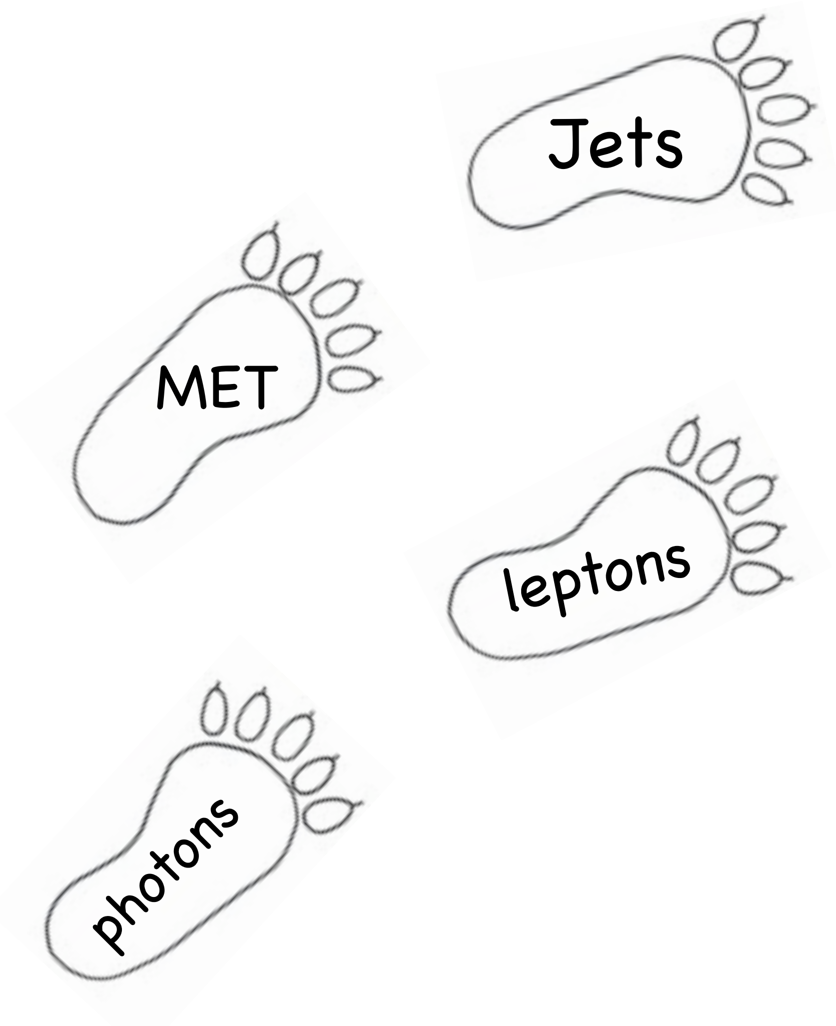
Subjets at the LHC

New Physics - new tools - new channels

Michael Spannowsky

University of Oregon

Don't run from the bear!
Hunt him down!

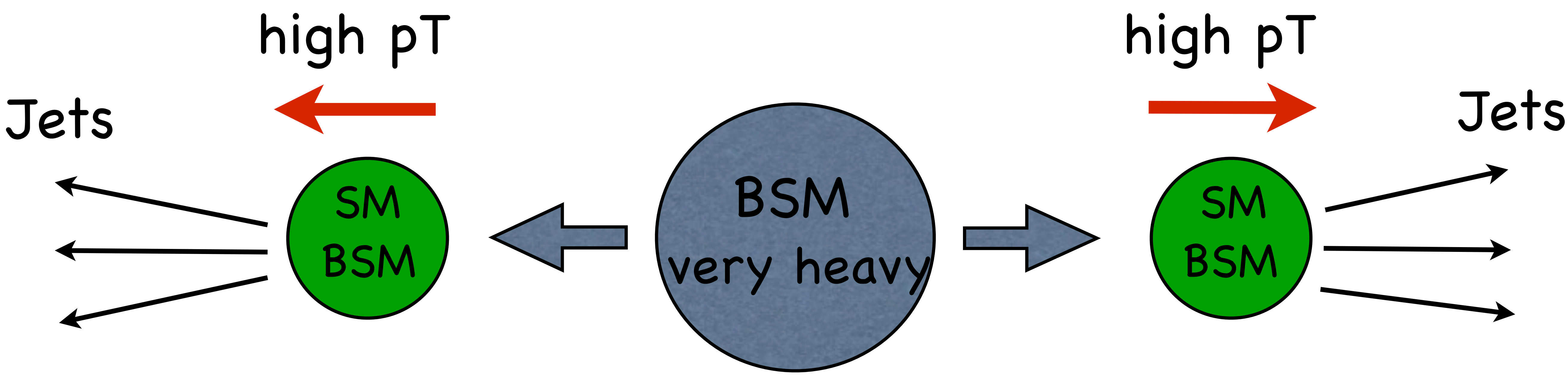


New energies long for new tools!

Outline

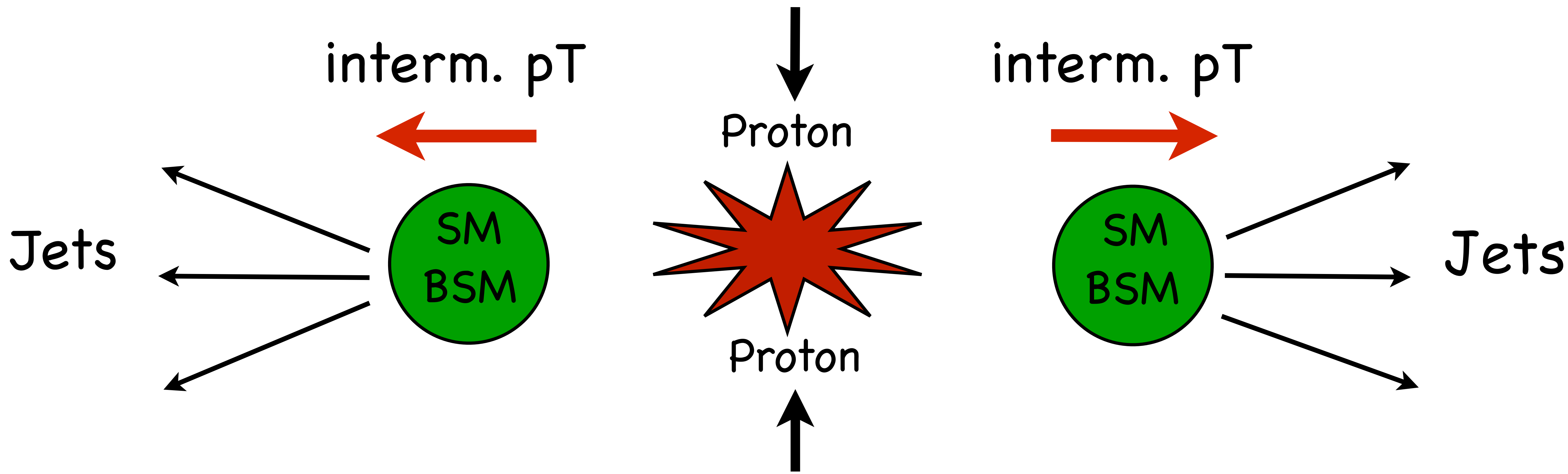
- scenarios where subjet techniques can pay off
- which subjet techniques are there
- do subjet techniques really pay off?

I. naturally highly boosted signal:



- At LHC elw scale particles produced beyond threshold
- Jets highly collimated
- Jet-parton matching breaks down
- Decay products and FSR has to be collected in a fat jet
- UE~R^4, jet grooming important for reconstruction

II. Only mildly boosted signal



Advantages:

- Jet resolution
- b-tagging
- signal reconstruction efficiency
- lepton identification efficiency
- Reduced combinatorial problems

[Thesis, Piacquadio] [ATL-PHYS-PUB-2009-088]

Disadvantages:

- Low cross section
- large ISR, UE, Pile-up contributions

need big jet cone
need jet grooming

Tools for jet substructure

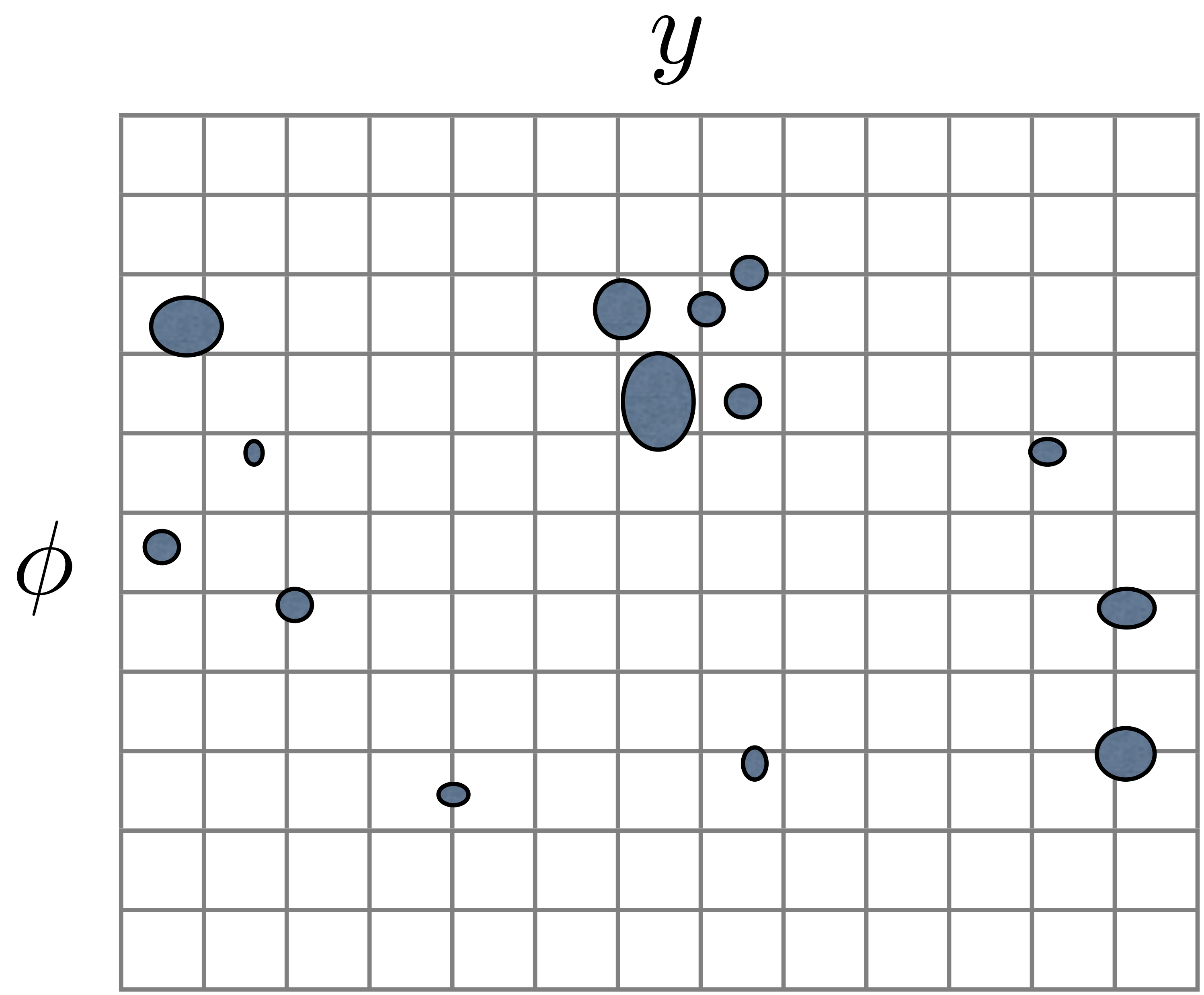
I. Subjet/grooming techniques

Filtering	[Butterworth et al. PRL 100 (2008)]
Pruning	[Ellis et al. PRD 80 (2009)]
Trimming	[Krohn et al. JHEP 1002 (2010)]

II. Techniques using jet energy flow

planar flow	[Thaler and Wang JHEP 07 (2008)] [Almeida et al. PRD 79 (2009)]
"pull"	[Galliccio and Schwartz PRL 105 (2010)]
template method	[Almeida et al. 1006.2035]

