Understanding the Impact of Pythia Hadronization in Top Quark Mass Determinations at the LHC

Doojin Kim

MC4BSM 2017, Menlo Park, CA, May 12, 2017

Gennaro Corcella, Roberto Franceschini and DK, to appear soon

Top Mass Measurement: Status

- Precision top mass measurement: **consistency check** of SM, higgs **vacuum stability** etc.
- Measurement at $\lesssim 0.5\%$ $\Rightarrow$ precision QCD
- Top quark mass (ATLAS + CMS preliminary LHC*top*WG, Aug. 2016)

ATLAS comb. (06/2016): $\mathbf{172.84} \pm \mathbf{0.34} \pm \mathbf{0.61}$

CMS comb. (09/2015): $\mathbf{172.44} \pm \mathbf{0.13} \pm \mathbf{0.47}$

- Statistical uncertainty: not a problem since LHC is a top factory, **systematics-limited**
- Systematics
  - ✓ experimental uncertainty: jet energy scaling, etc.
  - ✓ theory uncertainty: due to poor theoretical understanding, etc.

Measurement Techniques

- 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, arXiv:1501.07912]
  - 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**, in progress]
  - Many more which I can't exhaust

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Kinematics-based

Jets in the final state → JES

No jetty objects in the final state → no JES, Th. uncertainty

Why Different Strategy?

- ❑ Different methods have different sensitivity to systematics
  - ❖ **complementary** to one another
- ❑ **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

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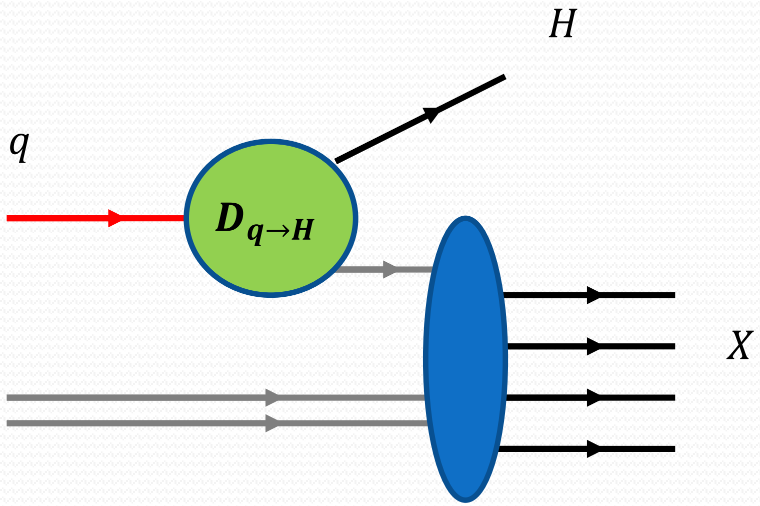
- <u>B-hadron observables</u>: **crucial** to understand the transformation from a quark to hadrons, but **challenging** because it is governed by non-perturbative QCD (similar conclusions hold for B-hadron decay length method [Hill, Incandela, Lamb (2005); CMS-PAS-TOP-12-030])

Filling the Gap



- Computing *fragmentation function*, $D_{q\to H}(z)$
- Precision data available at LEP [arXiv: 1102.4748, hep-ex/01120282] and SLC [hep-ex/0202031]
- For b quark, the extraction of the fragmentation function at NNLO in α_s available [Fickinger, Fleming, Kim, Merechetti (2016)]

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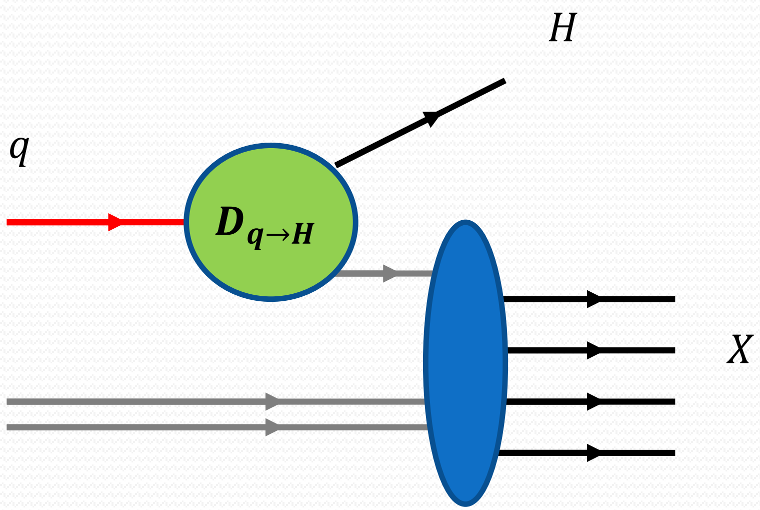

