Fragmentation Uncertainties in Hadronic Observables for Top-quark Mass Measurements

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LHC Top Working Group Meeting at CERN, May 16, 2018

In collaboration with Gennaro Corcella and Roberto Franceschini,
Nucl.Phys. B929 (2018) 485-526, arXiv:1712.05801

Top Quark Mass Measurements

- Precision m_{top} measurement: extremely important in both SM and BSM
- From standard/conventional approaches to alternative ones
  - Template method [ATLAS, Eur. Phys. J. C72 (2012)]
  - Ideogram method [CMS PAS TOP 14-001]
  - Matrix element method [DØ, Phys.Rev. D91 (2015) 112003]
  - Cross sections [ATLAS, Eur. Phys. K. C74 (2014), CONF 2014-053]
  - Endpoint method [CMS PAS TOP 11-027; CMS TOP 15-008]
  - b-jet energy-peak method [CMS PAS TOP 15-002]
  - Solvability method [**DK**, Matchev and Shyamsundar, in progress]
  - J/ψ method [CMS PAS TOP 15-014]
  - B-hadron 2D-decay length [CMS PAS TOP 12-030]
  - Leptonic final state [CMS PAS TOP 16-002]
  - **B-hadron observables** [Corcella, Franceschini and **DK**, Nucl.Phys. B929 (2018)]
  - Many more which I can't exhaust

SM top assumed (Template method through Cross sections)

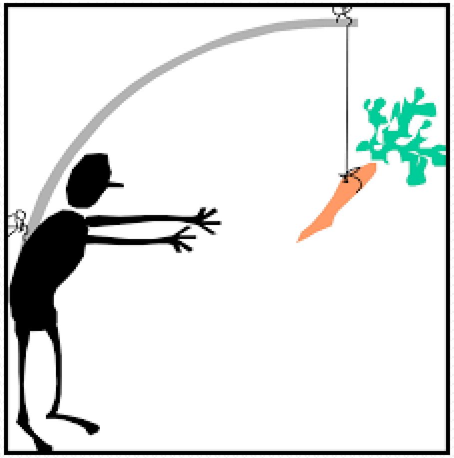
Kinematics-based (Endpoint method through J/ψ method)

Jets in the final state → JES (Template method through J/ψ method)

No jetty objects in the final state → no JES, Th. uncertainty (B-hadron 2D-decay length through Many more)

Motivation for Different Measurement Strategies

- From a <u>more experimental</u> point of view,
  - different methods having different sensitivity to systematics
  - complementary to one another



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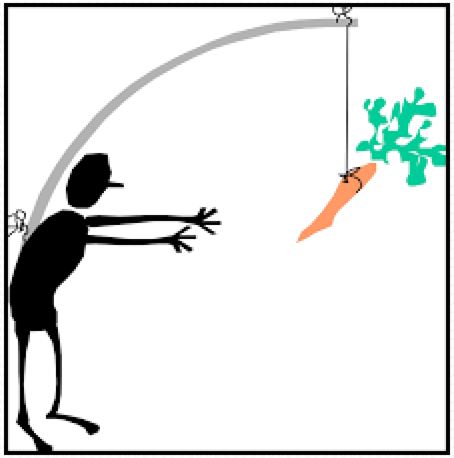
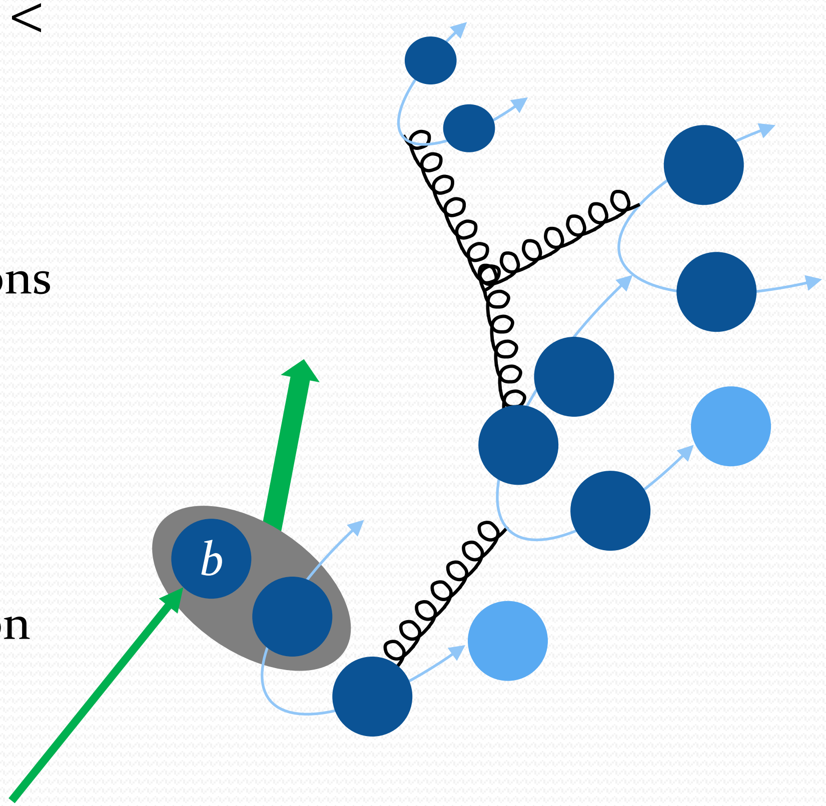


- From a more phenomenological point of view,
  - good exercise/testbed for new physics signature
  - pair-produced mother particles, invisible particles, multi-step decays, etc.
  - (Potentially) a new handle in search for new physics, e.g., *b* partner searches

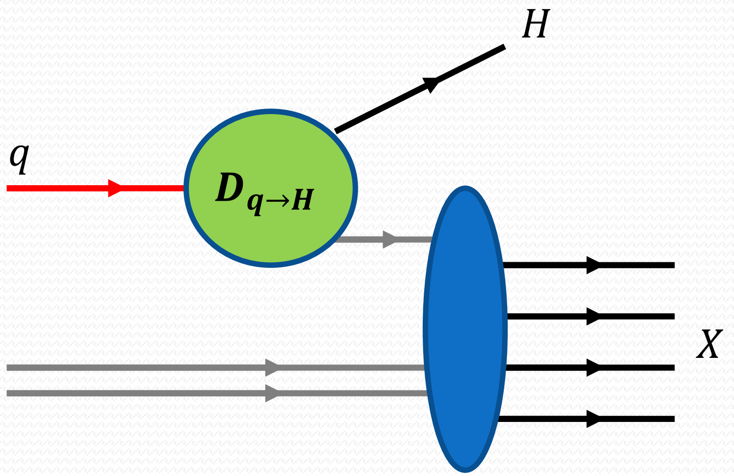
B-hadron Observables

- "**Pure tracker**" observables with $\delta_{sys} <$ 1% available
- **Crucial** to understand the transformation from a quark to hadrons

- However, **challenging** because it is governed by non-perturbative QCD (similar conclusions hold for B-hadron decay length method [Hill, Incandela, Lamb (2005); CMS-PAS-TOP-12-030])



Filling the Gap: Theoretical Approach



- Fitting fragmentation function, $D_{q\to H}(z)$
- Precision data available at LEP [arXiv: 1102.4748, hep-ex/01120282] and SLD [hep-ex/0202031]
- For b quark, the extraction of the fragmentation function at NNLO in α_s [Fickinger, Fleming, Kim, Mereghetti (2016)], NLO+NLL [Cacciari, Nason, Oleari (2005)]

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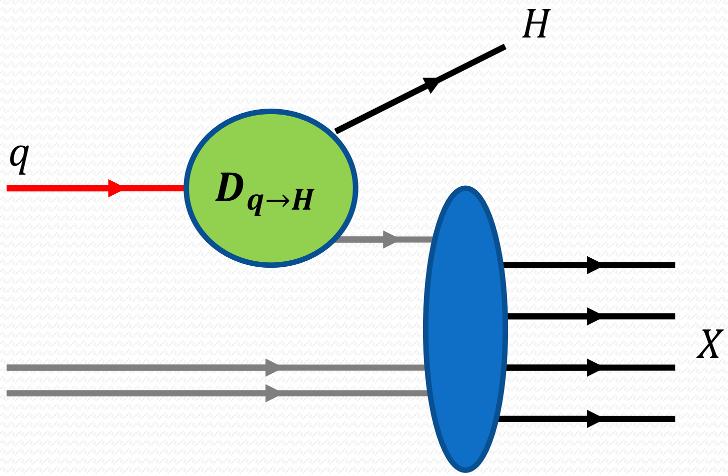

