Fragmentation Uncertainties in Hadron Observables for Top Quark Mass Measurements

Doojin Kim

LHC Top Working Group Meeting at CERN, November 22, 2016

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 $\lesssim 0.5\%$ ⇒ 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.
- Systematics – 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]

SM top assumed

- Endpoint method [CMS PAS TOP 11-027]
- b-jet energy-peak method [CMS PAS TOP-15-002]
- Solvability method [DK, Matchev and Shyamsundar, in progress]

Kinematics-based

- 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-meson observables** [Franceschini and DK, in progress]
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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.
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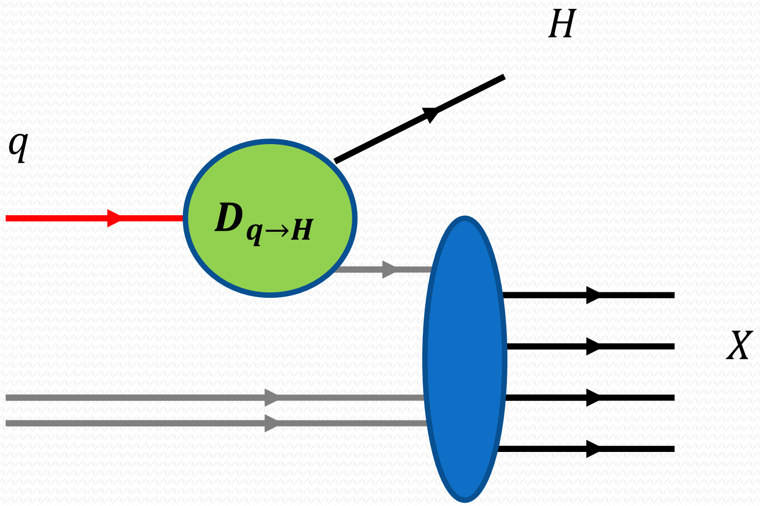
- ☐ **Crucial** to understand the transformation from a quark to hadrons, but **challenging** because it is governed by non-perturbative QCD

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)

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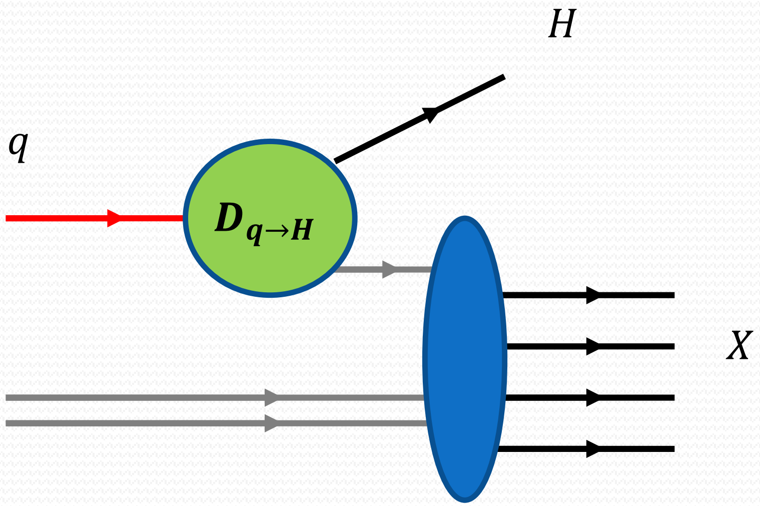

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- ☐ Higher order corrections necessary (including resummation sometimes)
- ☐ Relying on factorization of the cross section to a very high accuracy
- ☐ Not clear to apply lepton collider data to hardon colliders

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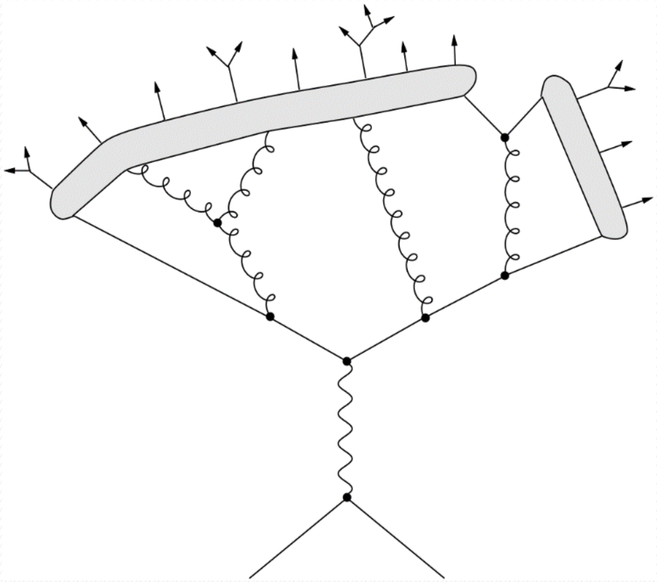

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- ☐ “Tuning” of the parameters to reproduce the available data

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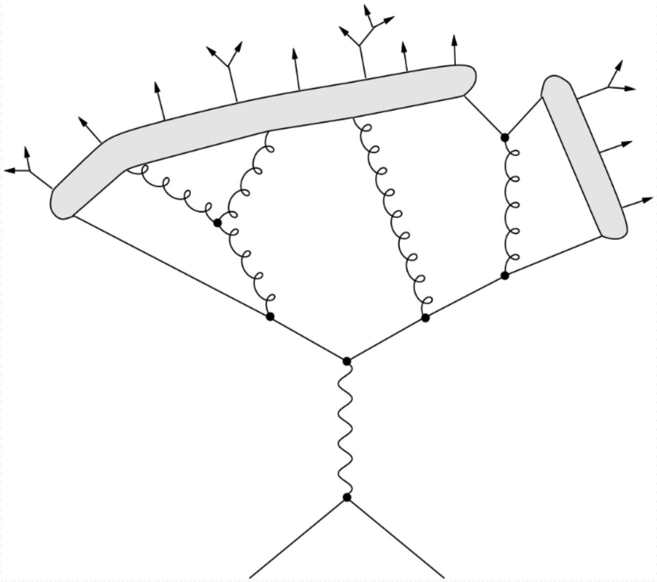

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- ❑ Should be test at hadron collider environment

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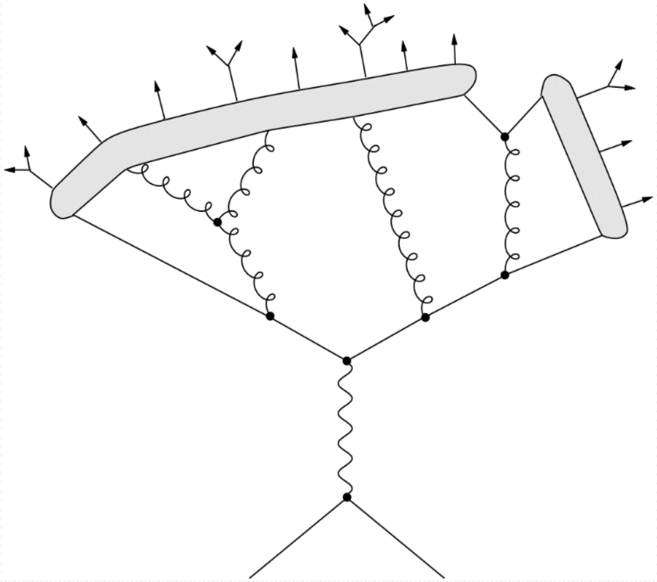

