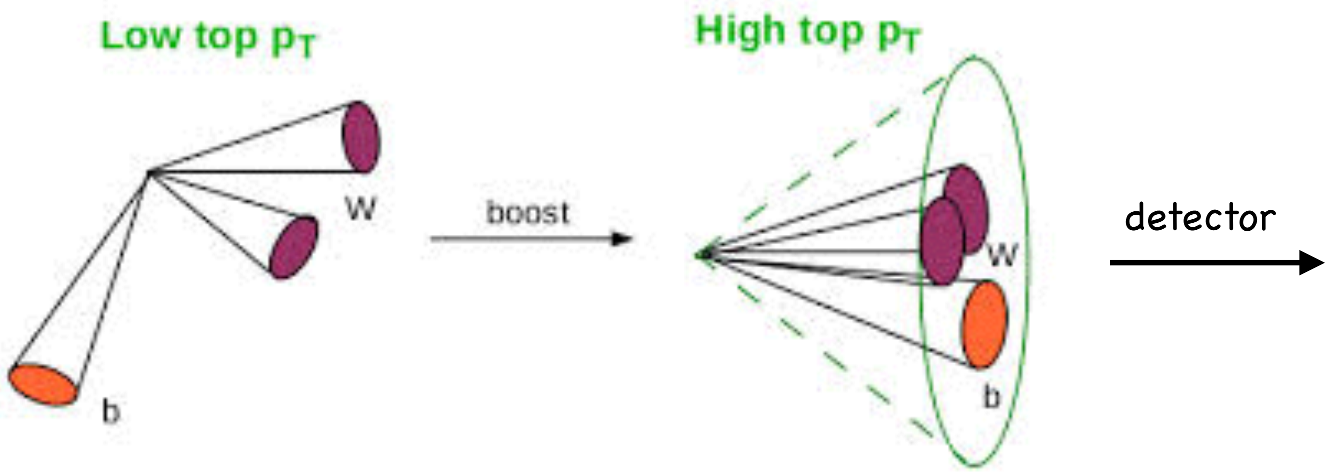
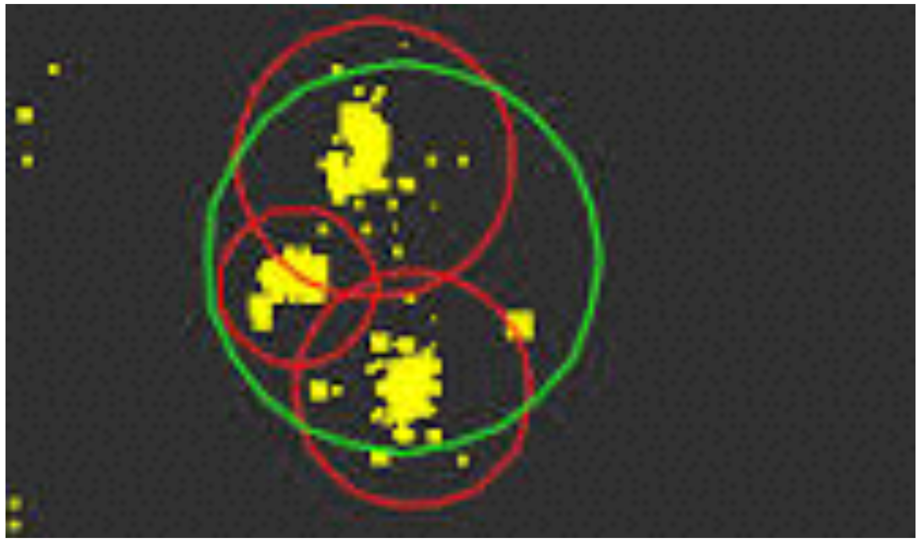
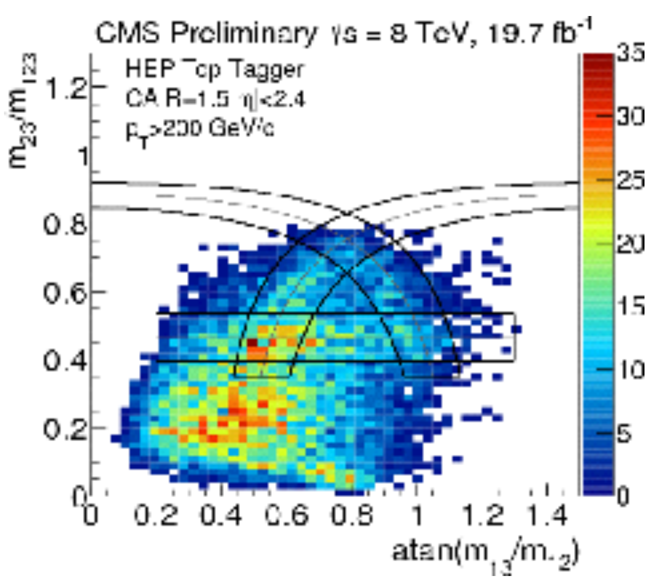


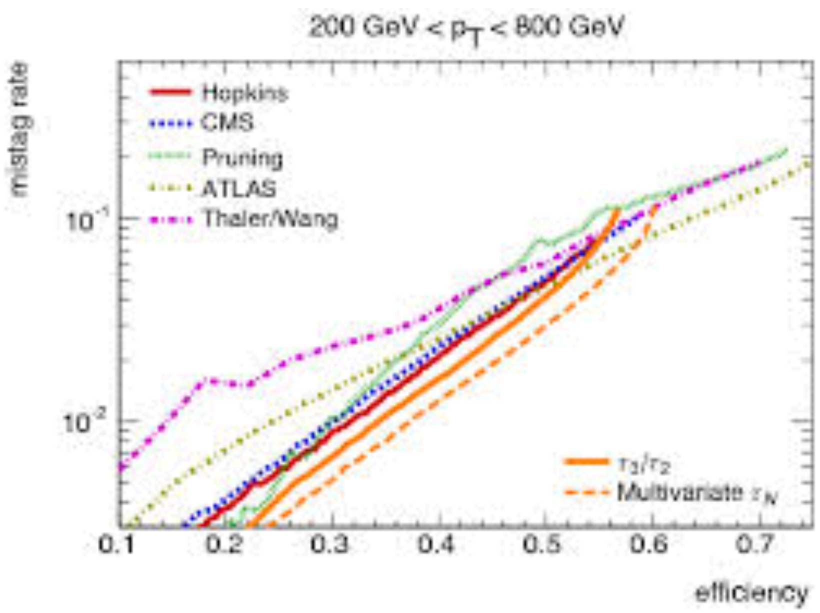


Tagging Boosted Resonances

Michael Spannowsky

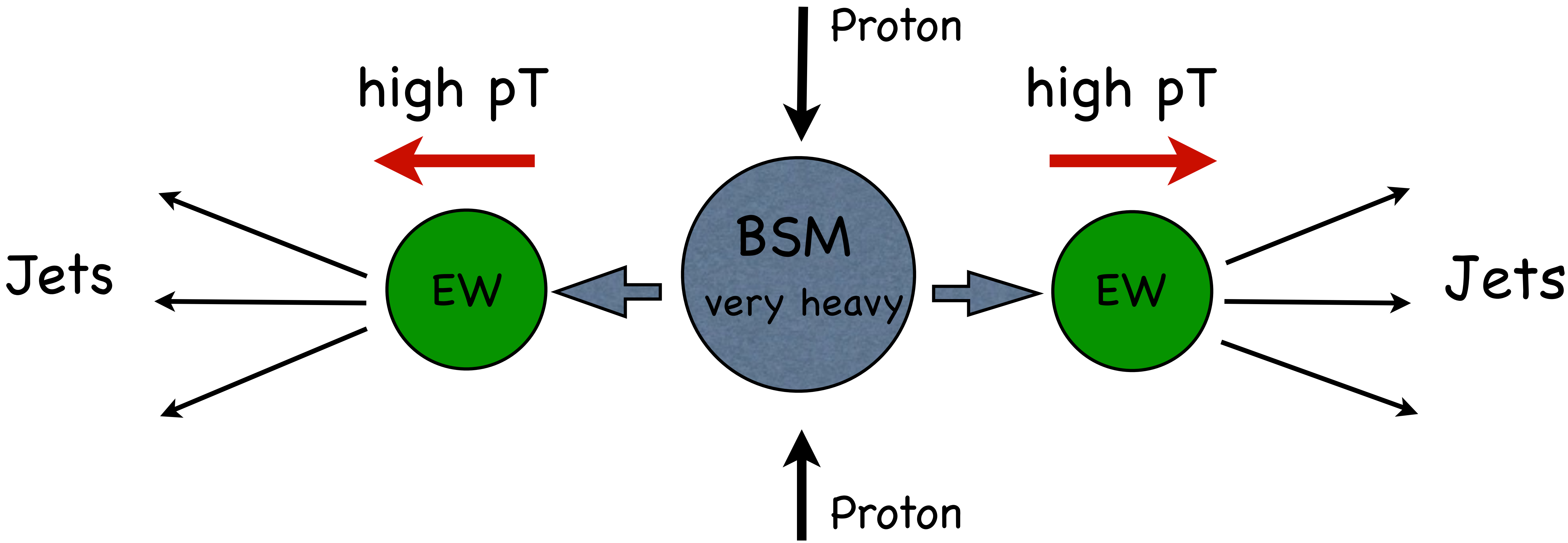
IPPP Durham





Resonance reconstruction in boosted final states

In many scenarios where resonances have to be measured they are produced with large transverse momentum



- For high pT jet substructure cannot be avoided
- Many reconstruction techniques have been proposed and compared

However, at the LHC many sources of radiation:

[Cacciari, Salam, Sapeta JHEP 1004]

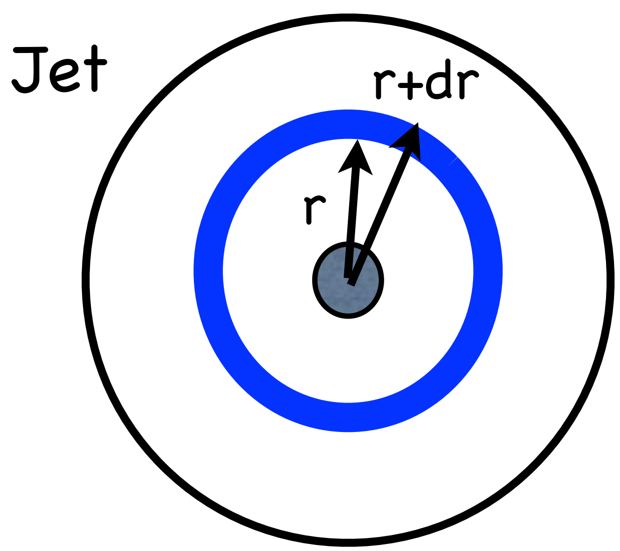
- **Pileup** → Can add up to 100 GeV of soft radiation per unit rapidity
- **Underlying Event** → $\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$ with $\Lambda_{\mathrm{UE}} \sim \mathcal{O}(10)$ GeV

[Dasgupta, Magnea, Salam JHEP 0802]

- **Initial state radiation (ISR)**
- **Hard radiation from many resonances in event**

→ Jet mass and internal structure will be affected by these sources

Rough argument for R^4 dependence:



UE has in first approximation a fix energy density Λ_{UE}. Consider hard jet core and a thin "ring" of UE radiation of thickness dr at radius r.

Because $\langle m_J^2 \rangle = \frac{\alpha_s}{2\pi} p_T^2 R^2$ for a quark jet, we find:

$$\langle \delta m_J^2 \rangle_{UE} = \frac{\alpha_s}{2\pi} \int_0^R p_T \, (2\pi r \, dr \, \Lambda_{UE}) \, r^2$$

$$= \alpha_s p_T \Lambda_{UE} \int_0^R r^3 dr = \alpha_s p_T \Lambda_{UE} R^4/4$$

The relevant kinematic pattern

smaller pT →

Business ↓

large pT, non-busy final state eg. Z'->tt	low pT, non-busy final state eg. pp->ttbar (Afb)
large pT busy final state eg. SUSY cascades top partner search	low pT, busy final state eg. ttH

The relevant kinematic pattern

smaller pT →

↓ Business

large pT,
non-busy final state
eg. Z'->tt

- Elw. scale resonance highly boosted
- Decay prods highly collimated -> R < 1.0
- Less sensitive to UE/ISR
- Subjet approach necessary
- Original motivation and many techniques

large pT
busy final state
eg. SUSY cascades
top partner search

The relevant kinematic pattern

smaller pT

Business

- Usually small signal CS
- But can be superior to standard analysis:
  - ➡ Event reconstruction impr.
  - ➡ b-tagging improved
  - ➡ combinatorial problem red.
- Big cone, sensitive to UE/ISR
- BDRS

low pT,
non-busy final state
eg. pp->ttbar (Afb)

low pT,
busy final state
eg. ttH

The relevant kinematic pattern

smaller pT

Business

large pT,
non-busy final state
eg. Z'->tt

low pT,

large pT
busy final state
eg. SUSY cascades
top partner search

- Hard radiation uncorrel. to hard interaction
- Increased comb. problem
- Additional criteria to select decay products

The relevant kinematic pattern

smaller pT →

Business ↓

- Most complicated
- Large cone, R > 1.2
- Sensitive to UE/ISR, hard uncorrelated radiation
- Only few approaches: HEPTopTagger, Shower deconstruction

low pT,
non-busy final state
eg. pp->ttbar (Afb)

low pT,
busy final state
eg. ttH

“Mano sinistra e destra del diavolo”

Groomers reduce active area of jet -> reduce sensitivity to pileup/UE

Taggers aim to identify objects based on their properties

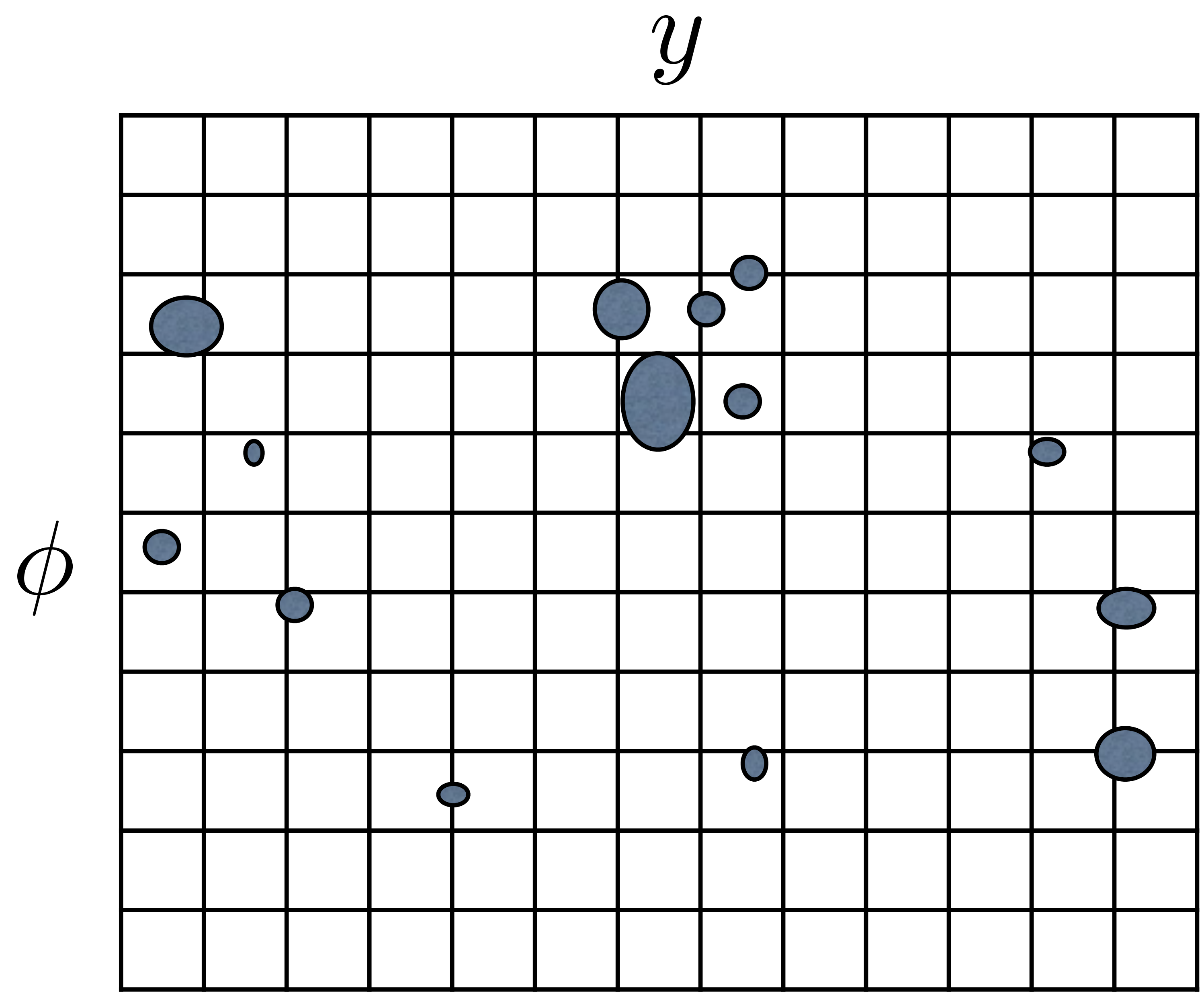
Grooming tools for jet substructure

Filtering [Butterworth et al. PRL 100 (2008)]

Pruning [Ellis et al. PRD 80 (2009)]

Trimming [Krohn et al. JHEP 1002 (2010)]