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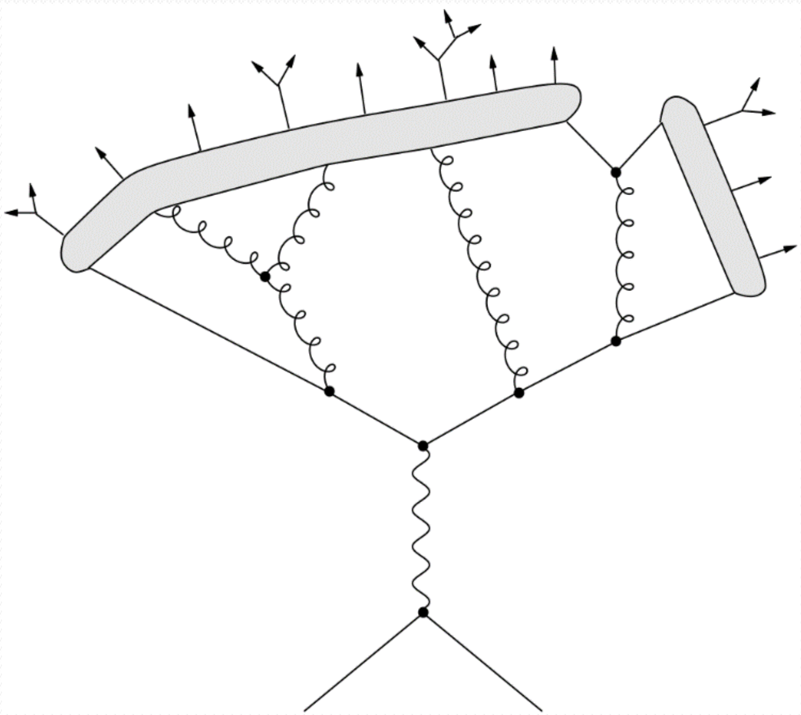
- Higher order corrections necessary (including resummation sometimes)
- Relying on factorization of the cross section to a very high accuracy
- Not guaranteed to work equally well when lepton collider data is applied to hardon colliders

Filling the Gap: Phenomenological Approach



- ❑ Employing hadronization model with phenomenological parameters [Andersson, Gustafson, Ingelman, Sjostrand (1983)]
- ❑ "Tuning" of the parameters to reproduce the available data

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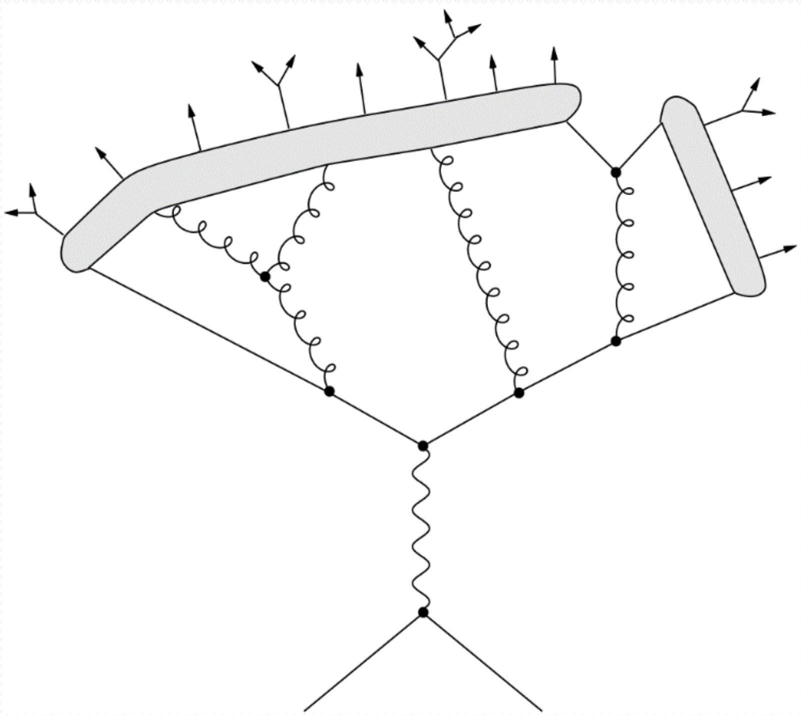

- ❑ Employing hadronization model with phenomenological parameters [Andersson, Gustafson, Ingelman, Sjostrand (1983)]
- ❑ "Tuning" of the parameters to reproduce the available data
- ❑ **Not obvious** that the tuned model (with $e^+e^- \to$ hadrons) describes the future data [D. d'Enterria et al. (2013)]
- ❑ Should be tested at hadron collider environment (**incredible amount of statistics** available!!)

Our Goal

- Top quark mass sensitivity to parameters
  - What parameters should be constrained to achieve better precision
  - How to constrain them

Our Goal

m_t **determination observables**

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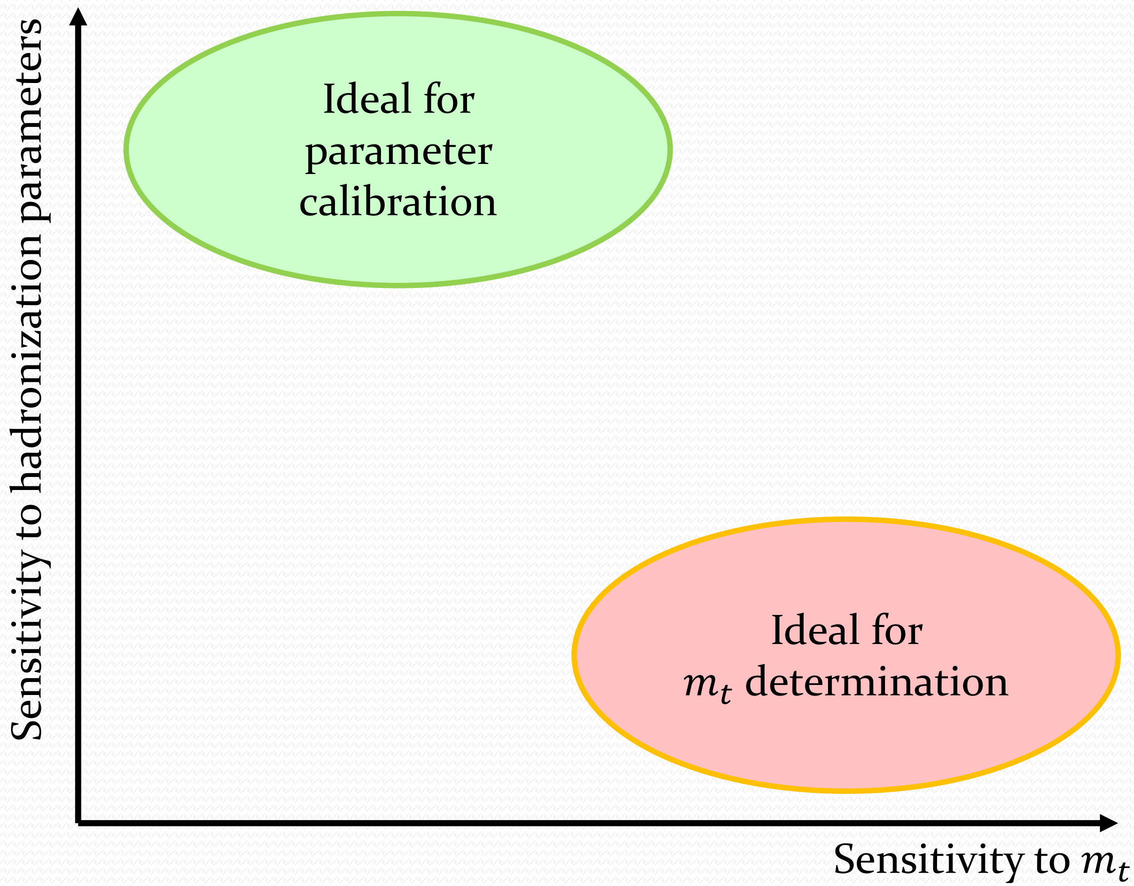
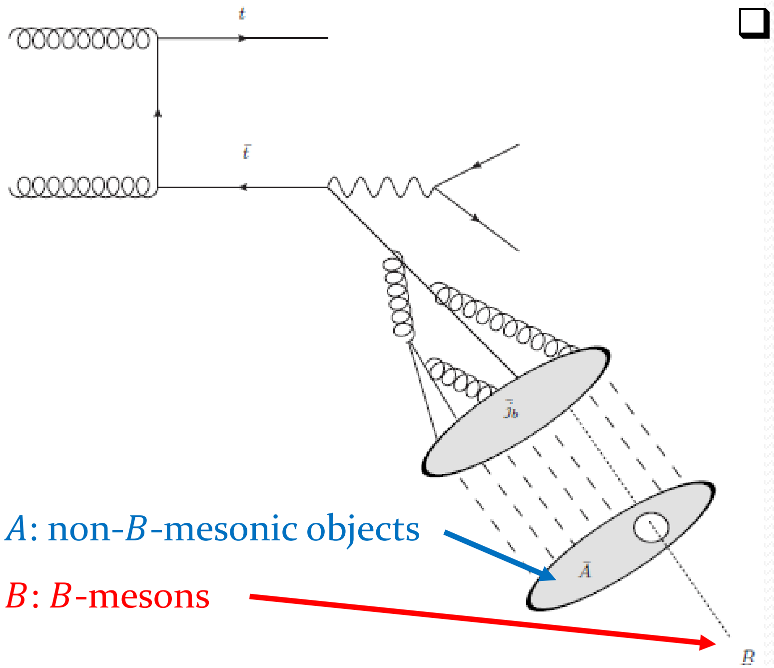
  - ➢ What parameters should be constrained to achieve better precision
  - ➢ How to constrain them

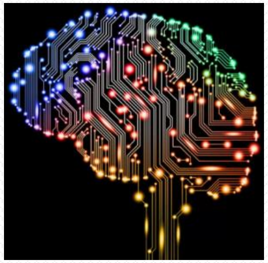
Calibration observables

Ideal Observables



Methodology in a Nutshell





- For a given input top mass,
  1) set relevant parameters (next slide),
  2) generate, shower, and hadronize leptonic $t\bar{t}$ events using PYTHIA 8.2.19,
  3) find anti-k_t jets using FastJet,
  4) find jets containing a B-hadron as a constituent, and extract its information,
  5) evaluate various B-hadron observables/ calibration variables along with (sometimes) leptons: Mellin moments, peak/endpoint,
  6) Correlate them with input top masses and find sensitivity measures (defined later),
  7) Repeat 1) through 6) for other parameter sets

