Higgs heavy flavour decay studies using jet probabilities

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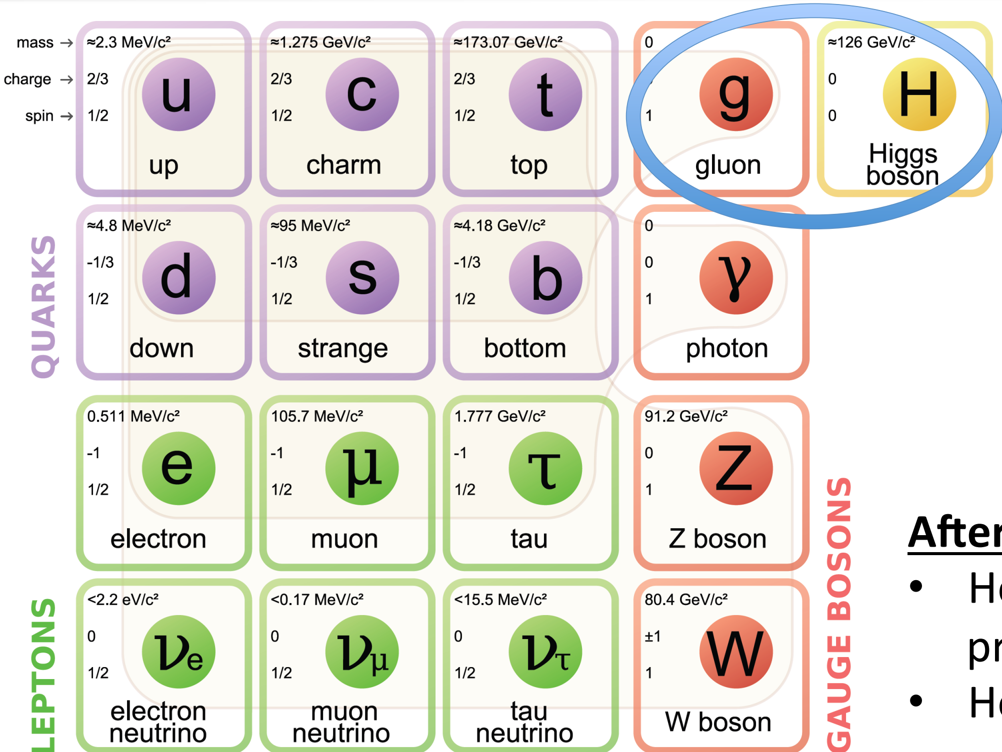
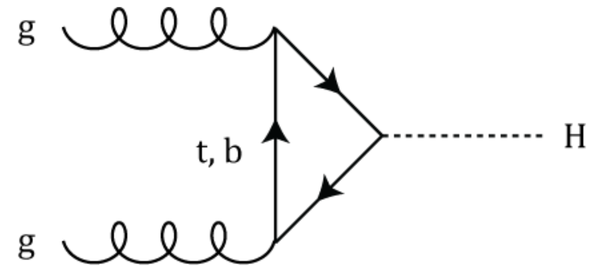
Speaker's affiliations :

LHeC Workshop, Chavannes-de-Bogis, June 25th, 2015

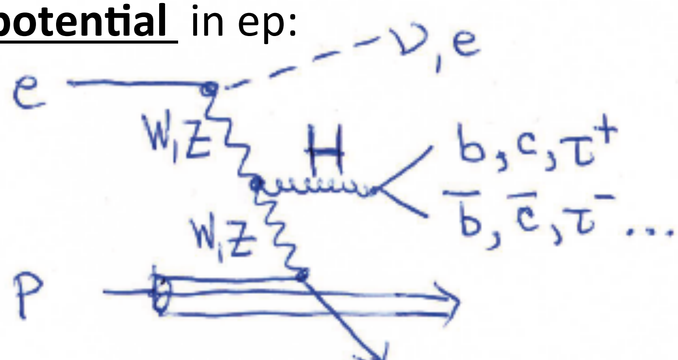
Standard Model Particles & QCD



Higgs discovery at LHC via gluon-gluon fusion



Higgs potential in ep:



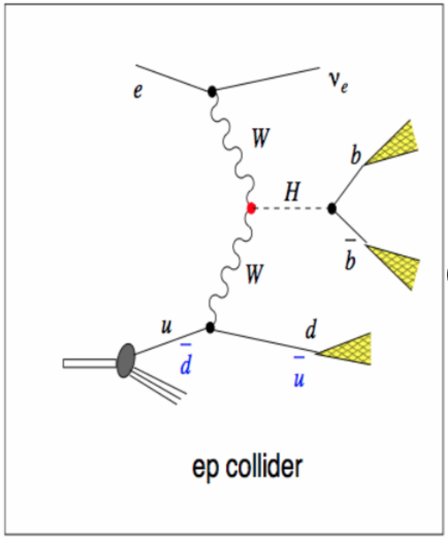
After the Higgs discovery:

- How can we reach a best understanding Higgs properties?
- How can we exploit best our highest energy machines for finding new physics/new particles? Synergies?
- **What role can ep colliders play here?**

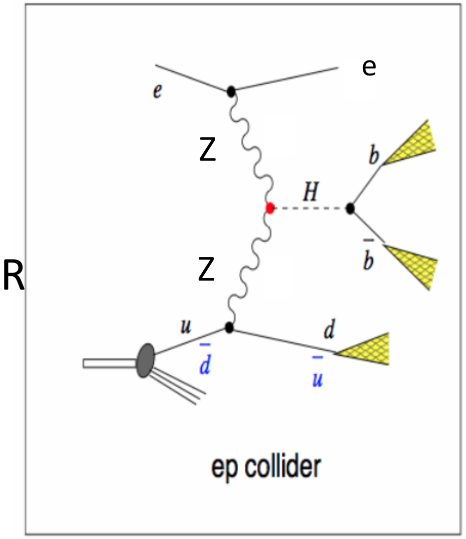
✓ Precision quark-gluon dynamics for sensitive searches (non-resonant NP contributions!).

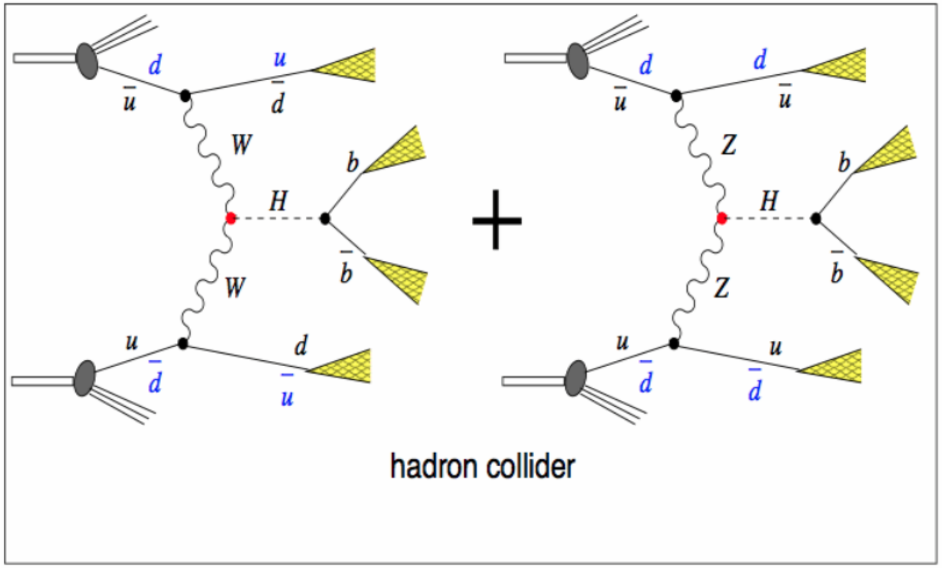
✓ **Compelling synergy for Higgs physics : explore SM Higgs with high precision to use Higgs as a portal to new physics**

VBF Higgs Production in ep (top) and pp (bottom)



OR





Higgs production in ep comes uniquely from either CC or NC

Pile-up in ep at 10^{34} is 0.1 @25ns
Clean(er) bb final state, S/B ~ 1
e-h Cross Calibration → Precision

ep:

Clean, precise reconstruction and easy distinction of WWZ and WWH without pile-up (<~0.1 events)
VBF: Small theoretical uncertainties!

Higgs production in pp comes predominantly from gg→ H

VBF cross section about 200fb (about as large as at the LHeC).

Pile-up in pp at 5 10^{34} is 150,@25ns
S/B very small for bb

Precision needs accurate PDFs & αS

CC DIS : SM Higgs in ep … and P_e=-0.8

M_h=125 GeV
polarised lepton beam

	E_e=60 GeV : √s= **1.3 TeV**				E_e=60 GeV : √s=**3.5 TeV**			
	CC e^-p	CC e^+p	NC ep	CC hh	CC e^-p	CC e^+p	NC ep	CC **hh**
cross section [fb]	109	58	20	0.01	566	380	127	0.24
polarised cross section [fb] P=-80%	**196**	N.A.	25	0.02	**1019**	N.A.	**229**	**0.43**

7 TeV LHC protons | **50 TeV FCC protons**

and

electrons from a 60 GeV energy recovery LINAC

ep Higgs "Facility" @ 1 ab^{-1}

→ **for first time a realistic option of an 1 ab^{-1} ep collider** (stronger e-source, stronger focussing magnets) and **excellent performance of LHC** (higher brightness of proton beam); ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

√s= **1.3 TeV**

→ need of different models :
cc: 'sm-full'

gg, γγ: **'heft'**

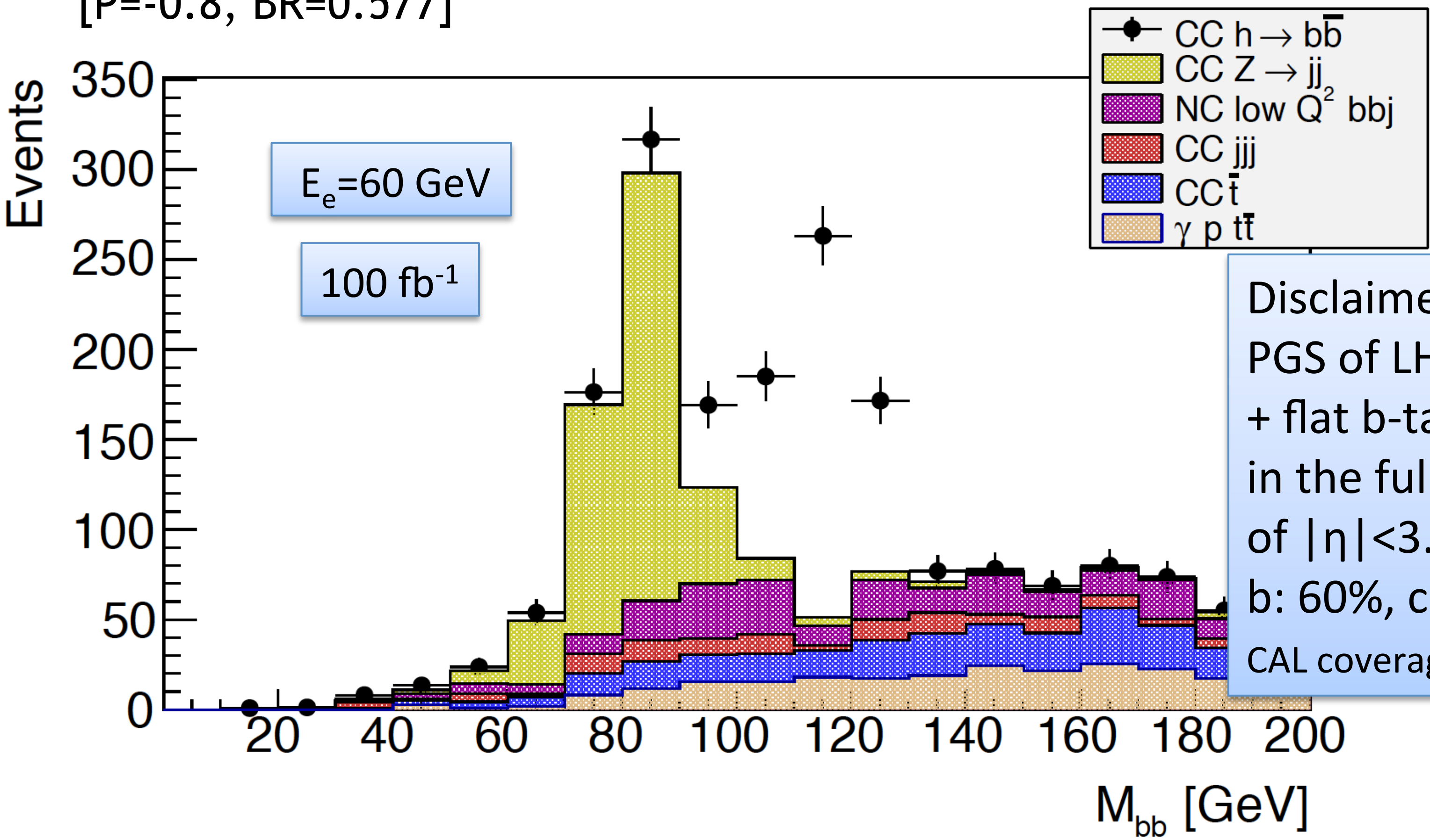
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