Jet/Event selection

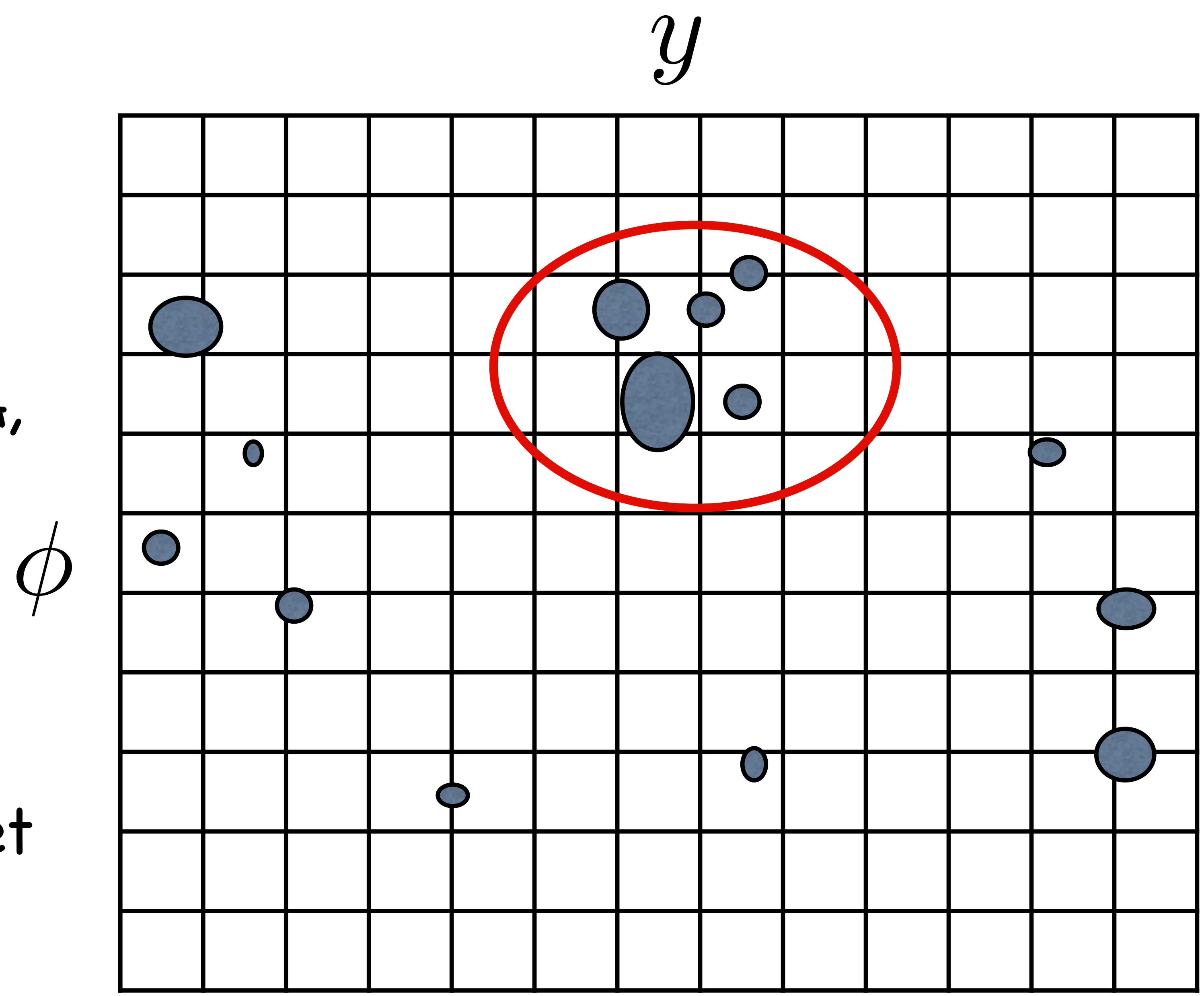


UE, ISR, Pile-up, hard interaction

Jet/Event selection

I. Locate hadronic energy deposit in detector by choosing initial jet finding algorithm, e.g. CA, R=1.2

II. Possible to impose jet selection cuts on fat jet



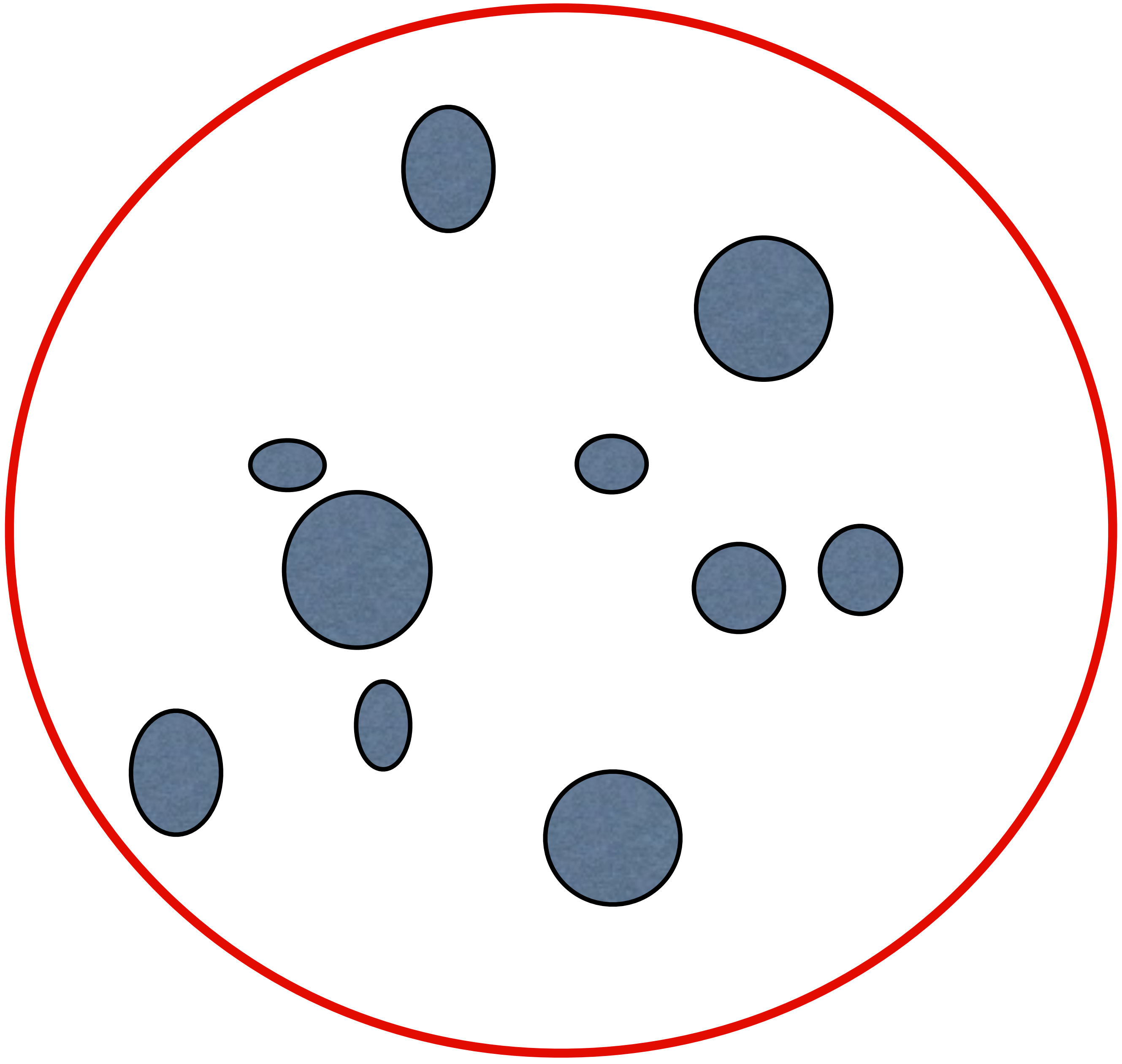
UE, ISR, Pile-up, hard interaction

Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

Filtering:
recombine n subjets

Trimming:
recombine subjets
which fulfill $P_{T,j} > f \times \Lambda$

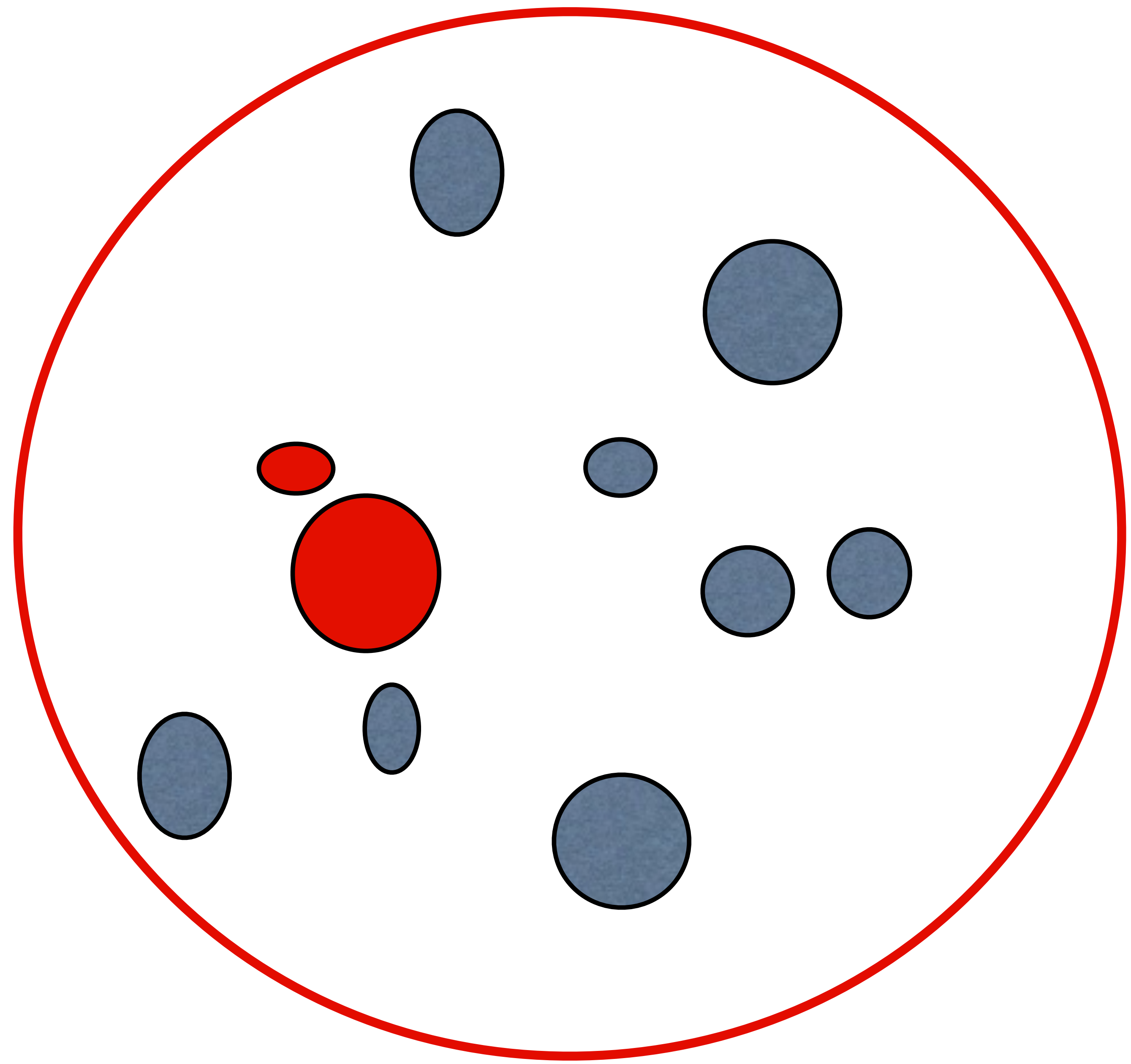


Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

Filtering:
recombine n subjets

Trimming:
recombine subjets which fulfill $P_{T,j} > f \times \Lambda$

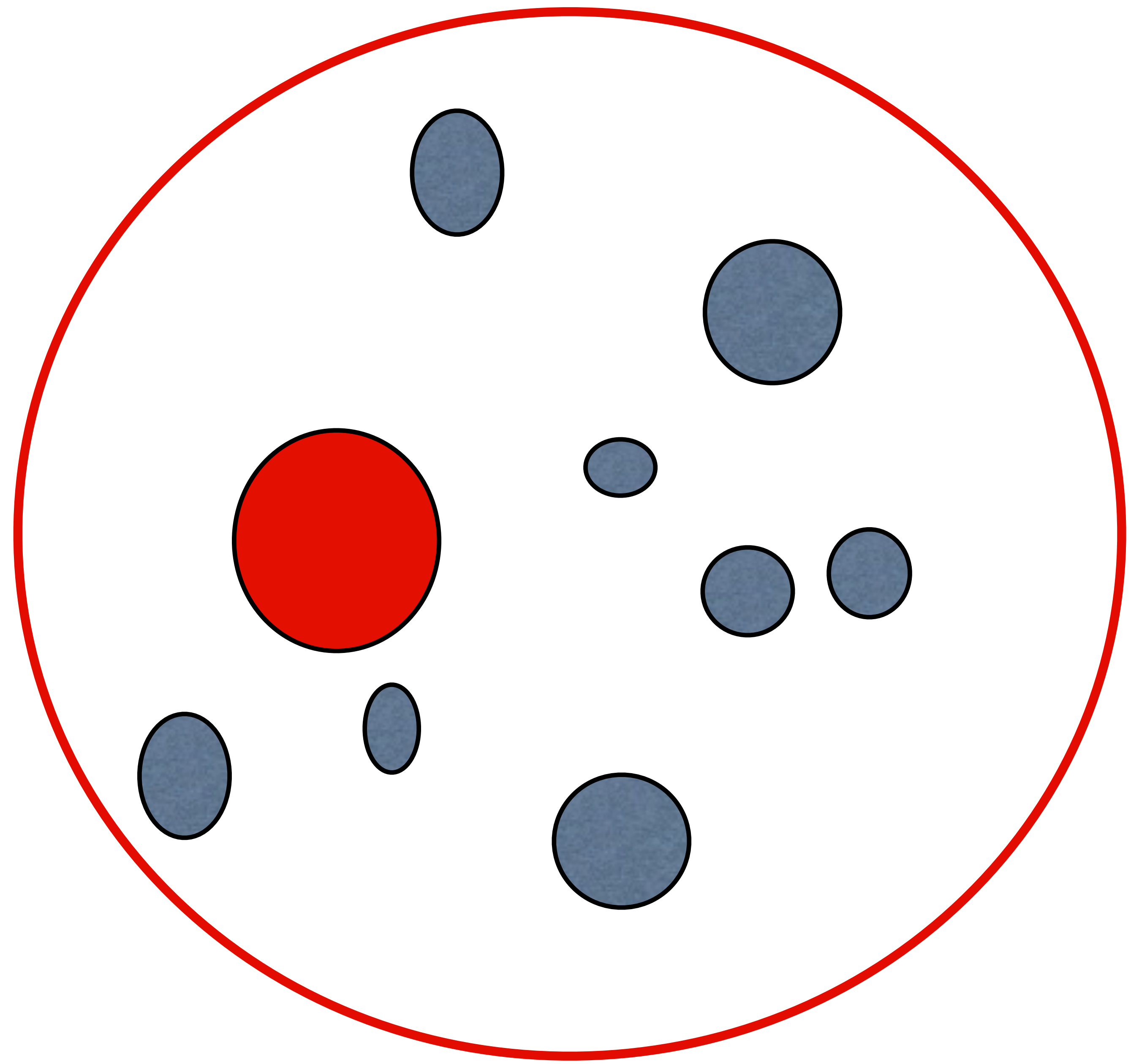


Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

Filtering:
recombine n subjets

Trimming:
recombine subjets which fulfill $P_{T,j} > f \times \Lambda$

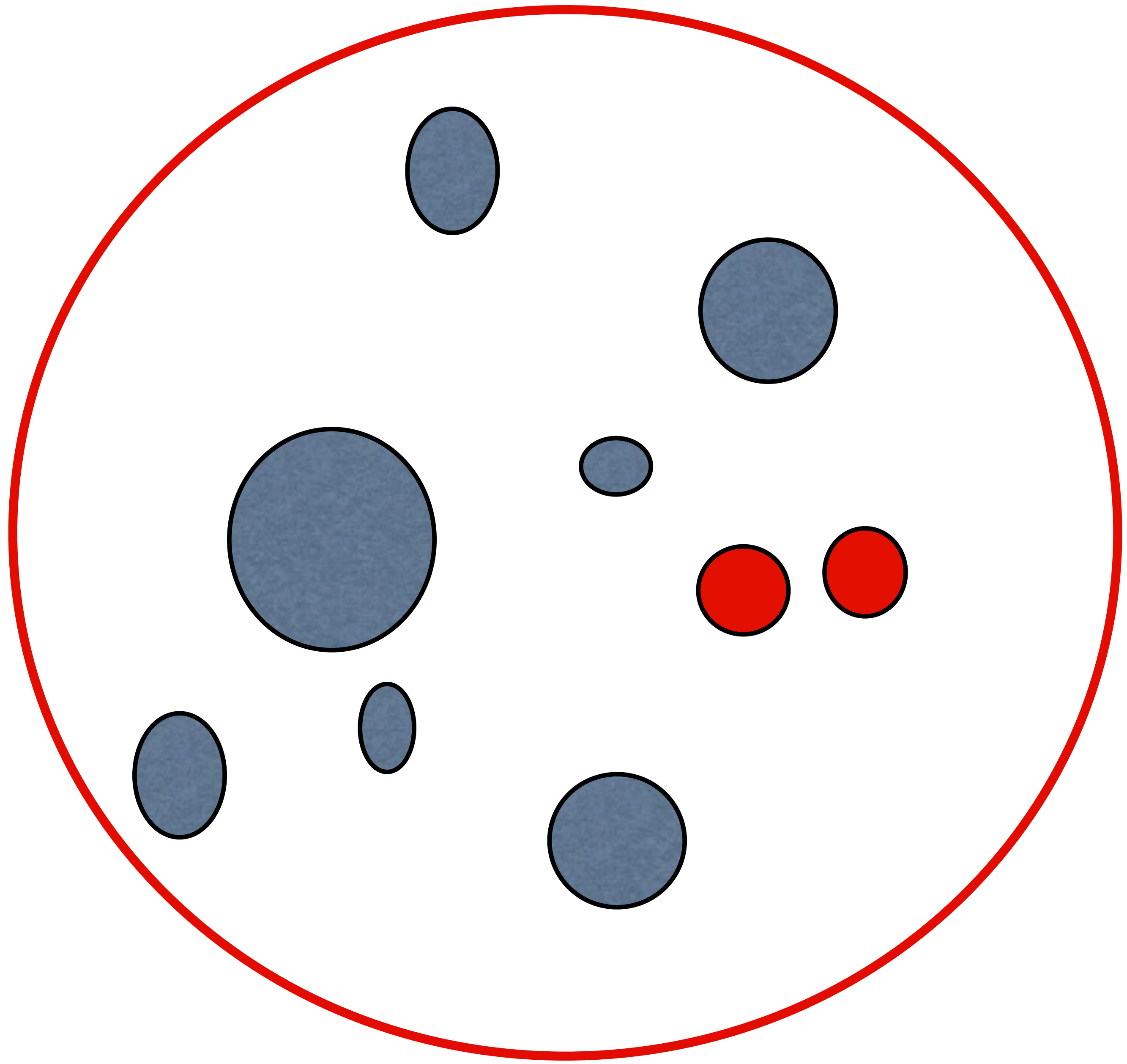


Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

Filtering:
recombine n subjets

Trimming:
recombine subjets which fulfill $P_{T,j} > f \times \Lambda$

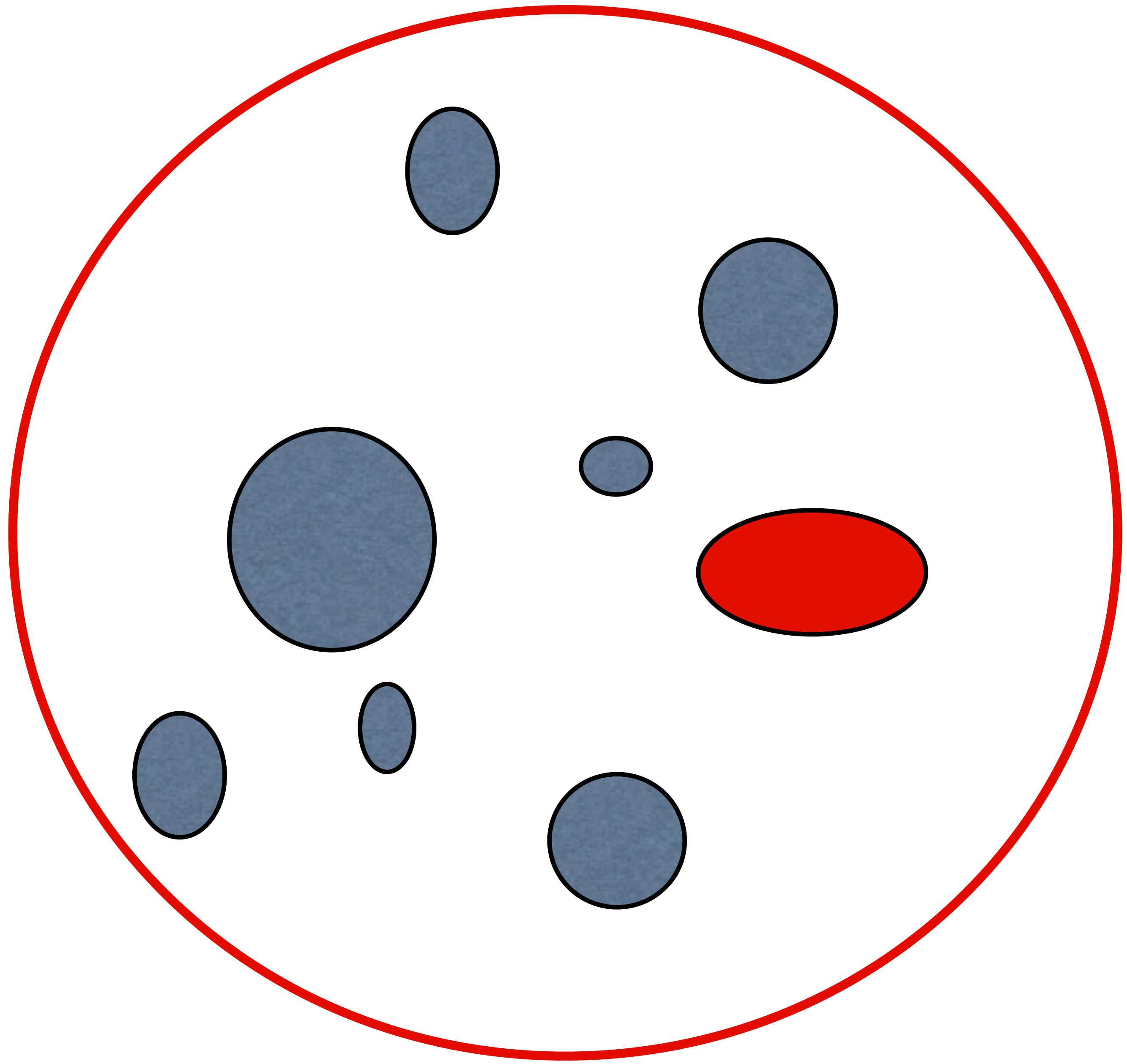


Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

Filtering:
recombine n subjets

Trimming:
recombine subjets which fulfill $P_{T,j} > f \times \Lambda$

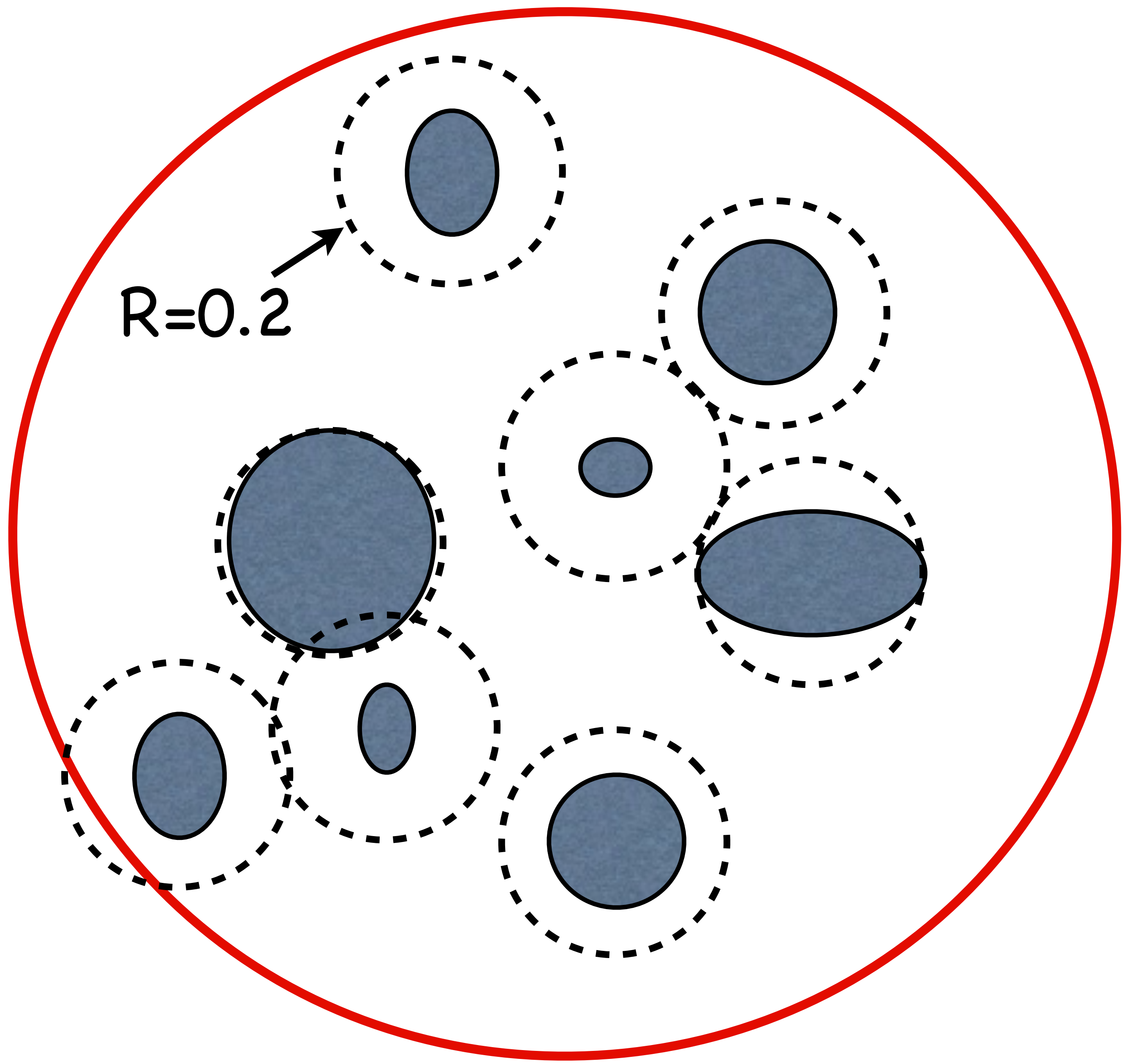


Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

Filtering:
recombine n subjets

Trimming:
recombine subjets which fulfill $P_{T,j} > f \times \Lambda$

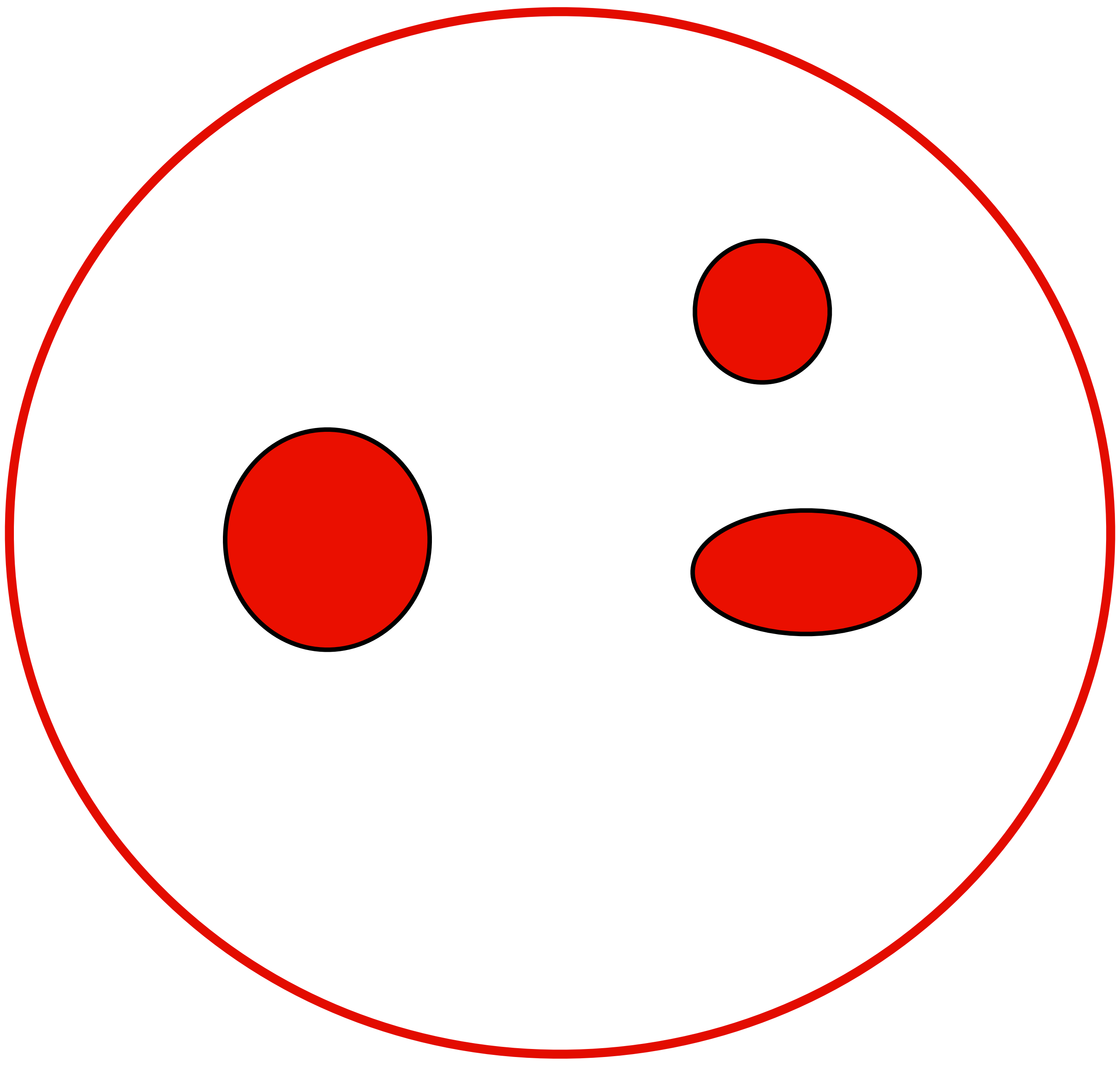


Filtering/Trimming

1. Recombine jet constituents with new alogrithm, eg CA, R=0.2

