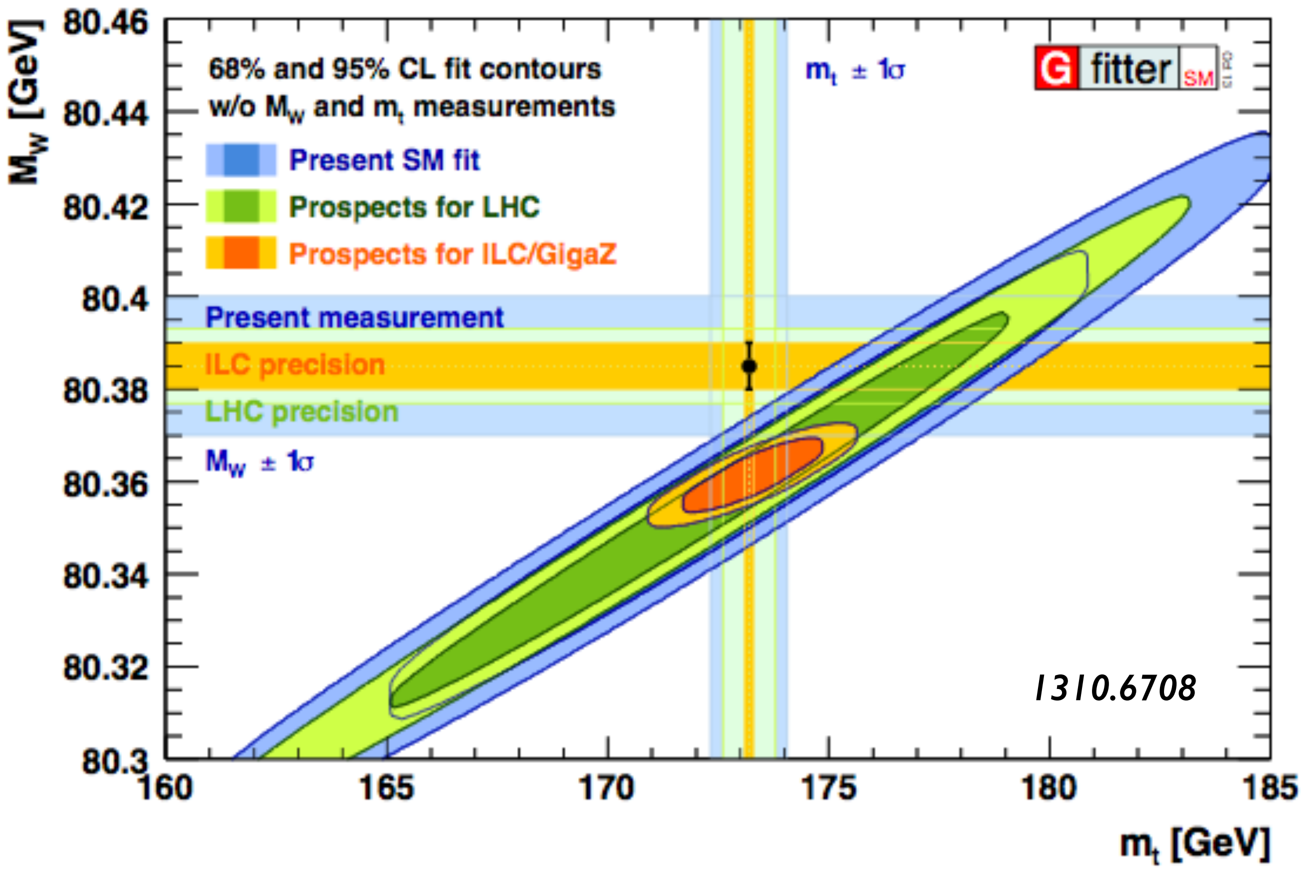
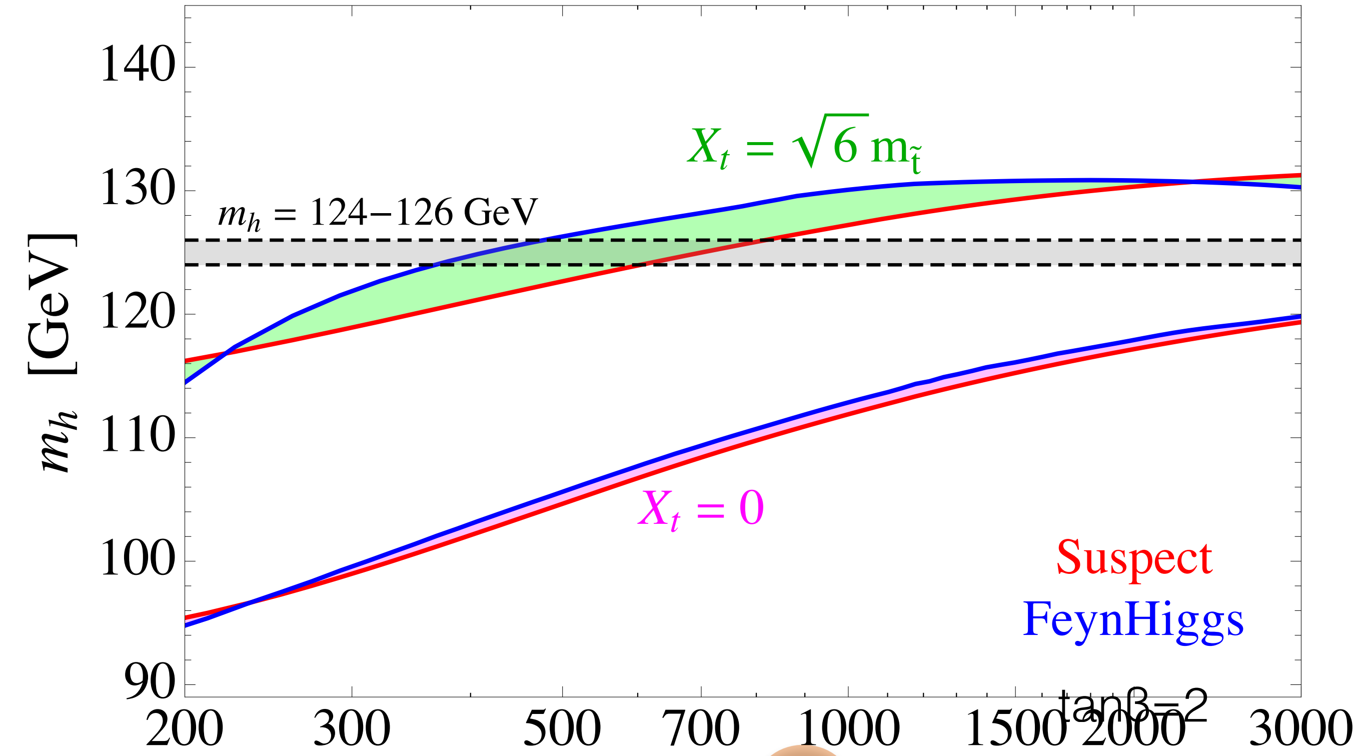
Energy peaks and future progress on the top quark mass measurement

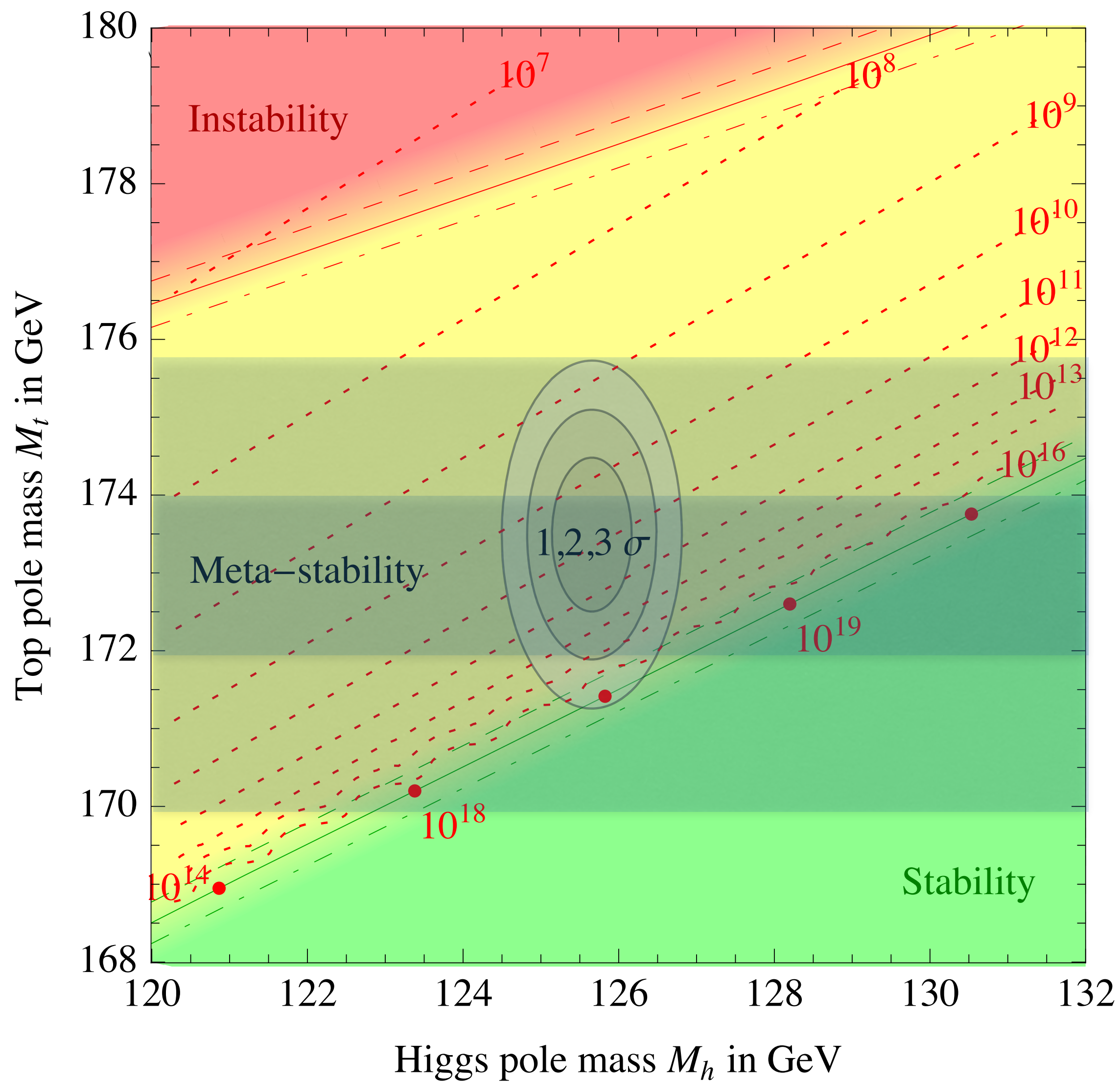
Roberto Franceschini
December 12th

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

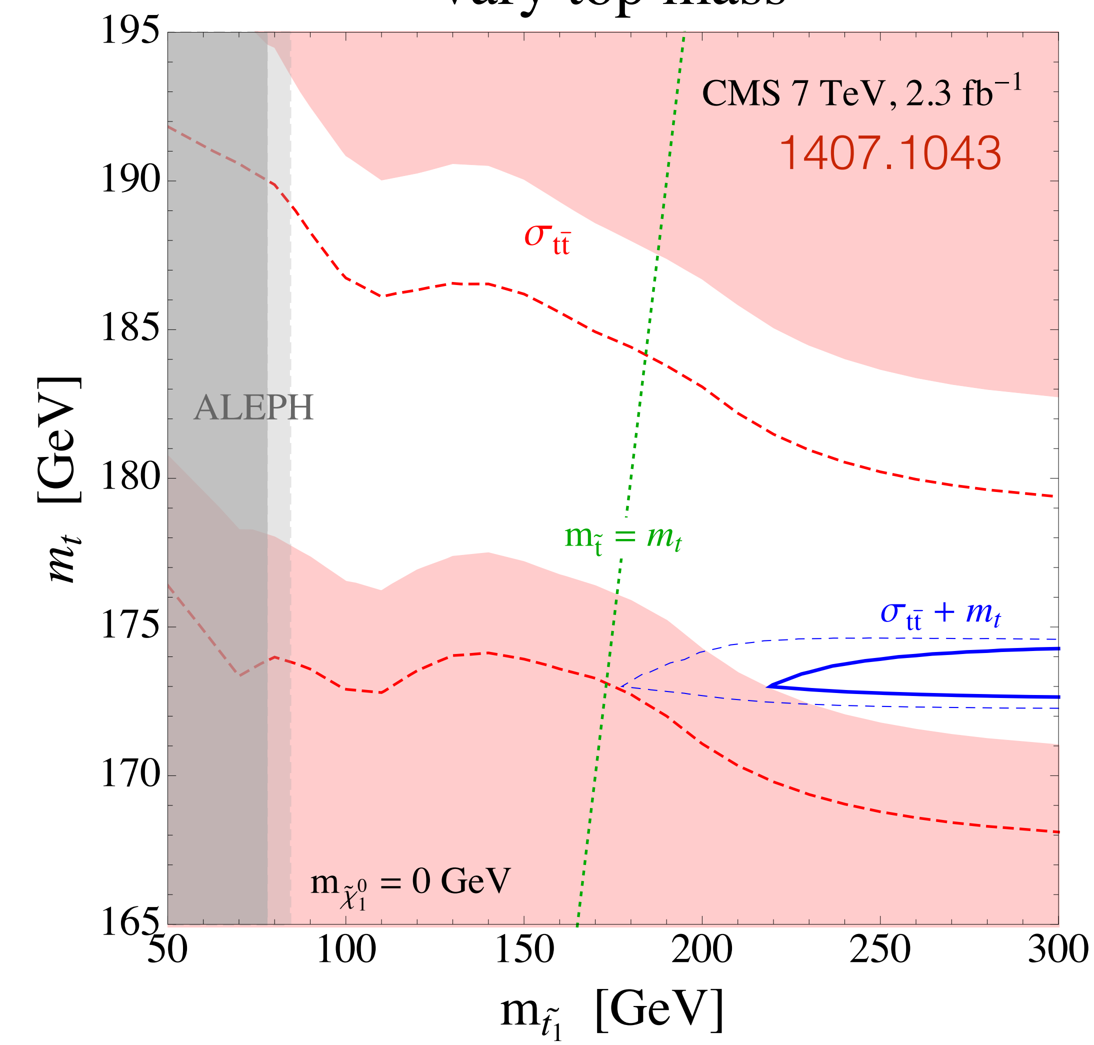




$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$



vary top mass



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

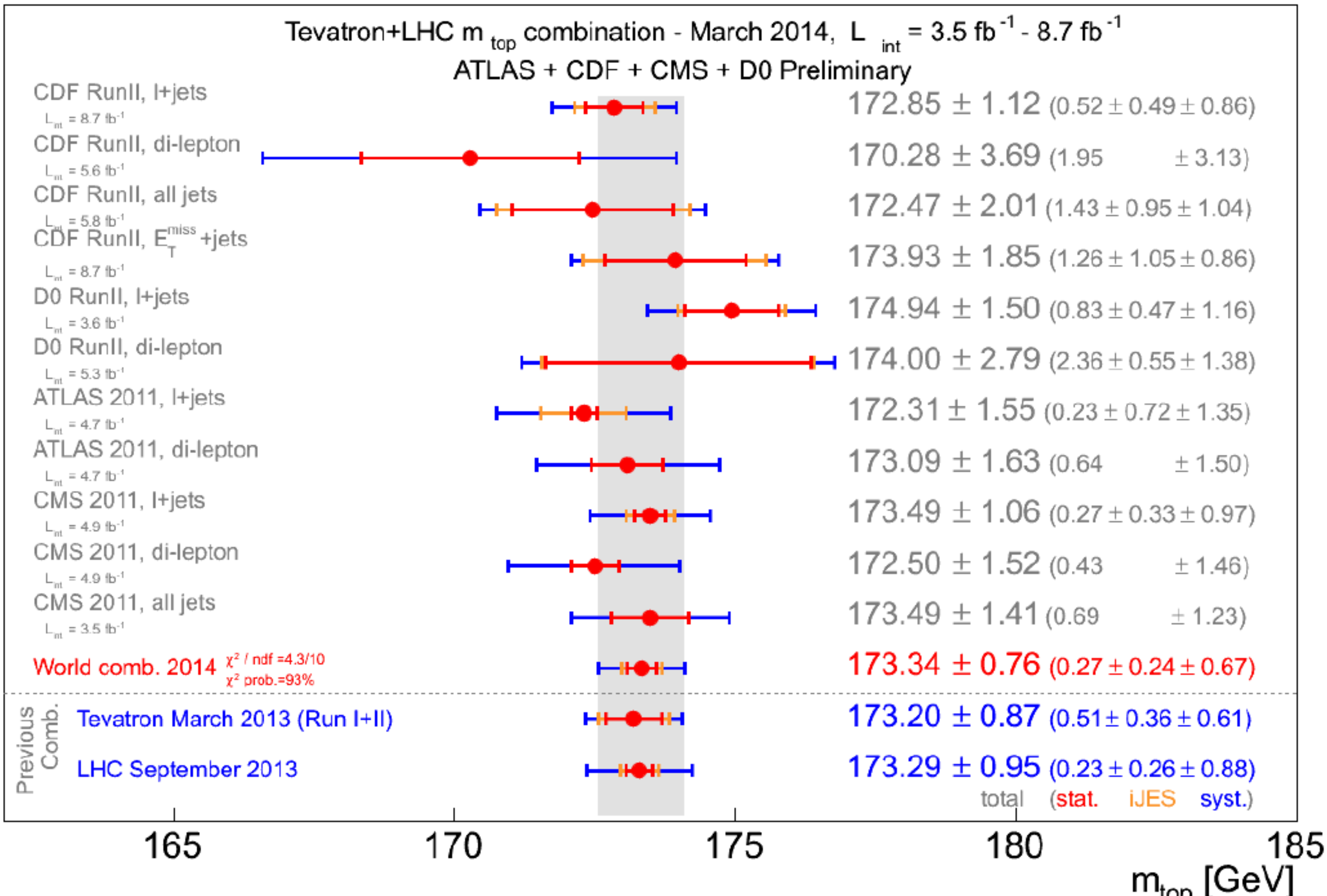
Experiment	$t\bar{t}$ final state	$\mathcal{L}_{\rm int}$ [fb^{-1}]	$m_{\rm top}$ ± (stat.) ± (syst.) [GeV]	Total uncertainty on $m_{\rm top}$ [GeV] ([%])		Reference
CDF	l+jets	8.7	→ 172.85 ± 0.52 ± 0.99 ←	1.12	(0.65)	[8]
	dilepton	5.6	170.28 ± 1.95 ± 3.13	3.69	(2.17)	[9]
	all jets	5.8	172.47 ± 1.43 ± 1.41	2.01	(1.16)	[10]
	$E_{\rm T}^{\rm miss}$+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]

LHC-7 is on par with TeVatron

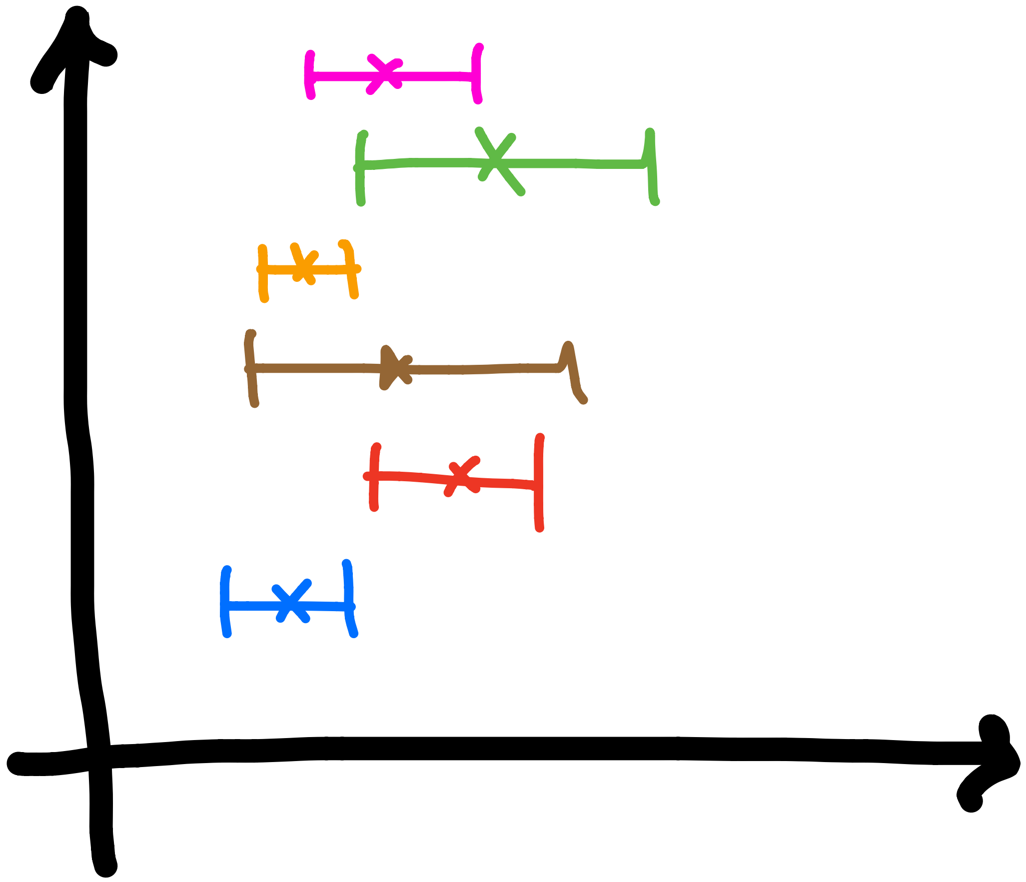
173.34± 0.27(stat) ± 0.71 (syst) GeV
dominated by systematics

l+jets
dilepton
all jets

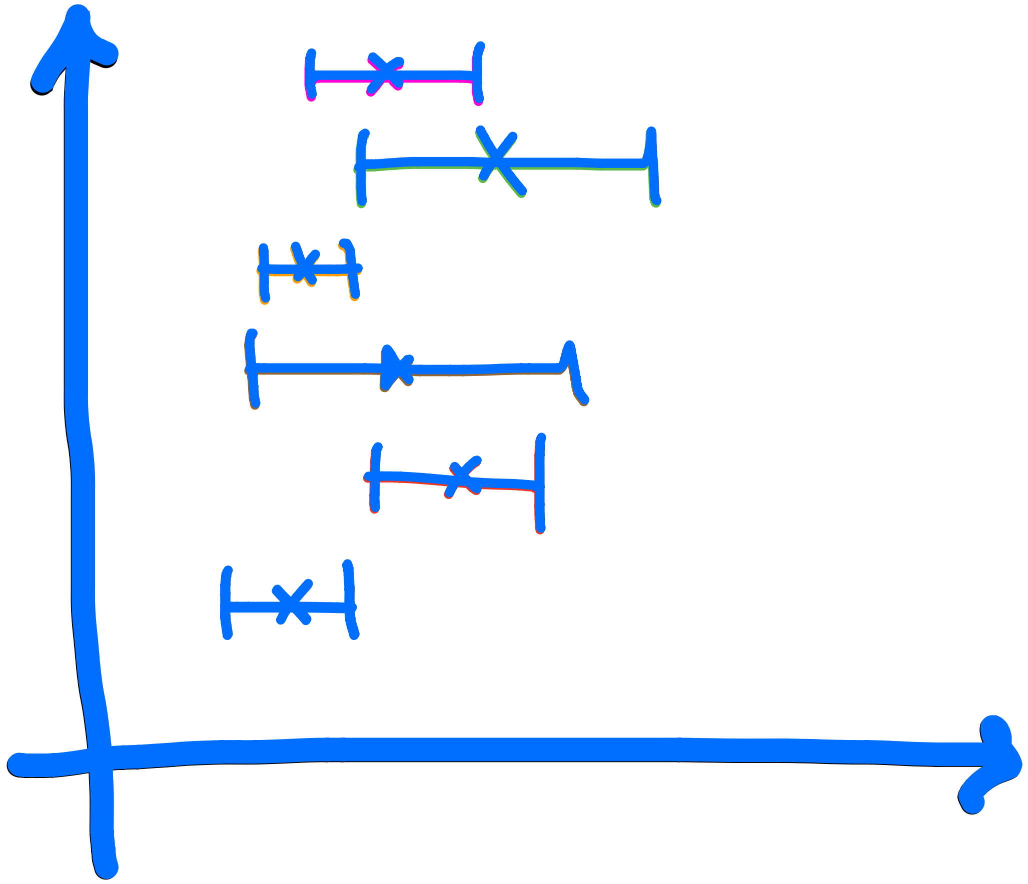
Many measurements



Many measurements?



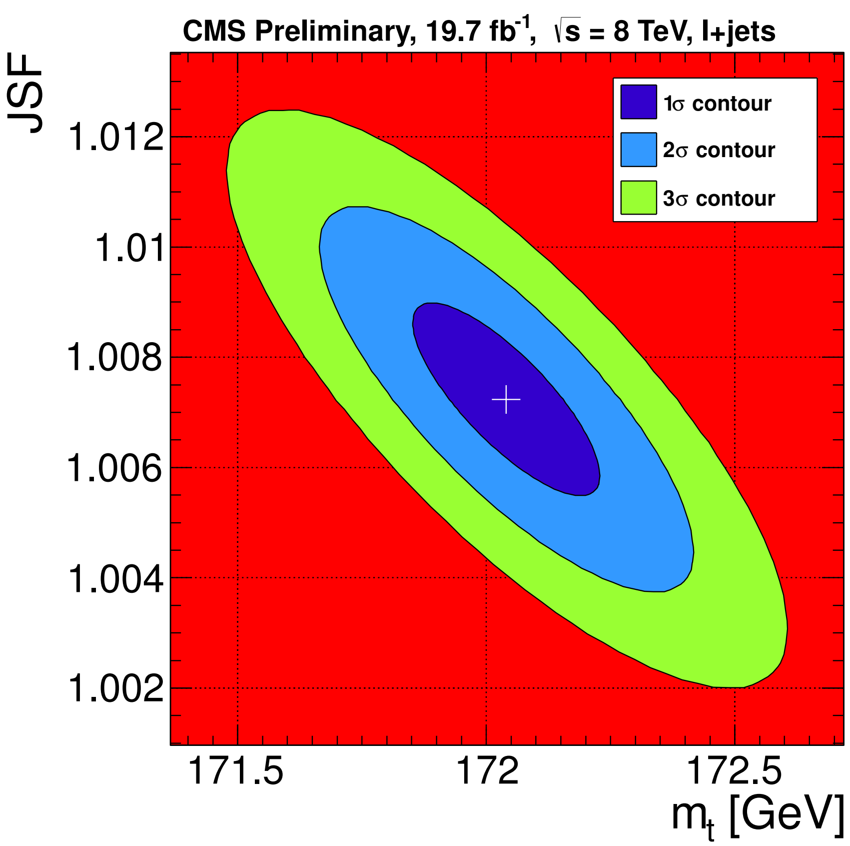
Many measurements?



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

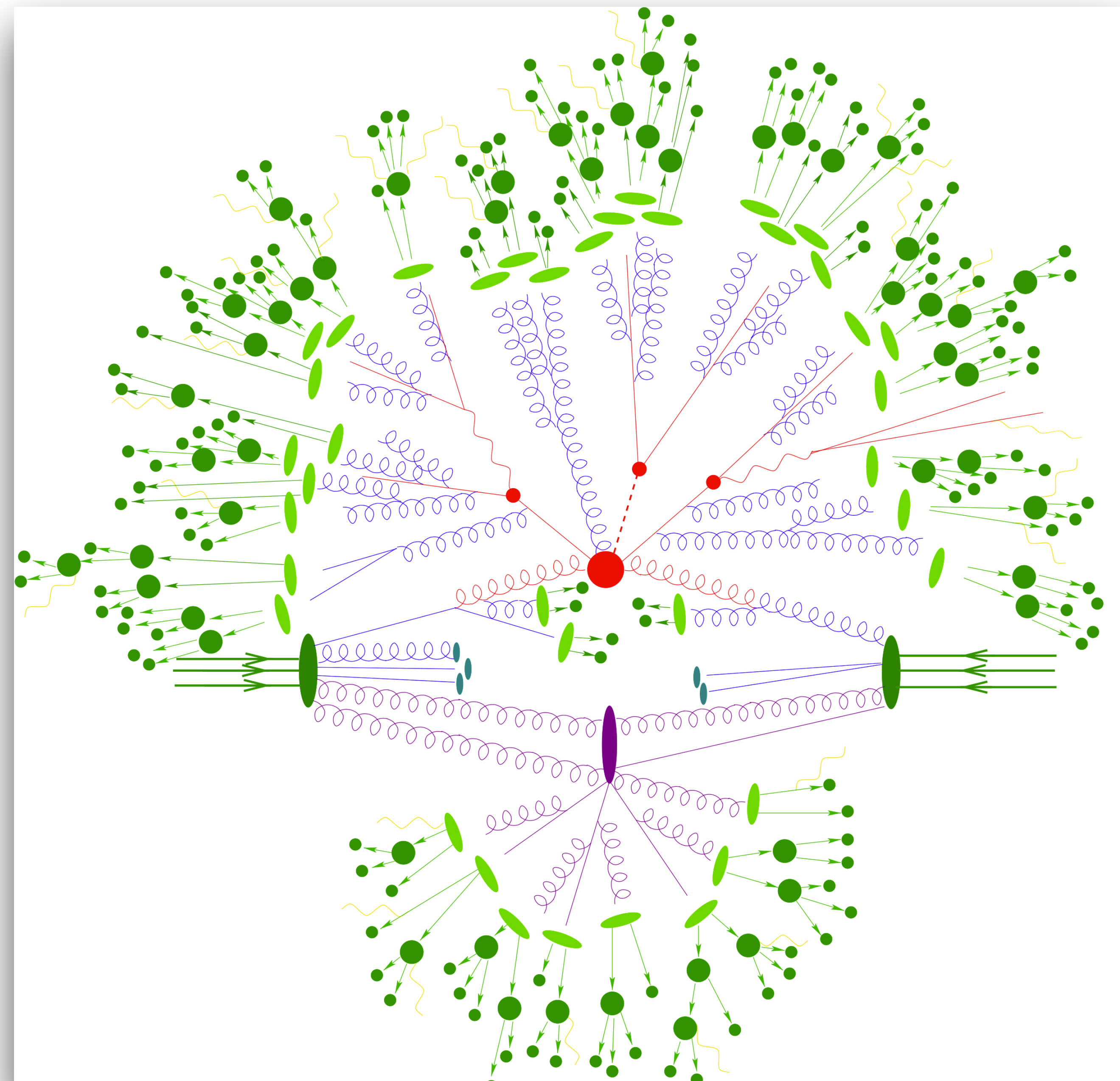
3D Method (Kinematic Fit)

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

Status

measurement at ≲0.5%! ⇒ *precision* QCD

- precision is systematics limited (JES, ..., hadronization)



- methods are (somewhat or tightly) tied to MC
- fundamentally based on a Leading Order picture
- mixed status w.r.t. effect of new physics

Each methods based on different assumptions/beliefs

- kinematics of the event (going beyond **$t\bar{t}$→ bWbW**)
- MC *choices* (NLO, scales range & functional form …

 … width treatment, color neutralization, radiation in decays, hadronization)

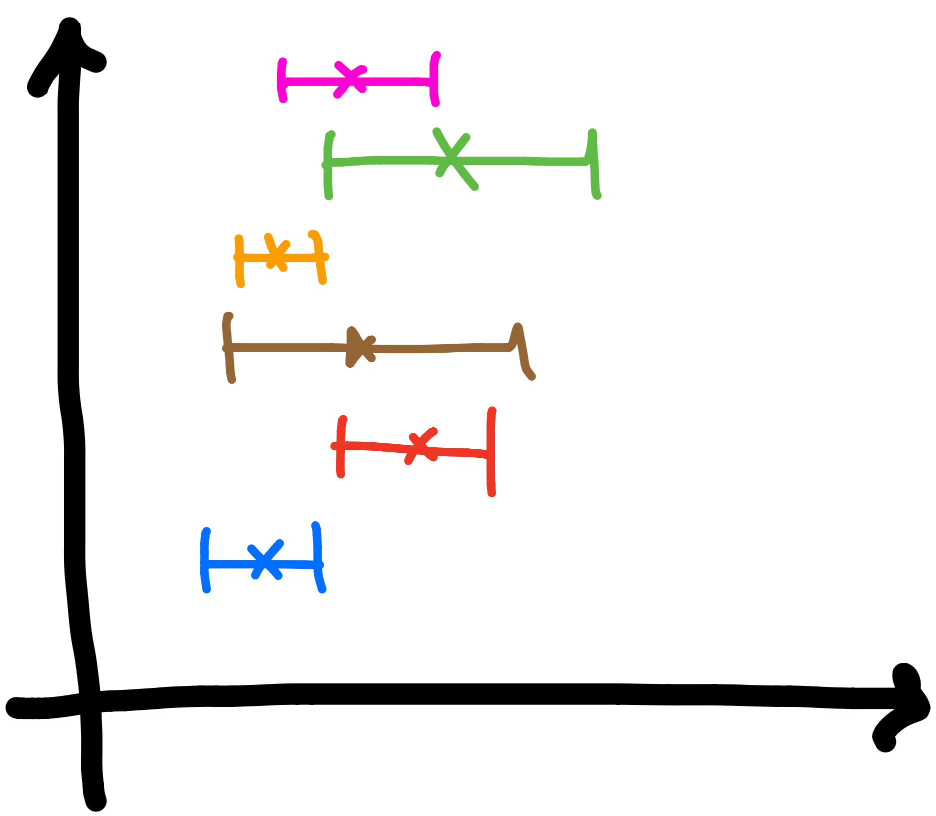
Ideal situation

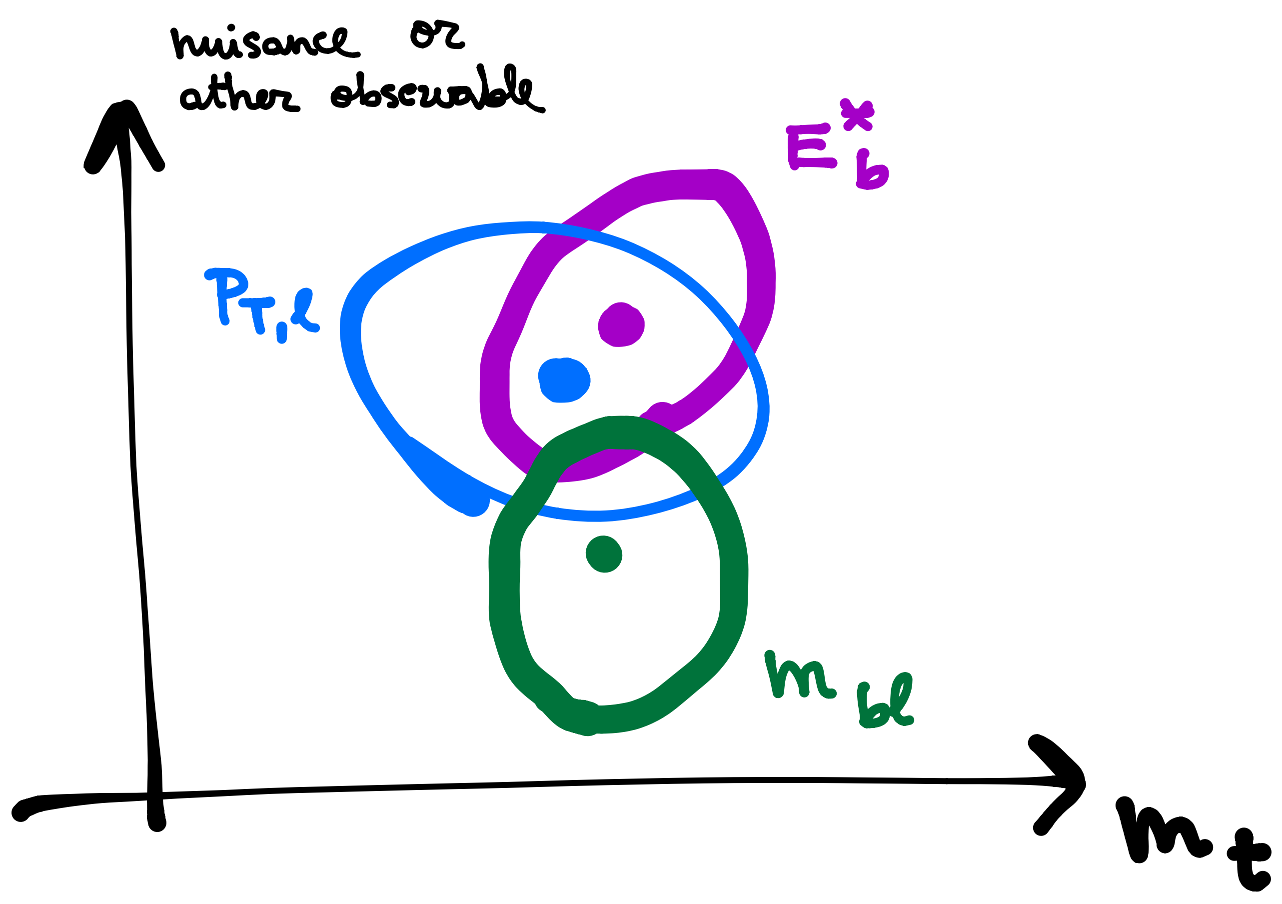
Have many inherently different methods

possibly based on different experimental objects/quantities

- deal with reconstructed jets
- only-leptons
- only-tracks

Many measurements

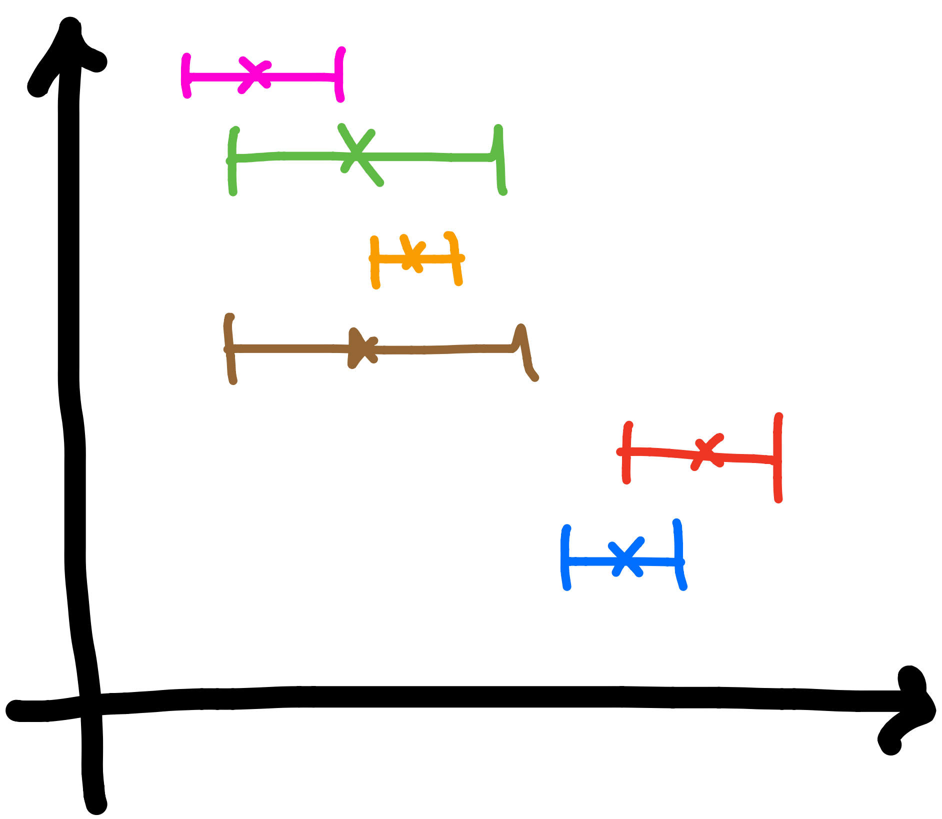


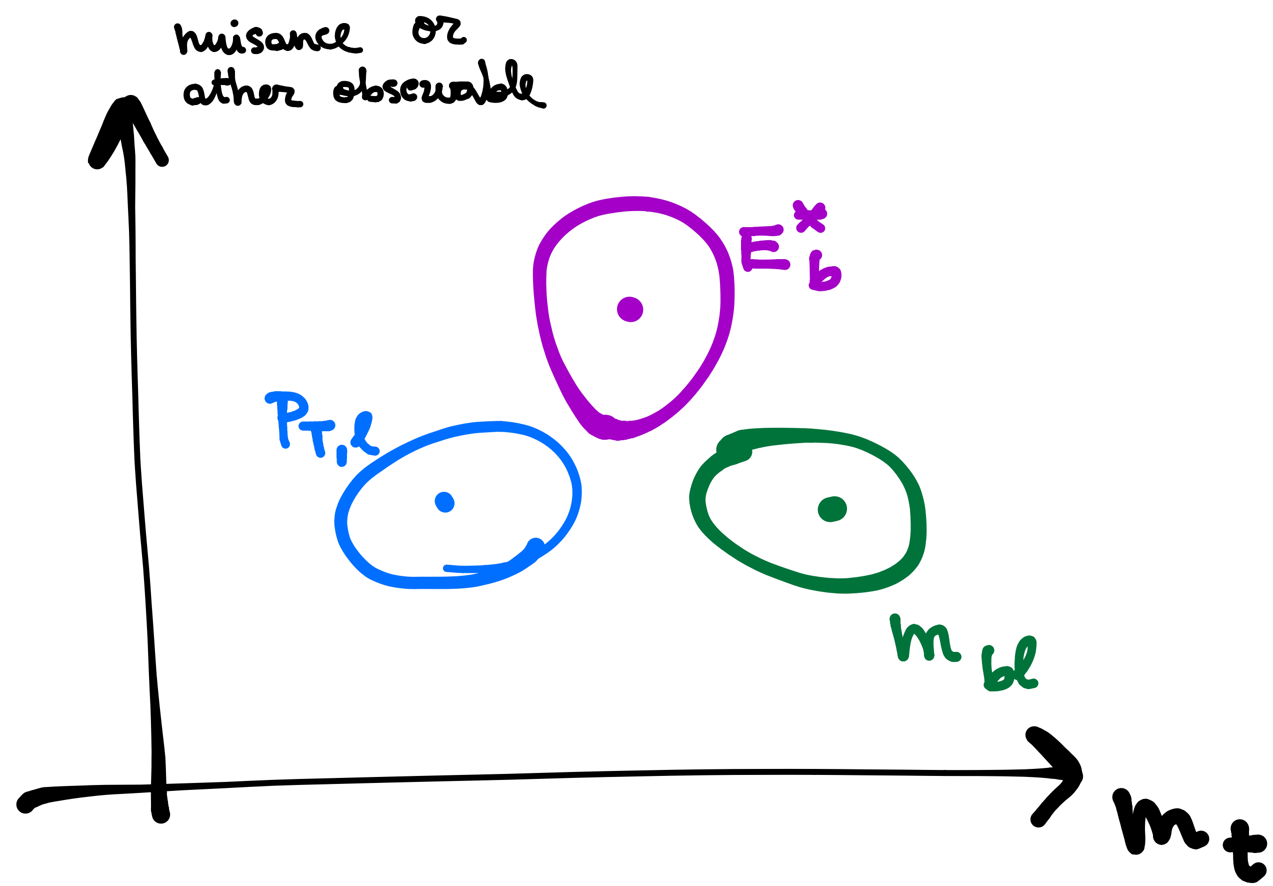


The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about "*single best measurement*"

