m_{top} from (energy peaks in the) B-hadrons decay length

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INFN Roma3

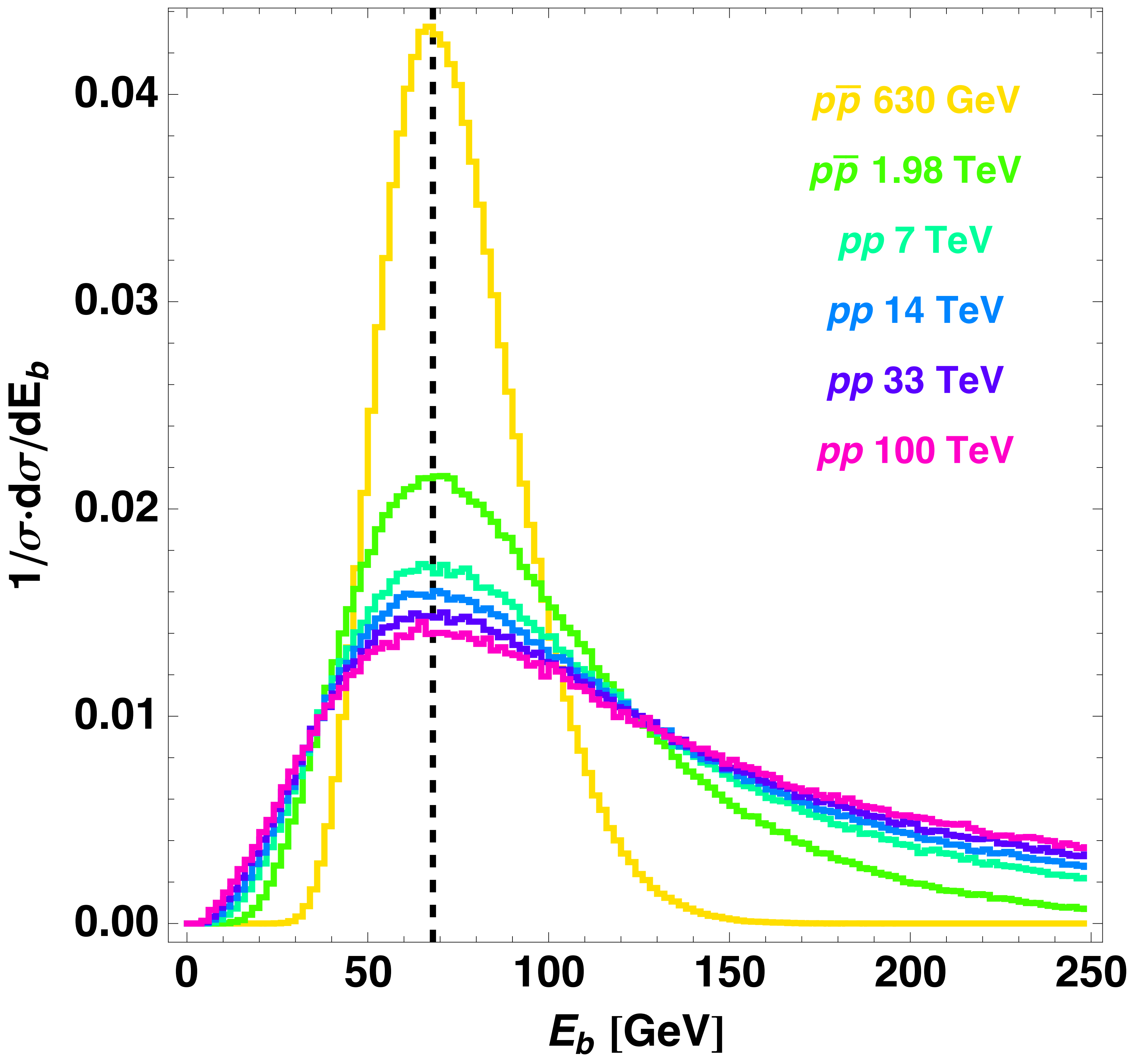
2204.02928 + WIP with S. Airen, K. Agashe, J. Incandela, D. Kim, D. Sathyan

A bit of history

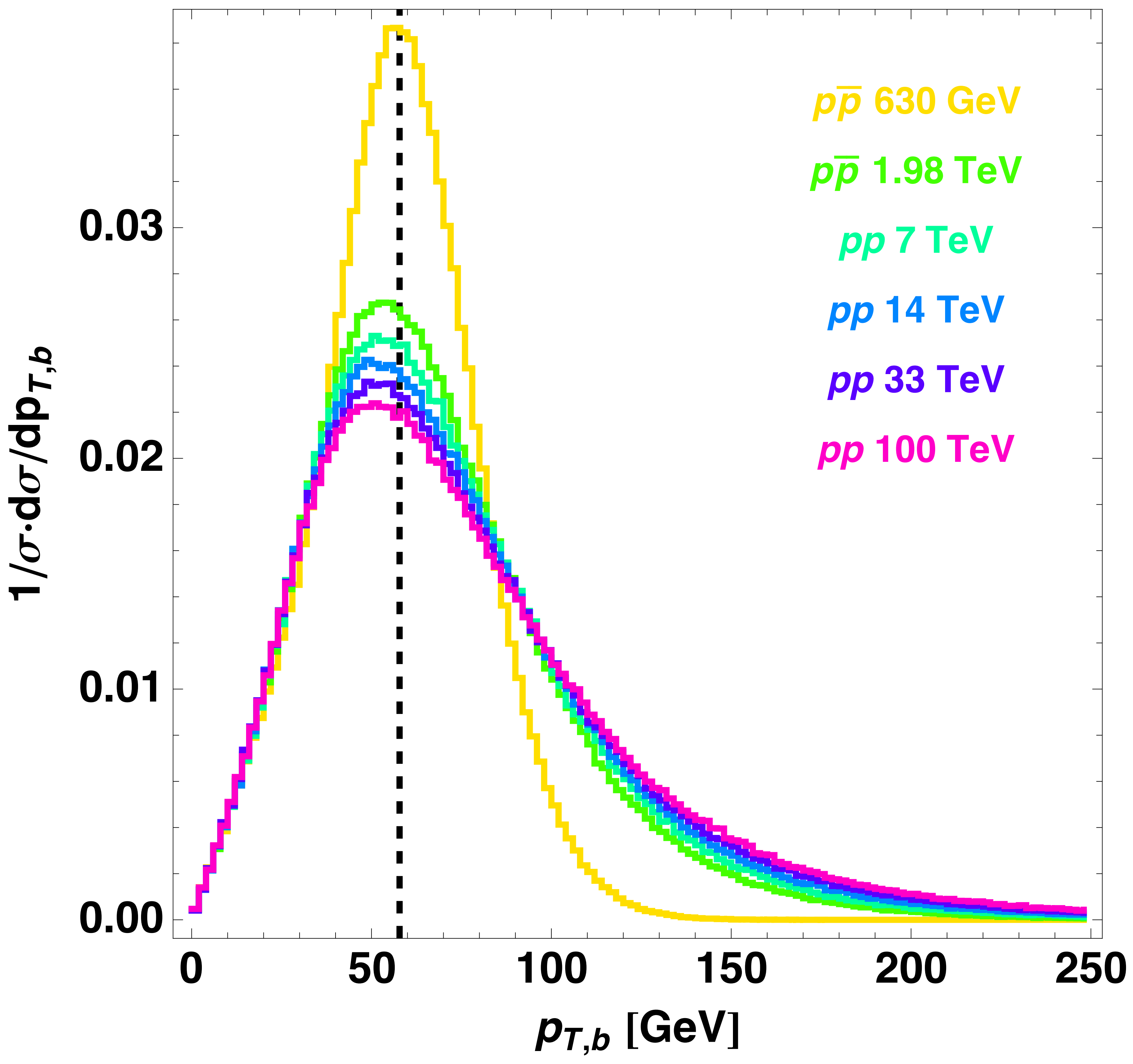
CIRCA 2012

How special is this invariance?

Shape changes, peak doesn't!



Shape changes, peak does too



The sensitivity to the **boost distribution** is the key

How special is this invariance?

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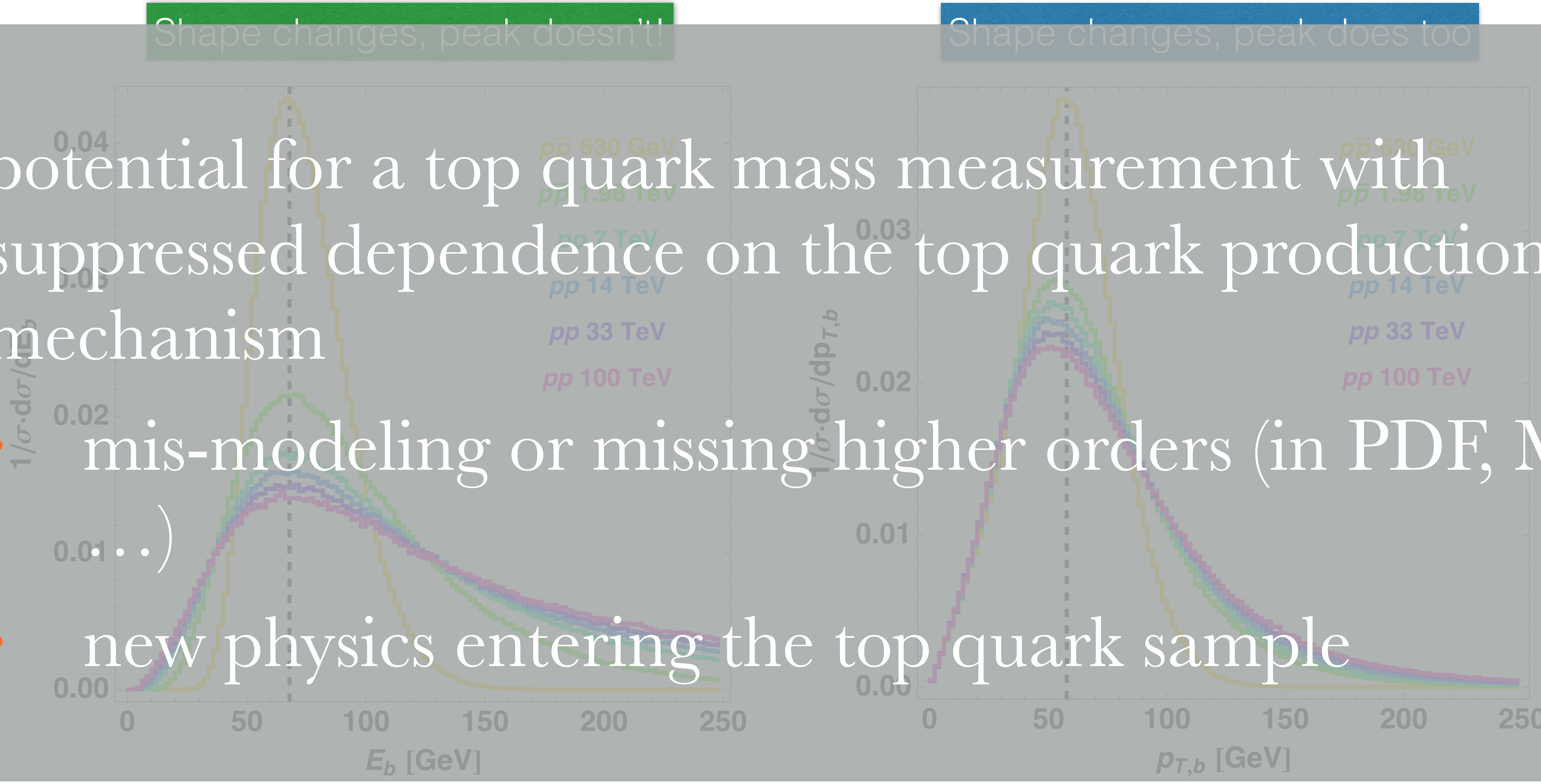
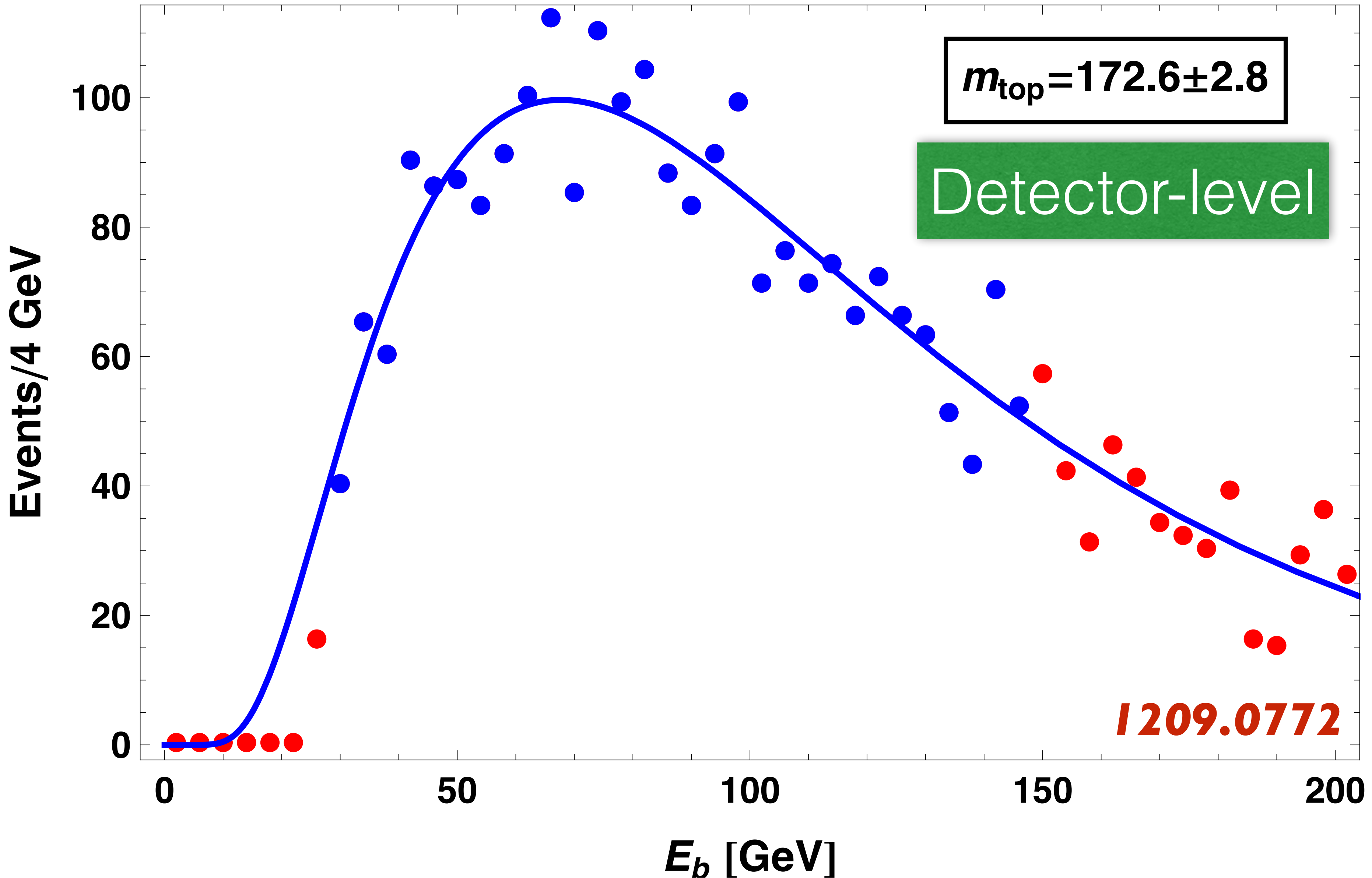


- potential for a top quark mass measurement with suppressed dependence on the top quark production mechanism
  - mis-modeling or missing higher orders (in PDF, ME, …)
  - new physics entering the top quark sample

The sensitivity to the **boost distribution** is the key

b-**jet** energy (LO+PS)

100 pseudo-experiments from MadGraph5+Pythia6.4+Delphes (**ATLAS-2012-097**)



2-parameters fit: peak position, width of the distribution

Proof of the concept: ***5/fb LHC 7 TeV***

m_{top}=173.1 ± 2.5 GeV (stat)

1209.0772 - Agashe Franceschini and Kim

message: LO effects are well under control

→ CMS at work!

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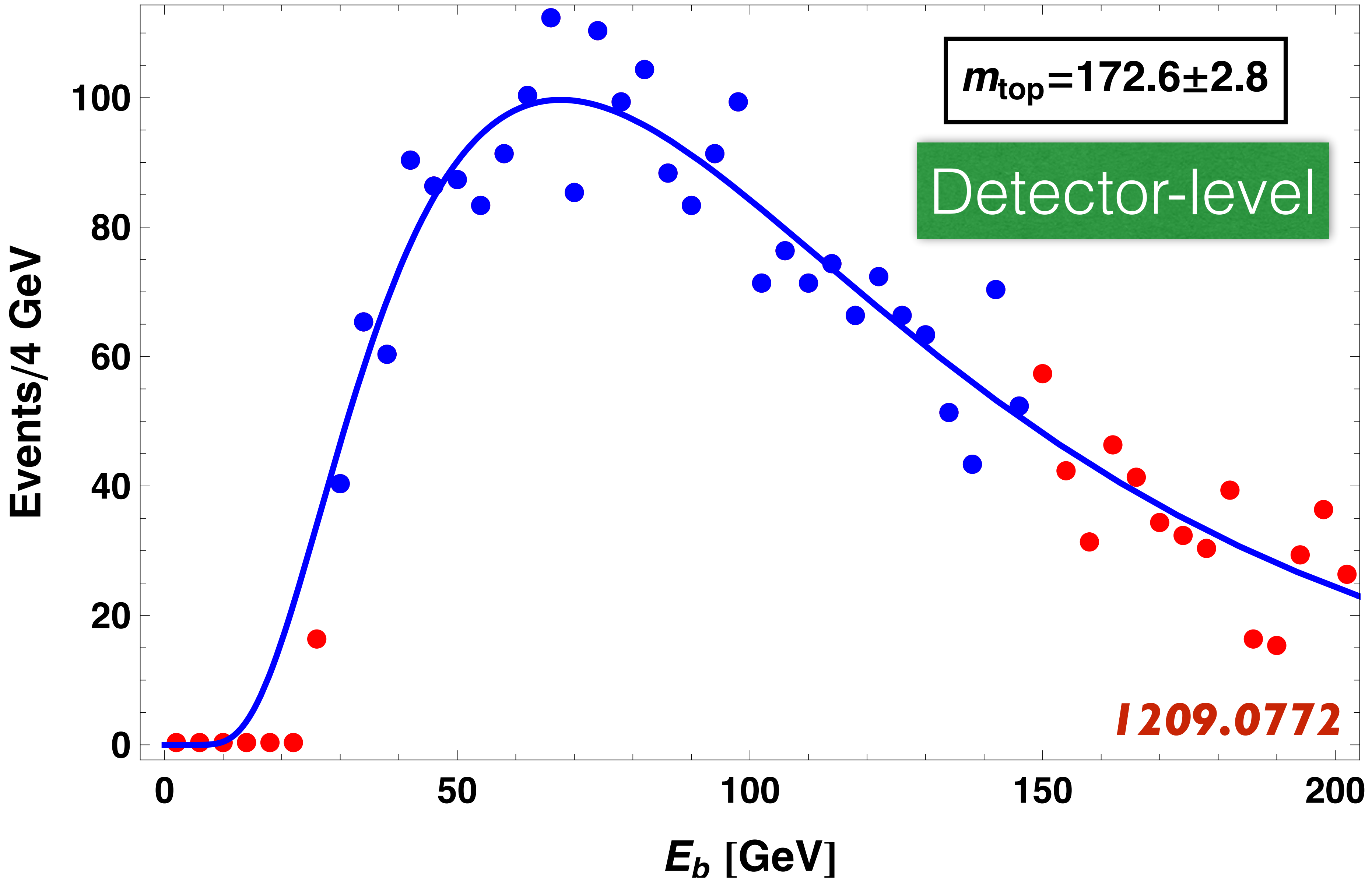

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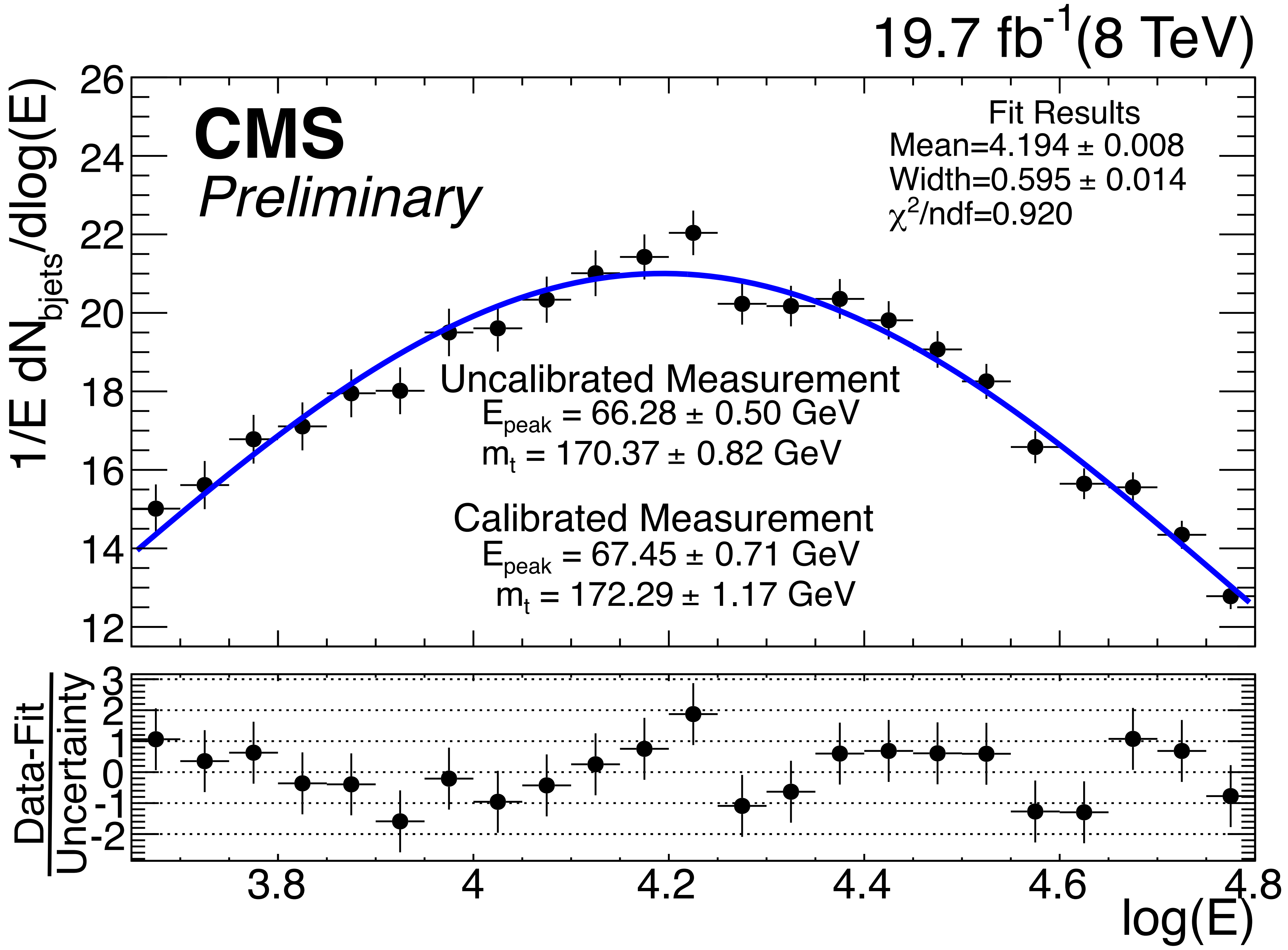
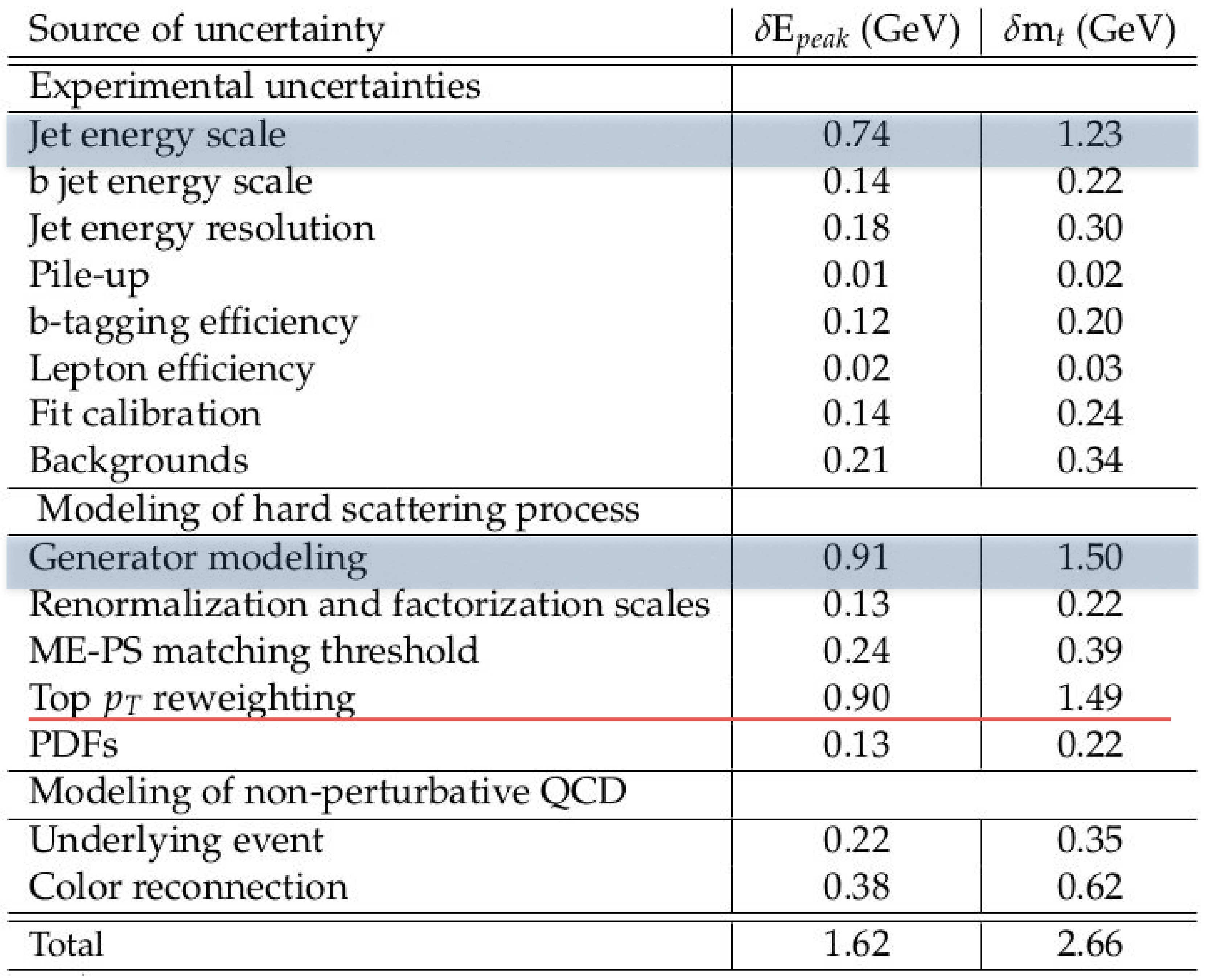
CIRCA 2015

CMS PAS TOP-15-002

$m_t = 172.29 \pm 1.17$ (stat.) ± 2.66 (syst.) GeV





Source of uncertainty	δE_{peak} (GeV)	δm_t (GeV)
Experimental uncertainties		
Jet energy scale	0.74	1.23
b jet energy scale	0.14	0.22
Jet energy resolution	0.18	0.30
Pile-up	0.01	0.02
b-tagging efficiency	0.12	0.20
Lepton efficiency	0.02	0.03
Fit calibration	0.14	0.24
Backgrounds	0.21	0.34
Modeling of hard scattering process		
Generator modeling	0.91	1.50
Renormalization and factorization scales	0.13	0.22
ME-PS matching threshold	0.24	0.39
Top p_T reweighting	0.90	1.49
PDFs	0.13	0.22
Modeling of non-perturbative QCD		
Underlying event	0.22	0.35
Color reconnection	0.38	0.62
Total	1.62	2.66

leading uncertainty from theory can be reduced

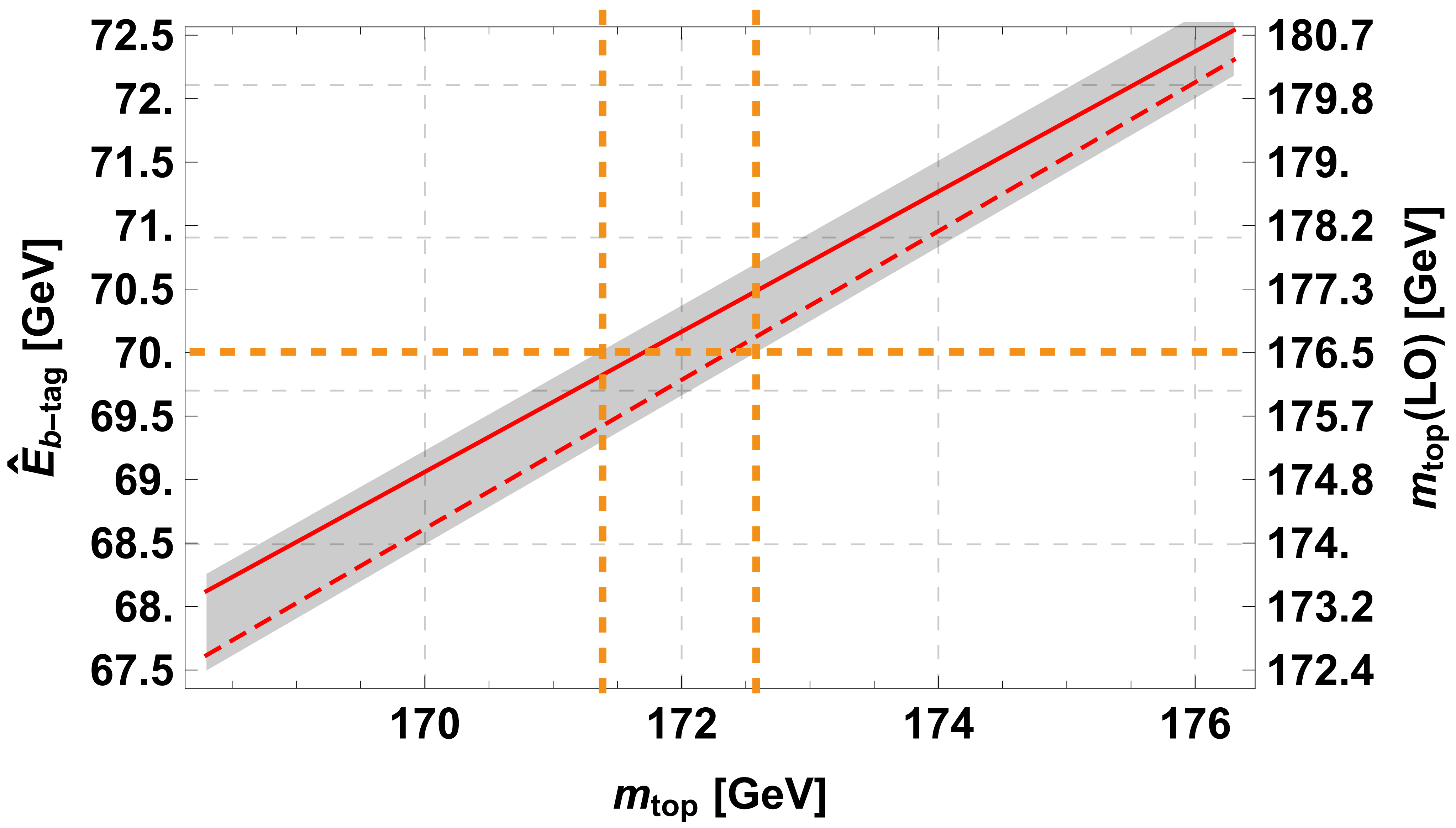
pT(top) reweighting smaller than other methods (Lxy, pTℓ …)

