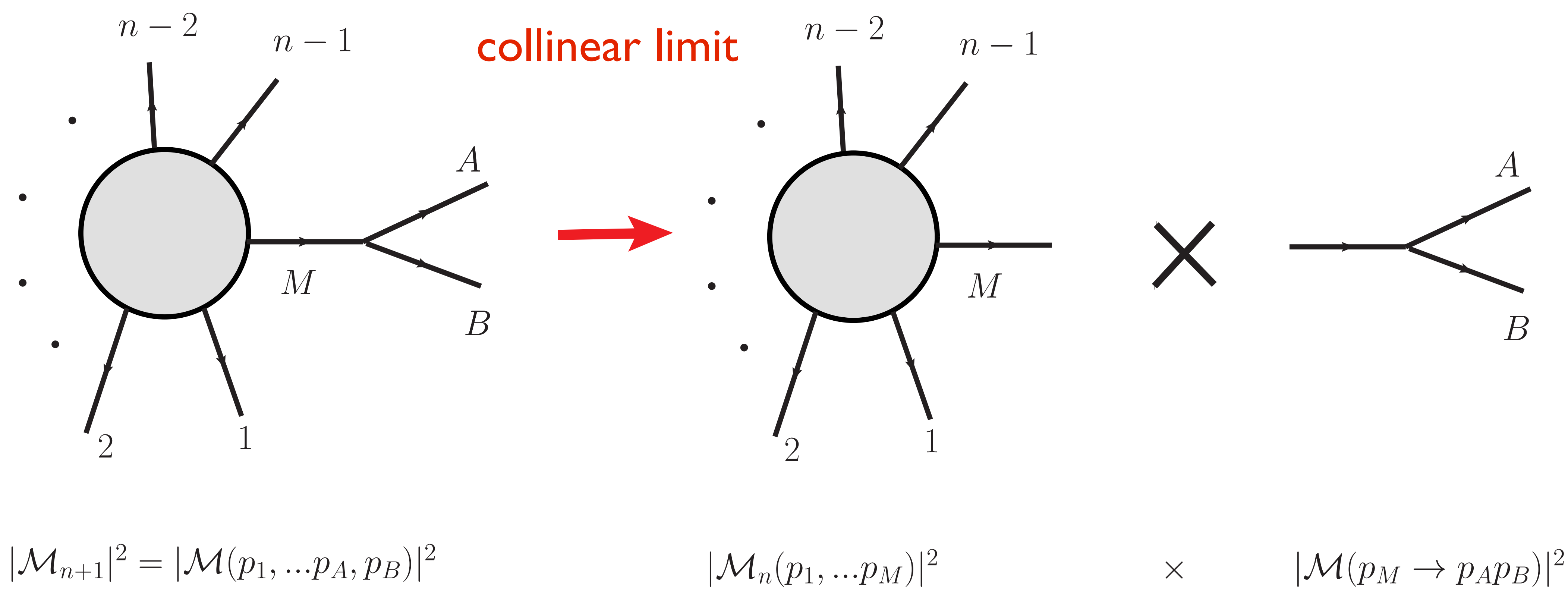
Collinear factorization



$|\mathcal{M}_{n+1}|^2 = |\mathcal{M}(p_1, ...p_A, p_B)|^2$ $\quad |\mathcal{M}_n(p_1, ...p_M)|^2$ $\quad \times \quad$ $|\mathcal{M}(p_M \to p_A p_B)|^2$

$$|\mathcal{M}_{n+1}|^2 d\Pi_{n+1} \simeq |\mathcal{M}_n|^2 d\Pi_n \frac{dt}{t} \frac{\alpha_S}{2\pi} P(z) dz d\phi$$

Collinear factorization



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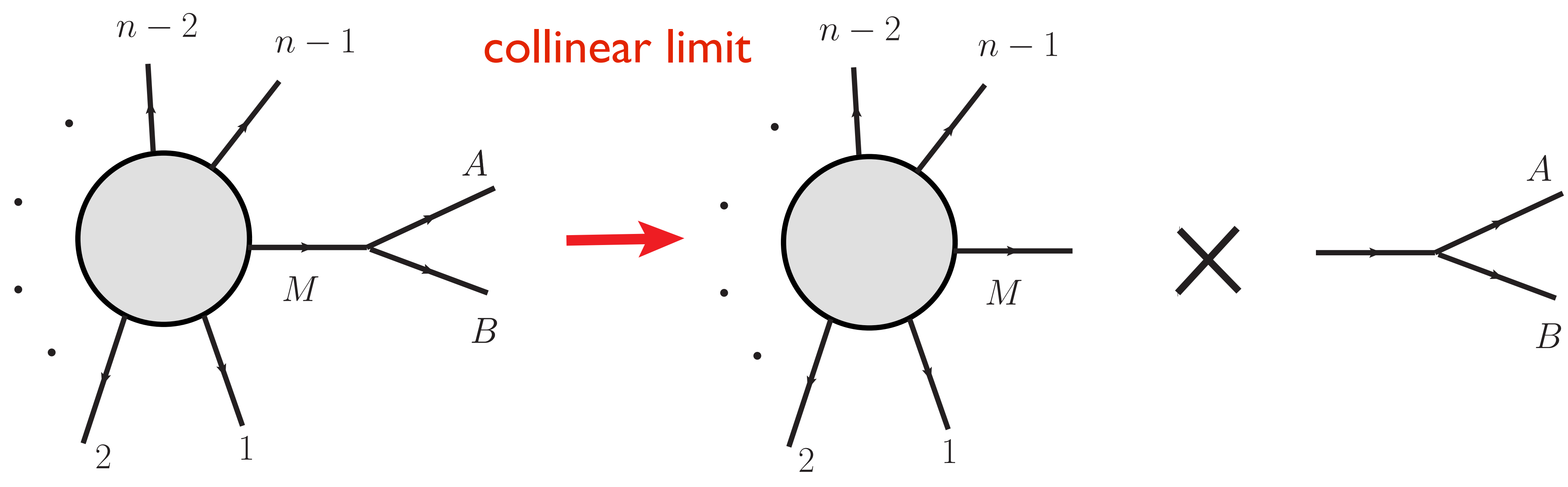
collinear singularity: t⇒0

Collinear factorization



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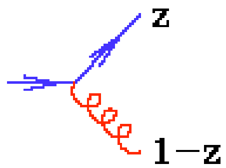
collinear singularity: t⇒0

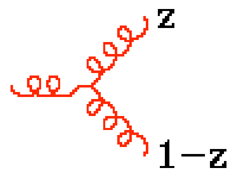
$P(z) \propto |\mathcal{M}(p_M \to p_A p_B)|^2$

Splitting function
IR singularity: z⇒0, 1

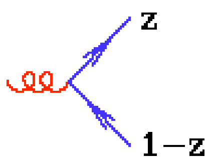
Splitting function, IR singular as z⇒0, 1



$$P_{q\to qg}(z) = C_F\,\frac{1+z^2}{1-z},$$



$$P_{g\to gg}(z) = C_A\left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right]$$



$$P_{g\to q\bar{q}}(z) = T_R\left[z^2 + (1-z)^2\right],$$

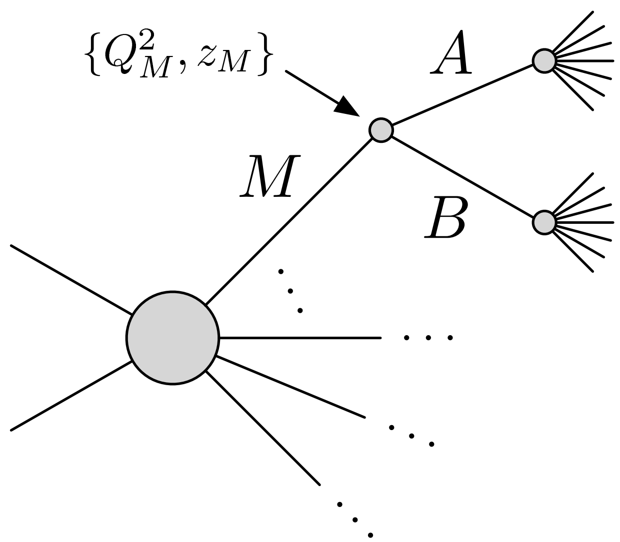
Combining with

$$|\mathcal{M}_{n+1}|^2 d\Pi_{n+1} \simeq |\mathcal{M}_n|^2 d\Pi_n \frac{dt}{t}\frac{\alpha_S}{2\pi}P(z)\,dz\,d\phi$$

Radiation wants to be collinear and soft

Shape of a jet: parton shower

- From the initial parton, a jet is built up by many radiations (splittings).



$Q_M{}^2 = t$

$$d\sigma^{\mathrm{QCD}}_{M\to A+B} = \frac{dQ^2_M}{2\pi}\frac{1}{Q^2_M}\; dz\frac{\alpha(\mu)}{2\pi}P_{M\to AB}(z)\Delta(\mu_{\mathrm{start}},\mu)$$

Prefers collinear radiation

$P \sim (z)^{-1}$ prefers soft radiation

QCD jet: a cluster of radiation

a) relatively soft

b) close to the direction of P_M

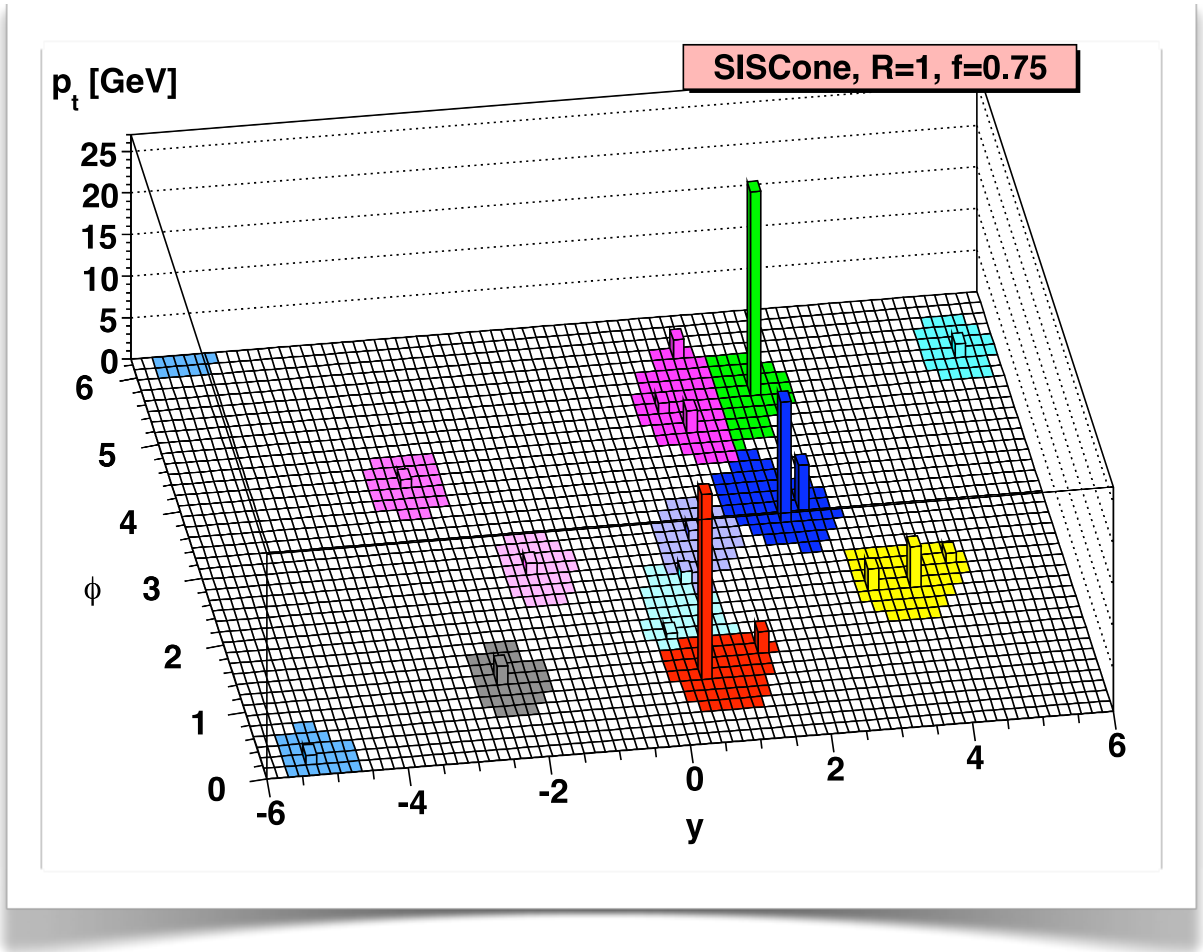
c) approximately symmetrical around P_M

Jet Algorithms.

A set of vectors $\{p_i\}$
Calorimeter towers...

Clustering ↓

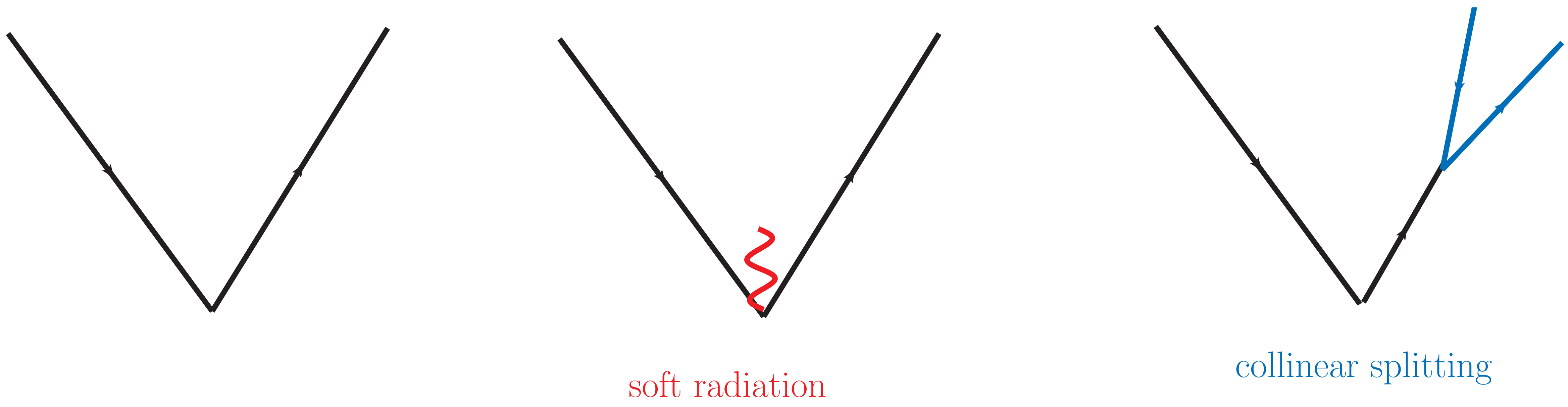
Jets: $\{P_j\}$



- Two type of decisions, based on two types criteria:
  - What to cluster.
  - When to stop cluster.

- Choice of the criteria determines the properties of the jets.

First consideration: IRC safety



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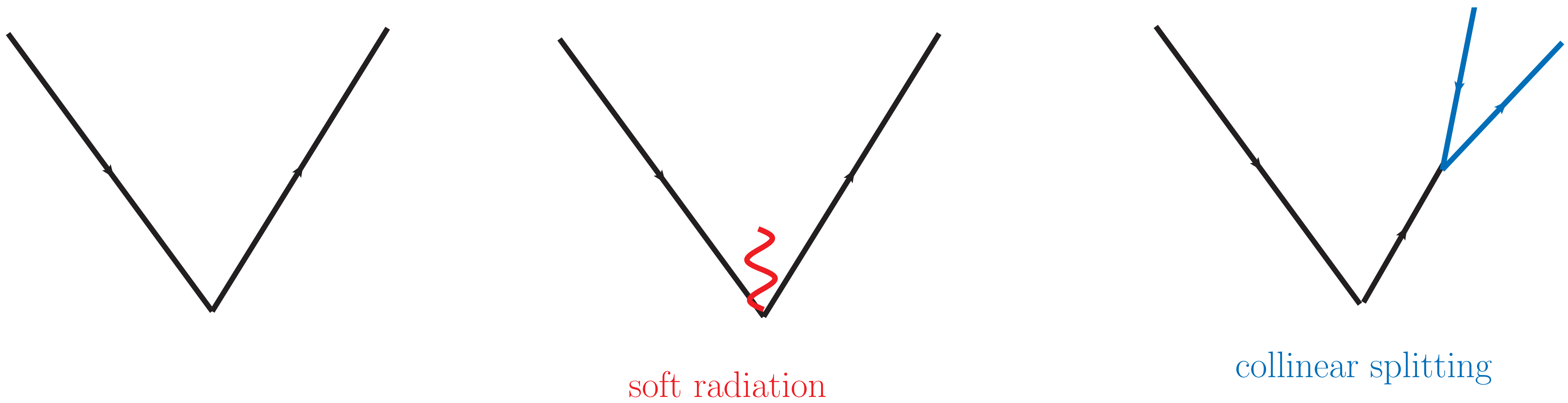

- Soft or collinear radiation should not be able to induce "large" changes in the observable.
- Otherwise we cannot compute and compare with experiments.

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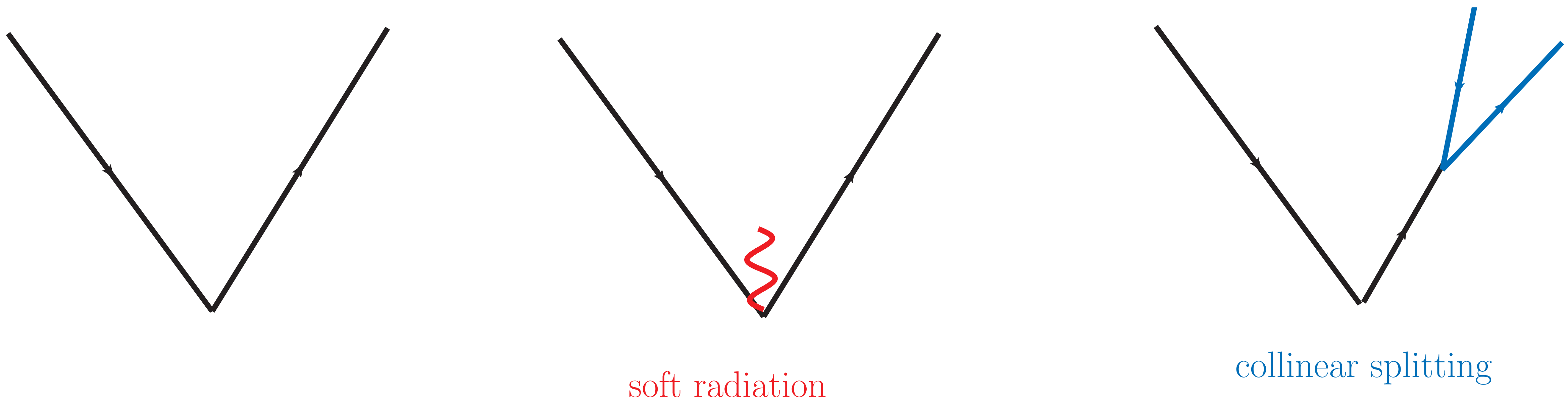


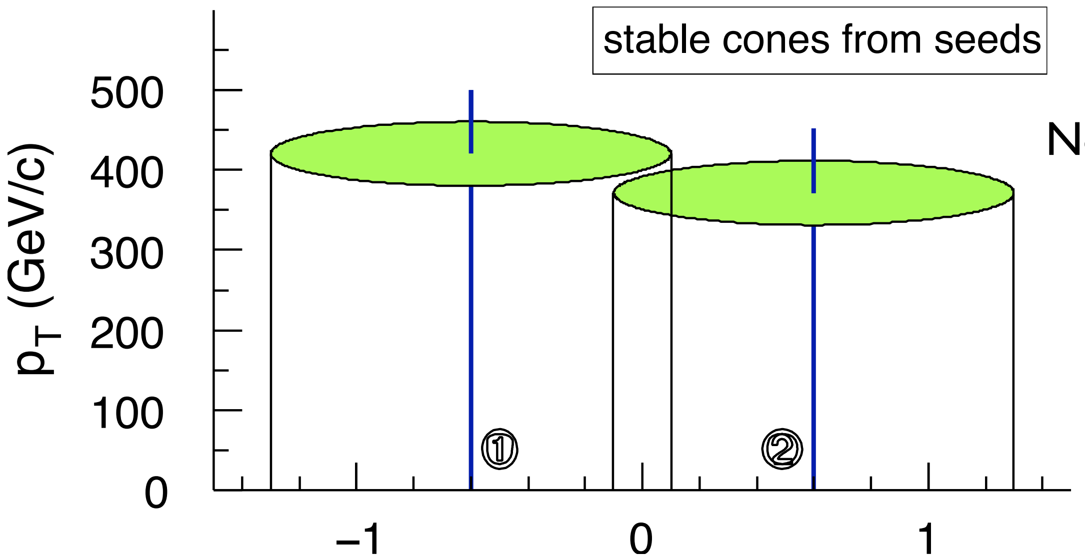
All of these should be 2 jet events!

