Precision top quark physics and beyond the Standard Model

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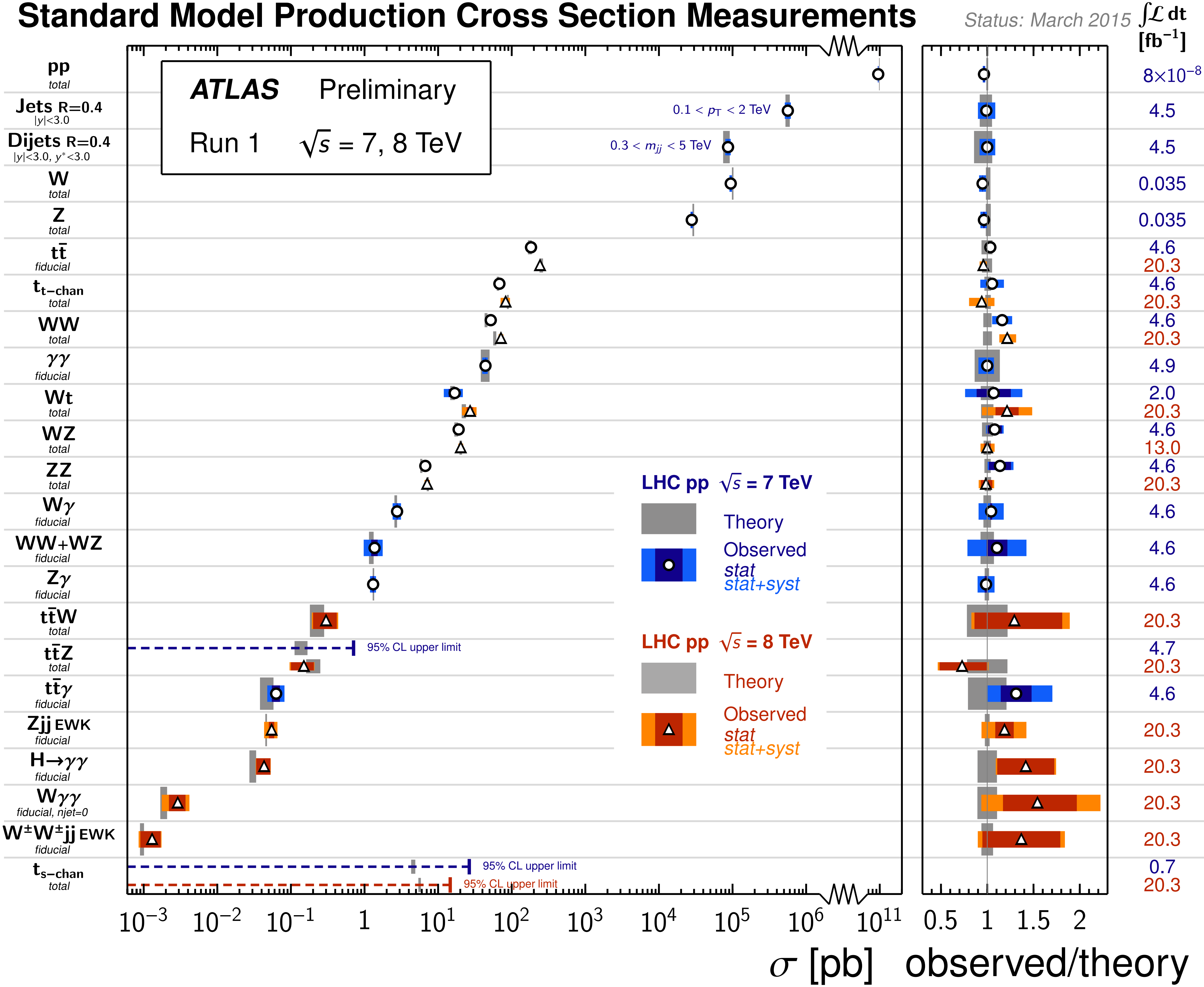
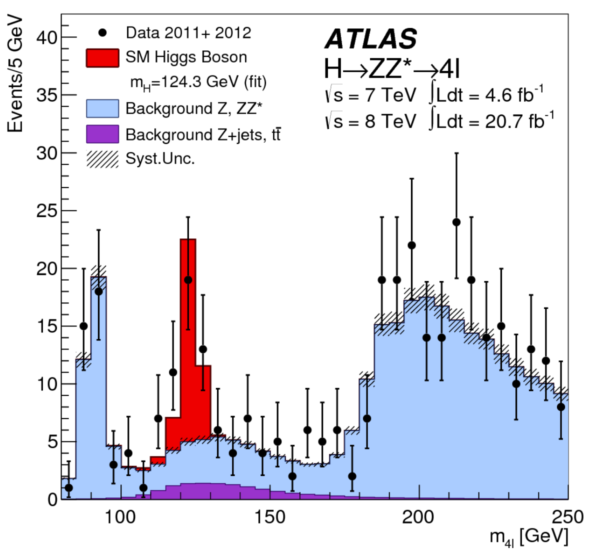
Rencontre de Physique des Particules
LAPTh Annecy, January 26th 2016

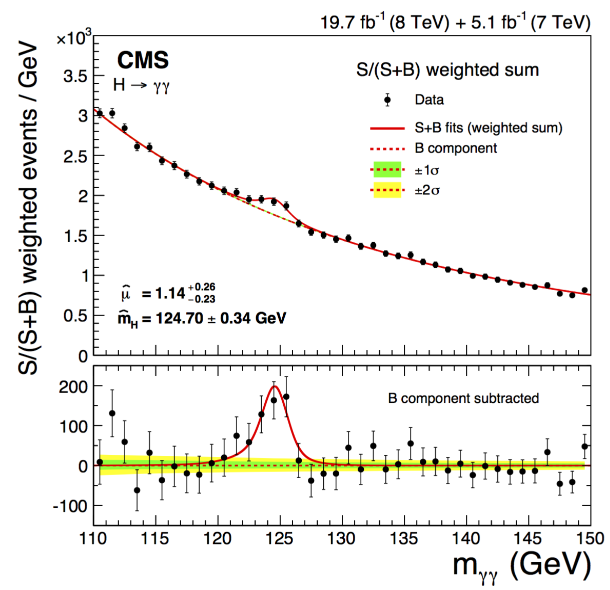
two most important slides from LHC so far

Standard Model Production Cross Section Measurements

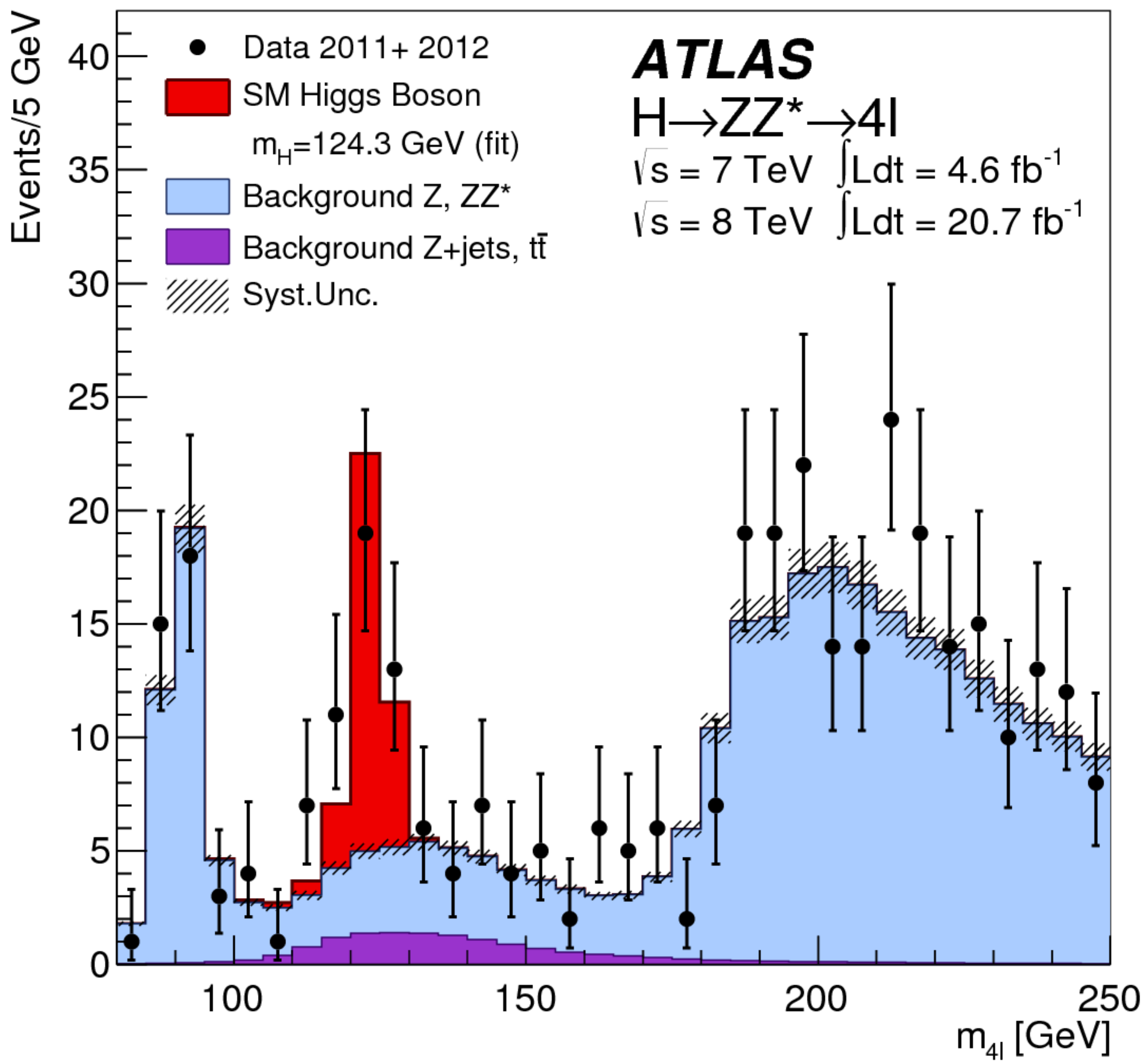


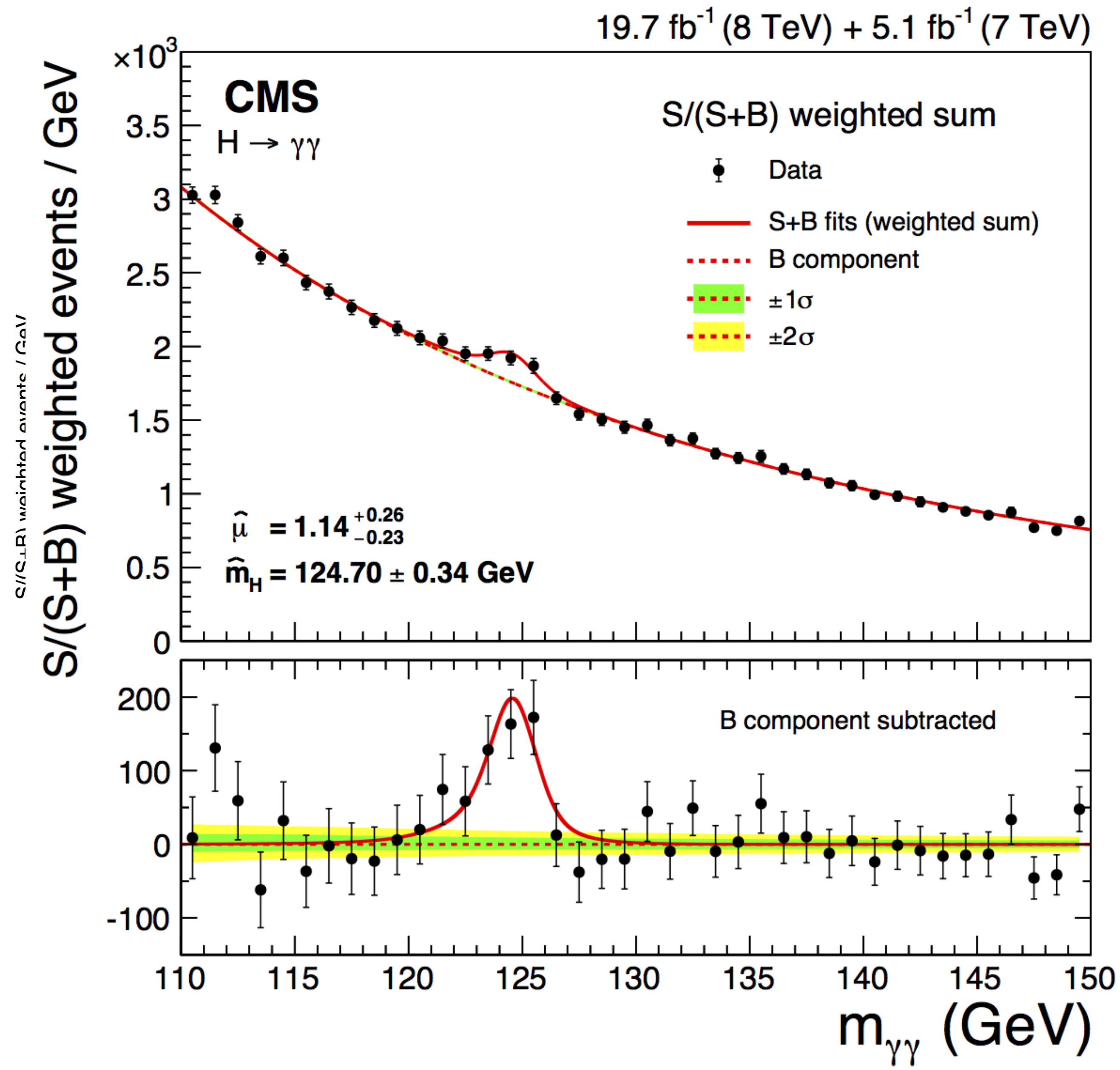
two (quite different) discoveries





two (quite different) discoveries

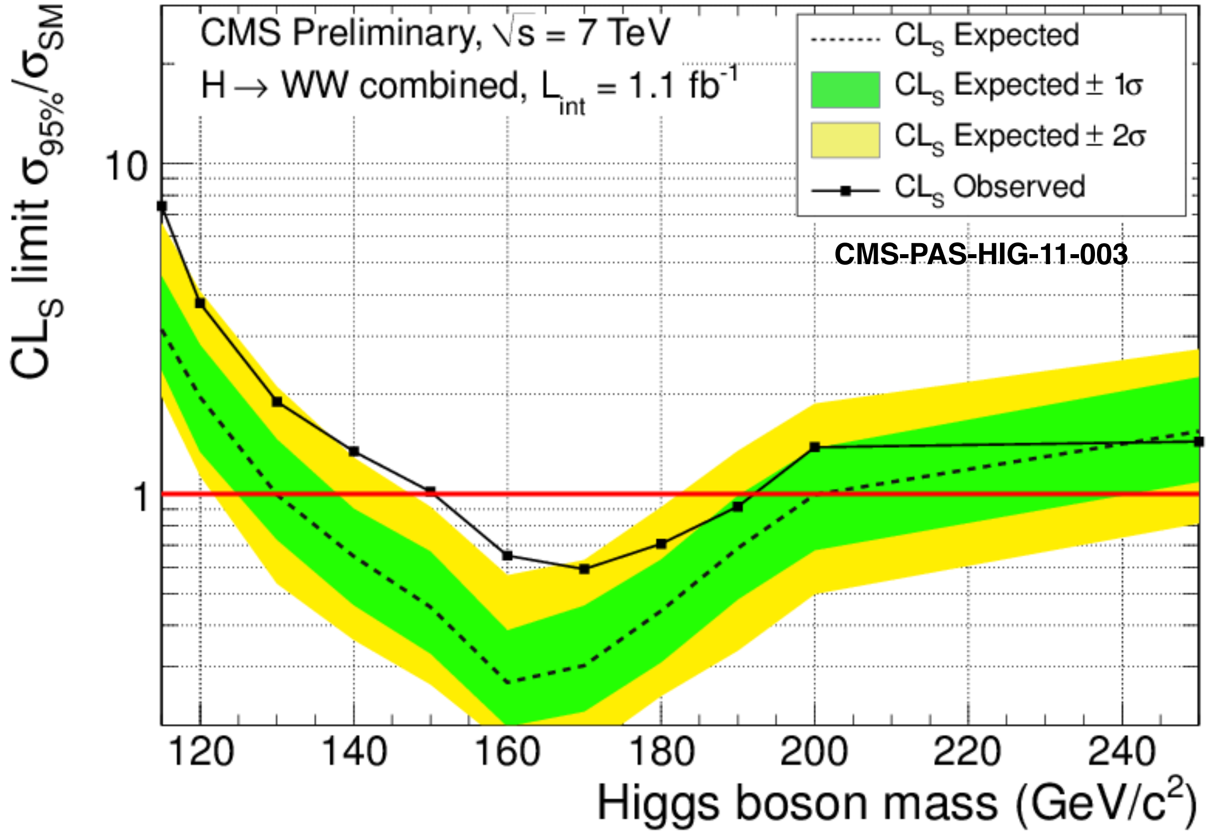


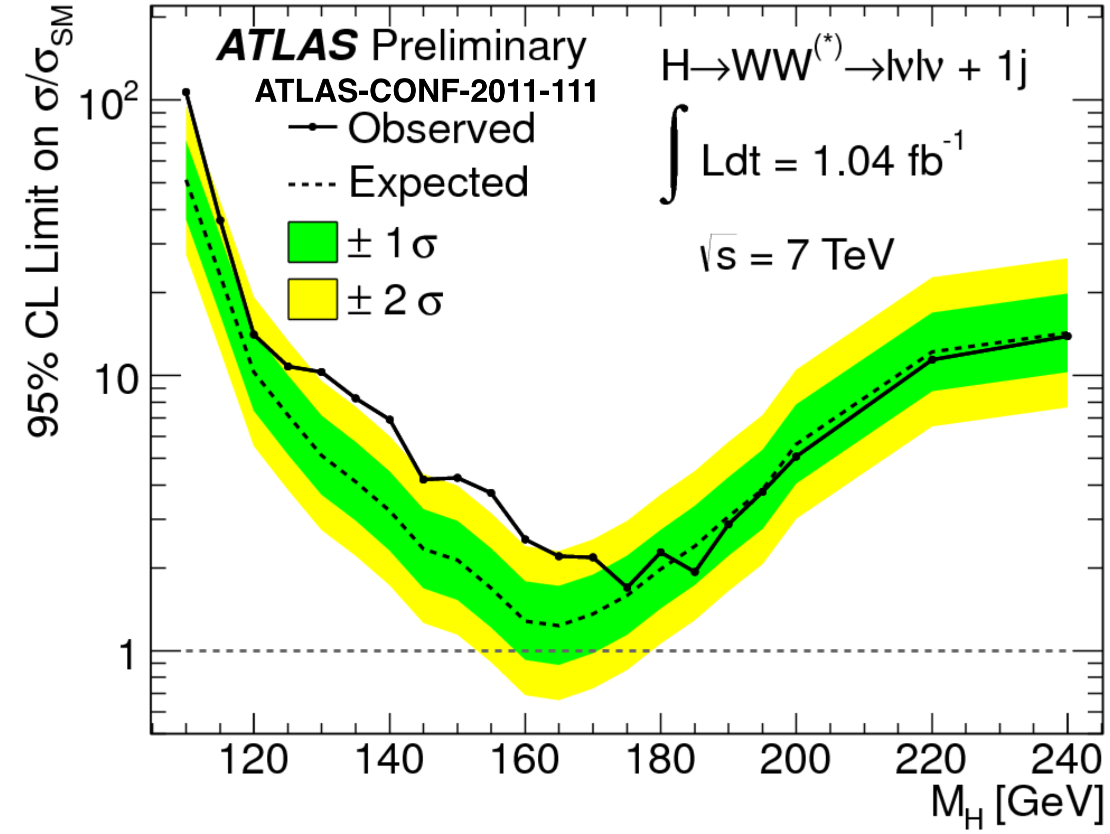


“easy” new physics
ruled out at Run1 (?)

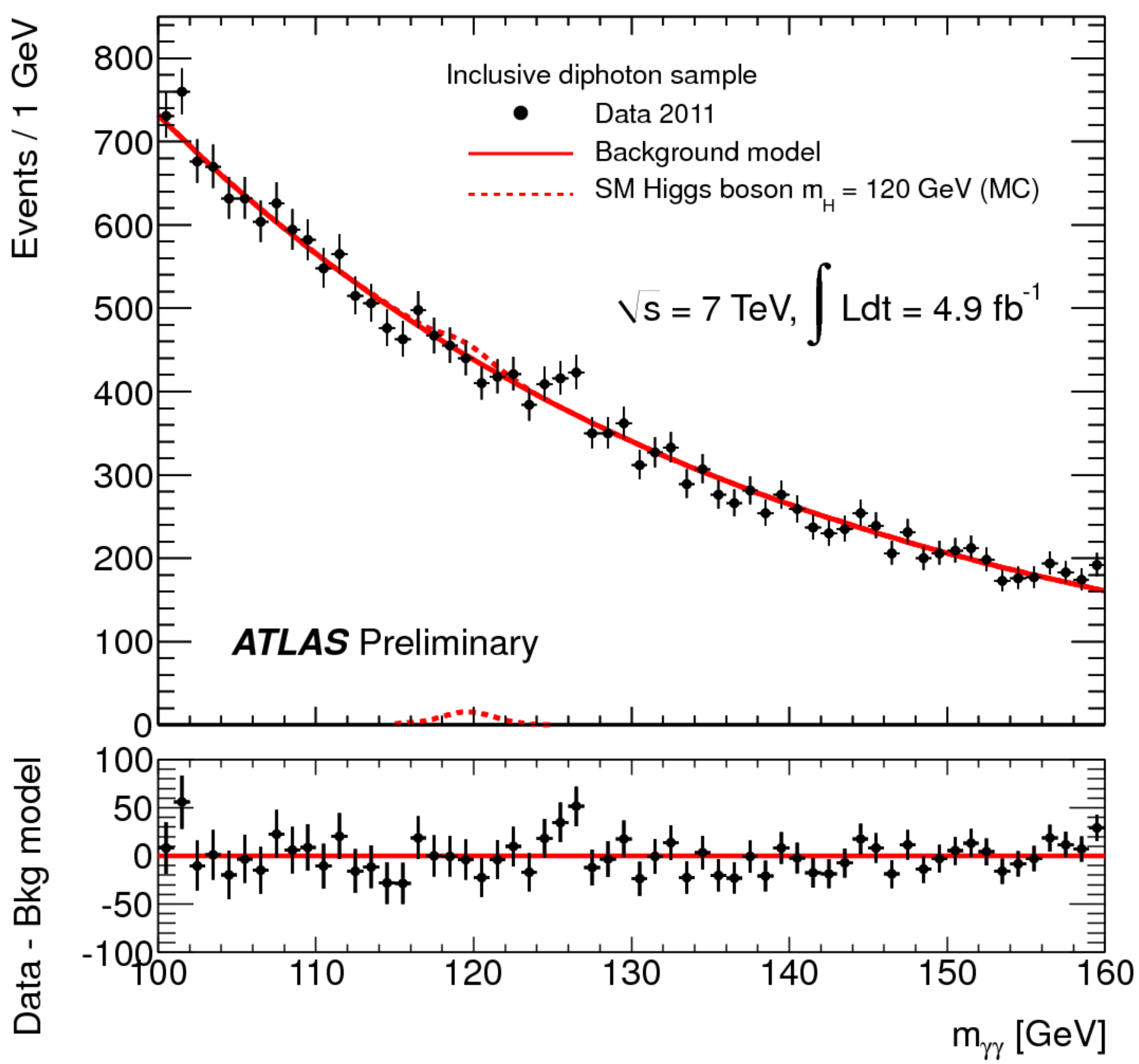
Run2 $\simeq$ Subtle New Physics

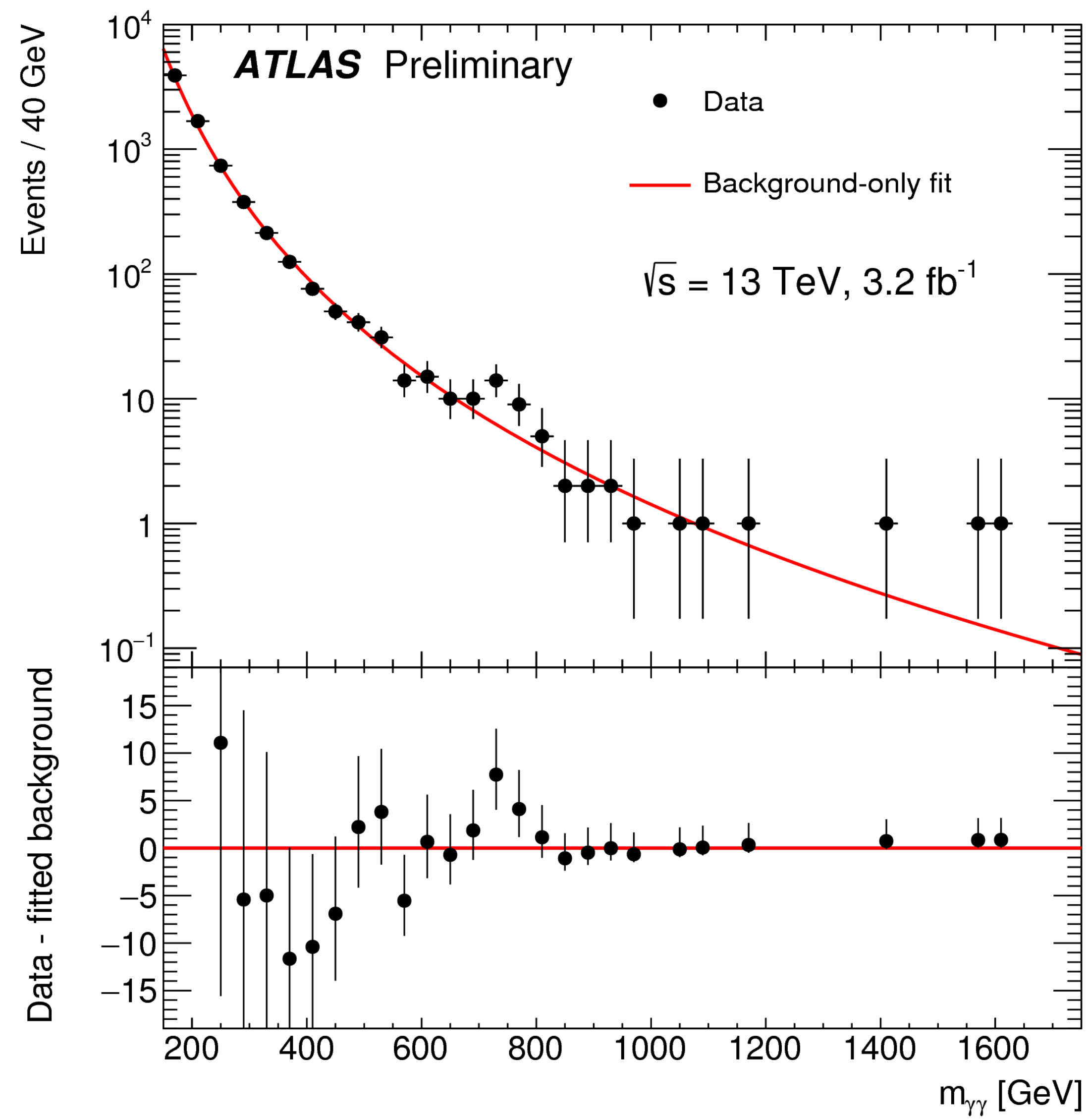
EPS 2011





Jamboree 2011-15





BSM means operating in this moving field

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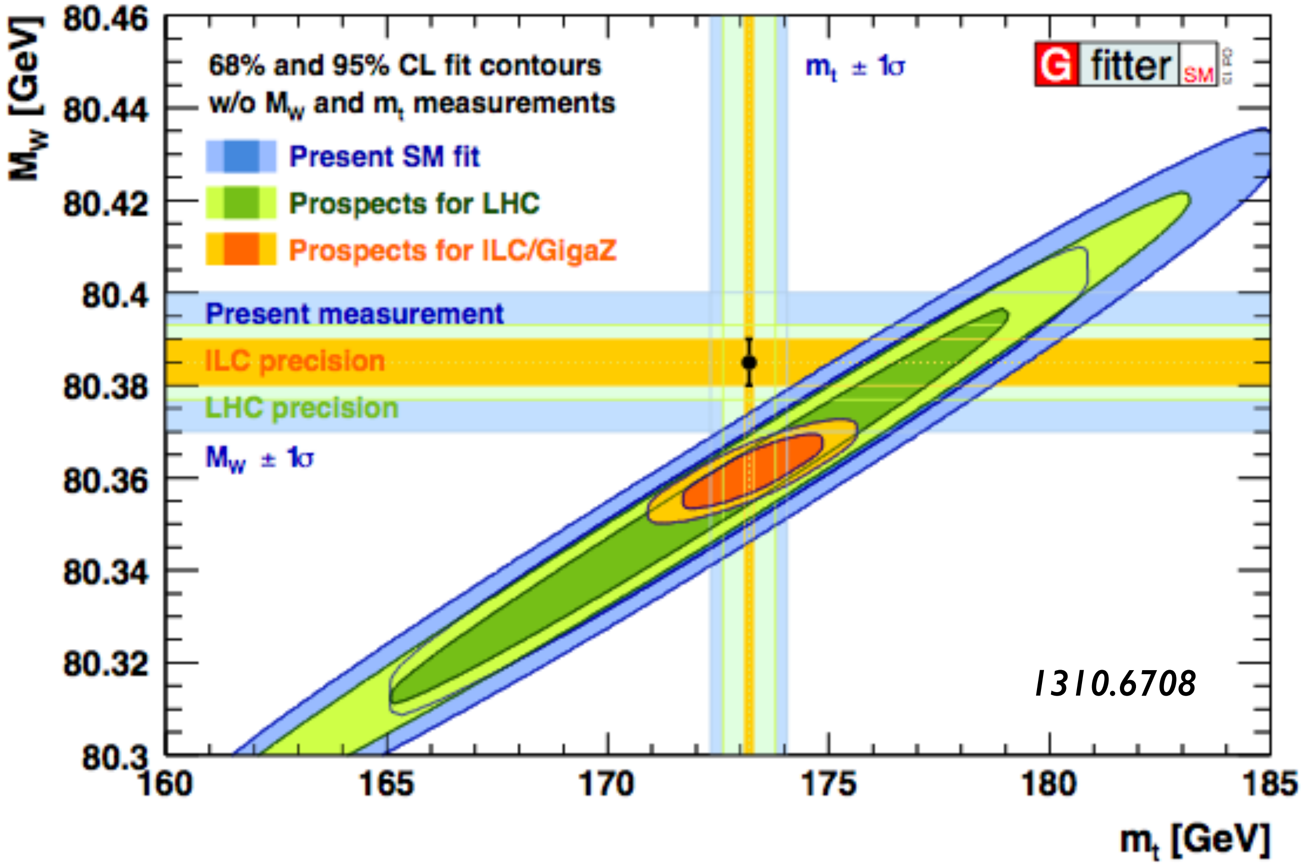
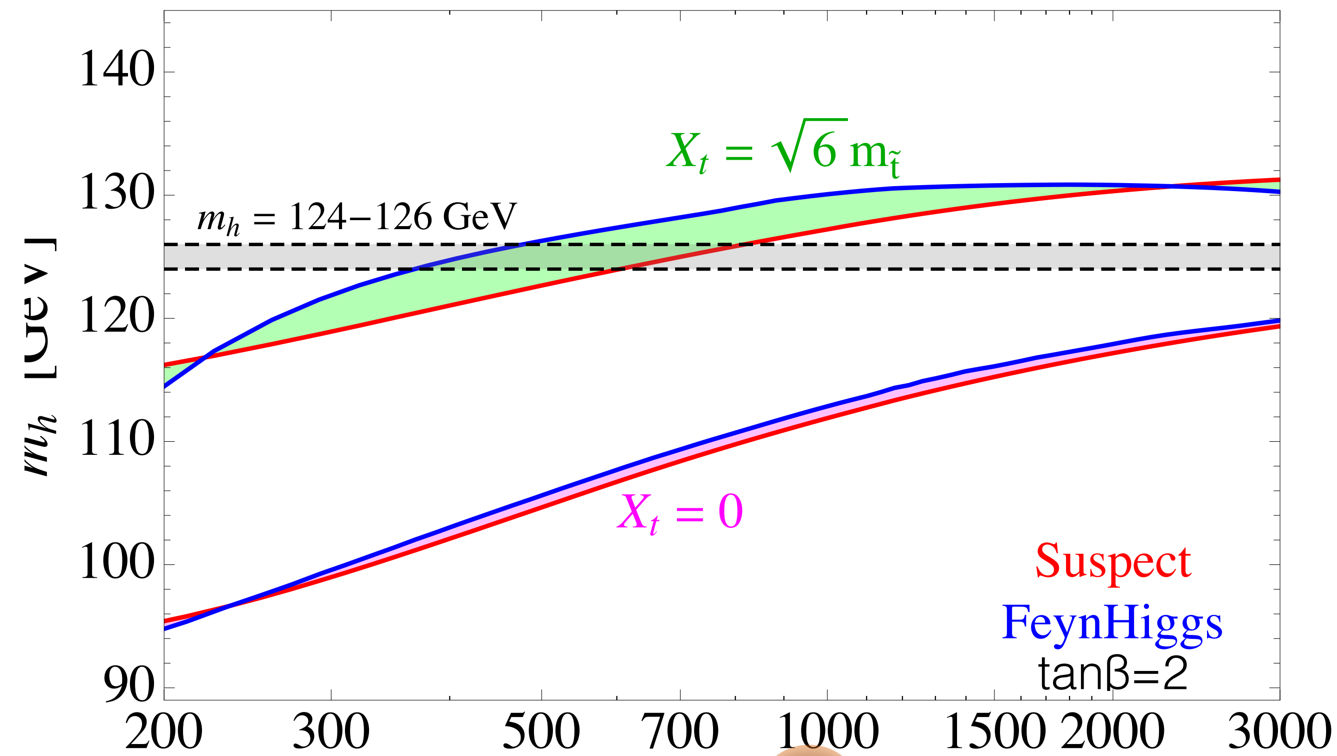
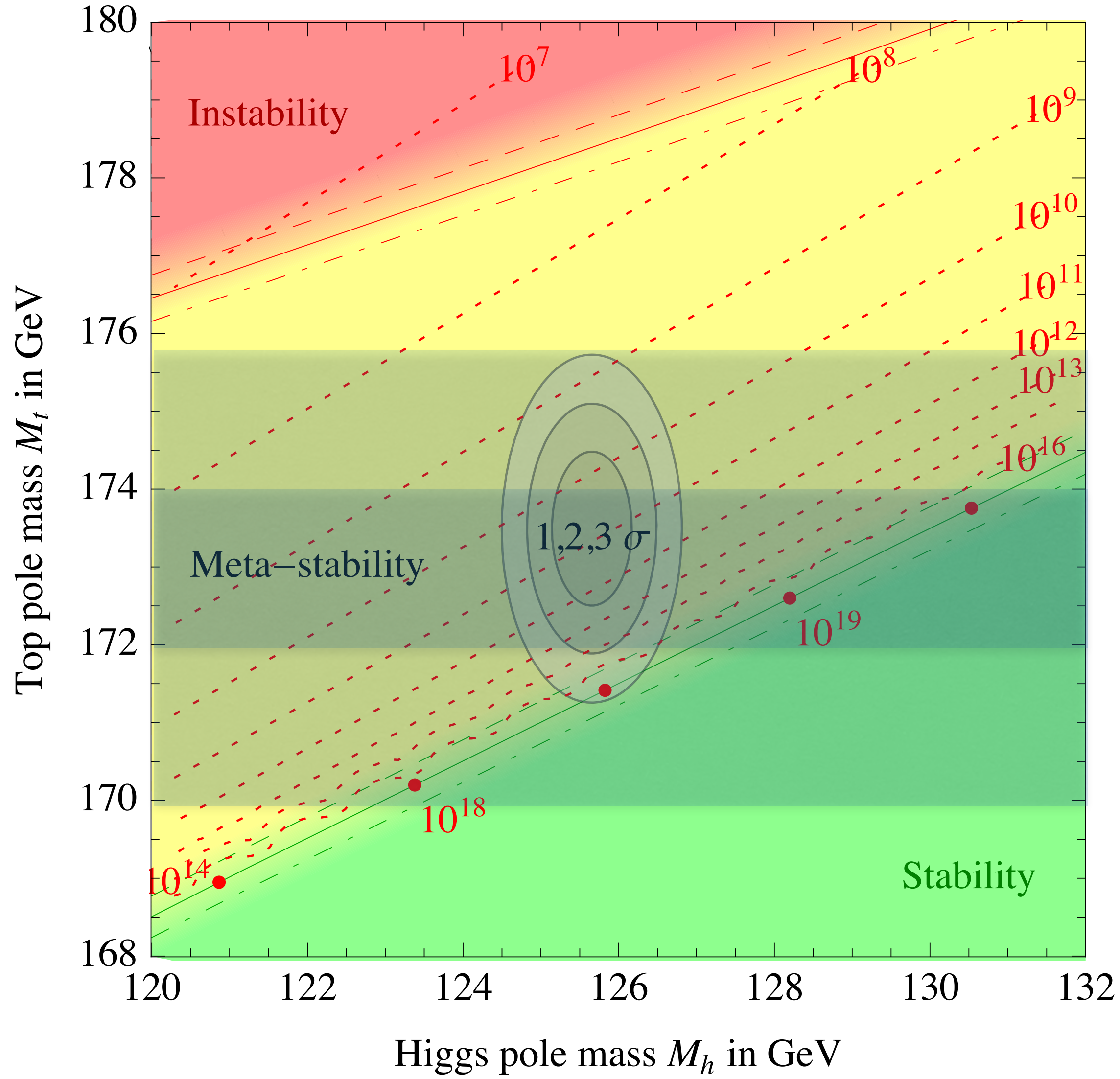
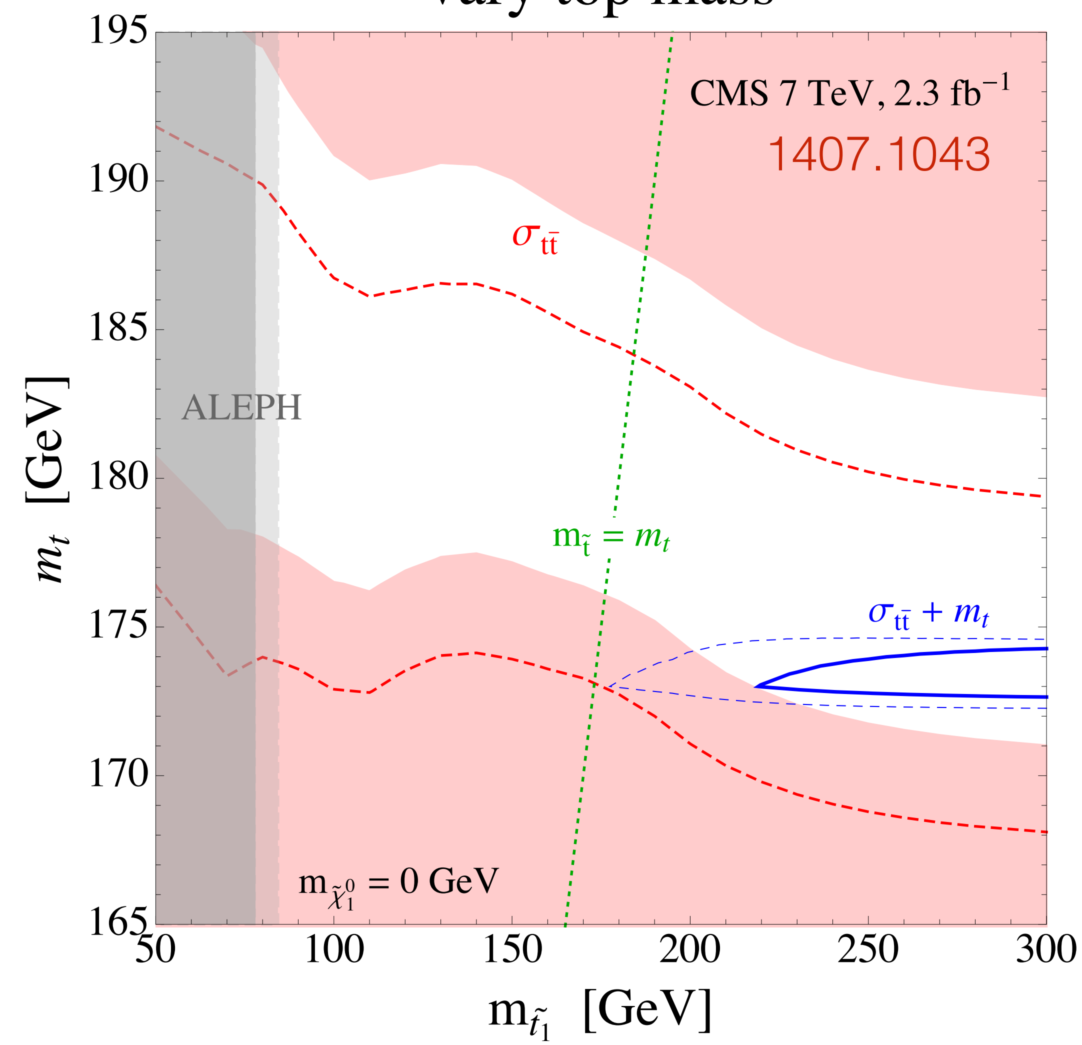




