# Top quark mass at the LHC: kinematics and beyond

Roberto Franceschini (CERN)

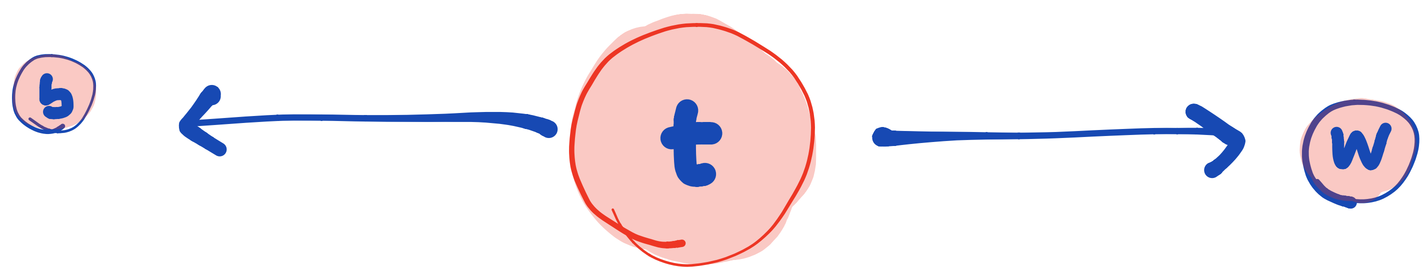
INFN LNF - Frascati May 7th 2015

Top mass: challenges in definition and determination

# $M = P_0$

$P = (M, 0, 0, 0)$

top → leptons and hadrons




**conservation of 4-momentum**

$P(\text{top}) = \Sigma_i \, p_i$   i={leptons & hadrons}

$\Sigma \, (|p|, \bar{p}) \rightarrow (M,0,0,0)$

# $M = P_0$

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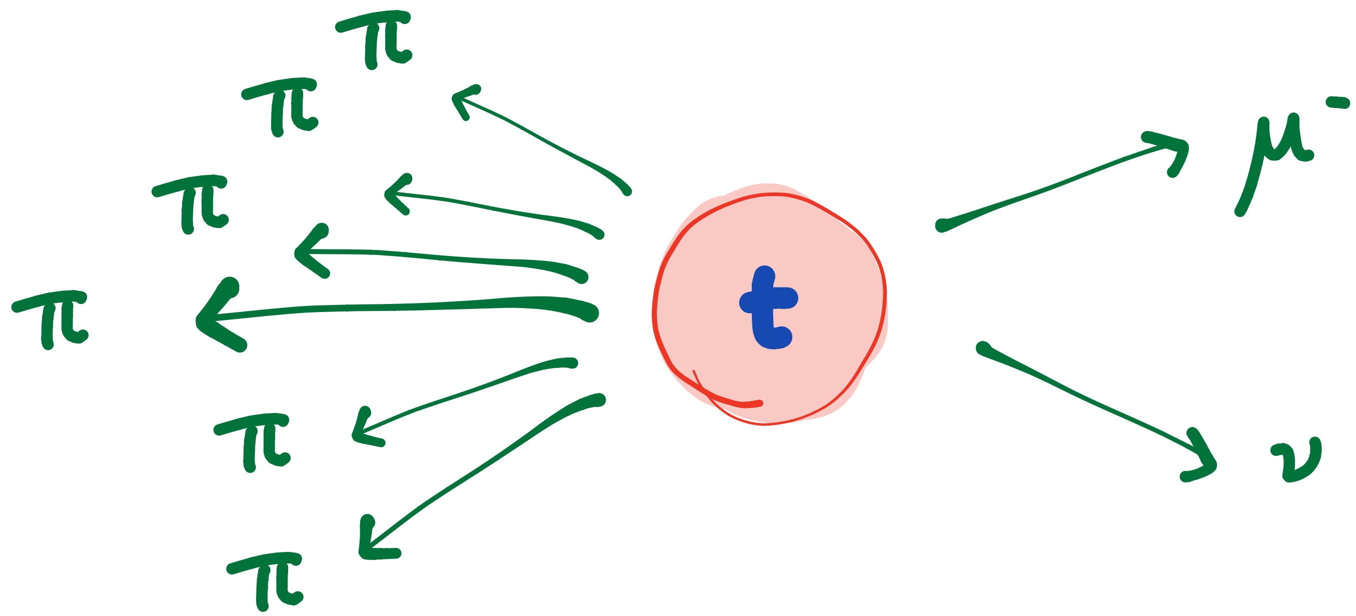


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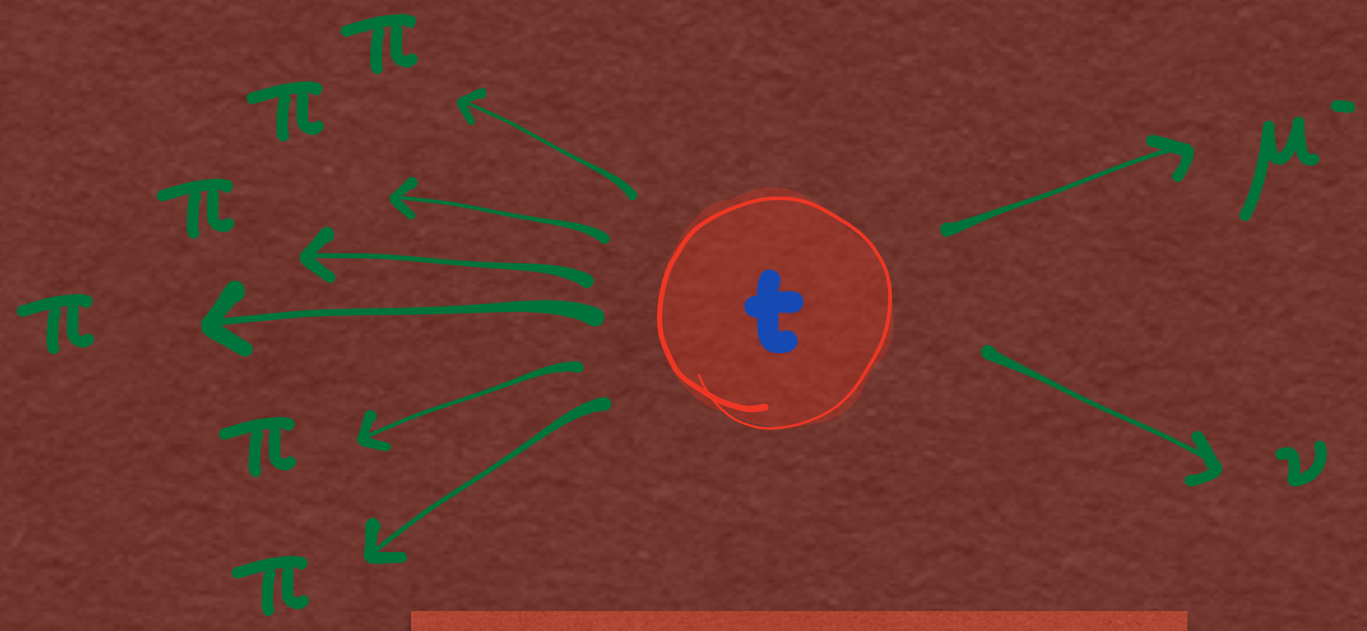


- isolated colored particle

The truth is that the mass of particle exceeds this intuition.
It is like the **measurement of a coupling** in the Lagrangian

**conservation of 4-momentum**

$P(\text{top}) = \Sigma_i\, p_i$ i={leptons & hadrons}

$\Sigma\,(|p|, \bar{p}) \to (M,0,0,0)$

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$P=(M,0,0,0)$

top → leptons and hadrons


- isolated colored particle

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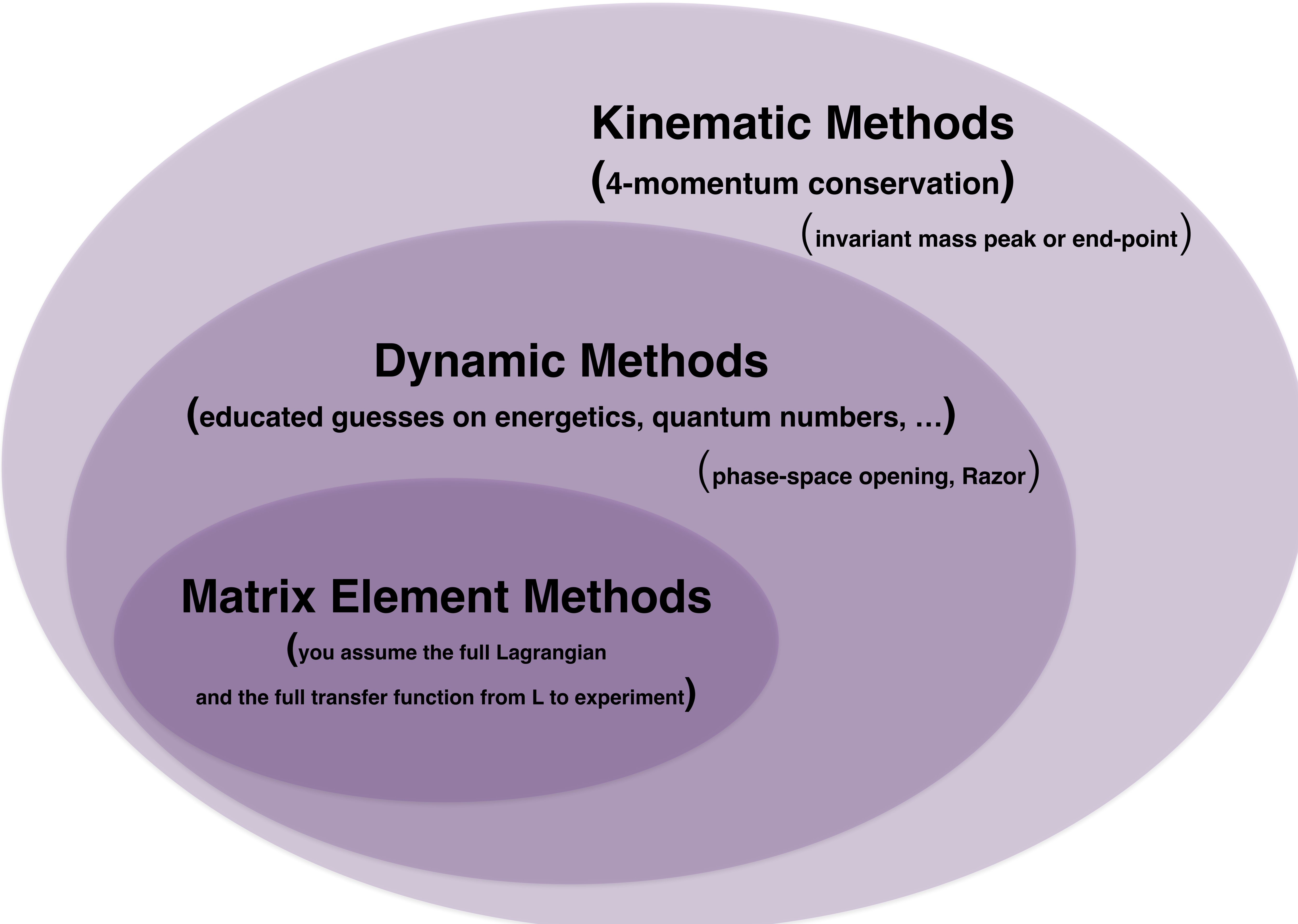
It is like the **measurement of a coupling** in the Lagrangian

$Obs(m_{top}, g_3, \ldots)$

# Which observable?


Kinematic Methods
(4-momentum conservation)
(invariant mass peak or end-point)
Dynamic Methods
(educated guesses on energetics, quantum numbers, ...)
(phase-space opening, Razor)
Matrix Element Methods
(you assume the full Lagrangian
and the full transfer function from L to experiment)

# Top mass from **one** event

PHYSICAL REVIEW D VOLUME 45, NUMBER 5 1 MARCH 1992

## Decay and polarization properties of the top quark

R. H. Dalitz
*Department of Theoretical Physics, Oxford University, 1 Keble Road, Oxford OX1 3NP, United Kingdom*

Gary R. Goldstein
*Department of Physics, Tufts University, Medford, Massachusetts 02155*
(Received 1 November 1991)

Polarization and angular distributions in the decay sequence $t \to bW^+, W^+ \to l^+ \nu_l$ are discussed for the standard model. Top quarks from $e^+e^- \to t\bar{t}$ are predicted to have large polarization but, even if not, the parity-violating effects in this decay chain are large and will test closely the detailed spin structure of the electroweak interactions involving the top quark. A means of analyzing $\bar{t}t$ decays following $\bar{t}t$ production in hadronic interactions is developed, leading to an illuminating construction. Its application is illustrated by the analysis of the candidate for top-antitop pair creation in $\bar{p}p$ collisions found by the Collider Detector at Fermilab (CDF) at 1.8 TeV center-of-mass energy. If this is really $\bar{t}t$ production, then the top-quark mass would be $125^{+19}_{-11}$ GeV/$c^2$.

PACS number(s): 14.80.Dq, 13.20.Jf, 13.88.+e

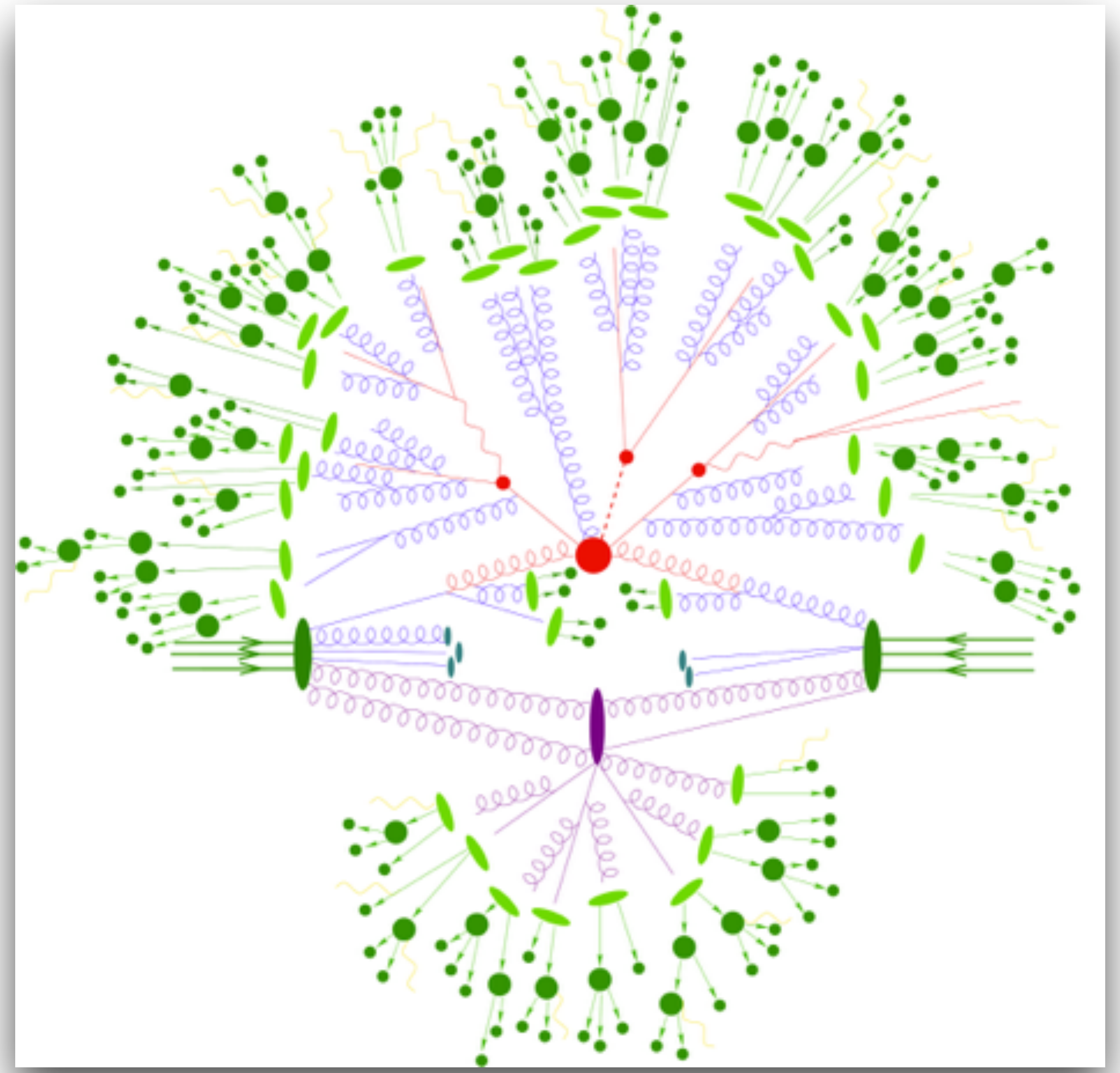
TABLE I. Measurements by CDF of their "$t\bar{t}$ candidate" event [12], specified in the laboratory frame, and the proposed identifications (id.) for the leptons and jets observed. $E_{\rm trans}$ denotes "transverse energy," while $\eta$ and $\phi$ denote the pseudorapidity and azimuthal angle in each case.

| | $p_x$ (GeV/$c$) | $p_y$ (GeV/$c$) | $p_z$ (GeV/$c$) | $E$ (GeV) | $E_{\rm trans}$ (GeV) | $\eta$ | $\phi$ (rad) | id. |
|---|---|---|---|---|---|---|---|---|
| $e^+$ | −21.18 | 23.61 | −28.56 | 42.68 | 31.72 | −0.81 | 2.30 | $t$ |
| $b$ jet | 18.71 | −6.27 | 25.25 | 33.26 | 19.73 | 1.07 | 5.96 | $t$ |
| $\mu^-$ | −0.62 | −43.69 | −38.64 | 58.33 | 42.54 | −0.80 | 4.70 | $\bar{t}$ |
| $\mu^+$ | −1.03 | 7.94 | −28.74 | 29.83 | 7.58 | −1.96 | 1.70 | $\bar{b} < \bar{t}$ |
| jet | 0.74 | 8.86 | −70.12 | 70.73 | 8.89 | −2.76 | 1.49 | $\bar{b} < \bar{t}$ |

# Status

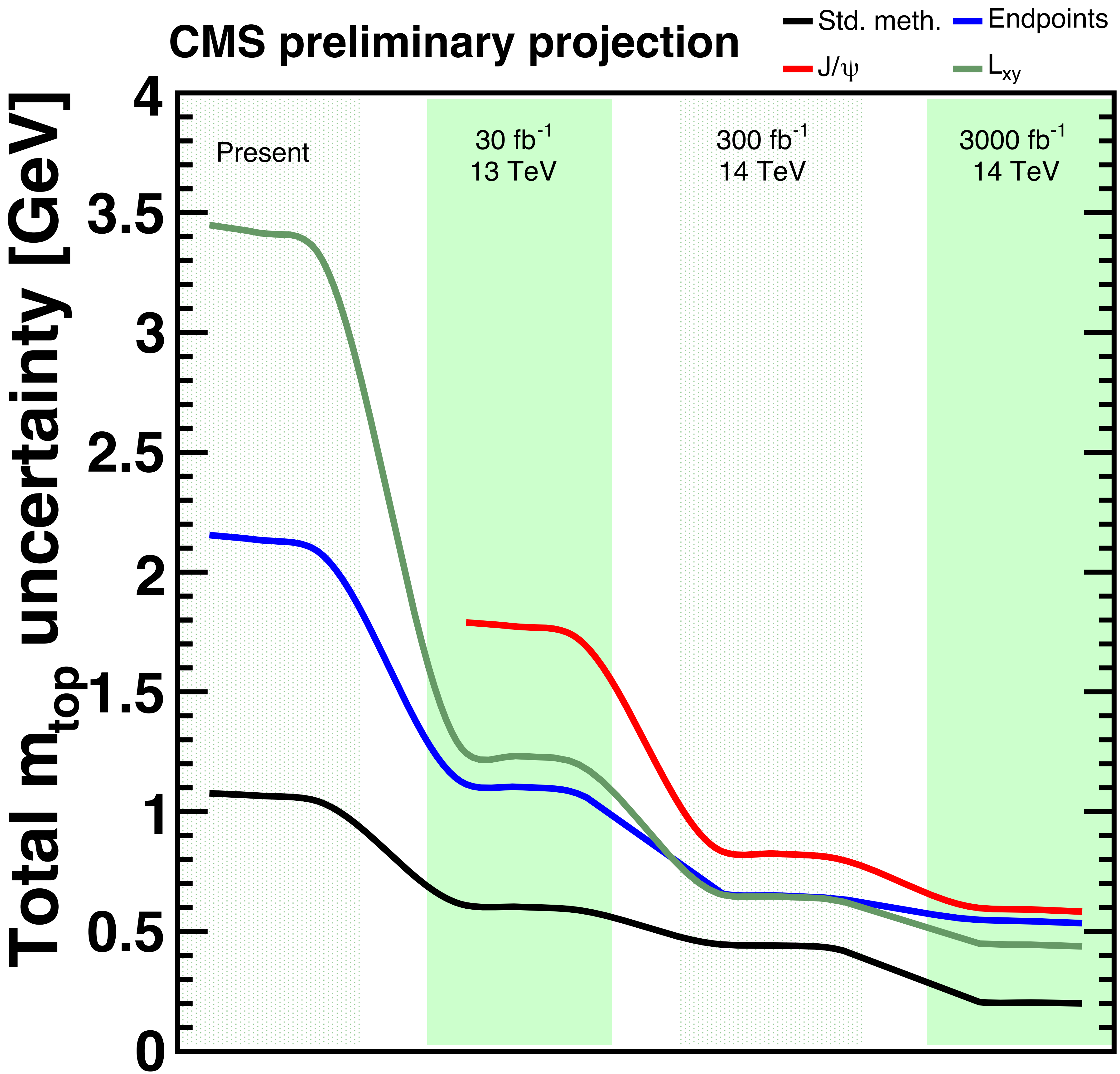
measurement at ≲0.5%! ⇒ *precision* QCD

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



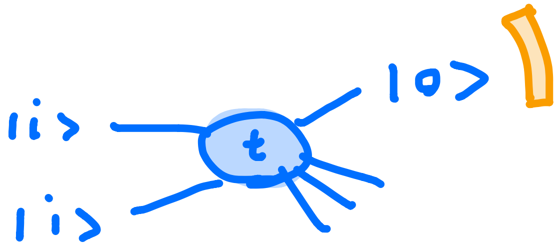
The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about "*single best measurement*"

# 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*




# Lxy decay length CMS-PAS-TOP-12-030

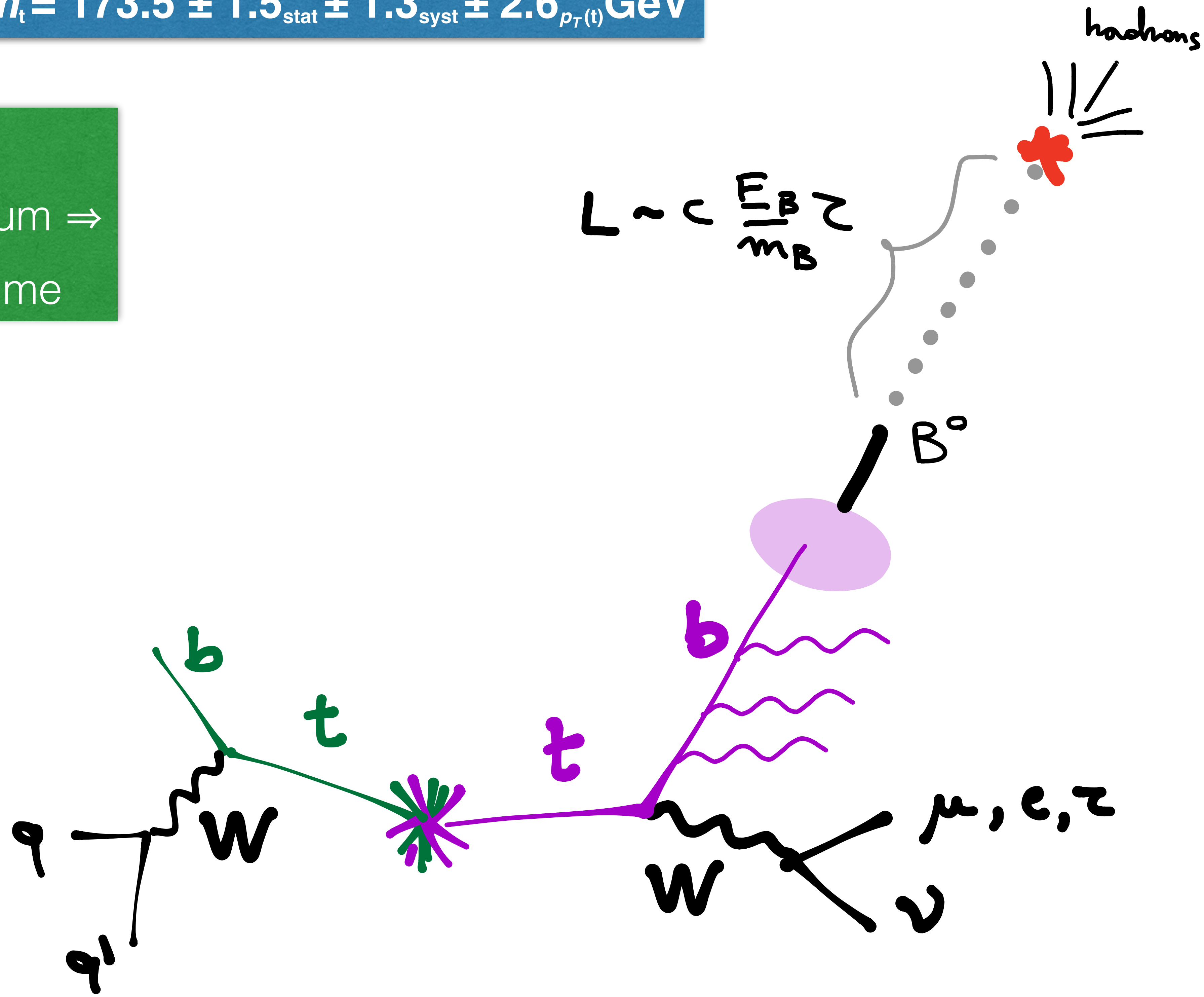
- B-hadron life-time - Lxy hep-ex/0501043

**$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T(t)}$ GeV**

larger top **mass** ⇒

⇒ large B hadron momentum ⇒

⇒ larger lab-frame life-time




dependence on the dynamics (e.g. production of top at LHC)

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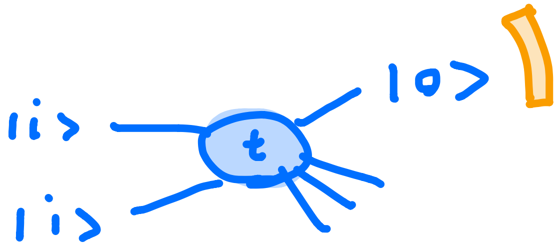