Jet/Event selection

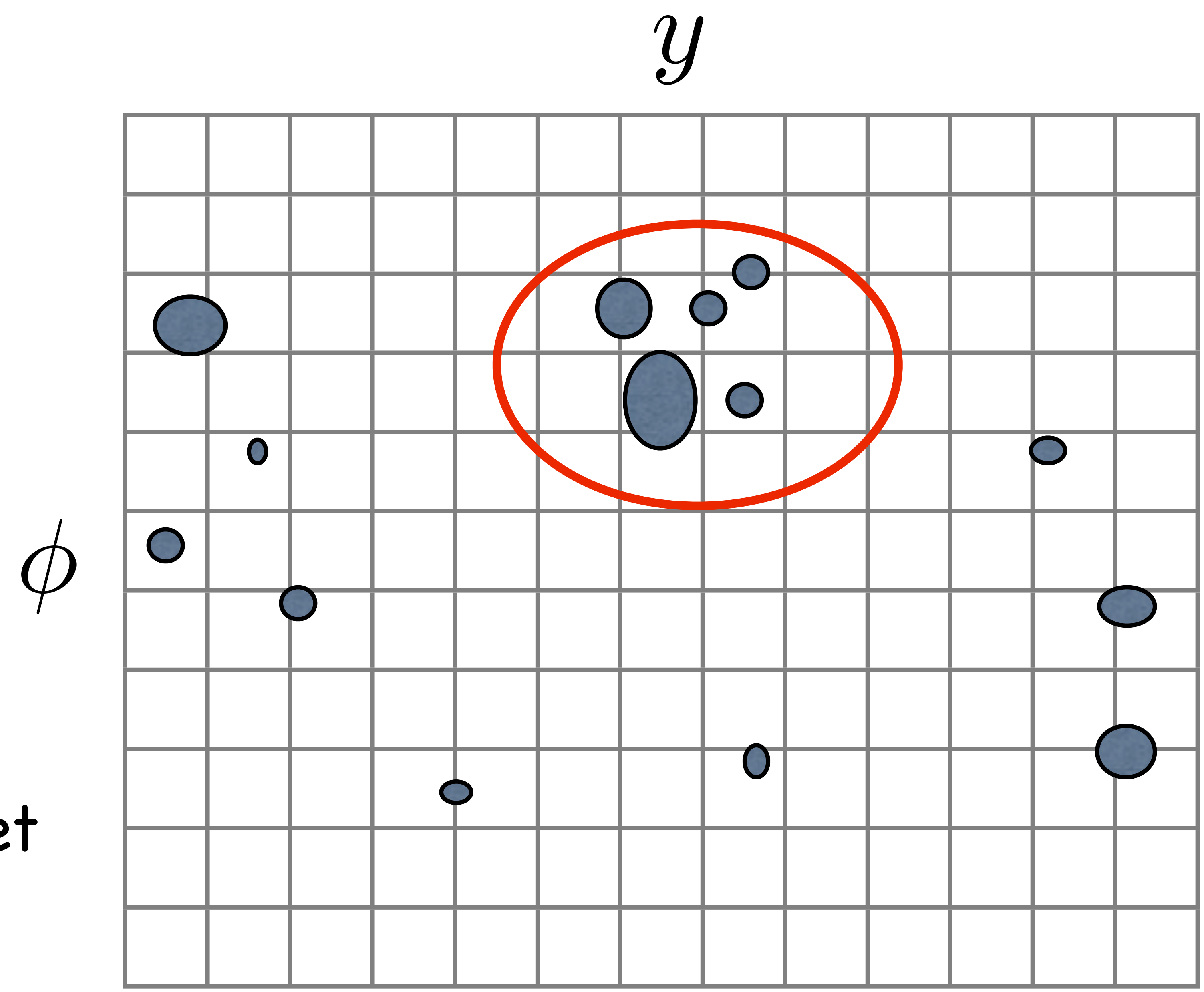


UE, ISR, Pile-up, hard interaction

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



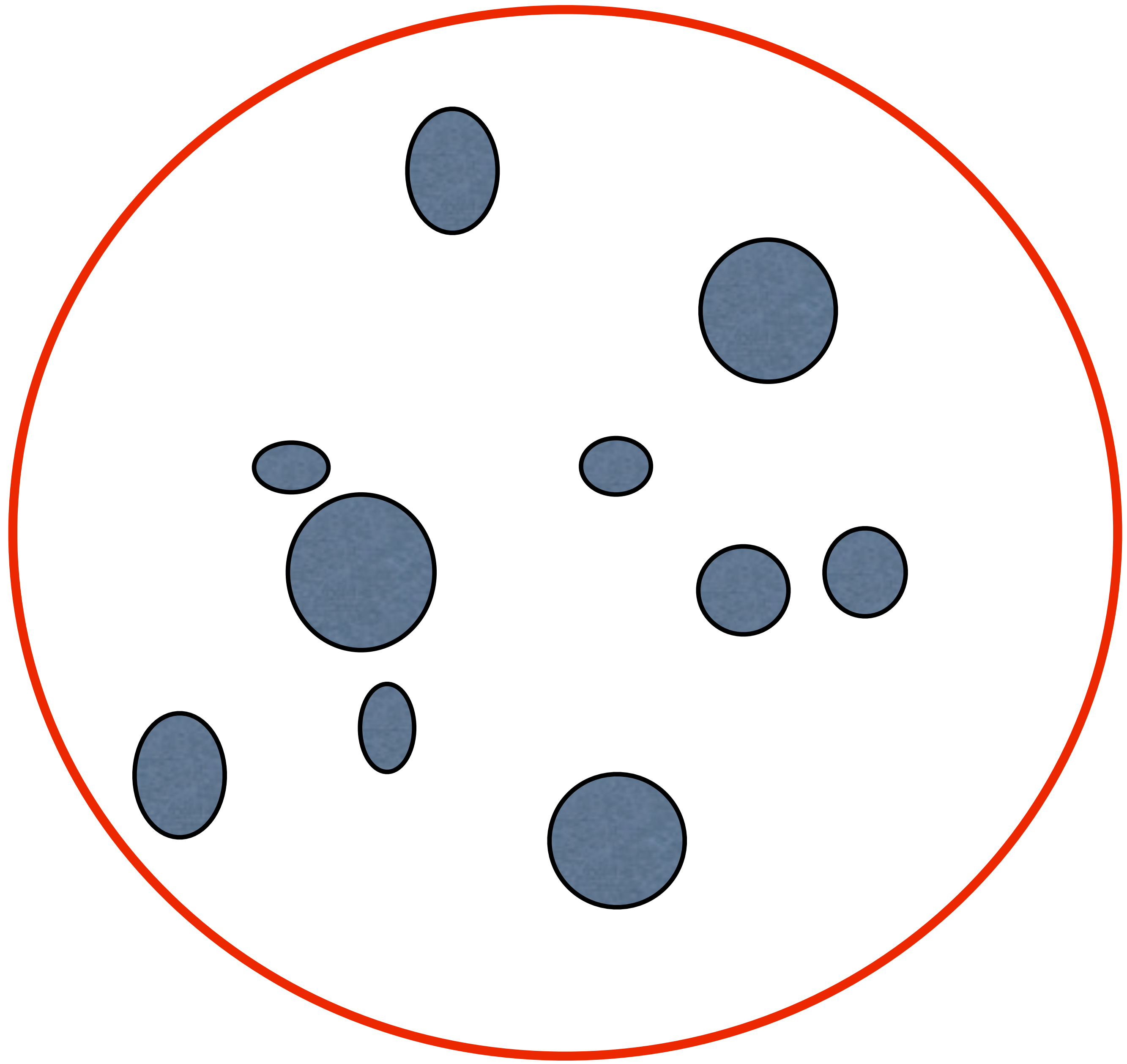
UE, ISR, Pile-up, hard interaction

Filtering/Trimming

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

Filtering:
recombine n subjets

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

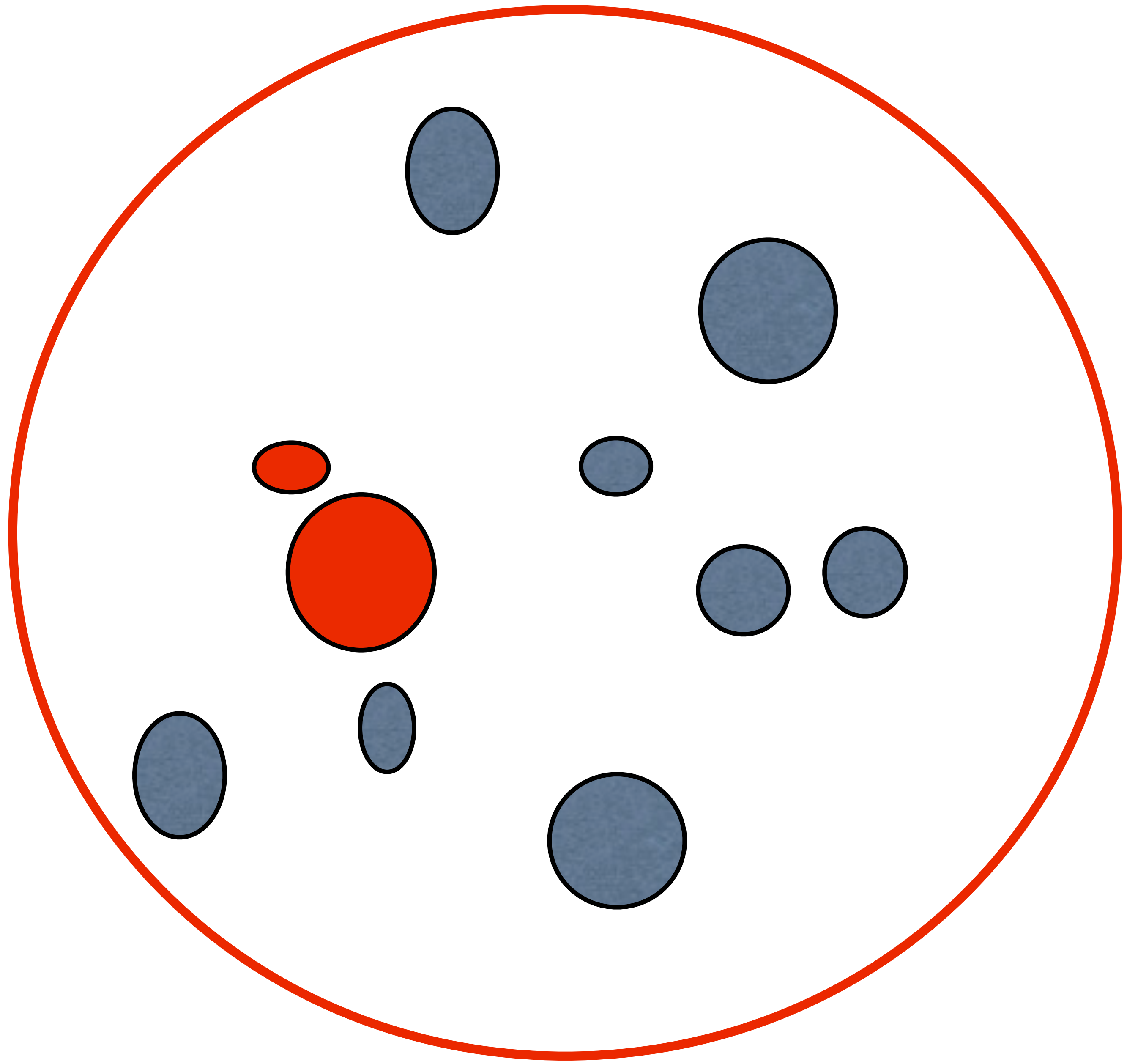


Filtering/Trimming

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

Filtering:
recombine n subjets

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

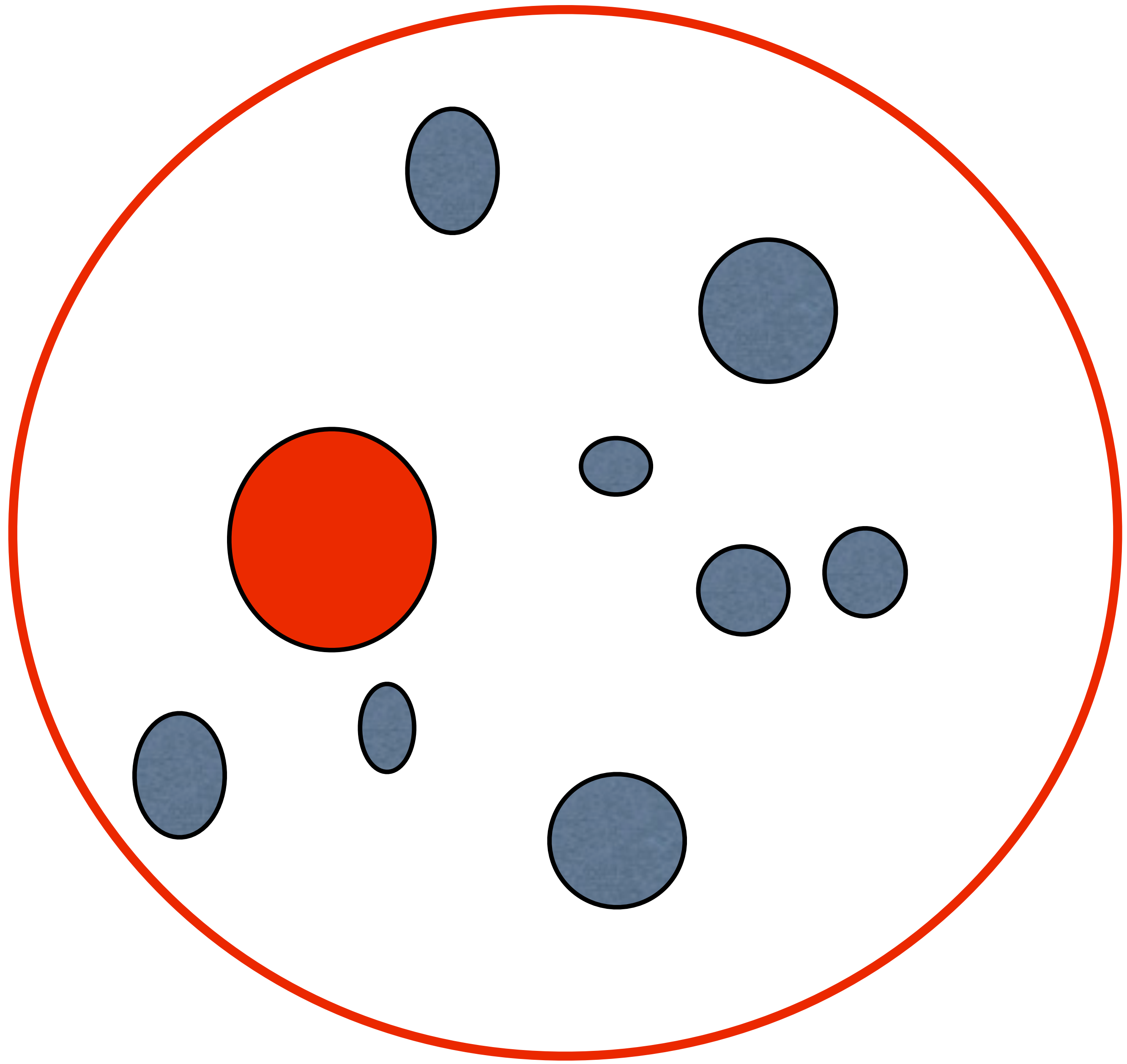


Filtering/Trimming

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

Filtering:
recombine n subjets

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

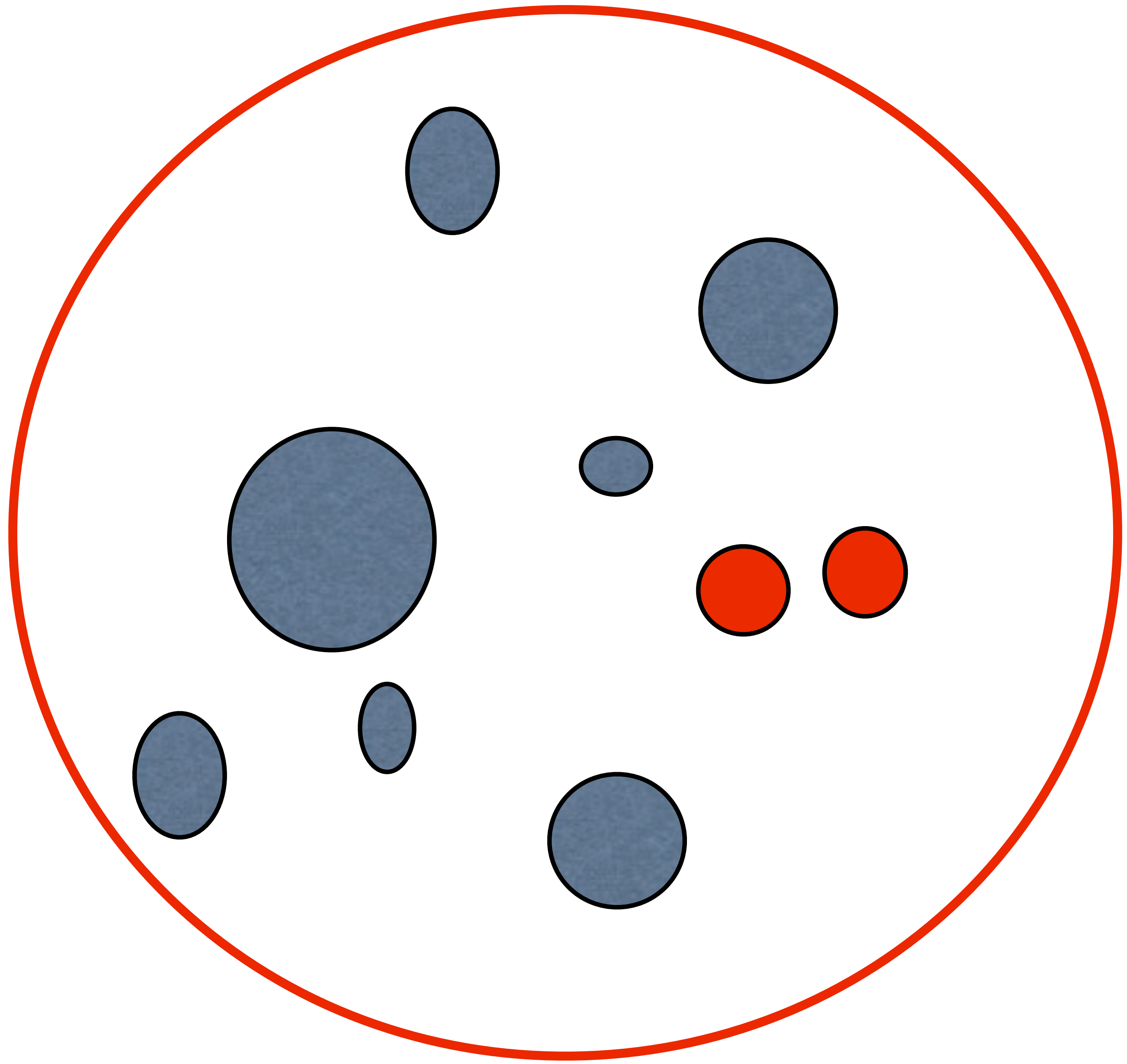


Filtering/Trimming

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

Filtering:
recombine n subjets

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

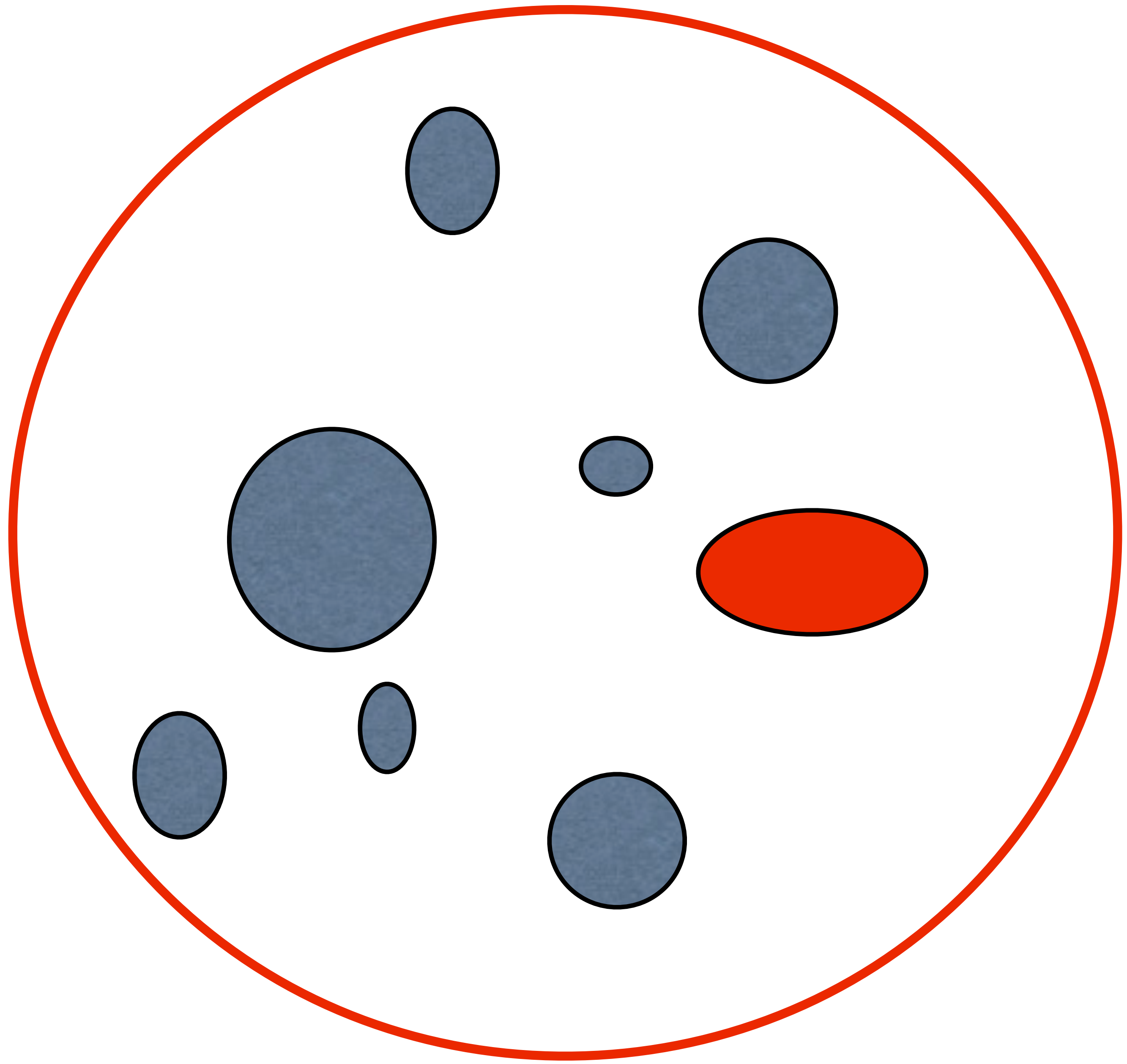


Filtering/Trimming

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

Filtering:
recombine n subjets

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

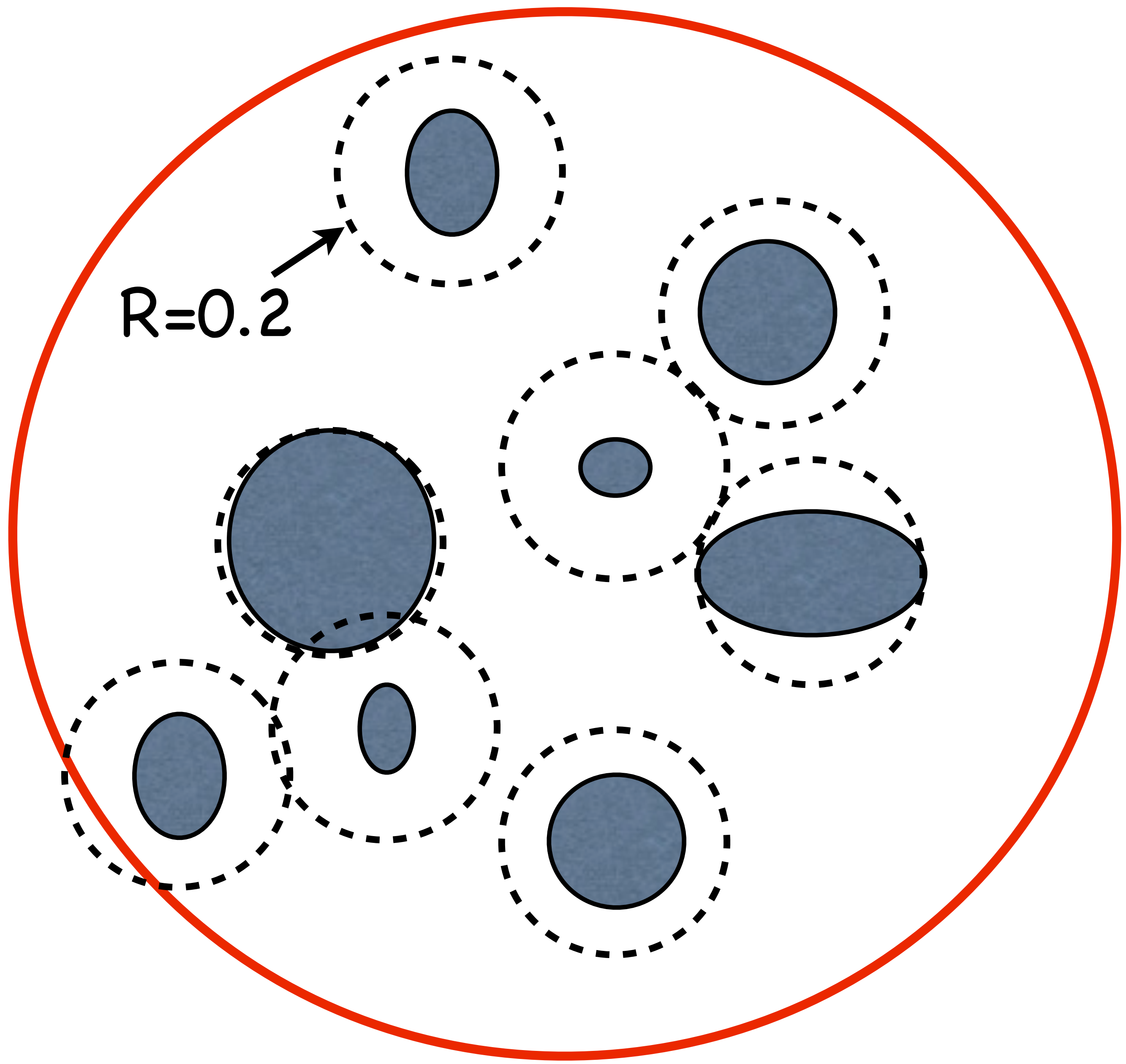


Filtering/Trimming

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

Filtering:
recombine n subjets

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

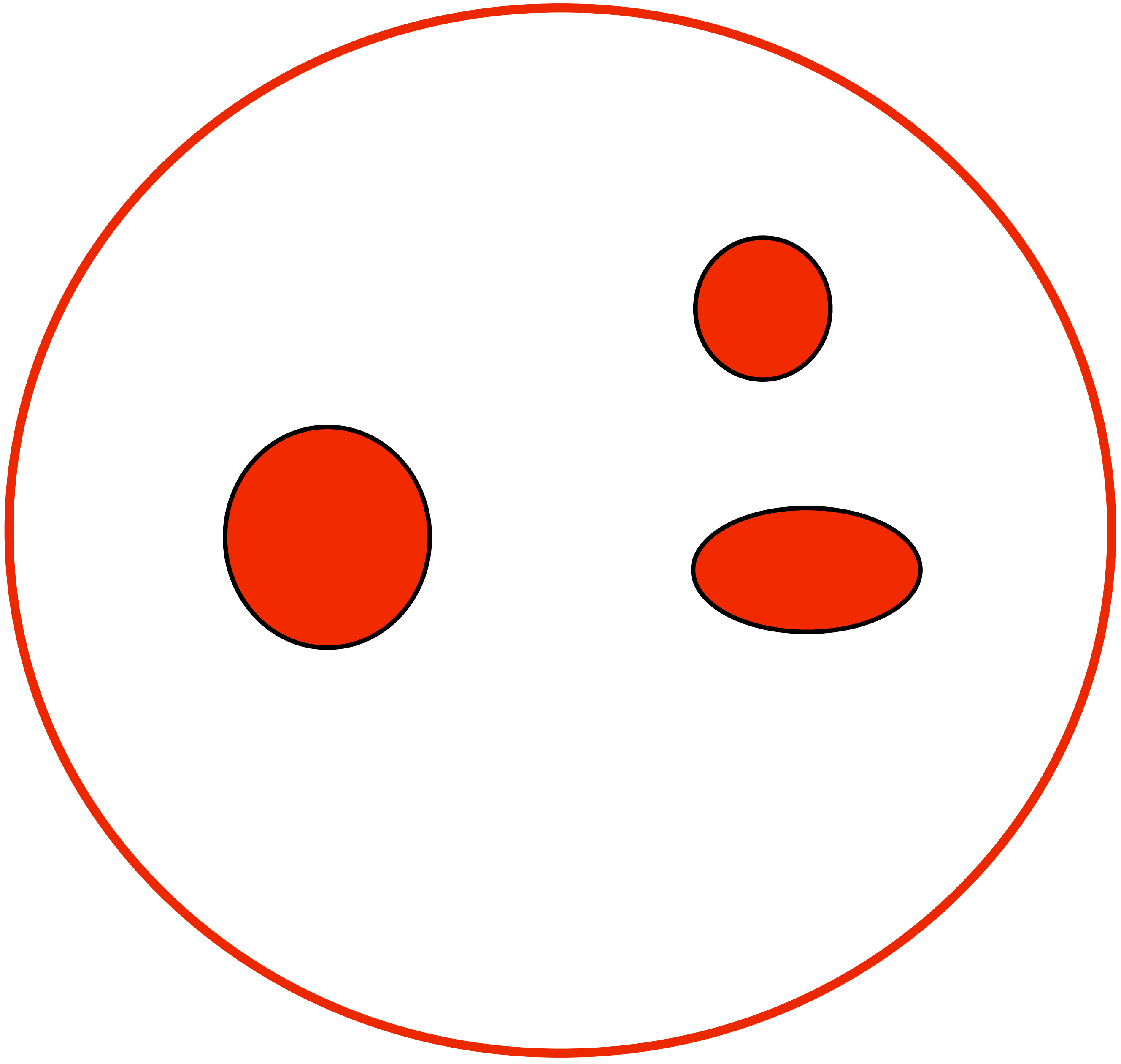


Filtering/Trimming

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

Filtering:
recombine n subjets

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

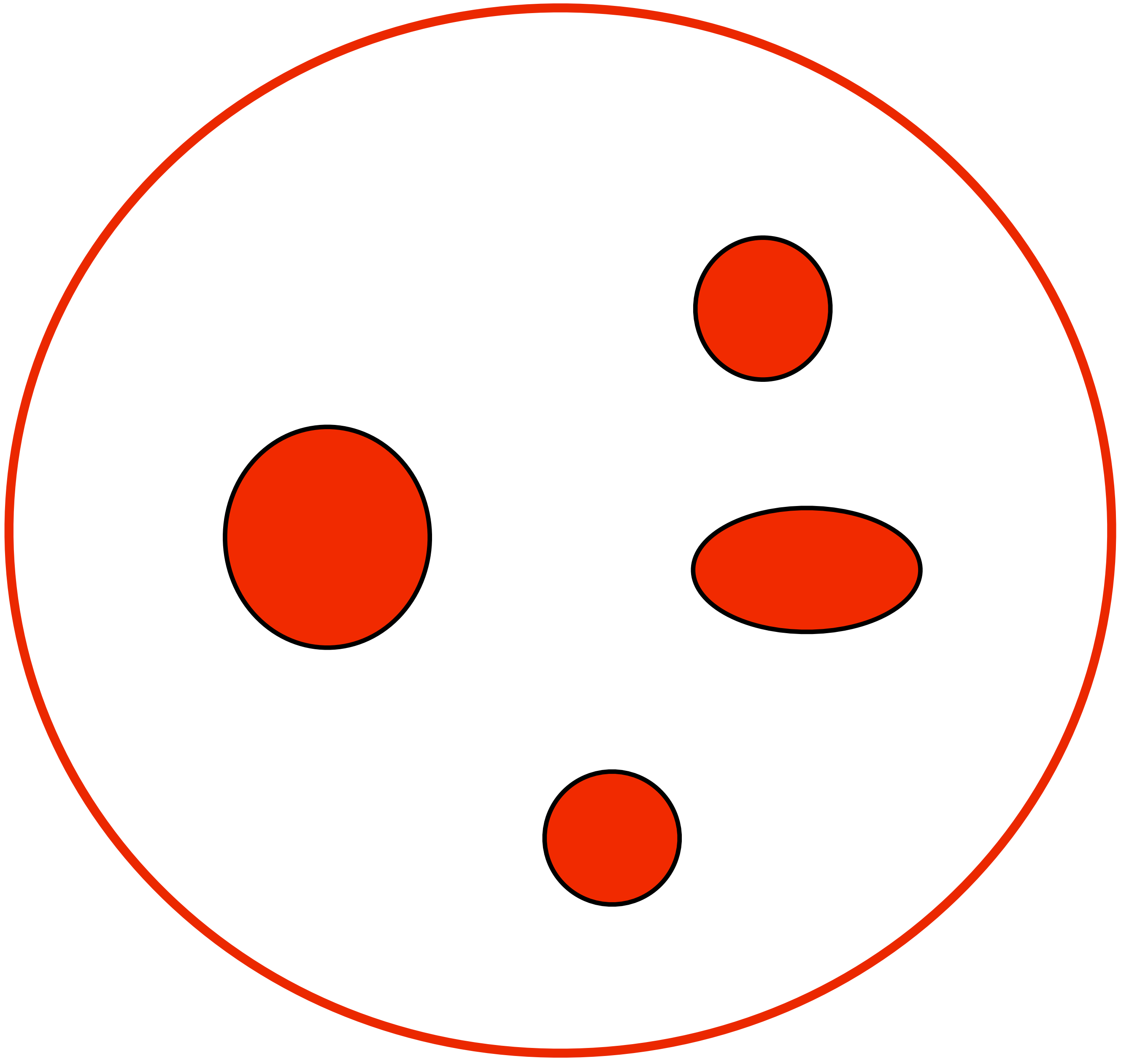


Filtering/Trimming

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

Filtering:
recombine n subjets

