Jet substructure

and

Top tagging

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Large c.o.m. energy makes LHC a BSM AND QCD machine

Recent technical developments

- High precision calculations for many legs
- Matching procedures (CKKW, MLM)
- IR safe and fast jet-algorithms
- Improved UE tunes

Main New Physics goal at LHC

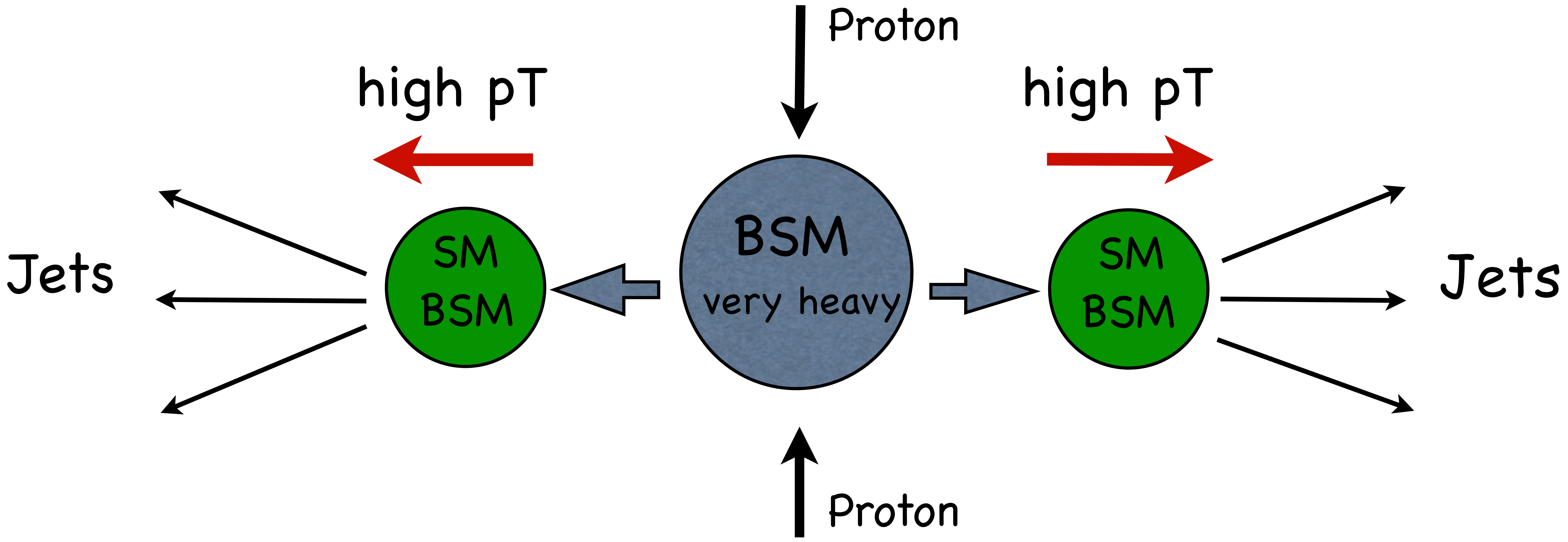
- Explain ELWS breaking

Plethora of Models!

- SUSY
- Extra Dim.
- Technicolor
- GUT

→ Probe EW scale physics at multi TeV collider

Boosted signal in New Physics search



- overlapping radiation
- jet-parton matching breaks down
- need big jet cone

How to construct/define a Jet

Want mapping of hadronic final state to hard-interaction partons

-> Jet-parton matching

Jet-parton-matching issues:

“Splash in“:
- Uncorrelated contributions of rest of collision (UE)
- Uncorrelated contributions of overlapping collisions (PU)

“Splash out“:
- Showering - LL resumed, soft-coll. emissions
- Hadronization - nonpert. re-organization into color singlets

Higher order perturbative contributions - IR safety

- Sequential recombination, e.g. inclusive kT algorithm [S.D. Ellis & Soper, '93]

Distance measure

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

$$d_{iB} = p_{Ti}^2$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

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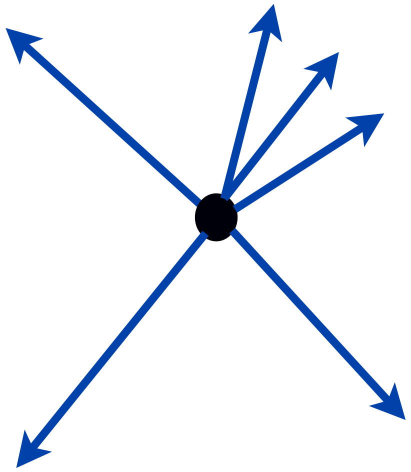

Minimum distance between jets is R

Only number of jets above pt cut is IR safe

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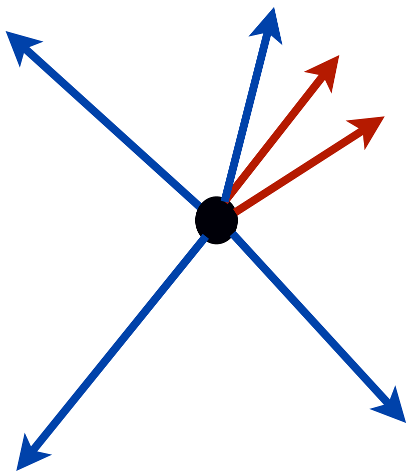

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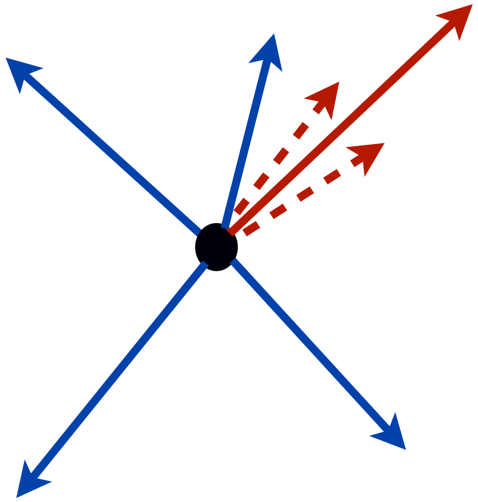

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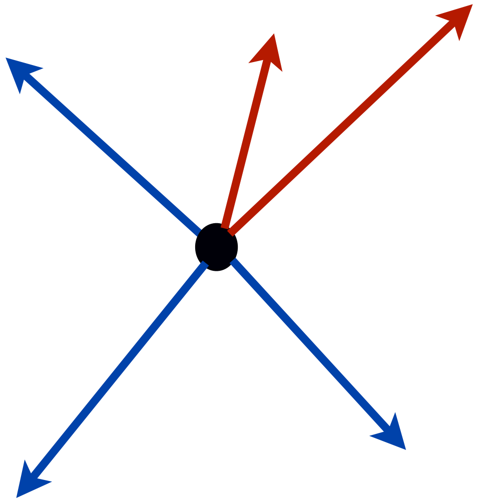

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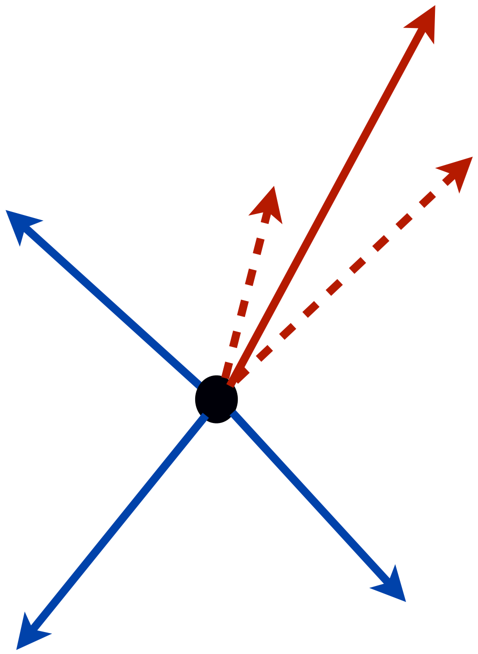

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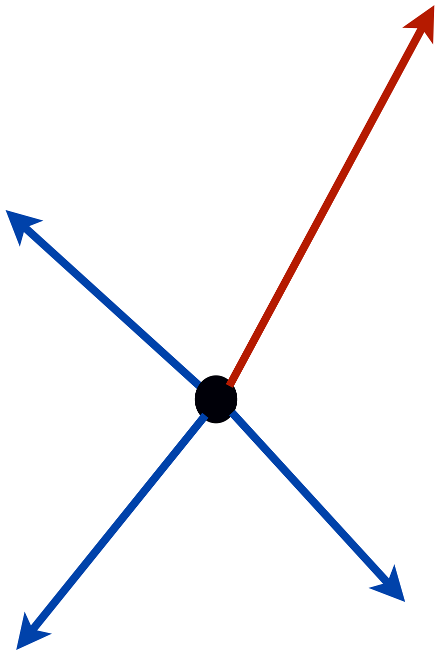

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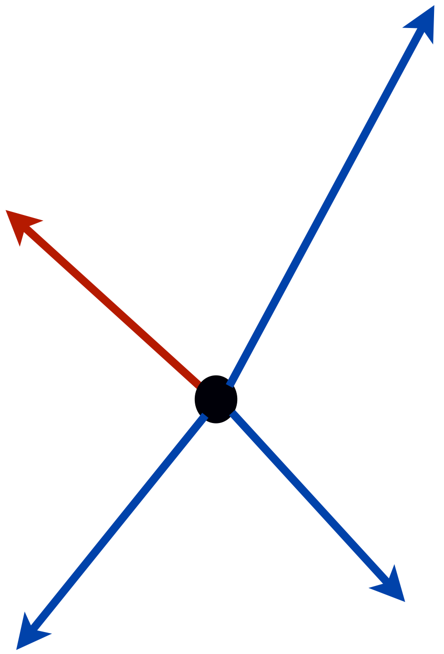

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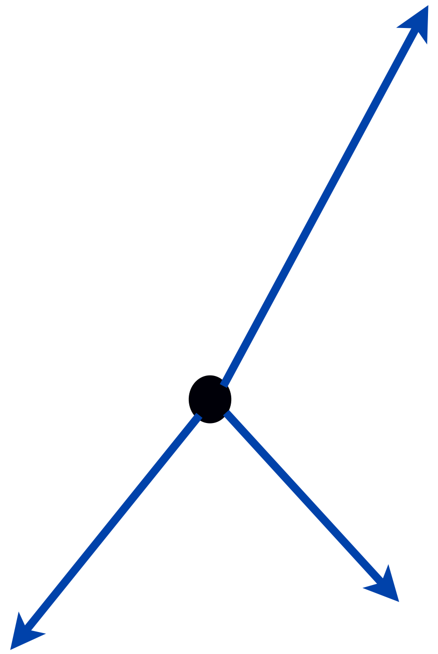

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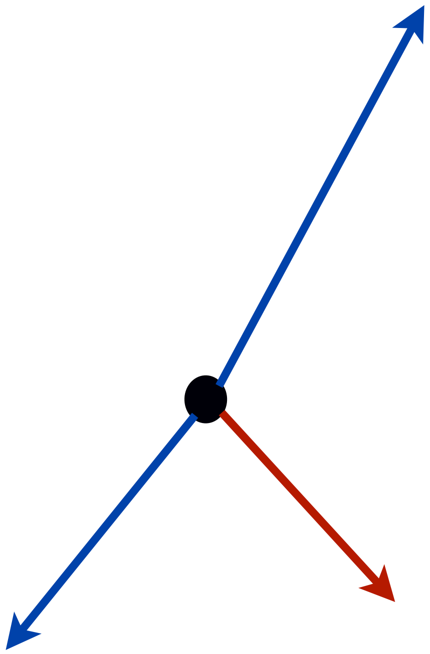

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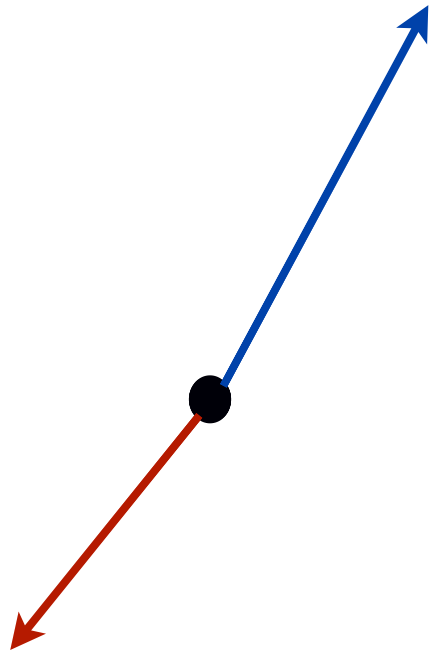

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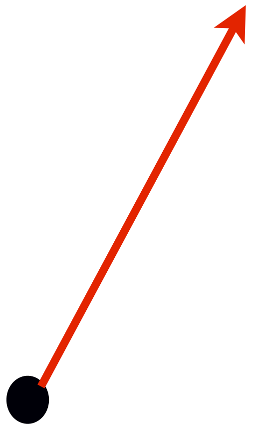

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Found 4 Jets

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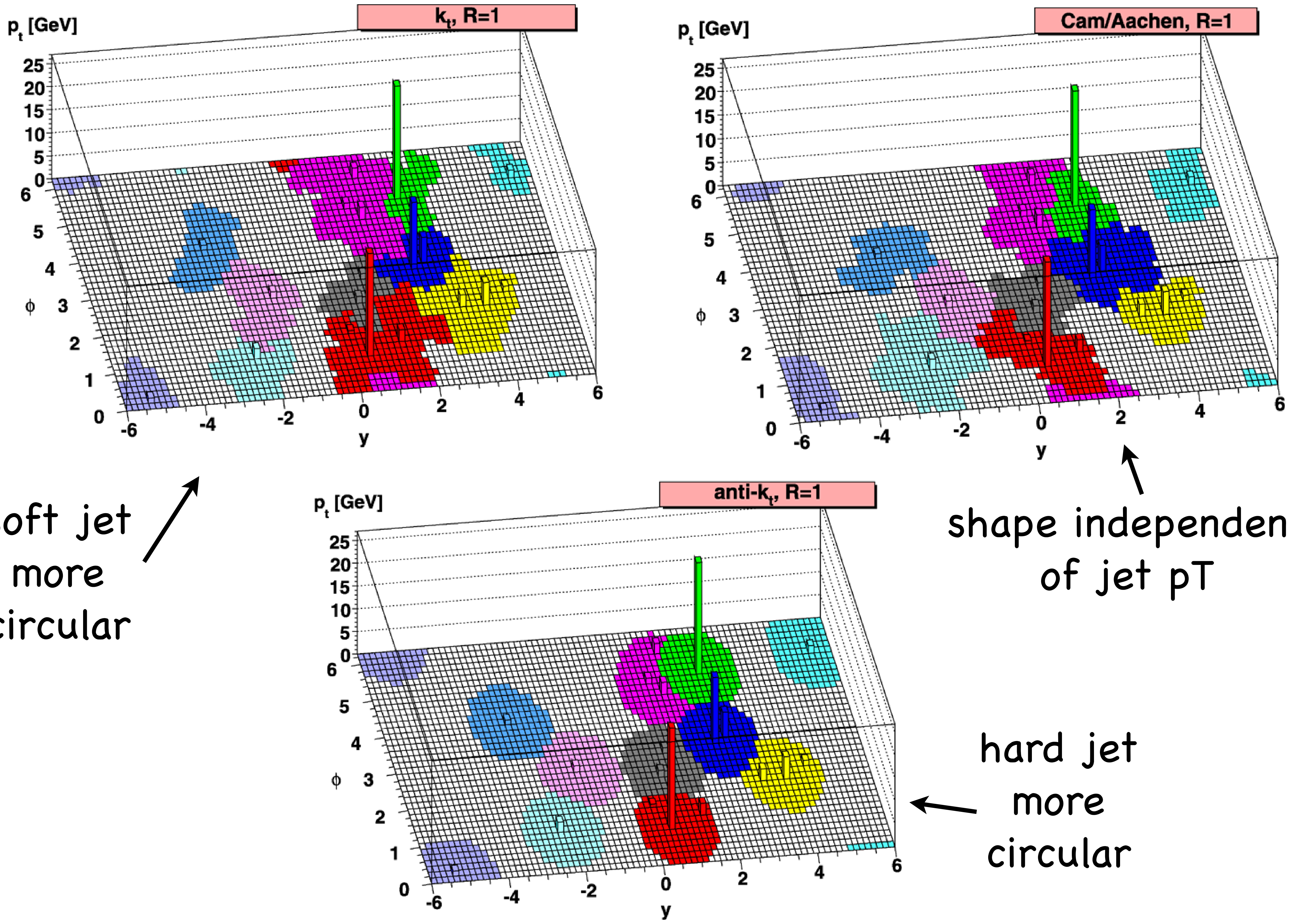
[G. Salam, Towards Jetography]



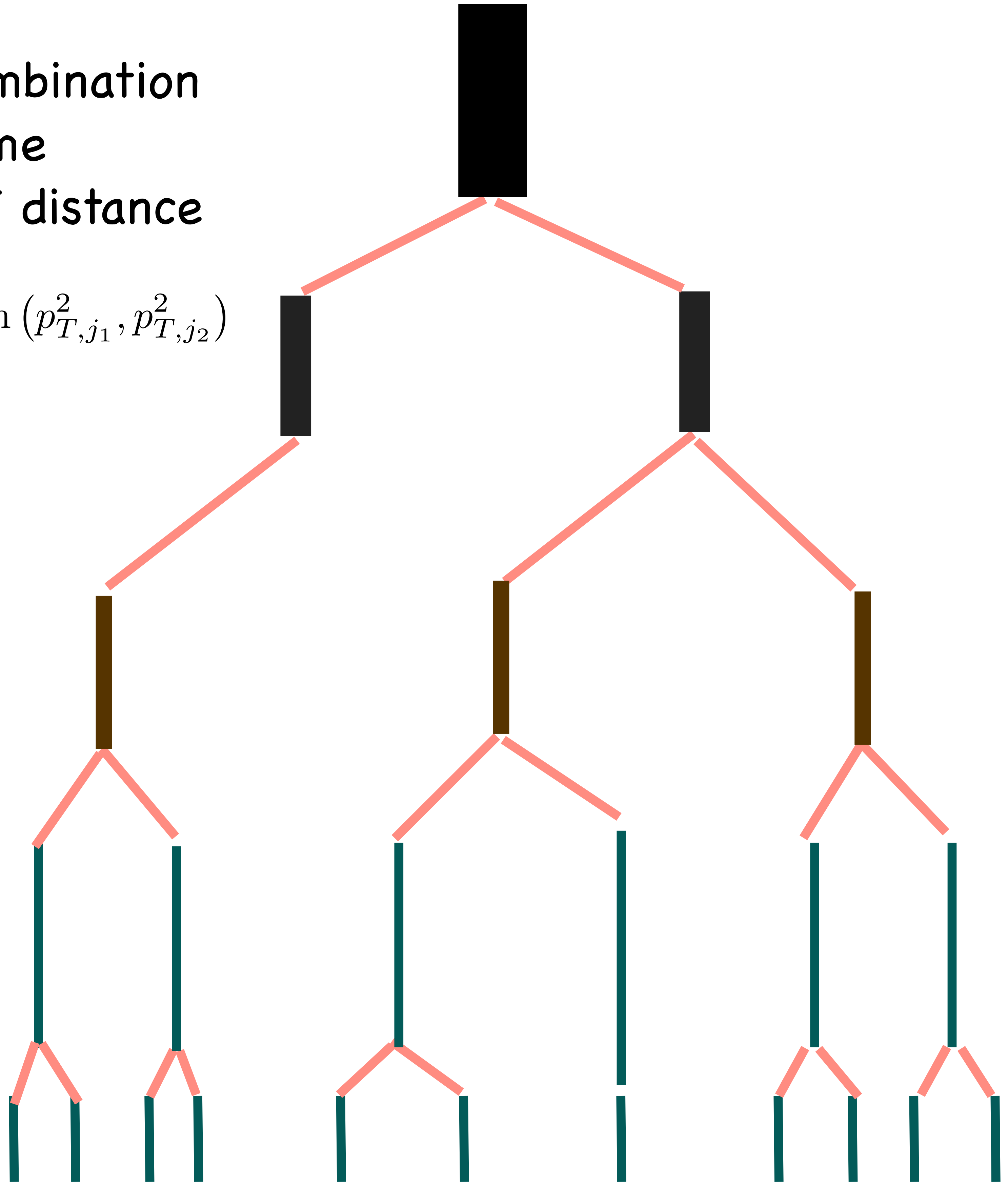
soft jet
more
circular

shape independent
of jet pT

hard jet
more
circular

order of recombination defined by some metric, e.g. kT distance

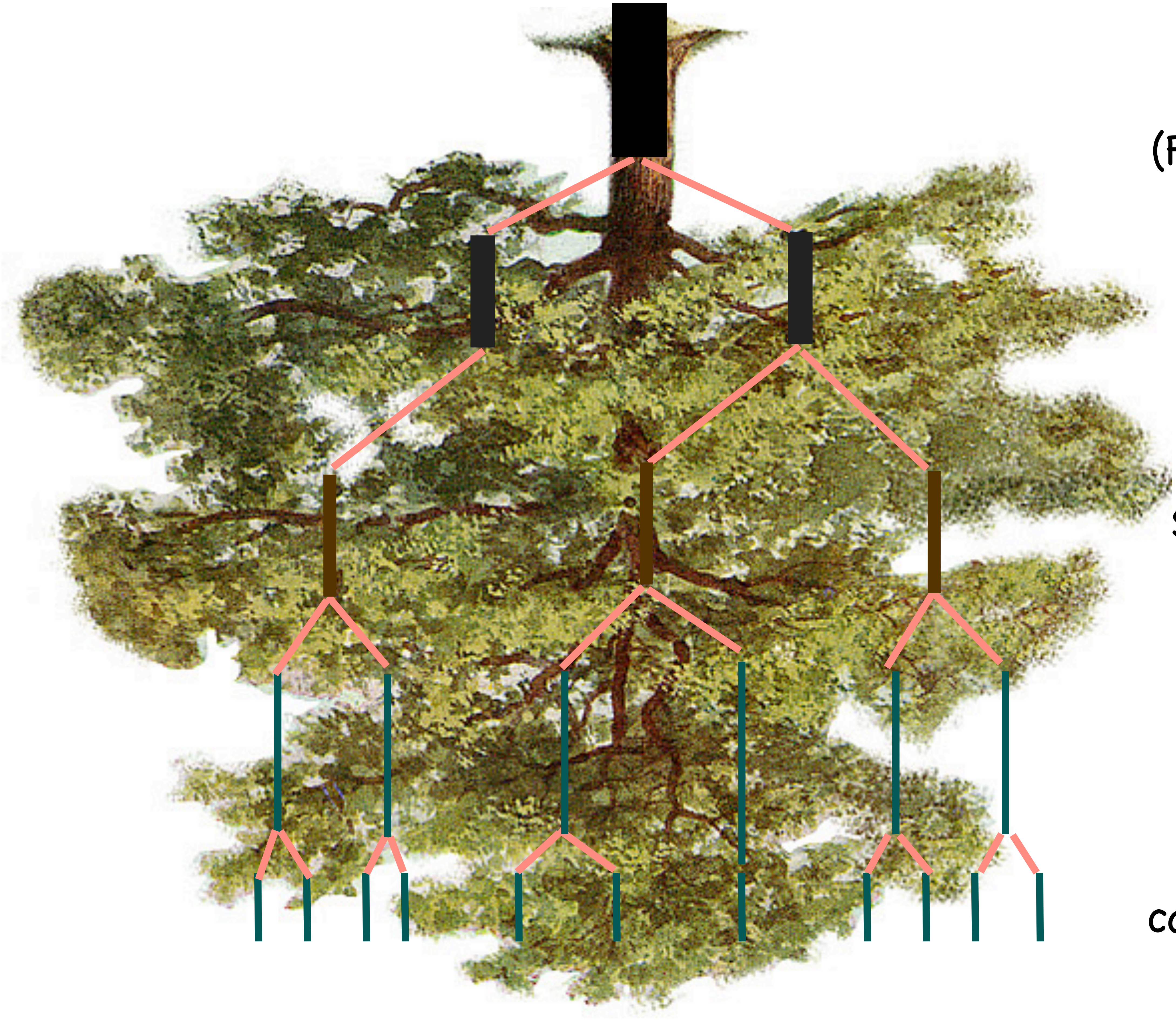
$$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{D^2} \, \min\left(p^2_{T,j_1}, p^2_{T,j_2}\right)$$



(Fat)Jet

Subjets

Jet constituents



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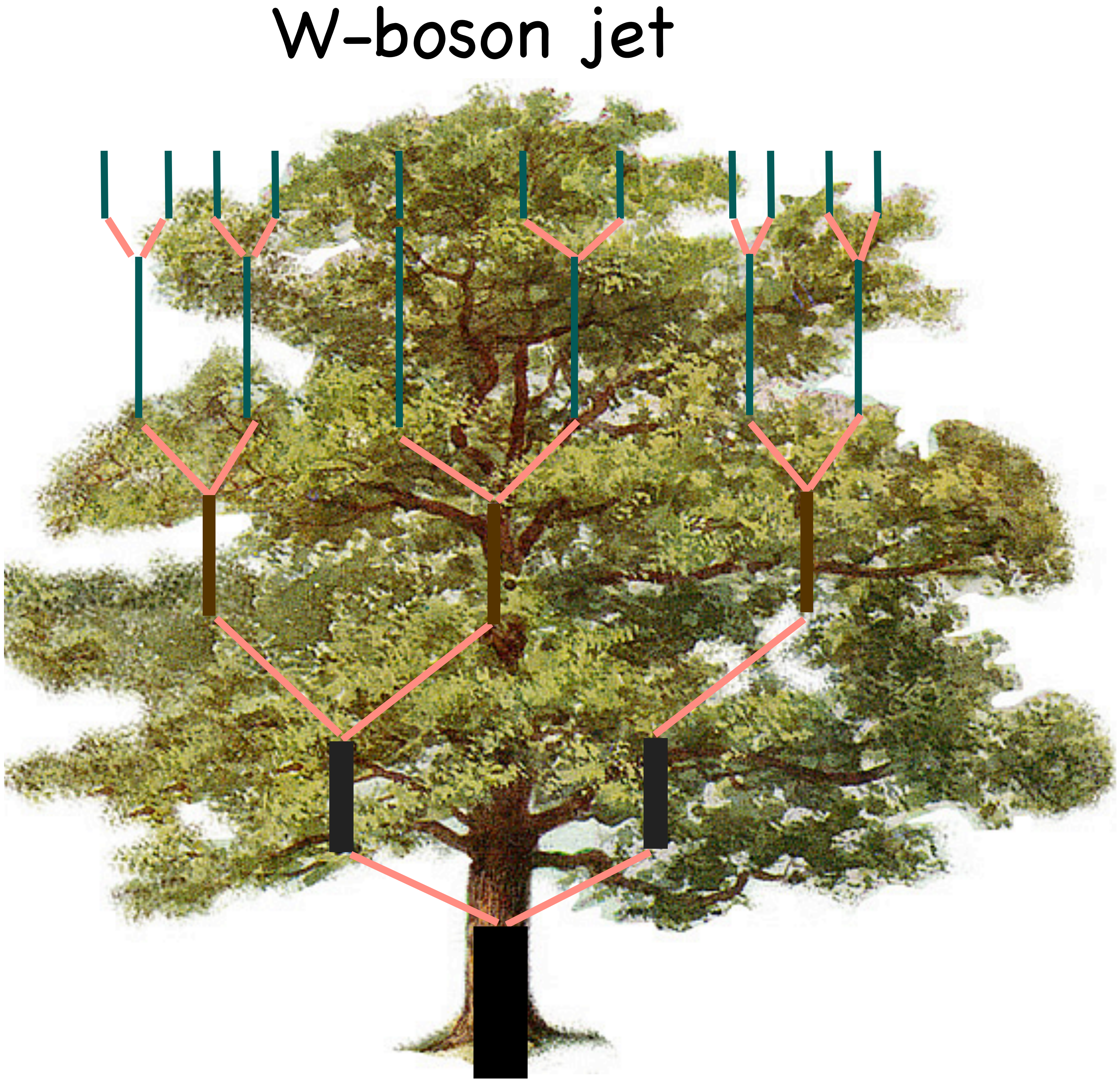
Subjets

Jet constituents

For jet substructure study reverse cluster history and analyze internal structure

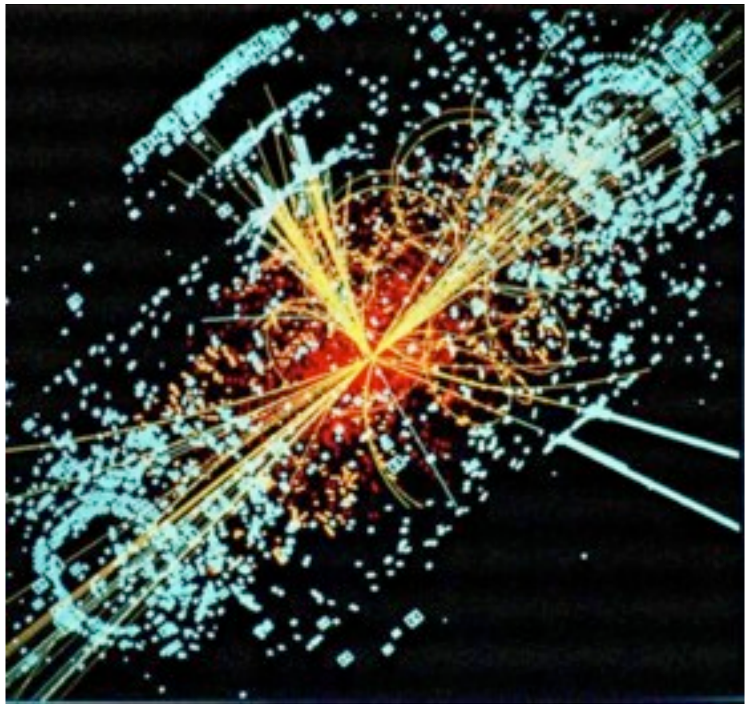


Jet definition not unambiguous: Which particles? How combined?

