New jet tools for discovering New Physics at the LHC

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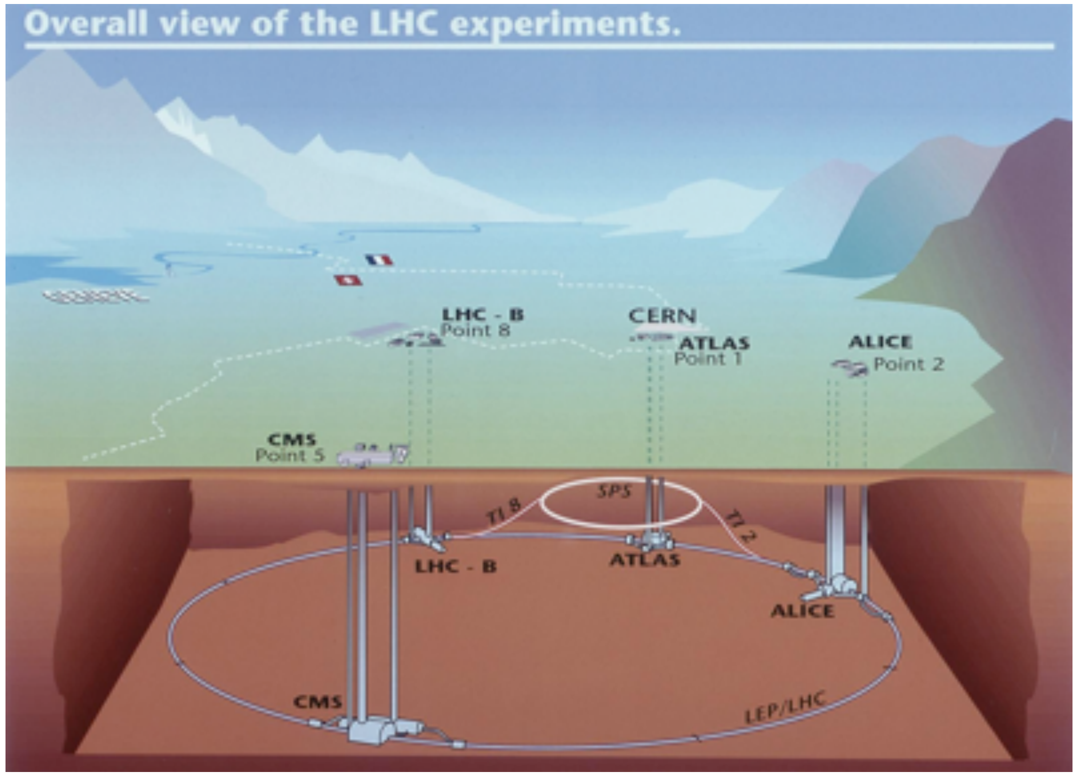
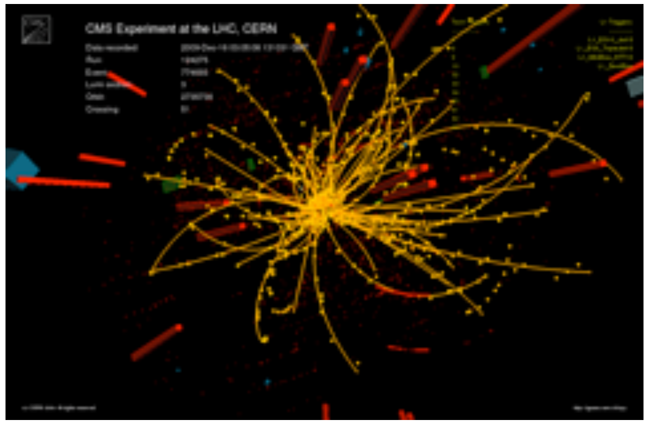
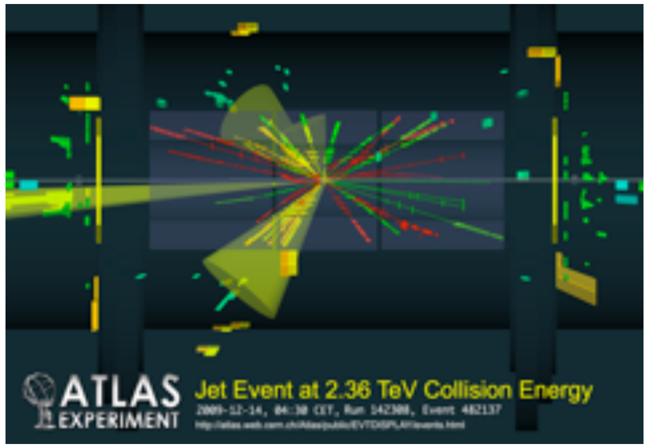
Outline

- Brief overview.
- Improving jet algorithms.
  - 2 examples.
- Jet substructure and new physics searches.
  - Boosted tops.
  - Higgs search.
  - New physics in WW scattering.
  - Heavy squark.
- Outlook.

LHC, the energy frontier.







- Many fundamental questions to be answered.
  - Electroweak symmetry breaking, origin of mass.
  - Dark matter.
  - Supersymmetry, extra-dimension ....

Major challenge:
Tackling hadronic final states

The importance of hadronic final state:

- “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.
  - TeV new physics states can decay to SM “heavy” particles, e.g. t, W, Z, often look like a cluster of hadrons.
- Understanding of basic structure of QCD and the properties of new physics has lead to the development of a set of modern tools which significantly enhanced the discovery potential.

Why is it hard?

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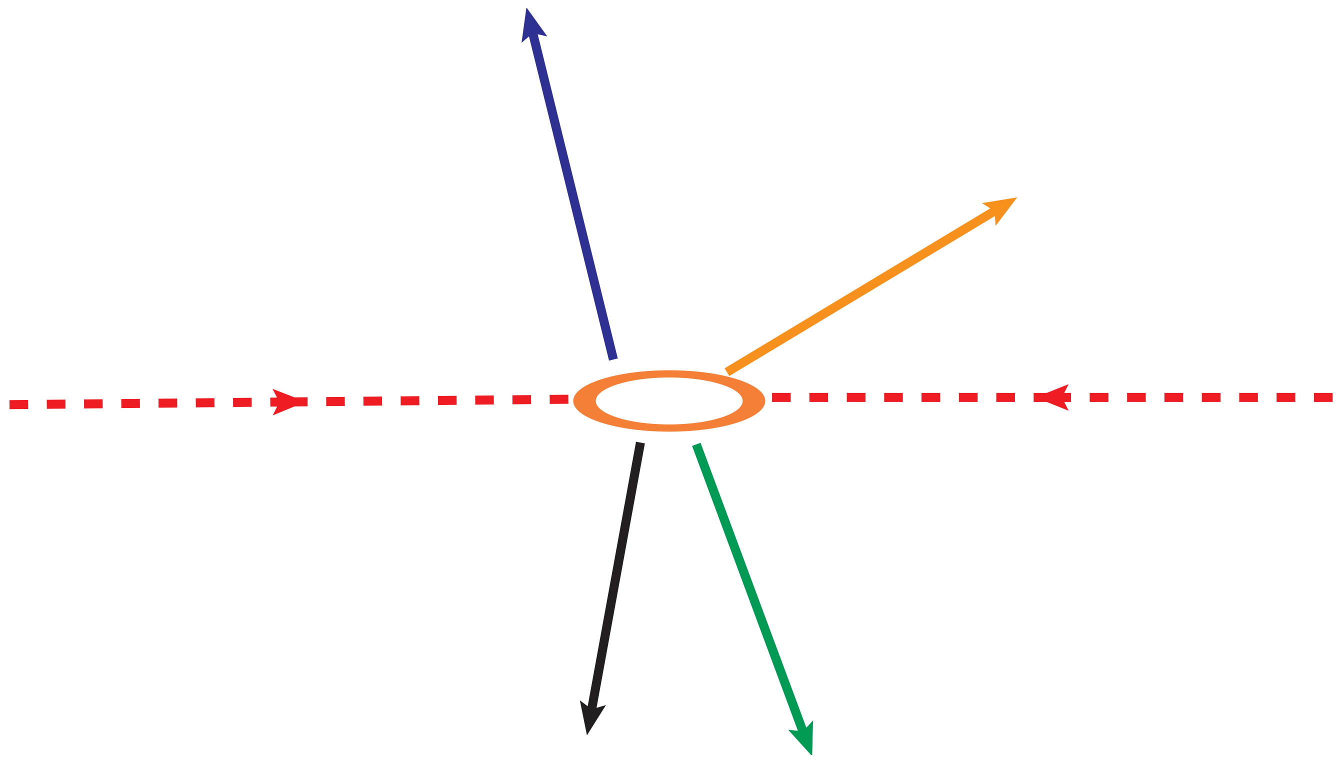

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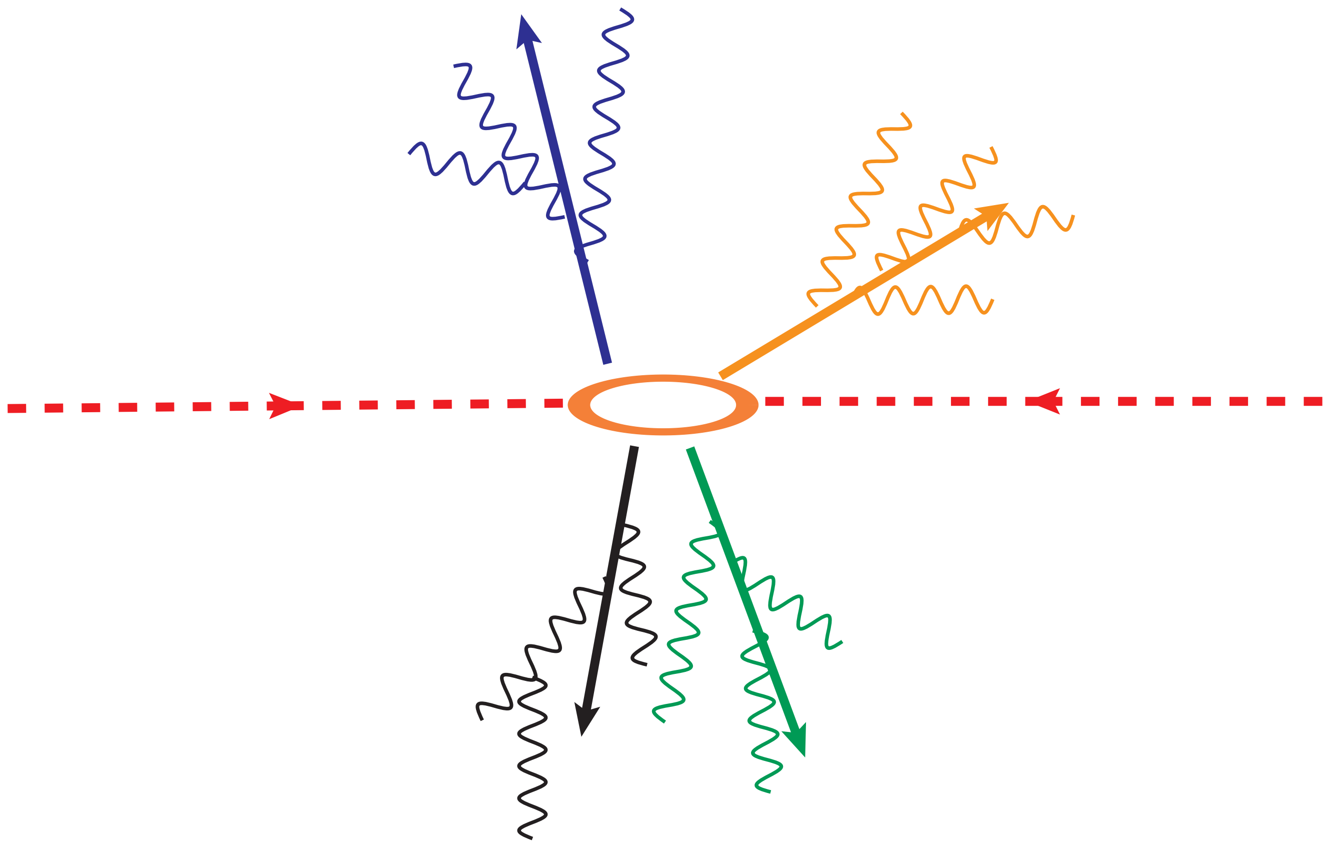

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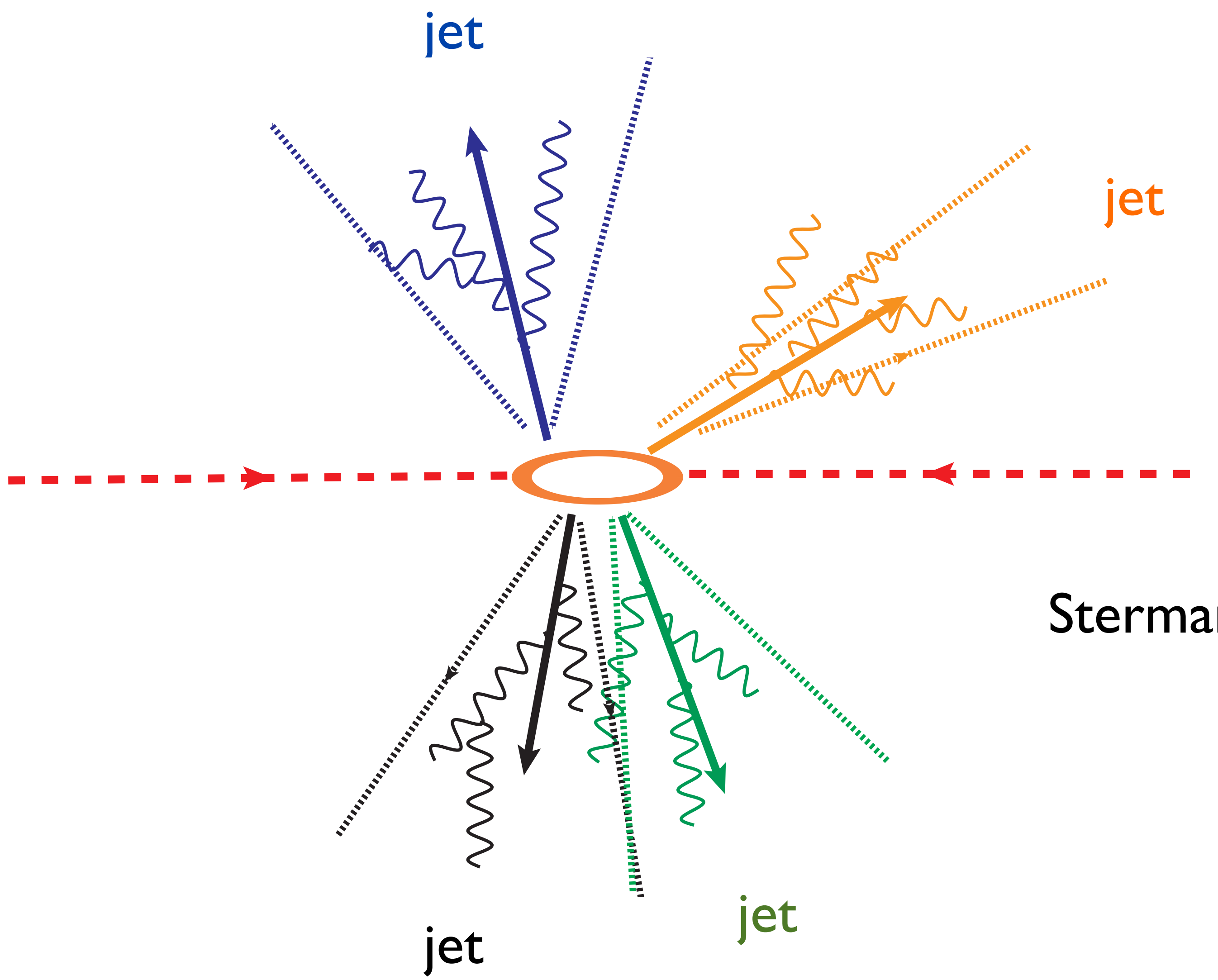
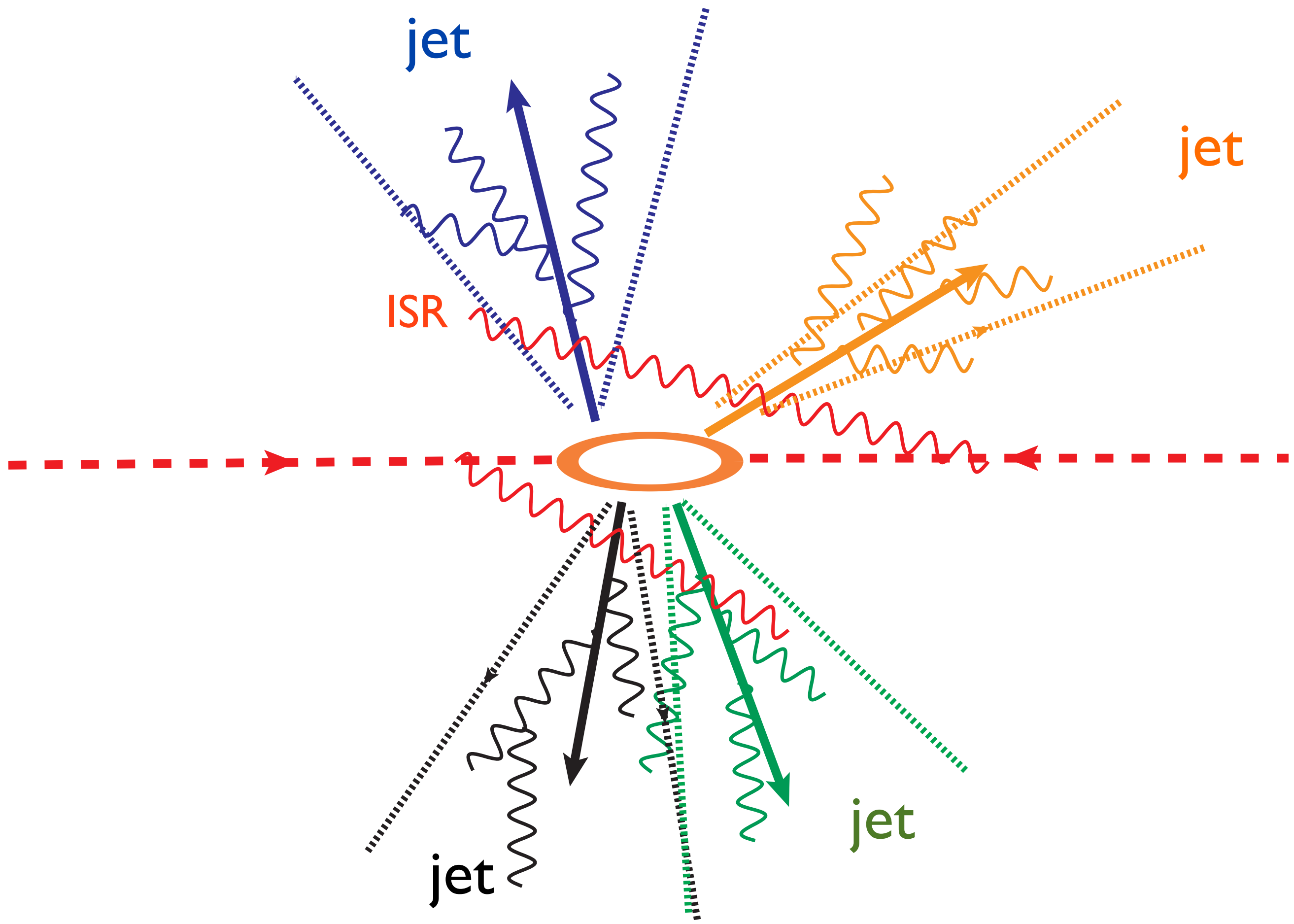


Sterman & Weinberg, PRL, 1977.

- We would like to preserve $p_{\rm jet} \simeq p_{\rm parton}$.

Why is it hard?



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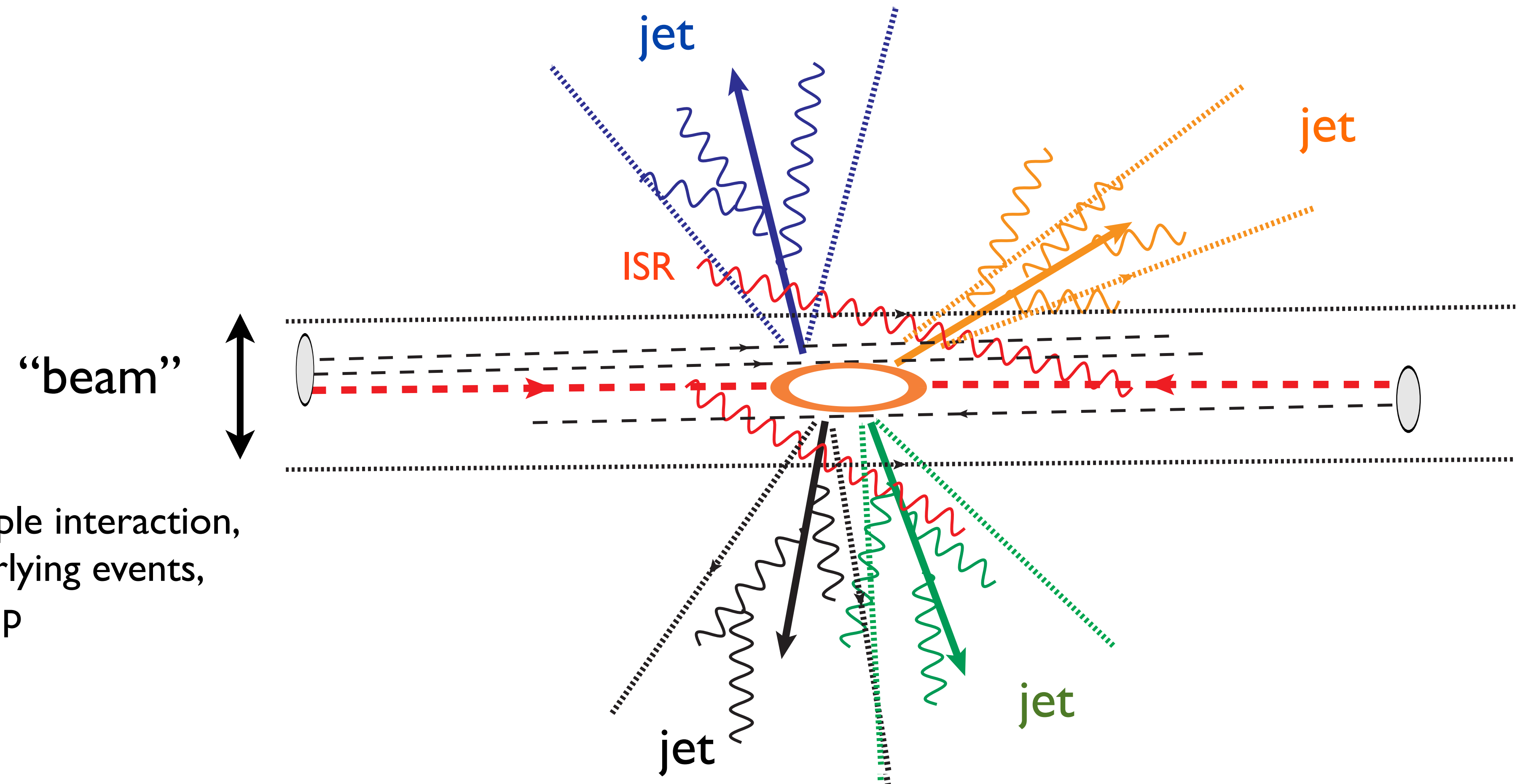
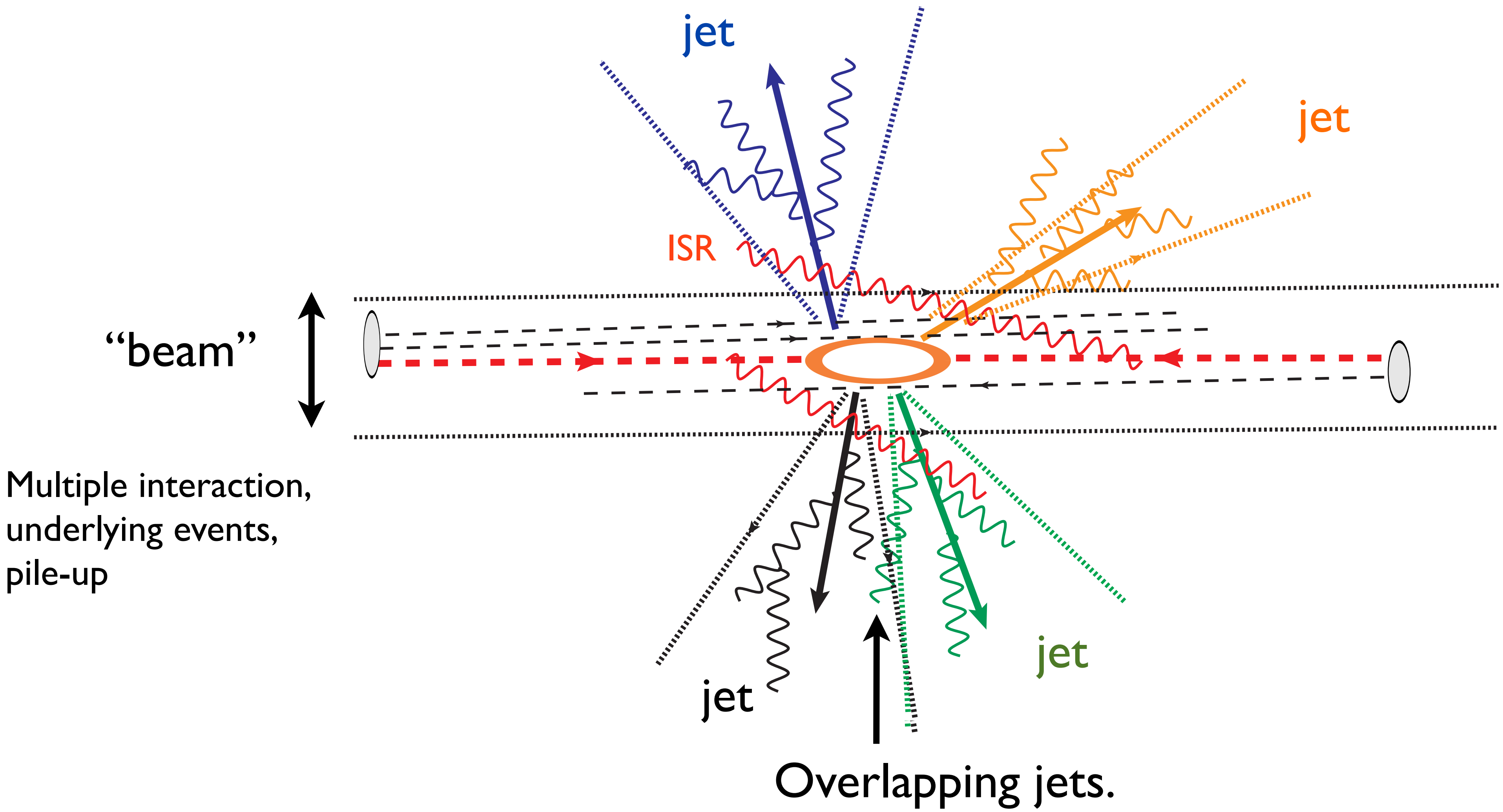


Multiple interaction,
underlying events,
pile-up

Why is it hard?



