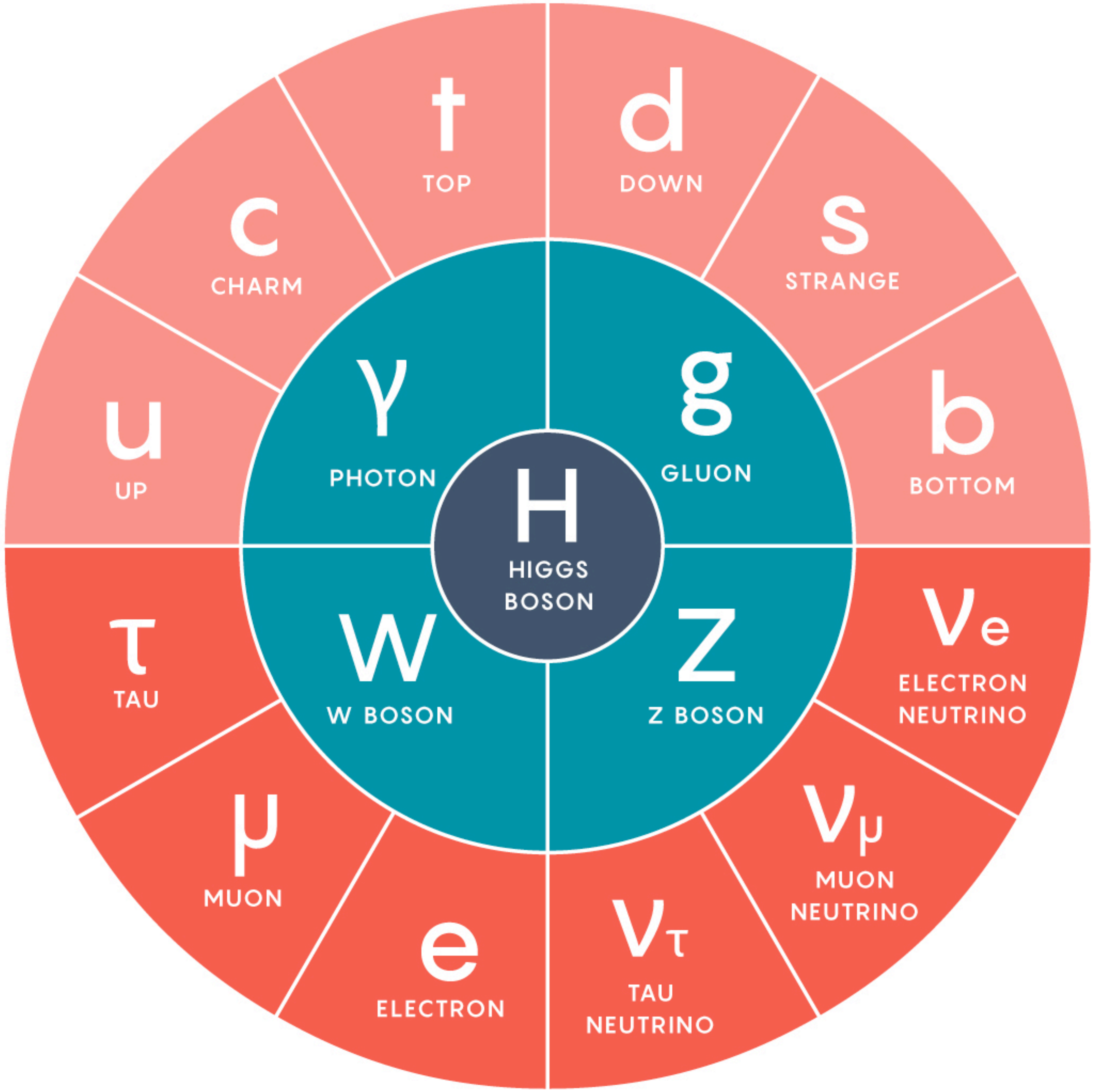
Honing in on the top quark and Higgs boson

Chris Pollard

WARWICK

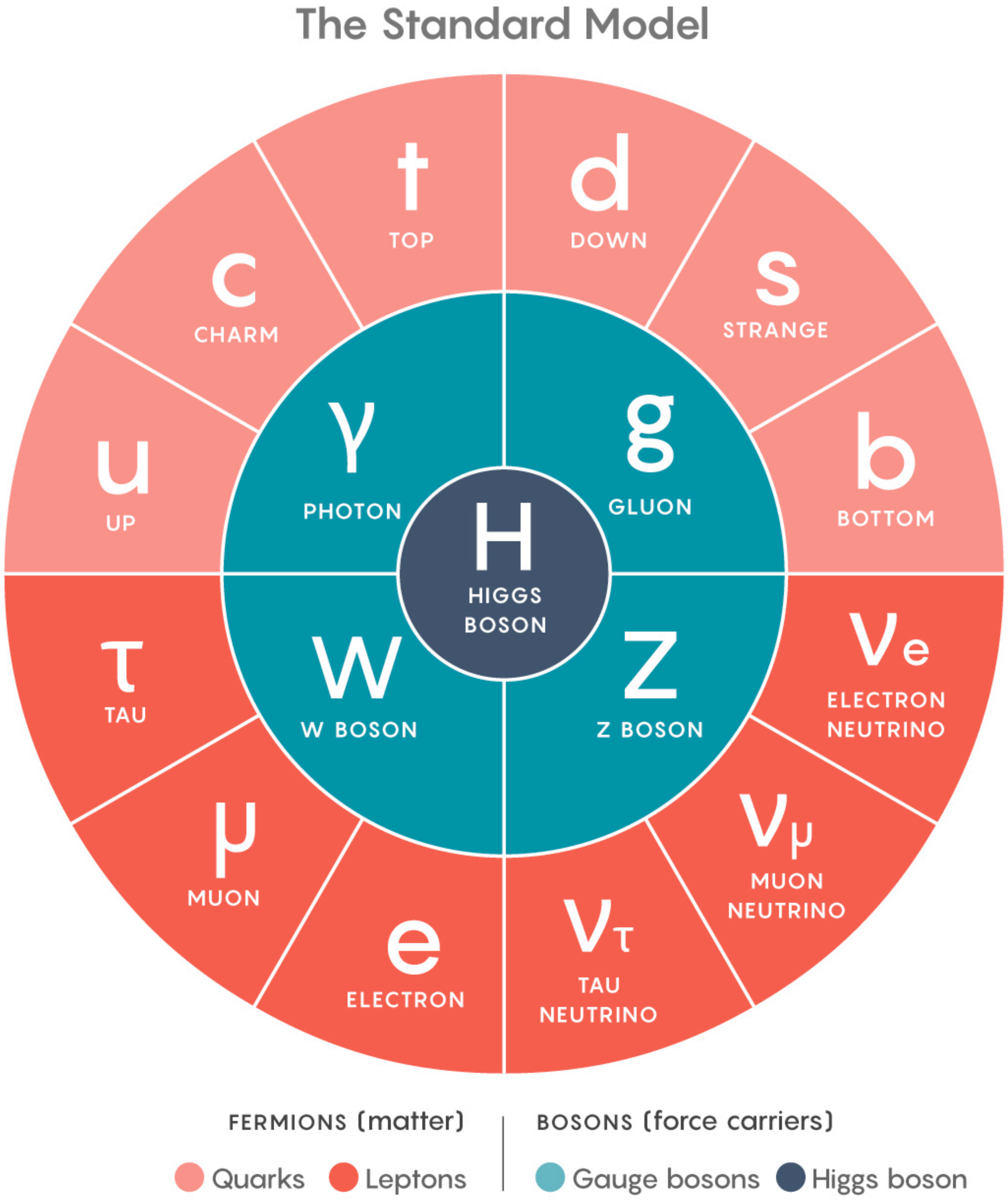


a convenient view of nature:

simple

elegant

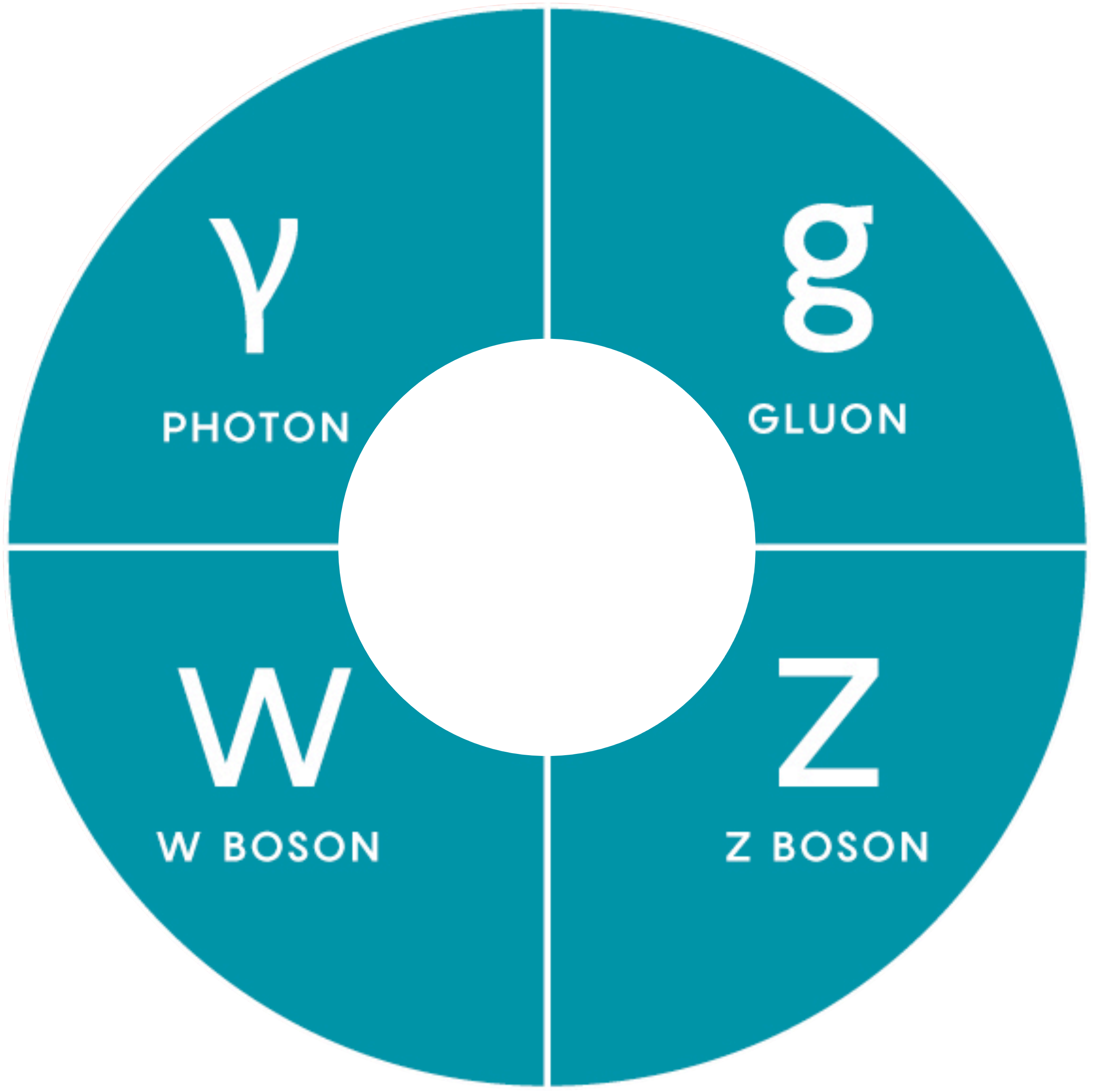
symmetric



$$SU(3) \times SU(2) \times U(1)$$

gauge symmetries

The Standard Model

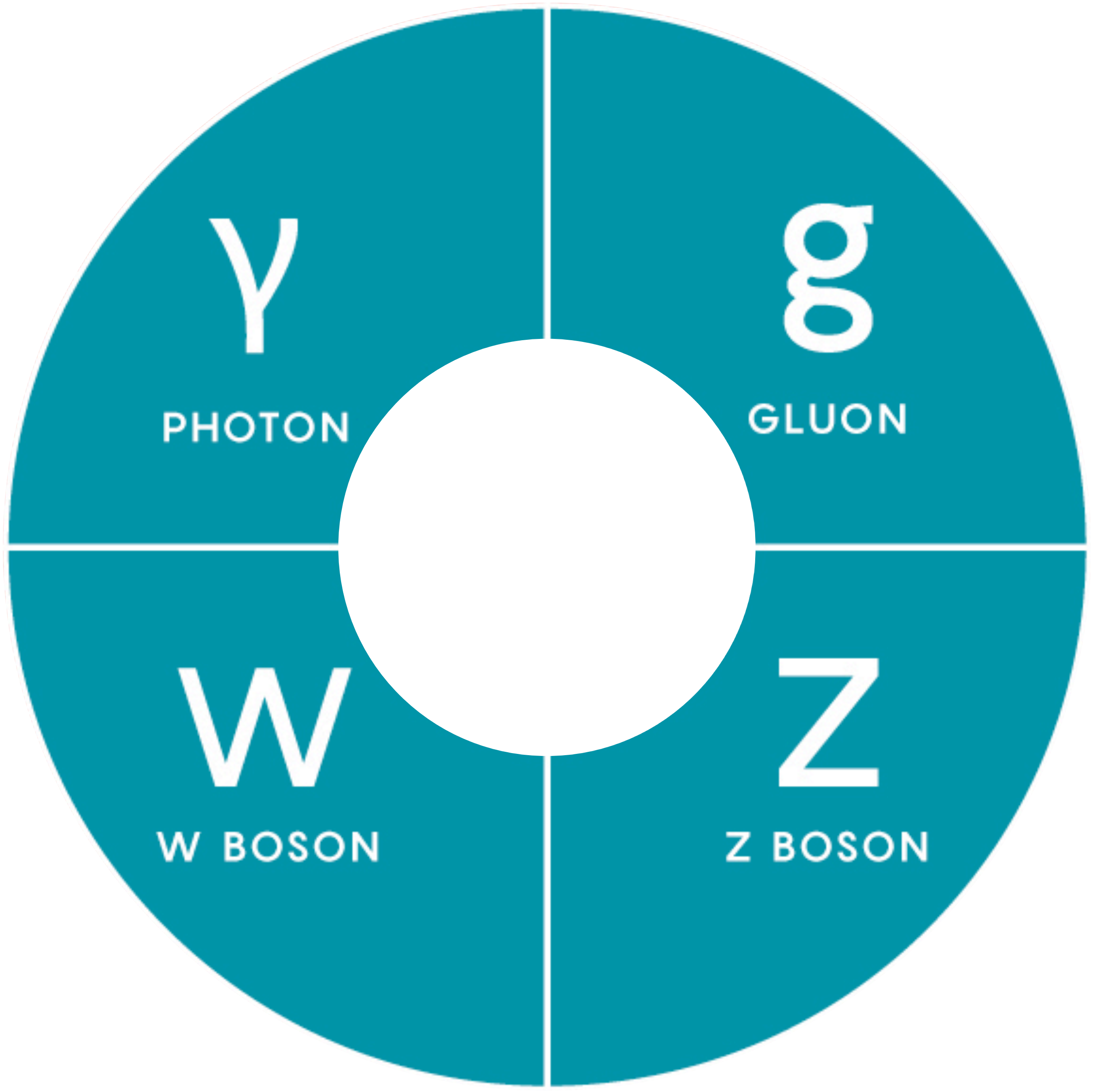


$$SU(3) \times \xcancel{SU(2)} \times U(1)$$

gauge symmetries

(but we've known for some time that the $SU(2)$ is broken)

The Standard Model



The Standard Model

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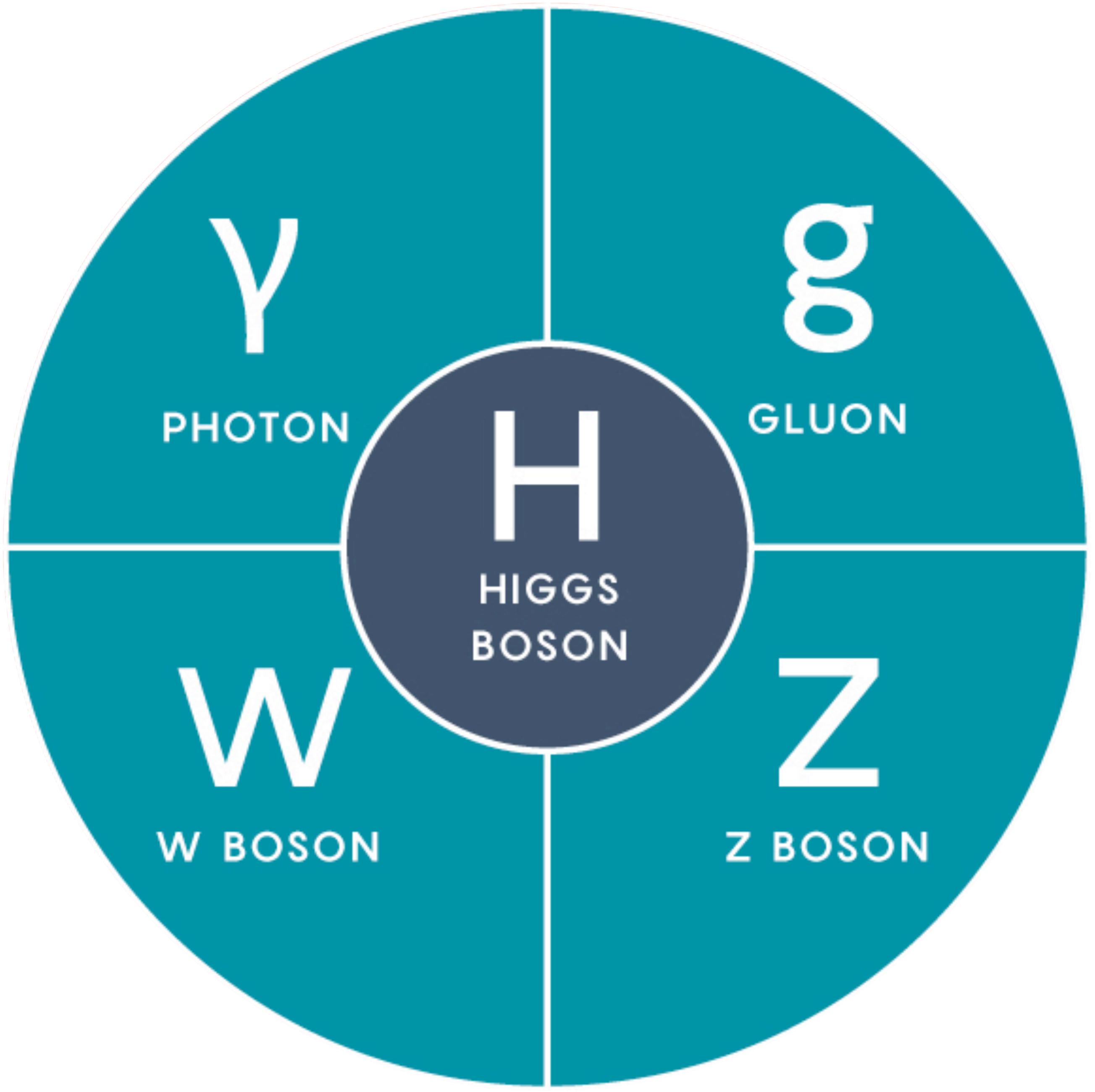
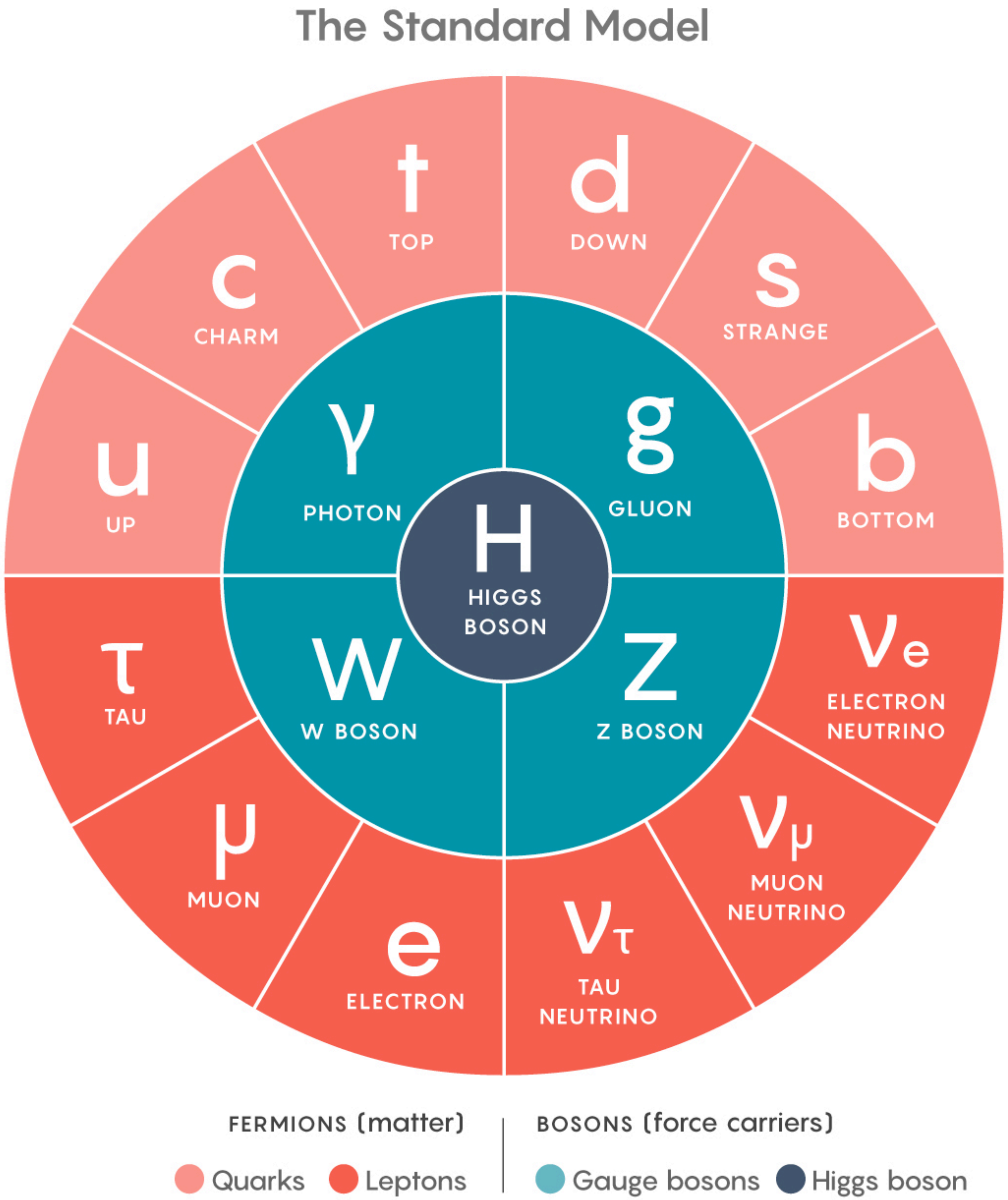
gauge symmetries

…and ***so far*** *the Higgs Boson appears to be doing the job*

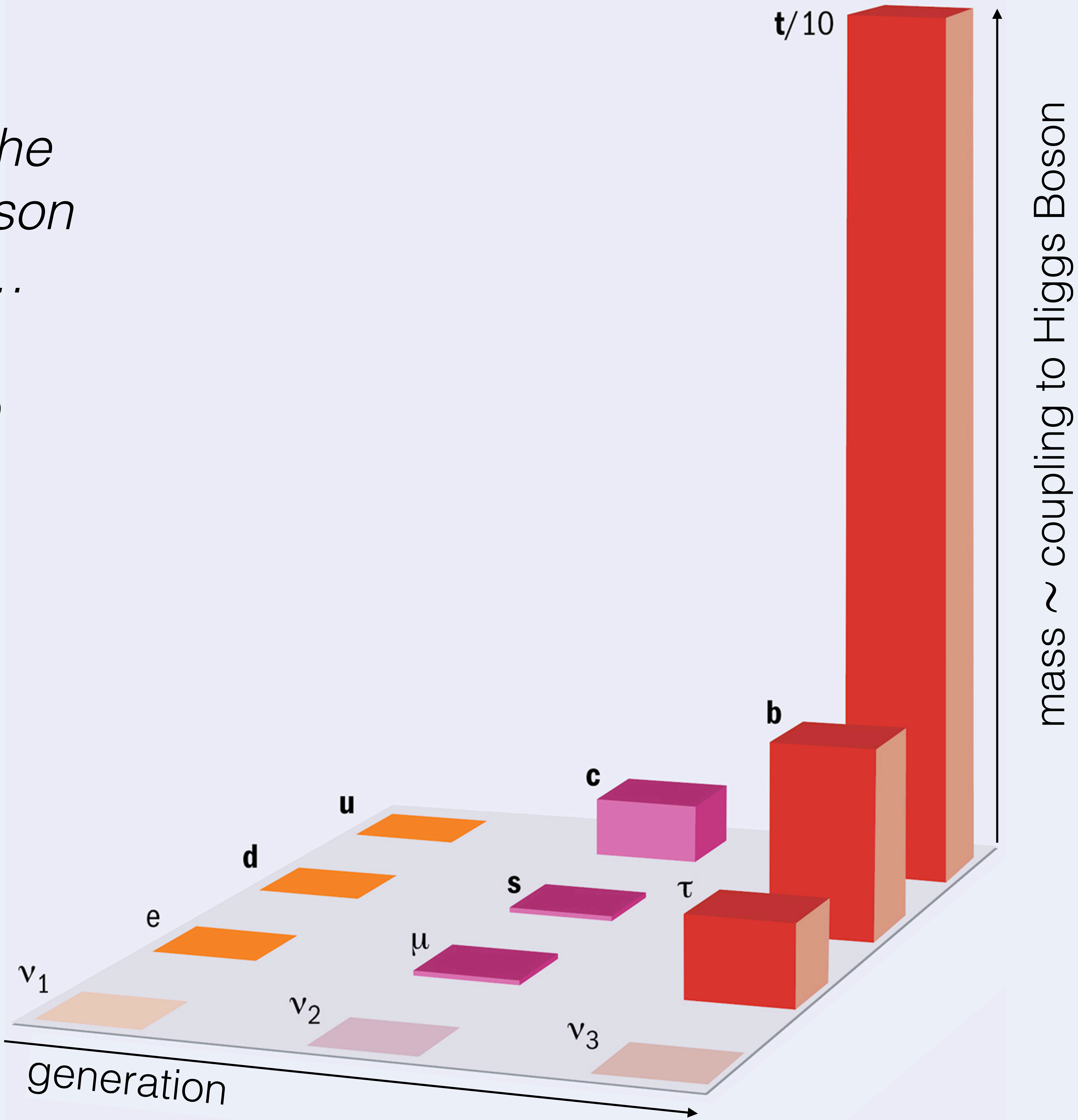


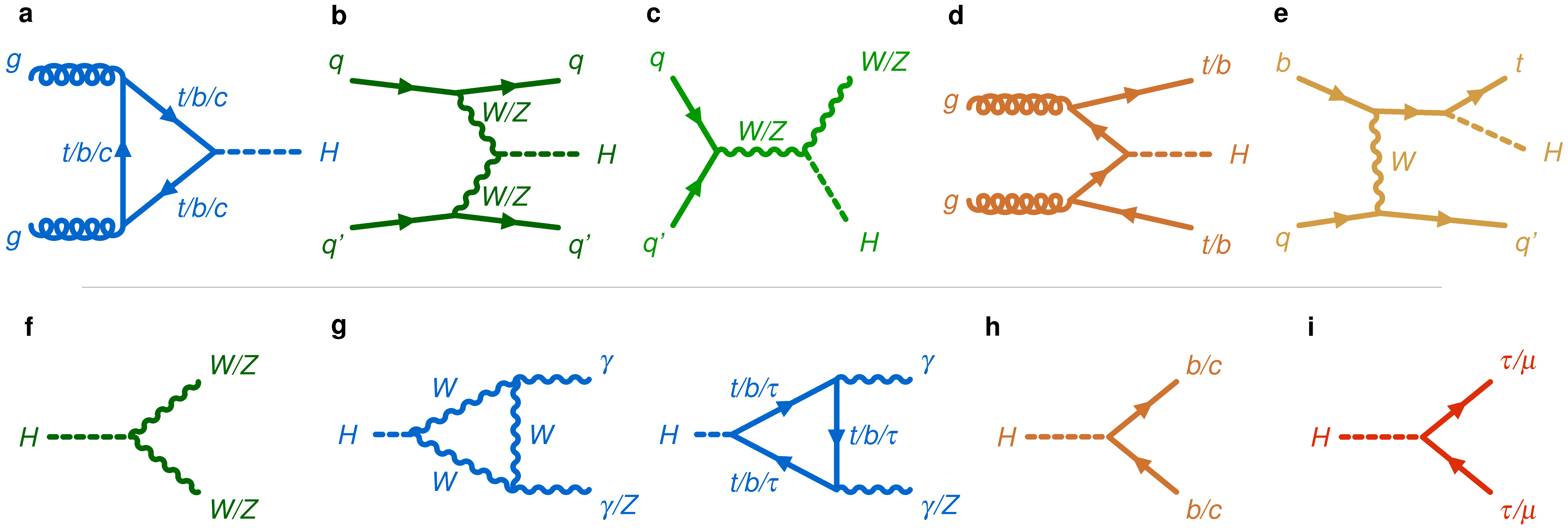
the Electroweak sector is not the only place where the Higgs Boson is "breaking" this flat picture…



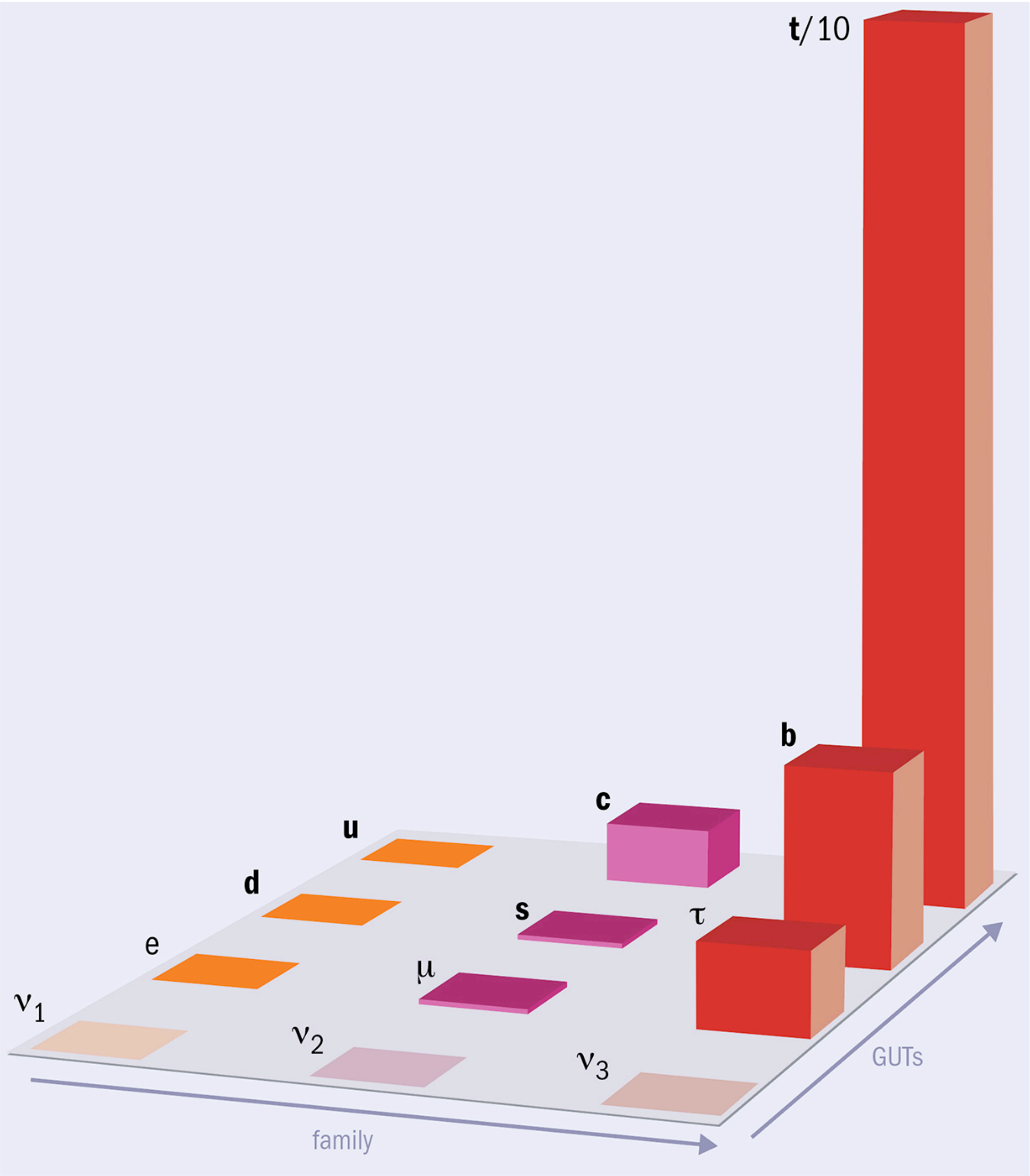
the Electroweak sector is not the only place where the Higgs Boson is "breaking" this flat picture…

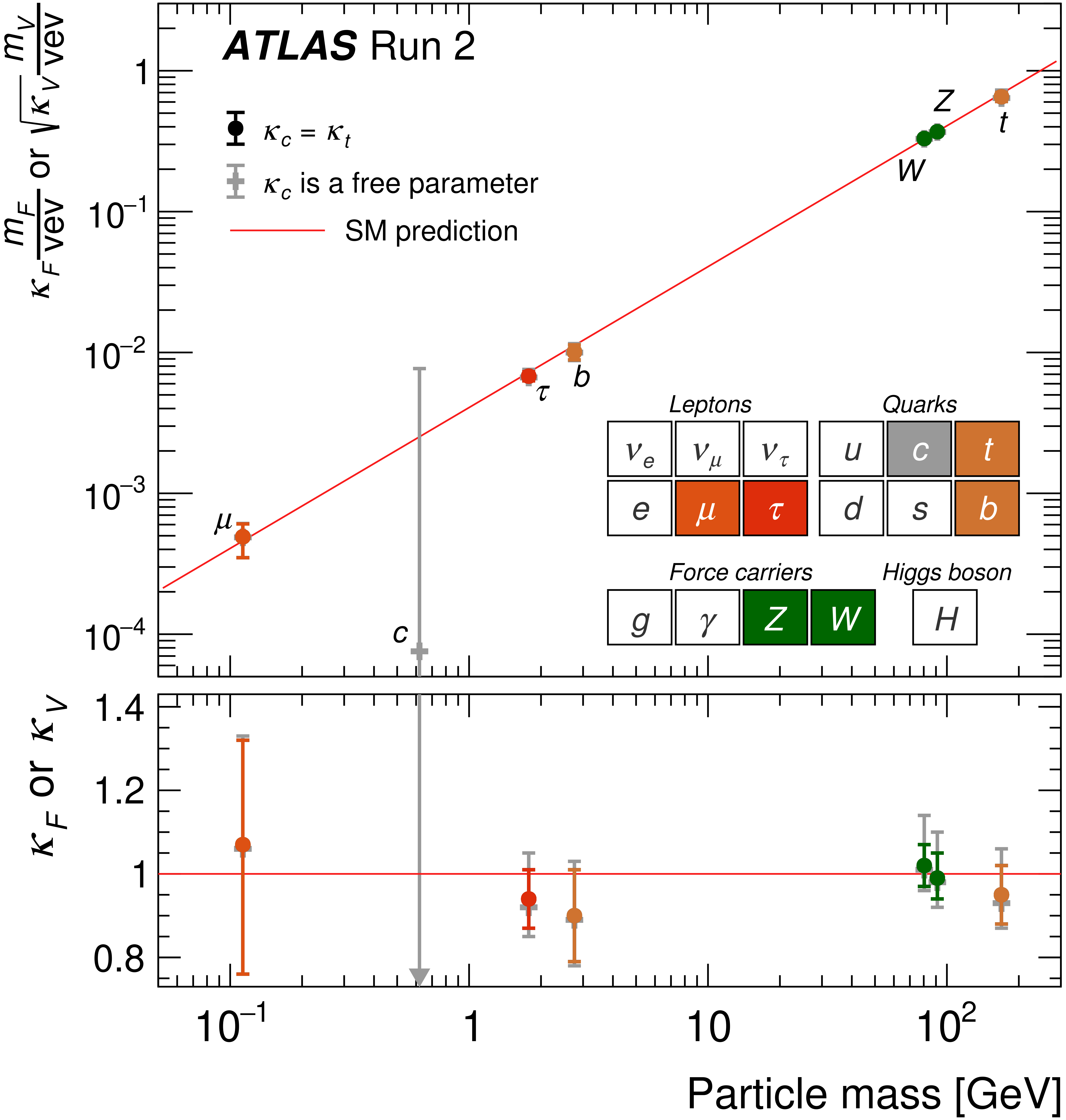
several orders of magnitude difference between fermion generations



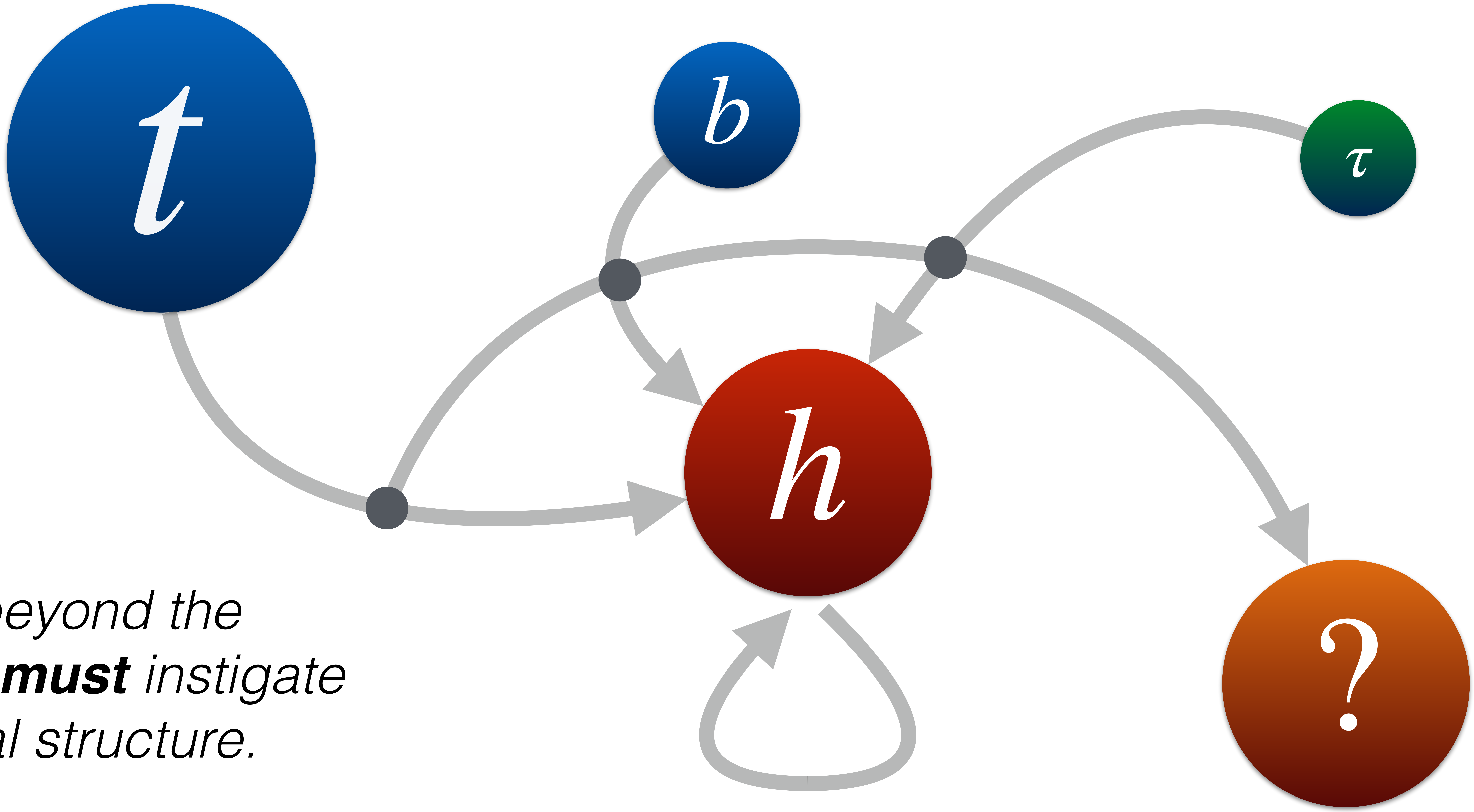


ATLAS have performed measurements and searches in ~all feasible Higgs production and decay modes.





so far there is no evidence of observed masses and Yukawa couplings deviating from expectation.



something beyond the Standard Model ***must*** *instigate this non-trivial structure.*

in this discussion we will focus on two measurements of LHC data: those of m_t and λ_{hhh}, and, crucially, how we are working to improve them.