Sequential rec. algorithms

$$d_{ij} = \min(p_{Ti}^{2n}, p_{Tj}^{2n}) \frac{\Delta R_{ij}^2}{R^2}\,, \quad \begin{cases} k_T: & \text{n=1}\,, \\ \text{C/A}: & \text{n=0}\,, \\ \text{anti}-k_T: & \text{n=-1}, \end{cases}$$

↓



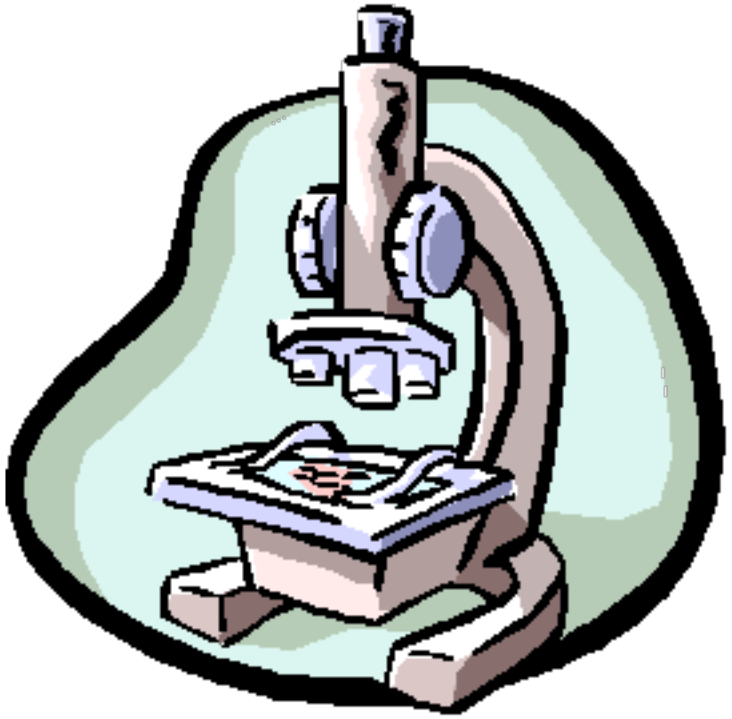
Recombination history

↓

Jet substructure

=

microscope for boosted resonance`s properties



Are we done?

In a perfect world (or an e+e- collider) this
would be most of the story

However, at the LHC many sources of radiation:

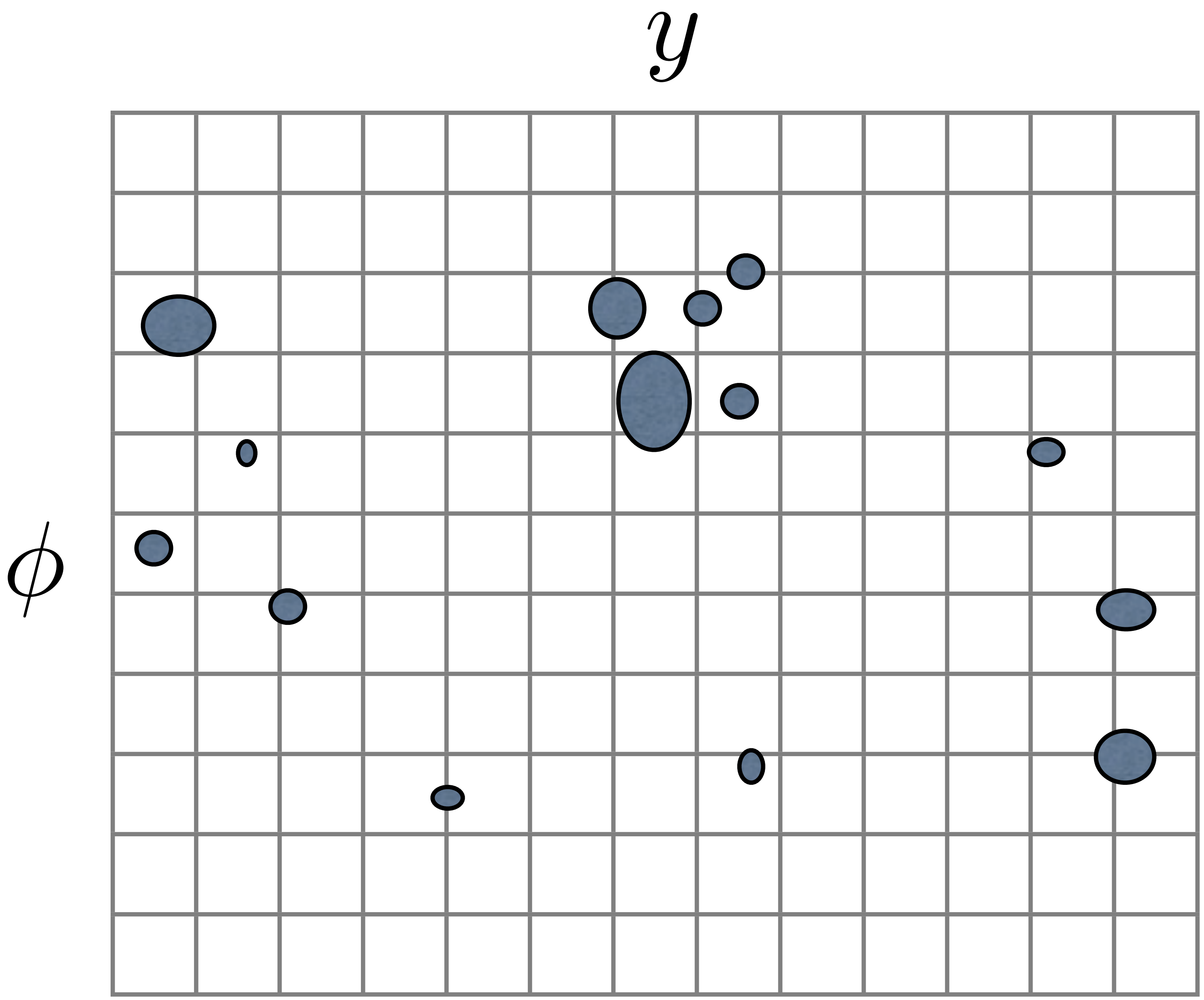
- Pileup → Can add up to 100 GeV of soft radiation per unit rapidity
- Underlying Event → $\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$ with $\Lambda_{\mathrm{UE}} \sim \mathcal{O}'(10)\ \mathrm{GeV}$
- Initial state radiation (ISR)
- Hard radiation from many resonances in event

⟶ Need methods to separate final state radiation (FSR) from rest of event

Jet grooming procedures	Filtering	[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]
	Pruning	[Ellis, Vermilion, Walsh PRD 80 (2009)]
	Trimming	[Krohn, Thaler, Wang JHEP 1002 (2010)]
2-pronged resonances	Mass-drop/Filtering and variations	[Butterworth, Davison, Rubin, Salam PRL 100 (2008)] [Plehn, Salam, MS PRL 104 (2010), Kribs, Martin, Roy, MS PRD 81 (2010)]
3-pronged resonances	y-splitter Top Tagger	[Butterworth, Cox, Forshaw PRD 55 (2002)] [Broijmans ATL-COM-PHYS-2008-001]
	energy flow	[Thaler, Wang JHEP 0807]
	Johns Hopkins Tagger	[Kaplan, et al. PRL 101 (2008)]
	HEP Top Tagger	[Plehn, MS, Takeushi, Zerwas JHEP 1010]
	tree-less approach	[Jankowiak, Larkoski JHEP 1106]
General methods	Template method	[Almeida et al. PRD 82 (2010)]
	N-subjettiness	[Kim PRD 83 (2011)] [Thaler, Van Tilburg JHEP 1103]
	Multi-variate	[Gallicchio et al. JHEP 1104]
	Shower deconstruction	[Soper, MS 1102.3480]

Jet grooming methods

Jet/Event selection:



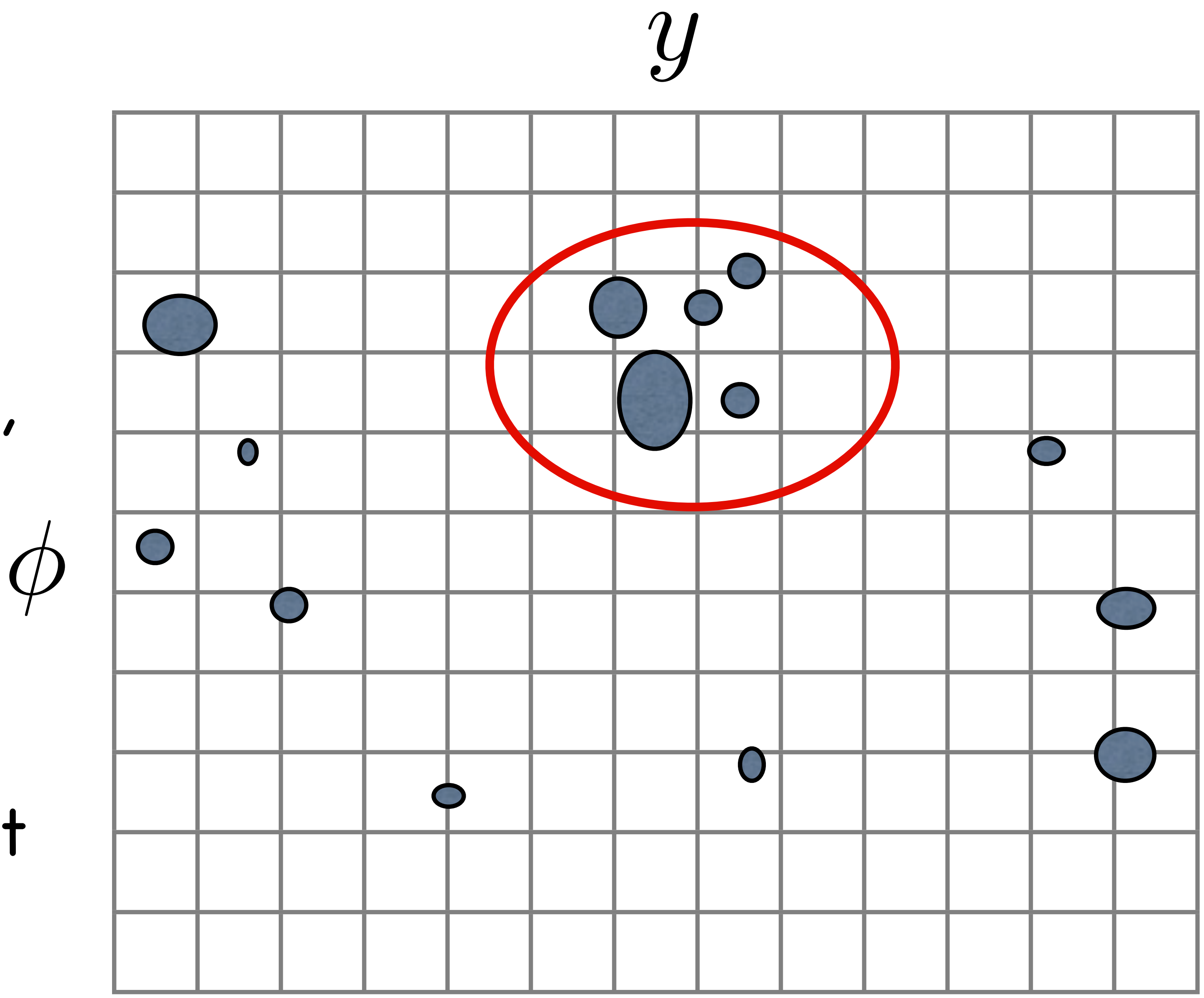
UE, ISR, Pile-up, hard interaction

Jet grooming methods

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



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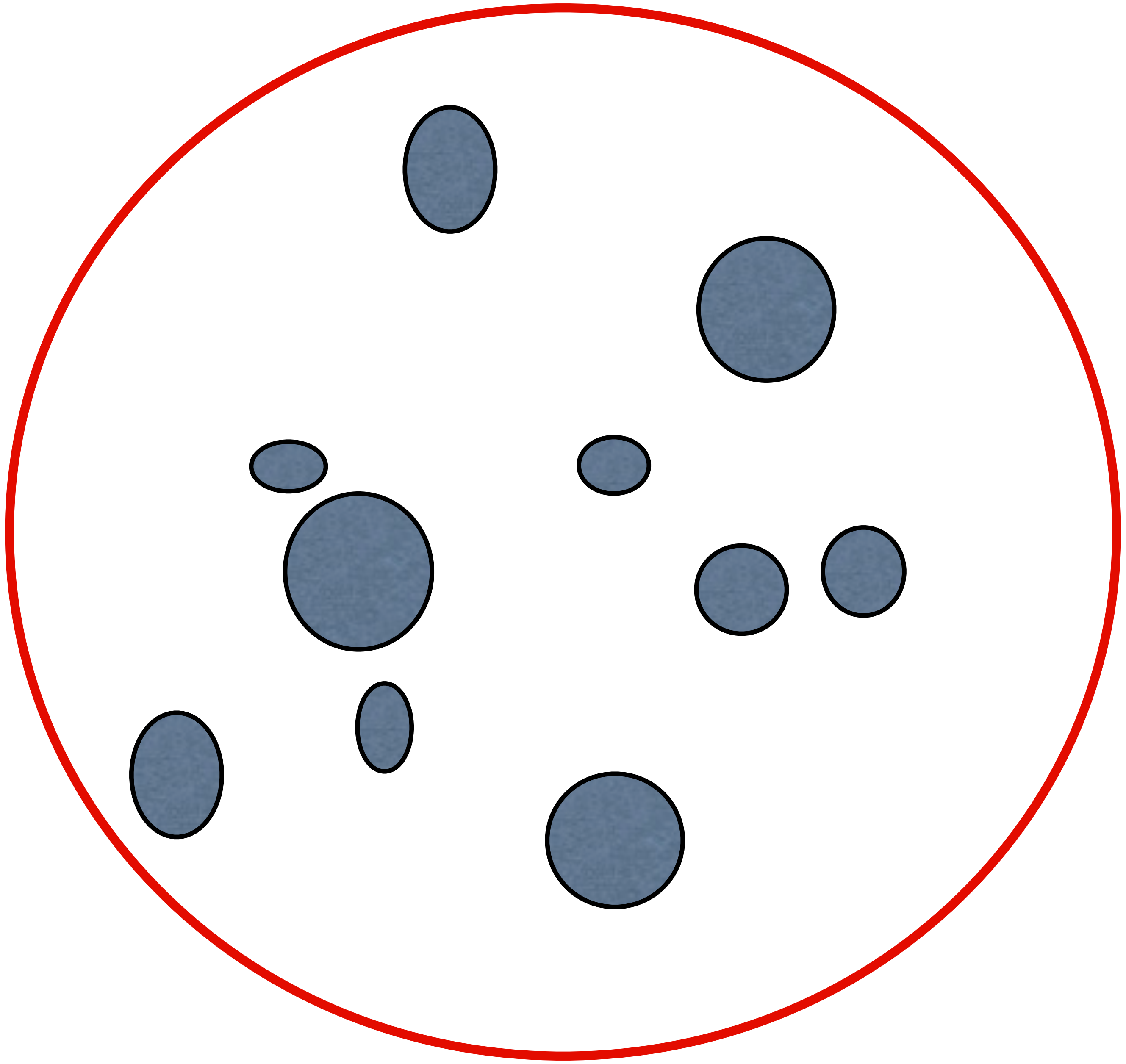
Filtering/Trimming

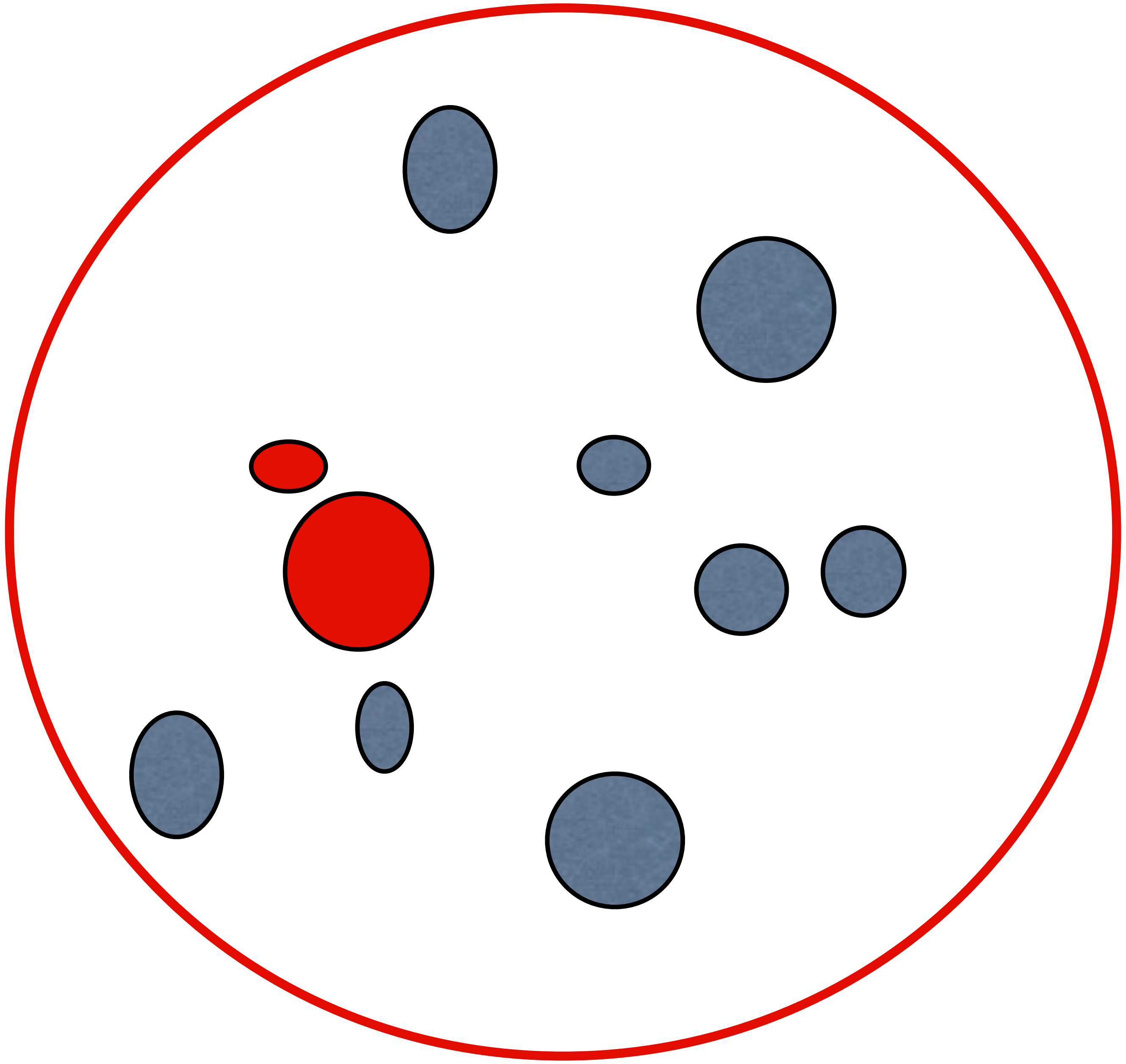


I. Recombine jet constituents with new algorithm, eg CA, R=0.2

Filtering:
recombine n subjets

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

Filtering/Trimming



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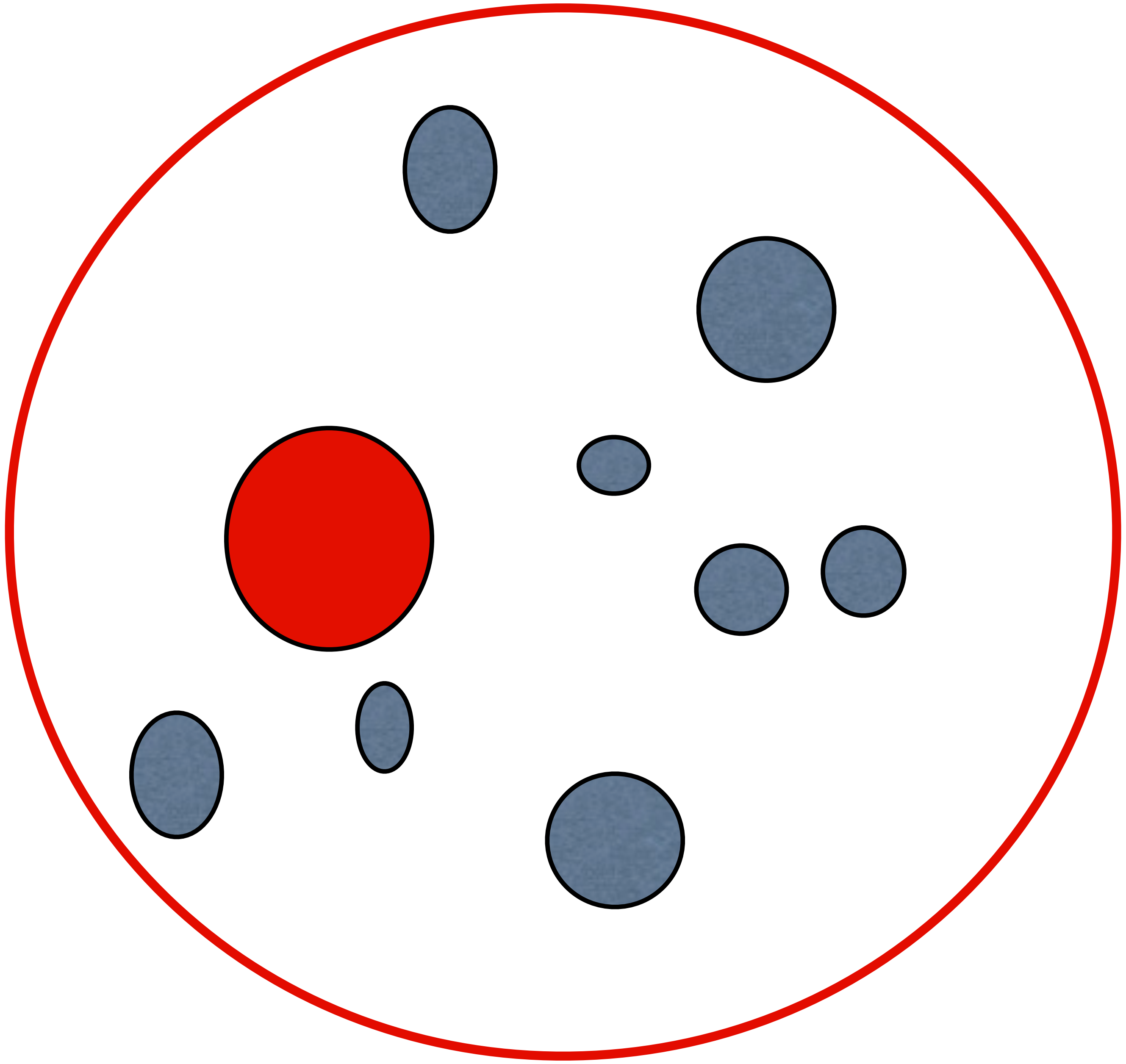

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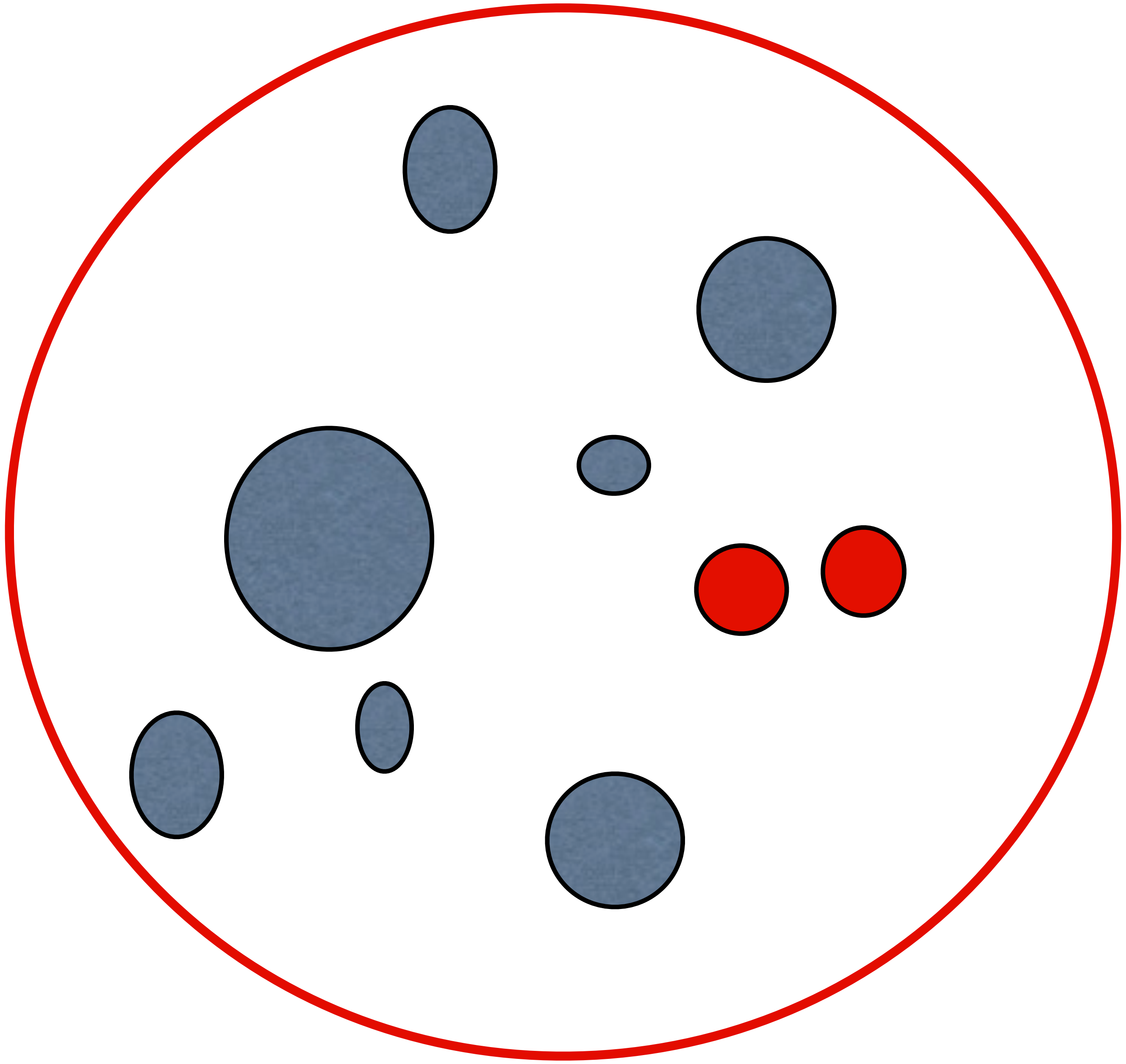

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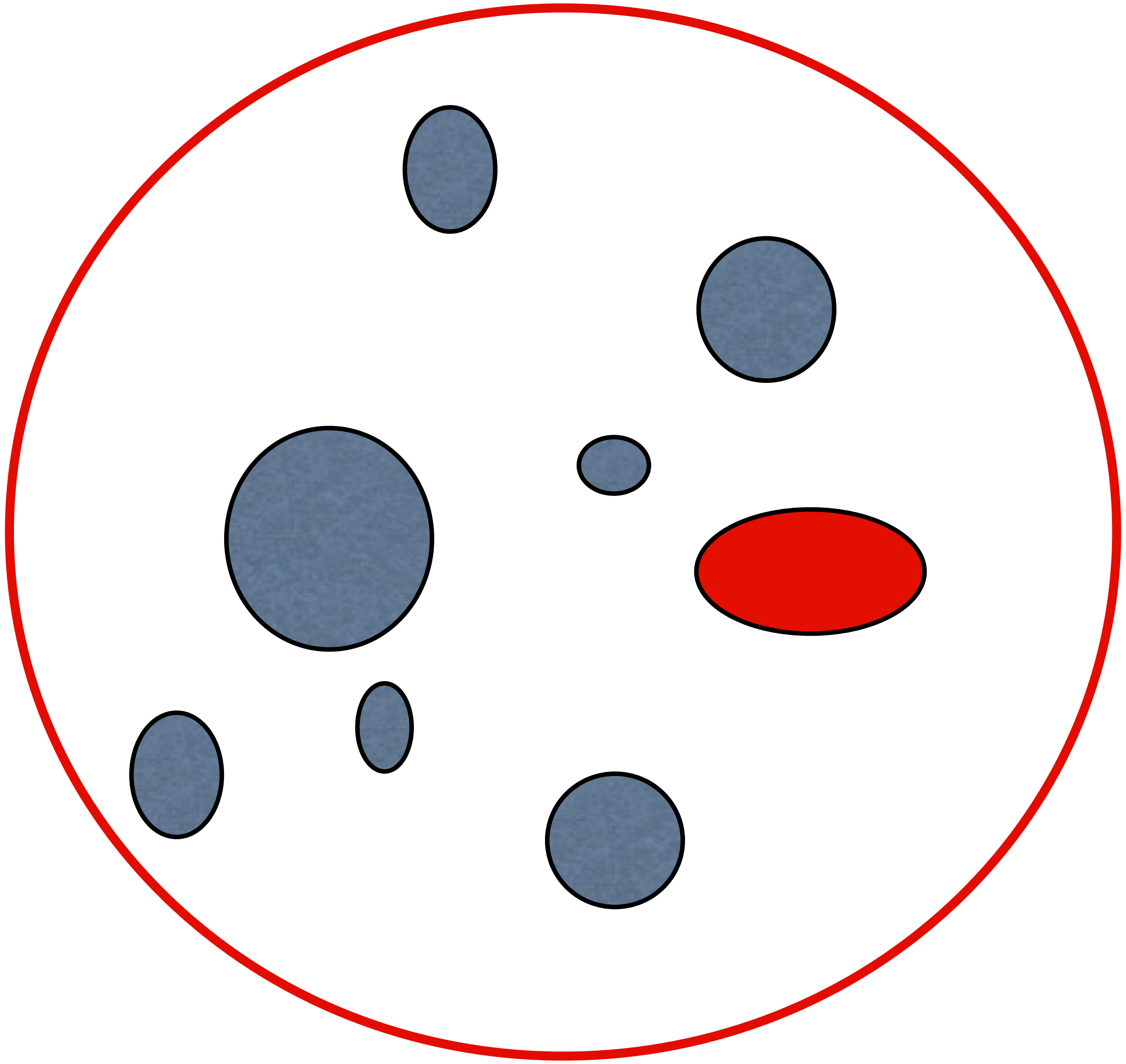

