Particle-level study of non-resonant HH→4b for HL-LHC

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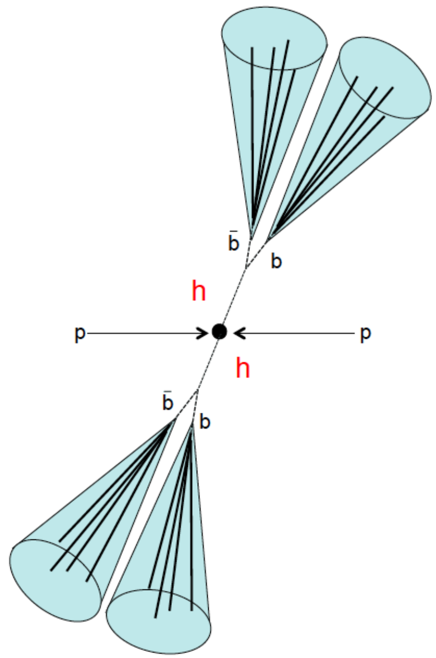
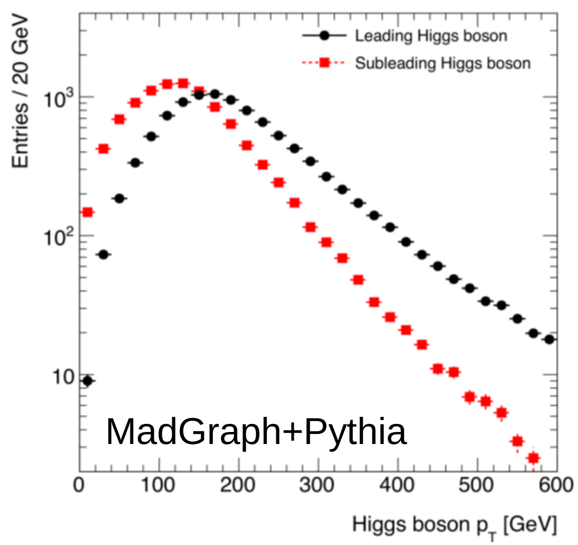
Outline

- Introduction
- Signal kinematics
- Signal and Background samples
- Event selection strategy
- Additional angular and kinematic variables
- Further considerations
- Conclusions

- Non-resonant Higgs-pair production a key goal for HL-LHC
  - NLO cross section ~35fb (e.g. arXiv: 1401.7340)
- HH⟶4b the most abundant final state: BR=$(0.577)^2$=~33%
  - But huge multi-jet and ttbar bkgs
- In arXiv:1307.0407, we showed that boosted X⟶HH⟶4b is a very sensitive topology for resonant Higgs-pair production
  - Using 4 b-tagged anti-k_t R=0.4 (akt4) jets
  - Confirmed by ATLAS and CMS Run-1 results
- But non-resonant HH has also relatively hard p_T spectrum
  - ~36% of events with both p_T>150GeV
  - ~17% of events with both p_T>200GeV
  - ~3% of events with both p_T>300GeV