$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$



vary top mass



Outline

- Precision top observables and subtle new physics signals

Precision Observable Programme on the TOP

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- Precision top observables and subtle new physics signals

Precision Observable Programme on the TOP

M_{top} related observables

measurement at ≲0.5%! ⇒ *precision* QCD

Distributions used for top mass should be well under control

Many observables have been proposed (*link*)

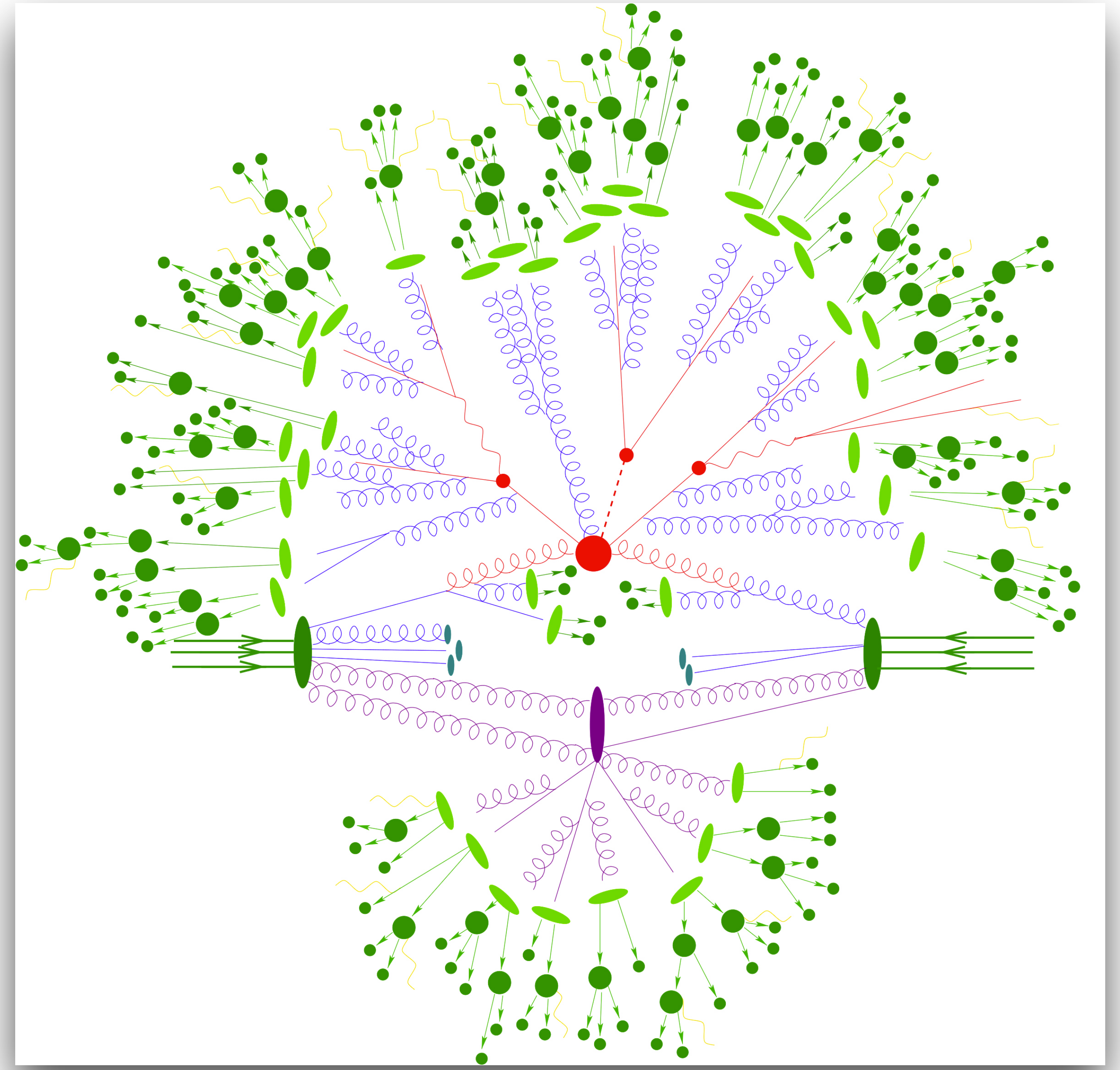
↓

Suitable to look for subtle effects

Status

measurement at ≲0.5%! ⇒ *precision* QCD

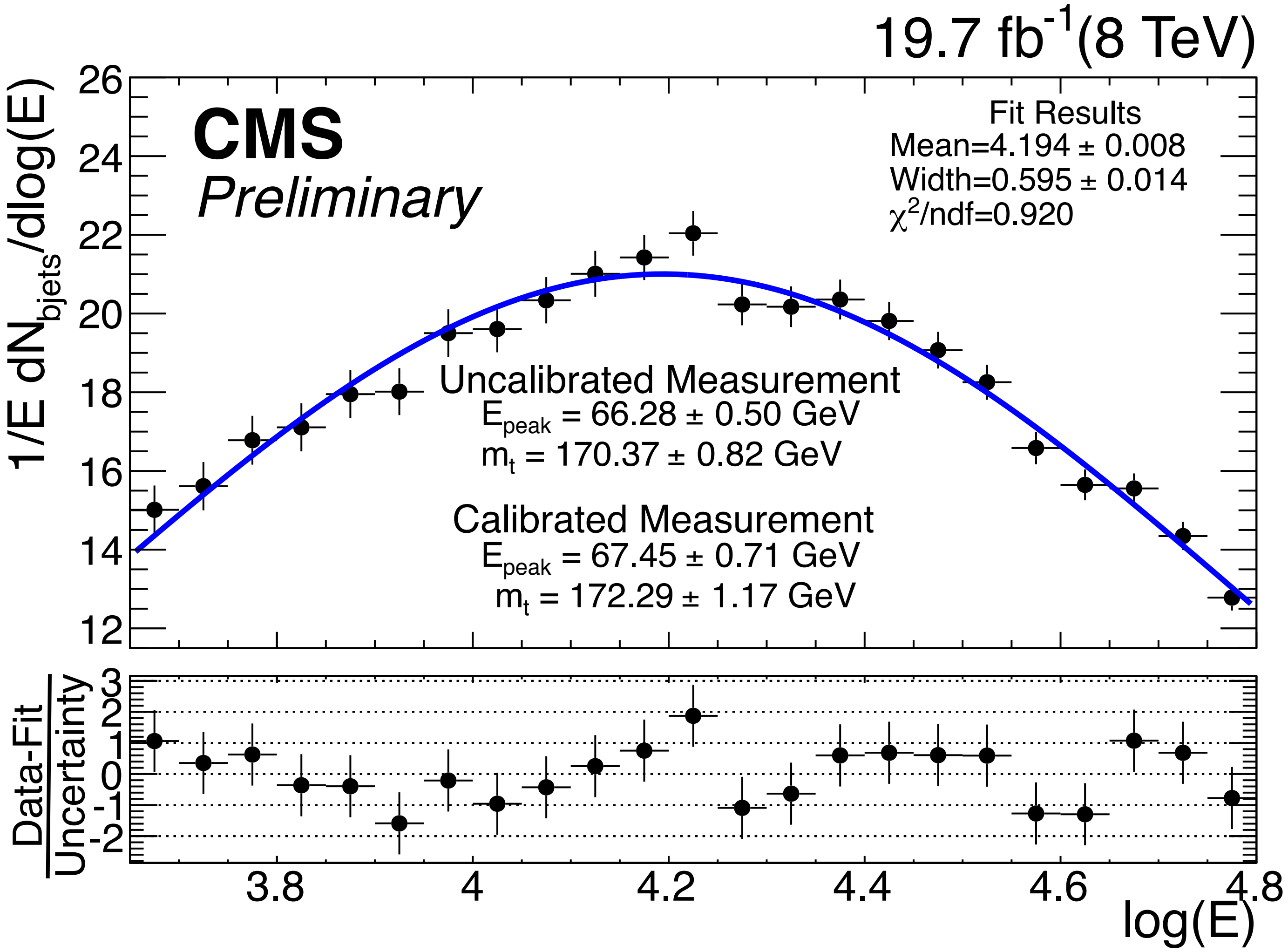
- precision is systematics limited (JES, …, hadronization)



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*”

CMS PAS TOP-15-002

m_t = 172.29 ± 1.17 (stat.) ± 2.66 (syst.) GeV



Source of uncertainty	δE_{peak} (GeV)	δm_t (GeV)
Experimental uncertainties		
Jet energy scale	0.74	1.23
b jet energy scale	0.14	0.22
Jet energy resolution	0.18	0.30
Pile-up	0.01	0.02
b-tagging efficiency	0.12	0.20
Lepton efficiency	0.02	0.03
Fit calibration	0.14	0.24
Backgrounds	0.21	0.34
Modeling of hard scattering process		
Generator modeling	0.91	1.50
Renormalization and factorization scales	0.13	0.22
ME-PS matching threshold	0.24	0.39
Top p_T reweighting	0.90	1.49
PDFs	0.13	0.22
Modeling of non-perturbative QCD		
Underlying event	0.22	0.35
Color reconnection	0.38	0.62
Total	1.62	2.66

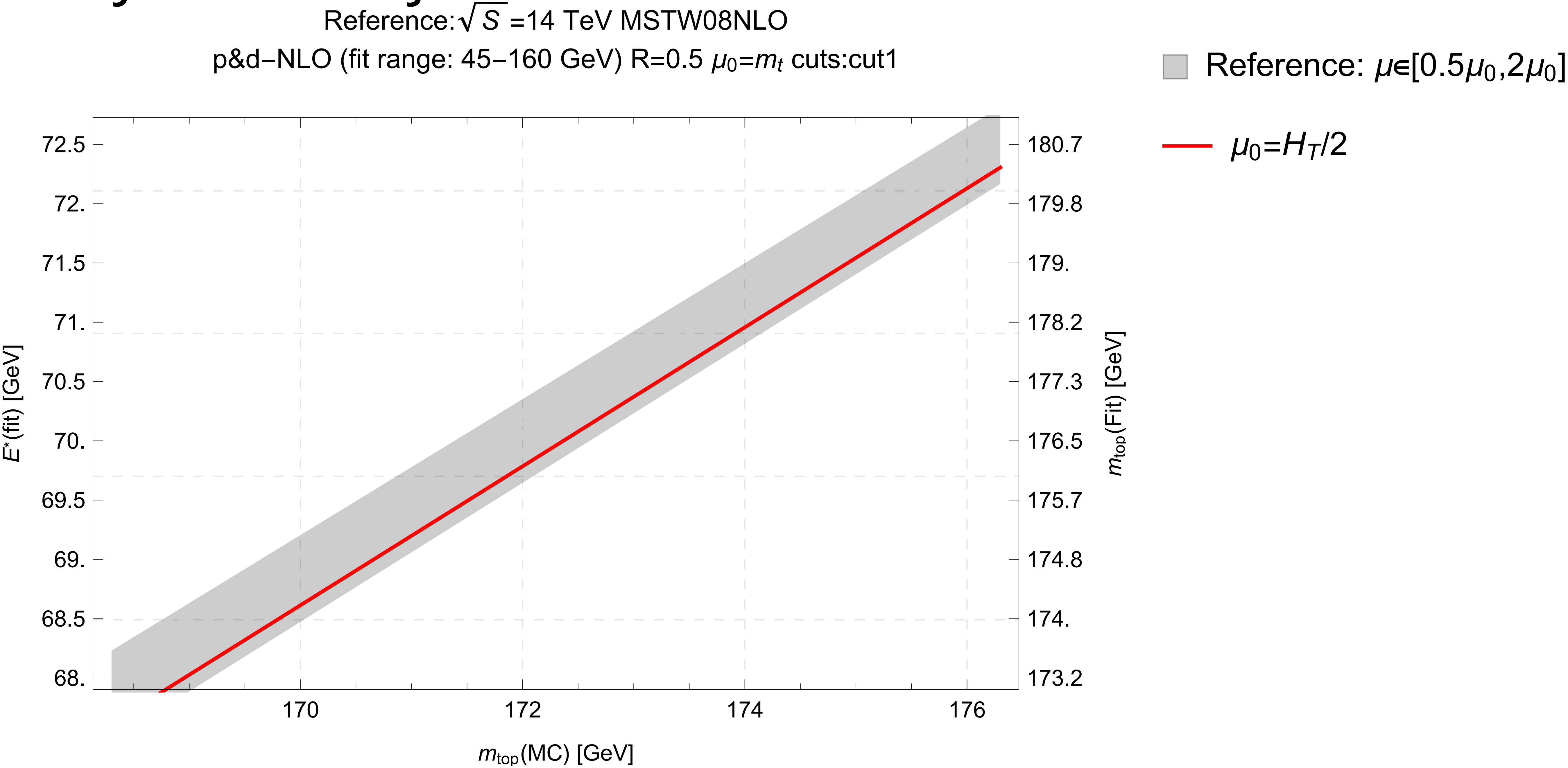
leading uncertainty from theory can be reduced

pT(top) reweighting smaller than other methods (Lxy, pTℓ …)

NLO E*(m_{top})

Agashe, RF, Kim, Schulze - in preparation

pT_j>30 GeV, η_j<2.4, $pT\ell$>20 GeV, $\eta\ell$<2.4



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

M_{top} related observables

Distributions used for top mass should be well under control

Many observables have been proposed (link)

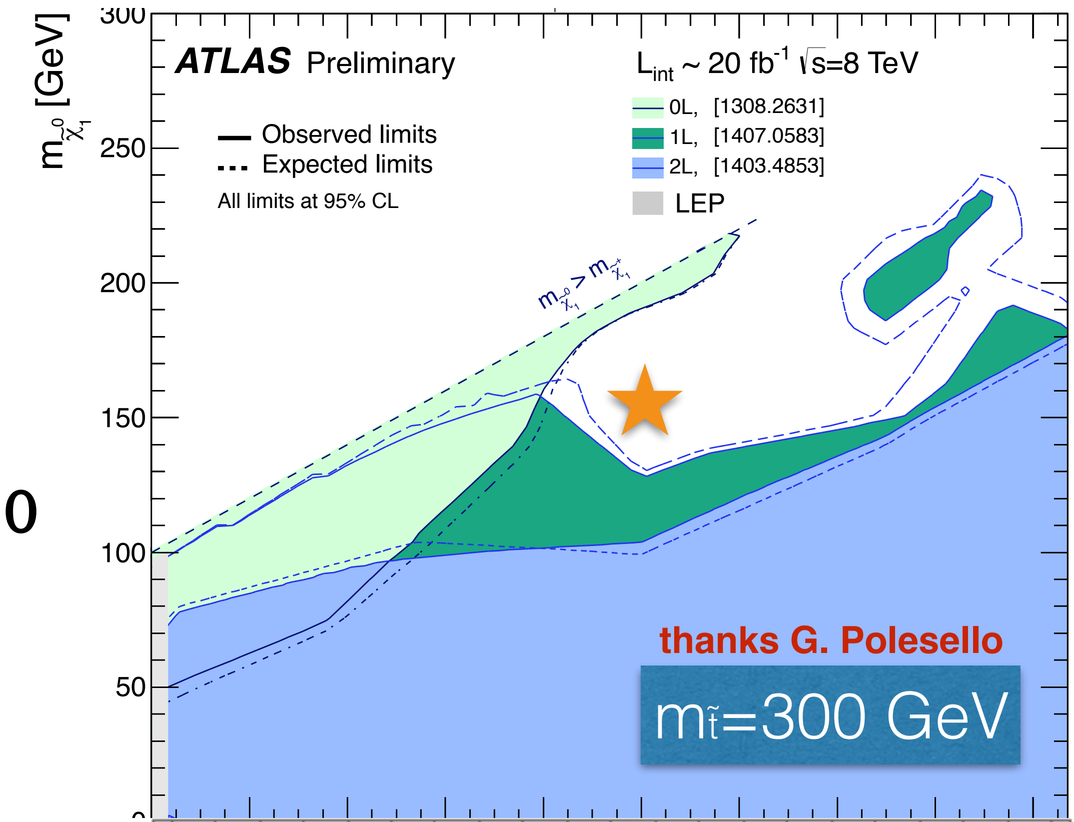
Suitable to look for subtle effects

my guess for $\tilde{t} \rightarrow t\chi^0$

- $\max(m_{b\ell,min})$ (truly?) unaffected
- m_{T2} larger end-point
- E_b affected by top polarization (maybe small)
- $p_{T\ell}$, L_{xy}, $s(ttj)$, affected by top boost (maybe small)

To know the answer we need to see signal injections

New physics effect on $m_{b\ell}$ and E_b

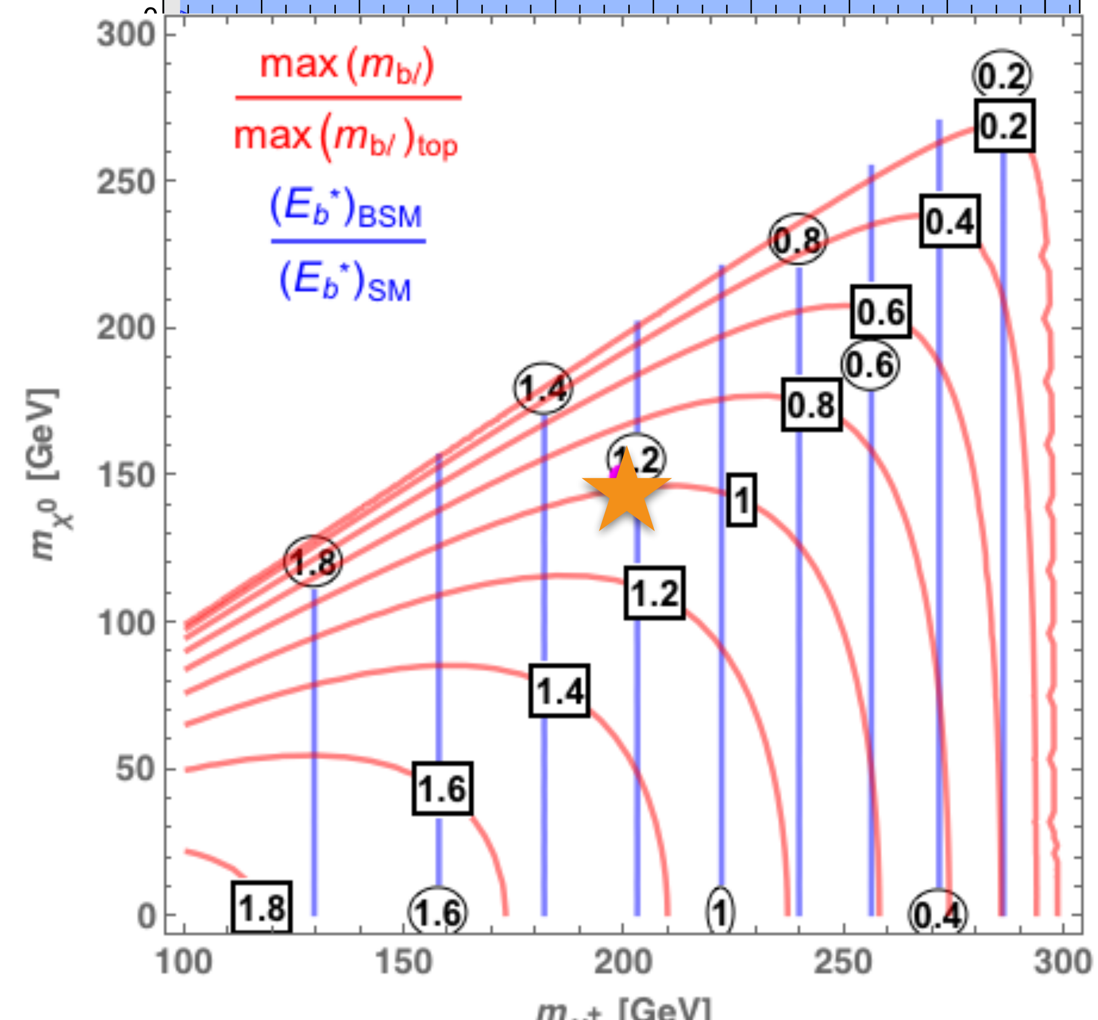


E_b and $m_{b\ell}$ behave differently

$t \rightarrow bW \rightarrow b\ell\nu$ ➡ $\tilde{t} \rightarrow b\,\chi^+ \rightarrow b\ell\nu\chi^0$

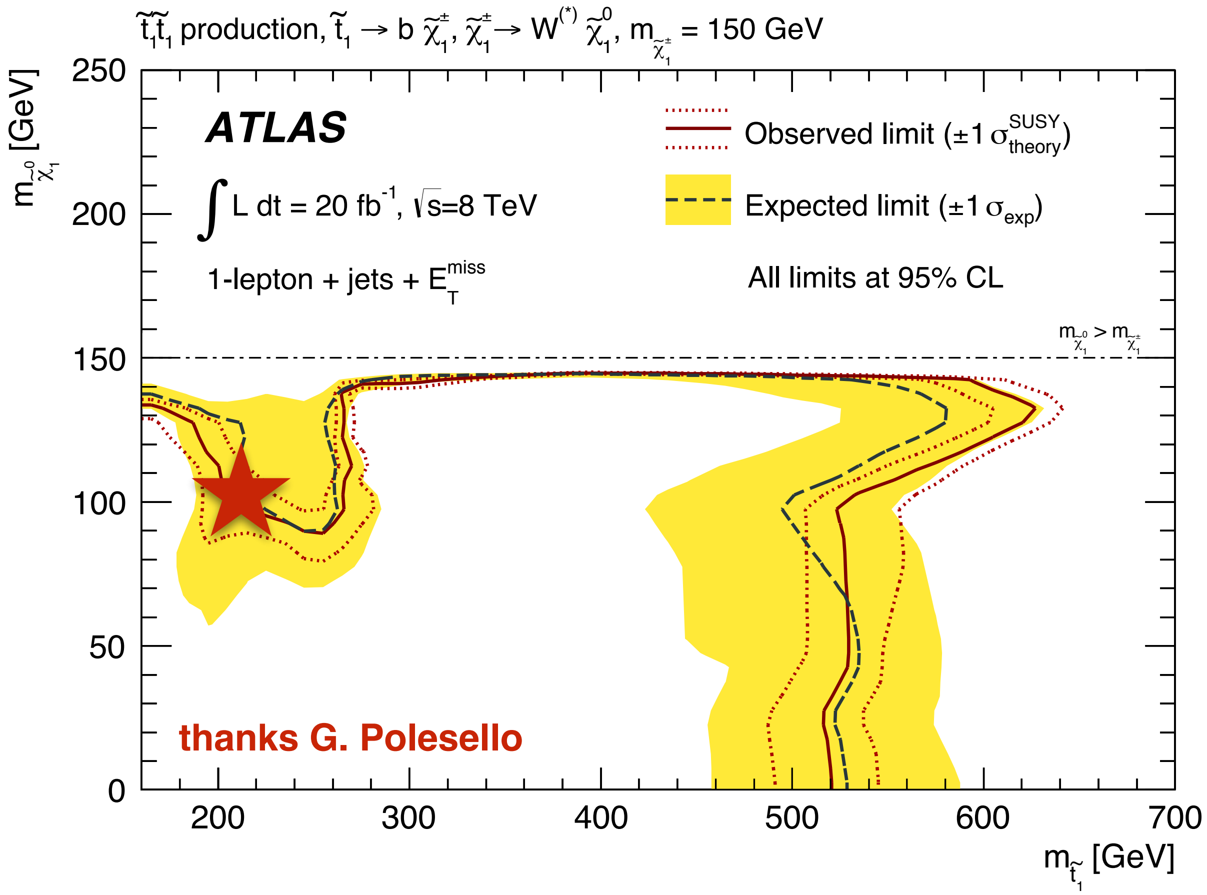
$$m_{b\ell}^{max}\Big|_{m_b=0} = \sqrt{\frac{(m_{\tilde{t}}^2 - m_{\chi^+}^2)(m_{\chi^+}^2 - m_{\chi^0}^2)}{m_\chi}}$$

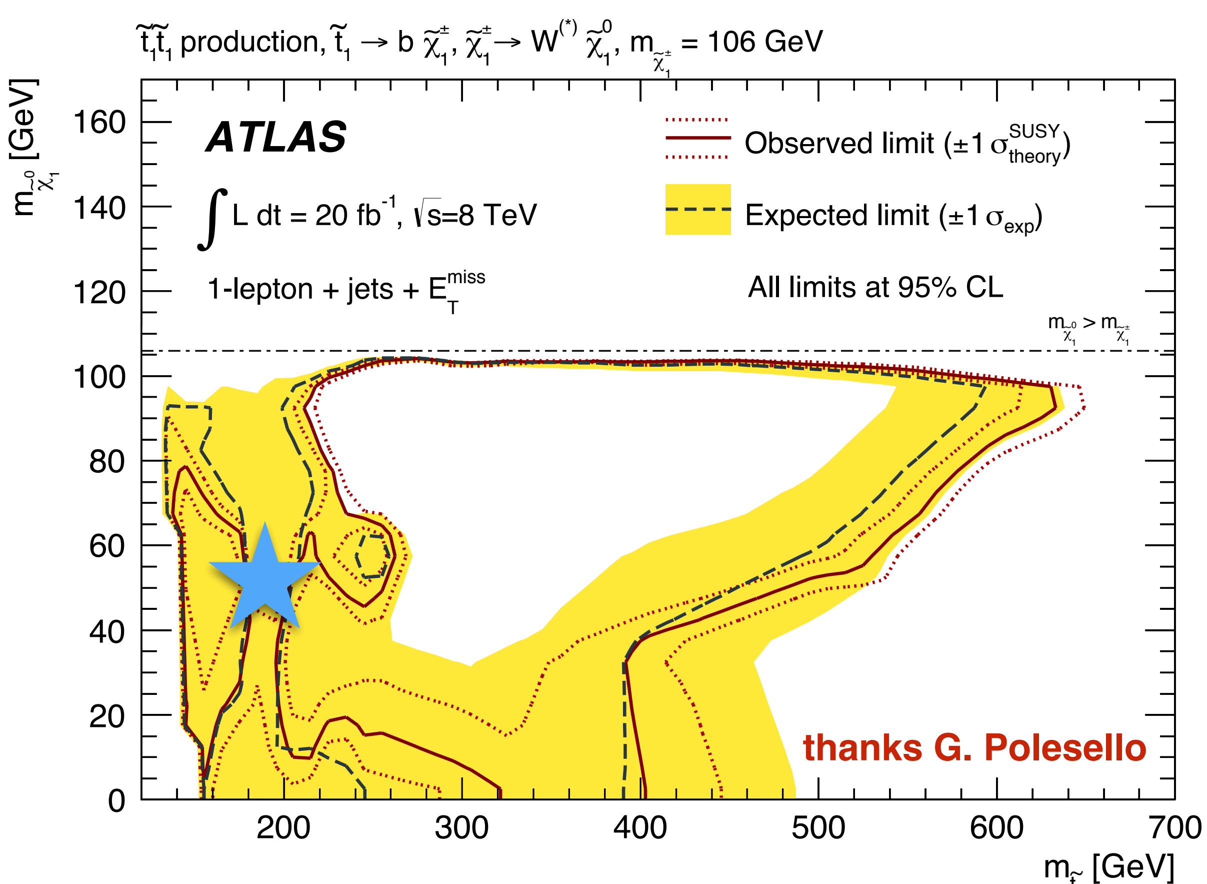
$$E_b^* = \frac{m_{\tilde{t}}^2 - m_{\chi^+}^2}{2\, m_{\tilde{t}}}$$

