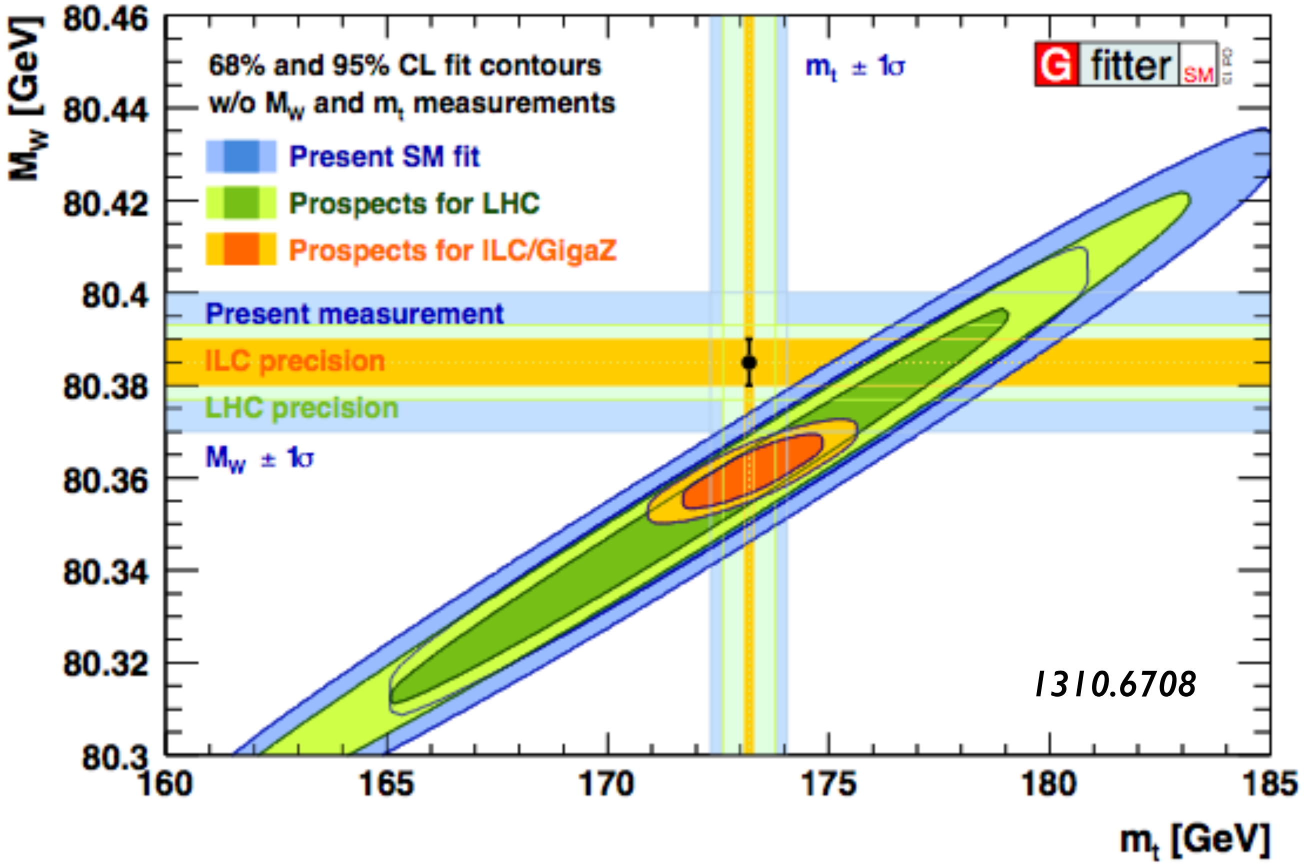
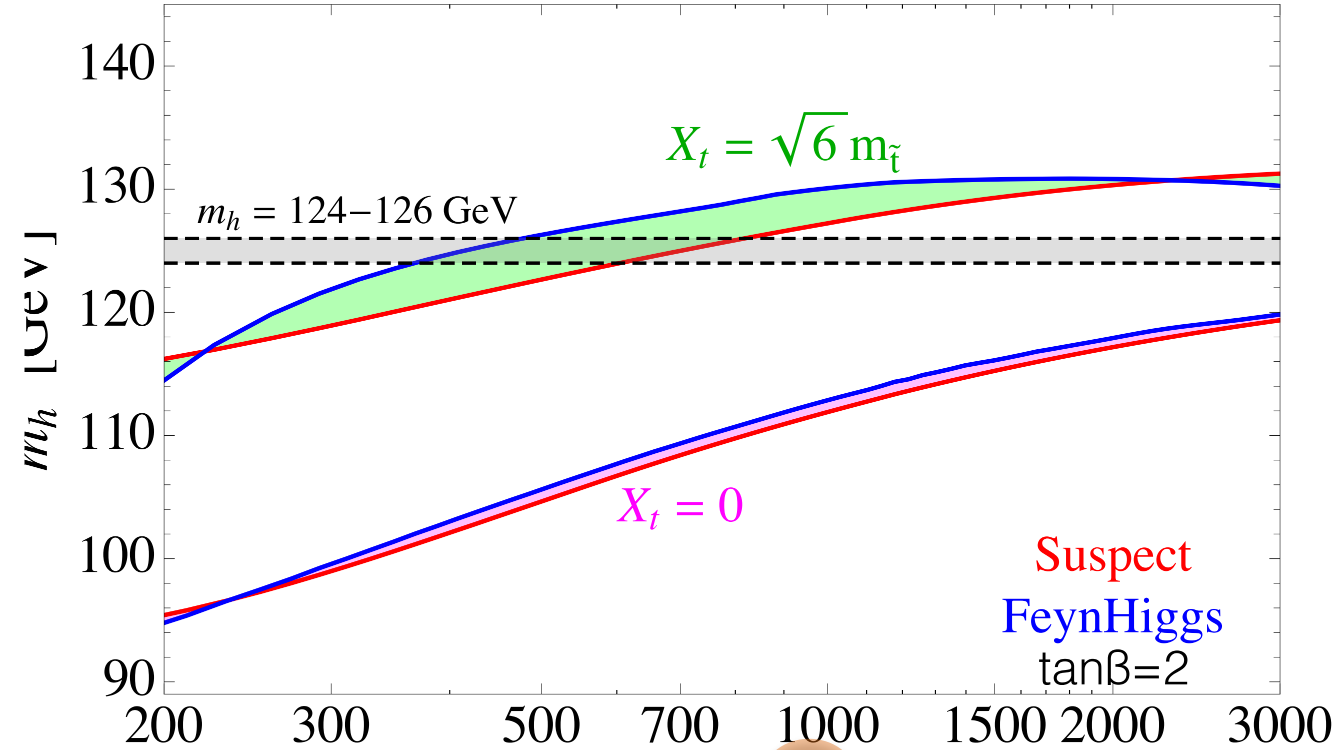
Top quark mass from the bottom (at NLO)

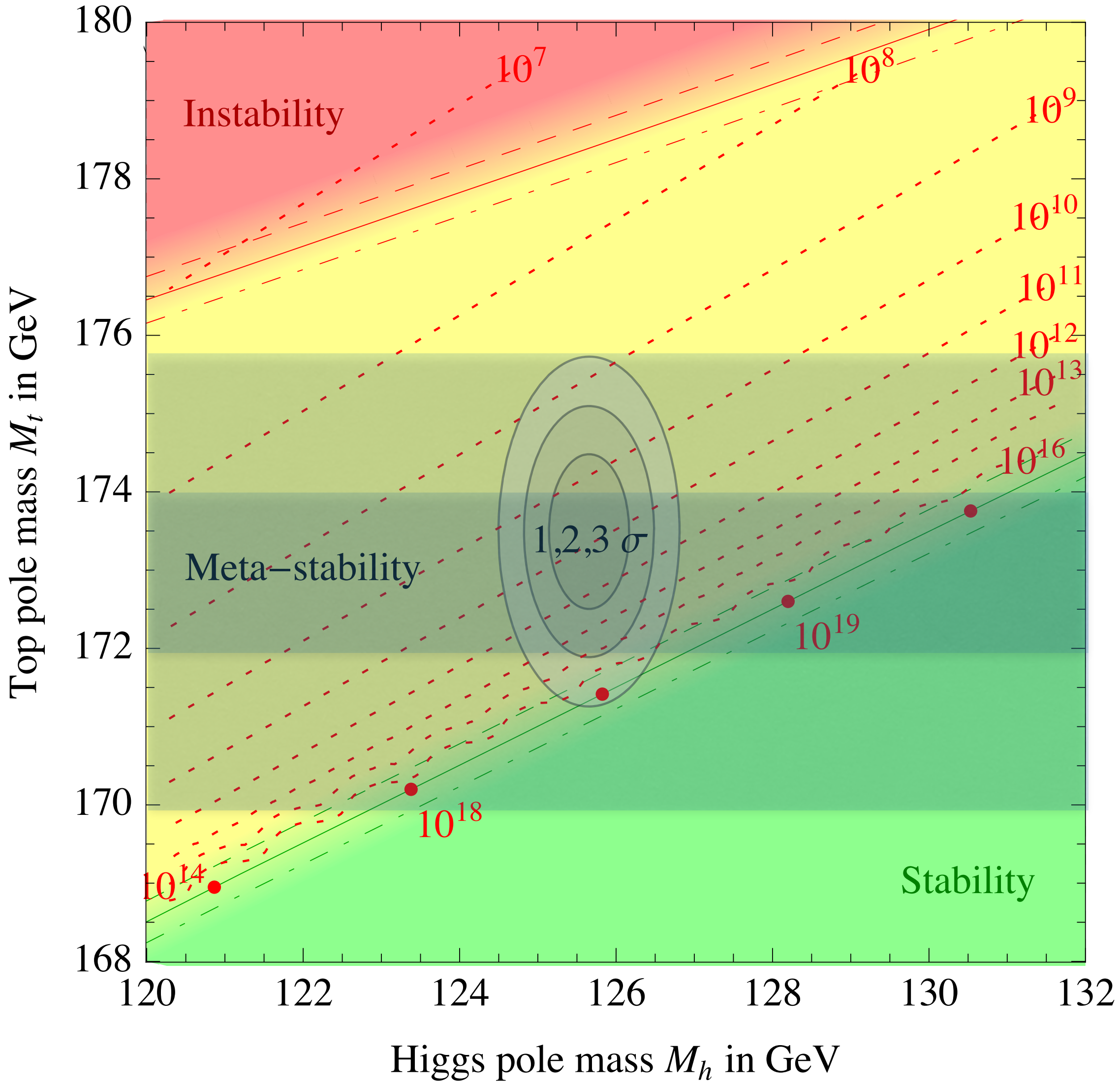
Roberto Franceschini (CERN)
April 9th 2015 (Portorož 2015)

Work in Progress with K. Agashe, D. Kim and M. Schulze

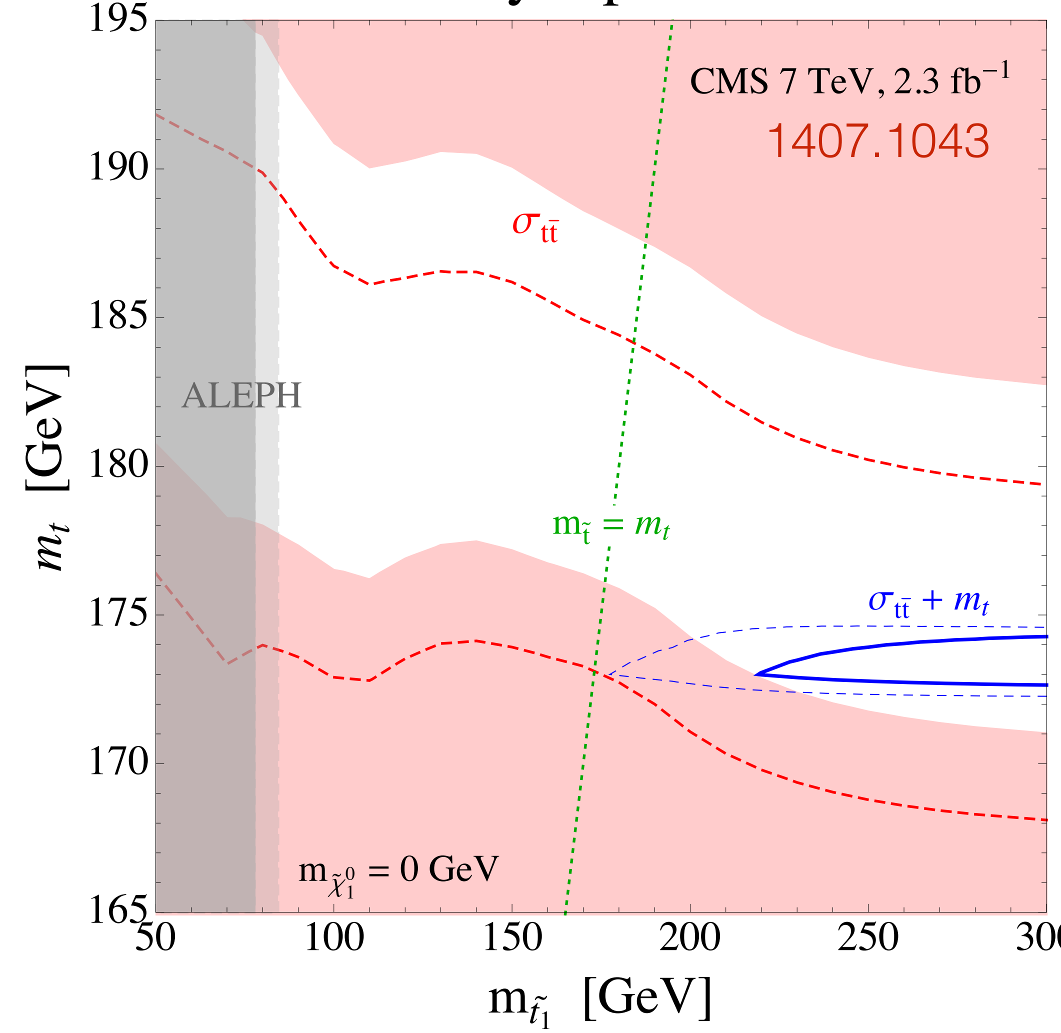




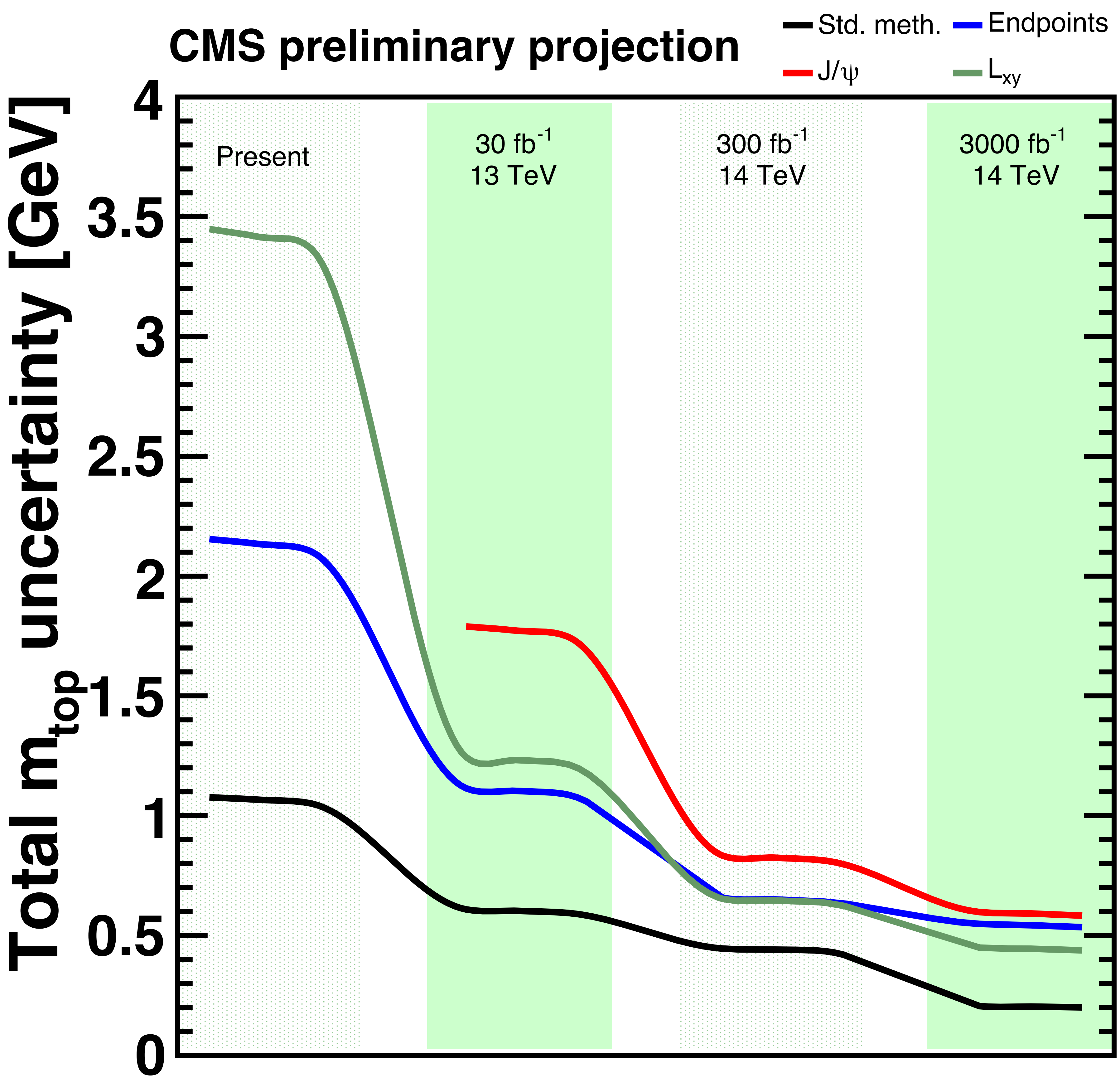
$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$



vary top mass



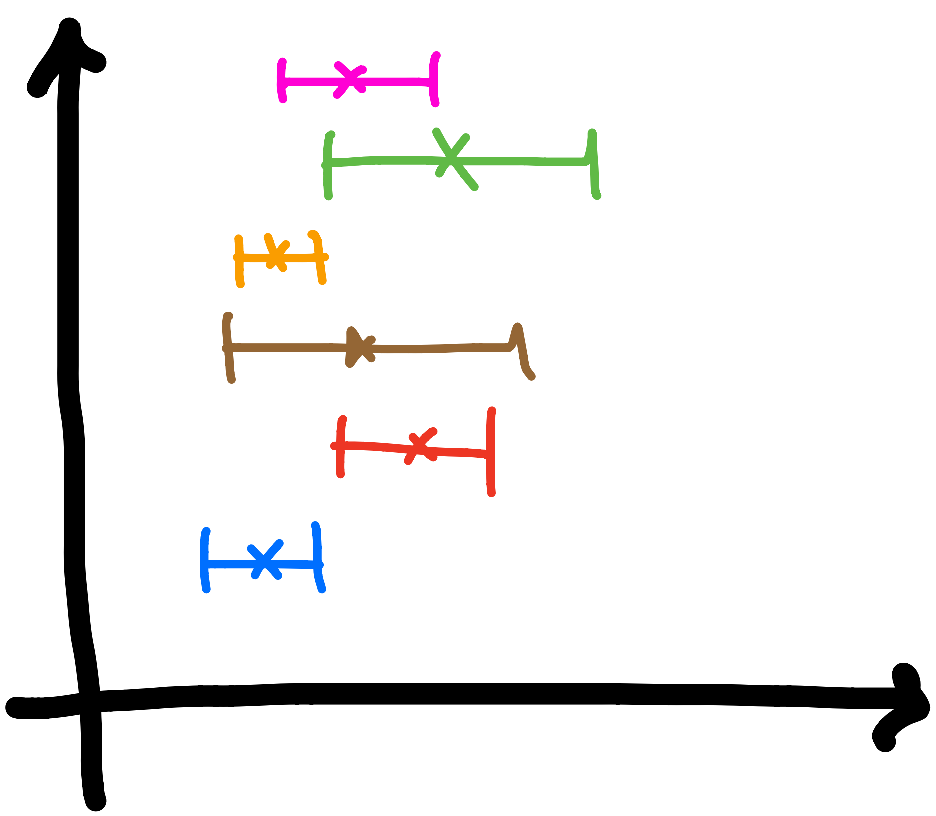
Global strategy

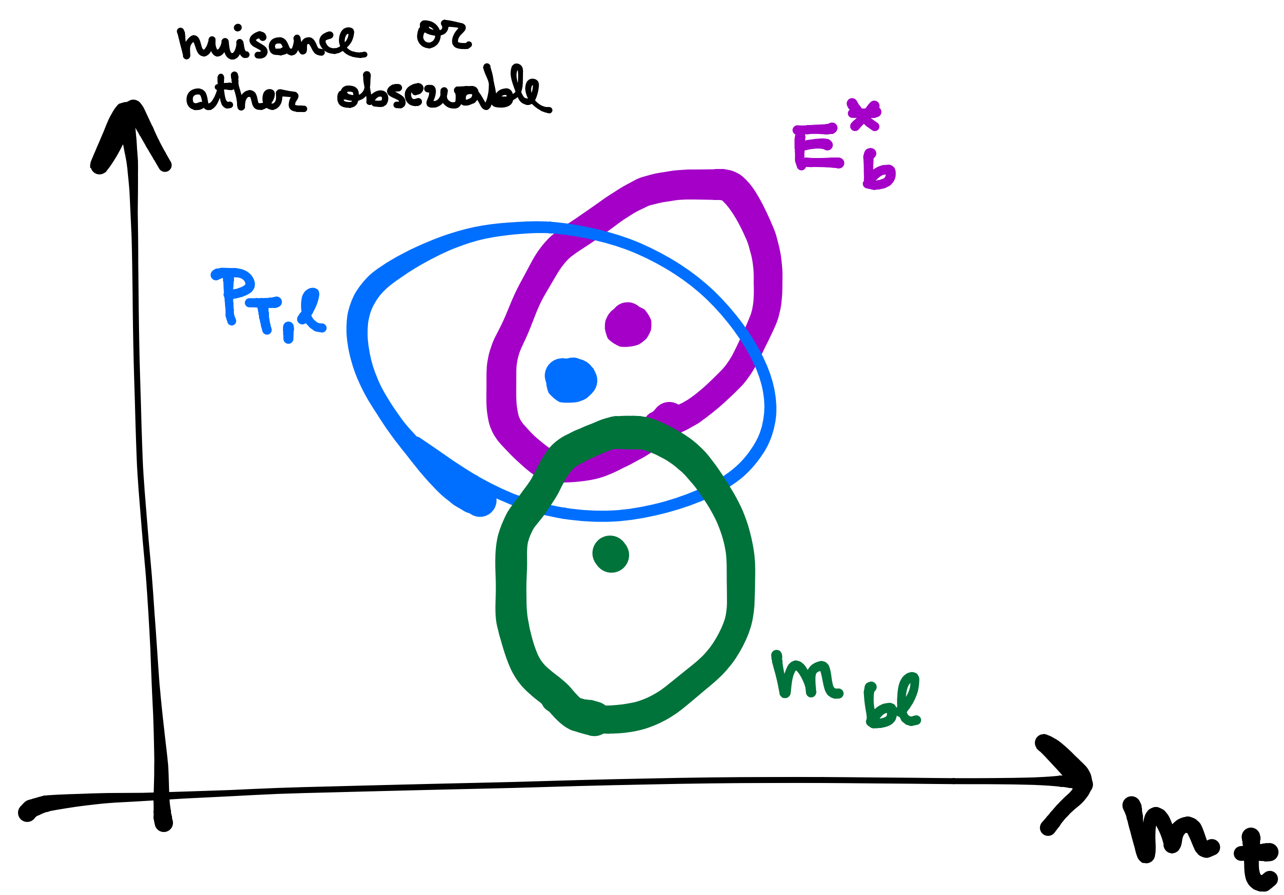


CMS-PAS-FTR-13-017

1310.0799 - Juste, Mantry, Mitov, Penin, Skands, Varnes, Vos, Wimpenny - Determination of the top quark mass circa 2013: methods, subtleties, perspective

Many measurements

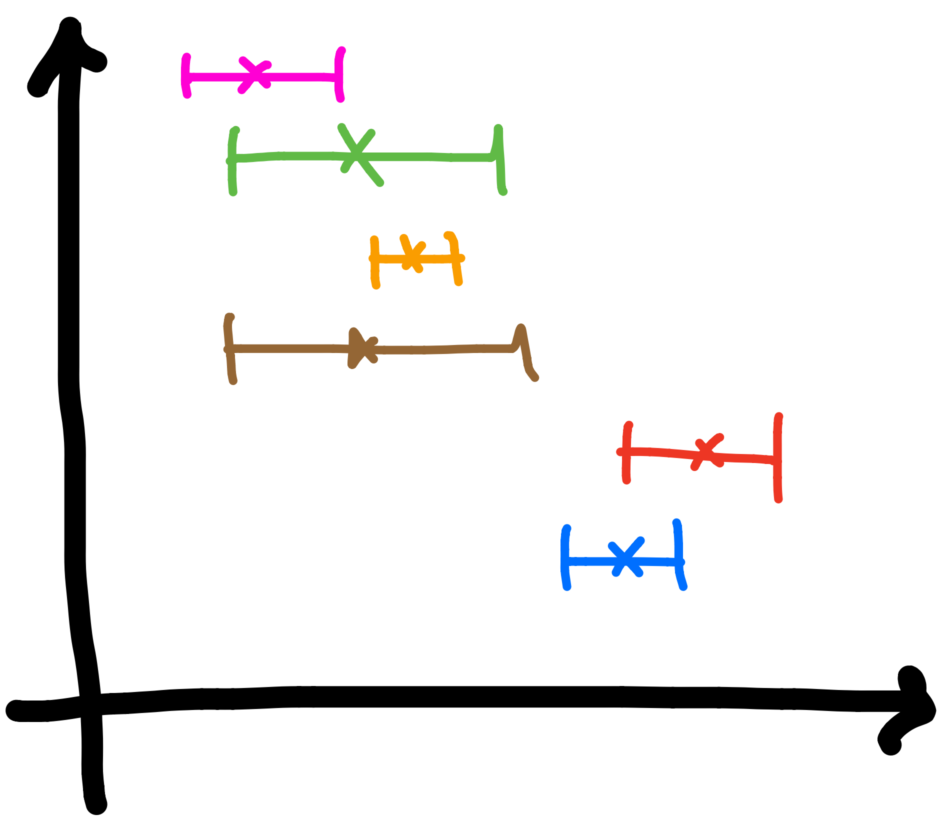


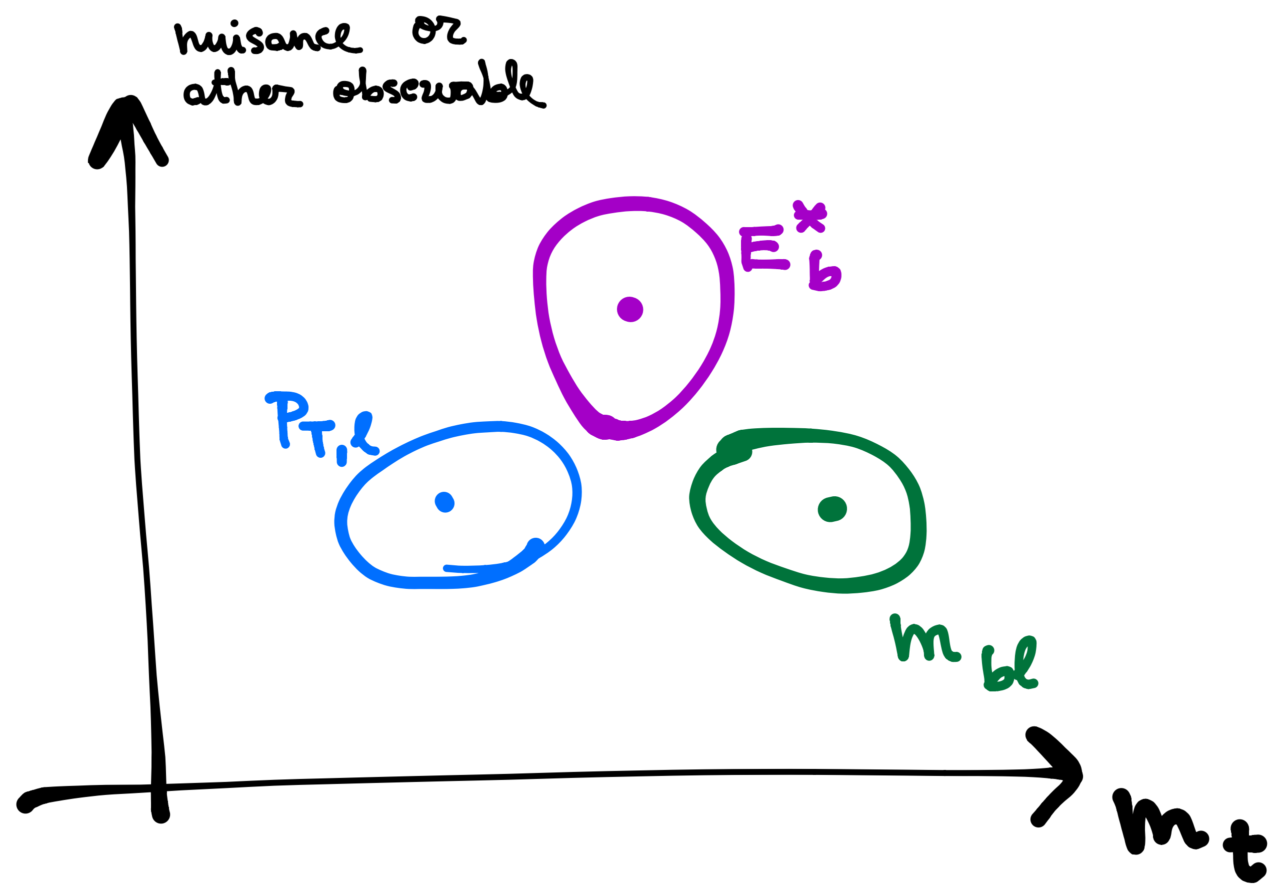


The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about "*single best measurement*"

Many measurements

due to different hypothesis, different mass measurement methods can result in significantly disagreeing measurements: **QCD or new physics effect?**





The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about “*single best measurement*”

(Alternative) Methods

- Energy Peaks 1209.0772 + WIP
- Generalized Medians 1405.2395
- Leptonic Mellin moments 1407.2763
- B-hadron life-time - L_{xy} hep-ex/0501043
- J/ψ exclusive hep-ph/9912320
- dσ(ttj) 1303.6415
- Inclusive σ(tt) 1307.1907

Energy Peaks

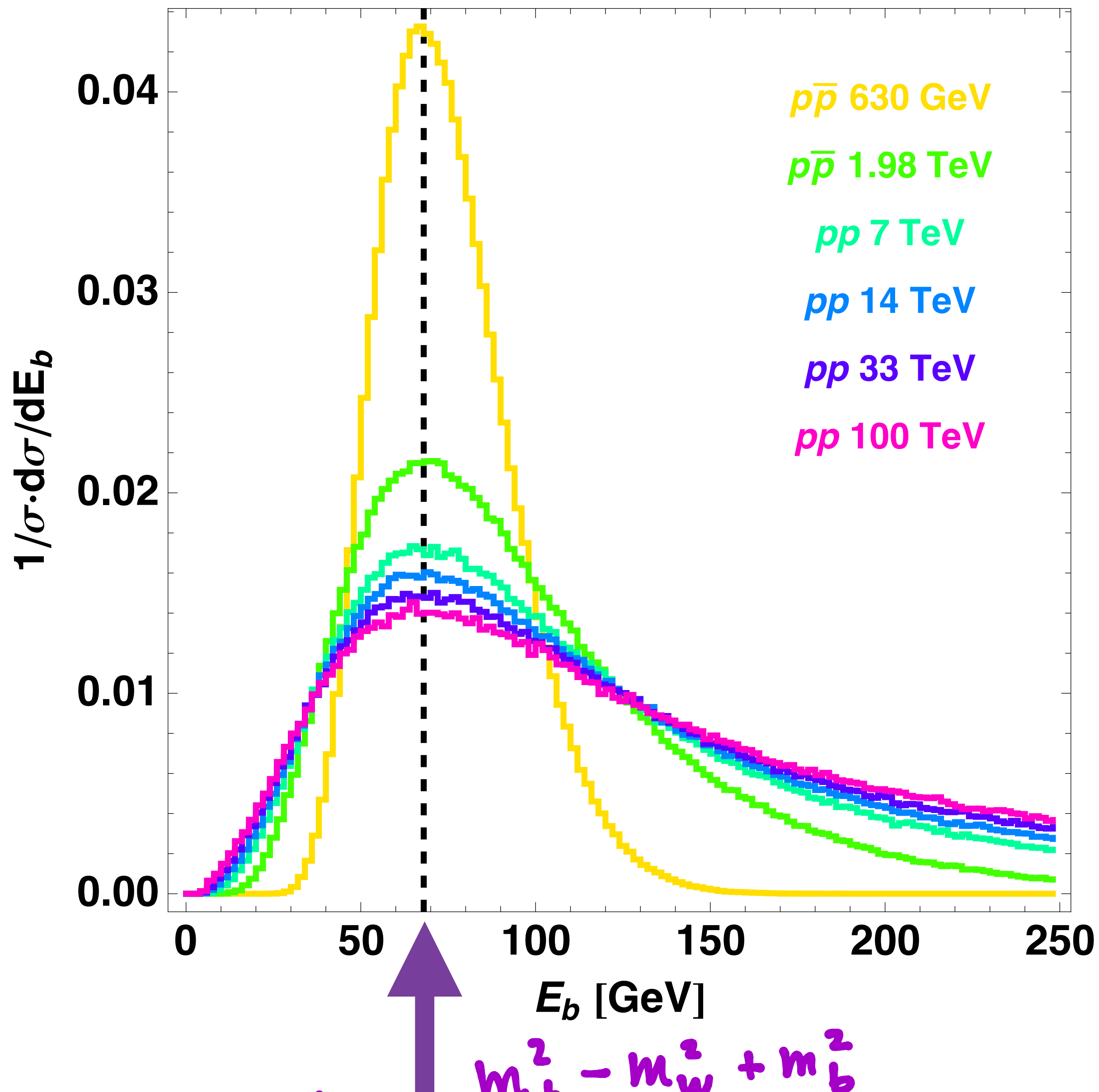
Lorentz *variant* quantities

Given suitable conditions, Lorentz variant quantities can tell us a lot about the invariants

How special is this invariance?

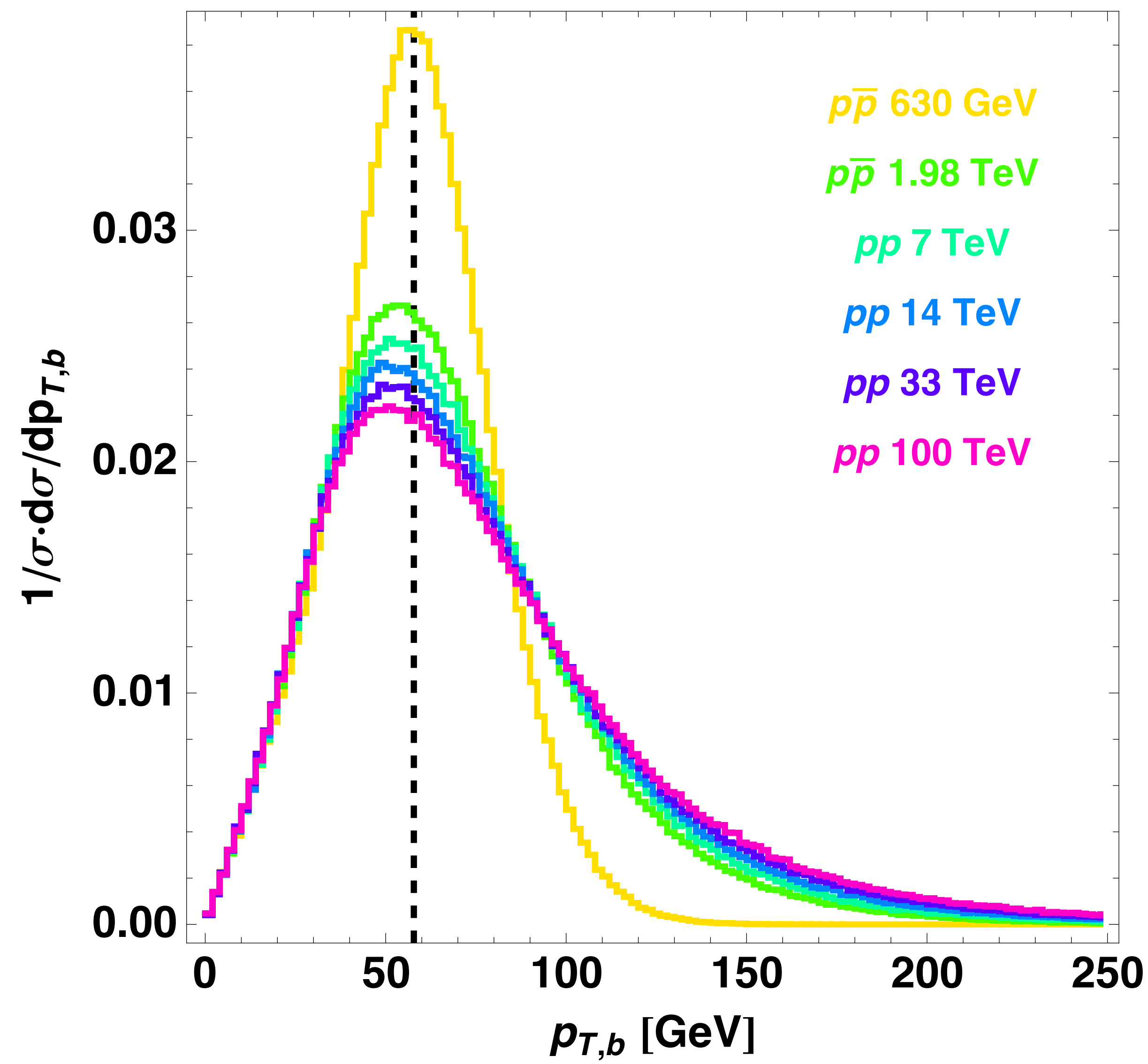
1209.0772 - Agashe, Franceschini and Kim

Shape changes, peak doesn't!



$$E_b^* = \frac{m_t^2 - m_W^2 + m_b^2}{2 m_t}$$

Shape changes, peak does too



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

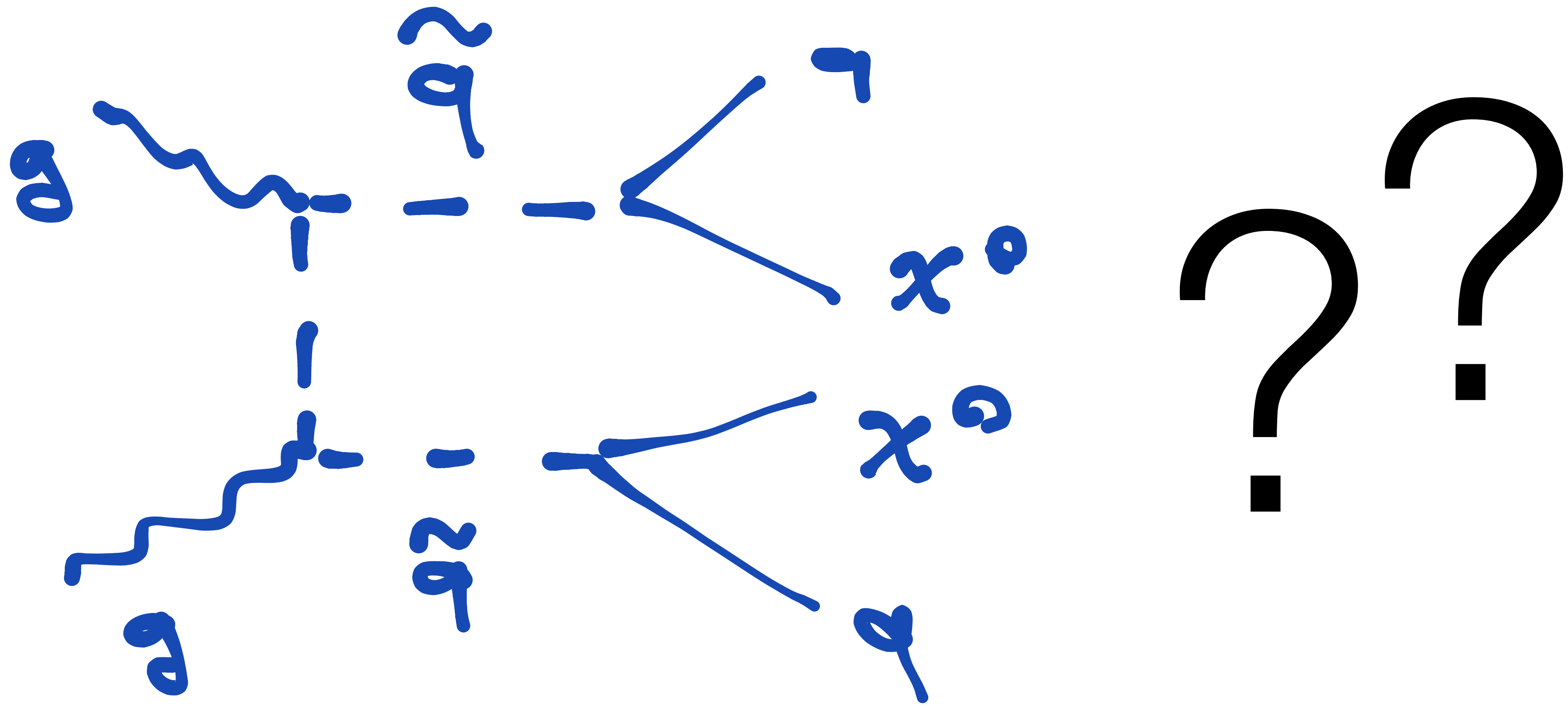
The Breit-Wigner peak substitute?

$$(p_{\mu_1} + p_{\mu_2})^2 \to m_Z^2$$

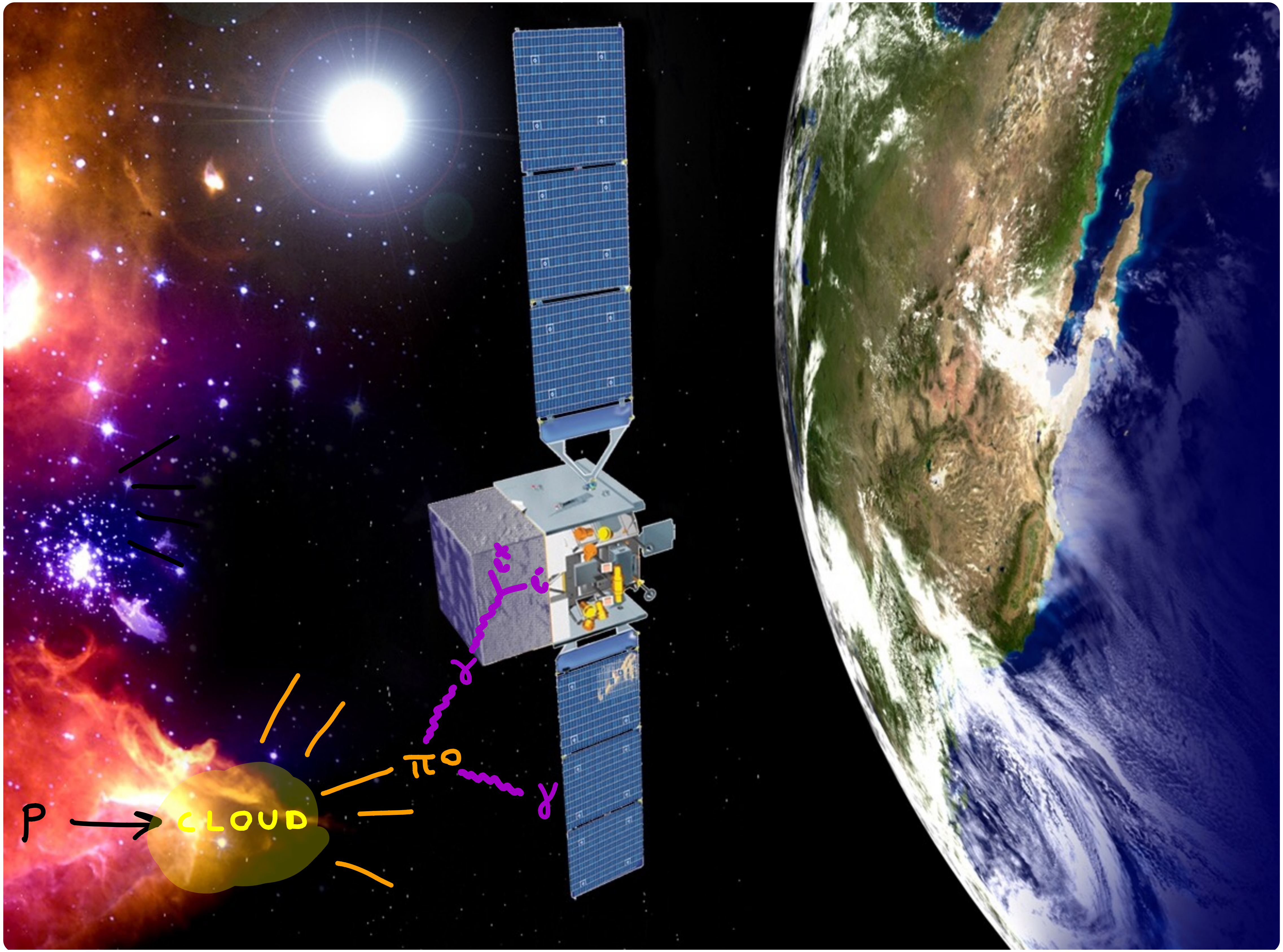
The Breit-Wigner peak substitute?

?

The Breit-Wigner peak substitute?