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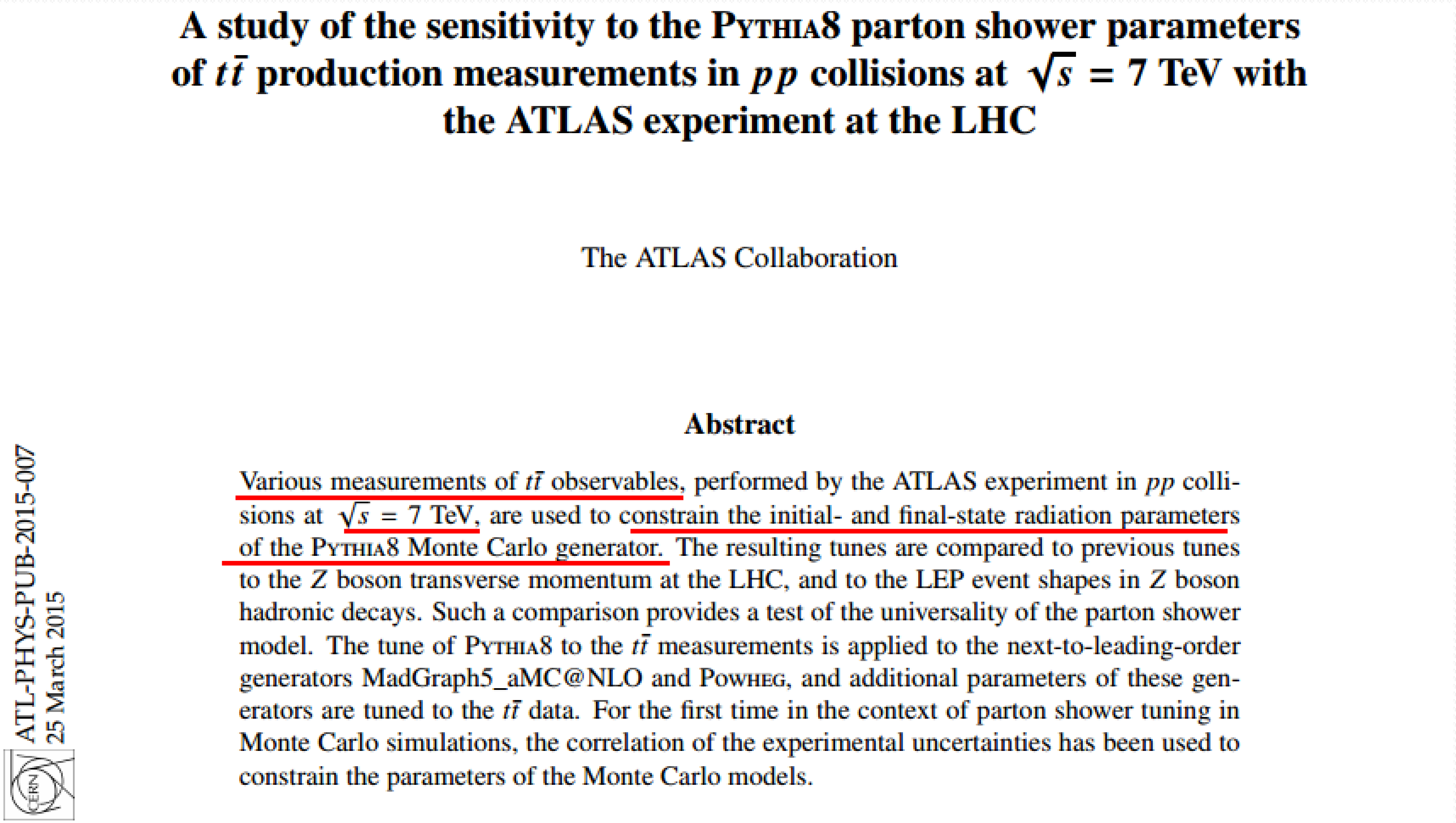
☐ **Our approach/goal**

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

“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.

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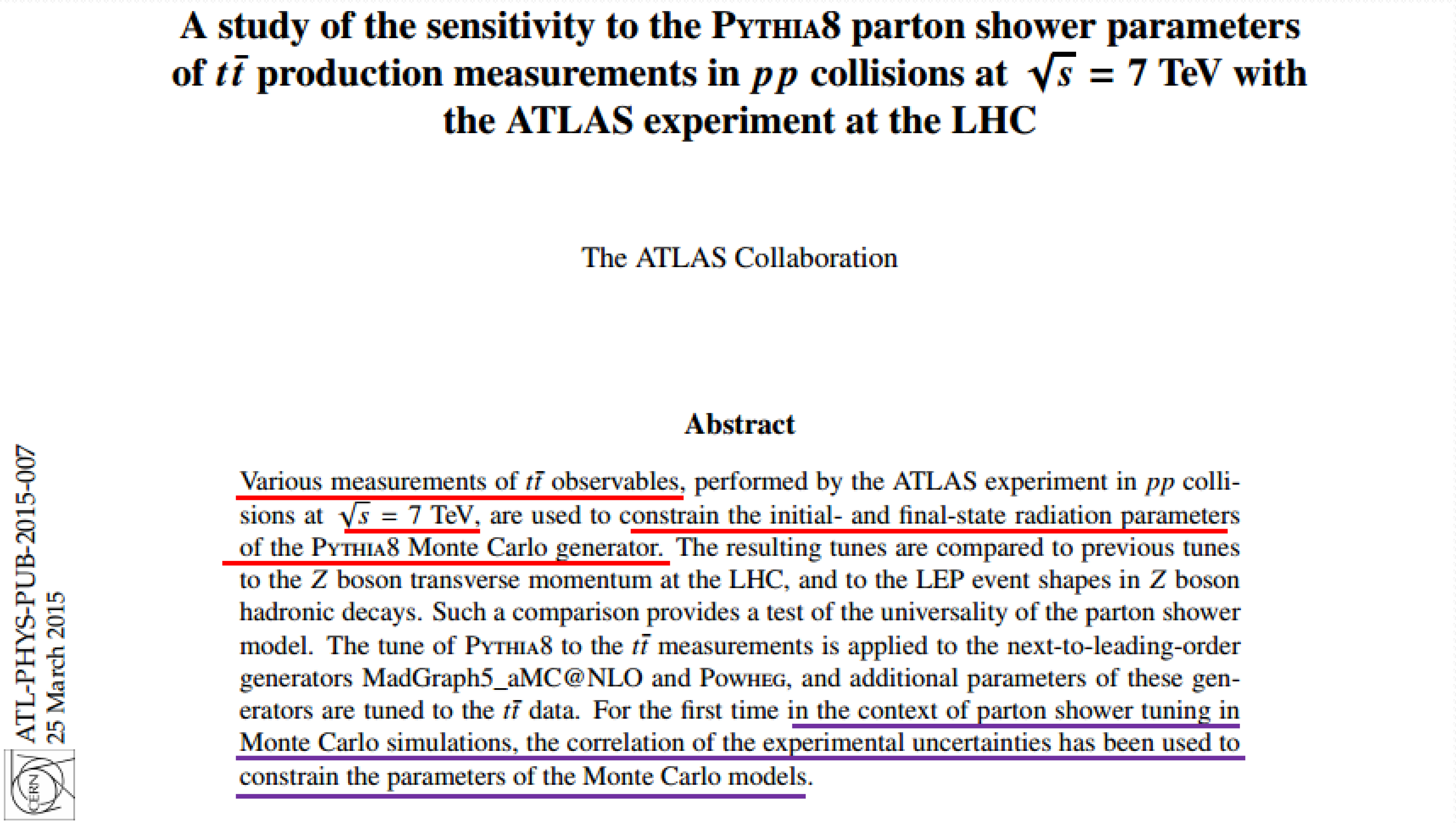