Many measurements

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





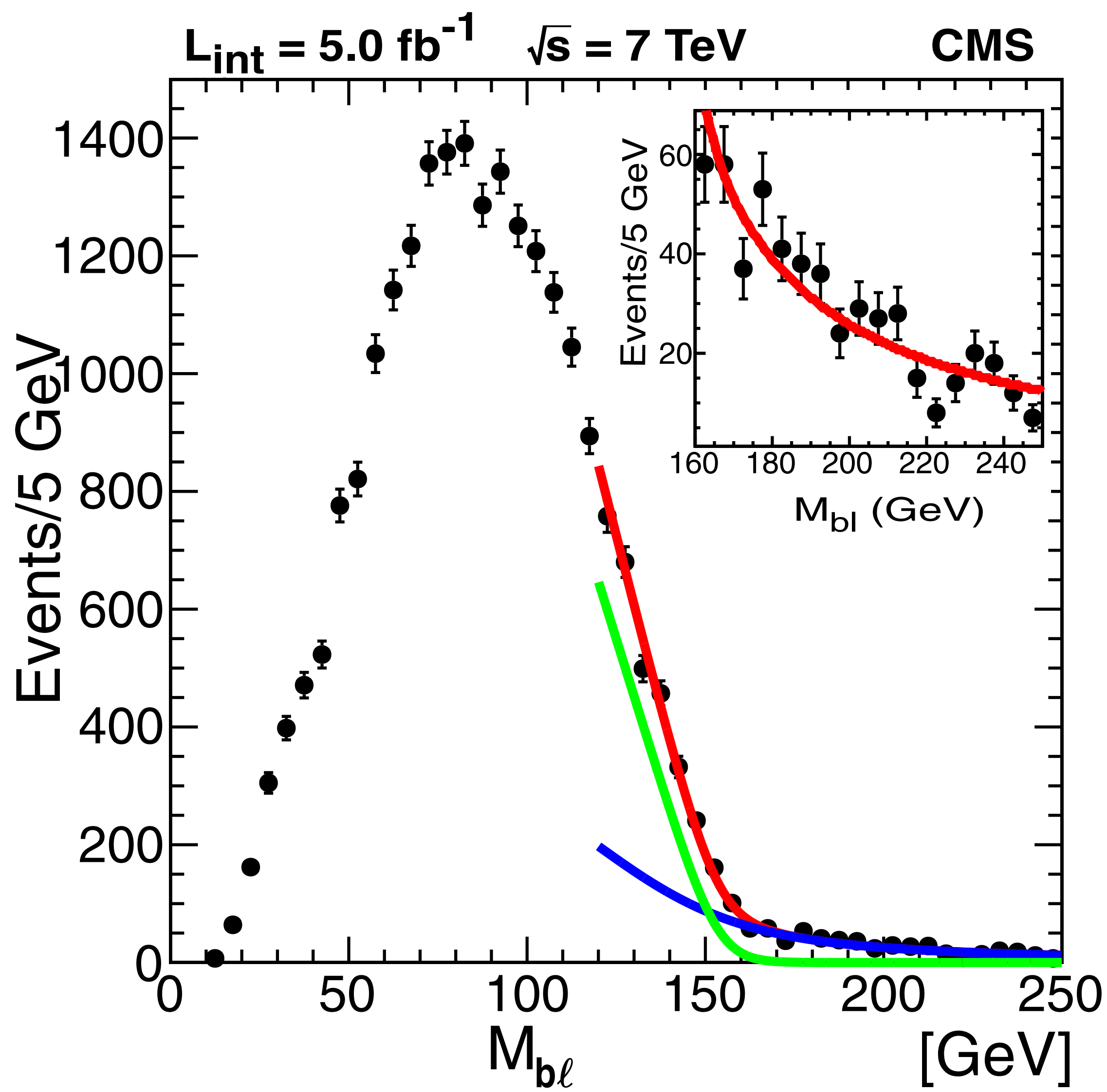
The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about "*single best measurement*"

CMS-TOP-11-027

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

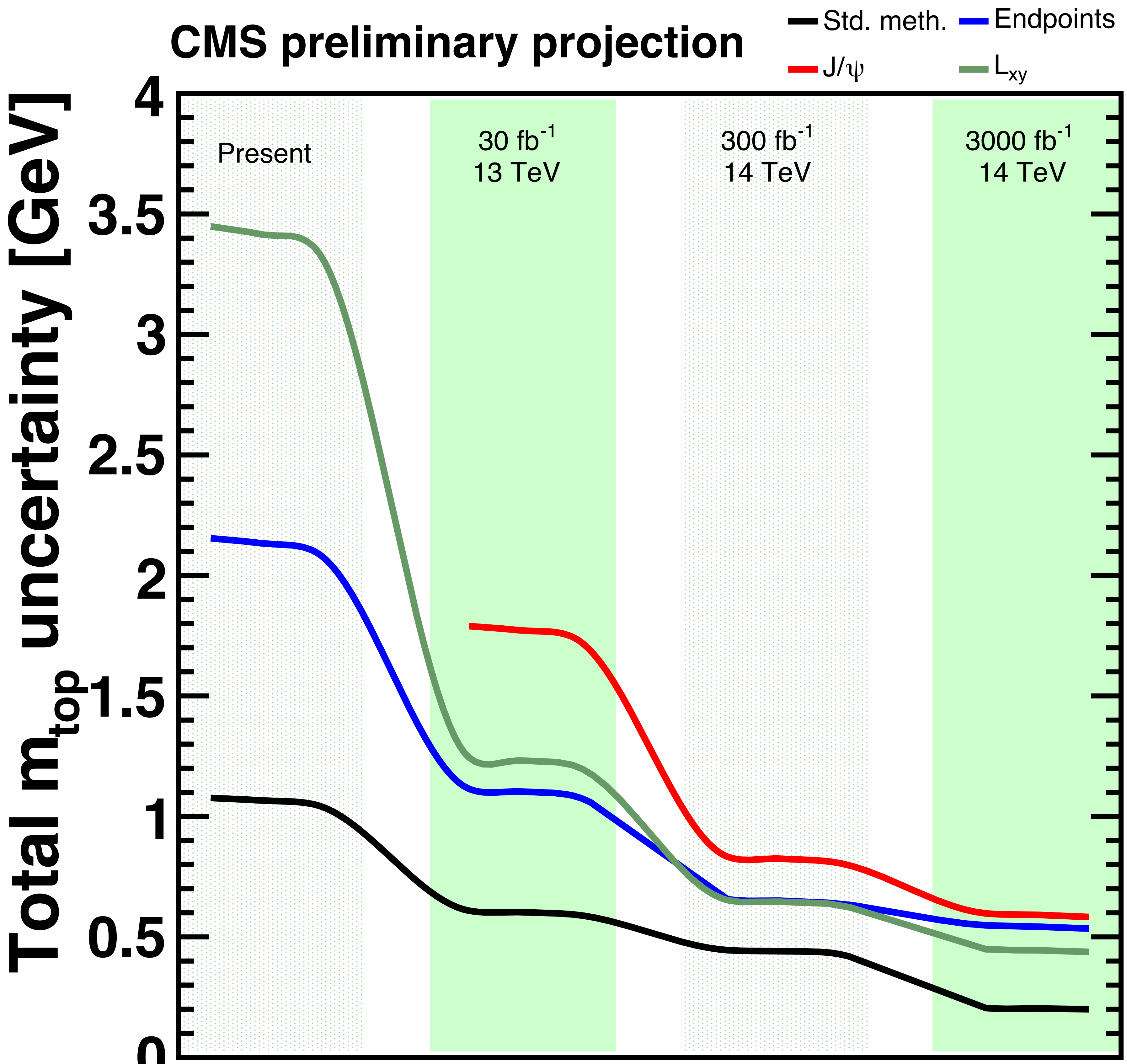
m(b,l) end-point

- 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	$^{+1.7}_{-2.1}$

Ideal situation



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

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, …)

Less ideal mass measurements

One particle is just lost

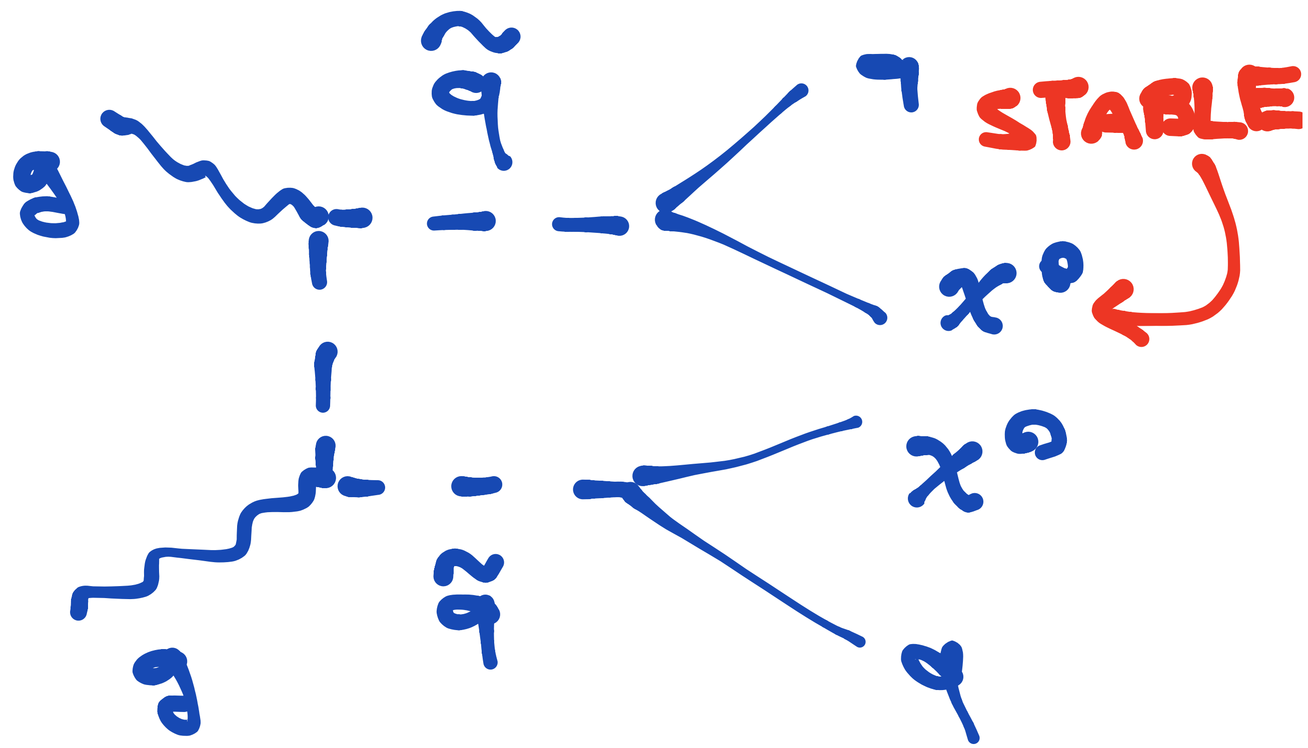
Need to come up with a trick

for example:

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

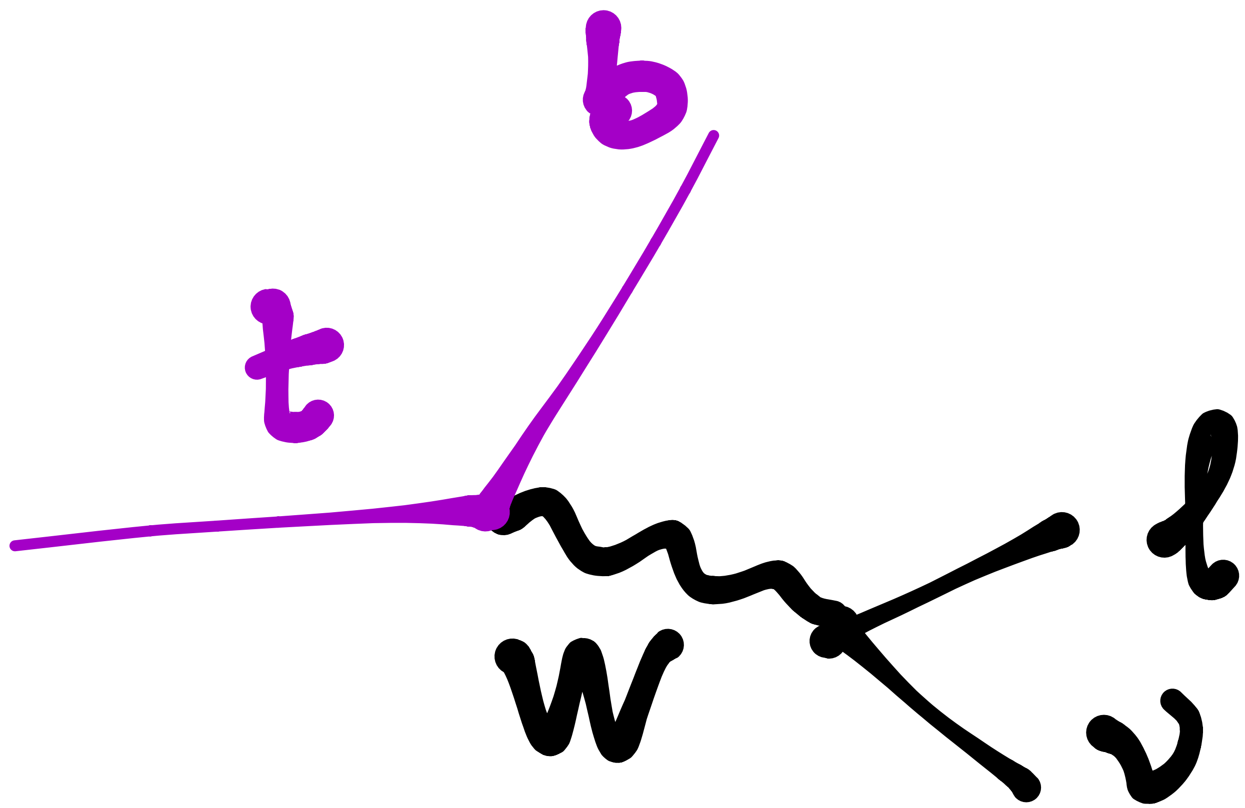
… and it can get worse

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



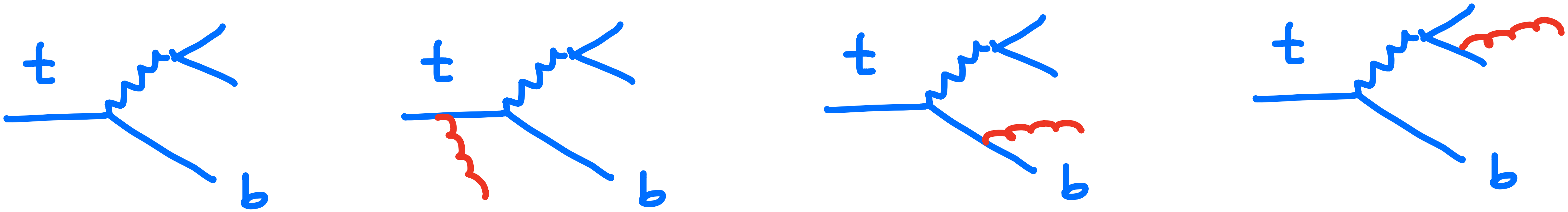
can we make a mass measurement without ever mentioning the unobservable particle χ?

“useful” top is semi-invisible

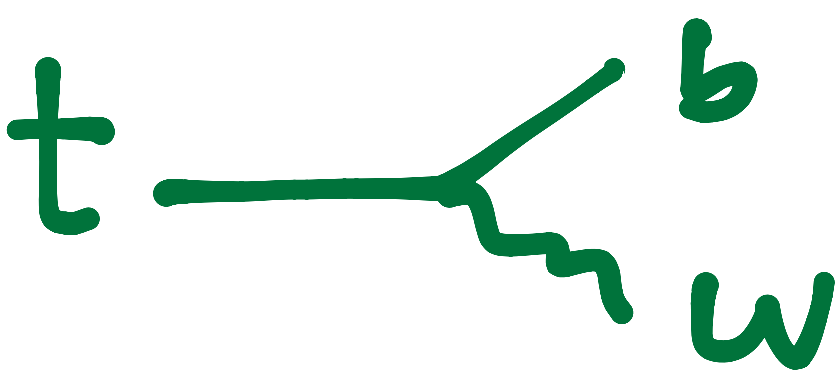


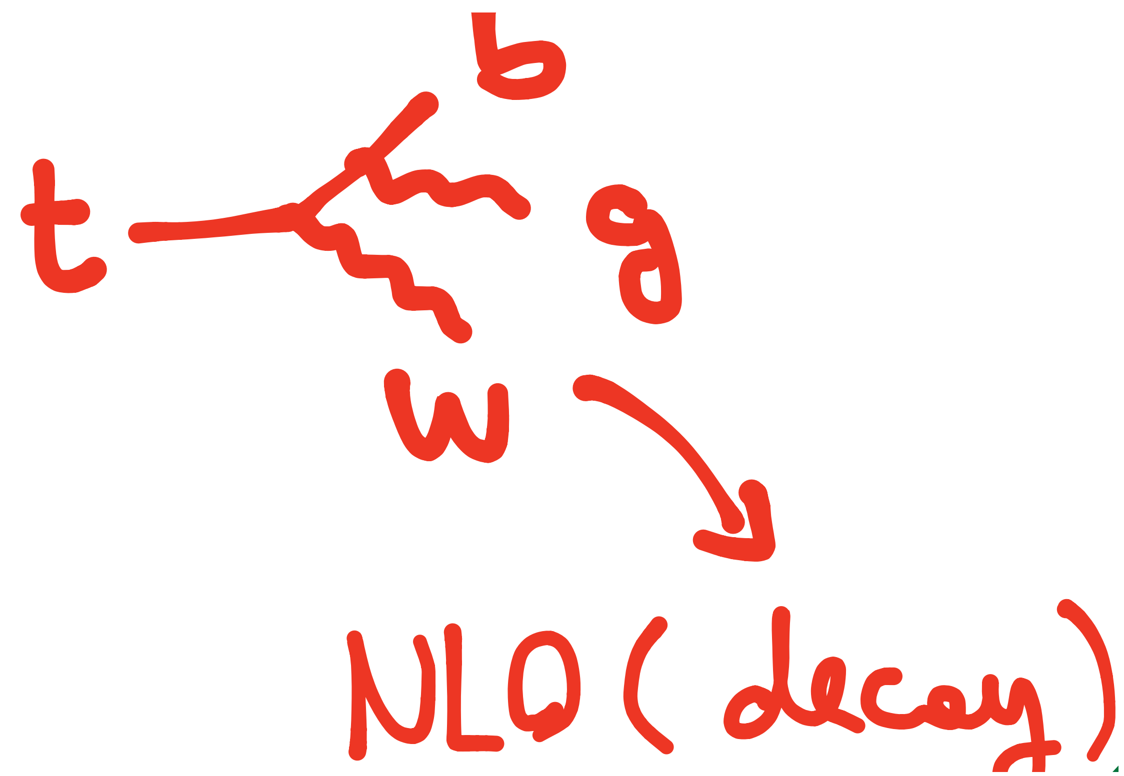
can we make a mass measurement without ever mentioning the unobservable particle ***W*** ?

To reconstruct or not to reconstruct?



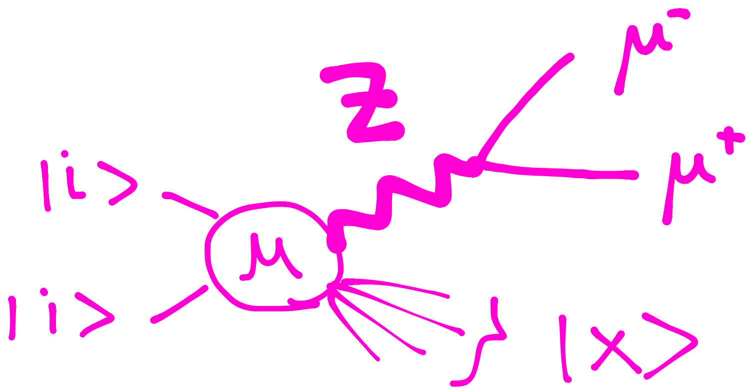
top quark reconstruction is entangled with *<u>some</u>* picture of the kinematics (fixed order?)



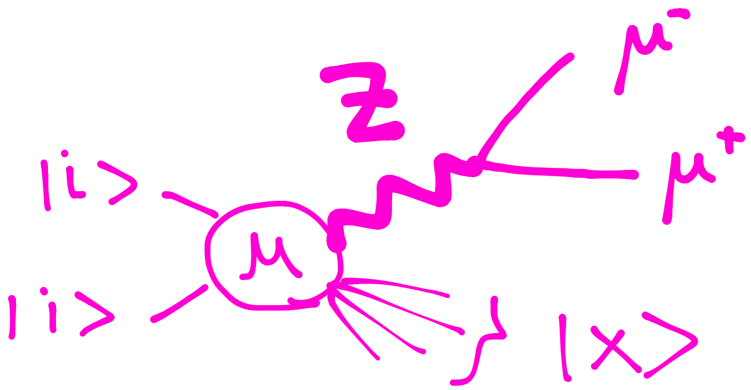


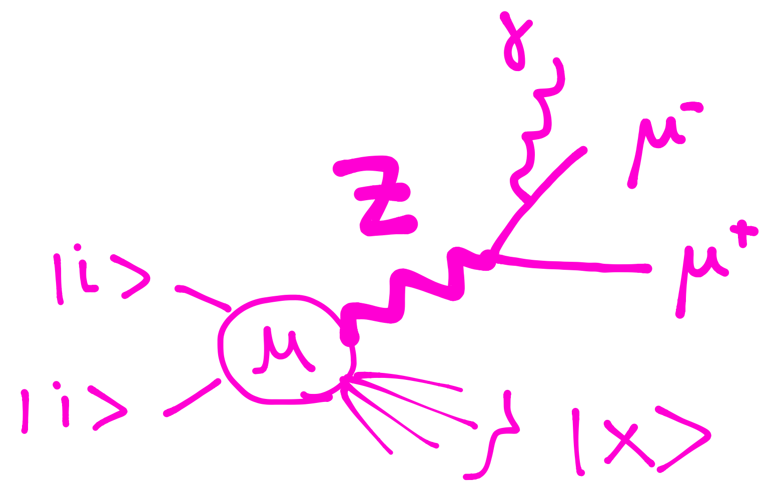
Top decay at NLO <u>just added</u> in current NLO+PS generators (1412.1828)

To reconstruct or not to reconstruct?



To reconstruct or not to reconstruct?





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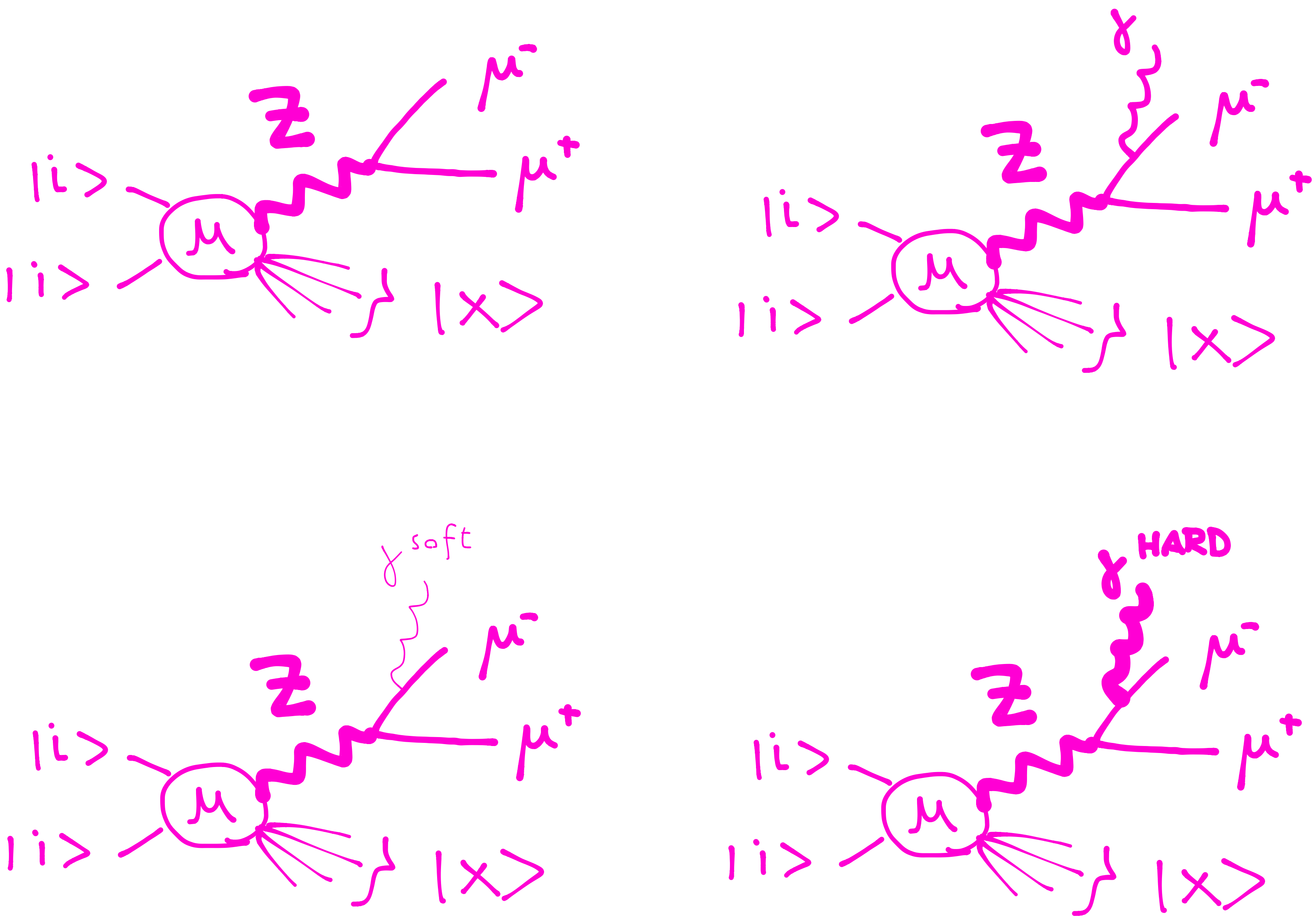

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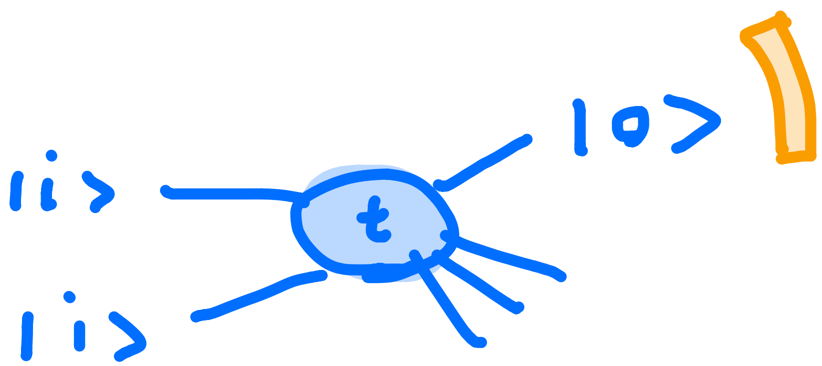
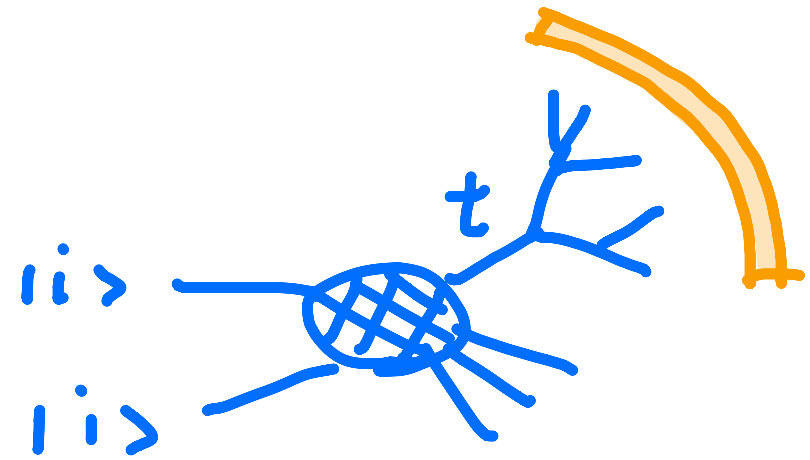




does (not) distinguish where
the final state came from (t, t*, bW, bWg, bqqg)

need (not) to define the top

might (not) depend on the production mechanism

…

(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 hep-ph/9912320
- dσ/ds(ttj) 1303.6415
- Inclusive σ(tt) 1307.1907

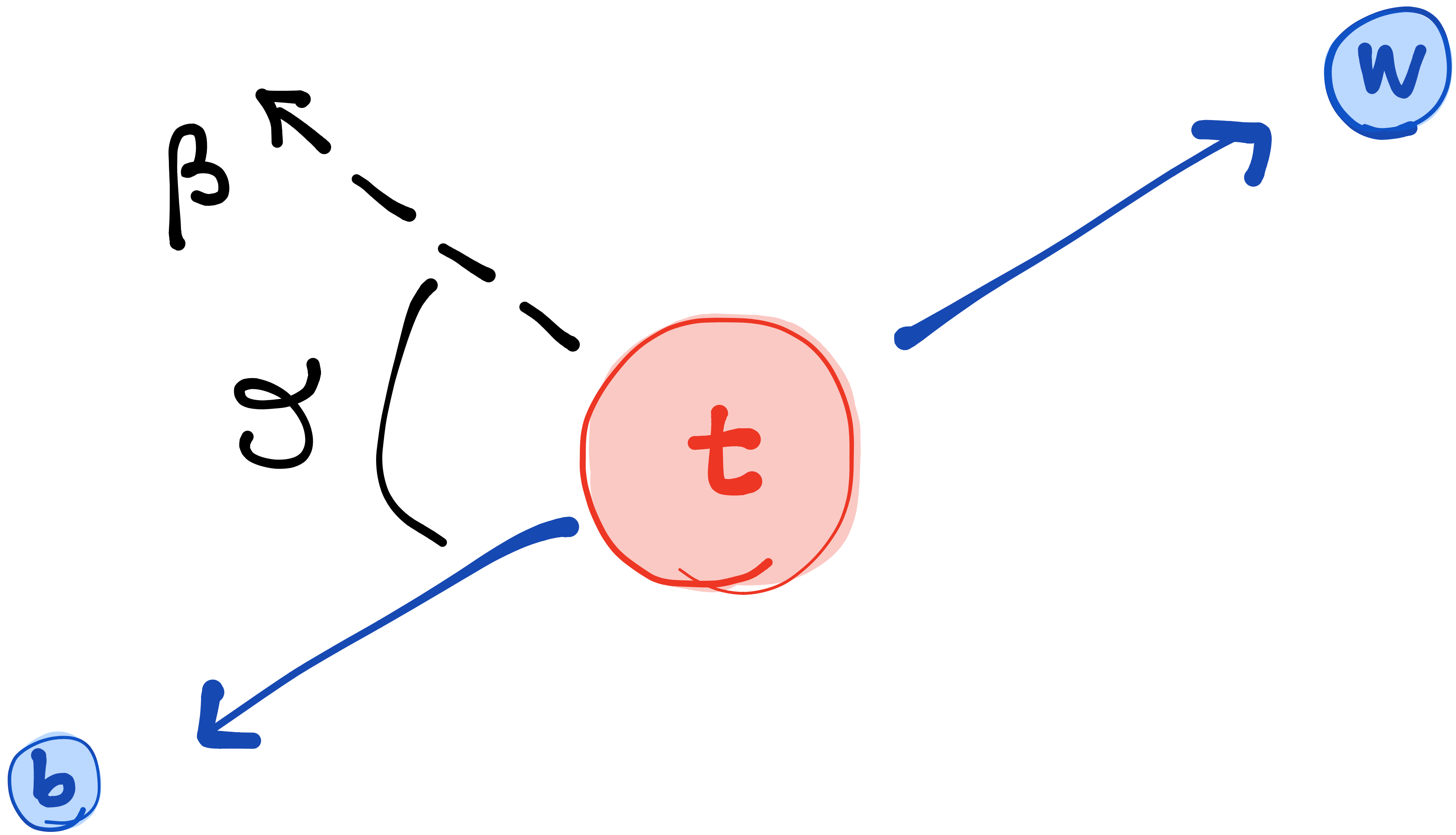
Lorentz *variant* quantities

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

Energy Peaks

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

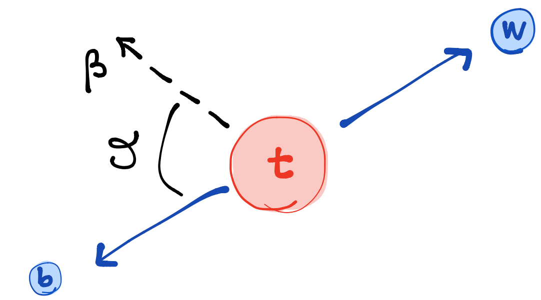
1209.0772 - Agashe, Franceschini and Kim



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

Event-by-event we cannot tell anything

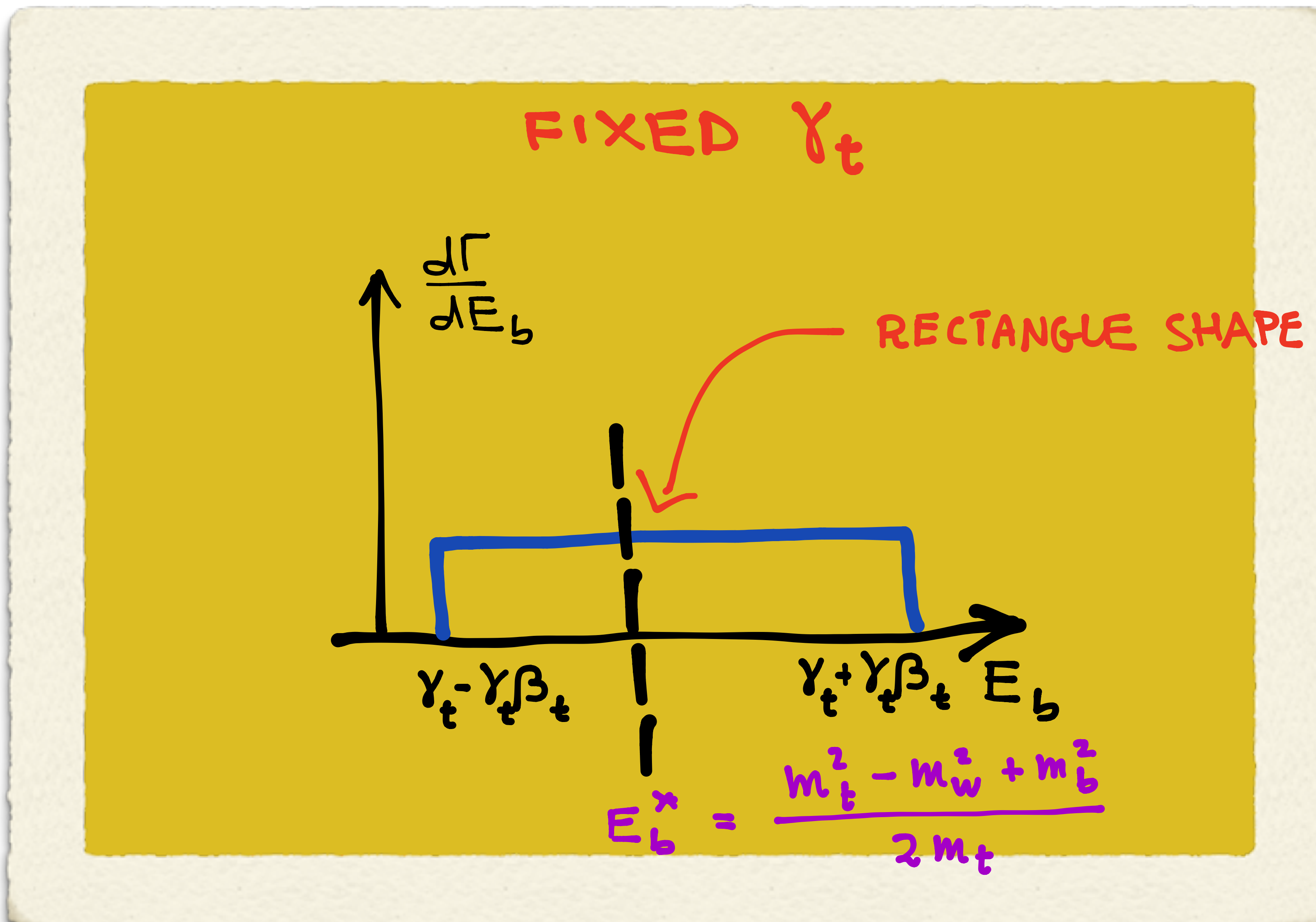
Fixed top boost decay



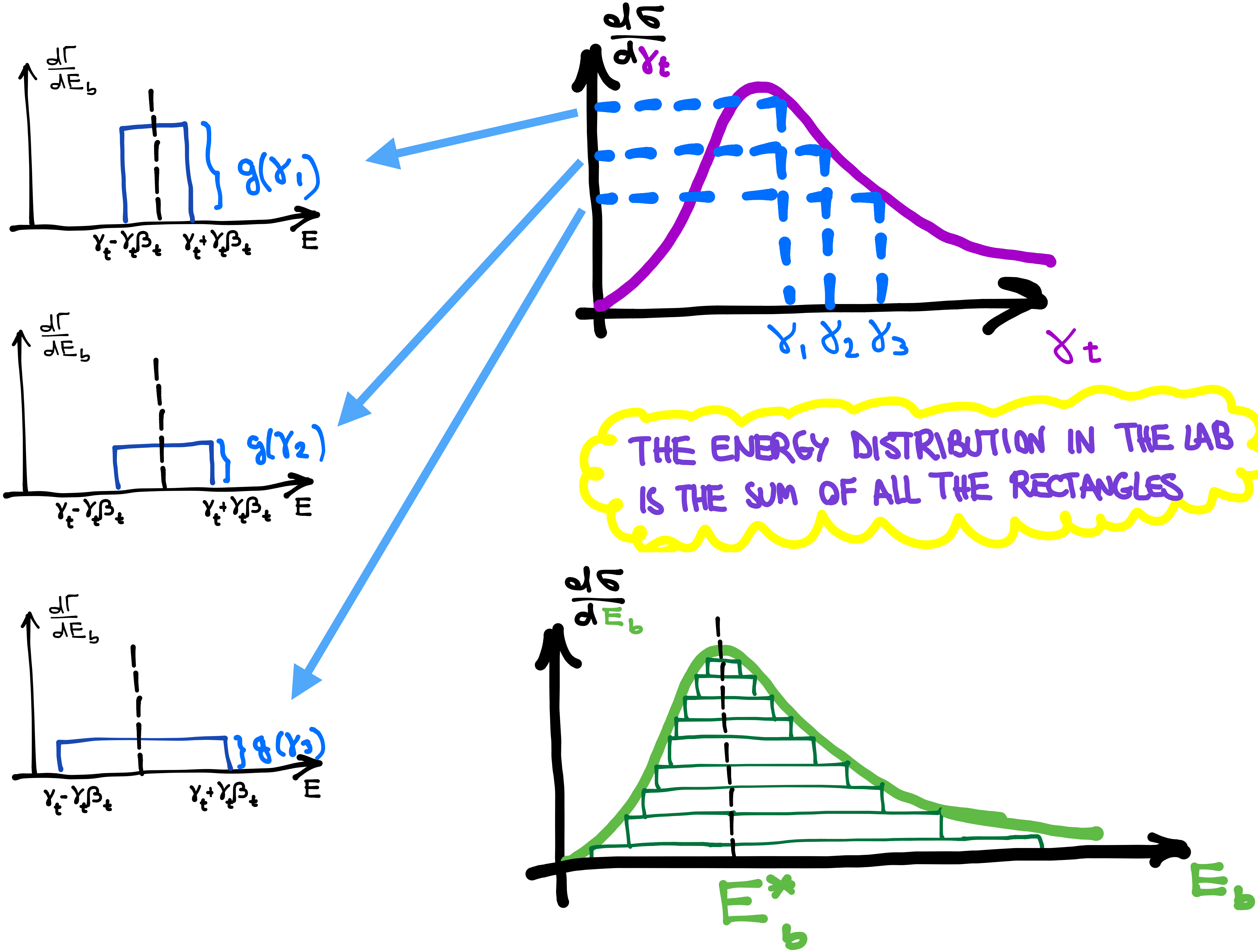
Massless b-quark (for now)

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

unpolarized top sample ⟶ cosθ is flat



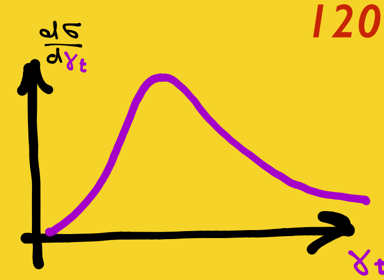
Summing over the top boosts



Lab-frame energy distribution

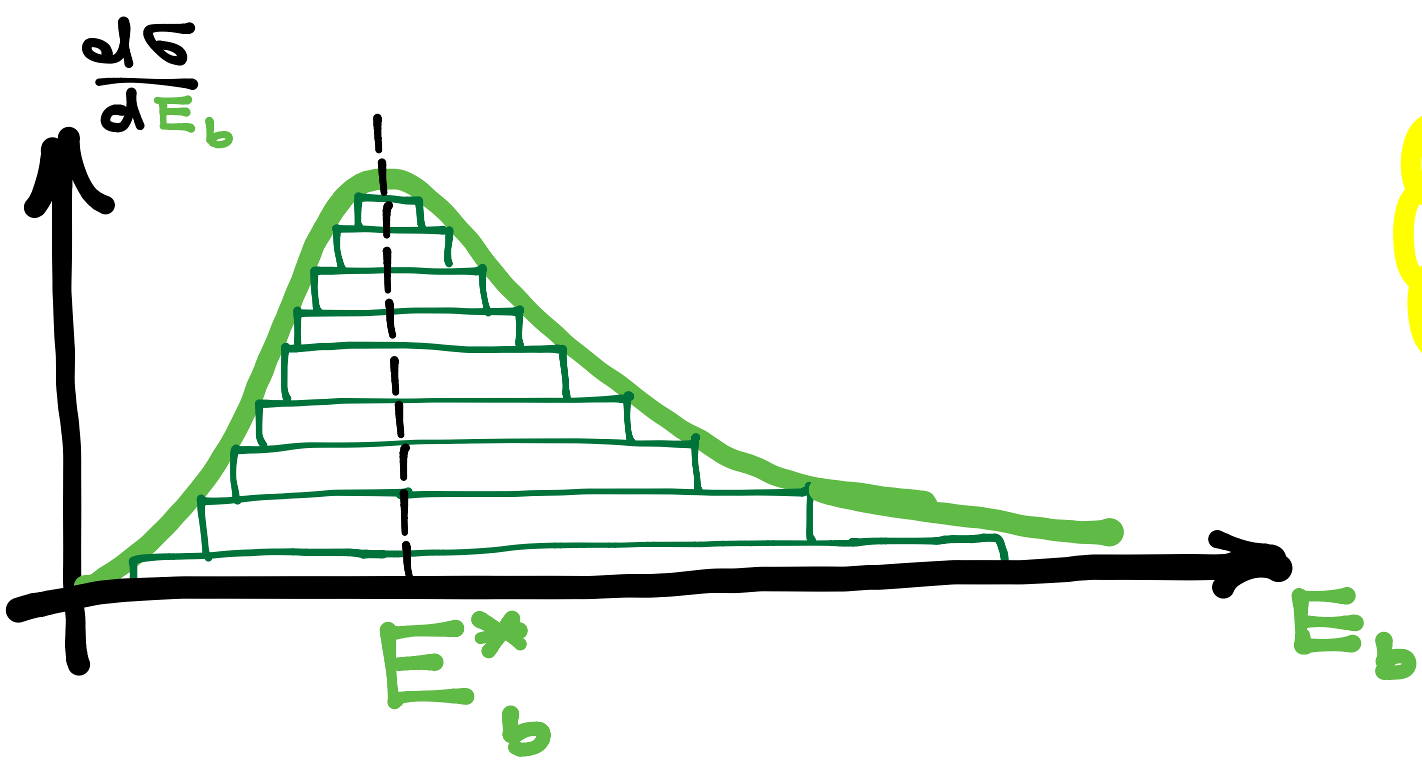
1209.0772 - Agashe, Franceschini and Kim

also Stecker 1971

for any top boost distribution 

the peak:

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



THE <u>FRAME-DEPENDENT</u> ENERGY DISTRIBUTION ENCODES THE <u>INVARIANT</u> E_d^* IN A VERY SIMPLE WAY

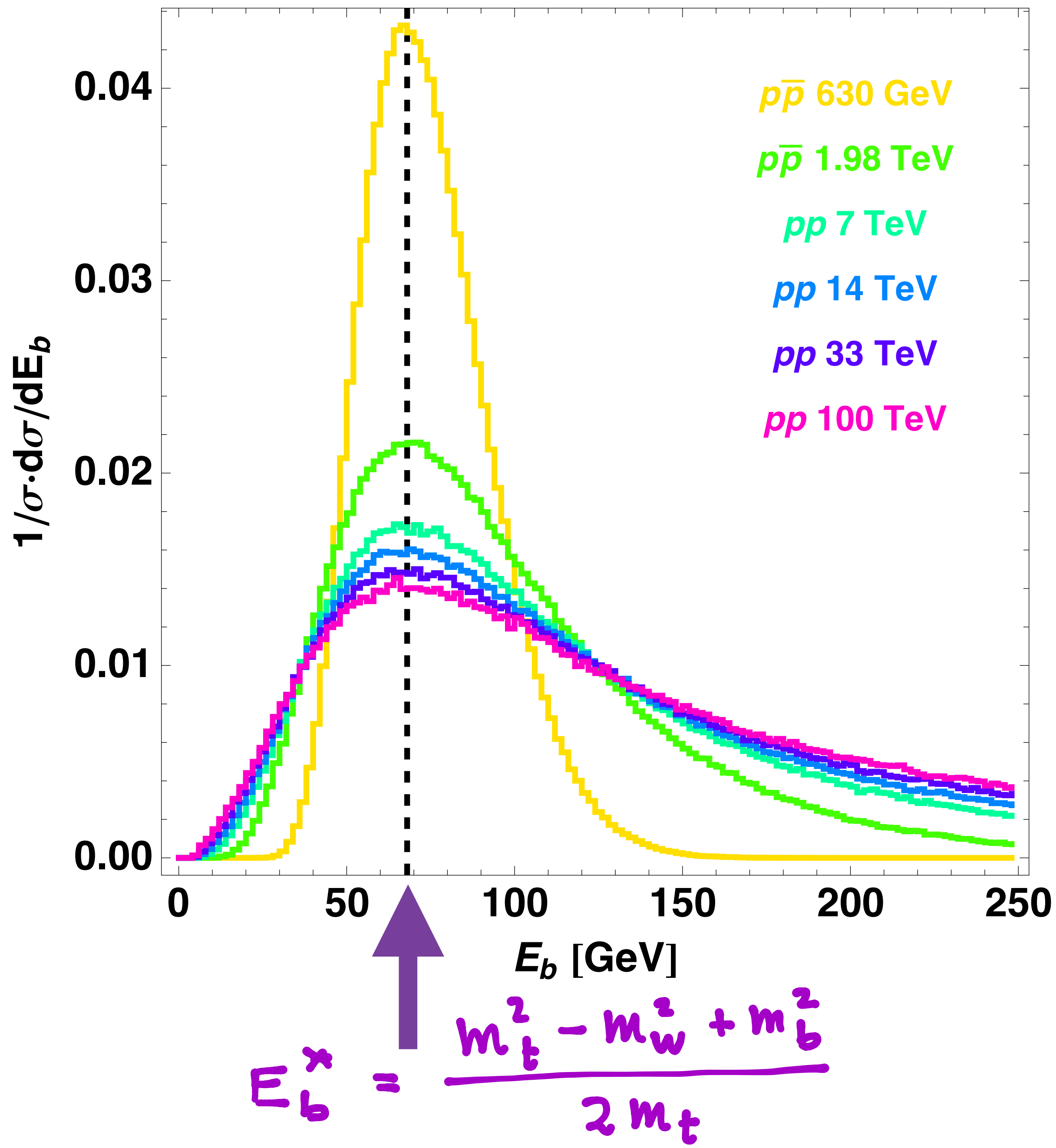
There is no difference when the b-mass is taken into account provided $\gamma_{top} < 500$

back

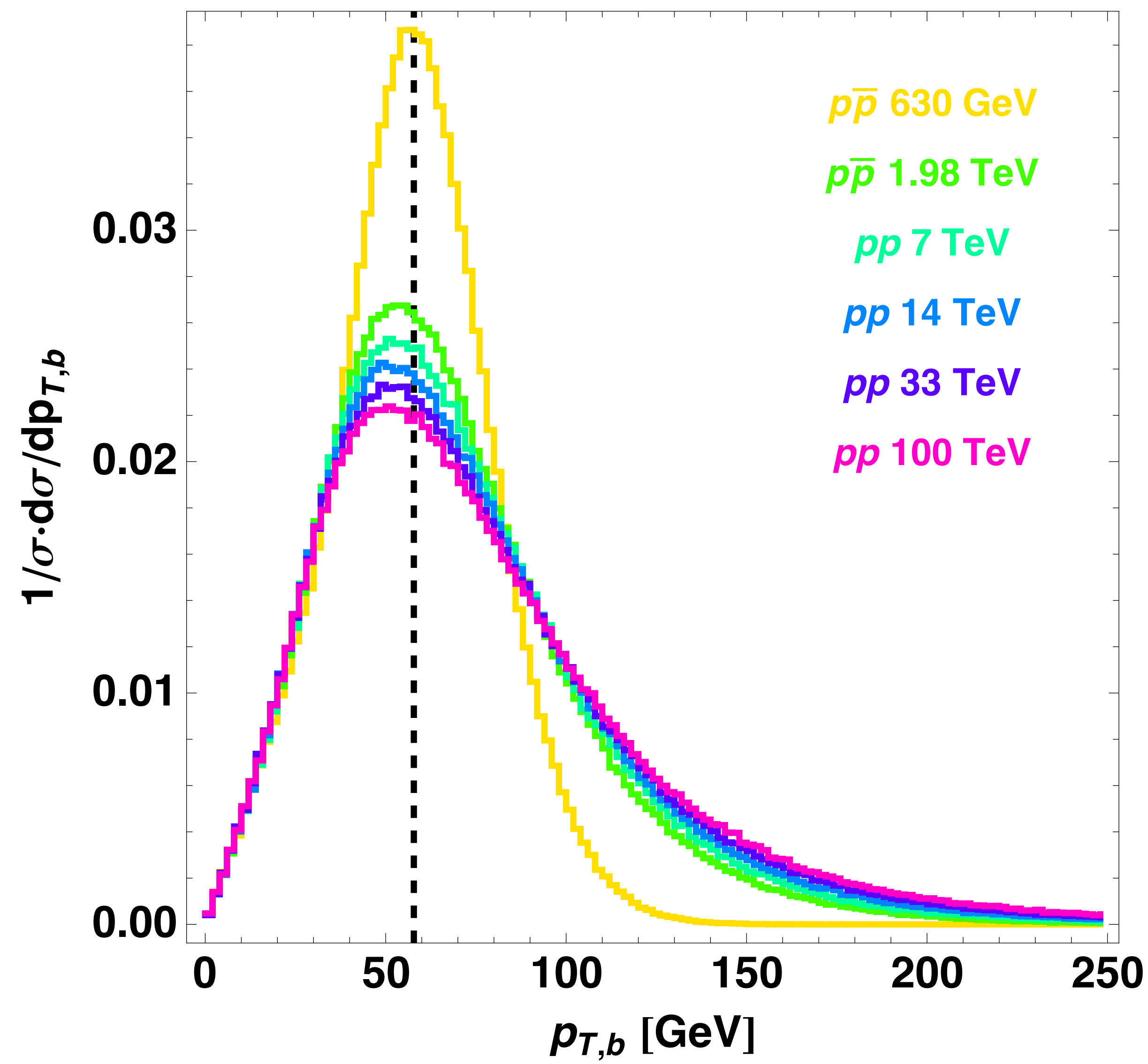
How special is this invariance?