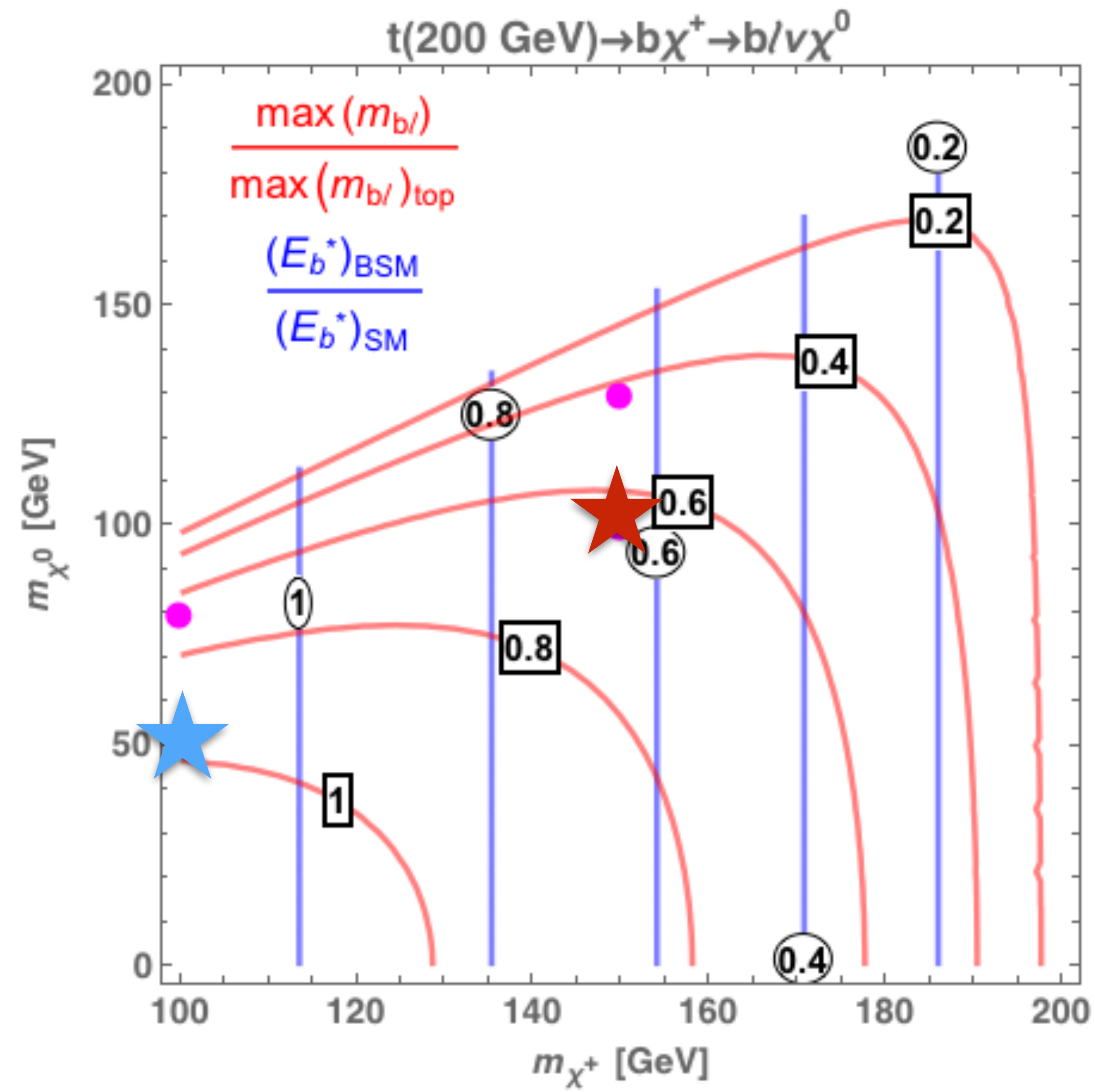


★ **Harder E_b, softer $m_{b\ell}$**

New physics effect on $m_{b\ell}$ and E_b



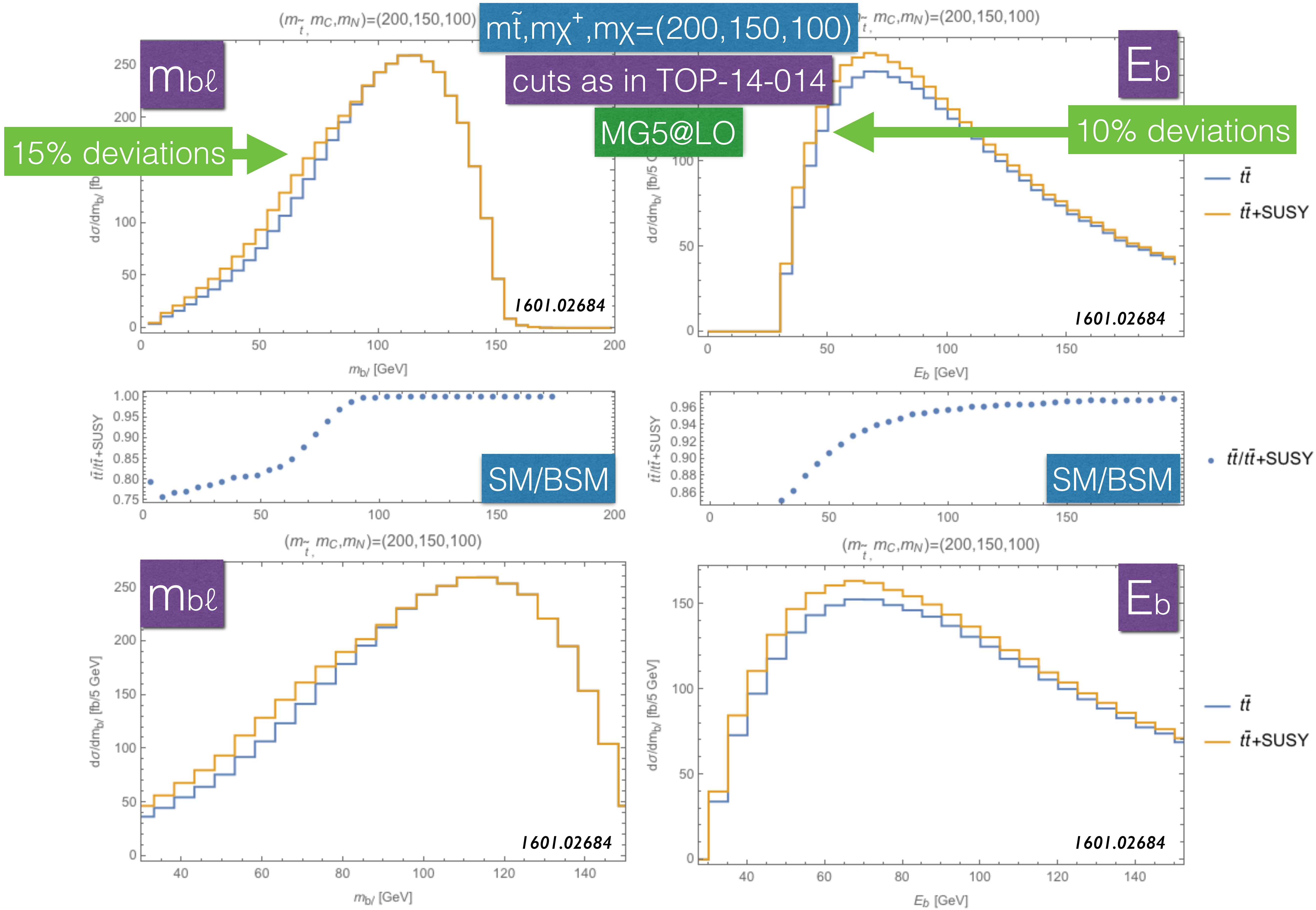




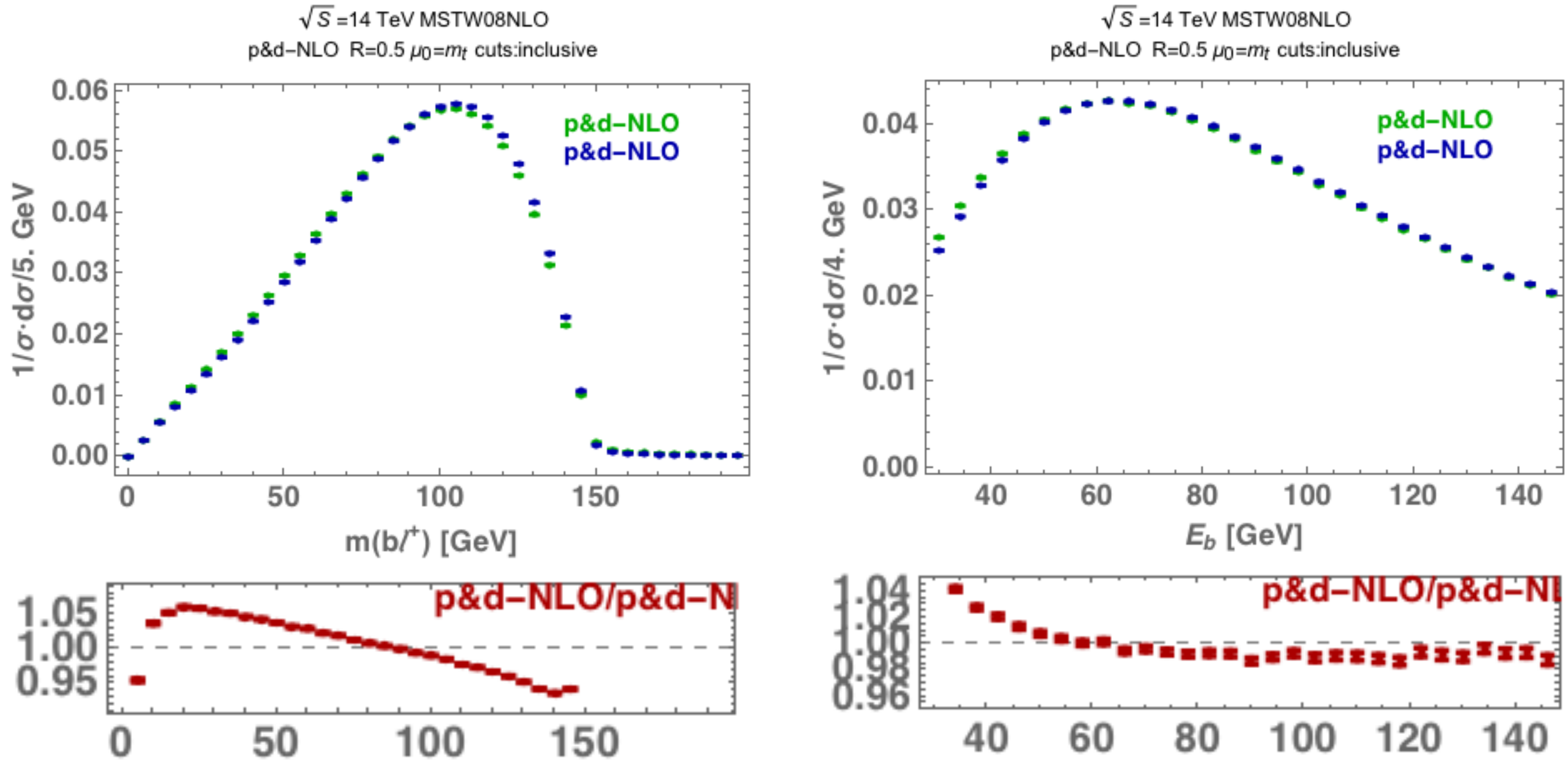
★ harder E_b, softer $m_{b\ell}$

★ softer E_b, softer $m_{b\ell}$

New physics effect on $m_{b\ell}$ and E_b



A first look at scale uncertainties



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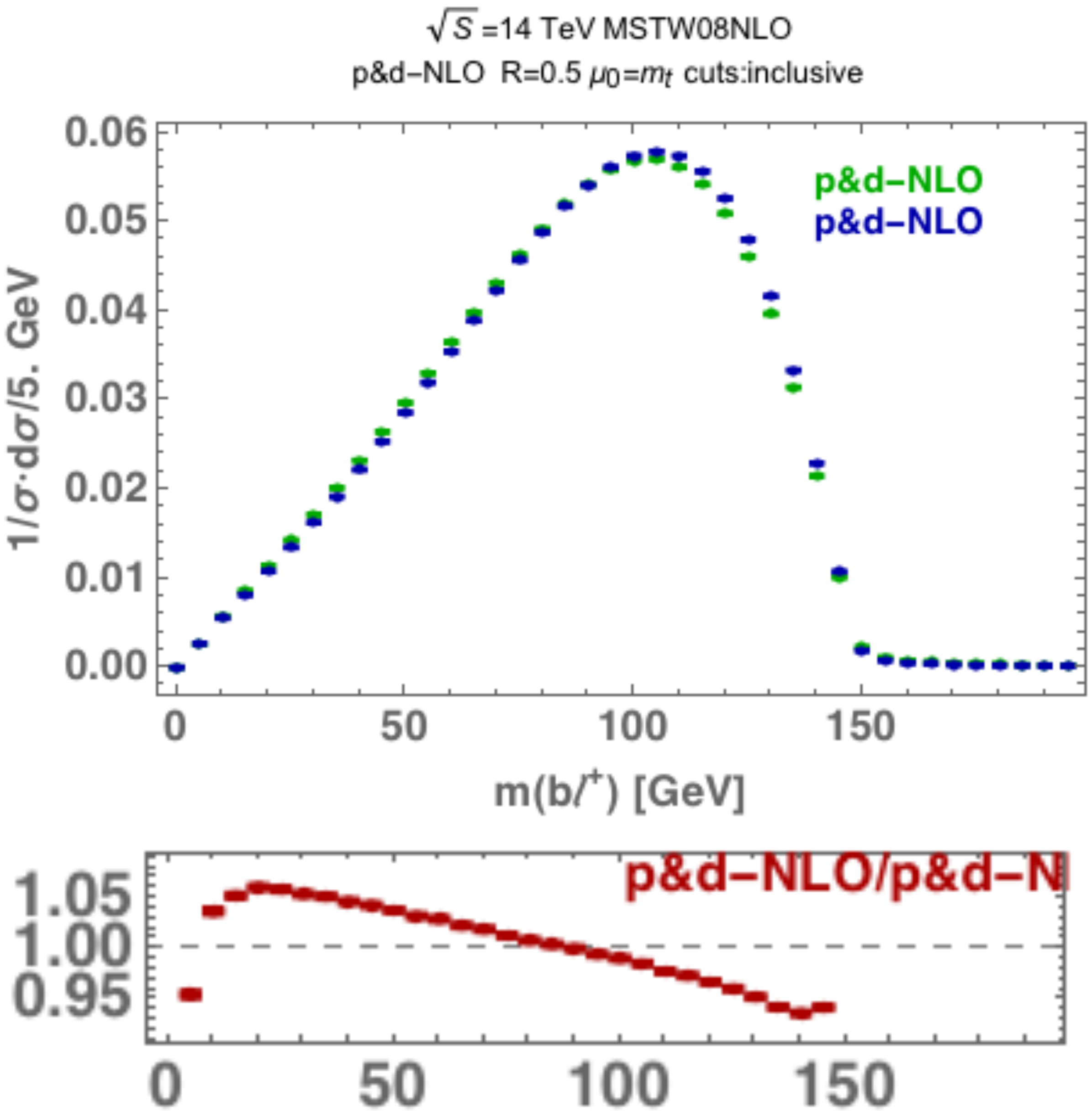

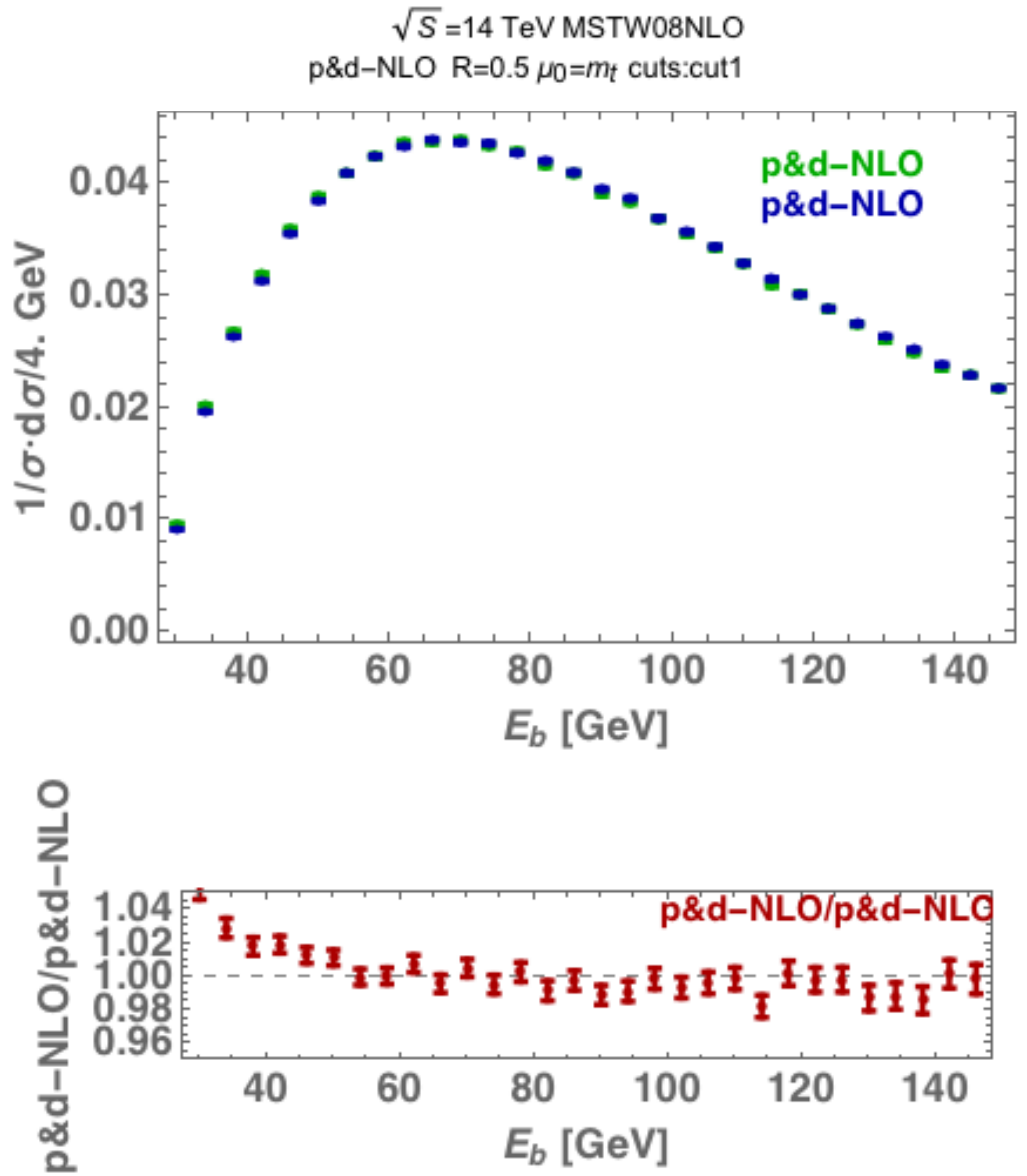

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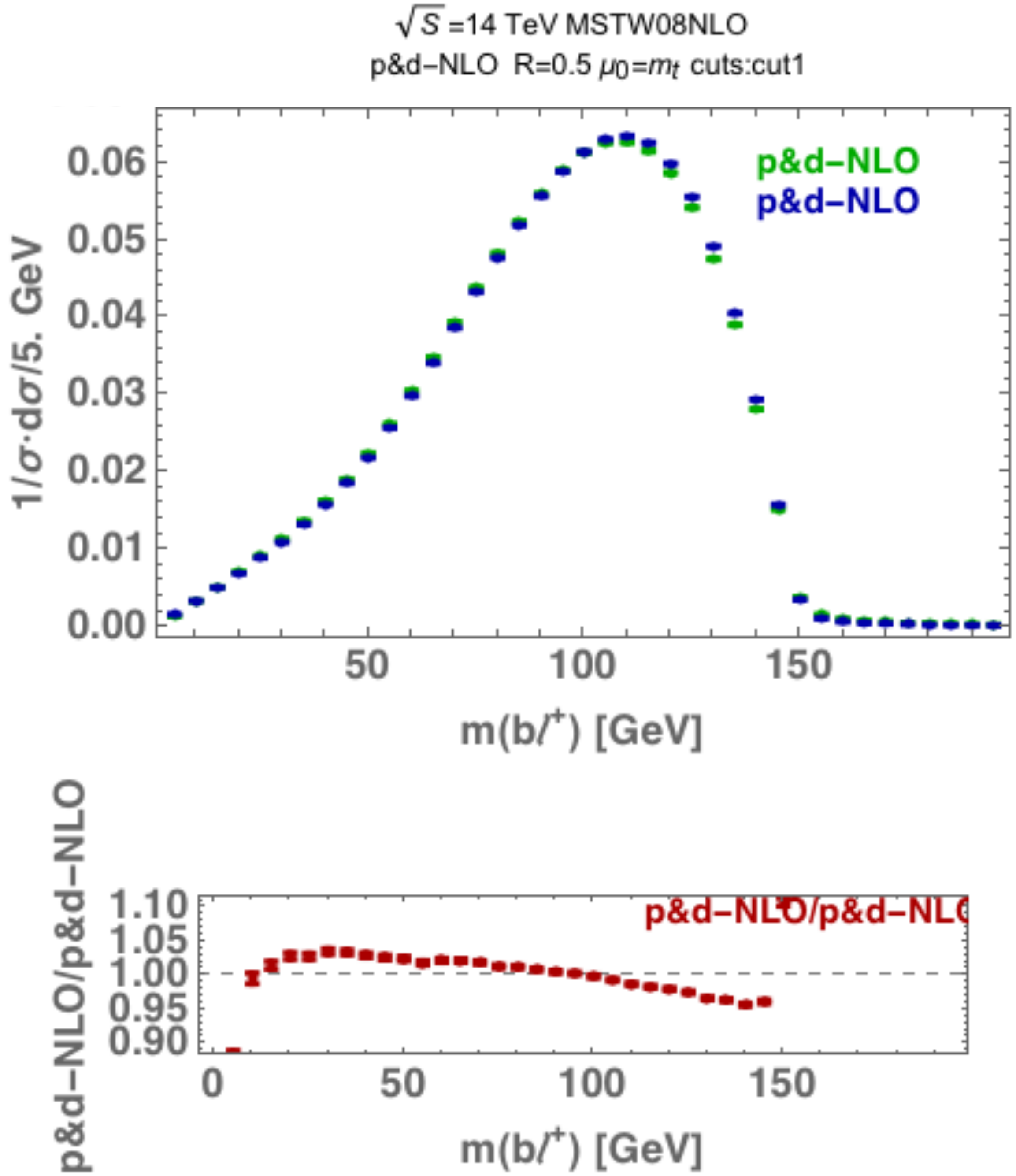
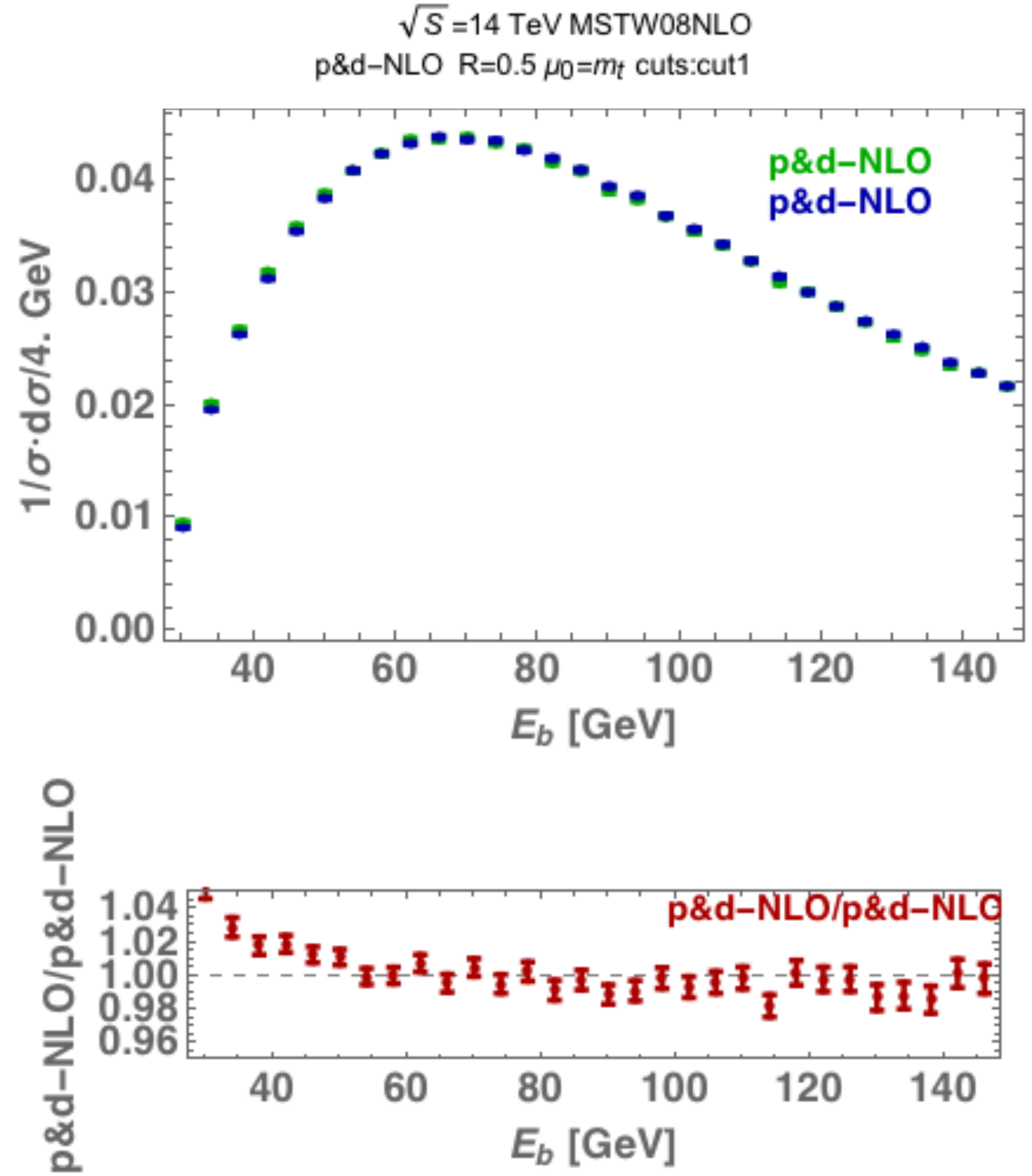
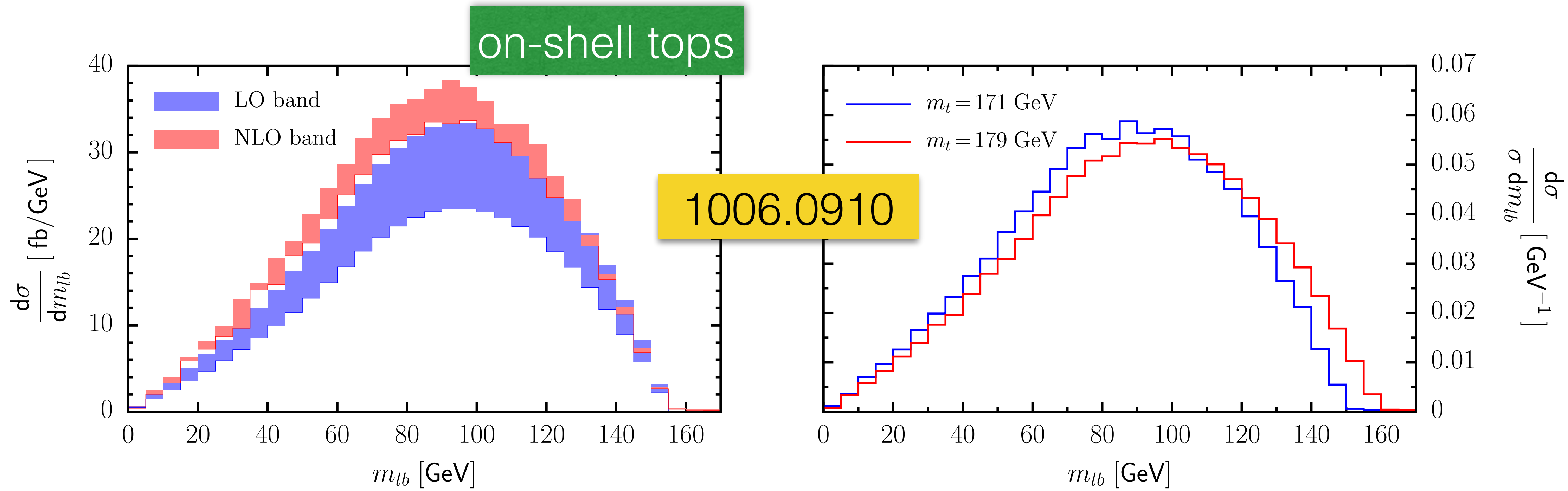
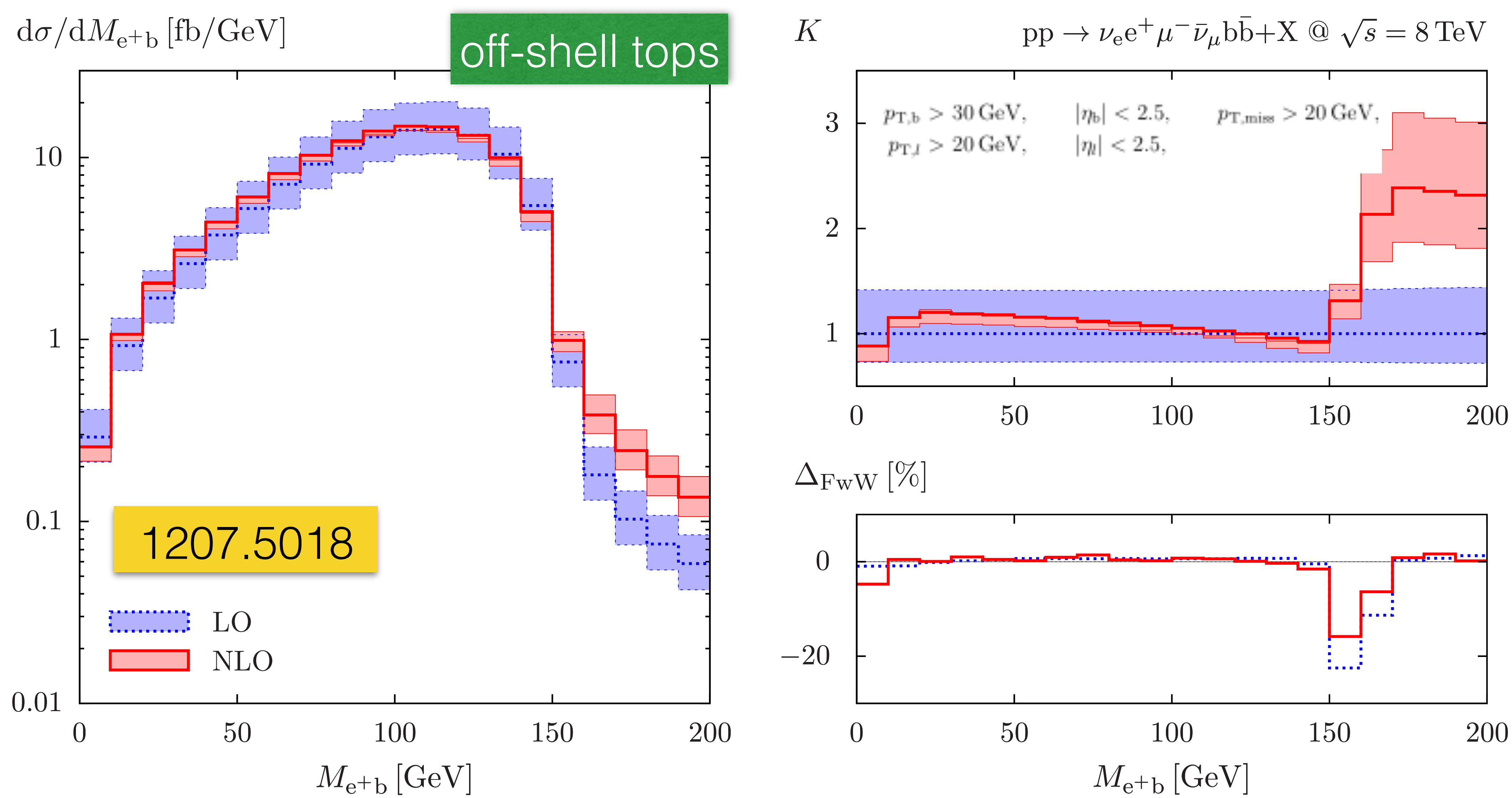


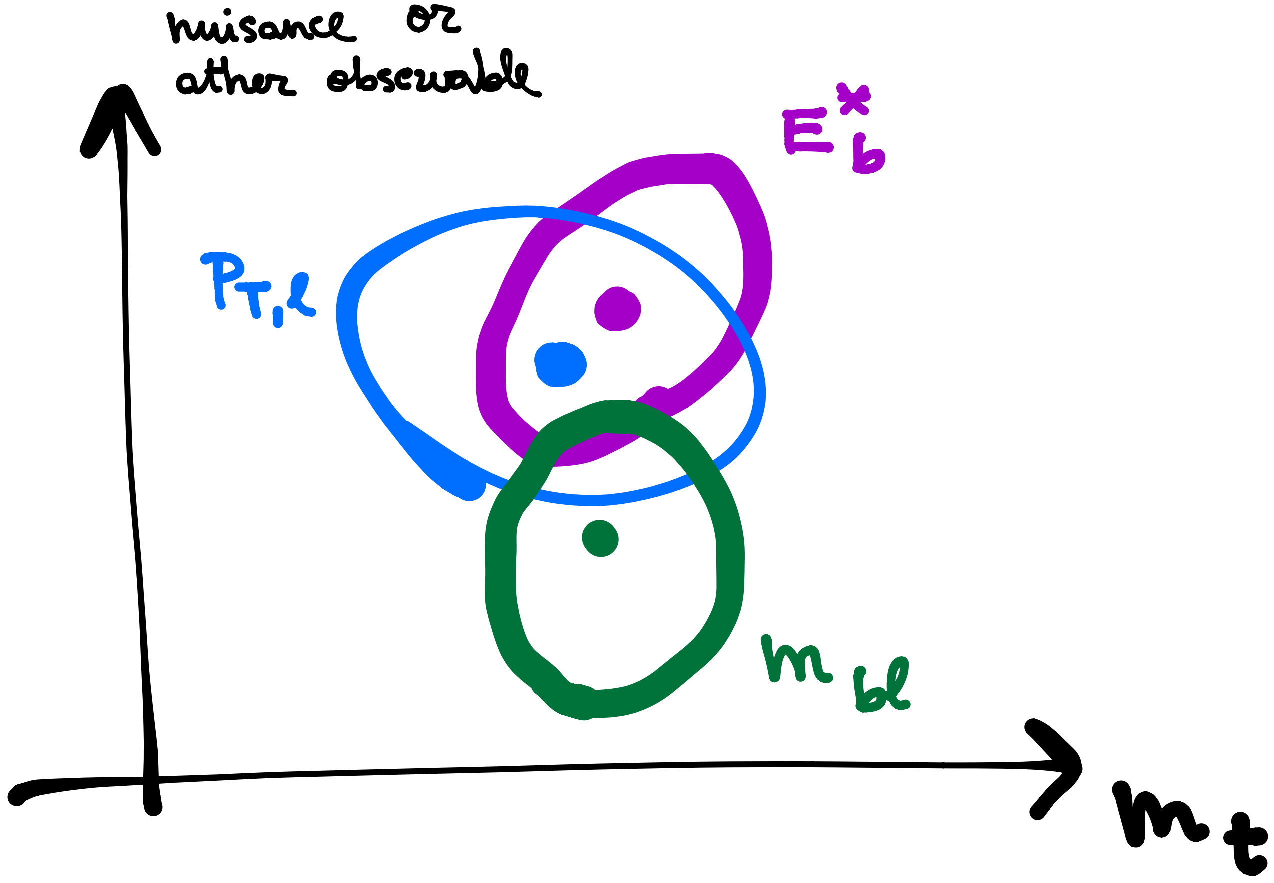


$m_{b\ell}$ at NLO


on-shell tops
1006.0910
LO band
NLO band
$\frac{d\sigma}{dm_{lb}}$ [fb/GeV]
m_{lb} [GeV]
$m_t = 171$ GeV
$m_t = 179$ GeV
$\frac{d\sigma}{\sigma\, dm_{lb}}$ [GeV^{-1}]
m_{lb} [GeV]


off-shell tops
$d\sigma/dM_{e^+b}$ [fb/GeV]
1207.5018
LO
NLO
M_{e^+b} [GeV]
K
$pp \to \nu_e e^+ \mu^- \bar{\nu}_\mu b\bar{b} + X$ @ $\sqrt{s} = 8$ TeV
$p_{T,b} > 30$ GeV, $|\eta_b| < 2.5$, $p_{T,miss} > 20$ GeV,
$p_{T,l} > 20$ GeV, $|\eta_l| < 2.5$,
Δ_{FwW} [%]
M_{e^+b} [GeV]

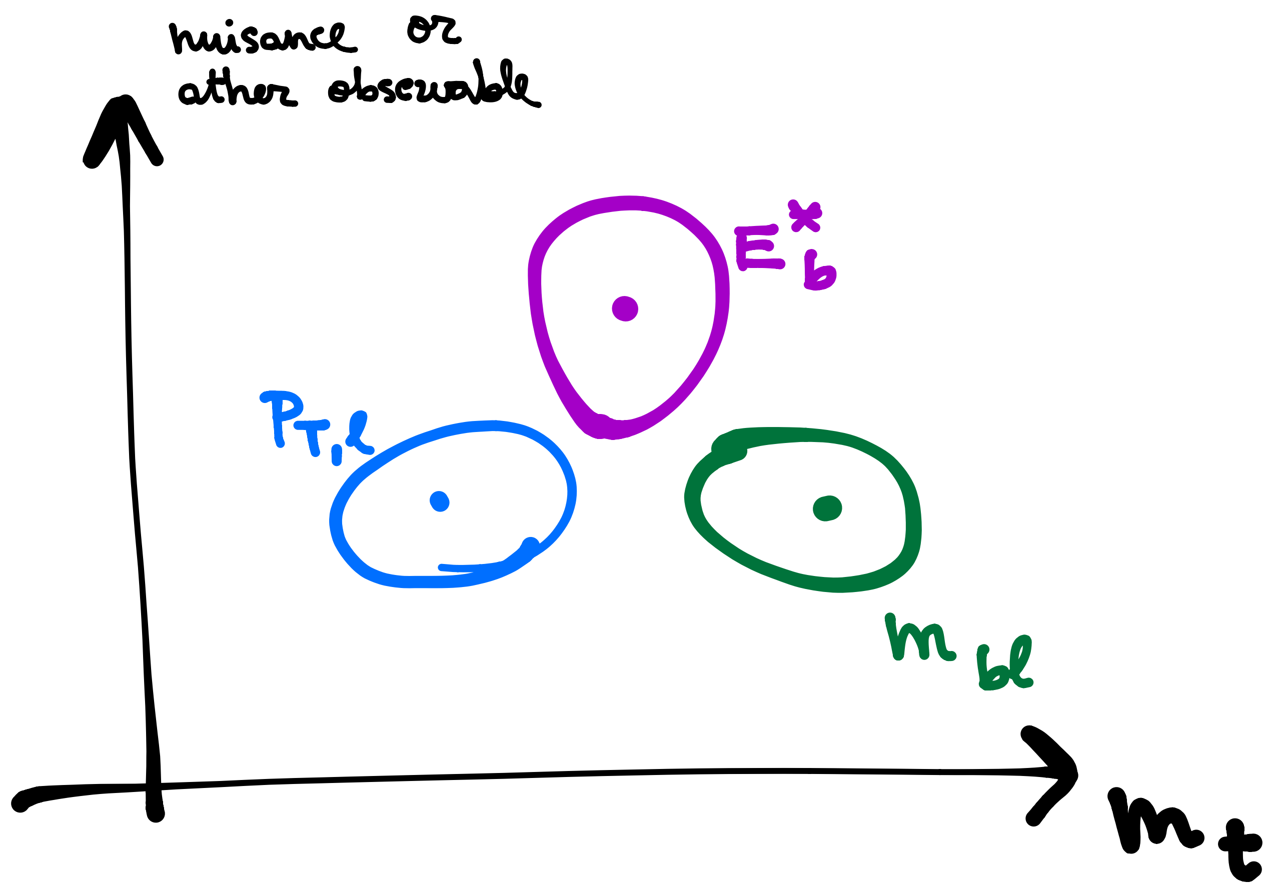
Many measurements



Use the <u>correlated effect in many observables</u> that is expected from a new physics source