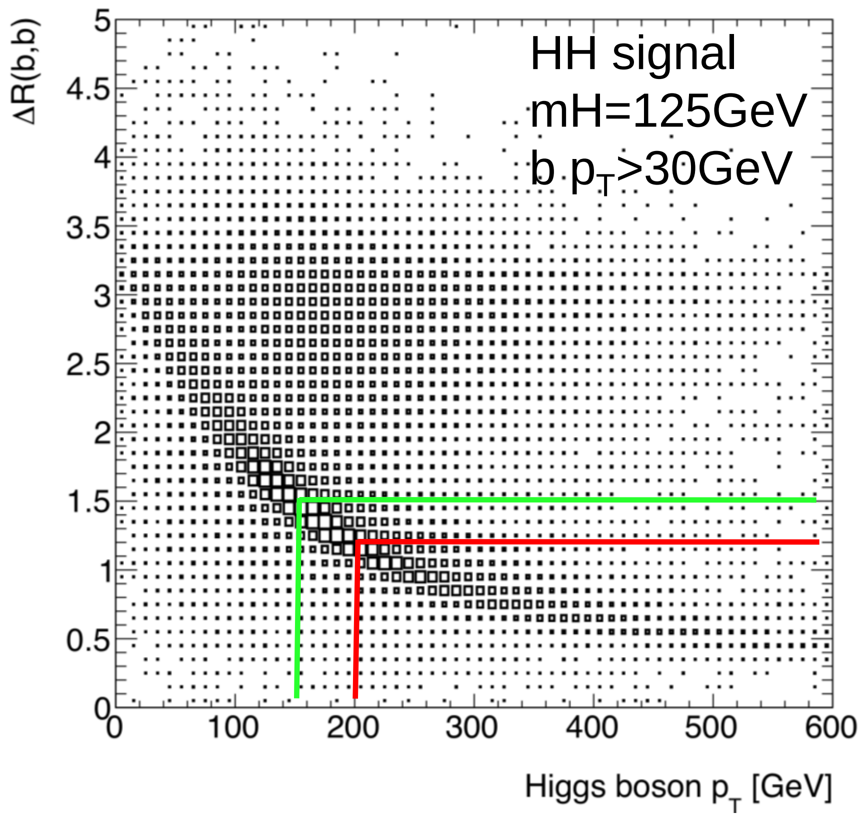


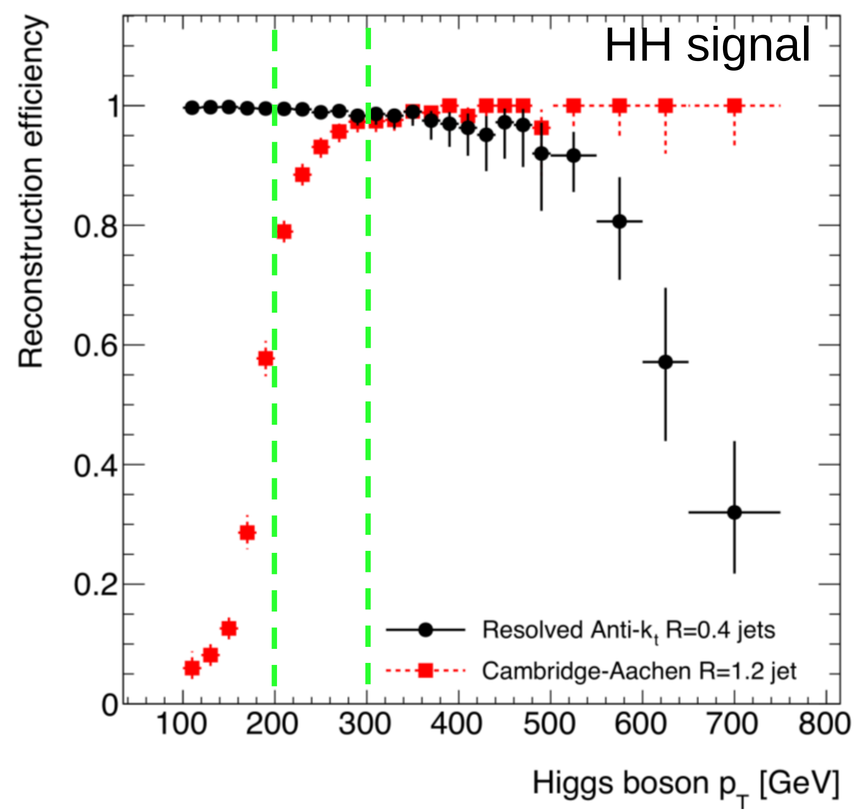


HH→4b kinematics at HL-LHC

□ ΔR between b-quarks from Higgs decay depends on Higgs p_T

- For p_T<~300GeV, it appears more appropriate/efficient to reconstruct the Higgs as two anti-kt R=0.4 jets rather than a single Cambridge-Aachen R=1.2 jet





Signal and Background samples

Process	Generator	PDF set	$\sigma \times$ BR [pb]
$HH \to b\bar{b}b\bar{b}$	MadGraph + Pythia	CTEQ6L1	$1.16 \cdot 10^{-2}$
$b\bar{b}b\bar{b}$	Sherpa	CT10	219
$b\bar{b}c\bar{c}$	Sherpa	CT10	477
$t\bar{t}$	Powheg + Pythia	CT10	212
$ZH \to b\bar{b}b\bar{b}$	Pythia	CTEQ6L1	$3.56 \cdot 10^{-2}$
$t\bar{t}H(\to b\bar{b})$	Pythia	CTEQ6L1	$1.36 \cdot 10^{-1}$
$H(\to b\bar{b})b\bar{b}$	MadGraph_aMc@nlo + Pythia	CTEQ6L1	$4.89 \cdot 10^{-1}$

- bbbb and bbcc filtered to have at least four partons with p_T>30GeV and $|\eta|$<2.7
  - NLO k-factor of 1.5 applied (Phys.Rev.Lett. 107 (2011) 102002)
  - Other multijet bkgs are negligible after b-tagging