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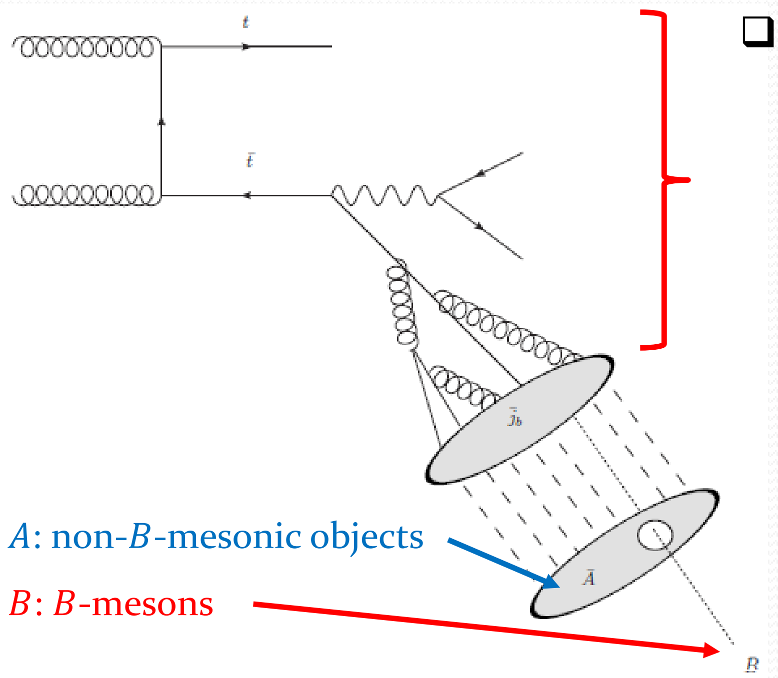

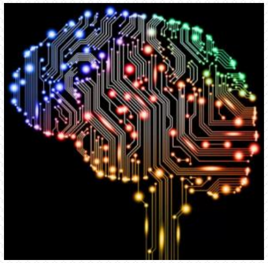

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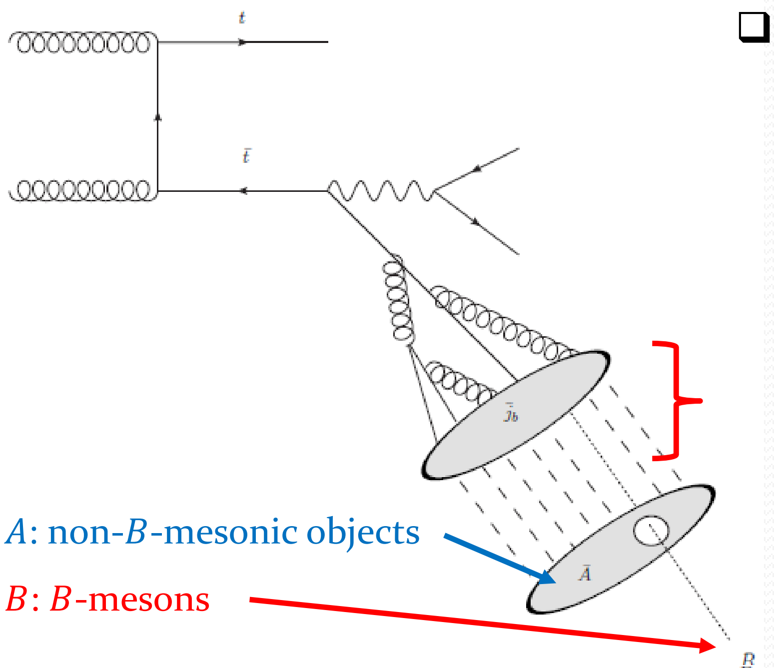

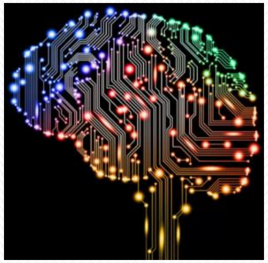

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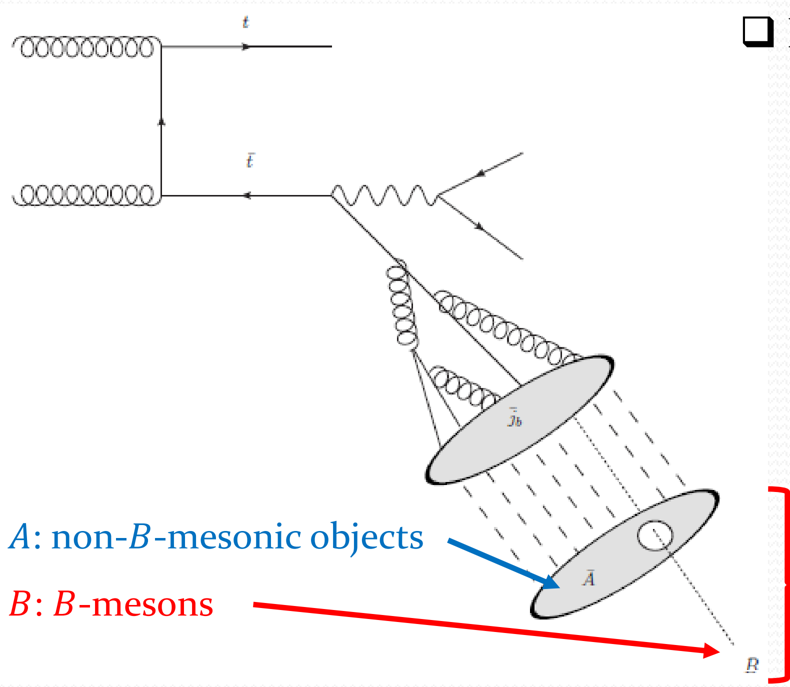

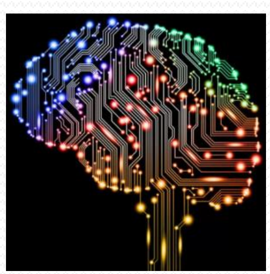

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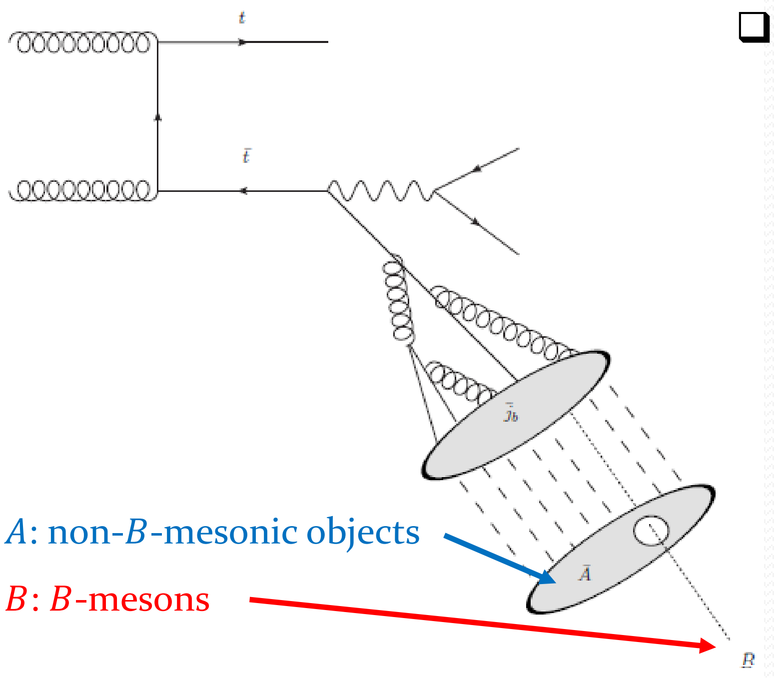

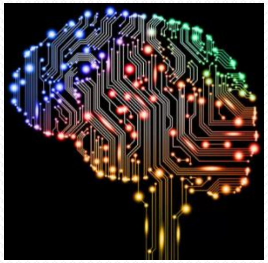

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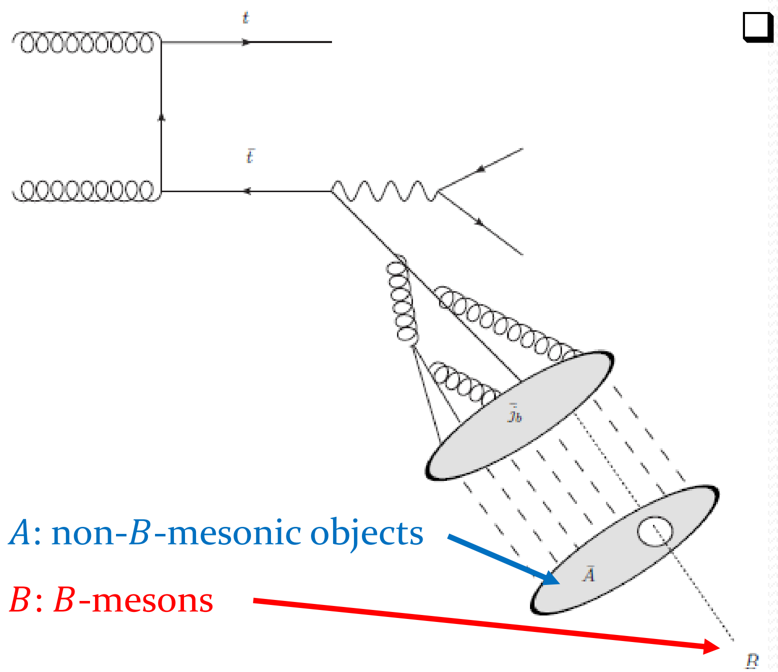