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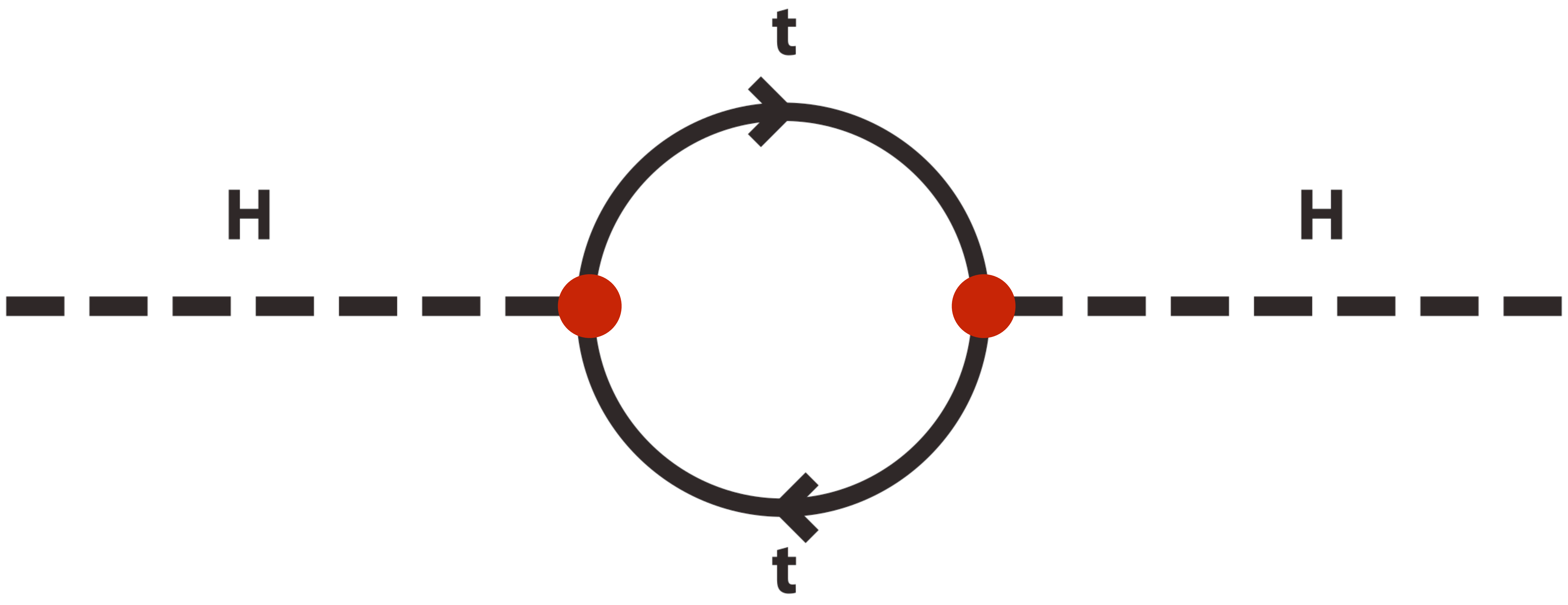
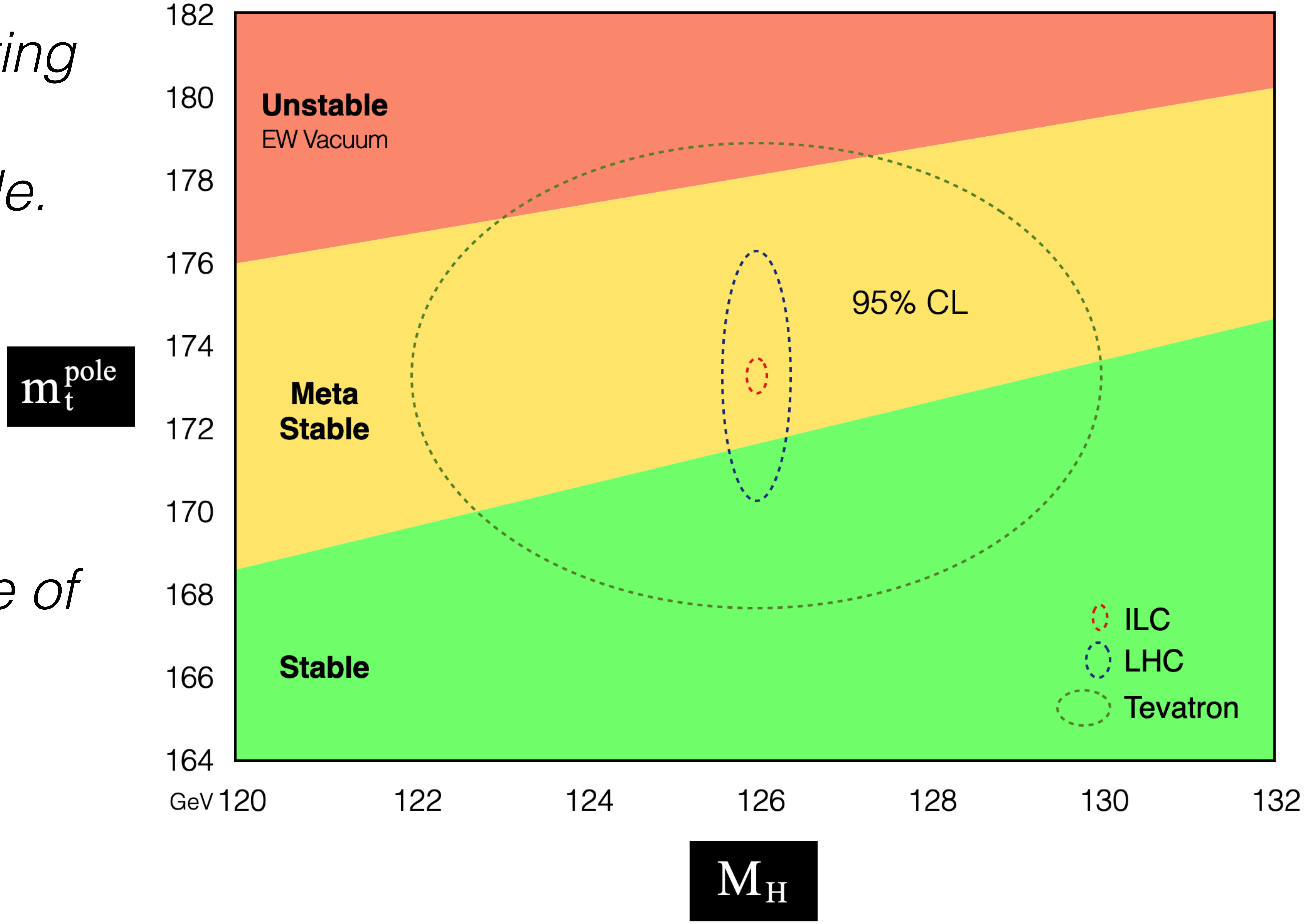
- under the assumption that the Yukawa coupling $g_X \leftrightarrow m_X$, measuring m_t is the most precise way to pin down the top ↔ Higgs coupling.
- since the top-Yukawa coupling is of order unity, its implications are enormous for Higgs phenomenology.



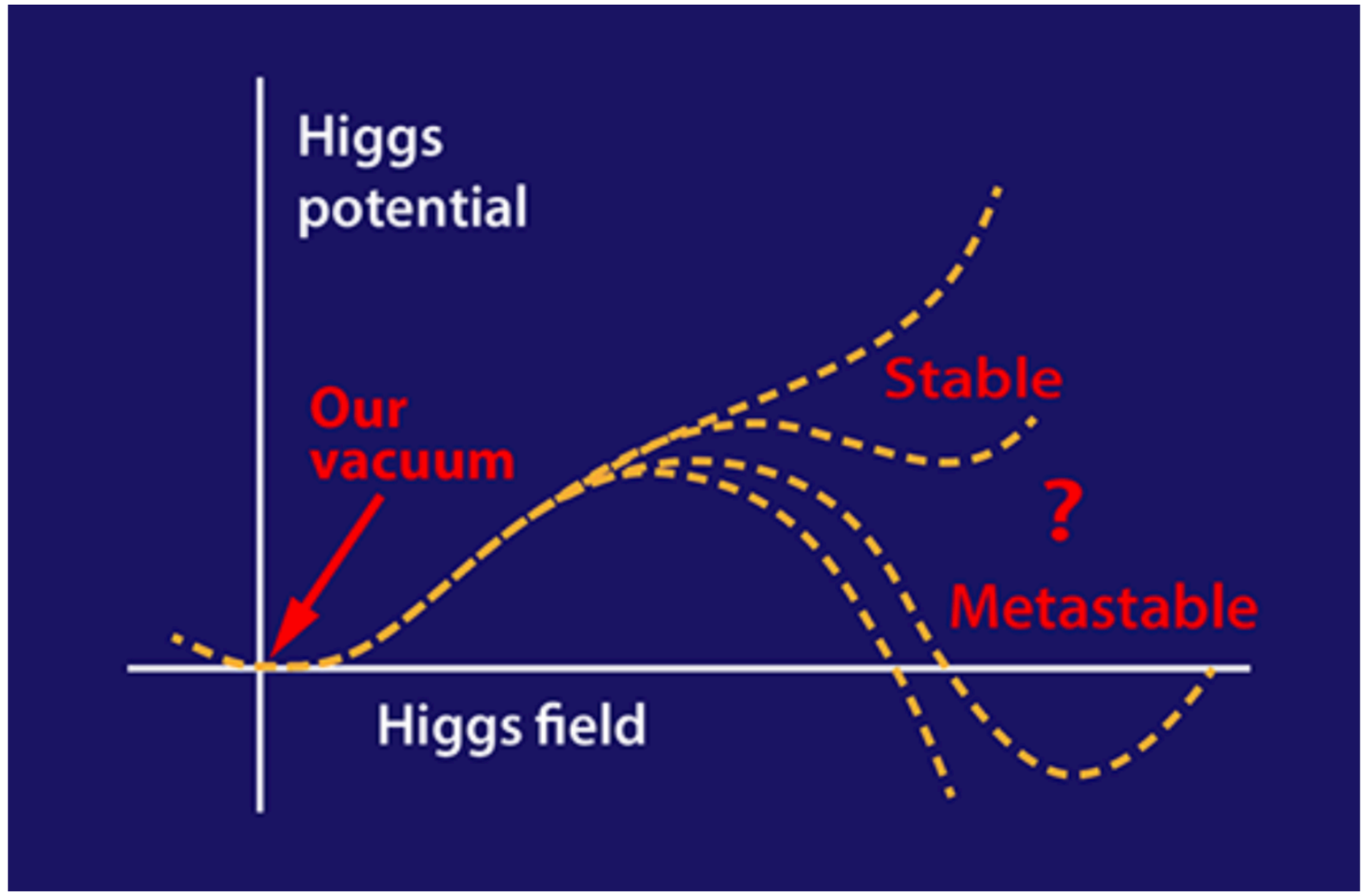
our knowledge of m_t one limiting factor in determining if the electroweak vacuum is stable.



NB: this assumes a SM shape of the Higgs field potential.

in this discussion we will focus on two measurements of LHC data: those of m_t and λ_{hhh}, and, crucially, how we are working to improve them.

- the Higgs boson self-coupling λ_{hhh} controls the shape of Higgs potential!
- the running of this coupling to high energy scales also has implications on the (meta) stability of Nature.



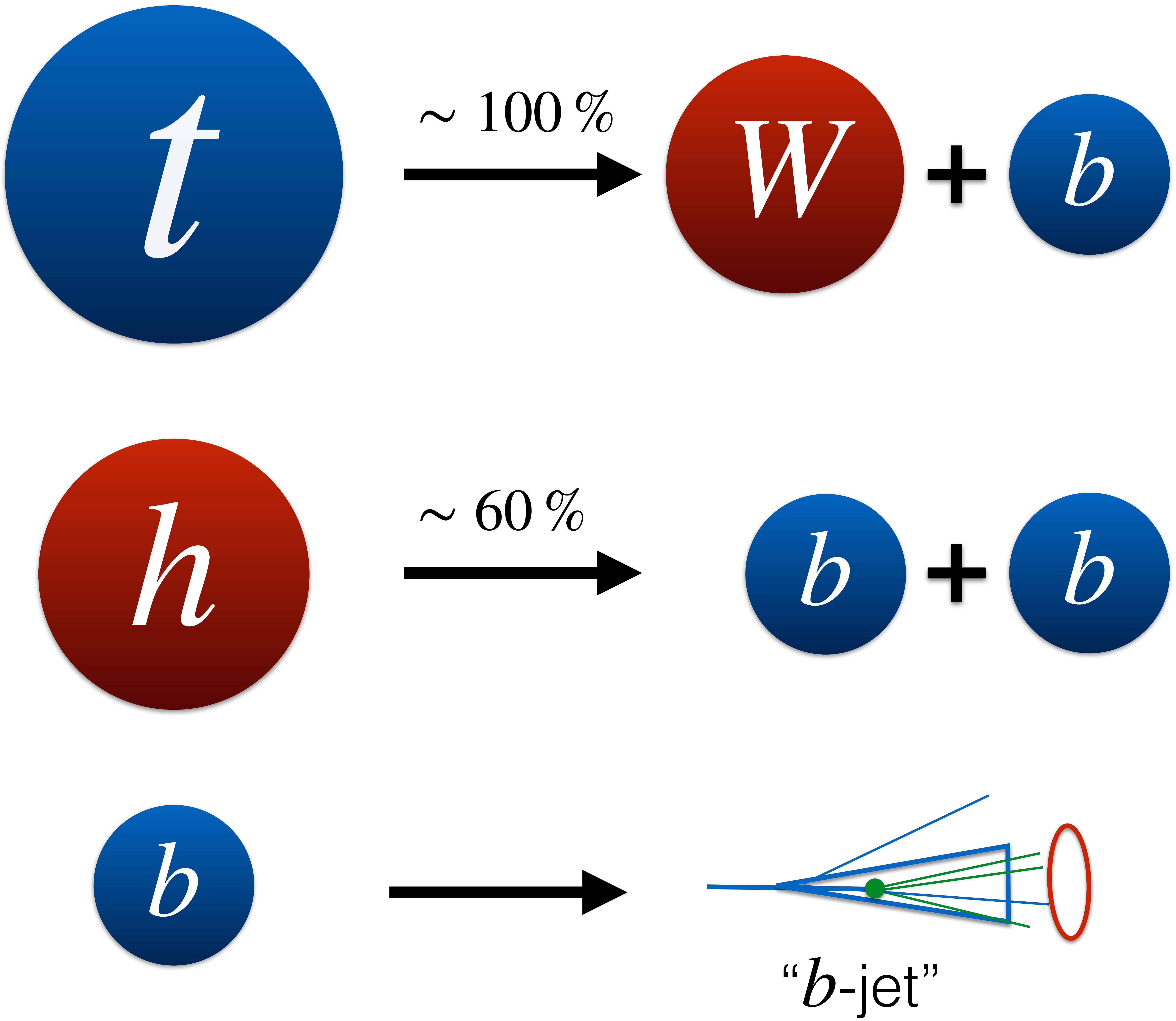
arXiv 2104.06821
Bass, Do Roeck, Kado

in this discussion we will focus on two measurements of LHC data: those of m_t and λ_{hhh}, and, crucially, how we are working to improve them.

- the Higgs boson self-coupling λ_{hhh} controls the shape of Higgs potential!
- the running of this coupling to high energy scales also has implications on the (meta) stability of Nature.
- the Higgs is the only known fundamental scalar with hypothesized contributions to inflation and couplings to dark matter/energy.
- in many scenarios, BSM values of λ_{hhh} drastically alter those implications!

how do we measure these quantities at the LHC?

experimental signatures



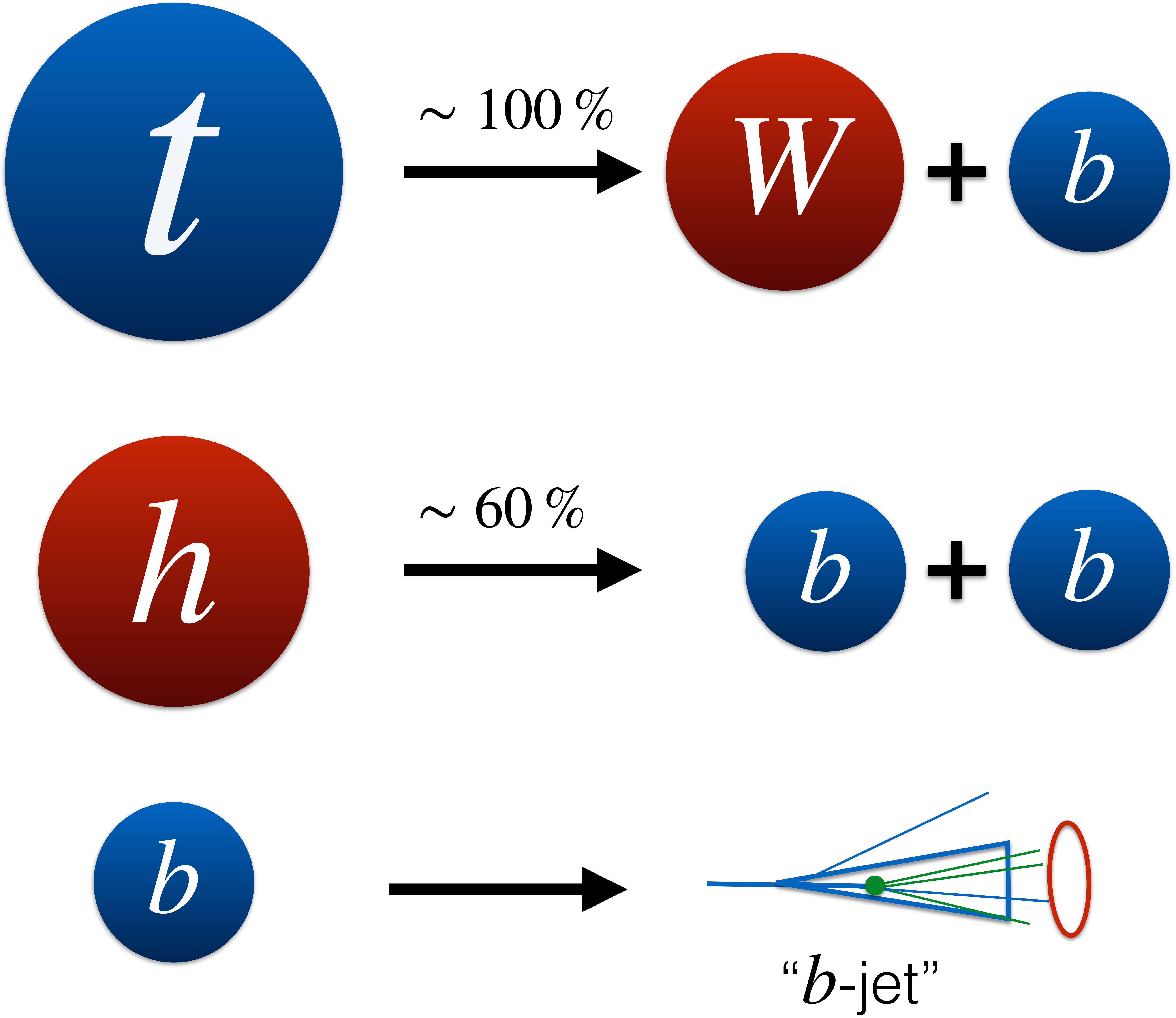
$$t \xrightarrow{\sim 100\,\%} W + b$$

$$h \xrightarrow{\sim 60\,\%} b + b$$

$$b \longrightarrow$$

“b-jet”

experimental signatures



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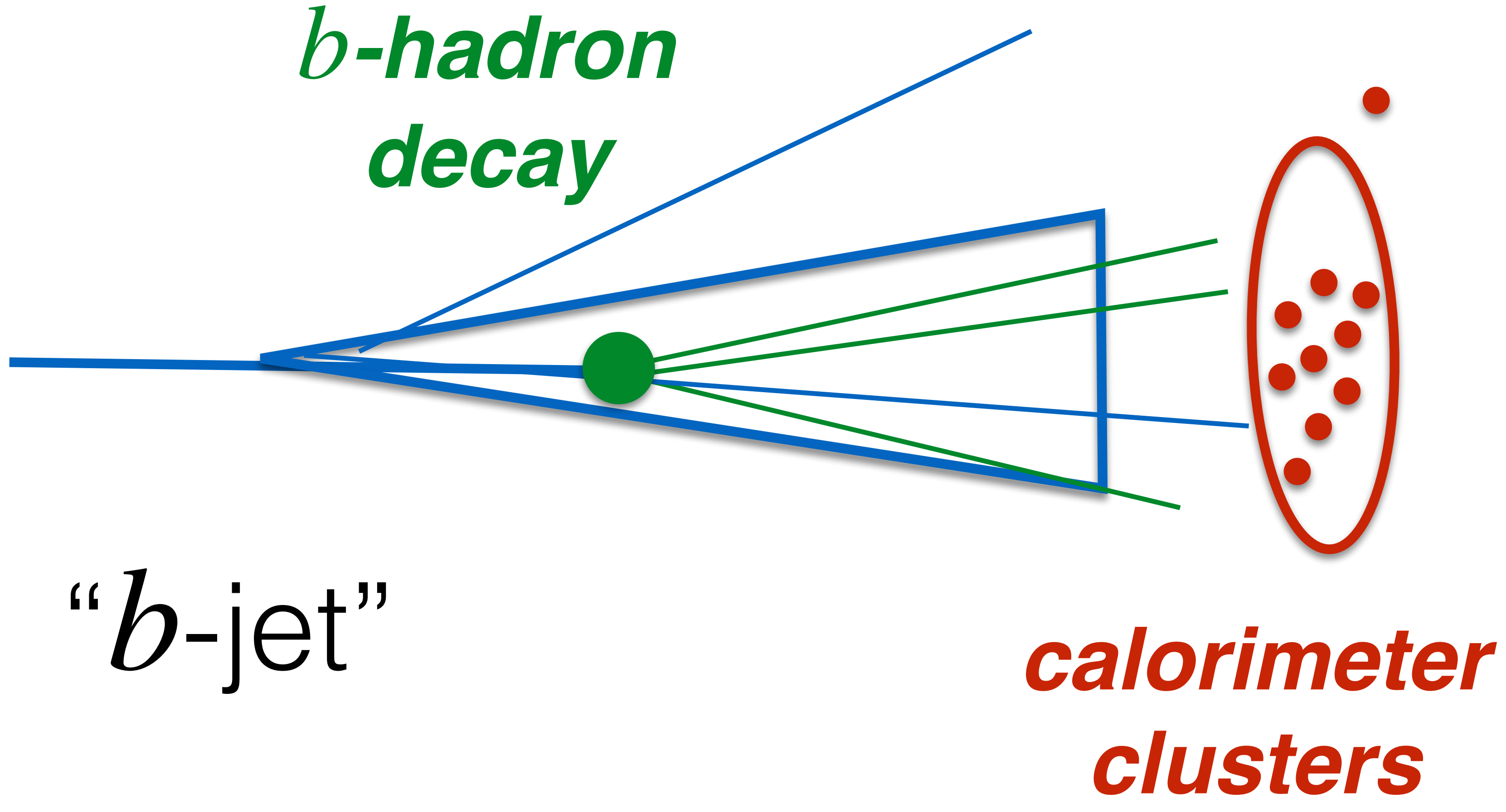

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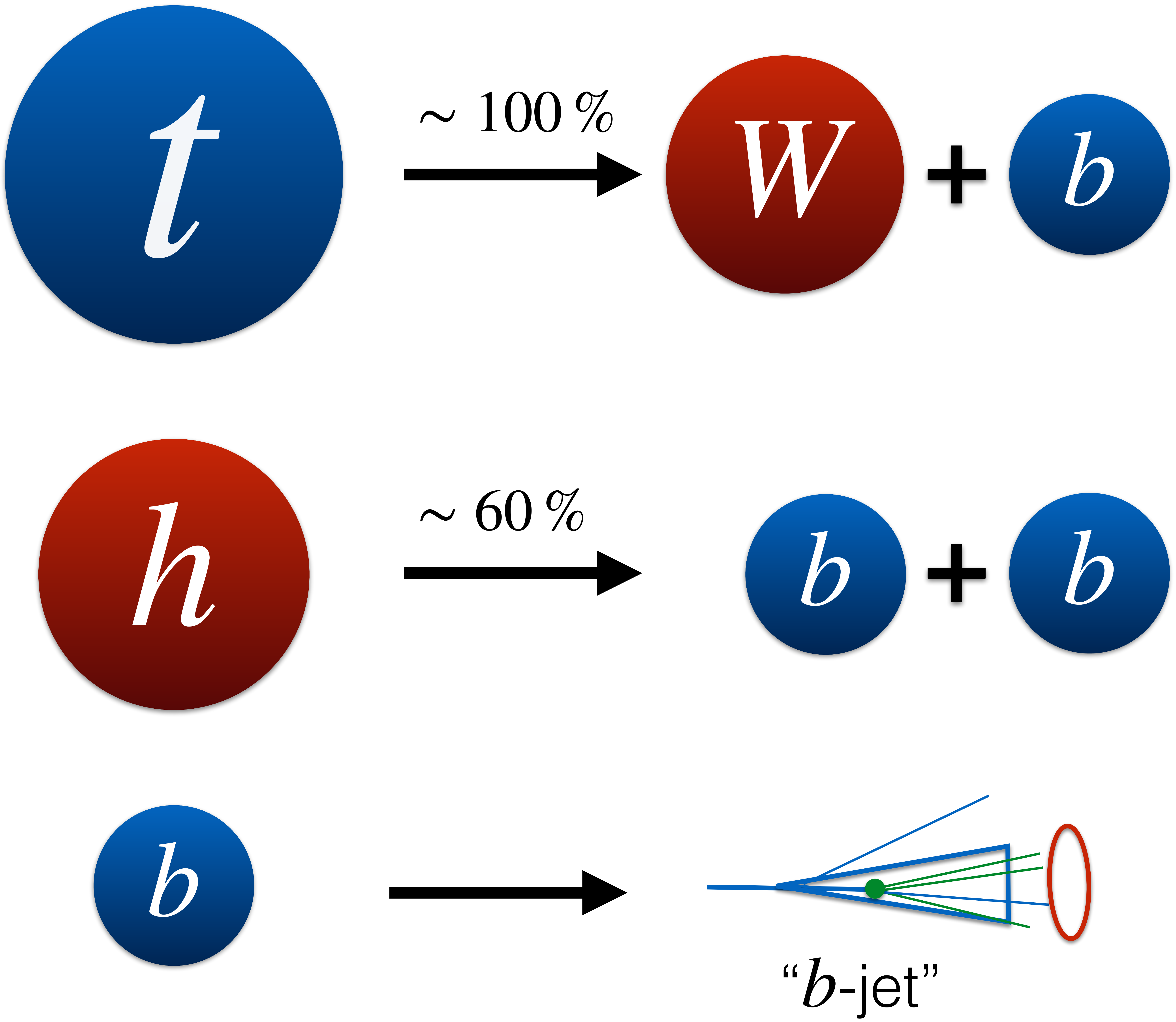

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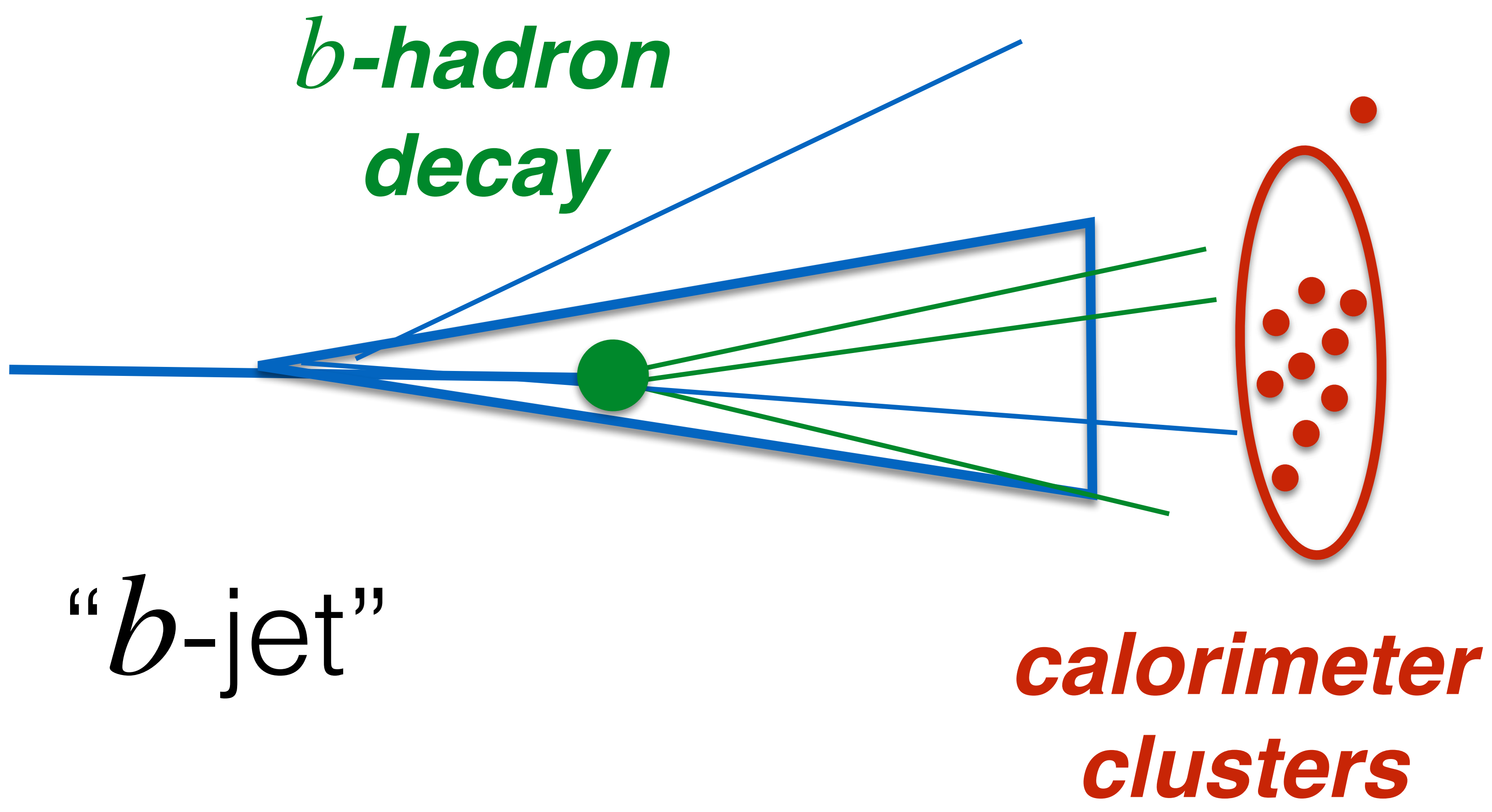
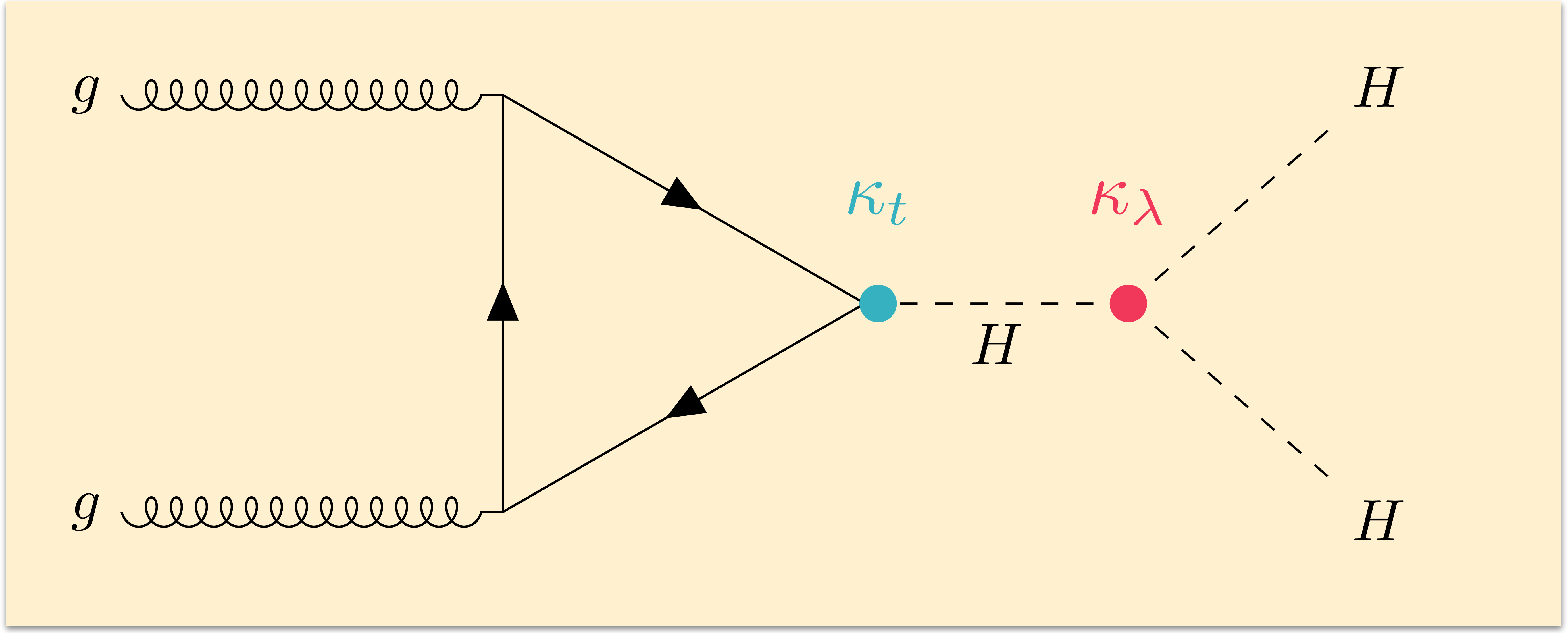


*the LHC is a hadron collider: there is an **enormous** background of particle jets without b-hadrons.*

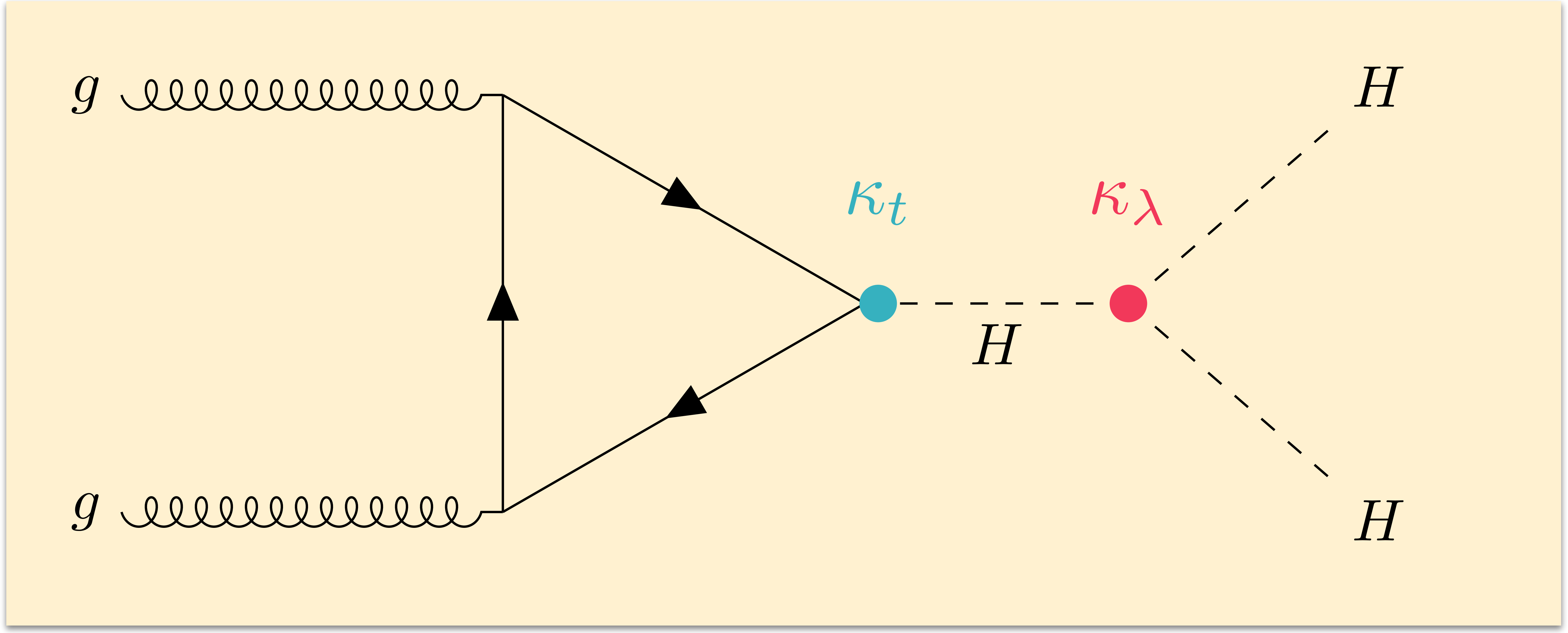
identification of b-jets is key.

measuring the Higgs self-coupling, λ_{hhh}



the most promising way to probe the Higgs self-coupling at the LHC is through measuring Higgs pair production.

$$\kappa_X = g_X / g_X^{\mathrm{SM}}$$



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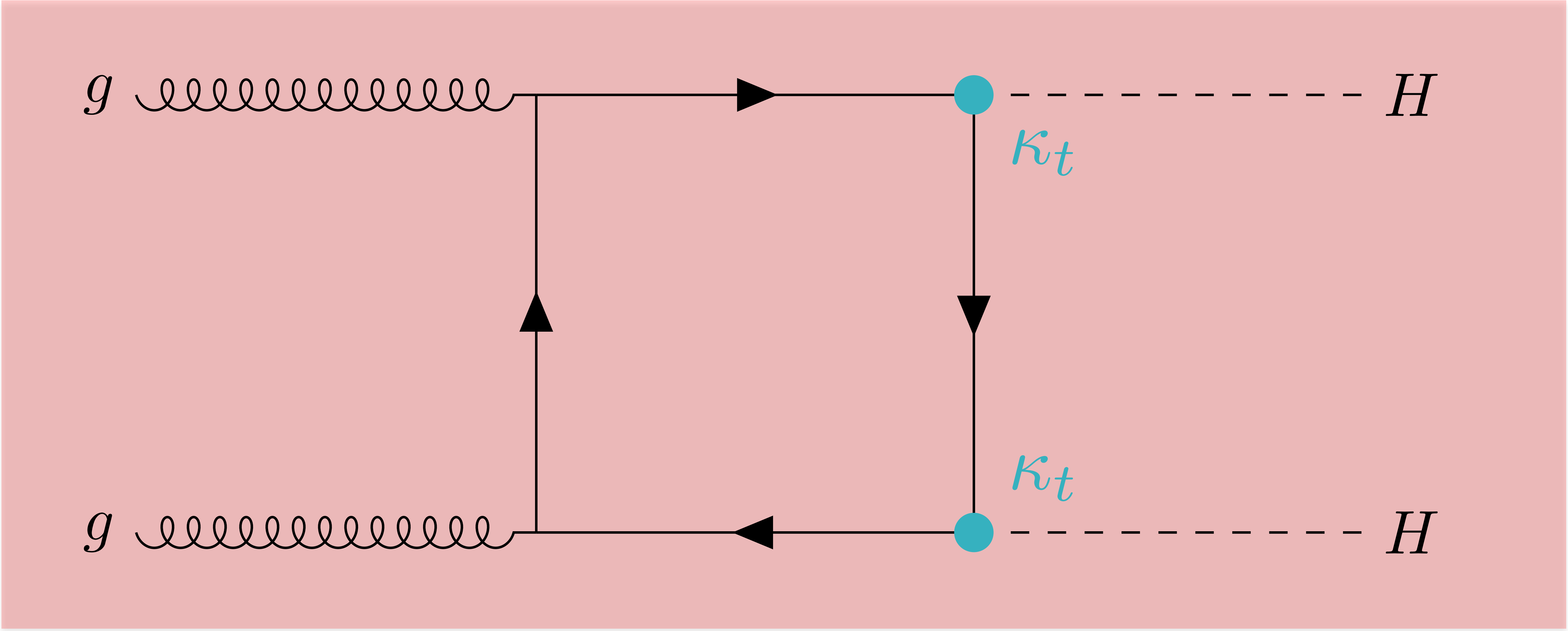

but there are confounding factors: e.g. strong (negative) interference with other production diagrams.