1209.0772 - Agashe, Franceschini and Kim

Shape changes, peak doesn't!

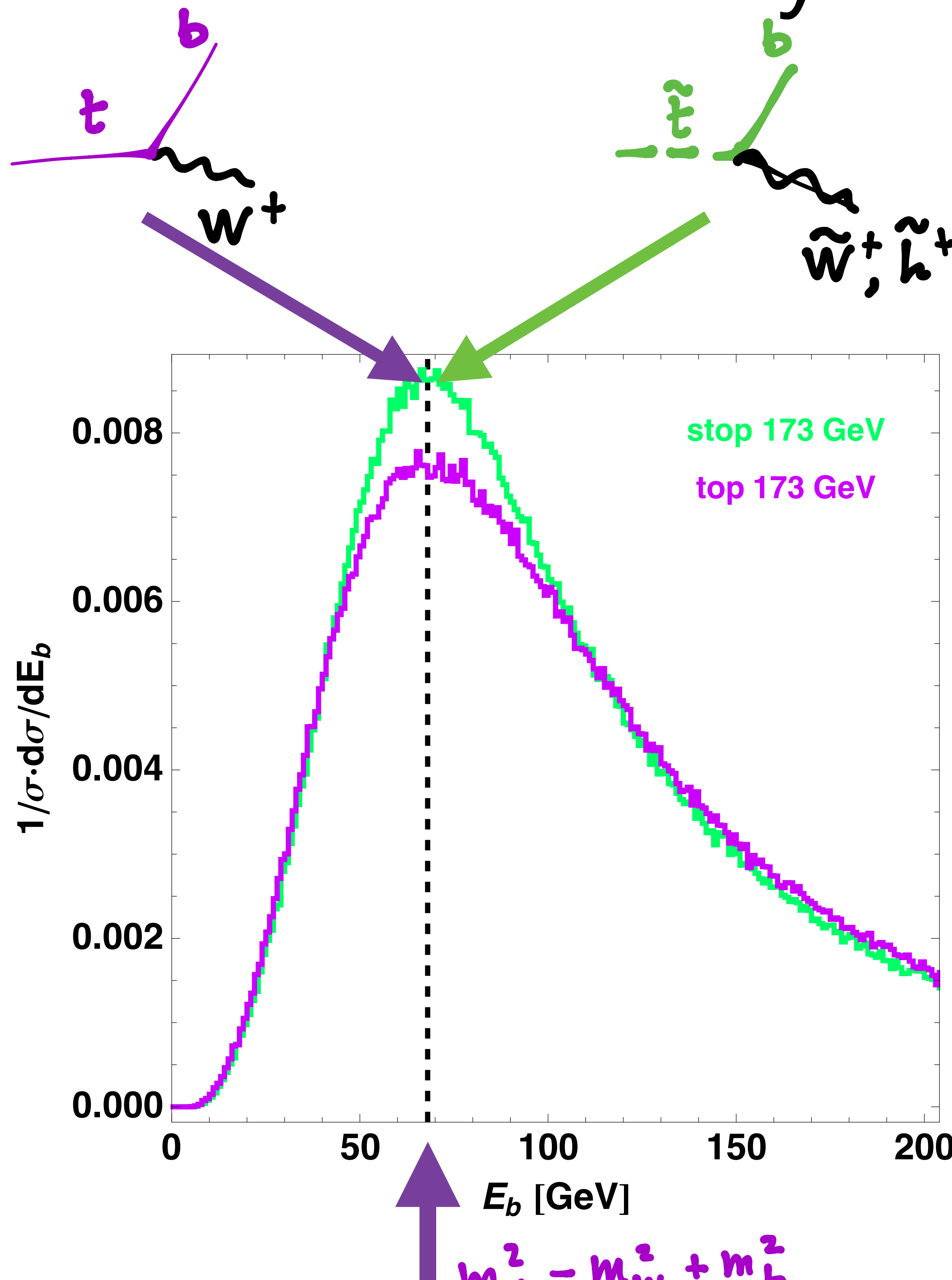


Shape changes, peak does too



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

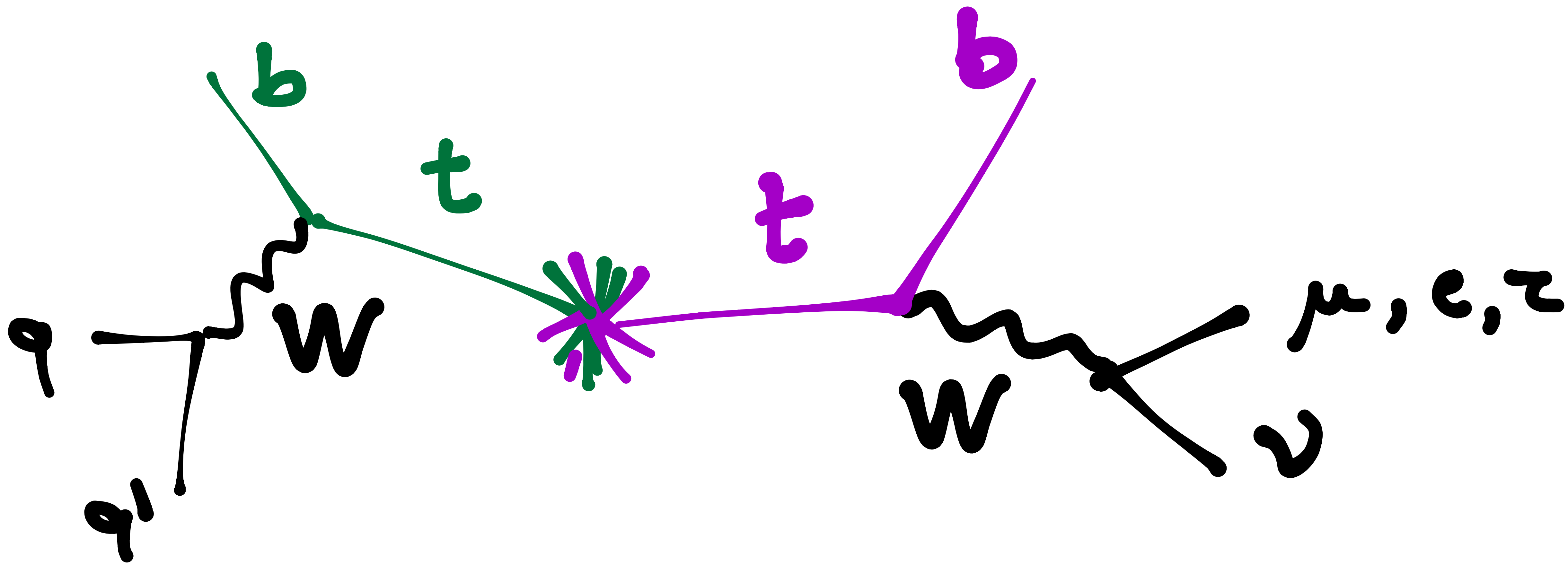
Independent of decay dynamics



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

captures the peak for both stop and top: pure kinematics

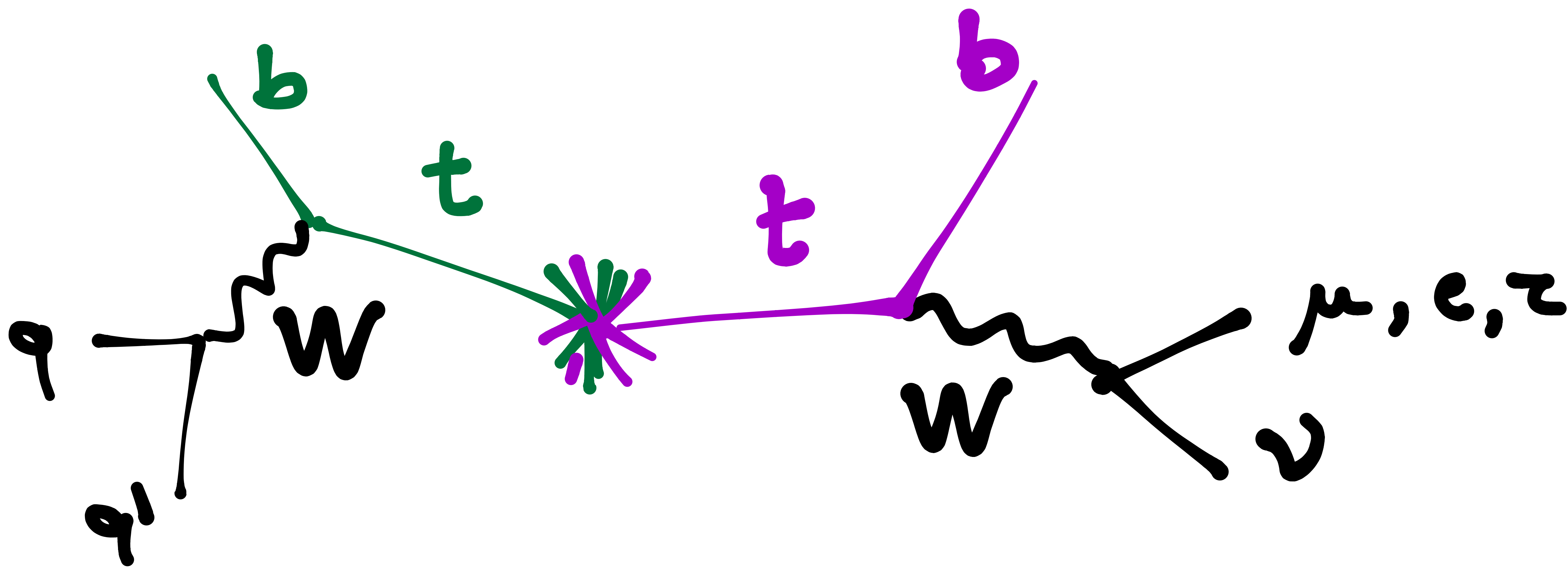
Applicable for any decay of W



W is just a spectator and is not used (barring selections, triggers)

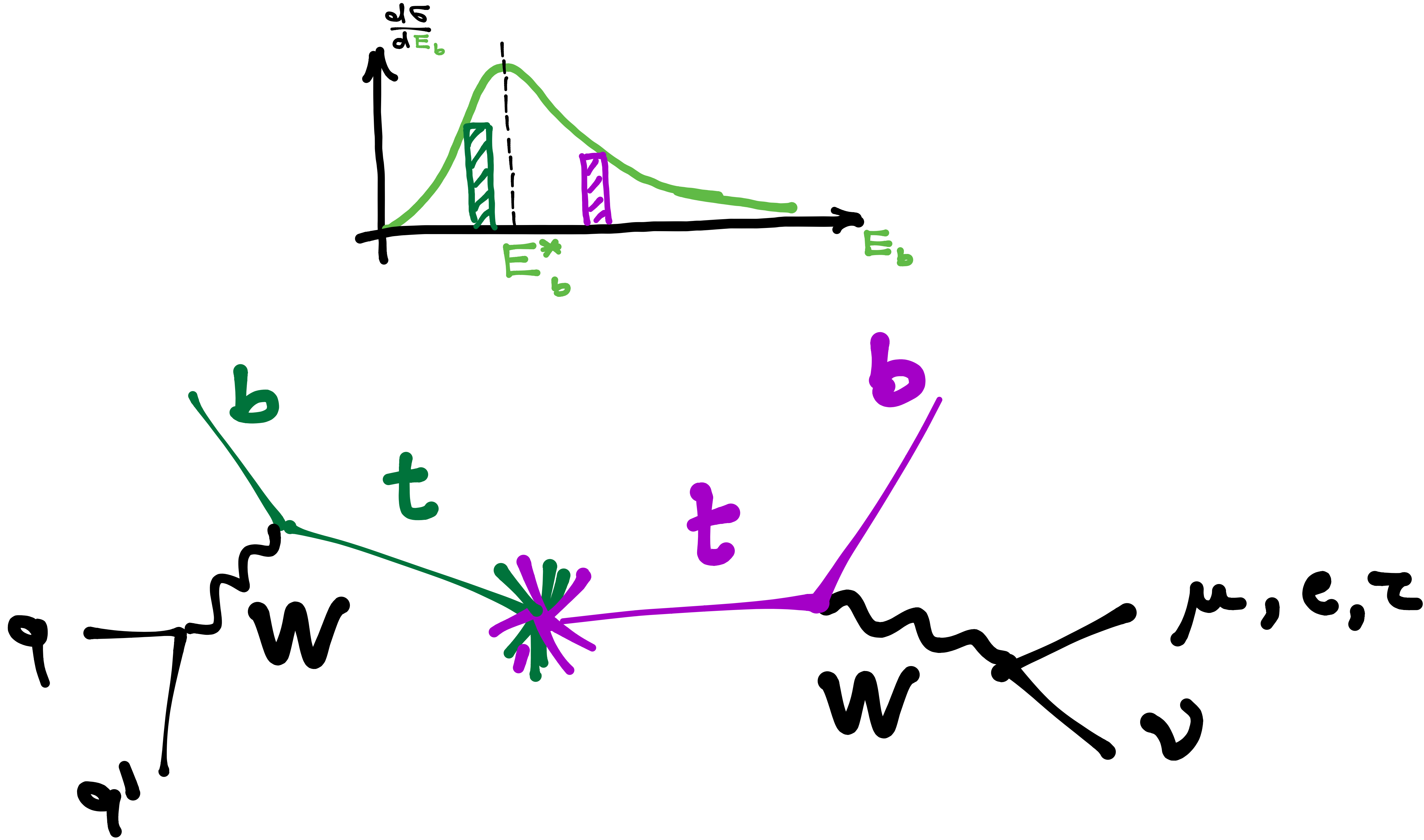
$W \to \tau\nu$ as good as $W \to \mu\nu$

No need to form combinations



just put 2 b per event into the histogram

No need to form combinations



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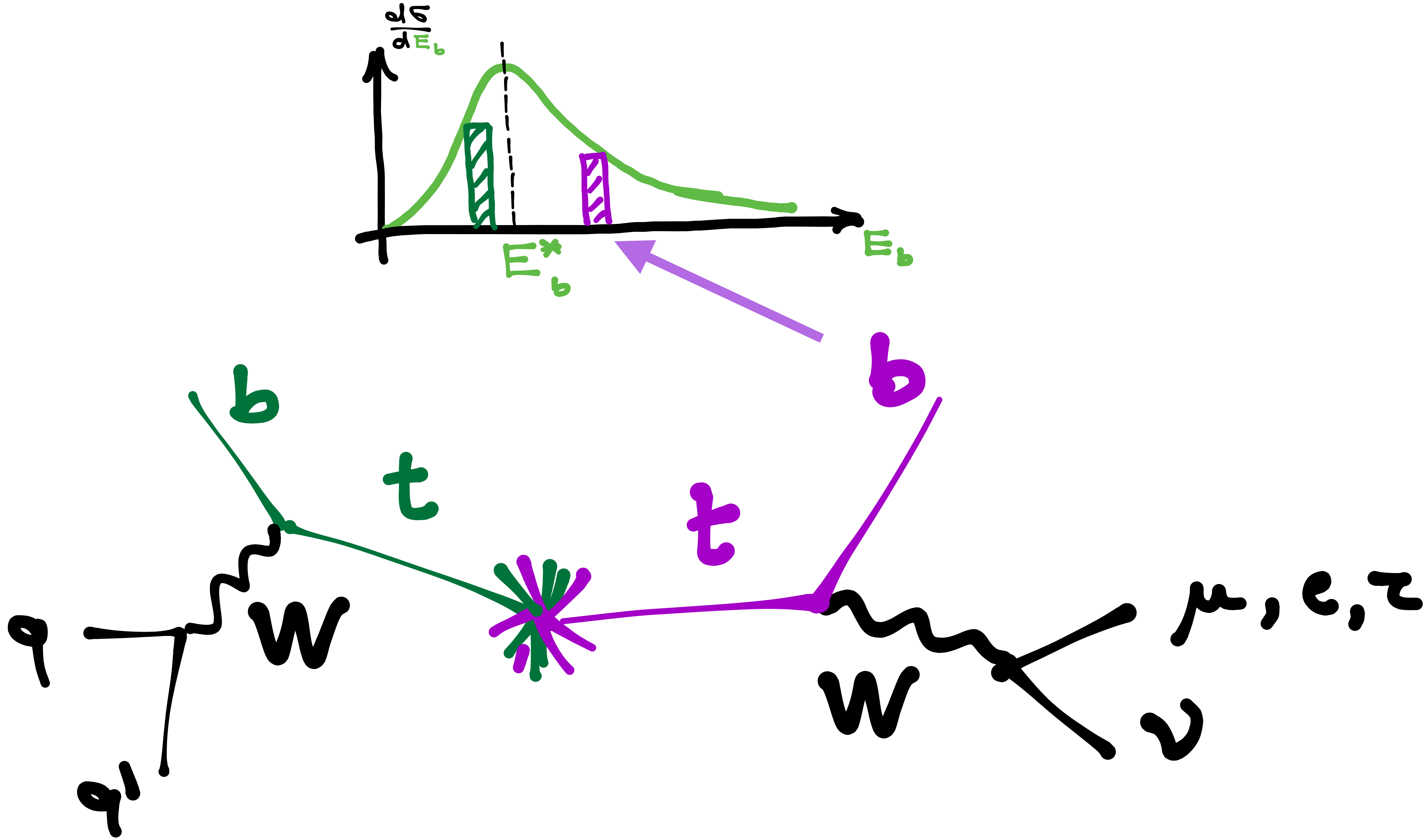

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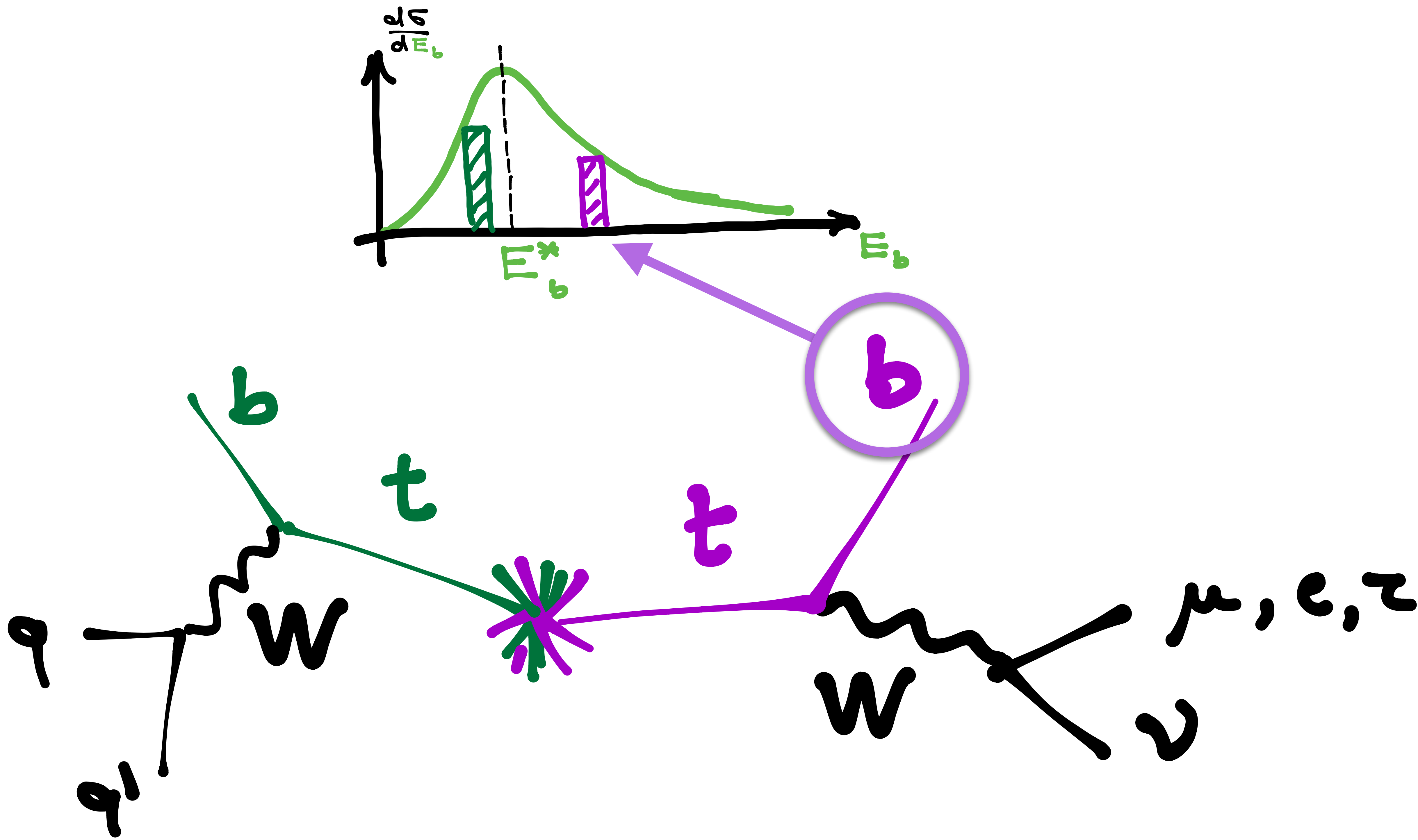

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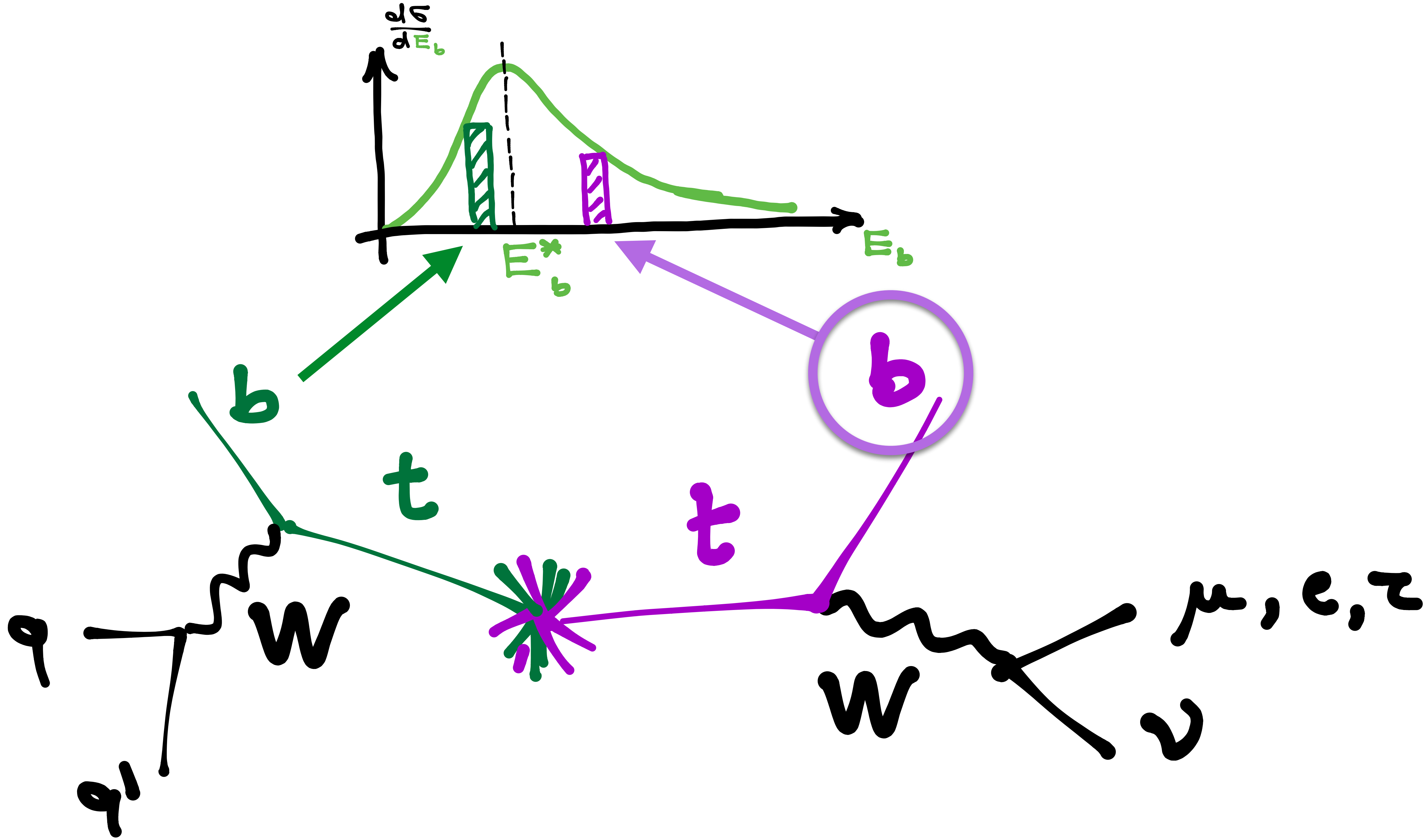

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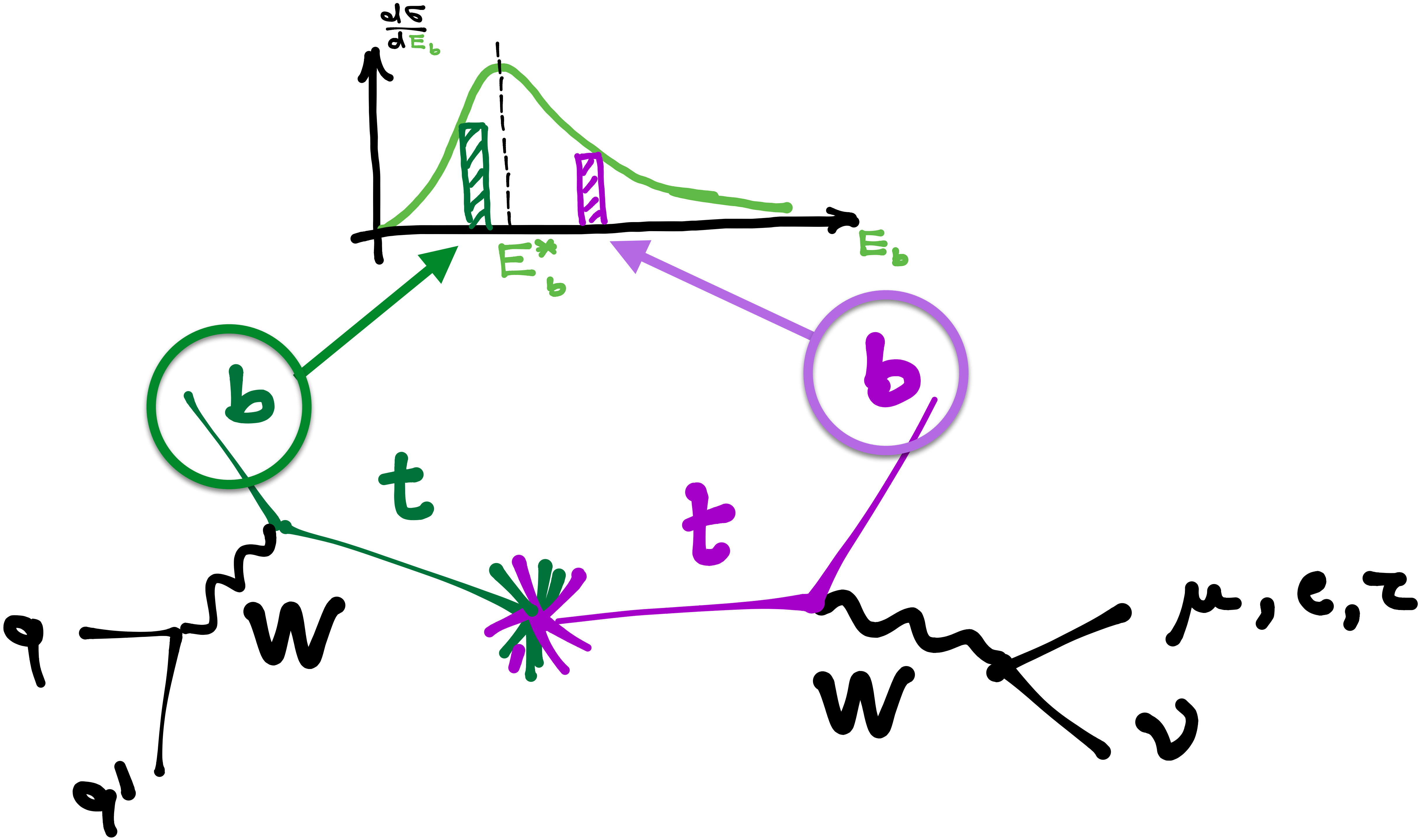
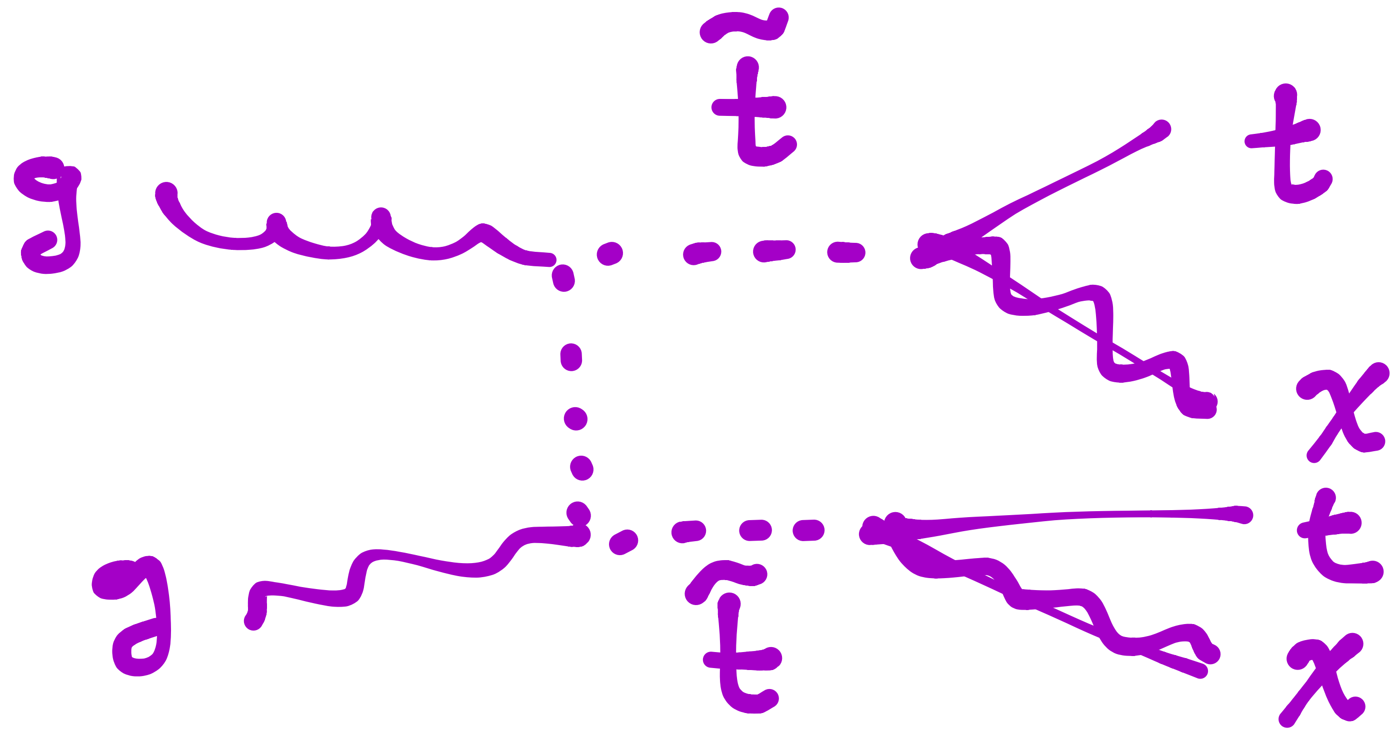


just put 2 b per event into the histogram

New physics in the top sample



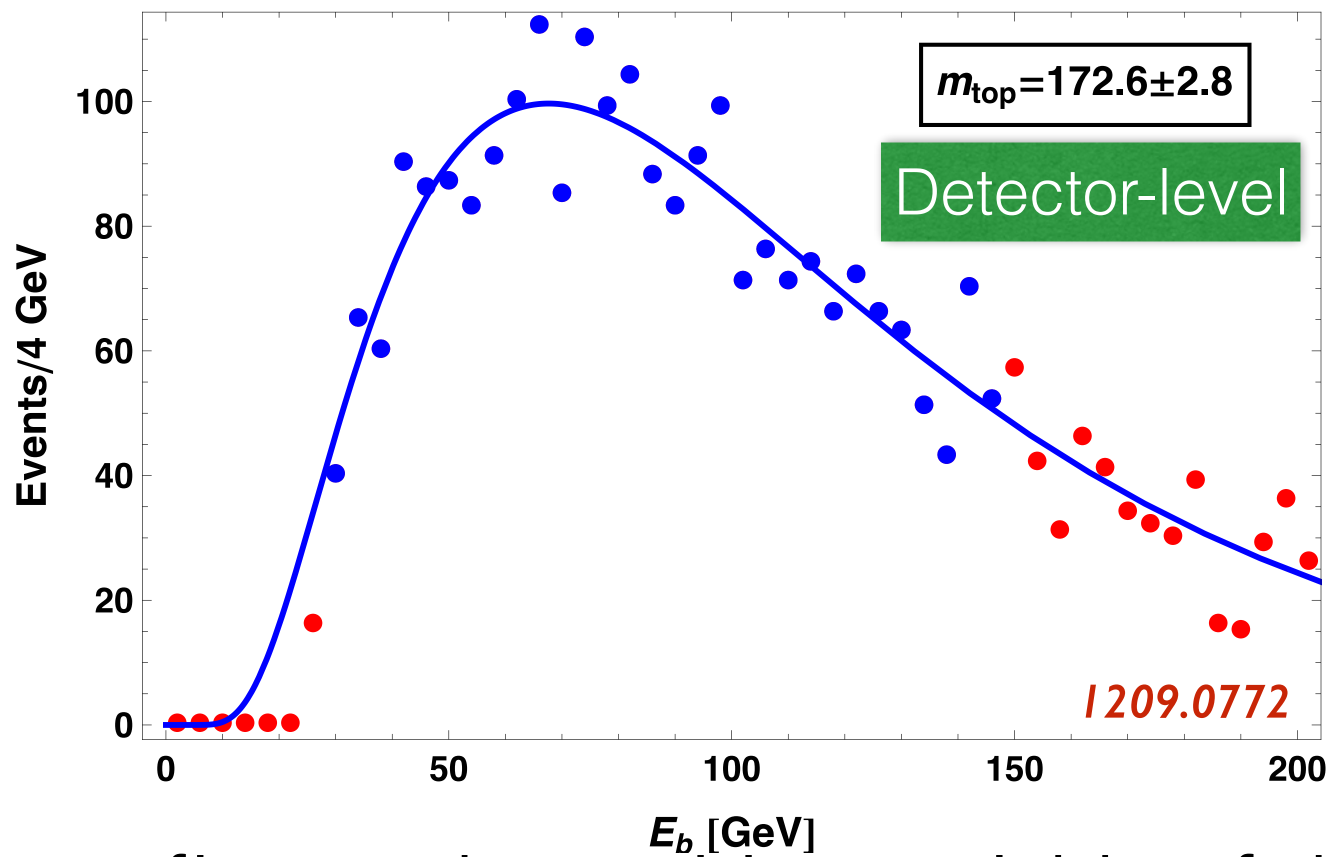
As long as it gives unpolarized real tops does not change the result

- properties similar to Lorentz invariants
- without the need to form combinations

Useful in practice?

b-**jet** energy

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

1209.0772 - Agashe Franceschini and Kim

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

very encouraging LO result with b-jet energy

after having explored a number of **new physics applications** of this idea

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

extension to NLO in progress

your inputs are very welcome

NLO virtues

Agashe, Franceschini, Kim, Schulze - in preparation

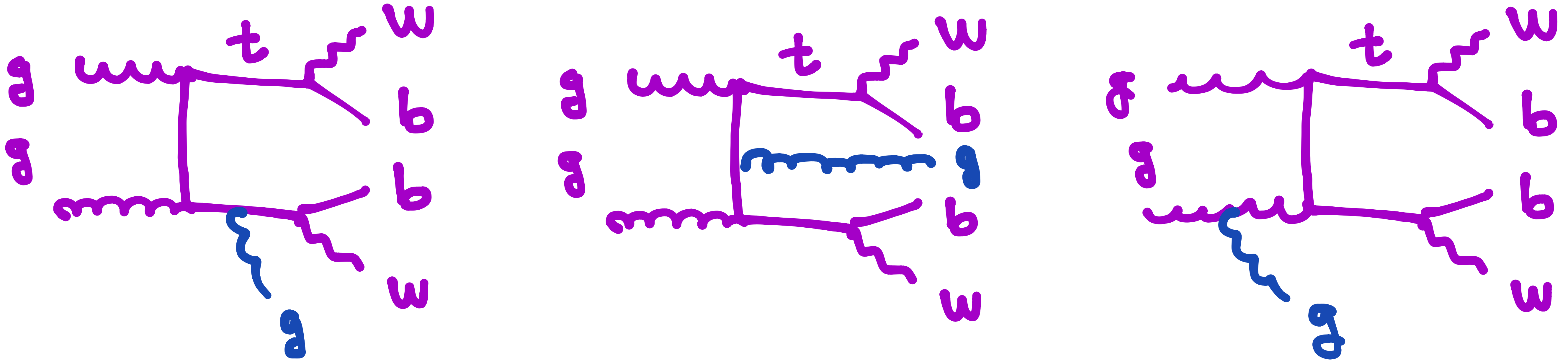
- **Invariance holds for pp→tt @ NLO**
- Not sensitive to Initial State Radiation
- Not sensitive to Parton Distribution Functions
- Not sensitive to the exact energy of the collider

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

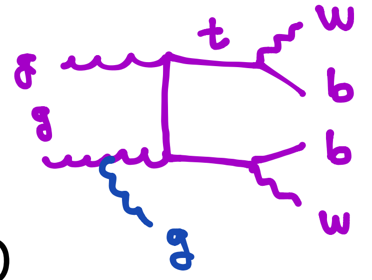
- Invariance holds for pp→tt @ NLO
- **Not sensitive to Initial State Radiation**
- Not sensitive to Parton Distribution Functions
- Not sensitive to the exact energy of the collider