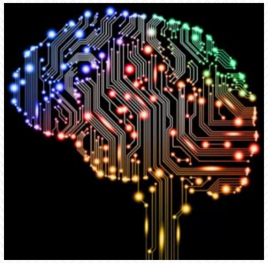

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Pythia Parameters

	PYTHIA8 parameter	range	Monash default
$p_{T,\min}$	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

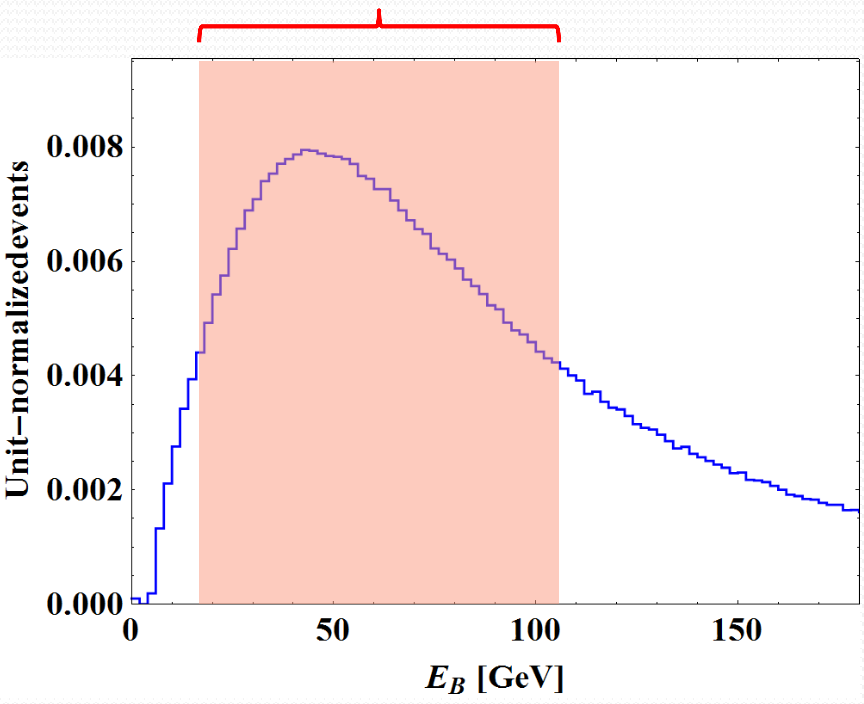
Showering parameters

Heavy flavor-specific had. parameters

Table 1: Ranges and central values of the parameters that we varied. Note that some values are not varied around the default values of the Monash tuning. For instance we run r_B around the mid-point between PYTHIA6.4 and PYTHIA8-MONASH values.

Measurements: Mellin Moment Analysis

Full Width Half Maximum (FWHM)



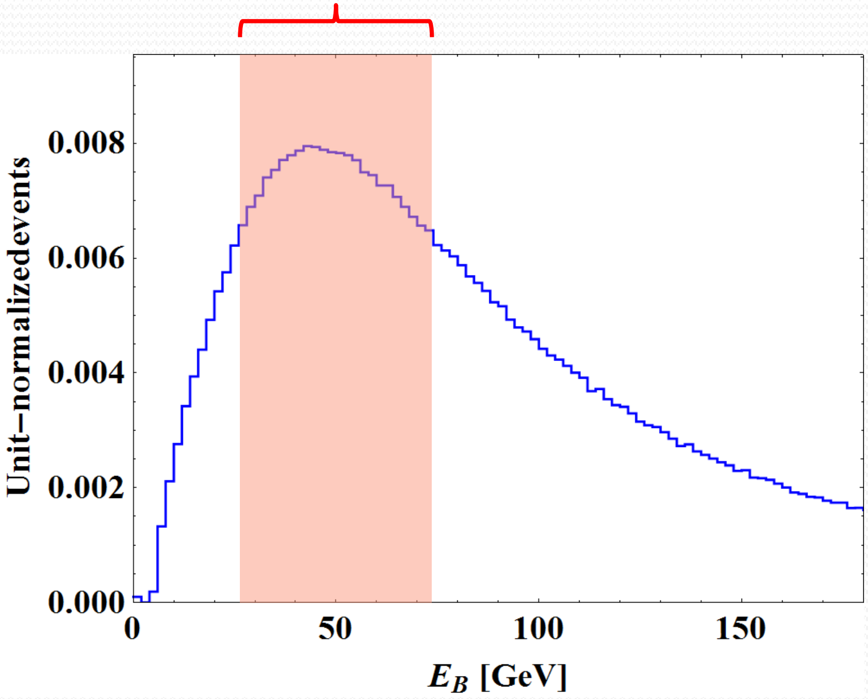
- First Mellin moment

$$\mathcal{M}_1 = \int_{FWHM} dx\, x f(x)$$

Average of x in the range

Measurements: Shape Analysis - Peak

Full Width at ¾ Maximum (yielding χ^2/dof~1)



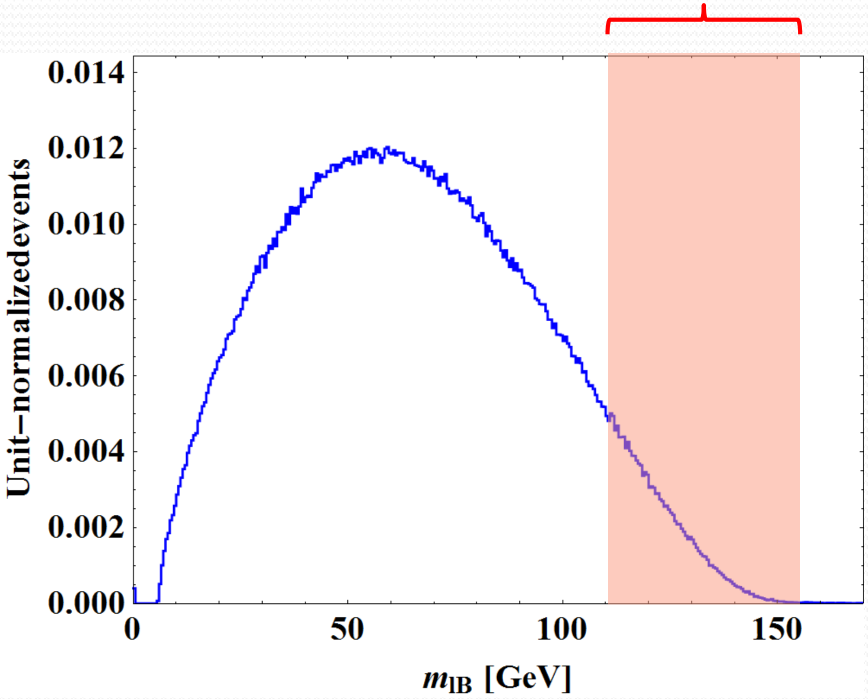
- Fitting template inspired by the one in [Agashe, Franceschini, **DK**, Phys.Rev. D88 (2012) 057701]

$$f(x) = p_1 \exp\left[-p_2\left(\frac{x}{p_3} + \frac{p_3}{x}\right)\right]$$

peak position

Measurements: Shape Analysis - Endpoint

~10% from the endpoint (yielding χ^2/dof~1)



- ❑ Fitting with a second-order polynomial

$$f(x) = p_1(x - x_m)^2 + p_2(x - x_m)$$

endpoint

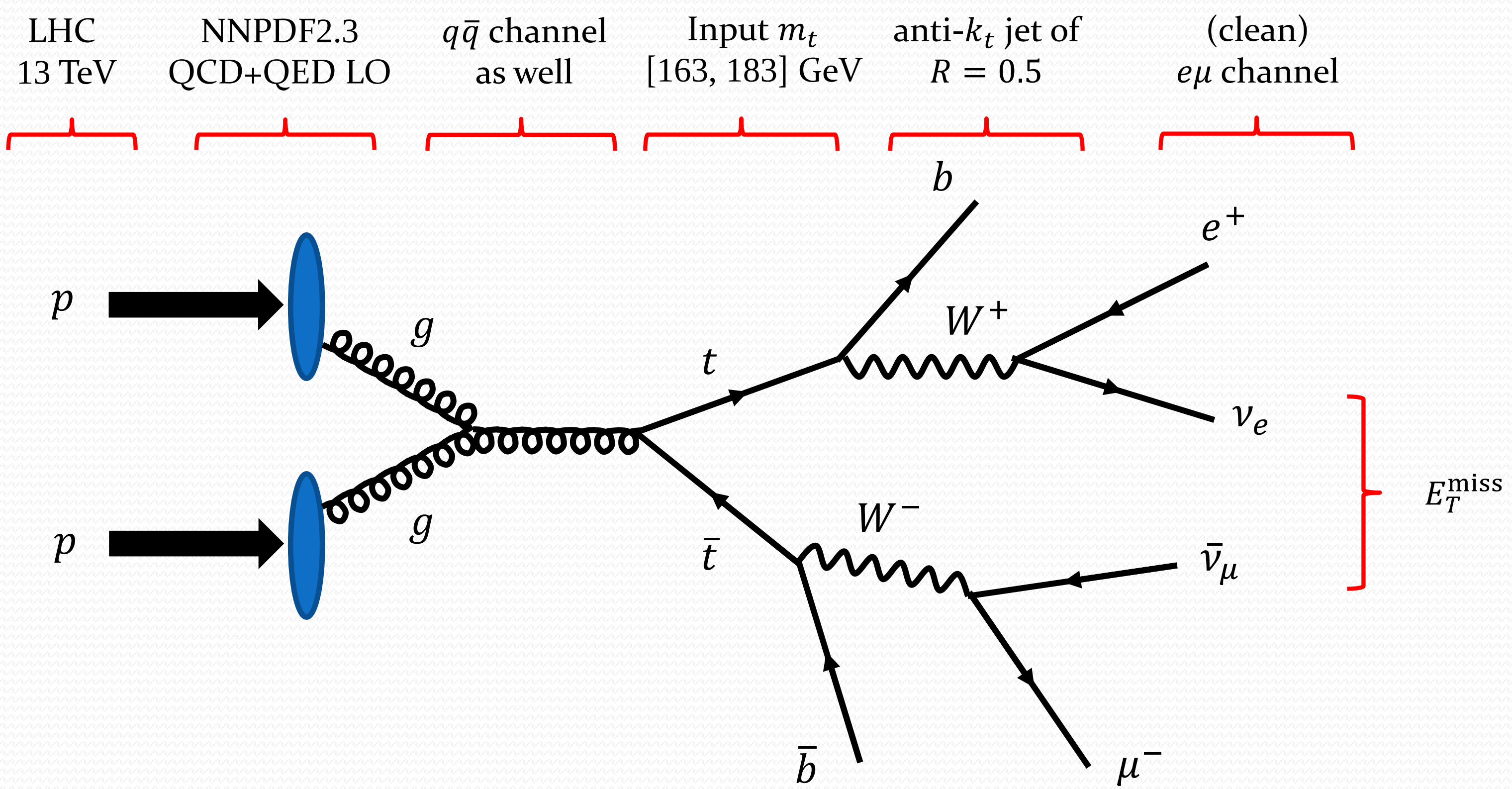
- ❑ Endpoints are insensitive to Pythia parameters (i.e., ideal for m_t determination).
- ❑ However, 10% bulk may reintroduce the sensitivity. ⇒ Fortunately, we have found that is not the case with smaller fit ranges.