- ttbar filtered to have at least one c or τ in the top decays and four partons/taus with p_T>30GeV and $|\eta|$<2.7
  - Others are negligible after b-tagging

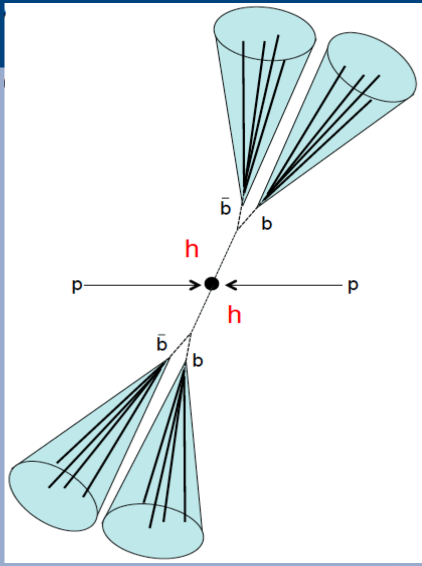
Jet selection

- $p_T > 40$ GeV
- $|\eta| < 2.5$

Event must contain at least four such jets, which are formed into dijets
Event is weighted by $\varepsilon_1\varepsilon_2\varepsilon_3\varepsilon_4$, with $\varepsilon_b = 0.7$, $\varepsilon_{c,\tau} = 0.2$, $\varepsilon_l = 0.01$

Dijet selection

- $p_T > 150$ GeV
- $\Delta R(jet, jet) < 1.5$
- At least two such dijets
- Dijet "12": $|m_{12} - 115| < 25$ GeV
- Dijet "34": $|m_{34} - 110| < 25$ GeV



Results at this point of selection

Requirement	HH	bbbb	bbcc	ttbar	Hbb	ZH	ttH
2 dijets	897	1.54×10^6	3.65×10^5	9.48×10^5	70.5	711	6.77×10^3
2 dijets m_H	628	2.21×10^5	5.18×10^4	2.4×10^5	22.2	290	1.65×10^3

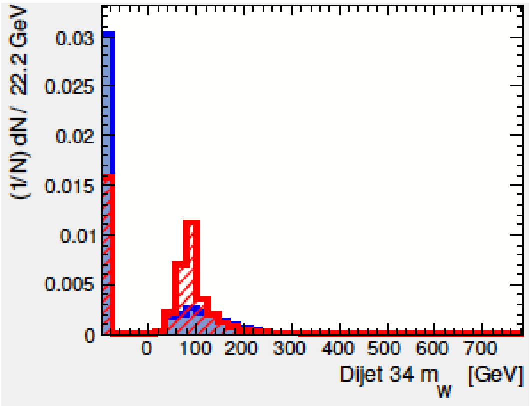
Requirement	S	B	S/B	$S/\sqrt{B}$
2 dijets	897	2.86×10^6	0.000314	0.531
2 dijets m_H	628	5.15×10^5	0.00122	0.876