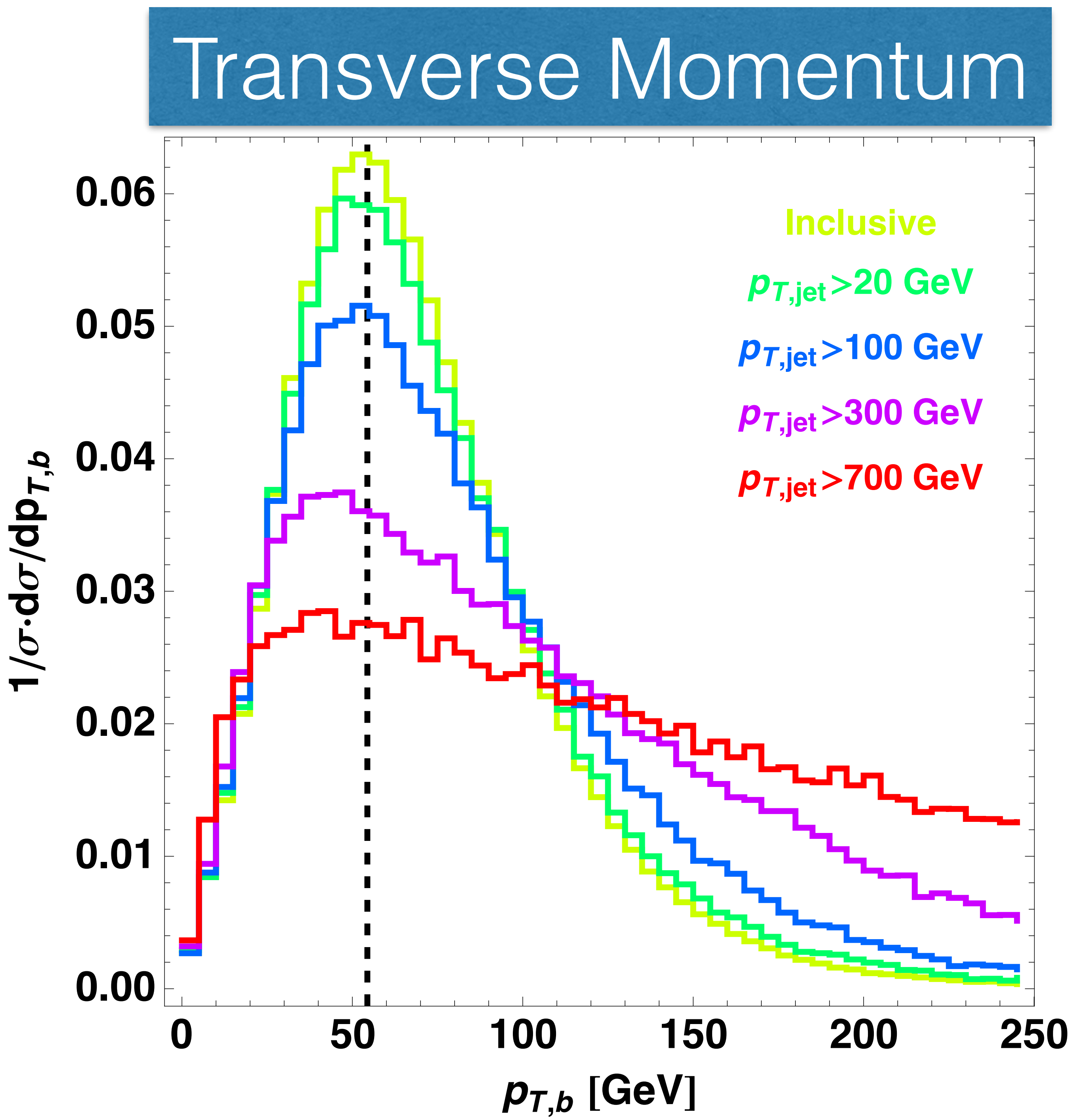
only sensitive to the NLO decay t→bWg

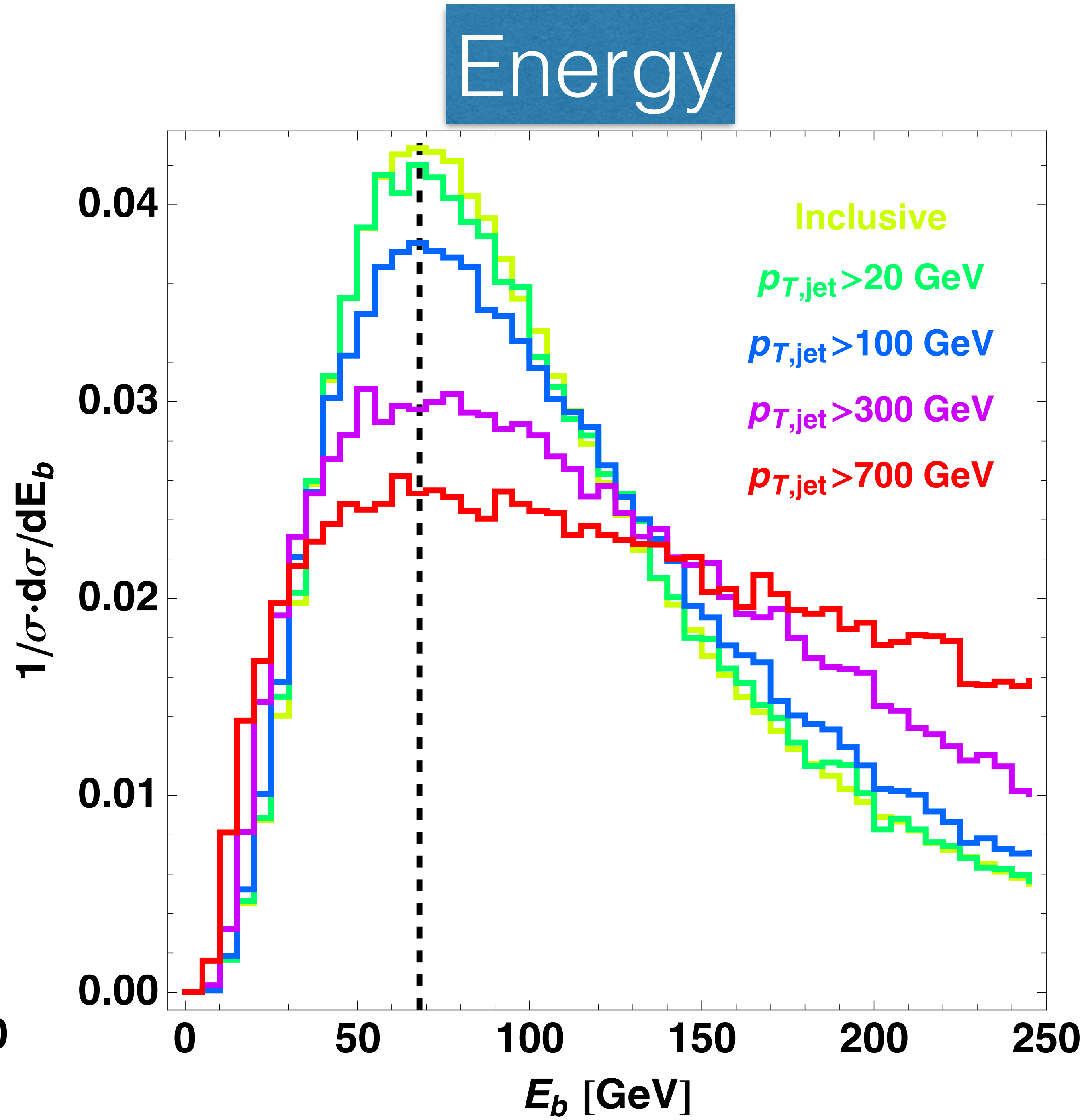
Effect of initial state radiation

ISR only affects the boost distribution of top

Agashe, Franceschini, Kim, Schulze - in preparation







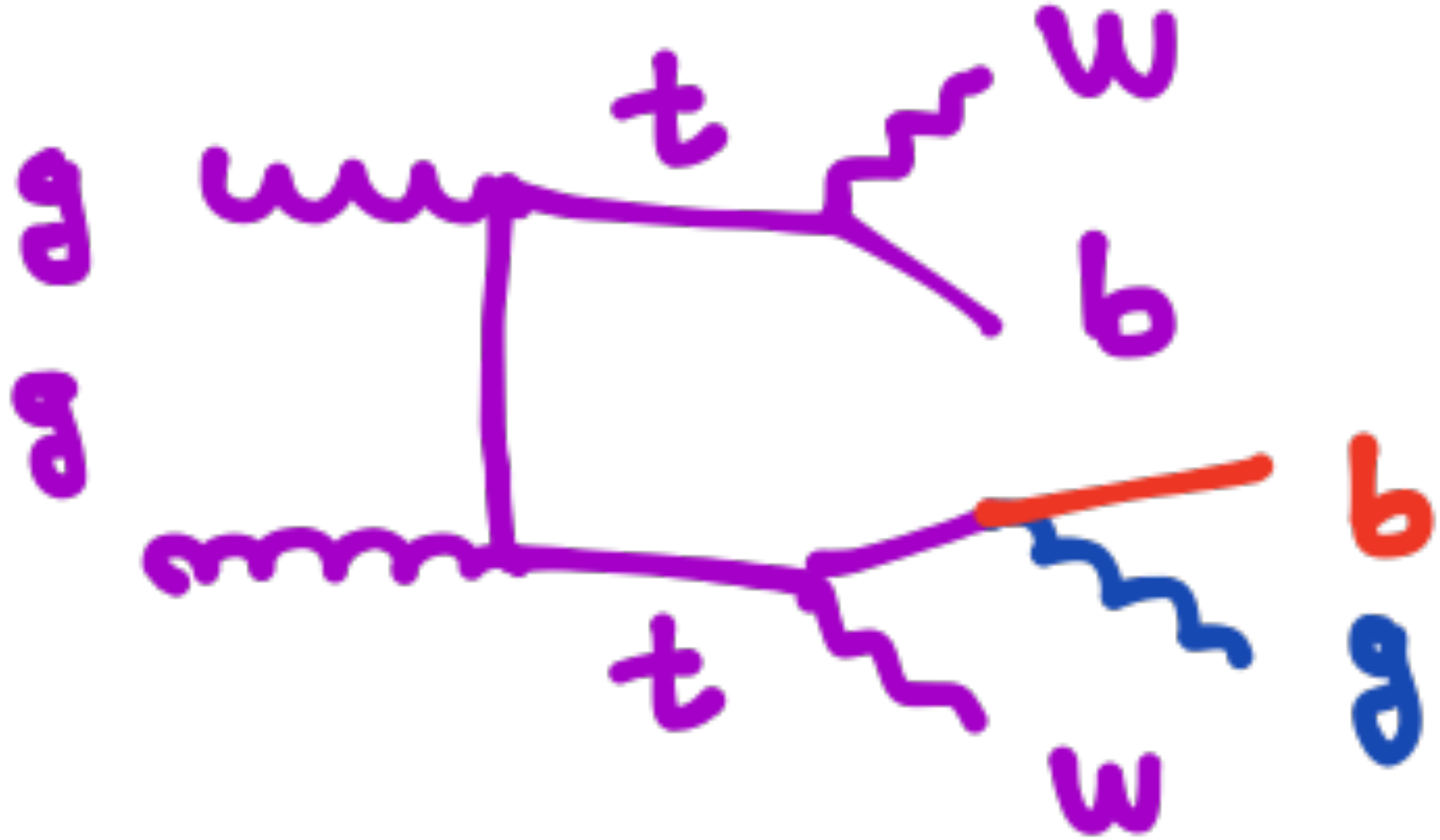
peak stability

NLO virtues

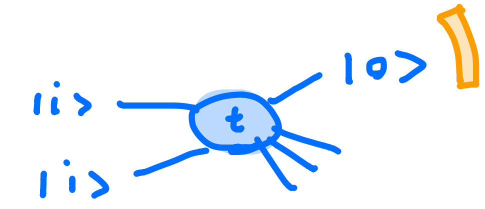
- Invariance holds for pp→tt @ NLO
- Not sensitive to Initial State Radiation
- **Not sensitive to Parton Distribution Functions**
- **Not sensitive to the exact energy of the collider**

only sensitive to the NLO decay t→bWg

Decay at NLO

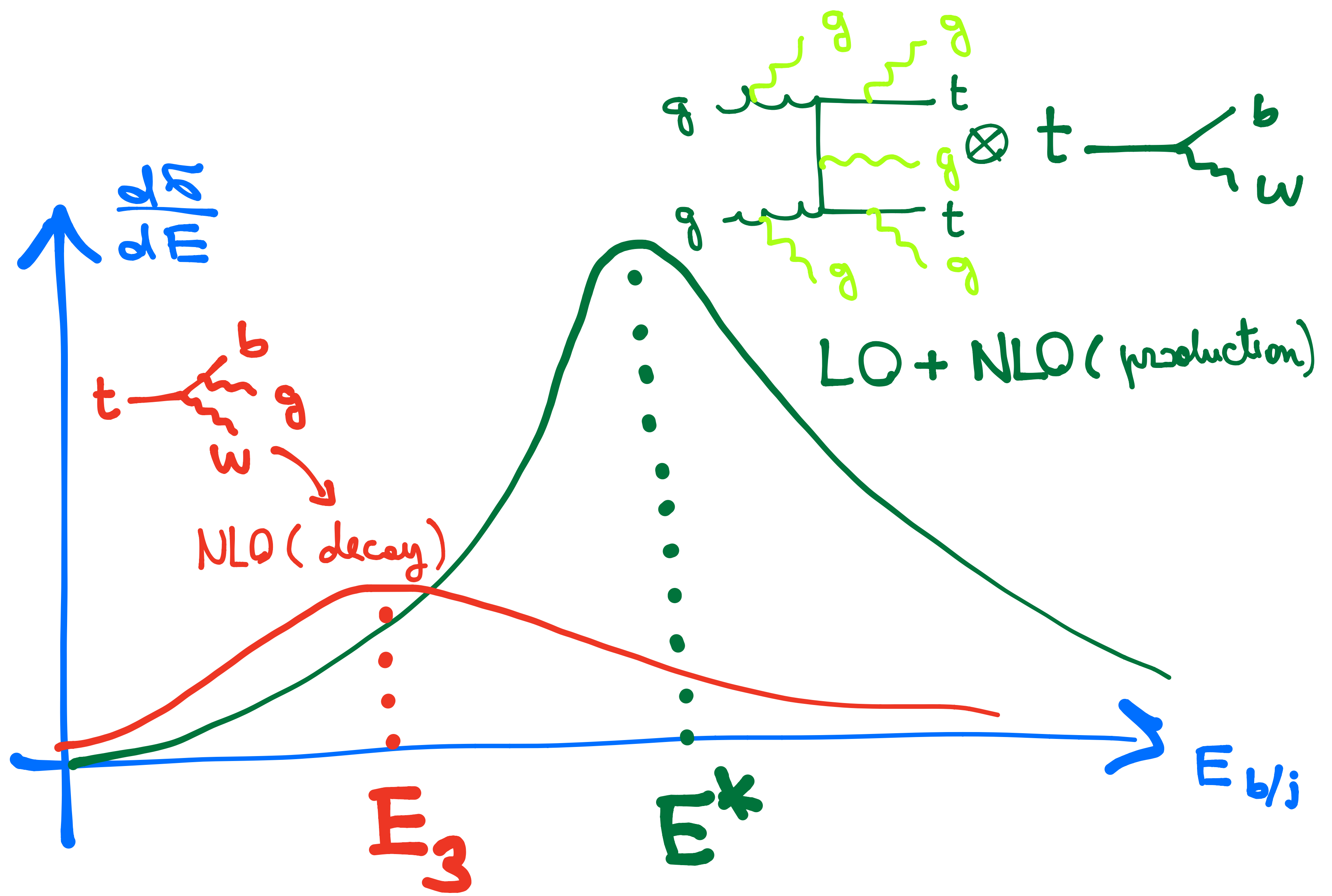


Peak shift at NLO



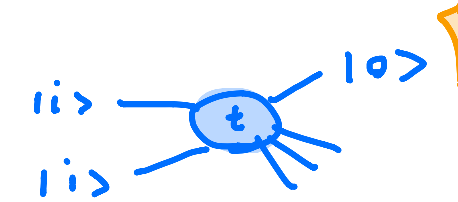
1212.5230 - Agashe, Franceschini, Kim, Wardlow

Agashe, Franceschini, Kim, Schulze - in preparation

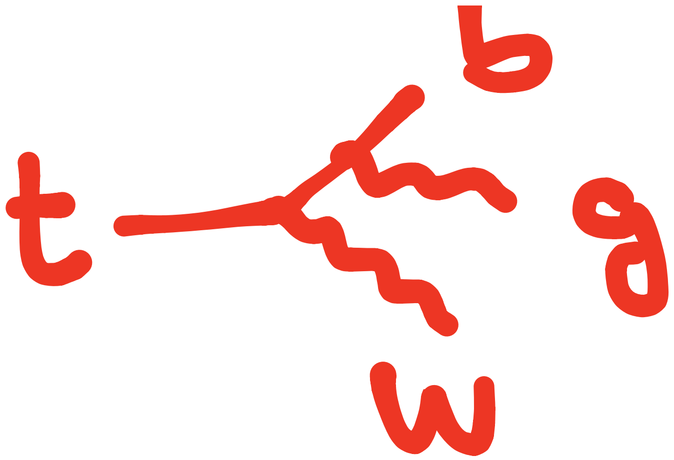


$$E^{peak} = E^{*} + O(1)\,\frac{\alpha}{4\pi}\,E_3$$

Peak shift at NLO

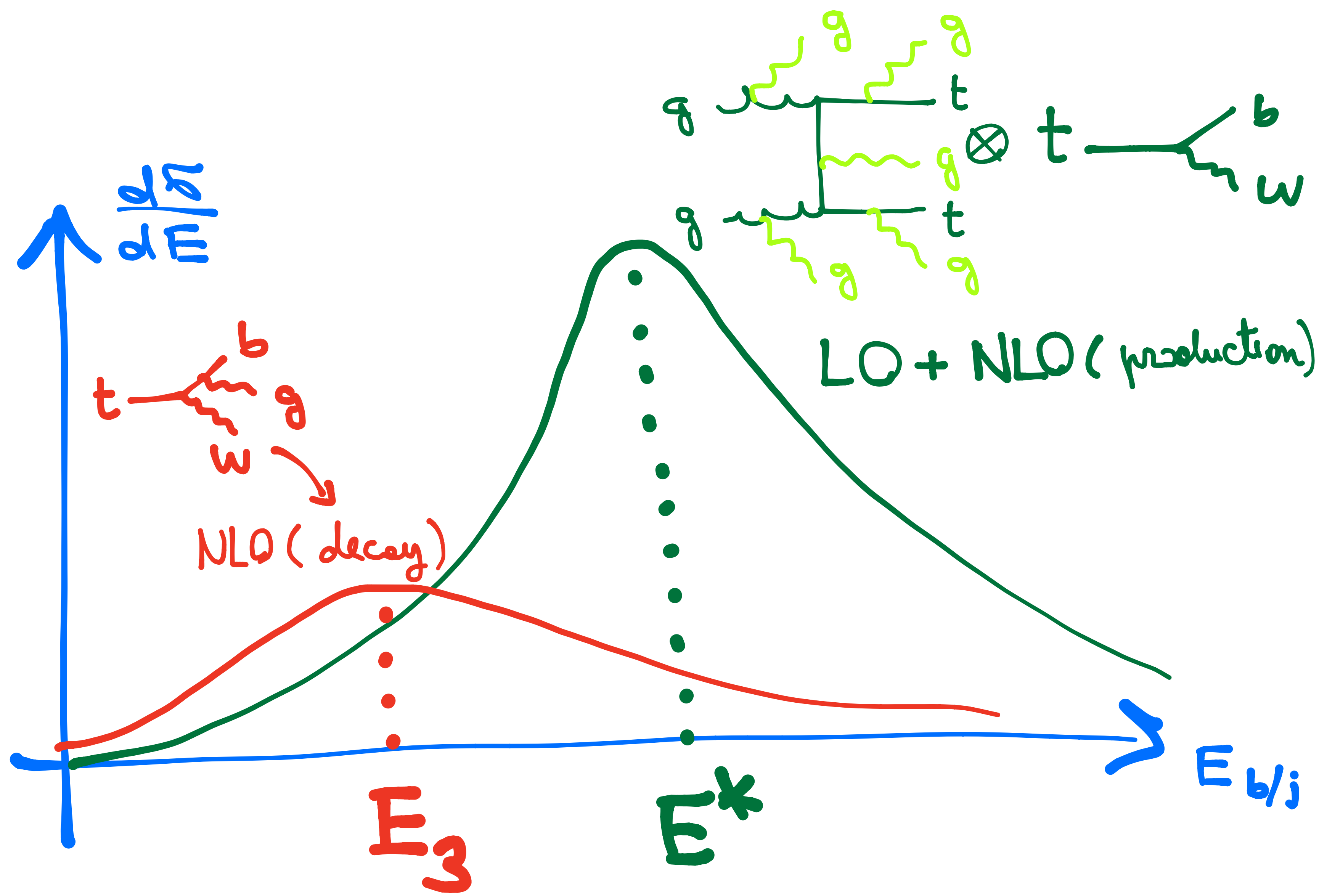


1212.5230 - Agashe, Franceschini, Kim, Wardlow
Agashe, Franceschini, Kim, Schulze - in preparation



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



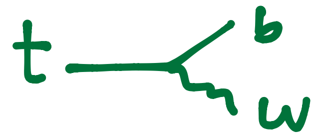
$$E^{peak} = E^*(1-\Delta_{TH}) + \Delta_{TH} E_3$$

Δ_{TH}=BR(t→bW**g**)/BR(t→bW)≃0.05

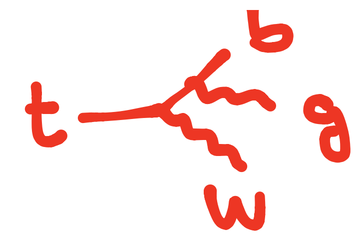
NLO: production & decay

(MCFM)

Agashe, Franceschini, Kim, Schulze - in preparation

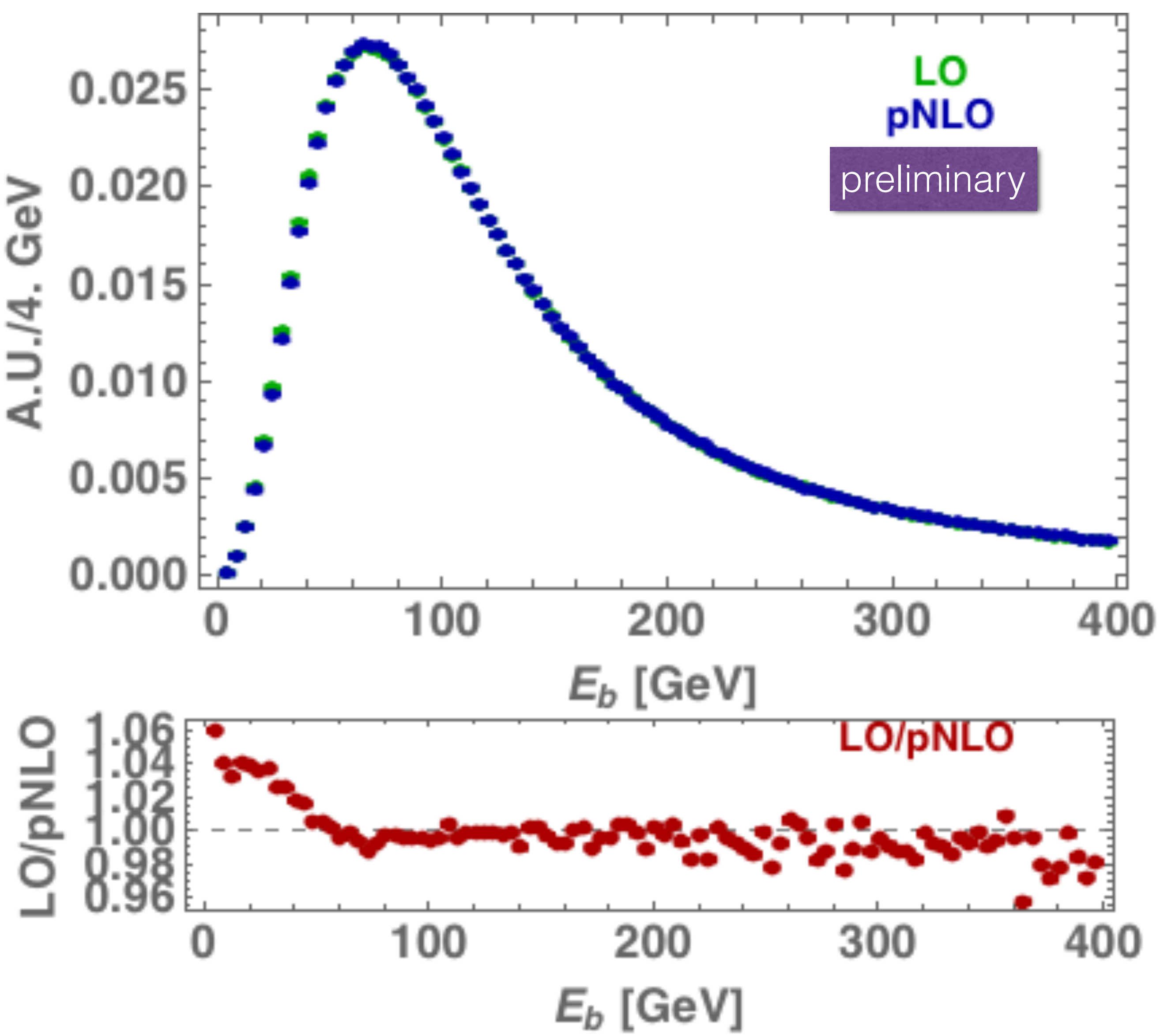


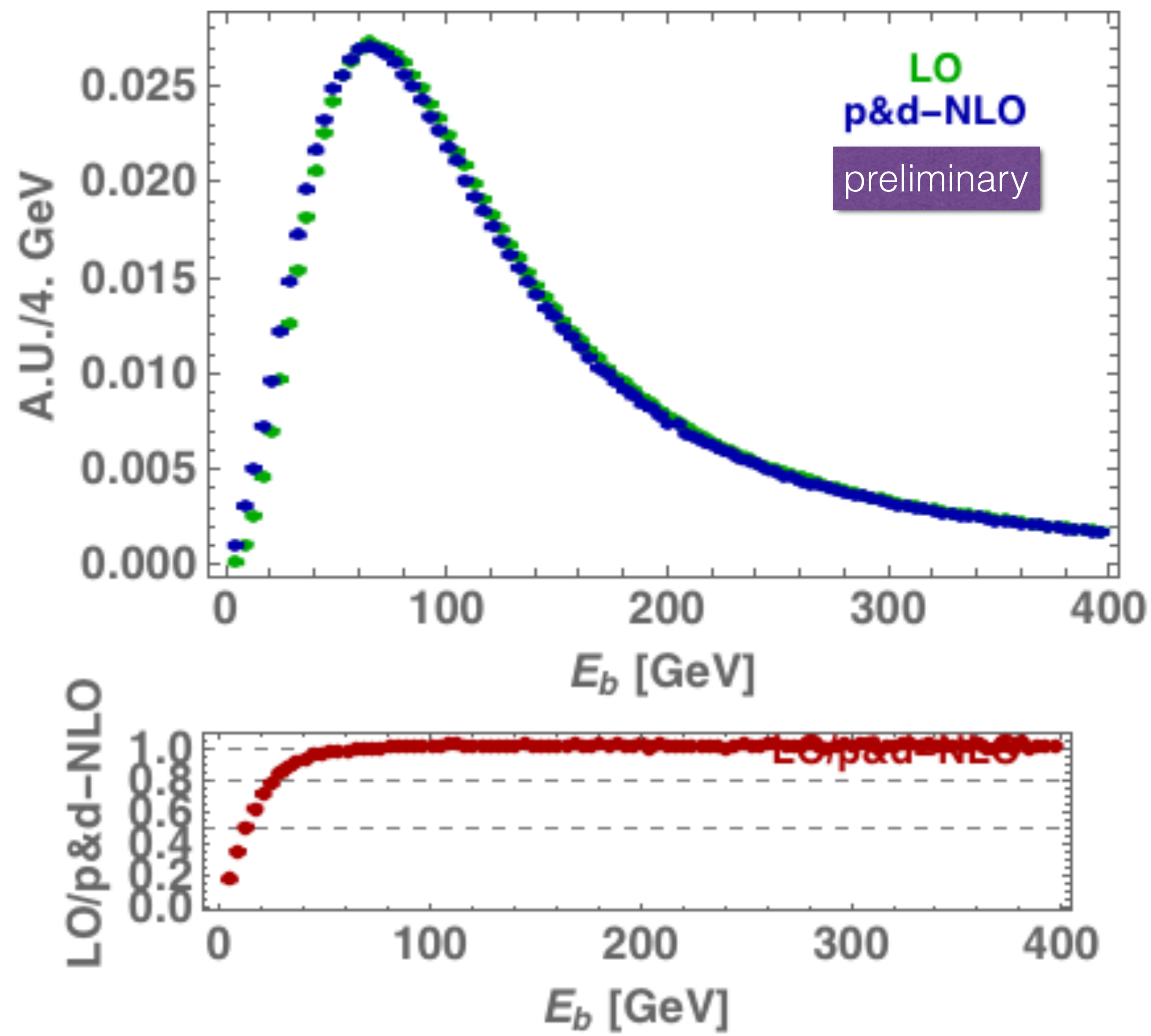
Energy of b

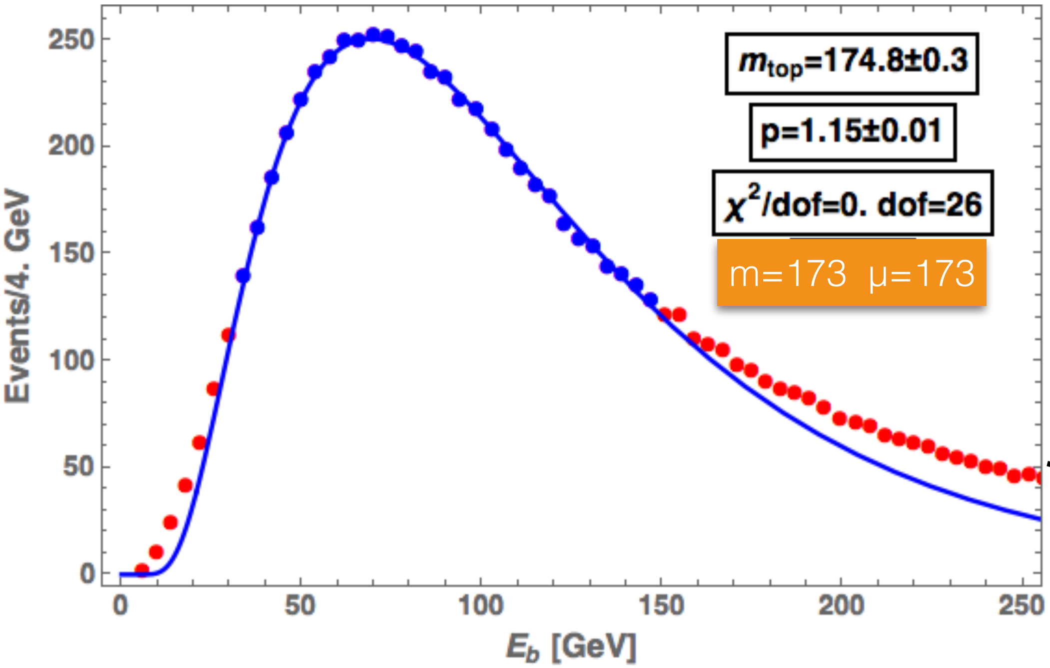


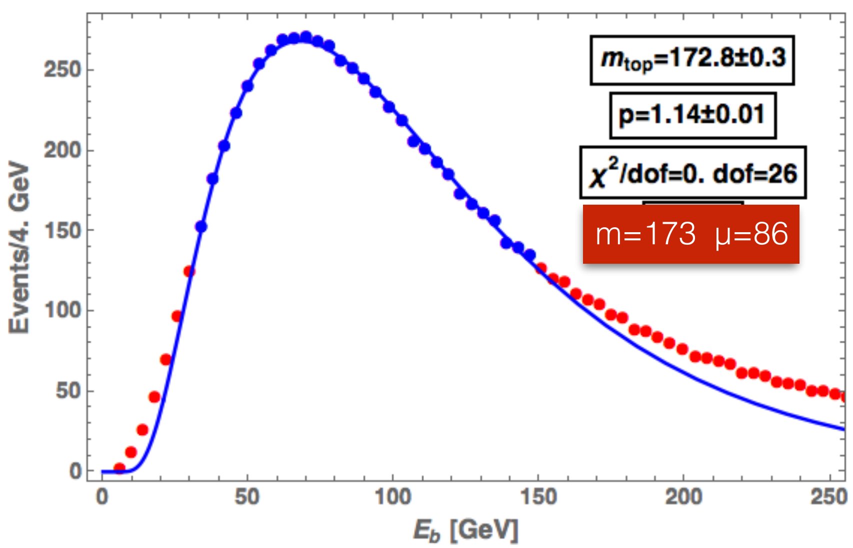
decay at LO

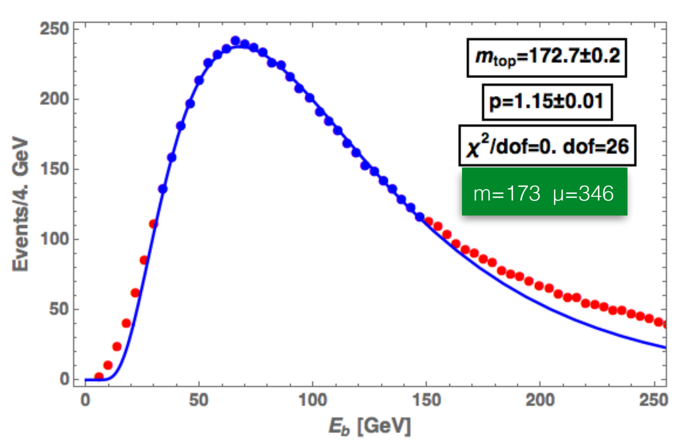
decay at NLO

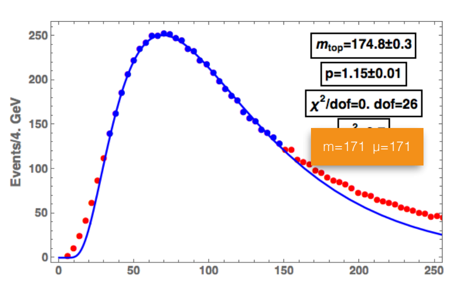


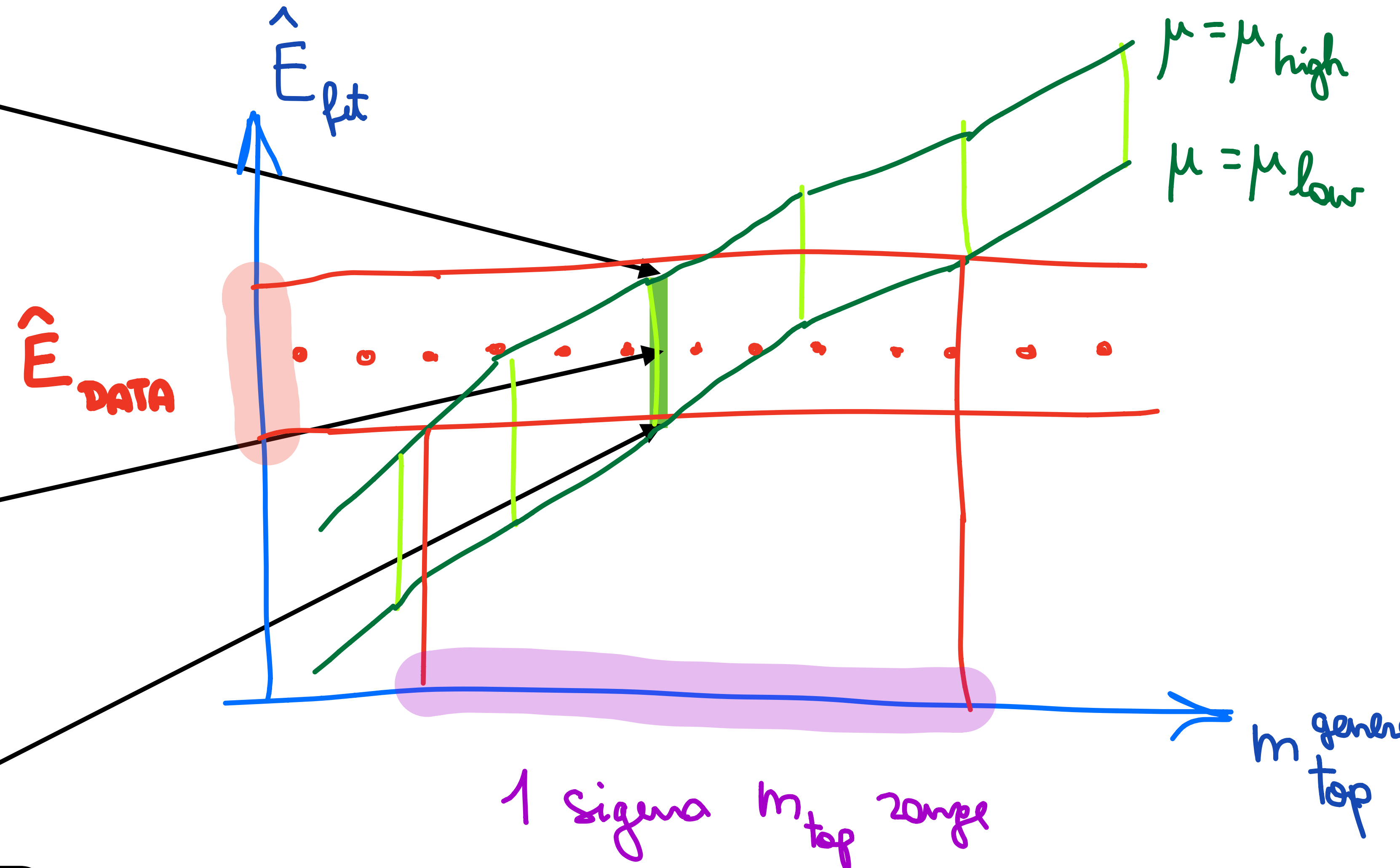












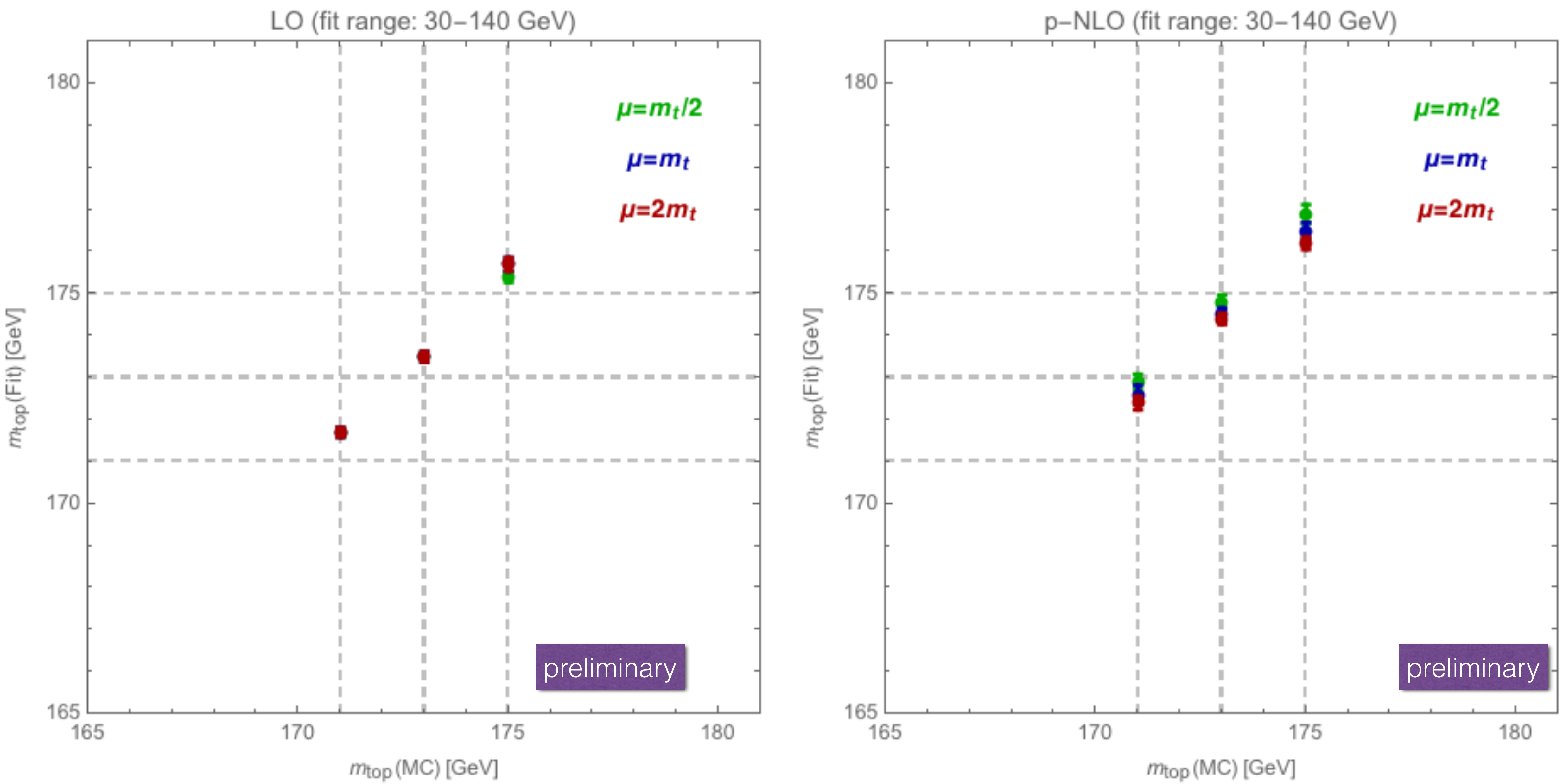
Best:

- narrow band between μ_{high} and μ_{low}
- steep E vs. m_{top} $E_b^* = \frac{m_t^2 - m_W^2 + m_b^2}{2 m_t}$

NLO: production

(MCFM)

Agashe, Franceschini, Kim, Schulze - in preparation

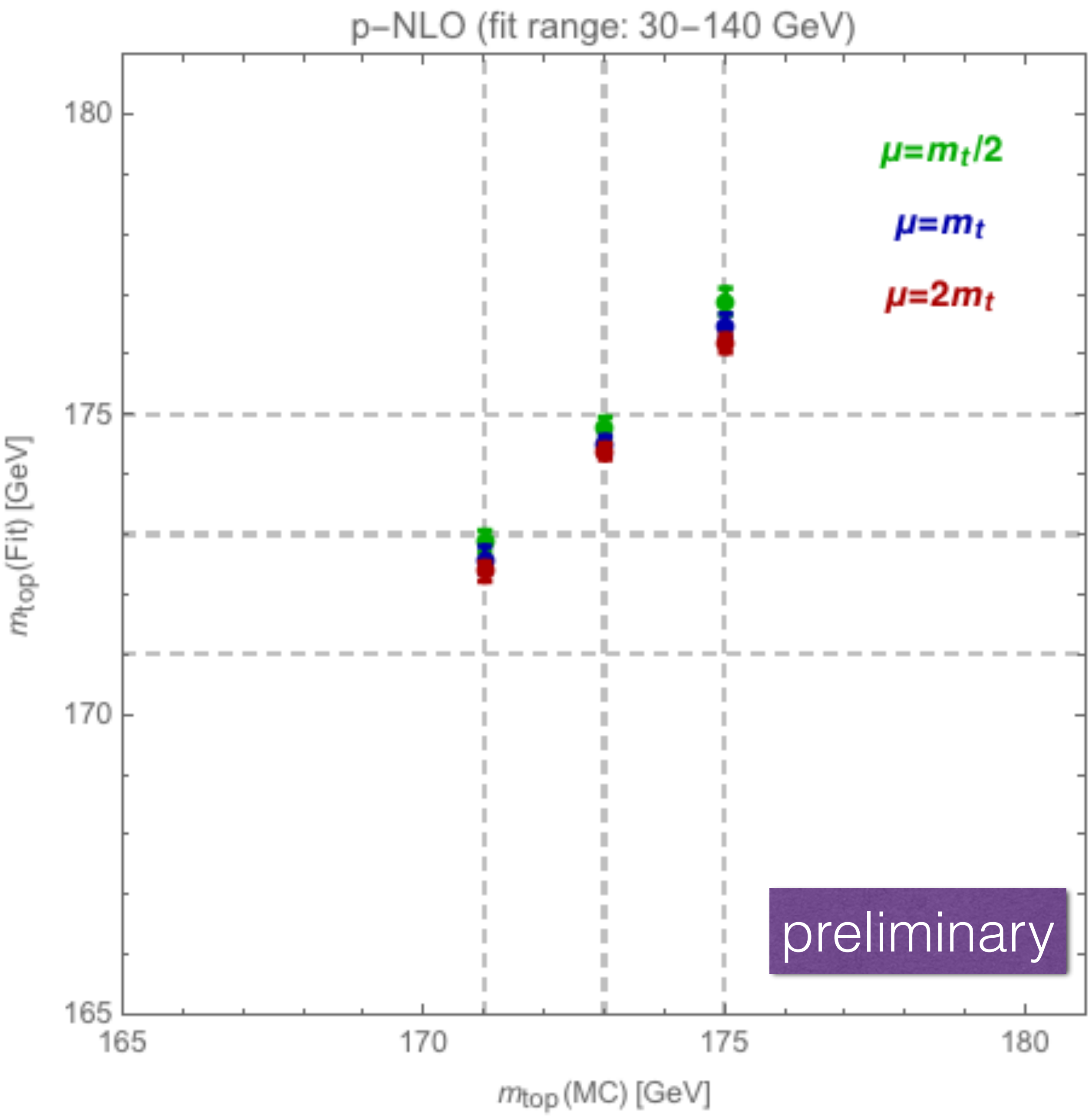


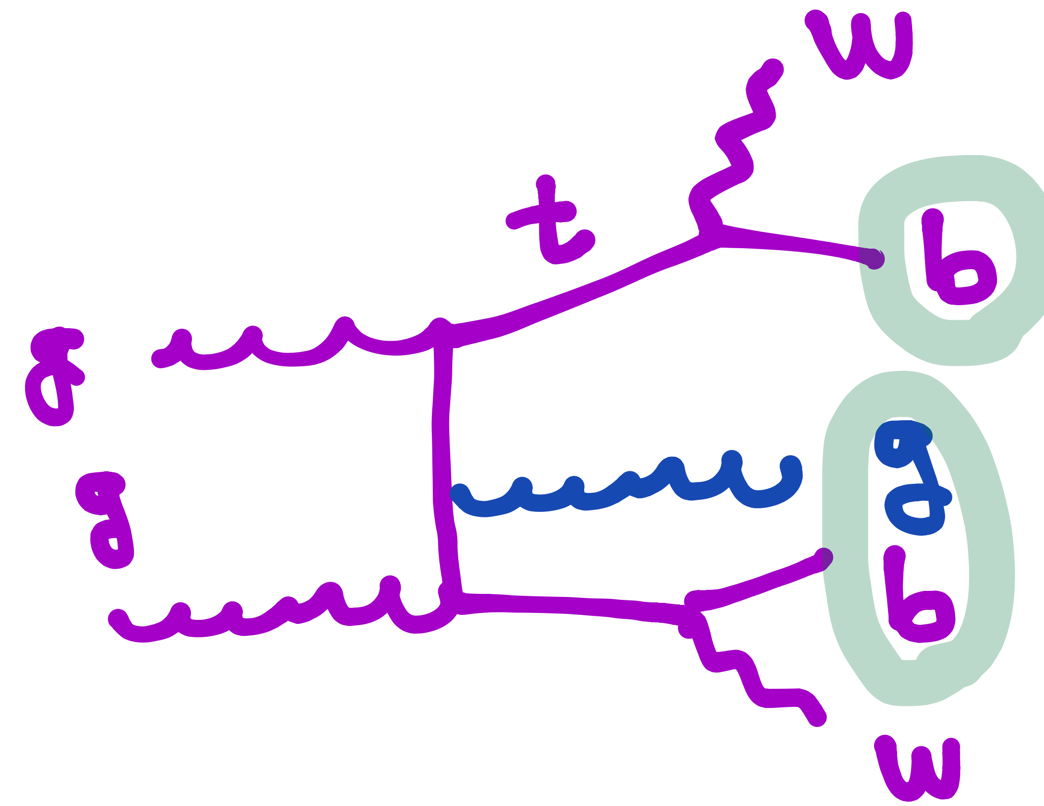
very little sensitive to the scale choice (less than 400 MeV on m_{top})

