Top quark mass from rare two-body decays $t \to B^0_{(s)}$ + jet in pp collisions at the LHC and FCC-hh

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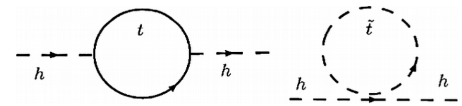
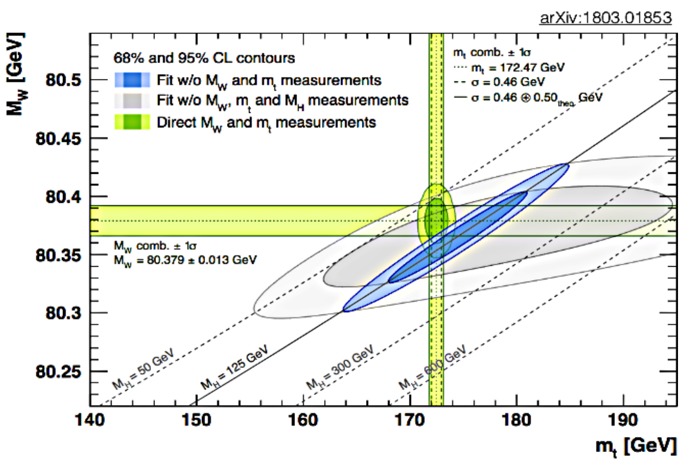
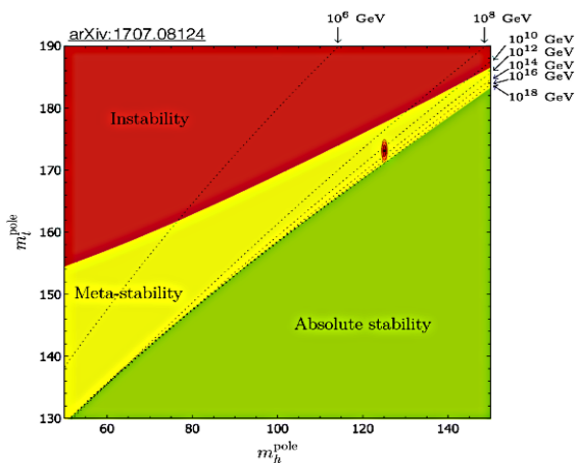
[Details in: DdE & HSS, **JHEP 07 (2020) 127** 2005.08102 [hep-ph]]

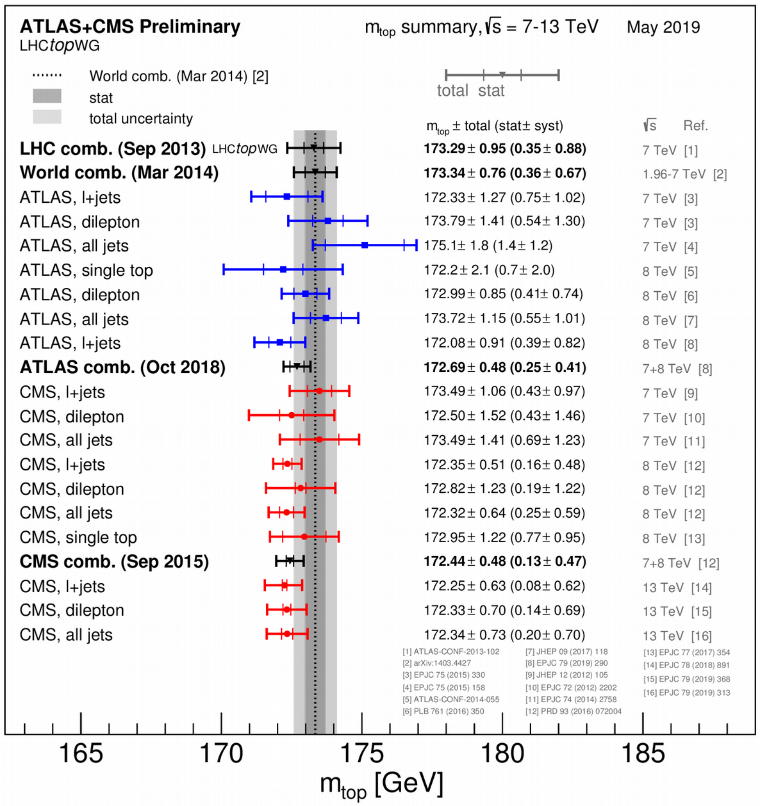
Top quark mass = fundamental SM parameter

- The top quark, the heaviest SM elementary particle, plays a key role for SM & BSM physics:
  - Largest coupling to Higgs (hierarchy problem).
  - Essential for testing overall SM self-consistency (indirect BSM searches).
  - Key role on the stability of the EW vacuum in the universe.