- Soft or collinear radiation should not be able to induce "large" changes in the observable.
- Otherwise we cannot compute and compare with experiments.

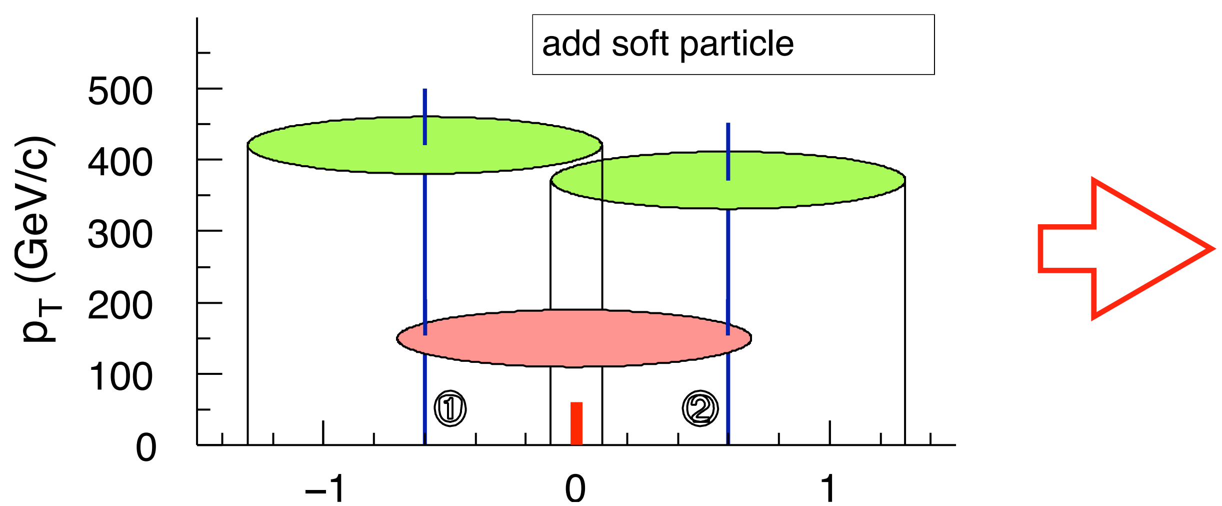
Seeded cone

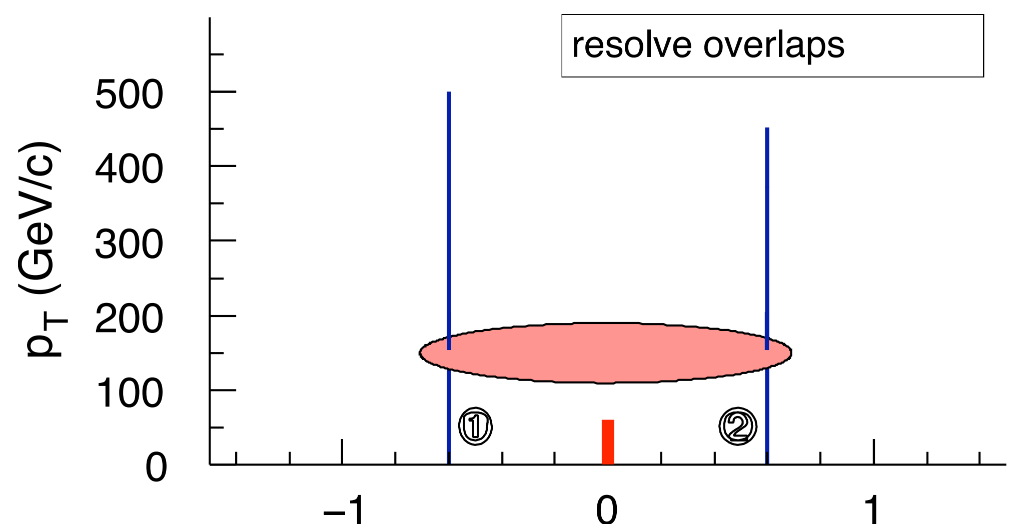
- Starting with a set of seeds (momenta which are "more likely" to be the centers of the jets).
- Draw a cone of certain size around each seed.
- Within each cone, add up all momenta. Use the new direct as the new seed.
- Iterate this process until we end up with stable cones.

Seeded Cone, IR unsafe



No other radiation with the radius of cones centered on the seeds "stable cone", clustering stops. 2 jets.

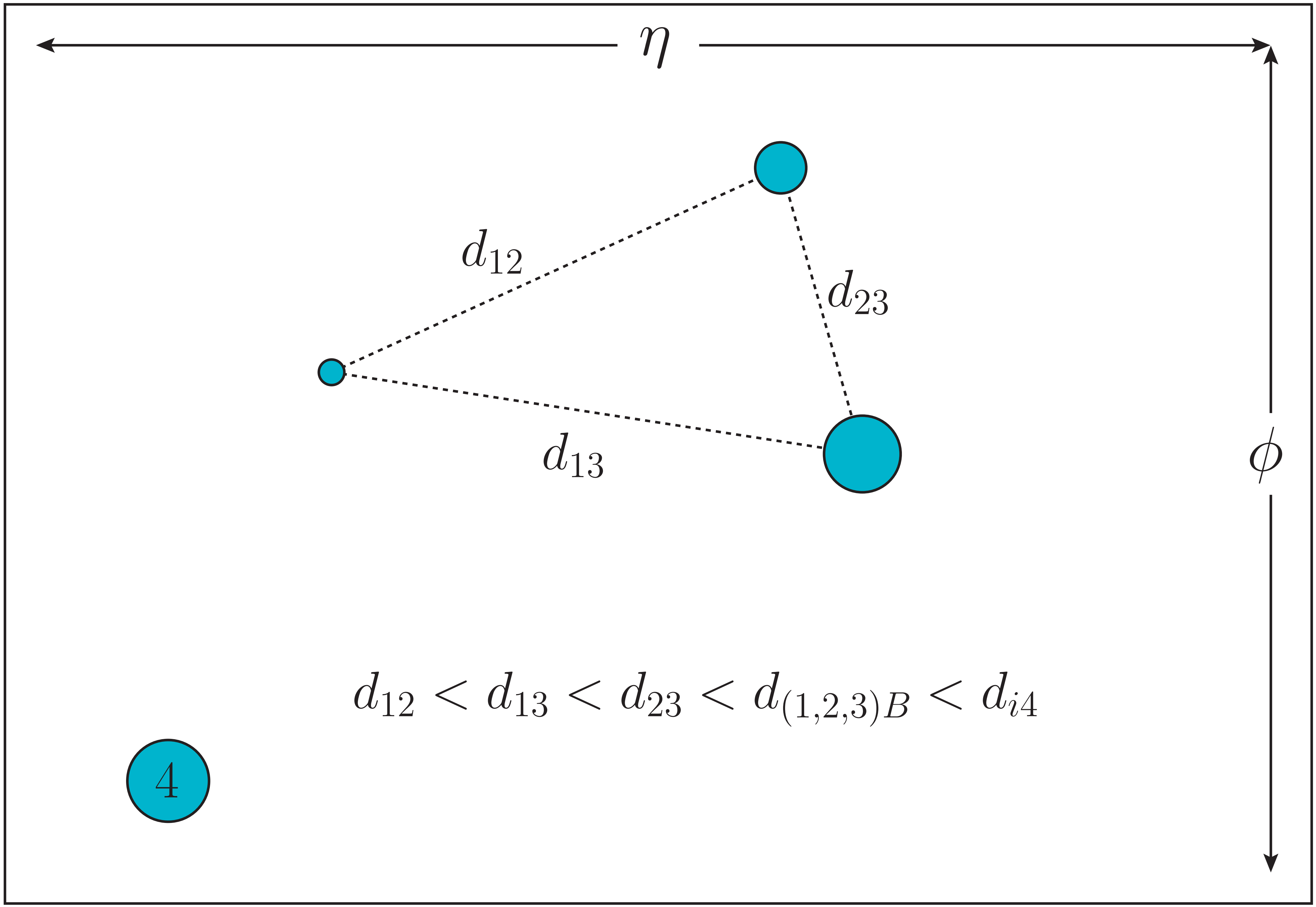




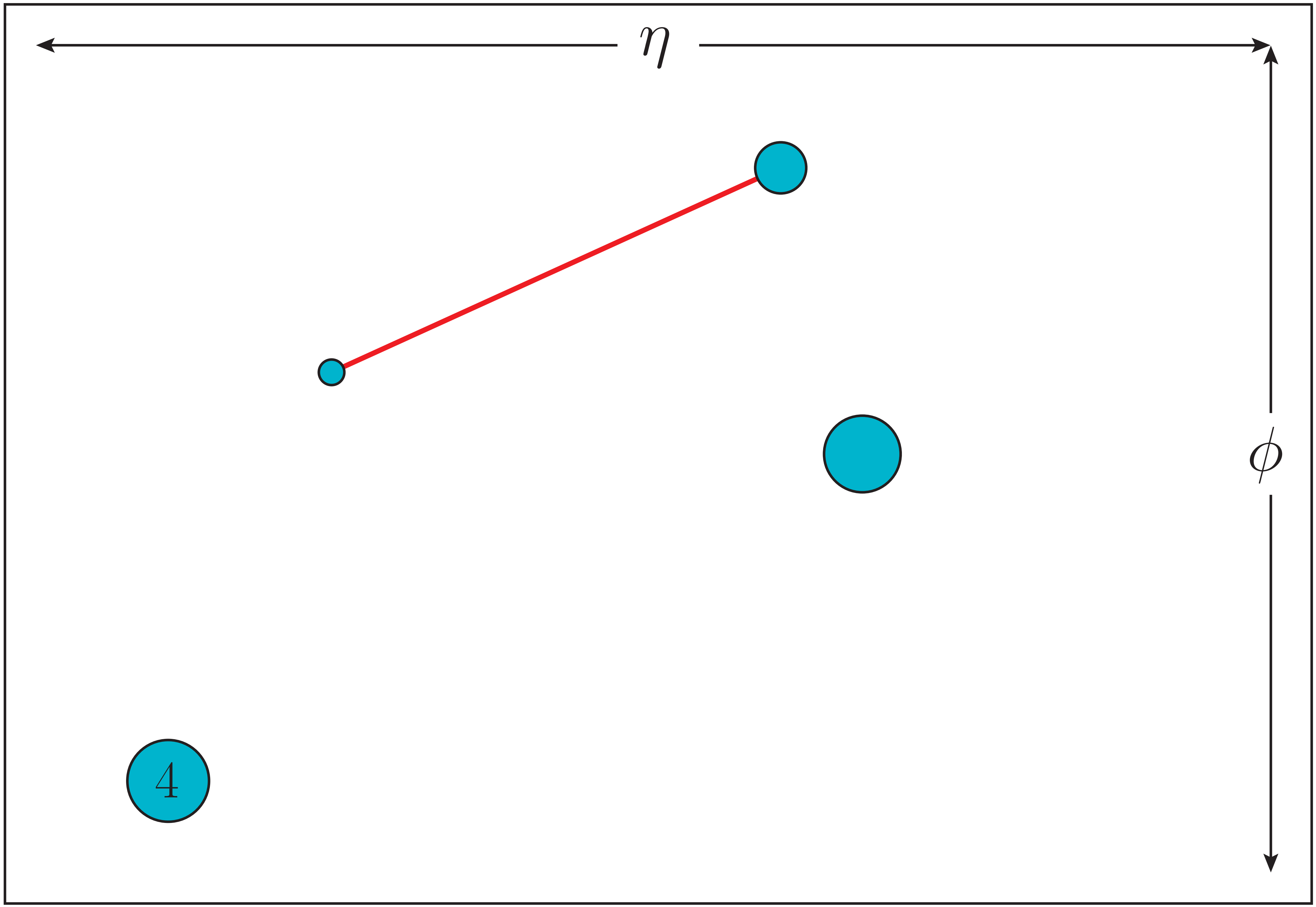
an event with 2 jets becomes an event with one jet because of a soft radiation

Sequential recombination jet algorithm

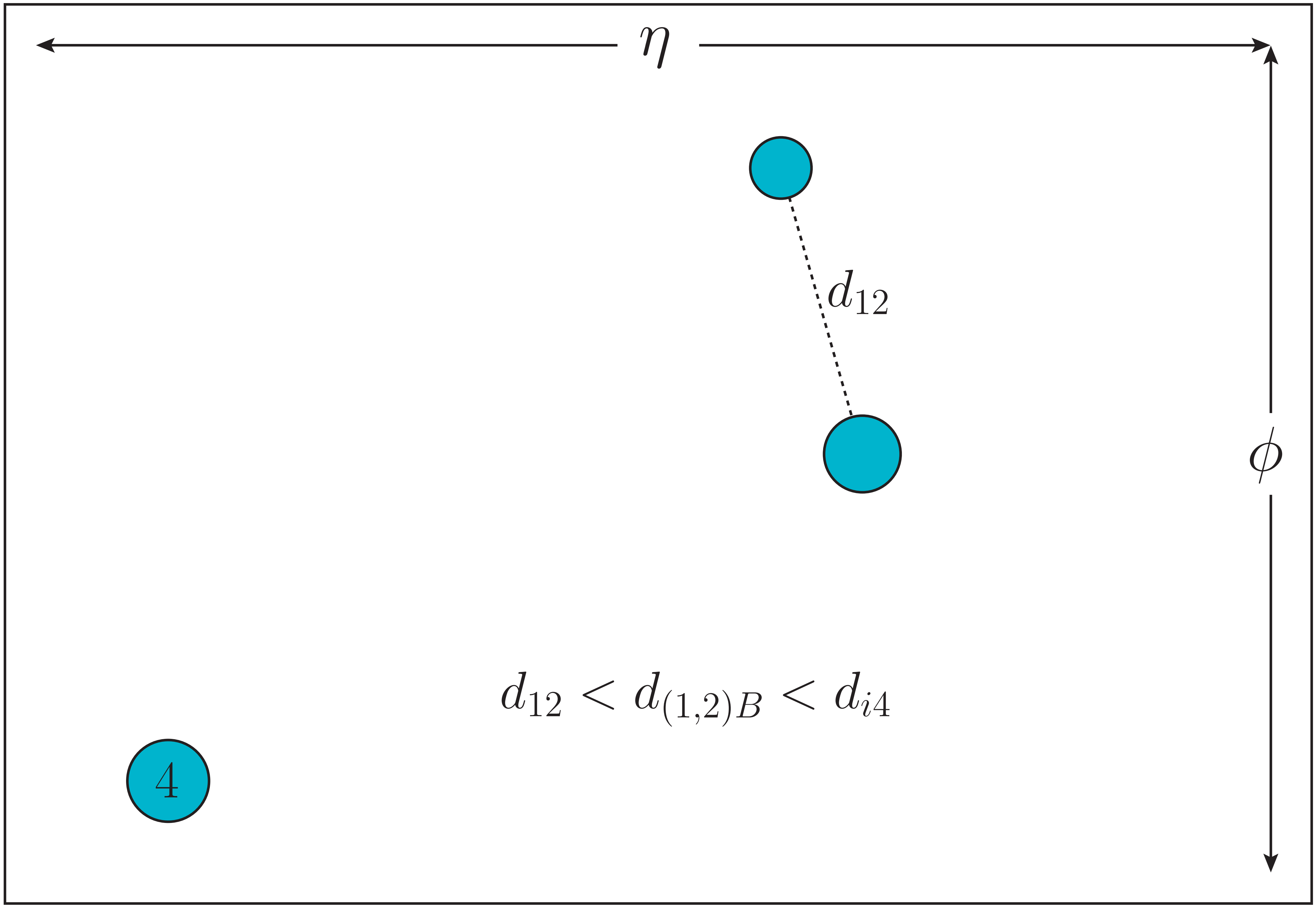
- Basic ingredients of a "sequential" jet algorithm.
- Two types of "distances"
  - Jet-jet distance: d_{ij} "when to cluster"
  - Jet-beam distance: d_{iB} "when to stop clustering"
- Pair wise comparison of all distances
  - If smallest distance at any stage in clustering is jet-jet, add together corresponding four-momenta, else take jet with smallest jet-beam distance and set it aside.
  - Repeat till all jets are set aside.