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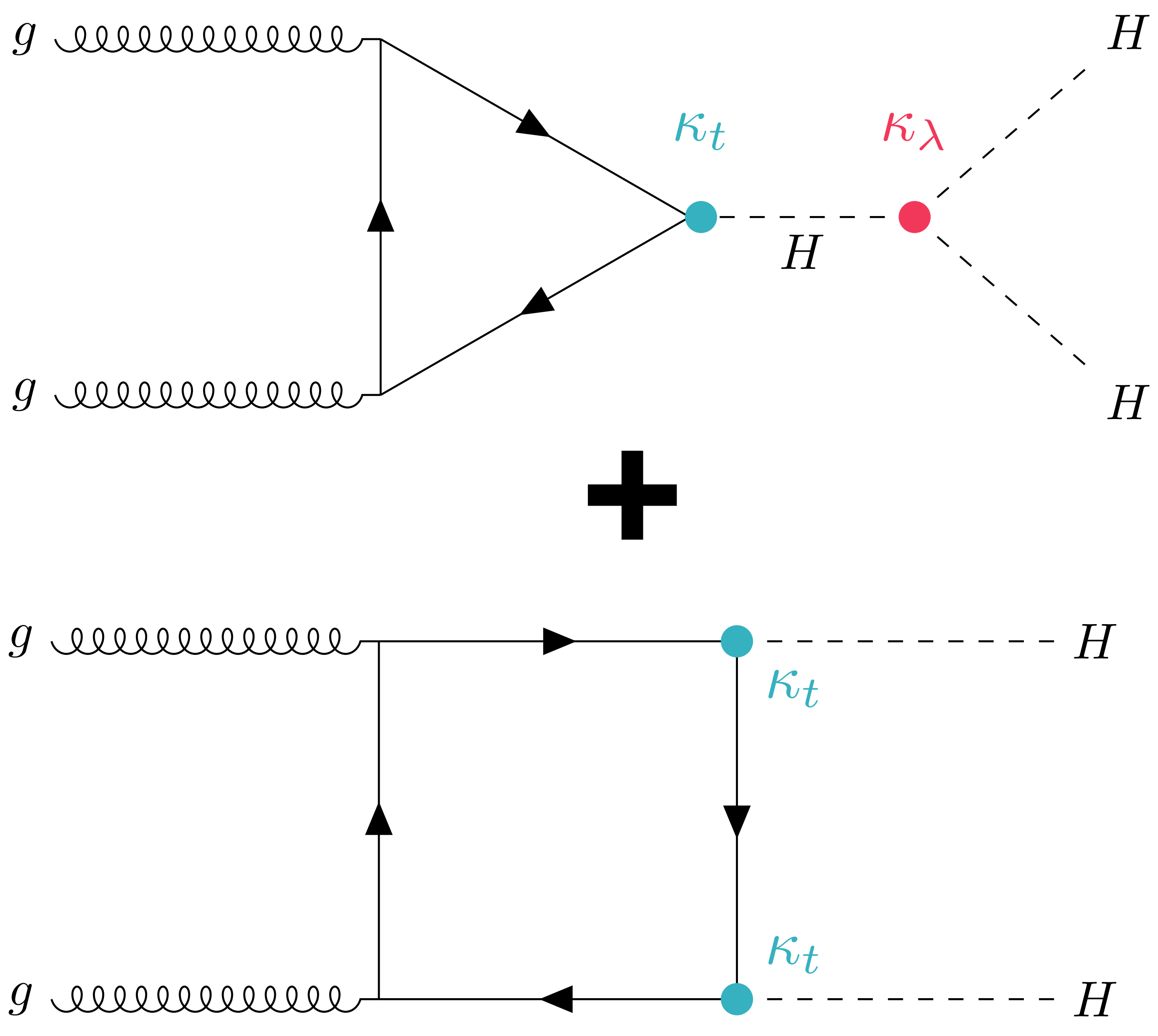
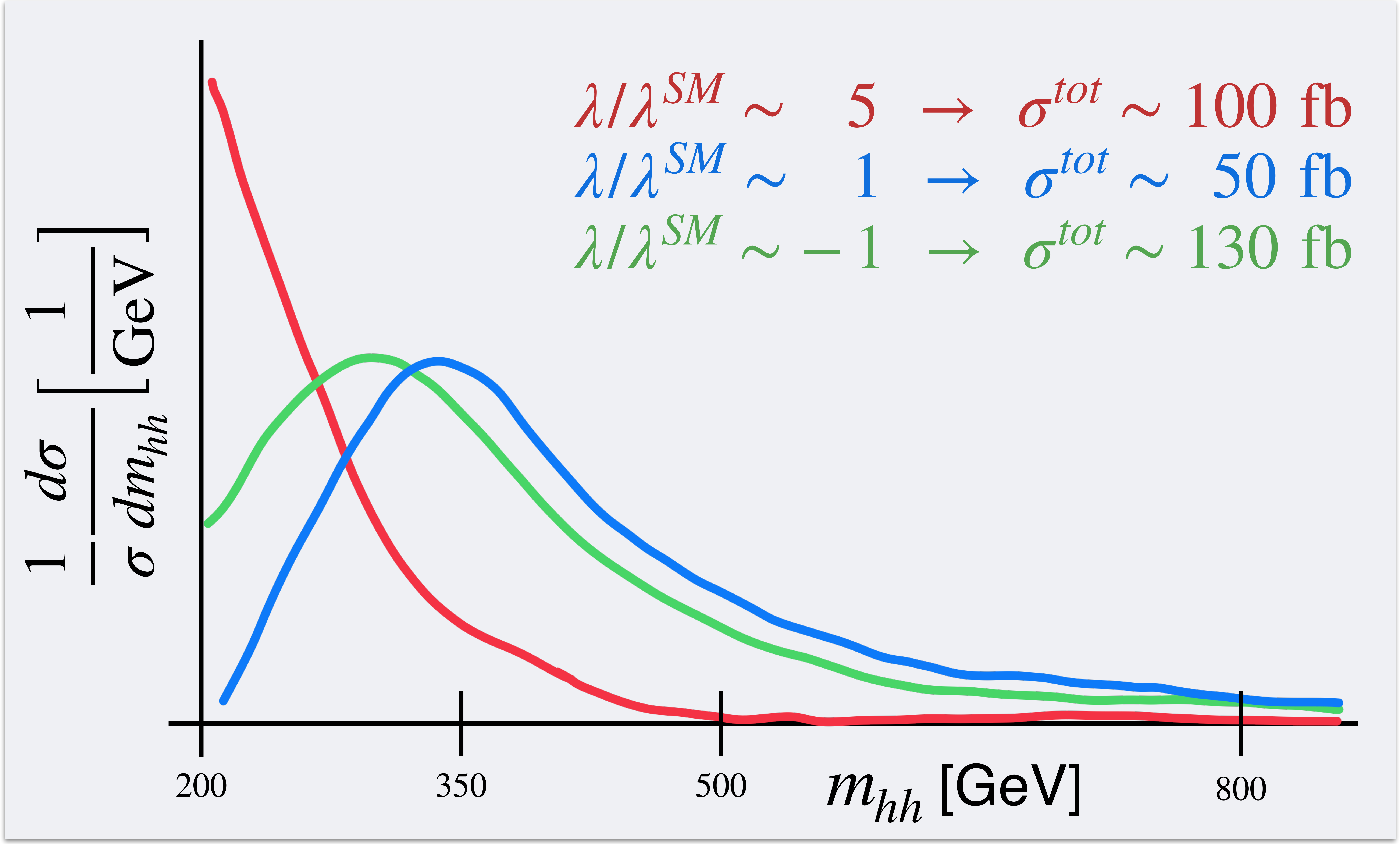
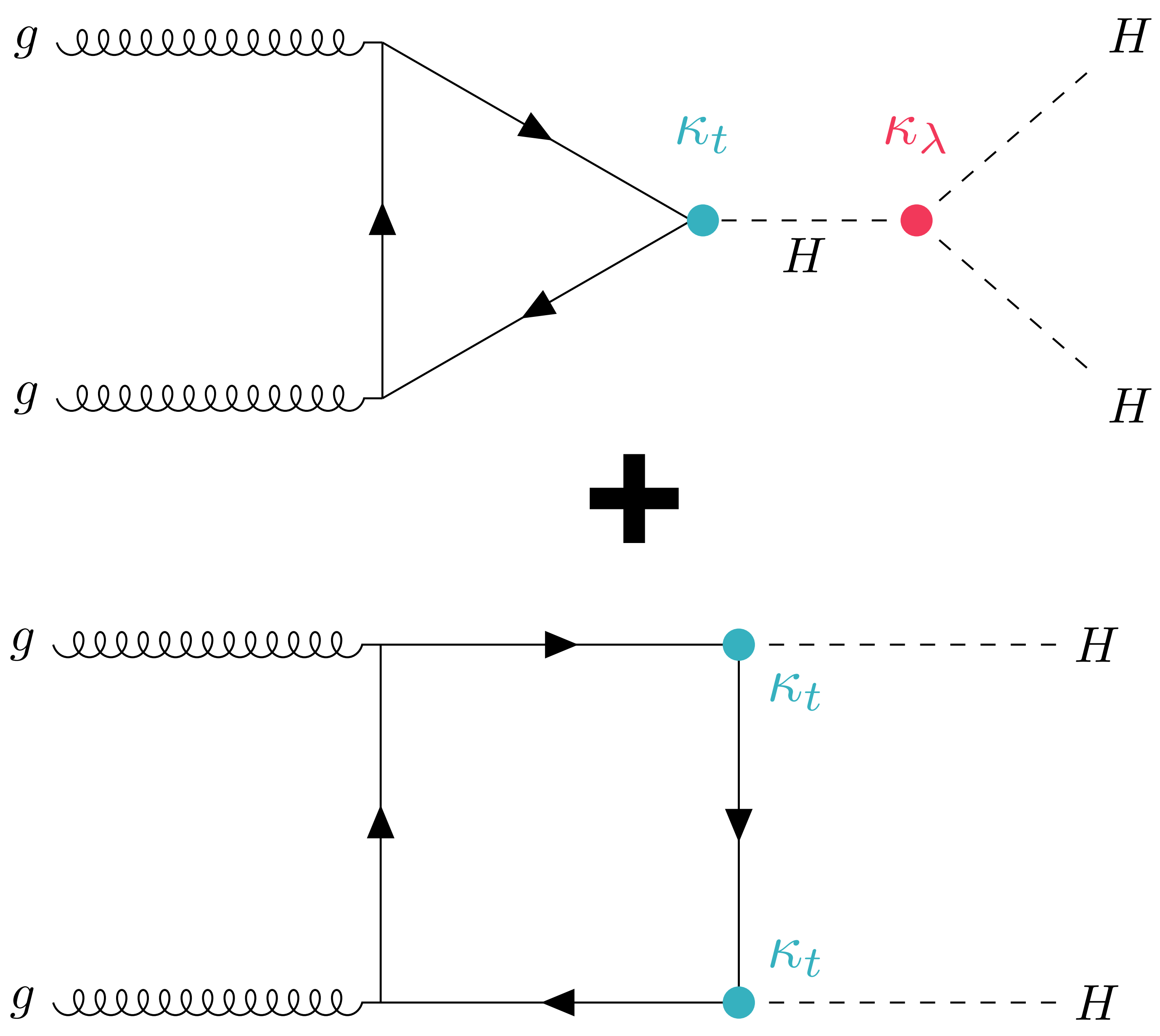
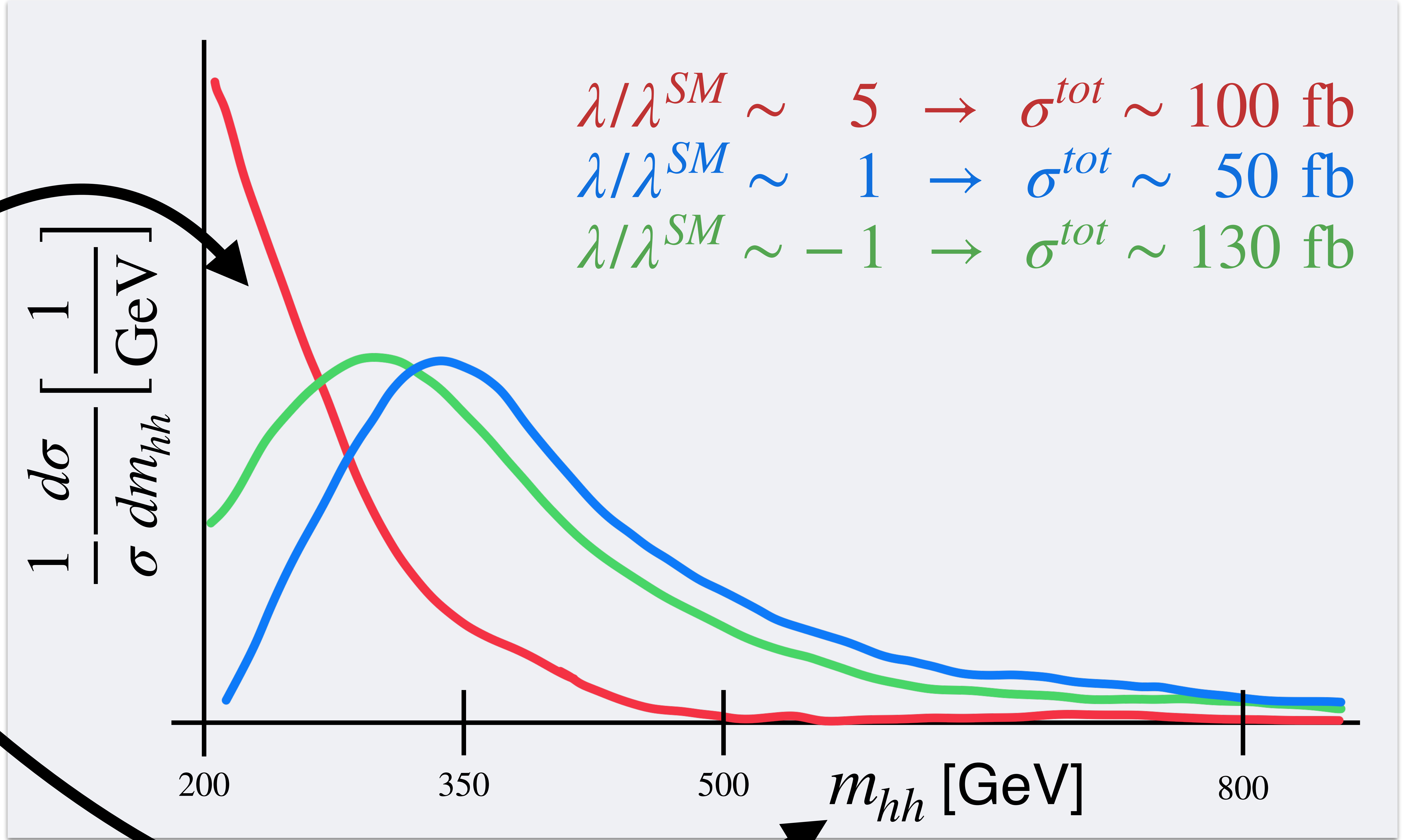


g
g
κ_t
κ_λ
H
H
H
+
g
g
κ_t
κ_t
H
H



$\lambda/\lambda^{SM} \sim 5 \rightarrow \sigma^{tot} \sim 100$ fb
$\lambda/\lambda^{SM} \sim 1 \rightarrow \sigma^{tot} \sim 50$ fb
$\lambda/\lambda^{SM} \sim -1 \rightarrow \sigma^{tot} \sim 130$ fb
$\frac{1}{\sigma}\frac{d\sigma}{dm_{hh}}\left[\frac{1}{\text{GeV}}\right]$
200
350
500
800
m_{hh} [GeV]





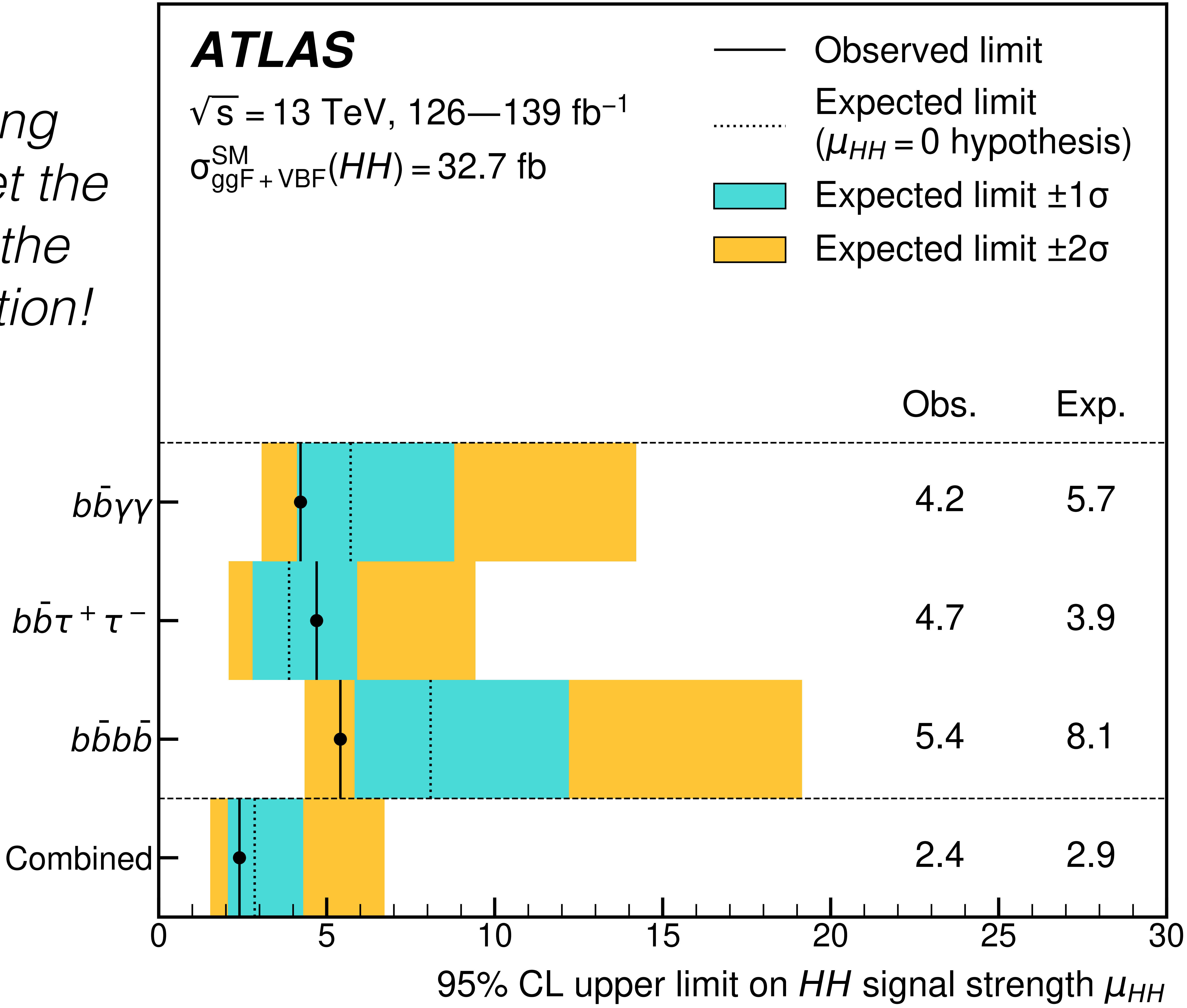
Higgs self-coupling mostly alters low m_{hh}.

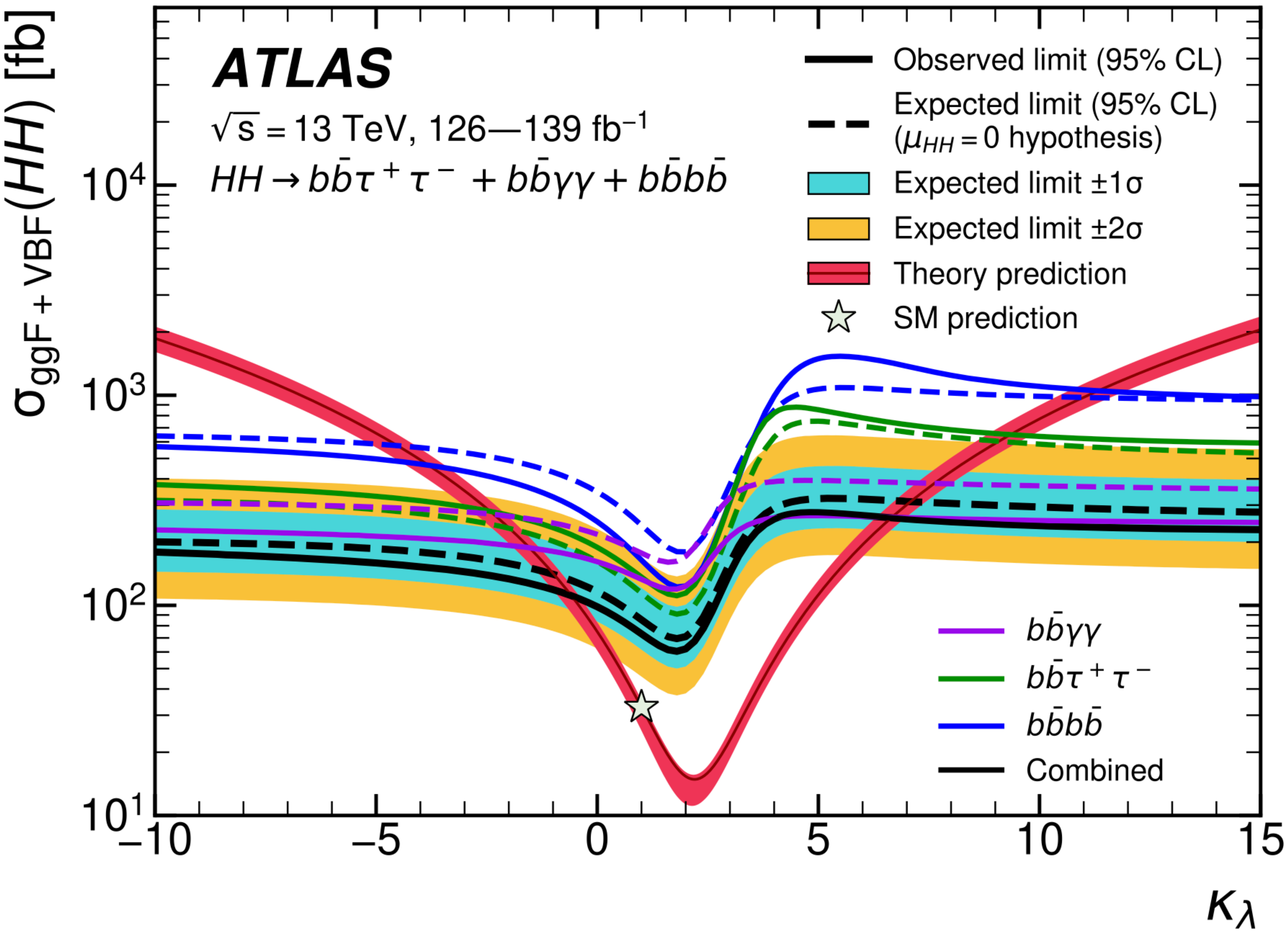
ATLAS have made outstanding progress in the last years to get the exclusion limits down to ~3x the Standard Model hh cross section!

largest recent improvements:

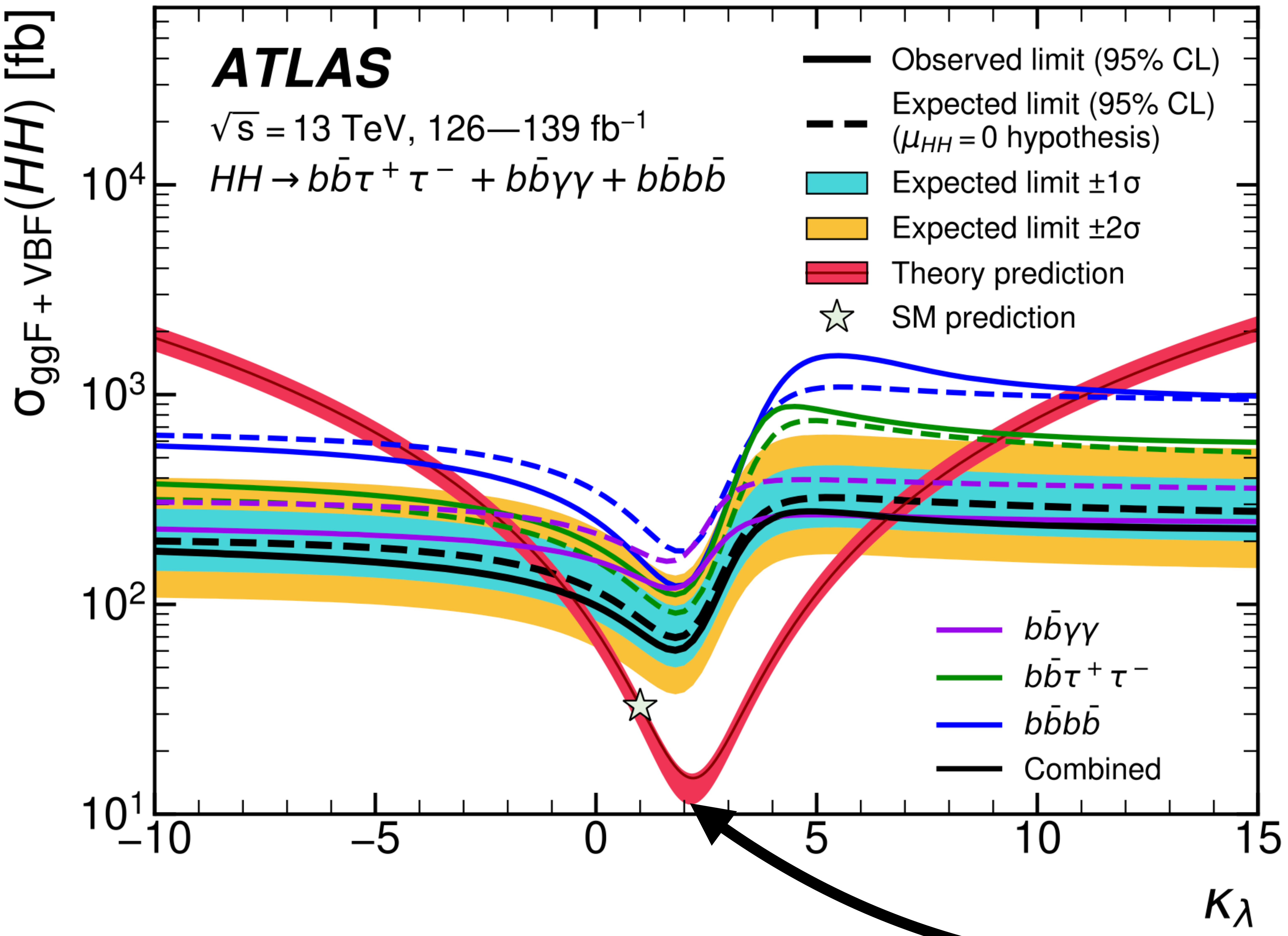
- b-jet identification

- deep learning-based background rejection





we have very nearly ruled out $\kappa_\lambda = 0$ *(no self-coupling).*



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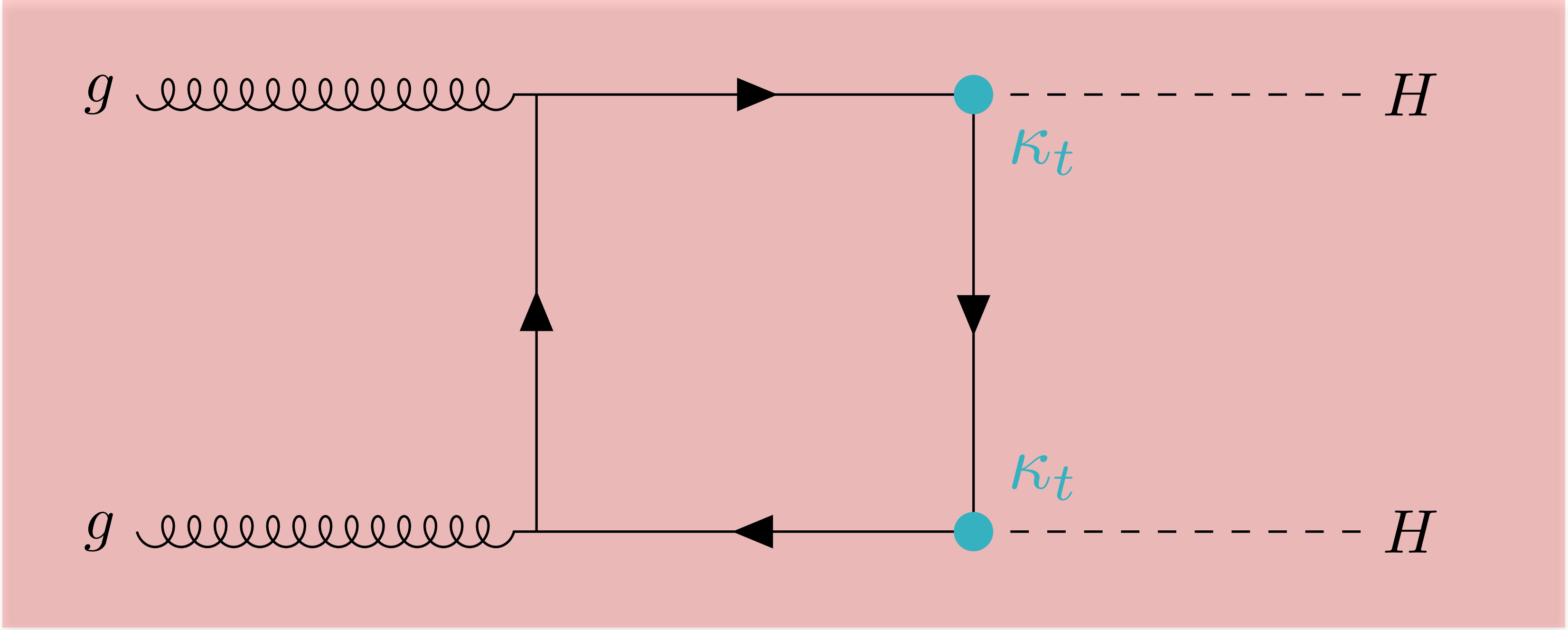
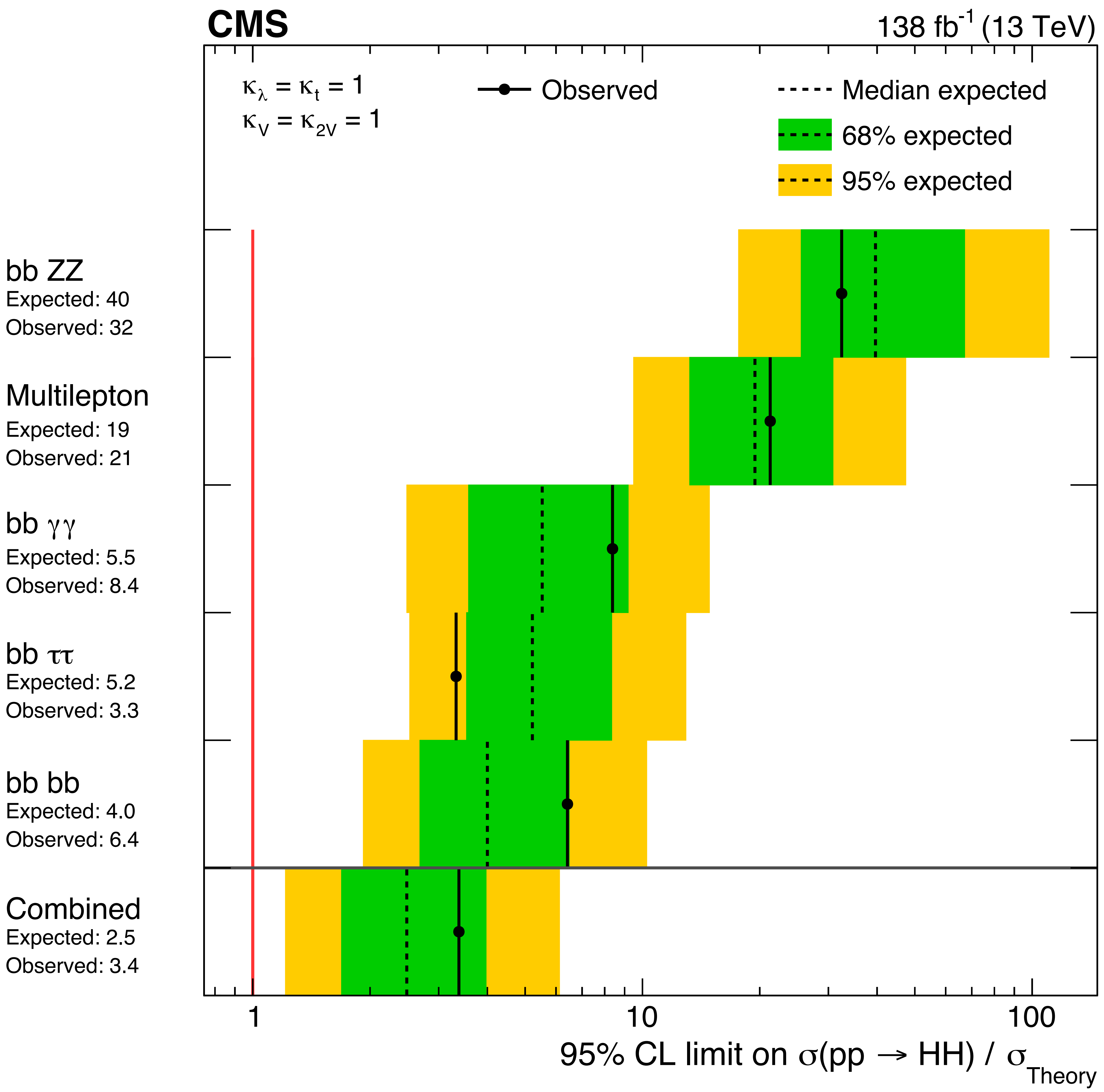
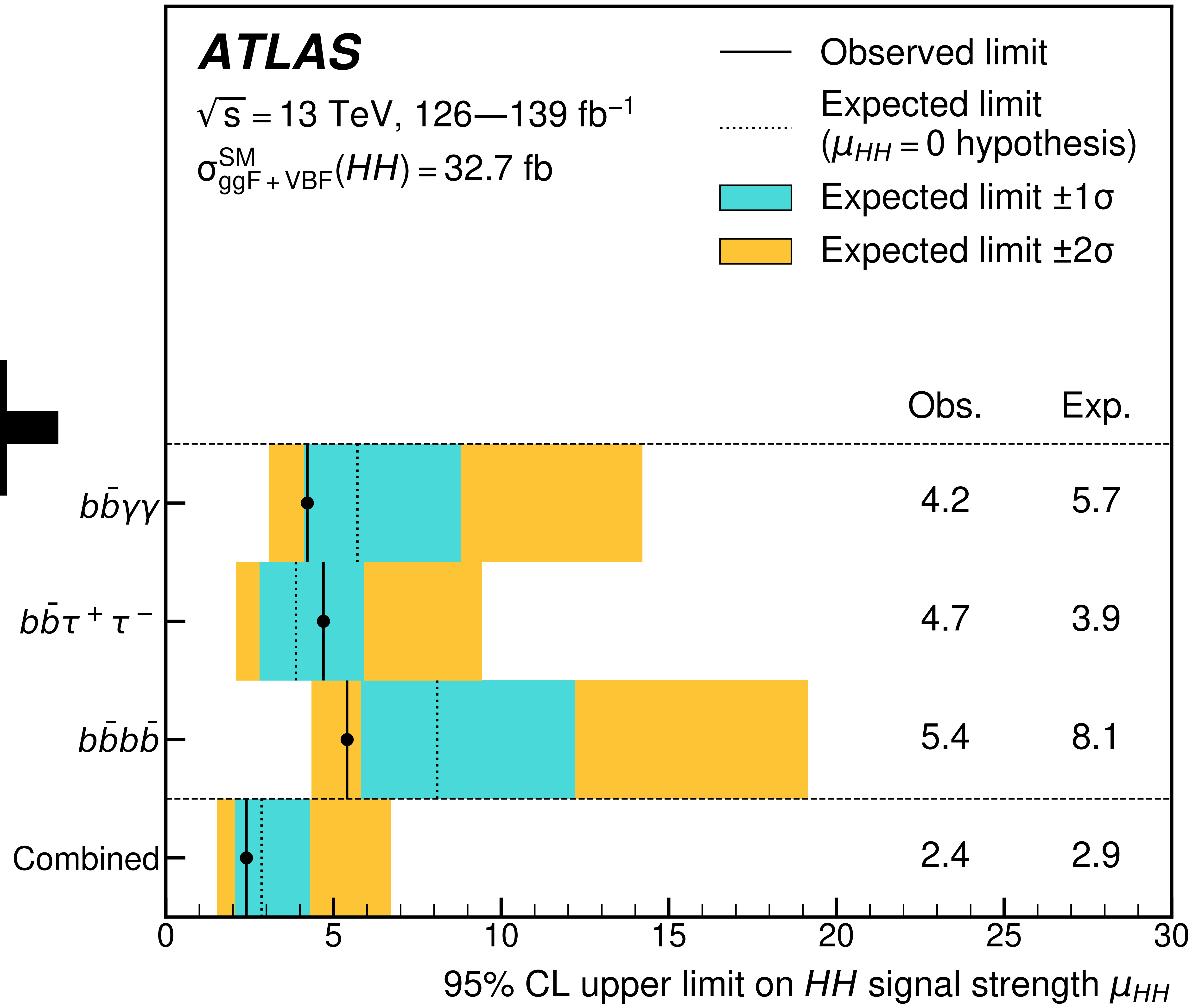
small, positive values of κ_λ remain elusive:

very large negative interference with box diagram!