CIRCA 2016

Beyond LO

Agashe, RF, Kim, Schulze - 1603.06536

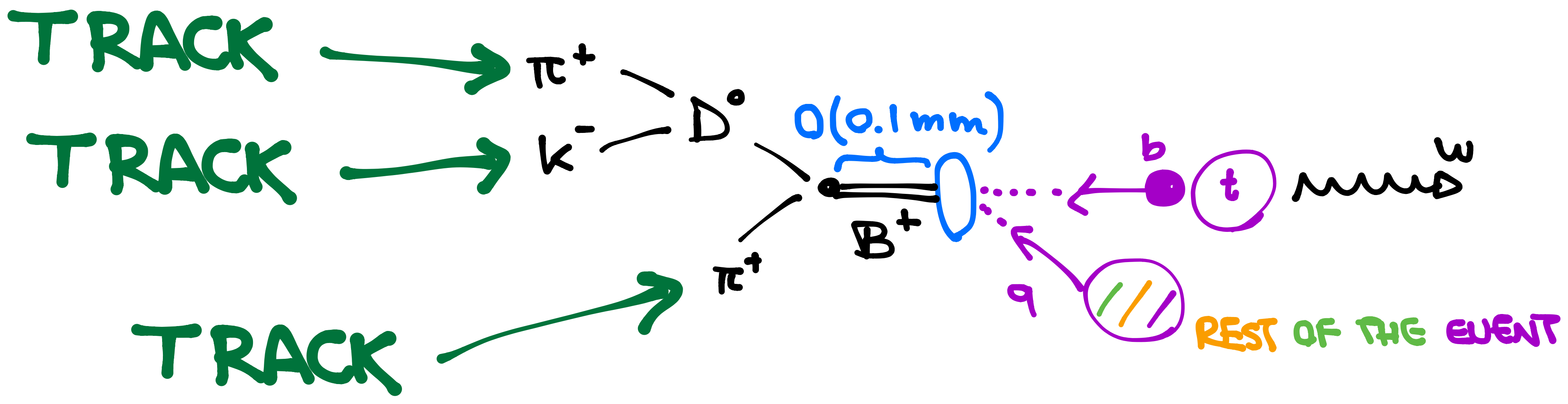
jet level



Δ(th)=±0.6 GeV @NLO

Beyond JES w/ hadrons

Agashe, RF, Kim, Schulze - 1603.06536



$B^+ \to$ 3 TRACKS

CIRCA 2016

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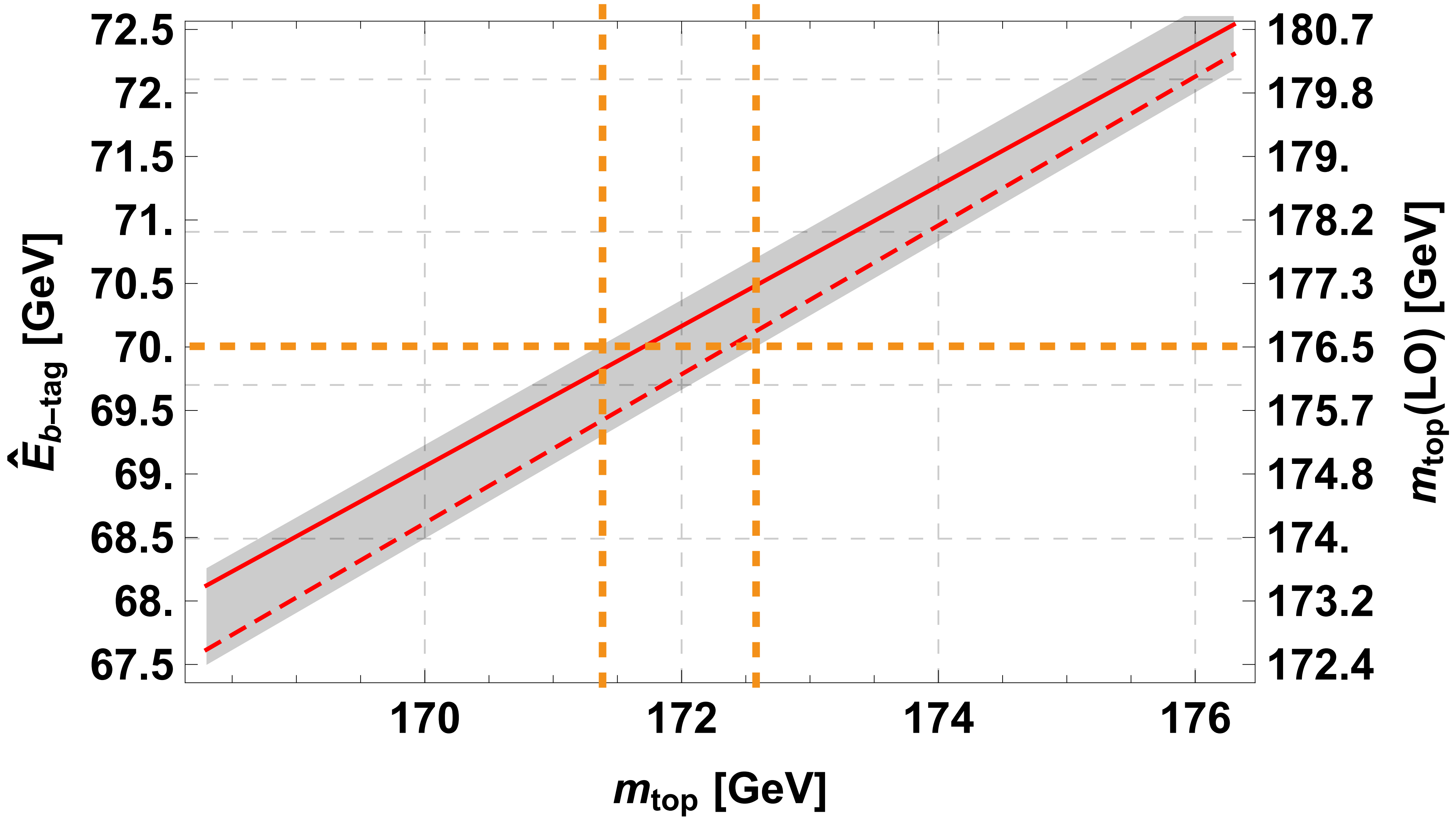

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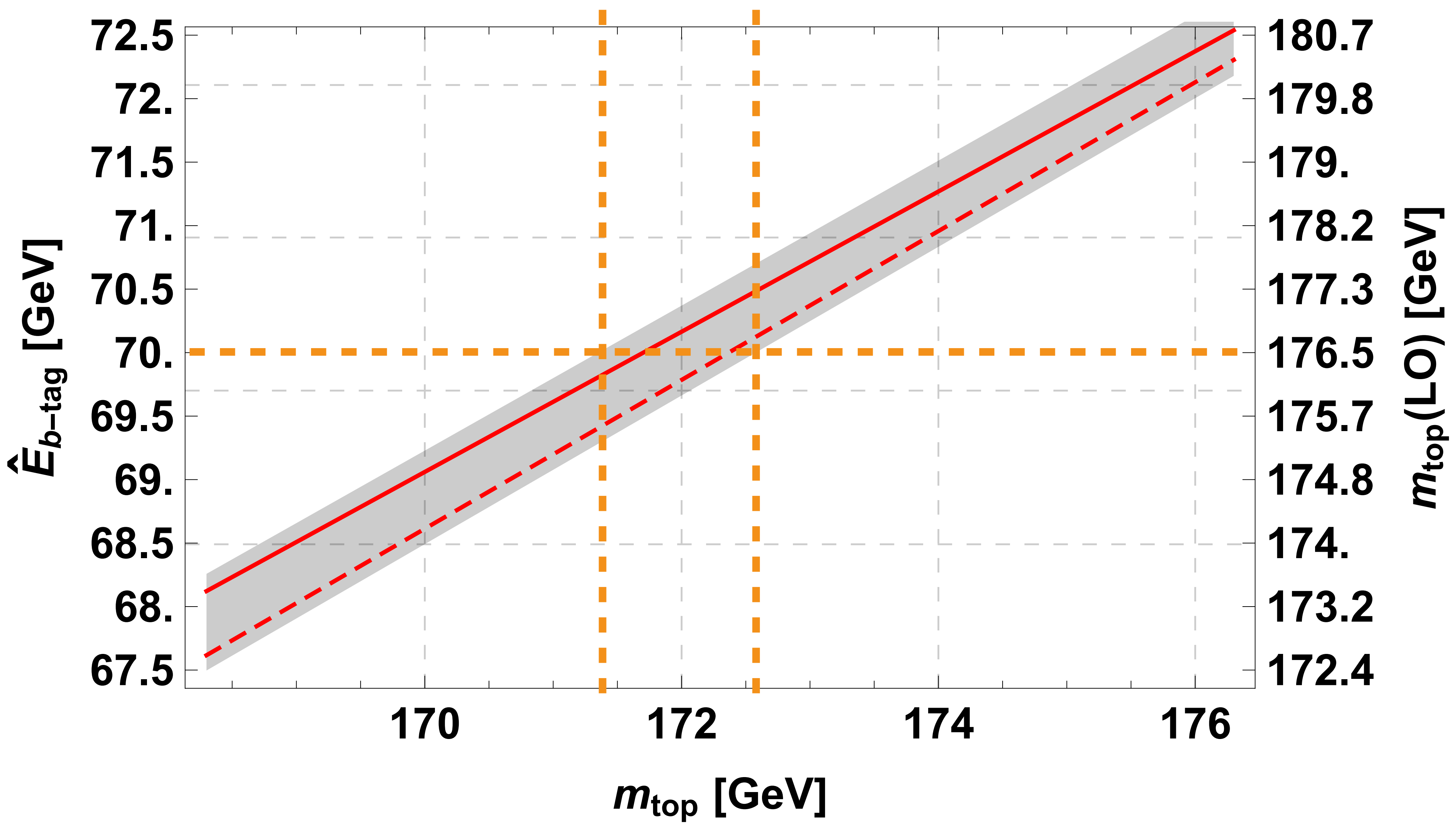

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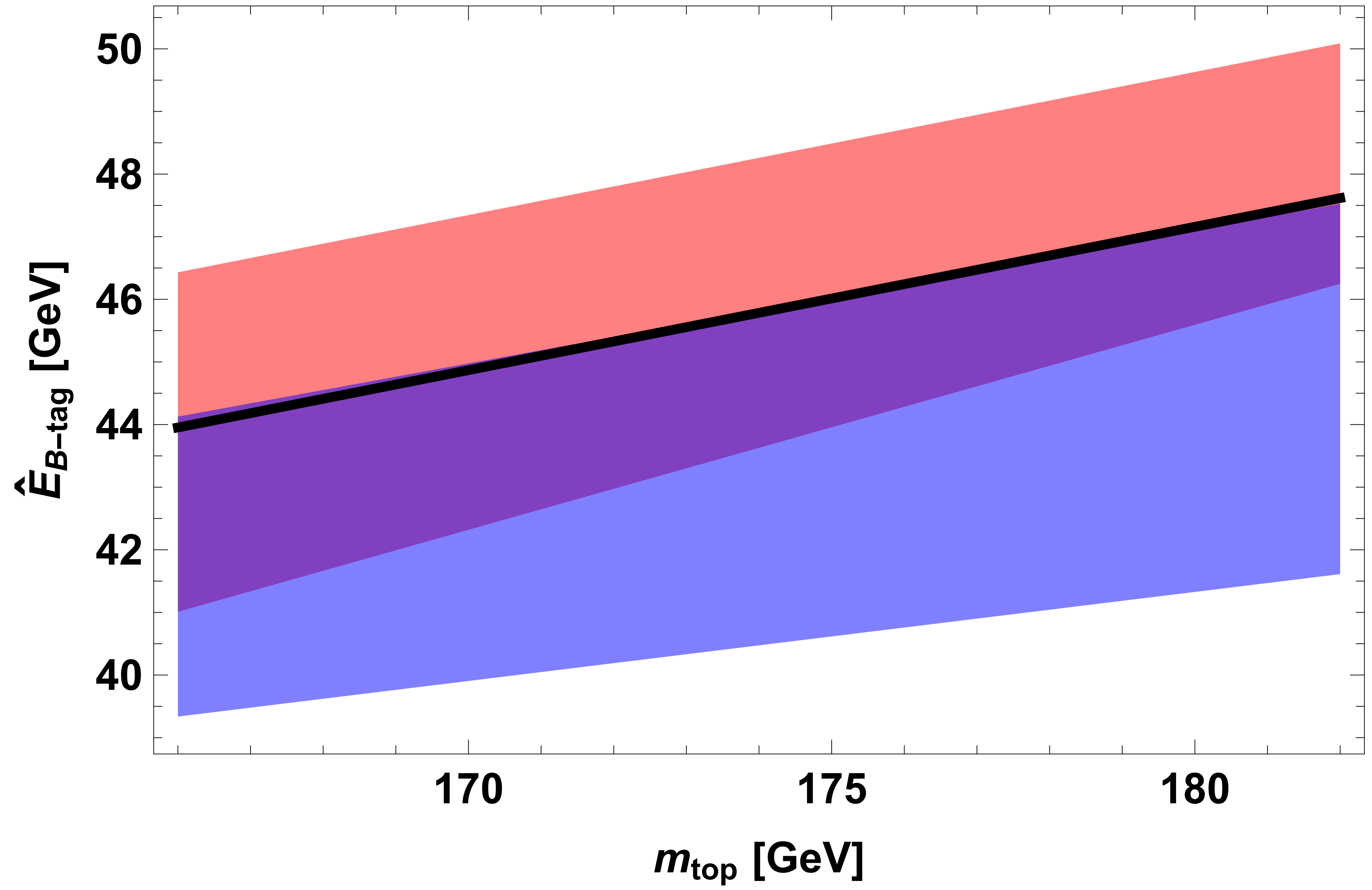

NLO sensitive to the scale choice: ±3.5 GeV on m_{top}

CIRCA 2016

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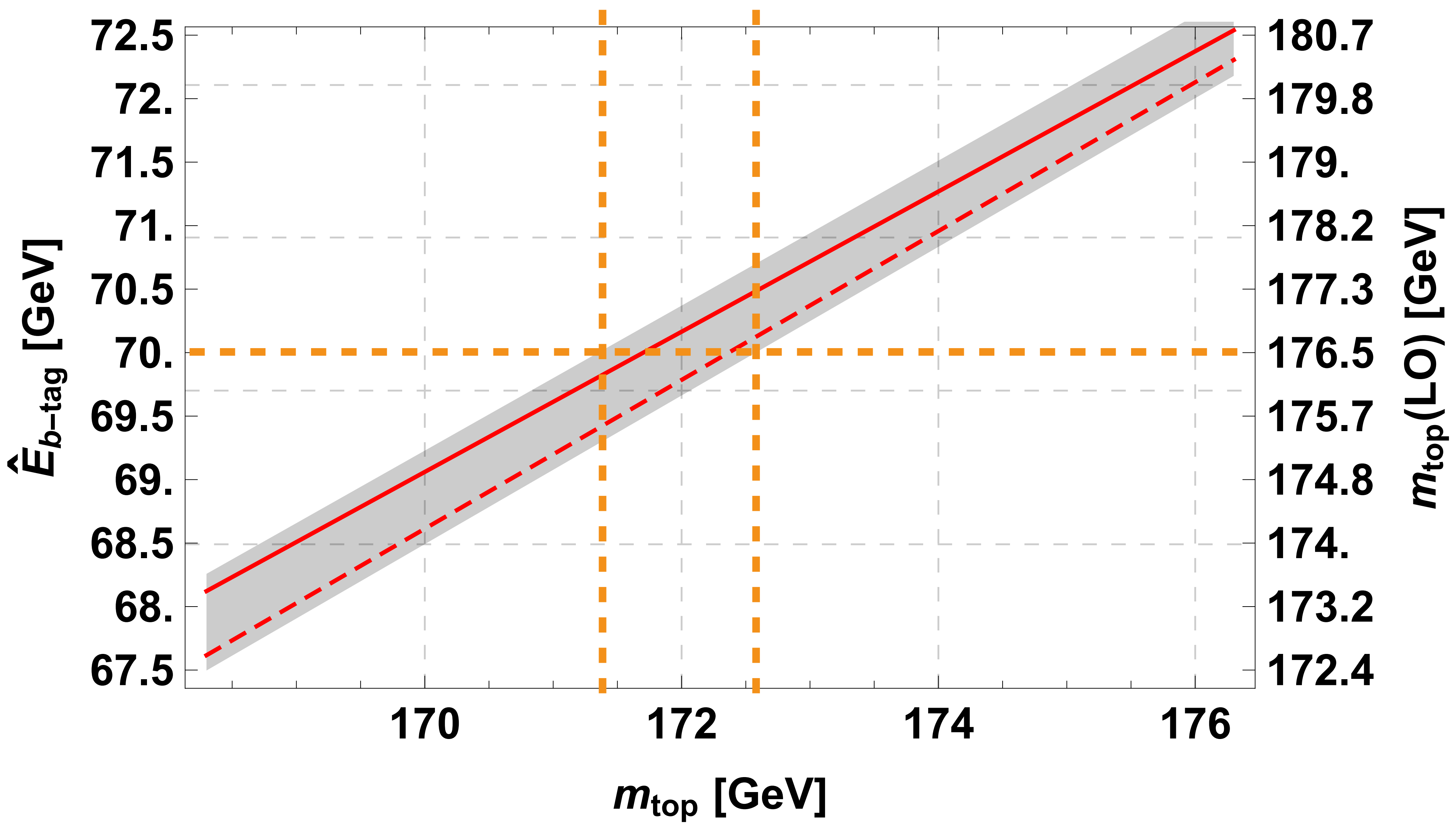
jet level



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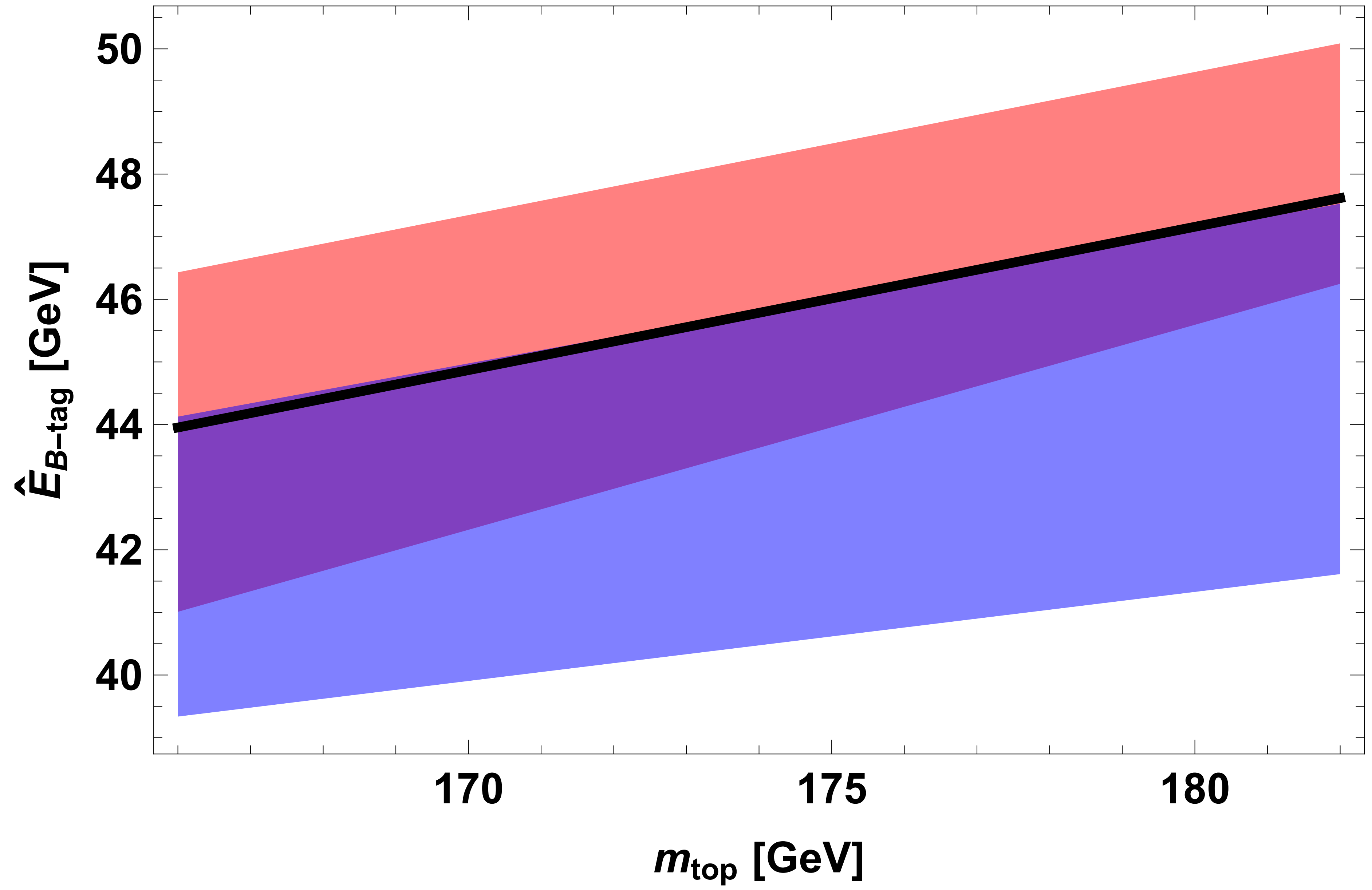

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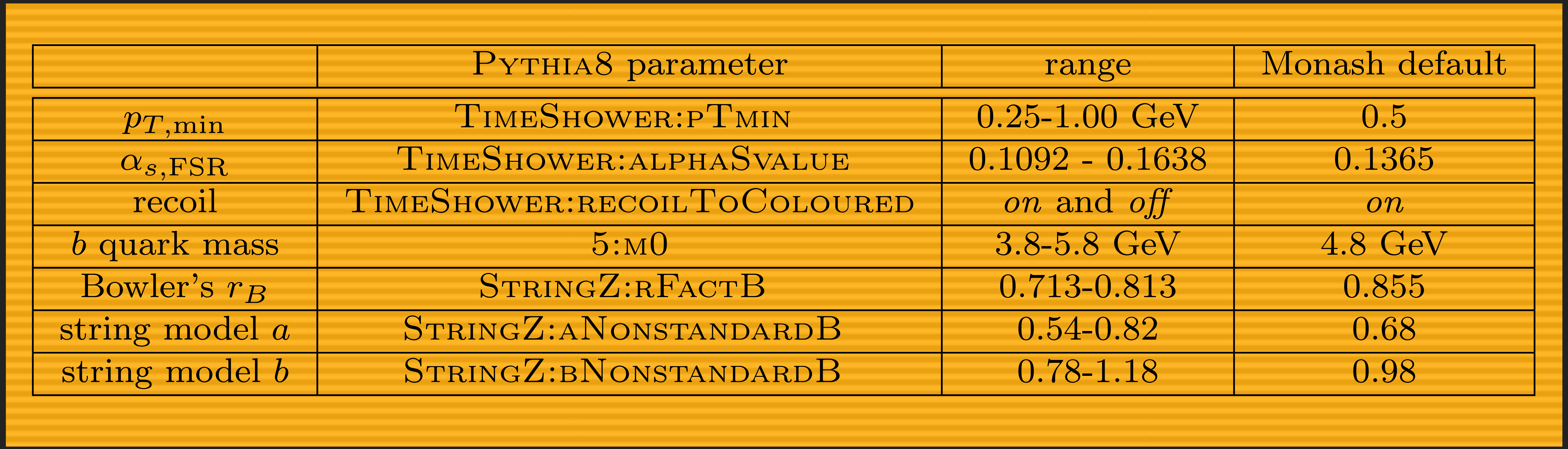
NNLO sensitive to the scale choice: ±3.5/(2?) GeV on m_{top}

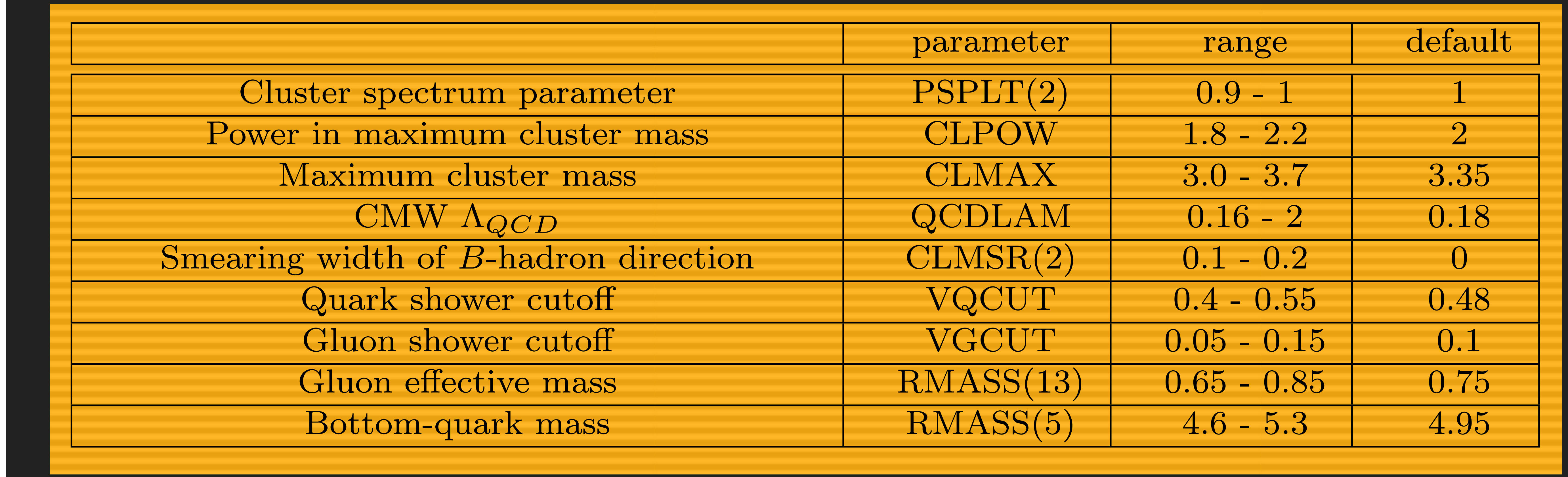
CIRCA 2017

Beyond JES w/ hadrons

Corcella, RF, Kim - 1712.05801



	Pythia8 parameter	range	Monash default
$p_{T,\mathrm{min}}$	TimeShower:pTmin	0.25-1.00 GeV	0.5
$\alpha_{s,\mathrm{FSR}}$	TimeShower:alphaSvalue	0.1092 - 0.1638	0.1365
recoil	TimeShower:recoilToColoured	*on* and *off*	*on*
b quark mass	5:m0	3.8-5.8 GeV	4.8 GeV
Bowler's r_B	StringZ:rFactB	0.713-0.813	0.855
string model a	StringZ:aNonstandardB	0.54-0.82	0.68
string model b	StringZ:bNonstandardB	0.78-1.18	0.98



	parameter	range	default
Cluster spectrum parameter	PSPLT(2)	0.9 - 1	1
Power in maximum cluster mass	CLPOW	1.8 - 2.2	2
Maximum cluster mass	CLMAX	3.0 - 3.7	3.35
CMW Λ_{QCD}	QCDLAM	0.16 - 2	0.18
Smearing width of B-hadron direction	CLMSR(2)	0.1 - 0.2	0
Quark shower cutoff	VQCUT	0.4 - 0.55	0.48
Gluon shower cutoff	VGCUT	0.05 - 0.15	0.1
Gluon effective mass	RMASS(13)	0.65 - 0.85	0.75
Bottom-quark mass	RMASS(5)	4.6 - 5.3	4.95