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

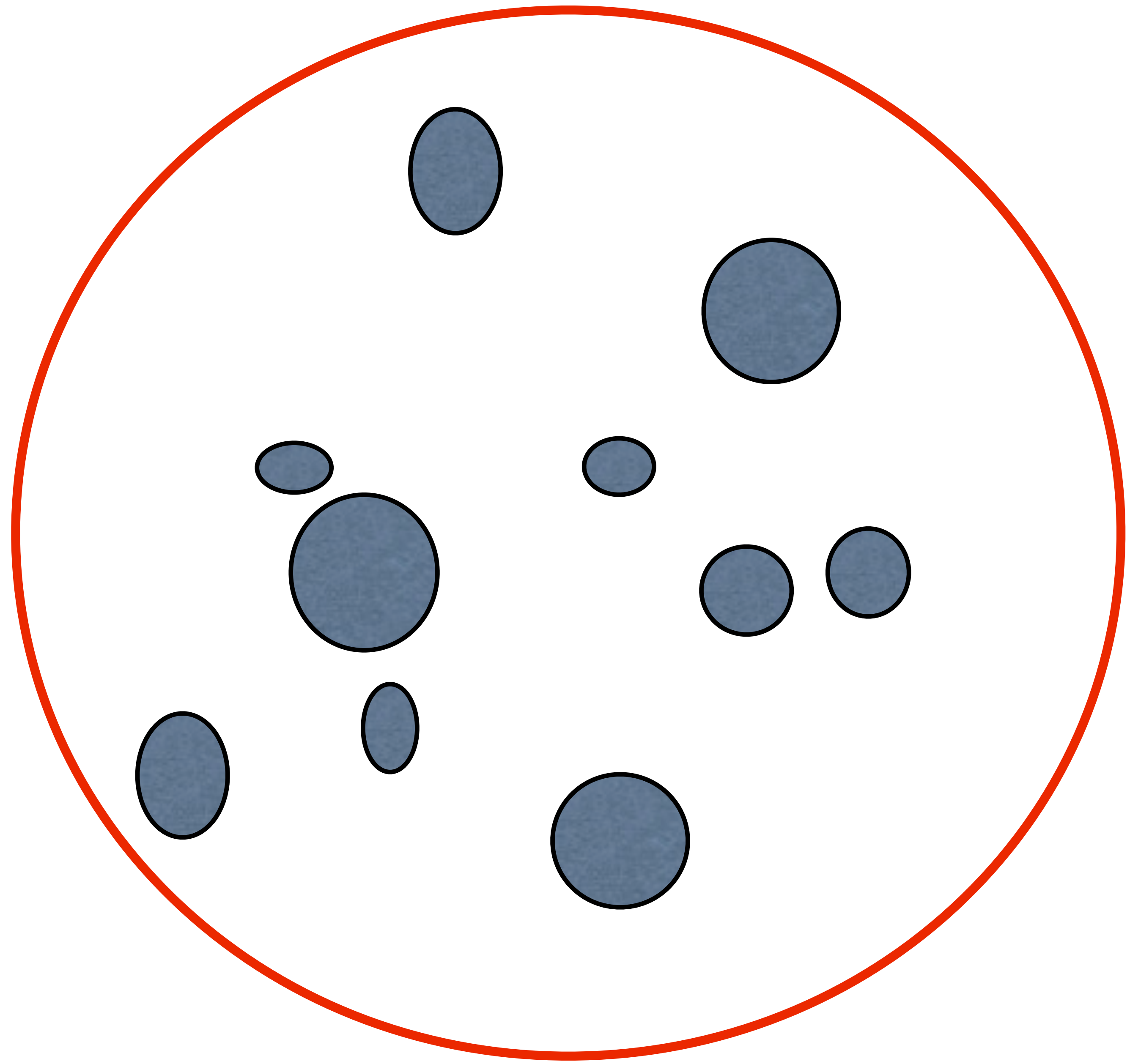


Pruning

Based on 2 conditions

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

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



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

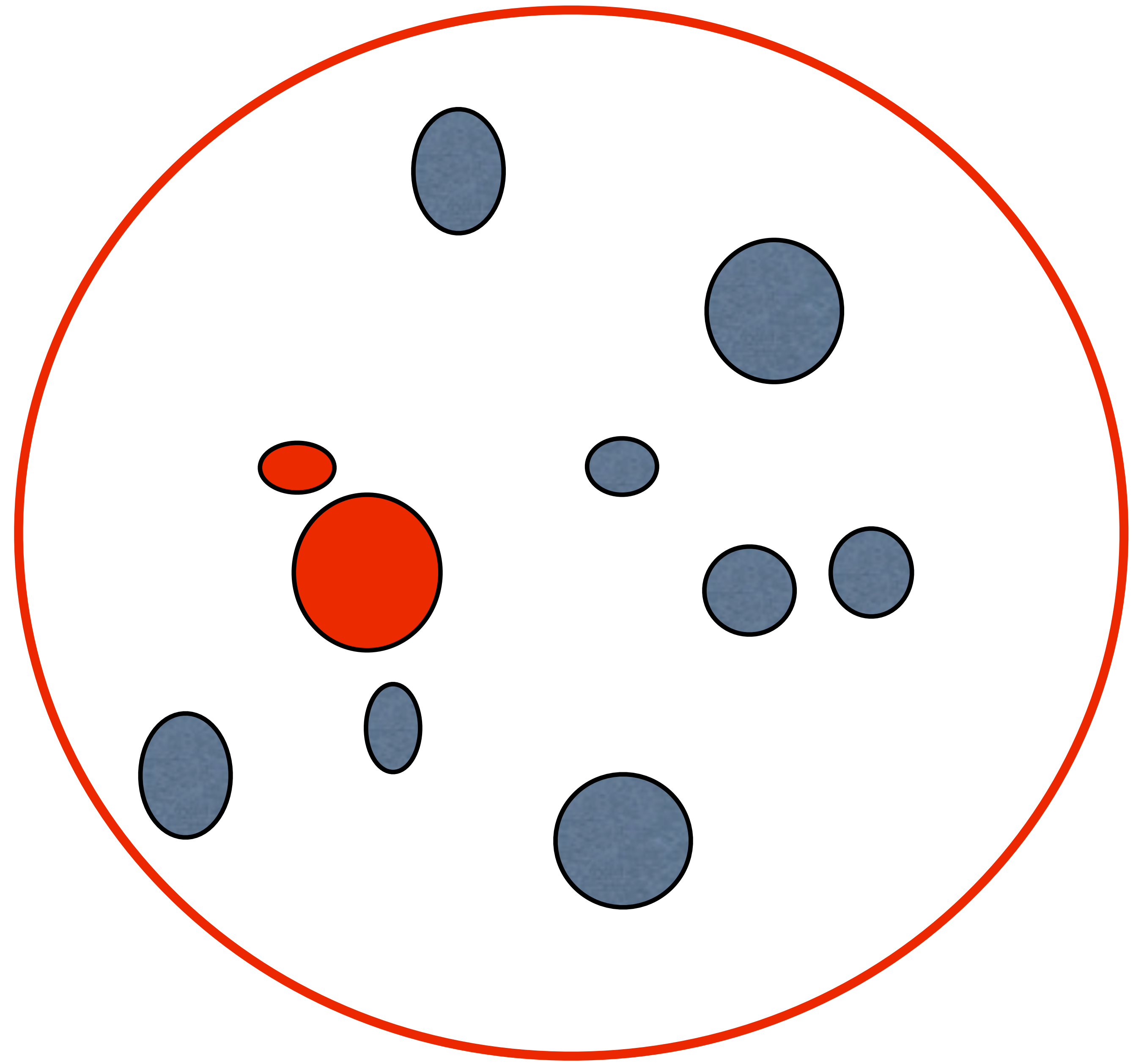
Pruning

Based on 2 conditions

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

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

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

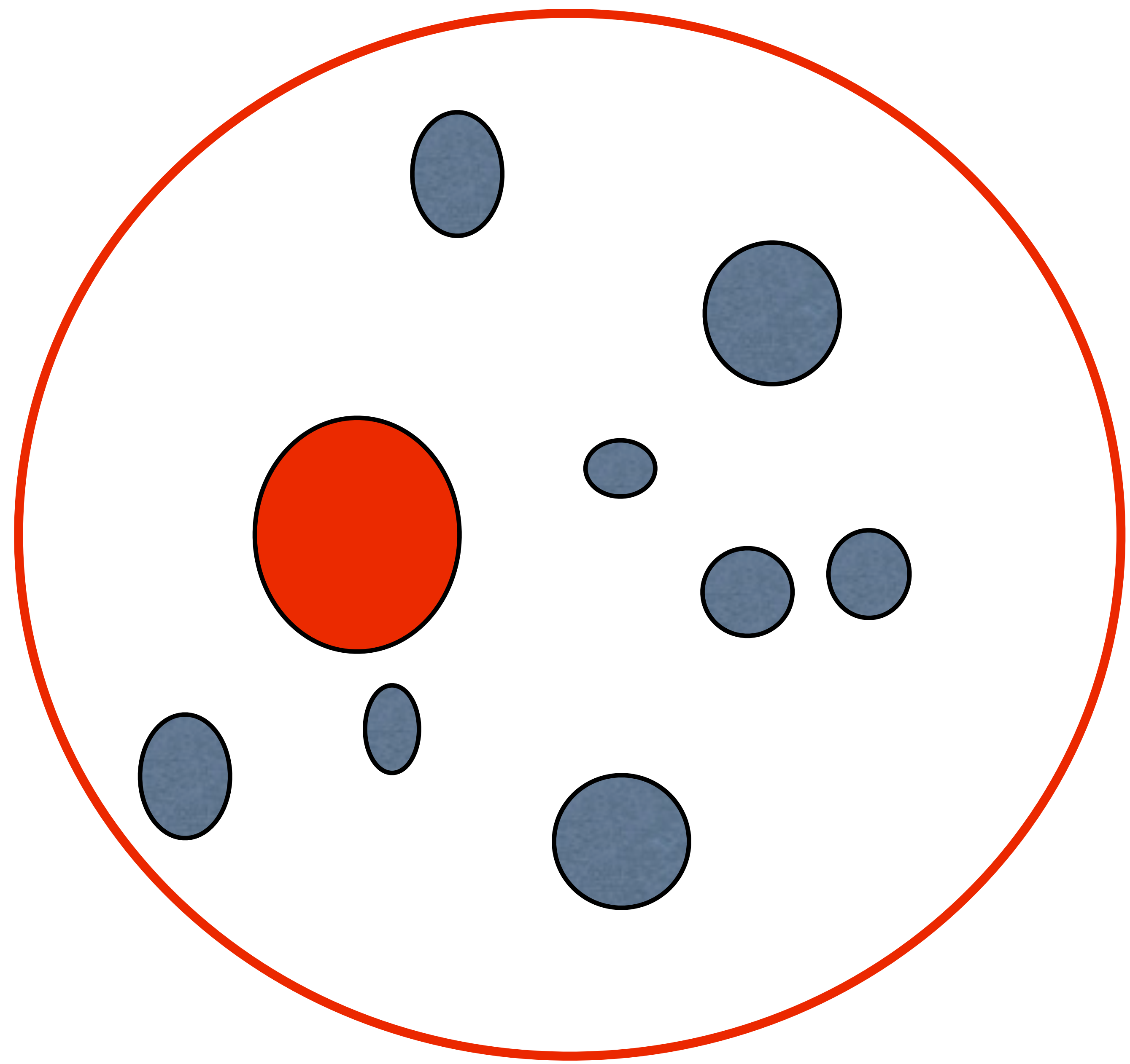


Pruning

Based on 2 conditions

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

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



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

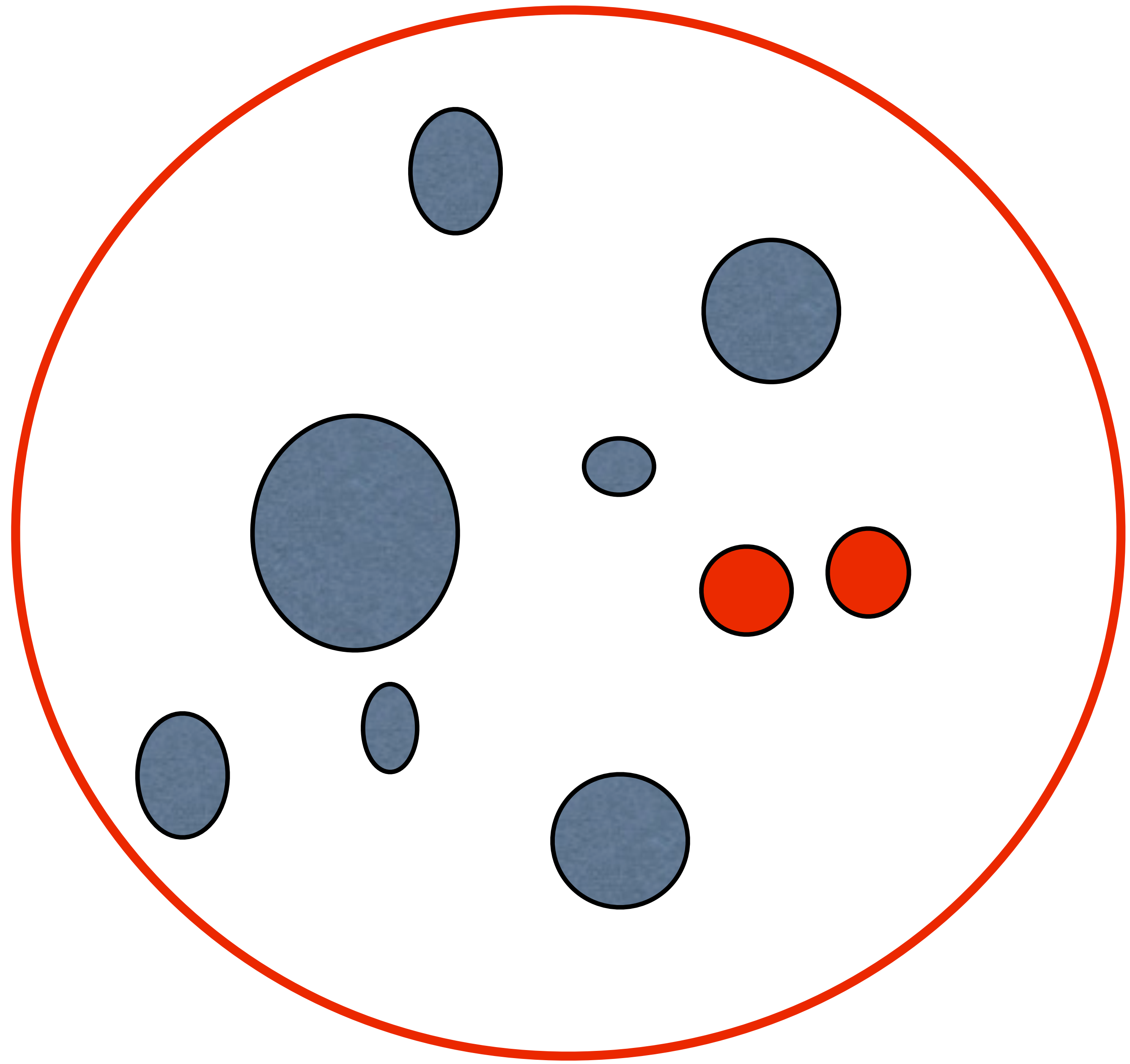
Pruning

Based on 2 conditions

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

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

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

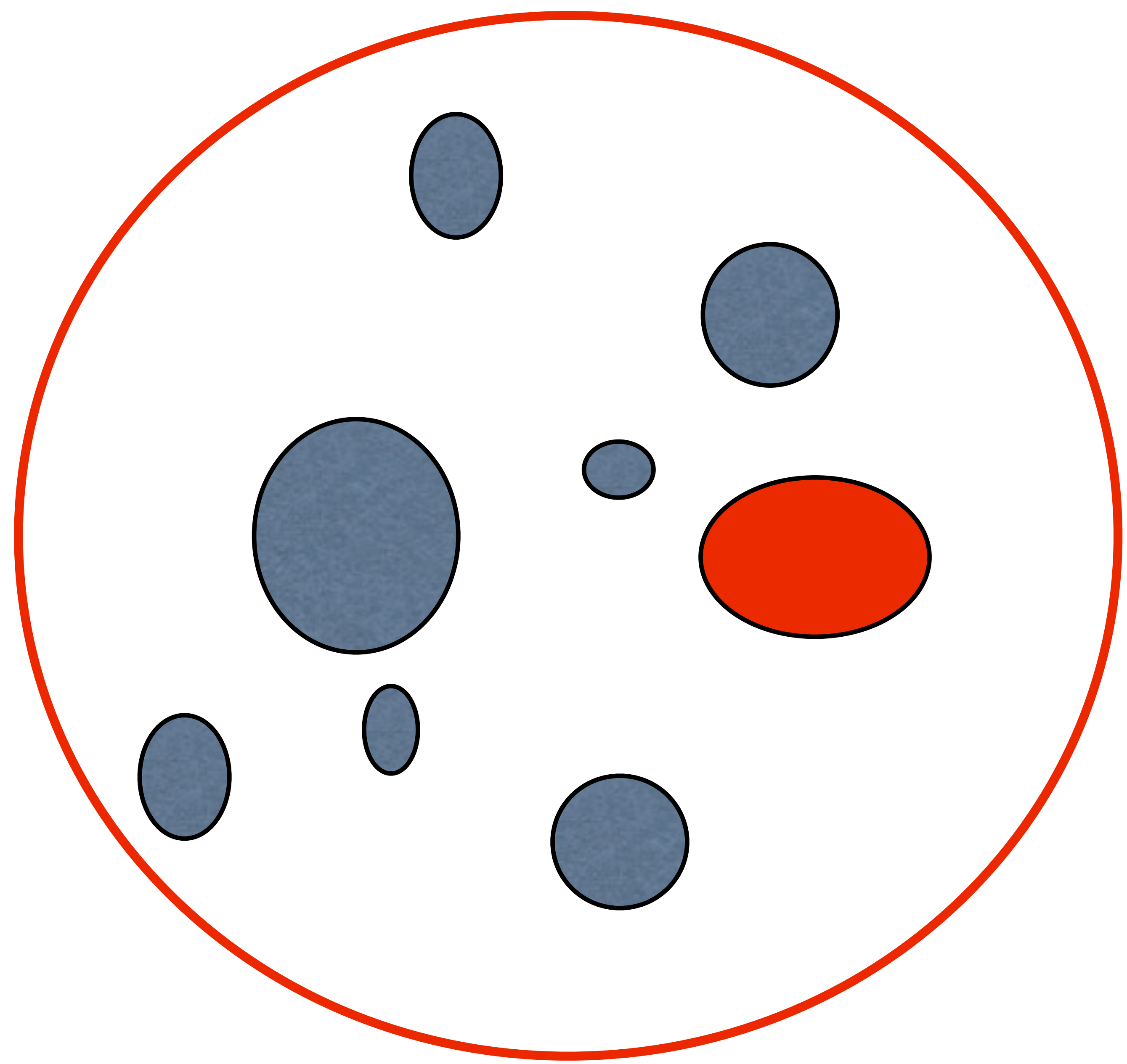


Pruning

Based on 2 conditions

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

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



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

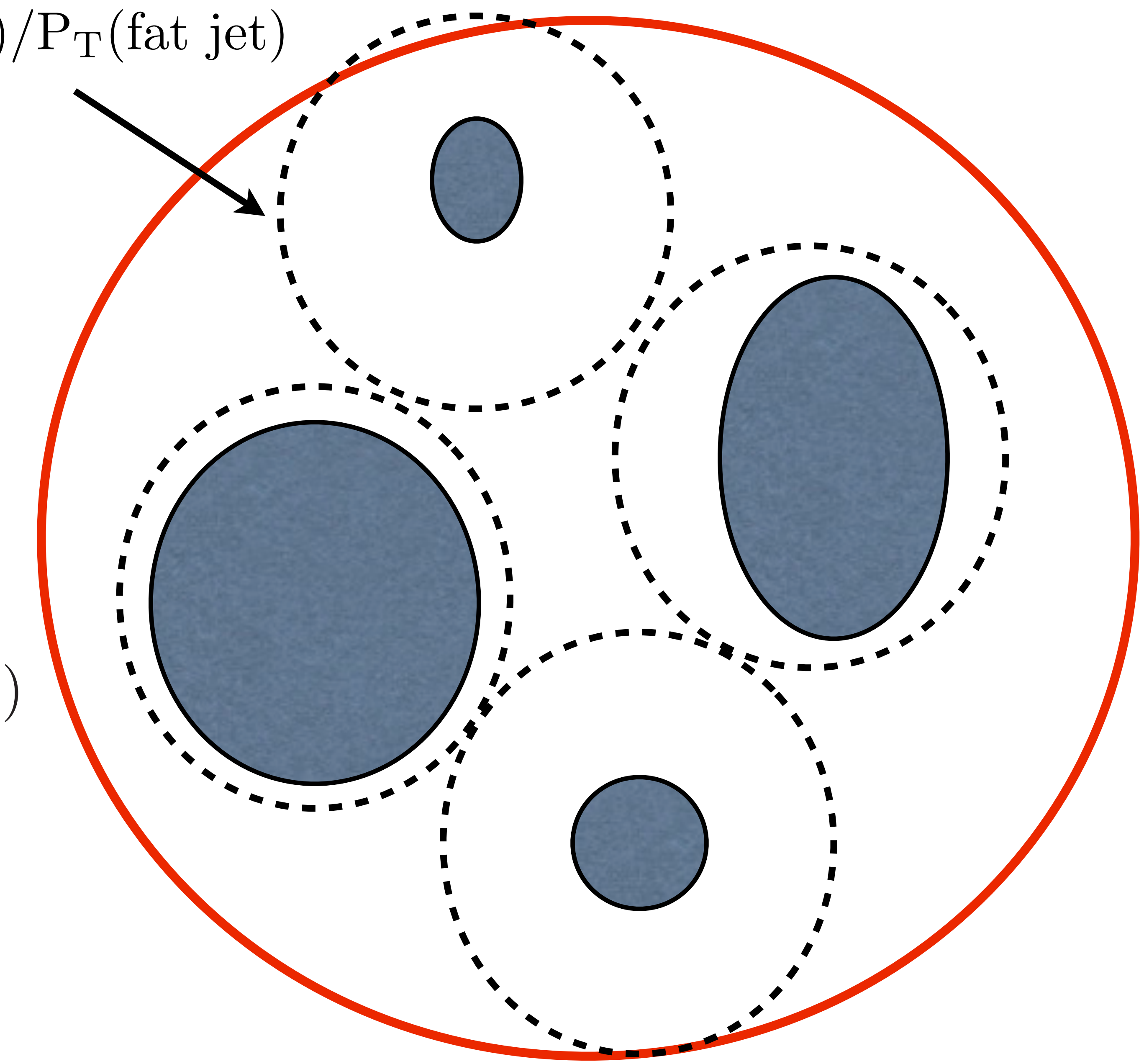
Pruning

Based on 2 conditions

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

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

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

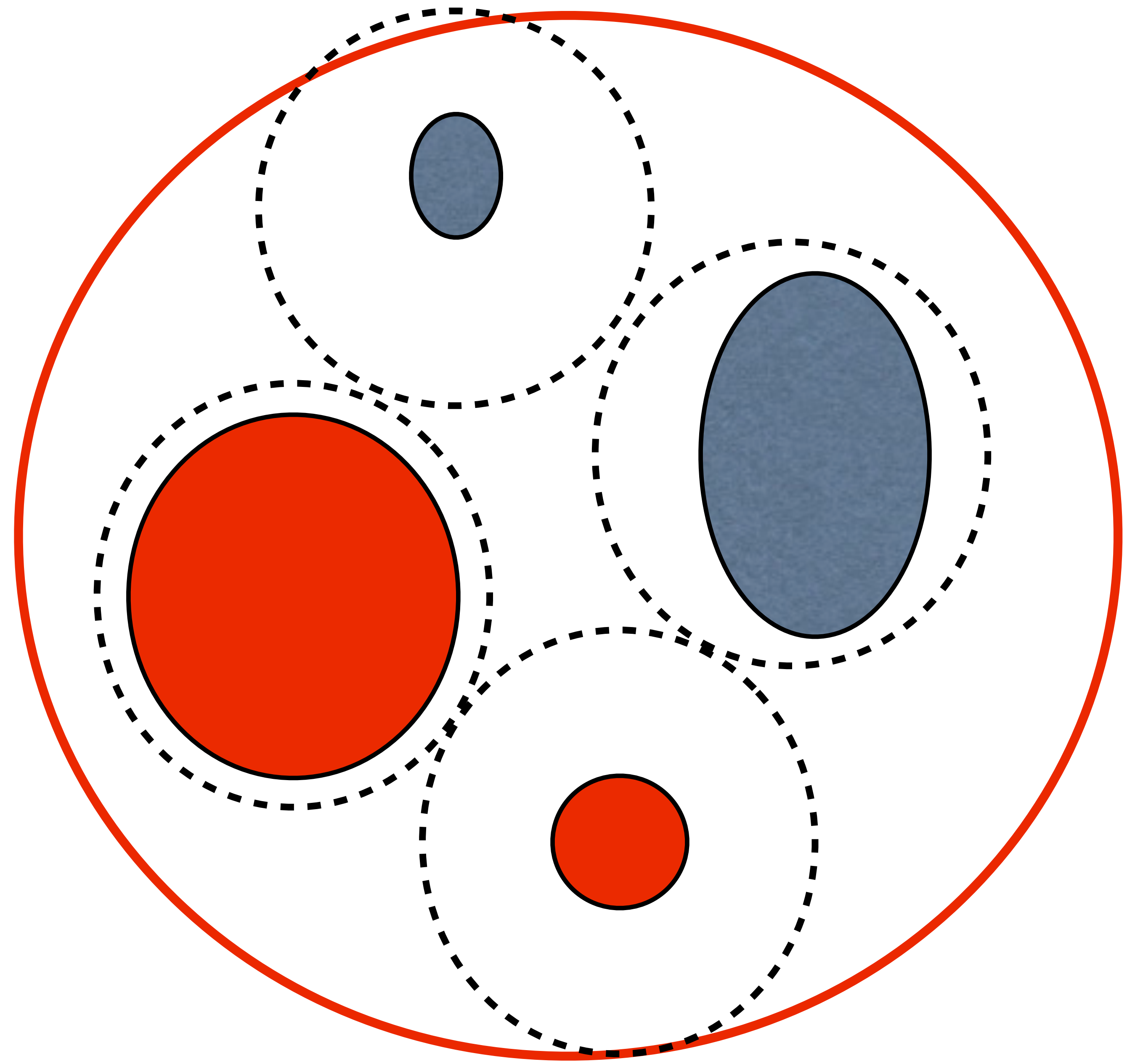


Pruning

Based on 2 conditions

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

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



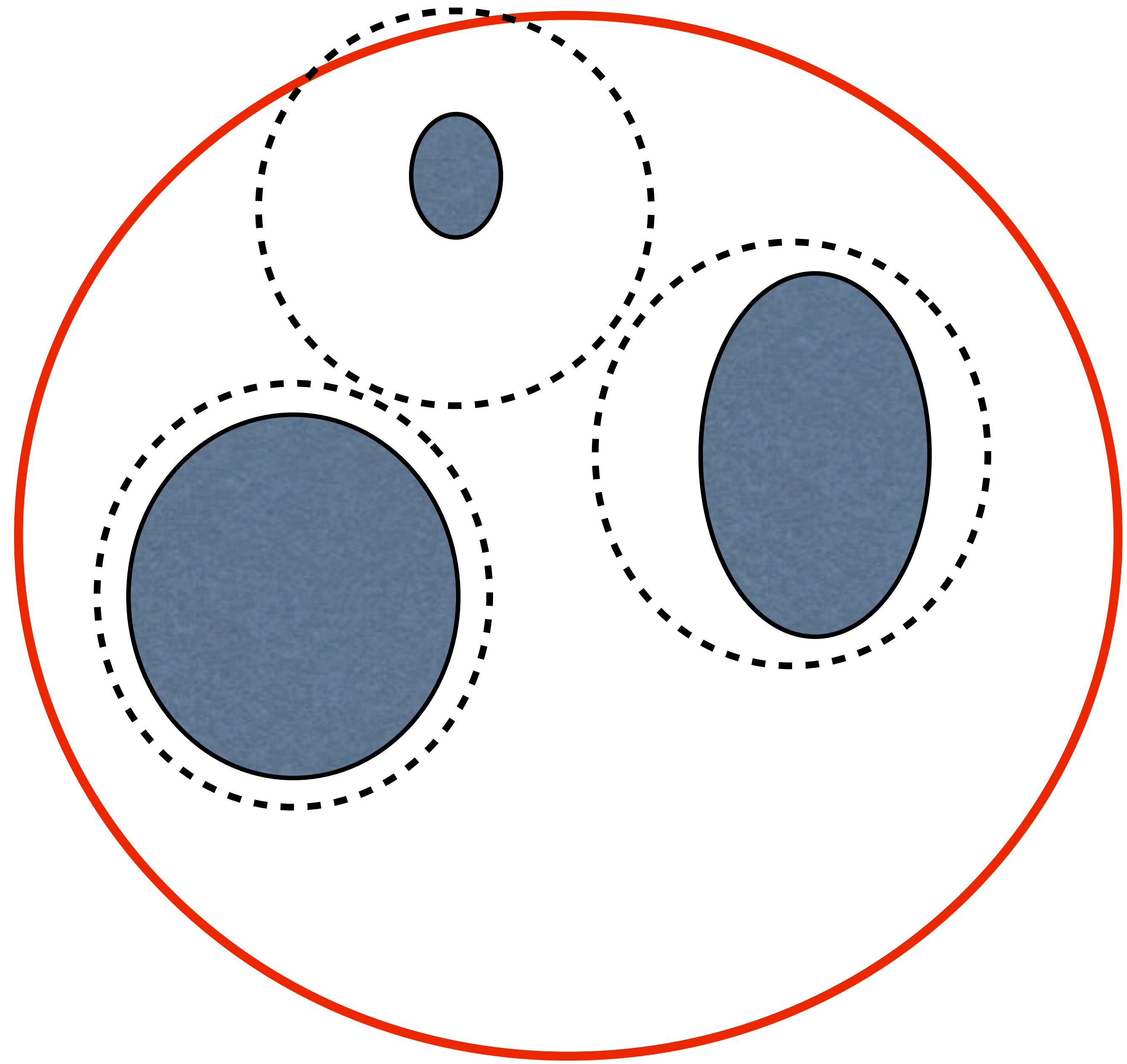
If both hold true,
eg. recombination is wide angle and asymmetric,
veto merging

