Top mass from the bottom energy peak

Roberto Franceschini (CERN)
in collaboration with K.Agashe, D.Kim, K.Wardlow

work in progress
and
1209.0772 - Agashe, Franceschini, Kim

BSM applications:

- *1309.4776 - Agashe, Franceschini, Kim*
- *1212.5230 - Agashe, Franceschini, Kim, Wardlow*
- *1403.3399 - Chen, Davoudiasl, Kim*

- Semi-invisible decays and mass measurement
- Lorentz variant quantities: *Energy Peaks*
- Features of the Energy Peak Invariance

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

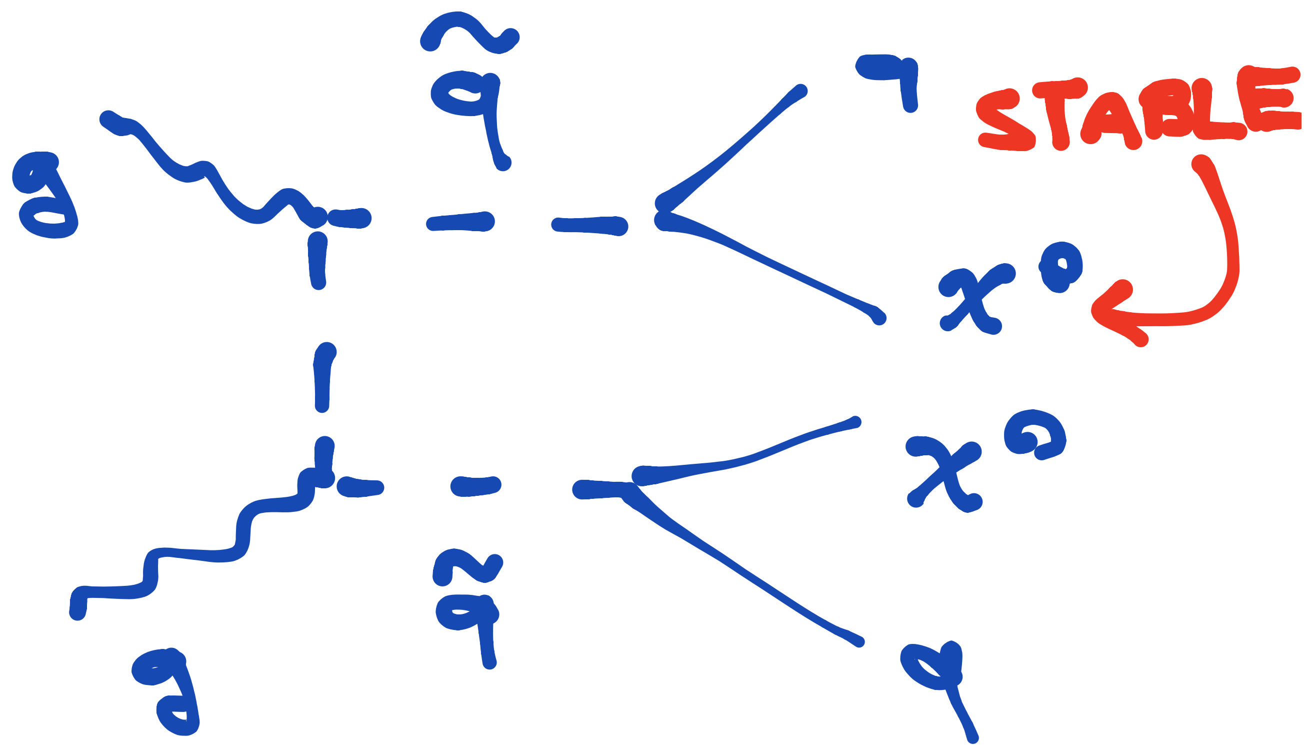
Need to come up with a trick

for example:

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

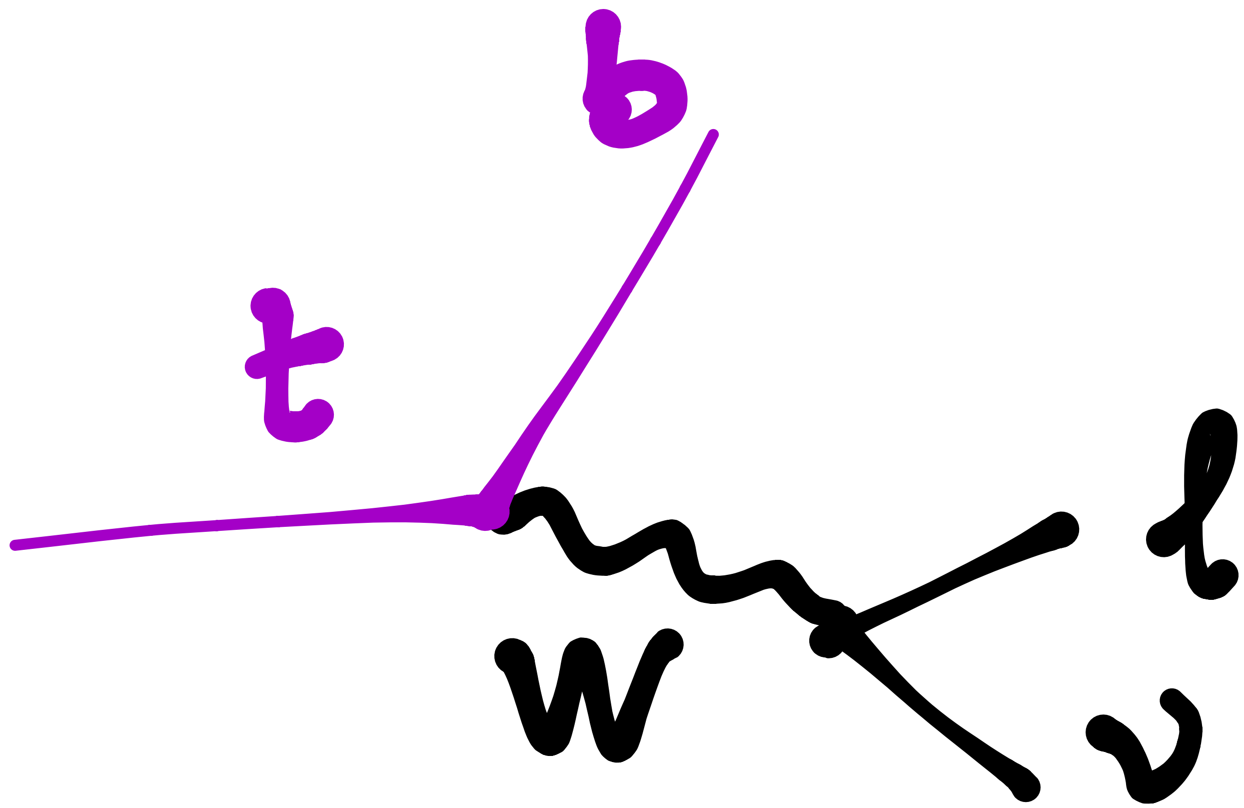
… and it can get worse

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***?

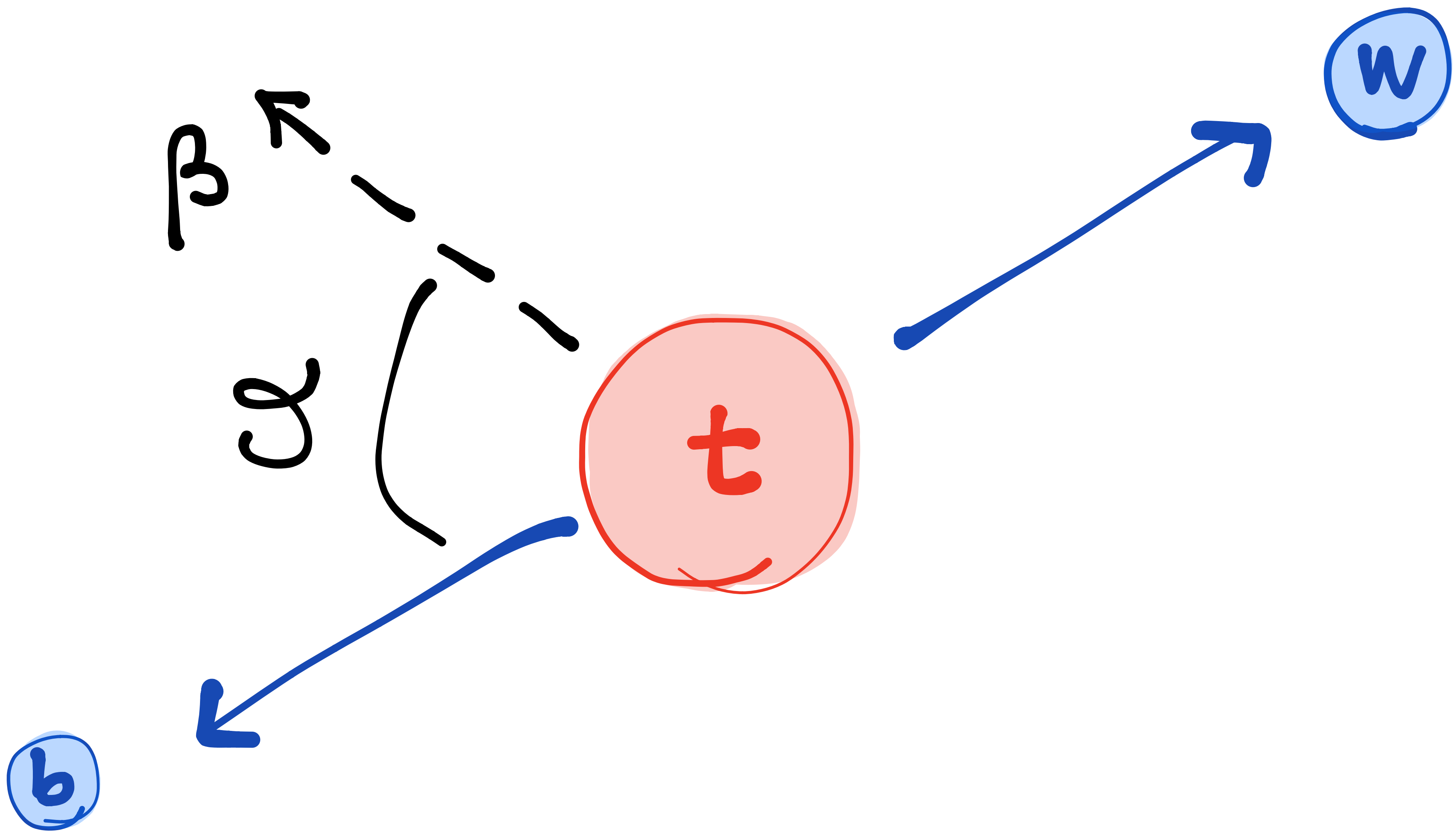
Lorentz *variant* quantities

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

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

1209.0772 - Agashe, Franceschini and Kim

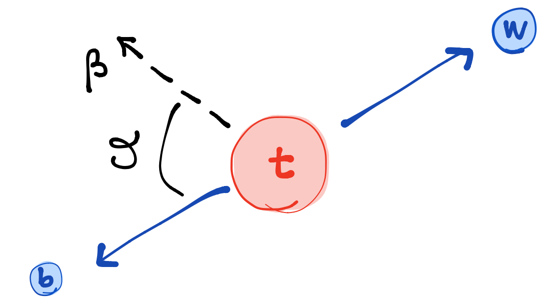
A simple, yet subtle, invariance



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

Event-by-event we cannot tell anything

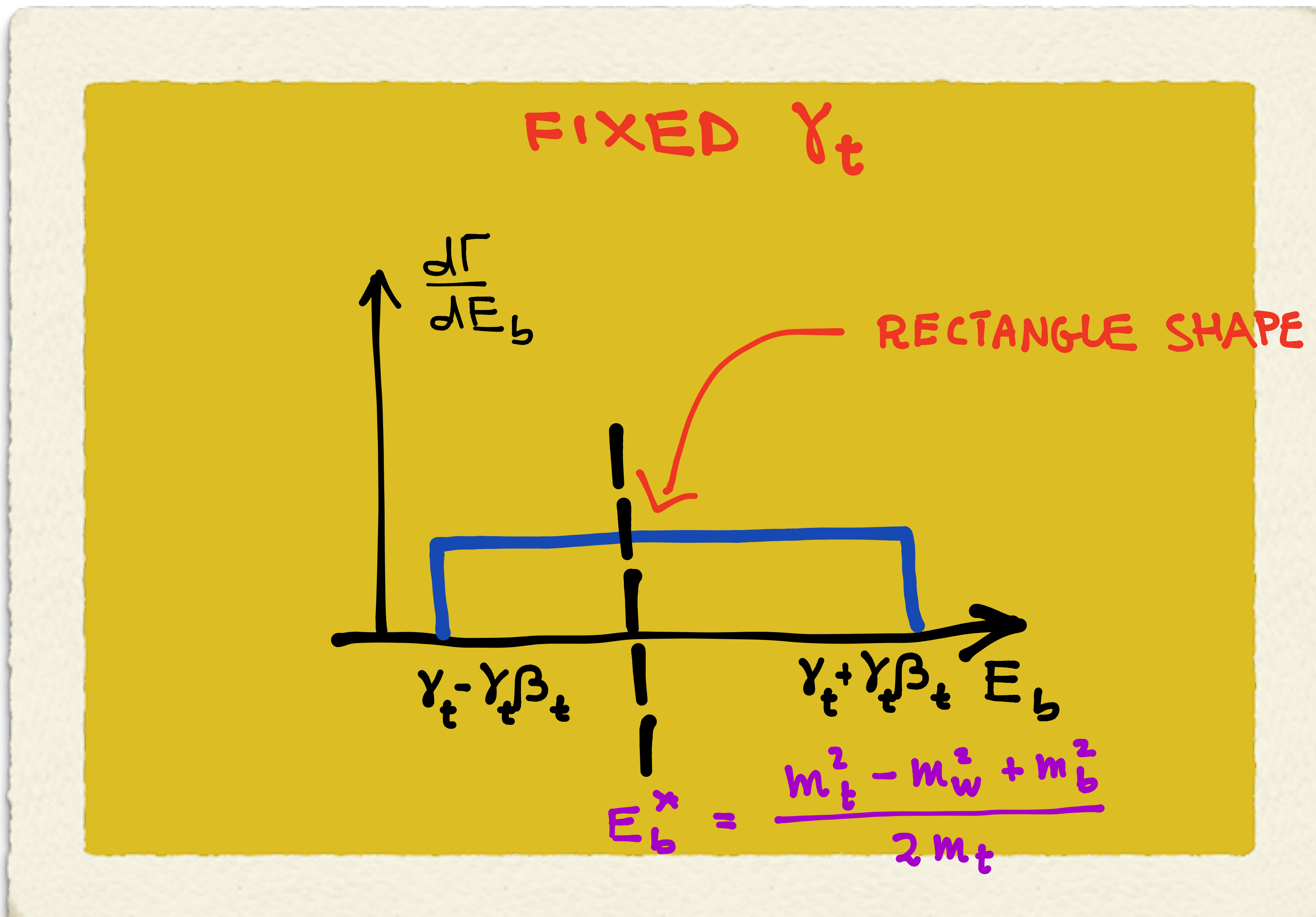
Fixed top boost decay



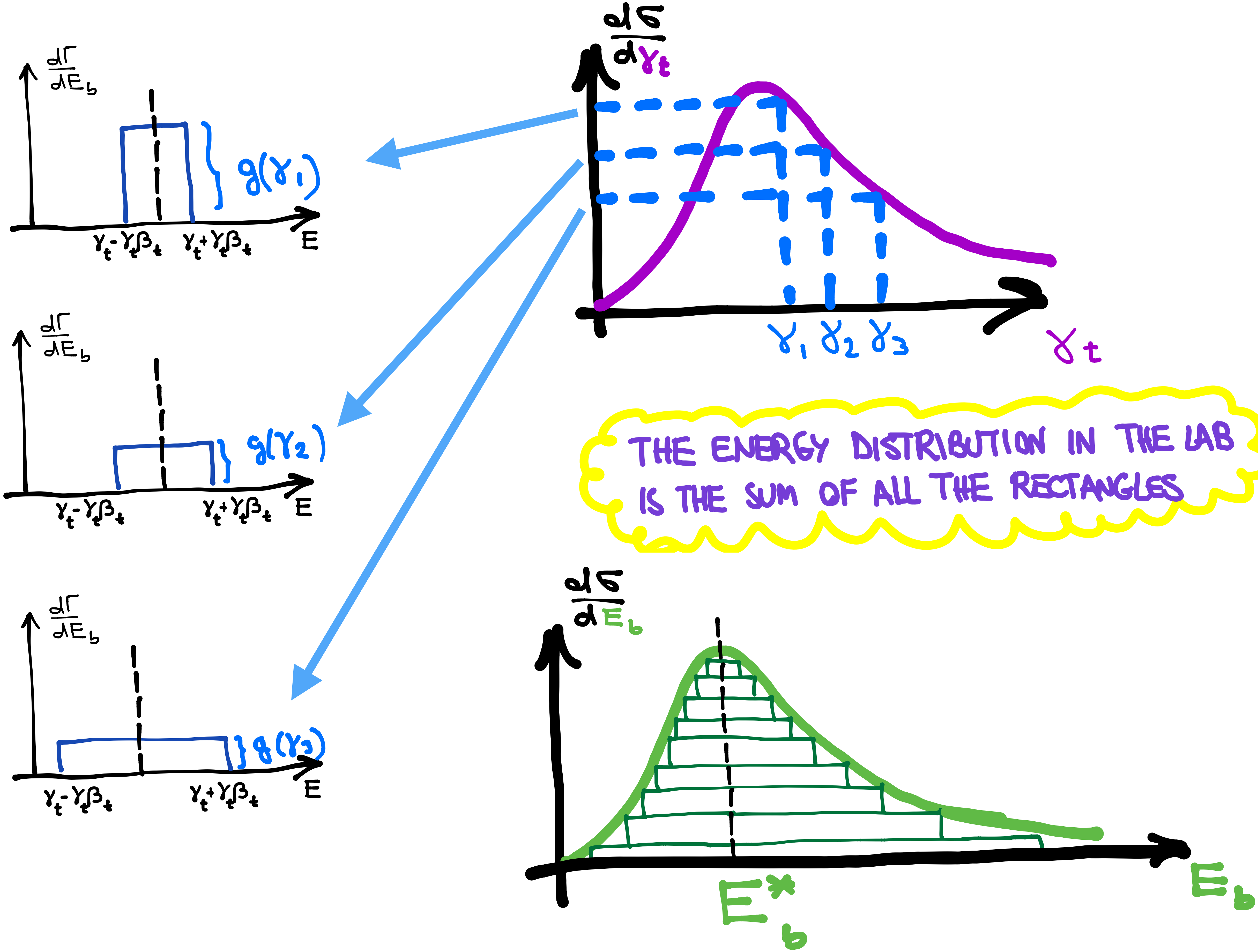
Massless b-quark (for now)

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

unpolarized top sample ⟶ cosθ is flat



Summing over the top boosts



Lab-frame energy distribution

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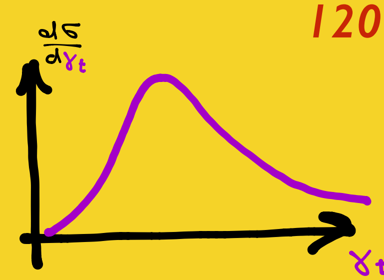
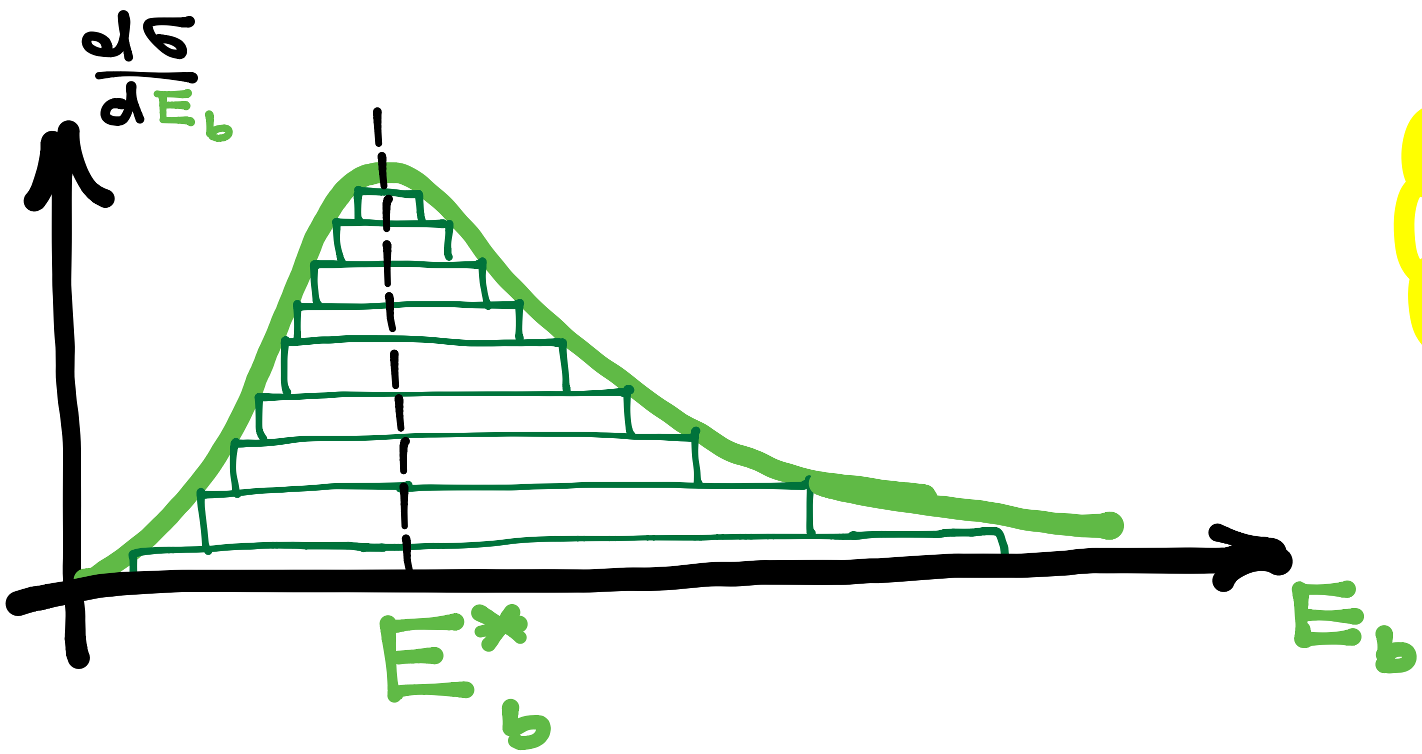
also Stecker 1971

for any top boost distribution 

the peak:

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

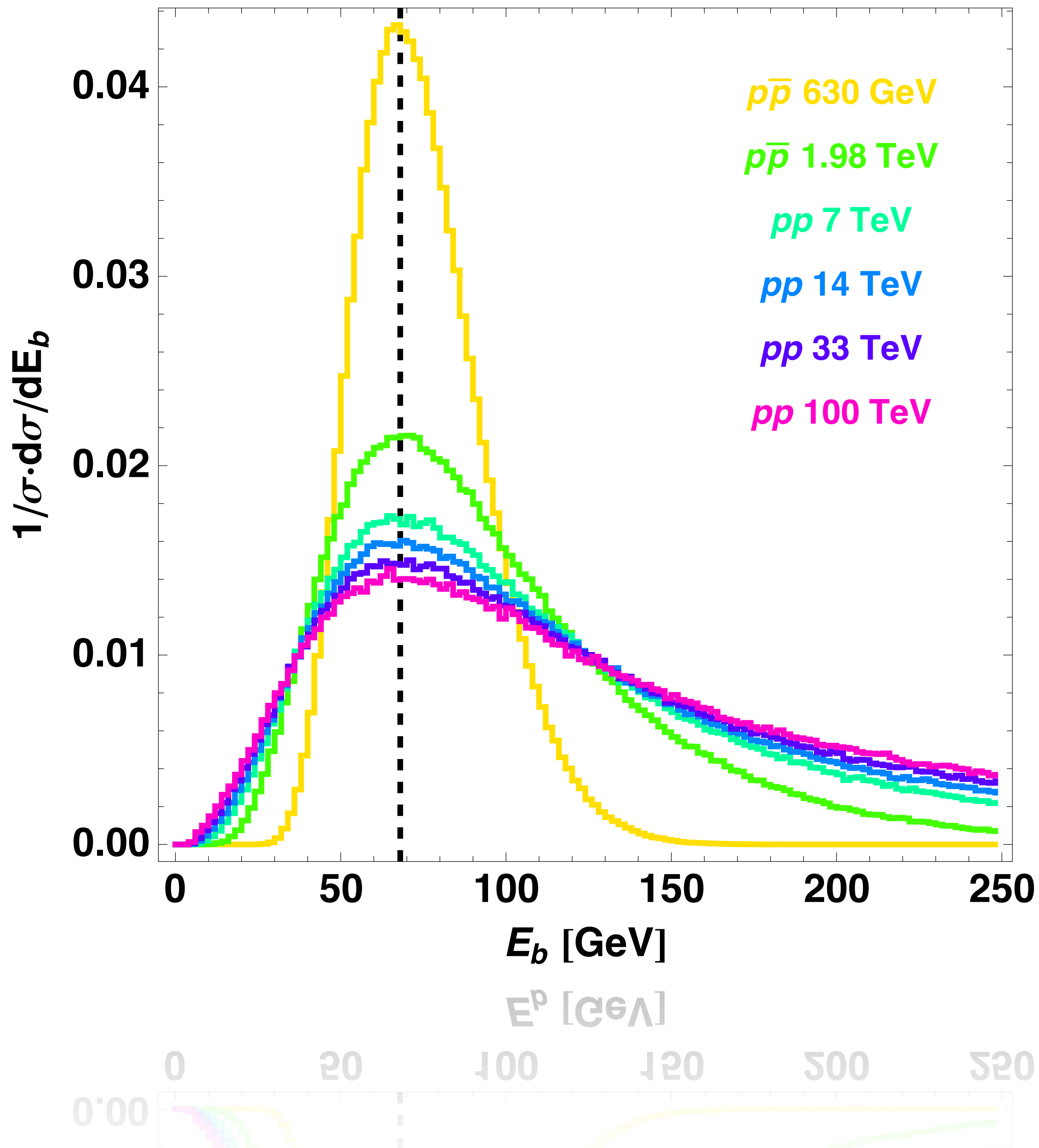


THE FRAME-DEPENDENT ENERGY DISTRIBUTION ENCODES THE INVARIANT E_d^* IN A VERY SIMPLE WAY

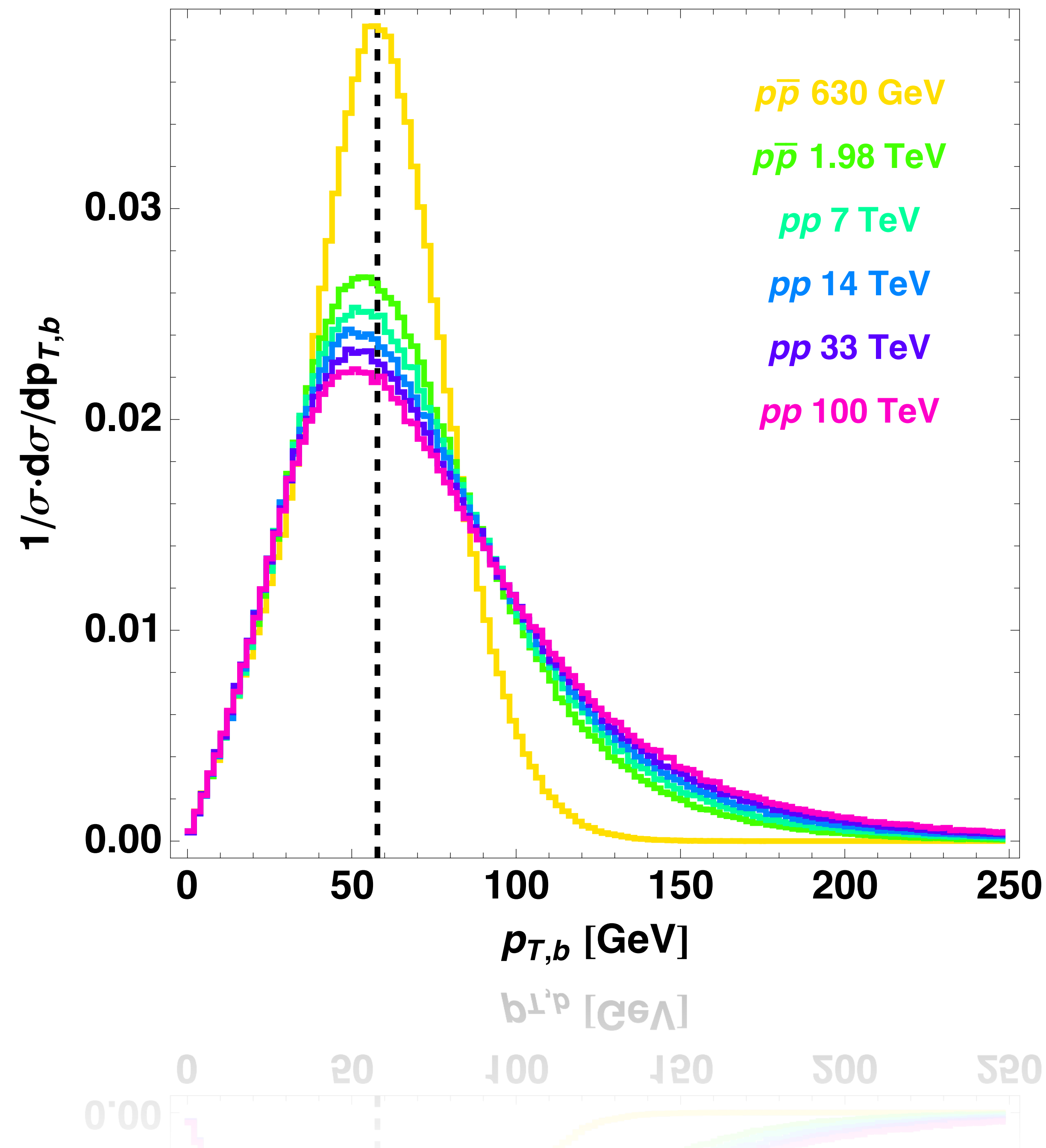
There is no difference when the b-mass is taken into account provided $\gamma_{top} < 500$

How special is this invariance?

Shape changes, peak doesn't!

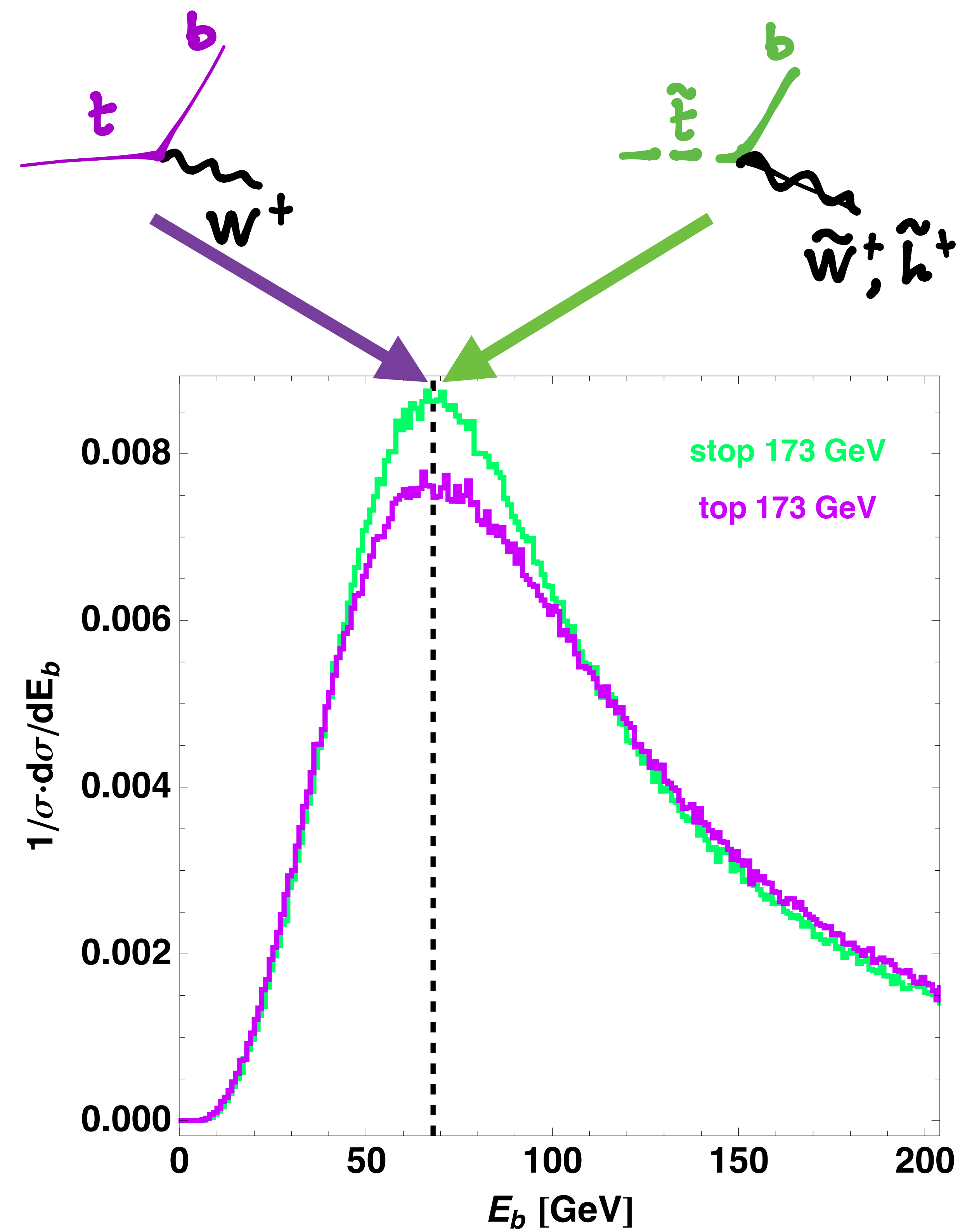


Shape changes, peak does too



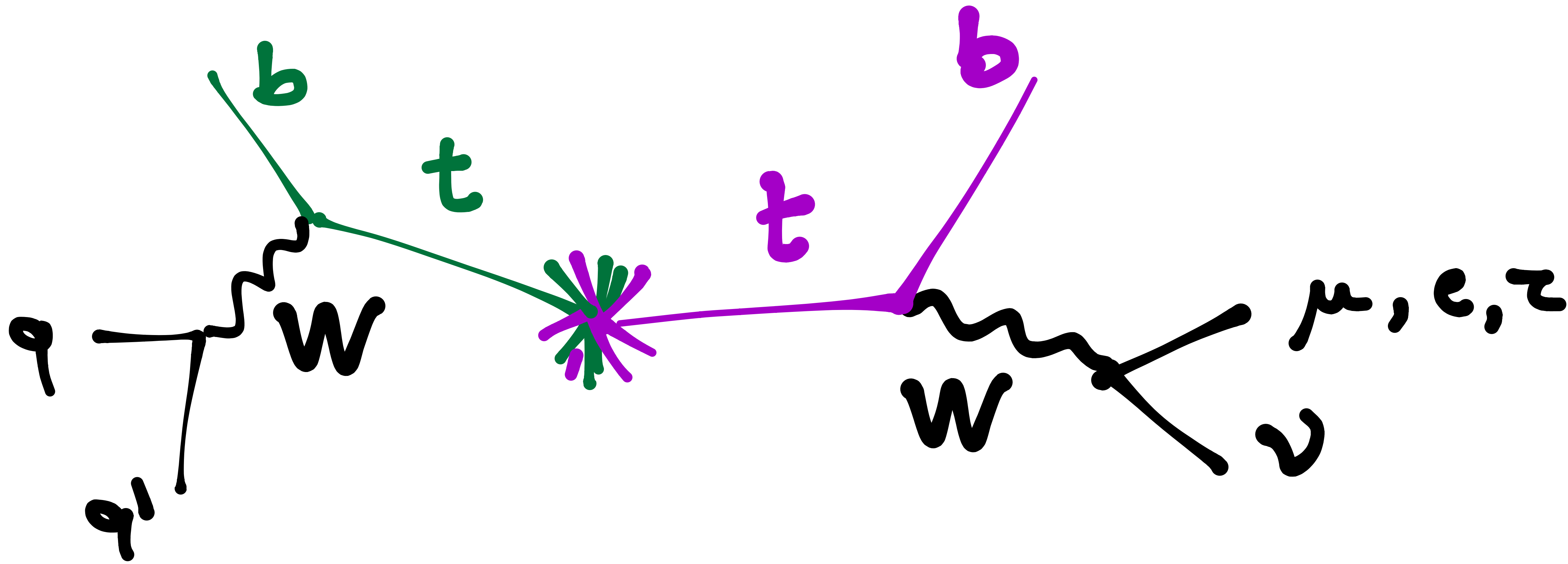
The sensitivity to the **boost distribution** is the key

Independent of decay dynamics



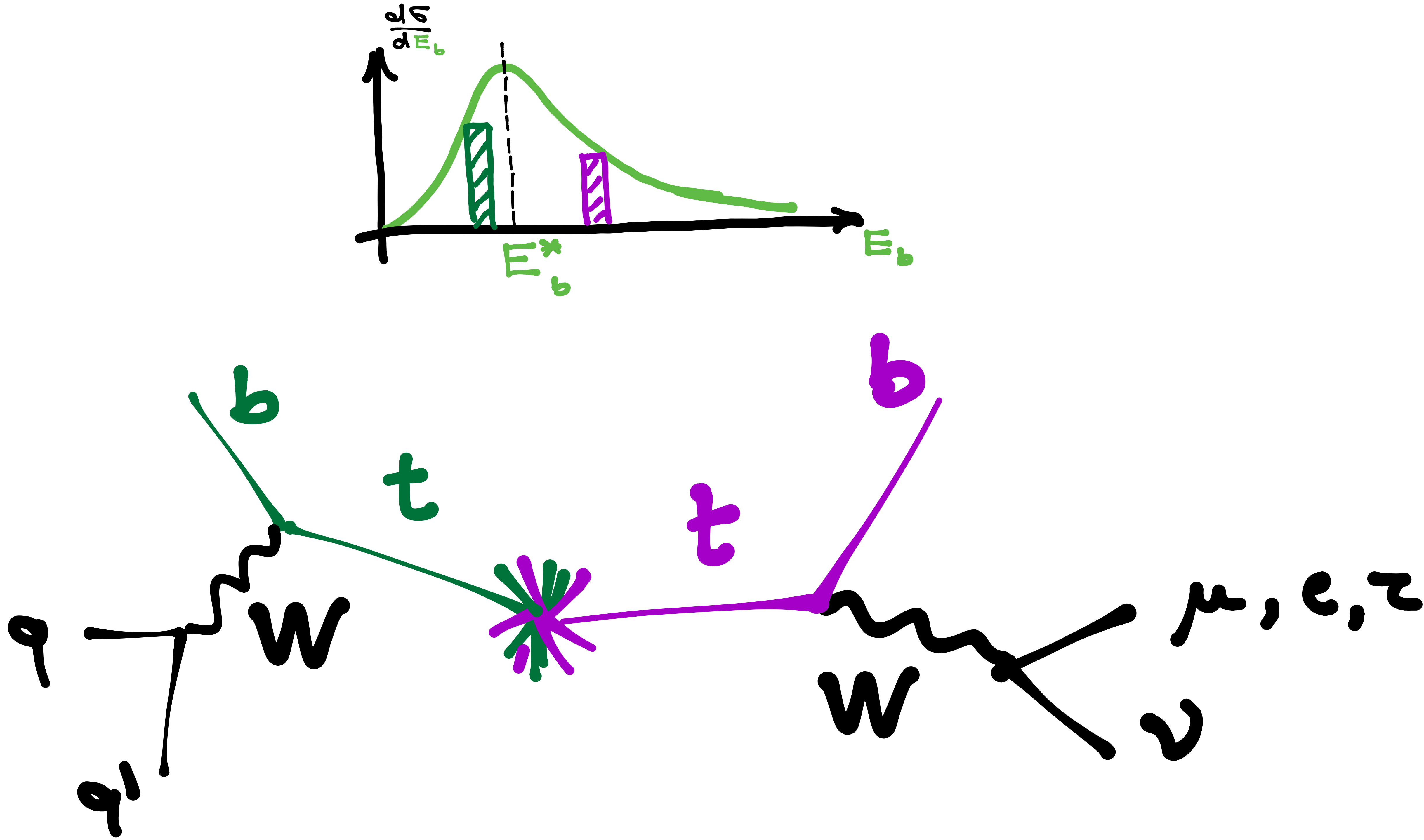
captures the peak for both stop and top: pure kinematics

No need to form combinations



just put 2 b per event into the histogram

No need to form combinations



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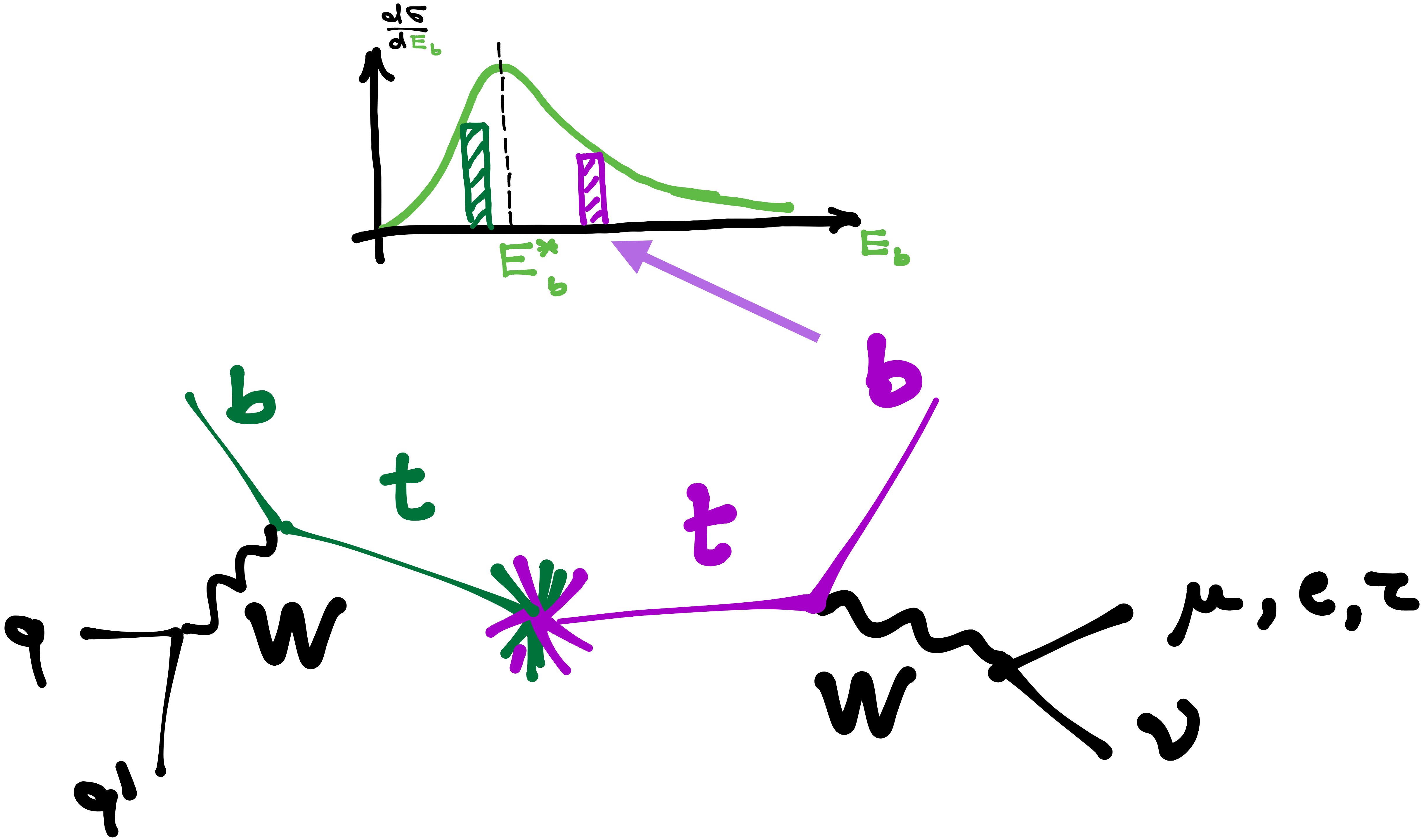