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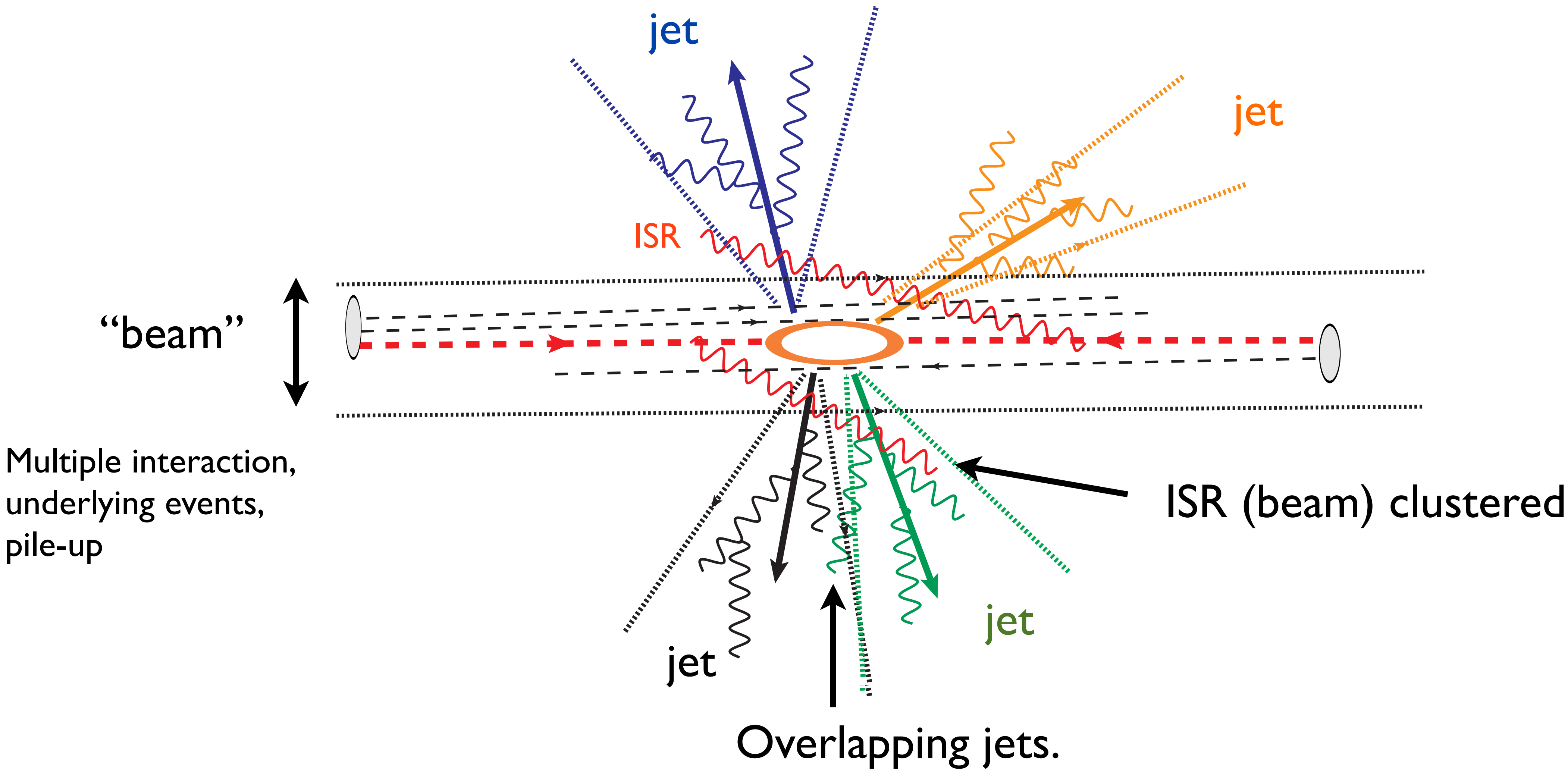

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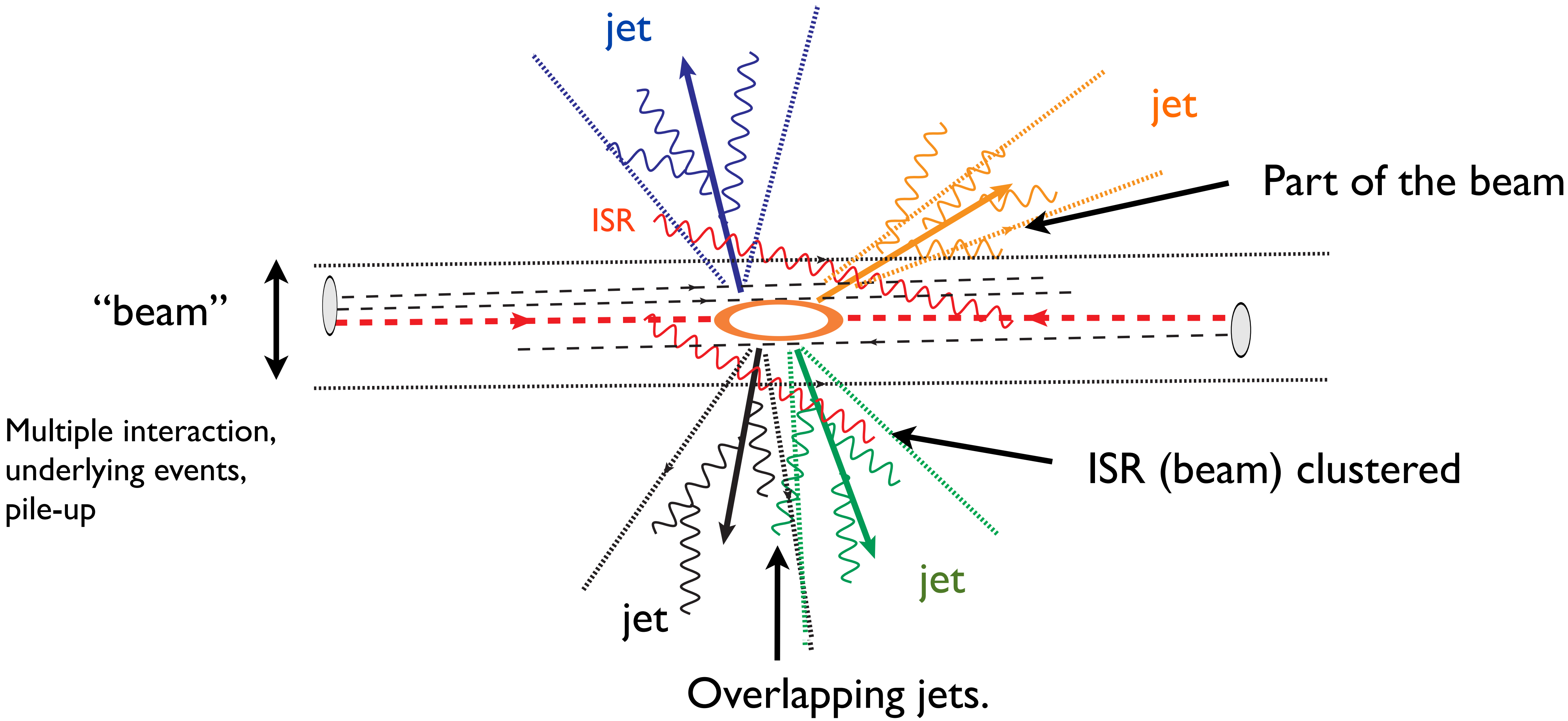

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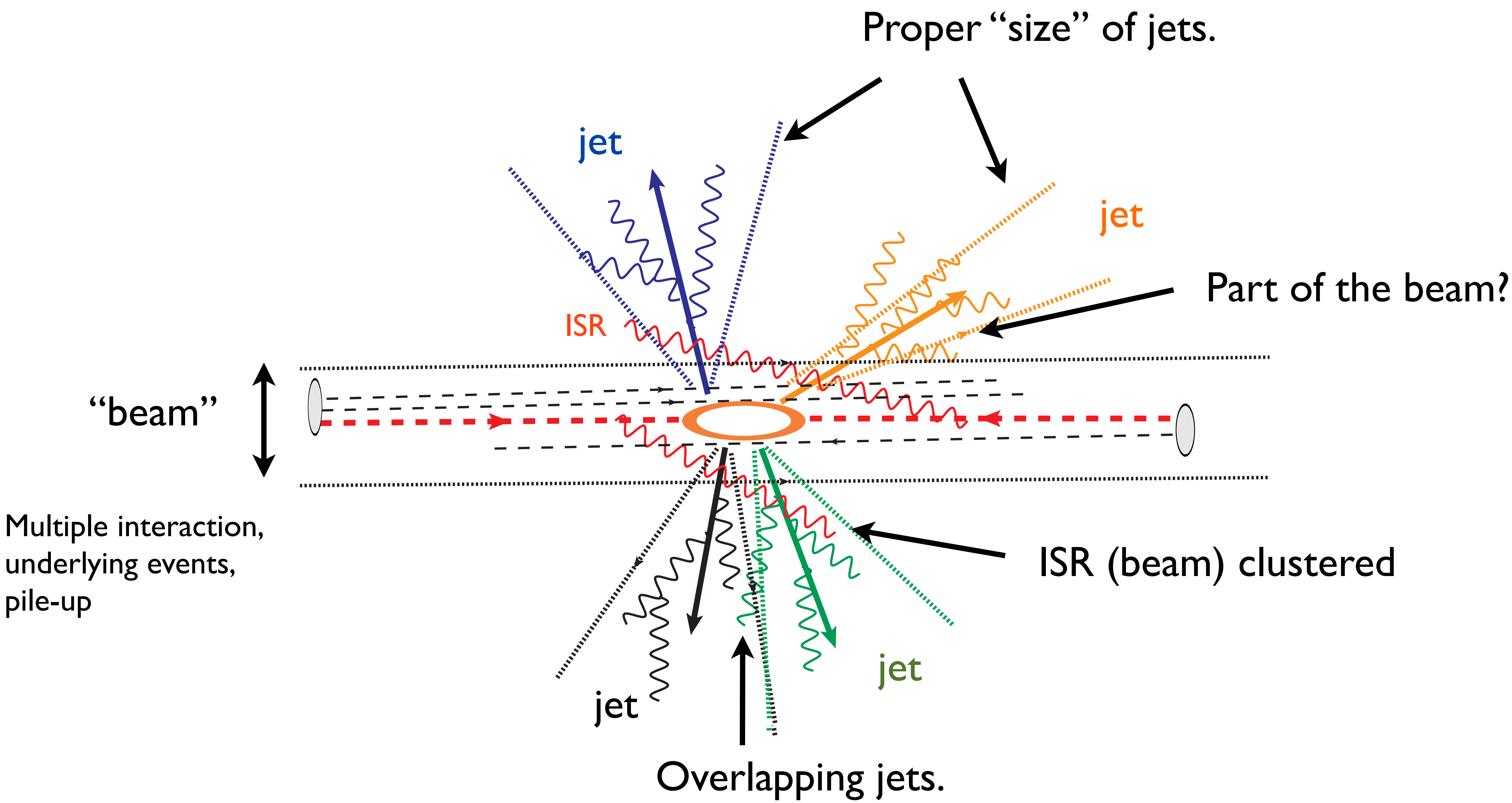

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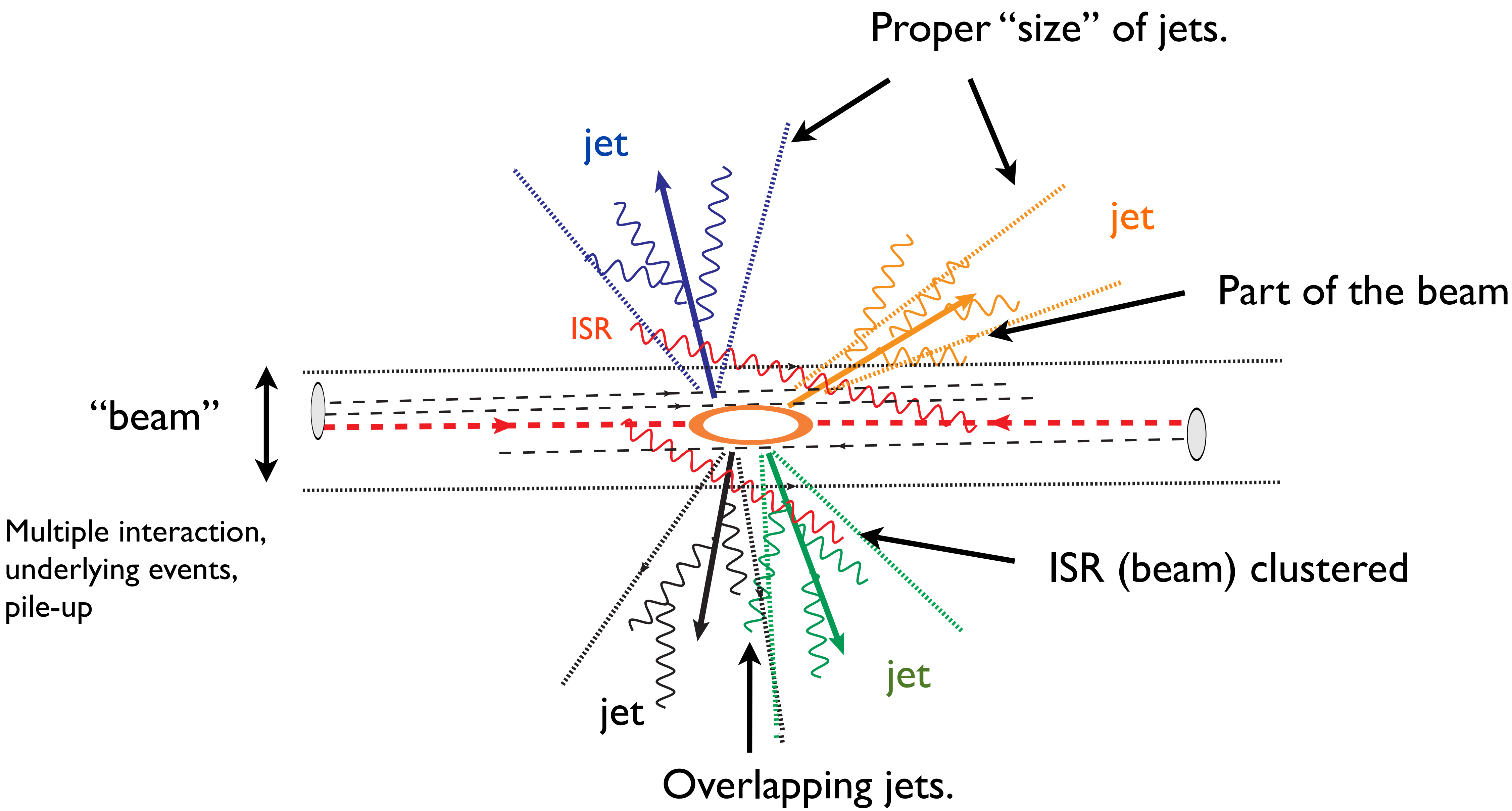


- To best preserve $p_{\rm jet} \simeq p_{\rm parton}$ we would like to:
  - Use "smart" jet shapes.
  - Control "contamination".

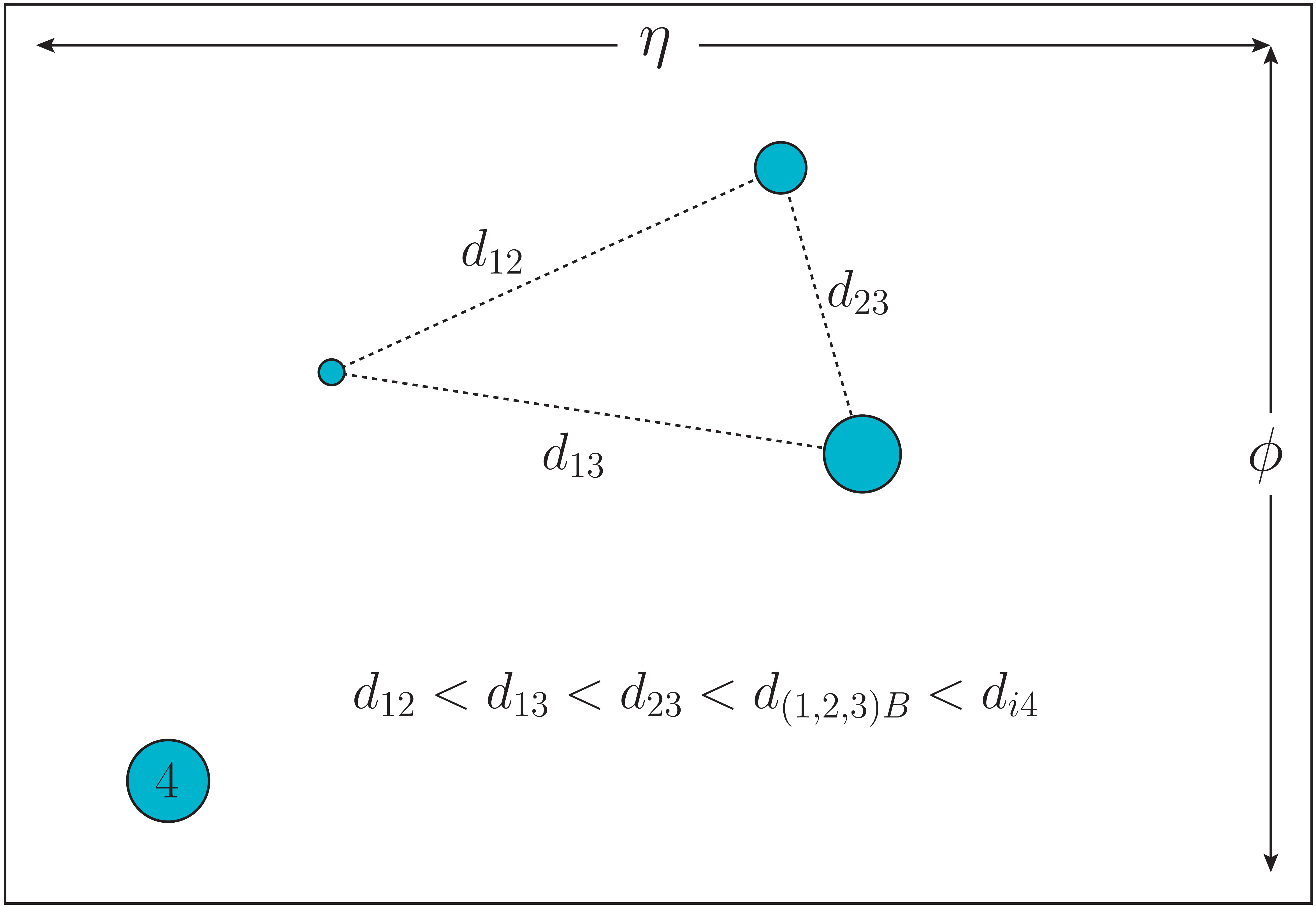
Two main characters of "better" jets

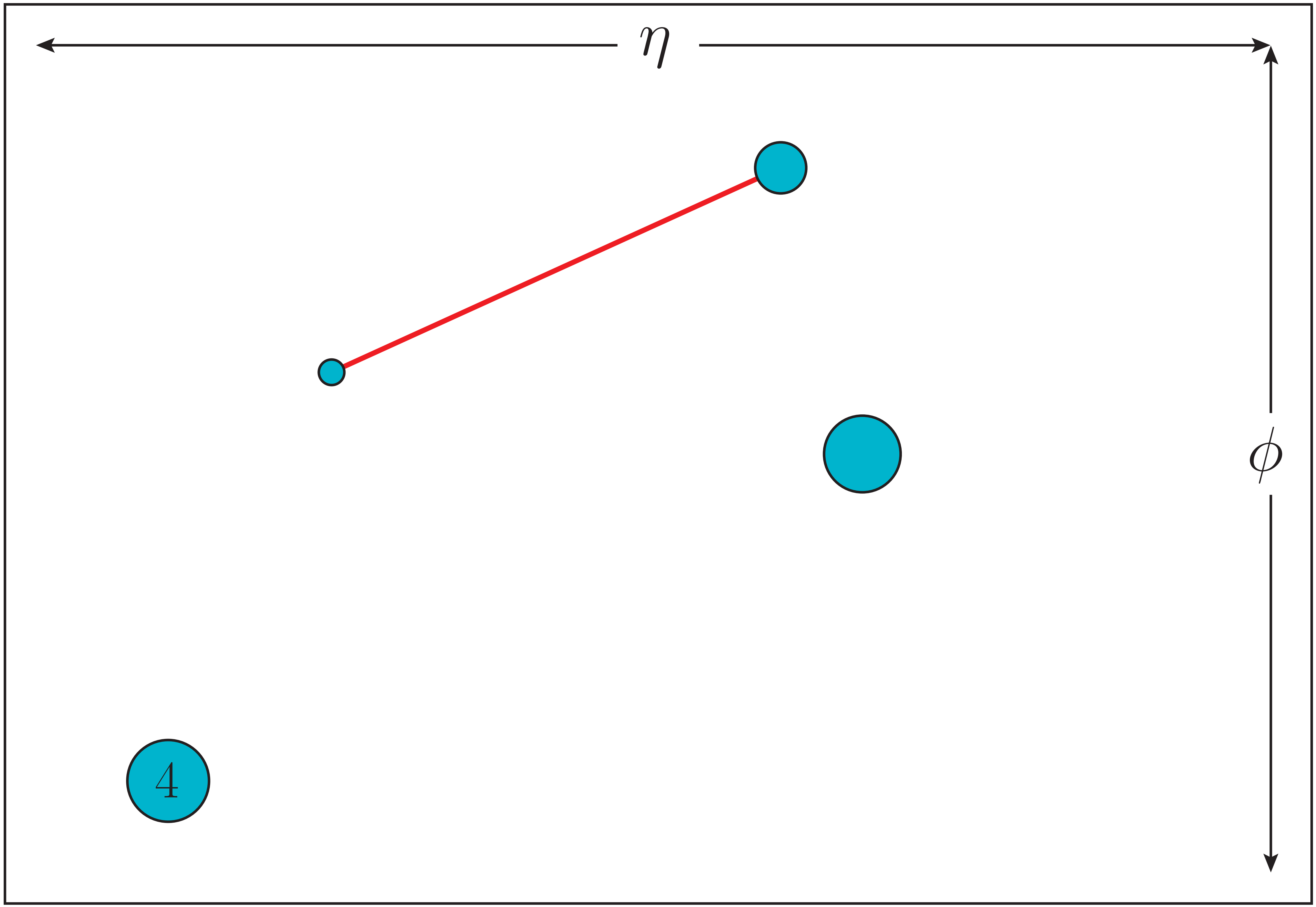
- Light parton initiated jets
  - No loss of FSR.
  - No contamination.
- boosted t, W Z initiated jets
  - How to distinguish them from the light parton QCD jets.