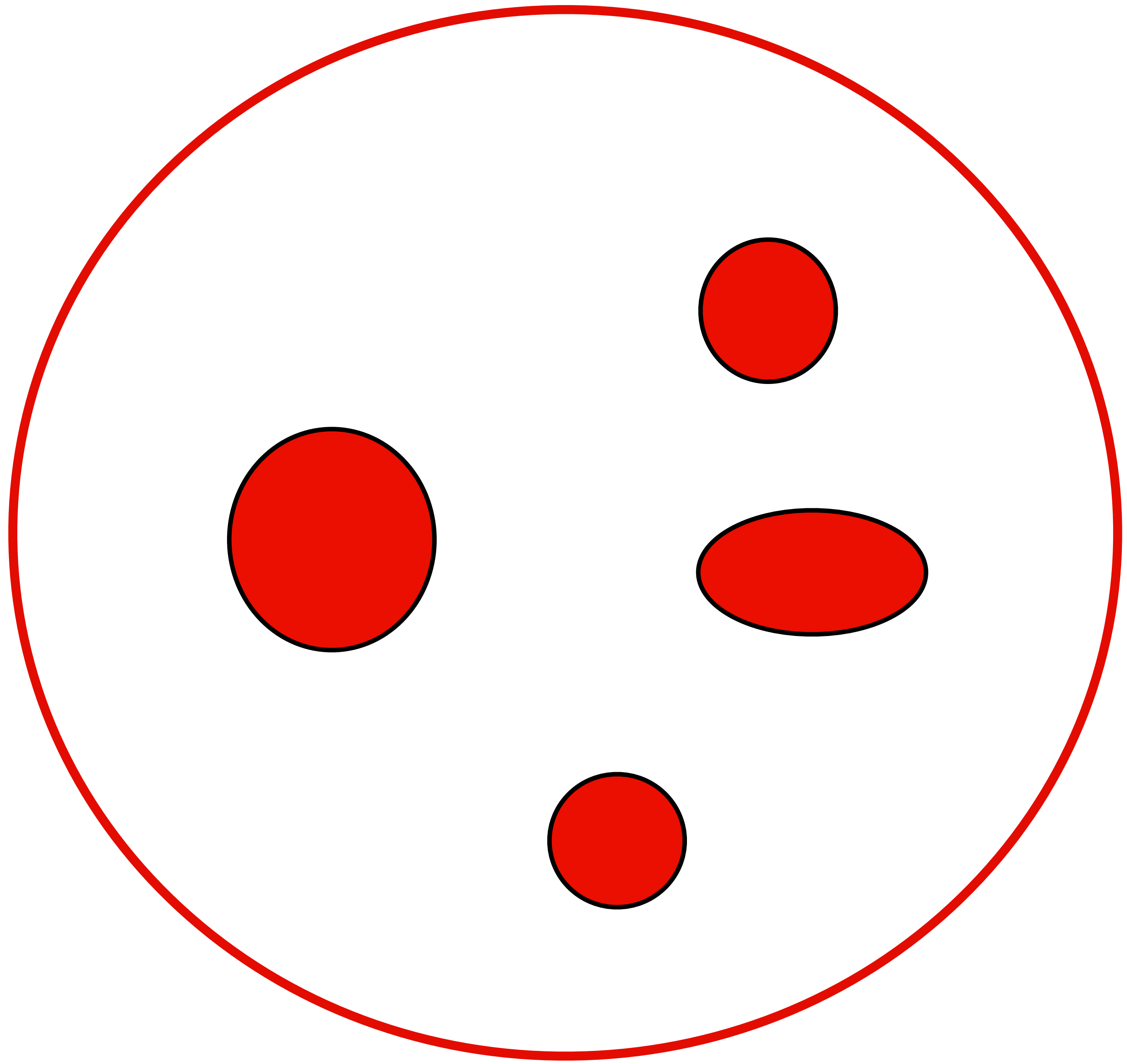
Filtering:
recombine n subjets

Trimming:
recombine subjets which fulfill $P_{T,j} > f \times \Lambda$



Filtering/Trimming

I. Recombine jet constituents with new alogrithm, eg CA, R=0.2



Filtering:
recombine n subjets

Trimming:
recombine subjets
which fulfill $P_{T,j} > f \times \Lambda$

fix choice   based on Jet property

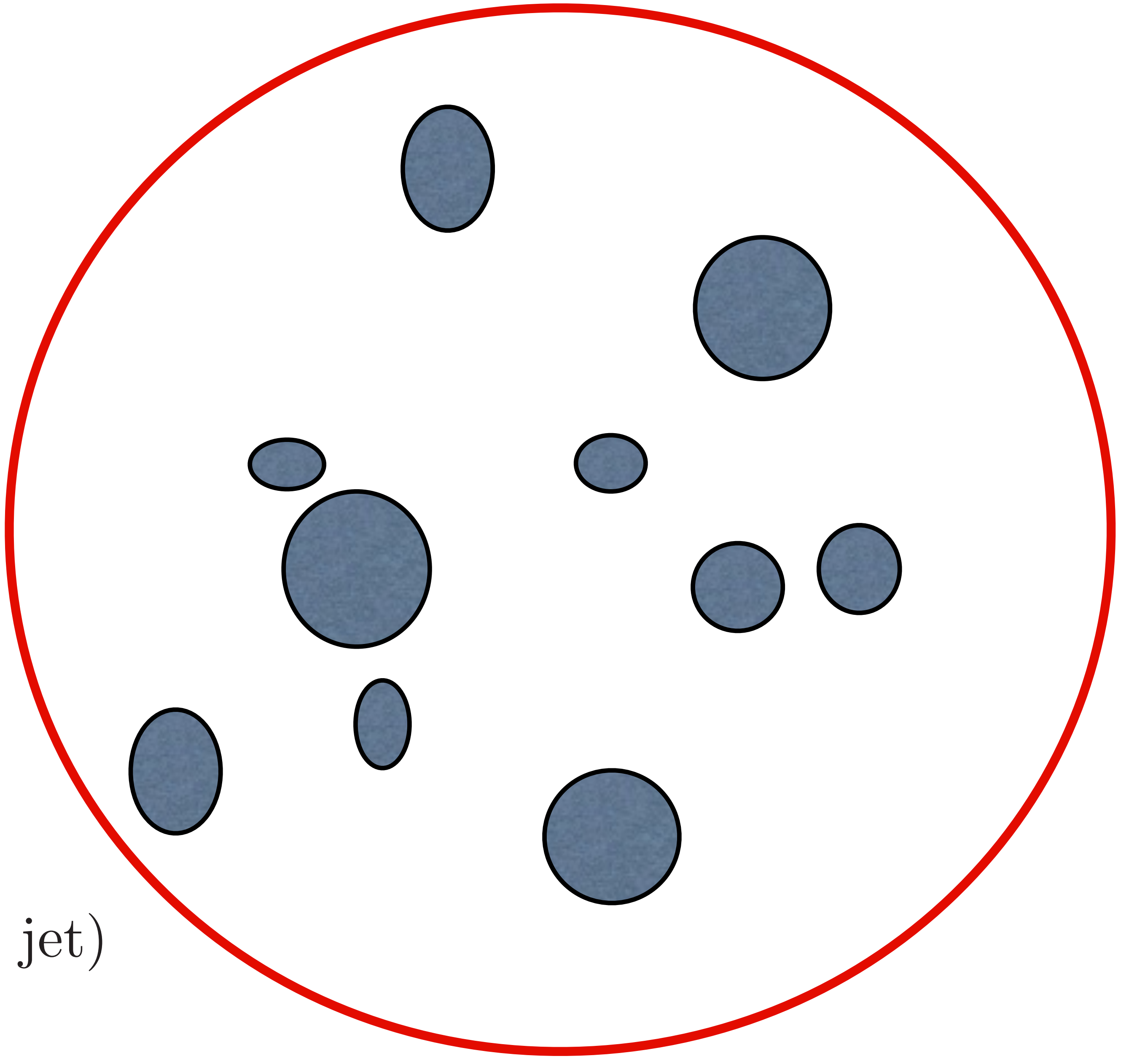
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\mathrm{cut}}$$

$$\Delta R_{ij} > D_{\mathrm{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$$



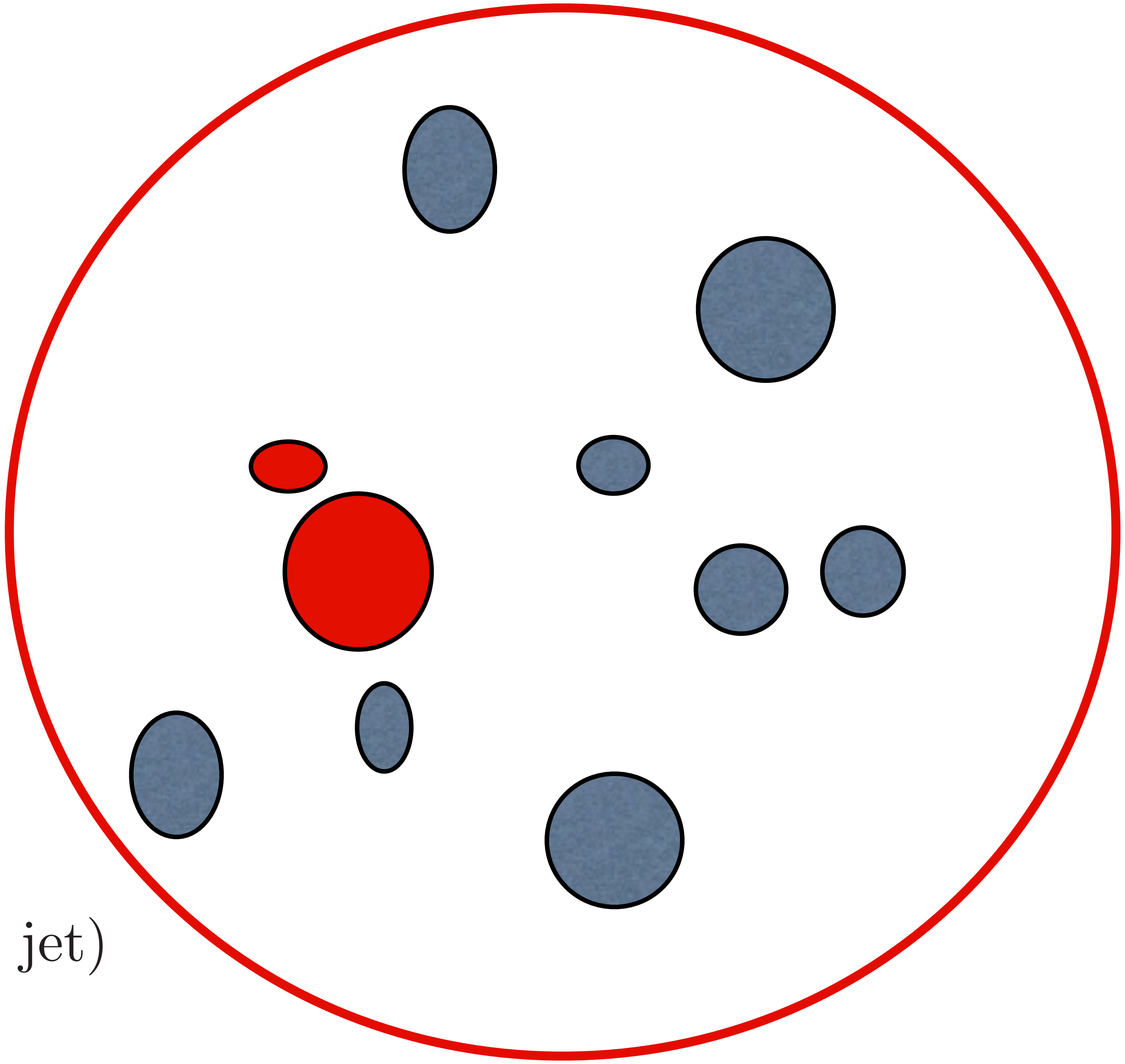
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\text{cut}}$$

✗ $\Delta R_{ij} > D_{\text{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$



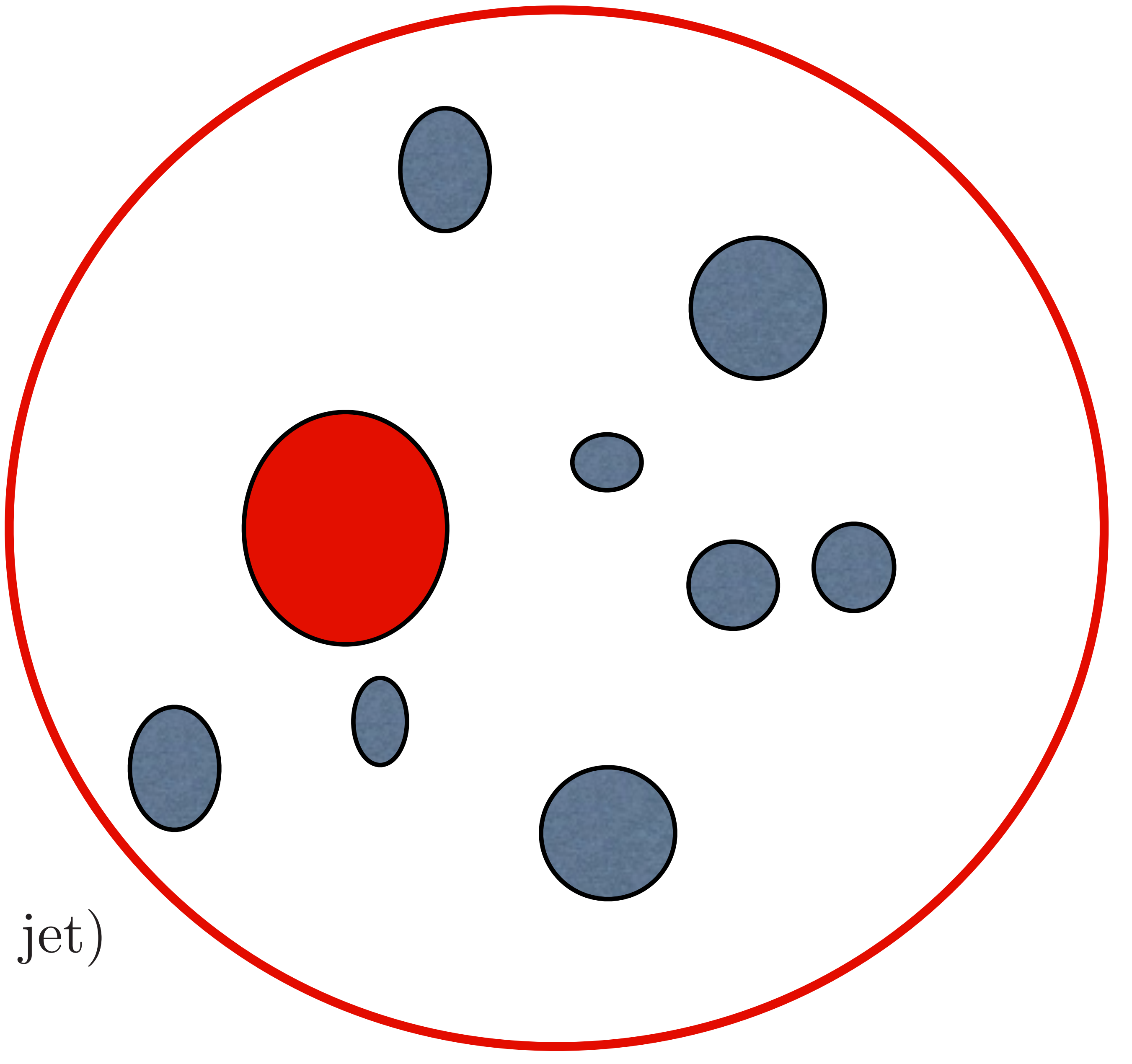
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\mathrm{cut}}$$

$$\Delta R_{ij} > D_{\mathrm{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$$



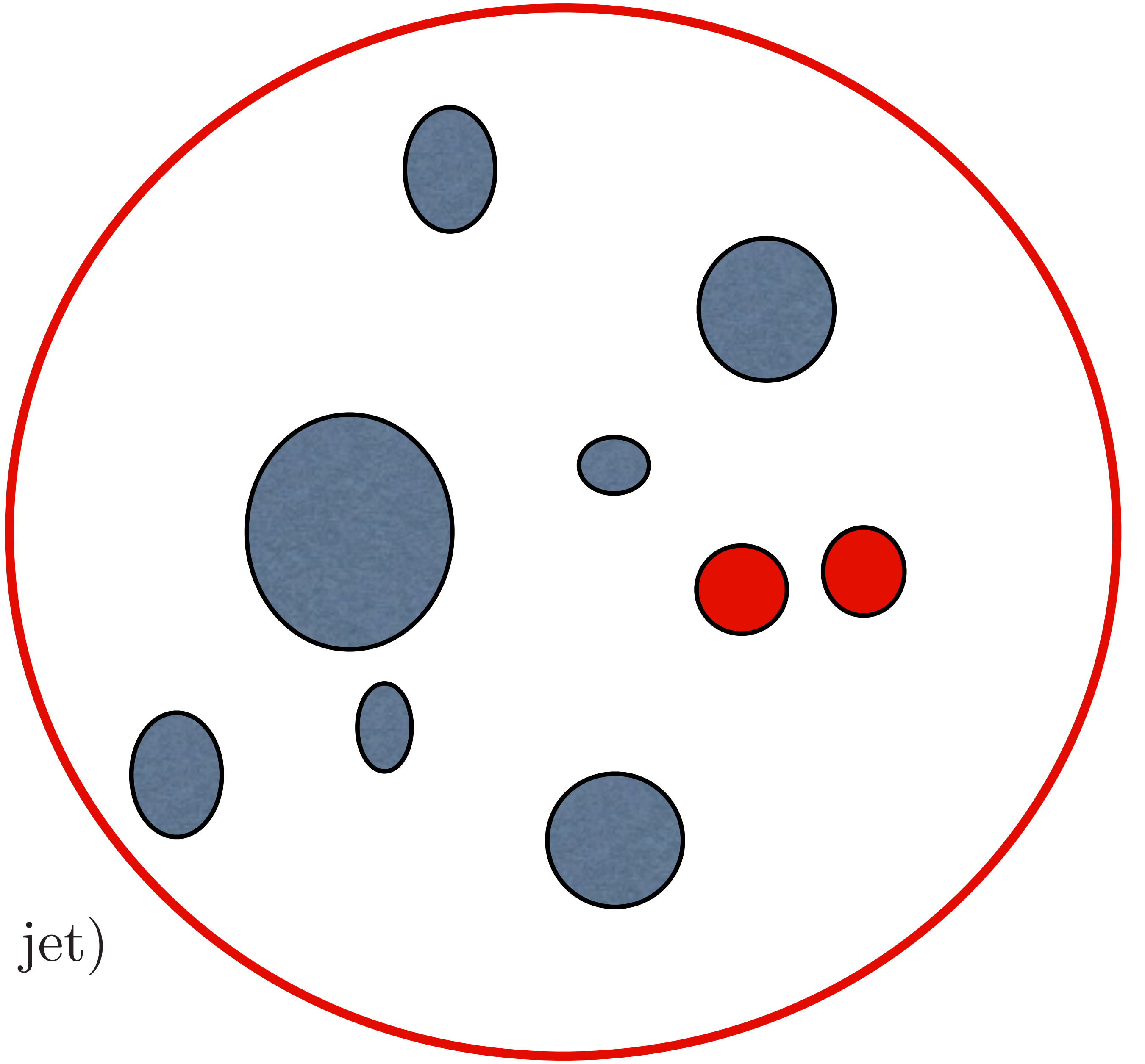
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\text{cut}}$$

✗ $\Delta R_{ij} > D_{\text{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$



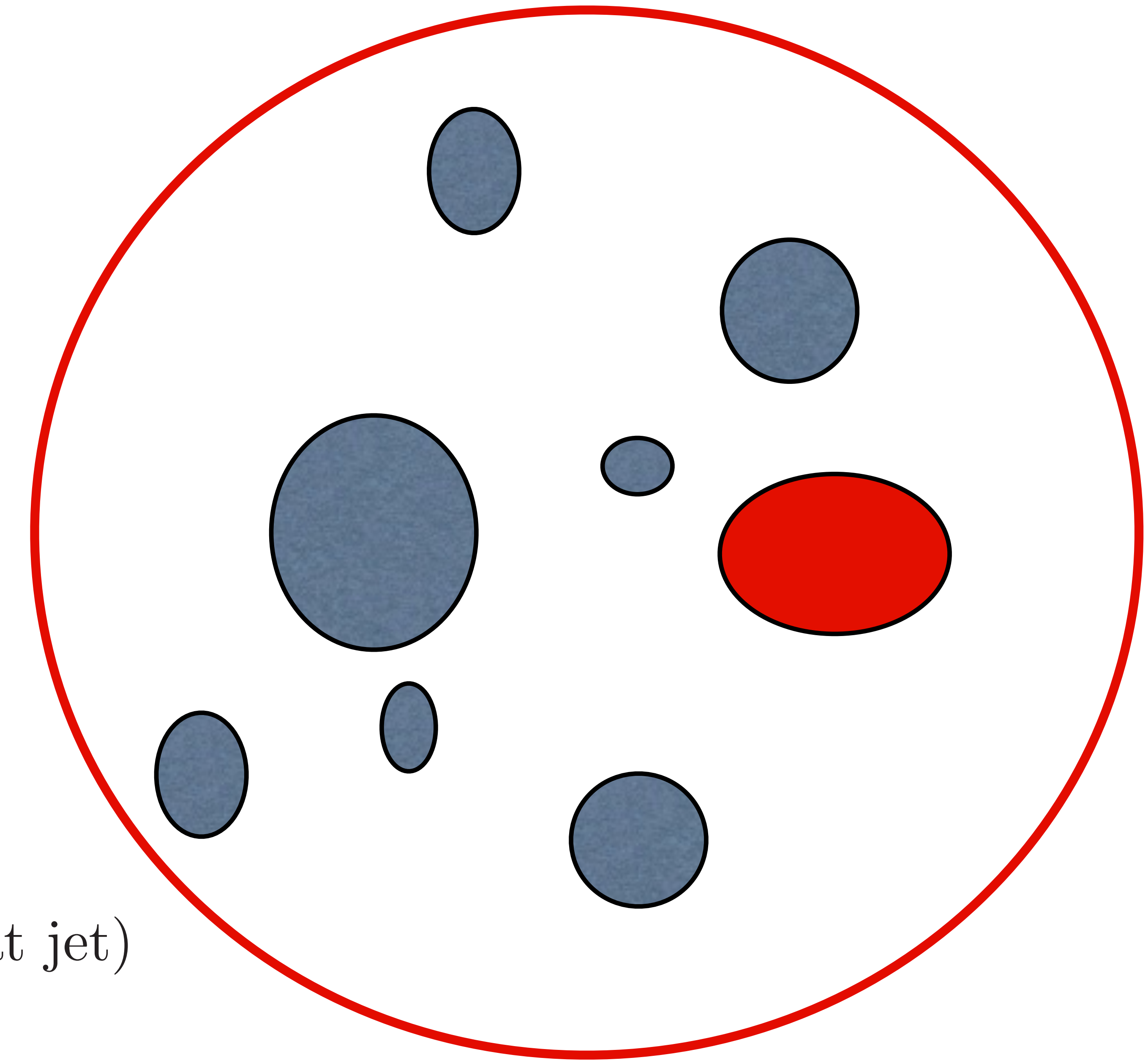
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

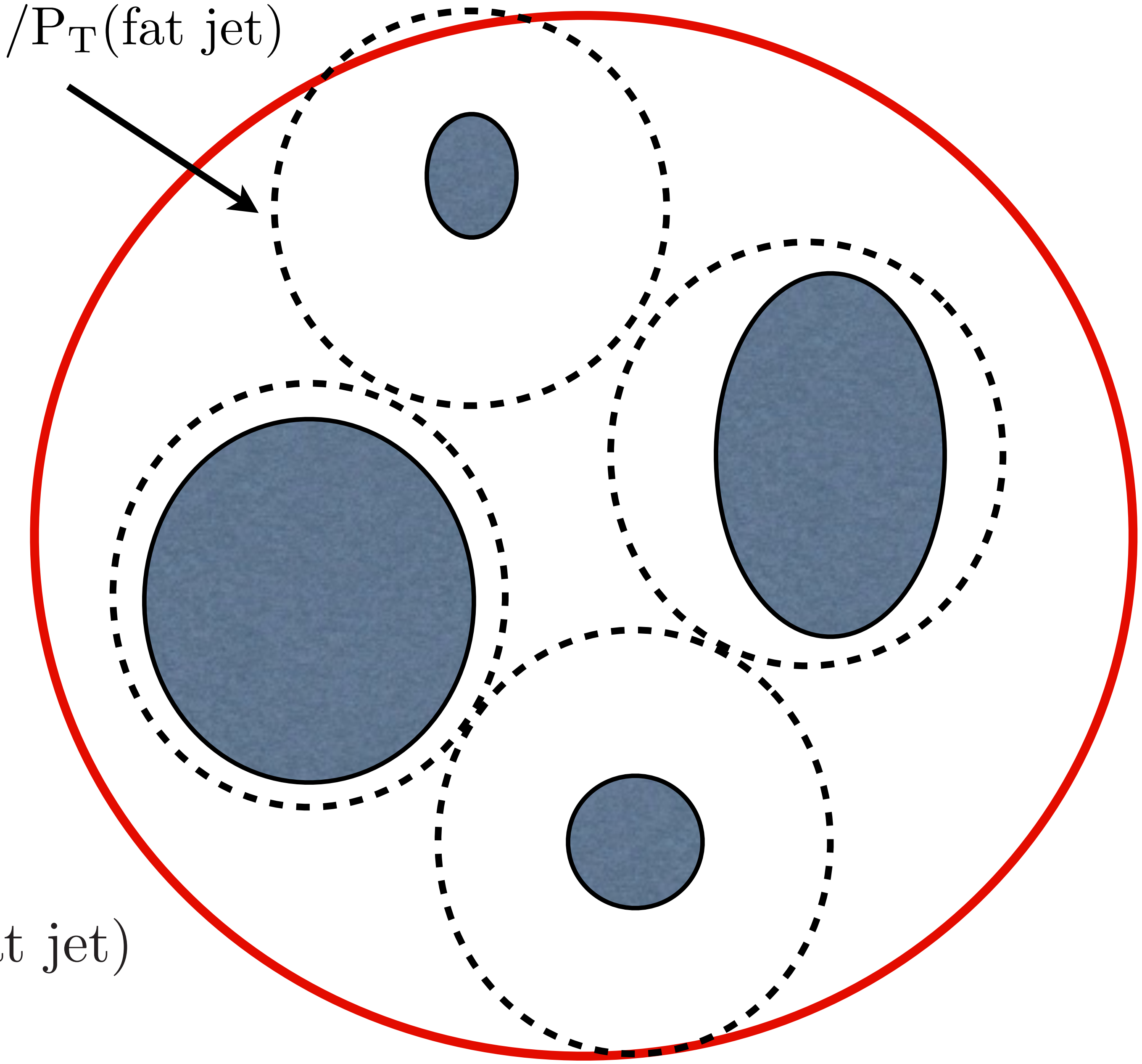
$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\rm cut}$$

$$\Delta R_{ij} > D_{\rm cut} = M(\text{fat jet})/P_T(\text{fat jet})$$



Pruning

$R = M(\text{fat jet})/\mathrm{P_T}(\text{fat jet})$



Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\text{cut}}$$

✓ $\Delta R_{ij} > D_{\text{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$

