

Update on the Left-Right twin higgs model

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U. Glasgow

ATLAS overview week
exotic physics group meeting
Wed. Oct. 10, 2007

Outline

- Introduction
- Twin Higgs model parameters/benchmark points
- $Z_H \rightarrow e^+e^-$: towards a model-independent fit
- W_H : high p_T b-tagging
- future plans

further information:

June 2007 Exotics group meeting: <http://indico.cern.ch/conferenceDisplay.py?confId=16473>

Les Houches workshop on physics at TeV colliders: di-lepton group (S. Ferrag), twin Higgs session (S. Su, M. Vos) http://www.lpthe.jussieu.fr/LesHouches07Wiki/index.php/Session_II

ATLAS b-tagging workshop (Marseille, May 2007):

<http://indico.cern.ch/conferenceOtherViews.py?confId=14475>

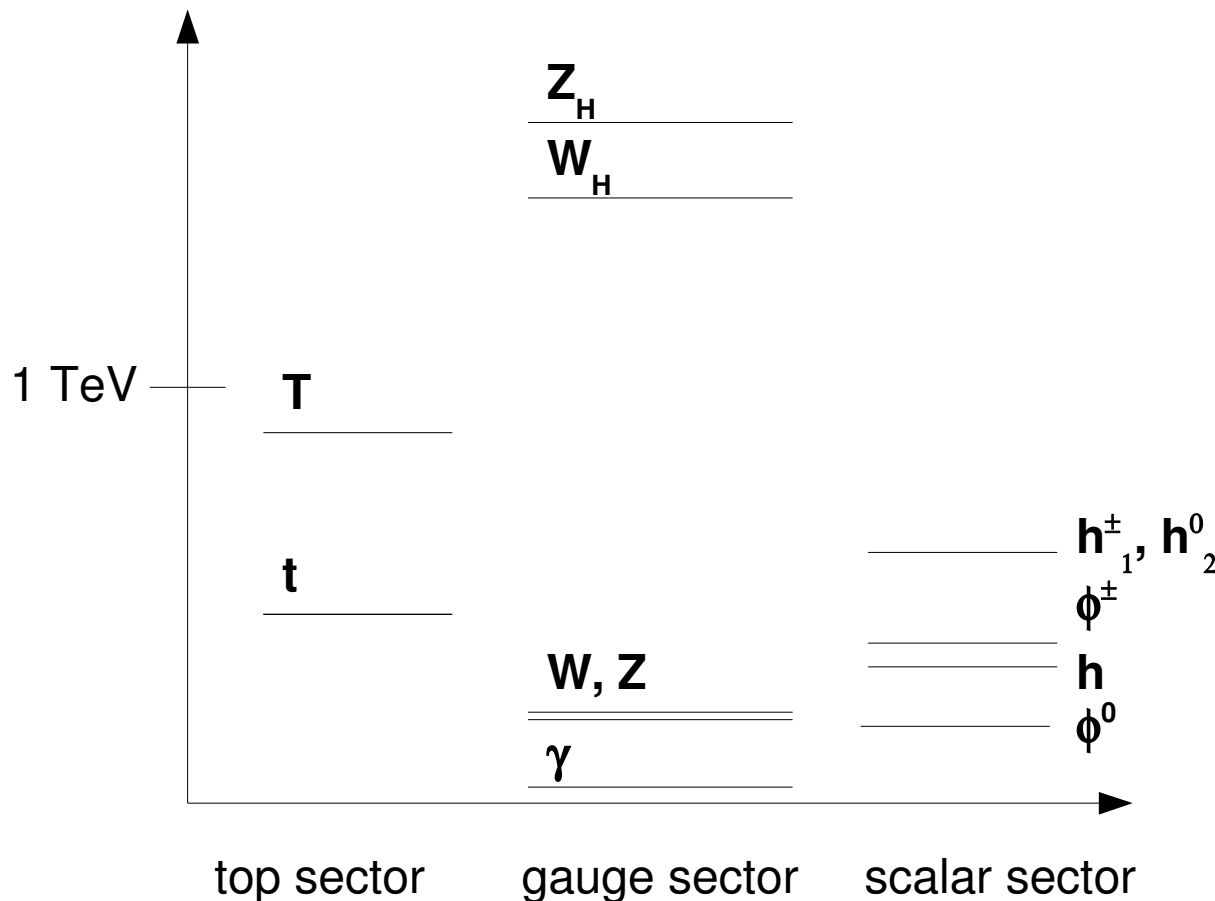
ATLAS flavour tagging meeting: <http://indico.cern.ch/conferenceDisplay.py?confId=21733>

Webpage: <http://fiic.uv.es/~vos/Atlas/TwinHiggs/>

Particle spectrum

Symmetry

$$U(4) \otimes U(4) \rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)$$



- masses of T , W_H , Z_H , ϕ , h not fixed by the model
- After fixing the masses, **NO** free parameters remain, cross-sections can be computed
- No A_H (photon partner)
- More complex scalar sector (h^0_2 is dark matter candidate)
- W_H is RIGHT-handed

Theory: Chacko et al. (hep-ph/0506256)

Phenomenology:

Goh and Su (hep-ph/0608330)₃

Phenomenology

$$Z_H \rightarrow e^+ e^-$$

likely discovery channel BR $\sim 2.5\%$

$$Z_H \rightarrow Zh$$

not studied so far

$$W_H \rightarrow e \nu_R$$

not studied so far. Absence of W_H leptonic decay
allow to distinguish Little Higgs from LR twin Higgs

$$W_H \rightarrow tb$$

much reduced BR with respect to little Higgs

$$W_H \rightarrow Tb$$

$$\hookrightarrow \phi^\pm b$$

$$\hookrightarrow tb$$

$$\hookrightarrow Wb$$

$$\hookrightarrow l\nu$$

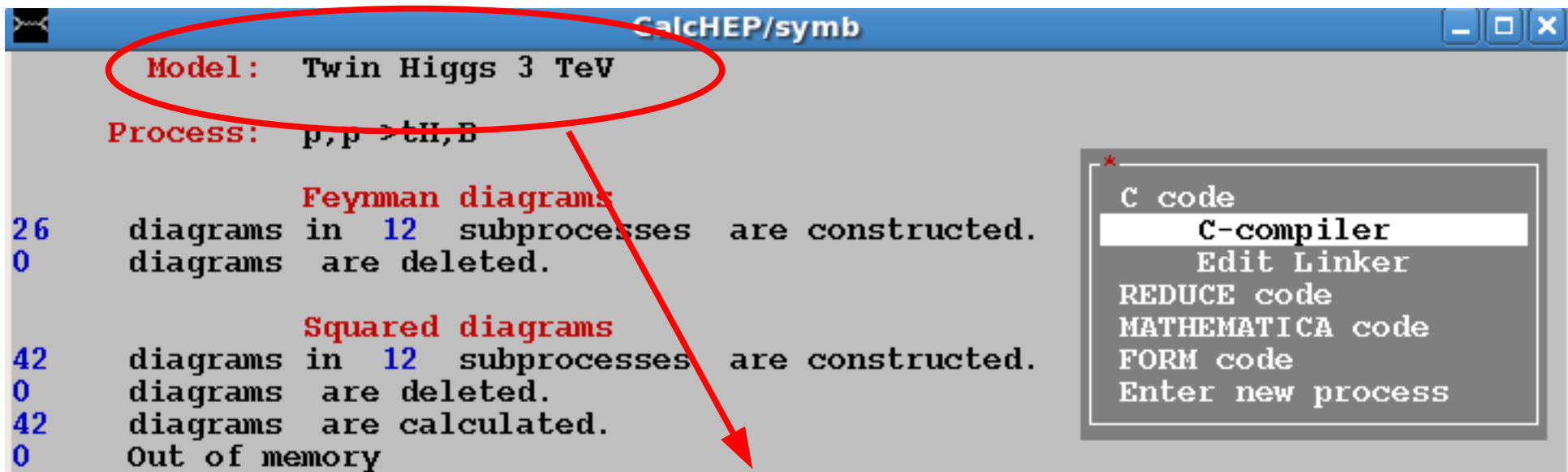
Cascade decays with signature: $4b + l + E_T^{\text{miss}}$
model test (not present in Little Higgs)

First results reported in june

<http://indico.cern.ch/conferenceDisplay.py?confId=16473>

Model parameters/benchmark points

Discussion with theorists (Shufang Su) during Les Houches workshop:
Compare our Pythia implementation of the cascade decays with calcHep predictions.



The screenshot shows the CalcHEP/symb window. The title bar is blue with the text 'CalcHEP/symb'. The main area has a light gray background. At the top, 'Model: Twin Higgs 3 TeV' is written in red and is circled with a red oval. Below it, 'Process: p,p -> tH, B' is written in red. Further down, 'Feynman diagrams' is written in red, followed by '26 diagrams in 12 subprocesses are constructed.' and '0 diagrams are deleted.' in blue. Then, 'Squared diagrams' is written in red, followed by '42 diagrams in 12 subprocesses are constructed.', '0 diagrams are deleted.', '42 diagrams are calculated.', and '0 Out of memory' in blue. On the right side, there is a menu with a red asterisk icon. The menu items are: 'C code', 'C-compiler' (highlighted with a white background), 'Edit Linker', 'REDUCE code', 'MATHEMATICA code', 'FORM code', and 'Enter new process'.

```
Model: Twin Higgs 3 TeV
Process: p,p -> tH, B

Feynman diagrams
26 diagrams in 12 subprocesses are constructed.
0 diagrams are deleted.

Squared diagrams
42 diagrams in 12 subprocesses are constructed.
0 diagrams are deleted.
42 diagrams are calculated.
0 Out of memory
```

- C code
- C-compiler**
- Edit Linker
- REDUCE code
- MATHEMATICA code
- FORM code
- Enter new process

**CalcHEP model for Twin Higgs,
thanks to Shufang Su**

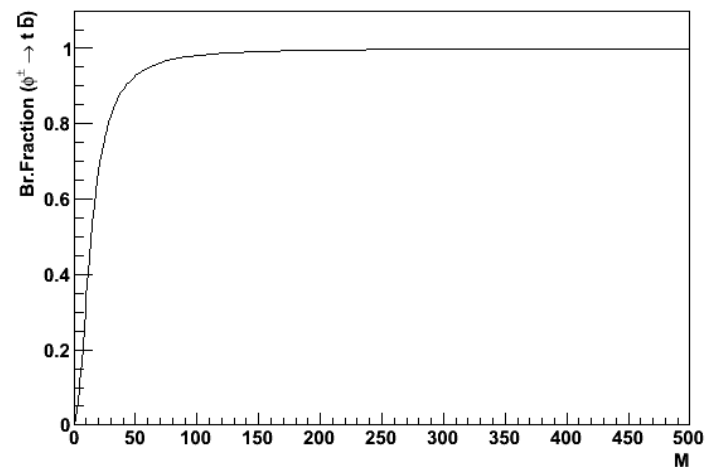
Model parameters/benchmark points

In Les Houches: lively discussion on the dependence of the phenomenology on model parameters:

- μ : introduces mass shift of the Higgs sector
- M : mixing T-t, determines branching ratio

Currently, benchmark points are all for $M=150$.

At very low M cascade decays through $\phi \rightarrow tb$ “disappear”.

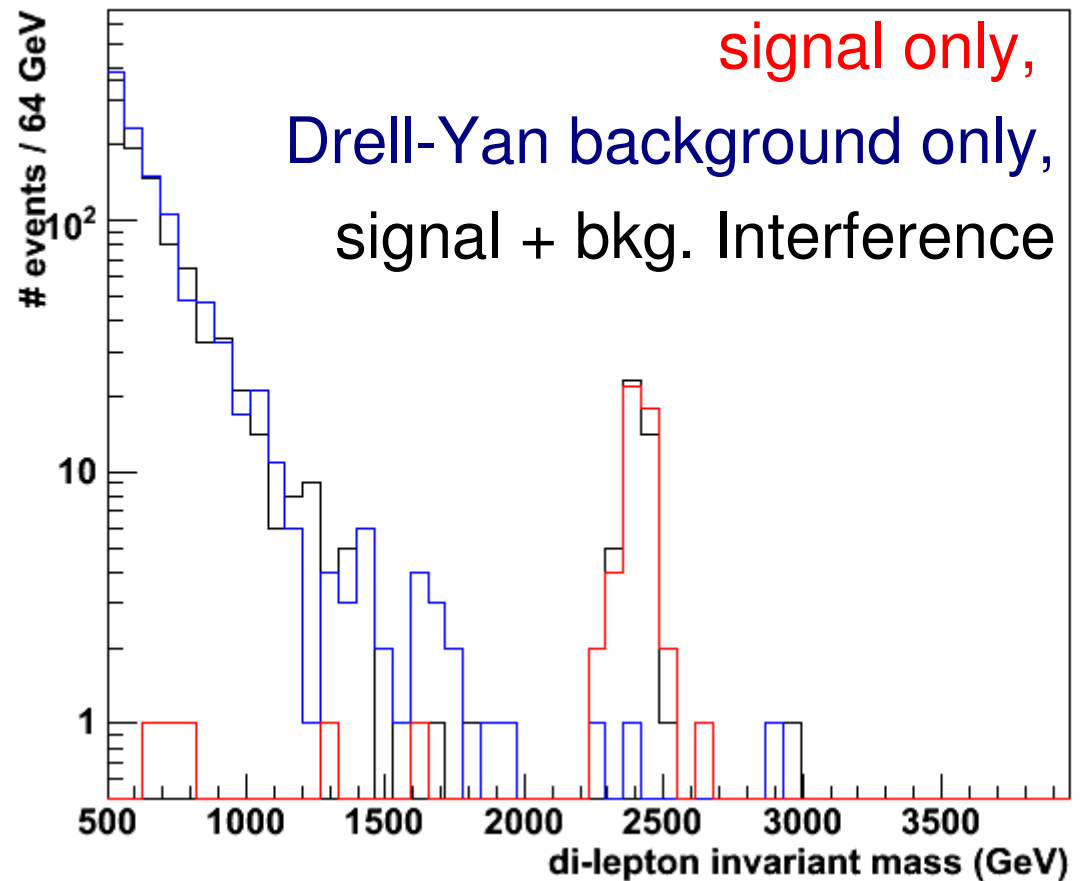


Di-leptons

$Z_H \rightarrow \text{di-leptons}$

likely discovery channel
for LR twin Higgs model.