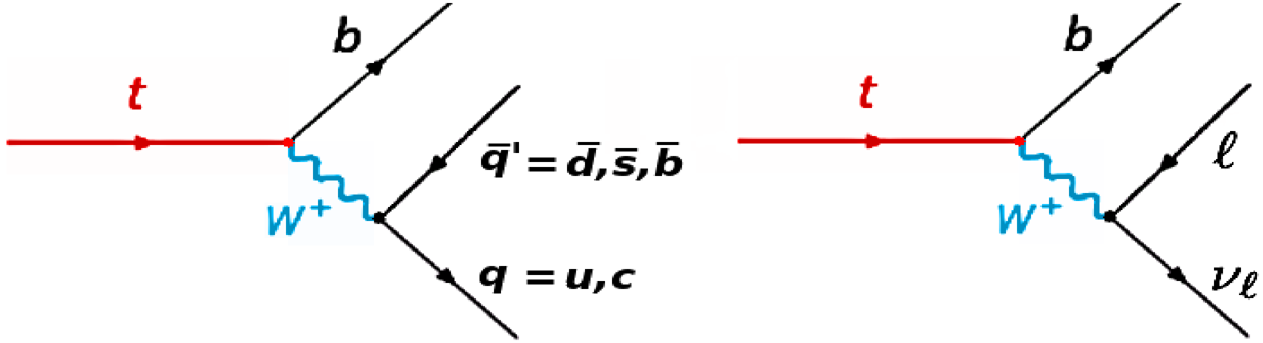




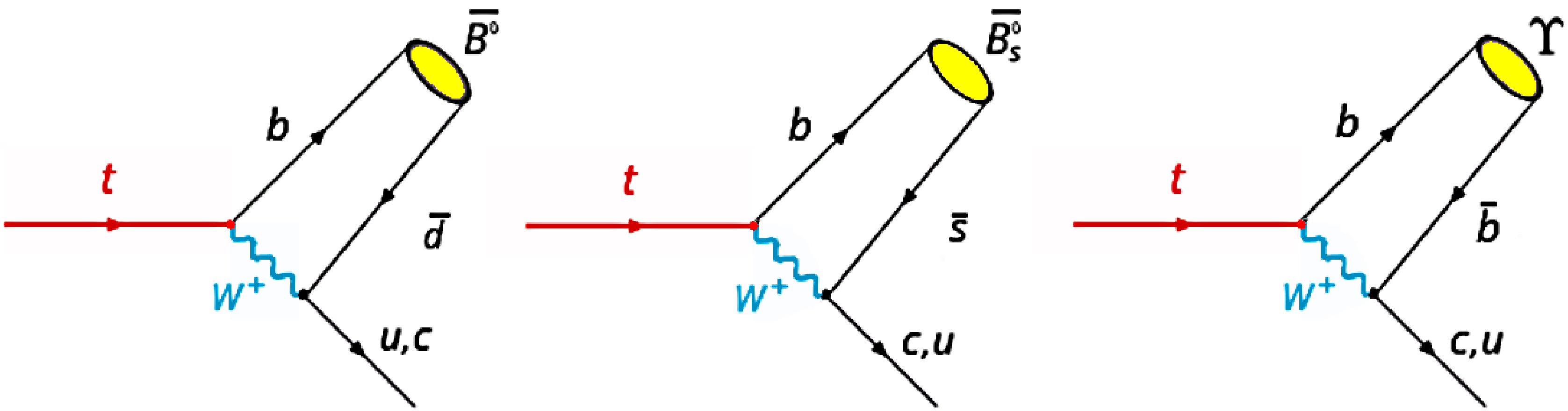
- m_t = 172.9±0.4 (direct), 173.1±0.9 (x-sect.) GeV
- ▶ New alternative direct m_t measurements?

Two-body decays of the top quark?

- Standard 3-body top decay into a b-quark plus W→2-quarks, 2-leptons (V_{tb}~1):



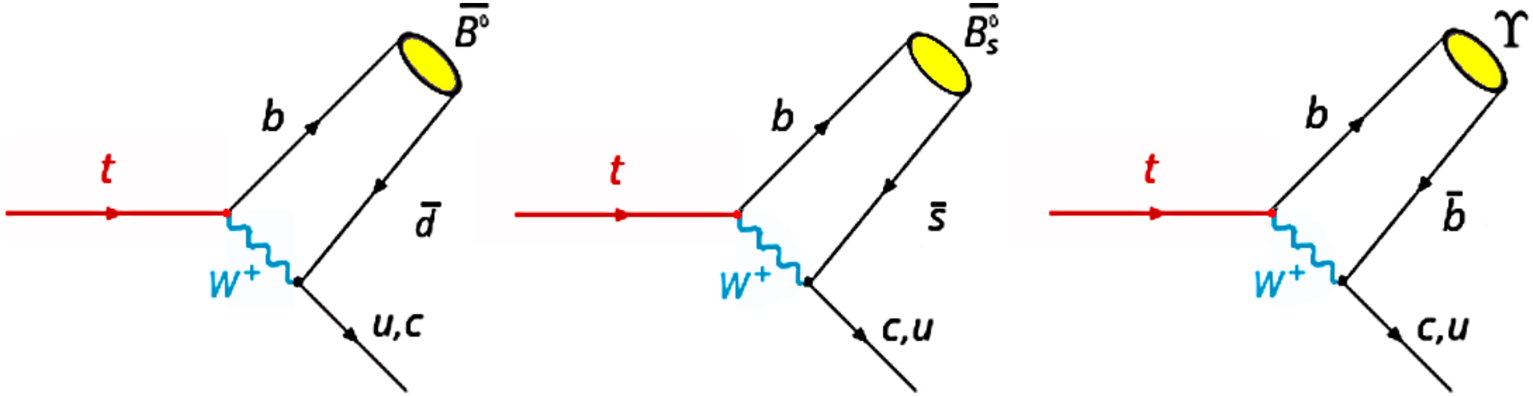
- Two-body decay of the top quark into a bottom-meson plus u,c-quark?



  - ▶ One quark from the W-decay recombines with the b-quark to form a B-meson bound state: (b,$\bar{d}$), (b,$\bar{s}$), or (b,$\bar{b}$). Such decays have never been studied before.
  - ▶ *What are expected branching ratios? Visible at LHC/FCC? Top mass from them?*

Two-body decays of the top quark

- Two-body decay of the top quark into a bottom-meson plus u,c-quark:



  - 4-momentum conservation between B, b, and q implies that the top-decay W boson is quite offshell: $m_W \approx m_t\sqrt{(m_q/m_b)}$ = 45 GeV.
  - Away-side u,c quark carries $p_T \approx m_t/2$ = 85 GeV, i.e. it is more boosted than the W decay quarks in standard t→bW→bqq' decays.

- Recombination of b+q quark to form B-meson well computable in the Non-Relativistic QCD (NRQCD) approach [*] typically used for quarkonia. Partial width of $(bq)_n$ meson determined via:

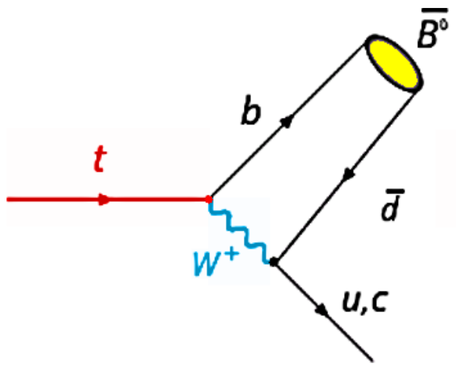
$$d\Gamma[a \to \overline{B} + X] = \sum_n d\hat{\Gamma}[a \to (b\bar{q})_n + X]\ \rho[(b\bar{q})_n \to \overline{B}]$$

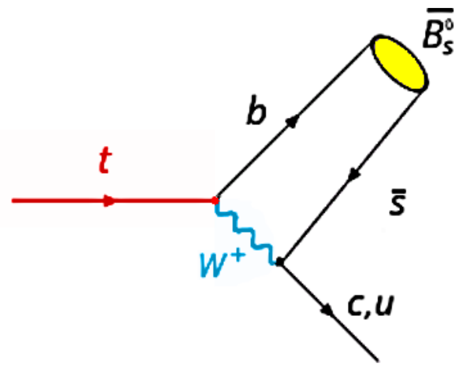
Sum over (color&angular) Fock states: $n = {}^{2s+1}L_J^{[c]}$

non-pQCD probability (NRQCD velocity power counting)

[*] E. Braaten, Y. Jia, and T. Mehen, PRD66 (2002) 034003.

NRQCD calculation of $t \to B^0_{(s)} + q$ decay





Only S-wave Fock states (higher states suppressed by $m_b/\Lambda_{QCD} \approx 20$)

$$d\Gamma[a \to \overline{B} + X] = \sum_n d\hat{\Gamma}[a \to (b\overline{q})_n + X]\, \rho[(b\overline{q})_n \to \overline{B}]$$

$$n = {}^1S_0^{[1]}, {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}$$

- HQ spin symmetry: Only 2 indep. non-pQCD probs, written as function of LDMEs:

$$\rho_1^{\overline{B}} \equiv \rho[(b\overline{q})_{{}^1S_0^{[1]}} \to \overline{B}], \qquad \langle \mathcal{O}^{\overline{B}}({}^1S_0^{[1]}) \rangle = 2N_c \frac{4m_b m_q^2}{3} \rho_{1,8}^{\overline{B}}$$

$$\rho_8^{\overline{B}} \equiv \rho[(b\overline{q})_{{}^1S_0^{[8]}} \to \overline{B}], \qquad \langle \mathcal{O}^{\overline{B}}({}^1S_0^{[8]}) \rangle = (N_c^2 - 1) \frac{4m_b m_q^2}{3} \rho_{1,8}^{\overline{B}}$$