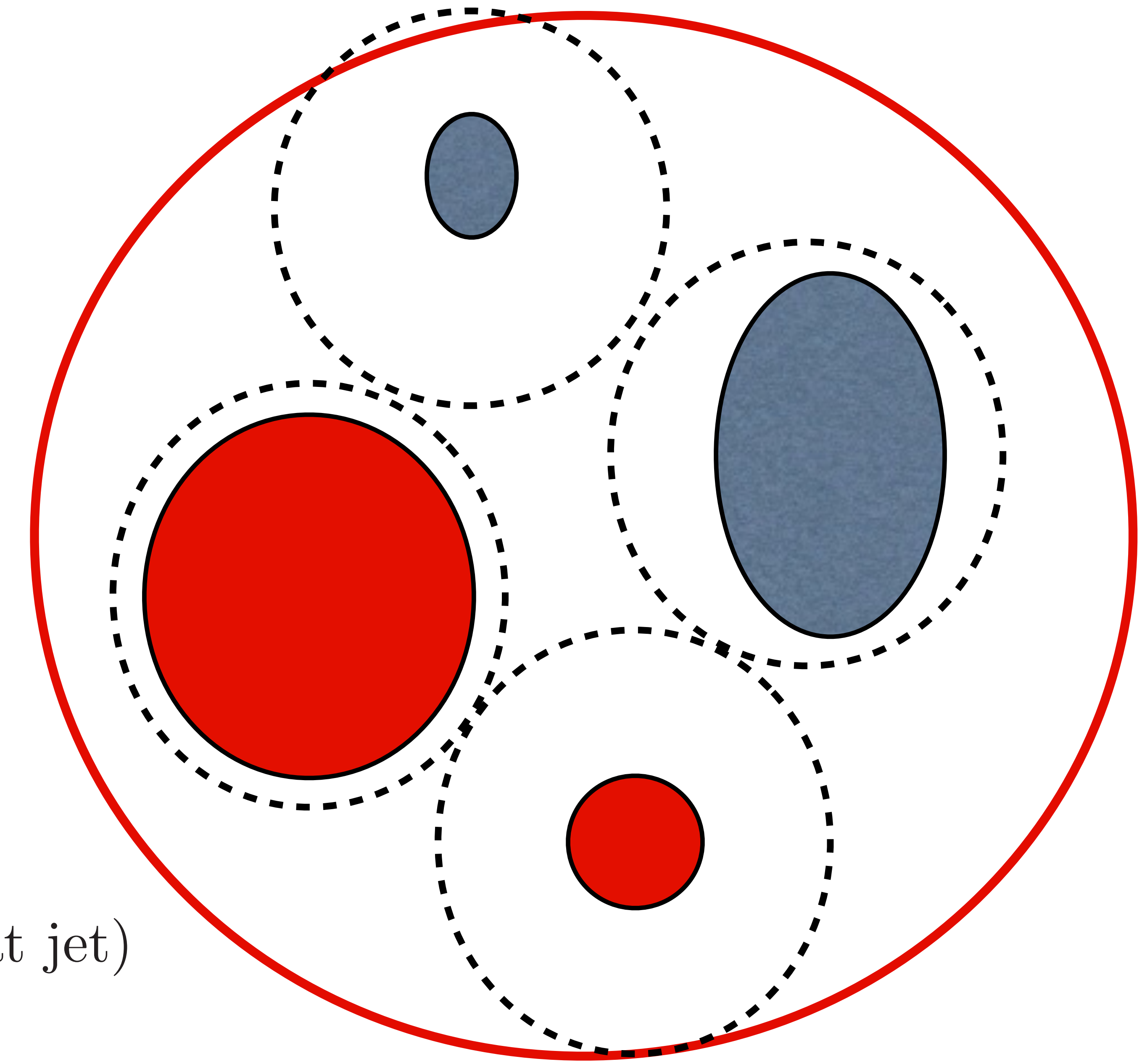
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

✓ $z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|}$

✓ $\Delta R_{ij} > D_{\text{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$



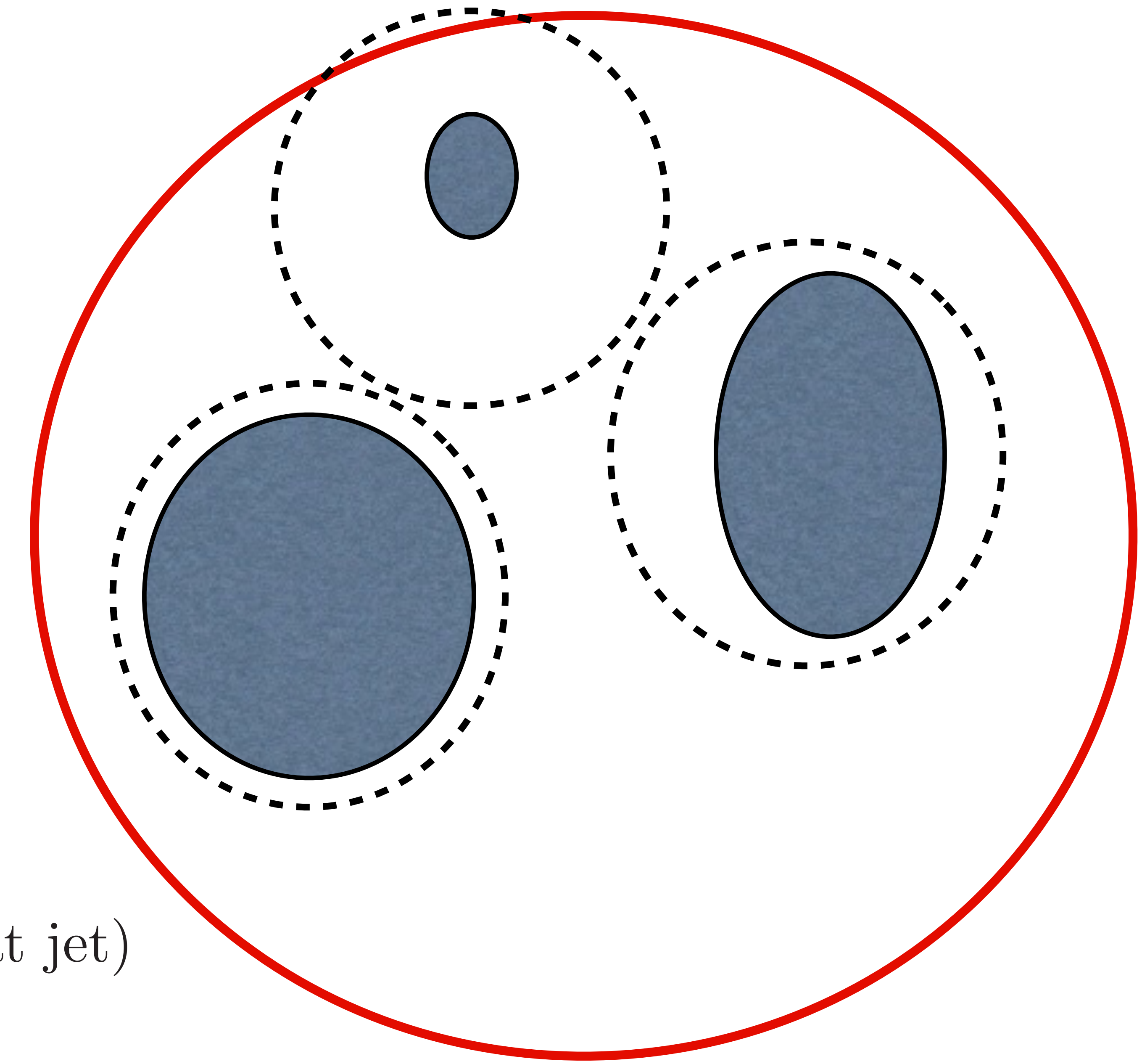
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\text{cut}}$$

$$\Delta R_{ij} > D_{\text{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$$



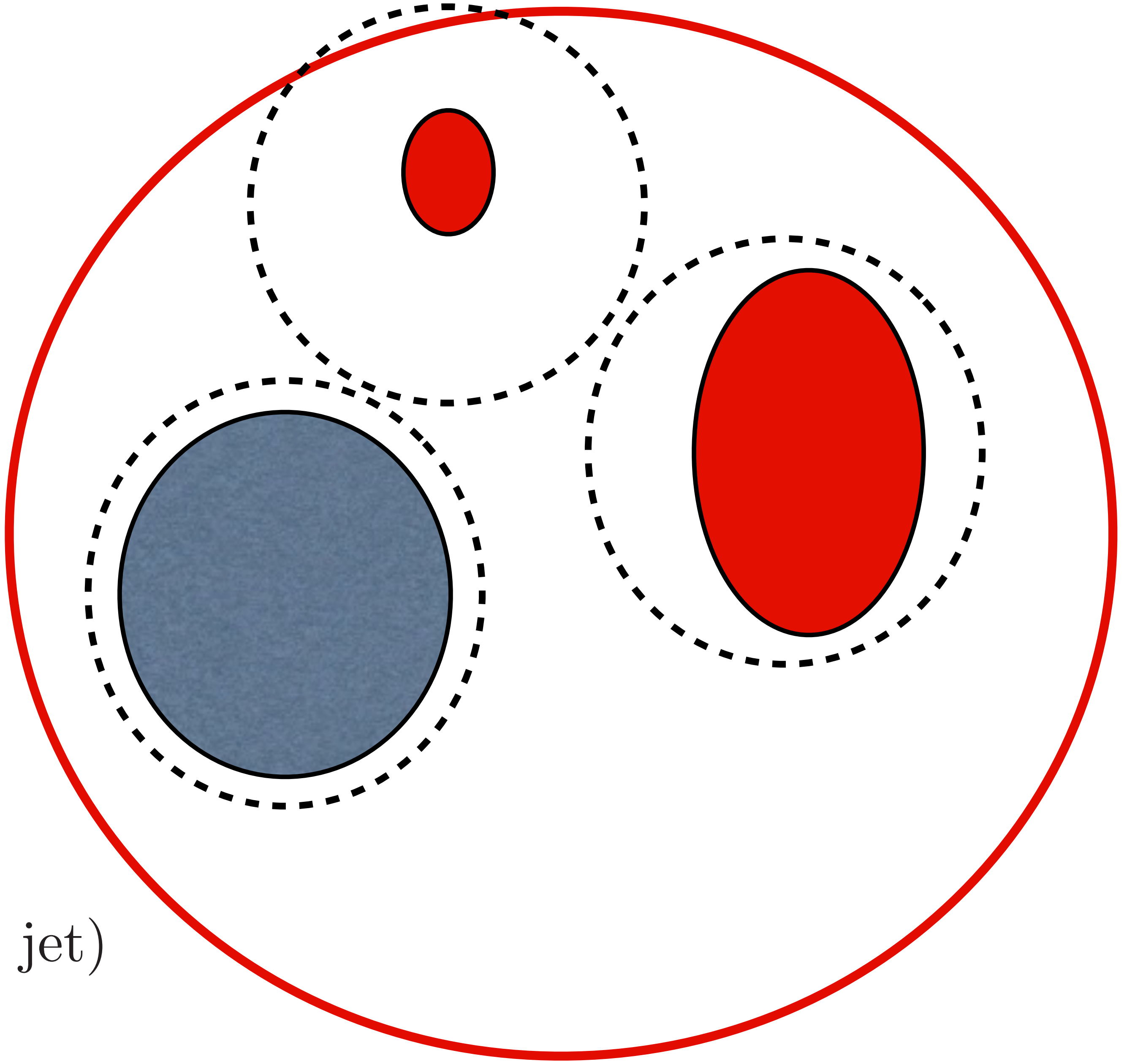
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

✓ $z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\mathrm{cut}}$

✓ $\Delta R_{ij} > D_{\mathrm{cut}} = M(\text{fat jet})/P_T(\text{fat jet})$



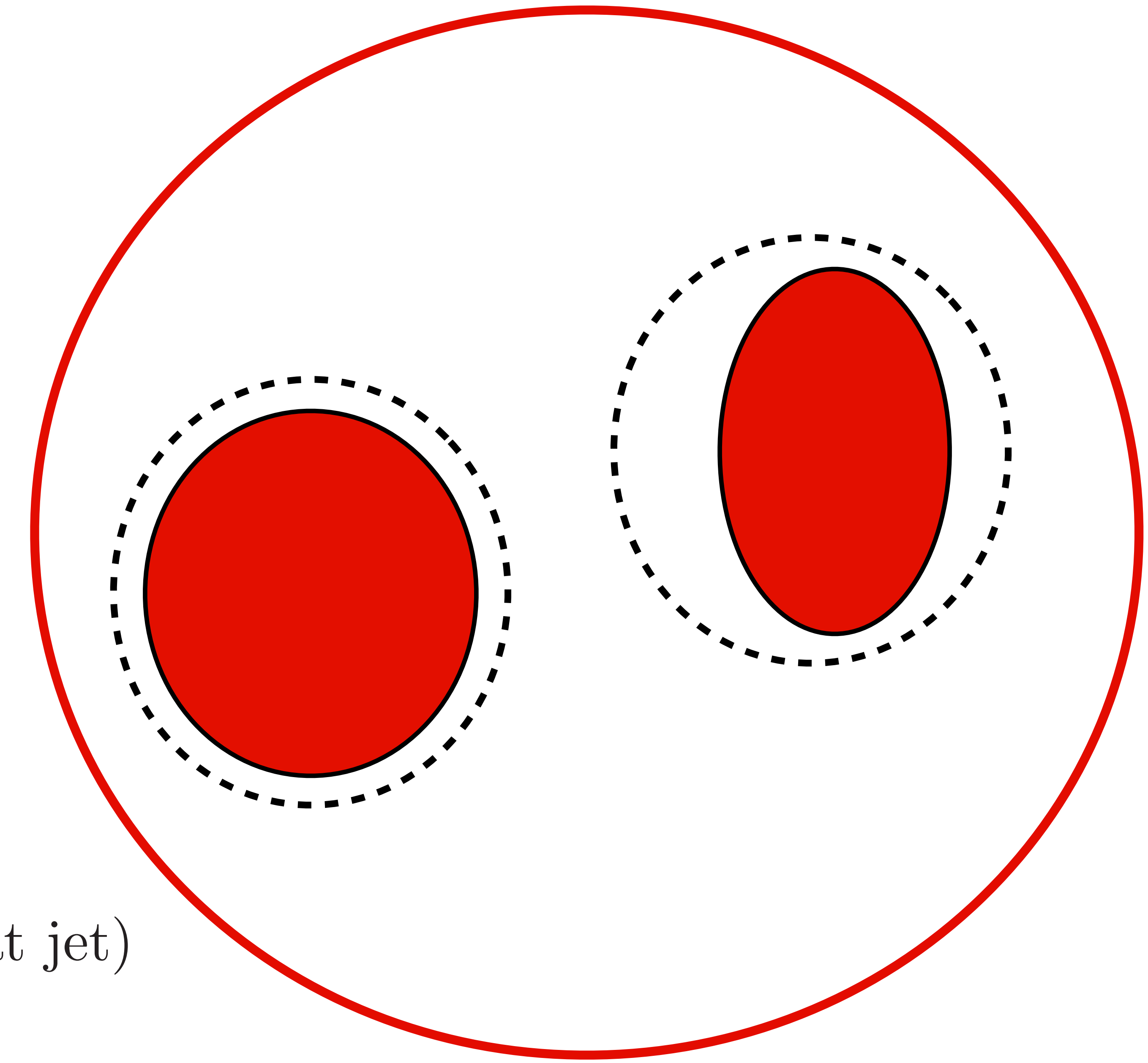
Pruning

Based on 2 conditions

If both hold true veto merging,
eg. recombination is wide angle and asymmetric

✗ $z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\mathrm{cut}}$

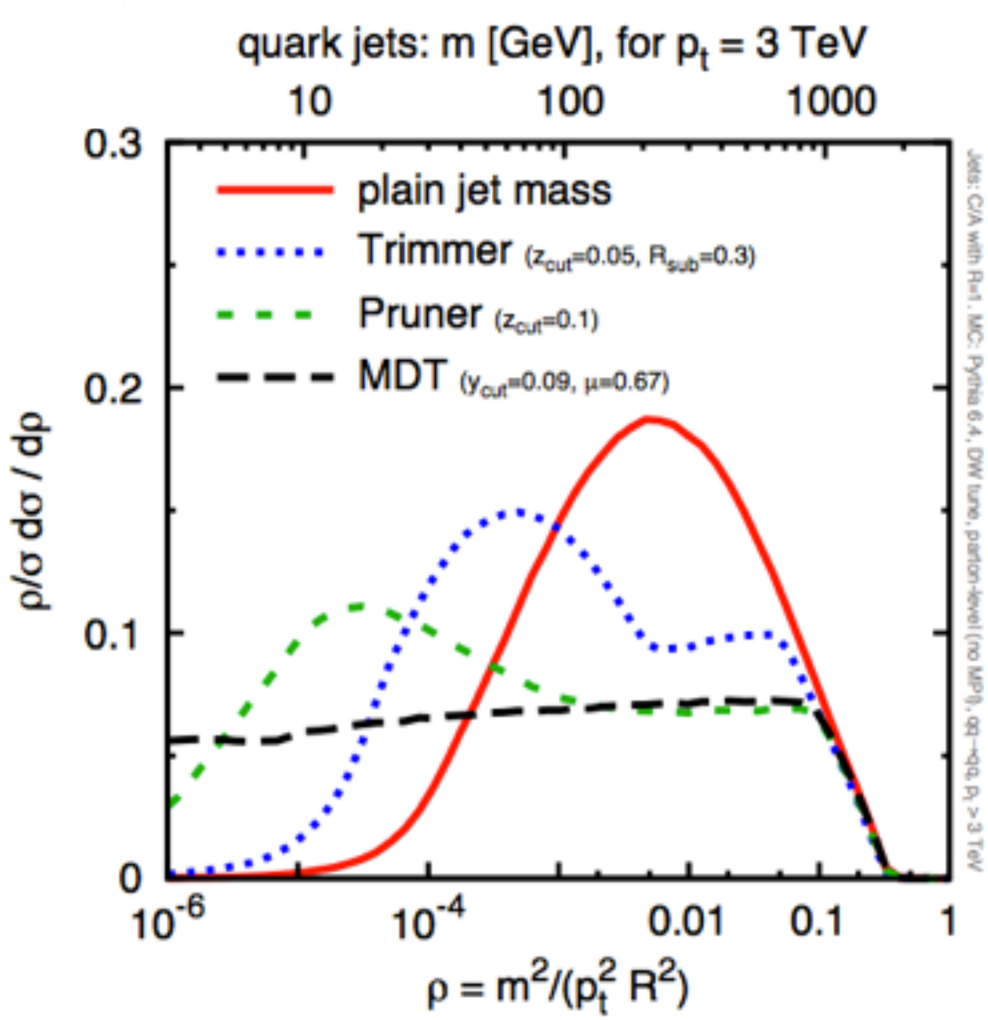
✓ $\Delta R_{ij} > D_{\mathrm{cut}} = M(\mathrm{fat\ jet})/P_T(\mathrm{fat\ jet})$



Grooming methods seem complicated but we can obtain theoretical understanding [Dasgupta, Fregoso, Marzani, Salam JHEP 1309]

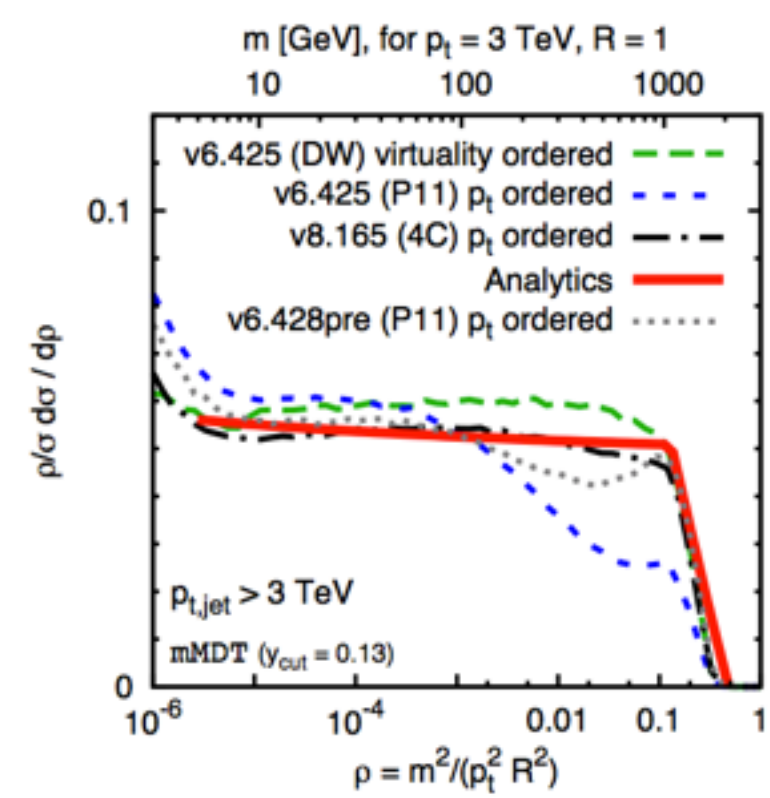
See also talks by Gregory Soyez and Andrzej Siodmok

one can calculate trimmed/pruned/filtered jet mass:

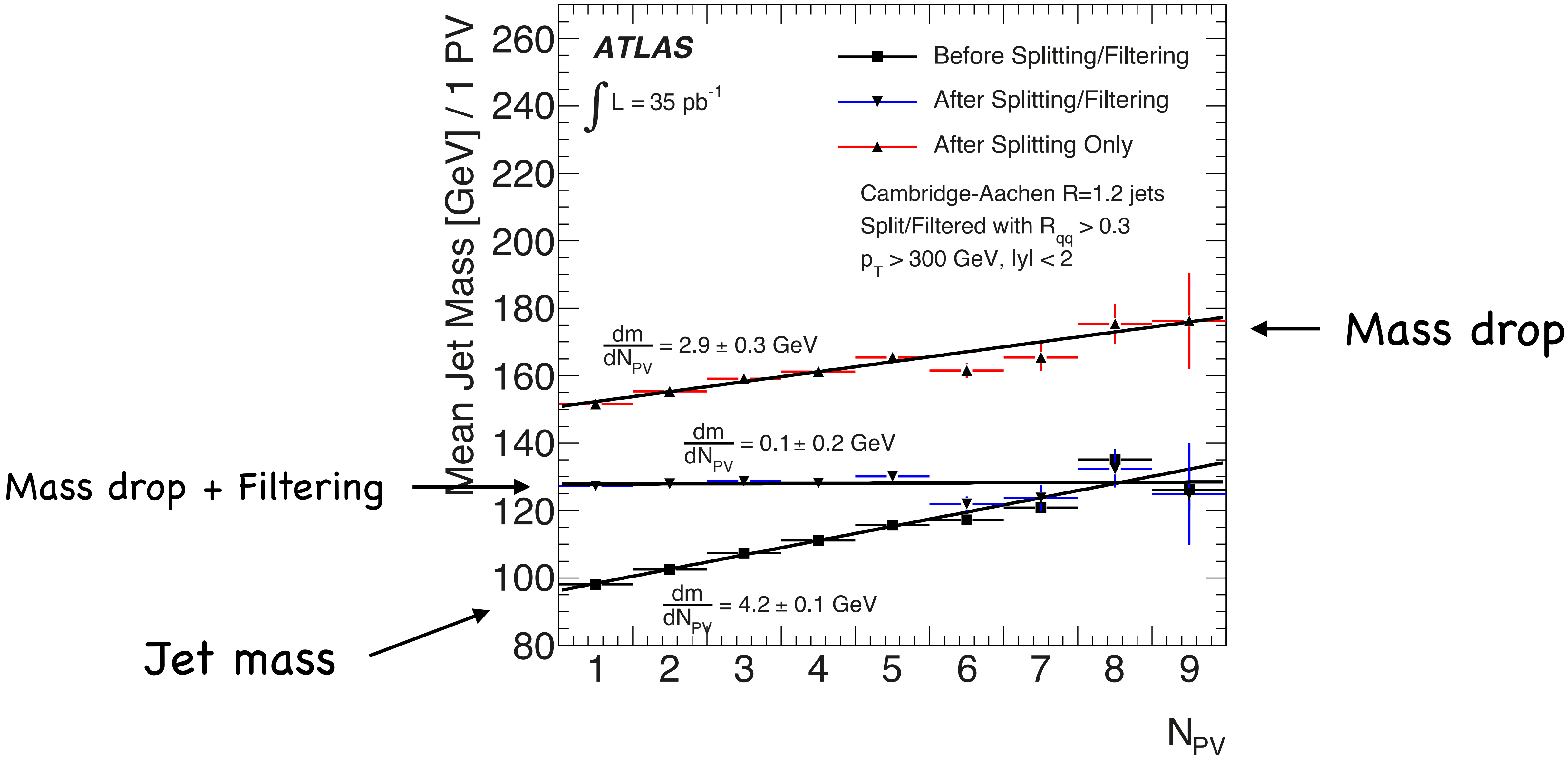


- Different methods show different logarithmic behaviour
  -> parameter need to be chosen wisely!