Generator level di-lepton mass distribution for 10 fb^{-1}



Di-leptons (with S. Ferrag)

Mass	luminosity for 3 sigma (fb ⁻¹)		luminosity for 5 sigma (fb ⁻¹)	
1196 GeV	0.068	(0.079)	0.19	(0.22)
1495 GeV	0.19	(0.19)	0.52	(0.52)
2407 GeV	2.04	(2.09)	5.5	(5.5)
3587 GeV	~ 27	(28)	~75	(77)

“Generator level” di-lepton discovery reach based on classical $S/\sqrt{(S+B)}$ analysis in 2σ mass window, S. Ferrag.

To be extended to a method taking full advantage of the invariant mass spectrum.

Di-leptons – mass resolution

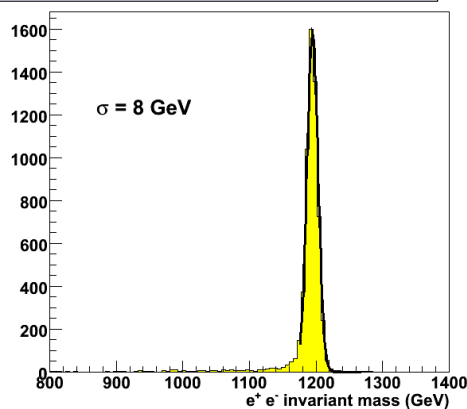
Mass	Natural width (GeV)	Di-lepton mass resolution (GeV)	
		Electrons	Muons
1.2 TeV	24	8	60
3.6 TeV	75	19	400

ATLFAST mass resolution for heavy resonances

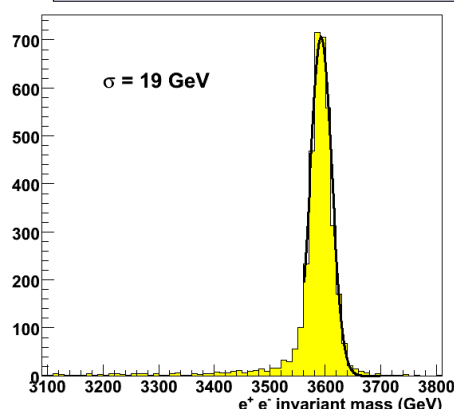
Electrons:

$$\Delta E/E = a / \sqrt{E} \oplus b \%$$

$\Delta M (e^+e^- @ 1.2 \text{ TeV})$
0.7 % / 8 GeV



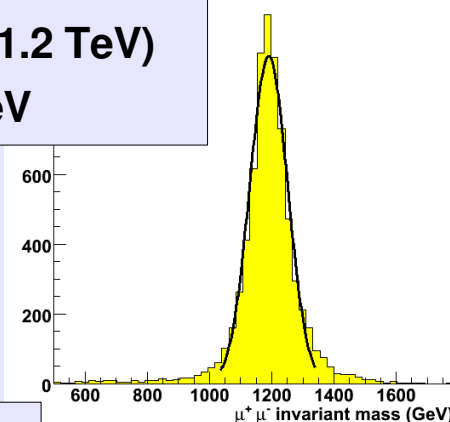
$\Delta M (e^+e^- @ 3.5 \text{ TeV})$
0.5 % / 19 GeV



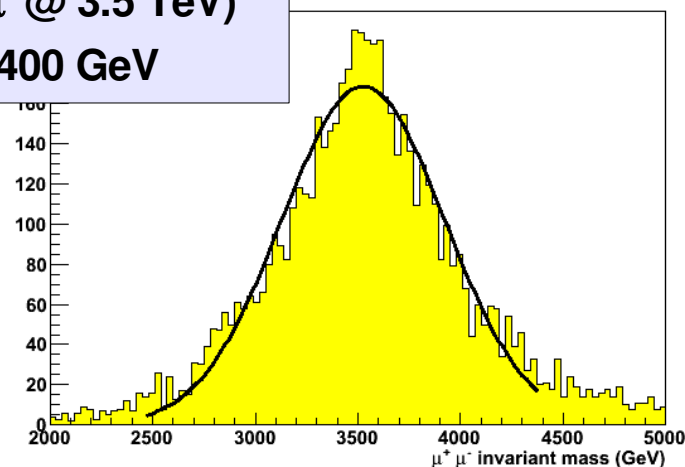
Muons:

$$\Delta p_T / p_T = c \times p_T$$

$\Delta M (\mu^+\mu^- @ 1.2 \text{ TeV})$
5 % / 61 GeV

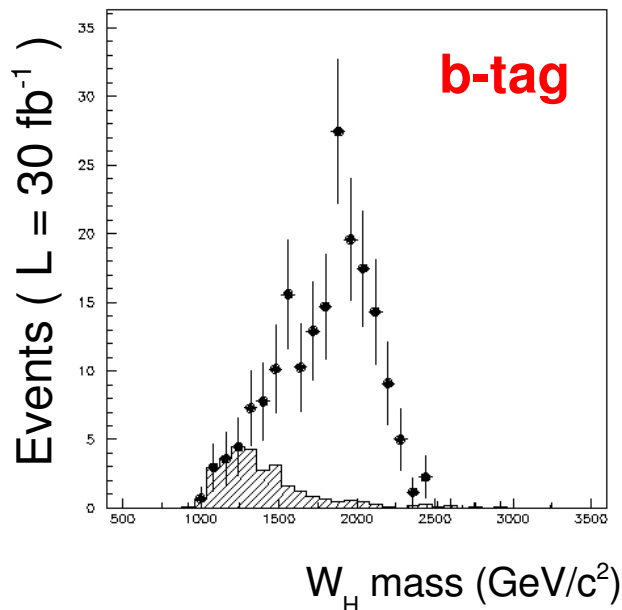
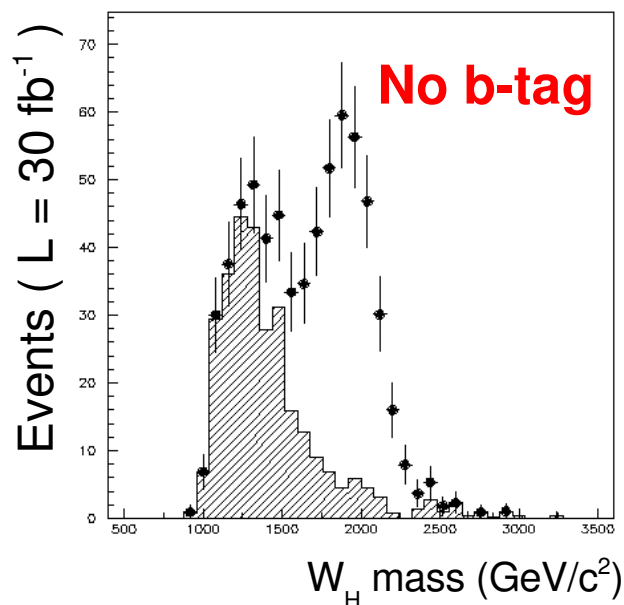


$\Delta M (\mu^+\mu^- @ 3.5 \text{ TeV})$
11 % / 400 GeV

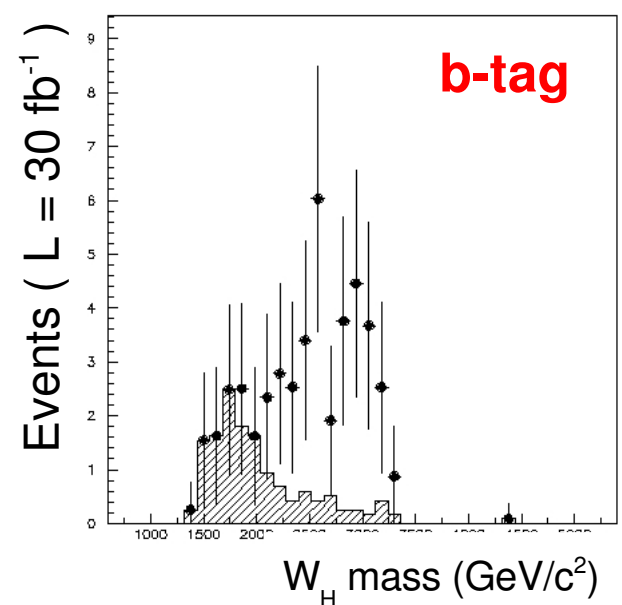
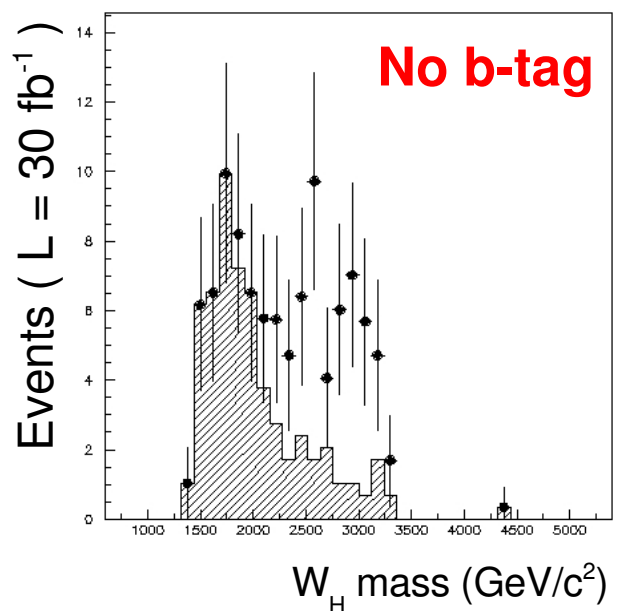


$W_H \rightarrow T b$ cascade decays

For details, see: <http://indico.cern.ch/conferenceDisplay.py?confId=16473>

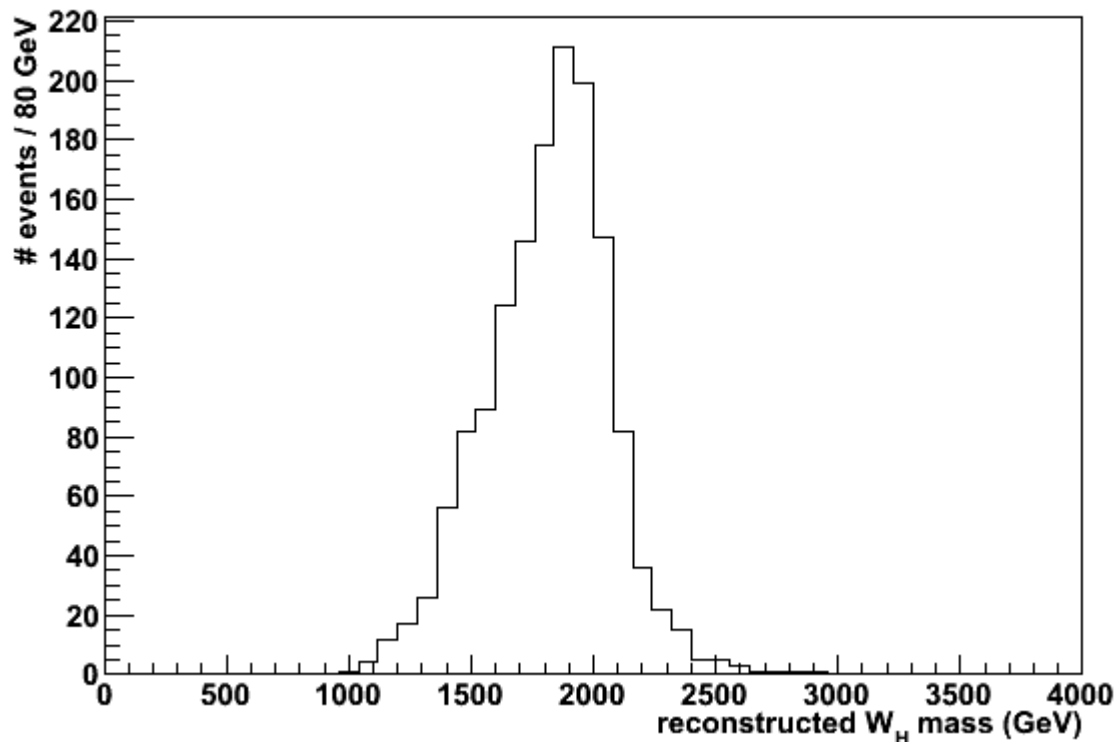


2 TeV	no b-tag	b-tag
N_{sig}	301	120
N_{tt}	48	4.8
N_{wj}	1.9	-
$N/\sqrt{B}$	43	55



3 TeV	no b-tag	b-tag
N_{sig}	38.3	26.8
N_{tt}	11.3	2.8
N_{wj}	1.4	-
$N/\sqrt{B}$	11	16

$$W_H \rightarrow Tb, m(W_H) = 2 \text{ TeV}/c^2$$



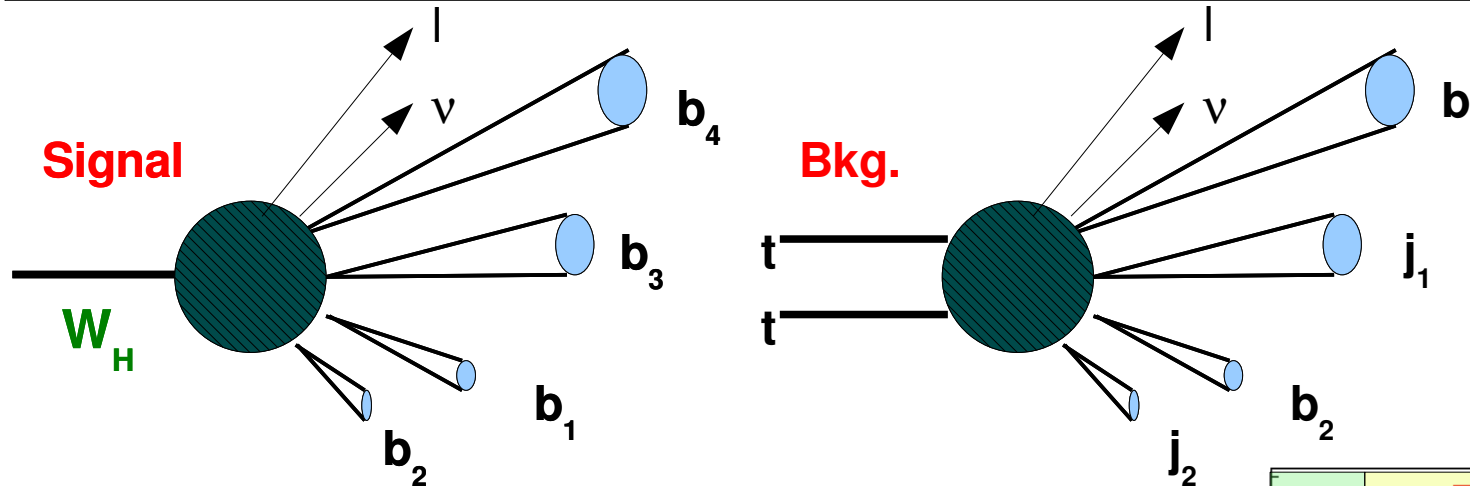
**Reprocessing the analysis
using official tools and
model parameters.**