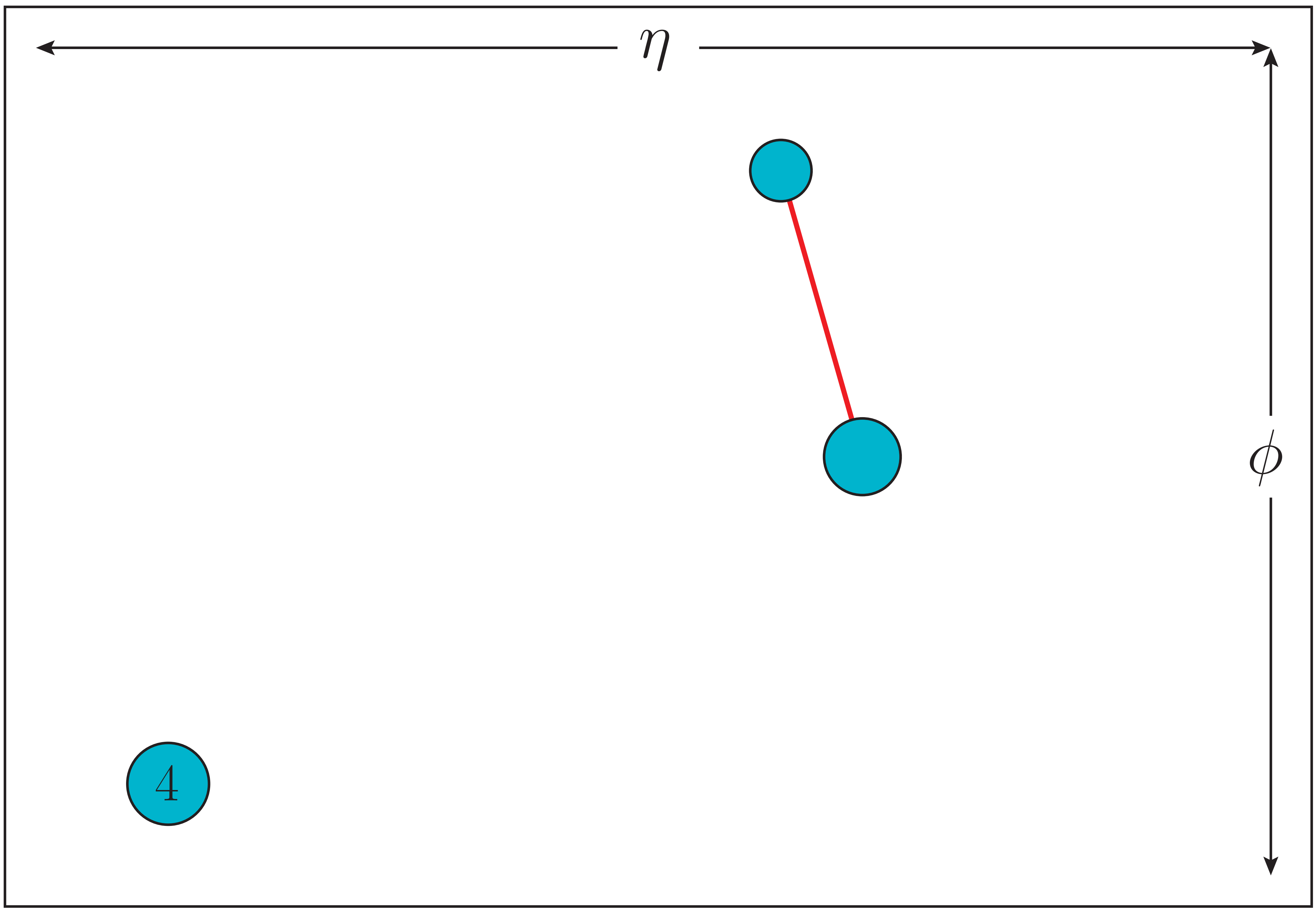


$$d_{12} < d_{13} < d_{23} < d_{(1,2,3)B} < d_{i4}$$



η
ϕ
4


η
d_{12}
ϕ
$d_{12} < d_{(1,2)B} < d_{i4}$
4


η
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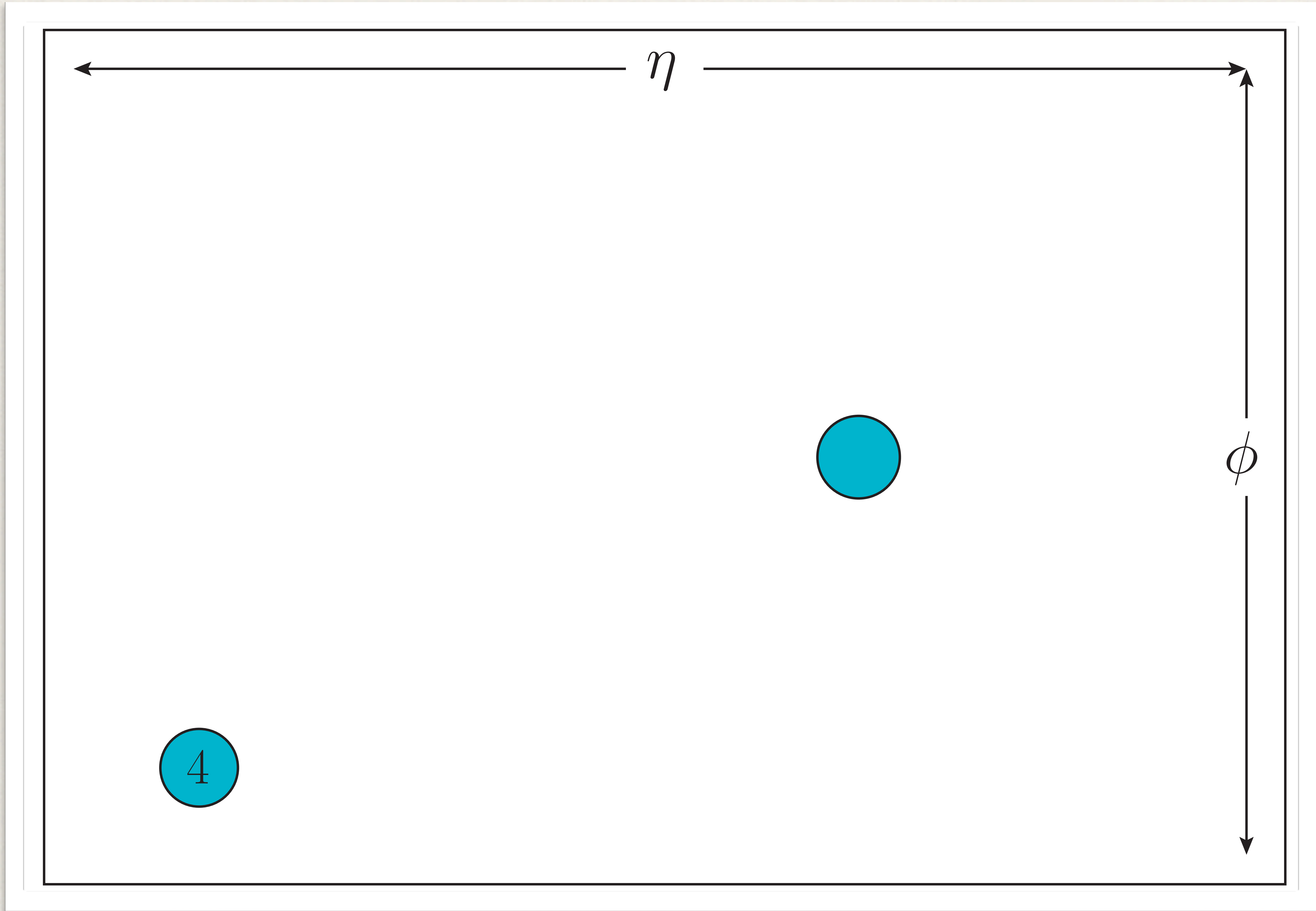
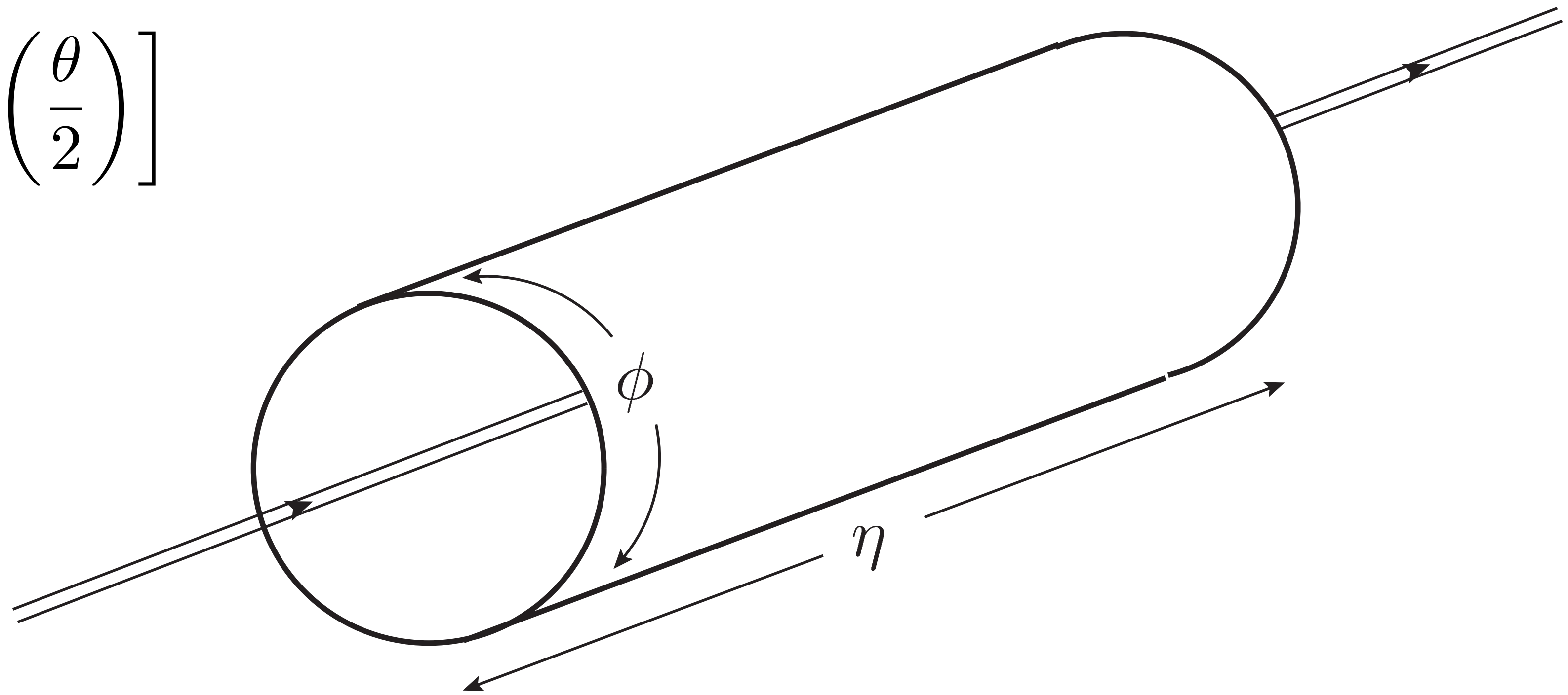


Done!

Coordinate System

$$\eta = -\ln\left[\cot\left(\frac{\theta}{2}\right)\right]$$

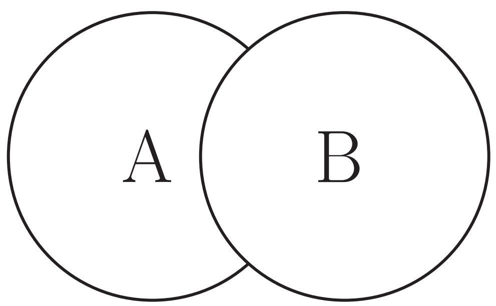


Distance measure: $(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$

Recombination Algorithms

- k_T algorithm

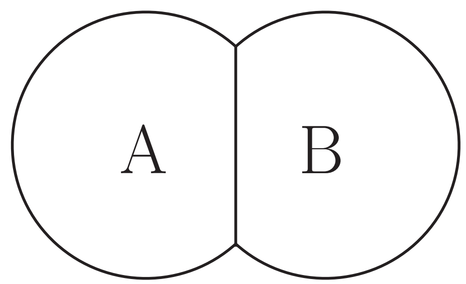
$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^2$$



k_T

- C/A algorithm

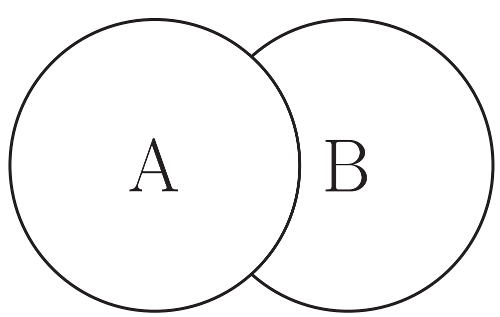
$$d_{ij} = \left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = 1$$



C/A

- anti-k_T algorithm

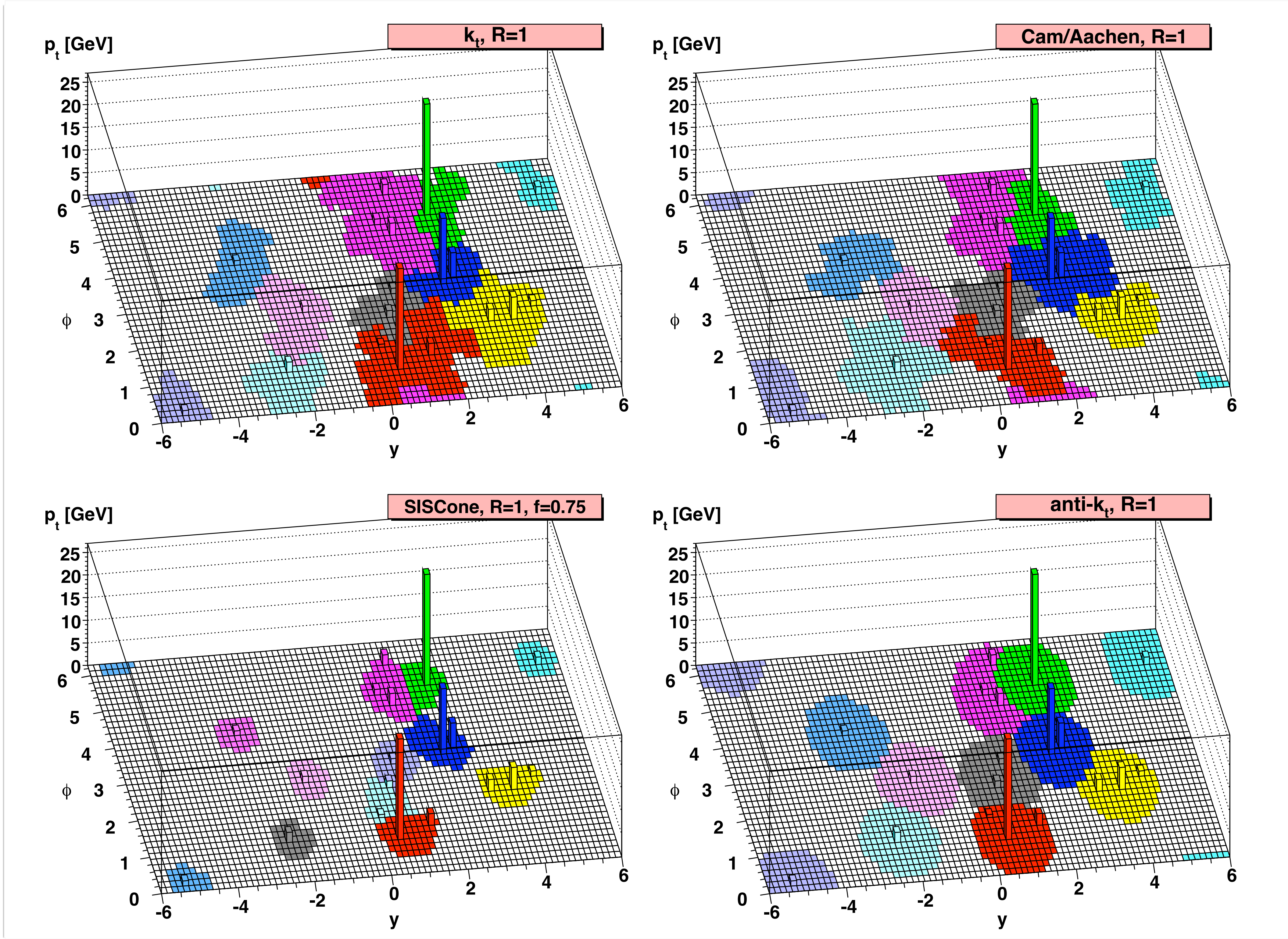
$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^{-2}$$



anti$-k_T$

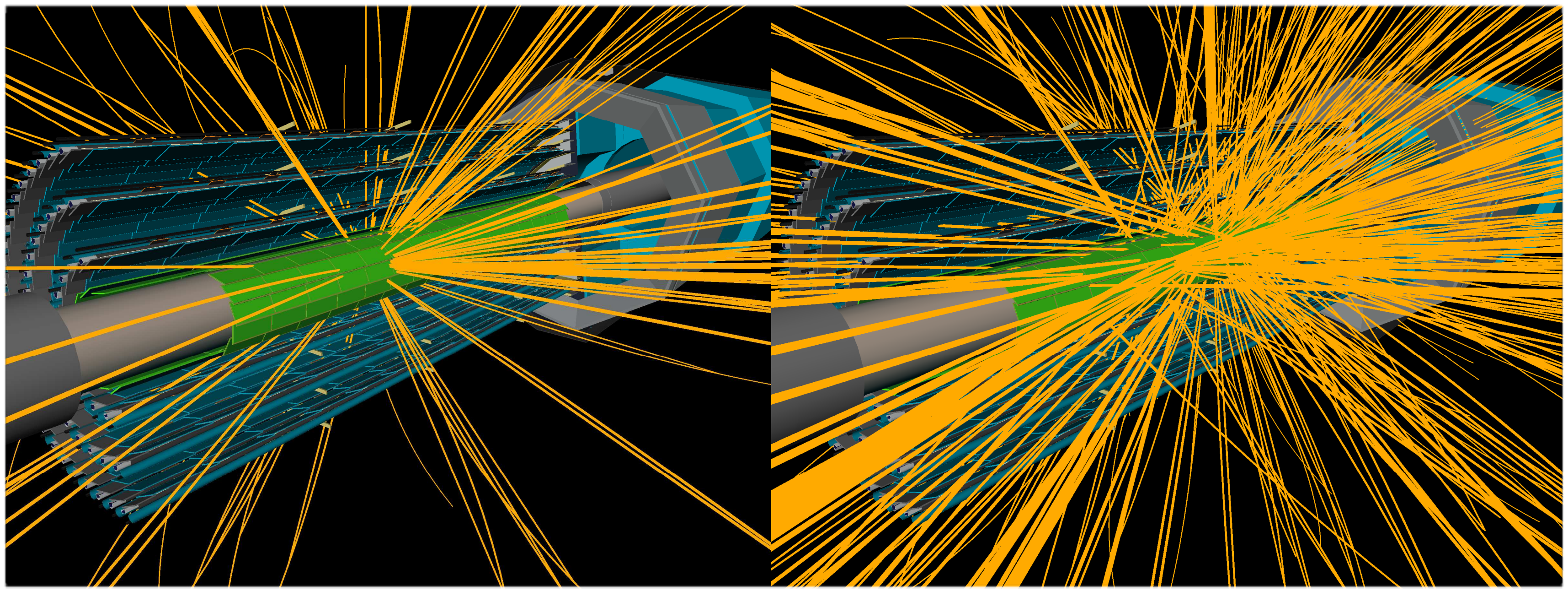
$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

$$p_T^A > p_T^B$$


k_t, R=1
Cam/Aachen, R=1
SISCone, R=1, f=0.75
anti-k_t, R=1
p_t [GeV]
ϕ
y

Messy environment

- Example: here's an event with 500 GeV dijets (left), and the same event with fifty pileup events (right).



- We'll encounter this level of pileup next year,
  - Somehow we're going to have to find new physics in this mess!

Some "clean up" procedure, filtering, pruning, trimming.