Many measurements

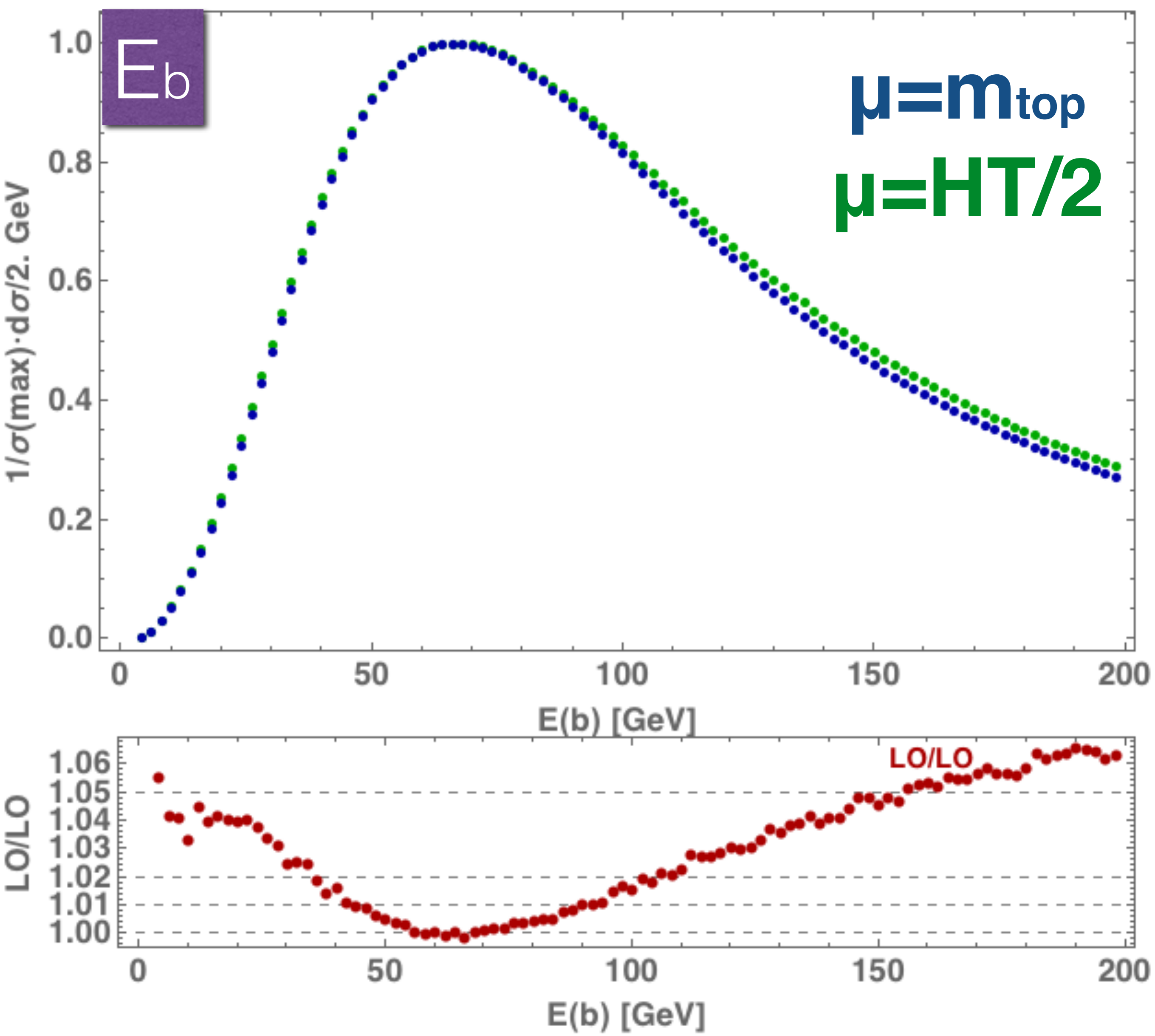
several different mass-sensitive observables can be used and give independently disagreement from the SM: **QCD or new physics effect?**



Use the correlated effect in many observables that is expected from a new physics source

Subtleties of the subtle effects

$\Delta m_{top} \lesssim 300$ MeV despite 5% deviations in the tails



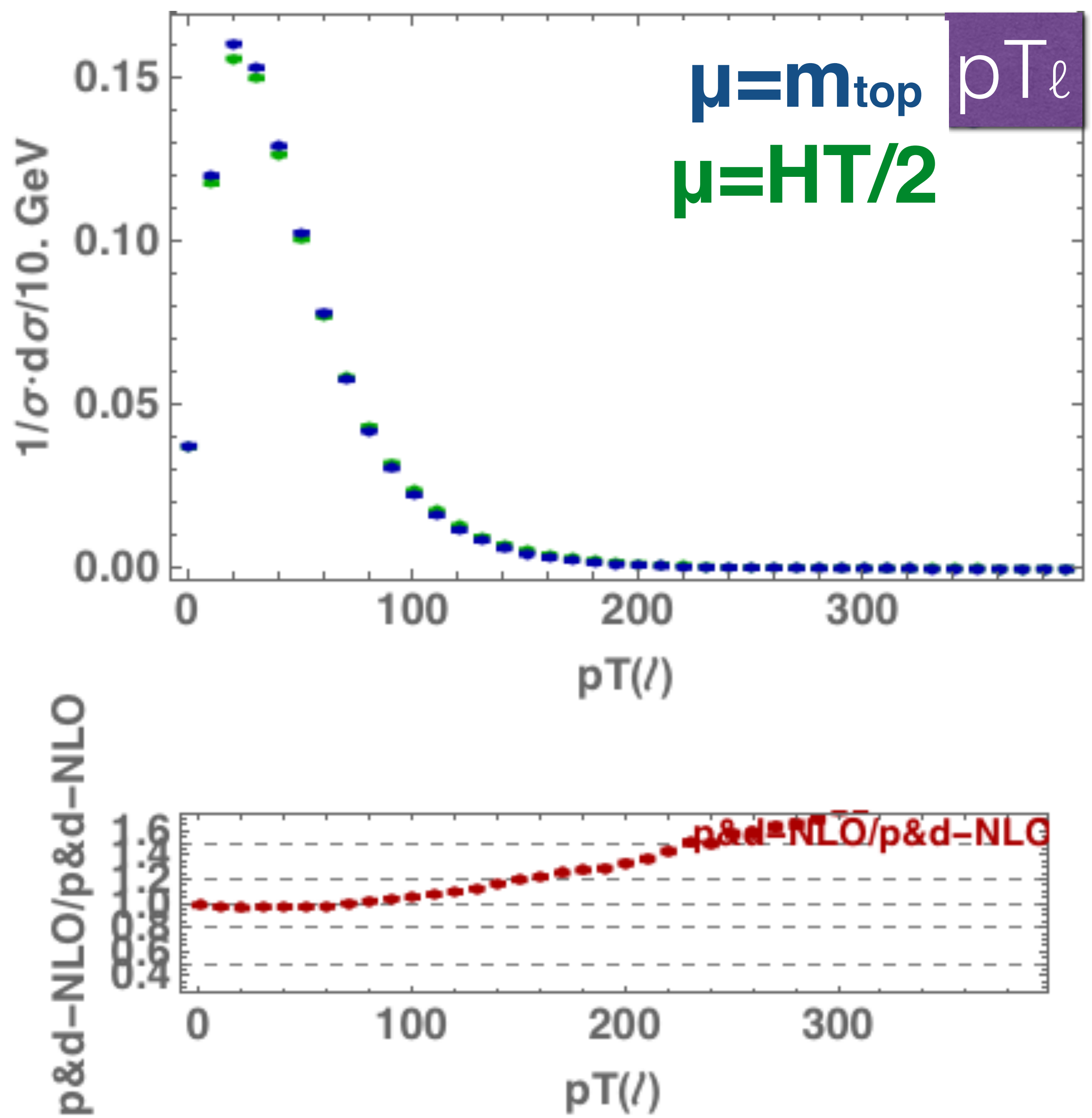
- despite “large” difference in the tails, m_{top} is unaffected
- good for m_{top}
- would be terrible if this was the effect of new physics sough for in m_{top}

search of new physics goes beyond, although get started from, mass measurement

… a delicate task

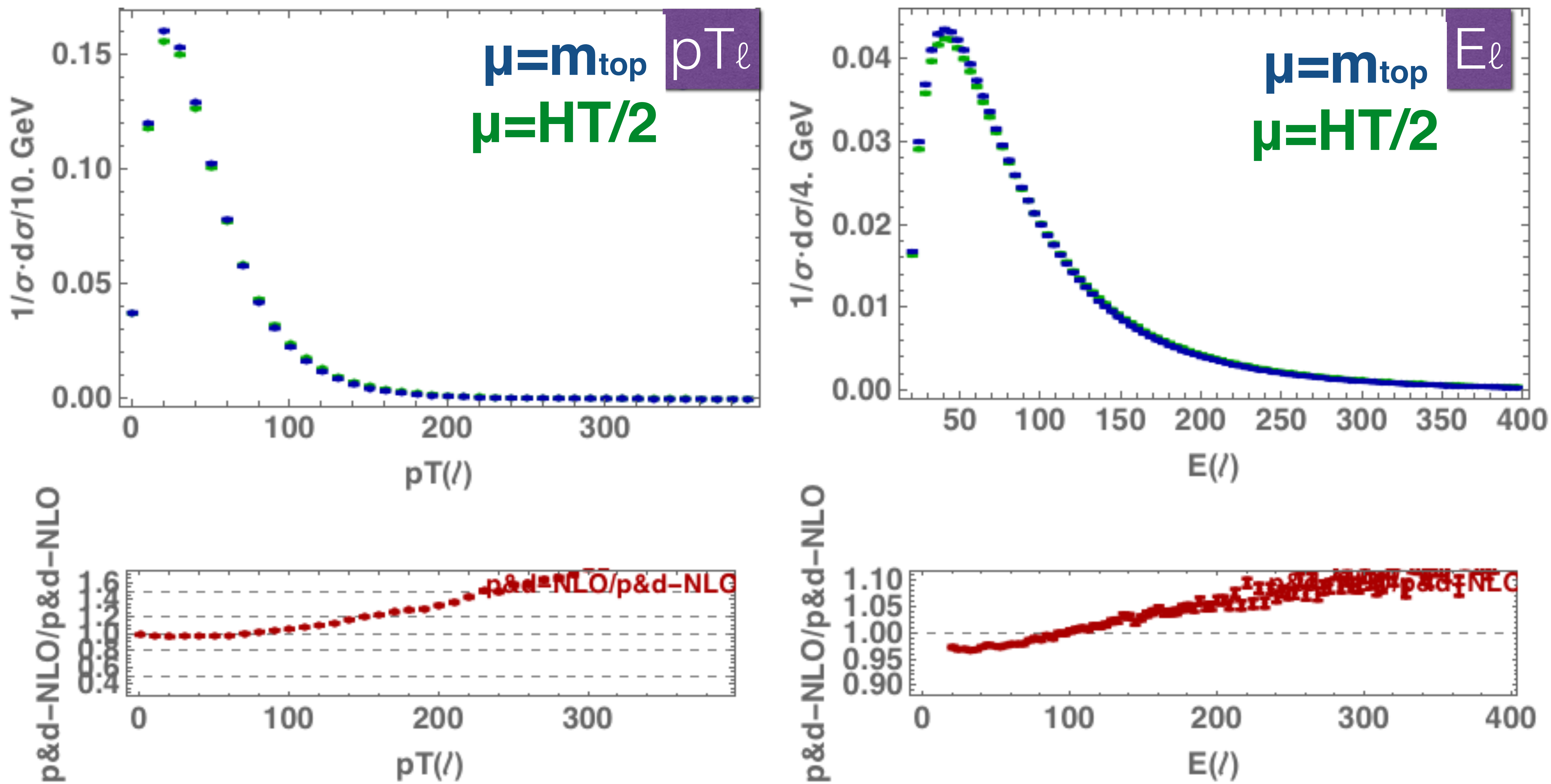
Subtleties of the subtle effects

$\Delta m_{top} \lesssim 1$ GeV and large deviations in the tails



- “large” difference in the tails, m_{top} is affected
- not too bad for m_{top} (1407.2763)
- would be terrible if this was the effect of new physics sough for in these tails

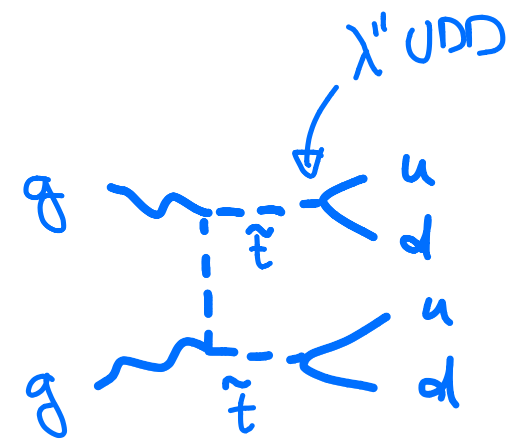
Subtleties of the subtle effects

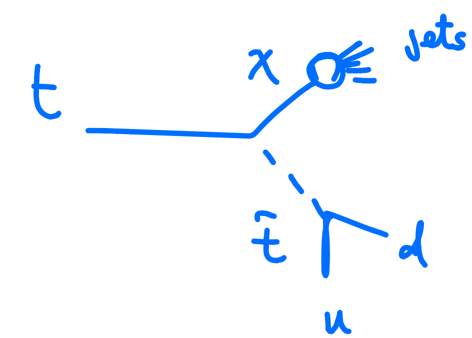


beyond RPC SUSY

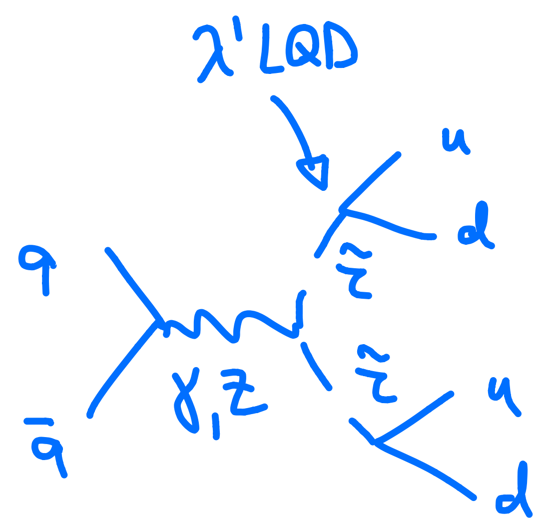
- generic "top-like" new physics

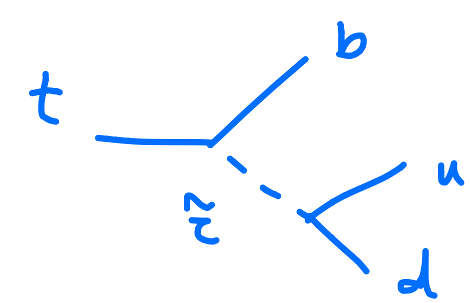
- RPV stop





- RPV stau



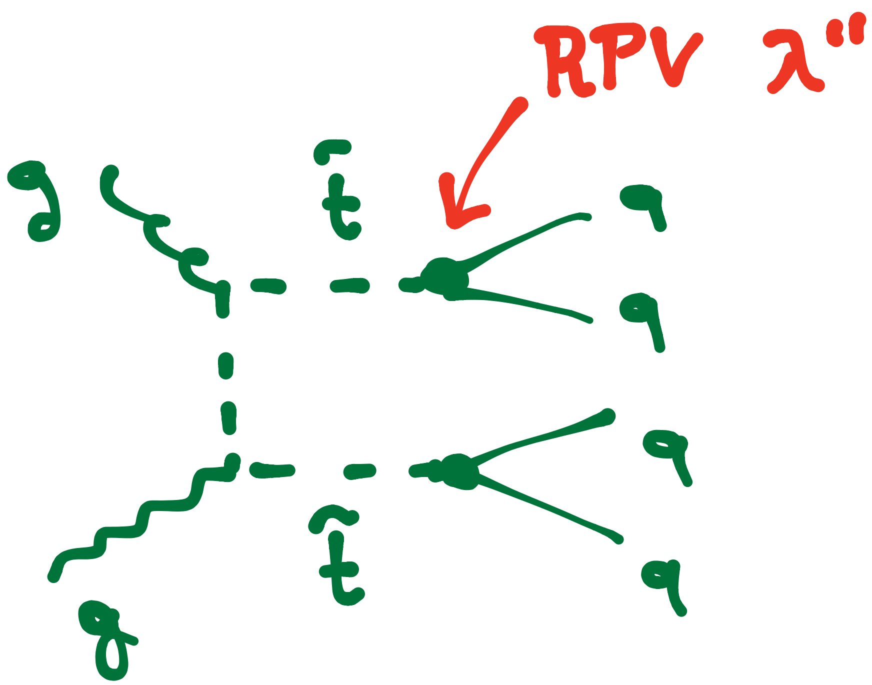


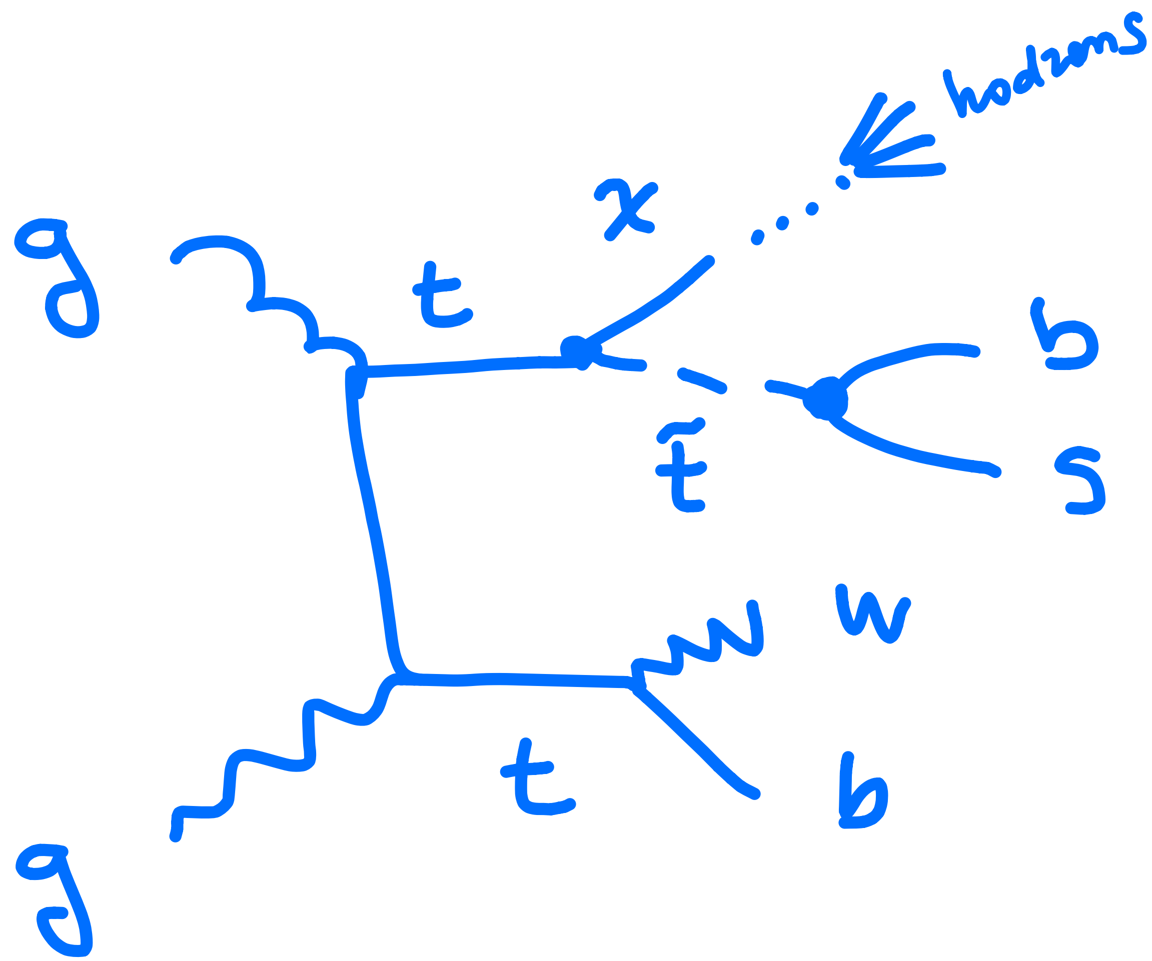
Top as a trigger

Ferretti, RF, Petersson, Torre, in progress

stops from top in RPV SUSY

hadronic stops in RPV SUSY





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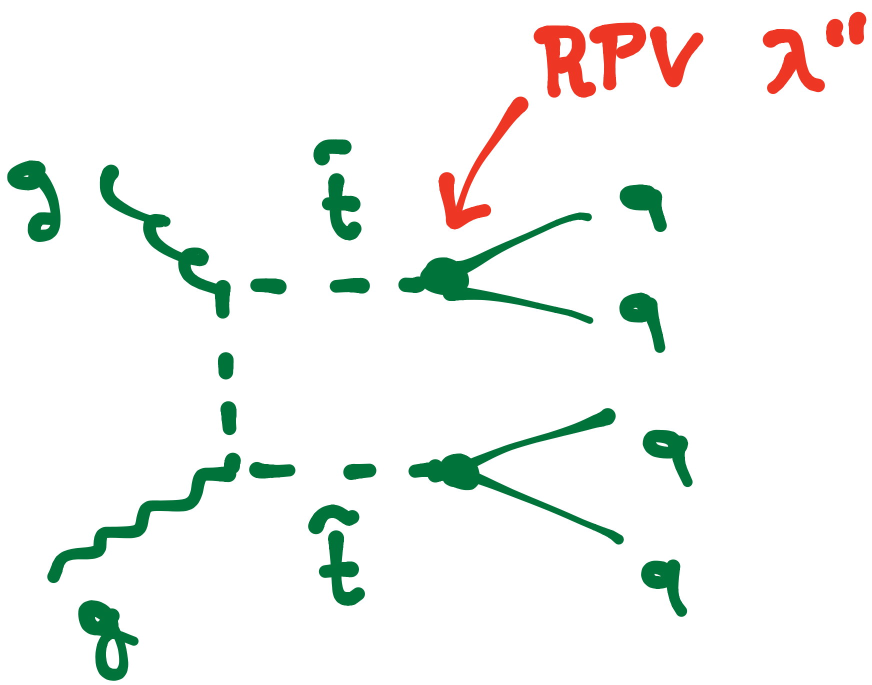

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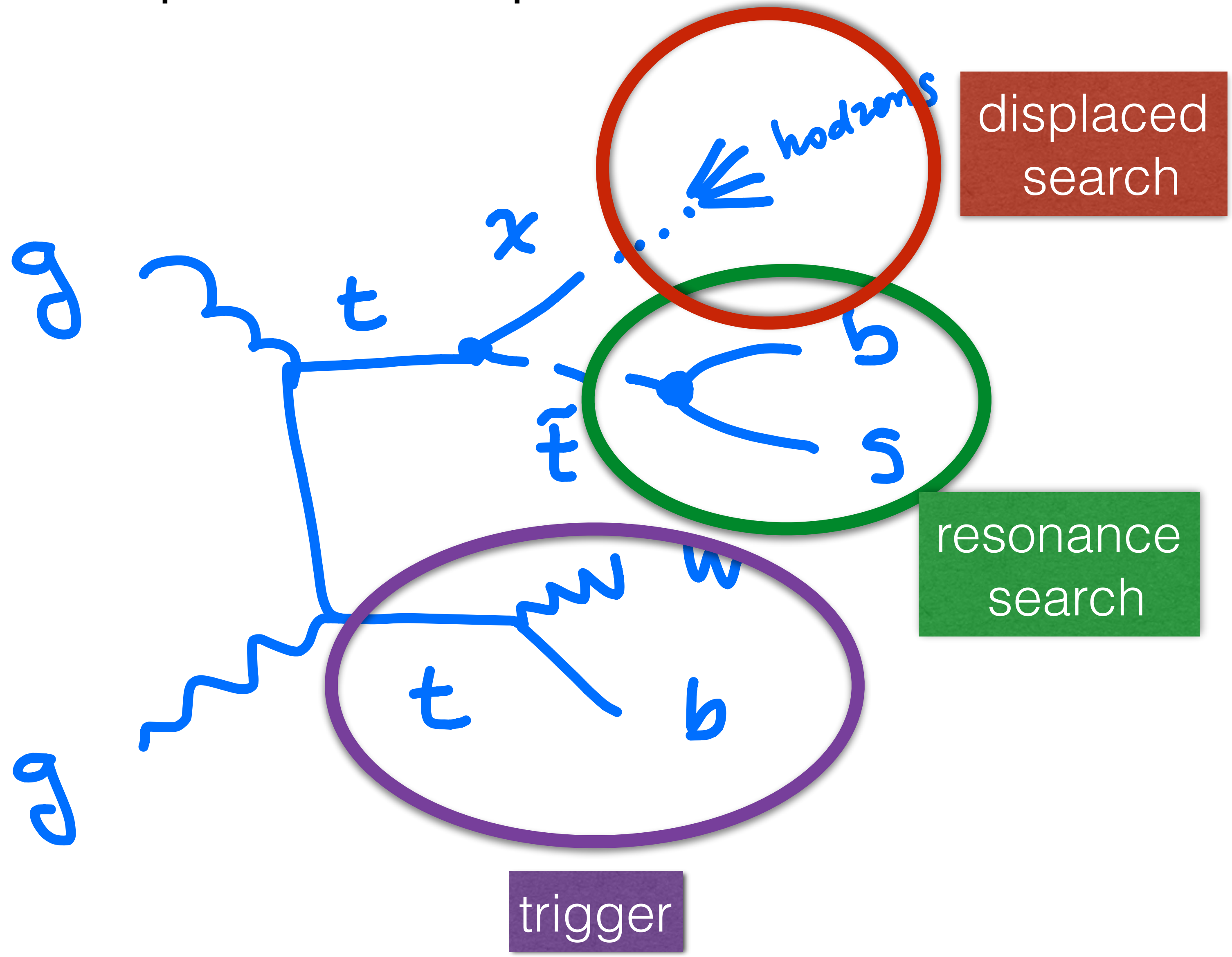

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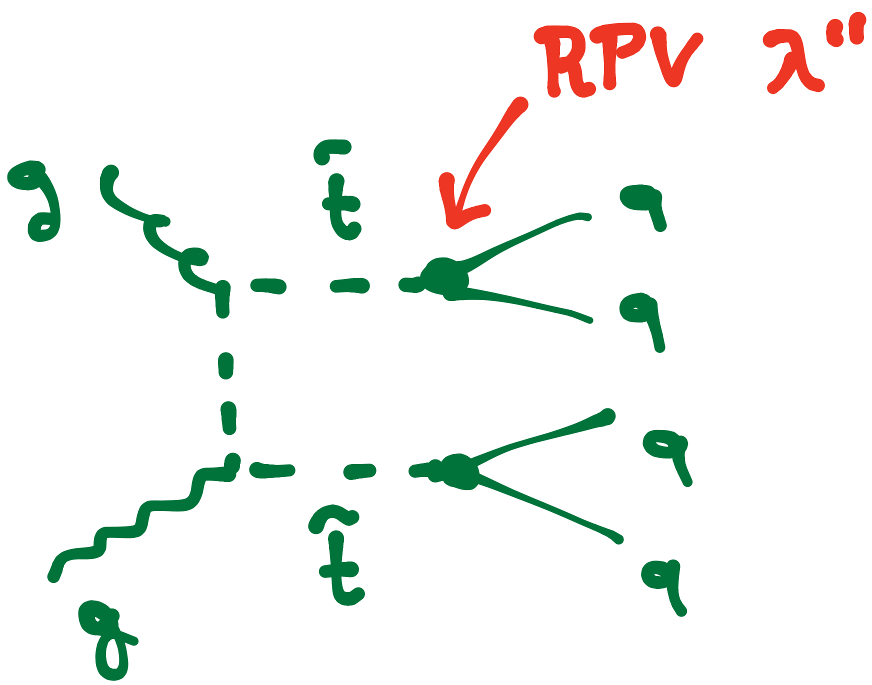

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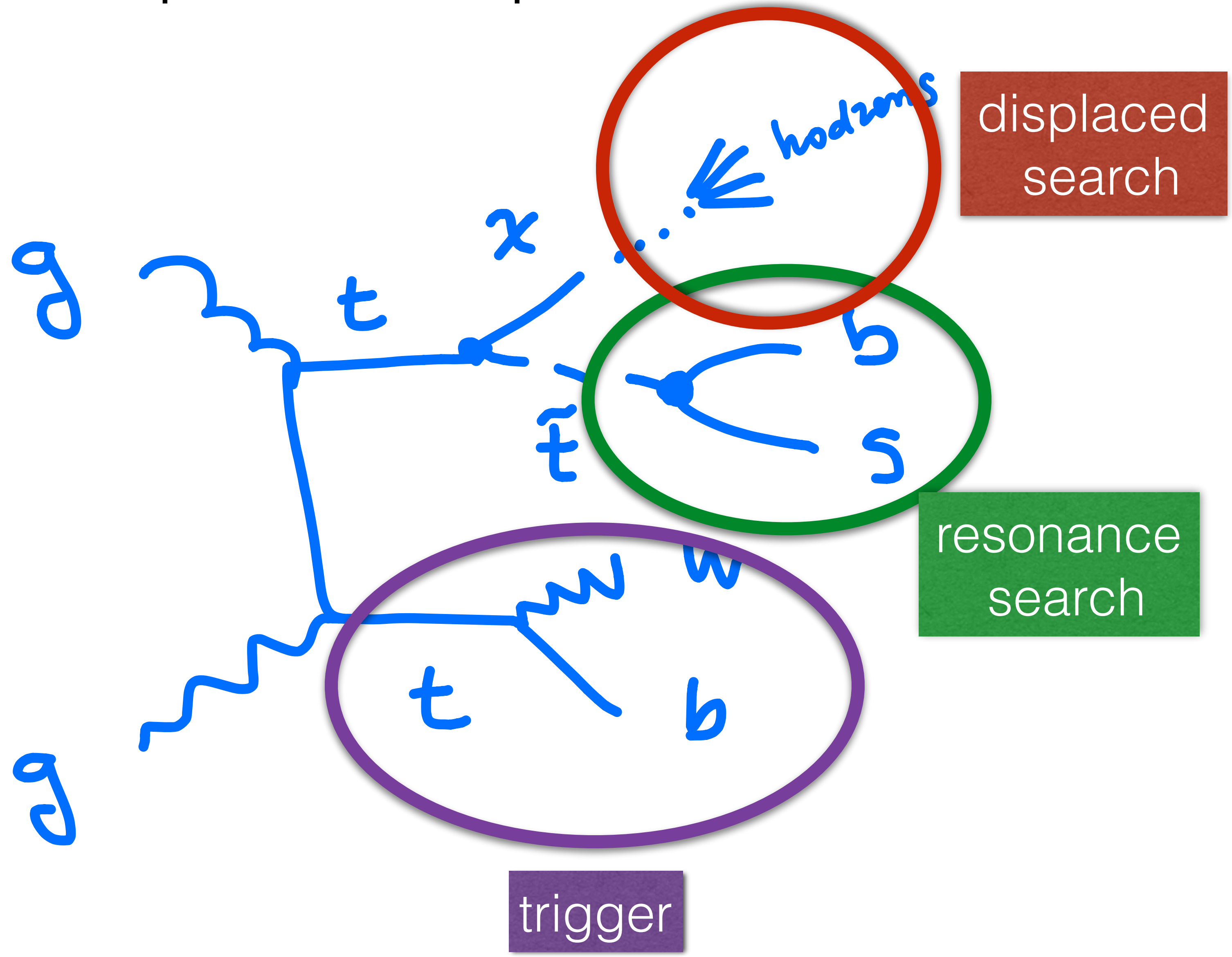

would appear in top properties measurements

Top as a trigger

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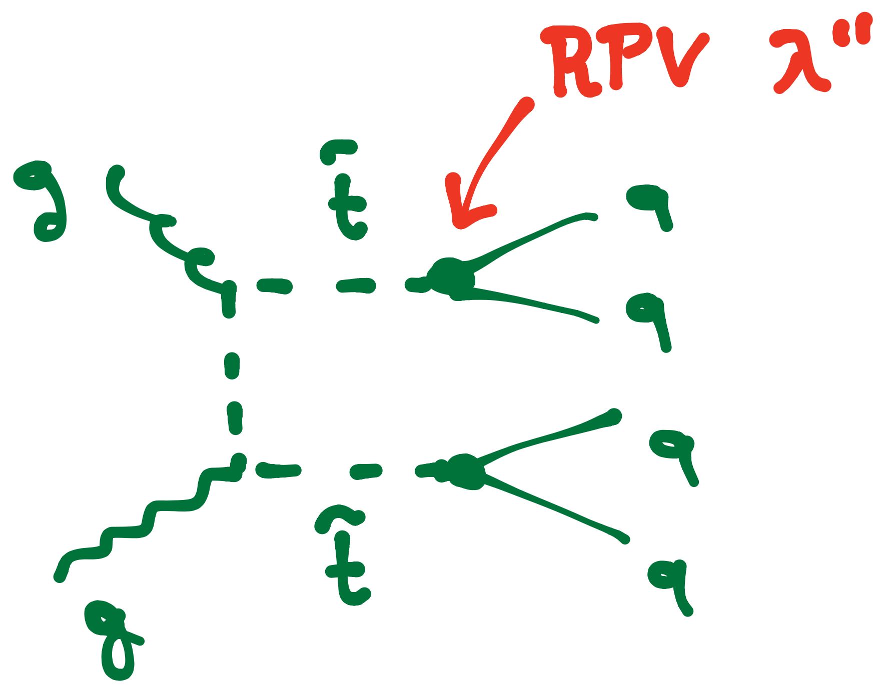