m_t Determination Observables

Observable	$\mathcal{M}_1$	Shape	Features
E_B	V	V (peak)	• Expecting inheritance of "invariance" property of the energy-peak in the b-jet energy spectrum
$E_{B_1} + E_{B_2}$	V	-	• Two B-meson tagging required
$P_{T,B}$	V	-	
$P_{T,B_1} + P_{T,B_2}$	V	-	• Two B-meson tagging required
$m_{B\ell}$	V	V	• True pairing (theory-level) • Experimental observable paring: the smaller in each combination
$m_{BB\ell\ell}$	V	-	• Two B-meson tagging required
m_{T2}	V	V	• (B) and $(B\ell)$ subsystems • True assignment (theory-level) for the $(B\ell)$ subsystems • Experimental observable paring for the $(B\ell)$ subsystems: the smaller of the two possible assignments • Different ISR and MET definitions
$m_{T2,\perp}$[1]	V	V	• ISR-free observables • (B) and $(B\ell)$ subsystems • Different ISR and MET definitions

[1]: Matchev and Park (2009)

Event Simulation



- PartonLevel:MPI = off, HadronLevel:Decay = off
- Cuts: $p_{T,j} > 30$ GeV, $|\eta_j| < 2.4$, $\quad p_{T,\ell} > 20$ GeV, $|\eta_\ell| < 2.4$.

Summary of Results: Mellin Moments

$\mathcal{O}$	Range	$\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})}$	$\Delta_\theta^{(m_t)}$						
			$\alpha_{s,FSR}$	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)
$m_{T2,B\ell,\text{true}}^{(\text{mET})}$	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)
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$m_{T2}^{(\ell\nu)}$	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)

$$\Delta_\theta^{(m_t)} = \frac{\delta m_t/m_t}{\delta\theta/\theta}$$

$$\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})} = \frac{\delta \mathcal{M}_\mathcal{O}/\mathcal{M}_\mathcal{O}}{\delta m_t/m_t}$$

Summary of Results: Mellin Moments

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$m_{T2}^{(\ell\nu)}$	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)
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$$\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})} = \frac{\delta \mathcal{M}_\mathcal{O}/\mathcal{M}_\mathcal{O}}{\delta m_t/m_t}$$

- Top quark mass measurements in B-hadron observables are **sensitive most to $\alpha_{s,\text{FSR}}$**, e.g., 10% uncertainty in $\alpha_{s,\text{FSR}}$ corresponds to $2-5\%$ uncertainty in the top quark mass ⇒ affecting radiation in the final state, in turn, changing energy scale of B-hadrons!
- Purely leptonic observables have least sensitivities to parameters, but less sensitivity to m_t ⇒ ***B-ℓ* system is a good compromise** as it has comparable sensitivity to m_t but smaller sensitivities to parameters.

Summary of Results: Shape

$\mathcal{O}$	Range	$\Delta_{m_t}^{(\mathcal{O})}$	$\Delta_\theta^{(m_t)}$						
			$\alpha_{s,FSR}$	m_b	$p_{T,\min}$	a	b	r_B	recoil
$E_{B,\mathrm{peak}}$	35-85	0.8(1)	-0.74(9)	-0.26(4)	0.05(1)	-0.04(2)	0.08(3)	-0.07(9)	-0.031(7)
$\breve{m}_{B\ell,\mathrm{true}}$	127-150	1.26(1)	0.017(6)	0.003(9)	-0.006(2)	-0.008(2)	0.008(7)	-0.016(6)	-0.00042(9)
$\breve{m}_{B\ell,\mathrm{min}}$	127-150	1.28(1)	-0.023(3)	-0.022(2)	0.006(3)	-0.008(3)	0.008(3)	-0.02(1)	-0.0001(6)
$\breve{m}_{T2,B\ell,\mathrm{true}}^{(\mathrm{mET})}$	150-170	0.98(2)	-0.01(2)	-0.023(3)	0.007(1)	-0.006(3)	0.010(4)	-0.011(9)	-0.0002(8)
$\breve{m}_{T2,B\ell,\mathrm{min}}^{(\mathrm{mET})}$	150-170	0.97(2)	-0.02(1)	-0.021(5)	0.006(2)	-0.006(3)	0.009(4)	-0.01(1)	-0.0001(8)
$\breve{m}_{T2,B\ell,\mathrm{min},\perp}^{(\mathrm{mET})}$	138-170	0.89(2)	-0.071(5)	-0.046(7)	0.012(2)	-0.011(7)	0.010(8)	-0.01(2)	-0.002(1)
$\breve{m}_{T2,B}^{(\mathrm{mET})}$	142-170	0.95(3)	-0.089(6)	-0.064(6)	0.018(1)	-0.017(4)	0.031(4)	-0.04(2)	-0.0028(8)
$\breve{m}_{T2,B,\perp}^{(\mathrm{mET})}$	126-170	0.94(4)	-0.07(1)	-0.04(1)	0.011(3)	-0.009(9)	0.02(1)	-0.03(4)	-0.001(2)

$$\Delta_\theta^{(m_t)} = \frac{\delta m_t/m_t}{\delta\theta/\theta}$$

$$\Delta_{m_t}^{(\mathcal{O})} = \frac{\delta\mathcal{O}/\mathcal{O}}{\delta m_t/m_t}$$

Summary of Results: Shape

$\mathcal{O}$	Range	$\Delta_{m_t}^{(\mathcal{O})}$	$\Delta_{\theta}^{(m_t)}$						
			$\alpha_{s,FSR}$	m_b	$p_{T,\min}$	a	b	r_B	recoil
$E_{B,\text{peak}}$	35-85	0.8(1)	-0.74(9)	-0.26(4)	0.05(1)	-0.04(2)	0.08(3)	-0.07(9)	-0.031(7)
$\breve{m}_{B\ell,\text{true}}$	127-150	1.26(1)	0.017(6)	0.003(9)	-0.006(2)	-0.008(2)	0.008(7)	-0.016(6)	-0.00042(9)
$\breve{m}_{B\ell,\min}$	127-150	1.28(1)	-0.023(3)	-0.022(2)	0.006(3)	-0.008(3)	0.008(3)	-0.02(1)	-0.0001(6)
$\breve{m}_{T2,B\ell,\text{true}}^{(\text{mET})}$	150-170	0.98(2)	-0.01(2)	-0.023(3)	0.007(1)	-0.006(3)	0.010(4)	-0.011(9)	-0.0002(8)
$\breve{m}_{T2,B\ell,\min}^{(\text{mET})}$	150-170	0.97(2)	-0.02(1)	-0.021(5)	0.006(2)	-0.006(3)	0.009(4)	-0.01(1)	-0.0001(8)
$\breve{m}_{T2,B\ell,\min,\perp}^{(\text{mET})}$	138-170	0.89(2)	-0.071(5)	-0.046(7)	0.012(2)	-0.011(7)	0.010(8)	-0.01(2)	-0.002(1)
$\breve{m}_{T2,B}^{(\text{mET})}$	142-170	0.95(3)	-0.089(6)	-0.064(6)	0.018(1)	-0.017(4)	0.031(4)	-0.04(2)	-0.0028(8)
$\breve{m}_{T2,B,\perp}^{(\text{mET})}$	126-170	0.94(4)	-0.07(1)	-0.04(1)	0.011(3)	-0.009(9)	0.02(1)	-0.03(4)	-0.001(2)

$$\Delta_{\theta}^{(m_t)} = \frac{\delta m_t/m_t}{\delta\theta/\theta}$$

$$\Delta_{m_t}^{(\mathcal{O})} = \frac{\delta\mathcal{O}/\mathcal{O}}{\delta m_t/m_t}$$

- Top quark mass measurements in shape observables are **less sensitive to $\alpha_{s,\text{FSR}}$** (except energy-peak in B-hadron energy spectrum) ⇒ kinematic endpoints are less affected by process dynamics
- Sensitivities of top quark mass to the **bottom mass** and the **Lund-Bowler parameter** become comparable!
- Statistics will be a major challenge in performing precision measurements of endpoints.