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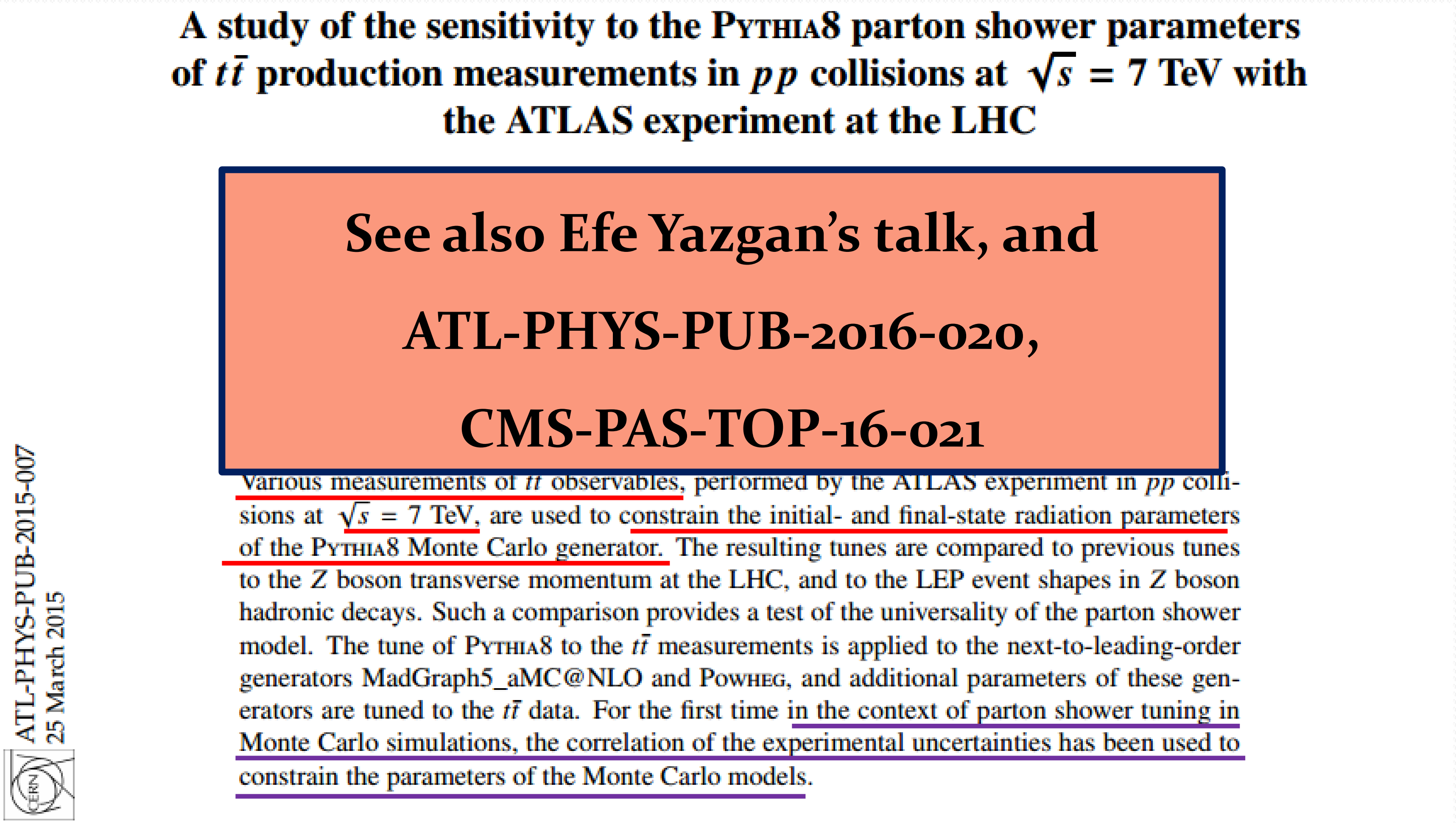

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See also Efe Yazgan’s talk, and

ATL-PHYS-PUB-2016-020,

CMS-PAS-TOP-16-021

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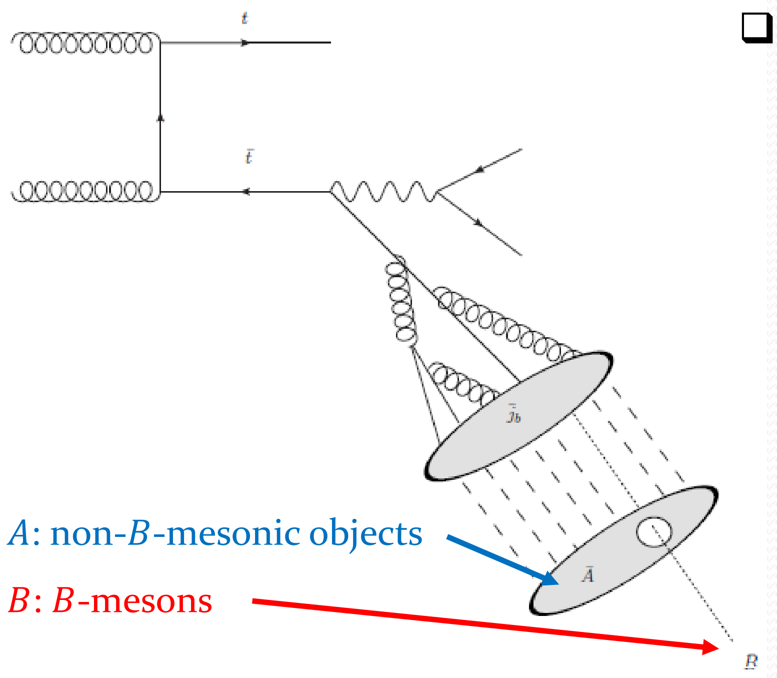
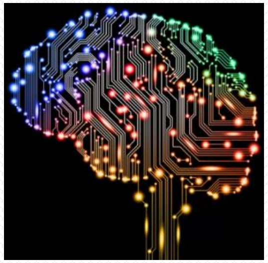
Strategy in a Nut-shell



A: non-B-mesonic objects

B: B-mesons



❑ 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-meson as a constituent, and extract its information,
5) evaluate various B-meson observables (next-to-next slide) along with leptons depending on observables: 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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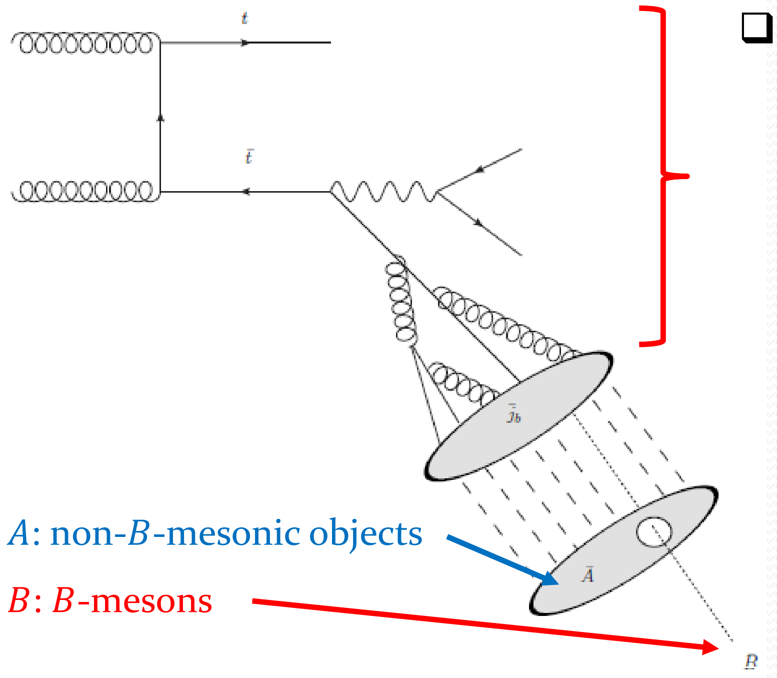

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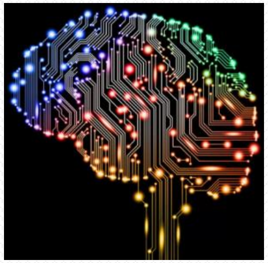