Beyond JES w/ hadrons

CIRCA 2017

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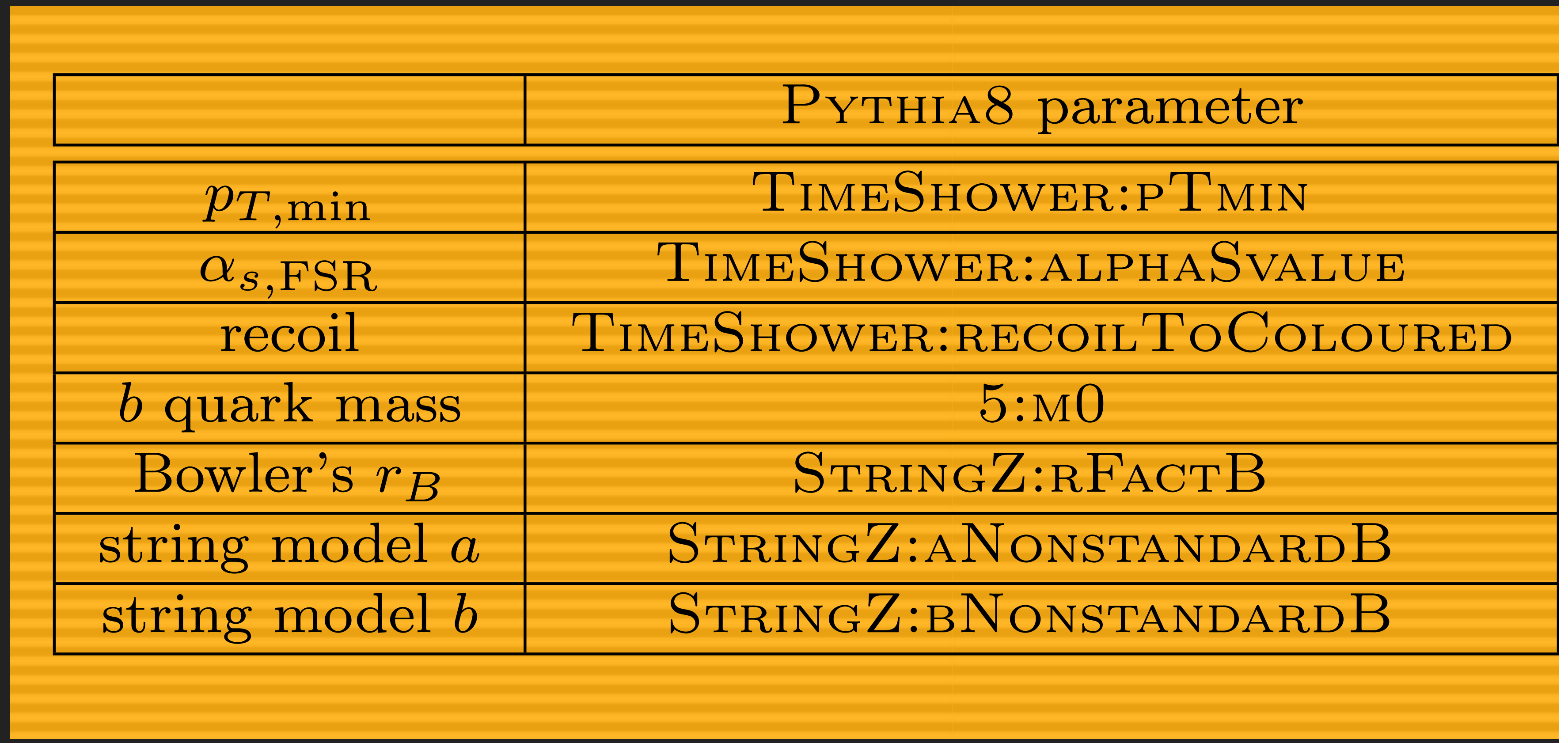
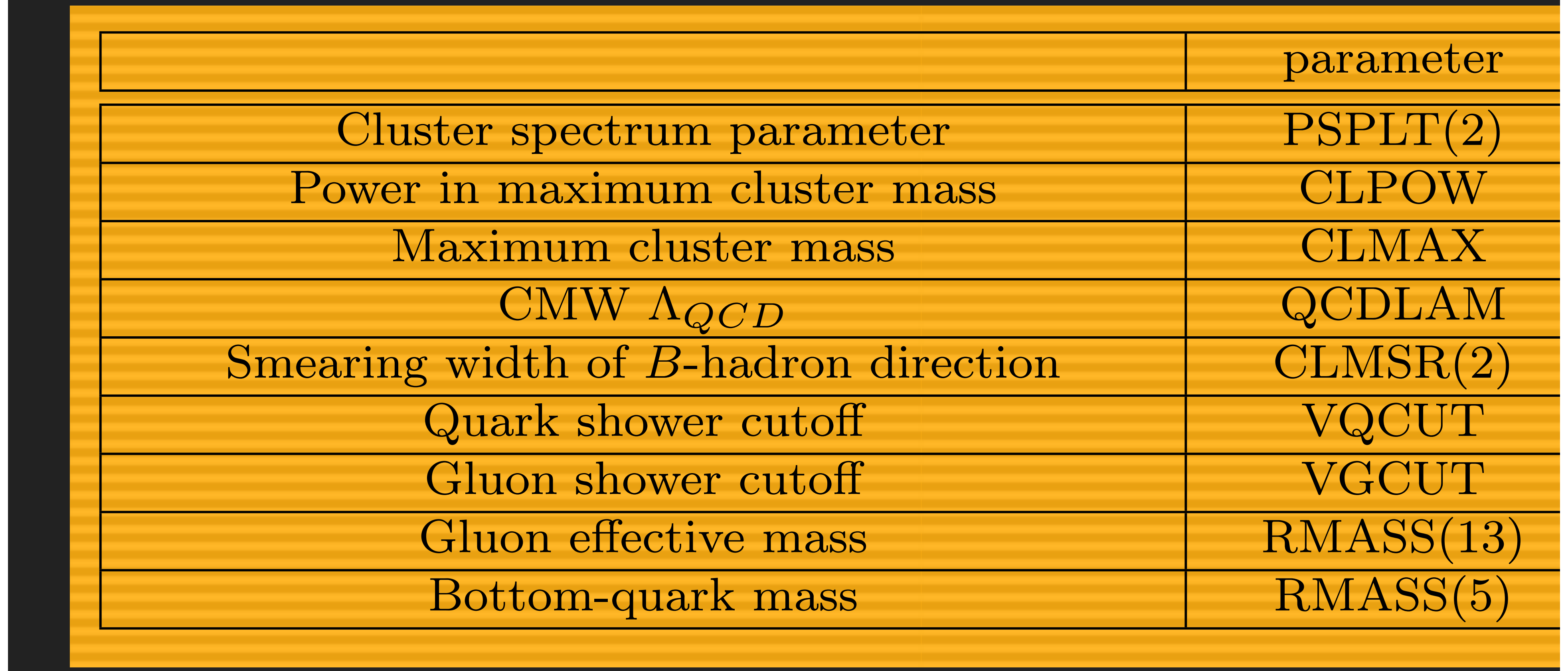


	PYTHIA8 parameter
$p_{T,\min}$	TIMESHOWER:PTMIN
$\alpha_{s,\mathrm{FSR}}$	TIMESHOWER:ALPHASVALUE
recoil	TIMESHOWER:RECOILTOCOLOURED
b quark mass	5:M0
Bowler's r_B	STRINGZ:RFACTB
string model a	STRINGZ:ANONSTANDARDB
string model b	STRINGZ:BNONSTANDARDB



	parameter
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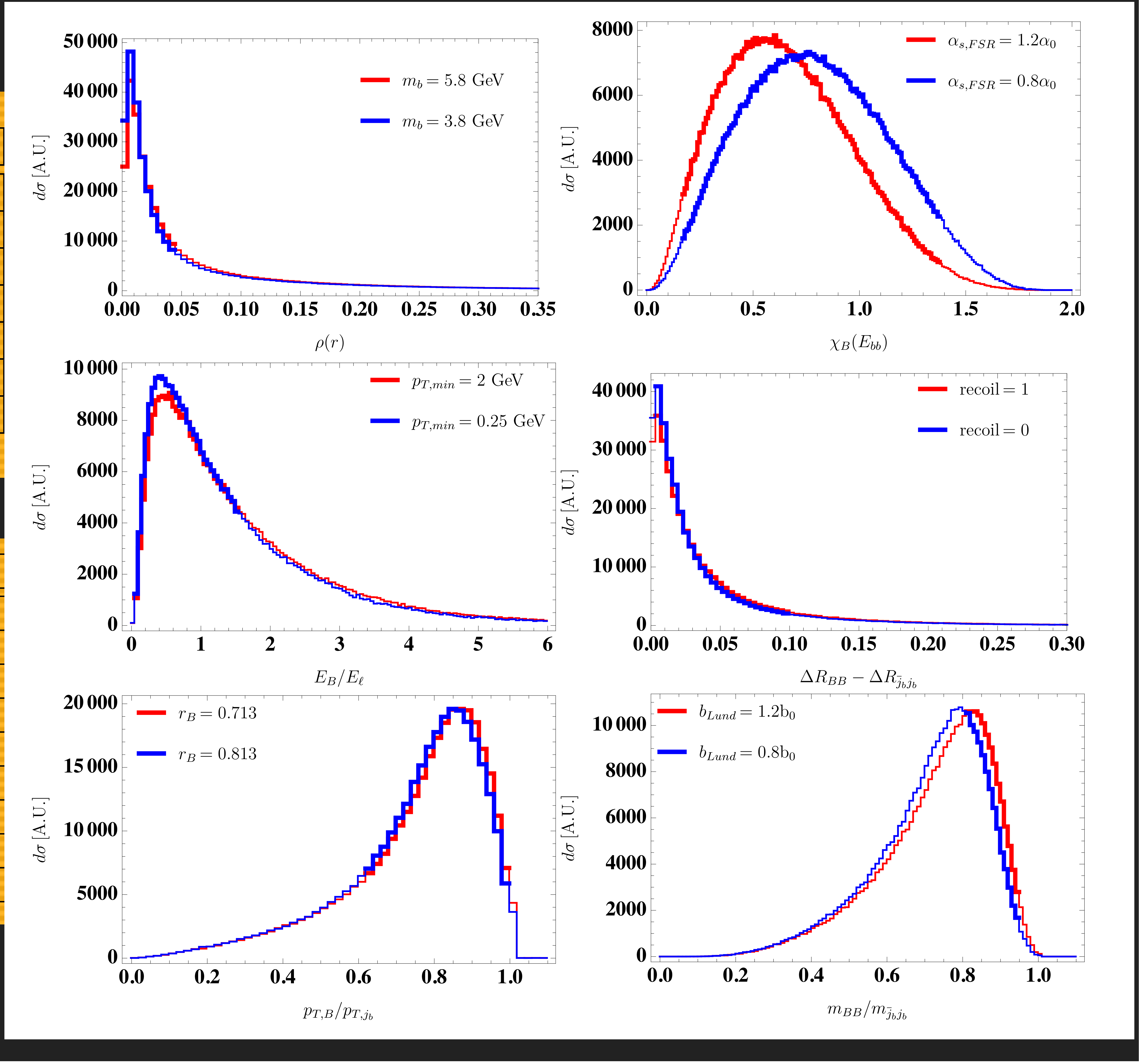

Beyond JES w/ hadrons

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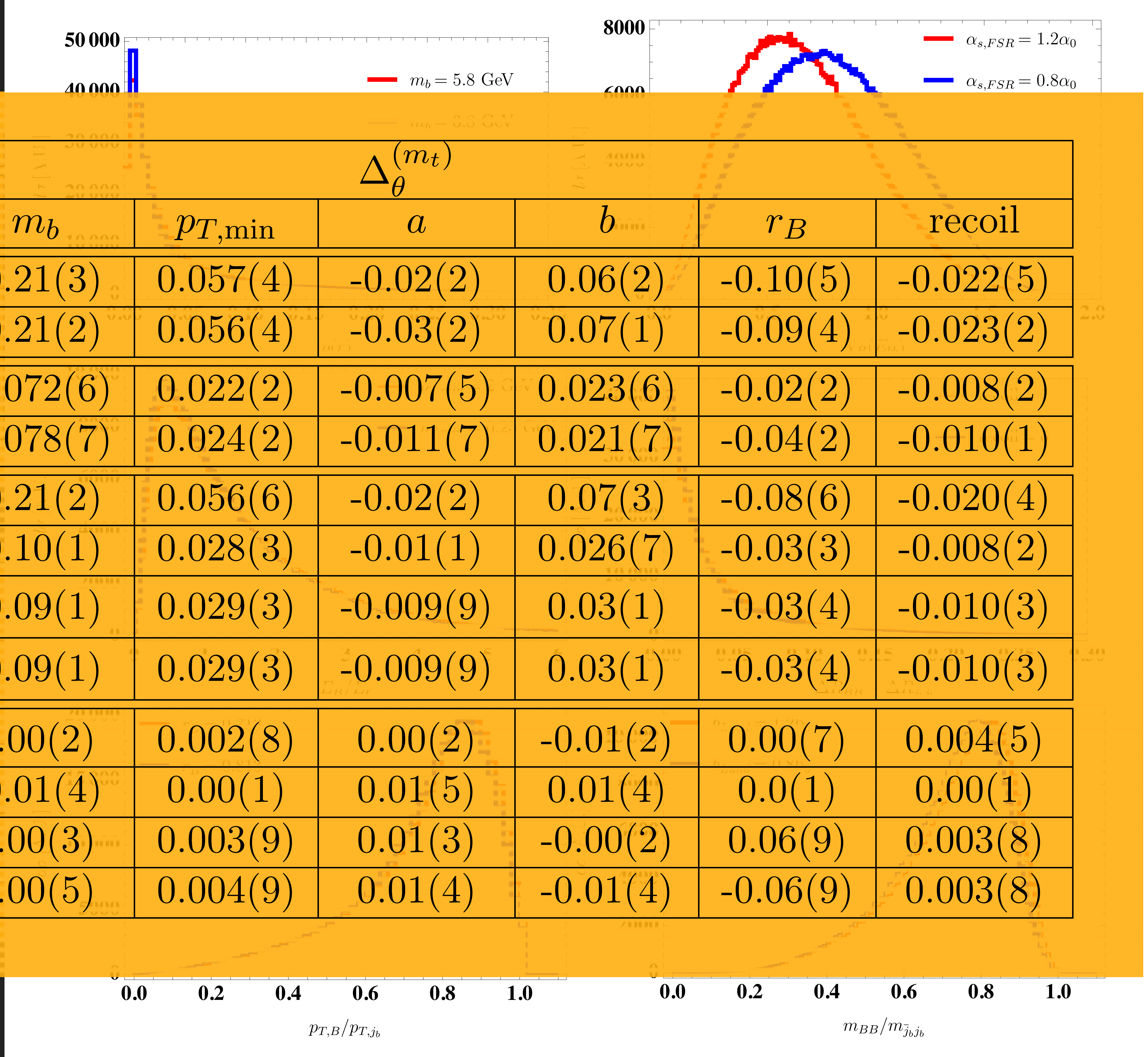

$\mathcal{O}$	Range	$\Delta^{(\mathcal{M}_\mathcal{O})}_{m_t}$	$\Delta^{(m_t)}_\theta$						
			$\alpha_{s,FSR}$	m_b	$p_{T,\min}$	a	b	r_B	recoil
E_B	28-110	0.92(5)	-0.52(2)	-0.21(3)	0.057(4)	-0.02(2)	0.06(2)	-0.10(5)	-0.022(5)
$p_{T,B}$	24-72	0.92(3)	-0.54(2)	-0.21(2)	0.056(4)	-0.03(2)	0.07(1)	-0.09(4)	-0.023(2)
$m_{B\ell,\text{true}}$	47-125	1.30(2)	-0.241(8)	-0.072(6)	0.022(2)	-0.007(5)	0.023(6)	-0.02(2)	-0.008(2)
$m_{B\ell^+,\min}$	30-115	1.16(2)	-0.282(5)	-0.078(7)	0.024(2)	-0.011(7)	0.021(7)	-0.04(2)	-0.010(1)
$E_B + E_B$	83-244	0.92(4)	-0.50(2)	-0.21(2)	0.056(6)	-0.02(2)	0.07(3)	-0.08(6)	-0.020(4)
$m_{BB\ell\ell}$	172-329	0.96(2)	-0.25(1)	-0.10(1)	0.028(3)	-0.01(1)	0.026(7)	-0.03(3)	-0.008(2)
$m^{(\text{mET})}_{T2,B\ell,\text{true}}$	73-148	0.95(3)	-0.27(1)	-0.09(1)	0.029(3)	-0.009(9)	0.03(1)	-0.03(4)	-0.010(3)
$m^{(\text{mET})}_{T2,B\ell,\min}$	73-148	0.95(3)	-0.27(1)	-0.09(1)	0.029(3)	-0.009(9)	0.03(1)	-0.03(4)	-0.010(3)
$m^{(\ell\nu)}_{T2}$	0.5-80	-0.118(7)	-0.03(2)	0.00(2)	0.002(8)	0.00(2)	-0.01(2)	0.00(7)	0.004(5)
$m_{\ell\ell}$	37.5-145	0.40(5)	-0.03(5)	-0.01(4)	0.00(1)	0.01(5)	0.01(4)	0.0(1)	0.00(1)
$E_\ell + E_\ell$	75-230	0.54(5)	-0.03(3)	0.00(3)	0.003(9)	0.01(3)	-0.00(2)	0.06(9)	0.003(8)
E_ℓ	23-100	0.48(4)	-0.02(5)	0.00(5)	0.004(9)	0.01(4)	-0.01(4)	-0.06(9)	0.003(8)

Beyond JES w/ hadrons

Corcella, RF, Kim - 1712.05801

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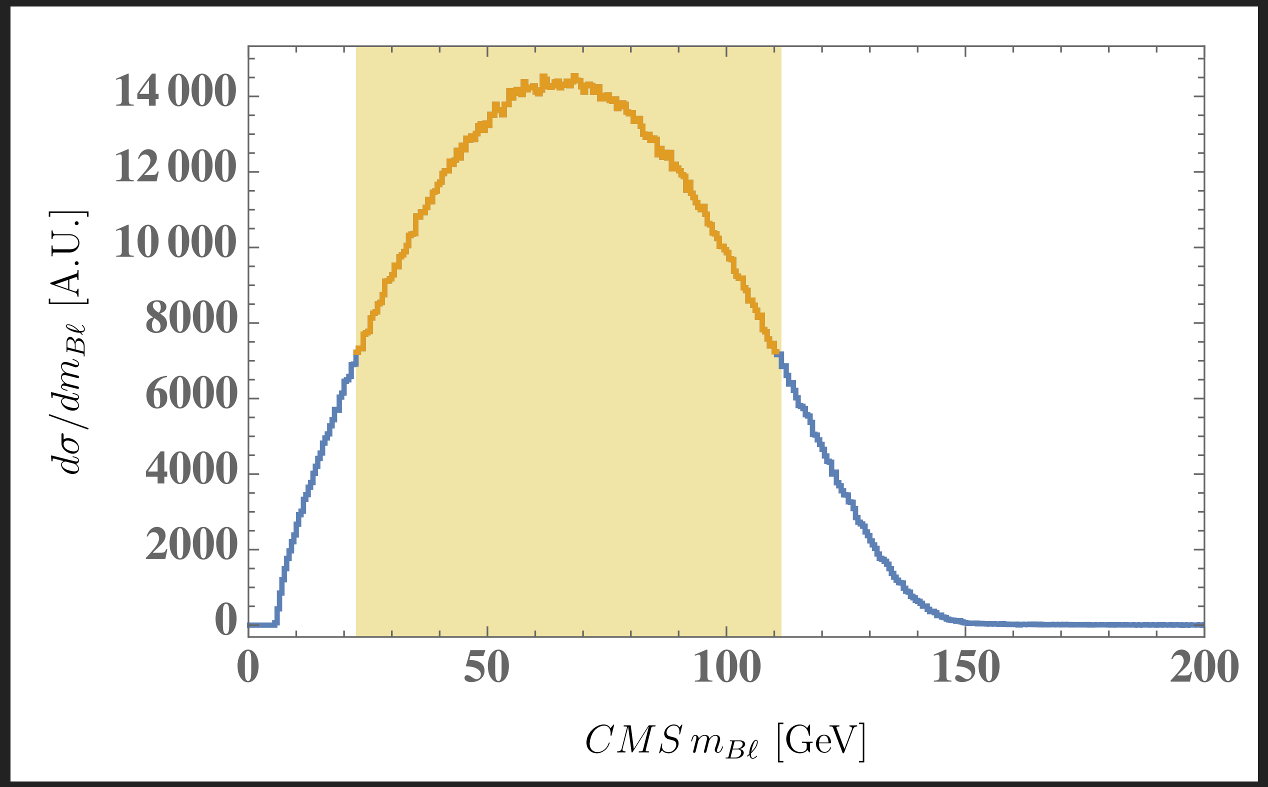
Monte Carlo calibration targets

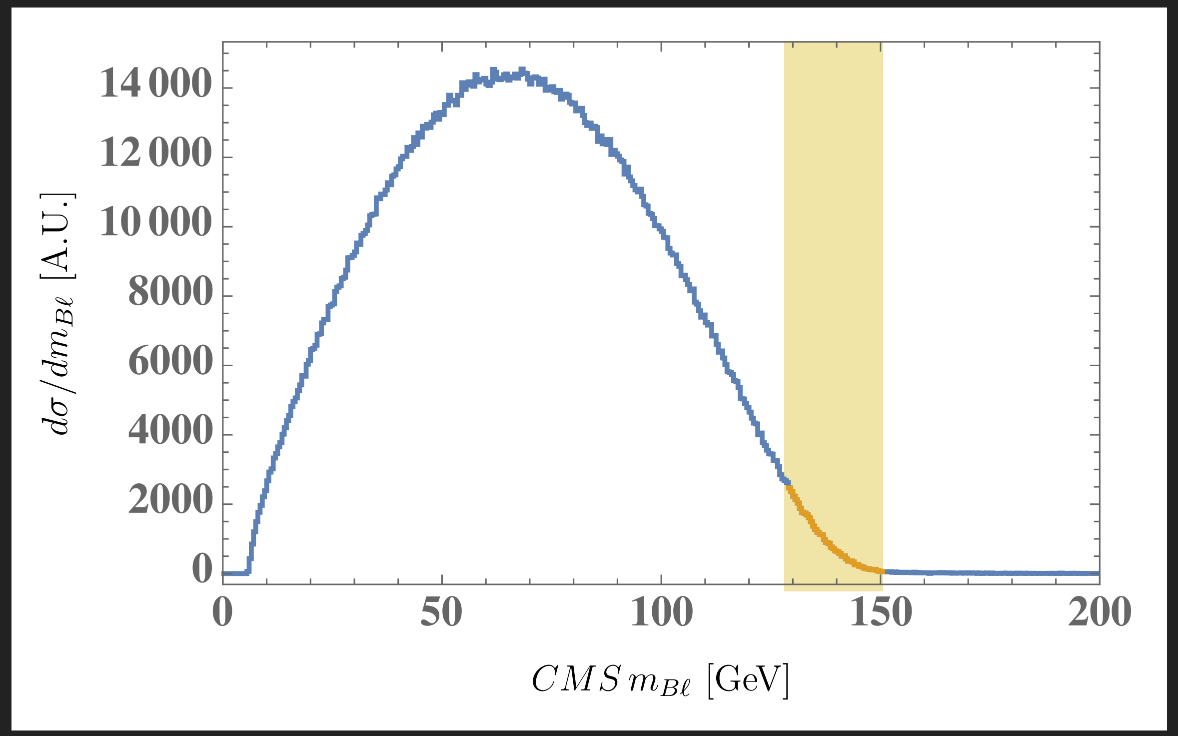


Pythia8

- α_s needed at 1%
- m_b needed at 3%
- all the rest needed at 10%

Herwig6

- $\Lambda_{QCD} \Rightarrow \alpha_s$ needed at 1%
- $m_{b,g}$ needed at 1%
- cluster mass spectrum (PSPLT, CLPOW, CLMAX) needed at 10%
- all the rest needed at "100%"



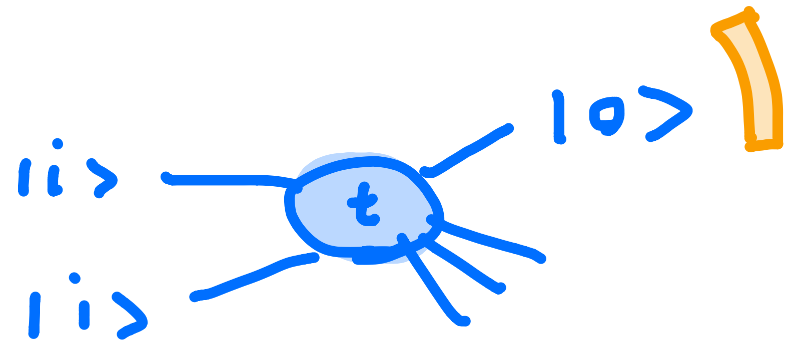
Pythia8

- α_s needed at 10%
- m_b needed at 10%
- r_B needed at 10%
- all the rest needed at "100%"

Herwig6

- $\Lambda_{QCD} \Rightarrow \alpha_s$ needed at 3%
- $m_{b,g}$ needed at 2%
- cluster mass spectrum (PSPLT, CLPOW, CLMAX) needed at 20%
- all the rest needed at "100%"

CIRCA 2015



Lxy decay length **CMS-PAS-TOP-12-030**

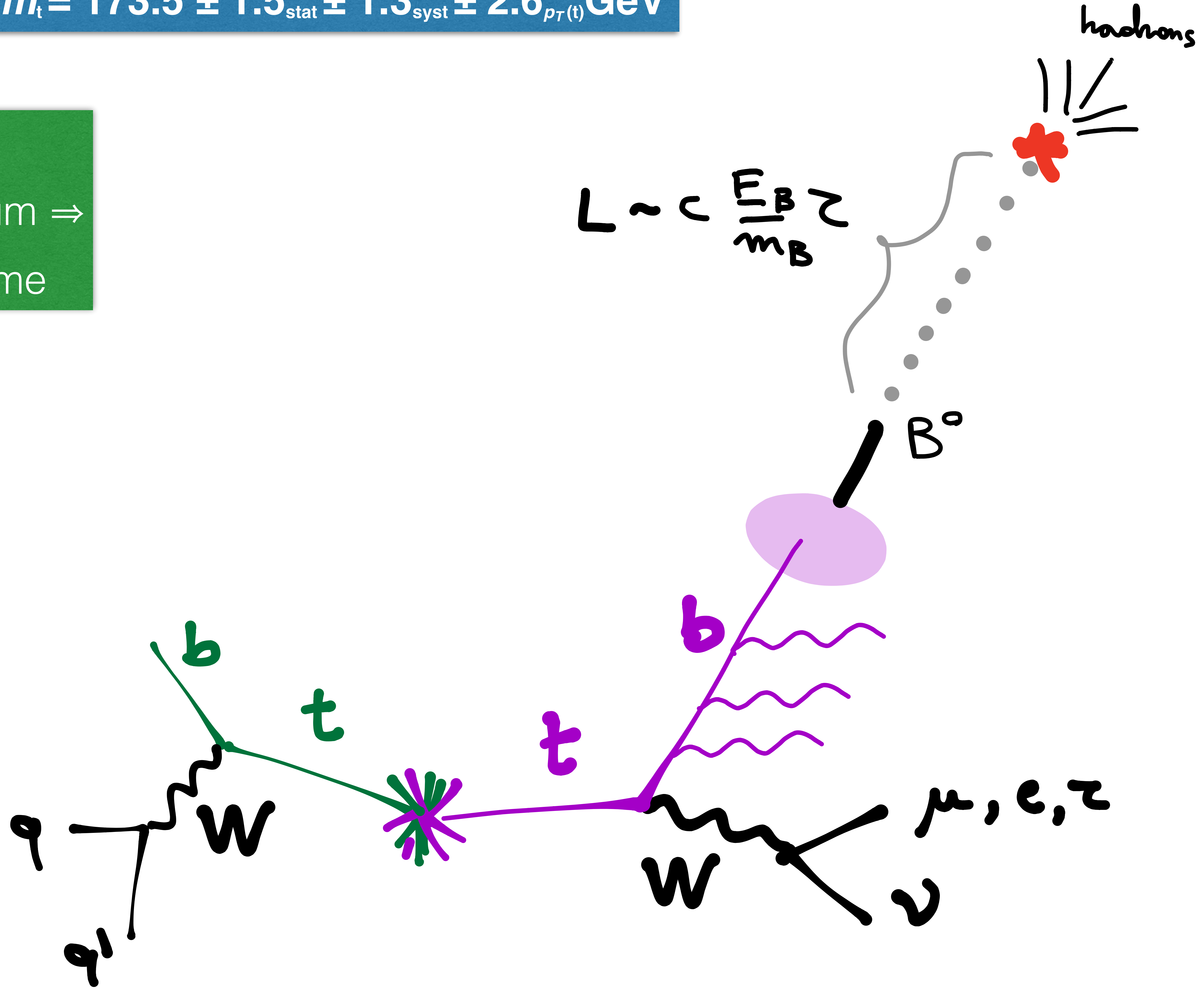
- B-hadron life-time - Lxy hep-ex/0501043

$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T(t)}$ GeV

larger top **mass** ⇒

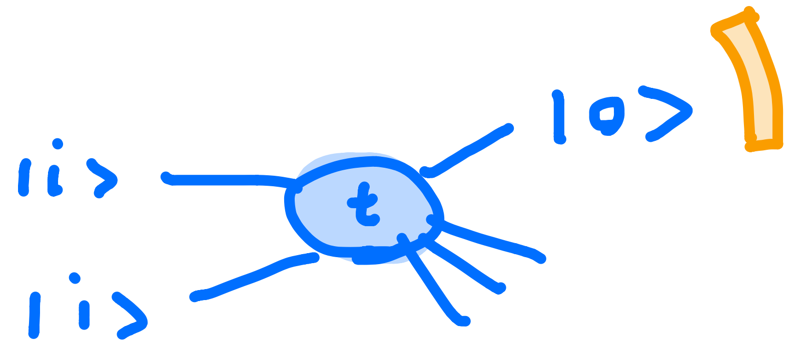
⇒ large B hadron momentum ⇒

⇒ larger lab-frame life-time



dependence on the dynamics (e.g. production of top at LHC)

CIRCA 2015



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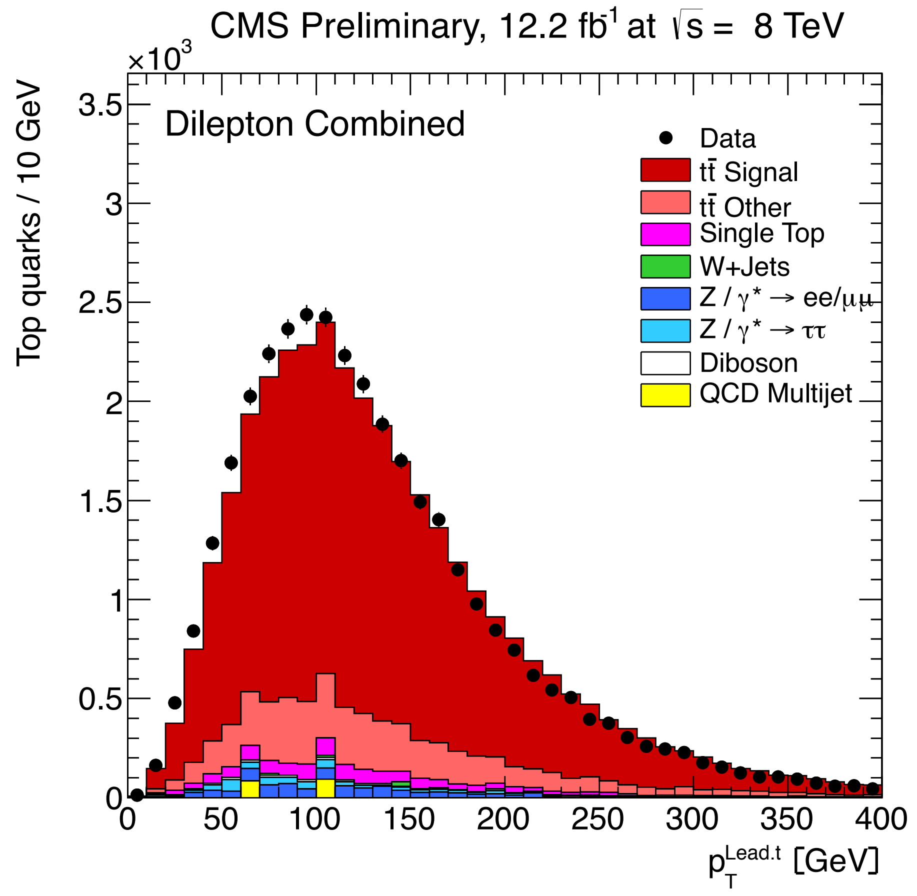

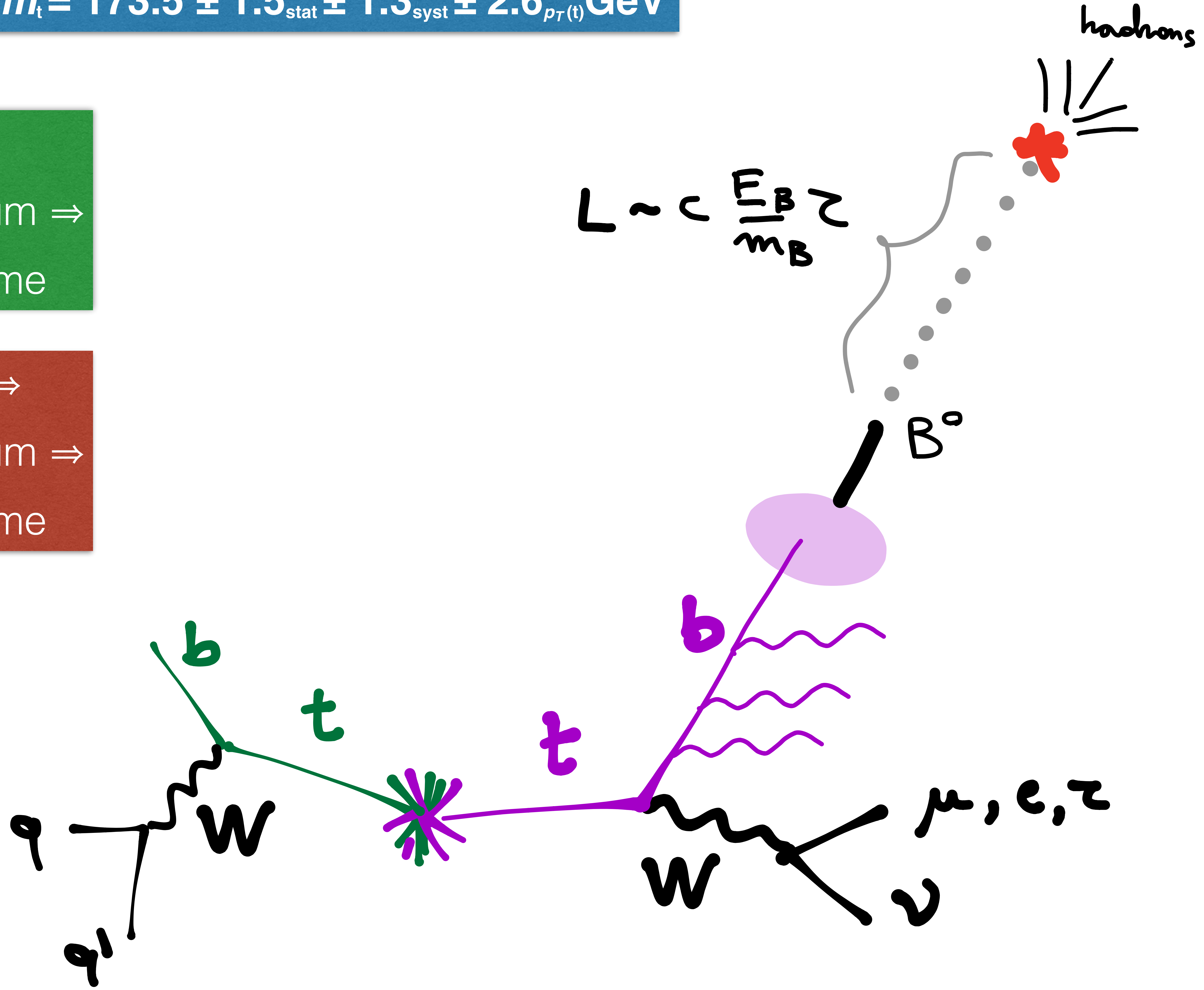

$$L \sim c\,\frac{E_B}{m_B}\tau$$

dependence on the dynamics (e.g. production of top at LHC)

Summary and outlook (back then)

- Jet-level $\frac{d\sigma}{dE_b}$ well under control from theory, NLO scale variation well under GeV on m_t, JES uncertainty as large as NLO scale variation
- Hadron-level $\frac{d\sigma}{dE_B}$ can can offer JES-free measurement via either **full reconstruction of a B-hadron energy in tracker** or **length measurement**
- Scale(s) variation(s) of FF point towards α_s expansion up to NN(N)LO, demanding MC parameters sensitivity. Issues probably common to all hadron-based methods.