New improved jet algorithms

Begin with jet algorithm

- An algorithm of clustering together "close by" objects.
- 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.


η
φ
d_{12}
d_{23}
d_{13}
$d_{12} < d_{13} < d_{23} < d_{(1,2,3)B} < d_{i4}$
4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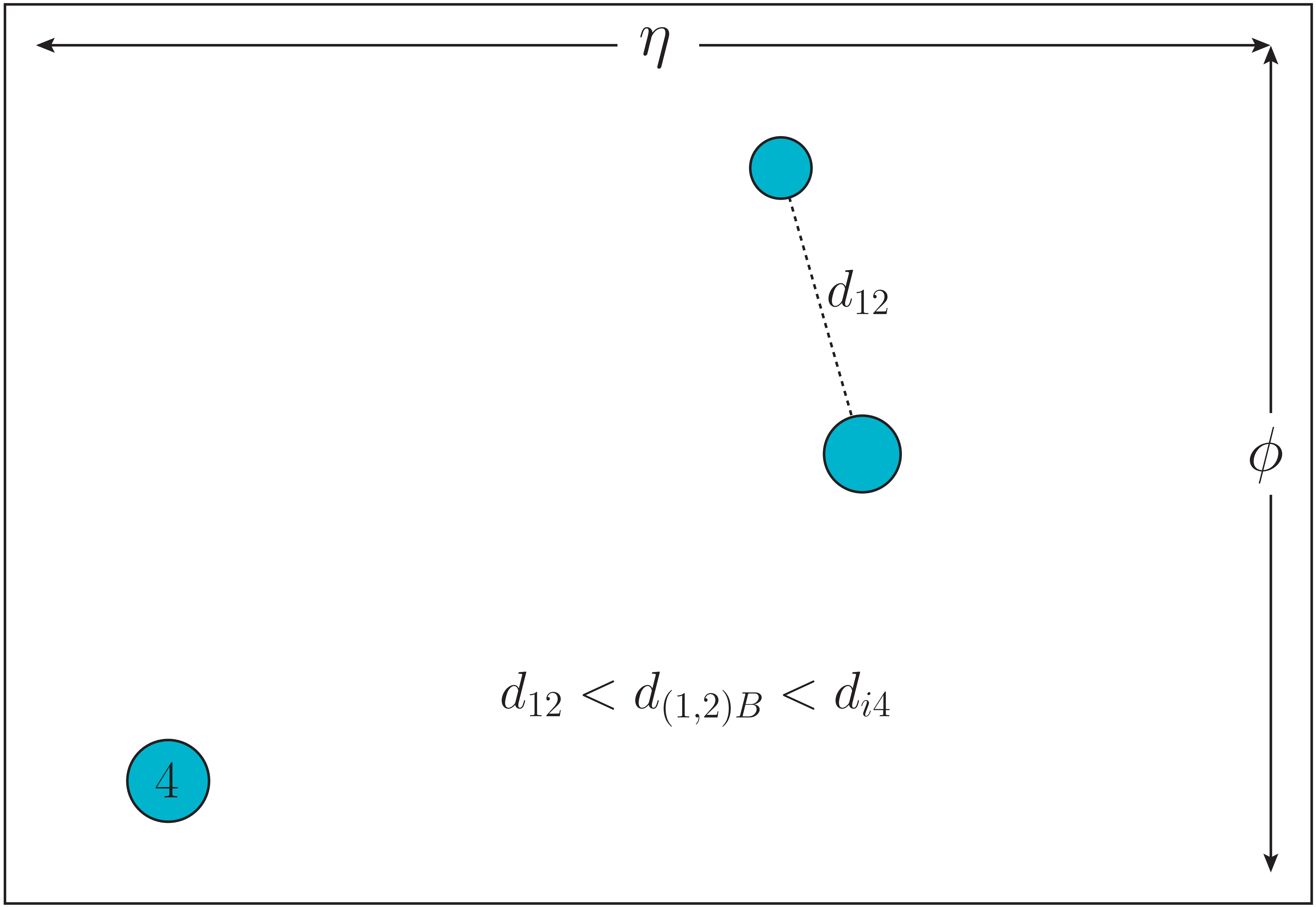

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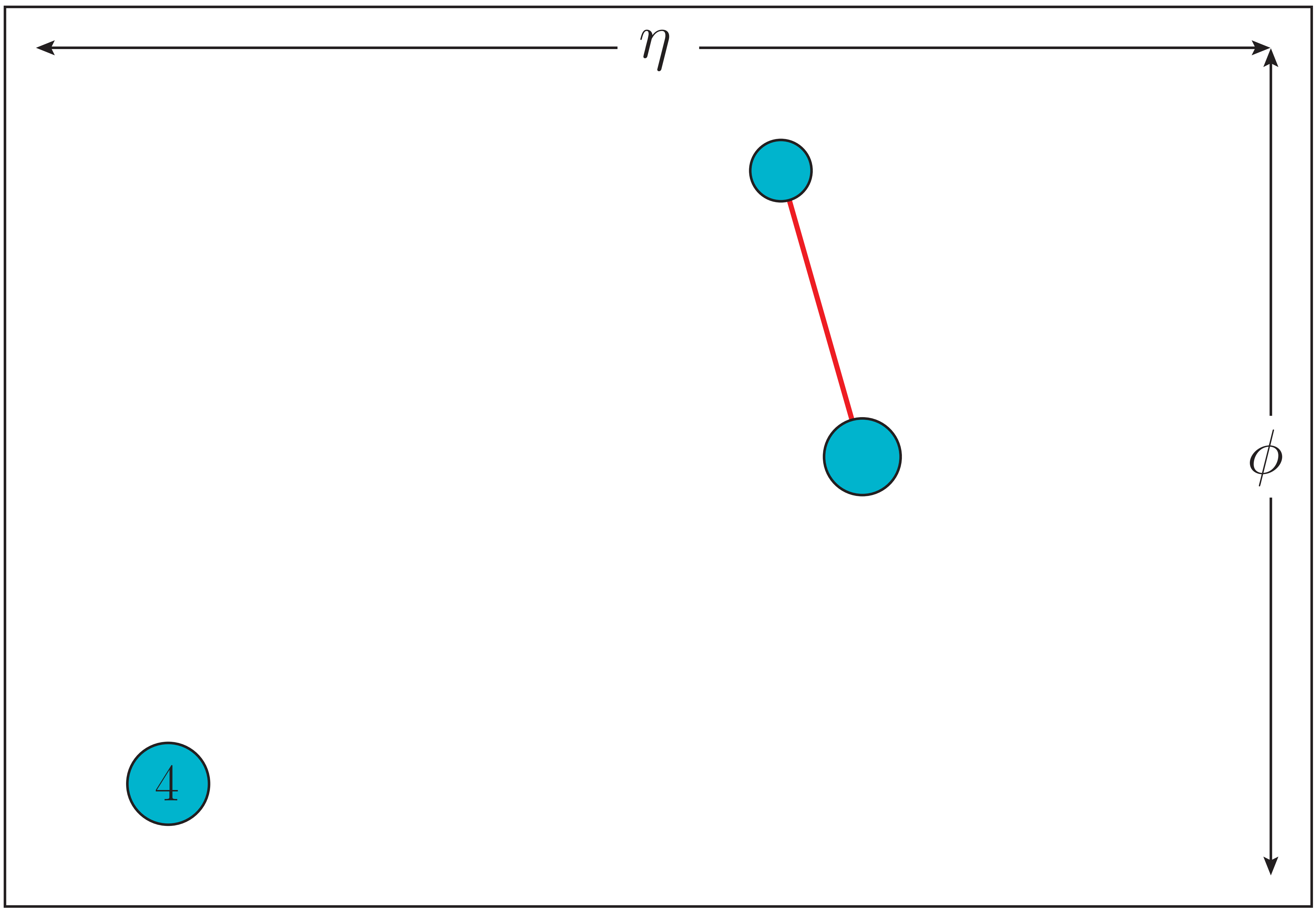
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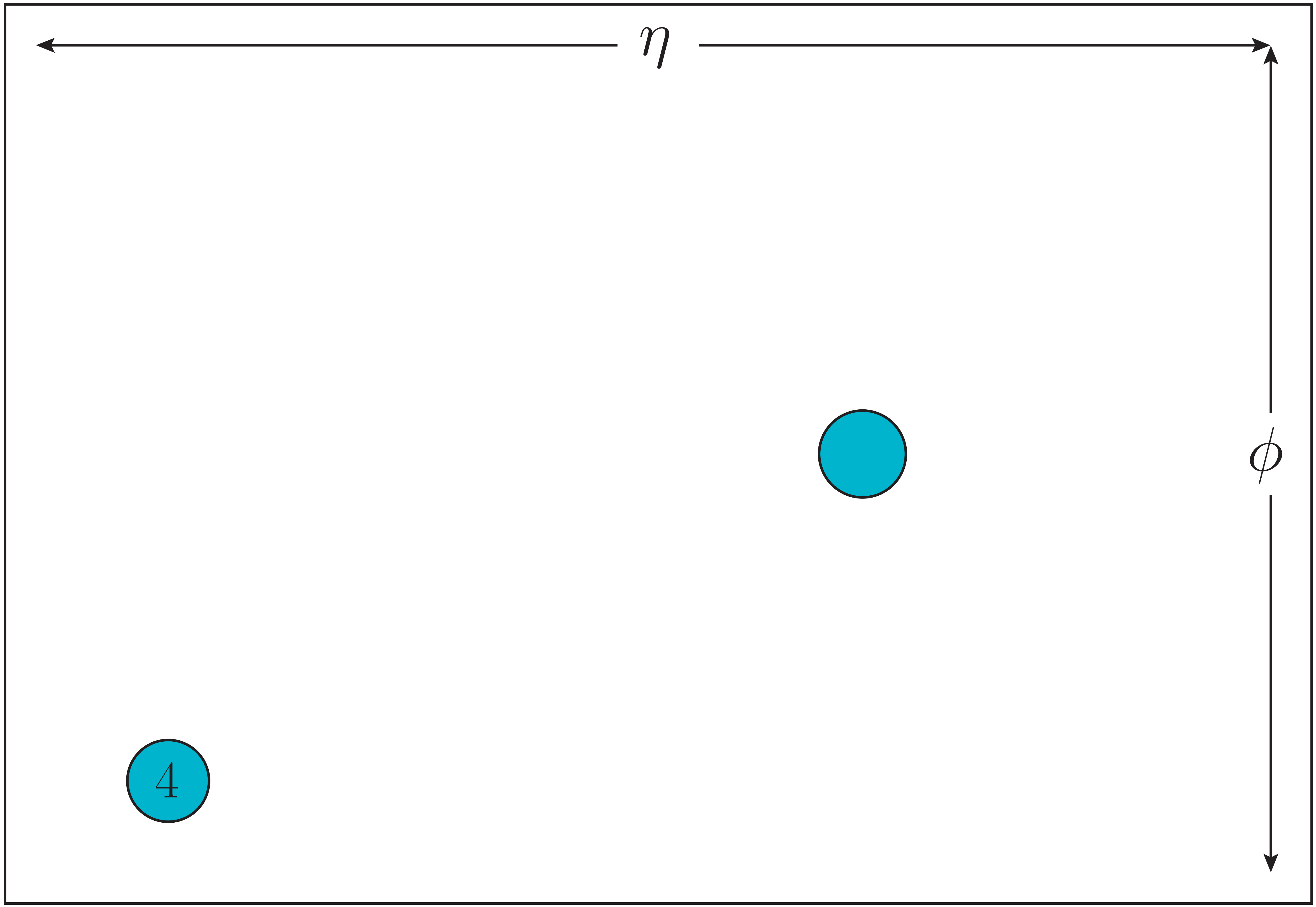

Done!

Standard Recombination Algorithms

- k_T algorithm

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

- C/A algorithm

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

- anti-k_T algorithm

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

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

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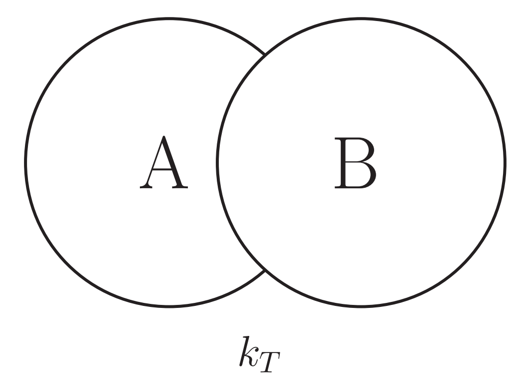

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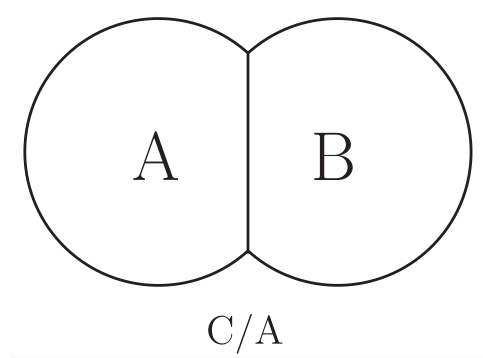

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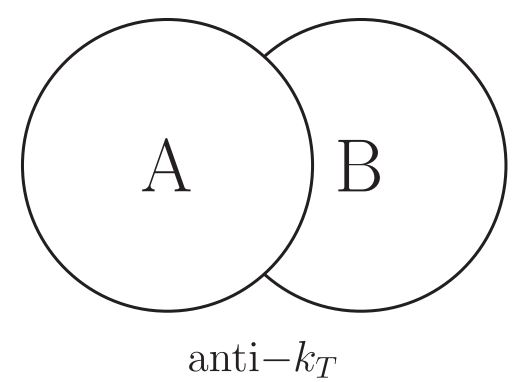
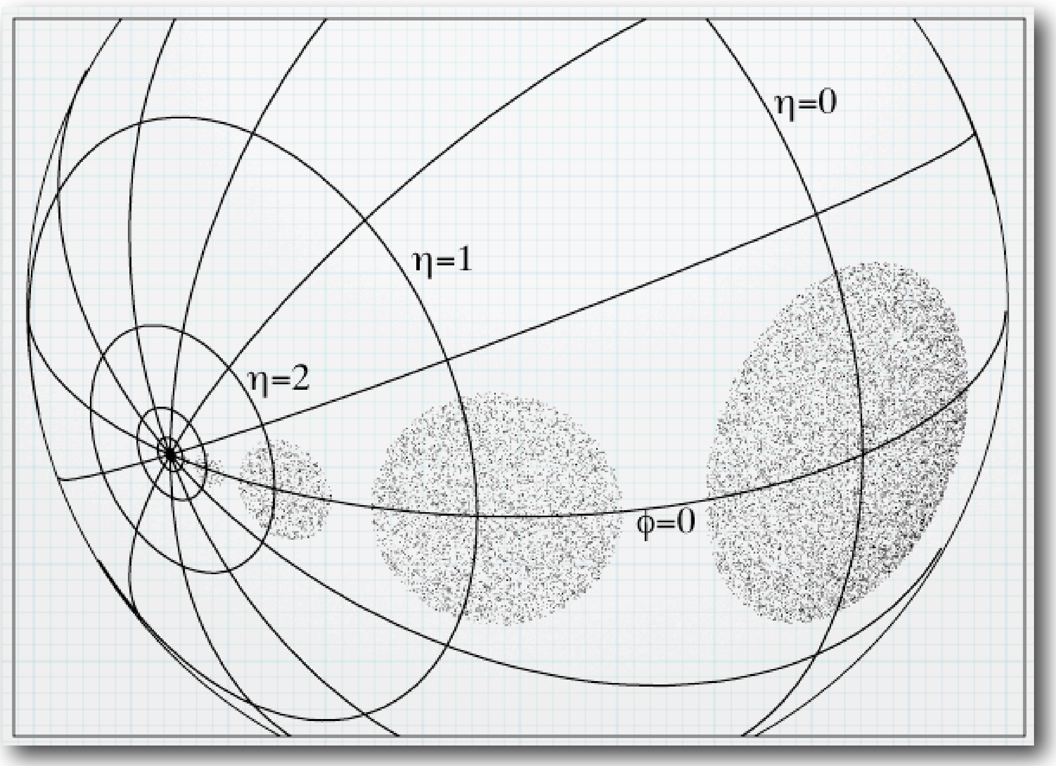


$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

$$p_T^A > p_T^B$$

Boost invariant dynamical jet shapes.

- Jets with fixed "cone" size in ΔR



$$(\Delta S)^2 \simeq (\Delta\theta)^2 + \sin^2\theta^2(\Delta\phi)^2$$

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

$$\Delta R \simeq \Delta S \cosh\eta$$

- Jets from new physics signal have different shapes (see later).
  - Risking either missing too much in the forward region or taking in too much extra radiation in the center.

$$\text{Outside the cone } \rightarrow \frac{\langle \delta p_{\mathrm{T}}^j \rangle}{p_{\mathrm{T}}^j} = \frac{\alpha_s}{\pi} L \log(\Delta R) + \ldots$$

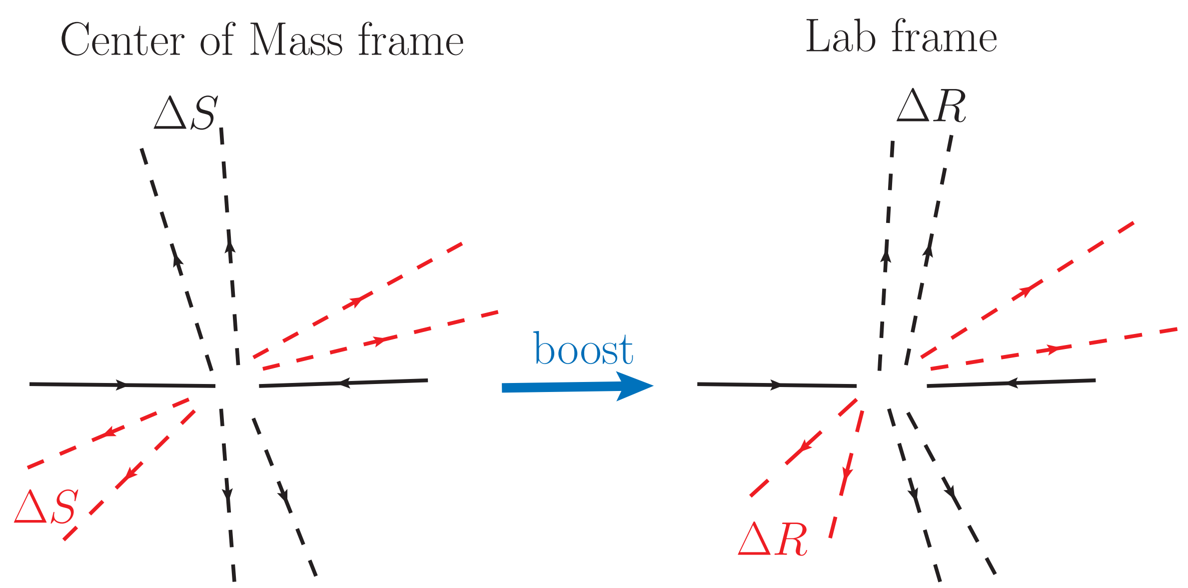
$$\text{Contamination: } \propto (\Delta R)^2$$

Smart jet shapes.

D. Krohn, J. Thaler, LTW, arXiv:0903.0392

- Jets from new physics resonances decay are likely to be isotropical in the resonance center of mass frame.

- Boost isotropical jets to the lab frame:



- For small opening angle: $E\Delta S \simeq p_T \Delta R$

- Therefore, we propose varying the jet size as

$$\Delta R \propto \frac{R_0}{p_T}$$

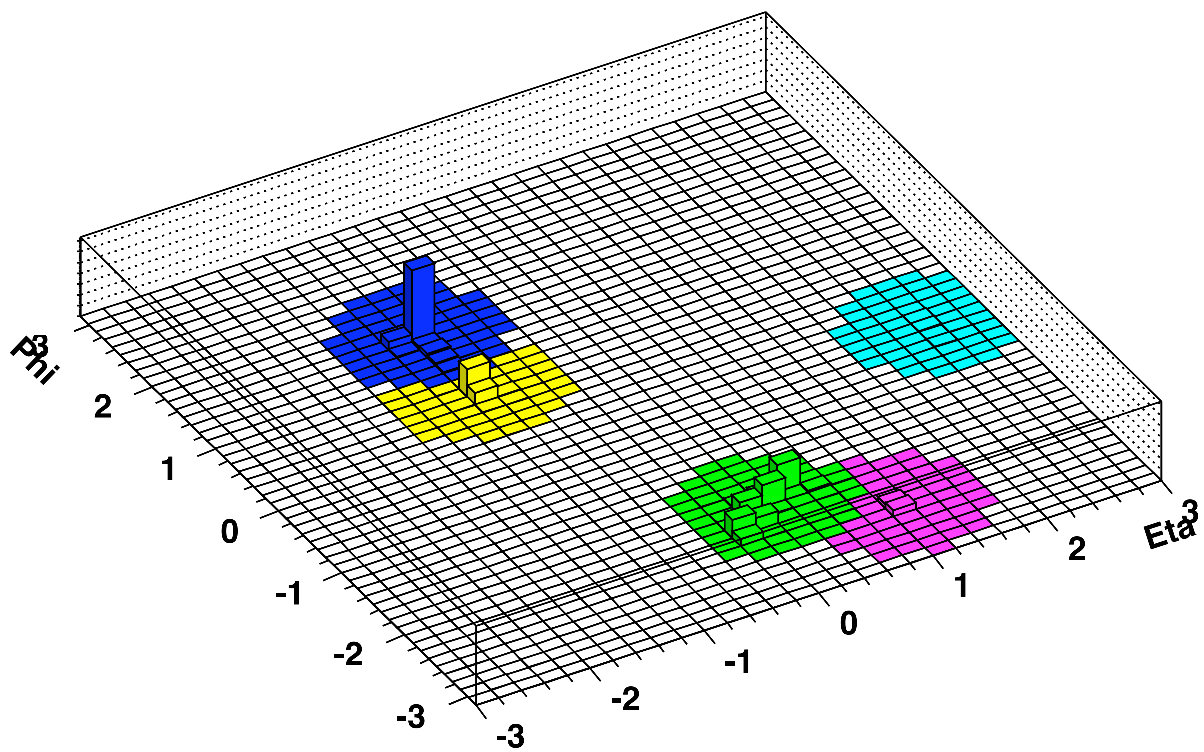
VR algorithm

Dynamical jet shape, boost invariant, infrared and collinear safe.

