Karlsruher Institut für Technologie

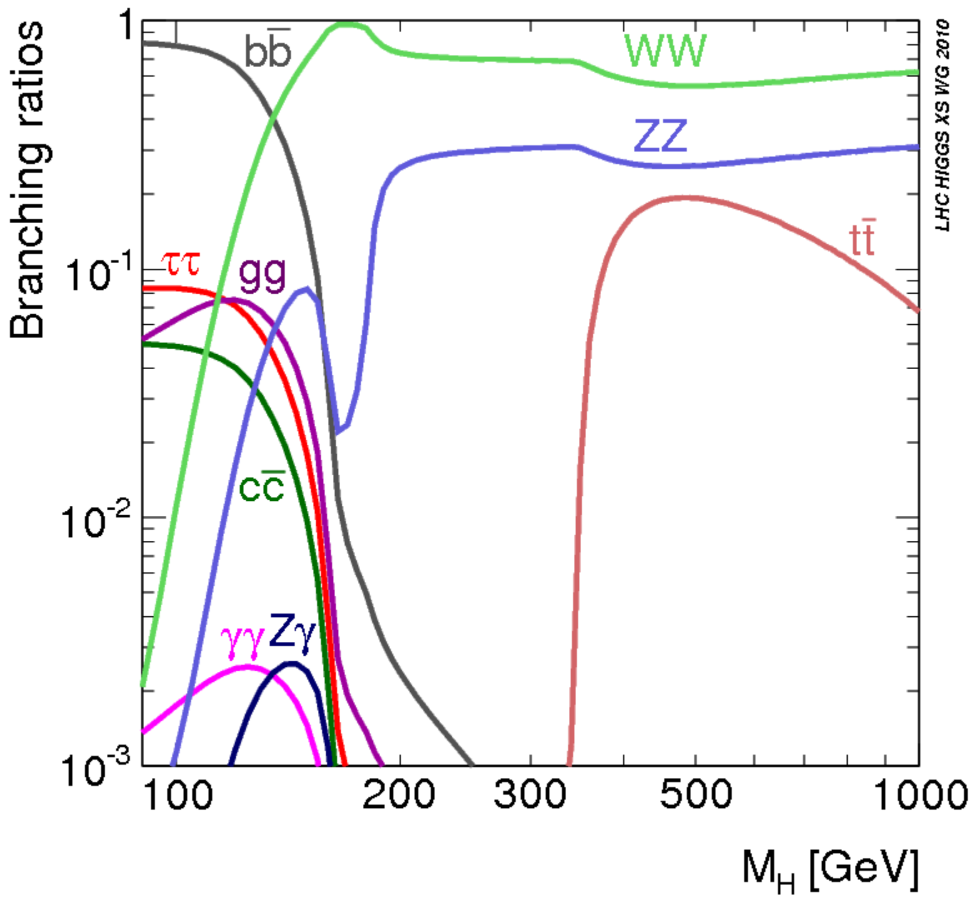
Boosted Higgs search

LHC-D Higgs meeting
1.12.10

C. Englert, C. Hackstein, M. Spannowski

Heavy Higgs decay

- Higgs boson coupling proportional to mass – most likely to decay into heaviest possible particle
- Heavy Higgs most likely to decay into vector bosons W,Z
- Heavy Higgs reconstruction requires to identify the Vector Boson decay products



Heavy Higgs decay via Vector Bosons

- Fully hadronic W/Z decays suffers from large QCD backgrounds (high jet multiplicity)
- Prefer the Vector Bosons to decay into muons (μ), which can be identified and measured easily
- Decay $W \rightarrow \mu \nu_\mu$ yields missing energy – bad for precise reconstruction
- Decay $Z \rightarrow \mu \mu$ can be measured very precisely
- $H \rightarrow ZZ \rightarrow 4\mu$ yields a very clean signal, 'gold plated mode'

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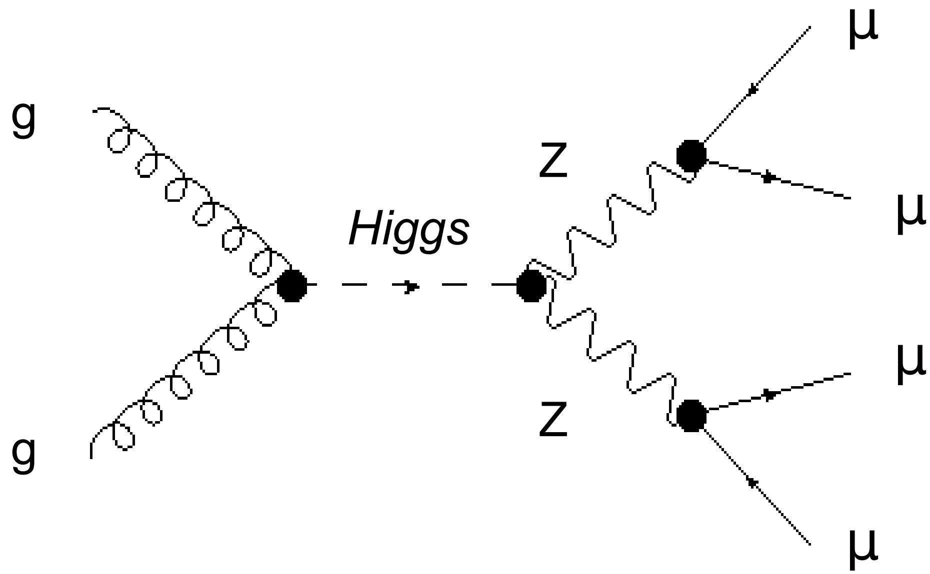
Gold plated mode

- Require 4 central, isolated muons
- Problem: $Z \rightarrow \mu\,\mu$ has a branching ratio of only 3.36 %



- That way, only $0.0336 \cdot 0.0336 \rightarrow 0.113$ % of the signal is used
- Even with combination of l=e,μ still small

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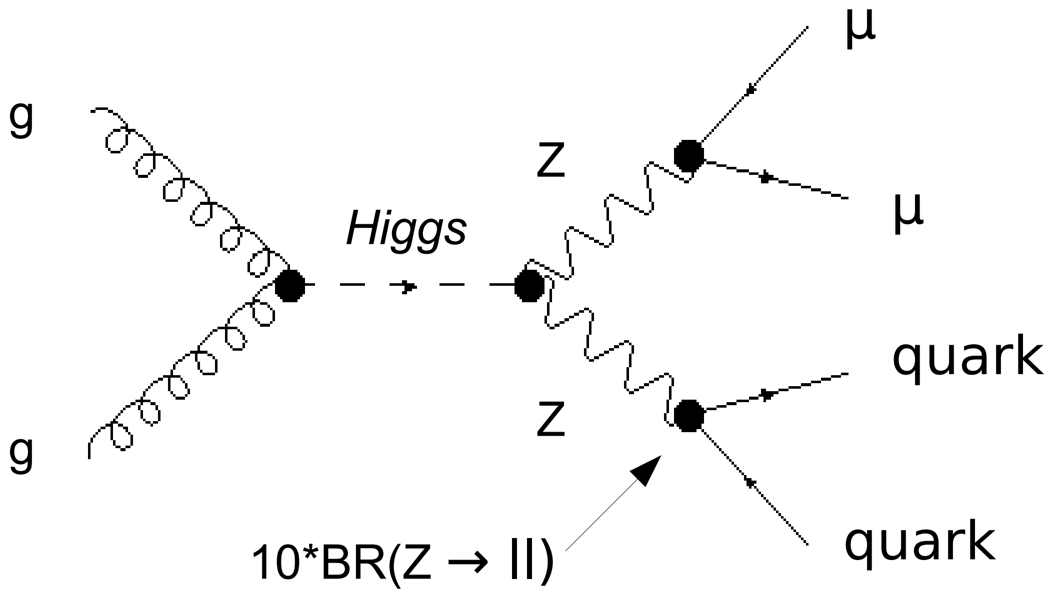
Gold plated mode extended

- Z → hadrons has a branching ratio of 69.9 %



- Idea: Use leptonically decaying Z to trigger event, reconstruct hadronically decaying Z using Subjet Analysis

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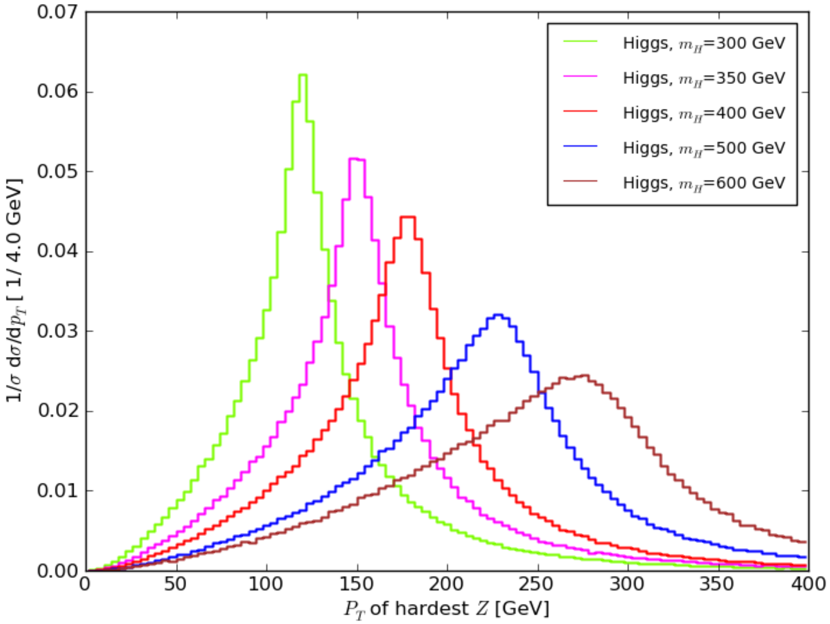
Semileptonic H → ZZ

- Semileptonic H → ZZ faces a lot of QCD backgrounds at the LHC – need more than just require "two jets" from the hadronic Z decay
- Use that Z boson from heavy Higgs decay is naturally boosted



Transverse momentum of hardest Z, m_H=300...600 GeV

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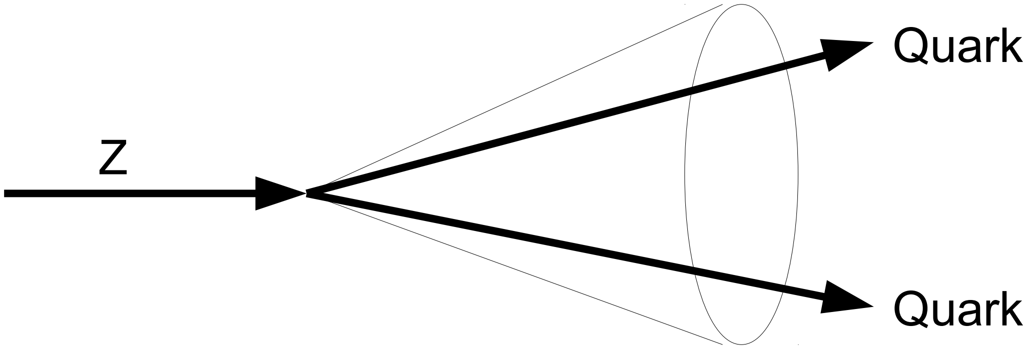
Boosted Z boson

- Jets from boosted Z boson are collimated in direction of Z movement



- Look for one “Fat Jet” instead of two normal ones (eg. Cambridge-Aachen (CA), $\Delta R = 1.2$)
- Look for substructure in Fat Jet

  Compare ZH/WH analysis [Butterworth et.al. PRL 100 (2008)]
- Apply “Jet Grooming” to reduce contamination from pile-up, underlying event etc.