ATHENA 12.0.6
“Les Houches”
benchmark points

Reconstruction of W_H cascade (nominal mass = 2 TeV)

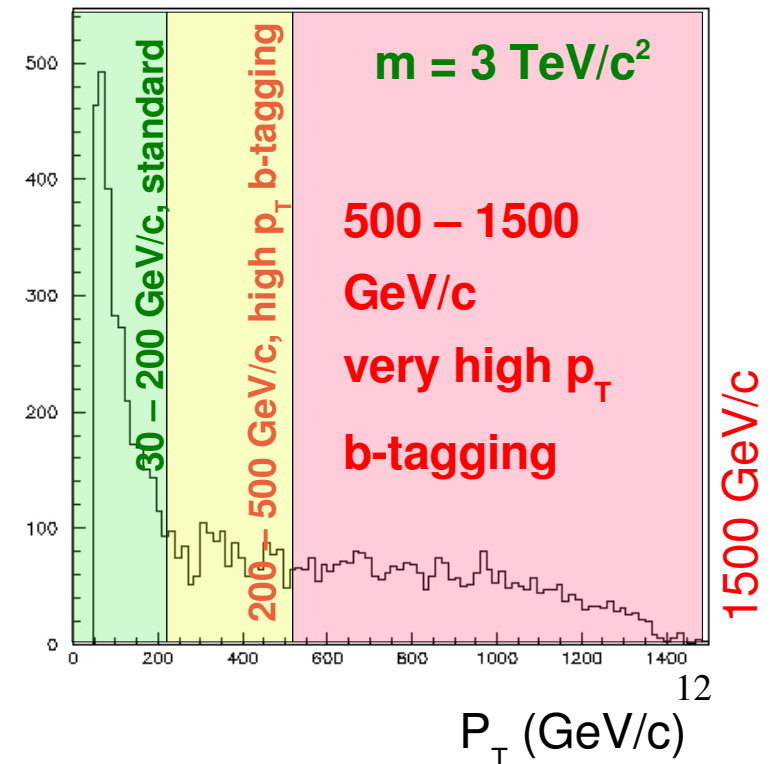
Step-by-step comparison hasn't yielded nasty surprises so far

tagging multi-jet events with high p_T b-jets



How to tag a signal of 4 b-jets against a background of 2 b + 2 j ?

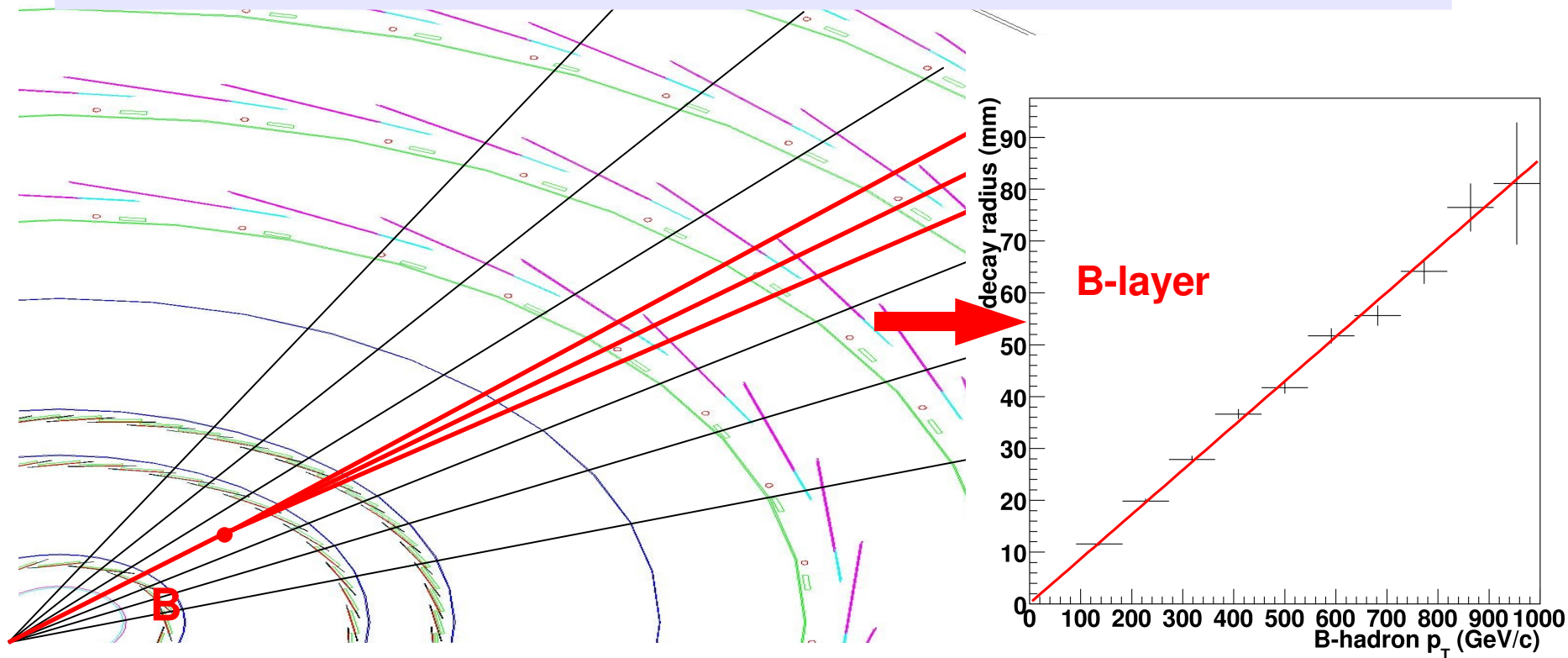
For multi-jet final states, with large variations in jet energy, **a 4 b-jet likelihood** from individual jet weights, is much more efficient than standard efficiency-rejection curves approach .



Very high p_T b-tagging (I)

Decay length $L = \gamma c \tau \rightarrow$ strongly enhanced for high p_T b-jets

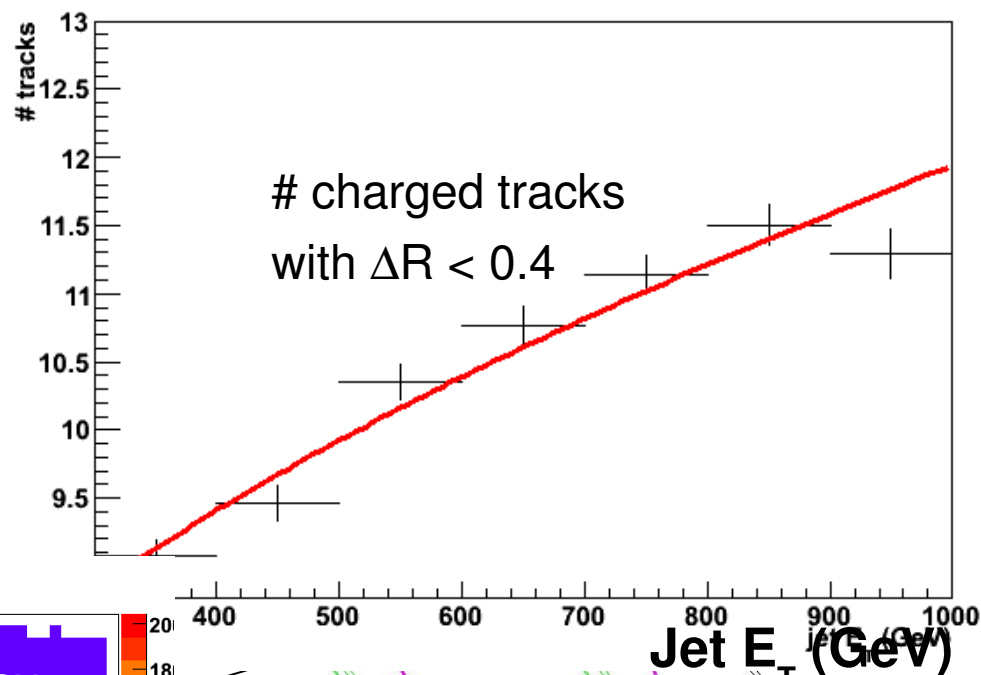
A significant fraction of B/D hadrons decays is close to and even beyond the B-layer



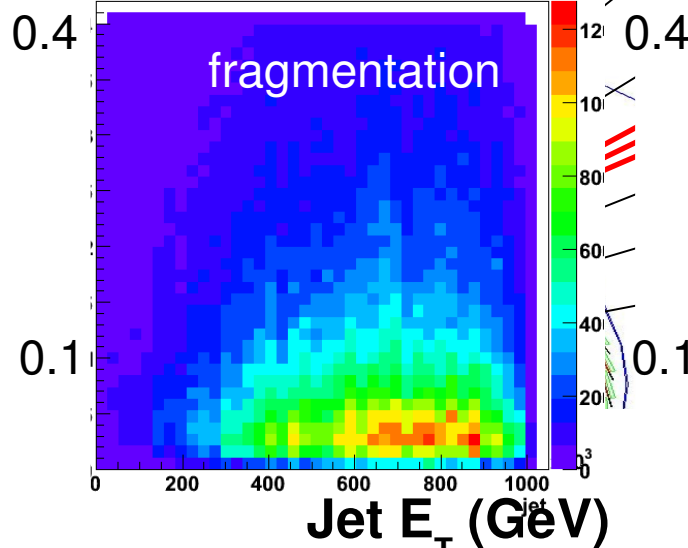
Very high p_T b-tagging (II)

number of (fragmentation) tracks increases significantly

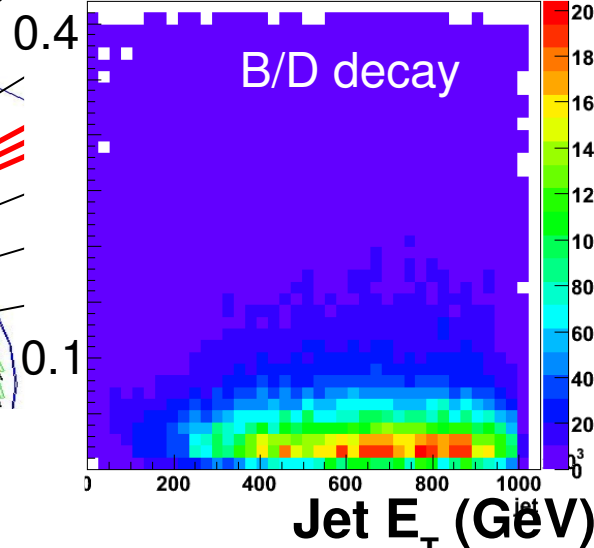
jets collimated into narrow cone.



ΔR (track -jet)

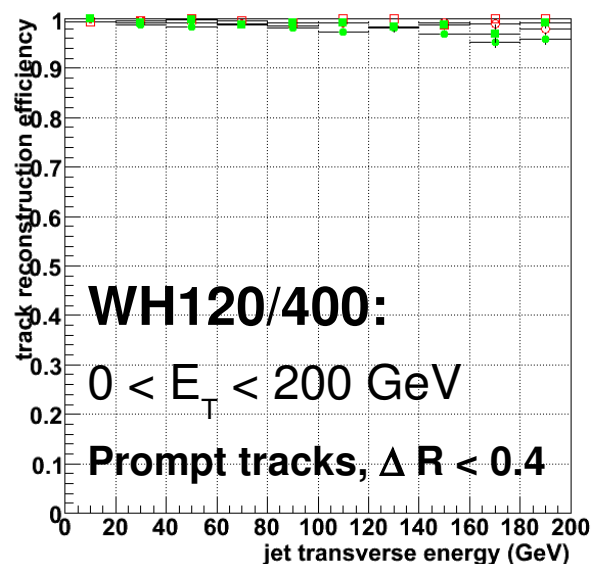


ΔR (track -jet)