Summary and outlook (back then)

- full B-hadron reconstruction in tracker not pursued yet
- length-based m_t measurement was identified as a bearing some potentially interesting remnant of the energy peak invariance, but no concrete technical solution to dig out this remnant
- other interesting applications identified for m_W and possibly cosmic rays physics

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Today's talk

- other interesting applications identified for m_W and possibly cosmic rays physics

Goal of the present work

SET TARGETS FOR THE CRITICAL ASPECTS OF THIS MEASUREMENT

- Propose a description of the hadron observable decay length rooted in the key elements of the successful jet-level method.
- Describe a template-fitting procedure that leverages the good understanding at the quark and jet-level, and allows to test the moving parts (e.g. hadronizaton, other MC aspects)

Goal of the present work

SET TARGETS FOR THE CRITICAL ASPECTS OF THIS MEASUREMENT

- Will not identify a set of tools/calculations that are best *today* to carry out the measurement
- Will try to identify the **weak points** of our chain of tools/computations and set targets for the improvements we need to get (likely similar to other hadron-based methods)
- Will show that starting from energy-peak considerations the m_t extraction from decay length can withstand changes in the top quark production kinematics, e.g. changes of $p_{T,t}$.

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TLDR

Our template

dep. on E_B

$$\frac{d\sigma}{d\ell_B} = \underbrace{\int dE_b \frac{d\sigma}{dE_b}} \int dE_B \underbrace{D(E_B, E_b)} \cdot \underbrace{\exp\left(\ell_B / \tau_0 c\beta\gamma\right)}$$

Proton PDF

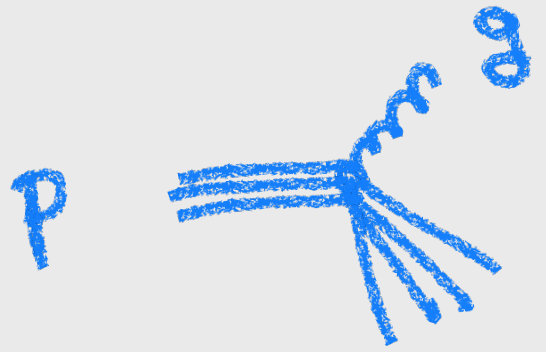
Top production

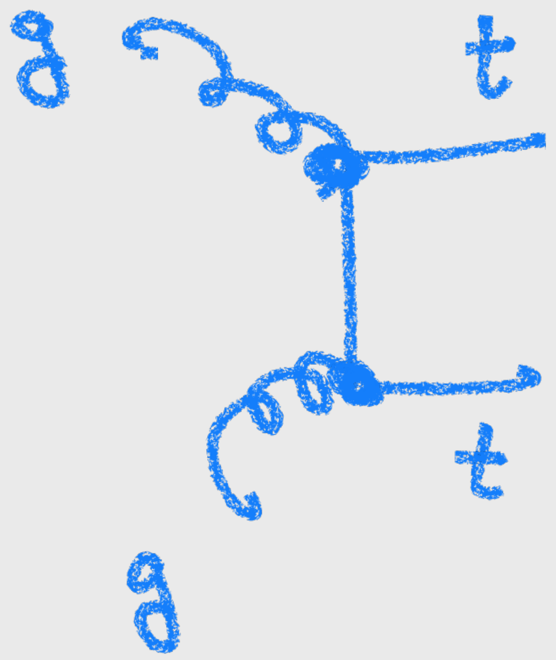
Top decay

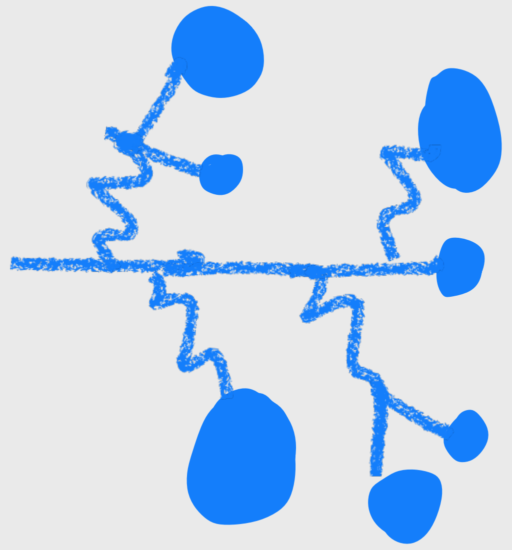
Shower+Hadronization

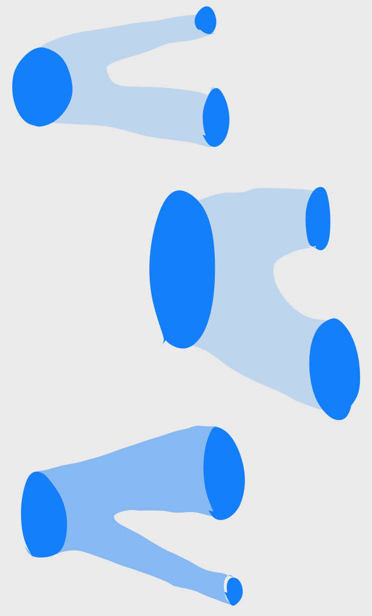
Decays

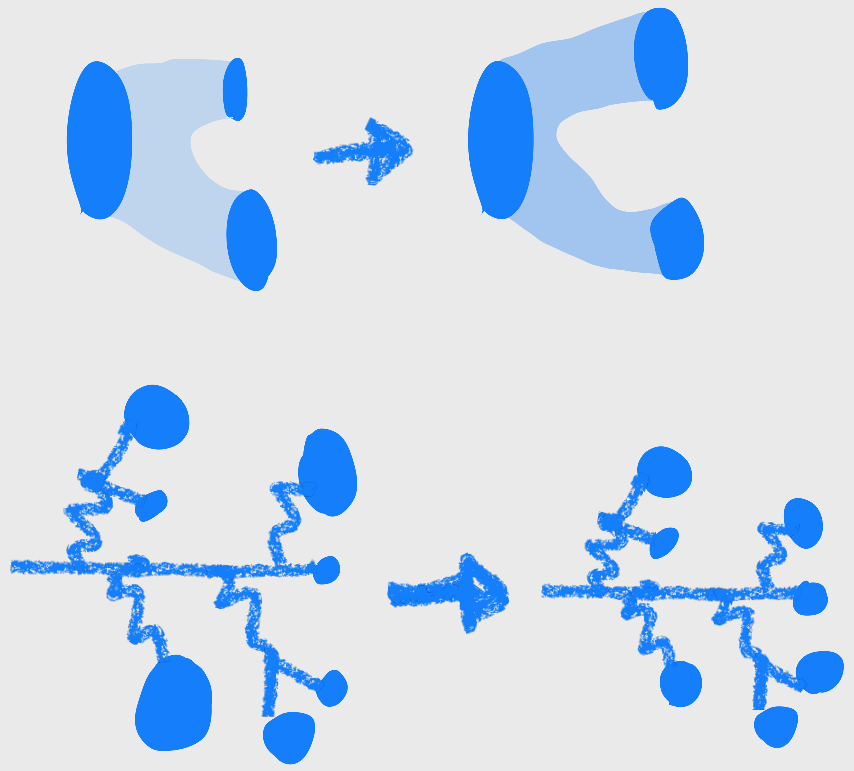
Adjustments, Recoil, ...











Our template

dep. on E_B

$$\frac{d\sigma}{d\ell_B} = \underbrace{\int dE_b \, \exp\left(\omega\left(\frac{E}{E^*}+\frac{E^*}{E}\right)^{\nu}\right)}_{} \int dE_B \, \underbrace{D(E_B, E_b)}_{} \cdot \underbrace{\exp\left(\ell_B/\tau_0 c\beta\gamma\right)}_{}$$

Proton PDF

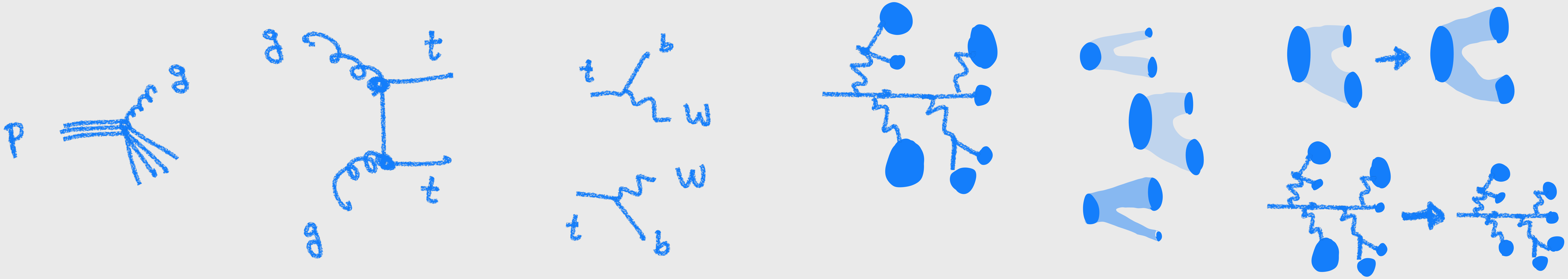
Top production

Top decay

Shower+Hadronization

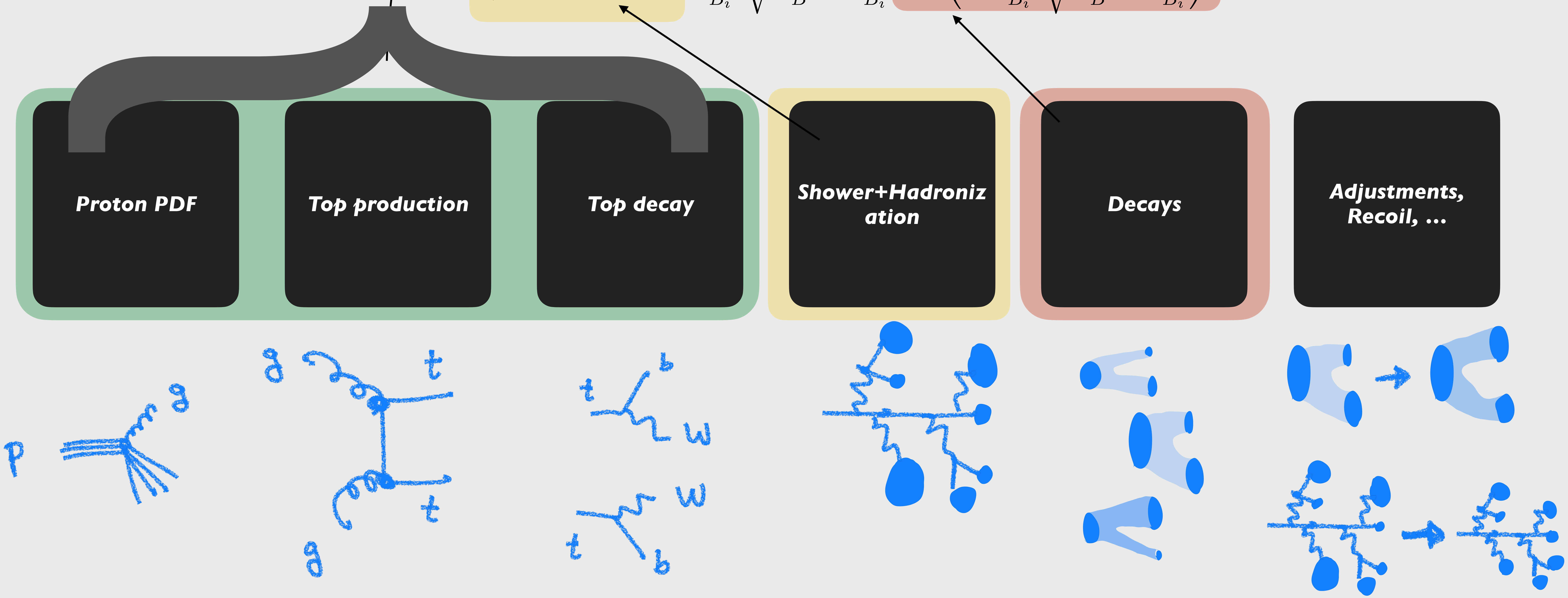
Decays

Adjustments, Recoil, …



Our template

$$G^{\text{fit}}\left(L_B; E_b^{\text{rest}}, w, \nu\right) = \int_{E_{B,\min}}^{E_b} dE_B \int_{E_{b,\min}}^{E_{b,\max}} dE_b \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{\text{rest}}}{E_b}\right)^{\nu}\right] \times$$
$$\sum_i D_i\left(\frac{E_{B_i}}{E_b}; E_b\right) \frac{f_i m_{B_i}}{c\tau_{B_i}^{\text{rest}}\sqrt{E_B^2 - m_{B_i}^2}} \exp\left(-\frac{L_B m_{B_i}}{c\tau_{B_i}^{\text{rest}}\sqrt{E_B^2 - m_{B_i}^2}}\right)$$



Proton PDF

Top production

Top decay

Shower+Hadronization

Decays

Adjustments, Recoil, ...

Our template

$$G^{\mathrm{fit}}\left(L_B; E_b^{\mathrm{rest}}, w, \nu\right) = \int_{E_{B,\mathrm{min}}}^{E_b} dE_B \int_{E_{b,\mathrm{min}}}^{E_{b,\mathrm{max}}} dE_b \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\mathrm{rest}}} + \frac{E_b^{\mathrm{rest}}}{E_b}\right)^{\nu}\right] \times$$

$$\sum_i D_i\left(\frac{E_{B_i}}{E_b}; E_b\right) \frac{f_i m_{B_i}}{c\tau_{B_i}^{\mathrm{rest}}\sqrt{E_B^2 - m_{B_i}^2}} \exp\left(-\frac{L_B m_{B_i}}{c\tau_{B_i}^{\mathrm{rest}}\sqrt{E_B^2 - m_{B_i}^2}}\right)$$

- select sample with b-jets $40\ \mathrm{GeV} < E_{bjet} < 450\ \mathrm{GeV}$
- we checked that JES impact on acceptance through E_b is reflected in 80 MeV in top quark mass for JES@1%
- conceivable to use track-only jets (not explored yet)

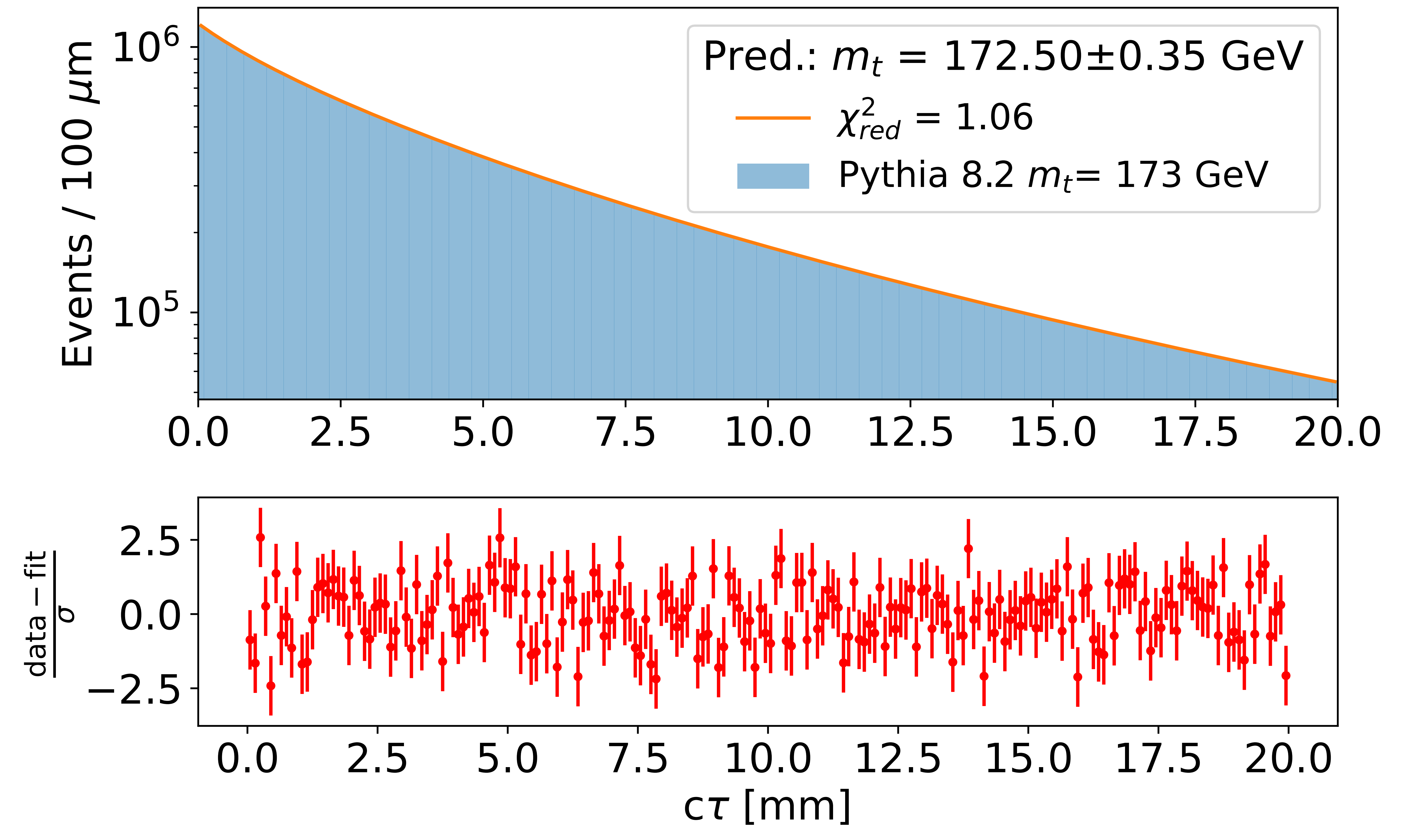
- compute the template using D_i from the MC-truth (will discuss related uncertainty)

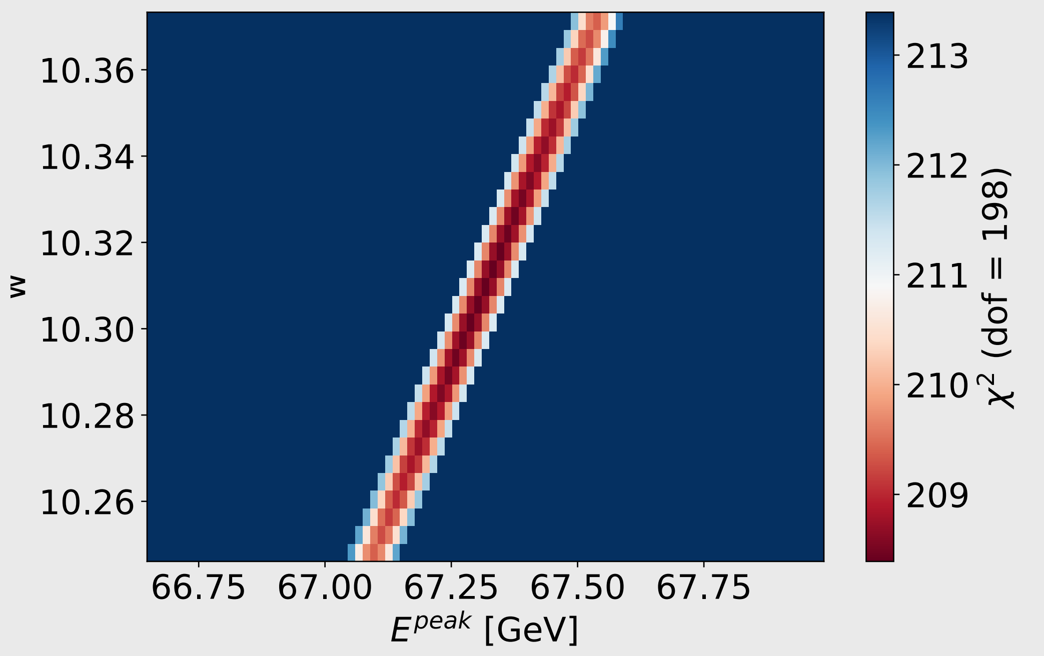
- compute template using f_i from MC-truth (will discuss related uncertainty)

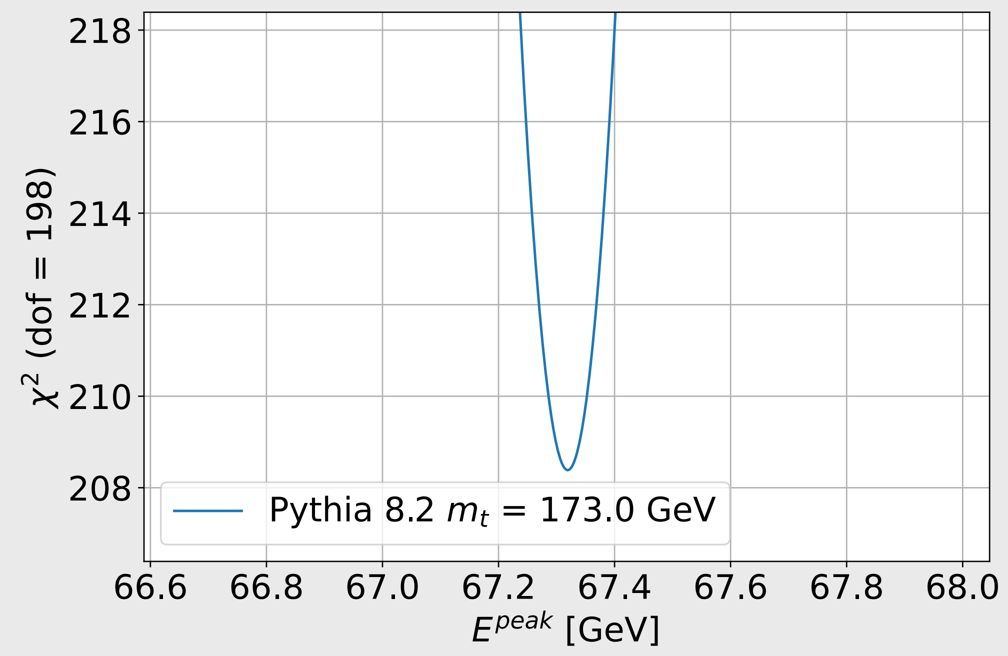
Our selection

		CMS charged-tracks	*our work*
$\ell + \text{jets}$	e	$p_T > 30$ GeV, $\eta < 2.4$	$p_T > 25$ GeV, $\eta < 2.4$
	μ	$p_T > 26$ GeV, $\eta < 2.1$	$p_T > 25$ GeV, $\eta < 2.1$
	j	$N_j \geq 4$, $p_T > 30$ GeV, $\eta < 2.5$	$N_j \geq 4$, $p_T > 25$ GeV, $\eta < 2.5$
$2\ell + \text{jets}$	e, μ	$p_T > 20$ GeV, $\eta < 2.4$	$p_T > 25$ GeV, $\eta < 2.4$
	SF	$M_{\ell\ell} > 20$ GeV, $\lvert M_{\ell\ell} - m_Z \rvert > 15$ GeV	$M_{\ell\ell} > 20$ GeV, $\lvert M_{\ell\ell} - m_Z \rvert > 15$ GeV
	OF	-	-
	j	$p_T > 30$ GeV, $\eta < 2.5$	$p_T > 25$ GeV, $\eta < 2.5$
		$E_T^{\text{miss}} > 40$ GeV	$E_T^{\text{miss}} > 40$ GeV

Our fit





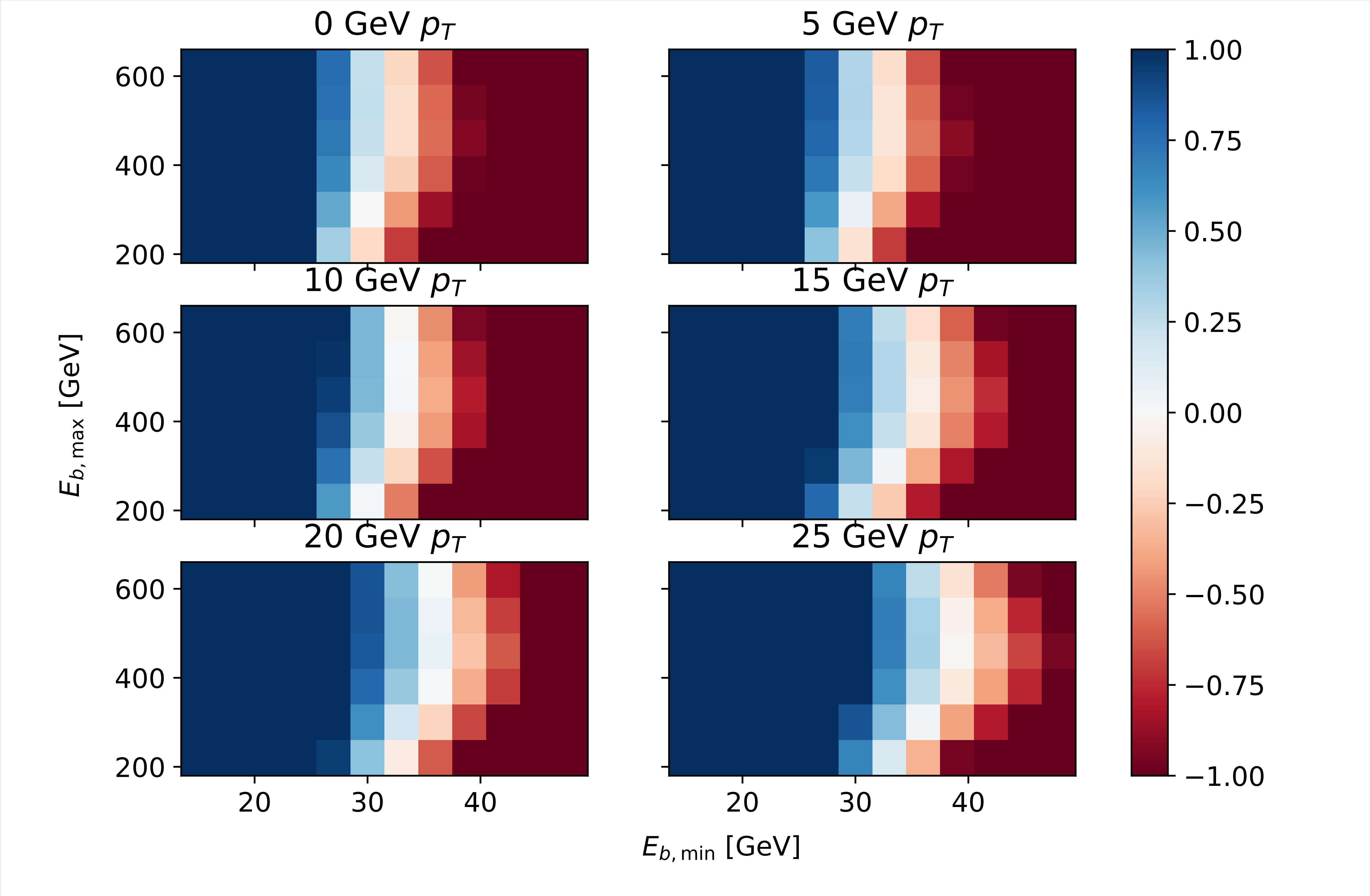


$$\delta m_t^{(E_B,\ peak)} = \frac{0.5\ \text{GeV}}{\sqrt{\mathcal{L}/100\,\text{fb}^{-1}}}(\text{stat.})$$

POTENTIAL FOR A COMPETITIVE MEASUREMENT WITH THE CURRENT DATA SET!