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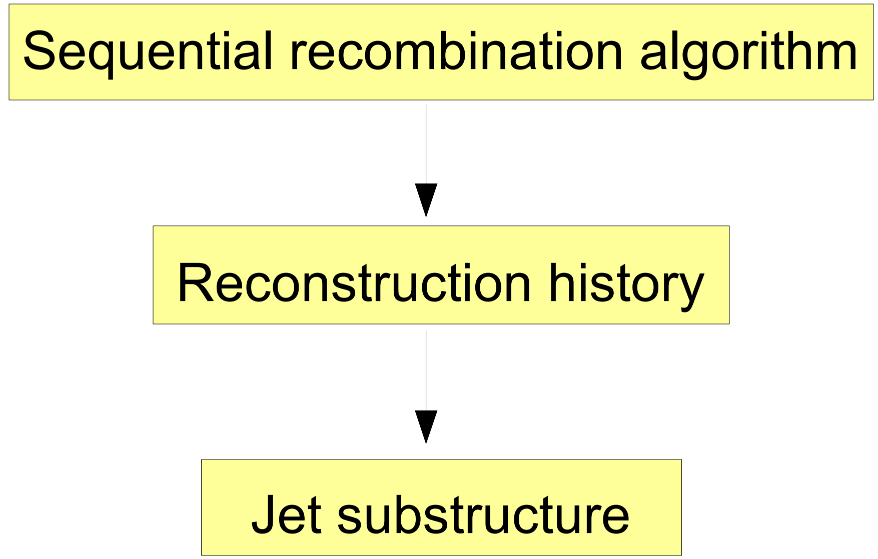
Subjet analysis



Three ways to investigate jet substructure:

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

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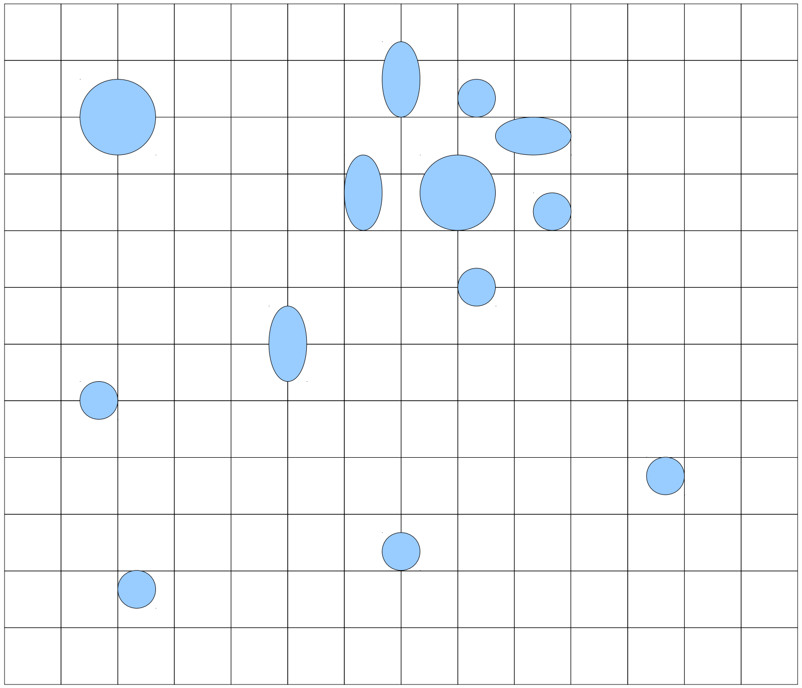
Jet/Event selection

- To simulate detector resolution: granularity for hadronic activity 0.1 x 0.1



Hard process, ISR, FSR, UE

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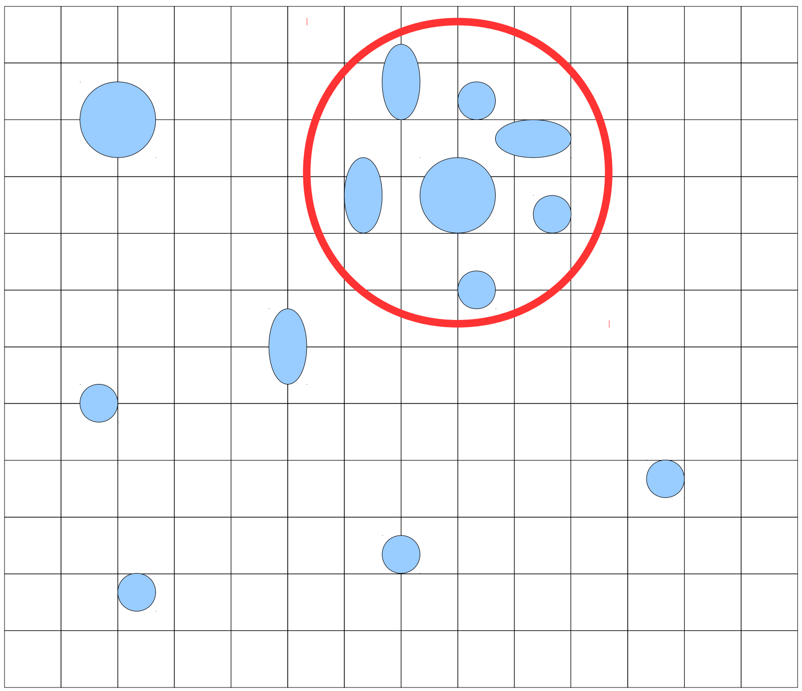
Jet/Event selection

- To simulate detector resolution: granularity for hadronic activity 0.1 x 0.1
- Locate hadronic energy deposit in detector by choosing initial jet finding algorithm, e.g. CA, R=1.2
- Apply selection cuts on fat jets and leptons:
  - 2 central, isolated muons
  - Muon pair in Z mass window
  - One central Fat Jet with P_T > 150 GeV
- Apply Subjet Analysis on Fat Jet



Hard process, ISR, FSR, UE

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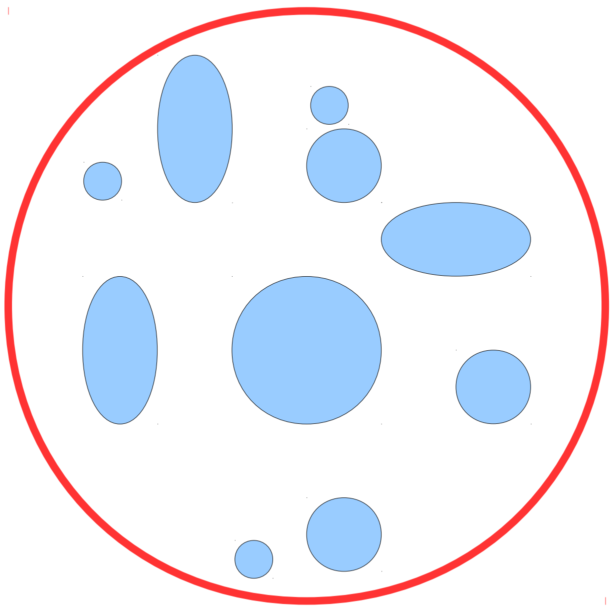
Filtering / Trimming

- Recluster jet constituents with new jet algorithm, e.g. CA, R=0.2



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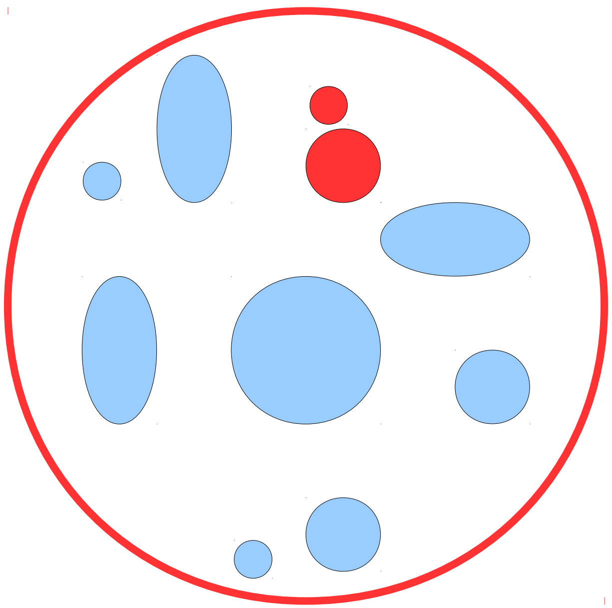

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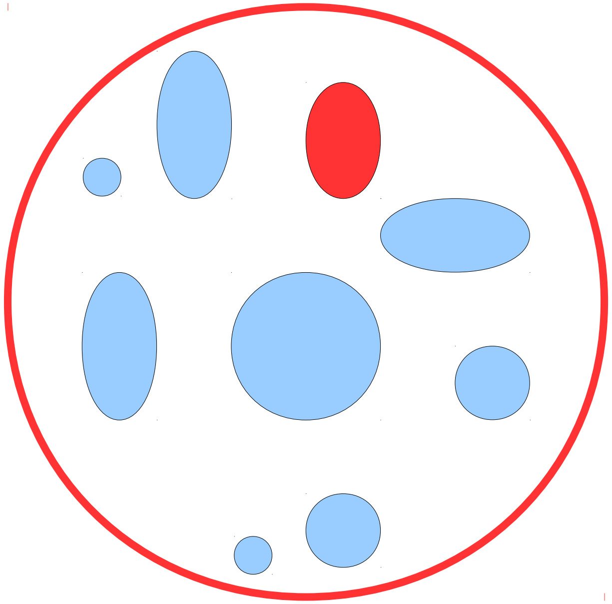

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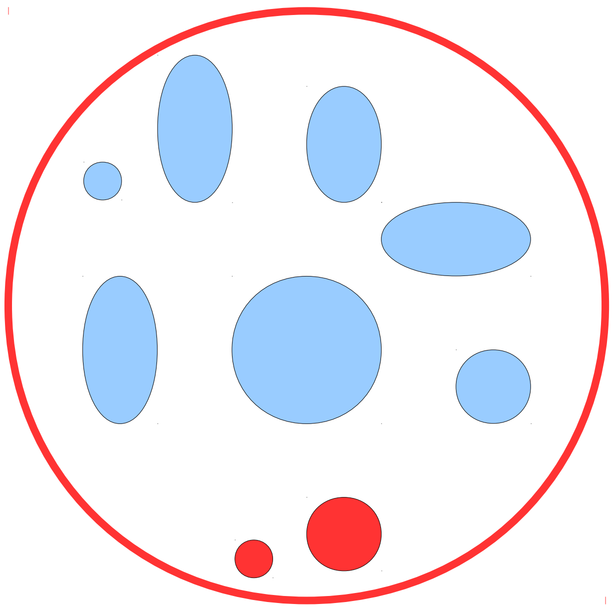

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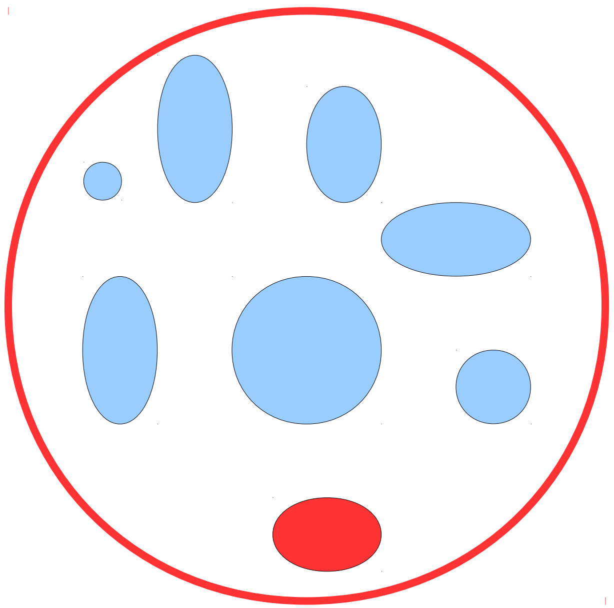

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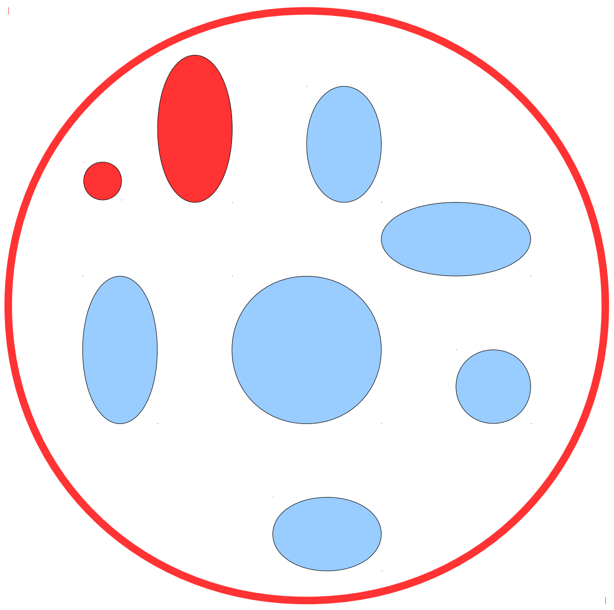