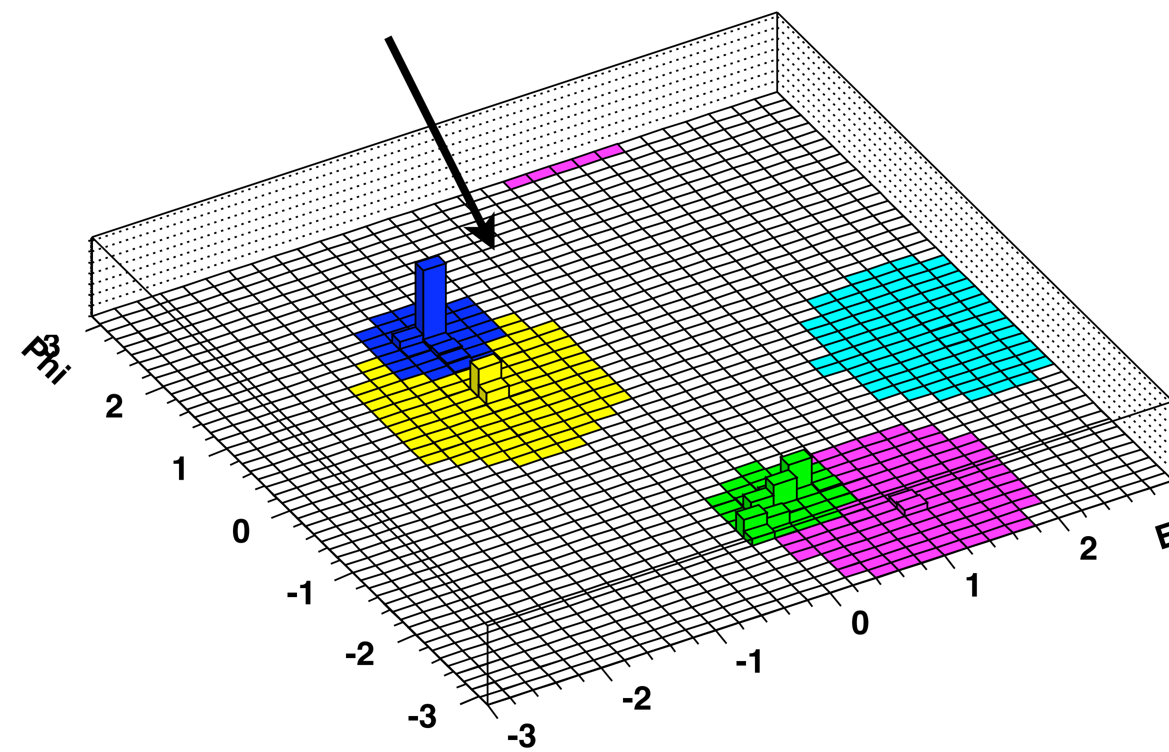
Effect of VR jets

$$gg \to \phi \to gg$$

$$\text{size} \propto \frac{1}{p_{\mathrm{T}}}$$



Fixed size



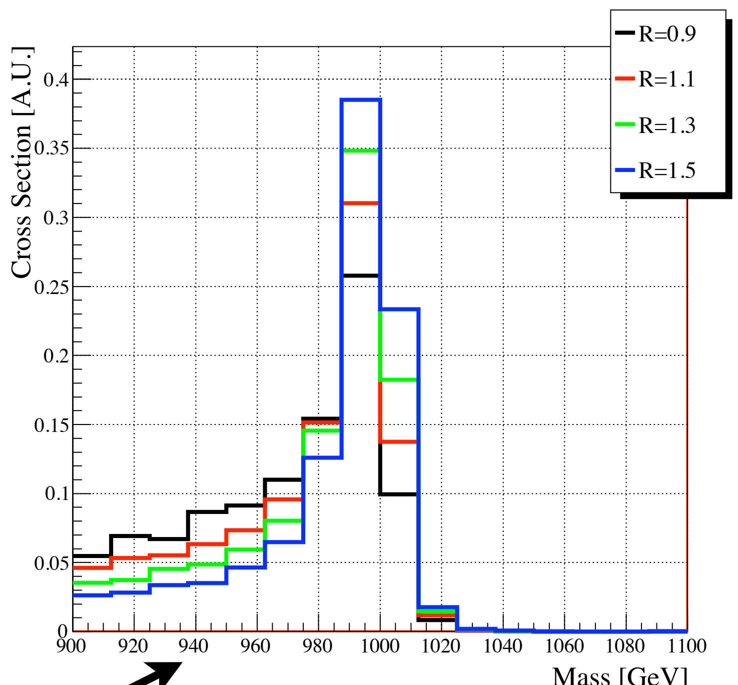
VR

- In VR algorithm, jet size is properly scaled, and appropriate for the underlying process.

Jet "trimming"

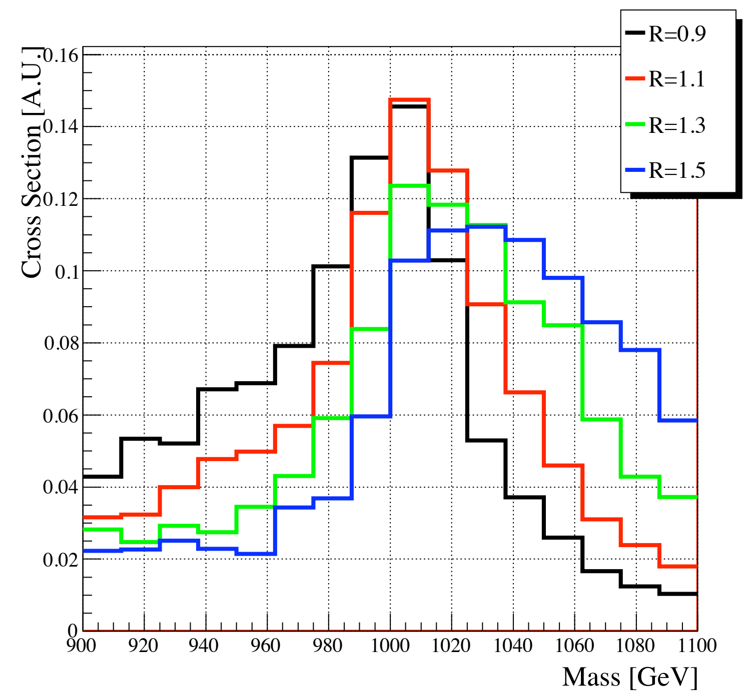
- Effect of the "contamination".
  - Initial state radiation (ISR), multiple interaction (MI), underlying events (UE), pile-up (PU).

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



$m^2 = (p_j^1 + p_j^2)^2 \simeq m_\phi^2$

FSR only
No contamination

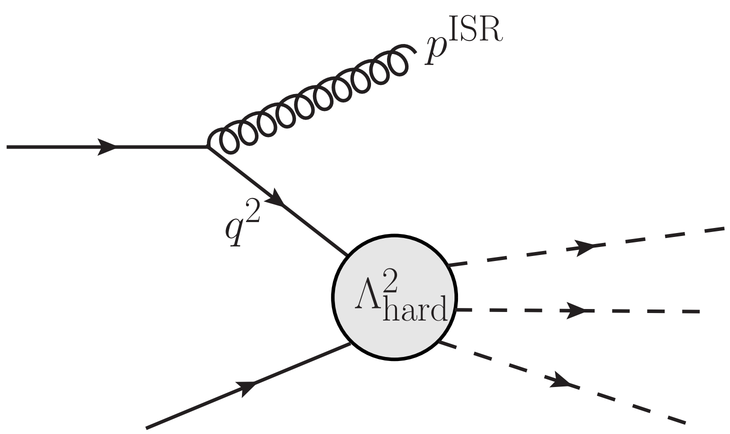


Including ISR, MI, UE, pile-up

Room for improvement!

A closer look at the soft radiations

- ISR scale with the hard collision



$$(p_T^{\rm ISR})^2_{\rm max} \simeq |q|^2 \leq \Lambda^2_{\rm hard}$$

$$\Lambda_{\rm hard}: \quad \text{hard interaction scale}$$

$$\frac{d\sigma}{d(p_{\rm T}^{\rm ISR})^2} \simeq \frac{1}{(p_{\rm T}^{\rm ISR})^2}\left(\alpha_s \log\left(\frac{\Lambda^2_{\rm hard}}{(p_{\rm T}^{\rm ISR})^2}\right) + O(\alpha_s^2)\right)$$

$$\langle p_{\rm T}^{\rm ISR}\rangle \propto (p_T^{\rm ISR})_{\rm max}$$

- MI, UE, and pileup “incoherent”, independent of the hard collision scale.
  - A “universal” soft background. $\delta(p_{\rm T}^j) \simeq \Lambda_{\rm soft}\left(\frac{\Delta R^2}{2} + ...\right)$

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.

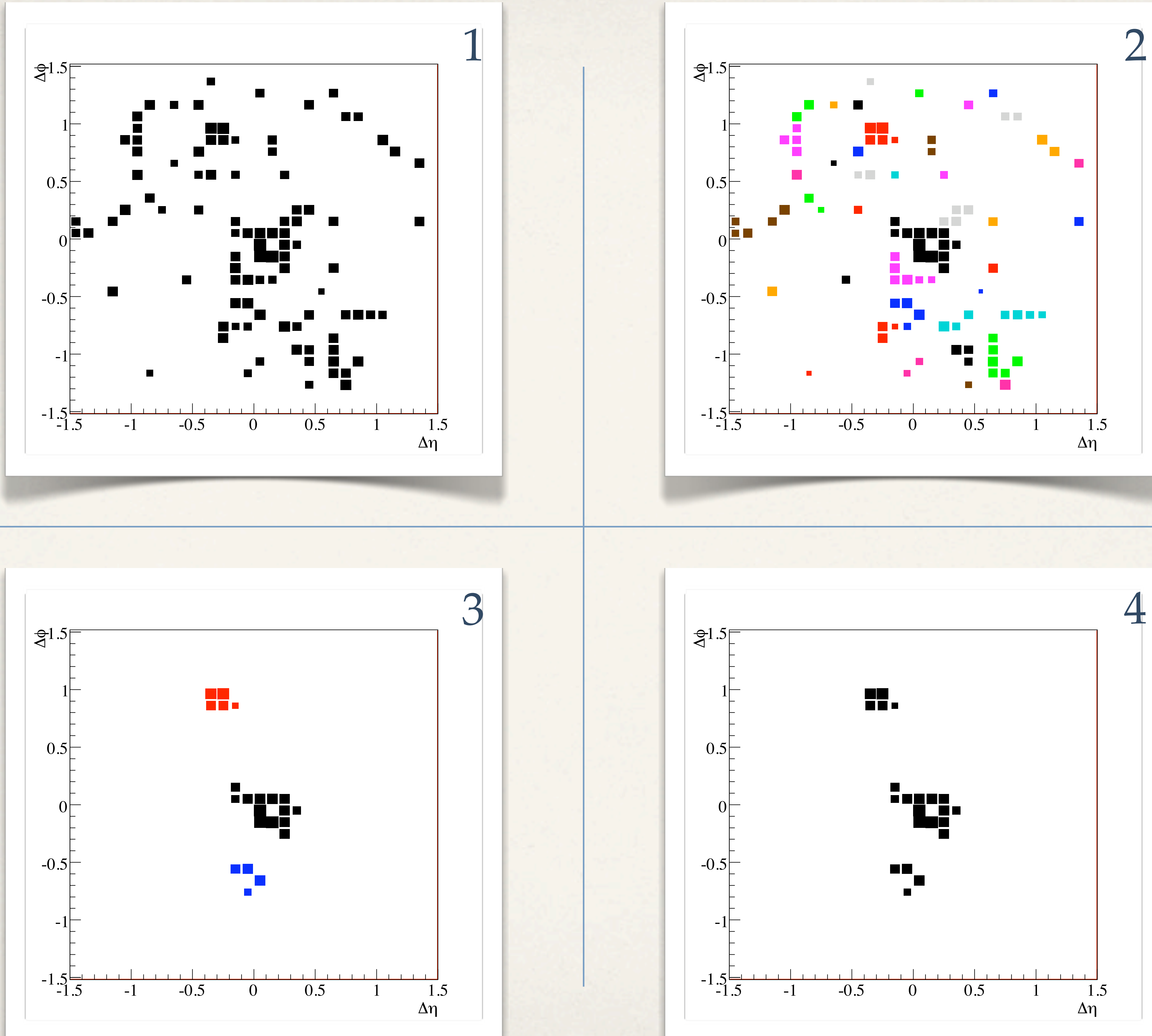
Related but different approaches:
Filtering: J. Butterworth, A. Davison, M. Rubin, G. Salam, arXiv:0802.2470
Pruning: S. Ellis, C. Vermilion, J. Walsh, arXiv:0903.5081

Start

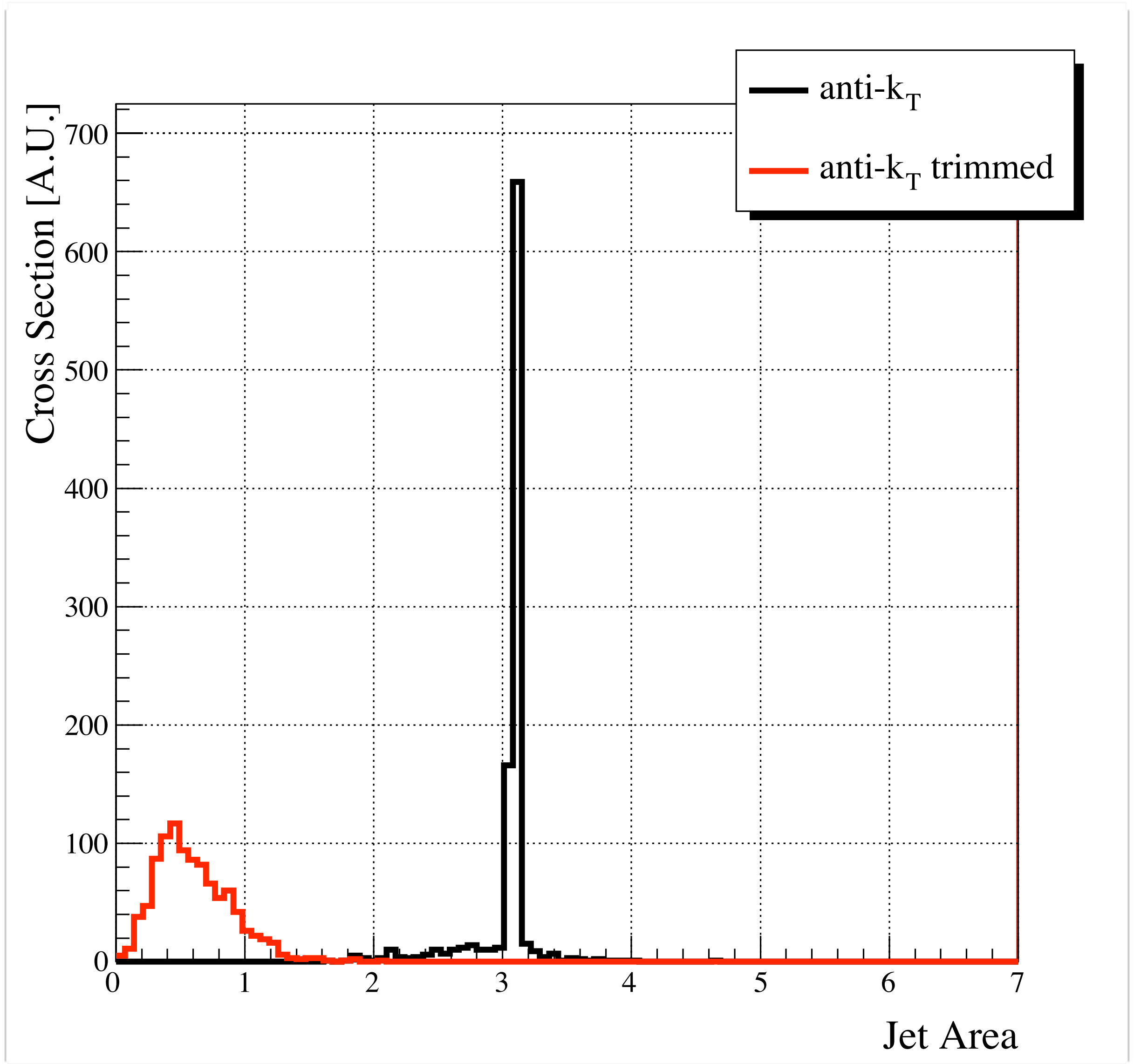
Cluster into subjets

Discard soft subjets

Reassemble

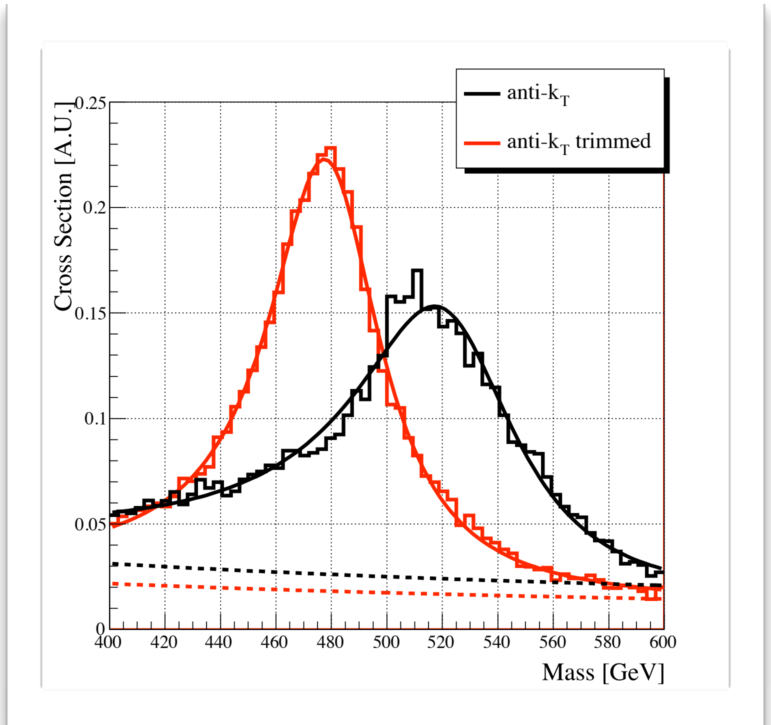


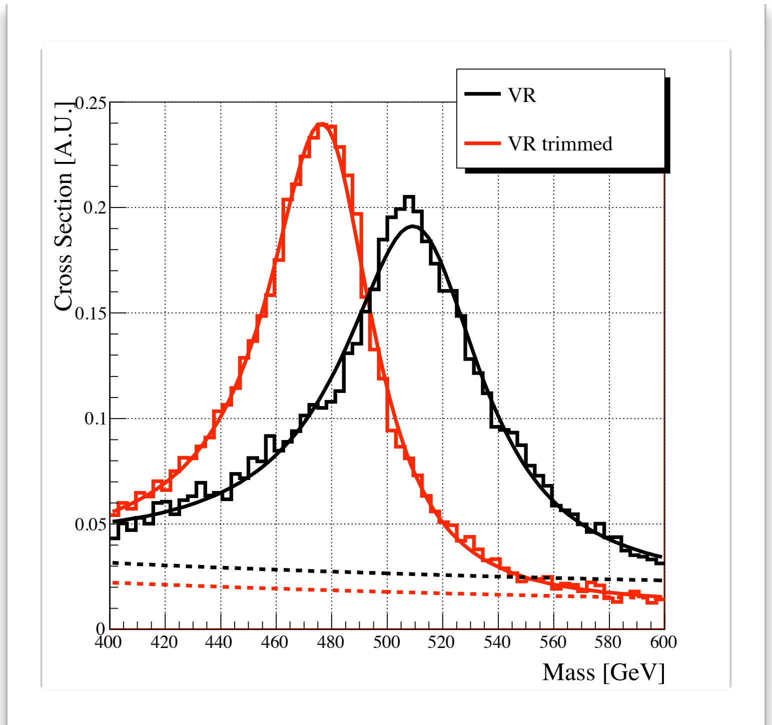
Reduced jet area



Simple test case: di-jet resonance

$$gg \to \phi \to gg$$





	Improvement	$f_{\rm cut}$, $N_{\rm cut}$	$R_{\rm sub}$	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 substructure, and applications in new physics searches.

Boosted tops.

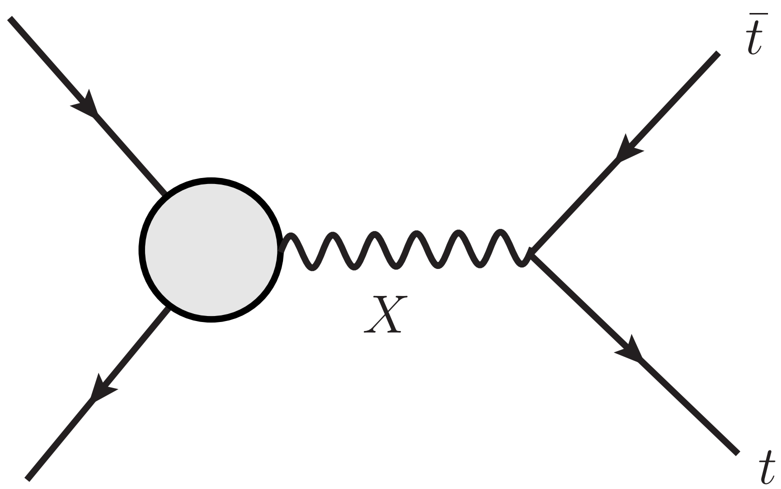
- Tops are interesting!
  - Top plays an important role in electroweak symmetry breaking.
  - Top generically couples to heavy new resonances which is an important part of TeV new physics.
  - Examples.
    - Composite top couples strongly to other composite resonances.

      Many examples.
      K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036
      M. Carena, B. Panes, A. Medina, N. Shah, C. Wagner, arXiv:0706.1281, 0712.0095
    - New heavy scalars couple like Higgs.

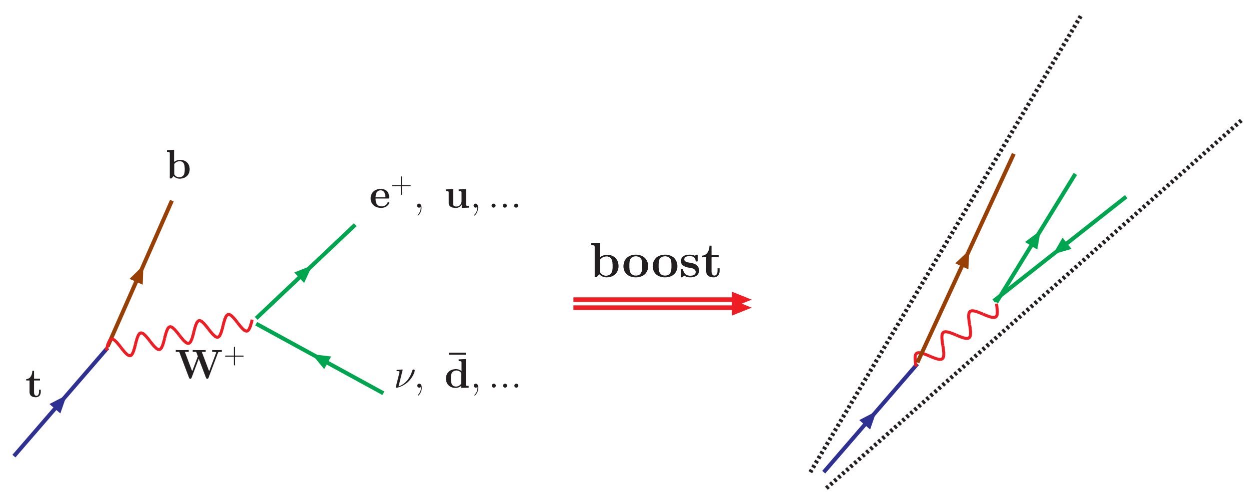
      For example: A. Manohar and M. Wise, hep-ph/0606172
  - A good example of subjet techniques.

Boosted top is also hard to identify.