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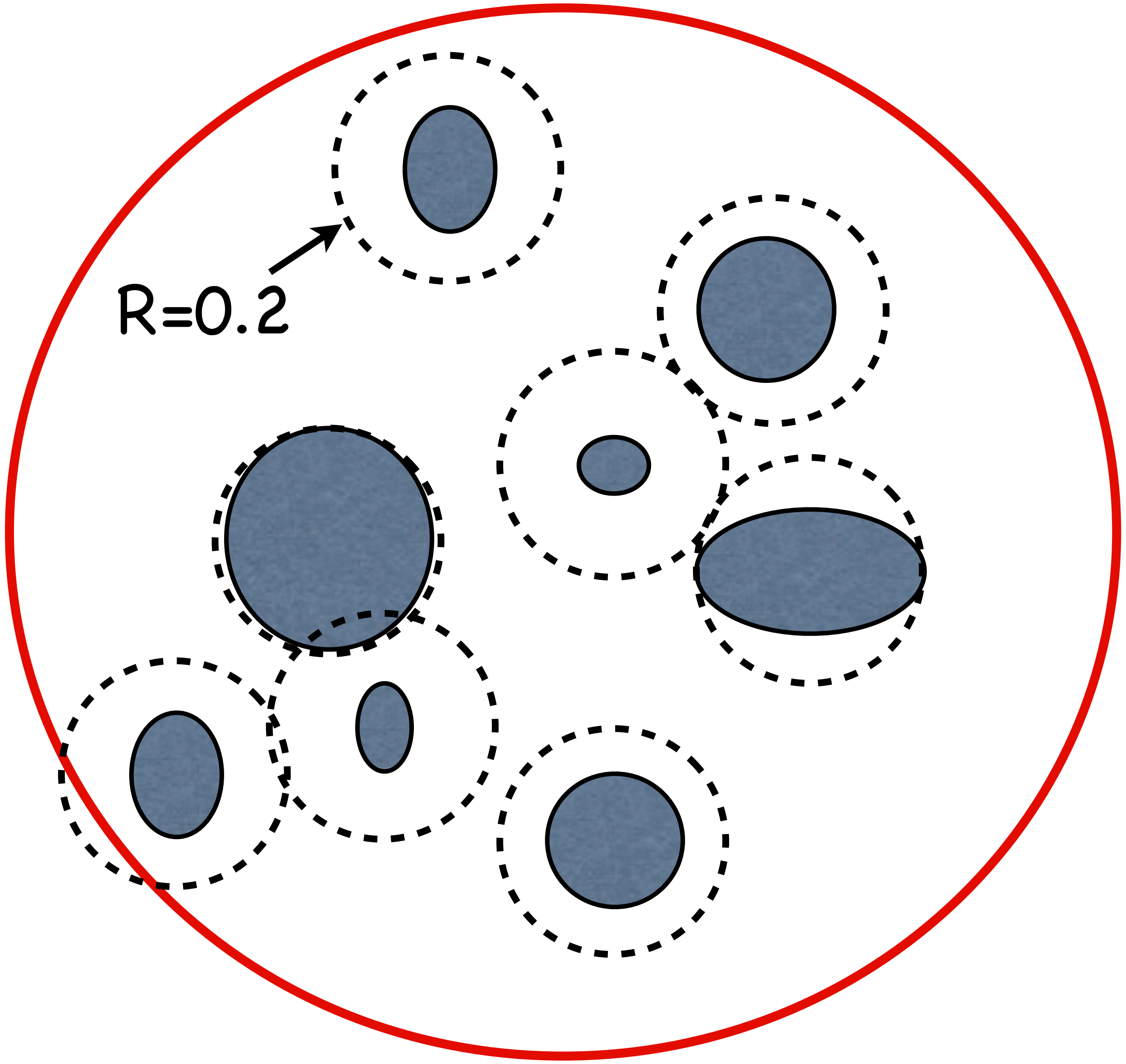

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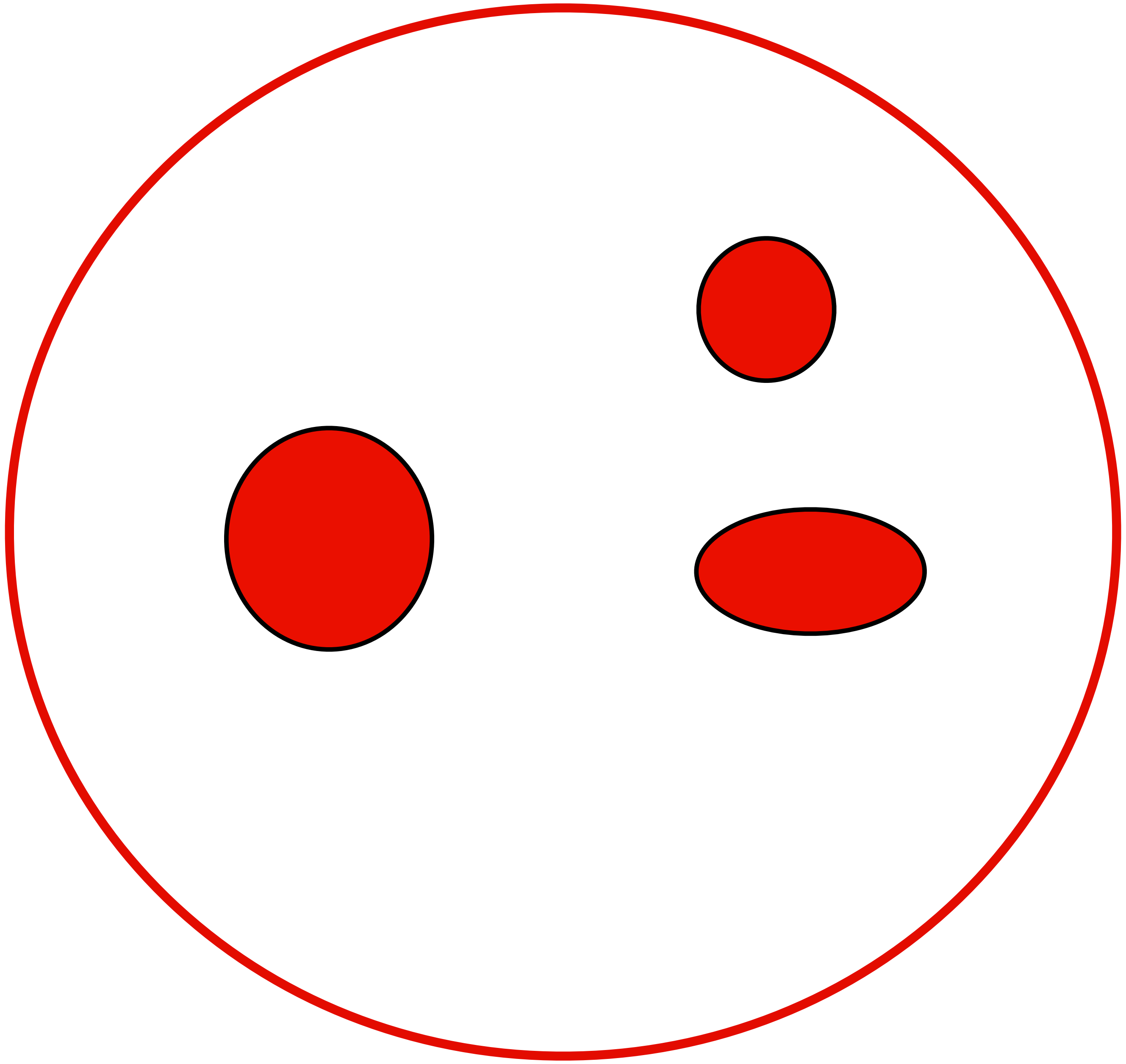
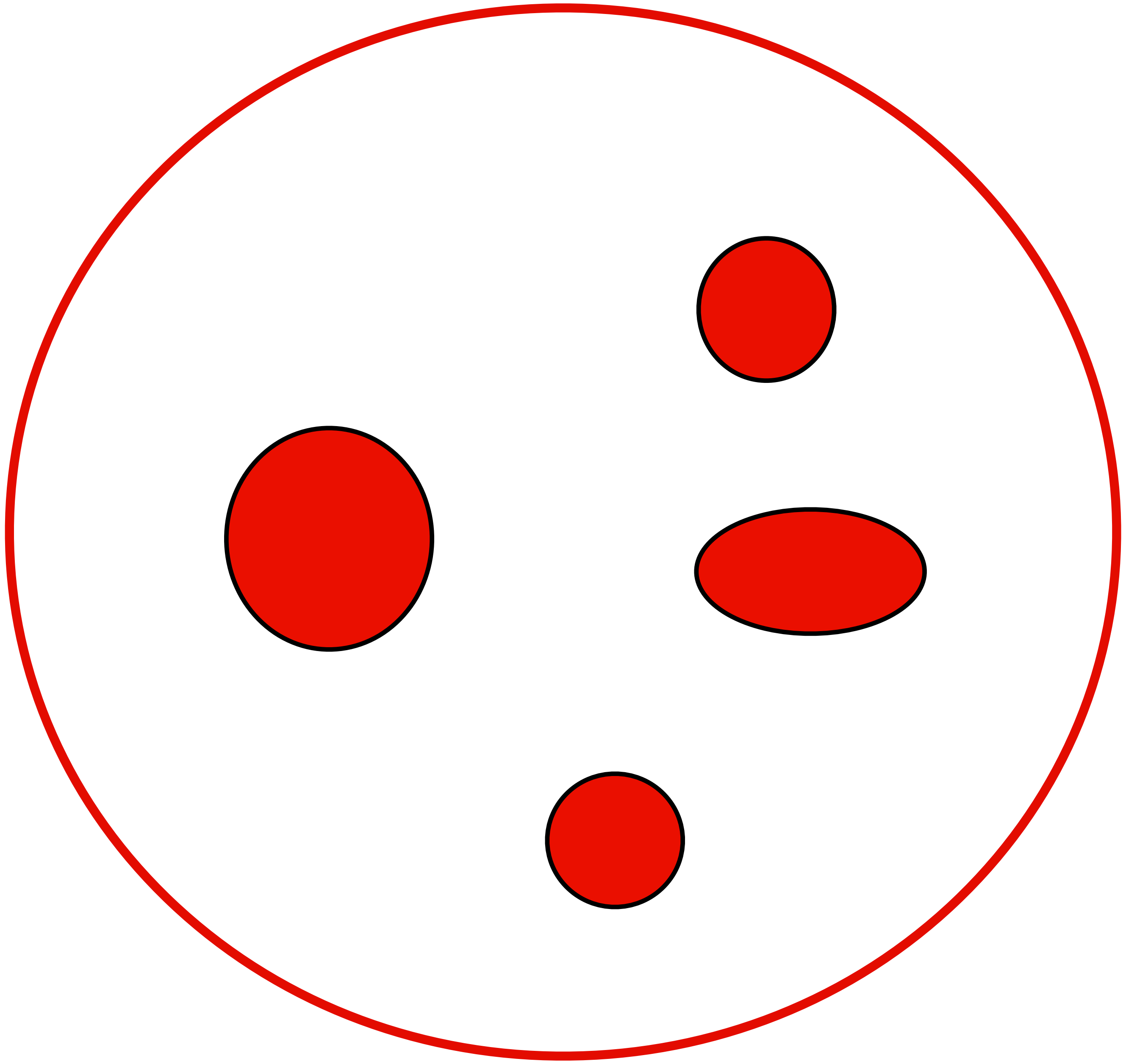


Filtering/Trimming



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

Filtering:
recombine n subjets

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

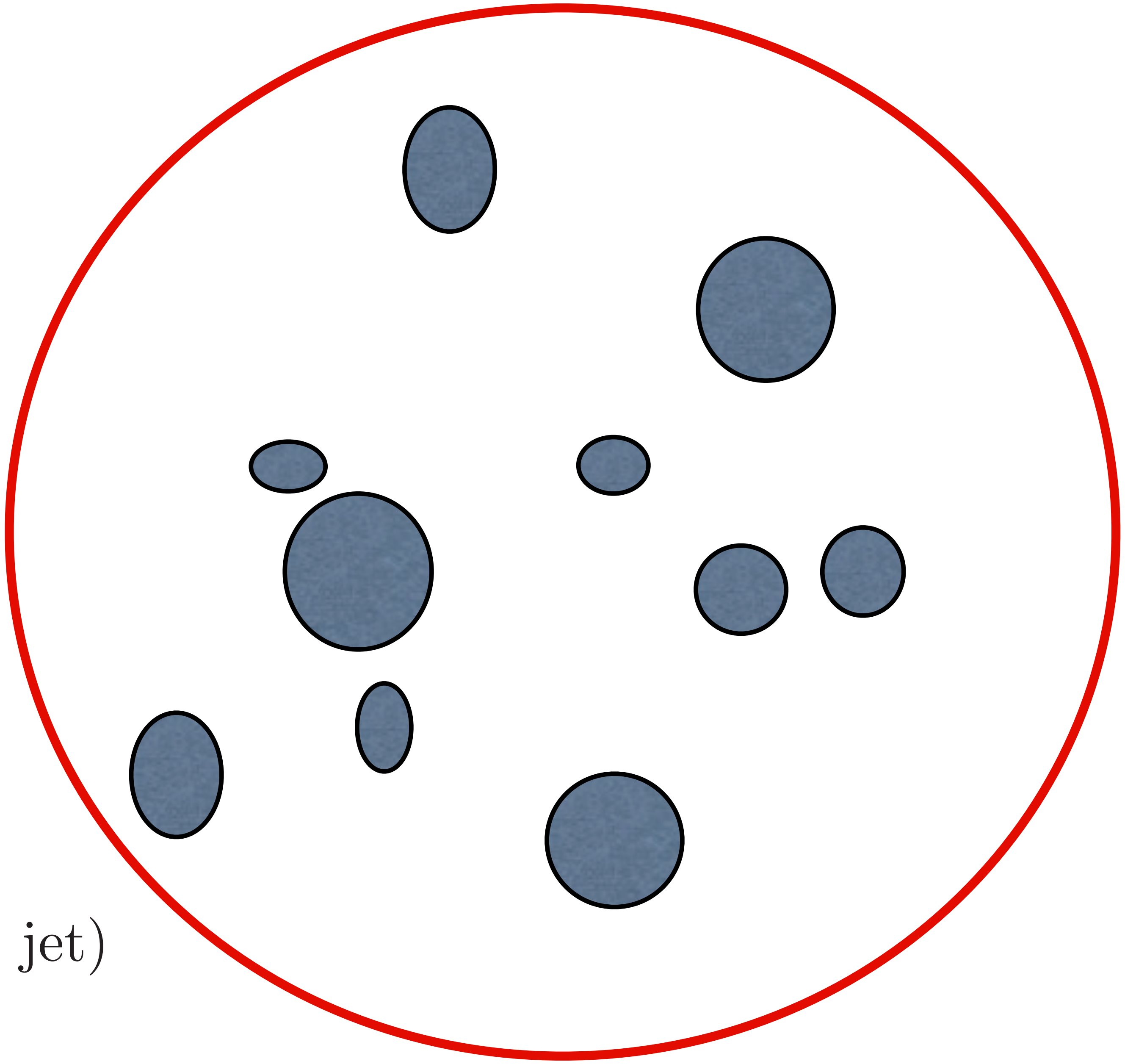
fix choice ↗ (f)   based on Jet property ↖ (Λ)

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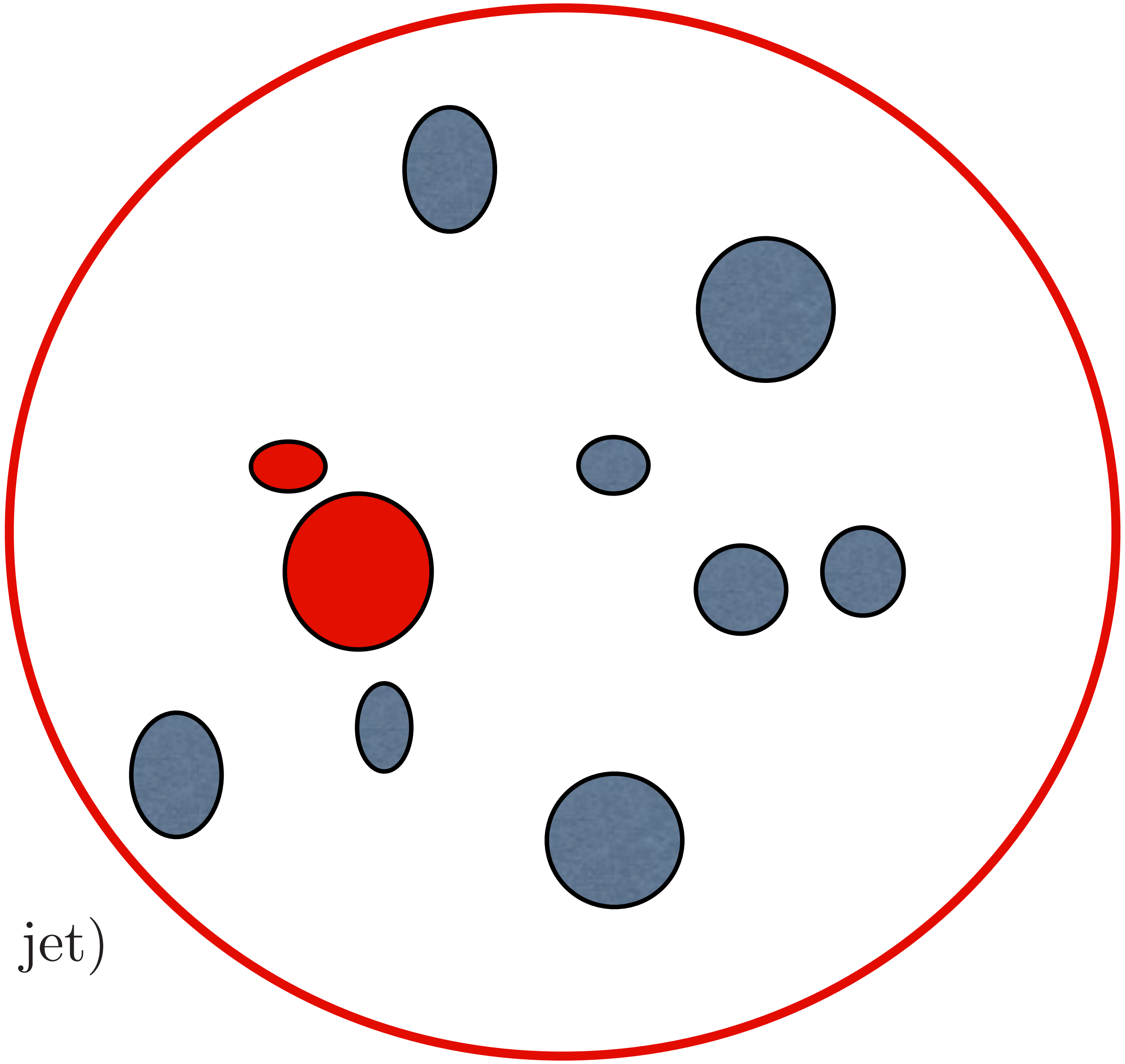
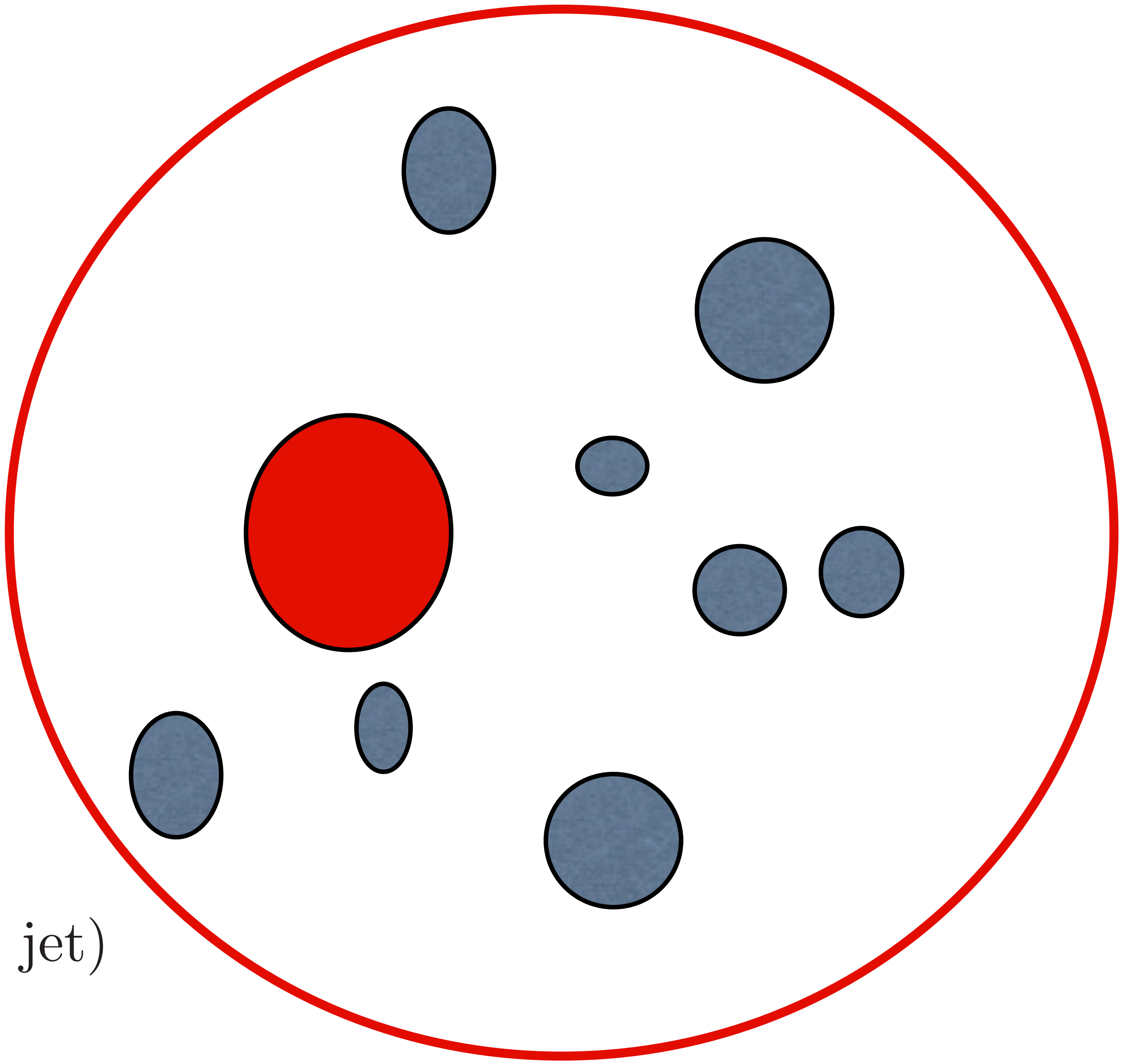
$$z = \frac{\min(p_{T,i}, p_{T,j})}{|\vec{p}_{T,i} + \vec{p}_{T,j}|} < z_{\mathrm{cut}}$$

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



Pruning



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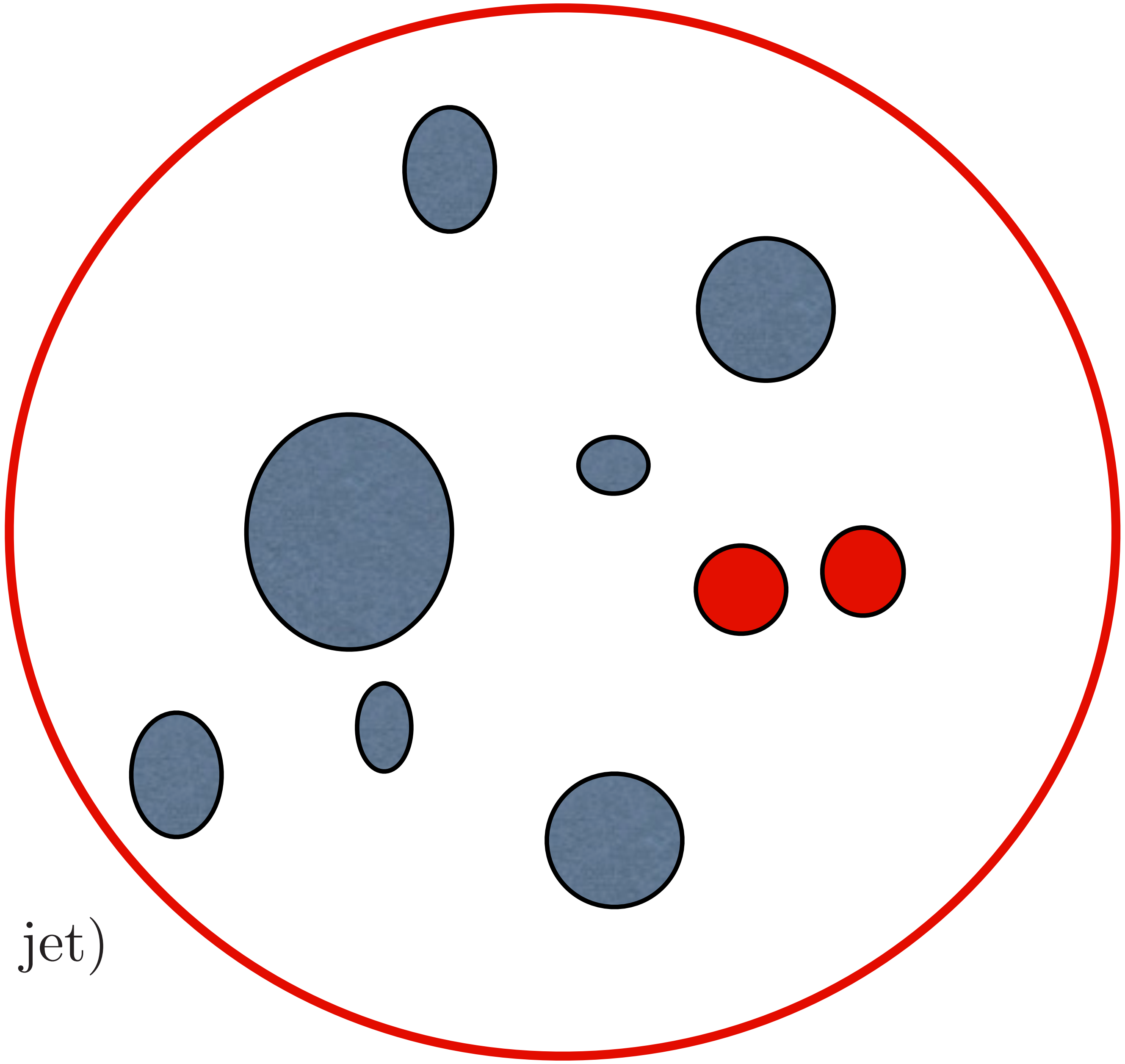

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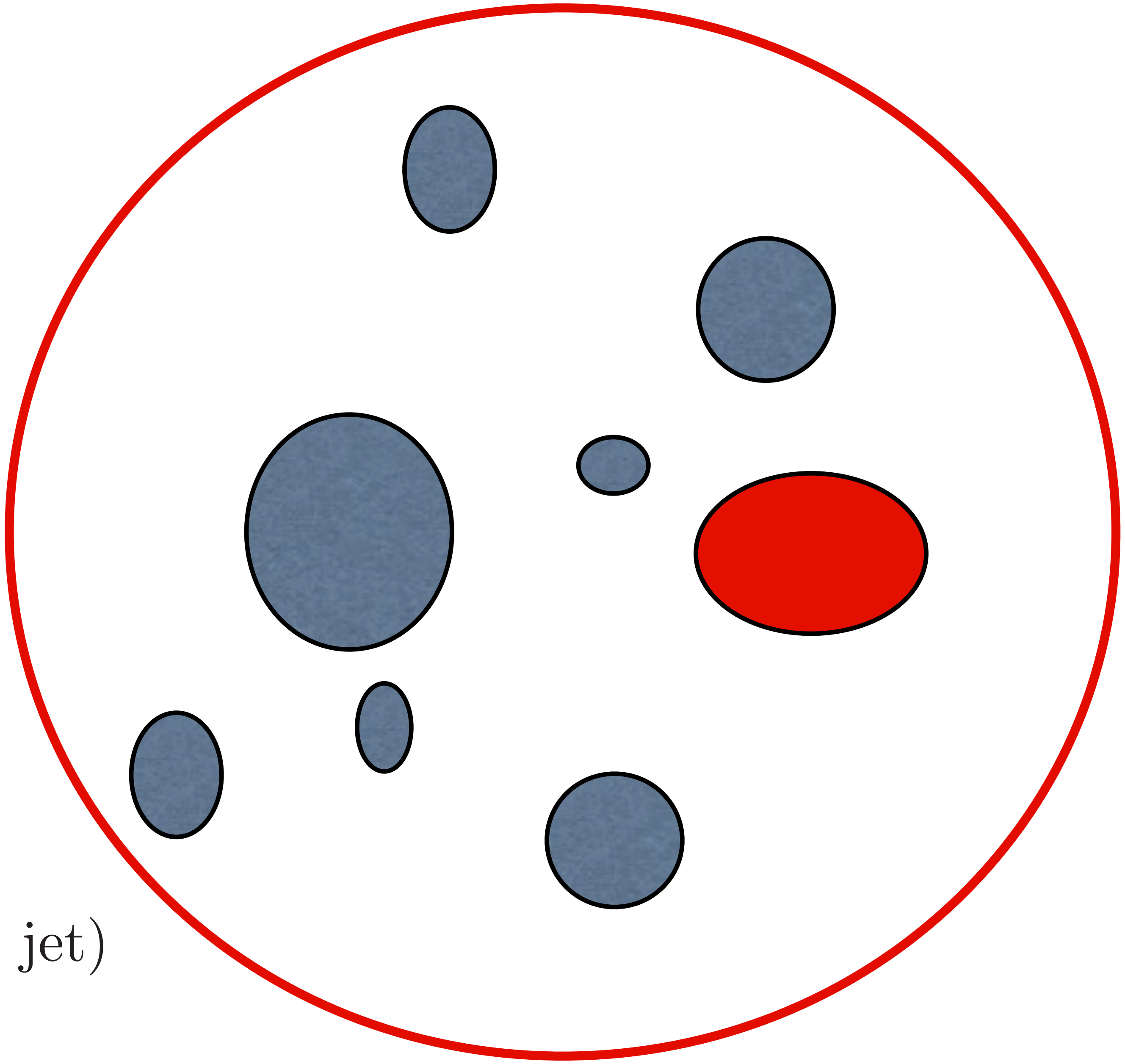
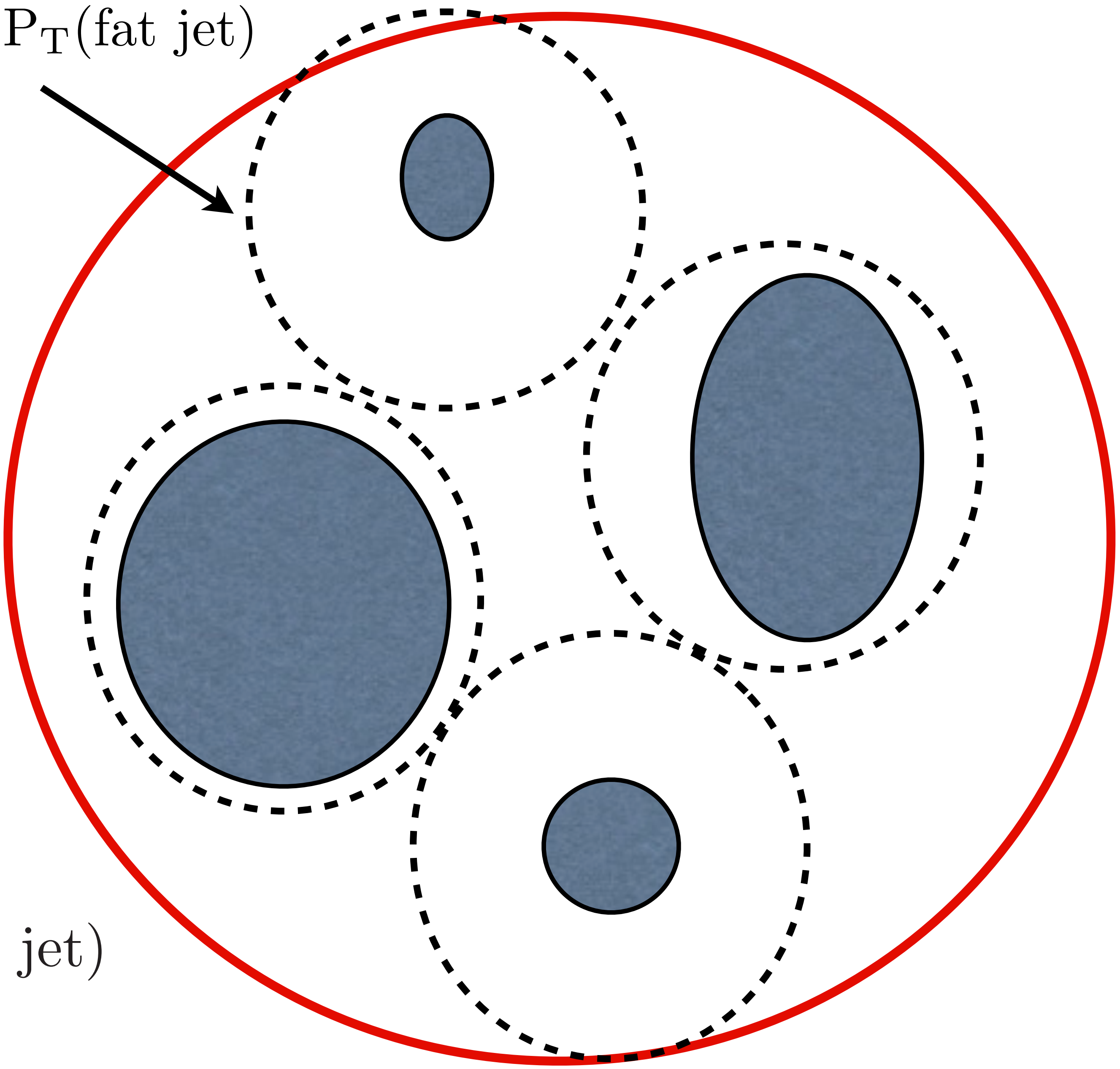