Cosmic peaks (Stecker 1971)



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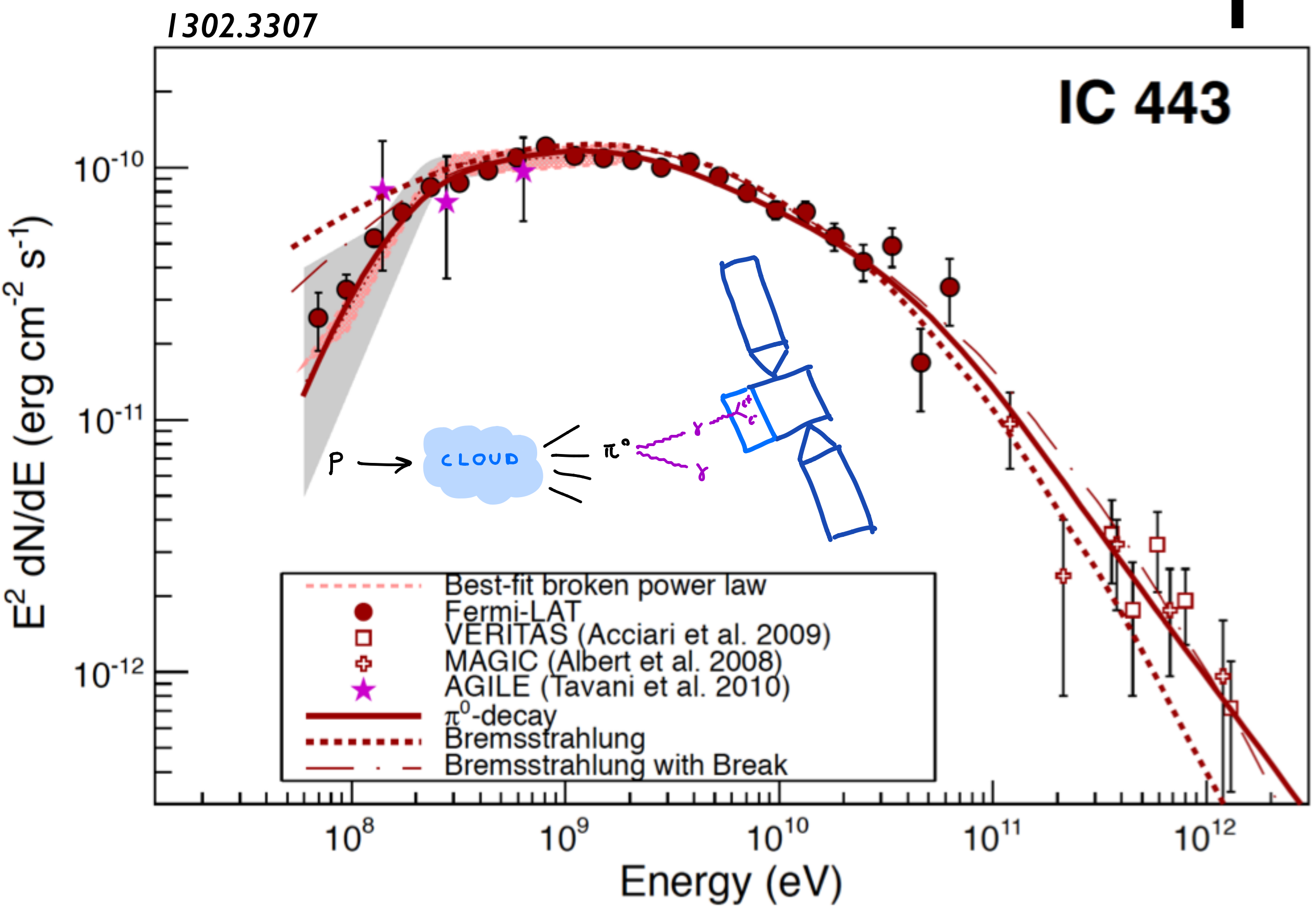
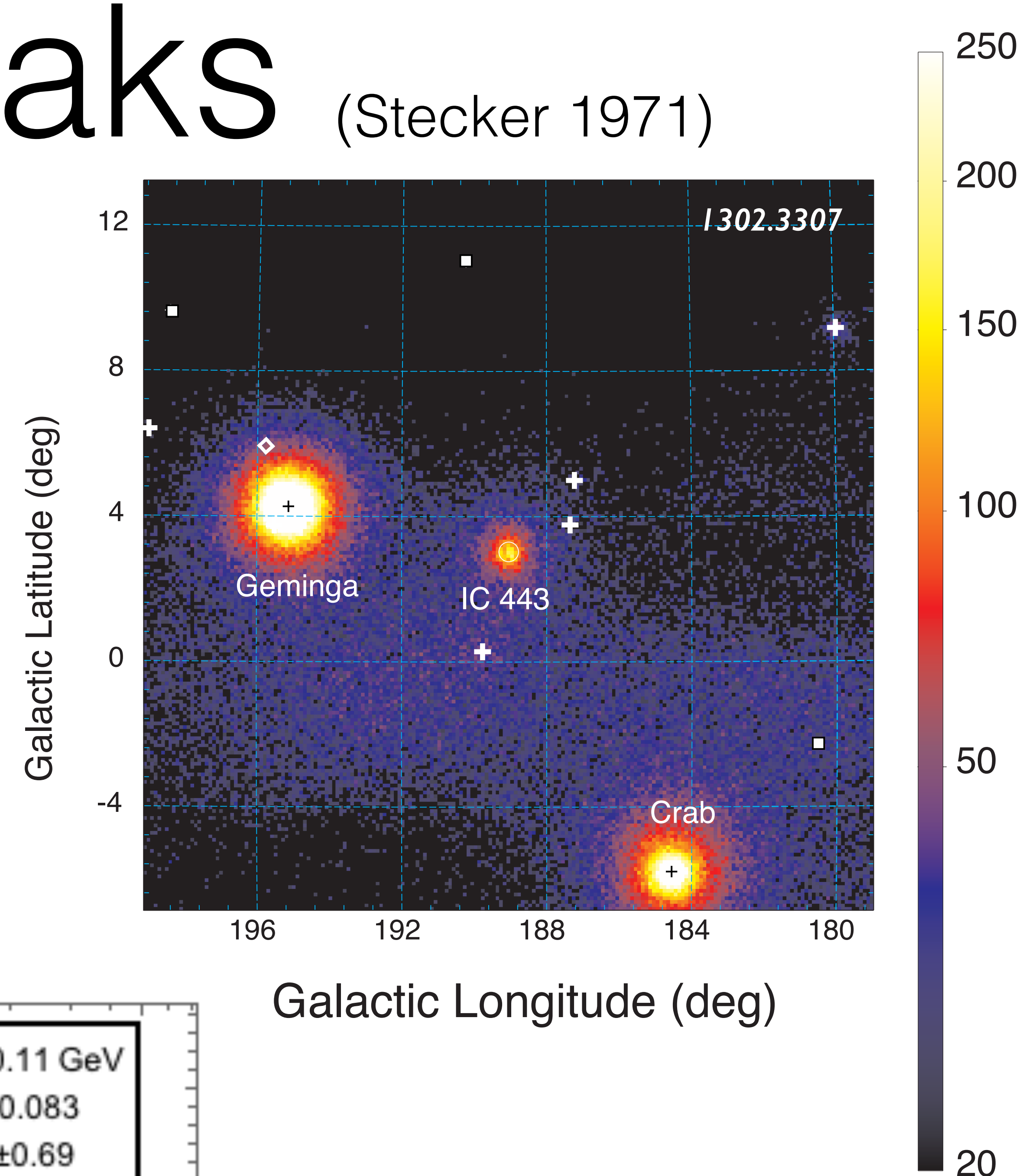
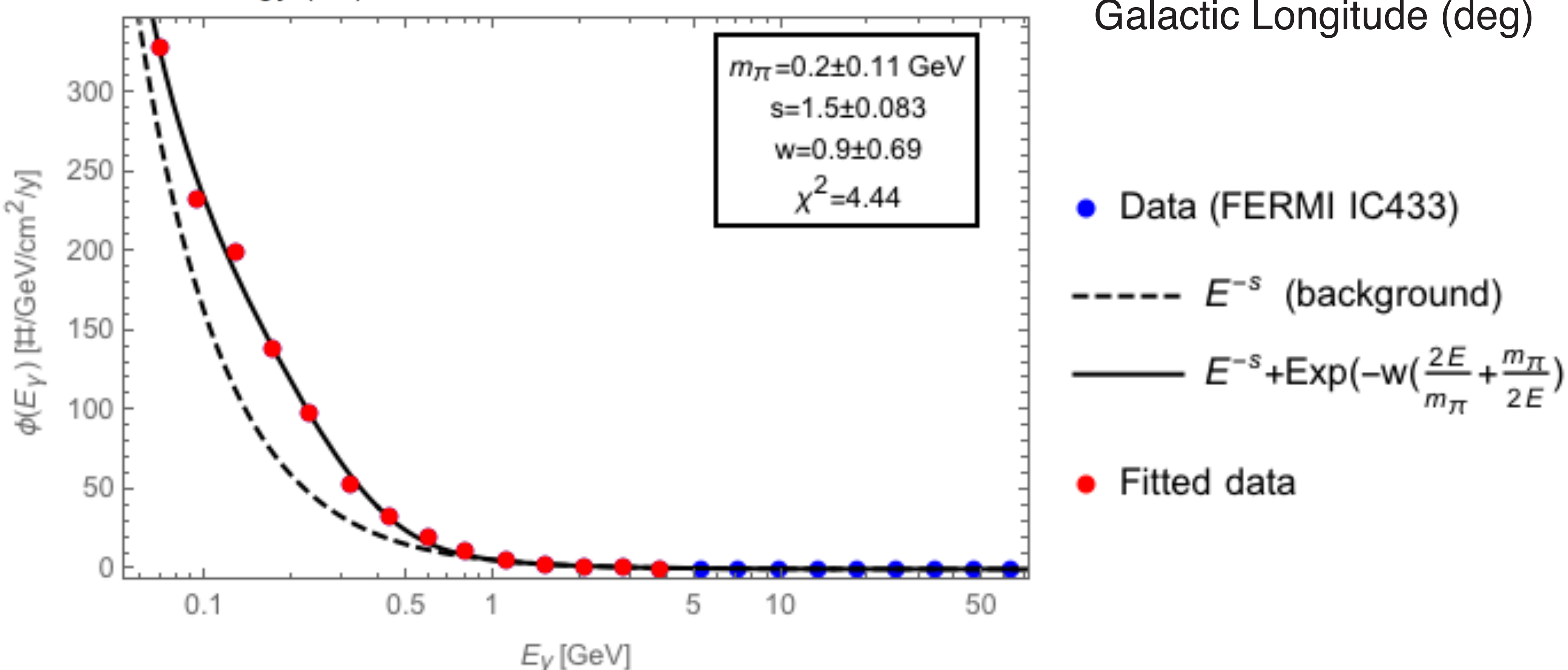






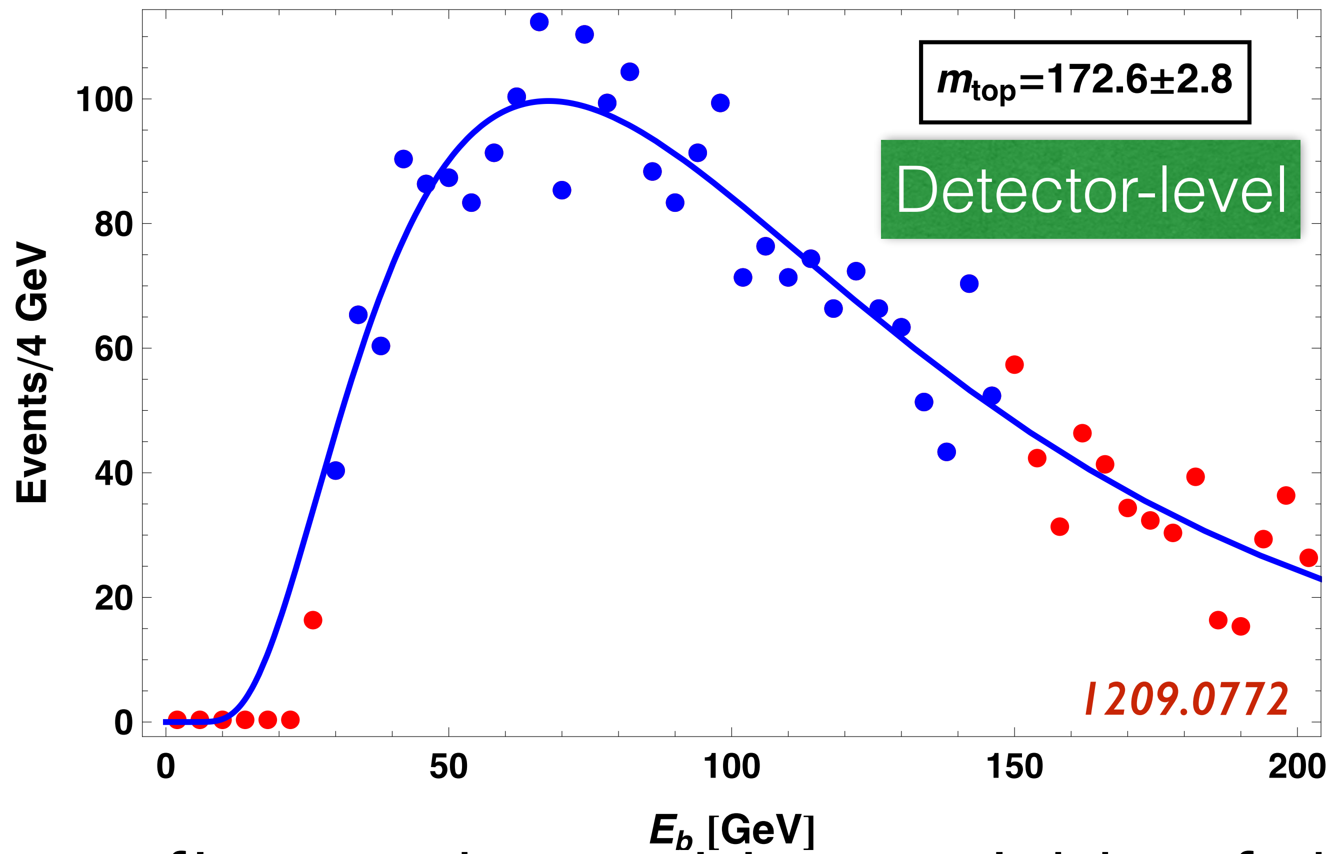
• properties similar to Lorentz invariants

Useful in practice?

$$E_b^* = \frac{m_t^2 - m_W^2 + m_b^2}{2 m_t}$$

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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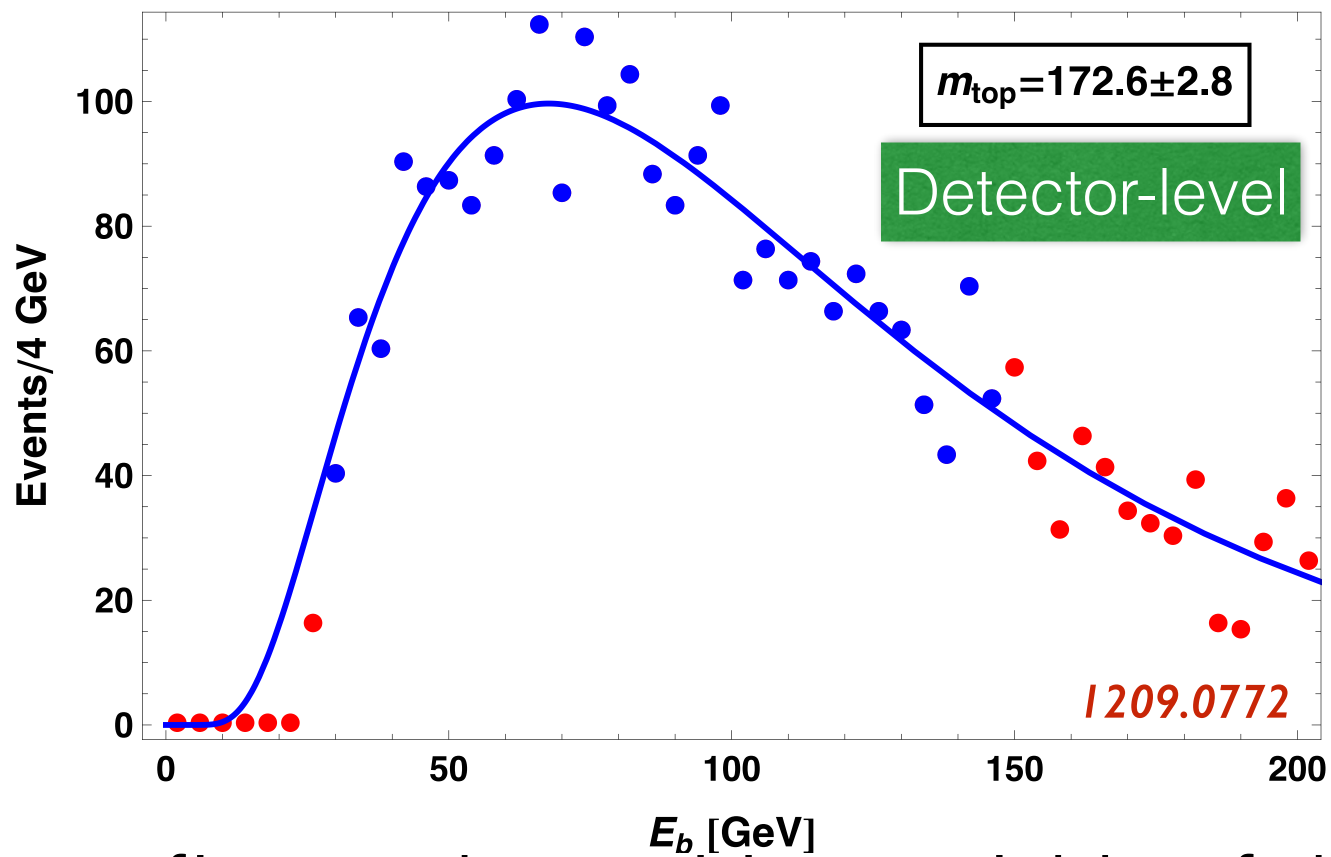

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Proof of the concept: ***5/fb LHC 7 TeV***

$m_{top} = 173.1(1 \pm \alpha/\pi) \pm 2.5$ GeV (stat)

1209.0772 - Agashe Franceschini and Kim

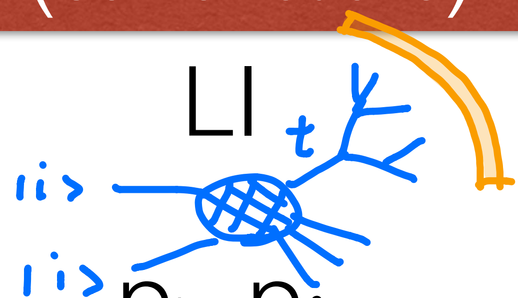
message: LO effects are well under control → CMS at work!

variations around Lorentz Invariance

needs two particles (combinations)

needs just one particle

LI

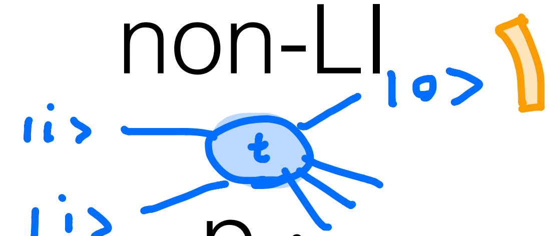


$p_b \cdot p_\ell$

"pheno"-LI

$\hat{E}_b$

non-LI



$p_{T\ell}$

radiation in decays breaks true-LI due to reconstruction

radiation in decays breaks pheno-LI due to 3-body

end-point is safe w.r.t radiation in decay

exclusiveness breaks pheno-LI

in practice we need the tail, which is sensitive to radiation

what is the "small parameter" Δ_{TH} that "breaks" (true or effective) LI?

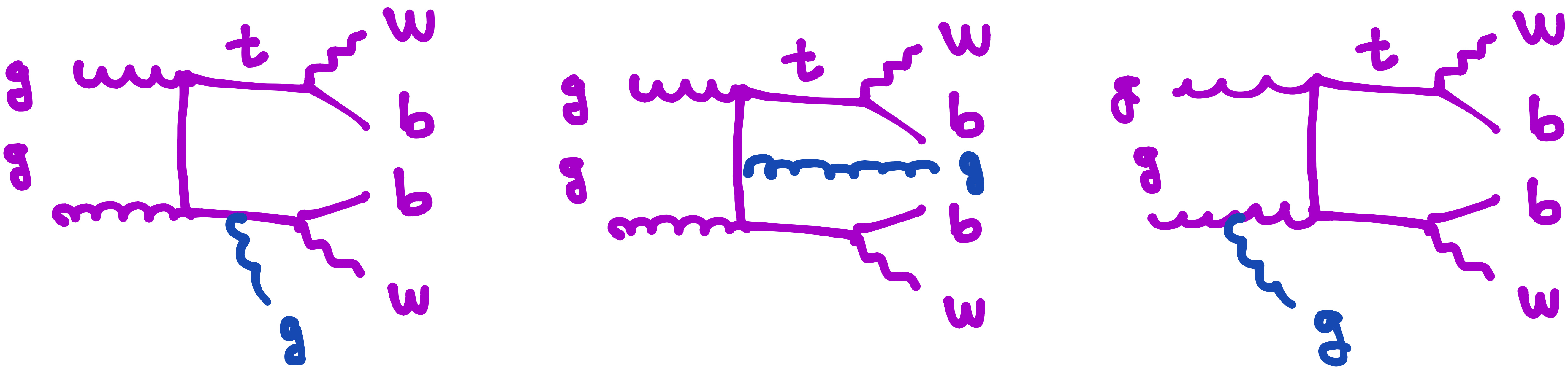
very encouraging LO result with b-jet energy

after having explored a number of **<u>new physics applications</u>** of this idea

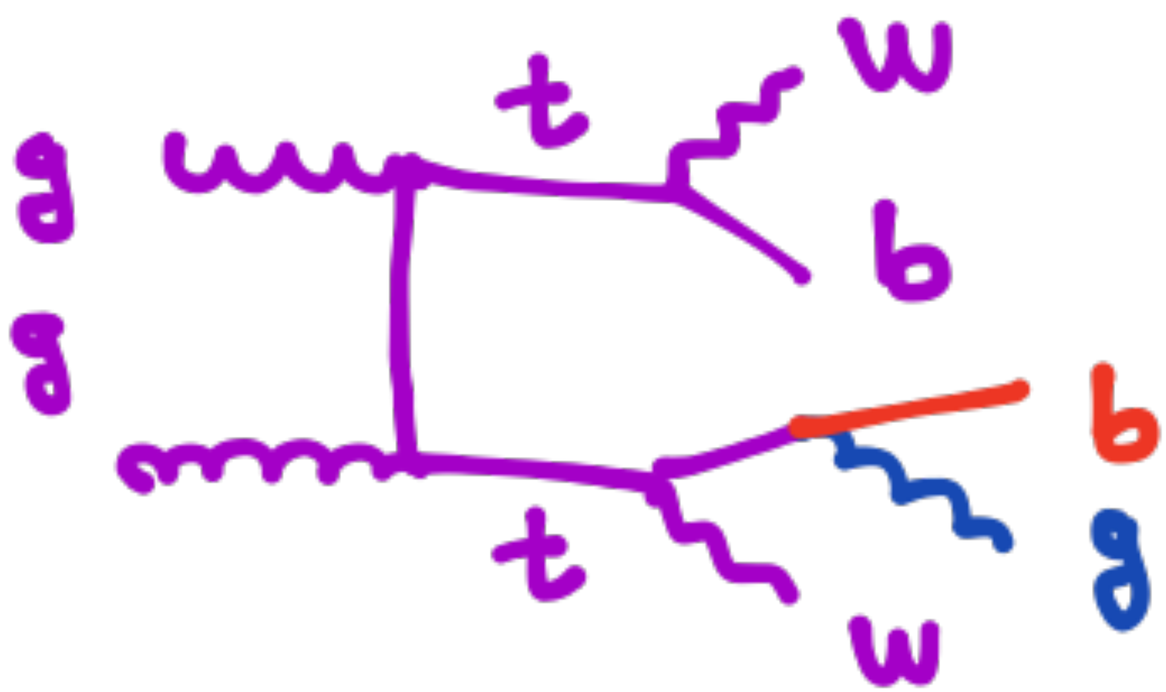
- *1212.5230 - Agashe, RF, Kim, Wardlow*
- *1309.4776 - Agashe, RF, Kim*
- *1403.3399 - Chen, Davoudiasl, Kim*
- *1503.03836 - Agashe, RF, Kim, Wardlow*
- *Agashe, RF, Kim, Hong - WIP*

study of <u>perturbative</u> effects at fixed NLO nearing completion

corrections to the production mechanism

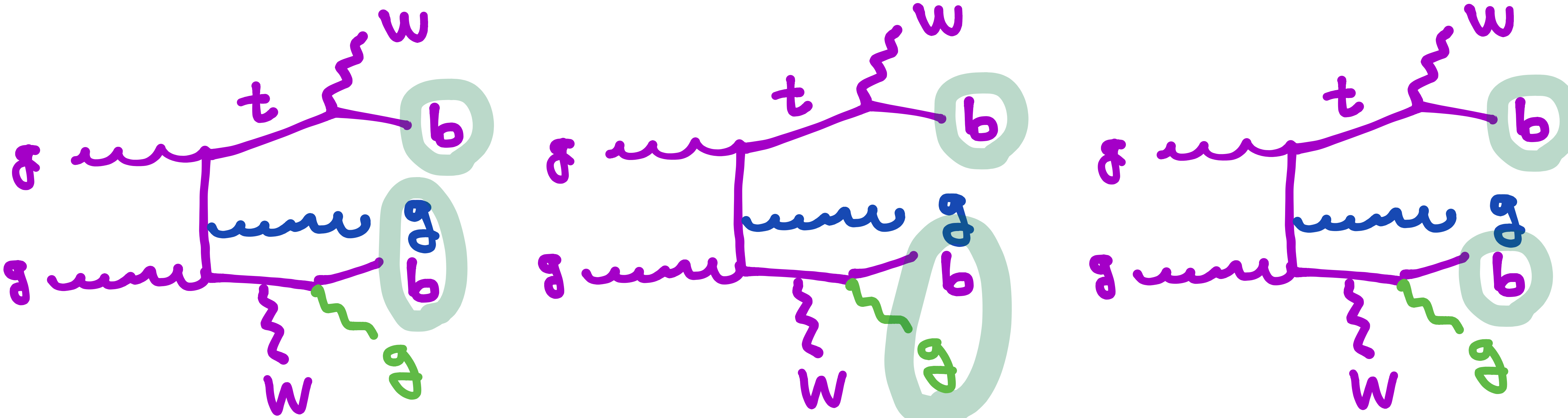


corrections to the top decay



NLO: production & decay

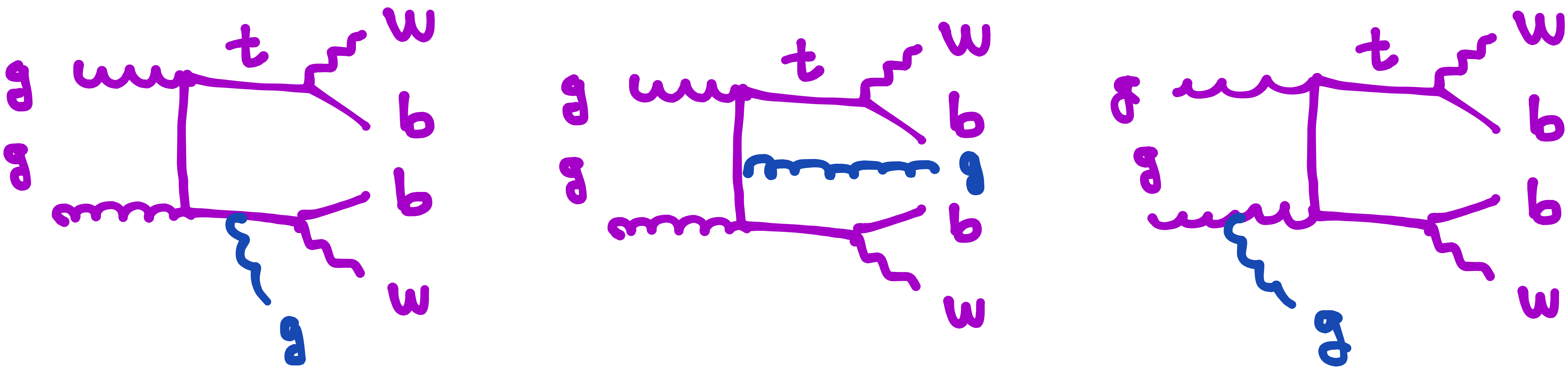
(MCFM) *Agashe, Franceschini, Kim, Schulze - in preparation*



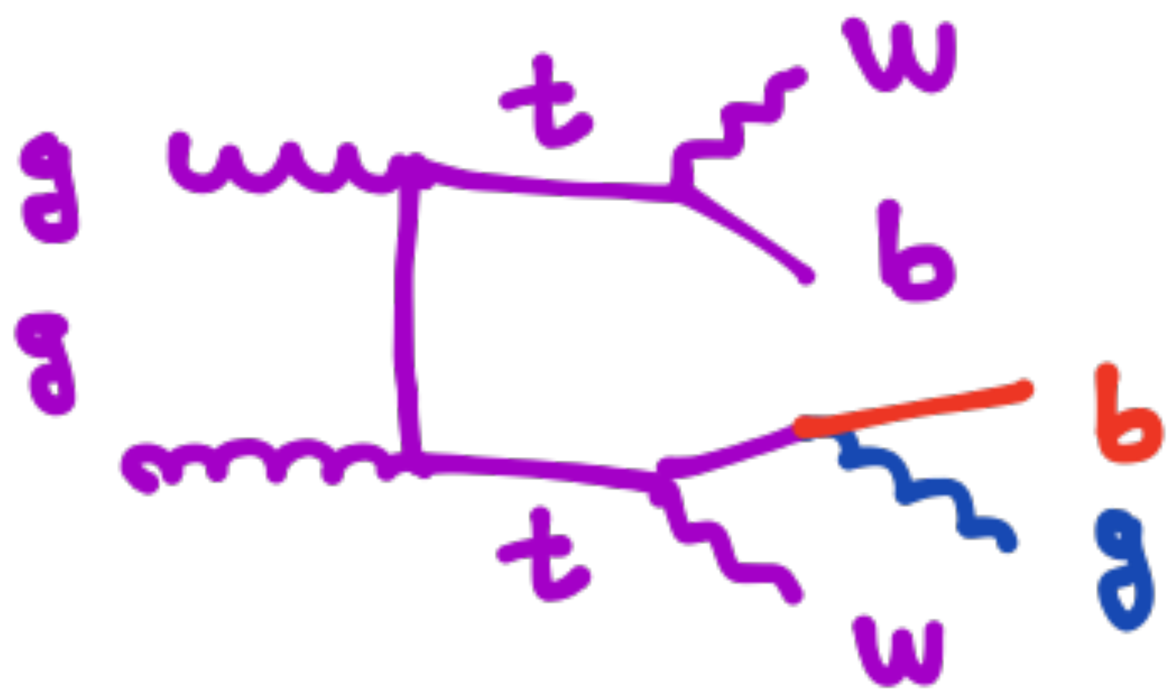
anti-kT jets

- resolved gluon from the top decay
- merged “extraneous” gluon
- reclustered bottom-gluon jets

Energy peak protected from some NLO

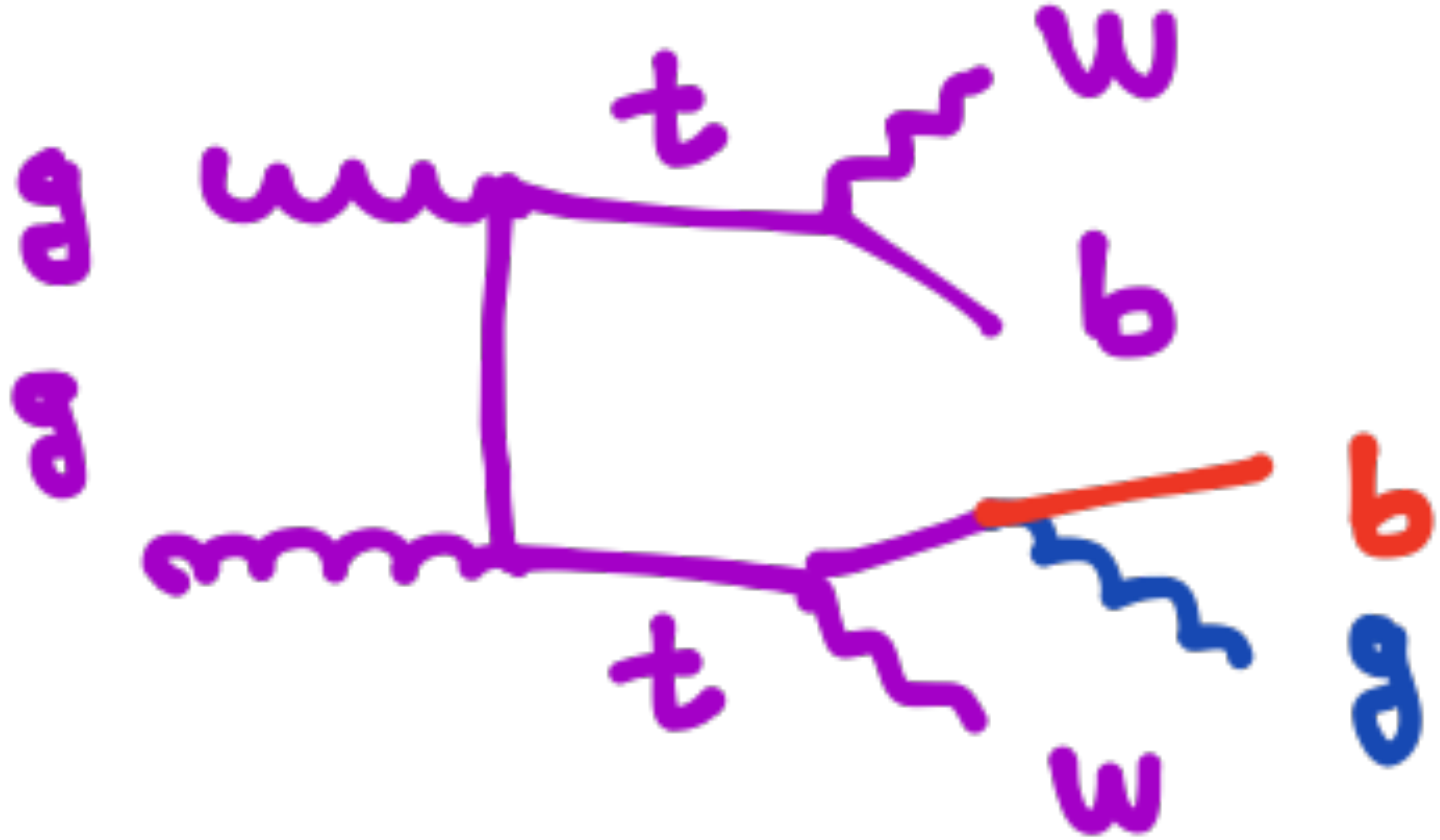


need to compute radiation in decay

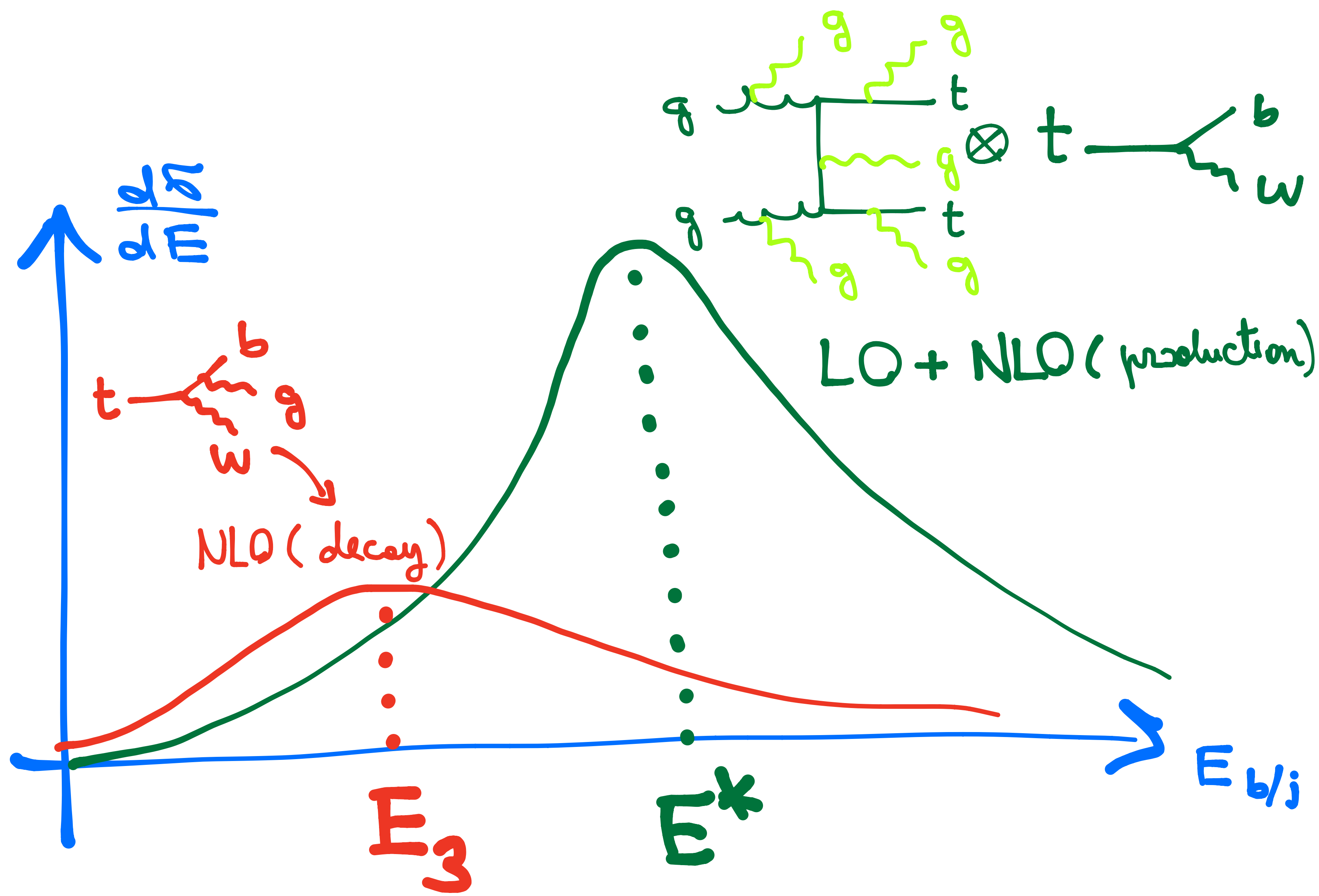


Decay at NLO

Agashe, Franceschini, Kim, Schulze - in preparation

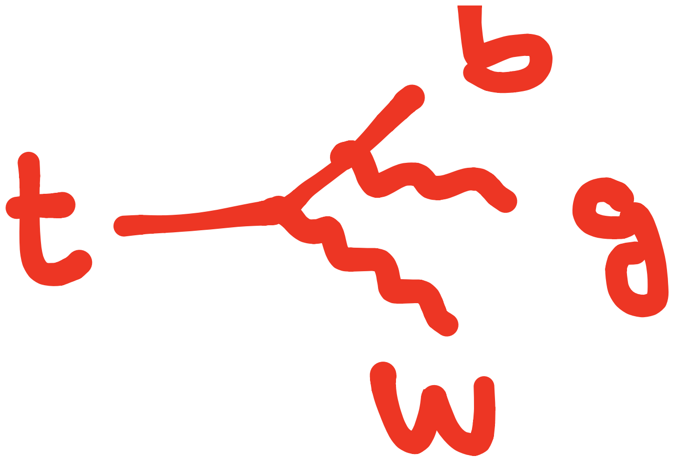


Peak shift at NLO



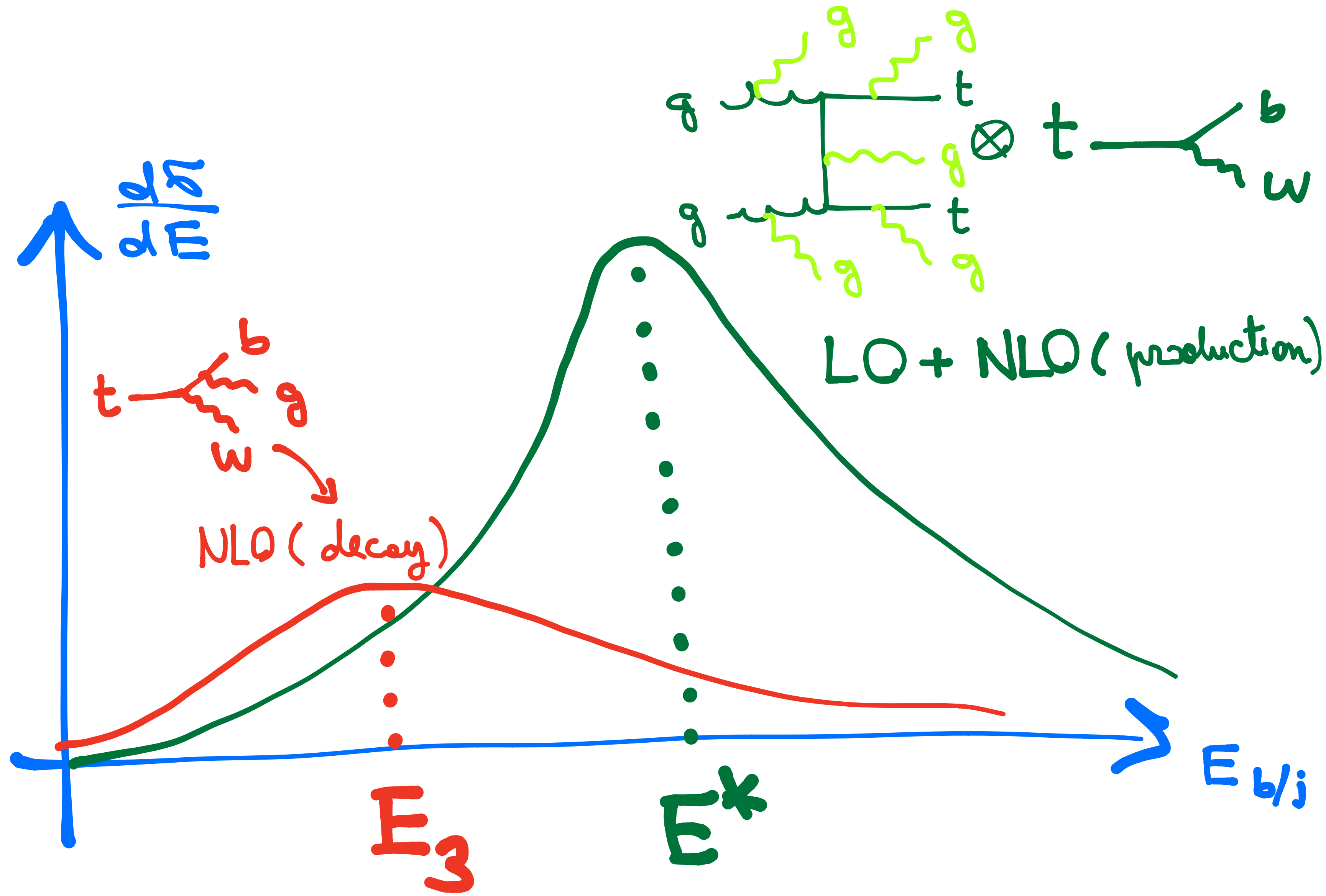
$$E^{peak} = E^{*} + O(1)\,\frac{\alpha}{4\pi}\,E_3$$

Peak shift at NLO



BR(t→bW**g**)
MadGraph5@LO

hard glue	Br
pT>30 GeV dR>0.2	0.061
pT>30 GeV dR>0.4	0.043
pT>20 GeV dR>0.2	0.10
pT>20 GeV dR>0.4	0.074

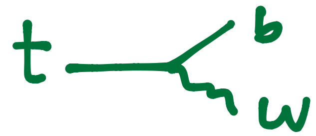


$$E^{peak} = E^{*}(1-\Delta_{TH}) + \Delta_{TH} E_3$$

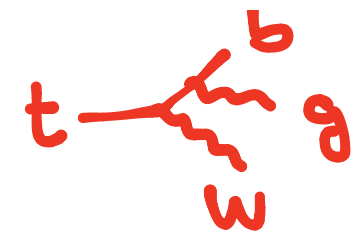
Δ_{TH}=BR(t→bW**g**)/BR(t→bW)≃0.05

NLO: production & decay

(MCFM)