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- Higher order corrections necessary (including resummation sometimes)
- Relying on factorization of the cross section to a very high accuracy
- Not clear to apply lepton collider data to hardon colliders

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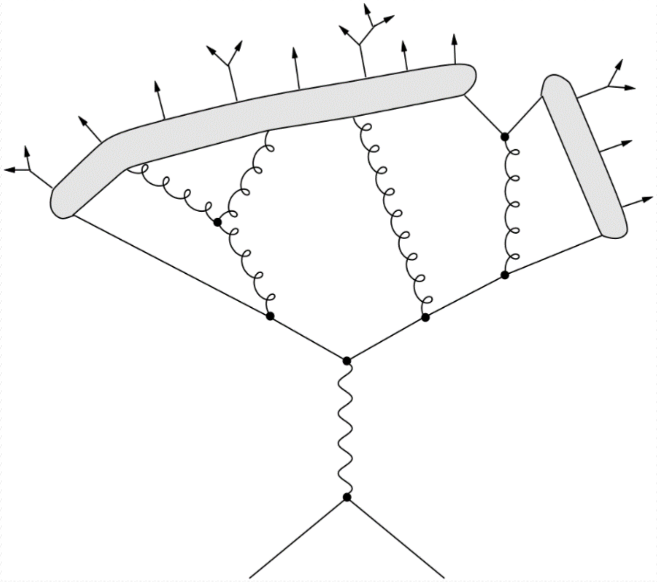

- ❑ Employing *hadronization model* with phenomenological parameters [Andersson, Gustafson, Ingelman, Sjostrand (1983)]
- ❑ "Tuning" of the parameters to reproduce the available data

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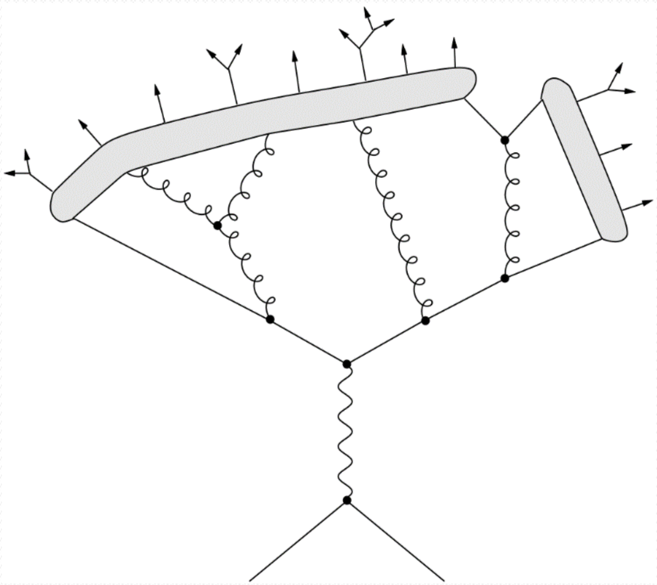

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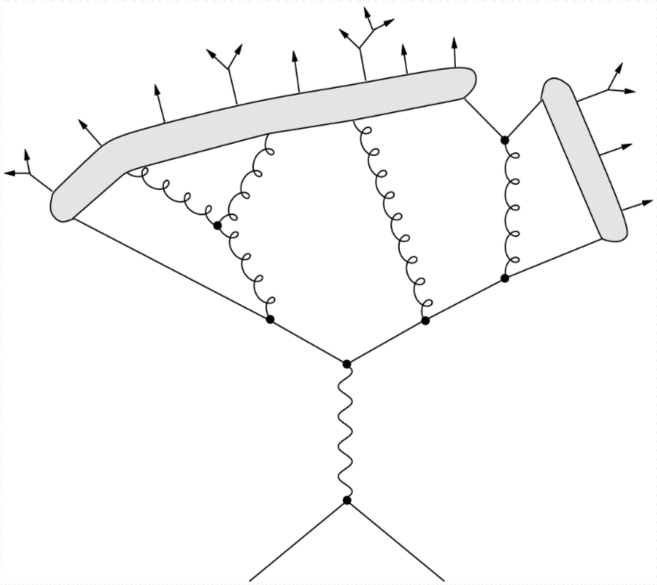

