HL-LHC Top and Standard Model Results from ATLAS

ECFA prep meeting, September 2016

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Introduction

- **FCNC Top**
  - Expected sensitivity of ATLAS to FCNC top quark decays $t \to Zq$ and $t \to Hq$
  - New PUB note for ECFA 2016: ATL-PHYS-PUB-2016-019
- **ssWW**
  - Studies of $W^{\pm}W^{\pm}$ boson scattering
  - Scoping document: https://cds.cern.ch/record/2055248/

FCNC Top

- Expected sensitivity to FCNC top quark decays estimated for 3000ifb at 14 TeV, <μ>=200
- 2 different channels: t→Zq and t→Hq
- 3 signal samples with different couplings

Type	Couplings	σ[fb]	$\mathcal{B}(10^{-5})$
	$\eta^L = \eta^R = 0.01$	10.6	2.67
"γ"	$X^L = X^R = 0.01$	3.77	9.38
"σ"	$\kappa^L = \kappa^R = 0.01$	5.50	13.7

- 3 different detector upgrade scenarios: reference, middle, low
  - reference: extended inner tracker and very forward muon tagger (up to |eta|=4.0)

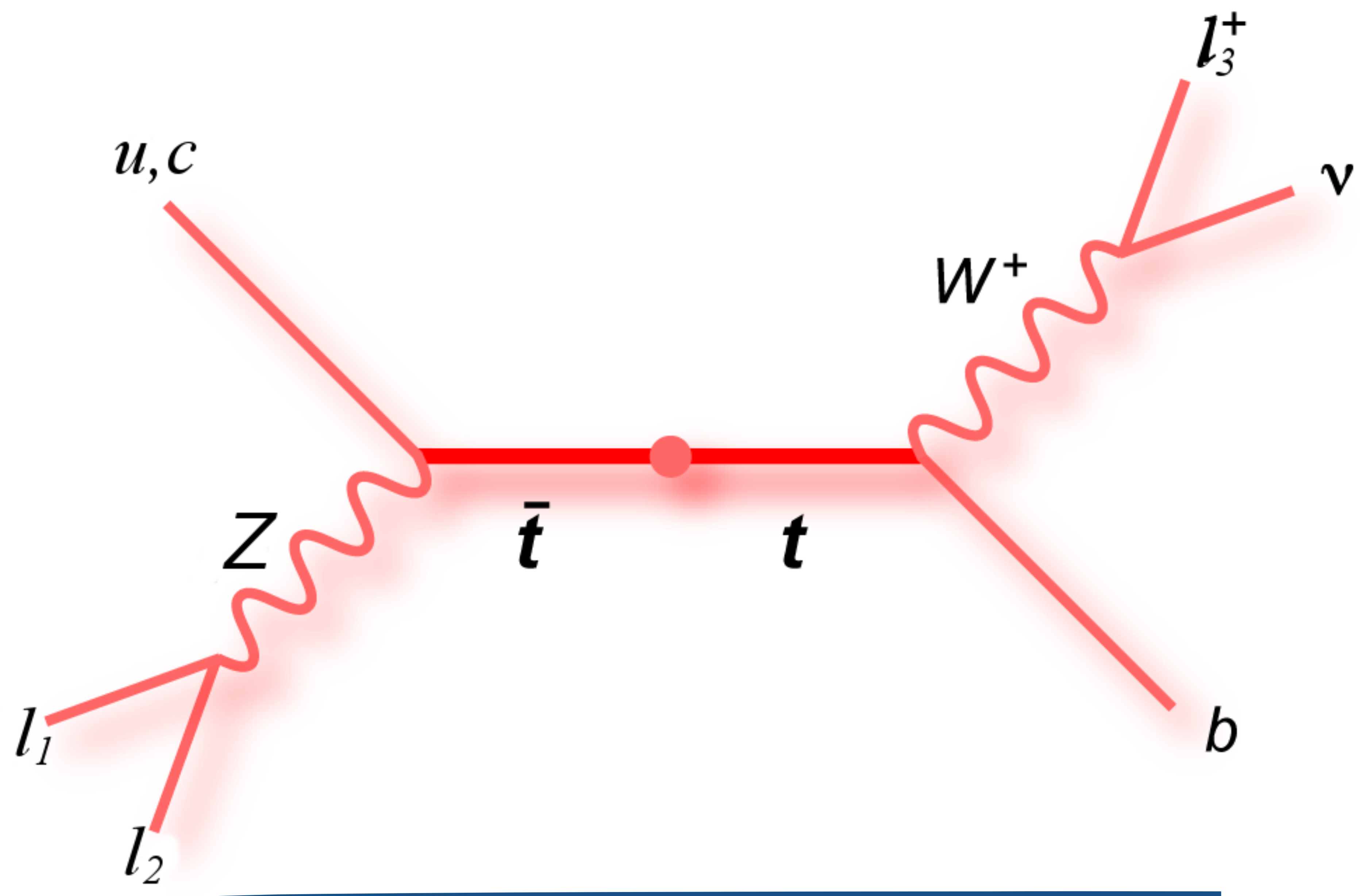
- Run 1 results:
  - Br(t→Zq) < 50×10^{-5}
  - Br(t→Hu(c)): $45(46) \times 10^{-4}$

- HL-LHC extrapolations:
  - 10×10^{-5}
  - 1.5×10^{-4}

FCNC Top

- Leptons
  - Tight ID
  - pT > 25 (30) GeV for t→Hq (Zq)
  - |eta| < 4.0 (reference); 3.2 (middle); 2.7 (low)
- Jets
  - pT > 30 GeV (40 for b-jets in t→Zq)

t→Zq



- Expected signal yields

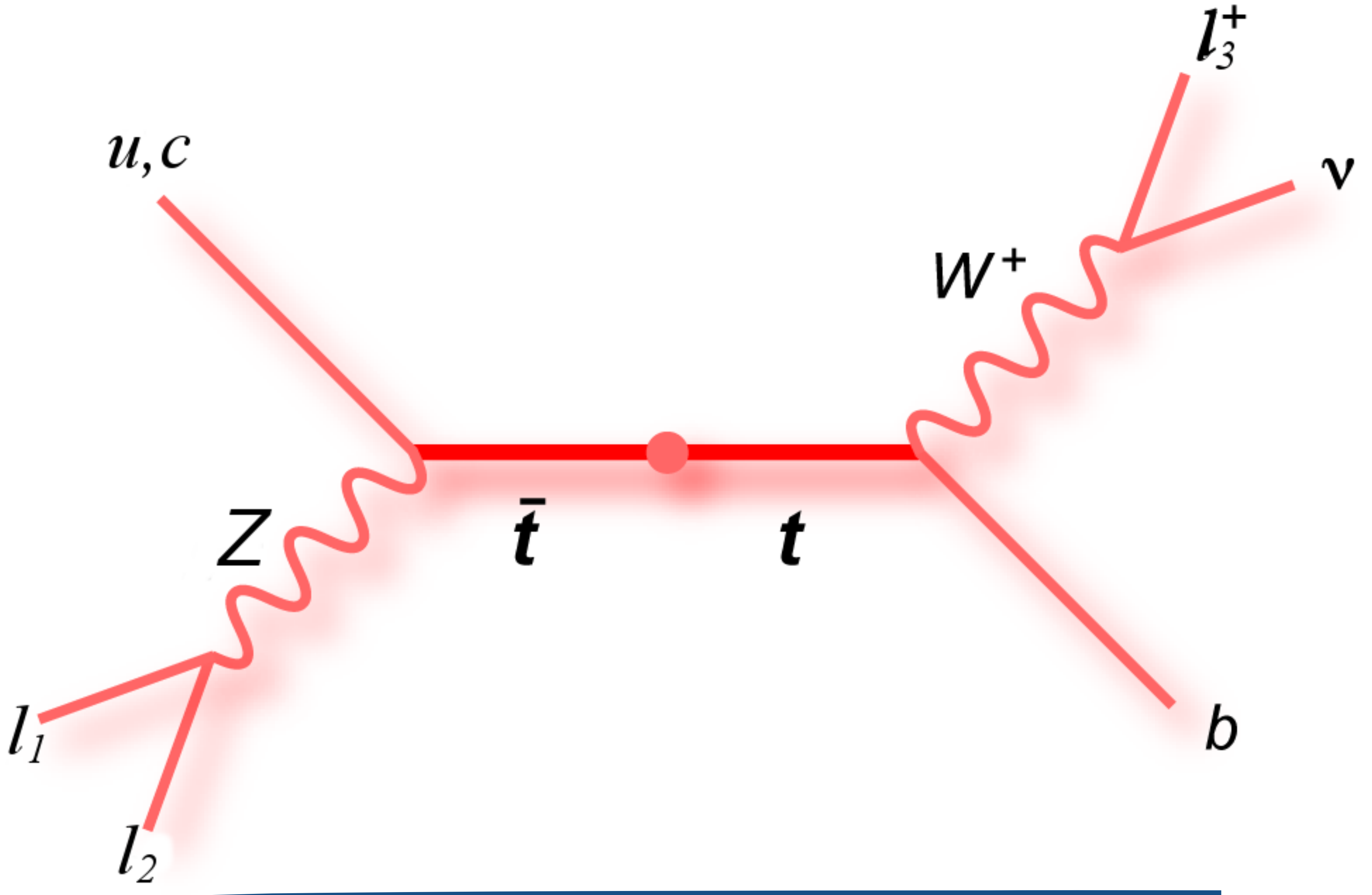
Process	Events		
	Reference	Middle	Low
"γ" t→Zu	589 ± 6	541 ± 6	444 ± 5
"σ" t→Zu	838 ± 9	761 ± 9	623 ± 8
"γ" t→Zc	490 ± 5	431 ± 5	348 ± 5
"σ" t→Zc	700 ± 8	611 ± 8	490 ± 7

- Exactly 3 leptons:
  - leptons 1,2 form OSSF pair in [65,115] GeV
  - lepton 3 within |eta| < 2.5
- At least 2 jets: one b-tagged, one not b-tagged

t→Zq

- Expected background yields:
  - tZ and tWZ estimated by scaling ttZ

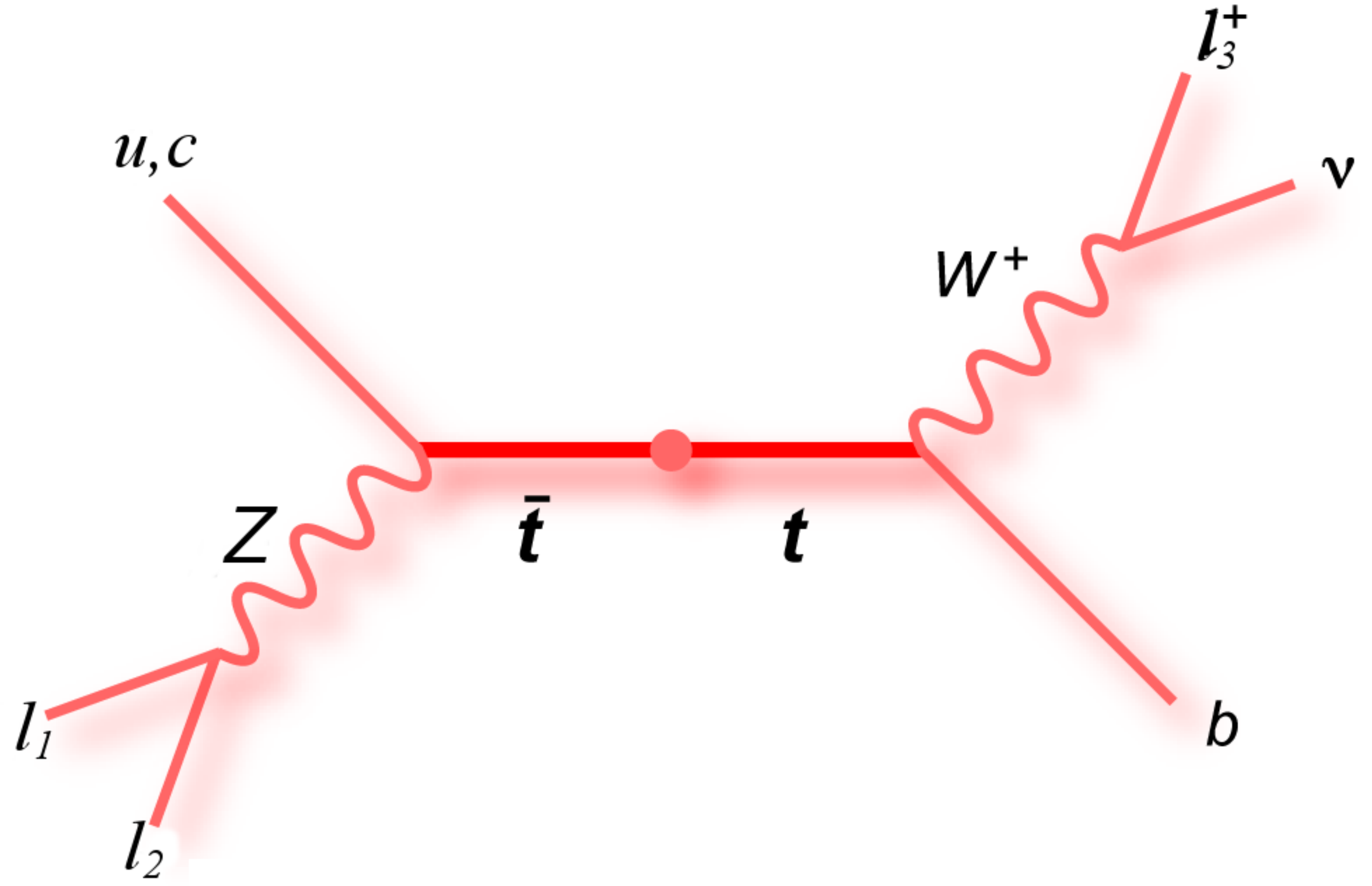
Process	Events Reference	Middle	Low
WZ	1900 ± 100	1430 ± 80	1070 ± 160
$t\bar{t}W$	580 ± 16	510 ± 15	390 ± 13
$t\bar{t}Z$	11600 ± 80	10660 ± 70	9040 ± 70
Z+jets	2150 ± 140	1680 ± 110	1130 ± 90
$t\bar{t}$	3950 ± 170	2280 ± 140	1300 ± 100
Wt	480 ± 130	480 ± 130	380 ± 110
tZ	5800	5330	4520
tWZ	1970	1810	1540
Total	28400	24200	19400