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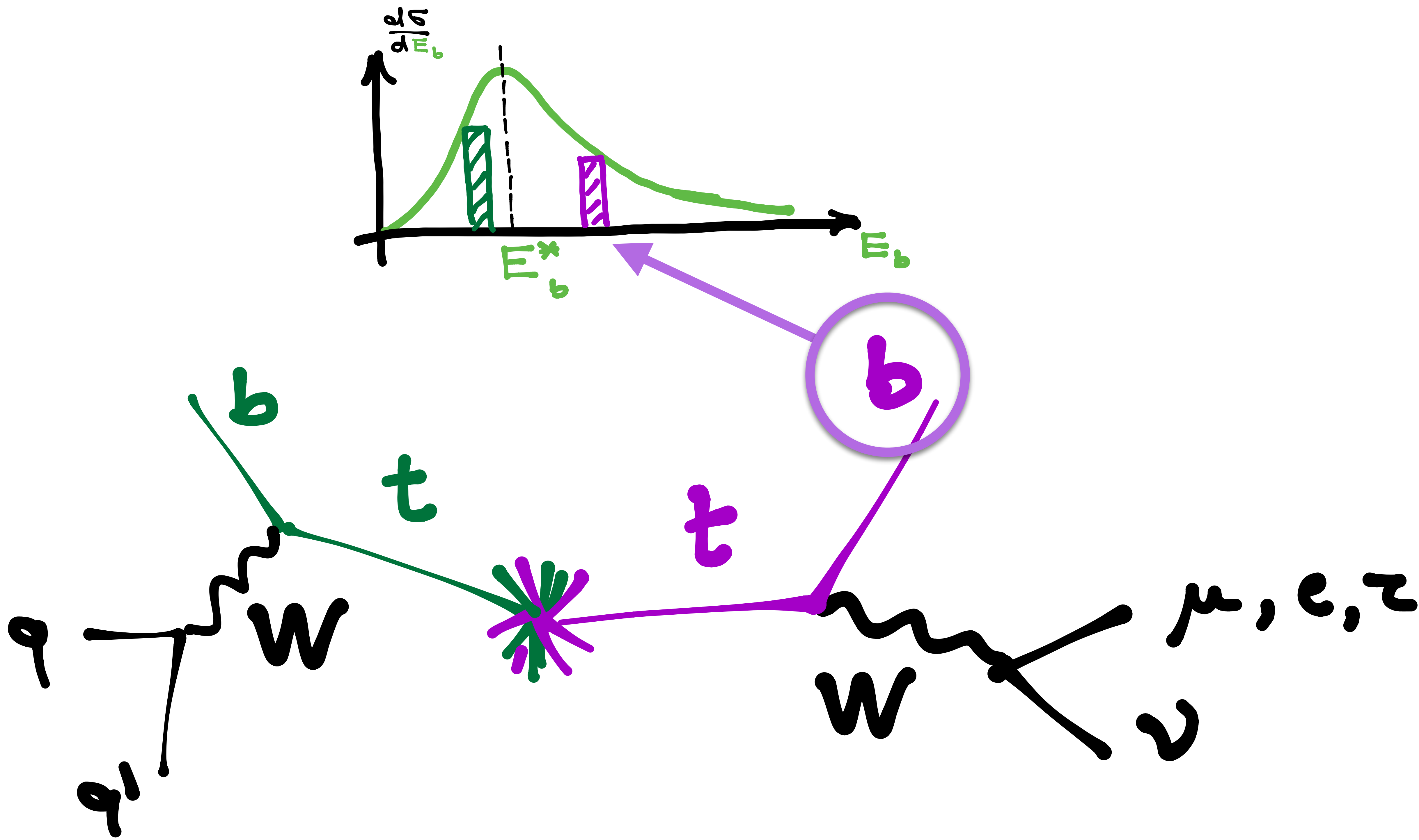

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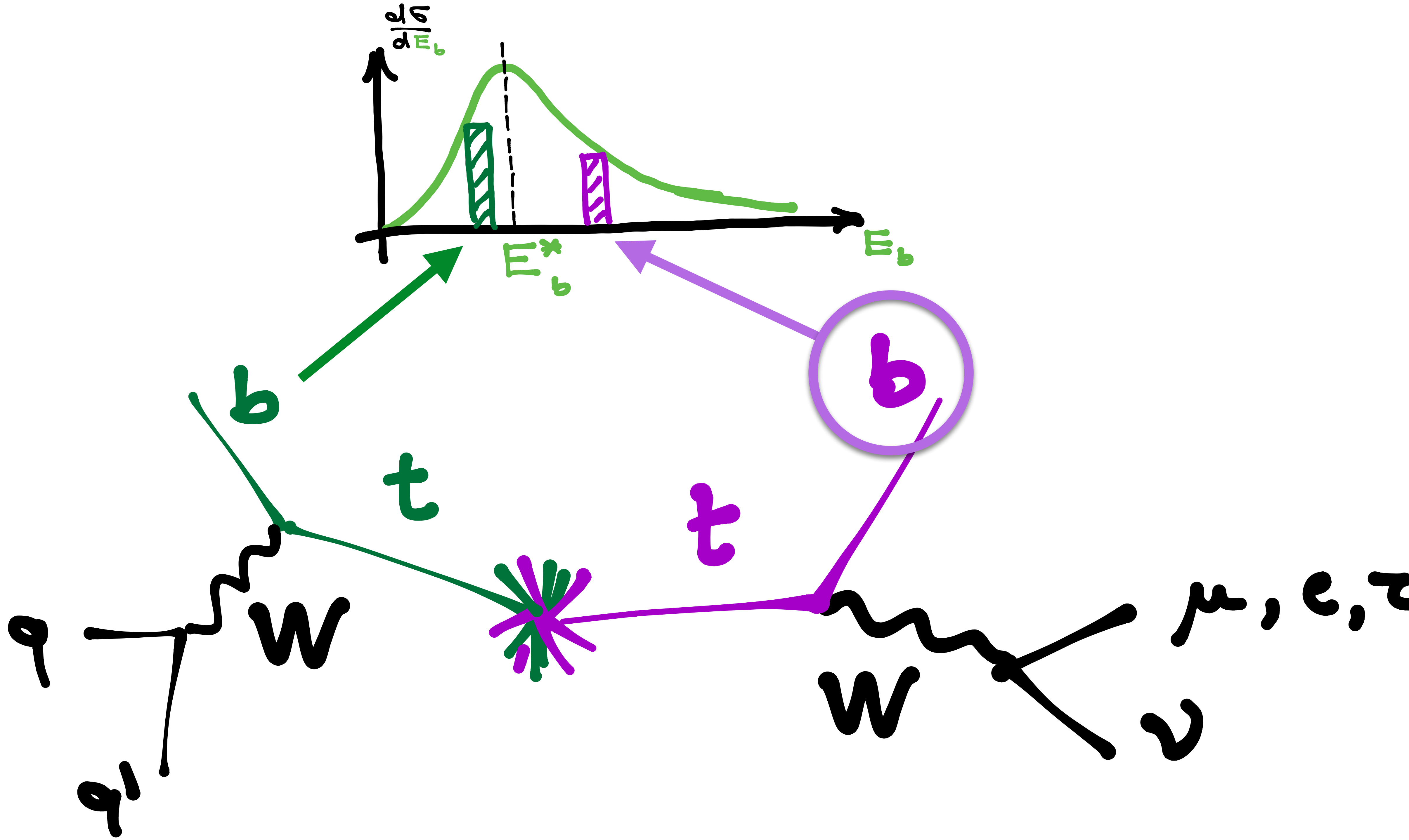
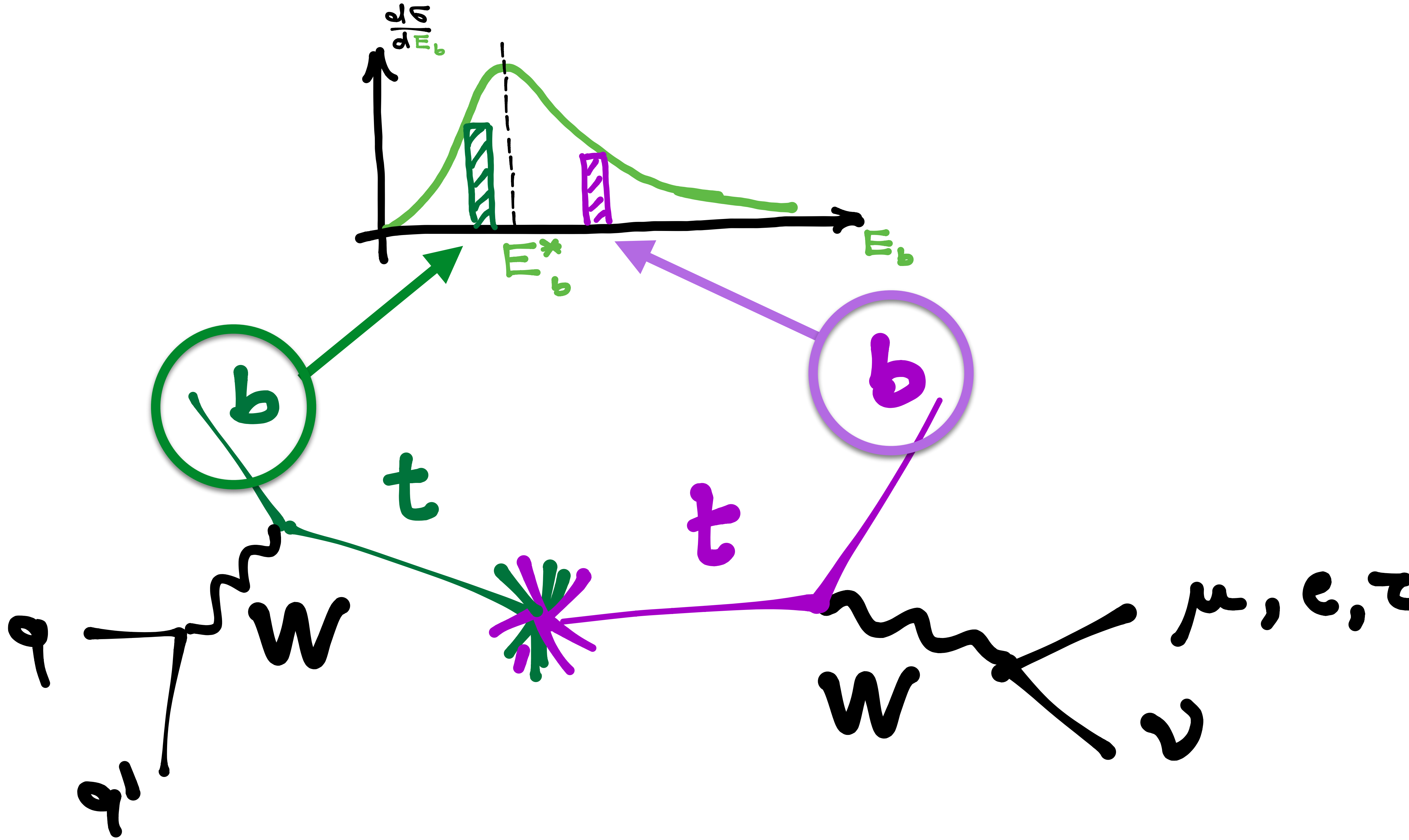


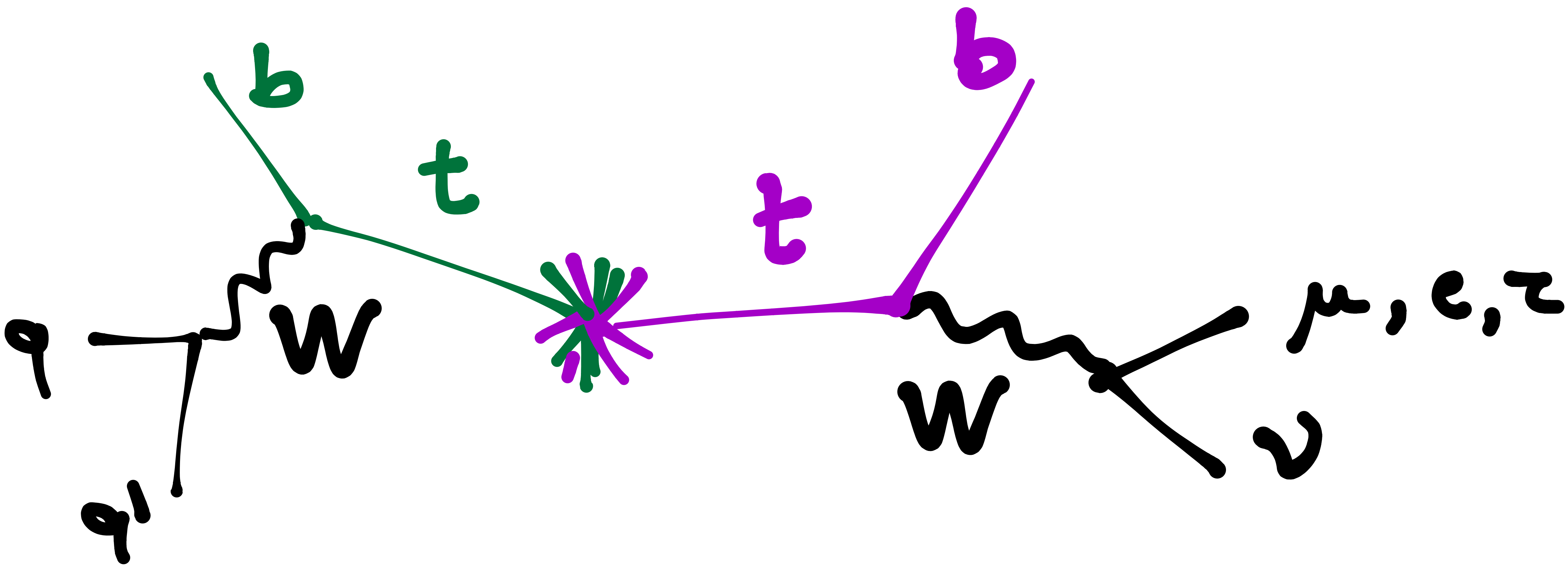
just put 2 b per event into the histogram

No need to form combinations



just put 2 b per event into the histogram

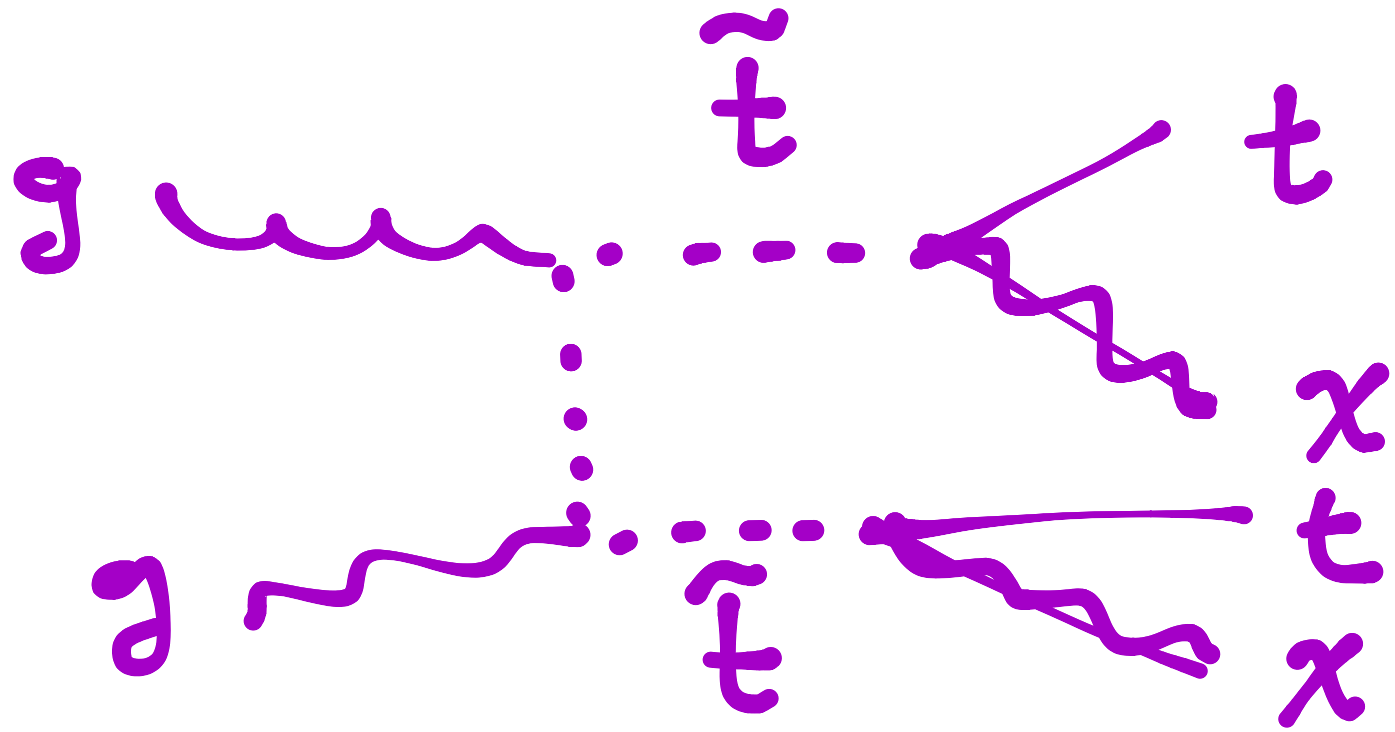
Applicable for any decay of W



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

W->τν as good as W->μν

New physics in the top sample



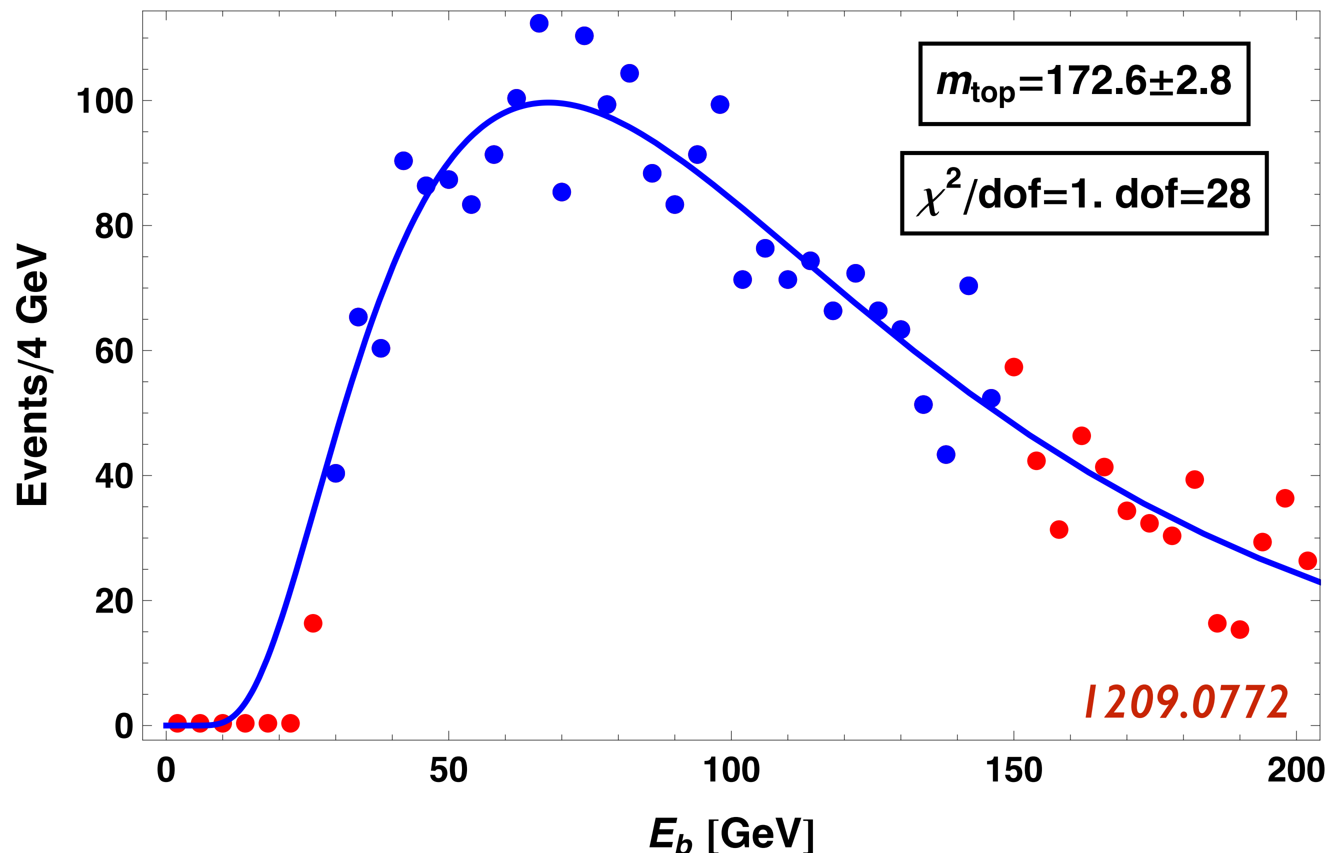
As long as it gives real tops
new physics does not change the result