calculation helped finding bug in Pythia 6



Most importantly, these methods do exactly what they are supposed to do:



Grooming removes sensitivity to soft radiation

Tagging Electroweak scale resonances

Tagging = Identify Object

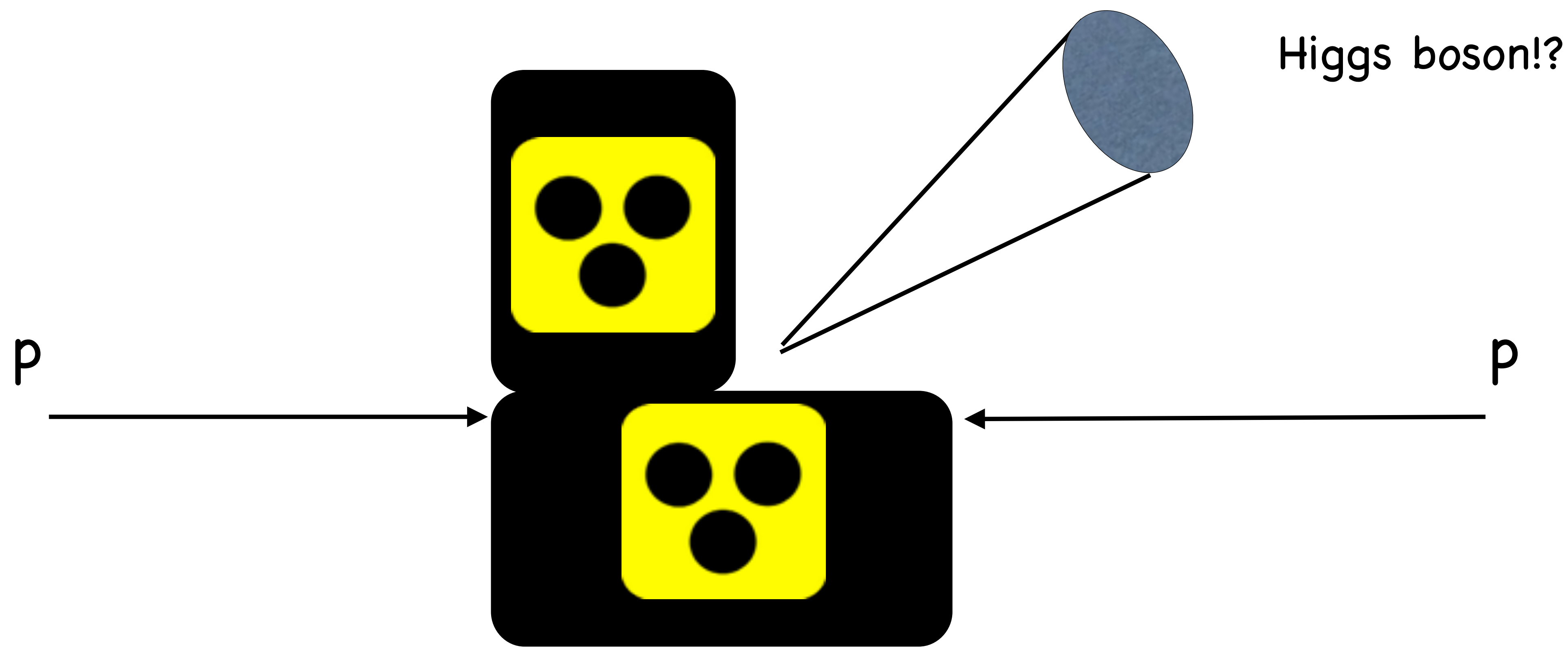
Identification exploits fact that quantum numbers of signal resonance different than backgrounds

Quantum numbers are: mass, colour, spin, couplings (width)

-> we need to construct observables which indicate different QN

Higgs: (125 GeV, 0, 0, 4 MeV) → Simplest! Success of BDRS
W/Z: (80-90 GeV, 0, 1, ~2 GeV) → Spin correlations
top: (170 GeV, 1/3, 1/2, ~2 GeV) → Only EW scale colored object

Taggers make use of fraction of event

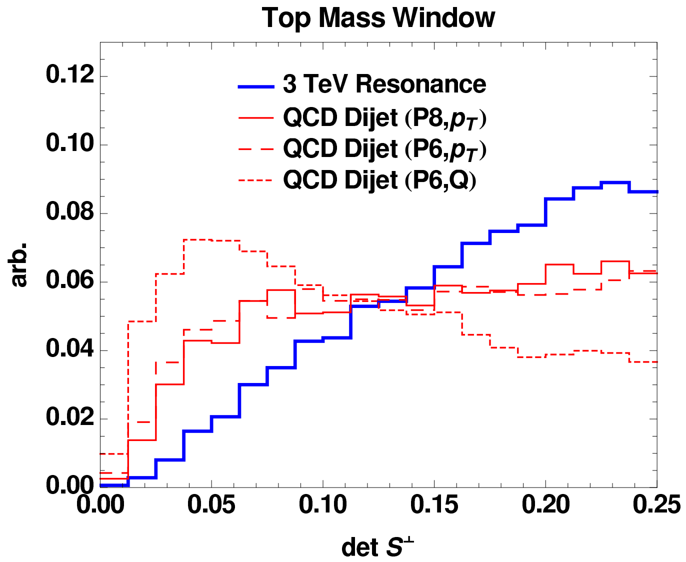


Tagger implicitly ignores rest of event, i.e. production mechanism

(strictly not correct)

Boson tagging approaches

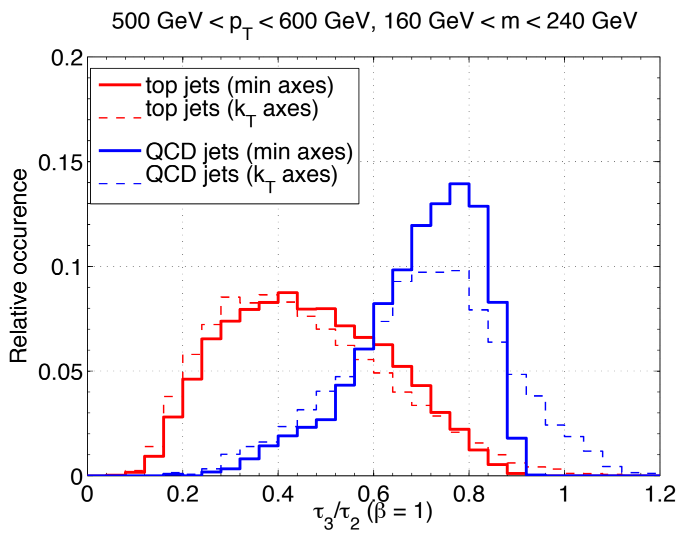
- Propagate event shape to jet shape:



- sphericity:

$$S^{\perp kl} = \frac{1}{\sum_{\alpha\in \text{jet}} |\vec{p}_\alpha^{\perp}|} \sum_{\alpha\in \text{jet}} \frac{\vec{p}_\alpha^{\perp k} \vec{p}_\alpha^{\perp l}}{|\vec{p}_\alpha^{\perp}|}$$

- N-subjettiness: [Thaler, Van Tilburg JHEP 1103]

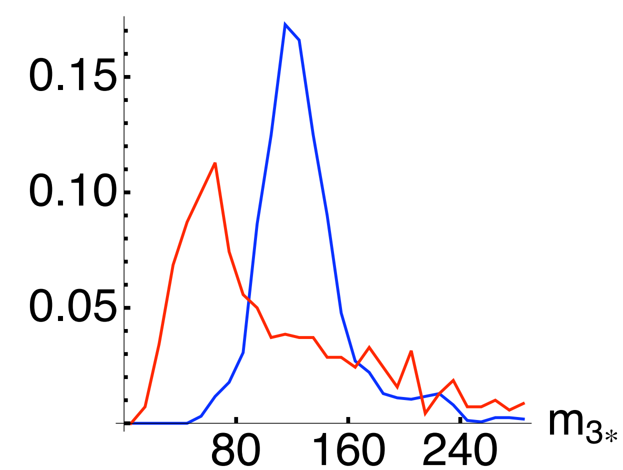


$$\tau_N = \frac{1}{\sum_{\alpha\in \text{jet}} p_{T,\alpha} R_0^\beta} \sum_{\alpha\in \text{jet}} p_{T,\alpha} \min_{k=1,\dots,N} (\Delta R_{k,\alpha})^\beta$$

- treeless approach: [Jankowiak, Larkoski JHEP 1106]

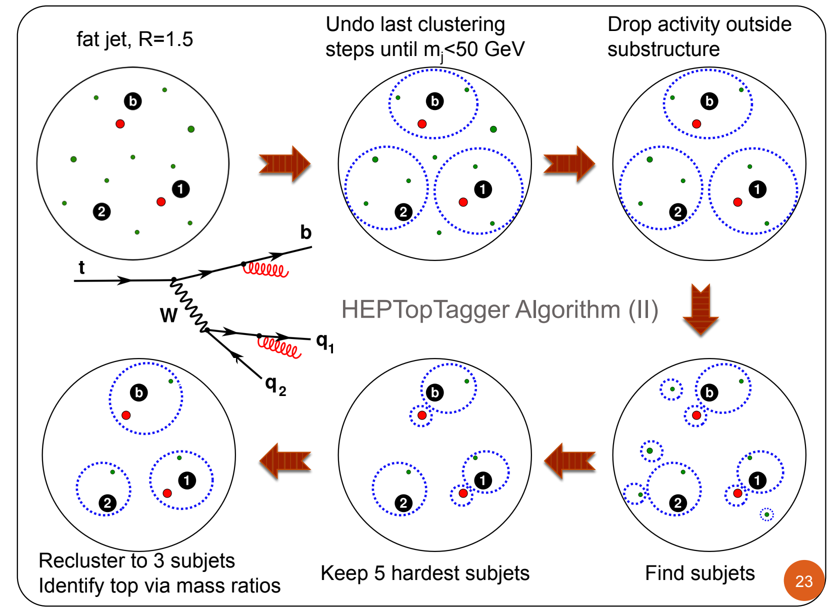
$$d_{j_1 j_2} = p_{T,j_1} p_{T,j_2} \, \Delta R^2_{j_1 j_2}$$

$$\mathcal{G}(R) = \frac{\sum_{j_1\neq j_2} d^{(\text{JADE})}_{j_1 j_2} \, \Theta(R - \Delta R_{j_1 j_2})}{\sum_{j_1\neq j_2} d^{(\text{JADE})}_{j_1 j_2}}$$



Boson tagging approaches

- **subjet based pronged reconstruction:**

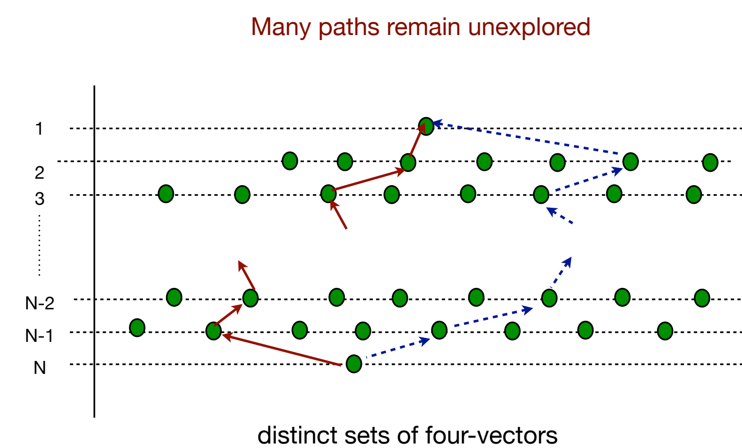


  - massdrop taggers:

    [Butterworth et al. PRL 100 (2008)]

    [Plehn et al. PRL 104 (2010)]

  - Qjets: [Ellis et al. PRL 108 (2012)]



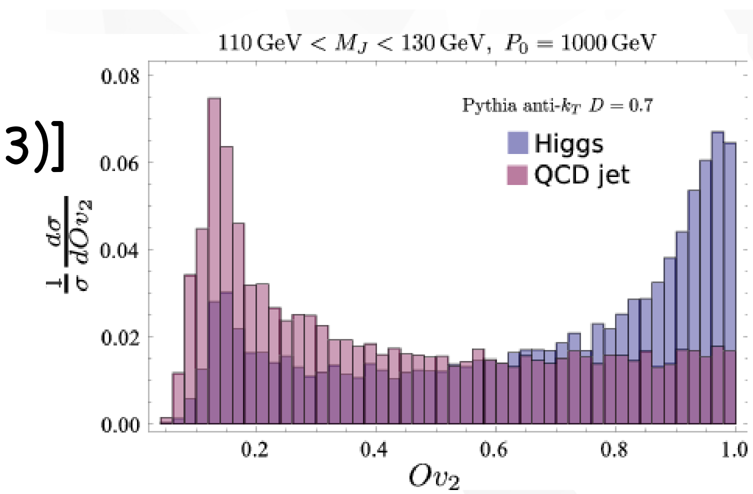
$$\omega_{ij}^{(\alpha)} \equiv \exp\left\{-\alpha\frac{(d_{ij}-d^{\min})}{d^{\min}}\right\}$$

$$d_{ij} = \begin{cases} d_{k_T} \equiv \min\{p_{Ti}^2, p_{Tj}^2\}\Delta R_{ij}^2 \\ d_{C/A} \equiv \Delta R_{ij}^2 \end{cases}$$

  - Template Method: [Almeida et al. PRD 82 (2010)]

    [Backovic, Juknevic, Perez JHEP (2013)]

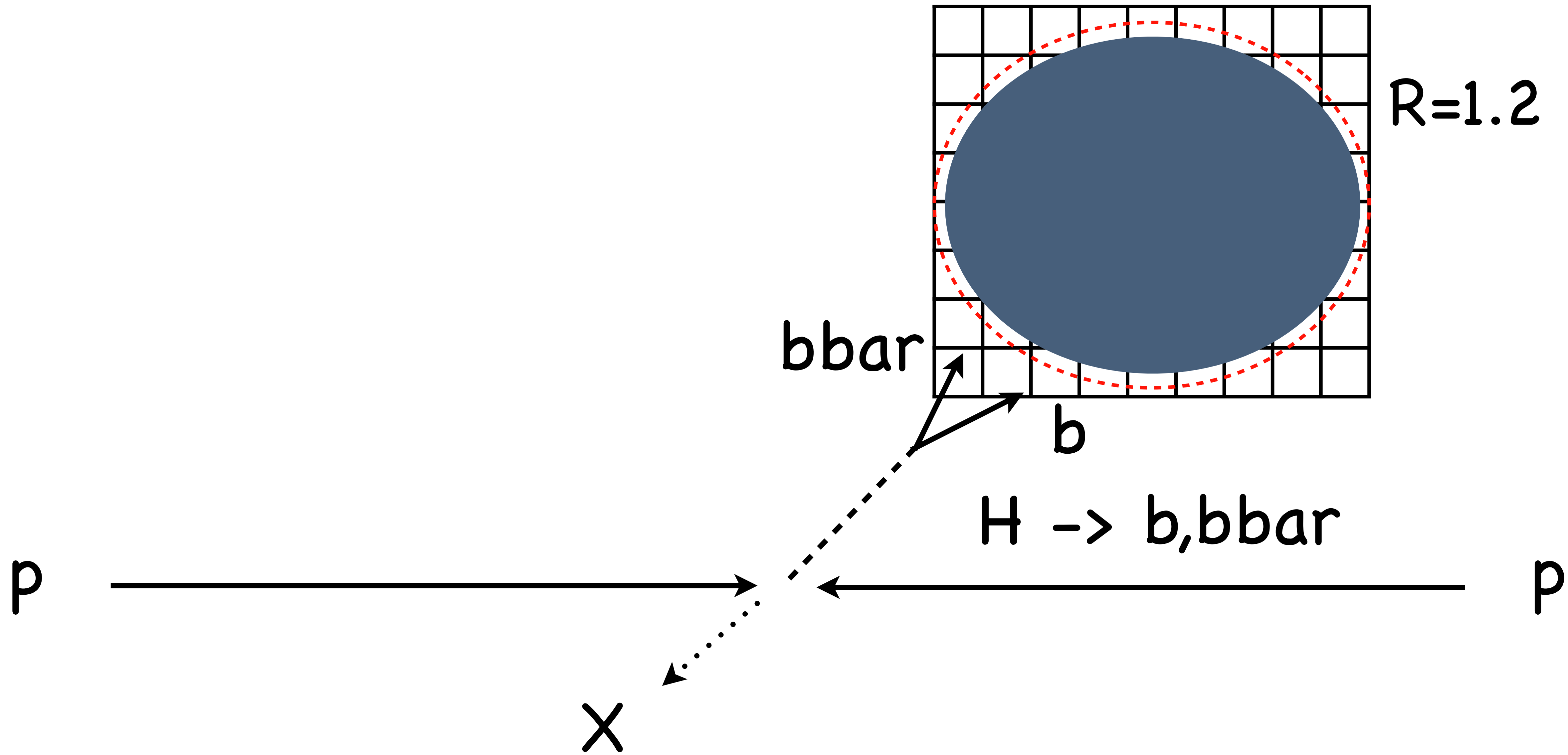
$$Ov_N(j,f) = \max_{\tau_N^{(R)}} \exp\left[-\sum_{a=1}^{N}\frac{1}{2\sigma_a^2}\left(\sum_{k=i_a-1}^{i_a+1}\sum_{l=j_a-1}^{j_a+1} E(k,l) - E(i_a,j_a)^{(f)}\right)^2\right]$$



Taggers access different information

e.g. BDRS [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \times \Gamma(H \to b\bar{b})$$



Taggers access different information

e.g. BDRS [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \times \Gamma(H \to b\bar{b})$$

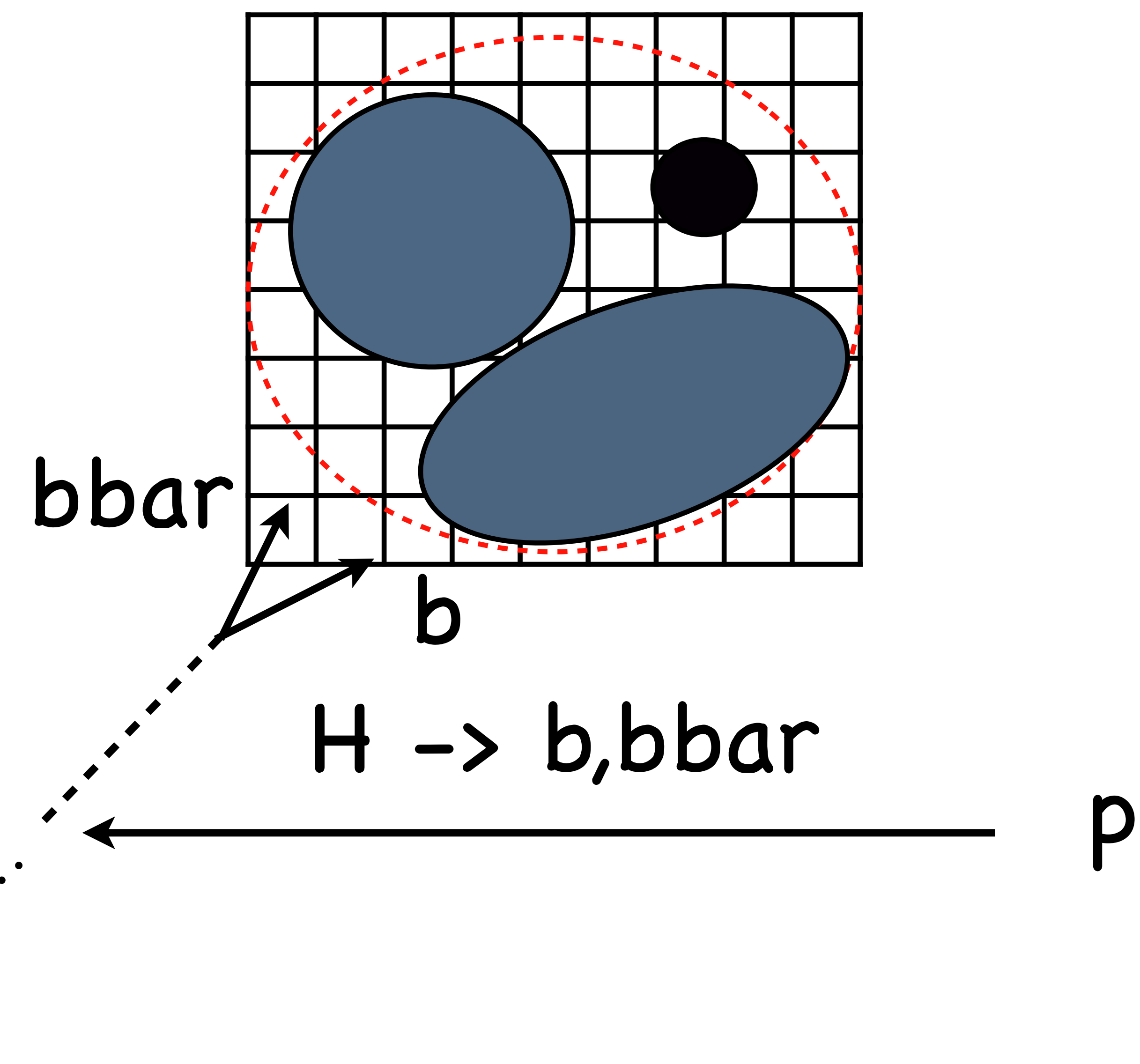
mass drop:

1) check for mass drop

$m_{j1} < 0.66\, m_j$

2) check "asymmetry"

$$y = \frac{\min\left(p_{t_{j1}}^2, p_{t_{j2}}^2\right)}{m_j^2} \Delta R_{j_1, j_2}^2 > y_{\rm cut}$$



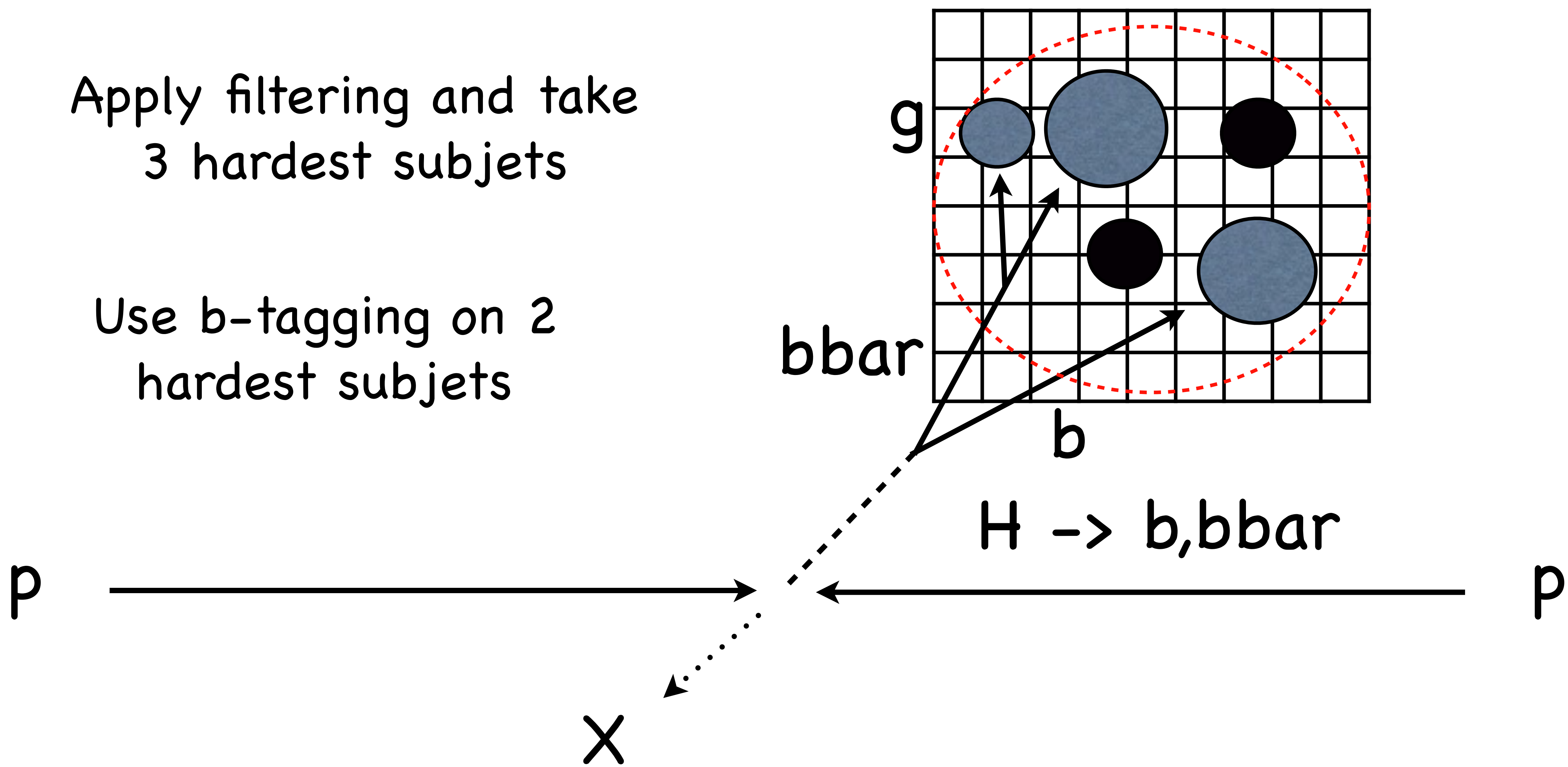
Taggers access different information

e.g. BDRS [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \times \Gamma(H \to b\bar{b})$$