Ultimate polarised e-beam of 60 GeV and LHC-p beams, 10 years of operation

➔ **Decay to bb is dominating HFL decay modes :**
Higgs decay to cc is factor 20 less likely than Hbb **times the ratio of detection efficiencies-squared !**

ICHEP14 poster H→$b\bar{b}$ results

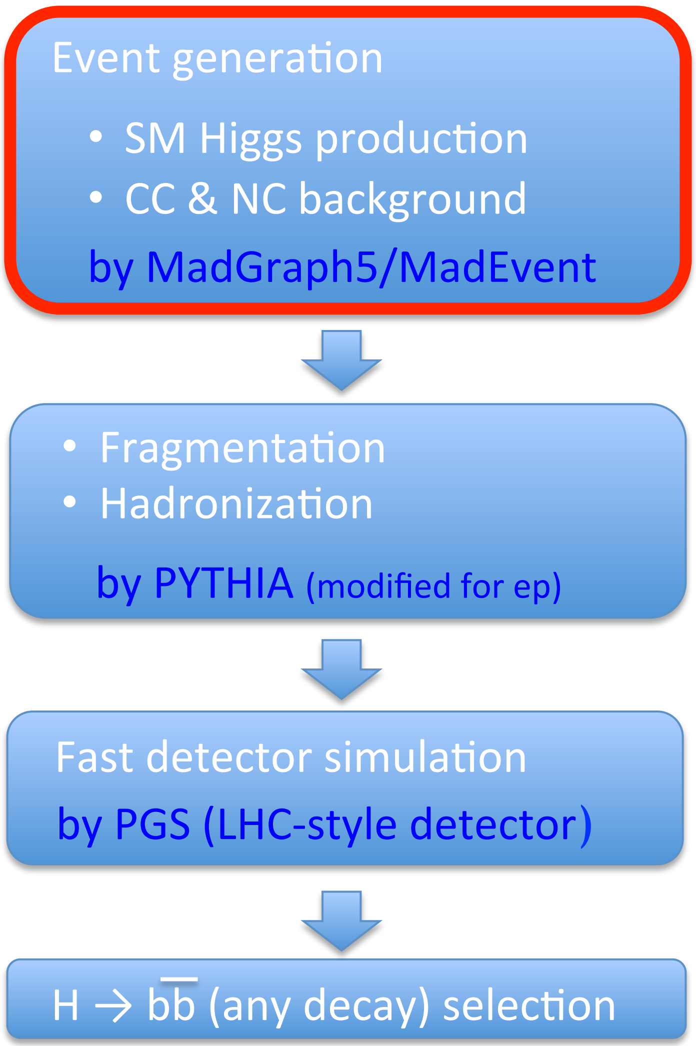
[P=-0.8, BR=0.577]



Disclaimer :
PGS of LHC detector
+ flat b-tagging
in the full tracking range
of |η|<3.0
b: 60%, c: 10%, udsg: 1%
CAL coverage until |η|<5.0

- → Master thesis Ellis Kay, University of Liverpool 2014, together with U. Klein
- → Dedicated background sample production including a first emulation of PHP background using either very low Q NC events or a monochromatic Photon beam of $0.8*E_e$
- → **Using parton-level b, c and light quark tags** and cut-based analysis
- → **a parton-tag will not be trusted for Hcc prospects and plain cuts are too harsh for Hcc**
- ➔ **use a real experimental method for HFL tagging based on jet lifetime probabilities**

Analysis framework - new developments



- Calculate cross section with tree-level Feynman diagrams using <u>pT of scattered quark as scale (CDR $\hat{s}$)</u> for ep processes like single t, Z, W, H

→ Standard HERA tools can NOT to be used !

- **NEW:** full update for Madgraph5 (CDR MG4)
- **Higgs mass 125 GeV as default for sm and sm-full** (for Hcc)→ BR corrected to 'best' HDECAY
- Fragmentation & hadronisation uses ep-**<u>customised</u>** <u>Pythia</u>.
- **NEW: interface to Delphes 'detector' →displaced vertices and signed impact parameter distributions!**

➔ powerful method to optimise detector tuning and S/N for various Higgs decays

Valid for ep only. Any other model (UFO) can be easily tested ➔ non-SM higgs, SUSY etc.

[eA needs modelling of nuclear fragmentation]

New developments … cont'd

- MG5 v2.1.1 PHP HFL production cross sections validated versus Pythia for HERA energies – done together with Olaf Behnke
- Dedicated signal and background samples produced – done together with Ellis Kay (Master thesis Liverpool, 2014)

➔ Pythia files available on Lxplus : 50 GB (*hep format)

➔ Pythia *hep files can be used by other analysers (c.f. M. Tanaka talk) and for full detector simulation tests (dd4hep, c.f. talk by A.Gaddi/P. Kostka)

- Various Delphes detector samples e.g. for different vertex resolutions, b-tagging etc (multiple x 50 GB for Delphes root files) – done together with Ellis Kay (CERN LHeC summer student 2014) and Alan Chan (Master thesis Liverpool 2015)
- **Huge amount of code development to prepare jet lifetime tagging and neural network analysis since last Summer**

Basic detector setup

60 GeV x 7000 GeV

see also M. Tanaka's talk

100 fb^{-1}

- CMS-like detector, B=3.8 T
- Generated and reconstructed jets with anti-kt R=0.9
- for generated and reconstructed jets : optional flat b and c-tagging up to eta=5 and pTjet>5 GeV based on partons ➔ used for cross checks ONLY!
- Fine 'LheC' calorimeters of 0.025 x 0.025 in eta and phi (c.f. Max Klein : 252 phi and 400 eta cells)
- Charged particle tracking up to eta=4.7
- Tracking and electron ID efficiencies set to 1
- ATLAS-style vertex resolution of 5 μm for p_T>5 GeV and 10 μm for p_T<5 GeV

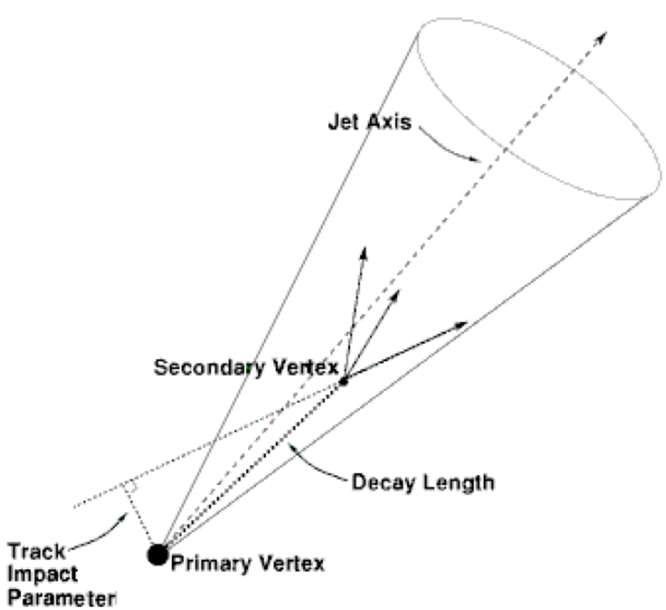
➔ code development for basic signed impact parameters and jet lifetime tags a la D0 and ATLAS

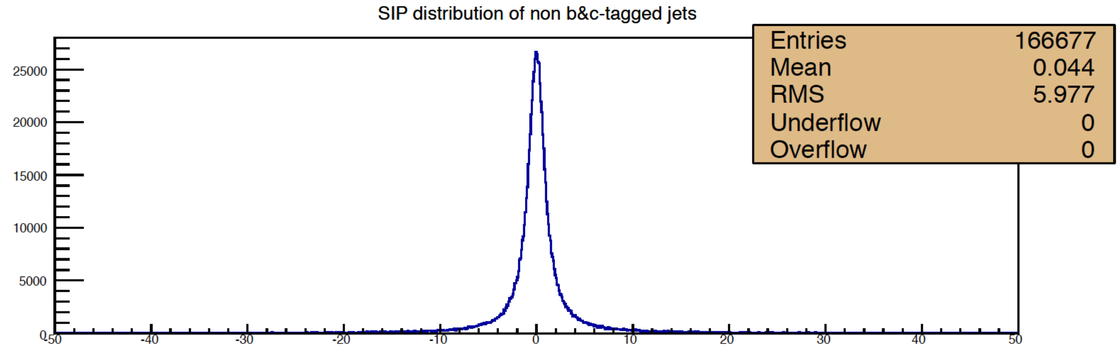
CC ep → jjj + $E_{T,miss}$: Signed impact parameter

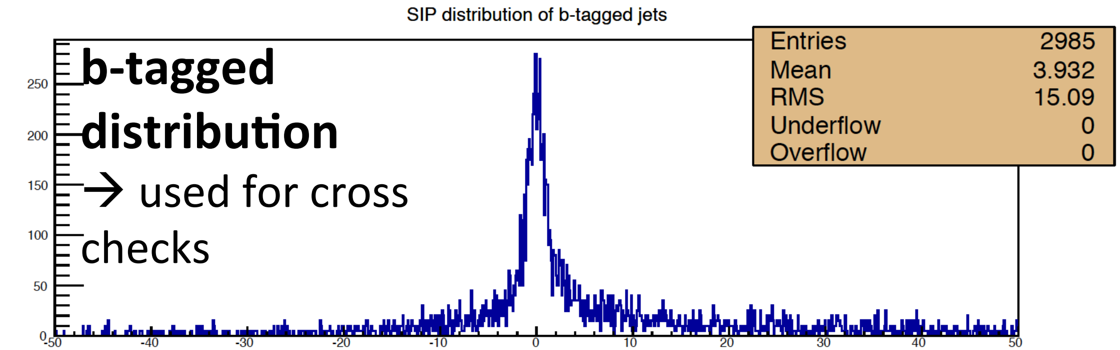
Light quarks and gluons

→ used for an unbiased track probability (no top, no higgs in CC jjj sample), isotropic distributions for all flavours