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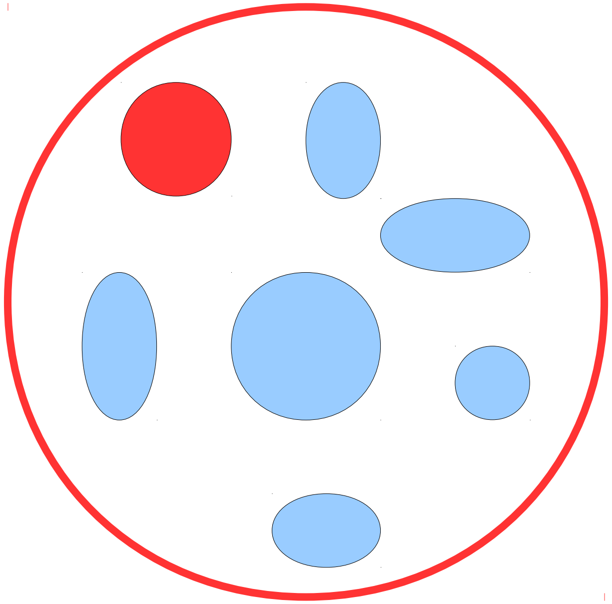

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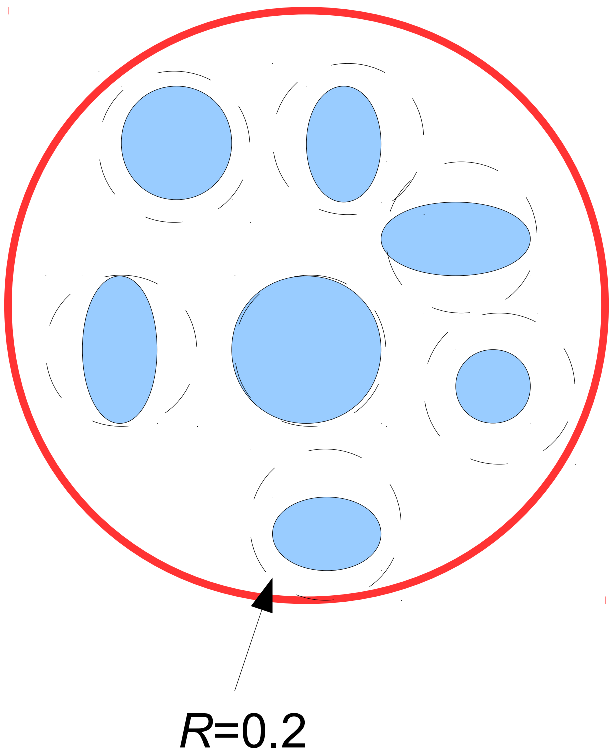
Filtering / Trimming

- Recluster jet constituents with new jet algorithm, e.g. CA, R=0.2
- Filtering: recombine n subjets

  need input on what to look for; also affects choice of R
- Trimming: recombine subjets which fulfill

$$P_{T,jet} > f \cdot \Lambda$$



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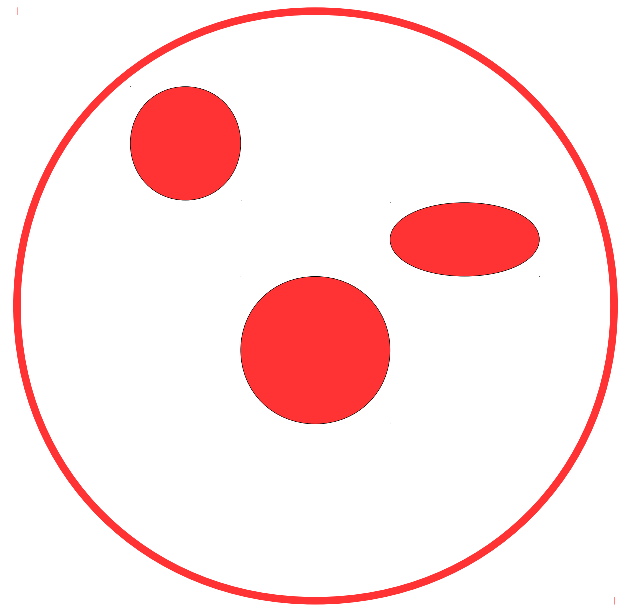

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$$P_{T,jet} > f \cdot \Lambda$$

Fix choice here: $f = 0.03$

Based on property of jets under investigation, here: Fat Jet p_T

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Pruning

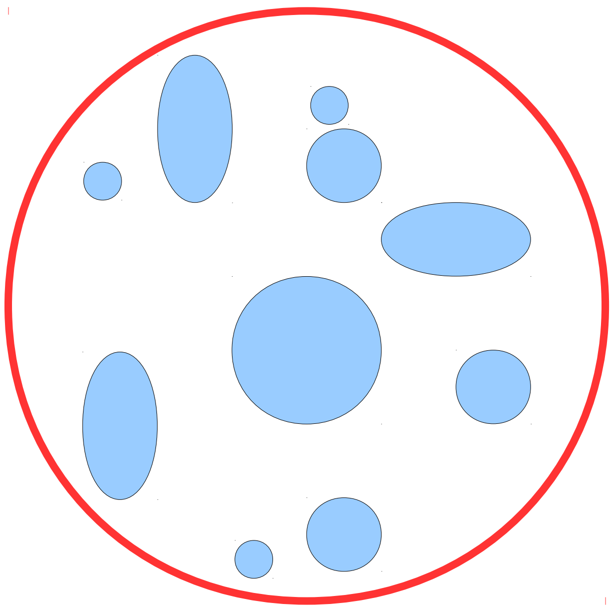
- Recluster jet constituents with new jet algorithm, e.g. k_T, $R = M_{\text{Fat Jet}} / P_{T,\text{ Fat Jet}}$

- Veto merging if two conditions hold true:
  - Recombination angle is wide

$$\Delta R_{ij} > D_{\text{cut}} = M_{\text{fat jet}} / P_{T,\text{fat jet}}$$

  - Recombination is asymmetric

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



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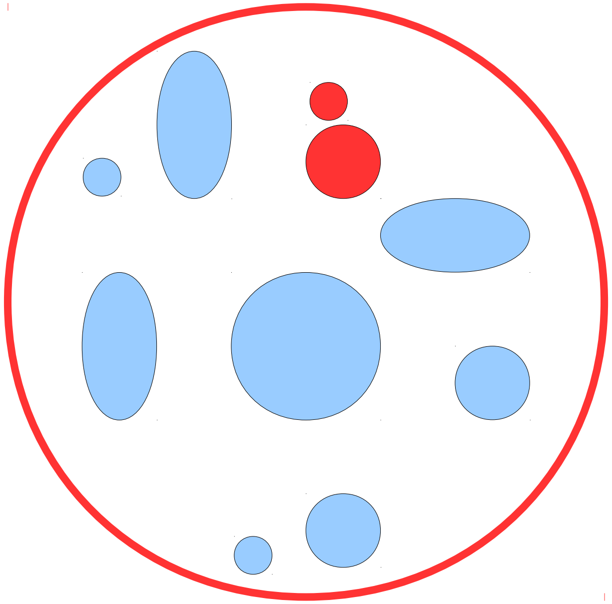

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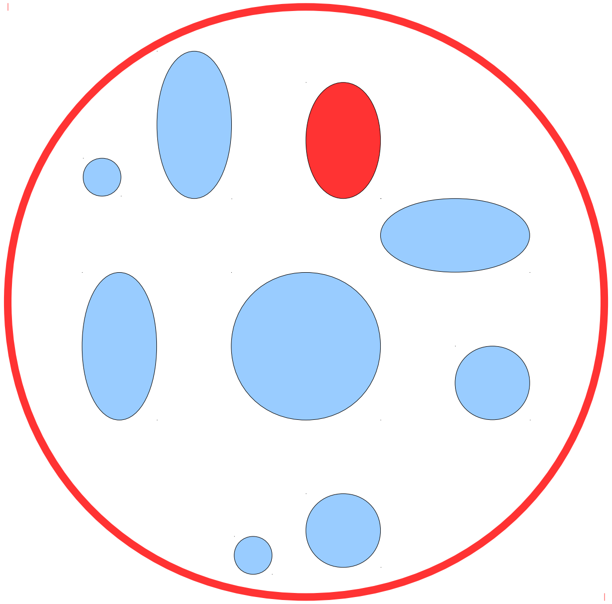

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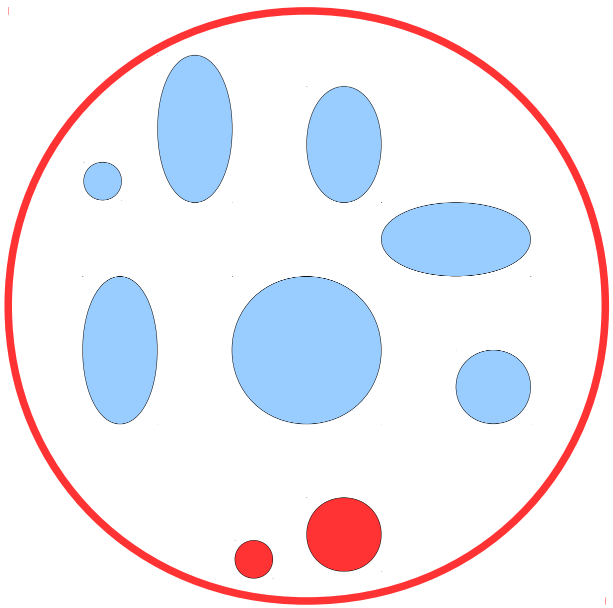

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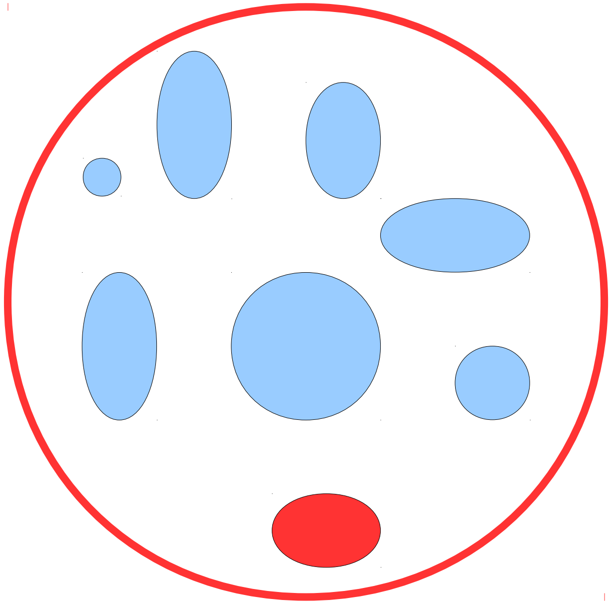

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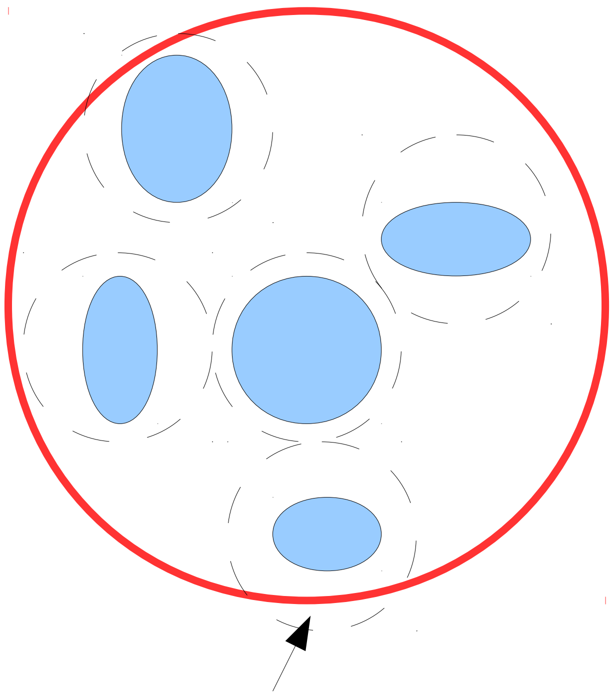