Jet energy/momentum errors

Lost Radiation (outside of the cone)

$$\langle \delta p_t \rangle_{\text{pert}} = \int \frac{d\theta^2}{\theta^2} \int dz \, \underbrace{p_t\big(\max[z, 1-z] - 1\big)}_{\delta p_t} \, \frac{\alpha_s\big(\theta\,(1-z)\,p_t\big)}{2\pi} \, P_{qq}(z)\, \Theta\big(\theta - f_{\text{alg}}(z) R\big) \,,$$

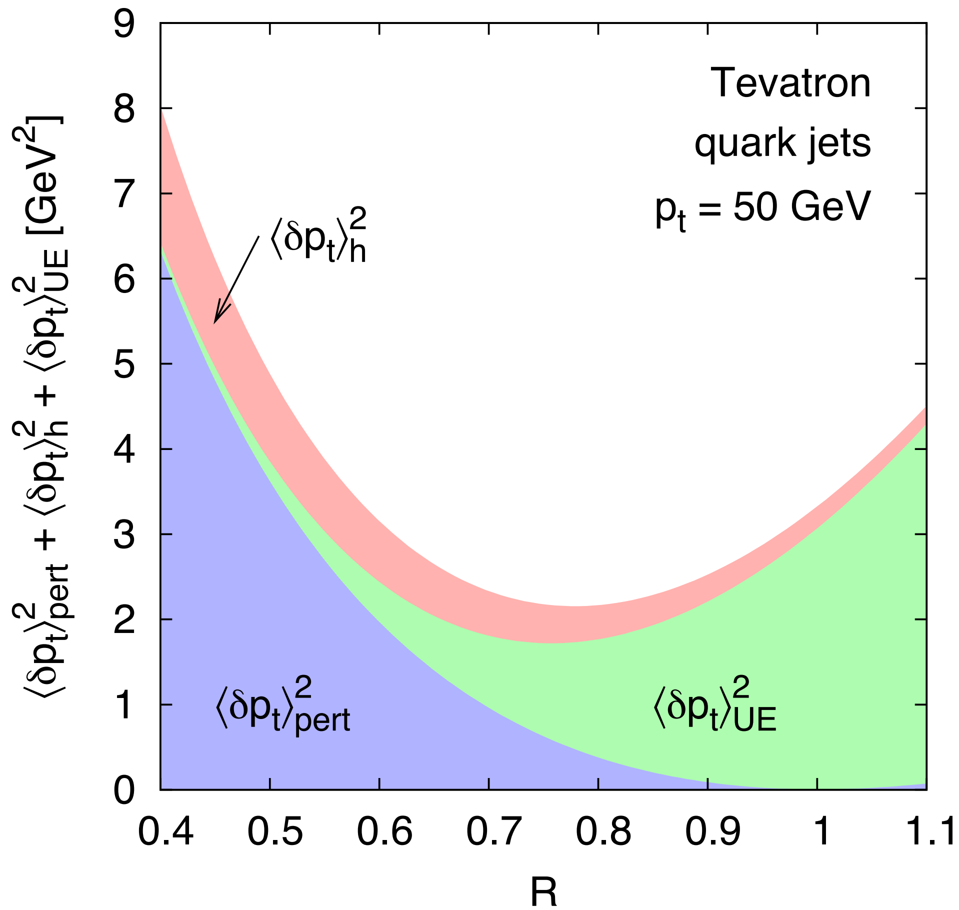
$$\Rightarrow \qquad \frac{\langle \delta p_t \rangle_{\text{pert}}}{p_t} = \frac{\alpha_s}{\pi} L_i \, \ln R + \mathcal{O}\left(\alpha_s\right)$$

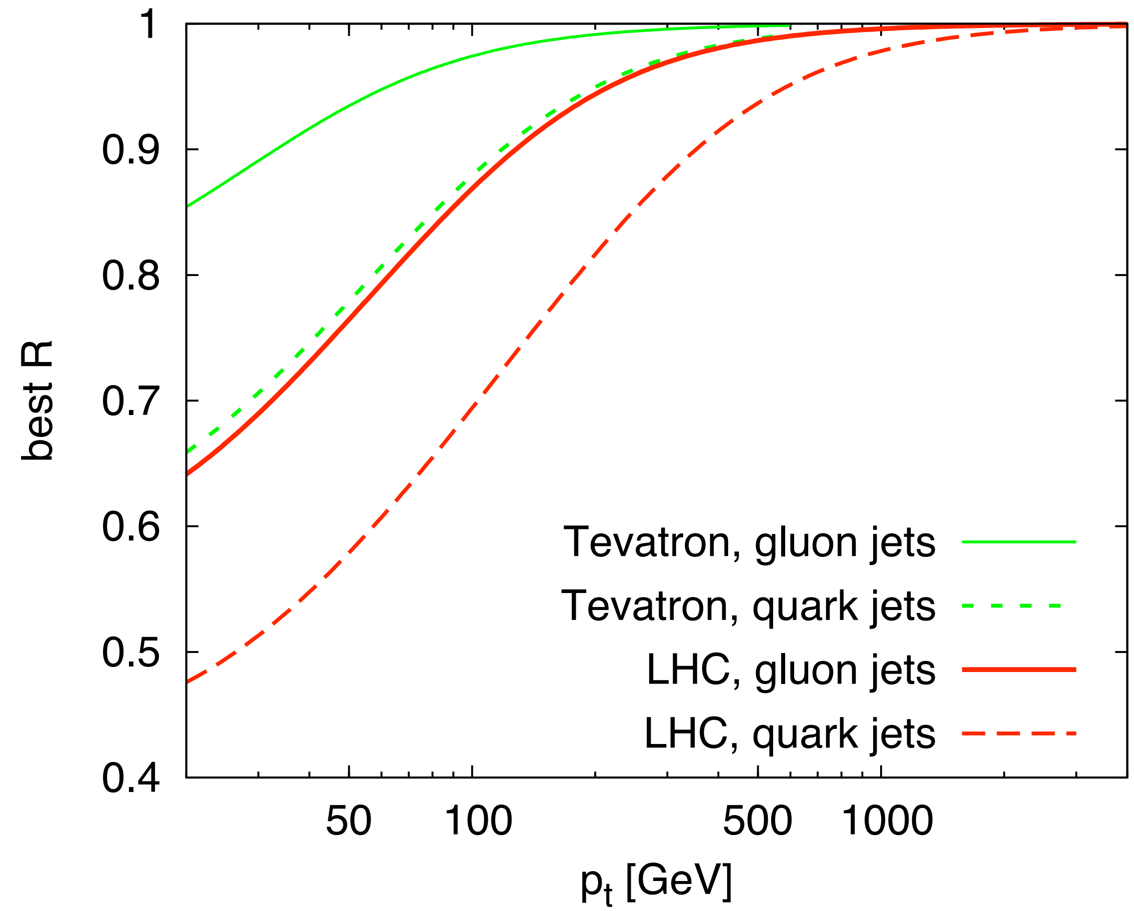
Uniform contamination: underlying events, pile-up ∝ jet area ∝ R^2

$$\langle \delta p_t \rangle_{\text{UE}} \simeq \Lambda_{\text{UE}} R J_1(R) = \Lambda_{\text{UE}} \left(\frac{R^2}{2} - \frac{R^4}{8} + \dots \right)$$

Shape of jets.

G. Salam, 0906.1833 "best" R





Shape of jets.

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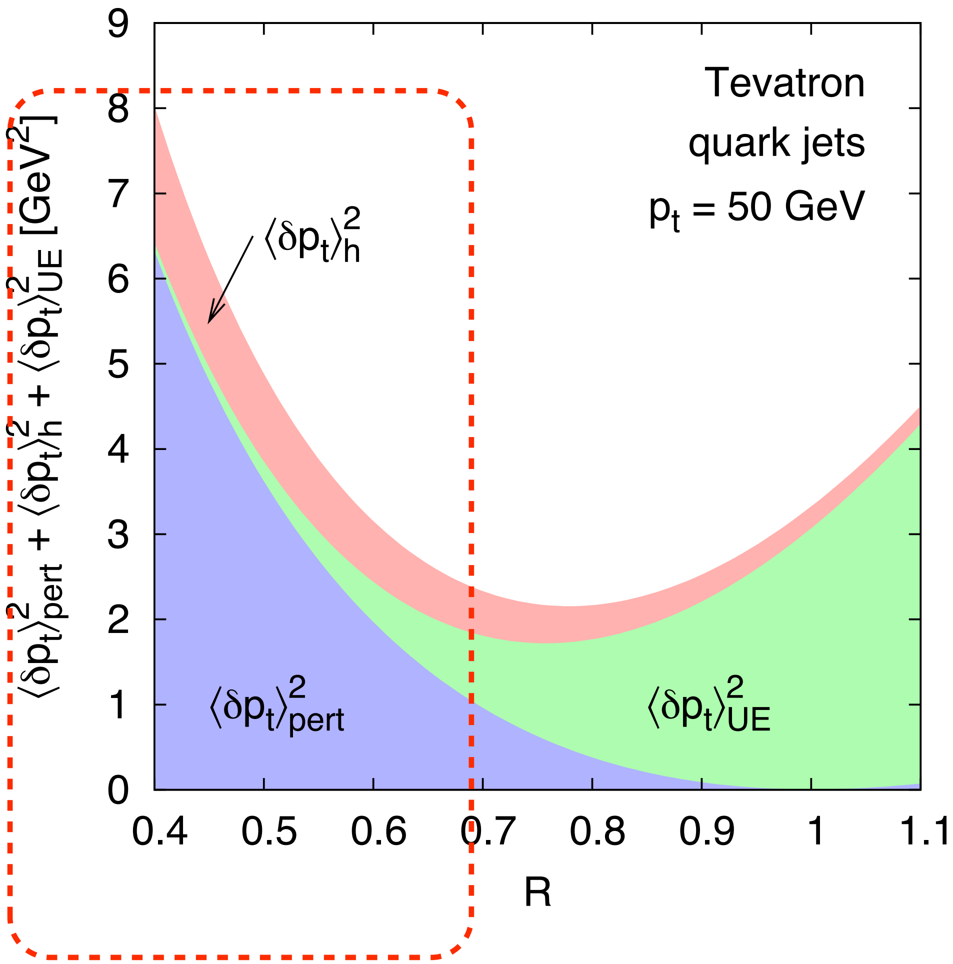
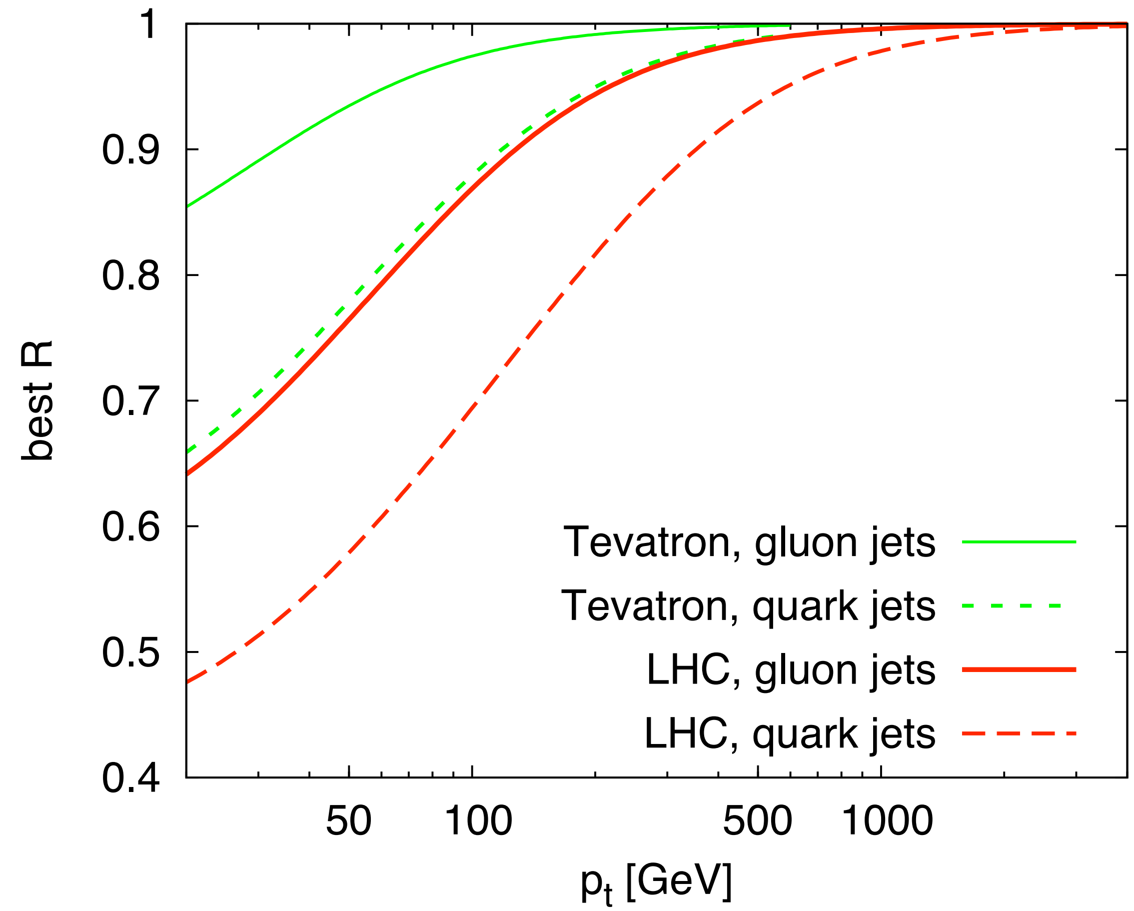
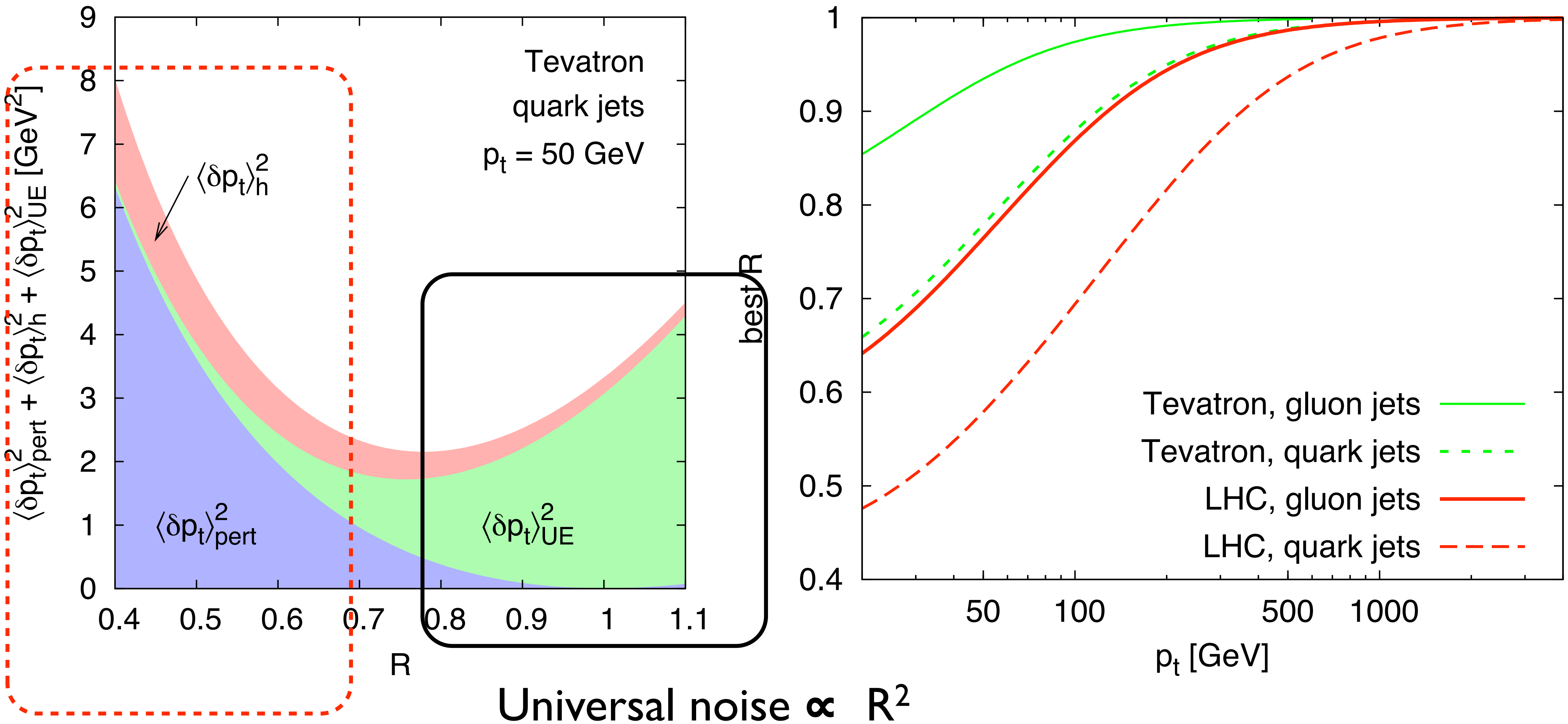




radiation out of the cone

Shape of jets.

G. Salam, 0906.1833 "best" R



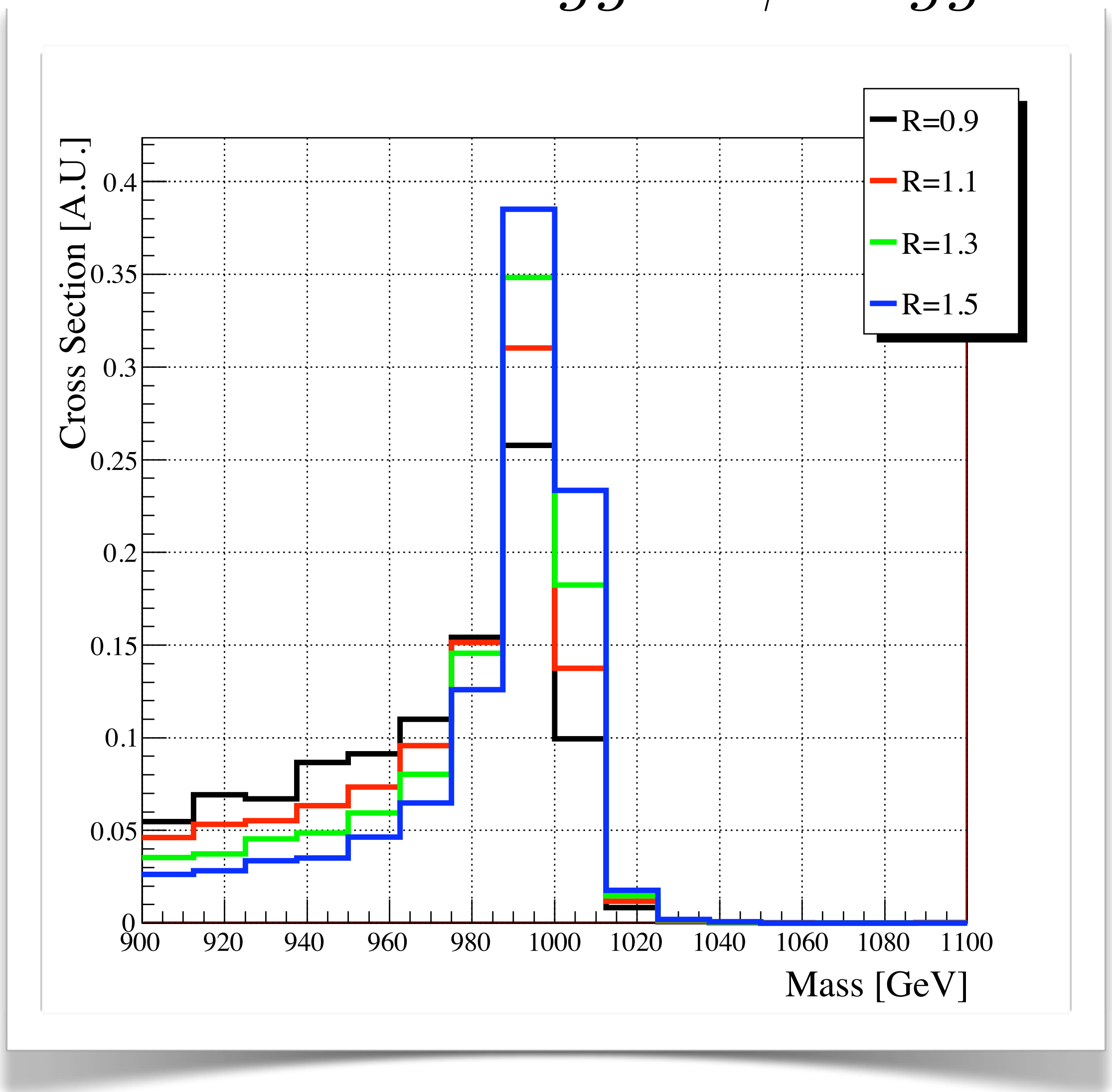
Universal noise ∝ R^2

radiation out of the cone

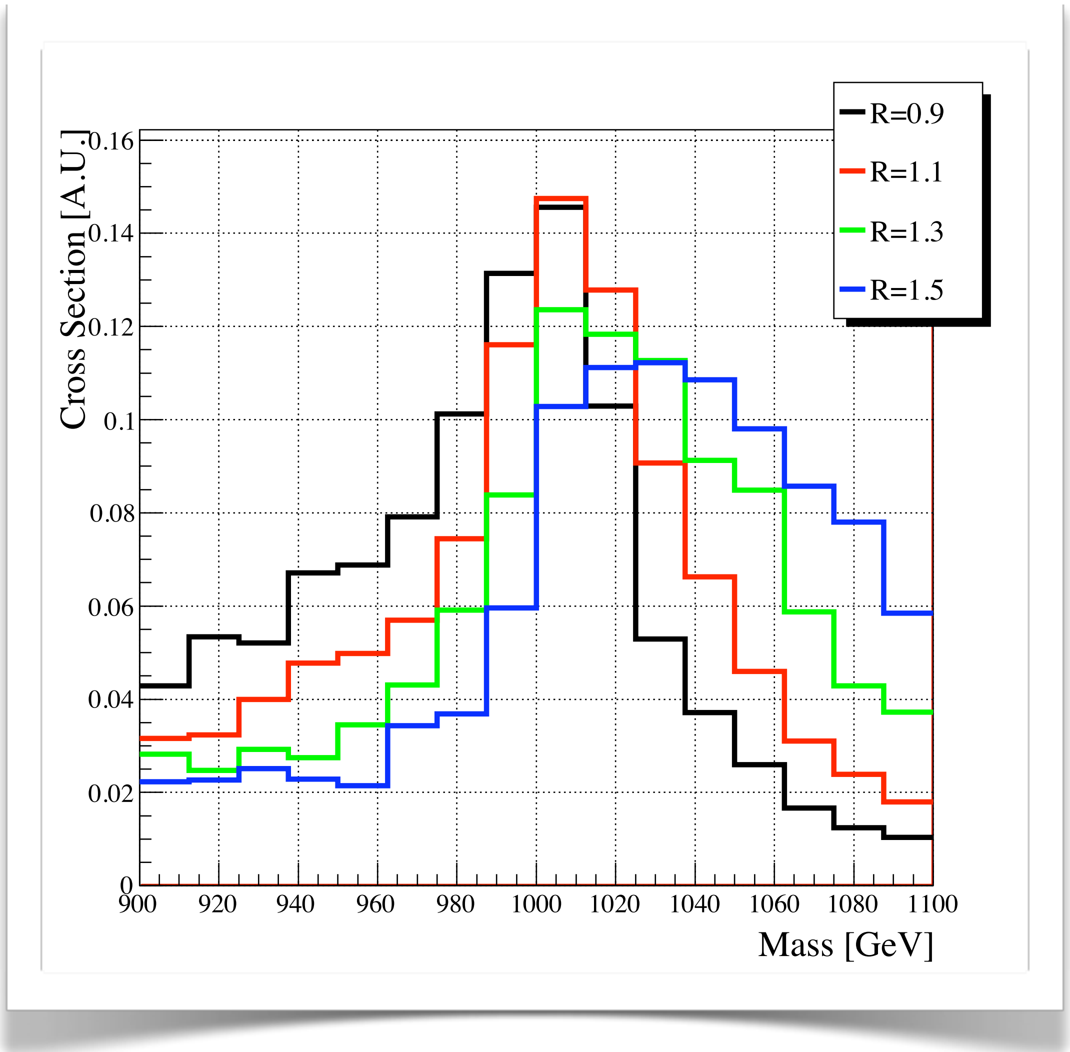
Going beyond anti-KT: "noise" control

- Noise: Initial state radiation (ISR), multiple interaction (MI), underlying events (UE), pile-up (PU).