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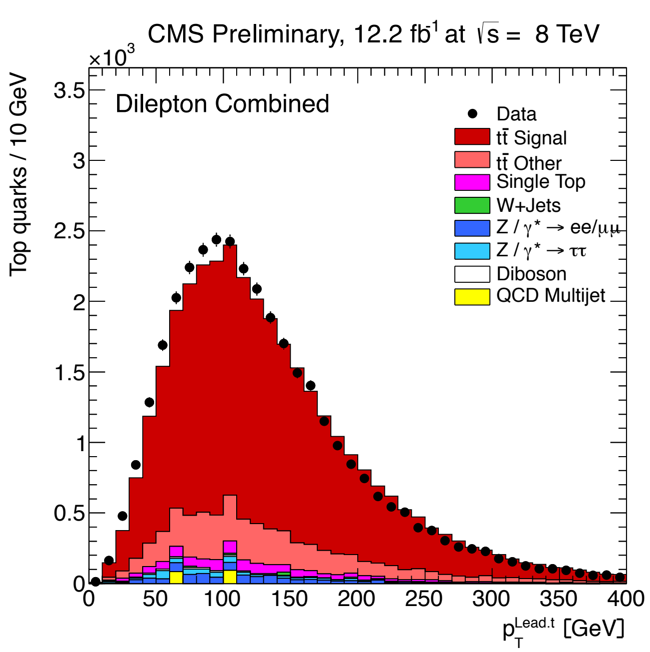
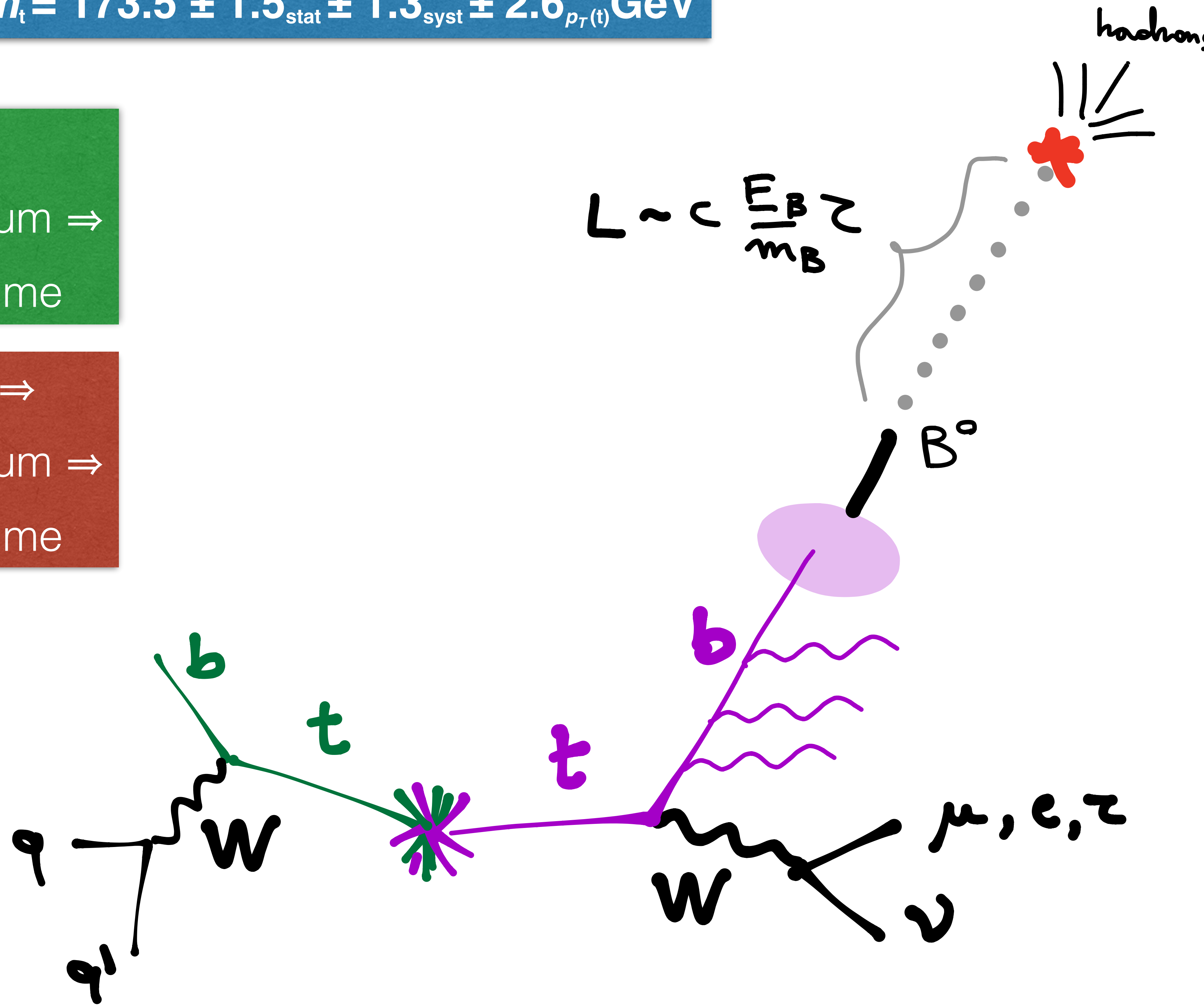
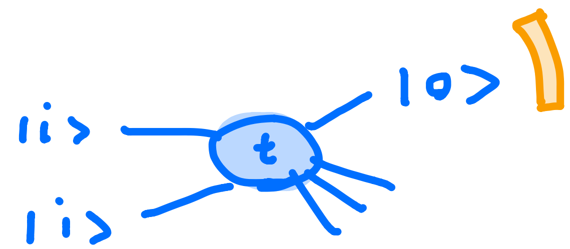



dependence on the dynamics (e.g. production of top at LHC)

# Dynamic Measurements




- **$|O\rangle$ = B** : B-hadron life-time - $L_{xy}$ hep-ex/0501043 CMS-PAS-TOP-12-030
- **$|O\rangle$ =** $\ell$ : Leptonic Mellin moments 1407.2763
- **$|O\rangle$ = b+$\ell$** : shape of m(b,l) CMS-PAS-TOP-14-014
- **$|O\rangle$ =** 3$\ell$ : shape of m($J/\psi \rightarrow \ell\ell$ ,l) hep-ph/9912320
- **$|O\rangle$ = $\ell$bbjj+j** : $d\sigma/d1/s(ttj)$ 1303.6415 ATLAS-CONF-2014-053

complexity

# Kinematic Methods

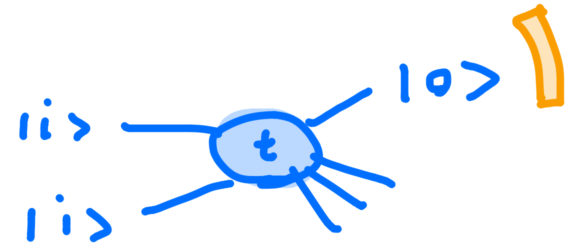
# Kinematic Methods

- fewer assumptions
  (just 4-momentum conservation)
- valid in case of new physics
  (we hope top quark is sensitive to new physics)
- uncertainties are easier to understand
- no longer limited by statistics
  (LHC=top factory)
- cannot be 1-loop precise ⇒ dynamics

  (loop=Lagrangian=beyond kinematics)

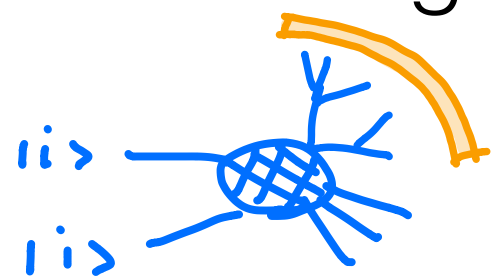
# Kinematic measurements

*single-particle*



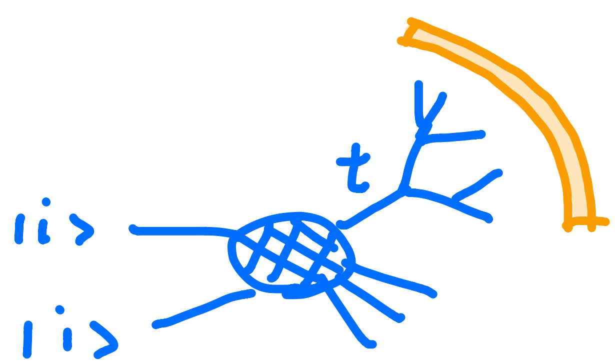
- $|O\rangle$ **= b or B** : peak of $d\sigma/dE_b$ 1209.0772
- $|O\rangle$ **=** $\ell$ : weighted average of $E_\ell$ 1405.2395

*sub-systems*



- $|O\rangle$ **= b+**$\ell$ : end-point of m(b,l) CMS-TOP-11-027
- $|O\rangle$ **=** 3$\ell$ : end-point of m($J/\psi \to \ell\ell$ ,l) hep-ph/9912320
- $|O\rangle$ **=** $\ell$**bbjj+j** : end-point of mT2 0801.5576 CMS-TOP-11-027

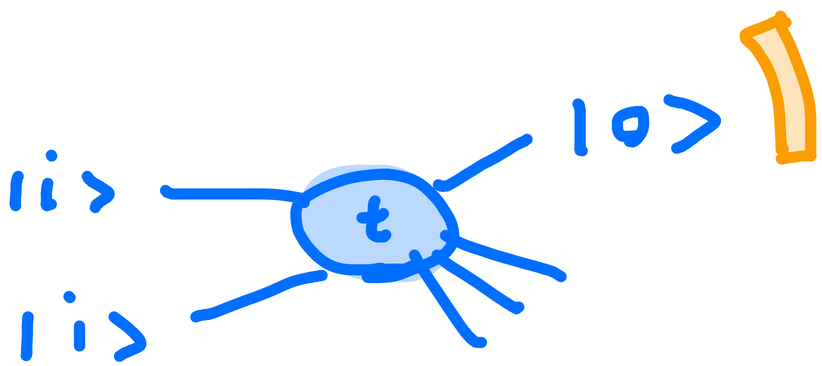
*top reconstruction*

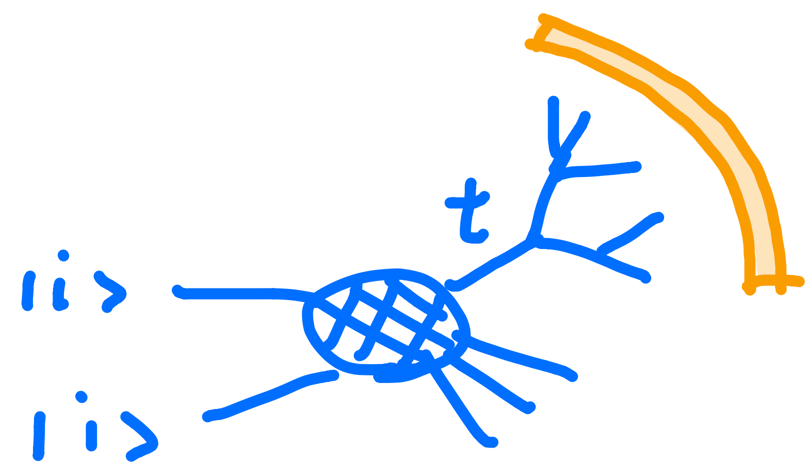


- $\ell$**bbjj(+j)** : kinematic fit 1209.0772, CMS-PAS-TOP-14-001

complexity

# To reconstruct or not to reconstruct?



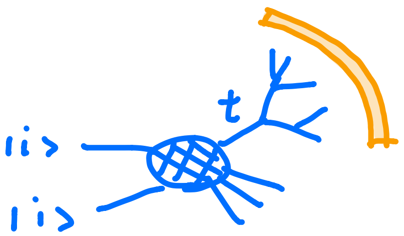




does (not) distinguish where
the final state came from (t, t*, bW, bWg, bqqg)

need (not) to define the top

might (not) depend on the production mechanism

…



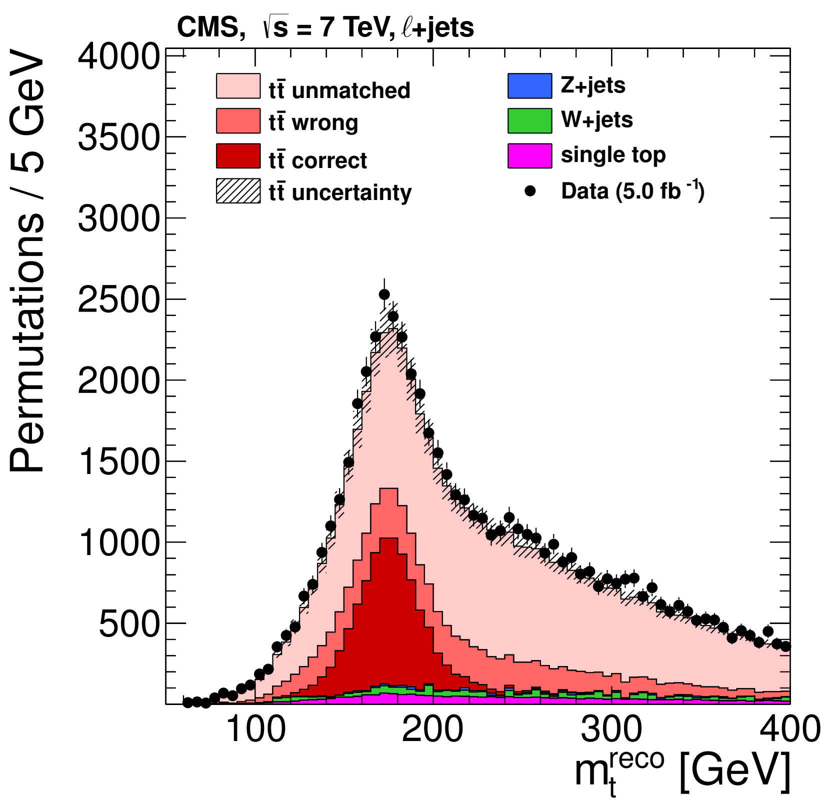
# CMS Ideogram (1209.2319)

most precise number about $m_{top}$ today (0.7 GeV CMS-PAS-TOP-14-001)

pp→ℓν bb jj

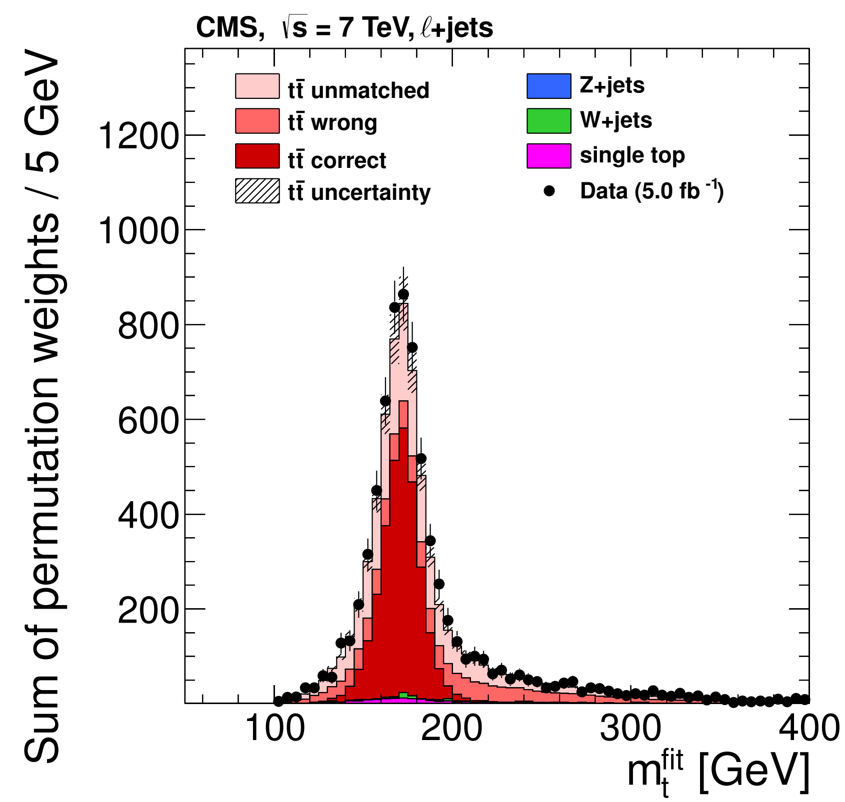
inputs: 4-momenta of ℓ, 2b,2j and mET vector

kinematic fit to "match" events on the pp→ **$t\bar{t}$**→ ℓν bb jj




(b)

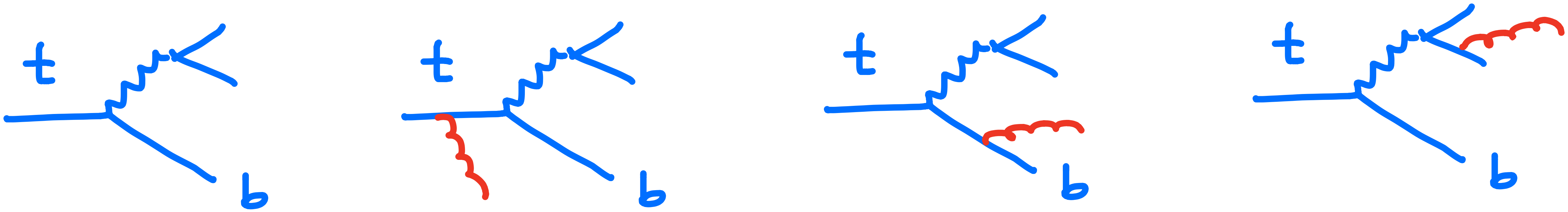
$\chi^2$ goodness of fit as criterion to discard/weight the kinematics



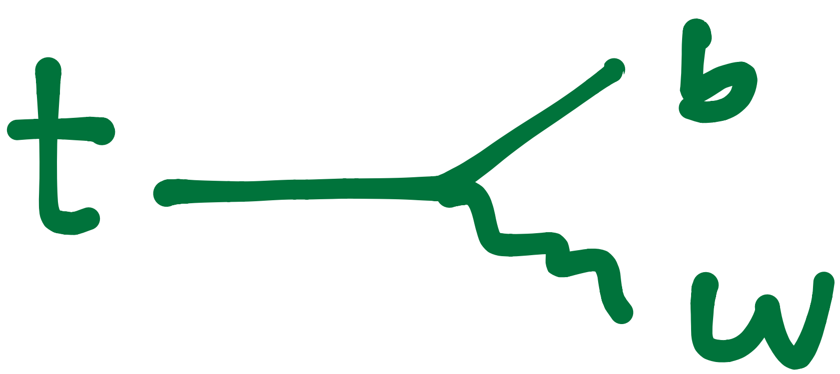

(d)

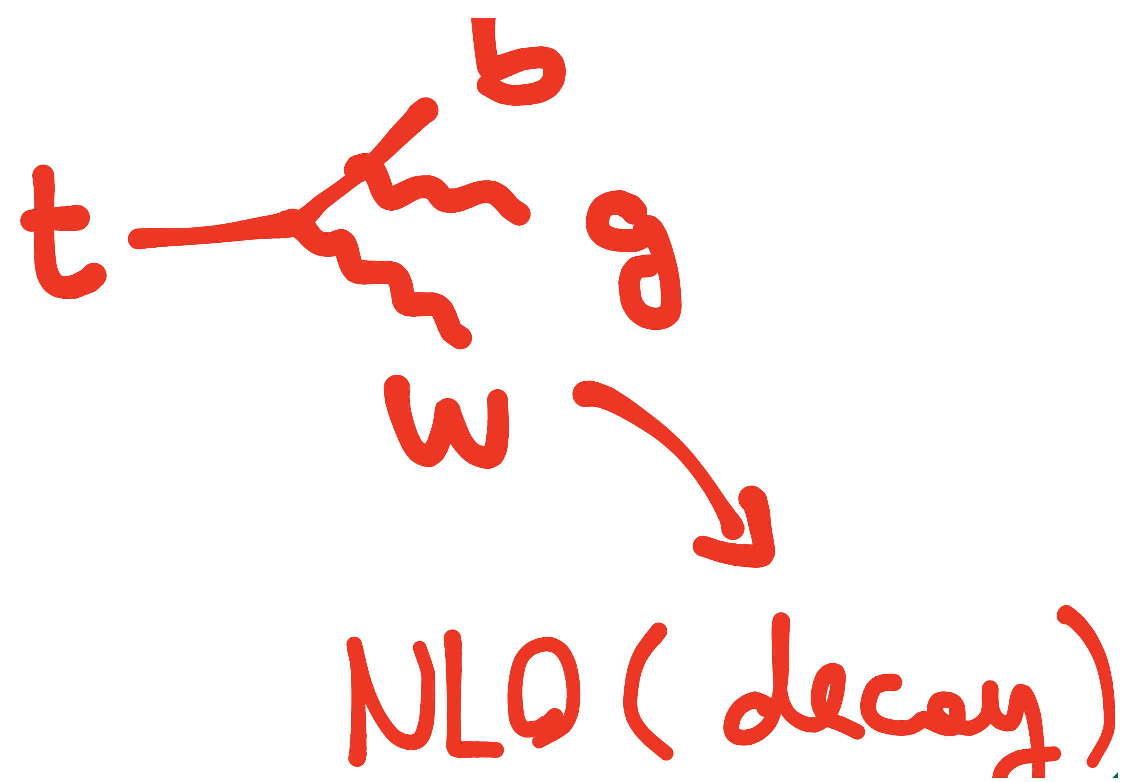
LO picture all over the places

# To reconstruct or not to reconstruct?




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

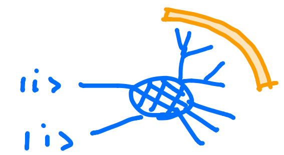


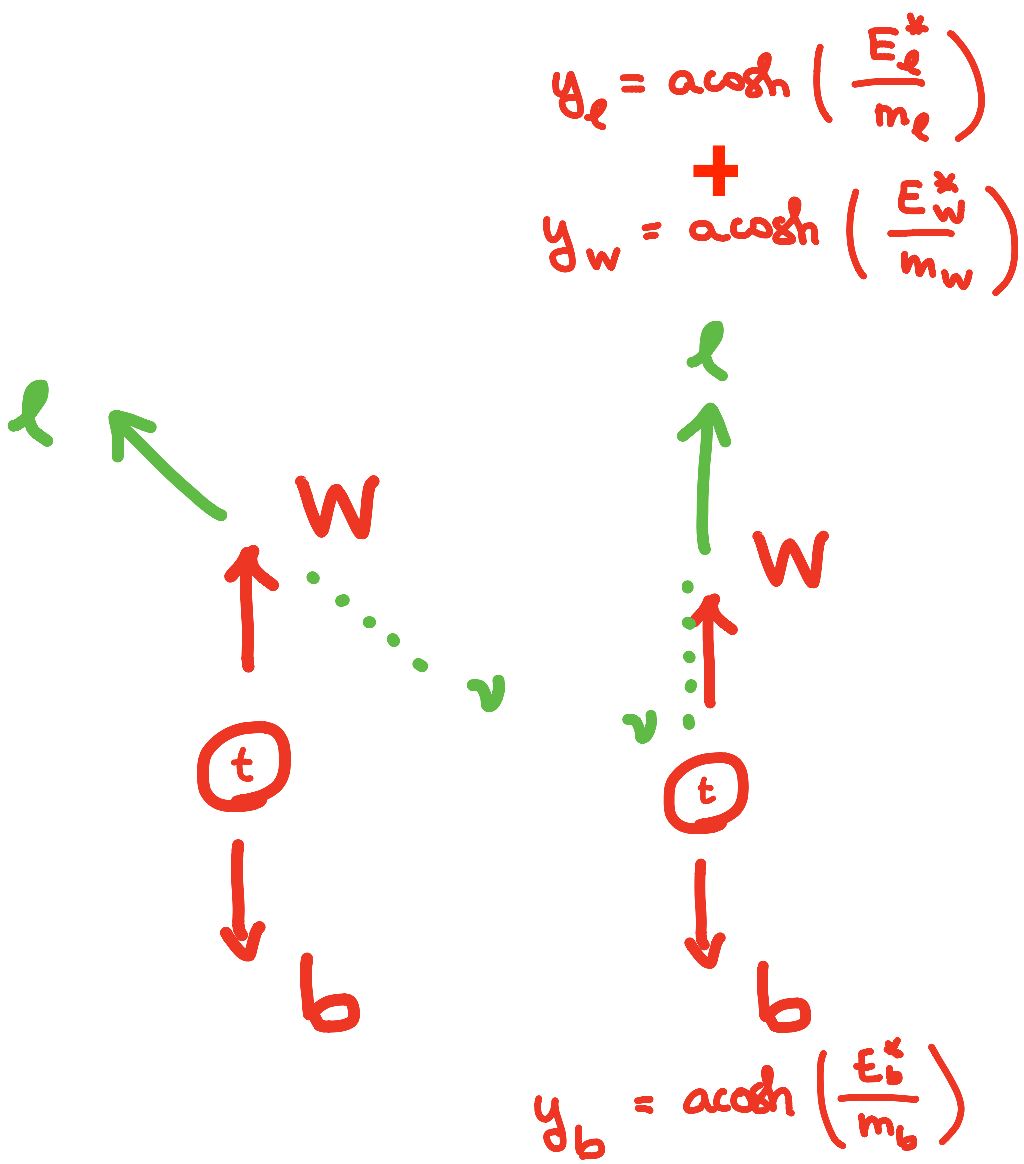




NLO+PS in 1412.1828

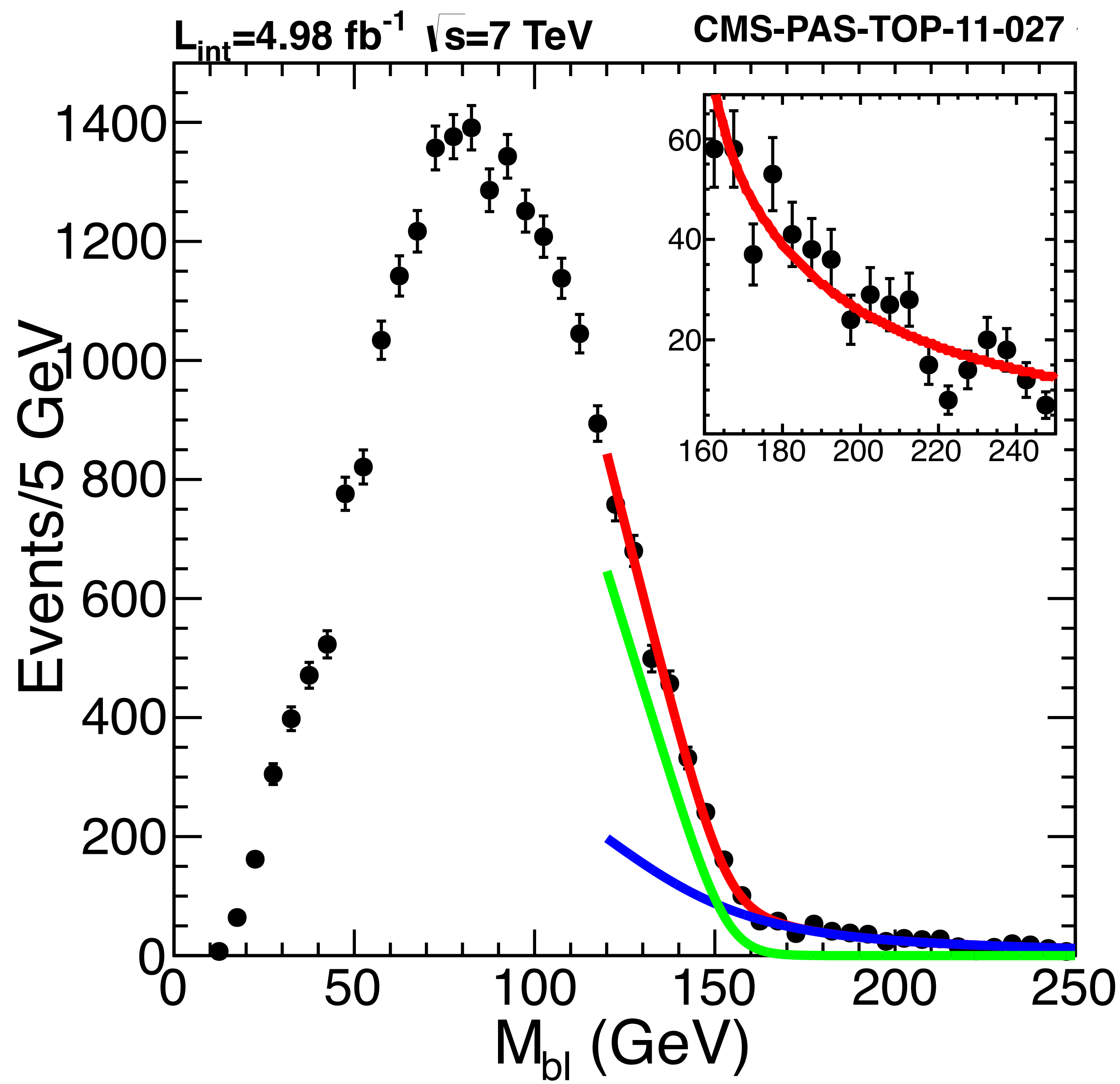
# Kinematic End-points (mT2, $m_{b\ell}$)

On-shell (LO) constraints






$M_{top} = 173.9 \pm 0.9(\text{stat}) \pm 1.8(\text{syst})$ GeV



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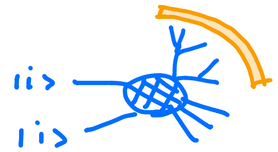

$$y_\ell = \text{acosh}\left(\frac{E^*_\ell}{m_\ell}\right)$$
$$+$$
$$y_W = \text{acosh}\left(\frac{E^*_W}{m_W}\right)$$
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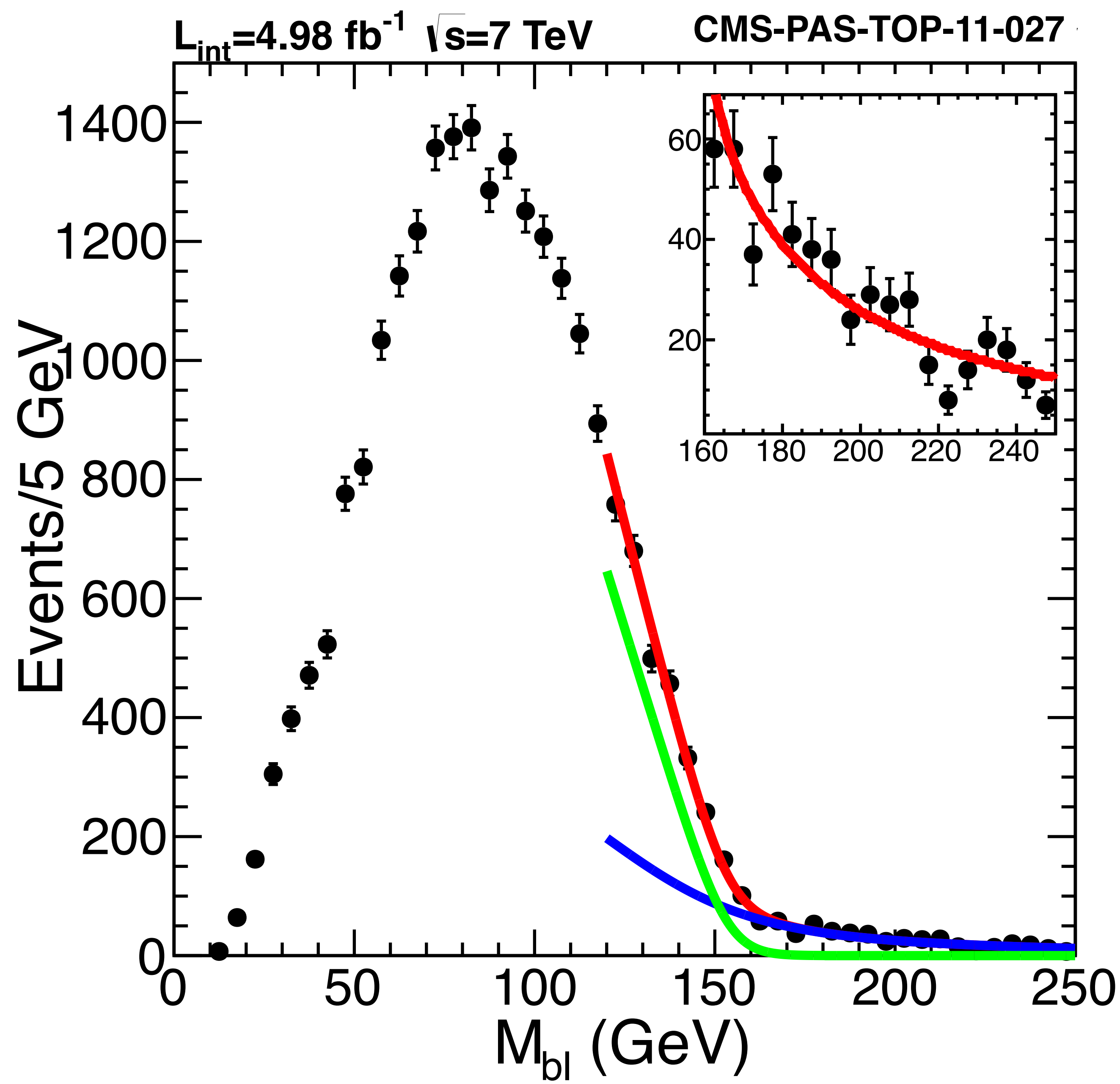