- Heavy resonance decay.



$$E_{\rm top} \simeq \frac{M_X}{2}$$



No isolated objects

- 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

B. Lillie, L. Randall, and LTW, hep-ph/0701166

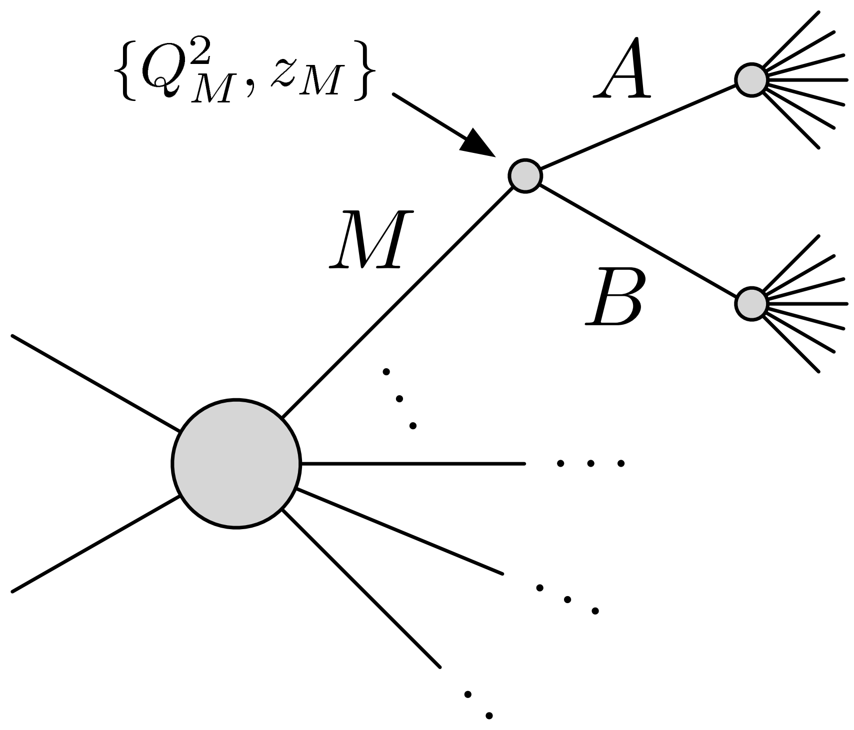
L. Almeida, S. Lee, G. Perez, I. Sung, J. Virzi, arXiv:0810.0934

(hadronic) Top tagging at the LHC

- Fully collimated tops look like QCD jets.
- Basic intuition
  - Top decay. $t \to bW(\to qq')$ 3 hard objects.
  - QCD: radiation.
- Energetic tops should lead to massive jets with some substructures.
- How well can this be distinguished from (massive) QCD jets?

QCD jets: parton shower

- A QCD jet is "built up" by many radiations (branching). A process is approximated by parton shower.



Branching $M \to A + B$ controlled by

Evolution variable: virtuality ("mass") Q_M, or , p_T

Energy fraction: $z = \min(E_A, E_B)/E_M$

QCD vs top jets:

- QCD jet:

No obvious feature in jet mass

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

evolution variable: $\mu^2 = Q_M^2 f(z)$

$$\Delta(\mu_{\rm start},\mu) = \exp\left[-\int_{\mu_{\rm start}}^{\mu} d\log\mu' \int \frac{d\phi}{2\pi}\int dz \frac{\alpha(\mu')}{2\pi} P_{M\to AB(z)}\right]$$

Sudakov factor: Radiate more.

$P_{M\to AB}(z)$: Altarelli-Parisi splitting function.

for $q \to qg,\; g \to gg, P(z) \propto 1/z$ IR singularity

- Top jet, first branching (decay):

$$d\sigma^{\rm decay}_{M\to A+B} = \frac{dQ_M^2}{2\pi}\frac{1}{Q_M^2}\; dz \frac{d\cos\theta}{dz}\delta(Q_M^2 - m_M^2)$$

$Q_M = m_{\rm top\ jet} \simeq m_{\rm top}$

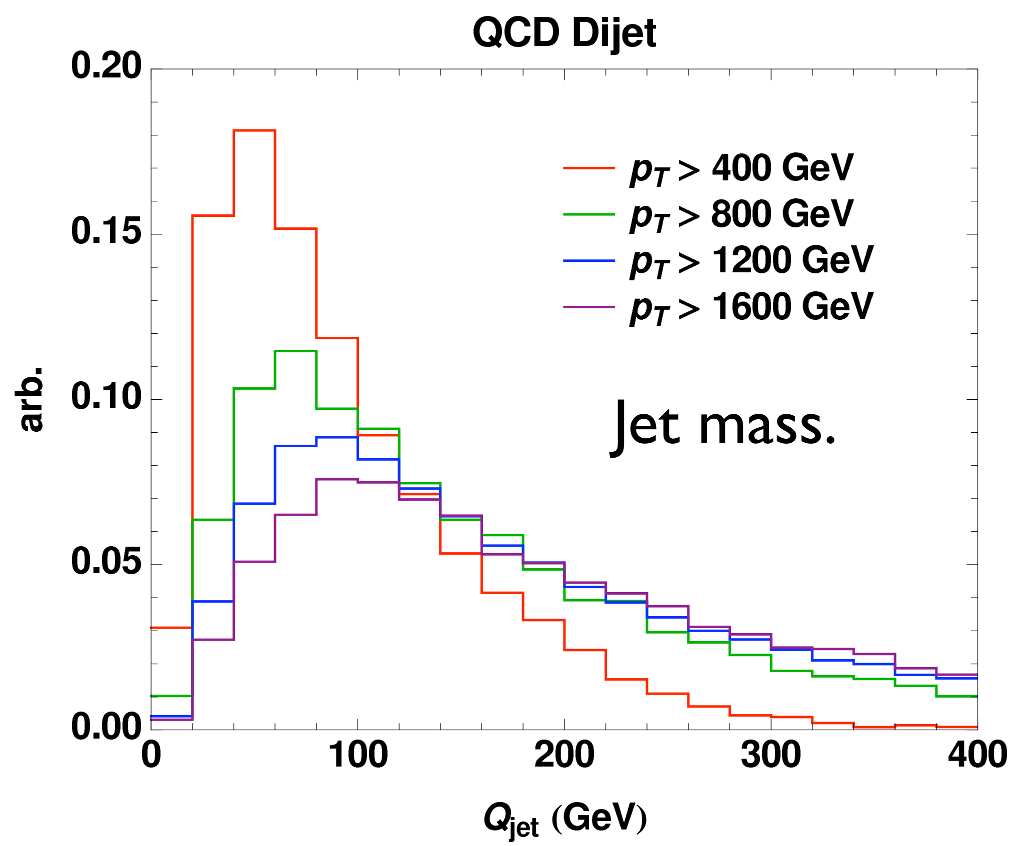
top decay: $t \to b + W,\; m_M = m_t,$

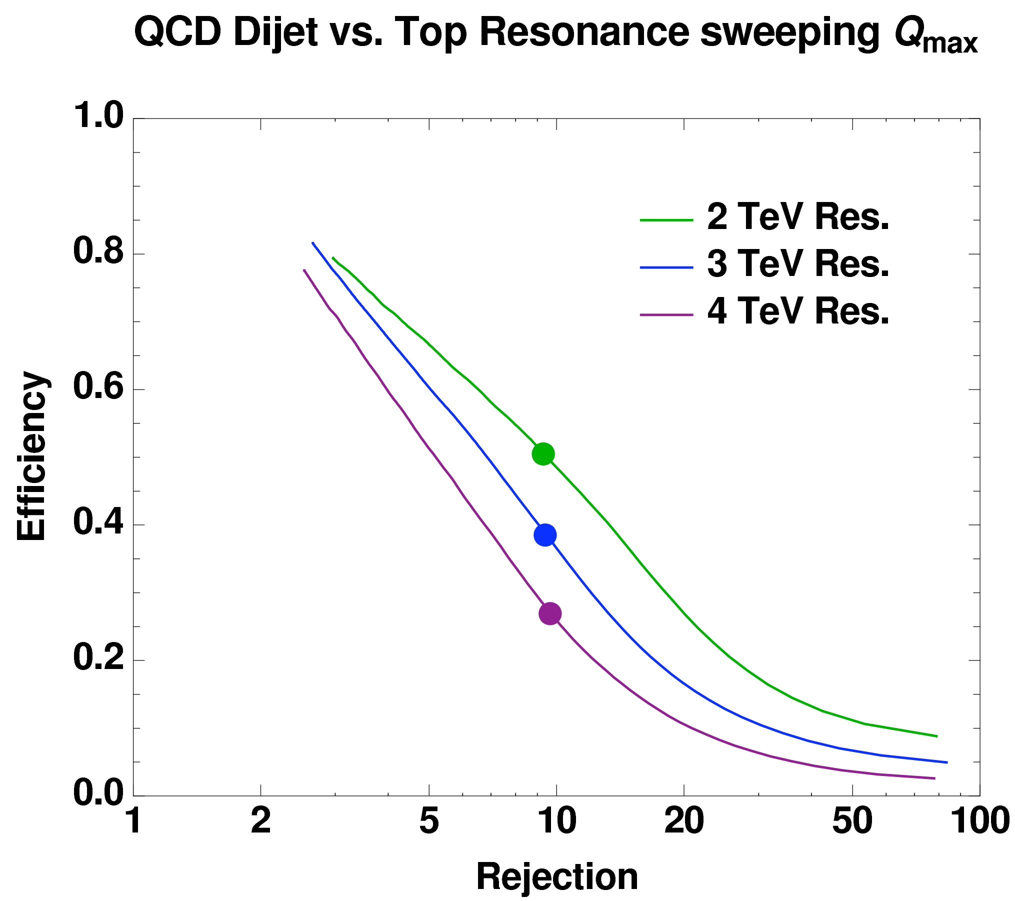
or, $W \to \bar{q}q',\; m_M = m_W$

Top tagging: jet mass

- QCD jets also have mass.

$$\langle M^2 \rangle \simeq \int \frac{d\theta^2}{\theta^2} \int dz\ p_{\mathrm{T}}^2 z(1-z)\theta^2\ \frac{\alpha_s(p_{\mathrm{T}})}{2\pi} P(z)\Theta(\Delta R - \theta)$$
$$\simeq C\frac{\alpha_s}{\pi} p_{\mathrm{T}}^2 (\Delta R)^2$$

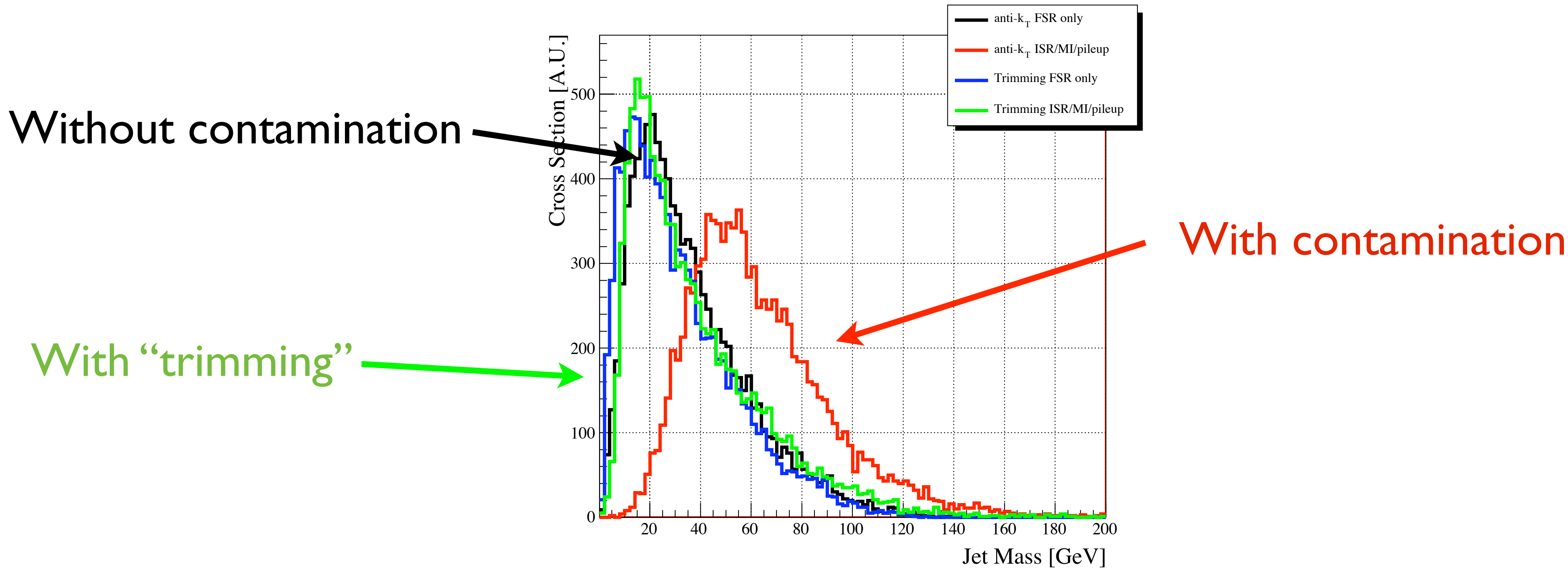




Using jet mass only.

Useful. Additional variable?

Additional help from new jet algorithm



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.

QCD vs top jets:

- QCD jet:

Prefers soft radiation ↙ $z \to 0$

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

evolution variable: $\mu^2 = Q^2_M f(z)$

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Sudakov factor:
Radiate more.

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- Top jet, first branching (decay):

$$d\sigma^{\text{decay}}_{M\to A+B} = \frac{dQ^2_M}{2\pi}\frac{1}{Q^2_M}\; dz\frac{d\cos\theta}{dz}\delta(Q^2_M - m^2_M)$$

z finite!

top decay: $t\to b+W,\;\; m_M = m_t,$

or, $W\to\bar{q}q',\;\; m_M = m_W$

z at the first branching can distinguish top from QCD jet.

Other choices of z-variables?

- Many possible choices

1. $z_{\text{cell}} = \frac{\min(E_A, E_B)}{E_A + E_B}$, $\qquad E_X \equiv \sum_{i \in X} E_i$,

2. $z_{\text{cut}} \equiv \frac{d_{\text{cut}}}{d_{\text{cut}} + Q_M^2} \to \frac{\min(E_A, E_B)}{E_A + E_B}$ where

$$d_{\text{cut}} = \min(p_{TA}^2, p_{TB}^2)\Delta R_{AB}^2, \qquad \Delta R_{AB}^2 \equiv (\phi_A - \phi_B)^2 + (\eta_A - \eta_B)^2$$

3. $z_{\text{LI}} = \frac{\min(p_{\text{ref}} \cdot p_A, p_{\text{ref}} \cdot p_B)}{p_{\text{ref}} \cdot (p_A + p_B)}$, with any p_{ref}

- Preserve IR singularity and approximation factorization at leading log as long as

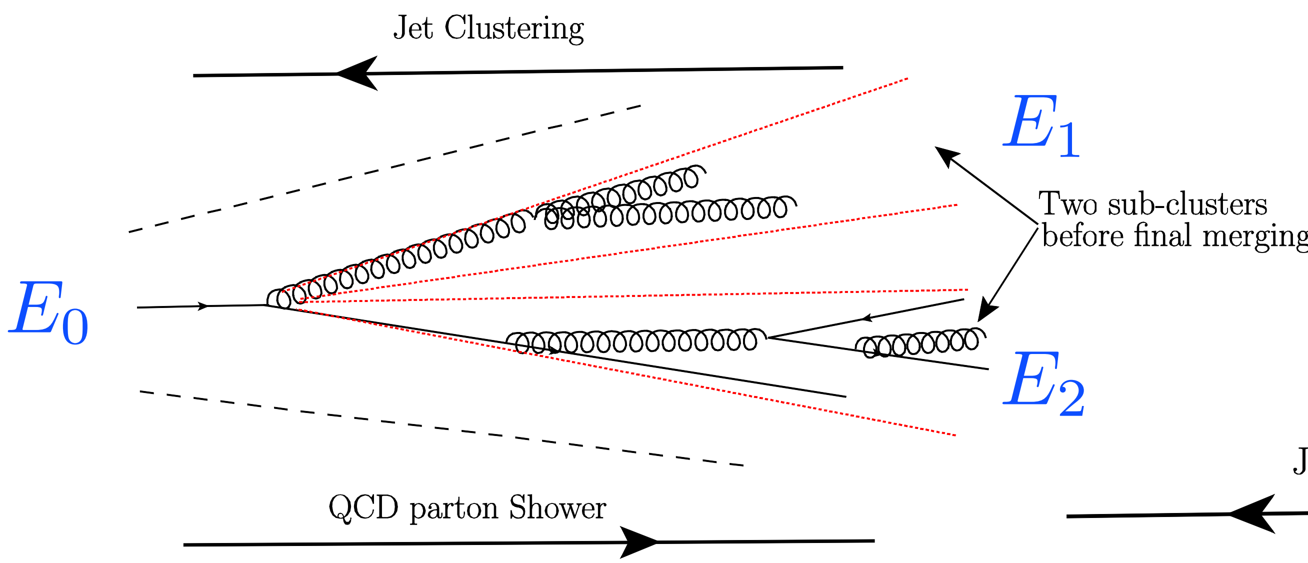
$$z \to \min(\mathrm{E_A}, \mathrm{E_B})/\mathrm{E_M} \text{ in collinear on-shell limit.}$$

Similar performance.

Substructure, z-finding

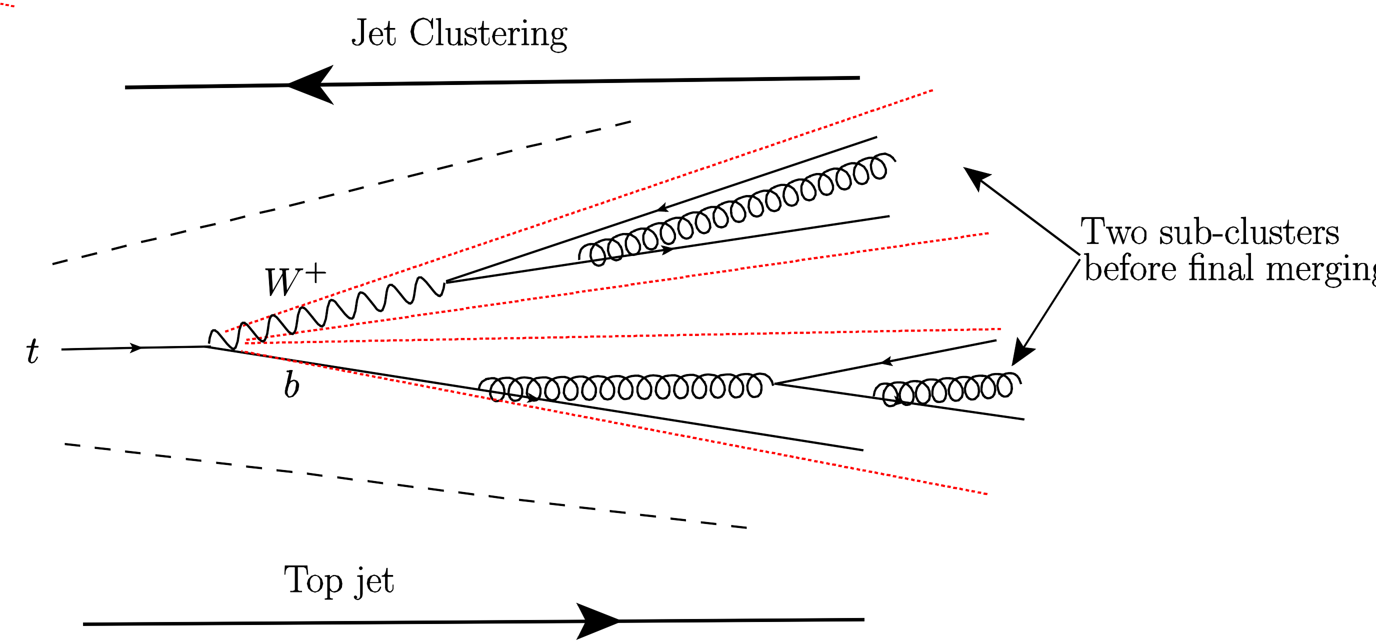
$z \to 0$ for QCD jet,

z finite for top jet.



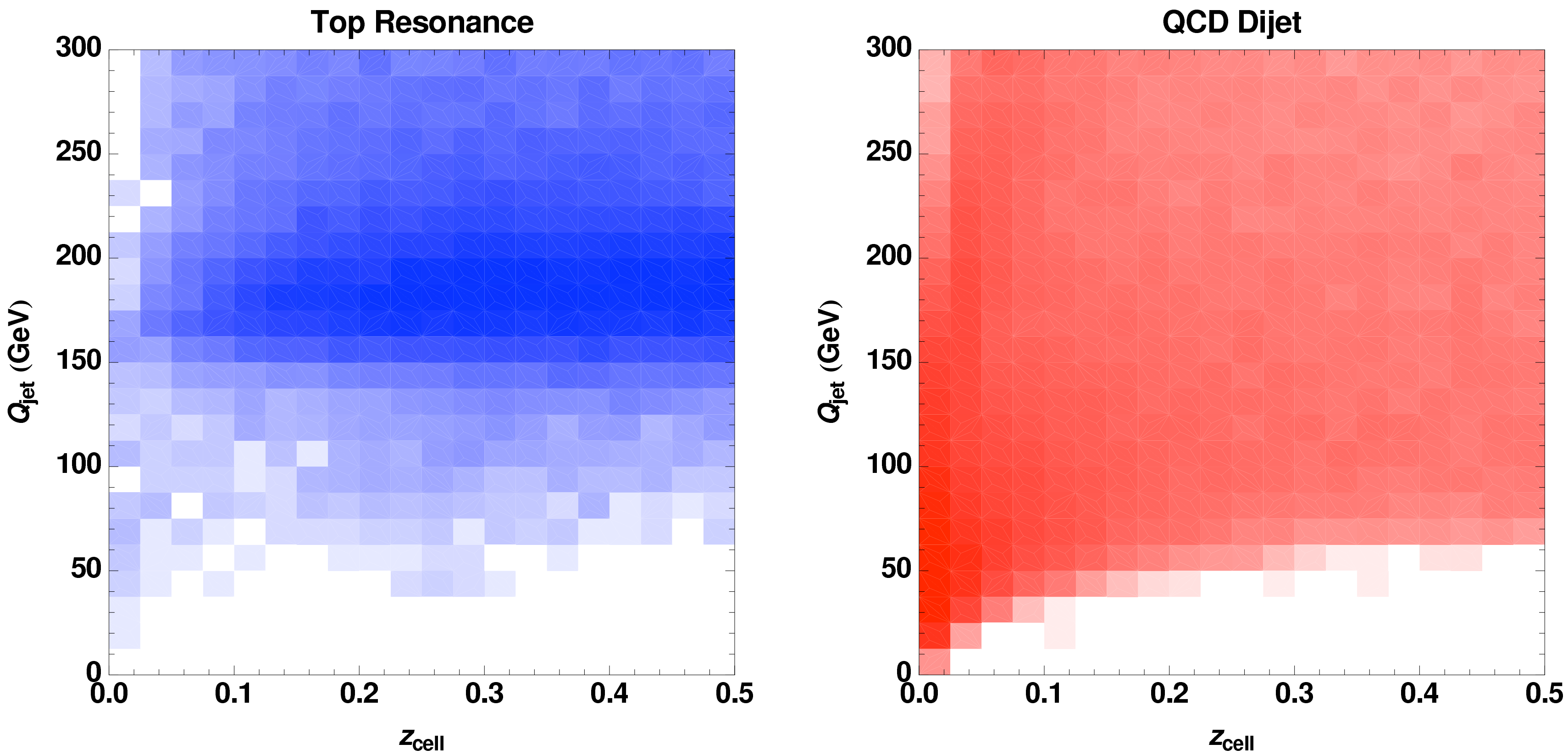
$$z = \frac{\min(E_1, E_2)}{E_0}$$

Q : jet mass

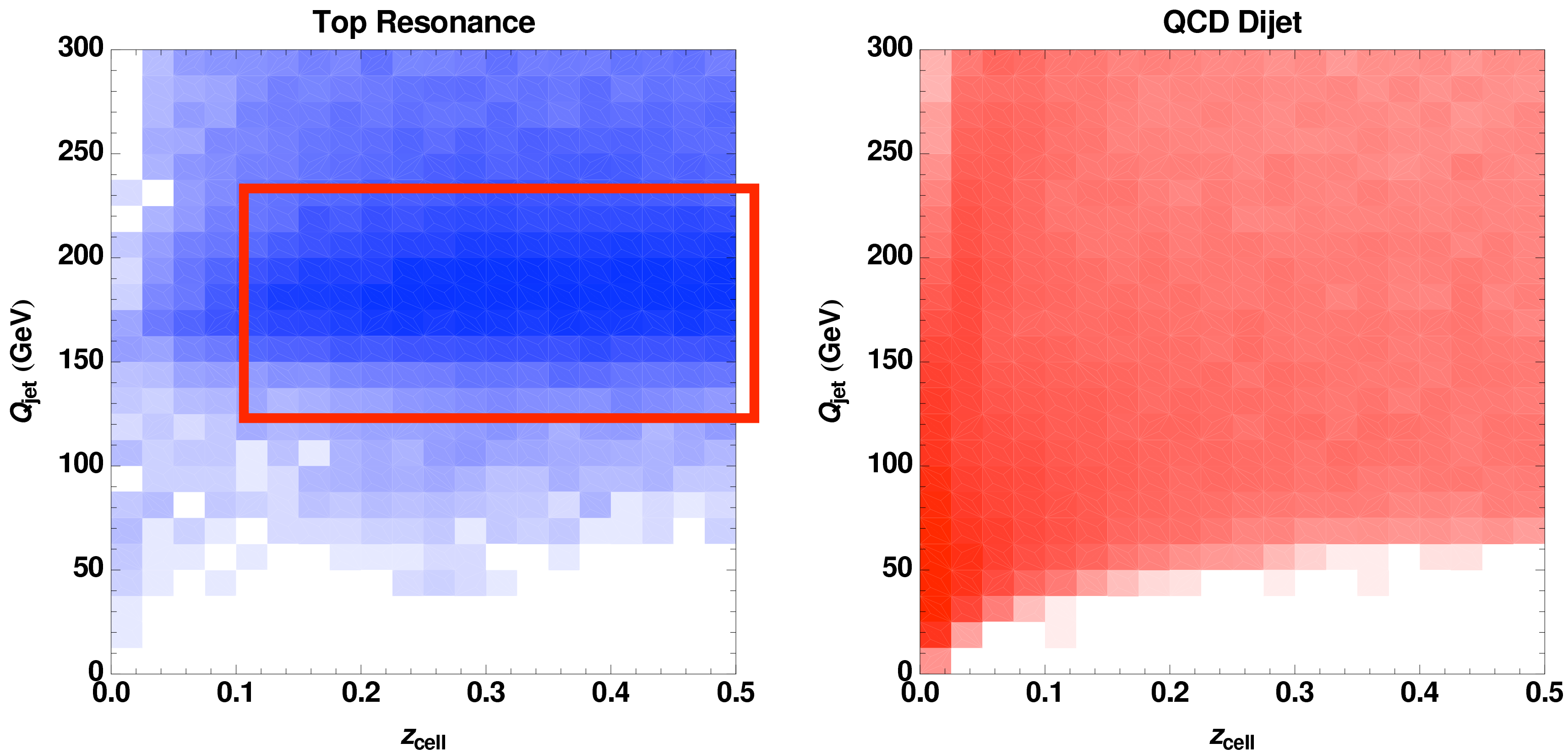


- Jet clustering history is approximately the inverse of parton shower.