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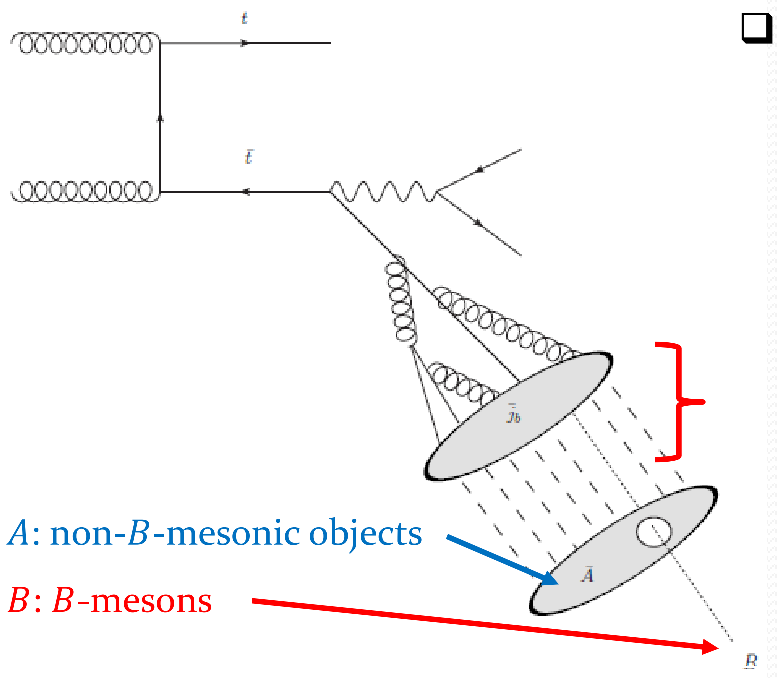

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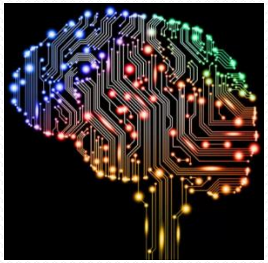

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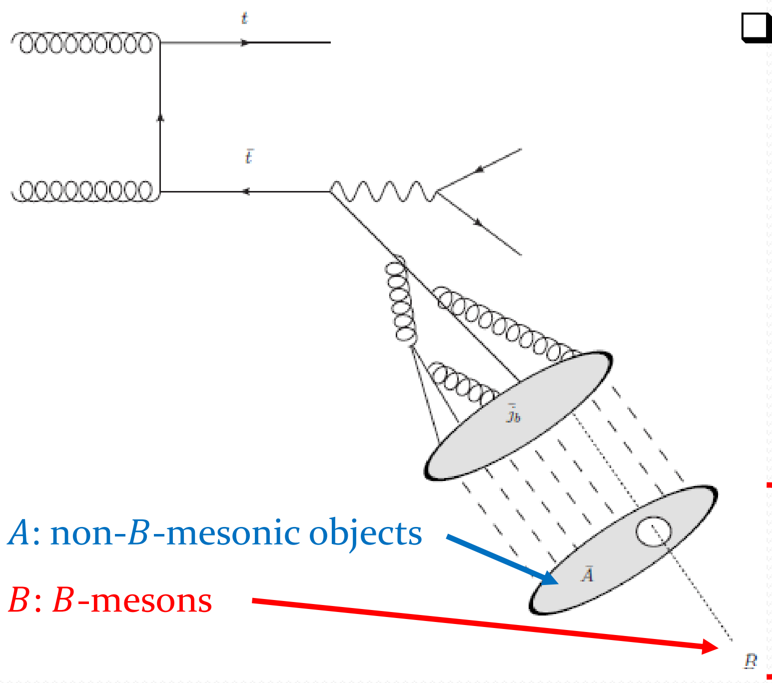

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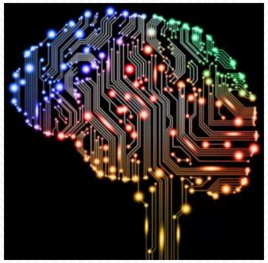

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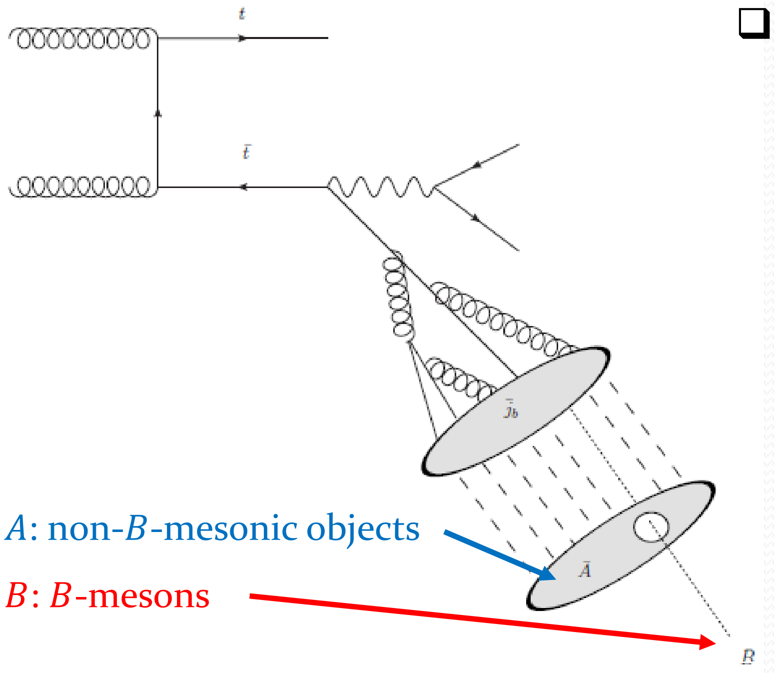

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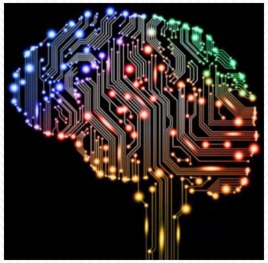

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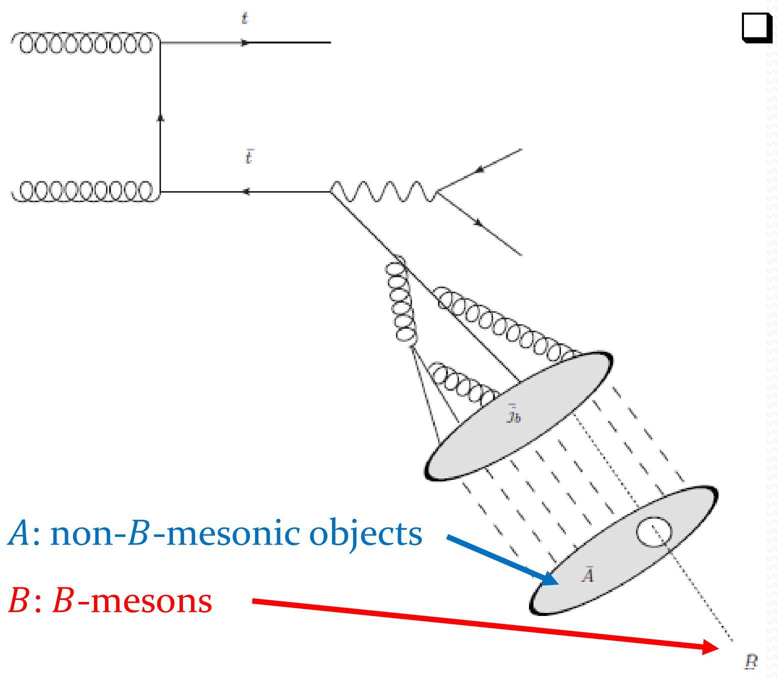

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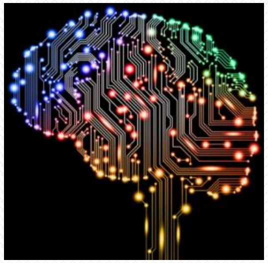

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B-meson-related Parameters

- ☐ Fully leptonic LO $t\bar{t}$ at the LHC 13 TeV with NNPDF2.3 QCD+QED LO 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