Pruning



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

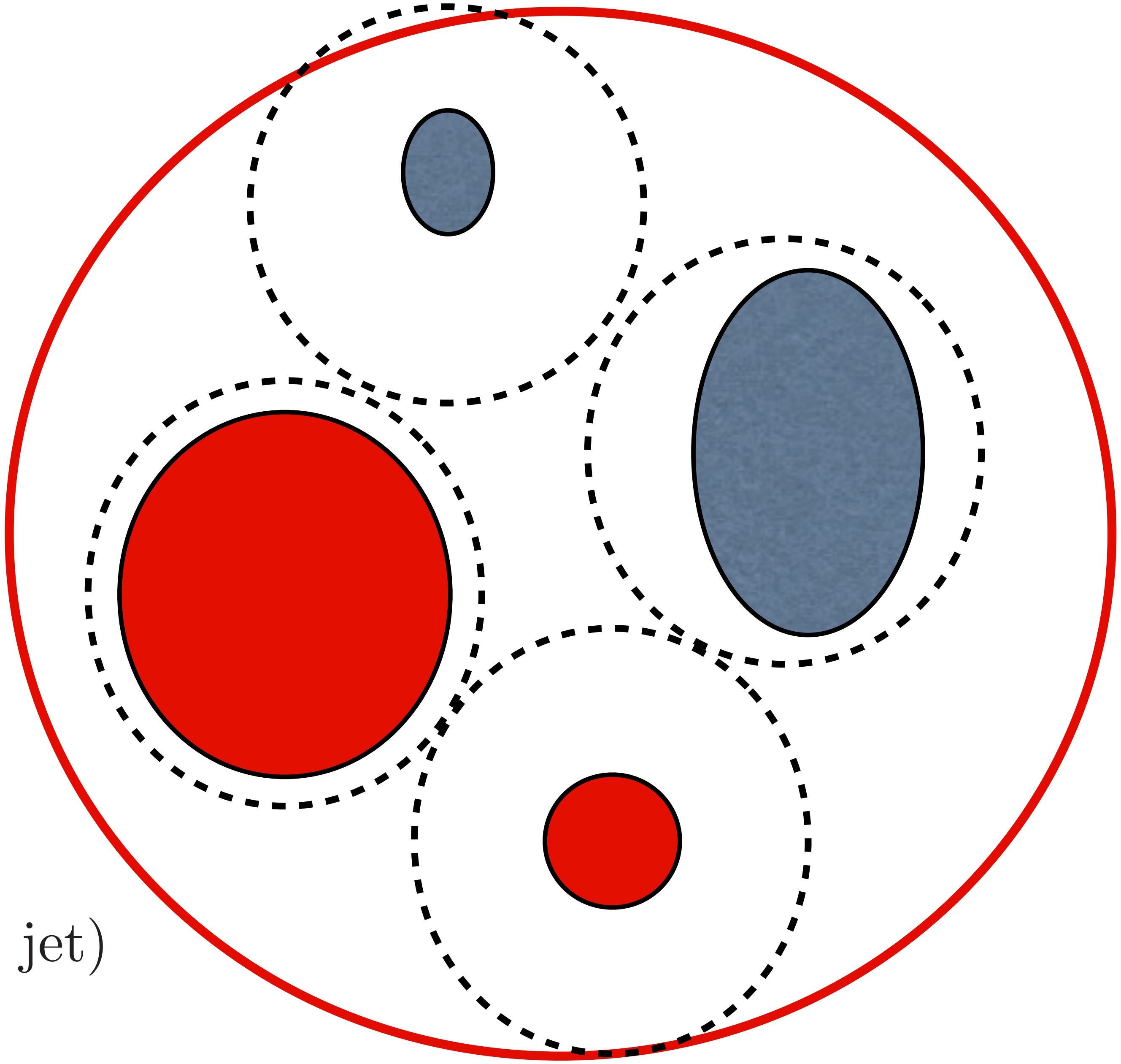
Based on 2 conditions

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



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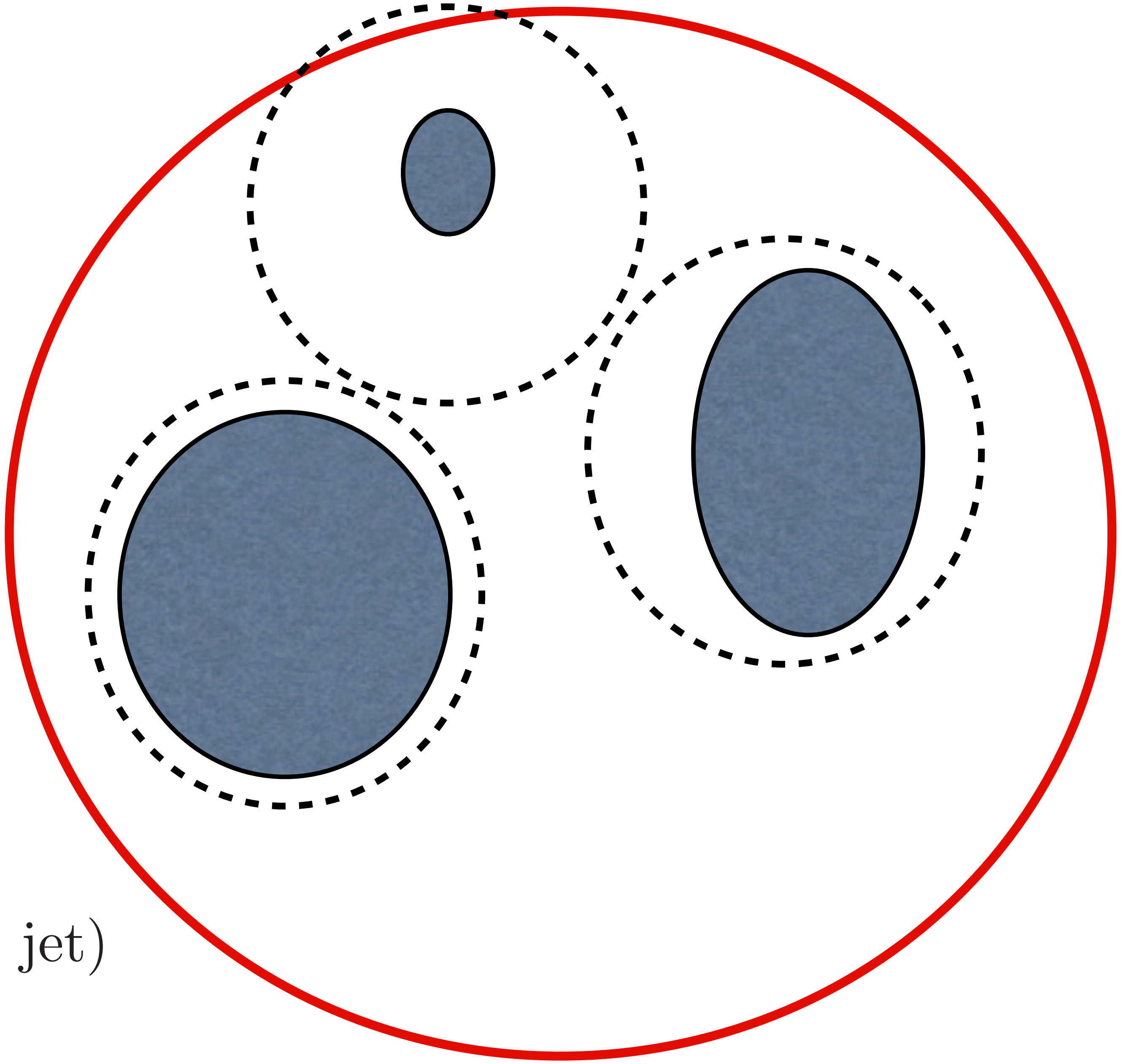

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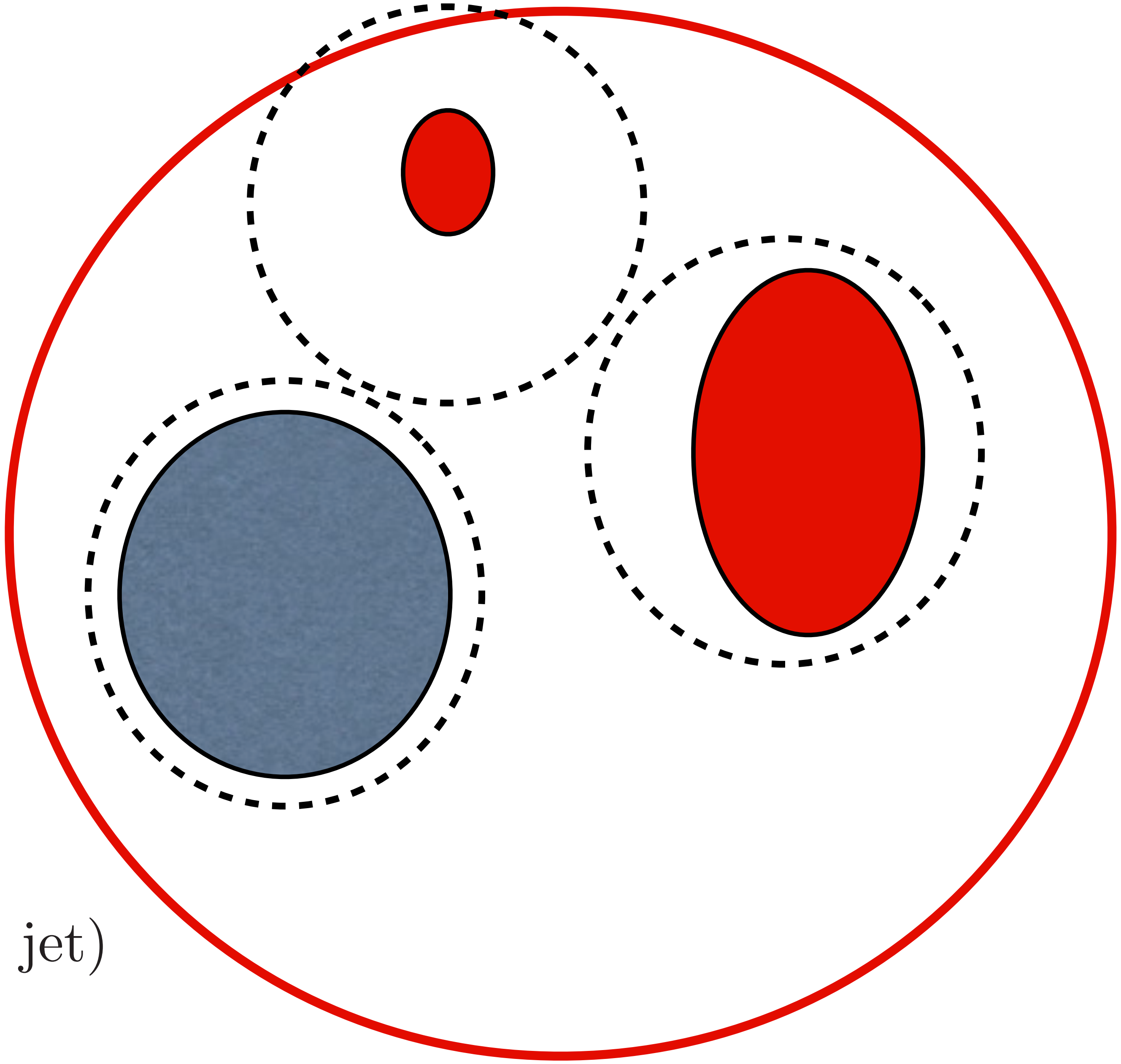

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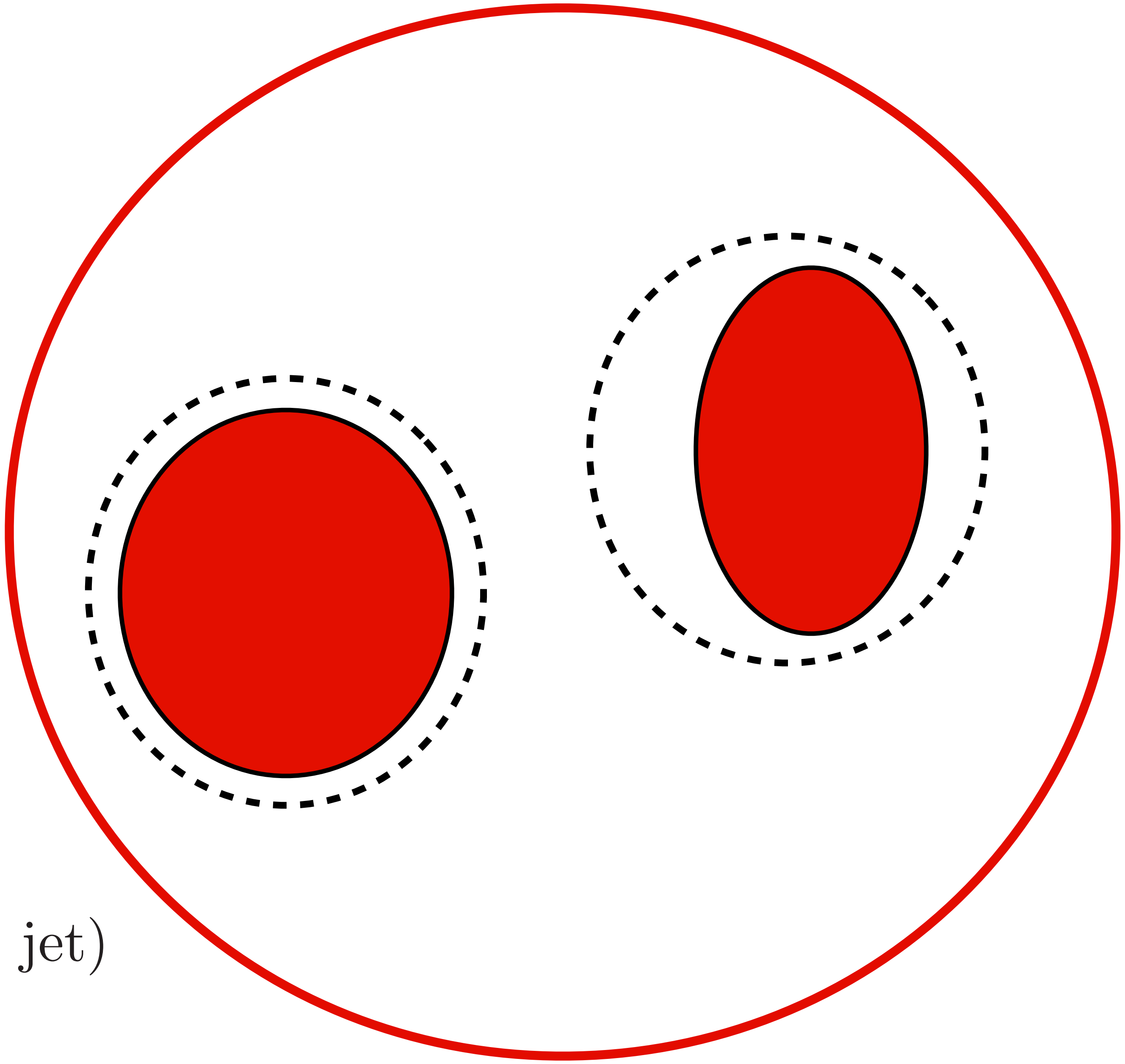

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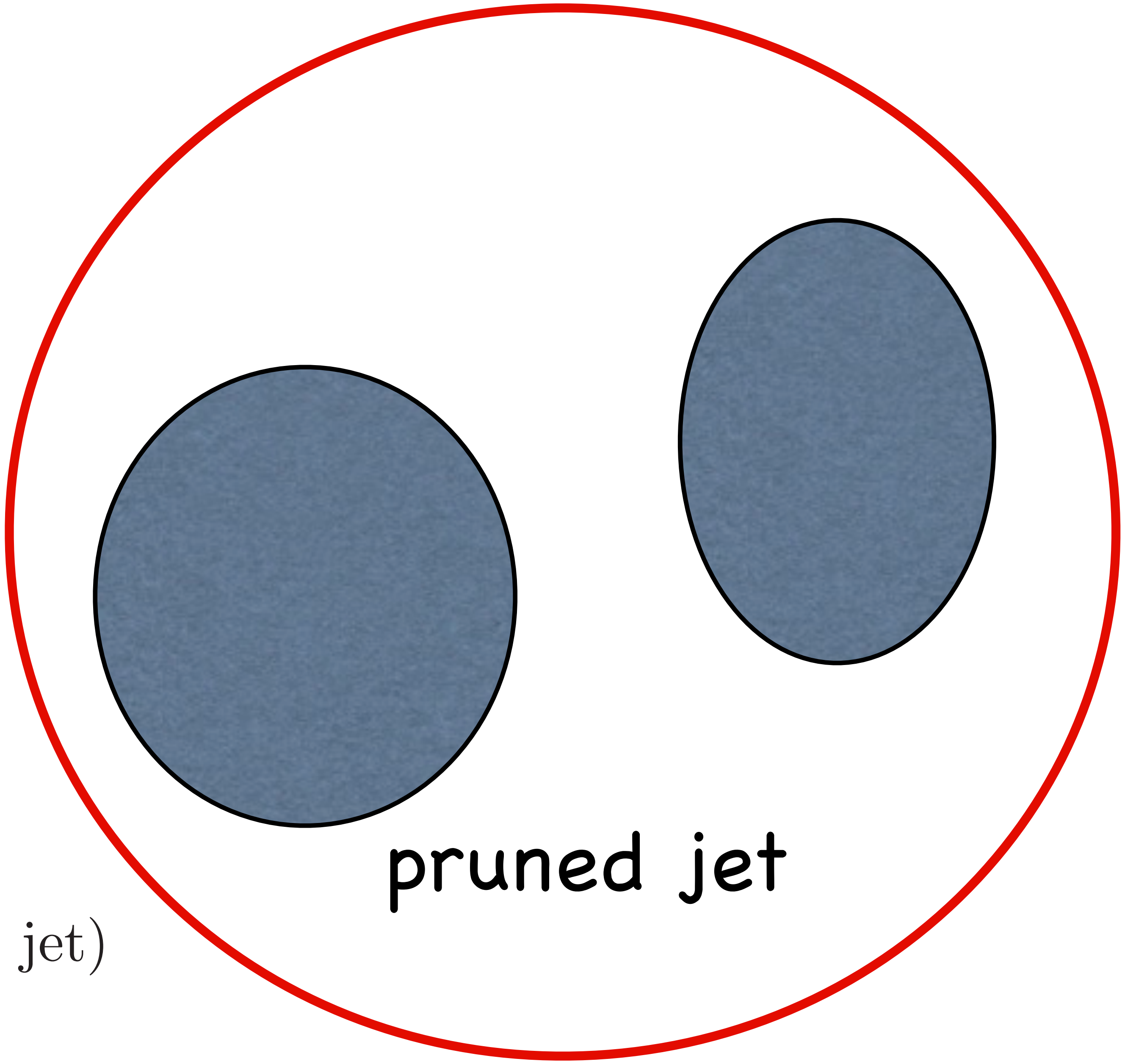
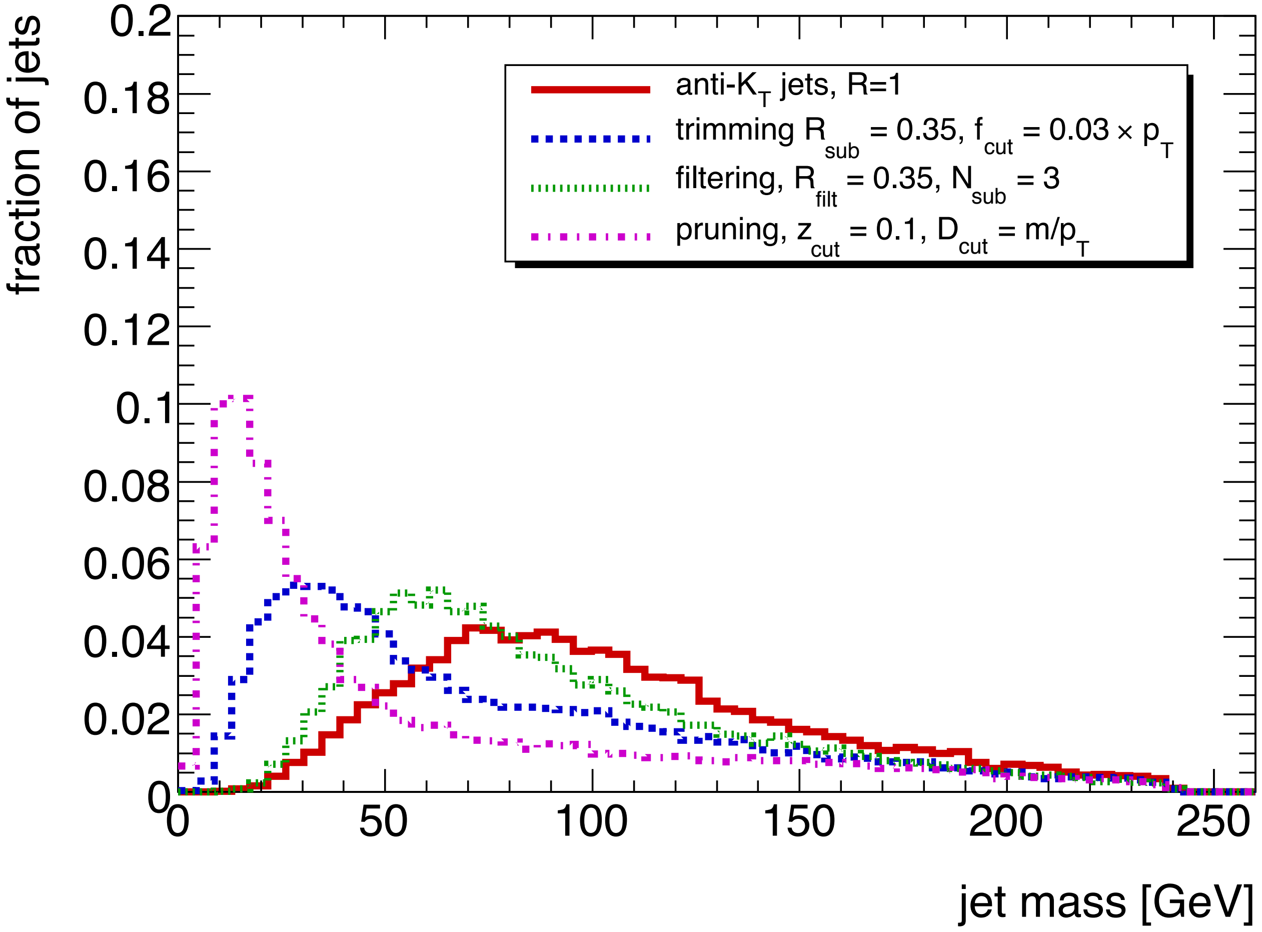
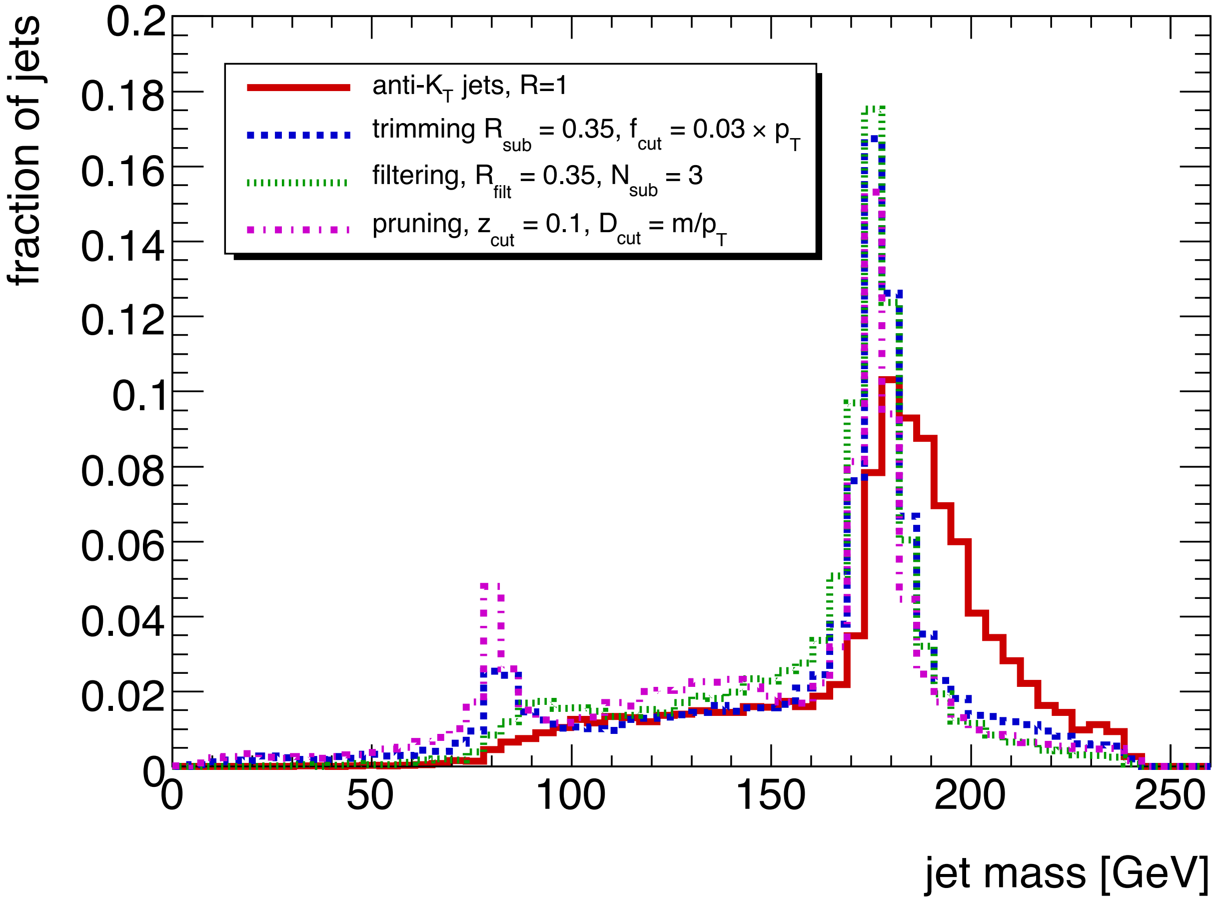


How much does UE/ISR affect fat-jet mass



(a) dijets, 500–600 GeV



(b) $t\bar{t}$, 500–600 GeV

see Boost 2010 proceedings [A. Abdesselam et al. EPJ C71 (2011)]