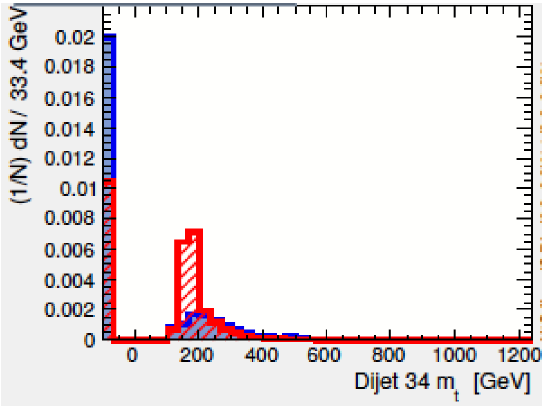
Numbers for 3000fb^{-1}

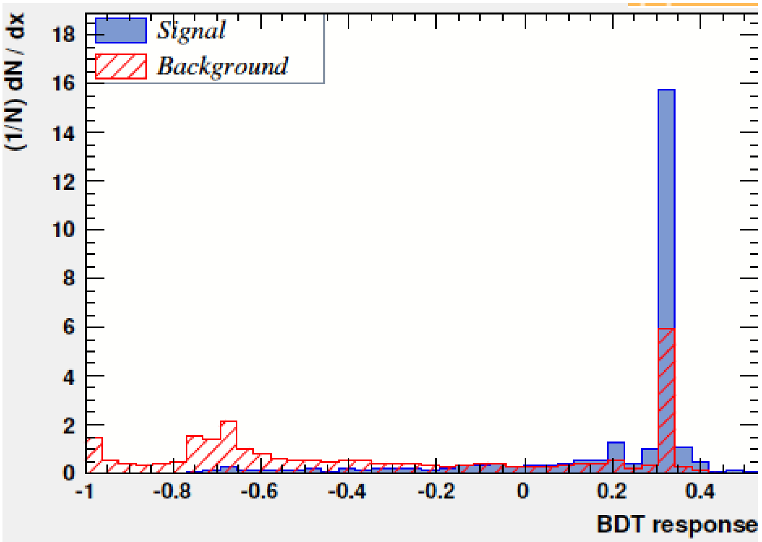
- Main conclusions at this point:
  - bbbb and ttbar dominate and are similar size
  - Single-Higgs processes similar size as signal
  - s/b very small (0.12%) and statistical significance ~0.9σ

Suppressing ttbar (ttbar veto)

- Remaining ttbar events are predominantly bcbc
- Suppress ttbar further by attempting to reconstruct the hadronic top decays
  - For each di-jet:
    - take least b-tagged jet (jet 2), look for nearby ($\Delta R<2$) jet with pT>40GeV(jet 3) and form m_{23} (the W from the top decay) and m_{123} (the top)
  - Form “ttbar veto” MVA







ttbar veto results

Requirement	HH	bbbb	bbcc	ttbar	Hbb	ZH	ttH
2 dijets	897	1.54×10^6	3.65×10^5	9.48×10^5	70.5	711	6.77×10^3
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Top Veto	562	2.01×10^5	4.63×10^4	9.73×10^4	19.5	266	664

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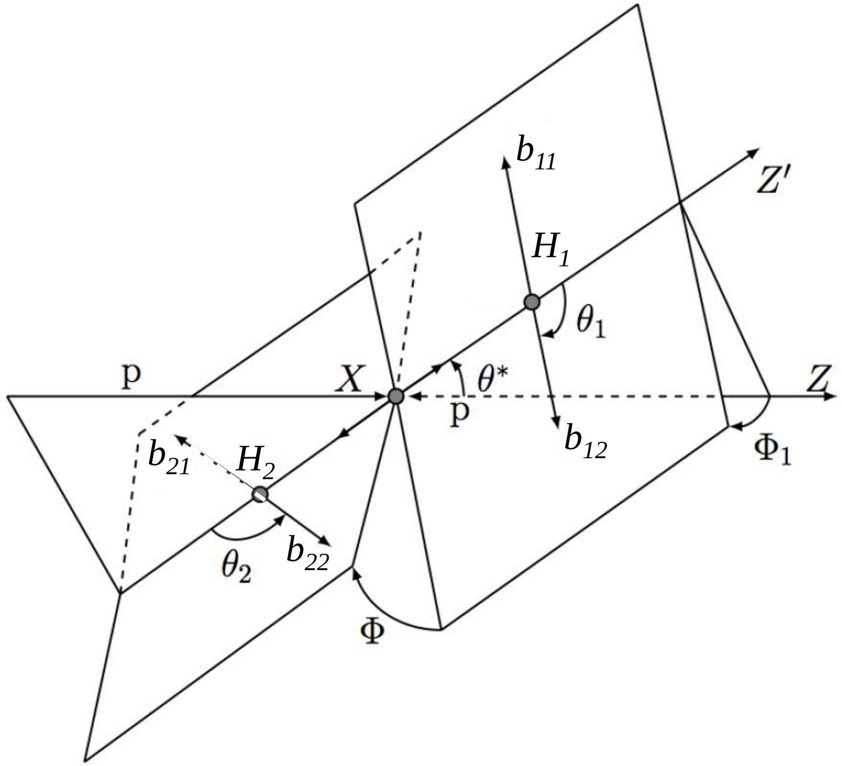
Top Veto	562	3.45×10^5	0.00163	0.956