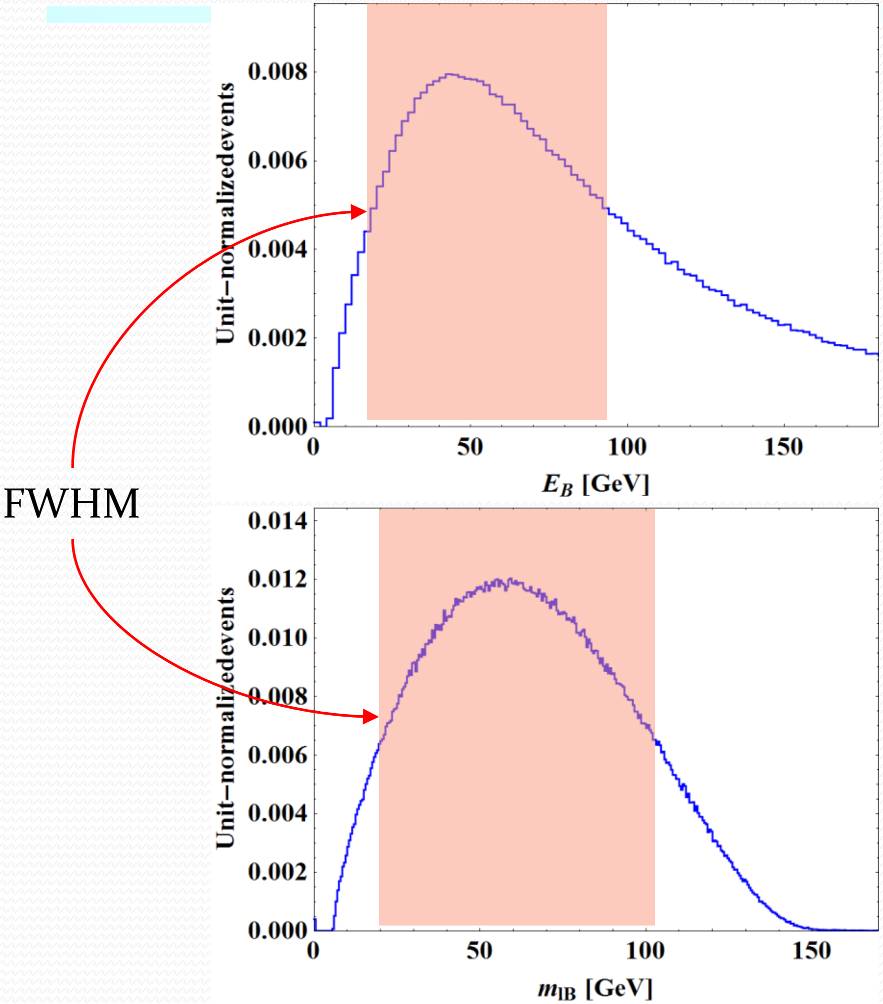
Parameter	PYTHIA8 setting	Variation range
r_b in the Bowler modification for heavy quarks	StringZ:rFactB	0.713 – 0.813
a parameter in the non-standard Lund ansatz for b quarks	StringZ:aNonstandardB	0.54 – 0.82
b parameter in the non–standard Lund ansatz for b quarks	StringZ:bNonstandardB	0.78 – 1.18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

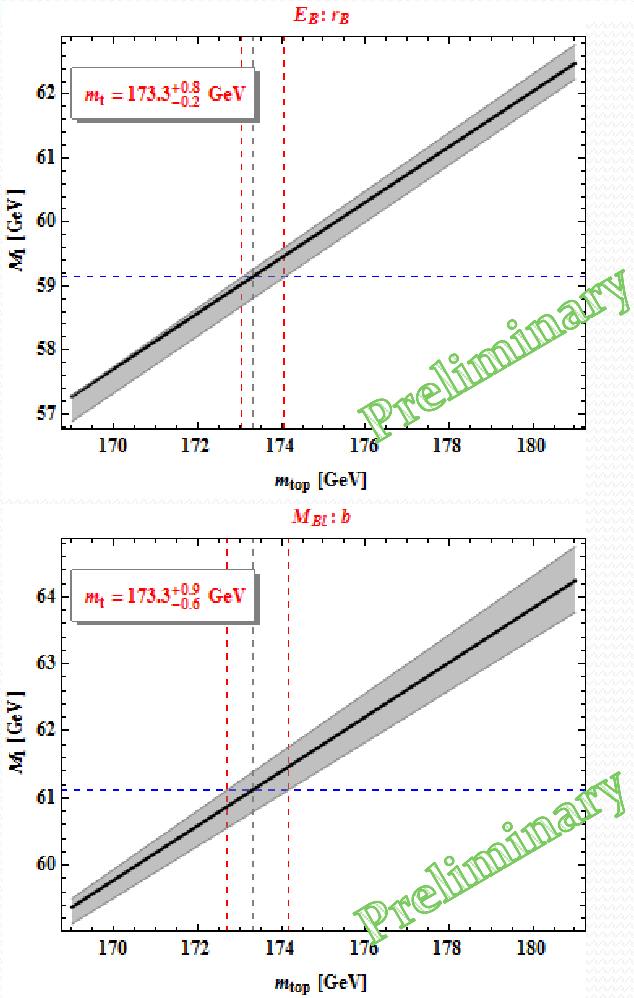
B-meson Observables

Observable	Mellin moment	Peak/Endpoint	Features
E_B	V	V	• 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 (only for $(B\ell)$ 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
$M_{T2,\perp}$	V (only for $(B\ell)$ subsystem)	V	• ISR-free observables • (B) and $(B\ell)$ subsystems

Results: Mellin Moment

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

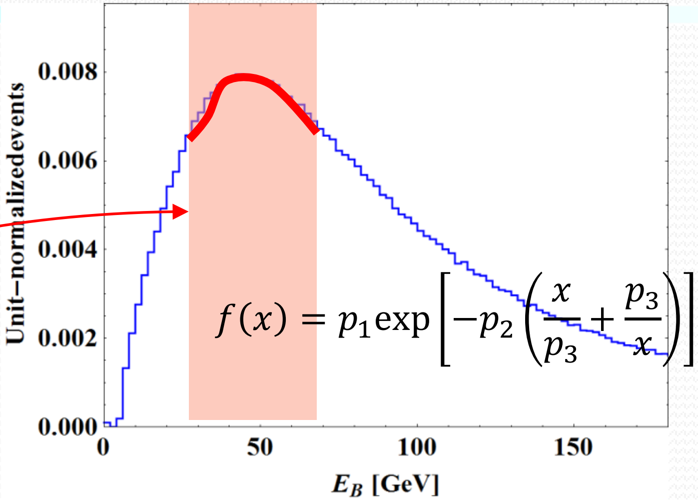




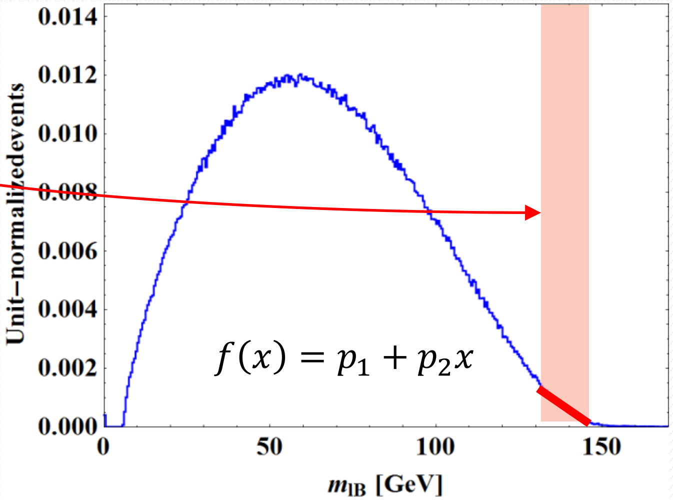
Results: Peak/Endpoint

Full width at ¾ height ($\chi^2/\mathrm{dof}\sim 1$)

