

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

Moriond-QCD 2021
(Virtual), 28th March – 3rd April 2021

David d'Enterria (CERN)
Huasheng Shao (LPTHE, Paris)

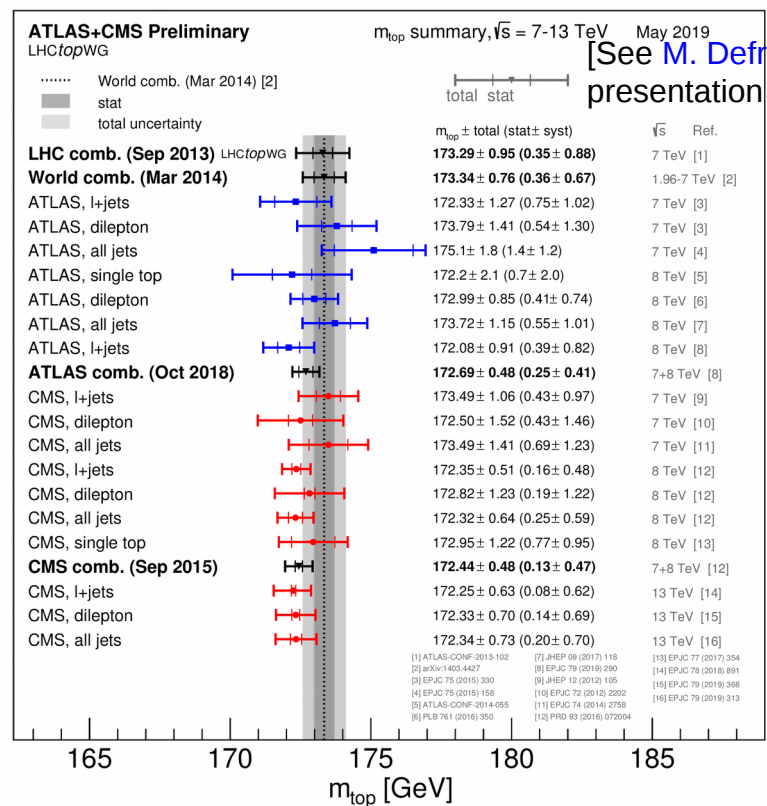
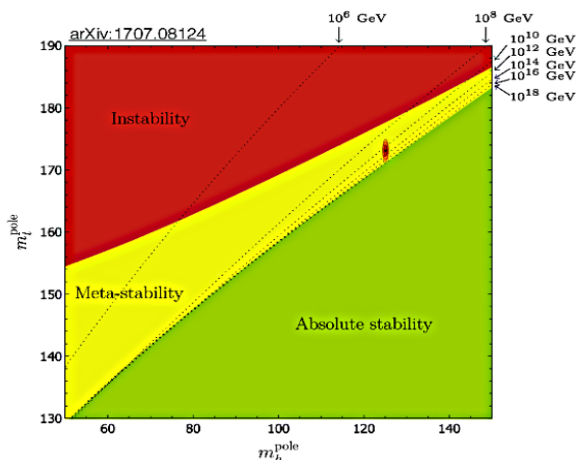
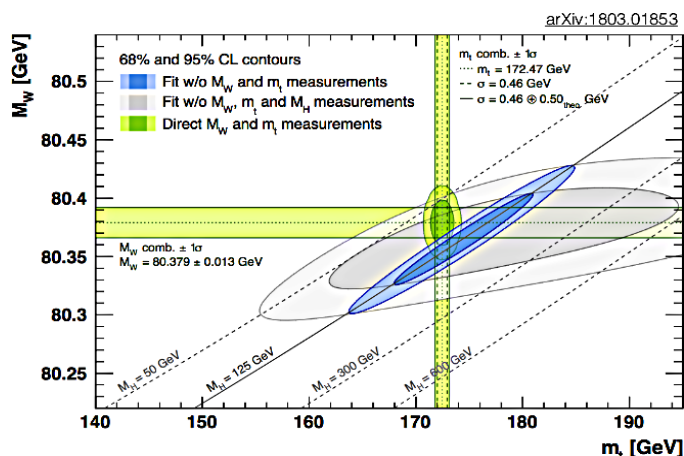
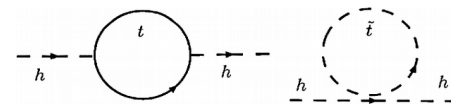
[Details in: DdE & HSS, JHEP 07 (2020) 127 [2005.08102 \[hep-ph\]](#)]

Backgd pic: Ski down Mont Valezan (2 years ago today at Moriond-QCD'19)

Top quark mass = fundamental SM parameter

- The top quark, the heaviest SM elementary particle, plays a **key role for SM & BSM** physics:

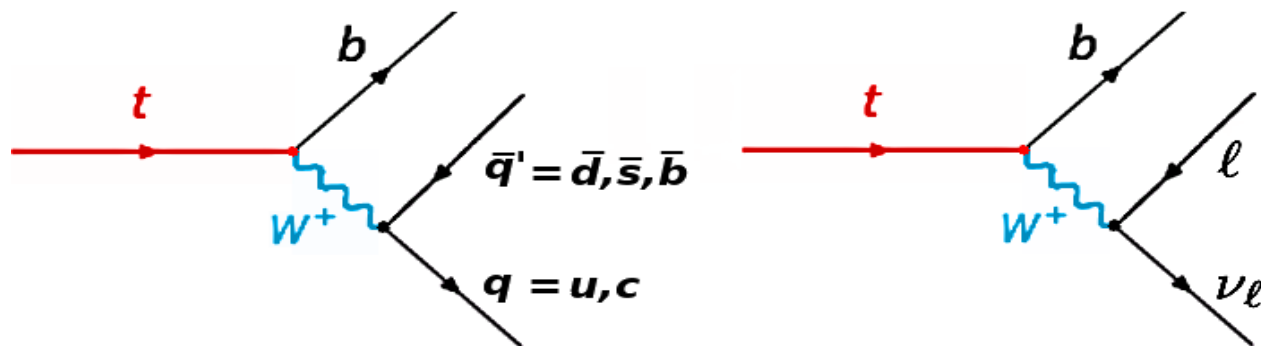
- **Largest coupling to Higgs** (hierarchy problem).
- Essential for **testing overall SM self-consistency** (indirect BSM searches).
- Key role on the **stability of the EW vacuum** in the universe.



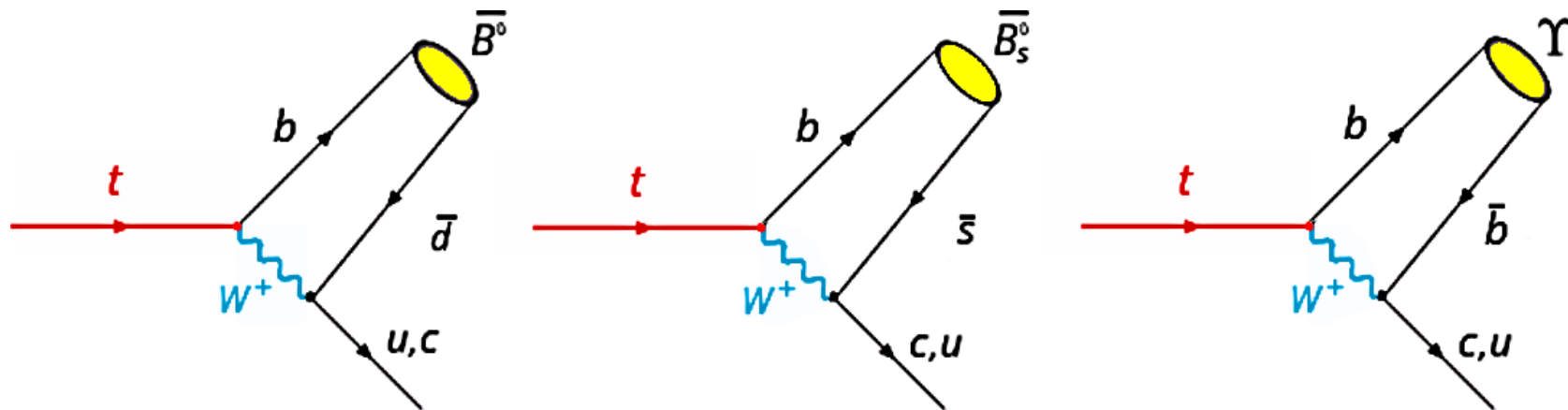
- $m_t = 172.9 \pm 0.4$ (direct), 173.1 ± 0.9 (x-sect.) GeV
- **New alternative direct m_t measurements?**

Two-body decays of the top quark?

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



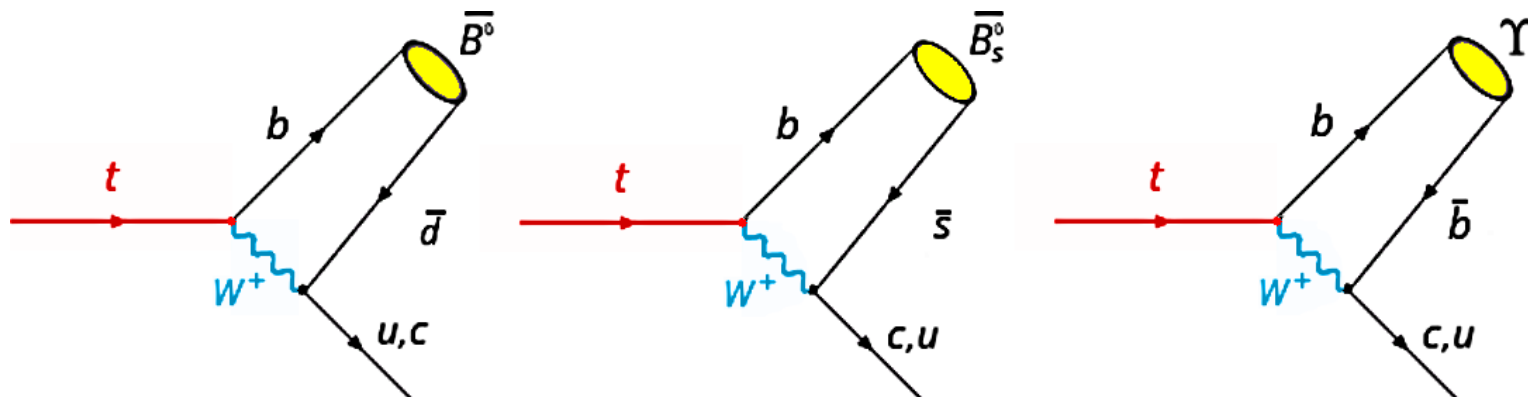
- Two-body decay of the top quark into a bottom-meson plus u,c-quark?