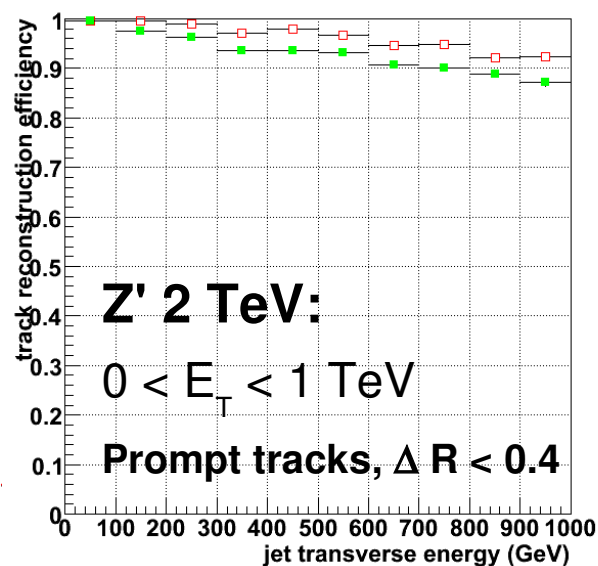
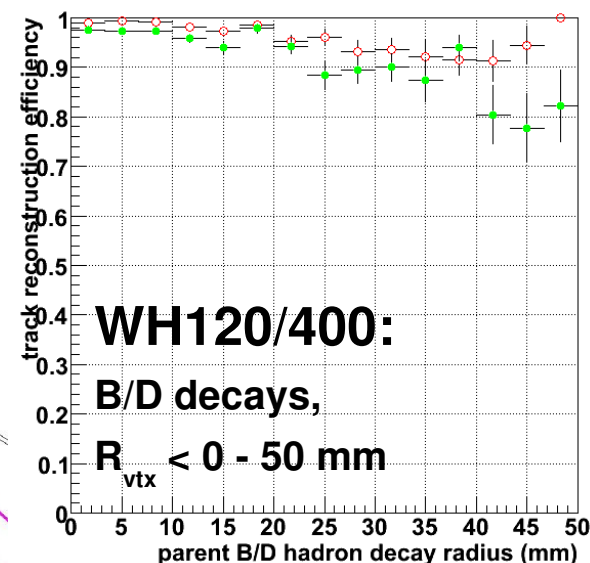
Track density stresses ID pattern recognition capabilities

Tracking in very high p_T jets (I)

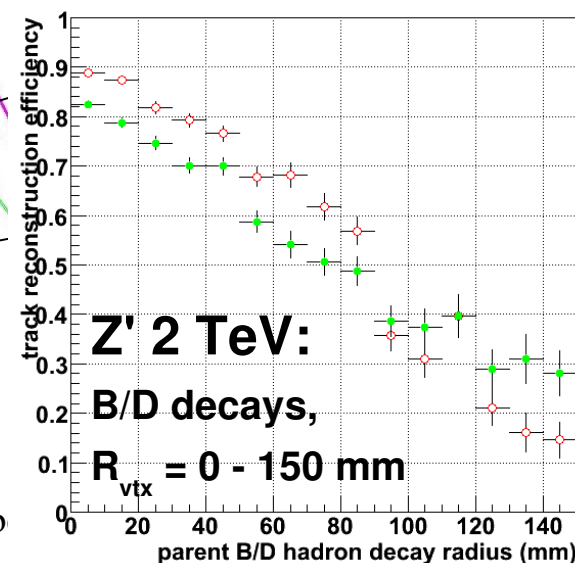


Reconstruction efficiency
 for “good” tracks >90%
 inside highest p_T jets!

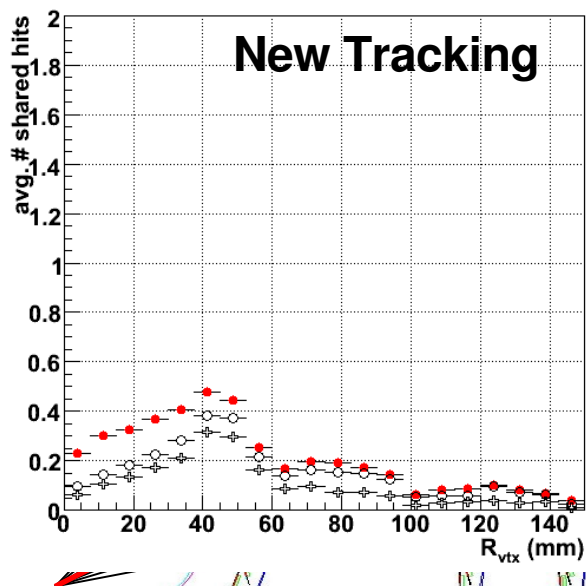
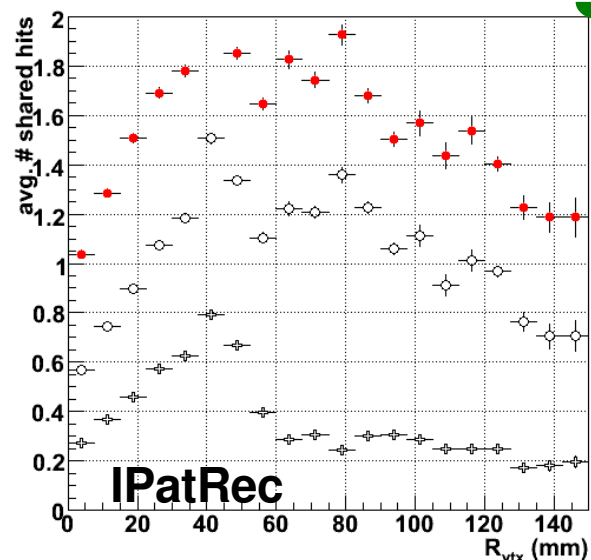
IpatRec
 New Tracking



displaced vertices present
 a real challenge



Tracking in very high p_T jets (II)



The sharing of hits becomes inevitable in dense jet cores, especially in case of displaced vertices

Situation dealt with quite differently by IpatRec and New Tracking (AmbiguityResolver)

Average number of shared hits per track, considering only efficient tracks from B/D decay

● total

○ in pixel detector

⊕ in B-layer

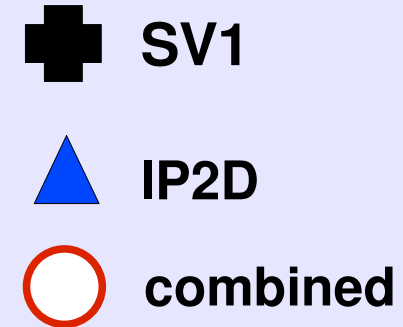
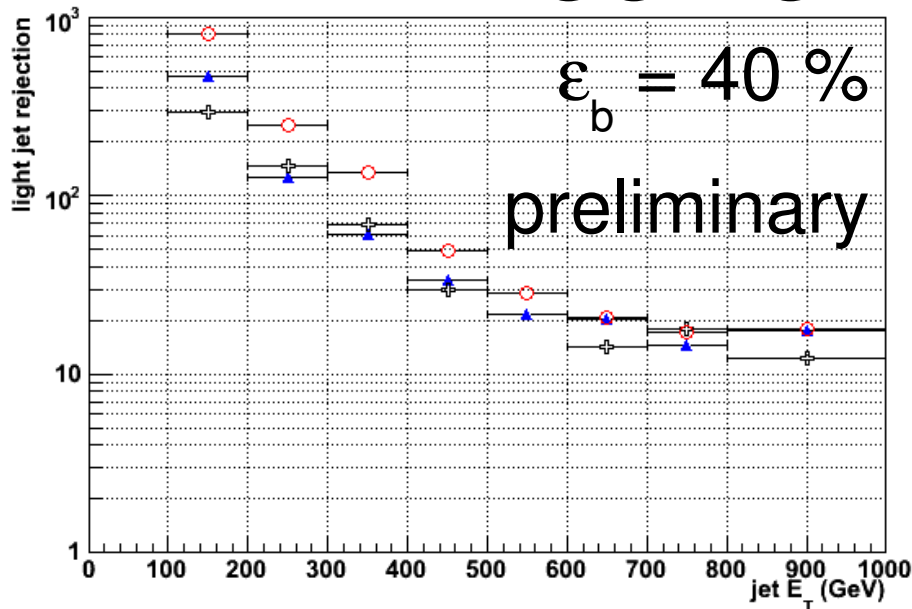
Tested several causes/remedies (in ATHENA 13) suggested by tracking experts (A. Salzburger, W. Liebig and others).

T. Lari working on tags for **pixel detector clusterizer** – test the impact of different algorithms on our sample

Different seeding schemes (back-tracking)...

Plenty of other possibilities

b-tagging in high p_T jets



using ATHENA 12.0.6,

B-tagging: mismatch of low p_T track quality cuts and high p_T reality. Re-tune parameters:

- lpatRec tracks
- shared hits
- jet-track association ΔR
- B-layer hit
- minimal track p_T

The high p_T b-tagging performance is not brilliant, but:

- greatly improved with respect to 12.0.6 out-of-the-box
- recovered previous “Rome” results with realistic assumptions on material, alignment
- results compatible with ATLFAST parameterization used for Twin Higgs study
- standard algorithm – works at low p_T as well. No recalibration of likelihoods

Thanks to b-tagging group (M. Lehmacher, V. Kostyukhin, L. Vacavant) for very useful discussions.

Summary and conclusions

- LR Twin Higgs benchmark points defined
- First look at di-lepton decay of heavy Z boson, likely discovery channel
- b-tagging for high and very high p_T jets in a “realistic environment” yields adequate performance for reconstruction of cascade decays
- The cascade decay
 $W_H \rightarrow Tb \rightarrow \phi^\pm bb \rightarrow tbbb \rightarrow Wbbbb \rightarrow 4b + l + E_t^{\text{miss}}$
can be observed with ATLAS and $L=30 \text{ fb}^{-1}$ for masses up to $m(W_H) \sim 3 \text{ TeV}/c^2$
- Starting to document some of this work (b-tagging CSC note, Twin Higgs ATLAS communication)

BACKUP SLIDES

Theoretical motivation

The (little) hierarchy or fine-tuning problem, or LEP-paradox:

“radiative corrections to the Higgs mass up to ultra-violet cut-off Λ yield a Higgs mass of order Λ unless there is a very delicate cancellation” (following approximately the phrasing [SN-ATLAS-2004-038])

The canonical recipee: “[the instability of the SM under quantum corrections] *suggests the existence of new physics at or close to a TeV [i.e. SUSY (with R-parity), (Large) Extra Dimensions] that protects the Higgs mass parameter of the SM against radiative corrections*”. (hep-ph/0506256)

Theoretical motivation (I)

Alternative solution to the (little) hierarchy problem:

“the Higgs is naturally light because it is the pseudo-Goldstone boson of an approximate global symmetry” (*phrasing from hep-ph/0506256*)

- **embed SM in larger symmetry group.**
- **Counterparts to SM particles are of the same statistics**
- **The larger symmetry, broken at some high scale Λ_H , protects the Higgs mass from one-loop corrections quadratic in Λ_H .**

(originally proposed in the 1970s, see Georgi and Pais, Phys. Rev. D 10, 539 (1974), Kaplan, Georgi, Dimopoulos, Phys. Lett. B 136, 183 (1984))

Theoretical motivation (II)

Twin Higgs model *Introduces a discrete symmetry: each SM particle is interchanged with a corresponding particle transforming under a twin SM gauge group.* EW precision data reproduced by construction: new particles may be light they do not transform under the SM gauge groups. **New physics is not necessarily charged under SM gauge groups!**

Mirror Twin Higgs model (Chacko, Goh, Harnik, hep-ph/0506256):
Discrete symmetry is identified with mirror parity. Collider phenomenology: invisible Higgs decay (ILC)

LR Twin Higgs model (Chacko, Goh, Harnik, JHEP 0601, 108 (2006)):
Discrete symmetry is identified with Left-Right symmetry.
Collider phenomenology: new particles around the electroweak scale (Goh, Suh, hep-ph/0608330)

Phenomenology – little Higgs

$$Z_H \rightarrow e^+e^- \quad \text{BR} \sim 4 \%$$

$$W_H \rightarrow e \nu_e \quad \text{BR} \sim 8 \%$$

mass reach ~ 5 TeV ($\cot \theta = 1$)

Other decays:

$$W_H \rightarrow tb \quad \text{BR} \sim 25 \%$$

mass reach ~ 2.5 TeV ($\cot \theta = 1$)

Model test:

$$Z_H \rightarrow Zh \rightarrow l^+l^-bb$$

mass reach ~ 2 TeV ($\cot \theta = 0.3$,
decay absent for $\cot \theta = 1$)

ATLAS study published in:
EPJ C39S2, 13 (2005)

Other studies:

ATL-PHYS-2006-003

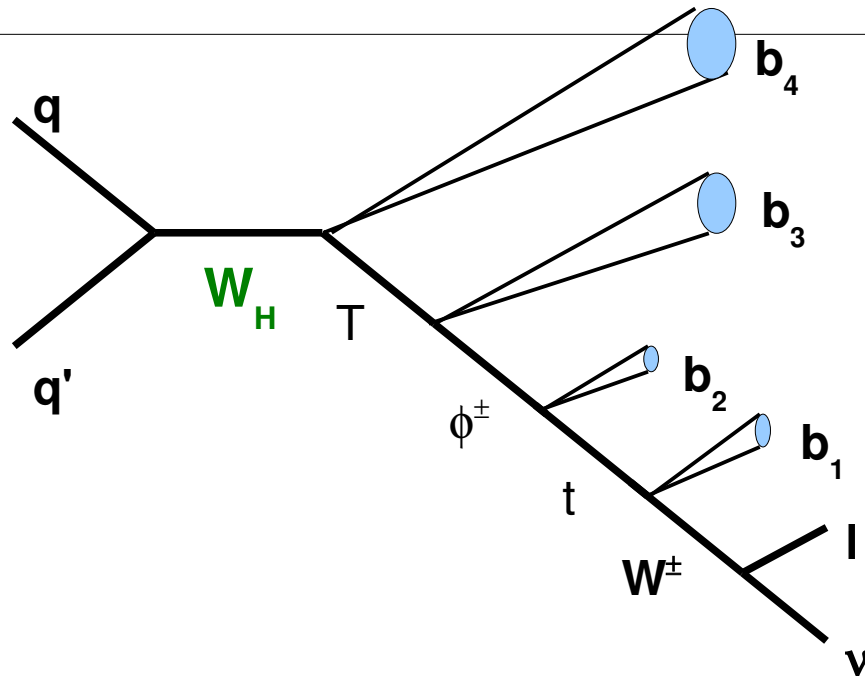
other W_H (1 TeV/c²) decays

Decay	signature	total B.R.	comment
$W_H \rightarrow Tb \rightarrow \phi^\pm bb \rightarrow 4b + l + E_t^{\text{miss}}$		3.2 %	<u>this contribution</u>
$\rightarrow bWb \rightarrow 2b + l + E_t^{\text{miss}}$		0.4 %	
$\rightarrow thb \rightarrow 4b + l + E_t^{\text{miss}}$		0.4 %	
$\rightarrow tZb \rightarrow 2b + 3l + E_t^{\text{miss}}$		0.01 %	very small rate/no bkg.
$\rightarrow t\phi^0 b \rightarrow 4b + l + E_t^{\text{miss}}$		0.1 %	
$\rightarrow tb \rightarrow 2b + l + E_t^{\text{miss}}$		0.8 %	cf. LittleHiggs BR=5%
$\rightarrow \phi^\pm \phi^0 \rightarrow 4b + l + E_t^{\text{miss}}$		0.5 %	<u>this contribution</u>
$\rightarrow qq \rightarrow 2 \text{ jets}$		73 %	QCD di-jet background