Pruning

Based on 2 conditions

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

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



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

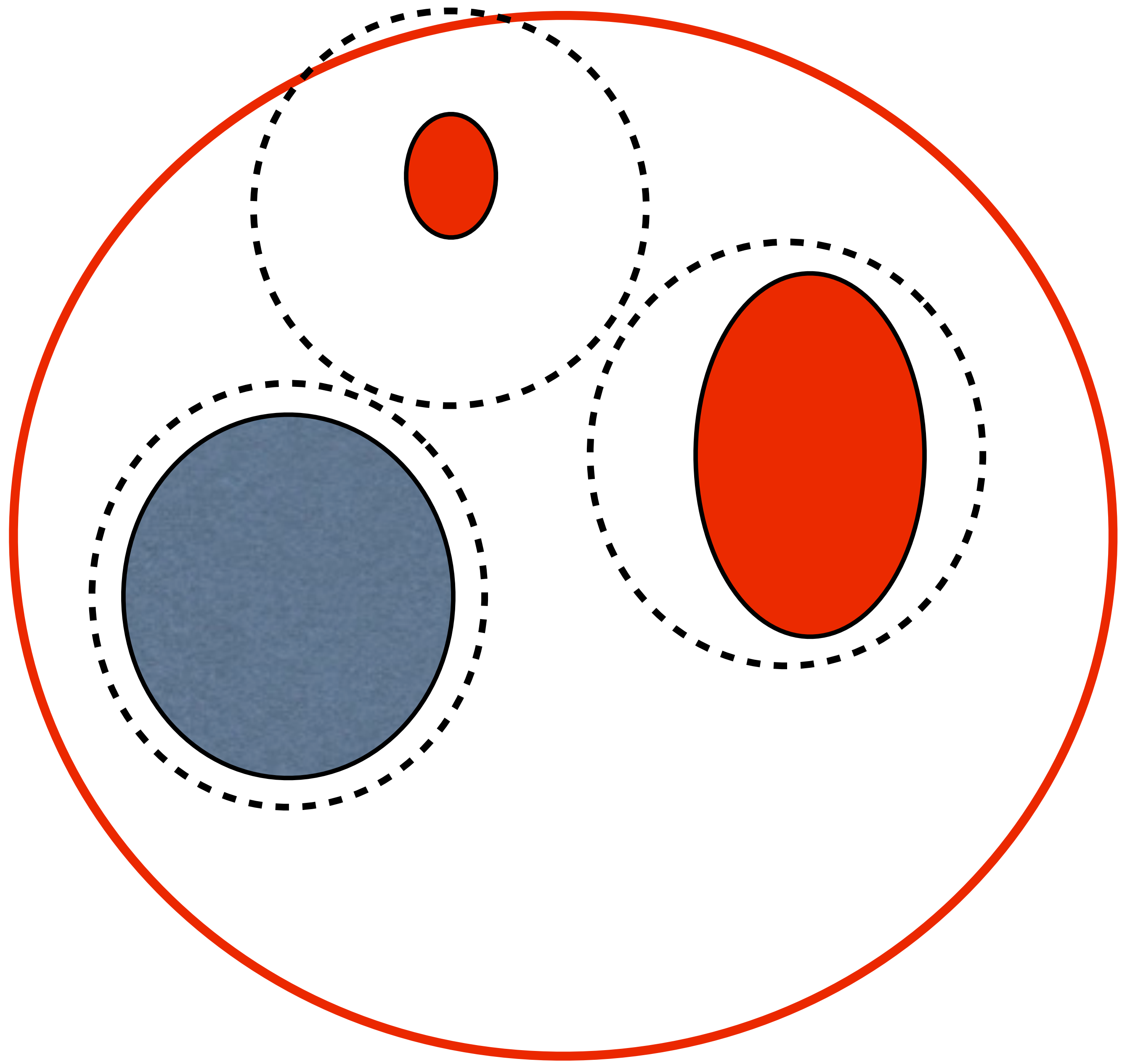
Pruning

Based on 2 conditions

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

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

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

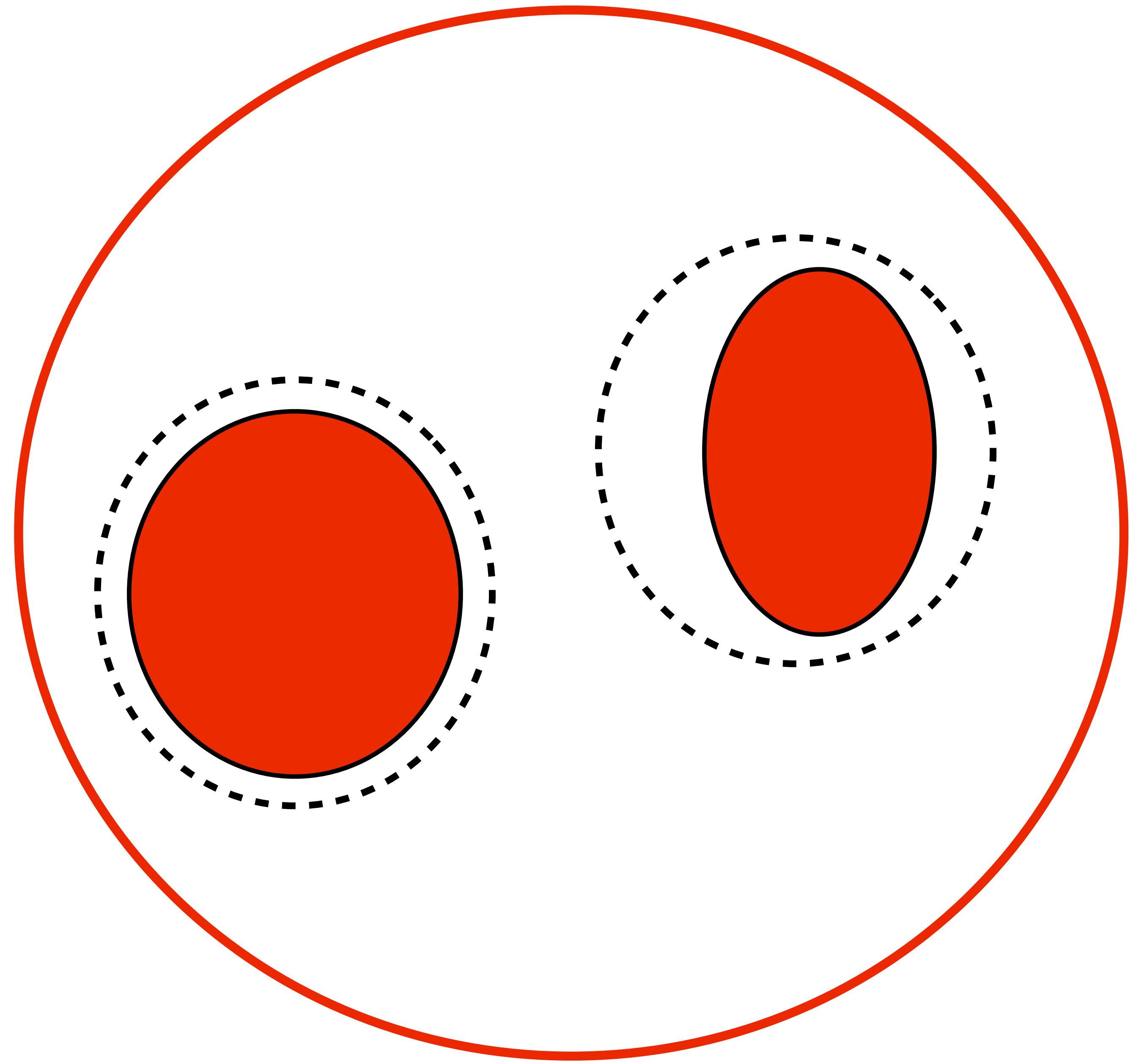


Pruning

Based on 2 conditions

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

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



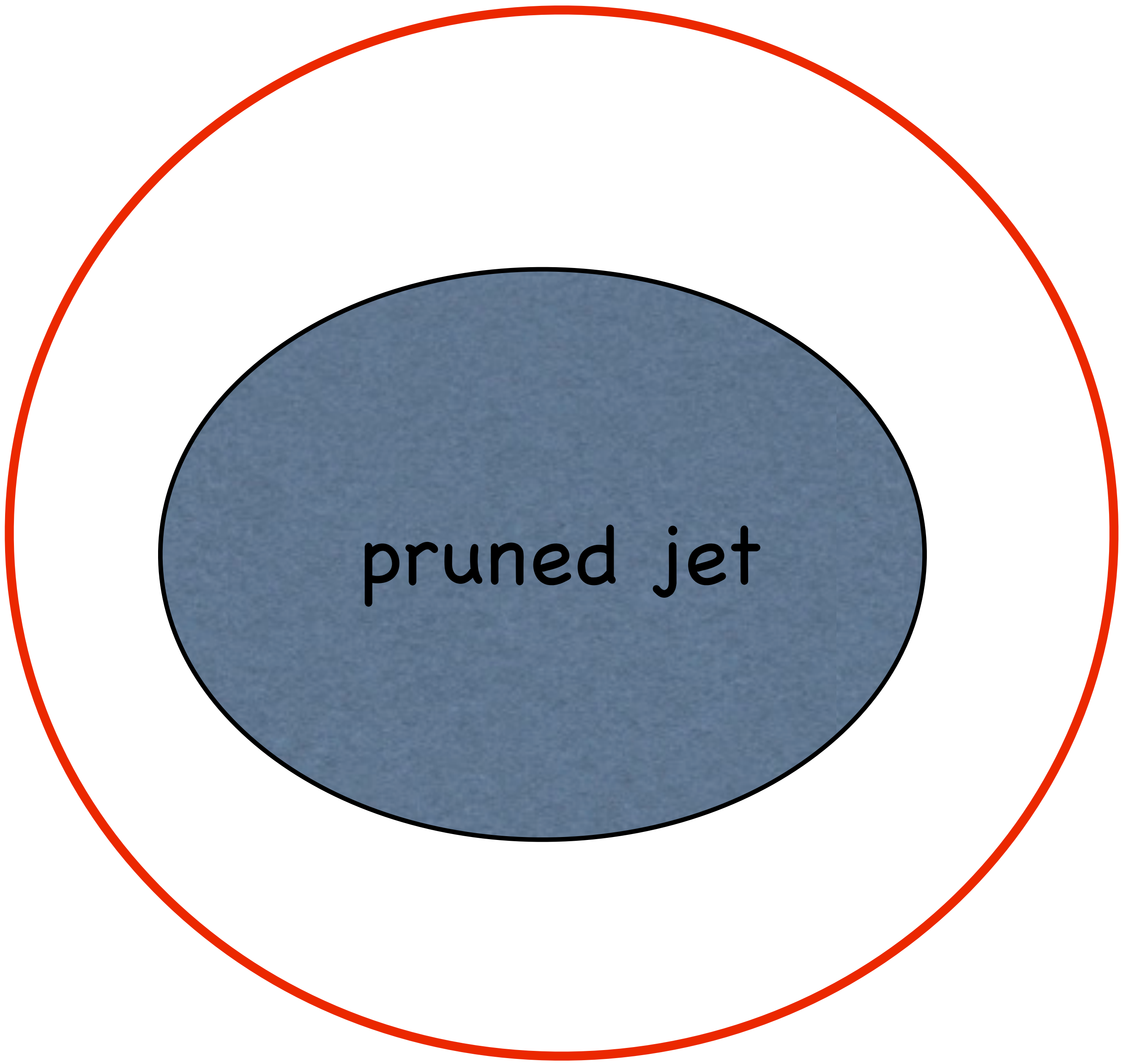
If both hold true,
eg. recombination is wide angle and asymmetric,
veto merging

Pruning

Based on 2 conditions

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

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

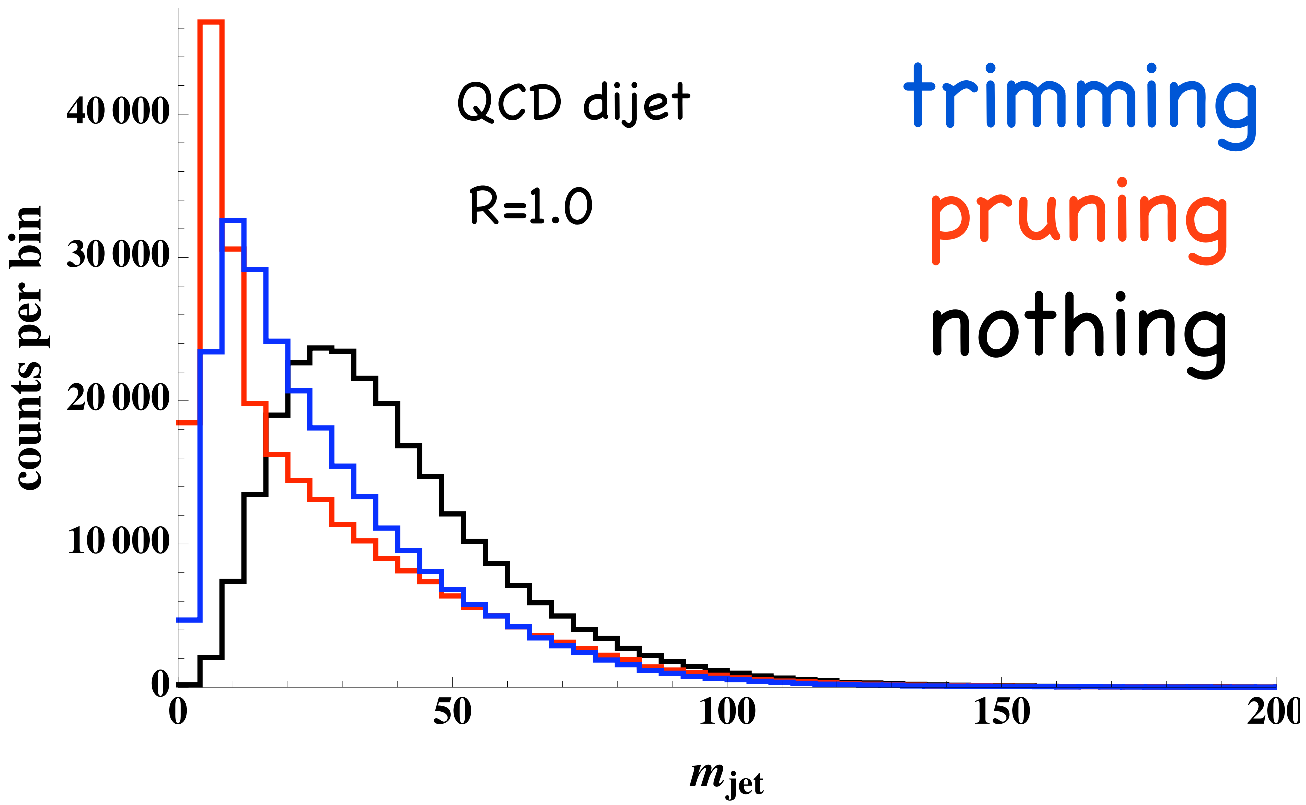


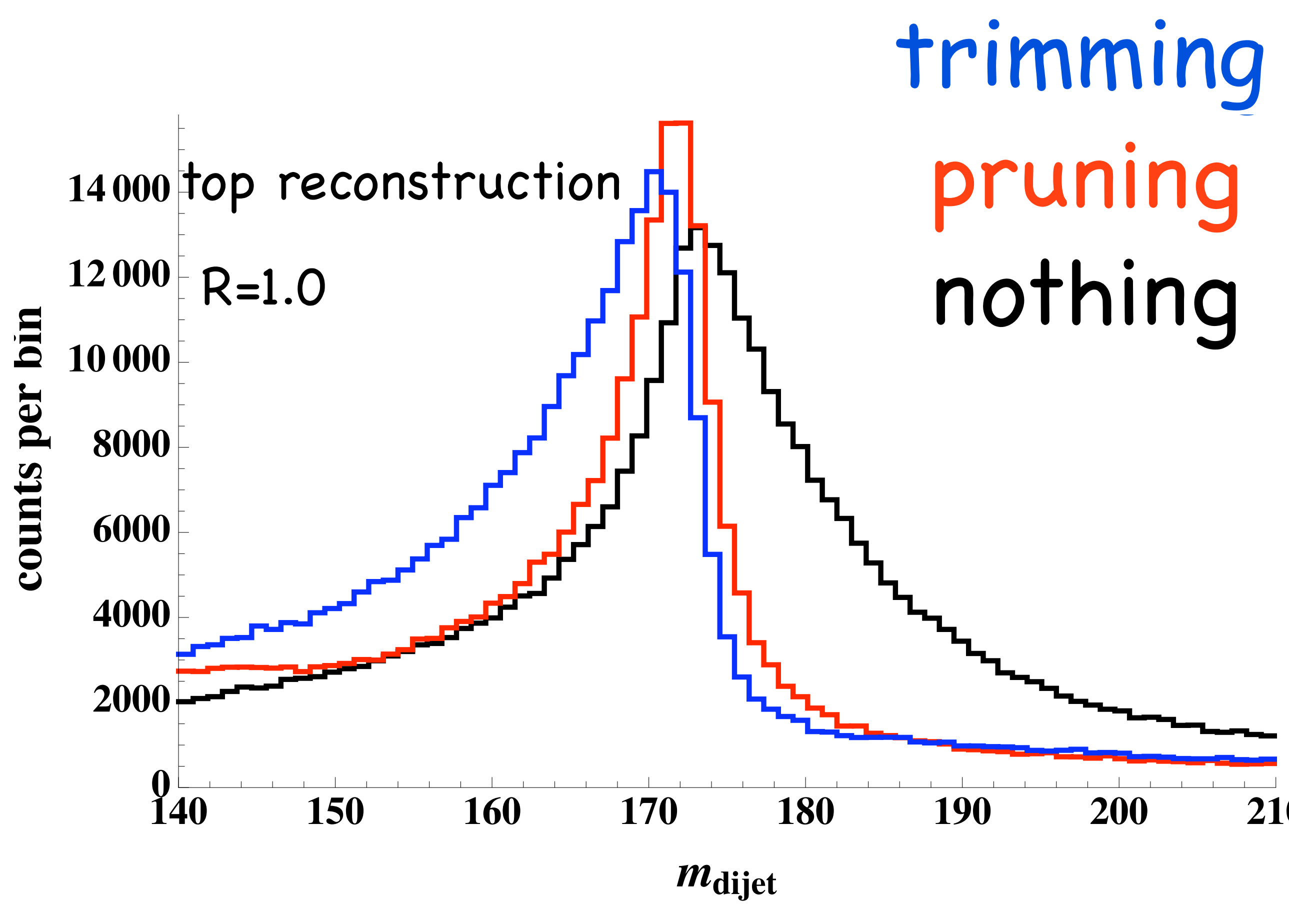
If both hold true,
eg. recombination is wide angle and asymmetric,
veto merging

Comparison of the techniques

Pruning/Trimming can be generic tagging tools

Filtering needs input what to look for





[Jon Walsh, http://silicon.phys.washington.edu/JetsWorkshop/JetModTalk.pdf]

Application of jet grooming techniques
to
New Physics searches

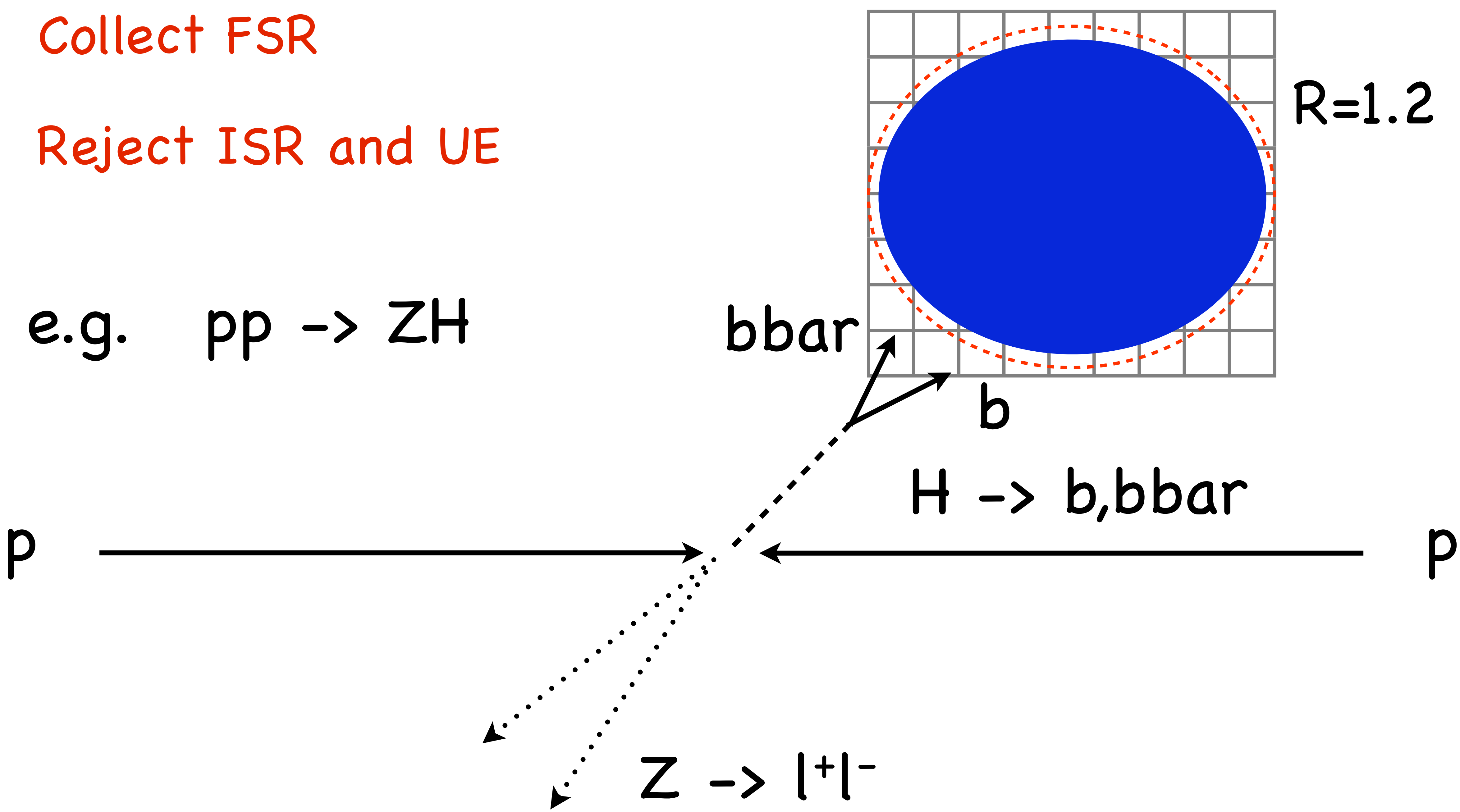
HV - Higgs discovery channel

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

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



HV - Higgs discovery channel

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

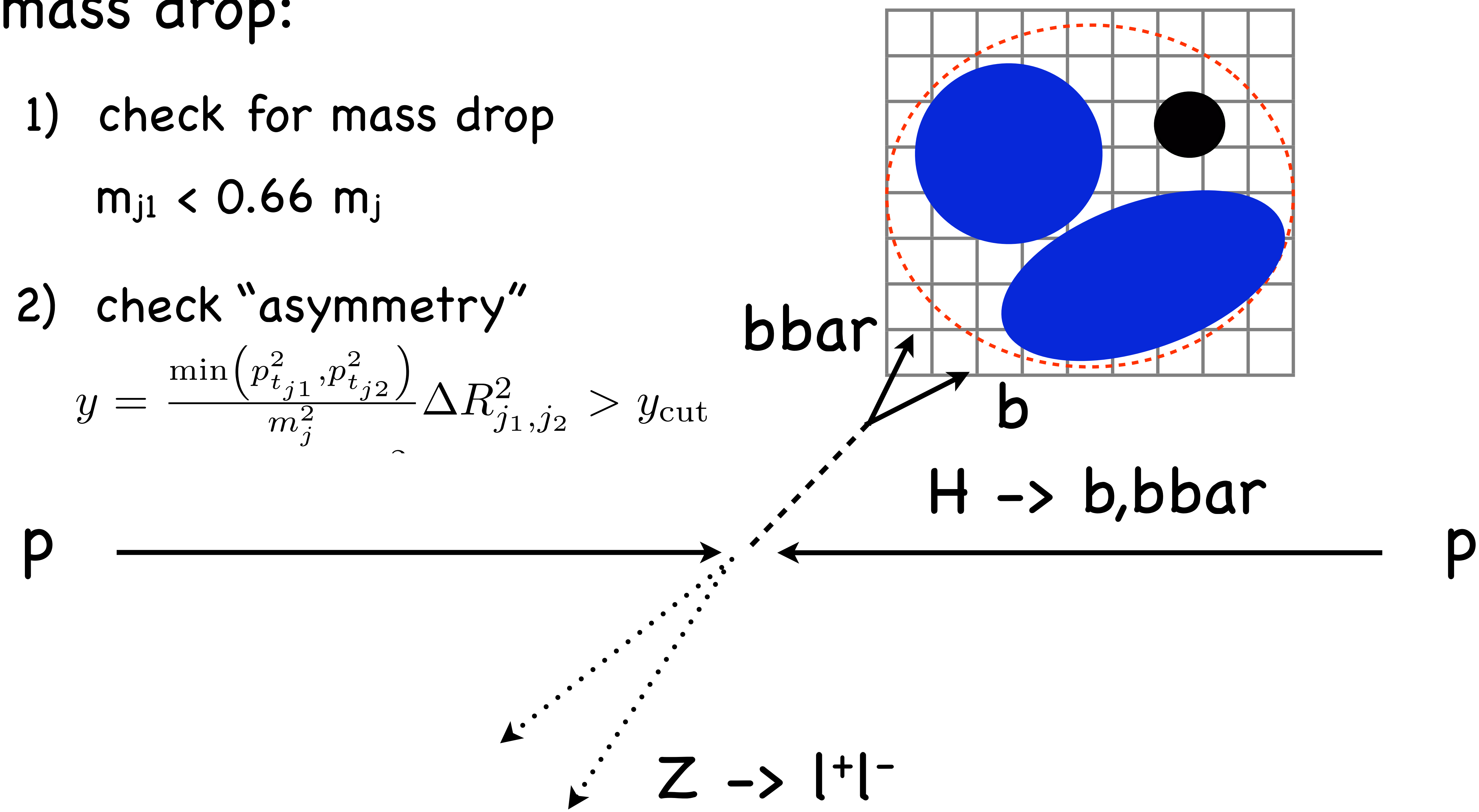
mass drop:

1) check for mass drop

   $m_{j1} < 0.66\ m_j$

2) check "asymmetry"

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

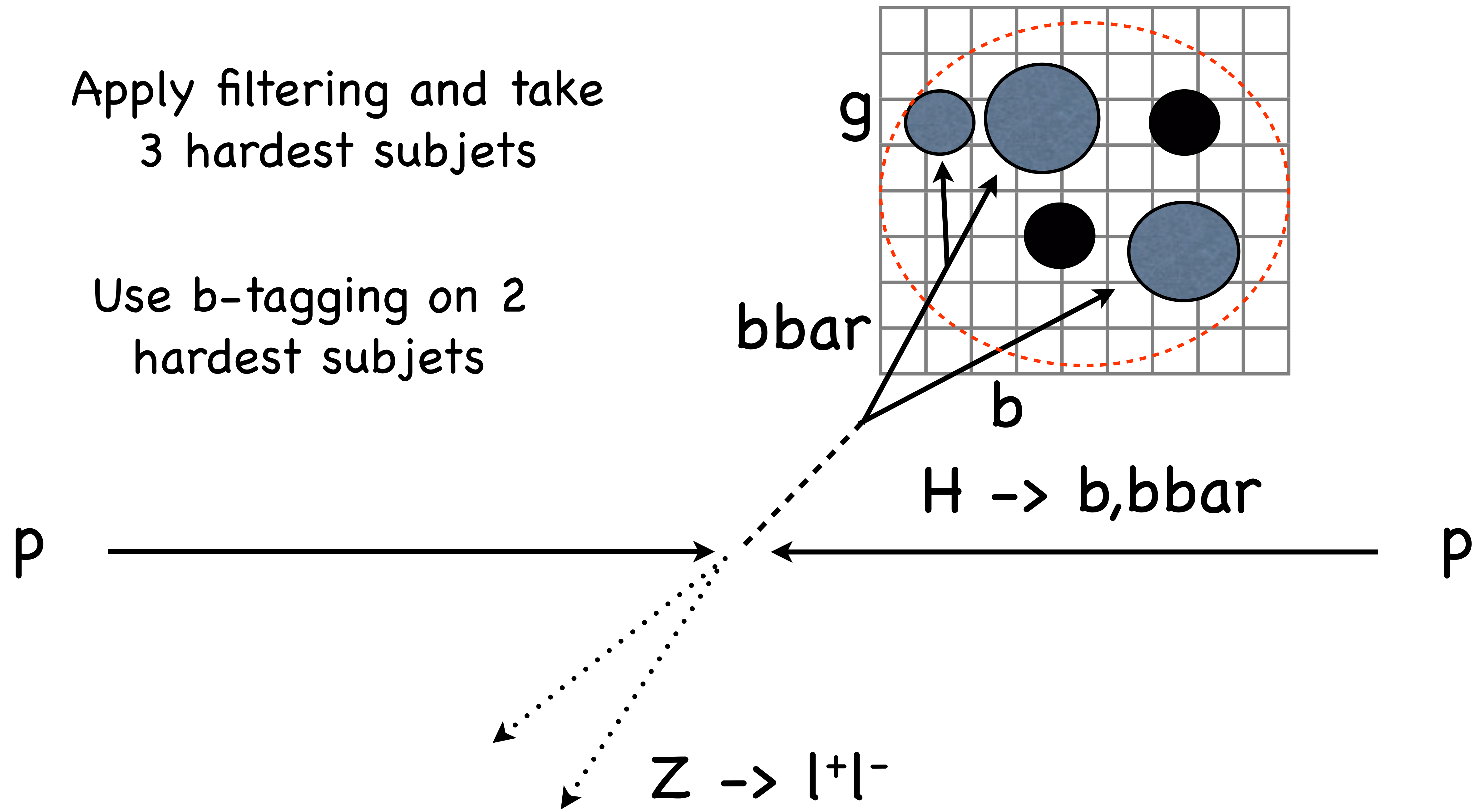


HV - Higgs discovery channel

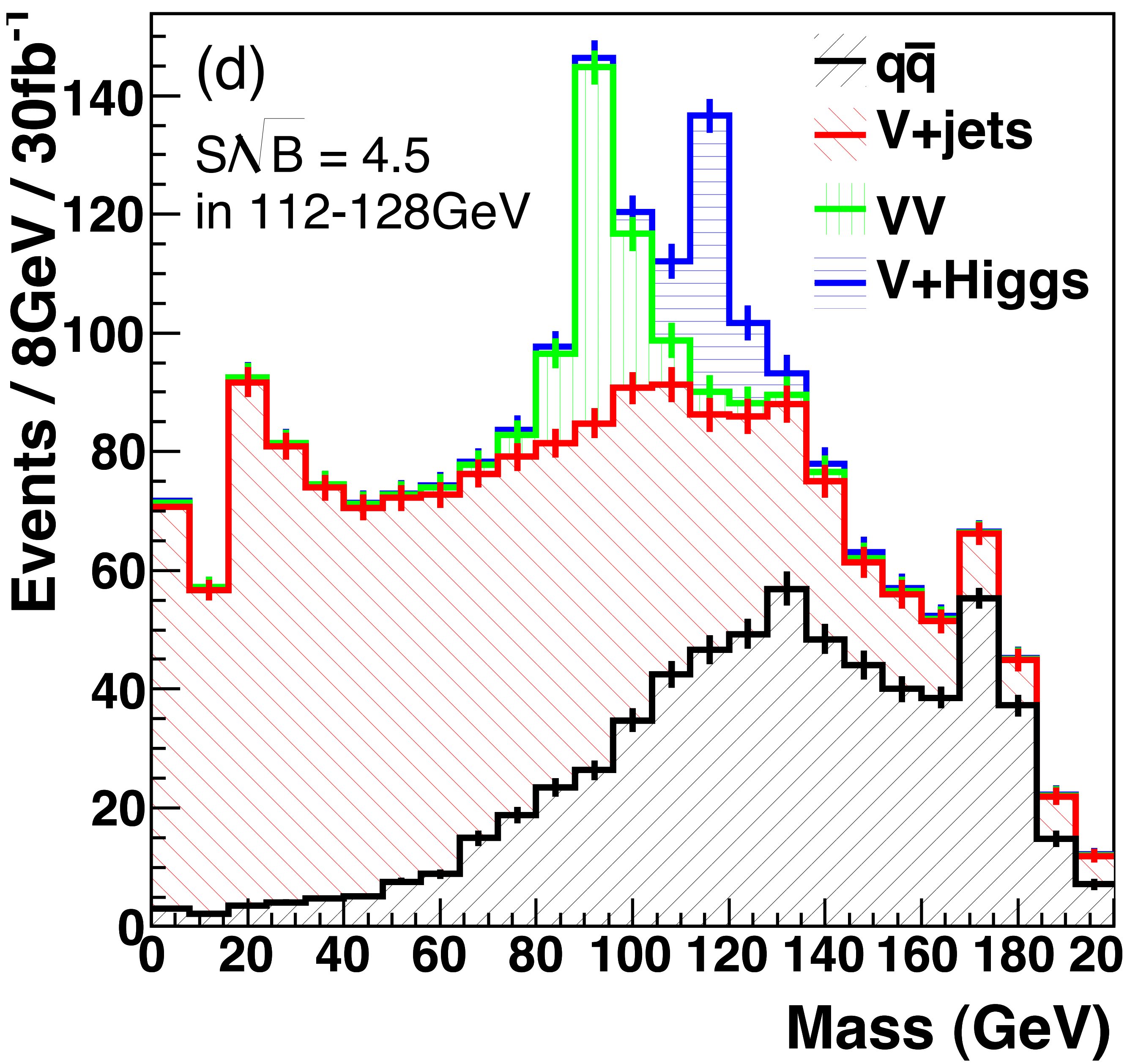
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets

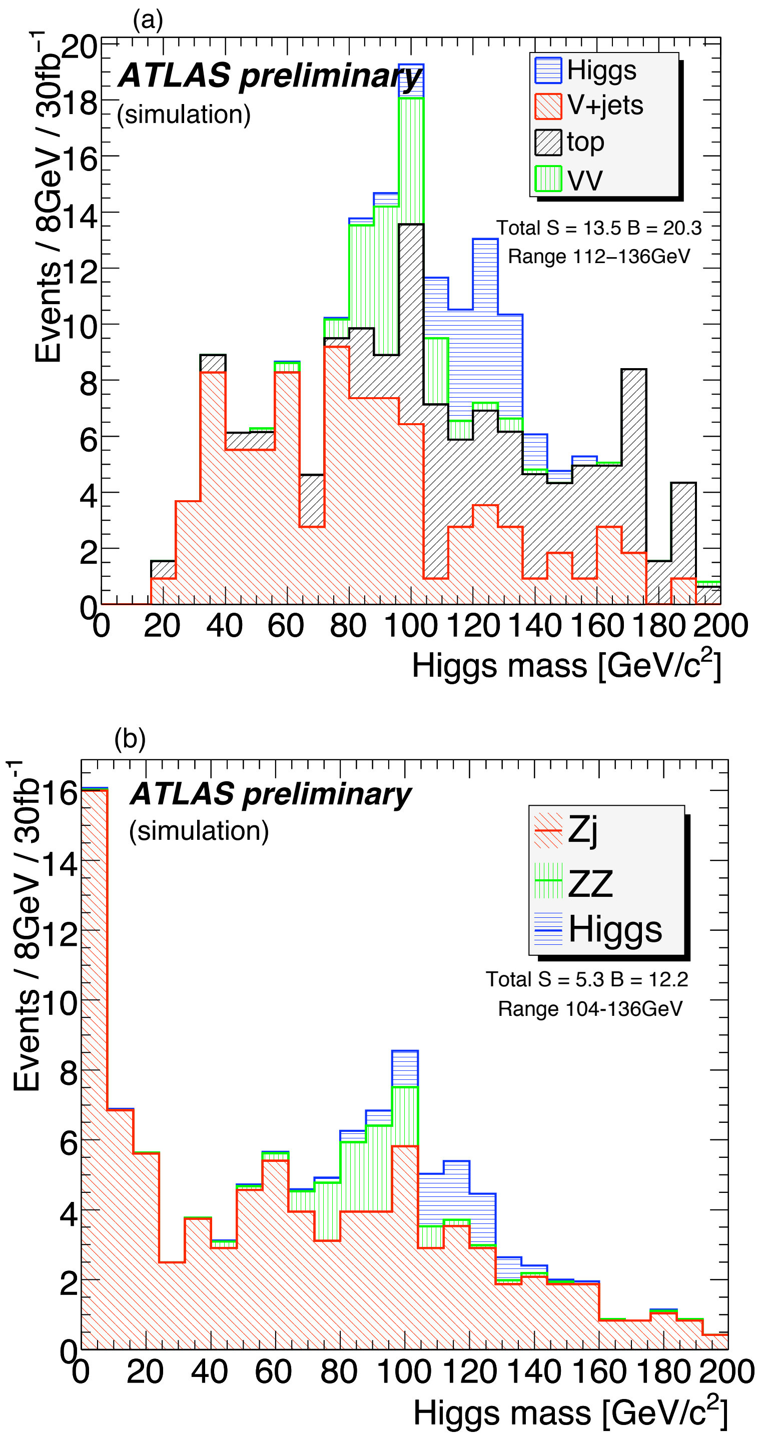


BDRS Result

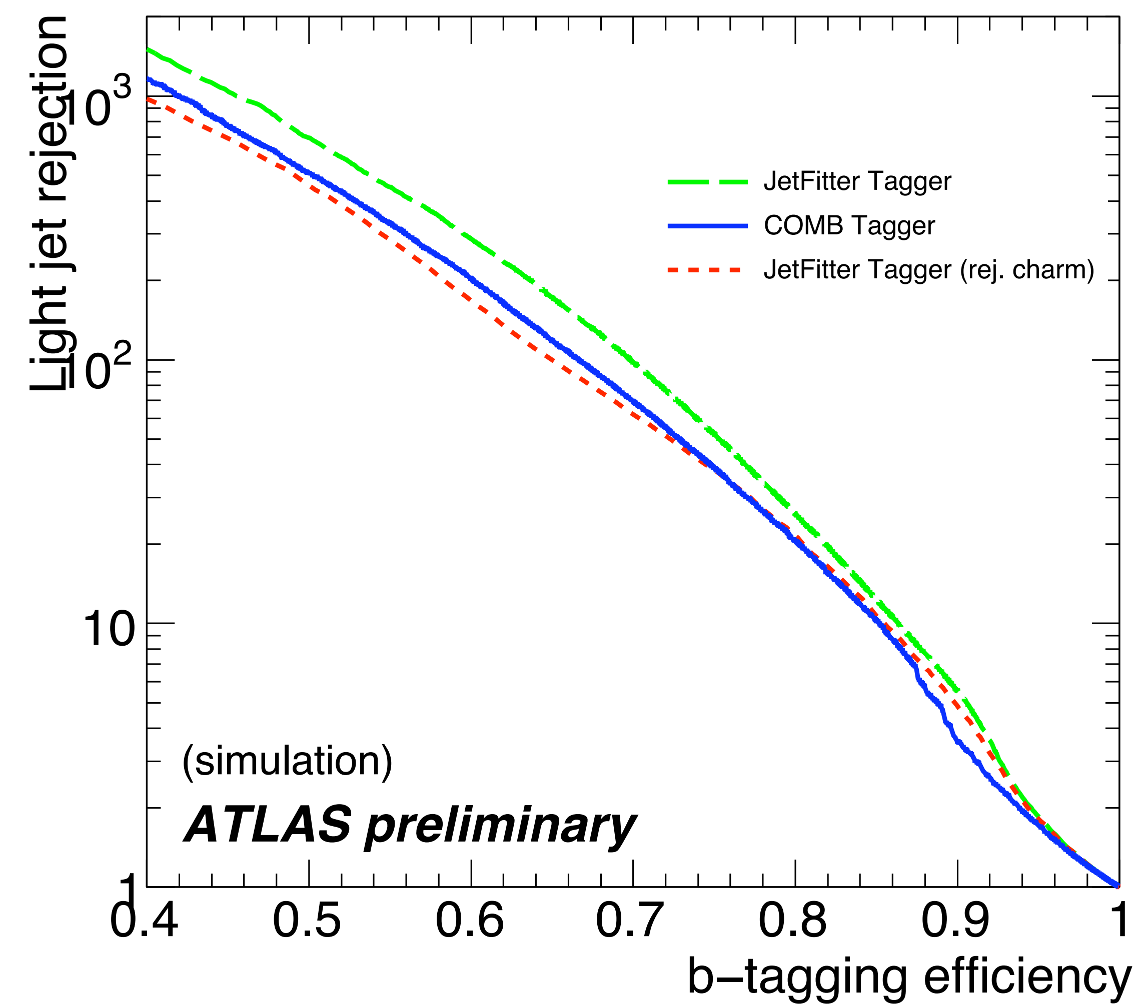


- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag

ATLAS Simulation



ATL-PHYS-PUB-2009-088 (Aug 2009)



$S_{BDRS} \approx 4.2$ versus $S_{ATLAS} \approx 3.7$

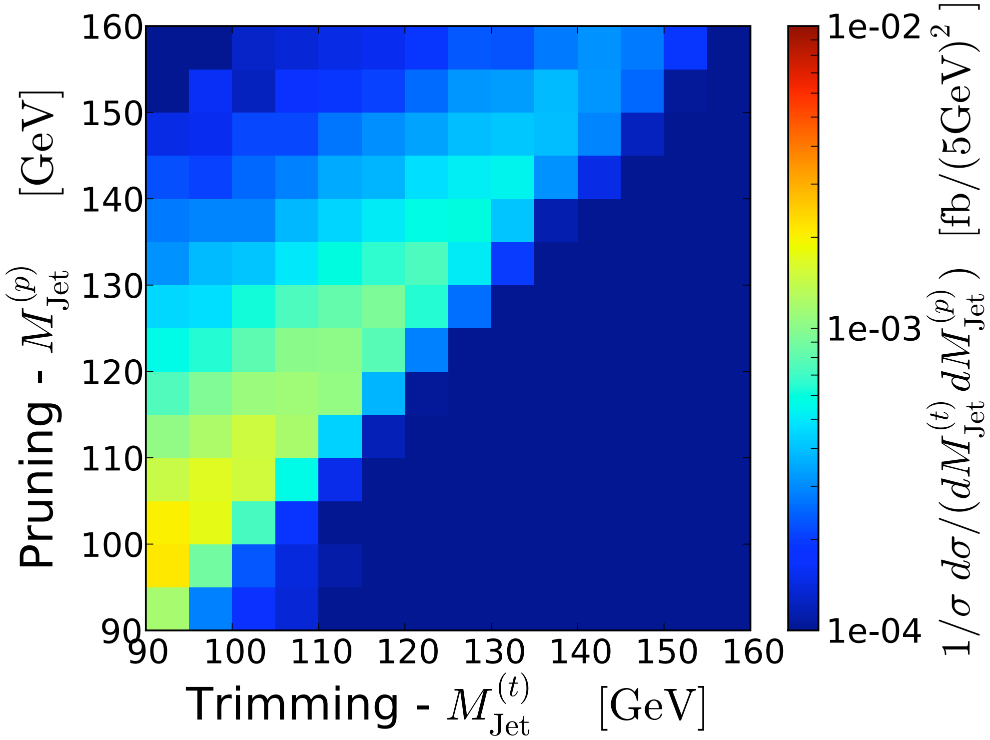
Grooming techniques work differently

Do they provide complementary information?

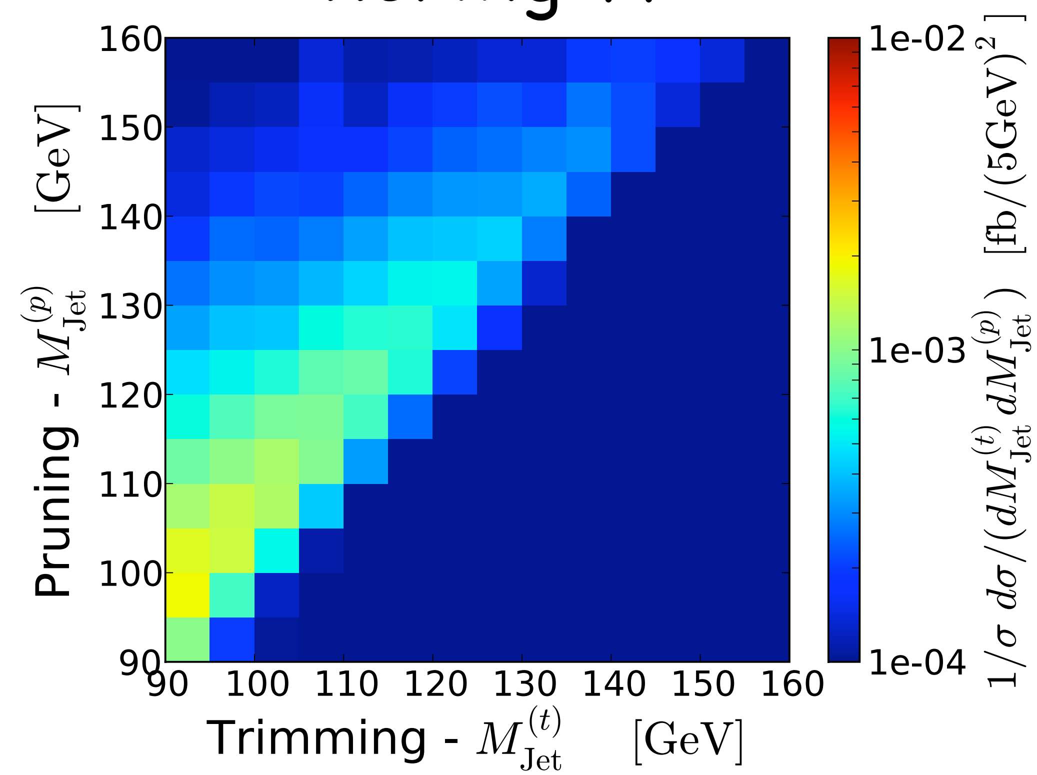
If yes,

combine them to gain more insights

Pythia 8



Herwig ++

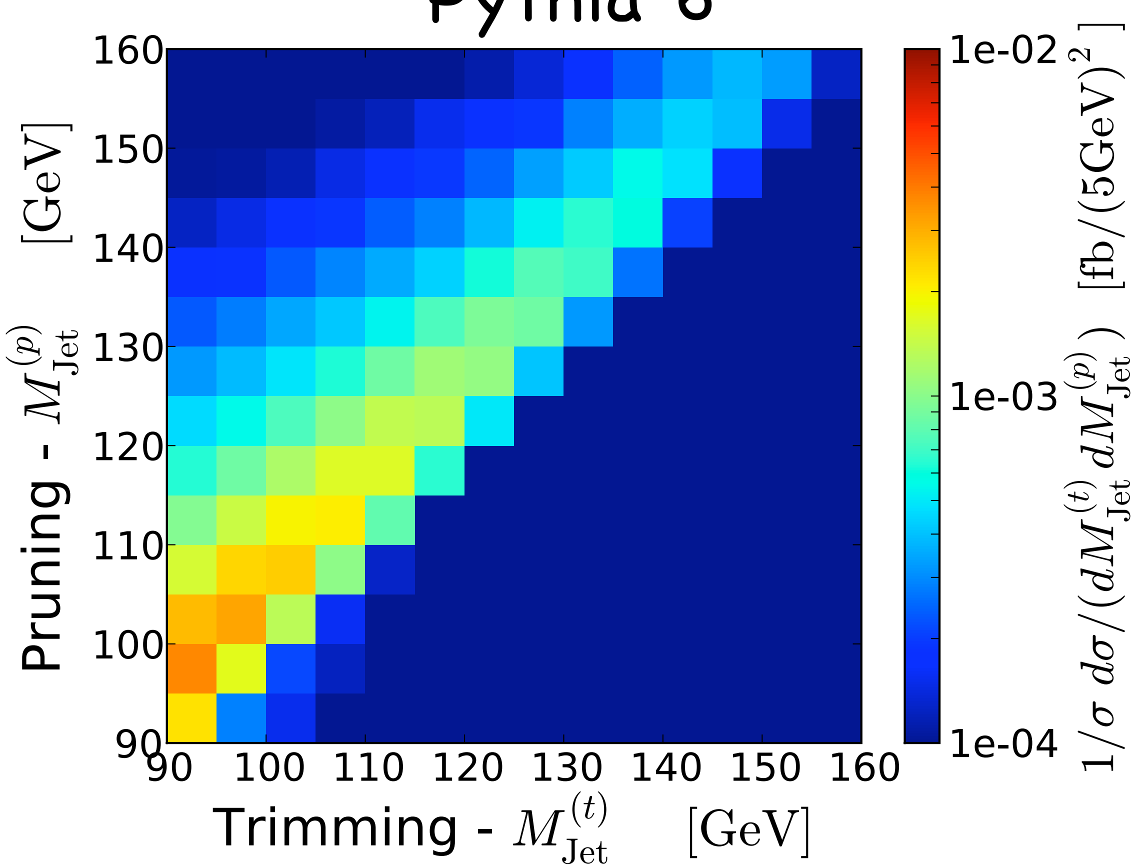


Dijet samples

hardest jet
pT > 150 GeV

with granularity and
cell pT > 0.5 GeV

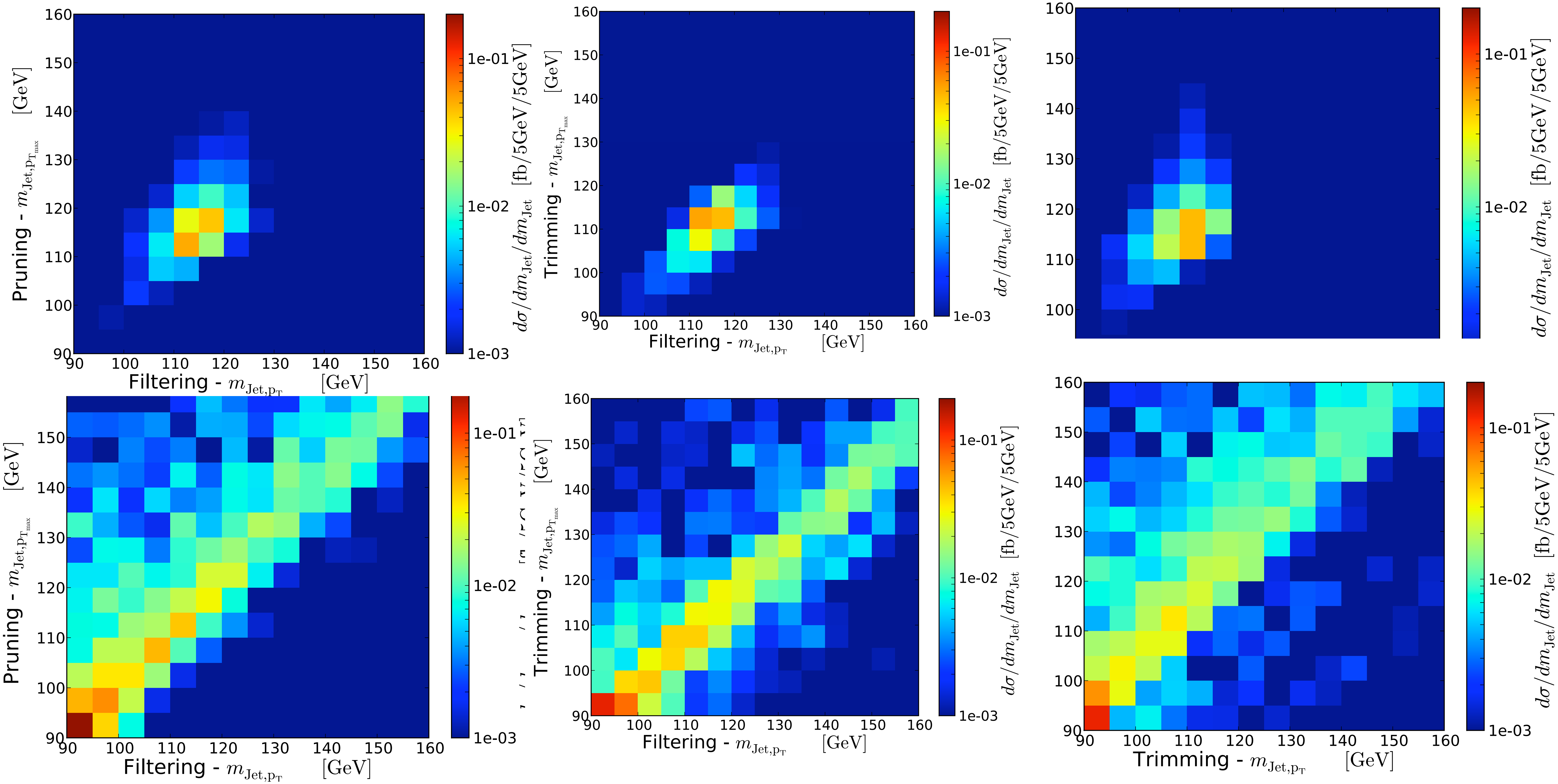
Pythia 6



chosen:
R=1.2
Pruning (CA)
Trimming (aKT,KT)

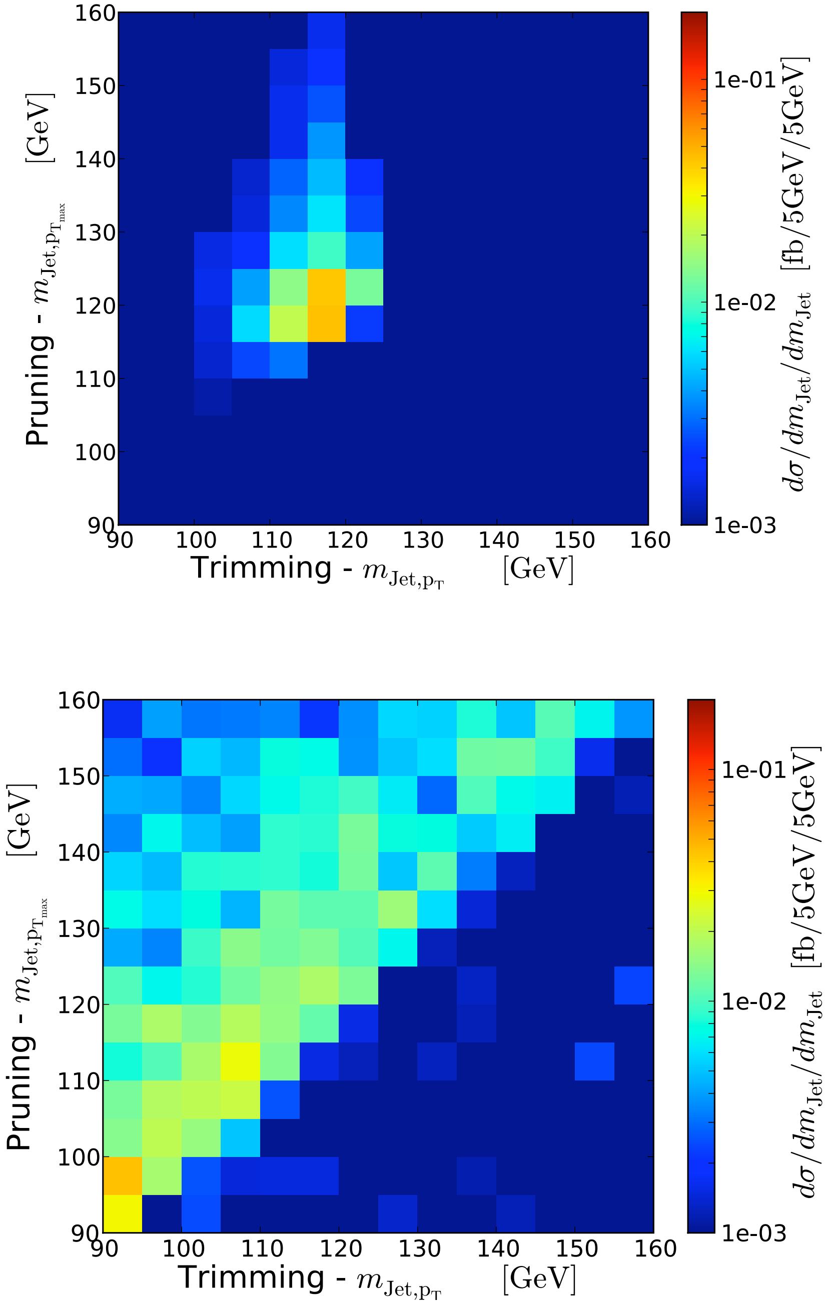
Combine Mass-Drop/Filtering with Pruning and Trimming

[Soper, MS JHEP 1008 (2010)]

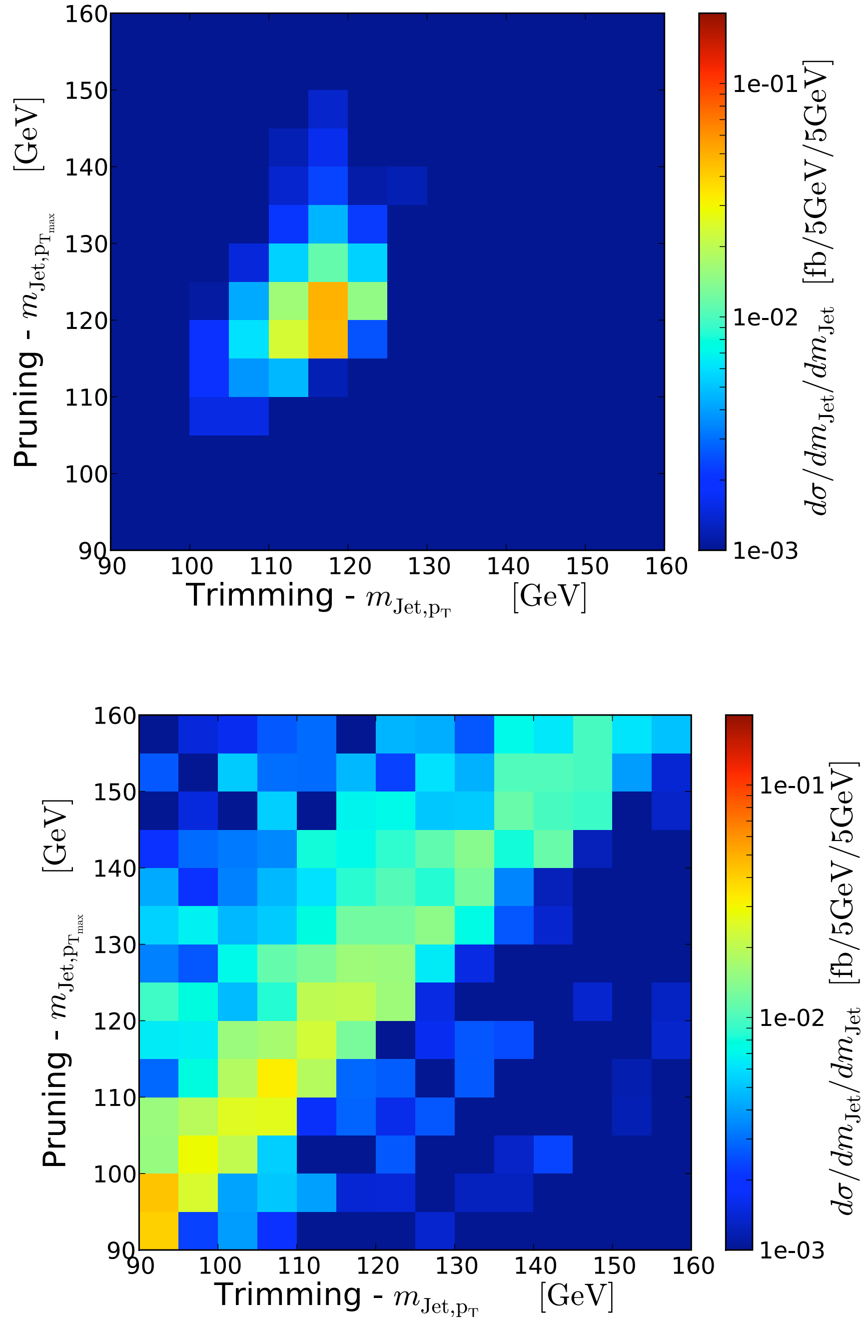


Pruning tuning:

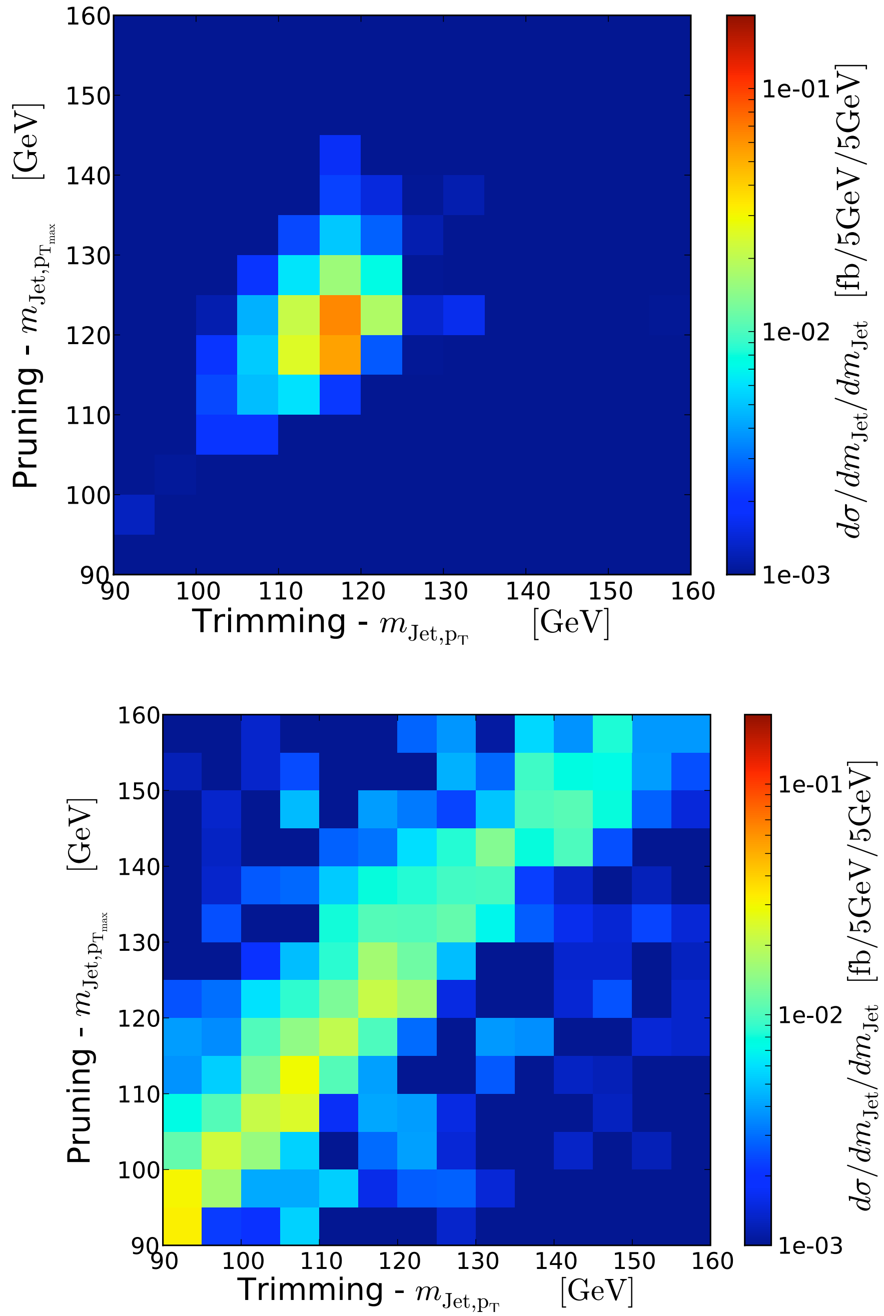
Z=0.05



Z=0.1



Z=0.2



Exploitation of asymmetry

Cut based approach

Exp. Likelihood Ratio $$\langle \mathcal{L}(\{n\}) \rangle_{\mathrm{SB}} = \sum_J \left[(s_J + b_J) \log \left(1 + \frac{s_J}{b_J} \right) - s_J \right]$$