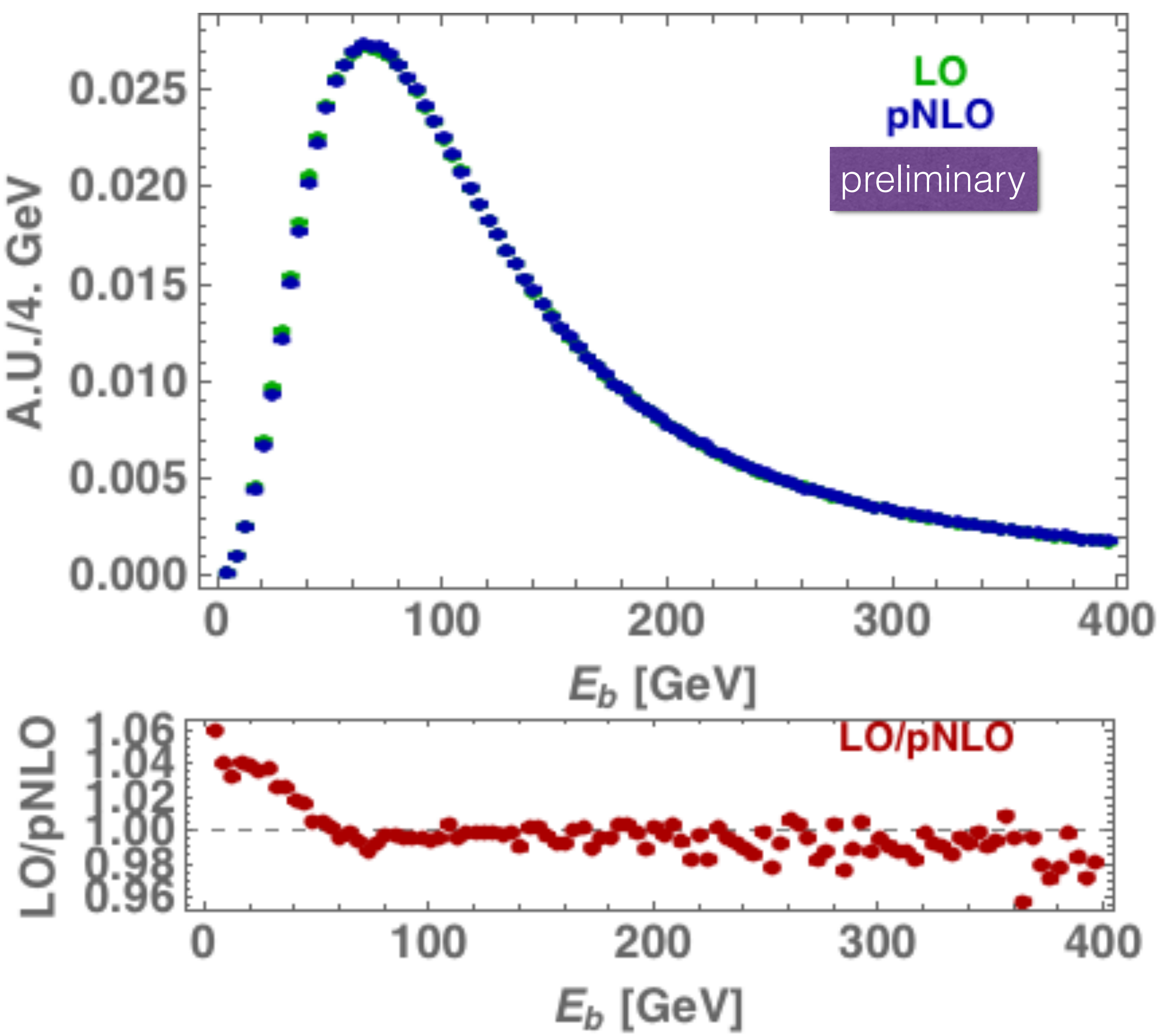


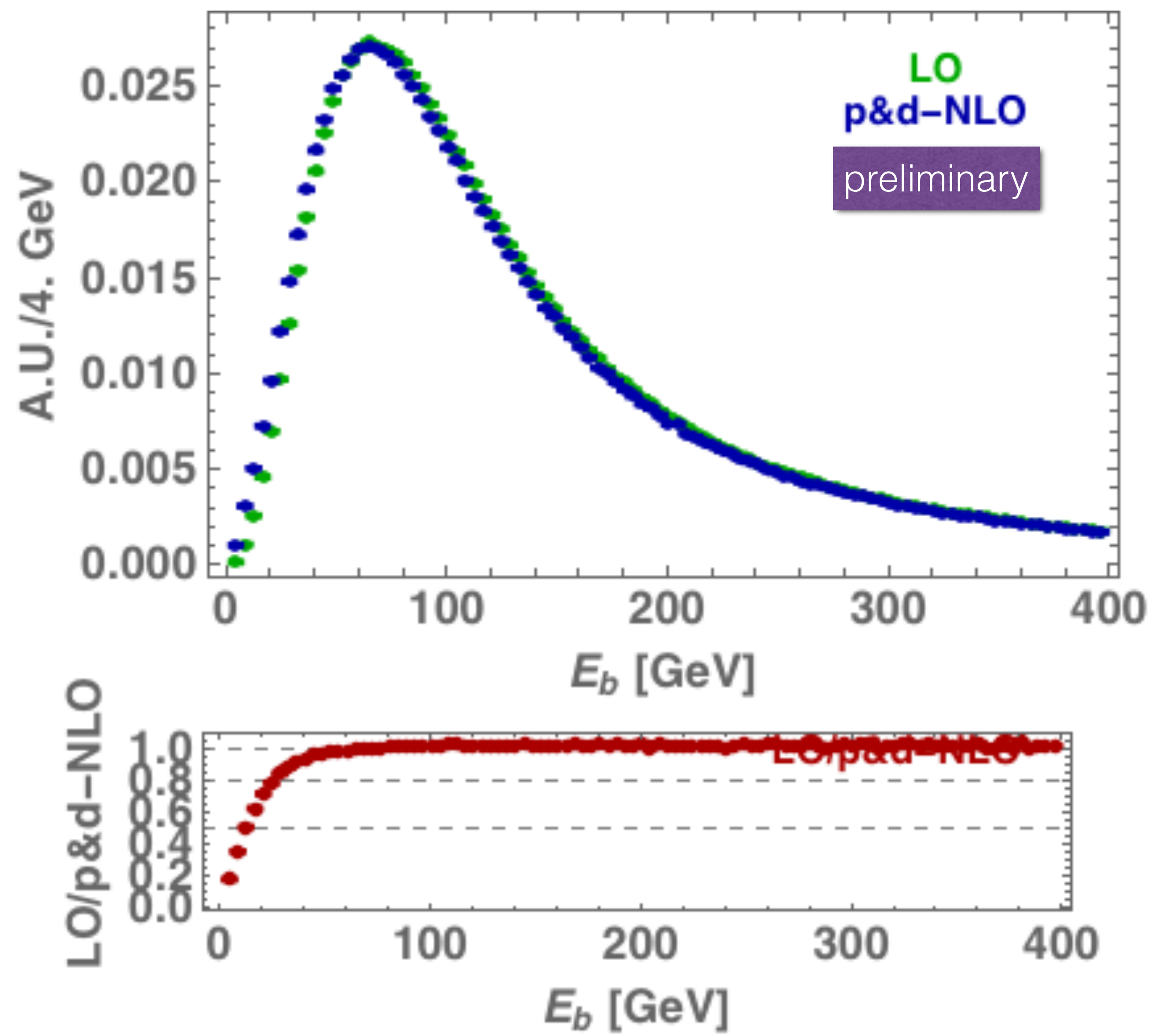
Energy of b



decay at LO

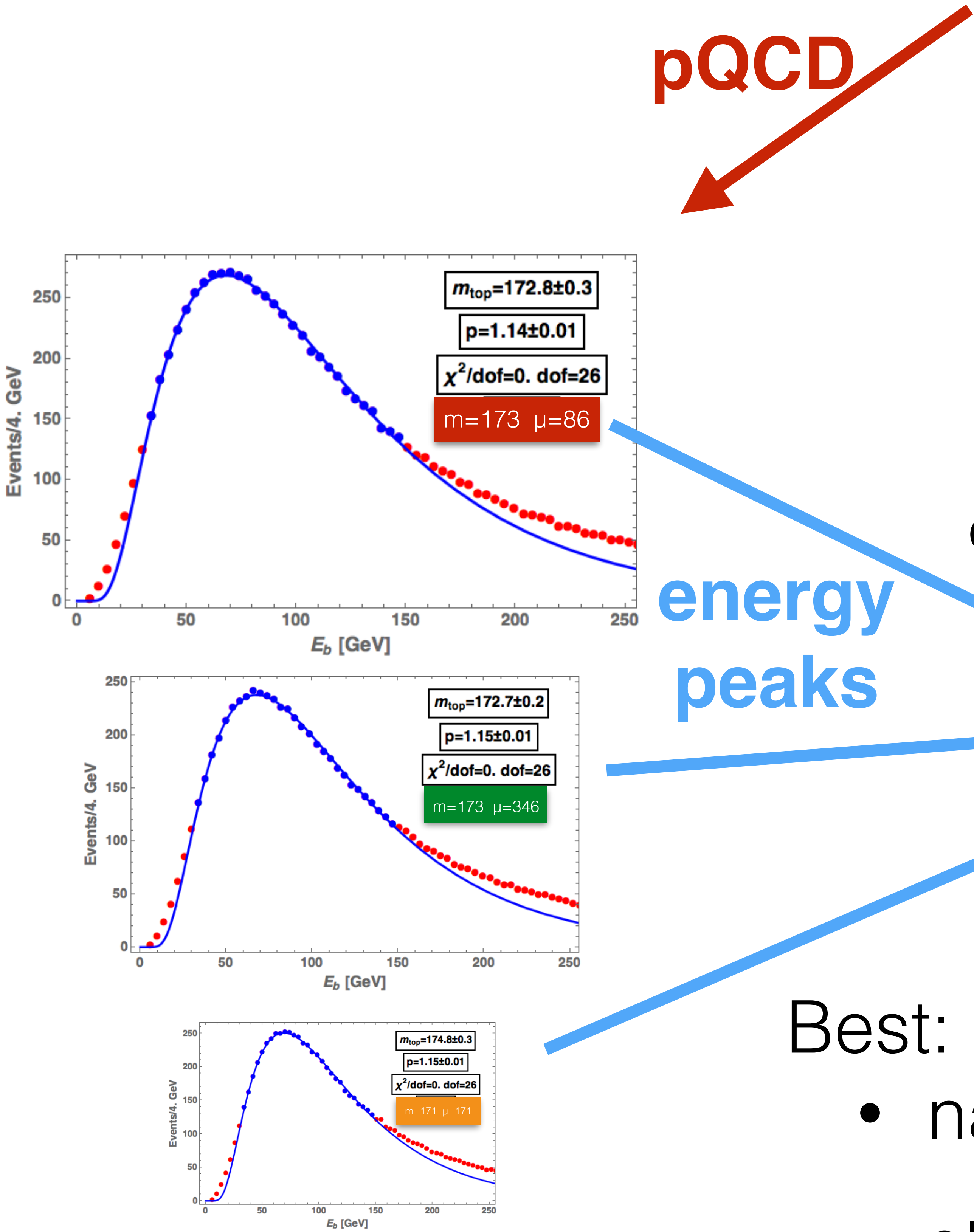
decay at NLO

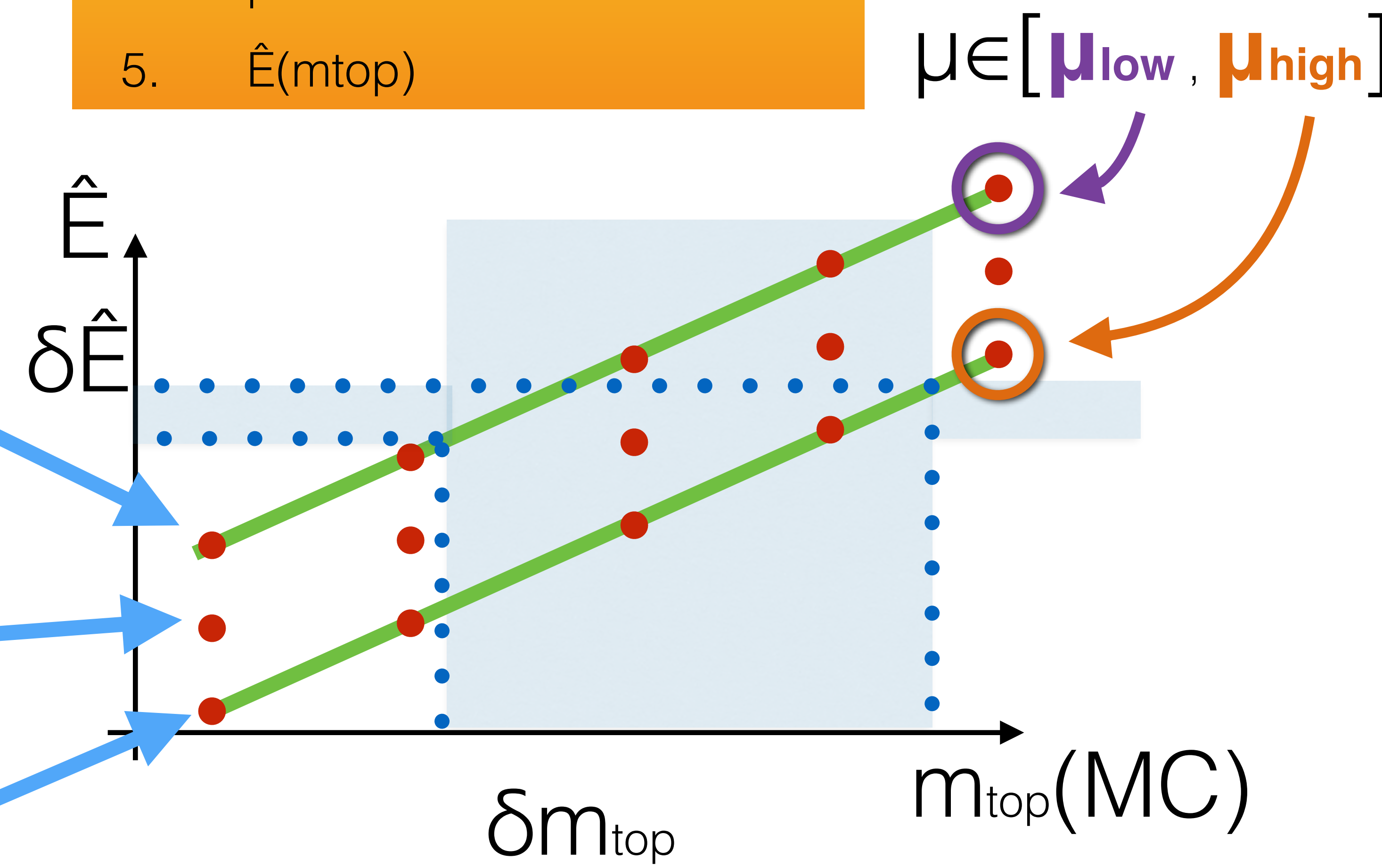




pQCD prediction: Ê(mtop)

1. pick top pole mass
2. pick ren./fact. scales
3. energy distribution dσ/dEb
4. peak of the distribution Ê
5. Ê(mtop)





Best:

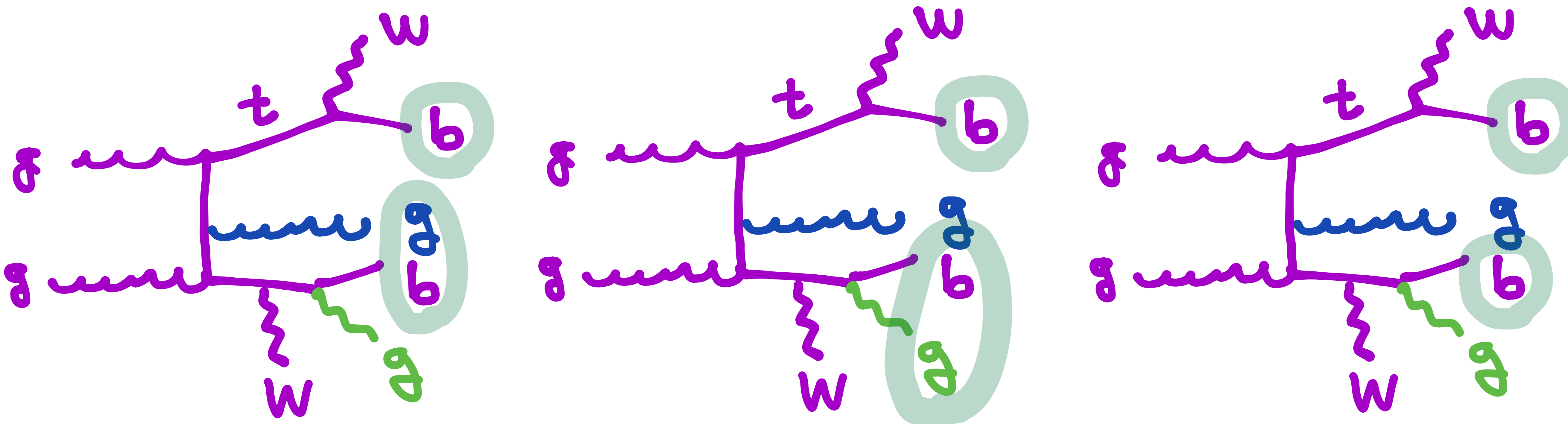
- narrow band between μhigh and μlow
- steep E vs. mtop

$$E_b^* = \frac{m_t^2 - m_W^2 + m_b^2}{2 m_t}$$

NLO: production & decay

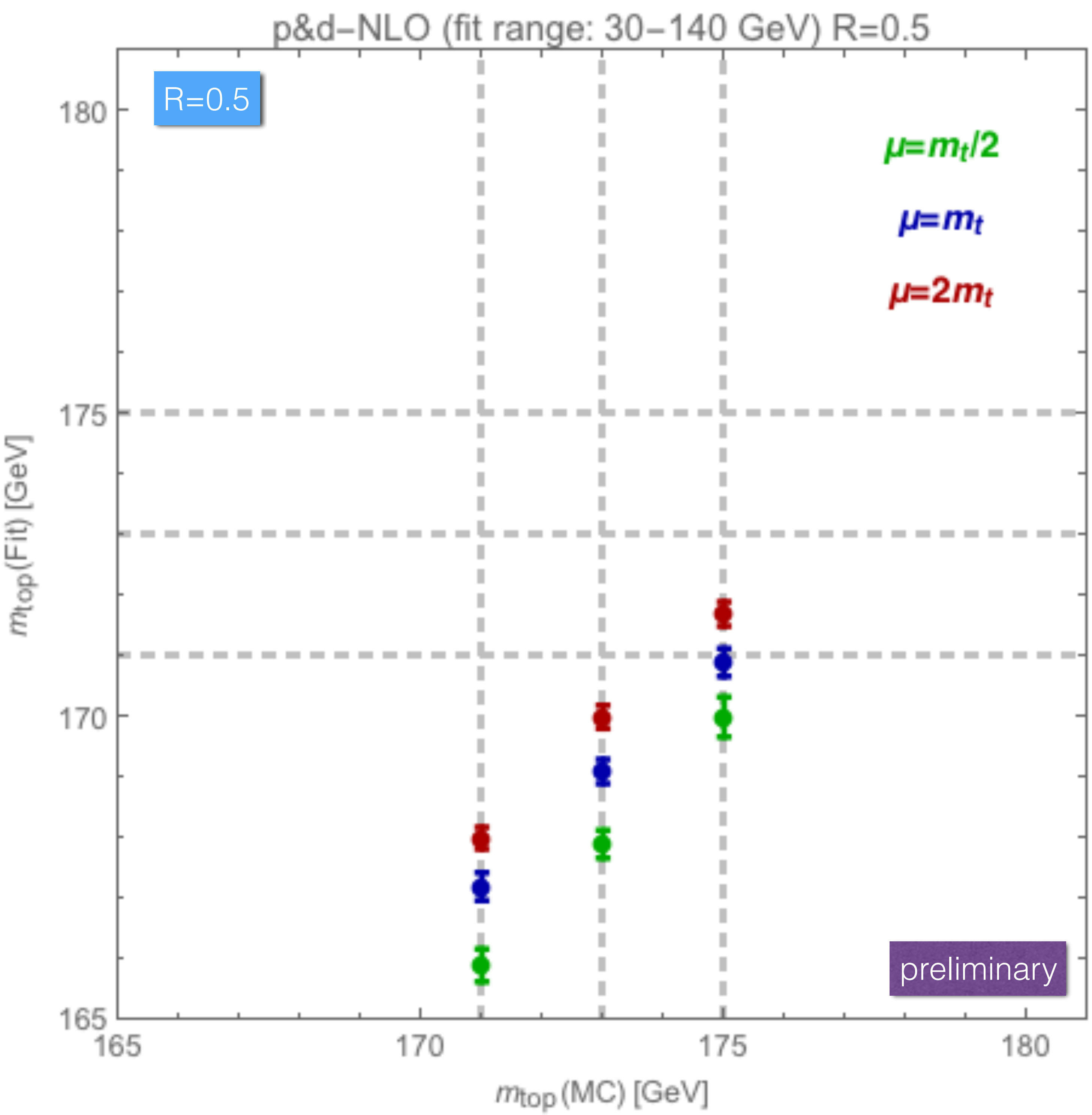
(MCFM)

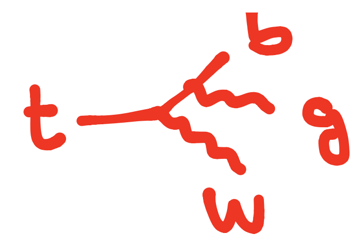
Agashe, Franceschini, Kim, Schulze - in preparation



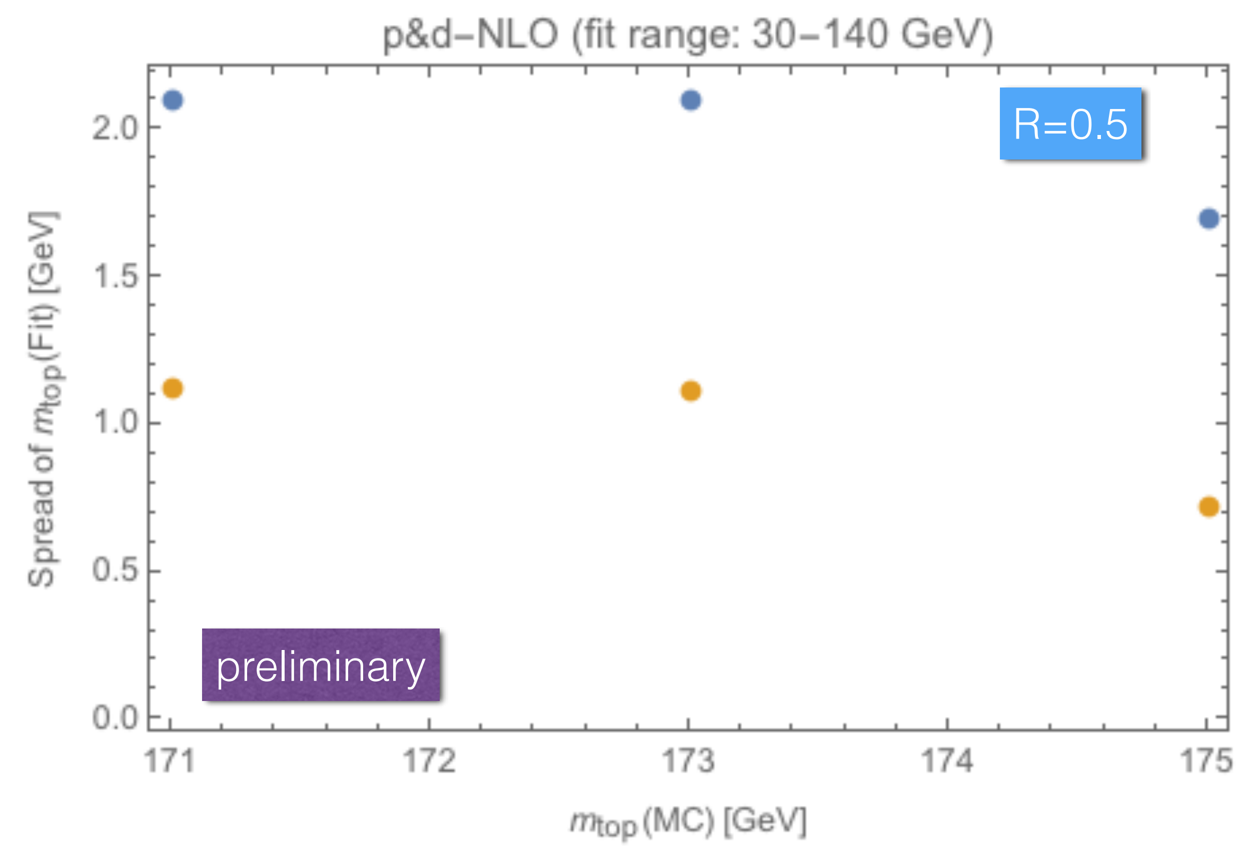
NLO: production & decay **(anti-kT R=0.5)**

(MCFM)





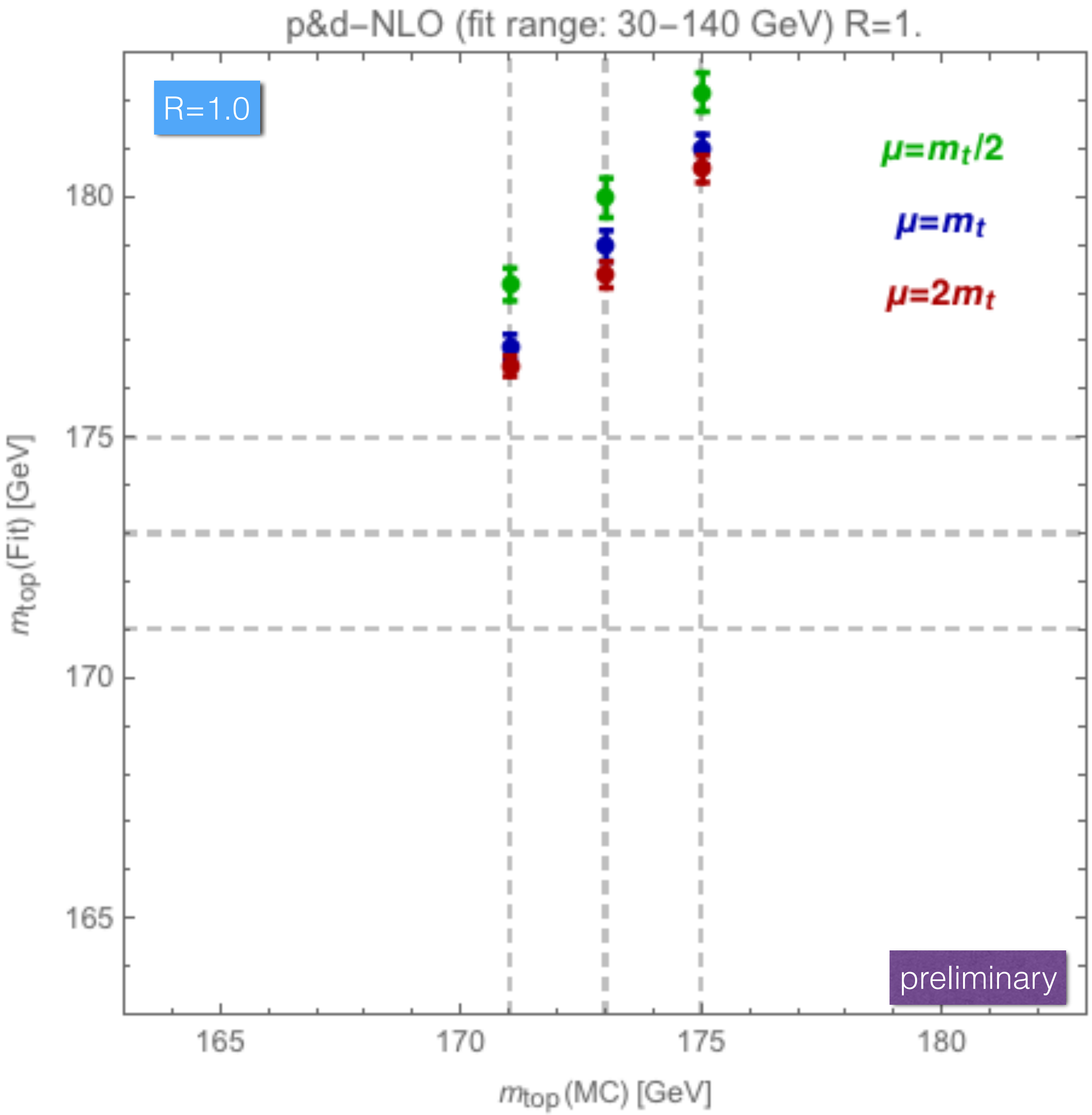
$|\delta| \sim \alpha_3 \sim 1/\mu$

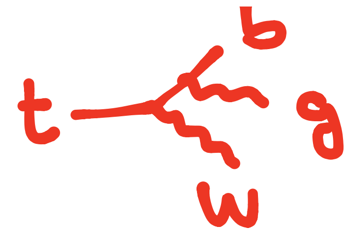


decay NLO sensitive to the scale choice: ±1 GeV on m_{top}

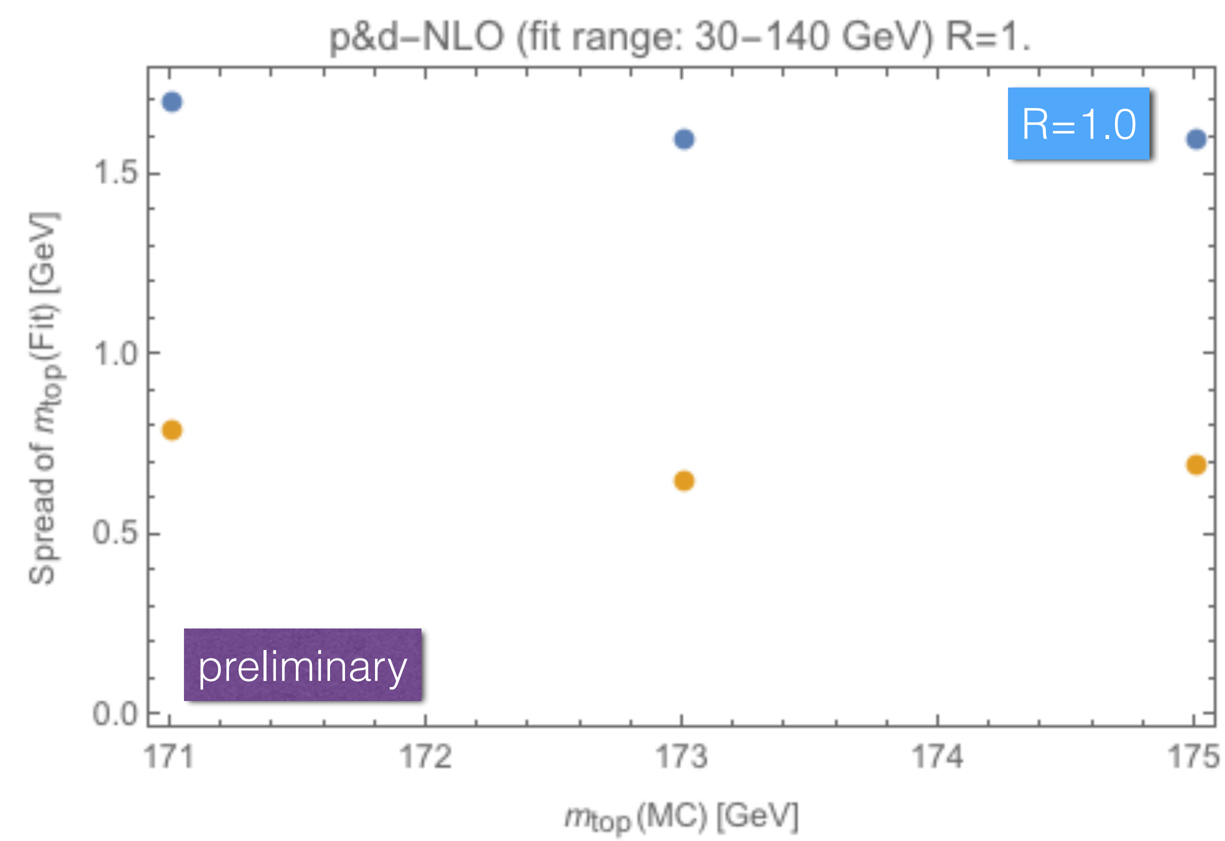
NLO: production & decay **(anti-kT R=1.0)**

(MCFM)





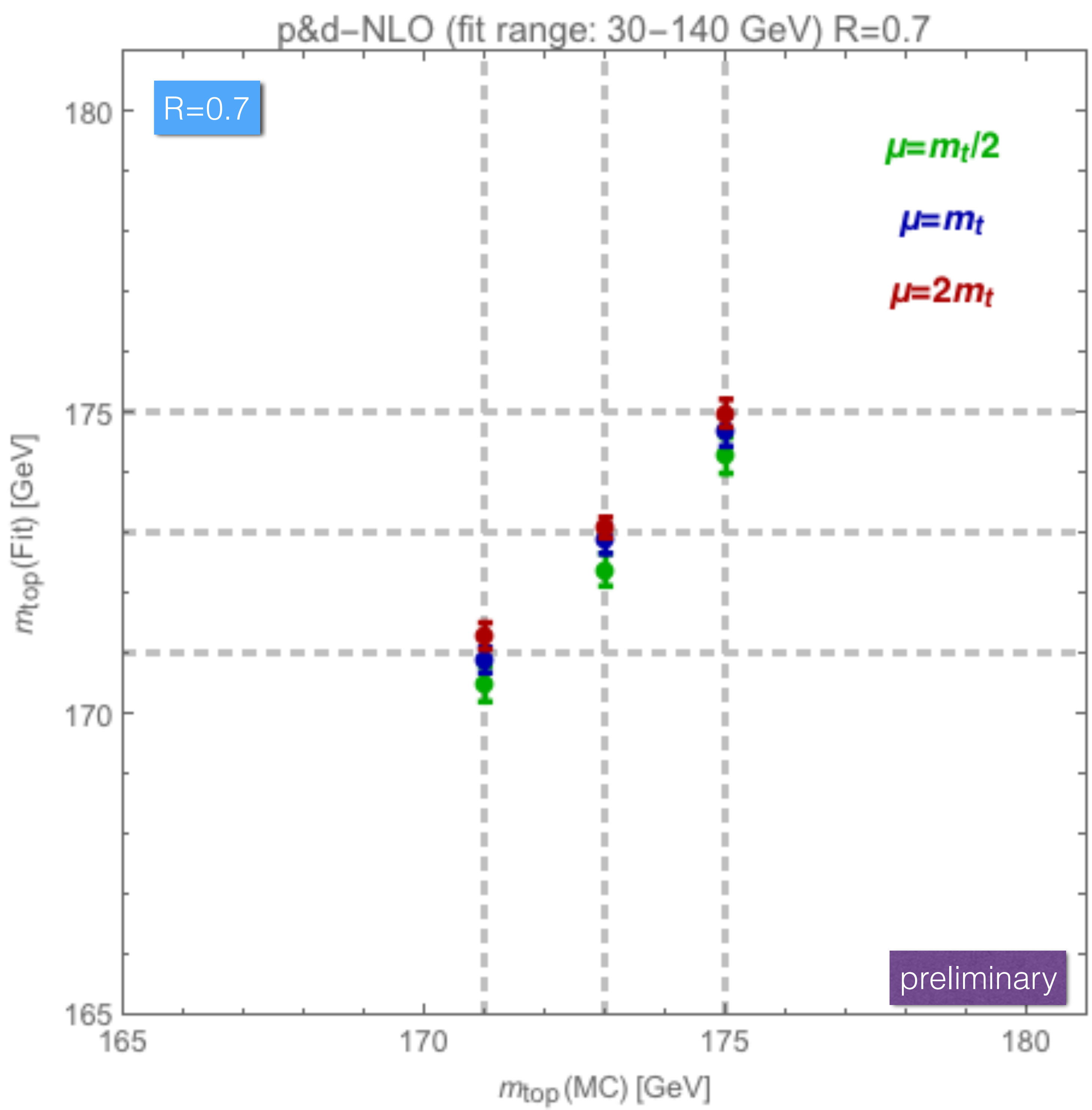
$|\delta| \sim \alpha_3 \sim 1/\mu$

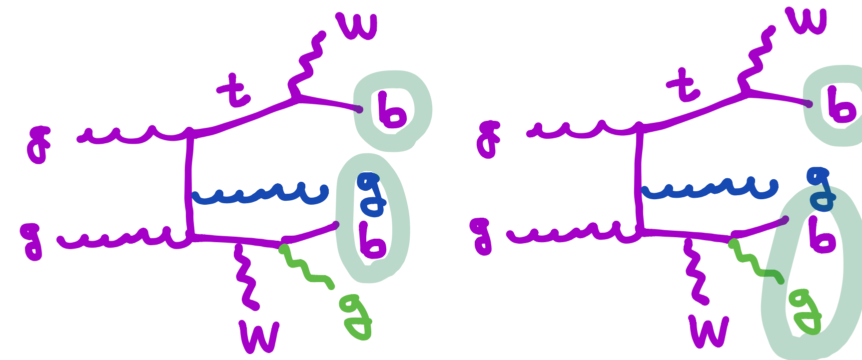


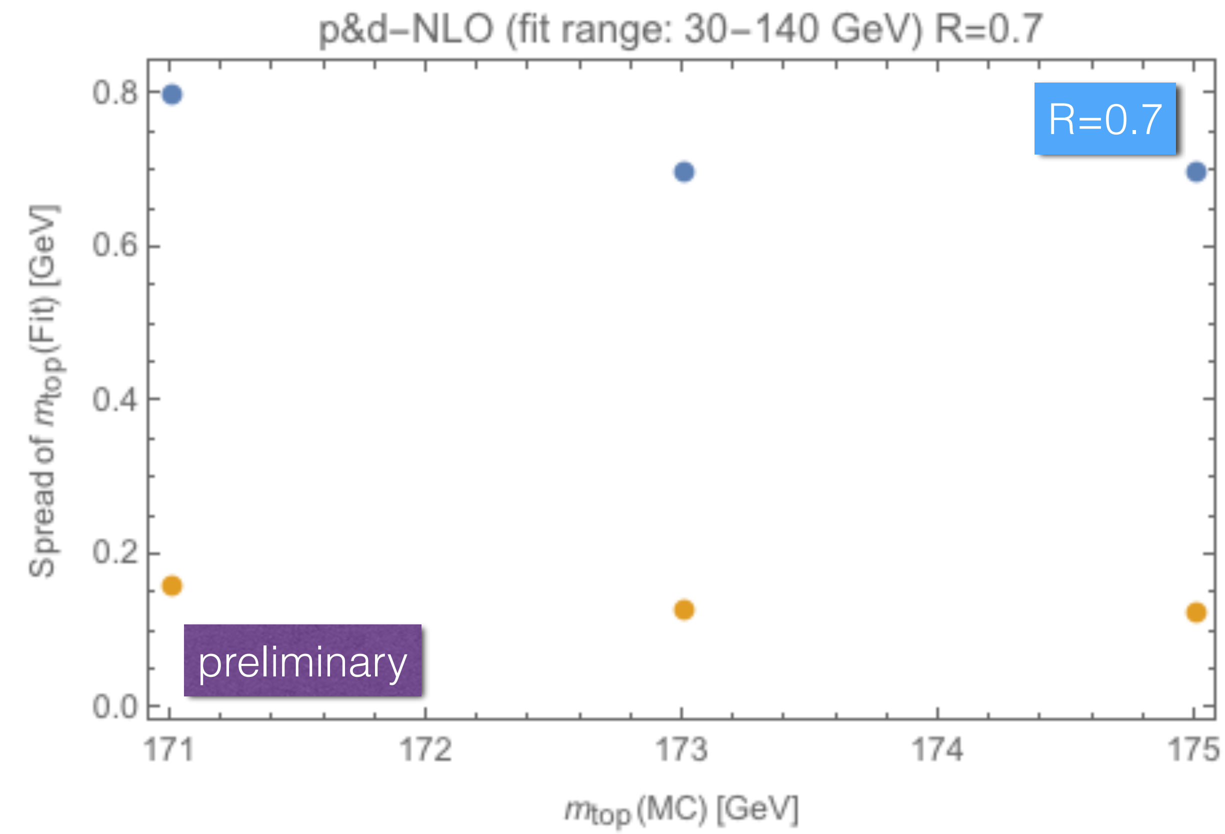
decay NLO sensitive to the scale choice: ±1 GeV on m_{top}

NLO: production & decay **(anti-kT R=0.7)**

(MCFM)





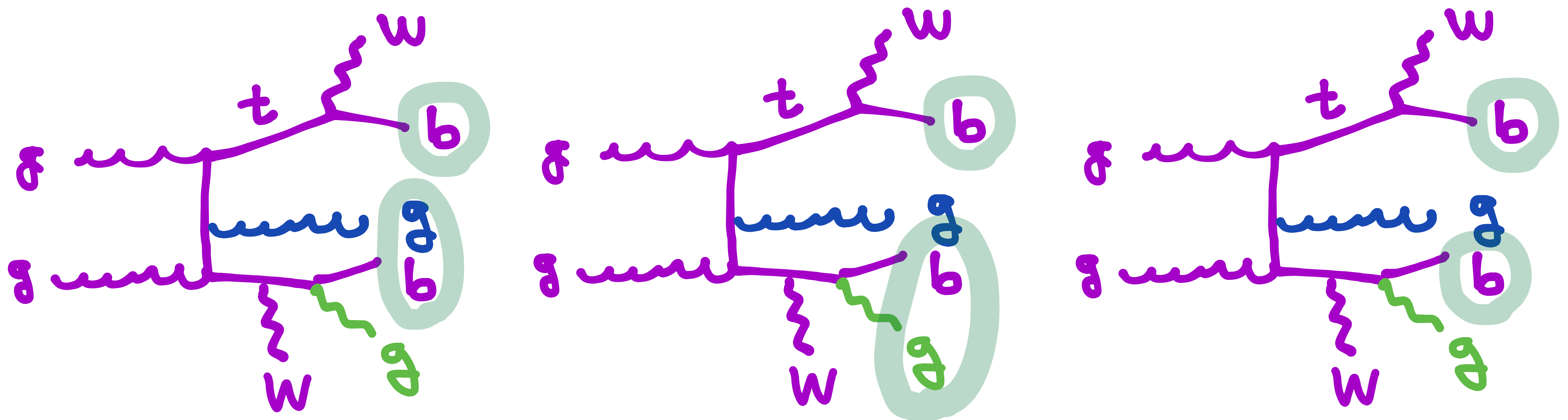


decay NLO sensitive to the scale choice: ±0.5 GeV on m_{top}

NLO: production & decay

(MCFM)

Agashe, Franceschini, Kim, Schulze - in preparation



$pp \to t\bar{t}\|_{NLO} \times t \to b\ell\nu\|_{LO}$			
$m_t = 173$ GeV	$R = 0.5$	$R = 0.7$	$R = 1.0$
$\mu = 2m_t^{(pole)}$	174.3(1)	175.9(1)	179.4(2)
$\mu = m_t^{(pole)}$	174.5(2)	176.3(2)	180.3(2)
$\mu = m_t^{(pole)}/2$	174.7(2)	176.9(2)	181.5(2)
δ_{th}	±0.2 GeV	±0.5 GeV	±1.0 GeV

$pp \to t\bar{t}\|_{NLO} \times t \to b\ell\nu\|_{NLO}$			
	$R = 0.5$	$R = 0.7$	$R = 1.0$
$\mu = 2m_t^{(pole)}$	170(2)	173.1(2)	178.4(3)
$\mu = m_t^{(pole)}$	169.1(2)	172.9(2)	179.0(3)
$\mu = m_t^{(pole)}/2$	167.9(2)	172.4(3)	180.0(3)
δ_{th}	±1 GeV	±0.4 GeV	±0.8 GeV

Mild corrections from NLO

Agashe, Franceschini, Kim, Schulze - in preparation

$$\hat{E} = E^{*}_{LO} \cdot \left[1 + f_{pol} + \epsilon_{FSR} \left(C_{bWg} + \underbrace{\delta_{int} + \delta_{PDFs} + \ldots}_{\delta_{prod}} \right) \right]$$

f_{pol}: $\leq 3 \cdot 10^{-3}$ $\quad$ ϵ_{FSR}: ≤ 0.1 $\quad$ C_{bWg}: O(1)

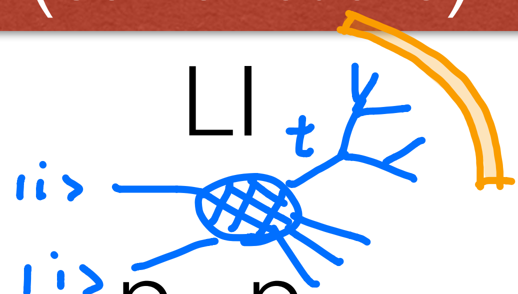
$$O_{NLO} = O_{LO} \cdot \left[1 + \underbrace{\delta_{int} + \delta_{PDFs} + \ldots}_{\delta_{prod}} \right]$$

variations around Lorentz Invariance

needs two particles (combinations)

needs just one particle

LI

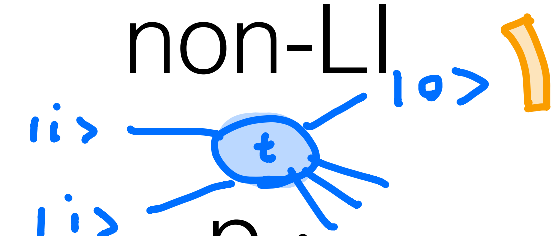


$p_b \cdot p_\ell$

"pheno"-LI

$\hat{E}_b$

non-LI



$p_{T\ell}$

radiation in decays breaks true-LI due to reconstruction

end-point is safe w.r.t radiation in decay

in practice we need the tail, which is sensitive to radiation

radiation in decays breaks pheno-LI due to 3-body

exclusiveness breaks pheno-LI

what is the "small parameter" Δ_{TH} that "breaks" (true or effective) LI?