Twin Higgs decay table for $M=150$ GeV [M is T-t mixing parameter]

Remark: None of the above decays are visible for $M \rightarrow 0$

Signature for $W_H (1 \text{ TeV}/c^2) \rightarrow Tb$



	$\langle p_T \rangle$ (GeV)
b_1	95
b_2	34
b_3	201
b_4	277
l	67
ν	80

particle	mass (GeV)	decay	BR
W_H	1000	Tb	(20%)
T	500	$\phi^\pm b$	(80%)
$\phi^\pm$	200	tb	(100%)
t	175	Wb	(100%)
W	80	lv	(21%)

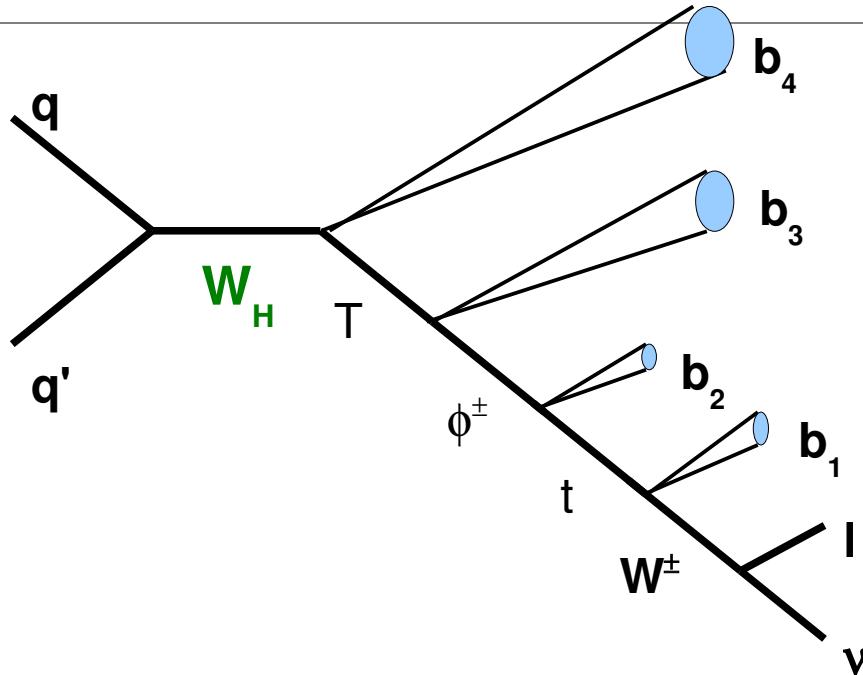
Simulation: Pythia + ATLFAST

X-section: $\sigma = 30 \text{ pb} \times \text{BR}$

Background: $tt, W+\text{jets}$

Luminosity: $L = 30 \text{ fb}^{-1}$

$W_H (1 \text{ TeV}/c^2) \rightarrow Tb$ selection cuts



Efficiency (kin. cuts only):

$$\epsilon_{\text{kin}} \sim 12 \%$$

Reconstruct masses

$$l + \nu \rightarrow W \quad p_T(l) > 25 \text{ GeV}/c, \\ E_T^{\text{miss}} > 25 \text{ GeV}/c$$

assume $p_z^{\nu} \parallel p_z^l$ to reconstruct W

$$\epsilon_l = 90\% \text{ (trigger + lepton ID)}$$

$$W + b_1 \rightarrow t \quad 25 < p_T(b_1) < 200 \text{ GeV}/c$$

$$t + b_2 \rightarrow \phi^{\pm} \quad 25 < p_T(b_2) < 100 \text{ GeV}/c$$

$$\phi^{\pm} + b_3 \rightarrow T \quad p_T(b_3) > 100 \text{ GeV}/c$$

$$T + b_4 \rightarrow W_H \quad p_T(b_4) > 150 \text{ GeV}/c$$

$$|\eta| < 2.5 \text{ for all leptons and jets}$$

Additional cuts

$$m(t) < 250 \text{ GeV}/c^2$$

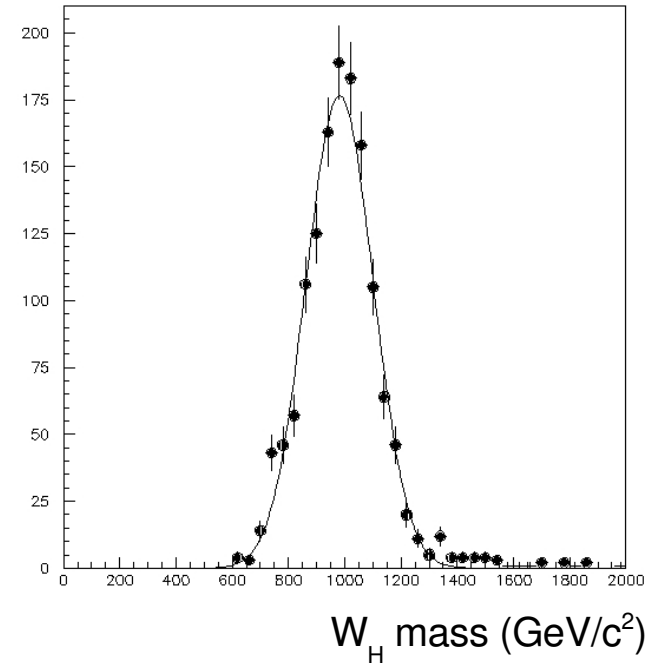
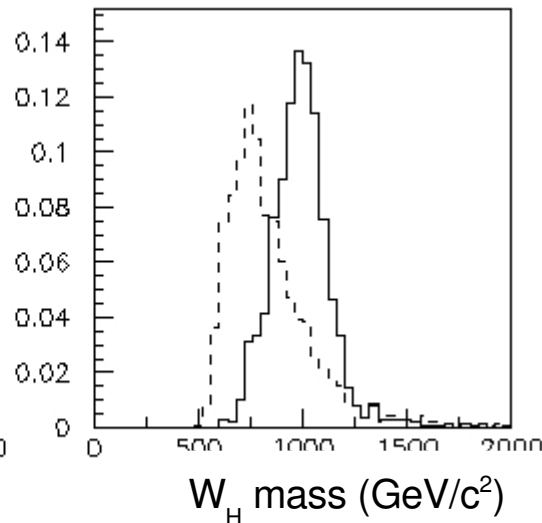
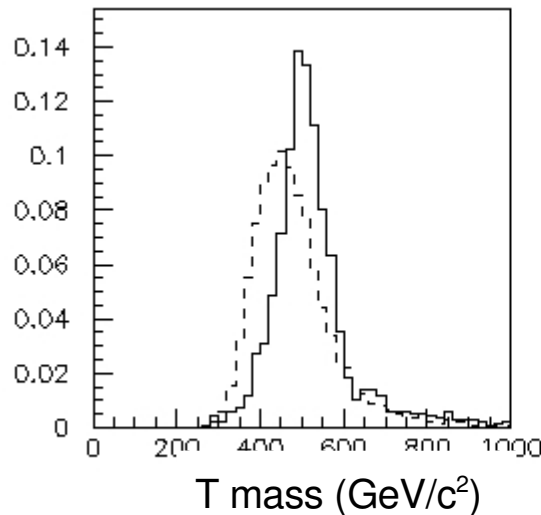
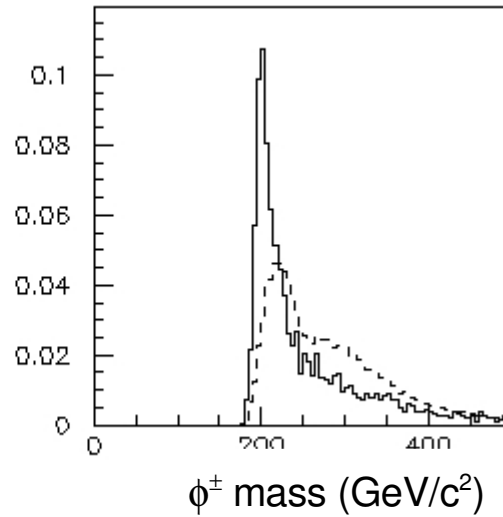
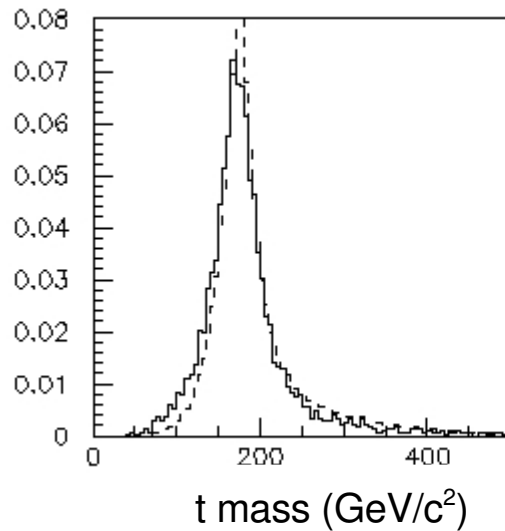
$$m(\phi^{\pm}) < 250 \text{ GeV}/c^2$$

$$m(T) < 700 \text{ GeV}/c^2$$

$$p_T(T) > 150 \text{ GeV}/c \text{ (jacobian peak)}$$

$W_H (1 \text{ TeV}/c^2) \rightarrow T b$ mass reconstruction

— signal
- - tt bkg



Reconstructed mass and width:

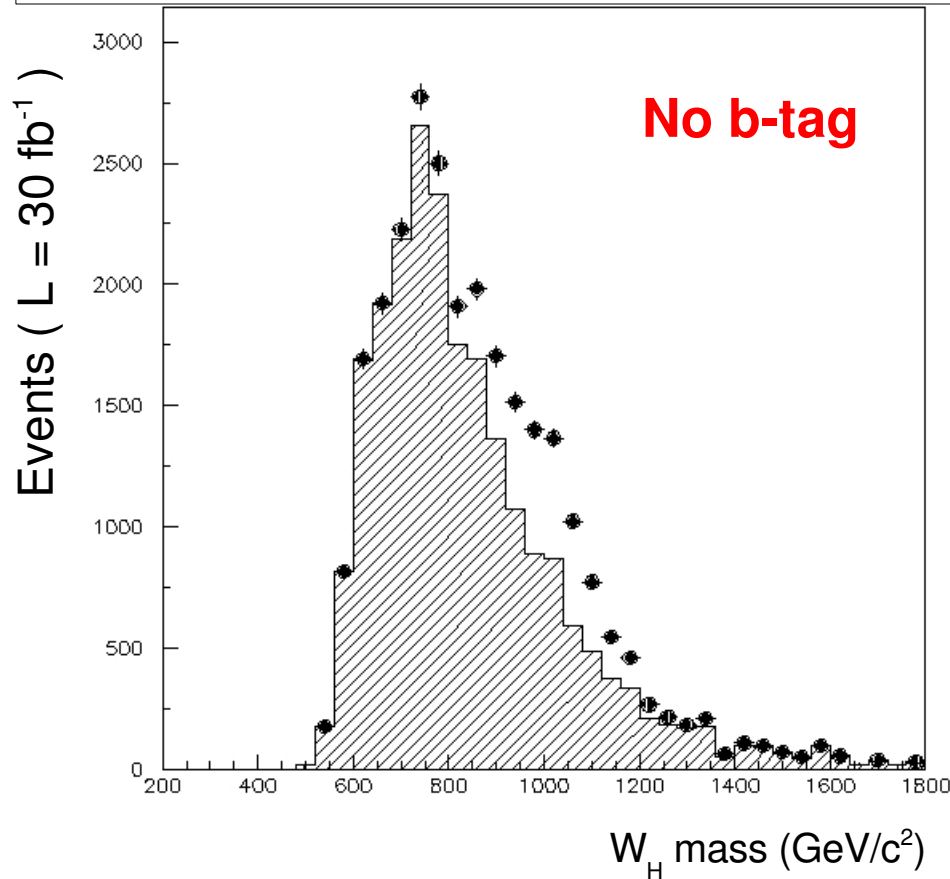
$$m = 982 \text{ GeV}/c^2$$

$$\sigma = 120 \text{ GeV}/c^2$$

Remark:

$$\Gamma(W_H) = 24 \text{ GeV}/c^2$$

W_H (1 TeV/c²) $\rightarrow$ Tb signal/bkg for L=30 fb⁻¹

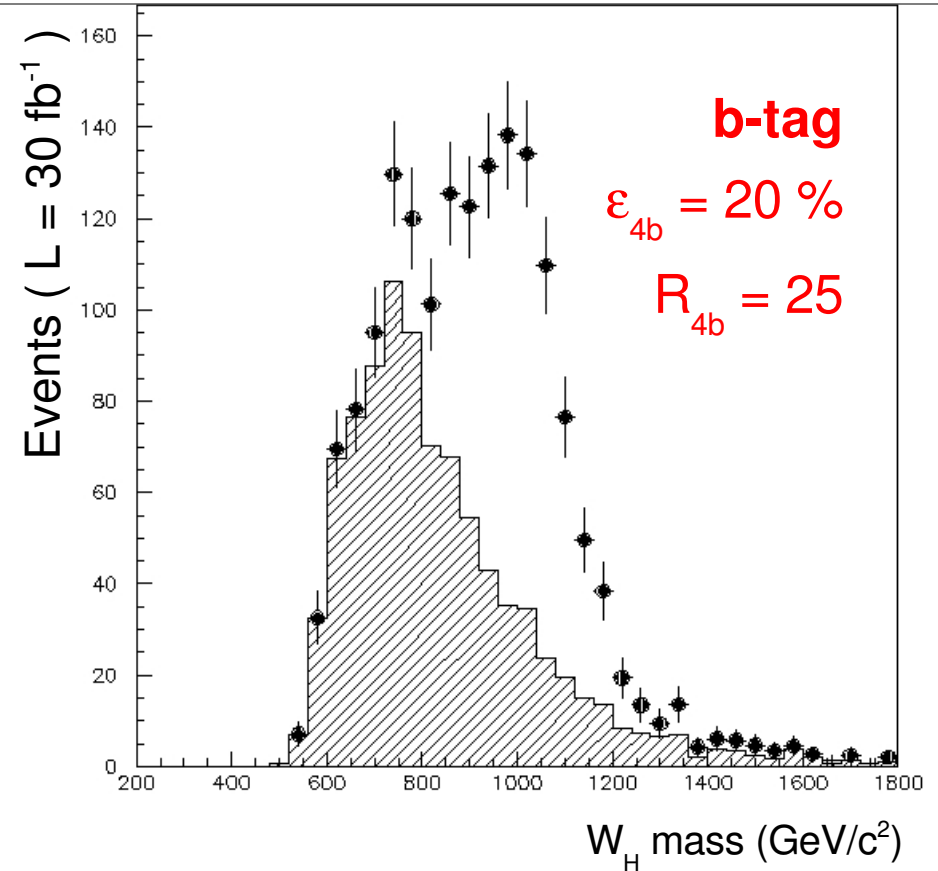


$$N_{\text{sig}} = 3253$$

$$N_{\text{tt}} = 9427$$

$$N_{\text{wj}} = 319$$

$$N/\sqrt{B} = 33$$



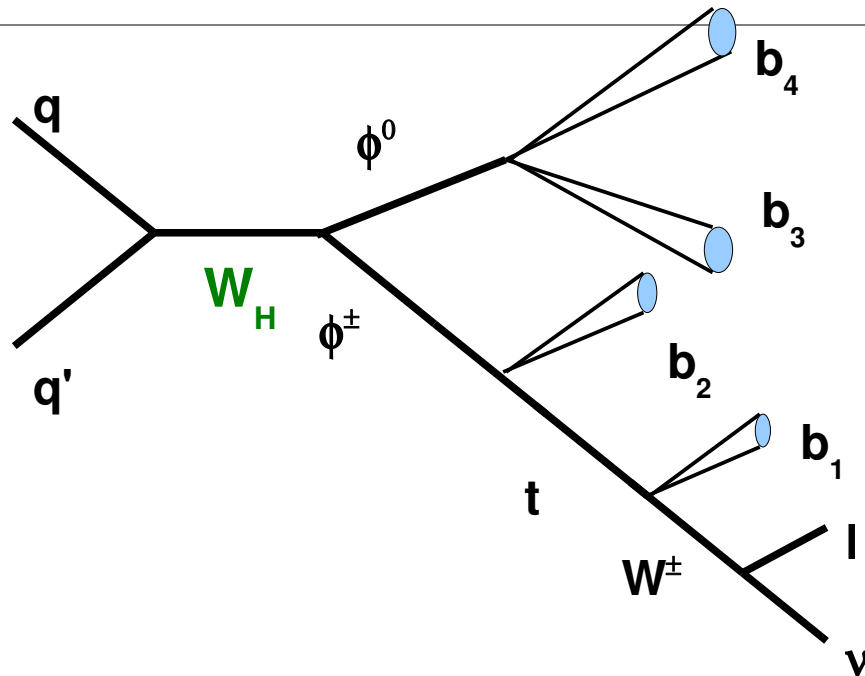
$$N_{\text{sig}} = 651$$

$$N_{\text{tt}} = 377$$

$$N_{\text{wj}} \sim 0$$

$$N/\sqrt{B} = 33$$

Signature for $W_H (1 \text{ TeV}/c^2) \rightarrow \phi^\pm \phi^0$



	$\langle p_T \rangle$ (GeV)
b_1	148
b_2	52
b_3	200
b_4	200
l	100
ν	121

particle	mass (GeV)	decay	BR
W_H	1000	$\phi^\pm \phi^0$	(3%)
$\phi^\pm$	200	tb	(100%)
ϕ^0	100	bb	(80%)
t	175	bW	(100%)
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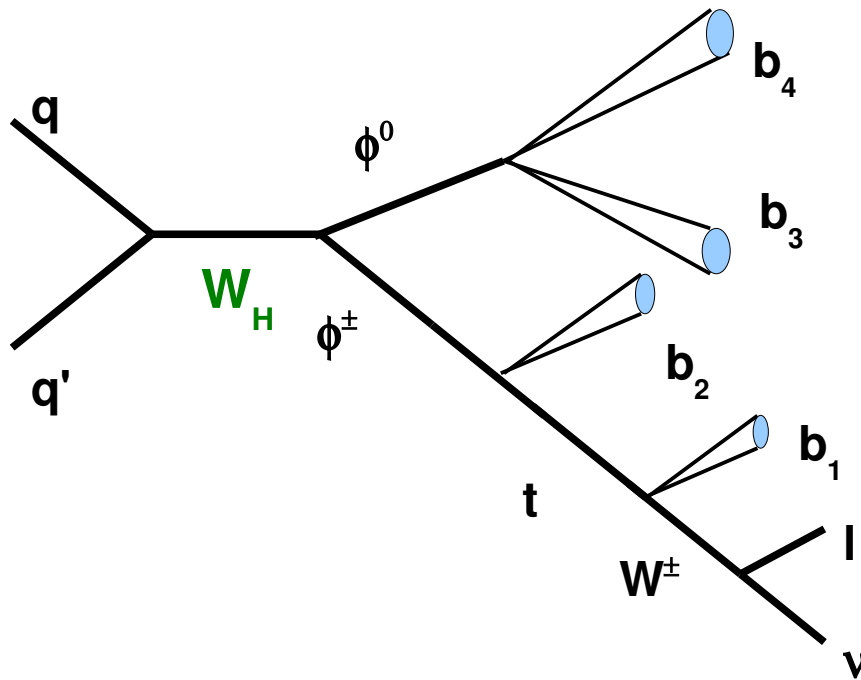
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Background: tt , W +jets

Luminosity: $L = 30 \text{ fb}^{-1}$

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Reconstruct masses

$$l + \nu \rightarrow W \quad p_T(l) > 25 \text{ GeV}/c, \\ E_T^{\text{miss}} > 25 \text{ GeV}/c$$

assume $p_z^\nu \parallel p_z^l$ to reconstruct W

$$\epsilon_l = 90\% \text{ (trigger + lepton ID)}$$

$$W + b_1 \rightarrow t \quad 25 < p_T(b_1) < 300 \text{ GeV}/c$$

$$t + b_2 \rightarrow \phi^\pm \quad 25 < p_T(b_2) < 150 \text{ GeV}/c$$

$$b_3 + b_4 \rightarrow \phi^0 \quad p_T(b_3, b_4) > 25 \text{ GeV}/c$$

$$\phi^\pm + \phi^0 \rightarrow W_H$$

$$|\eta| < 2.5 \text{ for all leptons and jets}$$

Additional cuts

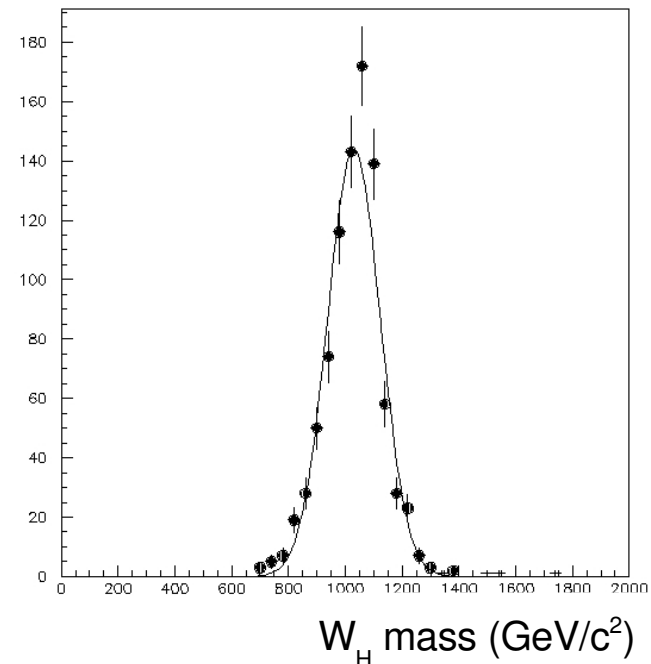
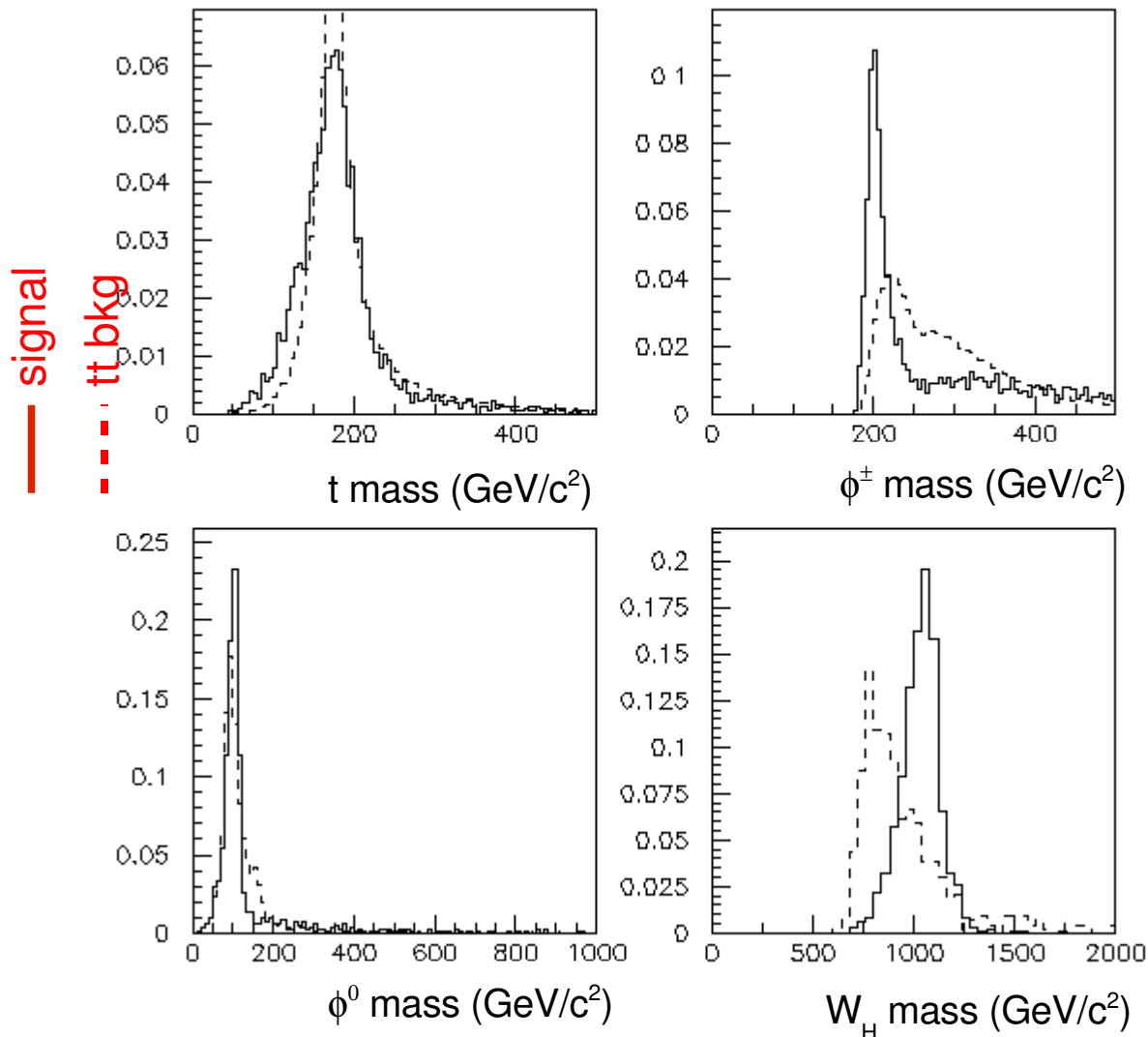
$$m(t) < 250 \text{ GeV}/c^2$$

$$m(\phi^\pm) < 250 \text{ GeV}/c^2$$

$$m(\phi^0) < 150 \text{ GeV}/c^2$$

$$p_T(\phi^\pm, \phi^0) > 300 \text{ GeV}/c \text{ (jacobian peak)}$$

$W_H (1 \text{ TeV}/c^2) \rightarrow \phi^\pm \phi^0$ mass reconstruction



Reconstructed mass and width:

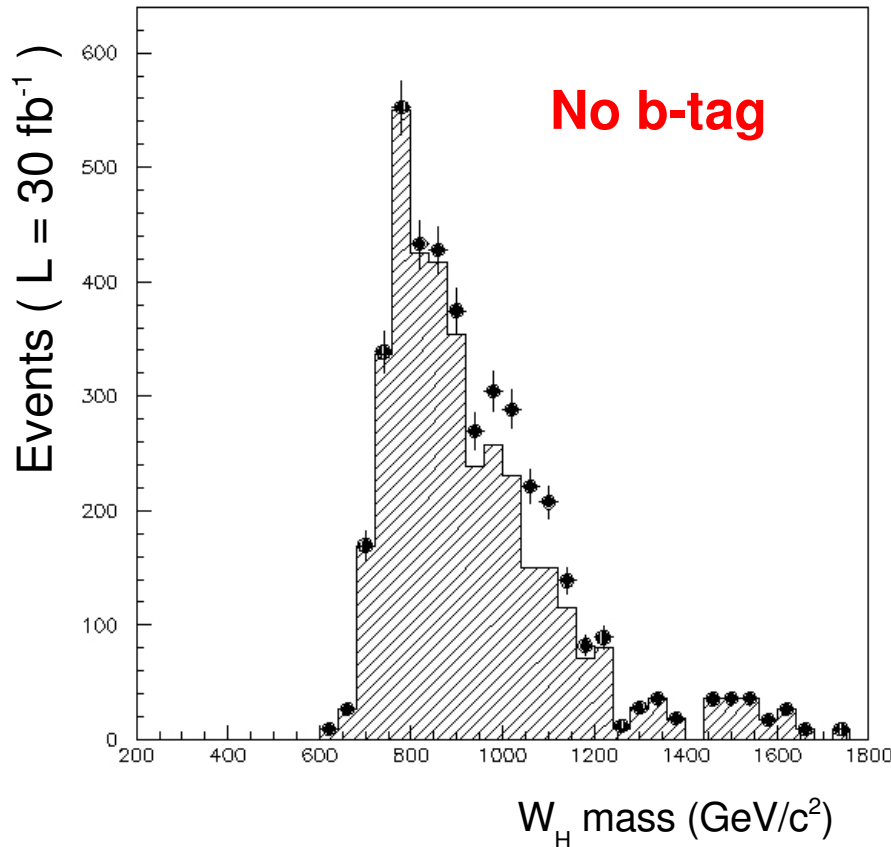
$$m = 1030 \text{ GeV}/c^2$$

$$\sigma = 93 \text{ GeV}/c^2$$

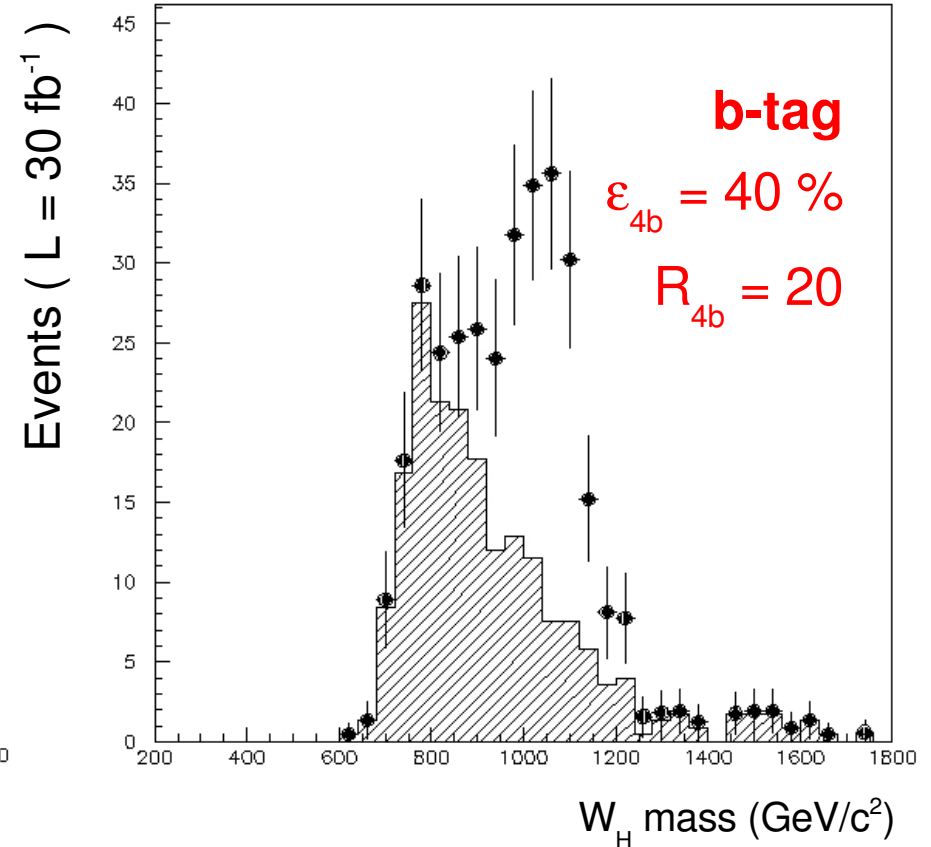
Remark:

$$\Gamma (W_H) = 24 \text{ GeV}/c^2$$

$W_H (1 \text{ TeV}/c^2) \rightarrow \phi^\pm \phi^0 \text{ signal/bkg for } L=30 \text{ fb}^{-1}$



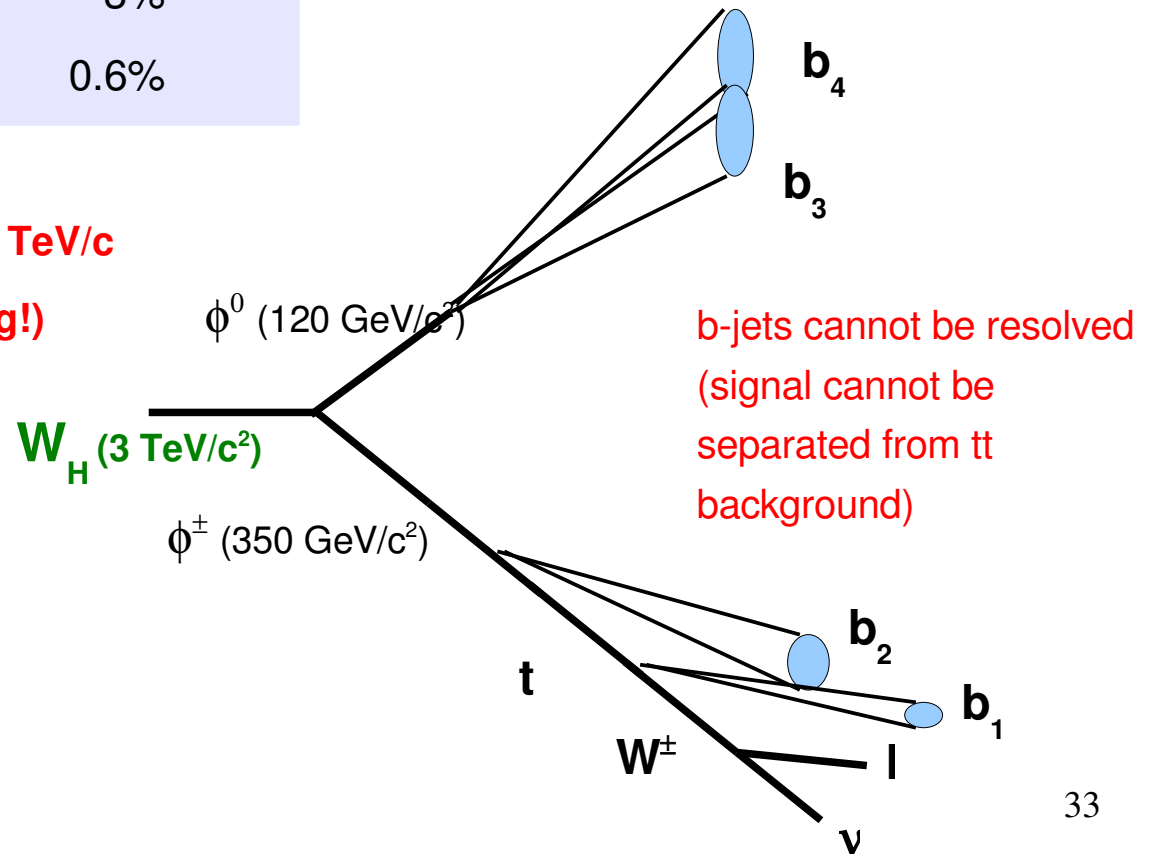
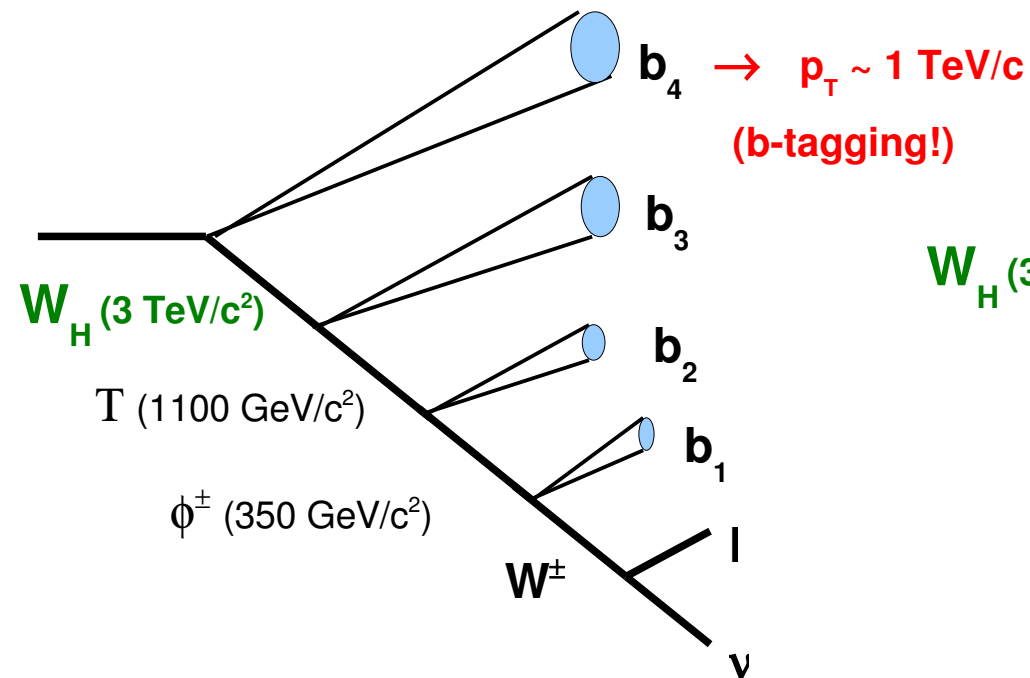
$$\begin{aligned} N_{\text{sig}} &= 337 \\ N_{\text{tt}} &= 1958 \\ N_{\text{wj}} &= 171 \\ N/\sqrt{B} &= 7 \end{aligned}$$



$$\begin{aligned} N_{\text{sig}} &= 135 \\ N_{\text{tt}} &= 98 \\ N_{\text{wj}} &\sim 0 \\ N/\sqrt{B} &= 14 \end{aligned}$$

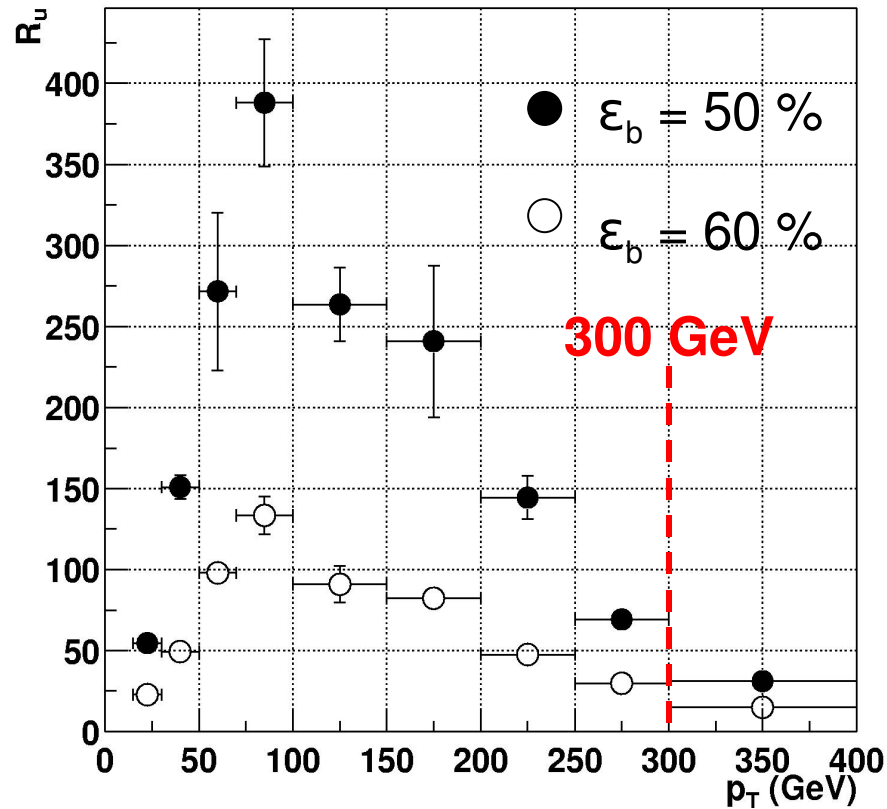
Mass dependence

$m(W_H)$	1 TeV/c ²	2 TeV/c ²	3 TeV/c ²
$\sigma(\text{pb})$	30	2	0.2
$M_T (\text{GeV}/c^2)$	500	800	1100
BR ($W_H \rightarrow T b$)	20%	25%	25%
BR ($W_H \rightarrow \phi^\pm \phi^0$)	3%	3%	3%
BR ($W_H \rightarrow t b$)	4%	3%	0.6%