$gg \to \phi \to gg$ $m_\phi = 1\ \text{TeV}$



FSR only



Including ISR, MI, UE, pile-up

Room for improvement!

Jet trimming.

D. Krohn, J. Thaler, LTW, arXiv:0912.1342

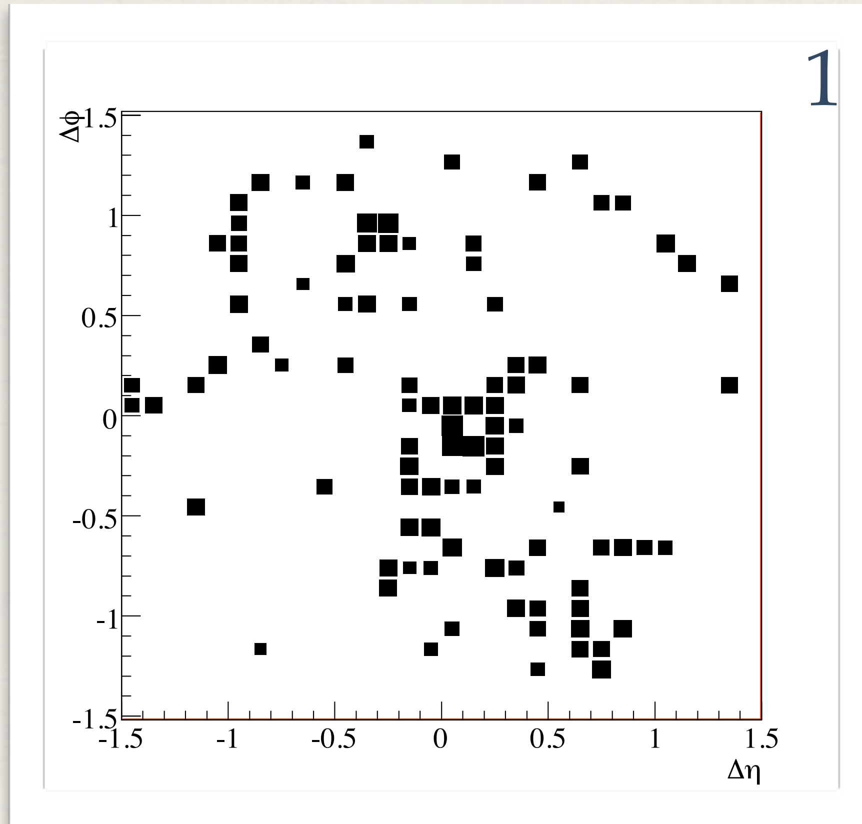
- Introducing a "cut" on soft radiation.
  - Discard "stuff" below the cut after jet clustering.
- Our implementation.
  - Cluster all calorimeter data using any algorithm
  - Take the constituents of each jet and recluster with smaller radius Rsub (Rsub = 0.2 seems to work well).
  - Discard the subjet i if $p_{Ti} < f_{\rm cut} \cdot \Lambda_{\rm hard}$ ⟵ ISR argument.
- Best choice of the hard scattering scale and fcut.
  - Process dependent.
  - Can be optimized experimentally.

Why is it possible to gain?

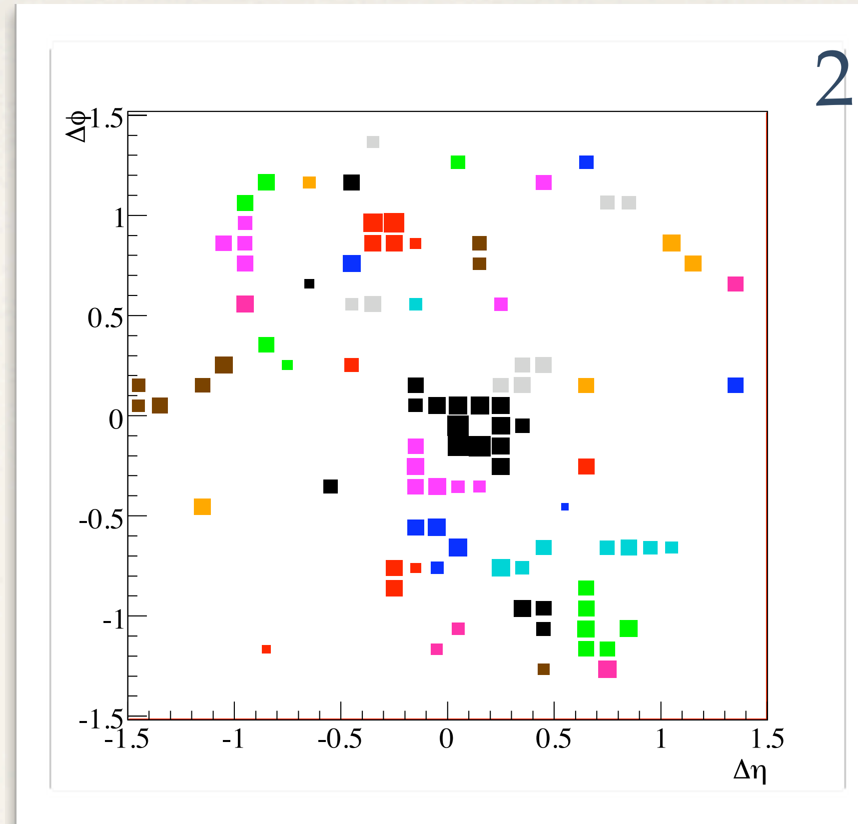
- MI, UE, and pile-up are incoherent soft background. They can be effectively removed with a cut on soft radiation.

- Both FSR (want to keep) and ISR (want to discard) have soft radiation, but
  - ISR: $d\sigma \propto \frac{dp_{\mathrm{T}}^{\mathrm{ISR}}}{p_{\mathrm{T}}^{\mathrm{ISR}}}$ no direction correlation.
  - FSR is controlled by both collinear and soft singularities:
    $$d\sigma \propto \frac{d(\Delta R)}{\Delta R} \times \frac{dp_{\mathrm{T}}^{\mathrm{FSR}}}{p_{\mathrm{T}}^{\mathrm{FSR}}}$$
    - Tends to be clustered into subjet, and kept.
  - Therefore, a soft cut on subjet relative to the jet energy flow could enhance FSR relative to ISR.

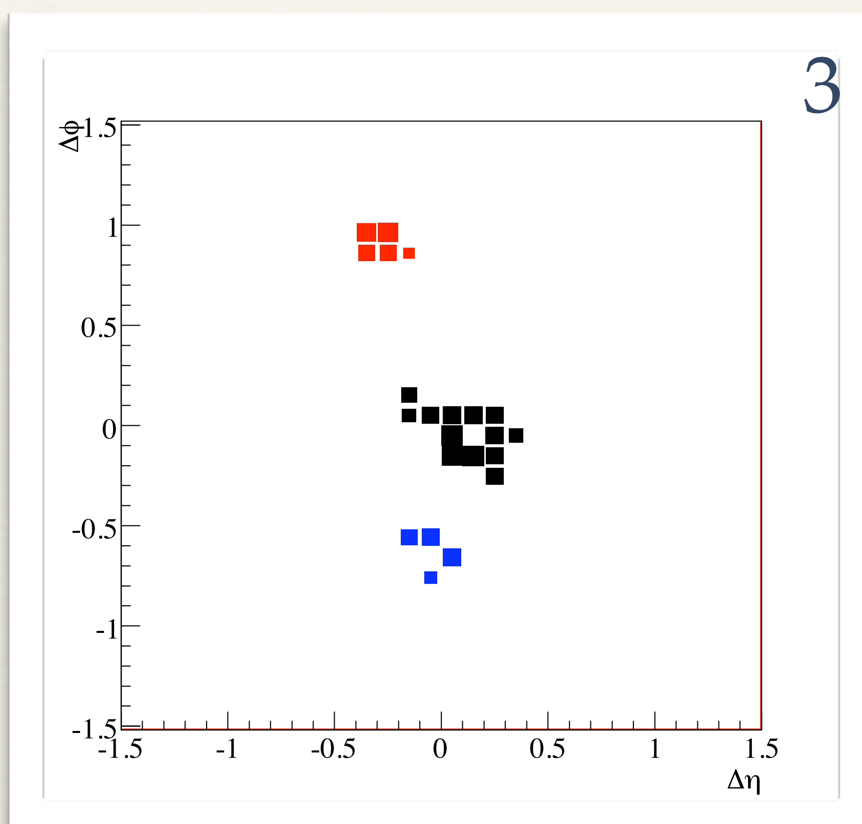
Start



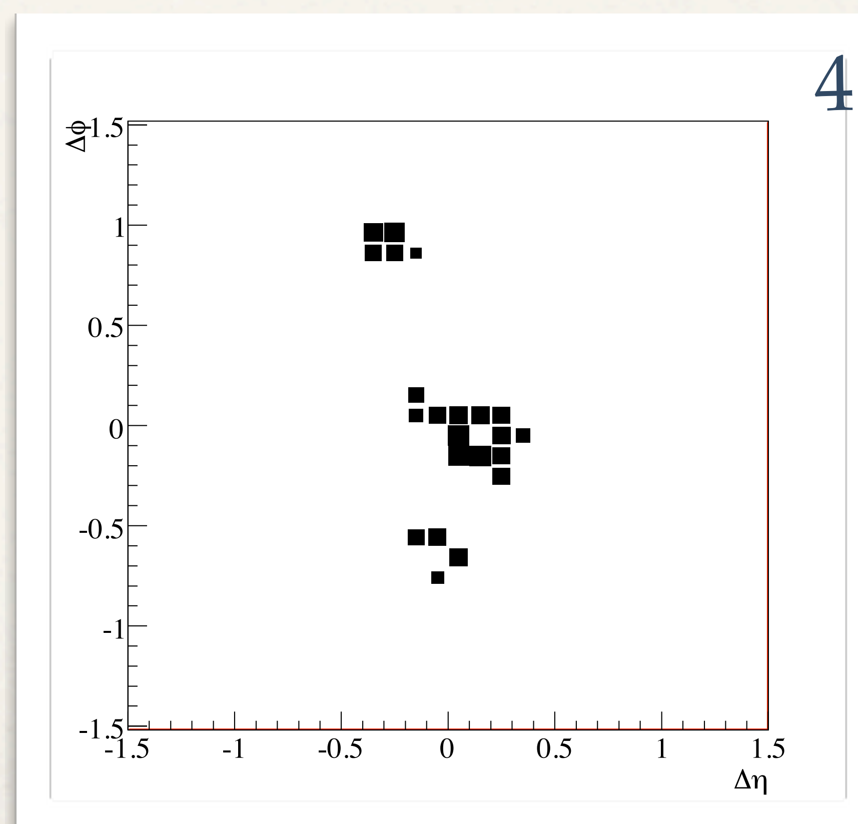
Cluster into subjets



Discard soft subjets

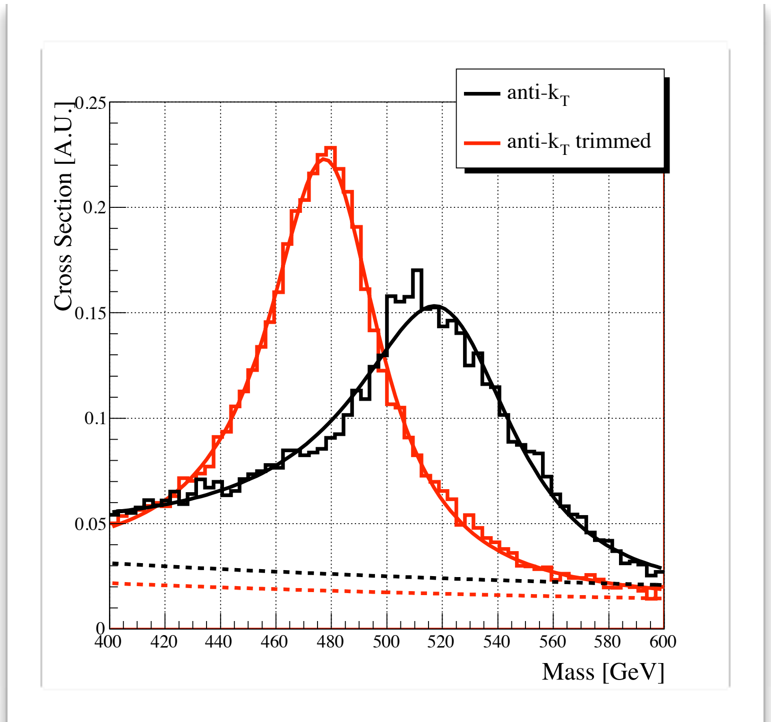


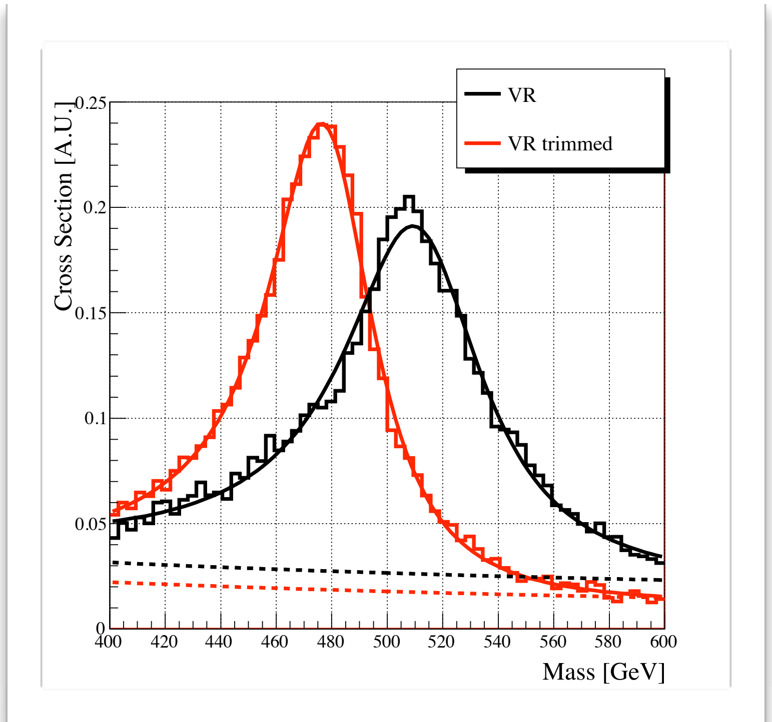
Reassemble



Simple test case: di-jet resonance

$$gg \rightarrow \phi \rightarrow gg$$





	Improvement	f_{cut}, N_{cut}	R_{sub}	R_0, ρ	Γ [GeV]	M [GeV]
anti-k_T	-	-	-	1.0*	71	522
anti-k_T (N)	40%	5*	0.2*	1.5*	62	499
anti-k_T $(f,\ p_T)$	59%	$3 \times 10^{-2*}$	0.2	1.5	52	475
anti-k_T $(f,\ H)$	61%	$1 \times 10^{-2*}$	0.2	1.5	50	478
VR	30%	-	-	200* GeV	62	511
VR (N)	53%	5	0.2	275* GeV	53	498
VR $(f,\ p_T)$	68%	3×10^{-2}	0.2	300* GeV	49	475
VR $(f,\ H)$	73%	1×10^{-2}	0.2	300* GeV	47	478

- We provide plugins fully compatible with Fastjet.

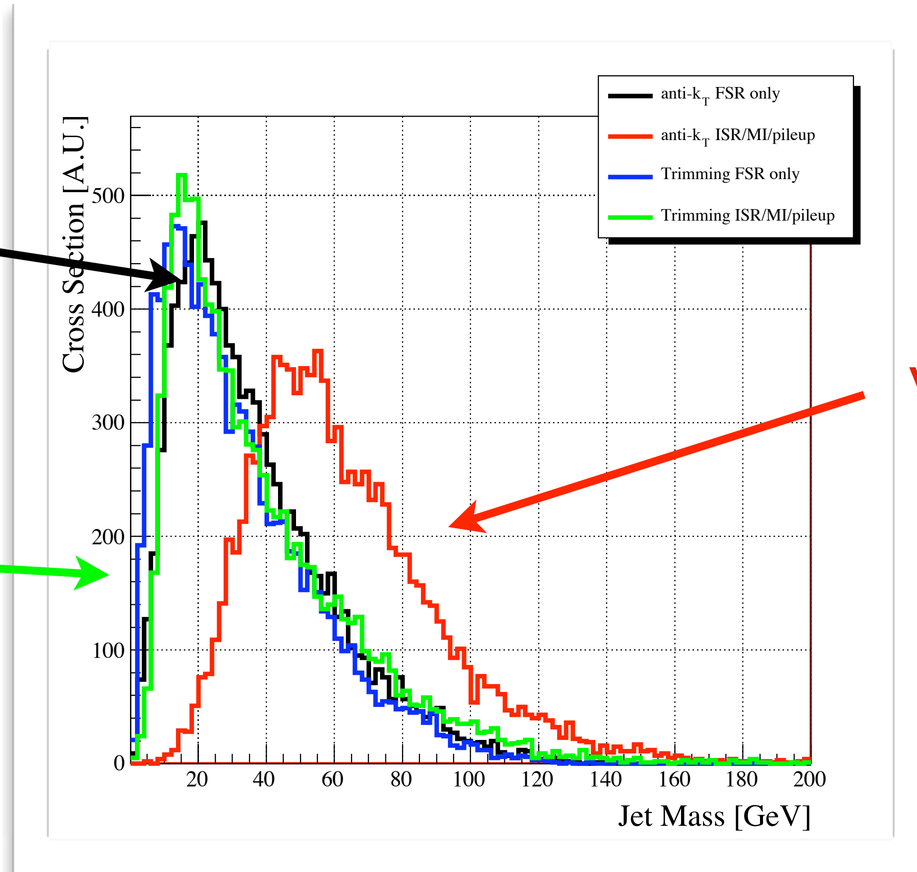
http://jthaler.net/jets/VR_Jets.html

http://jthaler.net/jets/Jet_Trimming.html

Jet mass: help from new jet algorithm

Without contamination

With "trimming"



With contamination

More faithful (smaller) jet mass for the background.