More (B hadron) peak observables

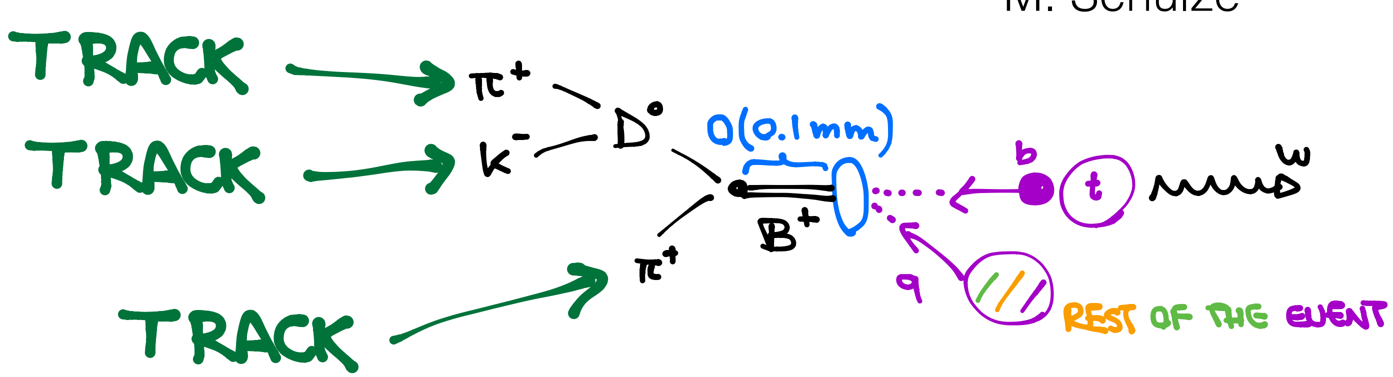
The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about "*single best measurement*"

$$\frac{d\sigma}{dE_b} \propto \frac{d\sigma}{d\gamma_b} \propto \frac{d\sigma}{d\lambda}$$

hadron energy peak

get the hadron energy entirely from tracks

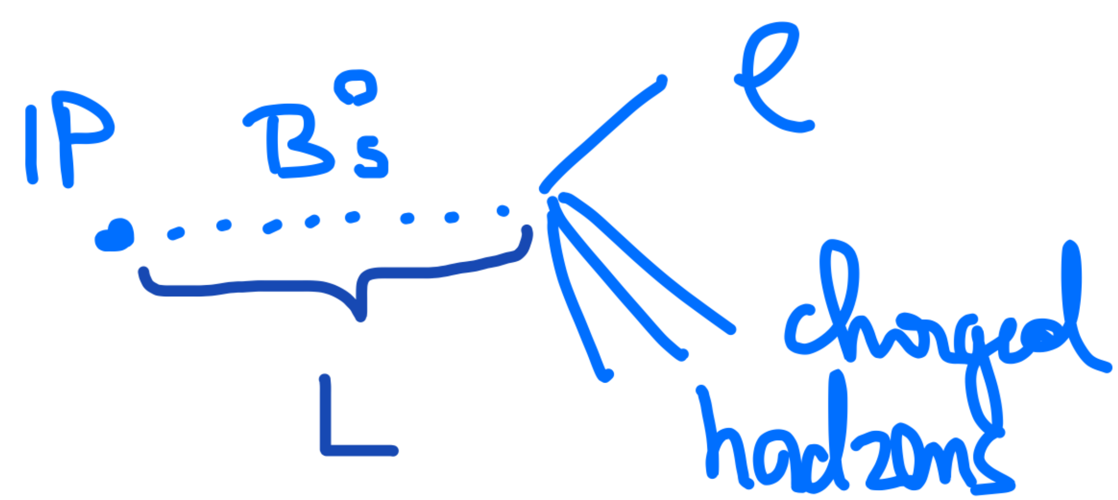
collaboration with
M. Schulze



exclusive B decays in the top sample

mean decay path peak

discussions with
J. Incandela



B **hadron** observables

B physics in the top sample

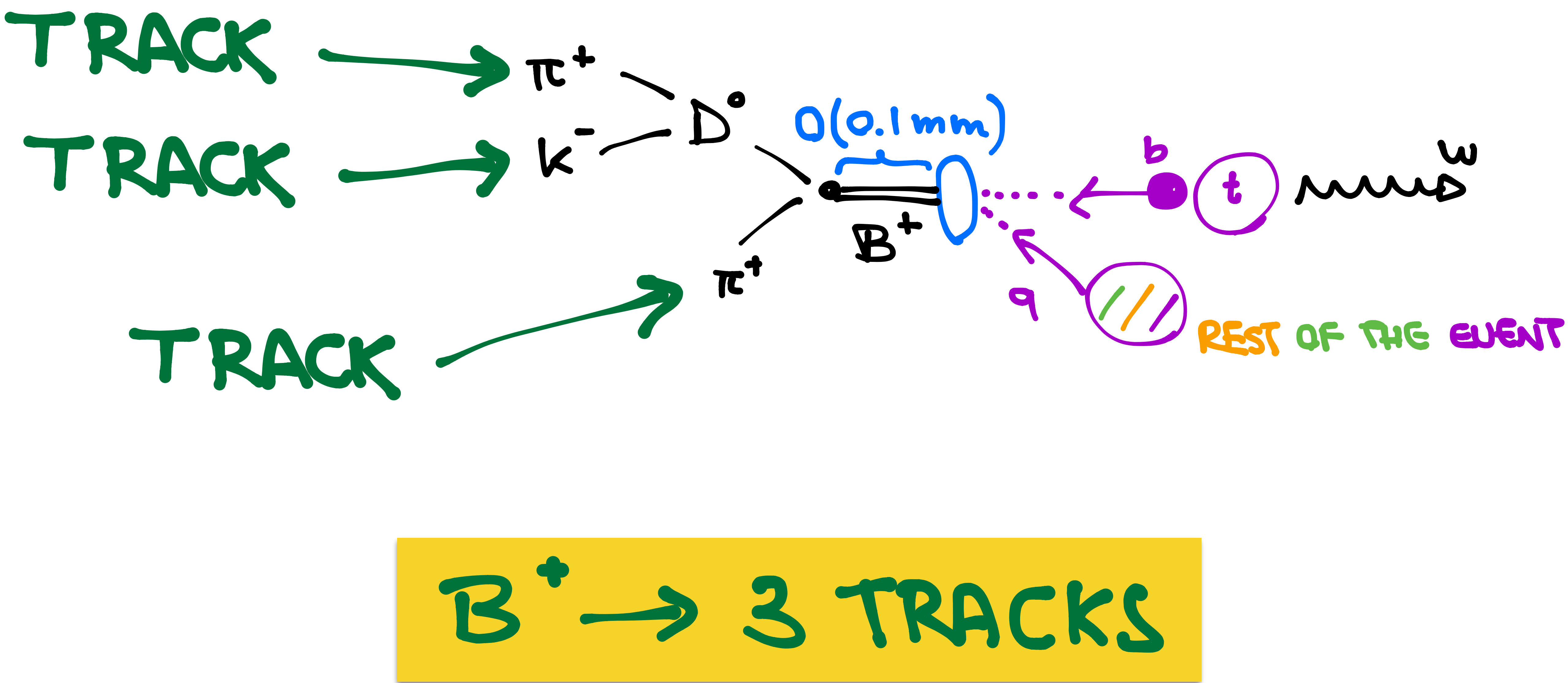
Fragmentation: the b quark energy peak is translated into a (broader) B hadron energy peak

- more exclusive final states
- non-JES uncertainties
- <u>hadronization uncertainties</u>

B hadron

energy peak

get the hadron energy entirely from tracks



Exclusive Decay

(Fully reconstructible with tracks)

J/psi modes

$$b \underset{few\cdot 10^{-3}}{\longrightarrow} J/\psi + X \underset{10^{-1}}{\longrightarrow} \ell\bar{\ell} + X$$

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

$$B^0 \underset{3\cdot 10^{-3}}{\longrightarrow} D^-\pi^+ \underset{10^{-2}}{\longrightarrow} K_S^0\pi^-\pi^+$$

$$B^0 \underset{3\cdot 10^{-3}}{\longrightarrow} D^-\pi^+ \underset{10^{-2}}{\longrightarrow} K^-\pi^+\pi^-\pi^+$$

$$B^0 \underset{3\cdot 10^{-3}}{\longrightarrow} D^-\pi^+ \underset{3\cdot 10^{-2}}{\longrightarrow} K_S^0\pi^+\pi^-\pi^+$$

$$B^- \underset{5\cdot 10^{-3}}{\longrightarrow} D^0\pi^- \underset{4\cdot 10^{-2}}{\longrightarrow} K^-\pi^+\pi^-$$

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

$$B^- \underset{5\cdot 10^{-3}}{\longrightarrow} D^0\pi^- \underset{6\cdot 10^{-3}}{\longrightarrow} K_S^0\rho^0\pi^-$$

$$B^- \underset{5\cdot 10^{-3}}{\longrightarrow} D^0\pi^- \underset{5\cdot 10^{-3}}{\longrightarrow} K^-\pi^+\rho^0\pi^-$$

B hadron
γ boost factor

$$\frac{d\sigma}{dE_b} \propto \frac{d\sigma}{d\gamma_b}$$

hadron energy peak → hadron boost peak

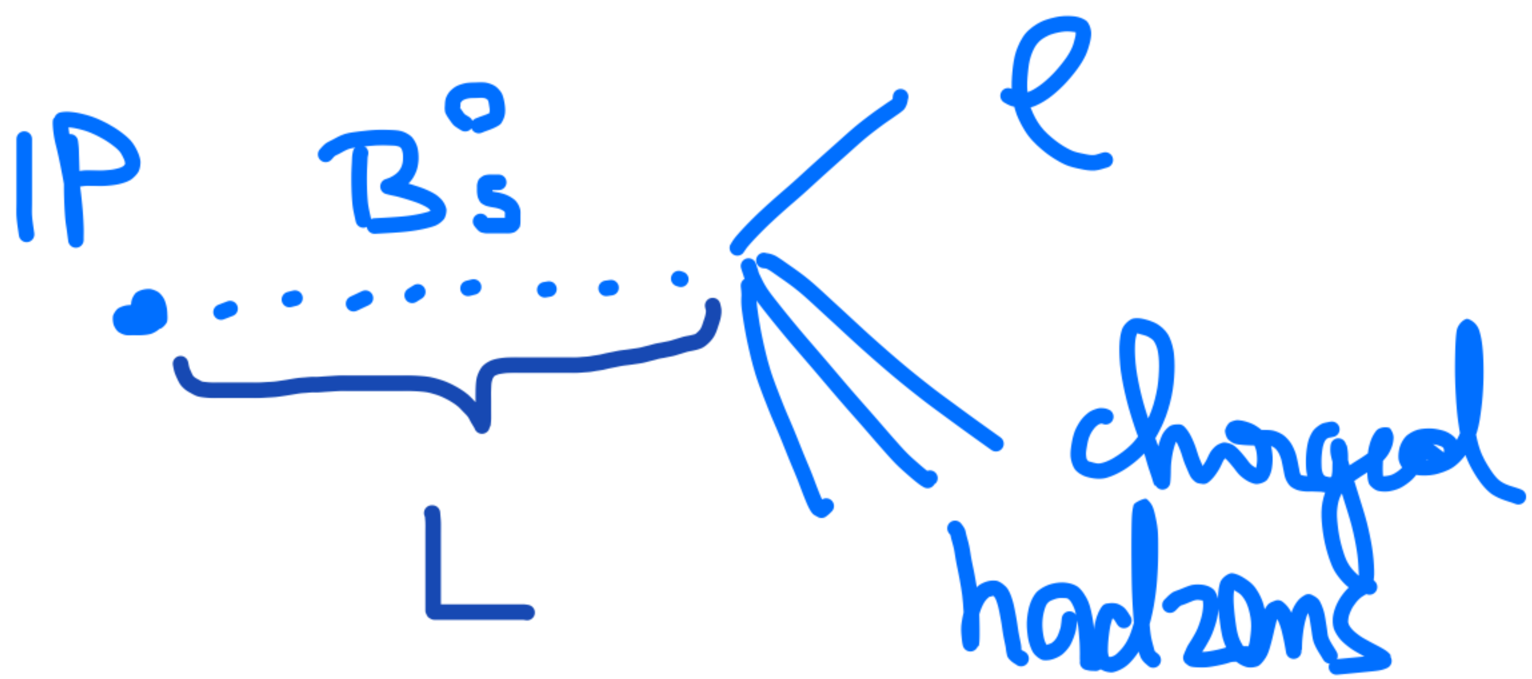
Does the **ratio** γ =E/m help to get rid of exp. uncertainties?

3D decay length

discussion with J. Incandela

Time of decays is harder to measure than the position

Experiments measure decay length L



Jet Energy Scale does not affect λ, nor L

Mean decay length invariance

$$\gamma = E/m$$

- A peak in the energy distribution of the b quark implies a peak in the boost factor distribution

- Not so interesting because the boost is not measured directly

However ...

For $\beta=1$ is

$$\tau'(\text{lab}) = \gamma\tau$$

$$\lambda = c\beta\tau'(\text{lab}) = c\tau\, E/m$$

E and λ distributions are the same up to a rescaling

up to m^2/E^2 effects the *mean* decay length of the *b* quark has a peak at the top rest frame value

How to get the distribution of λ from the observed L?

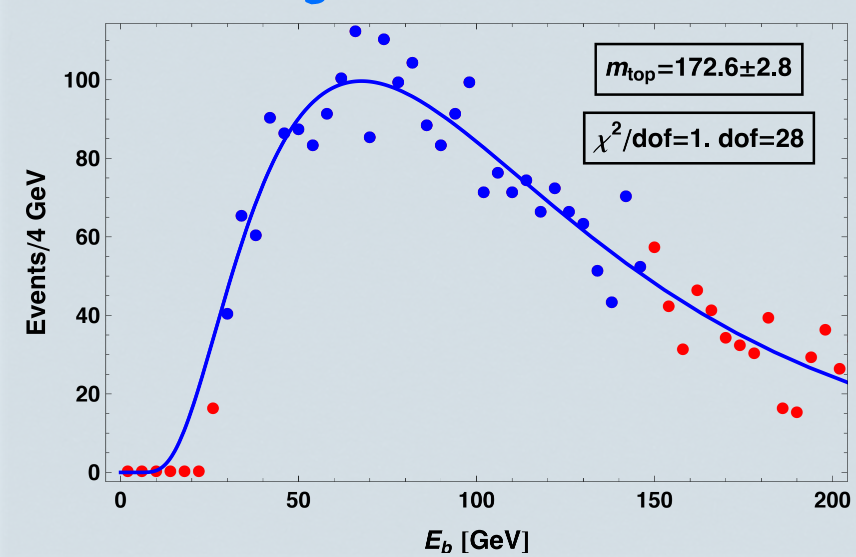
$$\frac{d\sigma}{dL} = \int e^{-L/\lambda} \otimes \mathrm{pdf}(\lambda)\, d\lambda$$

For now we just predicted the mode of pdf(λ)

1209.0772 - Agashe, Franceschini and Kim

from MC:
exponential ansatz work well

$$\frac{d\sigma}{dE_b} \propto e^{-w\left(\frac{E_b}{E^*} + \frac{E^*}{E_b}\right)}$$



$$\frac{d\sigma}{dE_b} \propto \frac{d\sigma}{d\gamma_b} \propto \frac{d\sigma}{d\lambda}$$

How to get the distribution of λ from the observed L?

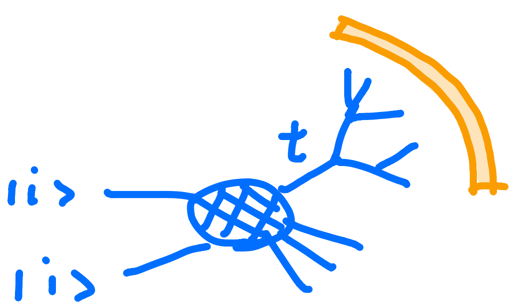
$$\frac{d\sigma}{dL} = \int e^{-L/\lambda} \otimes \mathrm{pdf}(\lambda)\, d\lambda$$

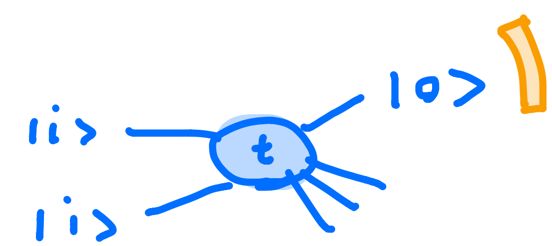
For now we just predicted the mode of pdf(λ)

$$\mathrm{pdf}(\lambda) = e^{-w\left(\frac{\lambda}{\lambda_0} + \frac{\lambda_0}{\lambda}\right)} ?$$

(moral) # Conclusions

1. Energy distributions as Breit-Wigner substitutes





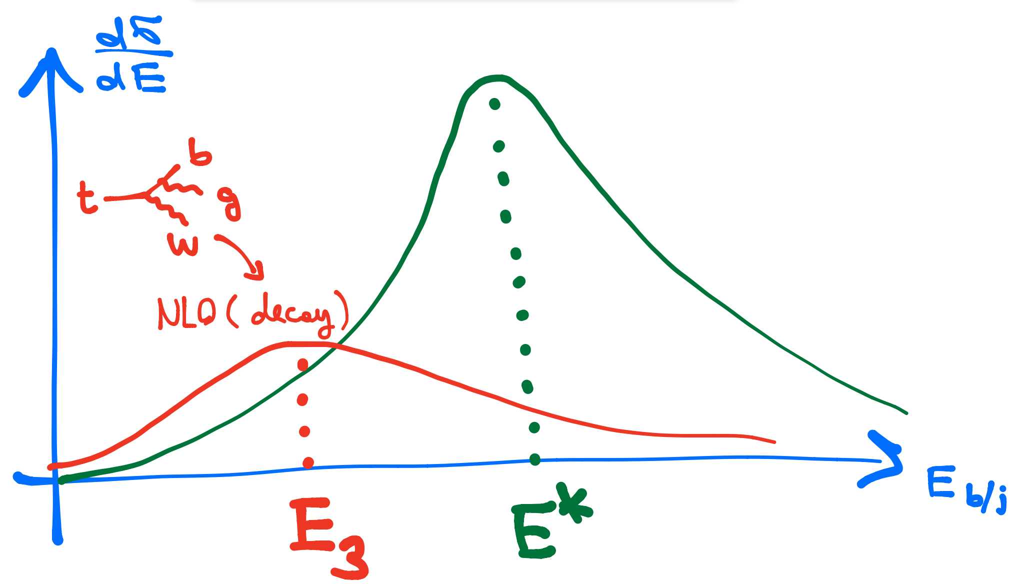
LI — “pheno”-LI — non-LI

$p_b \cdot p_\ell$ — $\hat{E}_b$ — $p_{T\ell}$ →

(moral) Conclusions

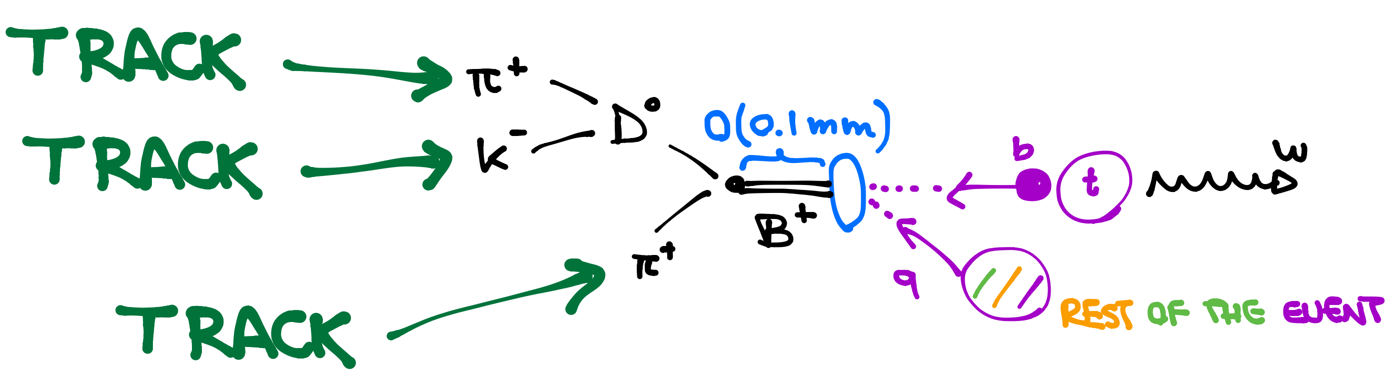
2. Extensive program with b-jets and B-hadrons

b-jet energy peak

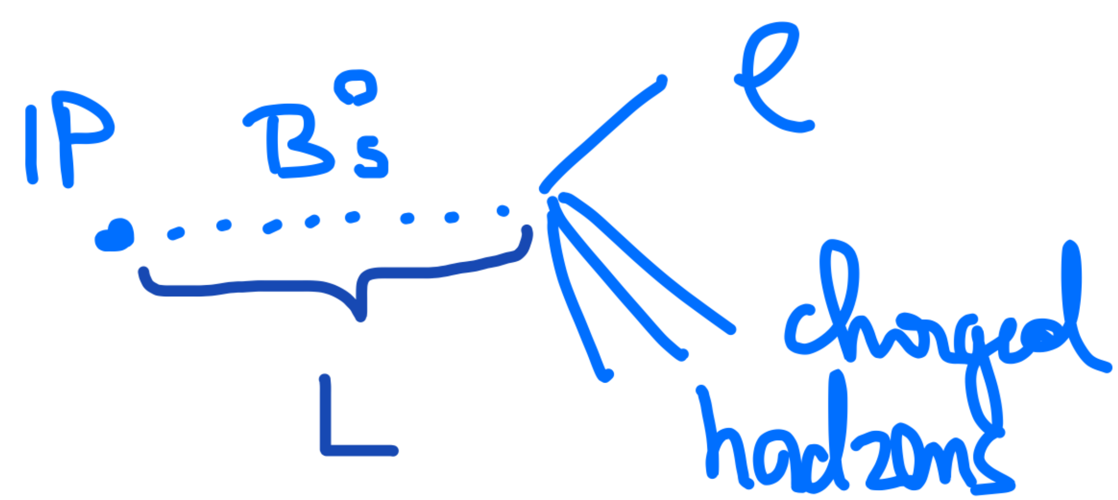


hadron energy peak

get the hadron energy entirely from tracks



mean decay path peak



(factual) Conclusions

Peak of b-jet energy distribution

- **“invariance” holds** when only **NLO production** corrections are considered

- full NLO gives **$\delta m_{top} \simeq \pm 1$ GeV scale sensitivity** for any jet size parameter R

$pp \to t\bar{t}\|_{NLO} \times t \to b\ell\nu\|_{LO}$			
$m_t = 173$ GeV	$R = 0.5$	$R = 0.7$	$R = 1.0$
$\mu = 2m_t^{(pole)}$	174.3(1)	175.9(1)	179.4(2)
$\mu = m_t^{(pole)}$	174.5(2)	176.3(2)	180.3(2)
$\mu = m_t^{(pole)}/2$	174.7(2)	176.9(2)	181.5(2)
δ_{th}	± 0.2 GeV	± 0.5 GeV	± 1.0 GeV

$pp \to t\bar{t}\|_{NLO} \times t \to b\ell\nu\|_{NLO}$			
	$R = 0.5$	$R = 0.7$	$R = 1.0$
$\mu = 2m_t^{(pole)}$	170(2)	173.1(2)	178.4(3)
$\mu = m_t^{(pole)}$	169.1(2)	172.9(2)	179.0(3)
$\mu = m_t^{(pole)}/2$	167.9(2)	172.4(3)	180.0(3)
δ_{th}	± 1 GeV	± 0.4 GeV	± 0.8 GeV

- chances that a **NNLO decay** description would be enough to make a solid prediction at **$\delta m_{top} \simeq 500$ MeV**

To Do (in progress)

- check scale sensitivity at R~0.82 (tt+jet @ NLO)
- check effects of cuts
- compare to moments of $d\sigma/dE_b$
- B-hadron energy

To Do (2)

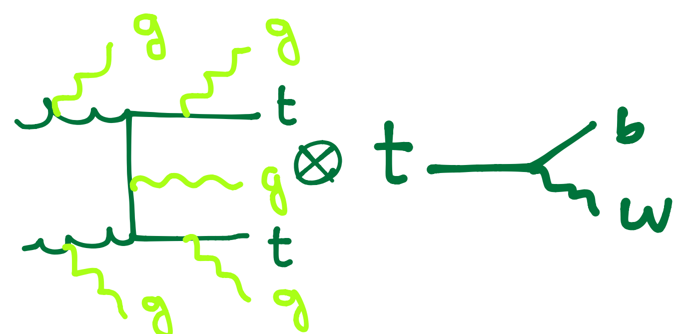
explore:

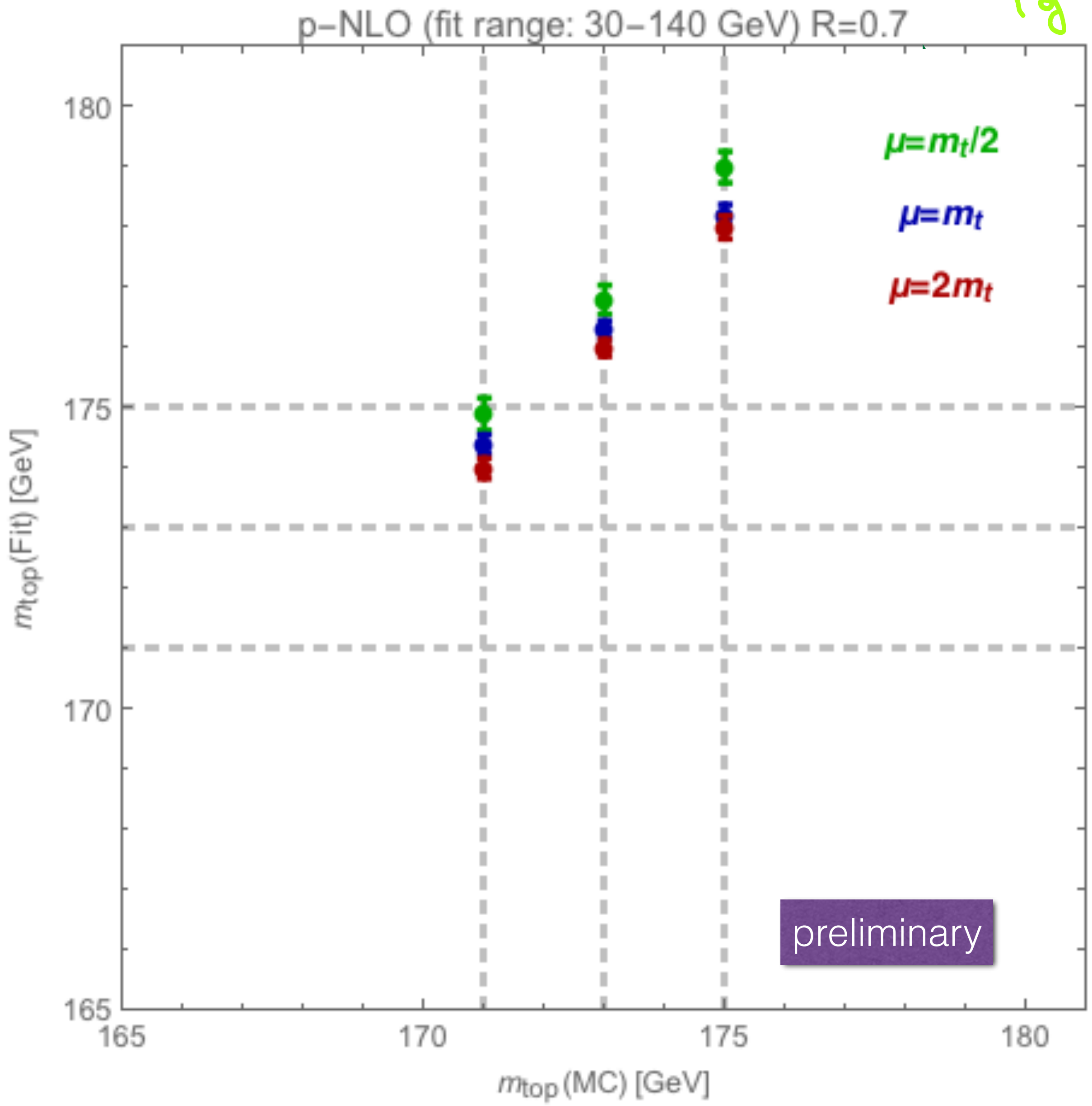
- tt vs. bWbW
- shower effects (NLO+PS Powheg)
- non-perturbative effects (color re-connection)

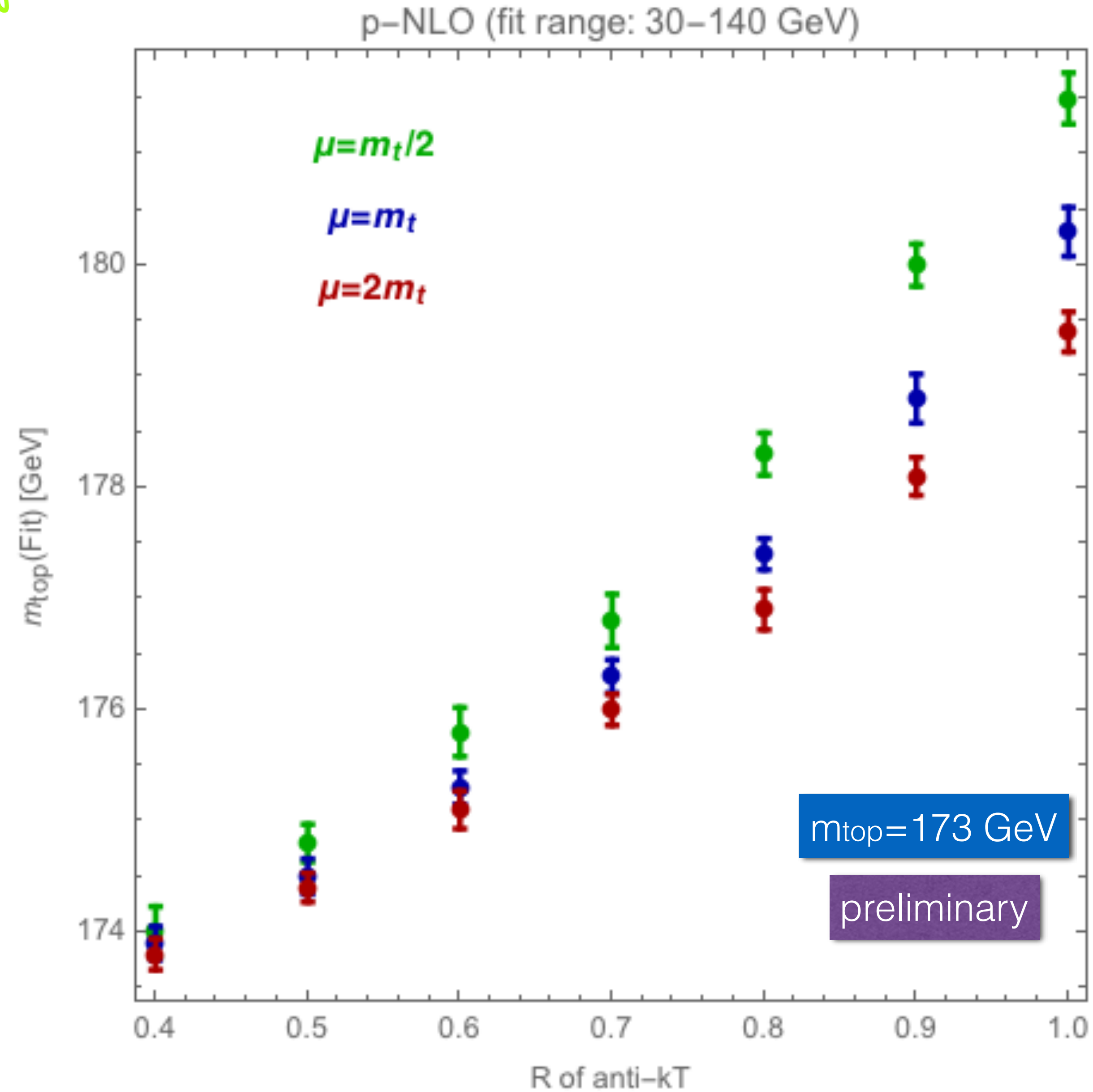
Extra

NLO: production

(MCFM)



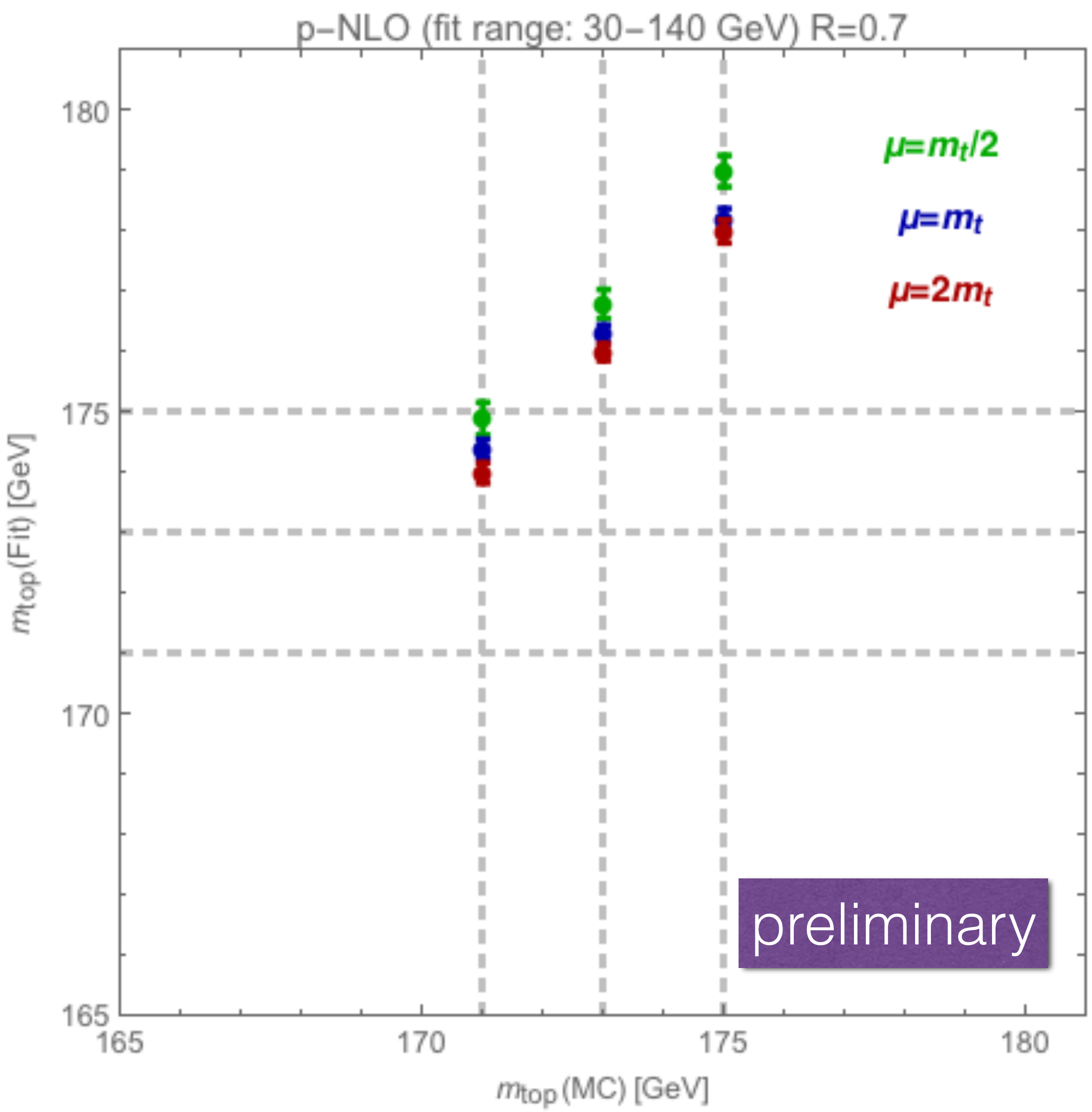


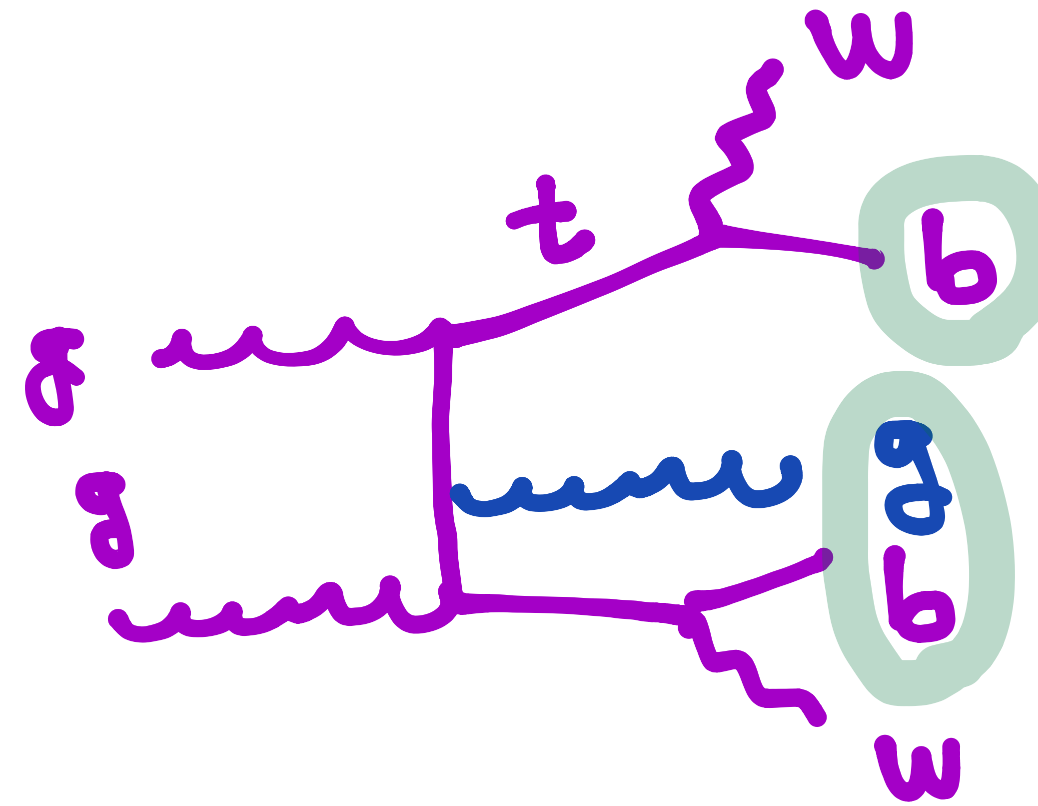


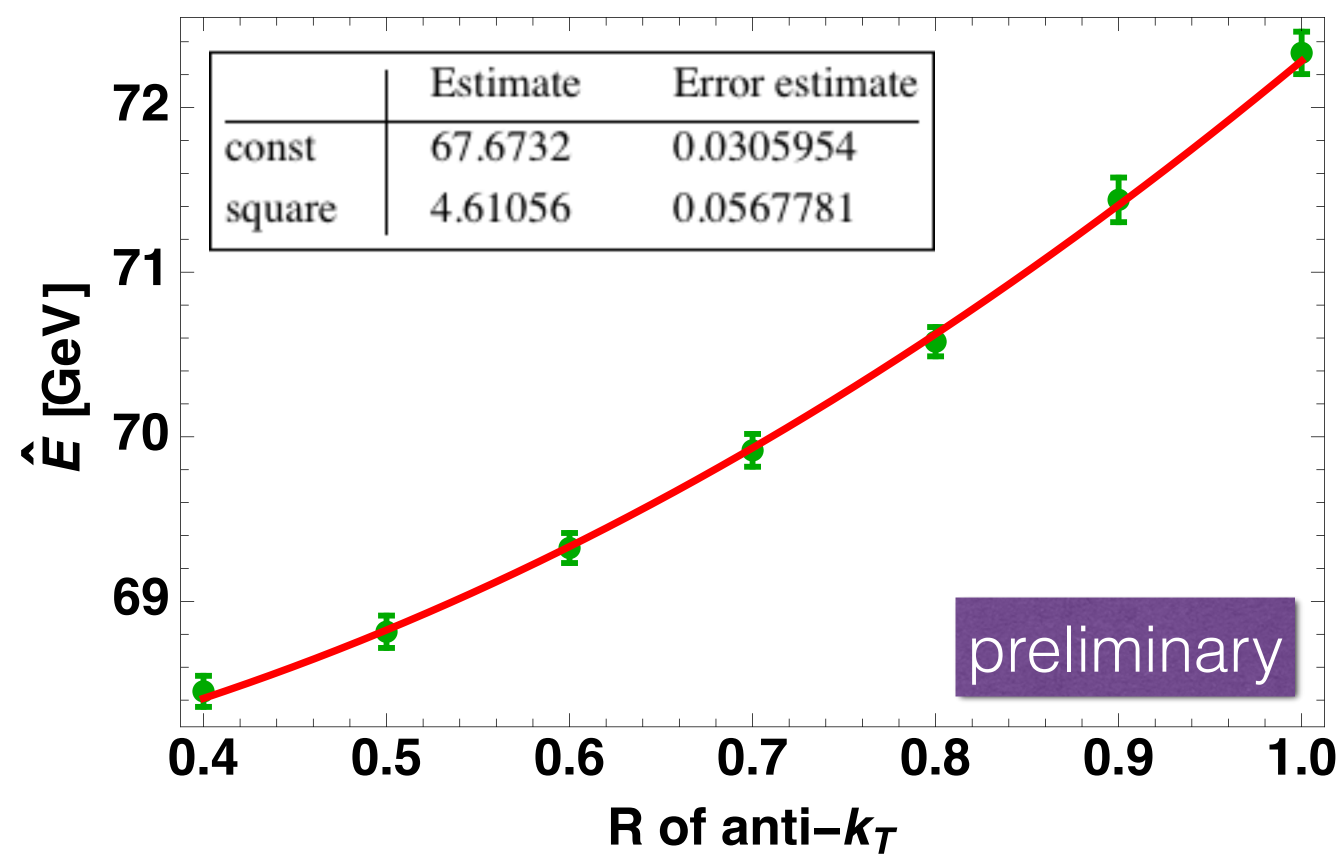
very little sensitive to the scale choice (less than 400 MeV on m_{top})

NLO: production

(MCFM)



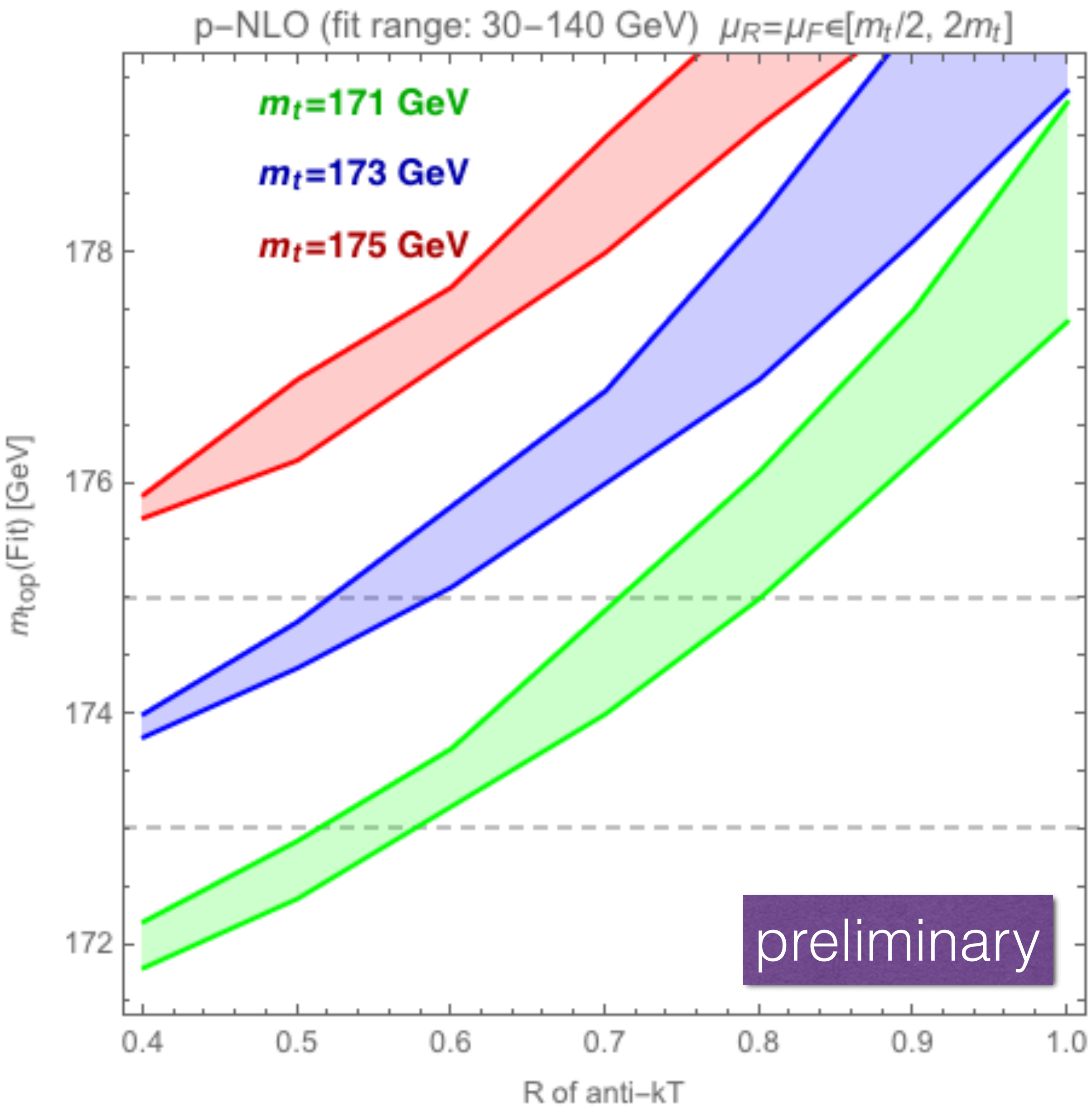


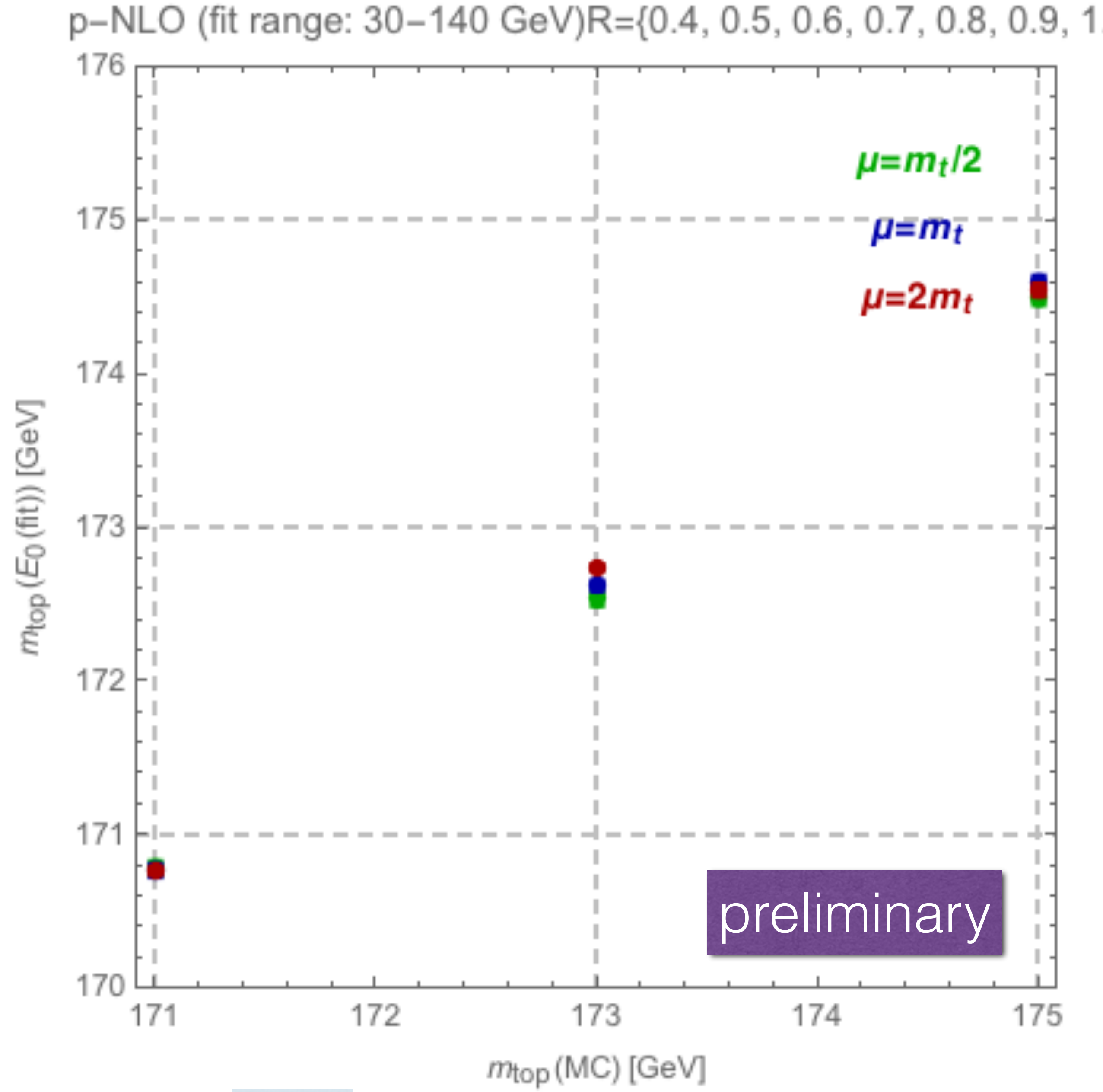


shift ~ R^p (p~2 jet area)
shift ~ 1/μ (real radiation)