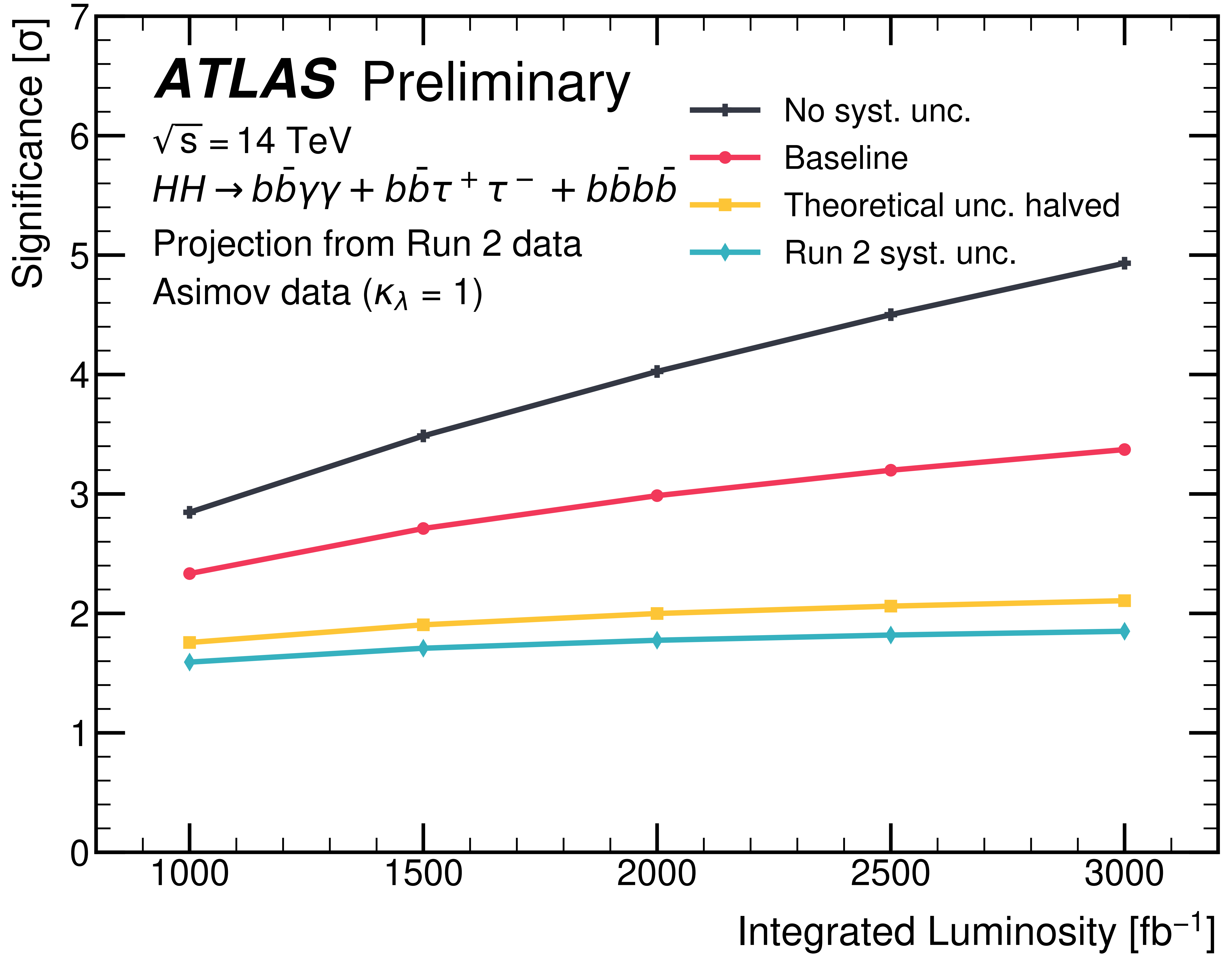
+



ATLAS + CMS may rule out $\kappa_\lambda = 0$ with a Run 2 combination, but we will still be far from observing hh production.

using current analysis strategies and uncertainties, we will not observe hh production even at the high-luminosity LHC.

what can we do to improve this search already in Run 3 in preparation for HL-LHC?



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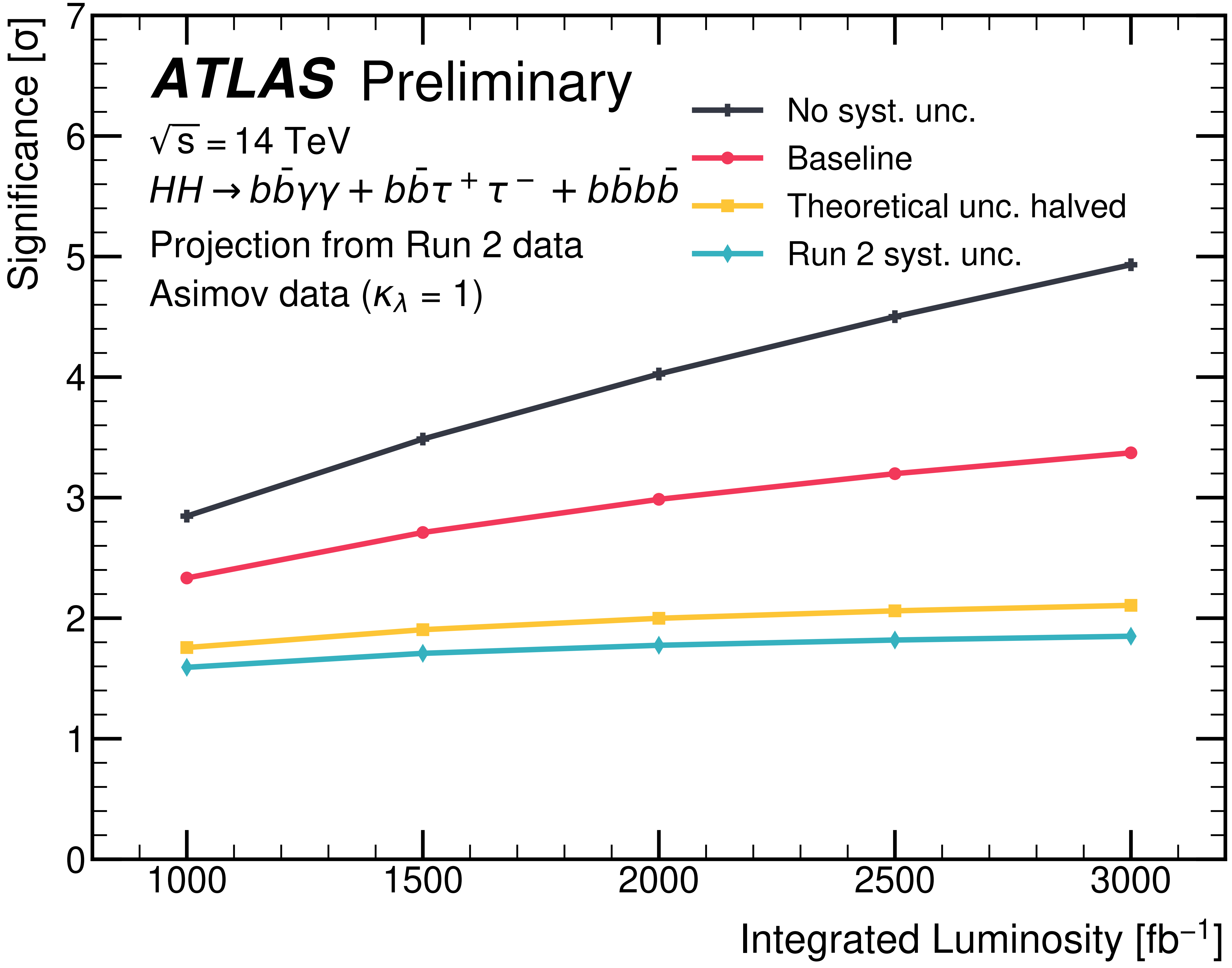
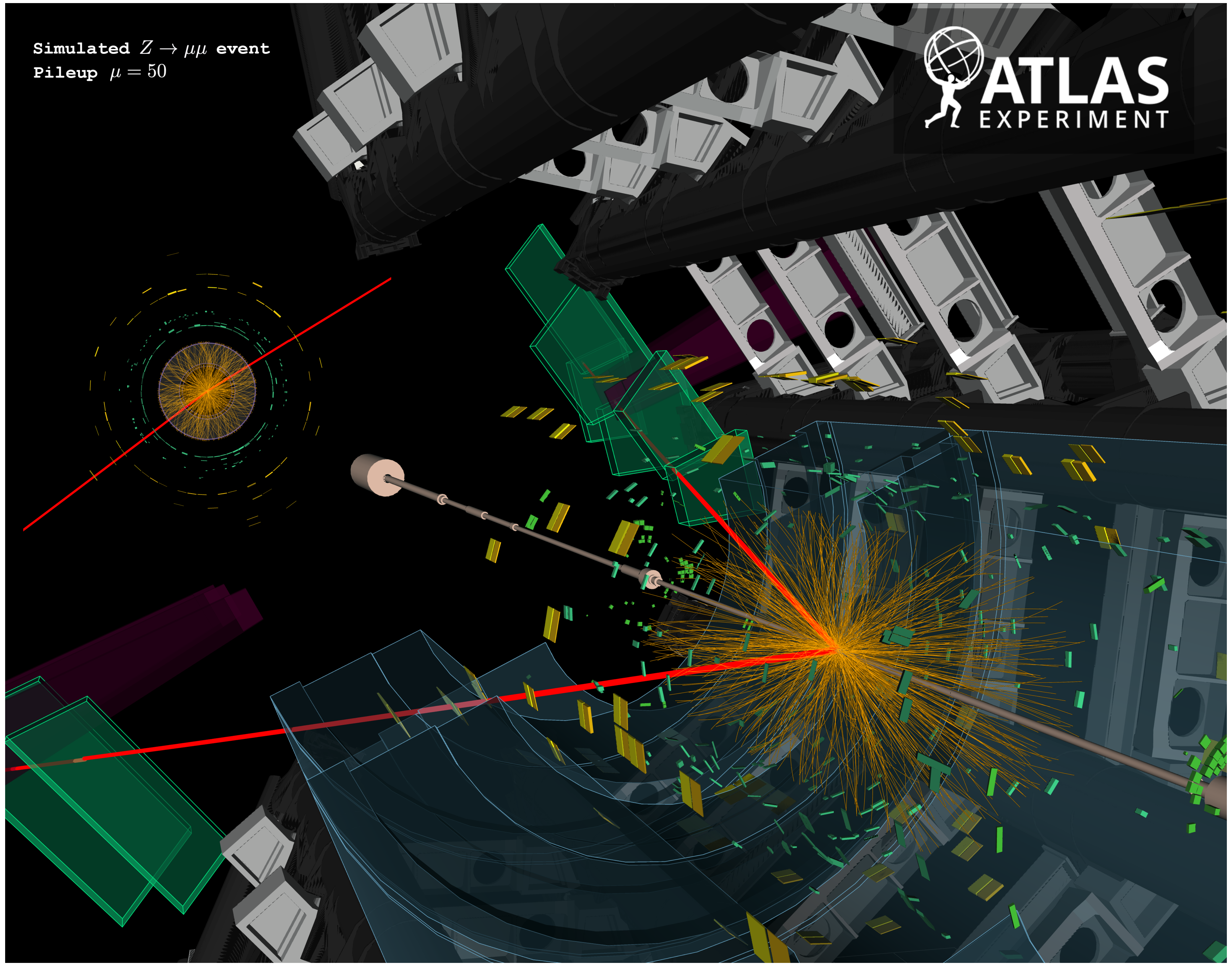
$bb\gamma\gamma$ and $bb\tau\tau$ channels currently have dominant statistical uncertainties.

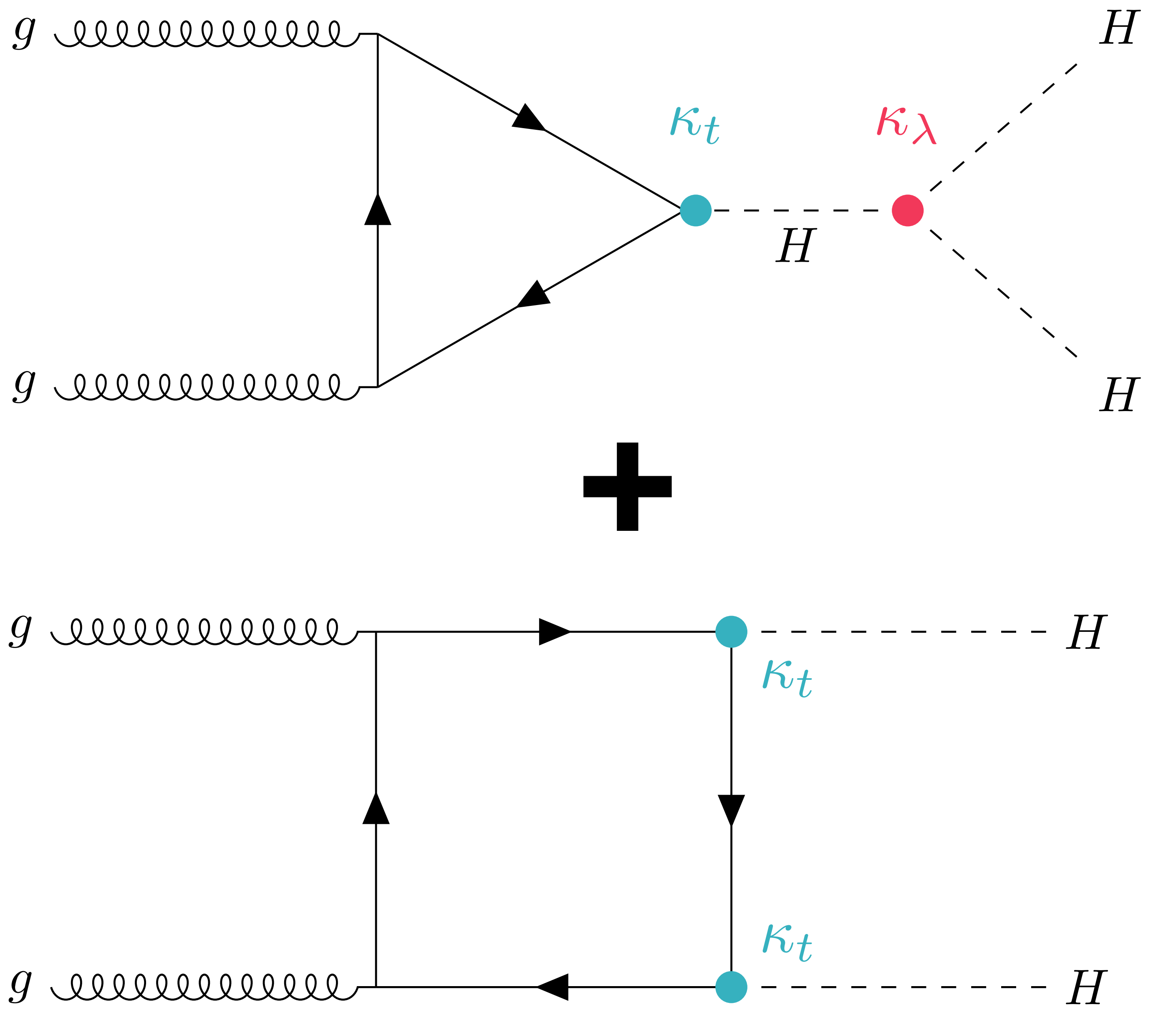
$bbbb$, however, has low signal acceptance and is systematically limited…

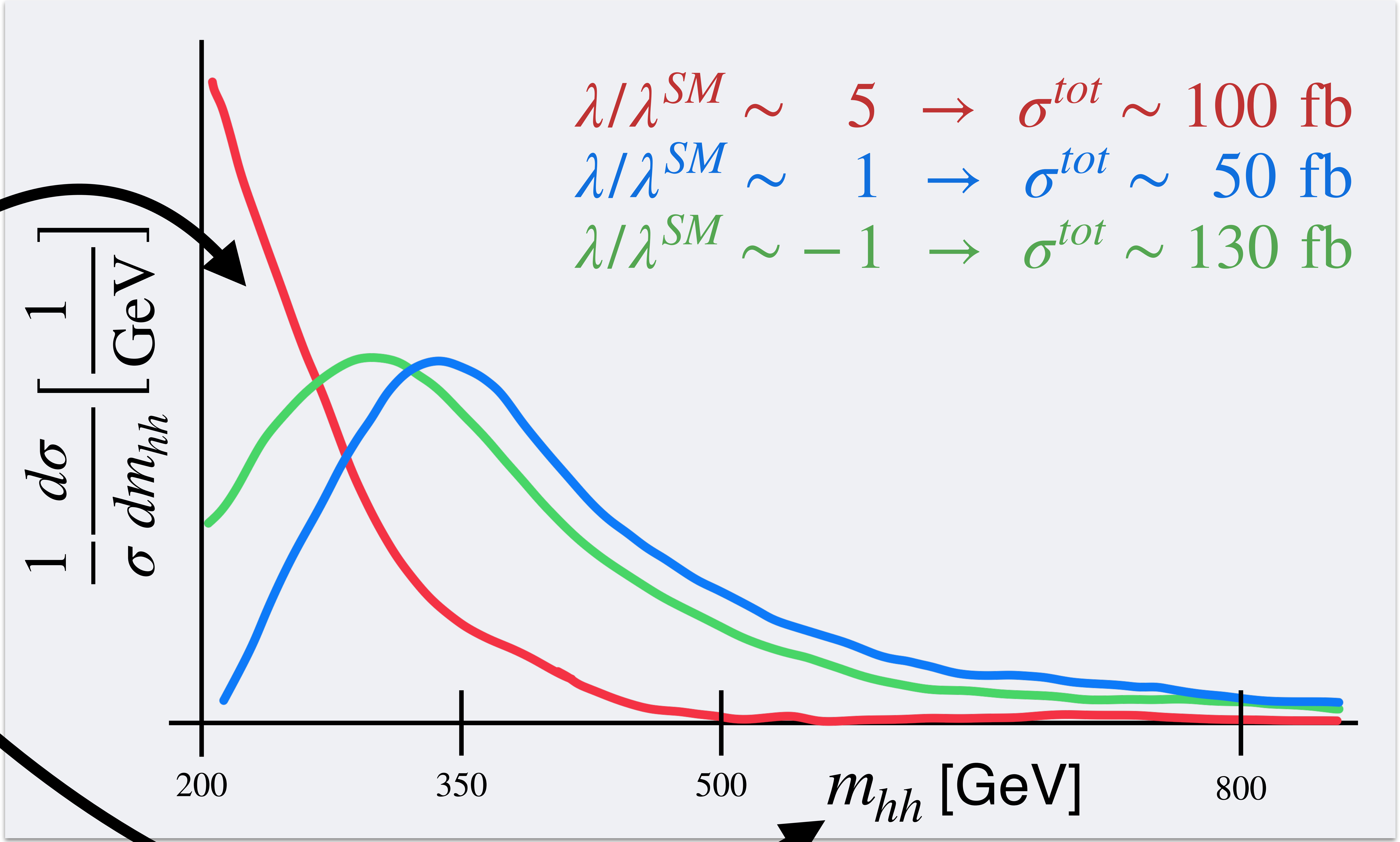


LHC collisions occur at ~40 MHz

- 40-60 collisions per crossing of proton bunches
- we cannot afford to write all of these data to disk!
- the ATLAS trigger system
  - ~100 kHz: hardware-based “Level 1”
  - ~3 kHz: software-based “High Level Trigger”
- hh production is allocated about 150 Hz of write-out rate in Run 3.







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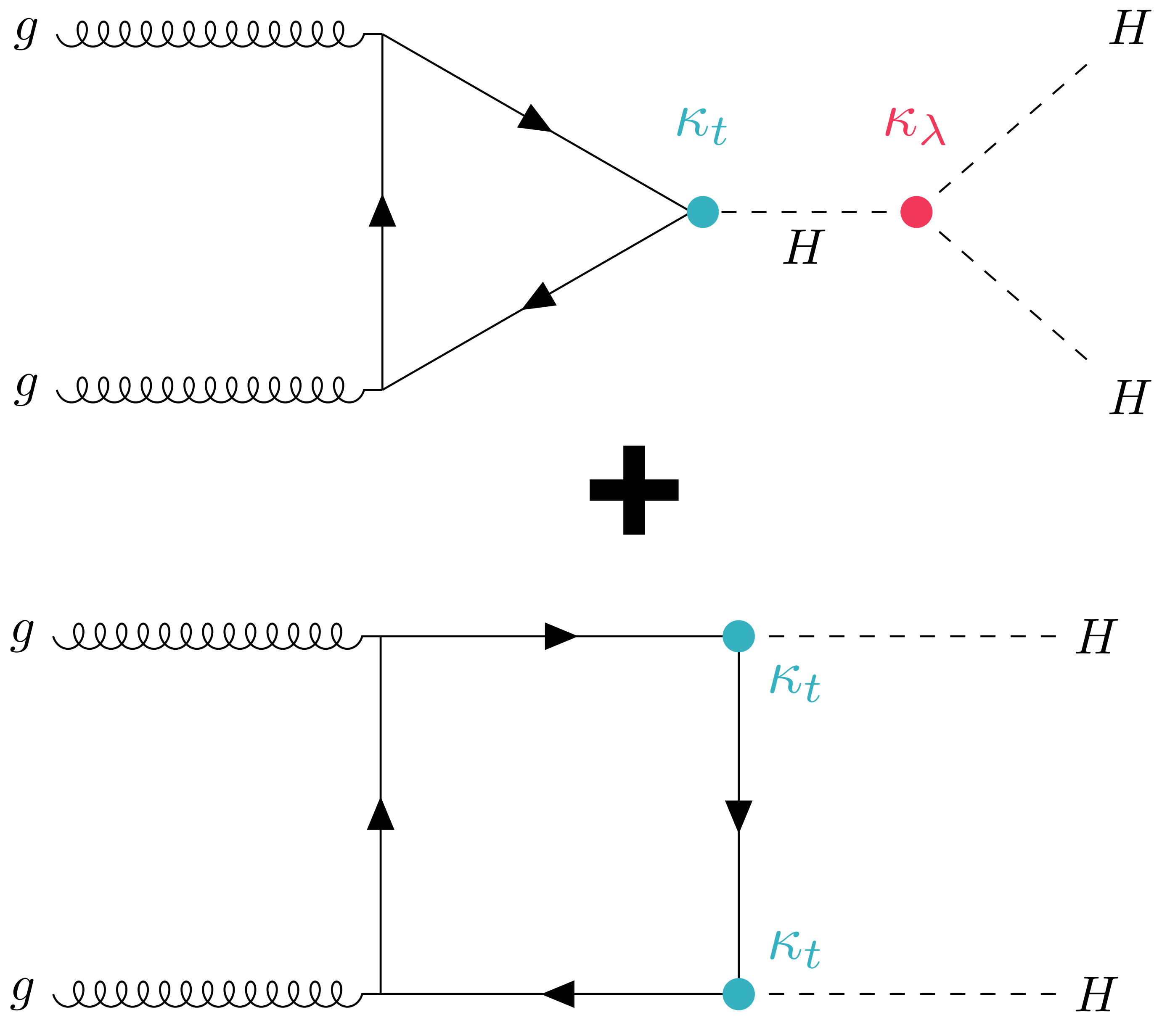
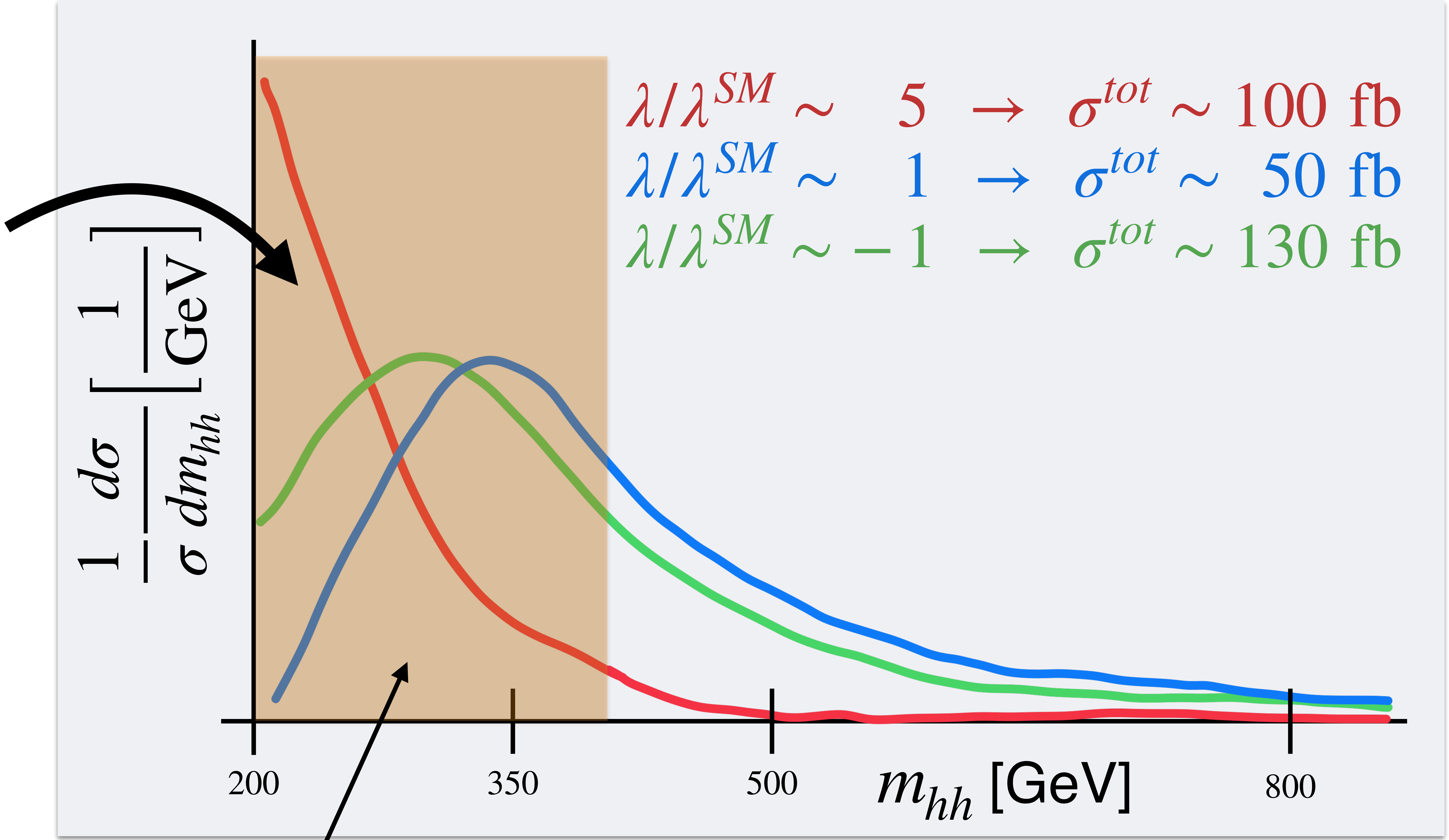
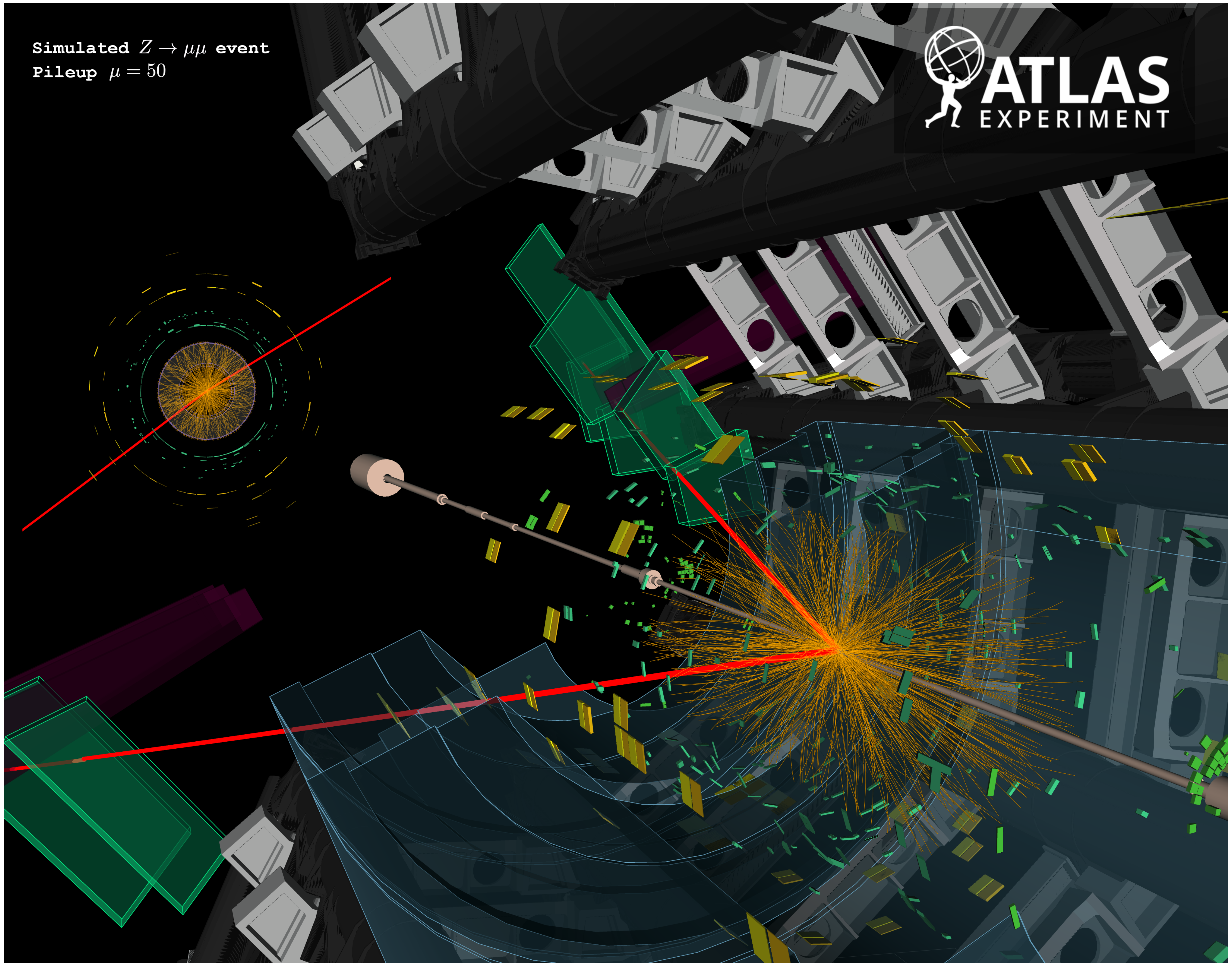
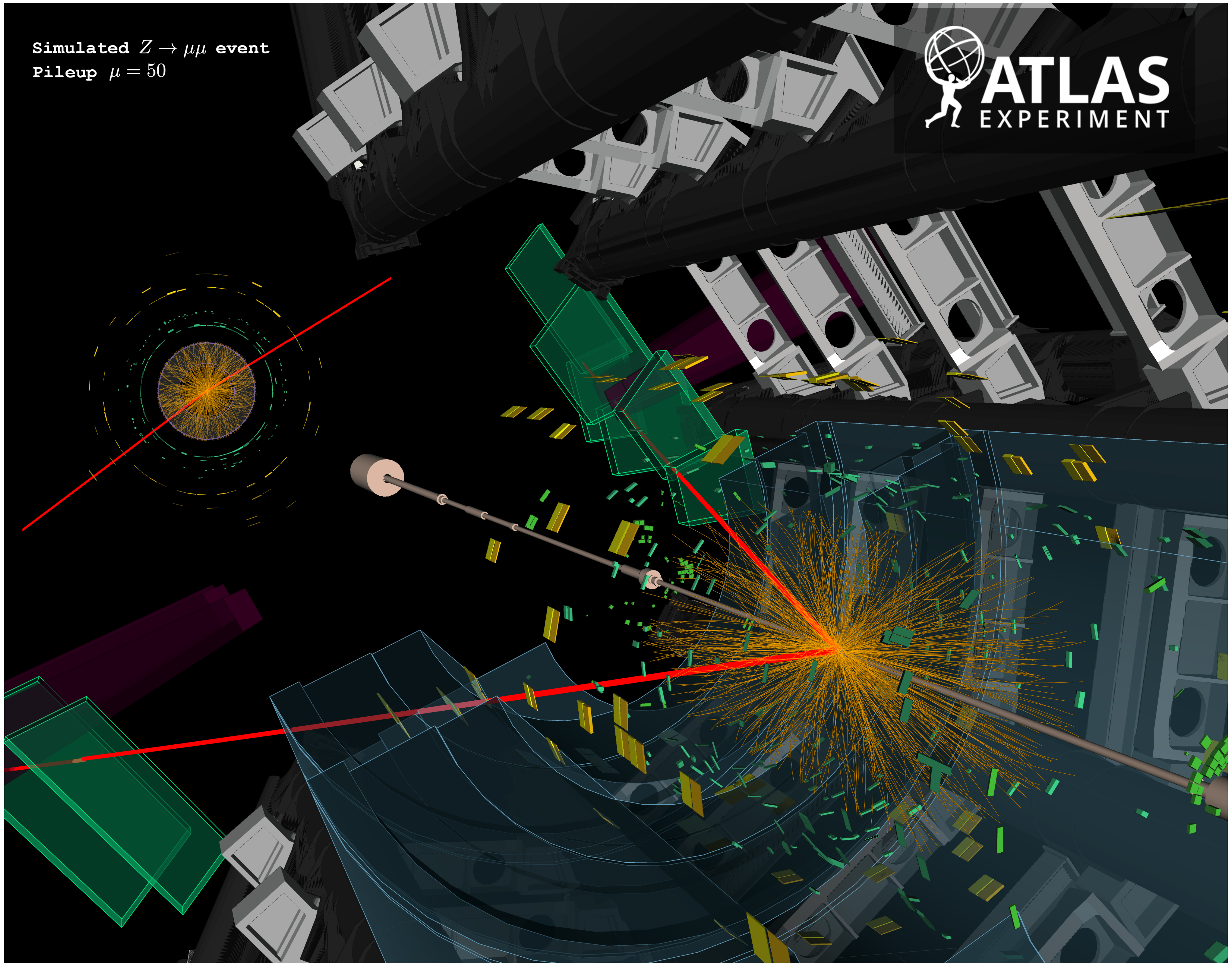




region in which Run 2 $\epsilon_{trigger} < 50\,\%$ in $bbbb$ channel!



the most expensive part in Run 3:
event-wide charged-particle
tracking:
~1.5s per event!

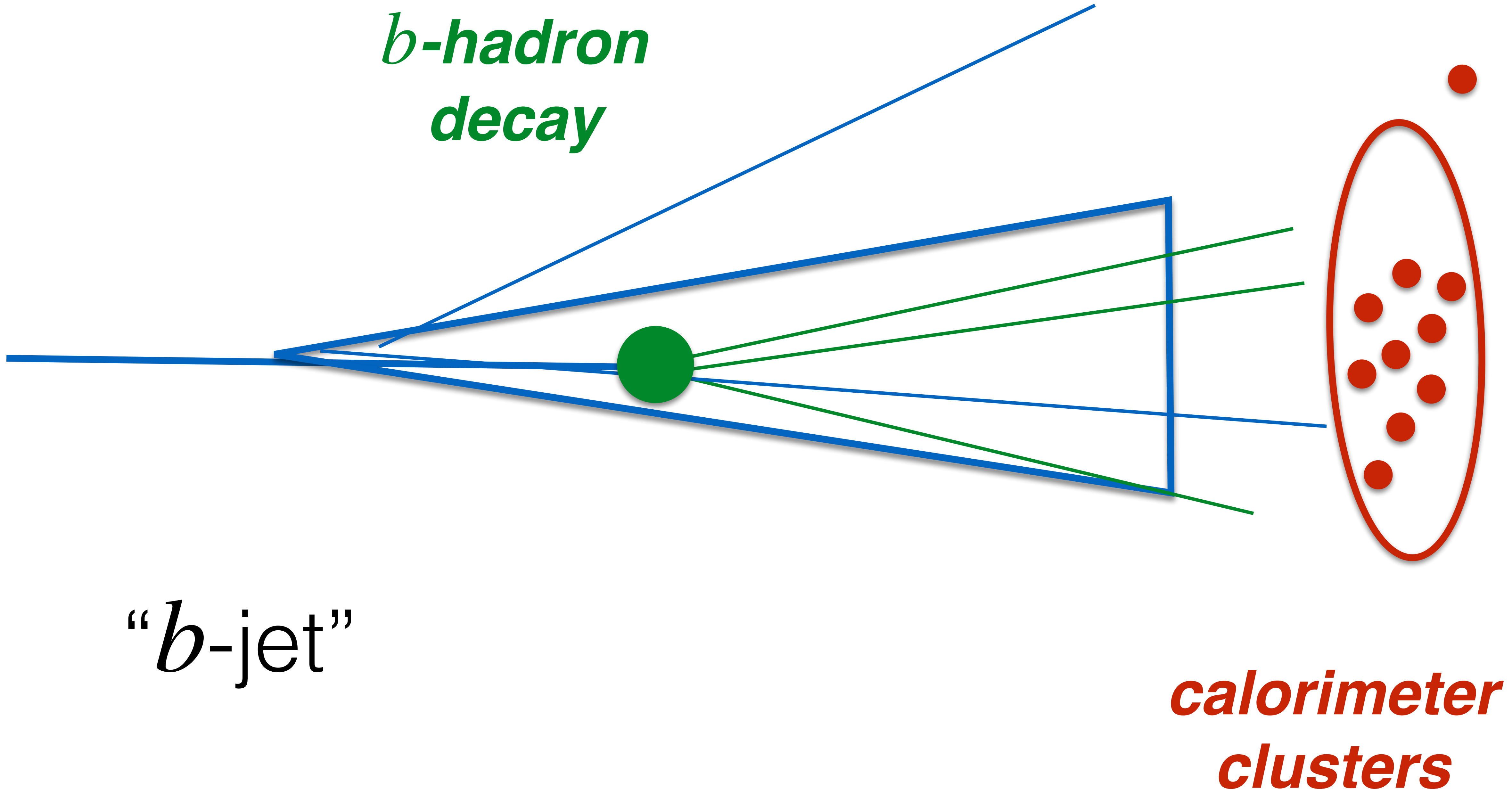


the most expensive part in Run 3: event-wide charged-particle tracking: ~1.5s per event!

even with tens of thousands of CPUs in the HLT “farm”,

we can only afford ~2 kHz of tracking rate for our hh triggers.

but for ~75% efficiency, incoming rate is ~10 kHz.



b-jet identification is the main handle we have vs backgrounds

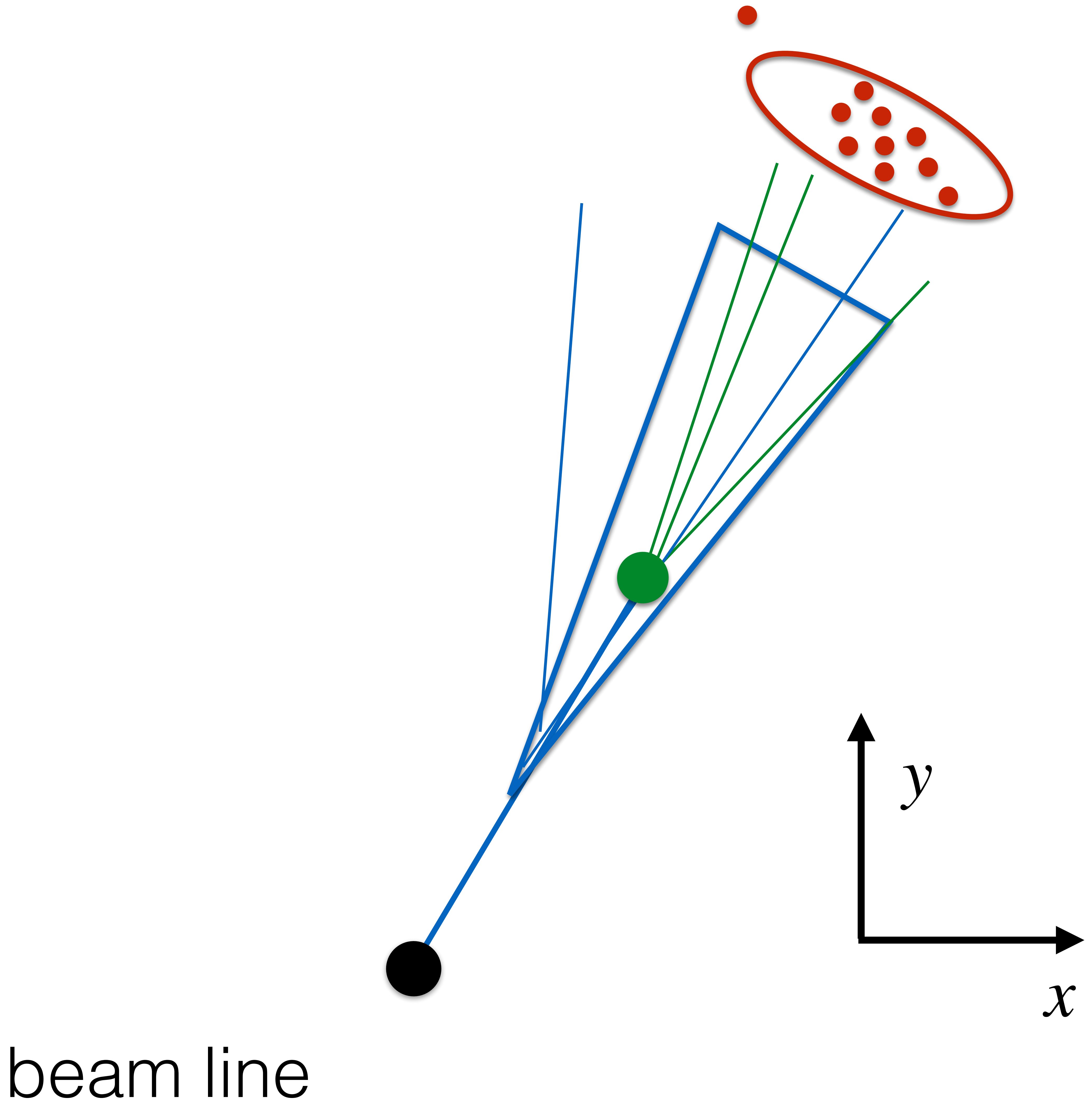
but usually it requires full-event tracking, primary vertex finding, etc.