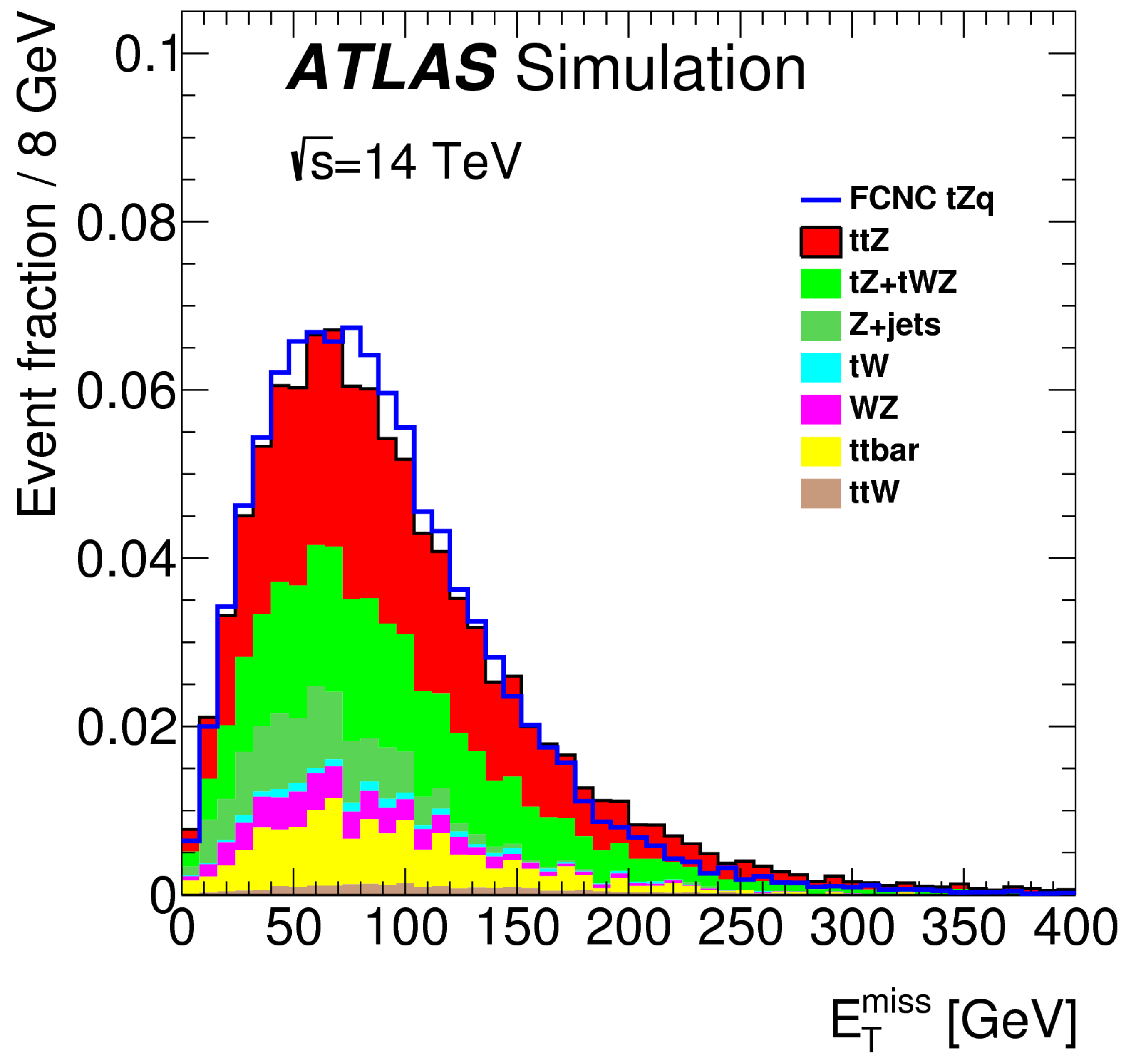


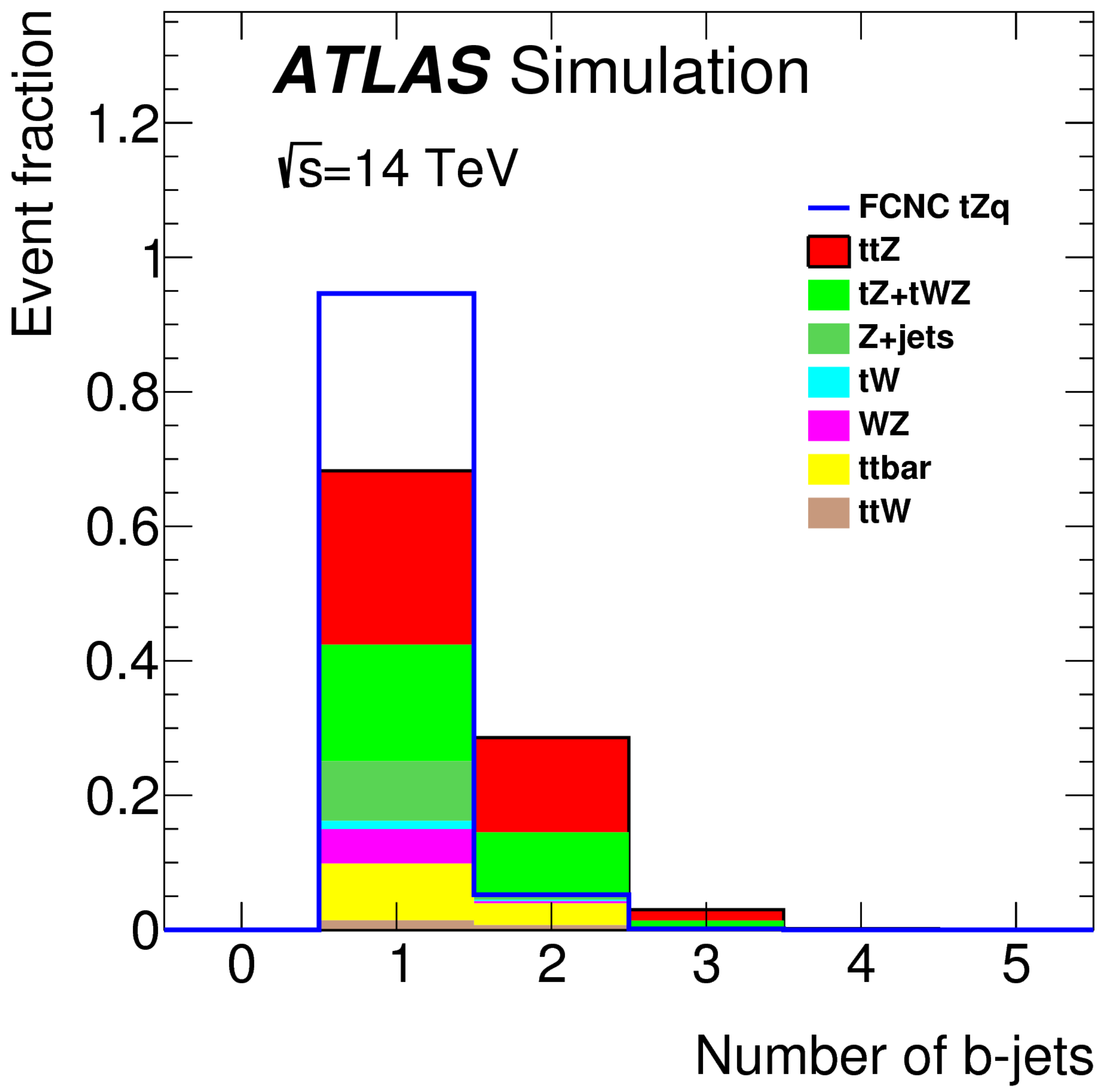
- Exactly 3 leptons:
  - leptons 1,2 form OSSF pair in [65,115] GeV
  - lepton 3 within |eta| < 2.5
- At least 2 jets: one b-tagged, one not b-tagged

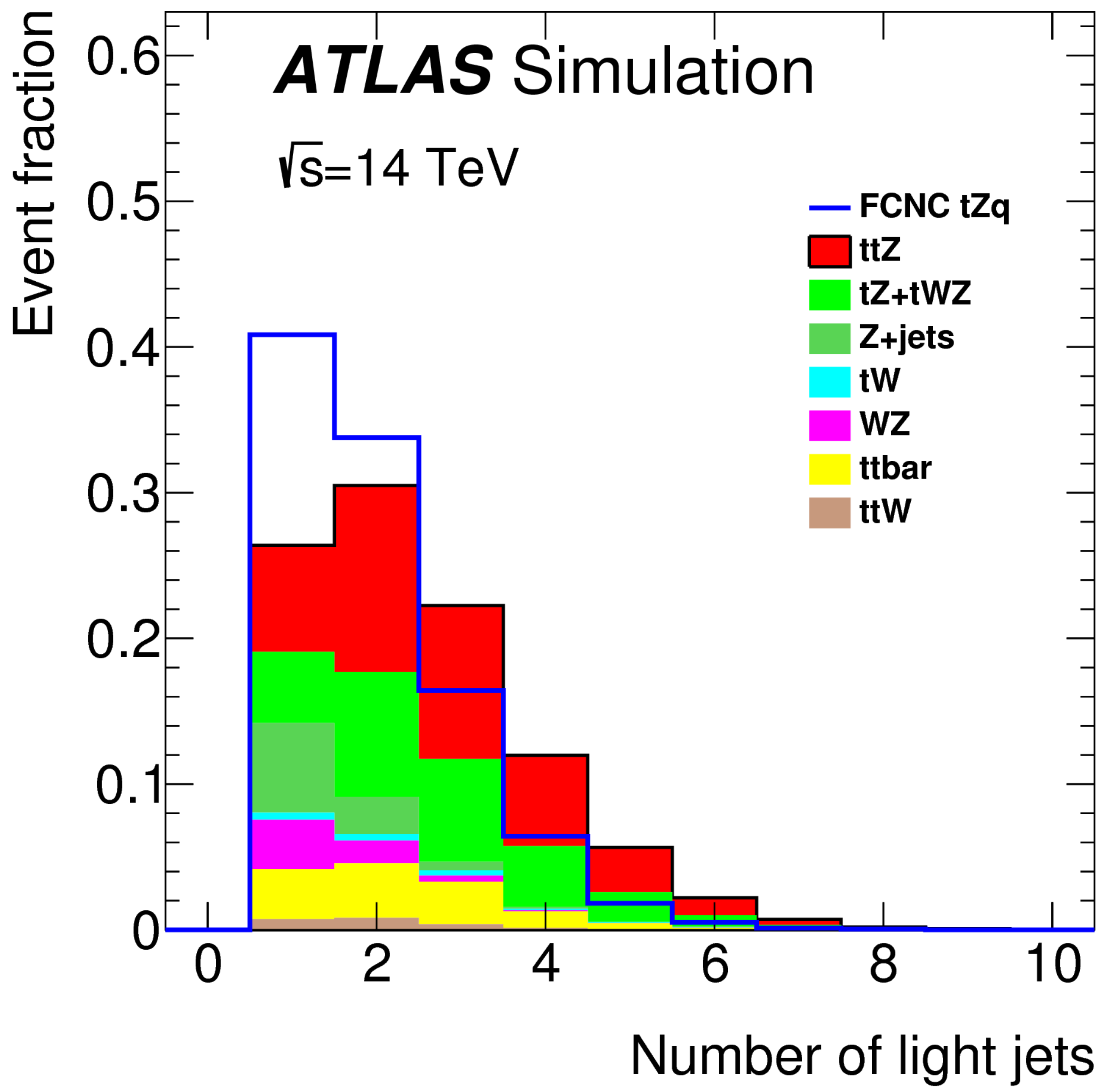
t→Zq

- ETmiss; n(b-jets); n(light-jets)
  - reference scenario









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t→Zq

- Kinematic reconstruction:

$$\chi^2 = \frac{\left(m_Z - m^{\text{reco}}_{\ell_1\ell_2}\right)^2}{\sigma_Z^2} + \frac{\left(m_W - m^{\text{reco}}_{\ell_3\nu}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m^{\text{reco}}_{\ell_3\nu j_b}\right)^2}{\sigma_{t\to Wb}^2} + \frac{\left(m_t - m^{\text{reco}}_{\ell_1\ell_2 j_u}\right)^2}{\sigma_{t\to Zq}^2}$$

- ν is four-mom of neutrino:
    - νT = ETmiss
    - νL = free parameter pZν - chosen to minimise X2
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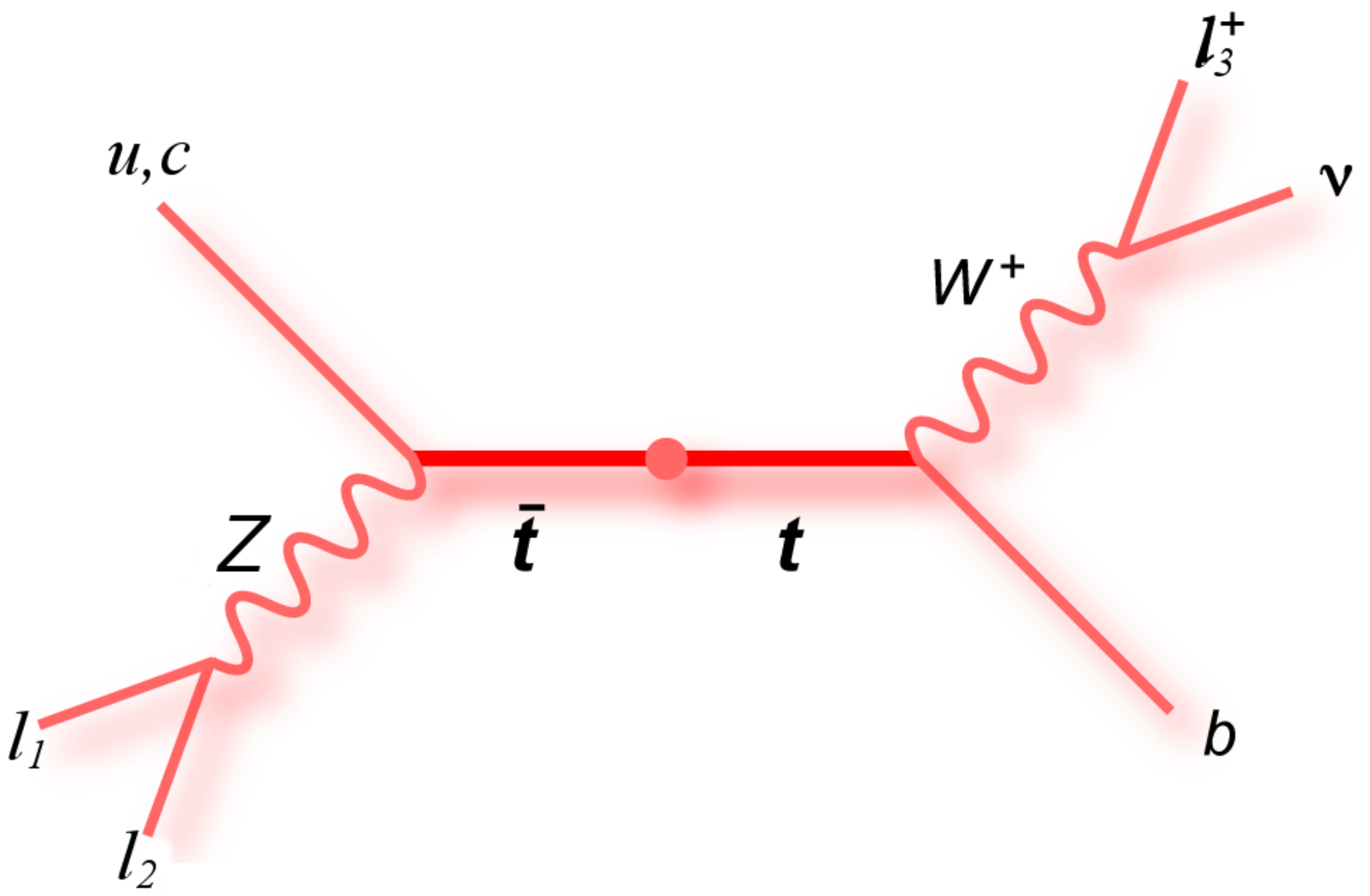
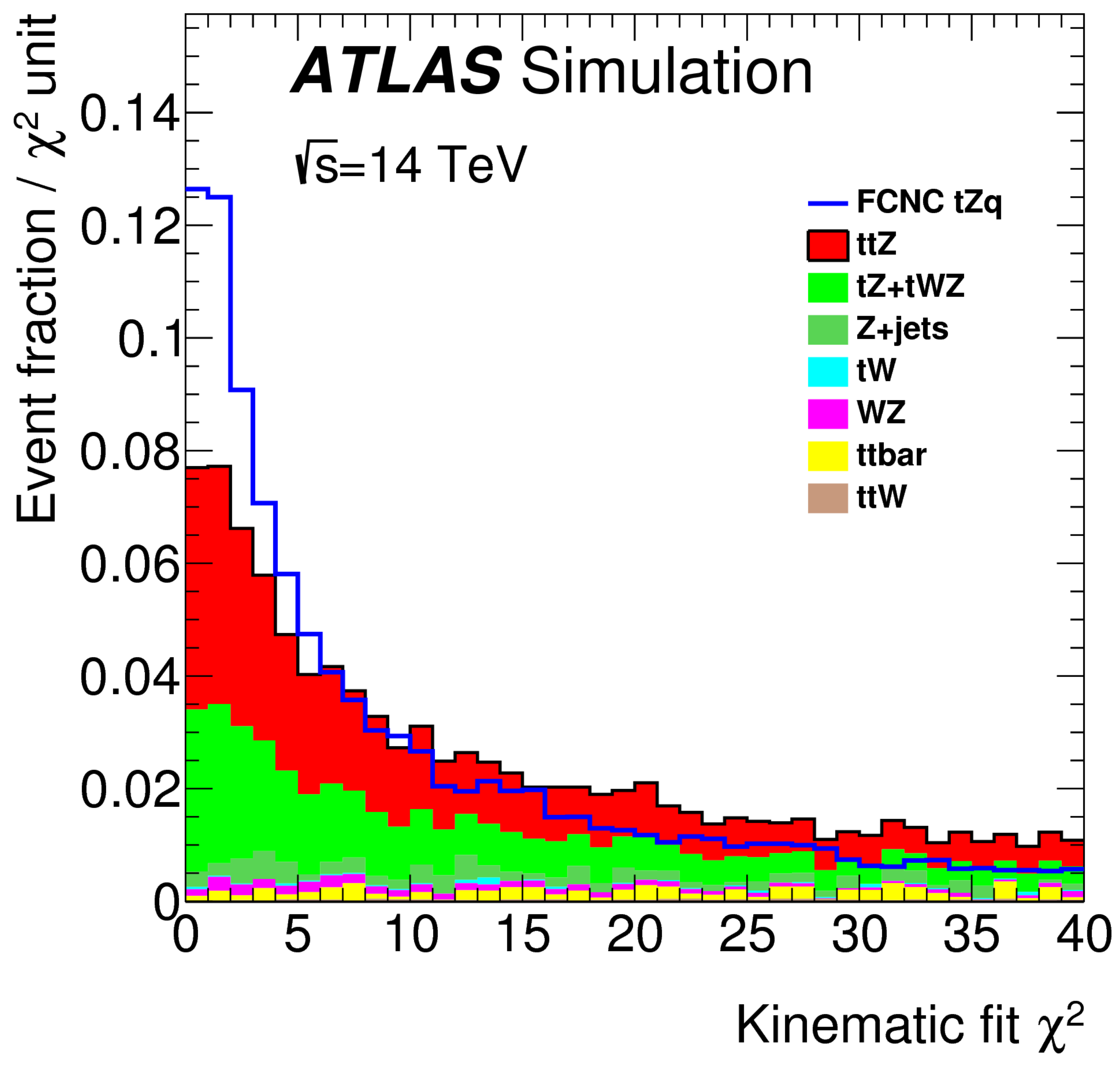
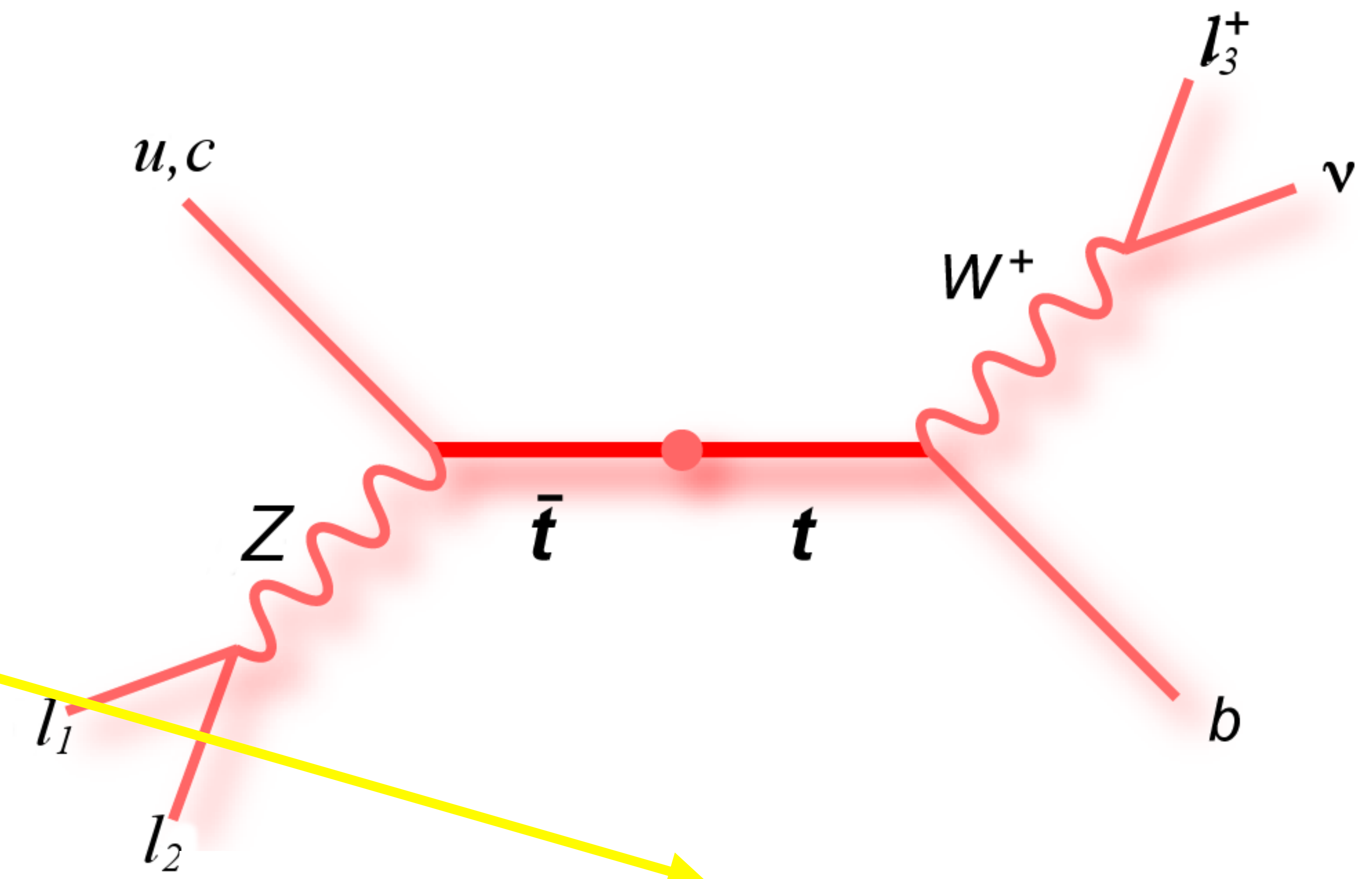
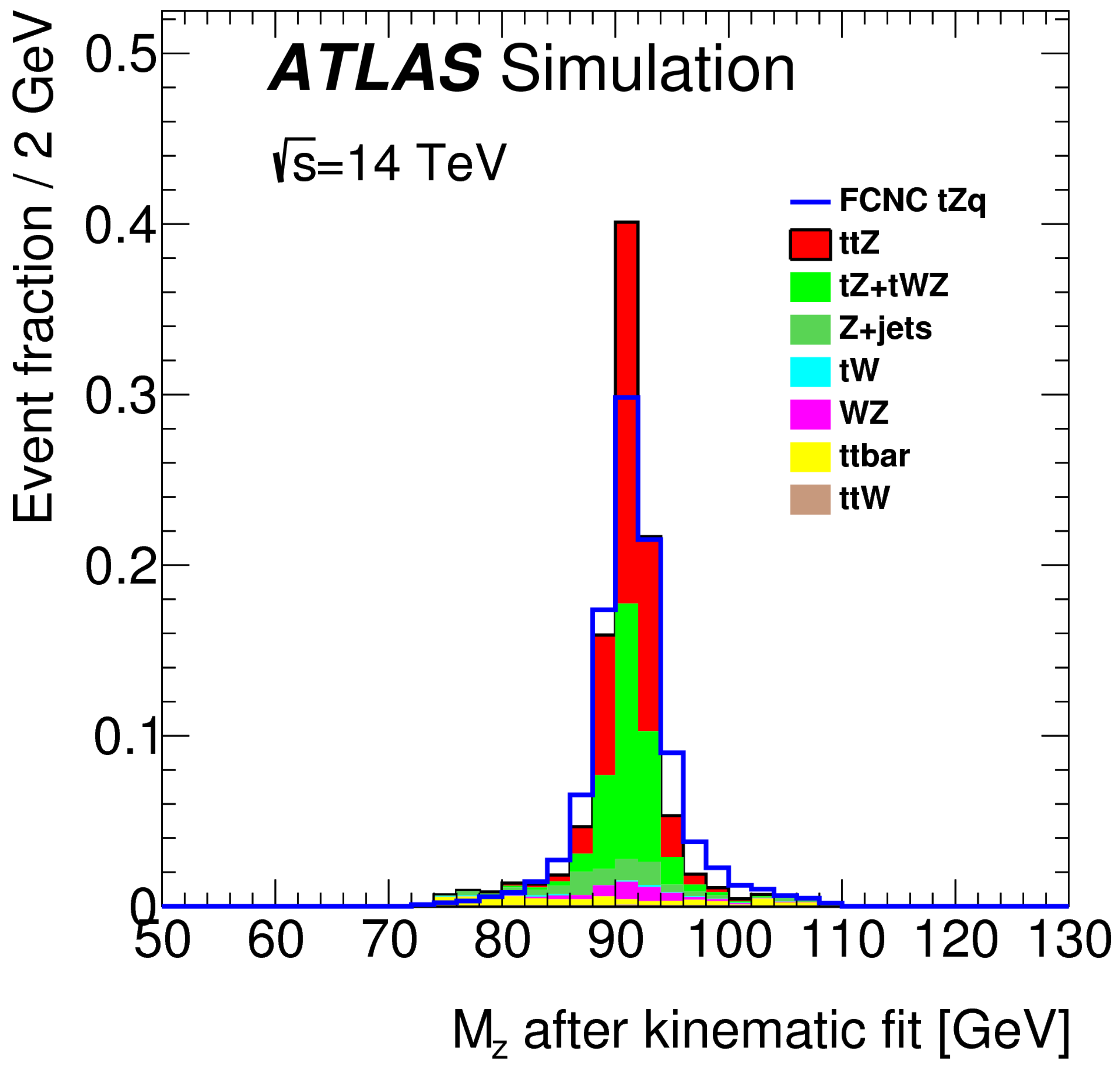