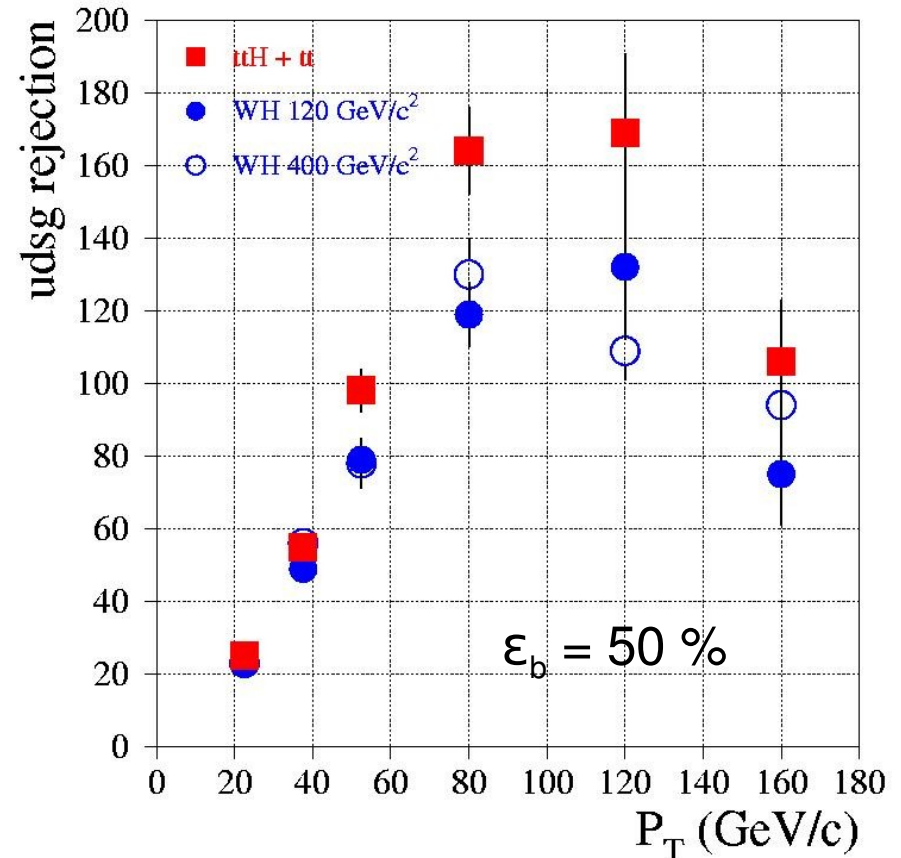
p_T dependence of b-tagging

ATL-COM-INDET-2003-017



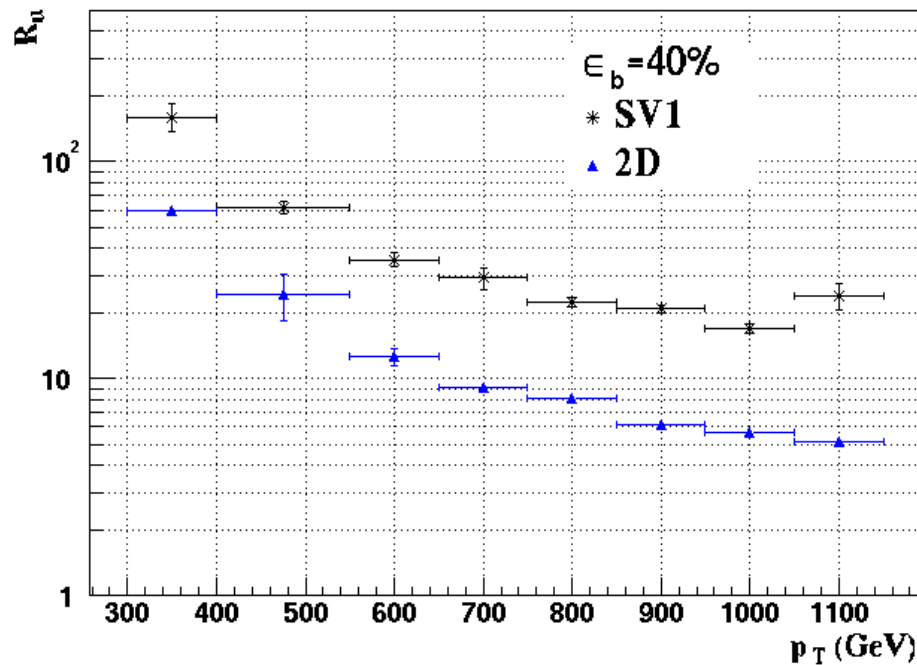
2D algorithm – DC1 data
 $pp \rightarrow W H (120 + 400 \text{ GeV})$
 $\searrow$
 $b b$

ATL-PHYS-2004-006



2D algorithm – DC1 data
 $W H + t t$ samples

p_T dependence in Z_H ($2 \text{ TeV}/c^2$) $\rightarrow$ bb samples



Full simulation

“Rome” samples = DC1 geometry

SV1 = secondary vertex based b-tag algorithm

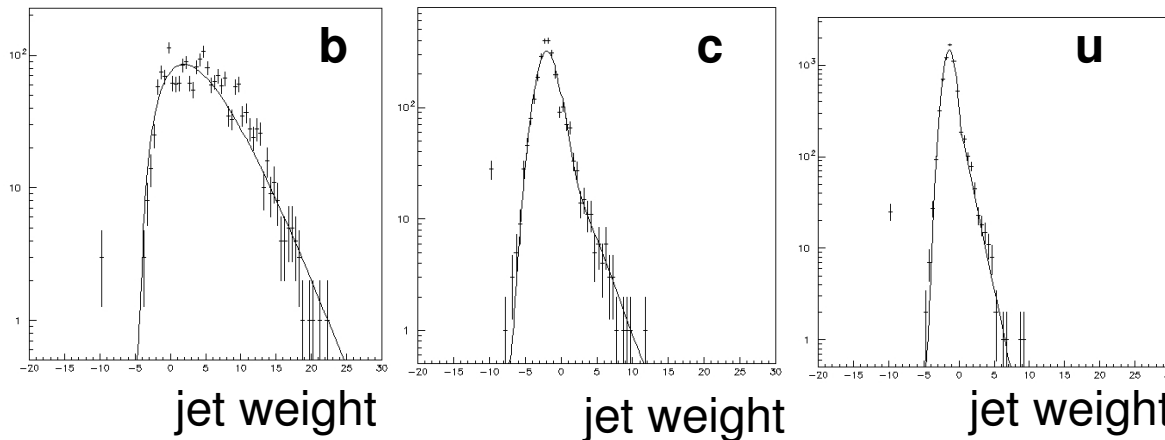
2D = signed IP significance tagger

Studies ongoing on CSC samples
(= DC3 geometry with updated material and residual misalignment)

Standard ATLAS tagging algorithms, without retuning

b-tagging likelihood weights

b-tag likelihood “weights” for $60 < p_T < 100$ GeV/c (2D signed IP significance algorithm - DC1 data)



$$\epsilon_b = 50\%$$

$$p_T = 100 \text{ GeV/c} \rightarrow R_u = 130$$

$$p_T = 500 \text{ GeV/c} \rightarrow R_u = 60$$

Parameterisation

b-jets $\rightarrow w^a e^{-bw}$

c-jets $\rightarrow w^c e^{-dw} + \text{gaussian}$

u-jets $\rightarrow e^{-ew} + \text{gaussian}$

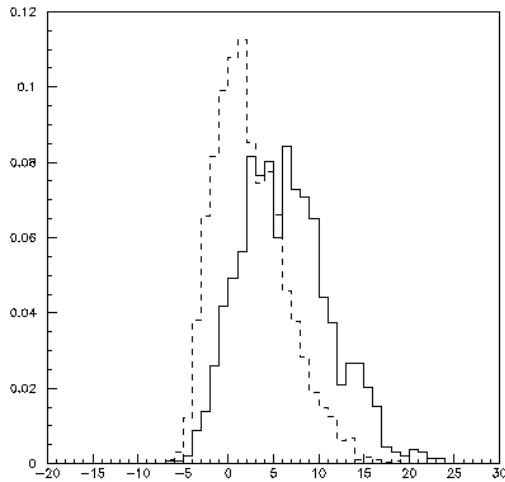
a,b,c,d,e determined on
full simulation for
several p_T bins

multi b-jet likelihood:

$$W_{\text{event}} = \sum_{\text{jets } j} w_j$$

b-tagging for $m(W_H) = 1 \text{ TeV}/c^2$

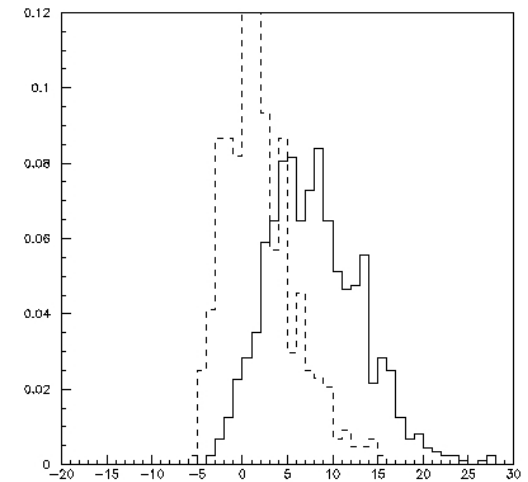
$$W_H \rightarrow T b \rightarrow 4b + l + E_t^{\text{miss}}$$



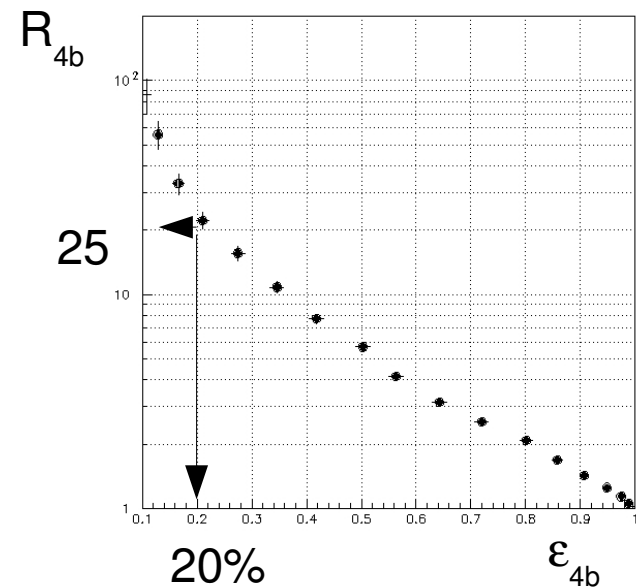
Event weight

— signal
- - - tt background

$$W_H \rightarrow \phi^+ \phi^0 \rightarrow 4b + l + E_t^{\text{miss}}$$

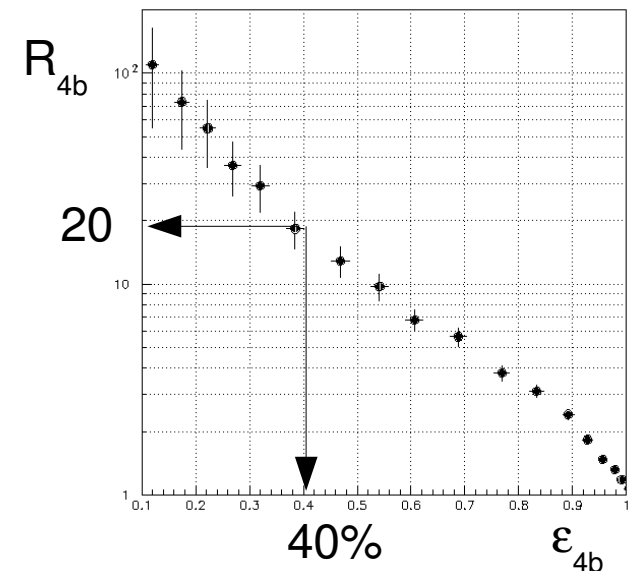


Event weight



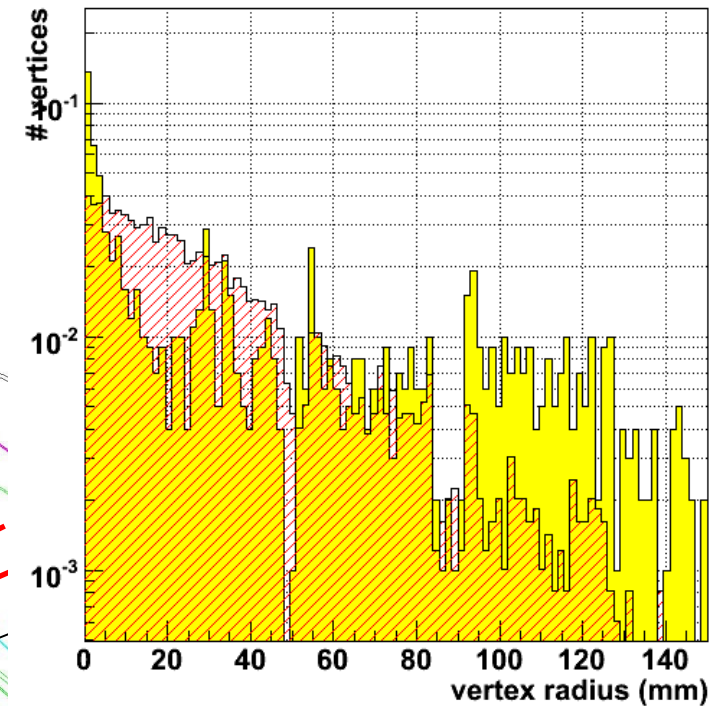
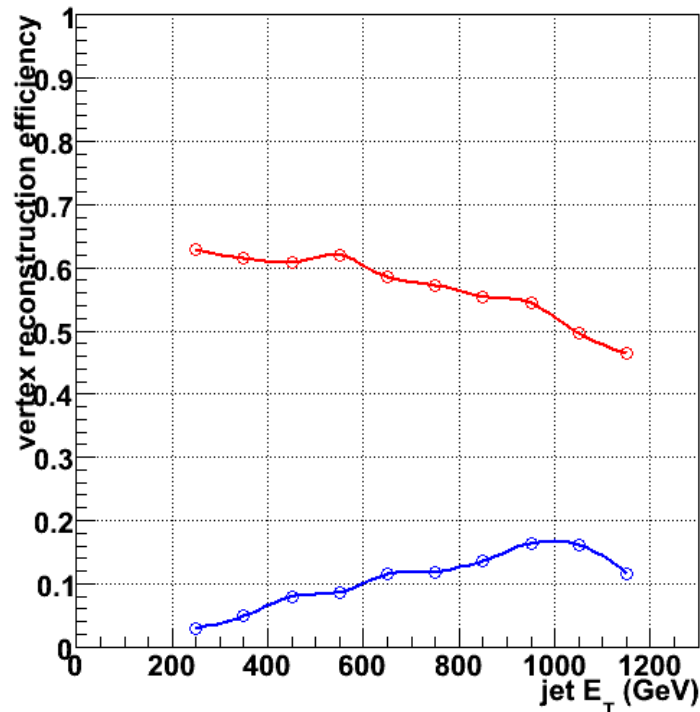
ϵ_{4b} = signal efficiency

R_{4b} = rejection against
tt background



vertexing in high p_T jets

VkalVrt: Vertex reconstruction efficiency in **b-jets** and **light jets**



VkalVrt: reconstructed vertex radius distribution for **b-jets** and **light jets**