	$M_{\mathrm{Jet}}^{(f)} \in W_f$	$M_{\mathrm{Jet}}^{(f)} \in W_f$ $M_{\mathrm{Jet}}^{(t)} \in W_t$	$M_{\mathrm{Jet}}^{(f)} \in W_f$ $M_{\mathrm{Jet}}^{(p)} \in W_p$	$M_{\mathrm{Jet}}^{(p)} \in W_p$ $M_{\mathrm{Jet}}^{(t)} \in W_t$	$M_{\mathrm{Jet}}^{(p)} \in W_p$ $M_{\mathrm{Jet}}^{(t)} \in W_t$
Signal cross section [fb]	0.20	0.18	0.17	0.17	0.16
Backgrnd cross section [fb]	0.30	0.20	0.17	0.16	0.13
s/b	0.67	0.90	1.0	1.1	1.3
$s/\sqrt{b}$ $(\int dL = 30\ \mathrm{fb}^{-1})$	2.0	2.2	2.3	2.3	2.4
$\langle \mathcal{L}(n) \rangle_{\mathrm{SB}}$ $(\int dL = 30\ \mathrm{fb}^{-1})$	1.7	1.9	2.0	2.1	2.2

Z=0.1 Z=0.05

Exploitation of asymmetry

Cut based approach

Exp. Likelihood Ratio $$\langle \mathcal{L}(\{n\}) \rangle_{\rm SB} = \sum_J \left[(s_J + b_J) \log \left(1 + \frac{s_J}{b_J} \right) - s_J \right]$$

	$M_{\rm Jet}^{(f)} \in W_f$	$M_{\rm Jet}^{(f)} \in W_f$ $M_{\rm Jet}^{(t)} \in W_t$	$M_{\rm Jet}^{(f)} \in W_f$ $M_{\rm Jet}^{(p)} \in W_p$	$M_{\rm Jet}^{(p)} \in W_p$ $M_{\rm Jet}^{(t)} \in W_t$	$M_{\rm Jet}^{(p)} \in W_p$ $M_{\rm Jet}^{(t)} \in W_t$
Signal cross section [fb]	0.20	0.18	0.17	0.17	0.16
Backgrnd cross section [fb]	0.30	0.20	0.17	0.16	0.13
s/b	0.67	0.90	1.0	1.1	1.3
$s/\sqrt{b}$ $(\int dL = 30\ {\rm fb}^{-1})$	2.0	2.2	2.3	2.3	2.4
$\langle \mathcal{L}(n) \rangle_{\rm SB}$ $(\int dL = 30\ {\rm fb}^{-1})$	1.7	1.9	2.0	2.1	2.2

Z=0.1 Z=0.05

Exploitation of asymmetry

Cut based approach

Exp. Likelihood Ratio $$\langle \mathcal{L}(\{n\}) \rangle_{\mathrm{SB}} = \sum_J \left[(s_J + b_J) \log \left(1 + \frac{s_J}{b_J} \right) - s_J \right]$$

	$M_{\mathrm{Jet}}^{(f)} \in W_f$	$M_{\mathrm{Jet}}^{(f)} \in W_f$, $M_{\mathrm{Jet}}^{(t)} \in W_t$	$M_{\mathrm{Jet}}^{(f)} \in W_f$, $M_{\mathrm{Jet}}^{(p)} \in W_p$	$M_{\mathrm{Jet}}^{(p)} \in W_p$, $M_{\mathrm{Jet}}^{(t)} \in W_t$	$M_{\mathrm{Jet}}^{(p)} \in W_p$, $M_{\mathrm{Jet}}^{(t)} \in W_t$
Signal cross section [fb]	0.20	0.18	0.17	0.17	0.16
Backgrnd cross section [fb]	0.30	0.20	0.17	0.16	0.13
s/b	0.67	0.90	1.0	1.1	1.3
$s/\sqrt{b}$ $(\int dL = 30\ \mathrm{fb}^{-1})$	2.0	2.2	2.3	2.3	2.4
$\langle \mathcal{L}(n) \rangle_{\mathrm{SB}}$ $(\int dL = 30\ \mathrm{fb}^{-1})$	1.7	1.9	2.0	2.1	2.2

Z=0.1 Z=0.05

Stronger as a team

Filtering

Trimming

Pruning

Pruning

Trimming

Filtering

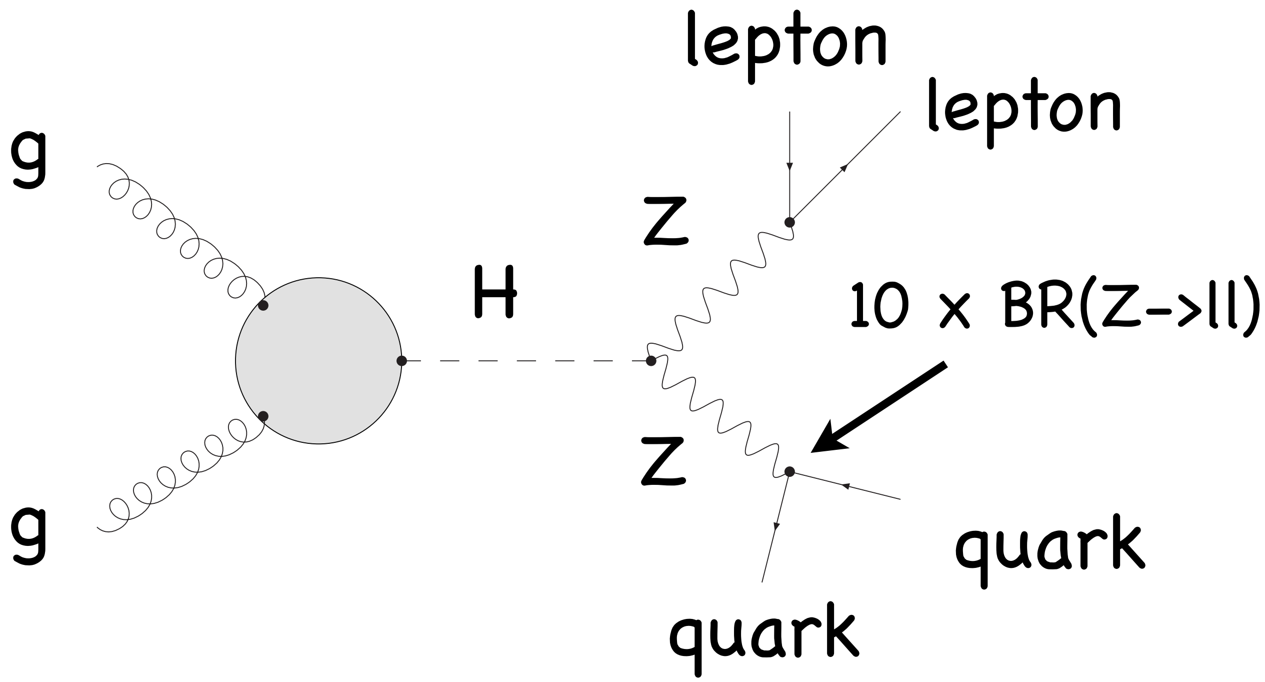
Generic resonance taggers should run comb. of procedures

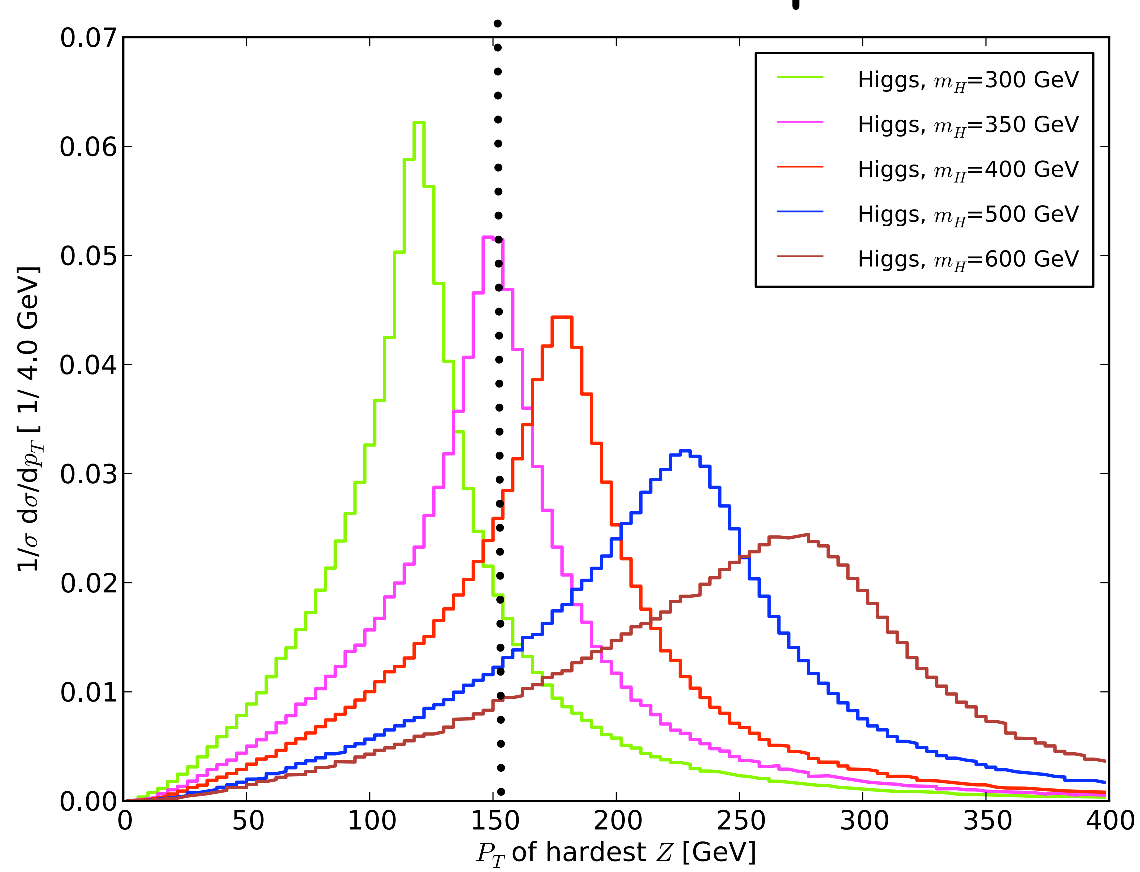
Maybe we can gain insight to improve on subjet procedures

Let`s check out one more application

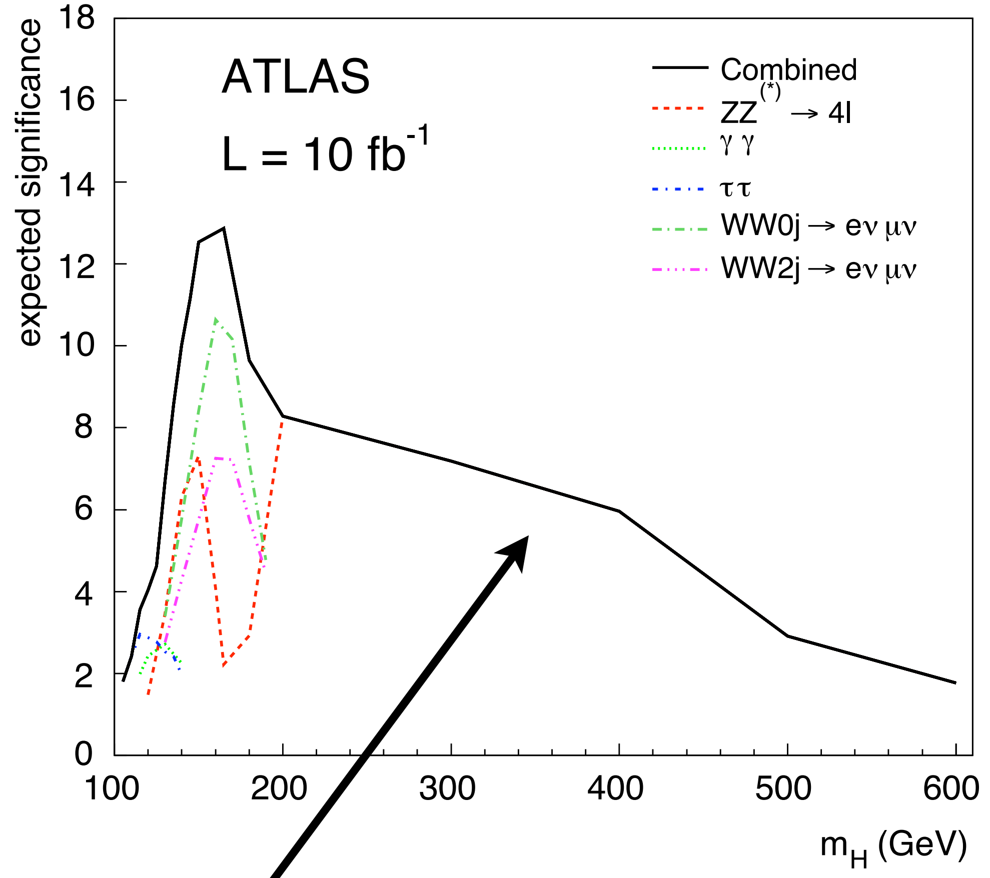
Heavy Higgs search in the 'forgotten channel'

Example for naturally boosted scenario





[ATLAS TDR, 2008]



gold plated mode

[Hackstein, MS 1008.2202]

Reconstruction in the 4 lepton gold plated mode:

- at least 4 isolated central muons
- 2 reconstructed Z bosons, requiring

$$m_Z - 10 \text{ GeV} < m_{\mu\mu} < m_Z + 10 \text{ GeV}.$$

Reconstruction in the semi-leptonic lljj mode:

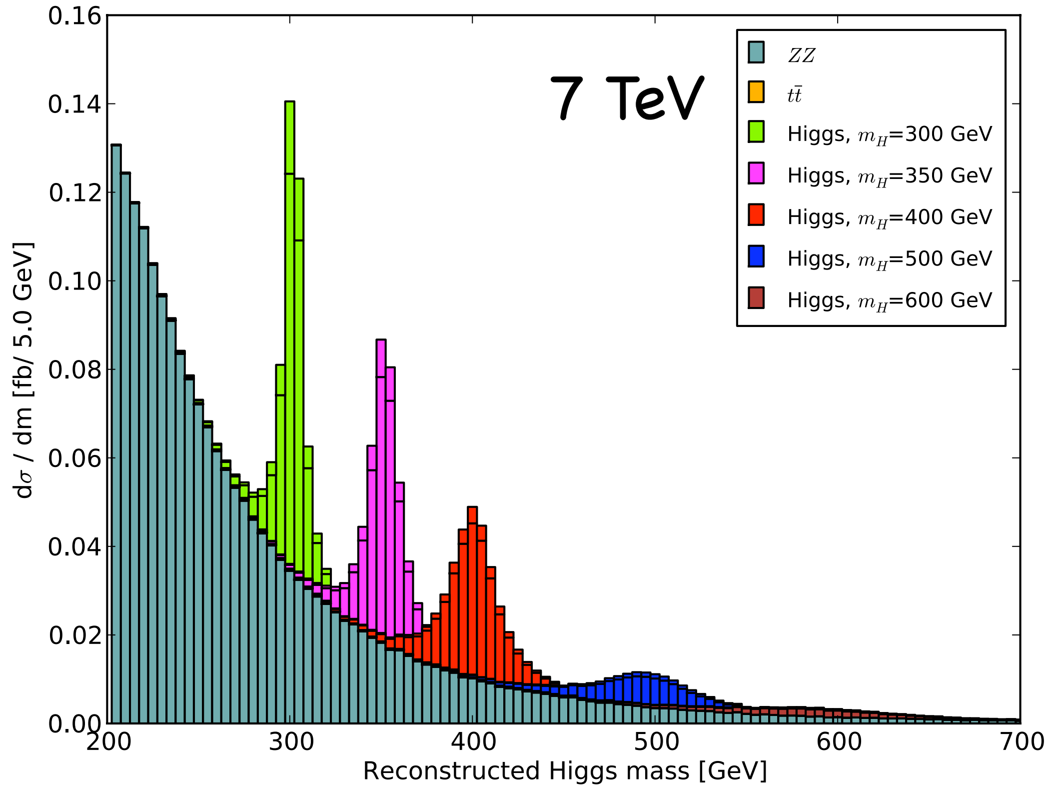
- Require fat jet (CA, R=1.2, pT>150 GeV)
- Leptonic Z reconstruction with two isolated central muons
- Hadronic Z reconstruction with filtering + mass drop
- Apply Pruning vs Trimming, requiring $m_Z^{\text{rec}} = m_Z \pm 10 \text{ GeV}.$

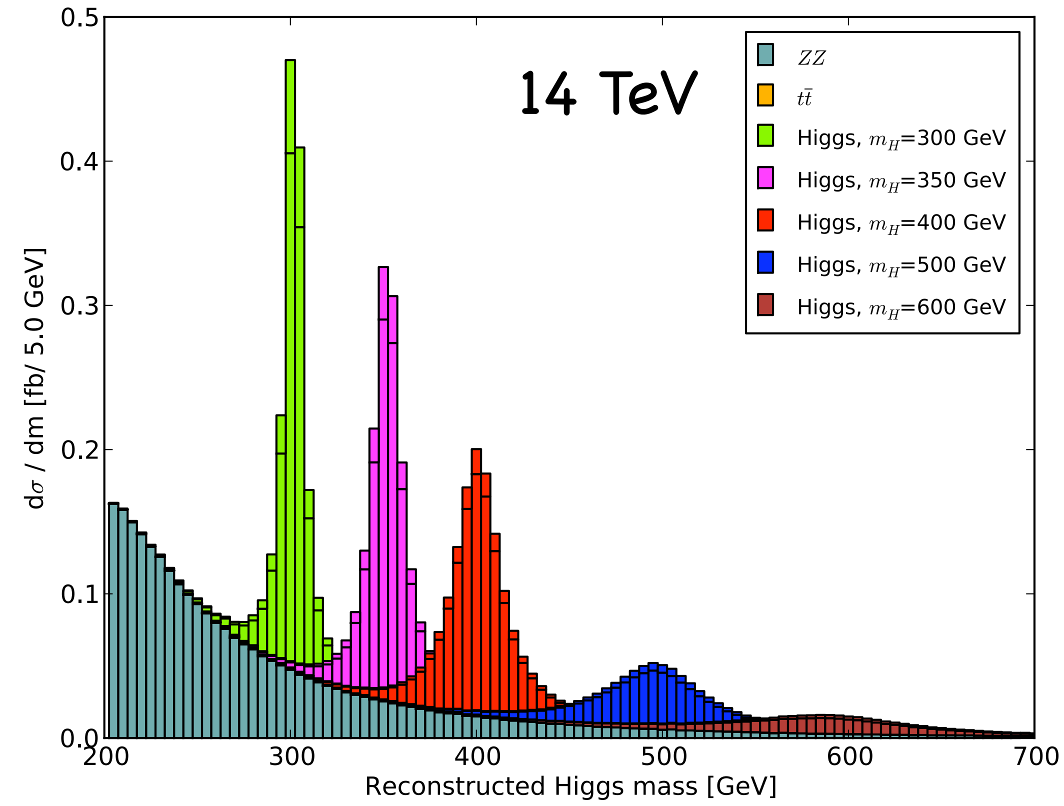
For calculation of significance take Higgs mass reconstruction with

$$(300 \pm 30,\ 350 \pm 50,\ 400 \pm 50,\ 500 \pm 70,\ 600 \pm 100) \text{ GeV}$$

'Gold plated mode' is great, but suffers from few events

[Hackstein, MS 1008.2202]

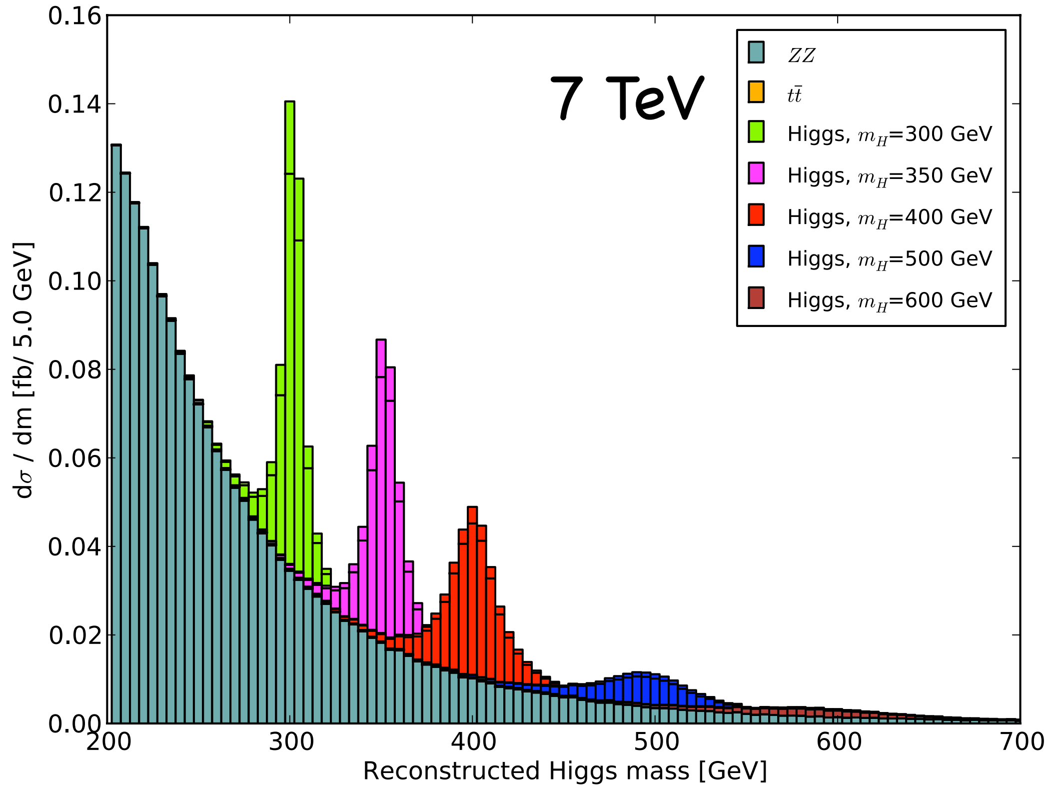


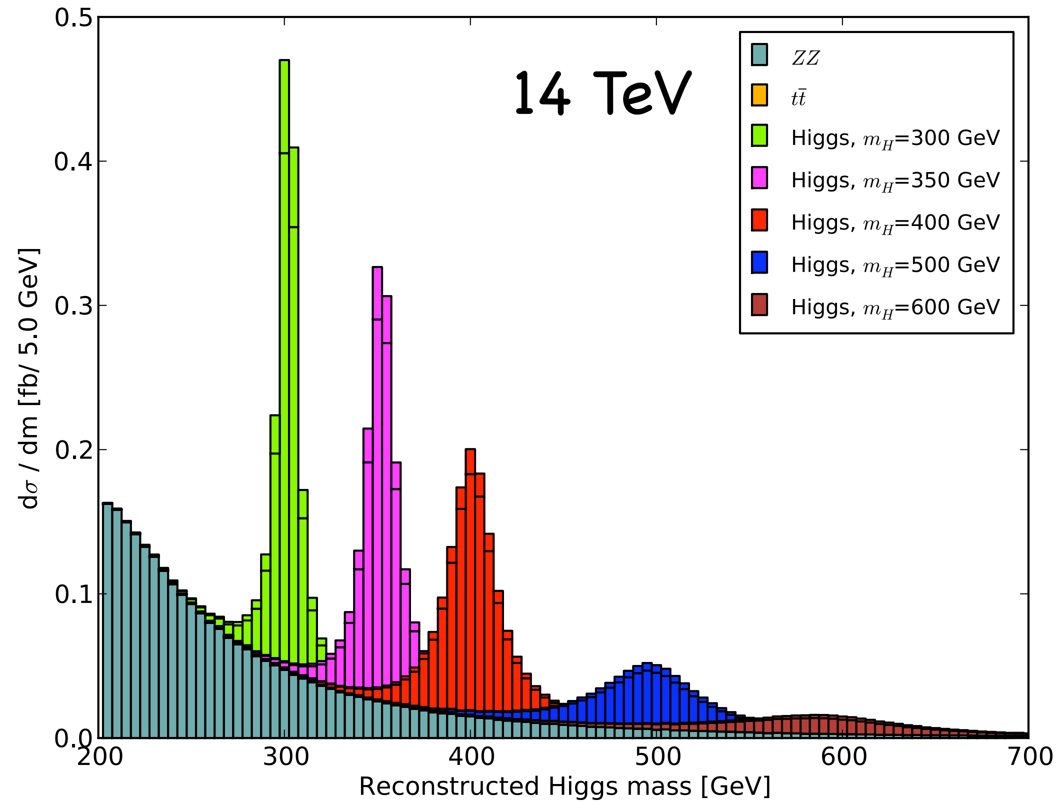


	7 TeV				14 TeV			
m_H [GeV]	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}_{10}$	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}_{10}$
300	0.35	0.42	0.8	1.7	1.39	0.56	2.5	5.9
350	0.35	0.38	0.9	1.8	1.52	0.53	2.9	6.6
400	0.28	0.21	1.3	1.9	1.34	0.31	4.4	7.6
500	0.11	0.11	1.0	1.1	0.65	0.18	3.7	4.9
600	0.05	0.07	0.7	0.6	0.30	0.12	2.5	2.7

'Gold plated mode' is great, but suffers from few events

[Hackstein, MS 1008.2202]