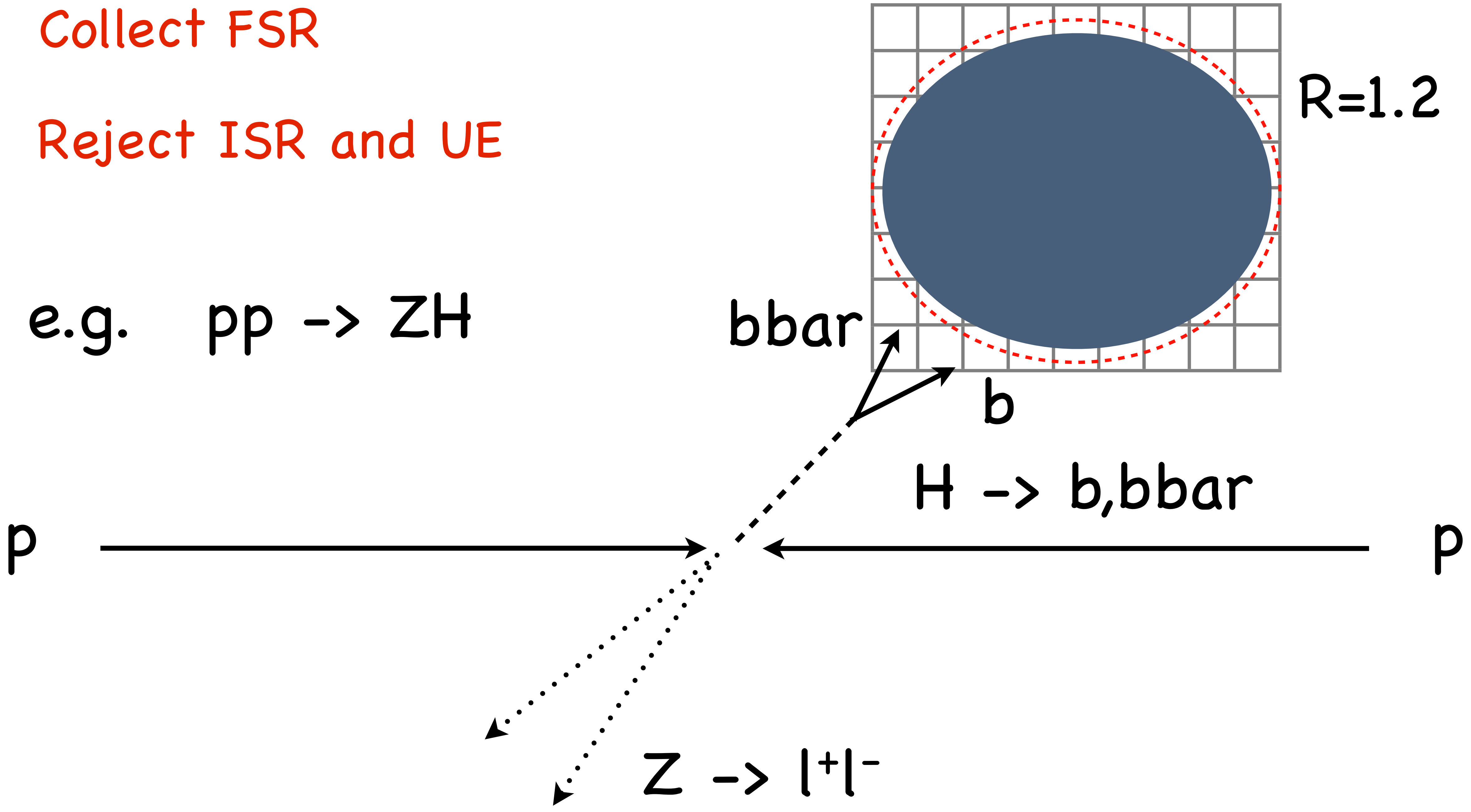
HV - Higgs discovery channel

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



R=1.2

bbar

b

H -> b,bbar

p

p

$Z \rightarrow l^+l^-$

HV - Higgs discovery channel

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

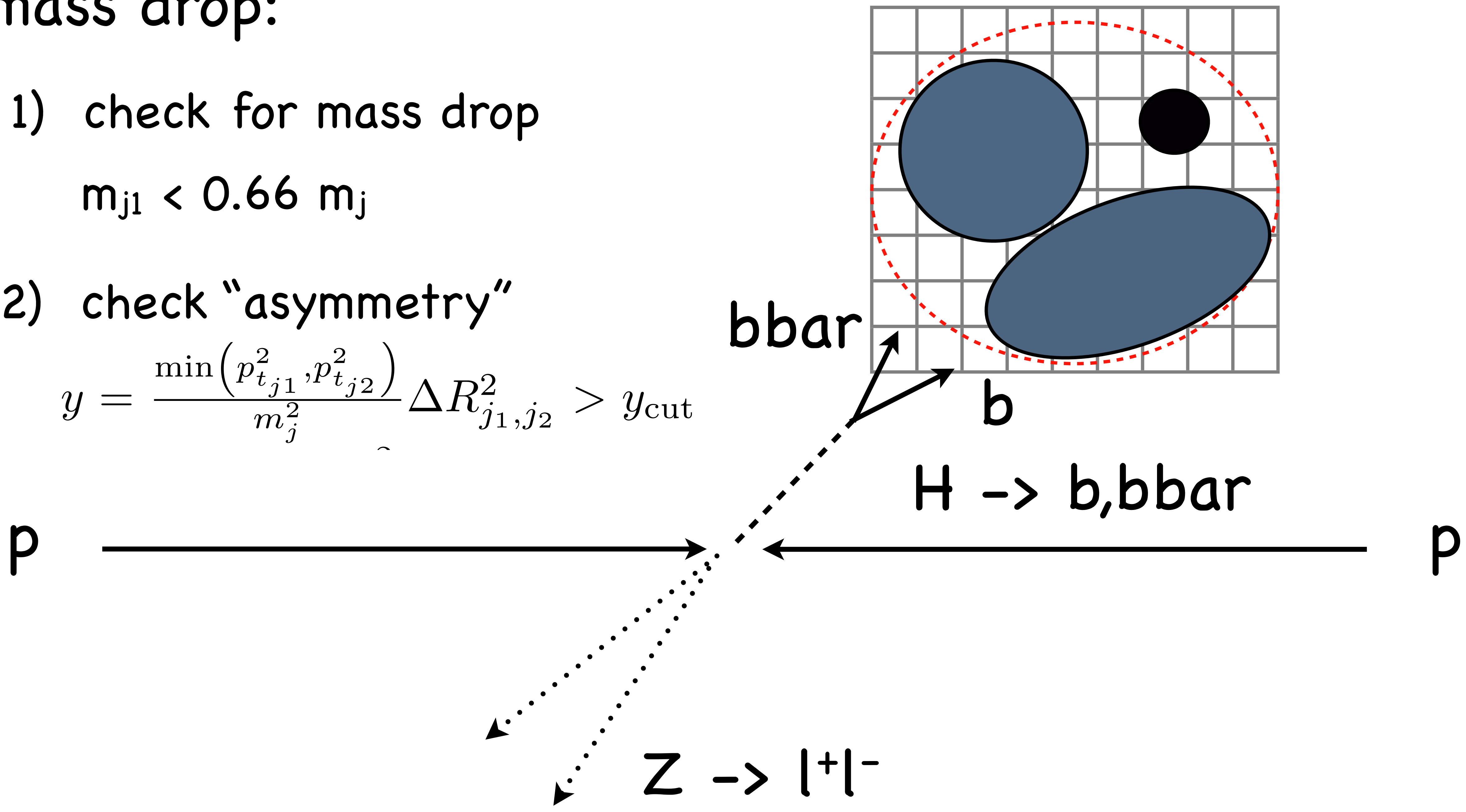
mass drop:

1) check for mass drop

   $m_{j1} < 0.66\ m_j$

2) check "asymmetry"

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



bbar

b

H -> b,bbar

p

p

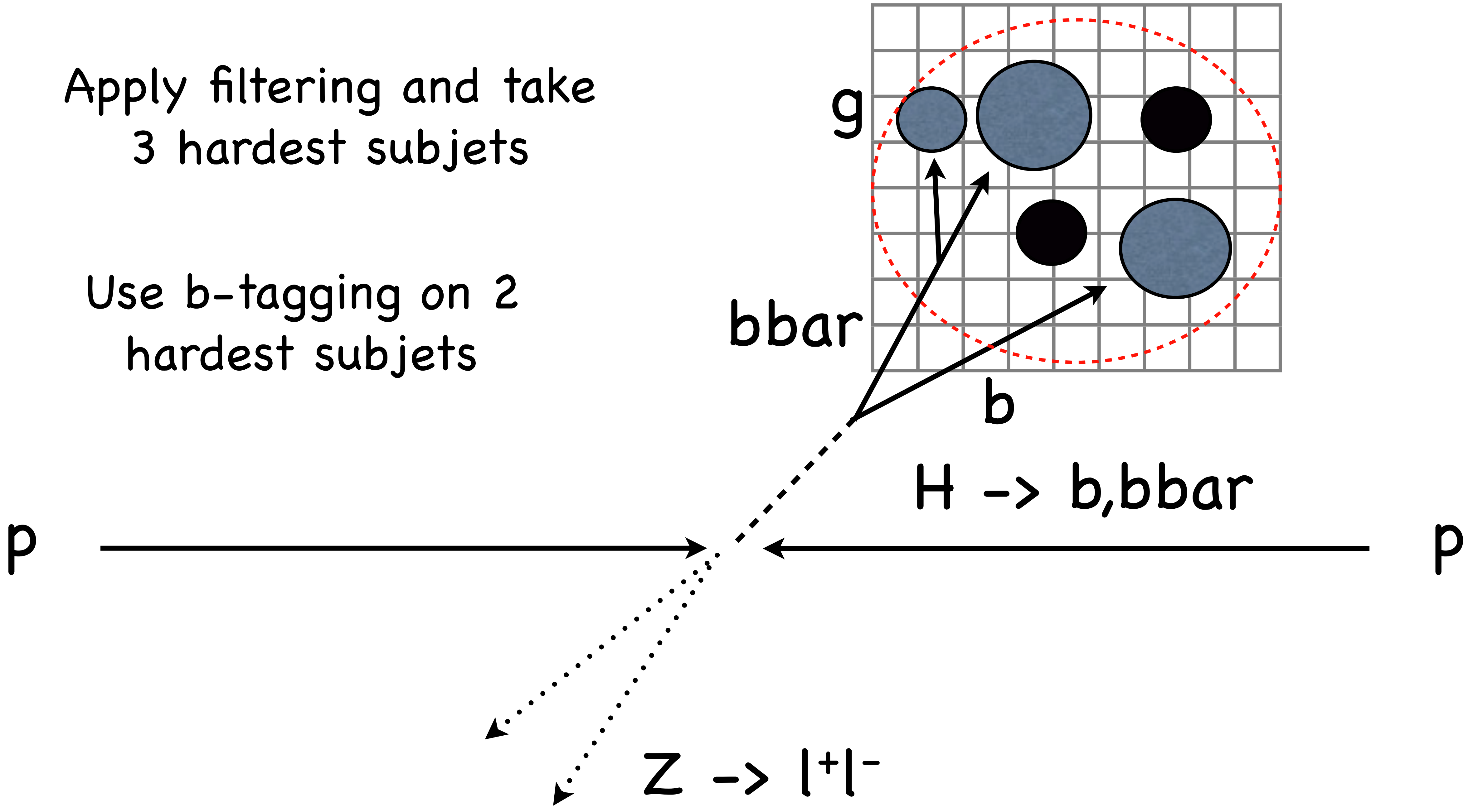
Z -> l^+l^-

HV - Higgs discovery channel

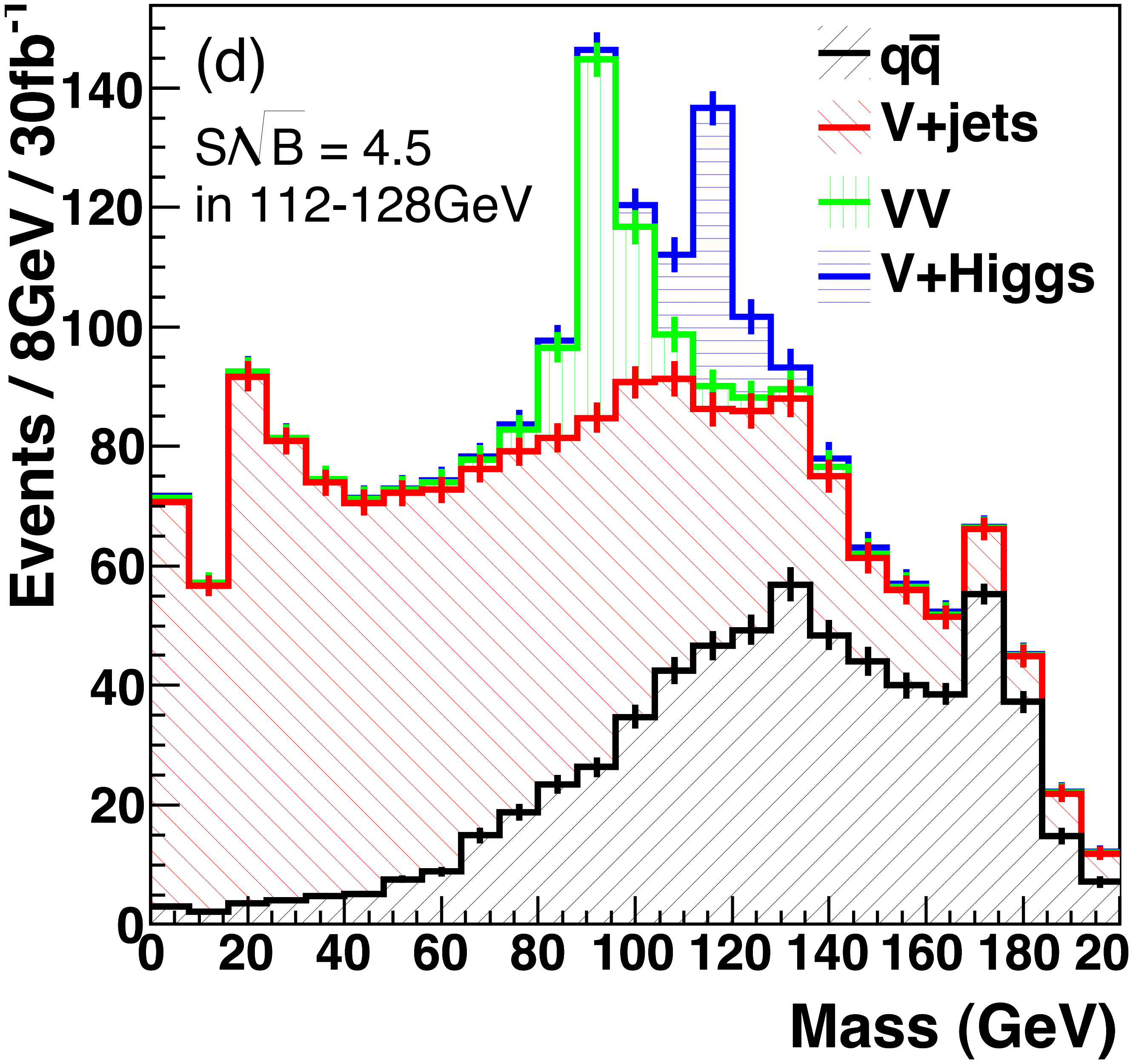
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets



BDRS Result



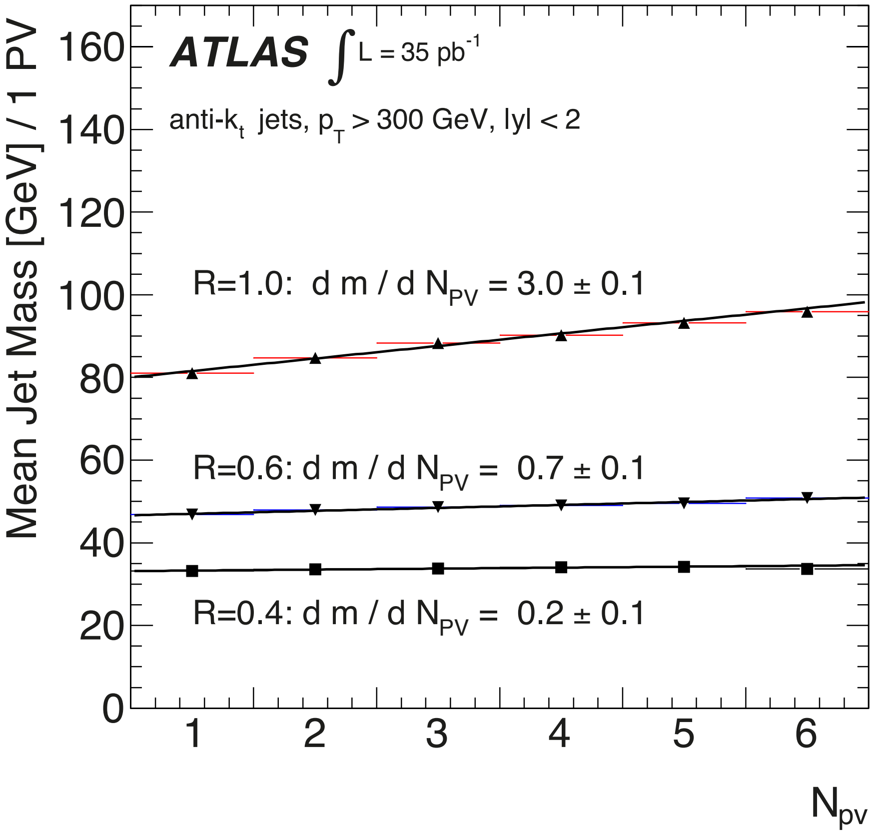
- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- Combination of HZ and HW channels

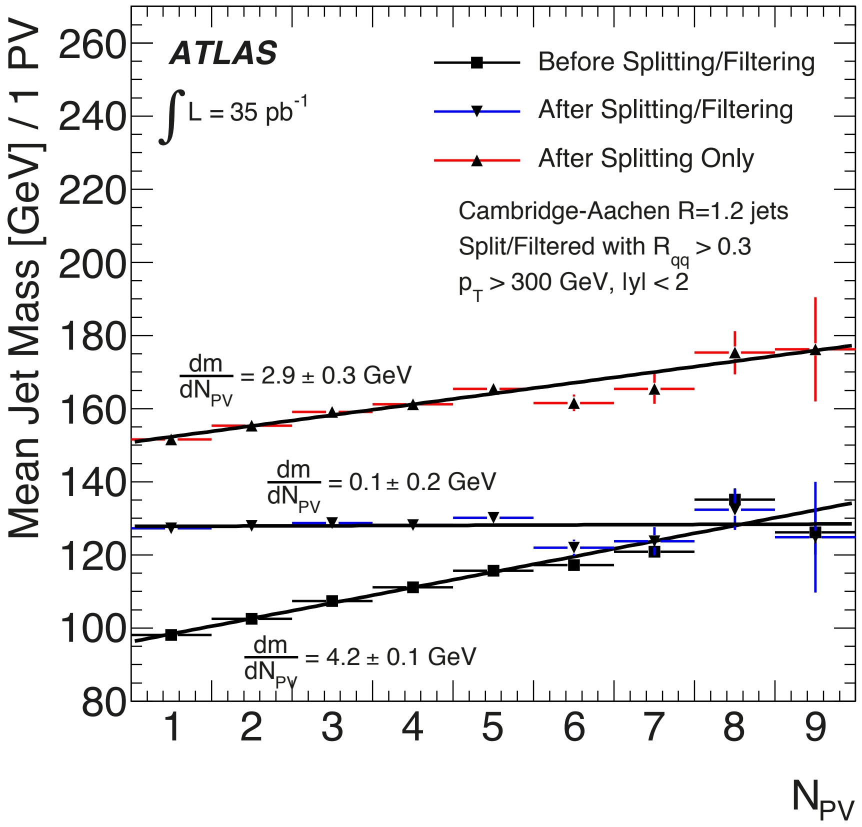
Confirmed in ATLAS full detector simulation

How about Data?

(see yesterdays paper 1203.4606)

- Jet mass in good agreement with MC
- y-splitter observable in good agreement with MC
- Massdrop + Filtering as predicted by MC
- Pileup under control so far:





All measurements indicate large potential for jet substructure techniques and good agreement with MC

top tagging at the LHC

- High pT tops come naturally with New Physics

  ⟶ Was initial motivation to study jet substructure

  [e.g. Agashe, et al. PRD 77 (2008)]

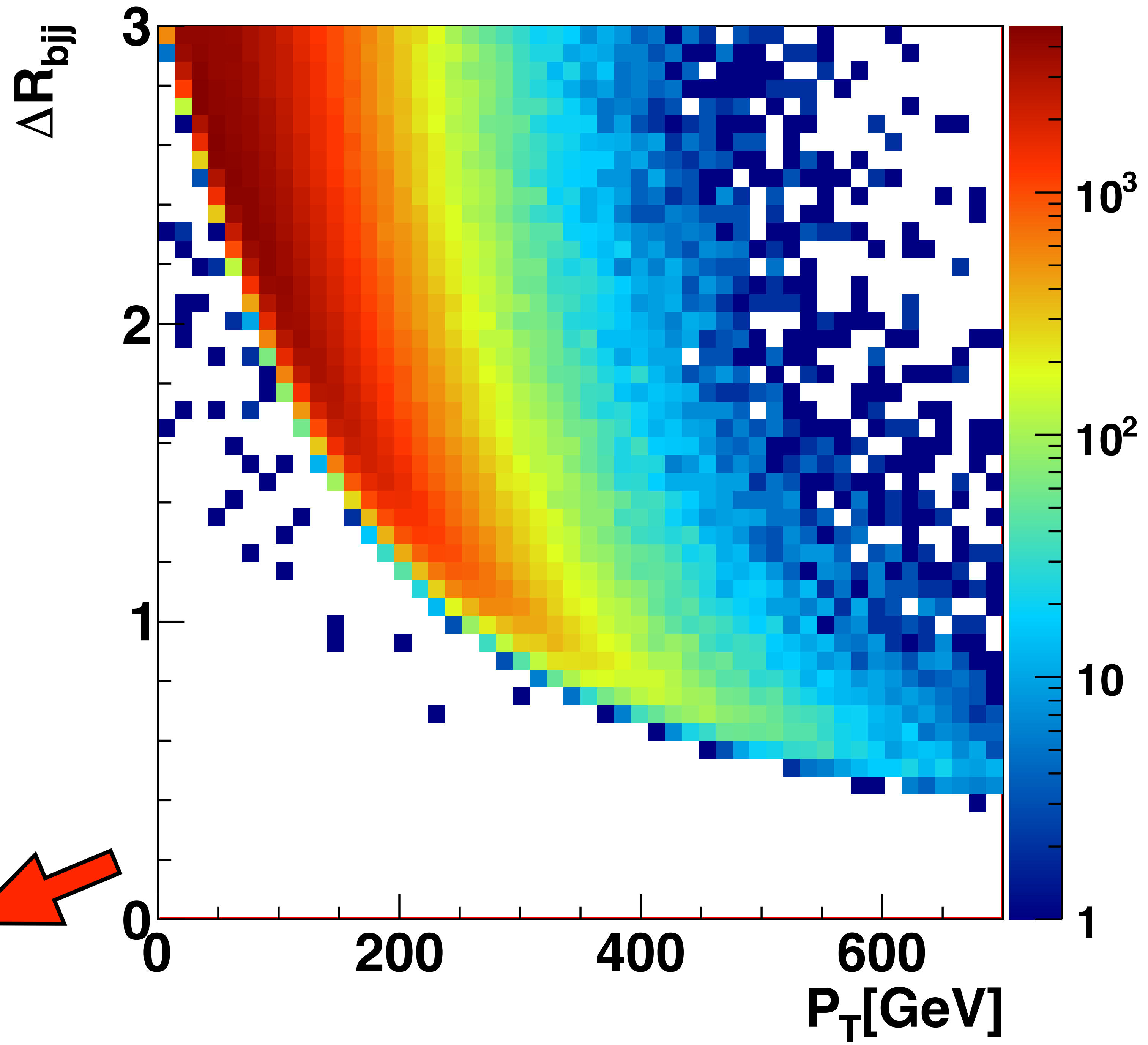
- Several approaches

  ⟶ Promote event shape to jet shape

  ⟶ Use internal structure of jet recombination history

- Allows for a very rich phenomenological application

Angular separation of boosted top's decay products in 14 TeV ttbar samples



top transverse momentum

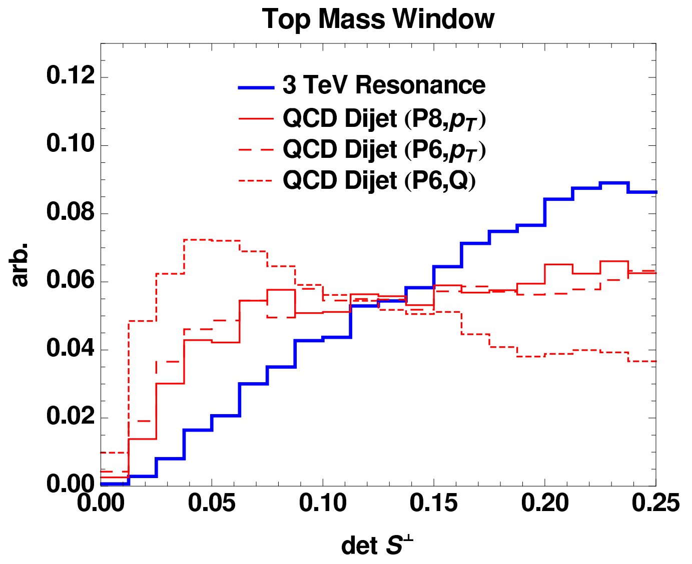
Maximum distance of top decay products

Need large cone if you want to do top tagging

Approach I: Propagate event shape to jet shape:

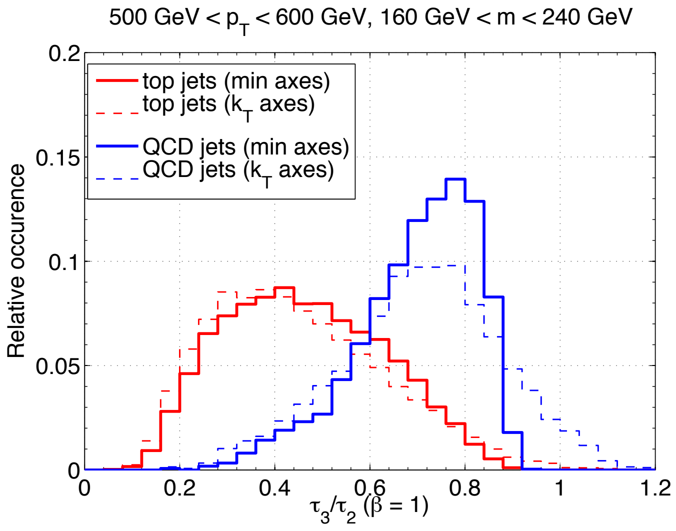
- sphericity:

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



- N-subjettiness:

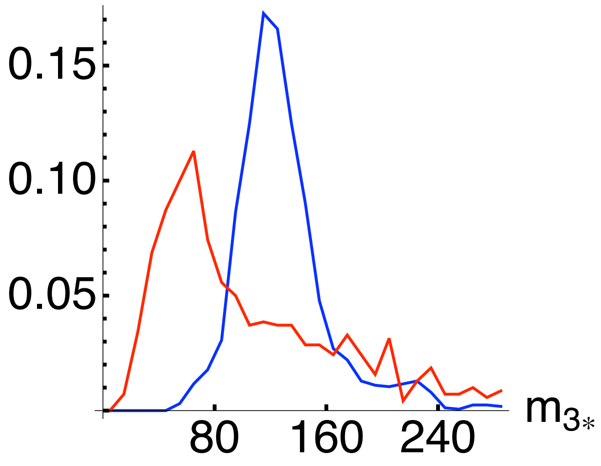
$$\tau_N = \frac{1}{\sum_{\alpha\in\text{jet}} p_{T,\alpha} R_0^\beta} \sum_{\alpha\in\text{jet}} p_{T,\alpha} \min_{k=1,\dots,N} (\Delta R_{k,\alpha})^\beta$$



- treeless approach:

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

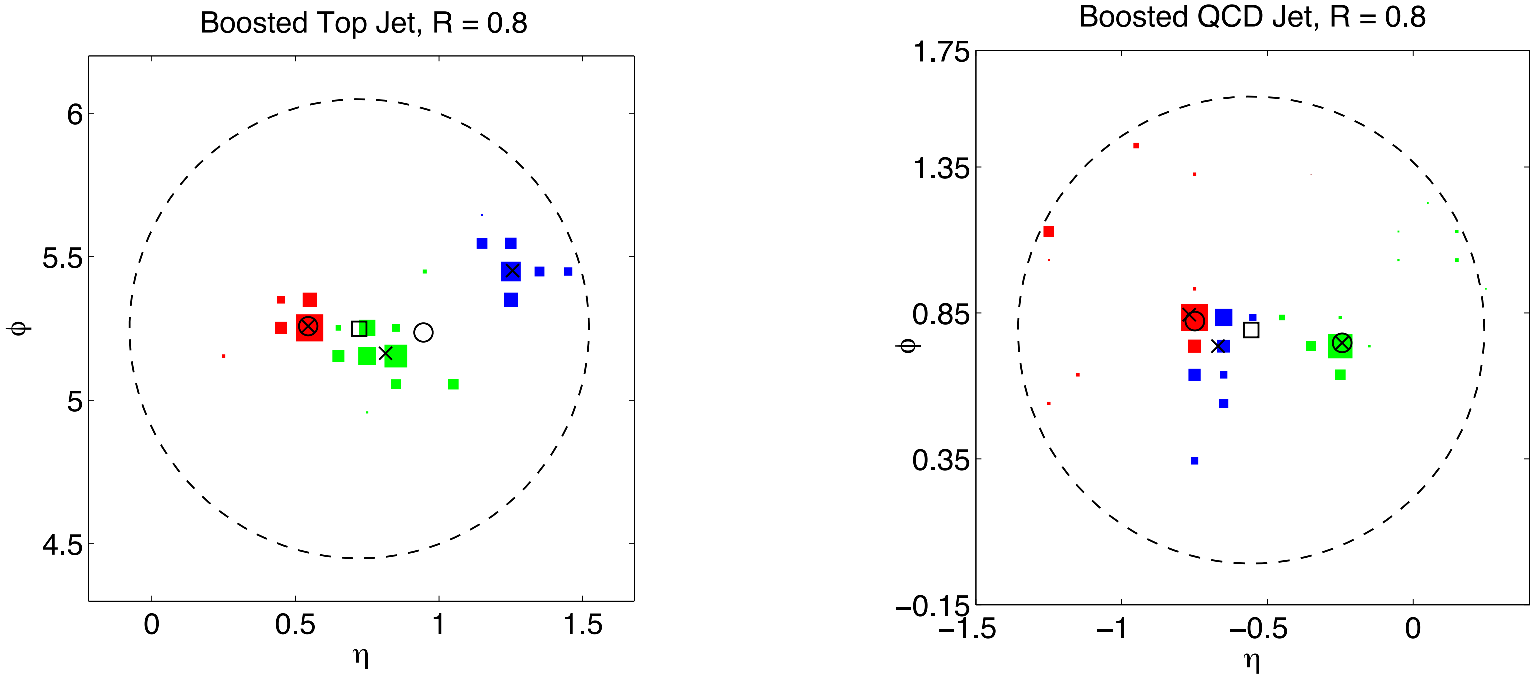
$$\mathcal{G}(R) = \frac{\sum_{j_1\neq j_2} d^{(\text{JADE})}_{j_1 j_2}\, \Theta(R - \Delta R_{j_1 j_2})}{\sum_{j_1\neq j_2} d^{(\text{JADE})}_{j_1 j_2}}$$