- 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:

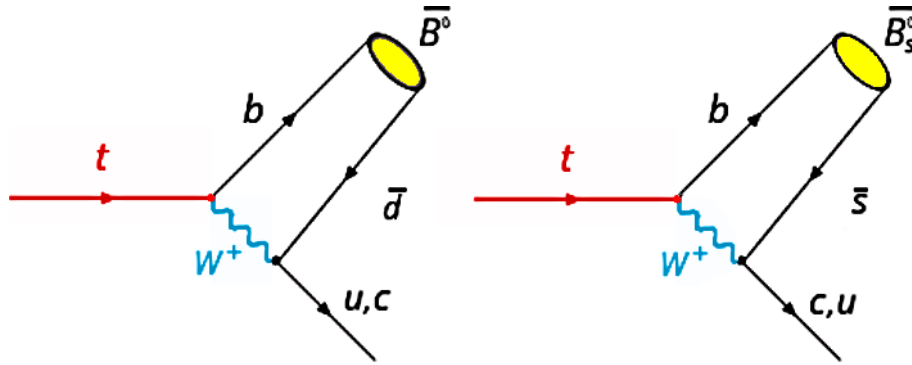


- ▶ 4-momentum conservation between B, b, and q implies that the top-decay W boson is quite offshell: $m_W \approx m_t \sqrt{(m_q/m_b)} = 45 \text{ GeV}$.
 - ▶ Away-side u,c quark carries $p_T \approx m_t/2 = 85 \text{ GeV}$, i.e. it is more boosted than the W decay quarks in standard $t \rightarrow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

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

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 $t \rightarrow B_{(s)}^0 + q$ decay



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

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

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

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

$$\rho_1^{\bar{B}} \equiv \rho[(b\bar{q})_{{}^1S_0^{[1]}} \rightarrow \bar{B}],$$

$$\langle \mathcal{O}^{\bar{B}}({}^1S_0^{[1]}) \rangle = 2N_c \frac{4m_b m_q^2}{3} \rho_{1,8}^{\bar{B}}$$

$$\rho_8^{\bar{B}} \equiv \rho[(b\bar{q})_{{}^1S_0^{[8]}} \rightarrow \bar{B}],$$

$$\langle \mathcal{O}^{\bar{B}}({}^1S_0^{[8]}) \rangle = (N_c^2 - 1) \frac{4m_b m_q^2}{3} \rho_{1,8}^{\bar{B}}$$

$$3\rho_{1,8}^{\bar{B}} = \rho[(b\bar{q})_{{}^3S_1^{[1,8]}} \rightarrow \bar{B}]$$

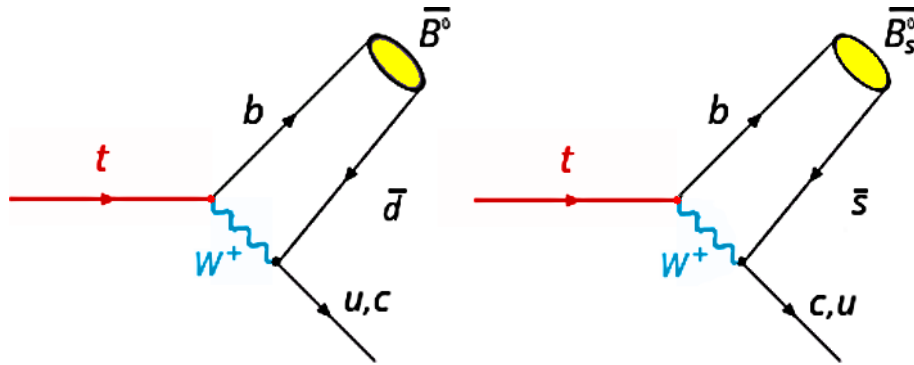
$$\langle \mathcal{O}^{\bar{B}}({}^3S_1^{[1,8]}) \rangle = 3\langle \mathcal{O}^{\bar{B}}({}^1S_0^{[1,8]}) \rangle$$

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

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

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

NRQCD calculation of $t \rightarrow B_{(s)}^0 + q$ decay



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

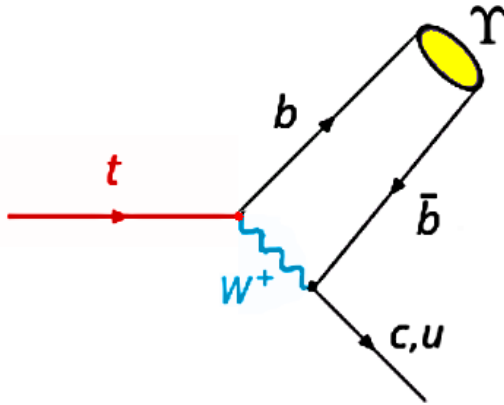
$$(t \rightarrow \bar{B}_s^0 + q + X) = \frac{|V_{qs}|^2}{|V_{qd}|^2} \Gamma(t \rightarrow \bar{B}^0 + q + X),$$

■ Final $t \rightarrow B^0(s) + q$ **partial widths & branching ratios** (for $\Gamma_t = 1.35$ GeV):

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

- ▶ 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: $t \rightarrow B^0+u$, B_s^0+c **dominate** ($\sim 50\%-50\%$)
- ▶ *[TH uncertainties large ($\sim 100\%$, knowledge of B-meson LDMEs) but result holds].*