NLO: production

(MCFM)



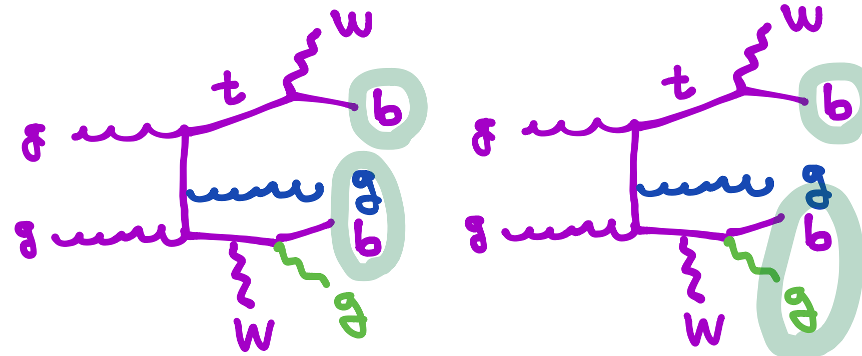


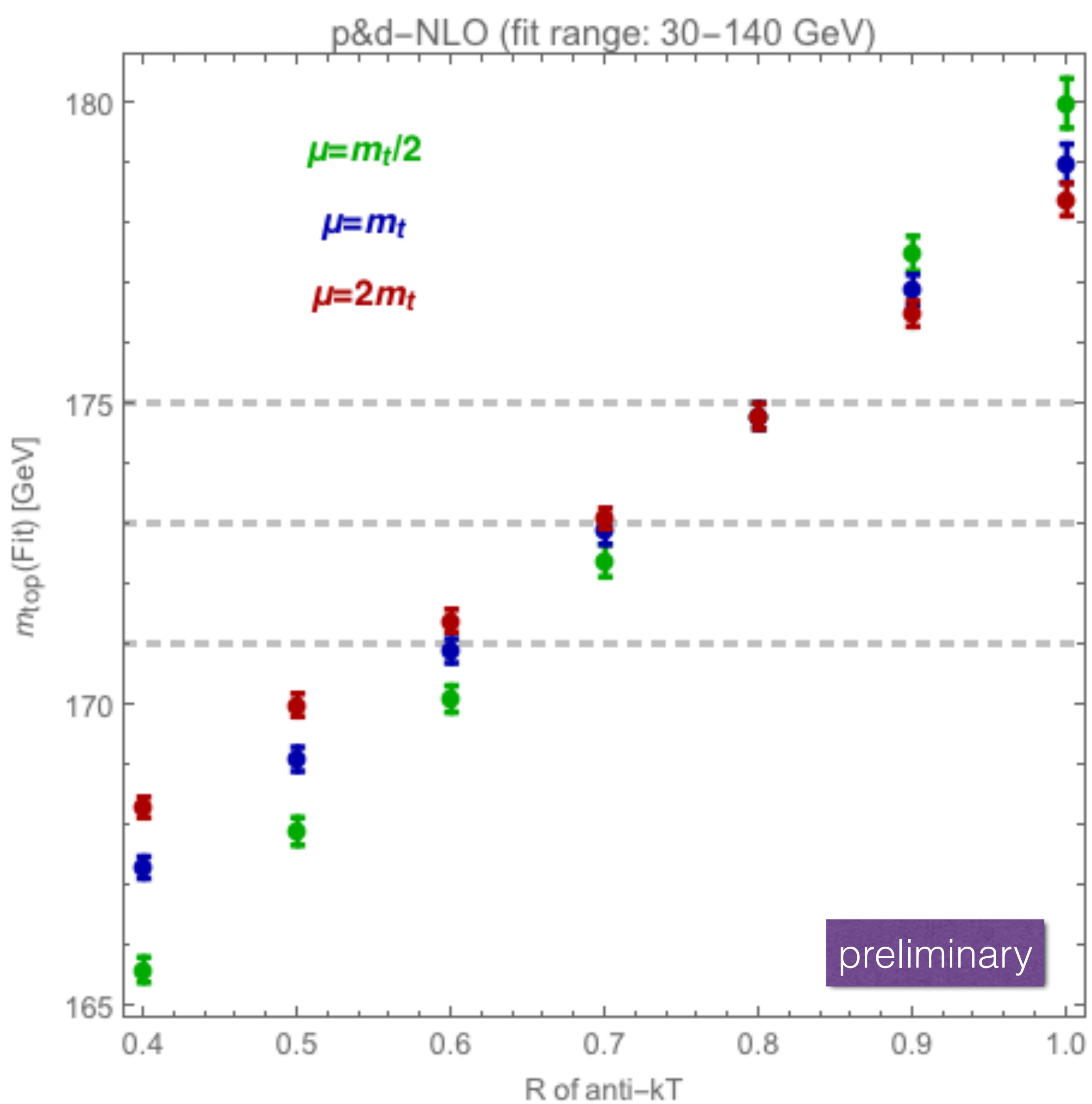
shift ~ R^p (p~2 jet area)
shift ~ 1/μ (real radiation)

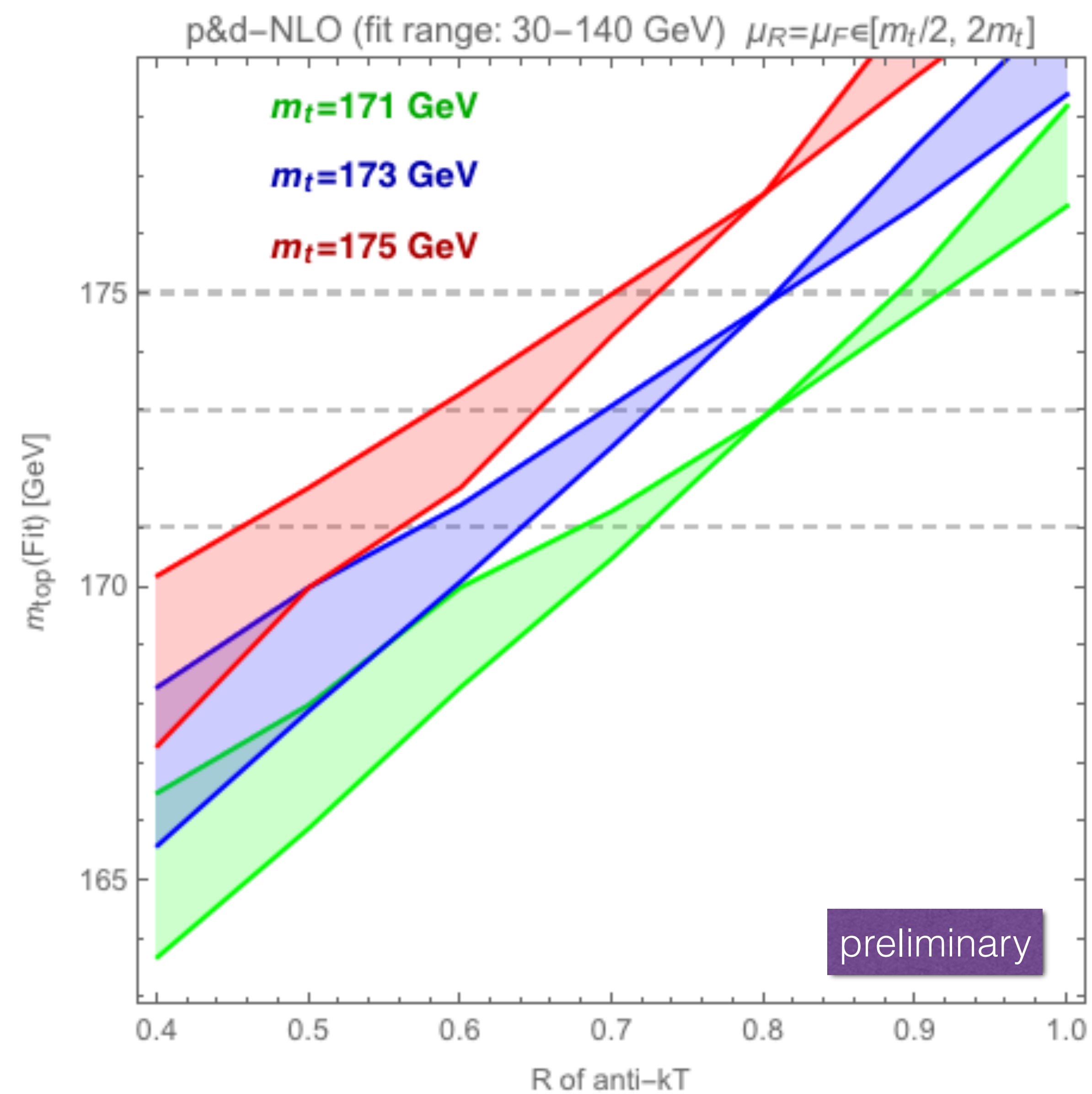
$$\hat{E} = E_0 + \alpha(\mu) \cdot p \cdot R^2 + \ldots$$

$$E_b^* = \frac{m_t^2 - m_w^2 + m_b^2}{2 m_t}$$

NLO: production & decay

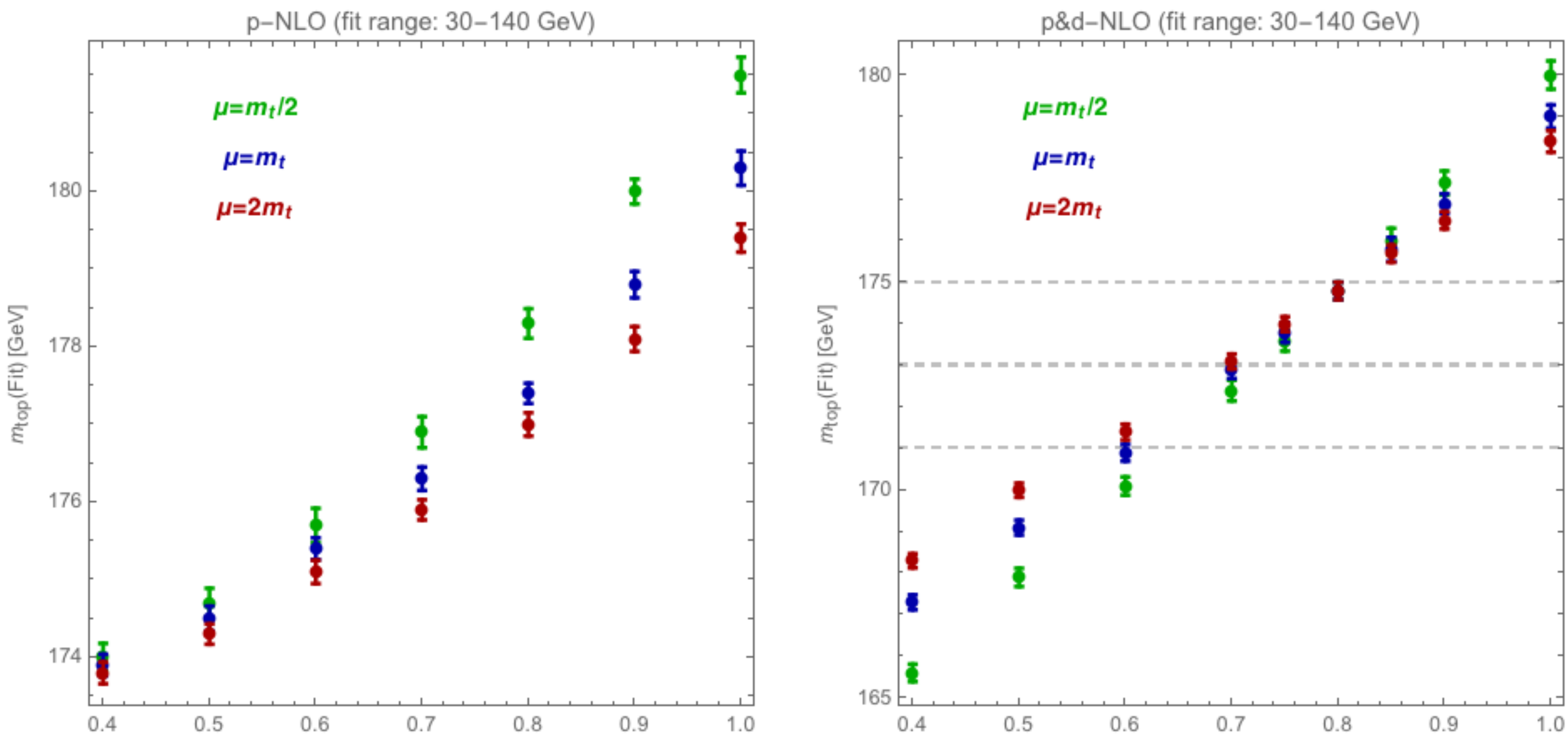




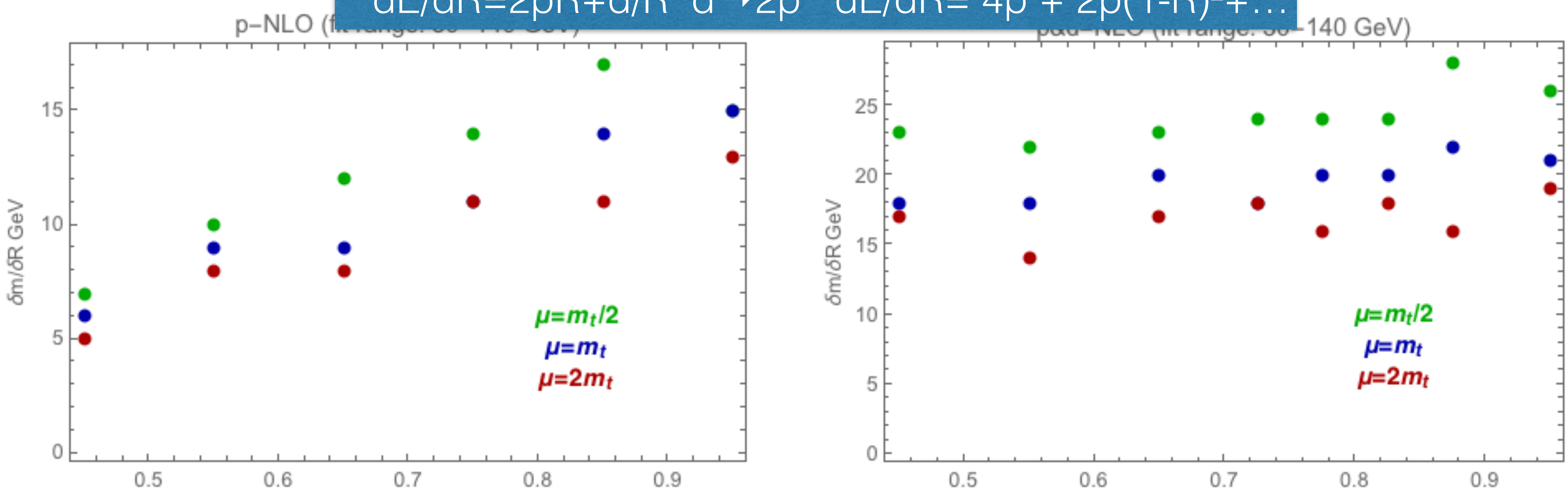


$$\hat{E} = E_0 + \alpha(\mu)\cdot[\, p\cdot R^2 + p\cdot \log R \,] + \ldots$$

decay NLO sensitive to the scale choice: ±1 GeV on m_{top}



dE/dR=2pR+d/R d→2p   dE/dR= 4p + 2p(1-R)^2+…



NLO virtues

Agashe, Franceschini, Kim, Schulze - in preparation

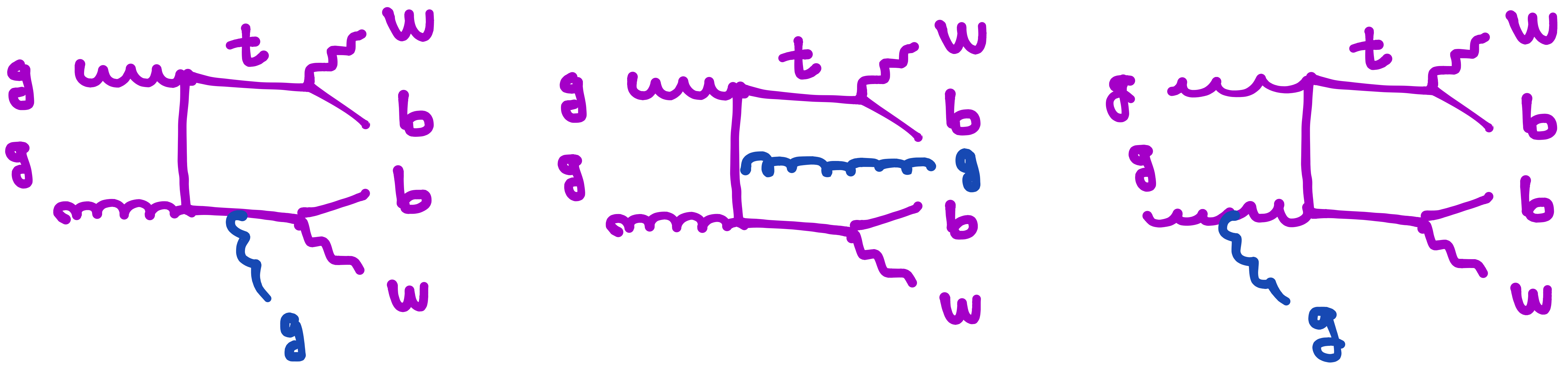
- **Invariance holds for pp→tt @ NLO**
- Not sensitive to Initial State Radiation
- Not sensitive to Parton Distribution Functions
- Not sensitive to the exact energy of the collider

only sensitive to the NLO decay t→bWg

Insensitive to production at NLO

Agashe, Franceschini, Kim, Schulze - in preparation

Production NLO only affects the boost distribution of top



The energy peak position is unchanged

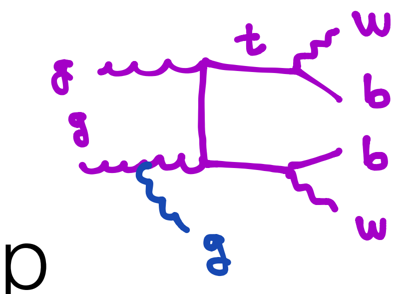
$$E_b^{peak} = \frac{m_t^2 - m_W^2 + m_{b/j}^2}{2m_t} = E_b^*$$

NLO virtues

- Invariance holds for pp→tt @ NLO
- **Not sensitive to Initial State Radiation**
- Not sensitive to Parton Distribution Functions
- Not sensitive to the exact energy of the collider

only sensitive to the NLO decay t→bWg

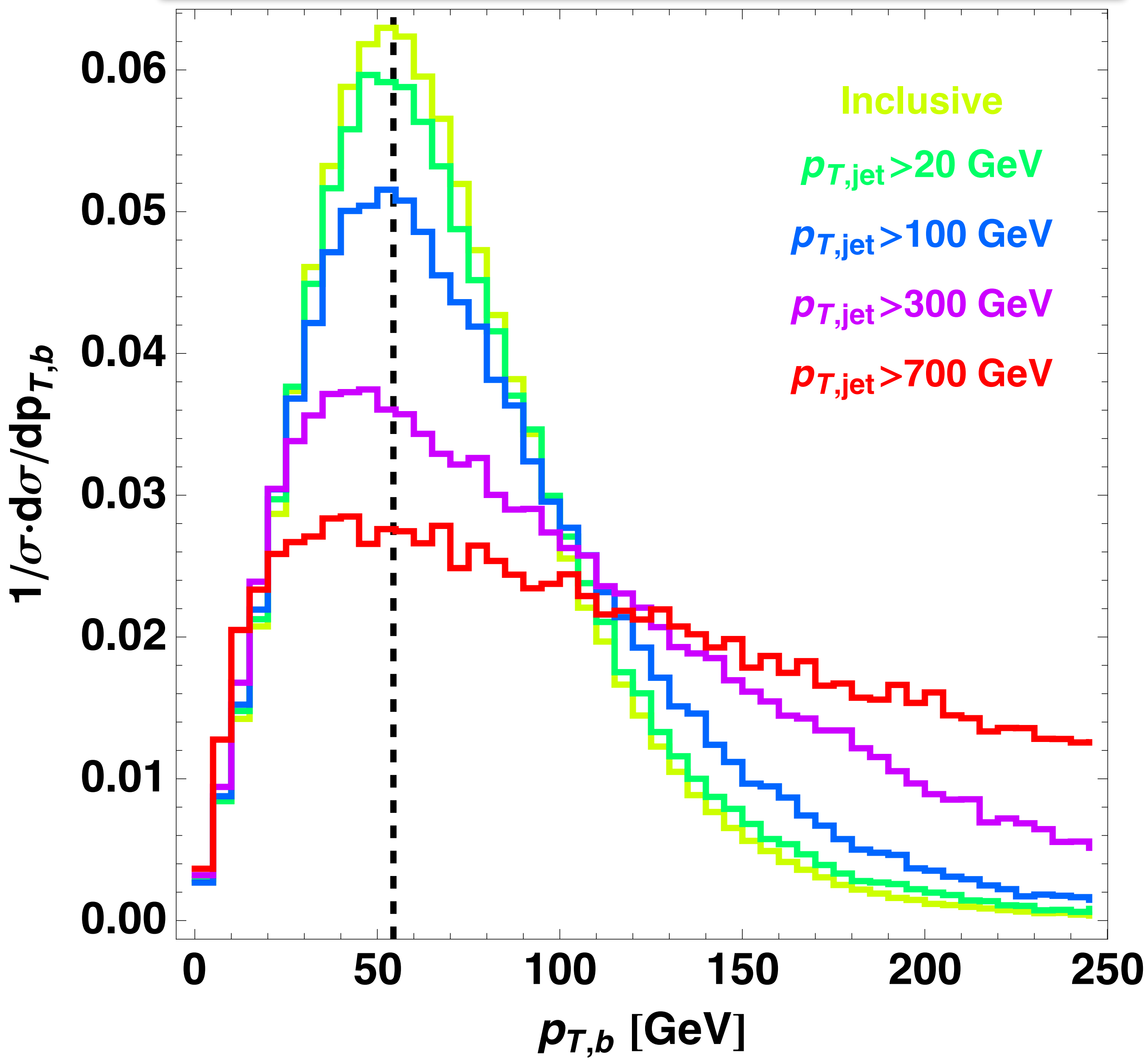
Effect of initial state radiation



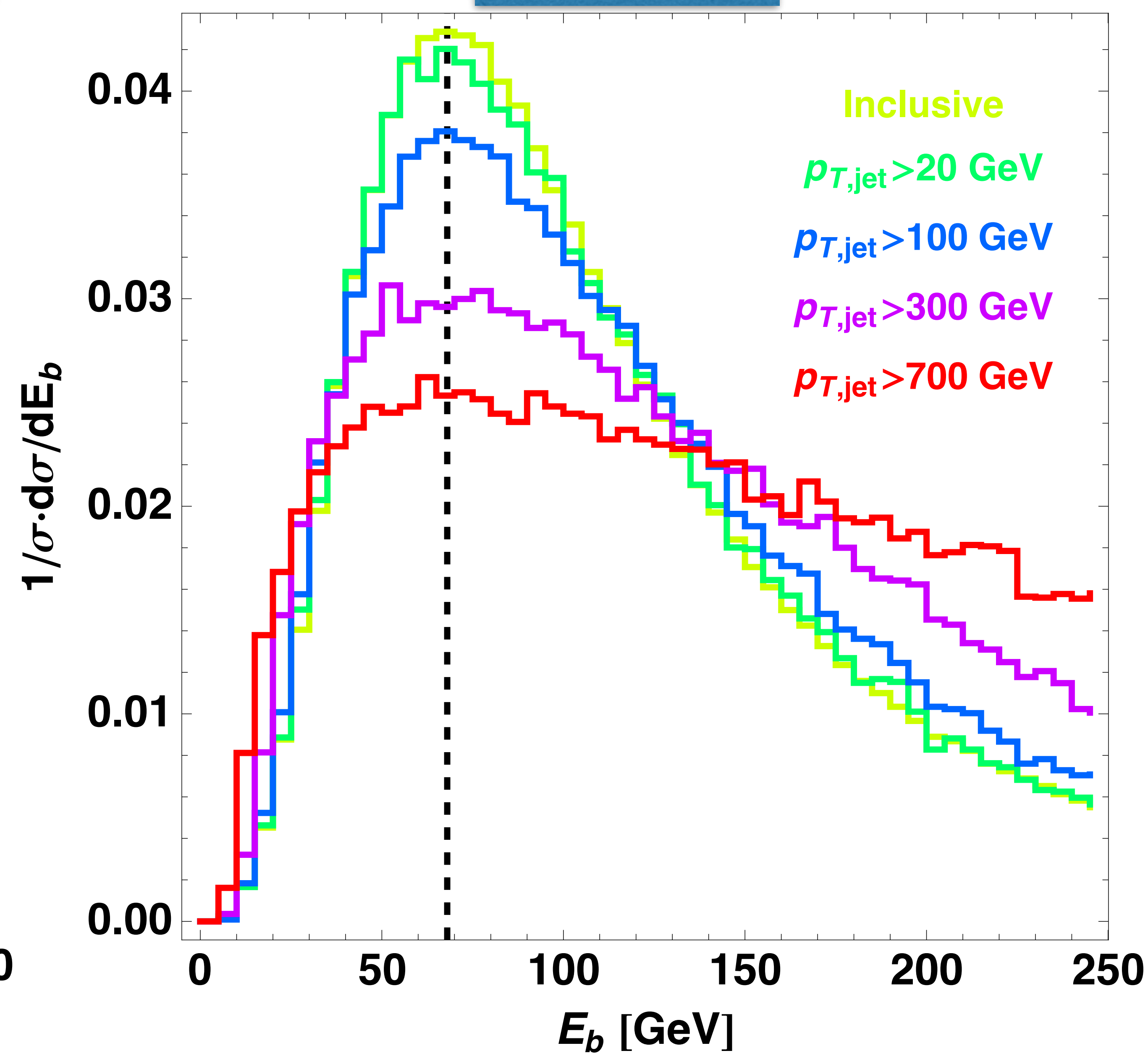
ISR only affects the boost distribution of top

Agashe, Franceschini, Kim, Schulze - in preparation

Transverse Momentum



Energy



peak stability

NLO virtues

- Invariance holds for pp→tt @ NLO
- Not sensitive to Initial State Radiation
- **Not sensitive to Parton Distribution Functions**
- **Not sensitive to the exact energy of the collider**

only sensitive to the NLO decay t→bWg

Top mass combination

1403.4427 - First combination of Tevatron and LHC measurements of the top-quark mass

LHC/Tevatron NOTE

ATLAS-CONF-2014-008
CDF Note 11071
CMS PAS TOP-13-014
D0 Note 6416

March 17, 2014

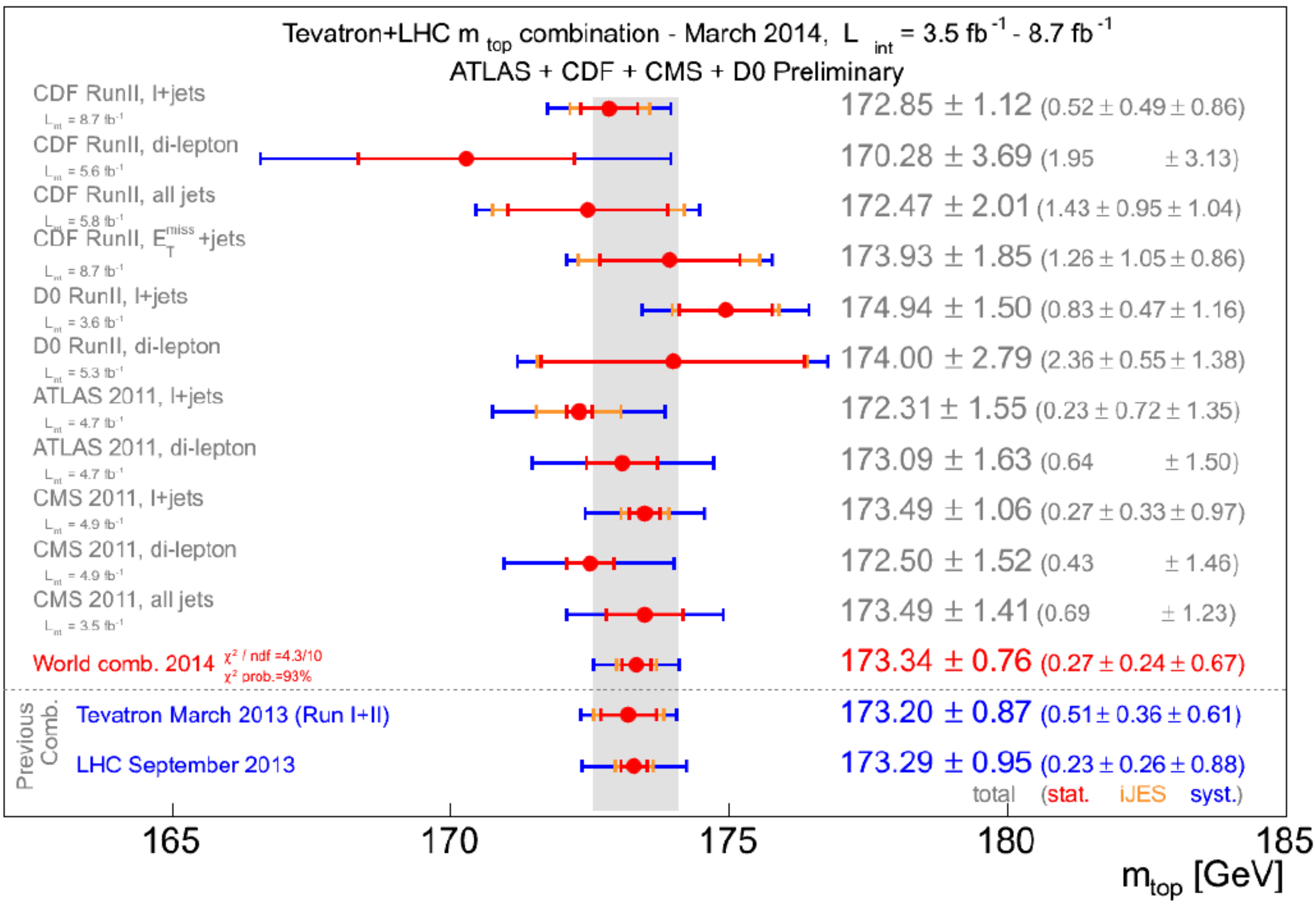
Experiment	$t\bar{t}$ final state	$\mathcal{L}_{int}$ [fb^{-1}]	m_{top} ± (stat.) ± (syst.) [GeV]	Total uncertainty on m_{top} [GeV] ([%])	Reference
CDF	l+jets	8.7	→ 172.85 ± 0.52 ± 0.99 ←	1.12 (0.65)	[8]
	dilepton	5.6	170.28 ± 1.95 ± 3.13	3.69 (2.17)	[9]
	all jets	5.8	172.47 ± 1.43 ± 1.41	2.01 (1.16)	[10]
	E_T^{miss}+jets	8.7	173.93 ± 1.26 ± 1.36	1.85 (1.07)	[11]
D0	l+jets	3.6	174.94 ± 0.83 ± 1.25	1.50 (0.86)	[12]
	dilepton	5.3	174.00 ± 2.36 ± 1.49	2.79 (1.60)	[13]
ATLAS	l+jets	4.7	172.31 ± 0.23 ± 1.53	1.55 (0.90)	[14]
	dilepton	4.7	173.09 ± 0.64 ± 1.50	1.63 (0.94)	[15]
CMS	l+jets	4.9	→ 173.49 ± 0.27 ± 1.03 ←	1.06 (0.61)	[16]
	dilepton	4.9	172.50 ± 0.43 ± 1.46	1.52 (0.88)	[17]
	all jets	3.5	173.49 ± 0.69 ± 1.23	1.41 (0.81)	[18]

l+jets
dilepton
all jets

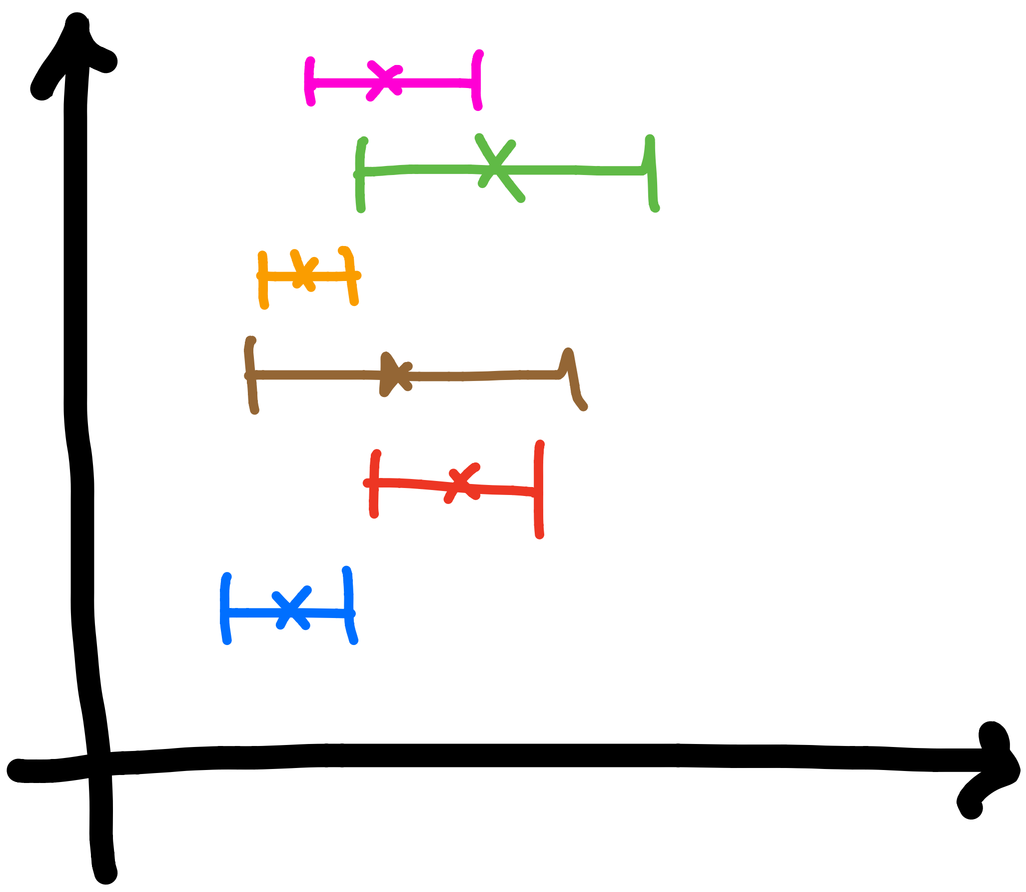
LHC-7 is on par with TeVatron

173.34± 0.27(stat) ± 0.71 (syst) GeV
dominated by systematics

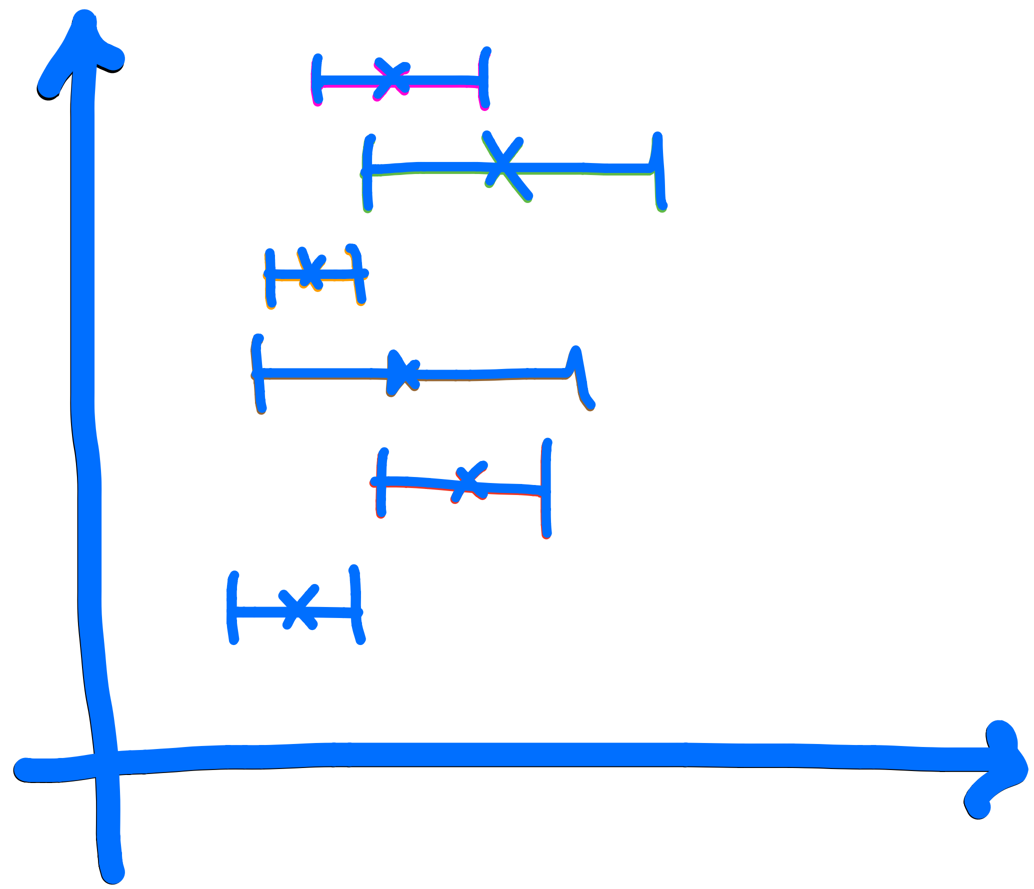
Many measurements



Many measurements?



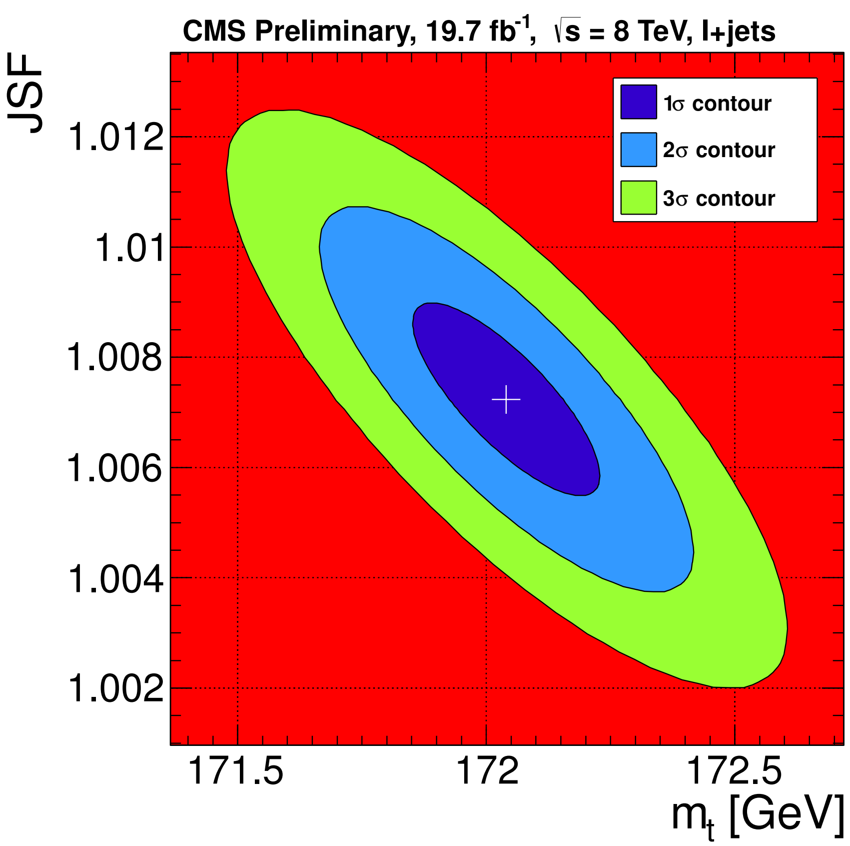
Many measurements?