- 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***

$m_{top} = 173.1 \pm 2.5$ GeV

1209.0772 - Agashe Franceschini and Kim

message: LO effects are well under control very encouraging LO result with b-jet energy

starting to think about NLO

your inputs are very welcome

NLO virtues

Agashe, Franceschini and Kim - in preparation

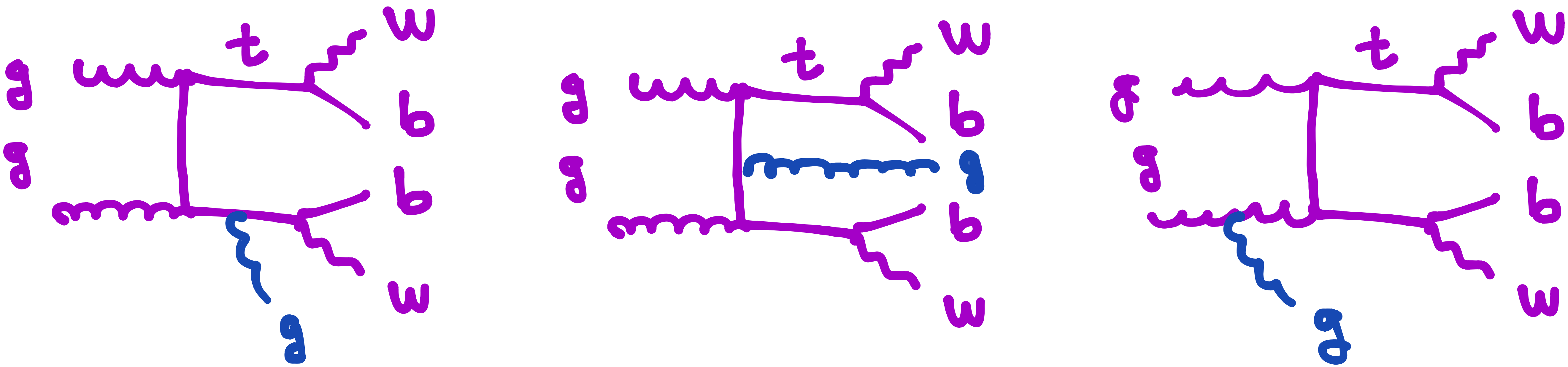
- **Invariance holds for pp->tt @ NLO**
- Not sensitive to Initial State Radiation
- Not sensitive to Parton Distribution Functions
- Not sensitive to the exact energy of the collider

only sensitive to the NLO decay t->bWg

Insensitive to production at NLO

Agashe, Franceschini and Kim - in preparation

Production NLO only affects the boost distribution of top



The energy peak position is unchanged

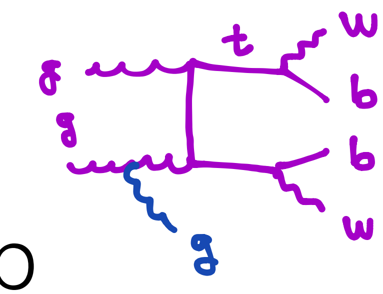
$$E_b^{peak} = \frac{m_t^2 - m_W^2 + m_{b/j}^2}{2m_t} = E_b^*$$

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

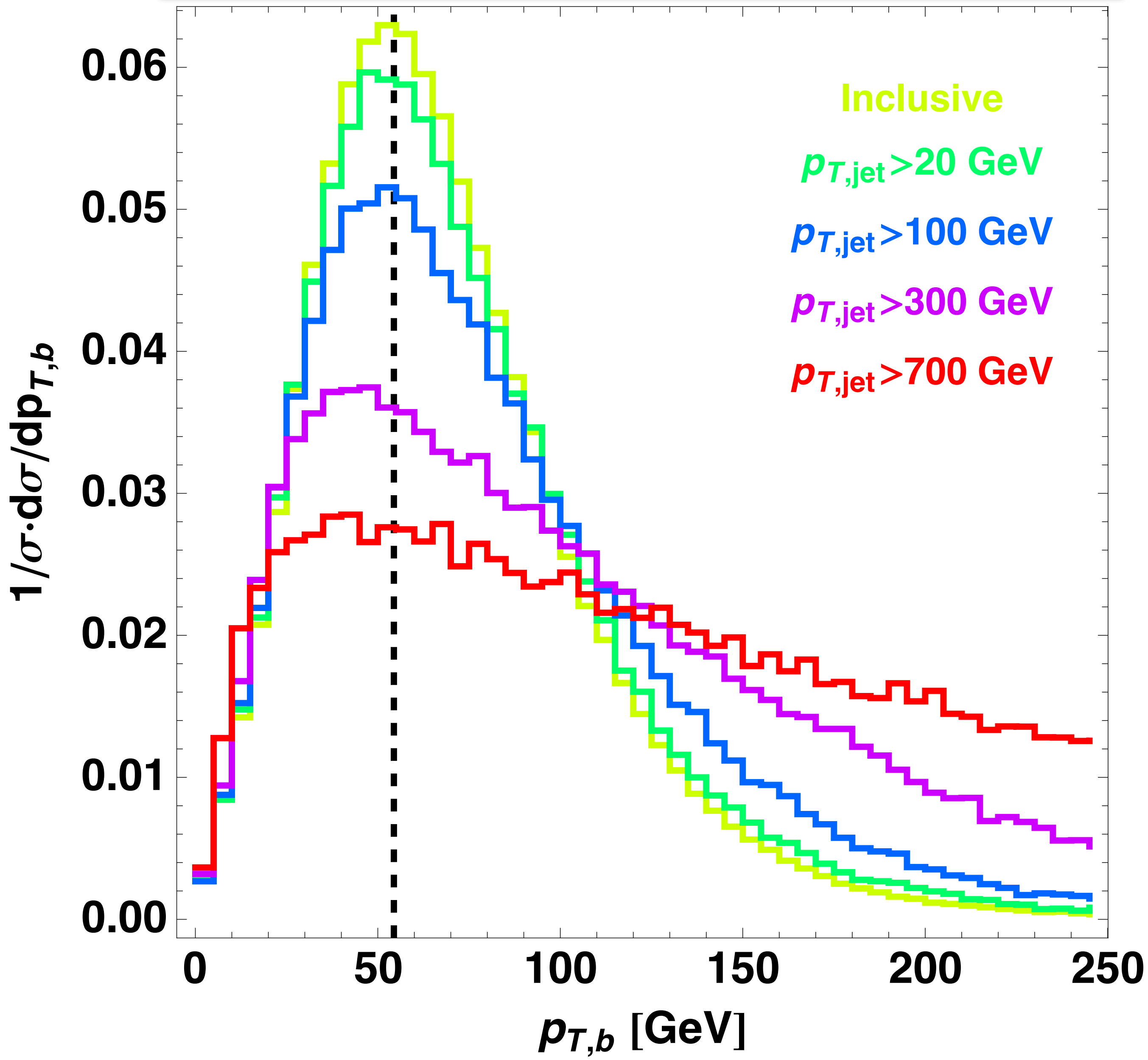
Effect of initial state radiation



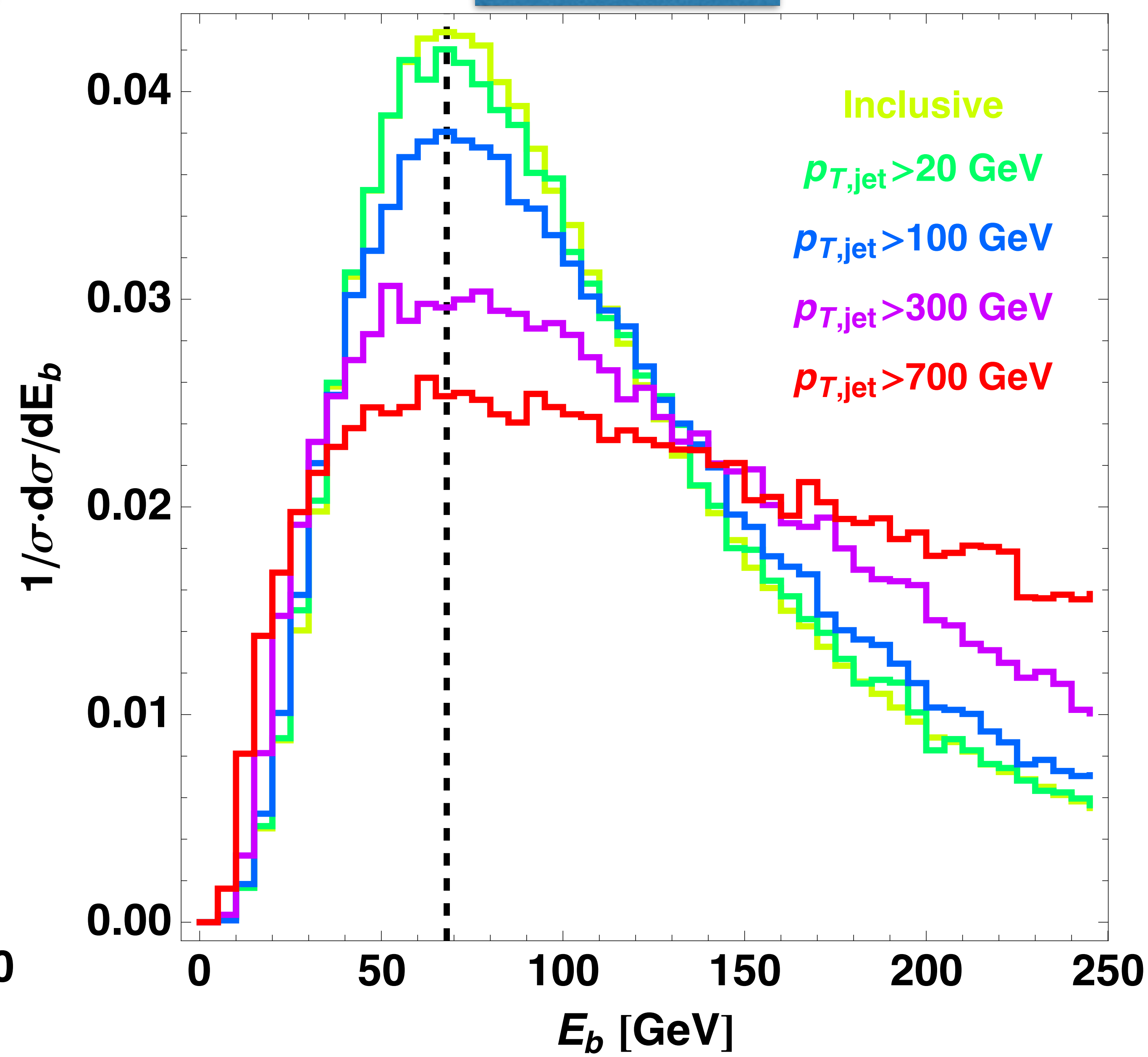
ISR only affects the boost distribution of top

Agashe, Franceschini and Kim - 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**
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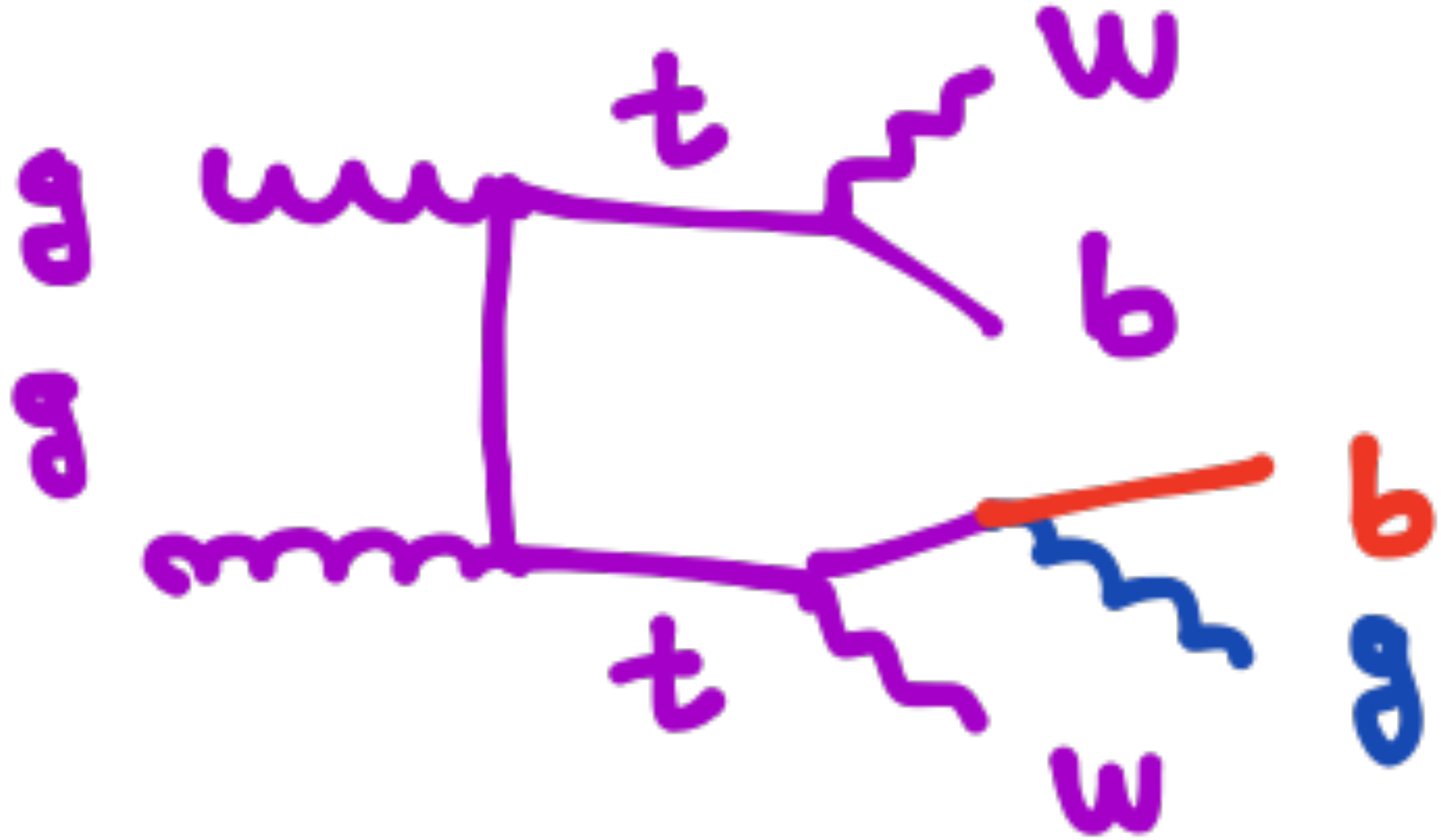
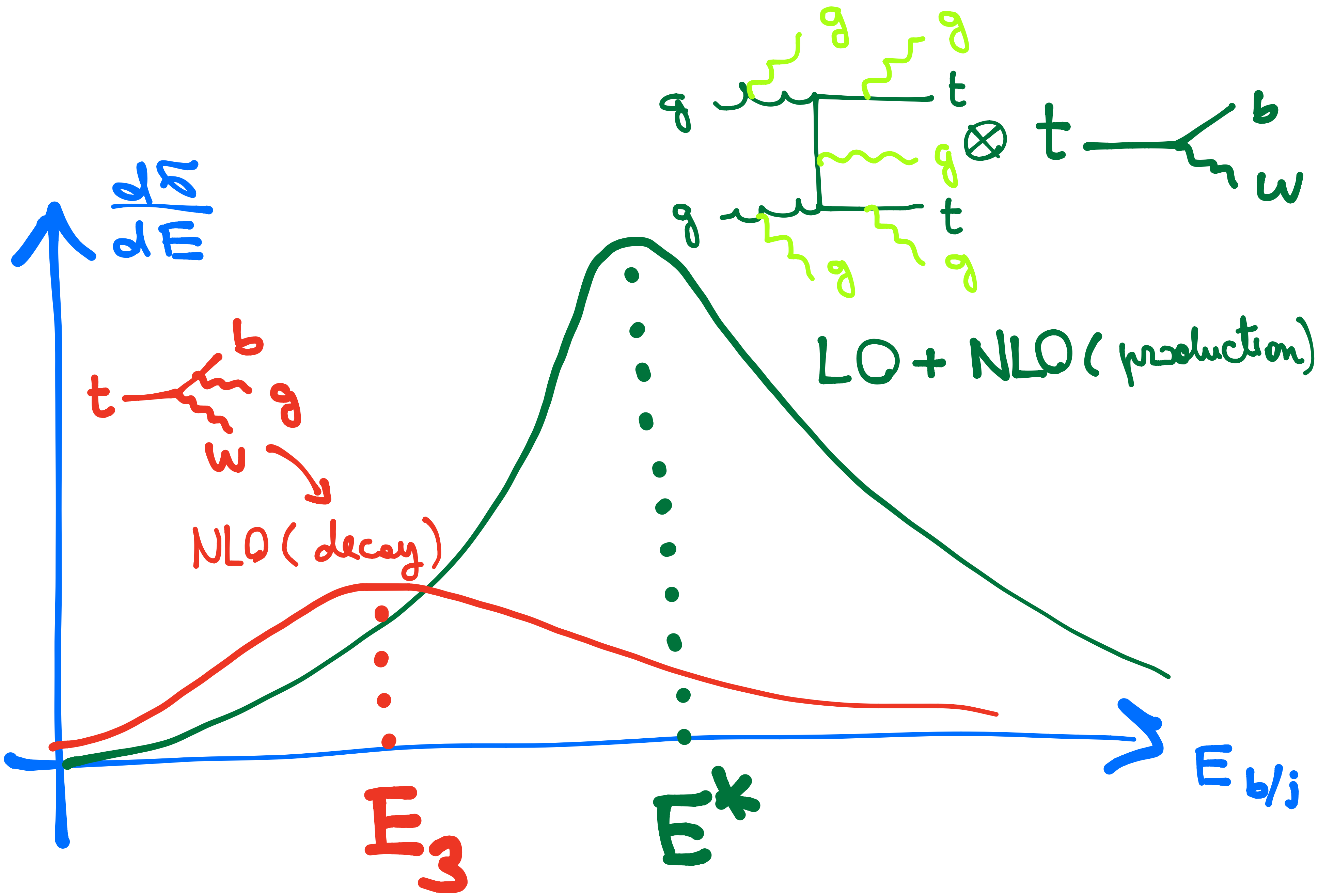
only sensitive to the NLO decay t->bWg

Decay at NLO



Peak shift at NLO

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



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

No observable free b quarks

- b-jet observables
  - jet **energy**
- B-hadron observables
  - hadron **energy**
  - hadron **boost**
  - hadron **decay length**

b-**jet** energy

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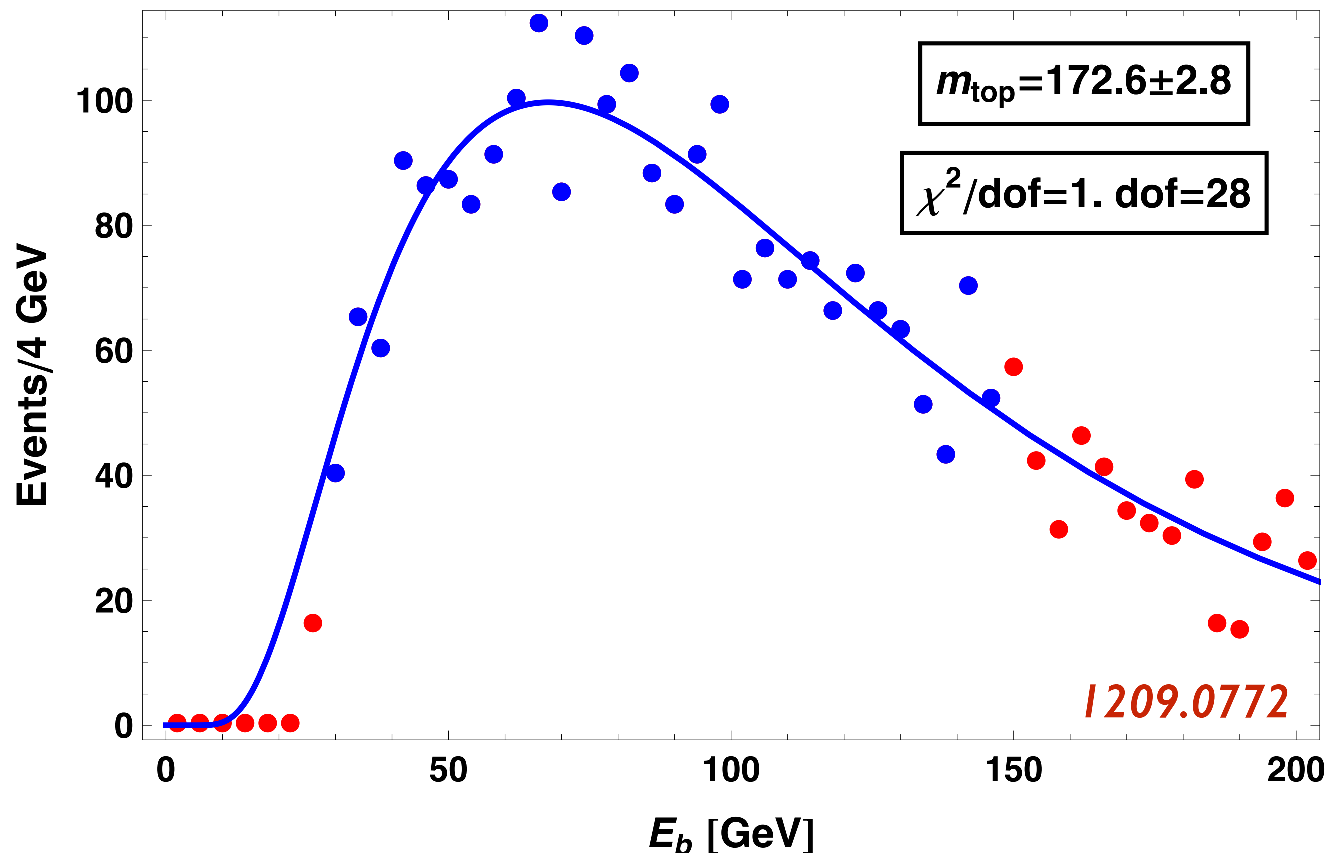