→ **Fit: Gaussian + 2 exponentials**

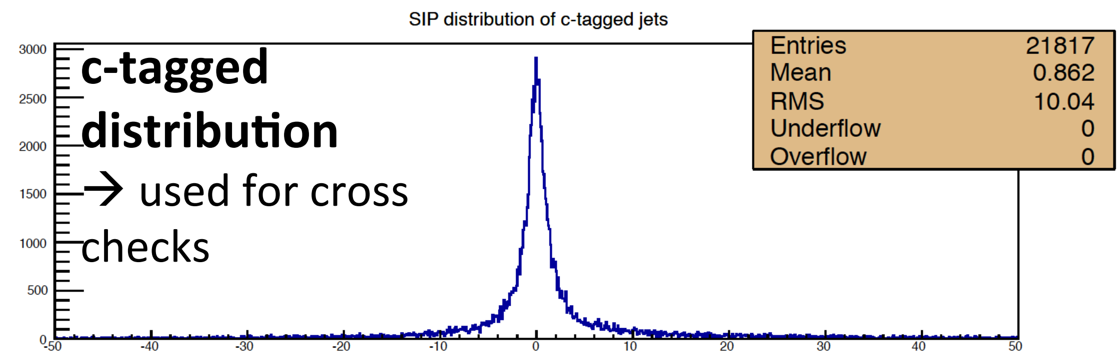






b-tagged distribution

→ used for cross checks



c-tagged distribution

→ used for cross checks

Track lifetime probability

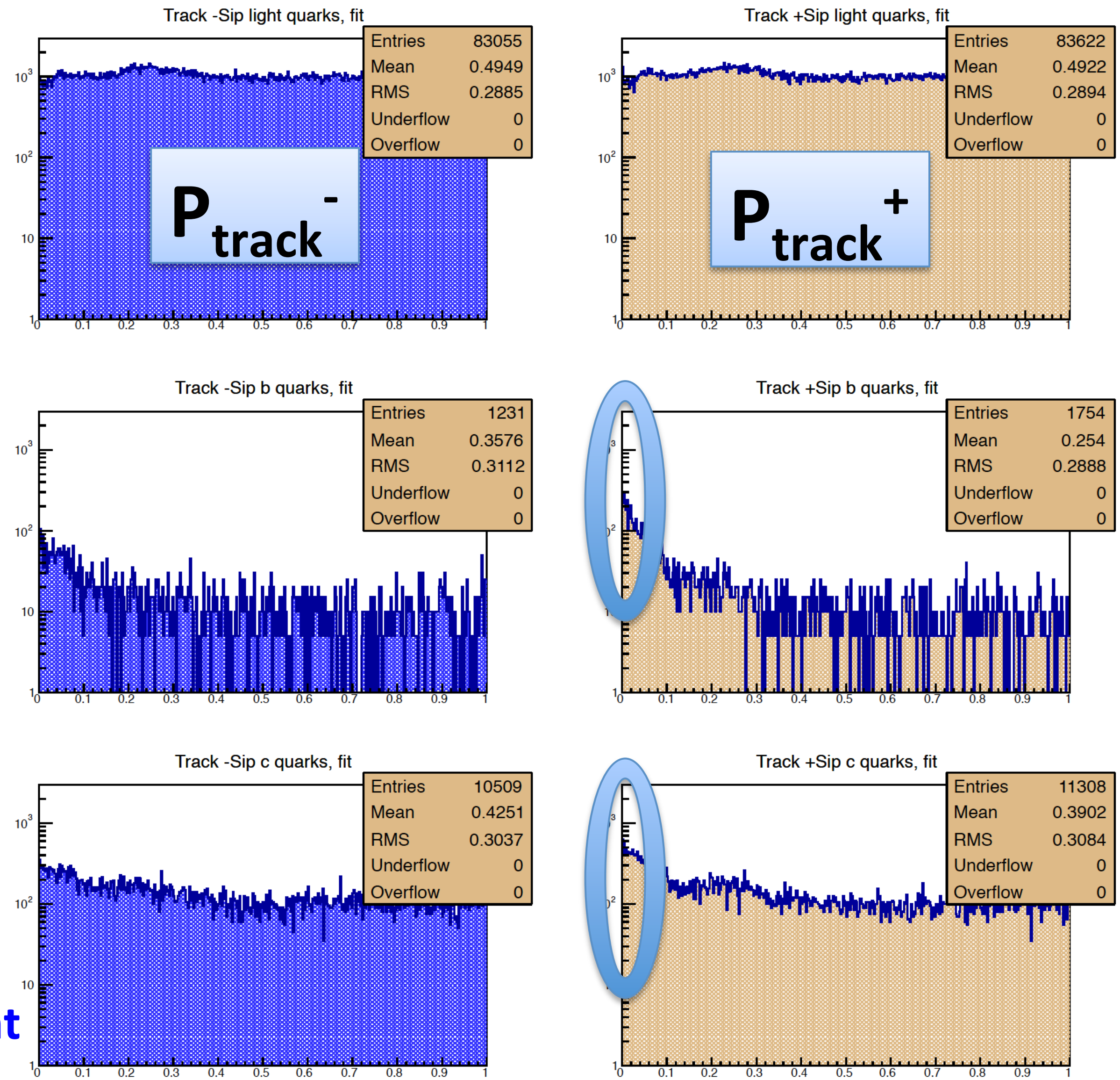
$$\mathcal{P}_{trk}(\mathcal{S}_{IP}) = \frac{\int_{-30}^{-|\mathcal{S}_{IP}|} \mathcal{R}(s)ds}{\int_{-30}^{0} \mathcal{R}(s)ds} ,$$

Light quarks and gluons
→ fast integration of SIP fit *mandatory!*

b-tagged distribution
→ used for cross checks

c-tagged distribution
→ used for cross checks

HFL tracks have a very low light track probability as expected.



Jet lifetime probability

Then all N_{trk}^{+} (N_{trk}^{-}) tracks in the jet, with a positive (negative) IP significance, can be used to compute a jet lifetime probability $\mathcal{P}_{jet}^{+}$ ($\mathcal{P}_{jet}^{-}$) [4]:

$$\mathcal{P}_{jet}^{\pm} = \Pi^{\pm} \times \sum_{j=0}^{N_{trk}^{\pm}-1} \frac{(-\log \Pi^{\pm})^{j}}{j!} \quad \text{with} \quad \Pi^{\pm} = \prod_{i=1}^{N_{trk}^{\pm}} \mathcal{P}_{trk}(\mathcal{S}_{IP<0}^{IP>0}) \ . \tag{5}$$

Using light quark distributions in denominator, and SIP of track in numerator

➔ I used range -50 to 50 µm

$$\mathcal{P}_{trk}(\mathcal{S}_{IP}) = \frac{\int_{-30}^{-|\mathcal{S}_{IP}|} \mathcal{R}(s)ds}{\int_{-30}^{0} \mathcal{R}(s)ds} \ ,$$

<u>**The Multi-step procedure at a glance:**</u>

1) obtain the SIP of tracks of the jet (NEW code!! using TREF arrays) → FIT

2) using the SIP fit: determination of track lifetime probabilities

3) determination of the jet lifetime probabilities based on track lifetime probabilities

➔ tracks in jets with deltaR<0.5 → details of track selection matter a lot

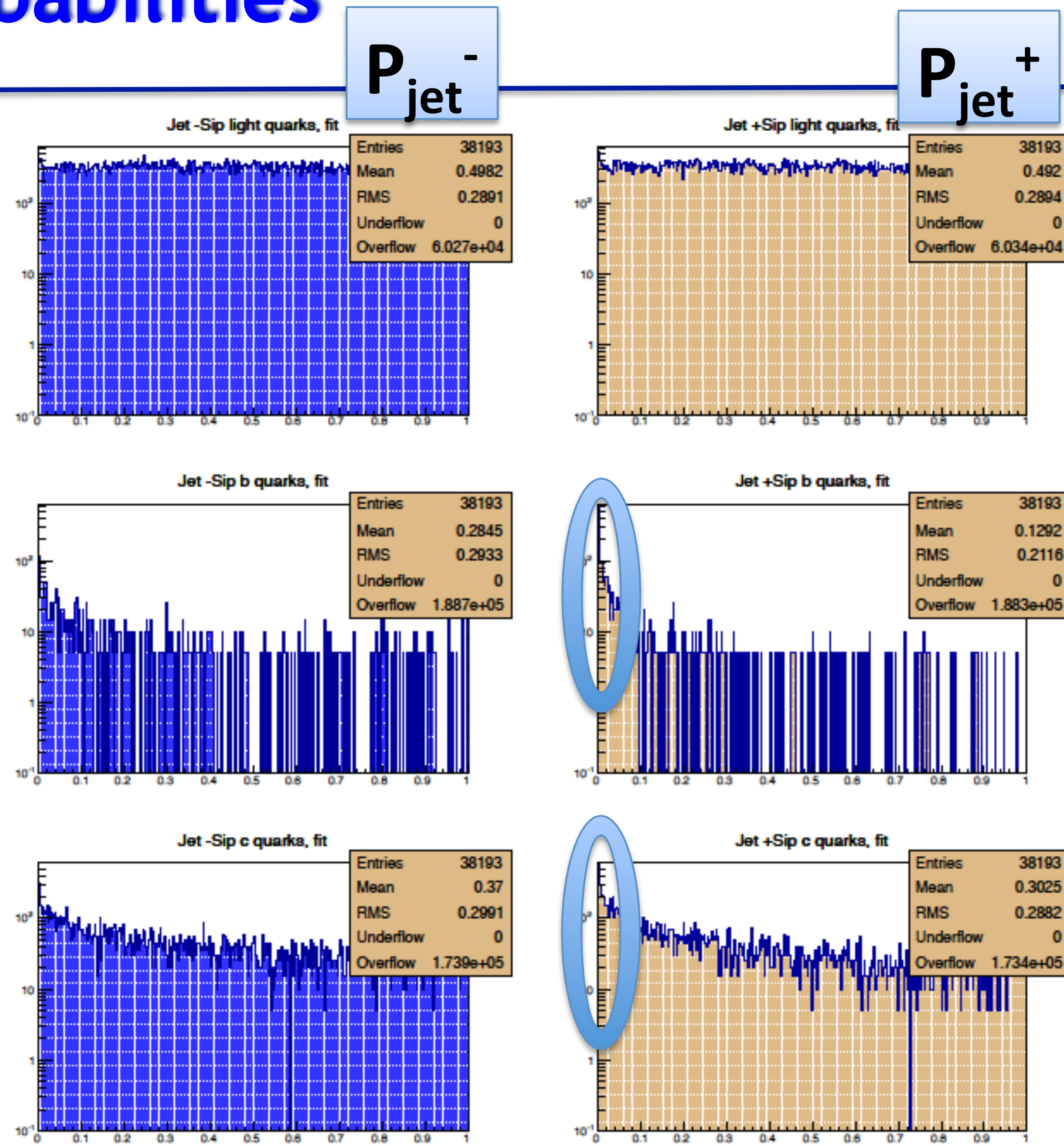
4) pass events to TMVA (BDT) to select signal and background events

Jet lifetime probabilities

light quarks and gluons

➔ **determination of the jet lifetime probabilities based on track lifetime probabilities**