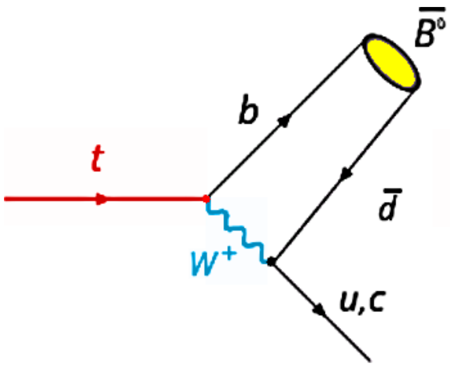
$$3\rho_{1,8}^{\overline{B}} = \rho[(b\overline{q})_{{}^3S_1^{[1,8]}} \to \overline{B}] \qquad \langle \mathcal{O}^{\overline{B}}({}^3S_1^{[1,8]}) \rangle = 3\langle \mathcal{O}^{\overline{B}}({}^1S_0^{[1,8]}) \rangle$$

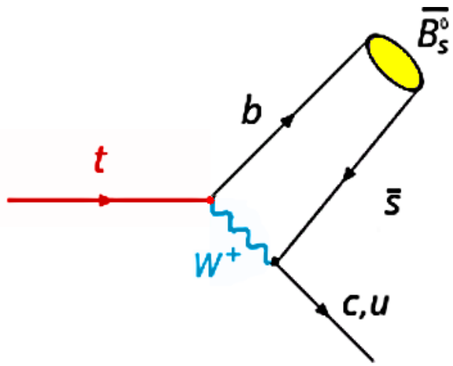
- Final partial widths computed by relating the $b \to B^0$ to known $c \to D^*$-meson FFs:

$$\Gamma(t \to \overline{B}^0 + q + X) = \left(\rho_1^{\overline{B}} + 8\rho_8^{\overline{B}}\right) |V_{qd}|^2 \frac{\alpha^2 \pi}{9} \frac{m_q^2 (m_t^2 - m_b^2)^2 (m_t^2 + m_b^2)}{m_t^3 m_W^4 \sin^4 \theta_w} \left[1 + \mathcal{O}\left(\frac{m_q}{m_b}\right)\right]$$

$$\Gamma(t \to \overline{B}_s^0 + q + X) = \frac{|V_{qs}|^2}{|V_{qd}|^2} \Gamma(t \to \overline{B}^0 + q + X), \quad \rho_{1,8}^{\overline{B}} = \frac{m_c}{m_b} \rho_{1,8}^{D} \ : \ \rho_1^{\overline{B}} = 0.4 \text{ and } \rho_8^{\overline{B}} = 0.8$$

NRQCD calculation of $t \to B^0_{(s)} + q$ decay





$$(t \to \overline{B}^0 + q + X) = \left(\rho_1^{\overline{B}} + 8\rho_8^{\overline{B}}\right) |V_{qd}|^2 \frac{\alpha^2 \pi}{9} \frac{m_q^2 (m_t^2 - m_b^2)^2 (m_t^2 + m_b^2)}{m_t^3 m_W^4 \sin^4 \theta_w} \left[1 + \mathcal{O}\left(\frac{m_q}{m_b}\right)\right]$$

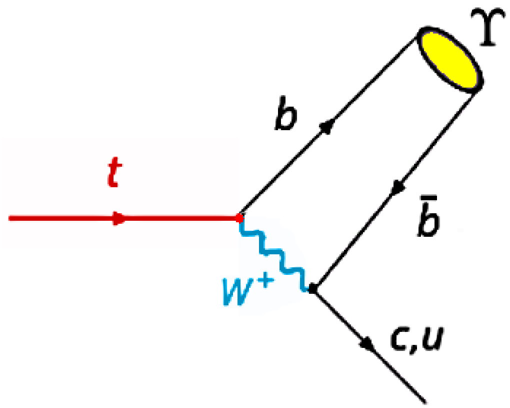
$$(t \to \overline{B}^0_s + q + X) = \frac{|V_{qs}|^2}{|V_{qd}|^2} \Gamma(t \to \overline{B}^0 + q + X),$$

- Final $t \to B^0(s)+q$ partial widths & branching ratios (for Γ_t = 1.35 GeV):

Decay mode	Partial decay width (GeV)	Branching fraction
$t \to \overline{B}^0 + u$	$5.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$
$t \to \overline{B}^0 + c$	$2.9 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$
$t \to \overline{B}^0_s + c$	$5.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$
$t \to \overline{B}^0_s + u$	$2.9 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$
$t \to \overline{B}^0_{(s)} + \text{jet (total)}$	$1.14 \cdot 10^{-4}$	$8.4 \cdot 10^{-5}$

- The top-quark has a small but non-negligible ($\sim 10^{-4}$) probability to decay into B+q
- Particular decays depend on $V_{qq'}$ values: $t \to B^0+u$, B^0_s+c dominate (~50%-50%)
- *[TH uncertainties large (~100%, knowledge of B-meson LDMEs) but result holds].*

NRQCD calculation of t → ϒ + q decay



- Exemplary NRQCD use case: Veloc. scaling v≈√0.1 valid
- S- and P-wave Fock states contribute.
- BUT, CKM-suppressed wrt. t→B+q: $|V_{cb,ub}|^2/|V_{ud,cs}|^2 \approx 10^{-3}$–$10^{-5}$

$$d\Gamma[a \to \overline{B} + X] = \sum_n d\hat{\Gamma}[a \to (b\bar{q})_n + X]\ \rho[(b\bar{q})_n \to \overline{B}]$$

- Non-pQCD probabilities as function of well-known bottomonia LDMEs:

For S-states:

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3S_1^{[1]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3S_1^{[1]})\rangle}{m_b^3}\frac{\Gamma_0(t \to (b\bar{b})_S + q)}{216}$$

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3S_1^{[8]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3S_1^{[8]})\rangle}{m_b^3}\frac{\Gamma_0(t \to (b\bar{b})_S + q)}{36}$$

$$\Gamma(t \to (H_{b\bar{b}})_{{}^1S_0^{[8]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^1S_0^{[8]})\rangle}{m_b^3}\frac{\Gamma_0(t \to (b\bar{b})_S + q)}{12}$$

For P-states:

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3P_0^{[8]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3P_0^{[8]})\rangle}{m_b^5}\frac{\Gamma_0(t \to (b\bar{b})_P + q)}{36},$$

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3P_1^{[8]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3P_1^{[8]})\rangle}{m_b^5}\frac{\Gamma_0(t \to (b\bar{b})_P + q)}{18}\left(1 - 2\frac{m_W^2}{m_t^2}\right)^2$$

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3P_2^{[8]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3P_2^{[8]})\rangle}{m_b^5}\frac{\Gamma_0(t \to (b\bar{b})_P + q)}{90},$$

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3P_0^{[1]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3P_0^{[1]})\rangle}{m_b^5}\frac{\Gamma_0(t \to (b\bar{b})_P + q)}{216},$$

$$\Gamma(t \to (H_{b\bar{b}})_{{}^3P_1^{[1]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3P_1^{[1]})\rangle}{m_b^5}\frac{\Gamma_0(t \to (b\bar{b})_P + q)}{108}\left(1 - 2\frac{m_W^2}{m_t^2}\right)^2$$