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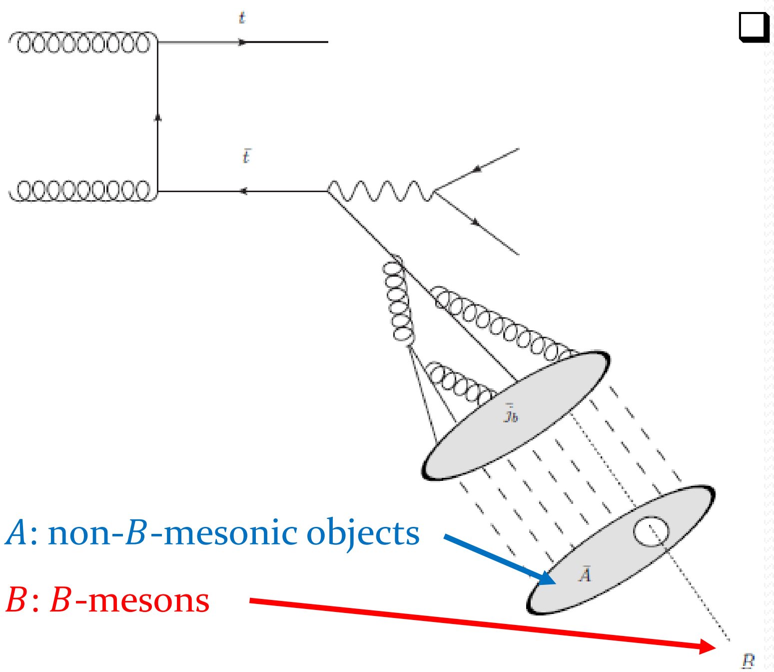
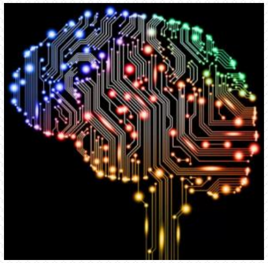
❑ **Our approach/goal**

- top quark mass *sensitivity to parameters*,
- *what should be constrained* to achieve better precision
- *how to constrain* them

Strategy in a Nut-shell





- 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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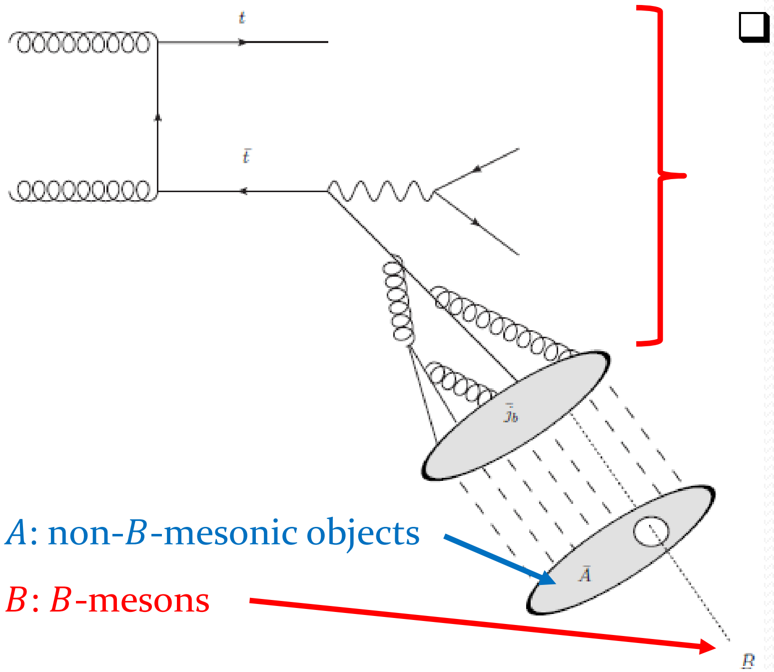

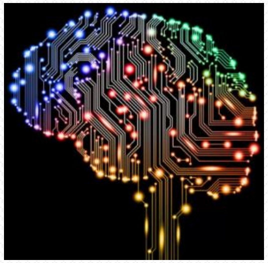

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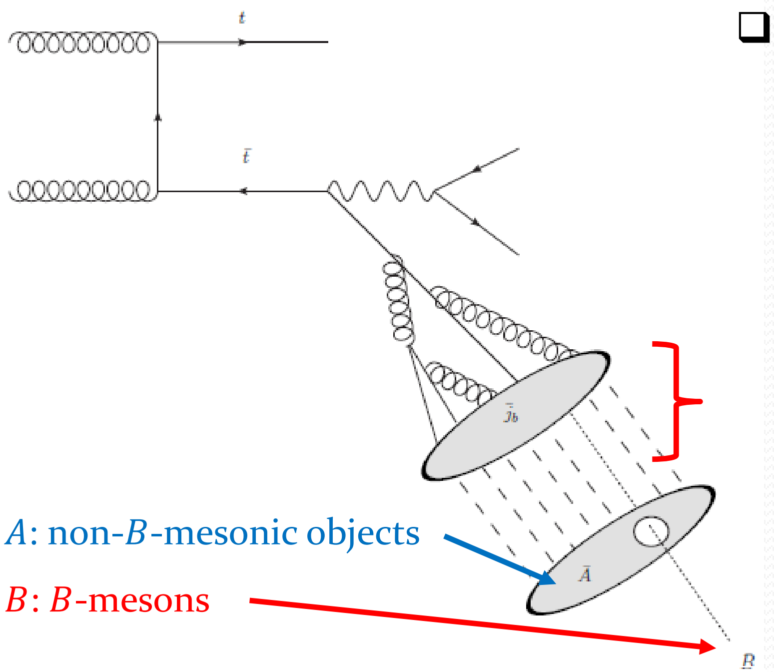