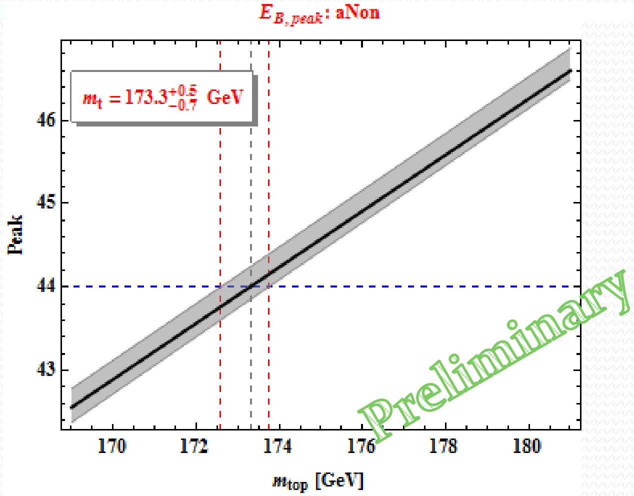
~5% from the endpoint ($\chi^2/\mathrm{dof}\sim 1$)

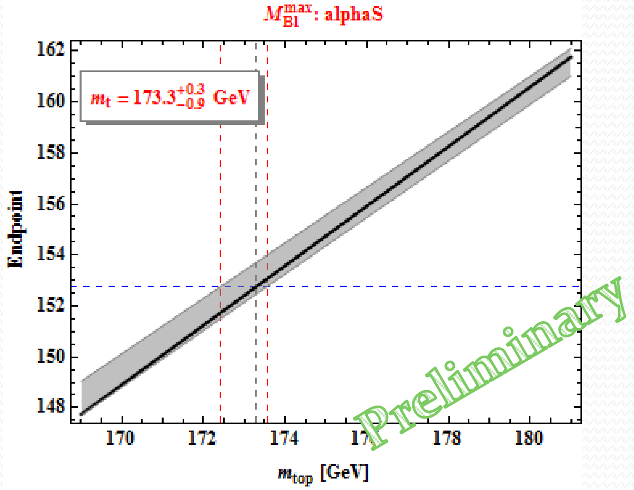


$$f(x) = p_1 \exp\left[-p_2\left(\frac{x}{p_3} + \frac{p_3}{x}\right)\right]$$



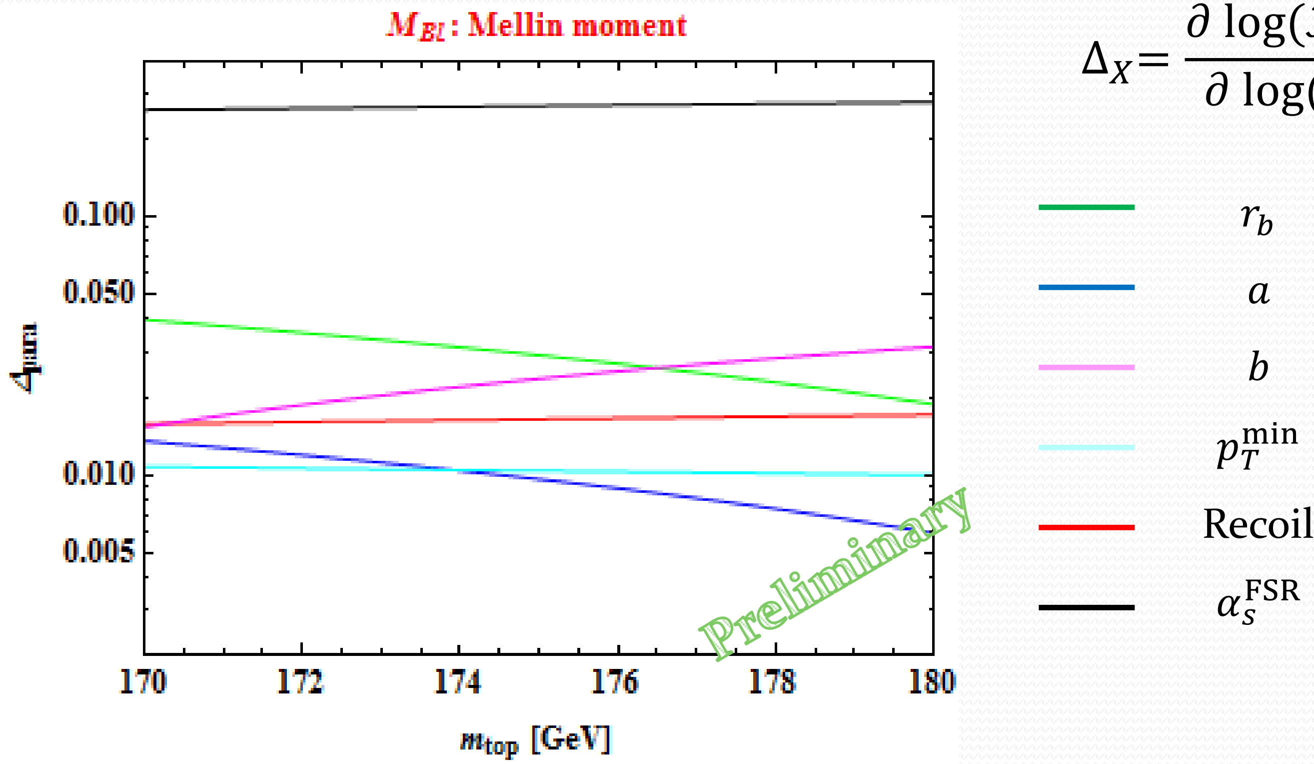
$$f(x) = p_1 + p_2 x$$





Results: Parameter Sensitivity

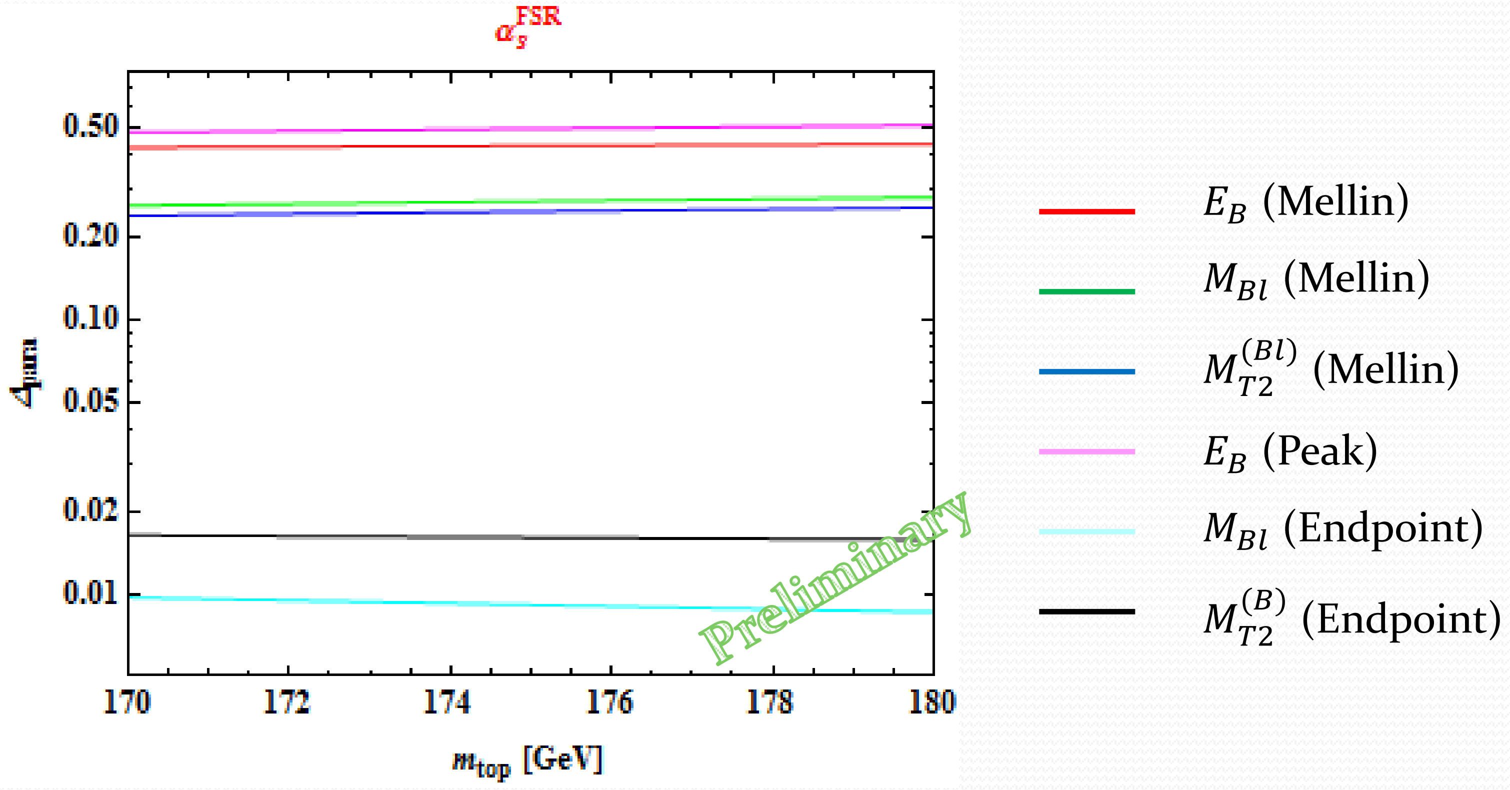
$$\Delta_X = \frac{\partial \log(\mathcal{M}_1)}{\partial \log(X)}$$



- ❑ For many observables, top quark mass is **most sensitive to α_s^{FSR}** (not surprisingly).