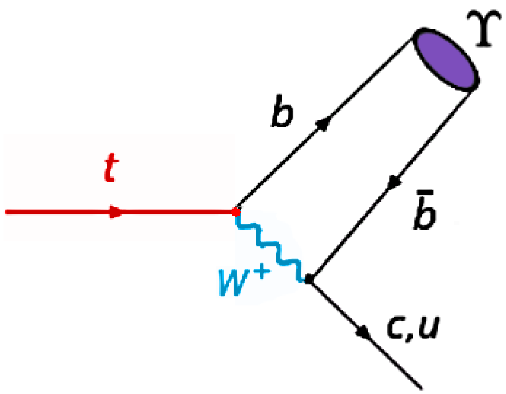
$$\Gamma(t \to (H_{b\bar{b}})_{{}^3P_2^{[1]}} + q) = \frac{\langle \mathcal{O}^{H_{b\bar{b}}}({}^3P_2^{[2]})\rangle}{m_b^5}\frac{\Gamma_0(t \to (b\bar{b})_P + q)}{540},$$

- …with the prefactor in the widths:

$$\Gamma_0(t \to (b\bar{b})_S + q) \equiv |V_{qb}|^2 \frac{\alpha^2 \pi m_t^3 m_b^2}{(m_t^2 - 2m_W^2)^2 \sin^4\theta_w}$$

$$\Gamma_0(t \to (b\bar{b})_P + q) \equiv |V_{qb}|^2 \frac{\alpha^2 \pi m_t^7 m_b^2}{(m_t^2 - 2m_W^2)^4 \sin^4\theta_w}$$

NRQCD calculation of t→ϒ + q decay



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$$d\Gamma[a \to \overline{B} + X] = \sum_n d\hat{\Gamma}[a \to (b\bar{q})_n + X]\, \rho[(b\bar{q})_n \to \overline{B}]$$

- t→ϒ+q partial widths for all bottomonia states & four sets of LDMEs:

top decay (bottomonium state)	Partial decay width (10^{-9} GeV) Set I	Set II	Set III	Set IV
$t \to \Upsilon(1S) + q$	1.62	2.01	1.61	1.36
$t \to \Upsilon(2S) + q$	0.71	0.23	0.67	0.57
$t \to \Upsilon(3S) + q$	0.51	0.47	0.42	0.37
$t \to \Upsilon(nS) + q$	2.84	2.71	2.70	2.30

- Final t→ϒ+q partial widths & branching ratios (for Γ_t = 1.35 GeV):

Decay mode	Partial decay width (GeV)	Branching fraction
$t \to \Upsilon(nS) + c$	$2.5 \cdot 10^{-9}$	$1.9 \cdot 10^{-9}$
$t \to \Upsilon(nS) + u$	$2.5 \cdot 10^{-11}$	$1.9 \cdot 10^{-11}$

- The top-quark has a very small (~10^{-9}) probability to decay into ϒ+c.
- *[Small TH uncertainties ~10%, thanks to good knowledge of b-bbar LDMEs].*

Experimental observation of $t \to B^0_{(s)} + q$?

- How many rare $\mathcal{O}(10^{-4})$ 2-body decays at HL-LHC (3 ab^{-1}), FCC-hh (20 ab^{-1})?

$\sqrt{s}$	$\sigma^{t\bar{t},\text{incl.}}_{\text{NNLO+NNLL}}$ (top++)
14 TeV	$980 \pm 17\,(\text{PDF})\,^{+24}_{-35}(\text{scale})$ pb
100 TeV	$34.80 \pm 1.20\,(\text{PDF})\,^{+1.00}_{-1.65}(\text{scale})$ nb

We expect $6 \cdot 10^9$, $1.5 \cdot 10^{12}$ top-quark pair events at the HL-LHC, FCC

($\times$250 more at FCC thanks to $\times$35 σ and $\times$7 $\mathcal{L}$)

- Number of $t \to B$+jet decays in triggered top-pair events at HL-LHC, FCC-hh:

  - Fully hadronic: $t\bar{t} \to W^+b\, W^-\bar{b} \to q\bar{q}'b\, q''\bar{q}'''\bar{b}$ ($\mathscr{B} = 45.7\%$)
  - Lepton+jets: $t\bar{t} \to W^+b\, W^-\bar{b} \to q\bar{q}'b\, \ell^-\nu_\ell\bar{b}$ ($\mathscr{B} = 43.8\%$)
  - Dileptons: $t\bar{t} \to W^+b\, W^-\bar{b} \to \ell^+\nu_\ell b\, \ell^-\nu_\ell\bar{b}$ ($\mathscr{B} = 10.5\%$)

Run MadGraph@NLO (NNPDF3.0) for pp → ttbar → 6j, ℓ+j at LHC/FCC

▶ Typical acceptance×efficiency for ttbar multi-jets & lepton+jets final states: ~20%

- At least 4 jets (reconstructed with the anti-k_T algorithm $R = 0.5$) with $p_T > 25$ GeV and $|\eta| < 3.0$ (5.0 at the FCC);
- A total scalar sum of transverse energy in the reconstructed jets above roughly twice the top mass, $H_T > 350$ GeV;
- At least 1 b jet tagged with a typical 75% efficiency;

- One isolated (cone radius $R_{\text{isol}} = 0.3$) charged lepton ℓ with $p_T > 30$ GeV and $|\eta| < 2.5$ ($|\eta| < 5.0$ at the FCC);
- At least 2 jets (reconstructed with the anti-k_T algorithm $R = 0.5$) with $p_T > 25$ GeV and $|\eta| < 3.0$ (5.0 at the FCC), and separated from the lepton by $\Delta R(\ell, j) > 0.4$;
- 1 b-jet tagged with a typical 75% efficiency;

$\sqrt{s}$	top-quark pair $\mathscr{B}$ × acceptance × efficiency losses: fully hadronic	ℓ+jets
14 TeV	$0.457 \times 0.57 \times 0.75 = 0.20$	$0.35 \times 0.64 \times 0.75 = 0.17$
100 TeV	$0.457 \times 0.76 \times 0.75 = 0.26$	$0.35 \times 0.71 \times 0.75 = 0.19$

Experimental observation of t → $B^0_{(s)}$ + q?

- How many rare $\mathcal{O}(10^{-4})$ 2-body decays at HL-LHC (3 ab^{-1}), FCC-hh (20 ab^{-1})?