NRQCD calculation of $t \rightarrow \Upsilon + q$ decay



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

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

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

For S-states:

$$\begin{aligned} \Gamma(t \rightarrow (H_{b\bar{b}})_{3S_1^{[1]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3S_1^{[1]}) \rangle}{m_b^3} \frac{\Gamma_0(t \rightarrow (b\bar{b})_S + q)}{216} \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{3S_1^{[8]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3S_1^{[8]}) \rangle}{m_b^3} \frac{\Gamma_0(t \rightarrow (b\bar{b})_S + q)}{36} \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{1S_0^{[8]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^1S_0^{[8]}) \rangle}{m_b^3} \frac{\Gamma_0(t \rightarrow (b\bar{b})_S + q)}{12} \end{aligned}$$

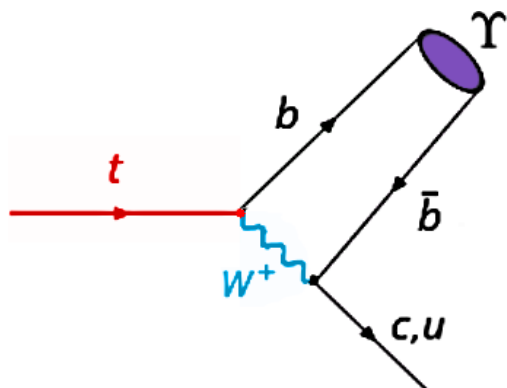
- ...with the prefactor in the widths:

$$\begin{aligned} \Gamma_0(t \rightarrow (b\bar{b})_S + q) &\equiv |V_{qb}|^2 \frac{\alpha^2 \pi m_t^3 m_b^2}{(m_t^2 - 2m_W^2)^2 \sin^4 \theta_w} \\ \Gamma_0(t \rightarrow (b\bar{b})_P + q) &\equiv |V_{qb}|^2 \frac{\alpha^2 \pi m_t^7 m_b^2}{(m_t^2 - 2m_W^2)^4 \sin^4 \theta_w} \end{aligned}$$

For P-states:

$$\begin{aligned} \Gamma(t \rightarrow (H_{b\bar{b}})_{3P_0^{[8]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3P_0^{[8]}) \rangle}{m_b^5} \frac{\Gamma_0(t \rightarrow (b\bar{b})_P + q)}{36}, \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{3P_1^{[8]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3P_1^{[8]}) \rangle}{m_b^5} \frac{\Gamma_0(t \rightarrow (b\bar{b})_P + q)}{18} \left(1 - 2\frac{m_W^2}{m_t^2}\right)^2 \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{3P_2^{[8]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3P_2^{[8]}) \rangle}{m_b^5} \frac{\Gamma_0(t \rightarrow (b\bar{b})_P + q)}{90}, \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{3P_0^{[1]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3P_0^{[1]}) \rangle}{m_b^5} \frac{\Gamma_0(t \rightarrow (b\bar{b})_P + q)}{216}, \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{3P_1^{[1]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3P_1^{[1]}) \rangle}{m_b^5} \frac{\Gamma_0(t \rightarrow (b\bar{b})_P + q)}{108} \left(1 - 2\frac{m_W^2}{m_t^2}\right)^2 \\ \Gamma(t \rightarrow (H_{b\bar{b}})_{3P_2^{[1]}} + q) &= \frac{\langle \mathcal{O}^{H_{b\bar{b}}}(^3P_2^{[1]}) \rangle}{m_b^5} \frac{\Gamma_0(t \rightarrow (b\bar{b})_P + q)}{540}, \end{aligned}$$

NRQCD calculation of $t \rightarrow \Upsilon + q$ decay



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

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

- $t \rightarrow \Upsilon + q$ **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
$t \rightarrow \Upsilon(1S) + q$	1.62	2.01	1.61	1.36
$t \rightarrow \Upsilon(2S) + q$	0.71	0.23	0.67	0.57
$t \rightarrow \Upsilon(3S) + q$	0.51	0.47	0.42	0.37
$t \rightarrow \Upsilon(nS) + q$	2.84	2.71	2.70	2.30

- Final $t \rightarrow \Upsilon + q$ **partial widths & branching ratios** (for $\Gamma_t = 1.35$ GeV):

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

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

Experimental observation of $t \rightarrow B_{(s)}^0 + q$?

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

\sqrt{s}	$\sigma_{\text{NNLO+NNLL}}^{t\bar{t}, \text{incl.}} \text{ (top++)}$
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 $\times 35 \sigma$ and $\times 7 \mathcal{L}$)

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

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

Run **MadGraph@NLO**
(**NNPDF3.0**) for
 $pp \rightarrow t\bar{t} \rightarrow 6j, \ell + j$ at LHC/FCC

- Typical acceptance \times efficiency for $t\bar{t}$ multi-jets & lepton+jets final states: $\sim 20\%$

- At least 4 jets (reconstructed with the anti- k_T algorithm $R = 0.5$) with $p_T > 25 \text{ GeV}$ 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, $H_T > 350 \text{ GeV}$;
- At least 1 b jet tagged with a typical 75% efficiency;
- One isolated (cone radius $R_{\text{isol}} = 0.3$) charged lepton ℓ with $p_T > 30 \text{ GeV}$ 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 $p_T > 25 \text{ GeV}$ 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 $\mathcal{B} \times \text{acceptance} \times \text{efficiency losses}$	
	fully hadronic	$\ell + \text{jets}$
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 $t \rightarrow B_{(s)}^0 + q$?