NLO: production

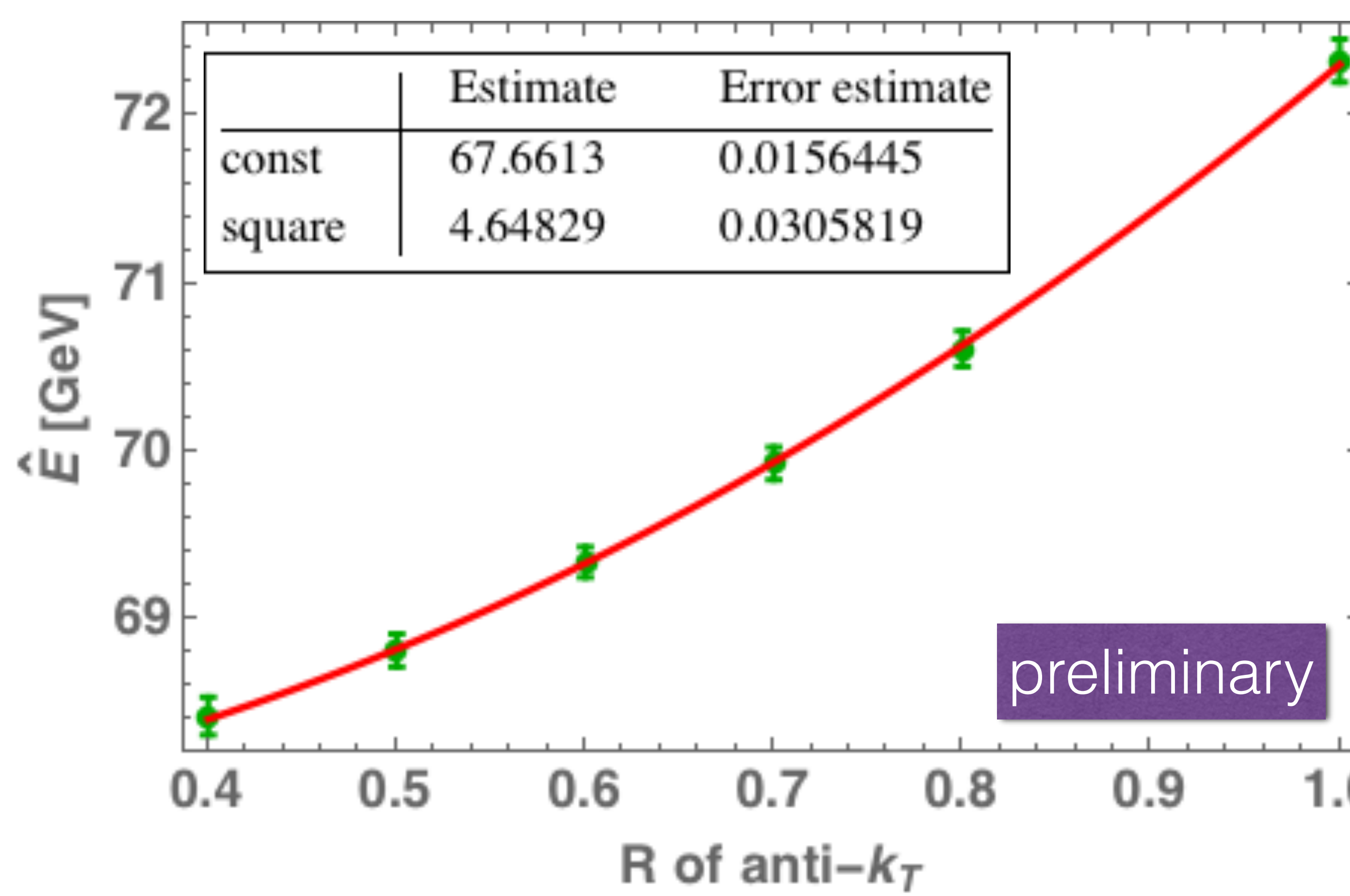
(MCFM)

Agashe, Franceschini, Kim, Schulze - in preparation



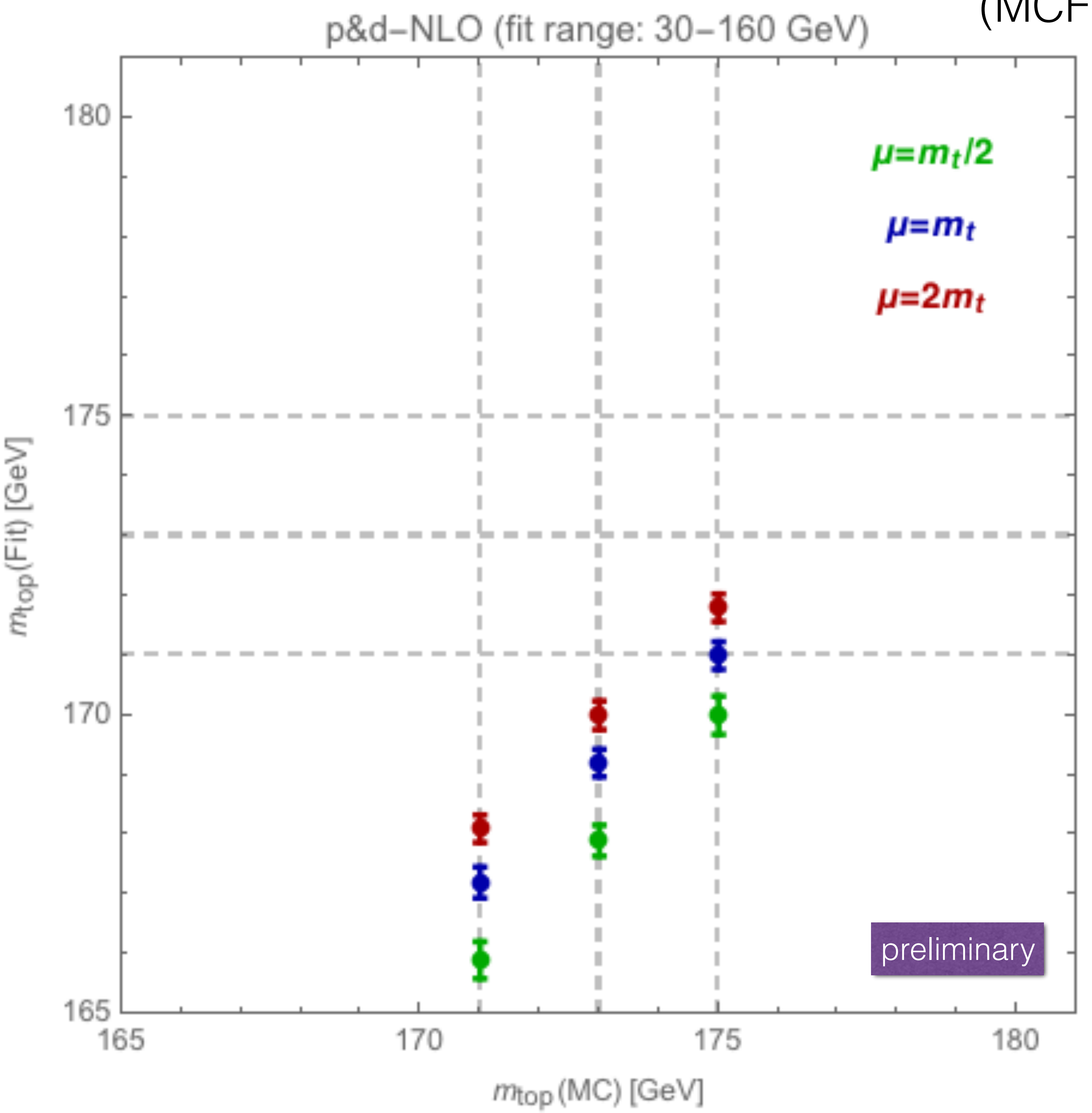


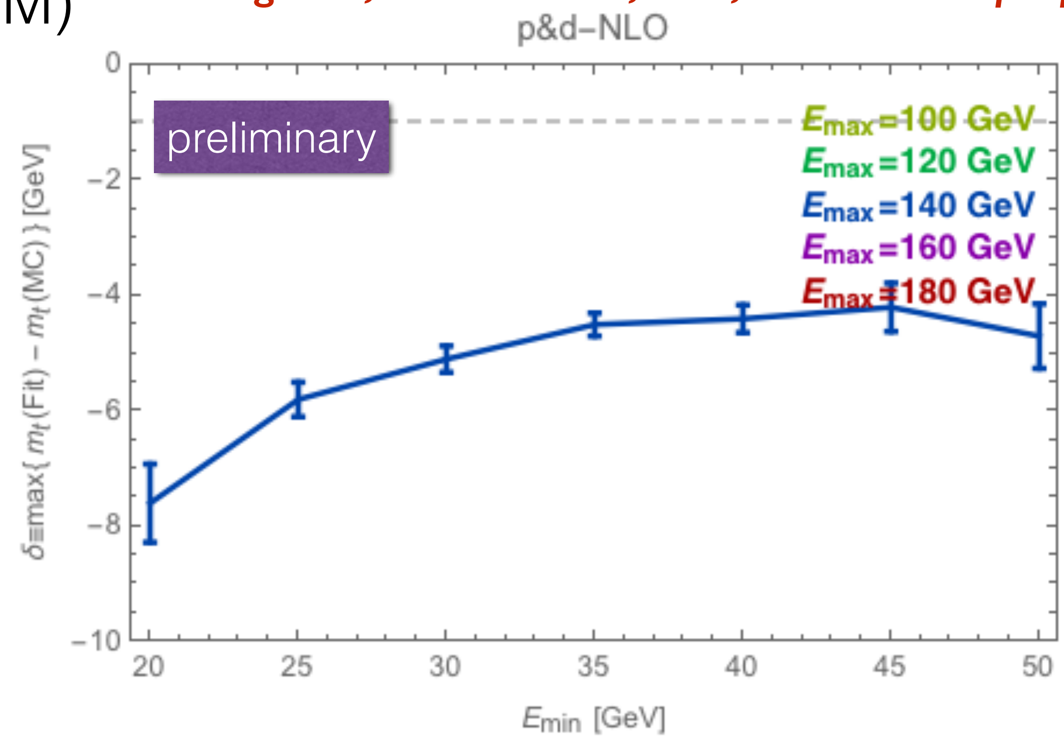
shift ~ R^p (p~2 jet area)
shift ~ 1/μ (real radiation)

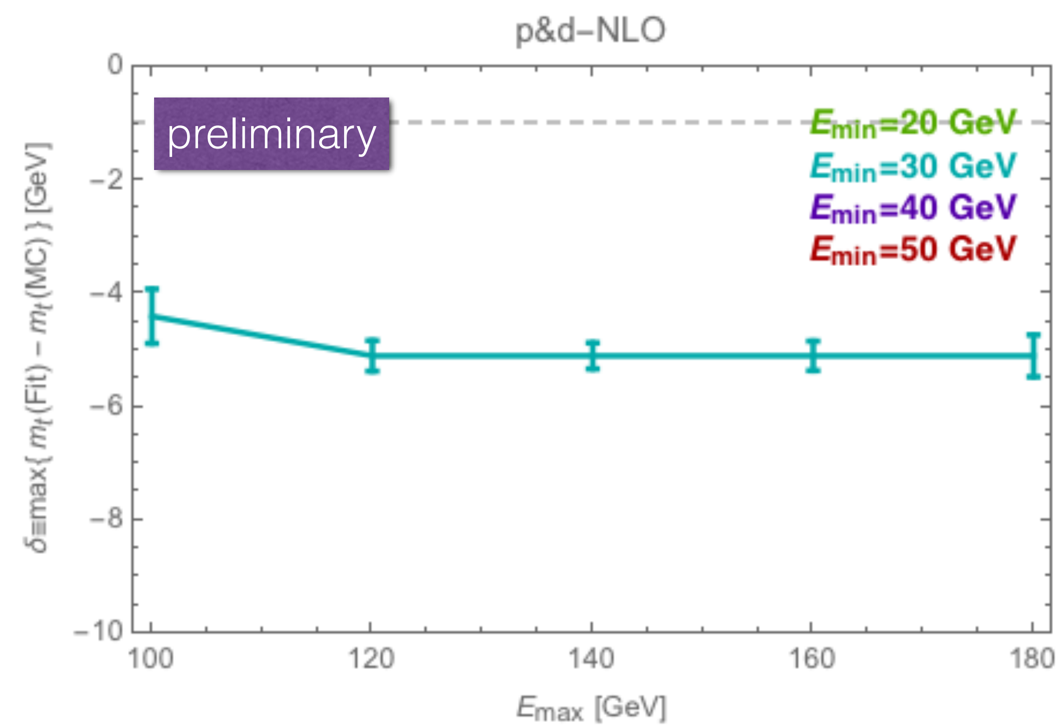


NLO: production & decay

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



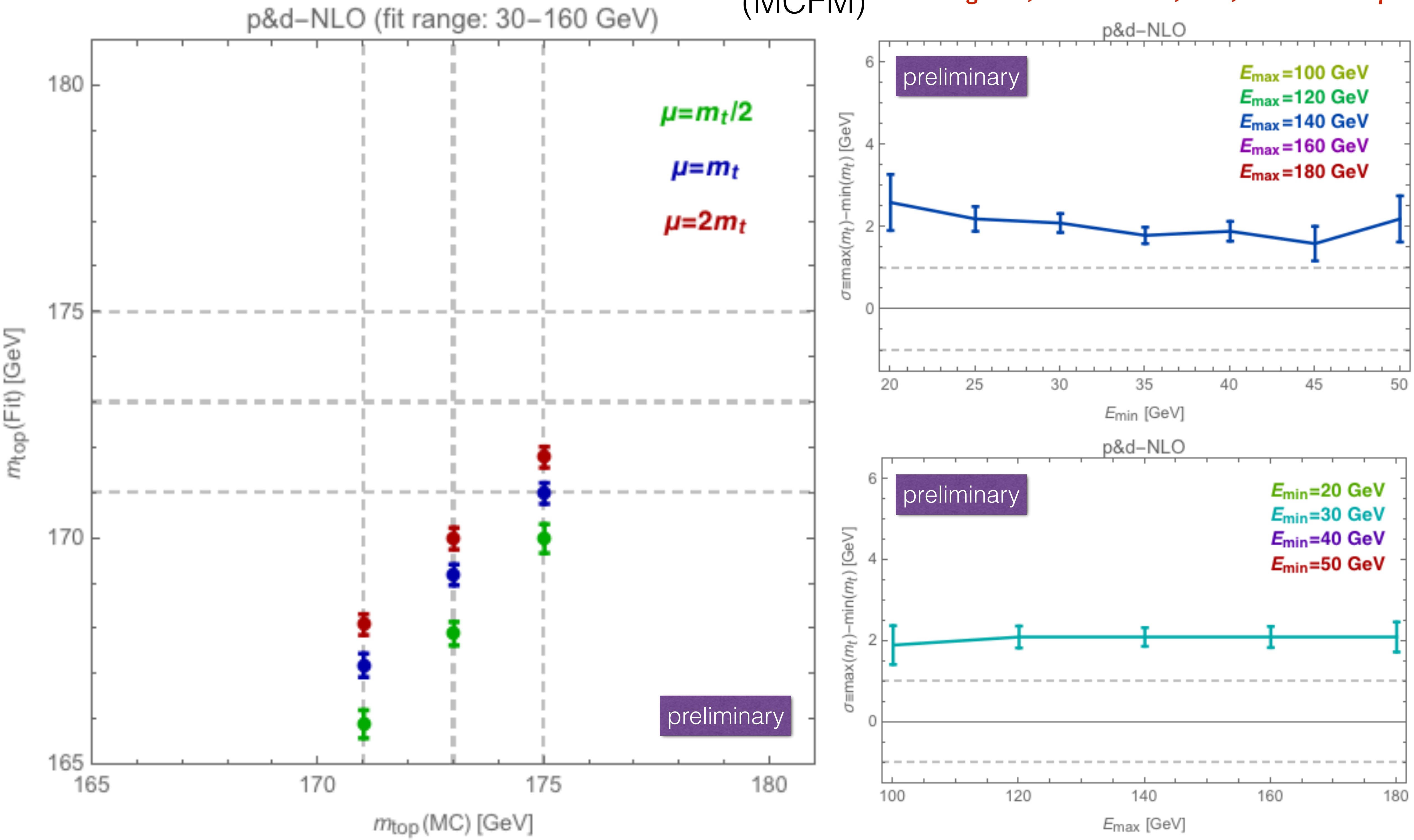




decay NLO sensitive to the scale choice: ±1 GeV on m_{top}

NLO: production & decay

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

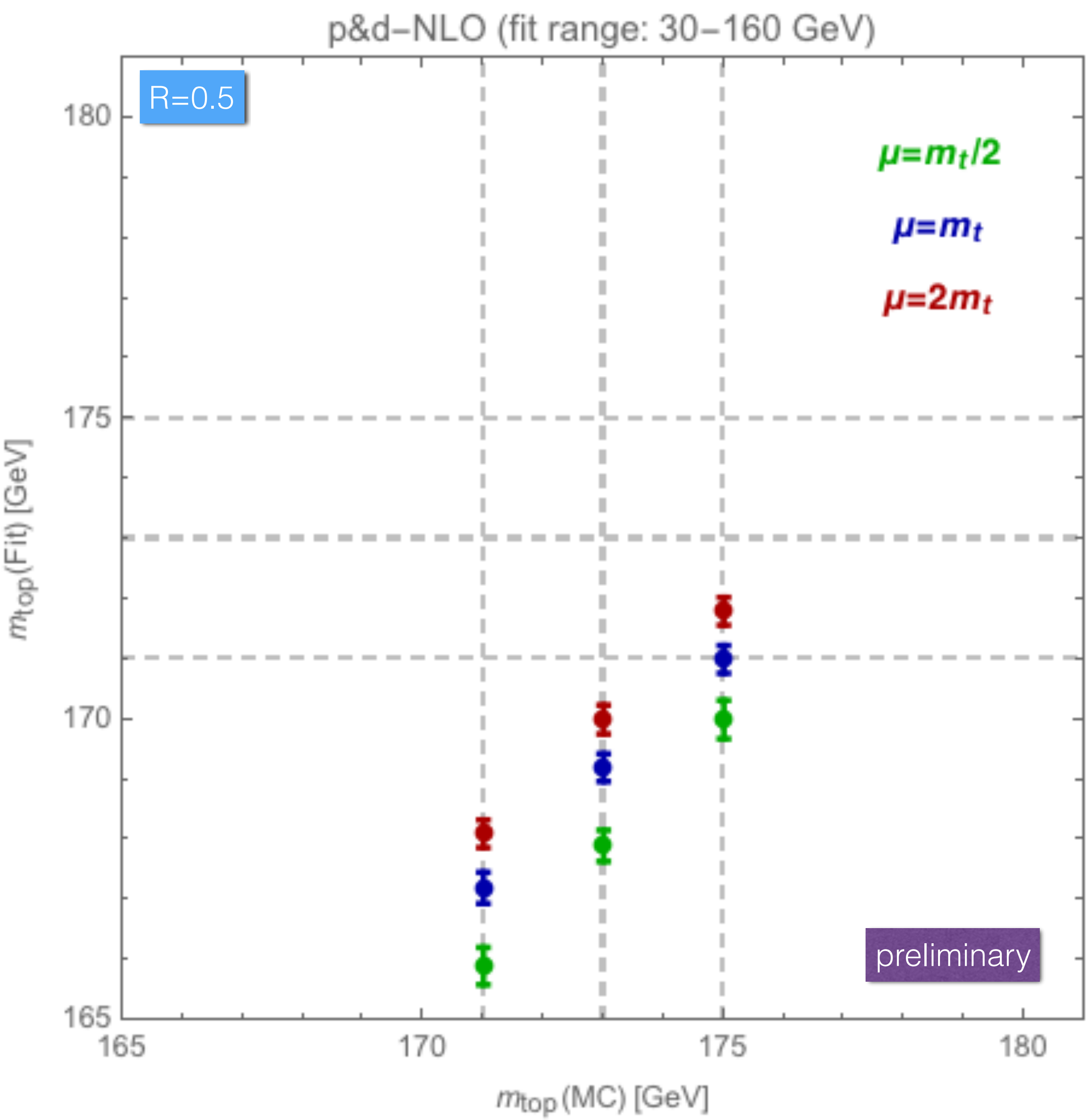


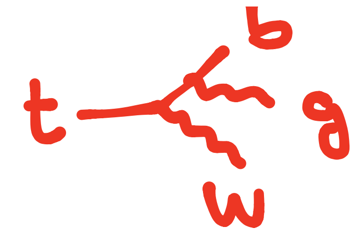
decay NLO sensitive to the scale choice: ±1 GeV on m_{top}

NLO: production & decay

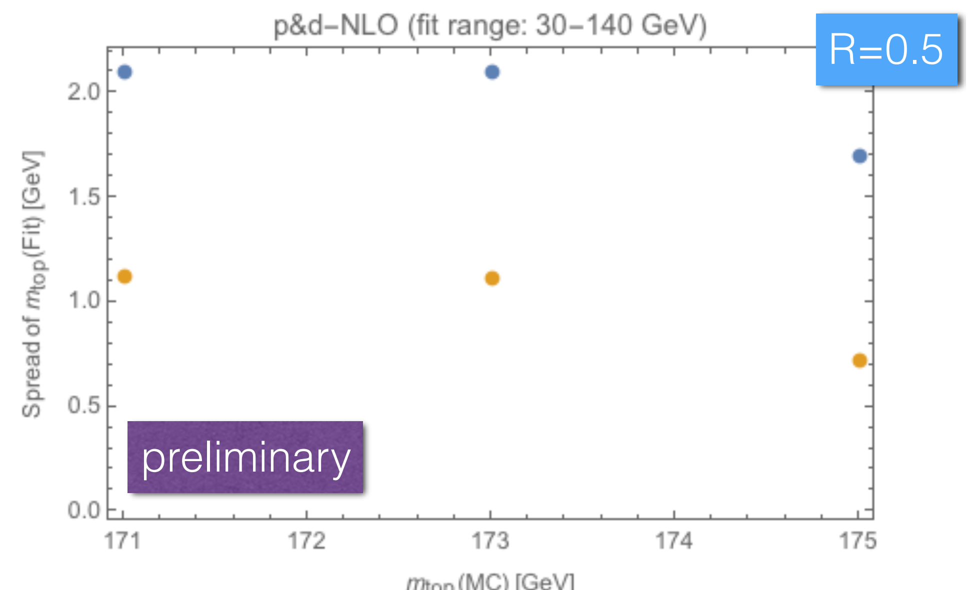
(MCFM)

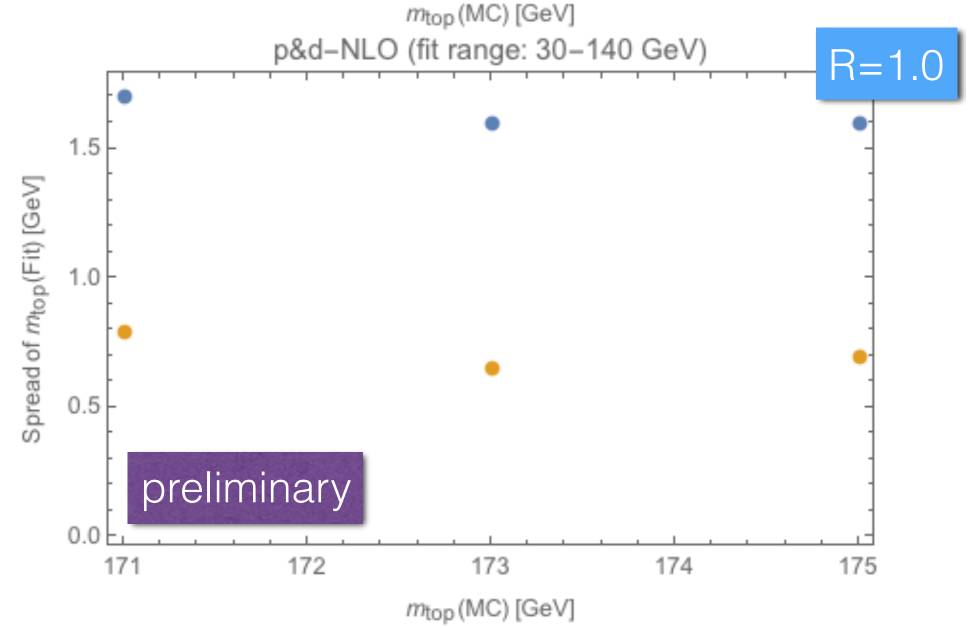
Agashe, Franceschini, Kim, Schulze - in preparation





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





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

Mild corrections from NLO

Agashe, Franceschini, Kim, Schulze - in preparation

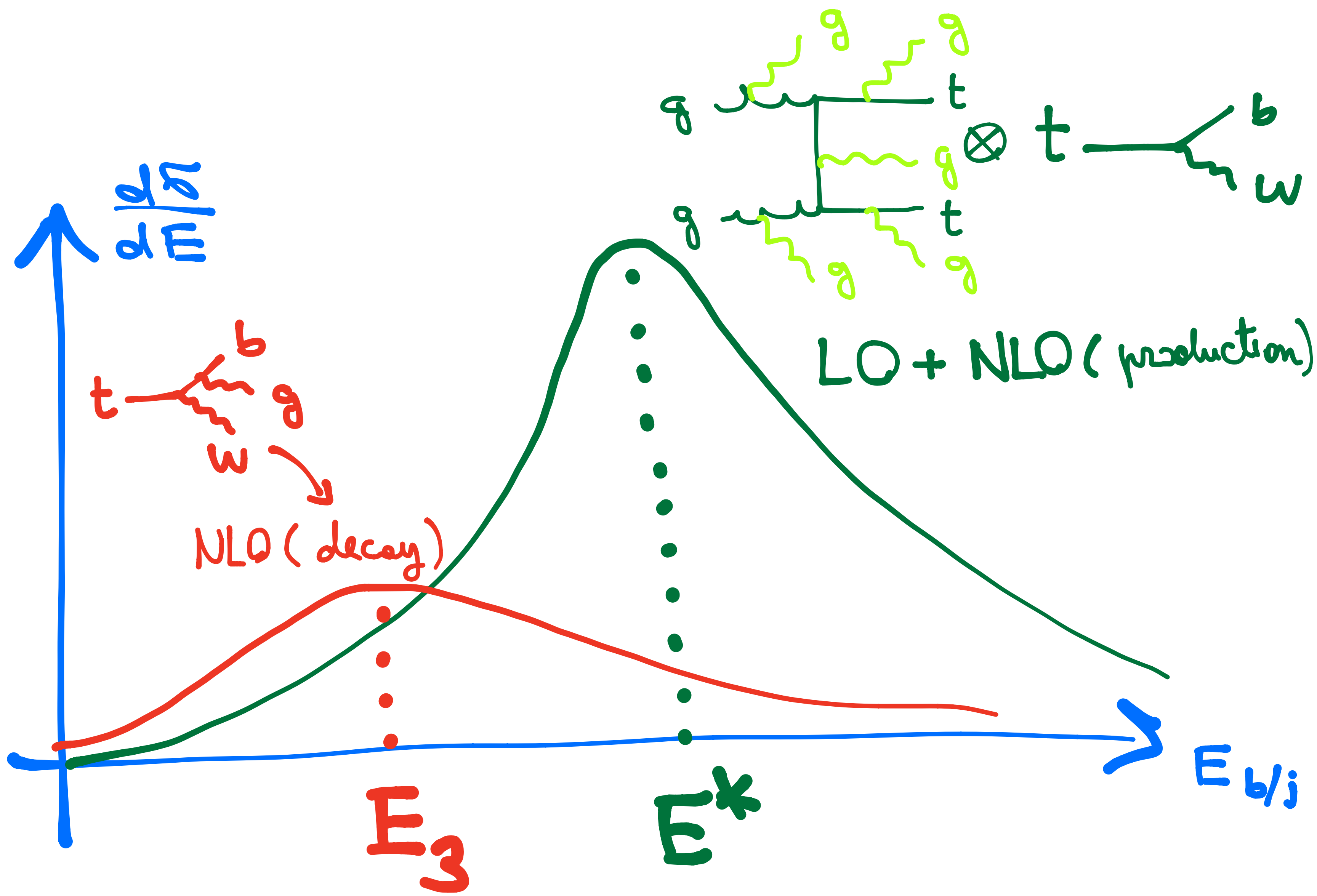
$$\hat{E} = E^*_{LO} \cdot \left[1 + f_{pol} + \epsilon_{FSR} \left(C_{bWg} + \underbrace{\delta_{int} + \delta_{PDFs} + \ldots}_{\delta_{prod}} \right) \right]$$

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

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

jet veto?

Agashe, Franceschini, Kim, Schulze - in preparation



t→bW**g** removed by a jet-veto? how about veto-uncertainties?

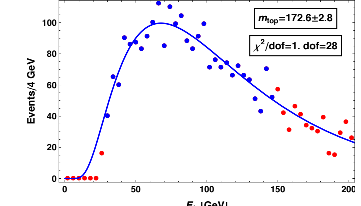
No quarks in the real world

. . .

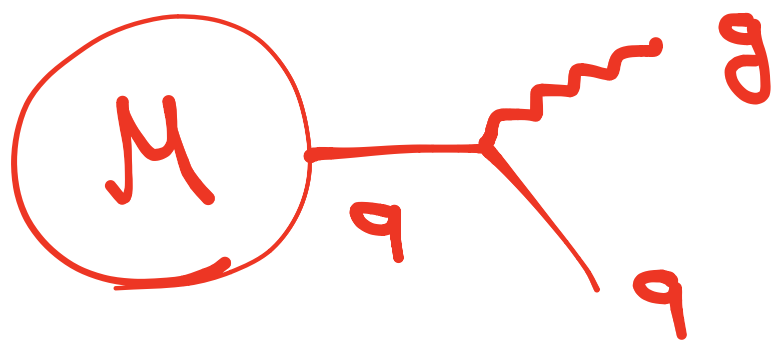
- b-jet observables *Agashe, Franceschini and Kim - in preparation*
  - jet **energy**

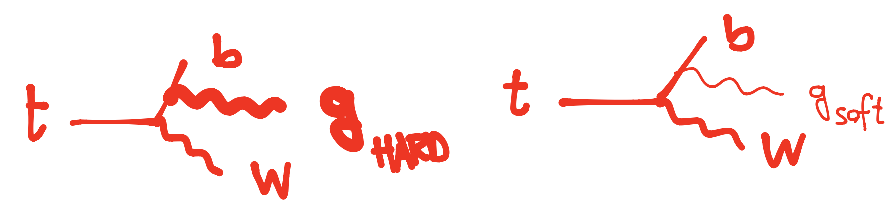
- B-hadron observables *Agashe, Franceschini and Kim - in preparation*
  - hadron **energy**
  - hadron **boost**
  - hadron **decay length**

Shower effects

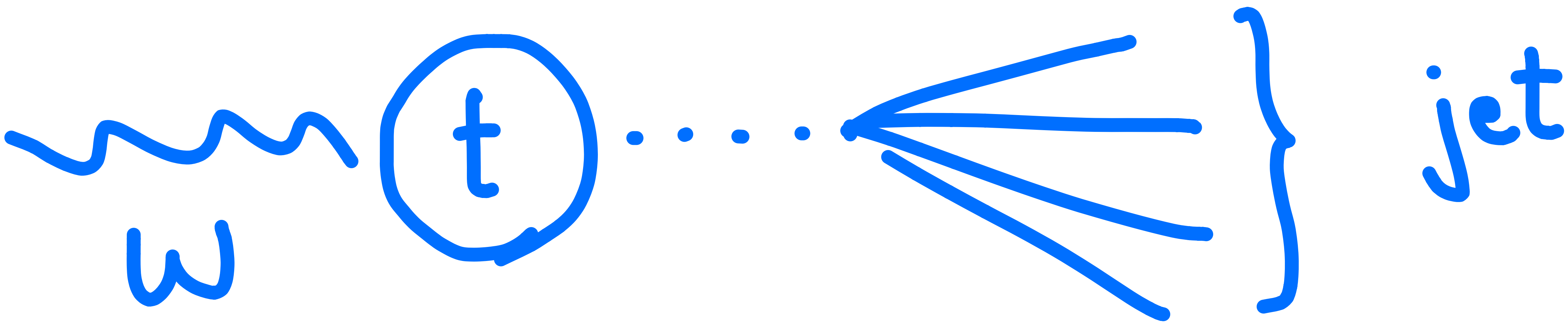


Agashe, Franceschini and Kim - in preparation





$$d\sigma(M+g) \propto d\sigma(M)\,\frac{d\vartheta}{\vartheta}\,\frac{dE_g}{E_g}$$



- the log-enhanced part of the phase-space is clustered in jets ⟶ use **jet mass**
- hard gluons are suppressed by $\alpha/4\pi$ ⟶ mild corrections

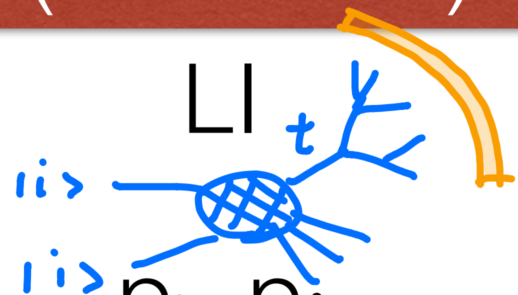
a case for fixed order or resummed energy distributions?

variations around Lorentz Invariance

needs two particles (combinations)

needs just one particle

LI

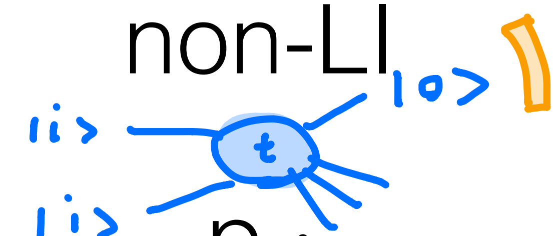


$p_b \cdot p_\ell$

“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

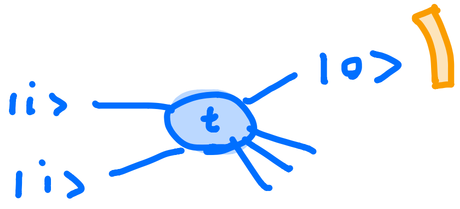
what is the “small parameter” Δ_{TH} that “breaks” (true or effective) LI?

Σ

We are not alone …

1405.2395

Generalized medians

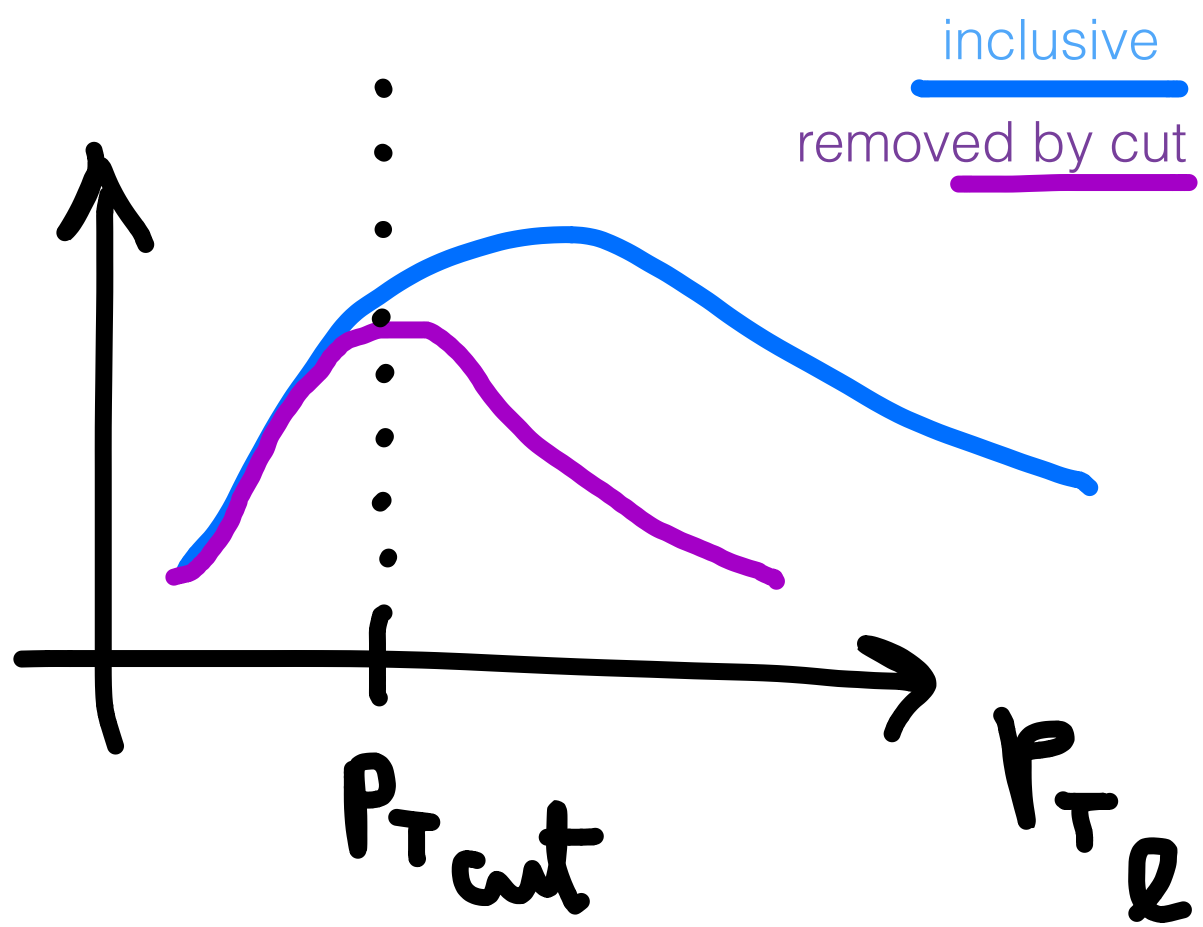


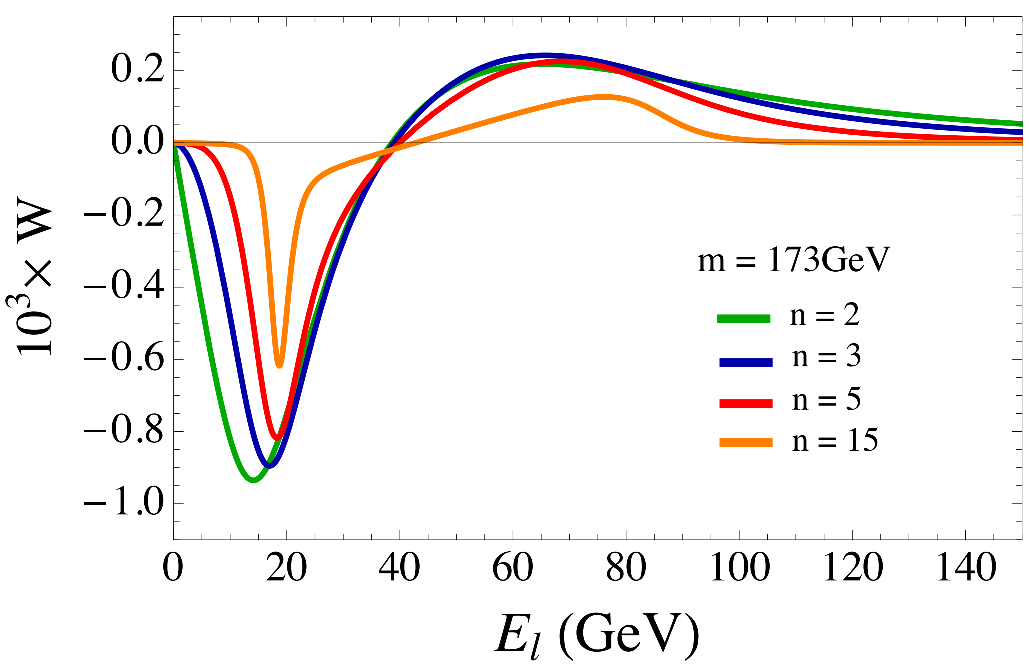
1405.2395

$$I(m)_w = \int dE_\ell \frac{d\Gamma}{dE_\ell} \cdot w(E_\ell, m)$$

inclusive integral over the lab-frame lepton Energy

$$\boxed{I(m=m_t)_w = 0}$$





		Signal stat. error	Fac. scale (signal)	JES (signal)	Background stat. error
n	2	0.4	$+1.5/-1.6$	$+0.0/-0.1$	0.4
	3	0.4	$+1.5/-1.5$	$+0.1/-0.3$	0.4
	5	0.5	$+1.4/-1.4$	$+0.2/-0.4$	0.5
	15	0.5	$+1.5/-1.3$	$+0.2/-0.6$	0.6

$\Delta_{TH} \sim 1 - \sigma_{exclusive}/\sigma_{inclusive} \sim 1$ - efficiency ~ 0.2

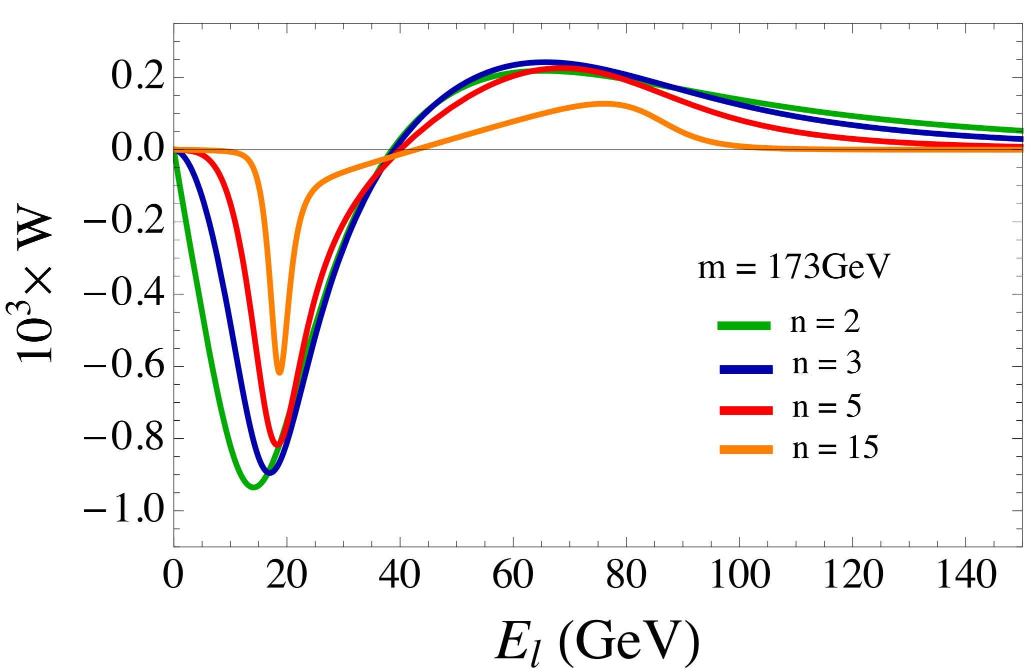
Generalized medians

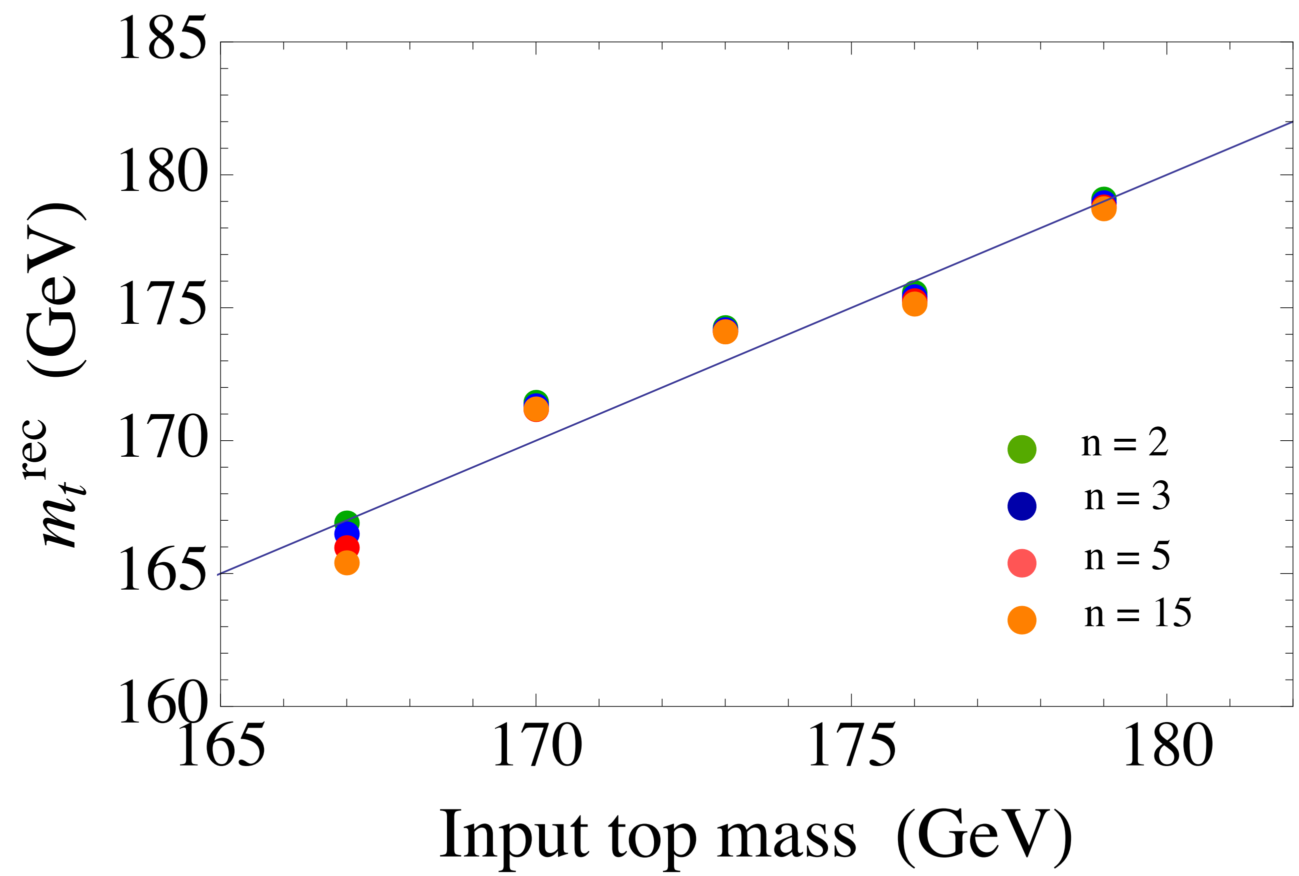
1405.2395

$$I(m)_w = \int dE_\ell \, \frac{d\Gamma}{dE_\ell} \cdot w(E_\ell, m)$$

inclusive integral over the lab-frame lepton Energy

$$\boxed{I(m = m_t)_w = 0}$$





Input top mass(GeV)	167	170	173	176	179
m_t^{rec}(GeV)	166.9	171.4	174.2	175.6	179.1