$\sqrt{s}$	$\sigma^{t\bar{t},\mathrm{incl.}}_{\mathrm{NNLO+NNLL}}$ (top++)
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- A total scalar sum of transverse energy in the reconstructed jets above roughly twice the top mass, $H_T > 350$ GeV;
- At least 1 b jet tagged with a typical 75% efficiency;

LHC: $N^{t\bar{t}\text{ full had.}}_{t\to\overline{B}^0_{(s)}+\text{jet}} \approx 1.5\cdot10^5$

FCC: $N^{t\bar{t}\text{ full had.}}_{t\to\overline{B}^0_{(s)}+\text{jet}} \approx 4\cdot10^7$

- One isolated (cone radius $R_{\mathrm{isol}} = 0.3$) charged lepton ℓ with $p_T > 30$ GeV and $|\eta| < 2.5$ ($|\eta| < 5.0$ at the FCC);
- At least 2 jets (reconstructed with the anti-k_T algorithm $R = 0.5$) with $p_T > 25$ GeV and $|\eta| < 3.0$ (5.0 at the FCC), and separated from the lepton by $\Delta R(\ell, j) > 0.4$;
- 1 b-jet tagged with a typical 75% efficiency;

LHC: $N^{t\bar{t}\ \ell+\text{jet}}_{t\to\overline{B}^0_{(s)}+\text{jet}} \approx 62\,000$

FCC: $N^{t\bar{t}\ \ell+\text{jet}}_{t\to\overline{B}^0_{(s)}+\text{jet}} \approx 1.6\cdot10^7$

Search for $t \to B^0_{(s)}$+jet via $B^0_{(s)} \to J/\varphi$+hh final states

- 6 exclusive $B^0_{(s)} \to J/\varphi$+hh decay channels with total branching ratios 10^{-5}–10^{-4}:

$\overline{B}^0_{(s)}$ meson decay mode	Total branching fraction (product of individual $\mathscr{B}$'s)	Acceptance LHC	Acceptance FCC
$\overline{B}^0 \to J/\psi(\mu^+\mu^-)\,K^{*0}(K^\pm\pi^\mp)$	$1.27 \cdot 10^{-3} \times 0.0596 \times 1 \approx 7.6 \cdot 10^{-5}$	50%	54%
$\overline{B}^0 \to J/\psi(\mu^+\mu^-)\,K^+\pi^-$	$1.15 \cdot 10^{-3} \times 0.0596 \approx 6.9 \cdot 10^{-5}$	62%	67%
$\overline{B}^0 \to J/\psi(\mu^+\mu^-)\,K^0_s(\pi^+\pi^-)$	$0.87 \cdot 10^{-3} \times 0.0596 \times 0.69 \approx 3.6 \cdot 10^{-5}$	52%	58%
$\overline{B}^0_s \to J/\psi(\mu^+\mu^+)\,\phi(K^+K^-)$	$1.08 \cdot 10^{-3} \times 0.0596 \times 0.49 \approx 3.2 \cdot 10^{-5}$	61%	64%
$\overline{B}^0_s \to J/\psi(\mu^+\mu^+)\,K^+K^-$	$0.79 \cdot 10^{-3} \times 0.0596 \approx 4.7 \cdot 10^{-5}$	63%	67%
$\overline{B}^0_s \to J/\psi(\mu^+\mu^+)\,\pi^+\pi^-$	$0.21 \cdot 10^{-3} \times 0.0596 \approx 1.25 \cdot 10^{-5}$	66%	68%

- Acceptances determined via PYTHIA8 simulations for all 6 final states in $tt \to B^0_{(s)}+X \to J/\varphi$+hh+X events in pp at $\sqrt{s}$ = 14, 100 TeV. Reco effic. assumed at ~0.5.

Top pair final state	$\overline{B}^0_{(s)}$ meson decay mode	Events after all selection cuts LHC (3 ab^{-1})	FCC (20 ab^{-1})
$t\bar{t} \to \overline{B}^0 + u, c$			
∘ fully hadronic	$\overline{B}^0 \to J/\psi(\mu^+\mu^-)\,K^+\pi^-$	3.1	1050
∘ ℓ+ jets		1.4	380
∘ fully hadronic	$\overline{B}^0 \to J/\psi(\mu^+\mu^-)\,K^{*0}(K^\pm\pi^\mp)$	2.7	940
∘ ℓ+ jets		1.2	340
∘ fully hadronic	$\overline{B}^0 \to J/\psi(\mu^+\mu^-)\,K^0_s(\pi^+\pi^-)$	1.3	470
∘ ℓ+ jets		0.6	170
Sum of all channels		10.2	3 300
$t\bar{t} \to \overline{B}^0_s + c, u$			
∘ fully hadronic	$\overline{B}^0_s \to J/\psi(\mu^+\mu^+)\,K^+K^-$	2.1	710
∘ ℓ+ jets		0.9	250
∘ fully hadronic	$\overline{B}^0_s \to J/\psi(\mu^+\mu^+)\,\phi(K^+K^-)$	1.4	460
∘ ℓ+ jets		0.6	170
∘ fully hadronic	$\overline{B}^0_s \to J/\psi(\mu^+\mu^+)\,\pi^+\pi^-$	0.6	200
∘ ℓ+ jets		0.3	70
Sum of all channels		5.7	1 900
TOTAL		16	5 200

- 5-thousand (~15) 2-body top-quark decays reconstructed at FCC-hh (LHC).

Search for $t \to B^0_{(s)}$+jet via $B^0_{(s)} \to$ D+h(h) final states

- 6 exclusive $B^0_{(s)} \to$ D+h(h) decay channels with total branching ratios ~10^{-4}:

$\overline{B}^0_{(s)}$ meson decay mode	Total branching fraction (product of individual $\mathcal{B}$'s)	Acceptance LHC	Acceptance FCC
$\overline{B}^0 \to D^+(K^-\pi^+\pi^+)\,\pi^-$	$2.52\cdot10^{-3}\times0.094\approx2.37\cdot10^{-4}$	55%	65%
$\overline{B}^0 \to \overline{D}^{*,+}(D^0(K^-\pi^+)\pi^+)\,\pi^-$	$2.74\cdot10^{-3}\times0.677\times0.039\approx7.2\cdot10^{-5}$	55%	65%
$\overline{B}^0 \to \overline{D}^0(K^-\pi^+)\,\pi^+\pi^-$	$0.88\cdot10^{-3}\times0.039\approx3.43\cdot10^{-5}$	75%	80%
$\overline{B}^0 \to D^+(K^-\pi^+\pi^+)\,K^-$	$0.186\cdot10^{-3}\times0.094\approx1.75\cdot10^{-5}$	55%	65%
$\overline{B}^0_s \to D^+_s(K^-K^+\pi^+)\pi^-$	$3.0\cdot10^{-3}\times0.055\approx1.6\cdot10^{-4}$	60%	60%
$\overline{B}^0_s \to \overline{D}^0(K^-\pi^+)\,K^-\pi^+$	$1.04\cdot10^{-3}\times0.039\approx4\cdot10^{-5}$	60%	65%

- Acceptances determined via PYTHIA8 simulations (ongoing) for all 6 final states in $tt \to B^0_{(s)}$+X $\to$ D+h(h)+X events in pp at $\sqrt{s}$ = 14, 100 TeV. Reco effic. assumed at ~0.5.