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

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

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 $\times 35 \sigma$ and $\times 7 \mathcal{L}$)

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

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

Run **MadGraph@NLO**
(**NNPDF3.0**) for
 $pp \rightarrow t\bar{t} \text{bar} \rightarrow 6j, \ell + j$ at LHC/FCC

- Typical acceptance \times efficiency for $t\bar{t}$ multi-jets & lepton+jets final states: $\sim 20\%$

- At least 4 jets (reconstructed with the anti- k_T algorithm $R = 0.5$) with $p_T > 25 \text{ GeV}$ 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, $\sum E_T > 350 \text{ GeV}$;
- At least 1 b jet tagged with a typical 75% efficiency;
- One isolated (cone radius $R_{\text{isol}} = 0.3$) charged lepton ℓ with $p_T > 30 \text{ GeV}$ 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 $p_T > 25 \text{ GeV}$ 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: $N_{t \rightarrow \bar{B}_{(s)}^0 + \text{jet}}^{t\bar{t} \text{ full had.}} \approx 1.5 \cdot 10^5$

FCC: $N_{t \rightarrow \bar{B}_{(s)}^0 + \text{jet}}^{t\bar{t} \text{ full had.}} \approx 4 \cdot 10^7$

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

FCC: $N_{t \rightarrow \bar{B}_{(s)}^0 + \text{jet}}^{t\bar{t} \ell + \text{jet}} \approx 1.6 \cdot 10^7$

Search for $t \rightarrow B_{(s)}^0 + \text{jet}$ via $B_{(s)}^0 \rightarrow J/\psi + hh$ final states

- 6 exclusive $B_{(s)}^0 \rightarrow J/\psi + hh$ decay channels with total branching ratios $10^{-5} - 10^{-4}$:

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

- Acceptances determined via **PYTHIA8** simulations for all 6 final states in $t\bar{t} \rightarrow B_{(s)}^0 + X \rightarrow J/\psi + hh + X$ events in pp at $\sqrt{s} = 14, 100$ TeV. Reco effic. assumed at ~ 0.5 .

Top pair final state	$\overline{B}_{(s)}^0$ meson decay mode	Events after all selection cuts	
		LHC (3 ab ⁻¹)	FCC (20 ab ⁻¹)
$t\bar{t} \rightarrow \overline{B}^0 + u, c$			
o fully hadronic	$\overline{B}^0 \rightarrow J/\psi(\mu^+\mu^-) K^+\pi^-$	3.1	1050
o ℓ + jets		1.4	380
o fully hadronic	$\overline{B}^0 \rightarrow J/\psi(\mu^+\mu^-) K^{*0}(K^\pm\pi^\mp)$	2.7	940
o ℓ + jets		1.2	340
o fully hadronic	$\overline{B}^0 \rightarrow J/\psi(\mu^+\mu^-) K_s^0(\pi^+\pi^-)$	1.3	470
o ℓ + jets		0.6	170
Sum of all channels		10.2	3 300
$t\bar{t} \rightarrow \overline{B}_s^0 + c, u$			
o fully hadronic	$\overline{B}_s^0 \rightarrow J/\psi(\mu^+\mu^+) K^+K^-$	2.1	710
o ℓ + jets		0.9	250
o fully hadronic	$\overline{B}_s^0 \rightarrow J/\psi(\mu^+\mu^+) \phi(K^+K^-)$	1.4	460
o ℓ + jets		0.6	170
o fully hadronic	$\overline{B}_s^0 \rightarrow J/\psi(\mu^+\mu^+) \pi^+\pi^-$	0.6	200
o 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 $t \rightarrow B_{(s)}^0 + \text{jet}$ via $B_{(s)}^0 \rightarrow D+h(h)$ final states

- 6 exclusive $B_{(s)}^0 \rightarrow D+h(h)$ decay channels with total branching ratios $\sim 10^{-4}$:

$\overline{B}_{(s)}^0$ meson decay mode	Total branching fraction (product of individual \mathcal{B} 's)	Acceptance	
		LHC	FCC
$\overline{B}^0 \rightarrow D^+(K^-\pi^+\pi^+)\pi^-$	$2.52 \cdot 10^{-3} \times 0.094 \approx 2.37 \cdot 10^{-4}$	55%	65%
$\overline{B}^0 \rightarrow \overline{D}^{*,+}(D^0(K^-\pi^+)\pi^+)\pi^-$	$2.74 \cdot 10^{-3} \times 0.677 \times 0.039 \approx 7.2 \cdot 10^{-5}$	55%	65%
$\overline{B}^0 \rightarrow \overline{D}^0(K^-\pi^+)\pi^+\pi^-$	$0.88 \cdot 10^{-3} \times 0.039 \approx 3.43 \cdot 10^{-5}$	75%	80%
$\overline{B}^0 \rightarrow D^+(K^-\pi^+\pi^+)K^-$	$0.186 \cdot 10^{-3} \times 0.094 \approx 1.75 \cdot 10^{-5}$	55%	65%
$\overline{B}_s^0 \rightarrow D_s^+(K^-K^+\pi^+)\pi^-$	$3.0 \cdot 10^{-3} \times 0.055 \approx 1.6 \cdot 10^{-4}$	60%	60%
$\overline{B}_s^0 \rightarrow \overline{D}^0(K^-\pi^+)K^-\pi^+$	$1.04 \cdot 10^{-3} \times 0.039 \approx 4 \cdot 10^{-5}$	60%	65%