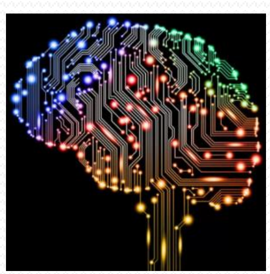

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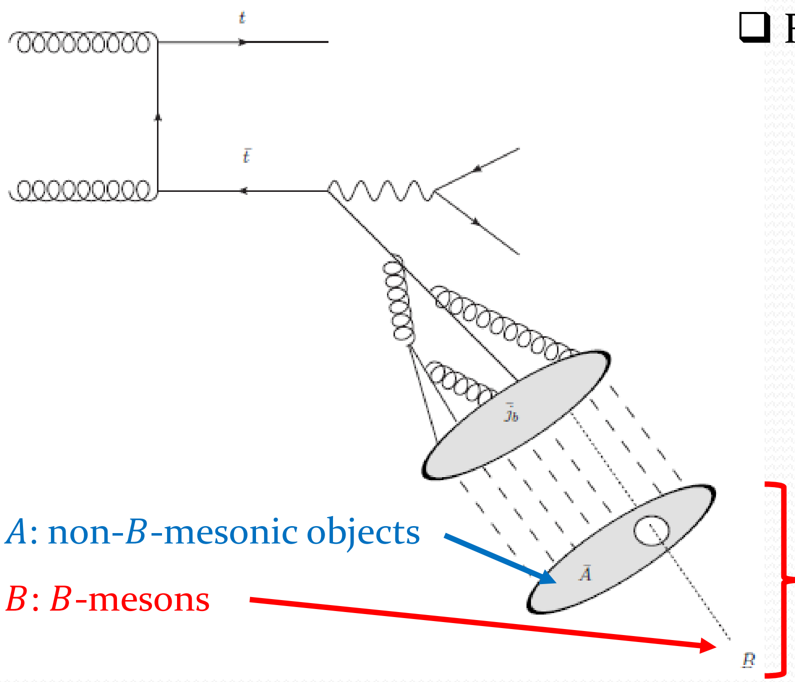

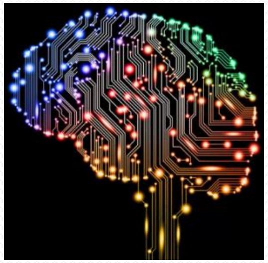

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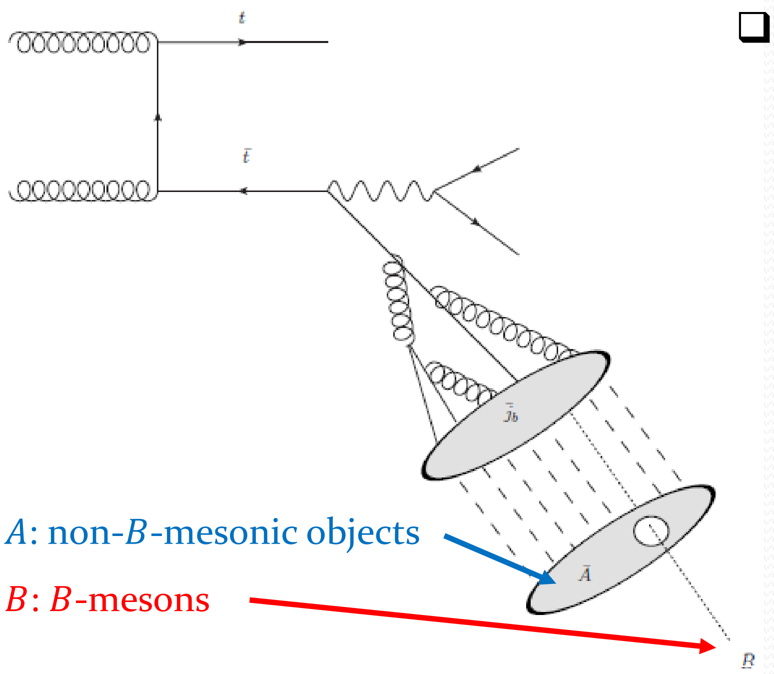