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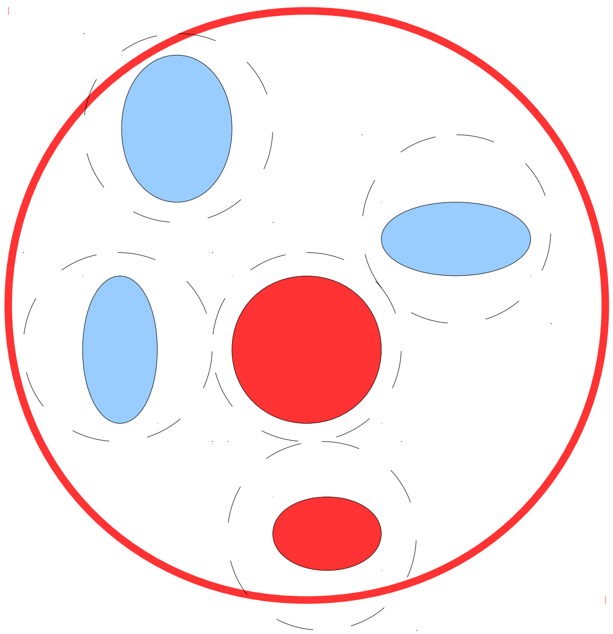

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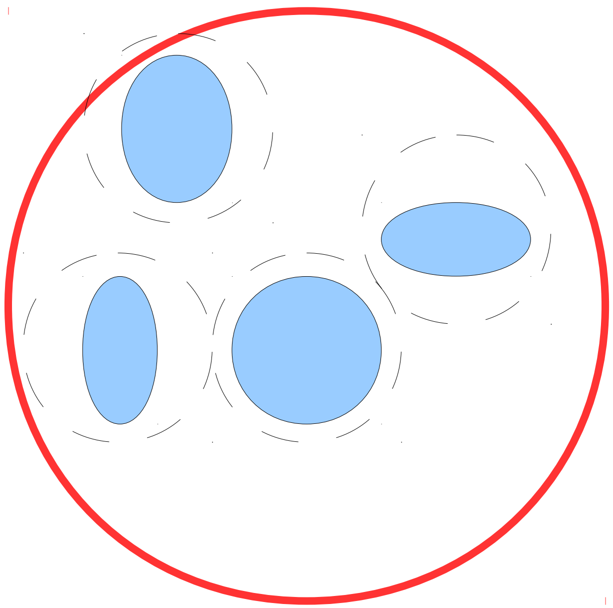

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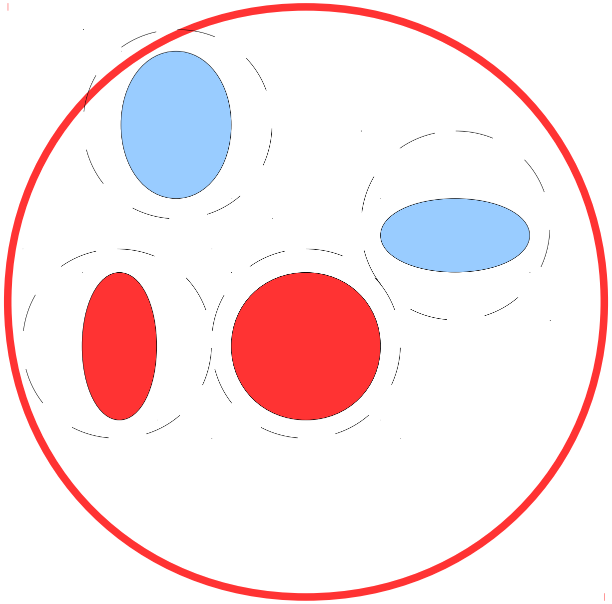

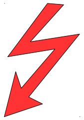

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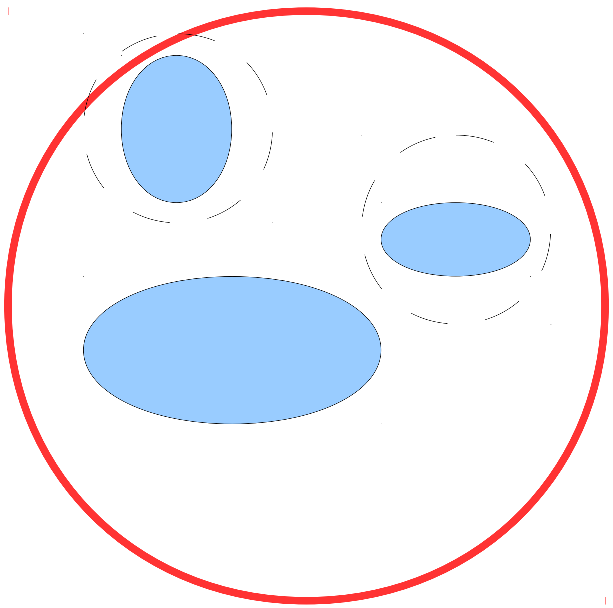

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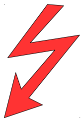

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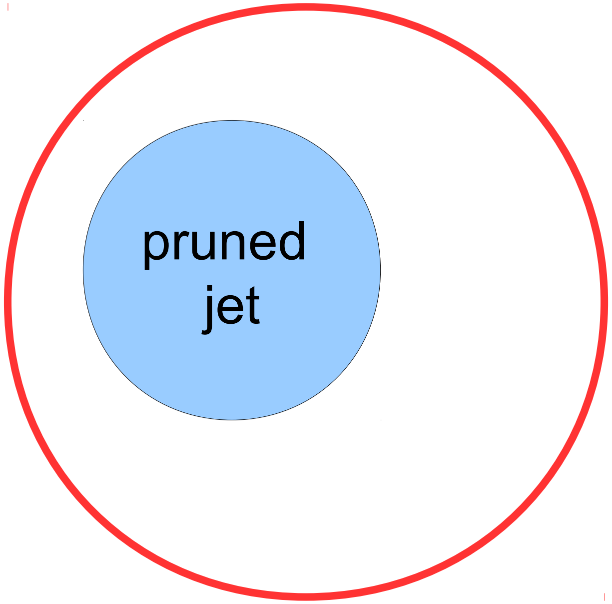
here: $z_{\text{cut}} = 0.1$



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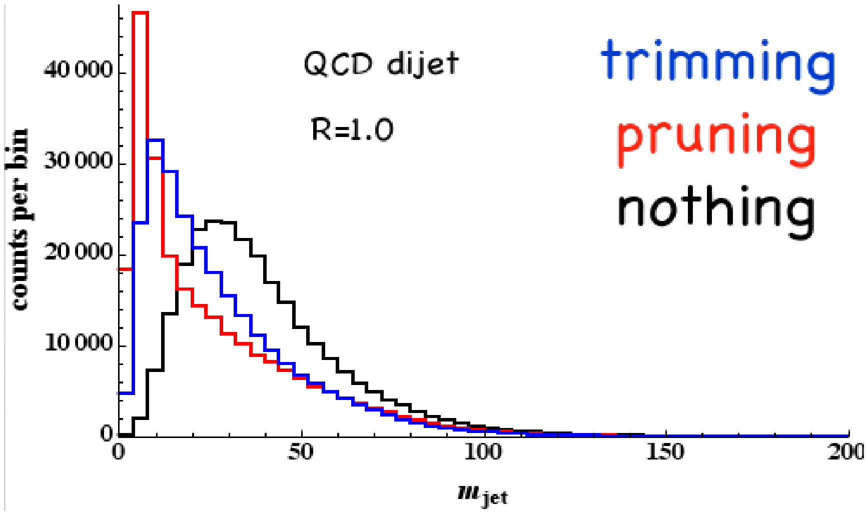
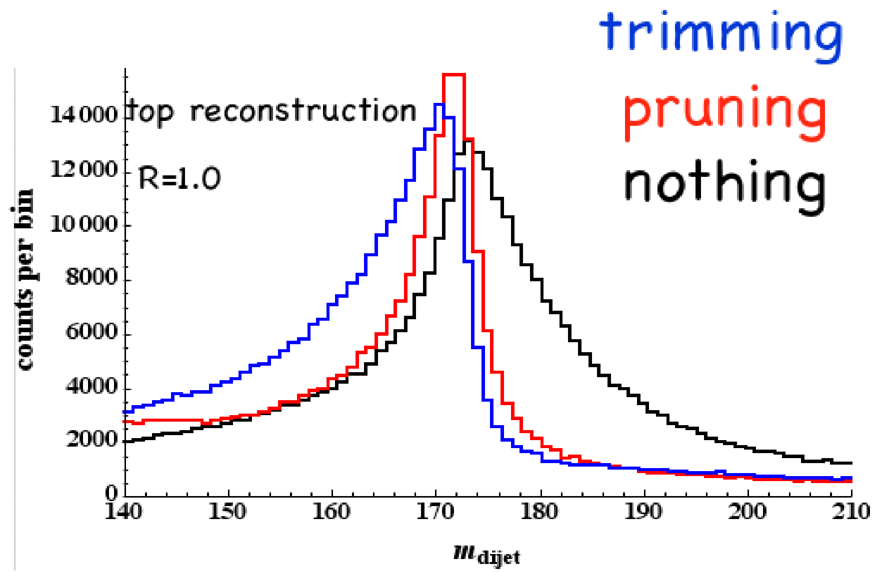
Comparison of the techniques

- Trimming / Pruning are generic tools
- Filtering needs to know what to look for





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

- Subjet techniques helpful to separate jets from resonances from pure QCD jets

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Combine Jet Grooming algorithms

- Subjet analysis procedures work different
- Do they also give different results?
- If yes, a combination of these methods gives more insight

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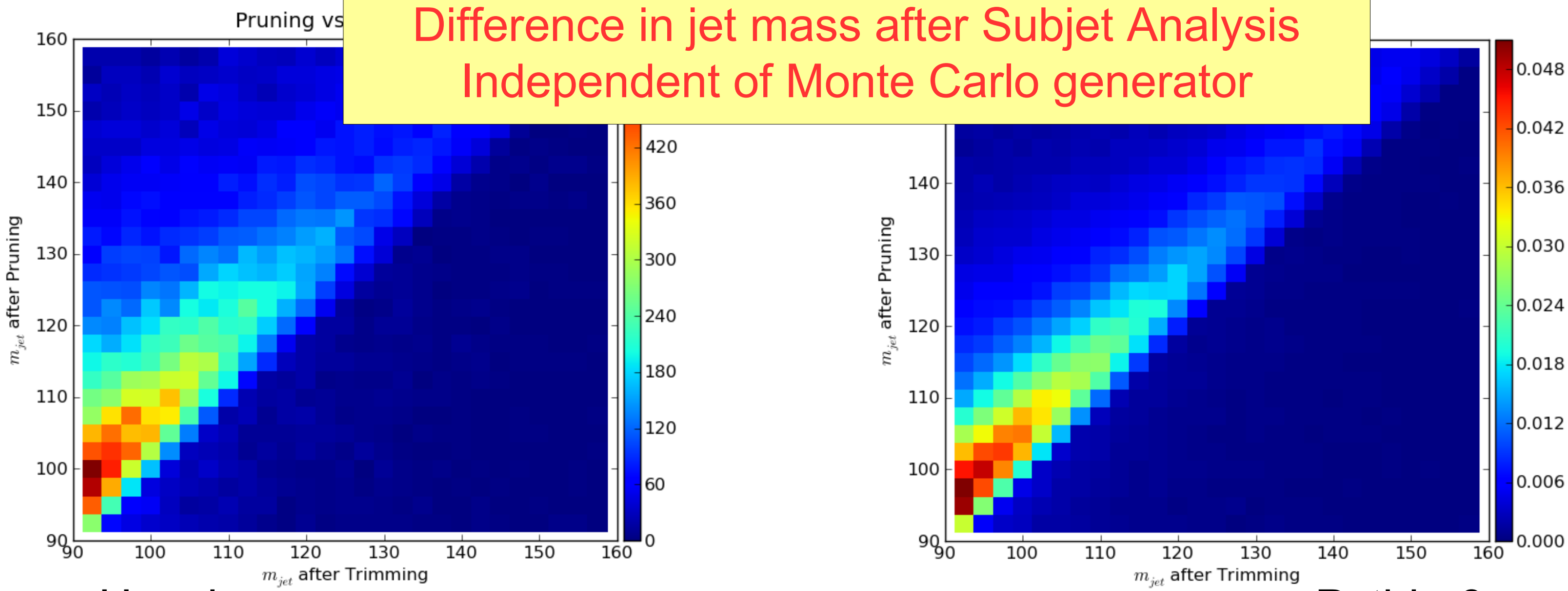
Trimming vs. Pruning