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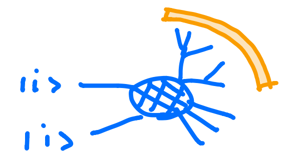

$$m_{b\ell}^{max}\Big|_{m_b=0} = \sqrt{\frac{(m_t^2 - m_W^2)(m_W^2 - m_\nu^2)}{m_W}}$$

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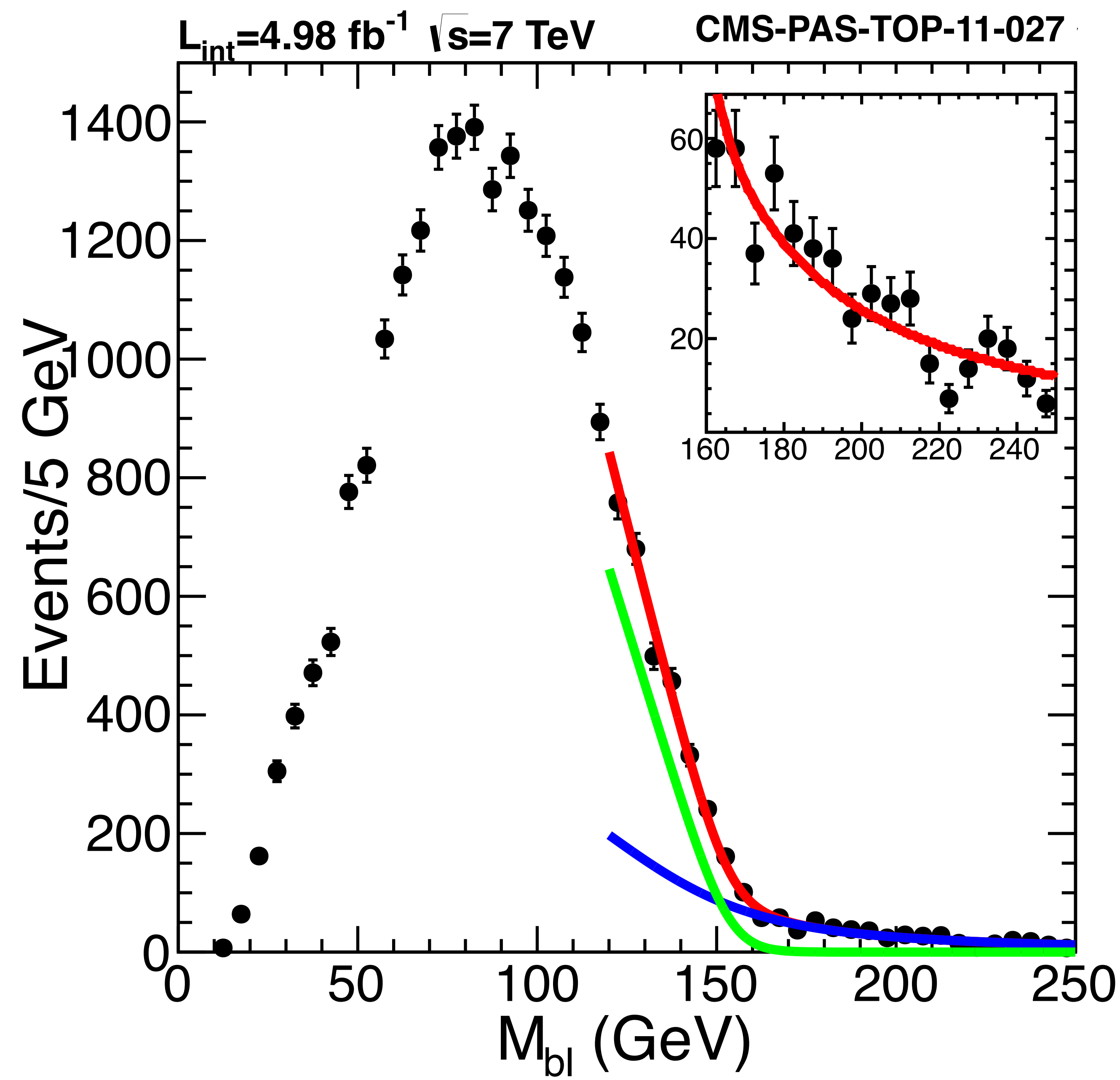

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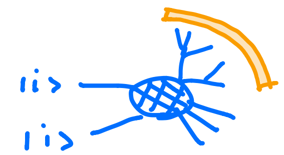

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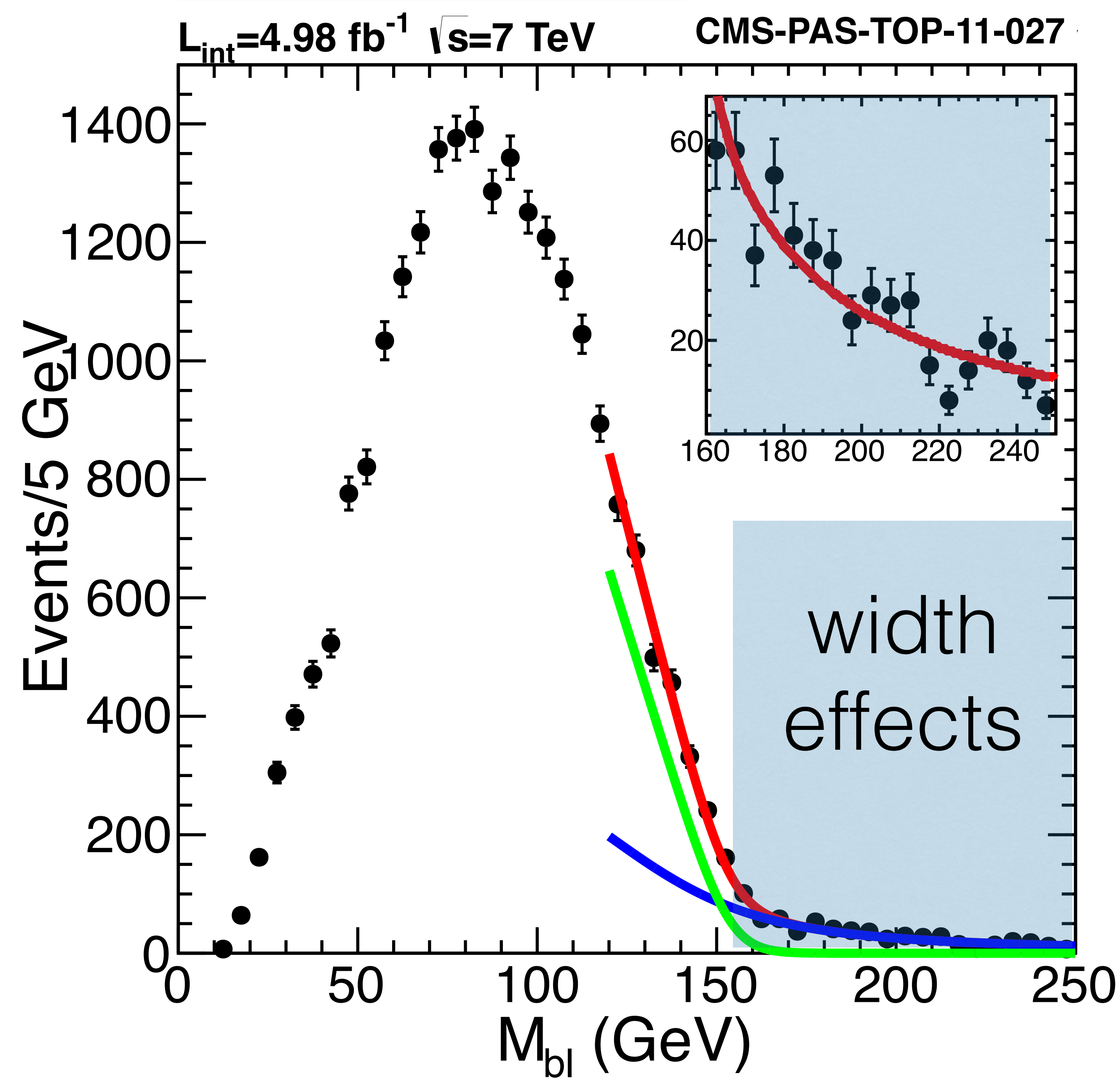
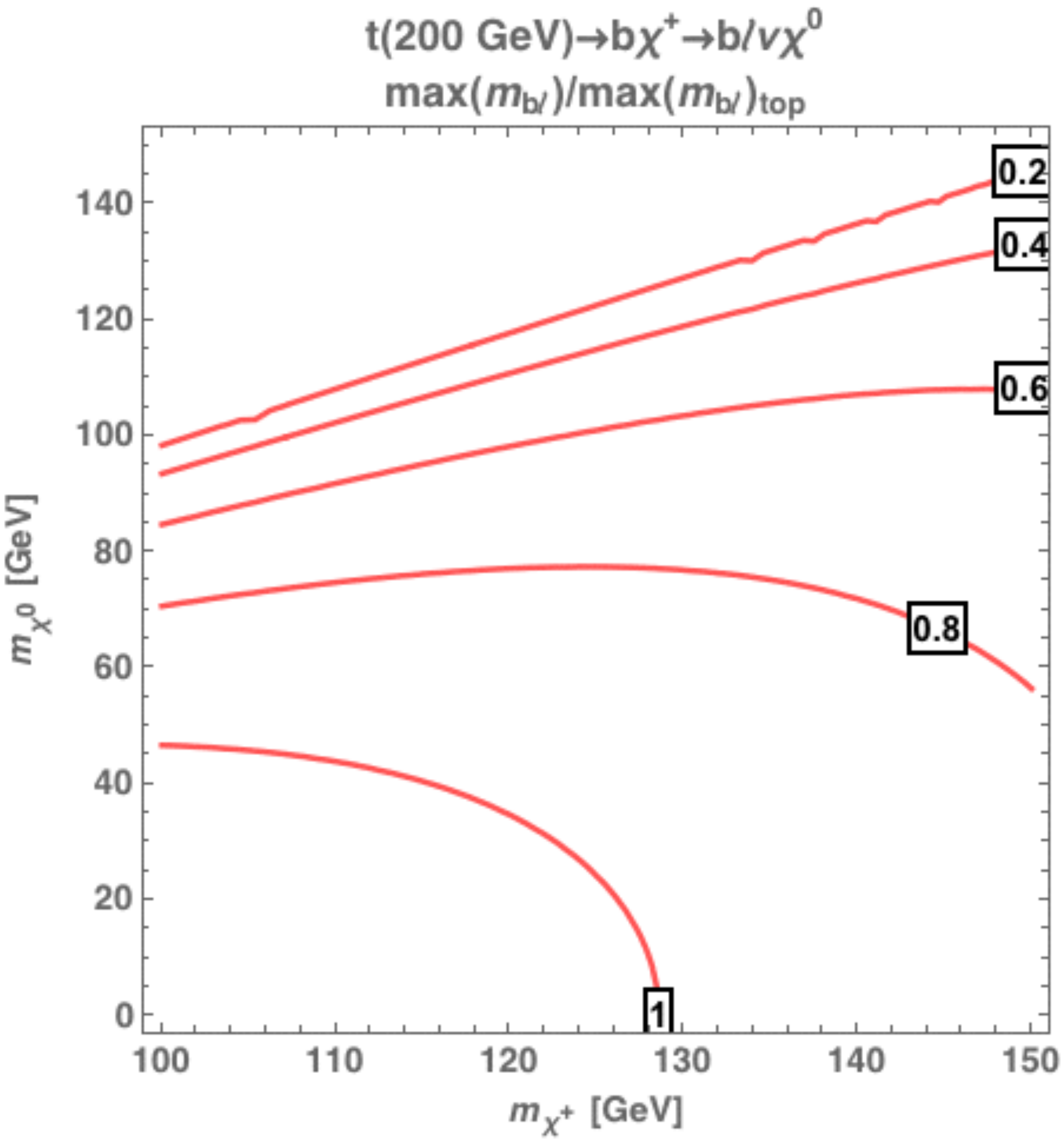
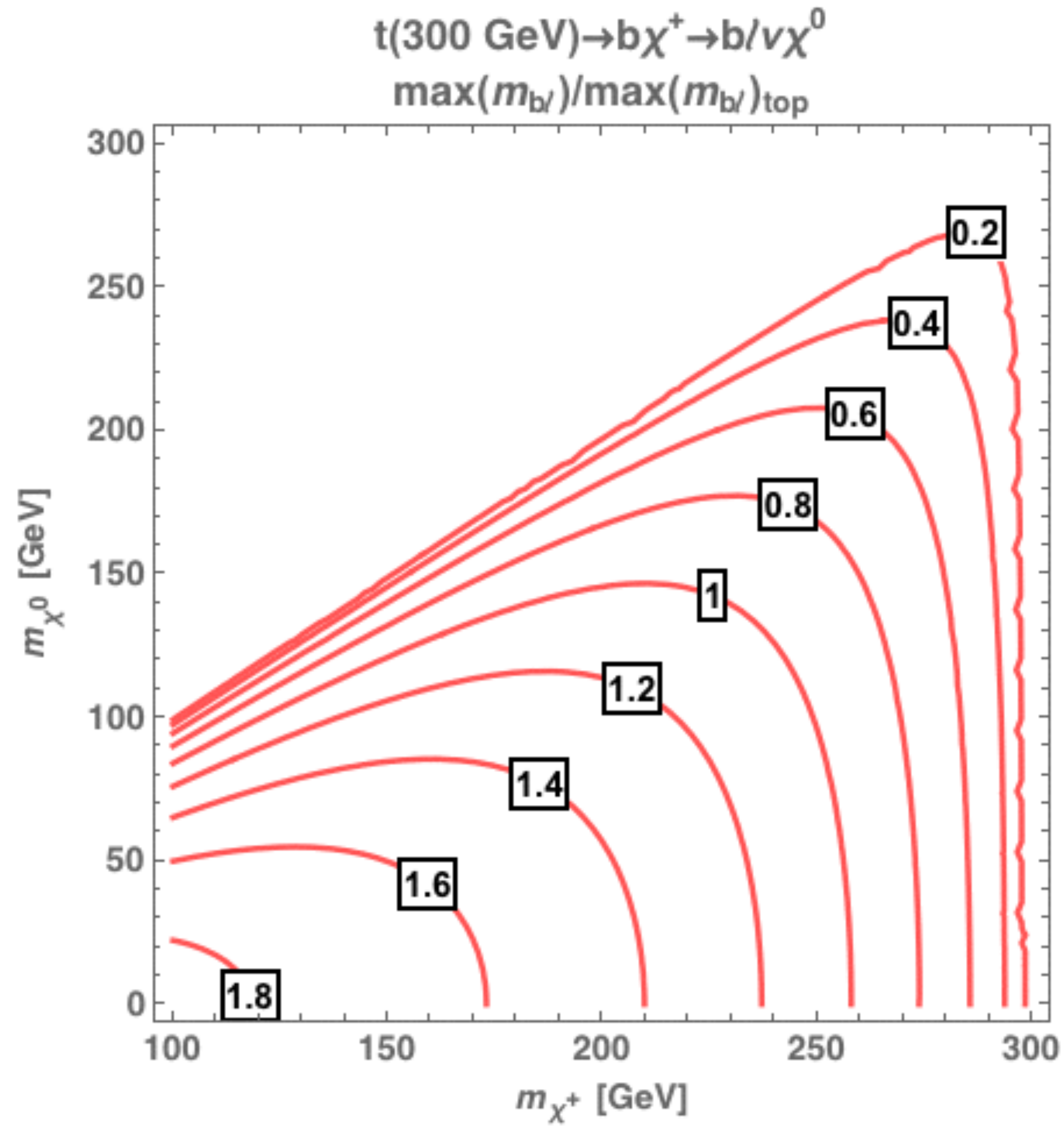


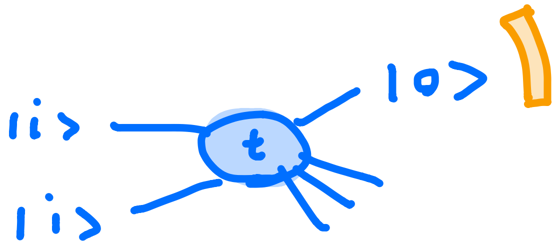
# New physics effect on $m_{b\ell}$

$\tilde{t} \to b\,\chi^+ \to b\ell\nu\chi^0$




$\delta m_{top} \lesssim 1$ GeV if $\tilde{t}$, $\chi^+$, $\chi$ are not excluded in direct searches



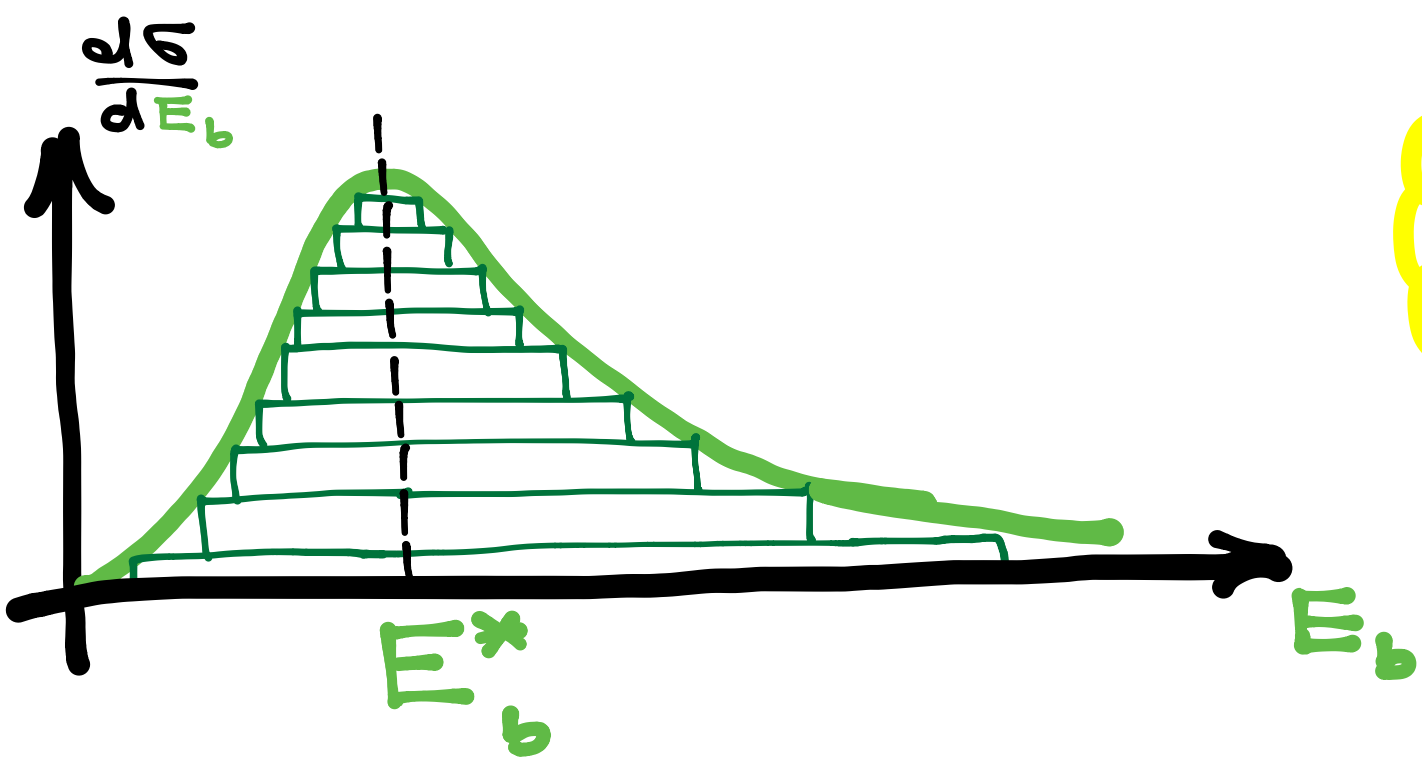

# Energy peaks

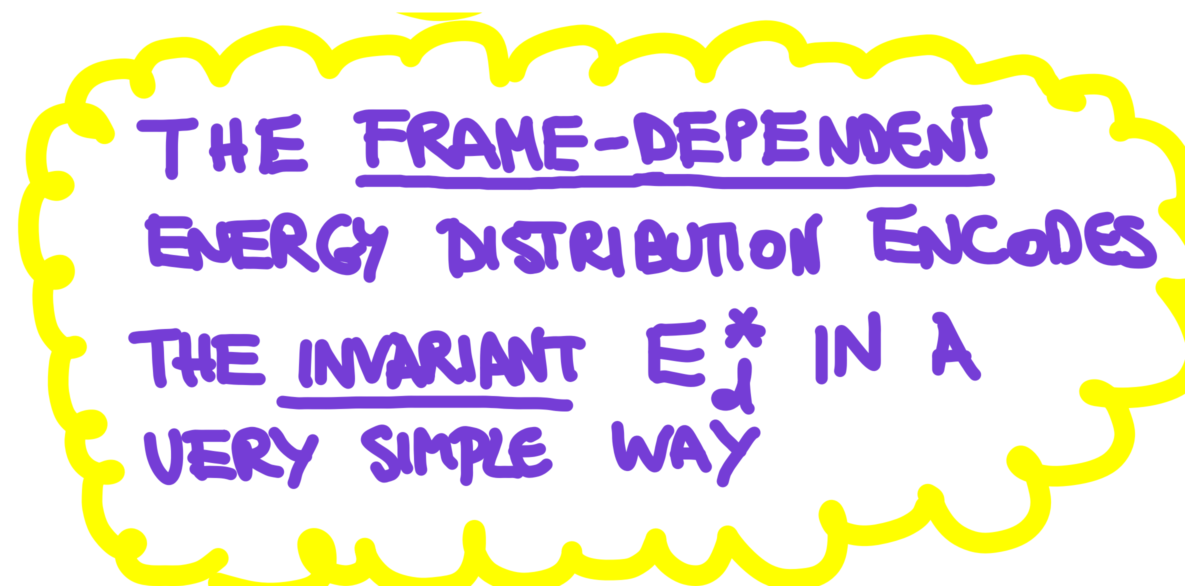
1209.0772

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



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

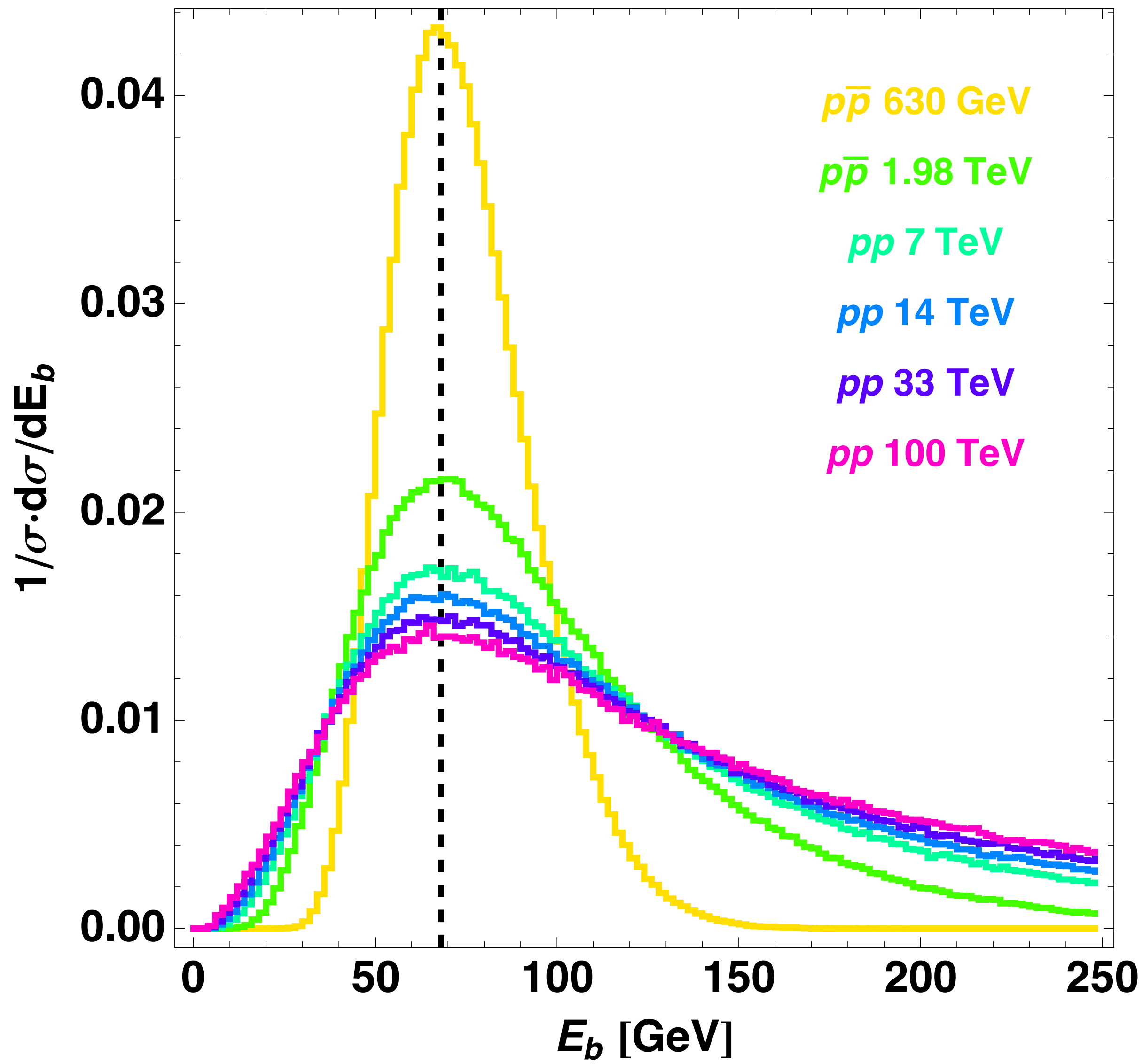


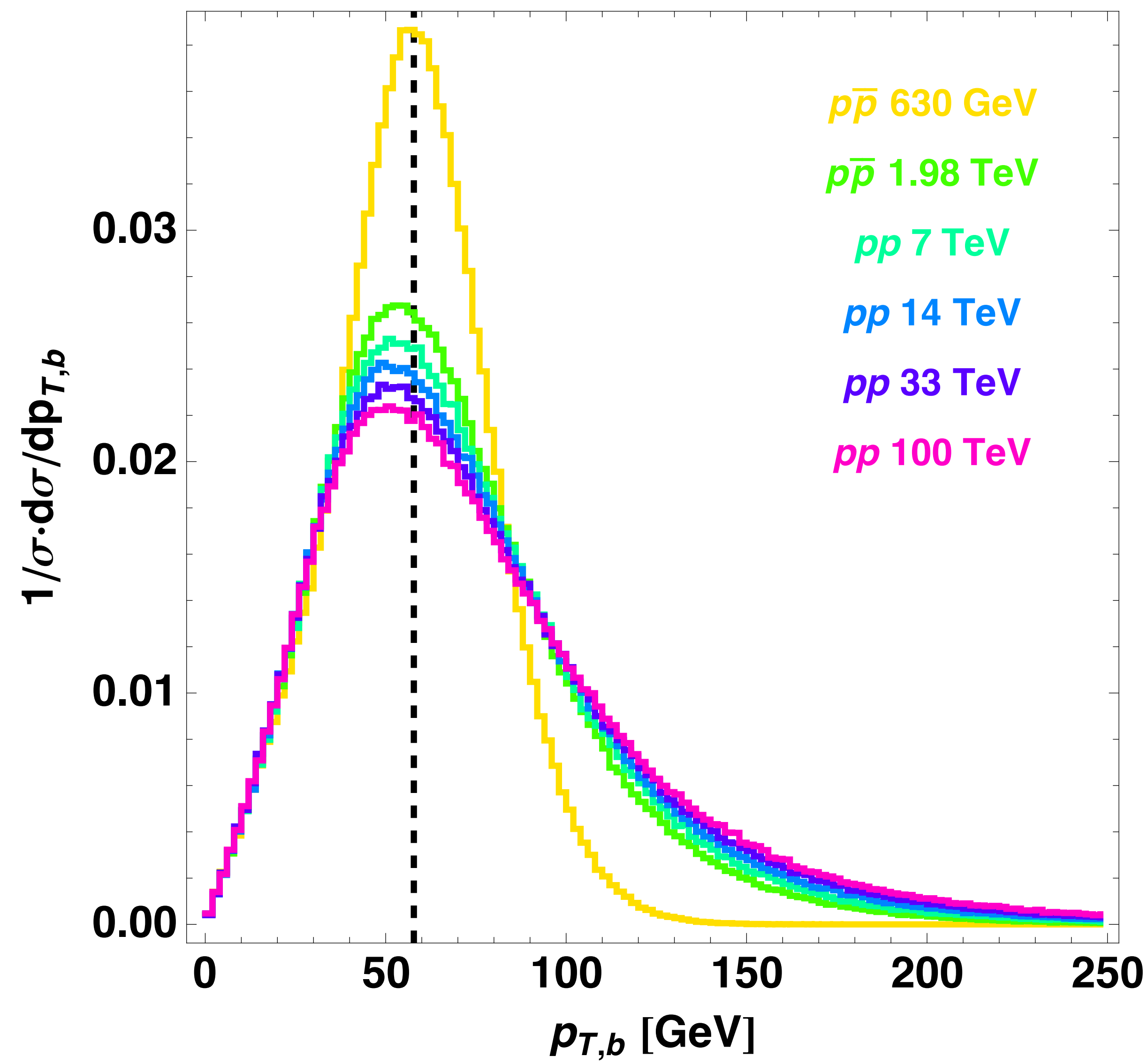

There is no difference when the b-mass is taken into account provided $\gamma_{top} < 500$

# How special is this invariance?

Shape changes, peak doesn't!