Uncertainties

Uncertainty in the definition of the template



- range of E_{b-jet} can bias the extracted top quark mass
- p_T cut for a j and ℓ can bias the extracted top quark mass
- getting wrong E_b at 1% is reflected in 80 MeV shift in top quark mass

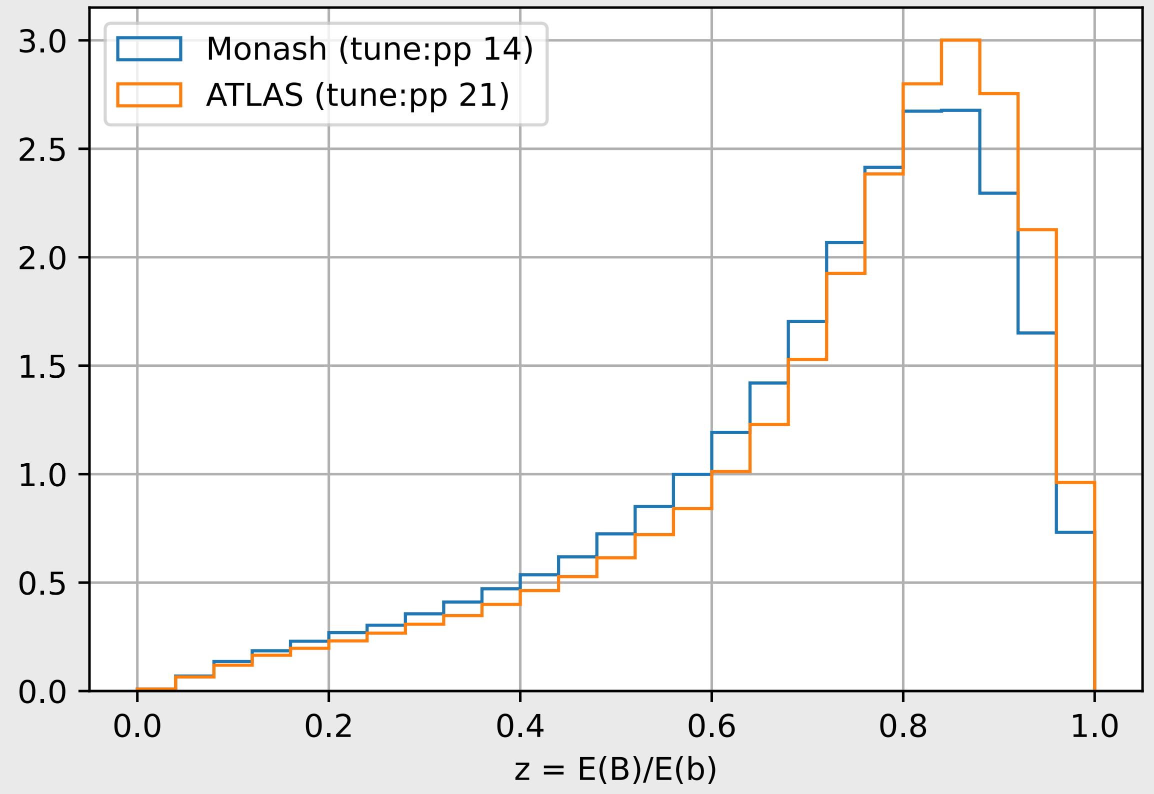
Uncertainty in the definition of the template

$$m_{B_i}, \Gamma_{B_i}, f_i$$

Hadron	Mass (MeV) [25]	Lifetime (10^{-12} s) [27]	Fraction
$B^{\pm}$	5279.34 ± 0.12	1.638 ± 0.004	42.9 %
B^0	5279.65 ± 0.12	1.519 ± 0.004	42.9 %
B_s^0	5366.88 ± 0.14	1.516 ± 0.006	9.5 %
Λ_b^0	5619.69 ± 0.17	1.471 ± 0.009	3.6 %

- Hadrons masses and lifetimes need to be know at least as precisely as the target for m_t. Current knowledge is sufficient for δm_t below 500 MeV
- As hadron masses and lifetimes are not too different among B-hadron species, the required knowledge of f_i can be $O(10)$ times worse than the target for m_t. Current knowledge might be fine, but better get rid of e^+e^- and $p\bar{p}$ if possible.

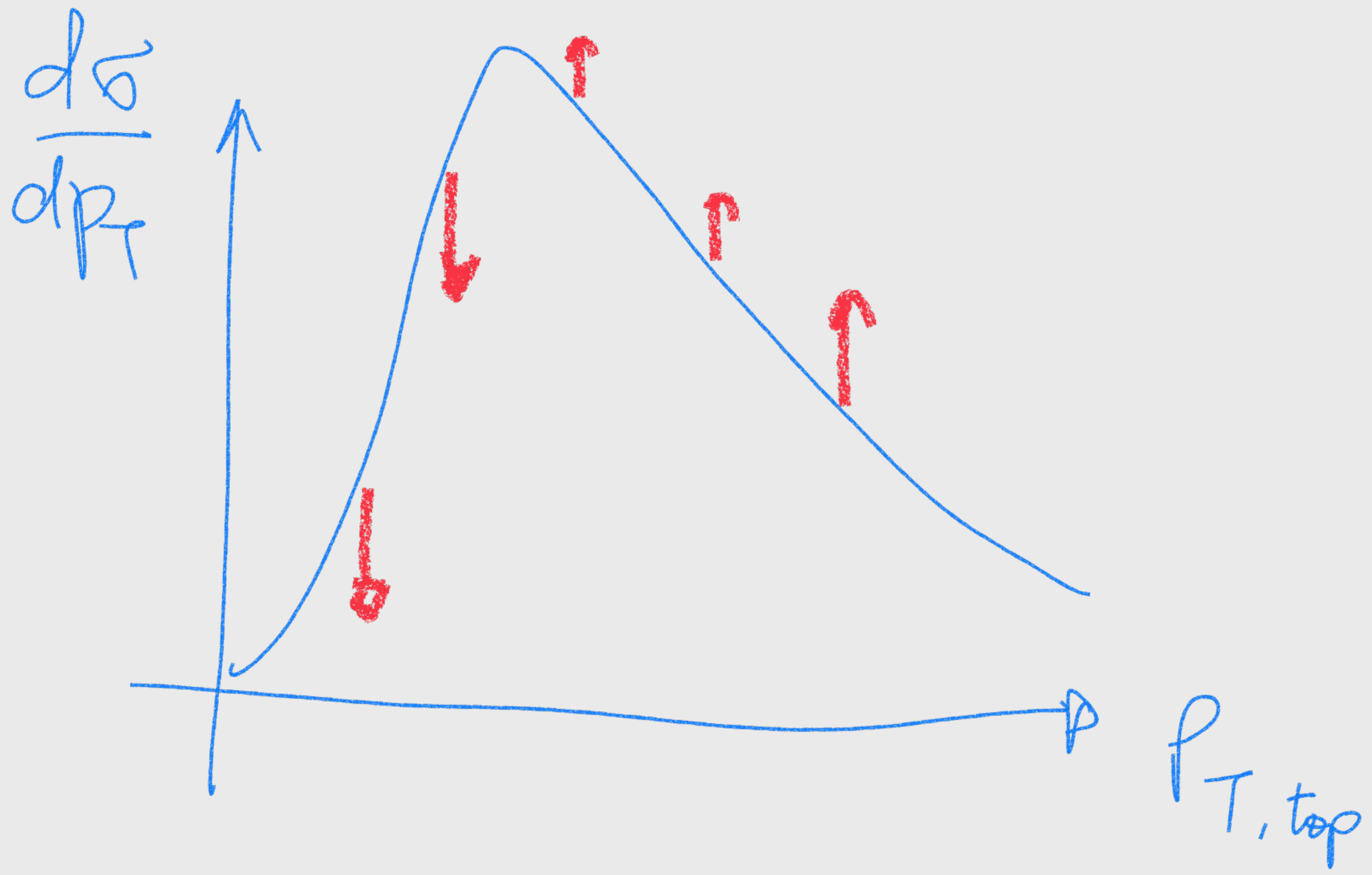
$$D_i$$



Mellin Moment	$\delta\langle z^n\rangle/\langle z^n\rangle$	$\delta m_t^{(171\to176)}$	Sensitivity
$\langle z\rangle$	0.53 %	3.5 GeV	3.8
$\langle z^2\rangle$	0.91 %		2.2
$\langle z^3\rangle$	1.23 %		1.6

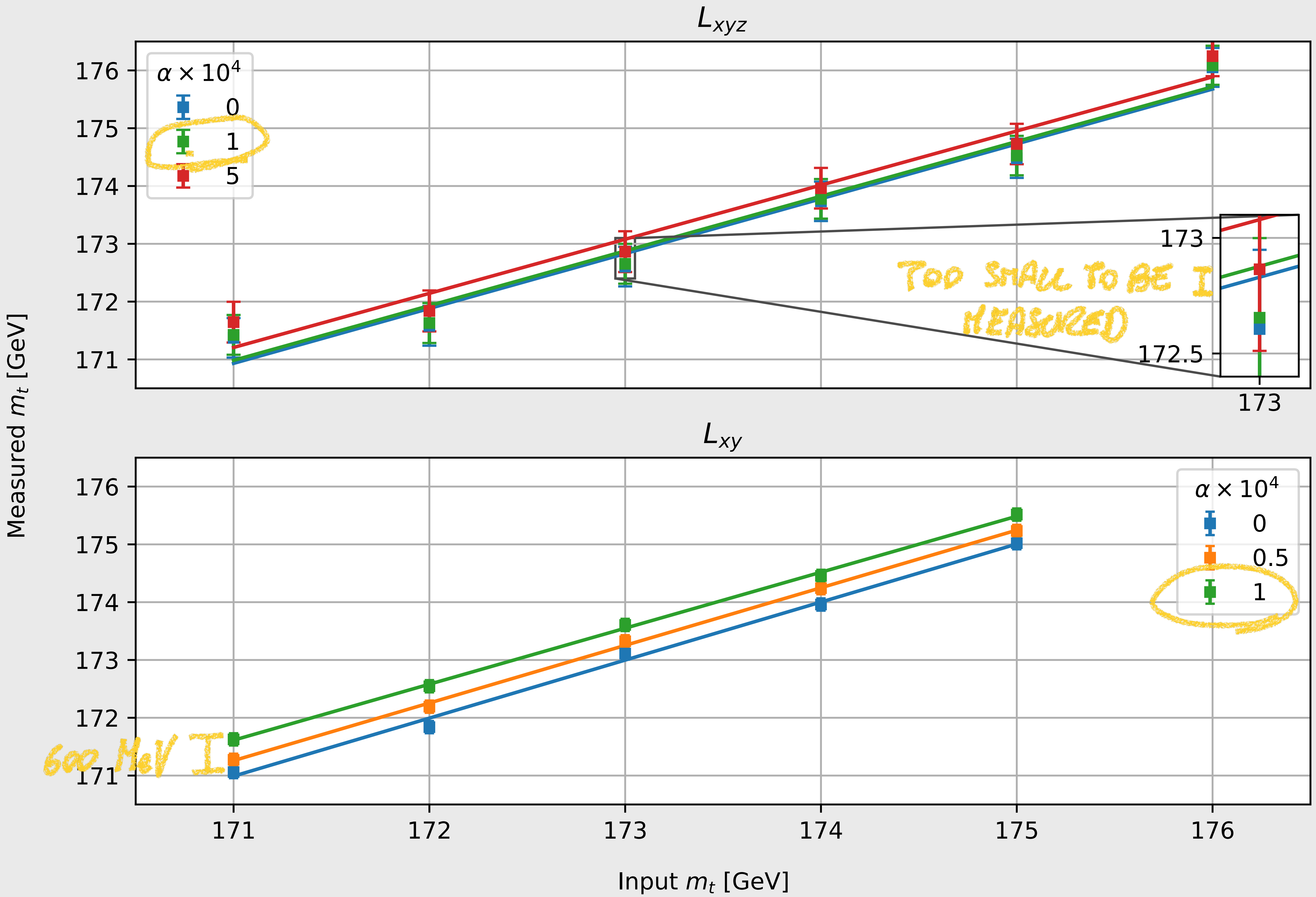
- evaluated with two methods: 1) based on just changing m_t and using the “wrong” D_i obtained for another m_t; 2) change tune of Pythia 8.2
- both exercises mapped onto Mellin moments of D_i
- D_i needs to be known few times better than target m_t

Uncertainty in the production mechanism



- Events reweighted according to top quark p_T
- χ^2 template fit for our energy-peak based template and for a template of simpler L_{xy}

$$\frac{\tilde{w}}{w} = 1 + \alpha\,\theta(p_t < 400)(p_t - 200)$$



Summary of uncertainties

$$\delta m_t^{(E_B,\ peak)} = \frac{0.5\ \text{GeV}}{\sqrt{\mathcal{L}/100\,\text{fb}^{-1}}}(\text{stat.})$$

“N³LO” $\oplus\, 0.5\ \text{GeV} \cdot \left(\frac{0.1\%}{\frac{\delta D_i}{D_i}}\right)$

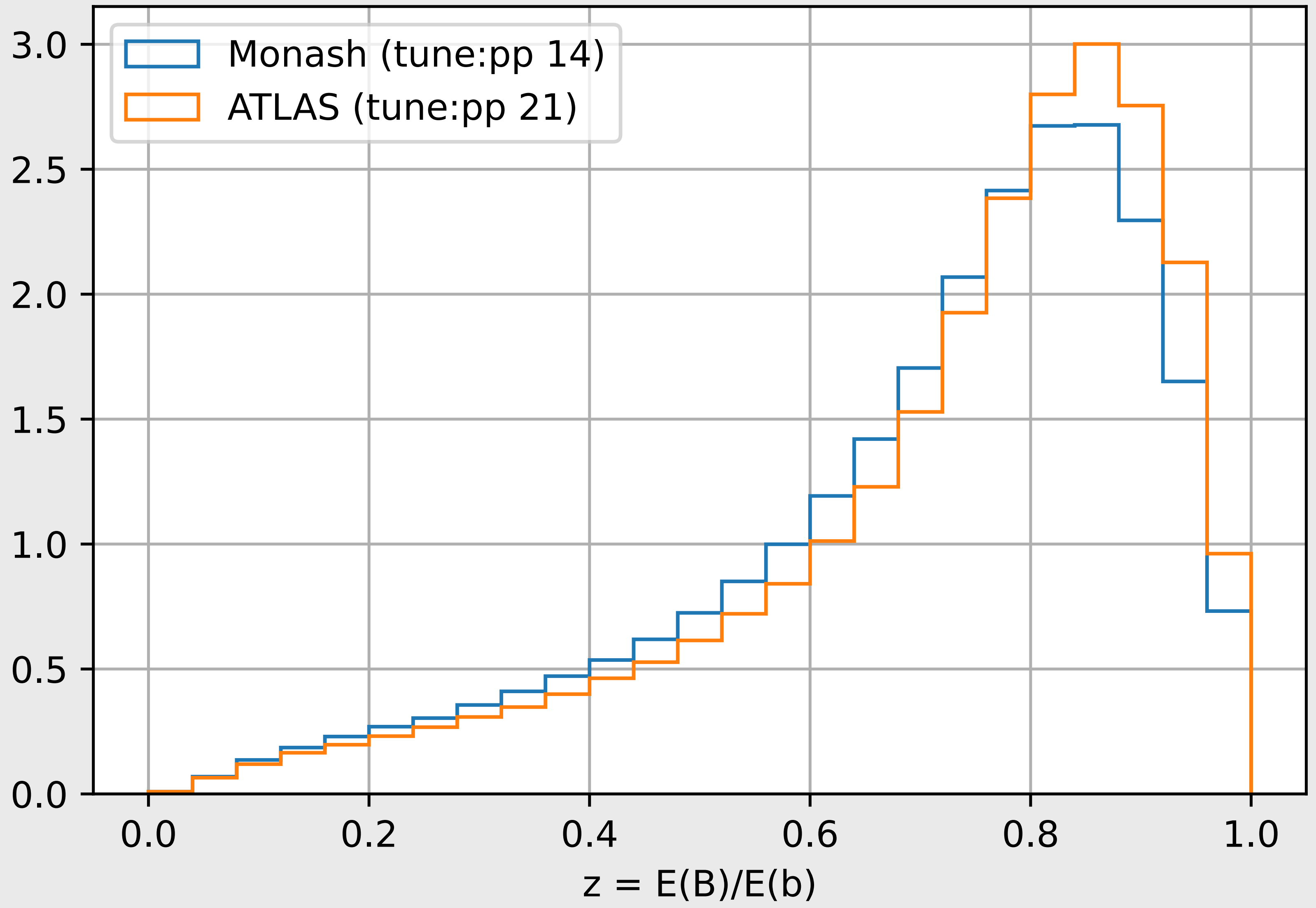
doable $\oplus\, 0.3\ \text{GeV} \cdot \left(\frac{5\%}{\frac{\delta f_i}{f_i}}\right)$

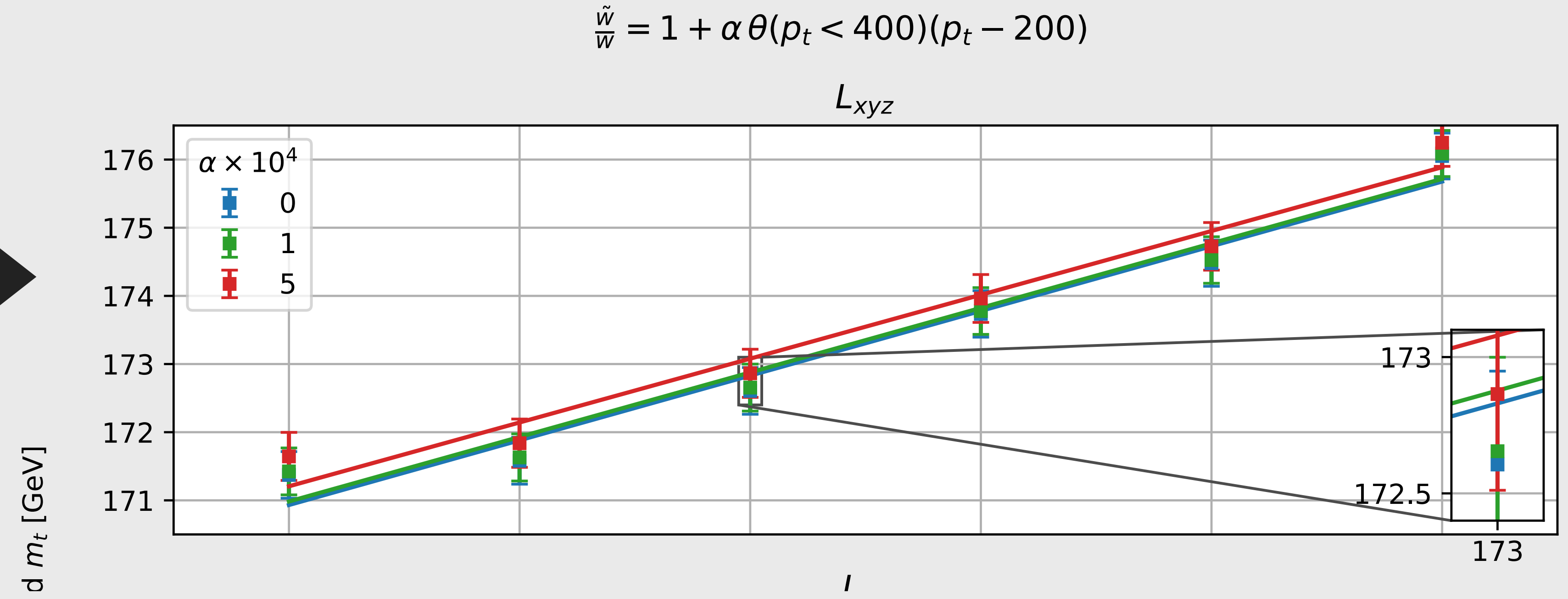
$\oplus_{p_{T,t}}$ negligible

$\oplus_{m_{B_i}}$ negligible

$\oplus_{\Gamma_{B_i}}$ negligible

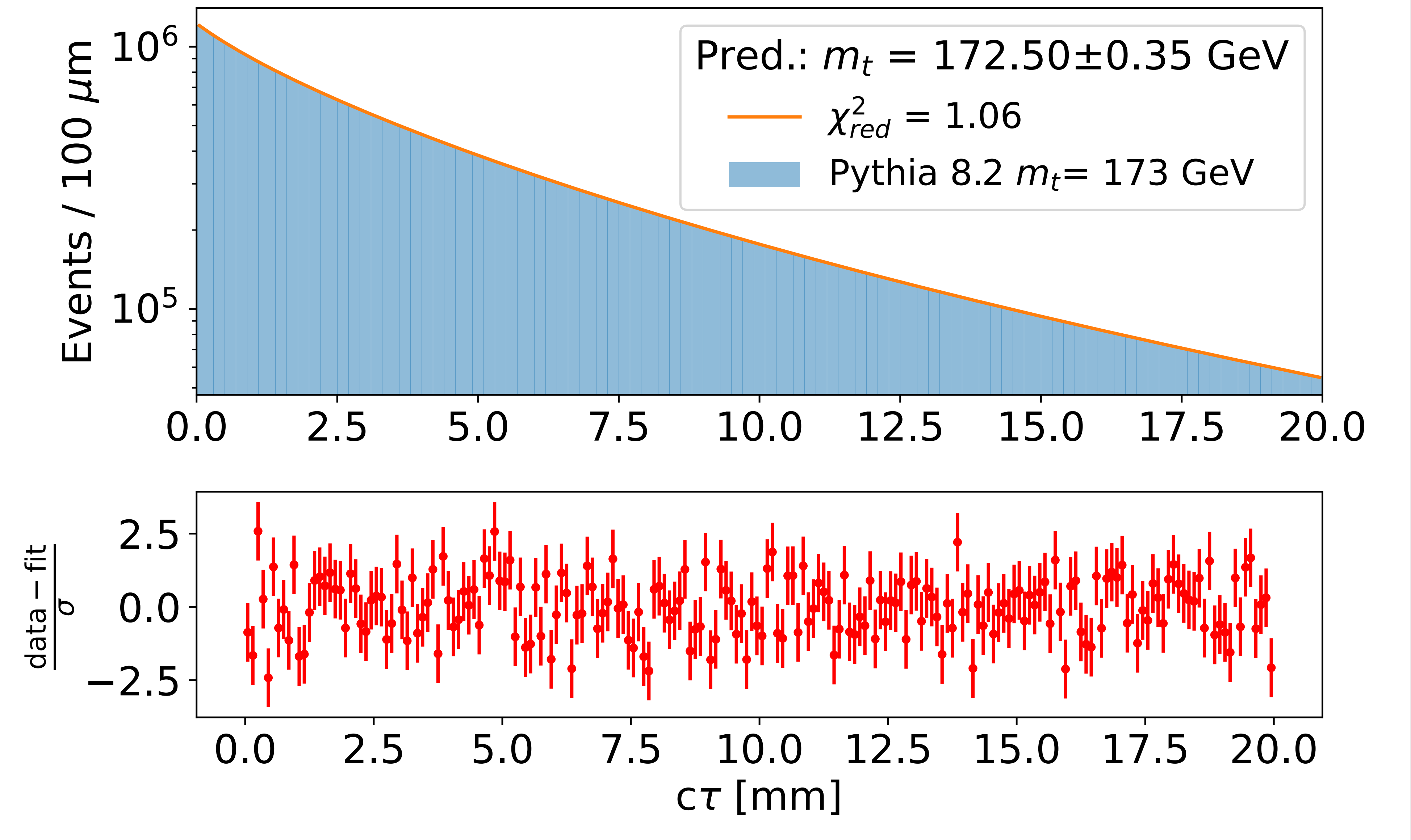
$\oplus_{JES}$ negligible





Summary and outlook

- Proof of principle for energy-peak based templates for decay length (and possibly related observables)
- Tiny dependence on top quark production kinematics
- Manageable dependence on B hadron “PDG listing”
- Motivates pushing hadronization, fragmentation, showering to next level to get firmer predictions on D_i
- Color reconnections and recoil effects worth being explored



$$\int_{E_{B,\mathrm{min}}}^{E_b} dE_B \int_{E_{b,\mathrm{min}}}^{E_{b,\mathrm{max}}} dE_b \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\mathrm{rest}}}+\frac{E_b^{\mathrm{rest}}}{E_b}\right)^{\nu}\right]\times$$

$$\sum_i D_i\left(\frac{E_{B_i}}{E_b};E_b\right)\frac{f_i m_{B_i}}{c\tau_{B_i}^{\mathrm{rest}}\sqrt{E_B^2-m_{B_i}^2}}\exp\left(-\frac{L_B m_{B_i}}{c\tau_{B_i}^{\mathrm{rest}}\sqrt{E_B^2-m_{B_i}^2}}\right)$$

Summary and outlook

- Proof of principle for energy-peak based templates for decay length (and possibly related observables)
- Tiny dependence on top quark production kinematics
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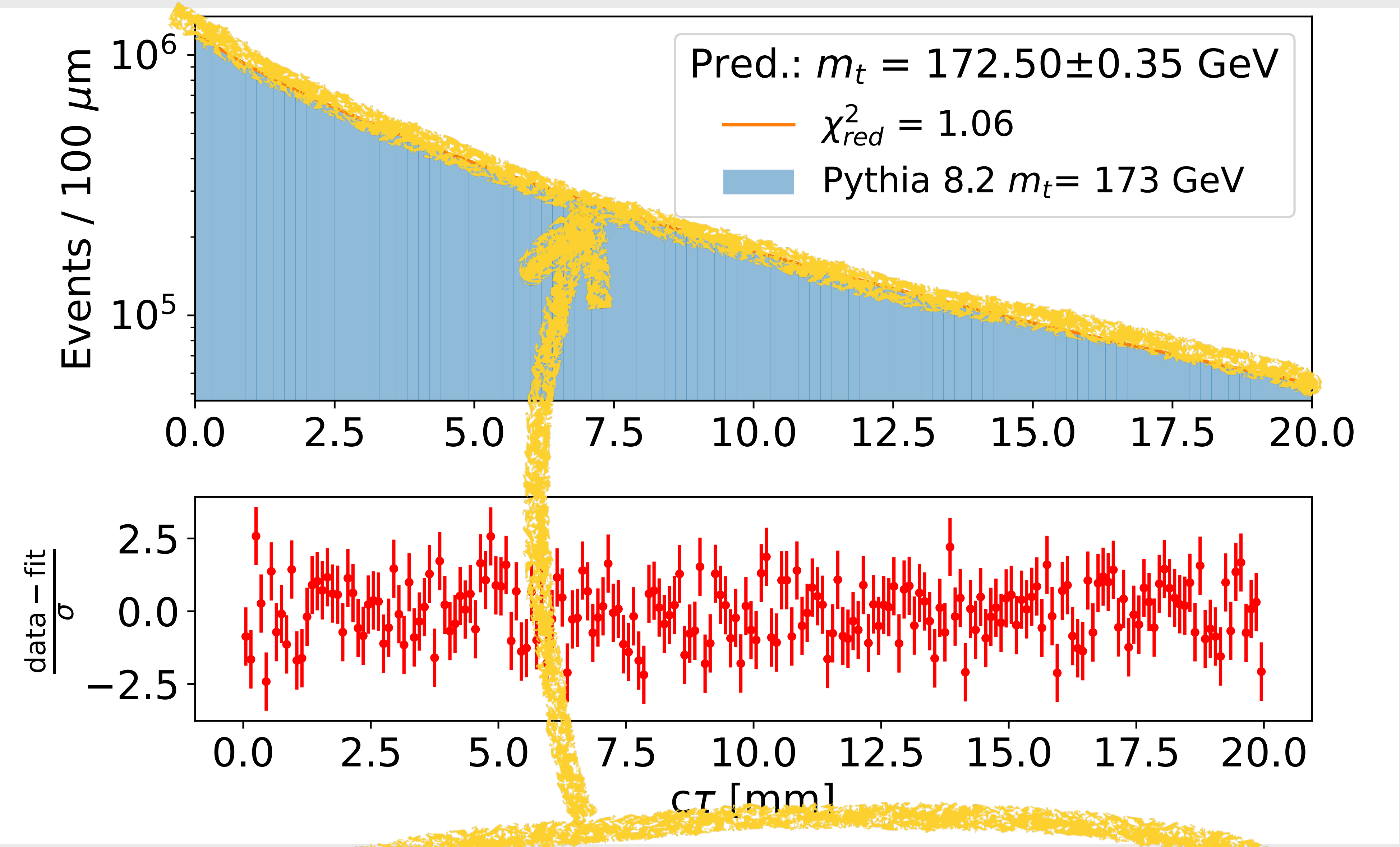
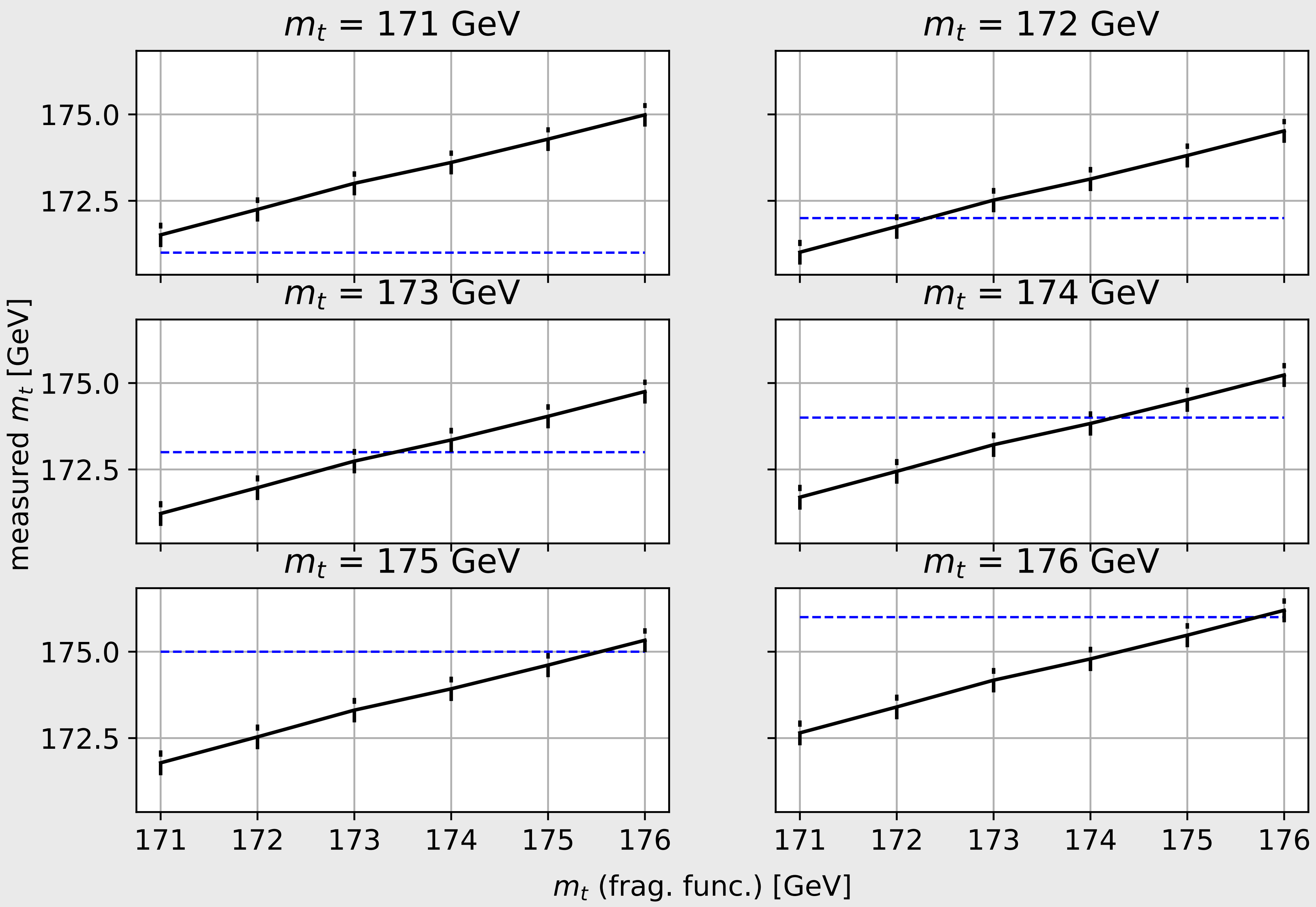


$$\int_{E_{B,\mathrm{min}}}^{E_b} dE_B \int_{E_{b,\mathrm{min}}}^{E_{b,\mathrm{max}}} dE_b \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\mathrm{rest}}}+\frac{E_b^{\mathrm{rest}}}{E_b}\right)^{\nu}\right]\times$$

$$\sum_i D_i\left(\frac{E_{B_i}}{E_b};E_b\right)\frac{f_i m_{B_i}}{c\tau_{B_i}^{\mathrm{rest}}\sqrt{E_B^2-m_{B_i}^2}}\exp\left(-\frac{L_B m_{B_i}}{c\tau_{B_i}^{\mathrm{rest}}\sqrt{E_B^2-m_{B_i}^2}}\right)$$

Thank you!