Moral from the Results

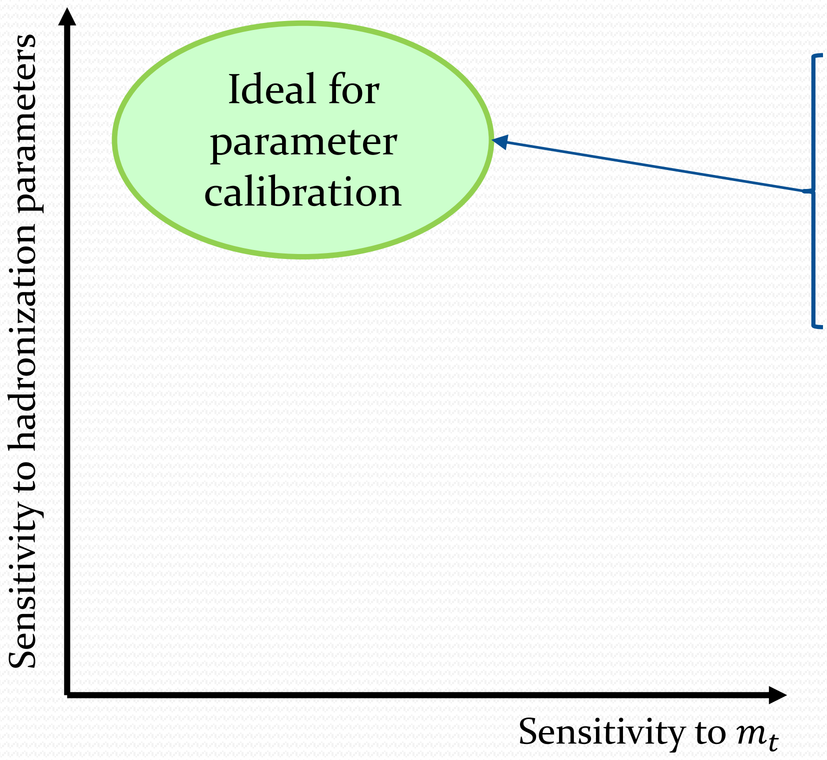
No perfect fit

- No ideal/perfect observables least sensitive to Pythia parameters, but highly sensitive to top quark mass whose associate channels come with enough statistics

  $\Rightarrow$ Calibrate the parameters

  $\Rightarrow$ **What to constrain** and **how to constrain**

Ideal Calibration Observables



- Ideal "in-situ" calibration observables: **no/little sensitivity** to (input) **top quark mass**, but having **decent sensitivities** to **hadronization and showering parameters** in $t\bar{t}$ events [see for similar effort, e.g. ATL-PHYS-PUB-2015-007]

- We don't know which is ideal or not a priori.
  $\Rightarrow$ Introduce many observables having different sensitivities to parameters in order to maximize the ability for calibration.

Selected Calibration Observables

- $\frac{p_{T,B}}{p_{T,j_b}}, \frac{E_B}{E_{j_b}}, \frac{E_B}{E_\ell}, \frac{E_B}{E_\ell+E_{\bar{\ell}}}$
- $m(j_b)\ \mathrm{GeV}^{-1}$
- $\rho(r) = \frac{1}{\Delta r}\frac{1}{E_j}\sum_{\mathrm{track}} E_{\mathrm{track}} \cdot \Theta(|r - \Delta R_{j,\mathrm{track}}| < \delta r)$: the radial jet energy density [ATLAS Collaboration, arXiv:1307.5749], $\Theta(x)$: Heaviside theta function
- $\chi_B(X_B) = \frac{2E_B}{X_B}$ with $X_B = m_{j_b j_{\bar{b}}}, \sqrt{s_{\mathrm{min},bb}}, \sum p_{T,j_{b/\bar{b}}}, E_{j_b} + E_{j_{\bar{b}}}$
- $\frac{m_{BB}}{m_{j_b j_{\bar{b}}}}$
- $\Delta\phi(j_b j_{\bar{b}}), \Delta R(j_b j_{\bar{b}}), \Delta\phi(BB), \Delta R(BB), |\Delta\phi(BB) - \Delta\phi(j_b j_{\bar{b}})|, |\Delta R(BB) - \Delta R(j_b j_{\bar{b}})|$

Different Information

- Calibration observables sensitive to hadronization and showering parameters
  - Variables $\frac{p_{T,B}}{p_{T,j_b}}$ and $\rho(r)$ are sensitive to the importance of the heavy-quark hadron in the jet and to the energy distribution in the jet ⇒ suitable to **probe the dynamics on the conversion of a single parton into a hadron**
  - χ_B variables are more sensitive to global nature (i.e., $b\bar{b}$ system) ⇒ probing **"cross-talk" between partons** in the process of forming color-singlet hadrons
  - Various aspects probed by different χ_B options

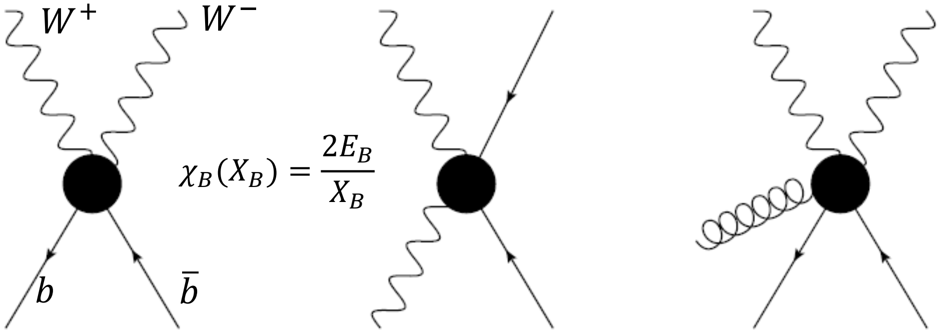


Figure 2: Three kinematical configurations distinguished by the X_B choices. The first two can have same $|p_{T,j_b}| + |p_{T,\bar{j}_b}|$ but differ for m_{bb}, whereas the first and the third differs for $\sqrt{s_{min}}$, despite having same m_{bb} and same $|p_{T,j_b}| + |p_{T,\bar{j}_b}|$.

Sensitivities investigated from different angles!!

Sensitivity Measure

- Sensitivity measure: $\Delta_{\theta}^{(\mathcal{M}_{\mathcal{O}})} = \frac{\delta\mathcal{M}_{\mathcal{O}}/\mathcal{M}_{\mathcal{O}}}{\delta\theta/\theta}$
  - $\mathcal{M}_{\mathcal{O}}$: Mellin moment of observable
  - θ: hadronization and showering parameters

- Observables with larger Δ: **best diagnostics** of the accuracy of the tunes

Summary of Results

$\mathcal{O}$	Range	$\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})}$	$\Delta_\theta^{(\mathcal{M}_\mathcal{O})}$						
			$\alpha_{s,FSR}$	m_b	$p_{T,\min}$	a	b	r_B	recoil
$\rho(r)$	0-0.04	-0.007(7)	0.78(1)	0.204(4)	-0.1286(8)	0.029(3)	-0.043(4)	0.056(7)	0.020(1)
$p_{T,B}/p_{T,j_b}$	0.6-0.998	-0.053(1)	-0.220(3)	-0.1397(8)	0.0353(5)	-0.0187(4)	0.0451(6)	-0.0518(9)	-0.0108(3)
E_B/E_{j_b}	0.6-0.998	-0.049(1)	-0.220(3)	-0.1381(8)	0.0360(5)	-0.0186(4)	0.0447(6)	-0.052(1)	-0.0107(3)
E_B/E_ℓ	0.05-1.5	-0.155(7)	-0.156(3)	-0.053(3)	0.0149(7)	-0.007(2)	0.016(2)	-0.016(10)	-0.0087(7)
$E_B/(E_\ell + E_{\bar{\ell}})$	0.05-1.0	0.021(5)	-0.231(2)	-0.082(4)	0.0228(4)	-0.011(2)	0.026(2)	-0.028(6)	-0.0113(3)
$m(j_{\bar{b}})/\text{GeV}$	8-20	0.229(3)	0.218(1)	0.022(1)	-0.0219(7)	0.000(1)	-0.001(1)	0.001(3)	0.0050(3)
$\chi_B(\sqrt{s_{\min,bb}})$	0.075-0.875	-0.177(4)	-0.262(4)	-0.086(1)	0.0255(3)	-0.0105(10)	0.027(1)	-0.031(3)	-0.0137(2)
$\chi_B\left(E_{j_b} + E_{j_{\bar{b}}}\right)$	0.175-1.375	-0.109(2)	-0.357(4)	-0.134(1)	0.0373(3)	-0.016(1)	0.040(1)	-0.045(4)	-0.0175(3)
$\chi_B(m_{j_b j_{\bar{b}}})$	0.175-1.375	-0.089(3)	-0.252(3)	-0.080(1)	0.0248(3)	-0.010(1)	0.024(1)	-0.028(5)	-0.0126(2)
$\chi_B\left(\lvert p_{T,j_b}\rvert + \lvert p_{T,j_{\bar{b}}}\rvert\right)$	0.46-1.38	-0.15(2)	-0.47(1)	-0.189(10)	0.054(3)	-0.023(10)	0.06(1)	-0.07(4)	-0.022(2)
$m_{BB}/m_{j_b j_{\bar{b}}}$	0.8-0.95	-0.0191(8)	-0.0623(7)	-0.0464(5)	0.0146(2)	-0.0093(3)	0.0180(4)	-0.0212(9)	-0.00296(10)
$\Delta\phi(j_b j_{\bar{b}})$	0.28-3.	-0.210(7)	0.027(3)	0.001(2)	-0.0014(5)	-0.000(3)	-0.000(1)	-0.003(9)	0.0003(5)
$\Delta R(j_b j_{\bar{b}})$	1.4-3.3	-0.071(3)	0.010(1)	0.0005(10)	-0.0004(2)	-0.000(1)	0.0004(9)	0.001(3)	0.0001(2)
$\Delta\phi(BB)$	0.28-3.	-0.207(7)	0.026(2)	0.001(1)	-0.0008(4)	0.000(4)	0.000(2)	-0.000(8)	0.0002(5)
$\Delta R(BB)$	1.4-3.3	-0.070(3)	0.009(1)	0.000(1)	-0.0003(2)	-0.0003(10)	0.0002(9)	-0.000(4)	0.0001(2)
$\lvert\Delta\phi(BB) - \Delta\phi(j_b j_{\bar{b}})\rvert$	0-0.0488	0.06(1)	0.734(6)	0.099(5)	-0.088(2)	0.006(5)	-0.004(5)	0.01(2)	0.026(2)
$\lvert\Delta R(BB) - \Delta R(j_b j_{\bar{b}})\rvert$	0-0.0992	0.10(1)	0.920(3)	0.079(5)	-0.075(1)	-0.000(4)	0.005(4)	-0.00(2)	0.0418(8)