- Asymmetry in QCD jet mass for trimming and pruning
- Require $P_{T,jet}$ > 150 GeV
- Selection: CA, R=1.2, Pruning CA, Trimming k_T

Difference in jet mass after Subjet Analysis
Independent of Monte Carlo generator



Herwig++ Pythia 6

- Exploitation of Trimming/Pruning asymmetry increases significance for WH/ZH channel by a factor two [Soper,Spannowsky JHEP 1008 (2010)]

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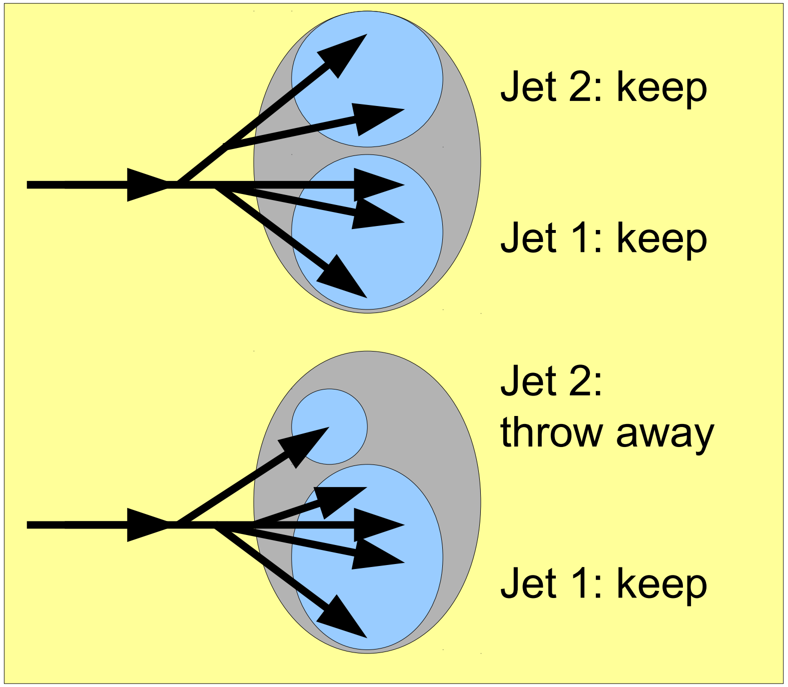
Back to the hadronically decaying Z boson

- Look for substructure in Fat Jet
  - Check for mass drop, $m_{j1} < 0.67\, m_j$
  - Check “asymmetry”

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



- If mass drop is met, apply Filtering
- Apply Trimming and Pruning

→ For all “Groomed” jets, require $m_Z^{rec} = m_Z \pm 10$ GeV

- Check if recombined Z bosons combine to Higgs mass, here:
  (300 ± 30, 350 ± 50, 400 ± 50, 500 ± 70, 600 ± 100) GeV

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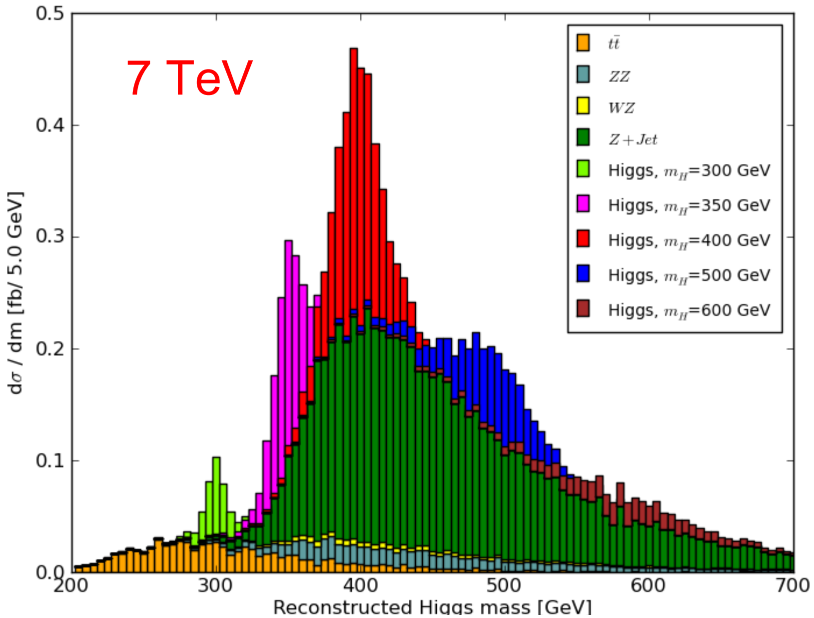
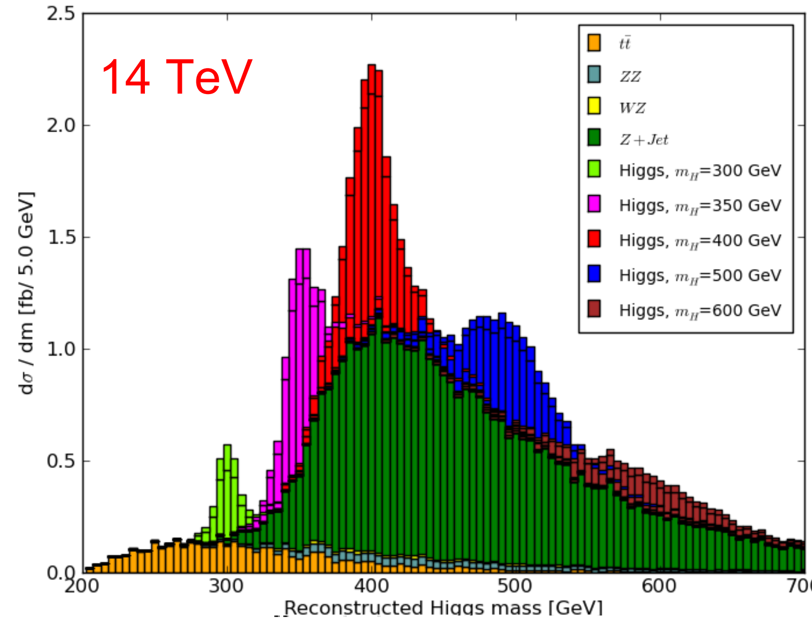
Final result, Higgs mass reconstruction

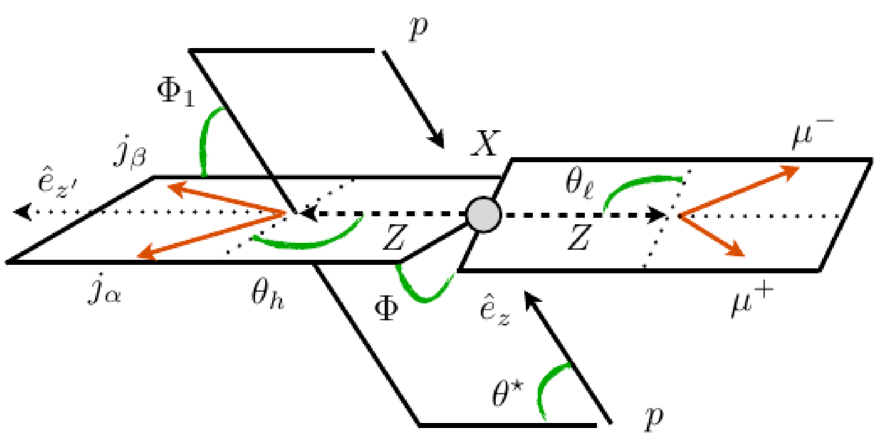




	m_H [GeV]	300		400		500		600	
	σ [fb]	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B	σ_S	σ_B
7 TeV	selection	3.37/0.89	907.3	8.89/0.97	907.3	4.91/0.70	907.3	2.19/0.46	907.3
	after analysis	0.29/0.12	0.39	2.02/0.24	3.97	1.11/0.18	3.33	0.46/0.12	1.97
	S/B	1.03		0.57		0.39		0.30	
	$S/\sqrt{B}_{10}$	2.0		3.6		2.2		1.3	
14 TeV	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	

General J^{CP} production and decay

- H → ZZ → 2μ 2e is "standard candle" to determine spin and *CP* properties of heavy higgs
- Is it possible to replace e^+e^- with 2 jets and still define planes?
- Impose rapidity ordering for jets, $y_\alpha < y_\beta$
- What remains of the difference in the angles after the selection?



$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\bigg|_{Z_h}, \quad \cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\bigg|_{Z_\ell},$$

$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\bigg|_X, \quad \cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'}) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\bigg|_X,$$

$$\cos\Phi = \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}}\bigg|_X$$

[Cabibbo, Maksymowicz '65] [Dell'Aquila, Nelson '85]
[van der Bij *et al.* '02] [Gao *et al.* '10] [DeRujula *et al.* '10]

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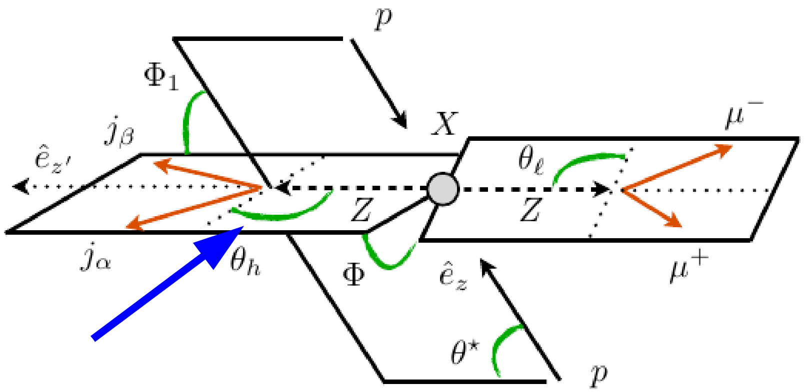
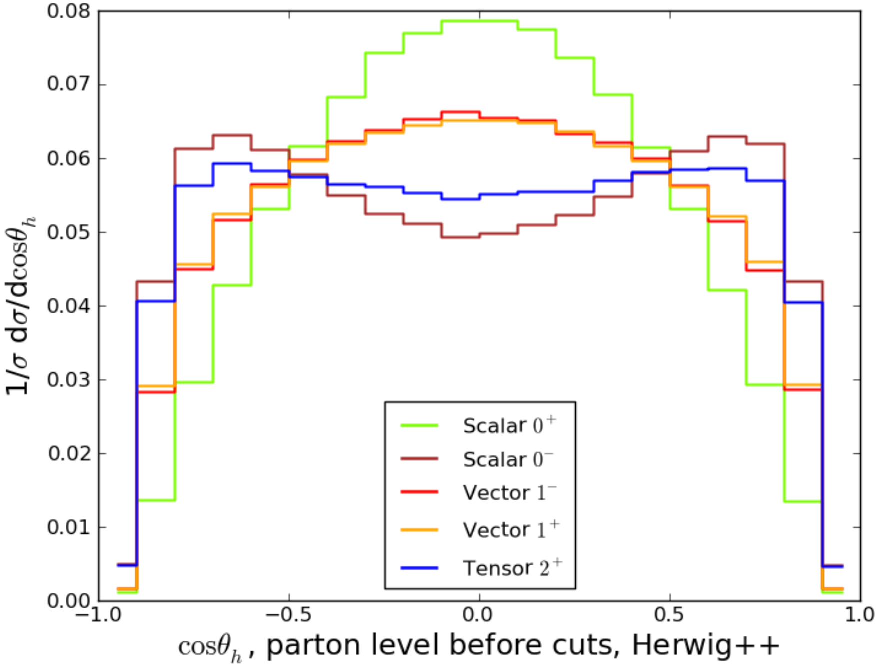
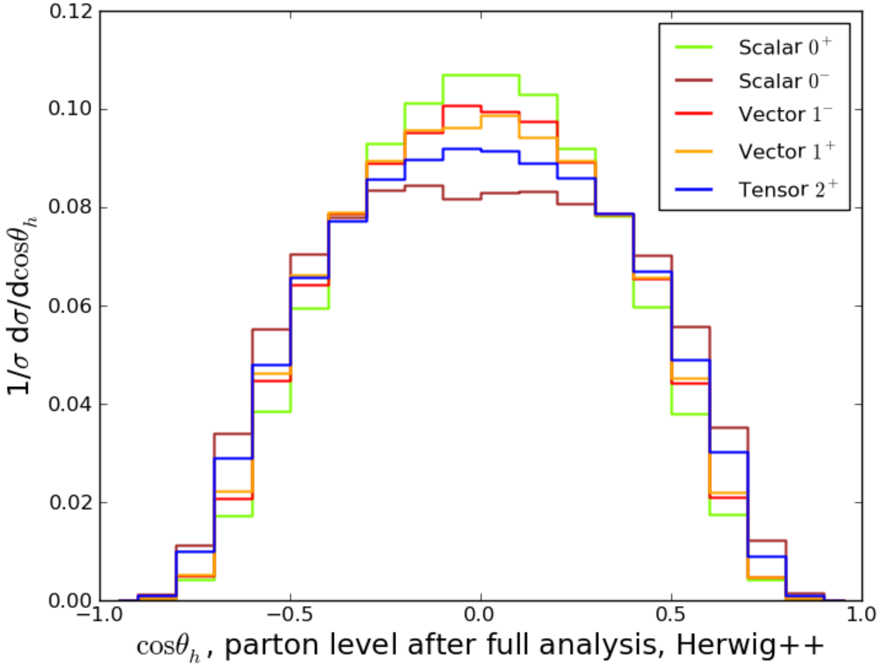
General J^{CP} production and decay