Apply filtering and take 3 hardest subjets

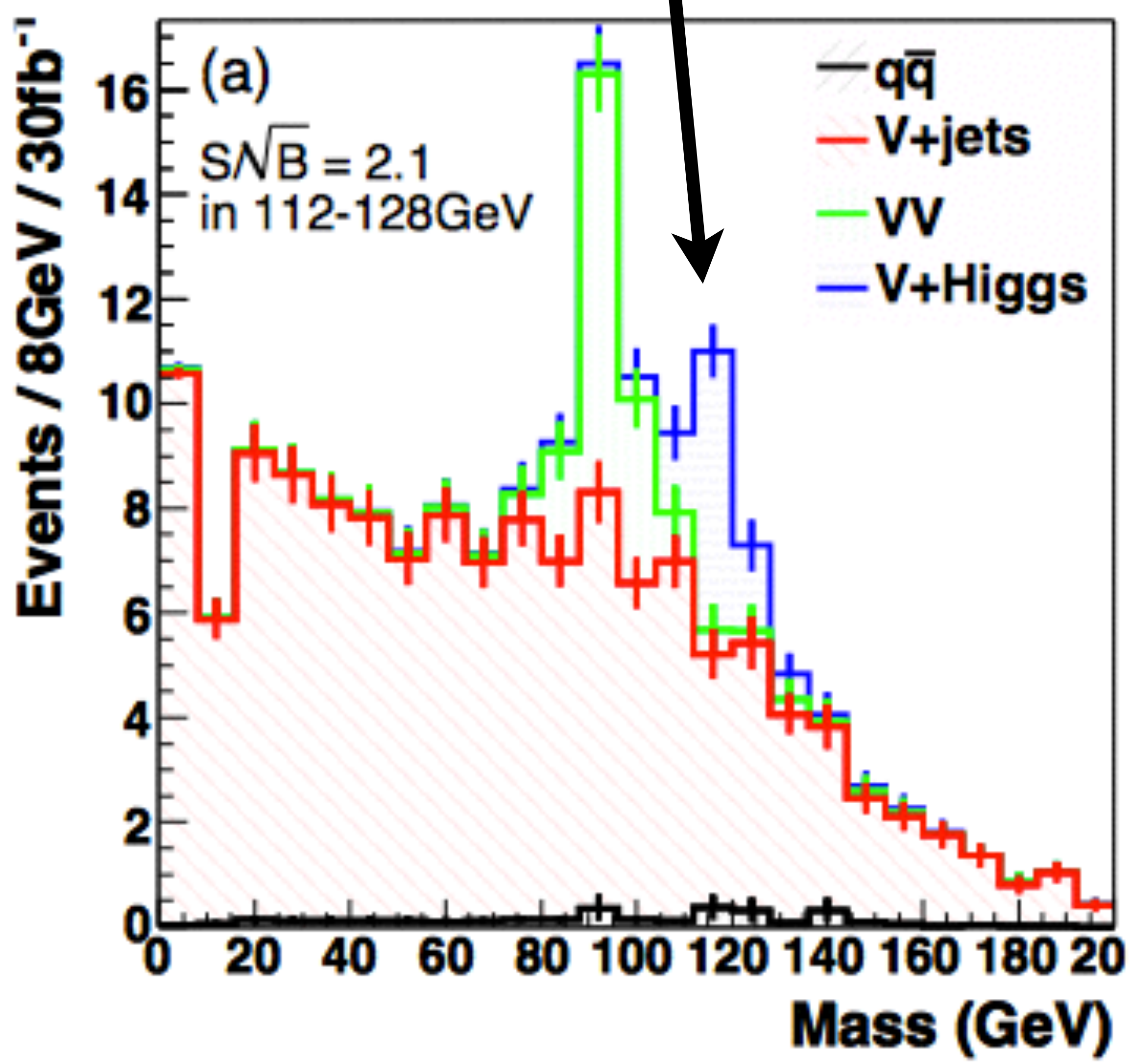
Use b-tagging on 2 hardest subjets



Taggers access different information

$$\sigma(pp \to HX) \times \frac{1}{(p_H^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \times \Gamma(H \to b\bar{b})$$

Higgs pT spectrum



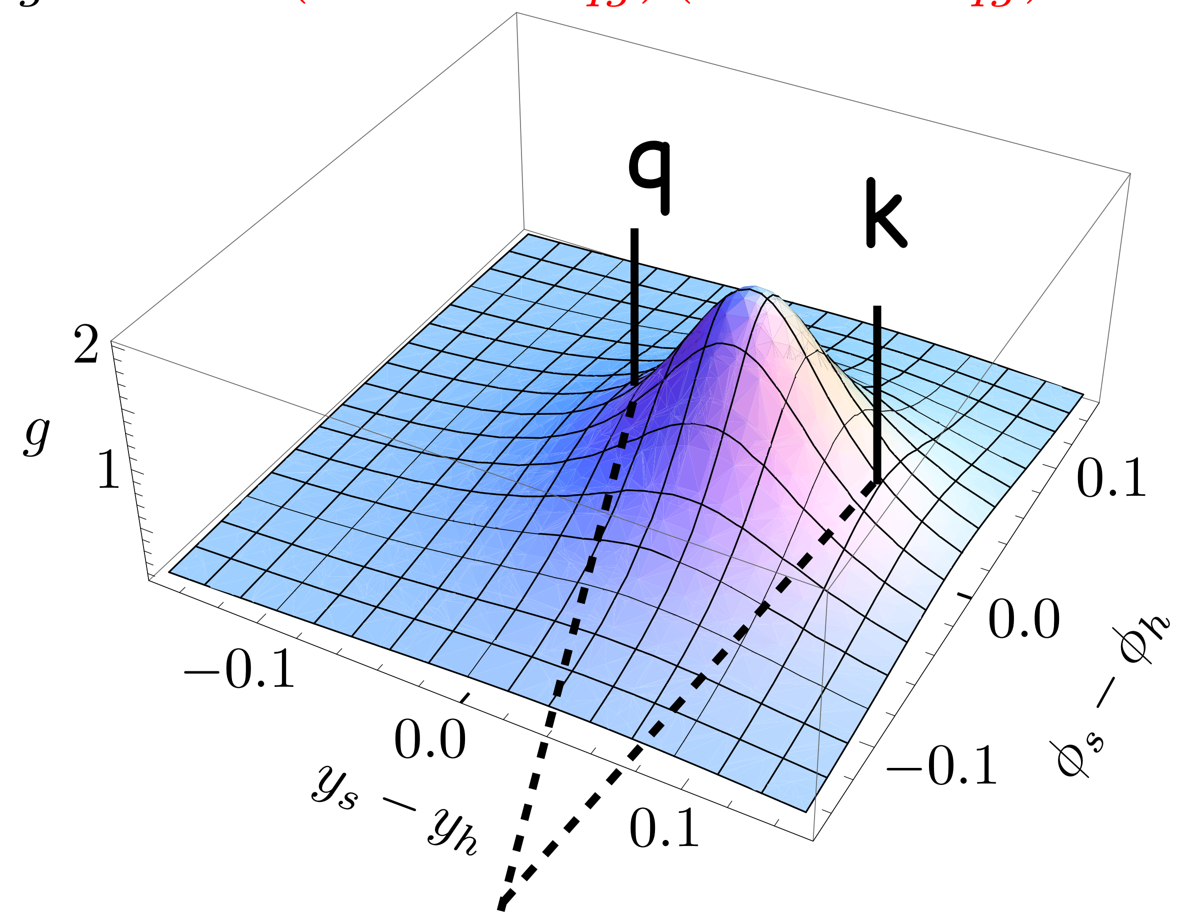
select final state

Taggers access different information

BDRS very successful, but could still be improved by taking color connection into account

$$\sigma(q\bar{q}g) = \sigma_0(q\bar{q}) \int C_F \frac{\alpha_s}{2\pi} \frac{dE_g}{E_g} d\cos\theta \frac{2(1-\cos\theta_{\bar{q}q})}{(1-\cos\theta_{qg})(1-\cos\theta_{\bar{q}g})}$$

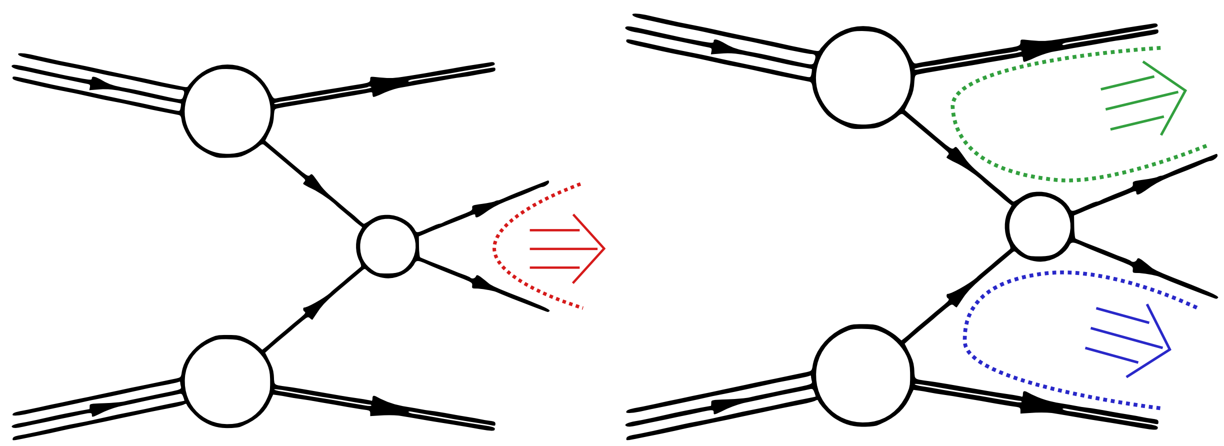
Soft gluon tends to be emitted into cone between quarks from Higgs decay



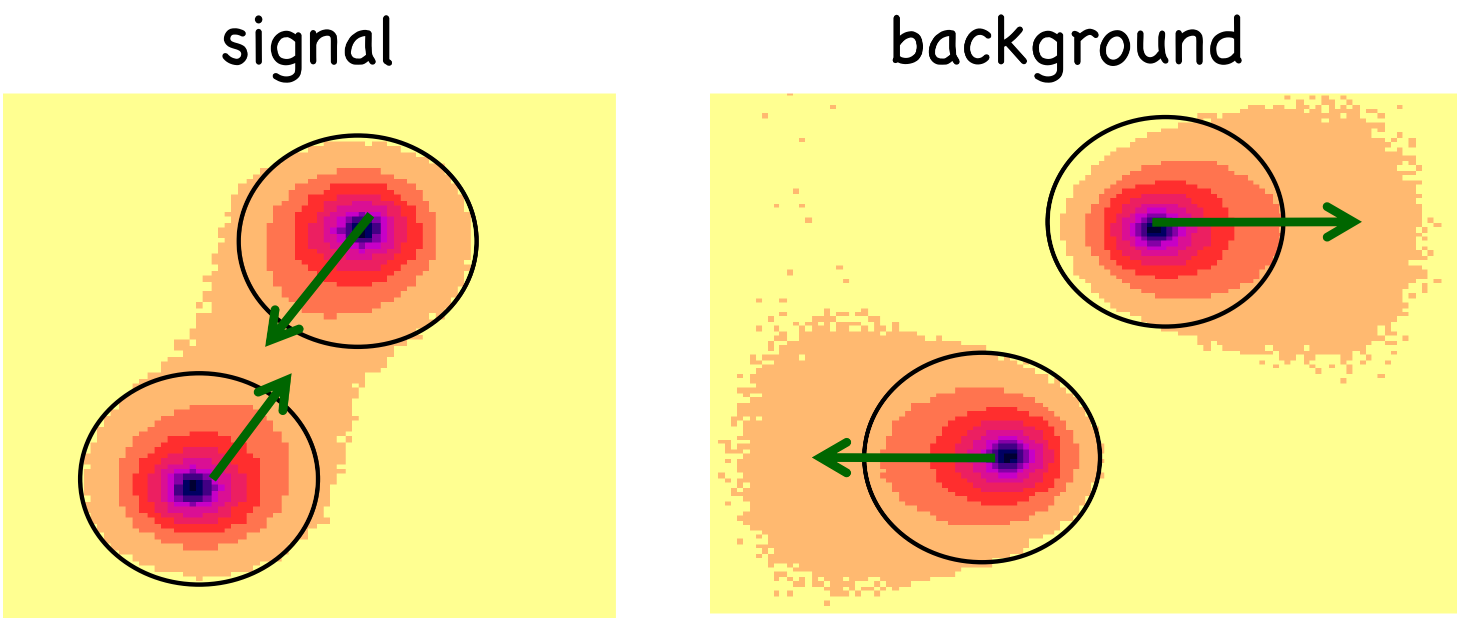
Higgs decay products

Pull designed to access color coherence

[Gallicchio and Schwartz PRL 105(2010)]



$$\vec{t} = \sum_{i \in \text{jet}} \frac{p_T^i \, |r_i|}{p_T^{\text{jet}}} \vec{r}_i$$



- Pull can access information not used by BDRS
- Studied in ATLAS, can help to identify top decay products

Boosted top quarks - a perfect test ground

- top itself is colored object

  -> top can radiate gluons

- decays electroweak into other colored objects

  -> decay products have spin/color correlations

- At LHC plenty of energy

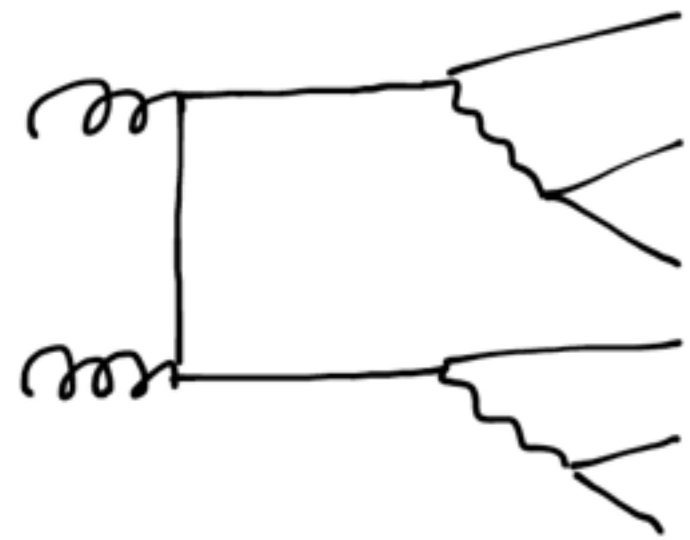
  -> tops produced beyond threshold

  -> lots of radiation in event

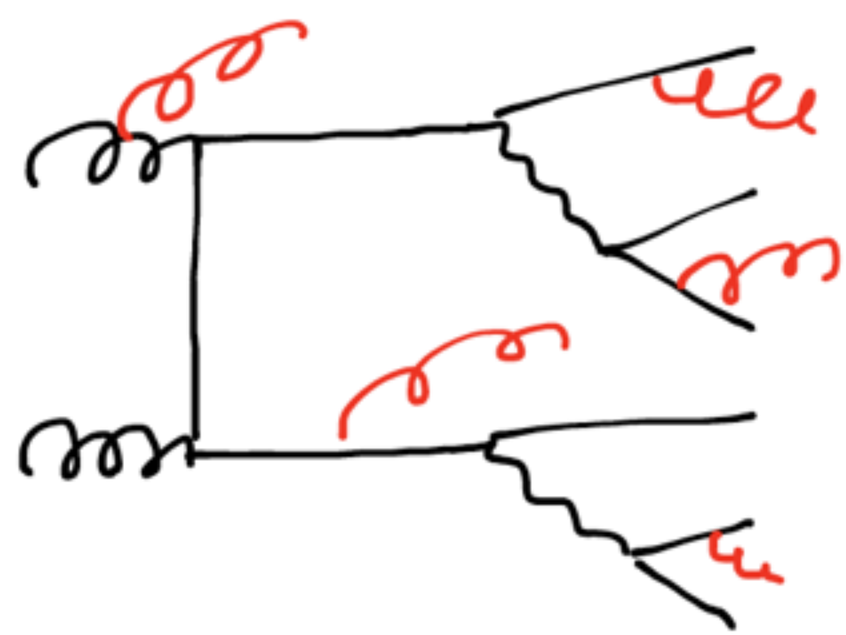
- Mass of top induces scale

  -> different kinematic regimes

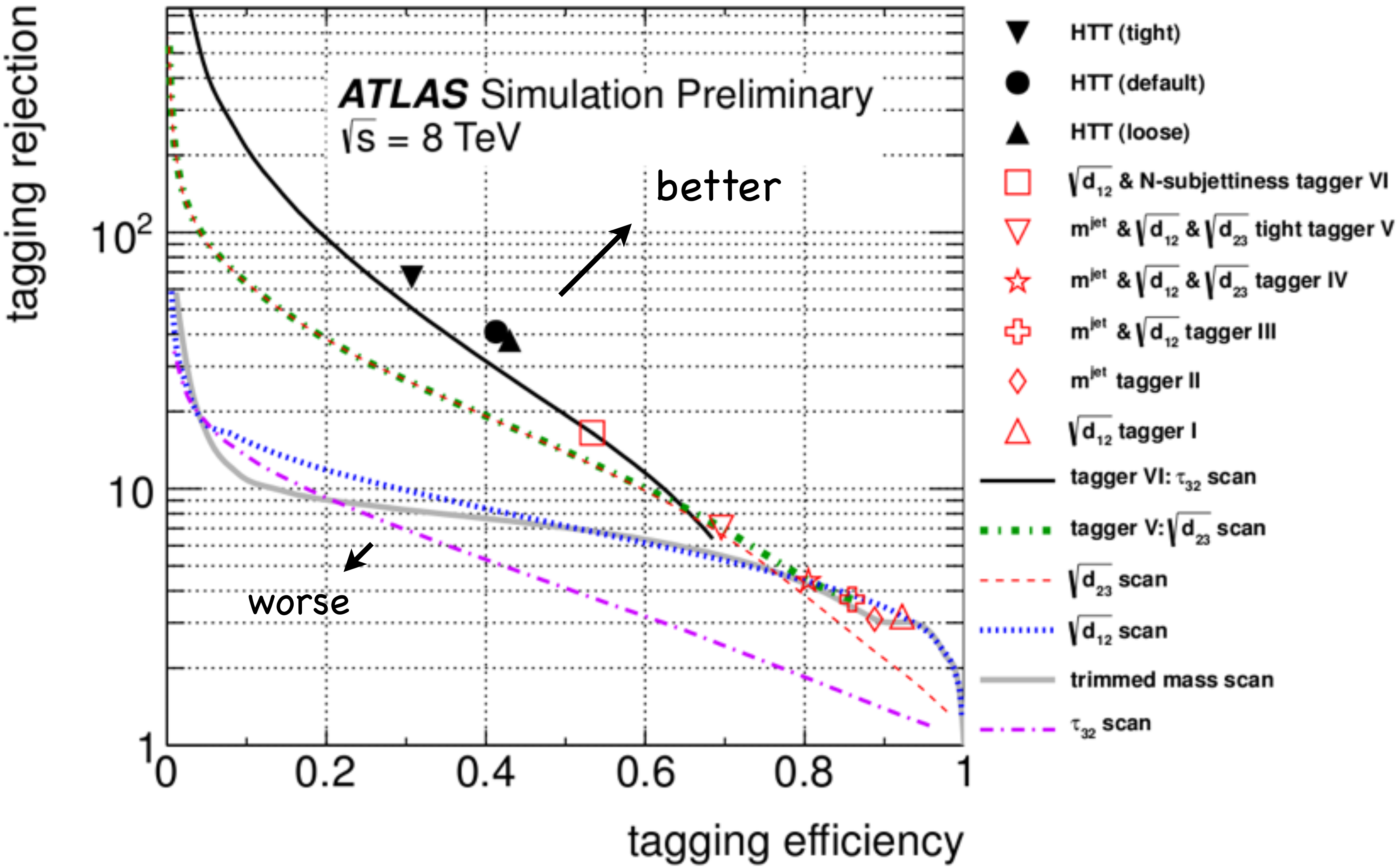
LO ttbar production



ttbar production + radiation

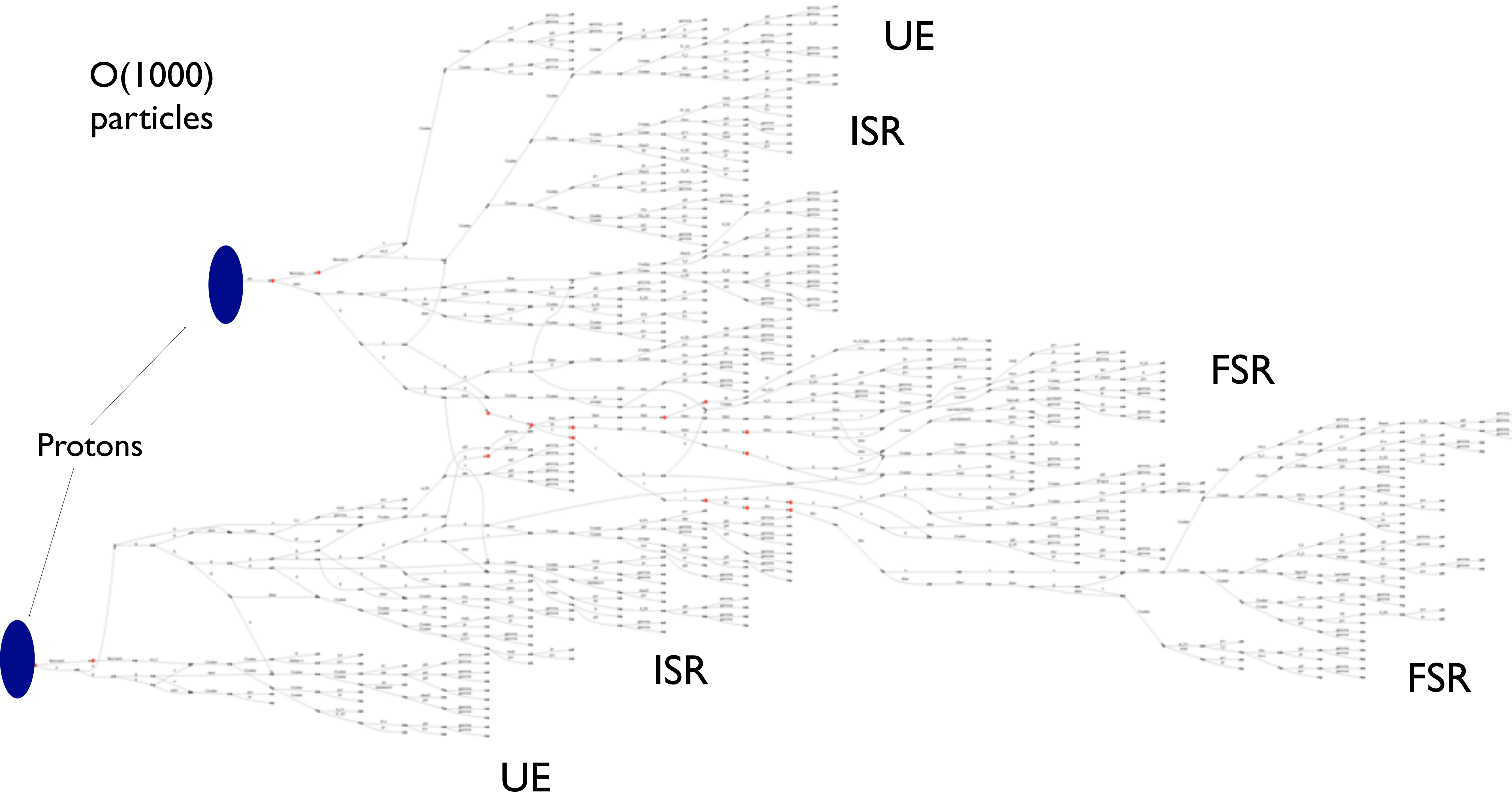


Comparison of top taggers



Question: Can theory guide us the way to improve taggers?