$\Delta_{TH} \sim 1 - \sigma_{exclusive}/\sigma_{inclusive} \sim 1$ - efficiency ~ 0.2

beyond JES …

More (B <u>hadron</u>) peak observables

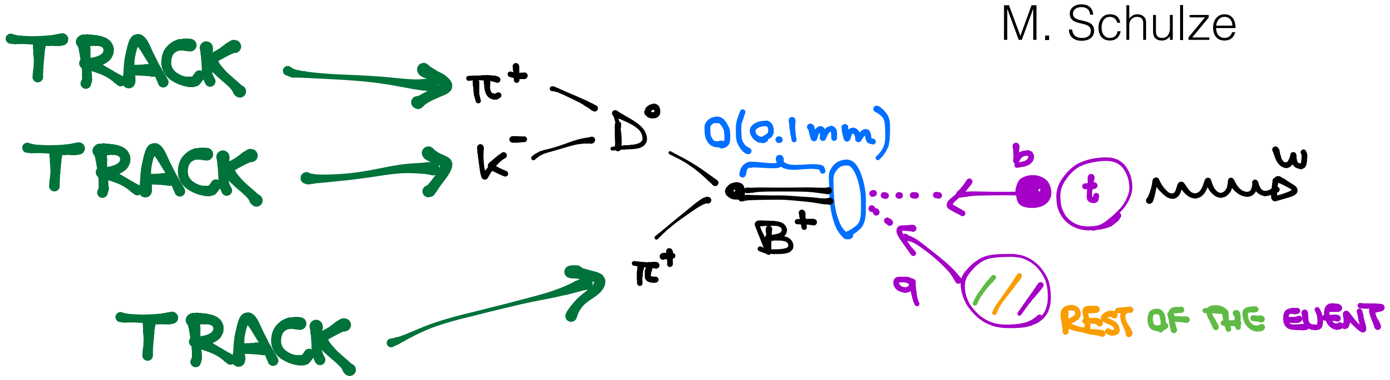
The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about "*single best measurement*"

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

hadron energy peak

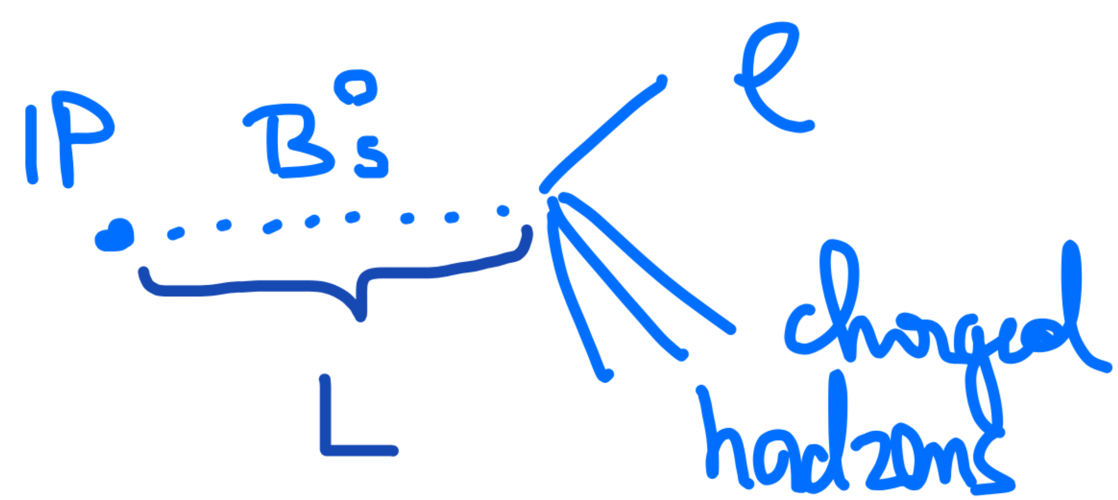
get the hadron energy entirely from tracks

collaboration with
M. Schulze



<u>mean</u> decay path peak

discussions with
J. Incandela



L_{xy} method *hep-ex/0501043*

J/ψ method *hep-ph/9912320*

More Peaks *Agashe, RF, Kim - in progress*

B **hadron** observables

B physics in the top sample

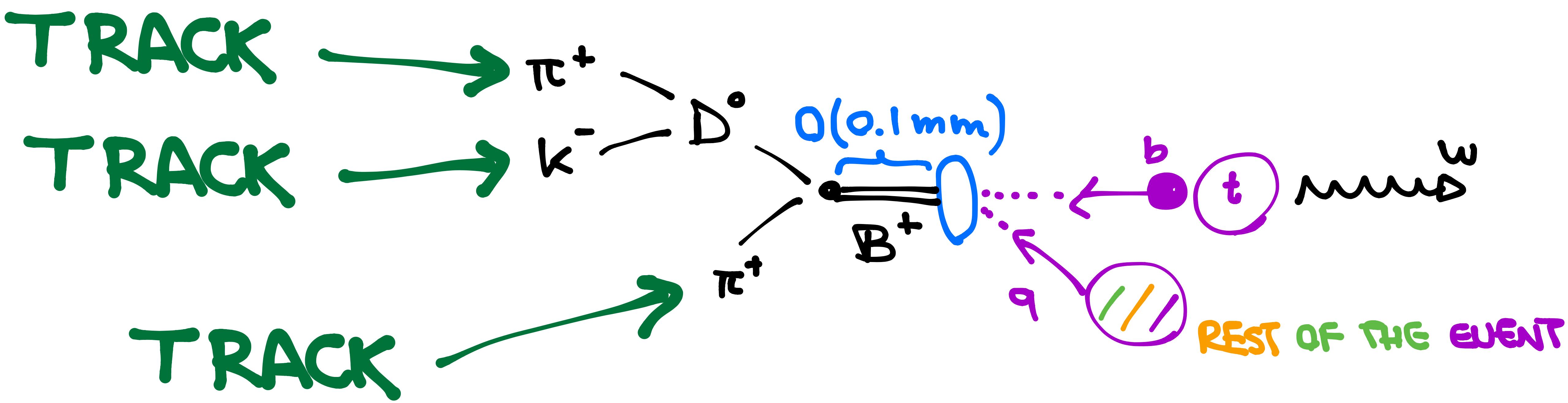
Fragmentation: the b quark energy peak is translated into a (broader) B hadron energy peak

- more exclusive final states
- non-JES uncertainties
- hadronization uncertainties

B <u>hadron</u>

energy peak

get the hadron energy entirely from tracks



B+ → 3 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

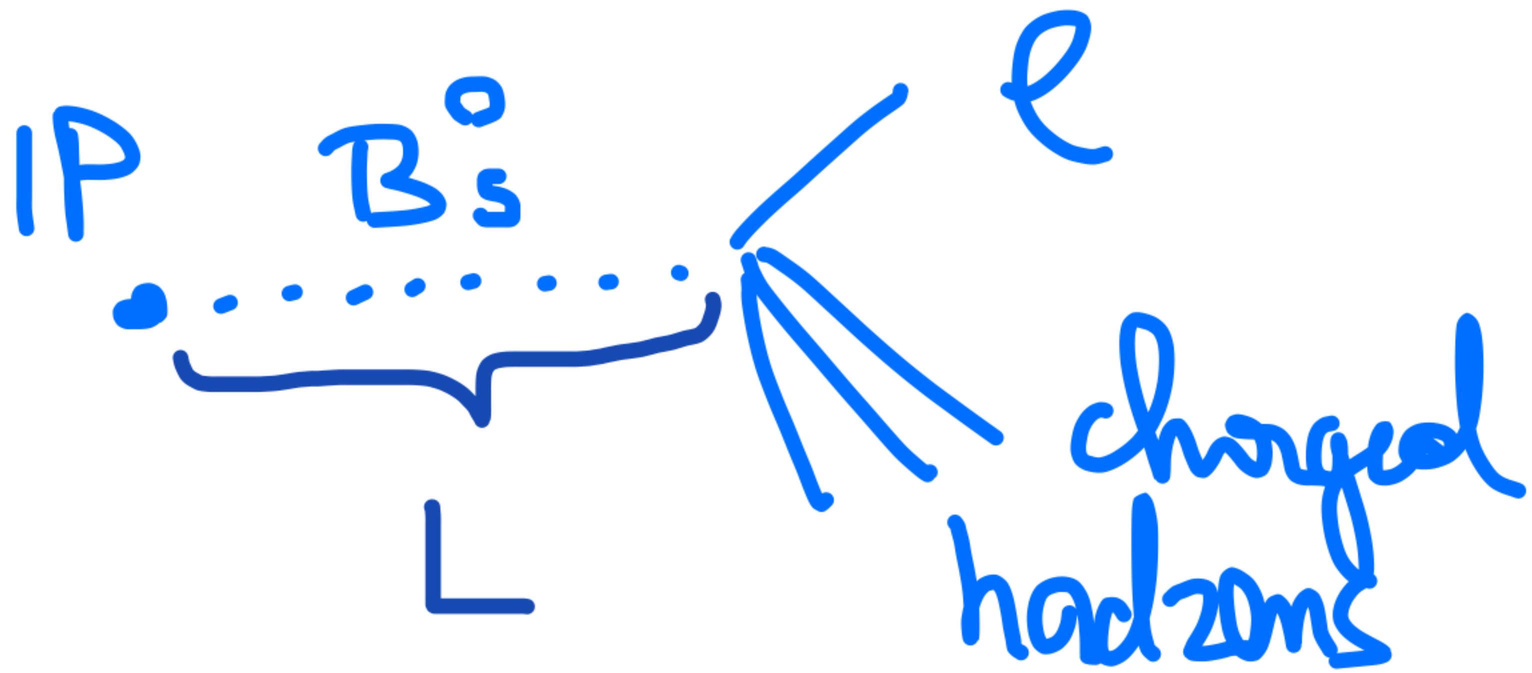
Does the **ratio** $\gamma = E/m$ help to get rid of exp. uncertainties?

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?

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

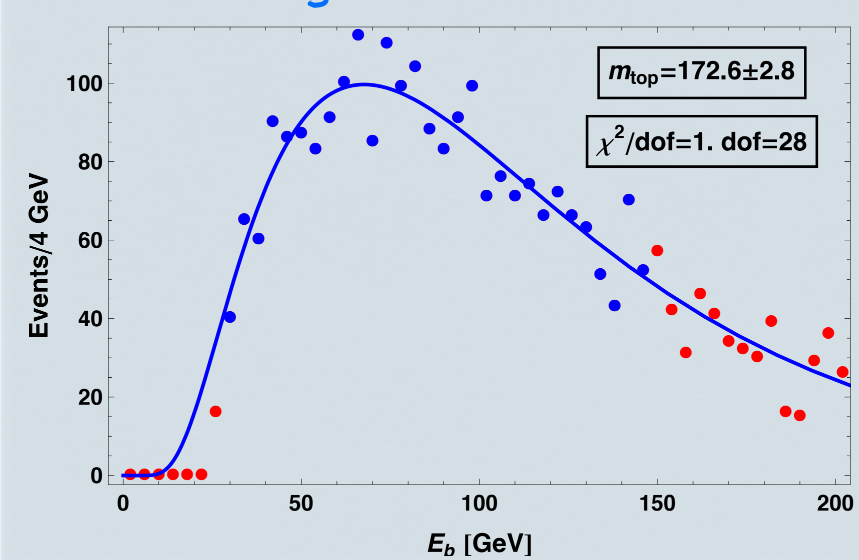
For now we just predicted the mode of pdf(λ)

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

1209.0772 - Agashe, Franceschini and Kim

from MC:
exponential ansatz work well

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



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)

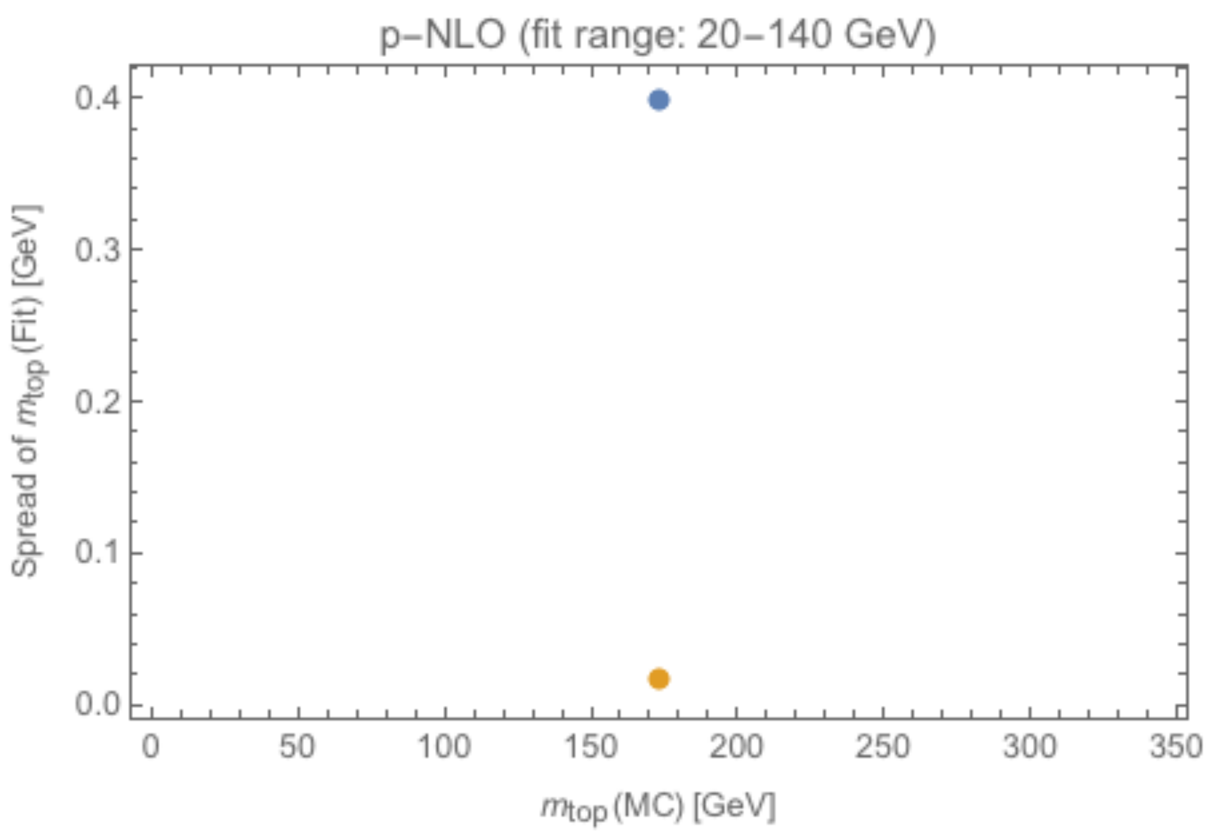
$$\mathrm{pdf}(\lambda) = e^{-w\left(\frac{\lambda}{\lambda_0} + \frac{\lambda_0}{\lambda}\right)} \;?$$

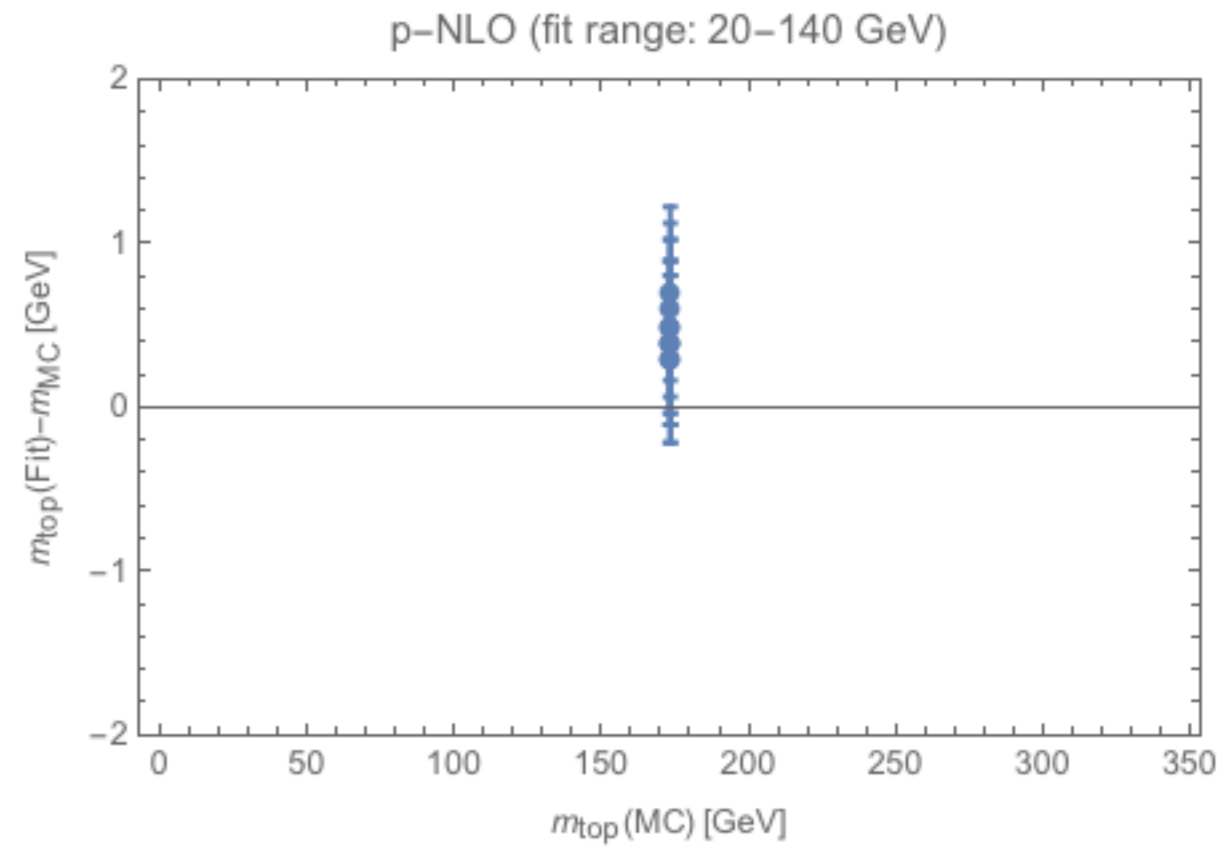
Summary

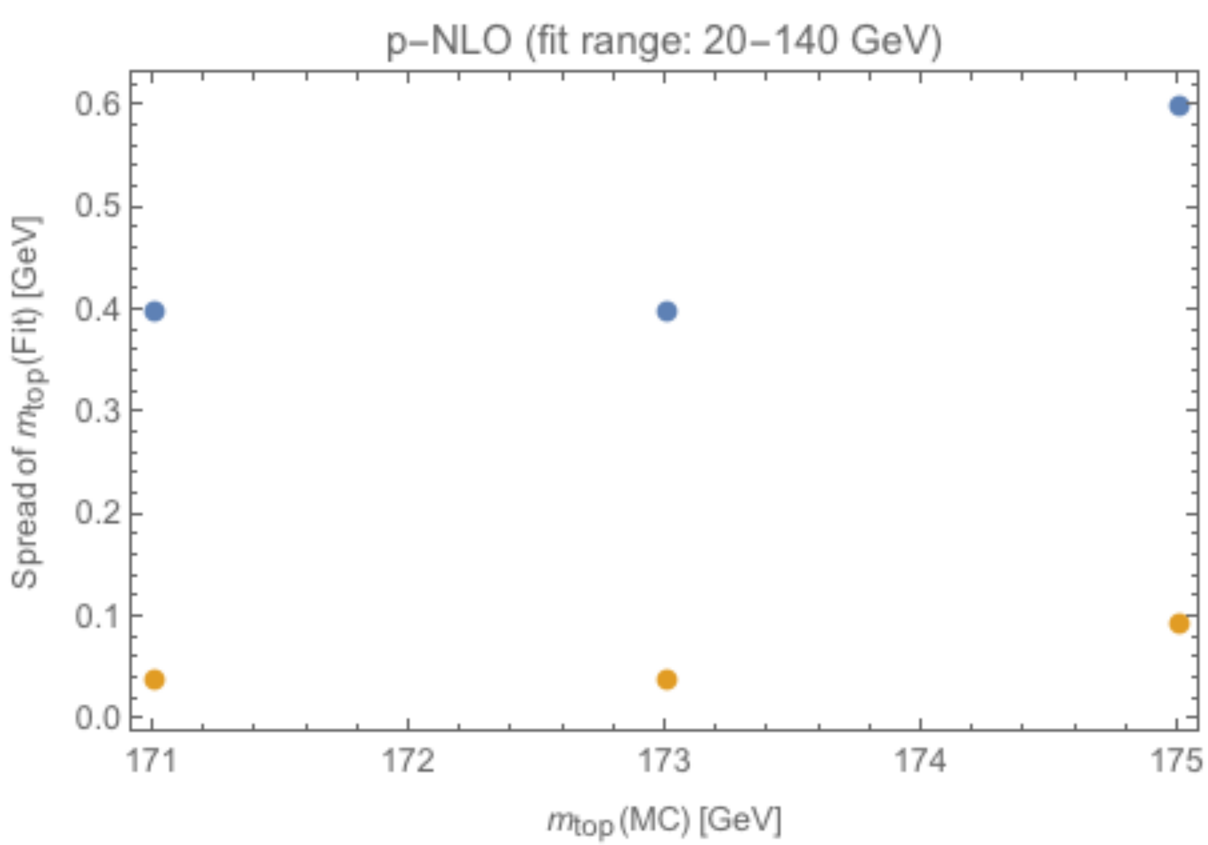
- 0.5% ⇒ precision QCD
- combination of methods ⇒ testing different assumptions
- to reconstruct or not?
- Energy peaks
- pheno-Lorentz invariance (Energy Peaks & Generalized Medians 1405.2395)
- first results for Energy Peaks @ NLO (production & decay)
- Beyond JES

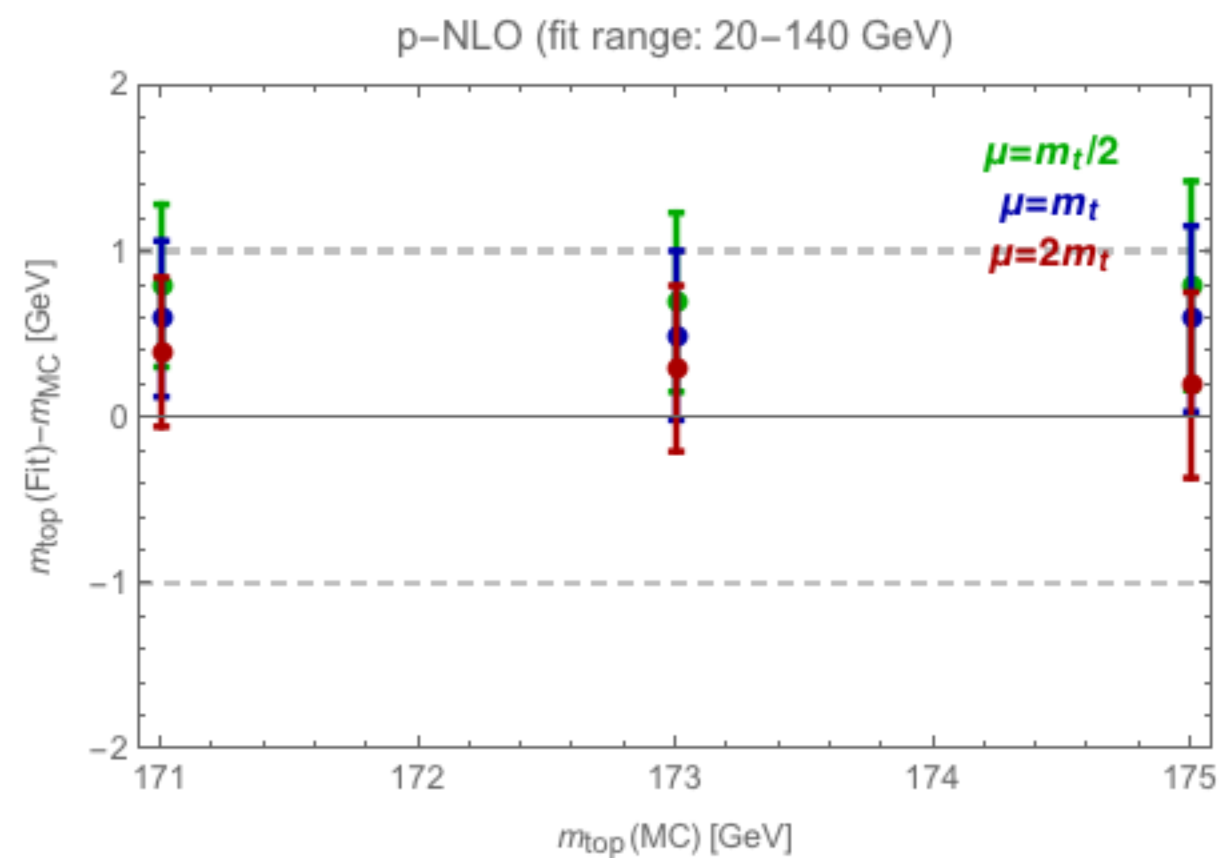
Back-up

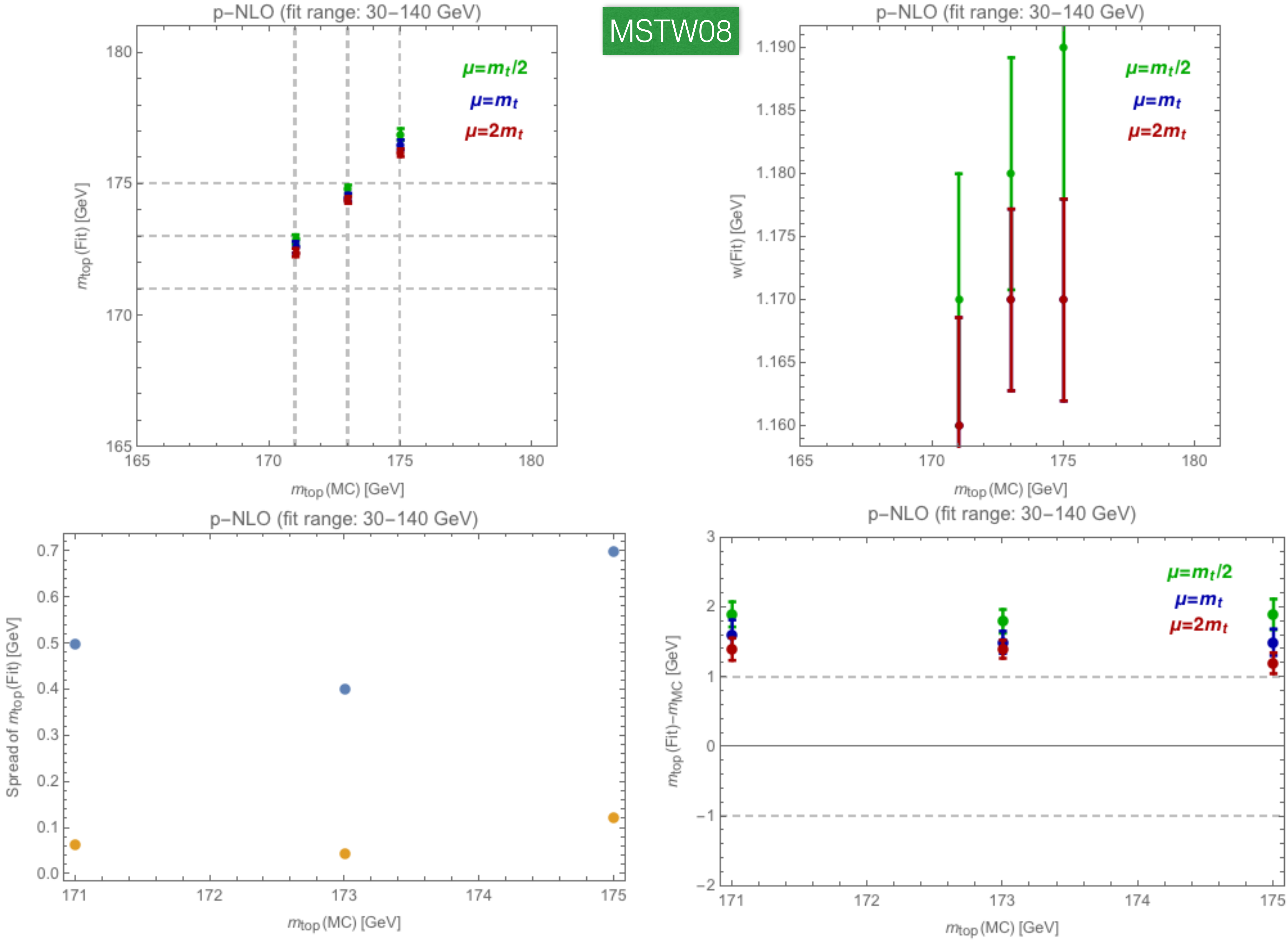
$\mu_F \neq \mu_R$


p−NLO (fit range: 20−140 GeV)
Spread of m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]

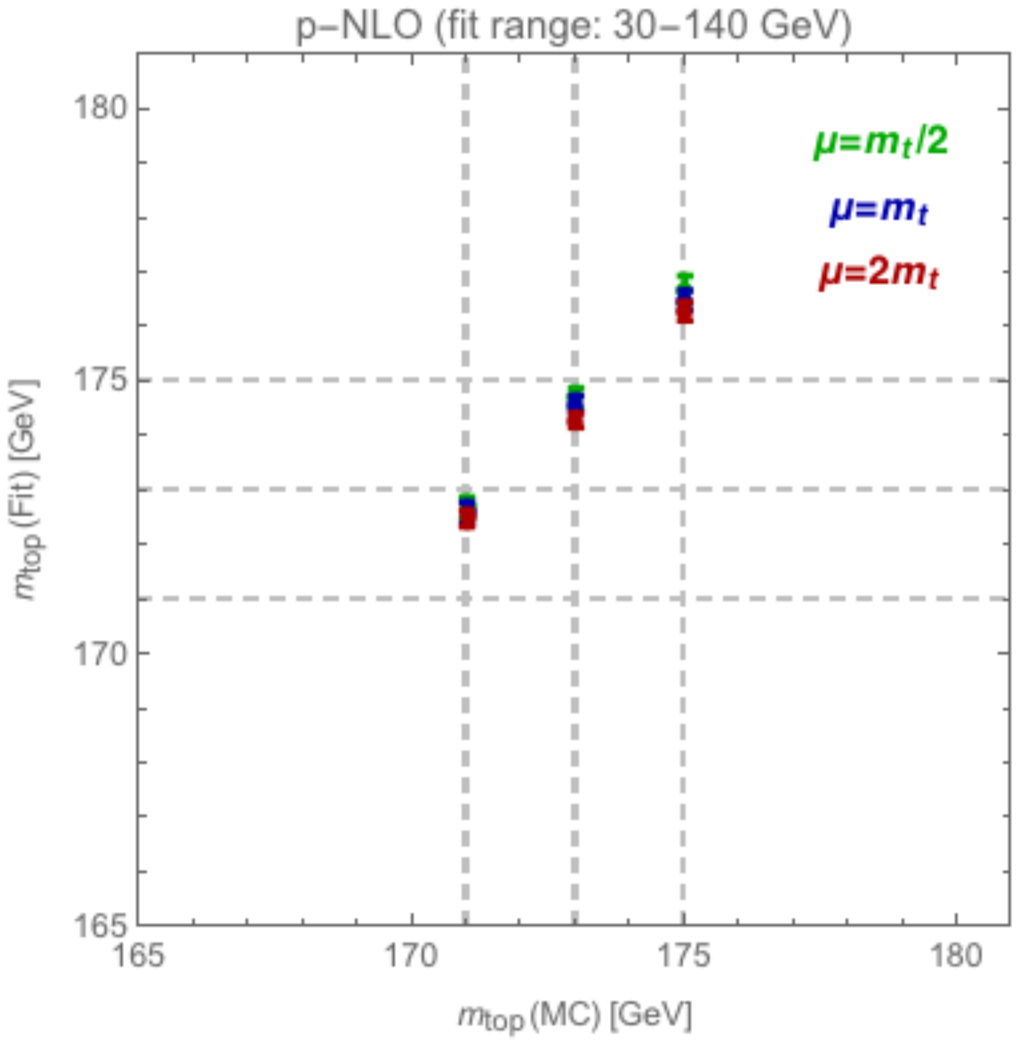

p−NLO (fit range: 20−140 GeV)
m_{top}(Fit)−m_{MC} [GeV]
m_{top}(MC) [GeV]

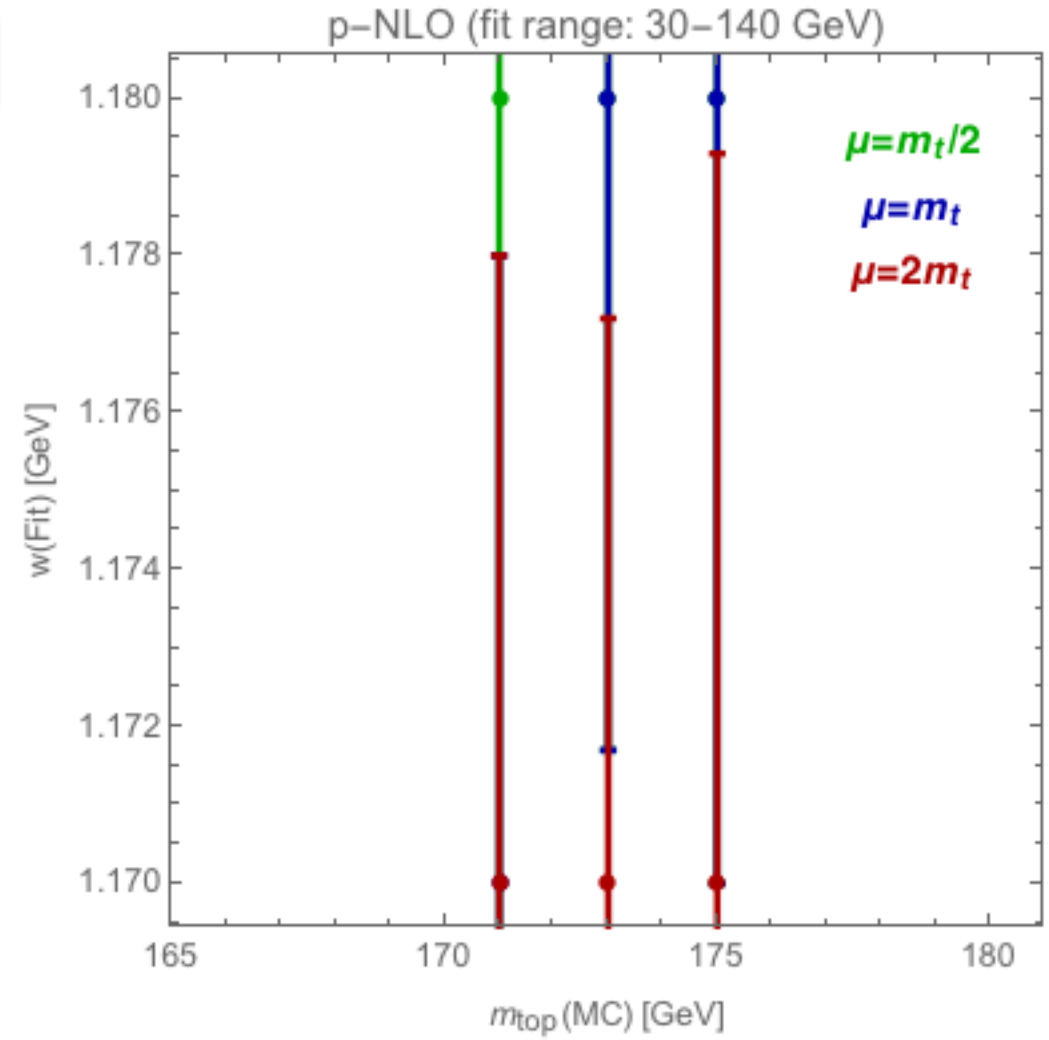

p−NLO (fit range: 20−140 GeV)
Spread of m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]

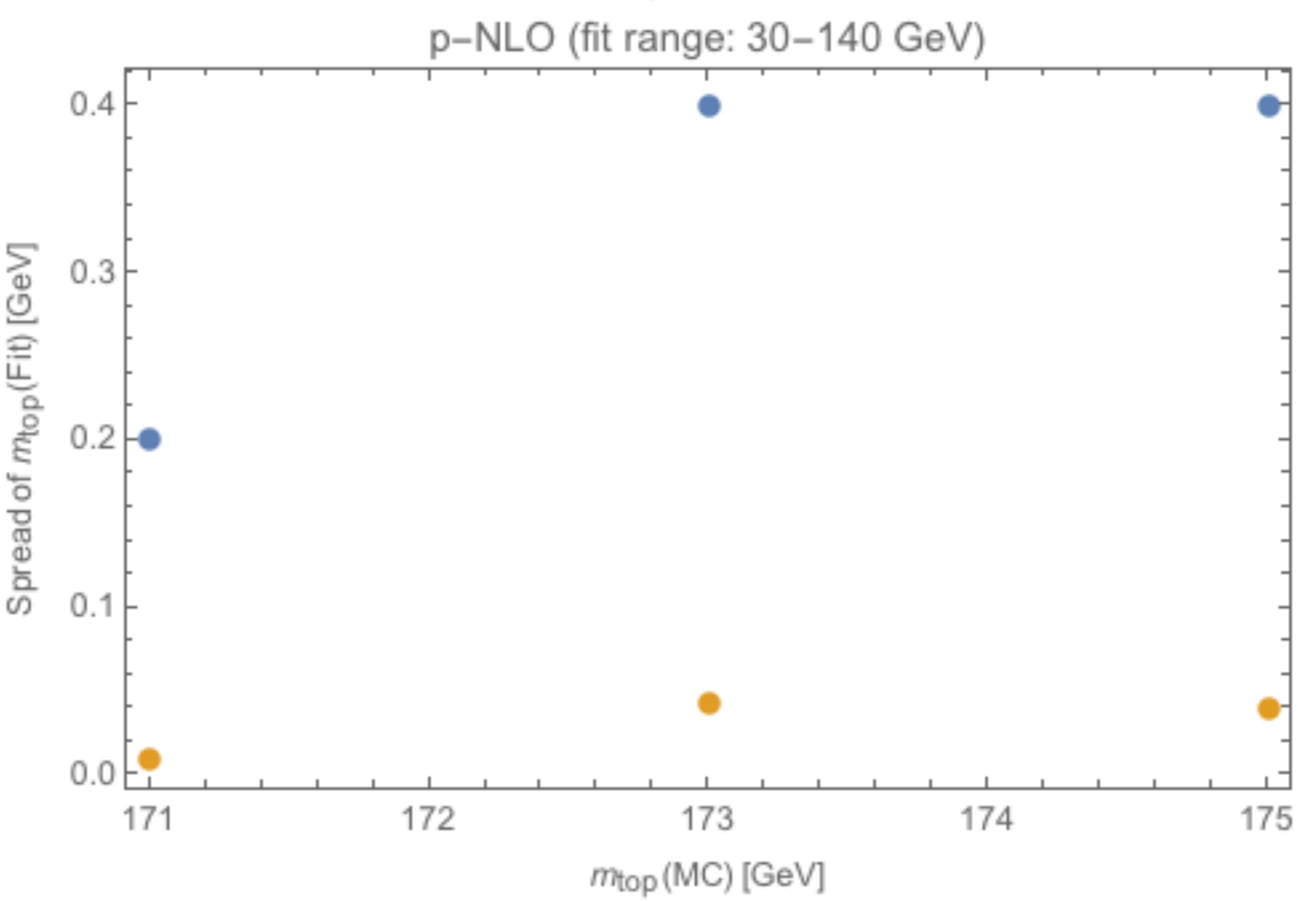

p−NLO (fit range: 20−140 GeV)
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
m_{top}(Fit)−m_{MC} [GeV]
m_{top}(MC) [GeV]

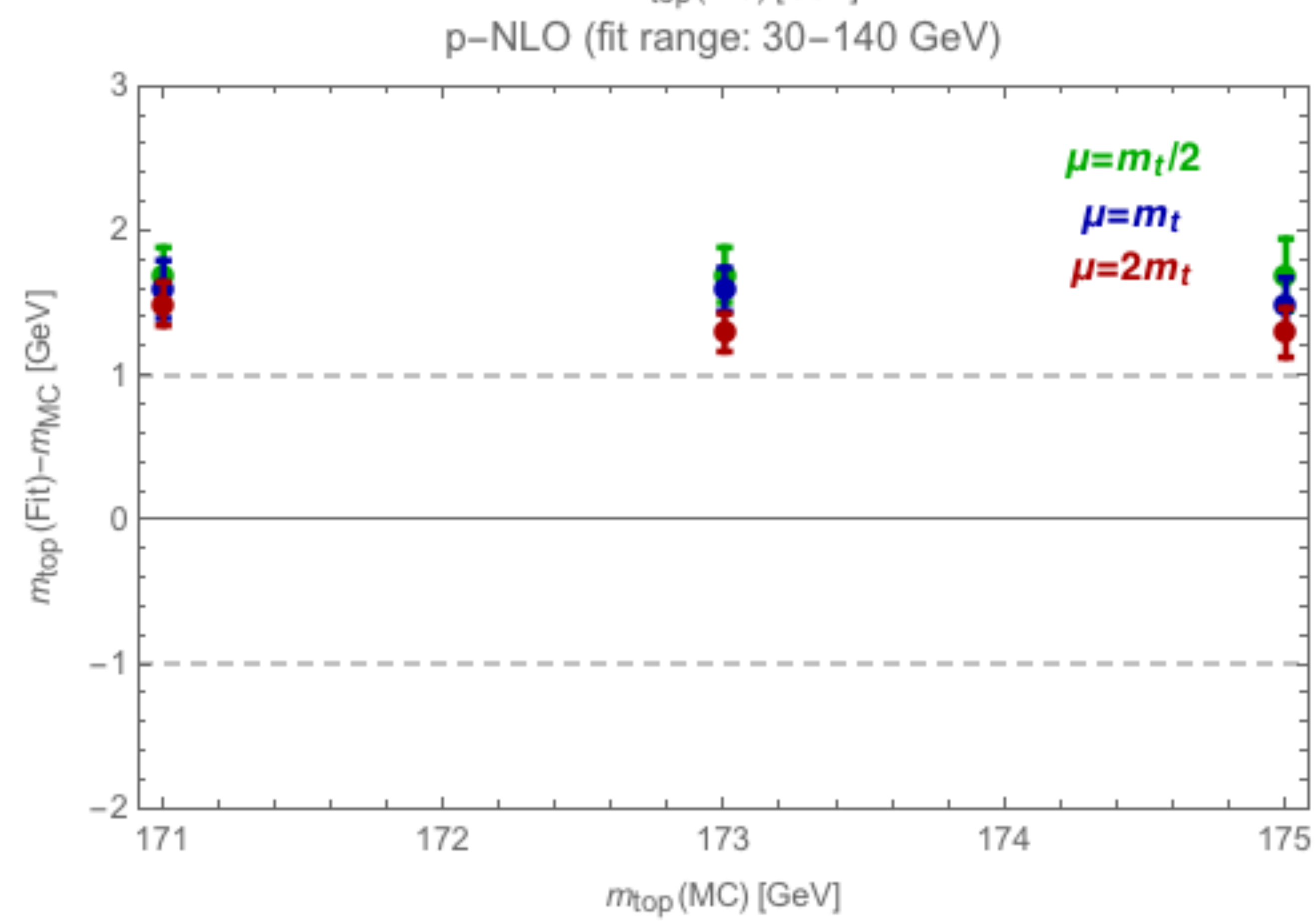

MSTW08
p–NLO (fit range: 30–140 GeV)
μ=m_t/2
μ=m_t
μ=2m_t
m_top(Fit) [GeV]
m_top(MC) [GeV]
w(Fit) [GeV]
Spread of m_top(Fit) [GeV]
m_top(Fit)–m_MC [GeV]