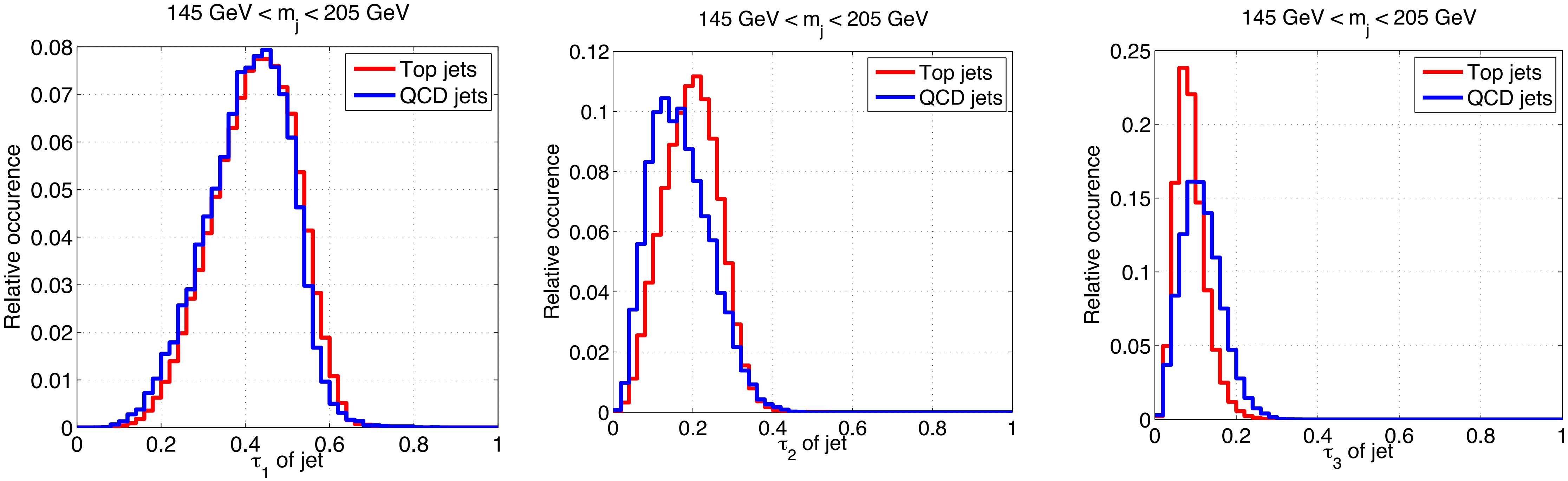
N-subjettiness: Degree to which a jet has N subjets

[Kim PRD 83 (2011)] [Thaler, Van Tilburg JHEP 1103] [Thaler, Van Tilburg JHEP 1202]

Top tagging by eye:

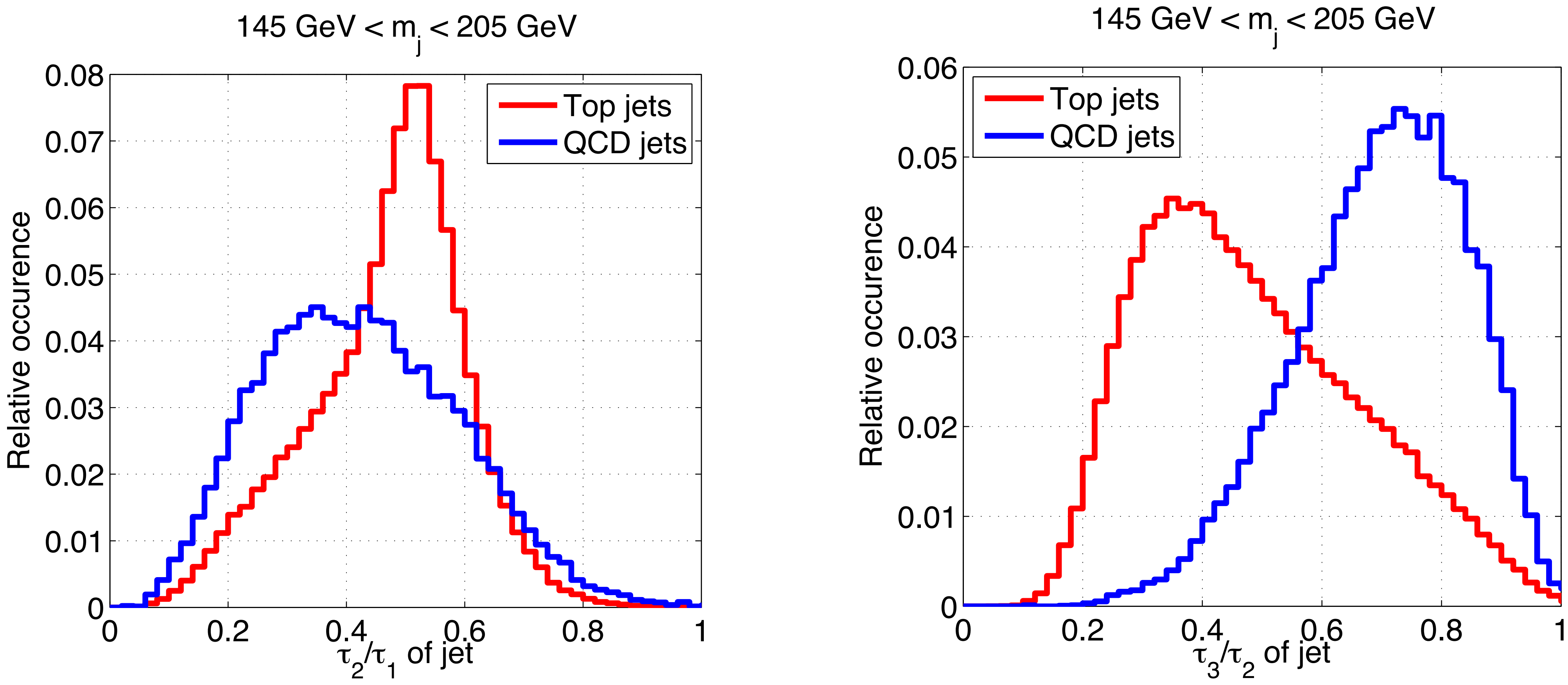


τ_1, τ_2 and τ_3 no good discriminators:



N-subjettiness: Degree to which a jet has N subjets

However, ratio of taus is good discriminator:

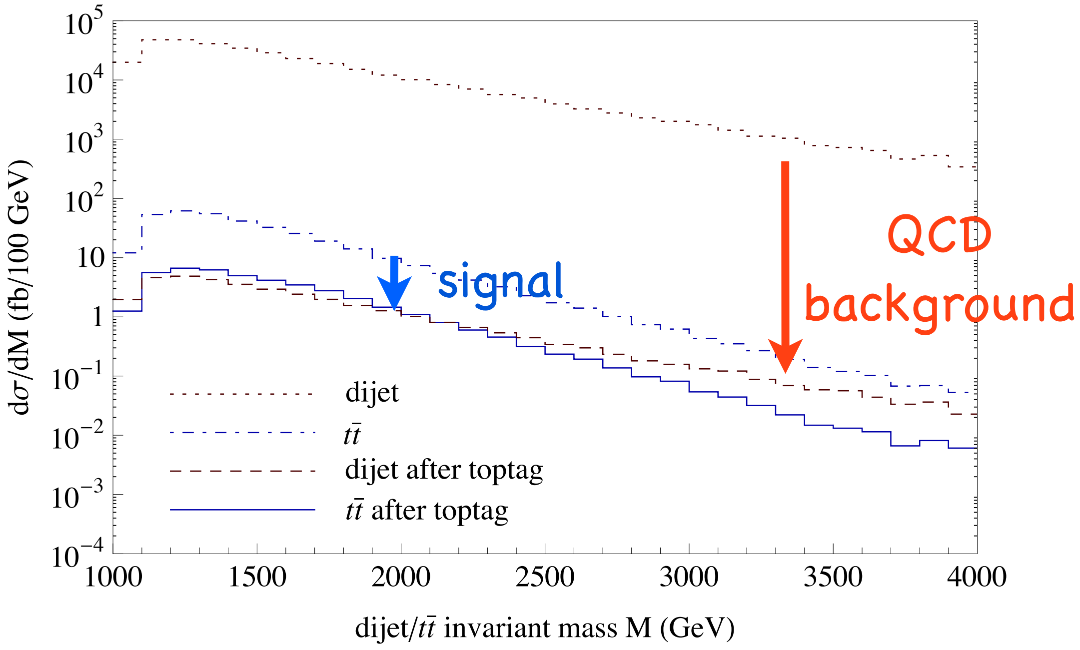


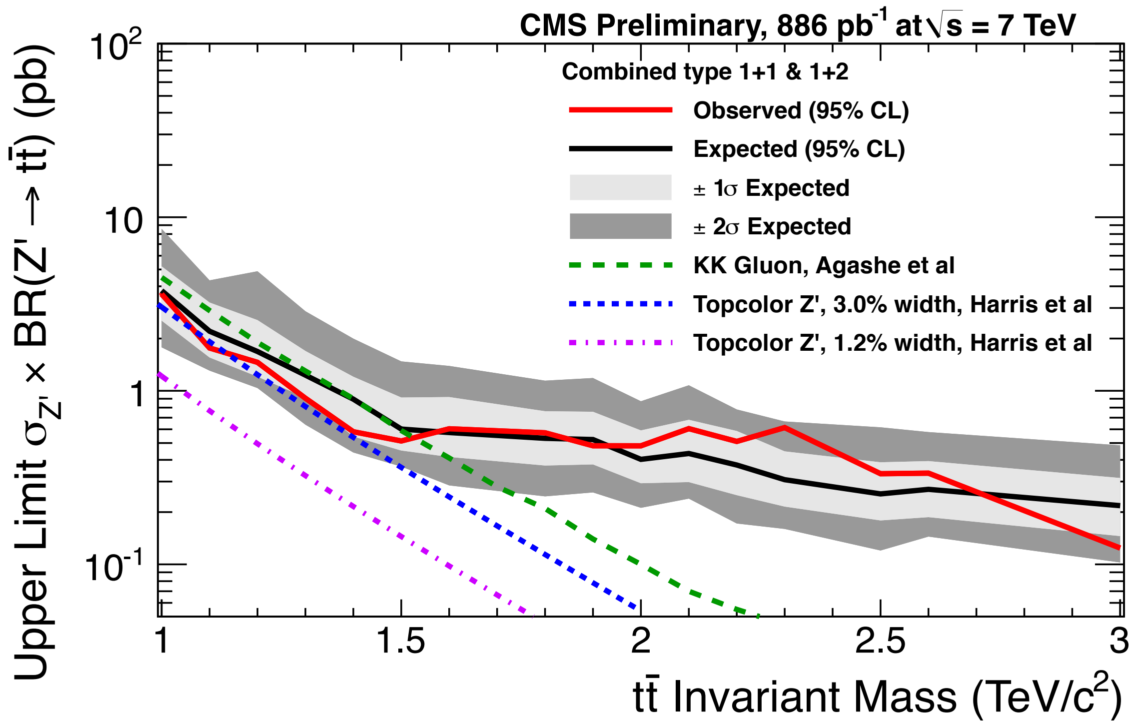
- τ_3/τ_2 is best discriminator for boosted tops
- In ratio effects from soft/uncorrelated radiation cancel

Approach II: Use hard subjets to reconstruct top

- Johns Hopkins/CMS Tagger

[Kaplan, Reherman, Schwartz, Tweedie PRL 101 (2008)]





- HEPTopTagger (Heidelberg-Eugene-Paris) (low pT tagger)

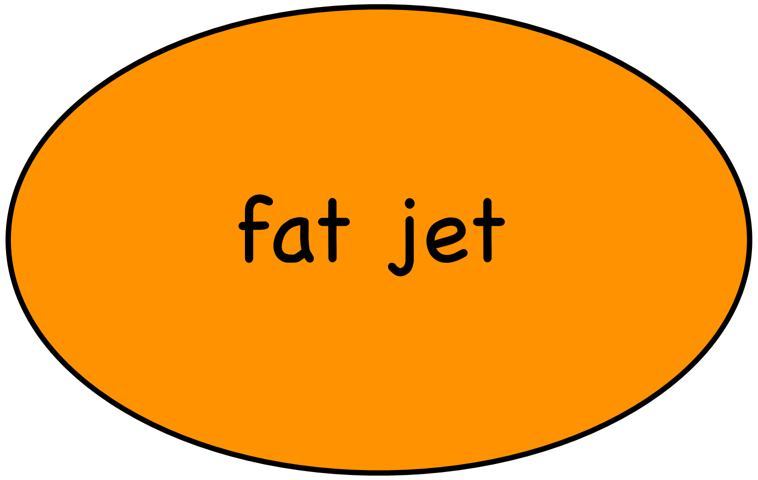
[Plehn, Salam, MS PRL 104 (2010) and Plehn, MS, Takeuchi, Zerwas JHEP (1010)]

How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{\mathrm{daughter}_1} < 0.8\, m_{\mathrm{mother}}$ to keep both daughters



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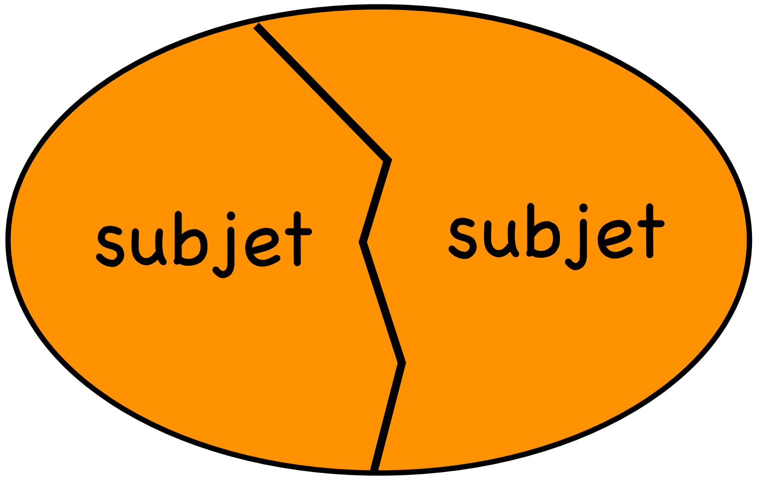

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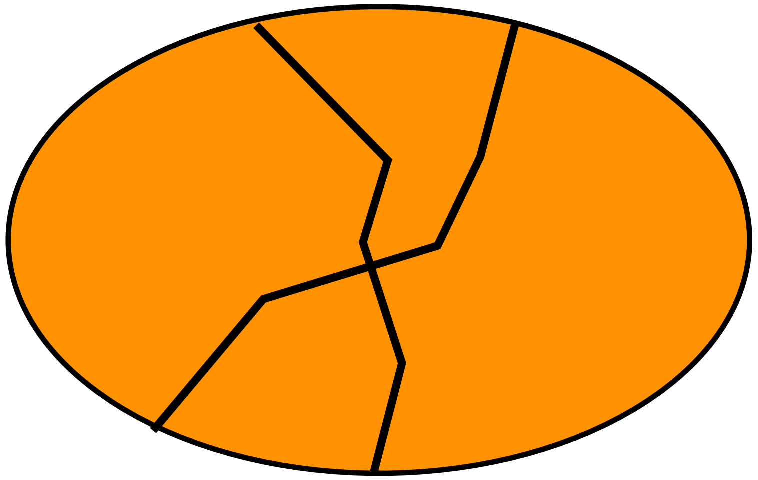

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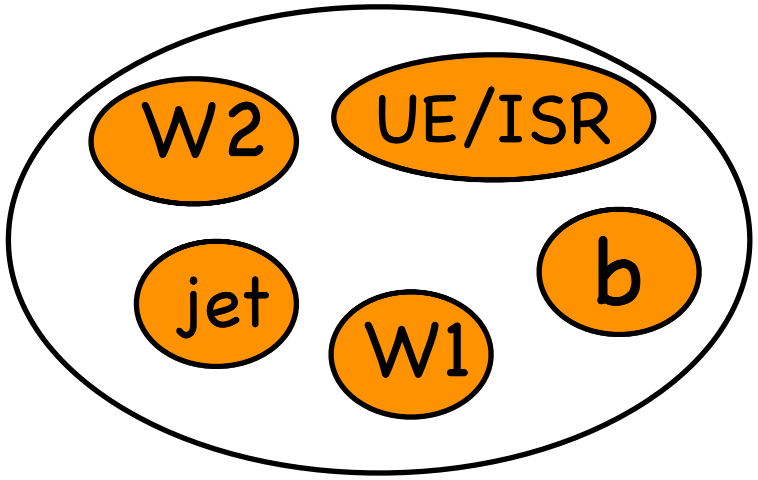
III. Apply jet grooming to get top decay candidates



How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{\text{daughter}_1} < 0.8\, m_{\text{mother}}$ to keep both daughters

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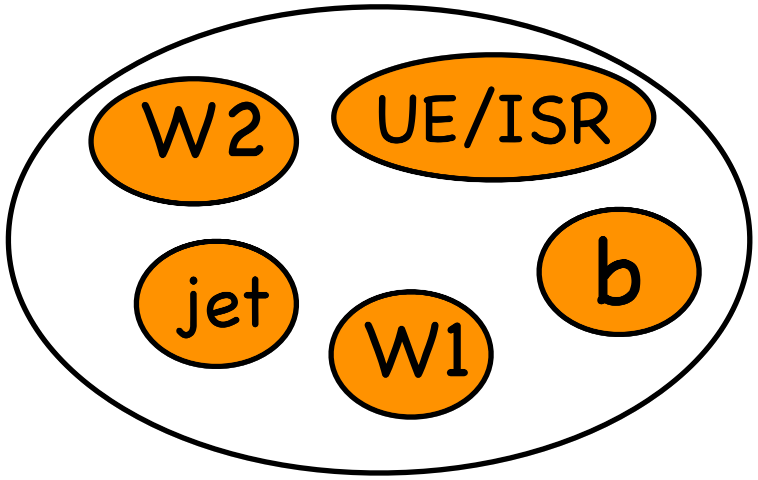
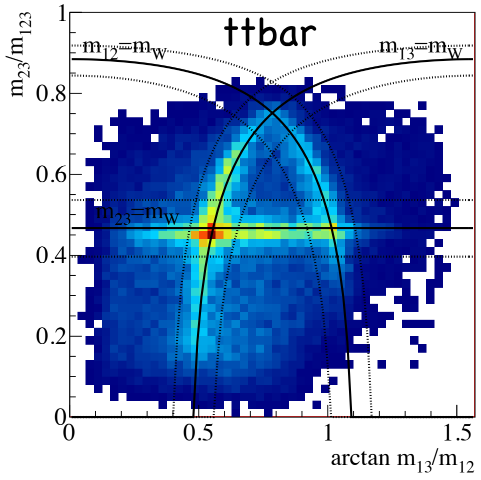
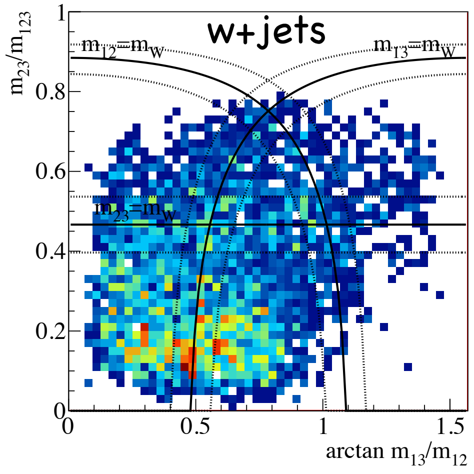
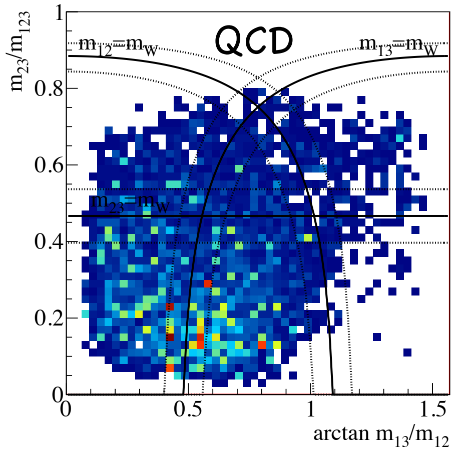


IV. Choose pairing based on kinematic correlation, e.g. top mass, W mass and invariant subjet masses

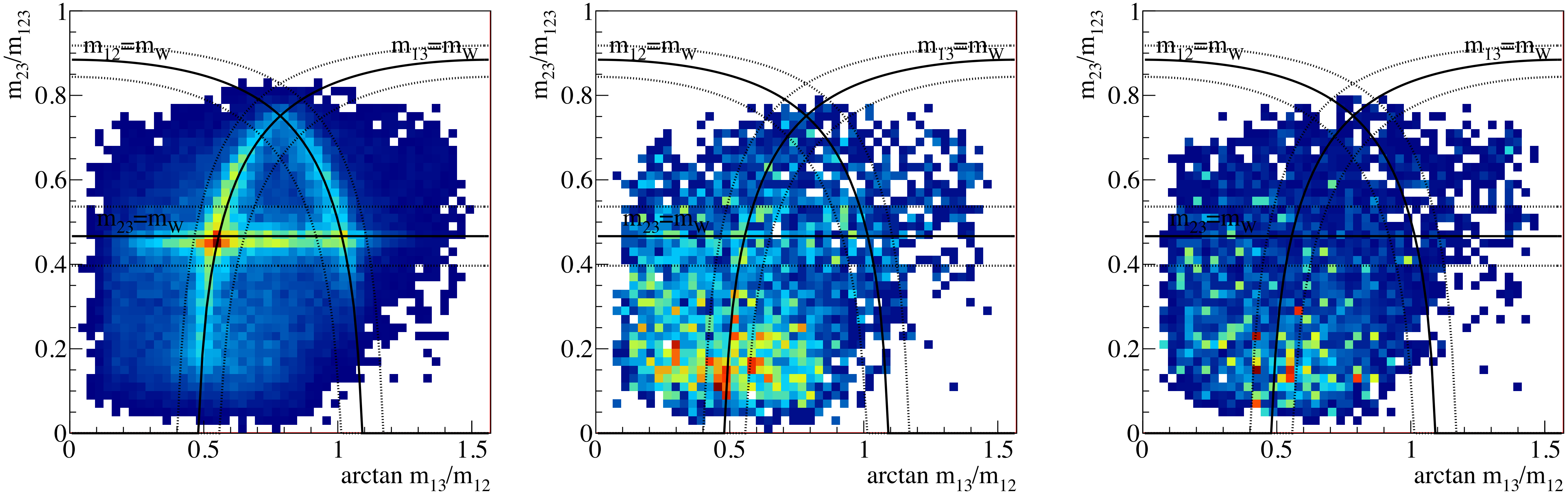






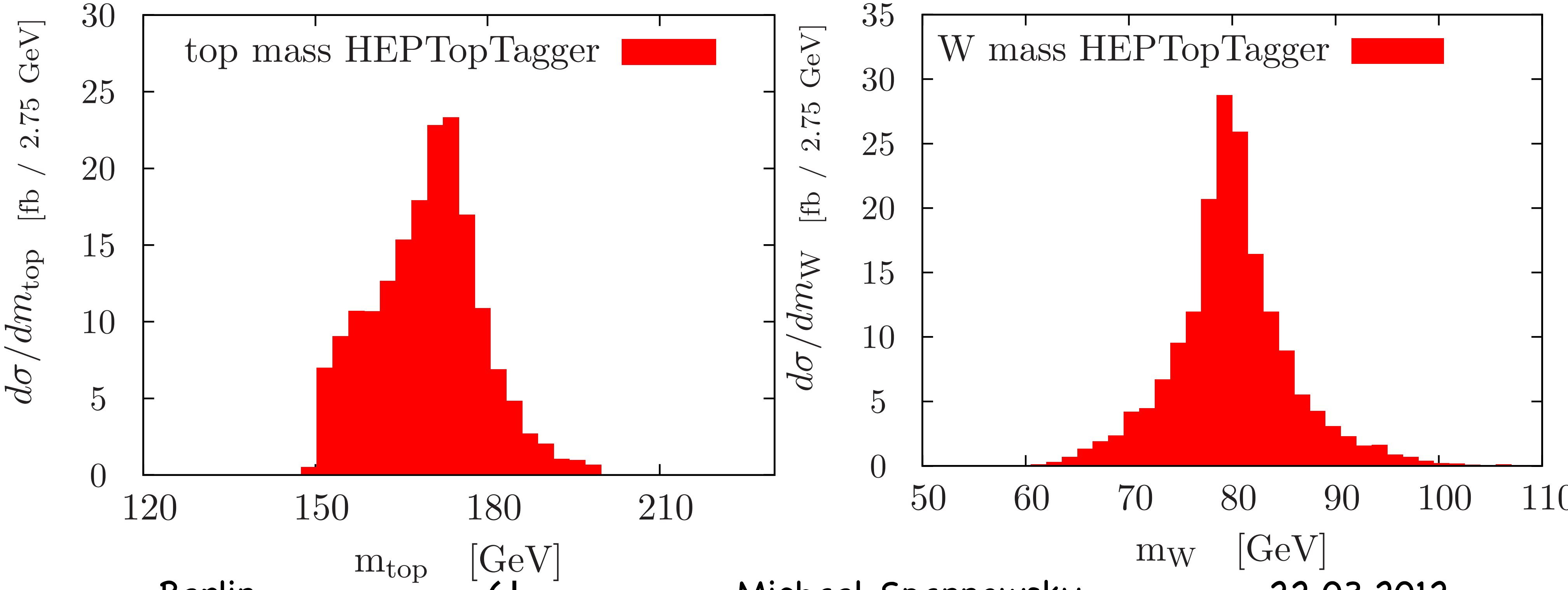
IV. check mass ratios

Cluster top candidate into 3 subjets j_1, j_2, j_3



No fix pairing for W mass reconstruction

Only invariants for reconstruction



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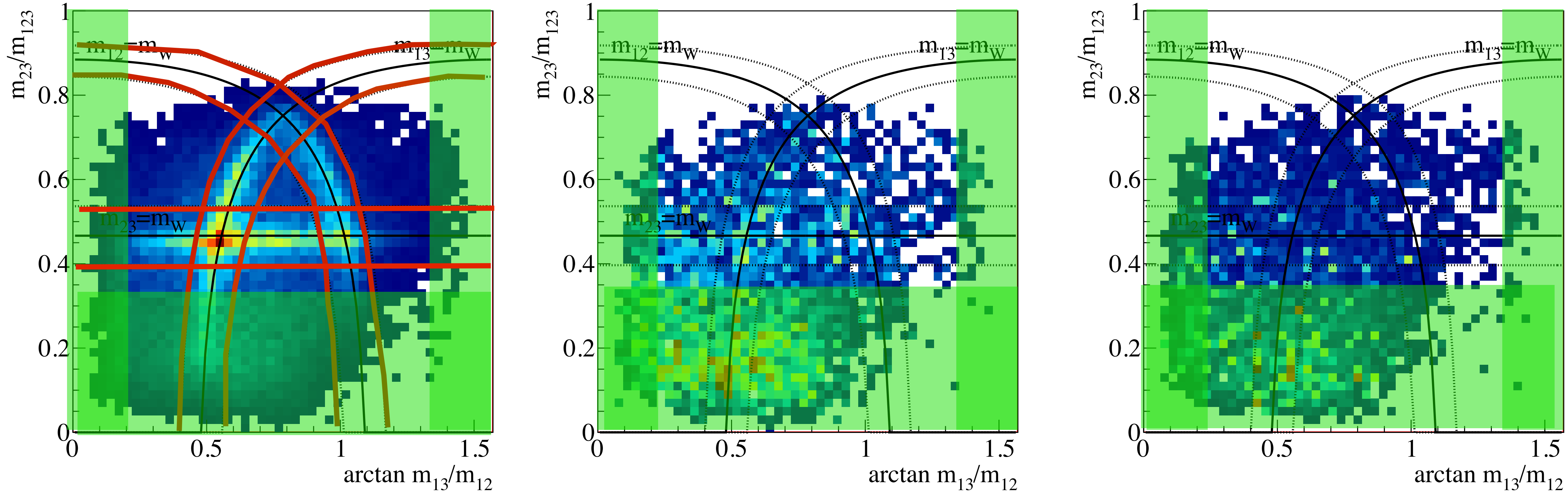