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

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

- 12 exclusive $B^0_{(s)} \rightarrow J/\phi + hh, D + h(h)$ 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 $t \rightarrow j(\text{bottom}) + j(\text{charm})$? [$t \rightarrow j(\text{bottom}) + j(u\text{-quark})$ swamped by backgd.]**
- Analysis of $t\bar{t}$ 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].**

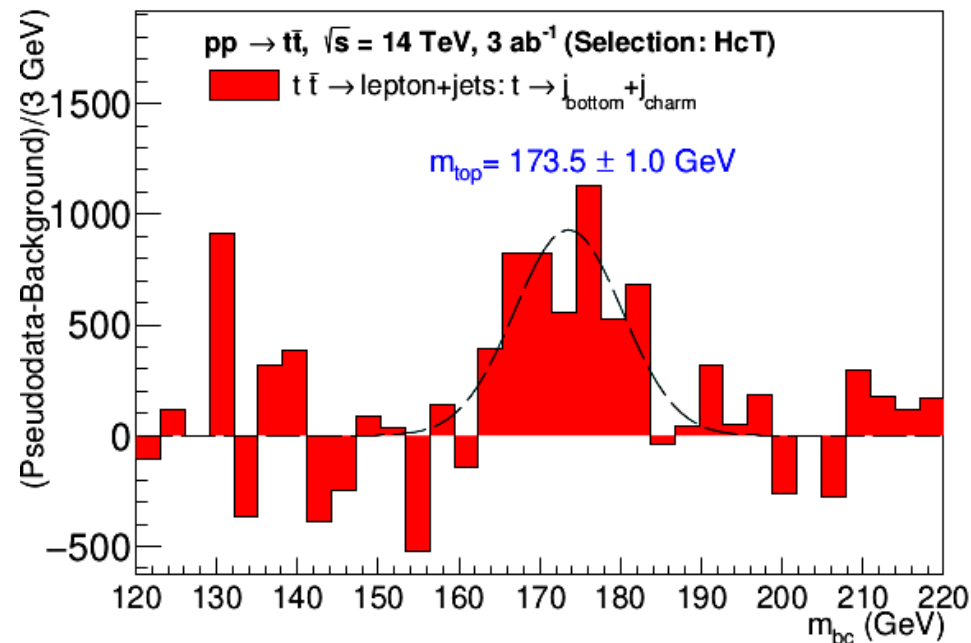
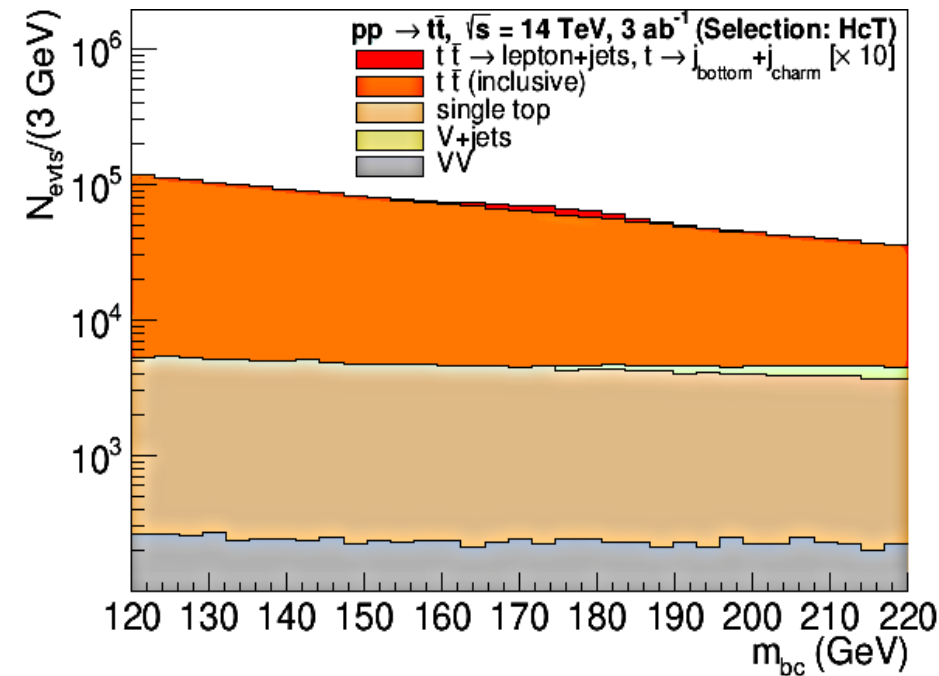
- MadGraph@NLO (NNPDF3.0) + PYTHIA8 PS simulation for all backgrounds:**
 - $pp \rightarrow t\bar{t} \rightarrow 6j, \ell + j$
 - single-t
 - W+jets, Z+jets
 - VV (V=W,Z)
 - QCD multi-jets

process	pp at $\sqrt{s} = 14$ TeV (3 ab^{-1})		pp at $\sqrt{s} = 100$ TeV (20 ab^{-1})	
	'HcT'	'LcT'	'HcT'	'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) $t \rightarrow b+c$ expected at FCC-hh (LHC).