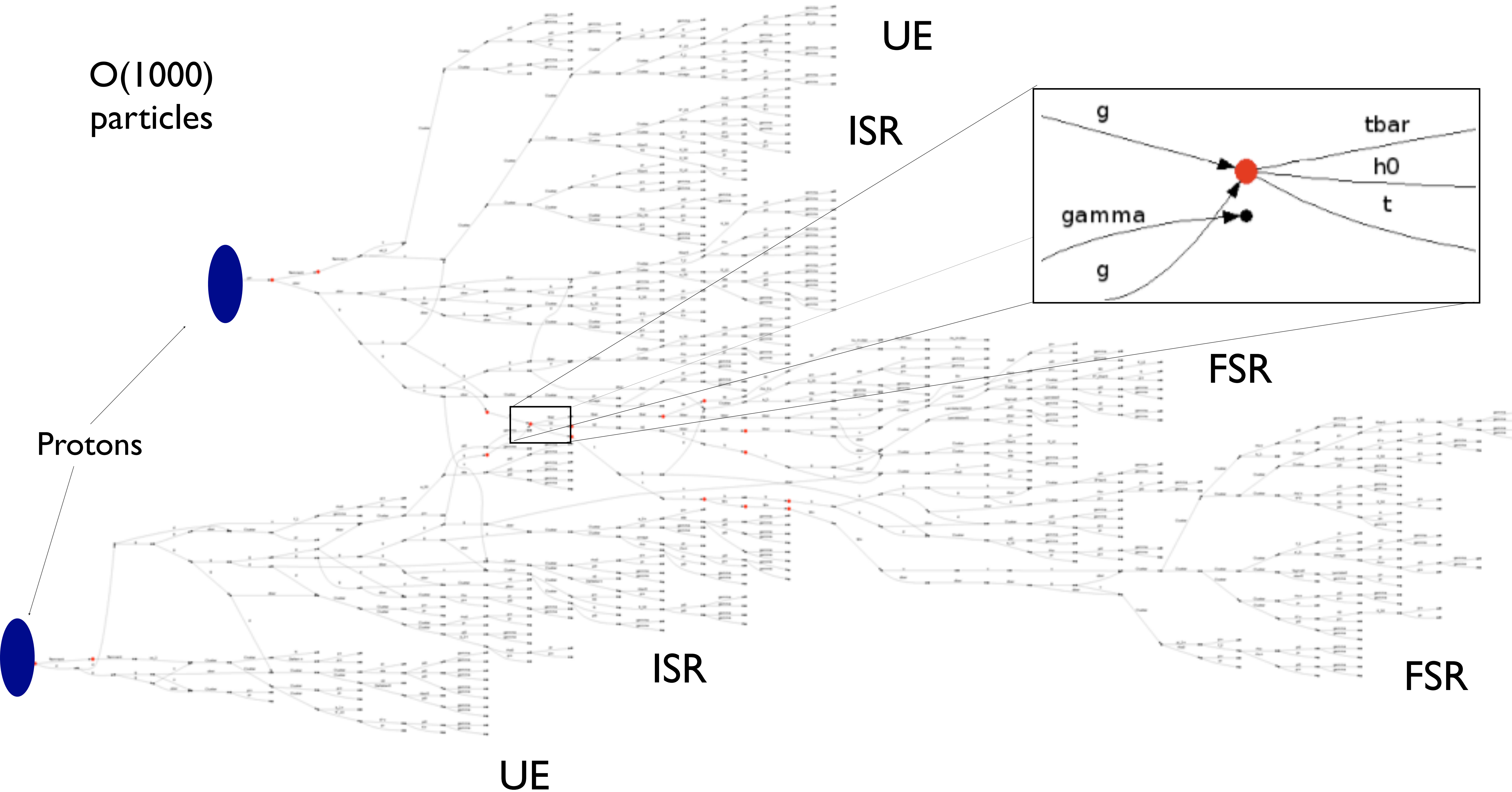
Is it possible to perform such hypothesis test given complexity of LHC events?



At least full event generators do a good job reproducing data...

Question: Can theory guide us the way to improve taggers?

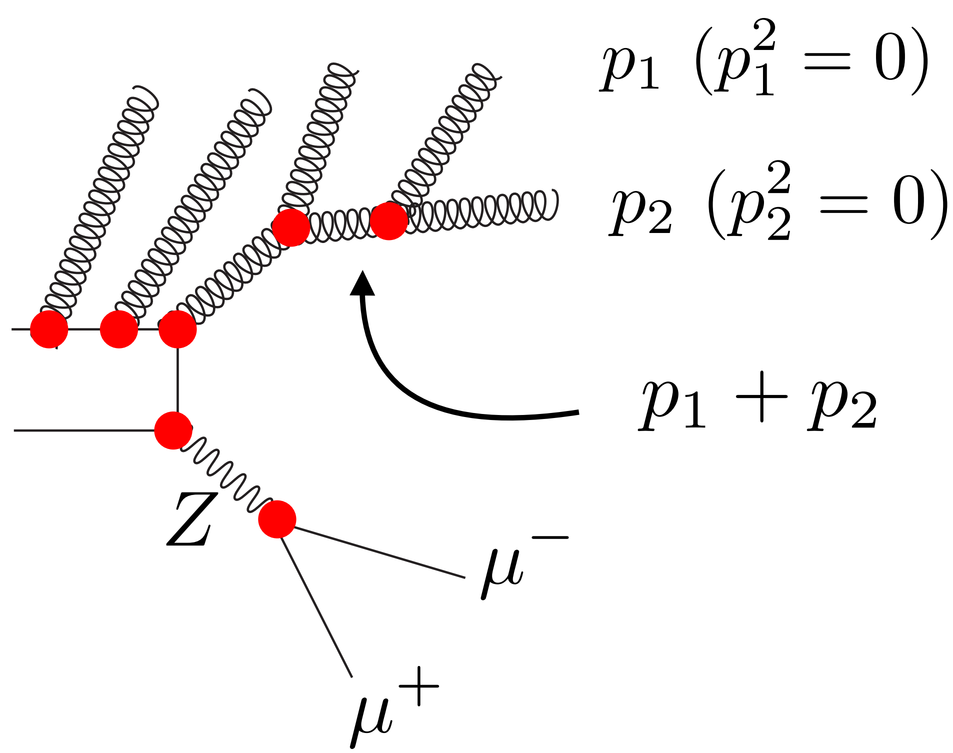
Is it possible to perform such hypothesis test given complexity of LHC events?



At least full event generators do a good job reproducing data...

Parton shower in a nutshell

The parton shower bridges the gap from the hard interaction scale down to the hadronization scale O(1) GeV



partons from the hard interaction emit other partons (gluons and quarks)

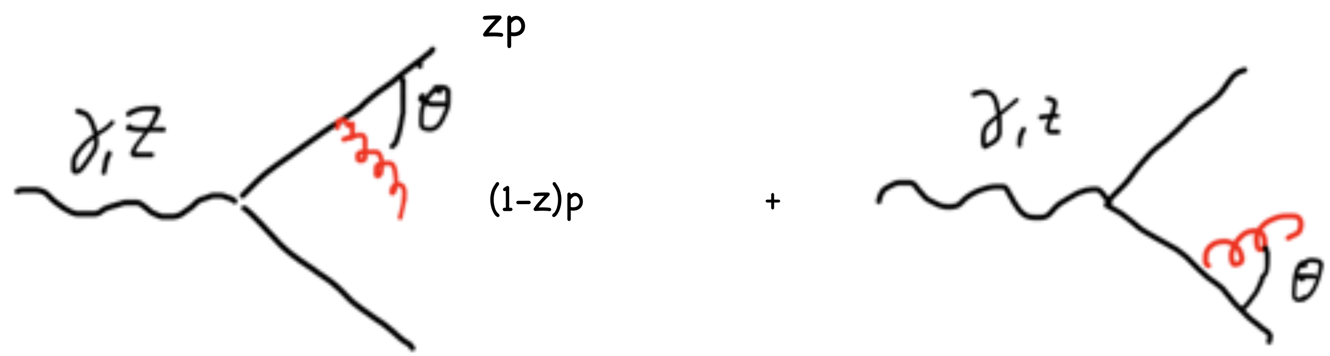
These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

Probability enhanced in soft and collinear region due to ~ $1/(p_1 + p_2)^2$

- If $p_1 \to 0$, then $1/(p_1 + p_2)^2 \to \infty$
- If $p_2 \to 0$, then $1/(p_1 + p_2)^2 \to \infty$
- If $p_2 \to \lambda p_1$, then $1/(p_1 + p_2)^2 \to \infty$

Example

$e^+e^- \to 3$ jets



Collinear limit:

$$d\sigma_{ee\to 3j} \approx \sigma_{ee\to 2j} \sum_{j\in\{q,\bar{q}\}} \frac{\alpha_s}{2\pi} \frac{d\theta_{jg}^2}{\theta_{jg}^2} P(z)$$

$$P_{q\to qg} = C_F \frac{1+z^2}{1-z} \qquad P_{g\to gg} = C_A \frac{(1-z(1-z))^2}{z(1-z)} \qquad P_{g\to q\bar{q}} = T_R n_f (z^2 + (1-z)^2)$$

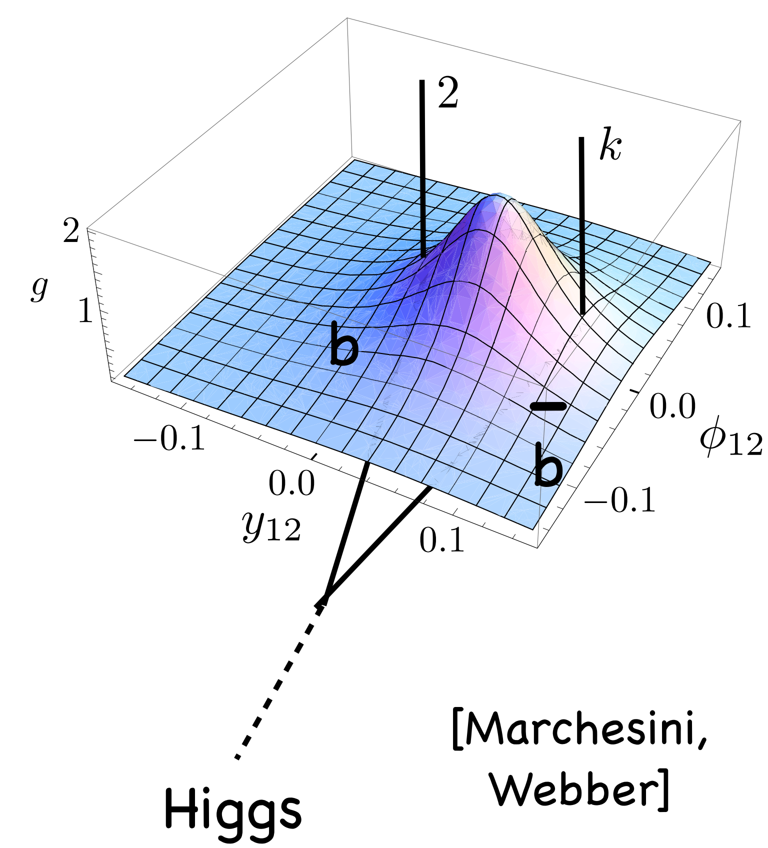
Soft limit: $E_g \to 0 \qquad k^\mu \ll p_i^\mu$ the matrix element for

$e^+e^- \to \bar{q}qg$ factorizes (Eikonal Current)

↓ dipole

$$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 g_s^2 C_F \frac{2p_1 \cdot p_2}{p_1 \cdot k \; p_2 \cdot k}$$

In the large Nc limit most radiation occurs in a cone between colour partners



[Marchesini, Webber]

Factorization of emissions and Sudakov factors allow semiclassical approximation of quantum process:

Sudakov form factor:

$$\mathcal{P}_{\text{nothing}}(0 < t \leq T) = \lim_{n->\infty} \Pi_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \leq T_{i+1})$$

$$= \lim_{n\to\infty} \Pi_{i=0}^{n-1} \left(1 - \mathcal{P}_{\text{something}}(T_i < t \leq T_{i+1})\right)$$

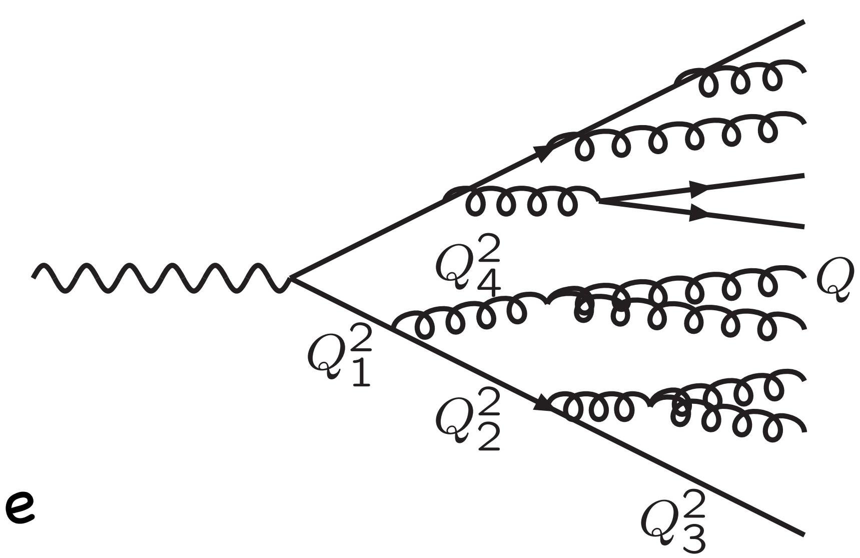
$$= \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

$$\Rightarrow \quad d\mathcal{P}_{\text{first}}(T) = d\mathcal{P}_{\text{something}}(T) \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

Sudakov form factor provides "time" ordering of shower:

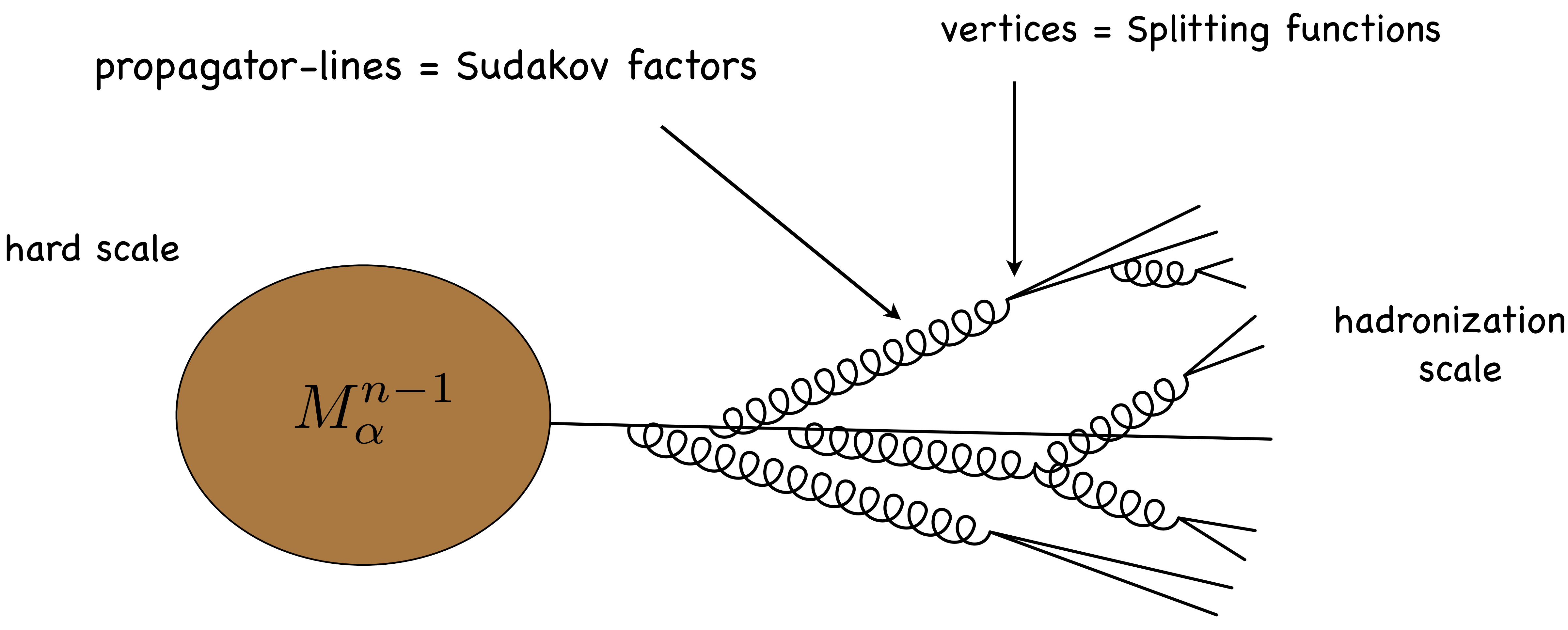
$$Q_1^2 > Q_2^2 > Q_3^2$$

low Q^2 ⟷ longer time

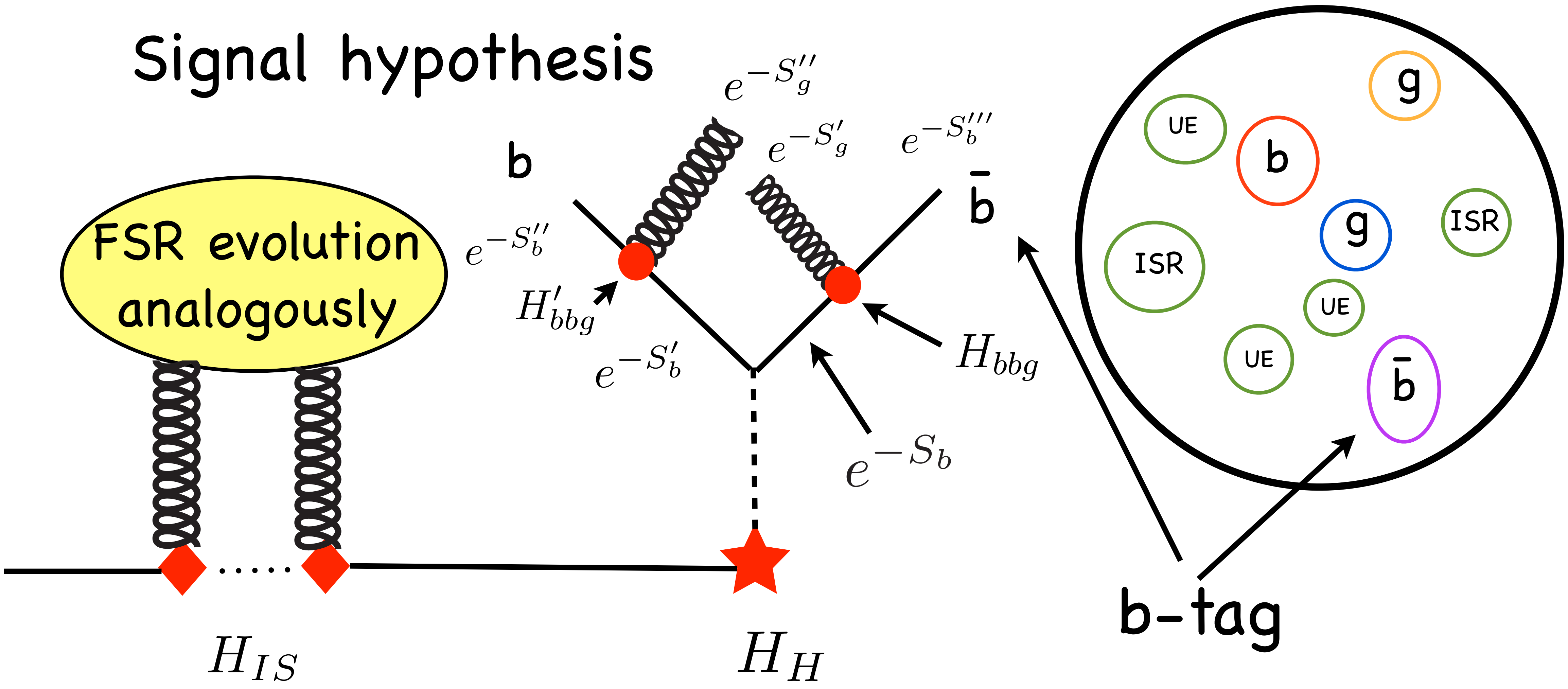


In summary:

The probability weights in the evolution from the hard interaction scale to the hadronization scale are given by Sudakov factors and splitting functions.



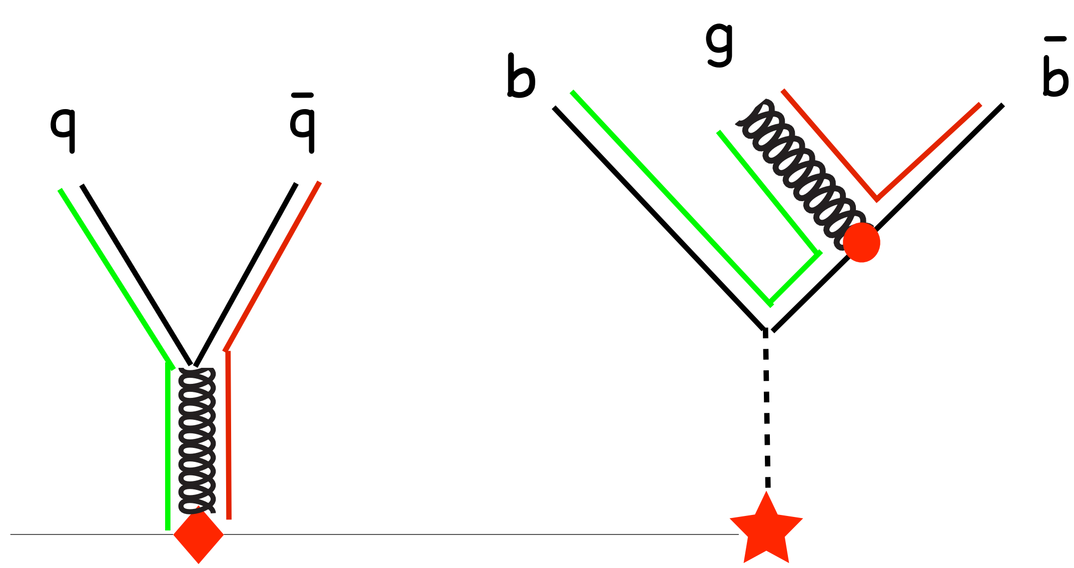
Signal hypothesis

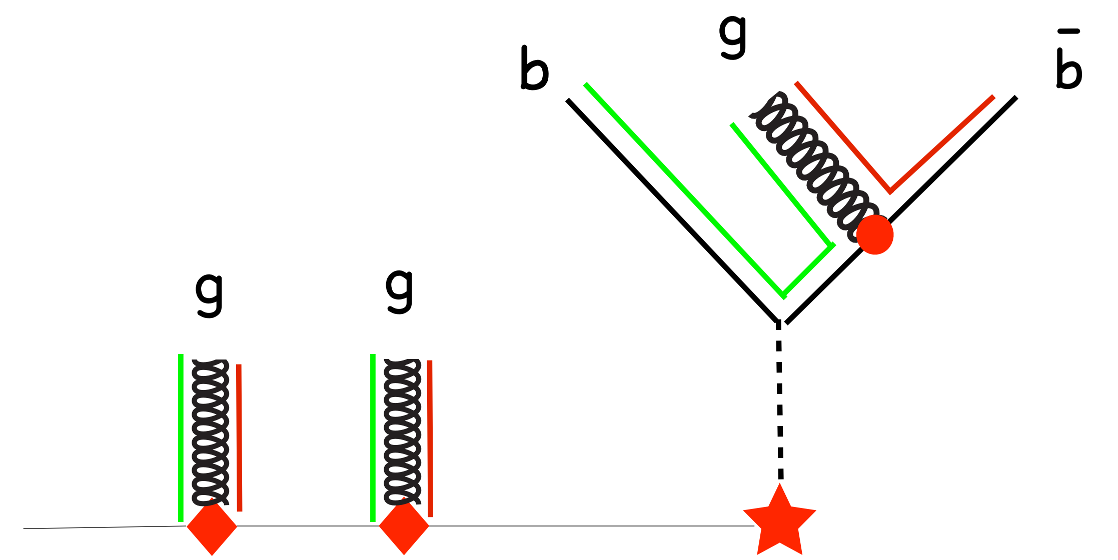


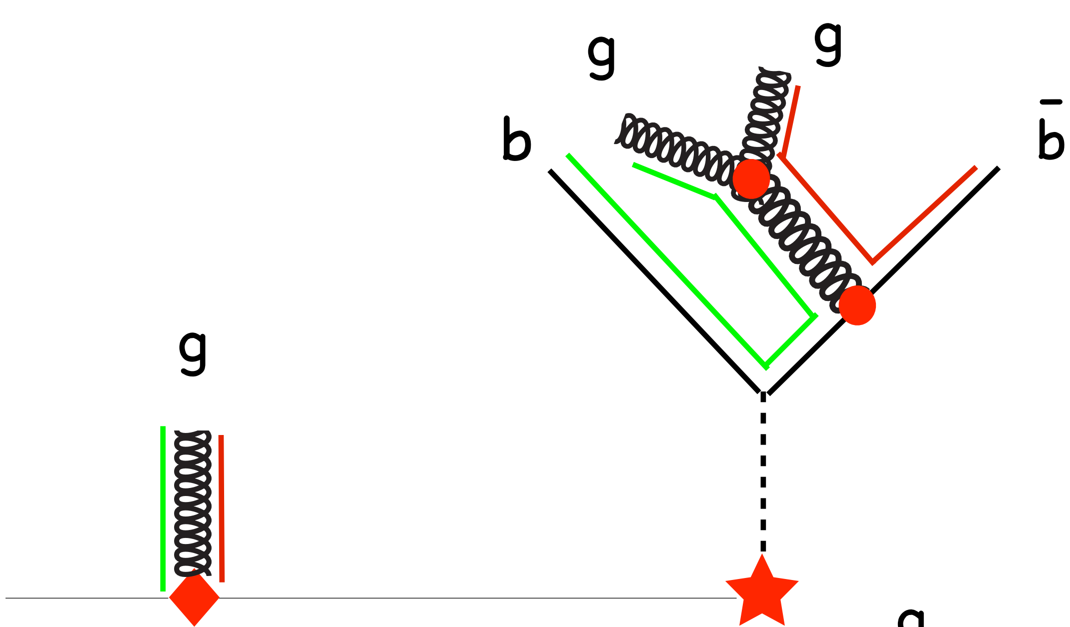
Wrapping up all factors gives weight for shower history