Numbers for 3000fb^{-1}

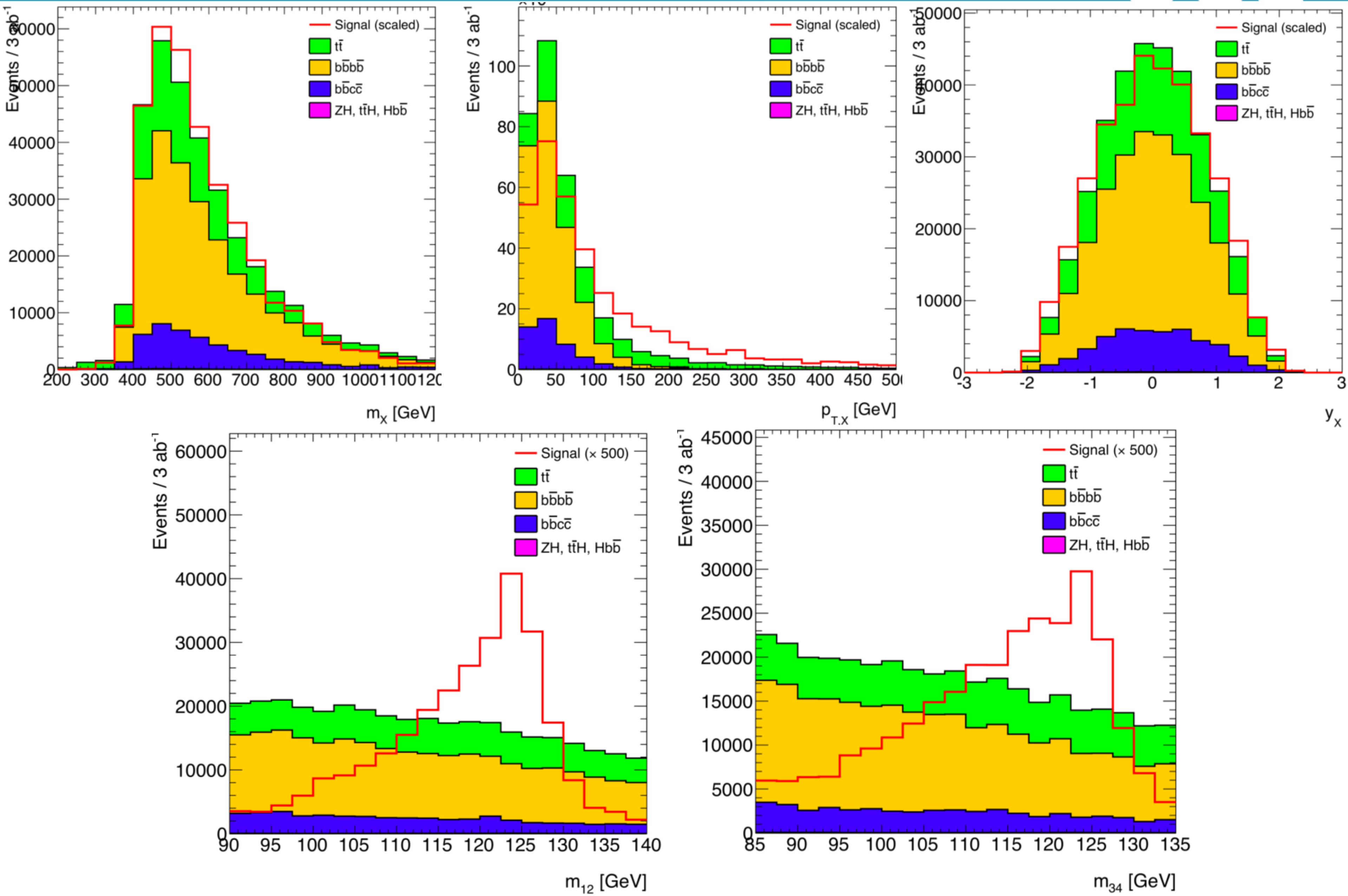
- For 90% signal efficiency, 60% ttbar rejection
- Slight improvement in s/b and statistical significance