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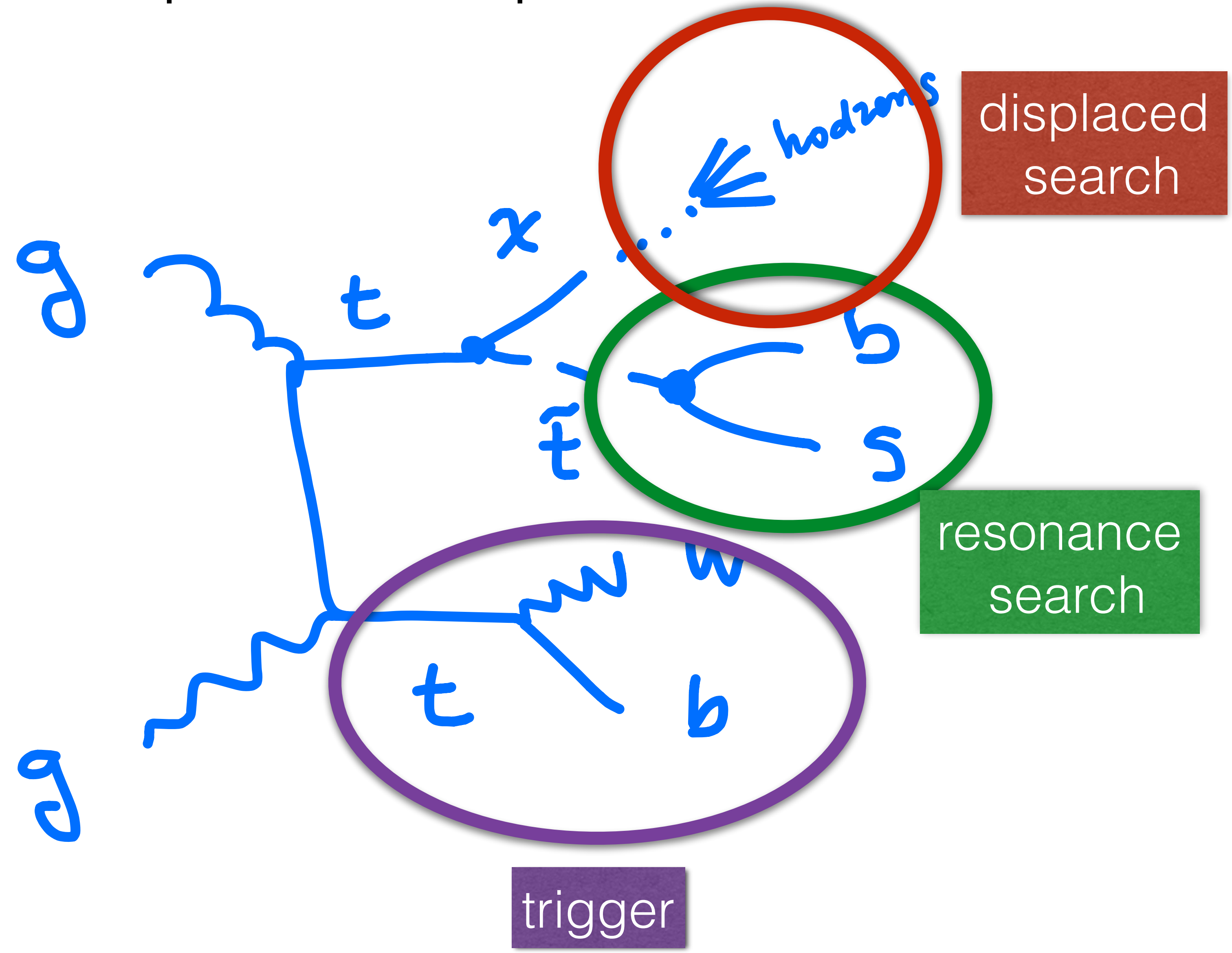

would appear in top properties measurements

CMS “BR” measurement 1506.05074
CMS “V_{tb}” measurement 1404.2292

Top as a trigger

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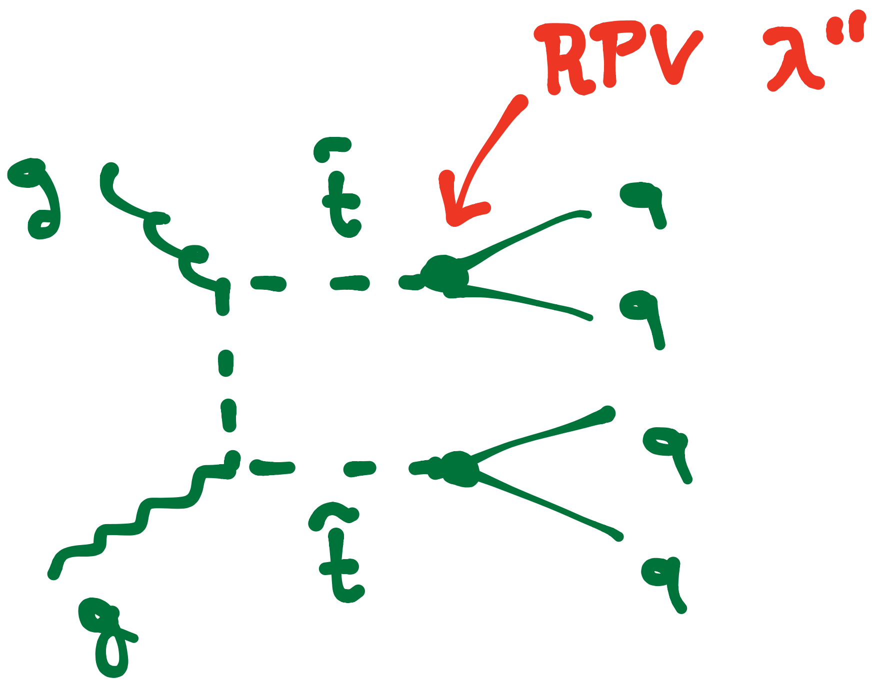
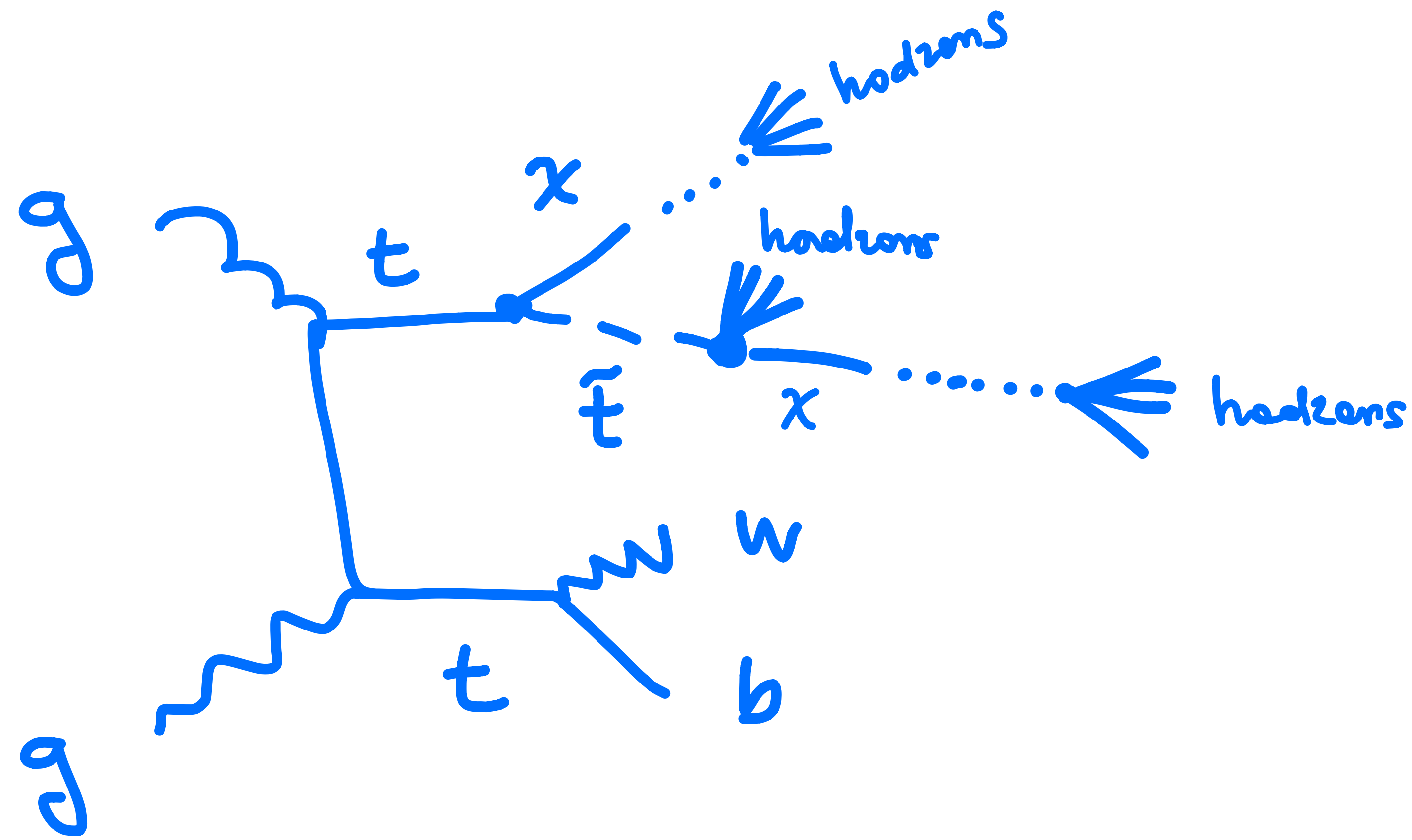
stops from top in RPV SUSY
+ more exotic models

hadronic stops in RPV SUSY





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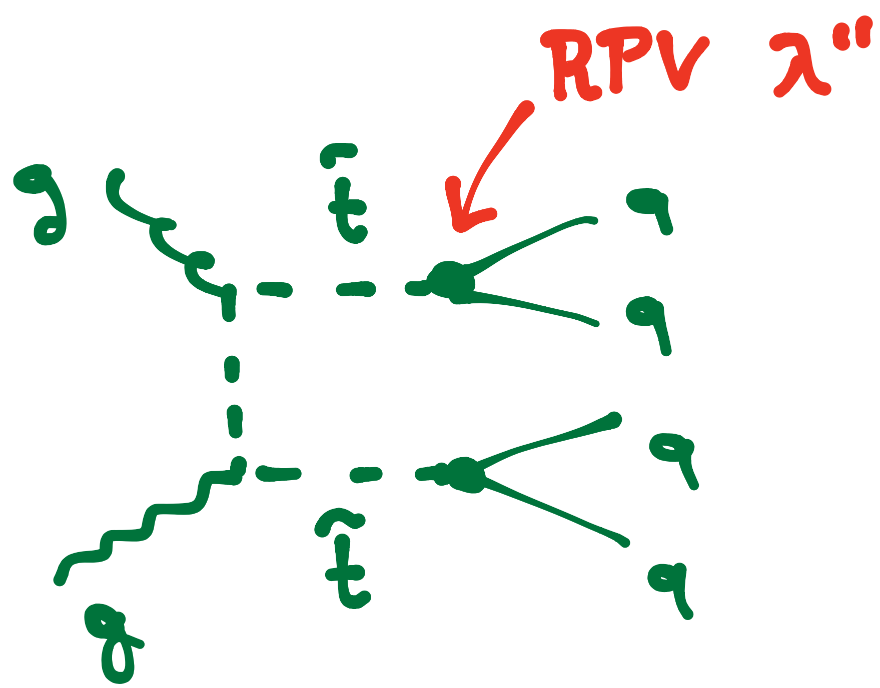

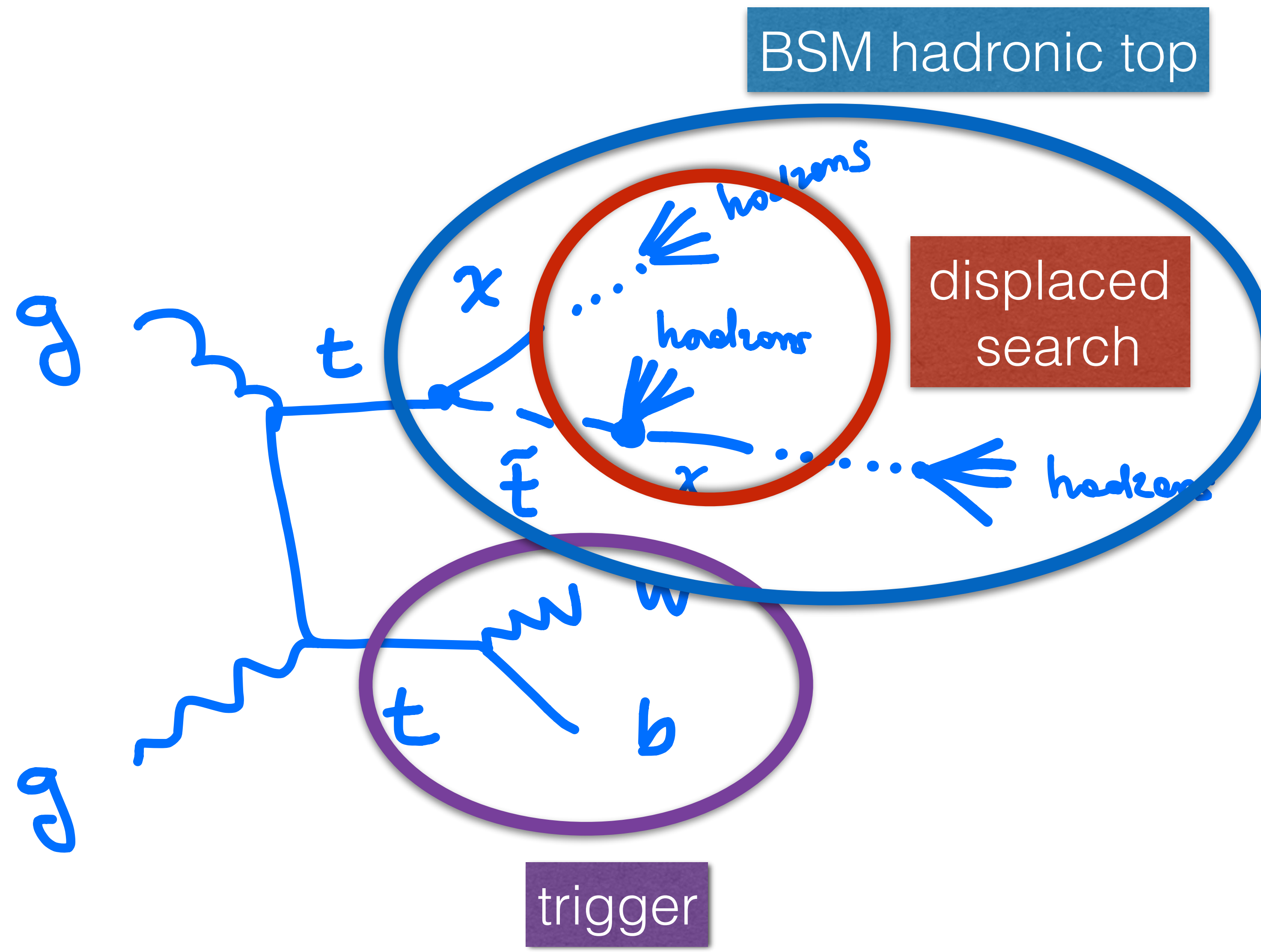

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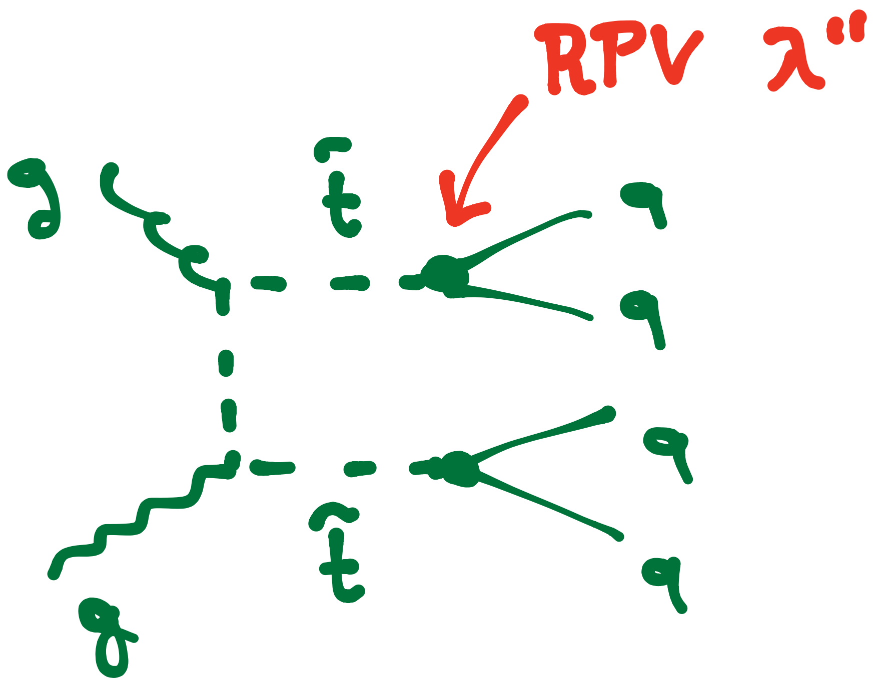

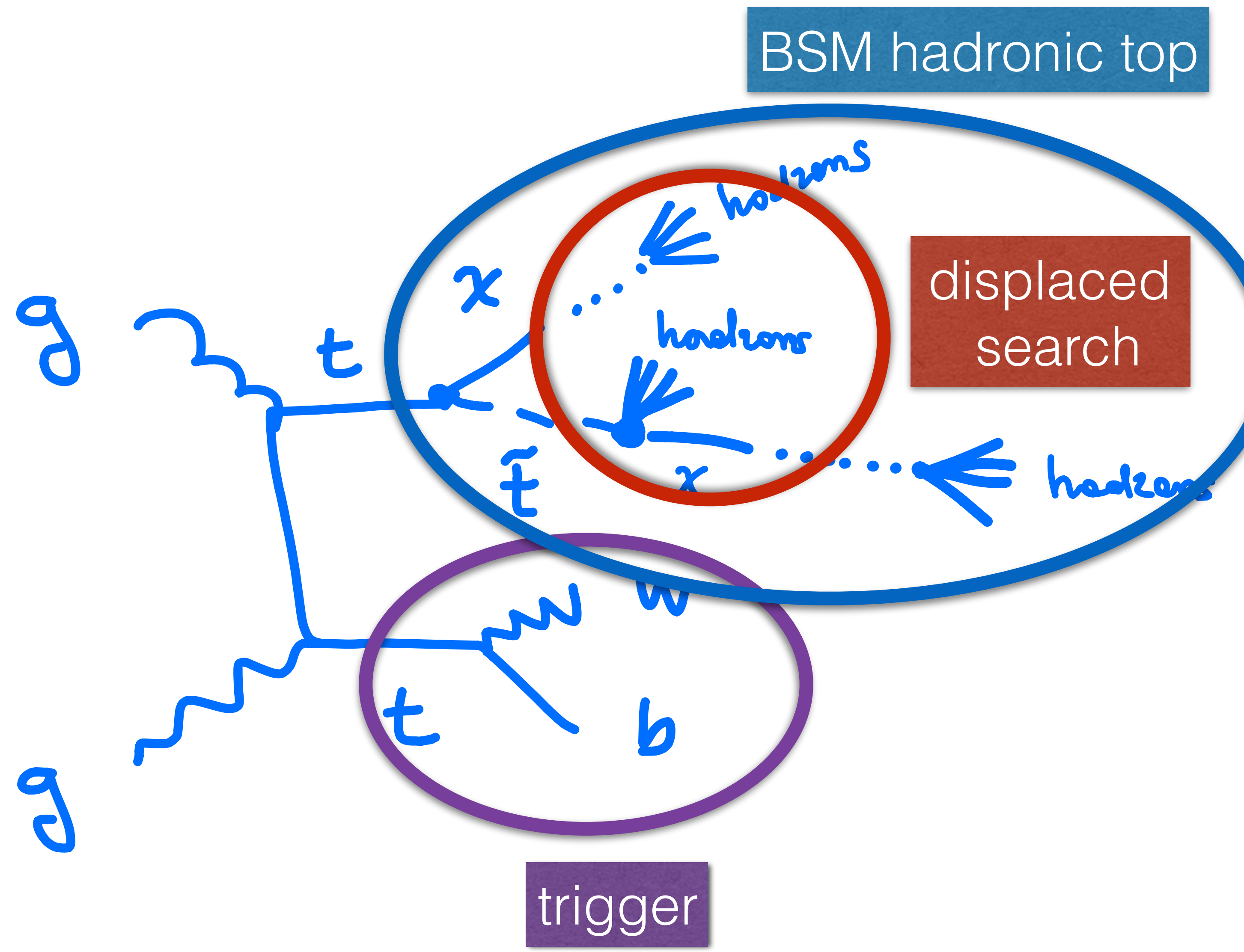

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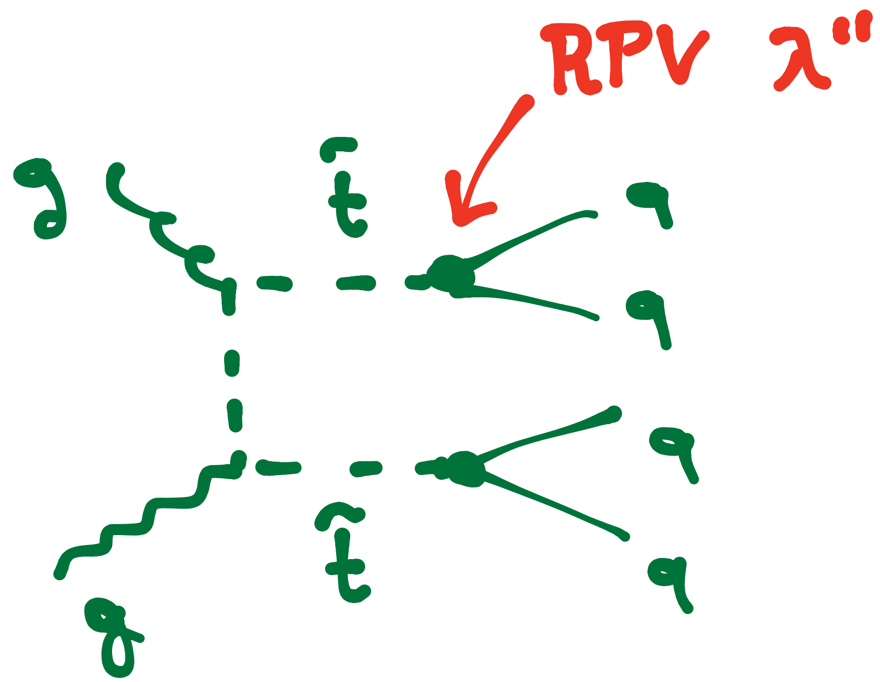
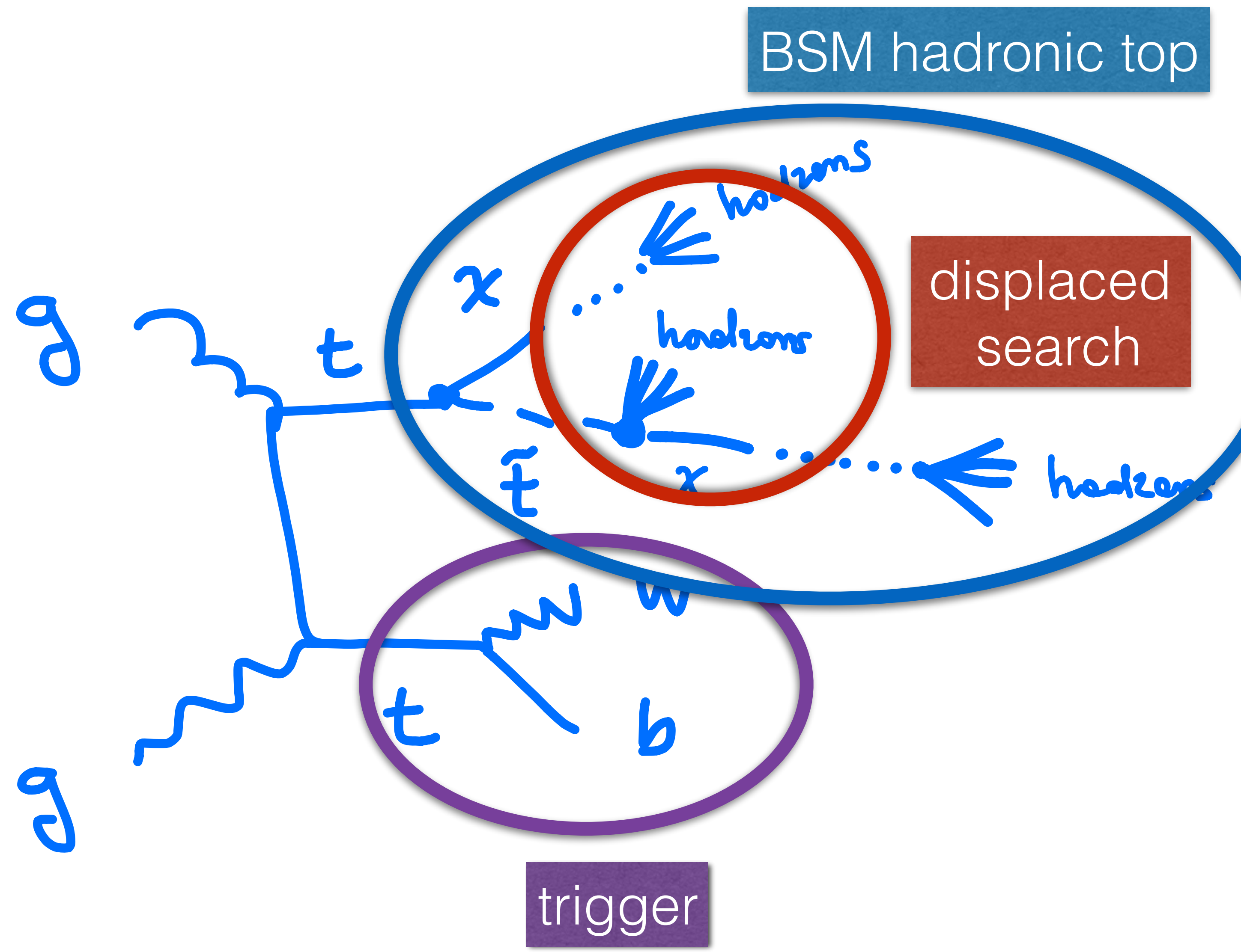
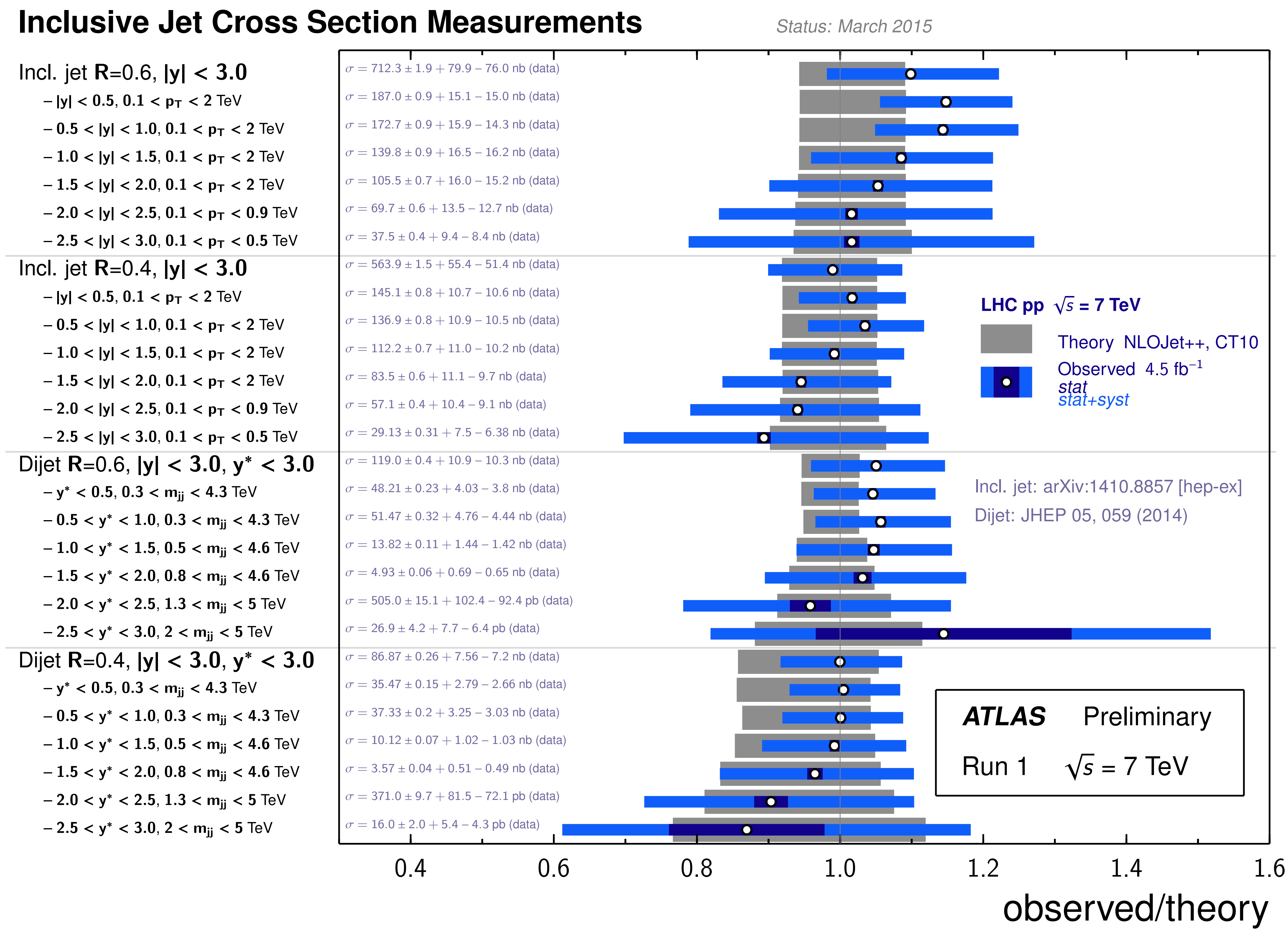




would appear in top properties measurements

CMS “BR” measurement 1506.05074
CMS “V_{tb}” measurement 1404.2292

Precision jet rates?



Conclusions

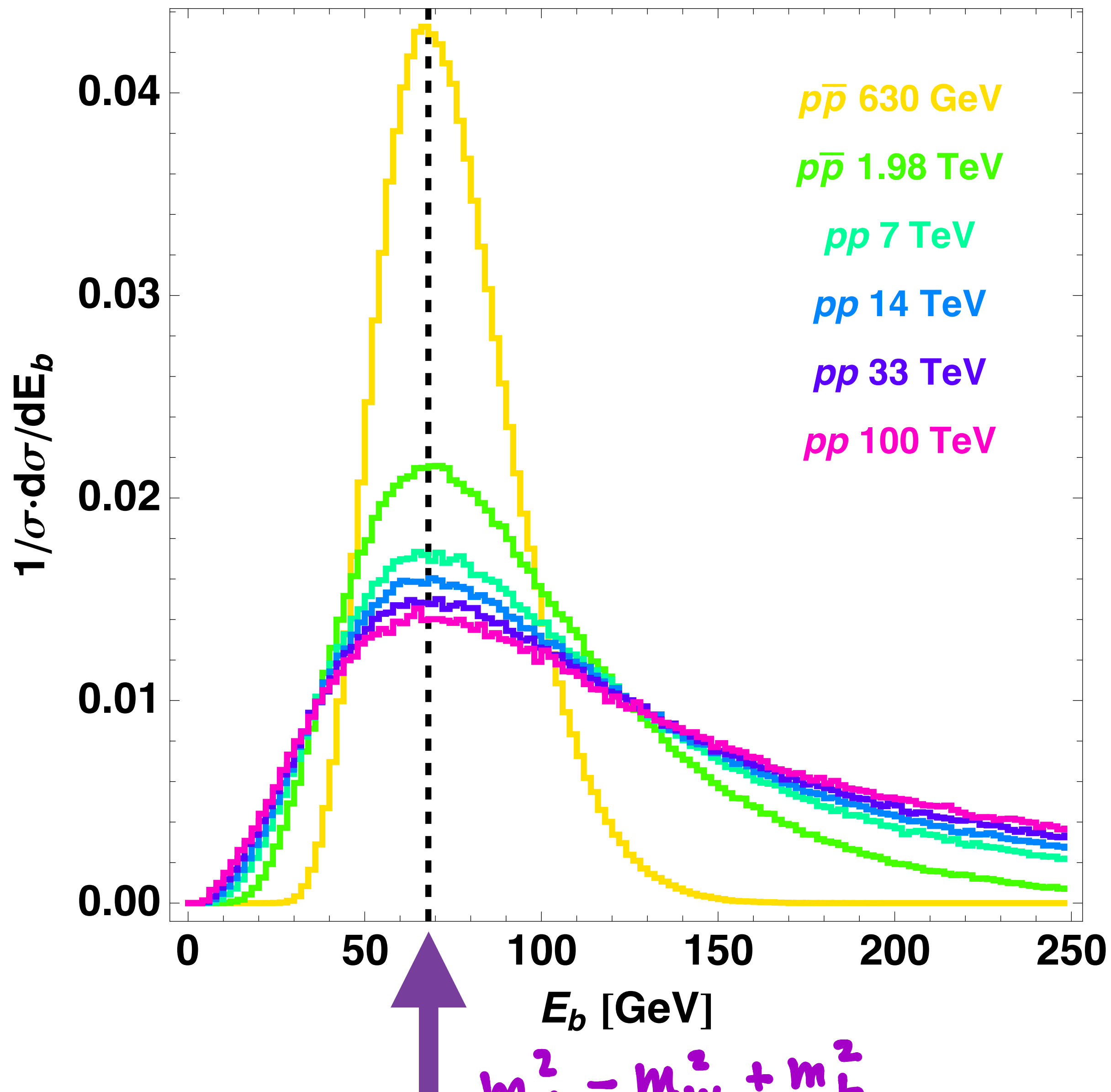
- Run2: more emphasis on precision in SM and BSM
- Many new observables for precision SM measurements (exciting new results e.g. CMS TOP-PAS-15-002)
- **Precision can be turned into an asset to search for BSM!**
- Top quark is ideal playground because of the precision QCD effort and motivation for BSM
- Mass-sensitive variables are an “obvious” set of observables to exploit
- Preliminary studies of precision on the shapes started
- Potentially far-reaching approach (RPC, RPV, top-like, …)
- Jet physics can soon be in the same status

Thank you!

How special is this invariance?

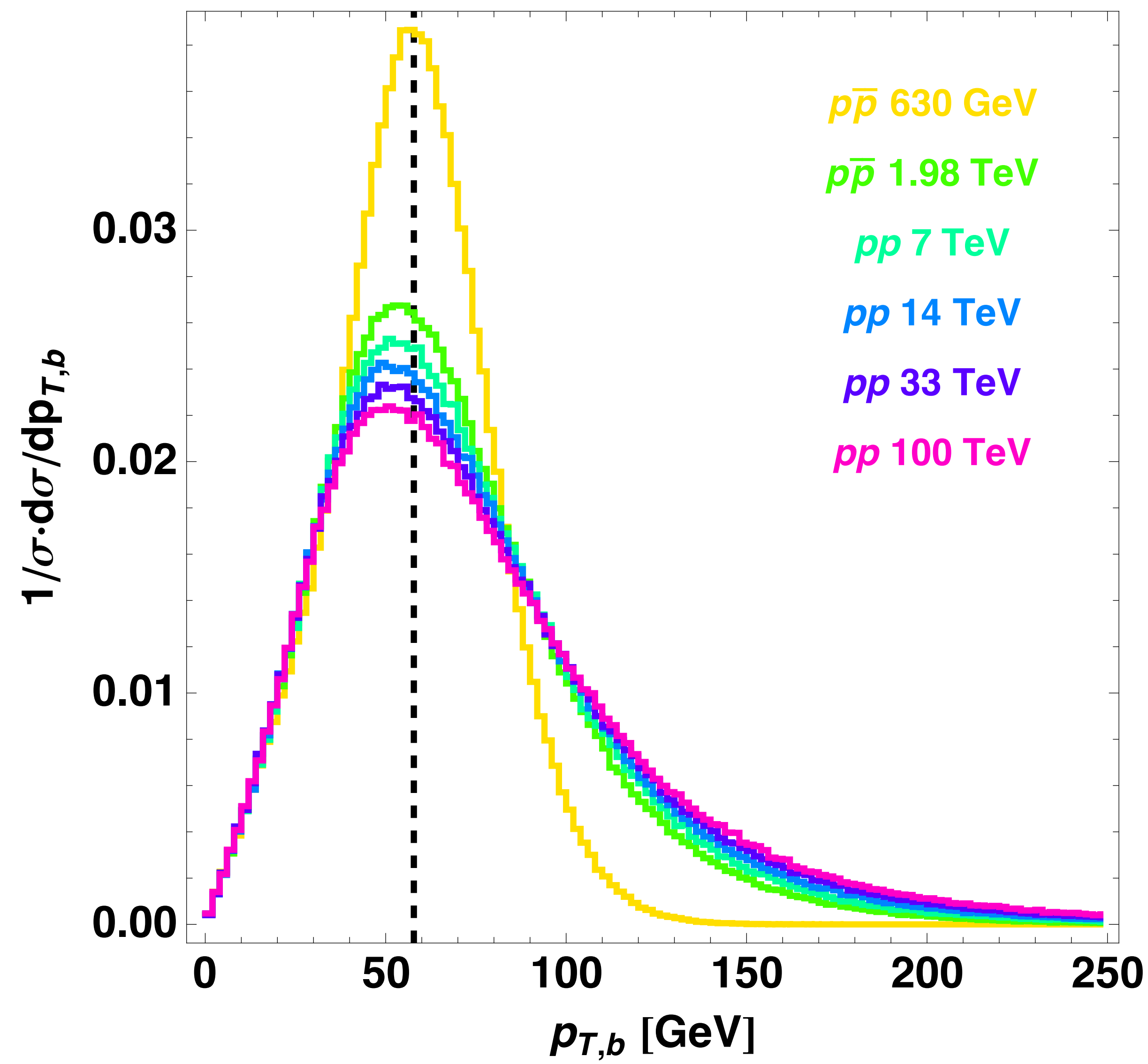
1209.0772 - Agashe, Franceschini and Kim

Shape changes, peak doesn't!