Top pair final state	$\overline{B}^0_{(s)}$ meson decay mode	Events after all selection cuts LHC (3 ab^{-1})	Events after all selection cuts FCC (20 ab^{-1})
$t\bar{t} \to \overline{B}^0 + u, c$			
∘ fully hadronic	$\overline{B}^0 \to D^+(K^-\pi^+\pi^+)\,\pi^-$	9.3	3 500
∘ ℓ+ jets		4	1 200
∘ fully hadronic	$\overline{B}^0 \to \overline{D}^{*,+}(D^0(K^-\pi^+)\pi^+)\,\pi^-$	2.8	1 100
∘ ℓ+ jets		1.2	380
∘ fully hadronic	$\overline{B}^0 \to \overline{D}^0(K^-\pi^+)\pi^+\,\pi^-$	1.8	630
∘ ℓ+ jets		0.8	220
∘ fully hadronic	$\overline{B}^0 \to D^+(K^-\pi^+\pi^+)\,K^-$	0.7	250
∘ ℓ+ jets		0.3	90
Sum of all channels		21.0	7 300
$t\bar{t} \to \overline{B}^0_s + c, u$			
∘ fully hadronic	$\overline{B}^0_s \to D^+_s(K^+K^-\pi^+)\pi^-$	7.1	2 200
∘ ℓ+ jets		3.0	800
∘ fully hadronic	$\overline{B}^0_s \to \overline{D}^0(K^-\pi^+)\,K^-\pi^+$	1.6	570
∘ ℓ+ jets		0.7	200
Sum of all channels		12.4	3 800
TOTAL		33	11 000

- 10-thousand (~30) 2-body top-quark decays reconstructed at FCC-hh (LHC).

Search for 2-body top decay via $t \to j_{bottom} + j_{charm}$

- 12 exclusive $B^0_{(s)} \to J/\varphi$+hh,D+h(h) decays are very clean, but have small BRs. Try instead to reconstruct the B-meson as a b-jet & search for the 2-body decay via $t \to$ j(bottom)+j(charm)? *[$t \to$ j(bottom)+j(u-quark) swamped by backgd.]*

- Analysis of ttbar ℓ+jets triggered events requiring N=3 jets w/ exactly 2 b-tags + 1 c-tag (p_T>80 GeV) within acceptance with (mis)tagging performances:
  - Bottom jets: b-jet tagging efficiency: 75%; b-jet mistagging probability for a c-quark: 5%, b-jet mistagging probability for *udsg* (light quarks or gluon): 0.5%.
  - Charm jets: Two different c-jet working points considered: (i) c-jet tagging efficiency: 65%, c-jet mistagging probability for a b quark: 10%, c-jet mistagging probability for *udsg*: 10% [**HcT**:]; and (ii) c-jet tagging efficiency: 35%, c-jet mistagging probability for a b-quark: 5%, and c-jet mistagging probability for *udsg*: 1% [**LcT**].

- MadGraph@NLO (NNPDF3.0) + PYTHIA8 PS simulation for all backgrounds:
  - pp $\to$ ttbar $\to$ 6j,ℓ+j
  - single-t
  - W+jets, Z+jets
  - VV (V=W,Z)
  - QCD multi-jets

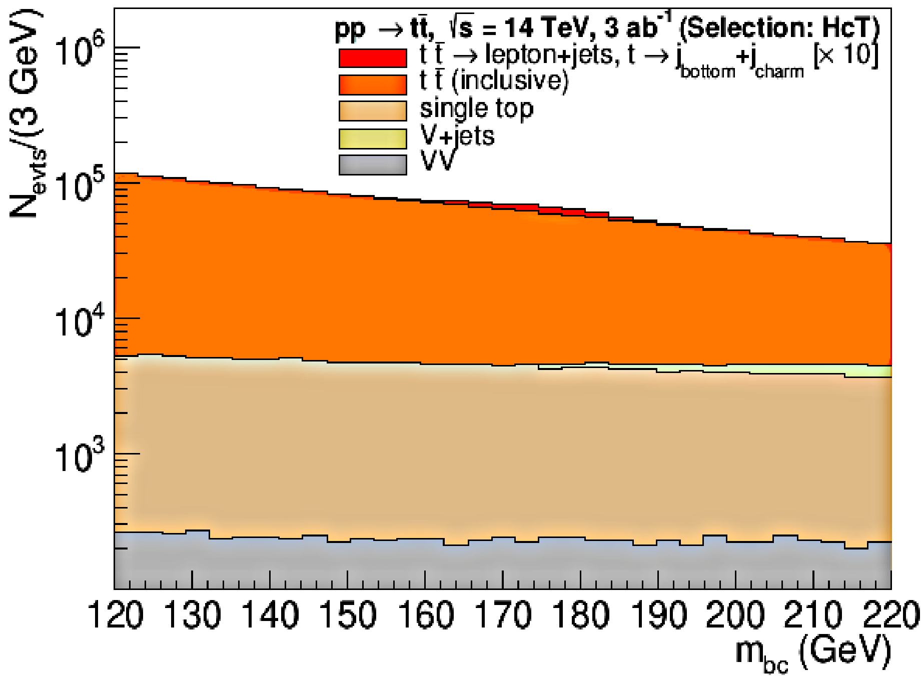
process	pp at $\sqrt{s}$ = 14 TeV (3 ab^{-1}) 'HcT'	pp at $\sqrt{s}$ = 14 TeV (3 ab^{-1}) 'LcT'	pp at $\sqrt{s}$ = 100 TeV (20 ab^{-1}) 'HcT'	pp at $\sqrt{s}$ = 100 TeV (20 ab^{-1}) 'LcT'
$t\bar{t}$ (signal)	5 300	2 500	$1.4 \cdot 10^6$	$7.5 \cdot 10^5$
$t\bar{t}$ (backgd.)	$2.1(1.7) \cdot 10^6$	$9.3(7.4) \cdot 10^5$	$3.0(2.4) \cdot 10^8$	$1.1(0.9) \cdot 10^8$
tW	$7.0(5.8) \cdot 10^4$	$3.1(2.5) \cdot 10^4$	$1.2(1.0) \cdot 10^7$	$4.7(4.4) \cdot 10^6$
t+jet	$7.8(6.6) \cdot 10^4$	$2.7(2.4) \cdot 10^4$	$1.1(1.0) \cdot 10^7$	$4.0(3.7) \cdot 10^6$
V+jet	$1.5(1.3) \cdot 10^5$	$7.6(7.6) \cdot 10^4$	$1.1(0.8) \cdot 10^7$	$1.1(0.8) \cdot 10^7$
VV	$7.7(6.3) \cdot 10^3$	$2.8(2.3) \cdot 10^3$	$9.1(7.3) \cdot 10^5$	$3.4(3.1) \cdot 10^5$
Multijet	$< 4.8 \cdot 10^4$	$< 4.8 \cdot 10^4$	$< 1.2 \cdot 10^7$	$< 1.2 \cdot 10^7$
$\mathcal{S}$ (std. dev.)	6.1	4.5	130.	110.