➔ ***tracks in jets with deltaR<0.5***



b-tagged distribution

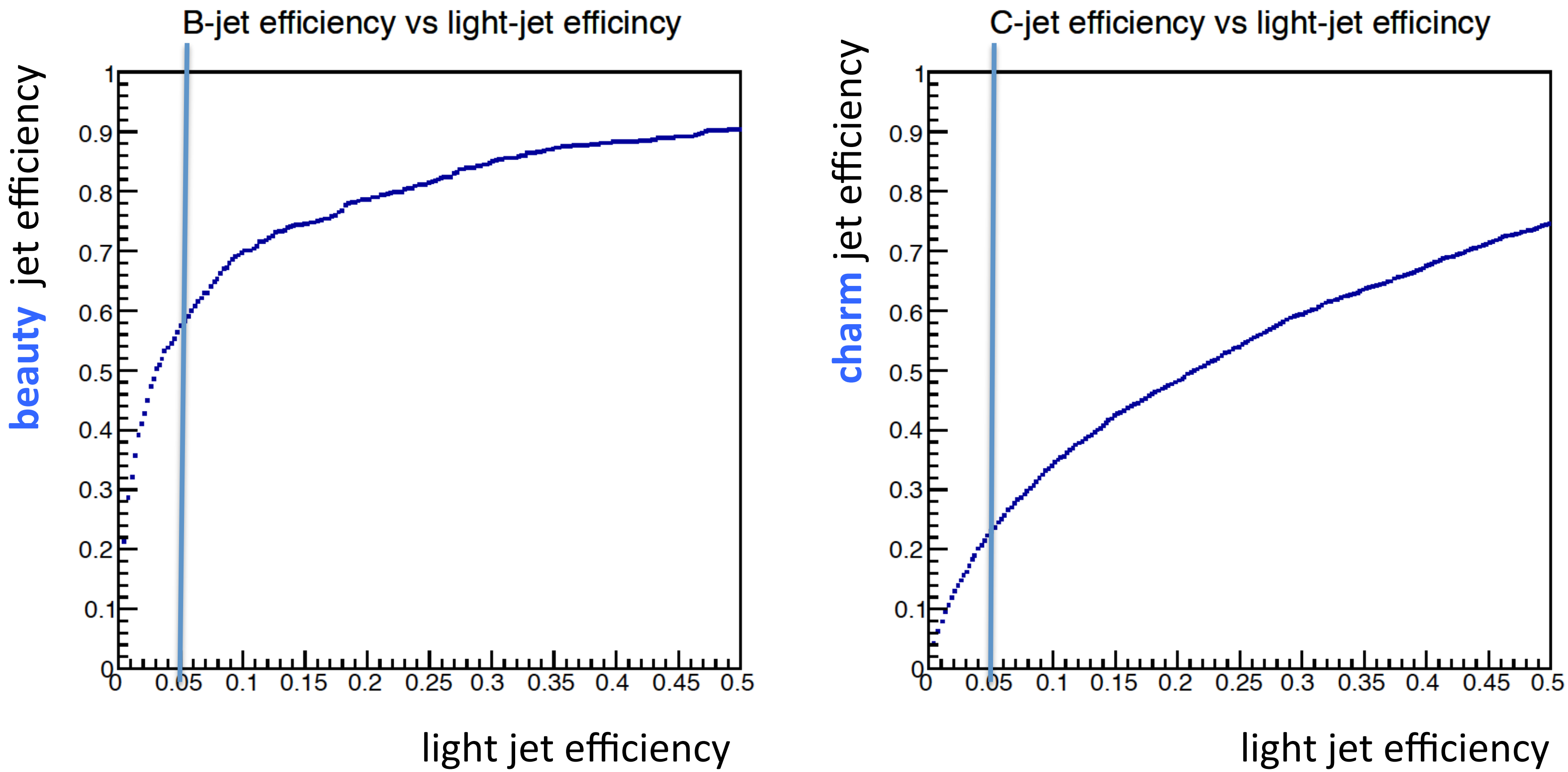
→ used for cross checks

c-tagged distribution

→ used for cross checks

HFL jets have a very low light jet probability as expected.

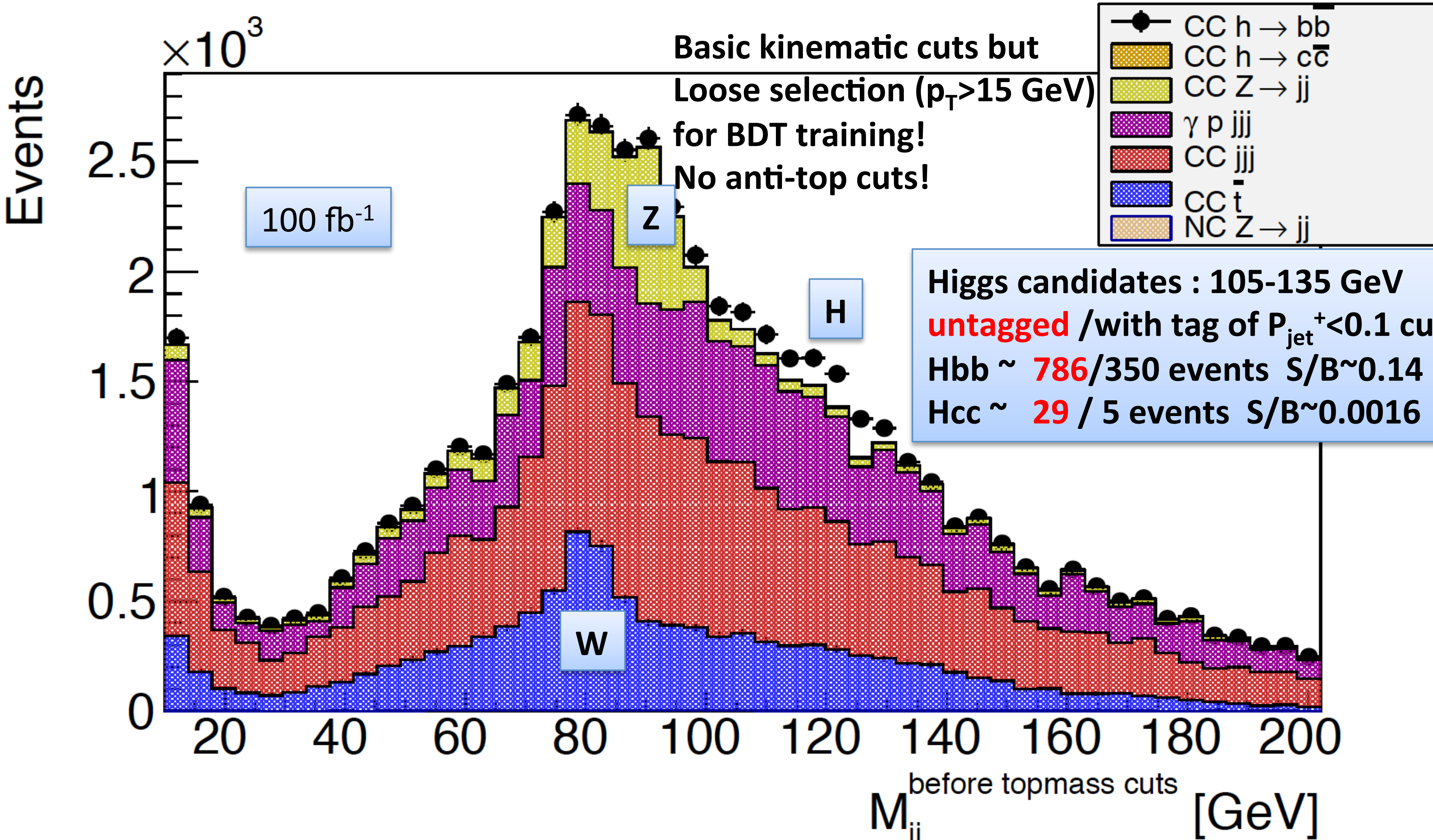
Work in Progress : HFL tagging efficiency



→ 2 dimensional efficiency plot → **B-tag efficiency is 60% & C-tag efficiency is 24%** but light jet efficiency is 5% still with this 'detector' setup (results are very similar to ATLAS)

→ **Ongoing : Further improve analysis & improve vertex resolution further using 2 prong approach : detector development and exploring existing vertex resolution parameterisations in Delphes for 'faster' optimisation**

Dijet Mass : two lowest eta jets - *untagged*



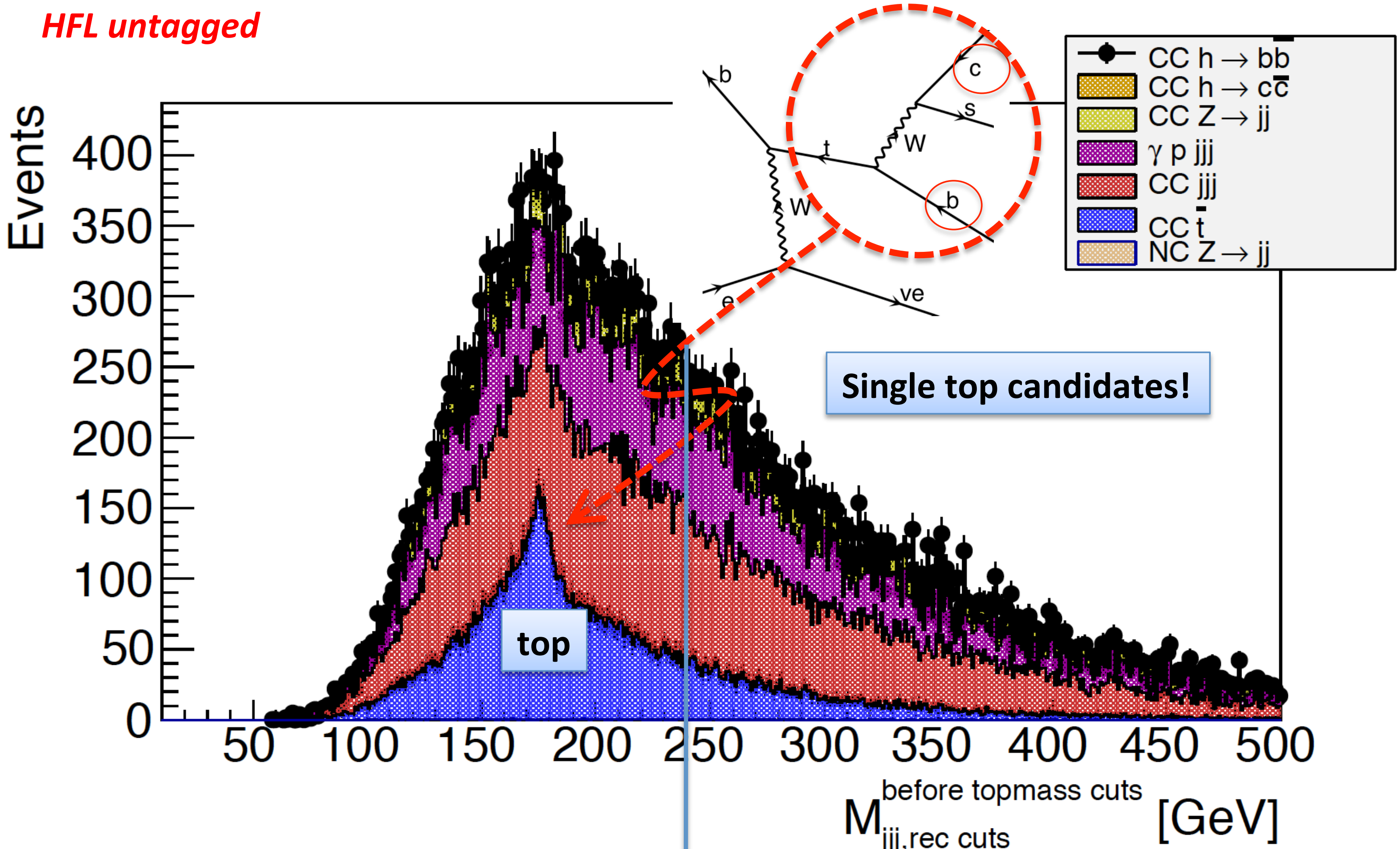
Basic kinematic cuts but Loose selection (p_T>15 GeV) for BDT training! No anti-top cuts!