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

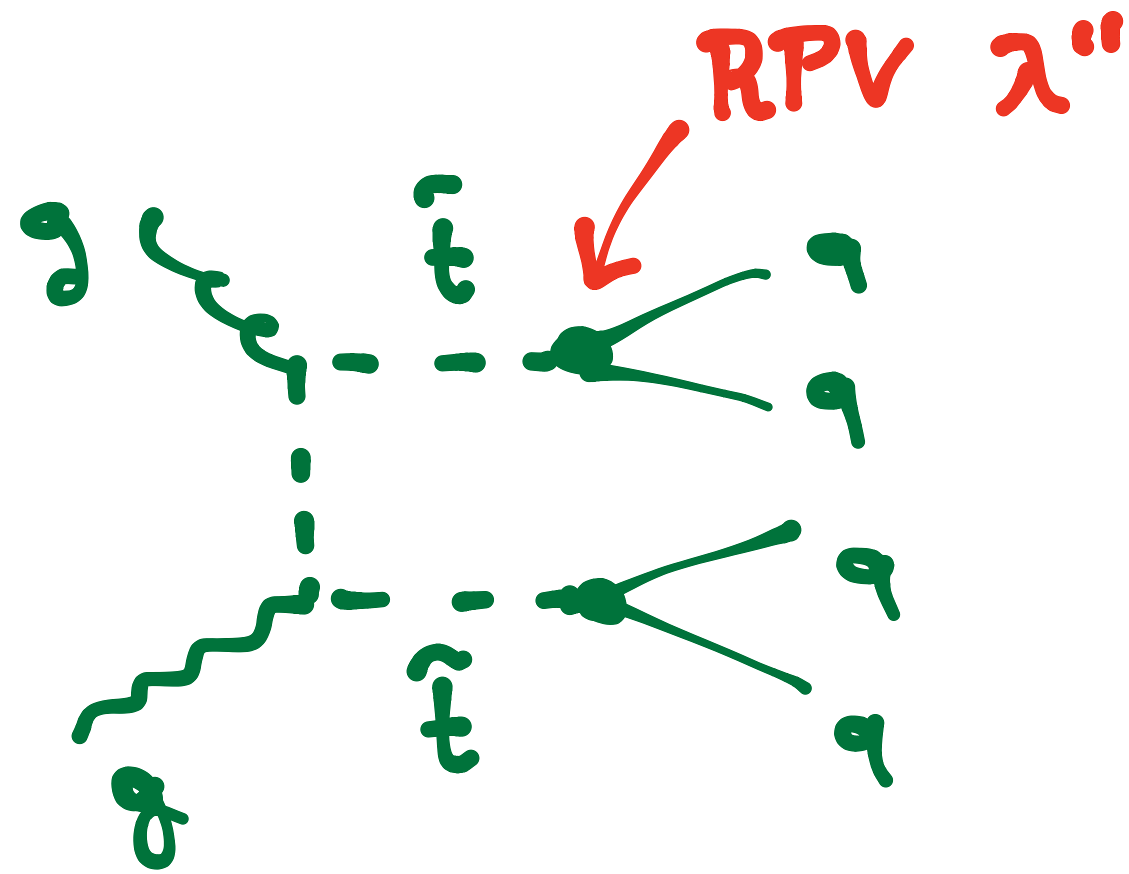
Shape changes, peak does too



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

Top as a trigger

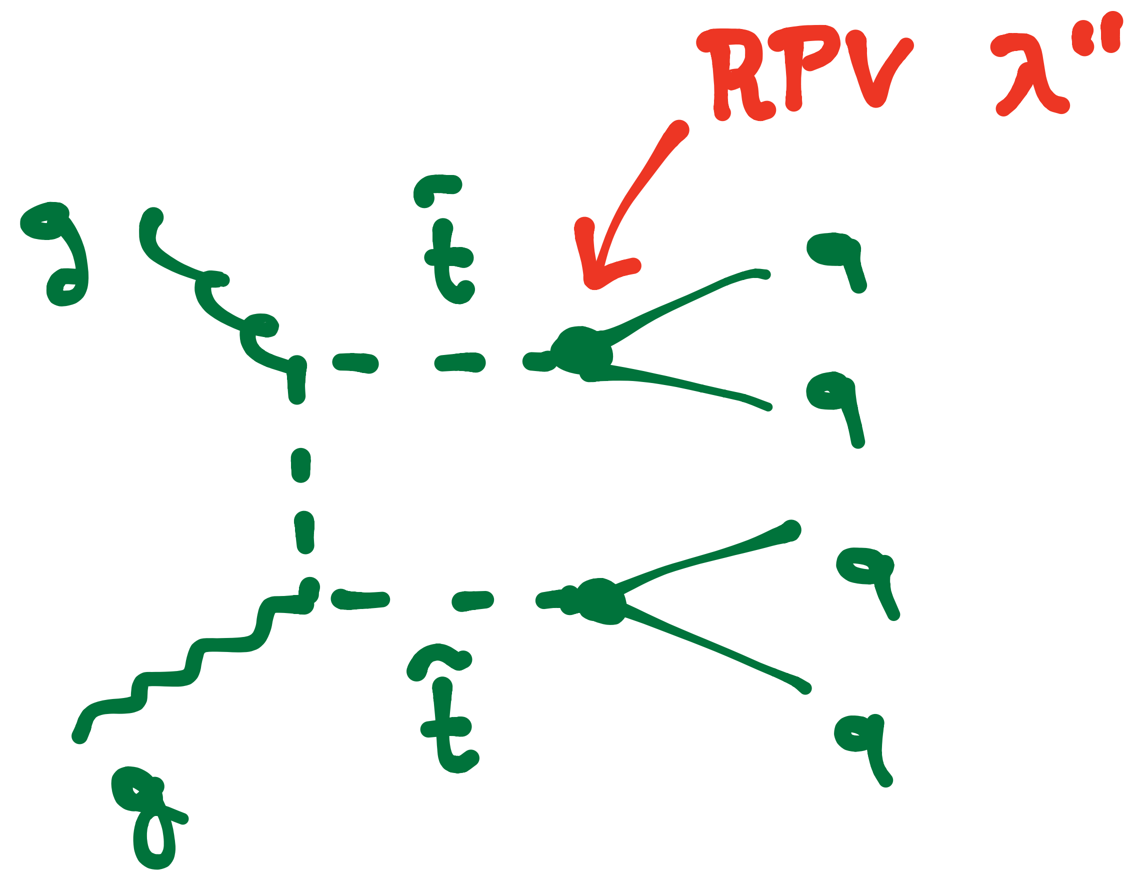
hadronic stops in RPV SUSY



large QCD cross-section for direct production

Top as a trigger

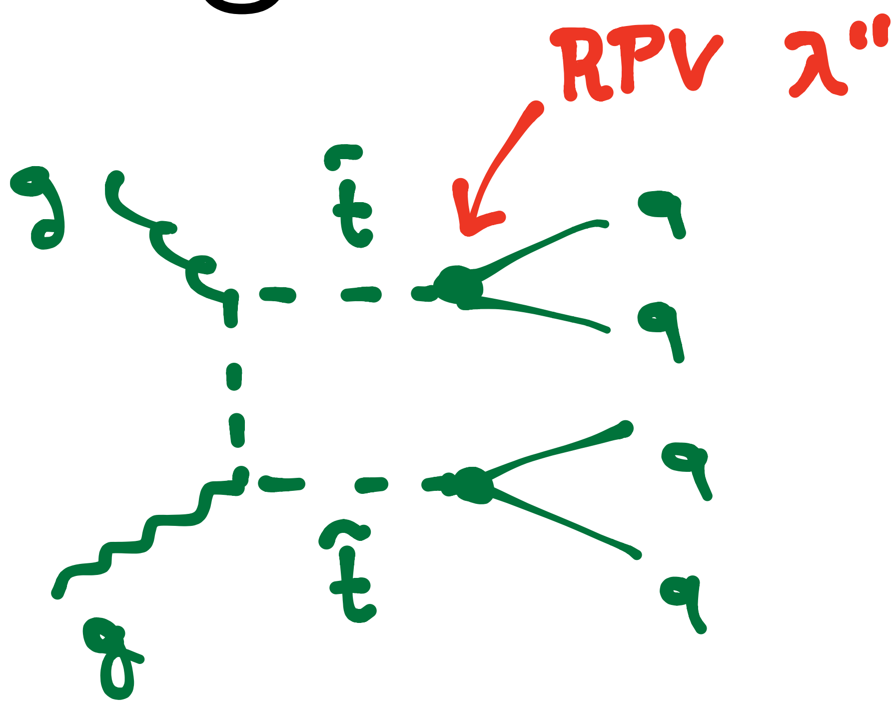
hadronic stops in RPV SUSY



large QCD cross-section for direct production

larger QCD background!

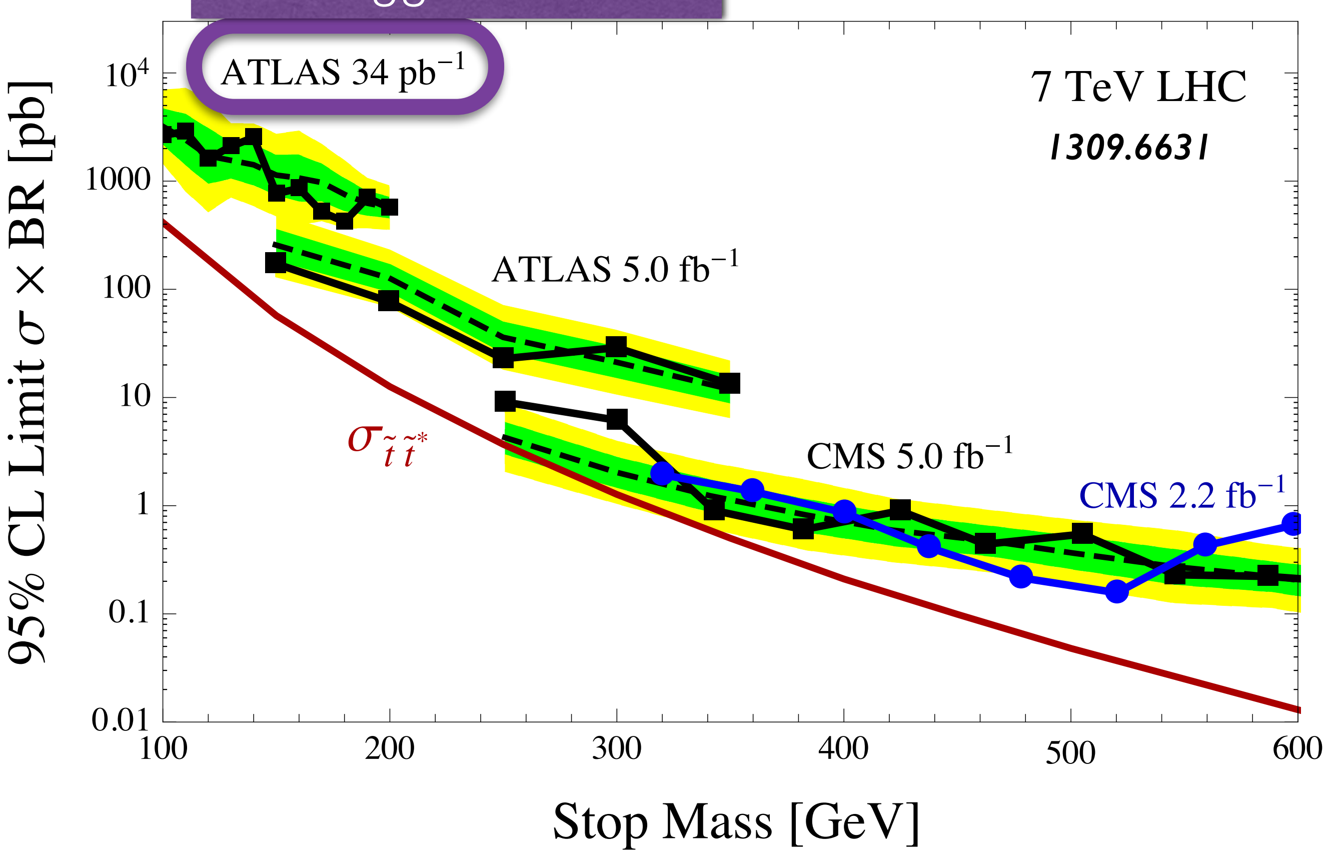
Light bumps are difficult

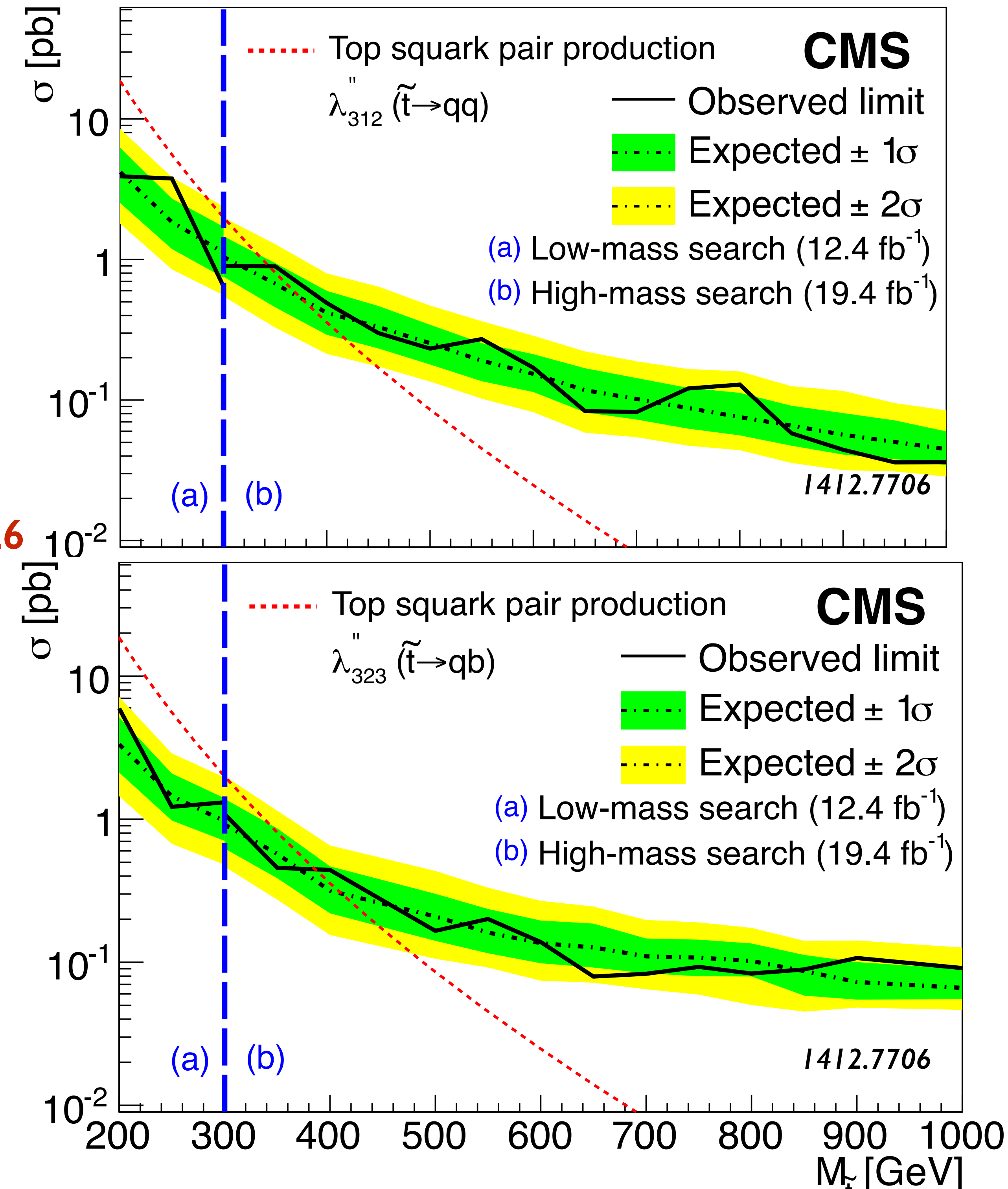


trigger is a killer at low mass

cut&count w/sub-structure in ATLAS-CONF-2015-026

lower trigger thresholds



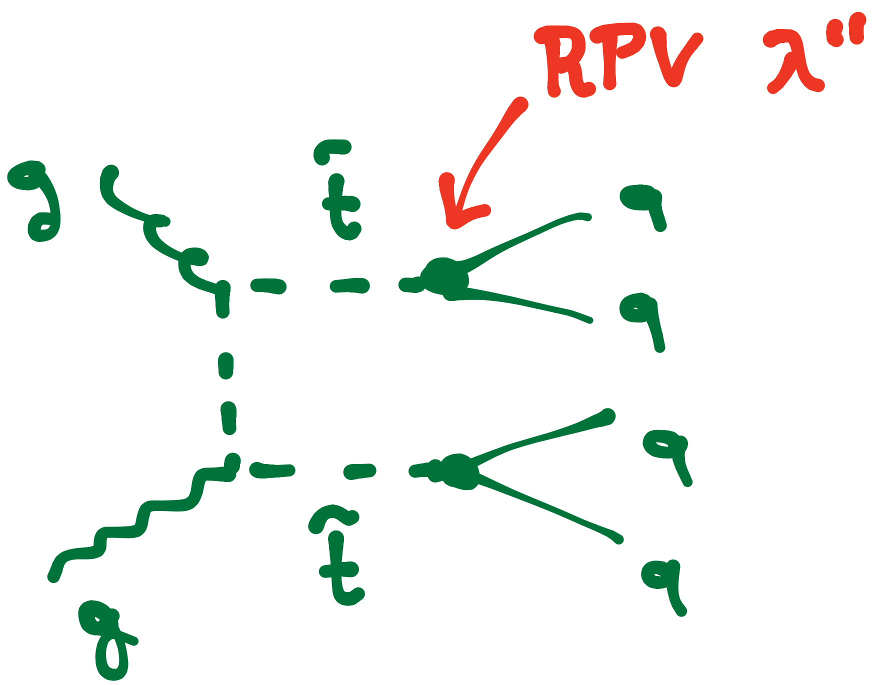


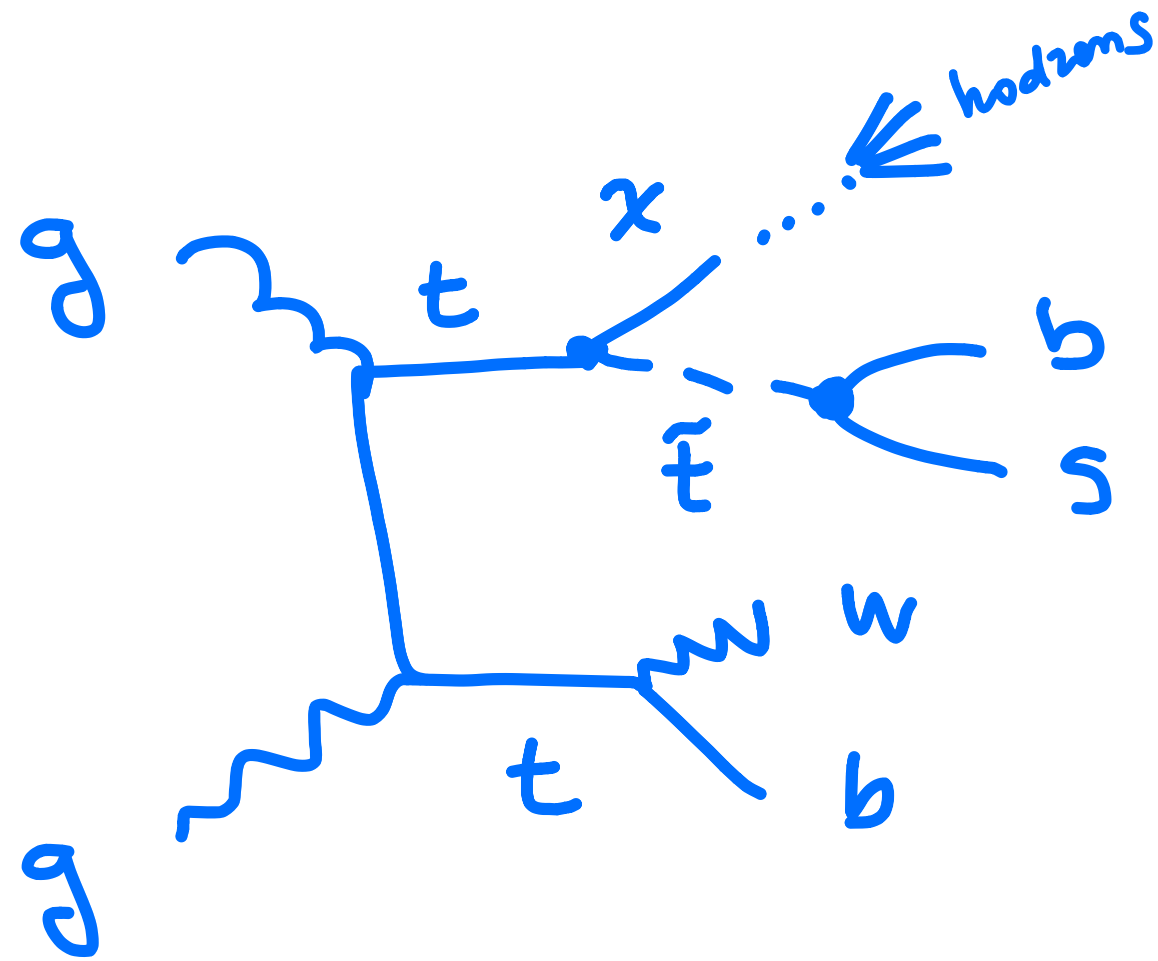
Top as a trigger

Ferretti, RF, Petersson, Torre, in progress

stops from top in RPV SUSY

hadronic stops in RPV SUSY





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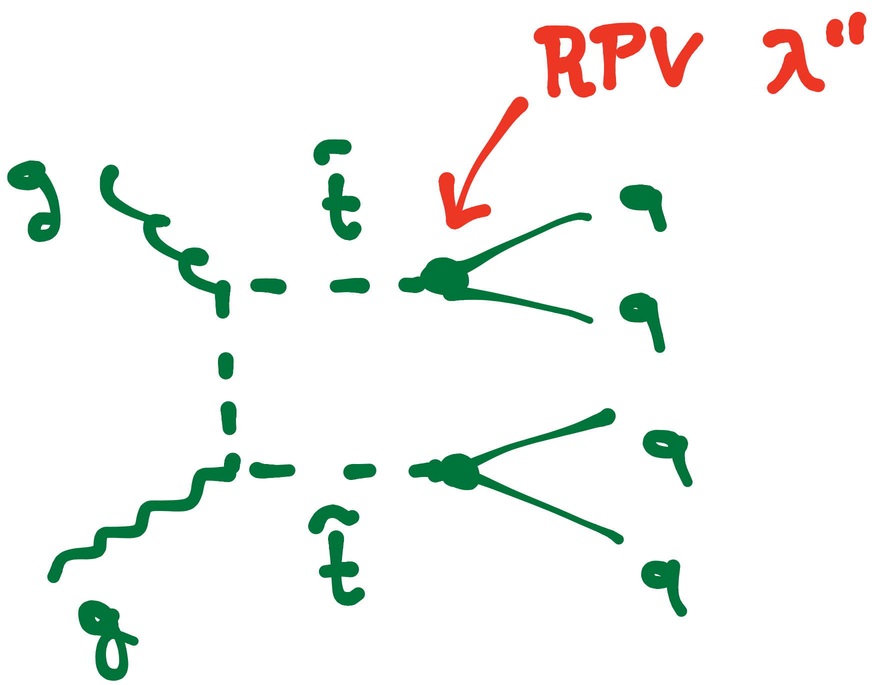
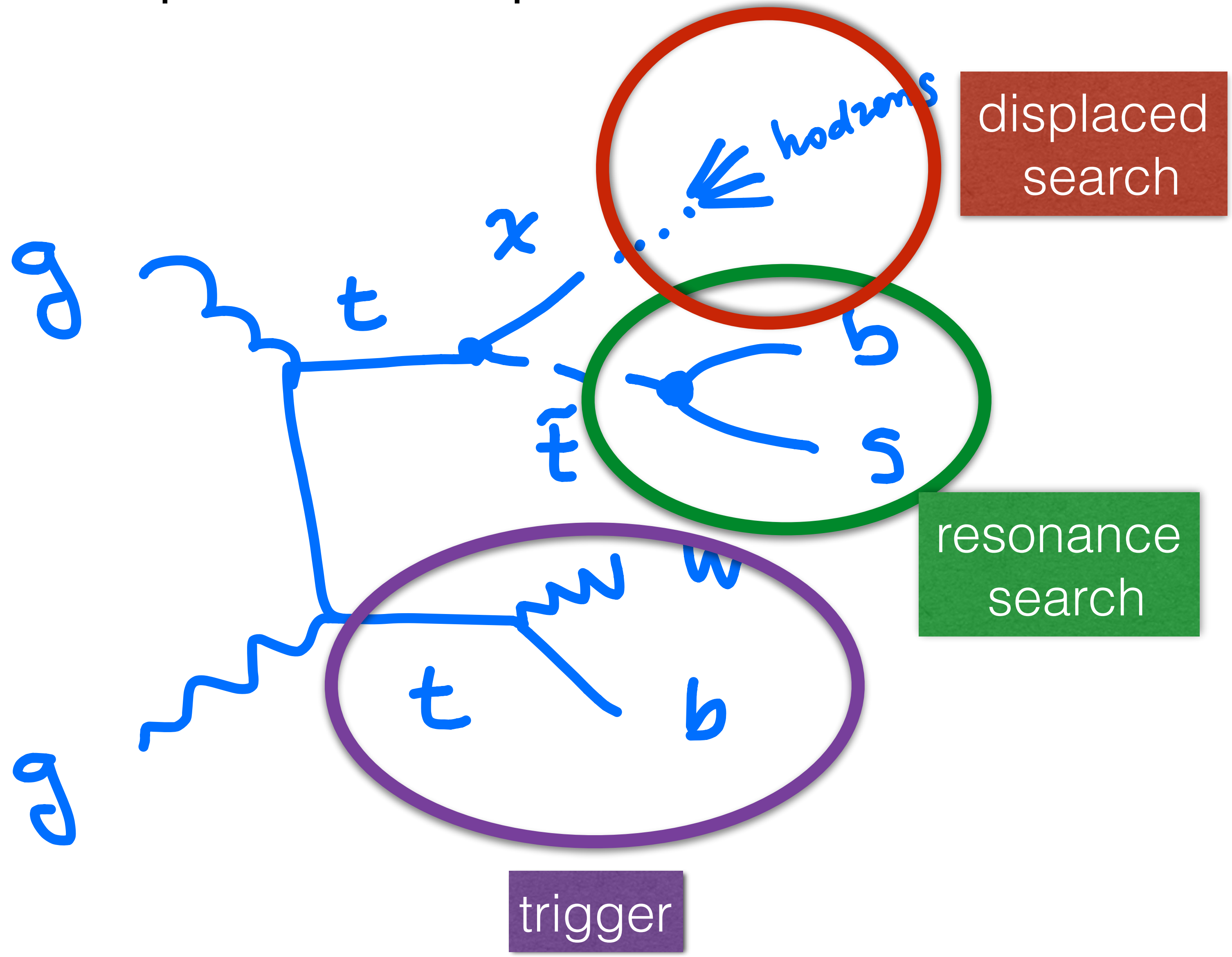


stops from top in RPV SUSY



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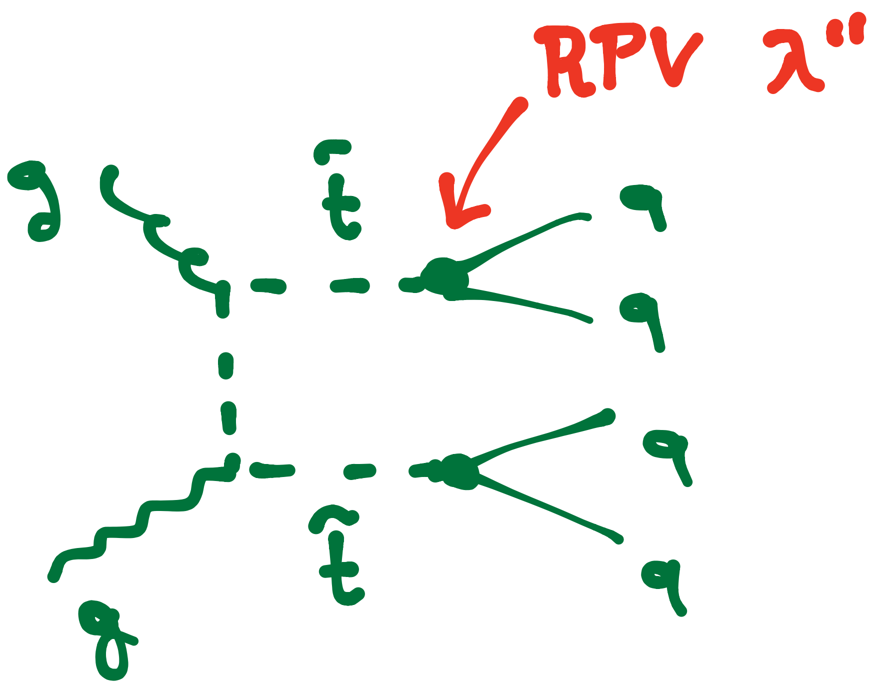
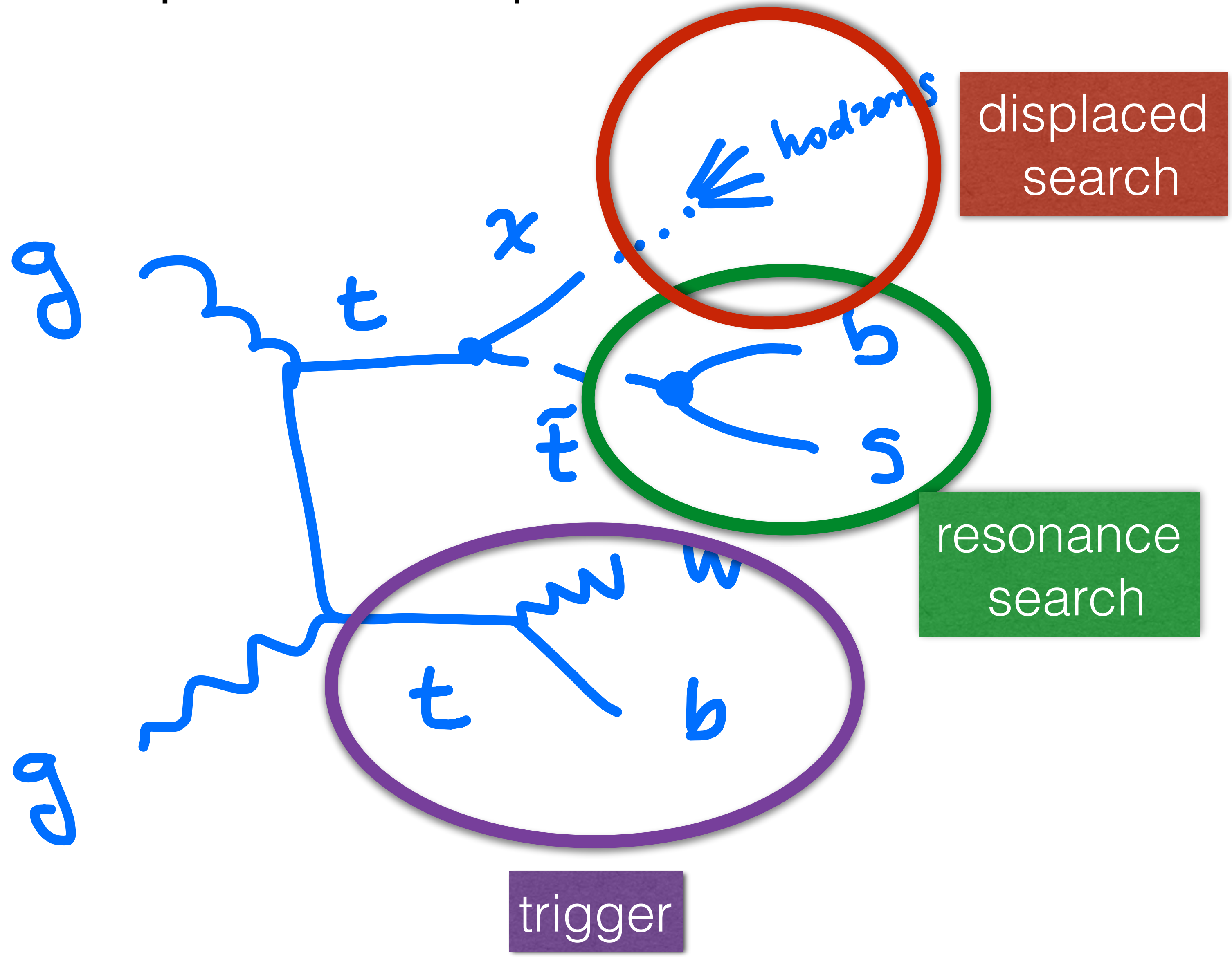