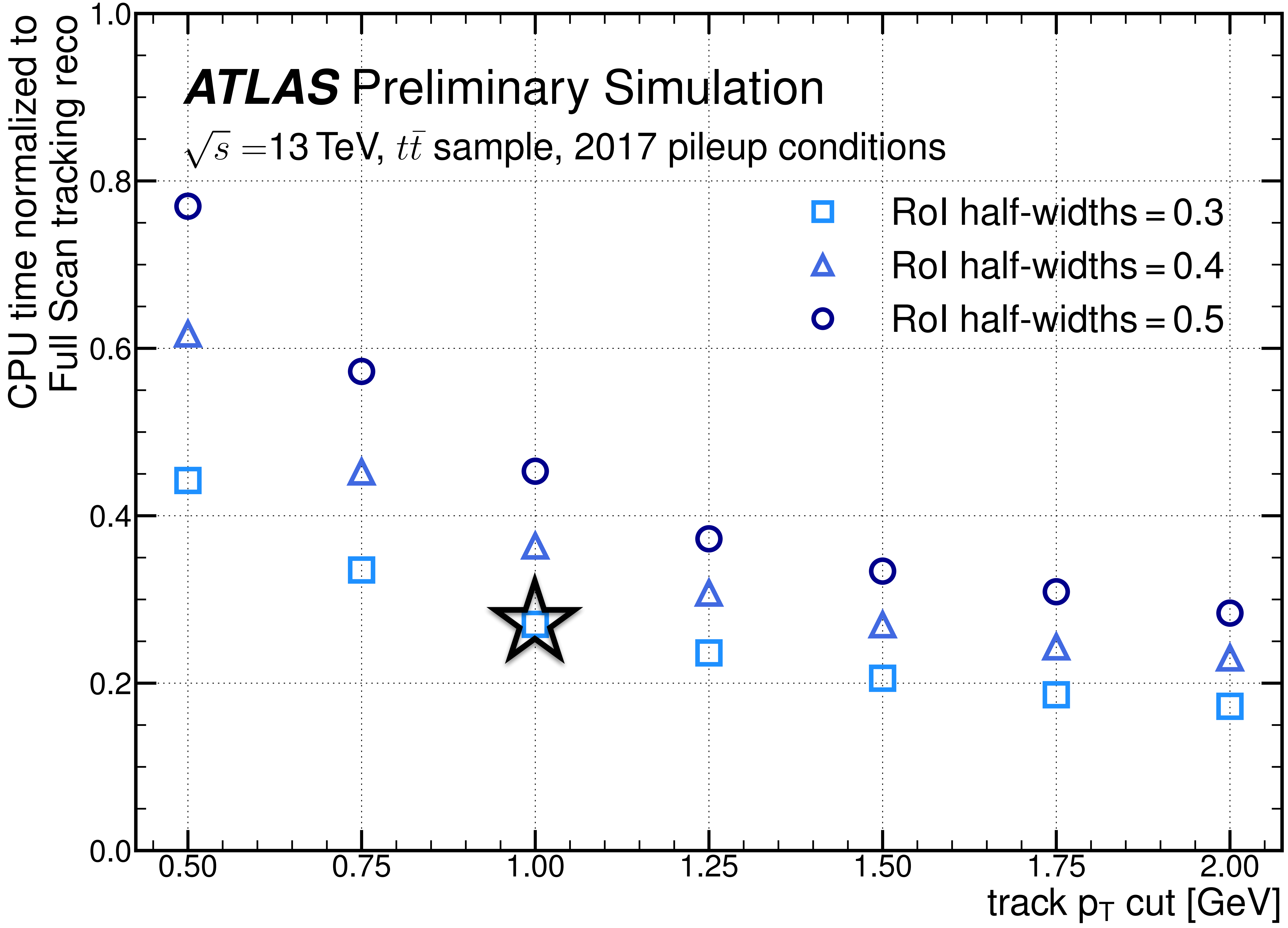
ATLAS recently developed very fast b-tagging algorithms designed specifically to run ***before*** *event-wide tracking.*

1) only reconstruct tracks inside jets

2) do not construct the primary vertex but look at track impact parameters w.r.t. the beamspot

3) use a modern machine-learning architecture (Deep Sets) to derive a flexible identification algorithm vs light-flavor jets





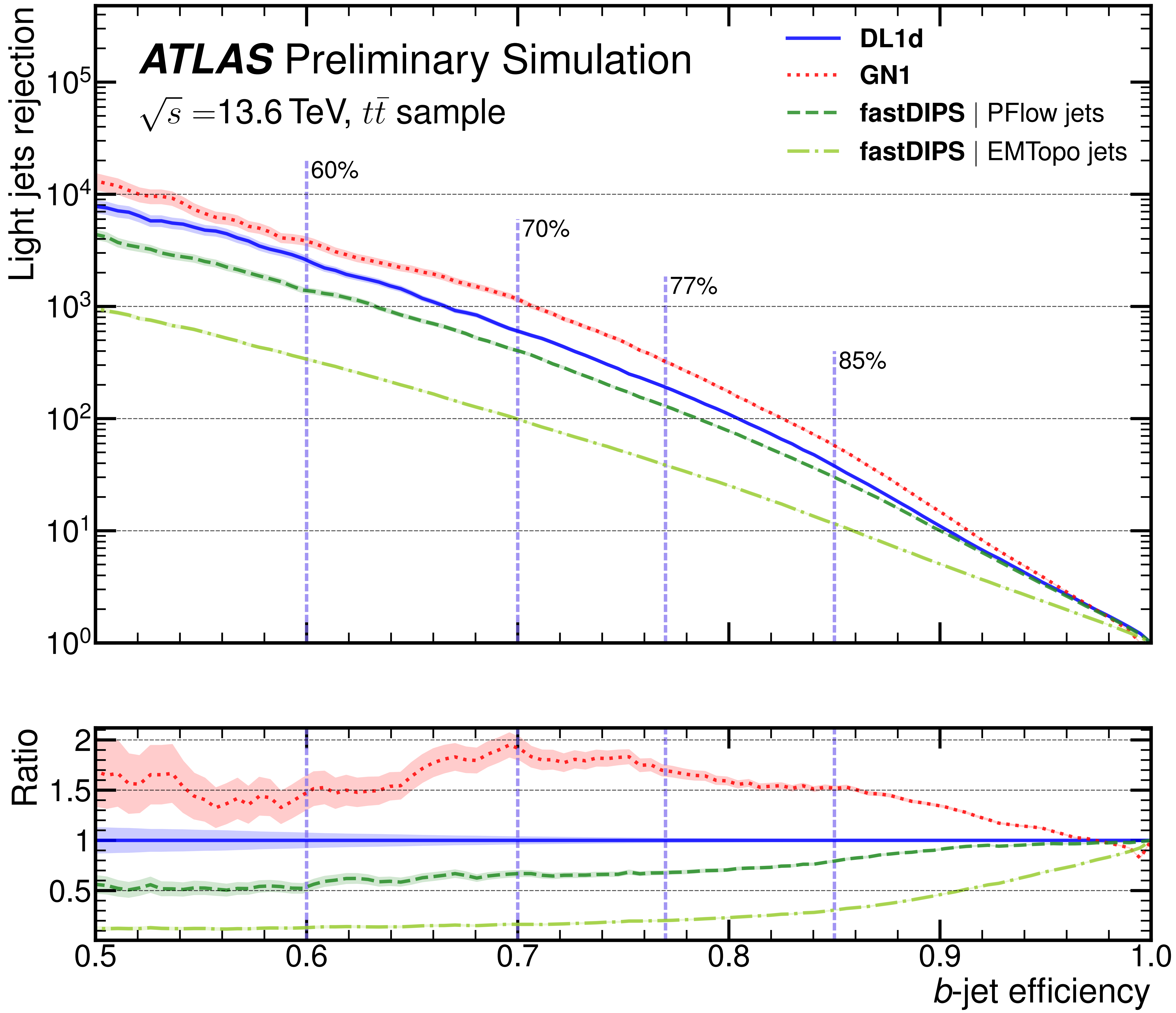
tracking only inside jets results in about a 4x speed-up in CPU time.

we reduce the background event rate from ***~8 kHz to ~1.5 kHz****,*

and maintain a ***98%*** $hh \rightarrow 4b$ ***efficiency****.*

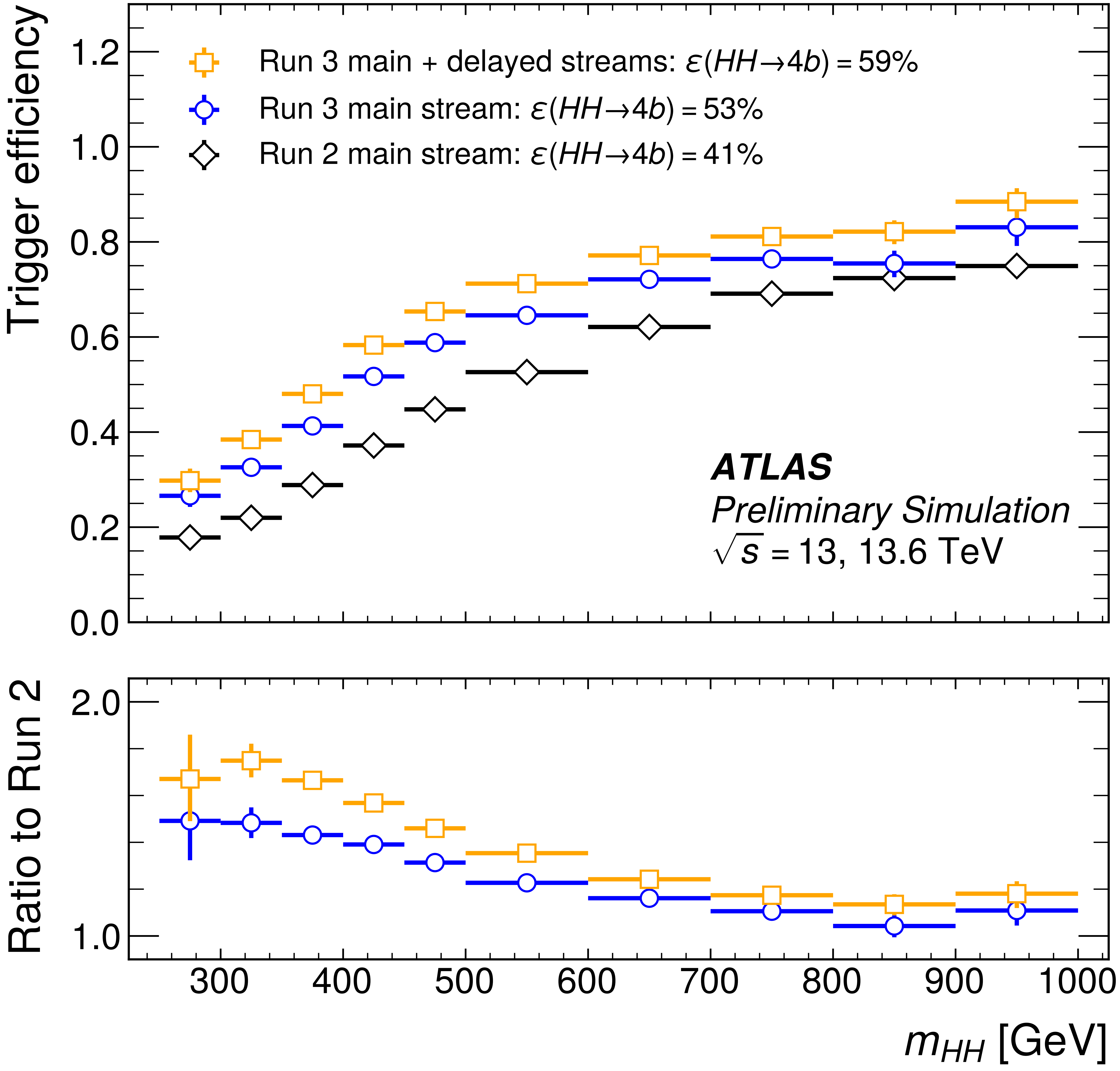
(more efficient than just identifying the correct primary vertex!)

- after this reduction in rate, we are capable of running conventional
  - event-wide tracking
  - and b-jet identification algorithms.
- but we gained an enormous amount of flexibility:
  - several available b-taggers running at different stages of the HLT with different CPU usage and background rejections



the impact on the search for hh is quite striking:

in Run 3 we are writing ~50% more $hh \to 4b$ events to disk than we did in Run 2!



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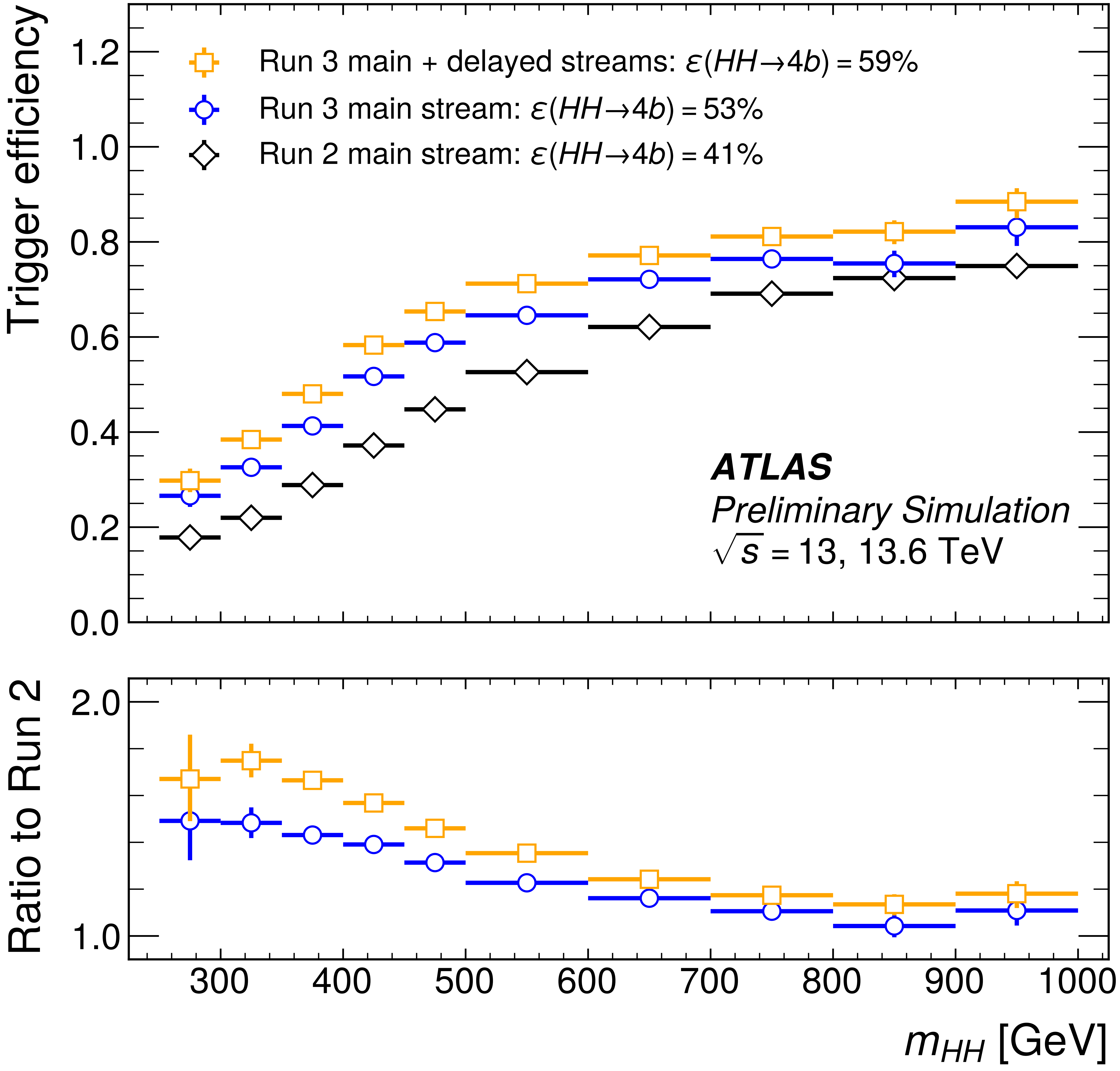
our new trigger strategy has benefits beyond just efficiency:

1) *acceptance is much higher in the interesting, low m_{hh} region.*
2) *the sculpting of backgrounds is substantially reduced.*



Run 3 data-taking has been going remarkably well.

projections are that we will ~double our available data in 2023.

stay tuned!

the impact on the search for hh is quite striking:

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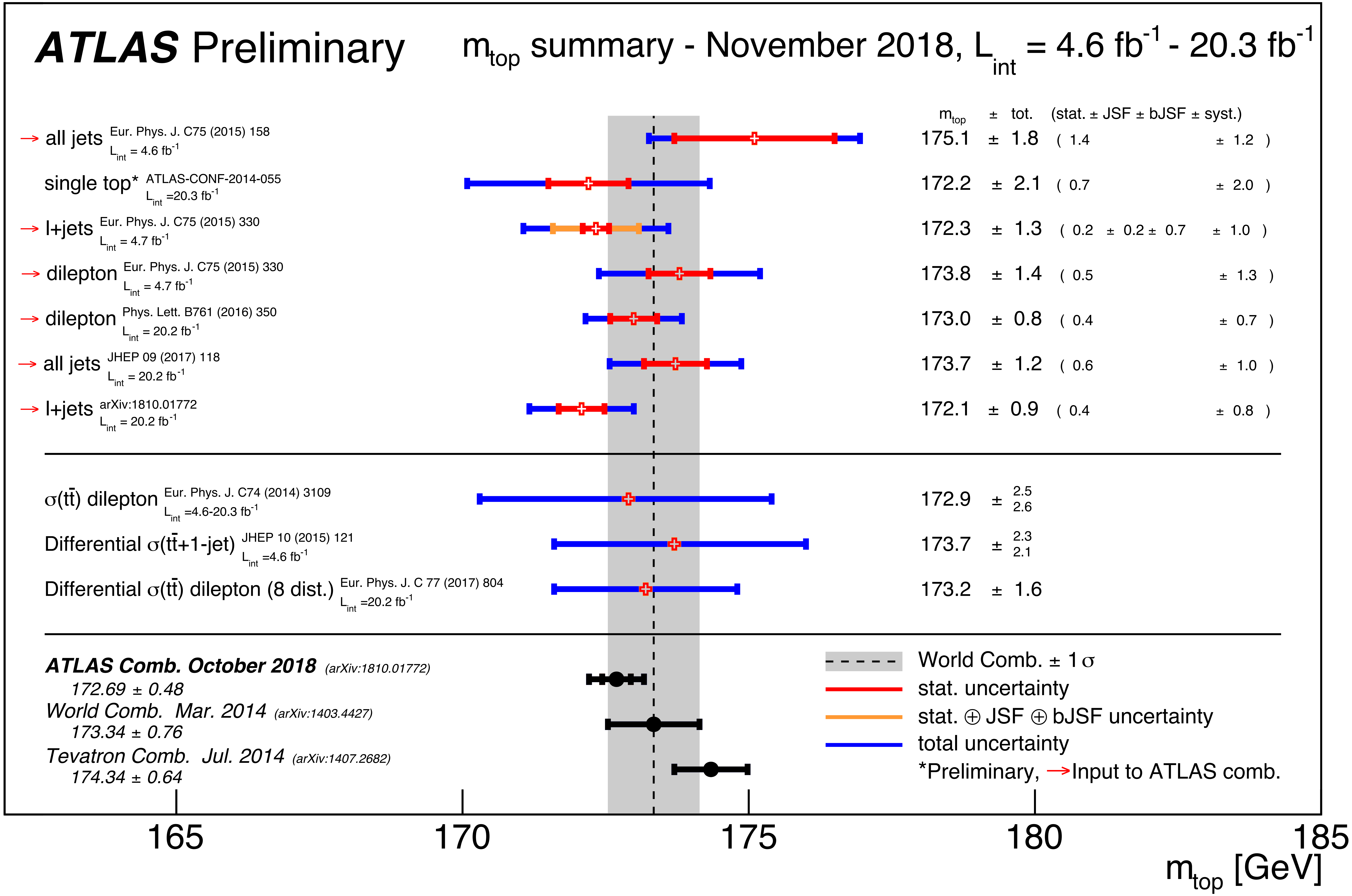
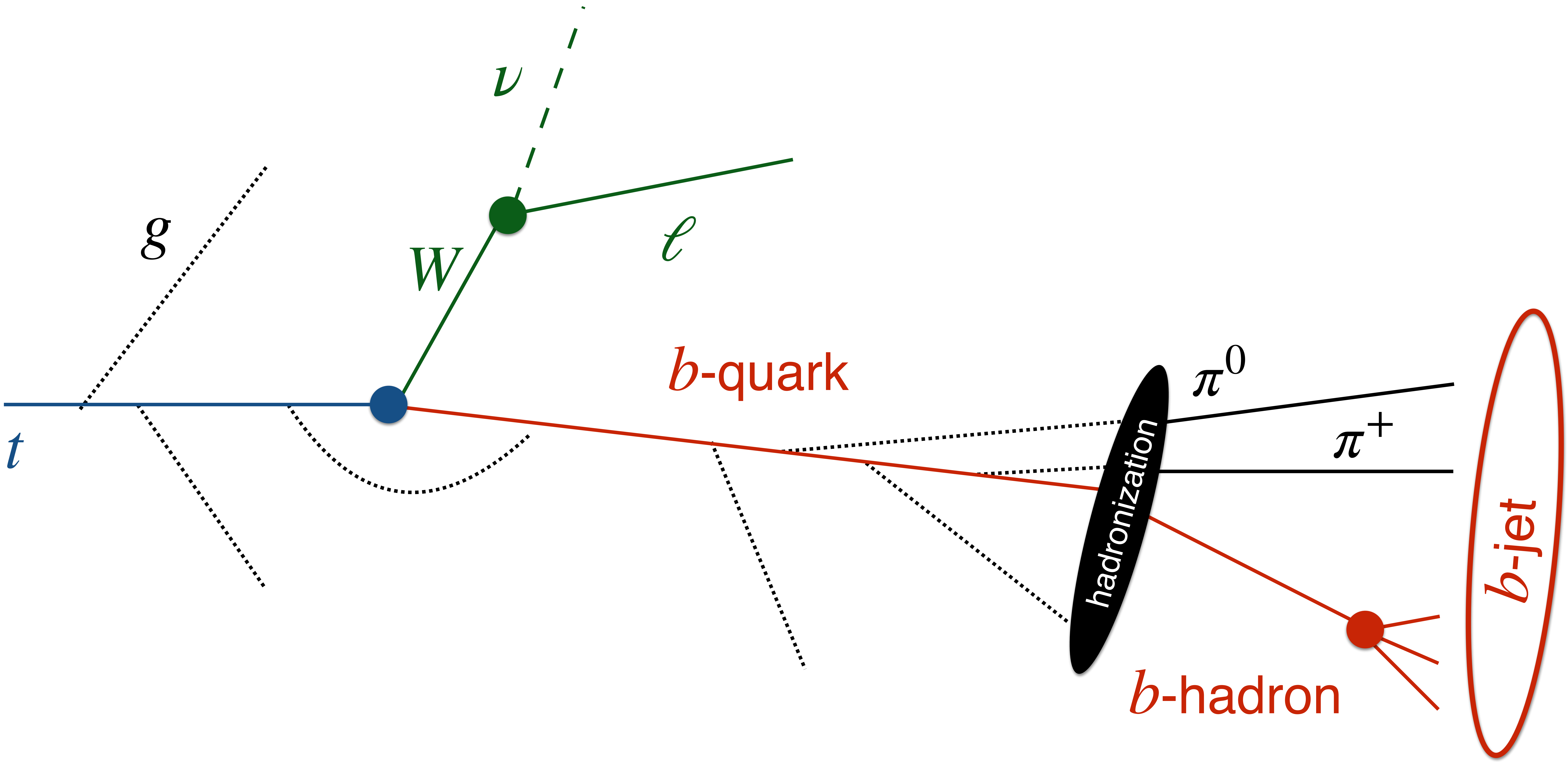
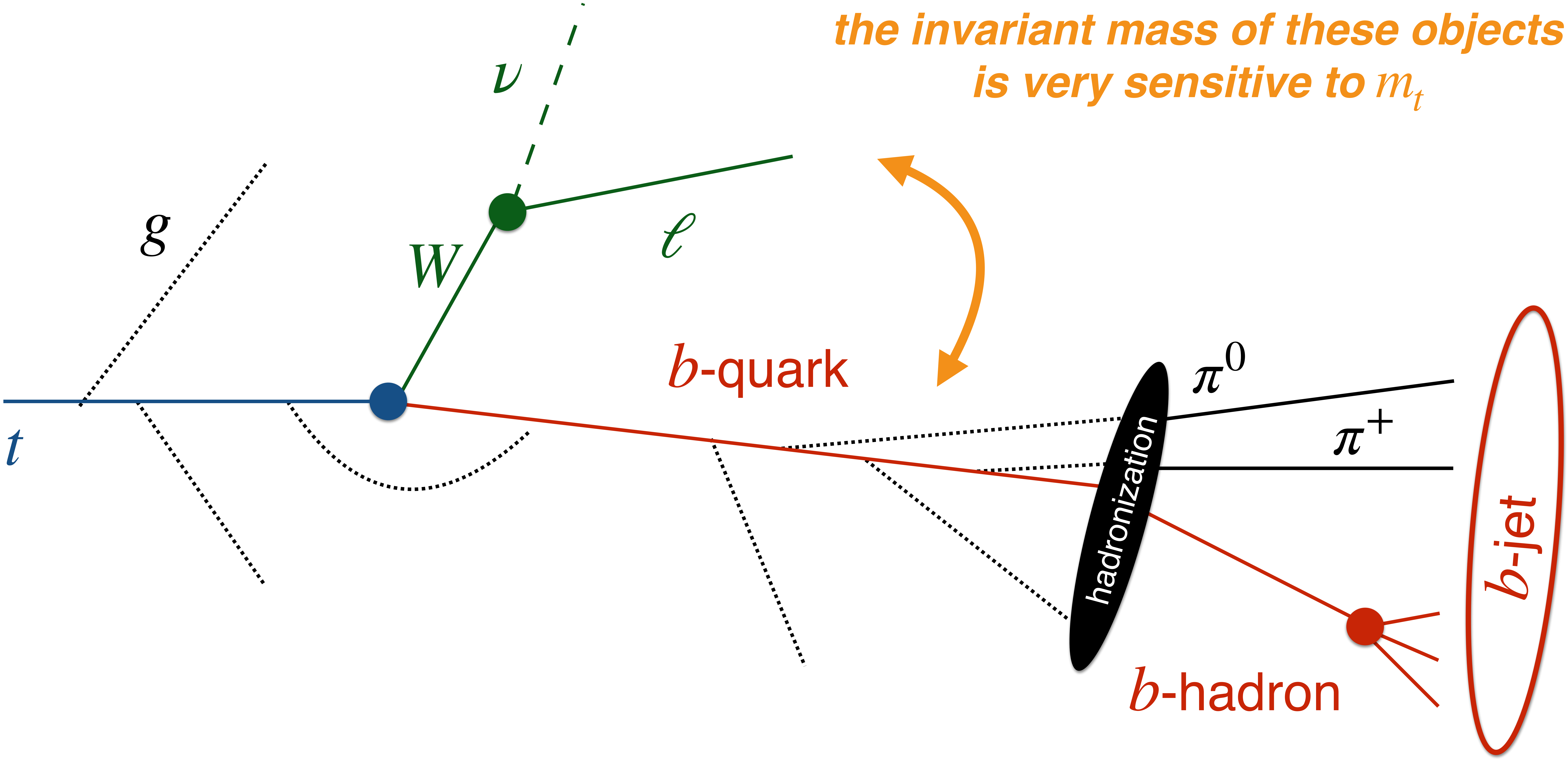
the top-quark mass, m_t



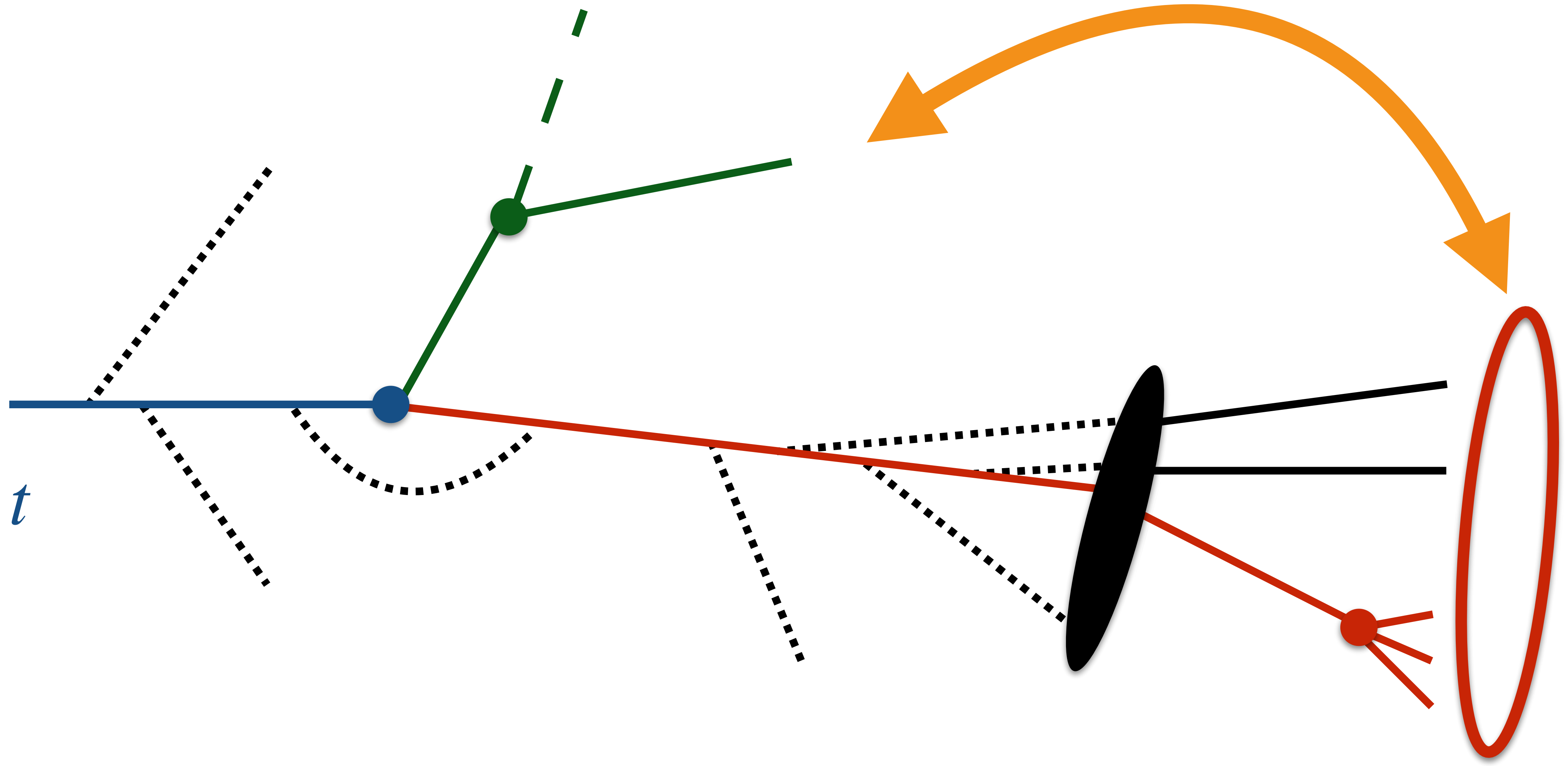
the ATLAS m_t state of affairs a few years ago: $m_t = 172.69 \pm 0.48\ \text{GeV}$

what does a top-quark decay actually look like?



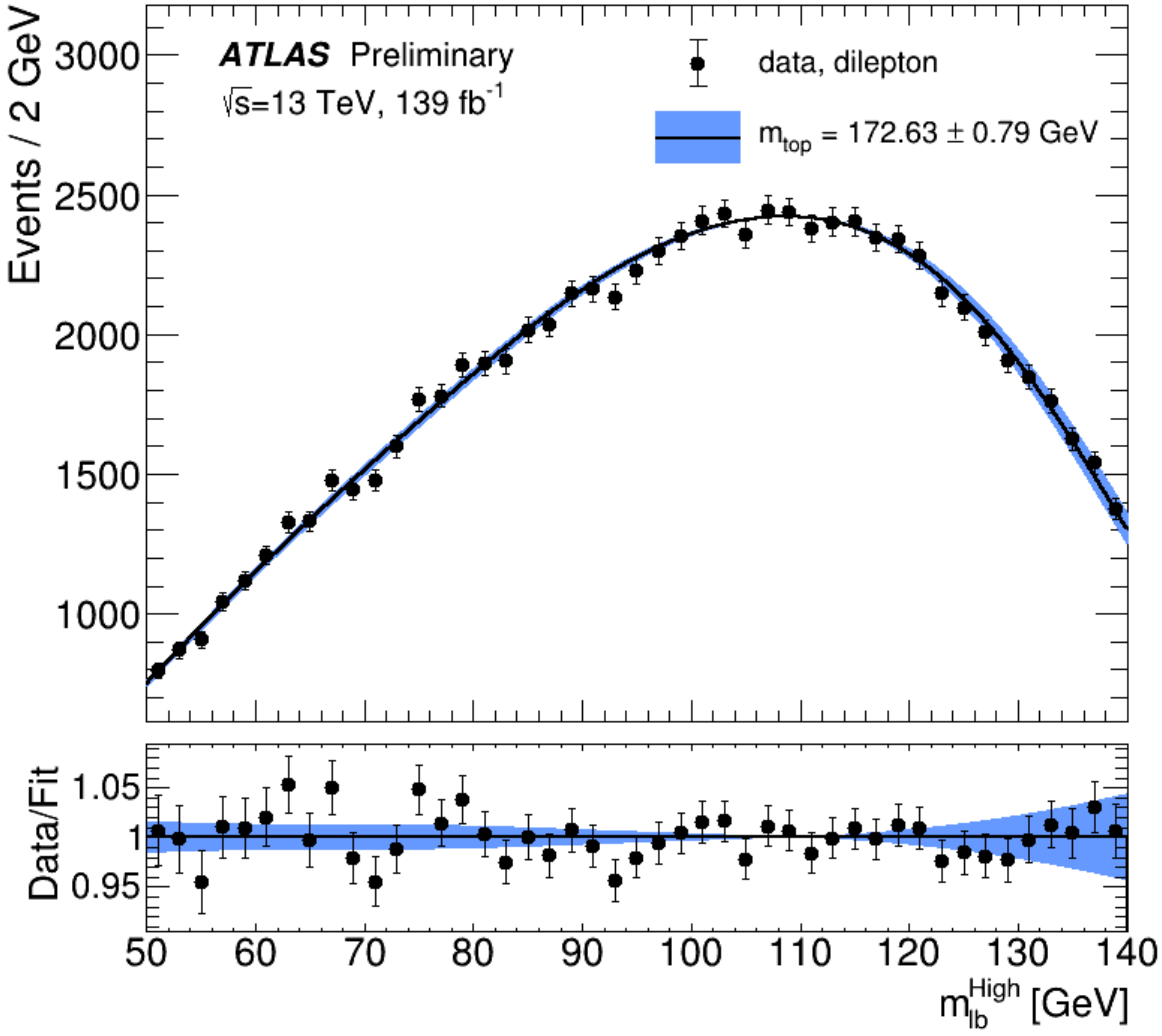


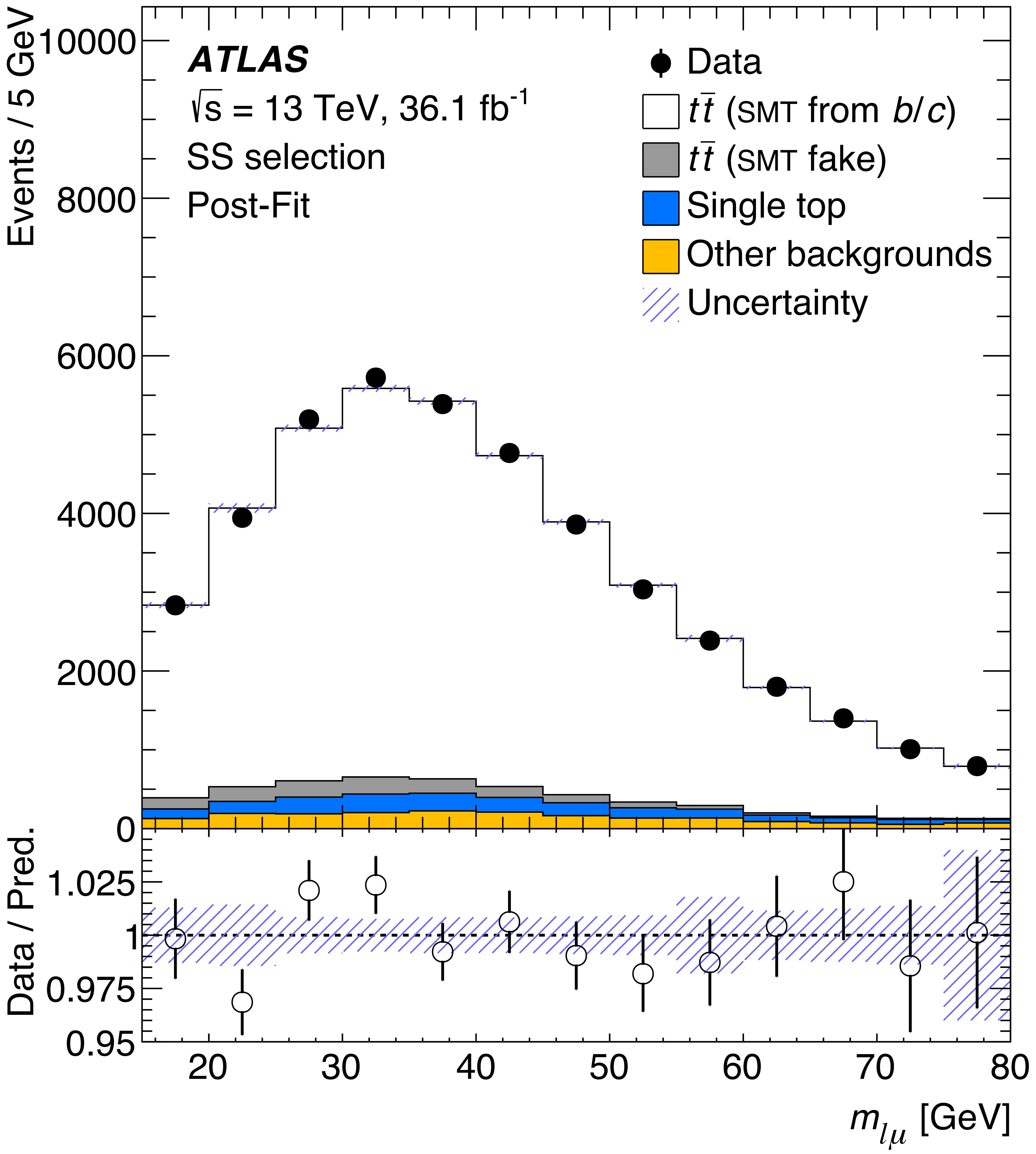
the invariant mass of these objects is very sensitive to m_t