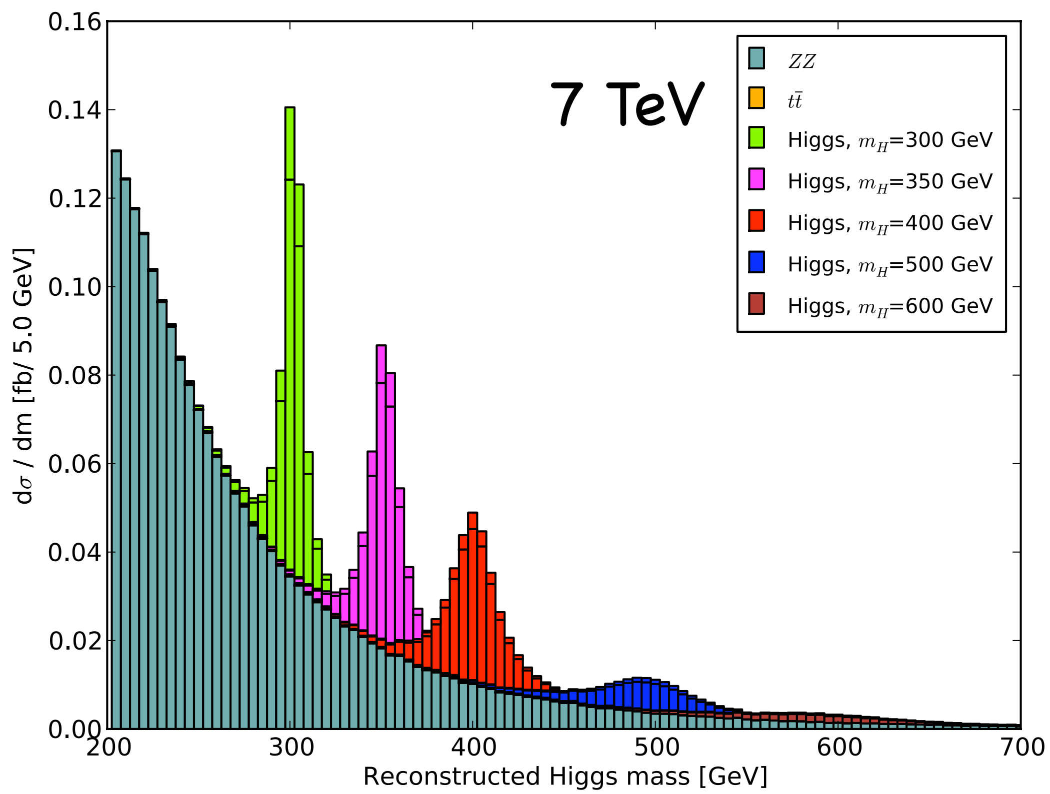


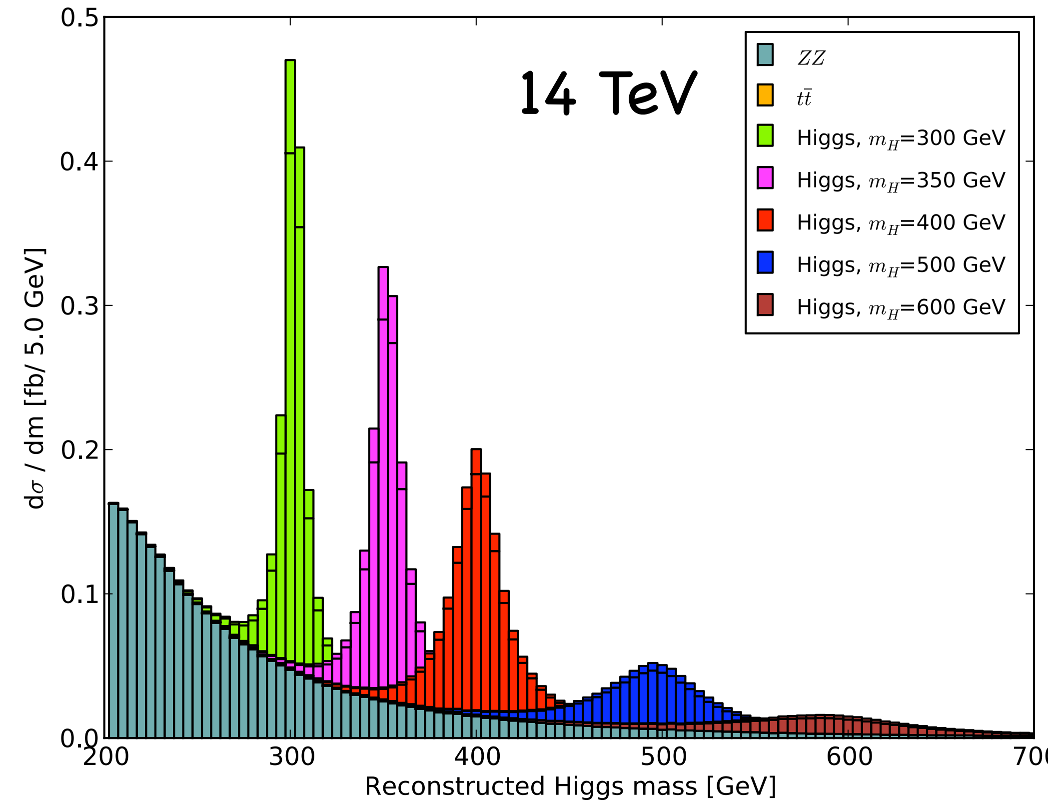


	7 TeV				14 TeV			
m_H [GeV]	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}_{10}$	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}_{10}$
300	0.35	0.42	0.8	1.7	1.39	0.56	2.5	5.9
350	0.35	0.38	0.9	1.8	1.52	0.53	2.9	6.6
400	0.28	0.21	1.3	1.9	1.34	0.31	4.4	7.6
500	0.11	0.11	1.0	1.1	0.65	0.18	3.7	4.9
600	0.05	0.07	0.7	0.6	0.30	0.12	2.5	2.7

‘Gold plated mode‘ is great, but suffers from few events

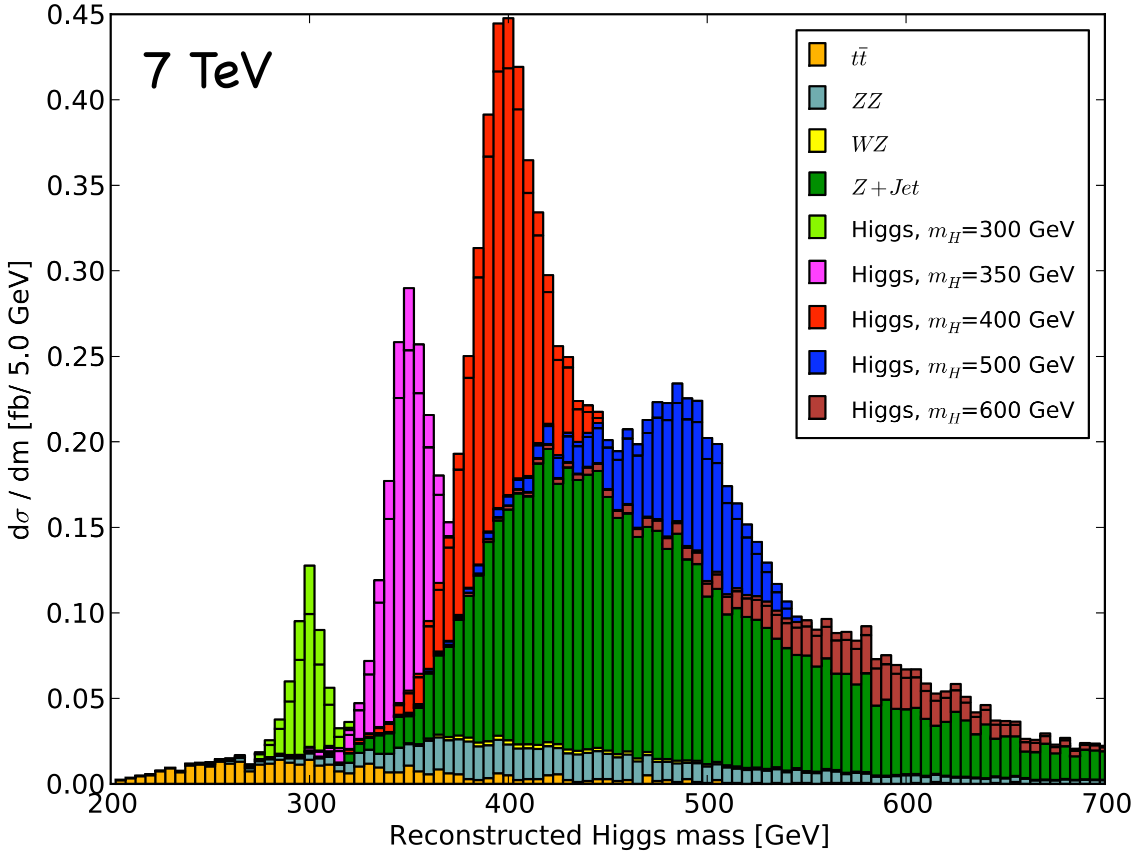
[Hackstein, MS 1008.2202]

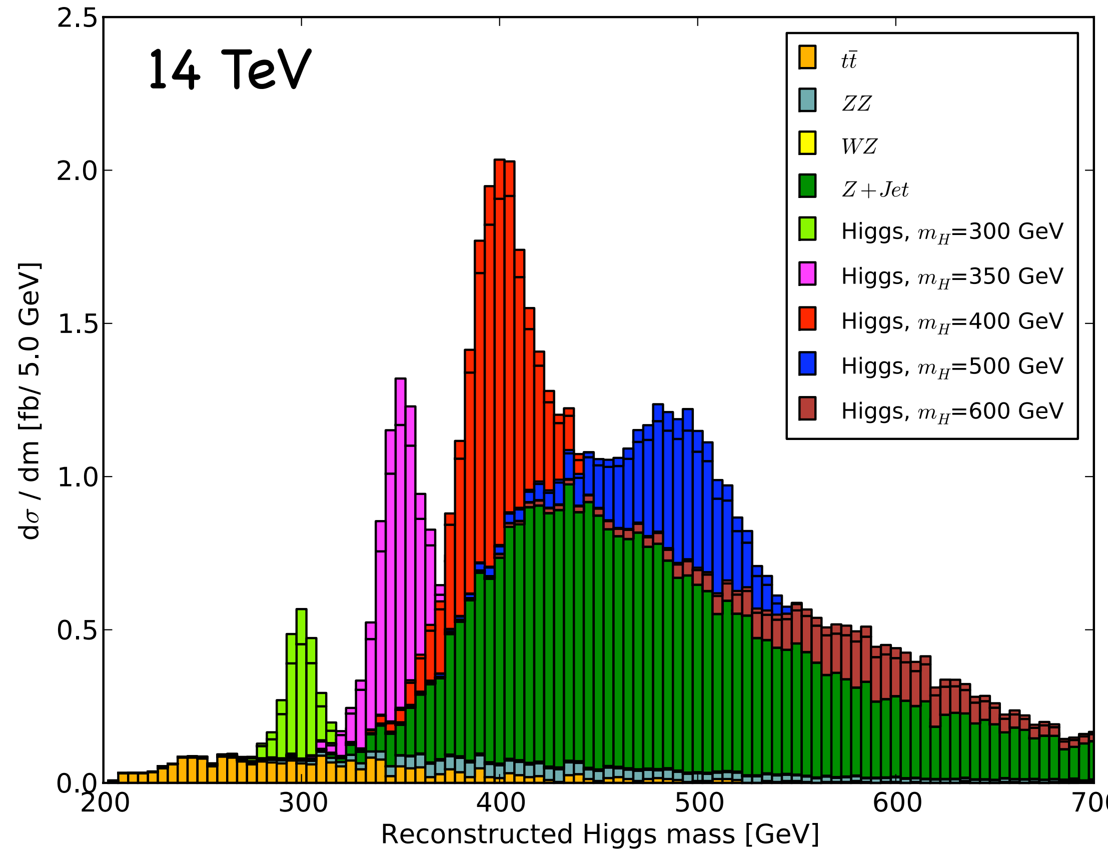




	7 TeV				14 TeV			
m_H [GeV]	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}_{10}$	σ_S [fb]	σ_B [fb]	S/B	$S/\sqrt{B}_{10}$
300	0.35	0.42	0.8	1.7	1.39	0.56	2.5	5.9
350	0.35	0.38	0.9	1.8	1.52	0.53	2.9	6.6
400	0.28	0.21	1.3	1.9	1.34	0.31	4.4	7.6
500	0.11	0.11	1.0	1.1	0.65	0.18	3.7	4.9
600	0.05	0.07	0.7	0.6	0.30	0.12	2.5	2.7

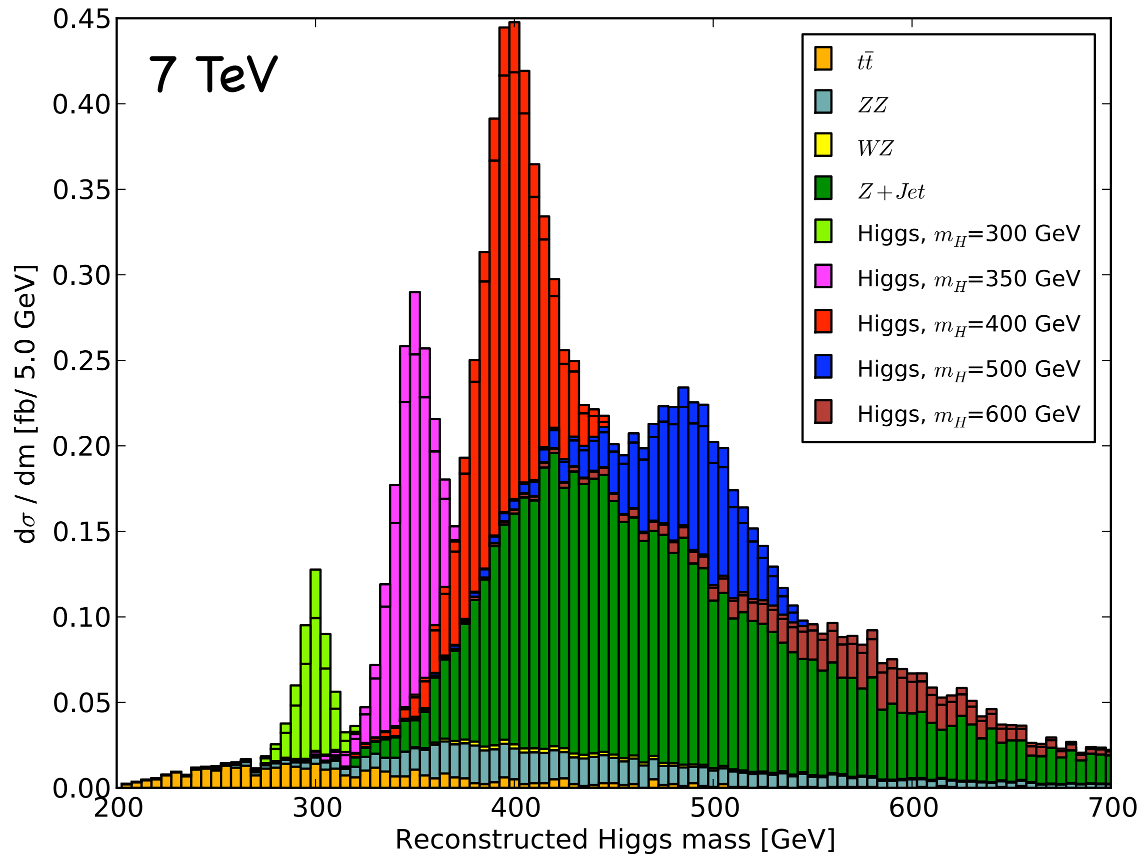
Semileptonic mode compensates worse S/B with more events

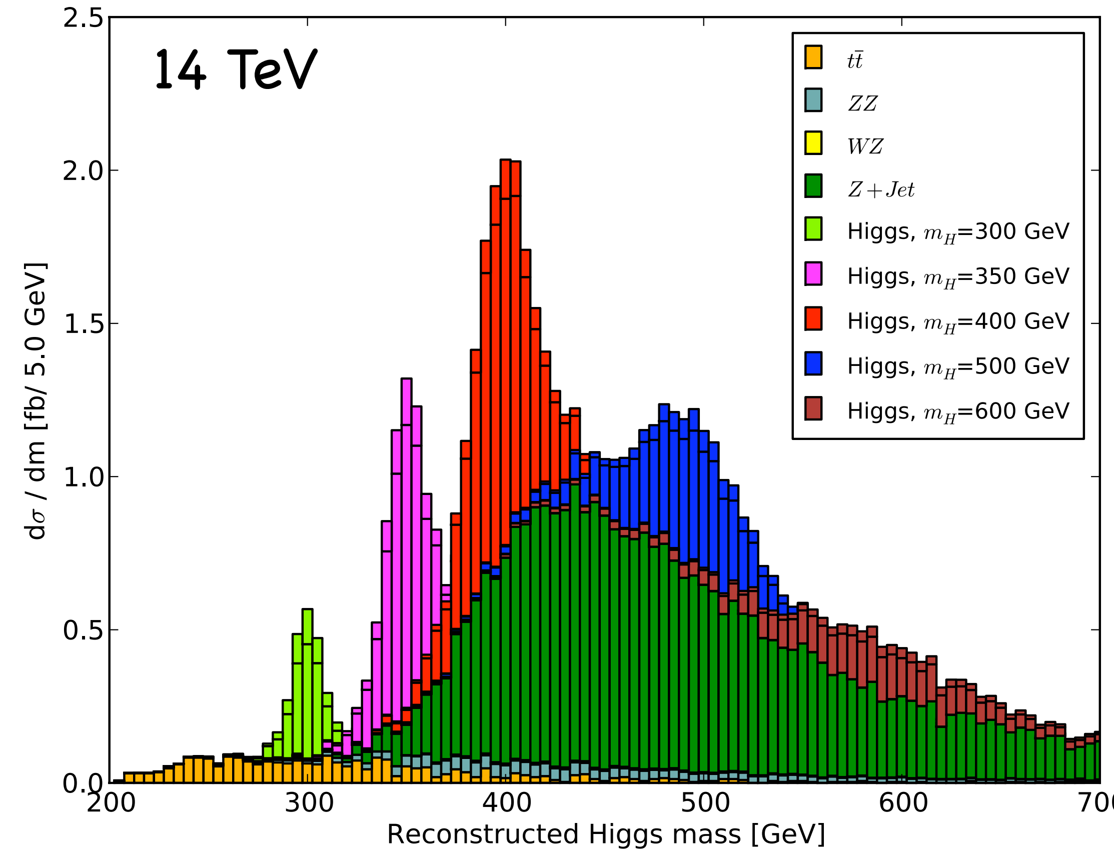




	m_H [GeV]	300		400		500		600	
	σ [fb]	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B
7 TeV:	selection	3.37/0.89	907.3	8.89/0.97	907.3	4.91/0.70	907.3	2.19/0.46	907.3
	after analysis	0.29/0.12	0.39	2.02/0.24	3.97	1.11/0.18	3.33	0.46/0.12	1.97
	S/B	1.03		0.57		0.39		0.30	
	$S/\sqrt{B}_{10}$	2.0		3.6		2.2		1.3	
14 TeV:	selection	17.97/3.83	6200	46.18/4.64	6200	29.48/3.87	6200	15.08/2.90	6200
	after analysis	1.34/0.48	2.10	8.96/1.07	19.21	6.32/1.00	18.01	3.15/0.77	11.83
	S/B	0.87		0.52		0.41		0.33	
	$S/\sqrt{B}_{10}$	4.0		7.2		5.5		3.6	

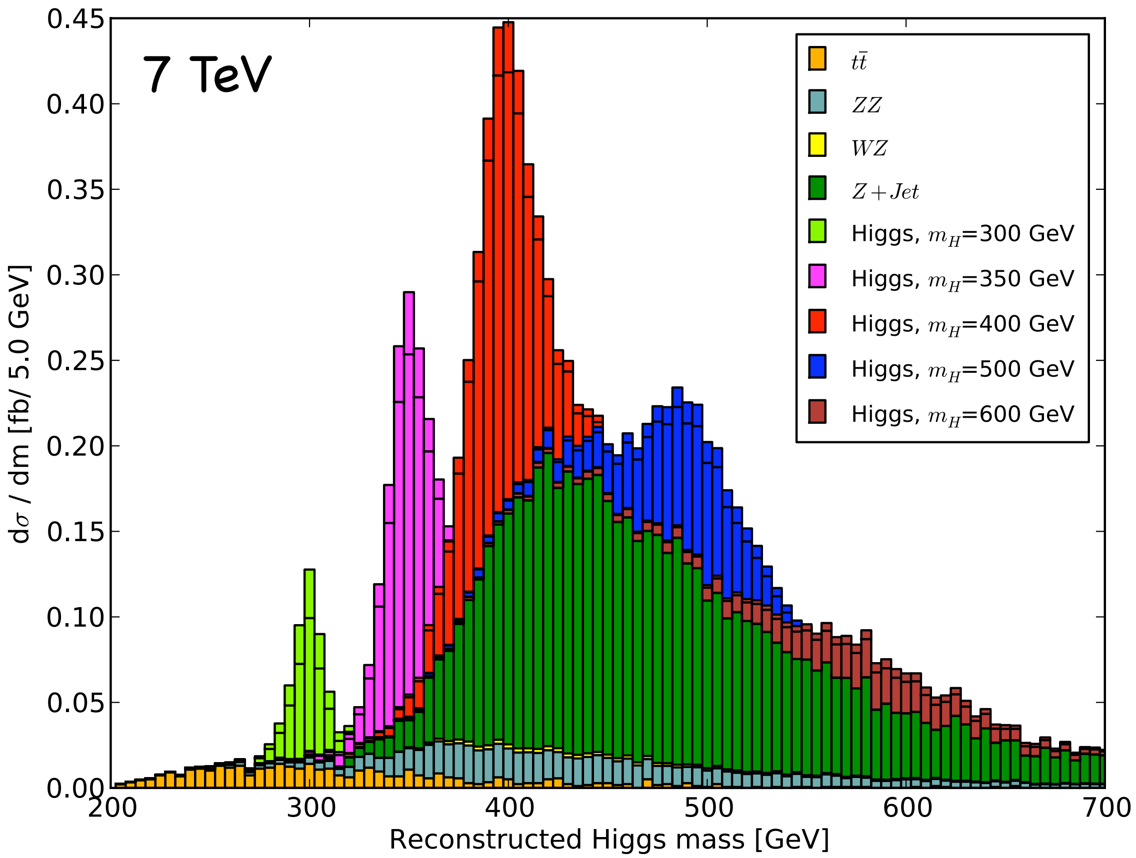
Semileptonic mode compensates worse S/B with more events

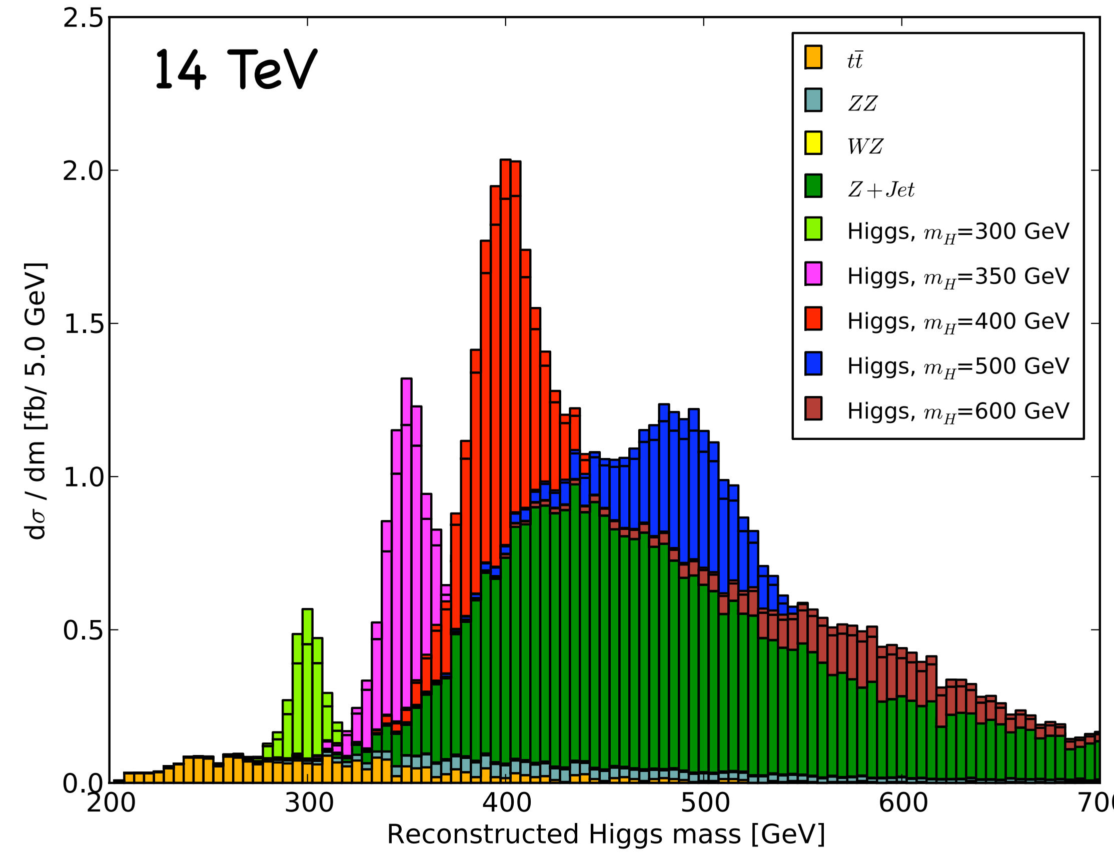




	m_H [GeV]	300		400		500		600	
	σ [fb]	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B
7 TeV:	selection	3.37/0.89	907.3	8.89/0.97	907.3	4.91/0.70	907.3	2.19/0.46	907.3
	after analysis	0.29/0.12	0.39	2.02/0.24	3.97	1.11/0.18	3.33	0.46/0.12	1.97
	S/B	1.03		0.57		0.39		0.30	
	$S/\sqrt{B}_{10}$	2.0		3.6		2.2		1.3	
14 TeV:	selection	17.97/3.83	6200	46.18/4.64	6200	29.48/3.87	6200	15.08/2.90	6200
	after analysis	1.34/0.48	2.10	8.96/1.07	19.21	6.32/1.00	18.01	3.15/0.77	11.83
	S/B	0.87		0.52		0.41		0.33	
	$S/\sqrt{B}_{10}$	4.0		7.2		5.5		3.6	

Semileptonic mode compensates worse S/B with more events

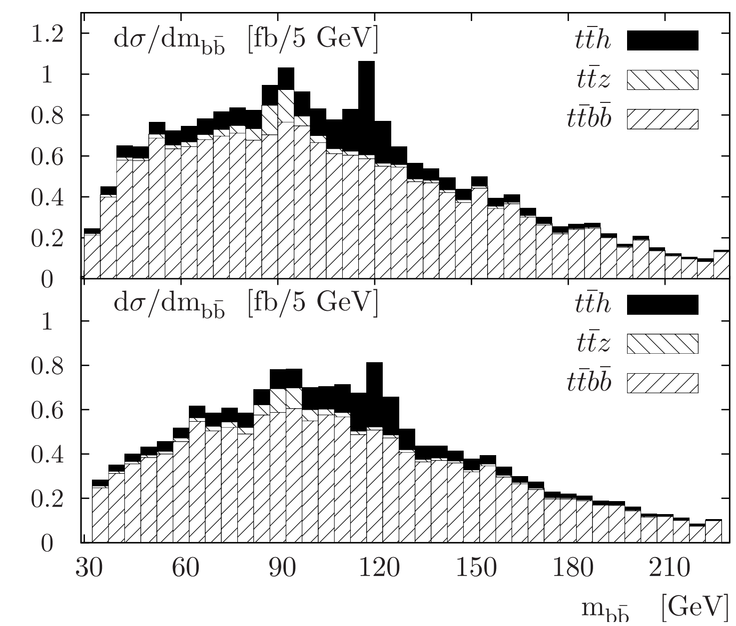




	m_H [GeV]	300		400		500		600	
	σ [fb]	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B
7 TeV:	selection	3.37/0.89	907.3	8.89/0.97	907.3	4.91/0.70	907.3	2.19/0.46	907.3
	after analysis	0.29/0.12	0.39	2.02/0.24	3.97	1.11/0.18	3.33	0.46/0.12	1.97
	S/B	1.03		0.57		0.39		0.30	
	$S/\sqrt{B}_{10}$	2.0		3.6		2.2		1.3	
14 TeV:	selection	17.97/3.83	6200	46.18/4.64	6200	29.48/3.87	6200	15.08/2.90	6200
	after analysis	1.34/0.48	2.10	8.96/1.07	19.21	6.32/1.00	18.01	3.15/0.77	11.83
	S/B	0.87		0.52		0.41		0.33	
	$S/\sqrt{B}_{10}$	4.0		7.2		5.5		3.6	

More Higgs searches in the SM and beyond

- tth [Plehn, Salam, MS PRL 104 (2010)]
  - Improvement of S/B from 1/9 to 1/2
  - Development of Higgs and top tagger for busy final state



- MSSM Higgs searches in cascade decays
  [Kribs, Martin, Roy, MS PRD 81 (2010) and 1006.1656]
  - Generic way of Higgs detection if decays of Neutralinos or Charginos to Higgs not too rare
  - Insensitive to large SUSY parameter space