CMS PAS TOP-14-001

172.04 ± 0.19 (stat.+JSF) ± 0.75 (syst.) GeV

Ideogram Method (Kinematic fit)



MG5+Py6 or POWHEG

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	$<$0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	$<$0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	$<$0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29

ATLAS-CONF-2013-046

m_{top} = 172.31 ± 0.23 (stat) ± 0.27 (JSF) ± 0.67 (bJSF) ± 1.35 (syst) GeV

3D Method (Kinematic Fit)

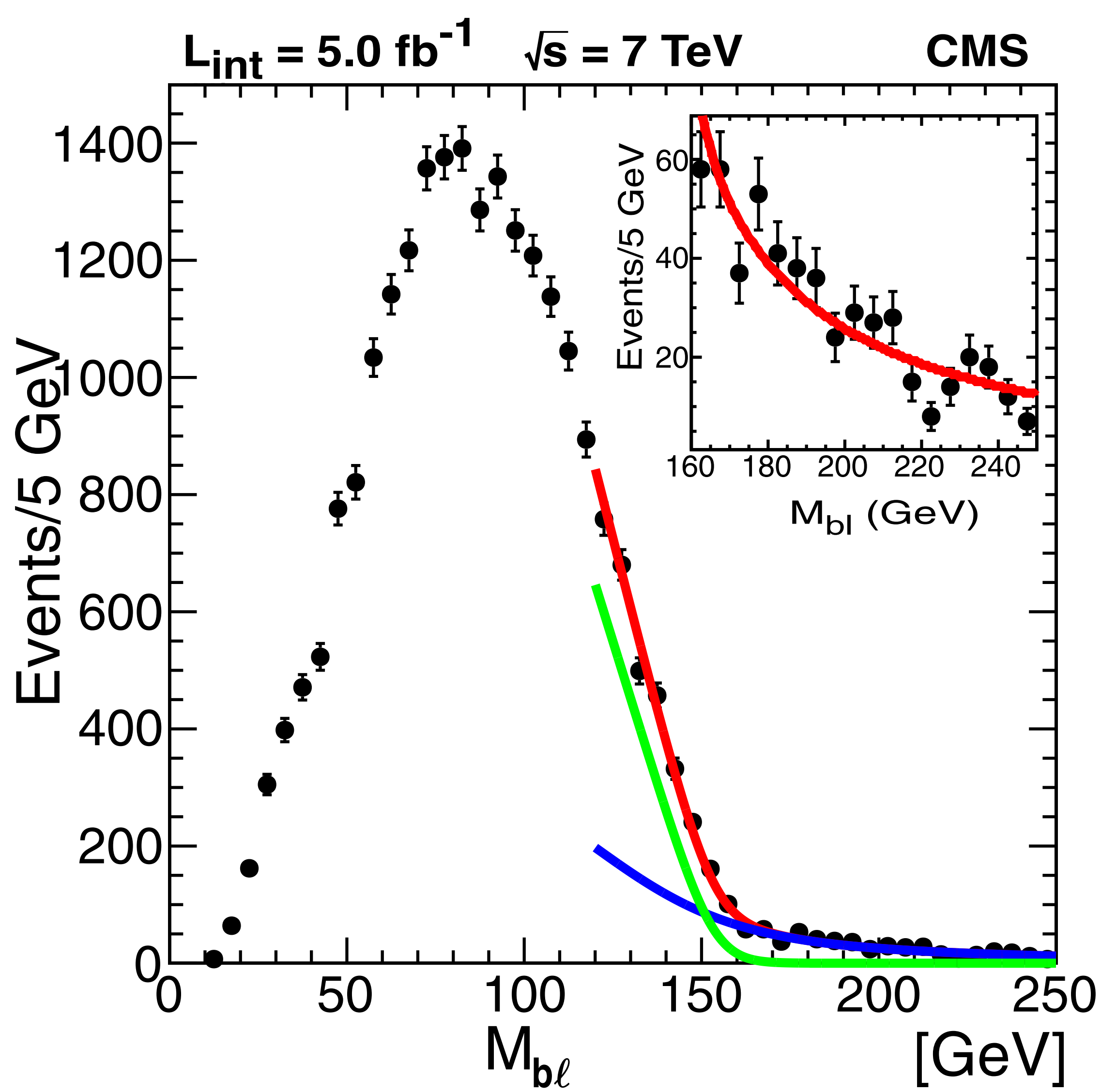
MC@NLO or POWHEG	2d-analysis		3d-analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	0.008	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

CMS-TOP-11-027

$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.1}\,(\text{syst.})\,\text{GeV}$

m(b,l) end-point

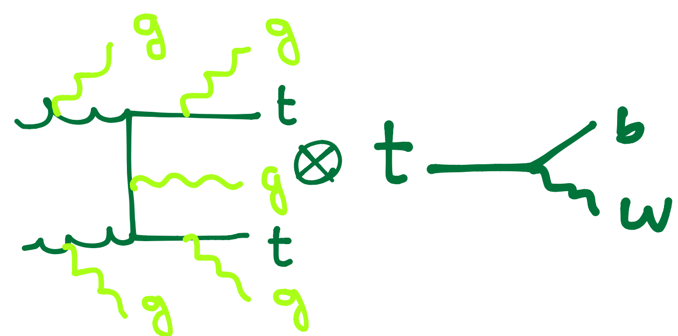
- robust to NLO
- robust to combinatorics
- robust to hadronization

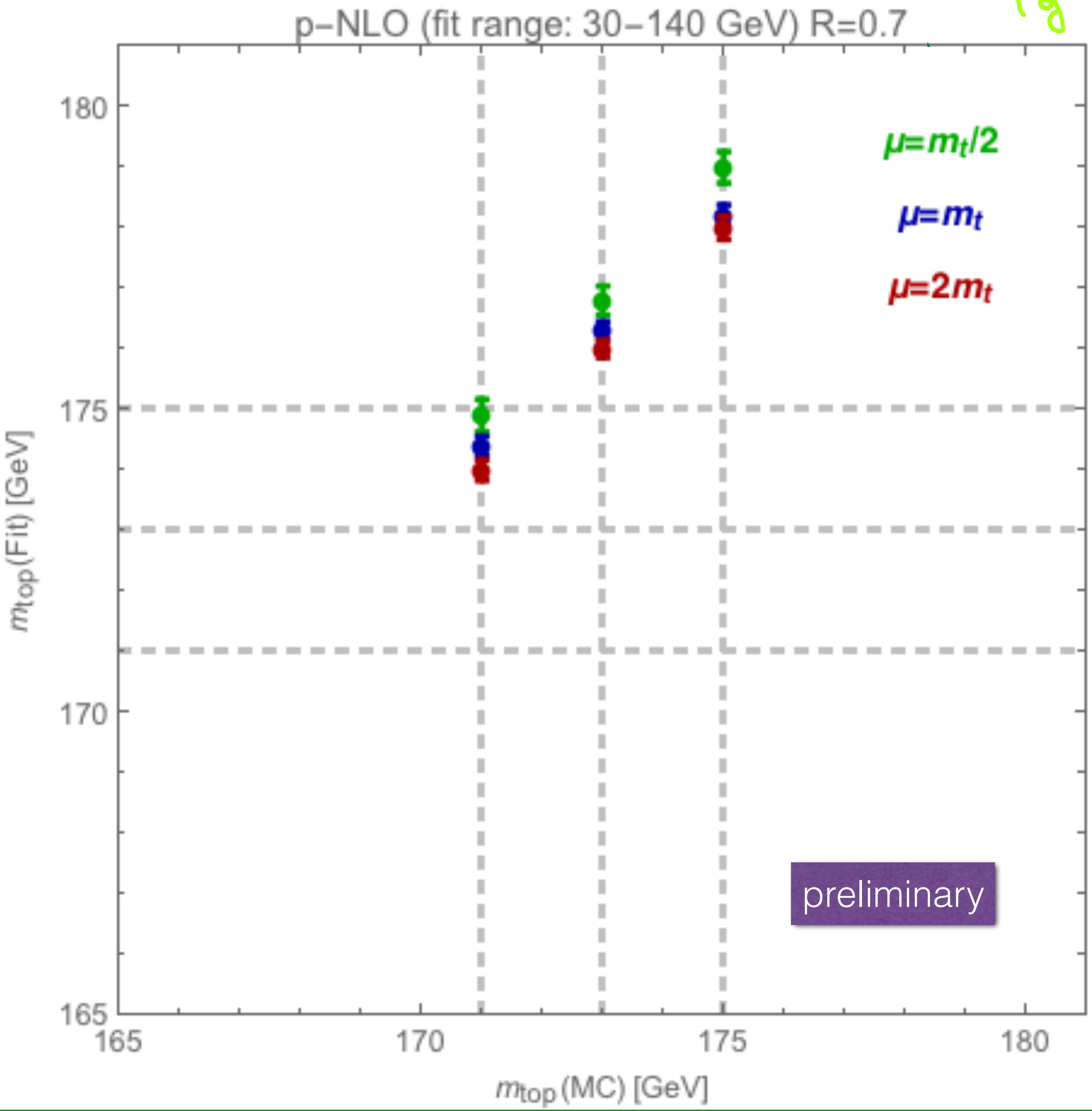


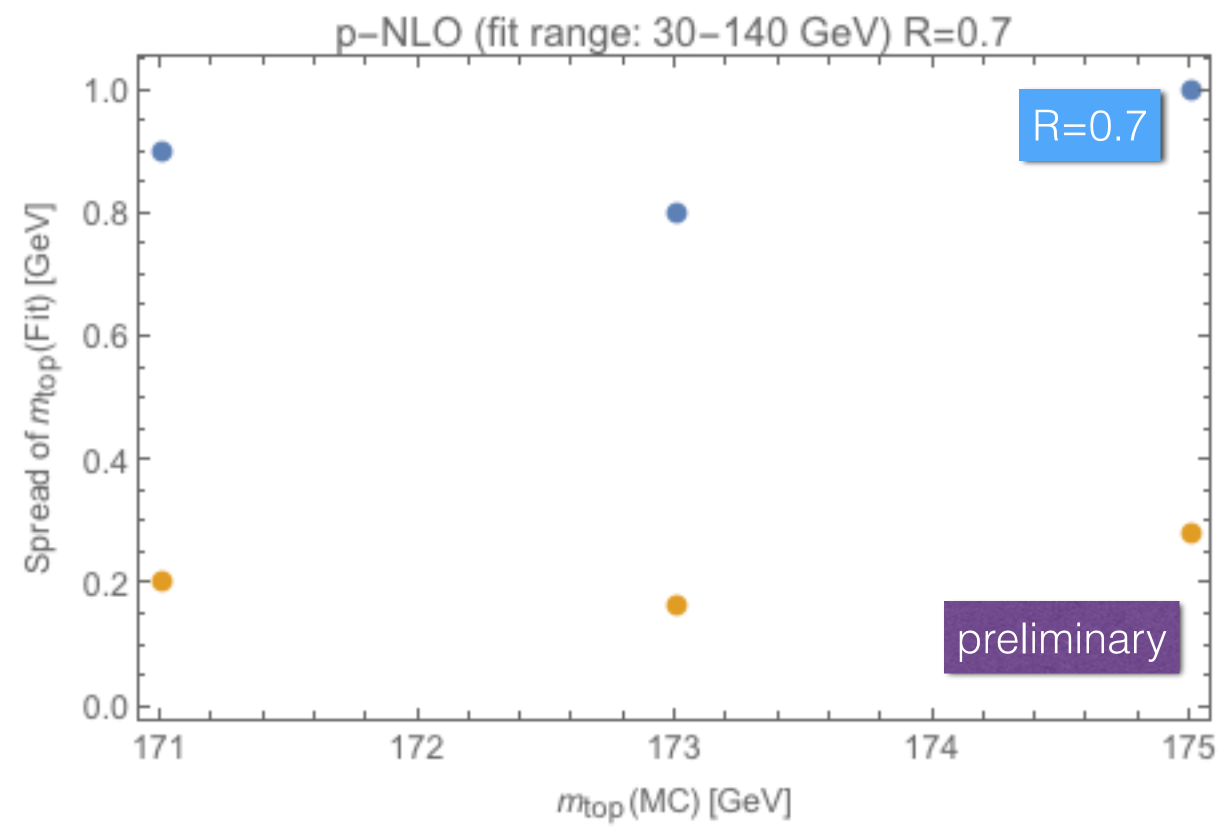
Source	δM_t (GeV)
Jet Energy Scale	$^{+1.3}_{-1.8}$
Jet Energy Resolution	± 0.5
Lepton Energy Scale	$^{+0.3}_{-0.4}$
Fit Range	± 0.6
Background Shape	± 0.5
Jet and Lepton Efficiencies	$^{+0.1}_{-0.2}$
Pileup	<0.1
QCD effects	± 0.6
Total	$^{+1.7}_{-2.1}$

NLO: production

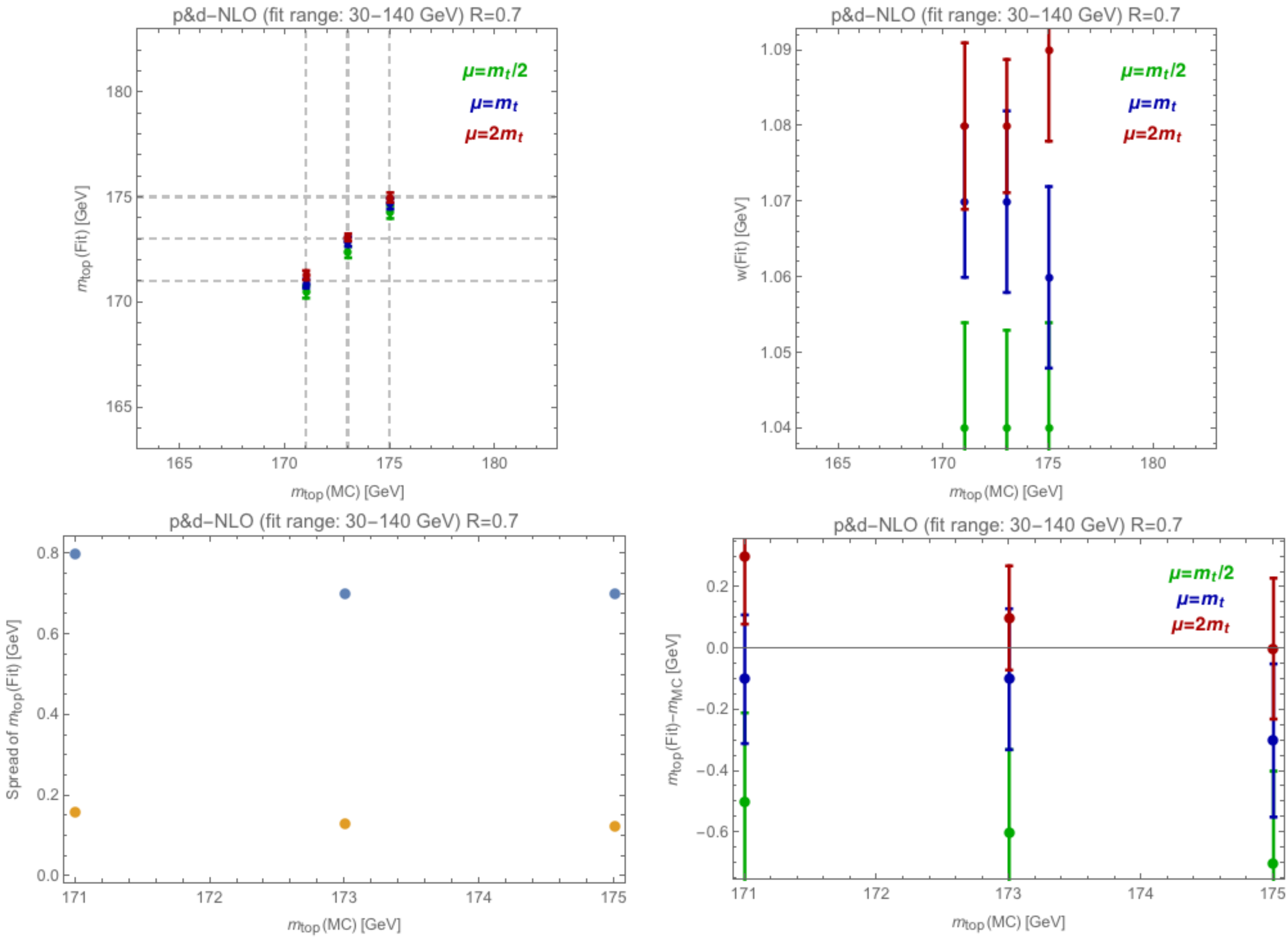
(MCFM)



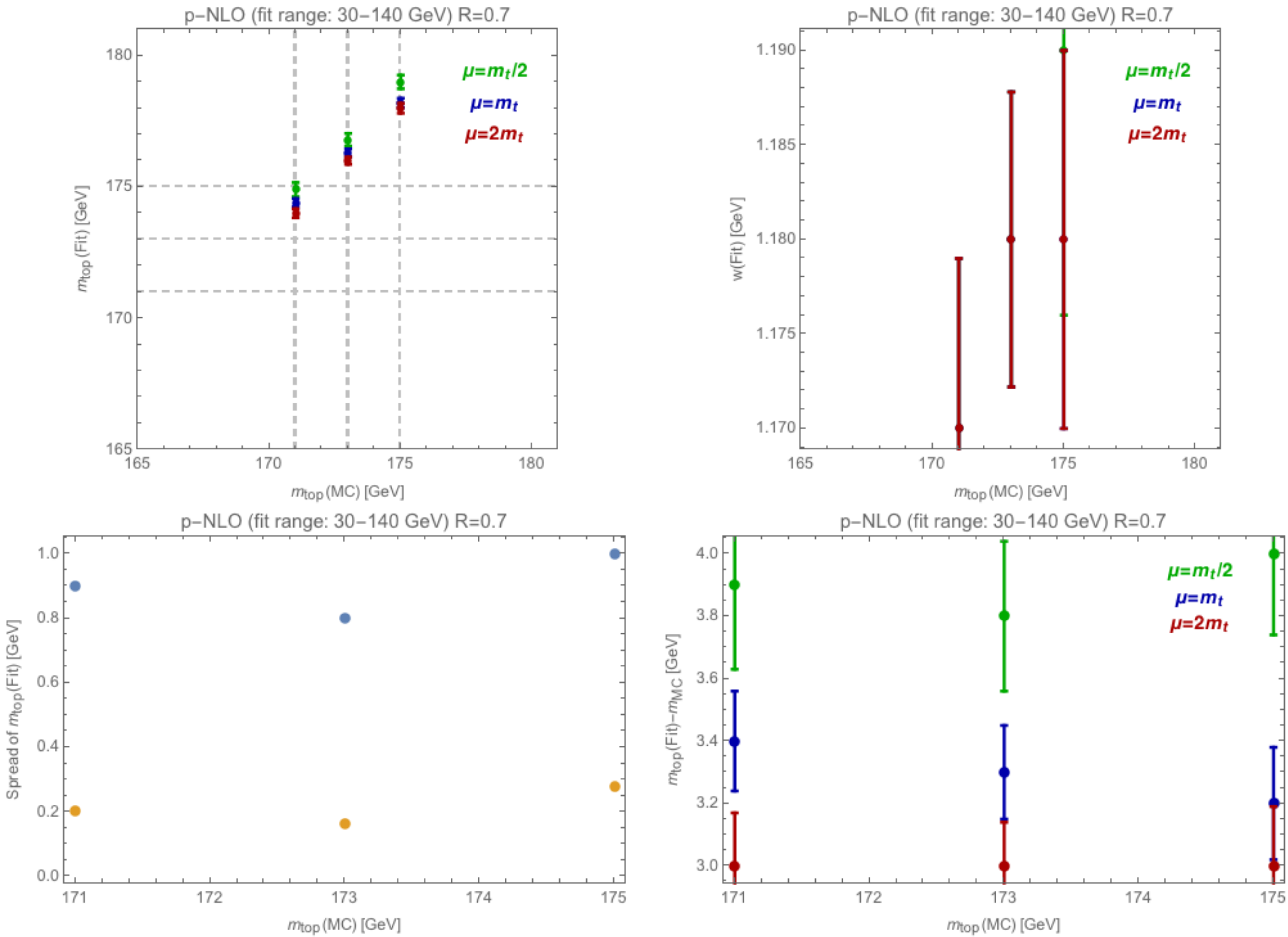




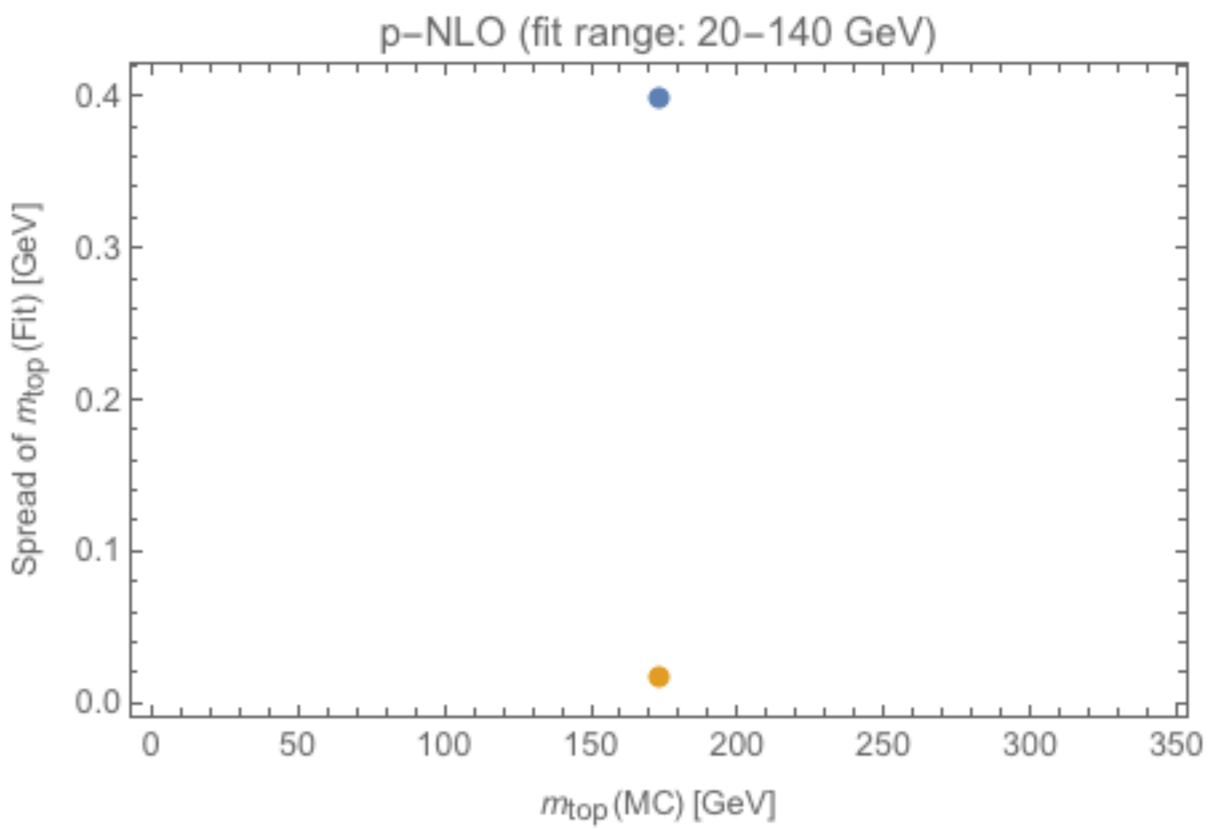
very little sensitive to the scale choice (less than 400 MeV on m_{top})

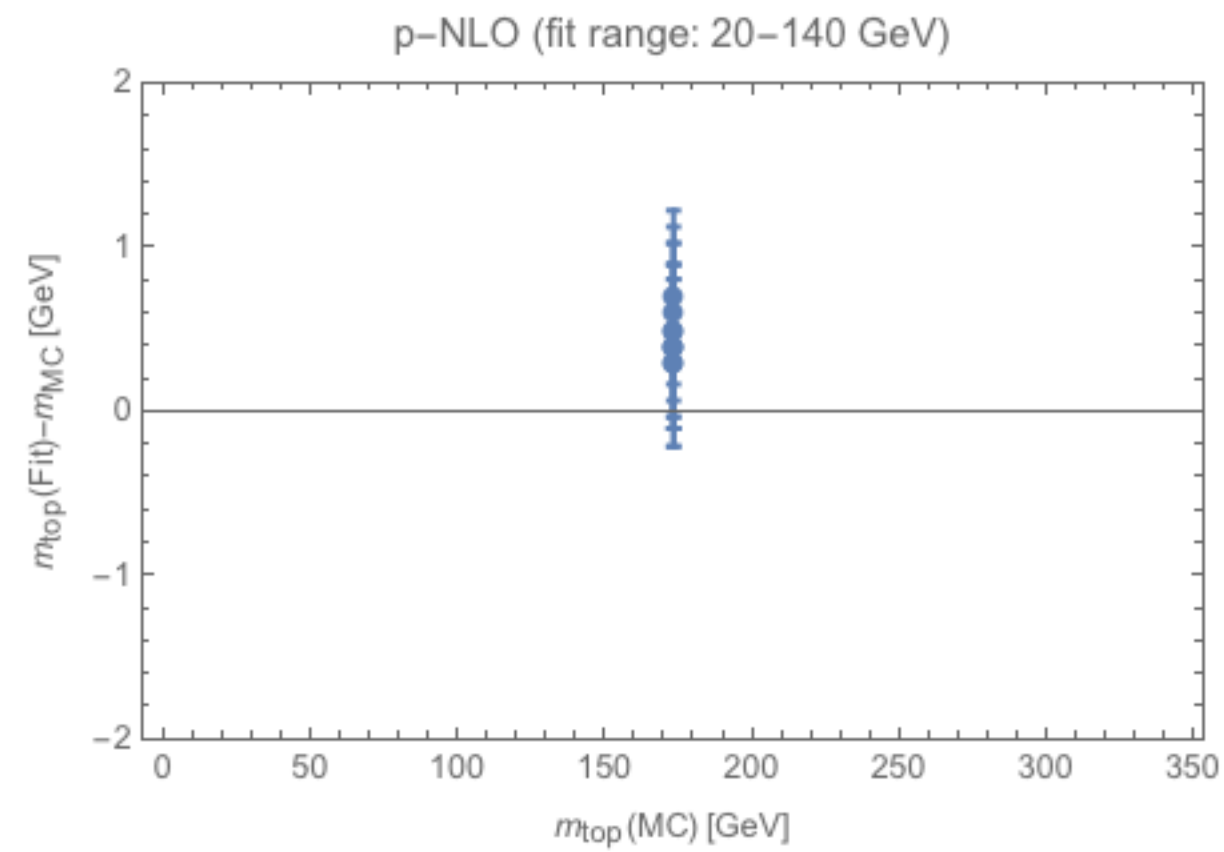


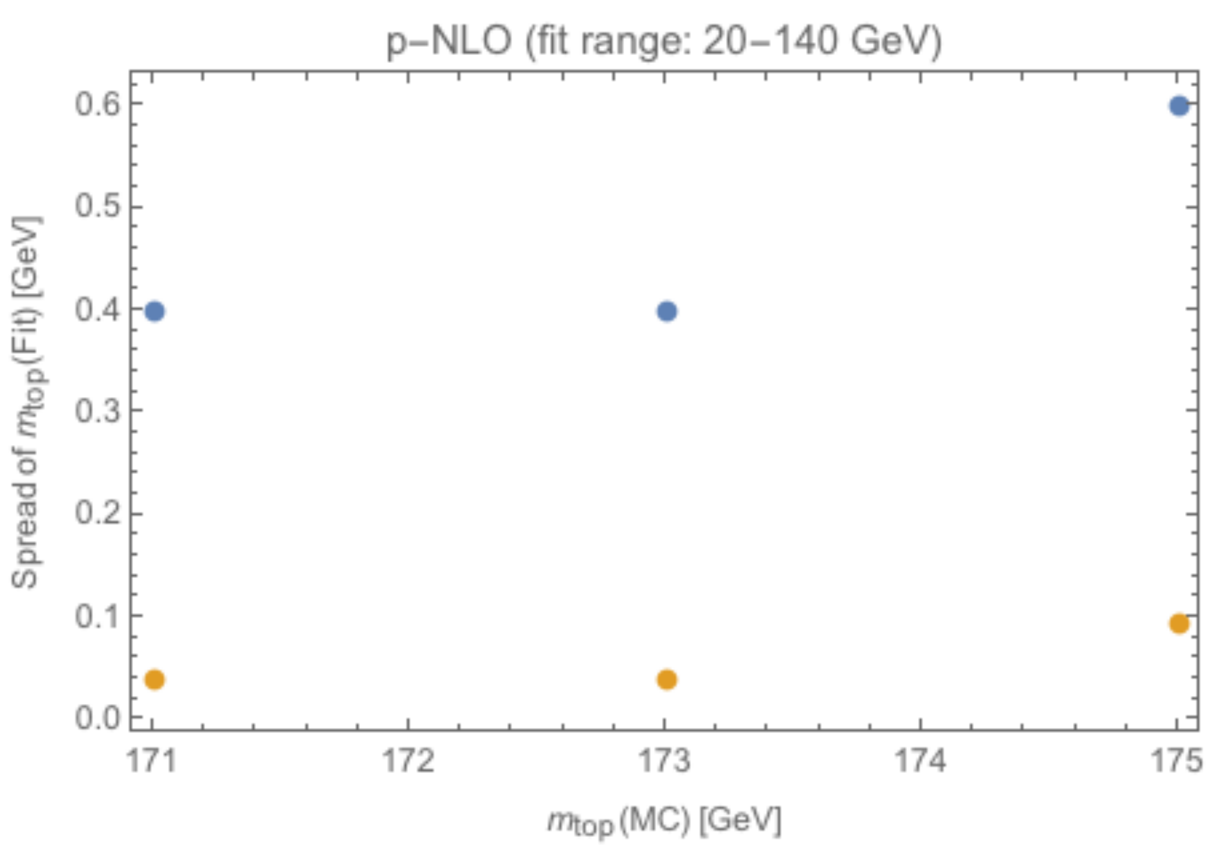
p&d−NLO (fit range: 30−140 GeV) R=0.7
μ=m_t/2
μ=m_t
μ=2m_t
m_top(Fit) [GeV]
m_top(MC) [GeV]
p&d−NLO (fit range: 30−140 GeV) R=0.7
μ=m_t/2
μ=m_t
μ=2m_t
w(Fit) [GeV]
m_top(MC) [GeV]
p&d−NLO (fit range: 30−140 GeV) R=0.7
Spread of m_top(Fit) [GeV]
m_top(MC) [GeV]
p&d−NLO (fit range: 30−140 GeV) R=0.7
μ=m_t/2
μ=m_t
μ=2m_t
m_top(Fit)−m_MC [GeV]
m_top(MC) [GeV]

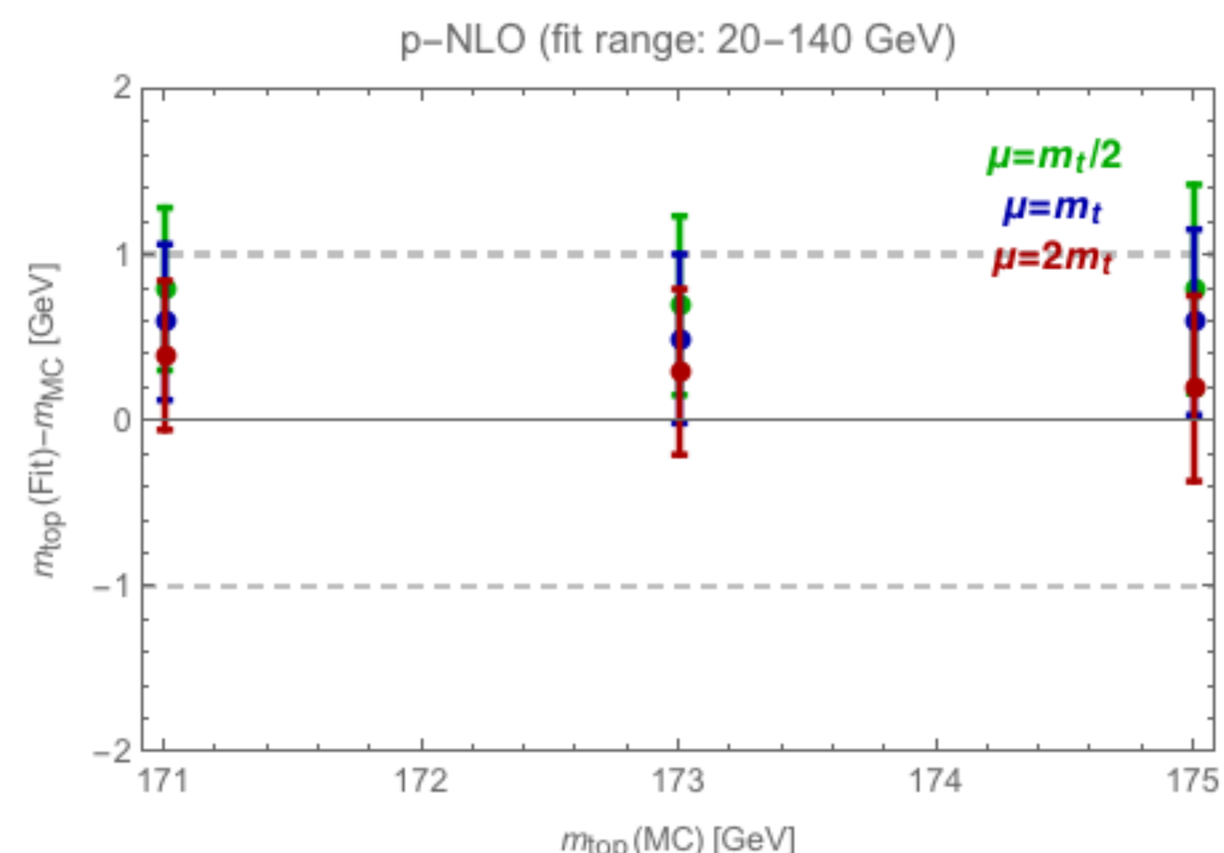

p–NLO (fit range: 30–140 GeV) R=0.7
m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
p–NLO (fit range: 30–140 GeV) R=0.7
w(Fit) [GeV]
m_{top}(MC) [GeV]
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
p–NLO (fit range: 30–140 GeV) R=0.7
Spread of m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]
p–NLO (fit range: 30–140 GeV) R=0.7
m_{top}(Fit)–m_{MC} [GeV]
m_{top}(MC) [GeV]
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$

$\mu_F \neq \mu_R$

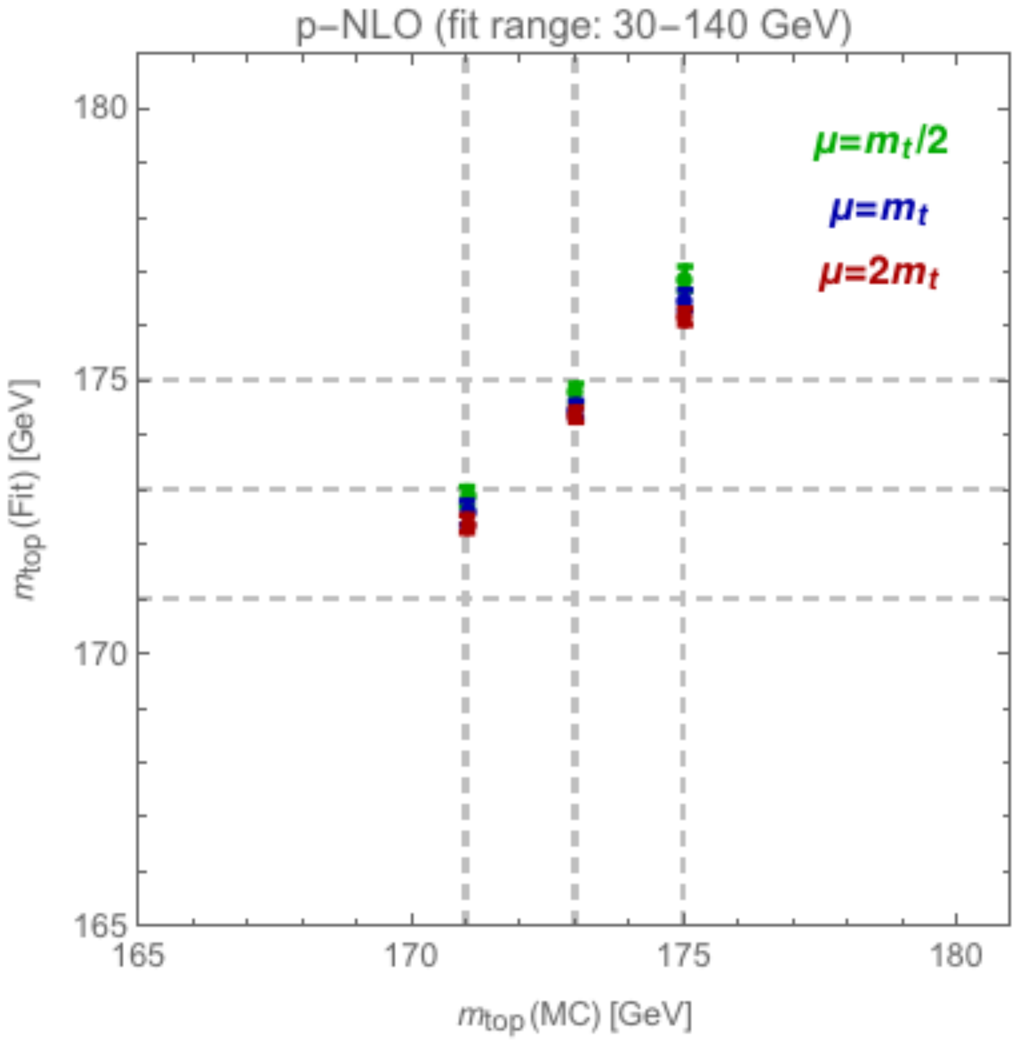

p–NLO (fit range: 20–140 GeV)
Spread of mtop(Fit) [GeV]
0.0
0.1
0.2
0.3
0.4
0
50
100
150
200
250
300
350
mtop (MC) [GeV]

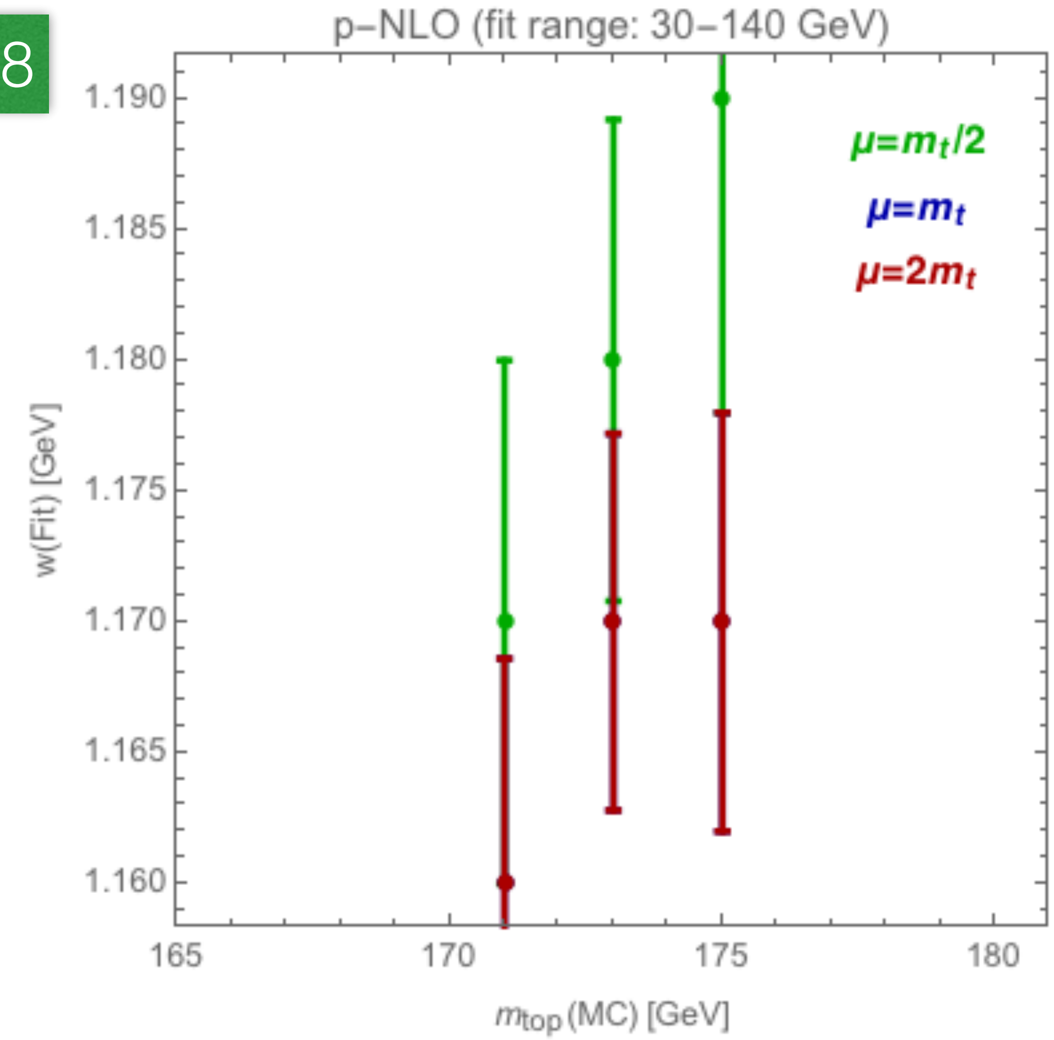

p–NLO (fit range: 20–140 GeV)
mtop(Fit)–mMC [GeV]
2
1
0
−1
−2
0
50
100
150
200
250
300
350
mtop (MC) [GeV]

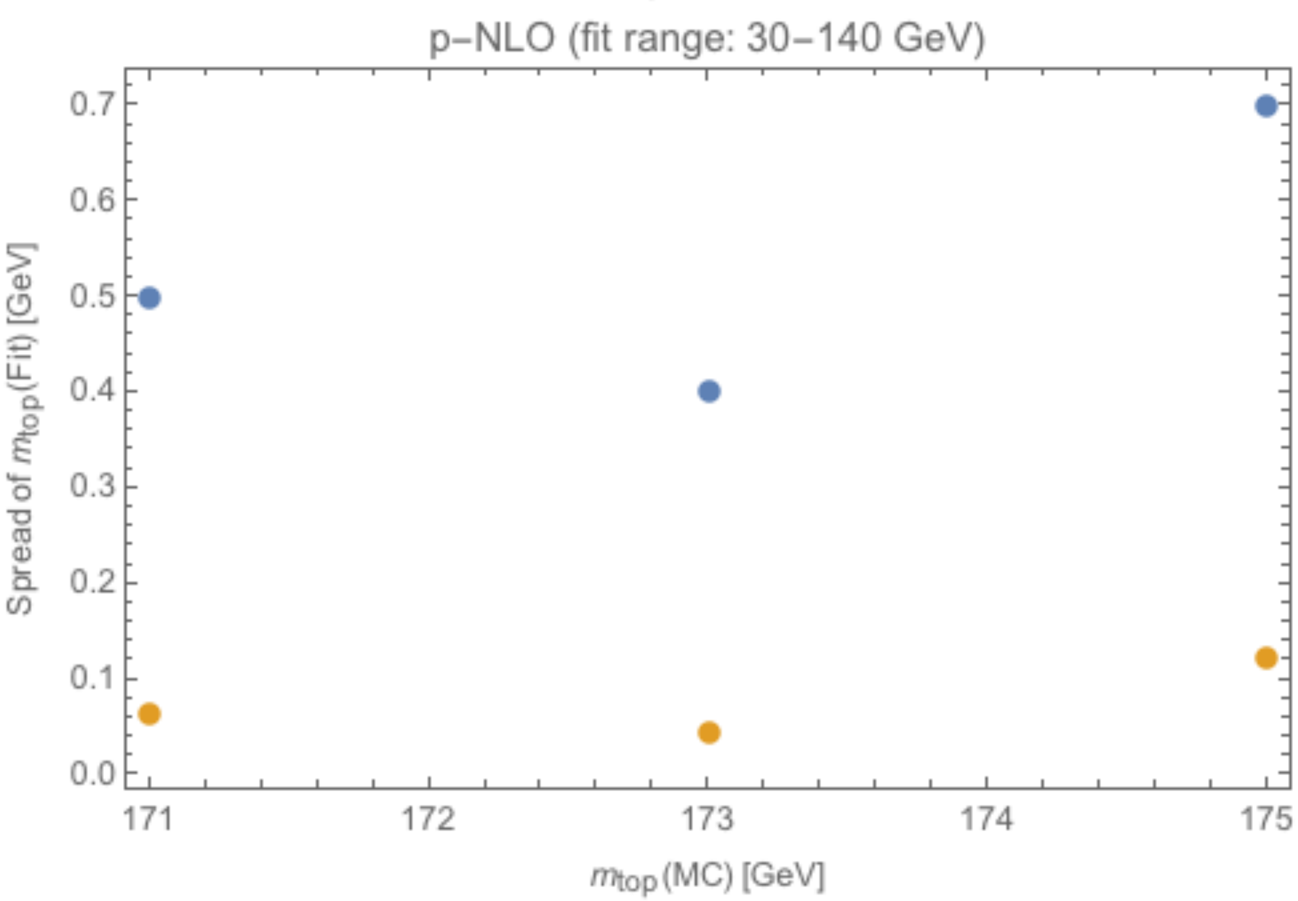

p–NLO (fit range: 20–140 GeV)
Spread of mtop(Fit) [GeV]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
171
172
173
174
175
mtop (MC) [GeV]

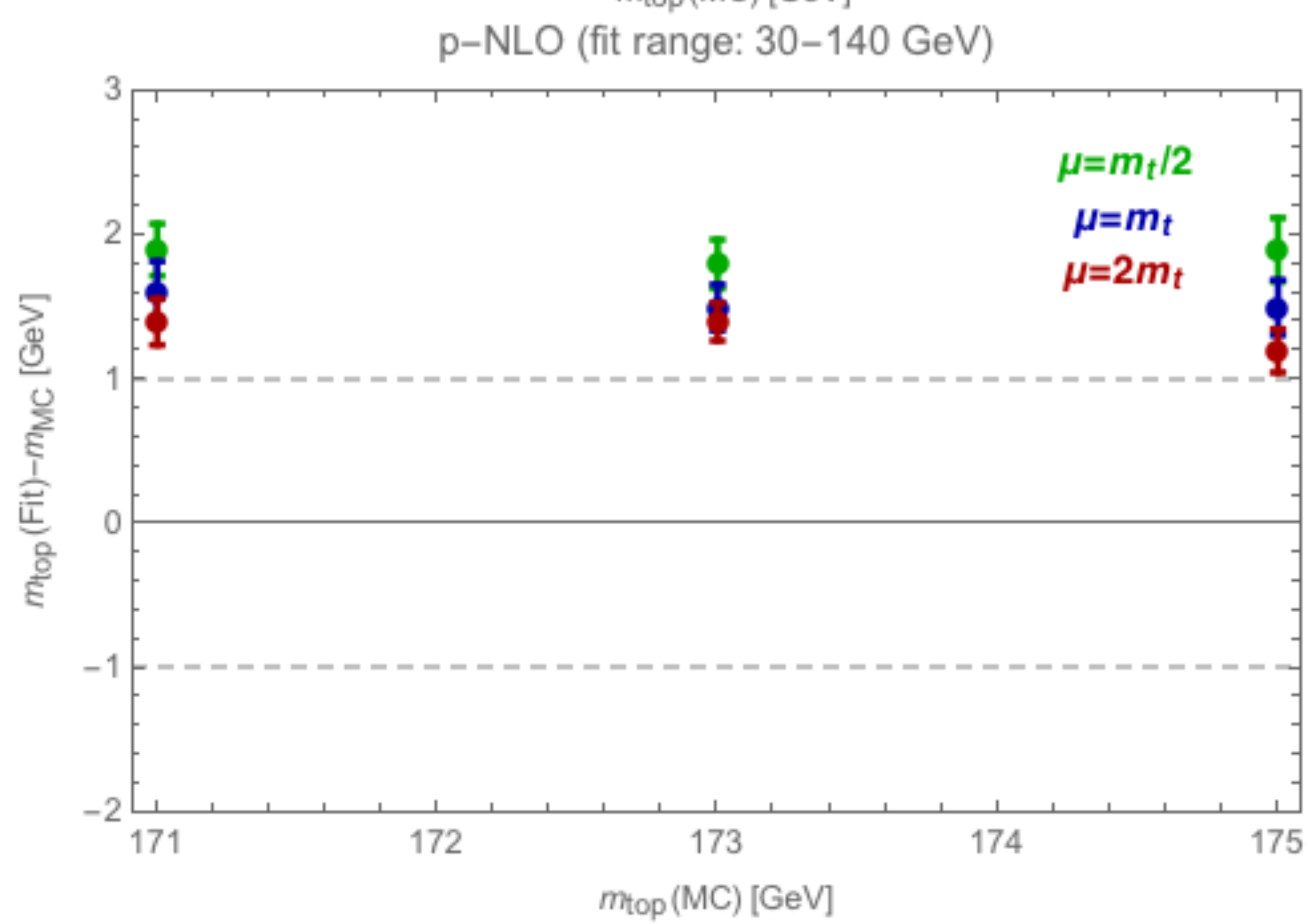

p–NLO (fit range: 20–140 GeV)
μ=mt/2
μ=mt
μ=2mt
mtop(Fit)–mMC [GeV]
2
1
0
−1
−2
171
172
173
174
175
mtop (MC) [GeV]

MSTW08

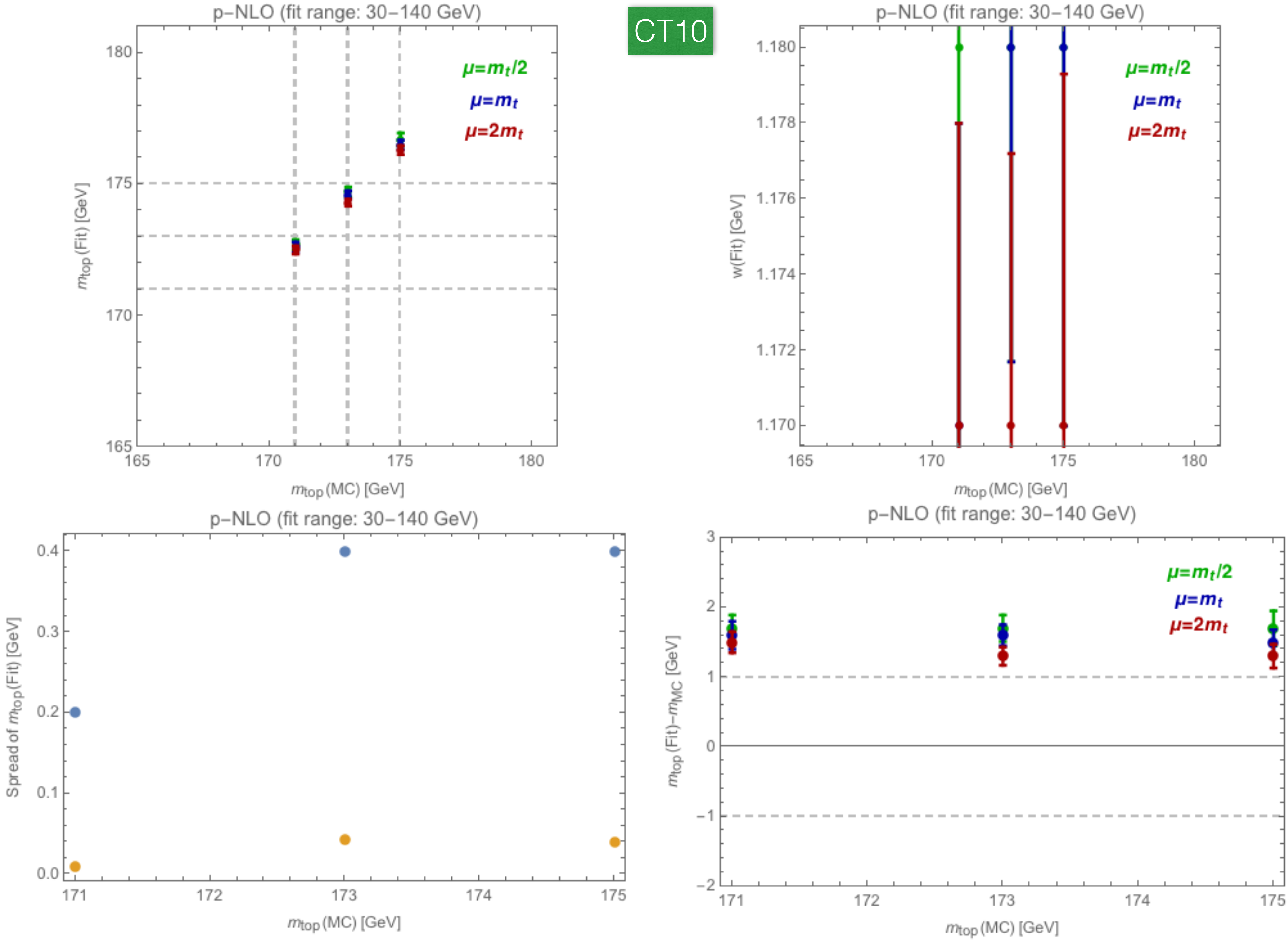

p–NLO (fit range: 30–140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
m_top (Fit) [GeV]
m_top (MC) [GeV]
165
170
175
180