- Effect of radiation contamination on the jet mass

$$\langle \delta M^2 \rangle \simeq (\Lambda_{\rm soft} + p_{\rm T}^{\rm ISR}) p_{\rm T}^{j} \left(\frac{(\Delta R)^4}{4} + ... \right)$$

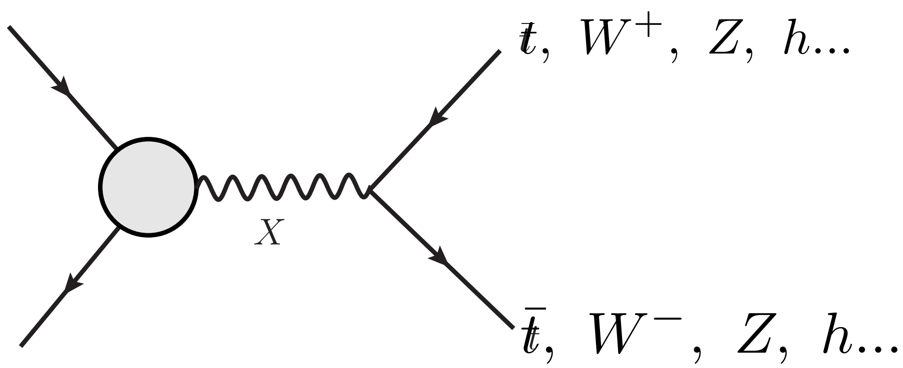
- Trimming gives large improvement by reducing effective jet size significantly.

Jet substructure

When to consider substructure

- Have to consider the boosted objects.

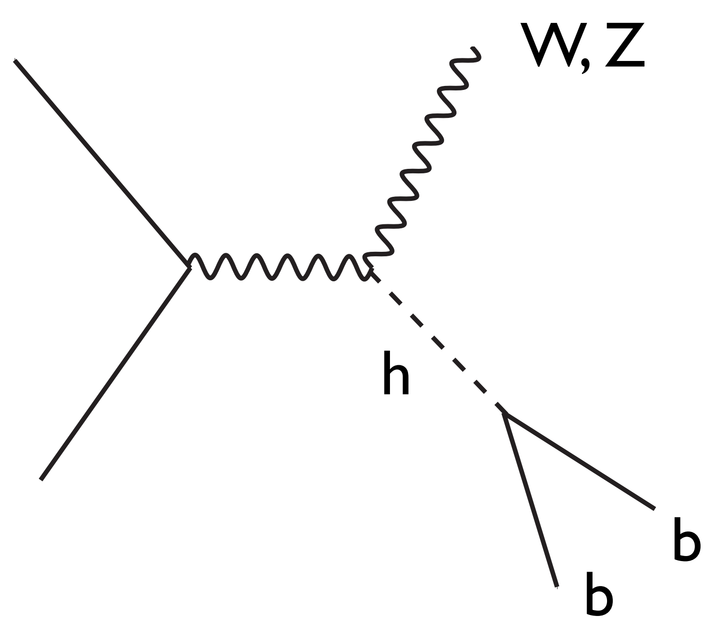
e.g.



For example, boost tops
Brooijmans; Lillie, Randall, LTW; Thaler, LTW;
D. Kaplan, K. Reherman, M. Schwartz, B. Tweedie;
L. Almeida, S. Lee, G. Perez, G. Sterman, I. Sung, J. Virzi
S. Chekanov and J. Proudfoot.
...

- It is beneficial to consider the boosted objects.

e.g.



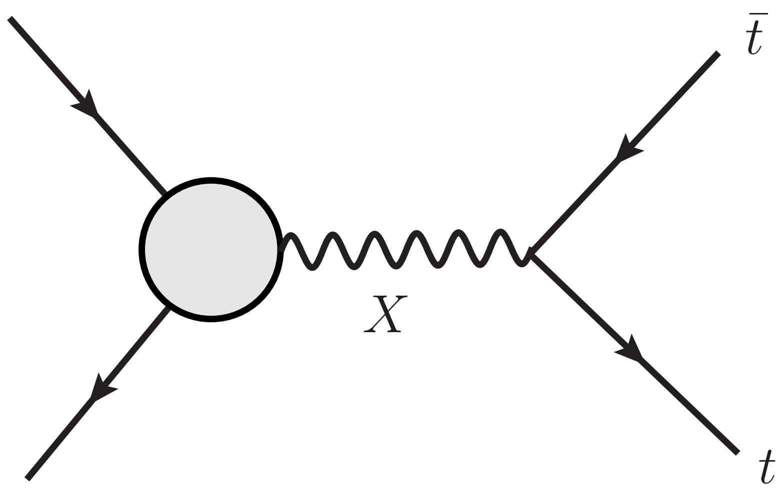
Lower combinatorics,
SM background boost differently.

Butterworth, Davidson, Bubin, Salam

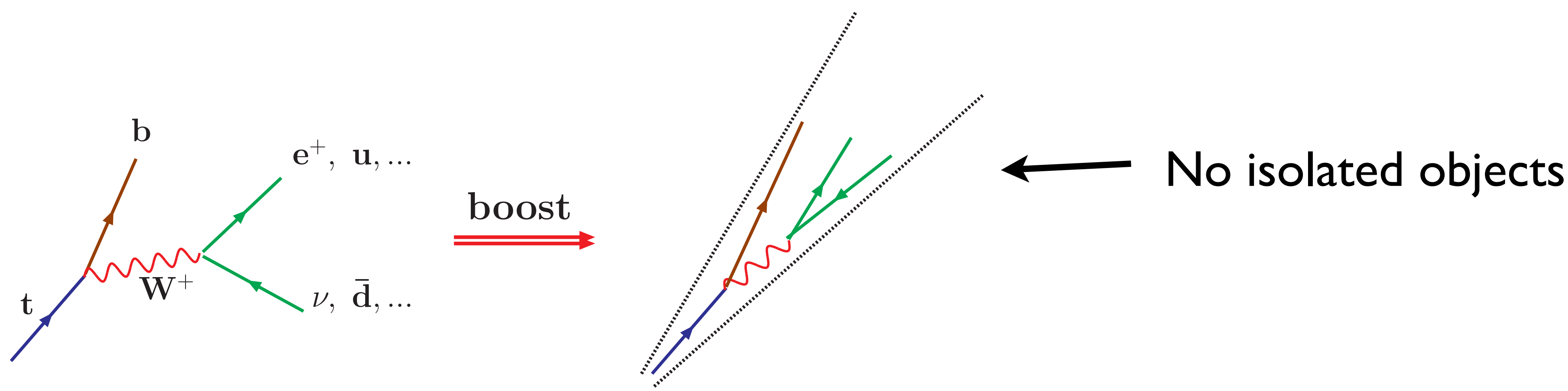
For a summary of recent developments: C. Vermilion, 1001.1335

For example, boosted top quark.

- Heavy resonance decay.



$$E_{\text{top}} \simeq \frac{M_X}{2} \qquad M_X \geq \text{TeV}$$

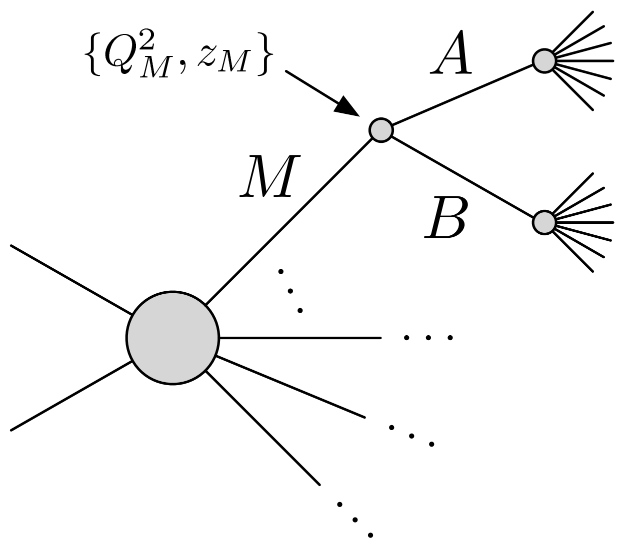


- For $m_{t\bar{t}} > 3$ TeV, $> 90\%$ events with at least one top fully collimated.
- Large fraction of events "2-object"-like. QCD $b\bar{b}$, jj background.
- A few % with lepton isolation

Lillie, Randall, and Wang, JHEP 0709:074, 2007

Shape of a jet: parton shower

- From the initial parton, a jet is built up by many radiations.



$$d\sigma^{\mathrm{QCD}}_{M\to A+B} = \frac{dQ_M^2}{2\pi}\frac{1}{Q_M^2}\,dz\,\frac{\alpha(\mu)}{2\pi}P_{M\to AB}(z)\Delta(\mu_{\mathrm{start}},\mu)$$

Prefers collinear radiation

P ~ $(z)^{-1}$ prefers soft radiation

QCD jet: a cluster of radiation

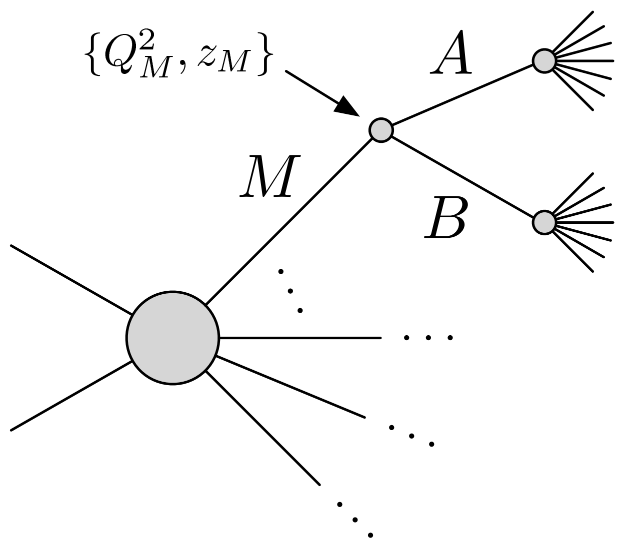
a) relatively soft

b) close to the direction of P_M

c) approximately symmetrical around P_M

Shape of a jet: parton shower

- From the initial parton, a jet is built up by many radiations.



$$d\sigma^{\rm QCD}_{M\to A+B} = \frac{dQ^2_M}{2\pi}\frac{1}{Q^2_M}\, dz \frac{\alpha(\mu)}{2\pi} P_{M\to AB}(z)\Delta(\mu_{\rm start},\mu)$$

Prefers collinear radiation

$P \sim (z)^{-1}$ prefers soft radiation

QCD jet: a cluster of radiation

a) relatively soft

b) close to the direction of P_M

c) approximately symmetrical around P_M

Q_M^2 (first splitting) = virtuality or "mass "of orginal parton

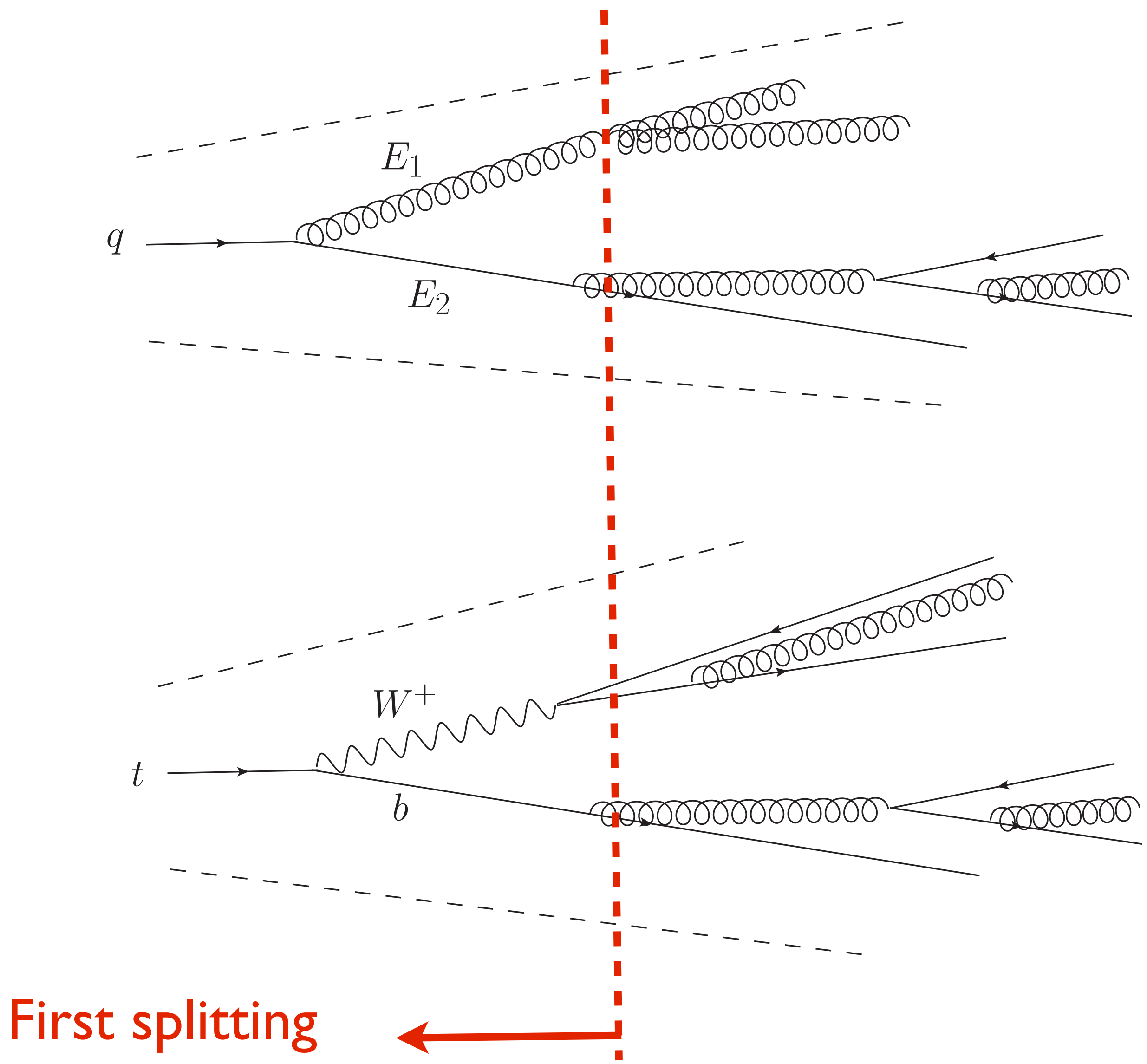
≈ jet mass

For QCD jets $\quad \frac{d\sigma}{dm^2_{jet}} \propto \frac{1}{m^2_{\rm jet}}$

(hadronic) Top tagging at the LHC

- Fully collimated tops look like QCD jets.

Basic distinction:
- QCD: radiation.
- Top decay: $t \to bW(\to qq')$ 3 hard objects.



Zooming in near the first splitting

QCD. Soft radiation: $z = \frac{\mathrm{Min}(E_1, E_2)}{E_1 + E_2} \to 0$

Jet mass: $d\sigma \propto \frac{1}{m_{\mathrm{jet}}^2}$

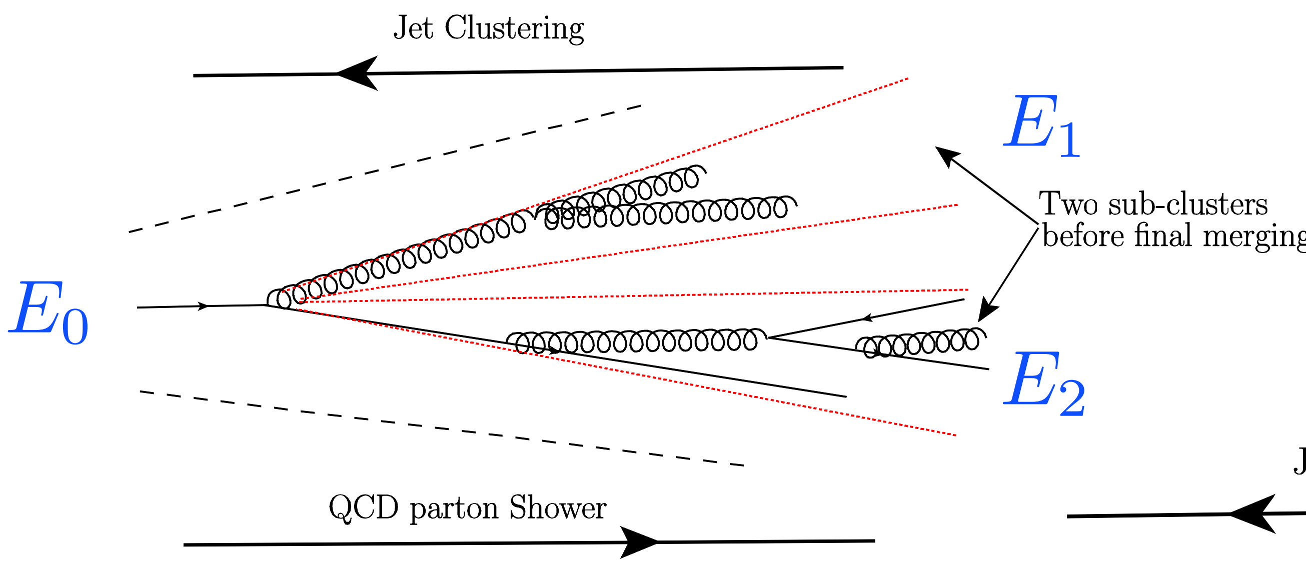
Top. Decay: $z = \frac{\mathrm{Min}(E_{\mathrm{W}}, E_b)}{E_{\mathrm{W}} + E_b} \to \text{finite}$

Jet mass: $m_{\mathrm{jet}} \simeq m_{\mathrm{top}}$

Building a microscope to look inside jets.

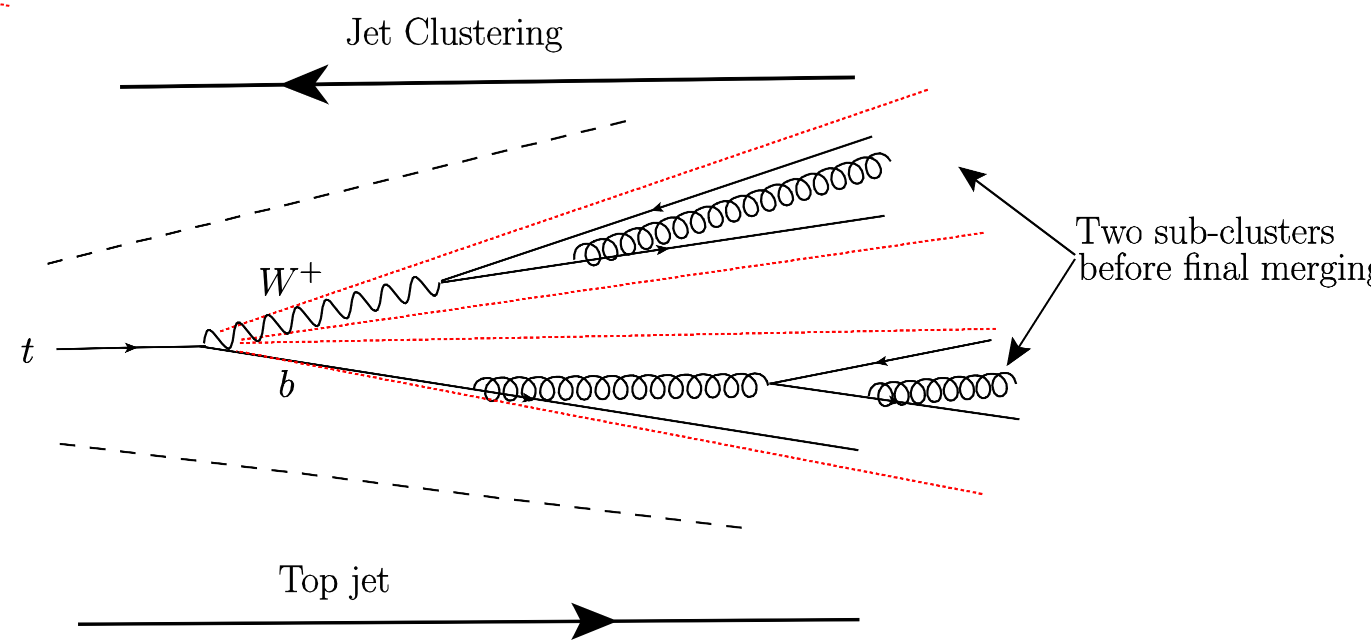
$z \to 0$ for QCD jet,

z finite for top jet.