Imapct of uncertainty on D_i



Mellin Moment	$\delta\langle z^n\rangle/\langle z^n\rangle$	$\delta m_t^{171\to176}$(10% reweighting)	Sensitivity
$\langle z\rangle$	2.8 %	1.7 GeV	3.5
$\langle z^2\rangle$	5.2 %		2.5
$\langle z^3\rangle$	7.2 %		1.4

Table 5. For each of the first three Mellin moments of the D_i we report: the difference between the default Pythia tune (Tune:pp 14) and the ATLAS tune (Tune:pp 21); the effect on the extracted m_t stemming from a 10% contamination of the ATLAS tune into the Monash tune; the sensitivity of the extracted m_t to each Mellin moment.

Mellin Moment	$\delta\langle z^n\rangle/\langle z^n\rangle$	$\delta m_t^{(171\to176)}$	Sensitivity
$\langle z\rangle$	0.53 %	3.5 GeV	3.8
$\langle z^2\rangle$	0.91 %		2.2
$\langle z^3\rangle$	1.23 %		1.6

Table 6. For each of the first three Mellin Moments of the fragmentation function we report: their change due to varying the m_t value that labels the D_i extracted from the Monte Carlo truth from 171 GeV to 176 GeV; the change on the extracted m_t due to using the D_i extracted from the Monte Carlo truth for $m_t = 176$ GeV on the data sample for $m_t = 171$ GeV; the sensitivity of the extracted m_t to each Mellin moment.

NNLO hadrons

FULLY INCLUSIVE PEAK STABILITY

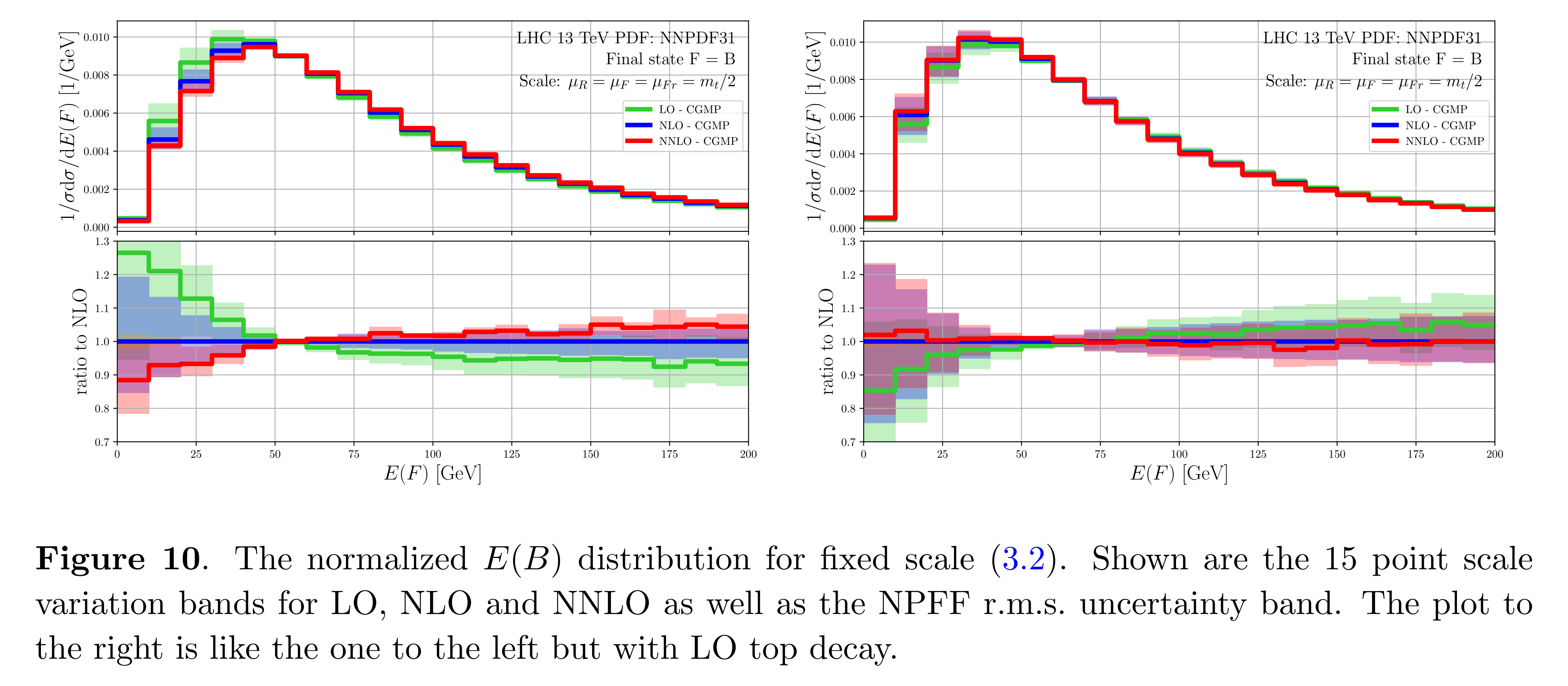


Figure 10. The normalized $E(B)$ distribution for fixed scale (3.2). Shown are the 15 point scale variation bands for LO, NLO and NNLO as well as the NPFF r.m.s. uncertainty band. The plot to the right is like the one to the left but with LO top decay.

m_t	LO	NLO	NNLO
171.5 GeV	37.553 (±0.106) $\left(^{+0.050}_{-0.061}\right)$	40.994 (±0.147) $\left(^{+1.178}_{-0.710}\right)$	42.957 (±0.329) $\left(^{+1.087}_{-0.818}\right)$
172.5 GeV	37.816 (±0.109) $\left(^{+0.051}_{-0.062}\right)$	41.277 (±0.158) $\left(^{+1.196}_{-0.717}\right)$	43.263 (±0.332) $\left(^{+1.073}_{-0.825}\right)$
173.5 GeV	38.093 (±0.113) $\left(^{+0.051}_{-0.061}\right)$	41.657 (±0.168) $\left(^{+1.250}_{-0.745}\right)$	43.528 (±0.222) $\left(^{+1.010}_{-0.778}\right)$
Lin. fit	LO	NLO	NNLO
$a =$	0.270 (±0.004)	0.329 (±0.028)	0.284 (±0.011)
$b =$	−8.755 (±0.708) GeV	−15.429 (±4.820) GeV	−5.666 (±1.816) GeV

Table 2. Values of $E_{\max}(B)$ for the absolute differential cross section with full top quark decay at LO, NLO and NNLO and for three different values of m_t. Positions are fit using eq. (3.9) and 5 GeV bins. Also given are the parameters of the linear fit eq. (3.7) at LO, NLO and NNLO.

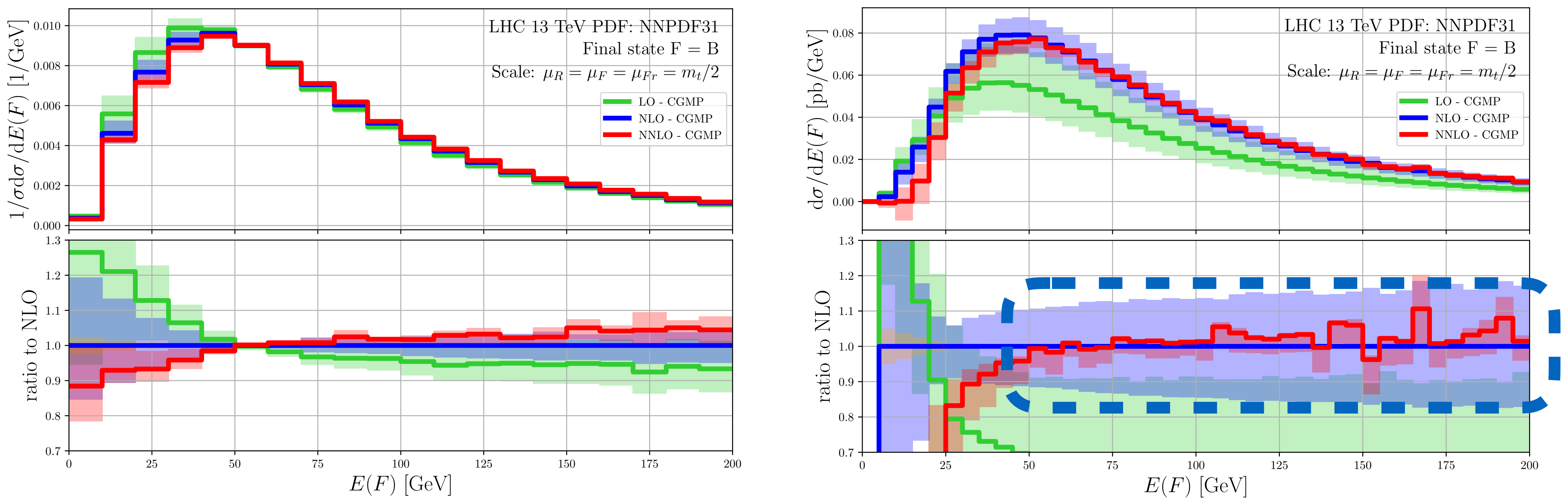
m_t	LO	NLO	NNLO
171.5 GeV	37.553 (±0.106) $\left(^{+0.050}_{-0.061}\right)$	36.744 (±0.169) $\left(^{+0.213}_{-0.313}\right)$	36.737 (±0.311) $\left(^{+0.081}_{-0.021}\right)$
172.5 GeV	37.816 (±0.109) $\left(^{+0.051}_{-0.062}\right)$	36.981 (±0.182) $\left(^{+0.223}_{-0.330}\right)$	37.010 (±0.227) $\left(^{+0.109}_{-0.019}\right)$
173.5 GeV	38.093 (±0.113) $\left(^{+0.051}_{-0.061}\right)$	37.319 (±0.193) $\left(^{+0.206}_{-0.296}\right)$	37.292 (±0.255) $\left(^{+0.113}_{-0.056}\right)$
Lin. fit	LO	NLO	NNLO
$a =$	0.270 (±0.004)	0.286 (±0.029)	0.278 (±0.003)
$b =$	−8.755 (±0.708) GeV	−12.237 (±4.962) GeV	−10.913 (±0.556) GeV

Table 3. As in table 2 but for LO top quark decay.

NNLO hadrons

EXCLUSIVE

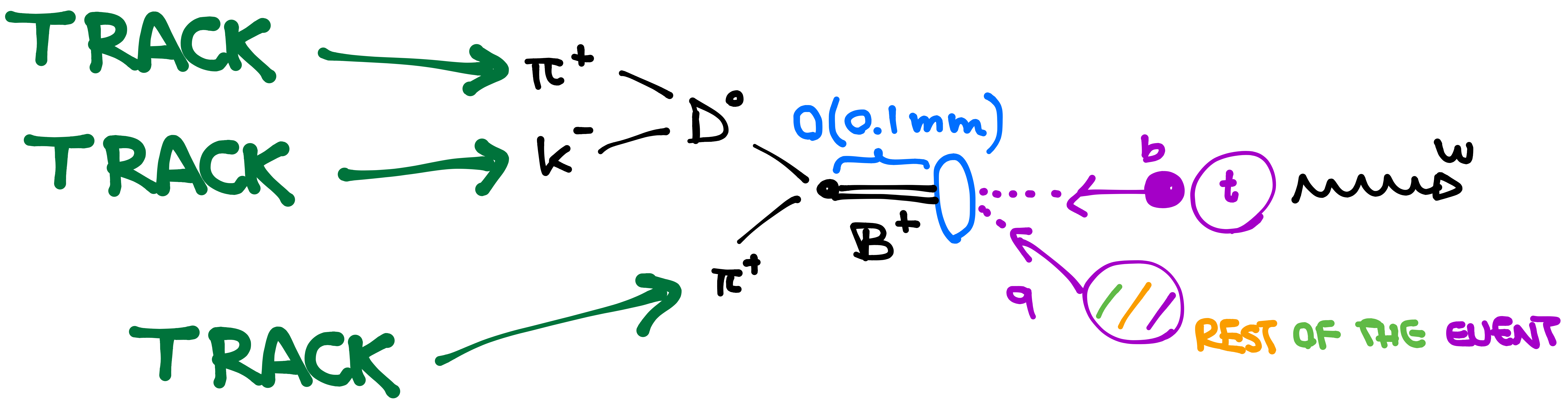
STABILITY ON QCD PERTURBATIONS



better stability for larger hadron energies above 40-50 GeV

B hadron **energy** peak

get the hadron energy entirely from tracks



$B^+ \rightarrow$ 3 TRACKS

Exclusive Decay

(Fully reconstructible with tracks)

J/psi modes

$$b \xrightarrow[few\cdot 10^{-3}]{} J/\psi + X \xrightarrow[10^{-1}]{} \ell\bar{\ell} + X$$

$$B_s^0 \to J/\psi\,\phi \to \mu^-\mu^+K^+K^-$$ 1106.4048

$$B^0 \to J/\psi\,K_S^0 \to \mu^-\mu^+\pi^+\pi^-$$ 1104.2892

$$B^+ \to J/\psi\,K^+ \to \mu^+\mu^-K^+$$ 1101.0131
1309.6920

$$\Lambda_b \to J/\psi\,\Lambda \to \mu^+\mu^-p\pi^-$$ 1205.0594

J/psi but no need to require leptonic W decay

D modes

$$B^0 \xrightarrow[3\cdot 10^{-3}]{} D^-\pi^+ \xrightarrow[10^{-2}]{} K_S^0\pi^-\,\pi^+$$

$$B^0 \xrightarrow[3\cdot 10^{-3}]{} D^-\pi^+ \xrightarrow[10^{-2}]{} K^-\pi^+\pi^-\,\pi^+$$

$$B^0 \xrightarrow[3\cdot 10^{-3}]{} D^-\pi^+ \xrightarrow[3\cdot 10^{-2}]{} K_S^0\pi^+\pi^-\,\pi^+$$

$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0\pi^- \xrightarrow[4\cdot 10^{-2}]{} K^-\pi^+\,\pi^-$$

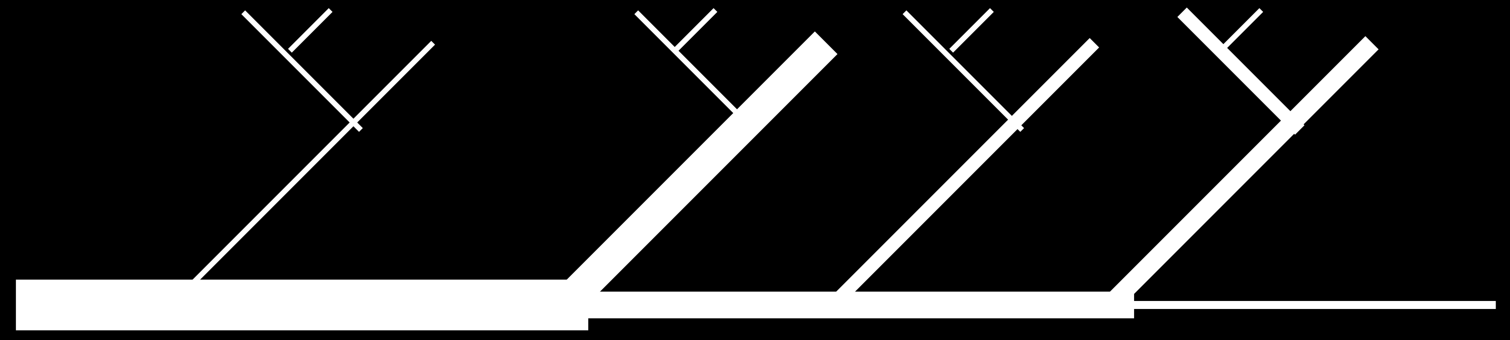
$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0\pi^- \xrightarrow[2\cdot 10^{-2}]{} K^{*,-}(892)\pi^+\,\pi^- \to K_S^0\pi^-\,\pi^+\,\pi^-$$

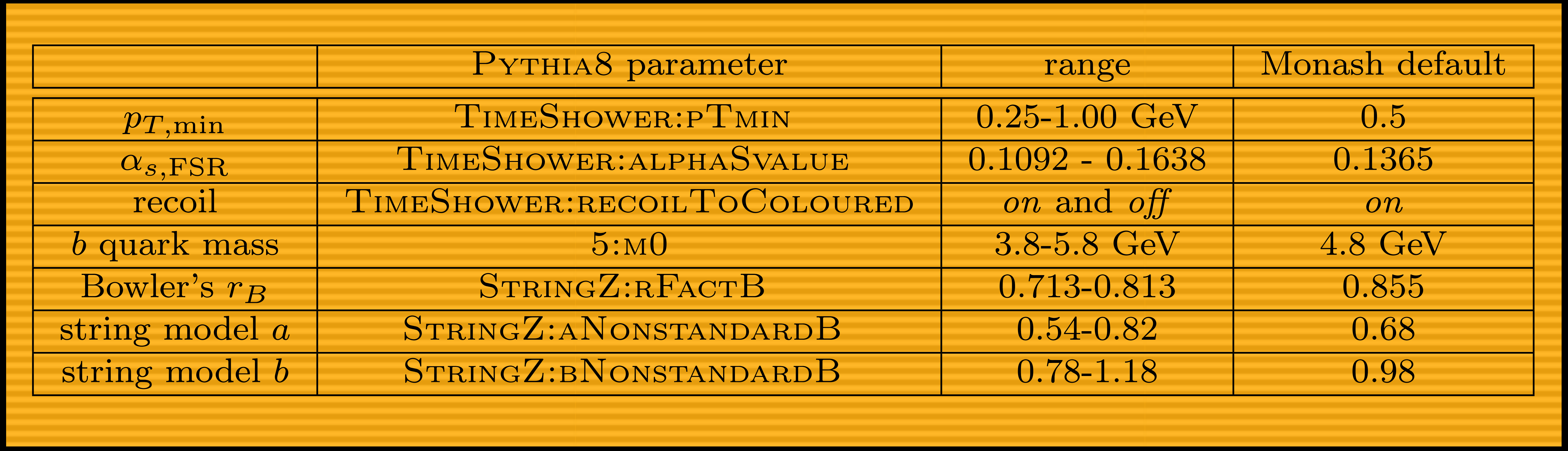
$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0\pi^- \xrightarrow[6\cdot 10^{-3}]{} K_S^0\rho^0\,\pi^-$$

$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0\pi^- \xrightarrow[5\cdot 10^{-3}]{} K^-\pi^+\rho^0\,\pi^-$$

EVENT GENERATORS

PYTHIA PARAMETERS

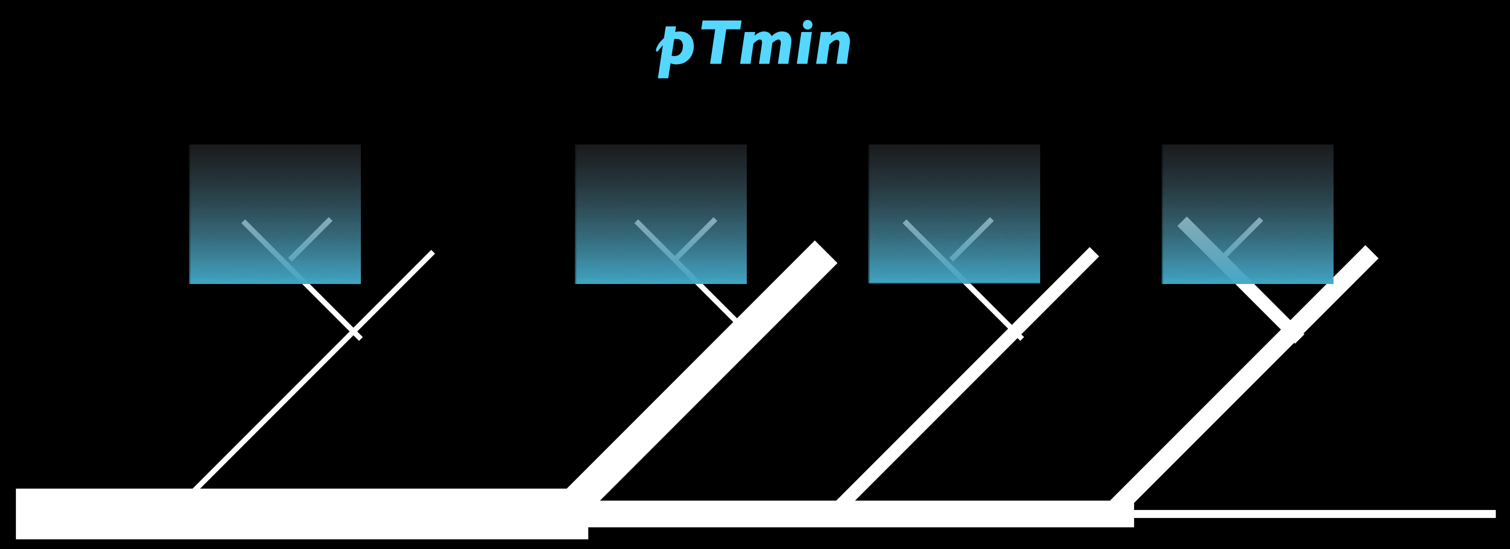


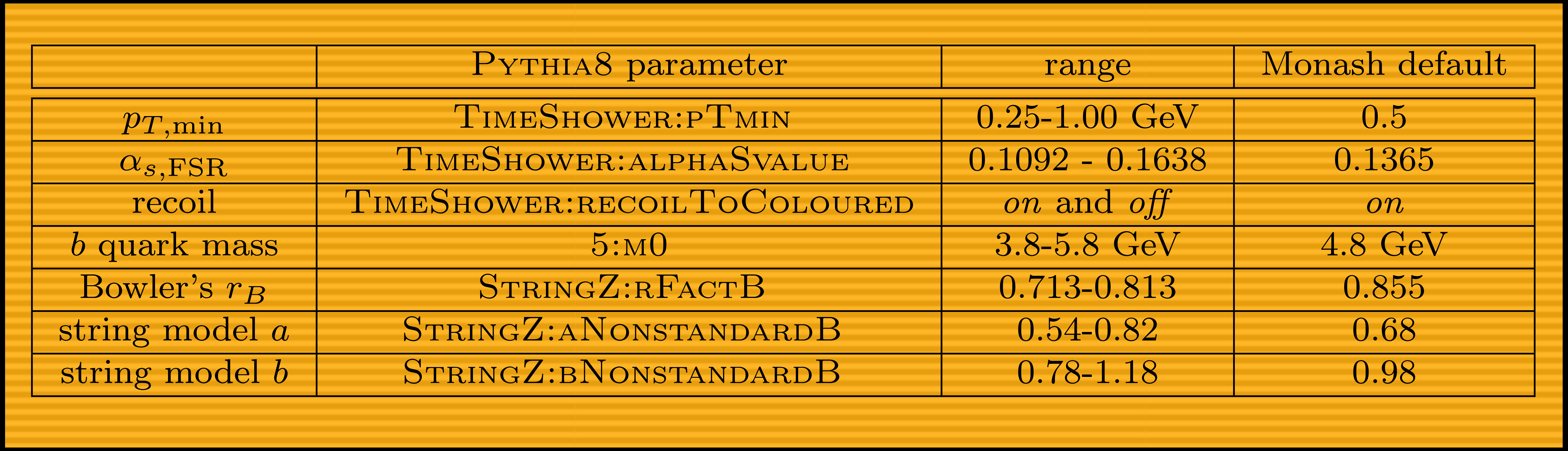


	Pythia8 parameter	range	Monash default
$p_{T,\mathrm{min}}$	TimeShower:pTmin	0.25-1.00 GeV	0.5
$\alpha_{s,\mathrm{FSR}}$	TimeShower:alphaSvalue	0.1092 - 0.1638	0.1365
recoil	TimeShower:recoilToColoured	*on* and *off*	*on*
b quark mass	5:m0	3.8-5.8 GeV	4.8 GeV
Bowler's r_B	StringZ:rFactB	0.713-0.813	0.855
string model a	StringZ:aNonstandardB	0.54-0.82	0.68
string model b	StringZ:bNonstandardB	0.78-1.18	0.98

EVENT GENERATORS

PYTHIA PARAMETERS





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EVENT GENERATORS

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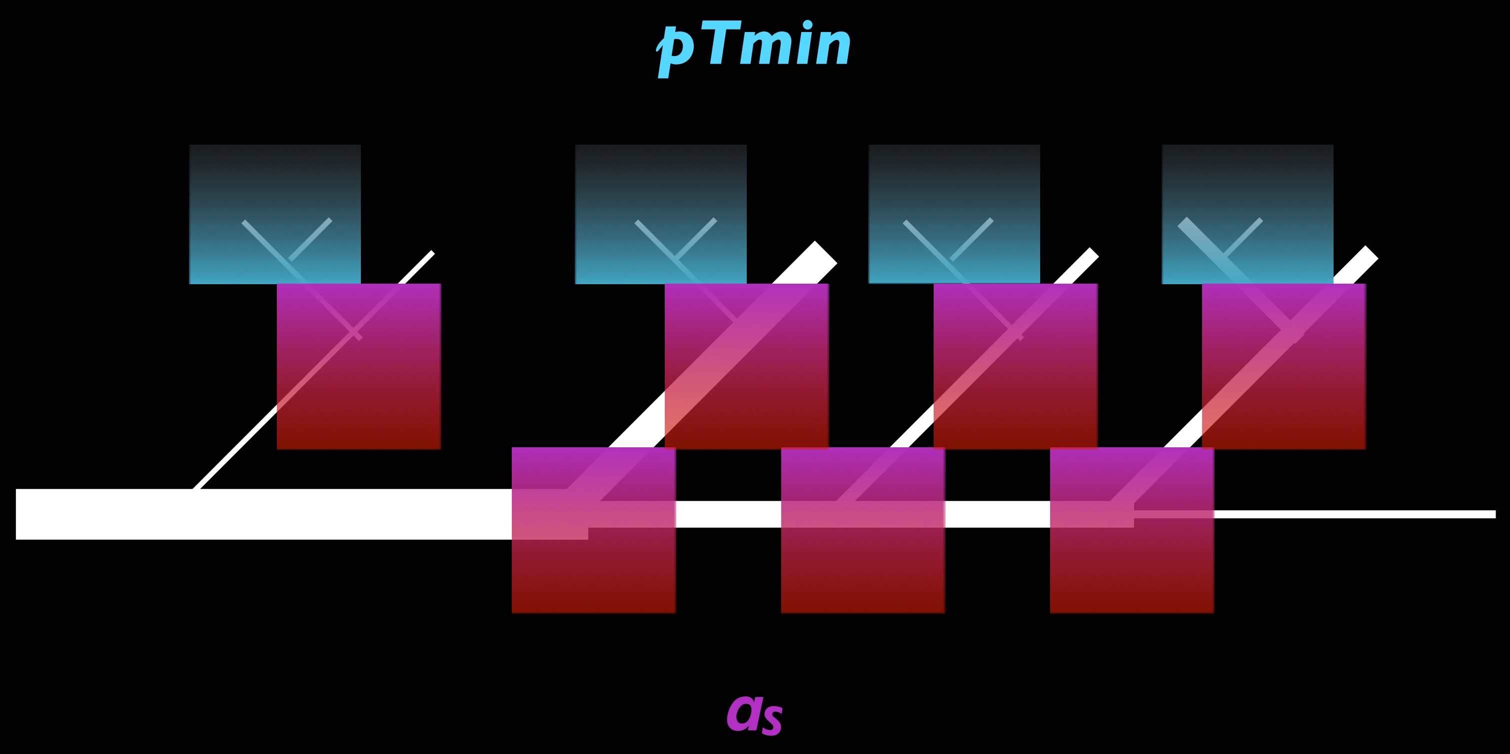