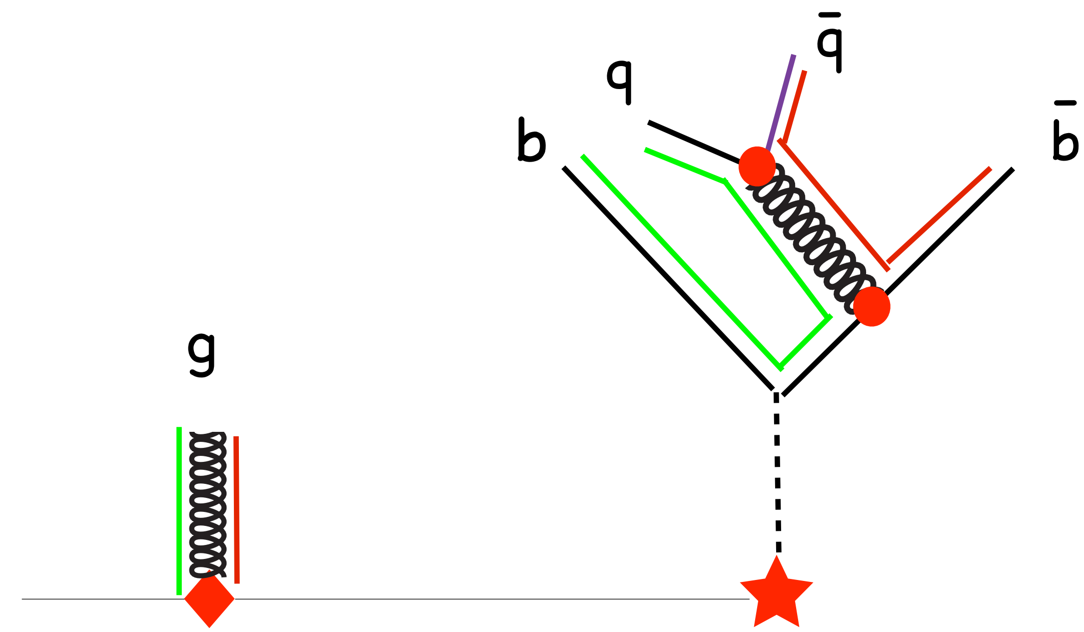
$$\chi = \frac{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_\mathrm{j} \mathrm{Signal_j}\right)}{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_\mathrm{j} \mathrm{Backg_j}\right)}$$

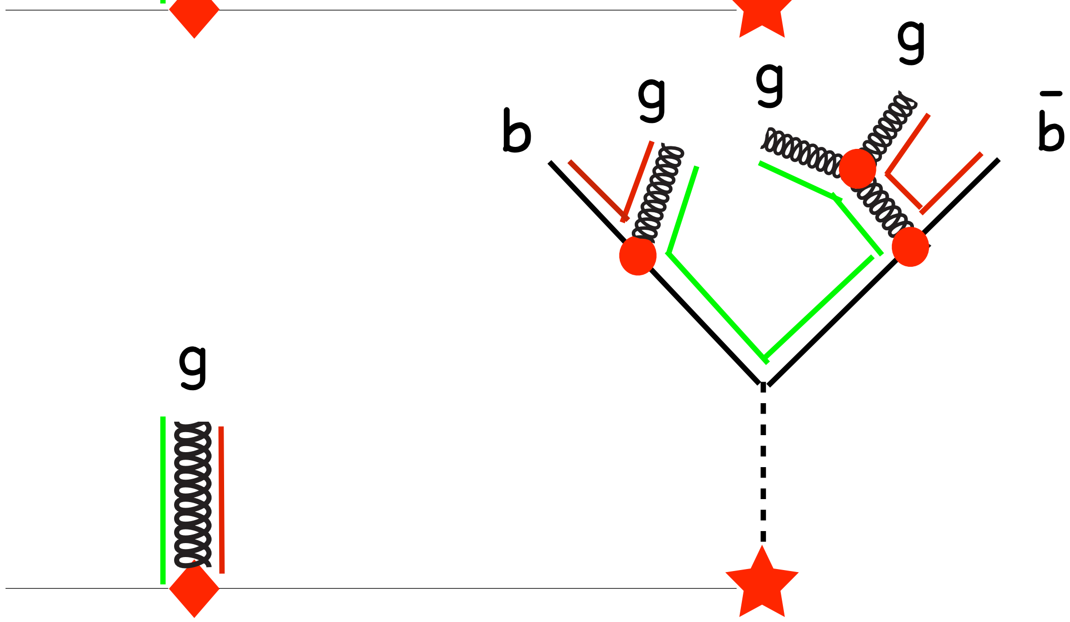
Here $\mathrm{Signal}_1 = \mathrm{H_H H_{split} e^{-S_{split}} H_{bbg} e^{-S'_b} e^{-S'''_b} e^{-S'_g} H'_{bbg} e^{-S''_b} e^{-S_b} e^{-S''_g}}$





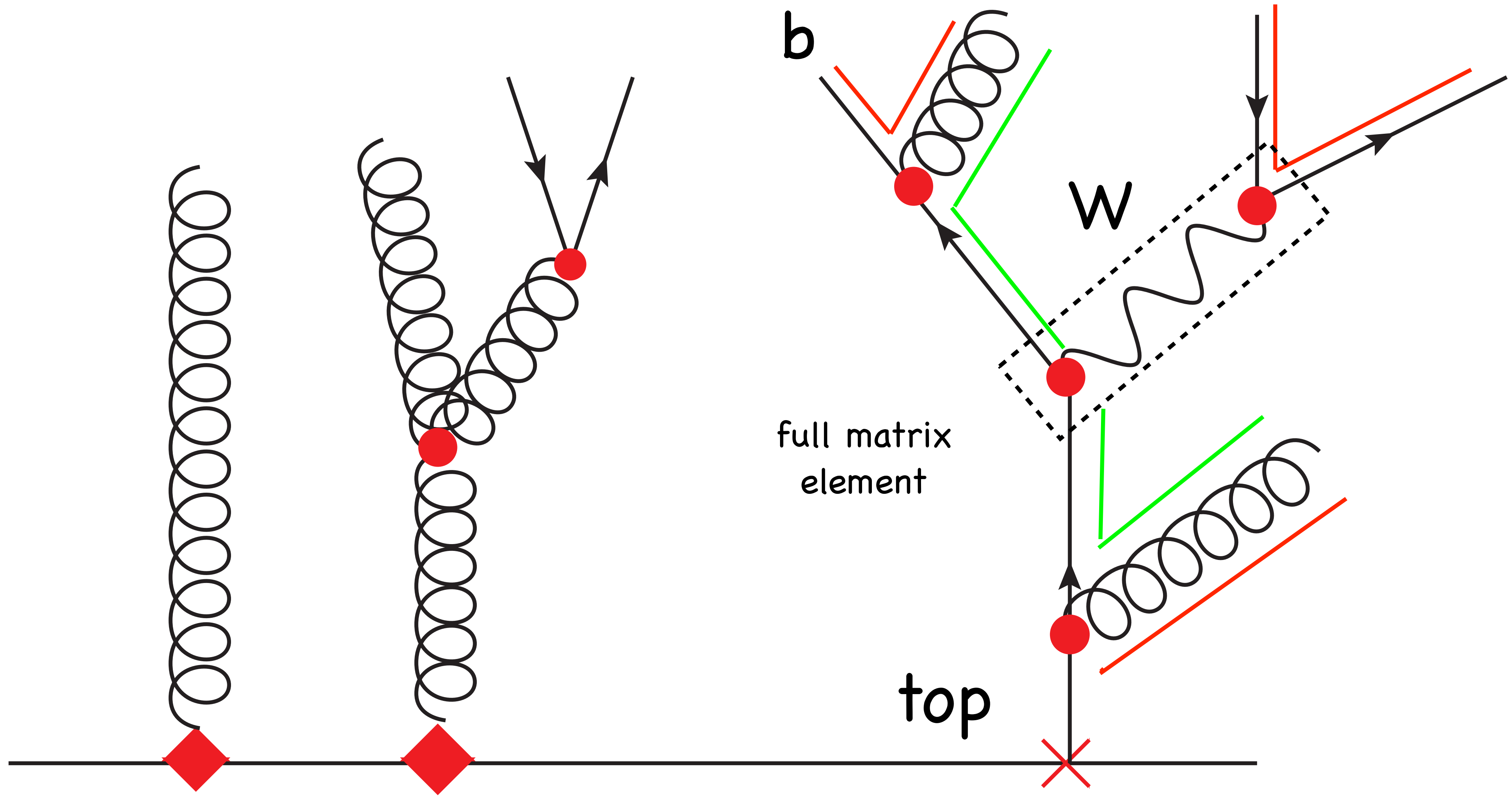






- And many more...
- And for all backgrounds...

Analogously for the top decay (more involved as top colored)

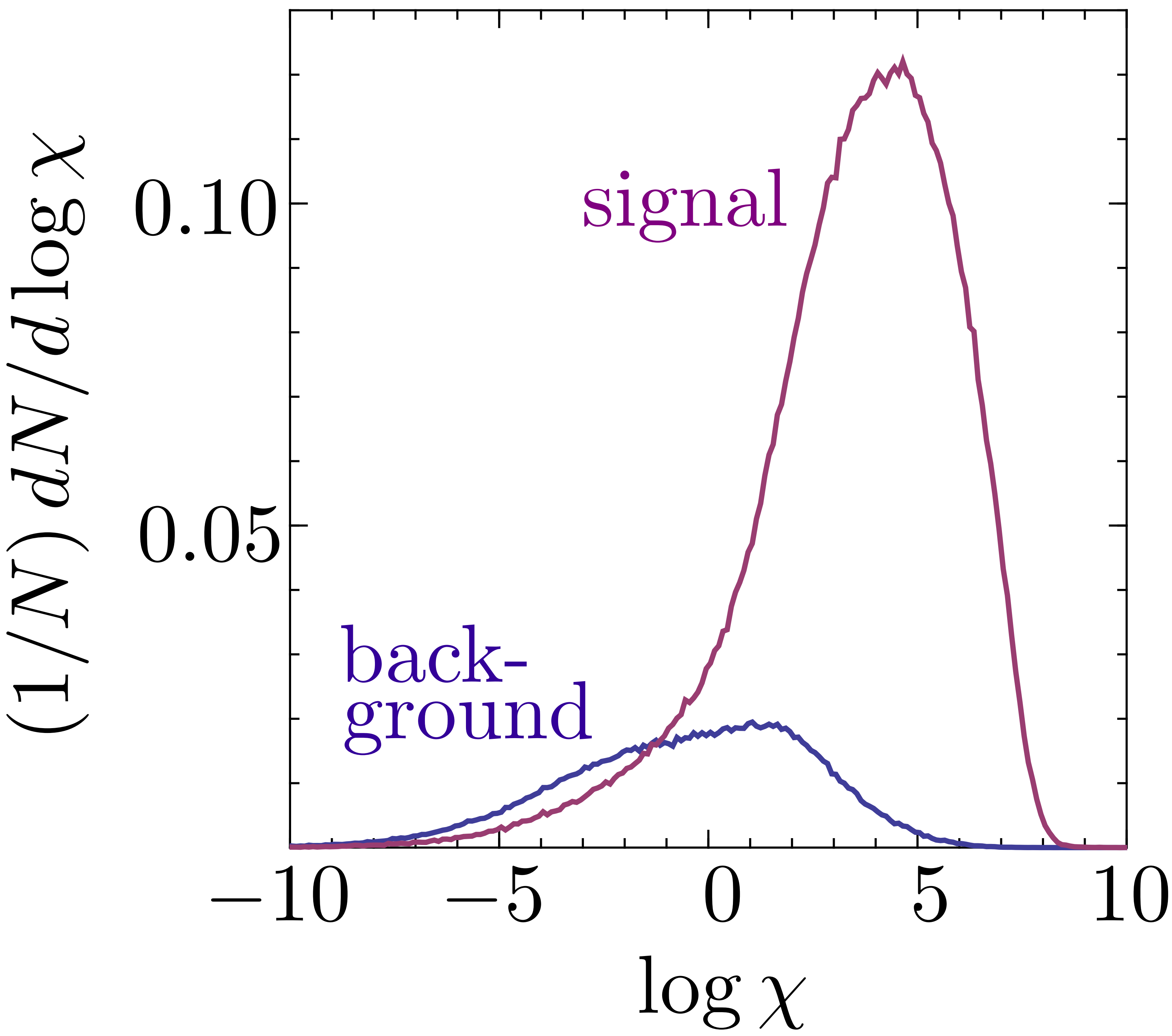


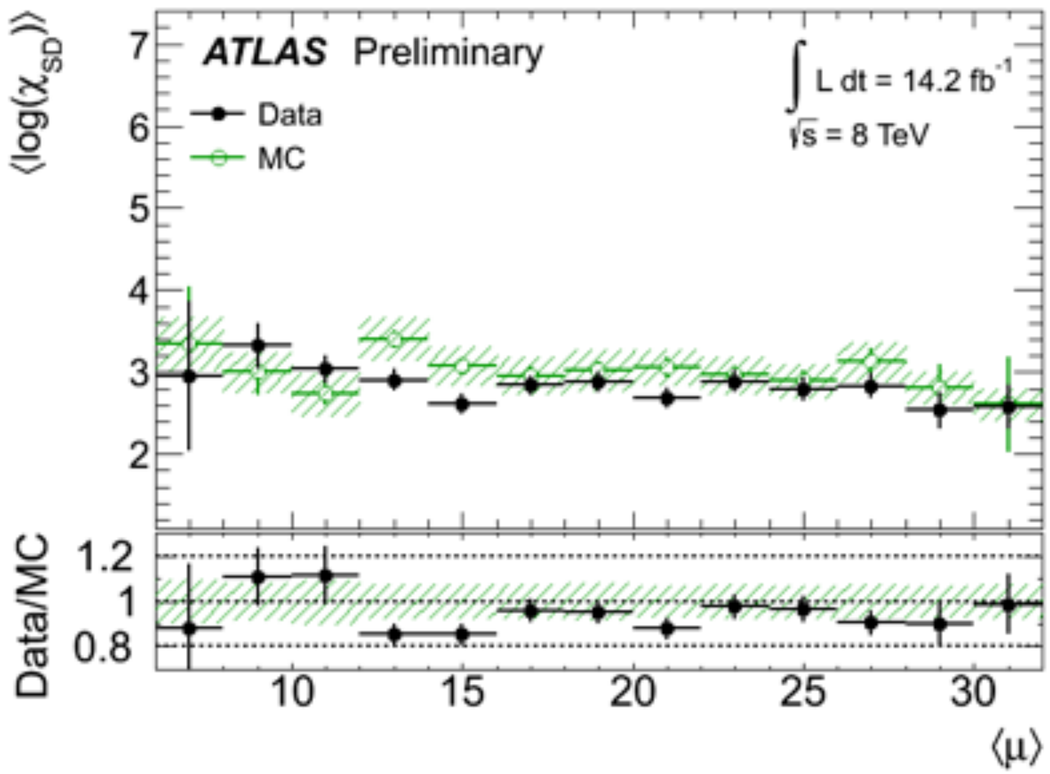
Conceptional difference compared to Higgs from last year:

- Splitting functions for massive emitter and spectator
- Full matrix element for top decay

$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})} = \frac{\sum_{\mathrm{histories}} H_{ISR} \cdots \sum_{\mathrm{histories}} |\mathcal{M}|^2 H_{\mathrm{top}} e^{-S_{t_1}} H^s_{tg} e^{-S_g} \ldots}{\sum_{\mathrm{histories}} H_{ISR} \cdots \sum_{\mathrm{histories}} H^b_g e^{S_g} H_{ggg} \cdots}$$

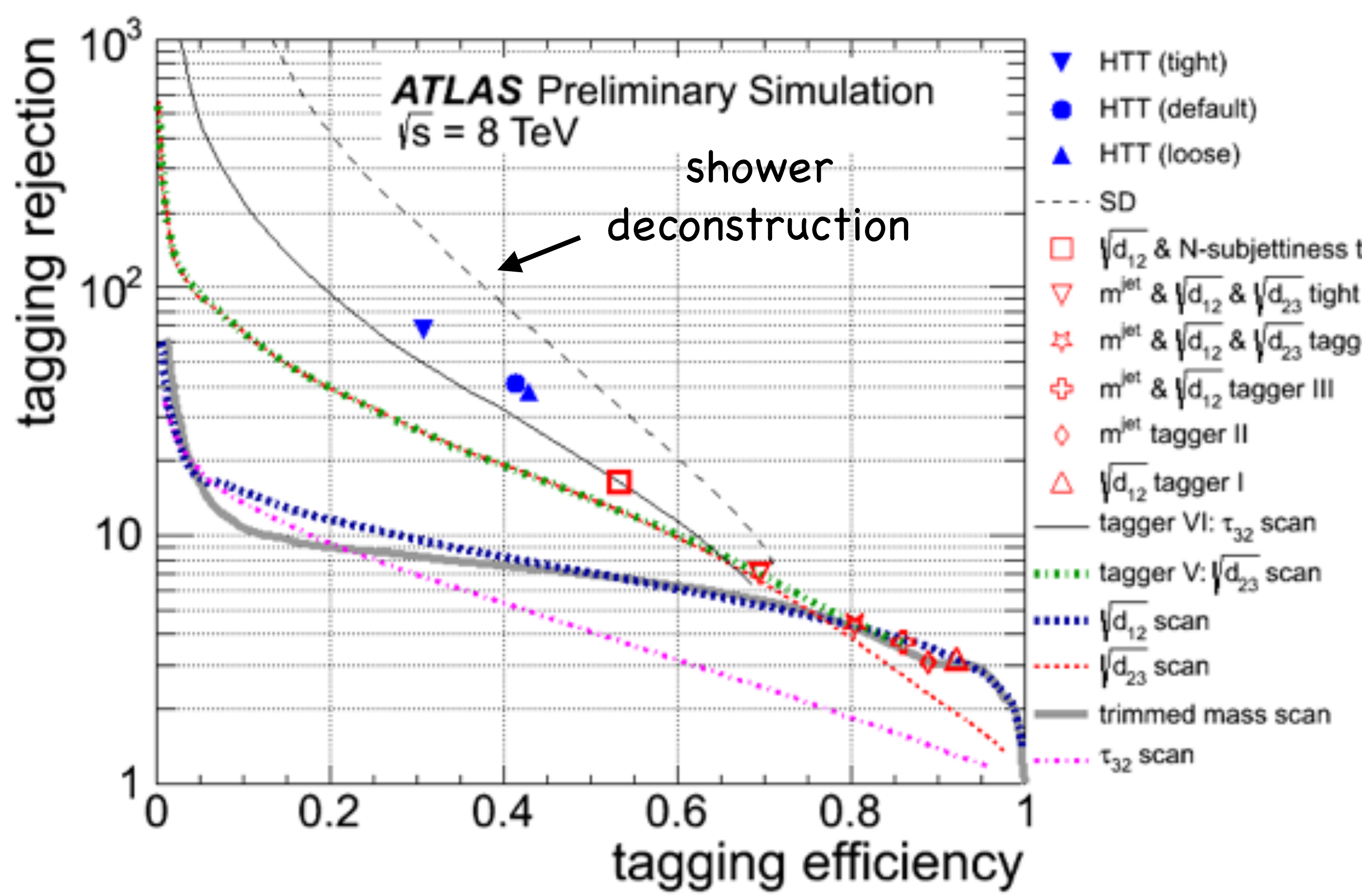
chi distribution for top vs QCD

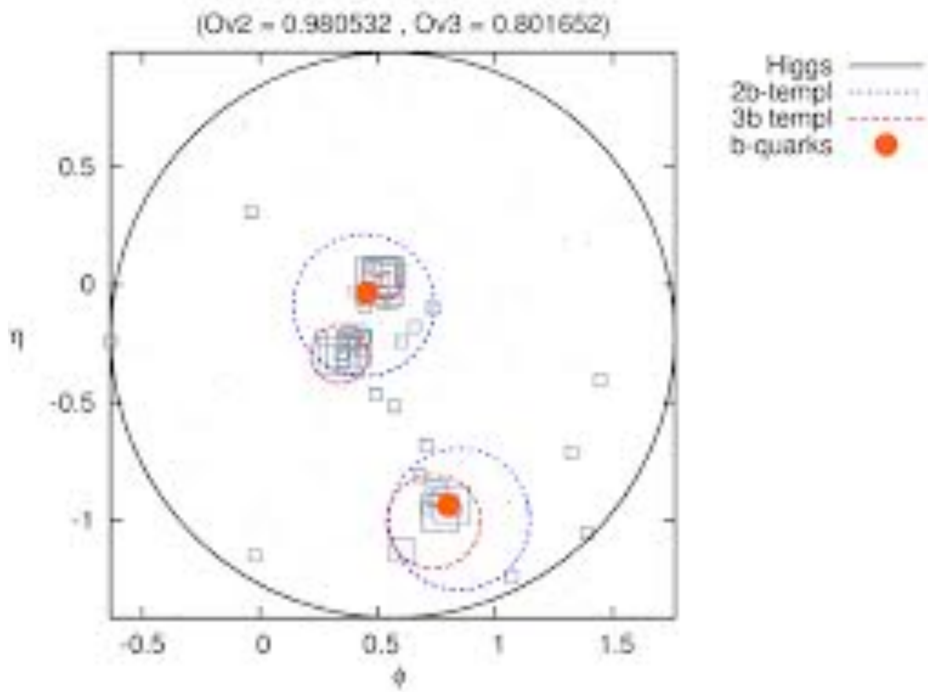




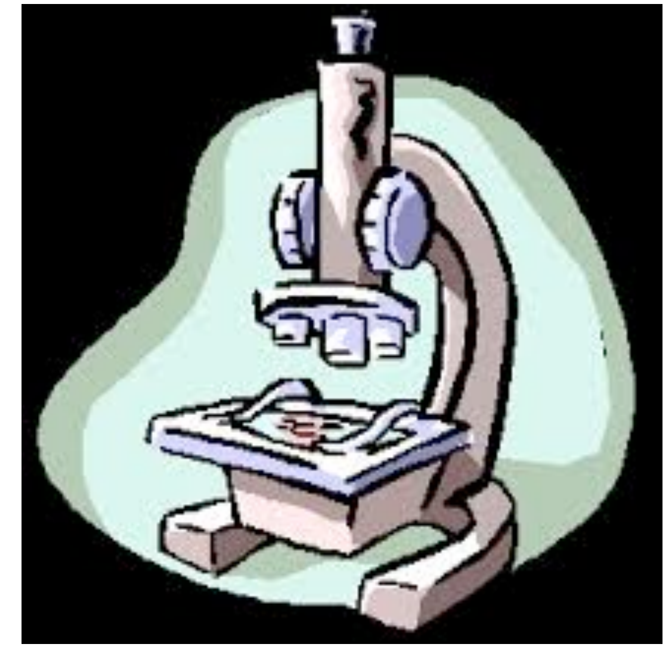
Chi distribution insensitive to pileup

Shower deconstruction tagger improves on best other taggers by factor 2-4 in S/B over large efficiency range





Summary



Tagging EW-scale resonances is necessary at 14/13 TeV LHC

Many methods have been proposed which exploit different physics

Experiments are studying many of them but physics potential still by far not fully exploited

For that purpose detailed understanding of QCD important