Search for 2-body top decay via $t \rightarrow j_{\text{bottom}} + j_{\text{charm}}$ (LHC)

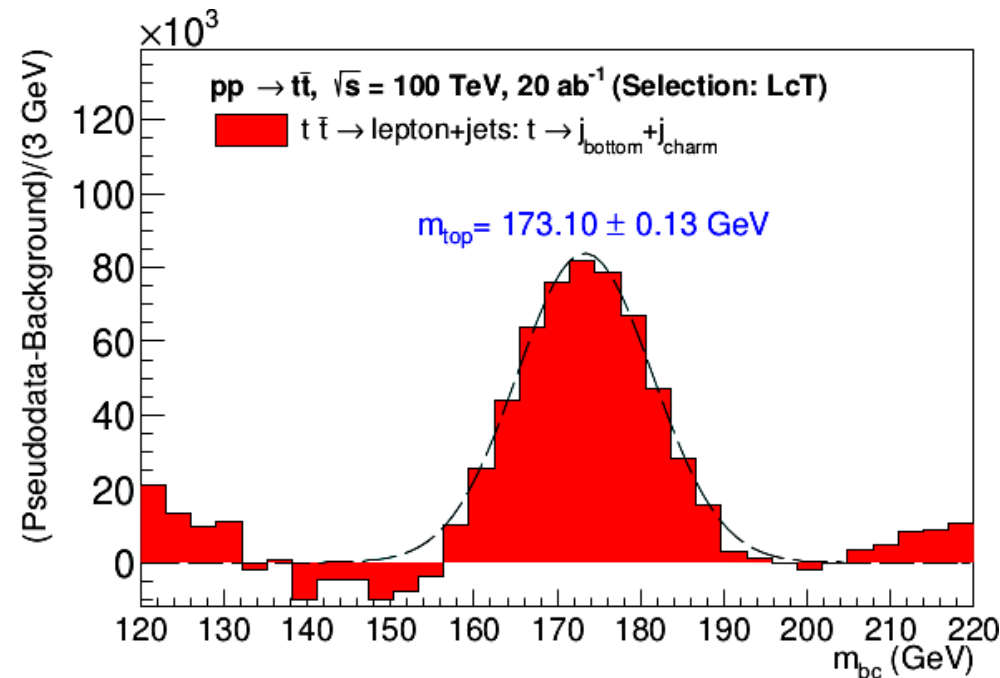
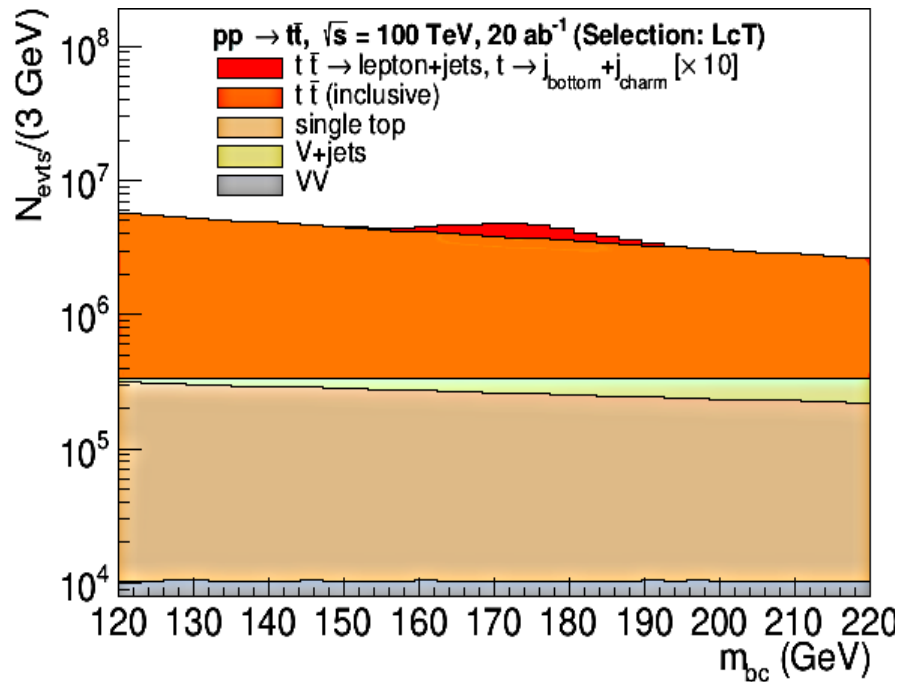
- Expected dijet **signal** $t \rightarrow b+c$ ($m_{jj} \sim 10$ GeV resolution) after cuts injected on top of MadGraph@NLO+ PYTHIA8 simulation for dominant $pp \rightarrow t\bar{t} \rightarrow 6j, \ell+j$ backgds
- Invariant **mass dijet** distribution for best (mis)tagging selection criterion:



- Observation warranted at **HL-LHC** (significance $>6\sigma$) for $t \rightarrow b+c$ signal.

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

- Expected dijet **signal** $t \rightarrow b+c$ ($m_{jj} \sim 10$ GeV resolution) after cuts injected on top of MadGraph@NLO+ PYTHIA8 simulation for dominant $pp \rightarrow t\bar{t} \rightarrow 6j, \ell+j$ backgds
- Invariant **mass dijet** distribution for best (mis)tagging selection criterion:



- Huge $t \rightarrow b+c$ signal (significance $>100\sigma$) over background at the FCC.