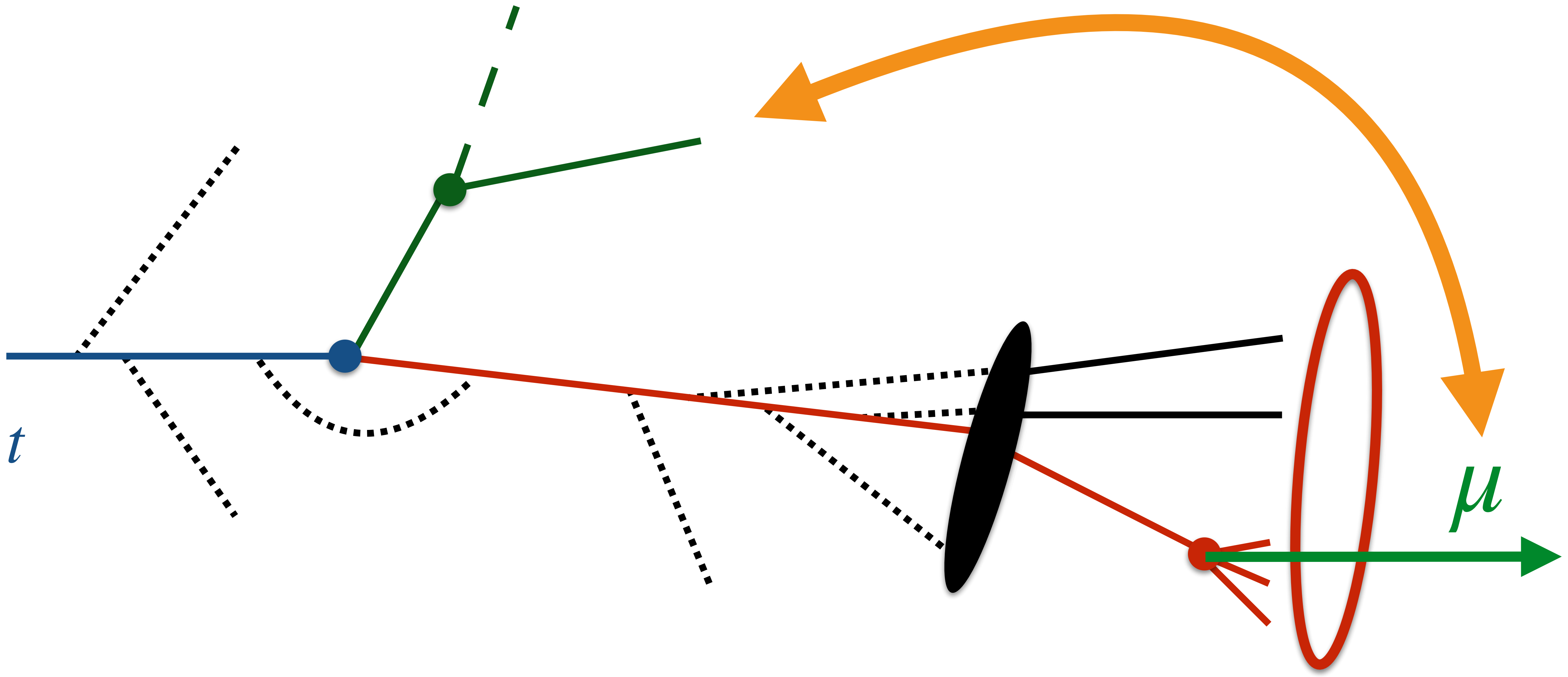


ATLAS recently measured m_t *via the invariant mass of the* W *lepton and the* b*-jet*

$$m_t = 172.63 \pm 0.79 \text{ GeV}$$

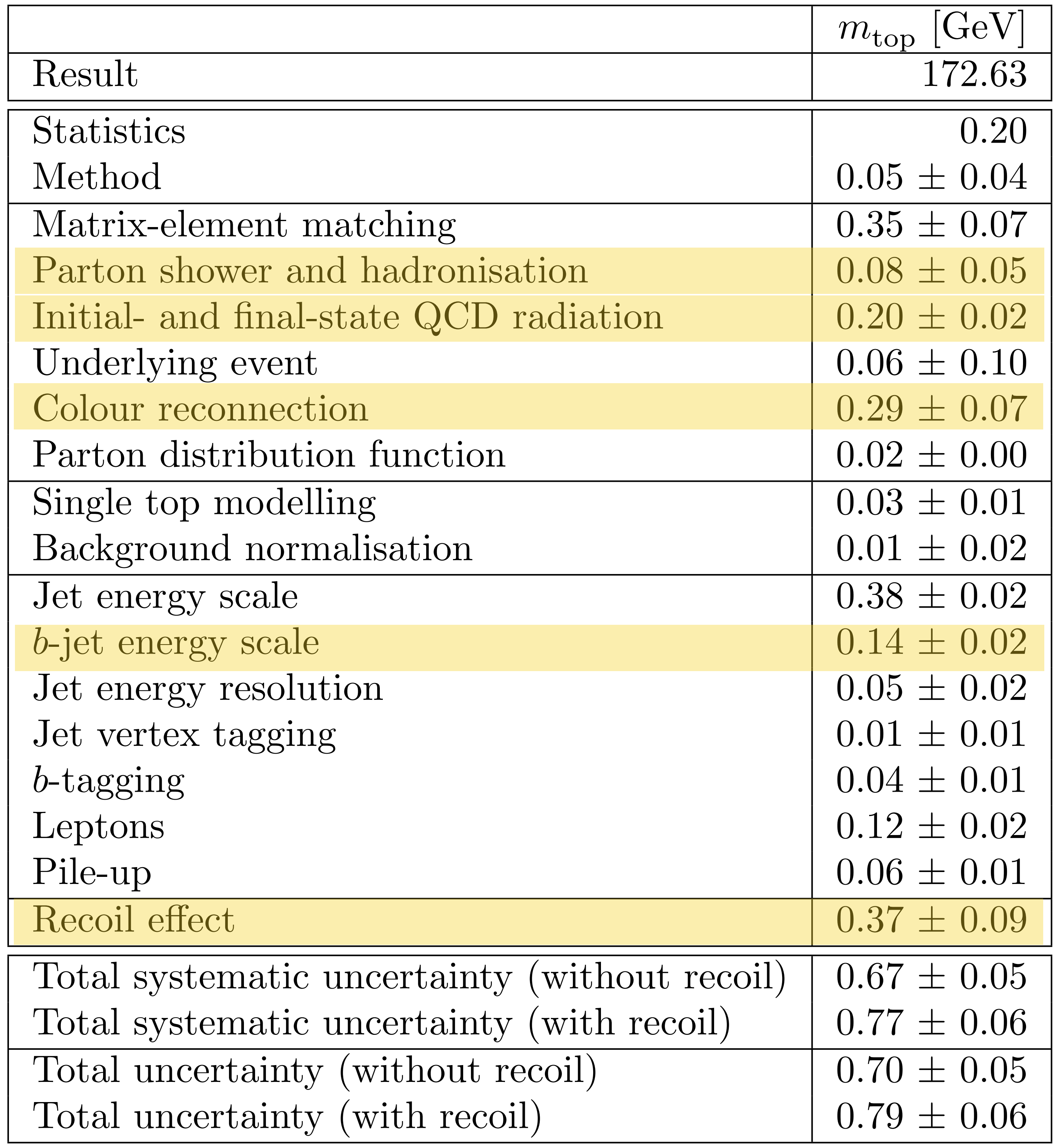




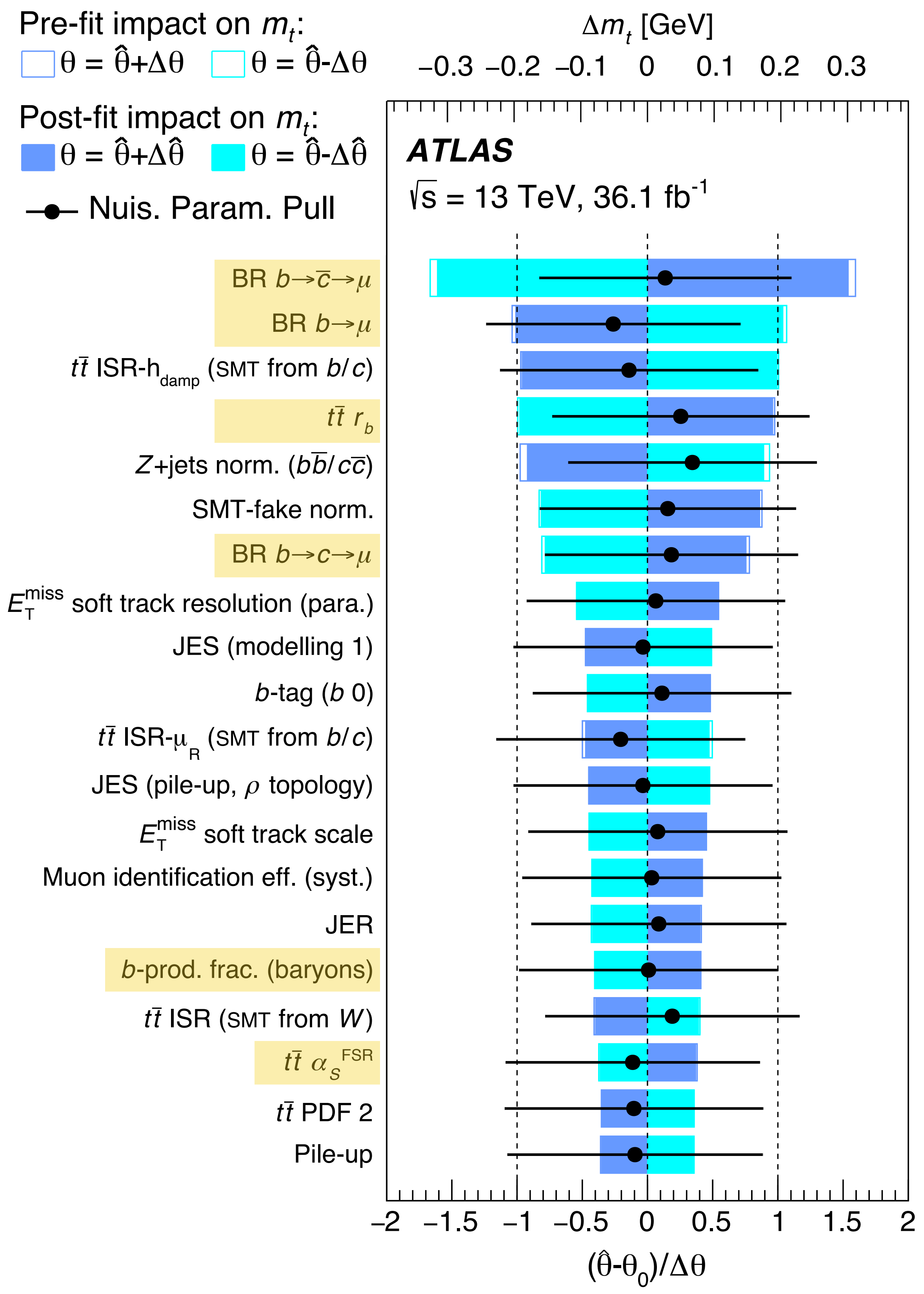


ATLAS also recently measured m_t via the invariant mass of the W lepton and a lepton from the b-hadron decay

$$m_t = 174.71 \pm 0.81 \text{ GeV}$$



	m_{top} [GeV]
Result	172.63
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.35 ± 0.07
Parton shower and hadronisation	0.08 ± 0.05
Initial- and final-state QCD radiation	0.20 ± 0.02
Underlying event	0.06 ± 0.10
Colour reconnection	0.29 ± 0.07
Parton distribution function	0.02 ± 0.00
Single top modelling	0.03 ± 0.01
Background normalisation	0.01 ± 0.02
Jet energy scale	0.38 ± 0.02
b-jet energy scale	0.14 ± 0.02
Jet energy resolution	0.05 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.12 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.37 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.79 ± 0.06



most dominant uncertainties come from QCD modeling in the top-quark decay, radiation/hadronization of the b-quark, and b-hadron decays.

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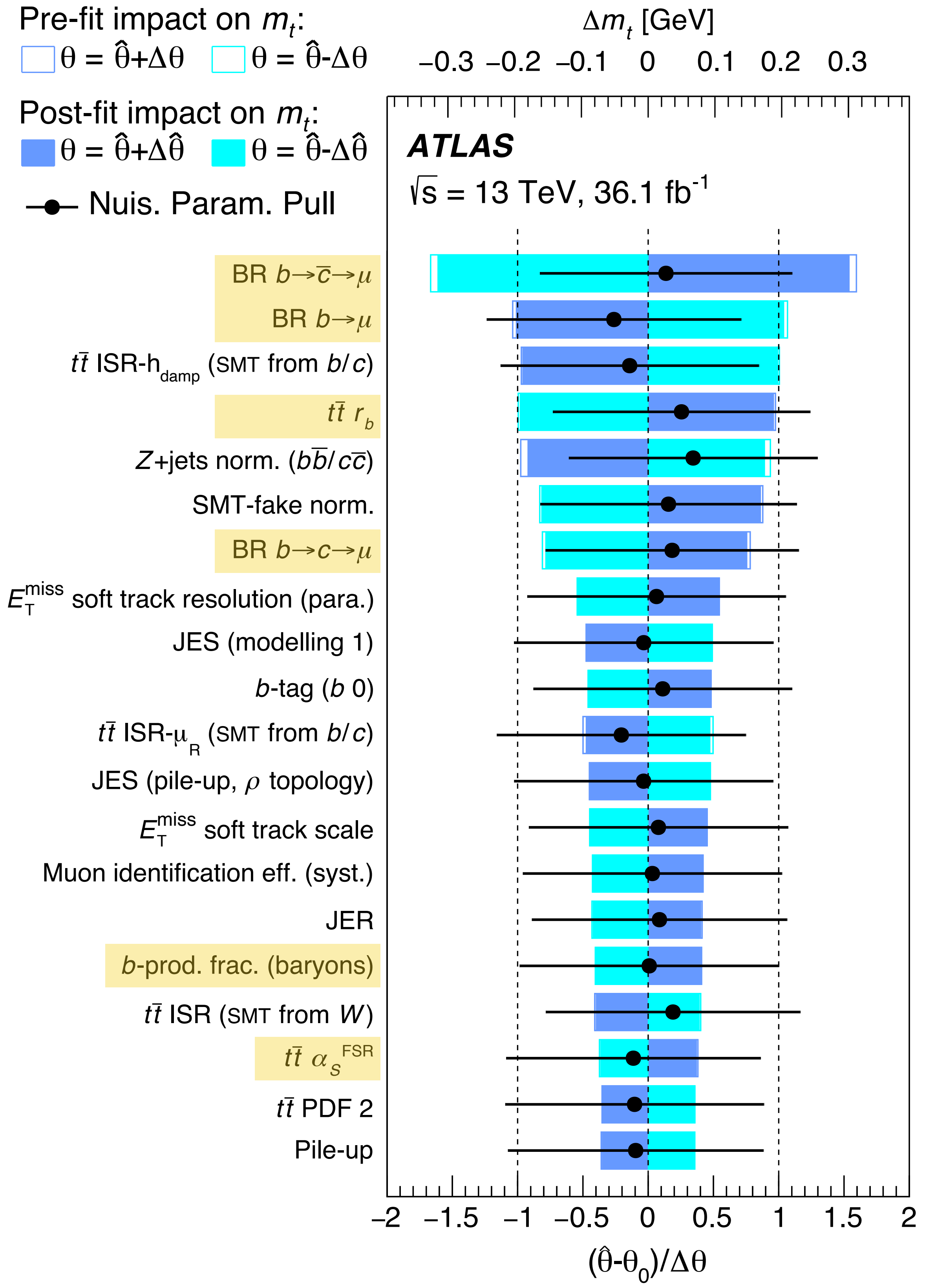

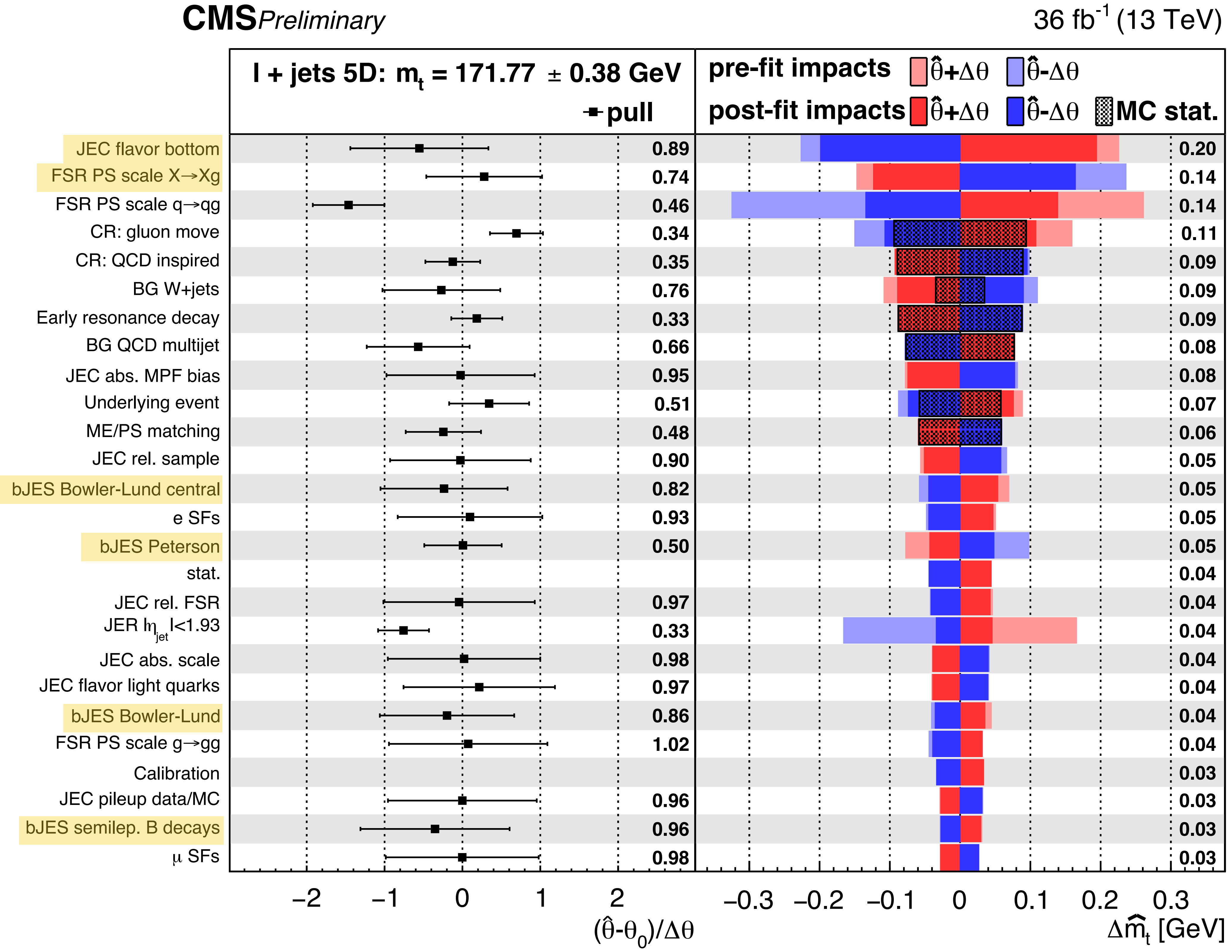

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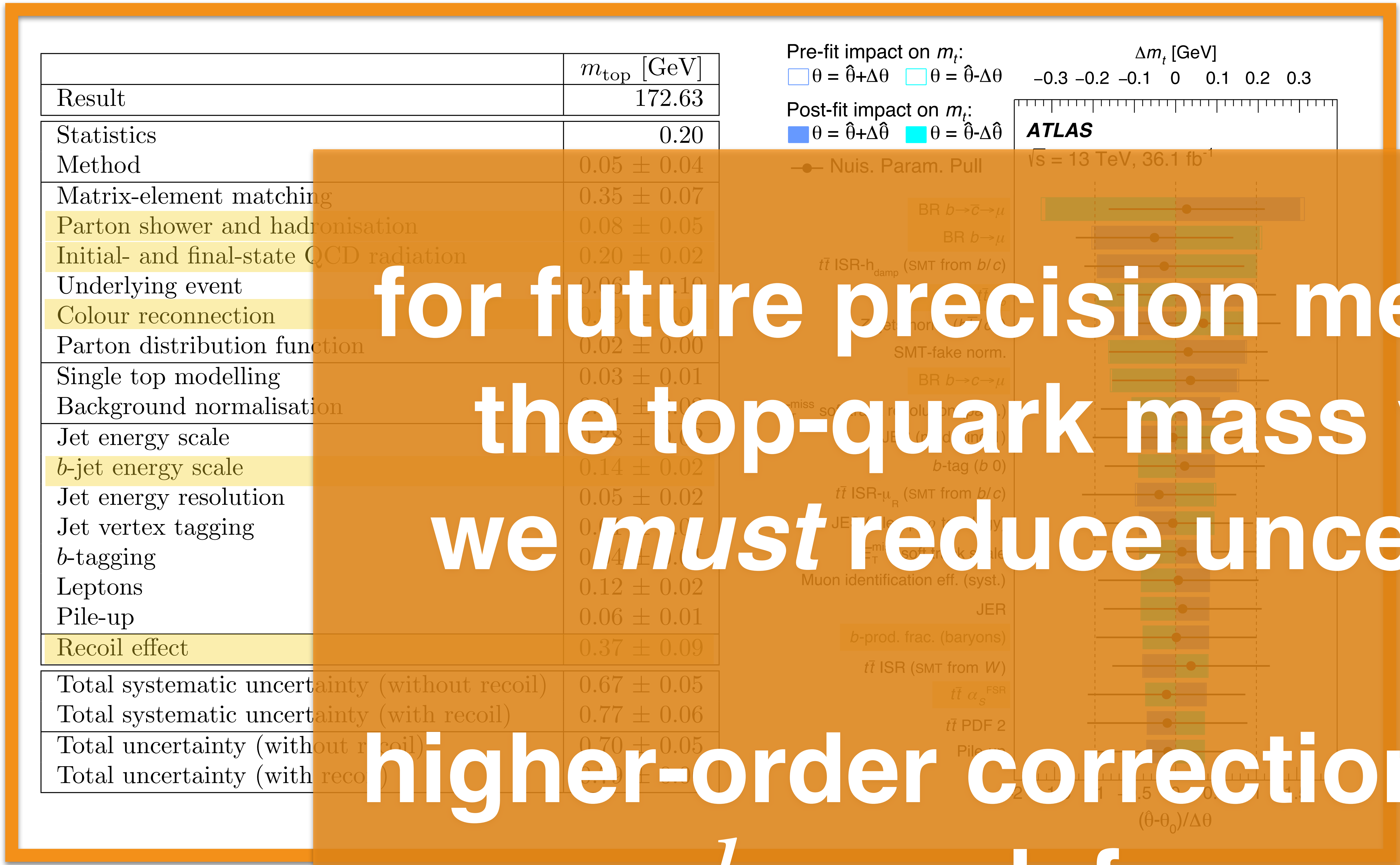
CMS see a very similar picture



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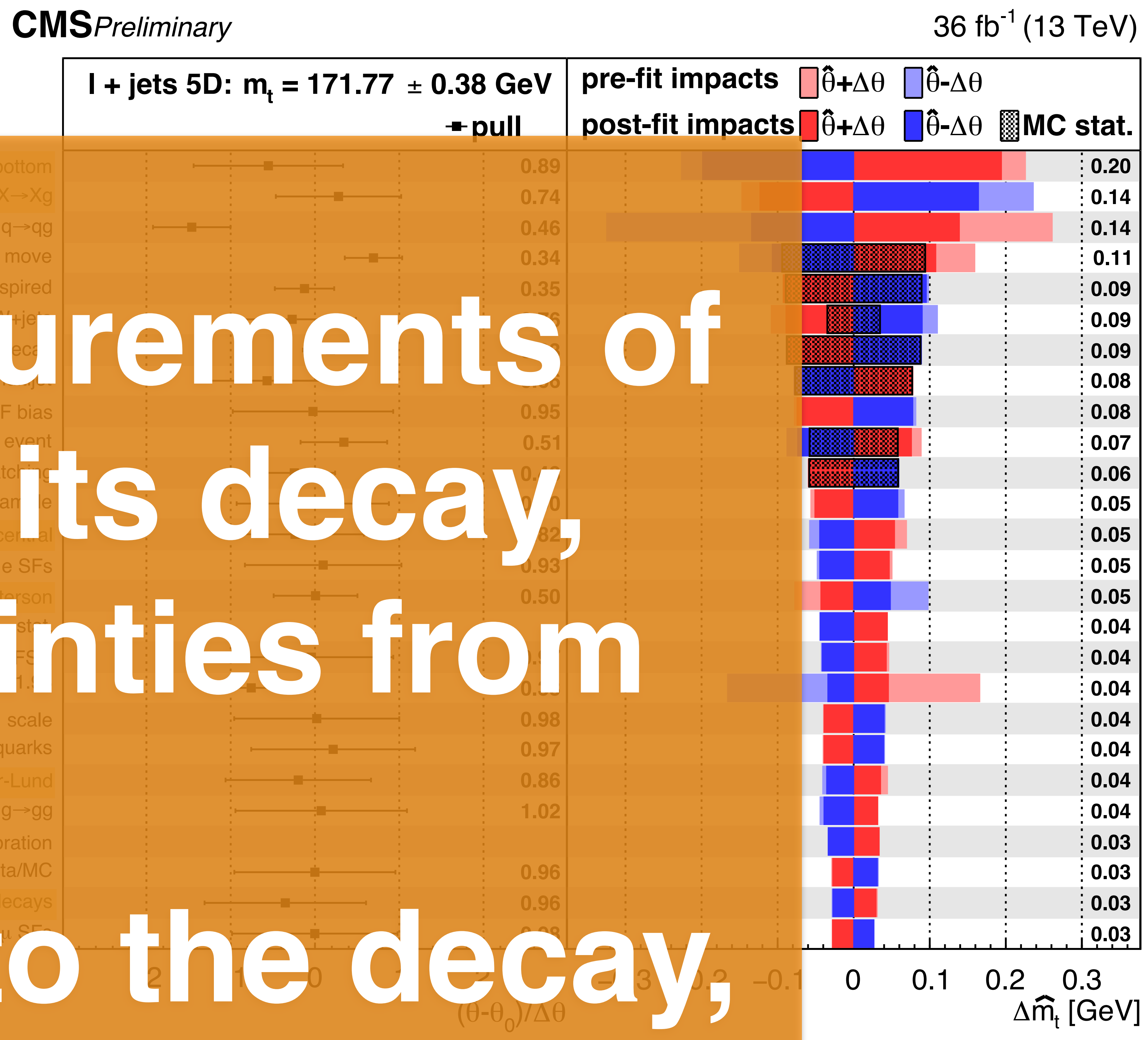
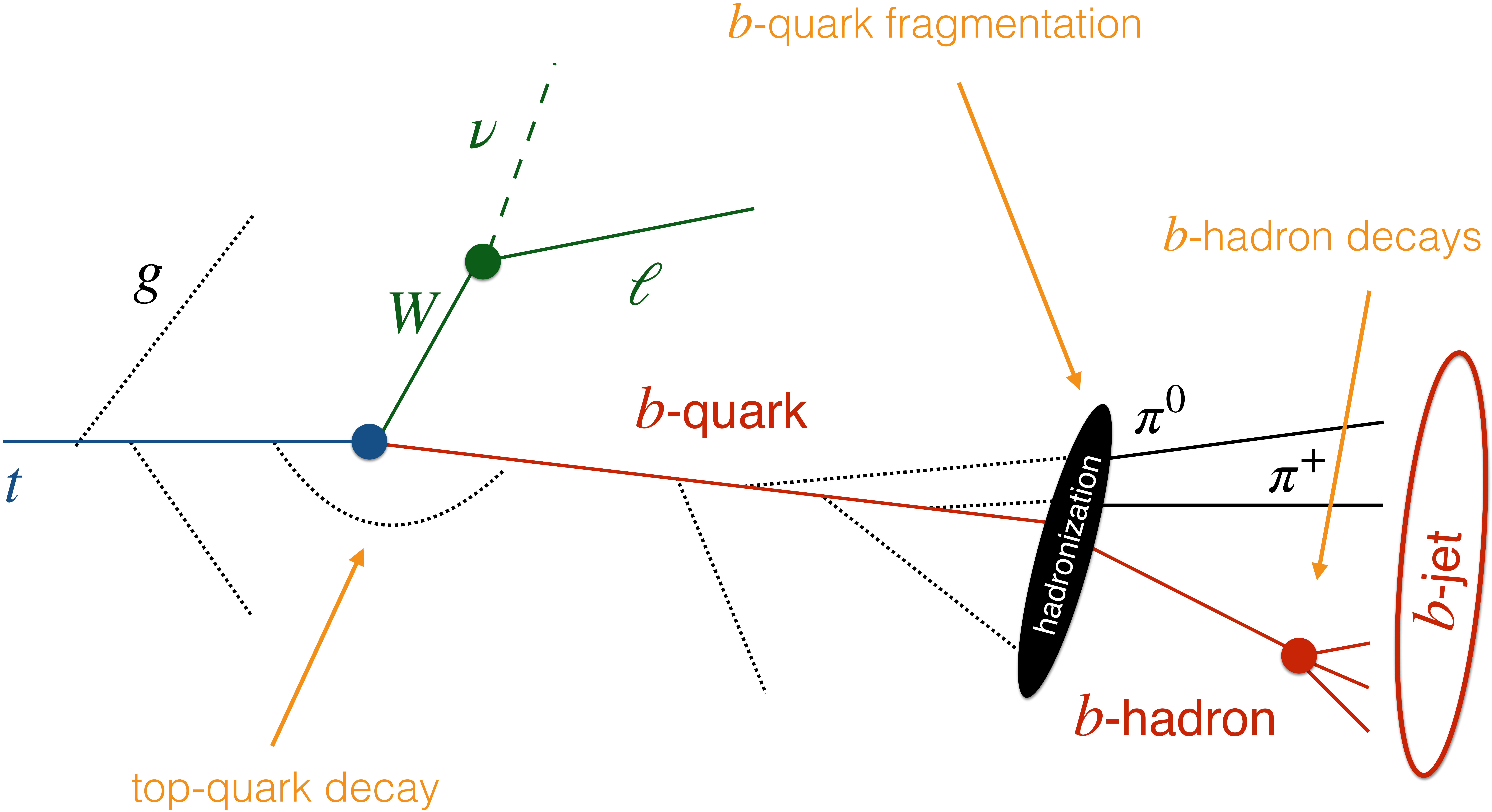


for future precision measurements of the top-quark mass via its decay, we *must* reduce uncertainties from

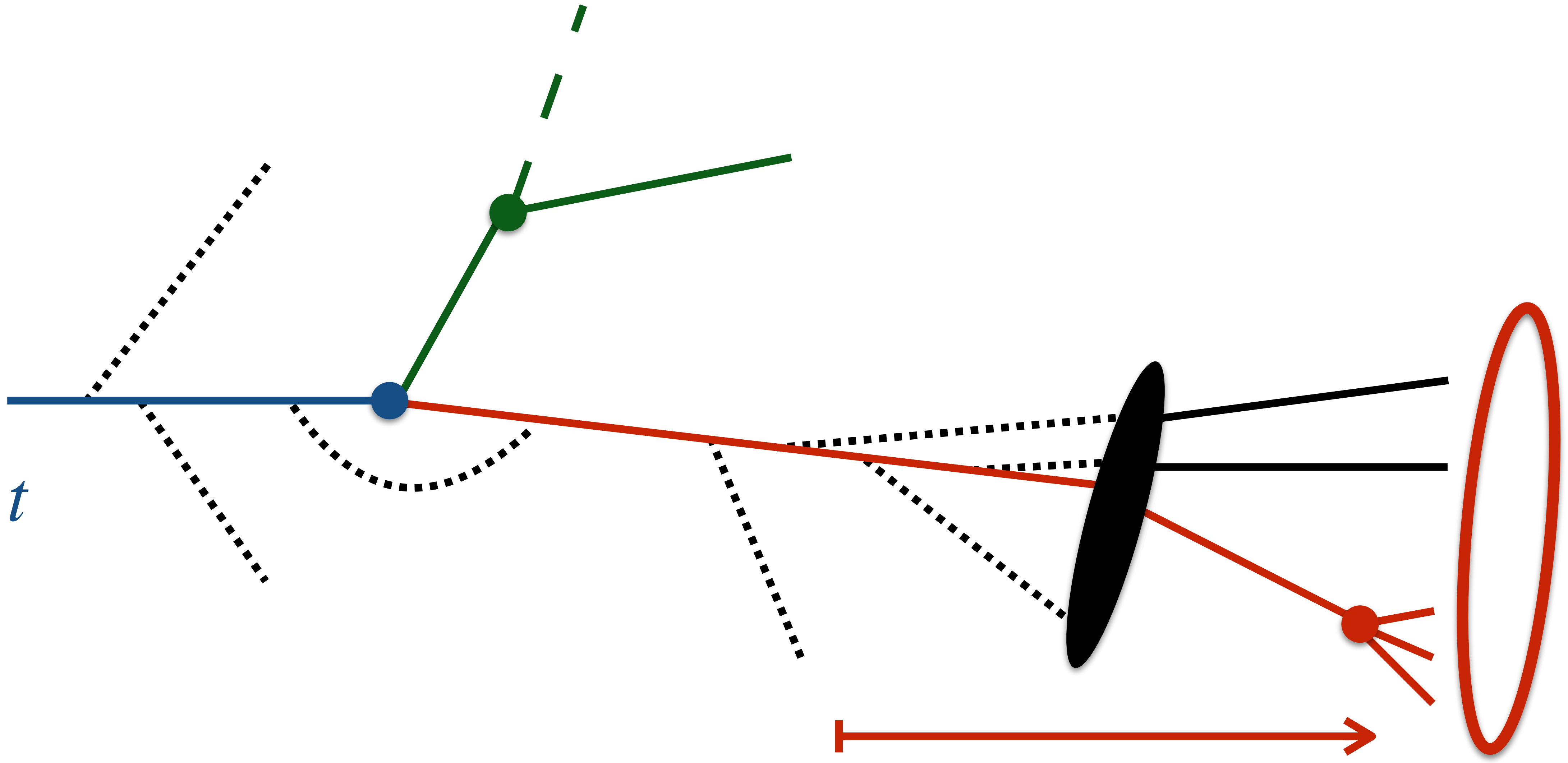
higher-order corrections to the decay, b-quark fragmentation, and b-hadron decays.

~all dominant uncertainties come from QCD modeling in the top-quark decay and radiation/hadronization of the b-quark.