Higgs candidates : 105-135 GeV
untagged /with tag of P_{jet}^{+}<0.1 cut
Hbb ~ 786/350 events S/B~0.14
Hcc ~ 29 / 5 events S/B~0.0016

Note : Photoproduction background is assumed to be untagged ('worst' scenario)!
→ addition of electron taggers will reduce the PHP considerably

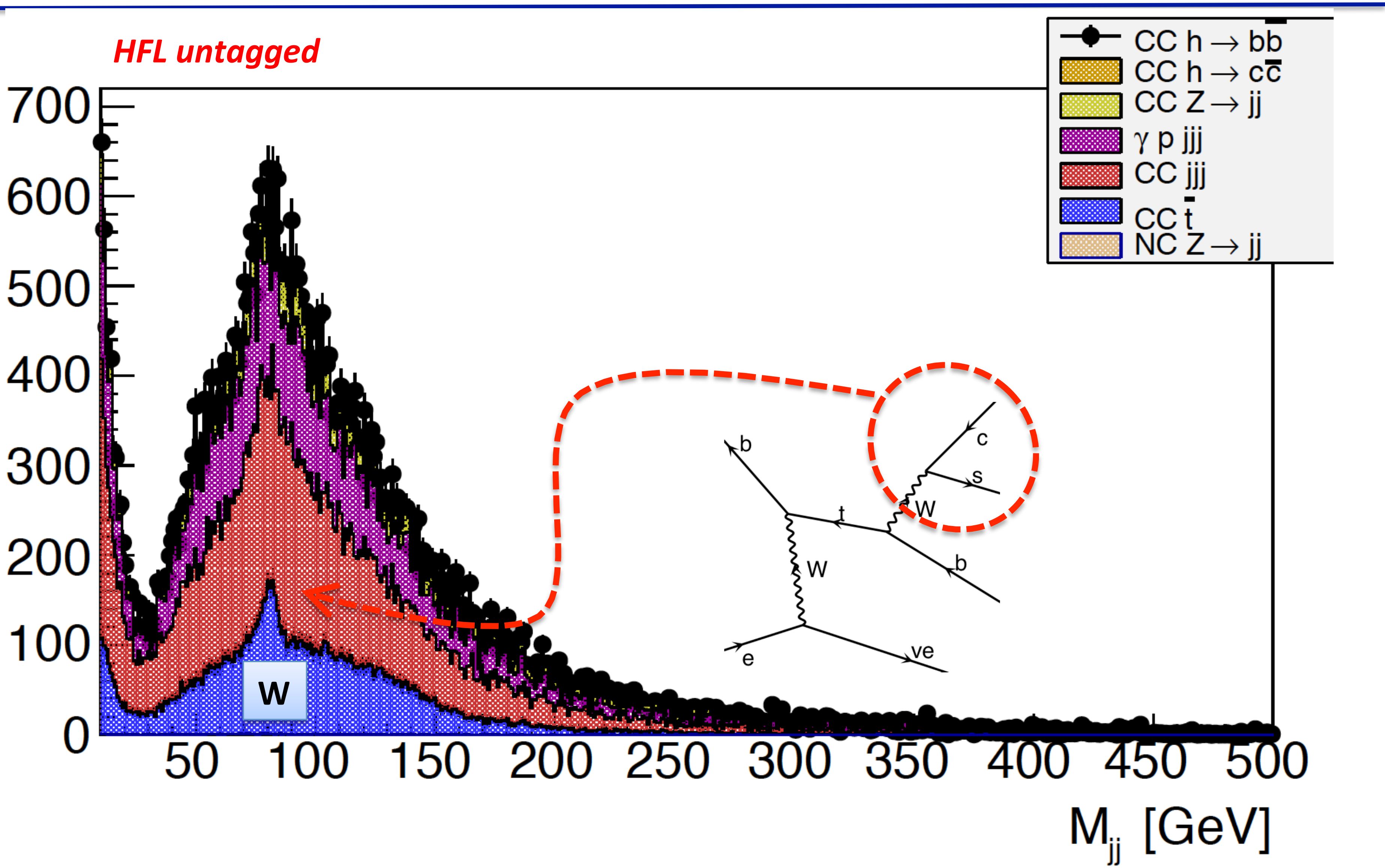
Top: Mass of three highest pT jets

HFL untagged



➔ usual cut to accept Higgs candidates BUT on cost of signal efficiency

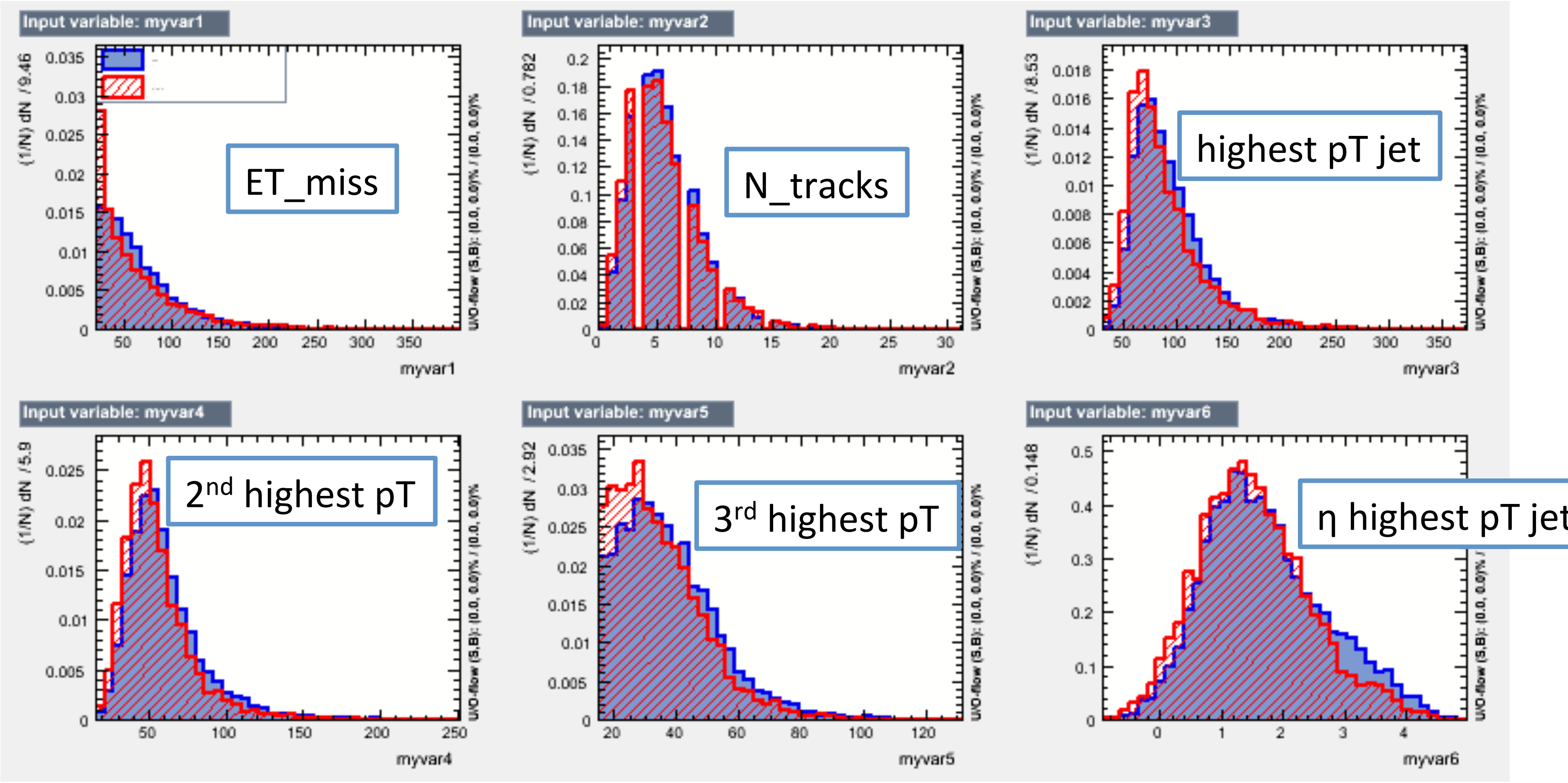
Dijet Mass : 2nd and 3rd lowest eta jet



BDT training - using 26 variables