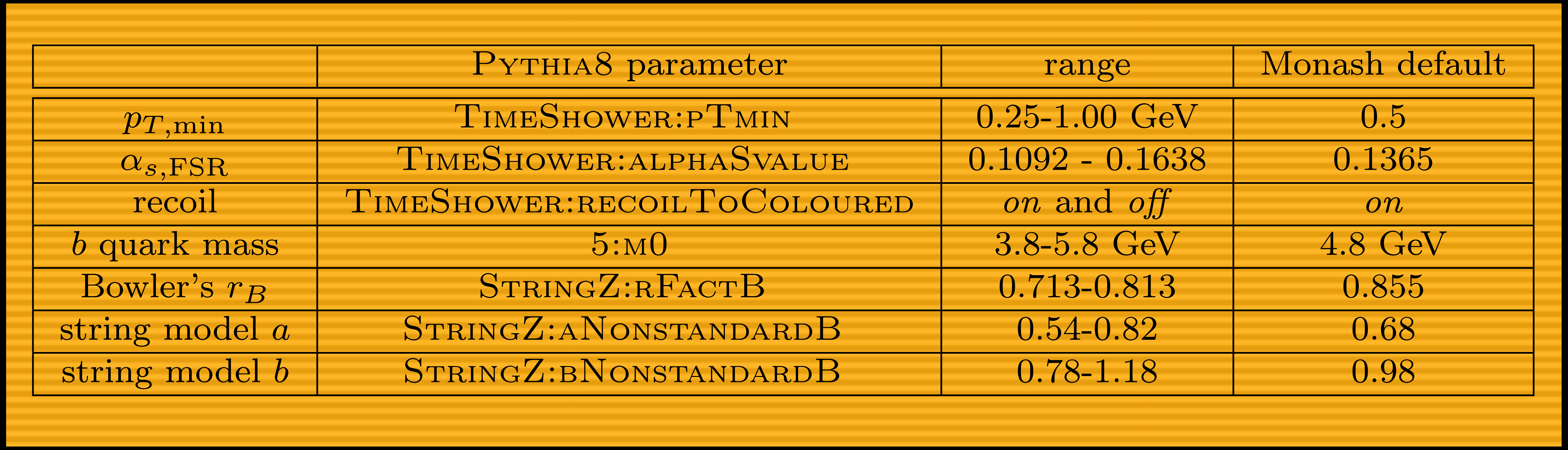

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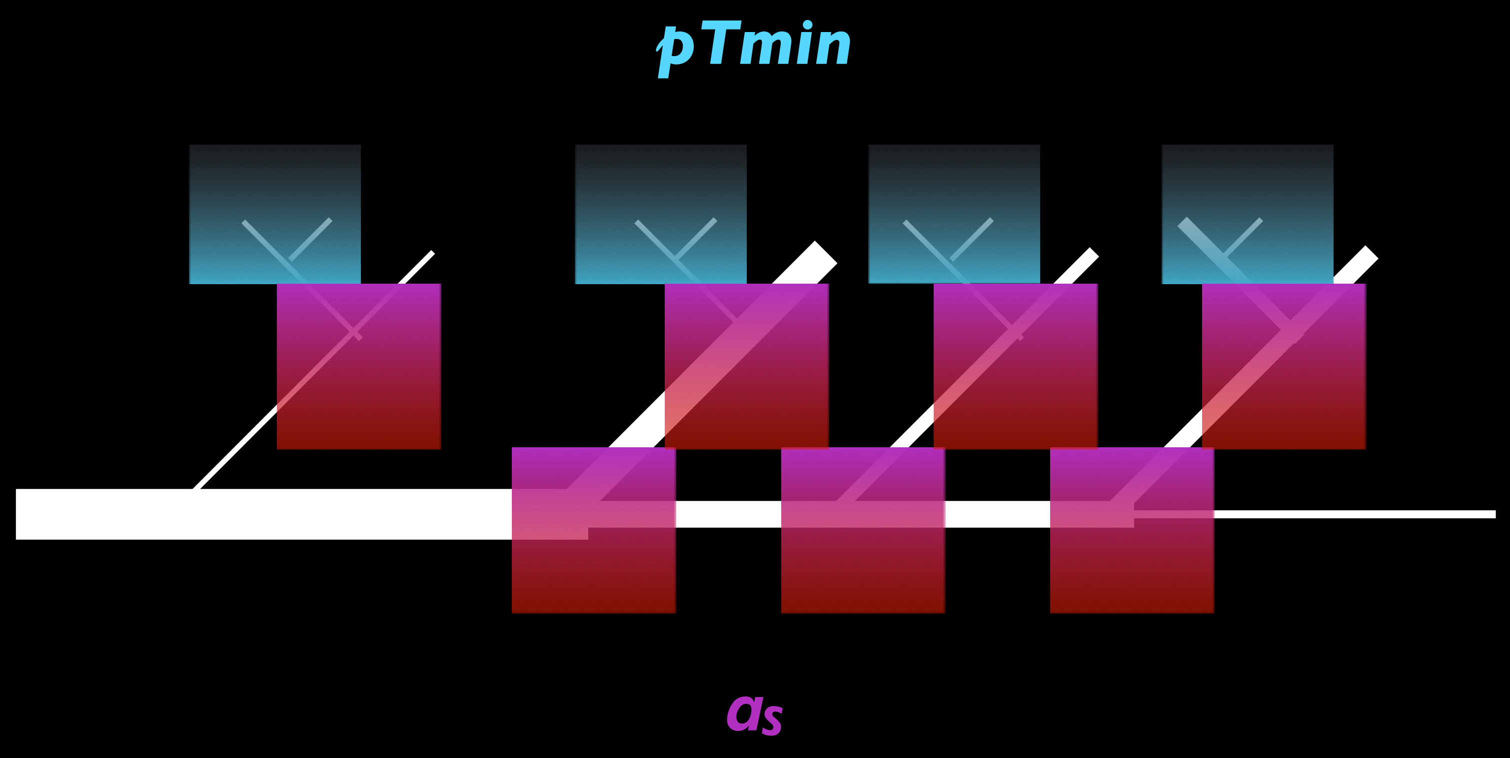
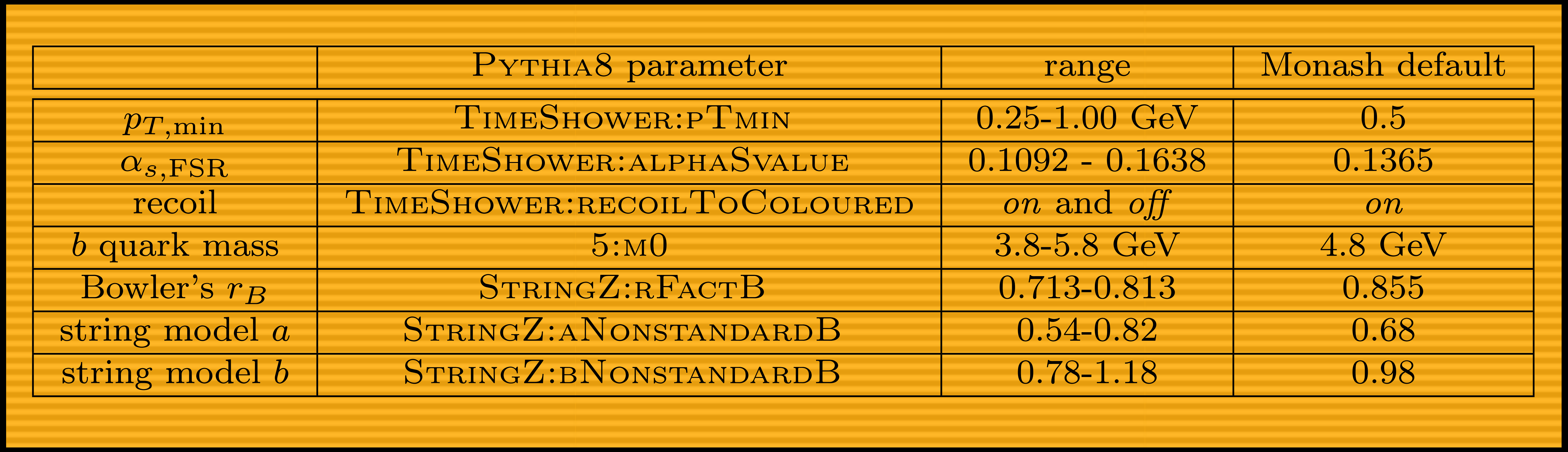
EVENT GENERATORS

PYTHIA PARAMETERS





	Pythia8 parameter	range	Monash default
$p_{T,\mathrm{min}}$	TimeShower:pTmin	0.25-1.00 GeV	0.5
$\alpha_{s,\mathrm{FSR}}$	TimeShower:alphaSvalue	0.1092 - 0.1638	0.1365
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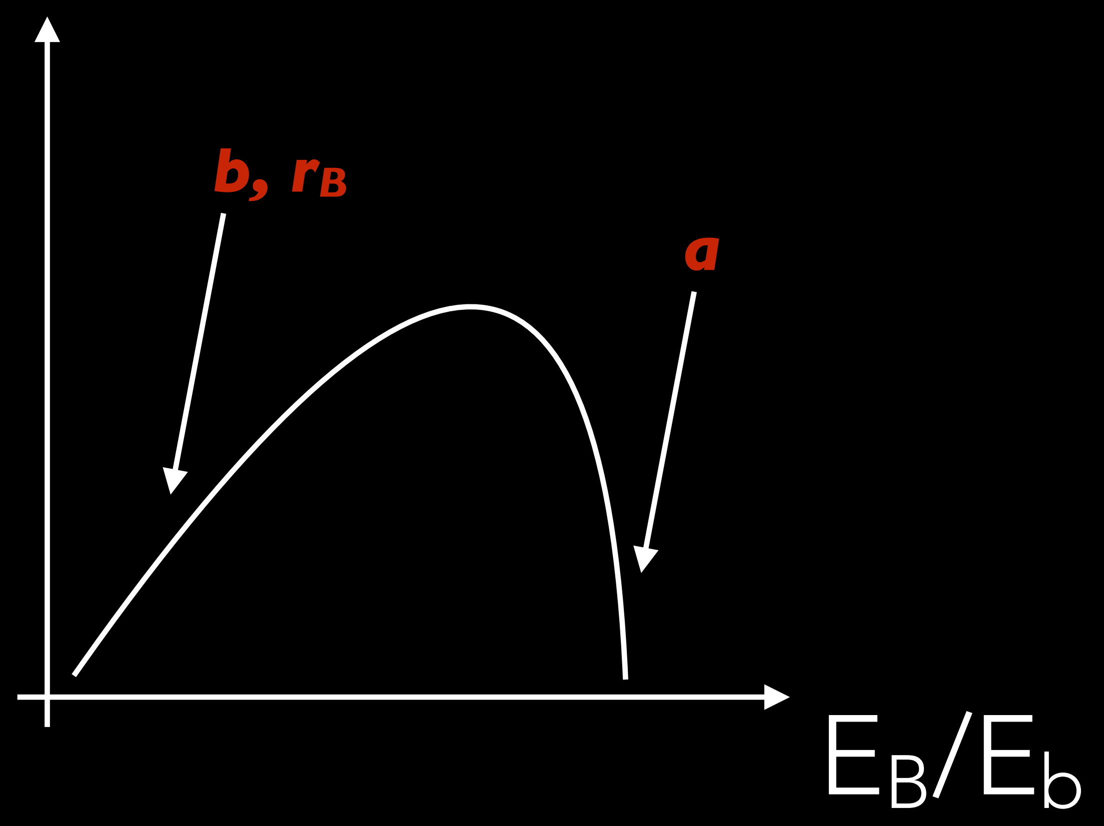

EVENT GENERATORS

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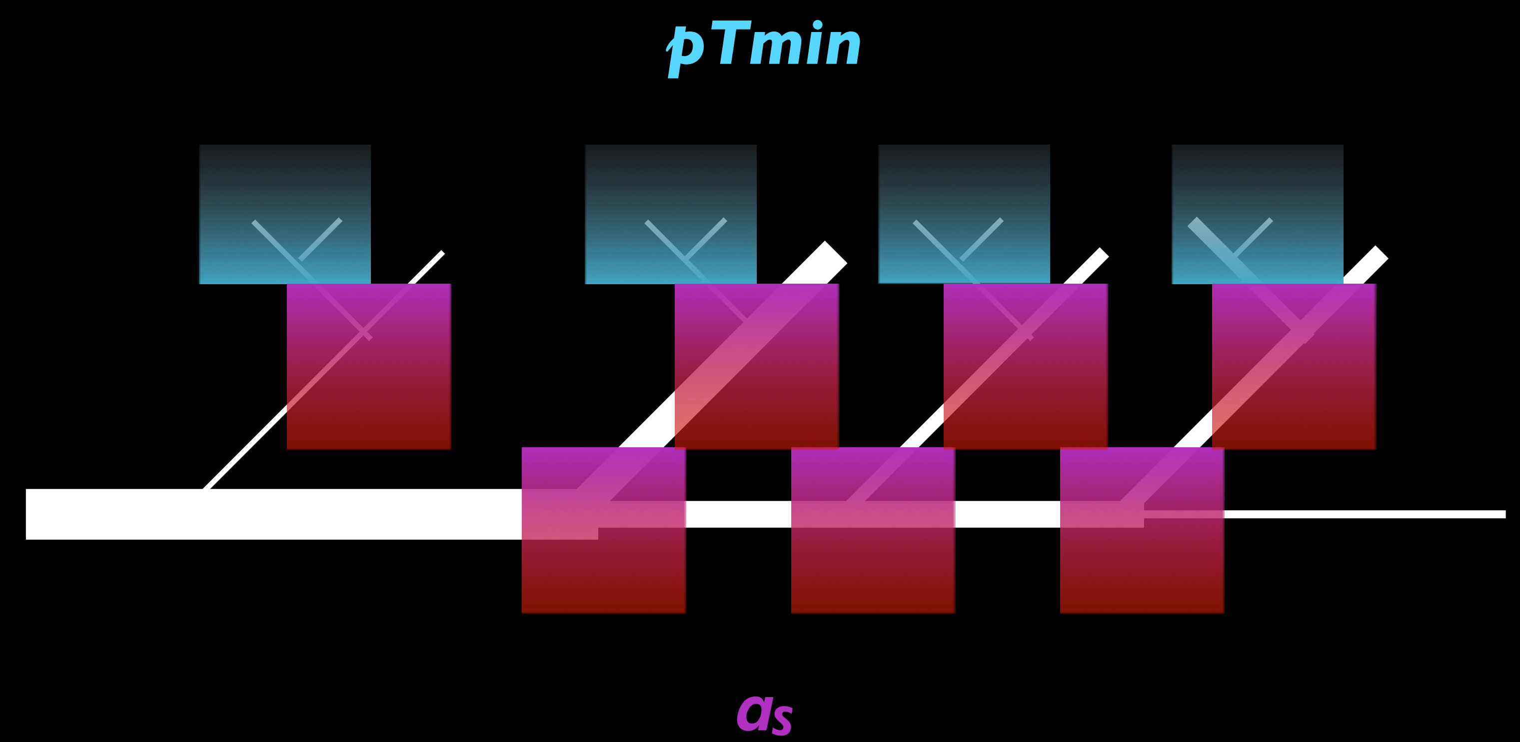
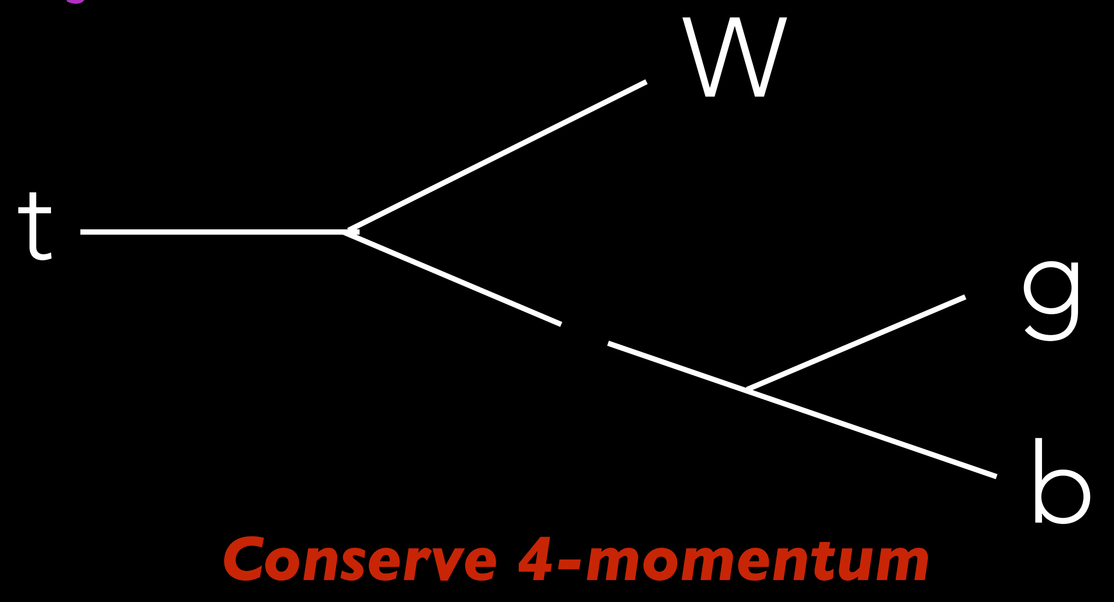
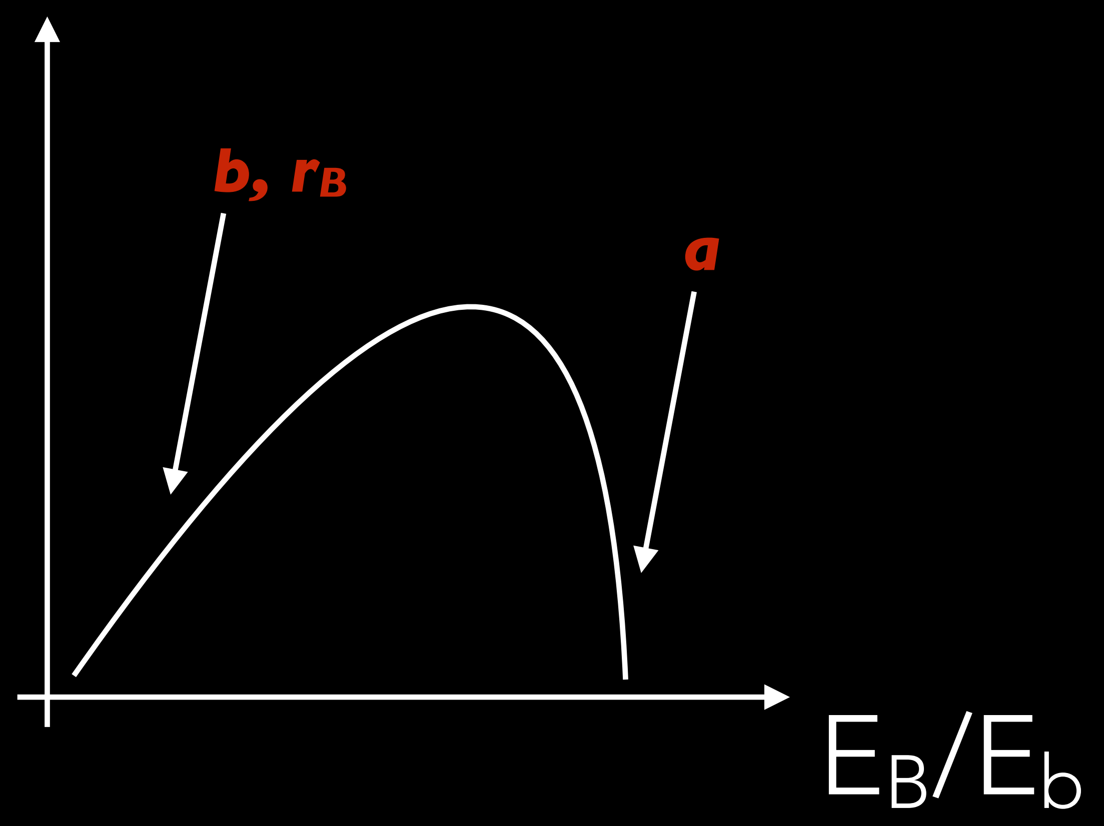
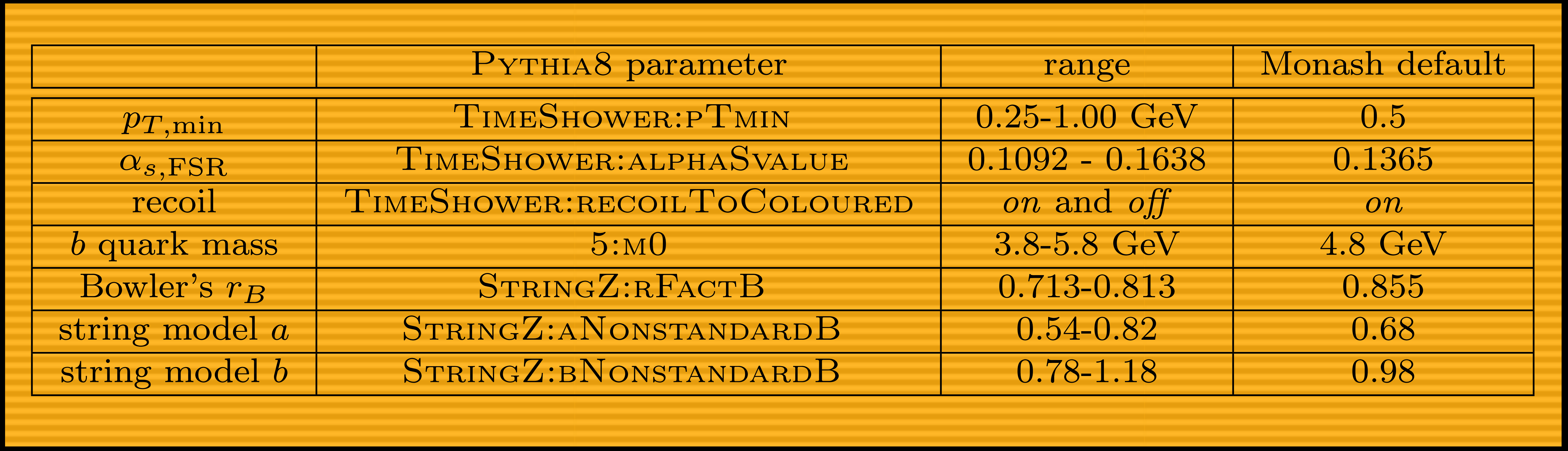




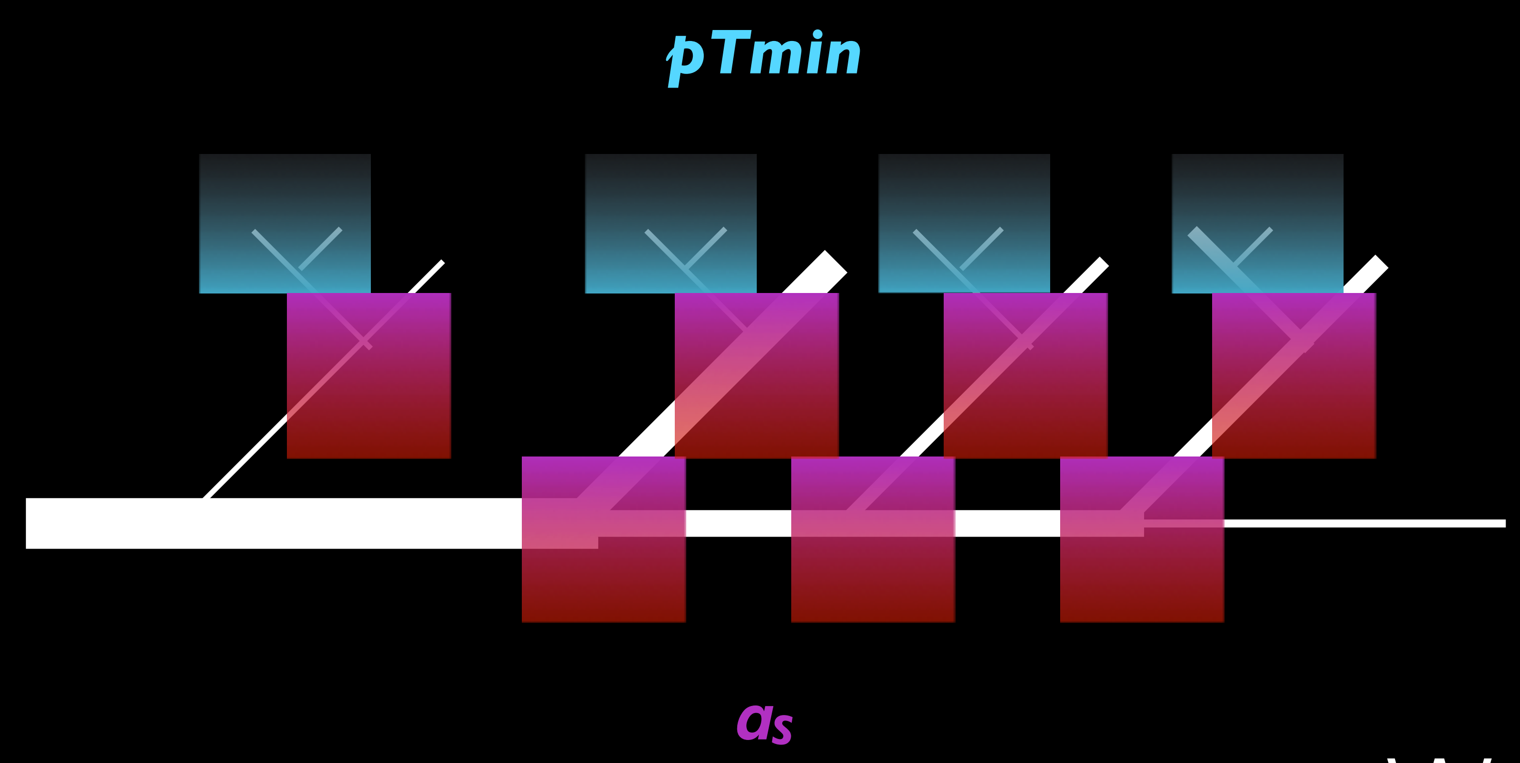


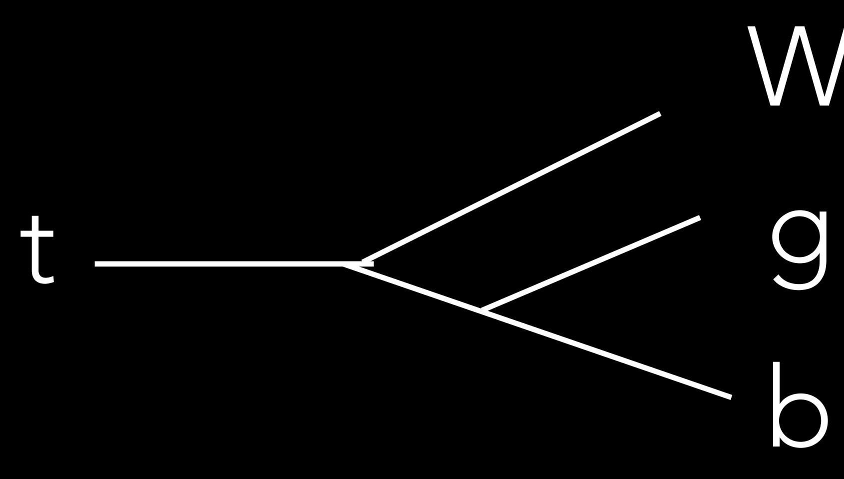


	Pythia8 parameter	range	Monash default
$p_{T,\mathrm{min}}$	TimeShower:pTmin	0.25-1.00 GeV	0.5
$\alpha_{s,\mathrm{FSR}}$	TimeShower:alphaSvalue	0.1092 - 0.1638	0.1365
recoil	TimeShower:recoilToColoured	*on* and *off*	*on*
b quark mass	5:m0	3.8-5.8 GeV	4.8 GeV
Bowler's r_B	StringZ:rFactB	0.713-0.813	0.855
string model a	StringZ:aNonstandardB	0.54-0.82	0.68
string model b	StringZ:bNonstandardB	0.78-1.18	0.98