CMS see a very similar picture



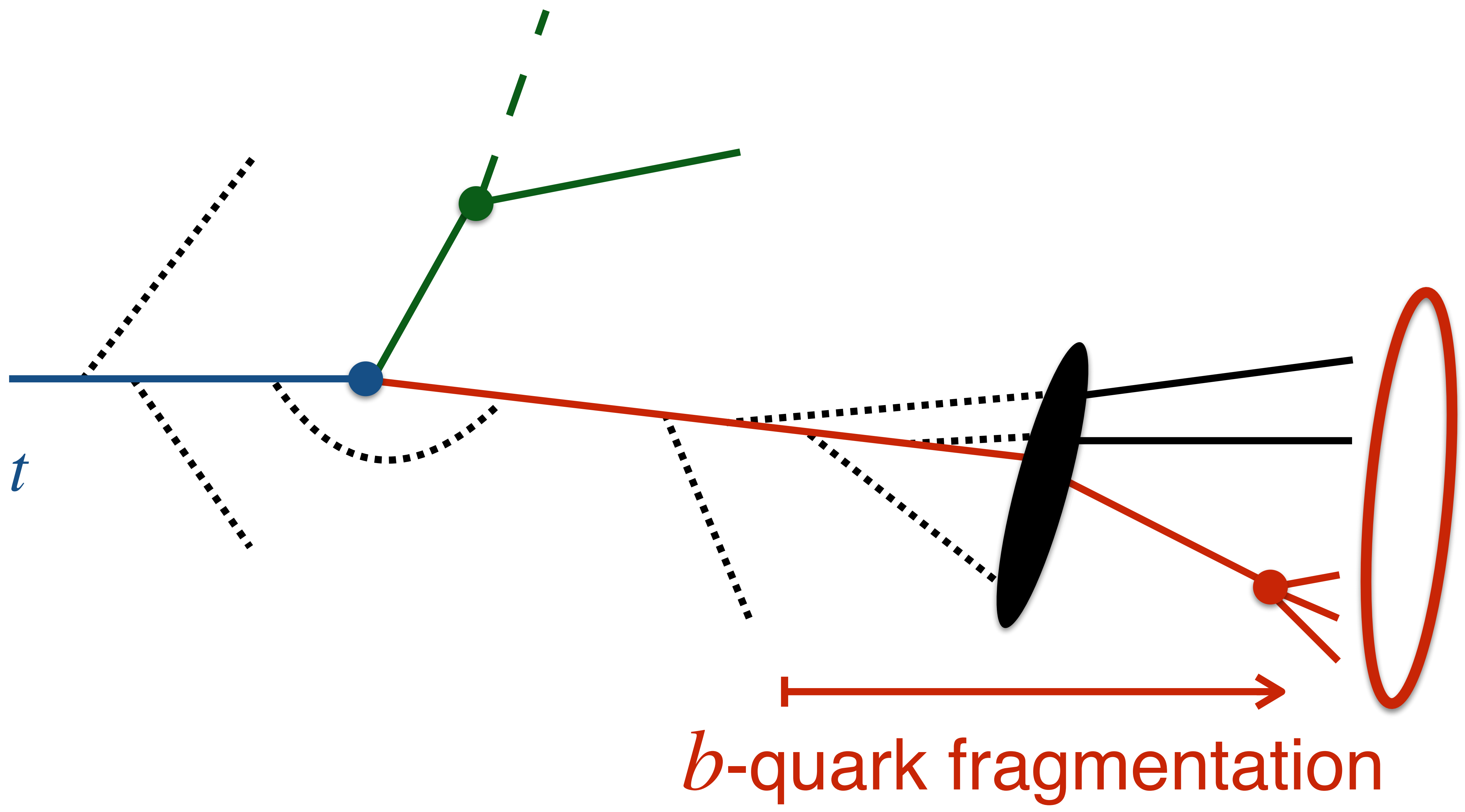
b-quark fragmentation
ν
b-hadron decays
g
W
ℓ
b-quark
π^0
π^+
t
hadronization
b-jet
b-hadron
top-quark decay



b-quark fragmentation

we do not have first-principals models for b*-quark fragmentation.*

historically we have tuned it to $ee \to Z \to bb$ *data and extrapolated to top-quark decays.*



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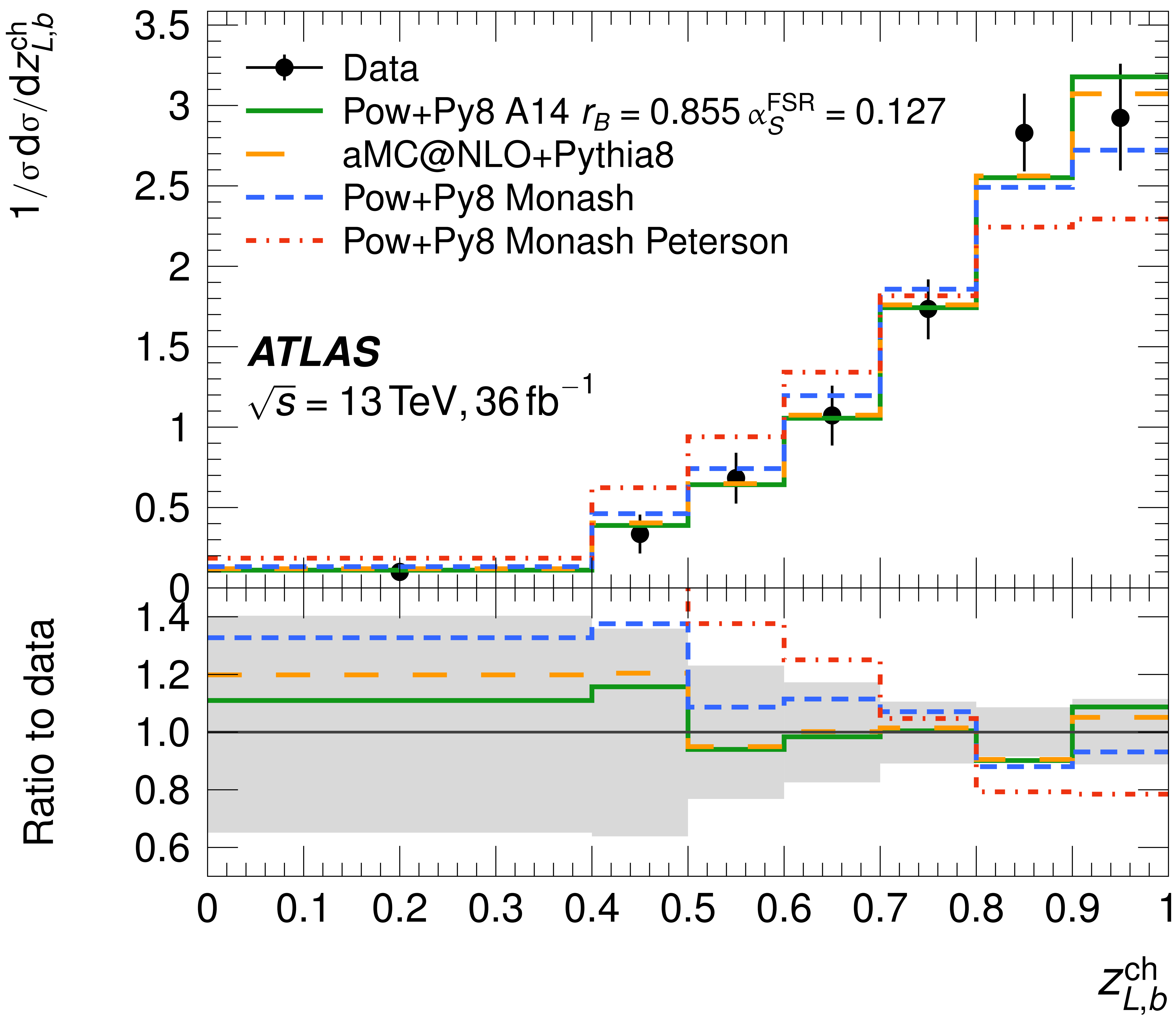
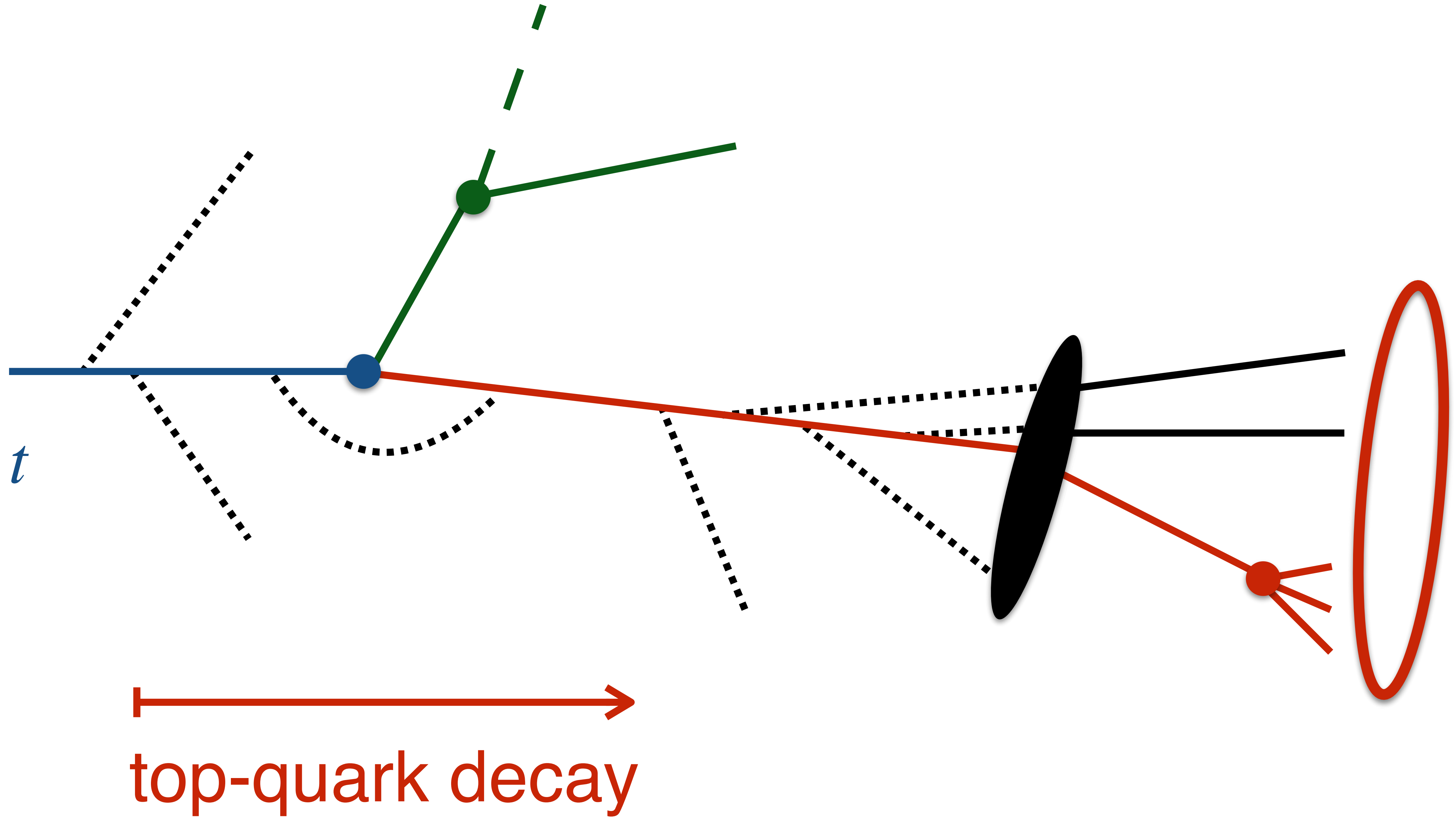


ATLAS recently published the first measurement of b-quark fragmentation in top-quark decays



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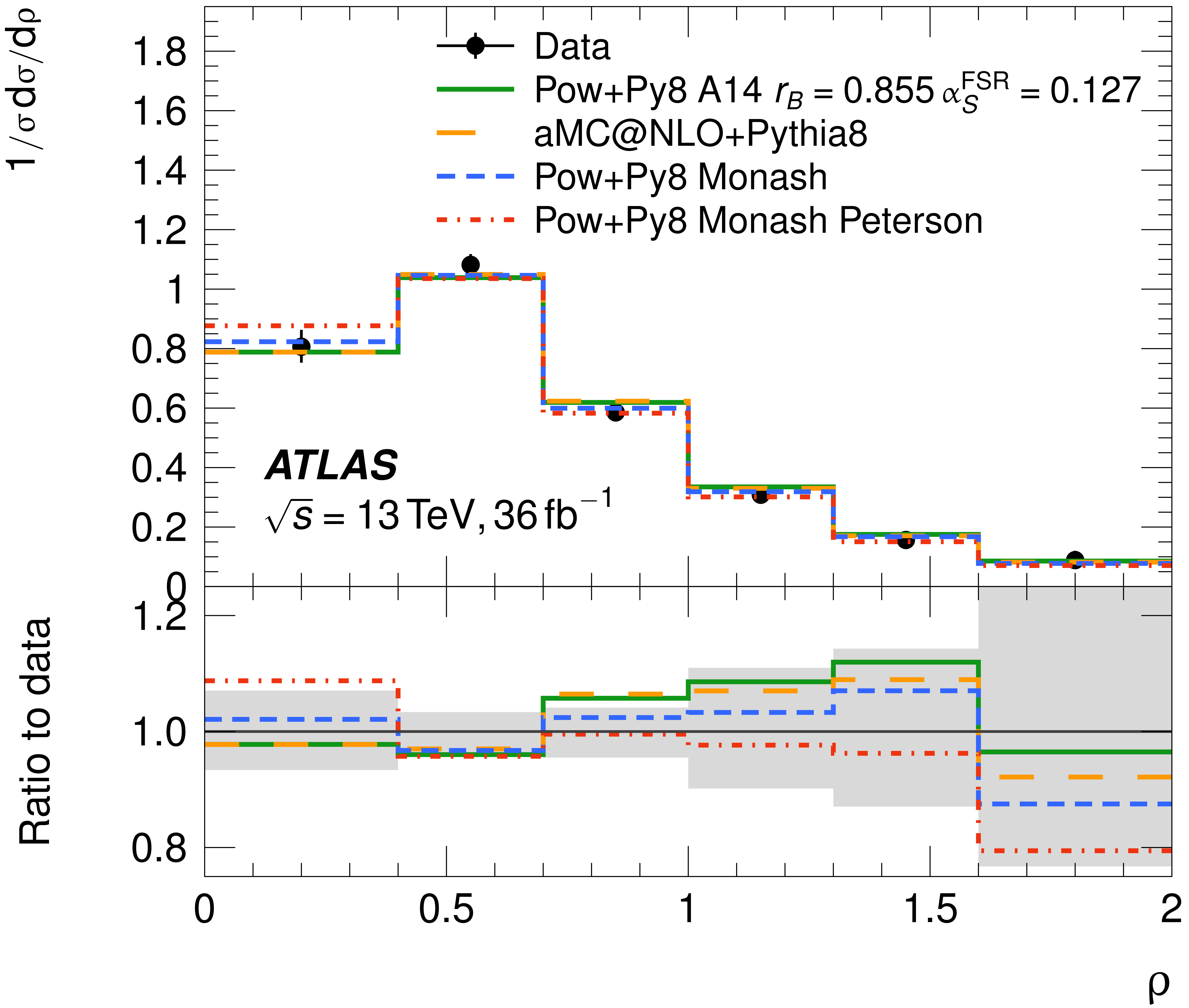
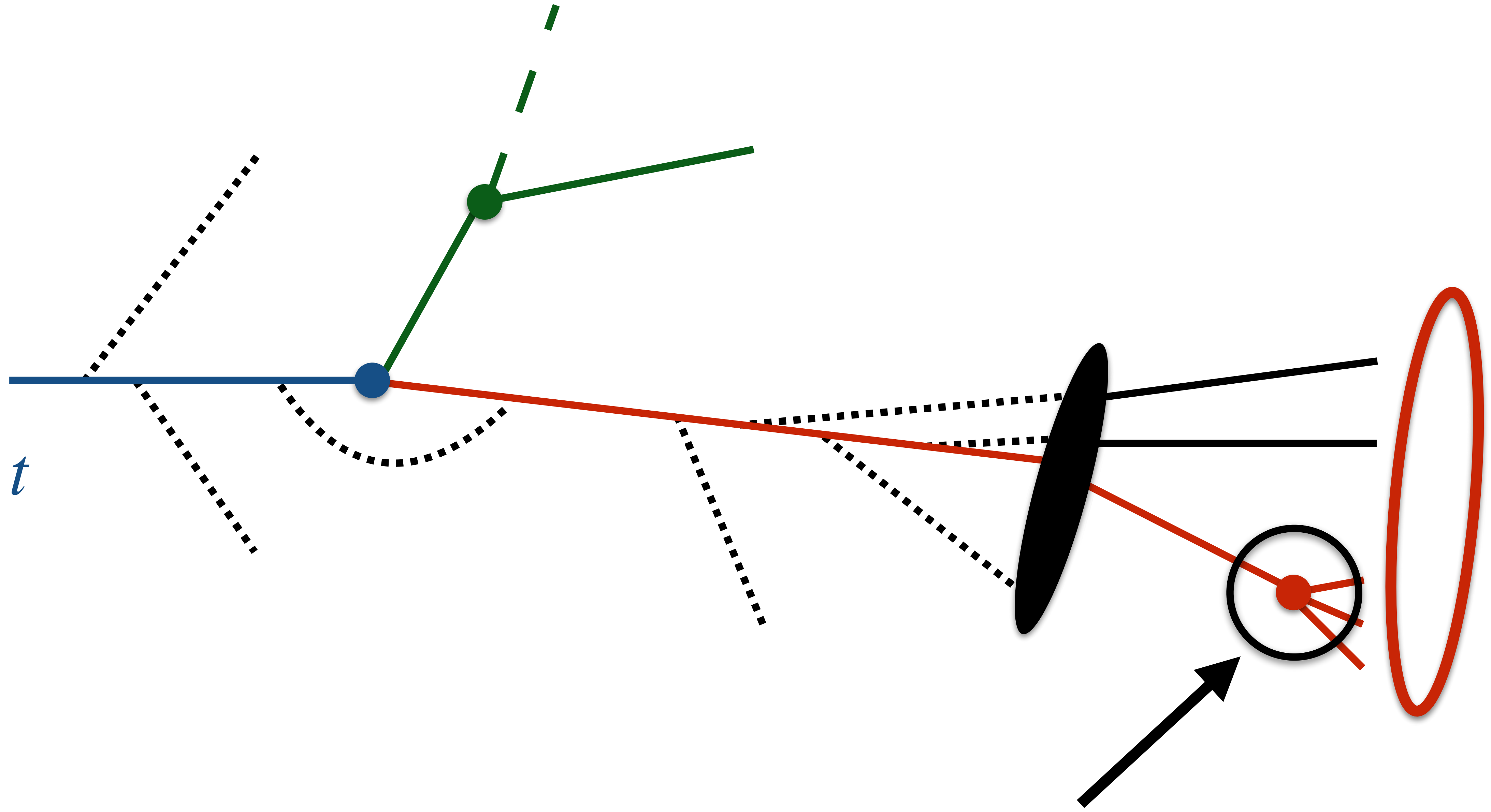


several observables sensitive to higher-order corrections of the top-quark decay were also measured

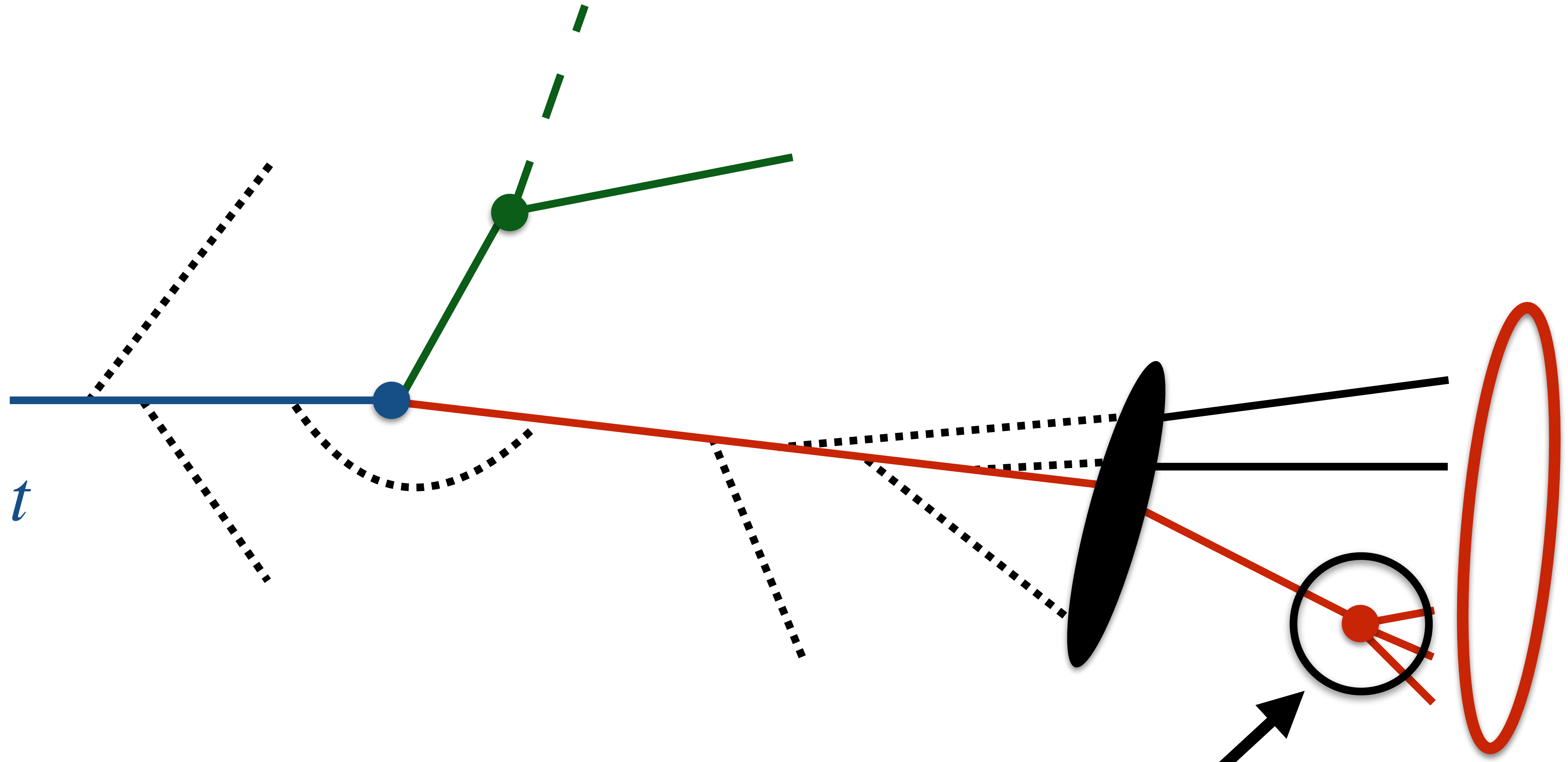


these measurements are
limited by the resolution of the
b-hadron decay vertex.

there are a few ways to improve here:

1) use more exclusive decay modes
(requires more data)

2) derive better secondary-vertex algorithms



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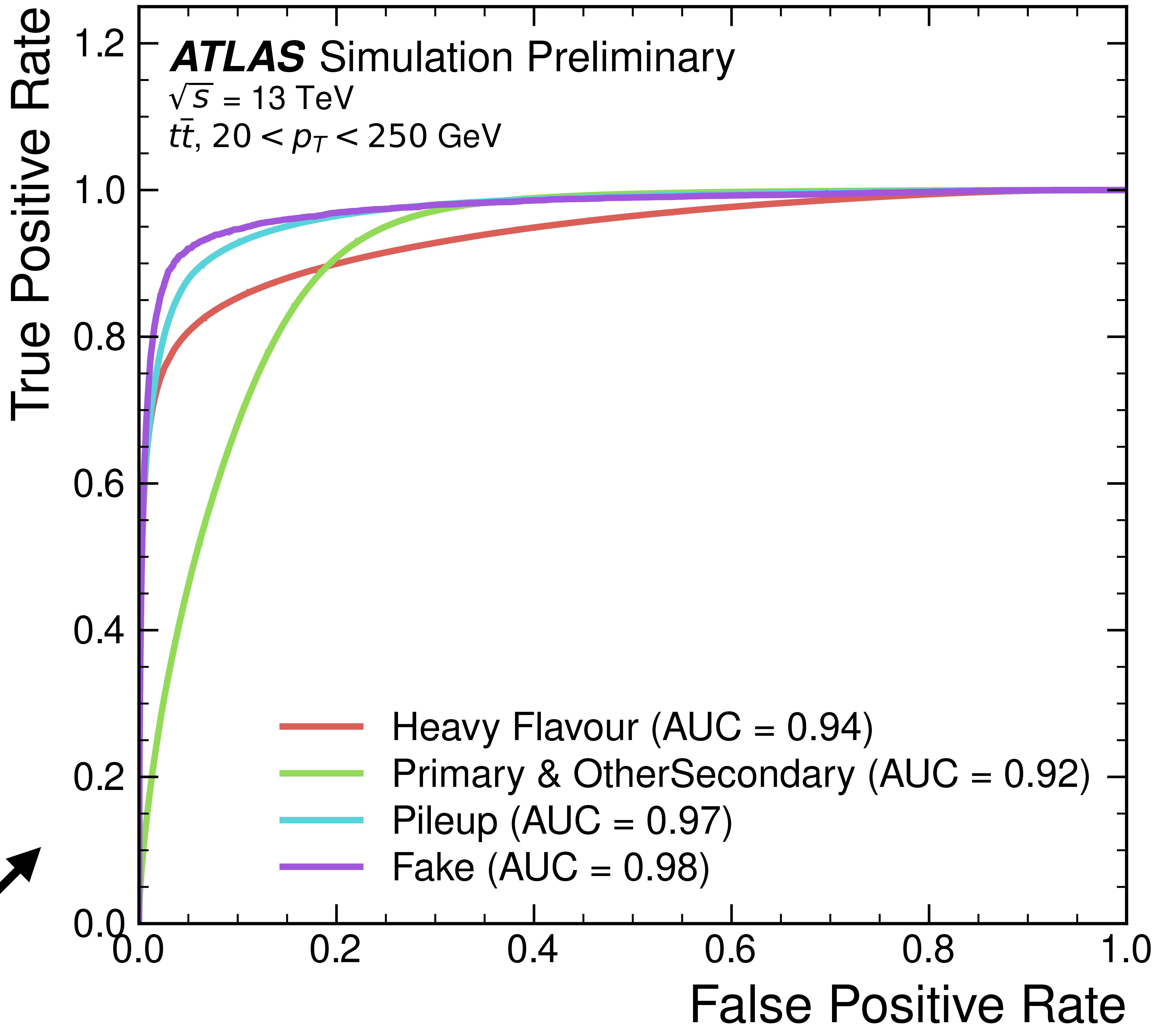
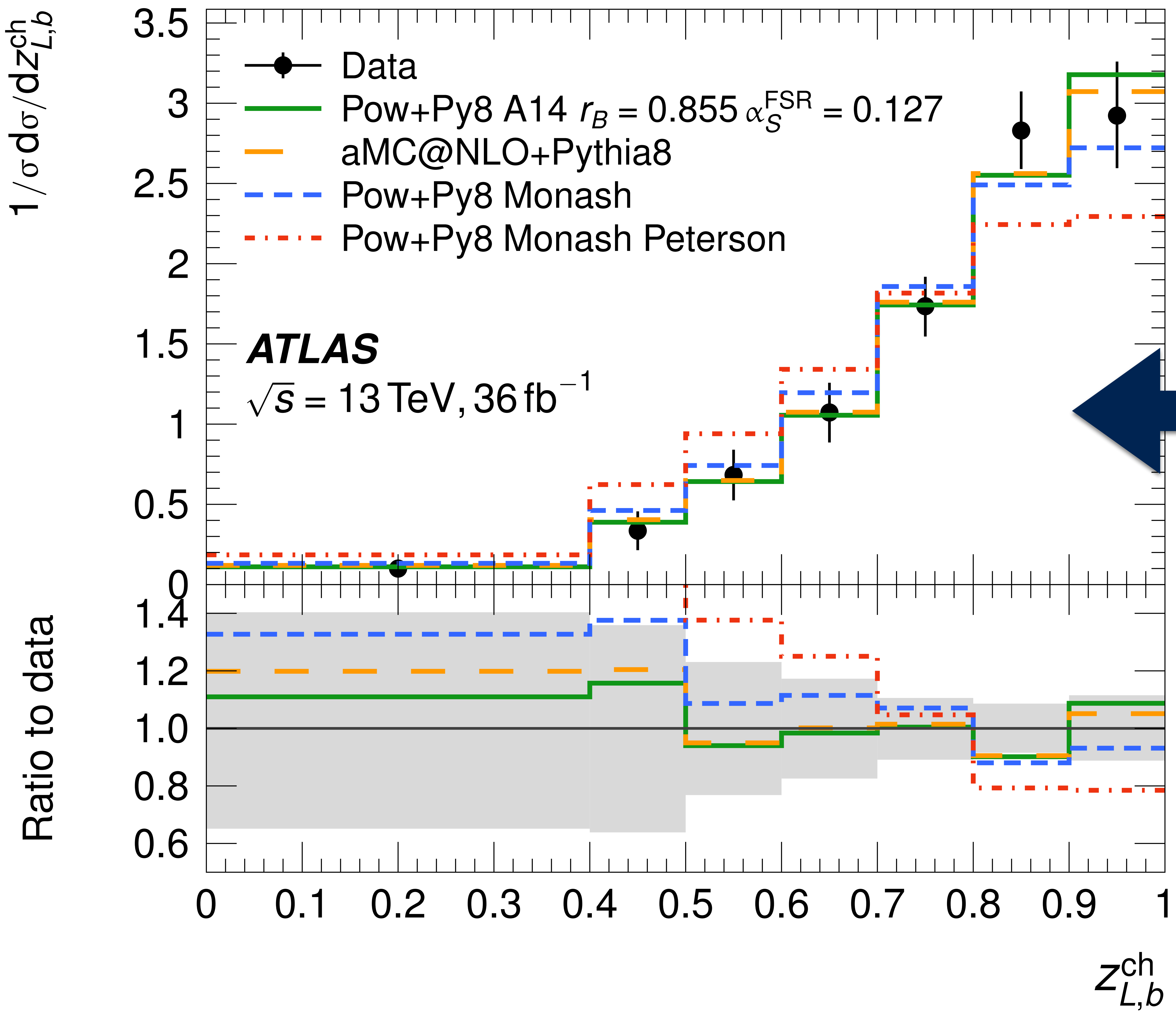
1) use more exclusive decay modes (requires more data)

2) derive better secondary-vertex algorithms

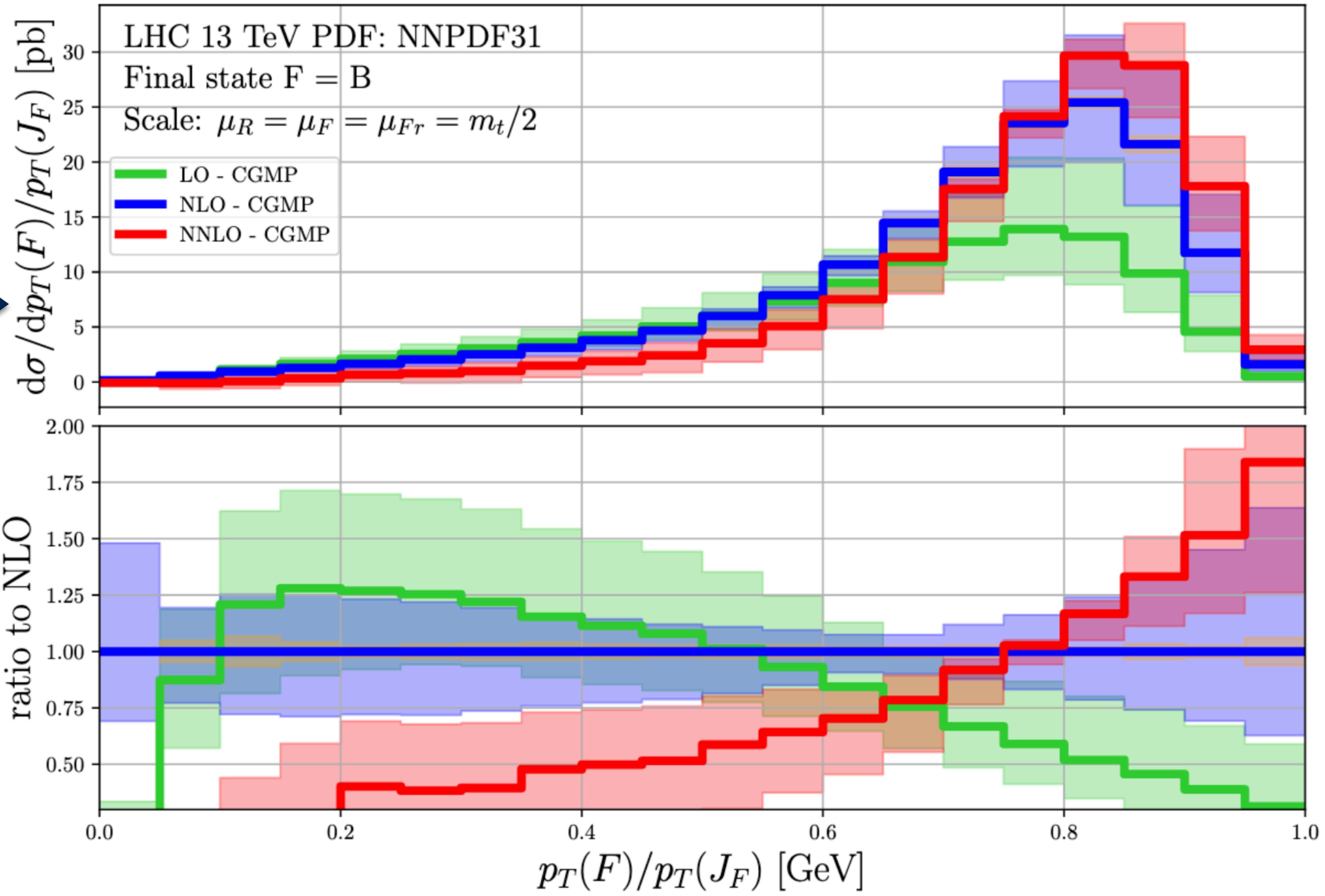
Graph Neural Network-based reconstruction is several factors better than conventional methods.





arXiv 2210.06078

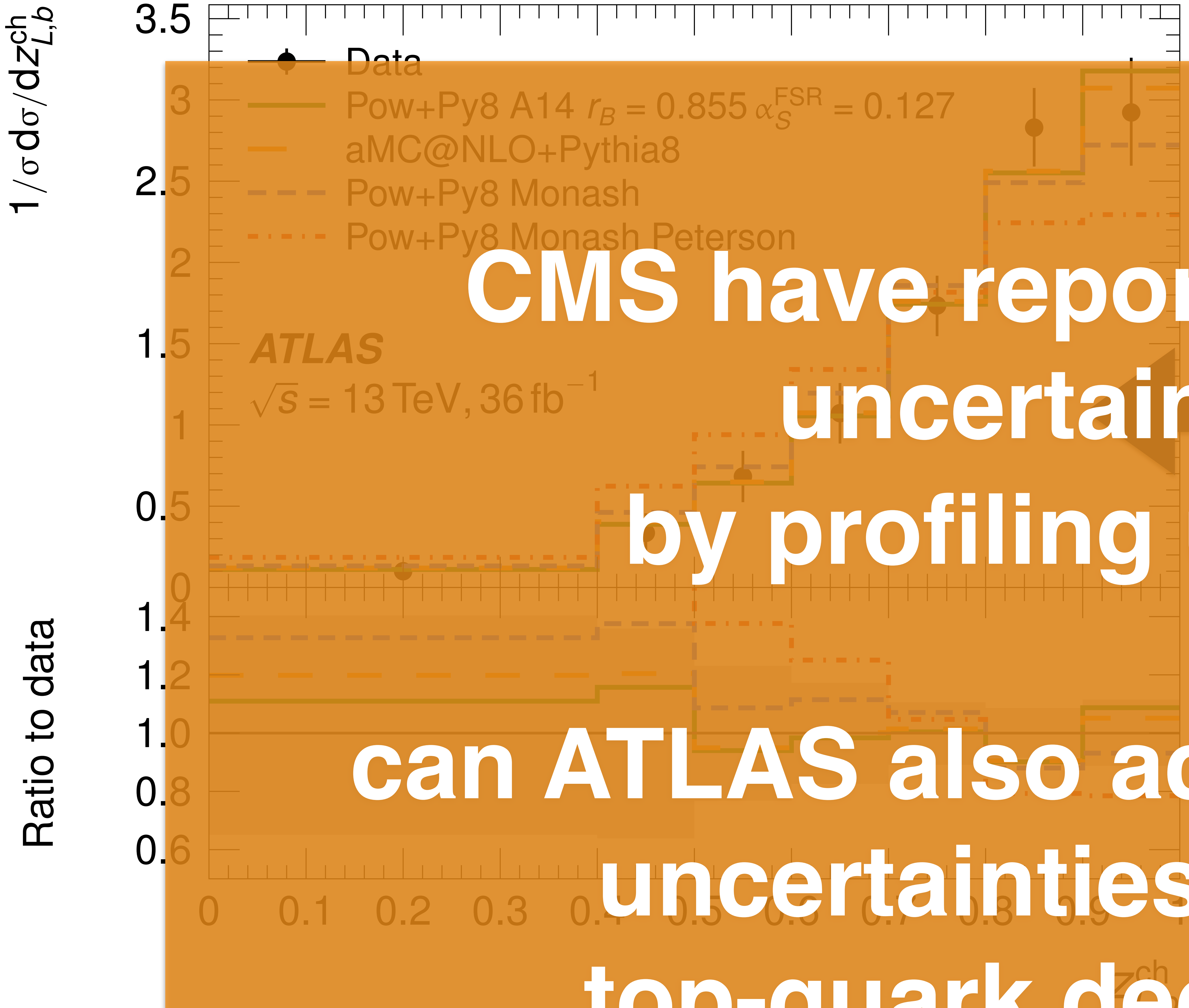
Czakon, Generet, Mitov, Poncelet

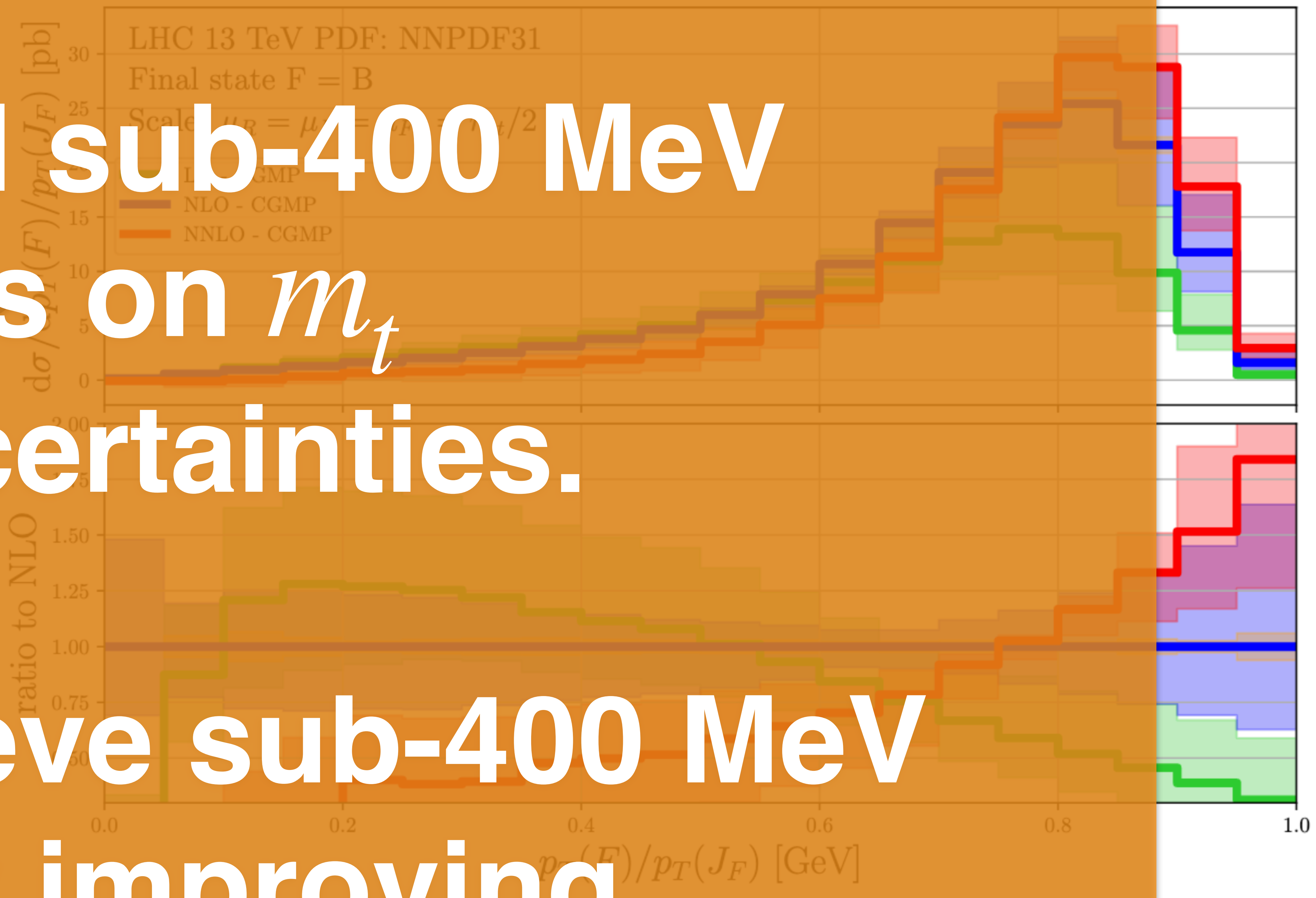


the theory community is also doing its part:
new NNLO calculations of b-fragmentation in top-quark decays
are much more precise than previously-available predictions.

arXiv 2210.06078

Czakon, Generet, Mitov, Poncelet





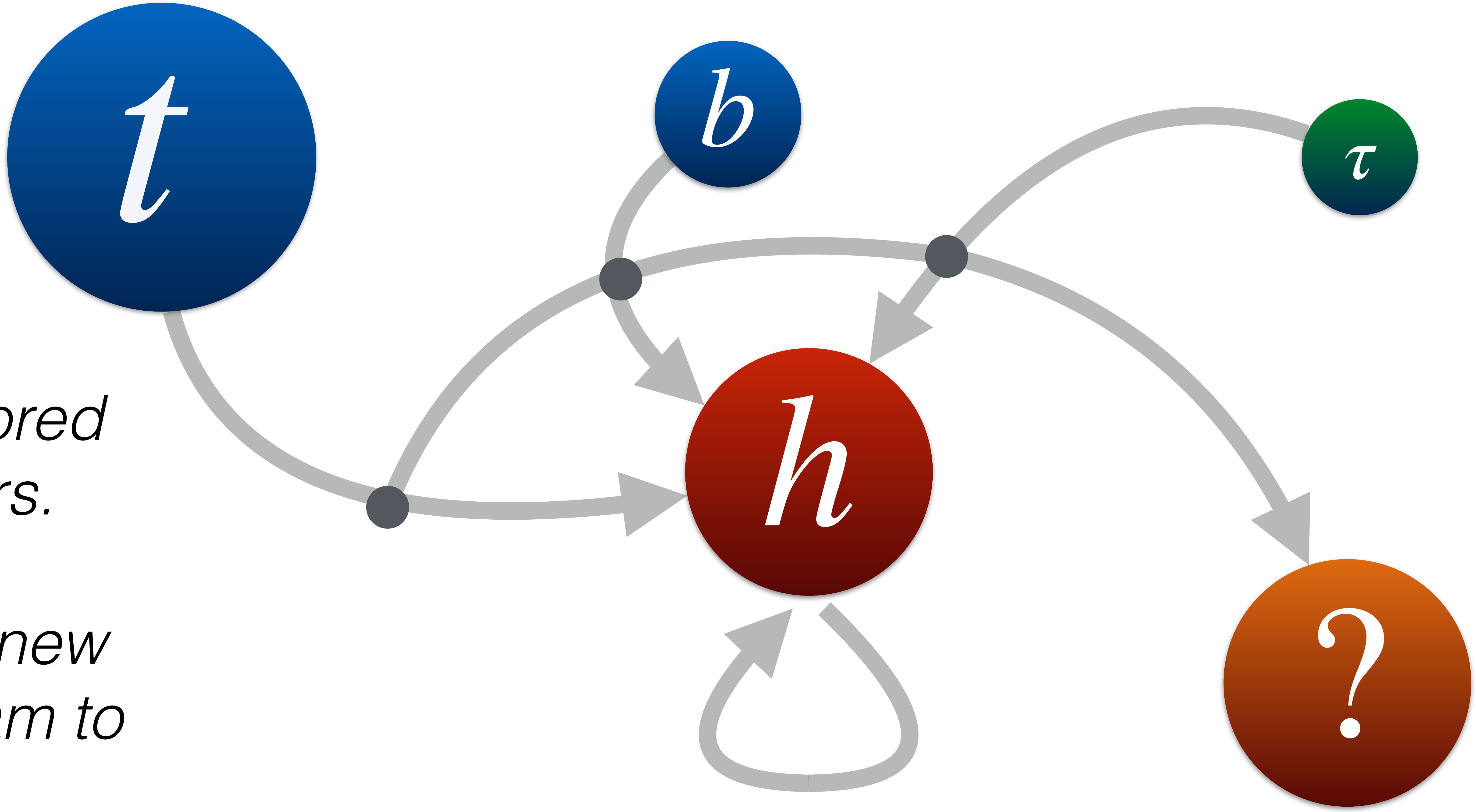
CMS have reported sub-400 MeV uncertainties on m_t by profiling uncertainties.