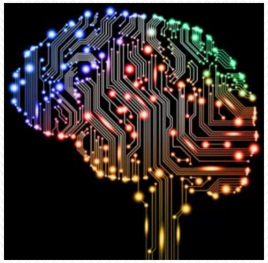

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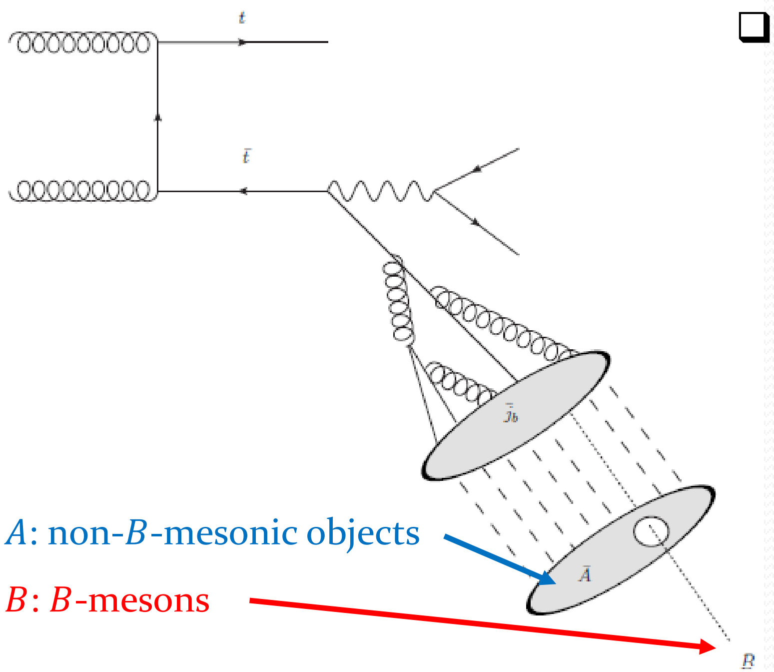

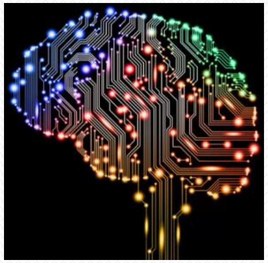

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B-hadron-related Parameters

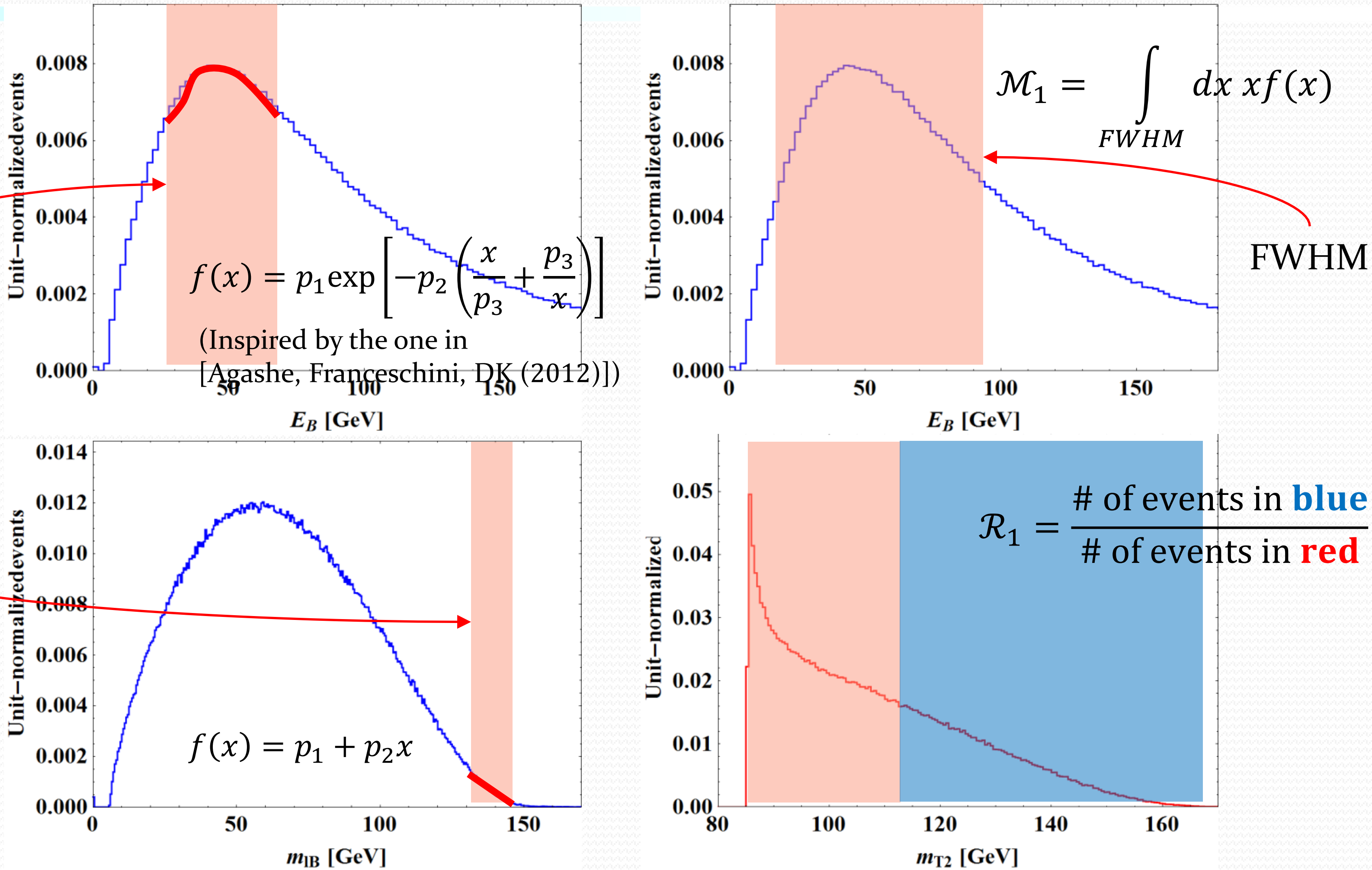
- $e\mu$ channel of LO $t\bar{t}$ $(gg/q\bar{q} \to t\bar{t})$ at the LHC 13 TeV with NNPDF2.3 QCD+QED LO, PartonLevel:MPI = off, HadronLevel:Decay = off, and anti-k_t jets of $R = 0.5$
- Input top quark mass varies from 170 GeV to 180 GeV by an interval of 1 GeV