Variables 1-6

105 < M_{jj} < 135 GeV



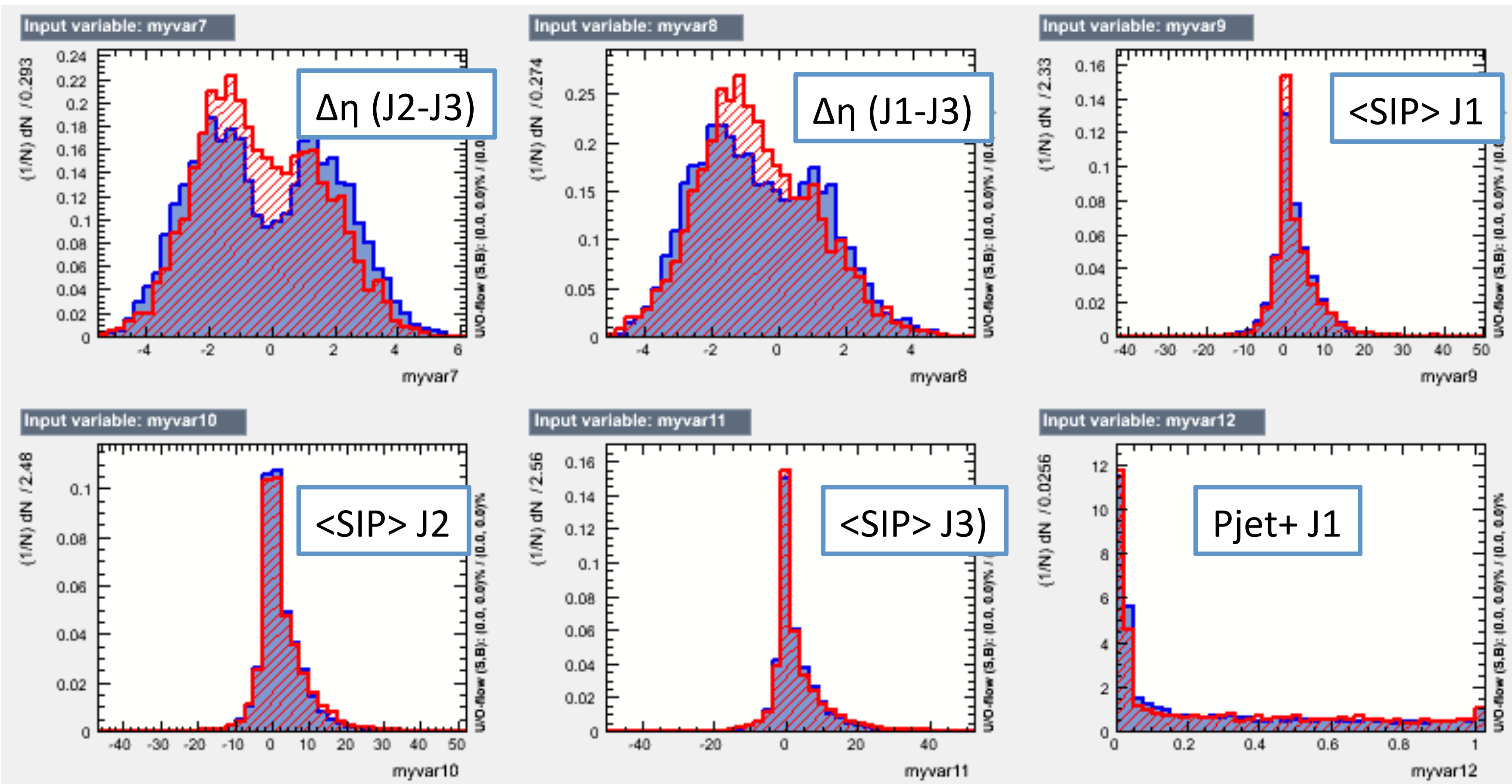
Blue : Signal

Red : Background

Variables 7 - 12

Blue : Signal
Red : Background

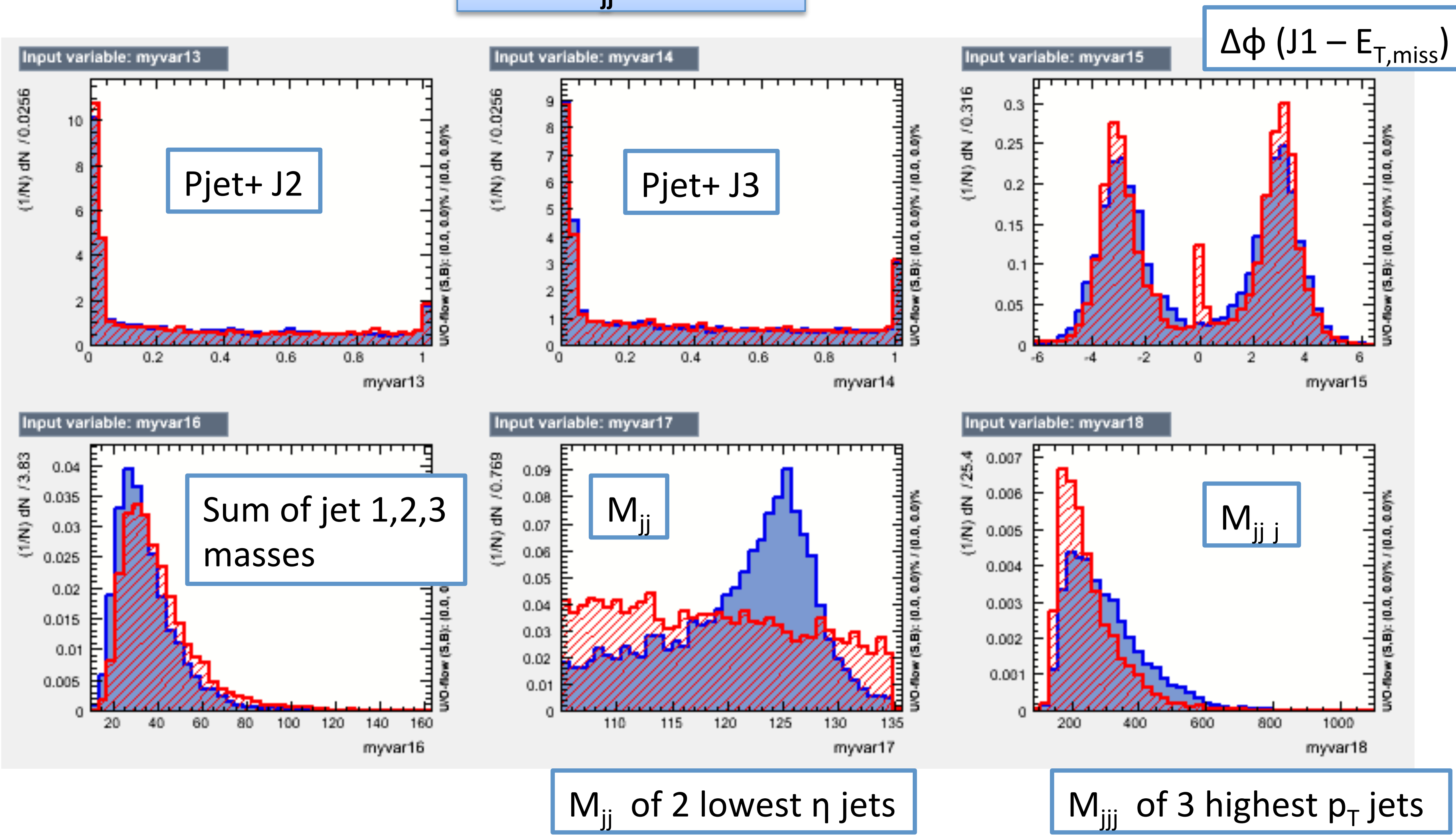
105 < M_{jj} < 135 GeV



Variables 13-18

Blue : Signal
Red : Background

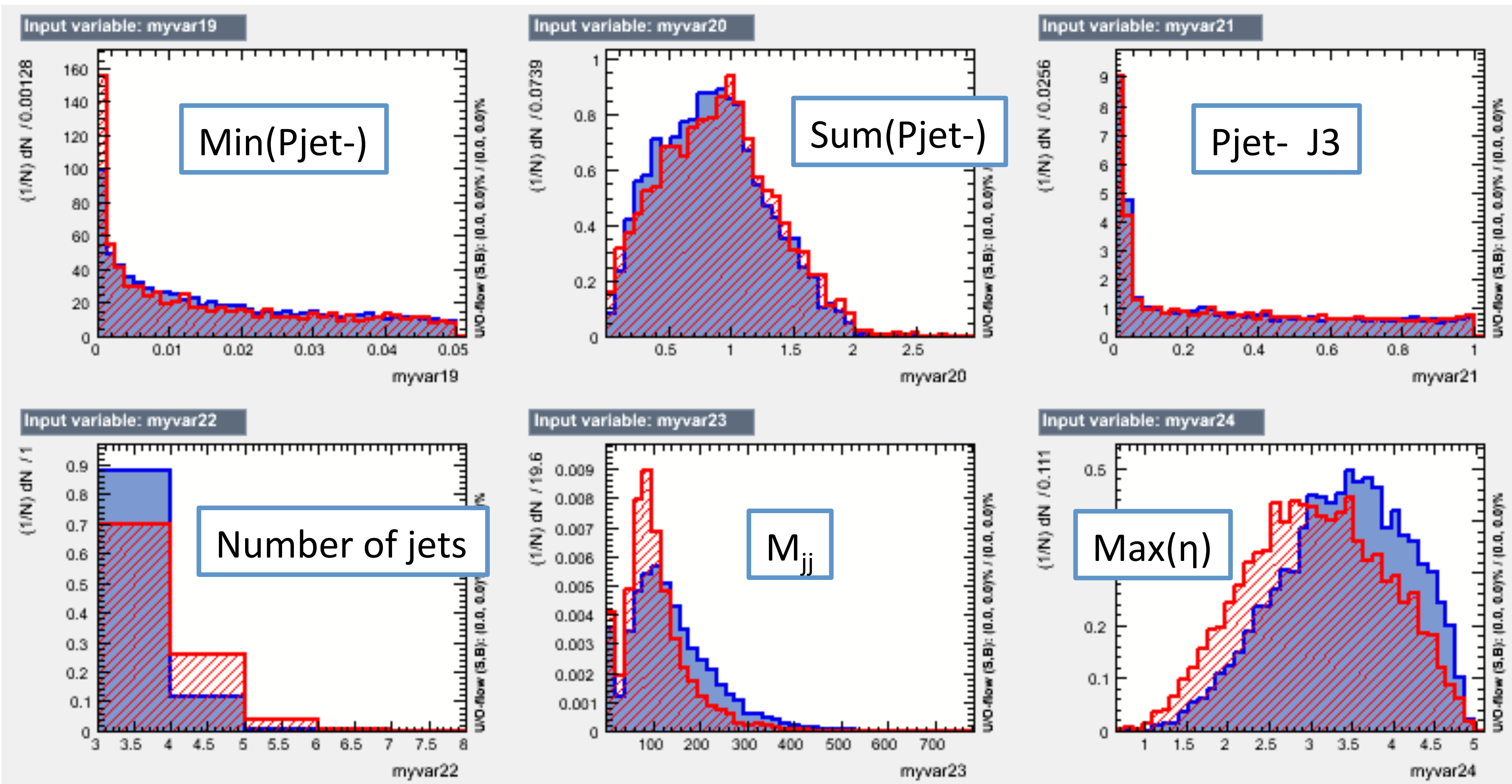
105 < M_{jj} < 135 GeV



Variables 19-24

Blue : Signal
Red : Background

105 < M_{jj} < 135 GeV



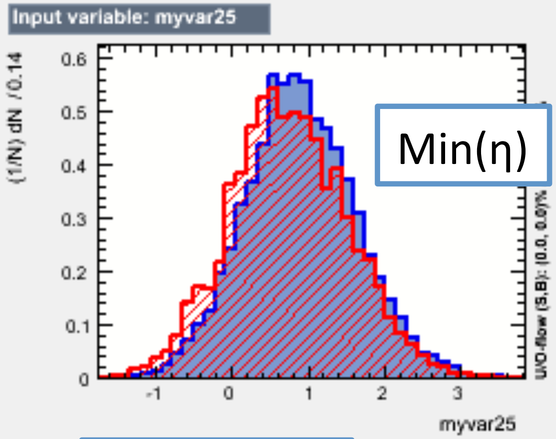
M_{jj} of 2[nd] and 3[rd] lowest η jets

most forward η jet

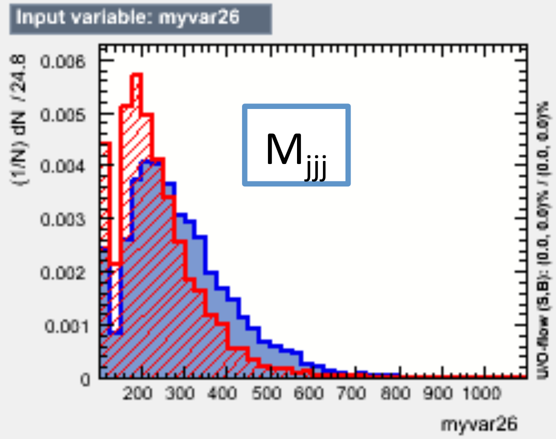