EVENT GENERATORS

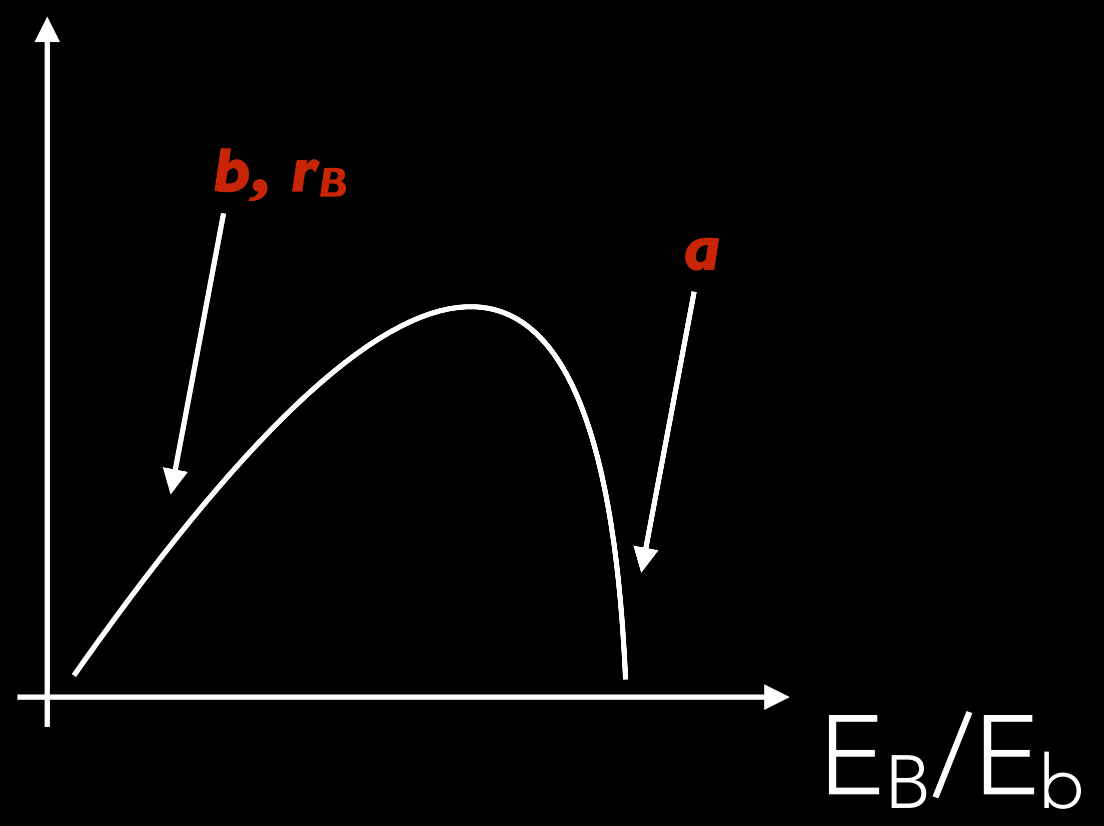
PYTHIA PARAMETERS

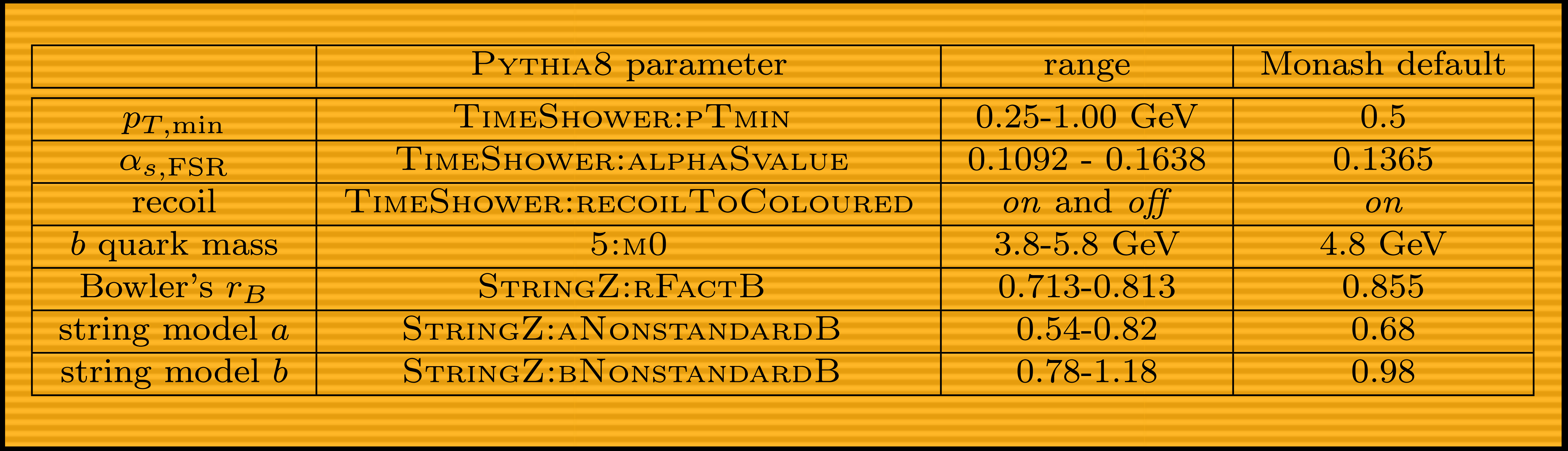




Conserve 4-momentum

Conserve 4-momentum

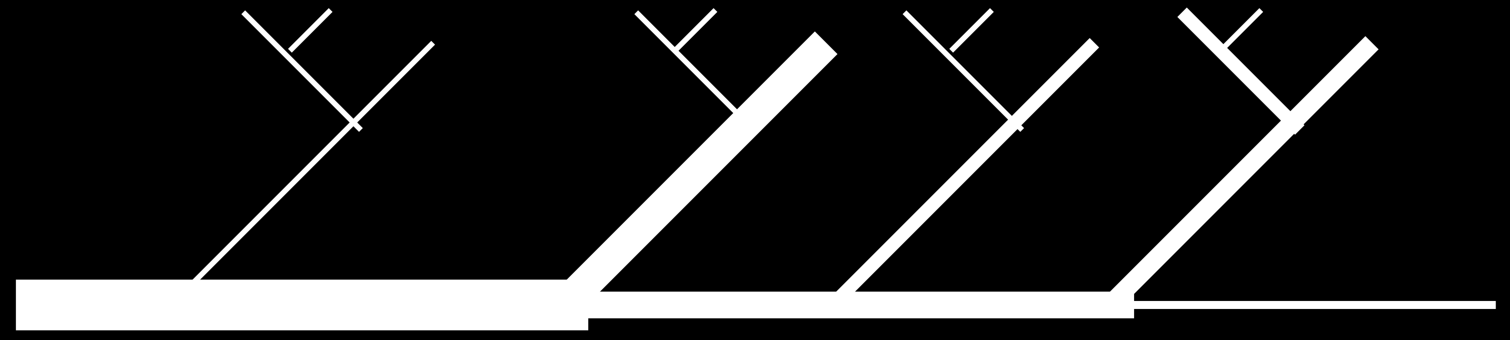


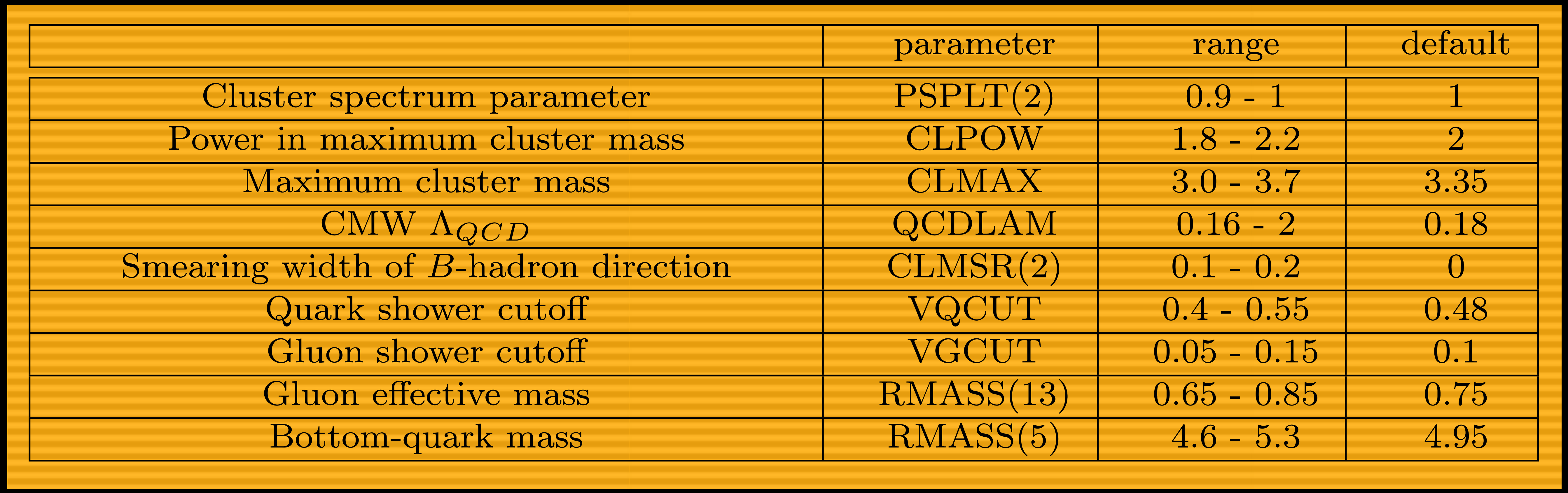


	PYTHIA8 parameter	range	Monash default
$p_{T,\mathrm{min}}$	TIMESHOWER:PTMIN	0.25-1.00 GeV	0.5
$\alpha_{s,\mathrm{FSR}}$	TIMESHOWER:ALPHASVALUE	0.1092 - 0.1638	0.1365
recoil	TIMESHOWER:RECOILTOCOLOURED	*on* and *off*	*on*
b quark mass	5:M0	3.8-5.8 GeV	4.8 GeV
Bowler's r_B	STRINGZ:RFACTB	0.713-0.813	0.855
string model a	STRINGZ:ANONSTANDARDB	0.54-0.82	0.68
string model b	STRINGZ:BNONSTANDARDB	0.78-1.18	0.98

EVENT GENERATORS

HERWIG PARAMETERS



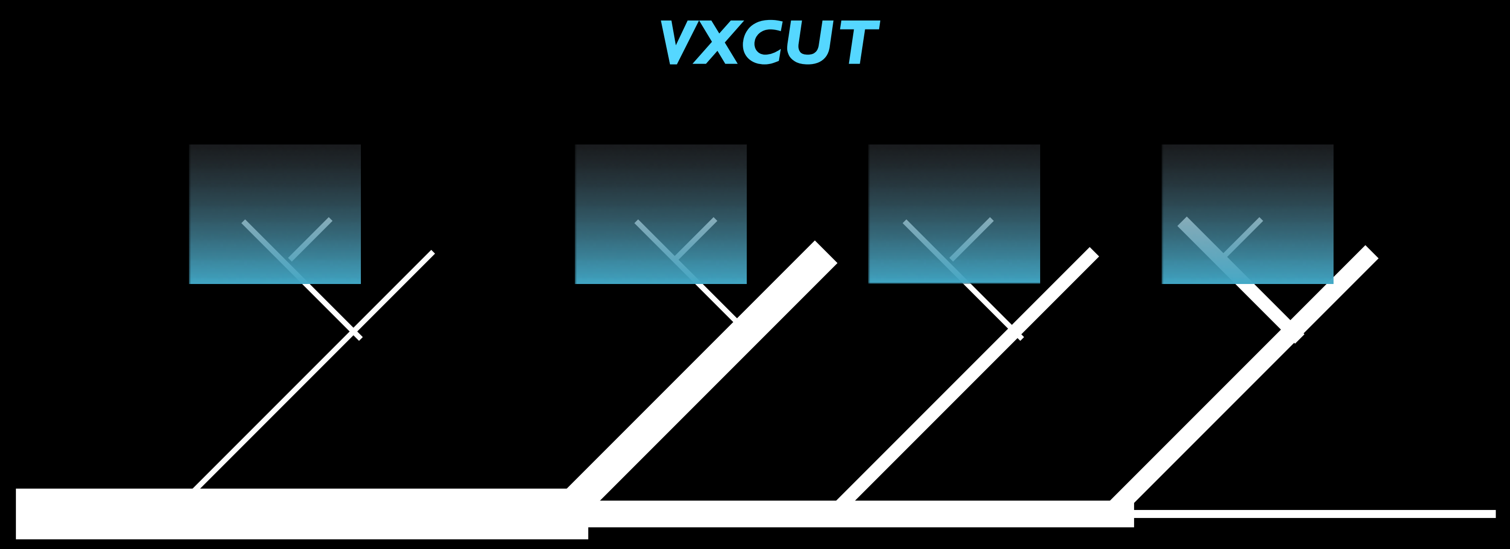


	parameter	range	default
Cluster spectrum parameter	PSPLT(2)	0.9 - 1	1
Power in maximum cluster mass	CLPOW	1.8 - 2.2	2
Maximum cluster mass	CLMAX	3.0 - 3.7	3.35
CMW Λ_{QCD}	QCDLAM	0.16 - 2	0.18
Smearing width of B-hadron direction	CLMSR(2)	0.1 - 0.2	0
Quark shower cutoff	VQCUT	0.4 - 0.55	0.48
Gluon shower cutoff	VGCUT	0.05 - 0.15	0.1
Gluon effective mass	RMASS(13)	0.65 - 0.85	0.75
Bottom-quark mass	RMASS(5)	4.6 - 5.3	4.95

MASS OF DAUGHTER CLUSTERS UNIFORMLY DISTRIBUTED IN M^{PSPLT}

EVENT GENERATORS

HERWIG PARAMETERS



	parameter	range	default
Cluster spectrum parameter	PSPLT(2)	0.9 - 1	1
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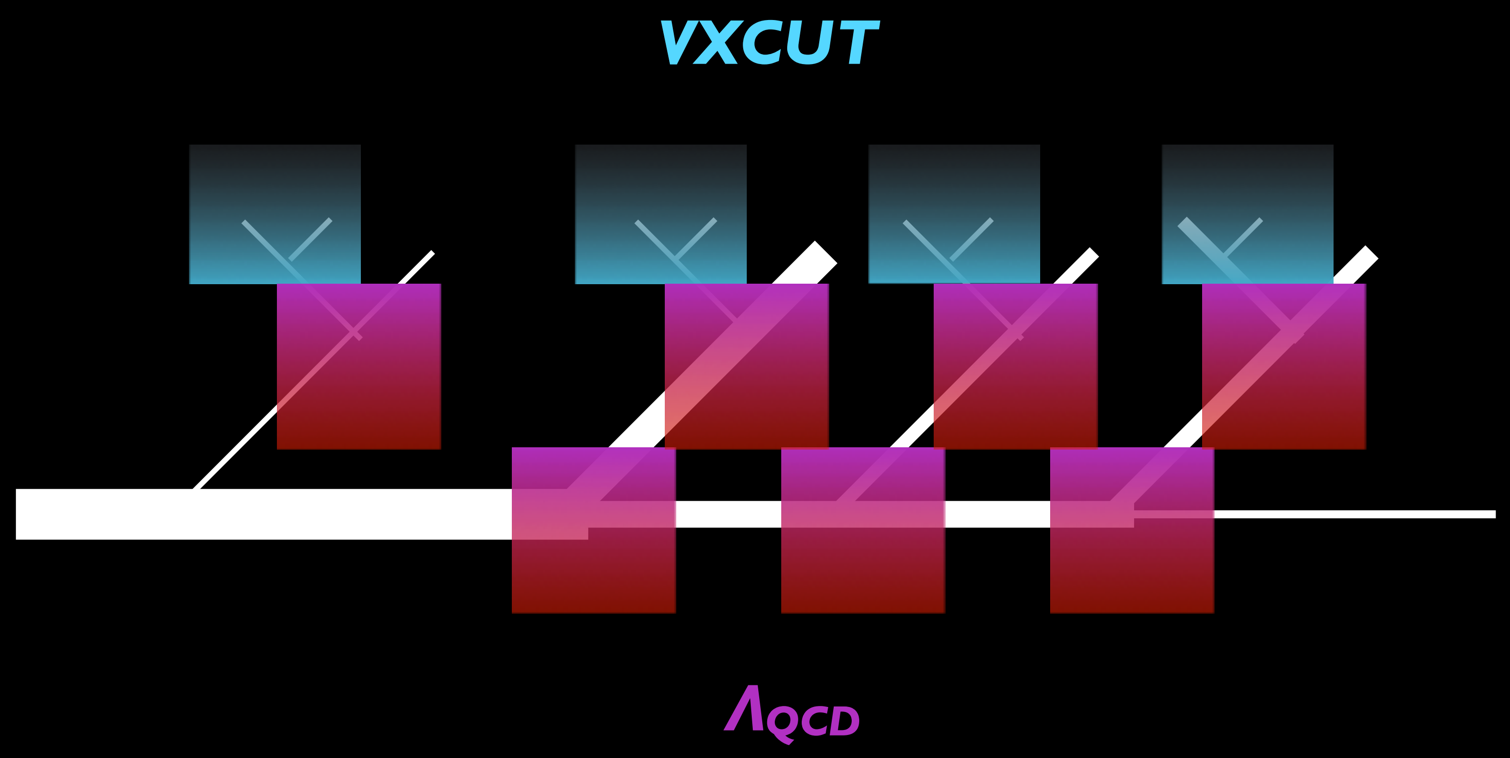
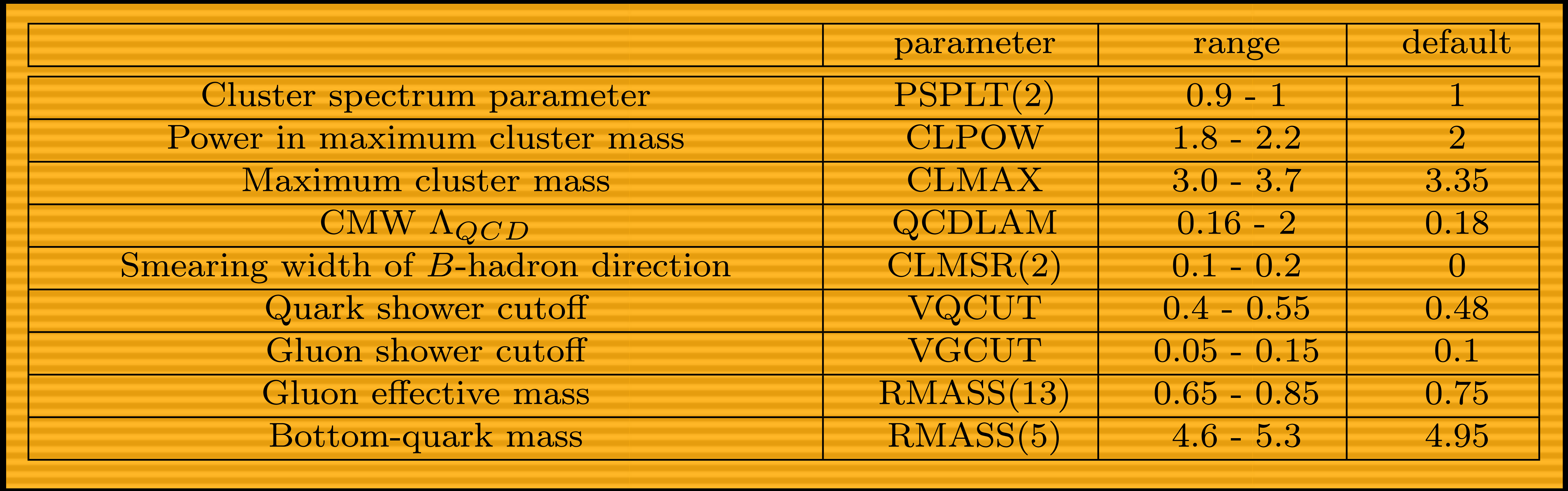
MASS OF DAUGHTER CLUSTERS UNIFORMLY DISTRIBUTED IN M^{PSPLT}

EVENT GENERATORS

HERWIG PARAMETERS





	parameter	range	default
Cluster spectrum parameter	PSPLT(2)	0.9 - 1	1
Power in maximum cluster mass	CLPOW	1.8 - 2.2	2
Maximum cluster mass	CLMAX	3.0 - 3.7	3.35
CMW Λ_{QCD}	QCDLAM	0.16 - 2	0.18
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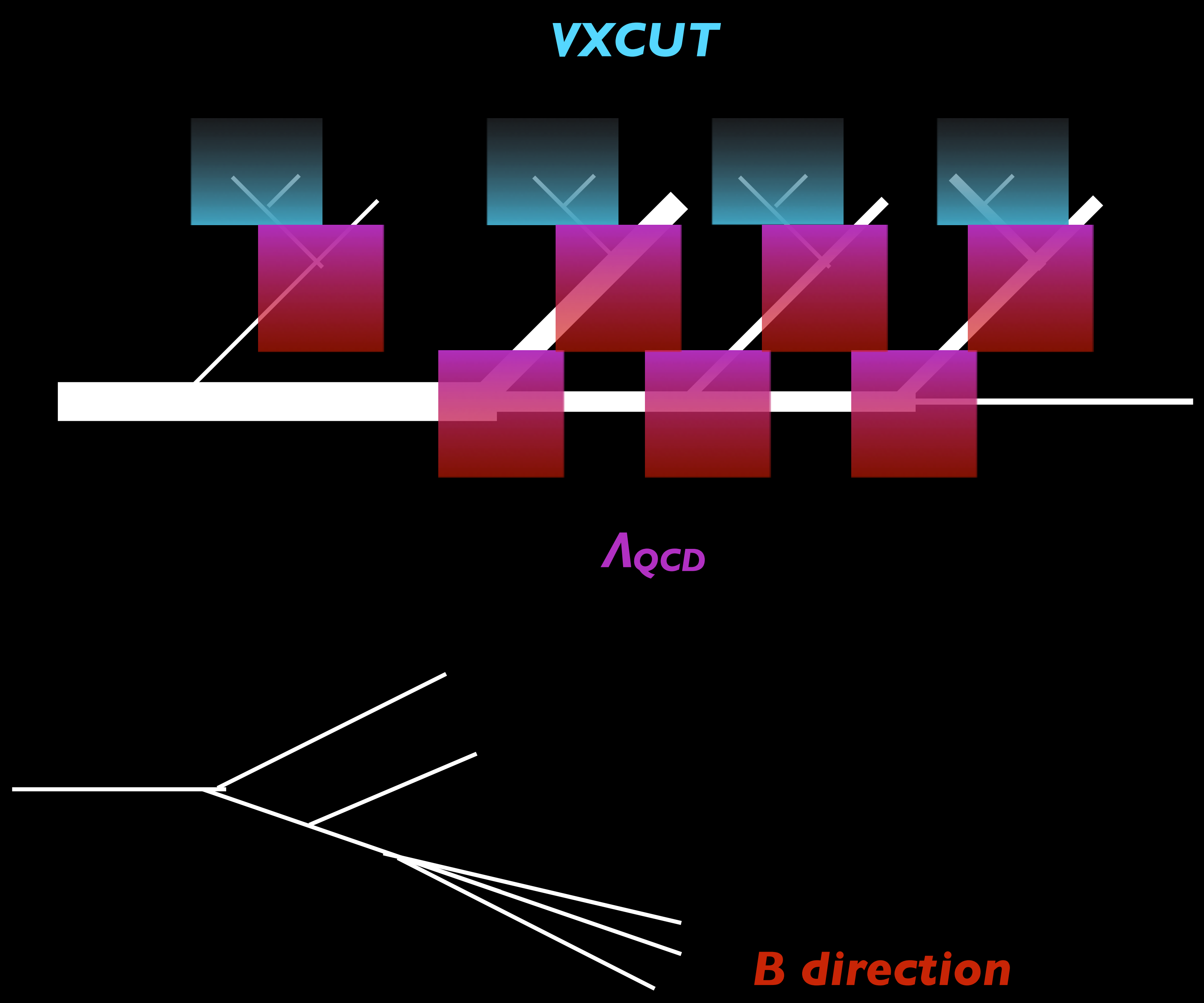
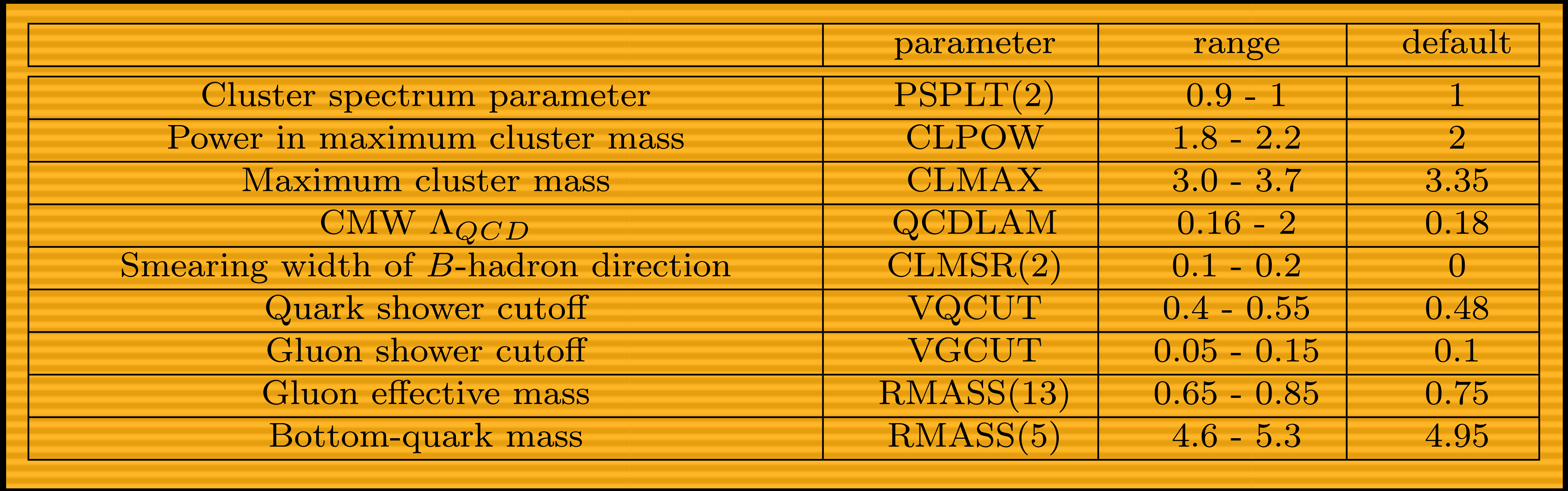
MASS OF DAUGHTER CLUSTERS UNIFORMLY DISTRIBUTED IN M^{PSPLT}

EVENT GENERATORS

HERWIG PARAMETERS





	parameter	range	default
Cluster spectrum parameter	PSPLT(2)	0.9 - 1	1
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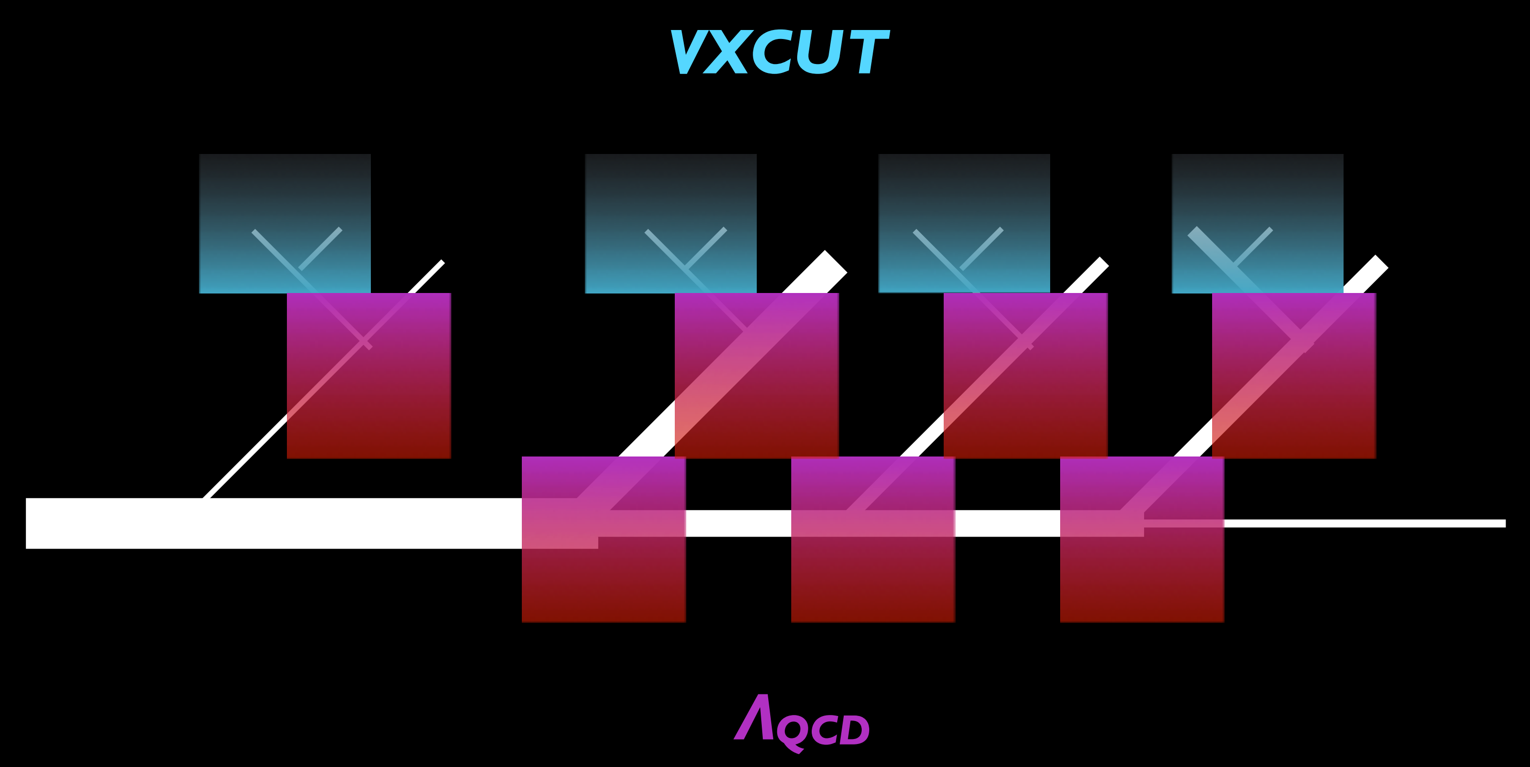
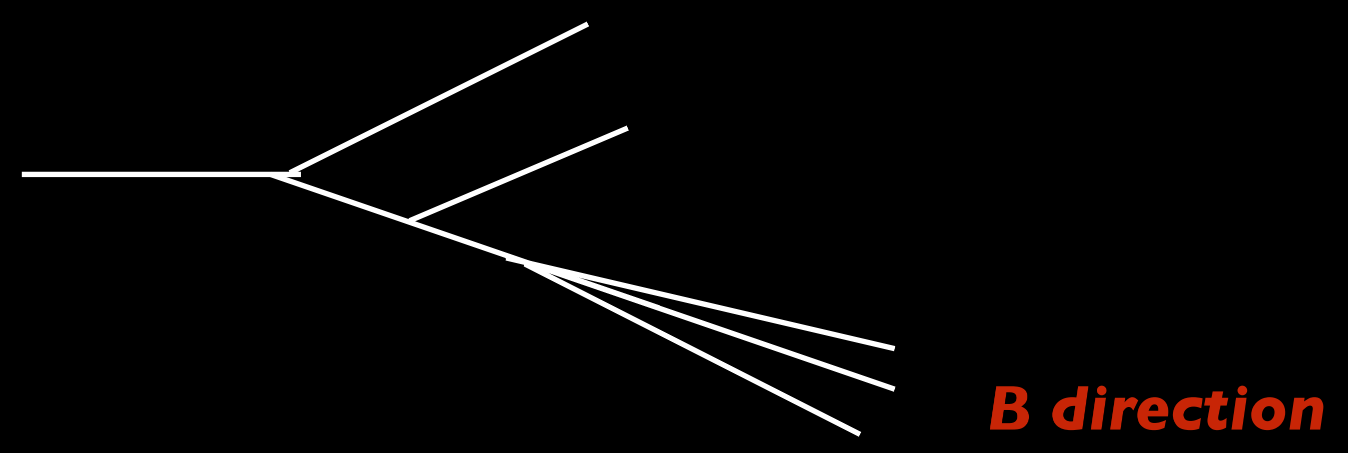
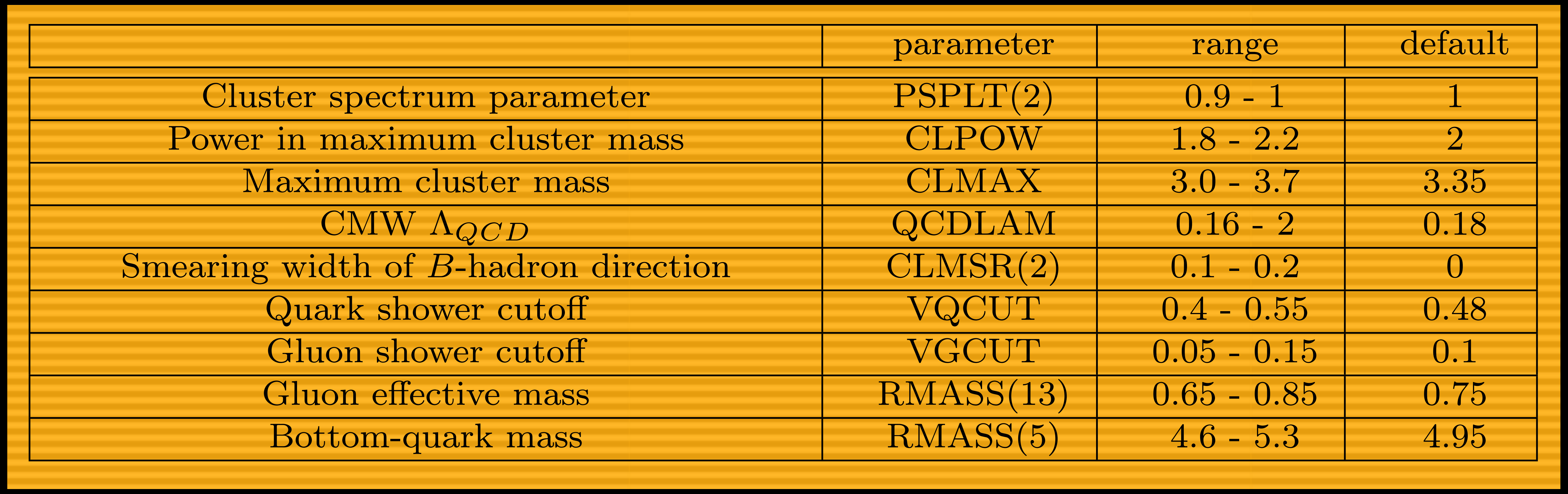
MASS OF DAUGHTER CLUSTERS UNIFORMLY DISTRIBUTED IN M^{PSPLT}

EVENT GENERATORS

HERWIG PARAMETERS







	parameter	range	default
Cluster spectrum parameter	PSPLT(2)	0.9 - 1	1
Power in maximum cluster mass	CLPOW	1.8 - 2.2	2
Maximum cluster mass	CLMAX	3.0 - 3.7	3.35
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Gluon effective mass	RMASS(13)	0.65 - 0.85	0.75
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$$M^{\texttt{CLPOW}} < \texttt{CLMAX}^{\texttt{CLPOW}} + (\texttt{RMASS}(i) + \texttt{RMASS}(j))^{\texttt{CLPOW}}$$

MASS OF DAUGHTER CLUSTERS UNIFORMLY DISTRIBUTED IN M^{PSPLT}