Parameter	PYTHIA8 setting	Variation range	
r_B in the Bowler modification for heavy quarks	StringZ:rFactB	0.713 – 0.813	Heavy flavor-specific hadronization parameters
a parameter in the non-standard Lund ansatz for b quarks	StringZ:aNonstandardB	0.54 – 0.82	
b parameter in the non–standard Lund ansatz for b quarks	StringZ:bNonstandardB	0.78 – 1.18	
$P_{T,\,\min}^{\mathrm{FSR}}$ [GeV]	TimeShower:pTmin	0.25 – 1.00	Showering parameters
recoiler switch	TimeShower:recoilToColoured	on or off	
$\alpha_s^{\mathrm{FSR}}\ (m_Z)$	TimeShower:alphaSvalue	0.1092 – 0.1638	
b quark mass [GeV]	5:m0	3.84 – 5.76	

Measurements: Peak/Endpoint, Mellin Moment

Full width at ¾ height ($\chi^2/\text{dof}\sim1$)

~5% from the endpoint ($\chi^2/\text{dof}\sim1$)



B-hadron Observables

Observable	Mellin moment ($\mathcal{M}_1$)	Peak/Endpoint	Features
E_B	V	V (i.e., 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_{T2}	V ($\mathcal{R}_1$ for (B) subsystem)	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 ($\mathcal{R}_1$ for (B) subsystem)	V	• ISR-free observables • (B) and $(B\ell)$ subsystems • Different ISR and MET definitions

[1]: K. Matchev and M. Park (2009)

Summary of Results: Mellin Moments

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

Mellin-1	$\Delta_\theta^{(m_t)}$					
	$\alpha_{s,FSR}$	$p_{T,\min}$	recoil	r_B	a	b
E_B	0.43	0.019	0.028	0.039	0.020	0.039
$E_B + E_B$	0.42	0.019	0.032	0.046	0.023	0.034
$p_{T,B}$	0.43	0.021	0.027	0.043	0.022	0.042
$p_{T,B} + p_{T,B}$	0.36	0.017	0.024	0.042	0.016	0.044
$m_{B\ell,\min}$	0.26	0.011	0.016	0.041	0.011	0.031
$m_{B\ell,\mathrm{true}}$	0.24	0.008	0.013	0.031	0.009	0.022
$m_{T2,B\ell,\mathrm{true}}^{(\mathrm{mET})}$	0.24	0.012	0.012	0.034	0.013	0.032
$m_{T2,B\ell,\min}^{(\mathrm{mET})}$	0.23	0.011	0.012	0.031	0.012	0.03
$m_{T2,B\ell,\min,\perp}^{(\mathrm{mET})}$	0.24	0.01	0.011	0.038	0.011	0.03
$m_{T2,B\ell,\mathrm{true}}^{(\mathrm{ISR})}$	0.21	0.007	0.01	0.022	0.008	0.022
$m_{T2,B\ell,\min}^{(\mathrm{ISR})}$	0.2	0.008	0.013	0.024	0.01	0.027
$m_{T2,B\ell,\min,\perp}^{(\mathrm{ISR})}$	0.22	0.01	0.01	0.03	0.013	0.03

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- Top quark mass measurements in these observables are **sensitive most to $\alpha_{s,\text{FSR}}$**, e.g., 10% uncertainty in $\alpha_{s,\text{FSR}}$ corresponds to $2-4\%$ uncertainty in the top quark mass ⇒ affecting radiation in the final state, in turn, changing energy scale of *B*-hadrons!