Variables 25 & 26

Blue : Signal
Red : Background

105 < M_{jj} < 135 GeV



lowest η jet

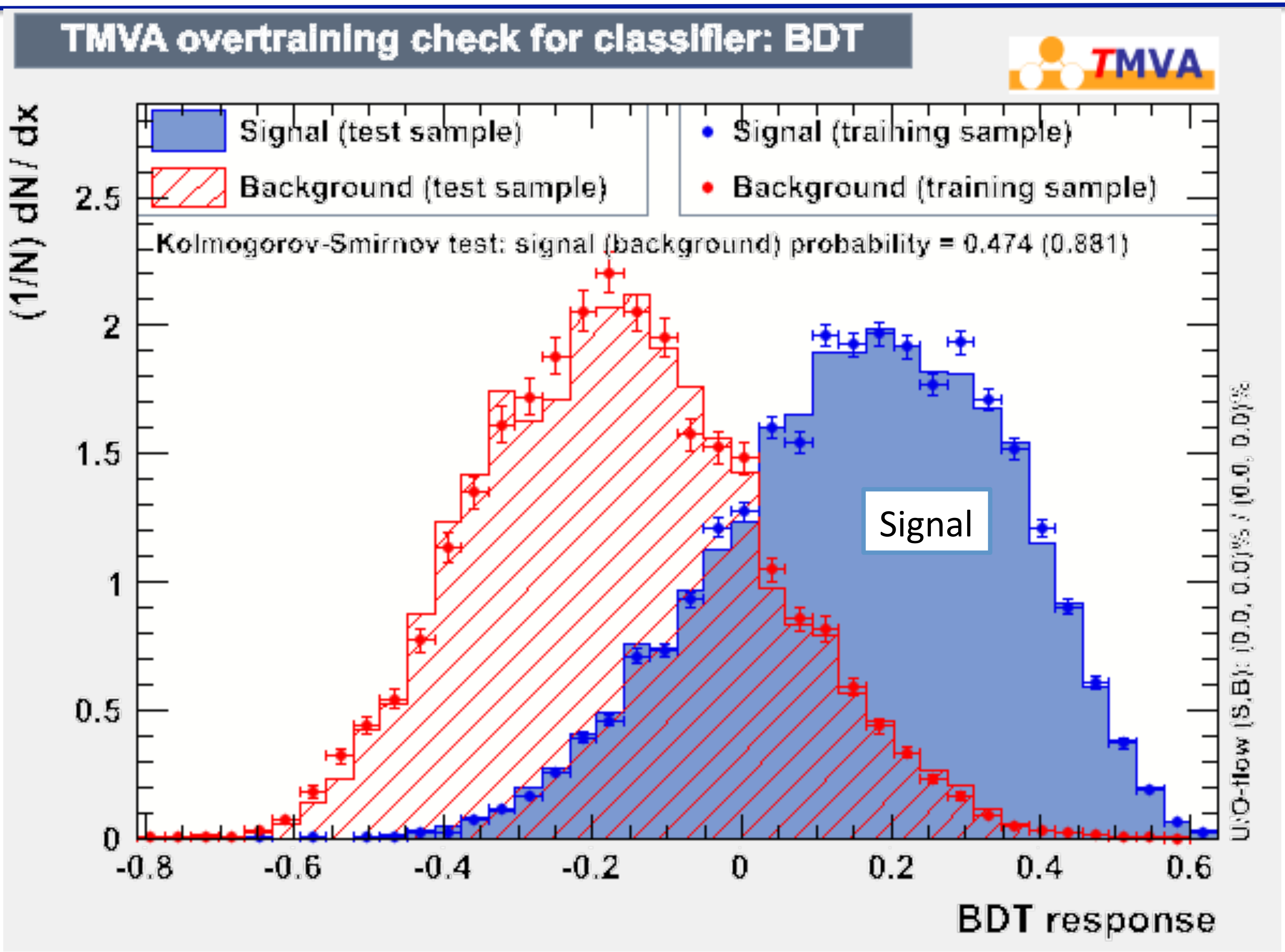


M_{jjj} of 3 lowest η jets

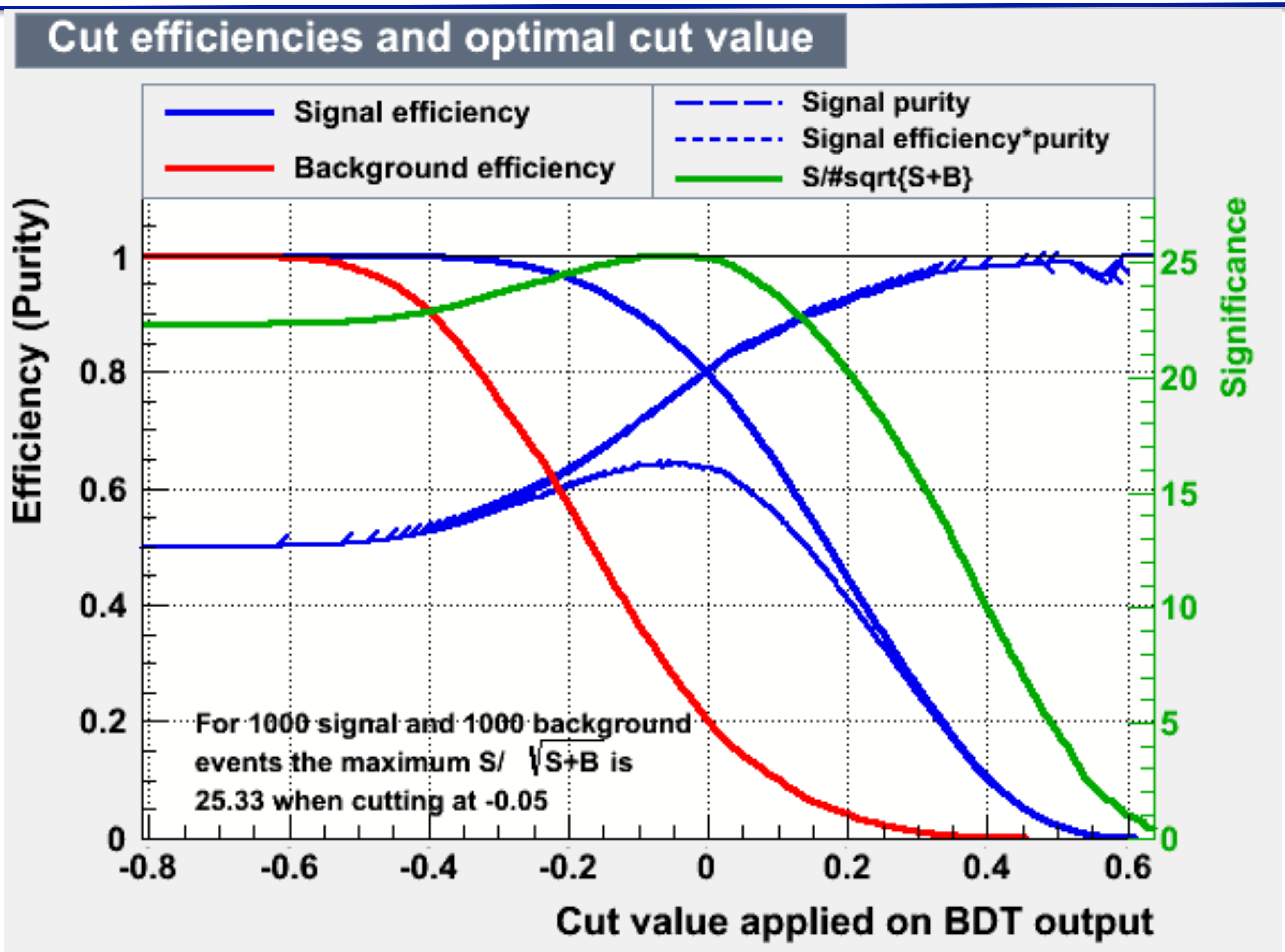
Disclaimer : This is an initial set of variables, also developed together with Jonas Waldendort, Master thesis University of Liverpool 2015

➔ initial results to show the huge potential of Higgs analysis at LHeC

BDT training check



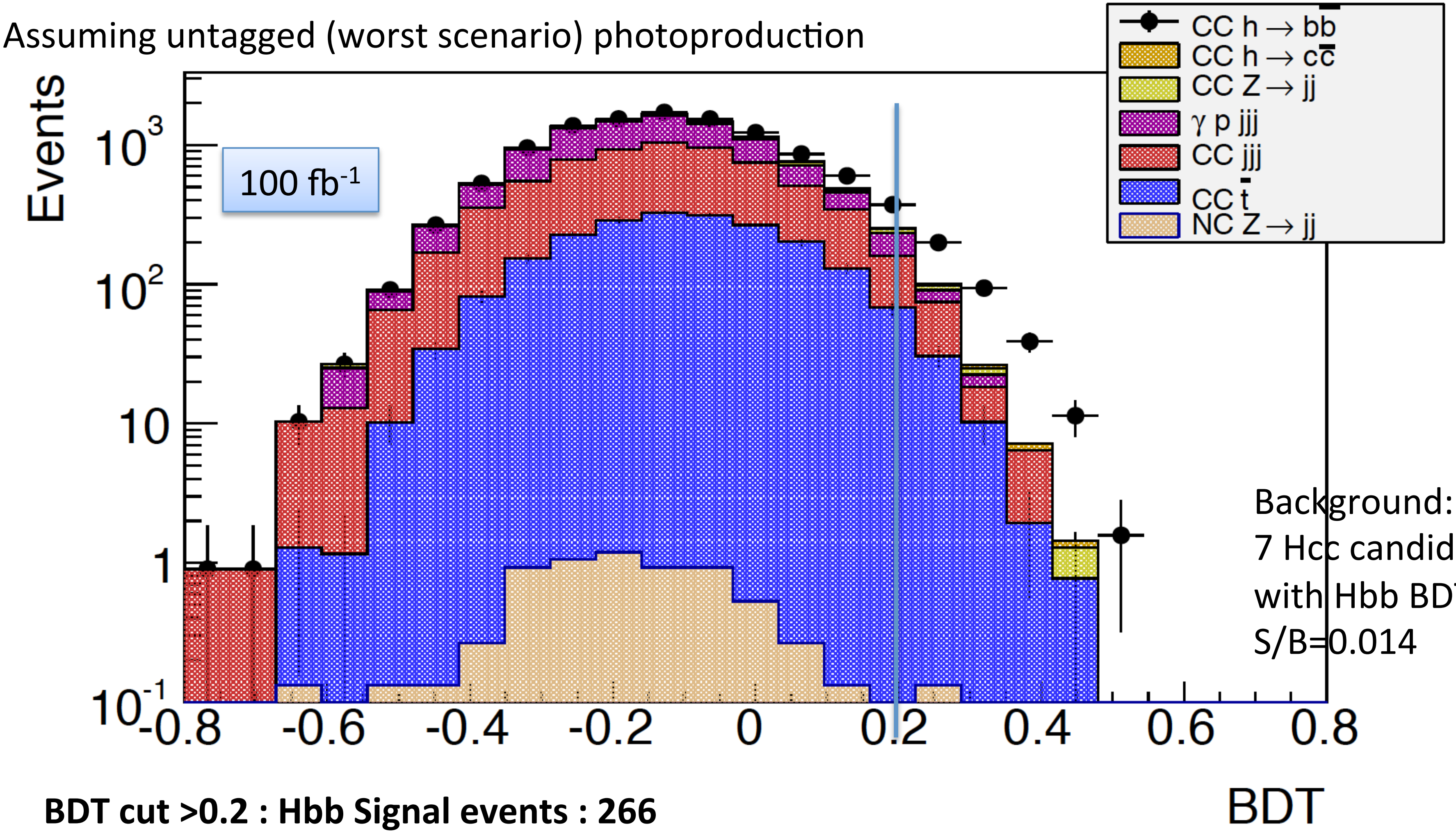
BDT efficiencies - training



First BDT results : Higgs→ bb

[P=-0.8, BR=0.577]