$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\Bigg|_{Z_h}$$





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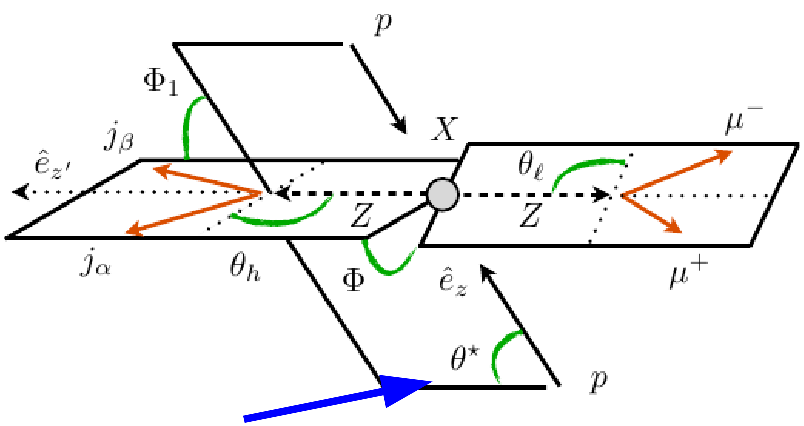
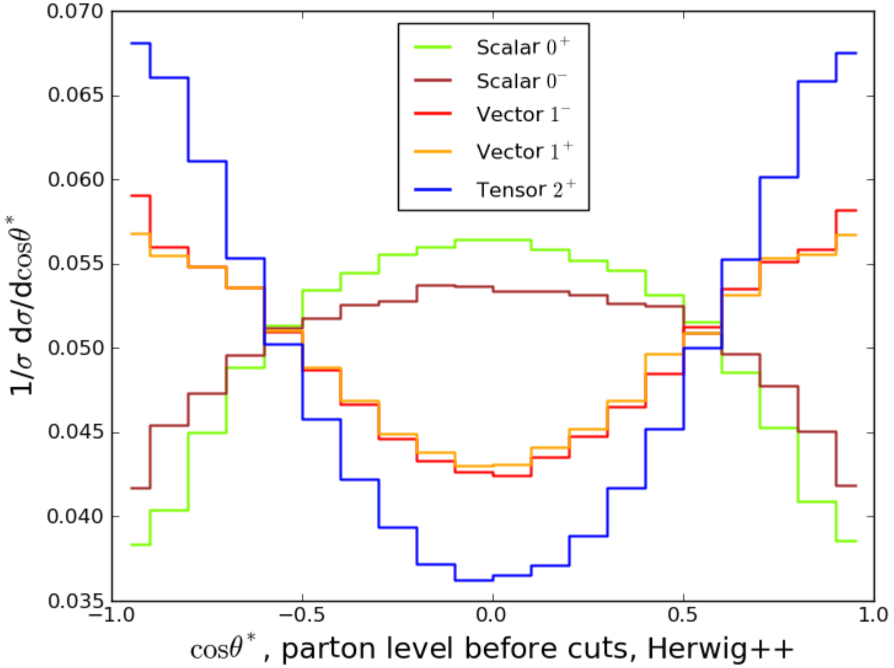
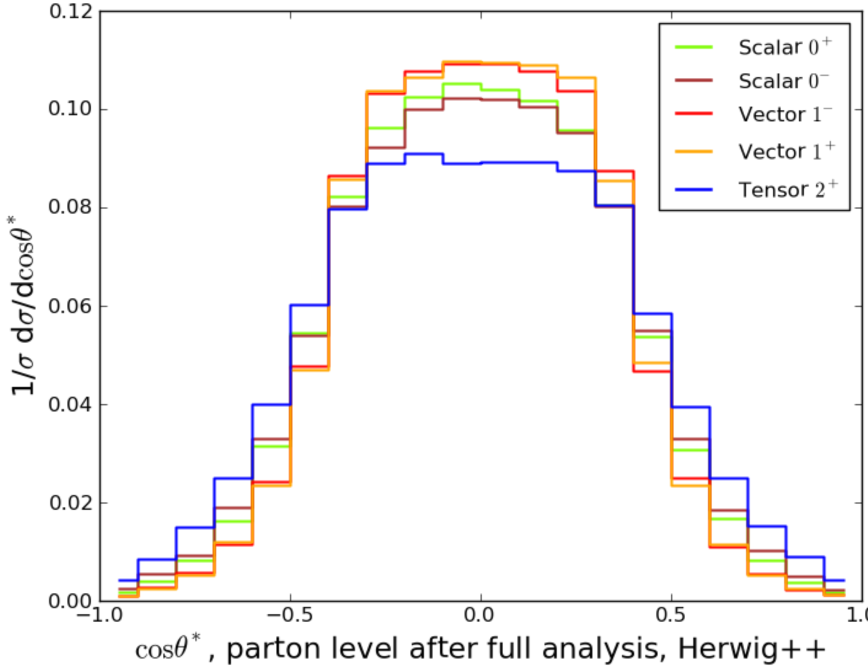


$$\cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}^2_{Z_\ell}}}\Bigg|_X$$





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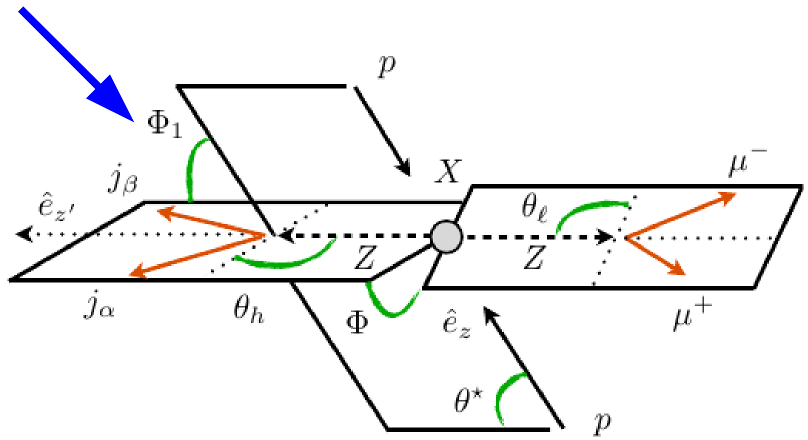
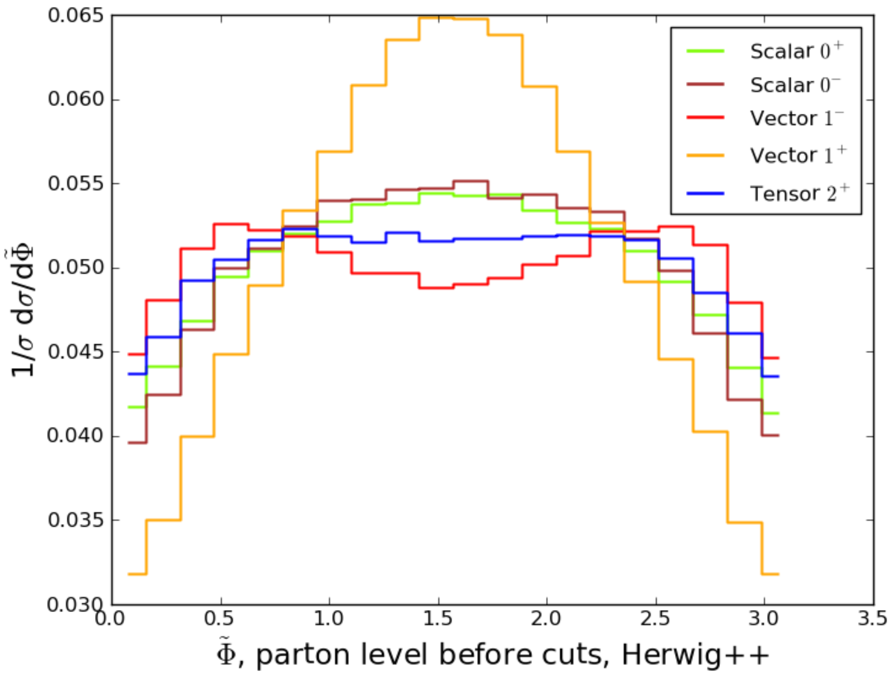
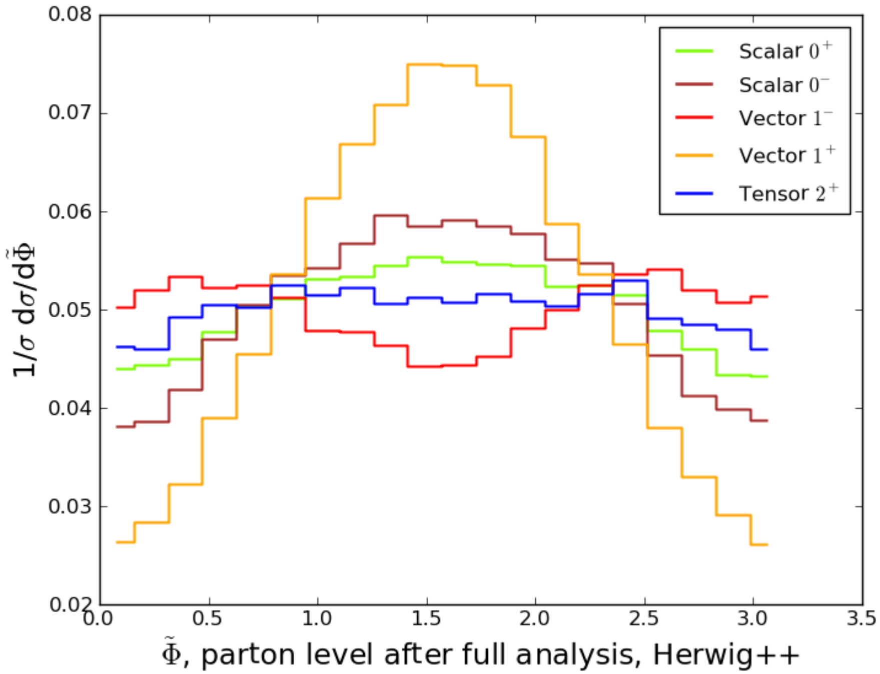


$$\cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'}) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X$$