Summary of Results: Shape

$\mathcal{O}$	$\Delta_\theta^{(m_t)}$					
	$\alpha_{s,FSR}$	$p_{T,\min}$	recoil	r_B	a	b
$E_{B,\mathrm{peak}}$	0.46	0.018	0.032	0.057	0.018	0.042
$\grave{m}_{B\ell,\min}$	0.0021	$< 10^{-3}$	$< 10^{-3}$	0.0038	0.0021	0.0017
$\grave{m}_{B\ell,\mathrm{true}}$	0.005	$< 10^{-3}$	$< 10^{-3}$	0.0035	0.0014	$< 10^{-3}$
$\grave{m}_{T2,B\ell,\mathrm{true}}^{(\mathrm{mET})}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.0029	0.0015	0.0014
$\grave{m}_{T2,B\ell,\min}^{(\mathrm{mET})}$	0.0016	$< 10^{-3}$	$< 10^{-3}$	0.0035	0.0012	$< 10^{-3}$
$\grave{m}_{T2,B\ell,\min,\perp}^{(\mathrm{mET})}$	0.016	$< 10^{-3}$	$< 10^{-3}$	0.0071	0.0019	0.0017
$\grave{m}_{T2,B\ell,\mathrm{true}}^{(\mathrm{ISR})}$	0.0067	0.0015	$< 10^{-3}$	0.0042	0.0021	0.0024
$\grave{m}_{T2,B\ell,\min}^{(\mathrm{ISR})}$	0.0063	0.0015	$< 10^{-3}$	0.0031	0.0021	0.0023
$\grave{m}_{T2,B\ell,\min,\perp}^{(\mathrm{ISR})}$	0.0056	$< 10^{-3}$	$< 10^{-3}$	0.0042	0.0016	0.0014

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$\grave{m}_{B\ell,\text{true}}$	0.005	$< 10^{-3}$	$< 10^{-3}$	0.0035	0.0014	$< 10^{-3}$
$\grave{m}^{(\text{mET})}_{T2,B\ell,\text{true}}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.0029	0.0015	0.0014
$\grave{m}^{(\text{mET})}_{T2,B\ell,\text{min}}$	0.0016	$< 10^{-3}$	$< 10^{-3}$	0.0035	0.0012	$< 10^{-3}$
$\grave{m}^{(\text{mET})}_{T2,B\ell,\text{min},\perp}$	0.016	$< 10^{-3}$	$< 10^{-3}$	0.0071	0.0019	0.0017
$\grave{m}^{(\text{ISR})}_{T2,B\ell,\text{true}}$	0.0067	0.0015	$< 10^{-3}$	0.0042	0.0021	0.0024
$\grave{m}^{(\text{ISR})}_{T2,B\ell,\text{min}}$	0.0063	0.0015	$< 10^{-3}$	0.0031	0.0021	0.0023
$\grave{m}^{(\text{ISR})}_{T2,B\ell,\text{min},\perp}$	0.0056	$< 10^{-3}$	$< 10^{-3}$	0.0042	0.0016	0.0014

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

- 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 Lund-Bowler parameter becomes comparable!
- Statistics will be a major challenge in performing precision measurements of endpoints.

Calibration Variables

- Calibration variables: **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]

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- $\frac{p_{T,B}}{p_{T,j_b}}$
- $\rho(r) = \frac{1}{\Delta r}\frac{1}{E_j}\sum_{\text{track}} E_{\text{track}} \cdot \Theta(|r - \Delta R_{j,\text{track}}| < \delta r)$: the radial jet energy density [ATLAS Collaboration, arXiv:1307.5749]

  $\Theta(x)$: Heaviside theta function
- $\chi_B = \frac{2E_B}{X_B}$ with $X_B = m_{bb}, \sqrt{s_{\min}}, \sqrt{s_{\min,bb}}, \sum p_{T,j_{b/\bar{b}}}$
- More under investigation

Don't call the Nobel Committee just yet: We forgot to calibrate the instruments before the experiment...