Additional angular/kinematic variables

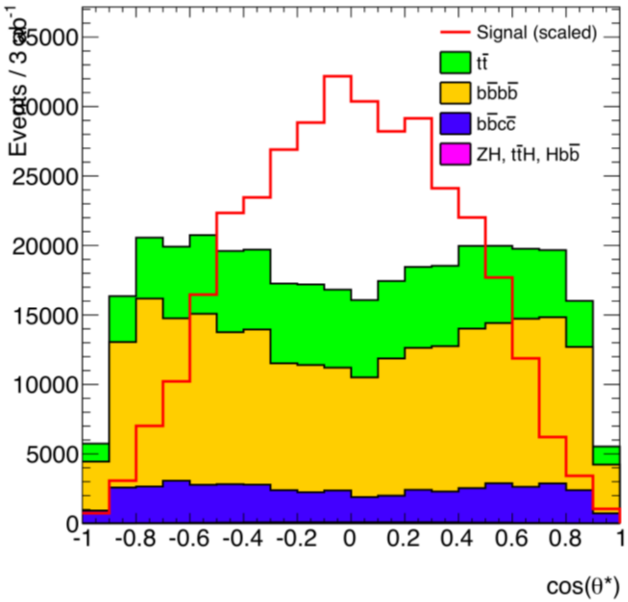


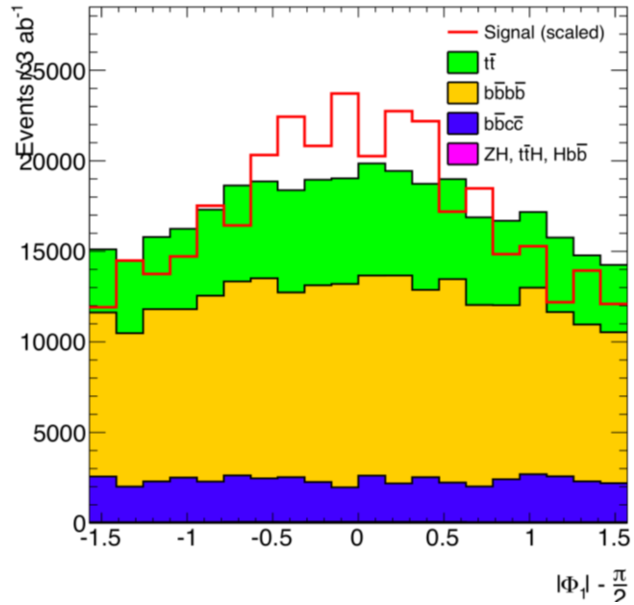
- 10 uncorrelated variables describe fully the kinematic and angular/spin information of the 4b system
  - m, y, p_T of the 4b system and masses of the two dijets
  - 3 decay angles (in resp. rest frames) & 2 angles between decay planes
- Used extensively in H→4leptons channel