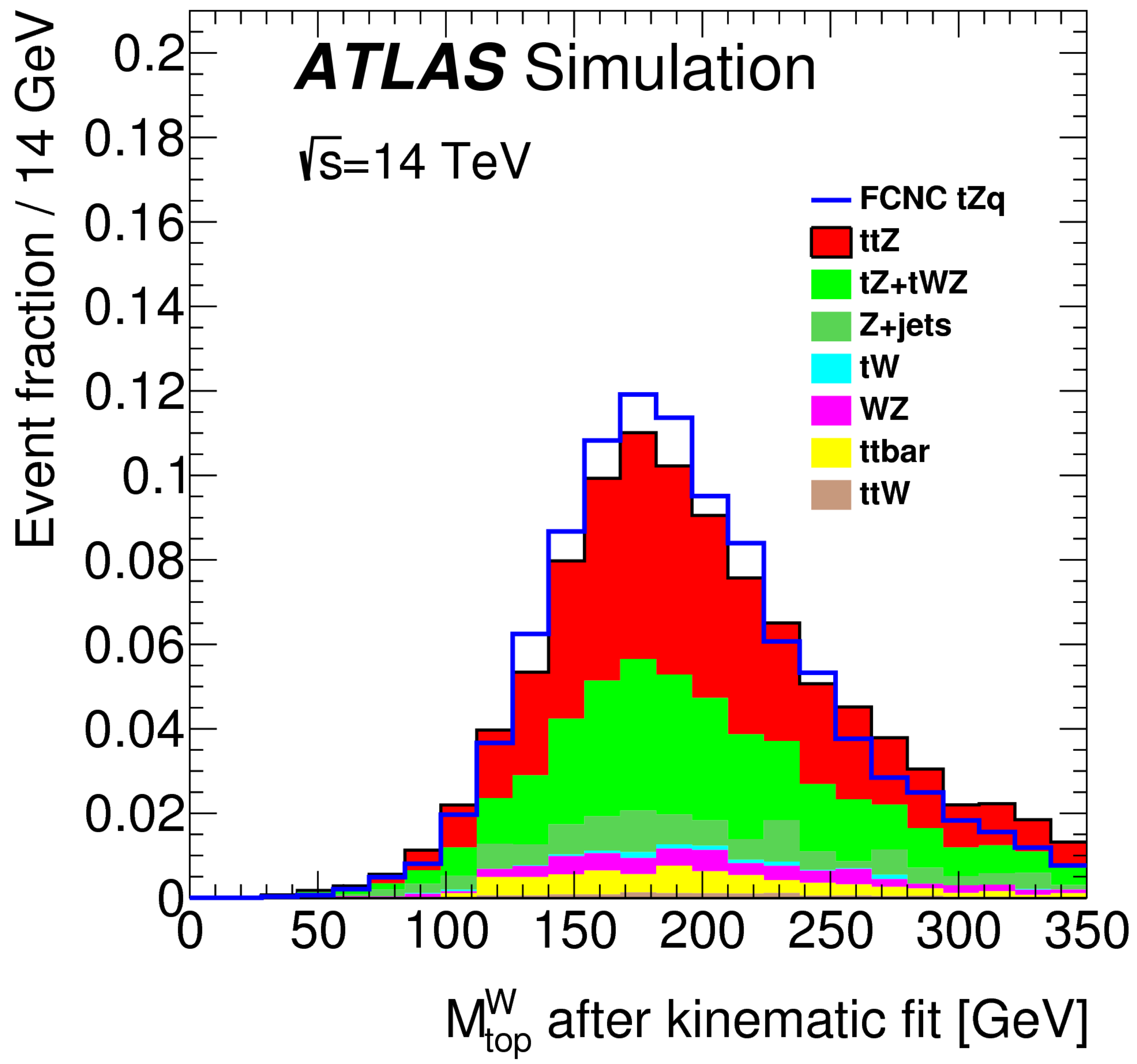


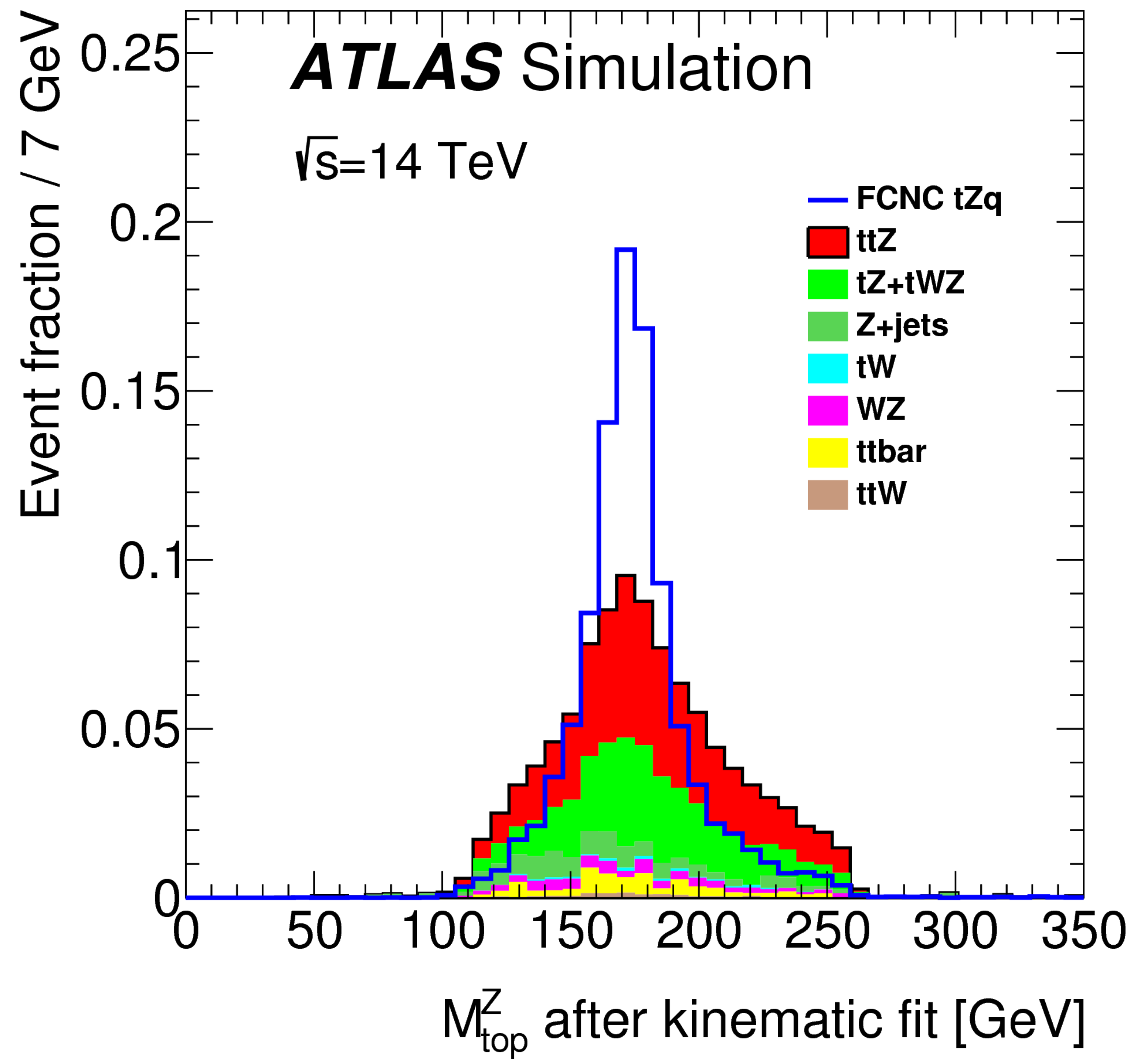
t→Zq

$$\chi^2 = \frac{\left(m_Z - m^{\rm reco}_{\ell_1\ell_2}\right)^2}{\sigma^2_Z} + \frac{\left(m_W - m^{\rm reco}_{\ell_3\nu}\right)^2}{\sigma^2_W} + \frac{\left(m_t - m^{\rm reco}_{\ell_3\nu j_b}\right)^2}{\sigma^2_{t\to Wb}} + \frac{\left(m_t - m^{\rm reco}_{\ell_1\ell_2 j_u}\right)^2}{\sigma^2_{t\to Zq}}$$