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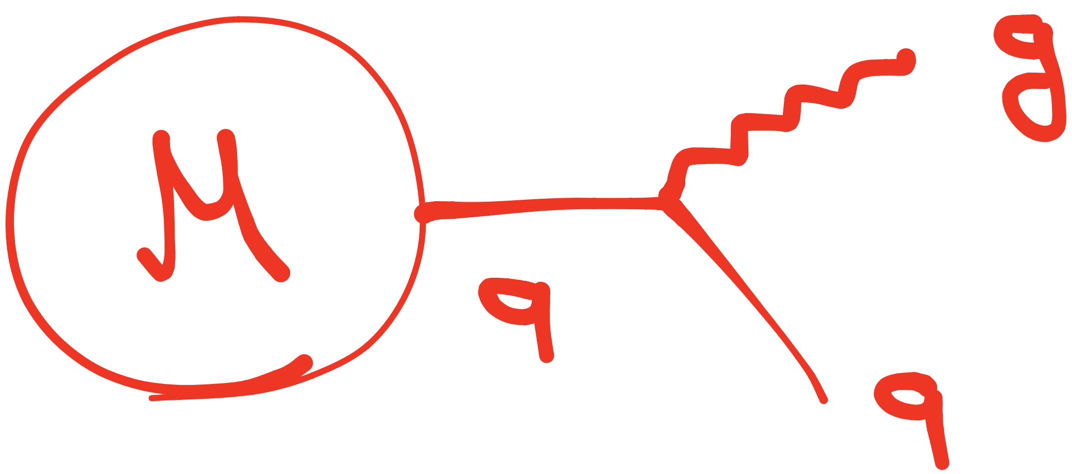
1209.0772 - Agashe Franceschini and Kim

message: LO effects are well under control

Mild corrections from NLO

Agashe, Franceschini and Kim - in preparation

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



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

- 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

B **hadron** observables

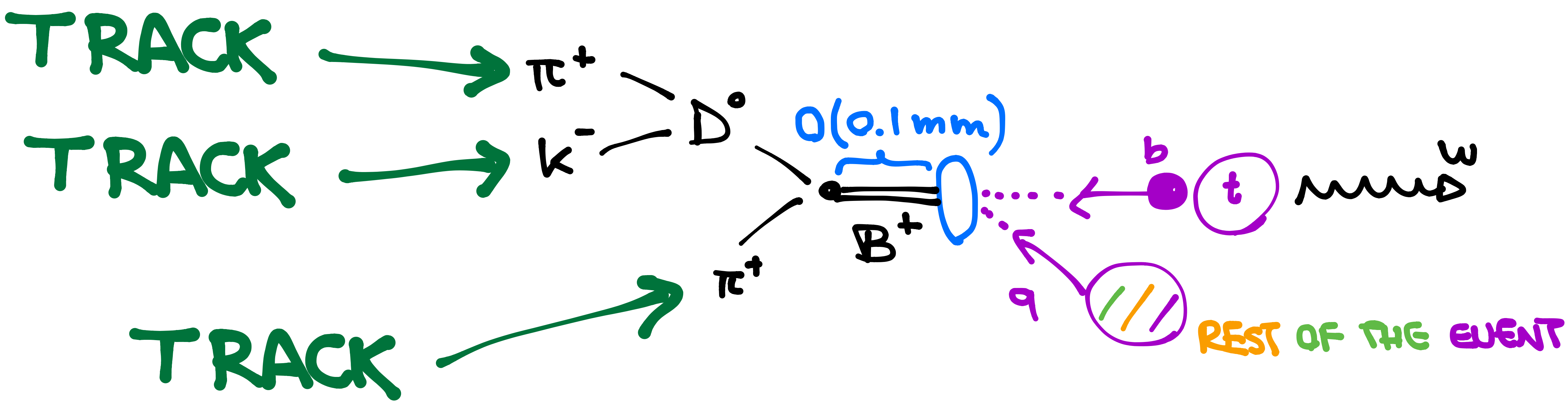
B physics in the top sample

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

- more exclusive final states
- non-JES uncertainties

B hadron
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

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

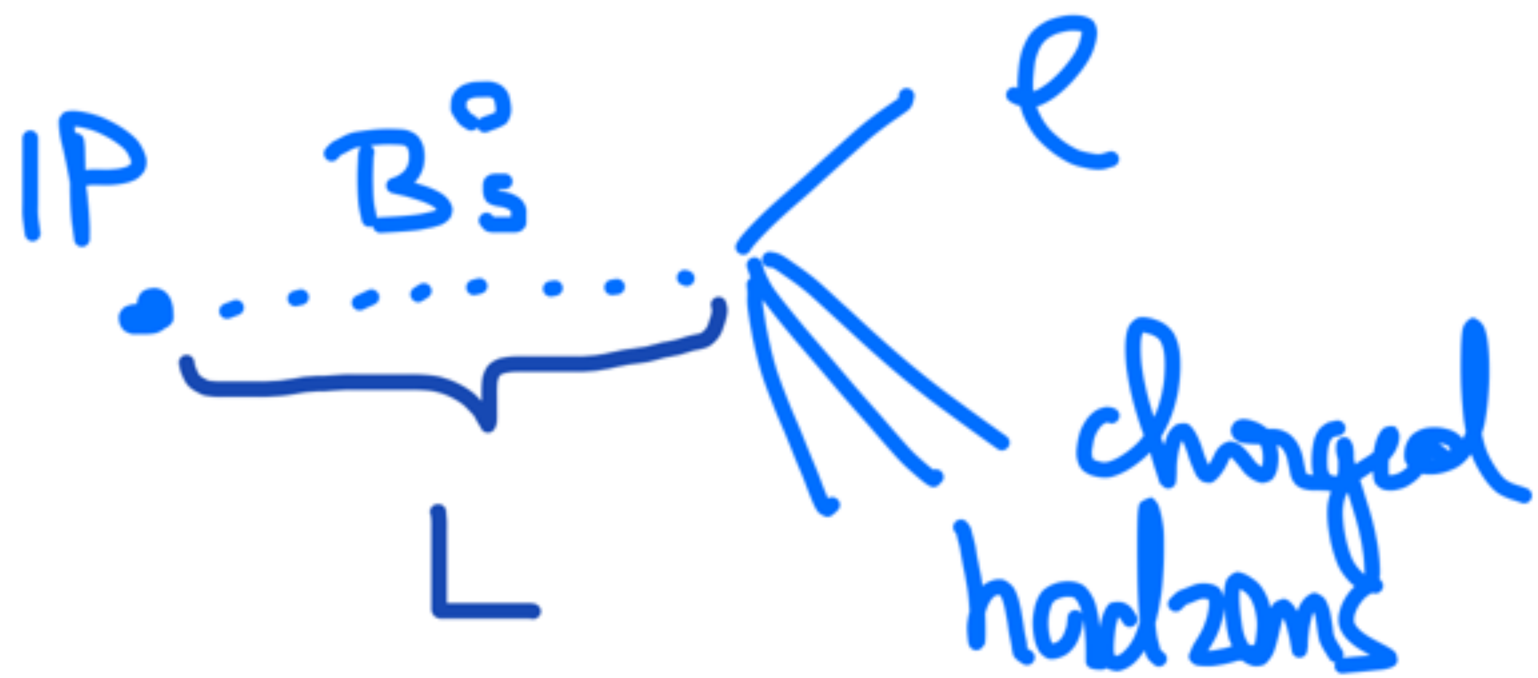
hadron energy peak ➡ hadron boost peak

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

3D decay length

length is yet another independent observable

discussions with J. Incandela



Conclusions

- Invariance of energy peak hold for pp->tt at NLO (all orders indeed)

- in principle does not need an exclusive W decay
- combinatoric ambiguities are entirely absent
- robust to new physics (null or in principle predictable effect)

- similar properties as invariant mass (not sensitive to production mode, ISR, collider energy)
- understanding NLO decay is crucial
- several "skins" : b-jet energy, B hadron (energy, boost, length)
- preliminary work from CMS to test the b-jet energy method on data

Backup

Selections of our short paper

ATLAS-2012-097 (7 TeV 4.7/fb)

ATLAS-2012-097 (7 TeV 4.7/fb)

*pT(e)>25 GeV
pT(mu)>20 GeV
*eta<2.1 for mu
*eta<2.5 for e

*m(ll)>15 GeV for ee,mumu not for emu

*Irel(0.3)>0.17 for e
Irel(0.3)>0.2 for mu

m(ll) Z-veto only for SF

aKt R=0.4
pTjet>25 GeV eta<2.5

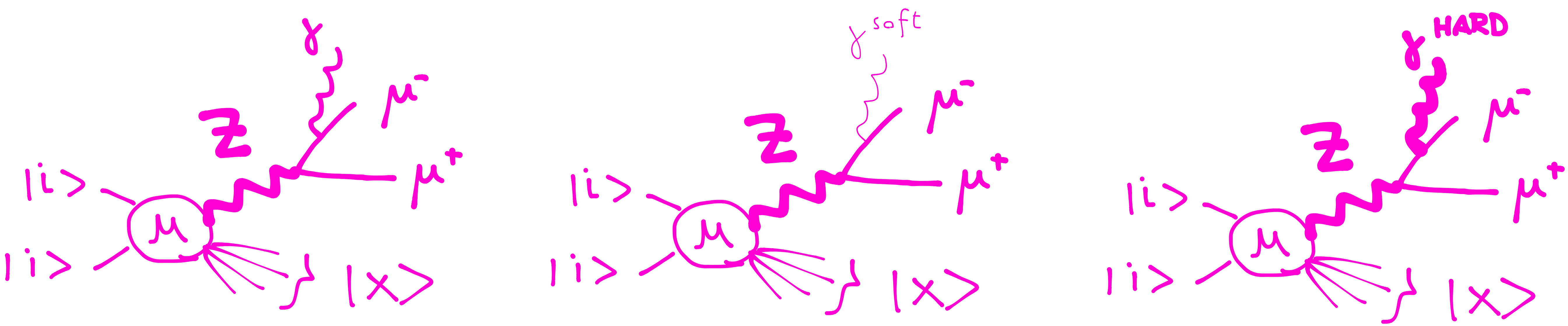
mET>40 GeV for ee,mumu
No mET cut for emu

HT>130 GeV for emu

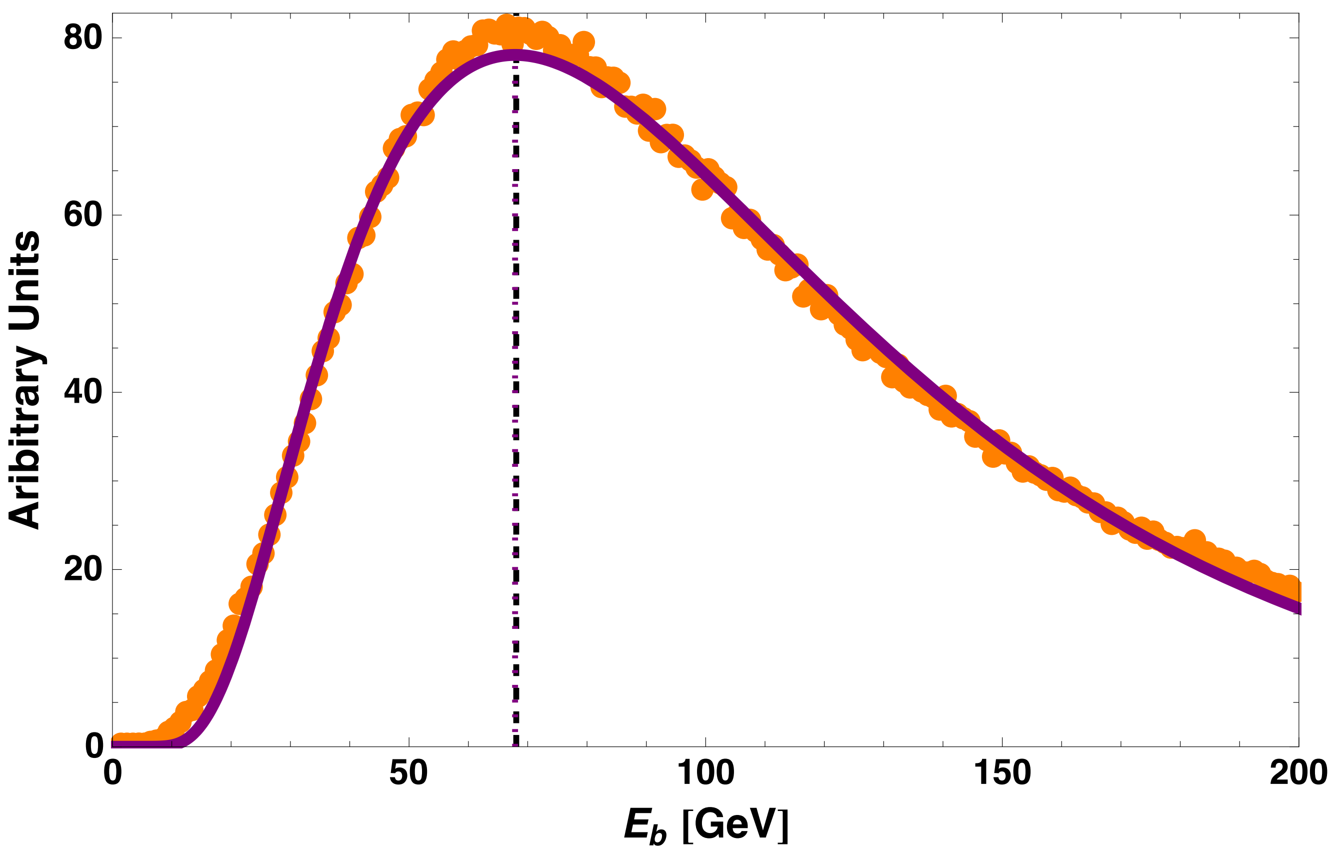
Source	N_{ee}	$N_{\mu\mu}$	$N_{e\mu}$
$t\bar{t}$	530 ± 50	1680 ± 170	4200 ± 400
$Z \to ee$ + jets	16 ± 6	–	–
$Z \to \mu\mu$ + jets	–	71 ± 28	–
$Z \to \tau\tau$ + jets	18 ± 7	70 ± 26	180 ± 70
diboson	8.4 ± 0.4	23.4 ± 1.2	67.2 ± 3.4
single top (Wt-channel)	26.8 ± 1.9	78 ± 6	204 ± 15
fake leptons	80 ± 40	43 ± 22	340 ± 170
$\sum$ MC + fake leptons	680 ± 60	1970 ± 180	5000 ± 400
observed	716	1970	5341

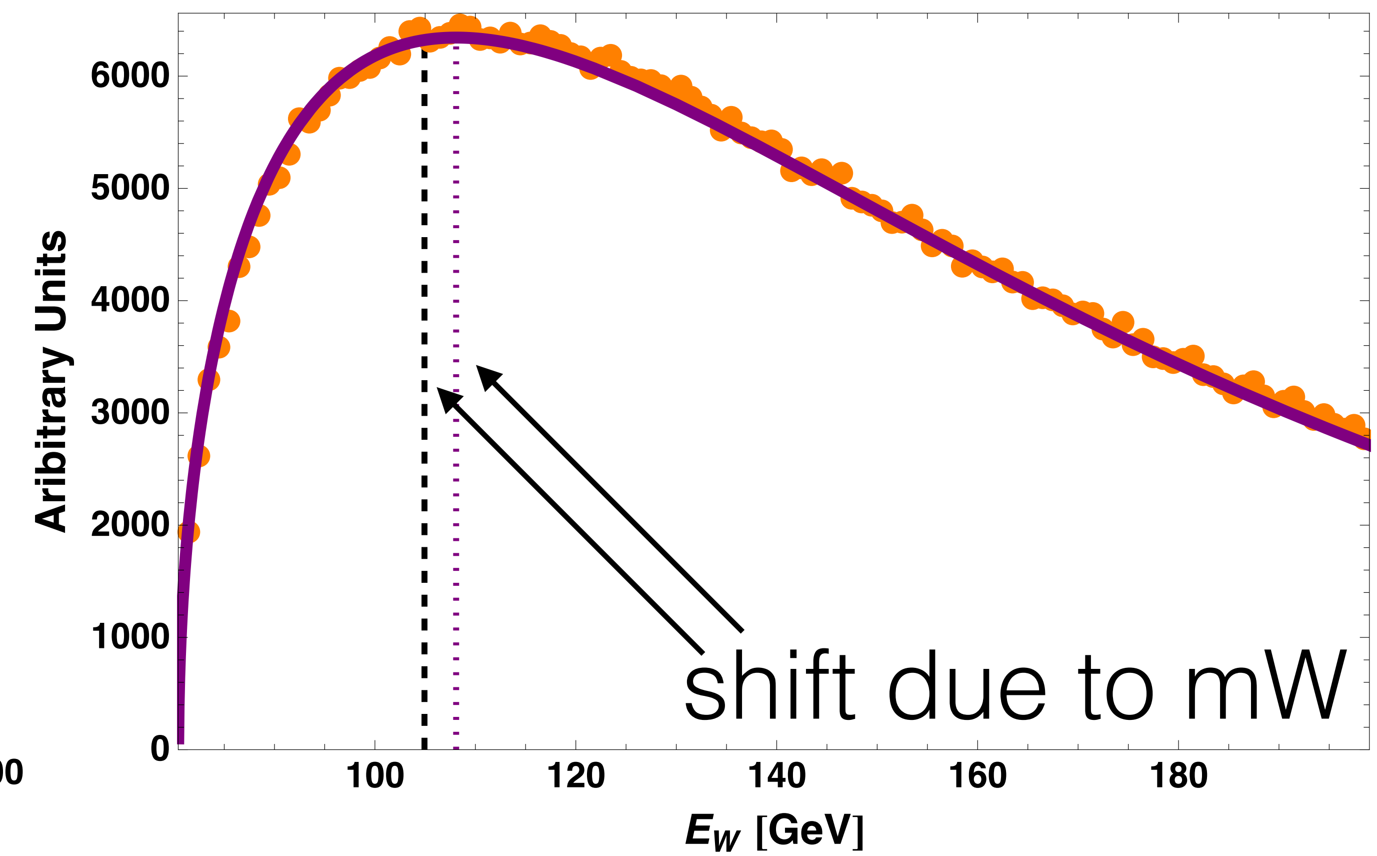
Ideal mass measurements

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



Massive daughter particles



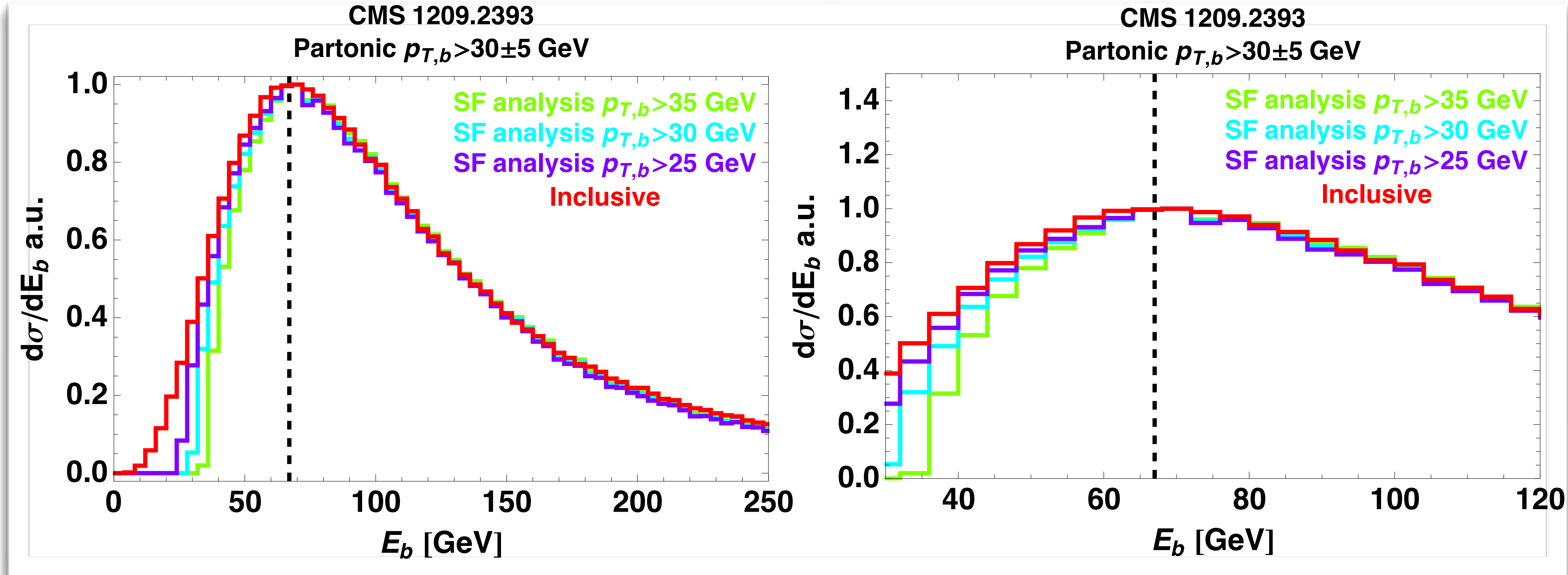


$$\gamma_{top} < 2\left(\frac{E^*_{daughter}}{m_{daughter}}\right)^2 - 1 \Rightarrow \begin{cases} \gamma_{top} < 500 & \text{for b} \\ \gamma_{top} < 2.4 & \text{for W} \end{cases}$$