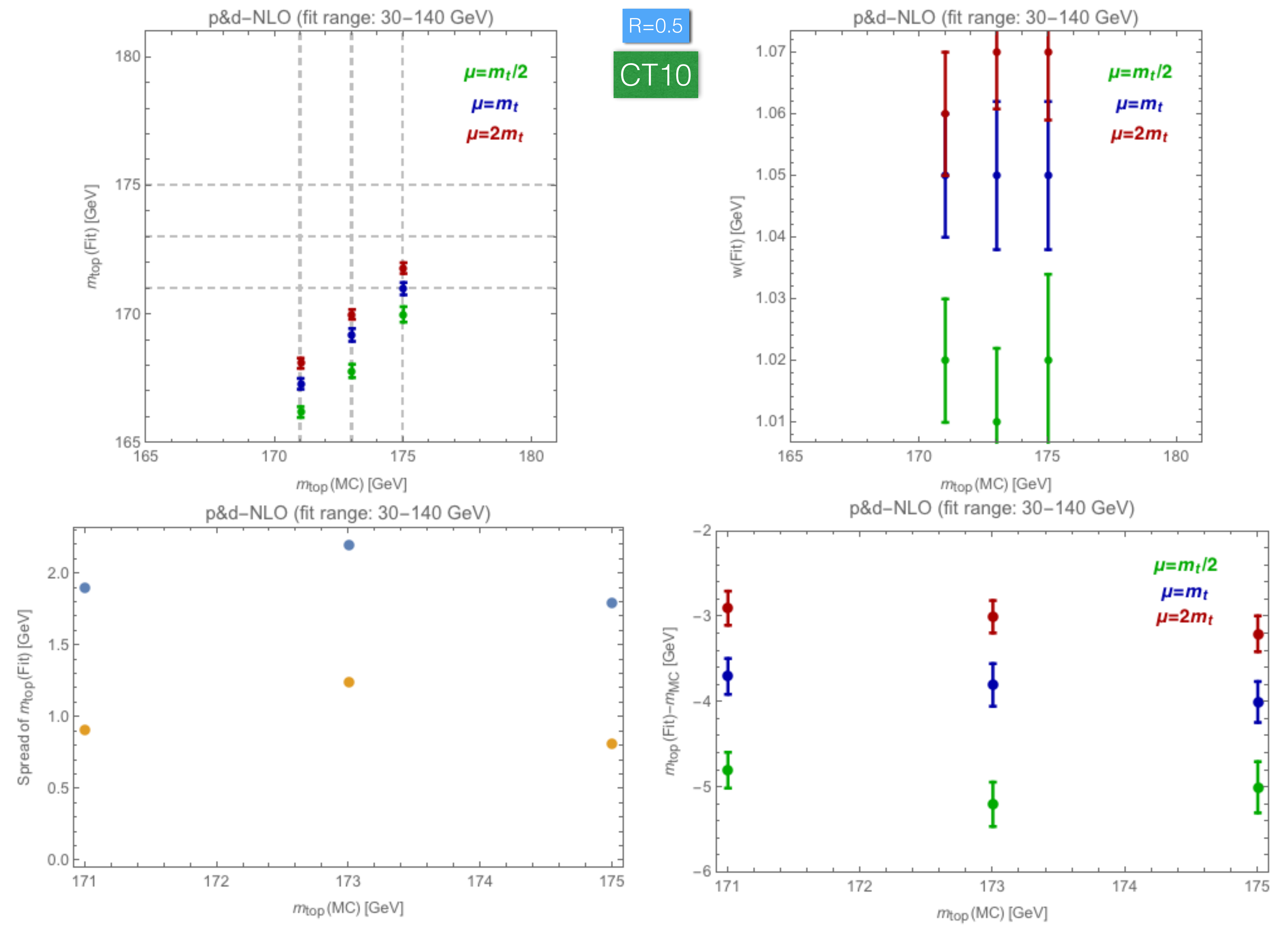
CT10


p–NLO (fit range: 30–140 GeV)
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
m_{top}(Fit) [GeV]
m_{top}(MC) [GeV]
165
170
175
180

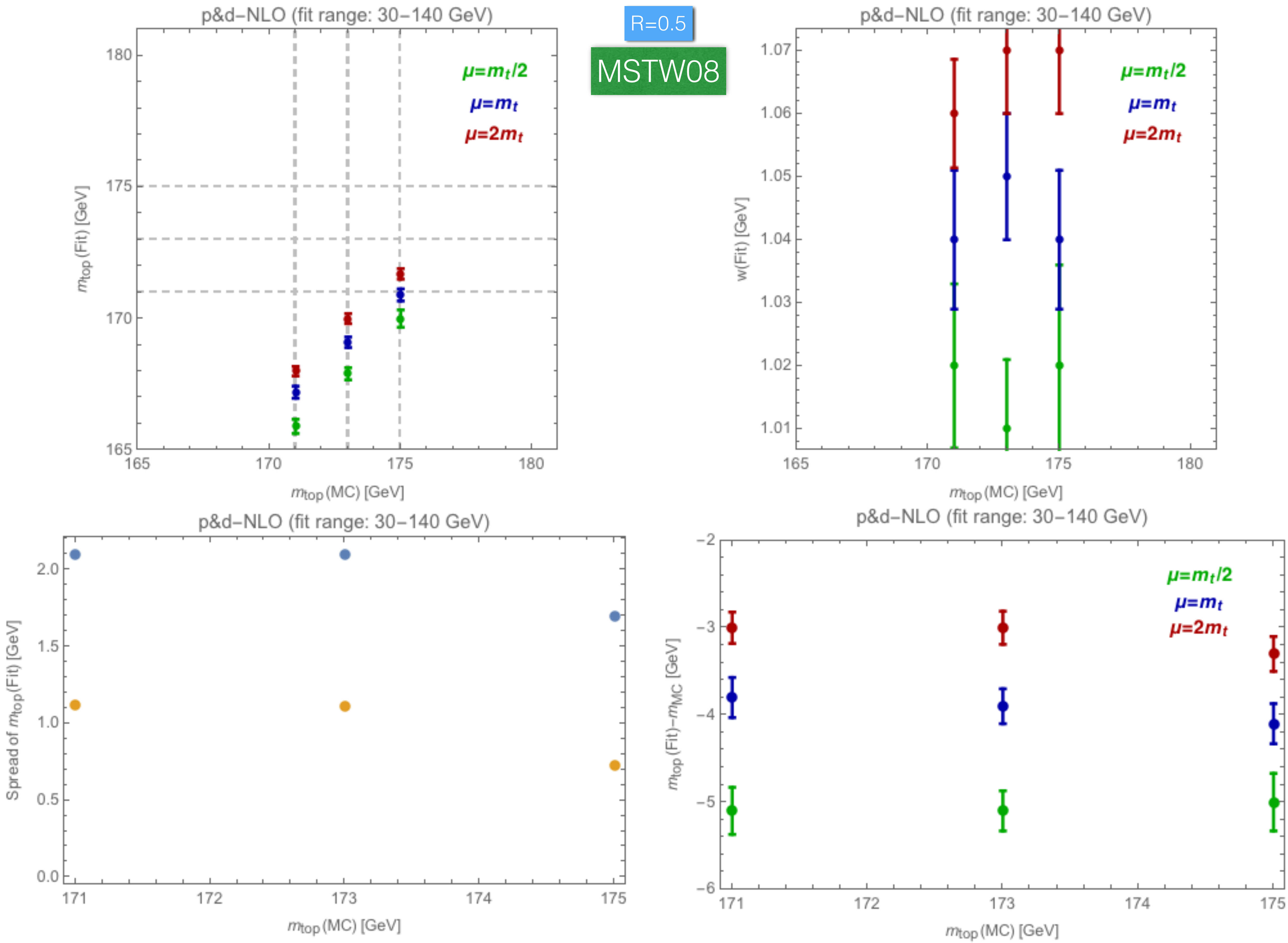

p–NLO (fit range: 30–140 GeV)
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
w(Fit) [GeV]
m_{top}(MC) [GeV]
1.170
1.172
1.174
1.176
1.178
1.180
165
170
175
180


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
171
172
173
174
175

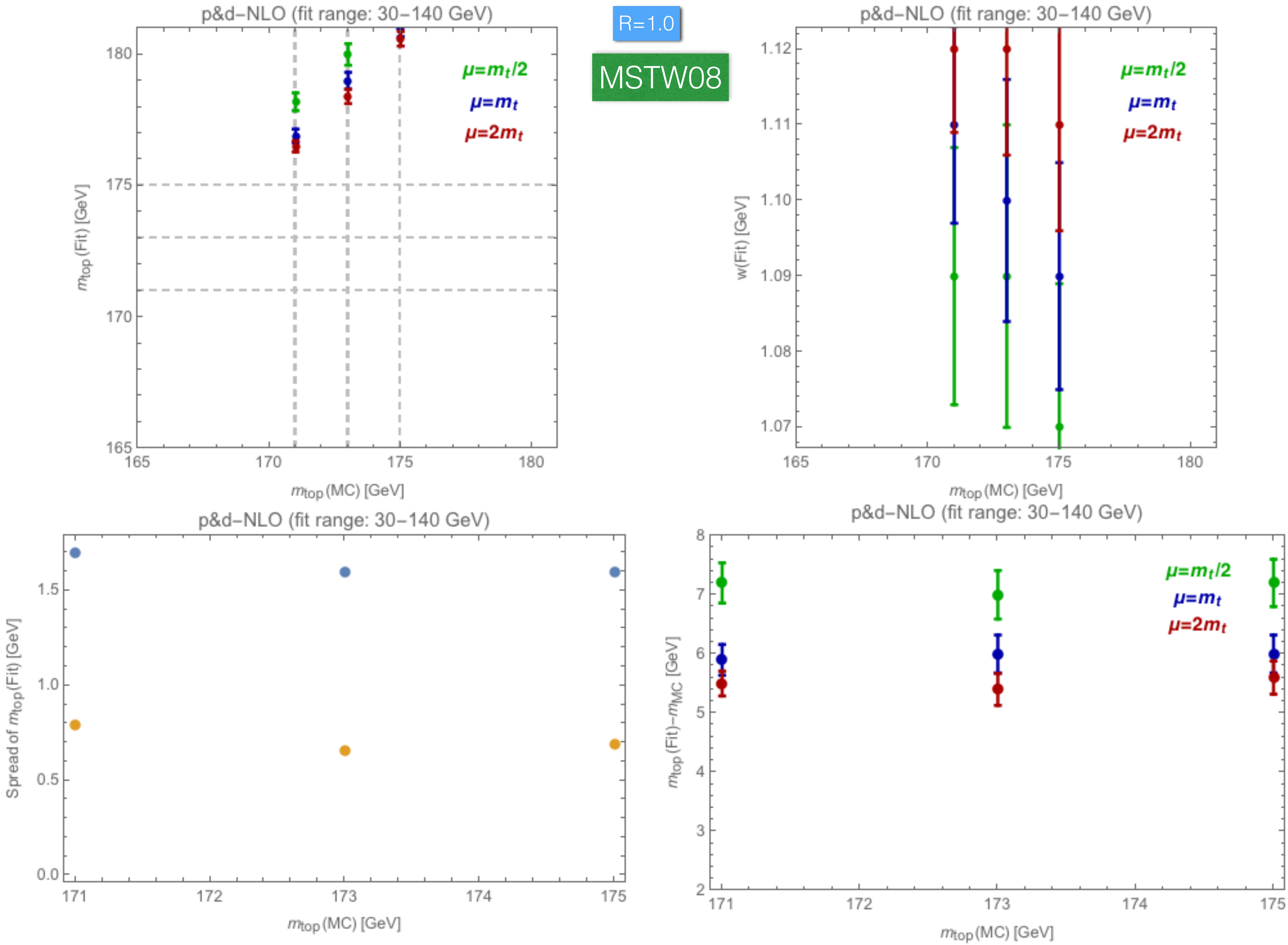

p–NLO (fit range: 30–140 GeV)
$\mu=m_t/2$
$\mu=m_t$
$\mu=2m_t$
m_{top}(Fit)–m_{MC} [GeV]
m_{top}(MC) [GeV]
–2
–1
0
1
2
3
171
172
173
174
175



R=0.5
CT10
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]
w(Fit) [GeV]
Spread of m_top(Fit) [GeV]
m_top(Fit)−m_MC [GeV]

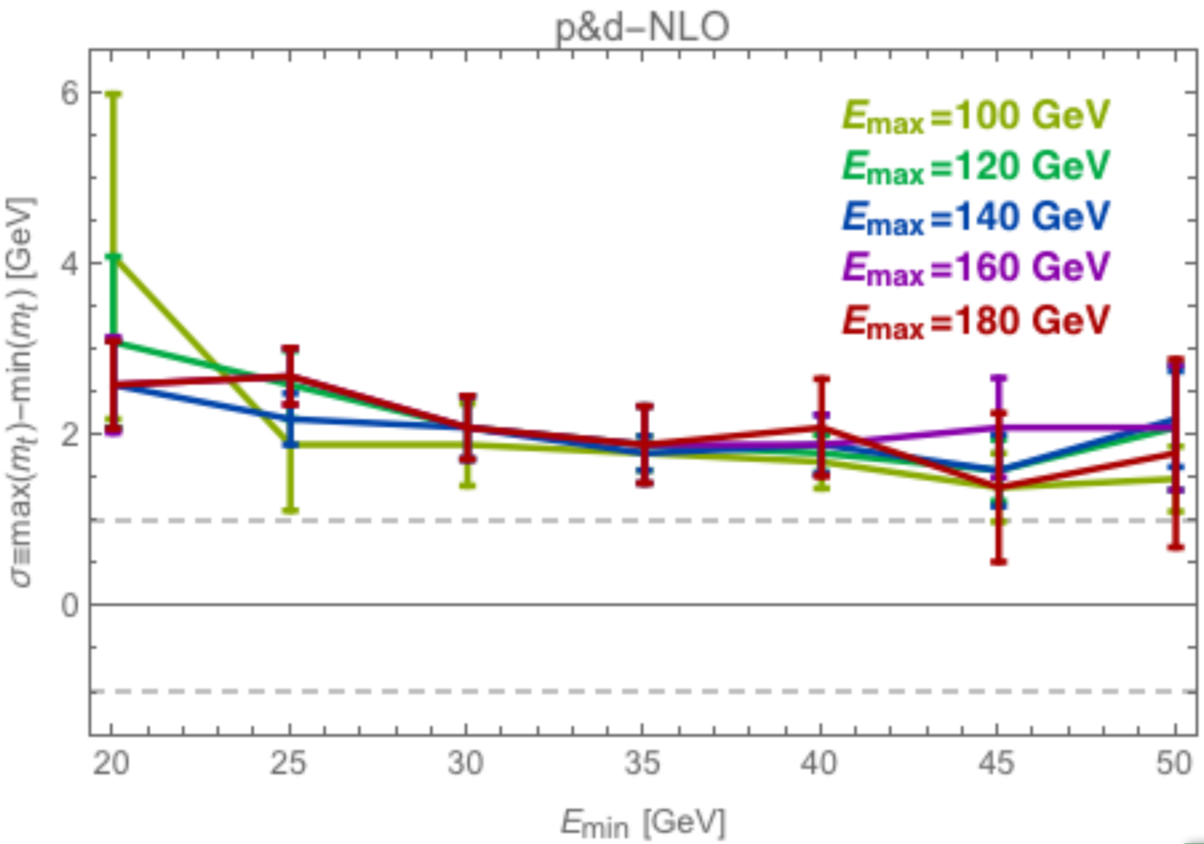


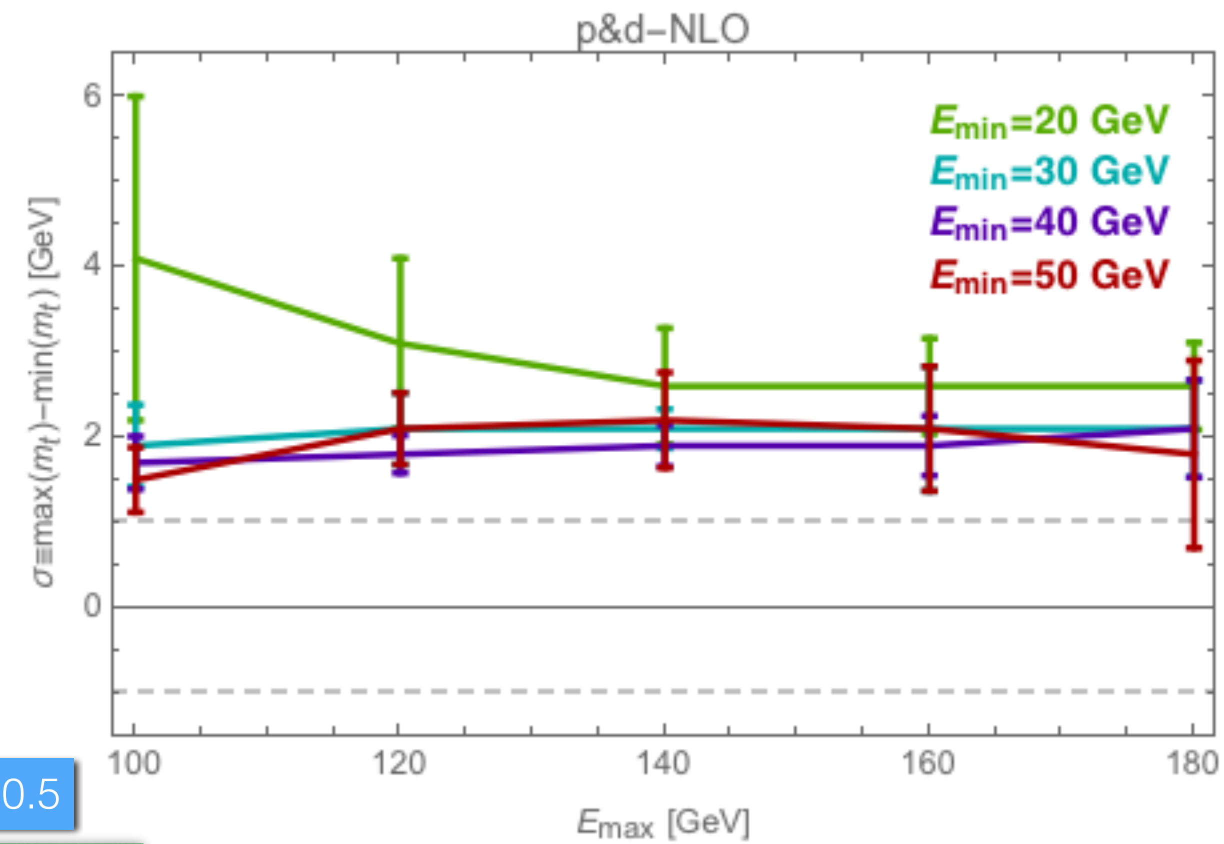
R=0.5
MSTW08
p&d−NLO (fit range: 30−140 GeV)
μ=mt/2
μ=mt
μ=2mt
mtop(Fit) [GeV]
mtop(MC) [GeV]
w(Fit) [GeV]
Spread of mtop(Fit) [GeV]
mtop(Fit)−mMC [GeV]



R=1.0
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]
w(Fit) [GeV]
Spread of m_top(Fit) [GeV]
m_top(Fit)−m_MC [GeV]

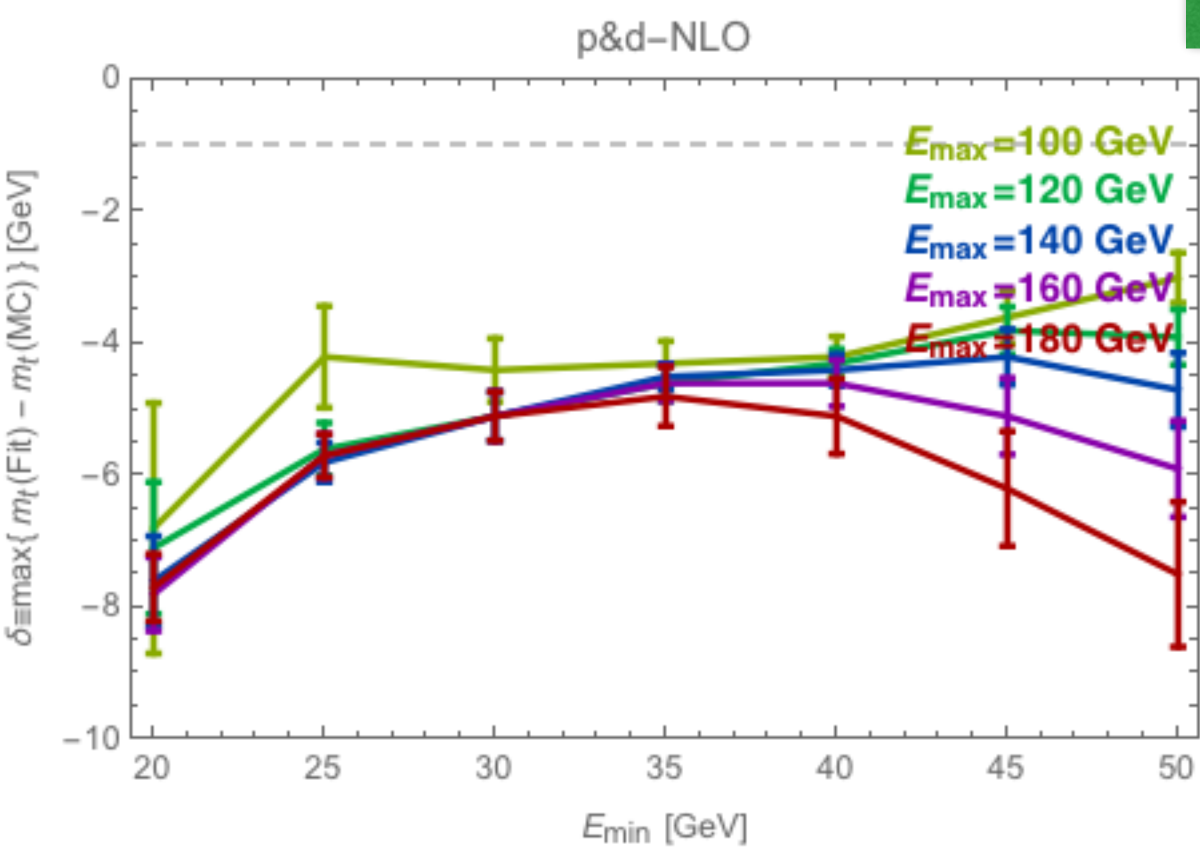
Fit Variations p&d-NLO

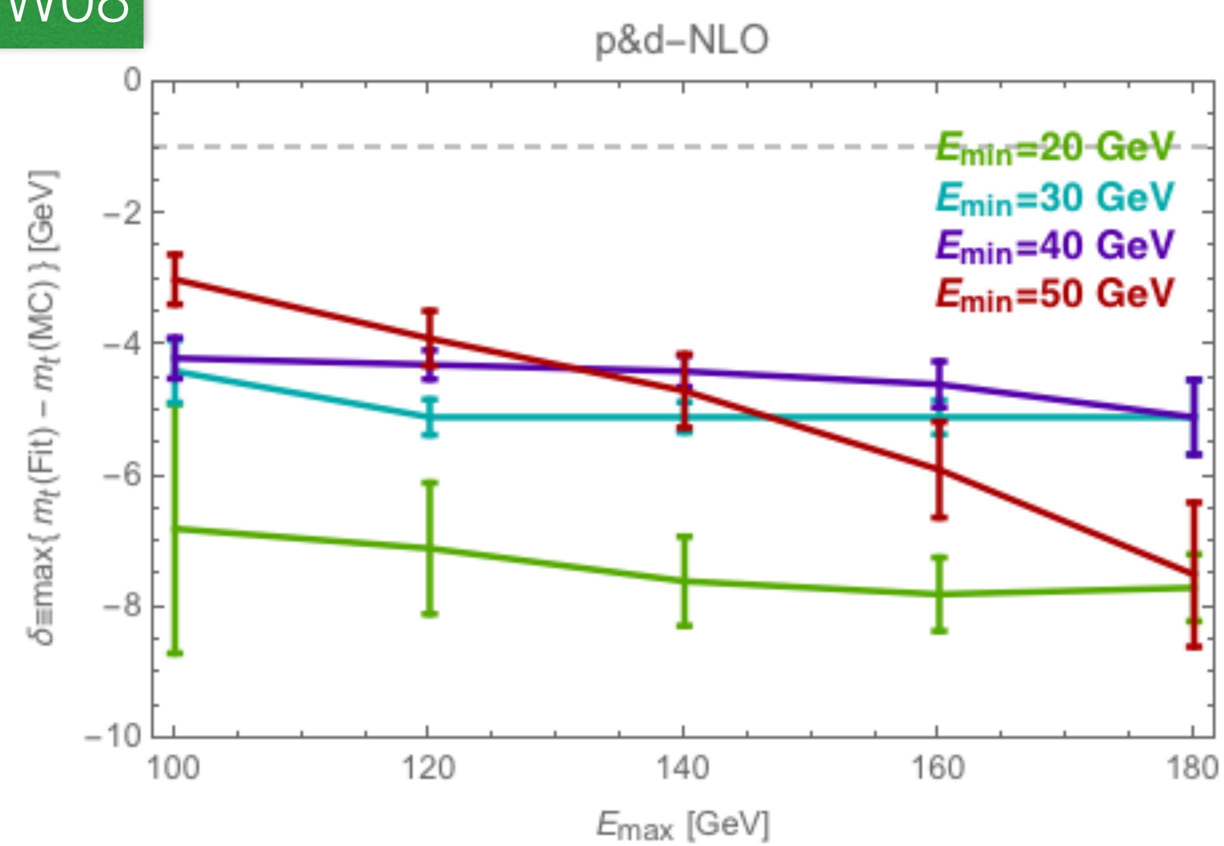




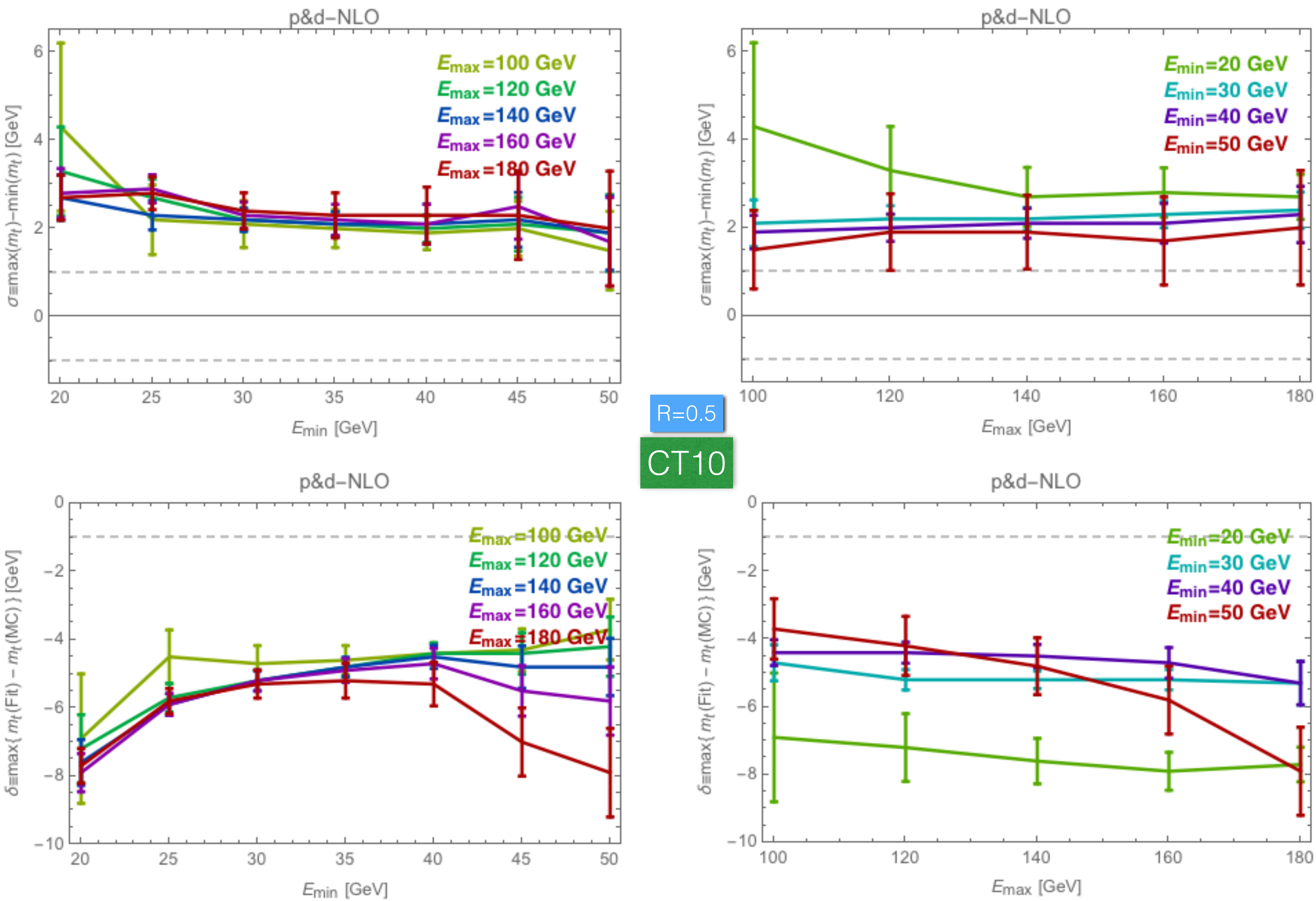
R=0.5

MSTW08

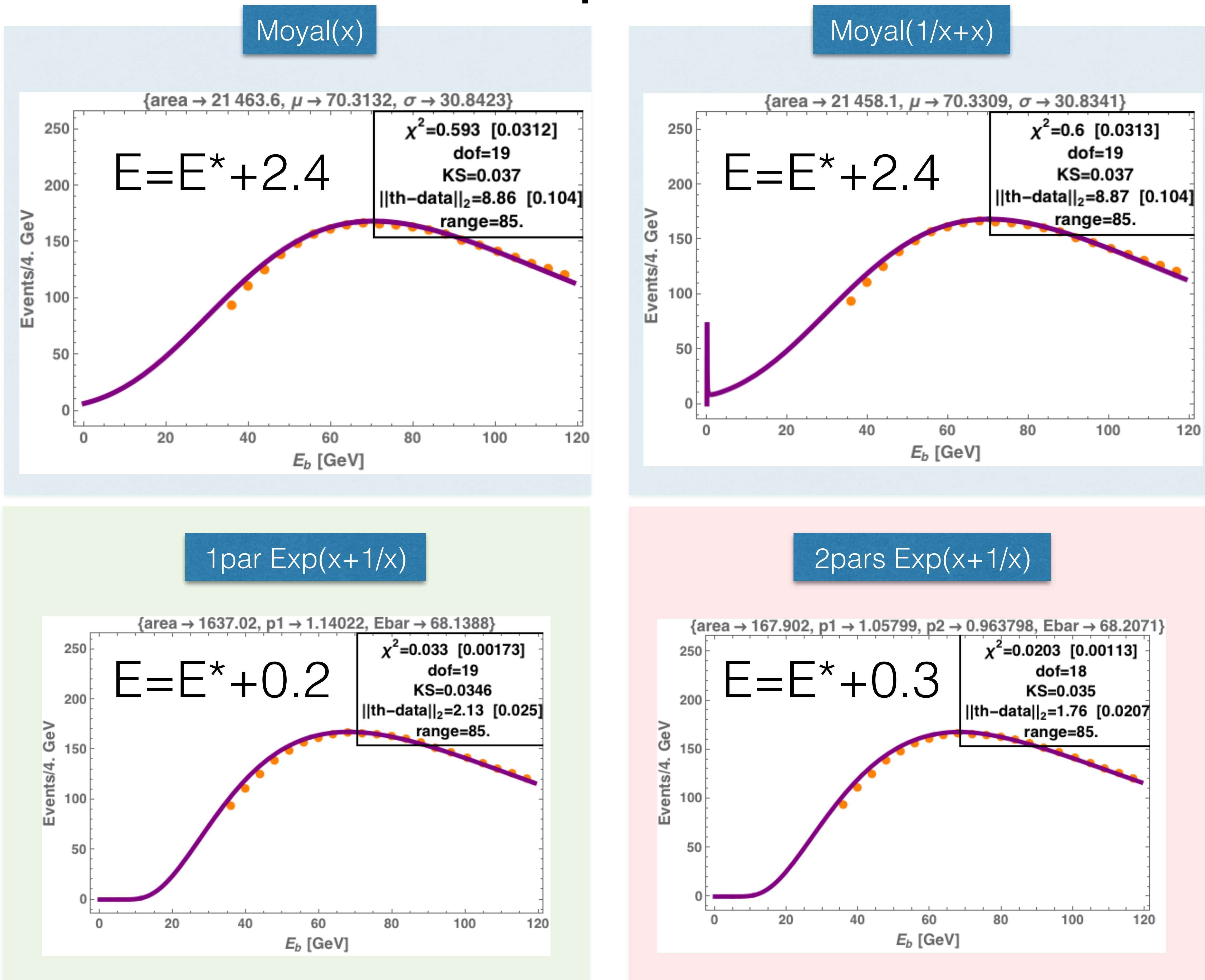




Fit Variations p&d-NLO



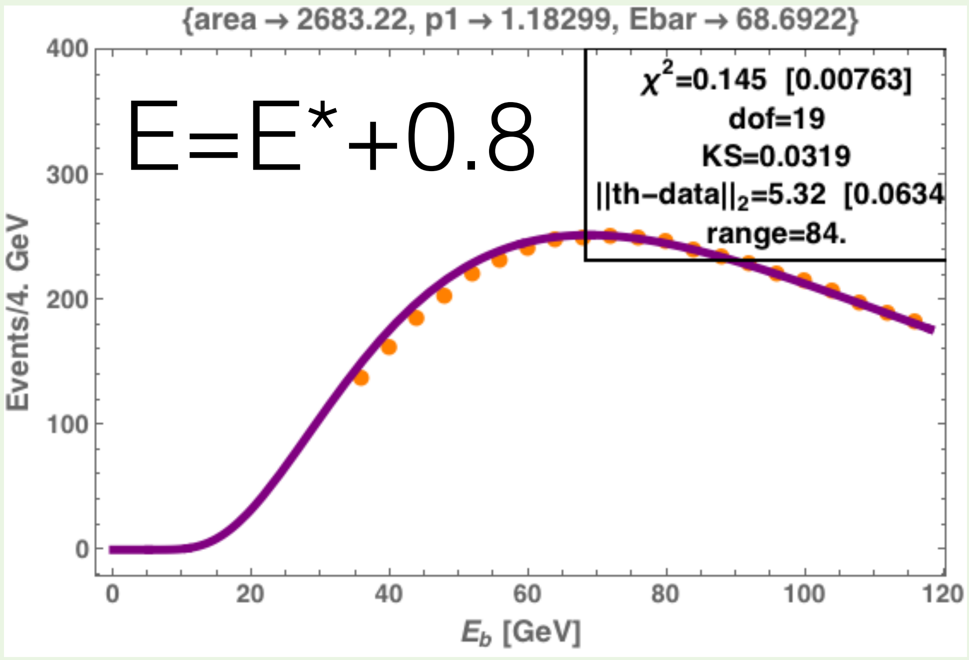
LO MCFM fixed $\mu = m_{top}$ (E=67.9 GeV)



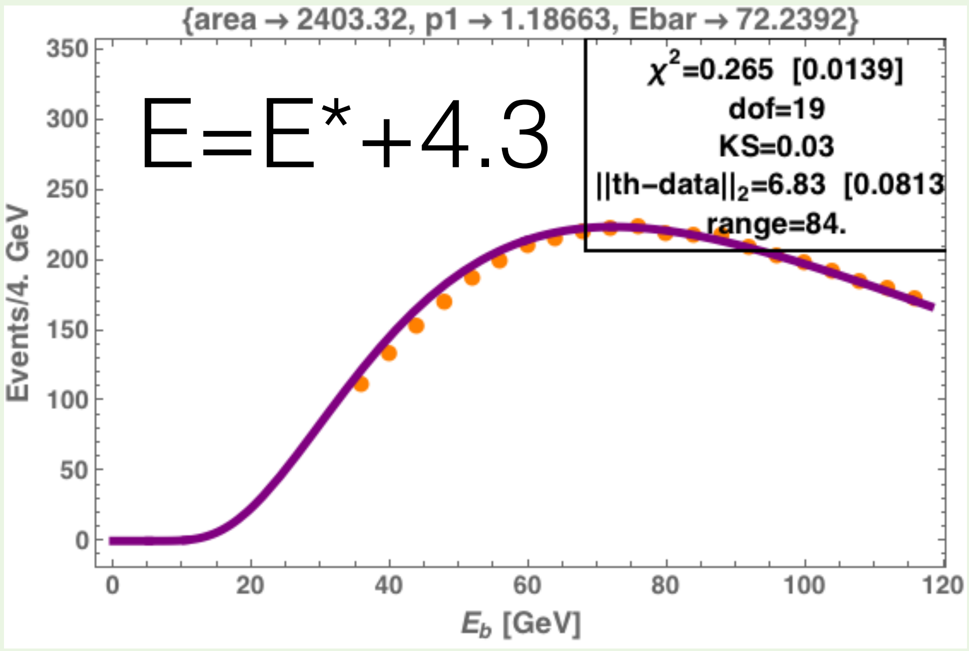
pNLO MCFM fixed $\mu = m_{top}$ (E=67.9 GeV)

1par Exp(x+1/x)

R=0.5



R=1.0



NLO

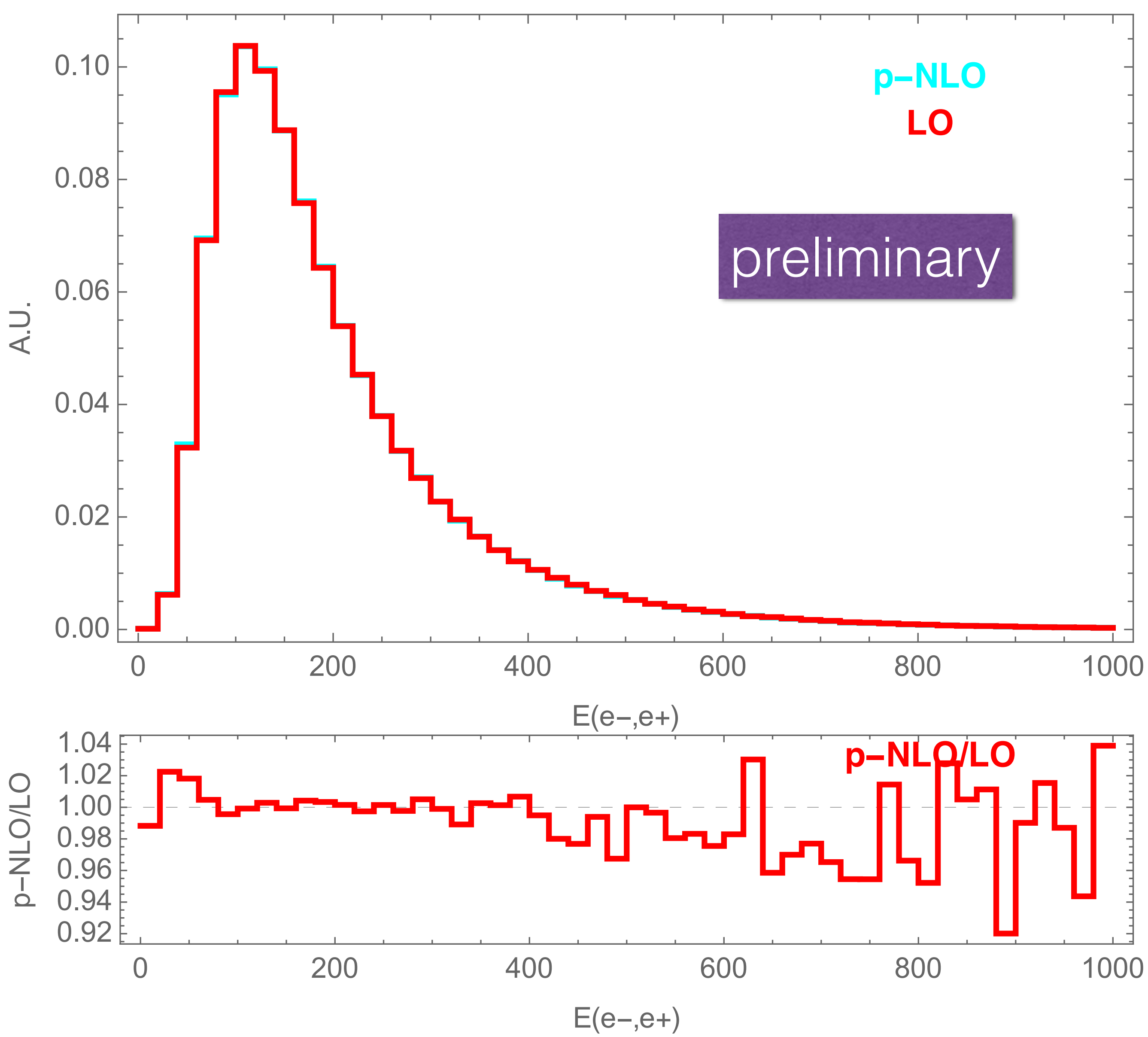
NLO: production & decay

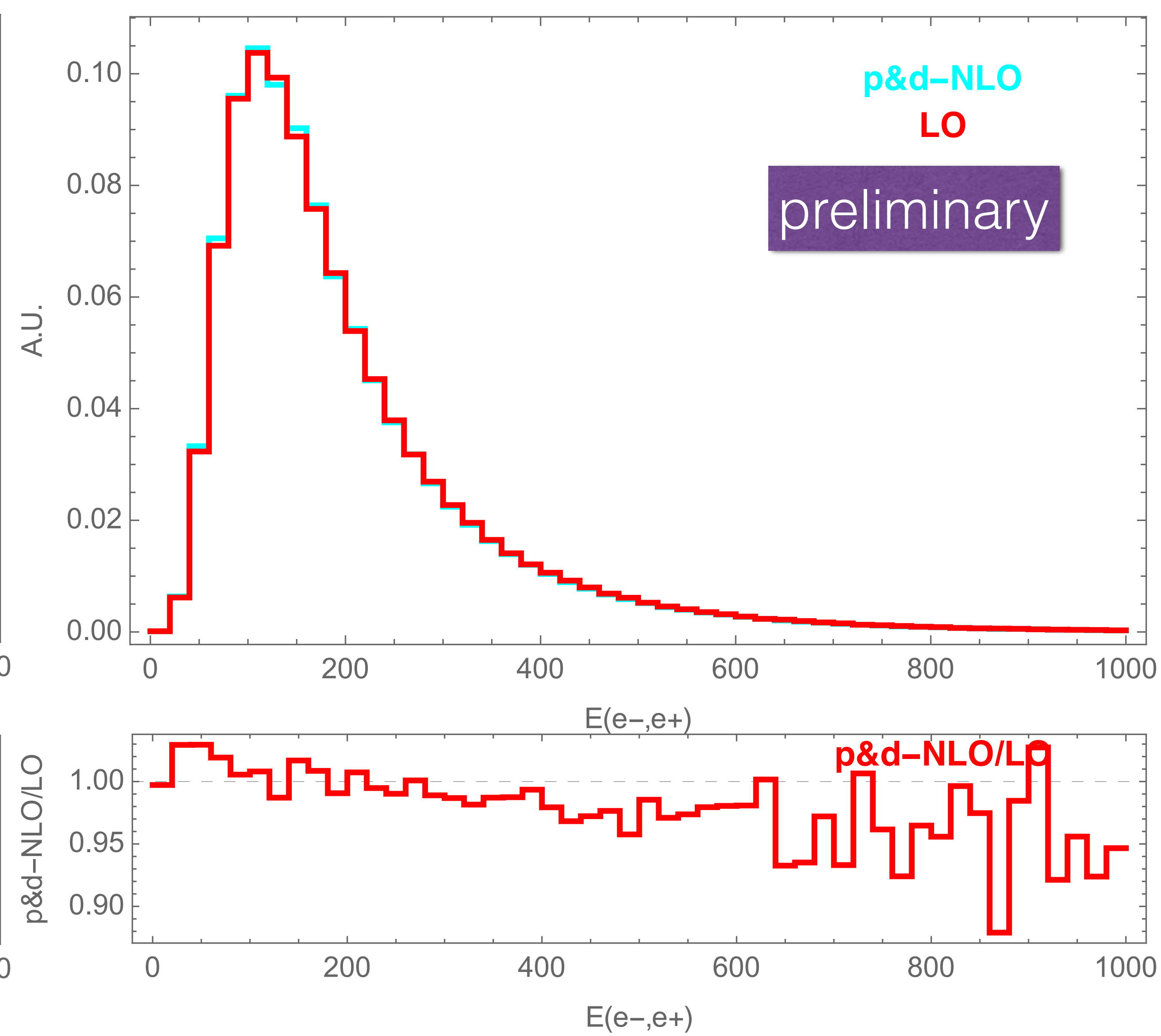
(MCFM)