Top jets vs QCD jets



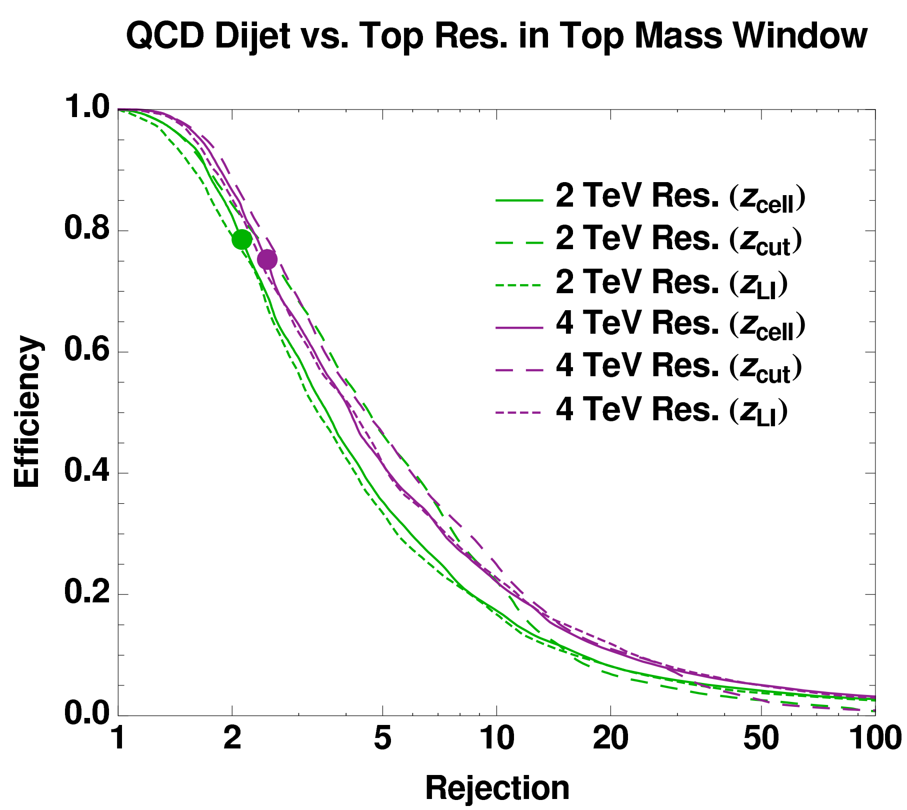
Top jets vs QCD jets



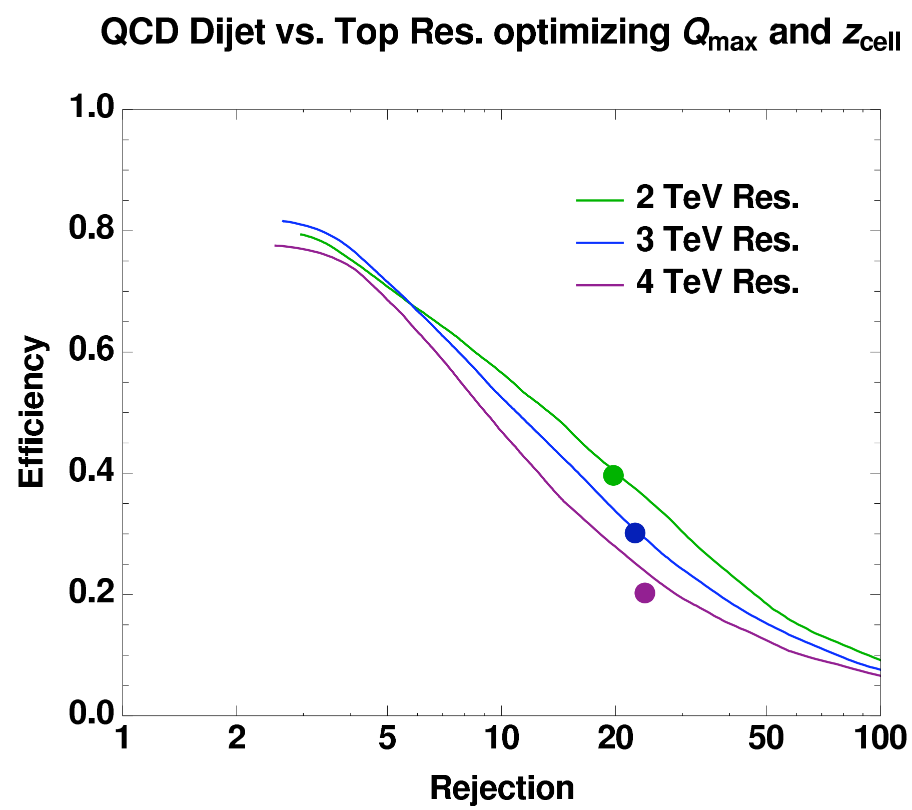
- Combined cuts on jet mass and z can enhance further the signal with respect to the background.

Top tagging efficiency

J. Thaler and LTW, arXiv:0806.0023.



Performance of different z variables.



Combined cuts

- z-variable gives an additional about factor of 2 enhancement in performance.
- Together with jet mass, an enhancement of 100 of S/B is possible.

Related studies:

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

Gustaaf H. Brooijmans, arXiv:0802.3715; CMS, CMS PAS JME-09-001

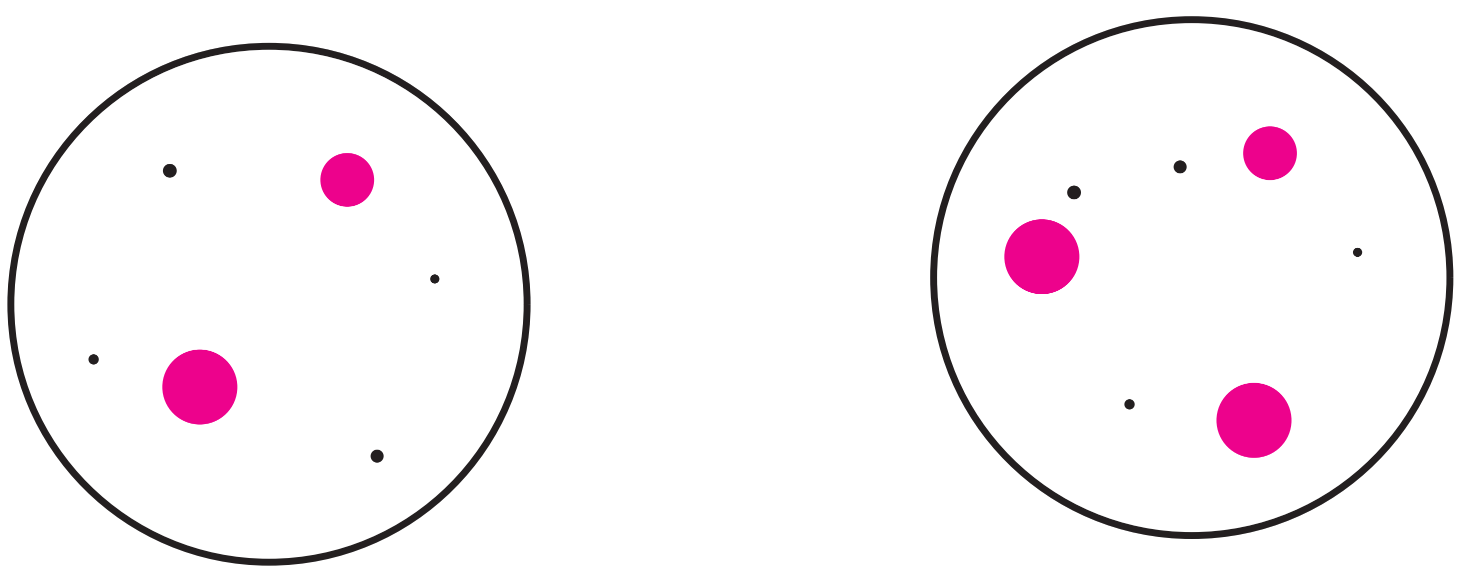
More jet shape variables.

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

$$S^{\perp ij} = \frac{\sum_{\alpha \in \mathrm{jet}} \frac{\vec{p}_\alpha^{\perp i} \vec{p}_\alpha^{\perp j}}{|\vec{p}_\alpha^{\perp}|}}{\sum_{\alpha \in \mathrm{jet}} |\vec{p}_\alpha^{\perp}|}.$$

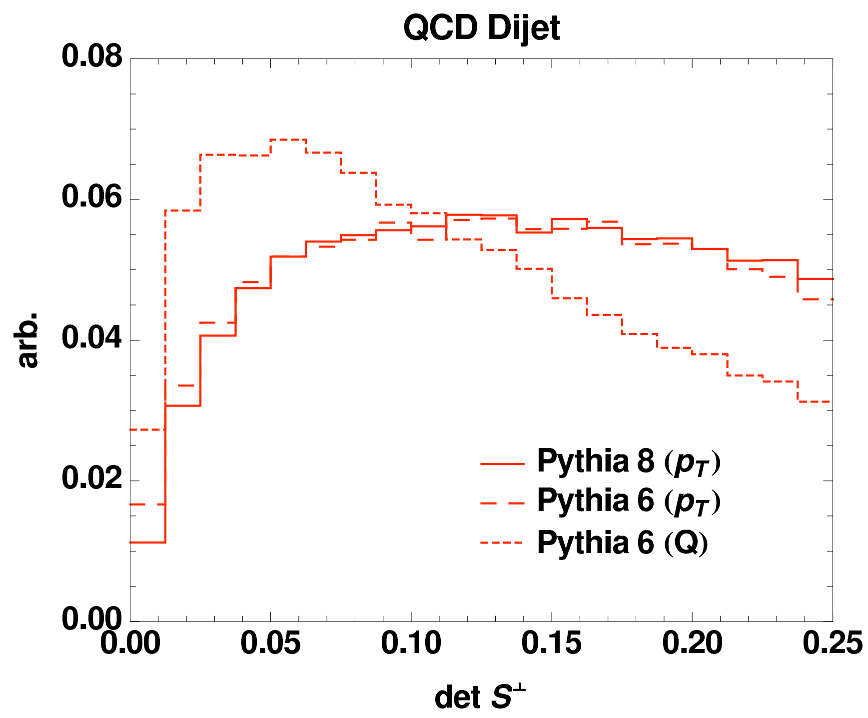
$\vec{p}_\alpha^{\perp i}$: w.r.t. jet axis, $i = 1, 2$

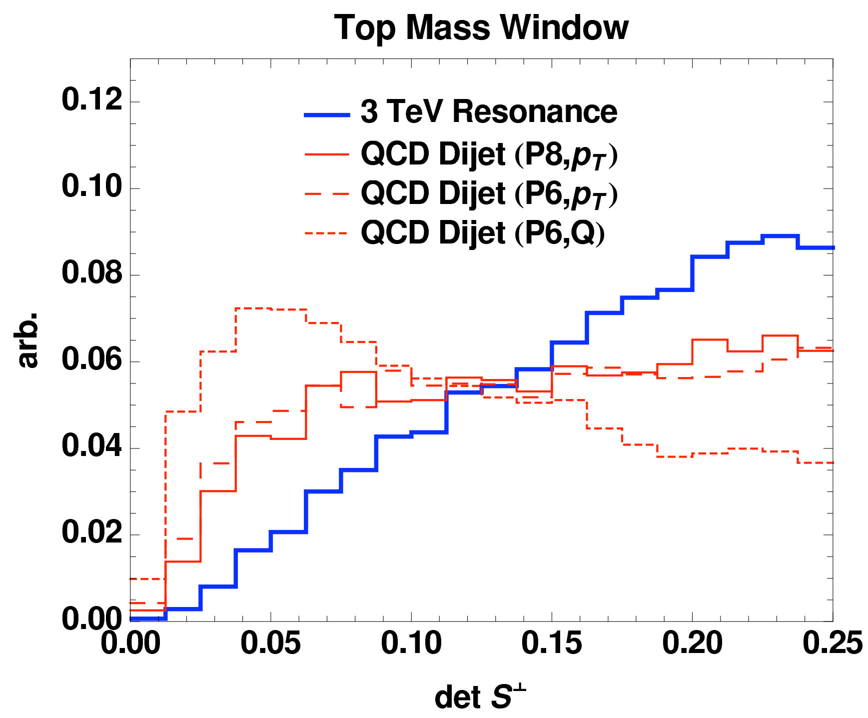
J. Thaler and LTW, arXiv:0806.0023.



$\det S^{\perp} = 0$ $\qquad$ $\det S^{\perp} \neq 0$

Using planar flow to identify top jets.





- $1 \to 3$ is not very well modeled by parton shower.
- Also affected by contamination from underlying events.

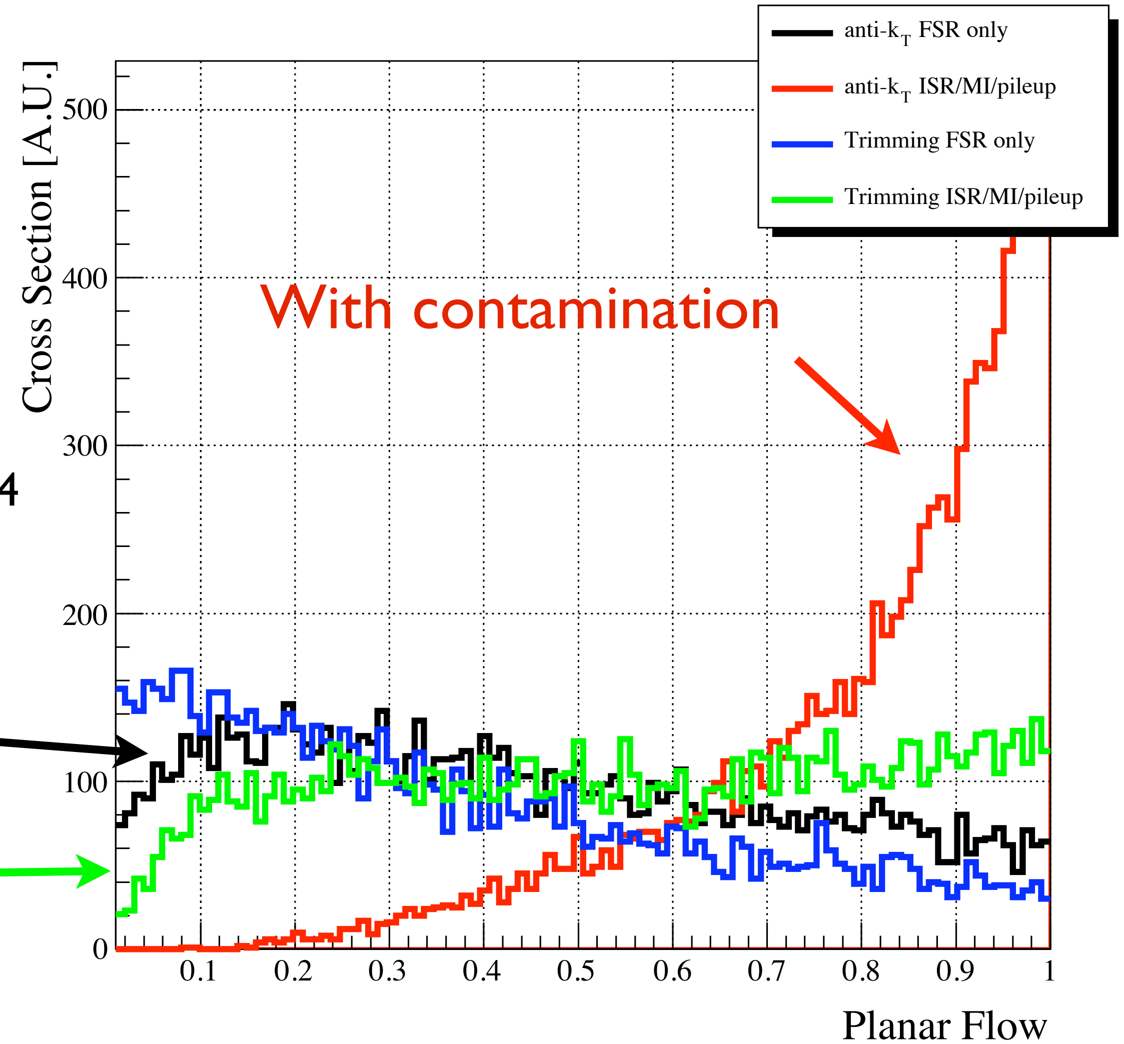
Better reconstruction of the jet shape

Planar flow

Defined in
L. Almeida, S. Lee, G. Perez,
G. Sterman, I. Sung, J Virzi, arXiv:0807.0234

With no contamination

With "trimming"



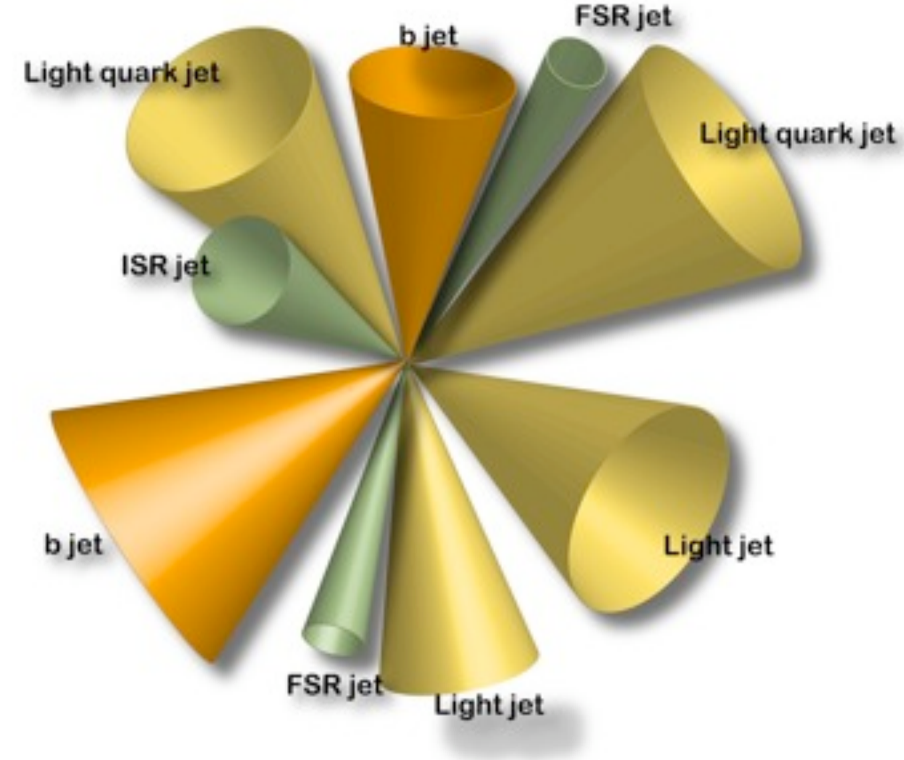
- Can be used to further improve top tagging. An additional factor of several possible.

- Interesting to compare with improved QCD calculation, using modern technologies such as SCET.

“Slow” tops, Standard Model top pair.

- For non-boosted tops, 6 objects in the final state. Very crowed event.

- Fully hadronic, 6+ jets, very hard.



- New VR algorithm can help since it has a dynamically adjustable size.

- We see at least $10\% - 20\%$ improvement.

D. Krohn, C. Popa, and LTW, in progress

Additional applications of top reconstruction in new physics signal.

- Top partner decay. $pp \to T'T' \to t\bar{t} + \not{E}_T$

  P. Meade, M. Reece, hep-ph/0601124
  T. Han, R. Mahbubani, D. Walker, and LTW, arXiv:0803.3820

- Gluino decay. $pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$

  B. Acharya, P. Grajek, G. Kane, E. Kuflik, K. Suruliz, and LTW, arXiv:0901.3367

- We expect new jet algorithms described here to help in both cases.

Hiding Higgs.

- Alternative decay channels can dramatically change Higgs search strategy.