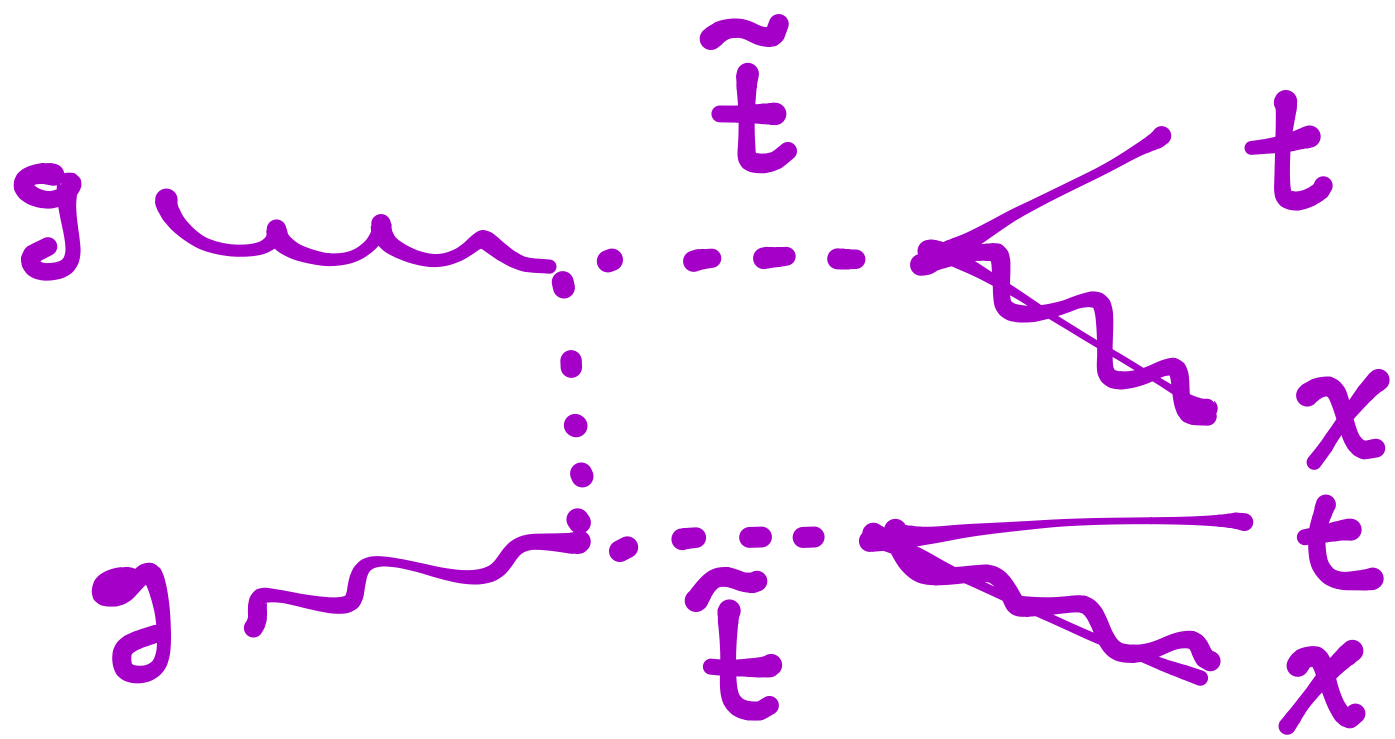



Shape changes, peak does too




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

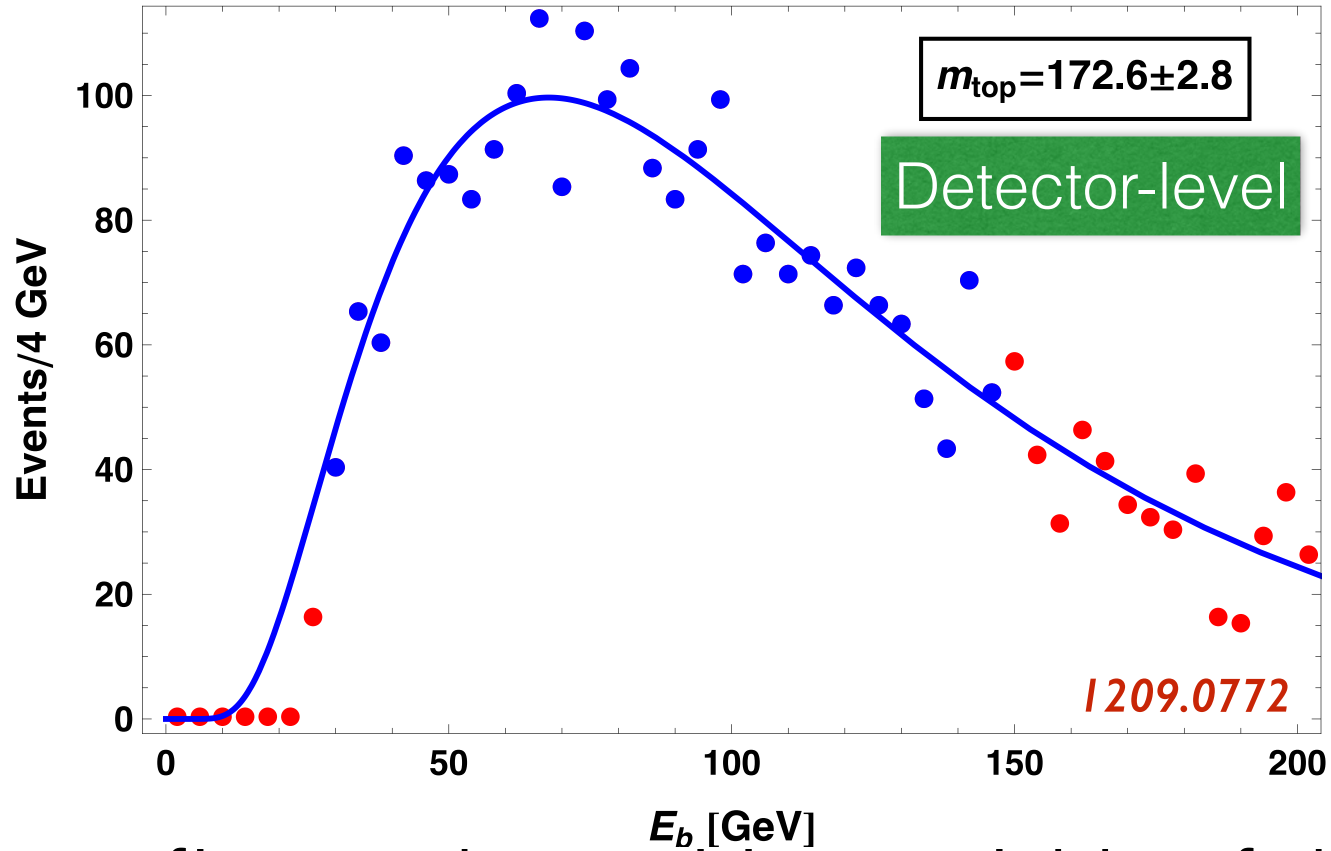
# New physics in the top sample




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

# 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, RF, and Kim*

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

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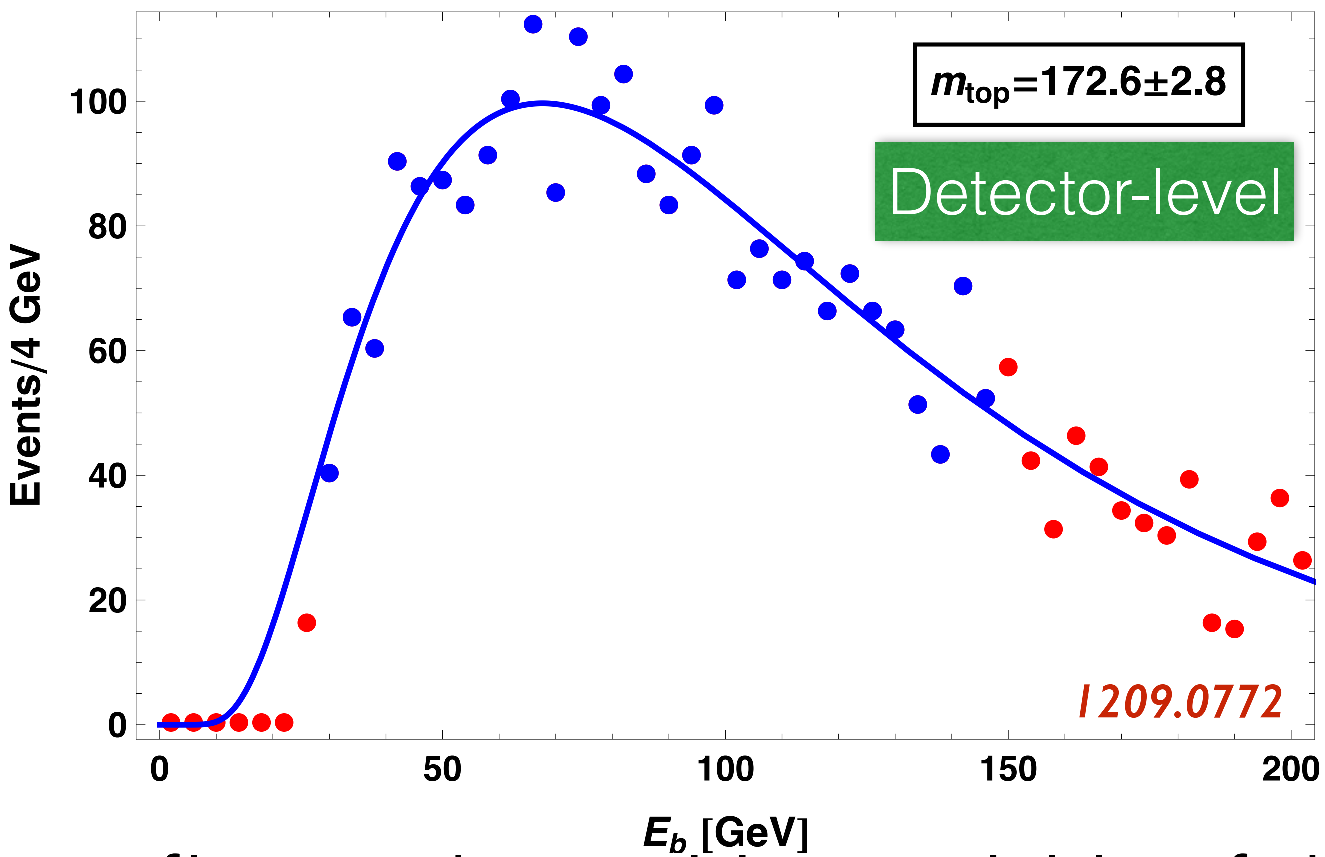


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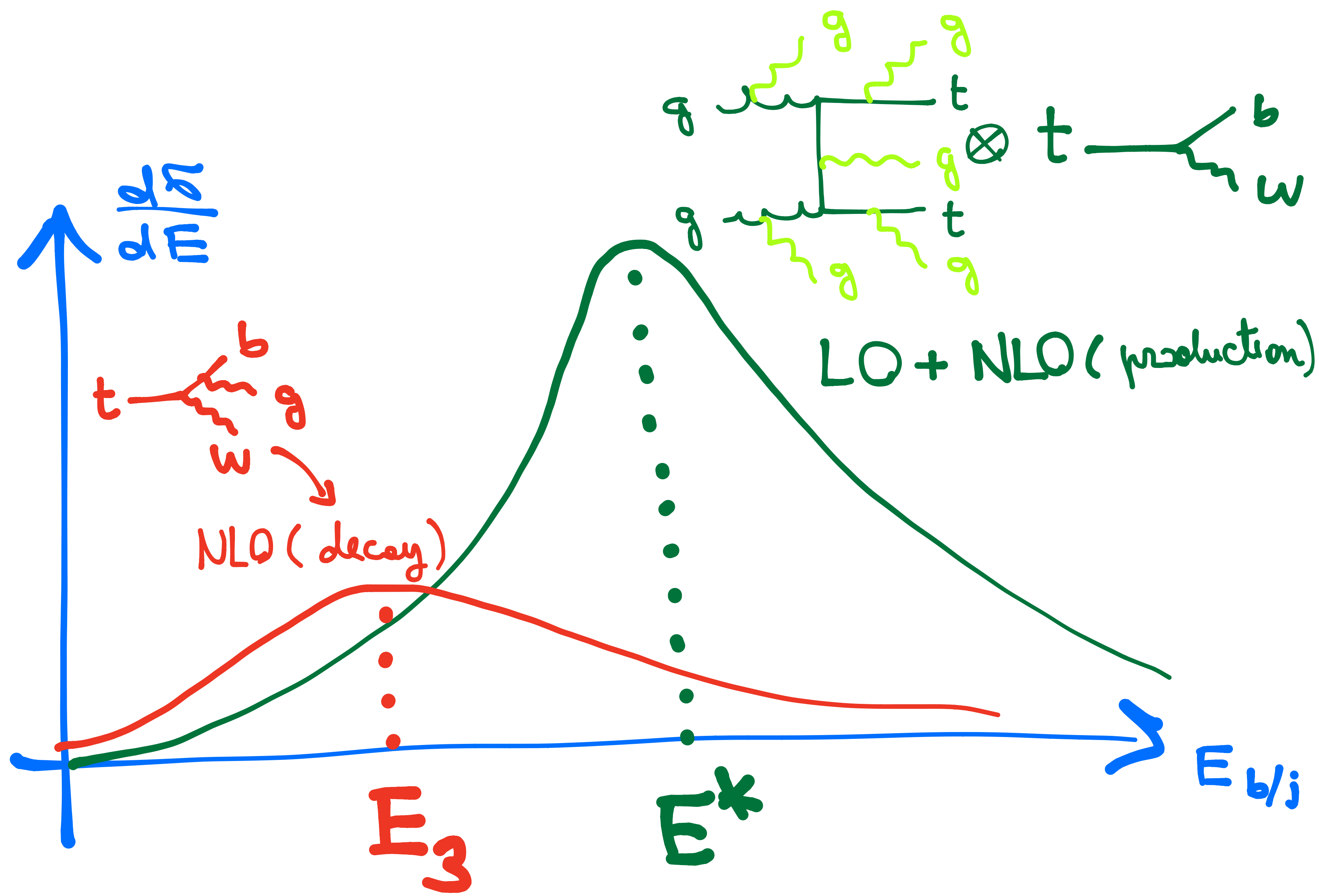
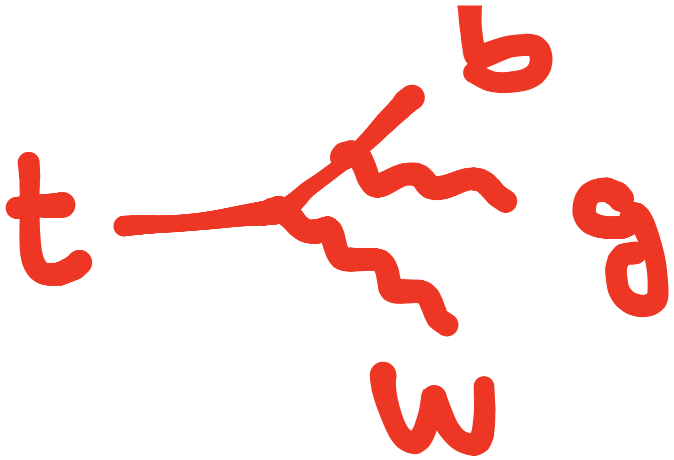
# Peak shift at NLO



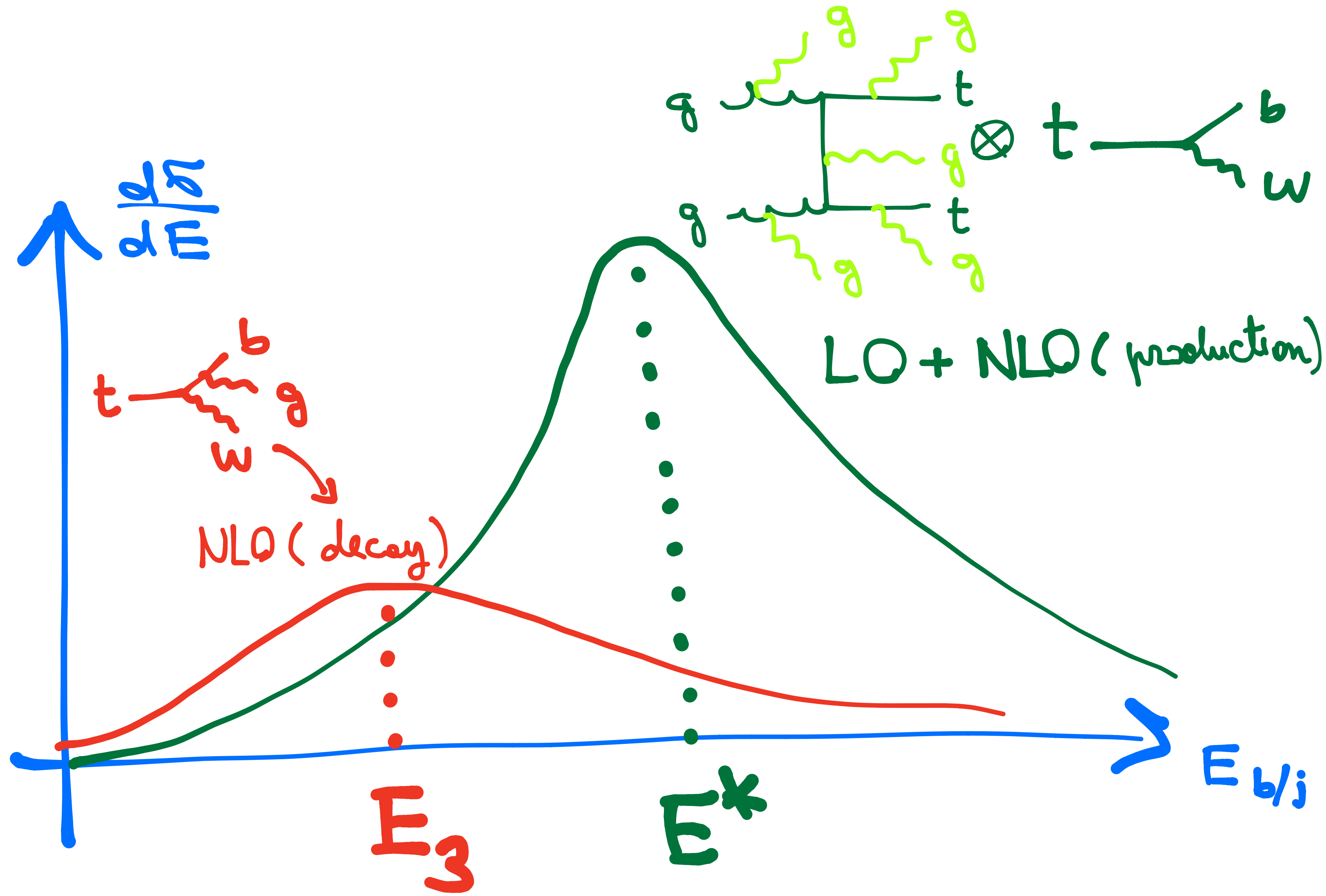

$$E^{peak} = E^{*} + O(1)\,\frac{\alpha}{4\pi}\,E_3$$

# 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 |



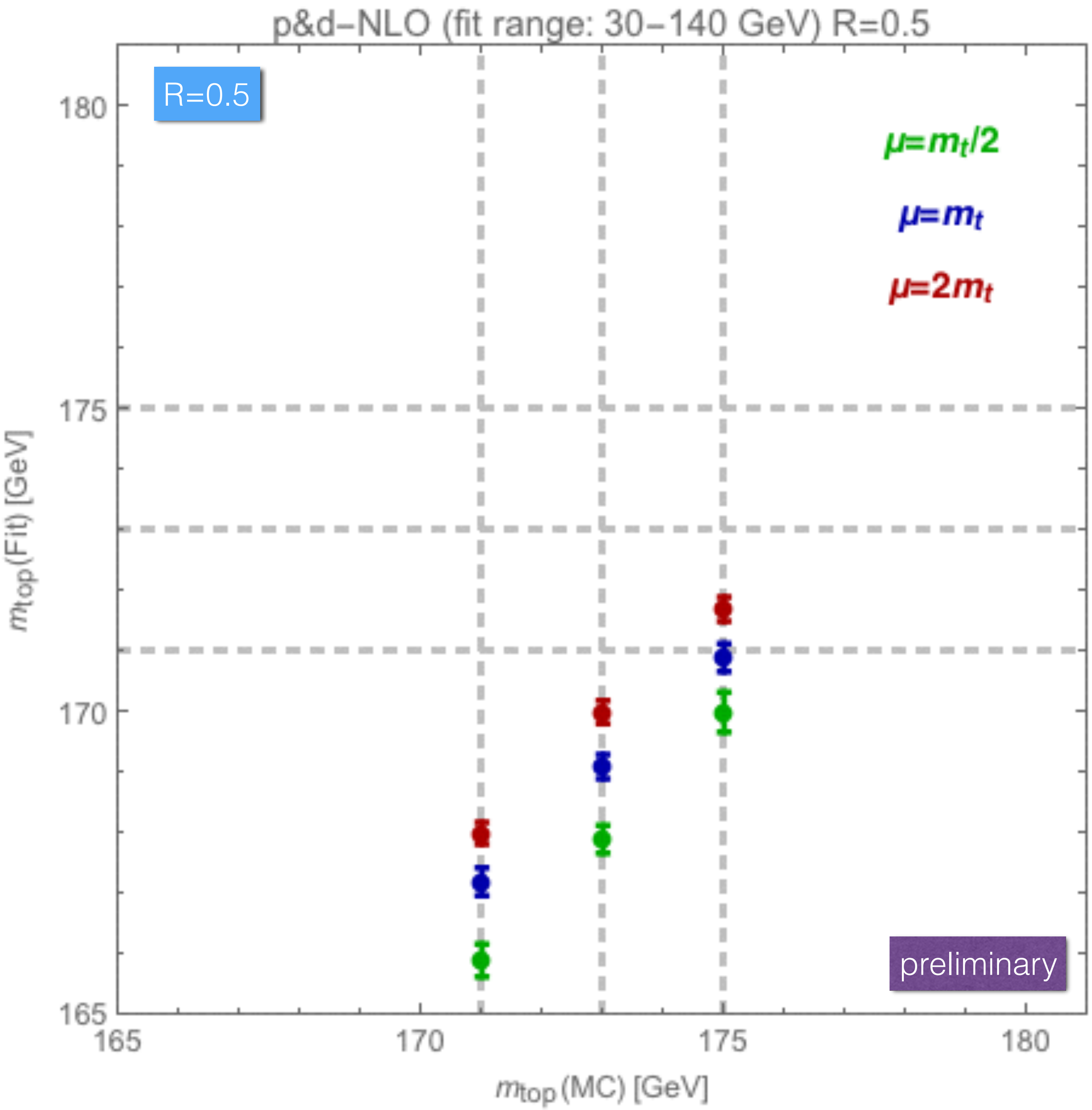

$$E^{peak} = E^{*}(1-\Delta_{TH}) + \Delta_{TH} E_3$$

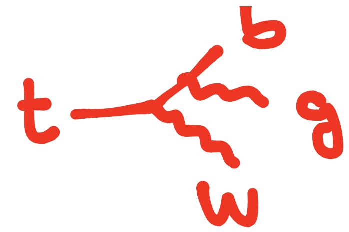
$\Delta_{TH}$=BR(t→bW**g**)/BR(t→bW)≃0.05

# NLO: production & decay

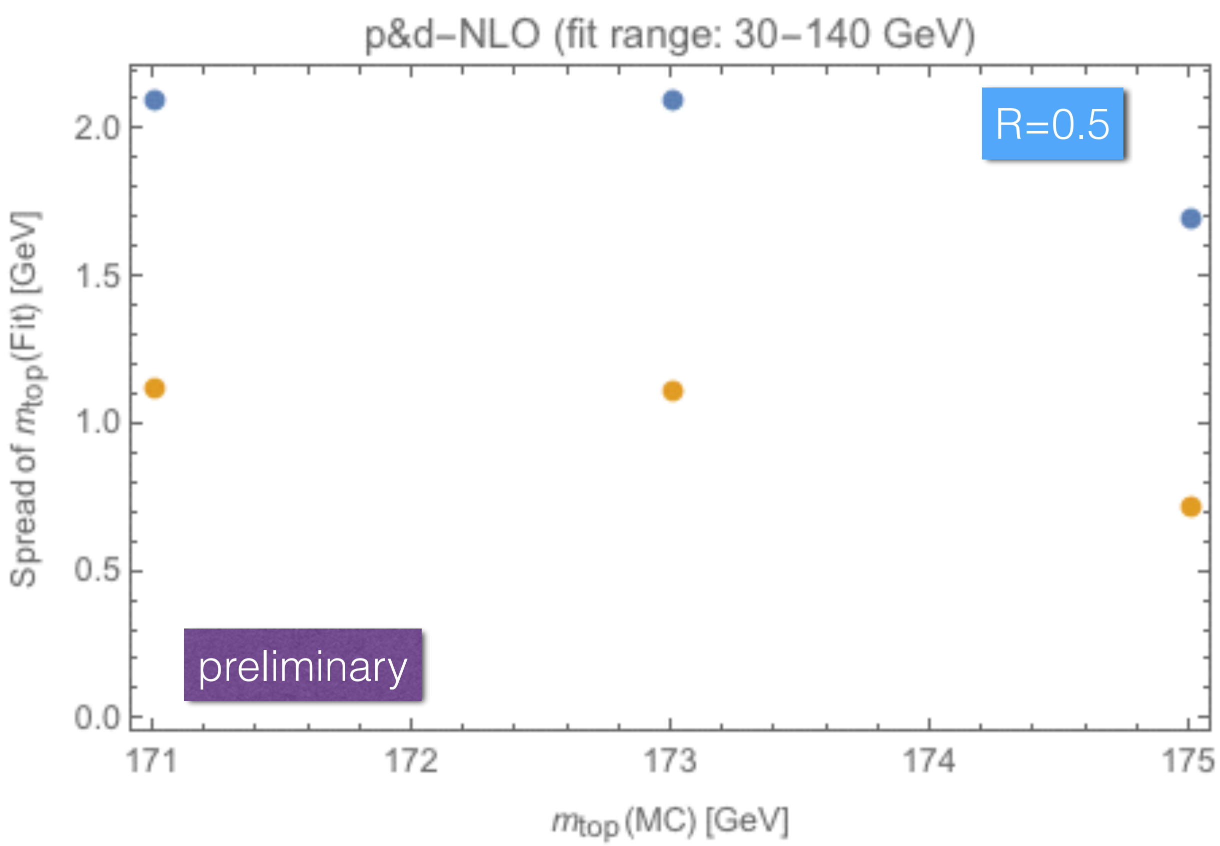
R=0.5

(MCFM)



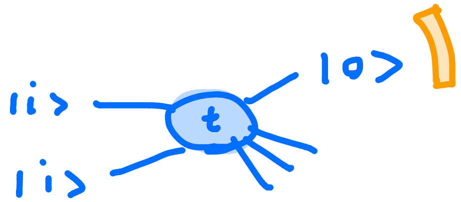




$|\delta| \sim \alpha_s \sim 1/\mu$




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

# Dynamic methods



# Theory biases

1407.2763

## Leptonic Mellin Moments

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

templates


**MC: correlate the leptonic shape to $m_{top}$**

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

# Subtleties for *any template method*

1407.2763

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

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

- <u>understand the combination</u>
- asses missing effects: NNLO, extra radiation types

effect of shower

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

ΔPS decreases at NLO (0 within 1σ)

large bias even at NLO - larger than already large ΔPS

understanding impact of shower:

- use of partonic NNLO
- can avoid speaking about mass in the "Montecarlo scheme"

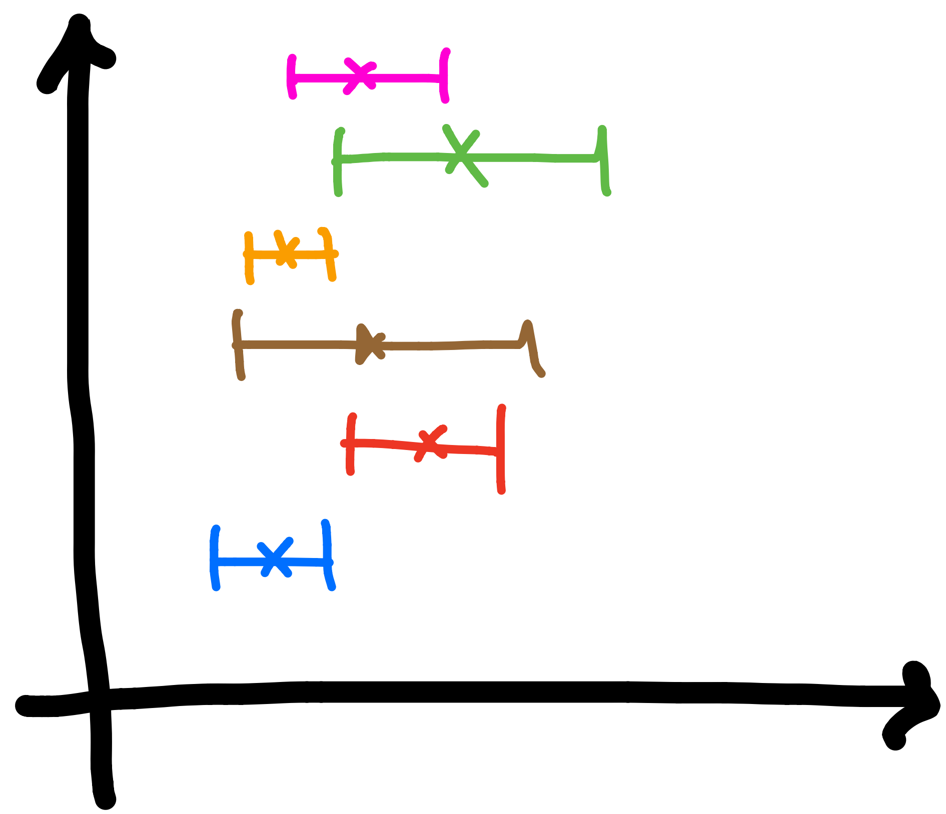
# Subtleties for *any template method*

1407.2763

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

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] |
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| $p_{T\bar{\ell}}$, $E_{\bar{\ell}}+E_{\ell}$, $p_{T\bar{\ell}}+p_{T\ell}$, $p_{T\bar{\ell}+\ell}$, $M_{\bar{\ell}+\ell}$ | |
|---|---|
| LO+PS+MS | $175.98^{+0.63}_{-0.69}$[16.9] |
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| LO+PS | $187.90^{+0.6}_{-0.6}$[428.3] |
| fNLO | $174.41^{+0.72}_{-0.73}$[96.6] |
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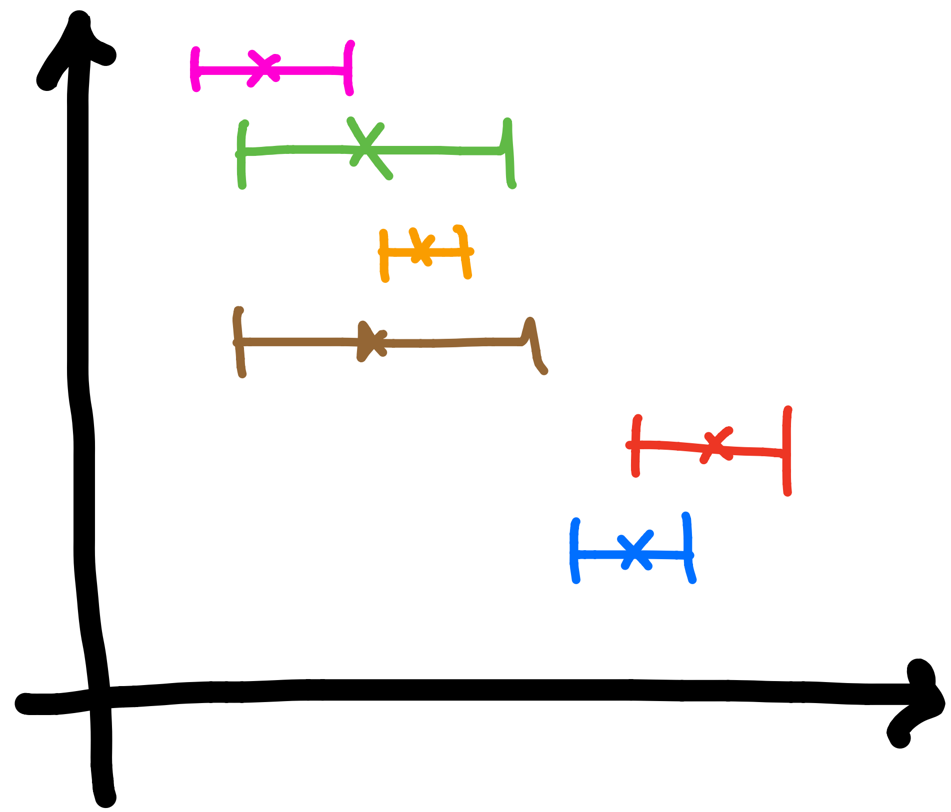
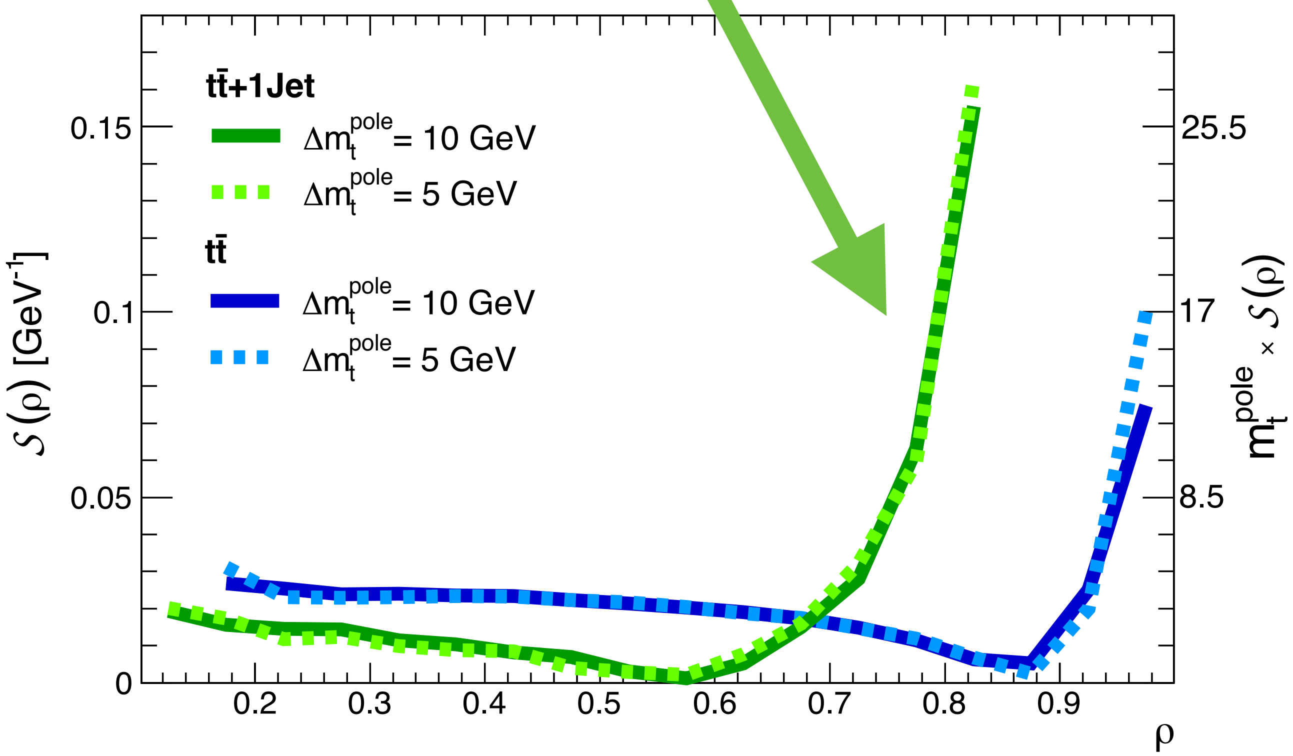


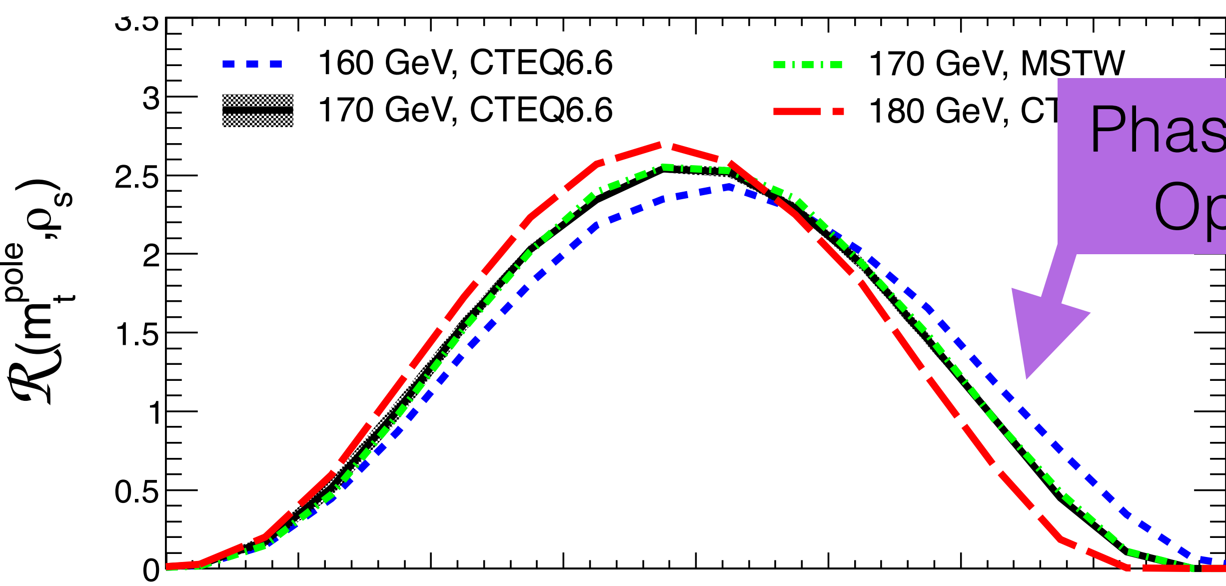
discrepancy highlights poor QCD description

1303.6415 ATLAS-CONF-2014-053

# dσ/d1/s(ttj) → phase-space opening

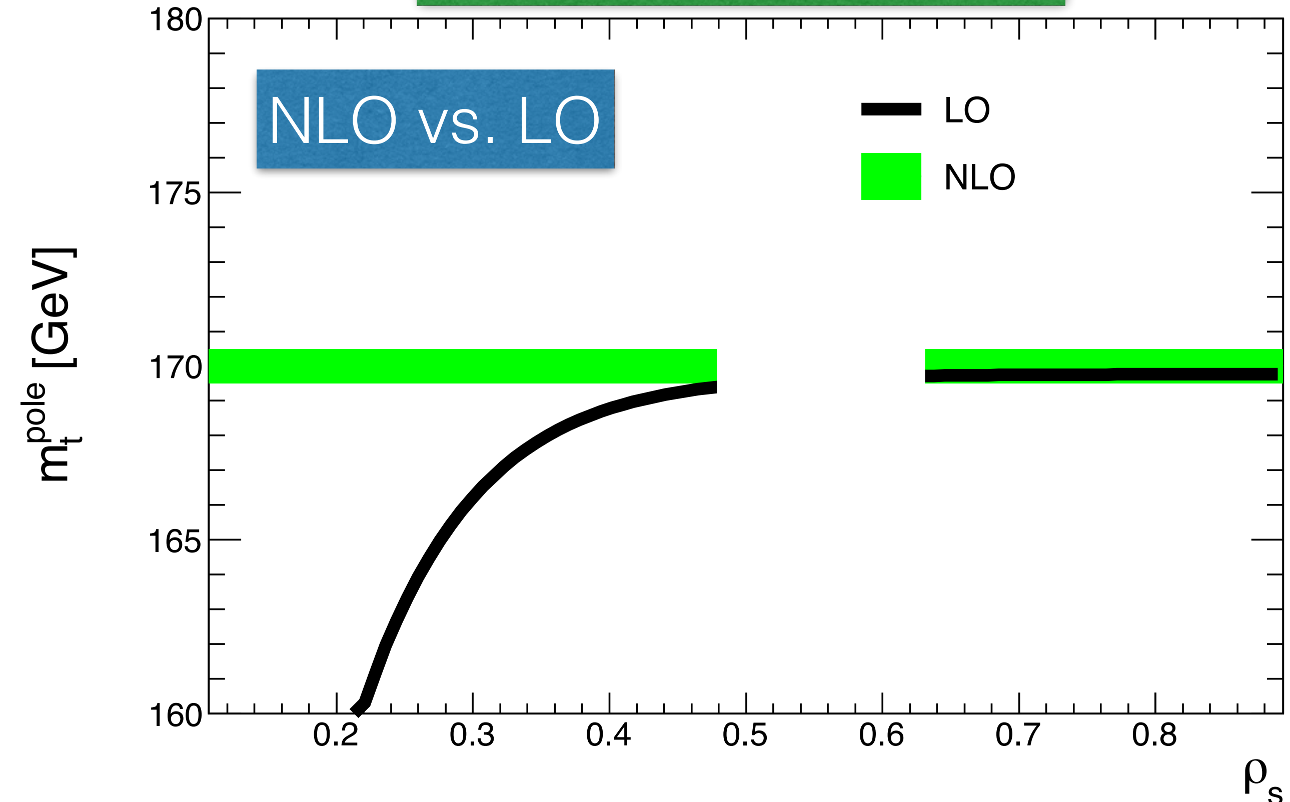
Why we do it

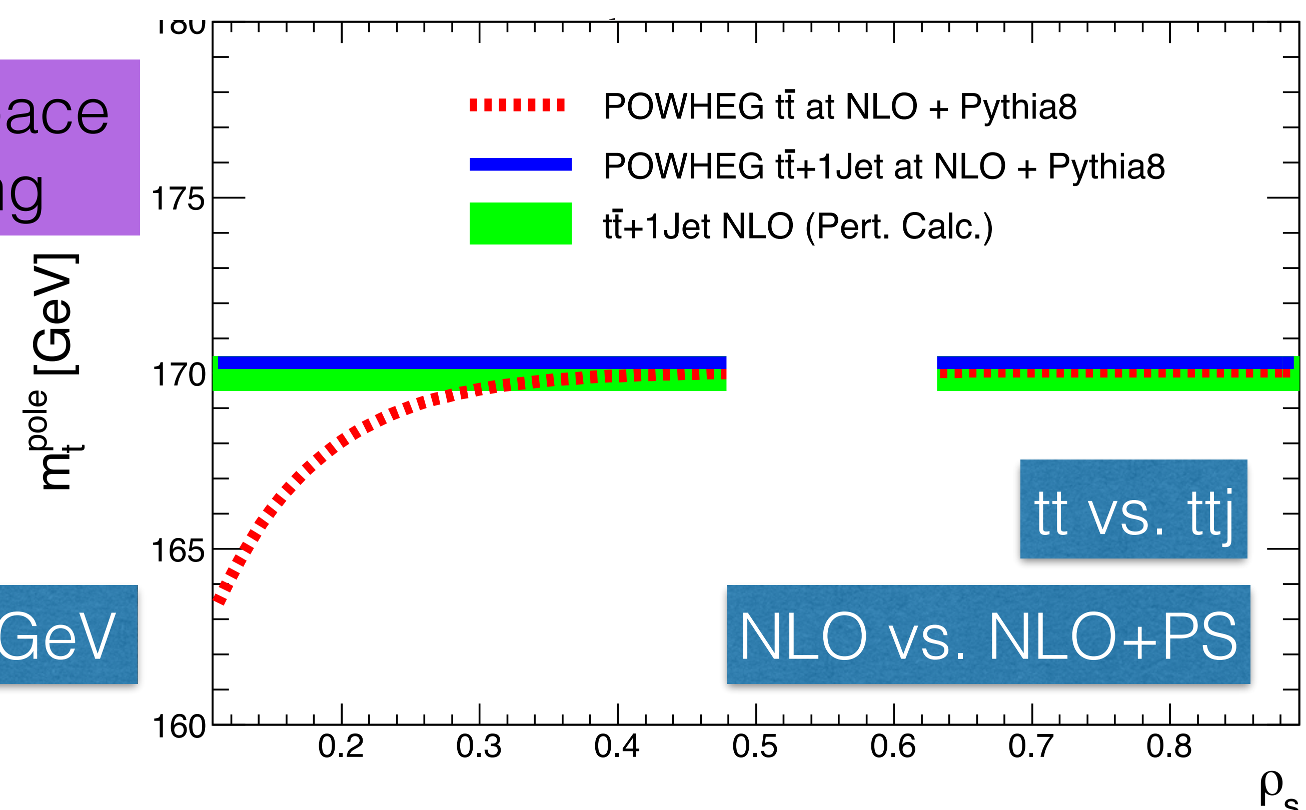



Phase-space Opening

Why we trust it




173.7 ± 1.5 (stat.) ± 1.4 (syst.)+1.0-0.5 (theo.) GeV

pole or MC mass? ⇒ another 500 MeV ?

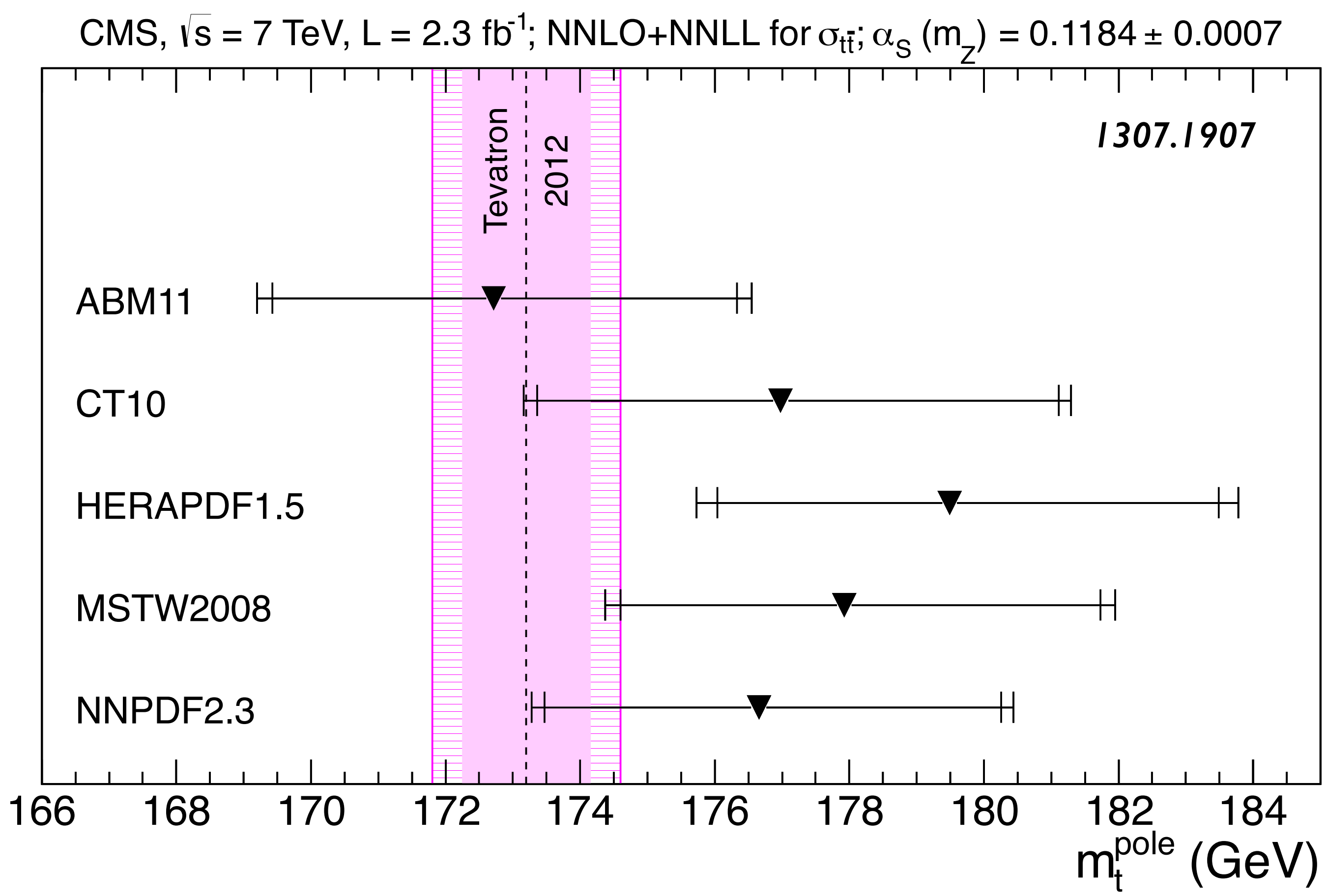
“Lagrangian measurements”

# Top quark mass from SM loops

**strong loops** **(if you know σ and strong coupling)**

- cross-section is a steep function of the mass (and of the energy of the collider)

**Assumes no new physics in top production and in $\alpha_s$**



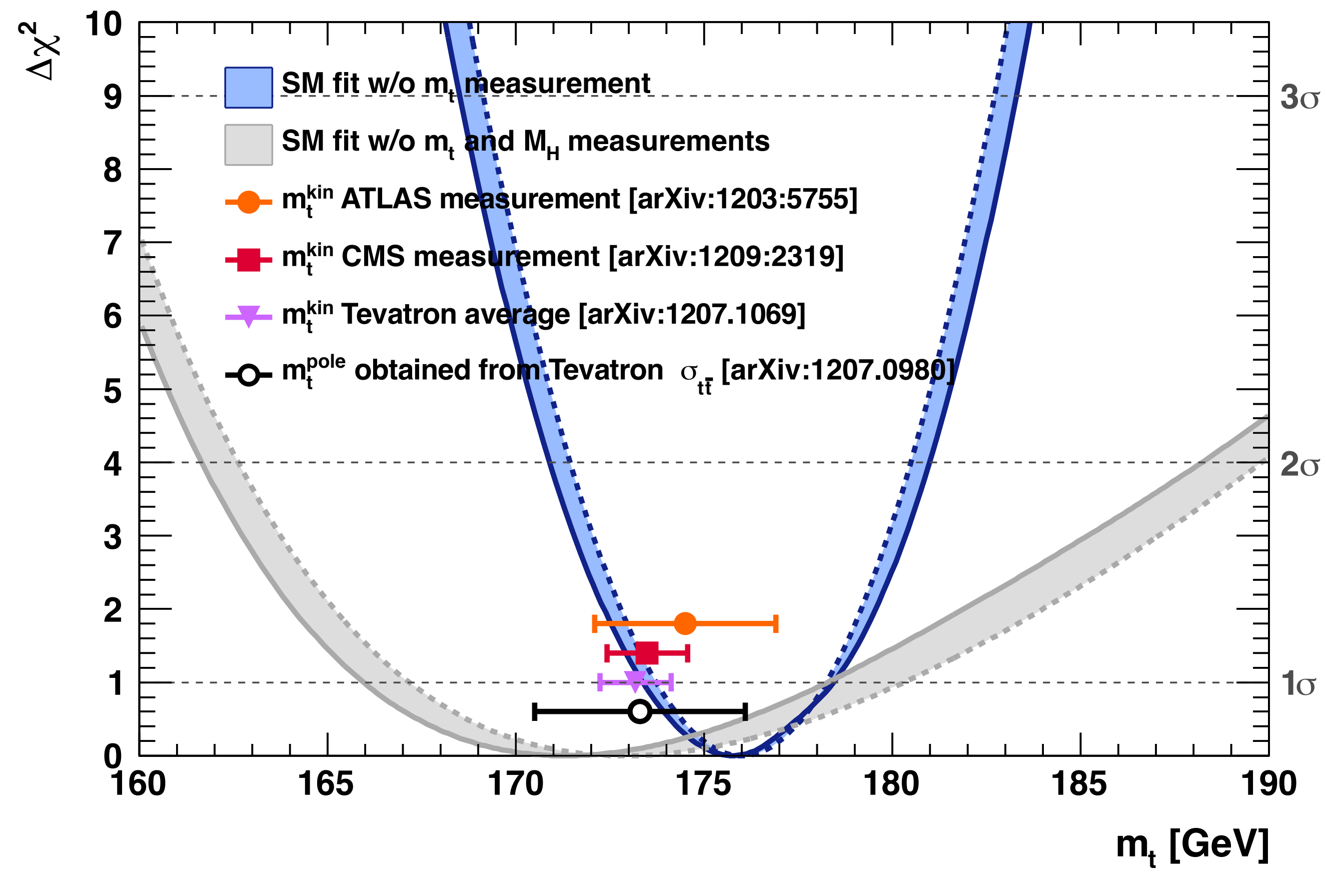

$$m_t = 176.7\,^{+3.8}_{-3.4}\ \text{GeV}$$

# Top quark mass from SM loops

- all masses are correlated at one-loop

**Assumes no new physics in electroweak sector**

**electroweak loops** (indirect)

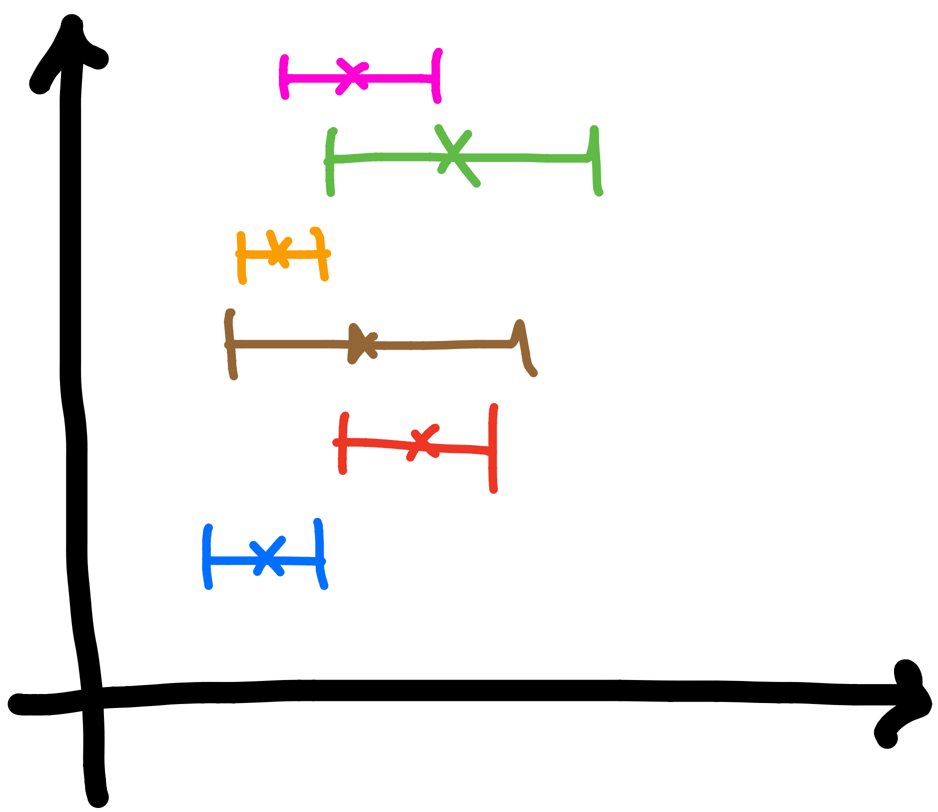



$$m_t = 175.8\,^{+2.7}_{-2.4}\ \mathrm{GeV}$$

# What to do?

**Compare different methods**

Observables: The more the merrier? the more the messier?