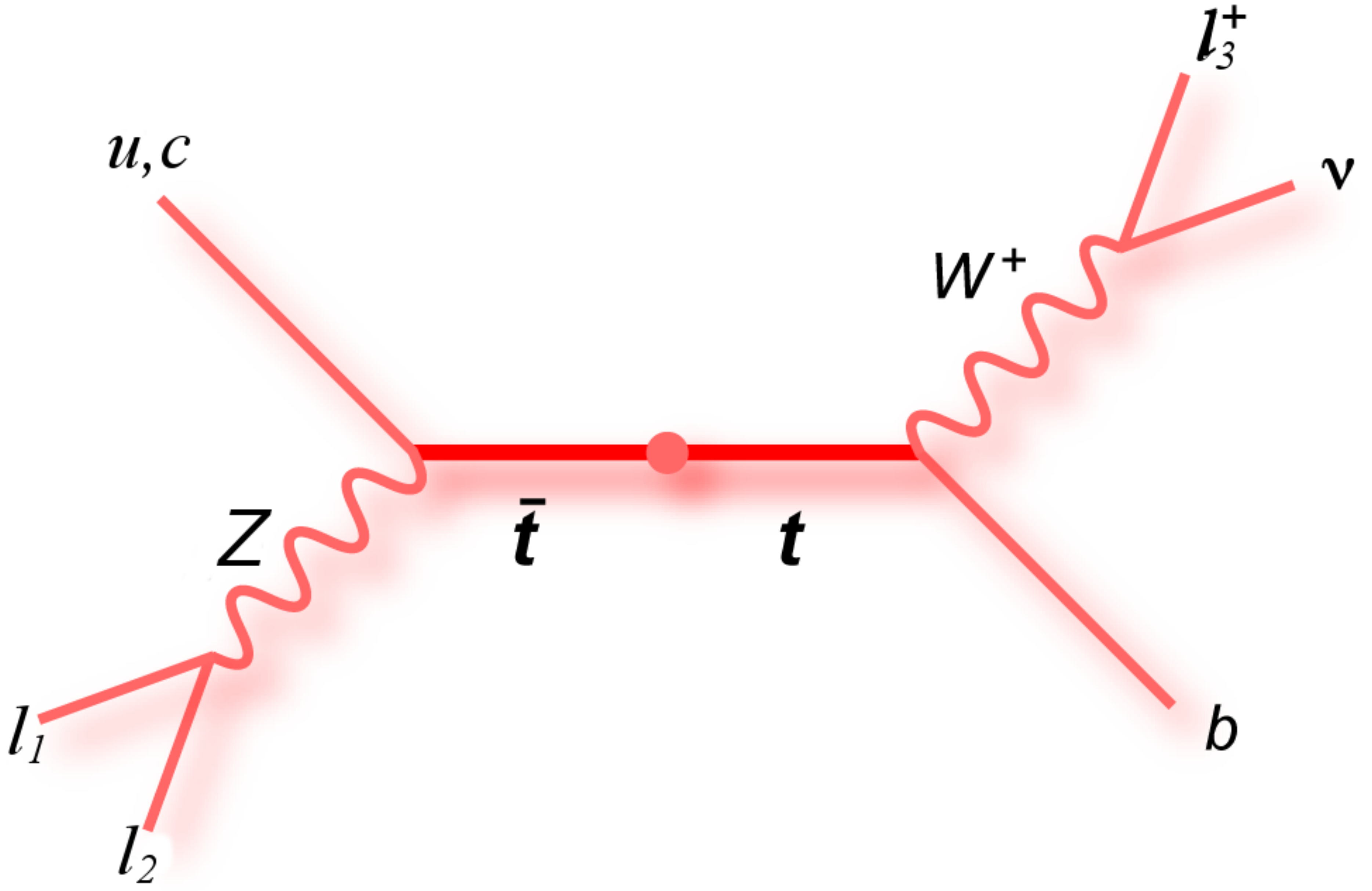








t→Zq

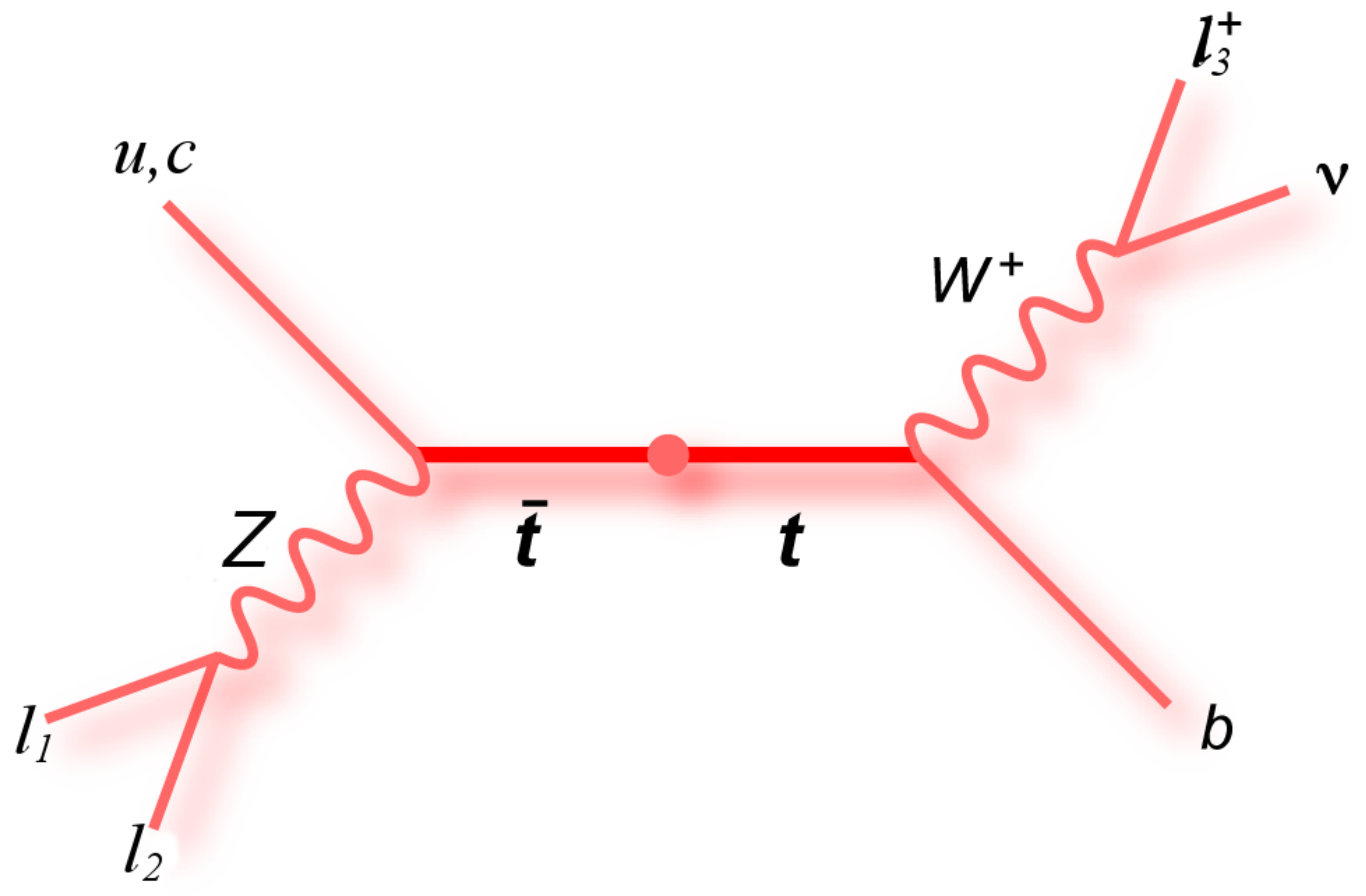


- B(t→Z u,c) 95% CL upper limits (no sys):
  - obtained from LH fit to X2 distribution

	"γ" $t \to Zu$	"σ" $t \to Zu$	"γ" $t \to Zc$	"σ" $t \to Zc$	"γ" $t \to Zu+Zc$	"σ" $t \to Zu+Zc$
Reference	$4.3 \cdot 10^{-5}$	$4.3 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$	$2.4 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$
Middle	$4.5 \cdot 10^{-5}$	$4.6 \cdot 10^{-5}$	$6.0 \cdot 10^{-5}$	$6.3 \cdot 10^{-5}$	$2.6 \cdot 10^{-5}$	$2.7 \cdot 10^{-5}$
Low	$5.1 \cdot 10^{-5}$	$5.2 \cdot 10^{-5}$	$6.7 \cdot 10^{-5}$	$7.0 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$	$3.0 \cdot 10^{-5}$

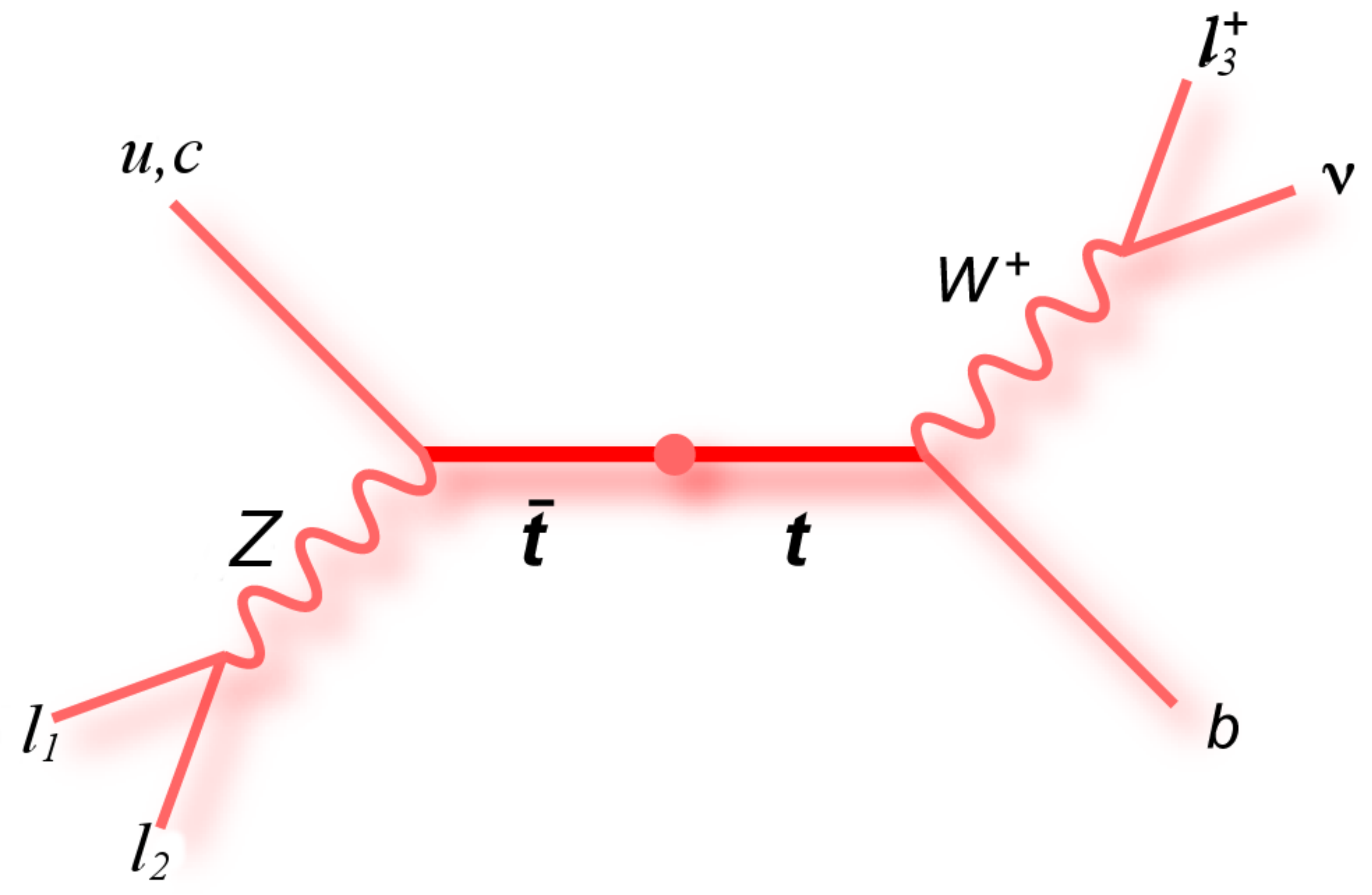
t→Zq

- Systematics



	Set A: Run 1 driven	Set B: HL-LHC predictions
Lumi: (theory)	2%	2%
WZ and signal xsec: (theory)	6%	6%
Z+jets and ttbar xsec: (data-driven)	62% (Run 1 fake rate)	30% (HL-LHC fake rate)
tZ and tWZ normalisation: (theory)	50%	10% (updated since Run 1)
ttV normalisation: (theory+data)	30%	6% (estimated from ttbar xsec)

$t \to Zq$



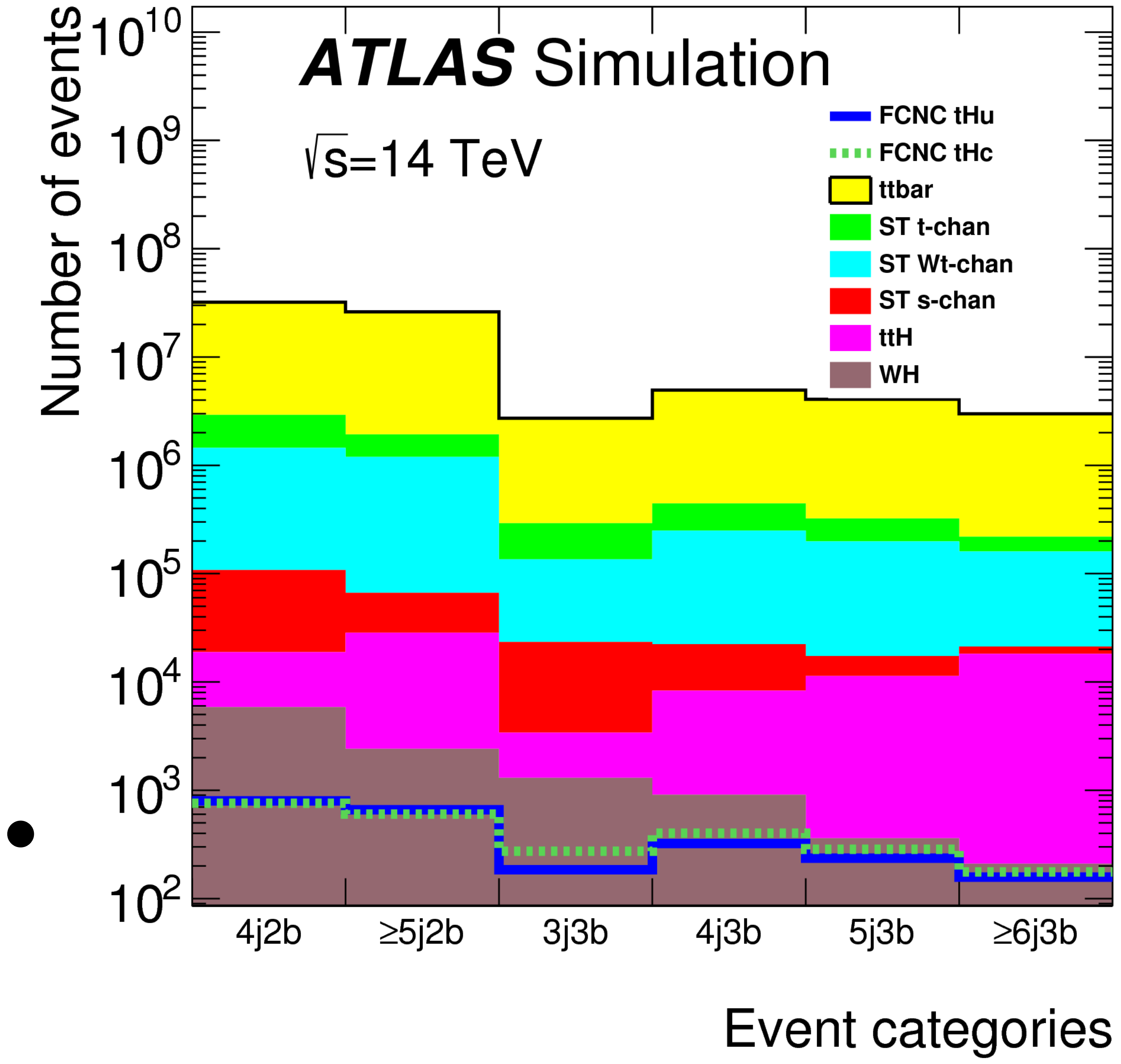
- $B(t \to Z\ u,c)$ 95% CL upper limits (with sys):
  - Significant degradation of sensitivity

Layout	Set	"γ" $t \to Zu$	"σ" $t \to Zu$	"γ" $t \to Zc$	"σ" $t \to Zc$	"γ" $t \to Zu+Zc$	"σ" $t \to Zu+Zc$
Reference	A	$18 \cdot 10^{-5}$	$16 \cdot 10^{-5}$	$41 \cdot 10^{-5}$	$36 \cdot 10^{-5}$	$13 \cdot 10^{-5}$	$12 \cdot 10^{-5}$
	B	$13 \cdot 10^{-5}$	$13 \cdot 10^{-5}$	$24 \cdot 10^{-5}$	$23 \cdot 10^{-5}$	$8.9 \cdot 10^{-5}$	$8.3 \cdot 10^{-5}$
Middle	A	$18 \cdot 10^{-5}$	$18 \cdot 10^{-5}$	$44 \cdot 10^{-5}$	$40 \cdot 10^{-5}$	$13 \cdot 10^{-5}$	$13 \cdot 10^{-5}$
	B	$13 \cdot 10^{-5}$	$13 \cdot 10^{-5}$	$26 \cdot 10^{-5}$	$25 \cdot 10^{-5}$	$9.0 \cdot 10^{-5}$	$8.9 \cdot 10^{-5}$
Low	A	$18 \cdot 10^{-5}$	$17 \cdot 10^{-5}$	$48 \cdot 10^{-5}$	$43 \cdot 10^{-5}$	$14 \cdot 10^{-5}$	$13 \cdot 10^{-5}$
	B	$14 \cdot 10^{-5}$	$13 \cdot 10^{-5}$	$29 \cdot 10^{-5}$	$28 \cdot 10^{-5}$	$9.8 \cdot 10^{-5}$	$9.3 \cdot 10^{-5}$