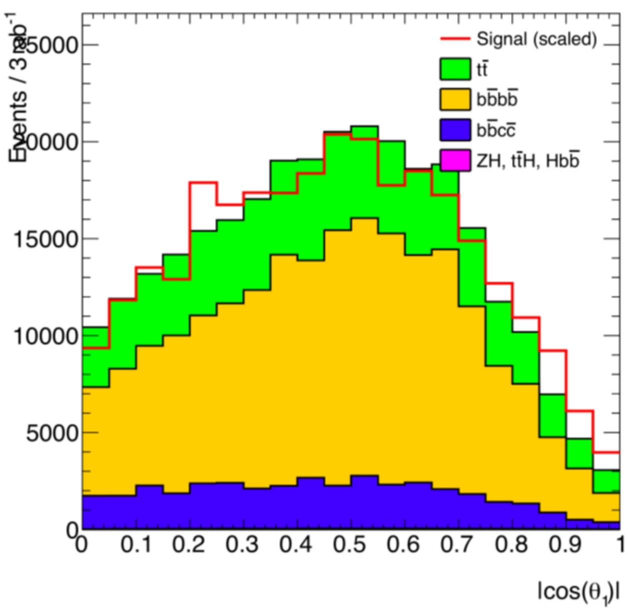
Kinematic variables

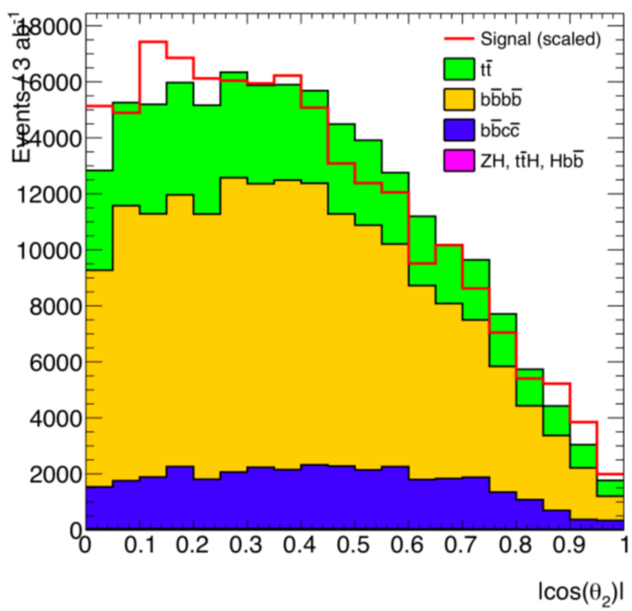


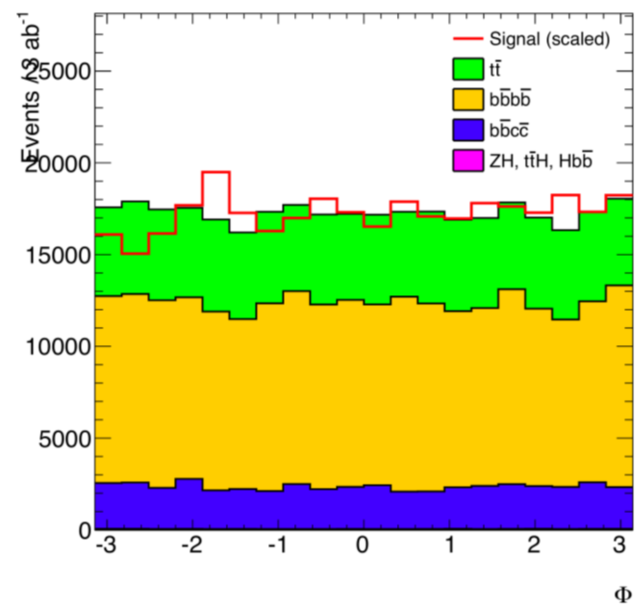
Angular variables



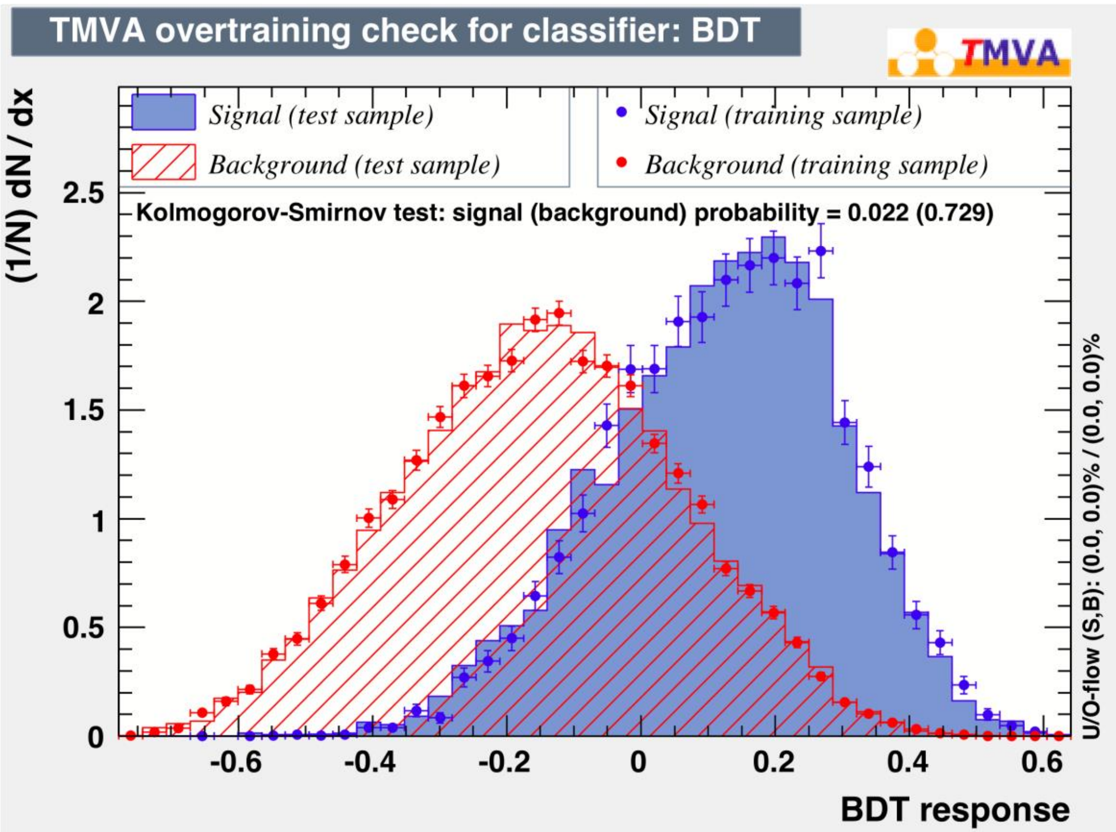


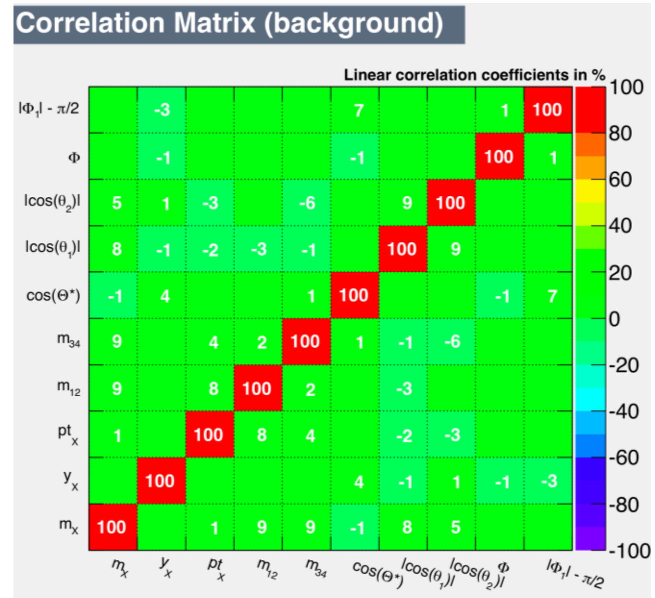


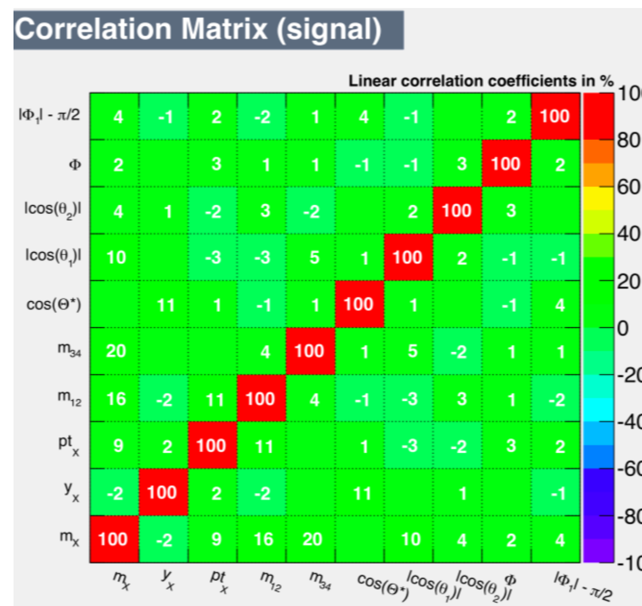




10-var MVA: $\mathcal{D}_{kin}$







Results with 10-var MVA

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Top Veto	562	2.01×10^5	4.63×10^4	9.73×10^4	19.5	266	664
MVA	300	1.52×10^4	3.29×10^3	1.34×10^4	5.51	23.5	202

Requirement	S	B	S/B	$S/\sqrt{B}$
2 dijets	897	2.86×10^6	0.000314	0.531
2 dijets m_H	628	5.15×10^5	0.00122	0.876
Top Veto	562	3.45×10^5	0.00163	0.956
MVA	300	3.21×10^4	0.00932	1.67

Numbers for 3000fb^{-1}

- A nearly ten-fold improvement in s/b and a very substantial increase in the statistical significance
  - ~x3 effective increase in statistics!

Further considerations

- The non-4b backgrounds can be suppressed more by better c/τ-jet rejection and/or by using the full shape of the b-tagging variables
  - E.g. for c/τ-jet rejection factor 10 (instead of 5)
    - the bbcc background becomes 5% of total bkg (instead of 10%)
    - the ttbar is reduced further (but still makes up a sizeable fraction of the total bkg)
    - s/b improves by ~30%
    - the statistical significance becomes ~2σ (instead of ~1.7σ)

- Additional sensitivity by using the full shape of $\mathcal{D}_{kin}$

- The p_T spectrum of the Higgs bosons in the signal holds the key in the sensitivity of the 4b channel

Conclusions

- Observing the SM Higgs-pair production is one of the key targets for HL-LHC, but will be one of the greatest challenges!

- HH→4b is the most abundant final state, but suffers from large backgrounds (multi-jets and ttbar)
  - Boosted topology and 4 b-tags (4 akt4 jets in 2 dijets with pT>150GeV) is the strategy to suppress backgrounds

- The use of 10 uncorrelated angular/kinematic variables offers significant improvement in the sensitivity of the 4b channel
  - ~1.0σ → ~1.7σ (~effective factor ~3 increase in statistics)

- Additional improvements can be achieved when using the full shape of the combined discriminant, as well as the shape of the b-tagging discriminant in the four jets