- 1 loop=beyond pure kinematics
- careful analysis of the effects that enter in the theory that links the data to “coupling” $m_{top}$

  *(scale magnitude, scale function, fixed order, parton shower effect)*
- possible effects of new physics

**different schemes**

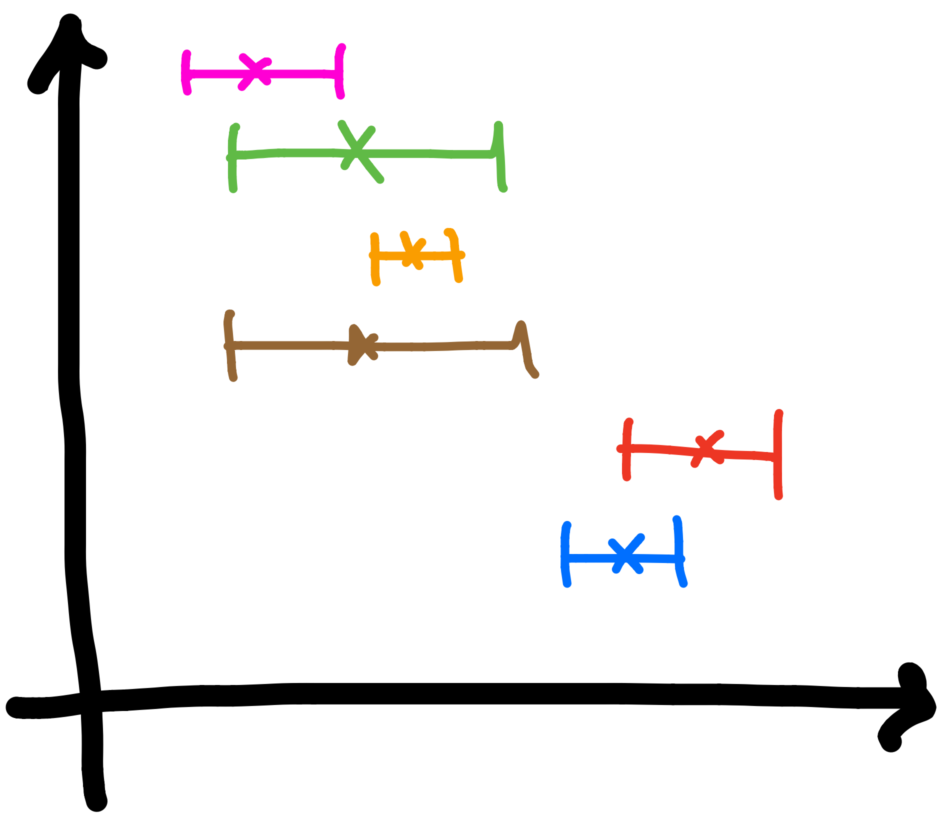
abandon pole for something else: **what?**

Differential distribution in $\overline{\text{MS}}$: is it enough to be happy at LHC?

# What to do?

**Compare different methods**

Observables: The more the merrier? the more the messier?



- <u>1 loop=beyond pure kinematics</u>
- careful analysis of the effects that enter in the <u>theory that links the data to "coupling"</u> $m_{top}$
  *(scale magnitude, scale function, fixed order, parton shower effect)*
- possible effects of <u>new physics</u>

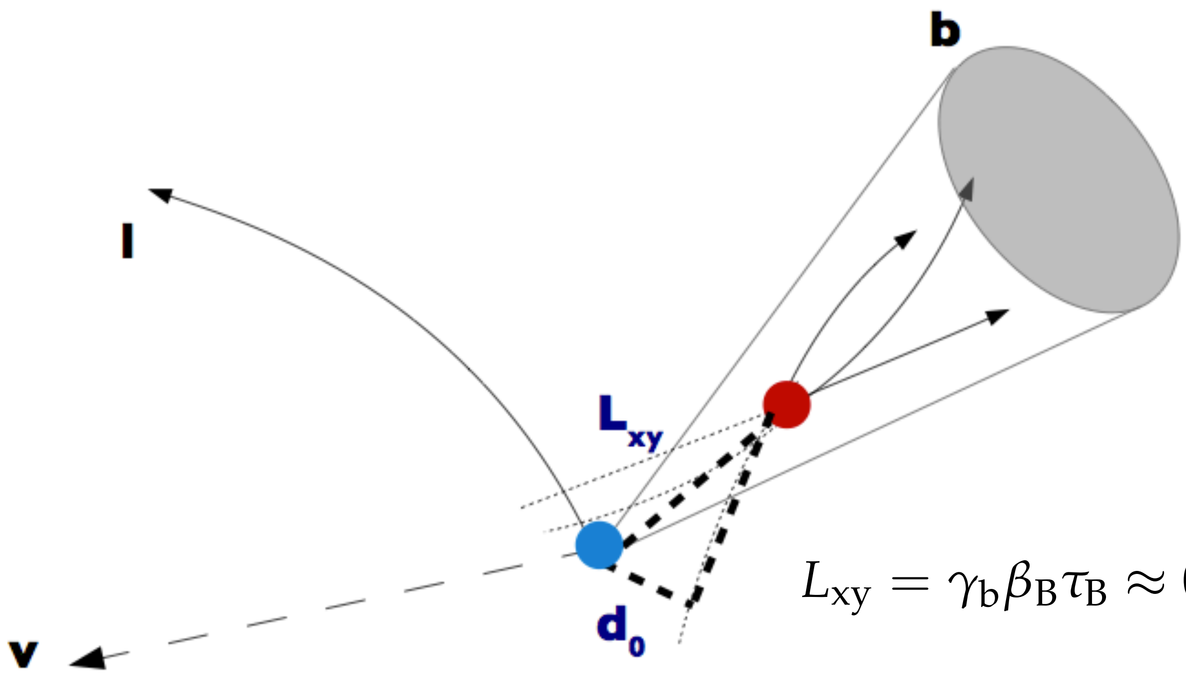
**different schemes**

abandon pole for something else: **what?**

Differential distribution in $\overline{MS}$: is it enough to be happy at LHC?

# Extra

# TOP-12-030




$$L_{xy} = \gamma_b \beta_B \tau_B \approx 0.4 \cdot \frac{m_t}{m_B} \beta_B \tau_B.$$

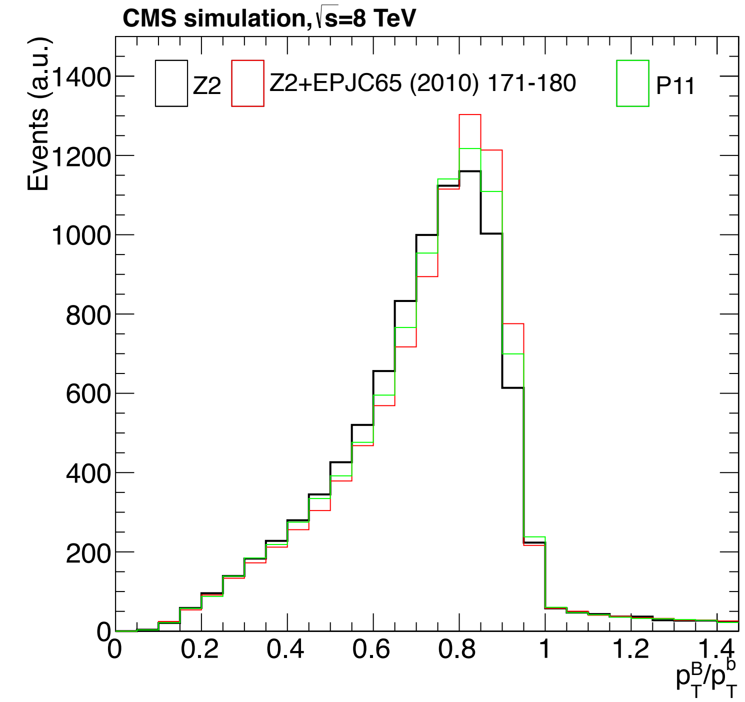



Figure 5: The transverse momentum fraction carried by the B hadron with respect to the b quark $p_T(B)/p_T(b)$ distributions for the nominal Z2* tune, the modified Z2* tune from [32] and the alternative P11 tune.

$$p = \frac{m_t}{2}\sqrt{1 - \left(\frac{M_W^2 - m_b^2}{m_t^2}\right)^2 - 4\left(\frac{M_W m_b}{m_t^2}\right)^2},$$

δL / mtop ~ 50μm / GeV

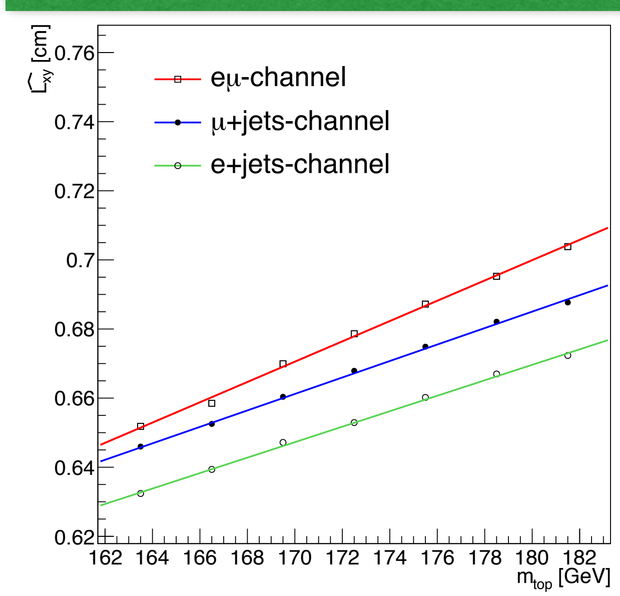
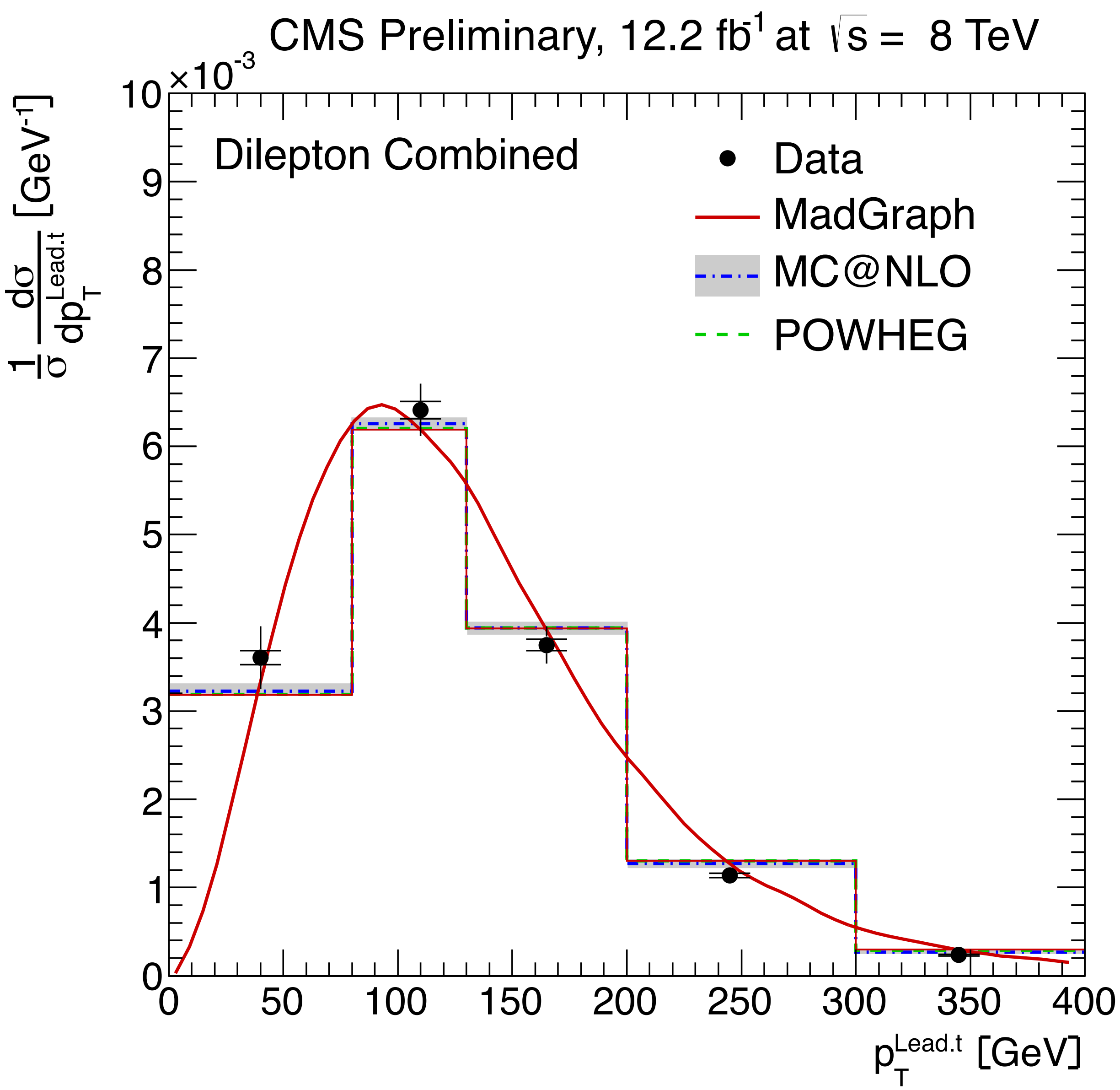


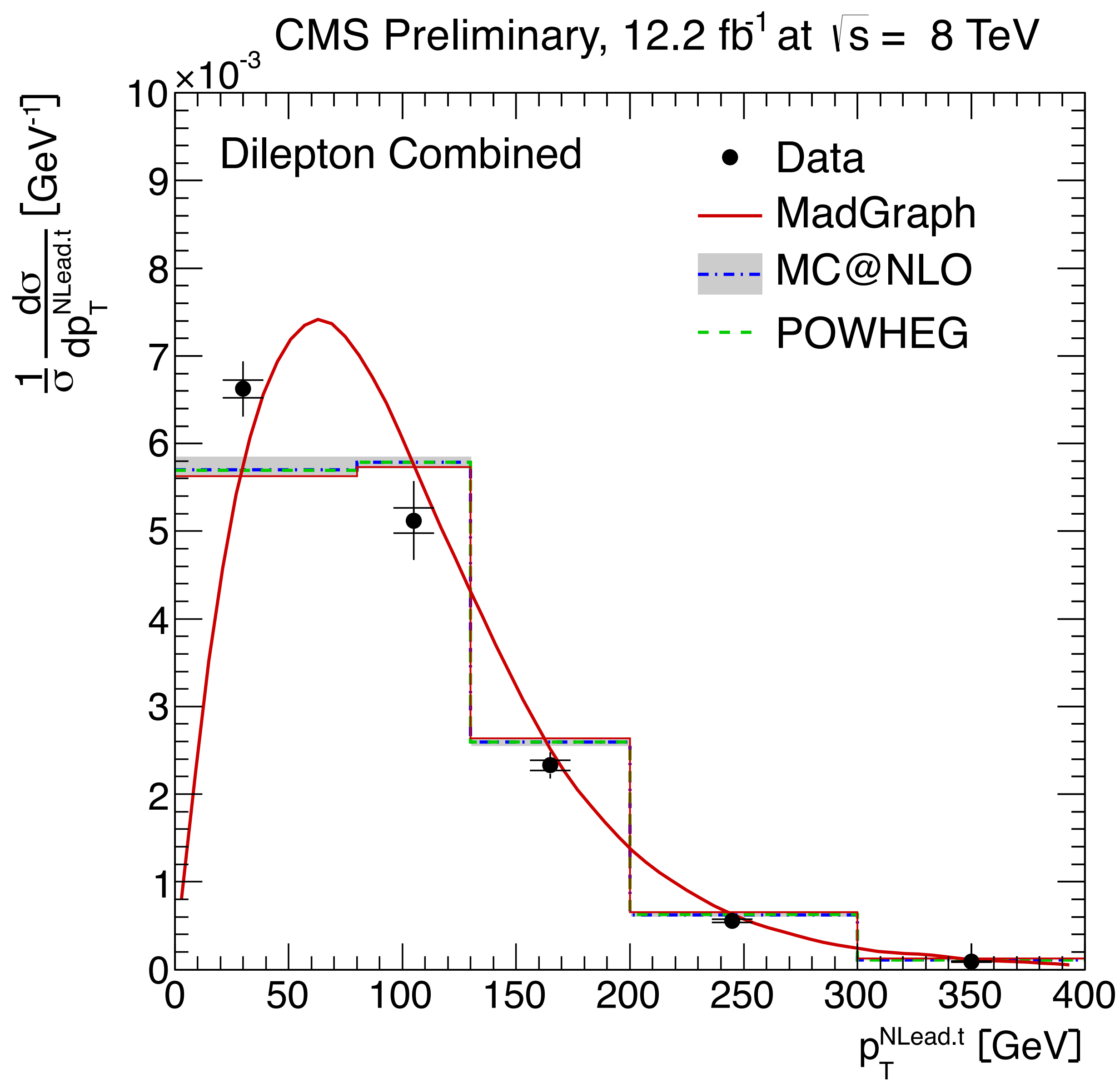

Figure 2: Median of the $L_{xy}$ distribution ($\widehat{L_{xy}}$) as a function of $m_t$ for all three channels as predicted from simulation. The colored lines show the linear parametrization of this dependence for the three different channels. The different slopes of the curves are due to the different kinematical selection applied in the different analysis channels.

Table 2: Statistical, experimental and theoretical systematic uncertainties on the measured top quark mass $m_t$ based on the median of the $L_{xy}$ distribution. The statistical errors on the uncertainties are also given.

| Source | | $\Delta m_t$[ GeV ] | | |
|---|---|---|---|---|
| | | $\mu$+jets | $e$+jets | $e\mu$ |
| Statistical | | 1.0 | 1.0 | 2.0 |
| Experimental | Jet energy scale | $0.30 \pm 0.01$ | $0.30 \pm 0.01$ | $0.30 \pm 0.01$ |
| | Multijet normalization ($\ell$+jets) | $0.50 \pm 0.01$ | $0.67 \pm 0.01$ | - |
| | W+jets normalization ($\ell$+jets) | $1.42 \pm 0.01$ | $1.33 \pm 0.01$ | - |
| | DY normalization ($\ell\ell$) | - | - | $0.38 \pm 0.06$ |
| | Other backgrounds normalization | $0.05 \pm 0.01$ | $0.05 \pm 0.01$ | $0.15 \pm 0.07$ |
| | W+jets background shapes ($\ell$+jets) | $0.40 \pm 0.01$ | $0.20 \pm 0.01$ | - |
| | Single top background shapes | $0.20 \pm 0.01$ | $0.20 \pm 0.01$ | $0.30 \pm 0.06$ |
| | DY background shapes ($\ell\ell$) | - | - | $0.04 \pm 0.06$ |
| | Calibration | $0.42 \pm 0.01$ | $0.50 \pm 0.01$ | $0.21 \pm 0.01$ |
| Theory | $Q^2$-scale | $0.47 \pm 0.13$ | $0.20 \pm 0.03$ | $0.11 \pm 0.08$ |
| | ME-PS matching scale | $0.73 \pm 0.01$ | $0.87 \pm 0.03$ | $0.44 \pm 0.08$ |
| | PDF | $0.26 \pm 0.15$ | $0.26 \pm 0.15$ | $0.26 \pm 0.15$ |
| | Hadronization model | $0.95 \pm 0.13$ | $0.95 \pm 0.13$ | $0.67 \pm 0.10$ |
| | B hadron composition | $0.39 \pm 0.01$ | $0.39 \pm 0.01$ | $0.39 \pm 0.01$ |
| | B hadron lifetime | $0.29 \pm 0.18$ | $0.29 \pm 0.18$ | $0.29 \pm 0.18$ |
| | Top quark $p_T$ modeling | $3.27 \pm 0.48$ | $3.07 \pm 0.45$ | $2.36 \pm 0.35$ |
| | Underlying event | $0.27 \pm 0.51$ | $0.25 \pm 0.48$ | $0.19 \pm 0.37$ |
| | Colour reconnection | $0.36 \pm 0.51$ | $0.34 \pm 0.48$ | $0.26 \pm 0.37$ |

# TOP-12-030


CMS Preliminary, 12.2 fb$^{-1}$ at $\sqrt{s}$ = 8 TeV
Dilepton Combined
Data
MadGraph
MC@NLO
POWHEG
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{Lead.t}}$ [GeV$^{-1}$]
$\times10^{-3}$
$p_T^{Lead.t}$ [GeV]


CMS Preliminary, 12.2 fb$^{-1}$ at $\sqrt{s}$ = 8 TeV
Dilepton Combined
Data
MadGraph
MC@NLO
POWHEG
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{NLead.t}}$ [GeV$^{-1}$]
$\times10^{-3}$
$p_T^{NLead.t}$ [GeV]

# 1212.2220

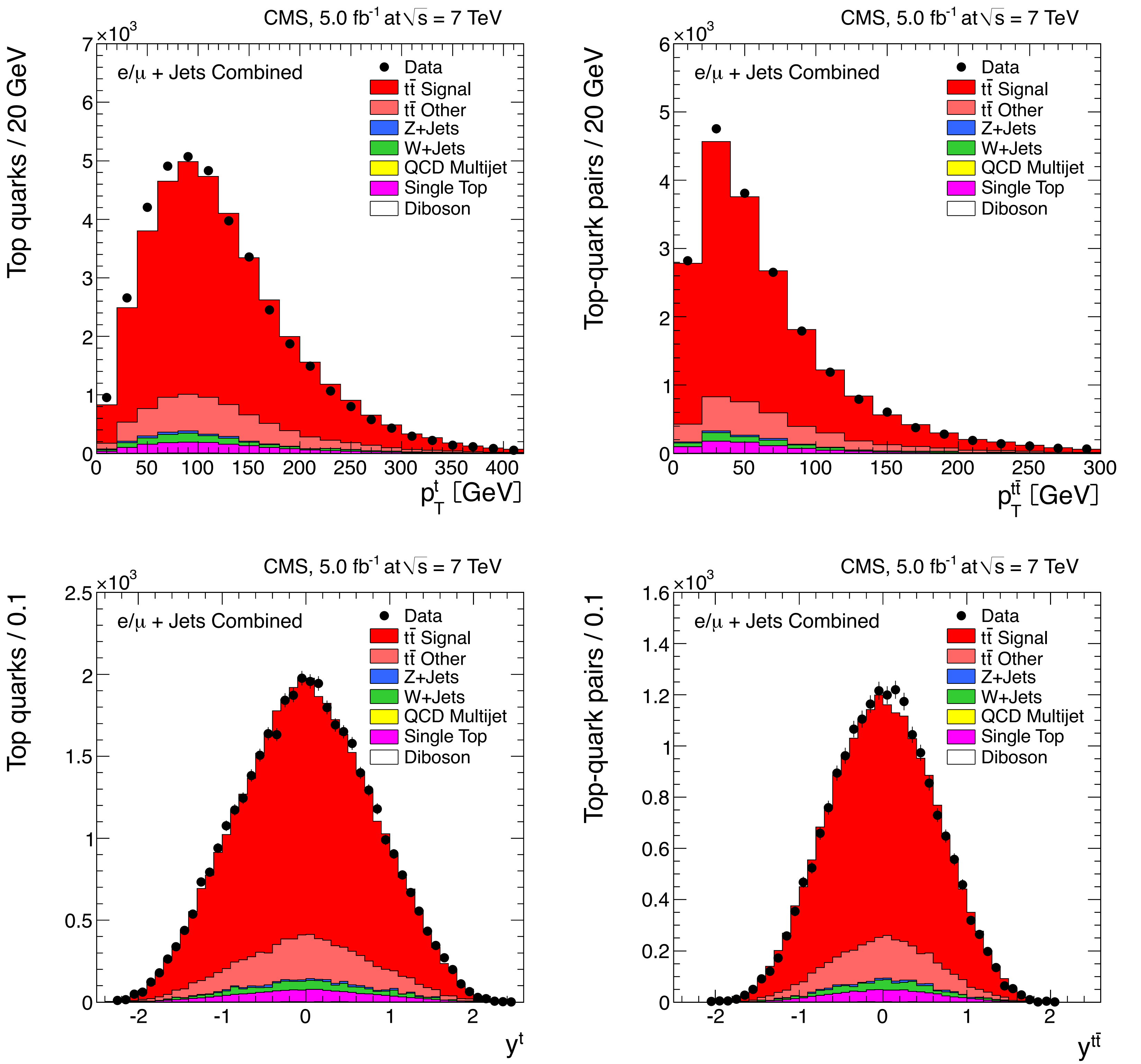



Figure 3: Distribution of top-quark and $t\bar{t}$ quantities as obtained from the kinematic reconstruction in the $\ell$+jets channels. The left plots show the distributions for the top quarks or antiquarks; the right plots show the $t\bar{t}$ system. The top row shows the transverse momenta, and the bottom row shows the rapidities.