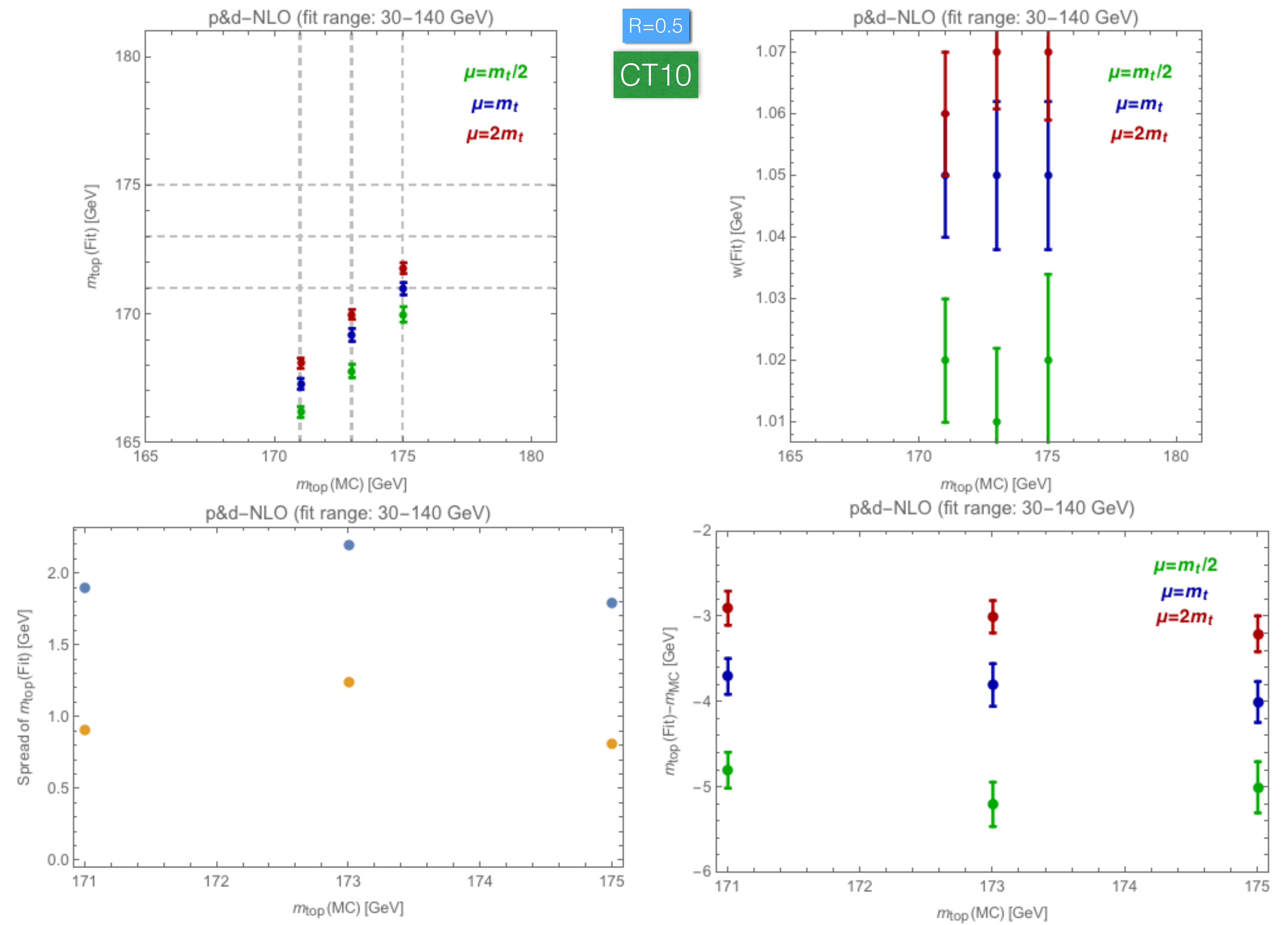

p–NLO (fit range: 30–140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
w(Fit) [GeV]
m_top (MC) [GeV]
1.160
1.165
1.170
1.175
1.180
1.185
1.190
165
170
175
180


p–NLO (fit range: 30–140 GeV)
Spread of m_top (Fit) [GeV]
m_top (MC) [GeV]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
171
172
173
174
175


p–NLO (fit range: 30–140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
m_top (Fit)–m_MC [GeV]
m_top (MC) [GeV]
−2
−1
0
1
2
3
171
172
173
174
175

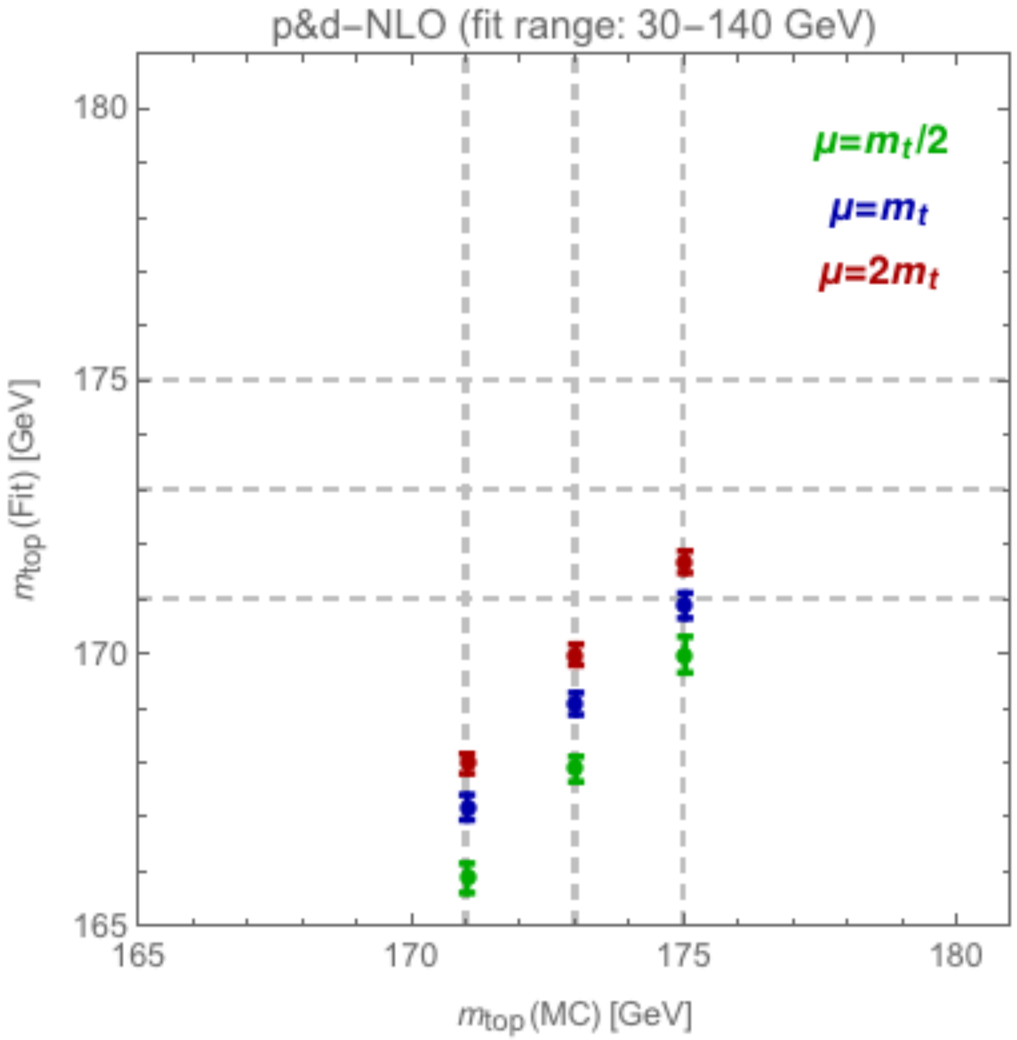
CT10


p–NLO (fit range: 30–140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
m_top(Fit) [GeV]
m_top(MC) [GeV]
w(Fit) [GeV]
Spread of m_top(Fit) [GeV]
m_top(Fit)−m_MC [GeV]

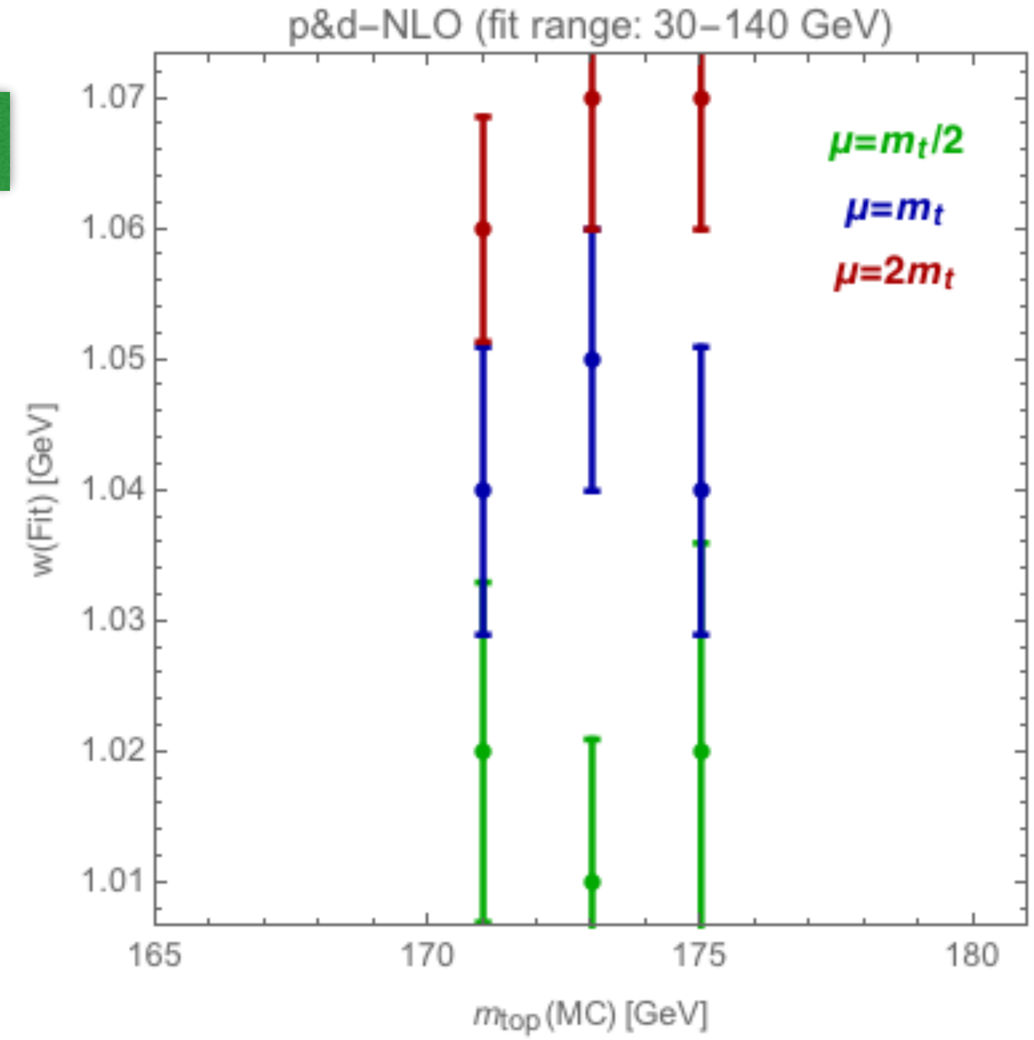

R=0.5
CT10
p&d–NLO (fit range: 30–140 GeV)
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]
w(Fit) [GeV]
Spread of m_{top}(Fit) [GeV]
m_{top}(Fit)–m_{MC} [GeV]

R=0.5

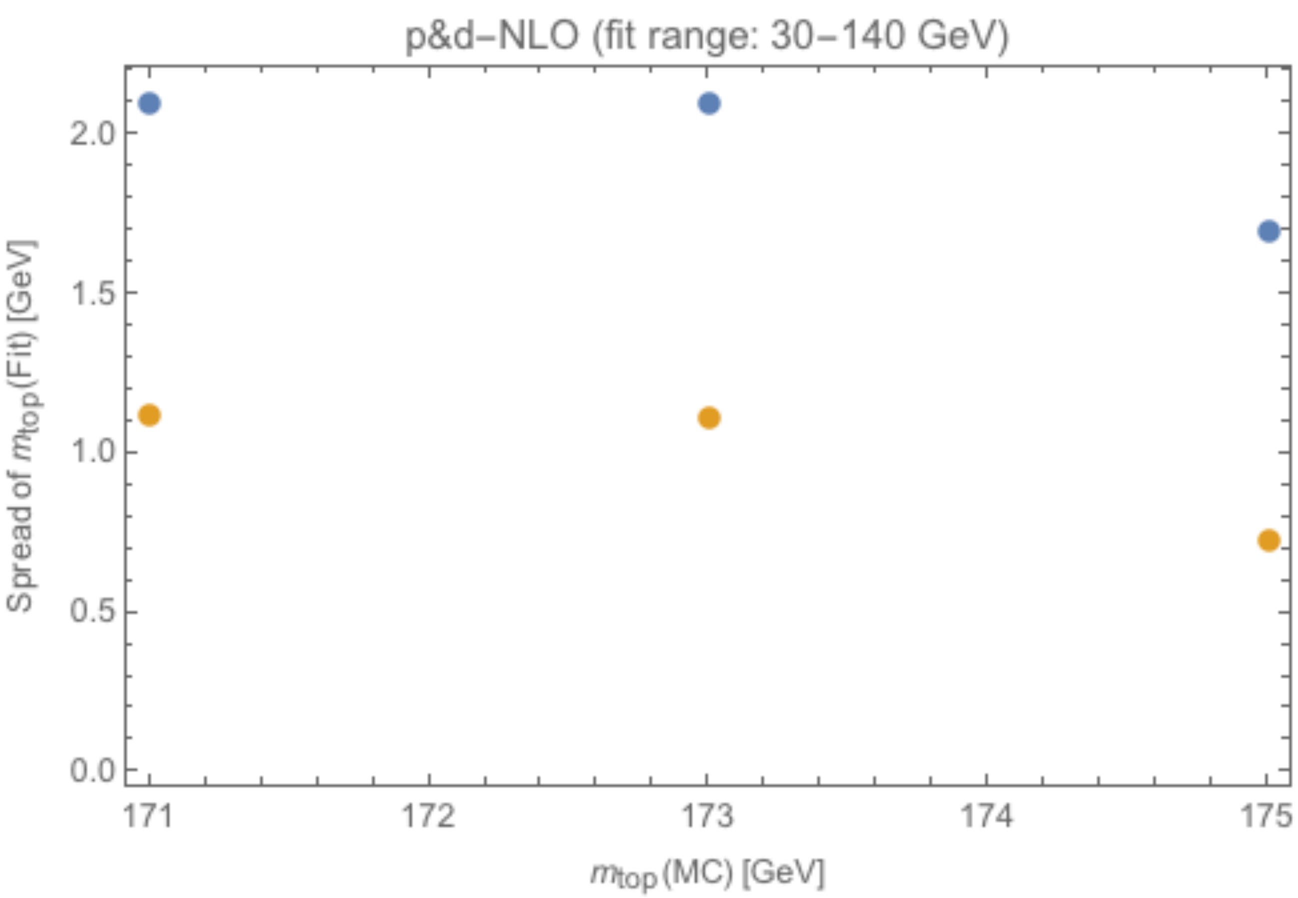
MSTW08



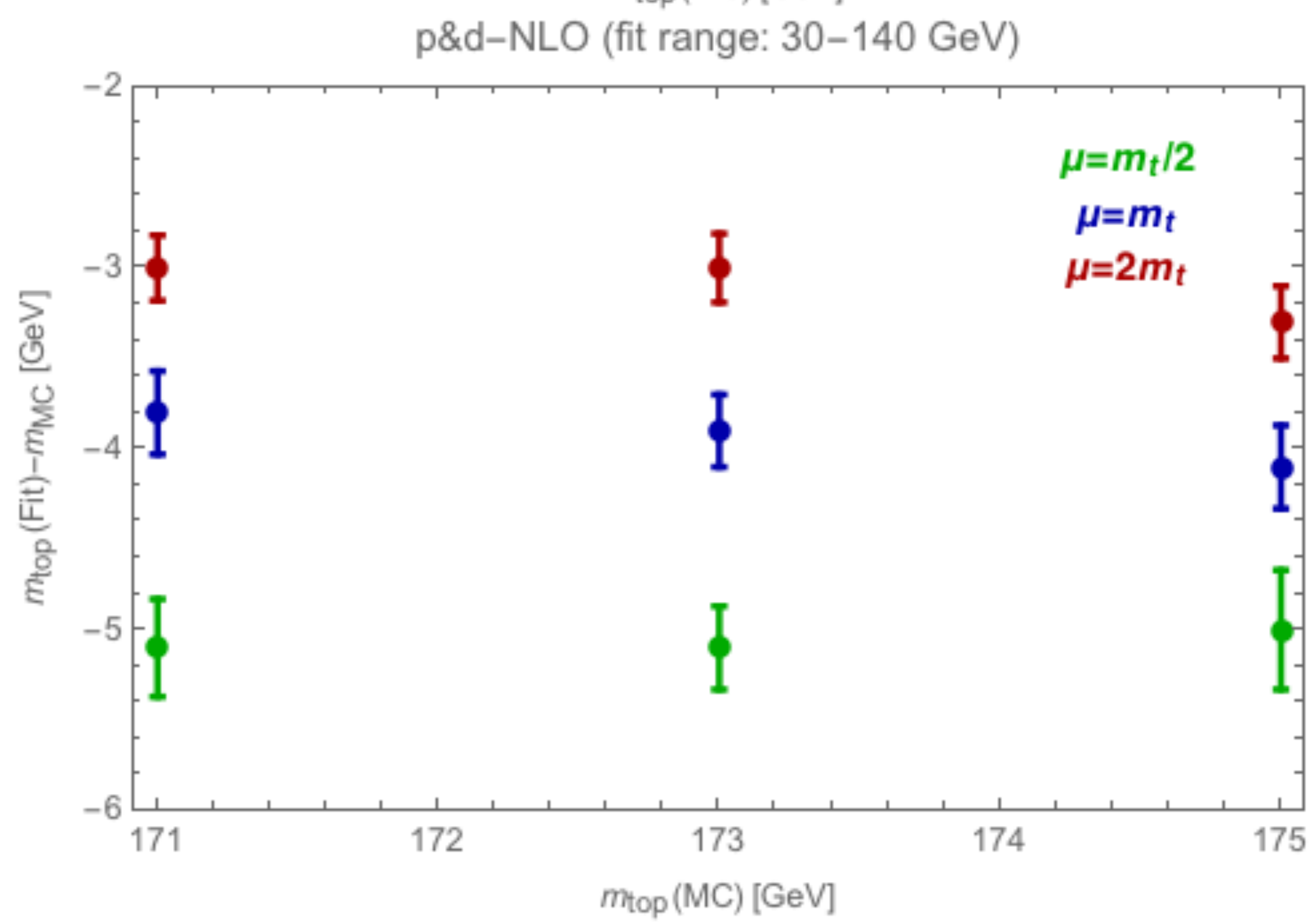
p&d−NLO (fit range: 30−140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
m_top (Fit) [GeV]
m_top (MC) [GeV]
165
170
175
180



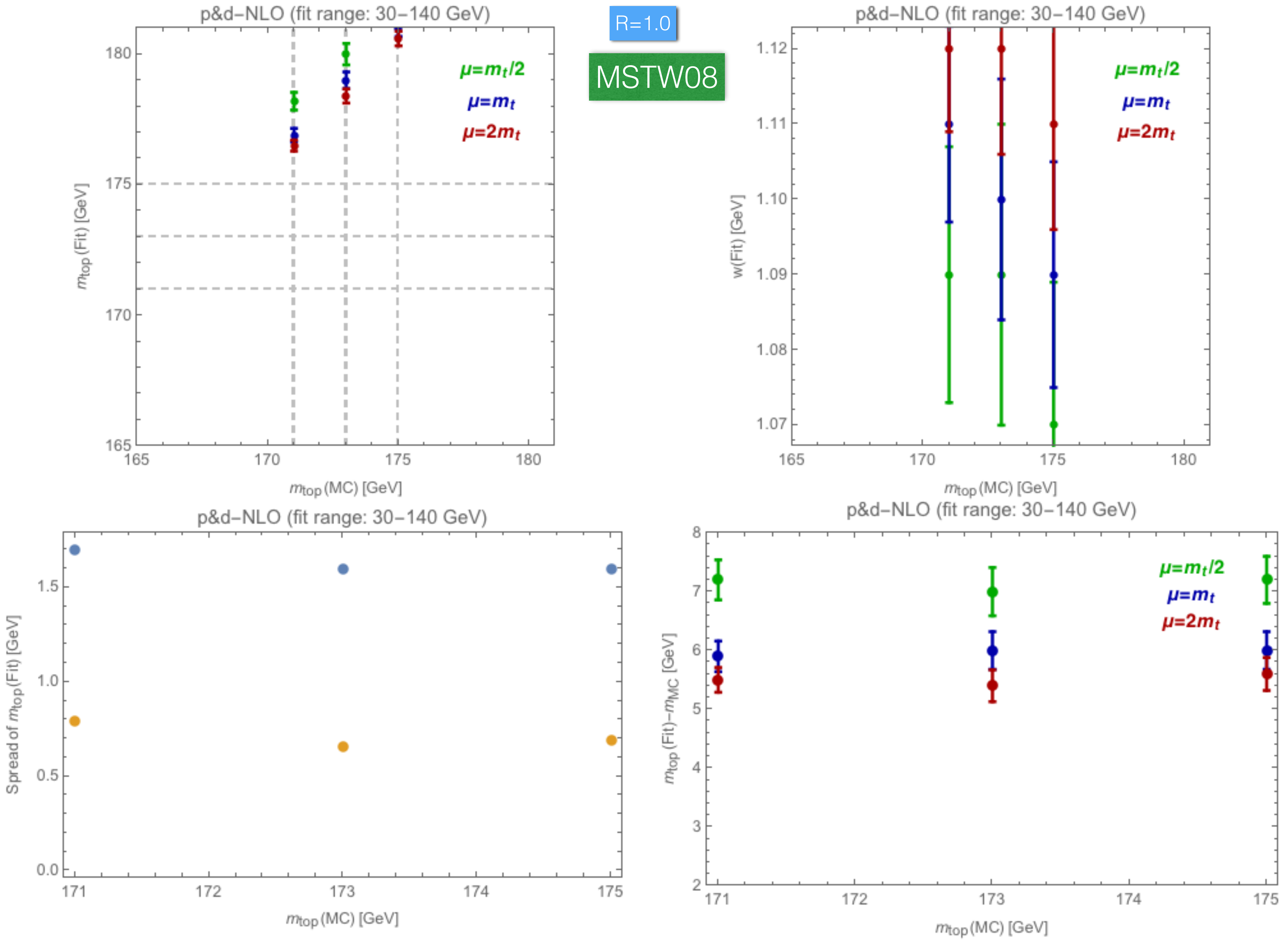
p&d−NLO (fit range: 30−140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
w(Fit) [GeV]
m_top (MC) [GeV]
1.01
1.02
1.03
1.04
1.05
1.06
1.07
165
170
175
180



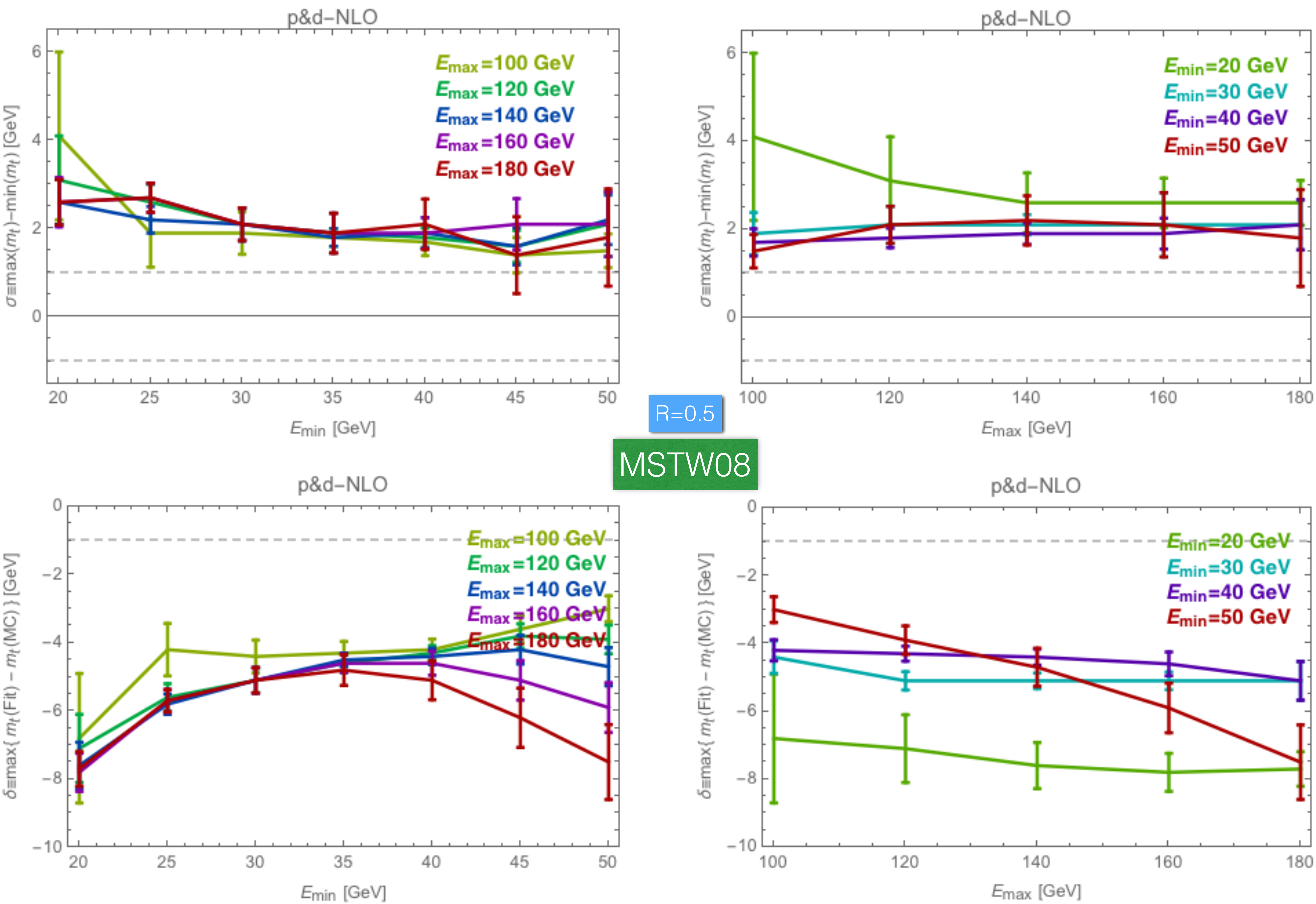
p&d−NLO (fit range: 30−140 GeV)
Spread of m_top (Fit) [GeV]
m_top (MC) [GeV]
0.0
0.5
1.0
1.5
2.0
171
172
173
174
175



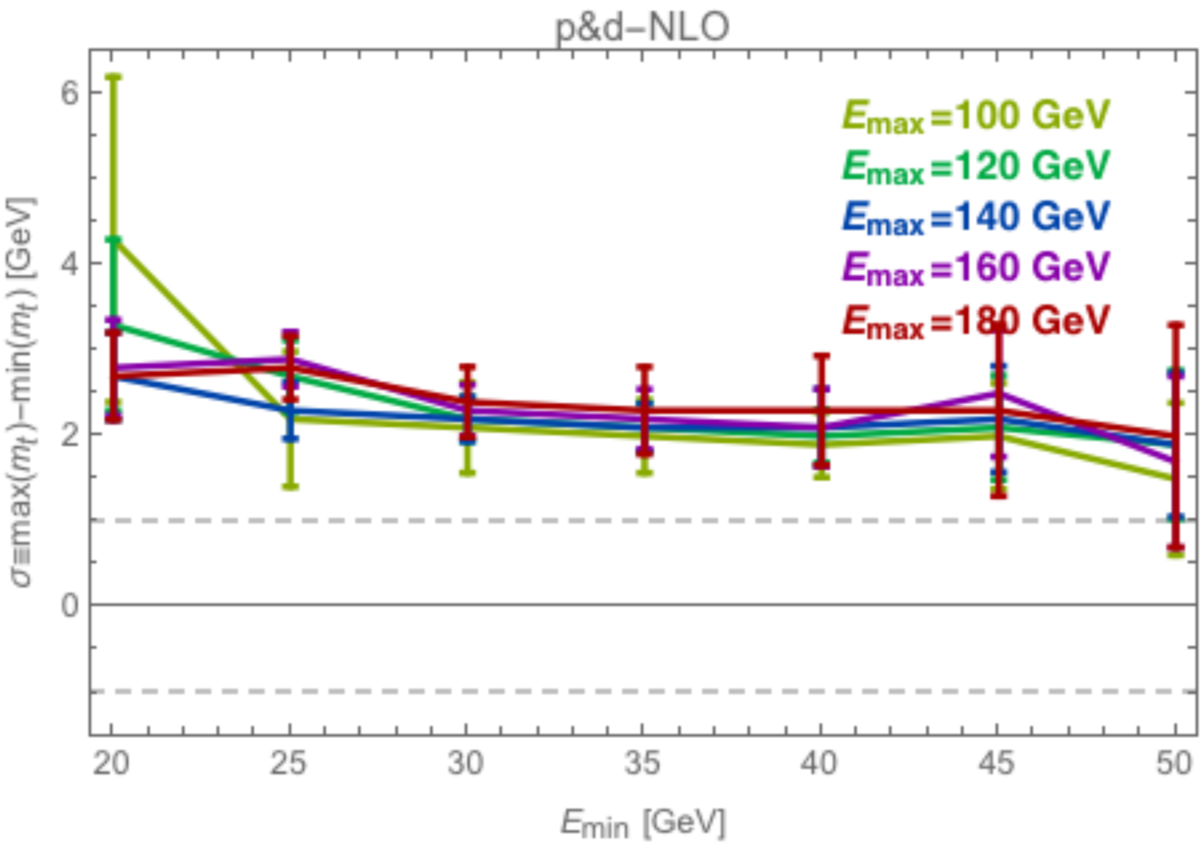
p&d−NLO (fit range: 30−140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
m_top (Fit)−m_MC [GeV]
m_top (MC) [GeV]
−2
−3
−4
−5
−6
171
172
173
174
175

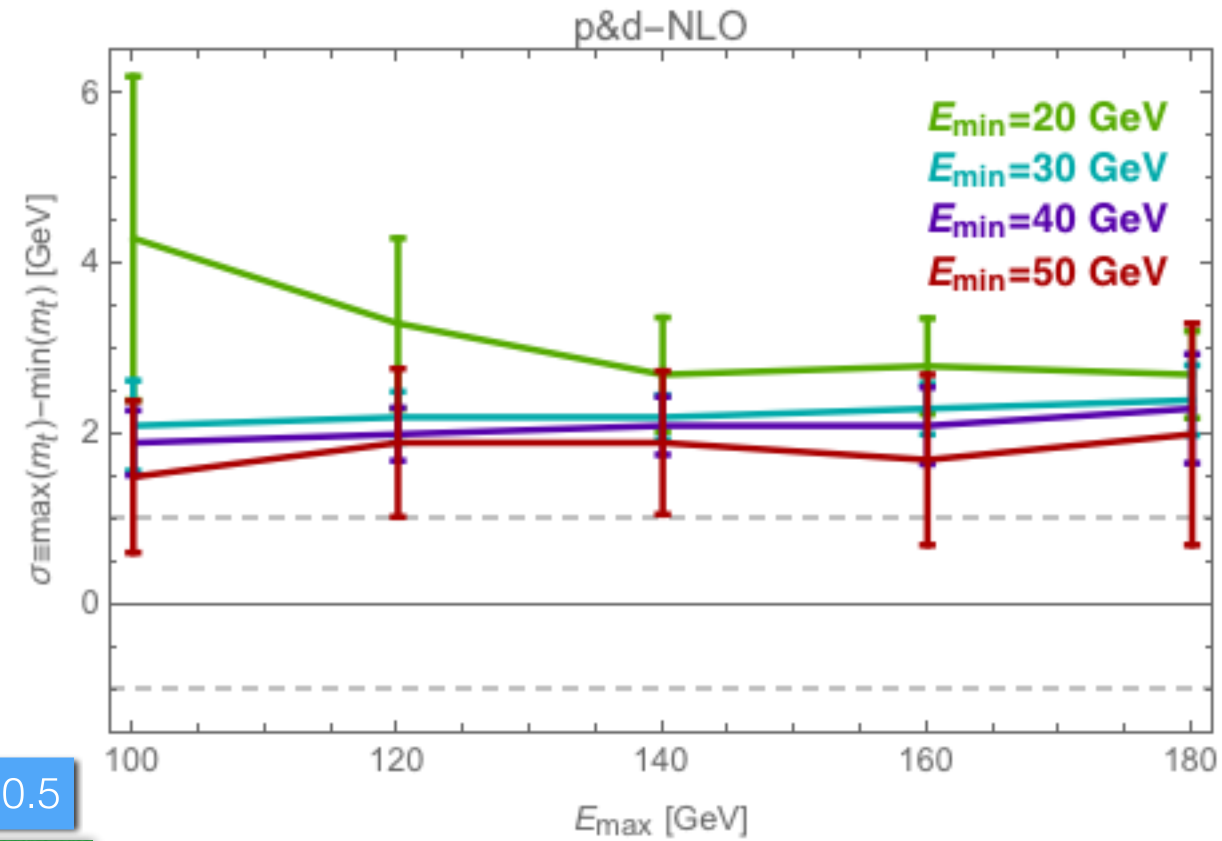

R=1.0
MSTW08
p&d–NLO (fit range: 30–140 GeV)
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]
w(Fit) [GeV]
Spread of m_{top}(Fit) [GeV]
m_{top}(Fit)−m_{MC} [GeV]

Fit Variations p&d-NLO



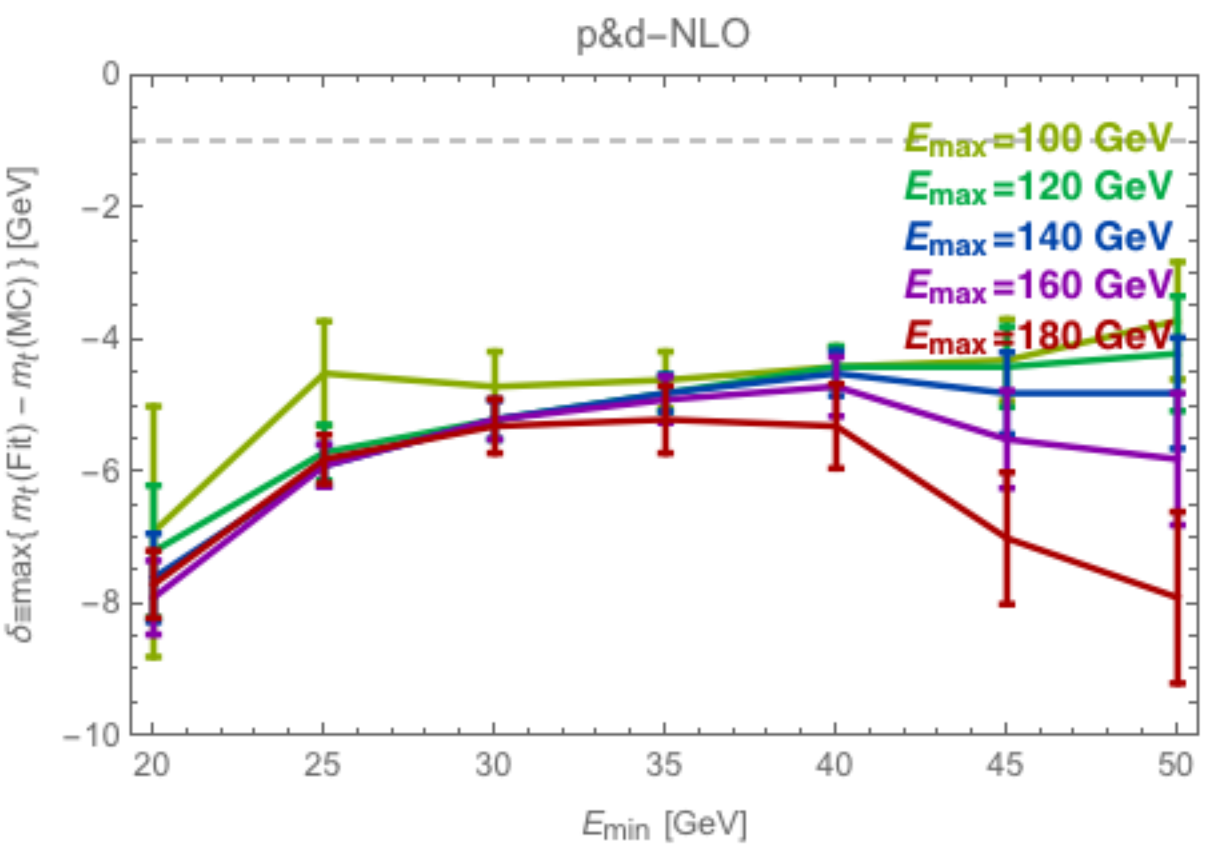
Fit Variations p&d-NLO

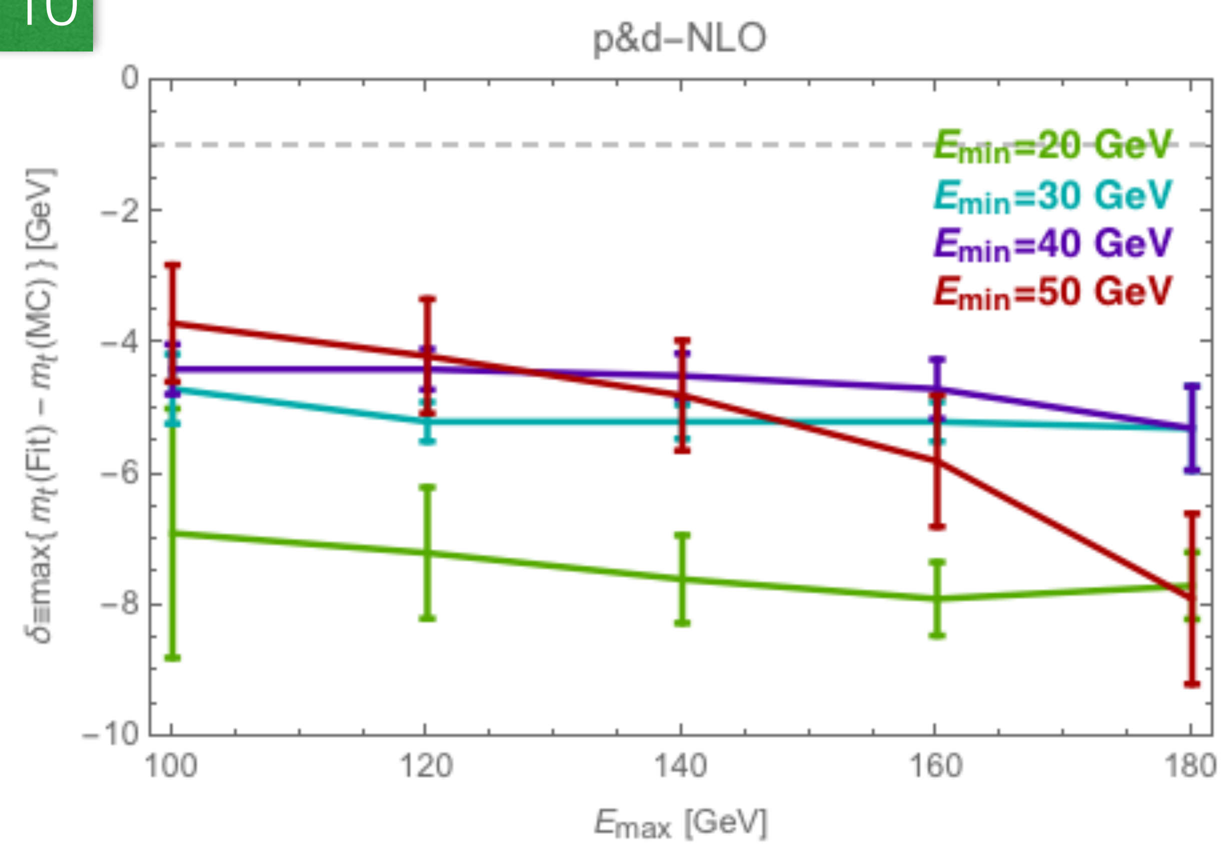




R=0.5

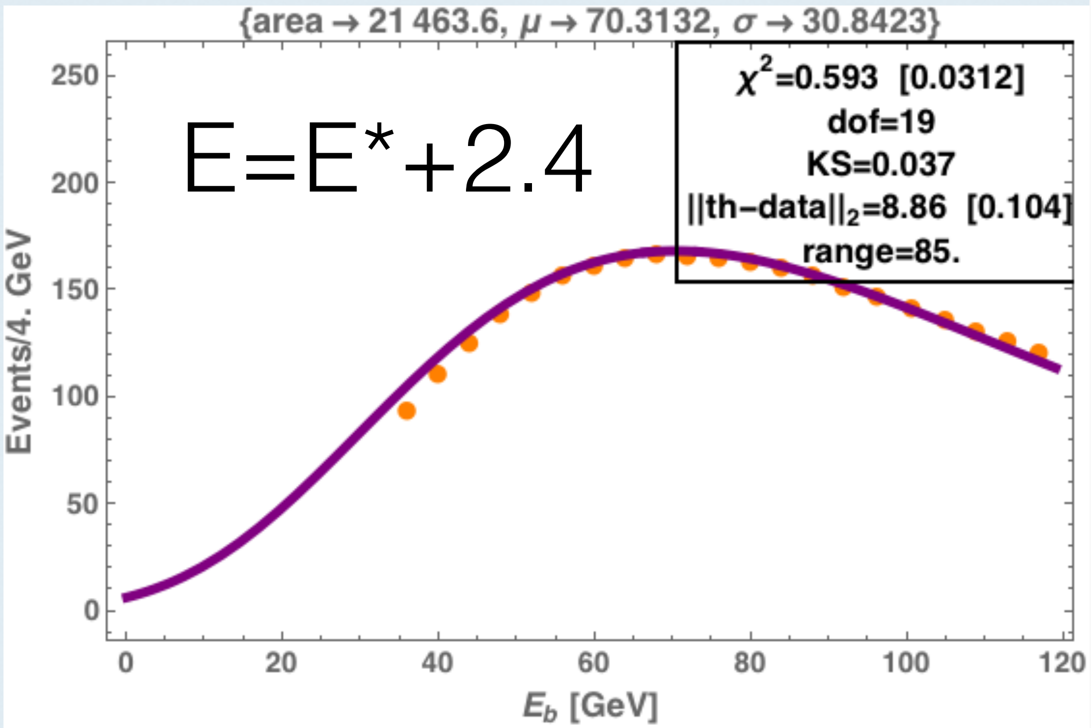
CT10



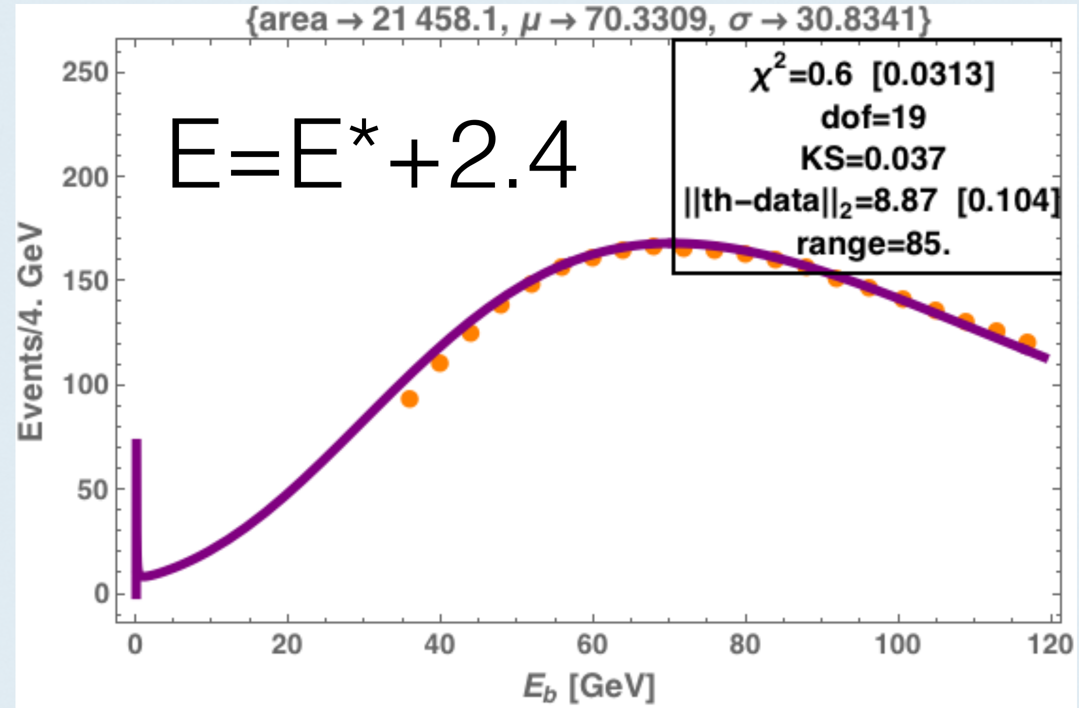


LO MCFM fixed μ=m_{top} (E=67.9 GeV)

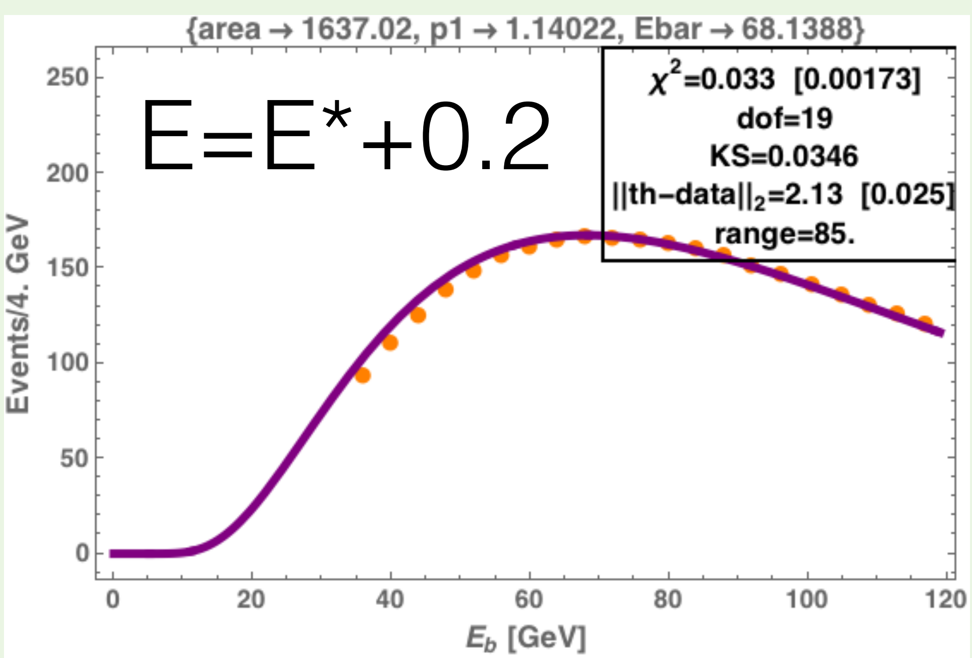
Moyal(x)