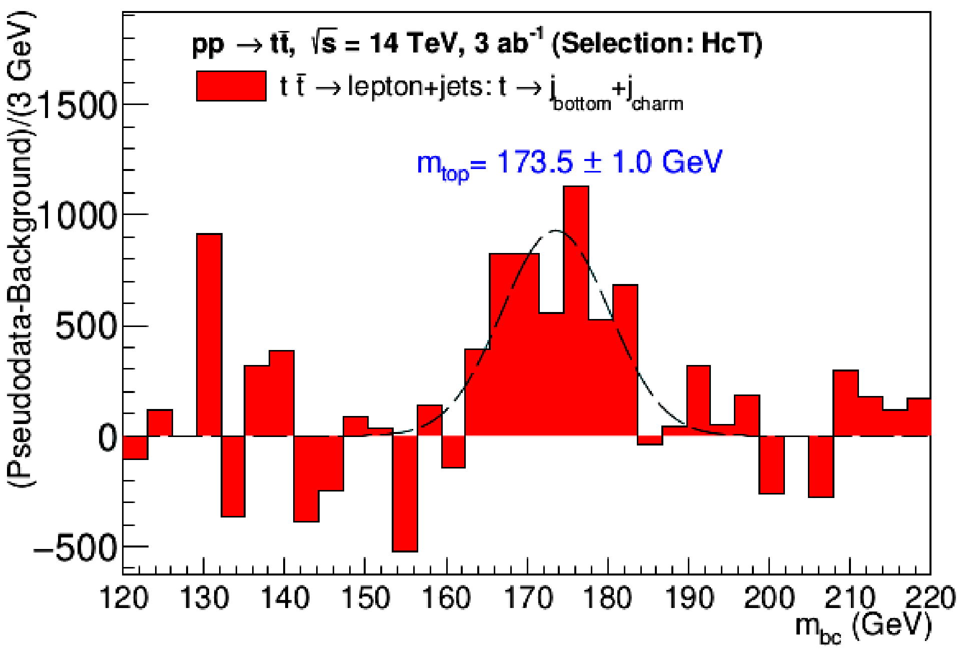
► Few million (thousands) $t \to$ b+c expected at FCC-hh (LHC).

Search for 2-body top decay via t→j_{bottom}+j_{charm} (LHC)

- Expected dijet signal t→b+c (m_{jj}~10 GeV resolution) after cuts injected on top of MadGraph@NLO+ PYTHIA8 simulation for dominant pp→ttbar→6j,ℓ+j backgds

- Invariant mass dijet distribution for best (mis)tagging selection criterion:



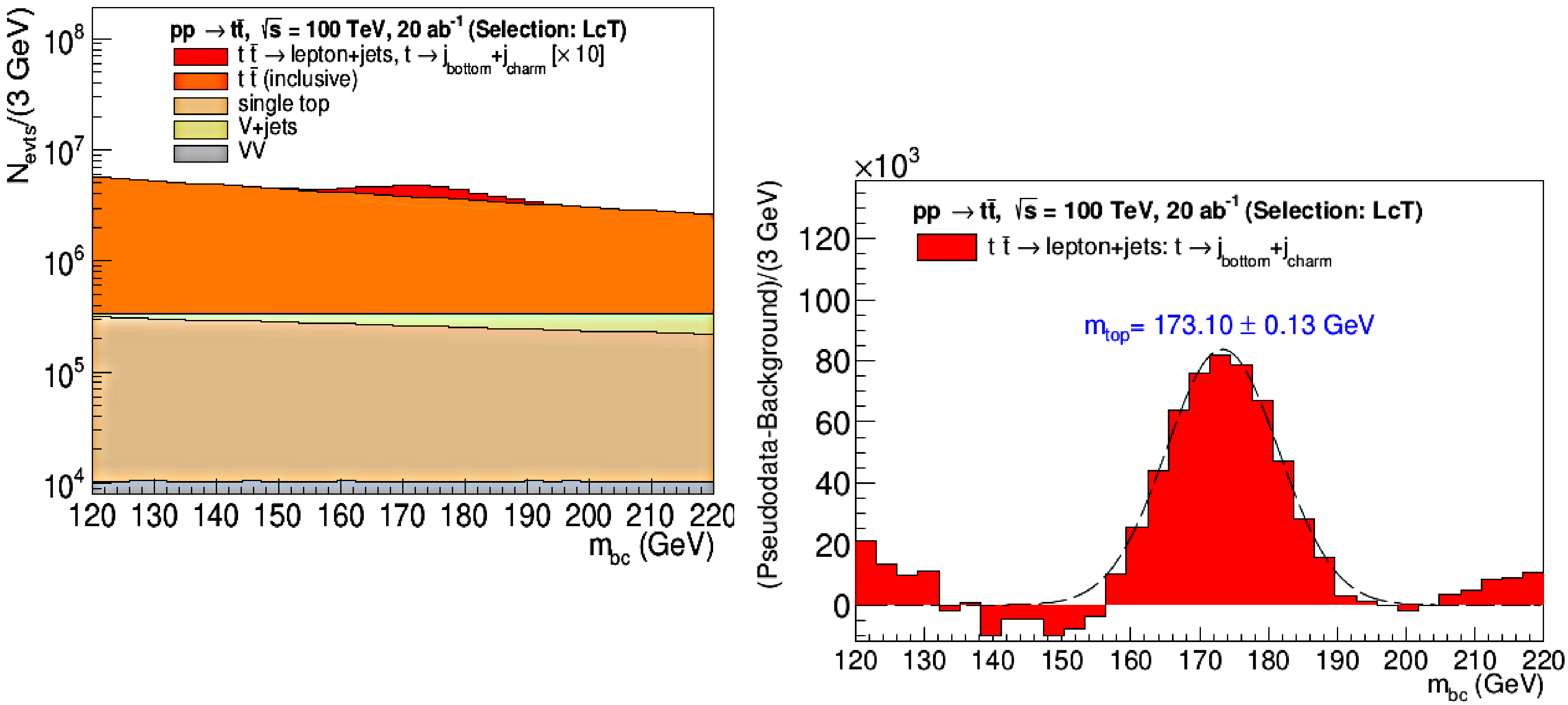


▶ Observation warranted at HL-LHC (significance >6σ) for t→b+c signal.

Search for 2-body top decay via $t \to j_{bottom} + j_{charm}$ (FCC)

- Expected dijet signal $t \to b+c$ (m_{jj}~10 GeV resolution) after cuts injected on top of MadGraph@NLO+ PYTHIA8 simulation for dominant $pp \to ttbar \to 6j, \ell+j$ backgds

- Invariant mass dijet distribution for best (mis)tagging selection criterion:



▶ Huge $t \to b+c$ signal (significance >100σ) over background at the FCC.

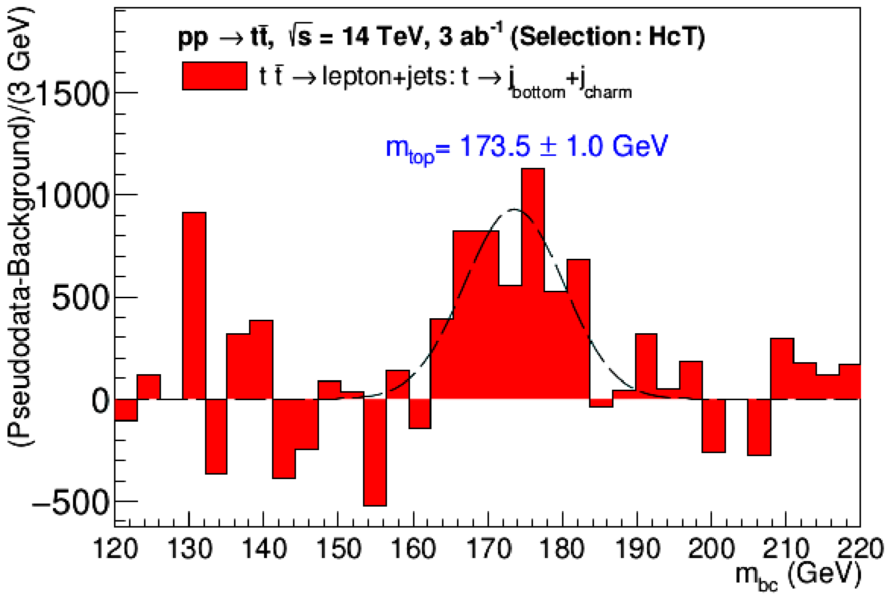
Top mass from $t \to j_{bottom} + j_{charm}$ invariant mass