stops from top in RPV SUSY

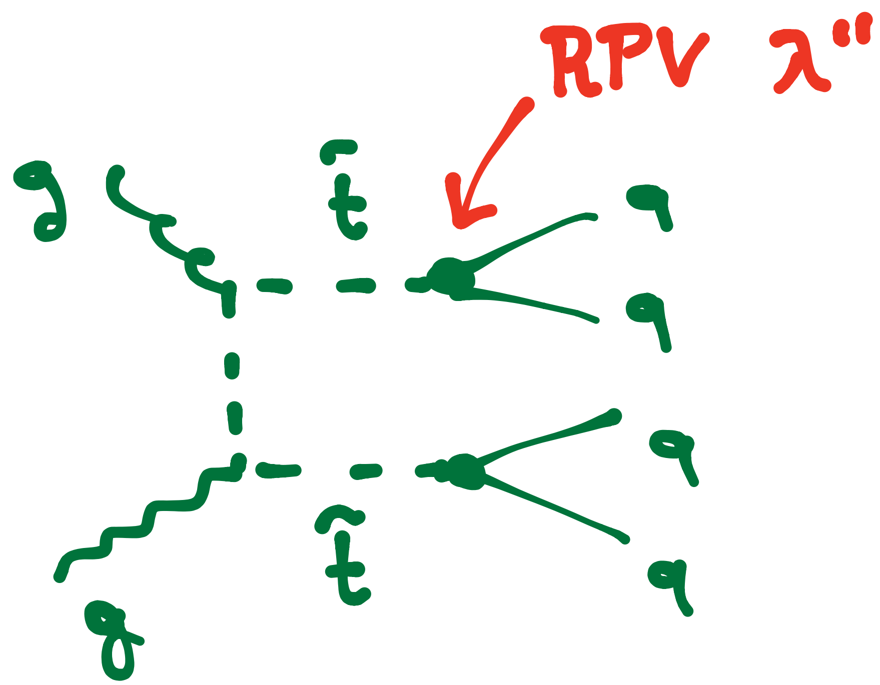


would appear in top properties measurements

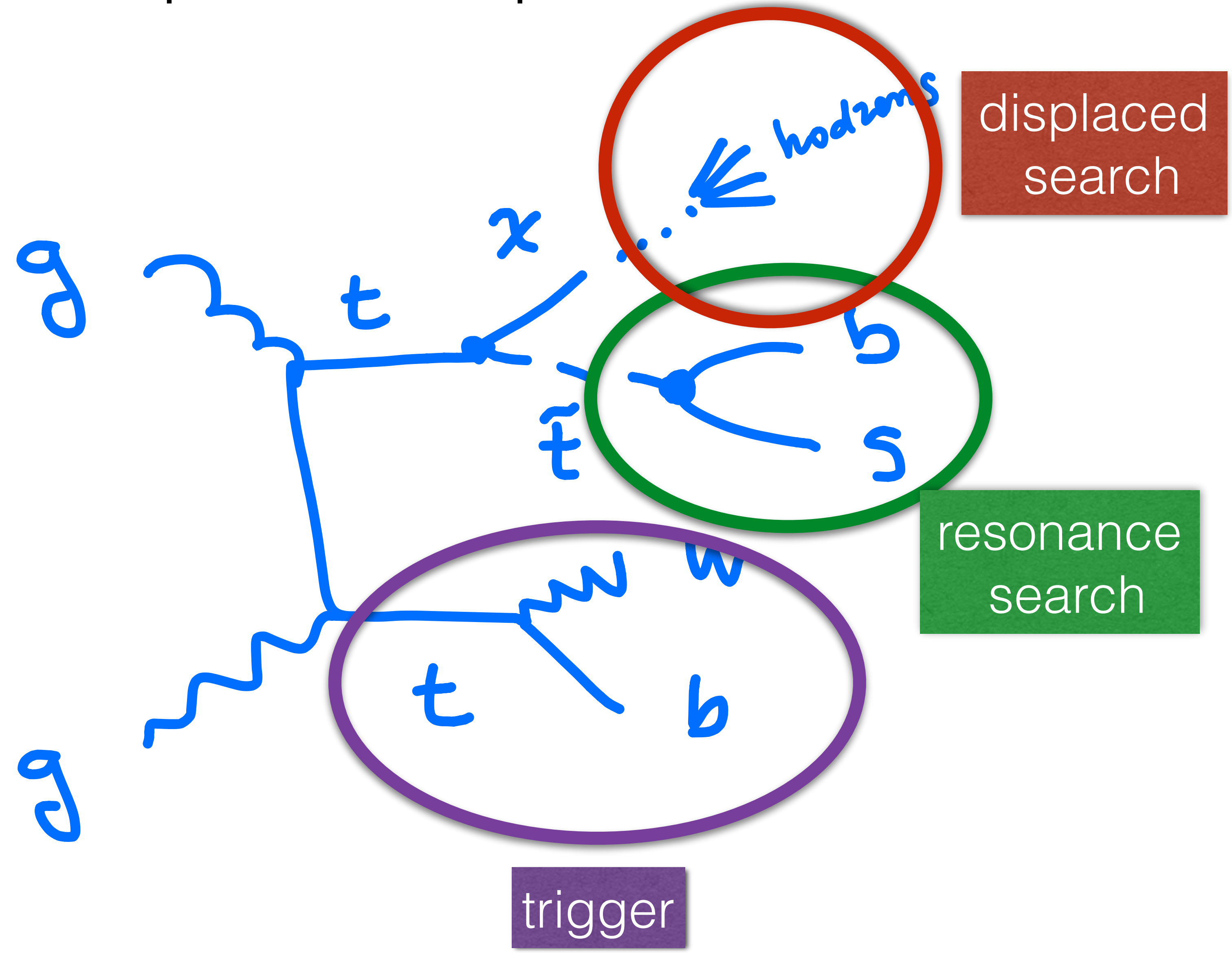
Top as a trigger

Ferretti, RF, Petersson, Torre, in progress

hadronic stops in RPV SUSY



stops from top in RPV SUSY



would appear in top properties measurements

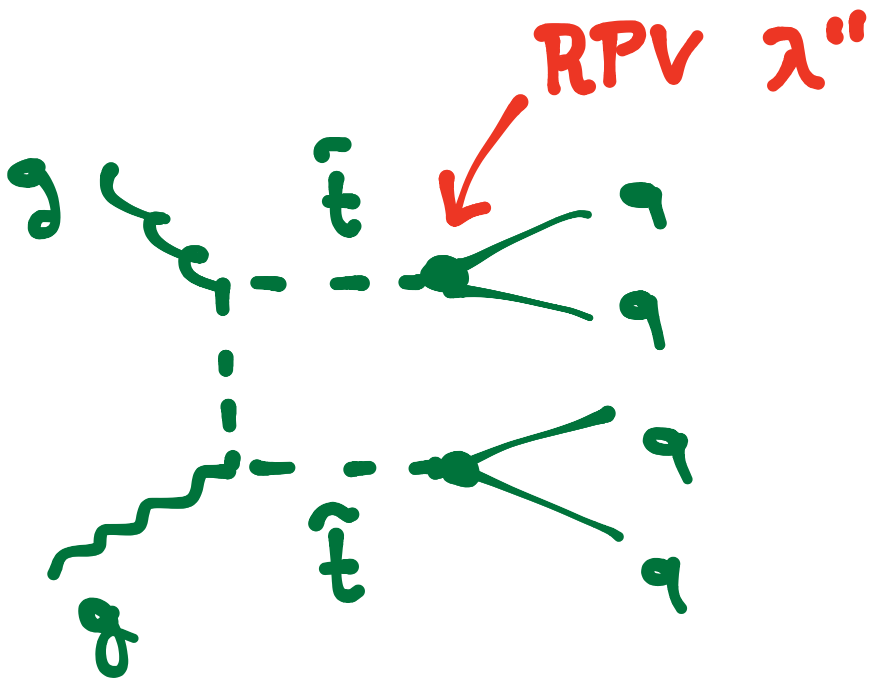
CMS "BR" measurement 1506.05074
CMS "Vtb" measurement 1404.2292

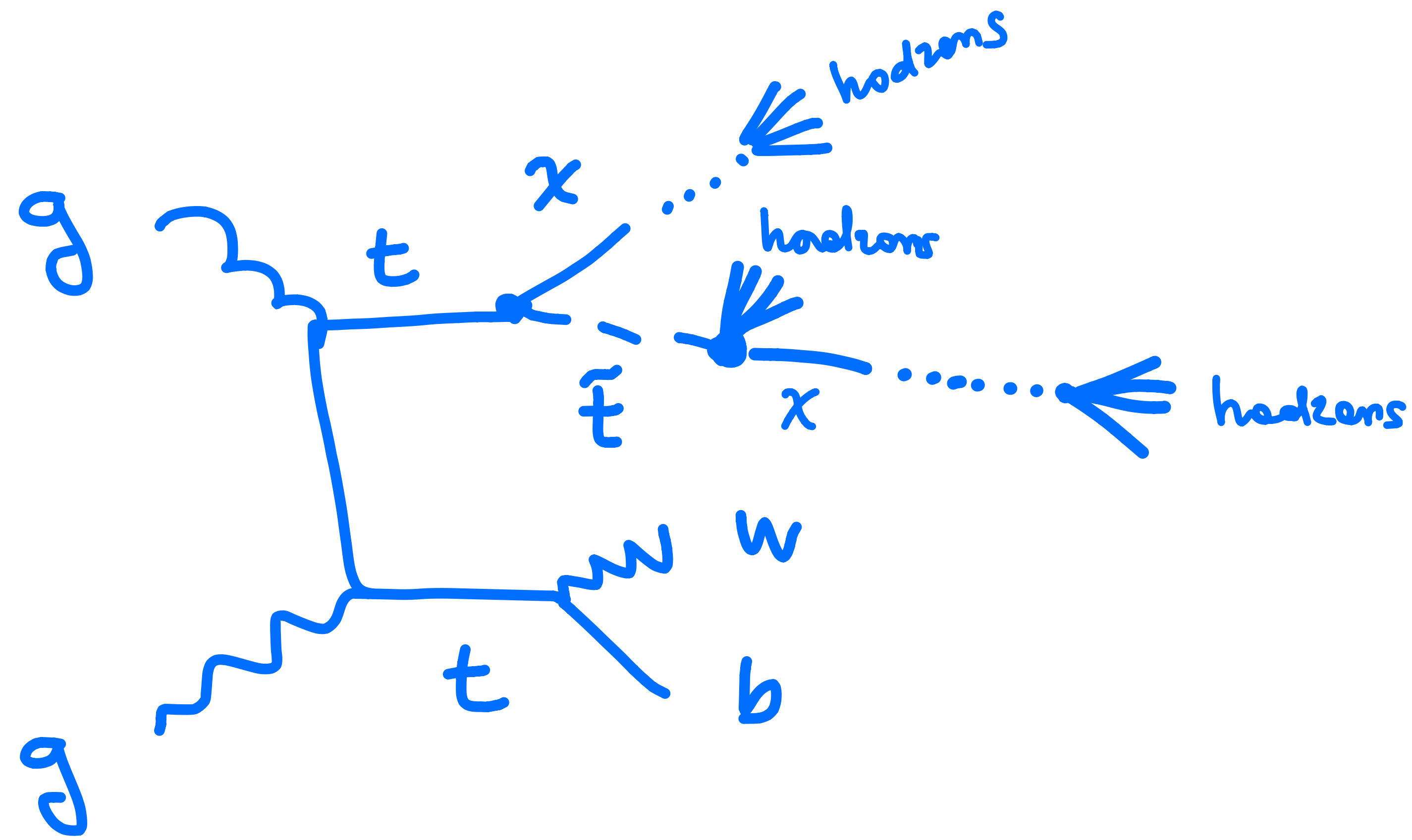
Top as a trigger

Ferretti, RF, Petersson, Torre, in progress

stops from top in RPV SUSY
+ more exotic models

hadronic stops in RPV SUSY





Top as a trigger

Ferretti, RF, Petersson, Torre, in progress

stops from top in RPV SUSY
+ more exotic models

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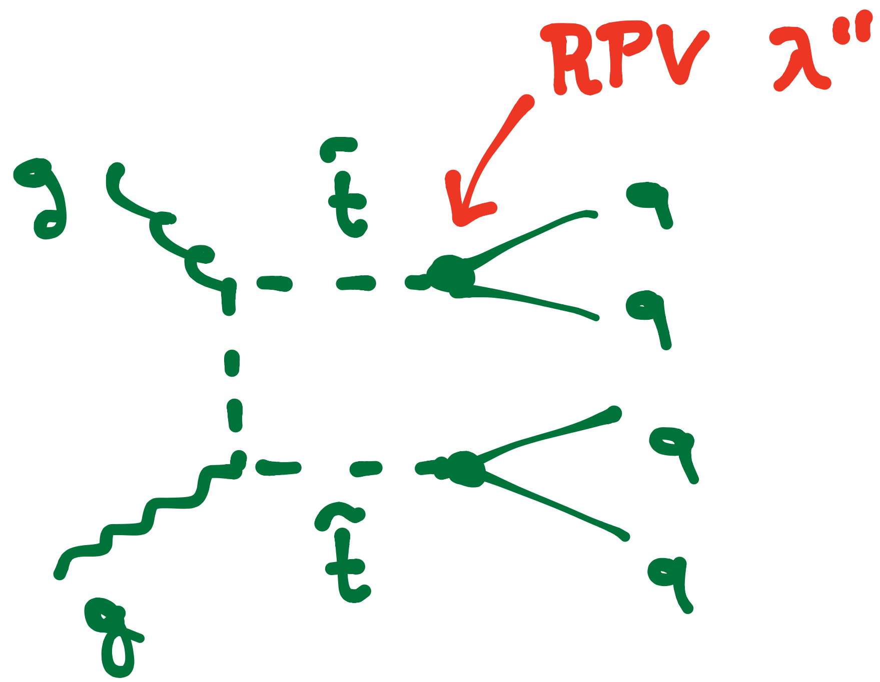
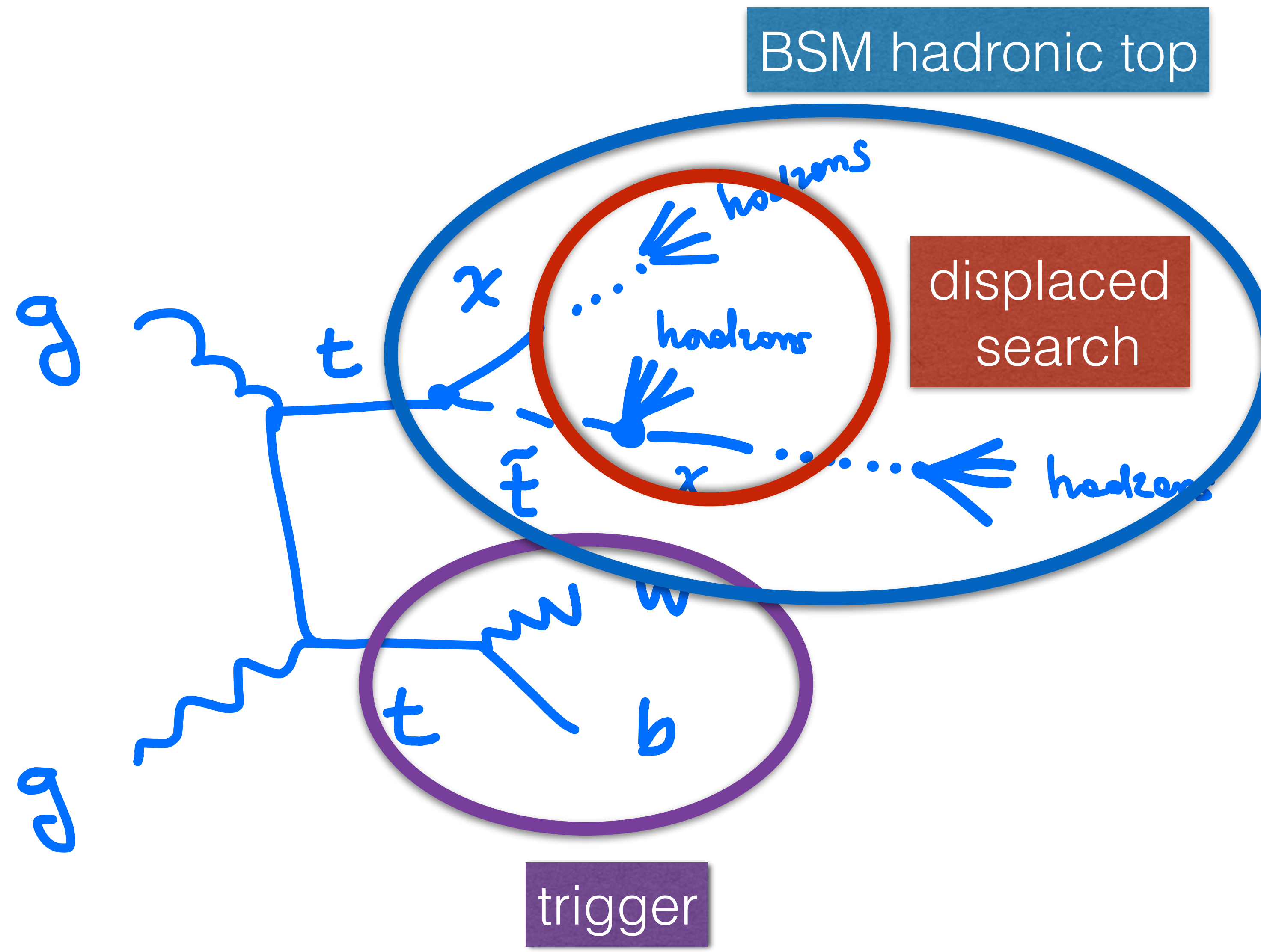


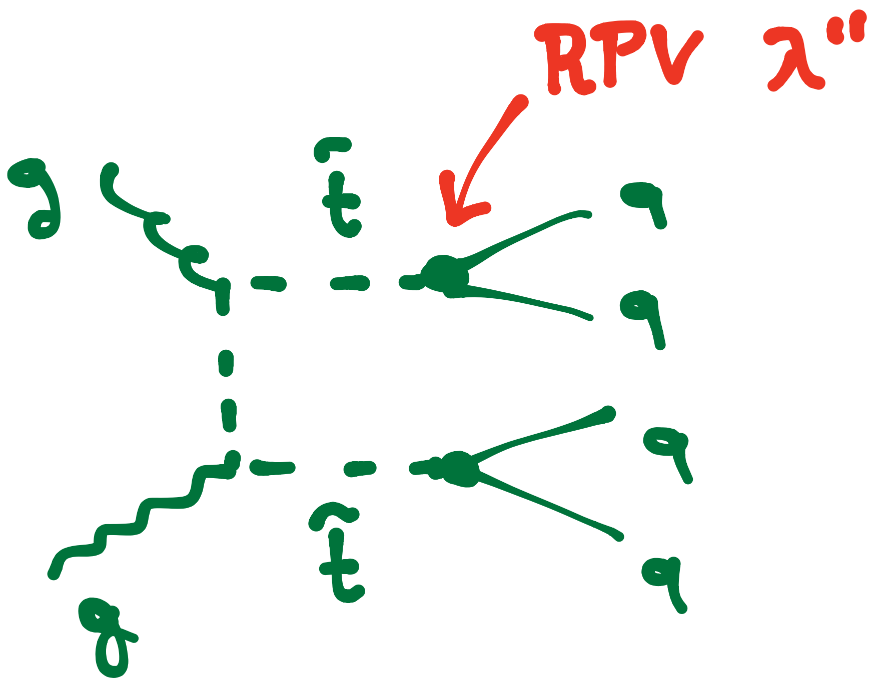


Top as a trigger

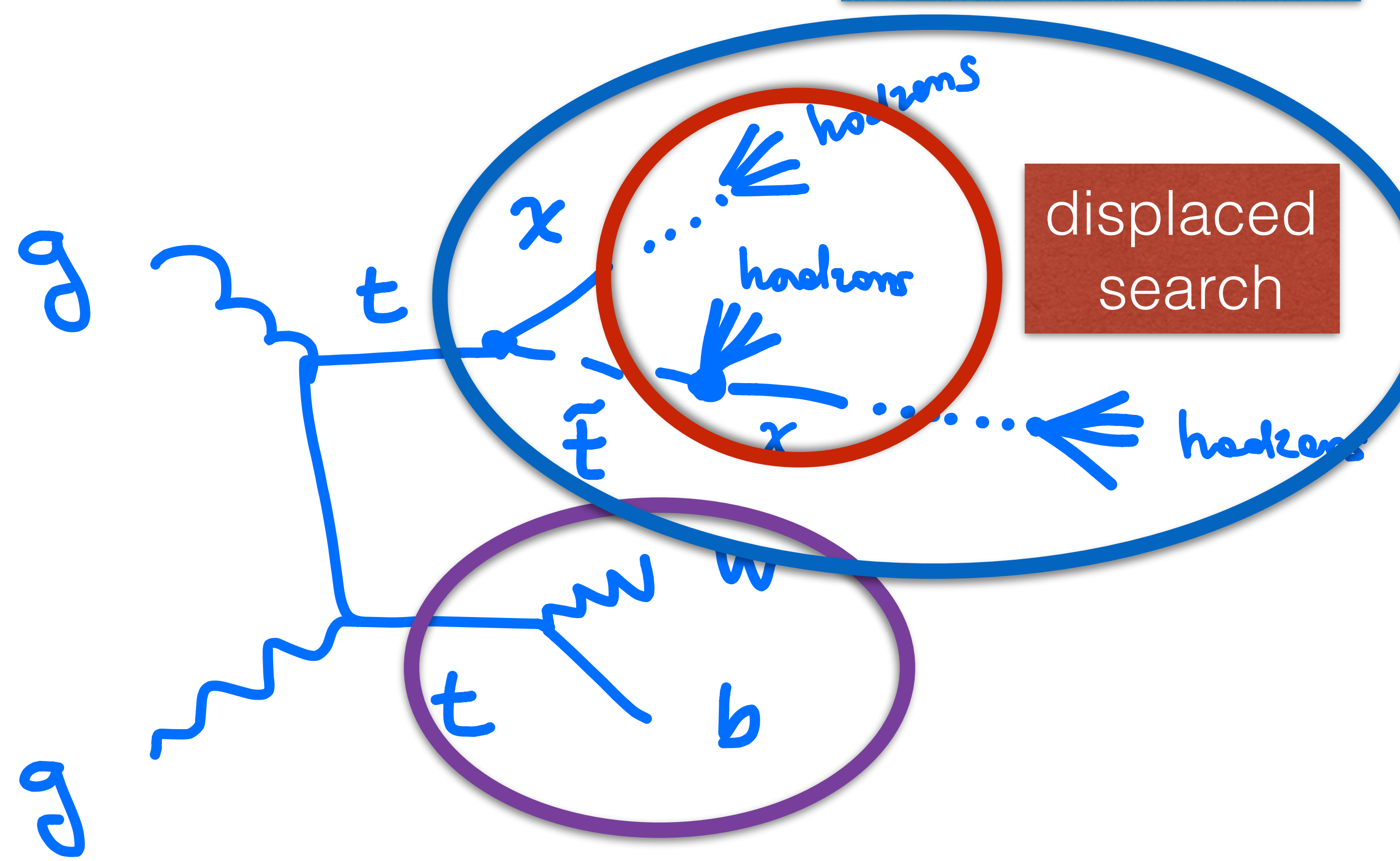
Ferretti, RF, Petersson, Torre, in progress

stops from top in RPV SUSY
+ more exotic models

hadronic stops in RPV SUSY



BSM hadronic top



trigger

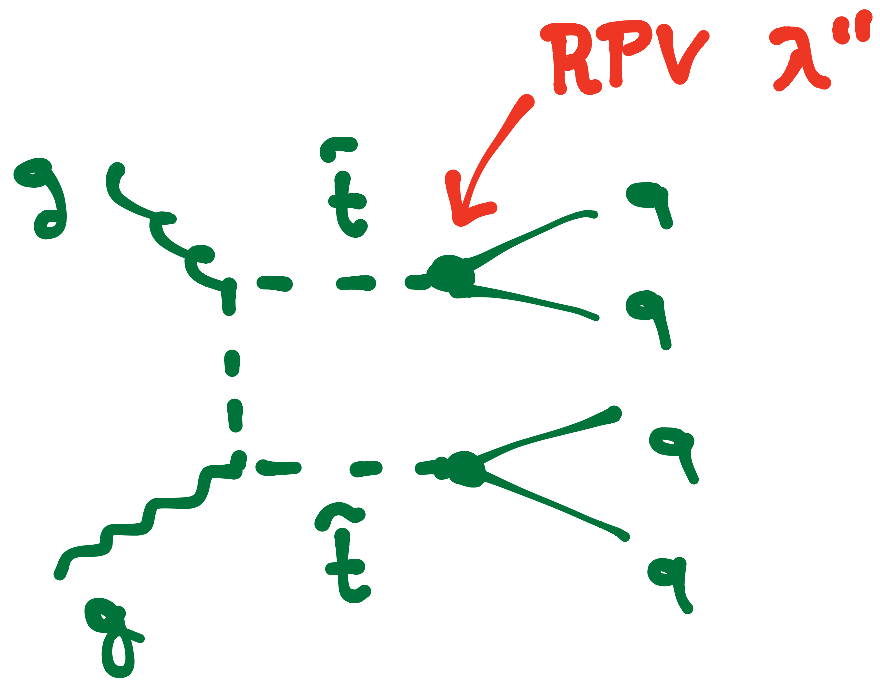
would appear in top properties measurements

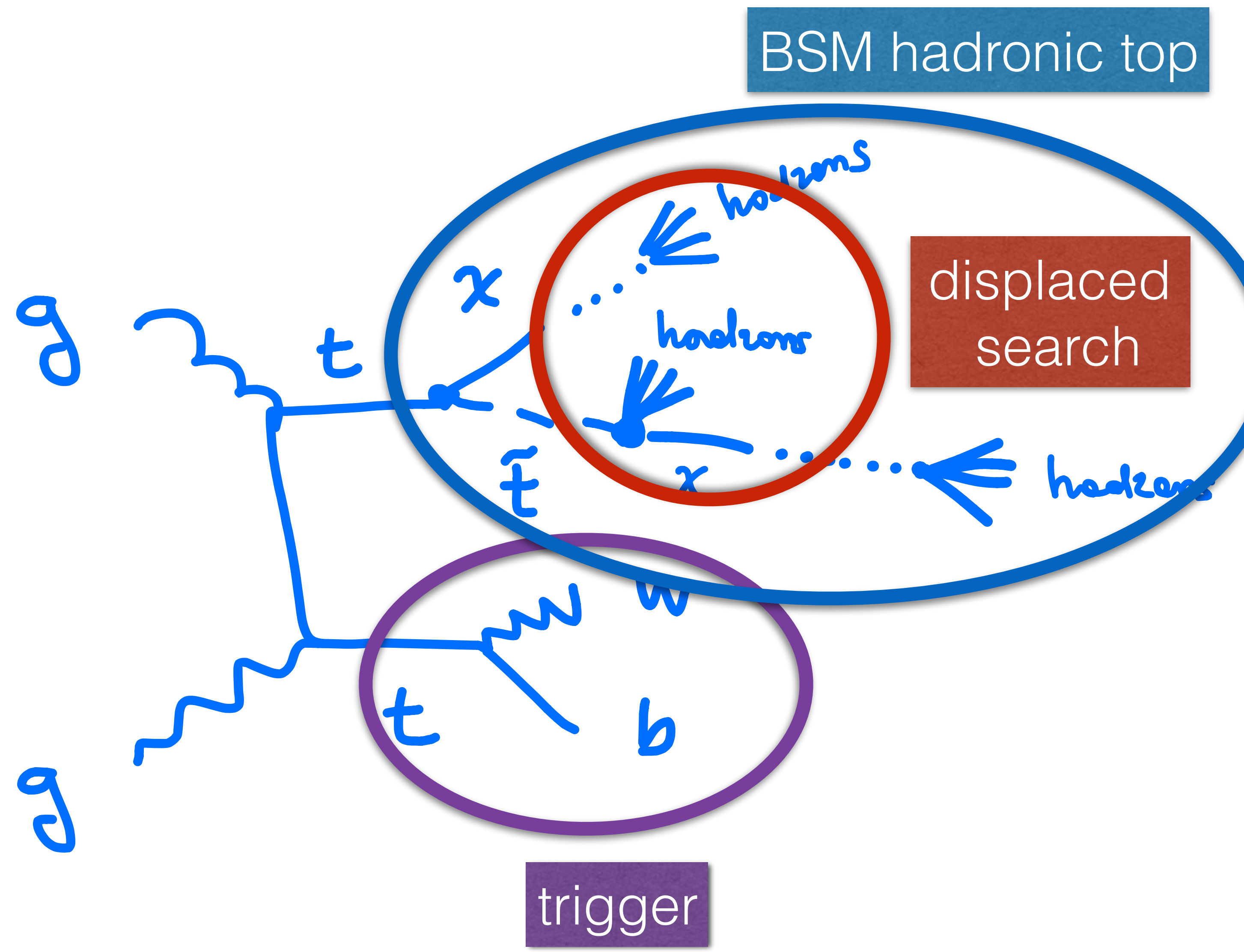
Top as a trigger

Ferretti, RF, Petersson, Torre, in progress

stops from top in RPV SUSY
+ more exotic models

hadronic stops in RPV SUSY

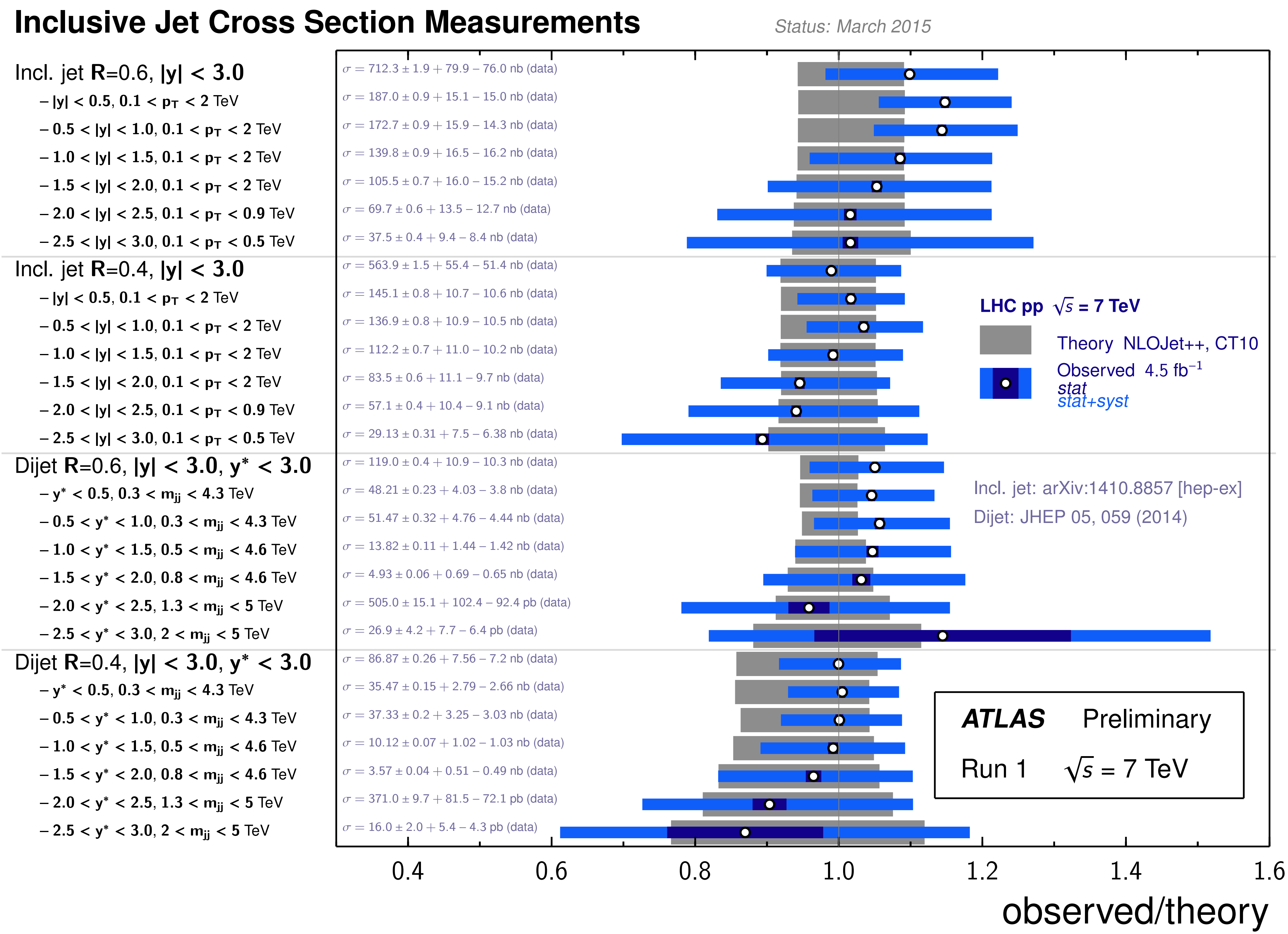




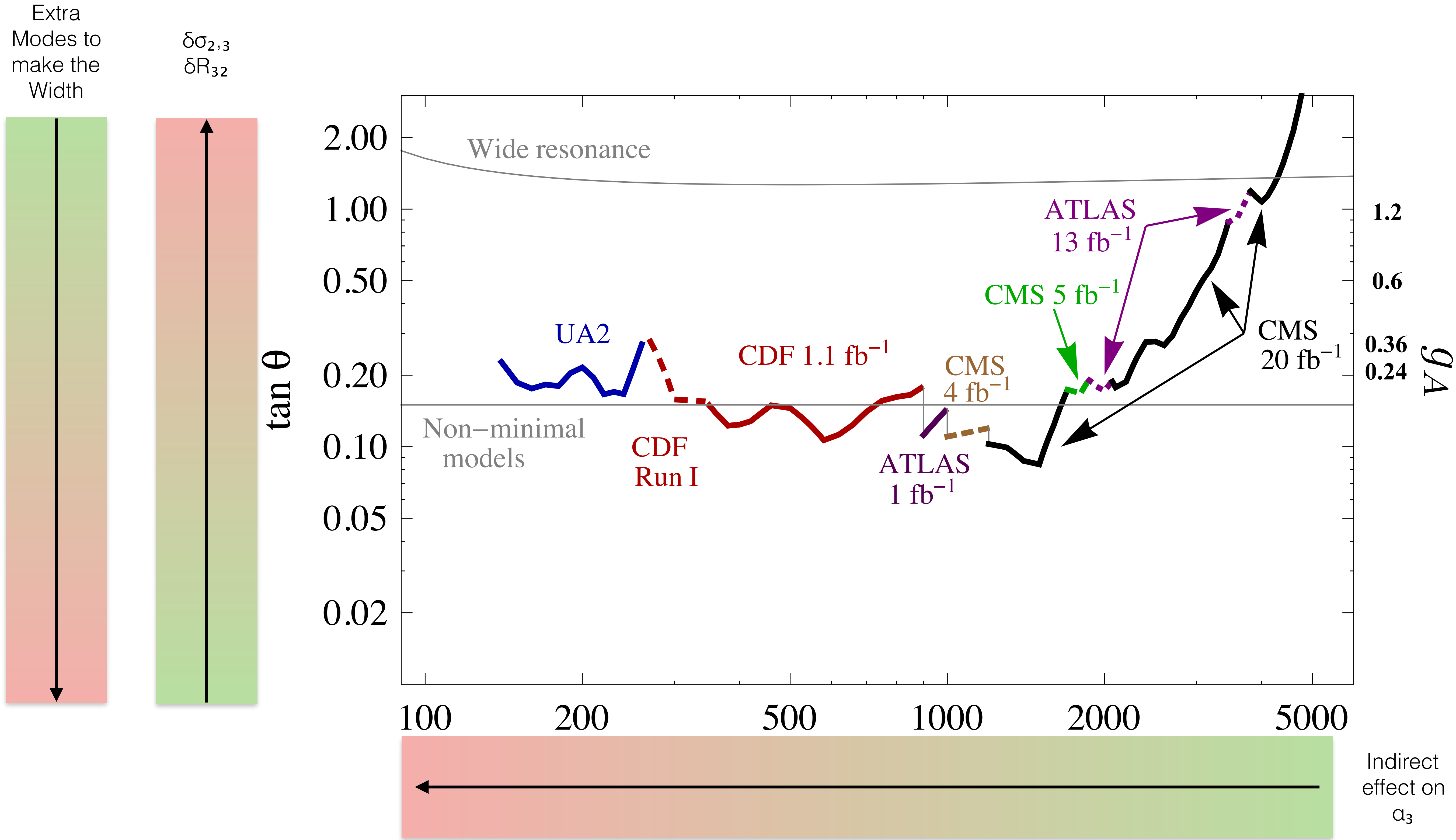
would appear in top properties measurements

CMS "BR" measurement 1506.05074
CMS "V_{tb}" measurement 1404.2292

Precision jet rates?