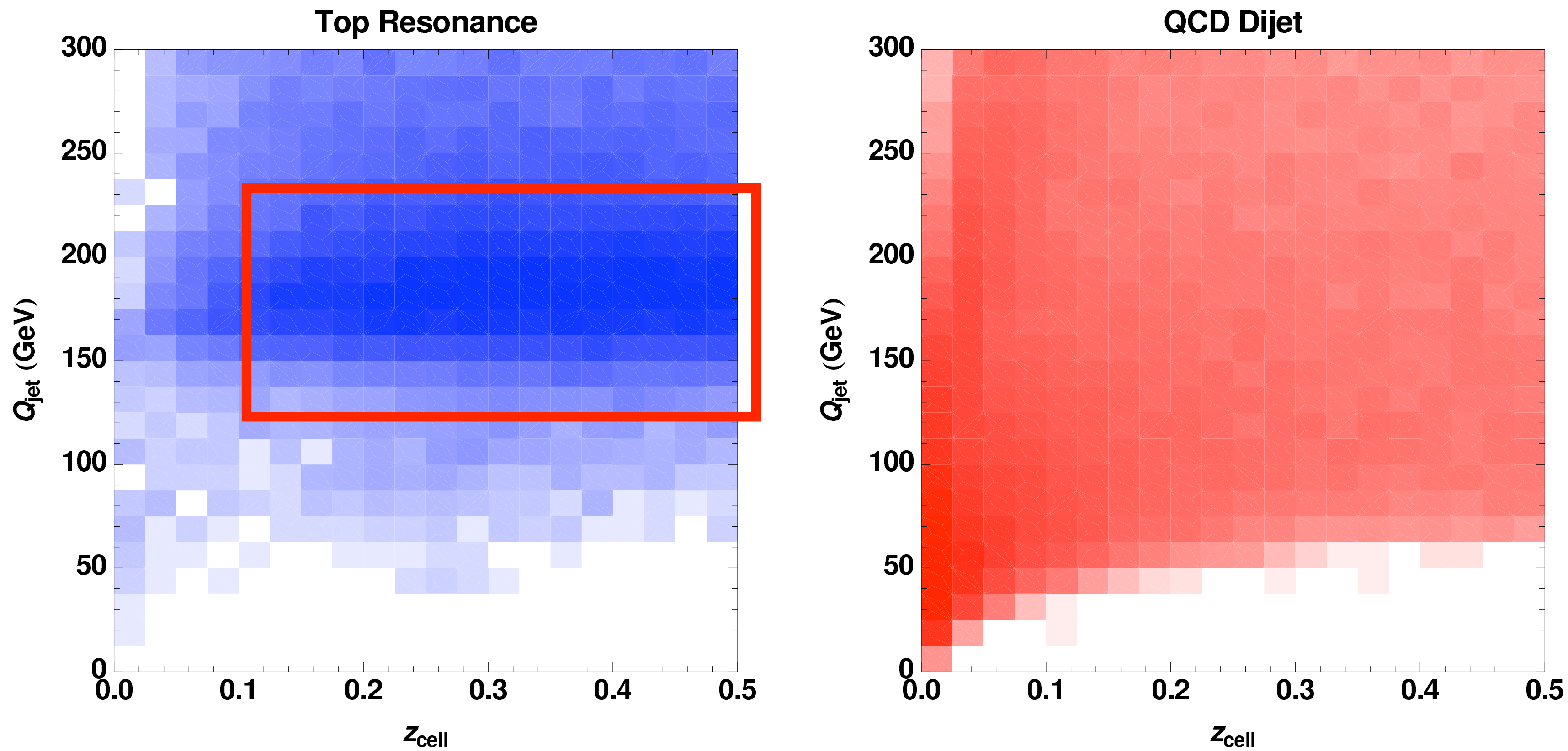
$$z = \frac{\min(E_1, E_2)}{E_0}$$

Q : jet mass



- The jet clustering history is approximately the inverse of the parton shower.

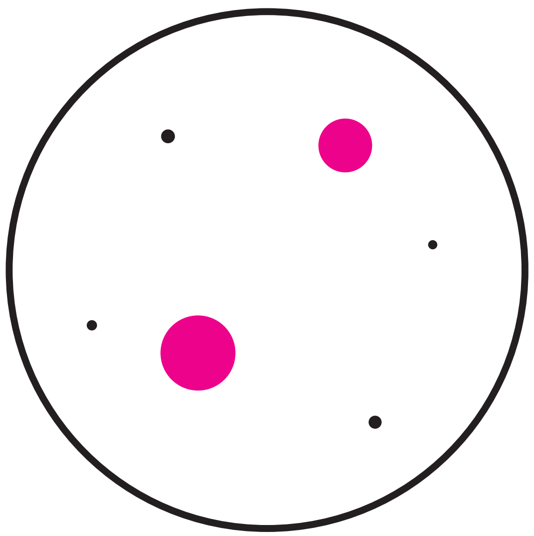
Top jets vs QCD jets



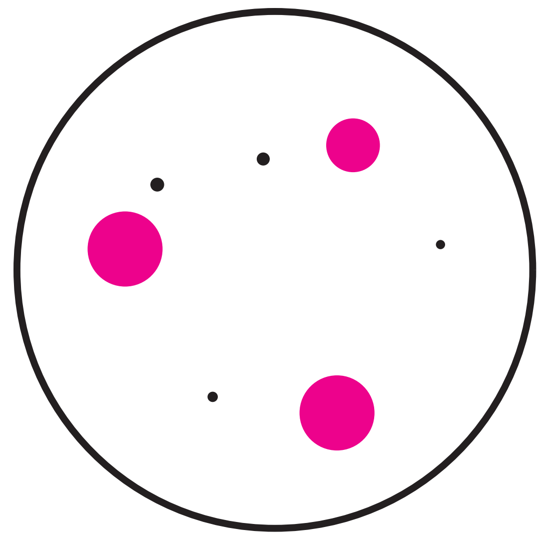
- Combined cuts on jet mass and z can enhance further the signal with respect to the background.

More jet shape variables.

- Top decay is more like 3-body. Span a "plane" perpendicular to the jet axis.
  - Transverse sphericity, or planar flow



Pf ≈ 0



Pf ≈ 1

$$I_w^{kl} = \sum_i w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i}$$

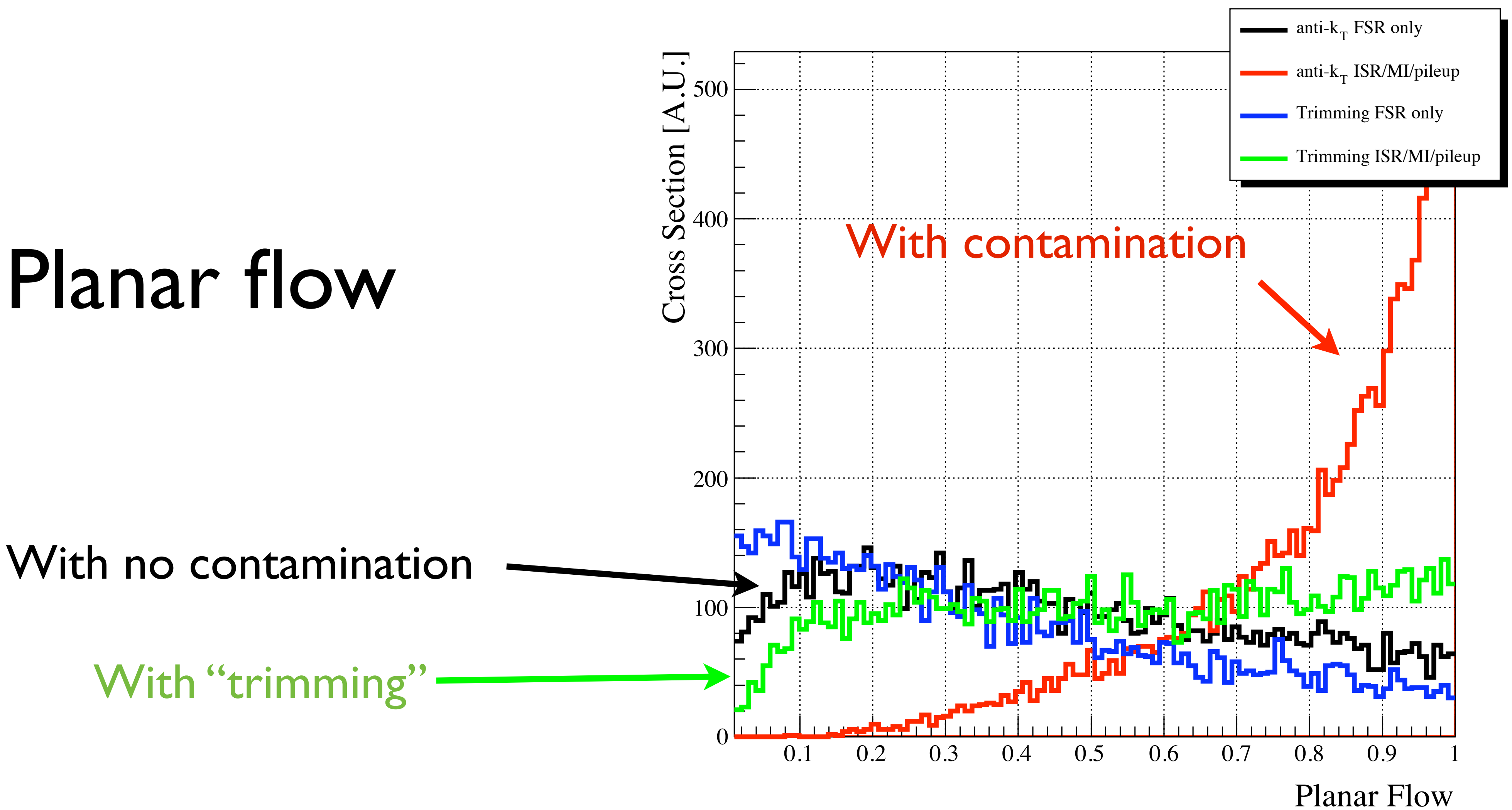
$$\lambda_1,\ \lambda_2 :\ 2 \text{ eigenvalues of } I_w^{kl}$$

$$\text{Pf} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

Thaler and LTW, arXiv:0806.0023.
Almeida, Lee, Perez, Sterman, Sung, Virzi, arXiv:0807.0234

Grooming gives better jet shape

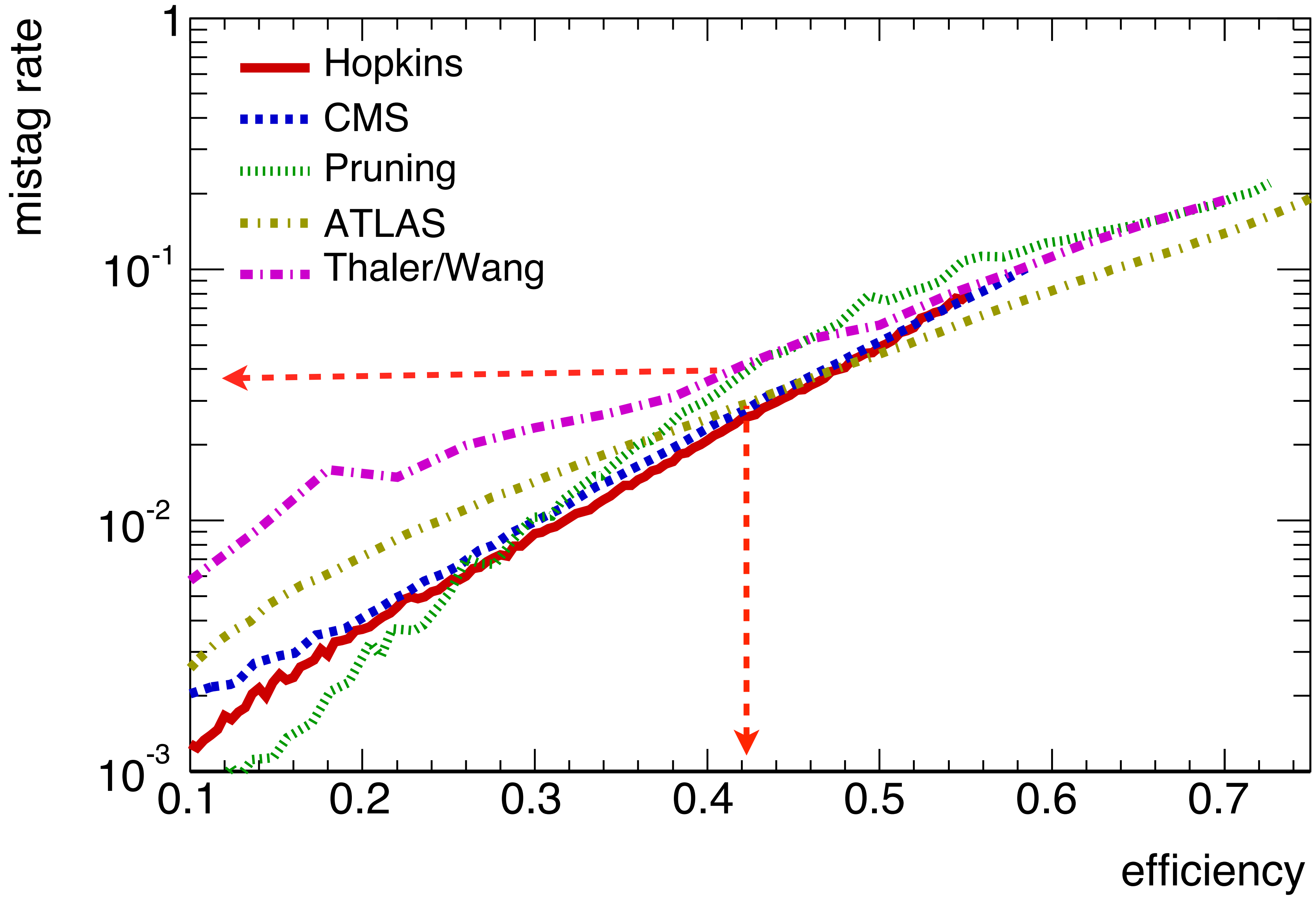
Planar flow



- Can be used to further improve top tagging. An additional factor of several possible.
- Interesting to compare with improved QCD calculation, using modern technologies such as SCET.

Various top taggers

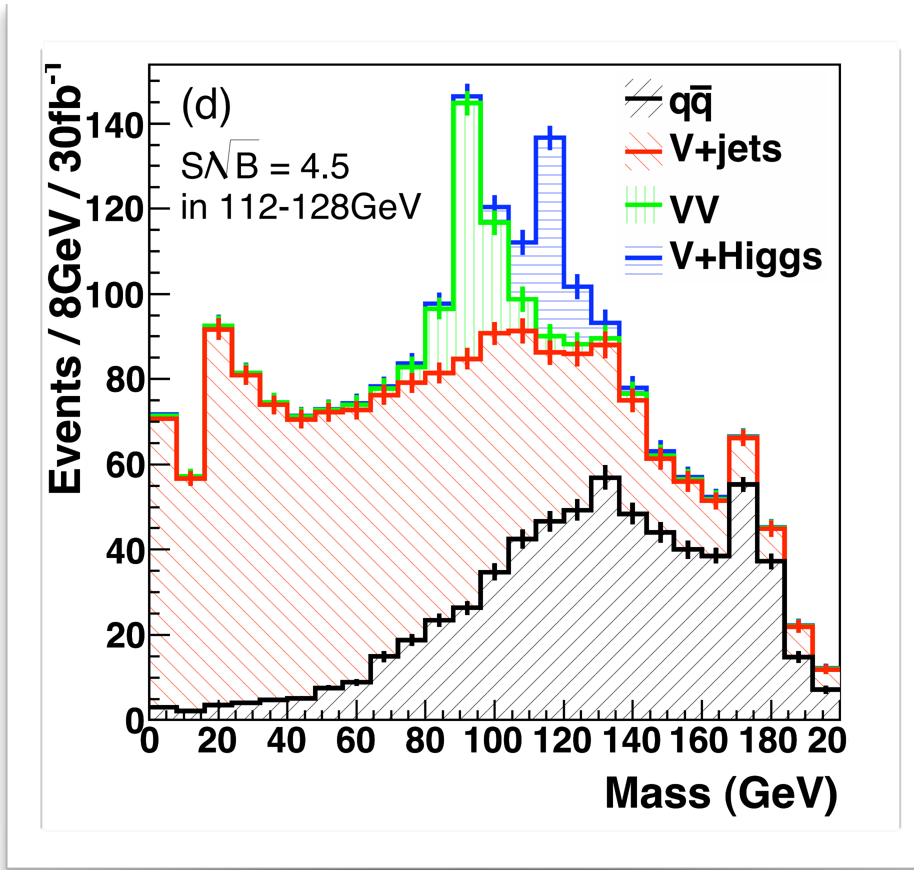
Boost 2010 proceeding, 1012.5421



G. Brooijmans, arXiv:0802.3715;
CMS Coll. CMS PAS JME-09-001
J. Thaler, LTW, arXiv:0806.0023
D. Kaplan, K. Reherman, M. Schwartz, B. Tweedie, arXiv: 0806.0848.
L. Almeida, S. Lee, G. Perez, G. Sterman, I. Sung, J. Virzi, arXiv:0807.0243
L. Almeida, S. Lee, G. Perez, G. Sterman, I. Sung, arXiv:1006.2035
Barger, Huang, 1102.3183

BDRS (+filtering)

Butterworth, Davison, Rubin, Salam, 0802.2470



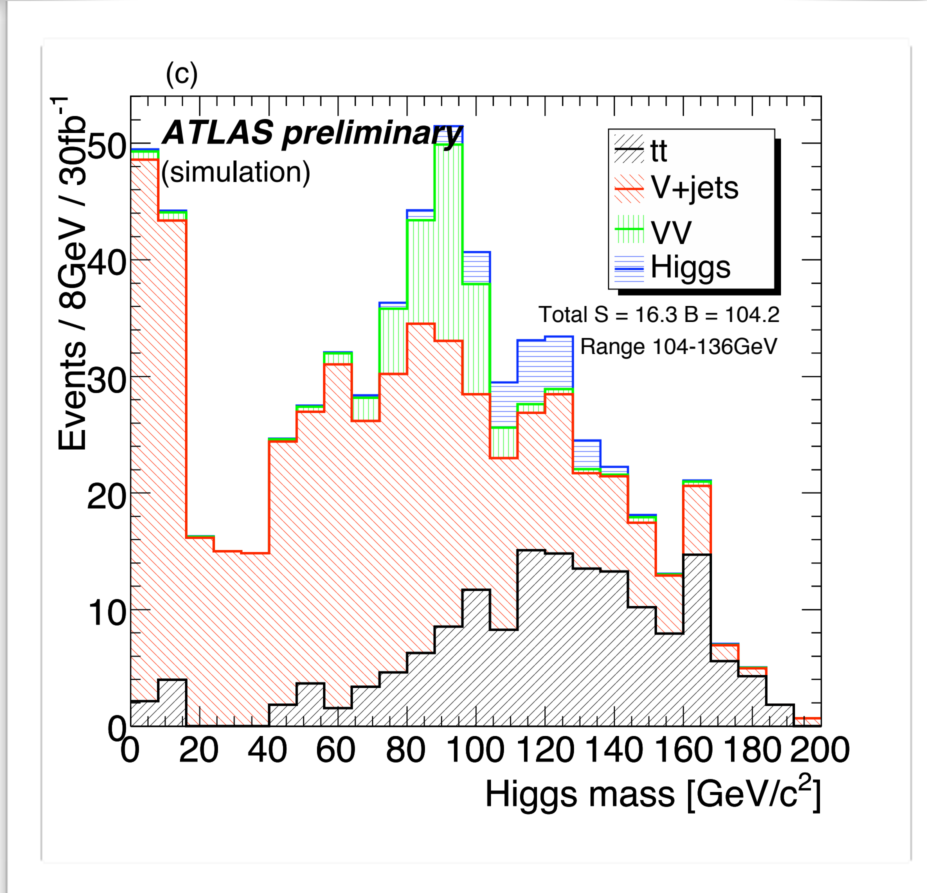
- Z+H and W+H with H->bb.
- Considered boosted Higgs.
  - Better acceptance. $p_T^h > 200$ GeV
  - backgroud such as ttbar boost differently.