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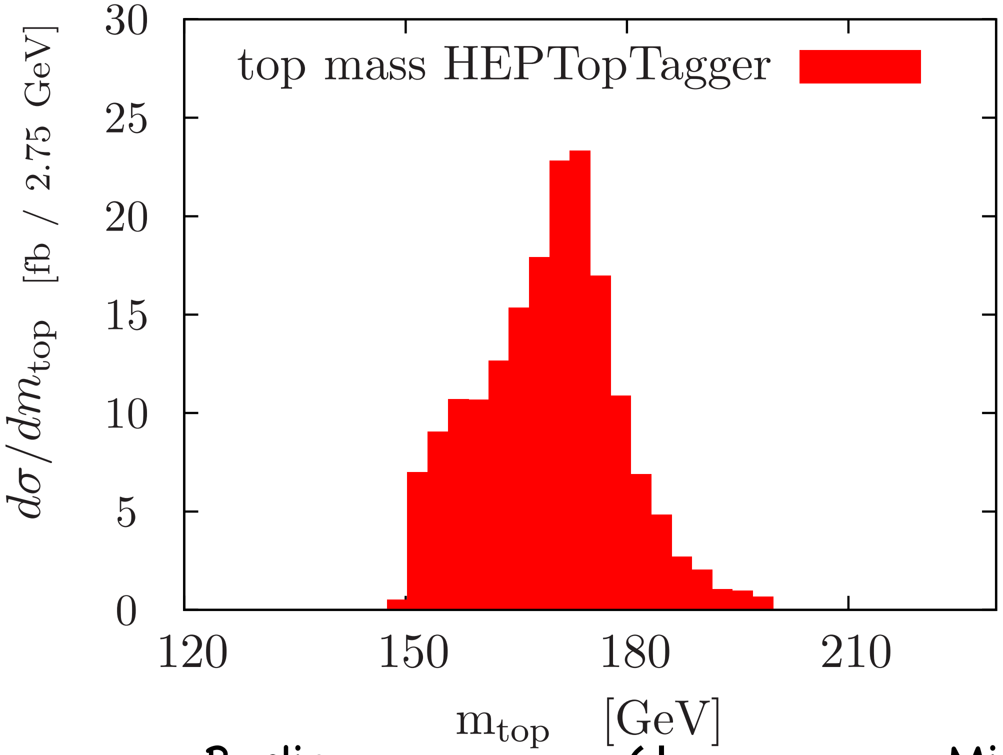
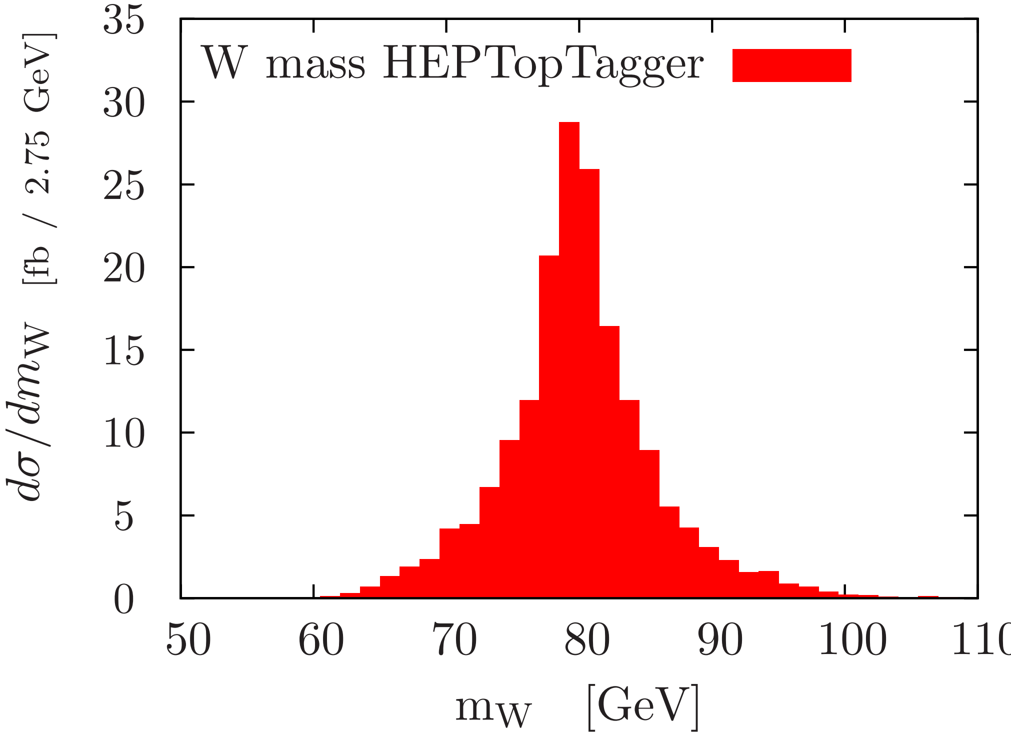
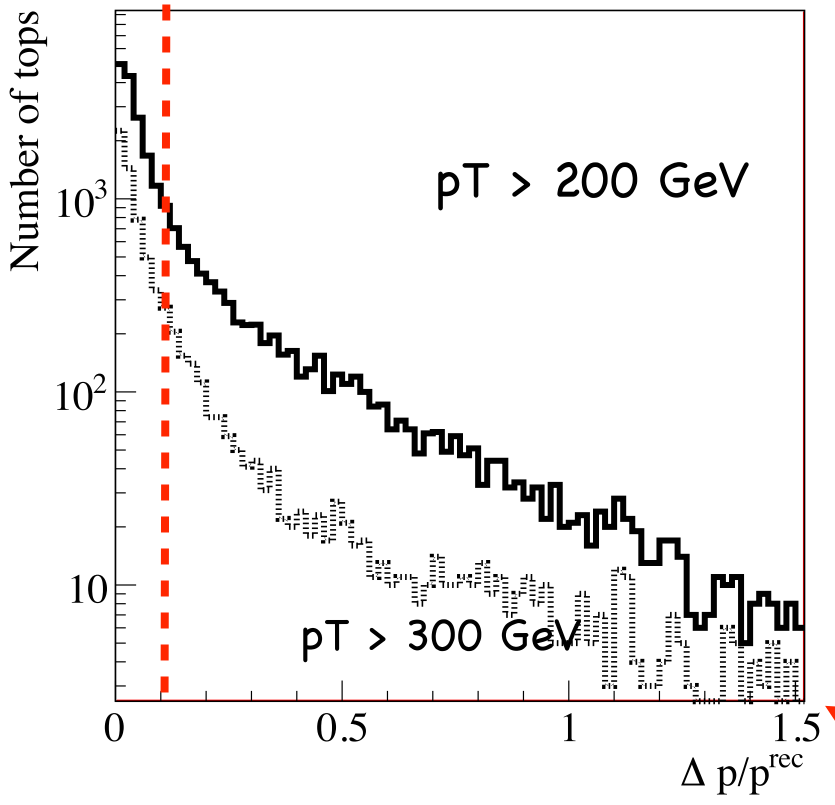
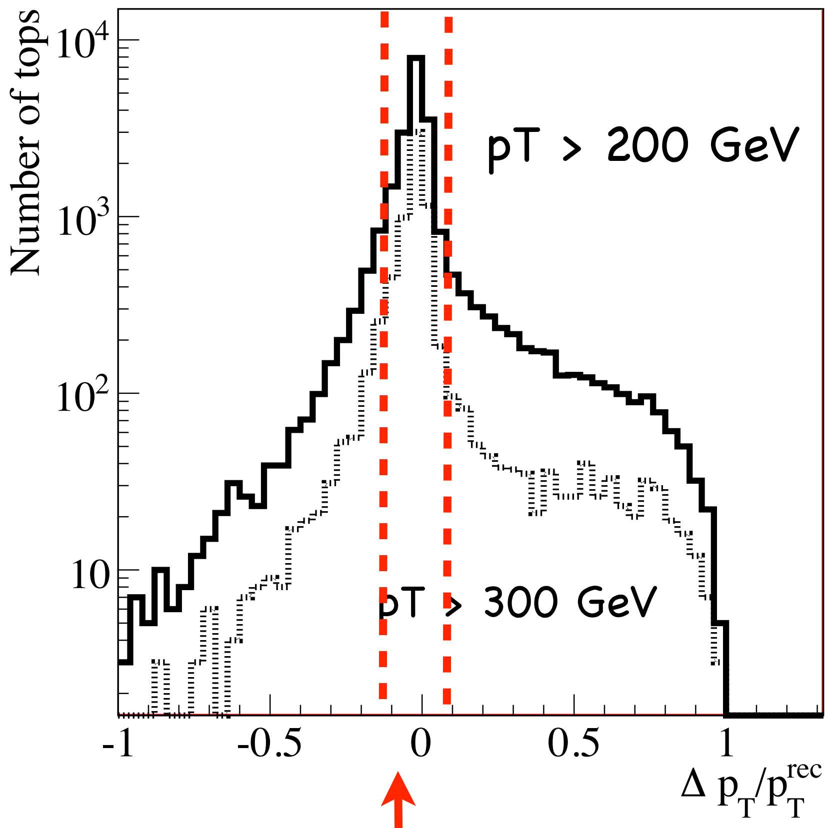
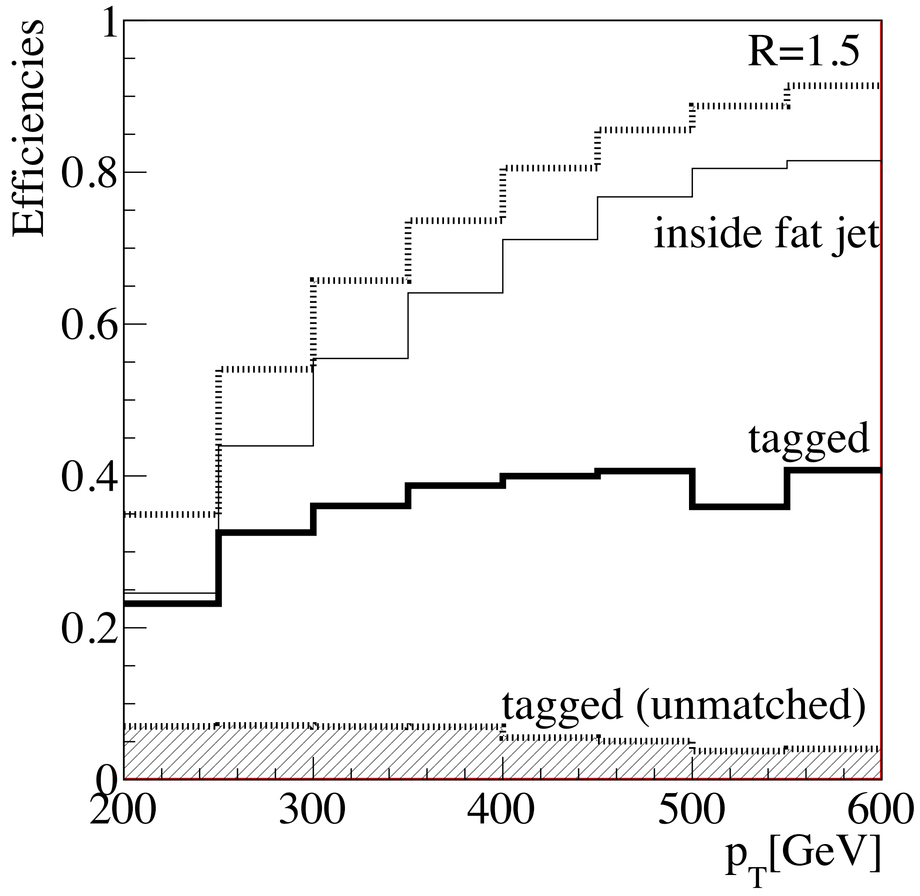




Top quark momentum reconstruction



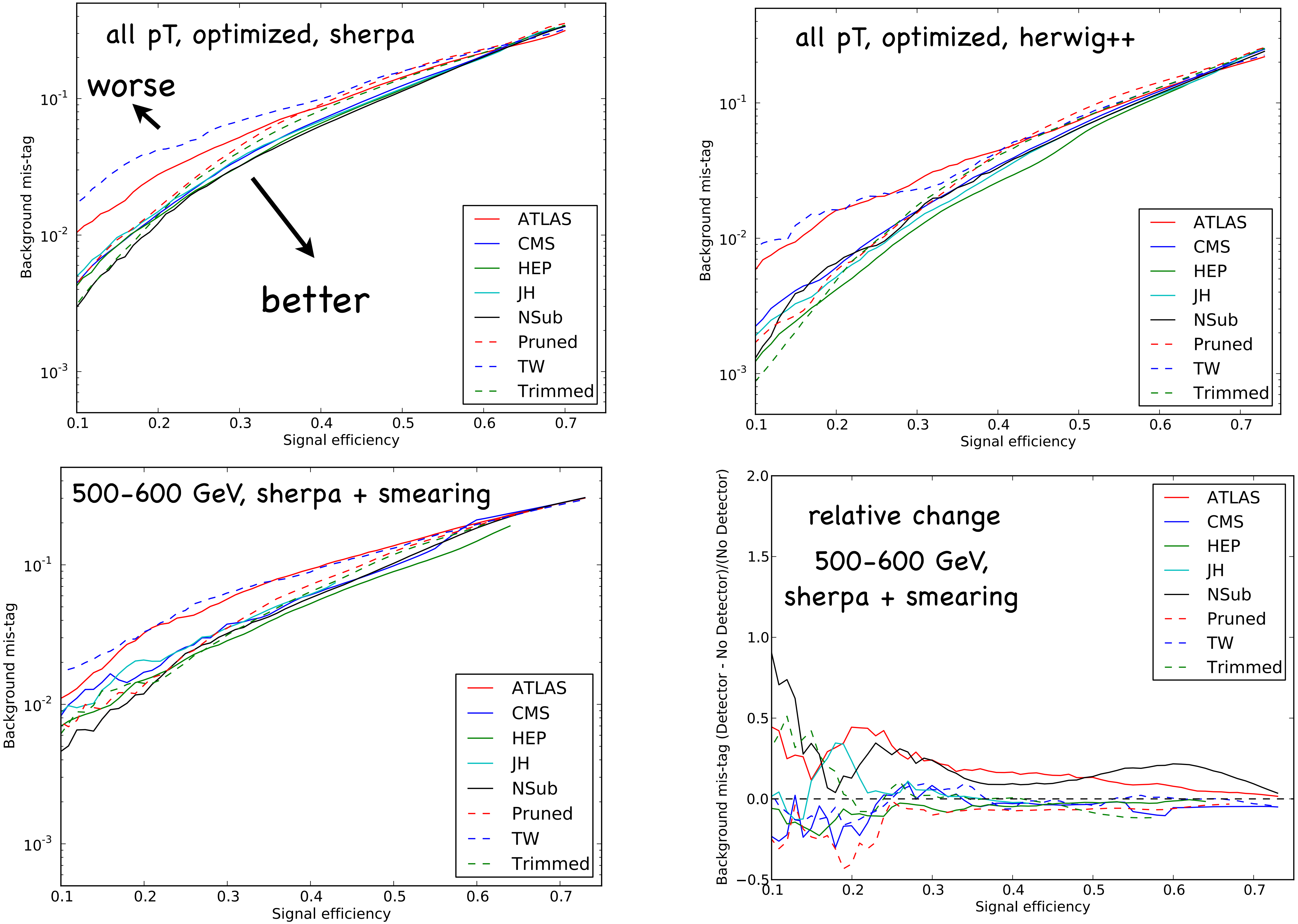




- Great reconstruction of top quark momentum

- 35% tagging efficiency
  2% W+jets fake rate

Comparison of top taggers (BOOST 2012 proceedings)



Selected Applications
(motivated by recent measurements)

- ATLAS, CMS and CDF indicate existence of lighte (125 GeV) Higgs
    - Want to measure couplings, e.g tth

      ⟶ In SM, tth only accessible if Higgs is light

    - 125 GeV heavy for Minimal Supersymmetric Standard Model

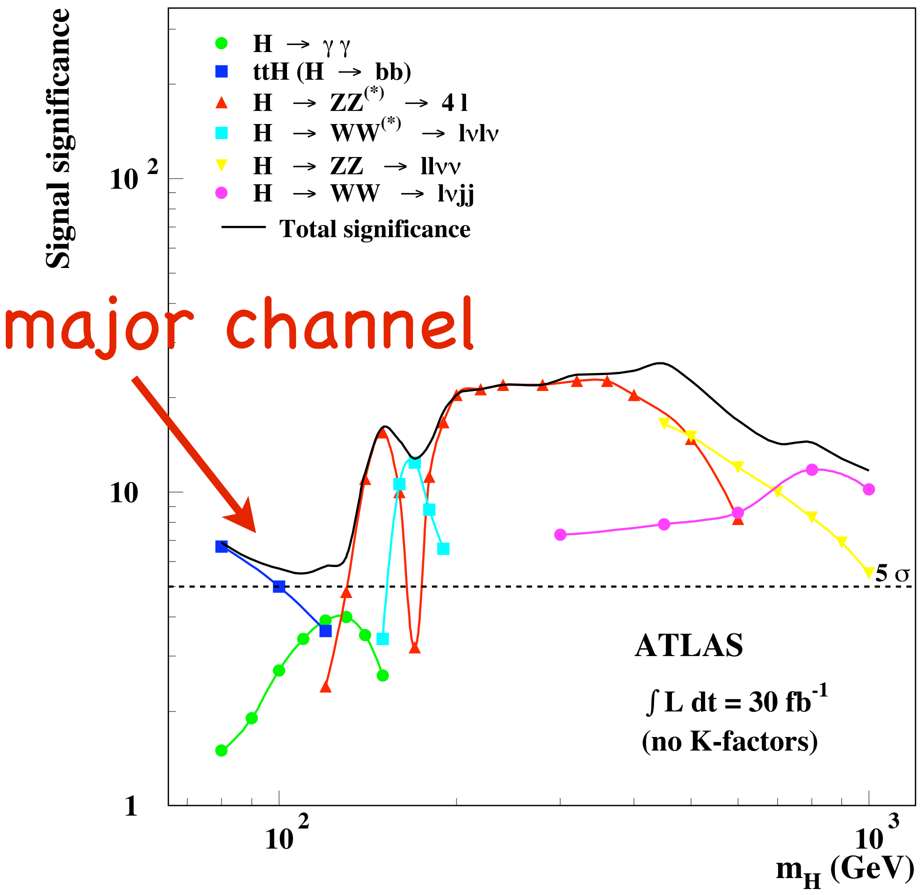
      ⟶ To ameliorate hierarchy problem and generate 'heavy' Higgs mass need light stop1 and heavy stop2

- CDF and D0 measure Afb consistently
    - Needs to be confirmed at the LHC

Applications: tth
as busy as it gets in the SM

Motivation:
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

High expectations:



tth major channel

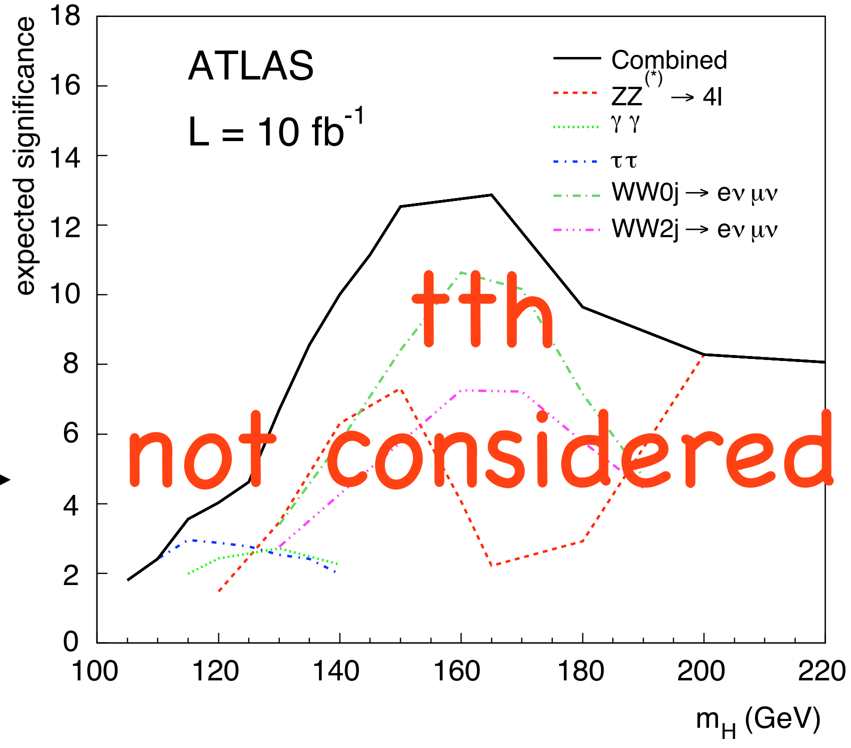
[ATLAS TDR 1999]

Cammin and Schumacher (ATLAS)

$S/B \simeq 1/9$

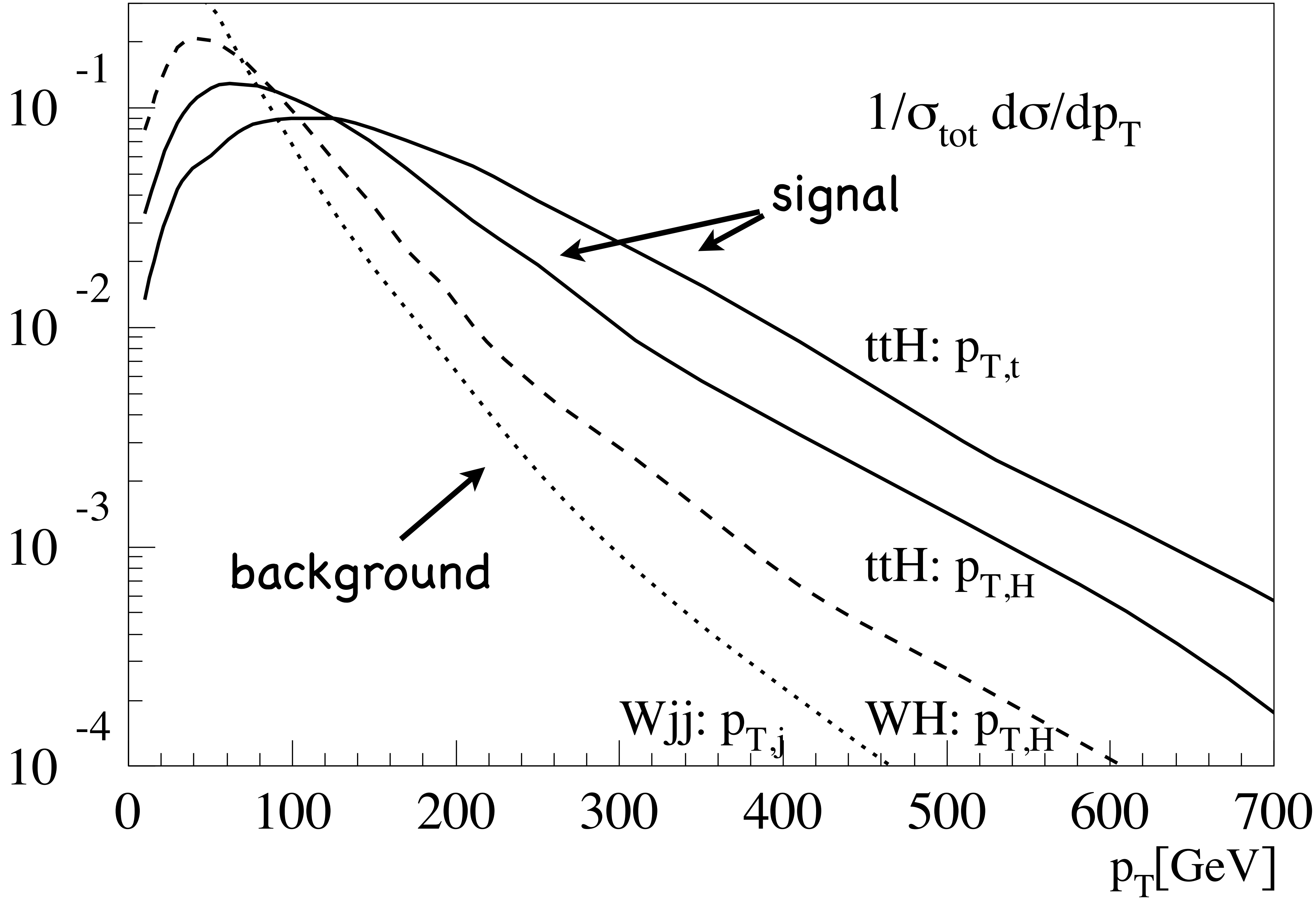
$S/\sqrt{B} \simeq 2.2$

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020



tth not considered

pT distributions relevant for tth



Problems in event reconstruction:

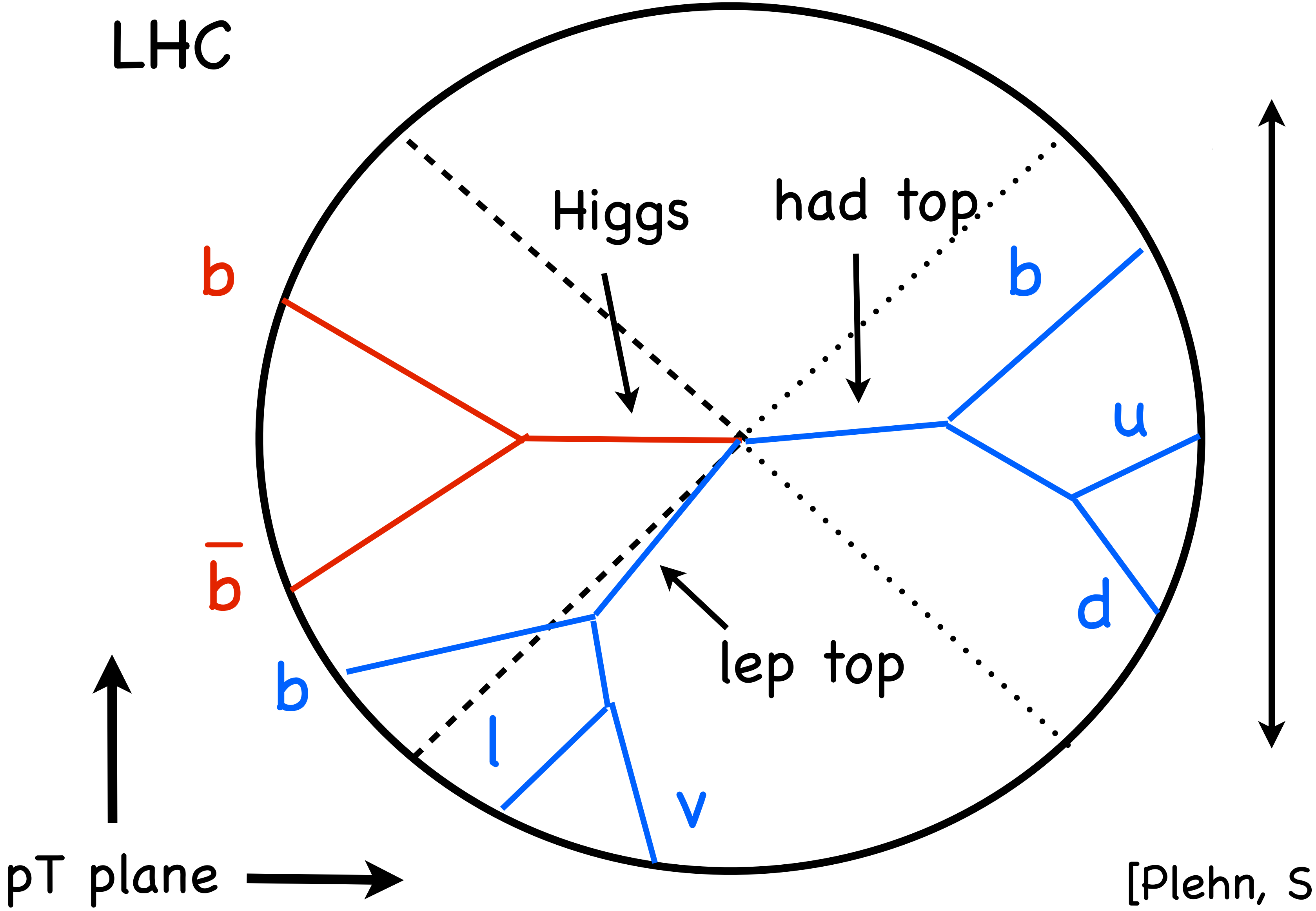
- (b-)jet multiplicity
- reconstruction efficiency

↔

Boost should help

but

need tagger for this environment



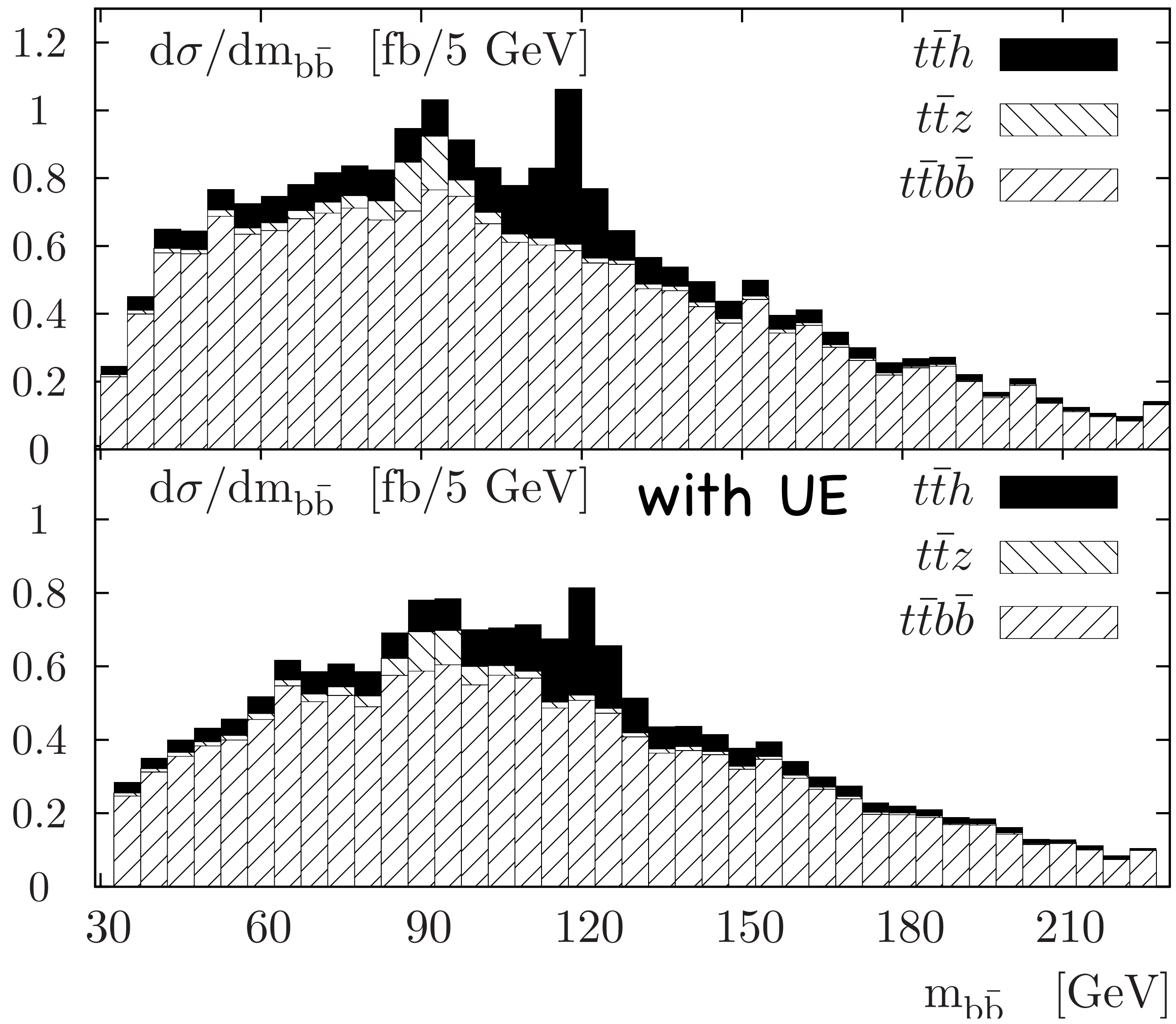
Cambridge/Aachen

jet algorithm

R=1.5

[Plehn, Salam, MS PRL 104 (2010)]