  → (Roughly) the more chance to have FSR, the softer distributions are

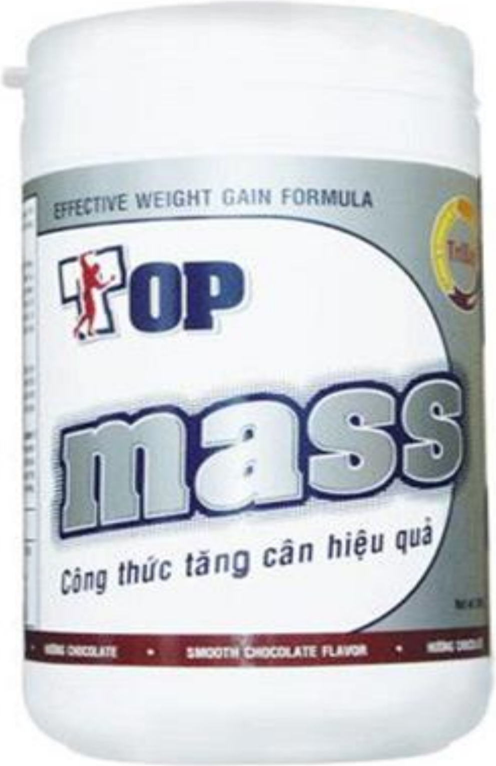
Results: Parameter Sensitivity



- ❑ Endpoint observables are **less sensitive to α_s^{FSR}**.

→ (Roughly) the endpoints are protected from FSR (with local data fits).

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
- B-meson observable method
  - Non-jetty nature
  - Most sensitive to α_s^{FSR}, so a better "tune" reduces the theoretical uncertainty of top mass in B-meson 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 ($\alpha_s^{\mathrm{FSR}} \rightarrow r_b \rightarrow \ldots$)
  - **$m_t^{\mathrm{ext}}|_{m_t^{\mathrm{in}}=173.3\ \mathrm{GeV}} = 173.3^{+0.6}_{-1.3}$ GeV** ($M_{Bl}/M_{T2}^{(B)}$ endpoints)
  - **$m_t^{\mathrm{ext}}|_{m_t^{\mathrm{in}}=173.3\ \mathrm{GeV}} = 173.3^{+0.5}_{-0.8}$ GeV** ($M_{T2}^{(B\ell)}$ endpoint w/ negligible sensitivity to α_s^{FSR})
- The same exercises with HERWIG will be available.

Thank you!

B-meson 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

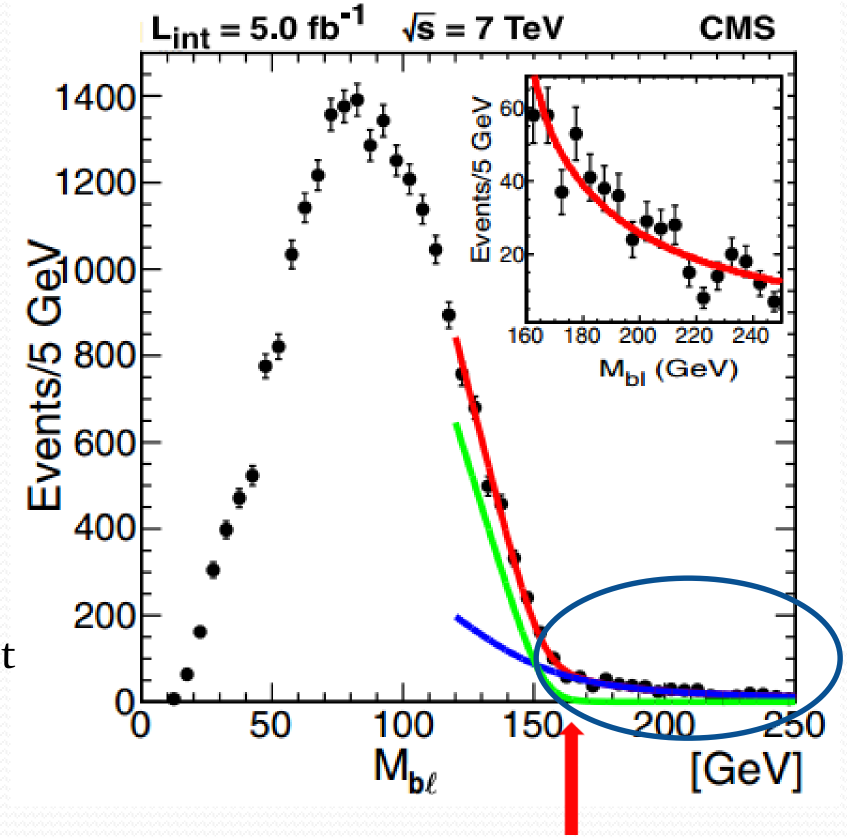
- $B^0 \xrightarrow[3\times10^{-3}]{} D^-\pi^+ \xrightarrow[10^{-2}]{} K_s^0\pi^-\pi^+$, $B^0 \xrightarrow[3\times10^{-3}]{} D^-\pi^+ \xrightarrow[10^{-2}]{} K^-\pi^+\pi^-\pi^+$,

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

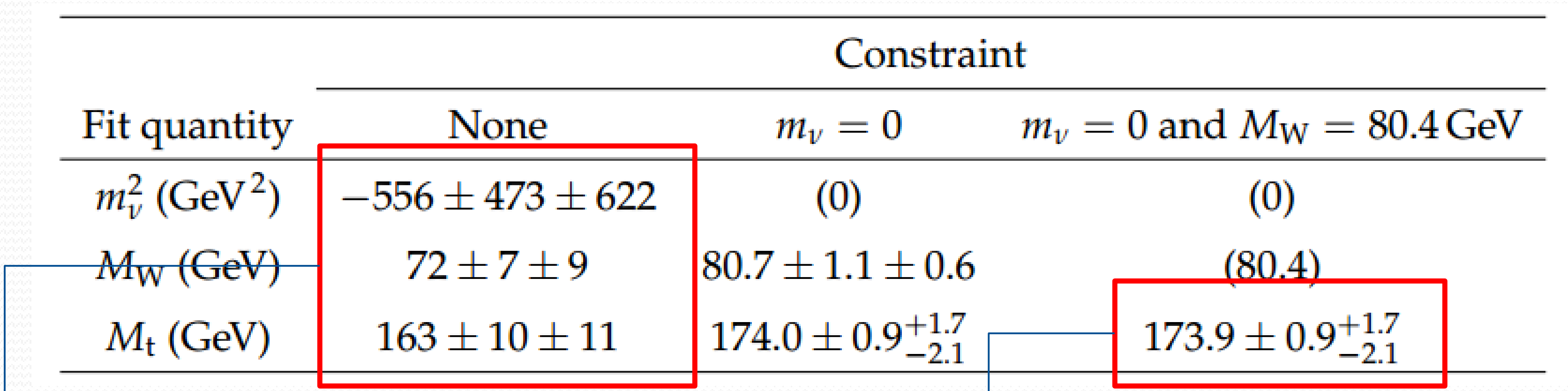
  $B^- \xrightarrow[5\times10^{-3}]{} D^0\pi^- \xrightarrow[6\times10^{-3}]{} K_s^0\rho^0\pi^-$, $B^- \xrightarrow[5\times10^{-3}]{} D^0\pi^- \xrightarrow[5\times10^{-3}]{} K^-\pi^+\rho^0\pi^-$