$4.5(8.2)\sigma$ with 14 TeV and 30(100) fb^{-1}

- Similar result reproduced by ATLAS

3.7σ with 14 TeV and 30 fb^{-1}

ATL-PHYS-PUB-2009-088



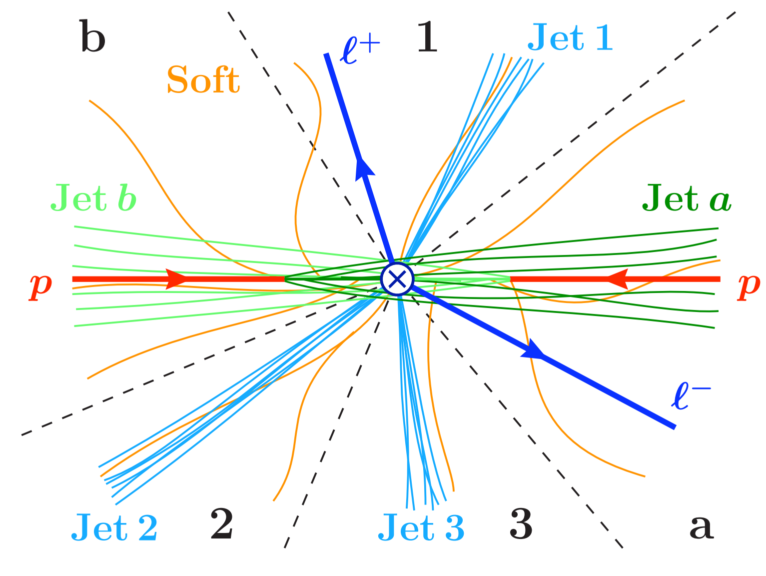
New developments: N-jettiness

Stewart, Tackmann, Waalewijn, 1004.2489

$$\mathcal{T}_N = \sum_k |\vec{p}_{kT}| \min\{d_a(p_k), d_b(p_k), d_1(p_k), d_2(p_k), \ldots, d_N(p_k)\}$$
$$\equiv \mathcal{T}_N^a + \mathcal{T}_N^b + \mathcal{T}_N^1 + \cdots + \mathcal{T}_N^N$$

N-jet like event

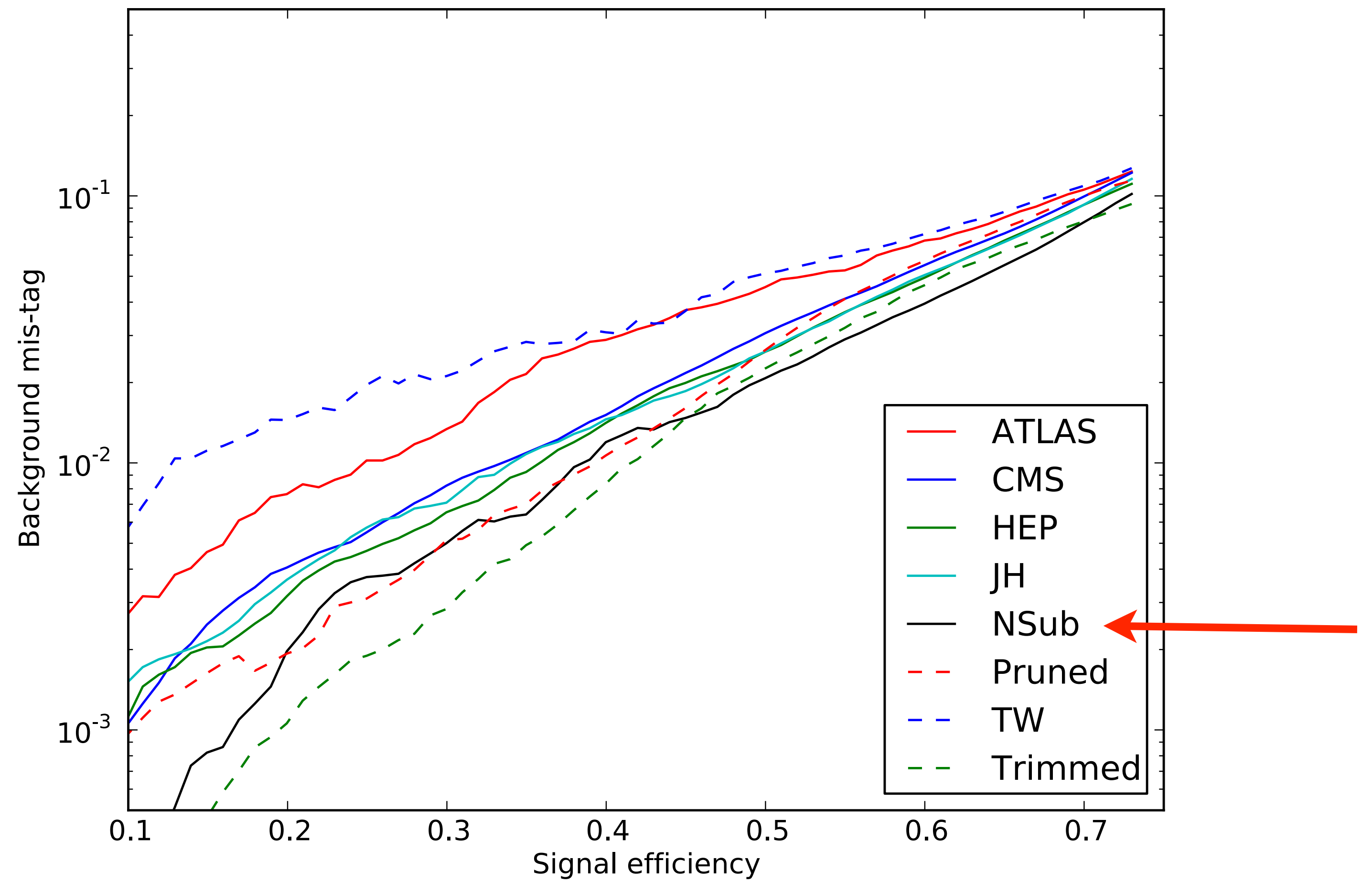
$$\tau_N \longrightarrow 0$$



- Using event shape instead of clustered jets.
- Allowing better QCD (SCET) treatments.
- Example: application in jet veto in Higgs searches.

N-subjettiness

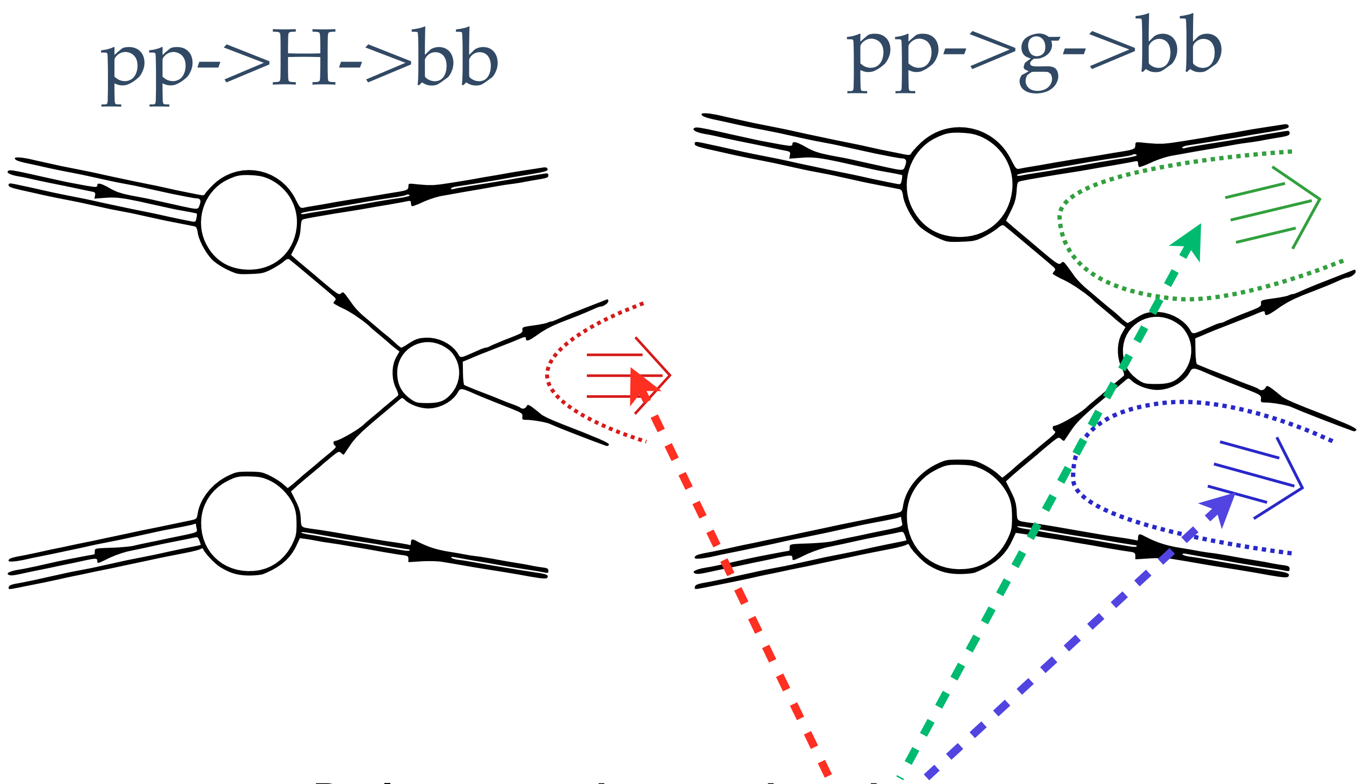
Boost 2011 proceeding



- Using the N-jettiness idea, but applies to number of subjects in a jet.
- Good substructure variable, one of the best top tagger

Superstructure

Gallicchio, Schwartz, 1001.5027



Relative enhanced radiation consentration

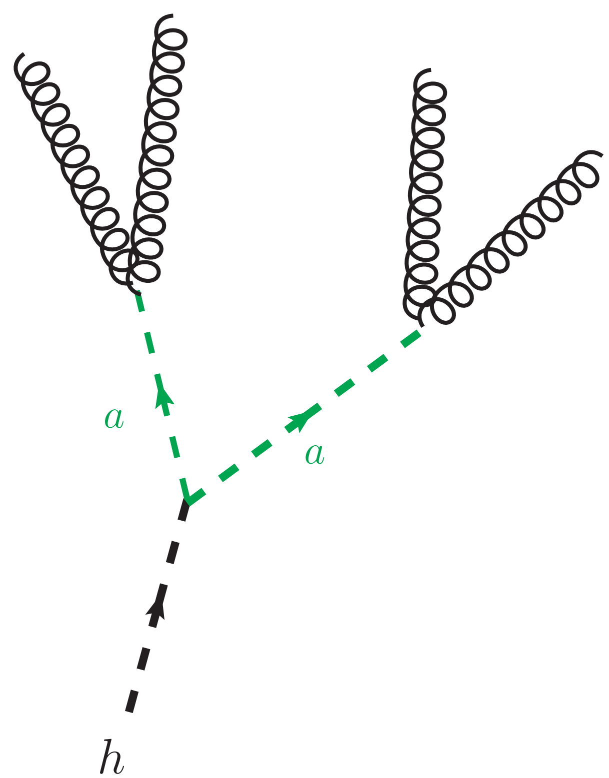
- Using more global information.
- Applications to other channels as well.

e.g., ttbar at Dzero, Haas Boston Jet Workshop

Unbury the Higgs.

$h \to aa \to gggg$, "buried"!

For example:
B. Bellazzini, C. Csaki, A. Falkowski, A. Weiler, arXiv:0910.3210, arXiv:0906.3026



Soft gluon jets,
considered impossible.

$h \to aa \to c\bar{c}c\bar{c}$, "charmful"?

$h \to aa \to 4\tau,\ 4b,\ \bar{b}b\bar{\tau}\tau$

For example:
P. Graham, A. Pierce, J. Wacker, hep-ph/0605162
M. Carena, T. Han, G. Huang, C. Wagner, arXiv:0712.2466

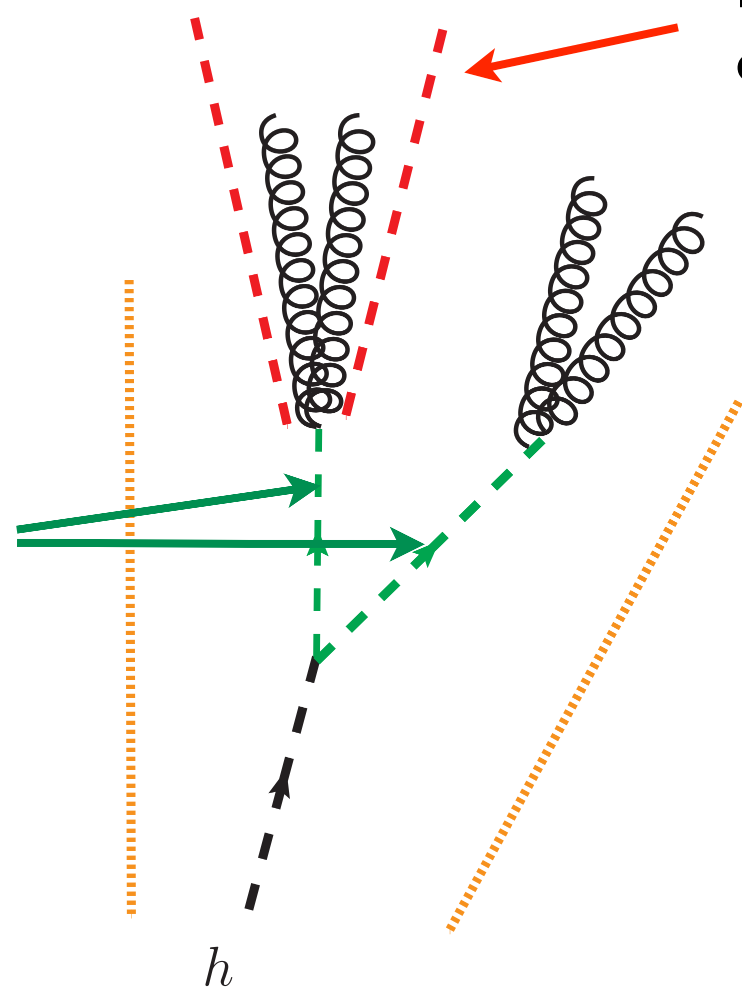
Unbury the Higgs.

$h \to aa \to gggg$, "buried"!

For example:
B. Bellazzini, C. Csaki, A. Falkowski, A. Weiler, arXiv:0910.3210, arXiv:0906.3026

Less radiation outside this cone

Two "equal "clusters



Boosting the Higgs.

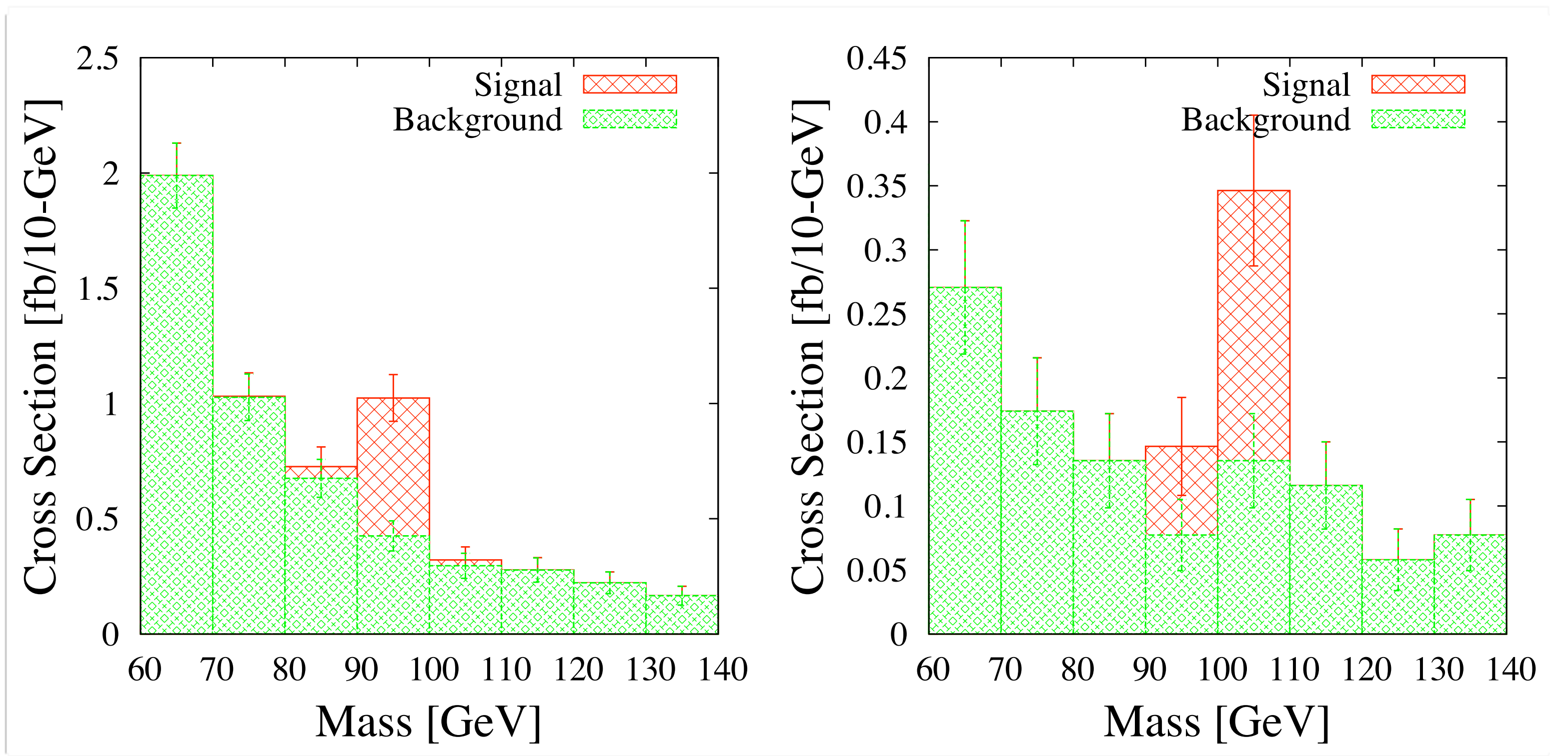
$h \to aa \to c\bar{c}c\bar{c}$, "charmful"?

$h \to aa \to 4\tau,\ 4b,\ \bar{b}b\bar{\tau}\tau$

For example:
P. Graham, A. Pierce, J. Wacker, hep-ph/0605162
M. Carena, T. Han, G. Huang, C. Wagner, arXiv:0712.2466

Encouraging results.

$$> 5\sigma \text{ at } 100 \text{ fb}^{-1}$$



W/Z+h ttbar+h

Chen, Nojiri, Sreethawong, 1006.1151
Falkowski, Krohn, Shelton, Thalapillil, and LTW, 1006.1650

Substructure can also be useful for

- From top/W/Z/Higgs from NP decay, early LHC prospects.
  - Resonance ttbar.
  - SUSY. Kribs, Martin, Roy, Spannowsky , 0912.4731, 1006.1656
  - Top partner to Higgs. Kribs, Martin, and Roy, 1012.2886
  - Z' to WW, Zh... Cui, Han, Schwartz, 1012.2077
    Katz, Son, Tweedie, 1010.5253
- Boosted NP particles.
  - Neutralino + RPV Butterworth, Ellis, Raklev, Salam, 0906.0728
  - Boosted gluino from squark. Fan, Krohn, Mosteiro, Thalapillil, 1102.0302