Calibration Variables

In what sense

- Calibration variables 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**

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  - 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

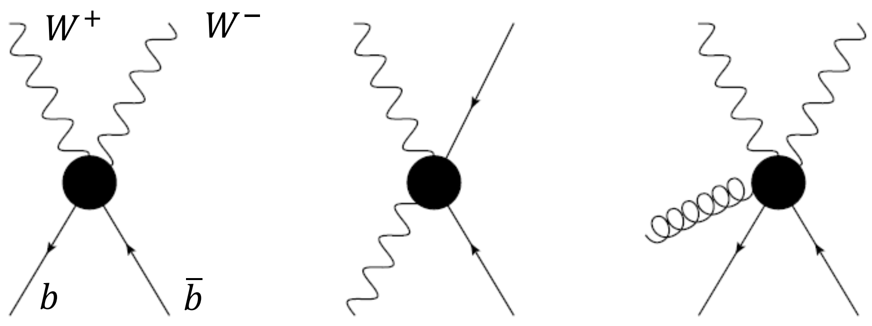

Figure 2: Three kinematical configurations distinguished by the X_B choices. The first two can have same $|p_{T,j_b}| + |p_{T,\bar{j}_b}|$ but differ for m_{bb}, whereas the first and the third differs for $\sqrt{s_{min}}$, despite having same m_{bb} and same $|p_{T,j_b}| + |p_{T,\bar{j}_b}|$.

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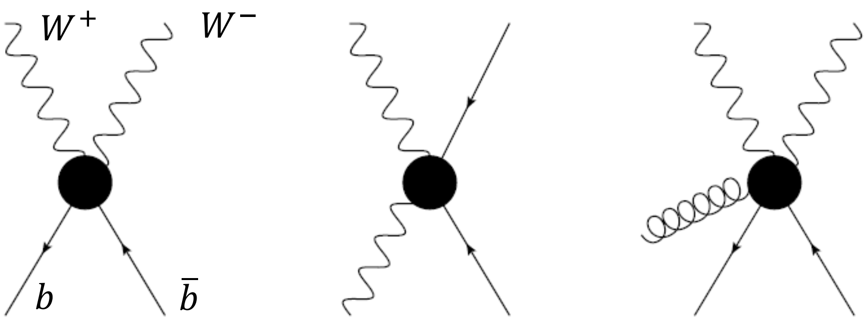

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Sensitivities investigated from different angles!!

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

$\mathcal{O}$	$\Delta_\theta^{(\mathcal{M}_\mathcal{O})}$						
	$\alpha_{s,\mathrm{FSR}}$	m_b	$p_{T,\mathrm{min}}$	recoil	r_B	a	b
$\rho(r)$	1.68	0.46	−0.11	0.023	0.034	0.016	−0.020
$\chi_B(\sqrt{s_{\mathrm{min},bb}})$	−0.58	−0.18	0.0090	−0.022	−0.018	−0.0089	0.019
$\chi_B(\sqrt{s_{\mathrm{min}}})$	−0.59	−0.16	0.0090	−0.033	−0.018	−0.0090	0.019
$\chi_B(\sum p_{T,j_{b/\bar{b}}})$	−0.44	−0.17	0.011	−0.0080	−0.024	−0.011	0.025
$\chi_B(m_{bb})$	−0.43	−0.19	0.0090	−0.014	−0.020	−0.0070	0.020
$p_{T,B}/p_{T,j_b}$	−0.16	−0.22	0.018	−0.016	−0.040	−0.022	0.047

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: best observables to adjust the tune for $t\bar{t}$ environment

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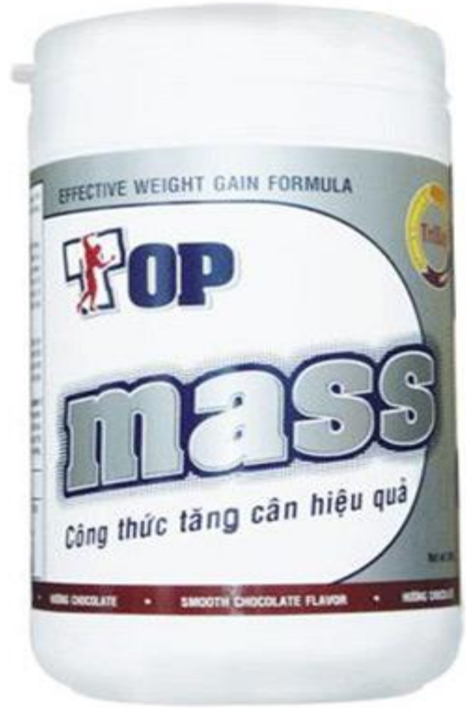
: best observables to adjust the tune for $t\bar{t}$ environment

- $\rho(r)$: (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)!!

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 **first** perform 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
  - α_s^{FSR} should be **constrained at 1-2% level**, while the others at 10-20% to achieve ~0.5% precision in m_t ($\alpha_s^{\mathrm{FSR}} \to r_b \to \ldots$)
  - Parameters can be **constrained/tuned by calibration observables probing various aspects**
- The same exercises with HERWIG will be available.



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

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

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

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

Correlation between Calibration Variables