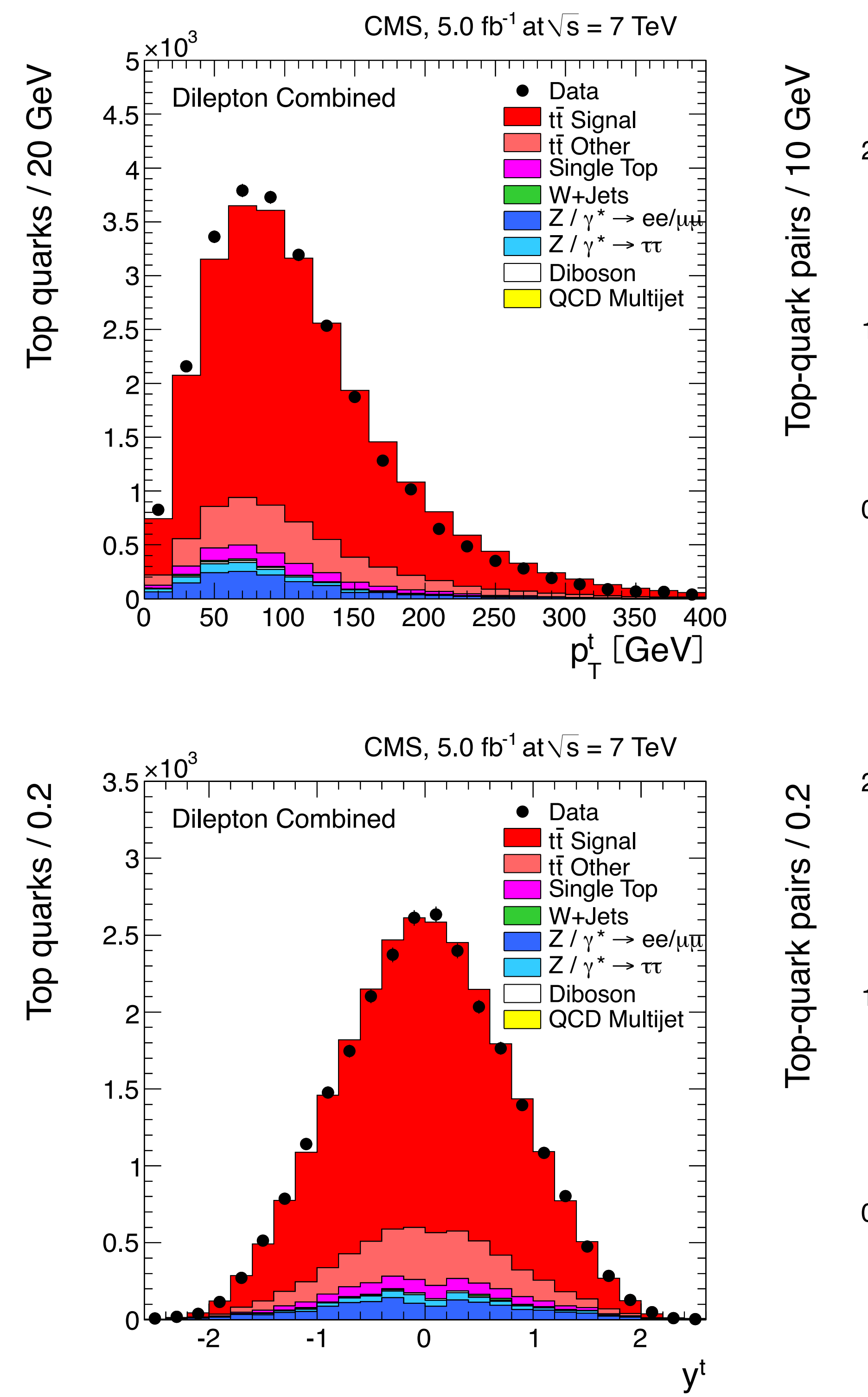
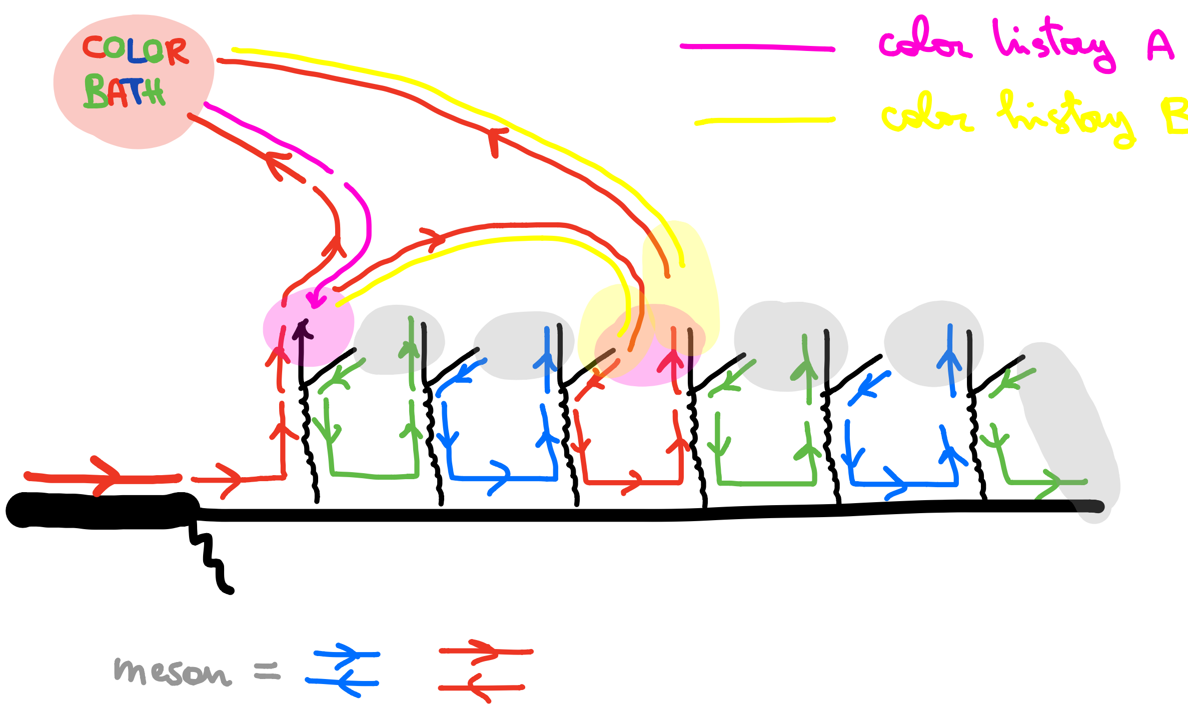
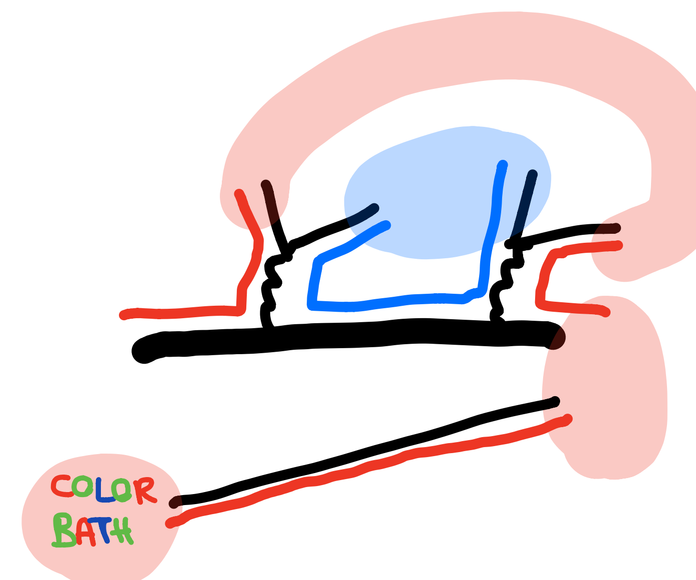
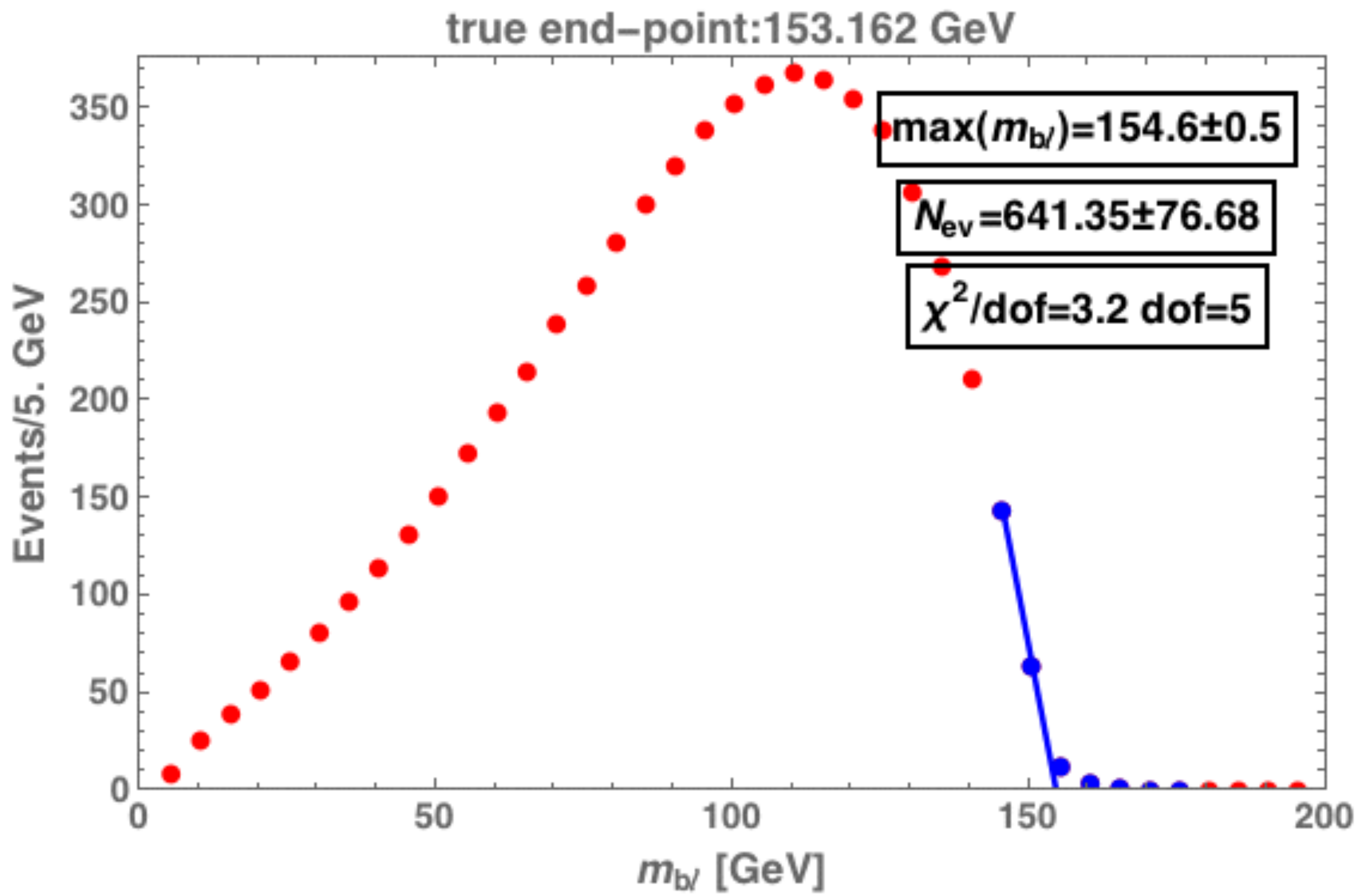


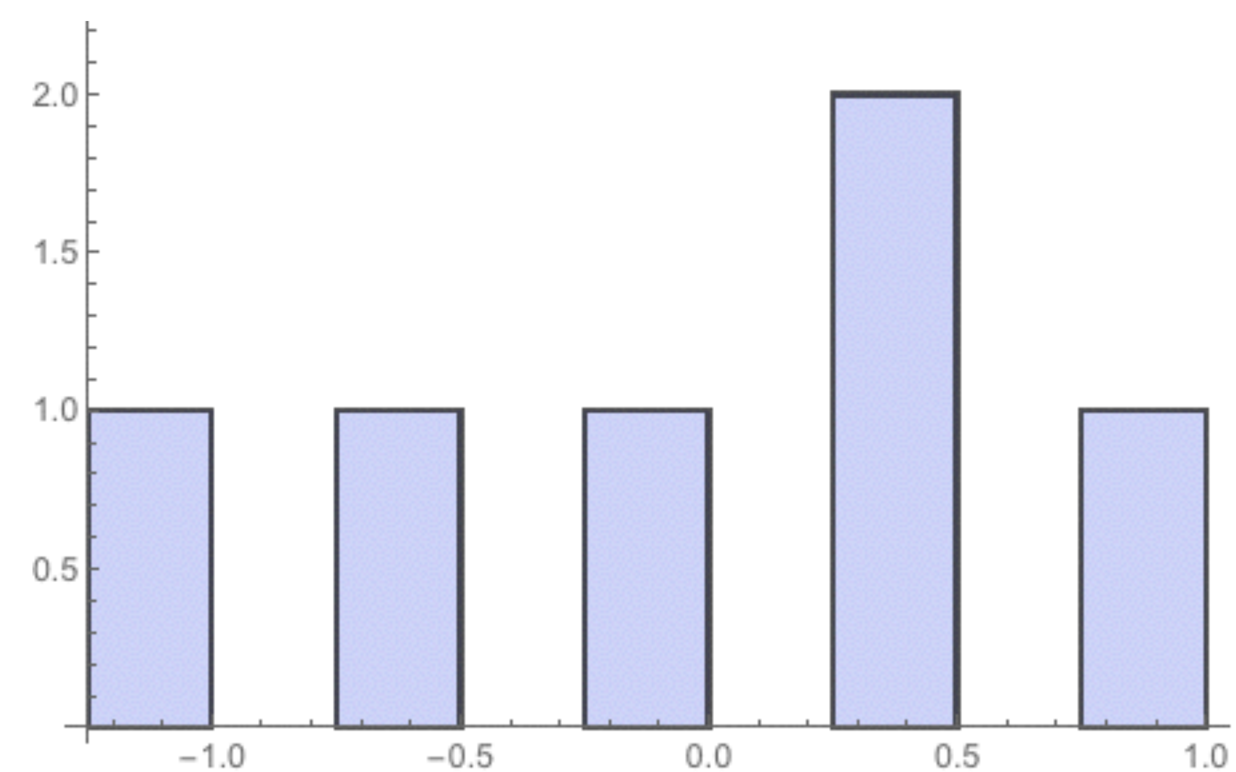

Figure 4: Distribution of top-quark and $t\bar{t}$ quantities
struction in the dilepton channels. The left plots show
antiquarks; the right plots show the $t\bar{t}$ system. The t
and the bottom row shows the rapidities. The $Z/\gamma^*$+je
(cf. Section 4.2).

# Color connection(s)




true end-point:153.162 GeV
max($m_{bl}$)=154.6±0.5
$N_{ev}$=641.35±76.68
$\chi^2$/dof=3.2 dof=5
Events/5. GeV
$m_{bl}$ [GeV]
0
50
100
150
200
250
300
350


2.0
1.5
1.0
0.5
−1.0
−0.5
0.0
0.5
1.0

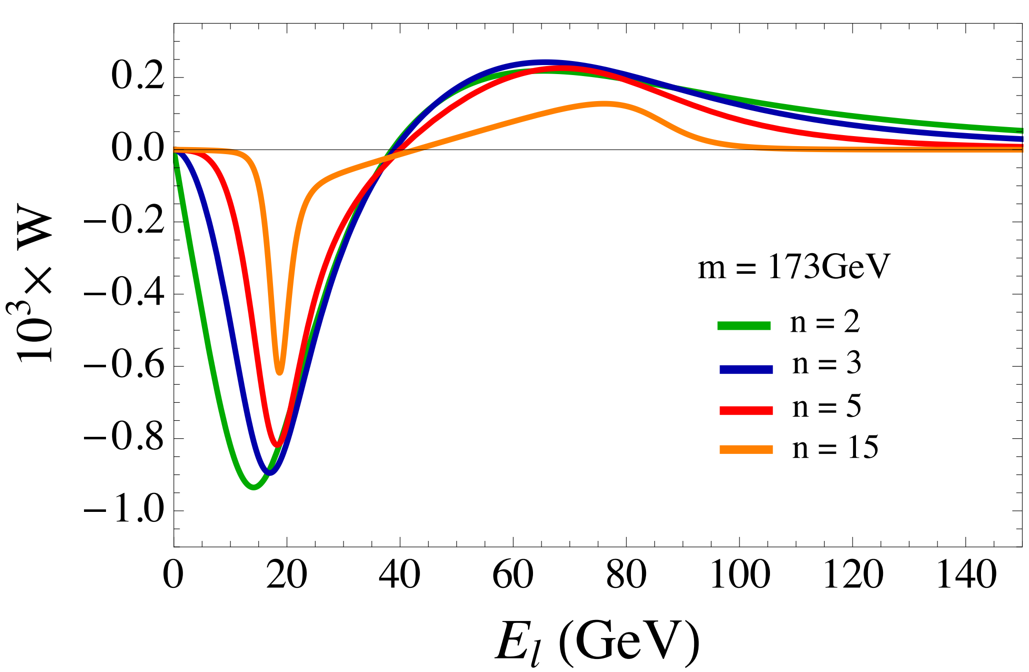
# Generalized medians

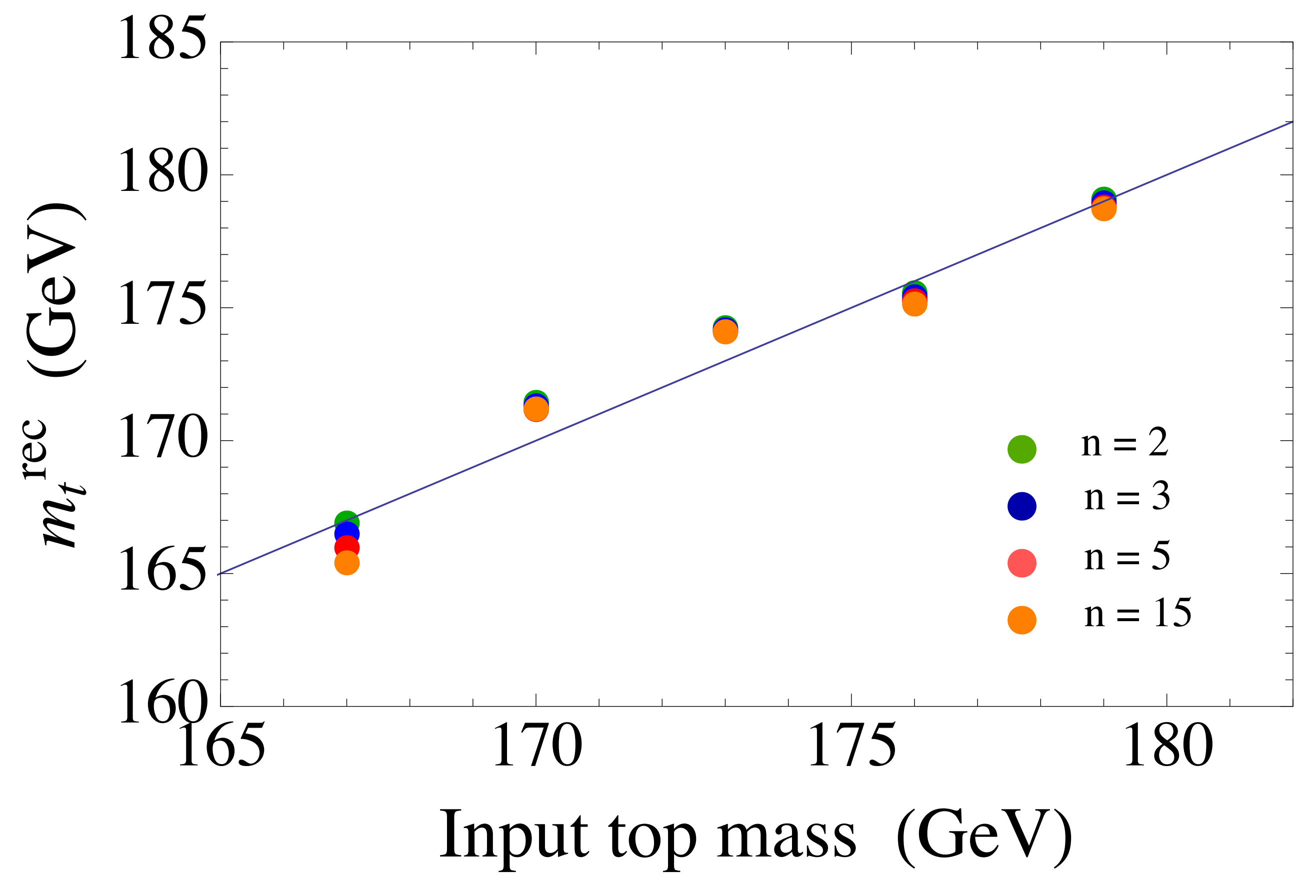
1405.2395

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

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 $\sim 0.2$

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

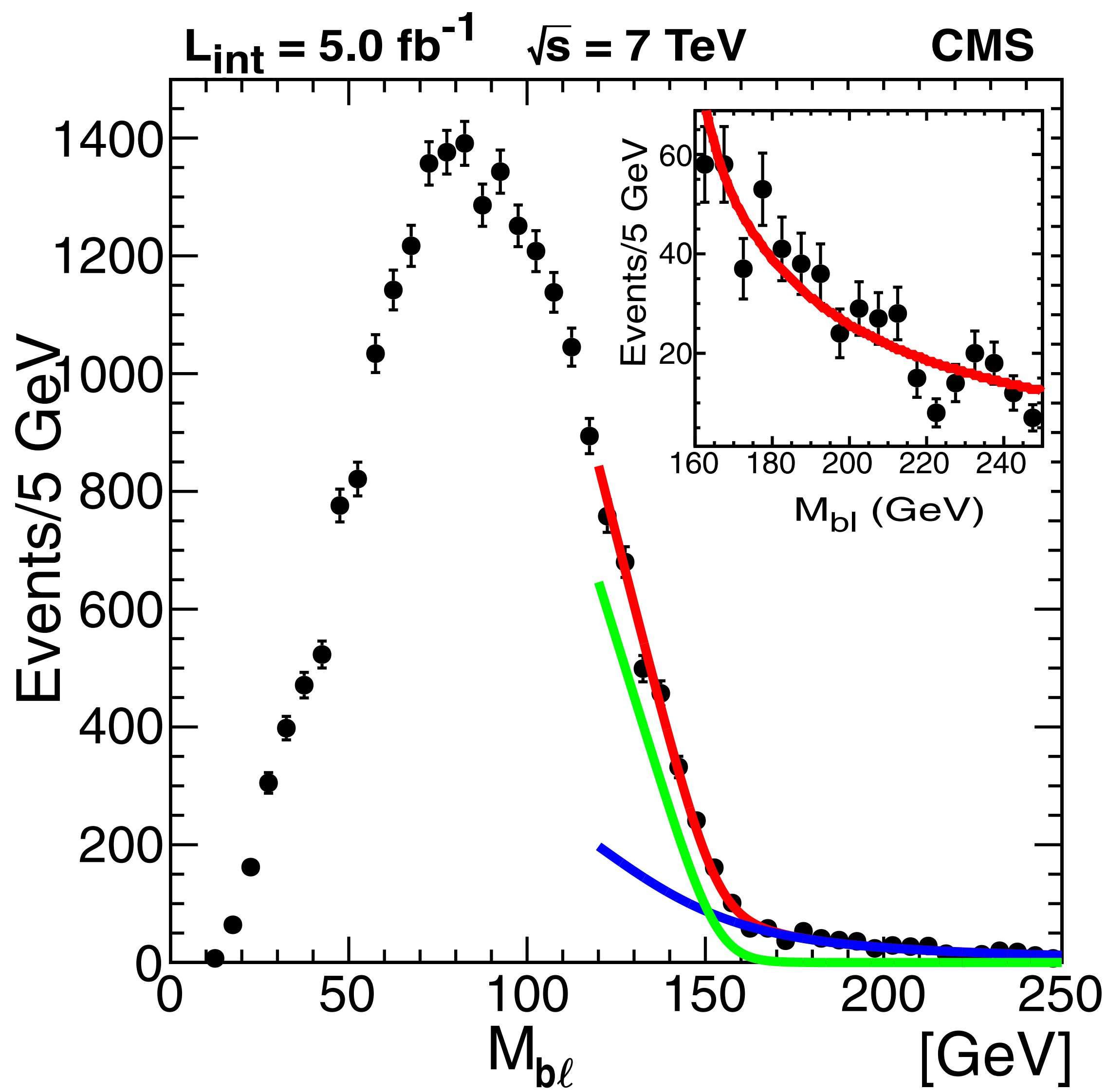
impact of shower: use of factorized NNLO

# 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

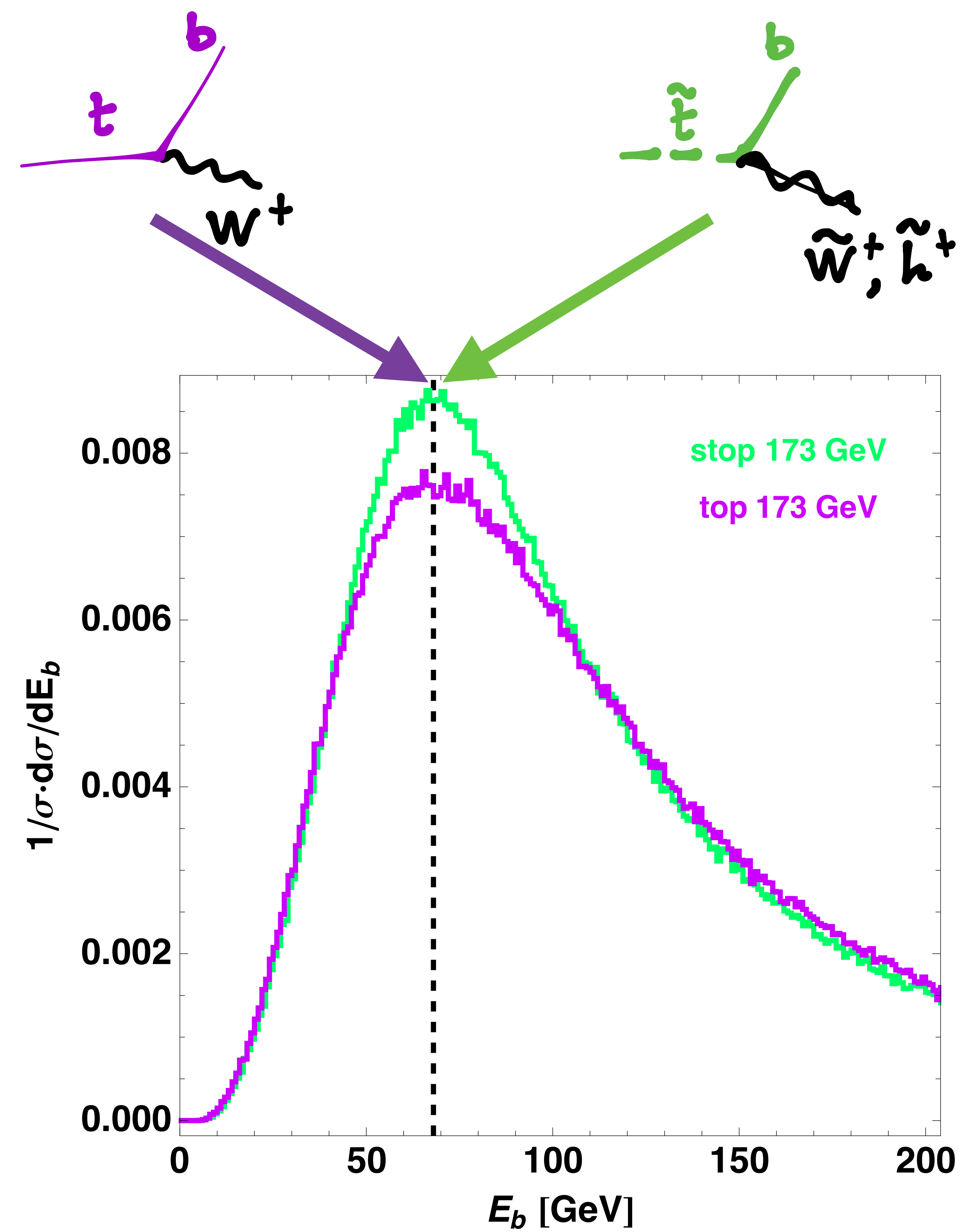
- robust to NLO
- robust to combinatorics
- robust to hadronization