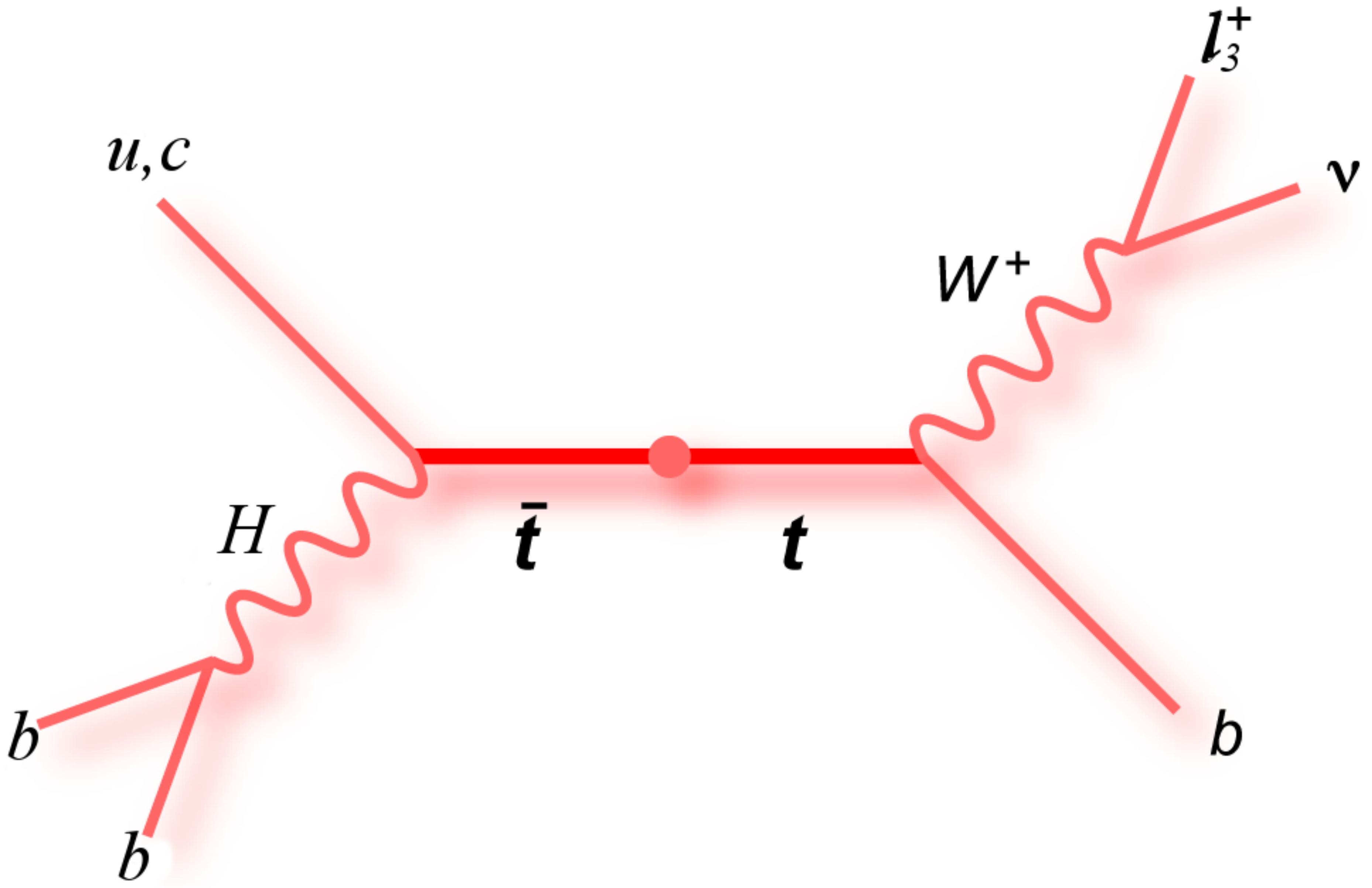
- $t \rightarrow Hq$

t→Hq

- Events split into 6 categories



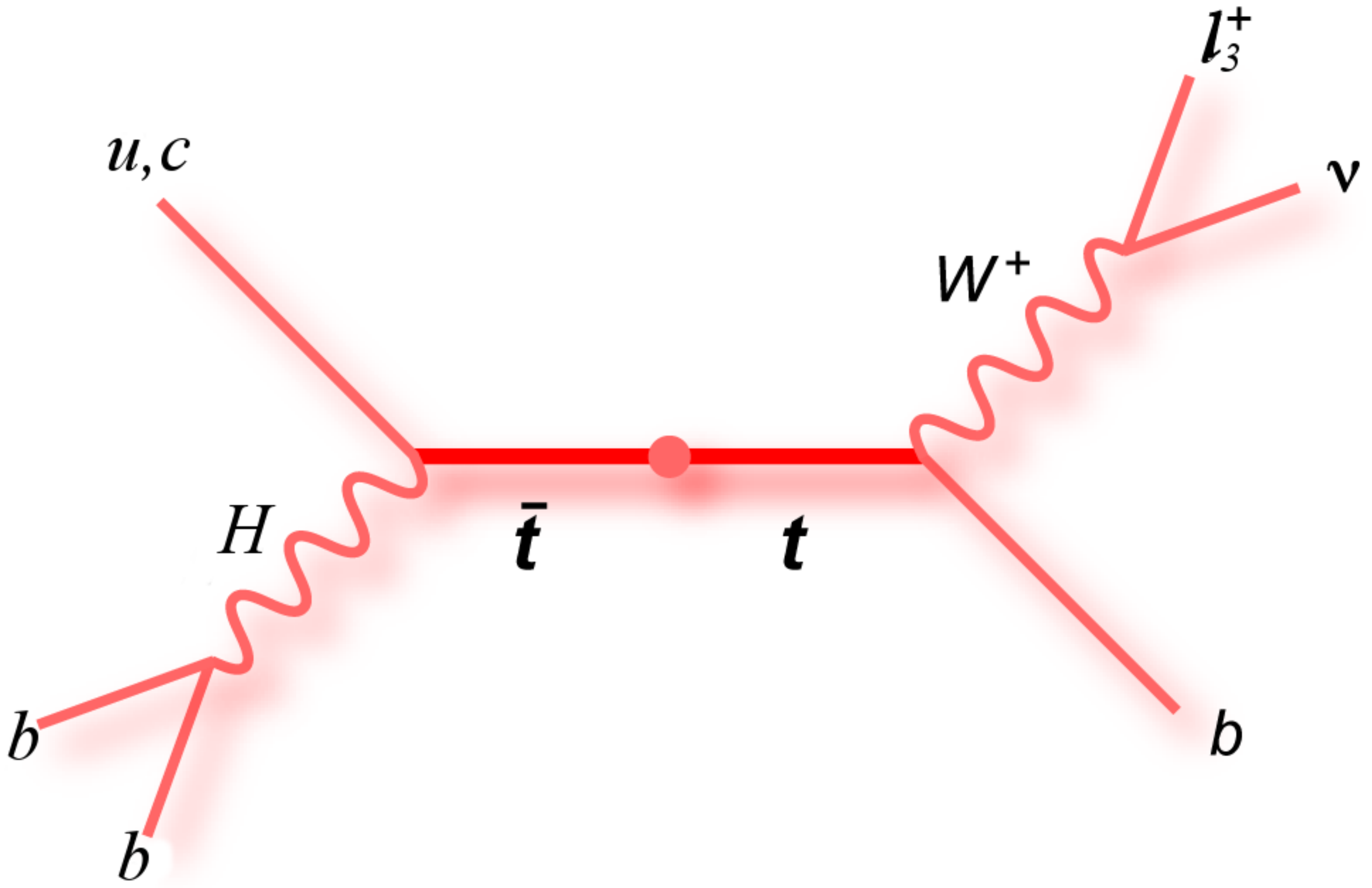
2 b-jets	3 b-jets
	3 jets
4 jets	4 jets
≥ 5 jets	5 jets
	≥ 6 jets

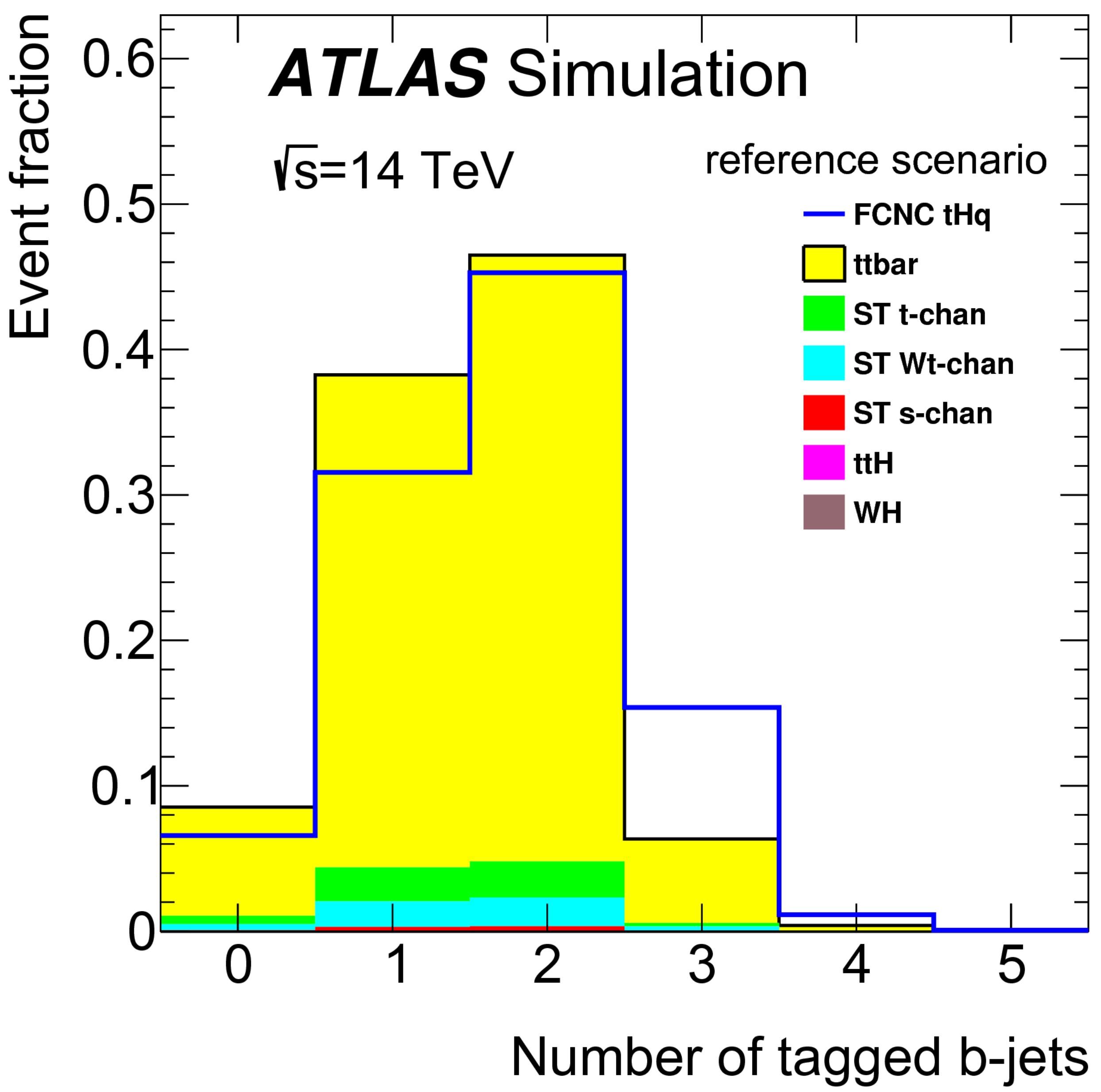


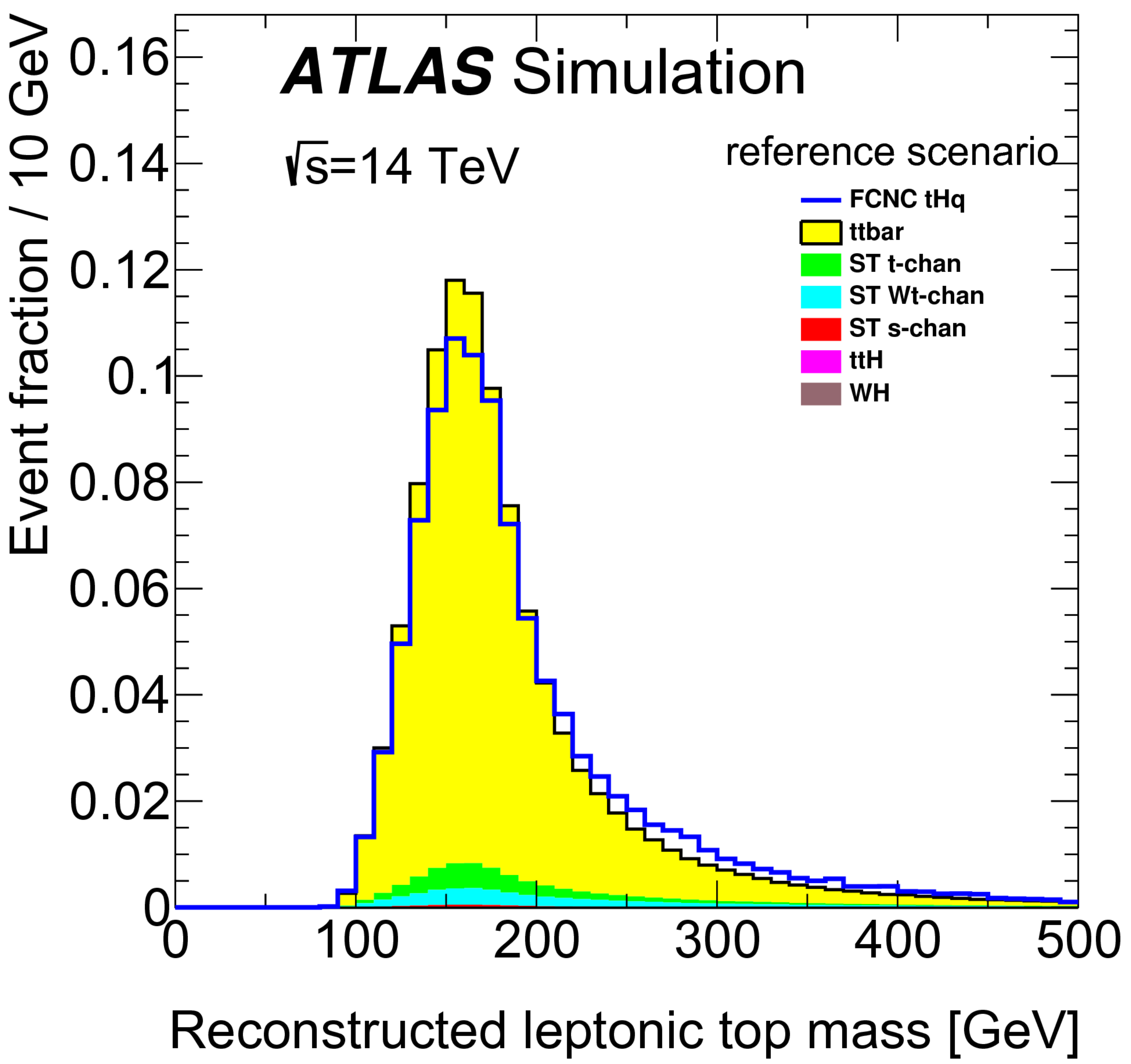
- One isolated lepton
- Two or Three b-tagged jets
- Non-btagged jets