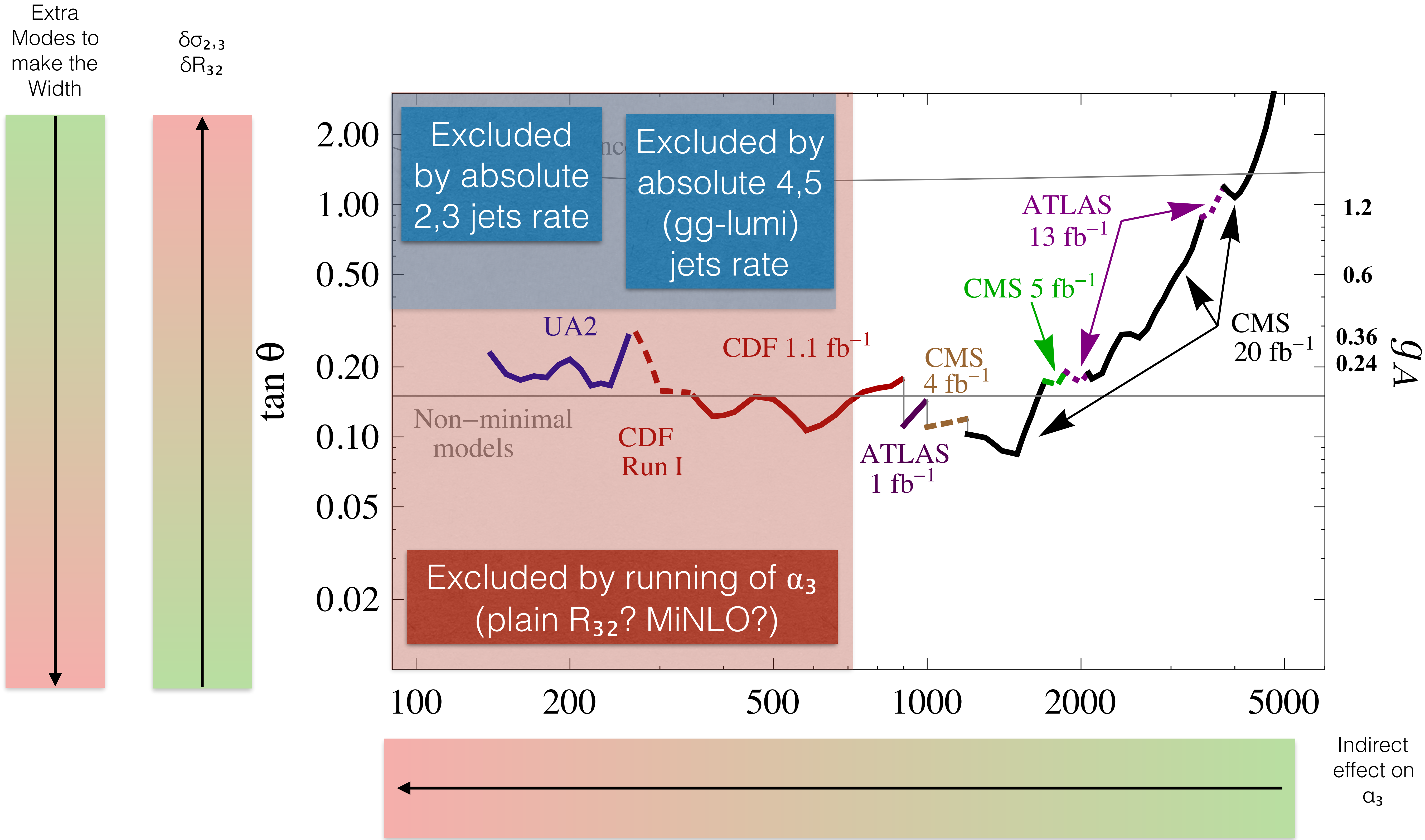


Limits $g_A = g_S \tan\theta$



$$\Gamma(G' \to jj) = \frac{5\alpha_s}{6}\tan^2\theta\, M_{G'}\left[1 + O\left(\frac{\alpha_s}{\pi}\right)\right] \qquad g_s \tan\theta\, \overline{q}\gamma^\mu T^a G'^{\,a}_\mu q \quad ,$$

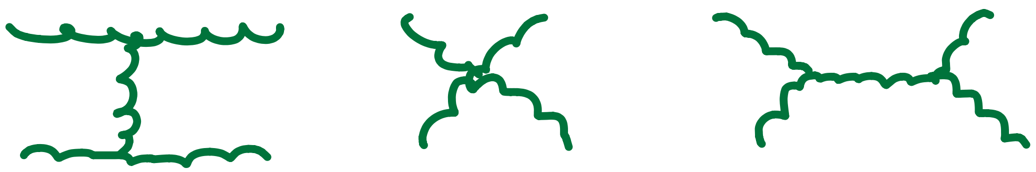
Limits $g_A = g_S \tan\theta$

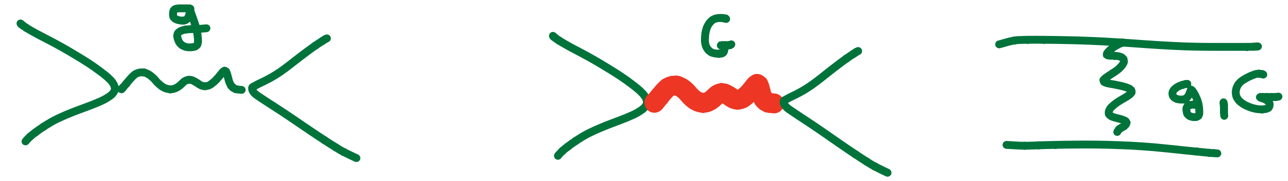


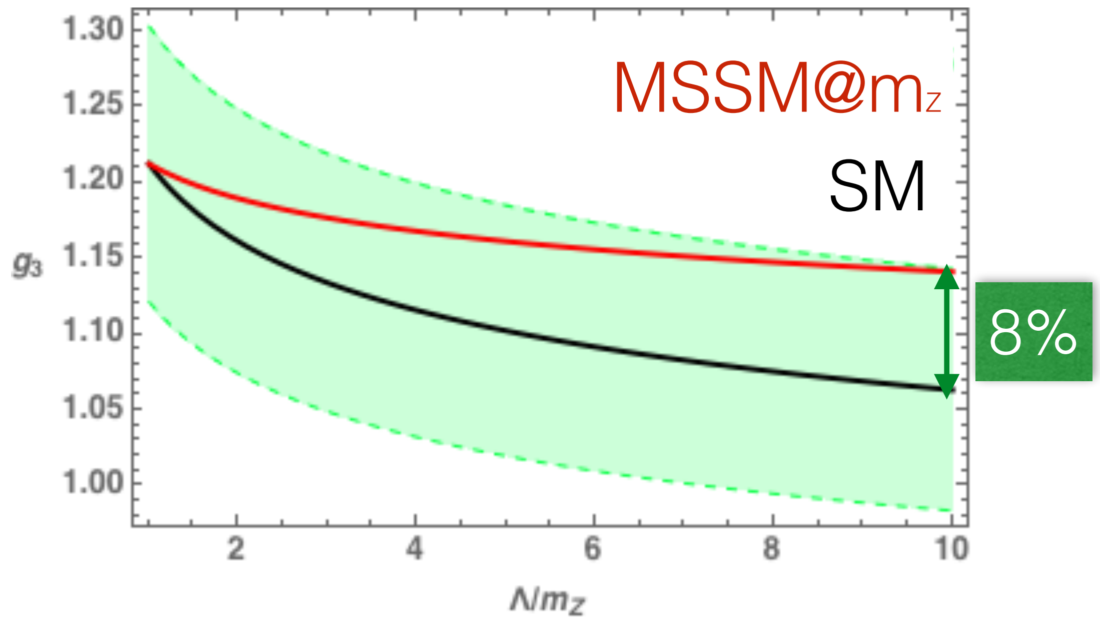
$$\Gamma(G' \to jj) = \frac{5\alpha_s}{6} \tan^2\theta \, M_{G'} \left[1 + O\left(\frac{\alpha_s}{\pi}\right)\right] \qquad g_s \tan\theta \, \overline{q}\gamma^\mu T^a G'^{\,a}_\mu q \ ,$$

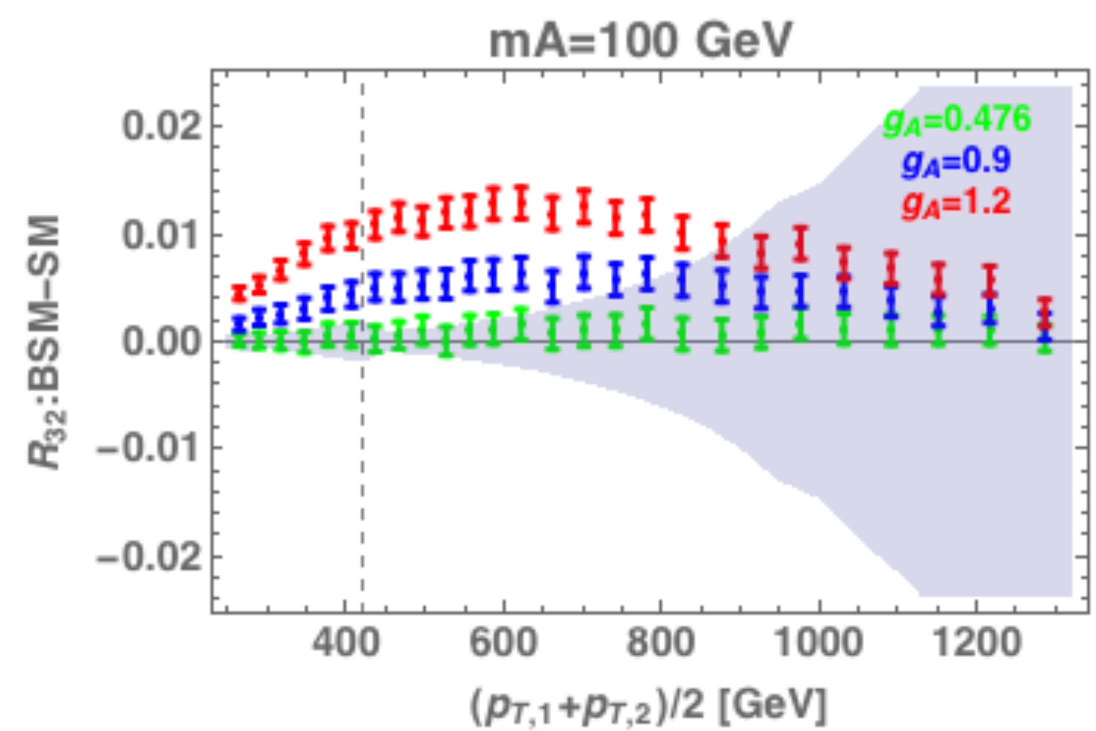
New light colored states

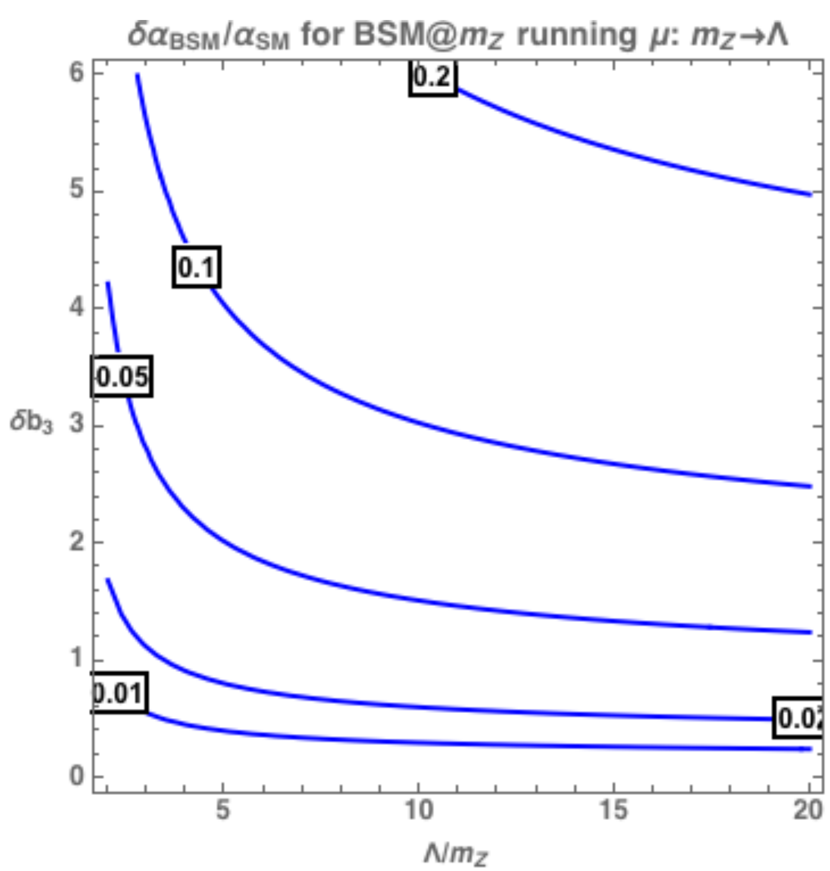
with M. Redi

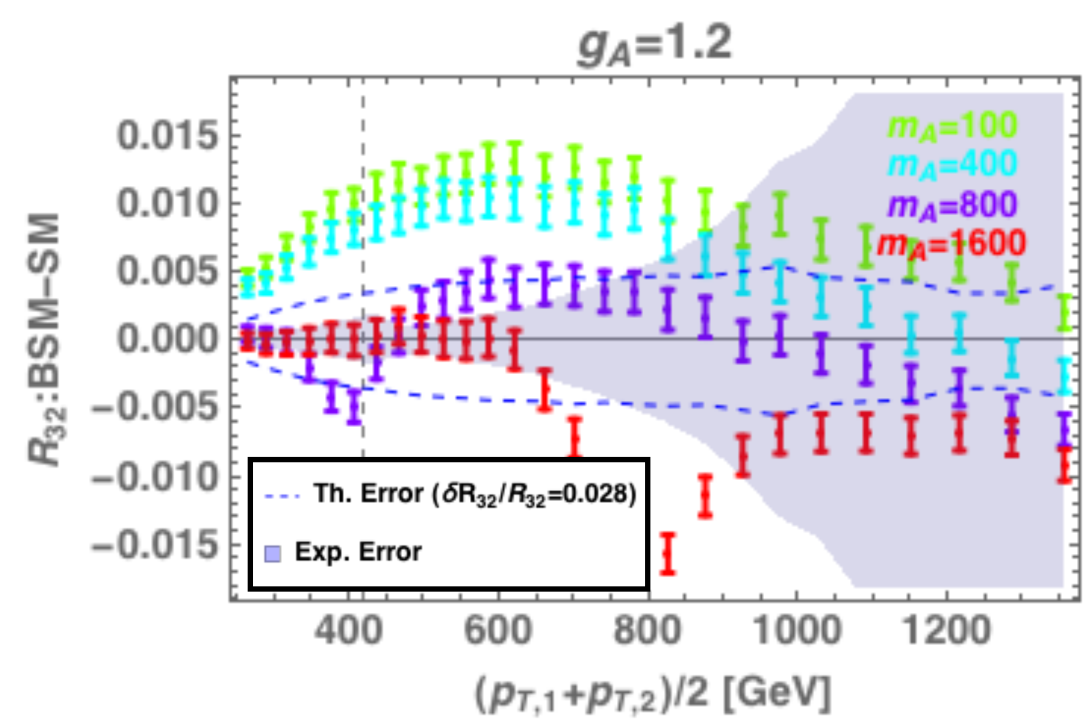






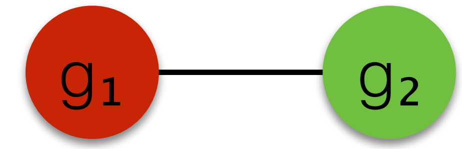






Thank you! (again)

A simple mixing model



$g_3 = g_1 \cdot \cos\theta = g_2 \cdot \sin\theta$

$$\Downarrow$$

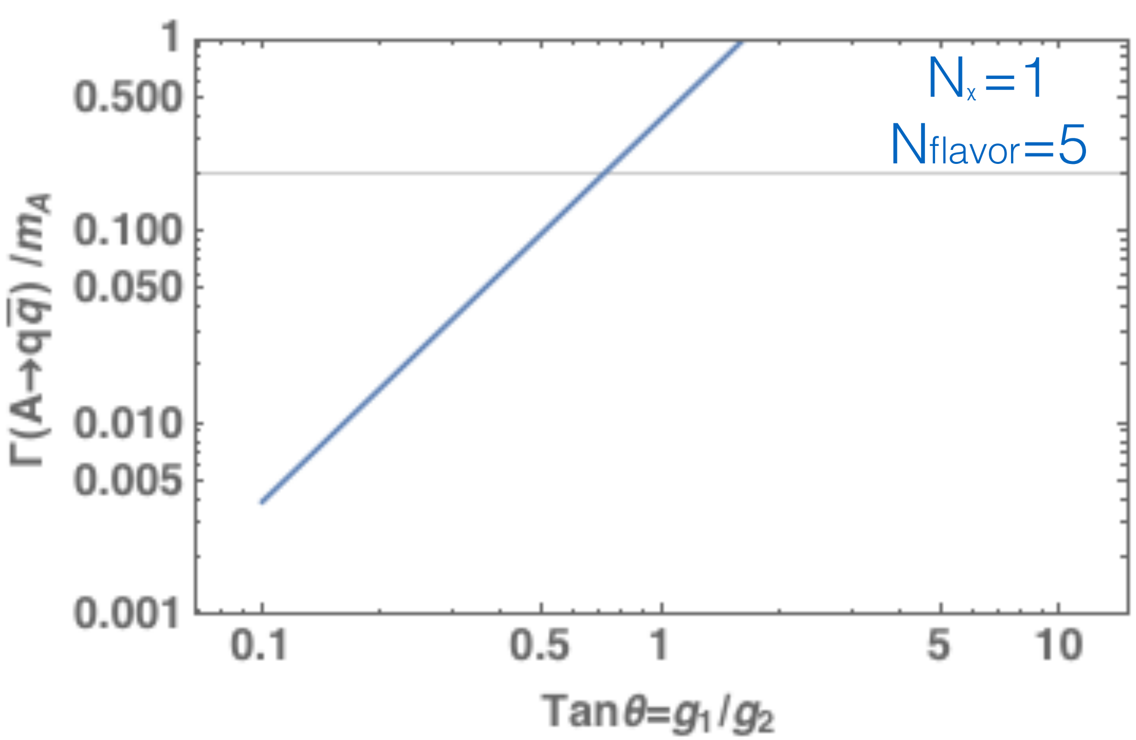
$$\begin{cases} g_1/g_2 = \tan\theta \\ 1/g_1^2 + 1/g_2^2 = 1/g_3^2 \\ \sqrt{(g_1^2 + g_2^2)} = g_3/\sin 2\theta \end{cases}$$

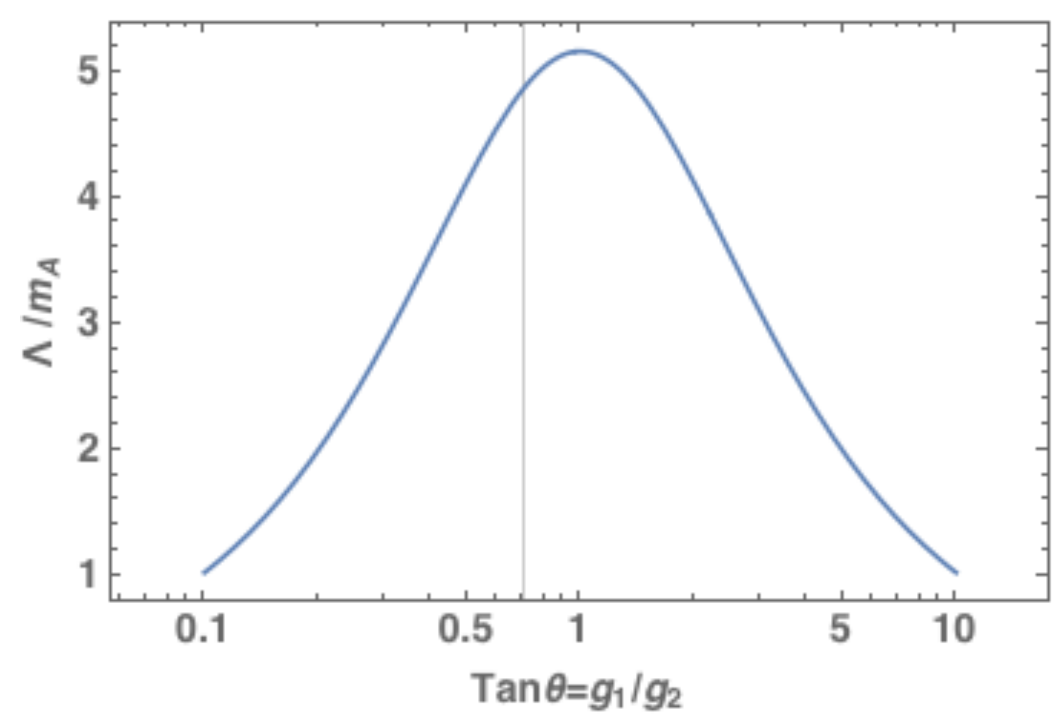
Q,u,d~(**3,1**) of $SU(3)_1, SU(3)_2$
vectorial fermions
(maybe stupid?)

$g_3 \tan\theta \cdot A\bar{\psi}\gamma\psi$

$\Gamma = \alpha_3 (\tan\theta)^2 \cdot M \cdot N_{flavor}/6 \cdot N_\chi$

$\Lambda = 4\pi \cdot f = 4\pi \cdot m_A/\sqrt{(g_1^2 + g_2^2)} =$
$= 4\pi \cdot m_A \cdot \sin 2\theta / g_3$





Each methods based on different <u>assumptions/beliefs</u>

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

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

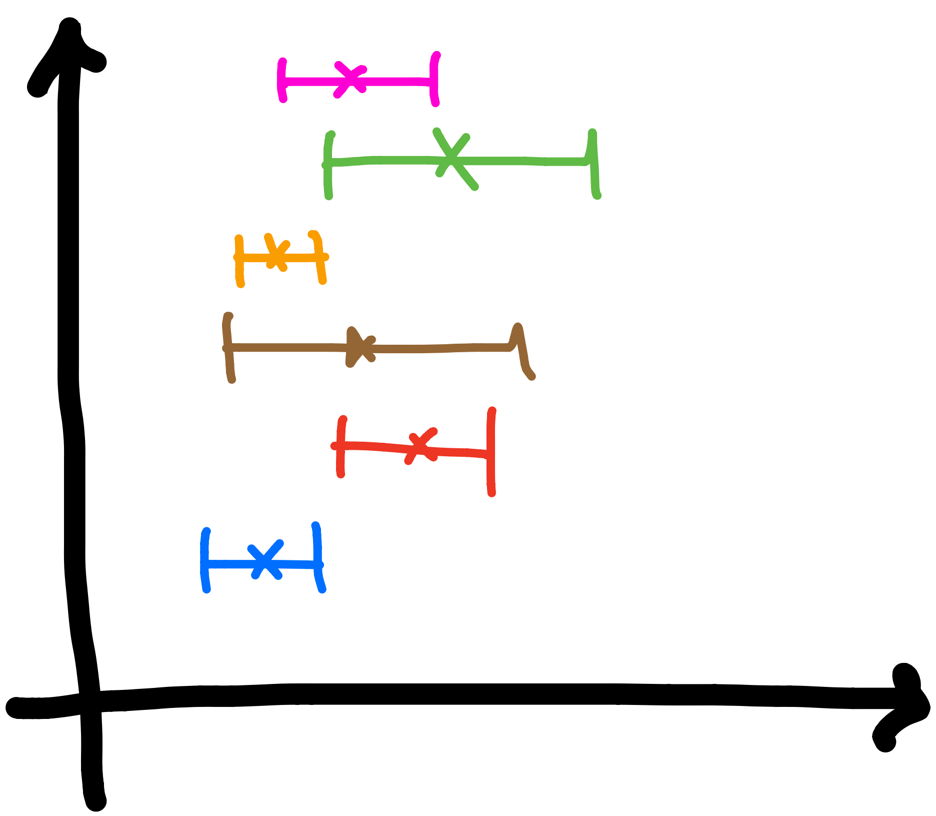
Ideal situation

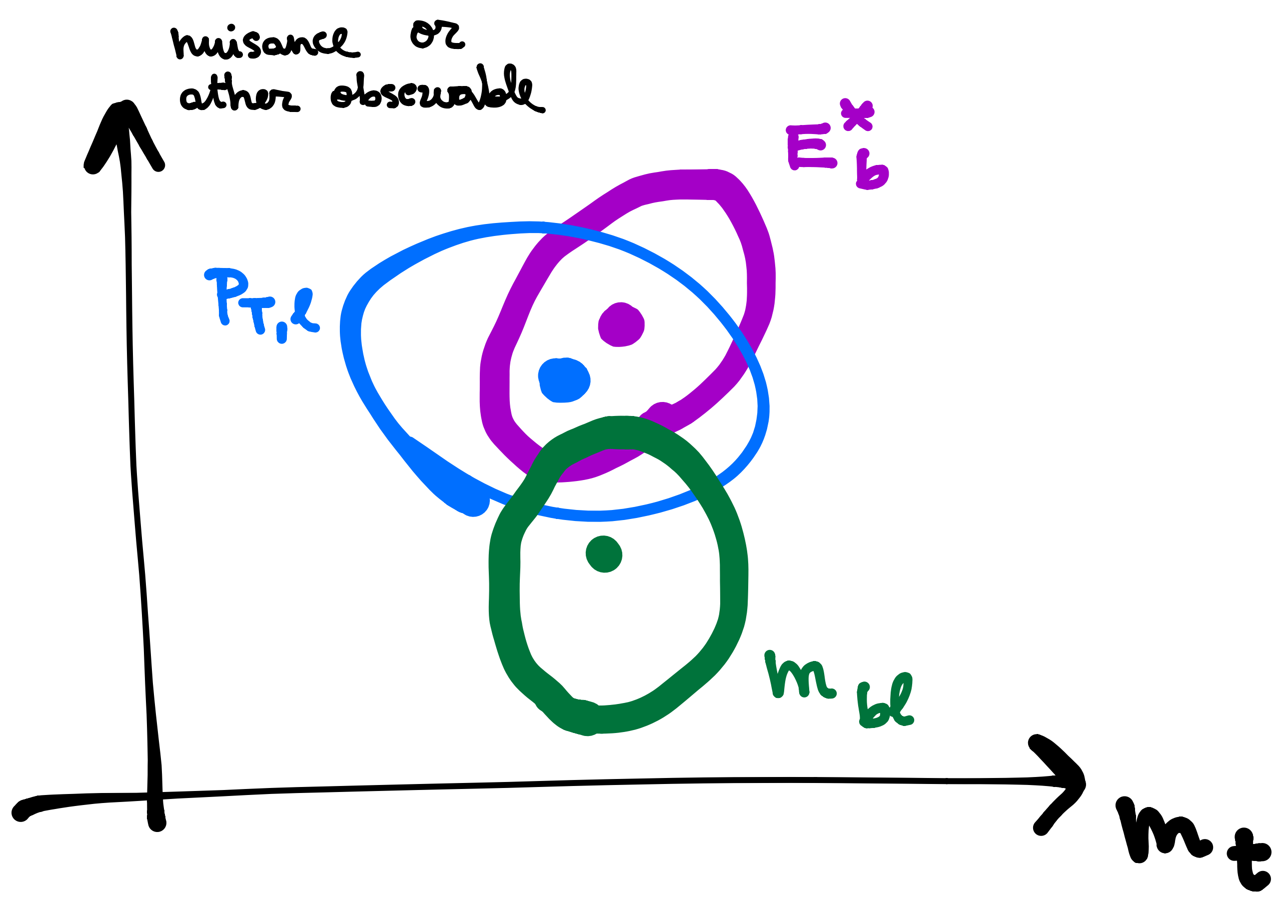
Have many inherently different methods

possibly based on different experimental objects/quantities

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

Many measurements

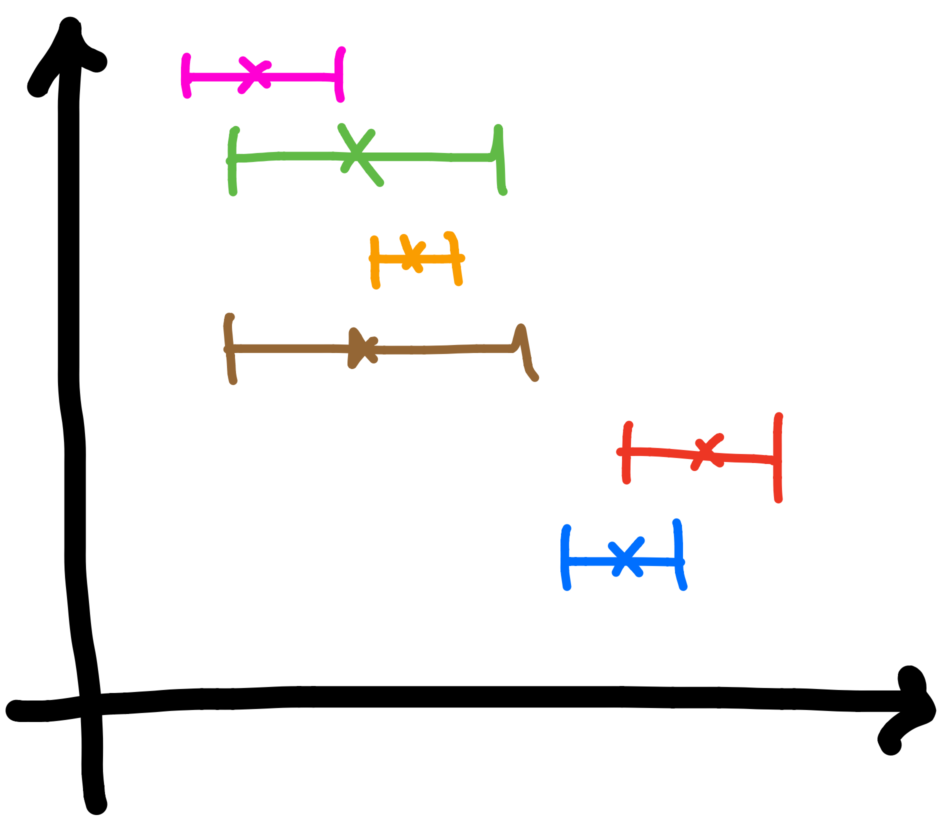


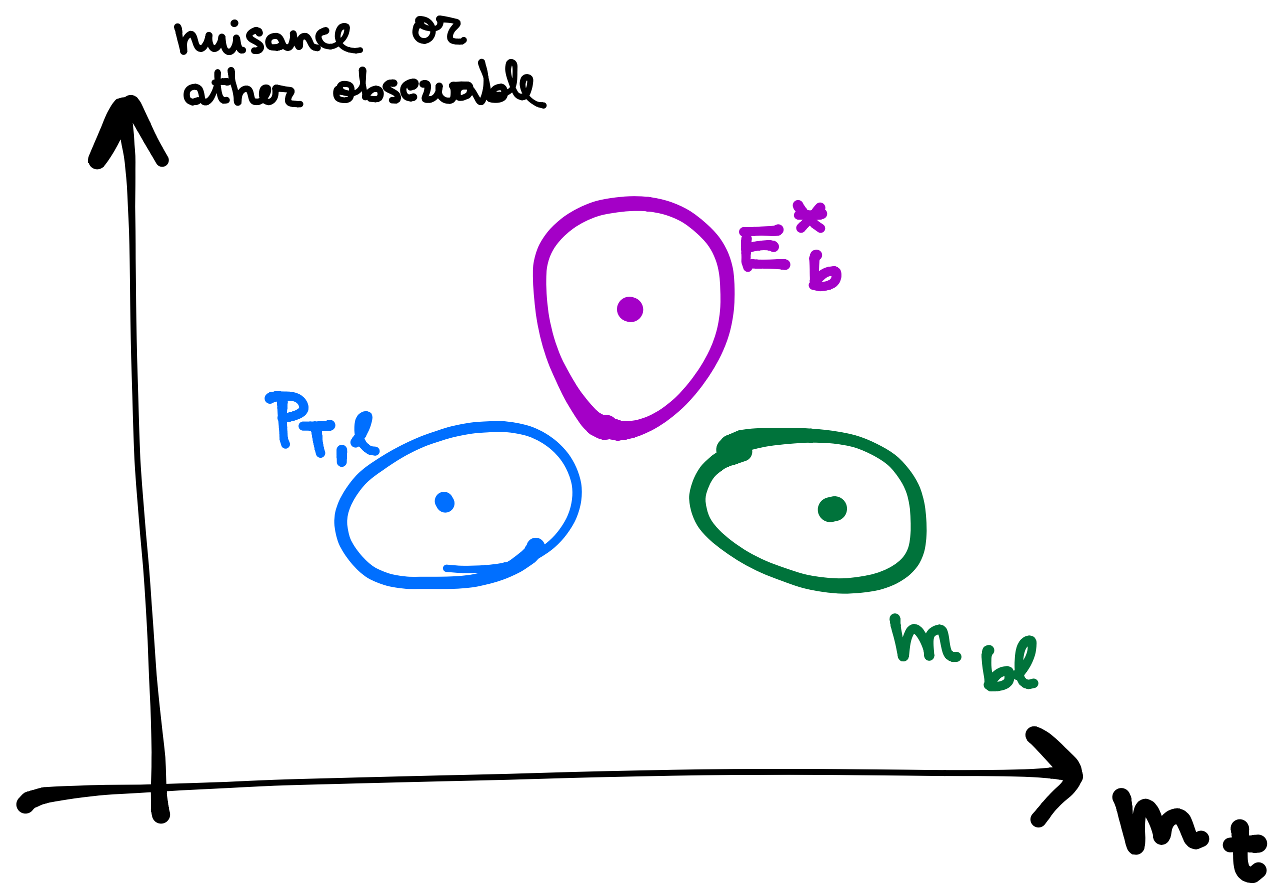


The strength of the future LHC top mass measurement will build on the **diversity of methods**
⇒ not very useful to talk about “*single best measurement*”

Many measurements

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





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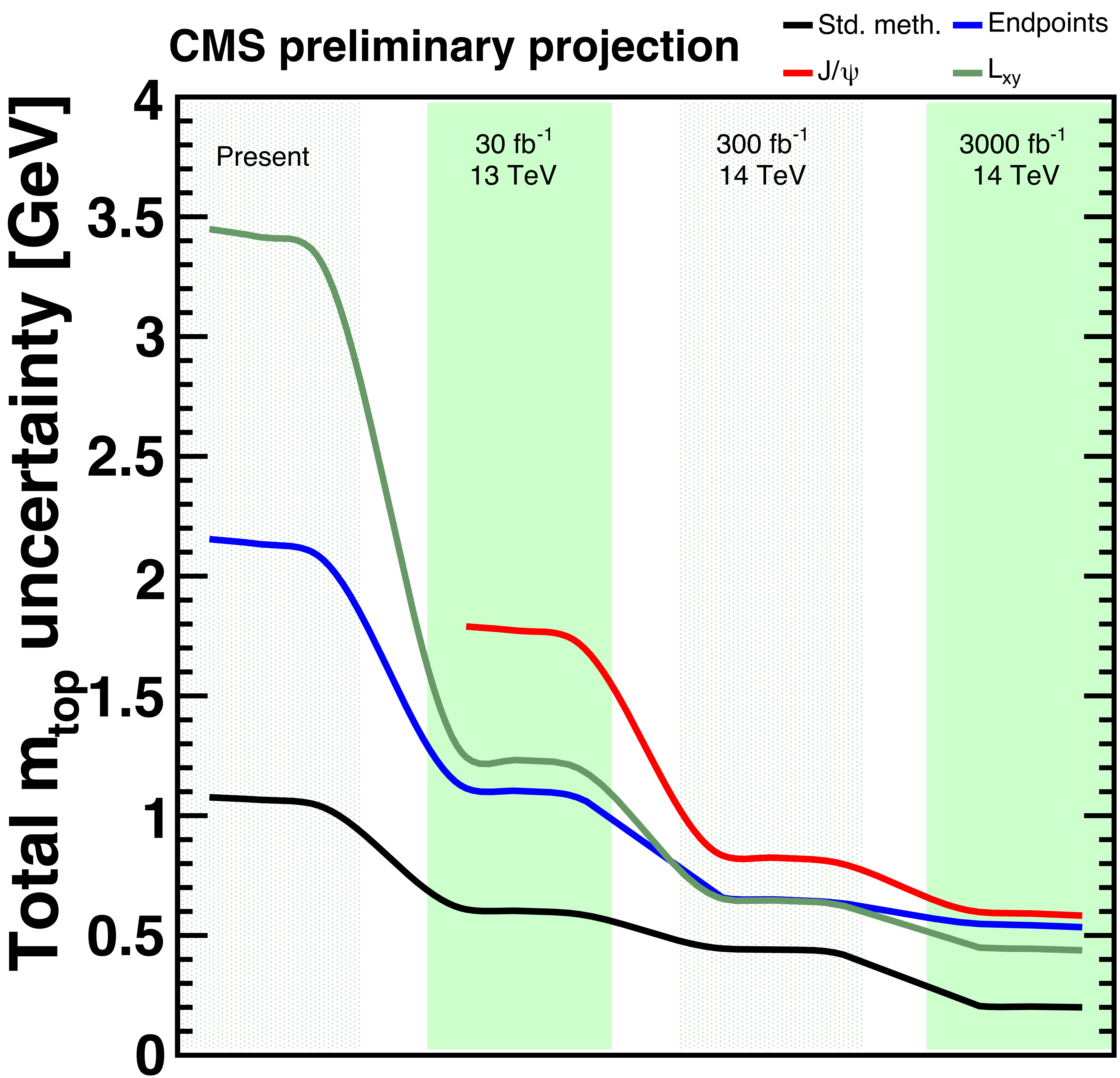
Ideal situation



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