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

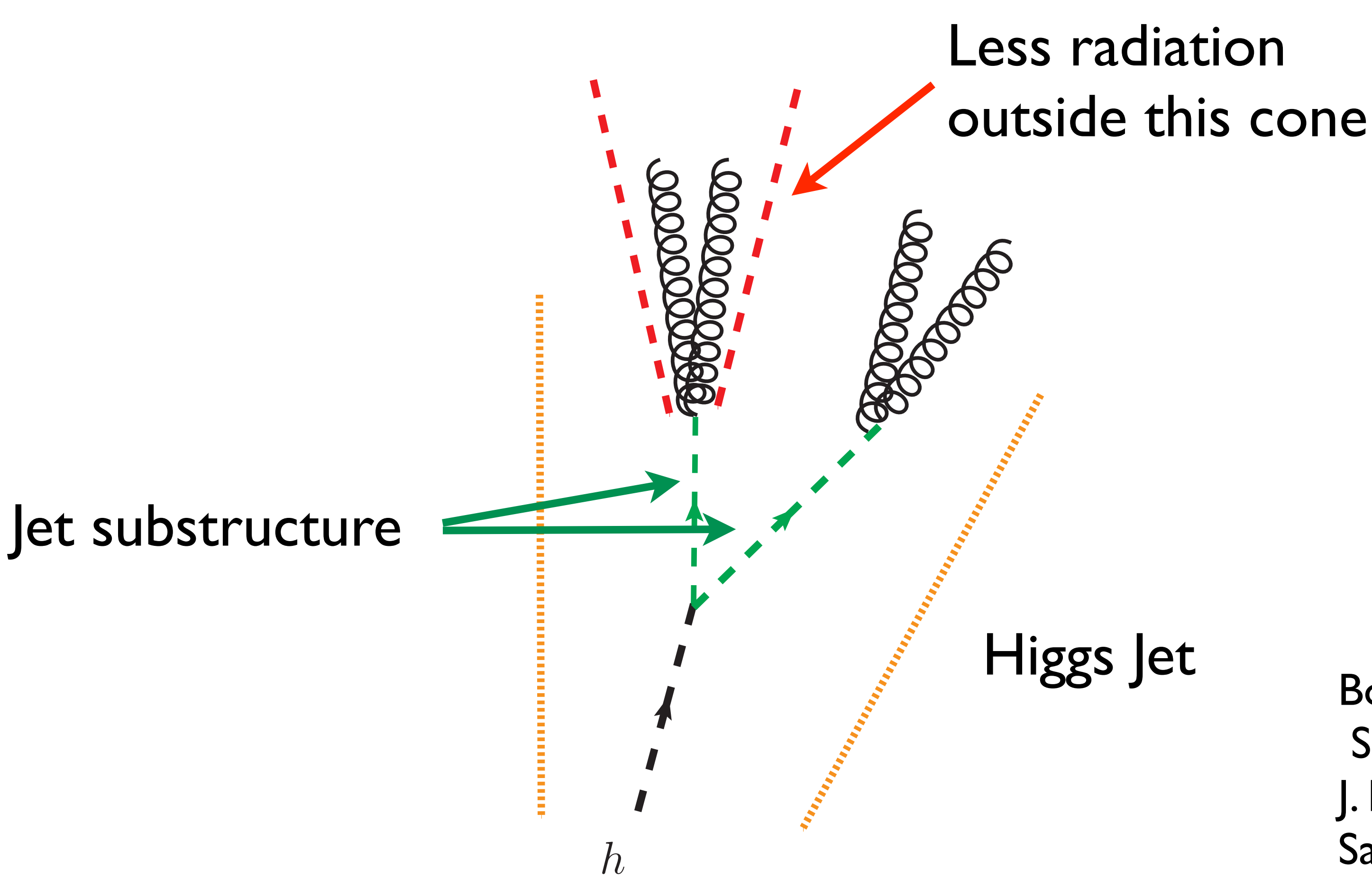
For example:
P. Graham, A. Pierce, J. Wacker, hep-ph/0605162
M. Carena, T. Han, G. Huang, C. Wagner, arXiv:0712.2466

$$h \to aa \to c\bar{c}c\bar{c},\ \ \text{“charmful”?}$$

$$h \to aa \to gggg,\ \ \text{“buried”!}$$

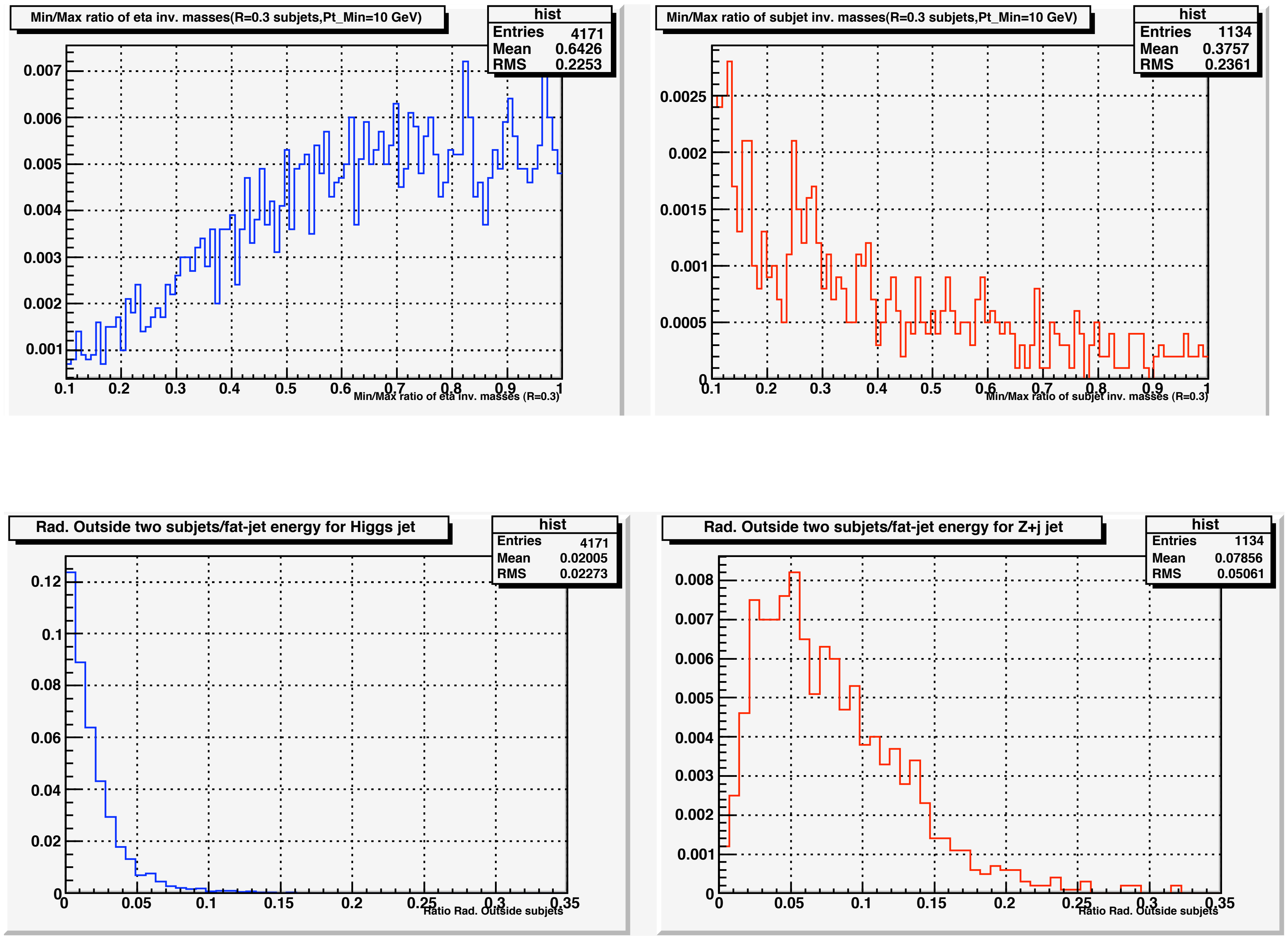
For example:
B. Bellazzini, C. Csaki, A. Falkowski, A. Weiler, arXiv:0910.3210, arXiv:0906.3026

- Why can new jet technology help?



Boosted Higgs, studied in the context of SM-like Higgs by
J. Butterworth, A. Davidson, M. Rubin, G. Salam, arXiv:0802.2470

Some preliminary results.



Higgs + Z signal

Z+jet background

A. Falkowski, D. Krohn, J. Shelton, A. Thalapillil, and LTW, in progress.

Encouraging results.

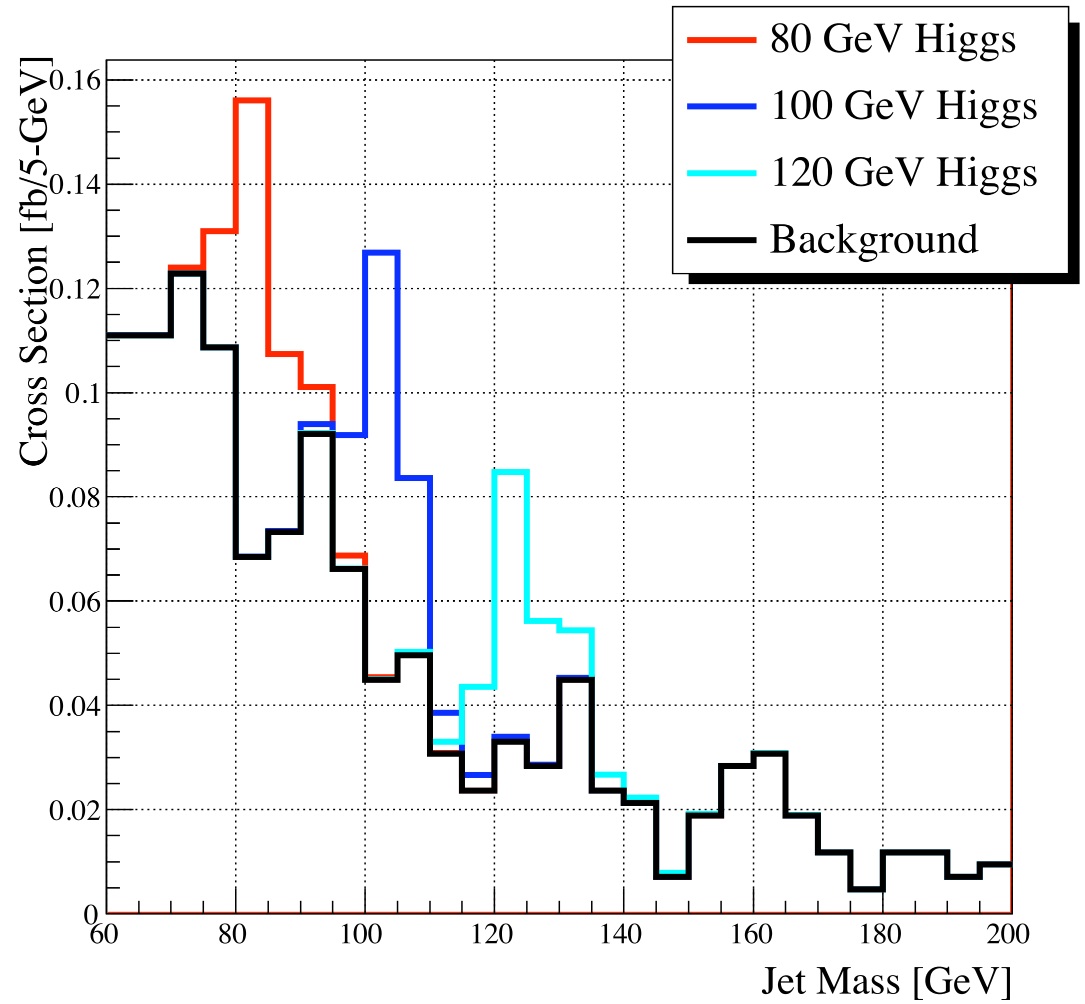
(rates in fb)

	$Z+h$			$Z+j$		
	$m_h = 80$	$m_h = 100$	$m_h = 120$	$m_h = 80$	$m_h = 100$	$m_h = 120$
Start	3.0	2.7	2.4	$4.2 \cdot 10^3$	$4.2 \cdot 10^3$	$4.2 \cdot 10^3$
m_j	1.8	1.6	1.0	$4.8 \cdot 10^2$	$2.3 \cdot 10^2$	$1.1 \cdot 10^2$
α	1.0	0.90	0.54	$5.1 \cdot 10^1$	$4.1 \cdot 10^1$	$2.6 \cdot 10^1$
β	0.13	0.13	0.09	$3.0 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$	$1.3 \cdot 10^{-1}$

jet mass → m_j

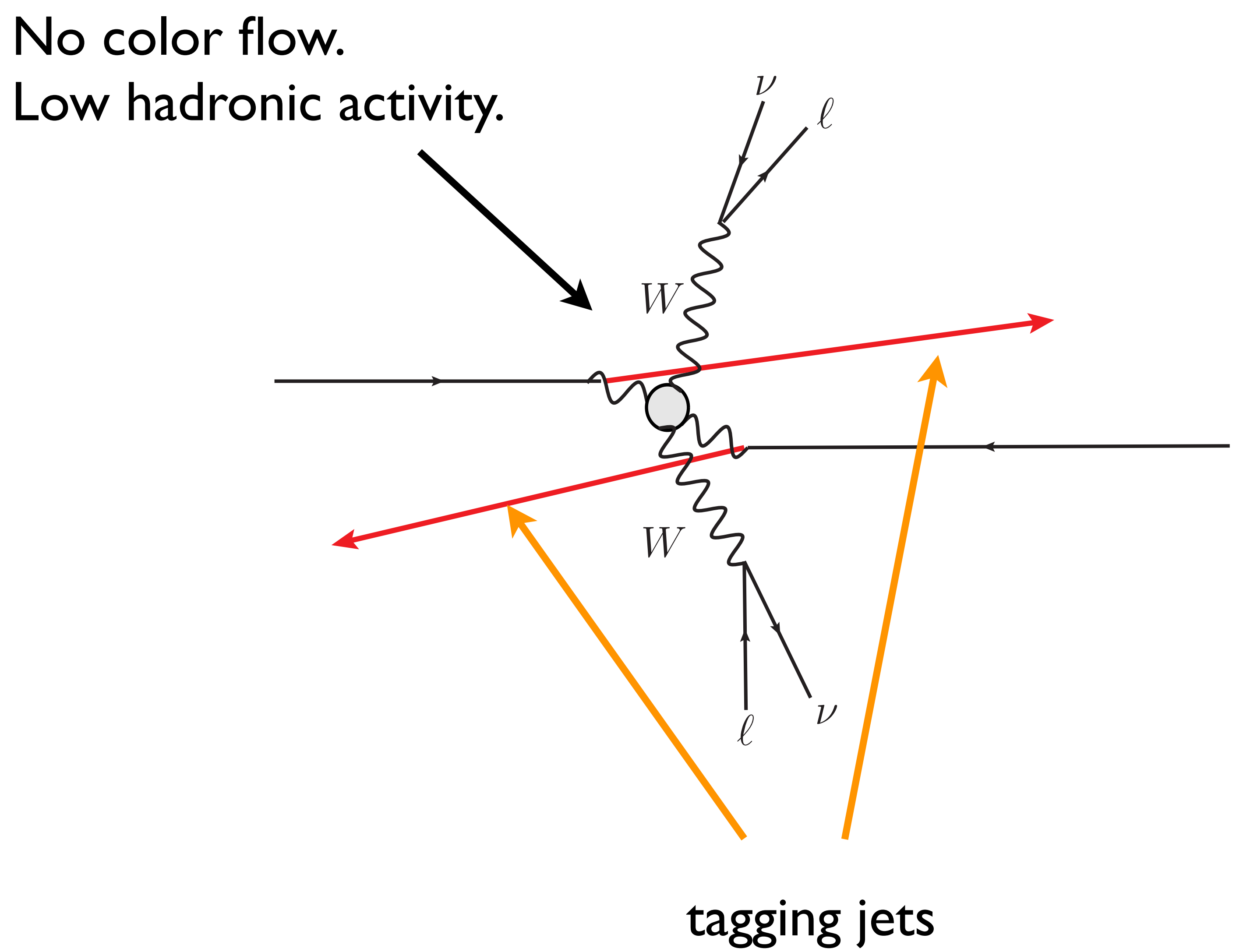
planar flow → α

radiation pattern → β



New physics in WW scattering

- Direct probe of electroweak symmetry breaking.
- Typical search strategy involves using leptonic mode, tagging the forward jets, and the so-called central jet veto.

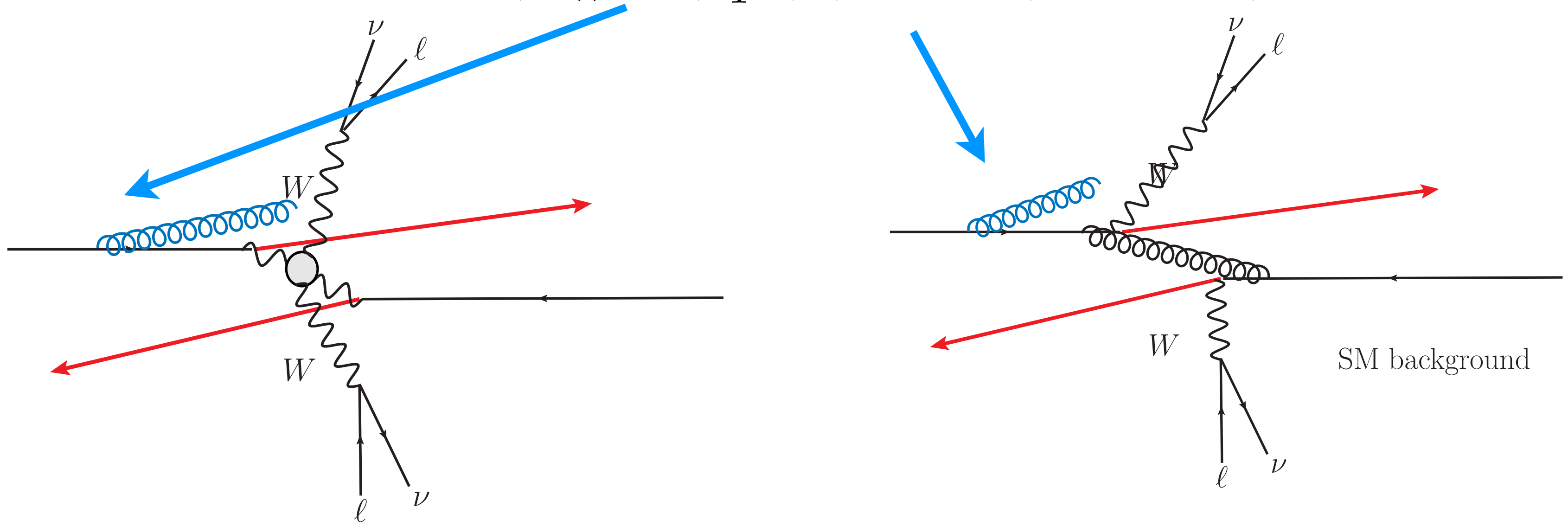


Problem with the traditional strategy.

- Initial state radiation can affect both jet tagging and central jet veto.

- Very sensitive to factorization scale.

$$\mu^2 = \beta(m_W^2 + (p_T^{\text{tag}})^2), \quad \beta \sim (\text{"order 1"})$$



Ambiguity can only be resolved with proper NLO (matrix element+matched parton shower).

- Use W polarization as a tool.

- Requires using the boosted hadronic W, and reconstruction based on the 2 subjets of the W-jet.

New strategy

T. Han, D. Krohn, LTW and W. Zhu, arXiv:0911.3656

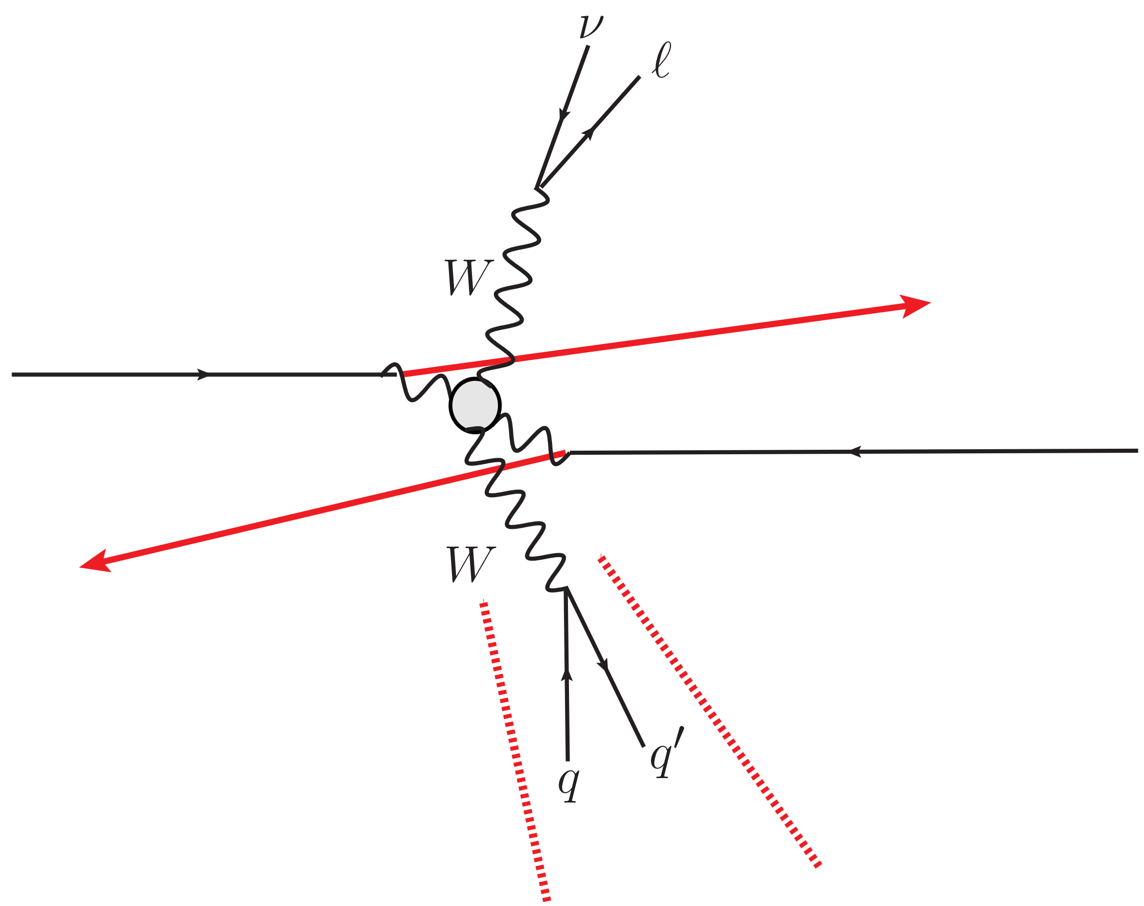
- Use jet substructure to help identify W boson.

  See also
  J. Butterworth, B. Cox, J. Forshaw, hep-ph/0201098

- Reconstruct the W rest frame, and measure W polarization.

- New physics generically predicts different longitudinal fraction.

- More robust, less sensitive to QCD corrections.



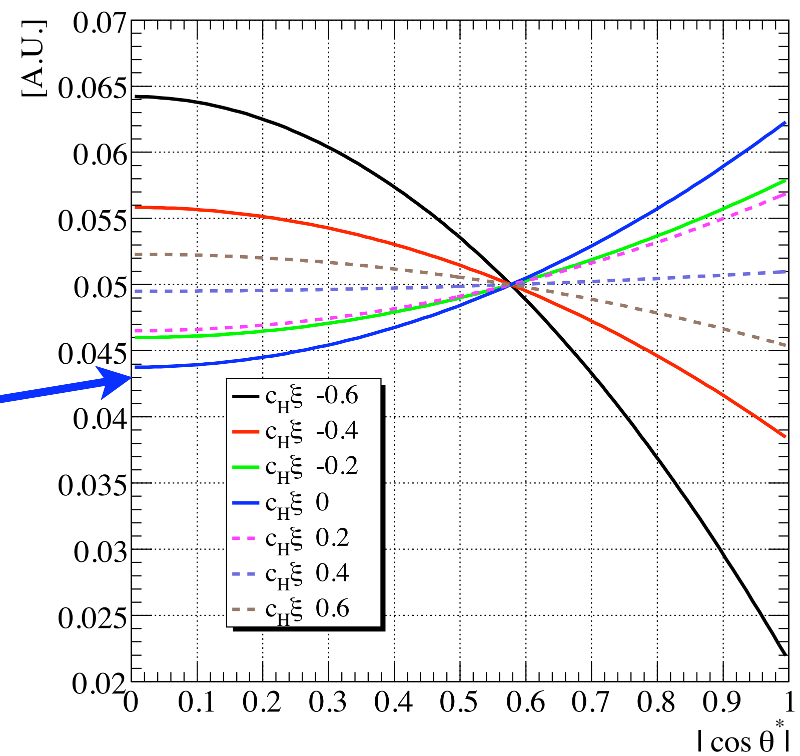
"W jet"
with sub-structure

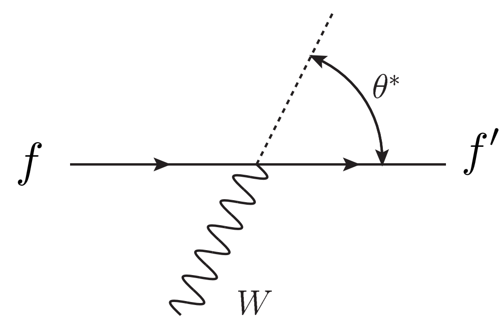
Effectiveness of W-polarization.