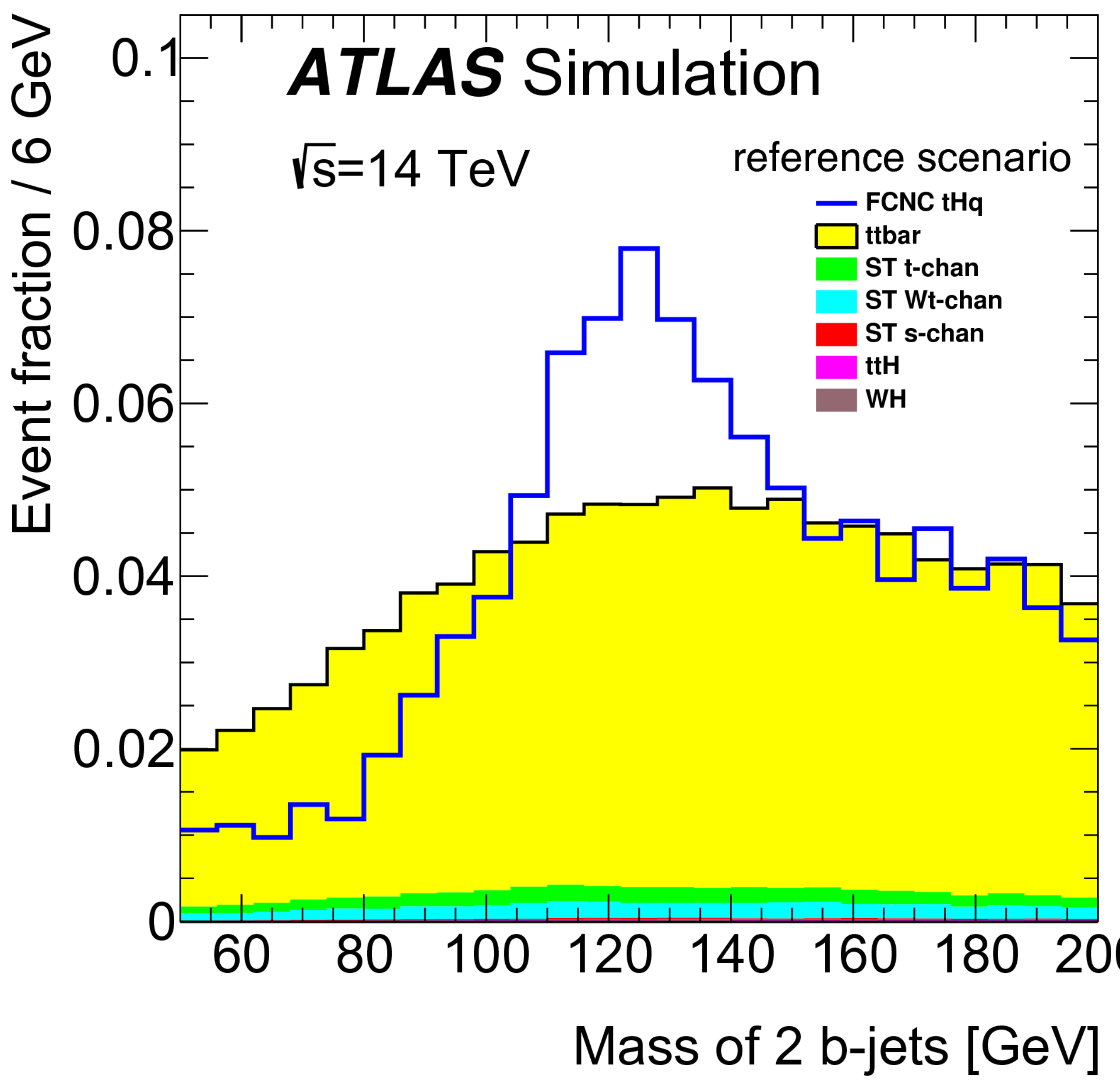
t→Hq

- n(b-jets); top mass; 2 b-jet mass
  - in reference scenrio

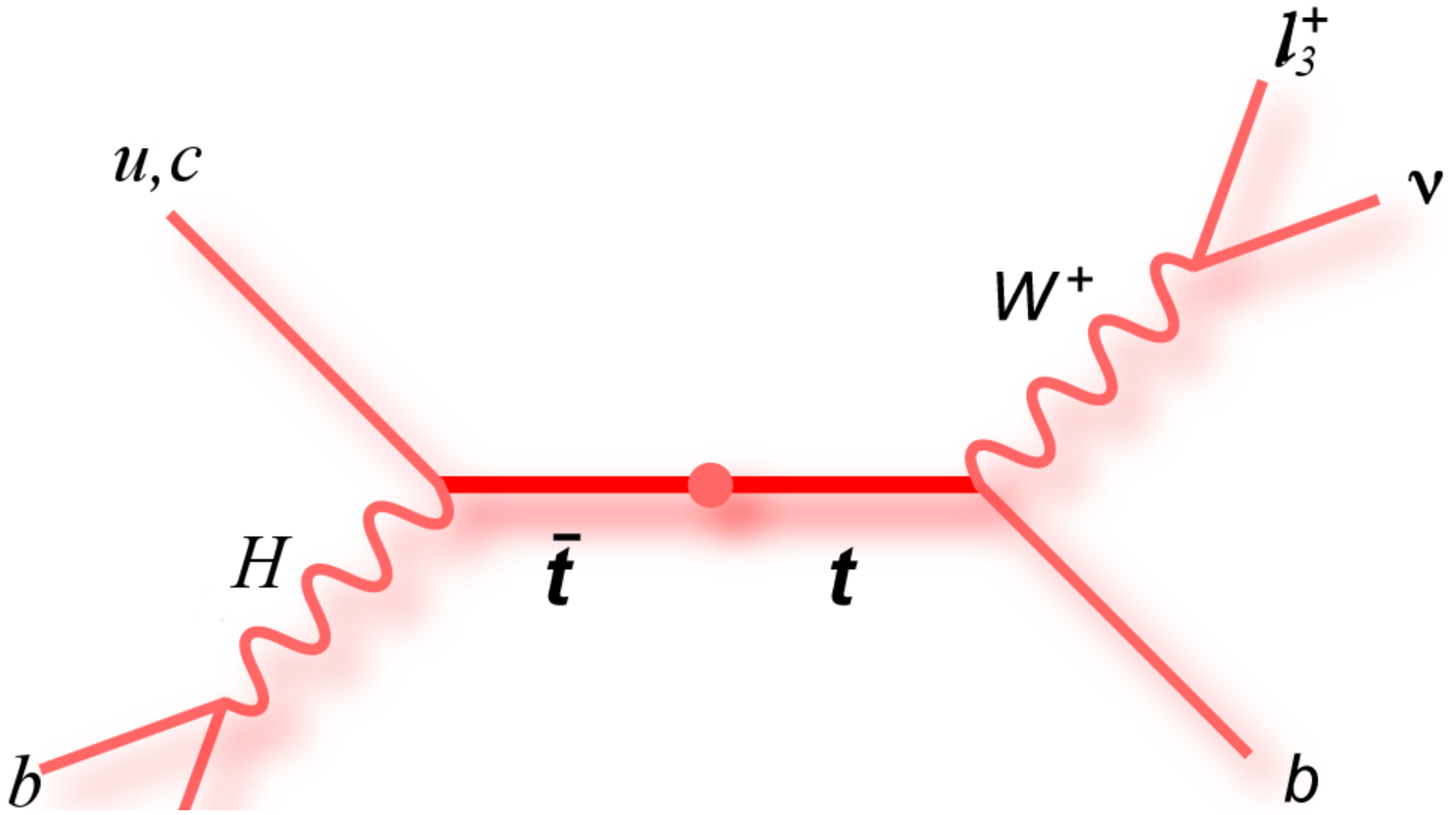








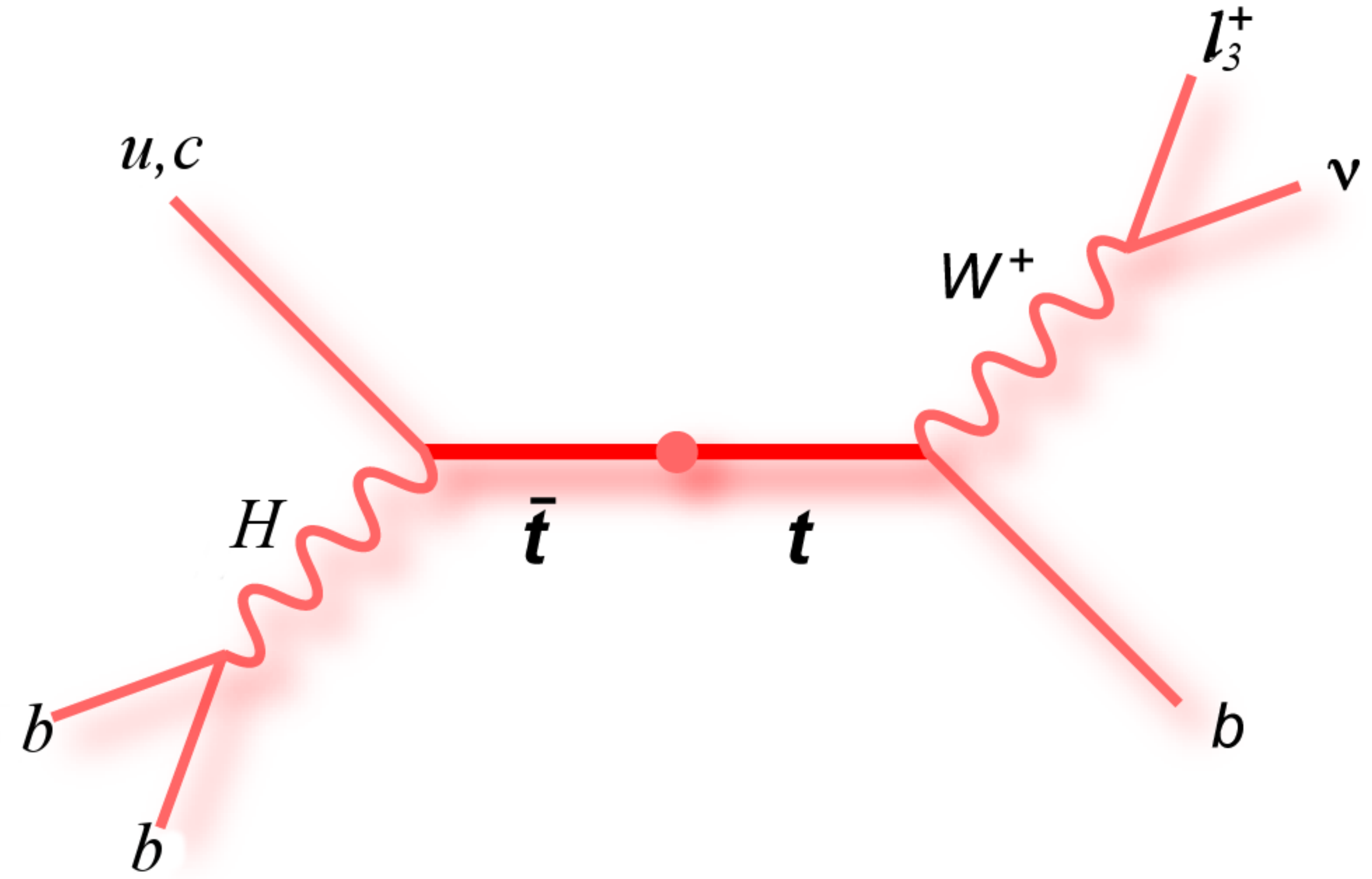
t→Hq



- Event yields for reference layout

Sample	4j2b	(≥ 5j)2b	3j3b	4j3b	5j3b	(≥ 6j)3b
$t \to Hu$ (ev)	798	660	185	322	236	158
$t \to Hc$ (ev)	759	604	274	402	285	176
$t\bar{t}$(10^5 ev)	292	242	24.3	45.0	37.5	27.7
Single top t-chan (10^5 ev)	14.7	7.29	1.56	1.95	1.24	0.587
Single top Wt chan (10^5 ev)	13.4	11.3	1.12	2.27	1.81	1.39
Single top s-chan (10^5 ev)	0.894	0.375	0.198	0.144	0.0648	0.0334
$t\bar{t}H$ (10^5 ev)	0.131	0.259	0.021	0.074	0.111	0.177
WH (ev)	5850	2410	1300	910	360	210
Total background (10^6 ev)	32.1	26.1	2.72	4.94	4.06	2.97

t→Hq



$$\mathcal{D} = \log(\mathcal{P}^{\text{Sig}}/\mathcal{P}^{\text{Bkg}})$$

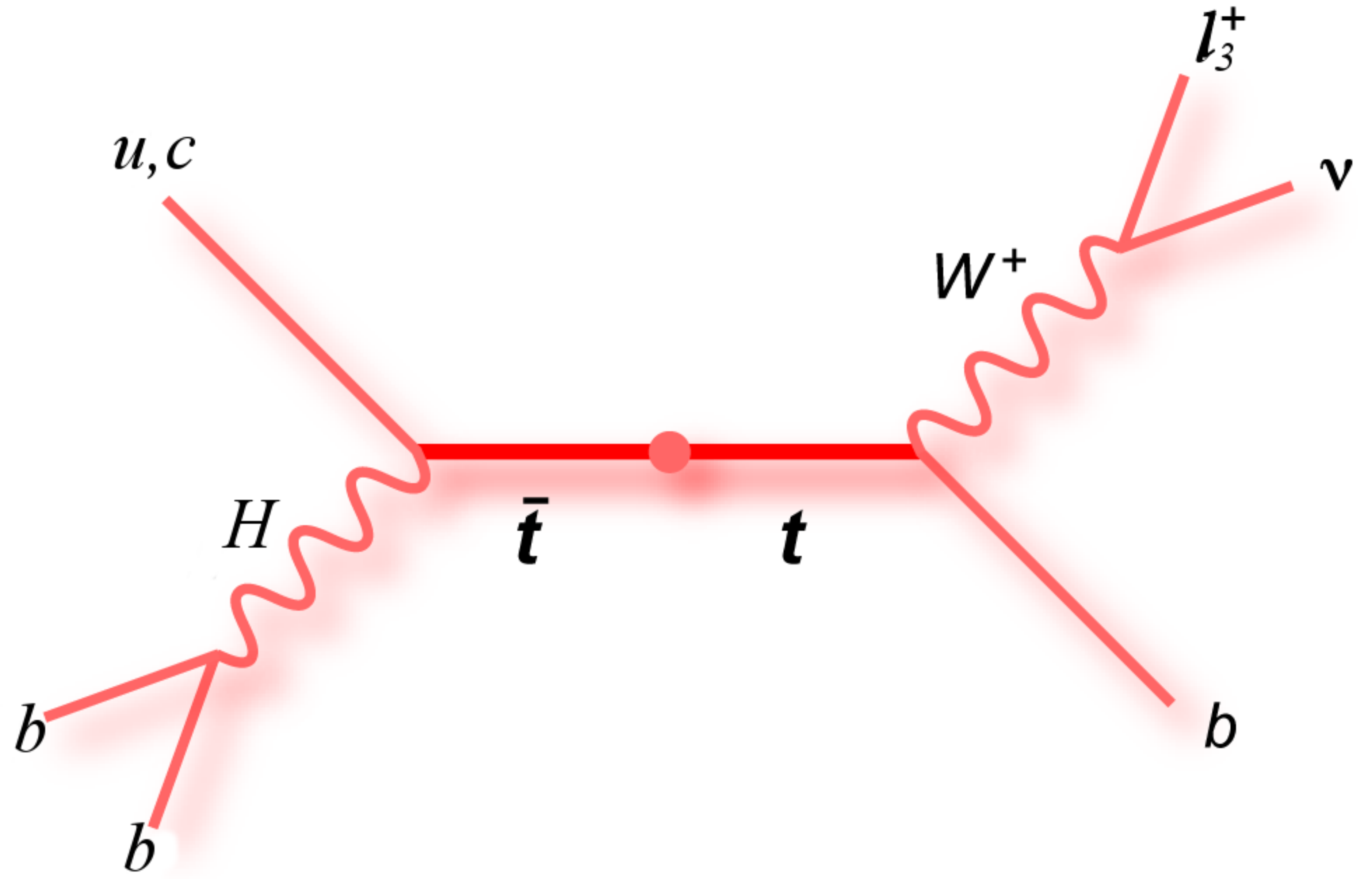
$$\mathcal{P}^{\text{Sig}} = M^t(b_1, \ell, E_{\text{T}}^{\text{miss}}) \cdot M^H(b_2, b_3) \cdot M^t(b_2, b_3, j) \cdot p_{\text{T}}(j)$$

$$\mathcal{P}^{\text{Bkg}} = M^t(b_1, \ell, E_{\text{T}}^{\text{miss}}) \cdot M^W(j_1, j_2) \cdot M^t(j_1, j_2, b_2) \cdot p_{\text{T}}(b_2)$$

- Analysis uses a discriminant for each category (probabilities and templates used in backup)

- Profile likelihood method used to establish limits

t→Hq

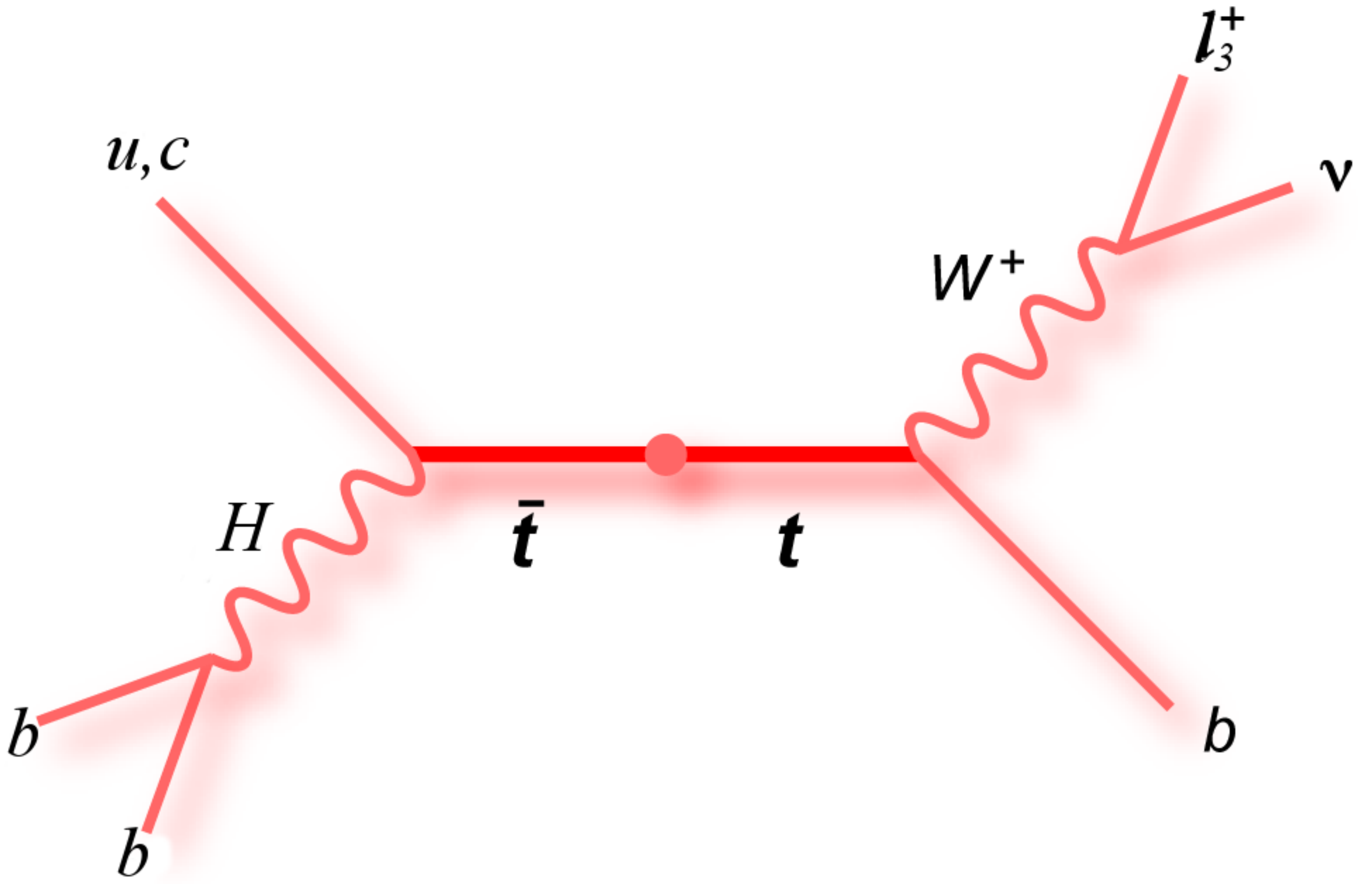


- B(t→H u,c) 95% CL upper limits (no sys):

-

	$t \to Hu$	$t \to Hc$	$t \to Hu + Hc$
Reference scenario	$1.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	$0.55 \cdot 10^{-4}$
Middle scenario	$1.2 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$0.58 \cdot 10^{-4}$
Low scenario	$1.4 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$0.66 \cdot 10^{-4}$

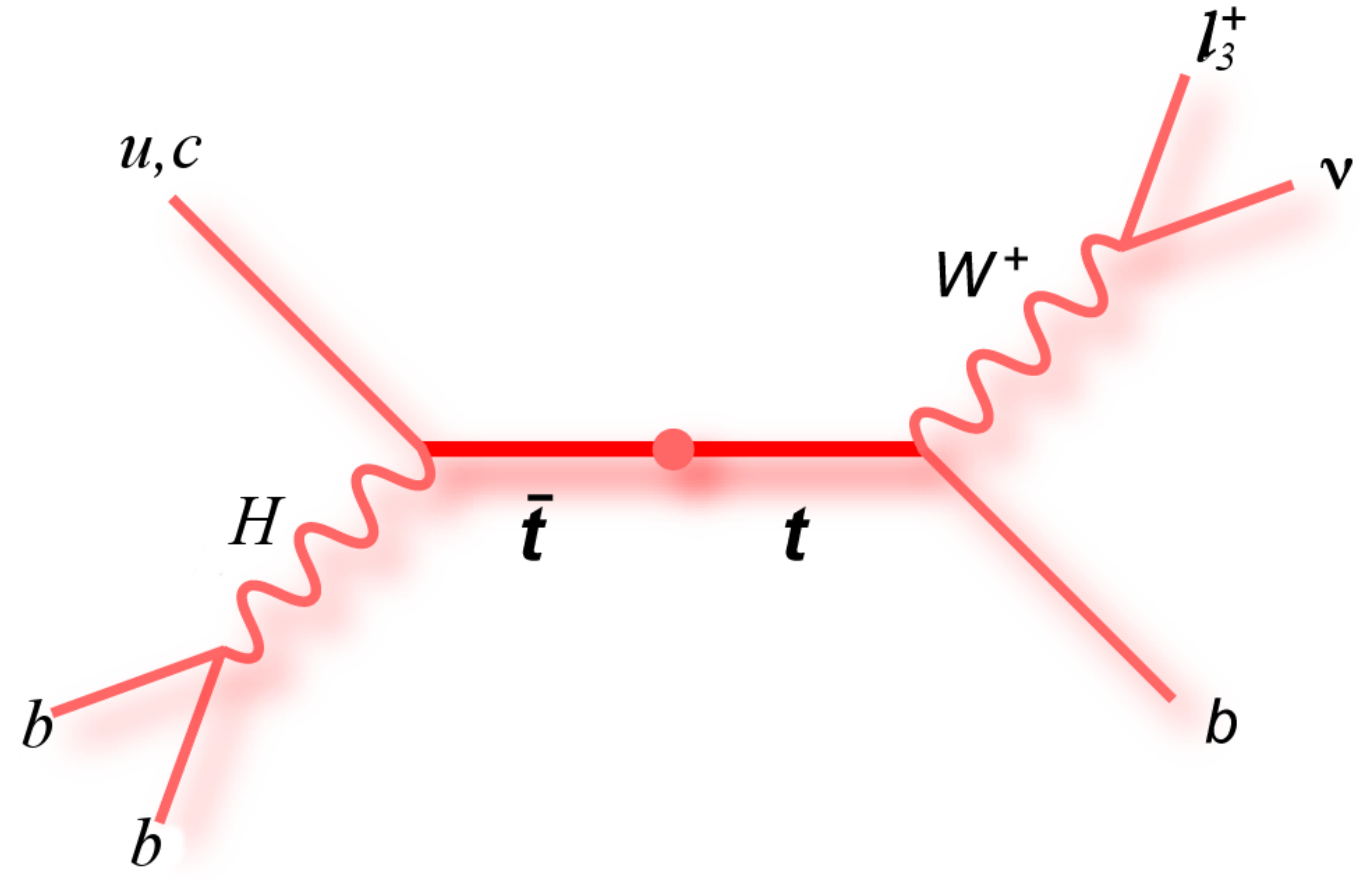
t→Hq



- Systematics

	Set A: Run 1 driven	Set B: HL-LHC predictions
Lumi: (theory)	2%	2%
ttbar normalisation	15%	6%
signal & non-ttbar normalisation	6%	6%
b-tagging	4%	2%
light jet fake rate	20%	10%

t→Hq



- B(t→H u,c) 95% CL upper limits (with sys):
  - Factor ~2 degradation

Layout	Set	$t\to Hu$	$t\to Hc$	$t\to Hu{+}Hc$
Reference	A	$2.4\cdot10^{-4}$	$2.0\cdot10^{-4}$	$1.1\cdot10^{-4}$
	B	$2.4\cdot10^{-4}$	$2.0\cdot10^{-4}$	$1.1\cdot10^{-4}$
Middle	A	$2.9\cdot10^{-4}$	$2.4\cdot10^{-4}$	$1.3\cdot10^{-4}$
	B	$2.9\cdot10^{-4}$	$2.4\cdot10^{-4}$	$1.3\cdot10^{-4}$
Low	A	$3.5\cdot10^{-4}$	$3.0\cdot10^{-4}$	$1.7\cdot10^{-4}$
	B	$3.5\cdot10^{-4}$	$3.0\cdot10^{-4}$	$1.7\cdot10^{-4}$