Energy of e + $\bar{e}$

decay at LO

decay at NLO





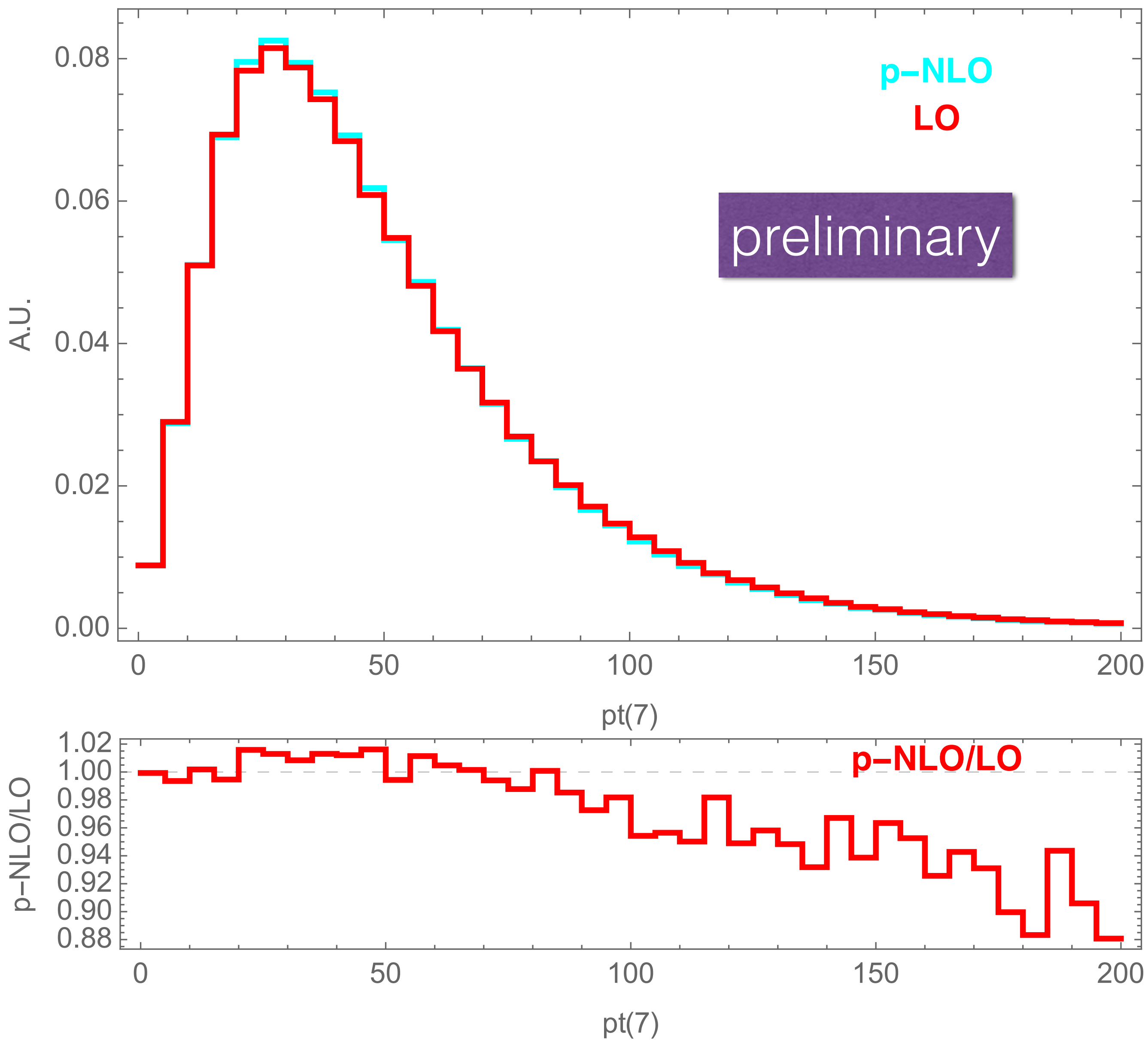
NLO: production & decay

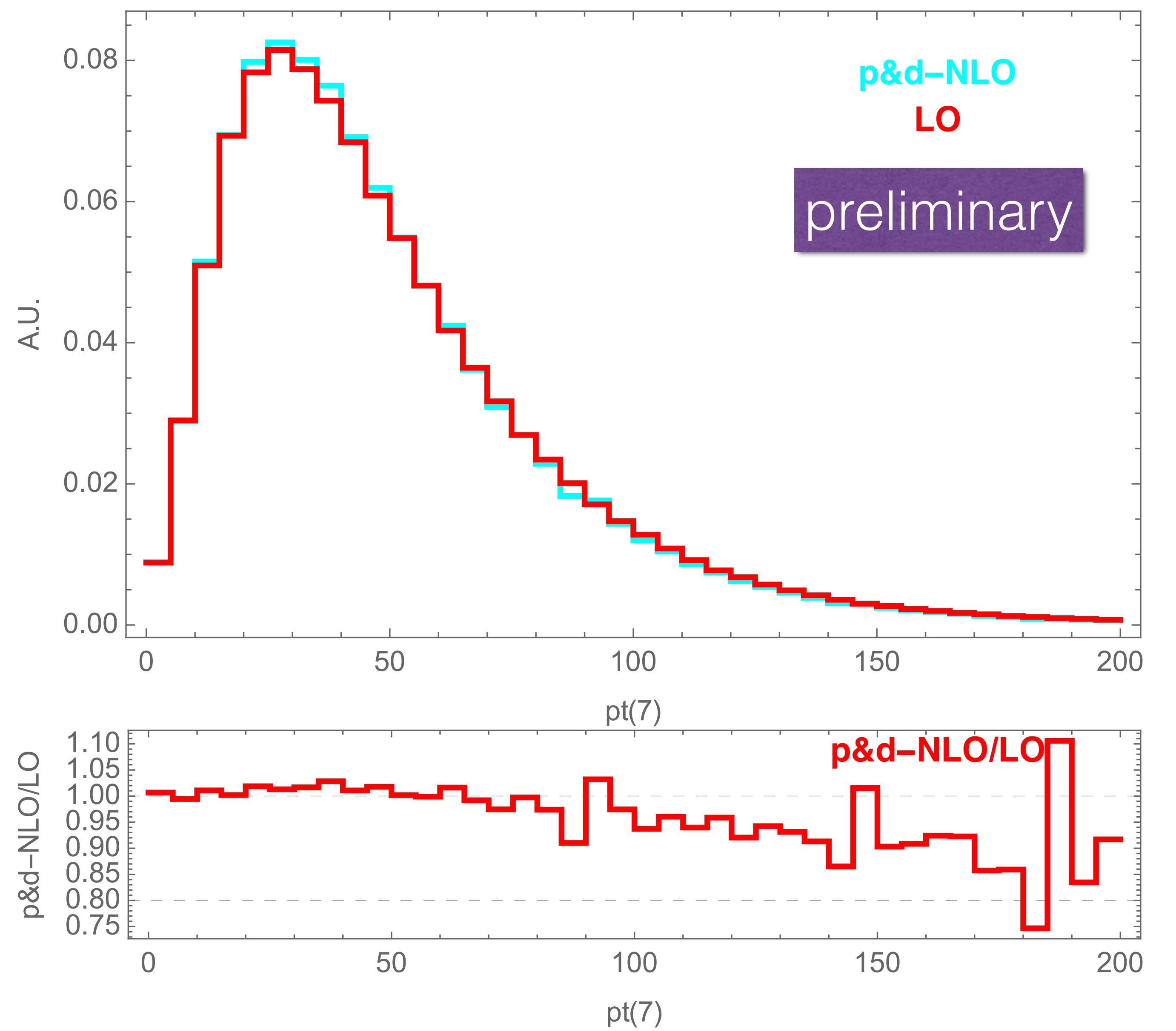
(MCFM)

$p_{T\ell}$

decay at LO

decay at NLO



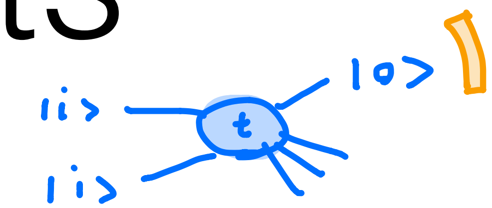


New methods

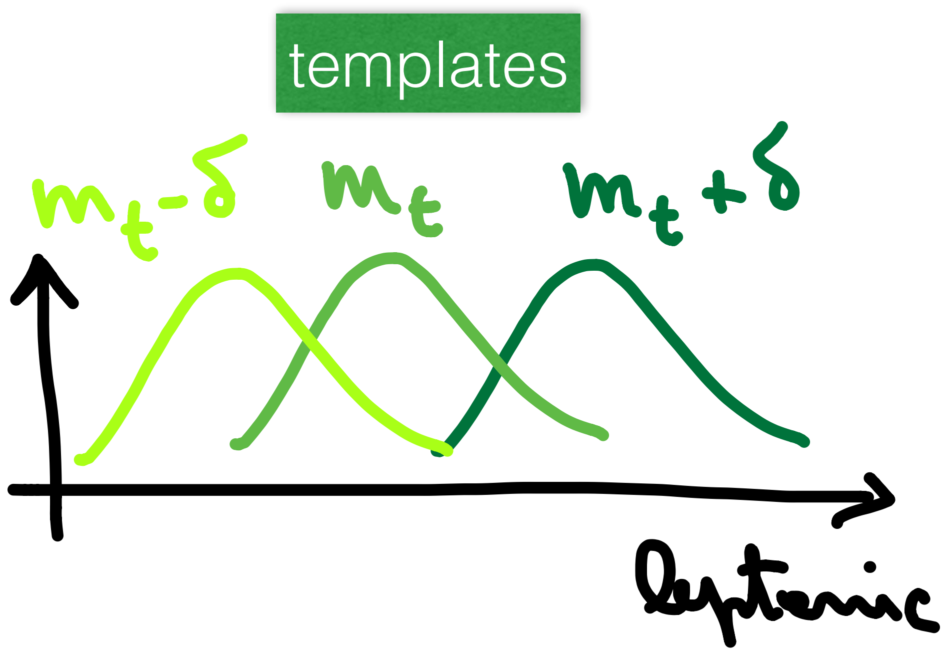
- Leptonic Mellin moments 1407.2763
- Generalized Medians 1405.2395

Leptonic Mellin moments

1407.2763



- Take “top like” events
- no explicit reconstruction of the top
- observe the shape of some distribution of the leptons

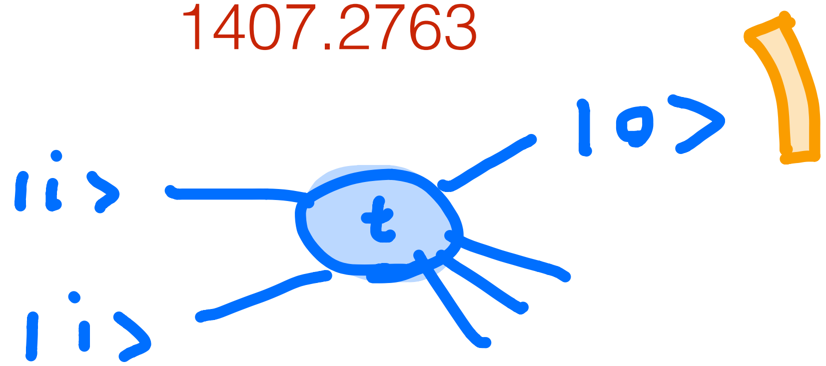


MC: correlate the leptonic shape to m_{top}

example: **pT of ℓ^+** (non-Lorentz invariant)
use Mellin’s moments to parametrize the shape

Leptonic Mellin moments

1407.2763



- no need for an "auxiliary" definition of "top"
- no fixed picture of the kinematics
- naturally an inclusive variable (pp→ ℓ^++tags+X)
- as clean as a lepton (theoretically and experimentally)

- anything that is not simulated might be harmful
- several theoretical subtle effects potentially relevant for *any template method*

Subtleties for *any template method*

1407.2763 - Frixione, S. and Mitov, A. - Determination of the top quark mass from leptonic observables

functional form of fact. scale

m_{top}= 174.32 (in the MC)

$$\hat{\mu}^{(1)} = \frac{1}{2} \sum_i m_{T,i} \,, \qquad i \in \{t, \bar{t}\} \,,$$

$$\hat{\mu}^{(2)} = \frac{1}{2} \sum_i m_{T,i} \,, \qquad i \in \text{ final state} \,,$$

$$\hat{\mu}^{(3)} = m_t \,,$$

scale	m_{top} from $p_{T\ell}$
1	$174.73^{+0.80}_{-0.79}[0.2]$
2	$174.78^{+0.90}_{-0.90}[0.6]$
3	$172.73^{+2.0}_{-1.2}[0.5]$
$1 \oplus 2 \oplus 3$	$174.46^{+0.99}_{-0.92}$

1 σ-th bias
σ-th might also change

rate and distributions might feel differently theory variations

Subtleties for *any template method*

1407.2763 - Frixione, S. and Mitov, A. - Determination of the top quark mass from leptonic observables

theory modeling: LO, NLO, LO+PS, NLO+PS (⊗ spin correlations)

- understand the combination
- asses missing effects: NNLO, extra radiation types

effect of shower

obs.	Δ_{PS}@NLO	bias@NLO	Δ_{PS}@LO	bias@LO
$p_{T\bar{\ell}}$	$-0.35^{+1.14}_{-1.16}$	$+0.12$	$-2.17^{+1.50}_{-1.80}$	-0.67
$p_{T\bar{\ell}+\ell}$	$-4.74^{+1.98}_{-3.10}$	$+11.14$	$-9.09^{+0.76}_{-0.71}$	$+14.19$
$M_{\bar{\ell}+\ell}$	$+1.52^{+2.03}_{-1.80}$	-8.61	$+3.79^{+3.30}_{-4.02}$	-6.43
$E_{\bar{\ell}}+E_{\ell}$	$+0.15^{+2.81}_{-2.91}$	-0.23	$-1.79^{+3.08}_{-3.75}$	-1.47
$p_{T\bar{\ell}}+p_{T\ell}$	$-0.30^{+1.09}_{-1.21}$	$+0.03$	$-2.13^{+1.51}_{-1.81}$	-0.67

impact of shower: use of partonic NNLO

Subtleties for *any template method*

1407.2763 - Frixione, S. and Mitov, A. - Determination of the top quark mass from leptonic observables

theory modeling: LO, NLO, LO+PS, NLO+PS (⊗ spin correlations)

effect of spin correlation

obs.	$\Delta_{\rm PS}$@NLO	bias@NLO	$\Delta_{\rm PS}$@LO	bias@LO
$p_{T\bar{\ell}}$	$+0.29^{+1.17}_{-1.14}$	$+0.41$	$-0.08^{+1.66}_{-1.96}$	-0.75
$p_{T\bar{\ell}+\ell}$	$-12.32^{+1.62}_{-2.13}$	-1.18	$-12.58^{+0.90}_{-0.94}$	$+1.60$
$M_{\bar{\ell}+\ell}$	$+9.45^{+2.36}_{-2.16}$	$+0.84$	$+8.00^{+3.74}_{-4.26}$	$+1.57$
$E_{\bar{\ell}}+E_{\ell}$	$+0.39^{+2.93}_{-3.16}$	$+0.16$	$-0.11^{+3.42}_{-4.16}$	-1.58
$p_{T\bar{\ell}}+p_{T\ell}$	$+0.22^{+1.12}_{-1.28}$	$+0.25$	$-0.06^{+1.65}_{-2.07}$	-0.73

impact of shower: use of factorized NNLO

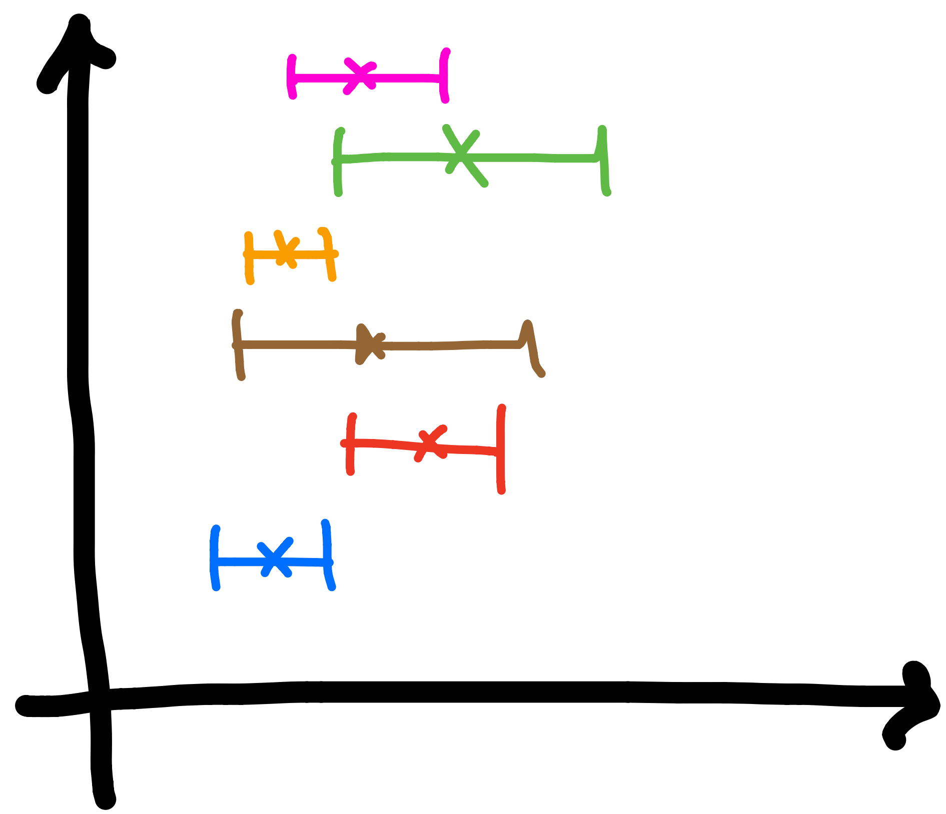
Subtleties for *any template method*

1407.2763 - Frixione, S. and Mitov, A. - Determination of the top quark mass from leptonic observables

theory modeling: LO, NLO, LO+PS, NLO+PS (⊗ spin correlations)

$p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_{\ell}$, $p_{T\bar{\ell}}+p_{T\ell}$	
LO+PS+MS	$173.61^{+1.10}_{-1.34}$ [1.0]
NLO+PS	$174.40^{+0.75}_{-0.81}$ [3.5]
LO+PS	$173.68^{+1.08}_{-1.31}$ [0.8]
fNLO	$174.73^{+0.72}_{-0.74}$ [5.5]
fLO	$175.84^{+0.90}_{-1.05}$ [1.2]

$p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_{\ell}$, $p_{T\bar{\ell}}+p_{T\ell}$, $p_{T\bar{\ell}+\ell}$, $M_{\bar{\ell}+\ell}$	
LO+PS+MS	$175.98^{+0.63}_{-0.69}$ [16.9]
NLO+PS	$175.43^{+0.74}_{-0.80}$ [29.2]
LO+PS	$187.90^{+0.6}_{-0.6}$ [428.3]
fNLO	$174.41^{+0.72}_{-0.73}$ [96.6]
fLO	$197.31^{+0.42}_{-0.35}$ [2496.1]



discrepancy highlights poor QCD description

Subtleties for *any template method*

1407.2763 - Frixione, S. and Mitov, A. - Determination of the top quark mass from leptonic observables

theory modeling: LO, NLO, LO+PS, NLO+PS (⊗ spin correlations)

$p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_\ell$, $p_{T\bar{\ell}}+p_{T\ell}$	
LO+PS+MS	$173.61^{+1.10}_{-1.34}[1.0]$
NLO+PS	$174.40^{+0.75}_{-0.81}[3.5]$
LO+PS	$173.68^{+1.08}_{-1.31}[0.8]$
fNLO	$174.73^{+0.72}_{-0.74}[5.5]$
fLO	$175.84^{+0.90}_{-1.05}[1.2]$

$p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_\ell$, $p_{T\bar{\ell}}+p_{T\ell}$, $p_{T\bar{\ell}+\ell}$, $M_{\bar{\ell}+\ell}$	
LO+PS+MS	$175.98^{+0.63}_{-0.69}[16.9]$
NLO+PS	$175.43^{+0.74}_{-0.80}[29.2]$
LO+PS	$187.90^{+0.6}_{-0.6}[428.3]$
fNLO	$174.41^{+0.72}_{-0.73}[96.6]$
fLO	$197.31^{+0.42}_{-0.35}[2496.1]$

discrepancy highlights poor QCD description

Subtleties for *any template method*

1407.2763 - Frixione, S. and Mitov, A. - Determination of the top quark mass from leptonic observables

theory modeling: LO, NLO, LO+PS, NLO+PS (⊗ spin correlations)

$p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_{\ell}$, $p_{T\bar{\ell}}+p_{T\ell}$	
LO+PS+MS	$173.61^{+1.10}_{-1.34}[1.0]$
NLO+PS	$174.40^{+0.75}_{-0.81}[3.5]$
LO+PS	$173.68^{+1.08}_{-1.31}[0.8]$
fNLO	$174.73^{+0.72}_{-0.74}[5.5]$
fLO	$175.84^{+0.90}_{-1.05}[1.2]$

$p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_{\ell}$, $p_{T\bar{\ell}}+p_{T\ell}$, $p_{T\bar{\ell}+\ell}$, $M_{\bar{\ell}+\ell}$	
LO+PS+MS	$175.98^{+0.63}_{-0.69}[16.9]$
NLO+PS	$175.43^{+0.74}_{-0.80}[29.2]$
LO+PS	$187.90^{+0.6}_{-0.6}[428.3]$
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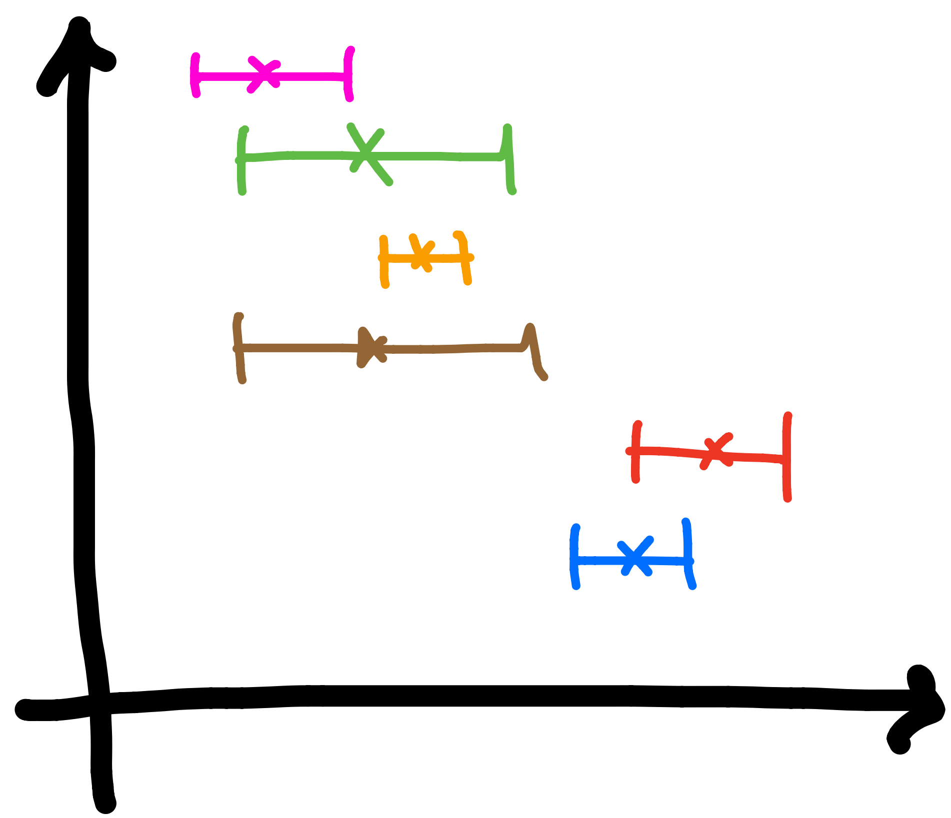


discrepancy highlights poor QCD description

Top mass combination

LHC/Tevatron NOTE

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

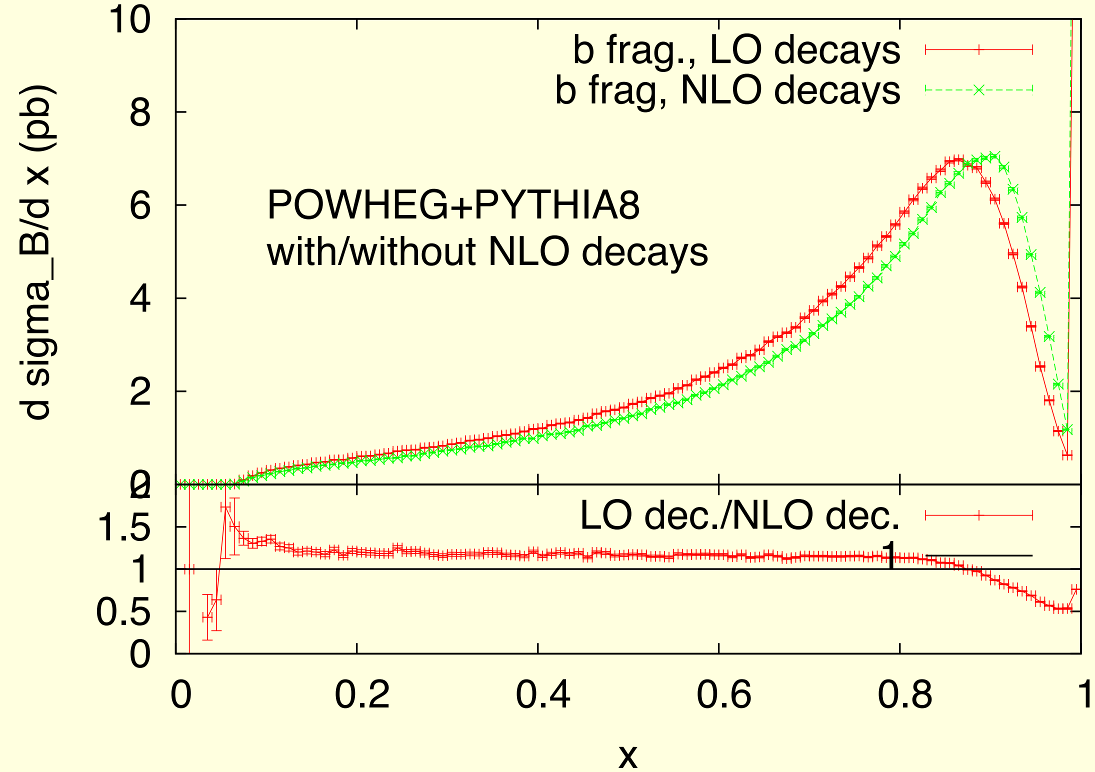
March 17, 2014

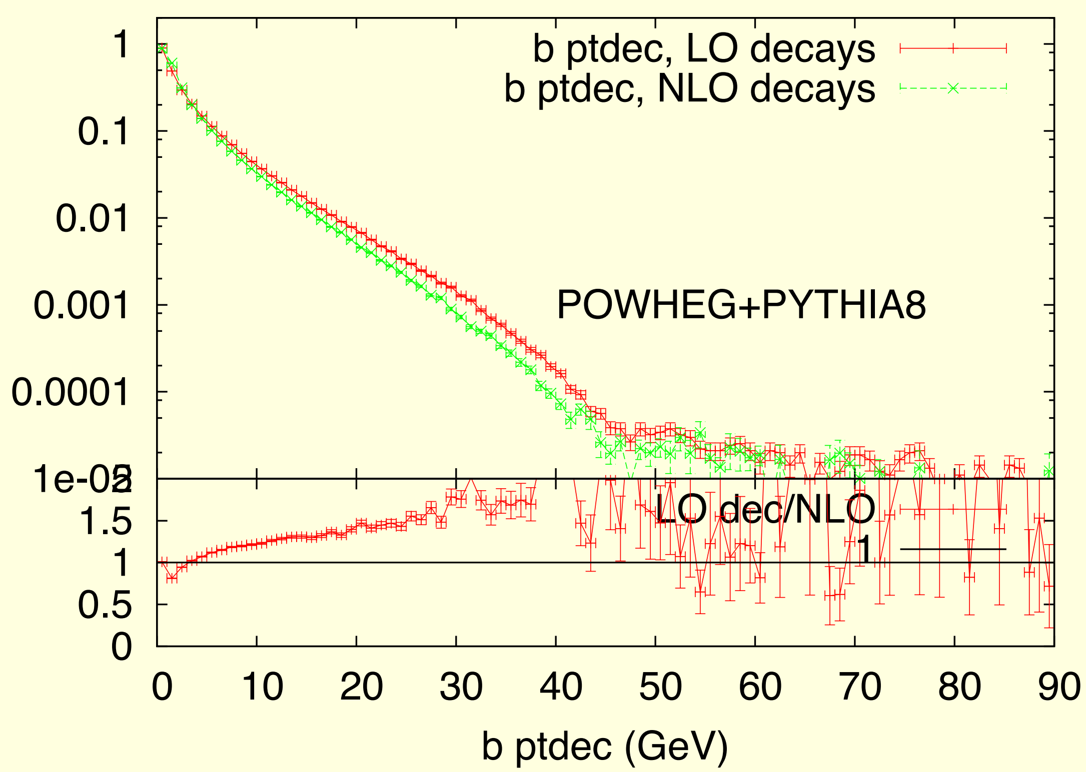
	Input measurements and uncertainties in GeV											
	CDF				D0		ATLAS		CMS			World
Uncertainty	l+jets	di-l	all jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	l+jets	di-l	l+jets	di-l	l+jets	di-l	all jets	Combination
m_{top}	172.85	170.28	172.47	173.93	174.94	174.00	172.31	173.09	173.49	172.50	173.49	173.34
Stat	0.52	1.95	1.43	1.26	0.83	2.36	0.23	0.64	0.27	0.43	0.69	0.27
iJES	0.49	n.a.	0.95	1.05	0.47	0.55	0.72	n.a.	0.33	n.a.	n.a.	0.24
stdJES	0.53	2.99	0.45	0.44	0.63	0.56	0.70	0.89	0.24	0.78	0.78	0.20
flavourJES	0.09	0.14	0.03	0.10	0.26	0.40	0.36	0.02	0.11	0.58	0.58	0.12
bJES	0.16	0.33	0.15	0.17	0.07	0.20	0.08	0.71	0.61	0.76	0.49	0.25
MC	0.56	0.36	0.49	0.48	0.63	0.50	0.35	0.64	0.15	0.06	0.28	0.38
Rad	0.06	0.22	0.10	0.28	0.26	0.30	0.45	0.37	0.30	0.58	0.33	0.21
CR	0.21	0.51	0.32	0.28	0.28	0.55	0.32	0.29	0.54	0.13	0.15	0.31
PDF	0.08	0.31	0.19	0.16	0.21	0.30	0.17	0.12	0.07	0.09	0.06	0.09
DetMod	<0.01	<0.01	<0.01	<0.01	0.36	0.50	0.23	0.22	0.24	0.18	0.28	0.10
b-tag	0.03	n.e.	0.10	n.e.	0.10	<0.01	0.81	0.46	0.12	0.09	0.06	0.11
LepPt	0.03	0.27	n.a.	n.a.	0.18	0.35	0.04	0.12	0.02	0.14	n.a.	0.02
BGMC	0.12	0.24	n.a.	n.a.	0.18	n.a.	n.a.	0.14	0.13	0.05	n.a.	0.10
BGData	0.16	0.14	0.56	0.15	0.21	0.20	0.10	n.a.	n.a.	n.a.	0.13	0.07
Meth	0.05	0.12	0.38	0.21	0.16	0.51	0.13	0.07	0.06	0.40	0.13	0.05
MHI	0.07	0.23	0.08	0.18	0.05	<0.01	0.03	0.01	0.07	0.11	0.06	0.04
Total Syst	0.99	3.13	1.41	1.36	1.25	1.49	1.53	1.50	1.03	1.46	1.23	0.71
Total	1.12	3.69	2.01	1.85	1.50	2.79	1.55	1.63	1.06	1.52	1.41	0.76

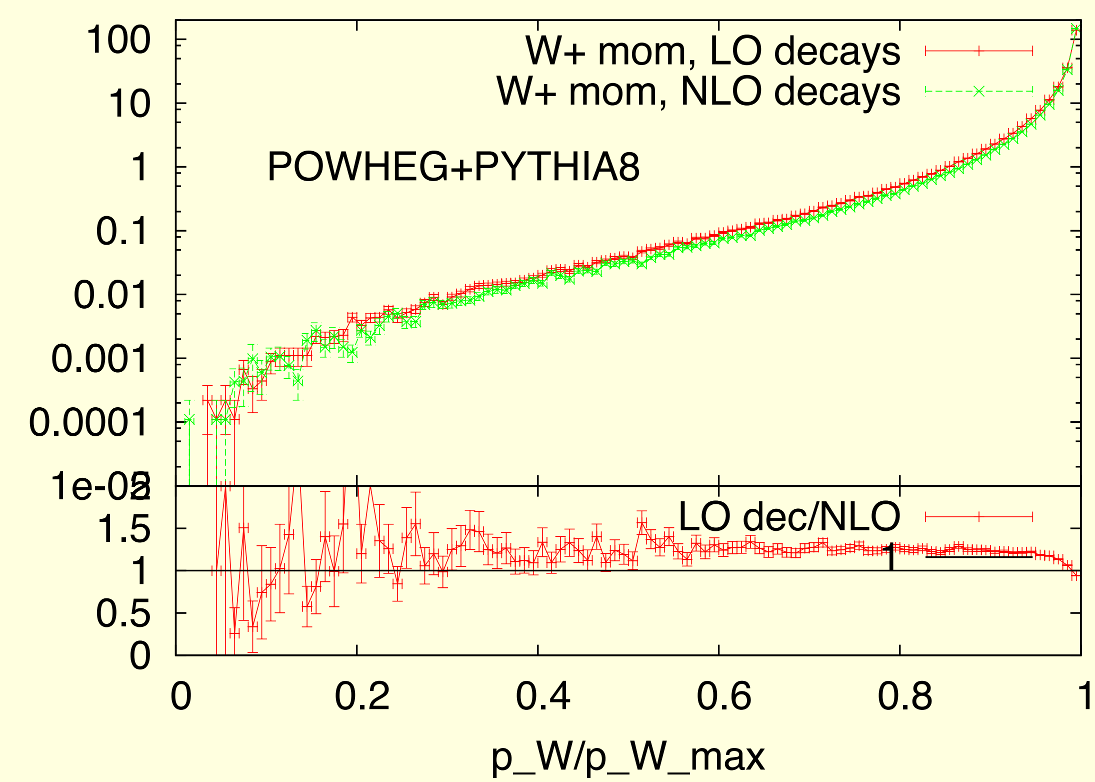
$t \rightarrow bW\mathbf{g}$

b fragmentation properties in t decays

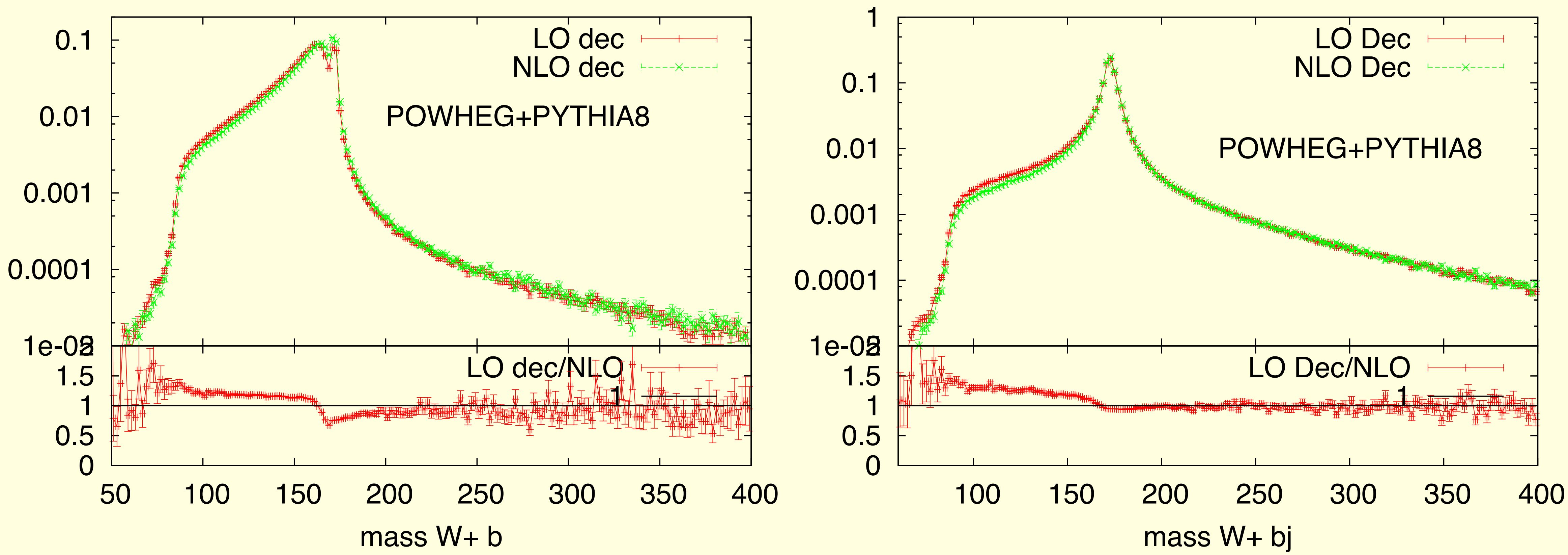
Observables computed in t rest frame.
b stands for hardest b flavoured hadron



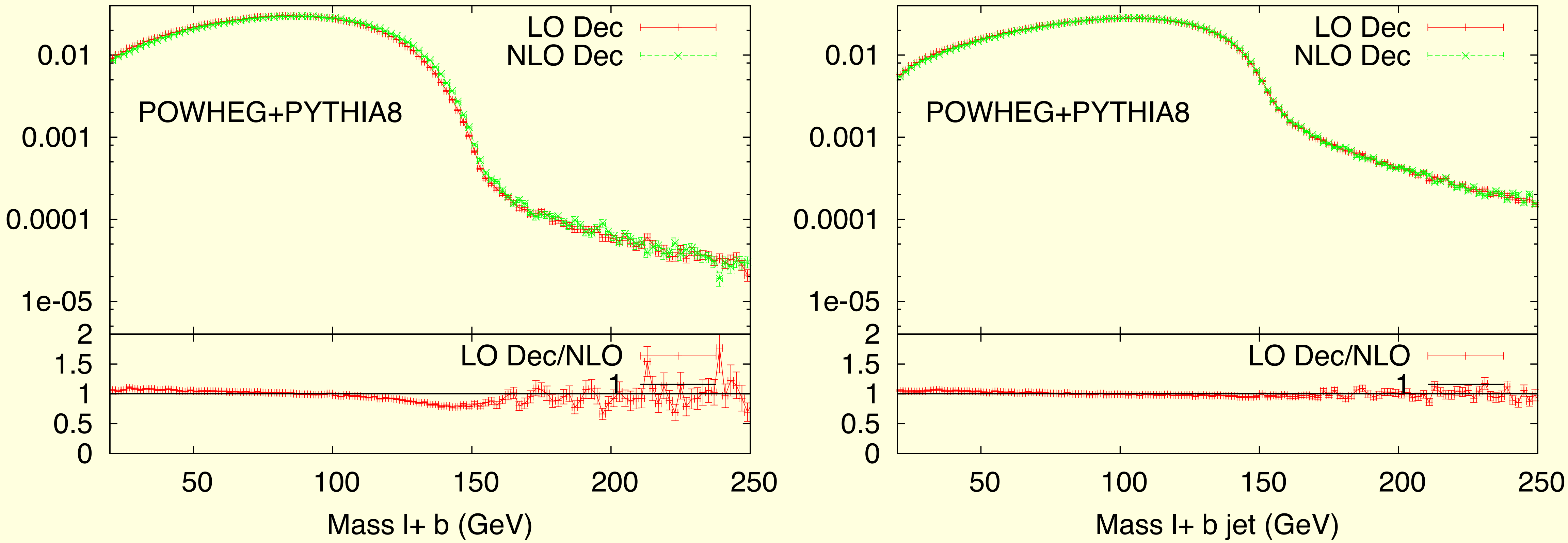




t mass pseudo observables



Notice small peak in W^+b plot, due to $x = 1$ peak in b fragmentation function.



Effect of different fragmentation behaviour shows up in M_{l+b}, but not in $M_{l+b\,\mathrm{jet}}$.

top mass**es**

Pole vs MSbar masses

$$m_{pole} = \overline{m} \times \left[1 + g_1 \frac{\bar{\alpha}}{\pi} + g_2 \left(\frac{\bar{\alpha}}{\pi}\right)^2 + g_3 \left(\frac{\bar{\alpha}}{\pi}\right)^3\right]$$

where

$$\overline{m} = m_{MS}(m_{MS})$$

$$\bar{\alpha} = \alpha(\overline{m})$$

$$g_1 = \frac{4}{3}$$

$$g_2 = 13.4434 - 1.0414 \sum_k \left(1 - \frac{4}{3}\frac{\overline{m}_k}{\overline{m}}\right)$$

$$g_3 = 0.6527\, n_l^2 - 26.655\, n_l + 190.595$$

Melnikov, van Ritbergen, Phys.Lett. B482 (2000) 99

In the range m_{top} = 171 – 175 GeV, α_S is ~constant, and, using the 3-loop expression above,

$$m_{pole} = \overline{m} \times [1 + 0.047 + 0.010 + 0.003] = 1.060 \times \overline{m}$$

showing an excellent convergence. In comparison, the expansion for the bottom quark mass behaves very poorly:

$$m^b_{pole} = \overline{m}^b \times [1 + 0.09 + 0.05 + 0.04]$$

Assuming that after the 3rd order the perturbative expansion of m_{pole} vs m_{MS} start diverging, the smallest term of the series, which gives the size of the uncertainty in the resummation of the asymptotic series, is of O(0.003 * m), namely O(500 MeV), consistent with Λ_{QCD}

This same O(α_S^3) term gives also: $\overline{m}^{(3-loop)} - \overline{m}^{(2-loop)} = 0.49\,\mathrm{GeV}$

Meson vs hvy-Q masses

Heavy meson ⟹ (point-like color source) + (light antiquark cloud):
properties of "light-quark" cloud are independent of mQ for $mQ \to \infty$

$$m_M = m_Q + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_Q}$$

$$m_{M^*} = m_Q + \bar{\Lambda} - \frac{\lambda_1 - \lambda_2}{2m_Q}$$

$$\langle M|\, \bar{h}_Q\, (iD)^2 h_Q\, |M\rangle = -\lambda_1\, \mathrm{tr}\{\, \overline{\mathcal{M}}\, \mathcal{M}\,\} = 2M\, \lambda_1\,,$$

$$\langle M|\, \bar{h}_Q\, s_{\alpha\beta} G^{\alpha\beta} h_Q\, |M\rangle = -\lambda_2(\mu)\, \mathrm{tr}\{\, i\sigma_{\alpha\beta}\, \overline{\mathcal{M}}\, s^{\alpha\beta} \mathcal{M}\,\} = 2d_M M\, \lambda_2(\mu)\,,$$

$d_{M^*} = -1$, $d_M = 3$

See e.g. Falk and Neubert, arXiv:hep-ph/9209268v1

where $\bar{\Lambda},\ \lambda_1,\ \lambda_2$ are independent of m_Q

From the spectroscopy of the B-meson system:

$m(B^*) - m(B) = 2\, \lambda_2/m_b \Rightarrow \lambda_2 \sim 0.15\ \mathrm{GeV}^2$

QCD sum rules: $\lambda_1 \sim 1\ \mathrm{GeV}^2$

QCD sum rules: $\Lambda = 0.5 \pm 0.07$ GeV

thus corrections of $O(\lambda_{1,2}/m_{top})$ are of O(few MeV) and totally negligible

M. Mangano @ TOP LHC WG meeting (21-23 May 2014)

Separation between mQ and Λ is however ambiguous:
renormalon ambiguity on the pole mass:

$$\delta m_{pole} = \frac{C_F}{2N_f|\beta_0|} e^{-C/2} m(\mu=m) \exp\left(\frac{1}{2N_f\beta_0\alpha(m)}\right)$$
$$= \frac{C_F}{2N_f|\beta_0|} e^{-C/2} \Lambda_{QCD} \left(\ln\frac{m^2}{\Lambda^2_{QCD}}\right)^{\beta_1/(2\beta_0^2)},$$

where $\beta_1 = -1/(4\pi N_f)^2 \times (102 - 38N_f/3)$ is the second coefficient of the β-function

δm_{pole}=270 MeV for mtop.

This is smaller than the difference between MSbar masses obtained using the 3-loop or 2-loop MSbar vs pole mass conversion.

It would be very interesting to have a 4-loop calculation of MSbar vs m_{pole}, to check the rate of convergence of the series, and improve the estimate of the m_{pole} ambiguity for the top

Beneke and Braun, Nucl. Phys. B426, 301 (1994)
Bigi et al, 1994