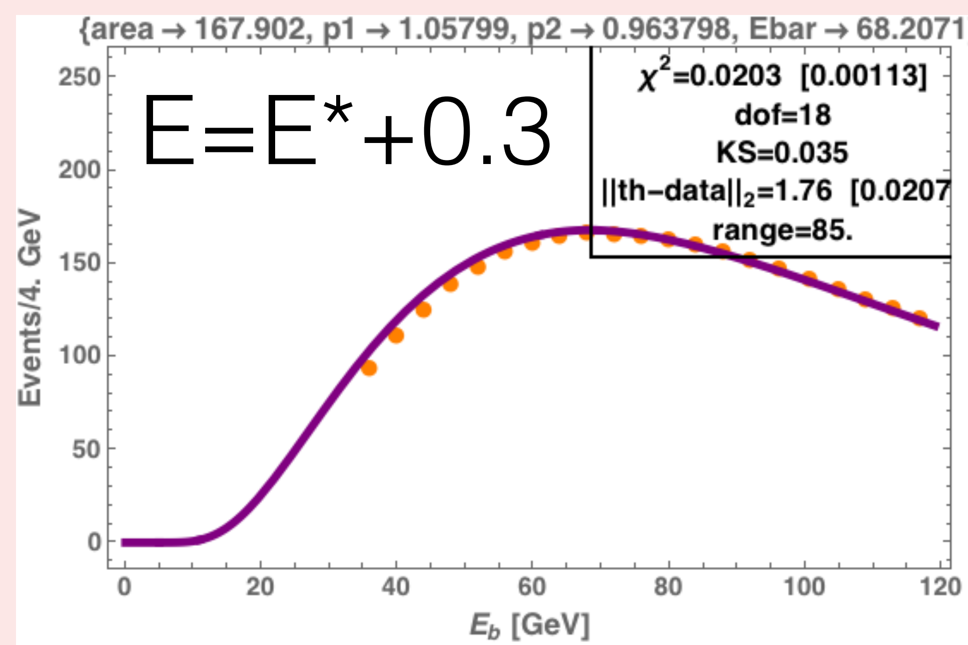
Moyal(1/x+x)



1par Exp(x+1/x)



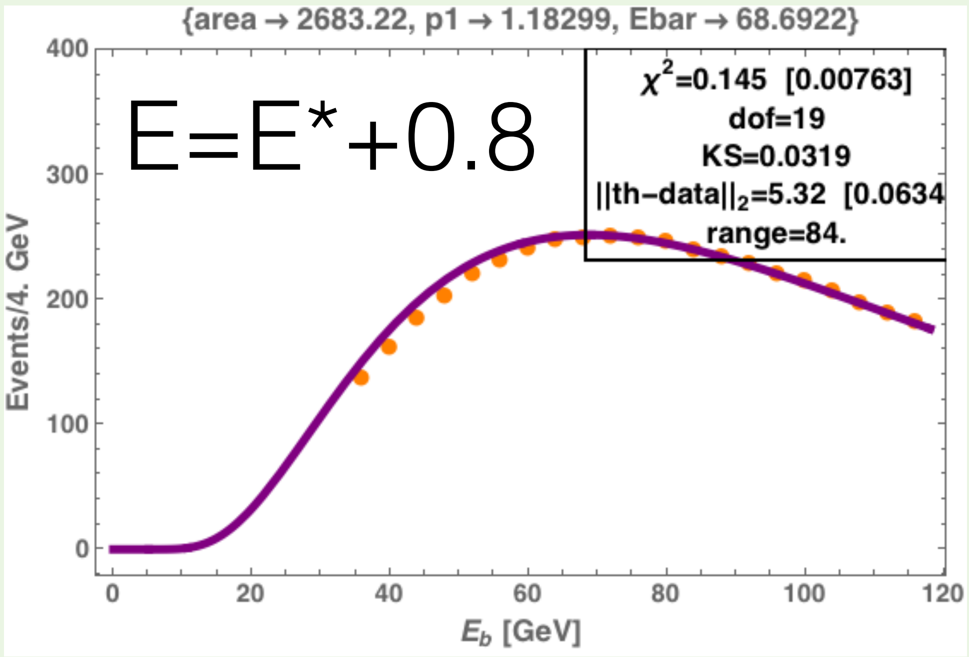
2pars Exp(x+1/x)



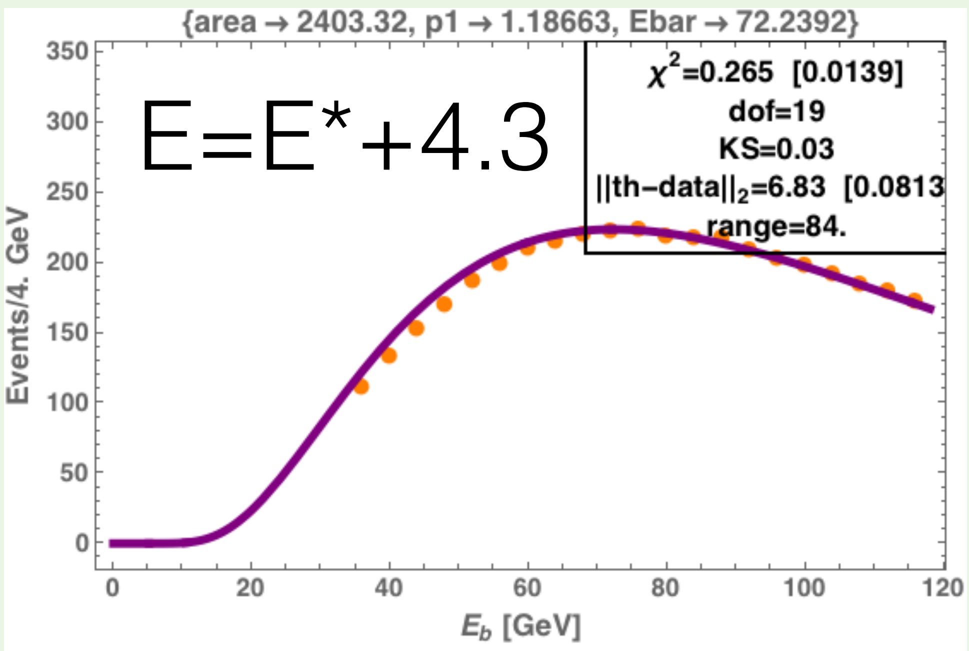
pNLO MCFM fixed $\mu = m_{top}$ (E=67.9 GeV)

1par Exp(x+1/x)

R=0.5

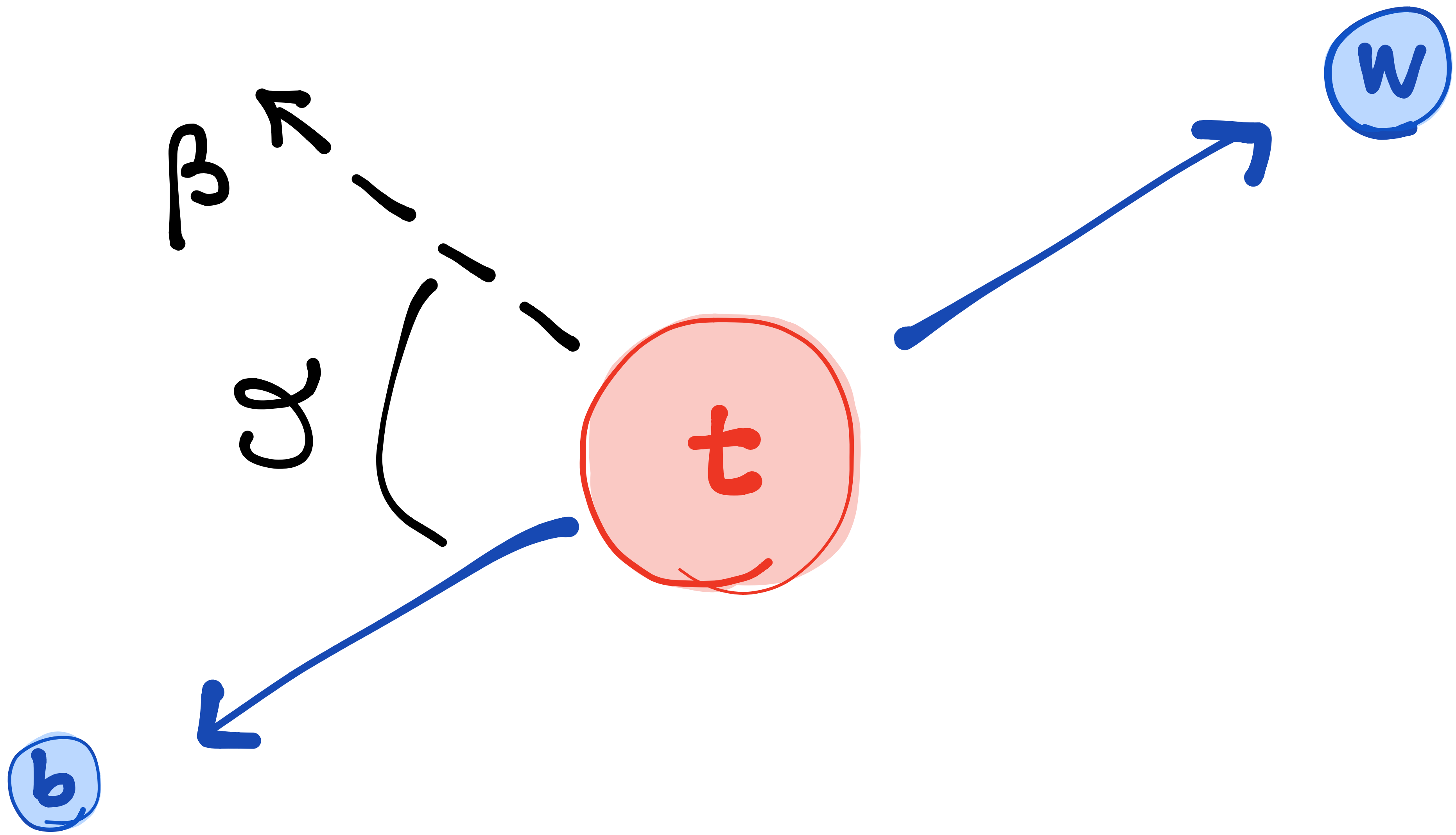


R=1.0



A simple, yet subtle, invariance of the two body decay

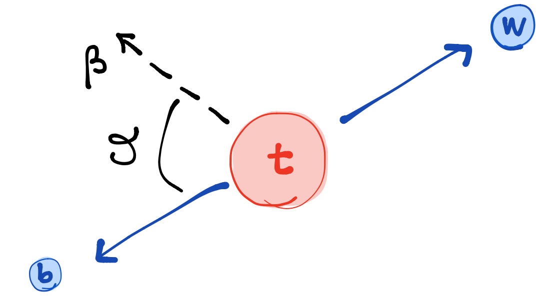
1209.0772 - Agashe, Franceschini and Kim



$$E_{lab,b} = E_b^* \gamma + p_b^* \gamma \beta \cos \vartheta$$

Event-by-event we cannot tell anything

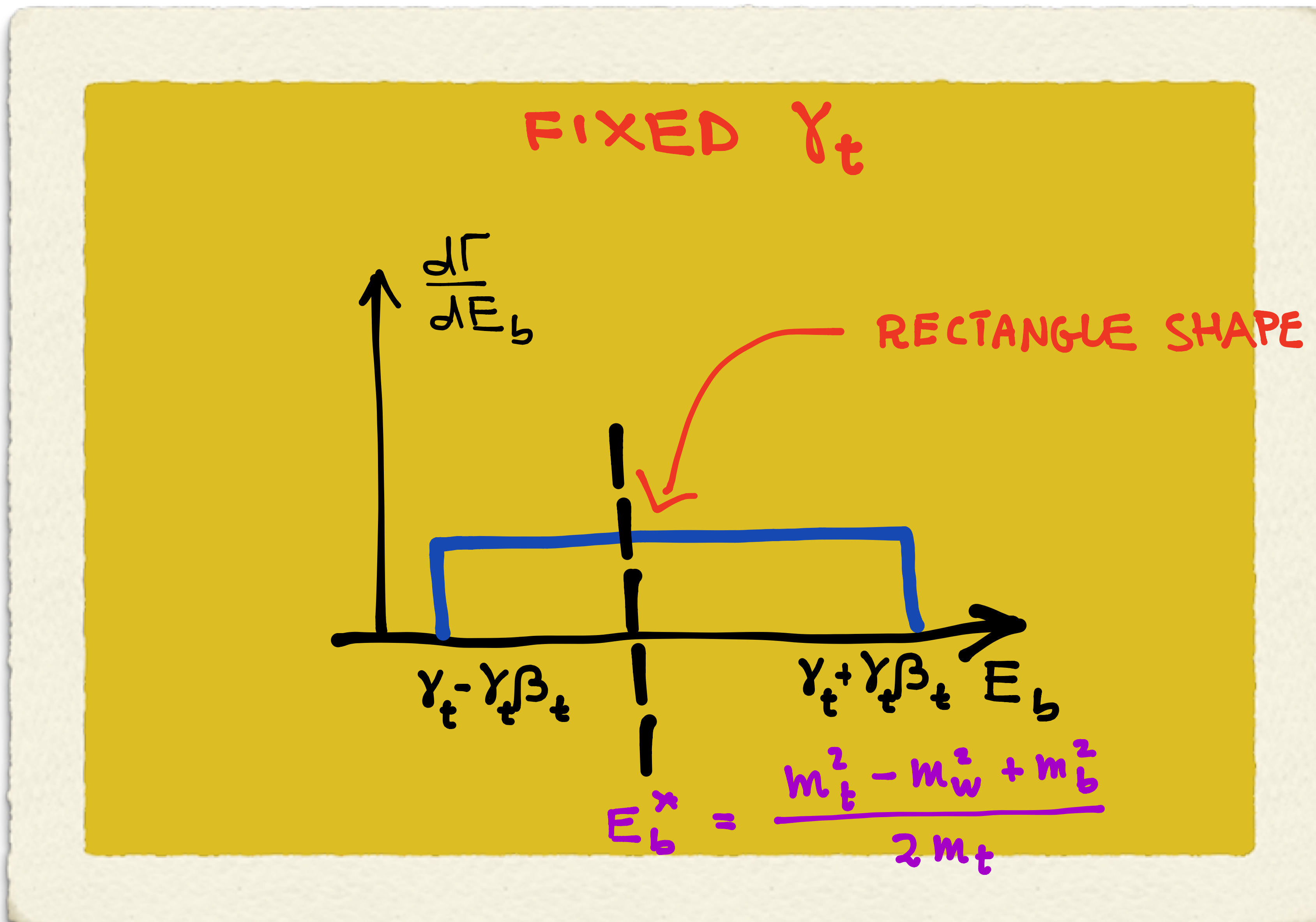
Fixed top boost decay



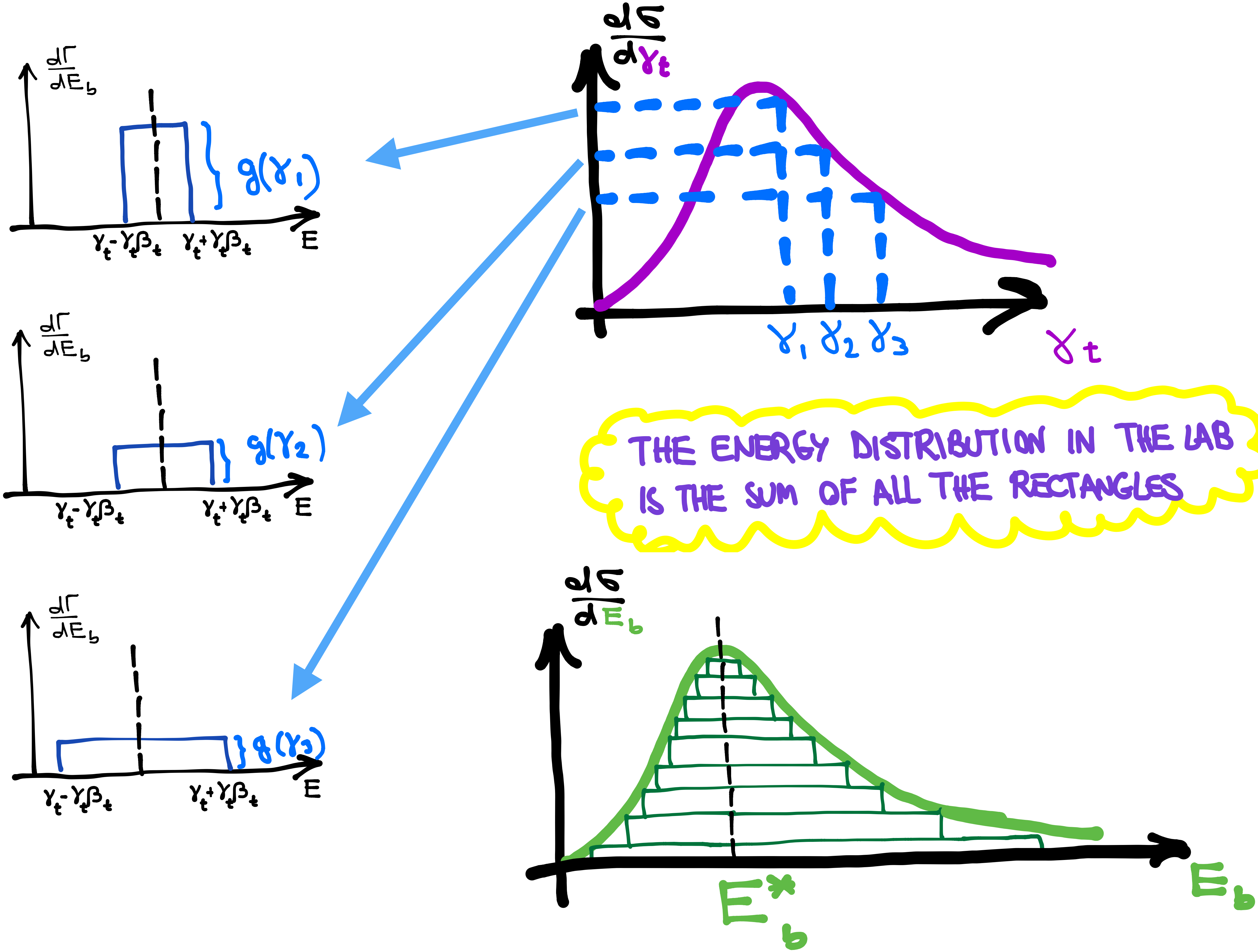
Massless b-quark (for now)

$$E_{lab,b} = E_b^*\left(\gamma + \gamma\beta\cos\vartheta\right)$$

unpolarized top sample ⟶ cosθ is flat

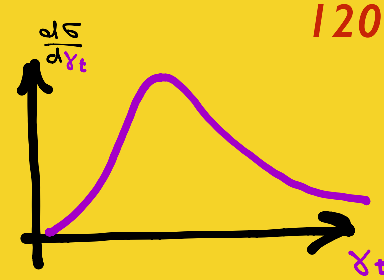


Summing over the top boosts

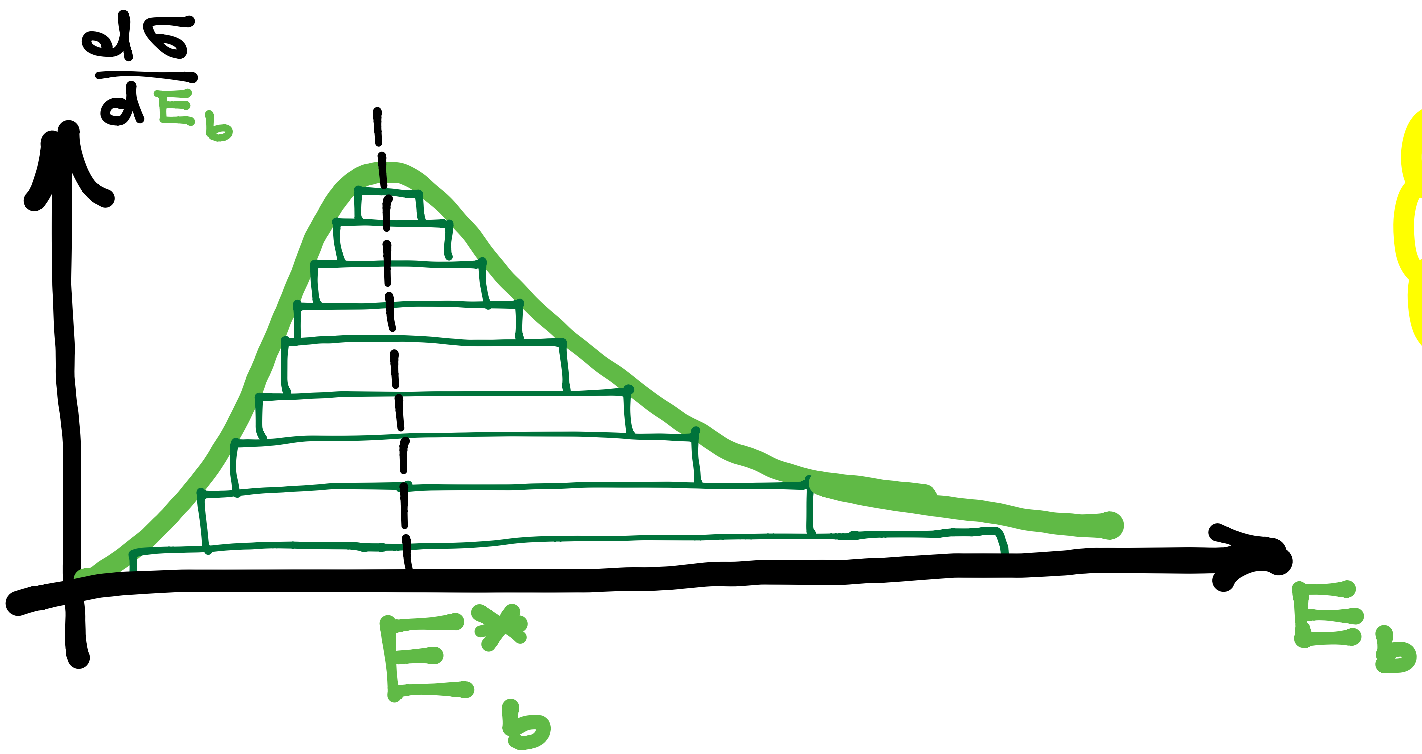


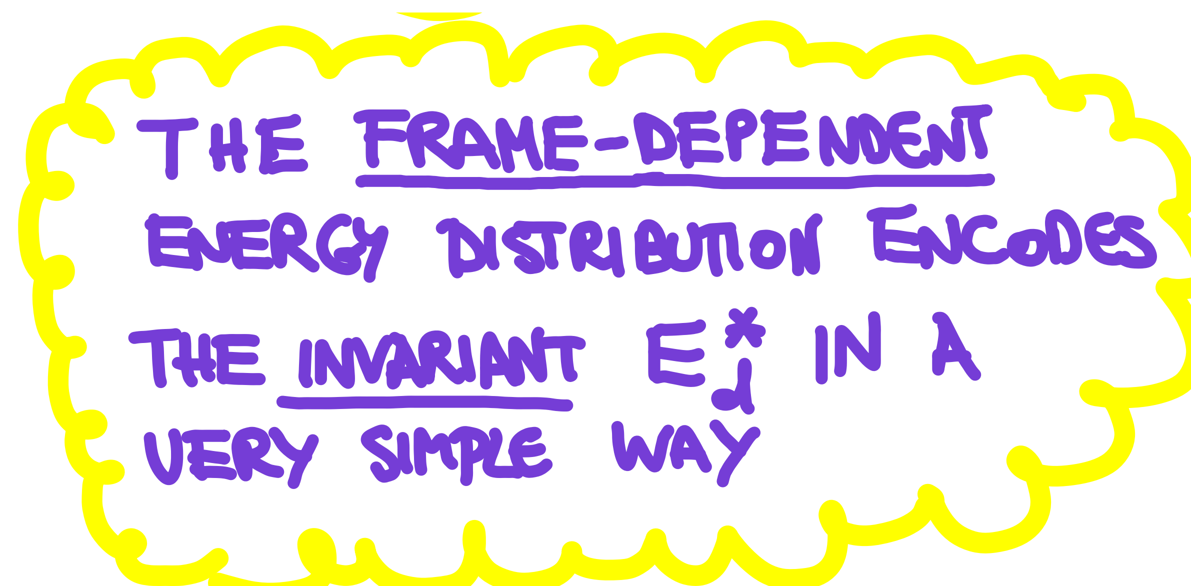
Lab-frame energy distribution

1209.0772 - Agashe, Franceschini and Kim
also Stecker 1971

for any top boost distribution  **the peak:**

- is the same as in the rest frame
- encodes invariant $E_b^* = \frac{m_t^2 - m_W^2 + m_b^2}{2 m_t}$





There is no difference when the b-mass is taken into account provided $\gamma_{top} < 500$

On mass measurements

- Lorentz invariants
- resonance reconstruction

Ideal mass measurements

$$(p_{\mu_1}+p_{\mu_2})^2 \rightarrow m_Z^2$$

Lorentz invariant

insensitive to:

- Parton Distribution Functions
- Production Mode (qq or gg, SM or BSM, ISR, …)

beware of radiation for precision measurement

Less ideal mass measurements

One particle is just lost

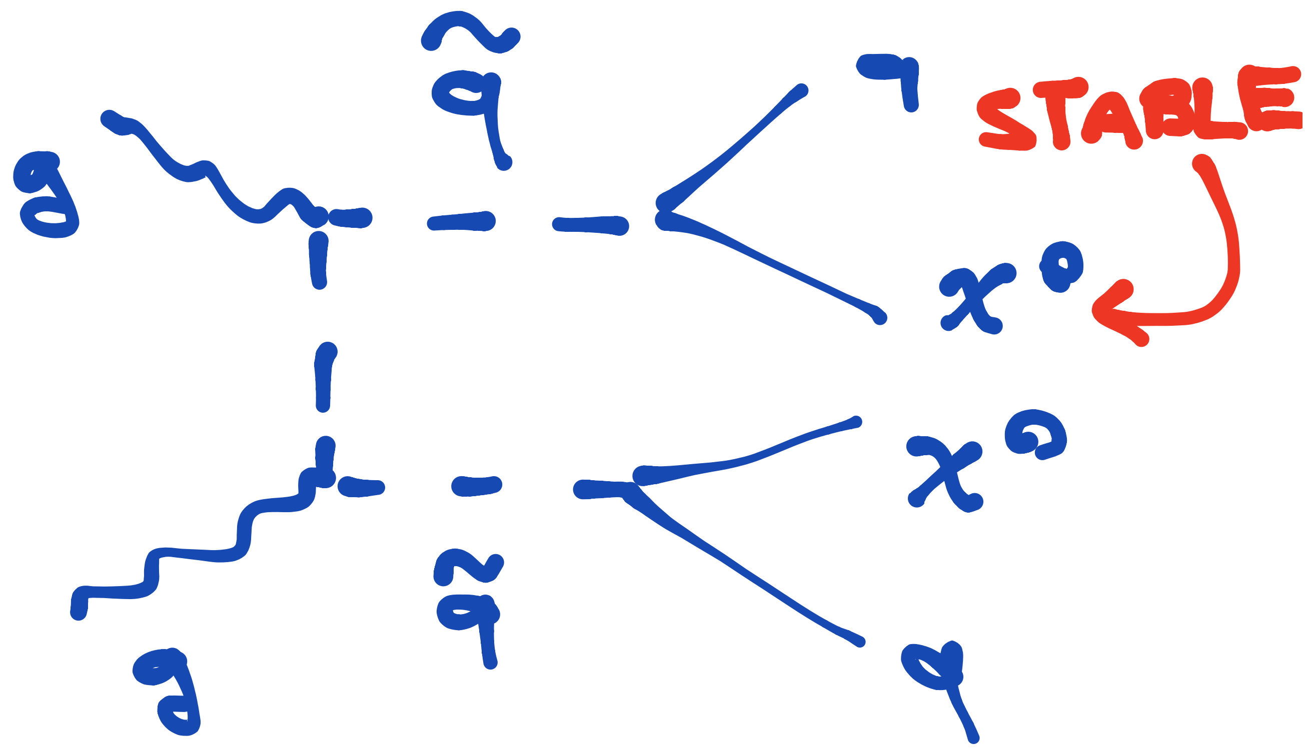
Need to come up with a trick

for example:

- Transverse Mass (use mET)
- pT (nuisances are back: qq or gg, SM or BSM, ISR, …)

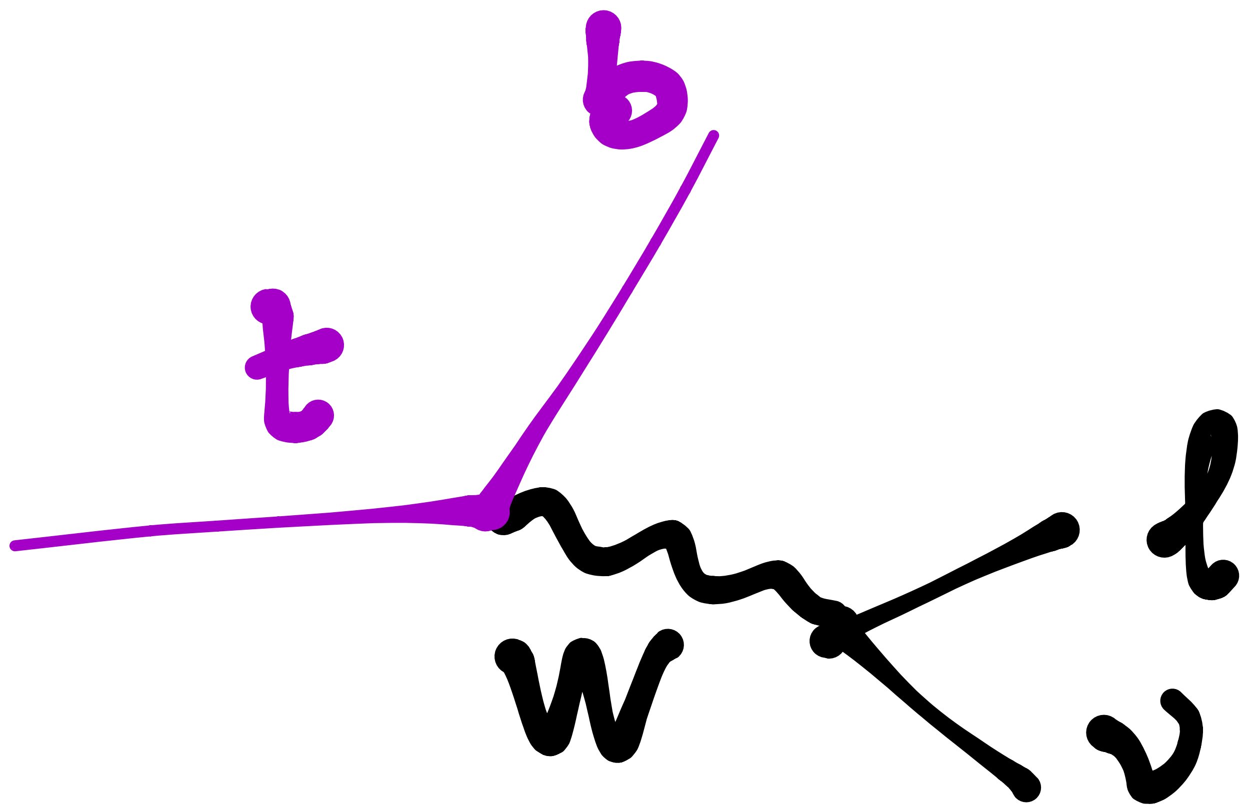
… and it can get worse

any BSM with some sort of Matter Parity (e.g. RPC SUSY)



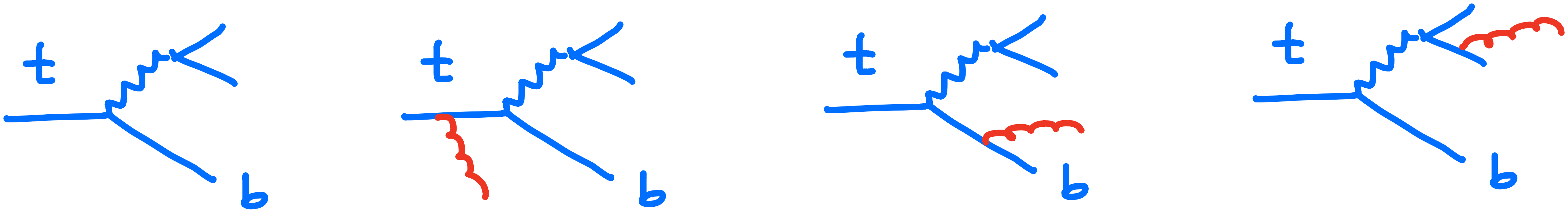
can we make a mass measurement without ever mentioning the unobservable particle χ?

“useful” top is semi-invisible

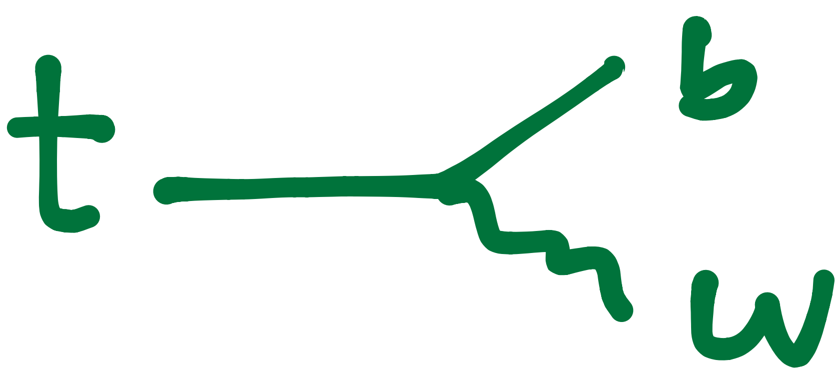


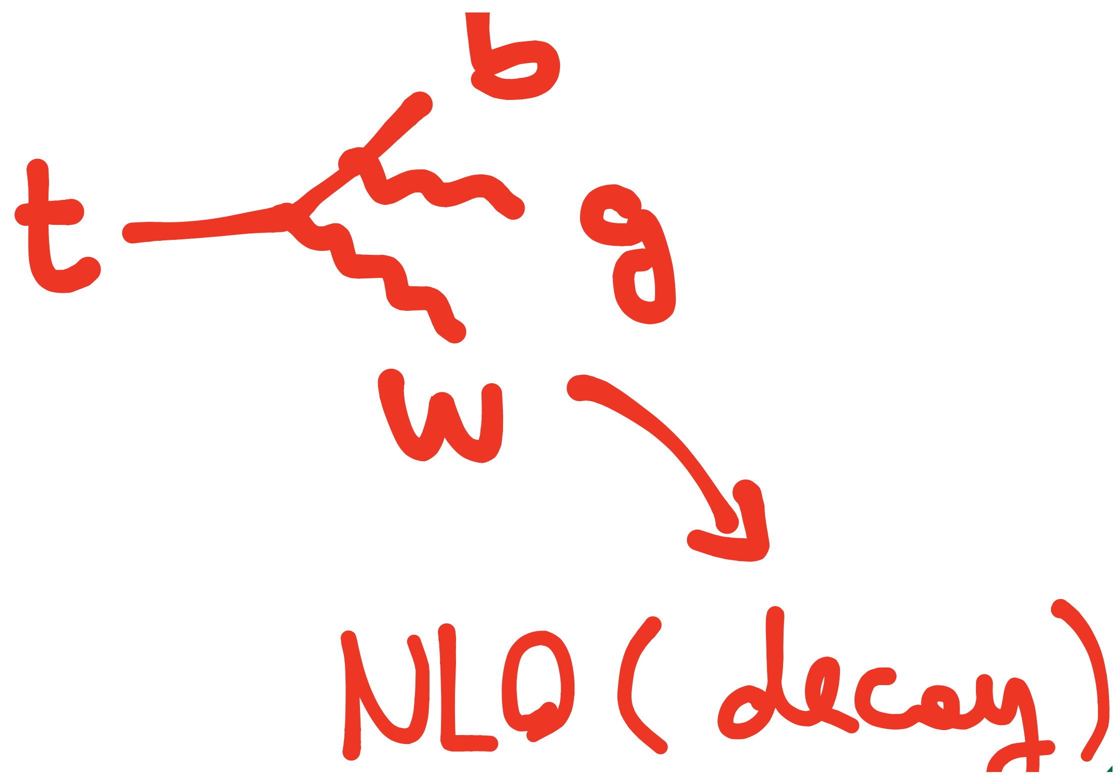
can we make a mass measurement without ever mentioning the unobservable particle ***W*** ?

To reconstruct or not to reconstruct?



top quark reconstruction is entangled with *some* picture of the kinematics (fixed order?)

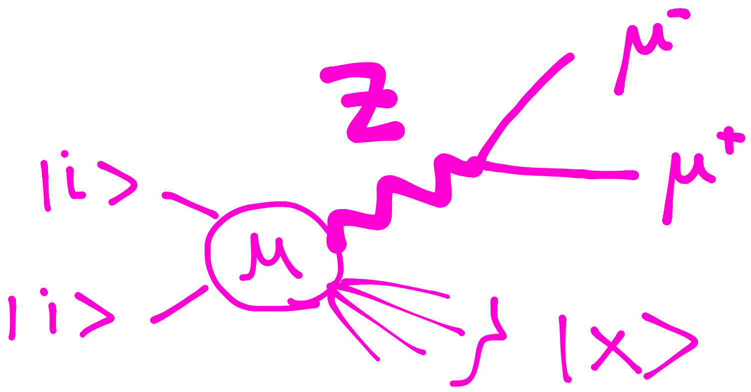


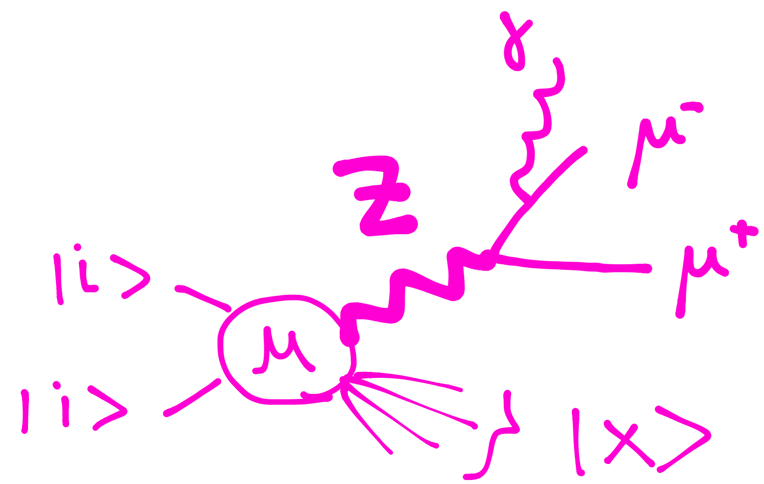


NLO+PS in 1412.1828

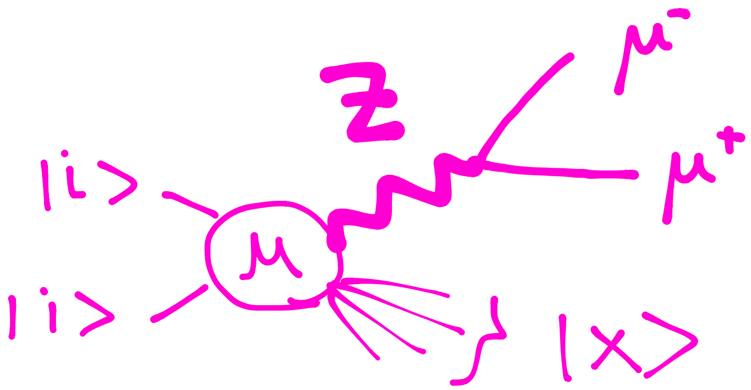
To reconstruct or not to reconstruct?

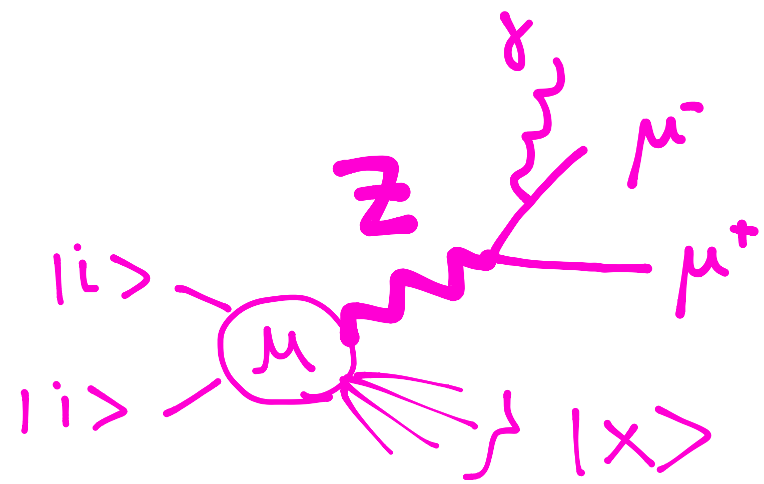
To reconstruct or not to reconstruct?

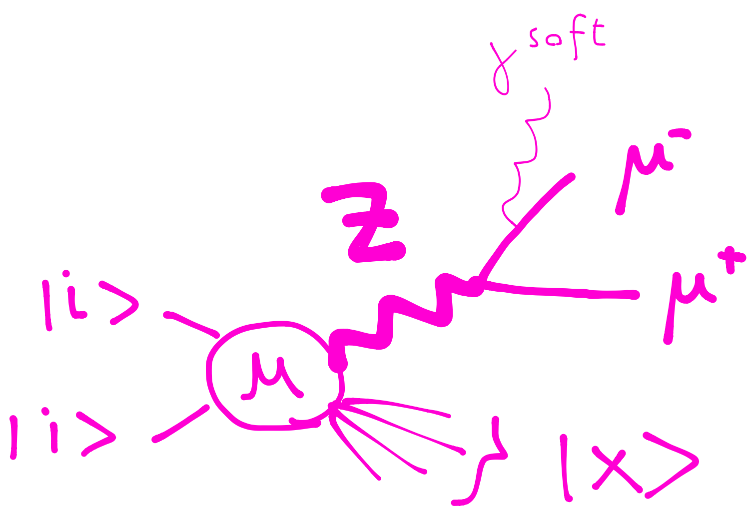


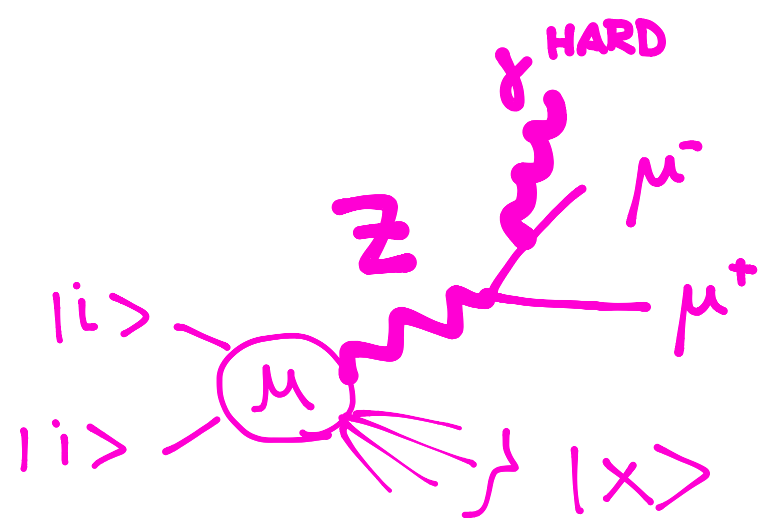


To reconstruct or not to reconstruct?

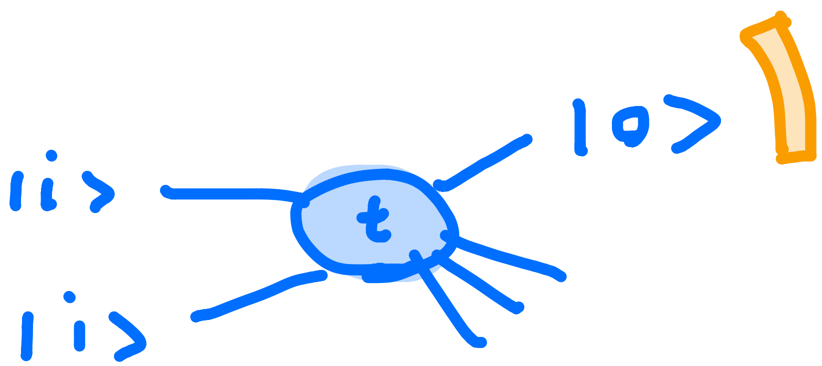


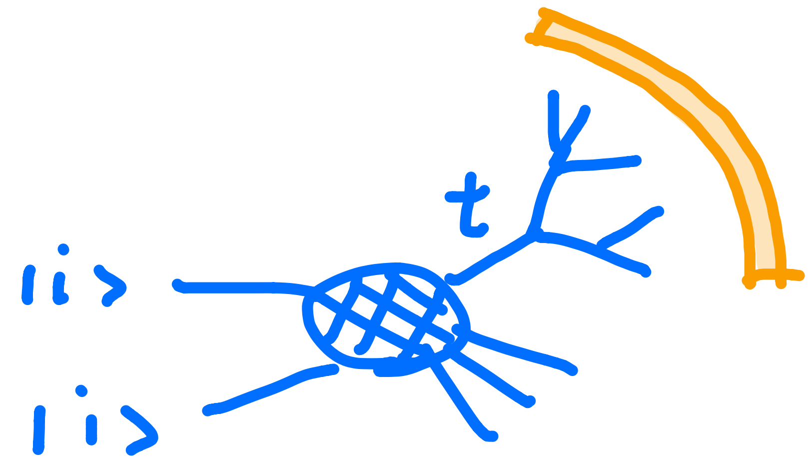






To reconstruct or not to reconstruct?





does (not) distinguish where
the final state came from (t, t*, bW, bWg, bqqg)

need (not) to define the top

might (not) depend on the production mechanism

…