Endpoint Method

- ❑ Three observables: $m_{b\ell}$, b and ℓ subsystem M_{T2} endpoints [CMS-TOP-11-027]
- ❑ Endpoint extraction: local data fit (around expected endpoints)
  - ❖ (Detector response-convoluted) Kinked-line function (for signal) + background model function
- ❑ Shift of endpoints [Alioli et al, (2012)]
  - ❖ Width effect, NLO correction, … (might give a systematic bias)



Endpoint Method



	Constraint		
Fit quantity	None	$m_\nu = 0$	$m_\nu = 0$ and $M_W = 80.4\,\mathrm{GeV}$
m_ν^2 (GeV^2)	$-556 \pm 473 \pm 622$	(0)	(0)
M_W (GeV)	$72 \pm 7 \pm 9$	$80.7 \pm 1.1 \pm 0.6$	(80.4)
M_t (GeV)	$163 \pm 10 \pm 11$	$174.0 \pm 0.9^{+1.7}_{-2.1}$	$173.9 \pm 0.9^{+1.7}_{-2.1}$

- **Simultaneous measurement** of three mass parameters
- **Good exercise** for mass determination of new particles

- **Best top mass** measurement (by endpoint method) assuming m_W and m_ν well-measured

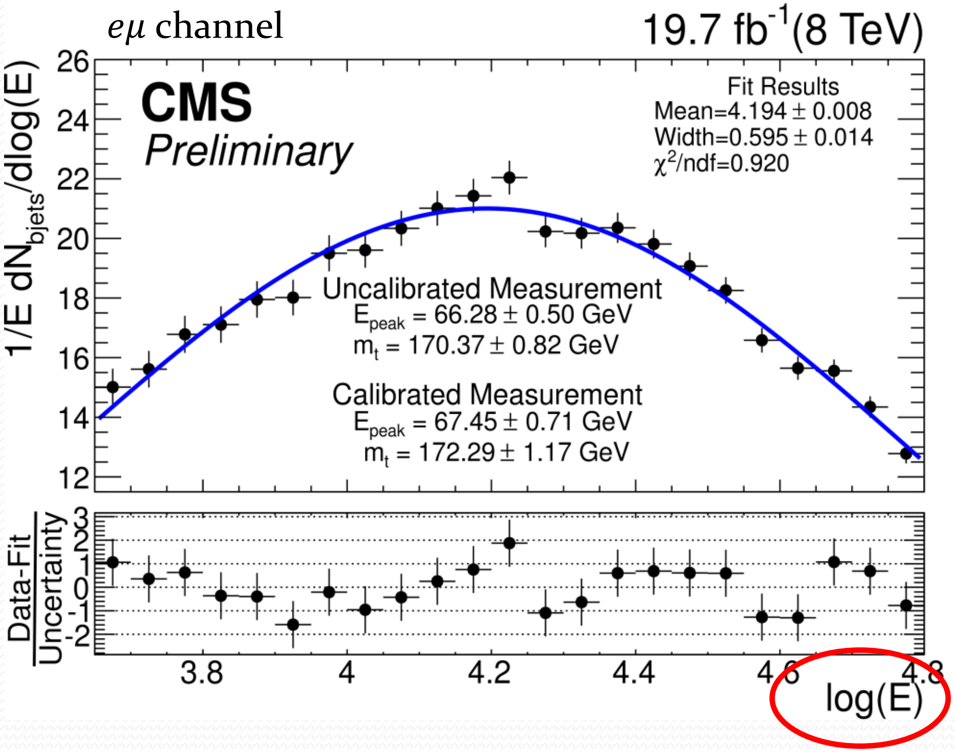
b-jet Energy-peak Method

- Based on the **LO** observation
- Dileptonic final state (cleanest channel)

$$t\bar{t} \rightarrow b\bar{b}e^{\pm}\mu^{\mp} + \nu_e\nu_\mu$$

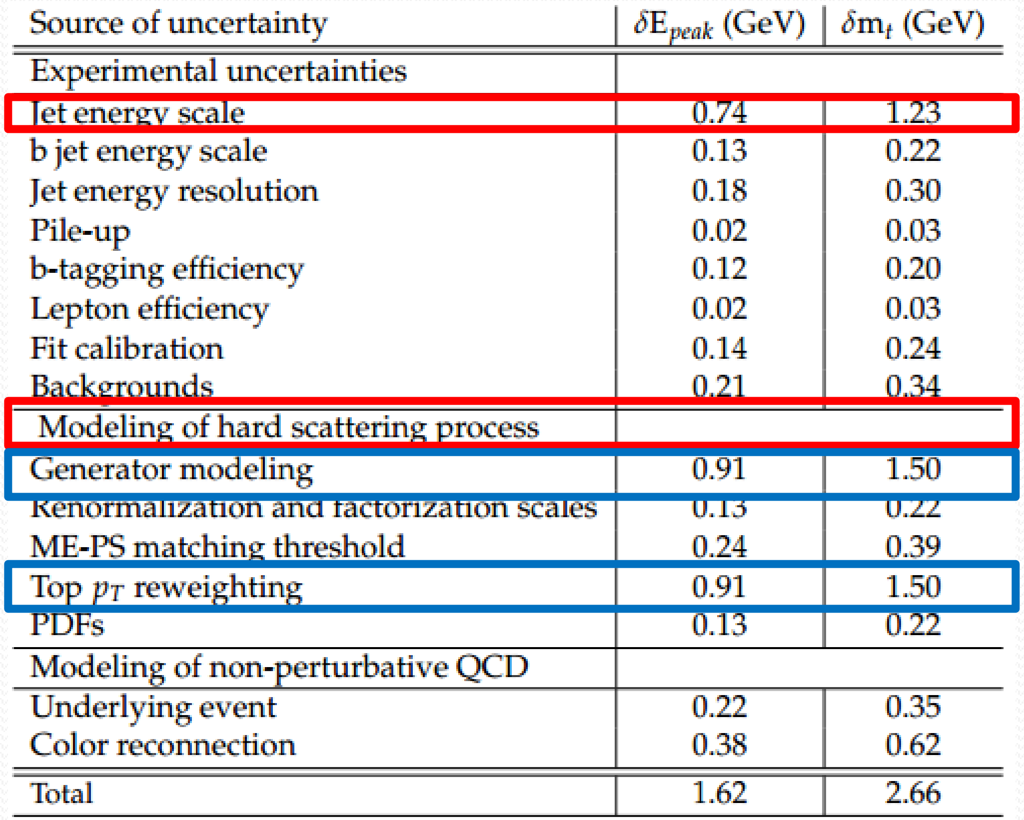
- Energy spectrum should be symmetric w.r.t. E_b^* in $\log E$
  - Gaussian fit near the peak region [CMS PAS TOP-15-002]
- **Best-fit top mass**

$$\boxed{m_t = 172.29 \pm 1.17 \pm 2.66\ \text{GeV}}$$



b-jet Energy-peak Method

Systematic uncertainties



Source of uncertainty	δE_{peak} (GeV)	δm_t (GeV)
Experimental uncertainties		
Jet energy scale	0.74	1.23
b jet energy scale	0.13	0.22
Jet energy resolution	0.18	0.30
Pile-up	0.02	0.03
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	0.91	1.50
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

- Statistical uncertainty of 1.17 GeV will be under control (more statistics coming up).
- Experimental uncertainty (mostly from JES) will be under control.
- Theoretical uncertainty is from modeling of hard scattering processes.
- Any chance to improve/understand the systematic uncertainty?
  - Study of **higher-order effects**