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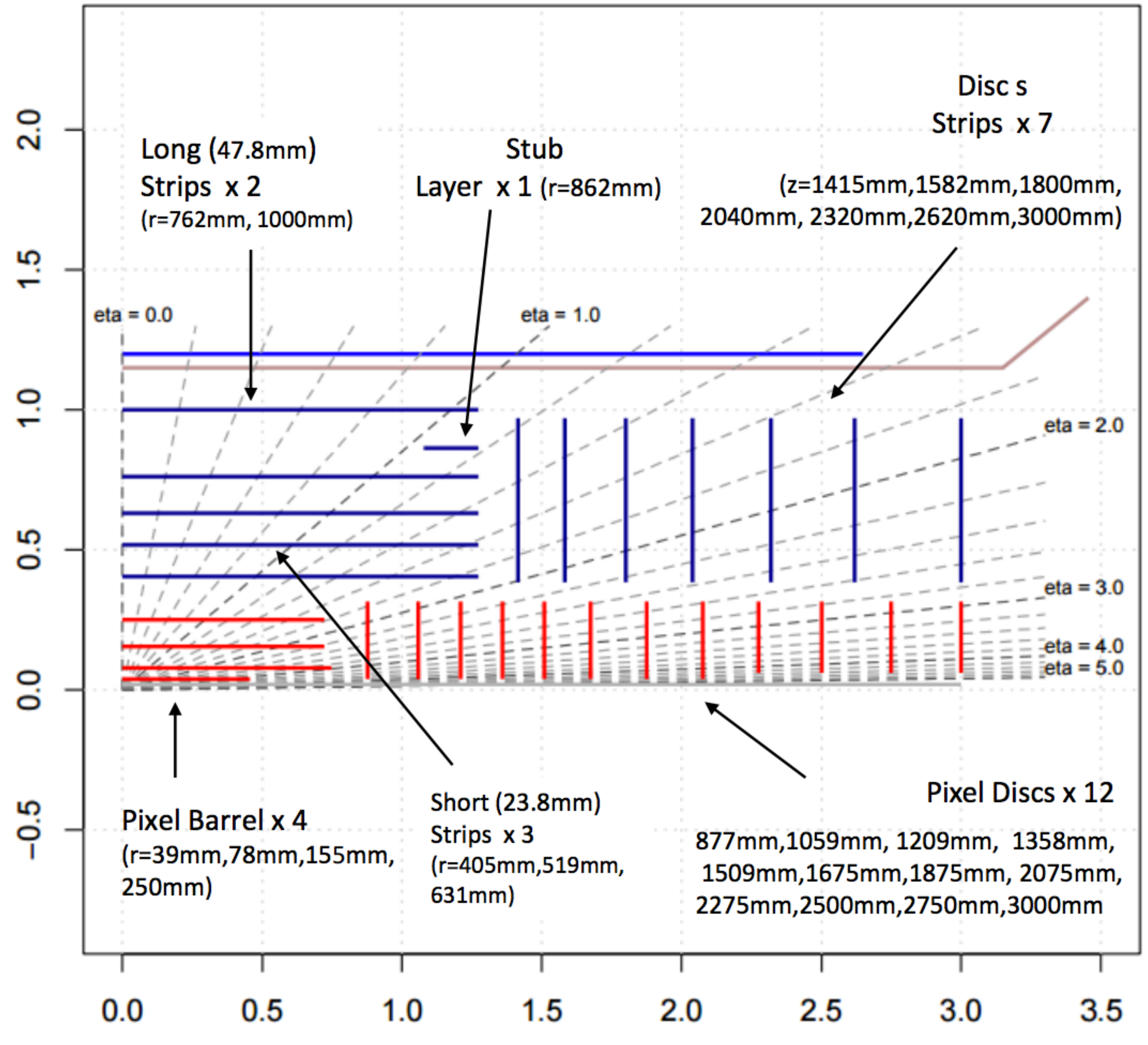
- ssWW

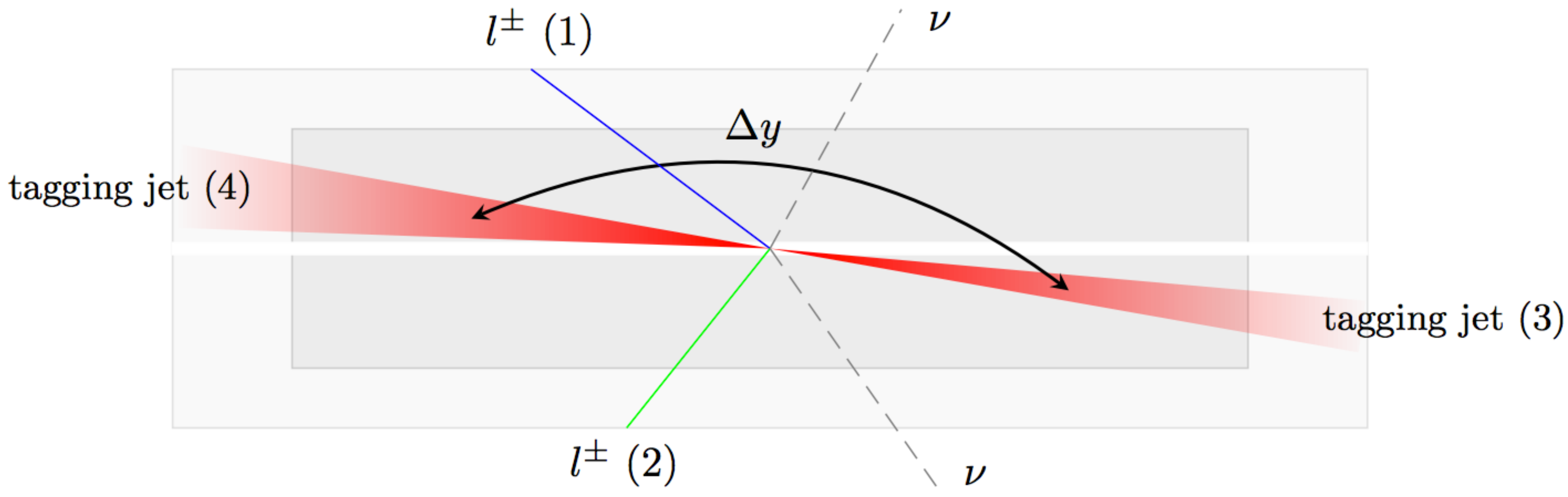
ssWW

- Context: the ATLAS Inner Detector will be replaced by an all-silicon tracker, the ITk. Several tracking scenarios were under consideration, which differ in the pseudo-rapidity coverage:
  - Bronze (Low) scenario: $|\eta| < 2.7$
  - Silver (Middle) scenario: $|\eta| < 3.2$
  - Gold (Reference) scenario: $|\eta| < 4.0$
- For the whole analysis, μ=200 was assumed.



ssWW

- **ssWW HL-LHC Analysis**
  - Two forward jets well separated in rapidity
  - Two same-sign leptons
  - ETmiss
  - Dominant backgrounds: ssWW QCD and WZ

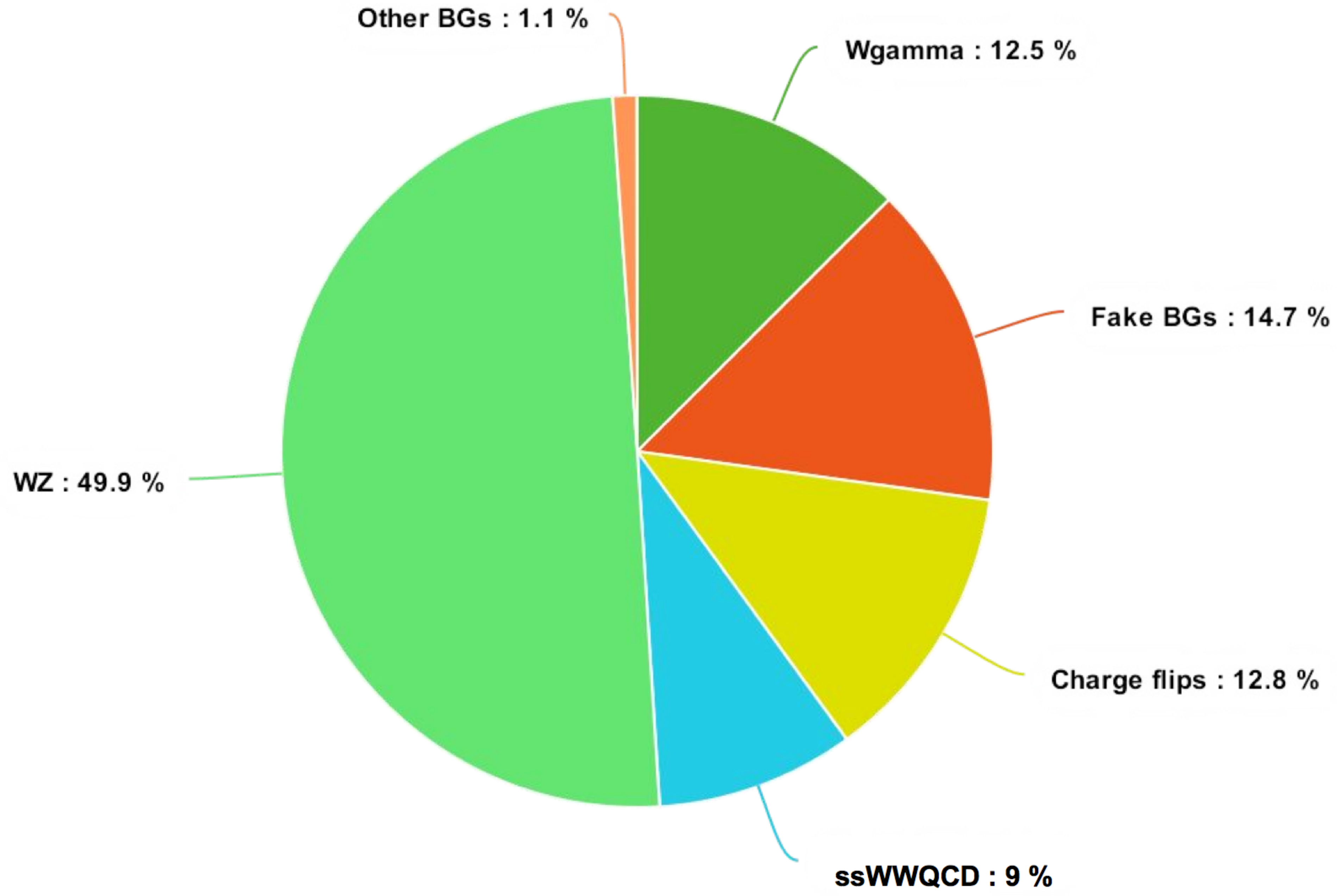


$$pp \to W^{\pm}W^{\pm}jj \to \ell^{\pm}\nu\ell^{\pm}\nu jj$$

Selection Name	Cut	Description
Lepton Selection	lepton trigger	single lepton trigger
	single lepton selection	lepton $p_{\mathrm{T}} > 25$ GeV; $\lvert\eta\rvert < 2.7, 3.2, 4.0$; $N_{lep} = 2$
	dilepton selection	$\Delta R_{ll} > 0.3$, $m_{ll} > 20$ GeV, like-sign leptons
	ee Z veto	$\lvert m_{ee} - m_Z\rvert > 10$ GeV
MET Selection	MET selection	MET > 40 GeV
Jet Selection	jet p_{T} selection	jet $p_{\mathrm{T}} > 30$ GeV, $\Delta R_{lj} > 0.3$
	jet η selection	jet $\lvert\eta\rvert < 4.5$
	jet multiplicity selection	$N_{jets} \geq 2$
	$\lvert\Delta\eta_{jj}\rvert$	$\lvert\Delta\eta_{jj}\rvert > 2.4$
	3rd lepton veto	remove events with ≥ 3 leptons with p_{T} >6 or 7 GeV
	m_{jj}	$m_{jj} > 500$ GeV

ssWW

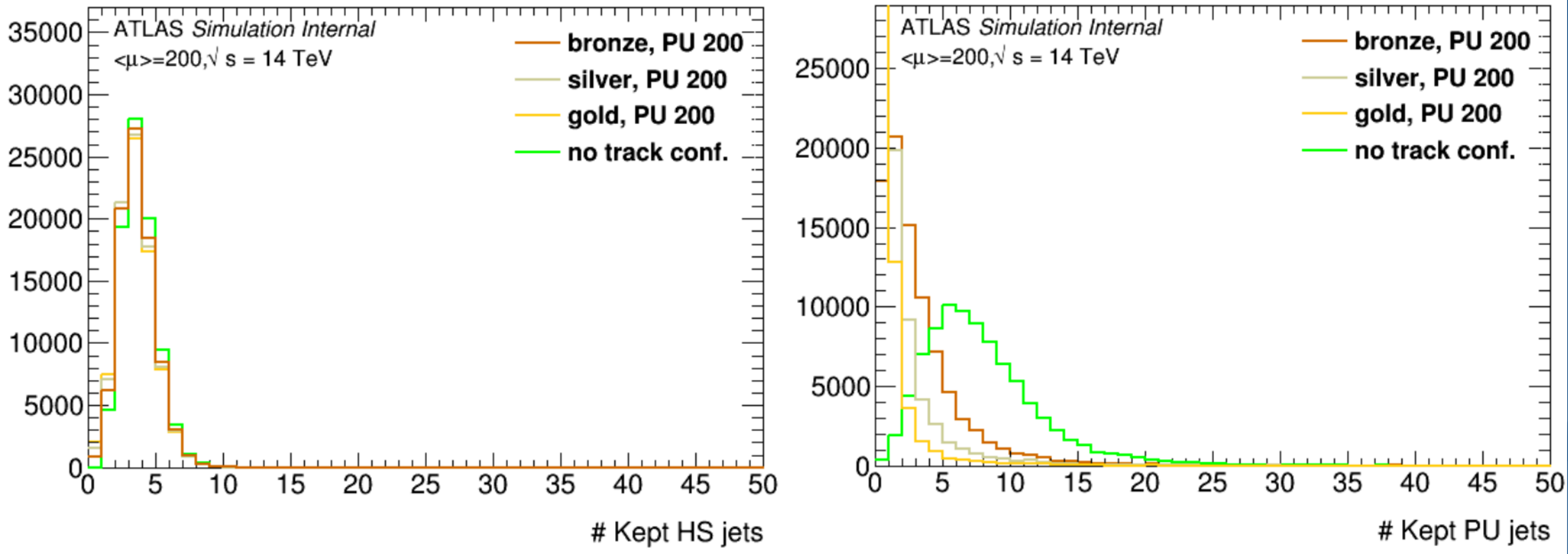
- The background contributions were estimated from data in the Run 1 analysis.



- For the SD analysis:
  - Model only ssWWQCD and WZ
  - Scale ssWWQCD and WZ by 1.7 to account for other backgrounds

ssWW

- HS vs PU jets for different scenarios



ssWW

- Main gains come from extended tracking:
  - greater lepton coverage (reduces WZ)
  - greater PU jet rejection (track confirmation)

$\langle\mu\rangle$	Significance, $Z_{\sigma B}$ at the HL-LHC $\sqrt{s}$ = 14 TeV, $\int \mathcal{L}dt$ = 3 ab^{-1} $W^{\pm}W^{\pm}jj$-EW Bronze $\lvert\eta\rvert < 2.7$	Silver $\lvert\eta\rvert < 3.2$	Gold $\lvert\eta\rvert < 4.0$
200	5.0 ± 0.2	6.1 ± 0.3	11.3 ± 0.6