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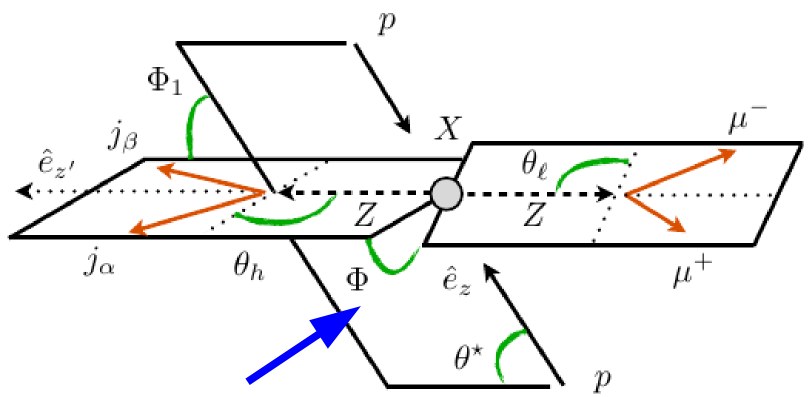
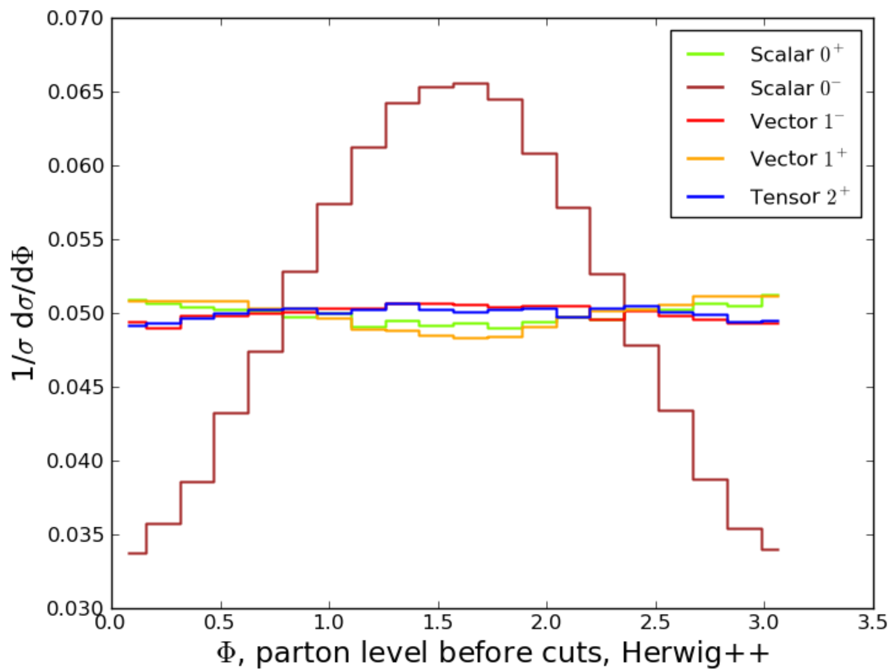
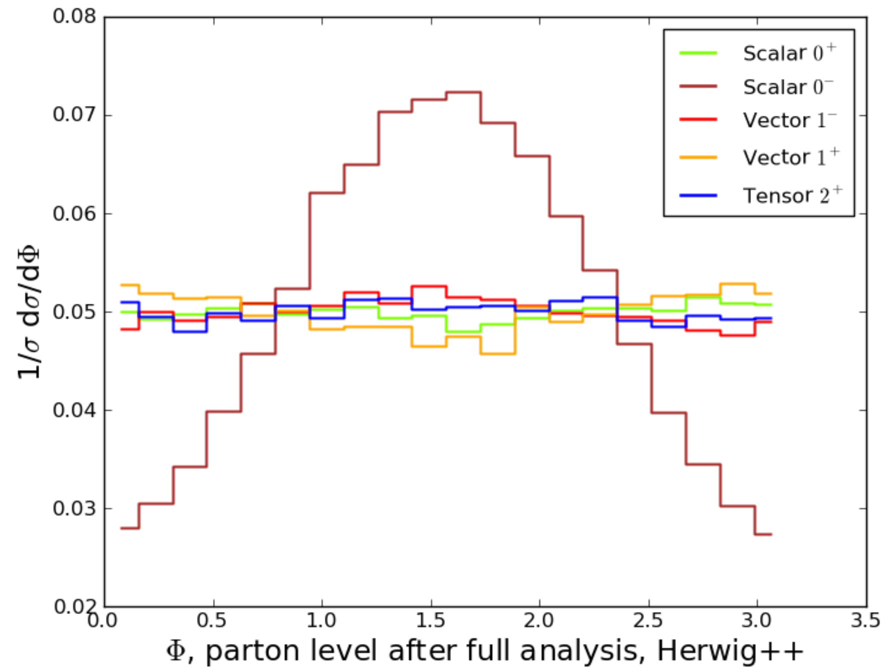
General J^{CP} production and decay



$$\cos\Phi = \left. \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)\cdot(\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}} \right|_X$$





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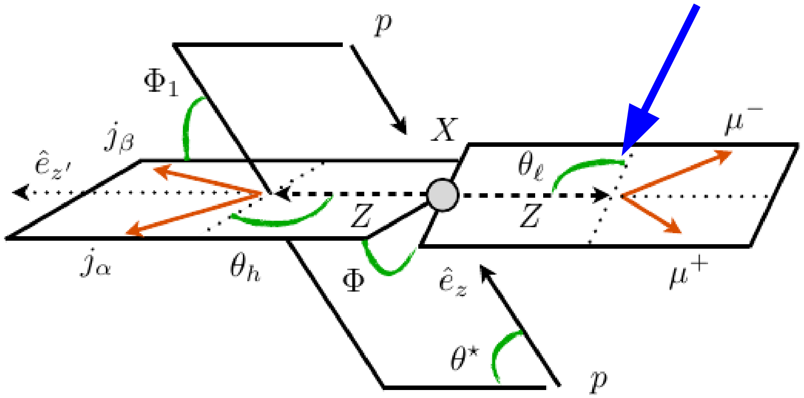
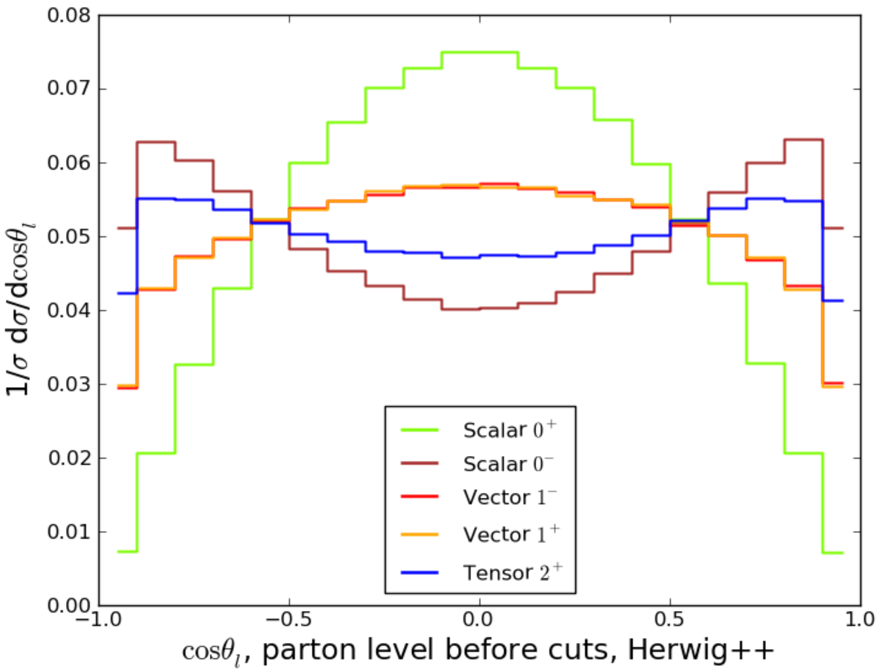
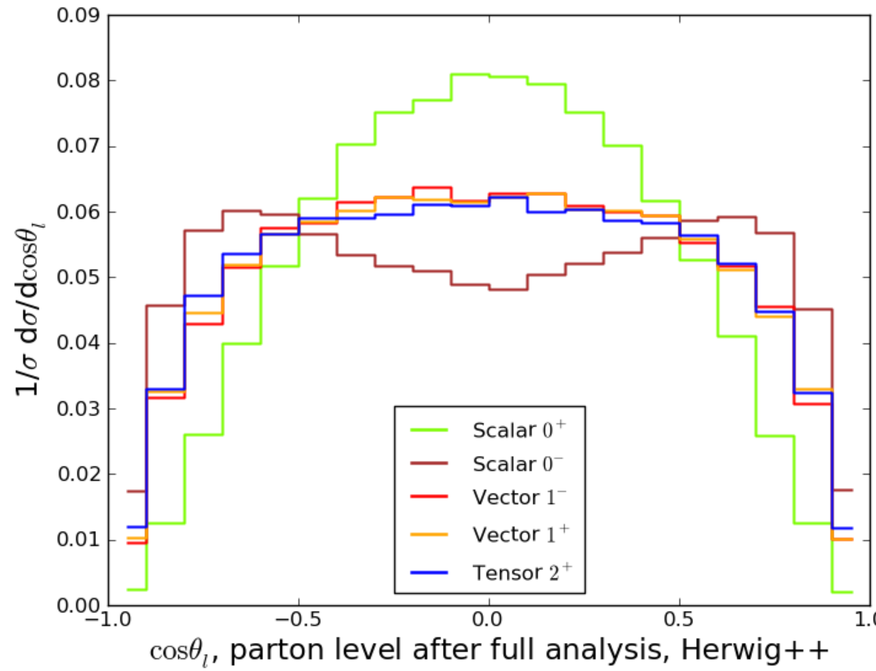


$$\cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\Bigg|_{Z_\ell}$$





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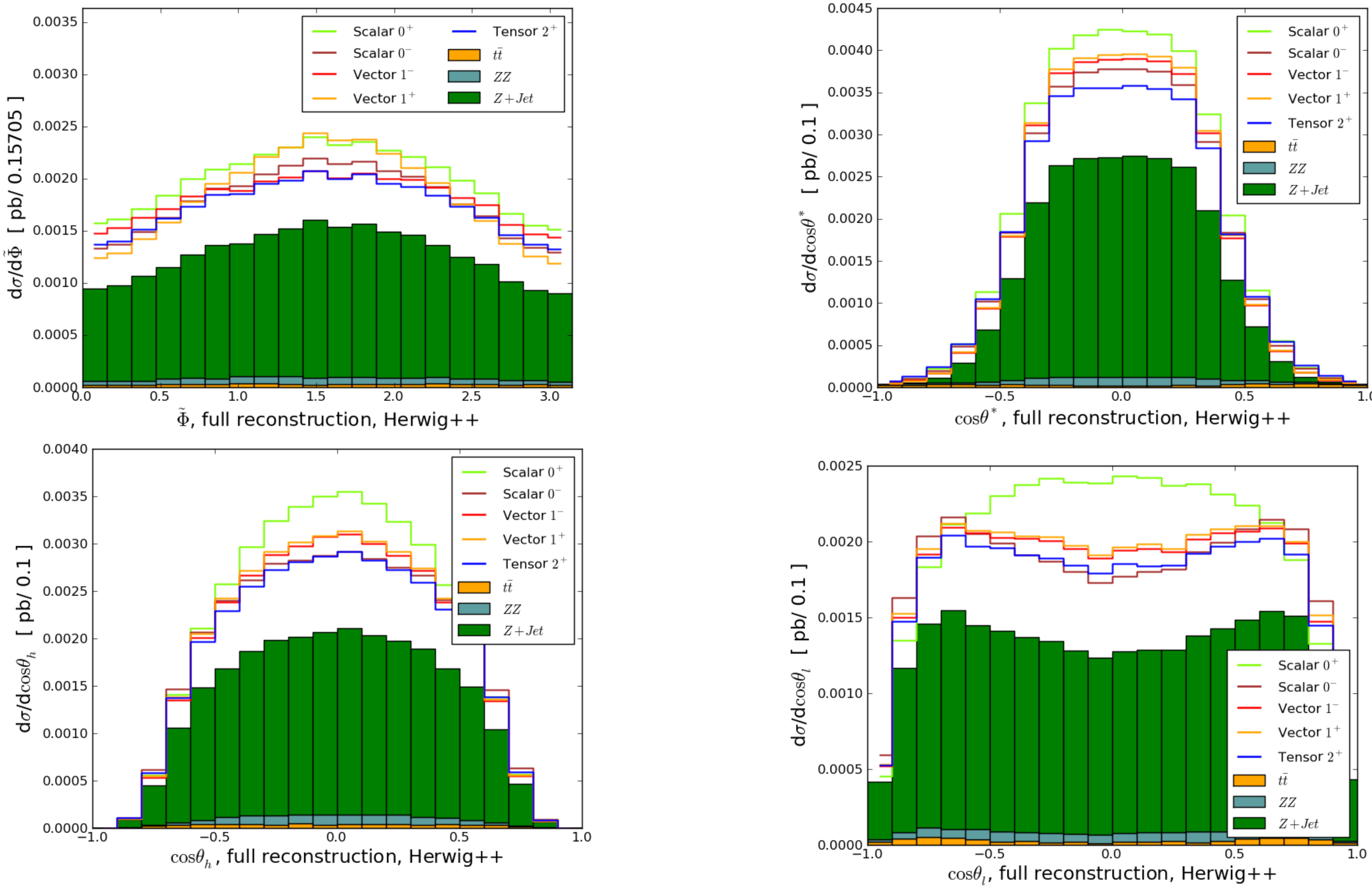
Angles, hadron level, after full analysis