Assuming untagged (worst scenario) photoproduction



Background:
7 Hcc candidates
with Hbb BDT
S/B=0.014

BDT cut >0.2 : Hbb Signal events : 266

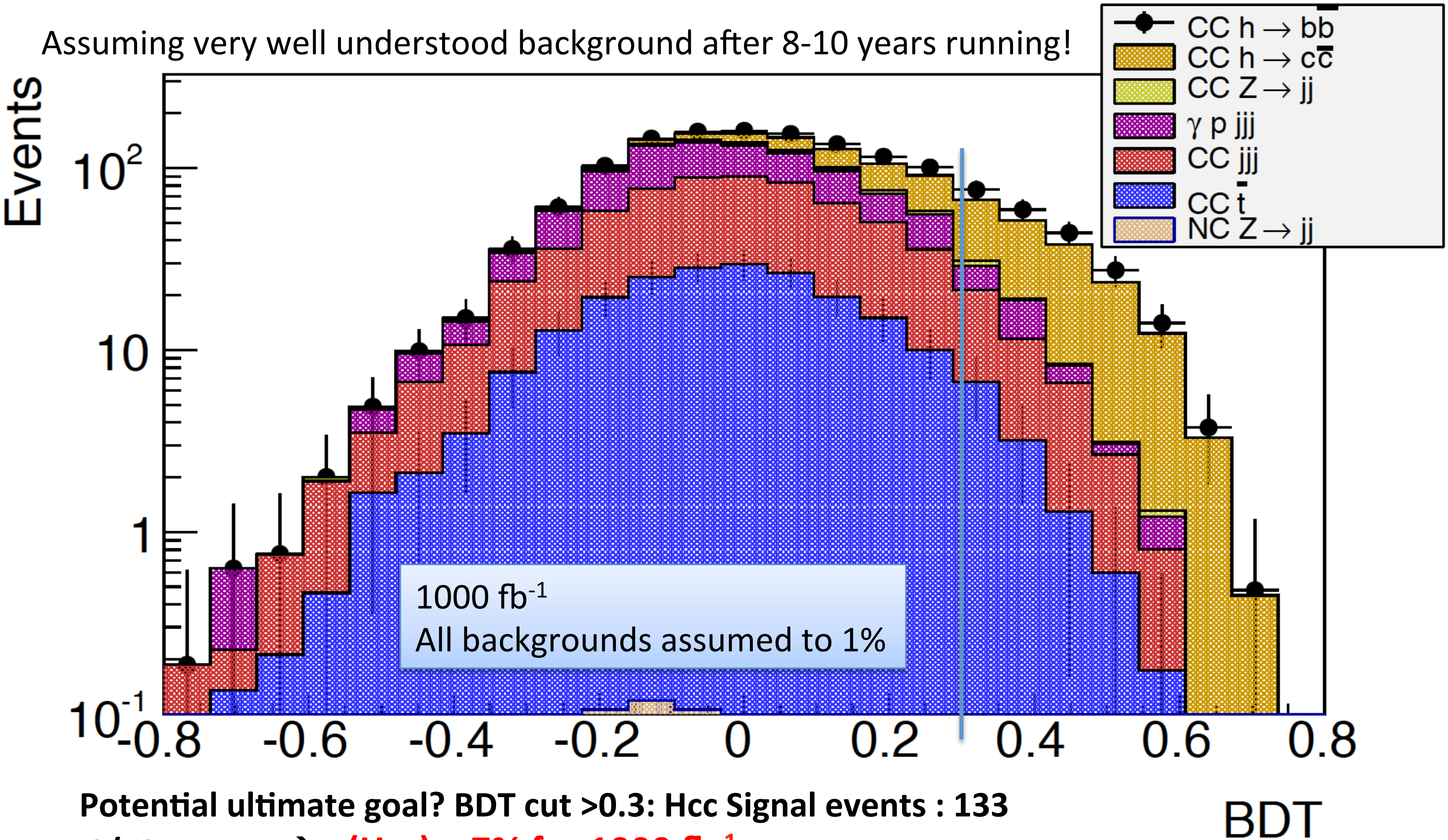
S/B = 1.16 and S/√S+B=12 → κ(Hbb) = 5% for 100 fb^{-1}

➔ κ(Hbb) = 1.5% for 1000 fb^{-1}

➔ First confirmation of CDR findings using jet lifetime tags!

Very first BDT results : Higgs→ cc

Assuming very well understood background after 8-10 years running!



Potential ultimate goal? BDT cut >0.3: Hcc Signal events : 133

S/√S+B=1.5 → κ(Hcc) = 7% for 1000 fb^{-1}

[assuming backgrounds to 10% (100%) κ(Hbb) = 17% (50%)]

→ There is a clear potential to measure Hcc at LHeC

Summary

- New samples have been produced to study *untagged* photoproduction backgrounds
- New full analysis chain has been developed using signed impact parameters and jet lifetime tags for a BDT analysis of Higgs to heavy flavour decays.
- The LHeC sensitivity to H→bb using jet lifetime tags could confirm the CDR-like findings : LHeC has the potential to measure **H → bb coupling with an S/B >~1 and to ~1% accuracy with 60 GeV** electron beam based on a luminosity of 10^{34} cm^{-2} s^{-1}.
- **Very first BDT based Hcc analysis results indicate that H→ cc coupling can be accessed at a high luminosity LHeC.**
- **Those are exciting prospects to measure other Higgs boson production channels at LHeC and strengthen the synergy with HL-LHC → this is the unique chance that CERN has a genuine Higgs factory complex running in beyond 202X.**

Additional material

Pile-up estimate for LHeC

- high luminosity option using $L=10^{34}\ cm^{-2}s^{-1}$ (LHeC) and $L=5x10^{34}\ cm^{-2}s^{-1}$ (HL-LHC) with 150 pile-up events (25 ns) [calculations by M. Klein]

➔ Pile-up events expected for LHeC <~0.1

Using pp LHC pile-up estimates

$$N(ep)=N(pp) \times s(yp)/s(pp) \times L(ep)/L(pp)$$
$$= 150 * 0.003 * 0.2$$
$$= 0.1$$

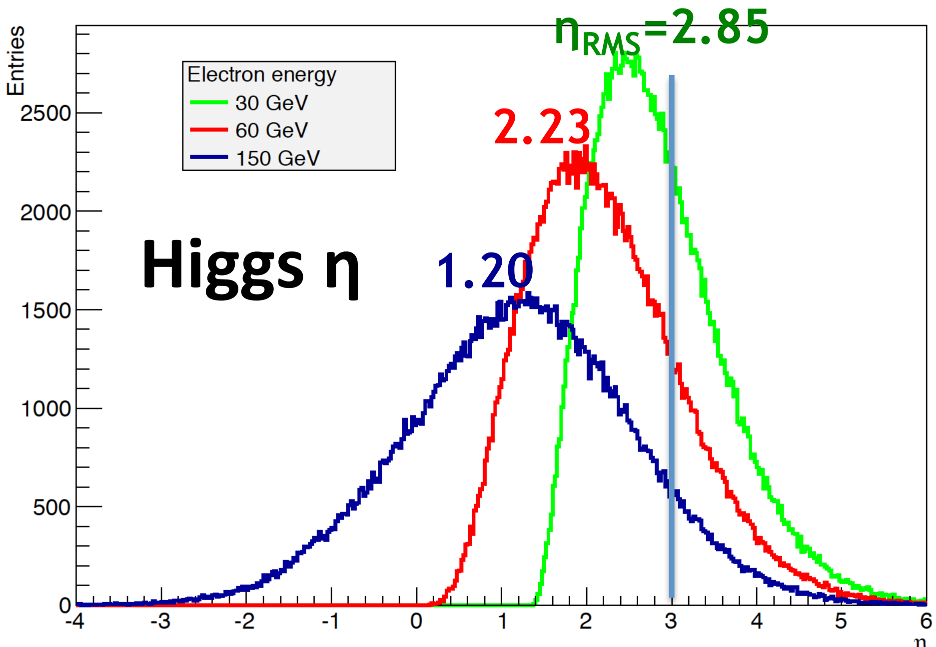
Direct calculation using total gamma-proton cross section of 300 µb

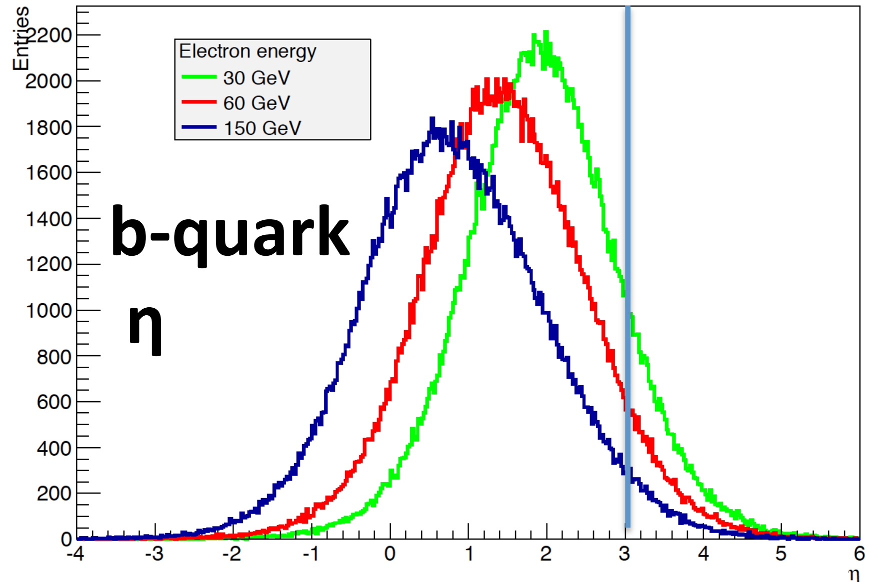
$$N(ep) = 300\ 10^{-6}\ 10^{-24}\ cm^2 \times 10^{34}\ cm^{-2}s^{-1} \times 25\ 10^{-9}s$$
$$= 0.075$$

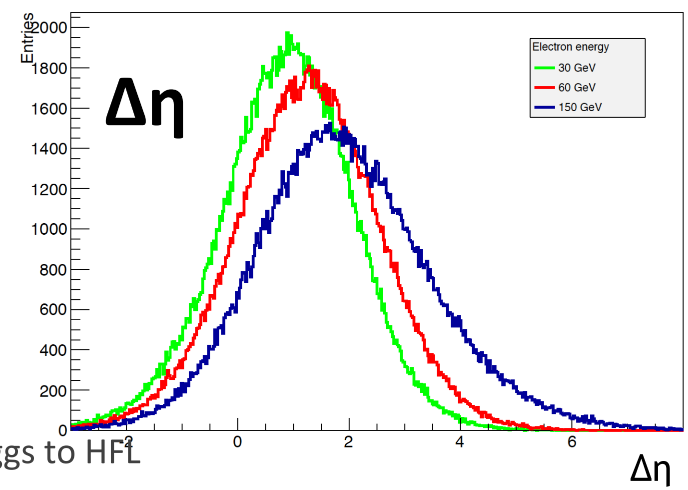
Higgs acceptance vs E_e

[after Higgs discovery M_H=125 GeV, E_p=7 TeV]

[Master thesis by Sergio Mandelli, Liverpool 2013]







- ➔ lowering of electron beam energy (more cost efficient) will challenge more detector design: worse separation between higgs and forward jet (Δη shrinks by 1 unit) and b-quarks from Higgs decay are more forward
- ➔ **stick with 60 GeV** E_e : decay products of Higgs scattered at ~28° (η~1.4)