- Two-body top-quark decay provides novel interesting possibilities for simple top mass extractions from 2-body invariant mass analysis of:

1) $m_{inv}(B^0$+jet) from 12 exclusive $B^0_{(s)} \to J/\varphi$+hh,D+h(h) final states plus jet:
   - ☻ Small systematical uncertainties dominated by single-jet energy scale.
   - ☹ Large stat.uncertainties dominated by small data samples (~50, 15000 evts at LHC,FCC)

2) m_{inv}(b-jet + c-jet):
   - ☻ Small statistical uncertainties (~million evts at FCC).
   - 😐 Moderate systematical uncertainties dominated by double-jet energy scale.

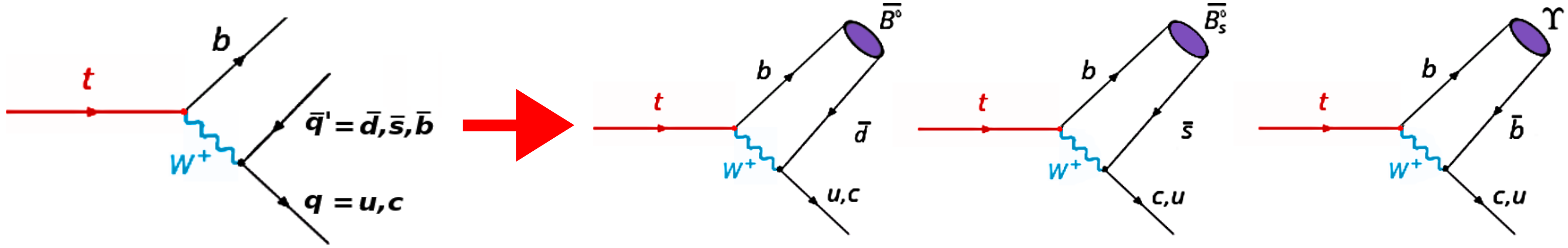
- Simple Gaussian fit of the backgd-subtracted m_{bc} distribution at LHC:



- Top mass extraction with ~1 GeV fit uncertainty.
- Dijet energy scale should be fitted concurrently & assoc. systematics propagated.
- Promising novel extraction of m_{top} with different systematics to other methods

Summary

- First-ever study of 2-body decays of a top-quark into B-meson + u,c jet:



- Partial widths & branching ratios computed in NRQCD recombination:

Decay mode	Partial decay width (GeV)	Branching fraction
$t \to \overline{B}^0 + u$	$5.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$
$t \to \overline{B}^0 + c$	$2.9 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$
$t \to \overline{B}^0_s + c$	$5.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$
$t \to \overline{B}^0_s + u$	$2.9 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$
$t \to \overline{B}^0_{(s)} + \text{jet (total)}$	$1.14 \cdot 10^{-4}$	$8.4 \cdot 10^{-5}$

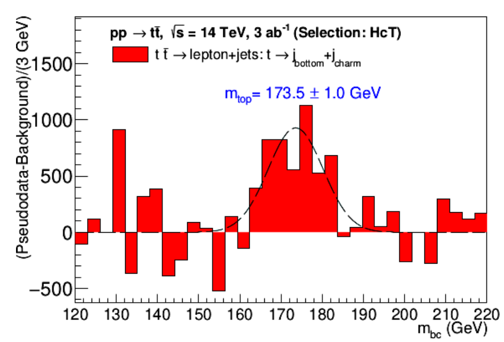
▶ Top-quark has small but visible (~10^{-4}) probability to decay into $t \to B^0 + u$, $B^0_s + c$.

▶ Top-quark has tiny (~10^{-9}) probability to decay into $\Upsilon + c$.

- Feasibility study in pp collisions at HL-LHC & FCC-hh with NNLO rates & MadGraph@NLO+PY8 simulations: exclusive channels & b+c dijet final state

pp system $\sqrt{s}$, $\mathcal{L}_{\rm int}$	Number of produced events expected: $t\bar{t}$	Number of produced events expected: $t \to \overline{B}^0_{(s)}$+jet	Number of 2-body top-quark events after $\mathcal{B} \times$ acceptance $\times$ efficiency cuts: $\overline{B}^0_{(s)} \to J/\psi\, hh$	$\overline{B}^0_{(s)} \to D^{0,\pm}_{(s)}\, h(h)$	$t \to b + c$
14 TeV, 3 ab^{-1}	$3 \cdot 10^9$	$2.5 \cdot 10^5$	16	33	5 300
100 TeV, 20 ab^{-1}	$7 \cdot 10^{11}$	$6 \cdot 10^7$	5 200	11 000	$1.4 \cdot 10^6$

- Novel precise method to measure top mass via simple invariant-mass analysis of 2-body final states:



Backup slides

$t \to j_{bottom} + j_{charm}$ background

- Cut-flow numbers for accumulated selection criteria for the dominant ttbar background:

Selection criteria	pp at $\sqrt{s}=14$ TeV (3 ab^{-1}) 'HcT'	pp at $\sqrt{s}=14$ TeV (3 ab^{-1}) 'LcT'	pp at $\sqrt{s}=100$ TeV (20 ab^{-1}) 'HcT'	pp at $\sqrt{s}=100$ TeV (20 ab^{-1}) 'LcT'
(0): none	$1.0 \cdot 10^9$	$1.0 \cdot 10^9$	$2.4 \cdot 10^{11}$	$2.4 \cdot 10^{11}$
(1): trigger (ℓ+jets)	$4.8 \cdot 10^8$	$4.8 \cdot 10^8$	$1.3 \cdot 10^{11}$	$1.3 \cdot 10^{11}$
(2): (1) + ($N_{j_b} = 2 \&\& N_{j_c} = 1$)	$8.2 \cdot 10^7$	$3.8 \cdot 10^7$	$2.3 \cdot 10^{10}$	$1.2 \cdot 10^{10}$
(3): (1) + (2) + $120 \leq m_{b,c} \leq 220$ GeV	$5.3 \cdot 10^7$	$2.6 \cdot 10^7$	$1.3 \cdot 10^{10}$	$7.3 \cdot 10^9$

Table 10. Total number of events expected for $t\bar{t} \to N_j + \ell^\pm + X$ with $\ell^\pm = \mu^\pm, e^\pm$, in pp collisions at $\sqrt{s} = 14$ and 100 TeV, passing the analysis criteria for the 'HcT' and 'LcT' charm jet reconstruction performances discussed in the text. The "trigger" row lists the number of events that pass the trigger cuts presented in subsection 3.1.2, and $N_{j_b} = 2 \,\&\&\, N_{j_c} = 1$ indicates the exact requirement of two b- and one c-quark jets reconstructed in the event with the kinematic criteria discussed in the text.