- A lot of information lost on the way, but some sensitivity remains



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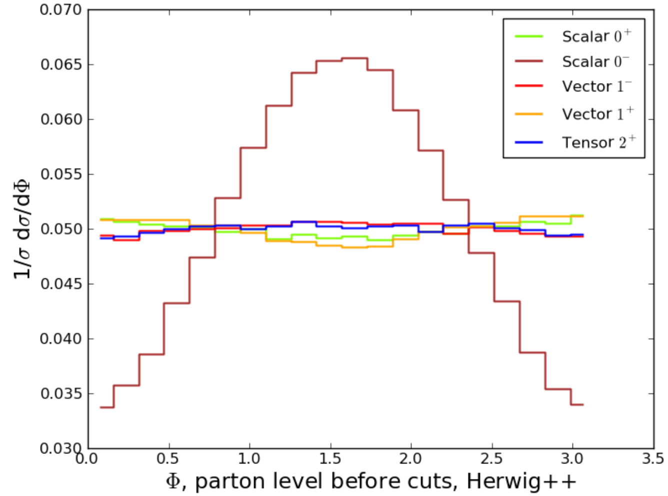
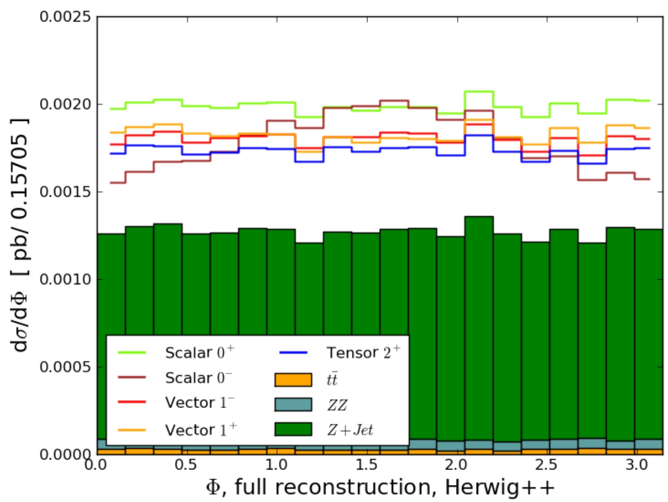
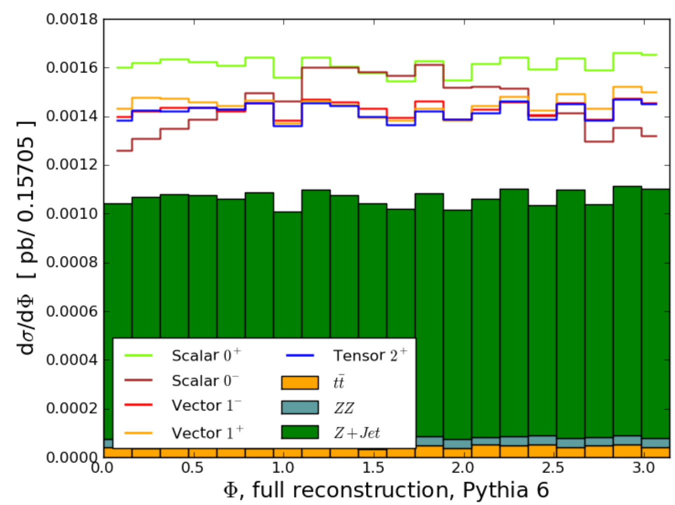
Angles, hadron level, after full analysis

- For most of the observables no dependence on the shower







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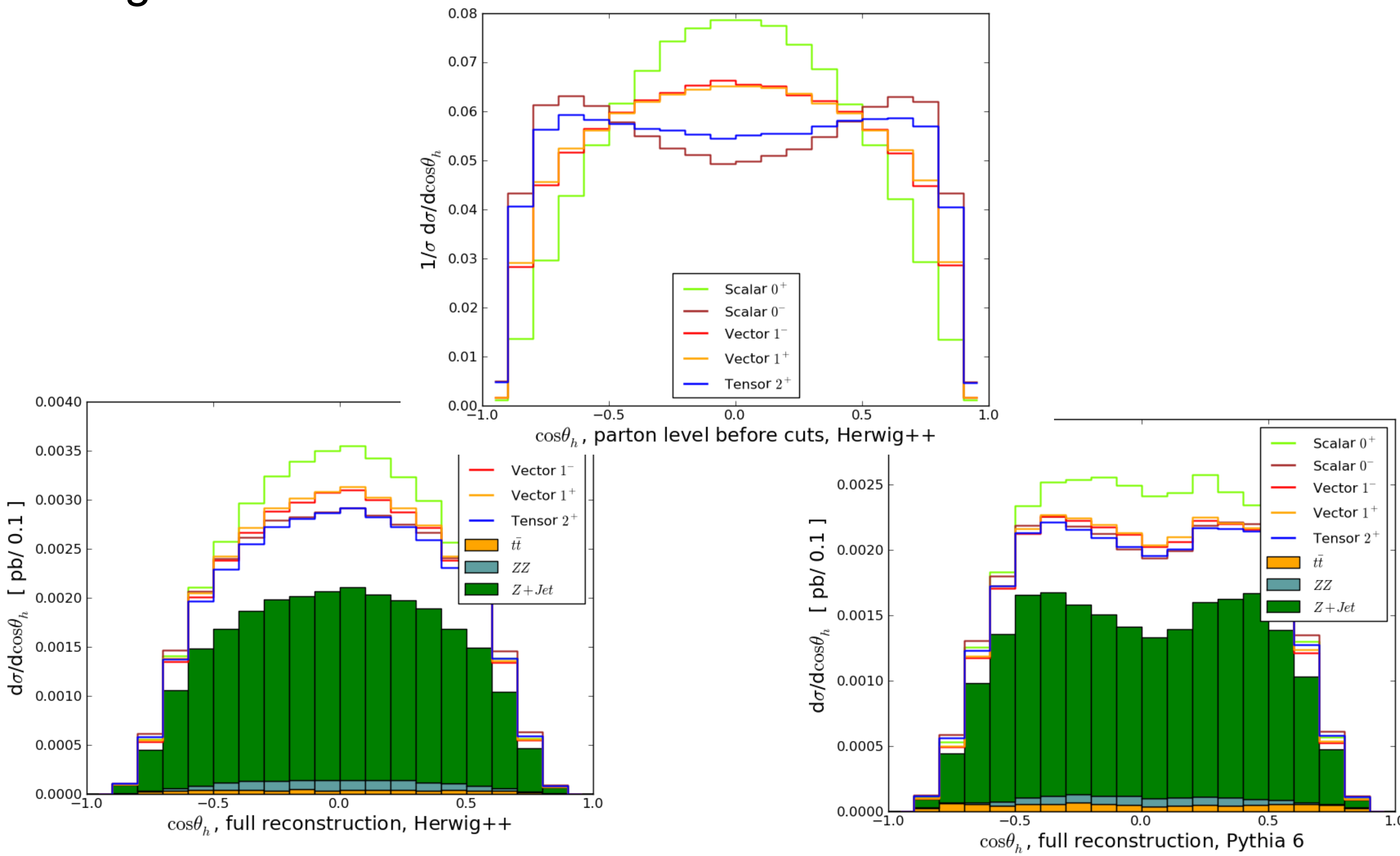
Angles, hadron level, after full analysis

- One observable depends extremly on the shower – by construction sensitive to inner structure of jet – background differs in Pythia and Herwig++!



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Conclusion and outlook

- Gold plated mode $H \rightarrow ZZ \rightarrow 4\mu$ provides excellent signal but limited statistical precision
- Subjet analysis allows to include hadronic Z decays, more background but possible to have increased $S/\sqrt{B}$
- Especially interesting should LHC run longer at 7(8) TeV – useful in combination with other channels for limits
- Subjet analysis can help determining the CP properties of a singly-produced resonance
- We provide an observable which is sensitive to parton showering

Backup

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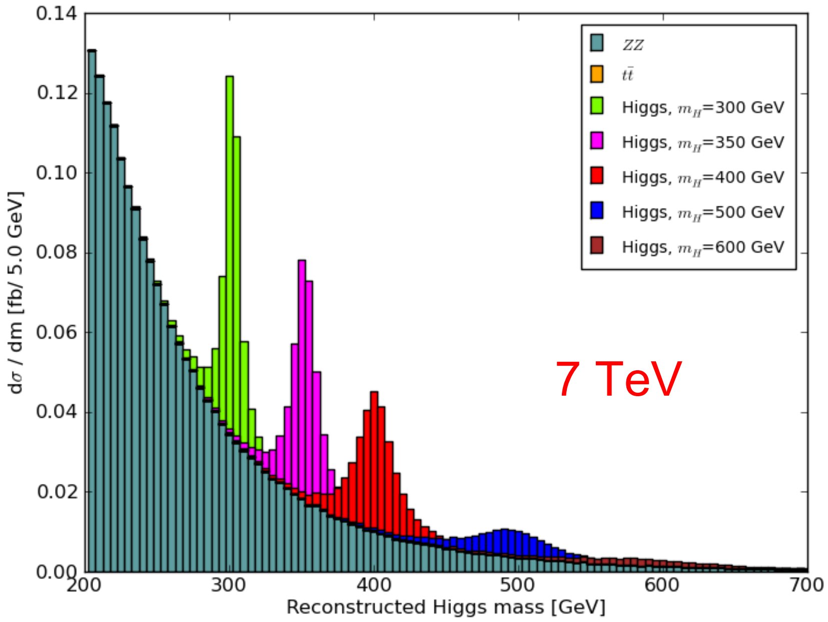
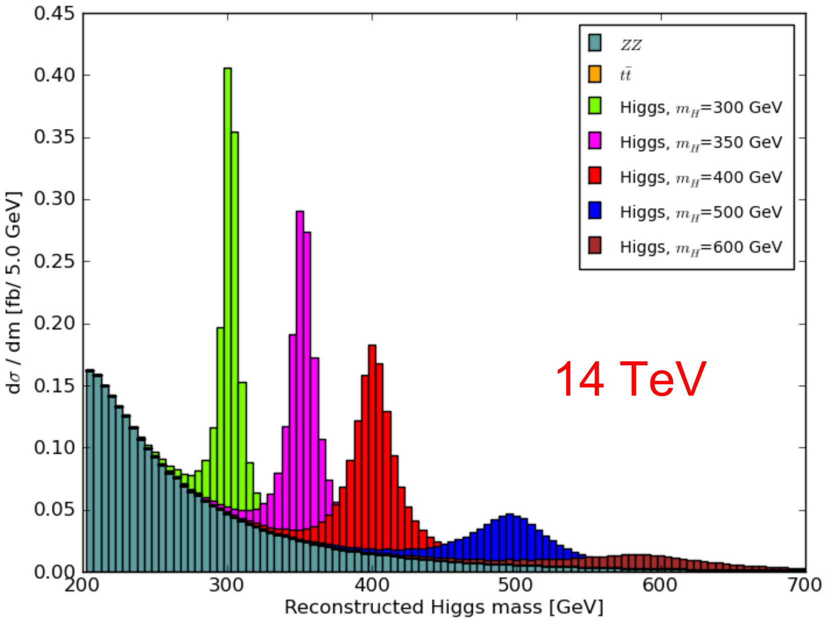
H → ZZ→ 4μ – comparison





	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

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