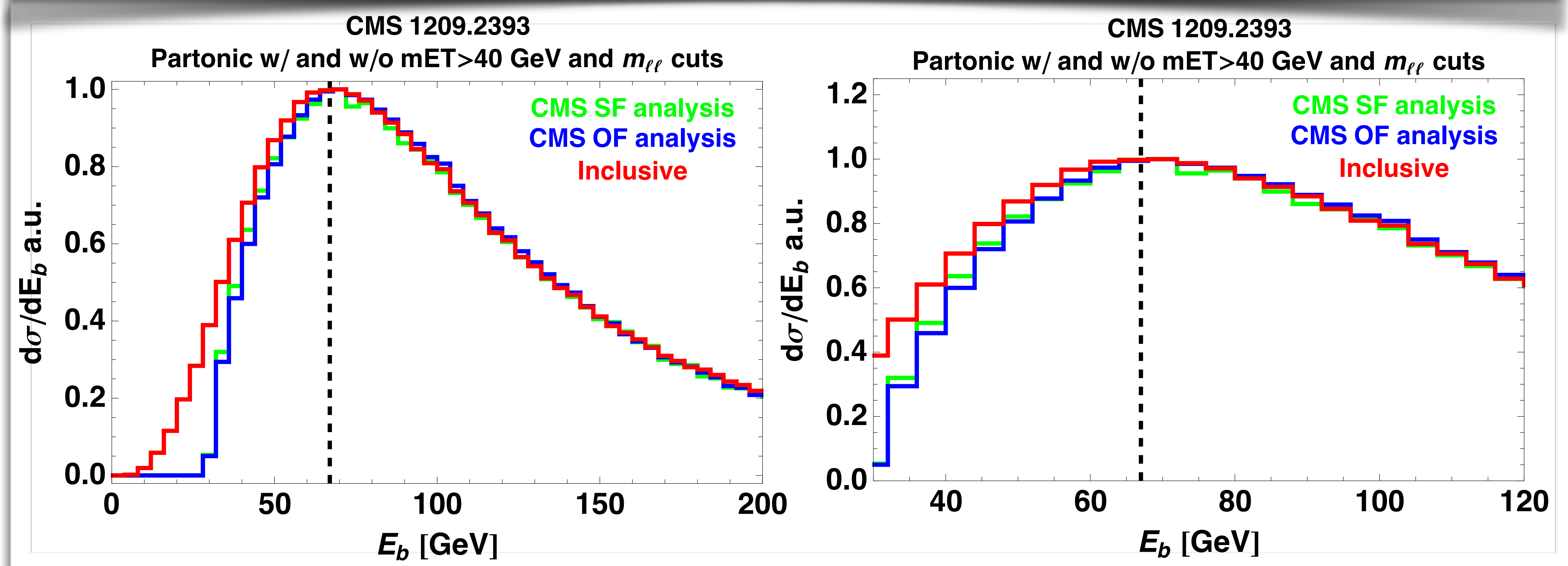
Sensitivity to Selections

Effect of not being inclusive

pT variations



mET and m(ll)



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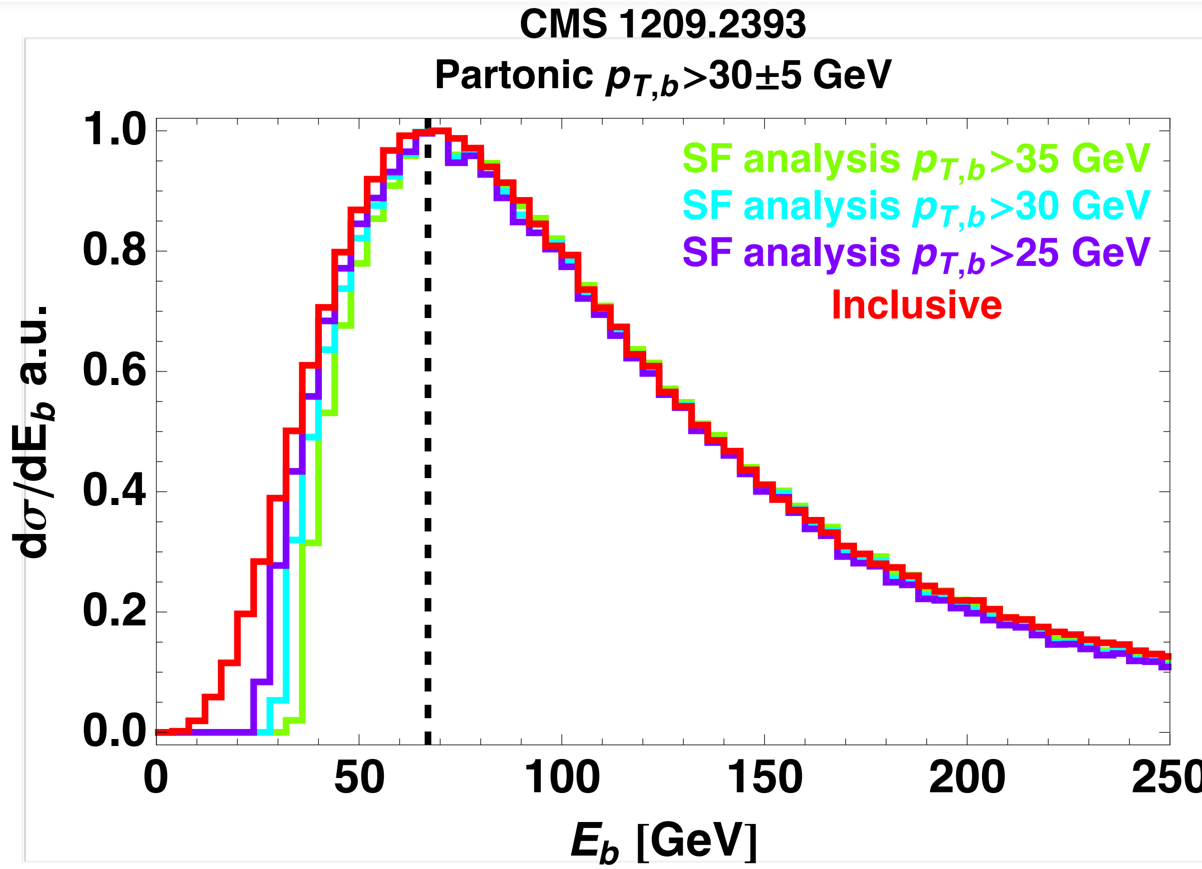
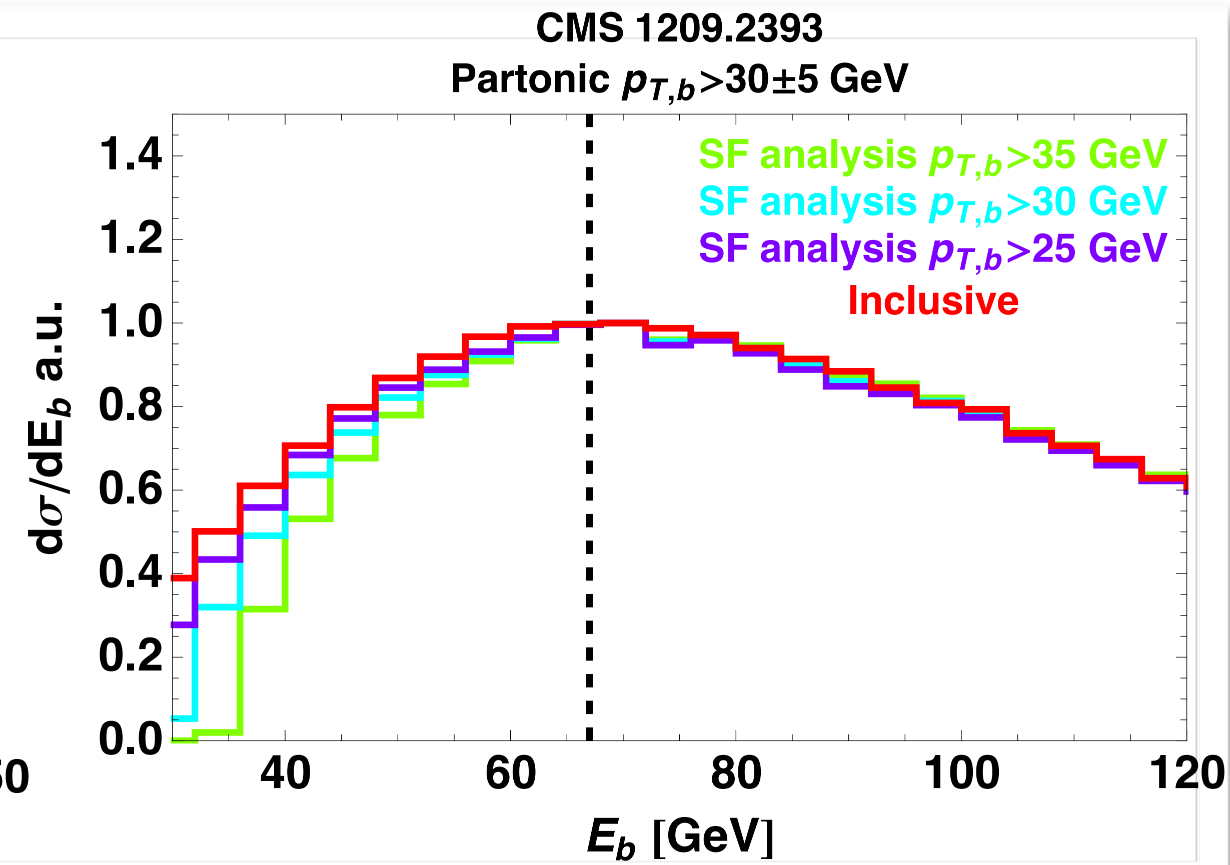
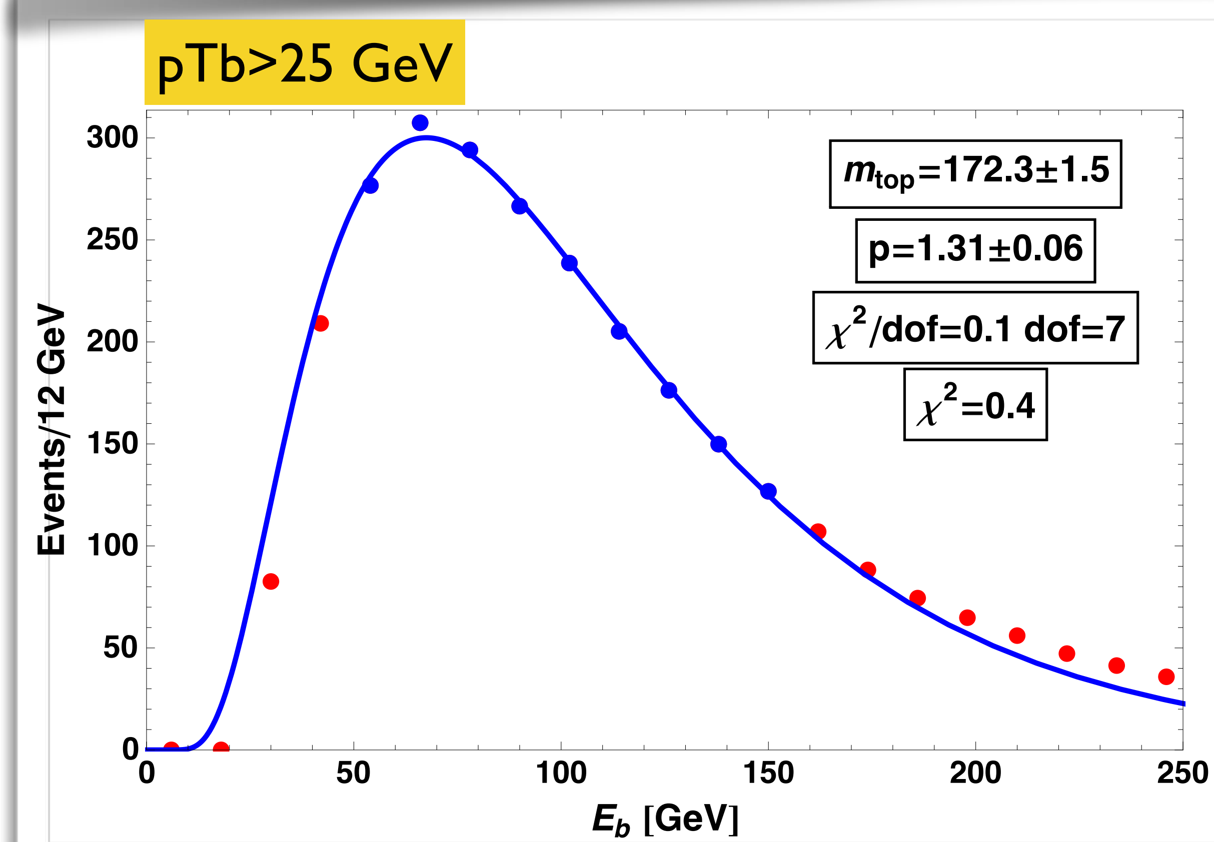
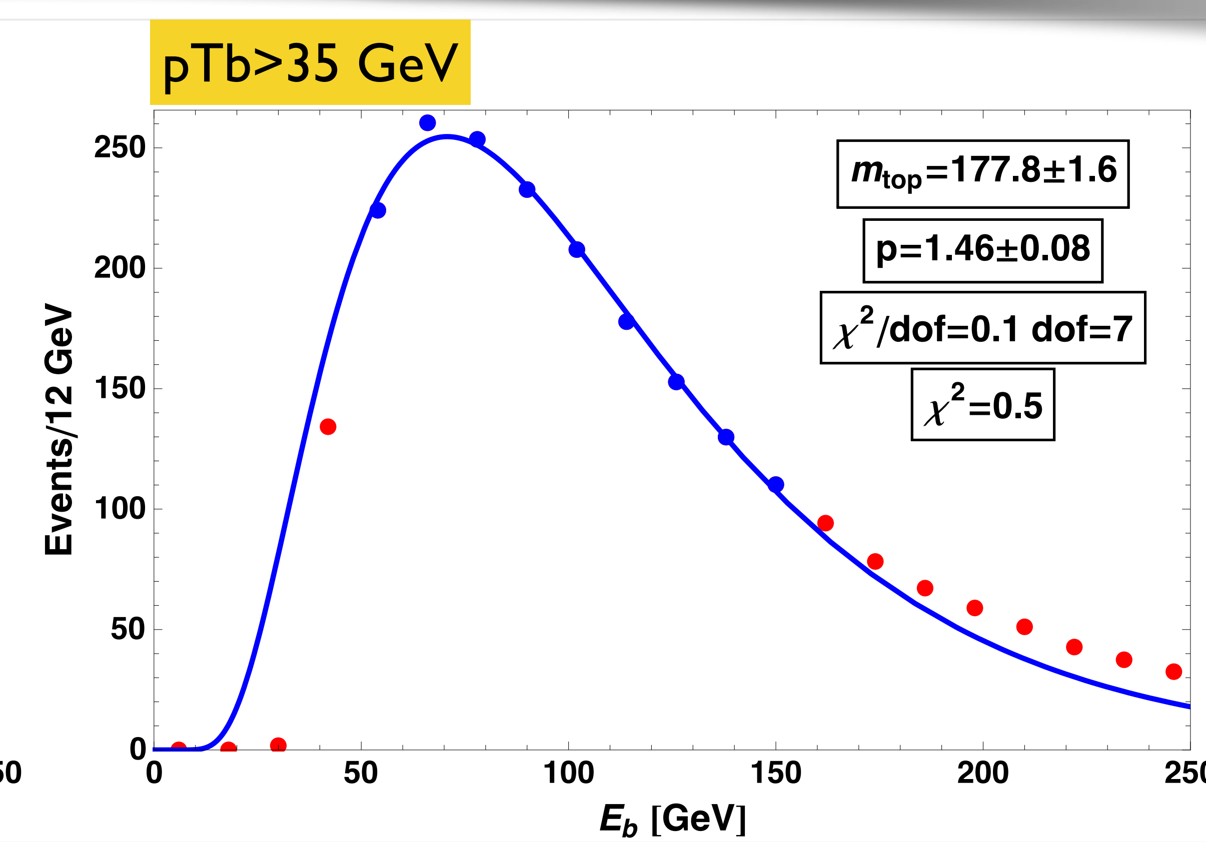


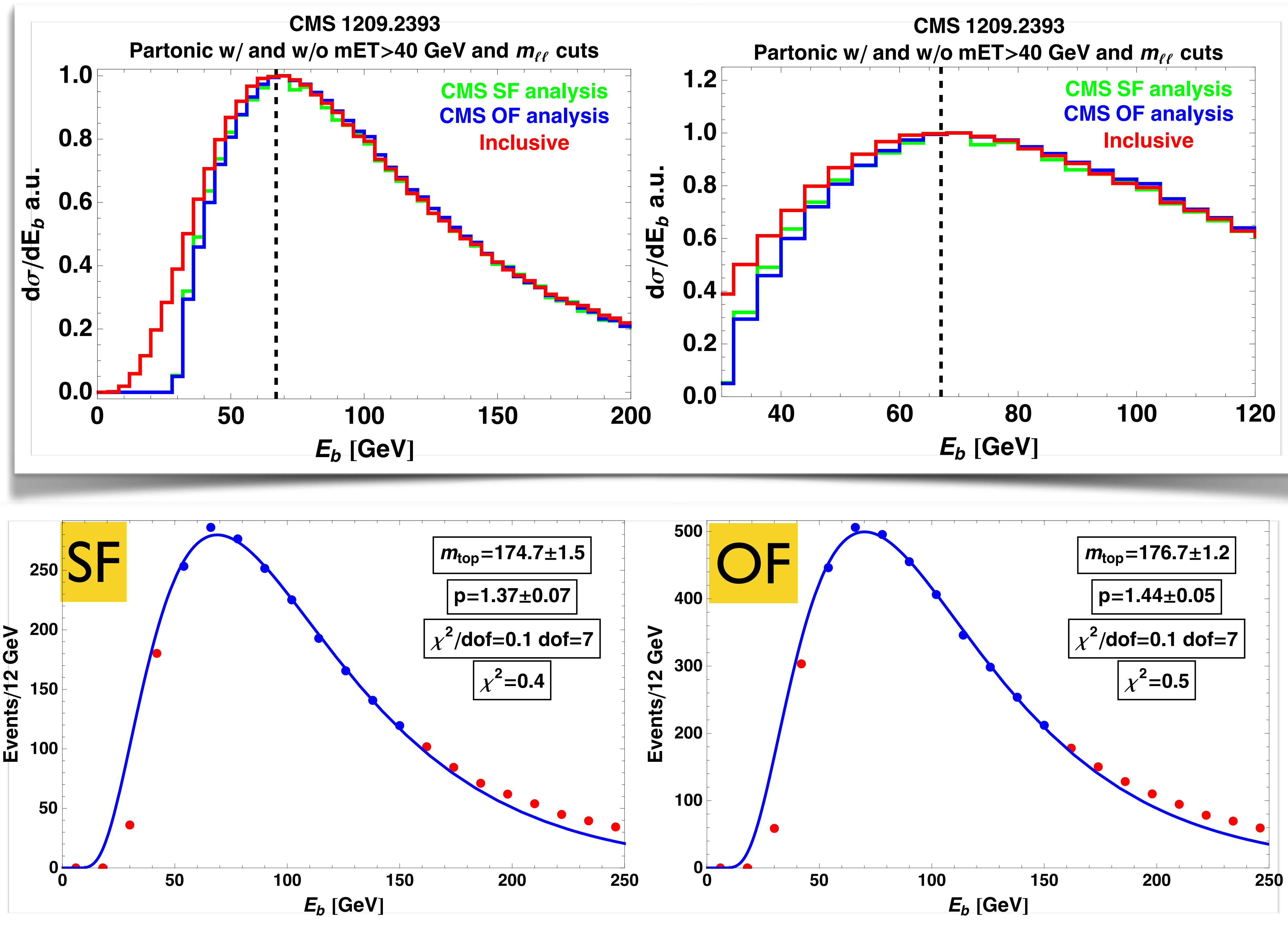






Effect of not being inclusive

mET and m(ll)



Fragmentation

Fragmentation Function at NLO+NLL

(from hep-ph/0110309)