Summary of Results

$\mathcal{O}$	Range	$\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})}$	$\Delta_\theta^{(\mathcal{M}_\mathcal{O})}$						
			$\alpha_{s,FSR}$	m_b	$p_{T,\min}$	a	b	r_B	recoil
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E_B/E_{j_b}	0.6-0.998	-0.049(1)	-0.220(3)	-0.1381(8)	0.0360(5)	-0.0186(4)	0.0447(6)	-0.052(1)	-0.0107(3)
E_B/E_ℓ	0.05-1.5	-0.155(7)	-0.156(3)	-0.053(3)	0.0149(7)	-0.007(2)	0.016(2)	-0.016(10)	-0.0087(7)
$E_B/(E_\ell + E_{\bar{\ell}})$	0.05-1.0	0.021(5)	-0.231(2)	-0.082(4)	0.0228(4)	-0.011(2)	0.026(2)	-0.028(6)	-0.0113(3)
$m(j_{\bar{b}})$/GeV	8-20	0.229(3)	0.218(1)	0.022(1)	-0.0219(7)	0.000(1)	-0.001(1)	0.001(3)	0.0050(3)
$\chi_B(\sqrt{s_{\min,bb}})$	0.075-0.875	-0.177(4)	-0.262(4)	-0.086(1)	0.0255(3)	-0.0105(10)	0.027(1)	-0.031(3)	-0.0137(2)
$\chi_B\left(E_{j_b} + E_{\bar{j}_b}\right)$	0.175-1.375	-0.109(2)	-0.357(4)	-0.134(1)	0.0373(3)	-0.016(1)	0.040(1)	-0.045(4)	-0.0175(3)
$\chi_B(m_{j_b j_{\bar{b}}})$	0.175-1.375	-0.089(3)	-0.252(3)	-0.080(1)	0.0248(3)	-0.010(1)	0.024(1)	-0.028(5)	-0.0126(2)
$\chi_B\left(\lvert p_{T,j_b}\rvert + \lvert p_{T,\bar{j}_b}\rvert\right)$	0.46-1.38	-0.15(2)	-0.47(1)	-0.189(10)	0.054(3)	-0.023(10)	0.06(1)	-0.07(4)	-0.022(2)
$m_{BB}/m_{j_b j_{\bar{b}}}$	0.8-0.95	-0.0191(8)	-0.0623(7)	-0.0464(5)	0.0146(2)	-0.0093(3)	0.0180(4)	-0.0212(9)	-0.00296(10)
$\Delta\phi(j_b j_{\bar{b}})$	0.28-3.	-0.210(7)	0.027(3)	0.001(2)	-0.0014(5)	-0.000(3)	-0.000(1)	-0.003(9)	0.0003(5)
$\Delta R(j_b j_{\bar{b}})$	1.4-3.3	-0.071(3)	0.010(1)	0.0005(10)	-0.0004(2)	-0.000(1)	0.0004(9)	0.001(3)	0.0001(2)
$\Delta\phi(BB)$	0.28-3.	-0.207(7)	0.026(2)	0.001(1)	-0.0008(4)	0.000(4)	0.000(2)	-0.000(8)	0.0002(5)
$\Delta R(BB)$	1.4-3.3	-0.070(3)	0.009(1)	0.000(1)	-0.0003(2)	-0.0003(10)	0.0002(9)	-0.000(4)	0.0001(2)
$\lvert\Delta\phi(BB) - \Delta\phi(j_b j_{\bar{b}})\rvert$	0-0.0488	0.06(1)	0.734(6)	0.099(5)	-0.088(2)	0.006(5)	-0.004(5)	0.01(2)	0.026(2)
$\lvert\Delta R(BB) - \Delta R(j_b j_{\bar{b}})\rvert$	0-0.0992	0.10(1)	0.920(3)	0.079(5)	-0.075(1)	-0.000(4)	0.005(4)	-0.00(2)	0.0418(8)

- $\rho(r)$: (typically) **most sensitive variable** to both hadronization and shower parameters
- Nevertheless, **other variables contain useful/orthogonal information** to constrain parameters (unless they are perfectly correlated)!!

Combined Constraining Power

- Expressing the table in the previous slide as a matrix form, we find

$$\frac{\delta \mathcal{M}_{\mathcal{O}i}}{\mathcal{M}_{\mathcal{O}i}} = \left(\Delta_\theta^{(\mathcal{M}_\mathcal{O})}\right)_{ij} \frac{\delta\theta_j}{\theta_j},$$

for parameter vector $\theta = \{\alpha_{s,FSR},\, m_b,\, p_{T,\text{min}},\, a,\, b,\, r_B,\, recoil\}$, and observable vector $O = \{\mathcal{O}_i\}$.

- Sensitivity of parameters as functions of observables would have the form of

$$\frac{\delta\theta_j}{\theta_j} = \left(\tilde{\Delta}_\theta^{(\mathcal{M}_\mathcal{O})}\right)_{ij} \frac{\delta \mathcal{M}_{\mathcal{O}i}}{\mathcal{M}_{\mathcal{O}i}}, \quad \text{where} \quad \tilde{\Delta}_\theta^{(\mathcal{M}_\mathcal{O})} \cdot \Delta_{m_t}^{(\mathcal{M}_\mathcal{O})} = \mathbb{1} \; .$$

- $\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})}$ is not usually a square matrix.

  $\Rightarrow$ A pseudo-inverse procedure [Penrose, Todd (1955); Dresden (1920)] and a singular value decomposition are needed for the analysis.

Combined Constraining Power: Result

- Resulting singular values:

  1.7, 0.26, 0.048, 0.0075, 0.0050, 0.0033, 0.0014

  ⇒ Two linear combinations of parameters may be constrained, in practice.

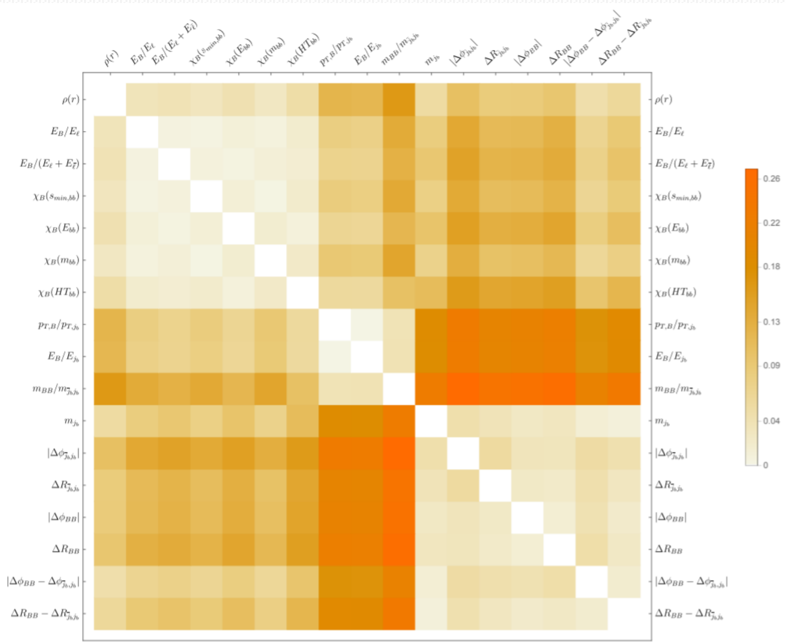


Figure 5: Angular distance between the directions in parameter space pointed by the rows of Table in the previous slide.