Results for tth



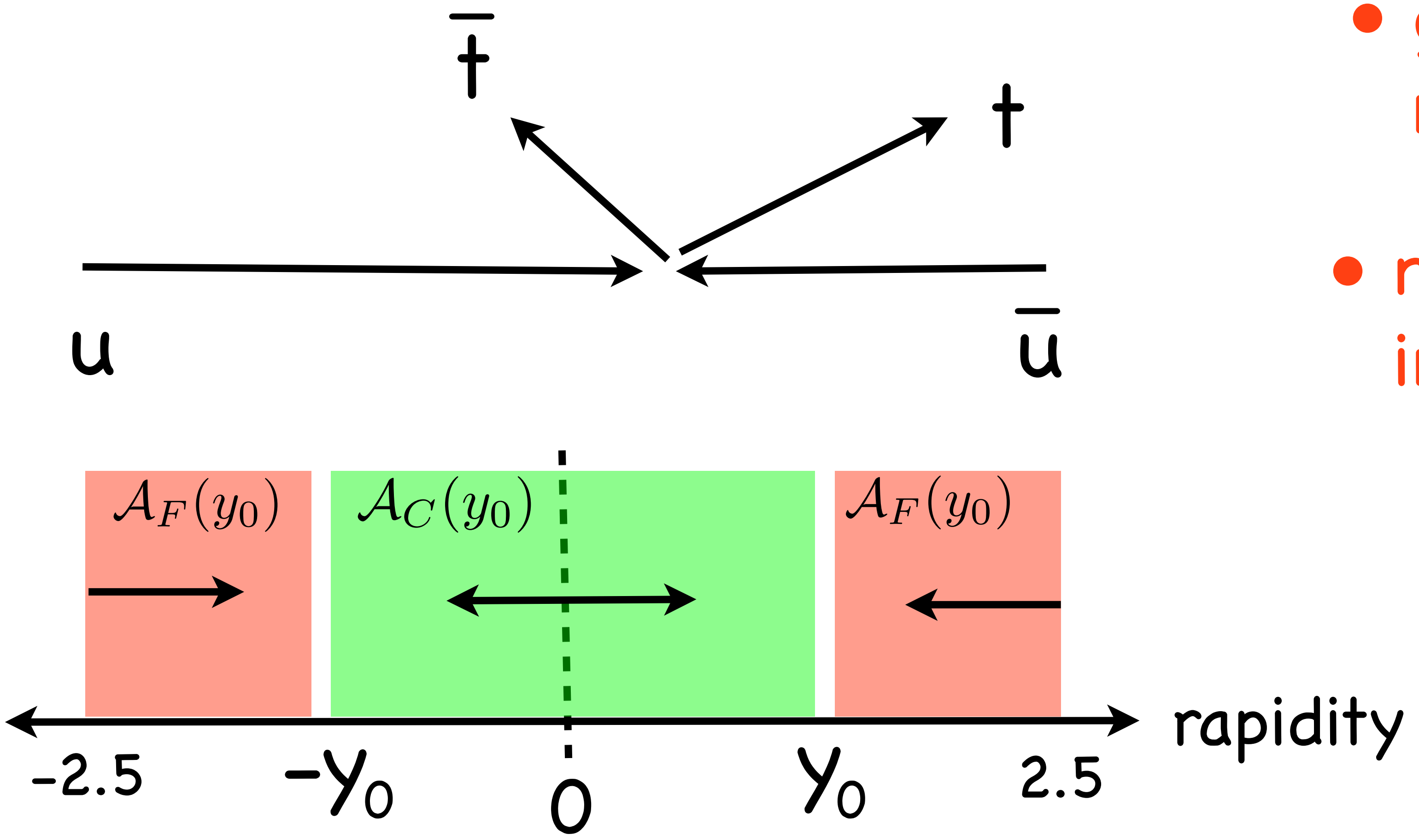
- 5 sigma sign. with 100 1/fb
- Development of Higgs and top tagger for busy final state
- Improvement of S/B from 1/9 to 1/2

→ tth might contribute to Higgs discovery

→ tth might be a window to Higgs-top coupling

Applications: Asymmetry at the LHC

- If CP conserved → FB becomes Charge asymmetry



- gg dominant prod. mode but symmetric
- need qq and qg initial state

$$\mathcal{A}_F(y_0) = \frac{N_t(y_0 < |y| < 2.5) - N_{\bar{t}}(y_0 < |y| < 2.5)}{N_t(y_0 < |y| < 2.5) + N_{\bar{t}}(y_0 < |y| < 2.5)},$$

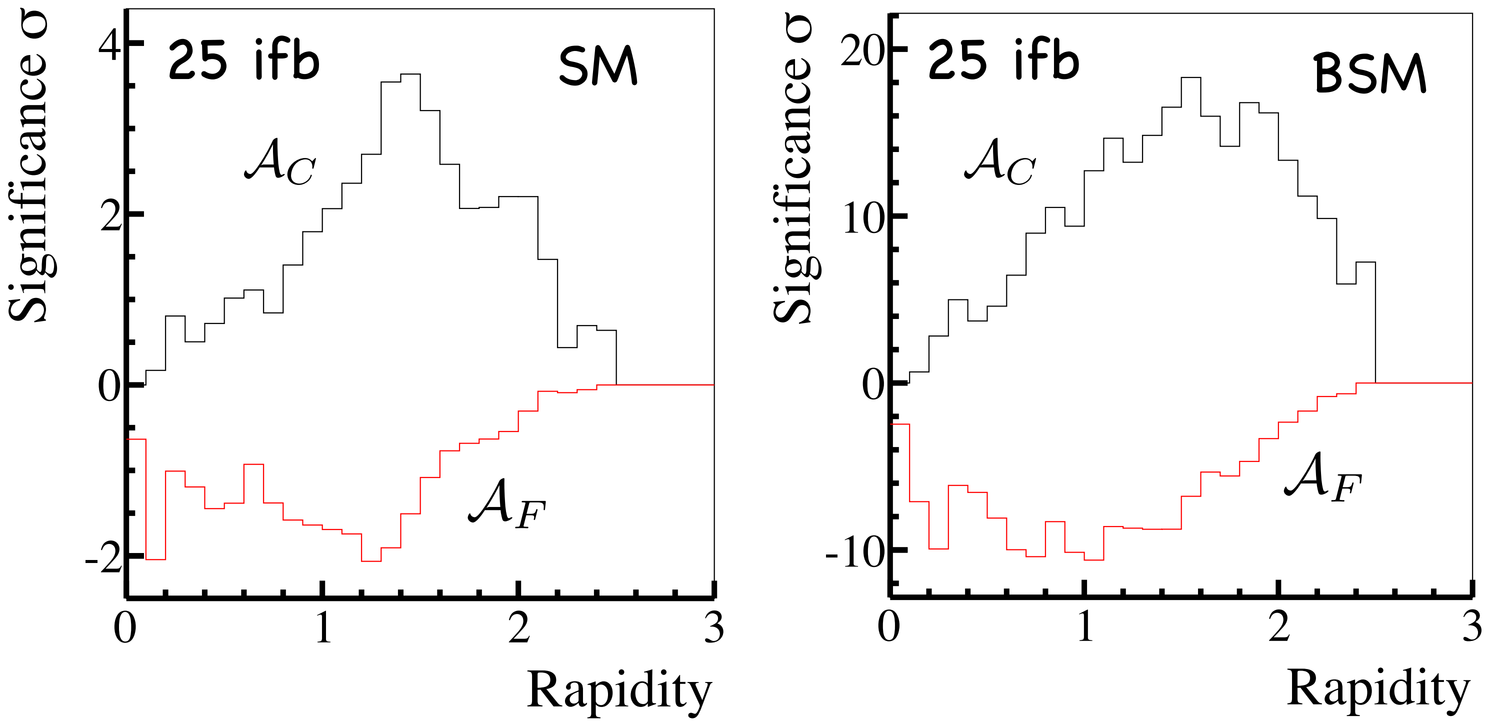
Study for charge asymmetry @ LHC

[Hewett, Shelton, MS, Tait, Takeuchi PRD 84 (2011)]

Event reconstruction: Consider moderately boosted semileptonic tops

- require isolated lepton with pT > 15 GeV, $y_l = y_{\text{lep. top}}$
- require jet with pT>200 GeV, use HEPTopTagger
- demand b-tag in hadronic top

$\longrightarrow$ W+jets negligible



14 TeV

- 5σ for SM after 60 ifb
- 5σ for BSM after 2 ifb

7 TeV

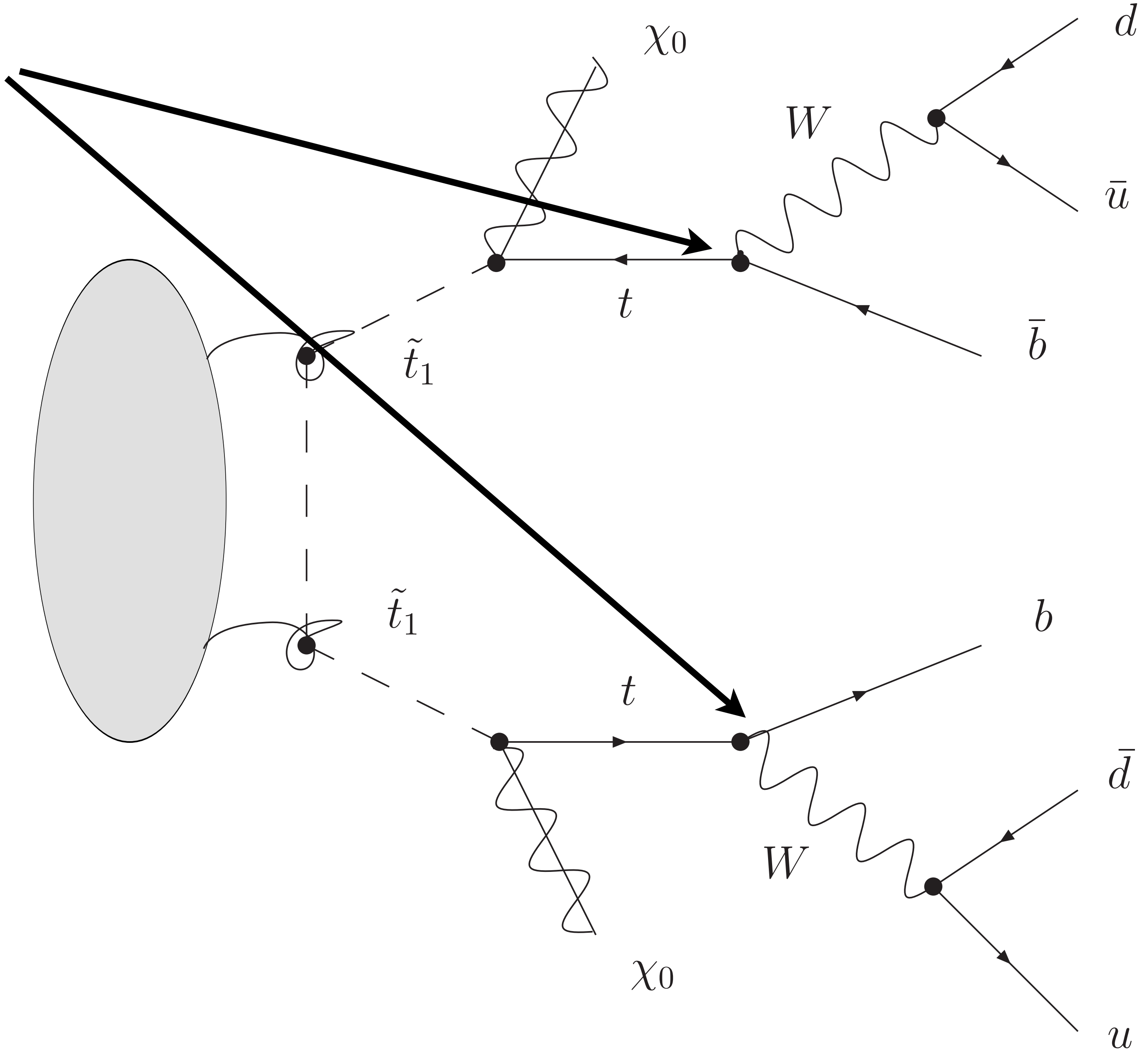
- 2.8σ for BSM after 10 ifb

BSM is Jung et al. (t-channel Z′)

Applications: stop reconstruction - hadronic top quarks

[Plehn, MS, Takeuchi JHEP 1010]

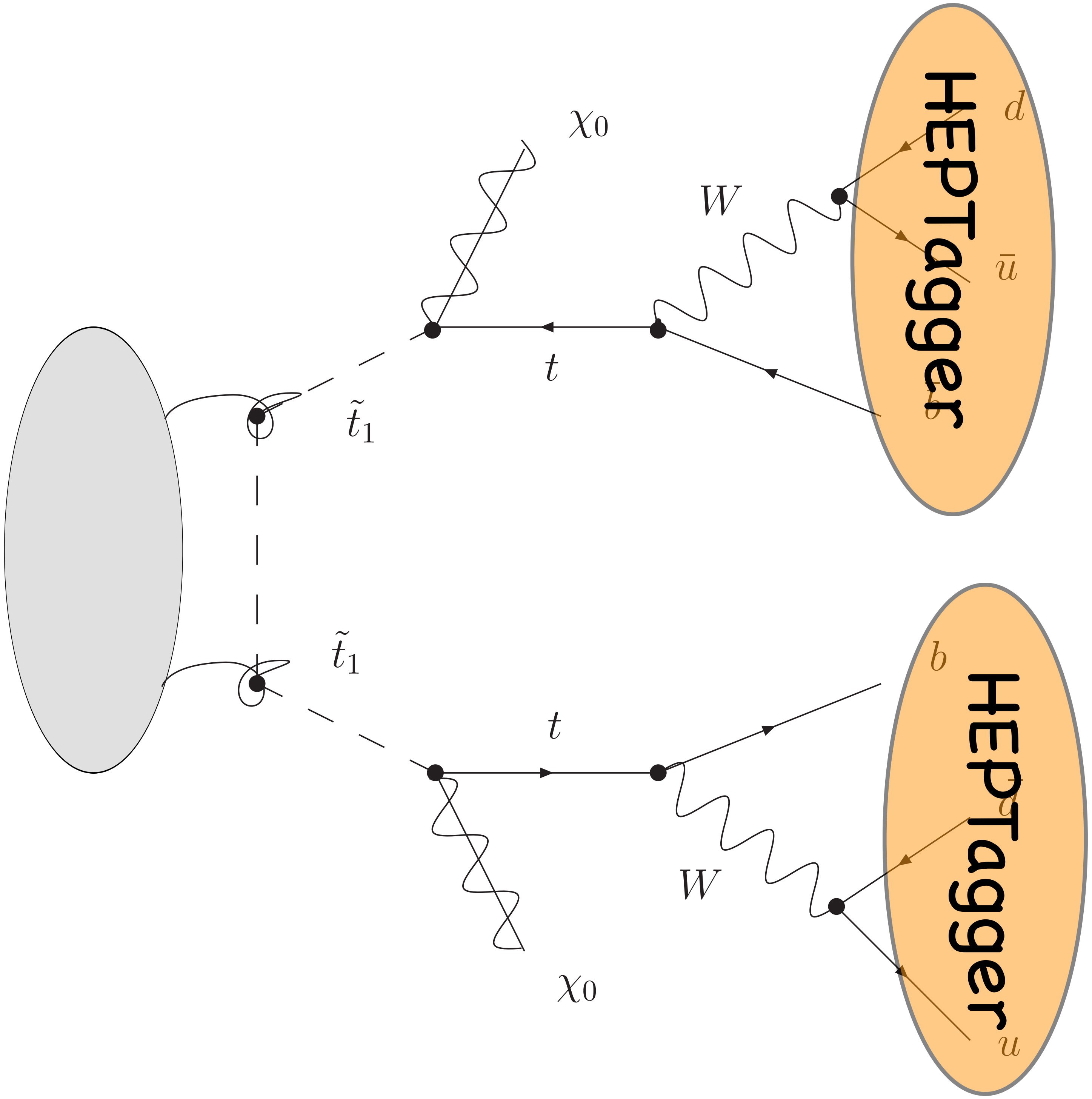
- Use purely hadronic top decay mode



Applications: stop reconstruction - hadronic top quarks

[Plehn, MS, Takeuchi JHEP 1010]

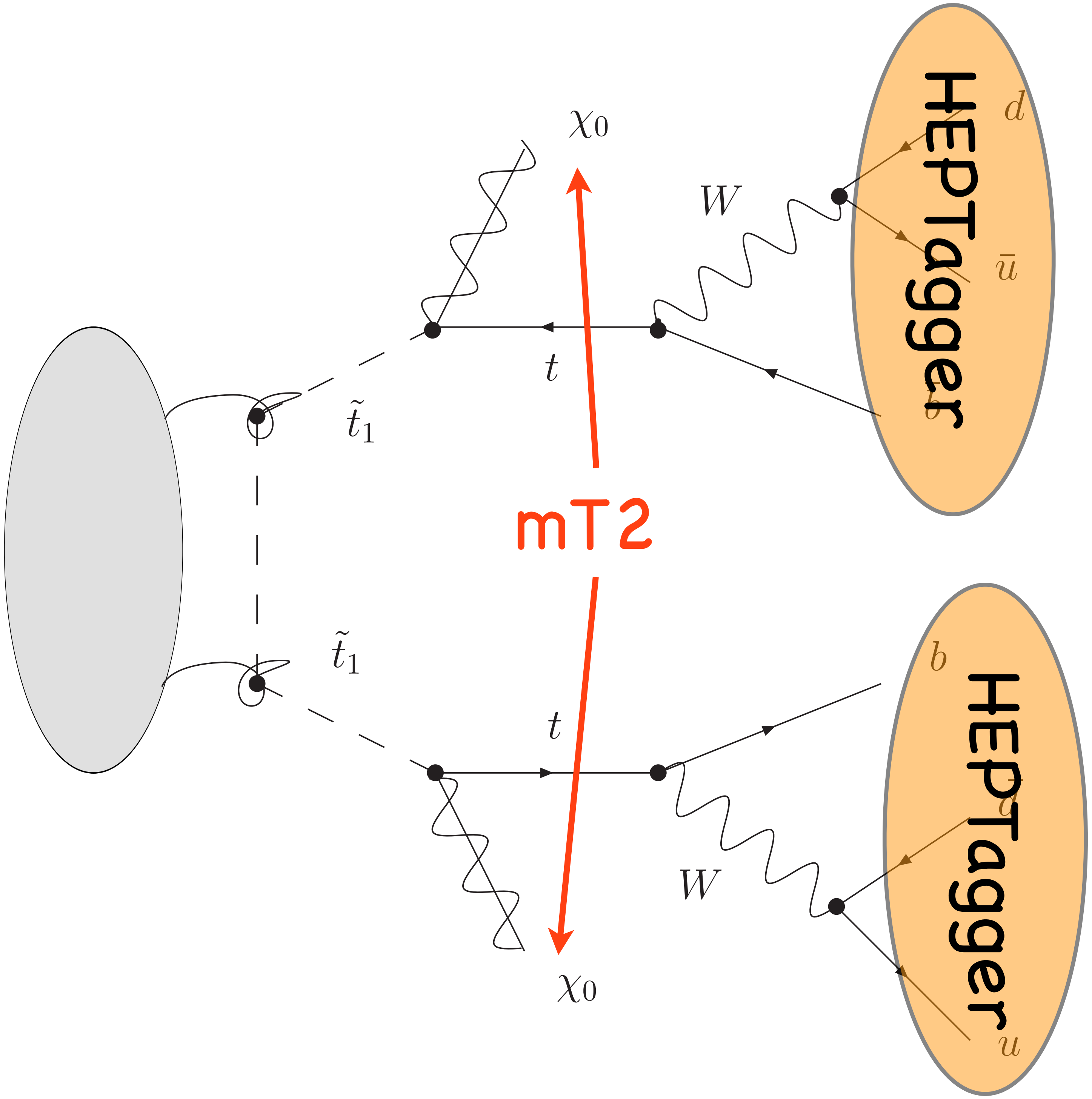
- Use purely hadronic top decay mode
- Use HEPTagger in hadronic final state -> 2 tagged tops



Applications: stop reconstruction - hadronic top quarks

[Plehn, MS, Takeuchi JHEP 1010]

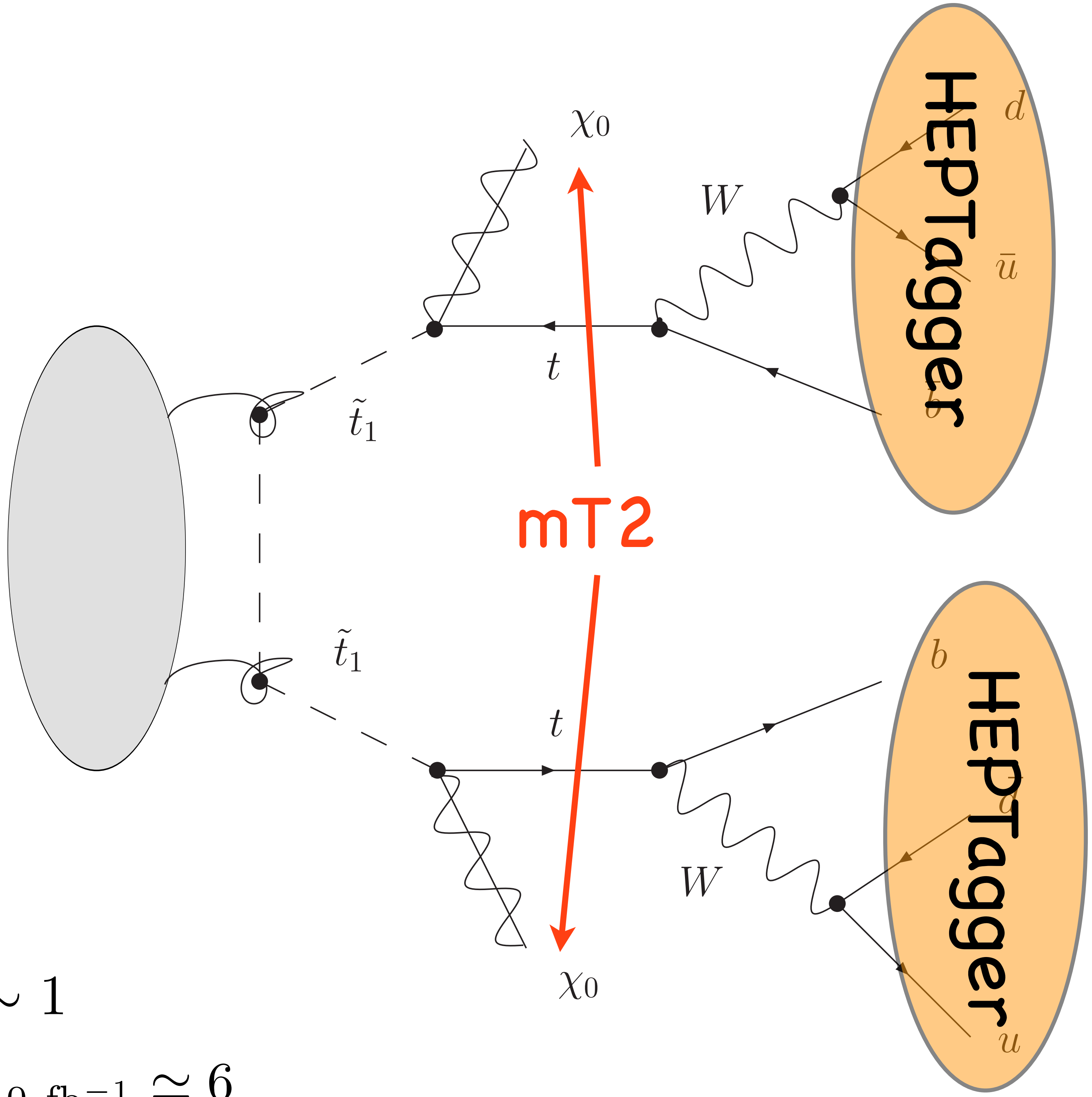
- Use purely hadronic top decay mode
- Use HEPTagger in hadronic final state -> 2 tagged tops
- Separation of ISR and hard process improves mT2



Applications: stop reconstruction - hadronic top quarks

[Plehn, MS, Takeuchi JHEP 1010]

- Use purely hadronic top decay mode
- Use HEPTagger in hadronic final state -> 2 tagged tops
- Separation of ISR and hard process improves mT2
- stop reconstructable over wide range



340 - 540 GeV stop:

$$S/B \sim 1$$

$$S/\sqrt{B}_{10\ \mathrm{fb}^{-1}} \simeq 6$$

All hadronic stop analysis

cuts:

2 fat jets: $p_{T,j} > 200/200$ GeV

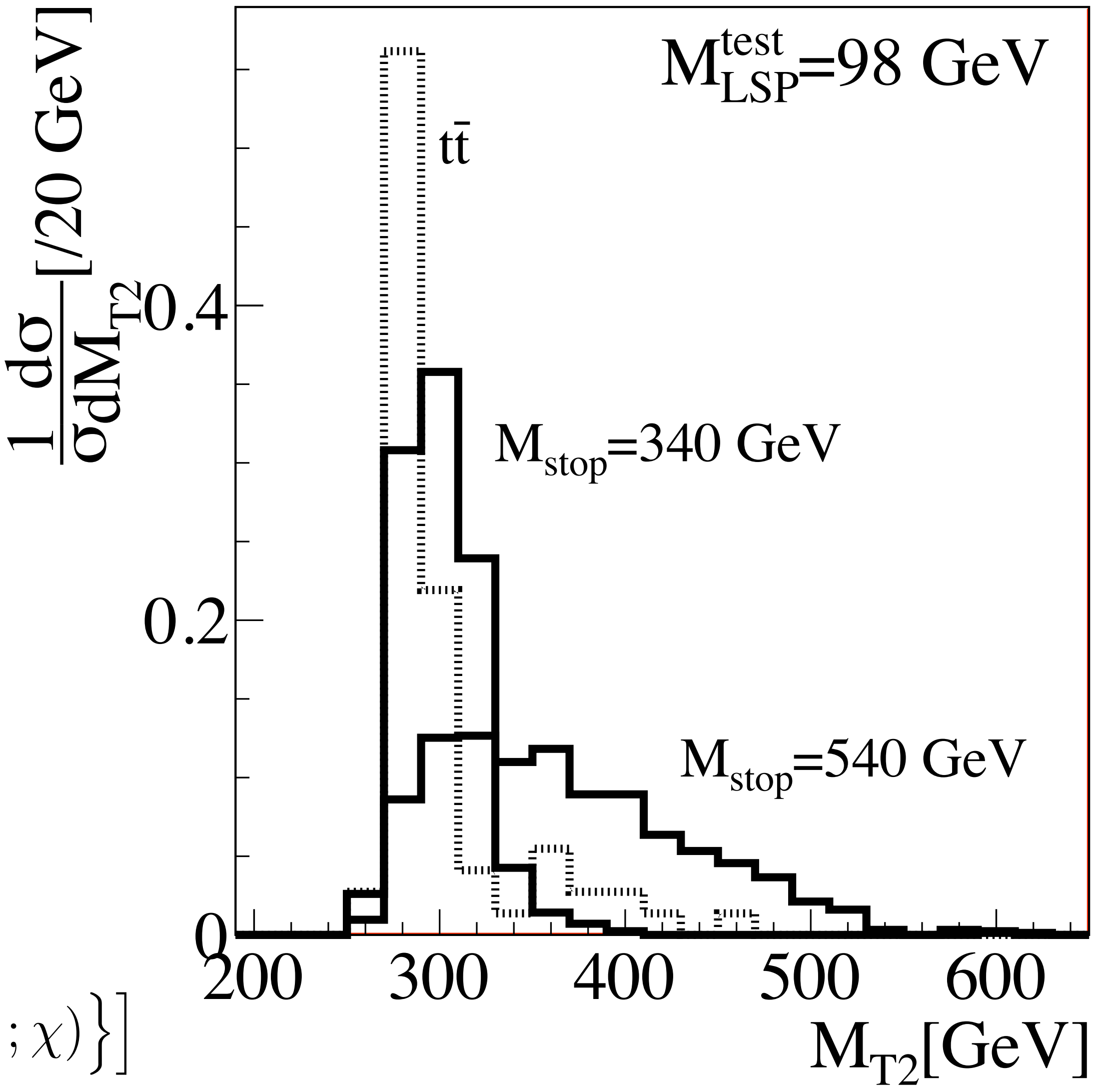
lepton veto

$\not{p}_T > 150$ GeV

2 tagged tops: $p_T^{\rm rec} > 200/200$ GeV

b tag for 1st tagged top

$m_{T2} > 250$ GeV



$$m_{T2}^2(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{p}_T}\left[\max\left\{m_T^2(\overset{t}{\mathbf{p}_T^{\pi^{(1)}}},\not{q}_T^{(1)};\chi),\ m_T^2(\overset{t}{\mathbf{p}_T^{\pi^{(2)}}},\not{q}_T^{(2)};\chi)\right\}\right]$$

	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\ \rm fb^{-1}}$
$m_{\tilde{t}}$[GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\not{p}_T > 150$ GeV	283	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$1.2 \cdot 10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2 \cdot 10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3 \cdot 10^{-2}$	
b tag	8.7	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim 0.2$	$\lesssim 0.05$	0.40	5.9
$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6.1

Tagger + mT2 go well together

Conclusions

Past	Present	Future
• IR-safe jet algorithm • Impact of soft radiation • Grooming techniques	• New reconst. ideas • Better theoretical underst. of jet obs. • Evaluation on data	• Application on data in large variety of new physics searches

- Jet substructure allows to access more information
  - Can be superior way to look for new physics
- Many tools are presently tested on data with good success
- Reconstruction of boosted top quarks is major application
- Jet substructure is an active field of research and will be relevant for a long time to come