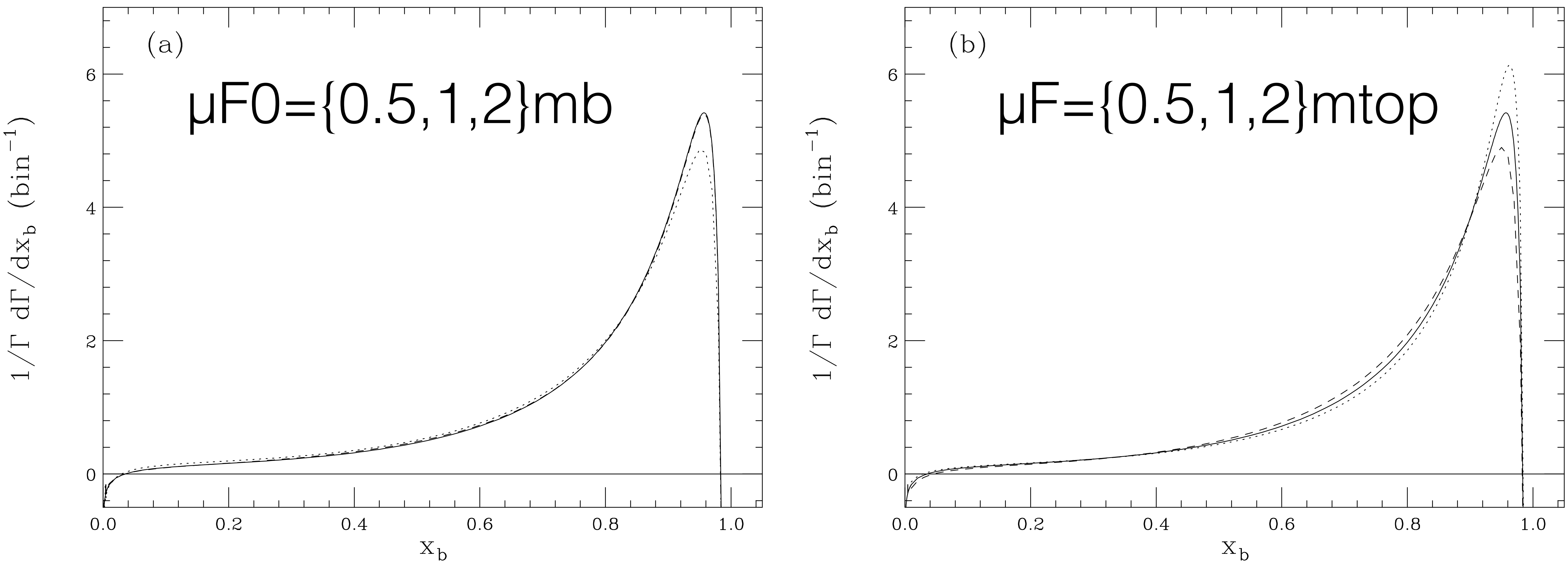
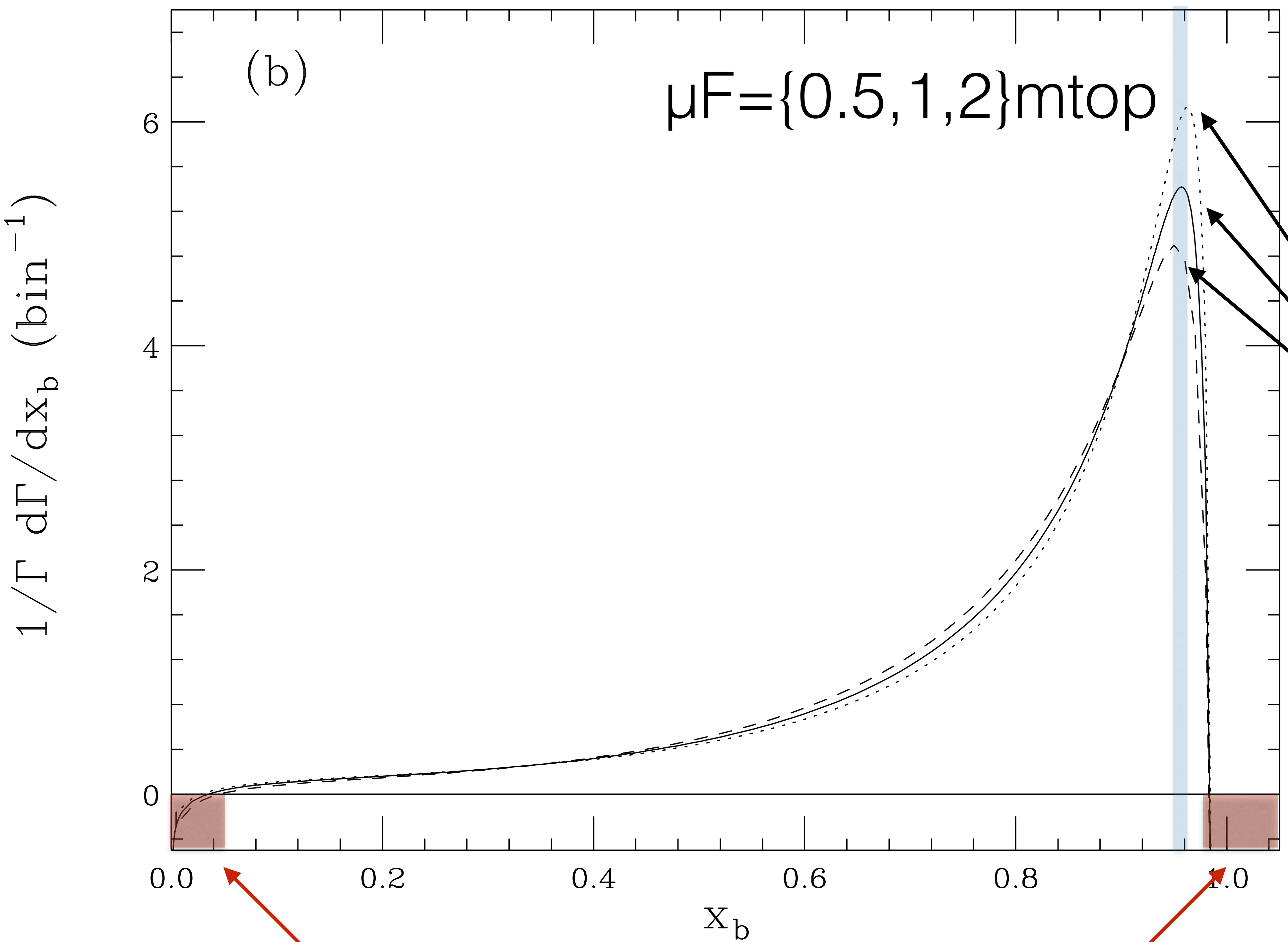


Figure 2: (a): x_b spectrum for $\mu_F = m_t$ and $\mu_{0F} = m_b/2$ (dots), $\mu_{0F} = m_b$ (solid) and $\mu_{0F} = 2m_b$ (dashes); (b): $\mu_{0F} = m_b$ and $\mu_F = m_t/2$ (dots), $\mu_F = m_t$ (solid) and $\mu_F = 2m_t$ (dashes). The renormalization scales are kept at $\mu = m_t$ and $\mu_0 = m_b$. All curves include NLL soft-gluon resummation in the initial condition of the perturbative fragmentation function.

Fragmentation Function at NLO+NLL

(from hep-ph/0110309)



- **Moments need to integrate over the whole range**
- **Peak position is less(?) sensitive to μF**

Negative Probability at small and large x

3D decay length

Boost 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

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 ...

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

For $\beta=1$ is

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

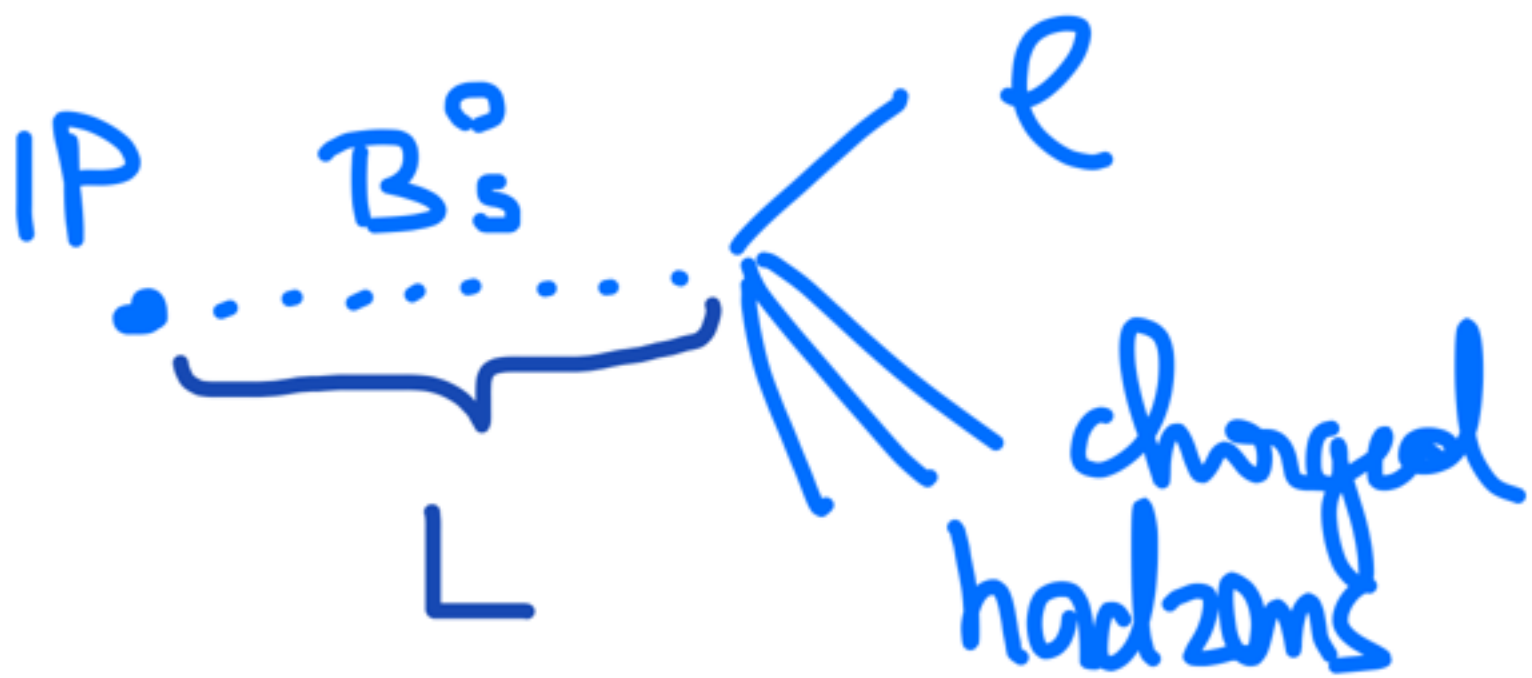
E and λ distributions are the same up to a rescaling

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

3D decay length

Time of decays is harder to measure than the position

Experiments measure decay length L



Jet Energy Scale does not affect λ, nor L

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

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

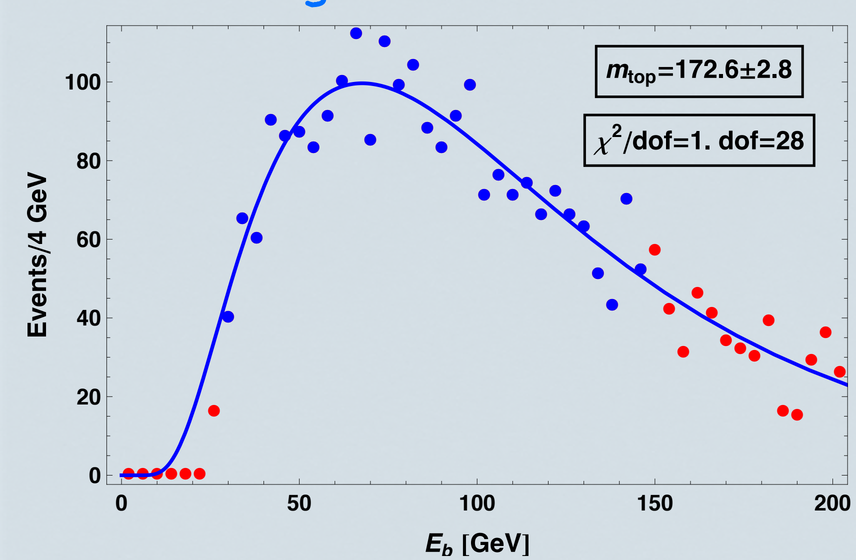
For now we just predicted the mode of pdf(λ)

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

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)

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

Useful for BSM

pure kinematics!

- applicable to Known Physics
- applicable to New Physics

THE RESULT APPLIES FOR BOTH KNOW PARTICLES OF THE SM AND FOR NEW PHYSICS

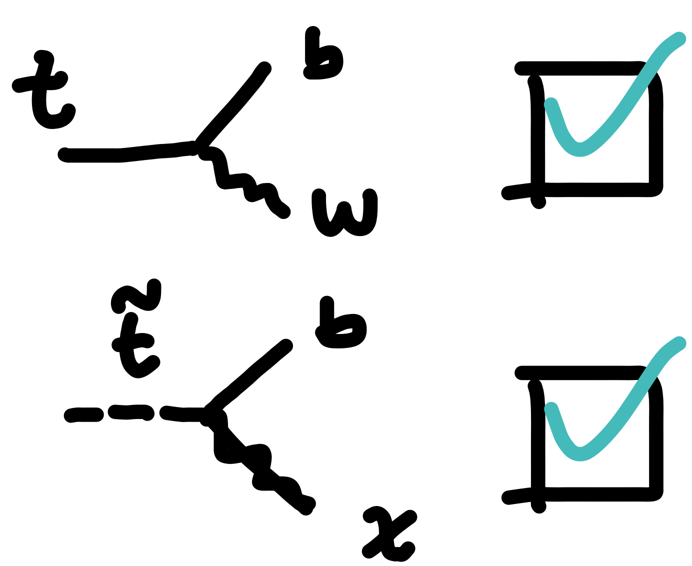
- NO NEED TO MEASURE THE OTHER DECAY PRODUCT

$\tilde{b} \to b \chi^0$

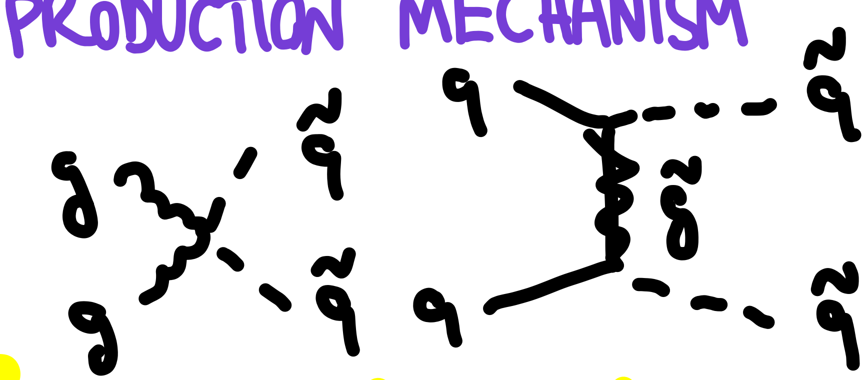
$w \to e \nu$

$t \to b w \to b e \nu$

1309.4776 - Agashe, Franceschini, Kim
1212.5230 - Agashe, Franceschini, Kim, Wardlow
1403.3399 - Chen, Davoudiasl, Kim

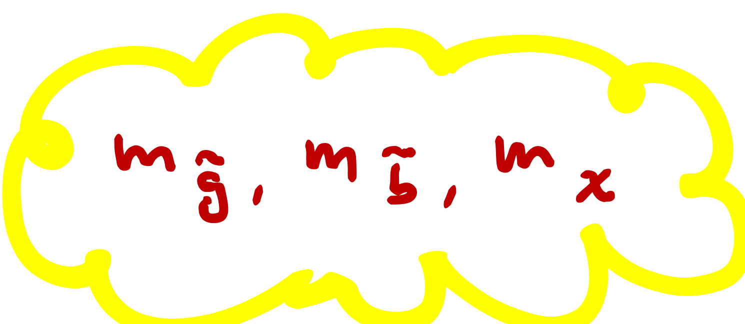


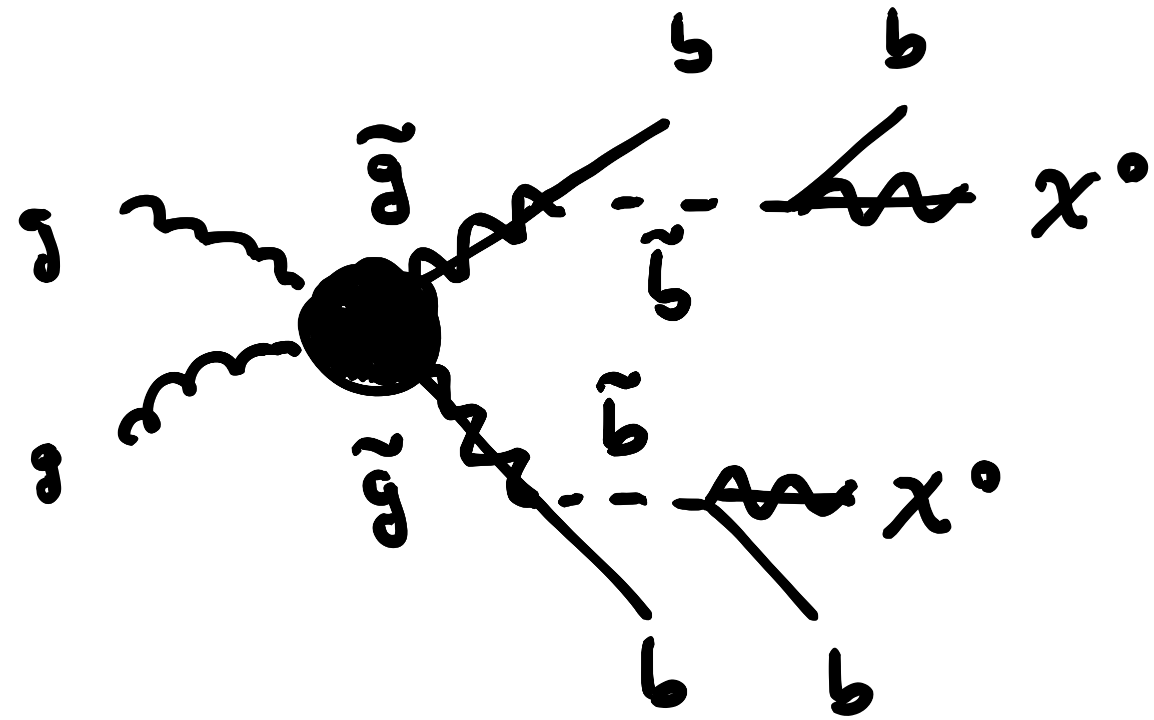
NO NEED TO KNOW THE EXACT PRODUCTION MECHANISM



SUSY spectrum reconstruction without MET

Agashe, Franceschini, Kim, Wardlow - 1309.4776





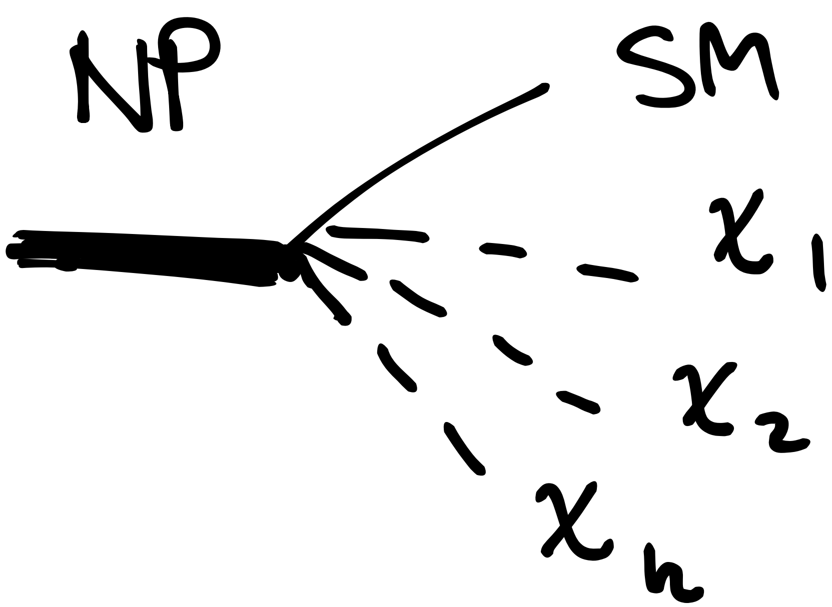
3-body theory

and

application to gluino 3-body is underway

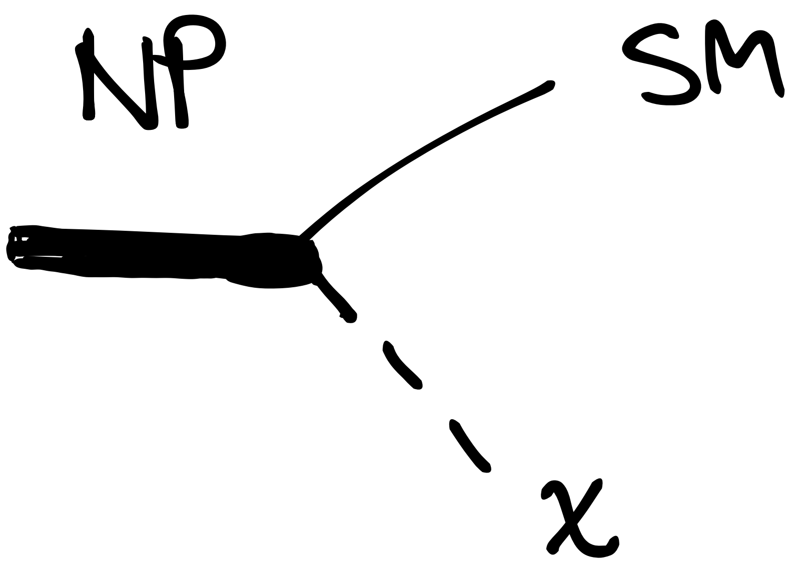
Counting Dark Matter particles at colliders