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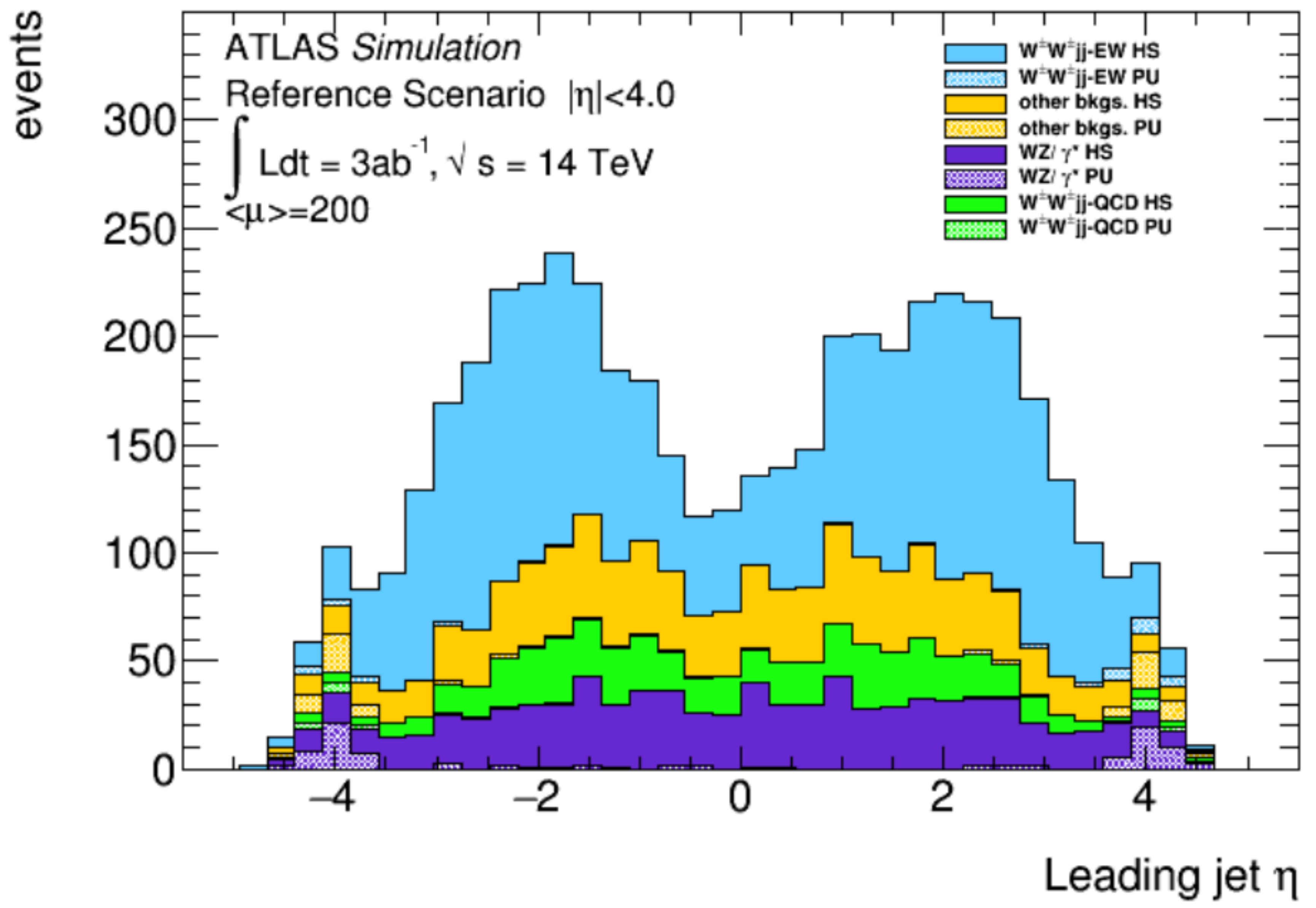
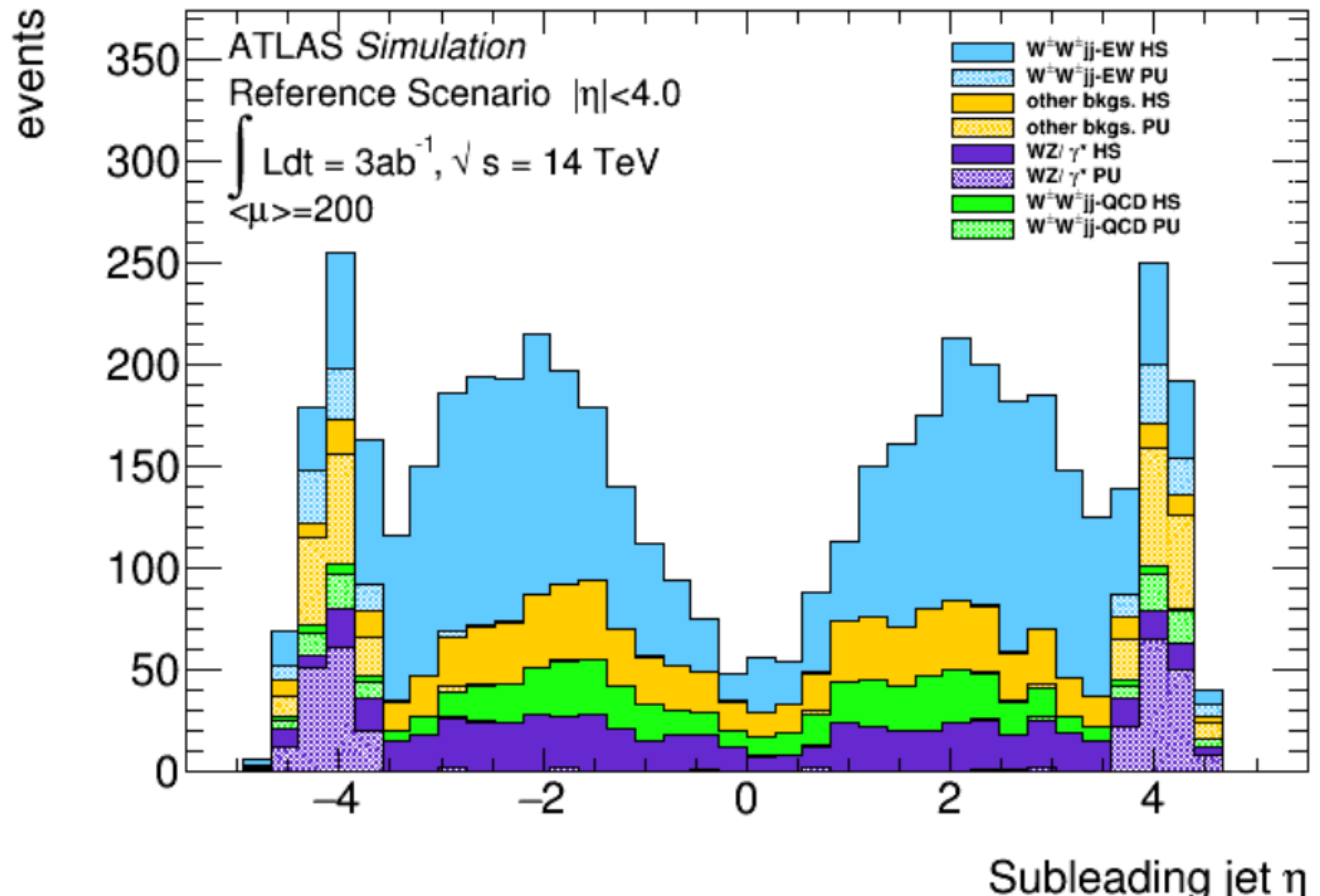
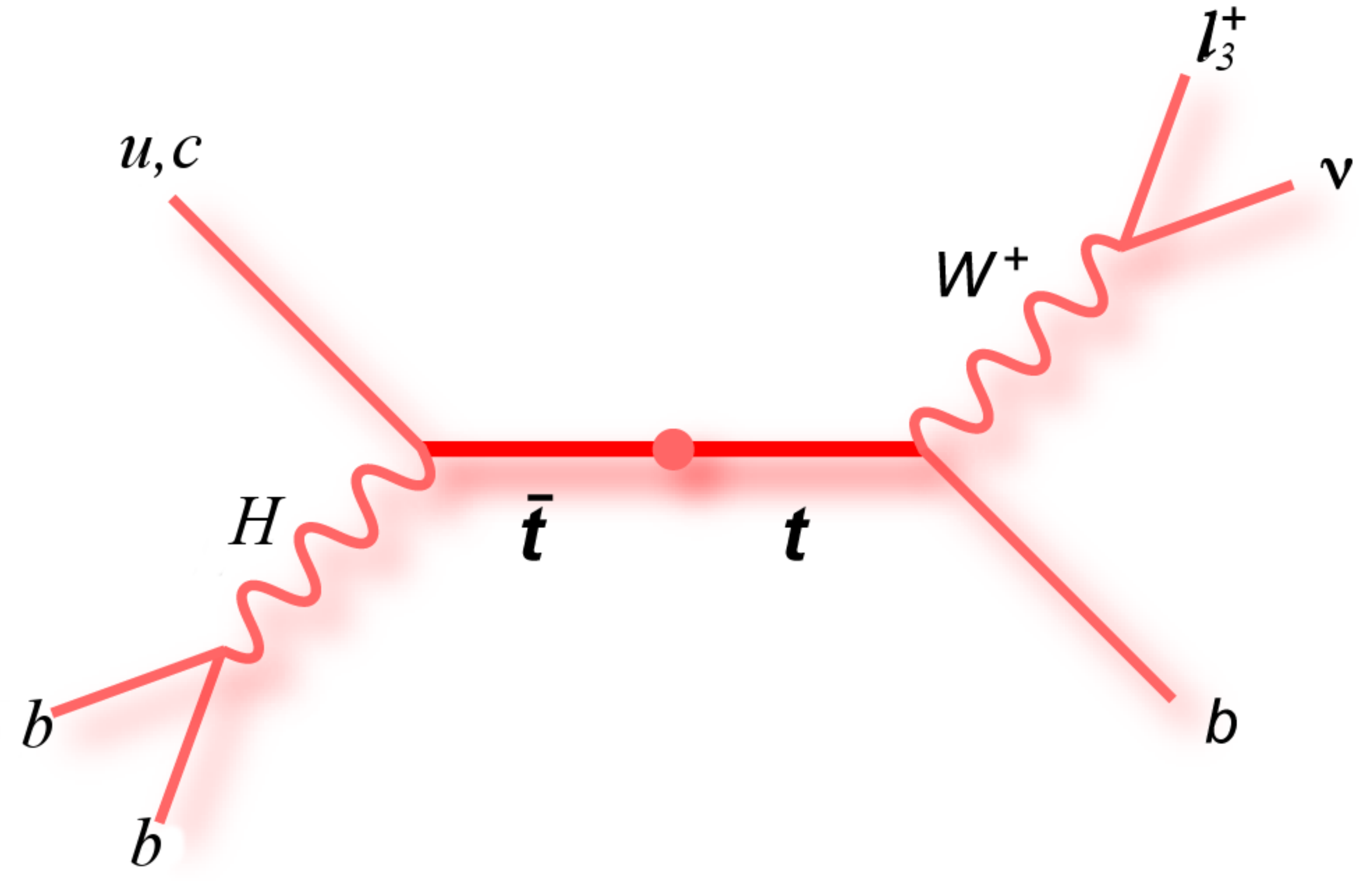




- Backup

t→Hq



$$\mathcal{D} = \log(\mathcal{P}^{\text{Sig}}/\mathcal{P}^{\text{Bkg}})$$

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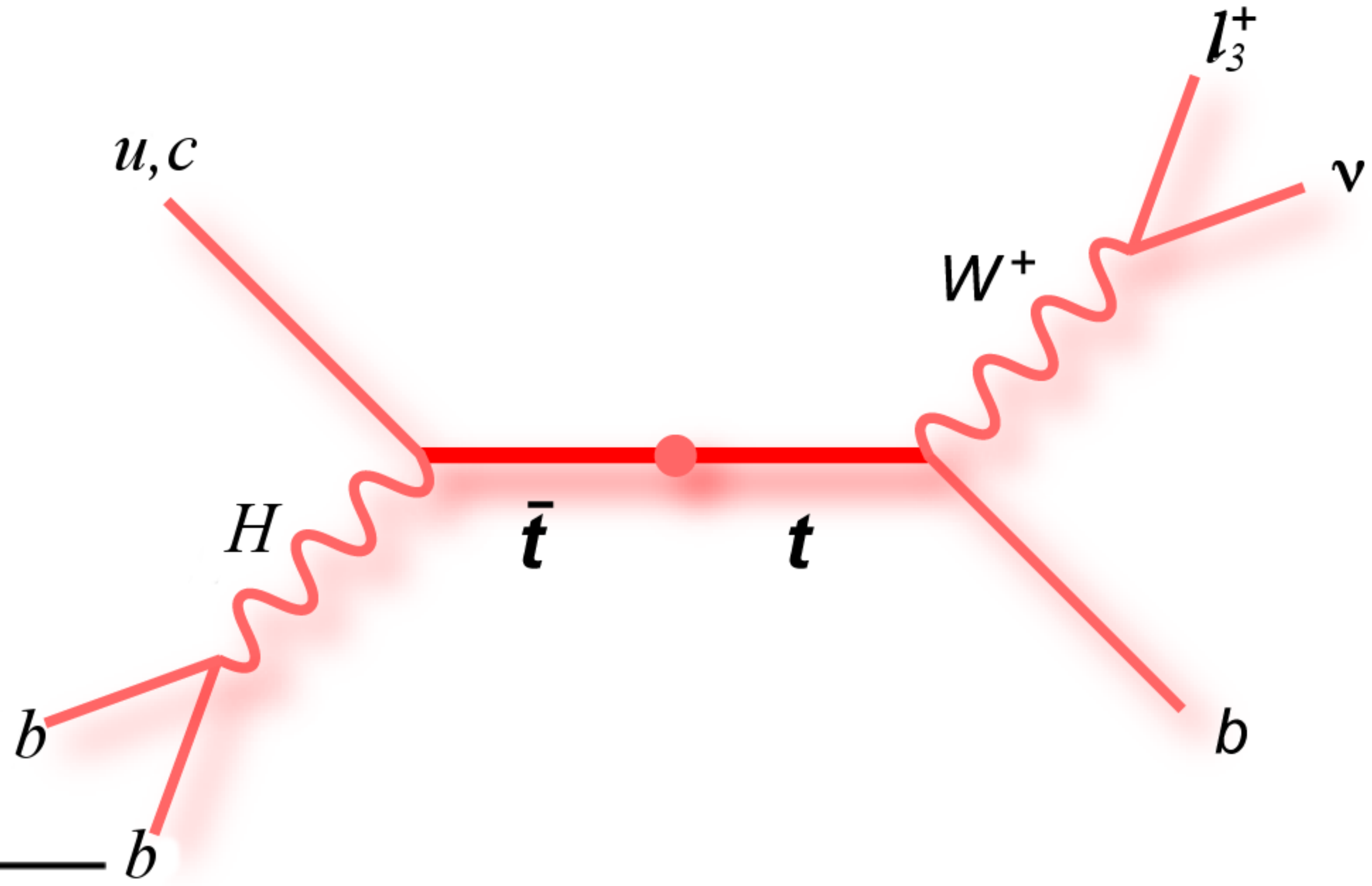
ε_b	b-tagging efficiency
$\varepsilon_{\mathcal{A}}$	Averaged probability to loose a b-jet due to acceptance in a signal event
ε_L^t	Probability to reconstruct the leptonic top decay
ε^W	Probability to reconstruct the W decay
ε^{tWq}	Probability to reconstruct the hadronic top decay if a W is reconstructed
ε^H	Probability to reconstruct the Higgs boson decay
ε^{tHq}	Probability to reconstruct the FCNC top decay if a Higgs boson is reconstructed

t→Hq

$$\mathcal{D} = \log(\mathcal{P}^{\text{Sig}}/\mathcal{P}^{\text{Bkg}})$$



$M_L^t(b, \ell, E_T^{\text{miss}})$	Resonance-like function describing a leptonic top decay
$\text{PS}_L^t(b, \ell, E_T^{\text{miss}})$	Non-reconstructable leptonic top decay invariant mass
$M^W(j_1, j_2)$	Resonance-like function describing the W decay
$\text{PS}^W(j_1, j_2)$	Non-reconstructable W decay invariant mass
$M_{\ominus}^{tWq}(j_1, j_2, b)$	Resonance-like function describing a hadronic top decay
$\text{PS}_{\ominus}^{tWq}(j_1, j_2, b)$	Non-reconstructable hadronic top decay invariant mass
$M^H(b_1, b_2)$	Resonance-like function describing a Higgs boson decay
$\text{PS}^H(b_1, b_2)$	Non-reconstructable Higgs boson decay invariant mass
$M_{\ominus}^{tHq}(b_1, b_2, j)$	Resonance-like function describing a FCNC top decay
$\text{PS}_{\ominus}^{tHq}(b_1, b_2, j)$	Non-reconstructable FCNC top decay invariant mass

SD Gold

	ssWW-EW			WZ			ssWWQCD		
	nevents	% stat. error	% eff.	nevents	% stat. error	% eff.	nevents	% stat. error	% eff.
Preselection	47034.8	0.339032	100	1.40938e+06	0.0731468	1	36059.2	0.223607	100
Trigger	37945.7	0.377458	80.6759	886715	0.0922185	0.62915	27472.4	0.25618	76.187
LeptonSelection	18810.7	0.536102	49.5726	450391	0.129394	0.507932	13280.2	0.36846	48.3403
DileptonSelection	18530.1	0.540146	98.5084	134157	0.237085	0.297868	13066	0.371468	98.3871
METCut	15372.3	0.593036	82.9584	111997	0.259482	0.834818	10740.4	0.409716	82.2009
JetPtCut	4808.9	1.0603	31.283	29871.6	0.502436	0.266718	3663.97	0.701482	34.1139
JetEtaCut	4774.3	1.06413	99.2805	29793.9	0.503091	0.9974	3660.73	0.701793	99.9114
nJetsCut	4774.3	1.06413	100	29793.9	0.503091	1	3660.73	0.701793	100
DeltaEtajj	3138.36	1.3125	65.7343	10352.8	0.853455	0.347482	891.203	1.42234	24.345
ThirdLepVeto	3051.86	1.33097	97.2438	1697.44	2.10772	0.16396	863.798	1.44473	96.9249
Mjj	2595.02	1.44338	85.031	892.082	2.90742	0.525544	541.068	1.82544	62.6383
LepCntr	2045.74	1.62564	78.8333	502.975	3.87202	0.563821	170.199	3.25472	31.4562

Table 2: The event yields and efficiencies are given for signal, $W^{\pm}W^{\pm}jj$-EW, and backgrounds, WZ/γ^{*}, and $W^{\pm}W^{\pm}jj$-QCD for $\int \mathcal{L}dt = 3$ ab^{-1} for the Gold scenario. Only statistical errors are reported.

SD Bronze

	ssWW-EW			WZ			ssWWQCD		
	nevents	% stat. error	% eff.	nevents	% stat. error	% eff.	nevents	% stat. error	% eff.
Preselection	47034.8	0.339032	100	1.40938e+06	0.0731468	1	36059.2	0.223607	100
Trigger	32190.7	0.409812	68.4402	725617	0.101943	0.514847	22753.9	0.281491	63.1015
LeptonSelection	15217.7	0.596041	47.2734	363211	0.144089	0.500554	9386.03	0.43828	41.2502
DileptonSelection	14977.1	0.600809	98.4191	105812	0.266957	0.291325	9199.06	0.442712	98.008
METCut	12990.3	0.645121	86.7343	92418.4	0.285648	0.873417	7932.84	0.476737	86.2353
JetPtCut	4299.63	1.12133	33.0989	28925.2	0.51059	0.312981	2702.46	0.816796	34.0667
JetEtaCut	4281.79	1.12367	99.5851	28889	0.510909	0.998749	2701.55	0.816932	99.9666
nJetsCut	4281.79	1.12367	100	28889	0.510909	1	2701.55	0.816932	100
DeltaEtajj	2816.14	1.38555	65.7702	11547.3	0.808109	0.399713	700.45	1.60437	25.9277
ThirdLepVeto	2740.45	1.40456	97.3123	3226.73	1.52872	0.279436	683.141	1.62457	97.529
Mjj	2291.73	1.53592	83.626	1759.28	2.07034	0.545221	416.303	2.08108	60.9396
LepCntr	1942.48	1.66829	84.7606	1269.88	2.43685	0.721817	215.814	2.89037	51.8406

Table 5: The event yields and efficiencies are given for signal, $W^\pm W^\pm jj$-EW, and backgrounds, WZ/γ^*, and $W^\pm W^\pm jj$-QCD for $\int \mathcal{L}dt = 3\ \text{ab}^{-1}$ for the Bronze scenario. Only statistical errors are reported.