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

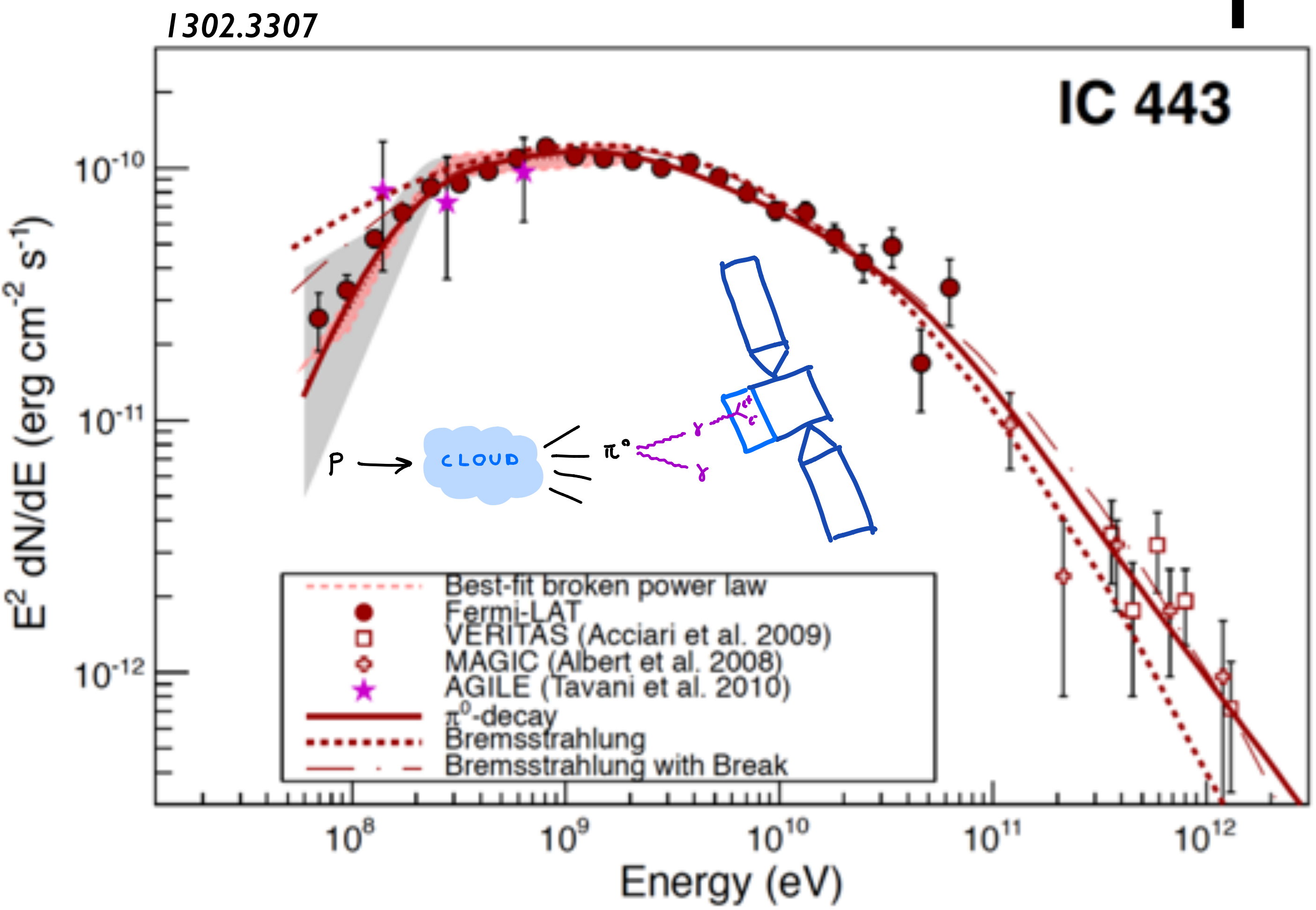
more Energy Peaks

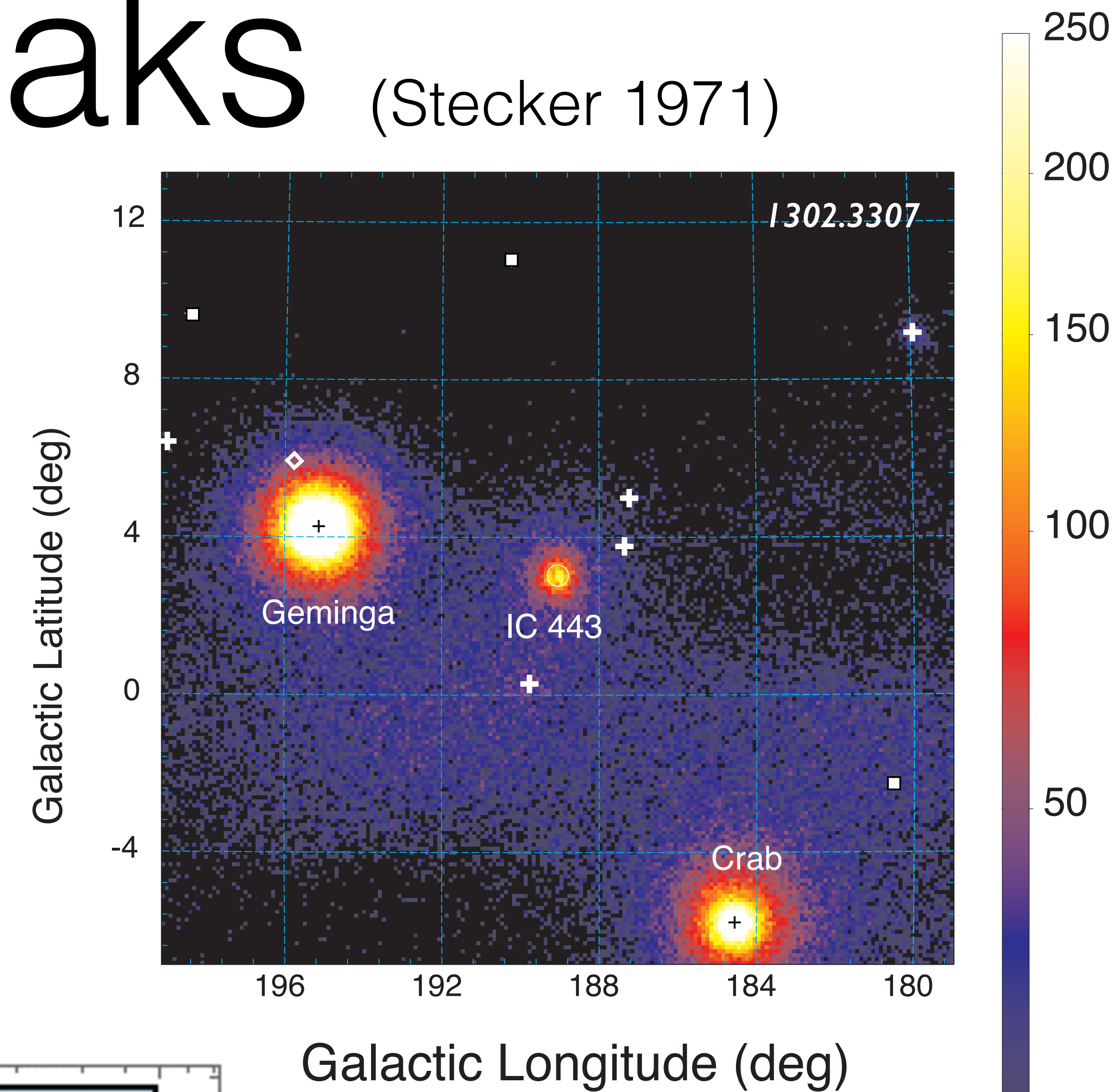
# Independent of decay dynamics

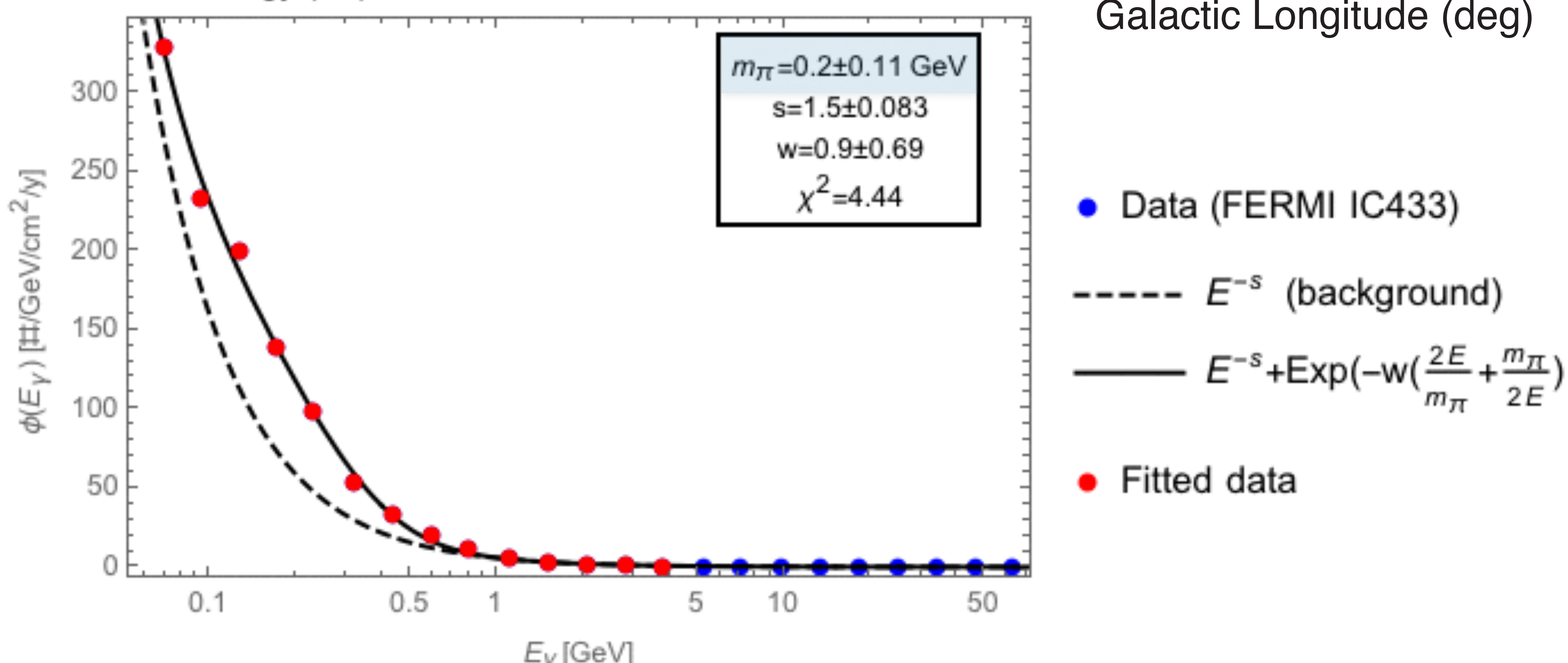



captures the peak for both stop and top: pure kinematics

# Cosmic peaks (Stecker 1971)



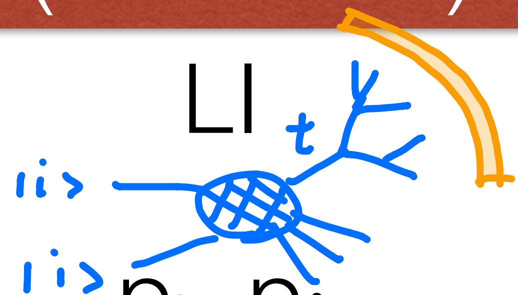



# variations around Lorentz Invariance

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

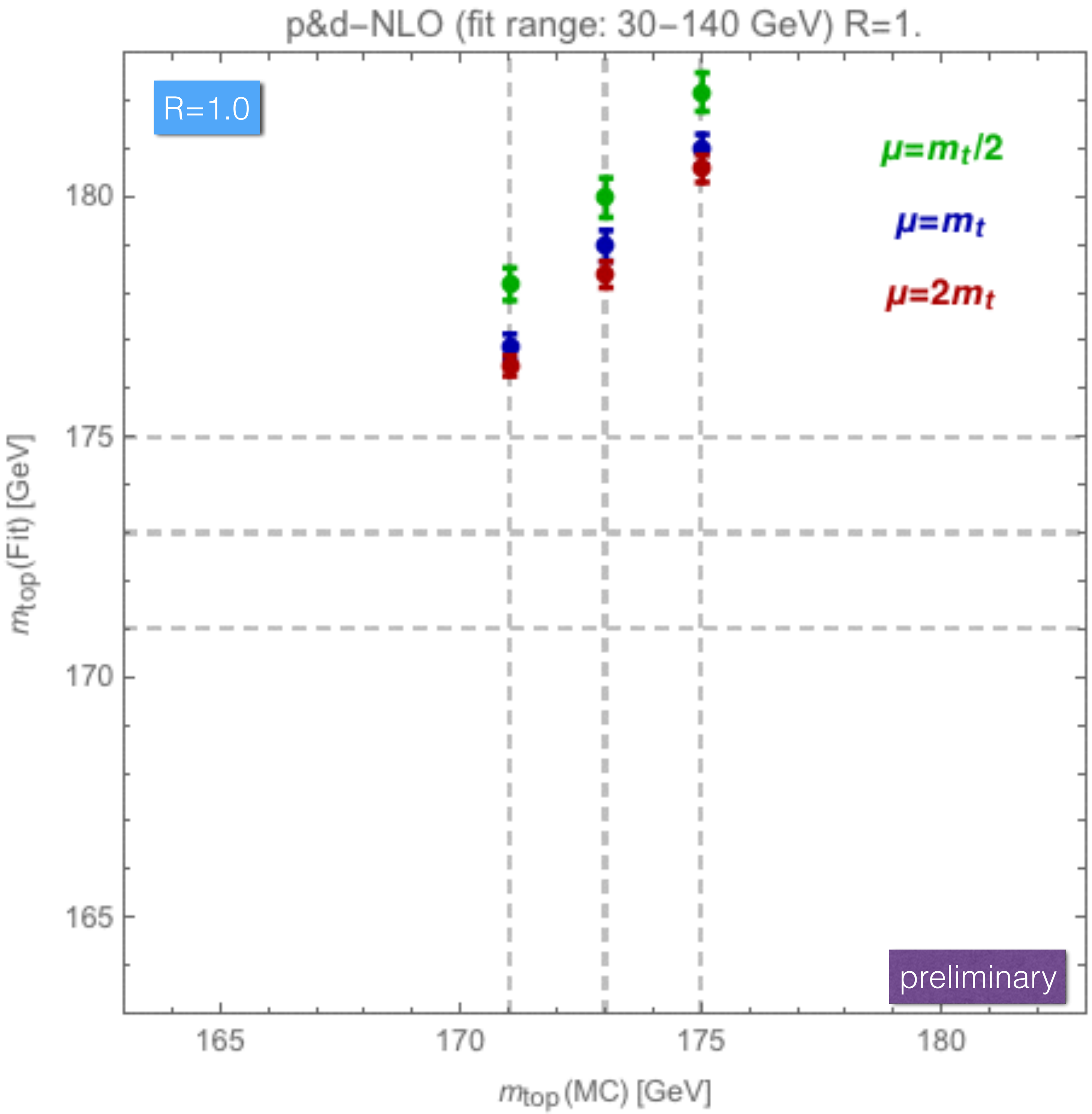
in practice we need the tail, which is sensitive to radiation

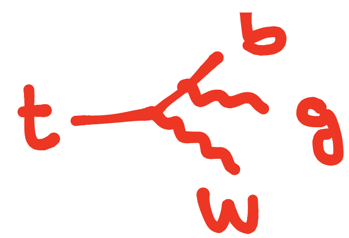
what is the "small parameter" $\Delta_{TH}$ that "breaks" (true or effective) LI?

# NLO: production & decay

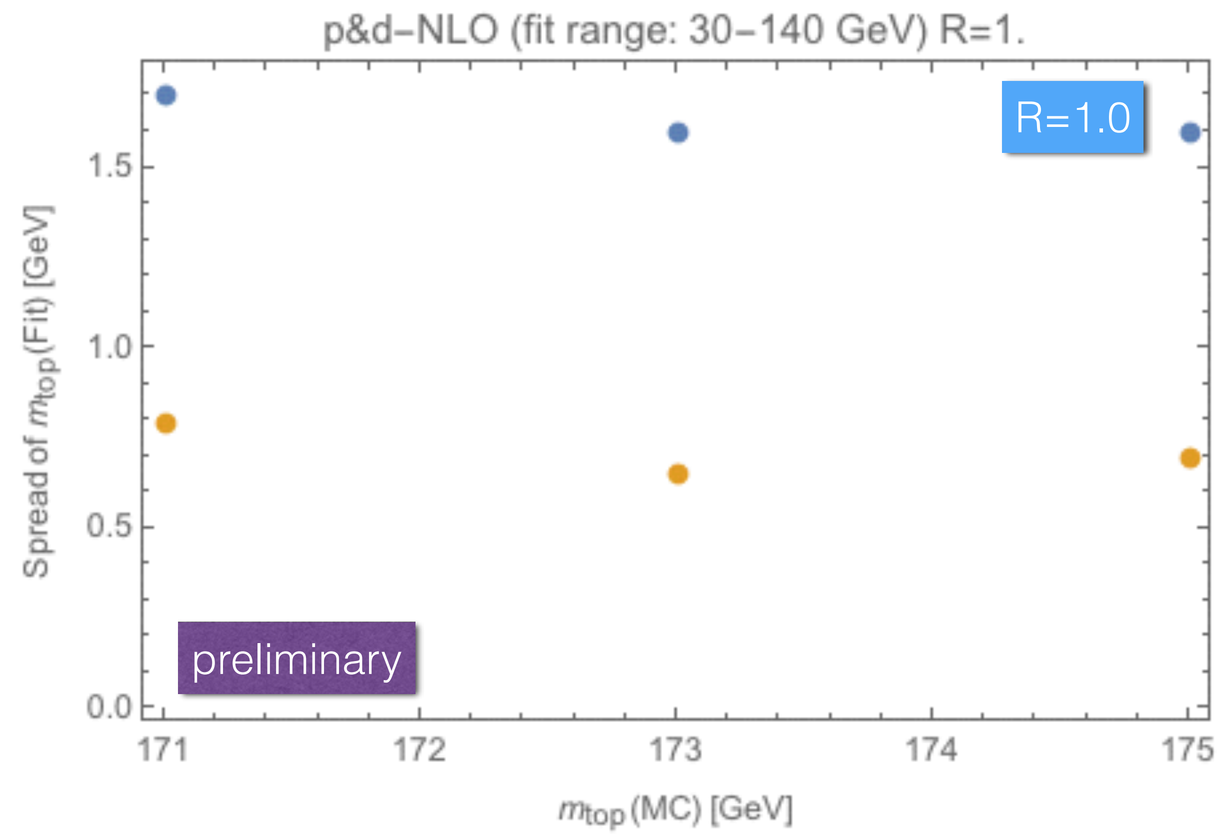
R=1.0

(MCFM)




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

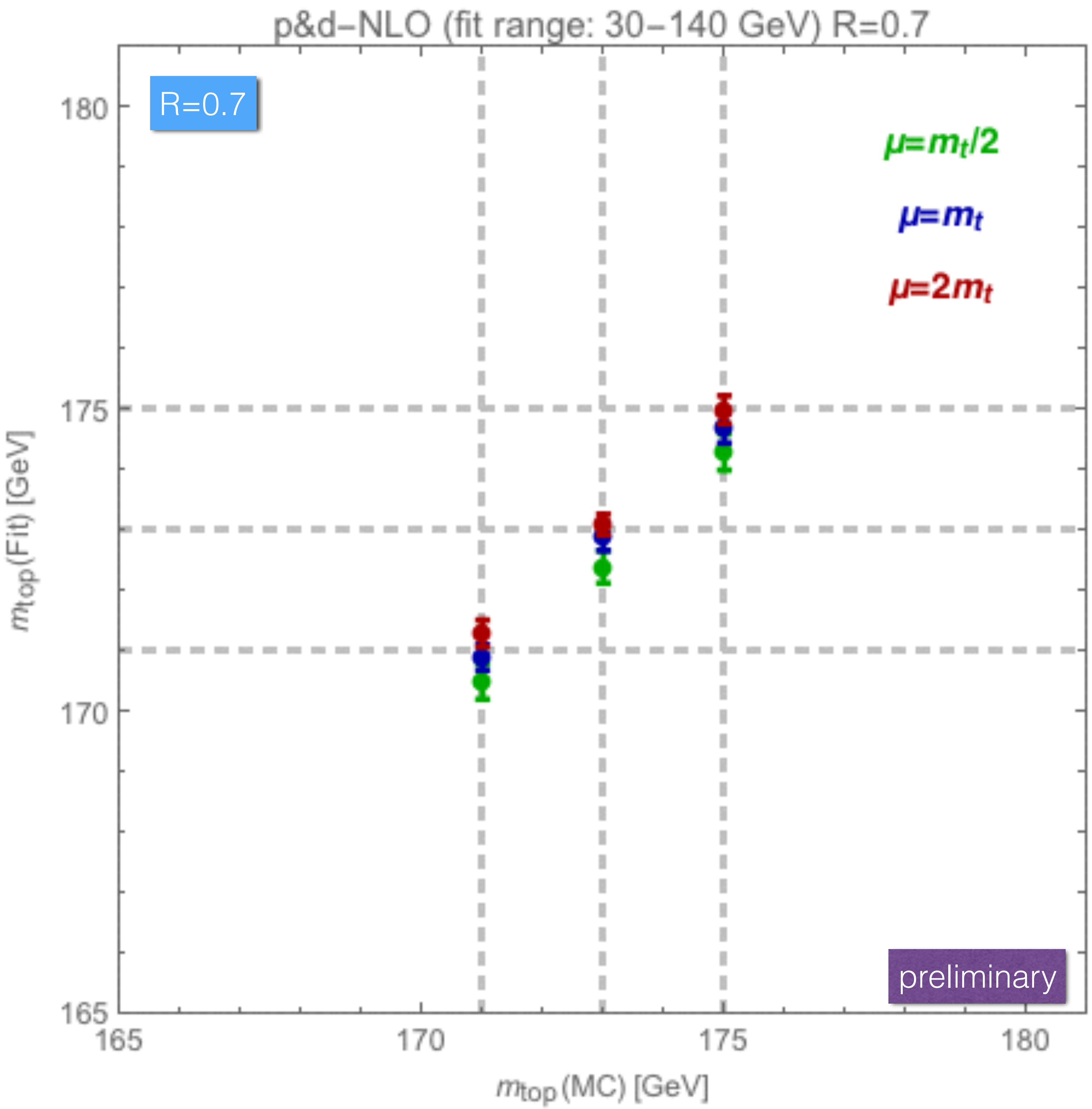


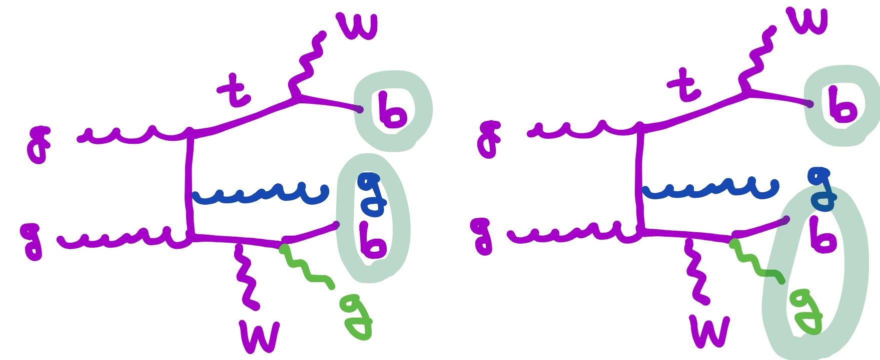

**decay NLO sensitive to the scale choice: ±1 GeV on $m_{top}$**

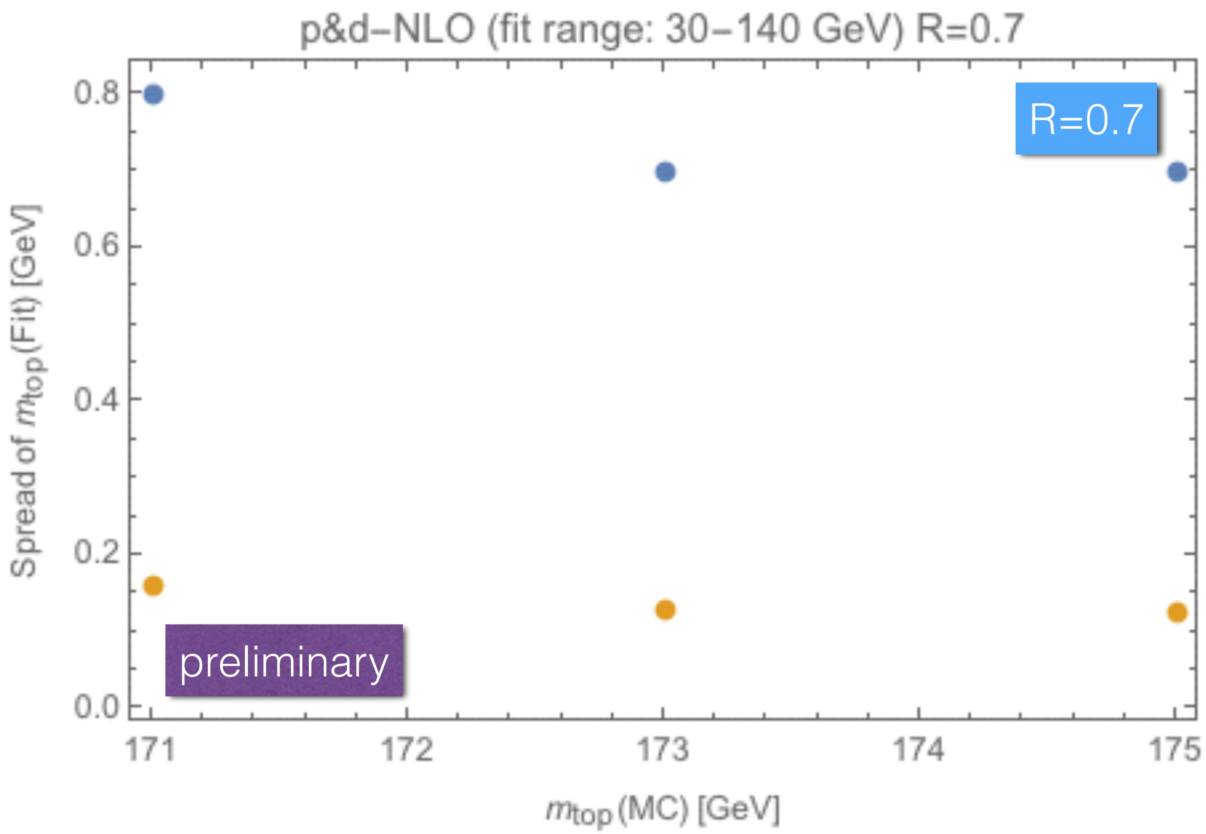
# NLO: production & decay

R=0.7

(MCFM)




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

# B **hadron** observables

B physics in the top sample

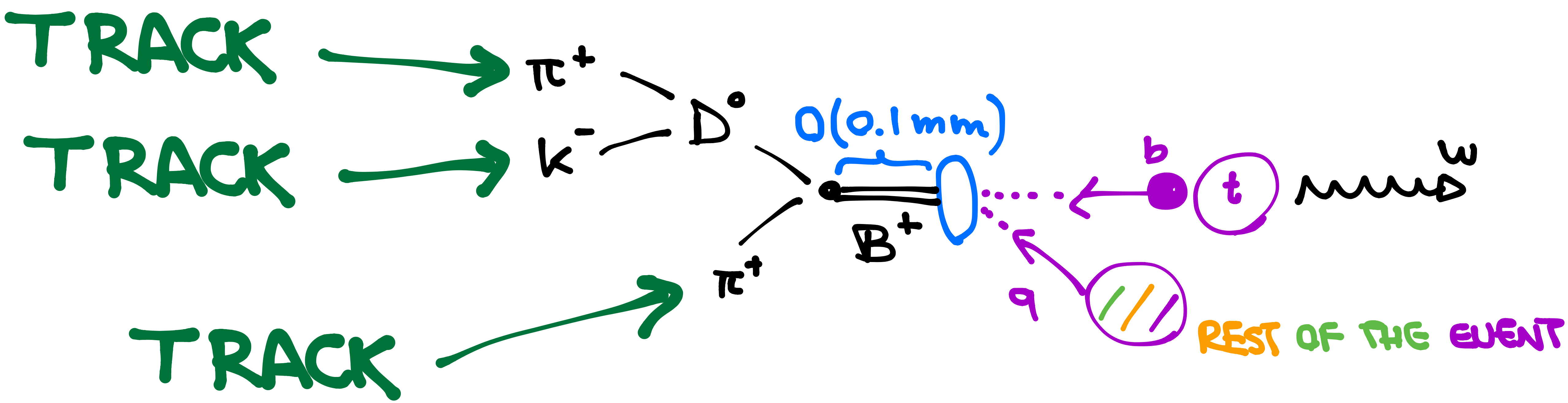
Fragmentation: the b quark energy peak is translated into a (broader) B hadron energy peak

- 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

$$b \xrightarrow[few \cdot 10^{-3}]{} J/\psi + X \xrightarrow[10^{-1}]{} \ell\bar{\ell} + X$$

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

$$B^0 \xrightarrow[3\cdot 10^{-3}]{} D^- \pi^+ \xrightarrow[10^{-2}]{} K_S^0 \pi^- \pi^+$$

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

$$B^0 \xrightarrow[3\cdot 10^{-3}]{} D^- \pi^+ \xrightarrow[3\cdot 10^{-2}]{} K_S^0 \pi^+ \pi^- \pi^+$$

$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0 \pi^- \xrightarrow[4\cdot 10^{-2}]{} K^- \pi^+ \pi^-$$

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

$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0 \pi^- \xrightarrow[6\cdot 10^{-3}]{} K_S^0 \rho^0 \pi^-$$

$$B^- \xrightarrow[5\cdot 10^{-3}]{} D^0 \pi^- \xrightarrow[5\cdot 10^{-3}]{} K^- \pi^+ \rho^0 \pi^-$$

# B hadron $\gamma$ boost factor

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

hadron energy peak → hadron boost peak

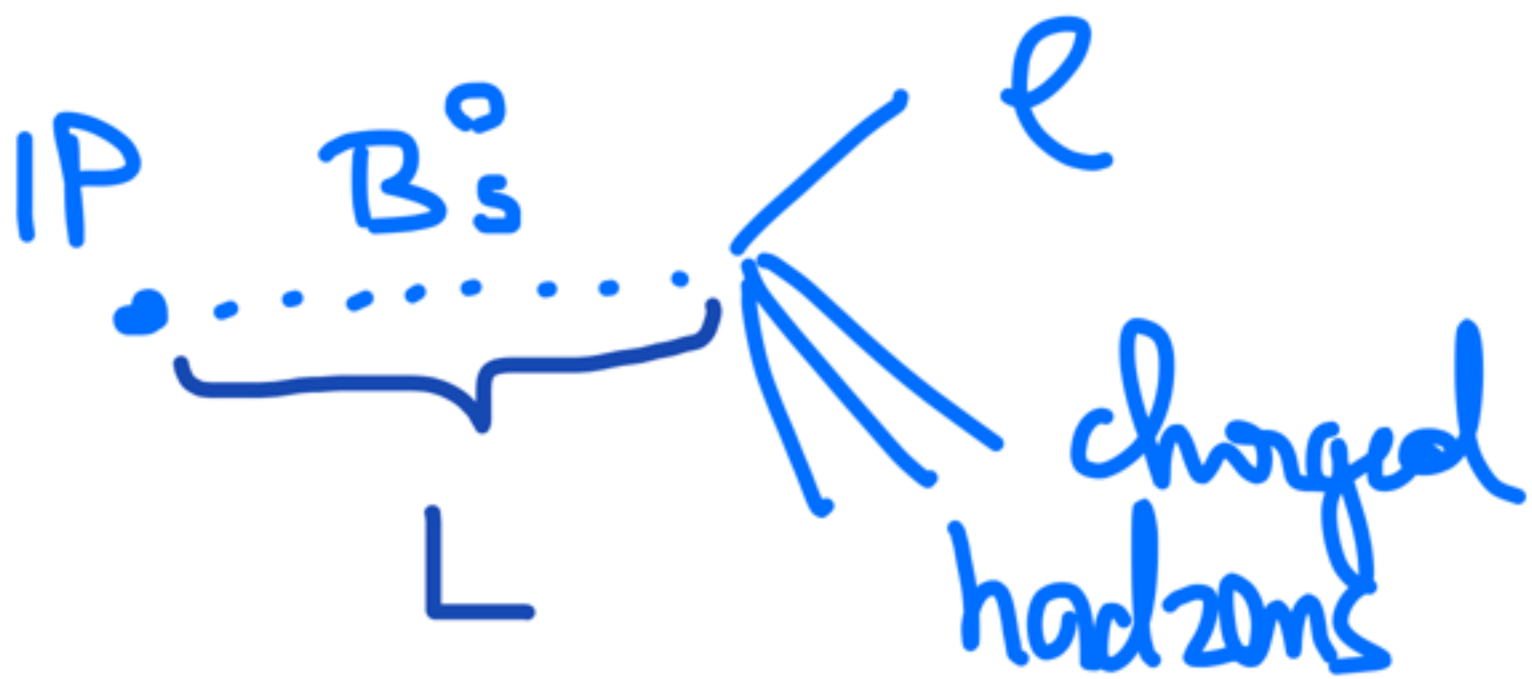
Does the **ratio** $\gamma = E/m$ help to get rid of exp. uncertainties?

# 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 $\lambda$ 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?

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

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

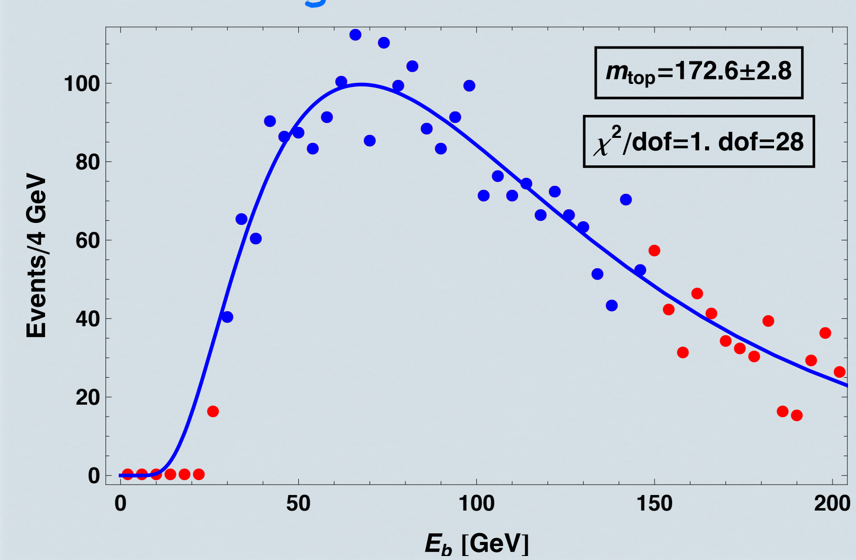
$$\frac{d\sigma}{dE_b} \propto \frac{d\sigma}{d\gamma_b} \propto \frac{d\sigma}{d\lambda}$$

*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?

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

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