Agashe, Franceschini and Kim - 1212.5230

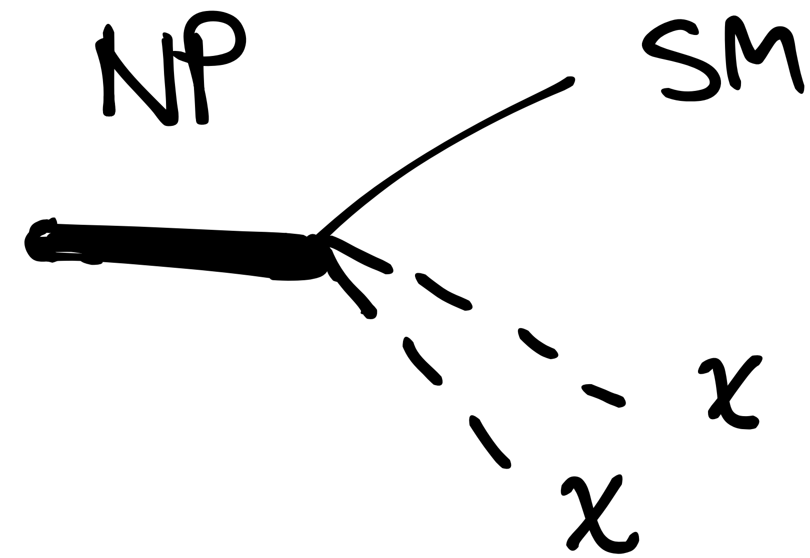


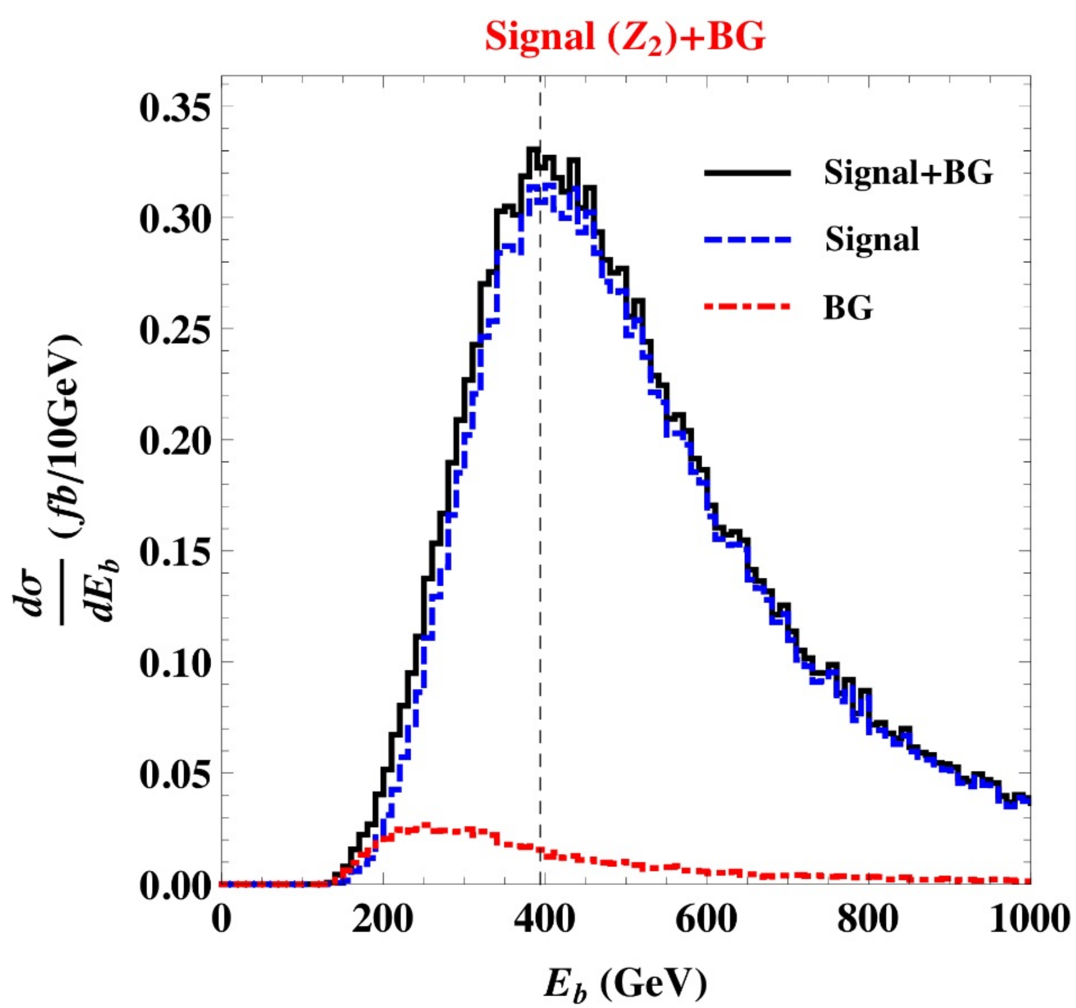
COUNT INVISIBLE PARTICLES IN SEMI-INVISIBLE DECAYS

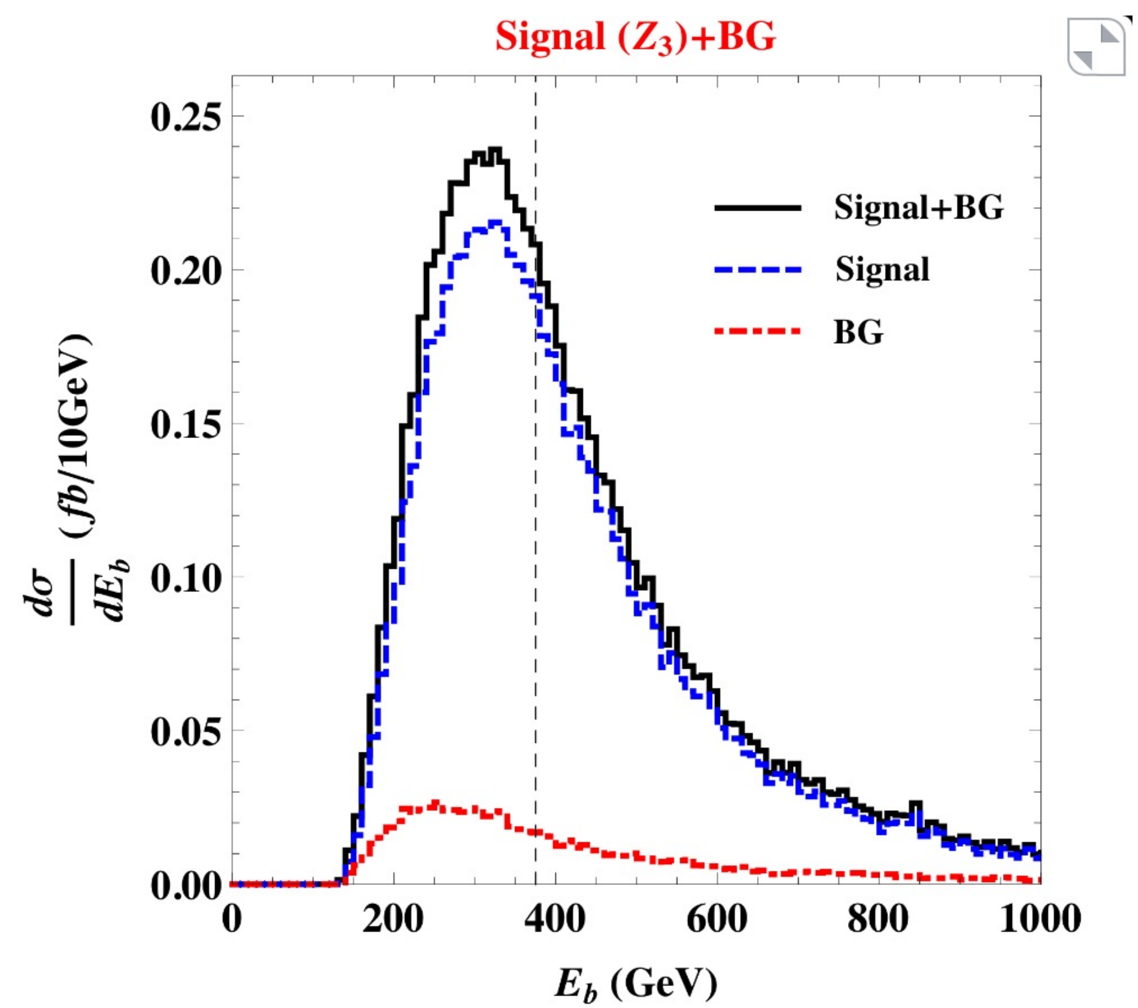
2-BODIES



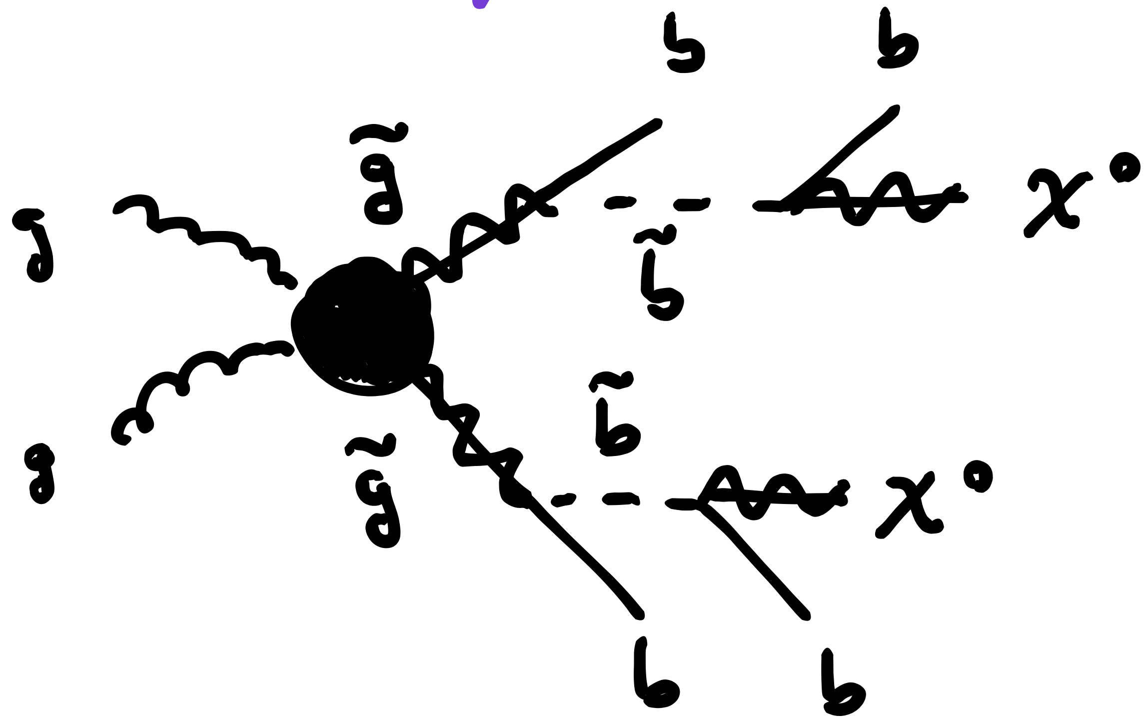
3-BODIES







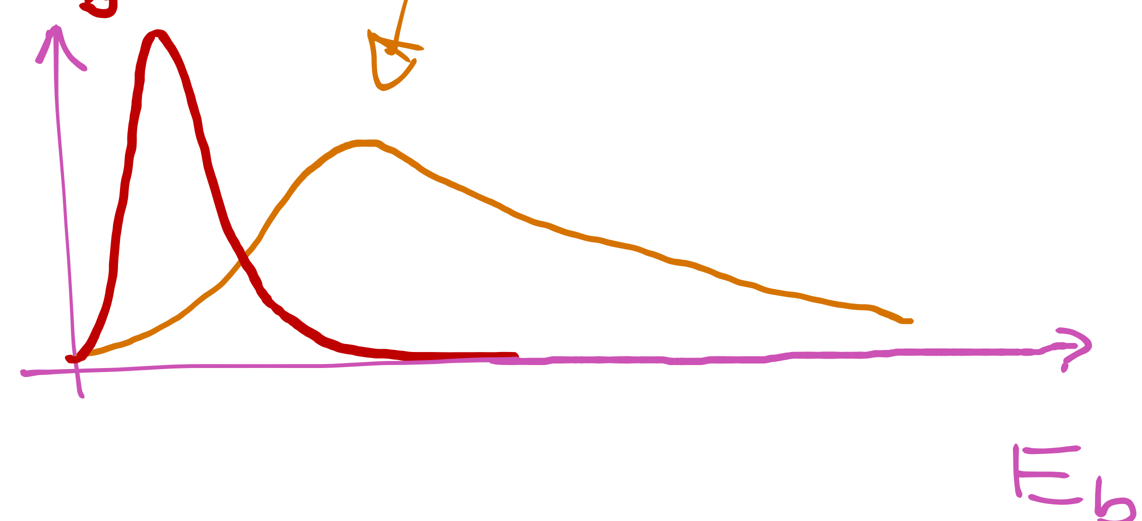
$pp \to \tilde{g}\tilde{g} \to b\tilde{b}\,b\tilde{b} \to 4b\,\not{E}_T$



TWO-STEPS DECAY ⇒

$$E_b^{peak} = \frac{m_{\tilde{g}}^2 - m_{\tilde{b}}^2}{2m_{\tilde{g}}}$$

$$E_b^{peak} = \frac{m_{\tilde{b}}^2 - m_{\chi}^2}{2m_{\tilde{b}}}$$



NO COMBINATORICAL ISSUES

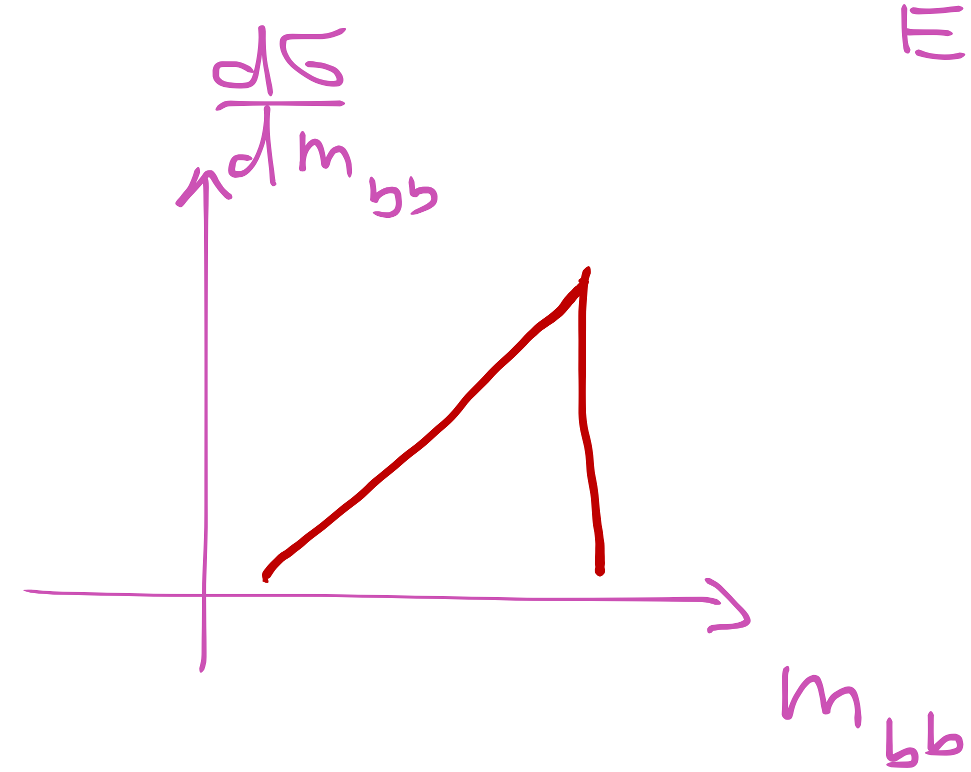
JUST LOOK AT $\frac{d\sigma}{dE_b}$

$$pp \to \tilde{g}\tilde{g} \to b\tilde{b}\, b\tilde{b} \to 4b\, \not{E}_T$$

$$E_{\tilde{b}_H} = \frac{m_{\tilde{b}}^2 - m_{\chi}^2}{2 m_{\tilde{b}}}$$

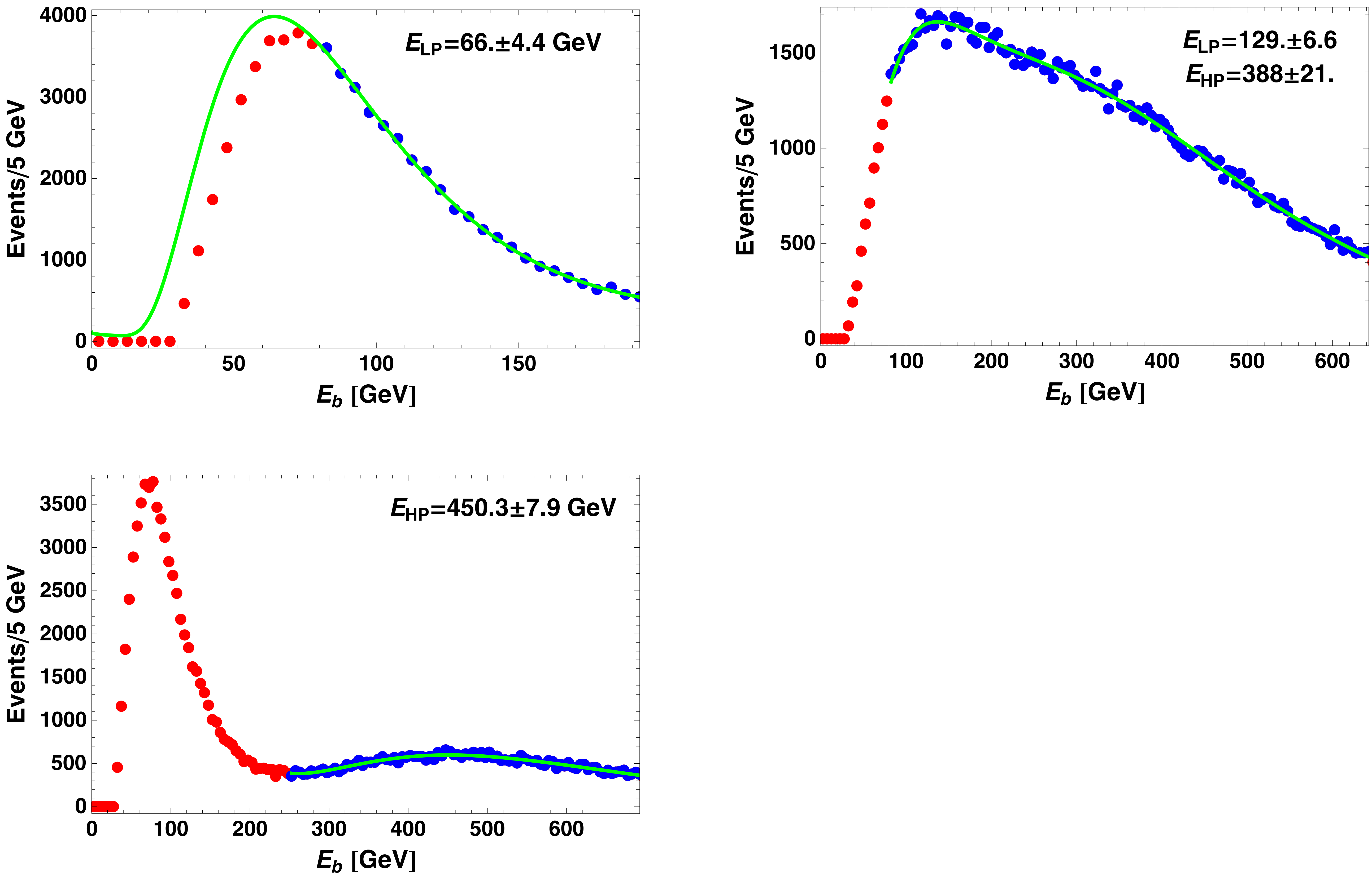
$$E_{\tilde{b}_L} = \frac{m_{\tilde{g}}^2 - m_{\tilde{b}}^2}{2 m_{\tilde{g}}}$$

$$m_{bb}^{max} = \sqrt{4 \frac{m_{\chi}}{m_{\tilde{b}}} E_{\tilde{b}_H} E_{\tilde{b}_L}}$$



- BACKGROUNDS Z+jets (mostly Z bbbb) & $t\bar{t}b\bar{b}$ (SUBDOM)
- CUTS MAY AFFECT THE ENERGY DISTRIBUTION

$$P_{T_{jet}} > X \Rightarrow E_{jet} > X$$



E_{LP}=66.±4.4 GeV
Events/5 GeV
E_b [GeV]
E_{LP}=129.±6.6
E_{HP}=388±21.
Events/5 GeV
E_b [GeV]
E_{HP}=450.3±7.9 GeV
Events/5 GeV
E_b [GeV]