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

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

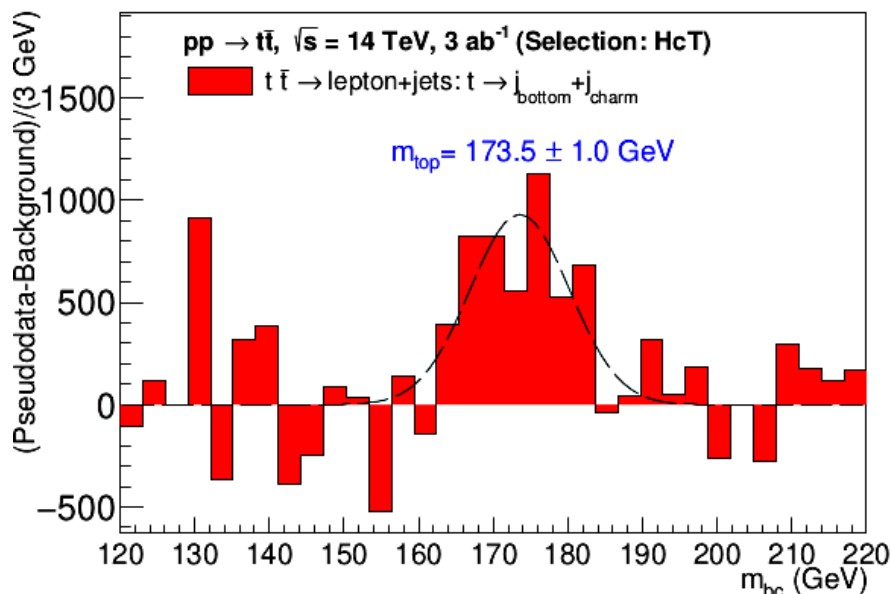
1) $m_{\text{inv}}(B^0 + \text{jet})$ from 12 exclusive $B^0_{(s)} \rightarrow J/\phi + hh, D + h(h)$ final states plus jet:

- ☺ Small systematical uncertainties dominated by single-jet energy scale.
- ☹ Large stat. uncertainties dominated by small data samples (~50, 15000 evts at LHC, FCC)

2) $m_{\text{inv}}(\text{b-jet} + \text{c-jet})$:

- ☺ Small statistical uncertainties (~million evts at FCC).
- ☹ Moderate systematical uncertainties dominated by double-jet energy scale.

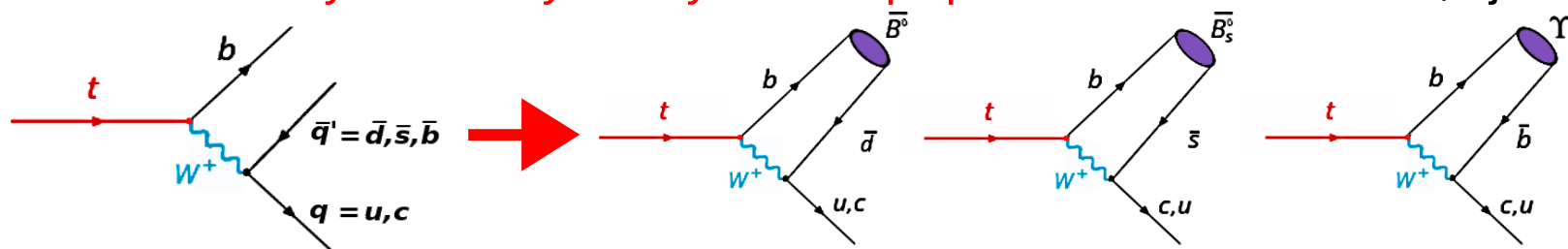
- Simple **Gaussian fit of the backgd-subtracted m_{bc} distribution** at LHC:



- ▶ 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:

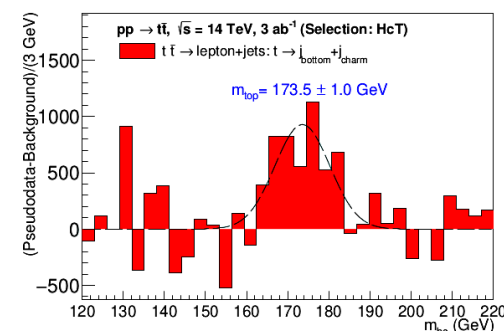
Decay mode	Partial decay width (GeV)	Branching fraction
$t \rightarrow \bar{B}^0 + u$	$5.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$
$t \rightarrow \bar{B}^0 + c$	$2.9 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$
$t \rightarrow \bar{B}_s^0 + c$	$5.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$
$t \rightarrow \bar{B}_s^0 + u$	$2.9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

- Top-quark has small but visible ($\sim 10^{-4}$) probability to decay into $t \rightarrow B^0 + u$, $B_s^0 + c$.
- Top-quark has tiny ($\sim 10^{-9}$) 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}_{int}	Number of produced events expected		Number of 2-body top-quark events after $\mathcal{B} \times \text{acceptance} \times \text{efficiency cuts}$		
	$t\bar{t}$	$t \rightarrow \bar{B}_{(s)}^0 + \text{jet}$	$\bar{B}_{(s)}^0 \rightarrow J/\psi hh$	$\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{0,\pm} h(h)$	$t \rightarrow b + c$
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

$t \rightarrow j_{\text{bottom}} + j_{\text{charm}}$ background

- Cut-flow numbers for accumulated selection criteria for the dominant $t\bar{t}$ background:

Selection criteria	pp at $\sqrt{s} = 14$ TeV (3 ab^{-1})		pp at $\sqrt{s} = 100$ TeV (20 ab^{-1})	
	'HcT'	'LcT'	'HcT'	'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) + $120 \leq m_{b,c} \leq 220 \text{ GeV}$	$5.3 \cdot 10^7$	$2.6 \cdot 10^7$	$1.3 \cdot 10^{10}$	$7.3 \cdot 10^9$

Table 10. Total number of events expected for $t\bar{t} \rightarrow N_j + \ell^\pm + X$ 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.