- Example: new physics parameterized by

$$c_H \xi \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H), \; \xi = v^2/f^2$$

SM prediction





$$P_\pm(\cos\theta^*) = \frac{3}{8}(1 \pm \cos\theta^*)^2$$

$$P_L(\cos\theta^*) = \frac{3}{4}(1 - \cos^2\theta^*)$$

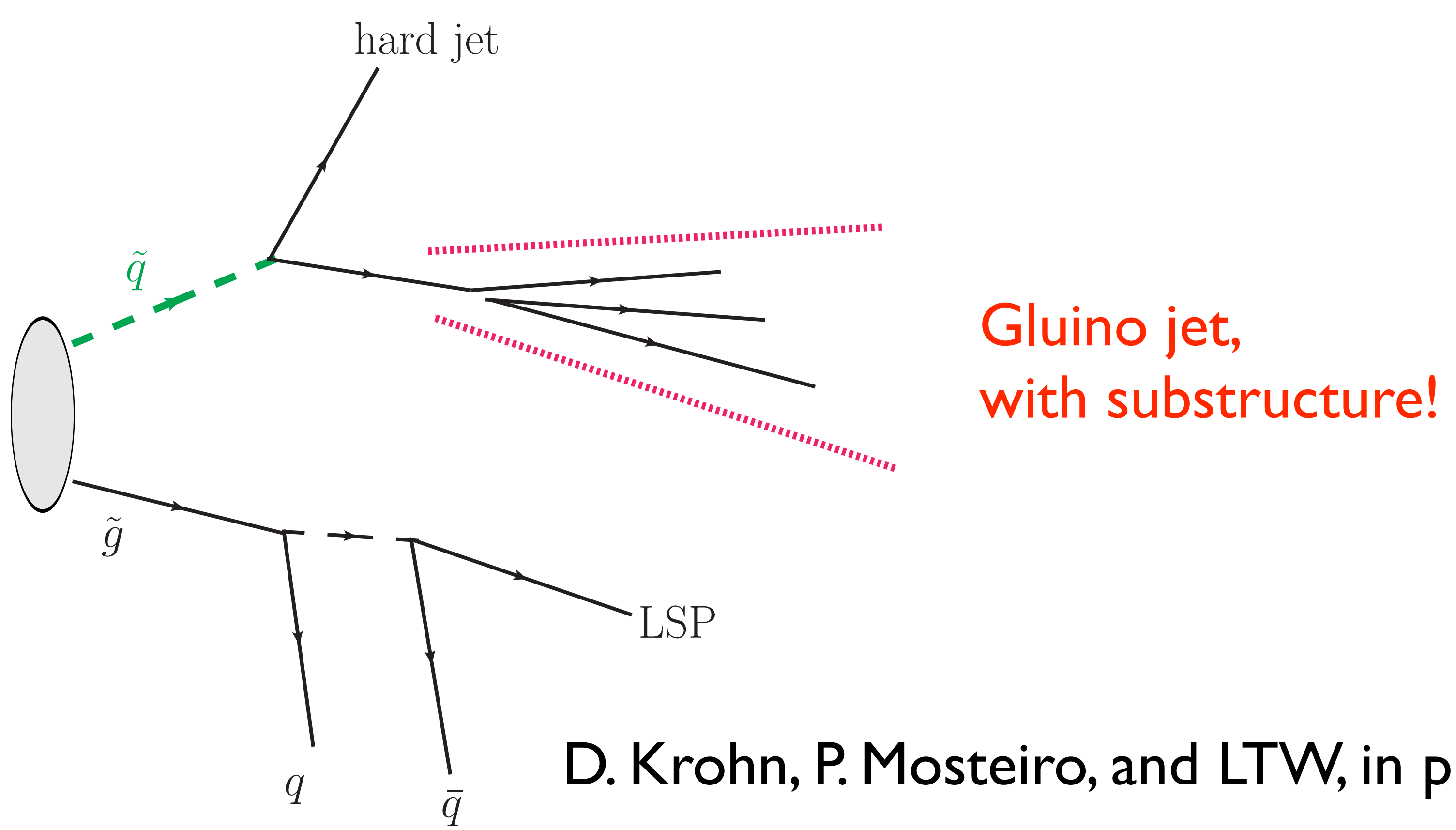
T. Han, D. Krohn, LTW and W. Zhu, arXiv:0911.3656

- Can certainly be useful for looking for new resonances in this channel as well.

$$W^+W^- \to X \to W^+W^-$$

Heavy squark.

- Scenarios with heavy squark, ~ several TeV, and light gluinos are appealing.
  - Flavor and CP "friendly".
  - A feature of many scenarios.
- Why can jet substructure help as well?



D. Krohn, P. Mosteiro, and LTW, in progress.

Conclusions

- Better handles on the hadronic final states are instrumental for discovery at the LHC.
- Based on consideration of QCD radiation, we proposed a set of carefully constructed new jet algorithms and substructure variables.
    - Much improved performance, jet mass, jet shape, etc.
    - We also demonstrate they can significantly enhance new physics signals in many important new physics channels.
        - Boosted or "slow" hadronic tops, WW scattering, Higgs search, heavy squark...
- Similar technique can be applied to Tevatron data.
- A promising direction. Stay tuned.

Extras

Infrared and collinear safety

- Infrared safety. No soft radiation can change the number and the directions of the hard jets.
  - VR is IR safe just like other sequential algorithms. Soft radiation clustered either near the end or at the beginning, not affecting hard dynamics.

- Collinear safety, jets are robust against colinear (within resolution) splittings.

$$\text{Require: } d_{ij} < d_{iB} \text{ if } \Delta R_{ij} < R_{\rm eff}(p_{{\rm T}(i+j)})$$

Satisfied by VR with $R_{\rm eff}(p_{{\rm T}i}) = \dfrac{\rho}{p_{{\rm T}i}}$

Implementation of the algorithm

D. Krohn, J. Thaler, LTW, arXiv:0903.0392

- Distance measures.

$$d_{iB} = p_{Ti}^{-2} R_{\rm eff}(p_{Ti})^2$$

$$d_{ij} = \min(\ p_{Ti}^{-2}, p_{Tj}^{-2}\ )(\Delta R)^2$$

- The "VR" algorithm

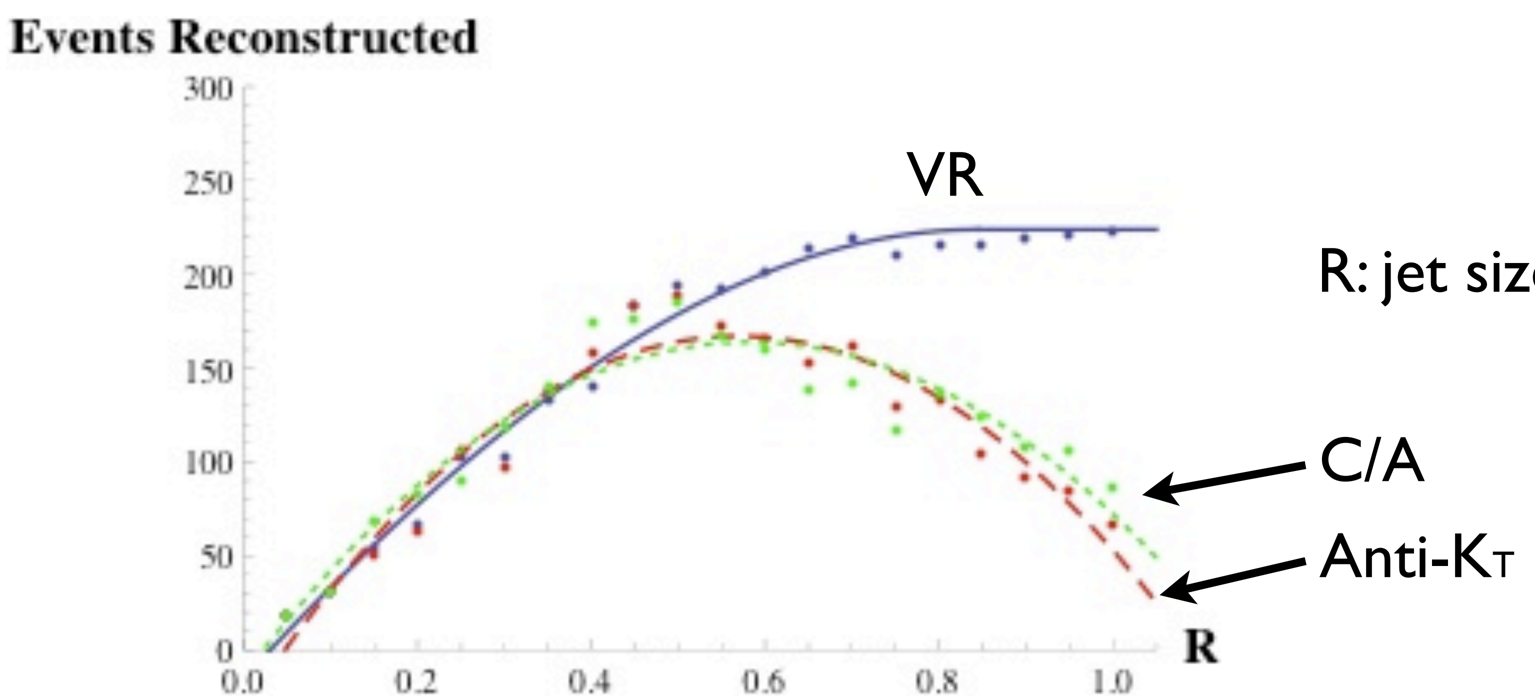
$$R_{\rm eff} = \frac{\rho}{p_T}$$

- Parameter ρ can be optimized.
    - VR works best if $\rho \leq 2p_T$

- Infrared and collinear safe.

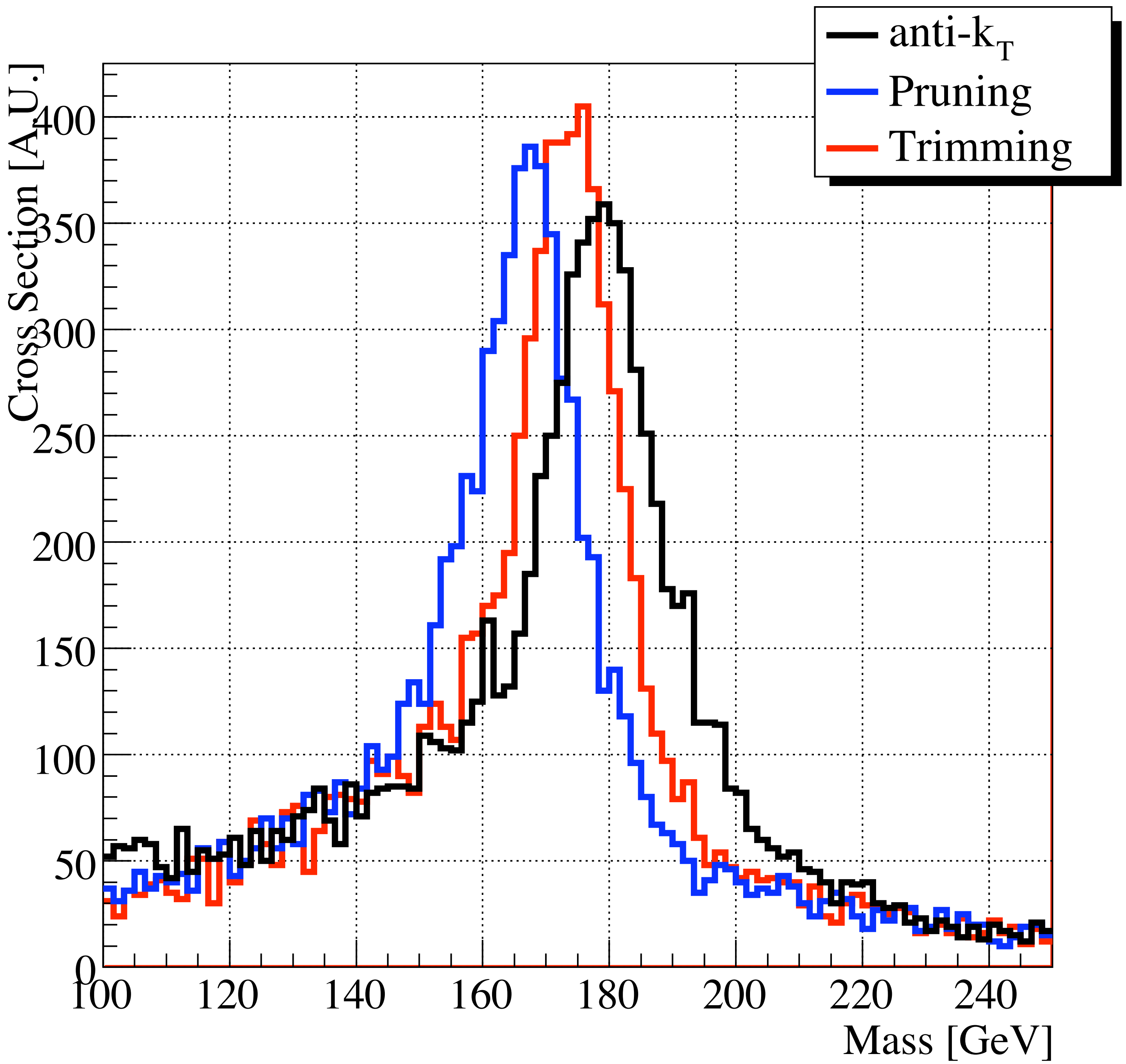
“Slow” tops, SM ttbar.

- For non-boosted tops, 6 objects in the final state. Very crowed event.
- Fully hadronic, 6 jets, very hard.
- New VR algorithm should help since it has a dynamically adjustable size.



R: jet size parameter

D. Krohn, C. Popa, and LTW, in progress

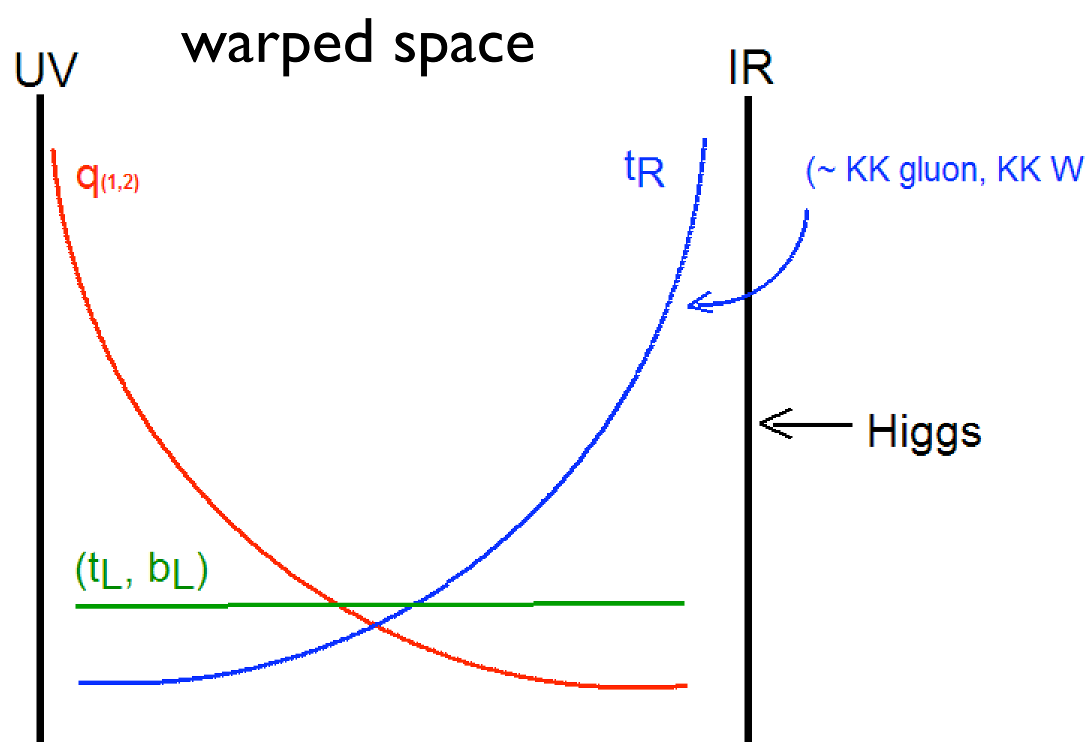

anti-k_T
Pruning
Trimming
Cross Section [A.U.]
0
50
100
150
200
250
300
350
400
100
120
140
160
180
200
220
240
Mass [GeV]

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: $d\sigma \propto \frac{dp_T^{ISR}}{p_T^{ISR}}$
  - FSR is controlled by both collinear and soft singularities:
    $$d\sigma \propto \frac{d(\Delta R)}{\Delta R} \times \frac{dp_T^{FSR}}{p_T^{FSR}}$$
  - Therefore, a soft cut relative to the jet energy flow could enhance FSR relative to ISR.

A model with warped extra-dimension



- Top is "composite", localized towards the IR brane.
- Top couples strongly to other "composite" states, KK-gluons, ...

K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036

Planar Flow

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

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

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

WW reach

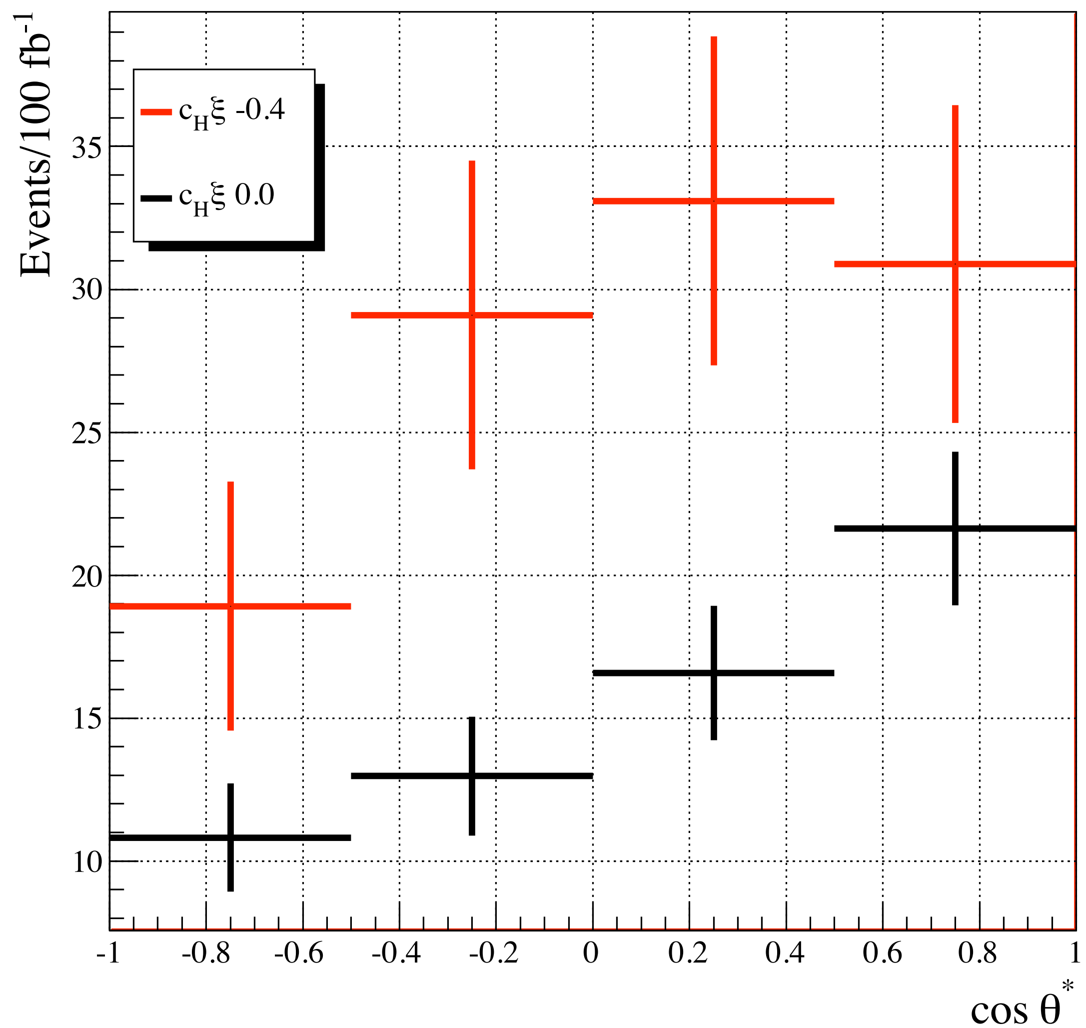


Figure 4: Projected distribution and associated statistical uncertainties of $\cos\theta^*$ for the leptonically decaying vector using 100 fb^{-1} of luminosity.

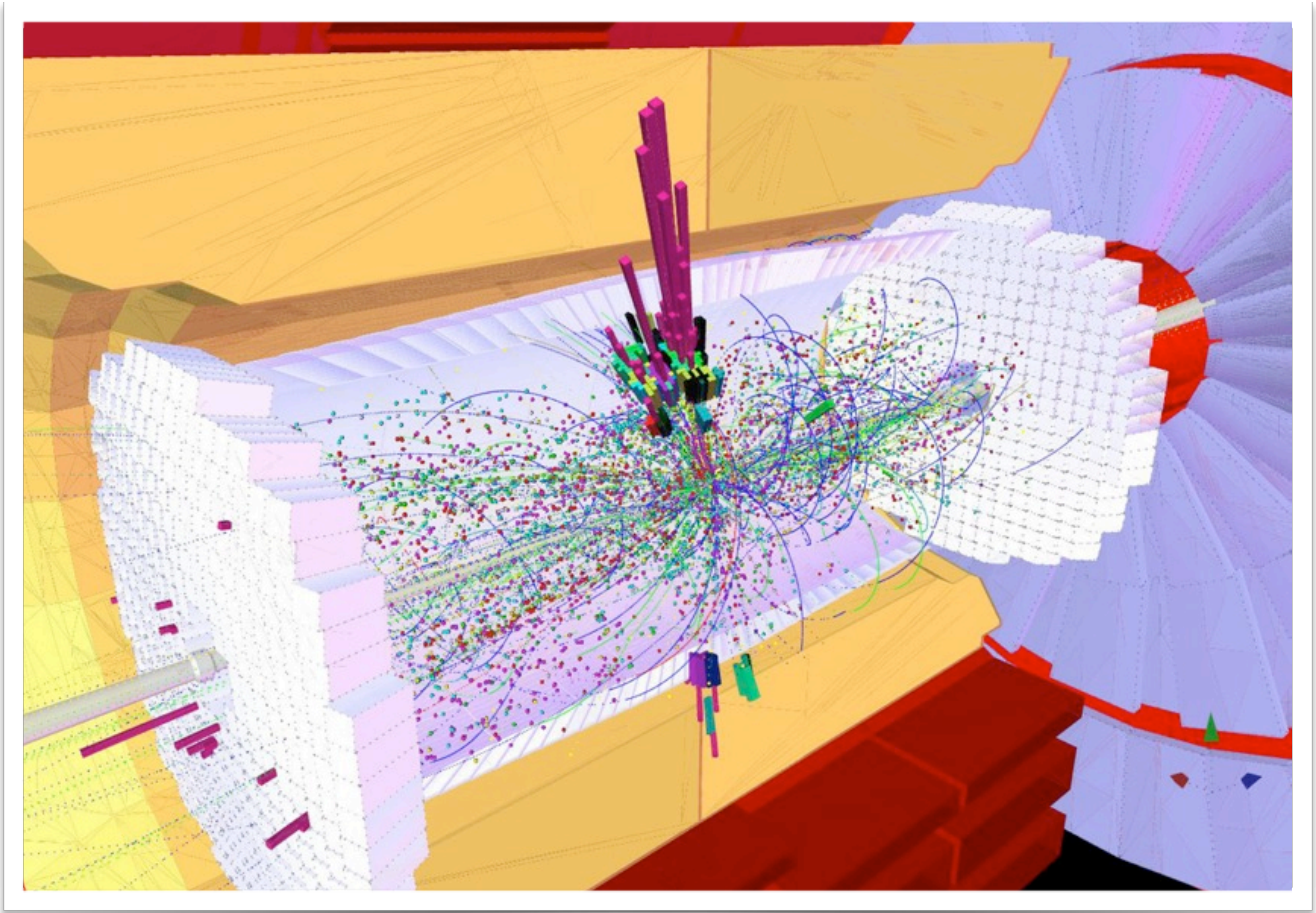
- Here are some example cross sections for a particular set of VBF cuts and for different anomalous couplings (labeled $c_H\xi$, which is 0 for the SM).

	Parton Level [fb]			Jet Level [fb]		
$c_H\xi$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$
0.4	0.95	0.81	0.73	0.53	0.38	0.26
0.2	0.82	0.72	0.64	0.43	0.33	0.24
0.0	0.73	0.64	0.57	0.40	0.29	0.21

Stable before parton shower

Sensitive afterward

- Basically, the central jet veto meant to reduce QCD backgrounds makes the analysis very sensitive to the treatment of the forward jets.



Event picture from http://cms.web.cern.ch/cms/Media/Images/Detector/index.html