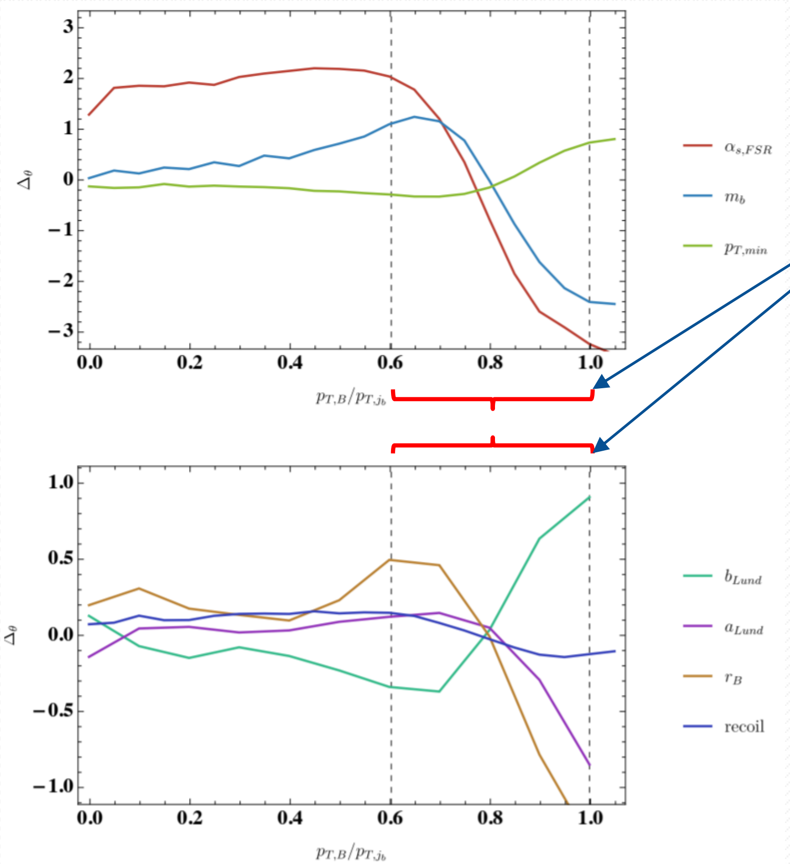
Most observables contain/access "similar" information

Alternative approaches motivated ⇒

Differential constraining power

Differential Constraining Power

- Study on the bin counts of a subset of the calibration observables.



FWHM to compute Mellin moments in previous slides ⇒ **averaging out** sensitivities to parameters

Selected Observables

$\mathcal{O}$	Range	N_{bins}
$\rho(r)$	0.-0.4	16
$p_{T,B}/p_{T,j_b}$	0.-0.99	11
E_B/E_ℓ	0.05-4.55	9
$\chi_B\left(E_{j_b}+E_{\bar{j}_b}\right)$	0.-2.	10
$m_{BB}/m_{j_b j_{\bar{b}}}$	0.-0.998	11
$\lvert\Delta R(BB)-\Delta R(j_b j_{\bar{b}})\rvert$	0.-0.288	9

Observables showing the greatest sensitivities in the absolute sense and the most distinct dependence on linearly independent combinations of Monte Carlo parameters

Differential Constraining Power: Results

- $p_{T,B}/p_{T,j_b}$: the best single set of differential constraining power

Singular values: 7.0, 1.8, 0.28, 0.11, 0.11, 0.037, 0.018

Improved a lot   Not yet enough

- Combined differential constraining power

Singular values: 15.0, 4.2, 0.75, 0.42, 0.27, 0.16, 0.13

Input observables measured at ~1% ⇒ 10% constraining on the most loosely constrained parameter combination

Implications on Constraining Parameters

- From the standard covariance matrix analysis, and assuming input observables measured at the level of 1% precision we find

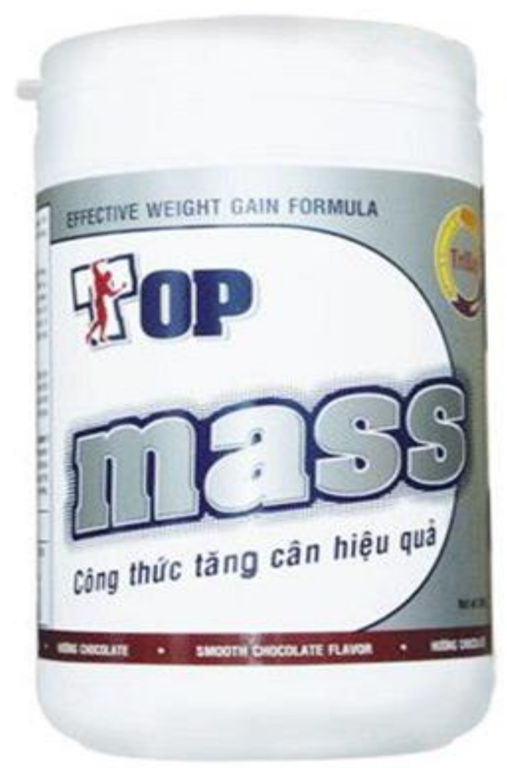
$\alpha_{s,FSR}$	m_b	$p_{T,\min}$	a	b	r_B	recoil
0.045	0.14	0.35	0.5	0.48	0.21	0.73

4% relative uncertainty to 70% relative uncertainty

- 0.1% precision (achievable at the HL-LHC if considering purely statistical uncertainties) $\Rightarrow$ will **achieve 0.4% to 7% relative uncertainties**!

Conclusions

- ❑ Different methods for top quark mass measurement: the more the messier? the more the merrier?!
  - ❖ Different sensitivity to systematics, **complementary** to one another, **good exercise for BSM** scenarios
- ❑ We, **for the first time**, performed a systematic study on B-hadron observable methods and potential impact of Pythia parameters on them.
  - ❖ Non-jetty nature ⇒ **free from JES**
  - ❖ Most sensitive to α_s^{FSR}, so a better "tune" reduces the theoretical uncertainty of top mass in B-hadron observables. (see Pedro's talk and the recent effort in CMS-PAS-TOP-17-013, CMS-PAS-TOP-17-015)
  - ❖ Parameters can be, "in-situ", **constrained/tuned by calibration observables** probing various aspects.
- ❑ Similar exercises done with HERWIG 6, and HERWIG 7 for future.



Thank you!

Back-up

"Tuning" of PYTHIA8 Parameters

A study of the sensitivity to the PYTHIA8 parton shower parameters of $t\bar{t}$ production measurements in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS experiment at the LHC

The ATLAS Collaboration

ATL-PHYS-PUB-2015-007
25 March 2015

Abstract

Various measurements of $t\bar{t}$ observables, performed by the ATLAS experiment in pp collisions at $\sqrt{s}$ = 7 TeV, are used to constrain the initial- and final-state radiation parameters of the PYTHIA8 Monte Carlo generator. The resulting tunes are compared to previous tunes to the Z boson transverse momentum at the LHC, and to the LEP event shapes in Z boson hadronic decays. Such a comparison provides a test of the universality of the parton shower model. The tune of PYTHIA8 to the $t\bar{t}$ measurements is applied to the next-to-leading-order generators MadGraph5_aMC@NLO and POWHEG, and additional parameters of these generators are tuned to the $t\bar{t}$ data. For the first time in the context of parton shower tuning in Monte Carlo simulations, the correlation of the experimental uncertainties has been used to constrain the parameters of the Monte Carlo models.

B-hadron Decay

- Fully reconstructible with tracks

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

- $B_s^0 \to J/\psi\phi \to \mu^-\mu^+K^-K^+$ (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)

D modes

- $B^0 \xrightarrow[3\times10^{-3}]{} D^-\pi^+ \xrightarrow[10^{-2}]{} K_s^0\pi^-\pi^+$, $B^0 \xrightarrow[3\times10^{-3}]{} D^-\pi^+ \xrightarrow[10^{-2}]{} K^-\pi^+\pi^-\pi^+$,

  $B^0 \xrightarrow[3\times10^{-3}]{} D^-\pi^+ \xrightarrow[3\times10^{-2}]{} K_s^0\pi^+\pi^-\pi^+$

- $B^- \xrightarrow[5\times10^{-3}]{} D^0\pi^- \xrightarrow[4\times10^{-2}]{} K^-\pi^+\pi^-$, $B^- \xrightarrow[5\times10^{-3}]{} D^0\pi^- \xrightarrow[2\times10^{-2}]{} K^{*-}(892)\pi^+\pi^- \to K_s^0\,\pi^+\pi^-\pi^+$,

  $B^- \xrightarrow[5\times10^{-3}]{} D^0\pi^- \xrightarrow[6\times10^{-3}]{} K_s^0\rho^0\pi^-$, $B^- \xrightarrow[5\times10^{-3}]{} D^0\pi^- \xrightarrow[5\times10^{-3}]{} K^-\pi^+\rho^0\pi^-$

Herwig Parameters & Results

	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

Table 2: HERWIG 6 parameters under consideration and ranges of their variation.

$\mathcal{O}$	$\Delta_{m_t}^{(\mathcal{M}_\mathcal{O})}$	$\Delta_\theta^{(m_t)}$								
		PSPLT	QCDLAM	CLPOW	CLSMR(2)	CLMAX	RMASS(5)	RMASS(13)	VGCUT	VQCUT
$m_{B\ell,\text{true}}$	0.52	0.036(4)	-0.008(2)	-0.007(5)	0.002(3)	-0.007(4)	0.058(1)	0.06(5)	0.003(1)	-0.003(3)
$p_{T,B}$	0.47	0.072(1)	-0.03(9)	-0.02(7)	0.0035(5)	-0.03(5)	0.11(9)	0.12(5)	0.0066(2)	-0.006(5)
E_B	0.43	0.069(7)	-0.026(7)	-0.017(5)	0.0038(9)	-0.01(2)	0.12(1)	0.12(2)	0.006(2)	-0.007(5)
E_ℓ	0.13	0.0005(5)	-0.04(3)	0.04(2)	-0.0002(2)	-0.004(4)	0.008(3)	0.008(2)	-0.002(5)	0.008(2)