- Searches for a very light Higgs $h \to \eta\eta \to 4g$
  [Chen et al. 1006.1151] [Falkowski et al. 1006.1650]
  - Possible to 'unbury' with subjet techniques

top tagging – a major application

Rough results for top quark with $p_t \sim 1$ TeV			
	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans '08	3,4 k_t subjets, d_{cut}	45%	5%
Thaler & Wang '08	2,3 k_t subjets, z_{cut} + various	40%	5%
Kaplan et al. '08	3,4 C/A subjets, $z_{cut} + \theta_h$	40%	1%
Ellis et al. '09	C/A pruning	10%	0.05%
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%
Chekanov & P. '10	Jet shapes	60%	10%
Almeida et al. '08–'10	Template + shapes	13%	0.02%
Plehn et al. '09–'10	C/A MD, θ_h/Dalitz [busy evs, $p_t \sim 300$]	35%	2%

Will focus on Plehn et al = HEPTopTagger (Heidelberg-Eugene-Paris)

HEPTopTagger is being tested in ATLAS framework with good results

HEPTopTagger

(Plehn, Salam, MS, Takeuchi)

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

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{j_1} < 0.8\ m_j$ to keep j_1 and j_2

III. Filter and choose pairing

Take 3 hard objetcs, filter them, take 5 filered subjets, keep pairing with best top mass

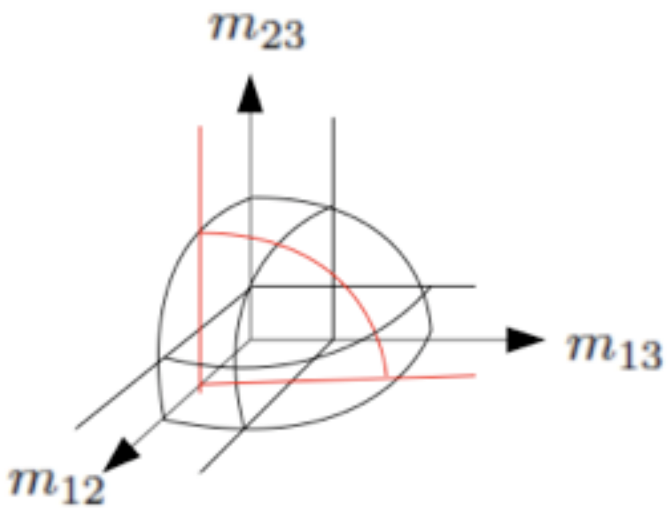
top candidate $|m_{jjj} - 172.3\ \mathrm{GeV}| < 25\ \mathrm{GeV}$

no b-tag, no W mass cut yet

IV. check mass ratios

Cluster top candidate into 3 subjets j_1, j_2, j_3

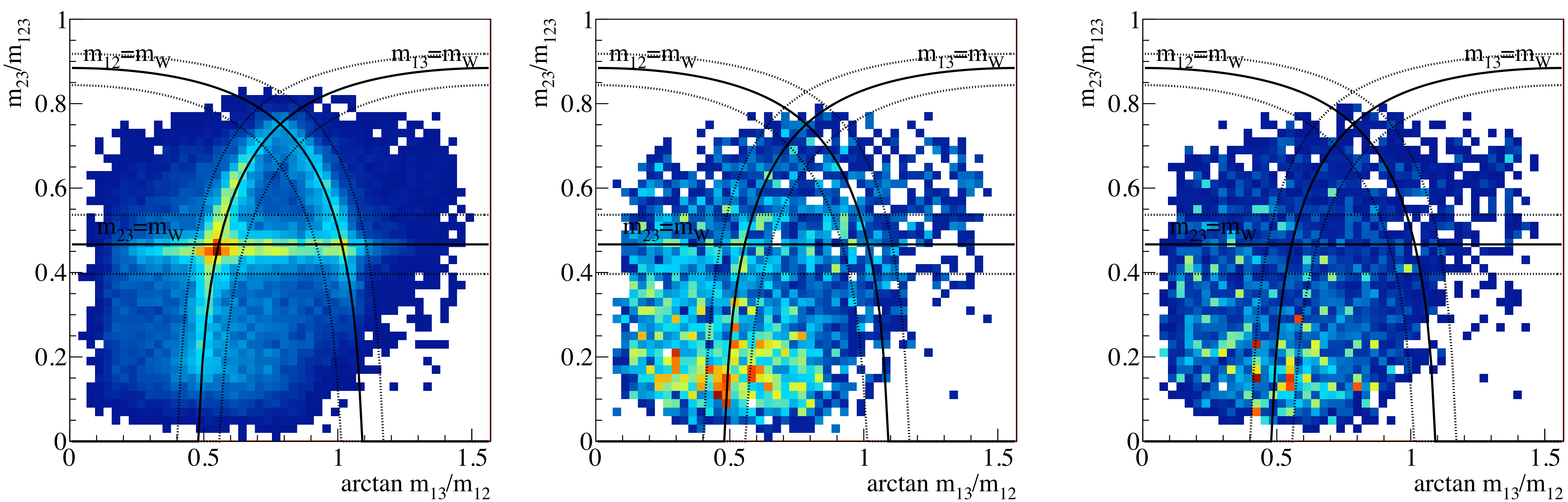
$$m_t^2 \equiv m_{123}^2 = (p_1 + p_2 + p_3)^2 = (p_1 + p_2)^2 + (p_1 + p_3)^2 + (p_2 + p_3)^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$$



$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max} \quad \text{and} \quad 0.2 < \arctan \frac{m_{13}}{m_{12}} < 1.3$$

$$R_{\min}^2 \left(1 + \left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1 - \left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2 \left(1 + \left(\frac{m_{13}}{m_{12}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

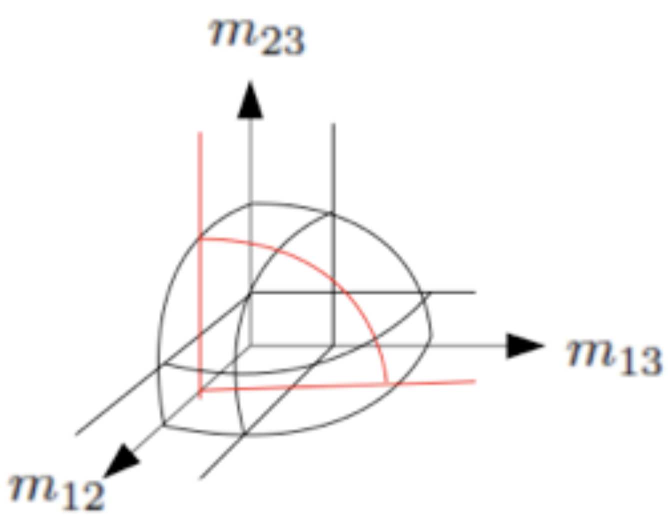
$$R_{\min}^2 \left(1 + \left(\frac{m_{12}}{m_{13}}\right)^2\right) < 1 - \left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2 \left(1 + \left(\frac{m_{12}}{m_{13}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$



IV. check mass ratios

Cluster top candidate into 3 subjets j_1, j_2, j_3

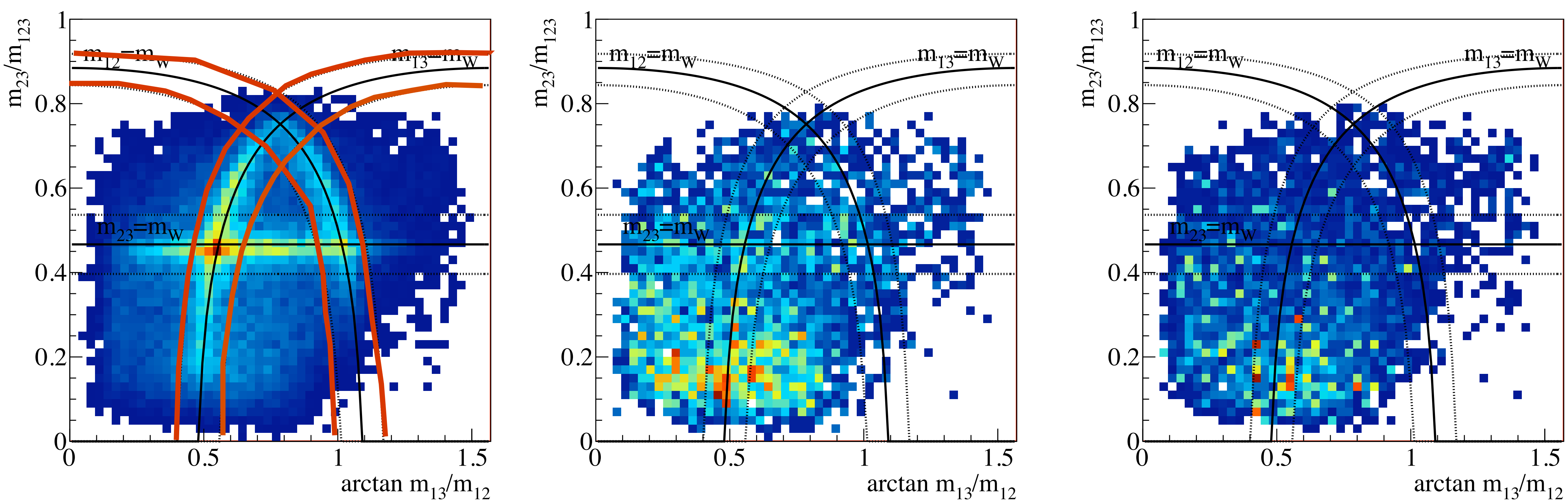
$$m_t^2 \equiv m_{123}^2 = (p_1+p_2+p_3)^2 = (p_1+p_2)^2 + (p_1+p_3)^2 + (p_2+p_3)^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$$



$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max} \quad \text{and} \quad 0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

$$R_{\min}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

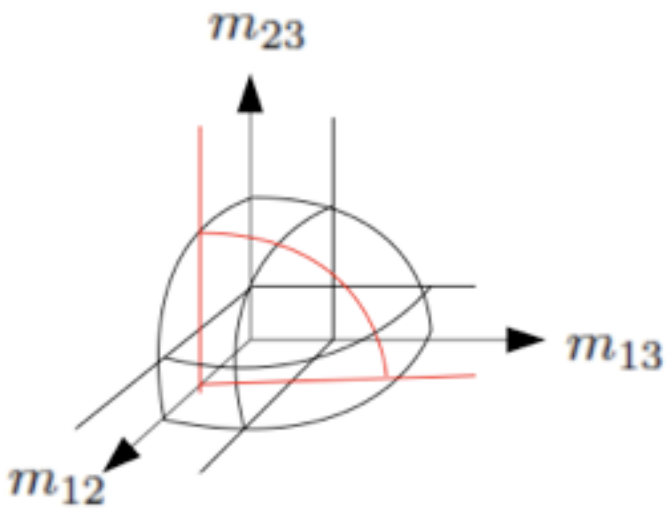
$$R_{\min}^2\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$



IV. check mass ratios

Cluster top candidate into 3 subjets j_1, j_2, j_3

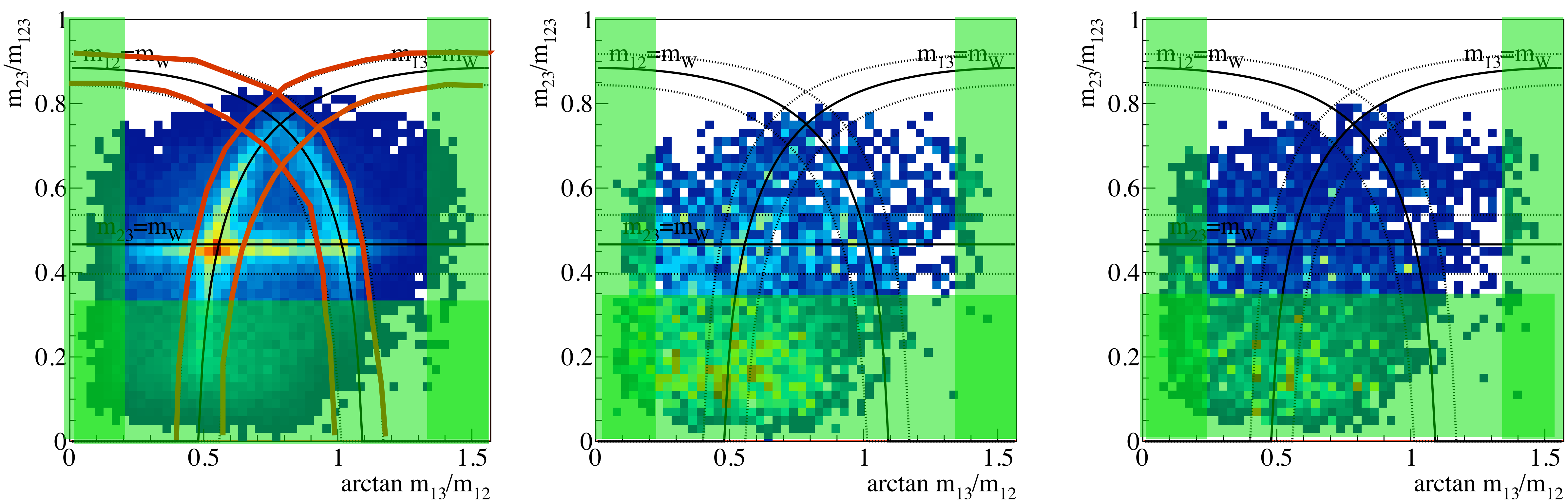
$$m_t^2 \equiv m_{123}^2 = (p_1+p_2+p_3)^2 = (p_1+p_2)^2 + (p_1+p_3)^2 + (p_2+p_3)^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$$



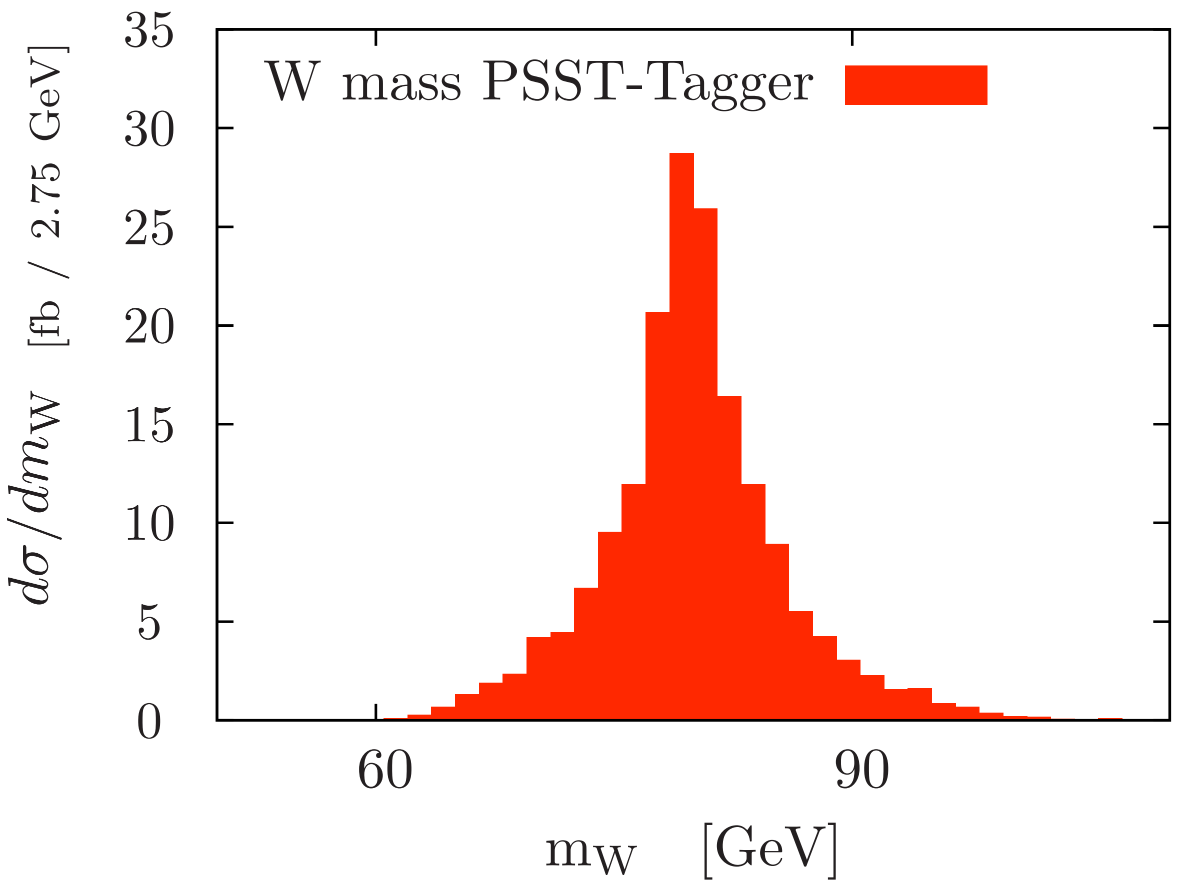
$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max} \quad \text{and} \quad 0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

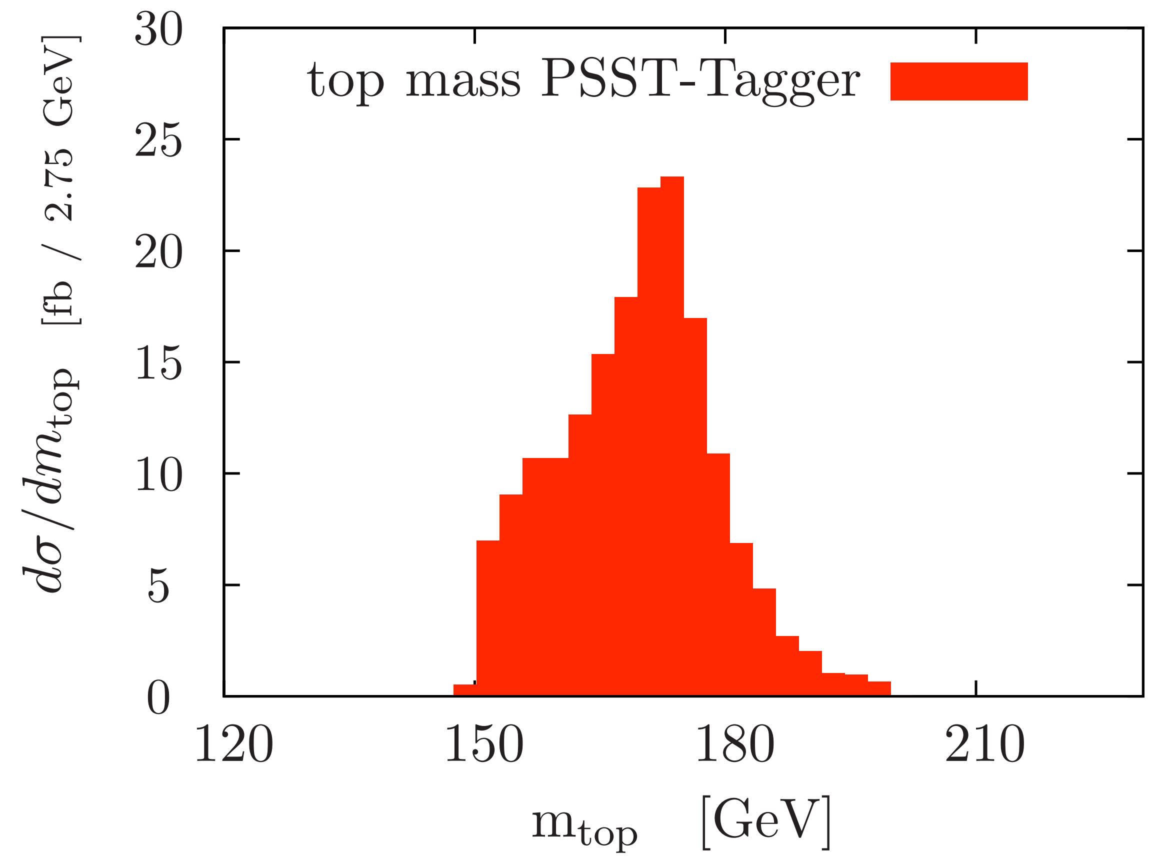
$$R_{\min}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

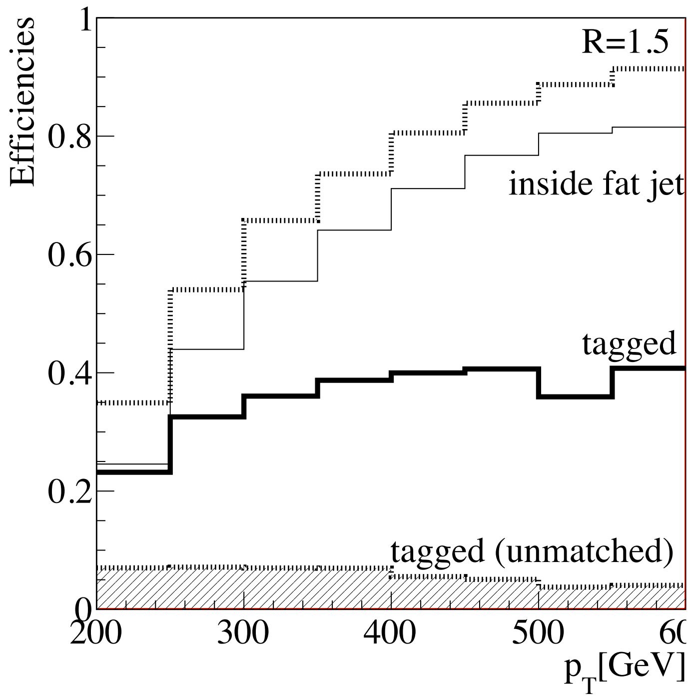
$$R_{\min}^2\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

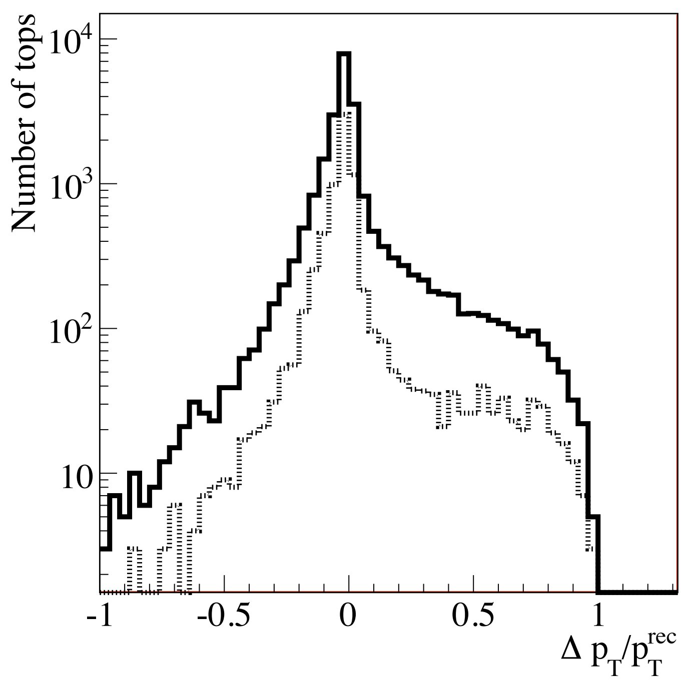


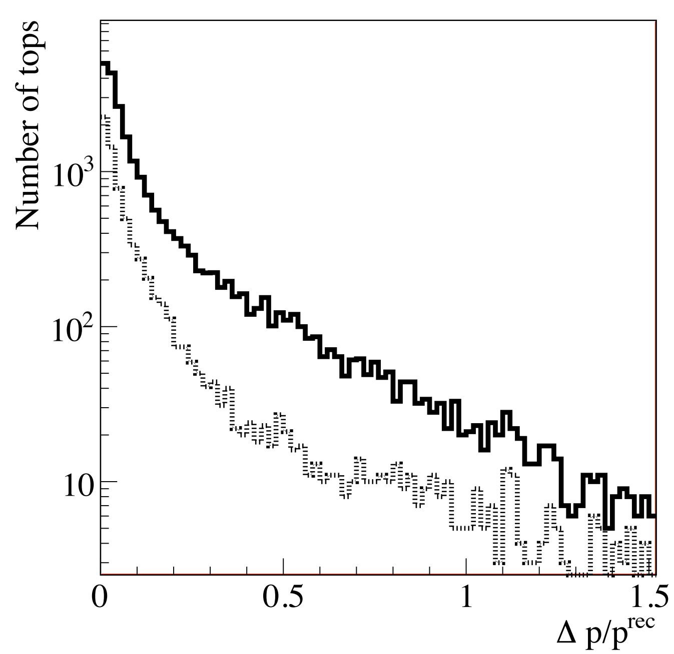
Results

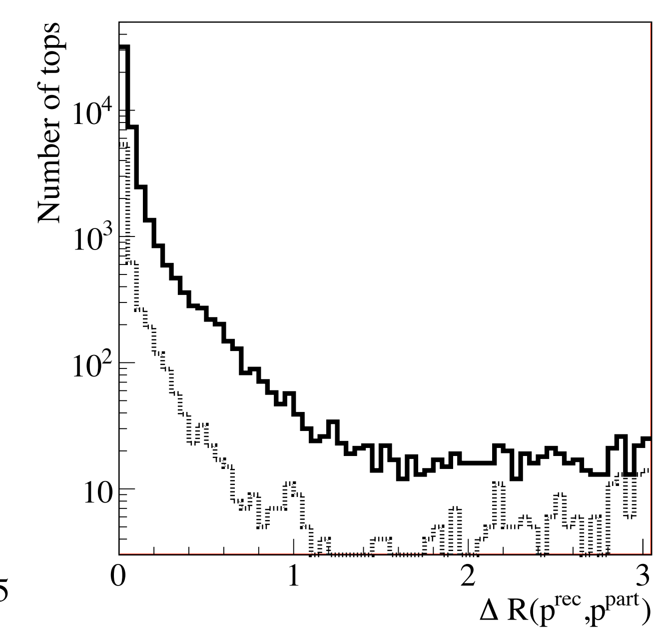

W mass PSST-Tagger
$d\sigma/dm_W$ [fb / 2.75 GeV]
m_W [GeV]


top mass PSST-Tagger
$d\sigma/dm_{top}$ [fb / 2.75 GeV]
m_{top} [GeV]


Efficiencies
R=1.5
inside fat jet
tagged
tagged (unmatched)
p_T[GeV]


Number of tops
$\Delta p_T/p_T^{rec}$


Number of tops
$\Delta p/p^{rec}$


Number of tops
$\Delta R(p^{rec},p^{part})$

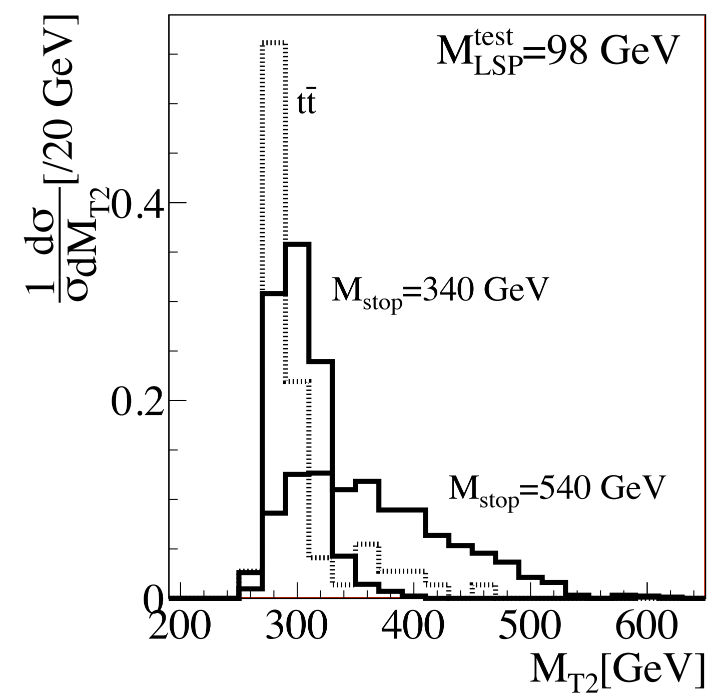
HEPTopTagger in stop search

(Plehn, MS, Takeuchi, Zerwas)

$$pp \to \tilde{t}_1 \tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0) \to (bjj\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0)$$

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



	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	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

Conclusion

Jet substructure yields new possibility to improve on NP searches

On MC level improved reconstruction of resonances by removal of UE and Pile-up contributions

Studies are promising,
tools and taggers should be tested with early data