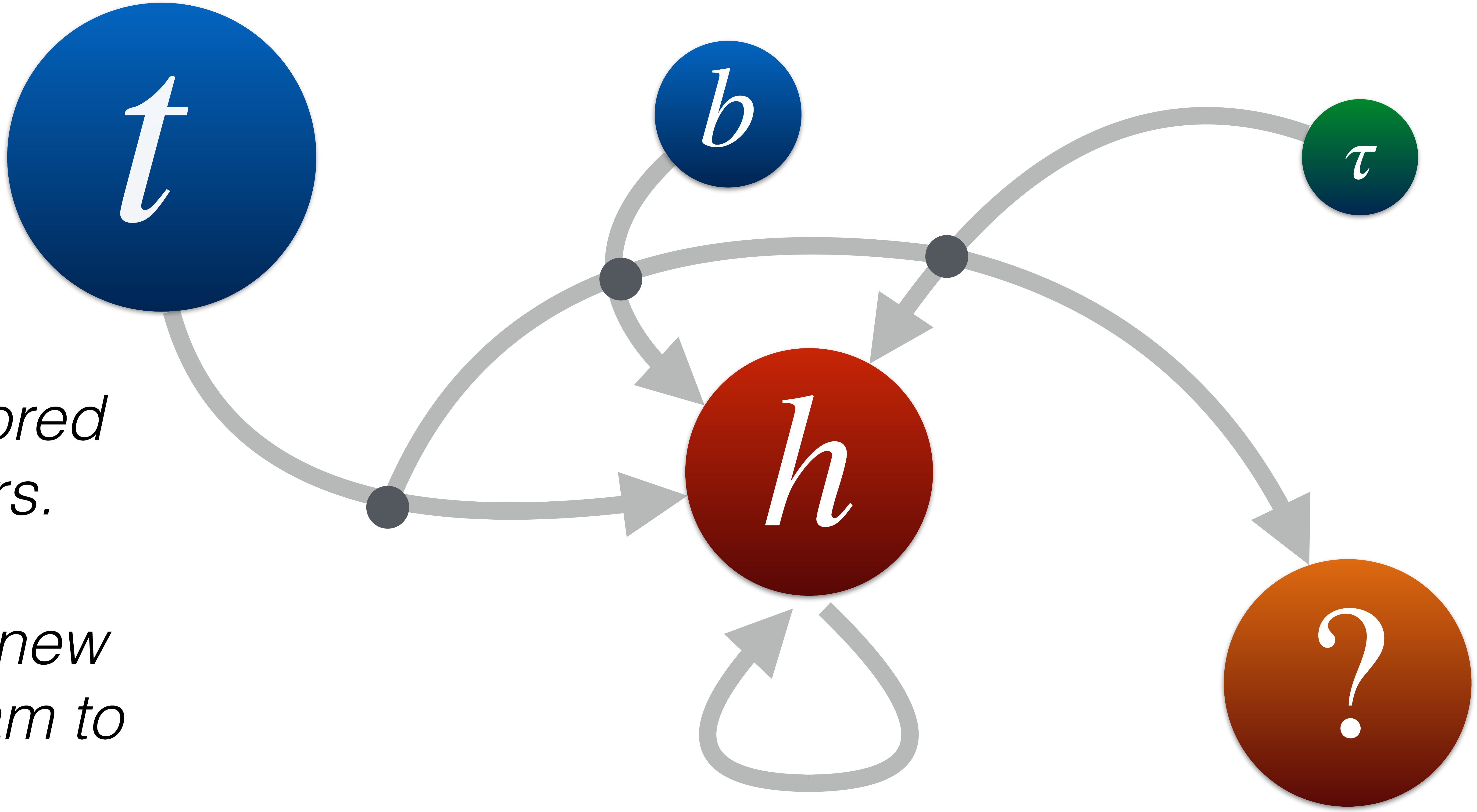
can ATLAS also achieve sub-400 MeV uncertainties by improving top-quark decay modeling?

the theory community is also doing their part: new NNLO calculations of b-fragmentation in top-quark decays are much more precise than previously-available predictions.

there is still much to be explored in the top and Higgs sectors.

we're constantly developing new techniques across our program to hone in on both particles.





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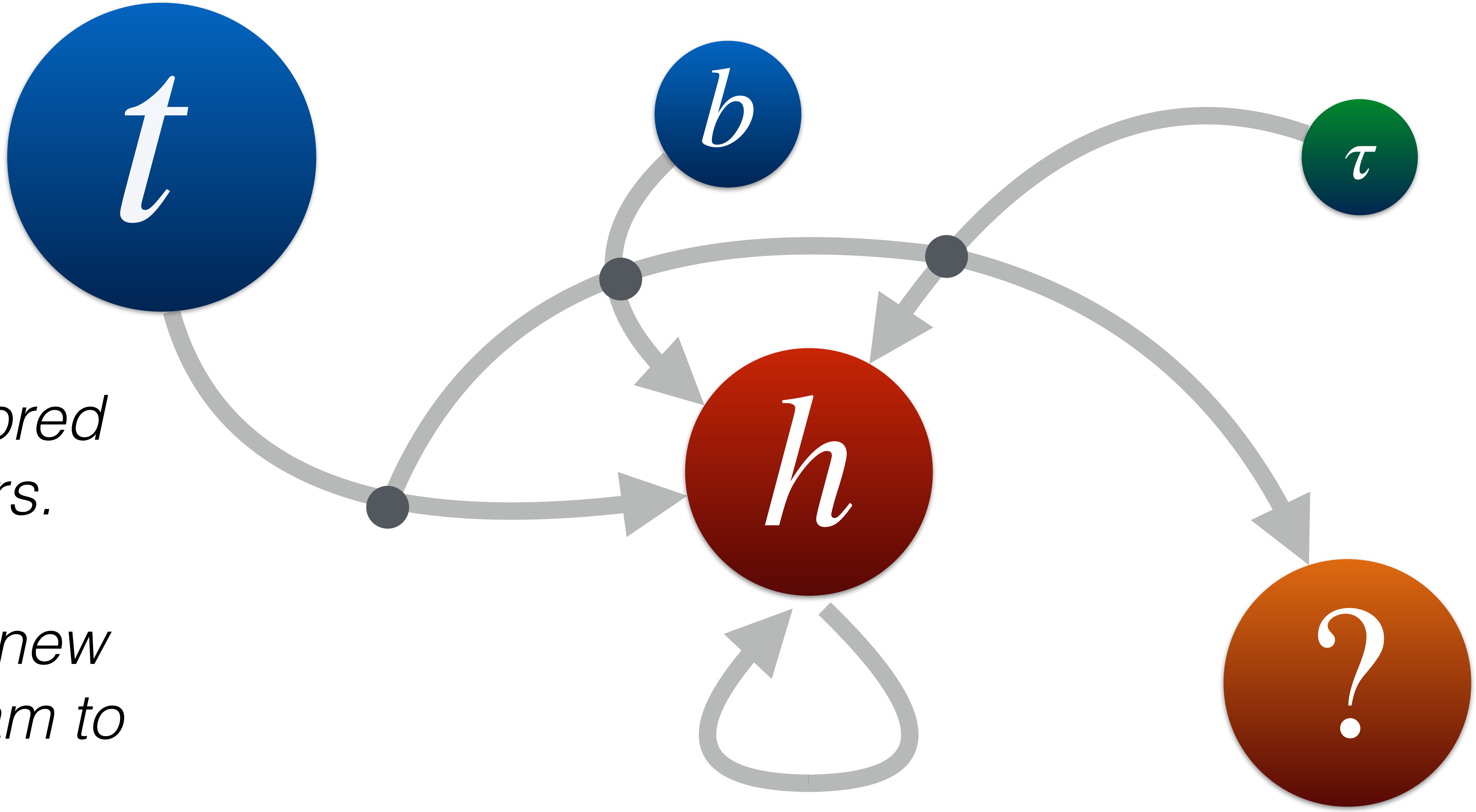
progress in the very-fast identification of b-jets have proven extremely beneficial to our Run 3 search for hh production.



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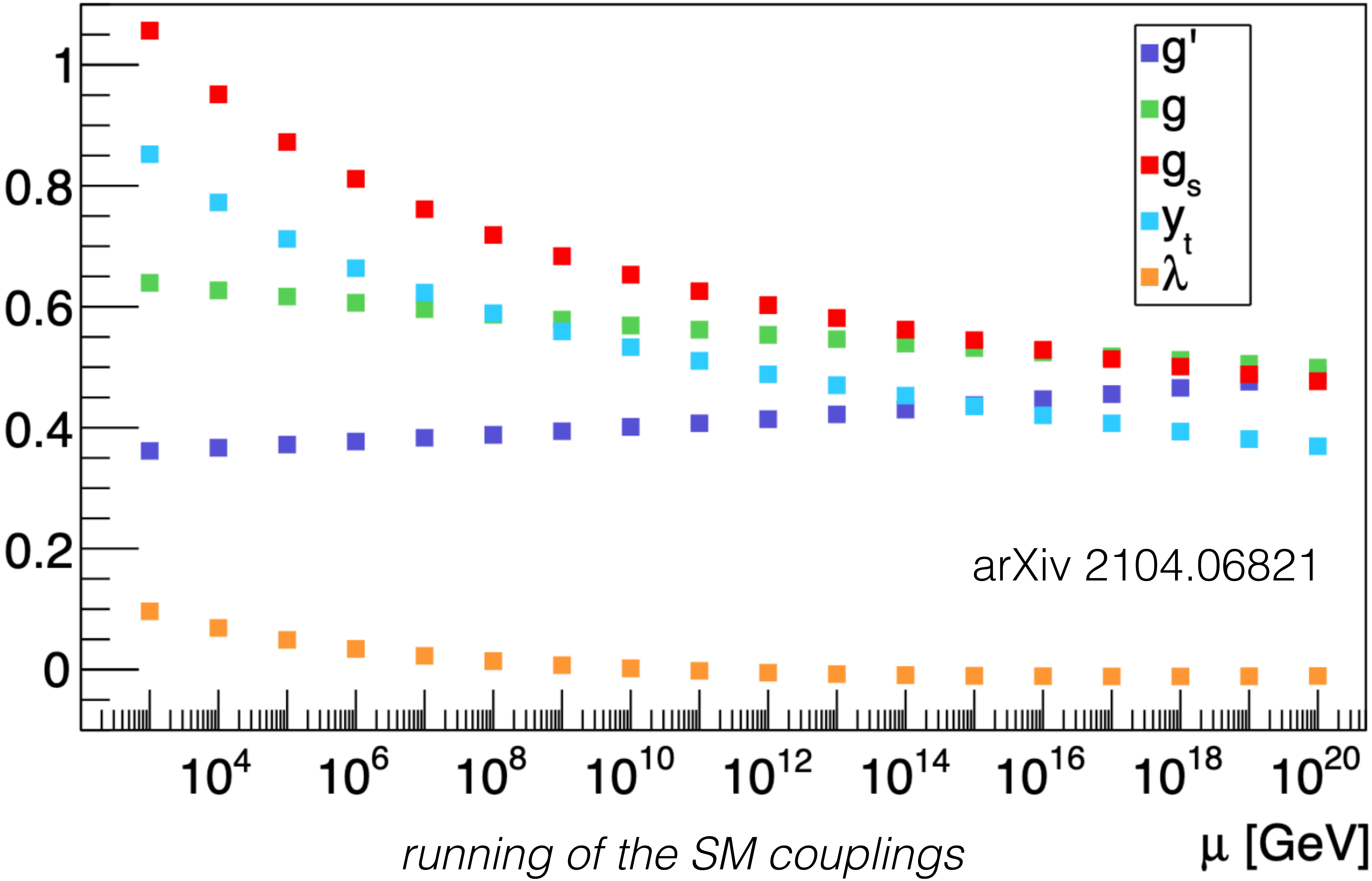
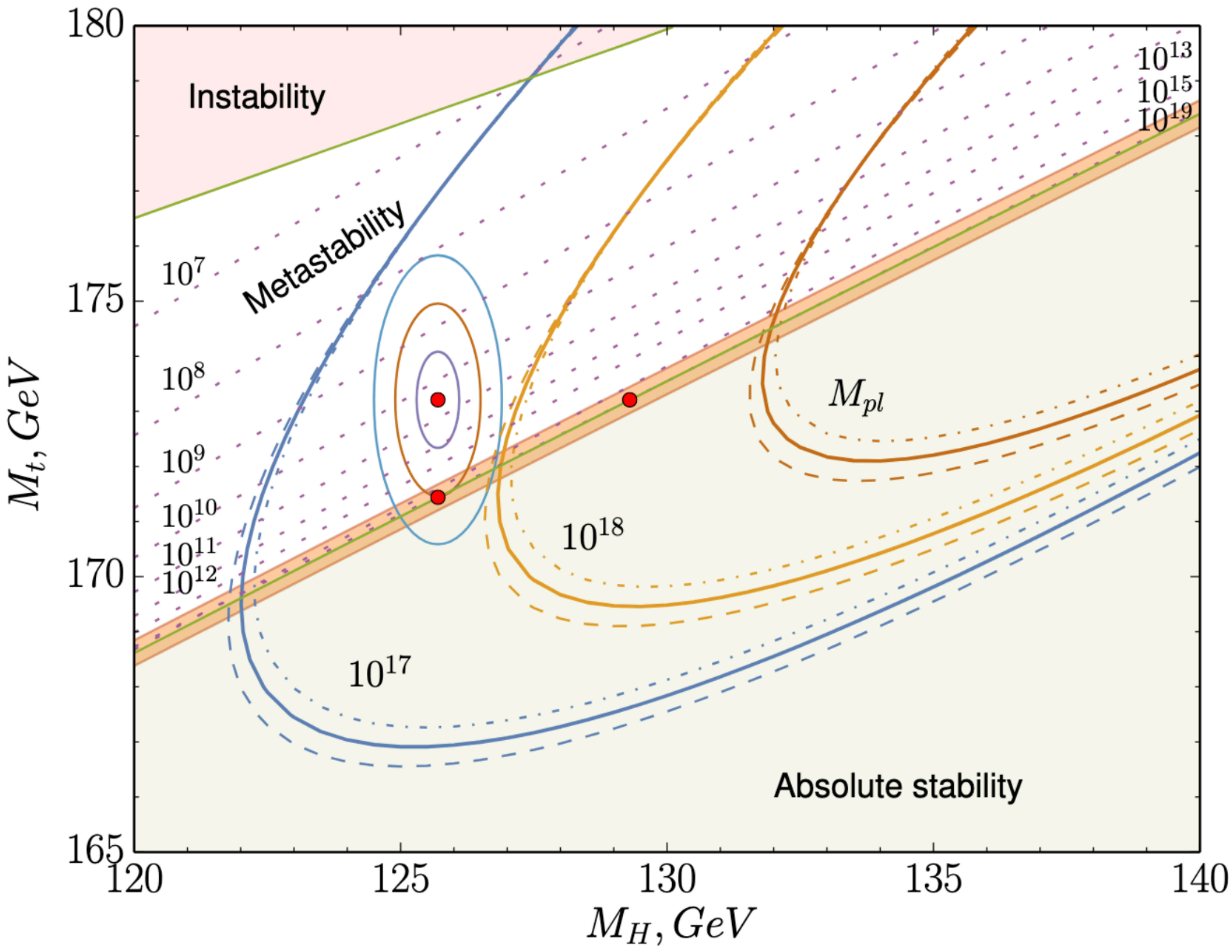
a stronger understanding of top-quark decays is still needed to improve sensitivity to m_t, but there are promising recent developments.

bonus

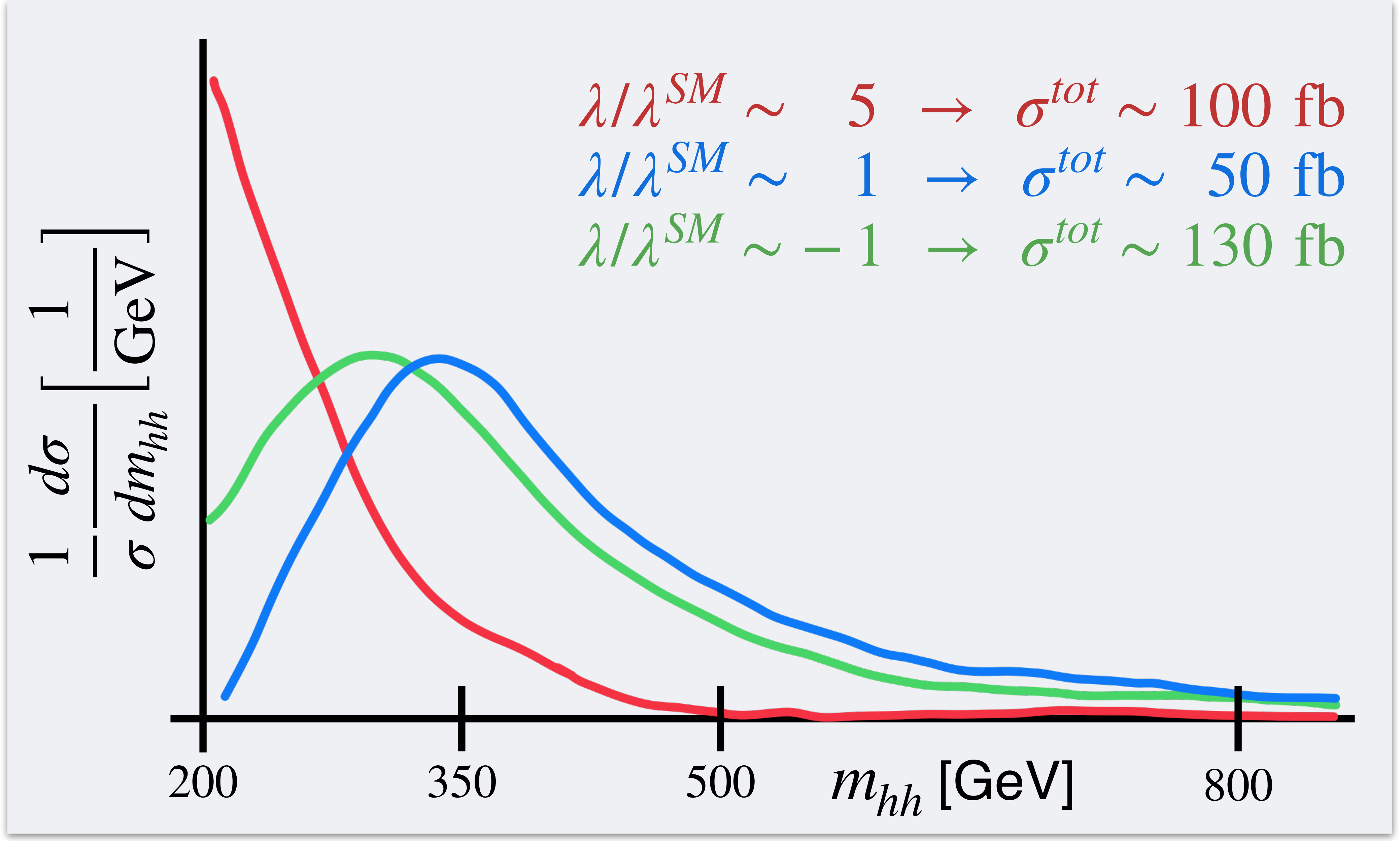


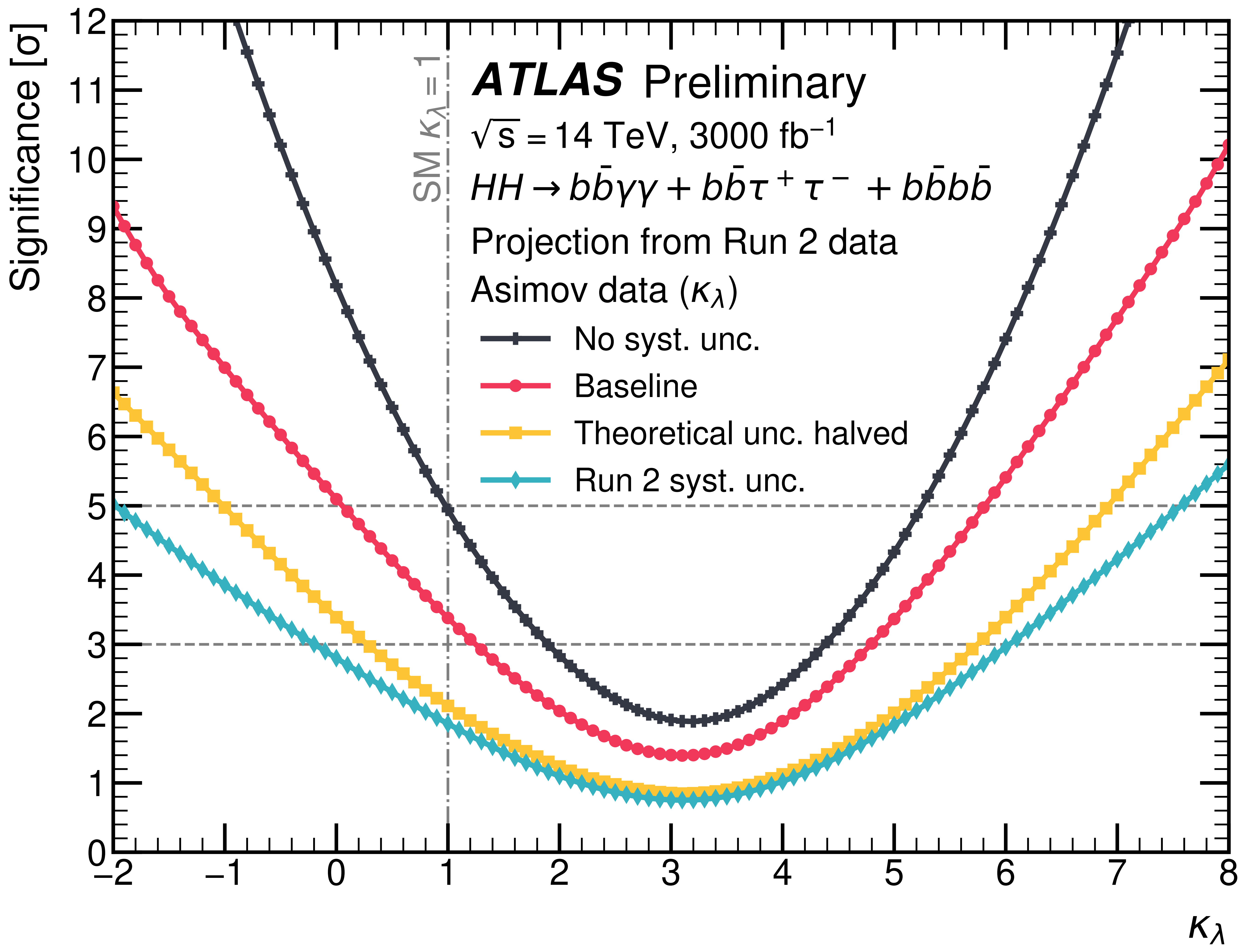
arXiv 2104.06821

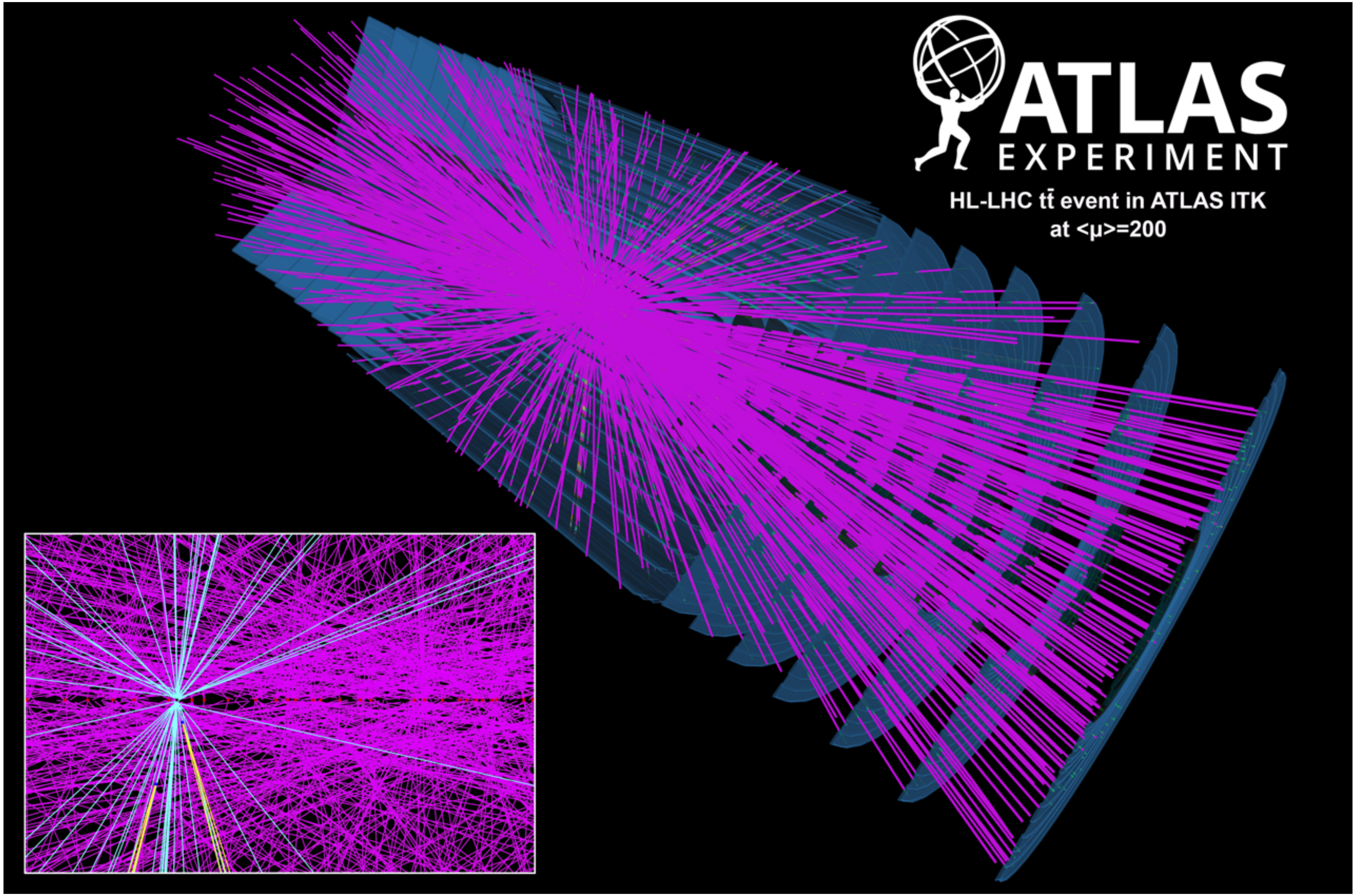
running of the SM couplings

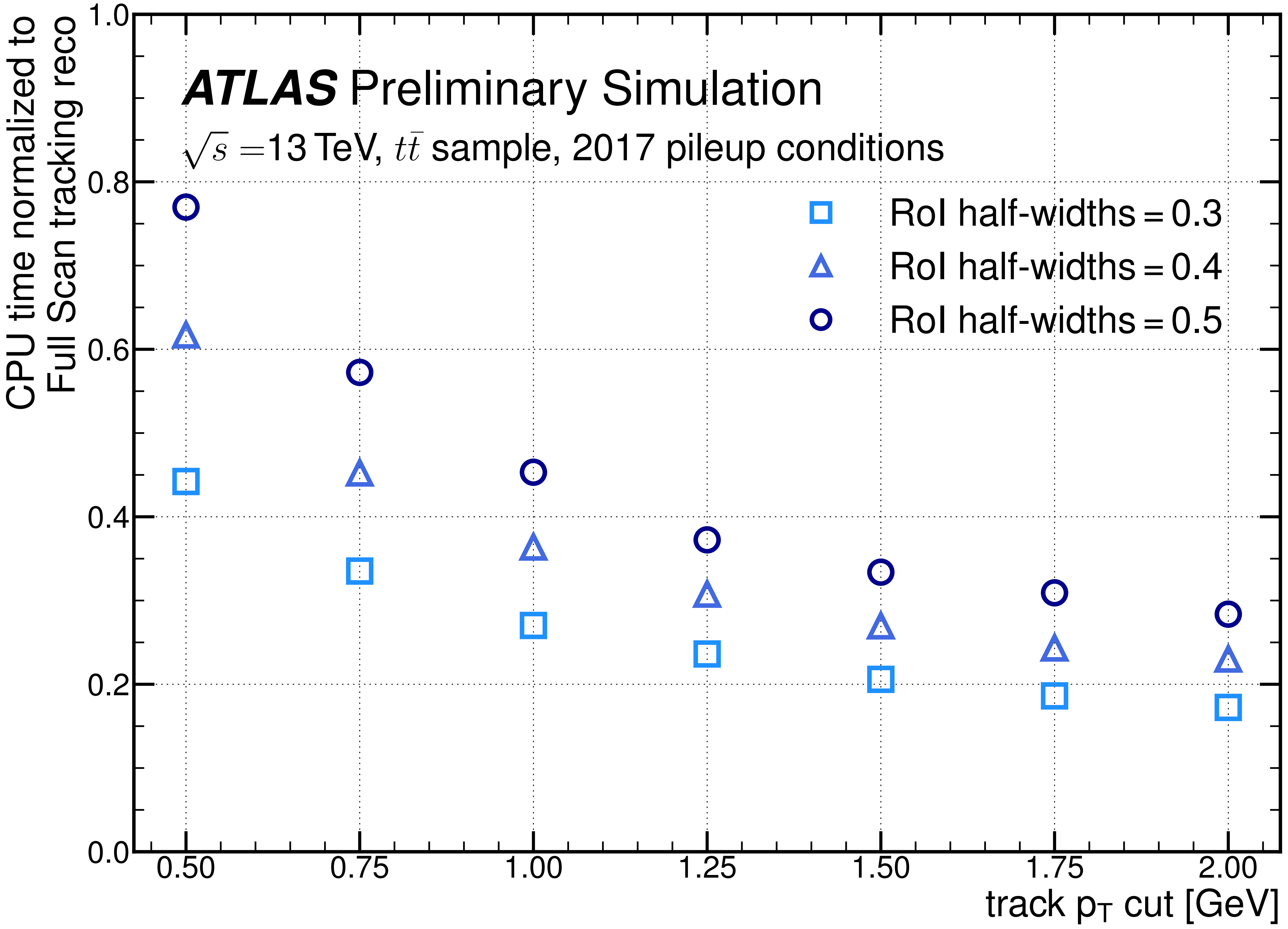


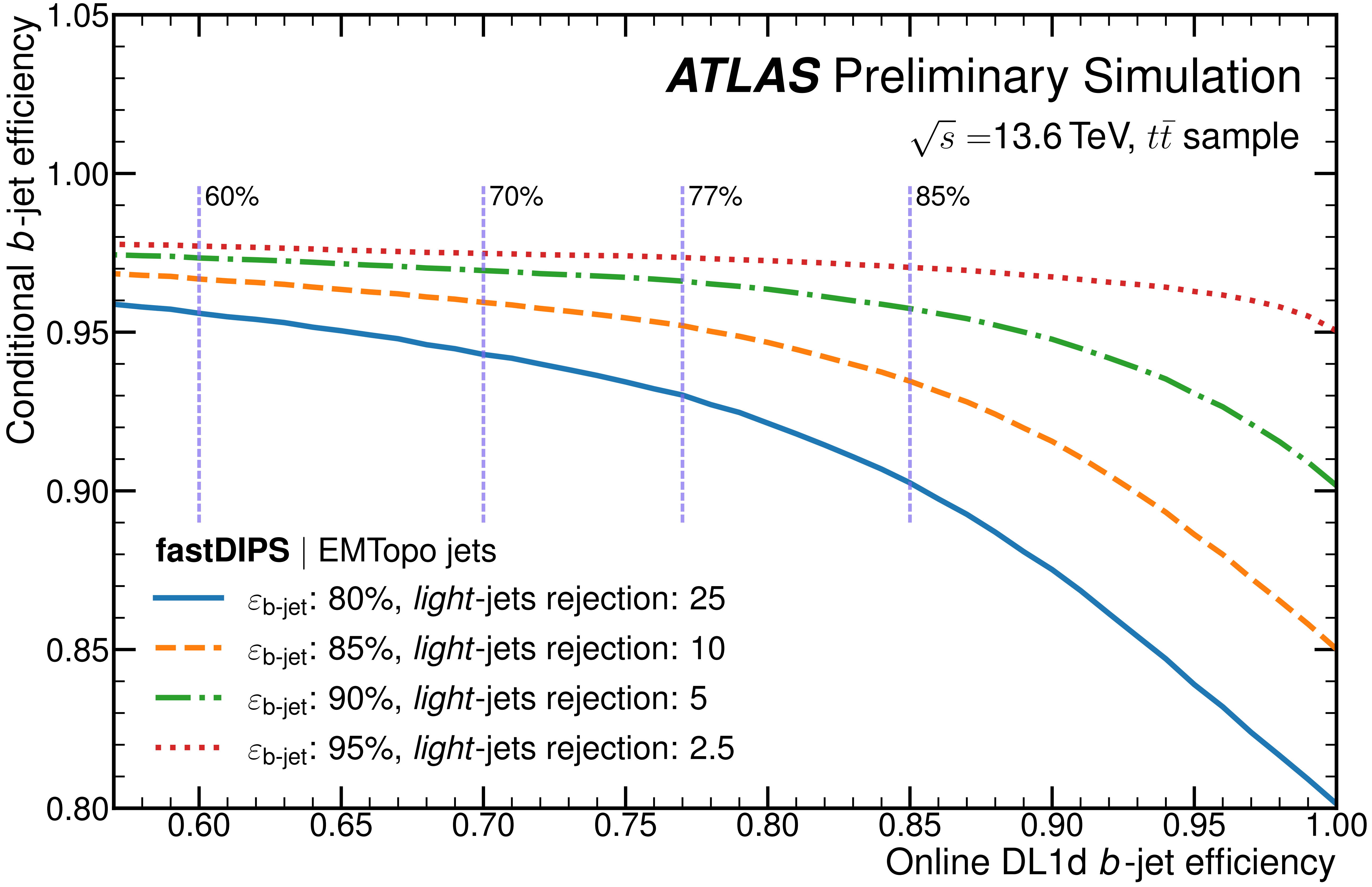
arXiv 2104.06821


$\lambda/\lambda^{SM} \sim 5 \rightarrow \sigma^{tot} \sim 100$ fb
$\lambda/\lambda^{SM} \sim 1 \rightarrow \sigma^{tot} \sim 50$ fb
$\lambda/\lambda^{SM} \sim -1 \rightarrow \sigma^{tot} \sim 130$ fb
$\frac{1}{\sigma}\frac{d\sigma}{dm_{hh}}\left[\frac{1}{\mathrm{GeV}}\right]$
200
350
500
m_{hh} [GeV]
800

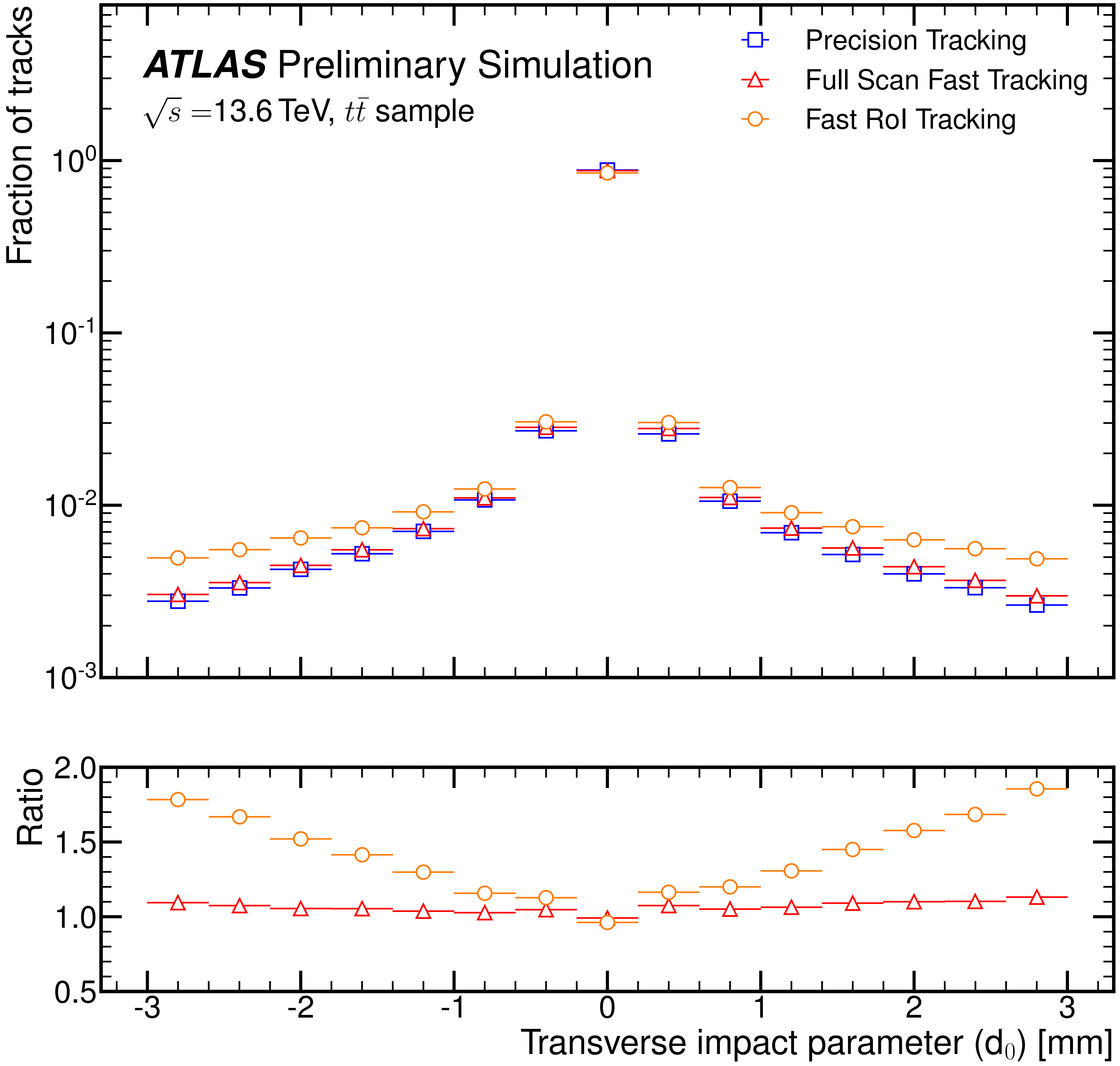

ATLAS Preliminary
$\sqrt{s} = 14$ TeV, 3000 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma + b\bar{b}\tau^+\tau^- + b\bar{b}b\bar{b}$
Projection from Run 2 data
Asimov data (κ_λ)
No syst. unc.
Baseline
Theoretical unc. halved
Run 2 syst. unc.
SM $\kappa_\lambda = 1$
Significance [σ]
0
1
2
3
4
5
6
7
8
9
10
11
12
−2
−1
0
1
2
3
4
5
6
7
8
κ_λ

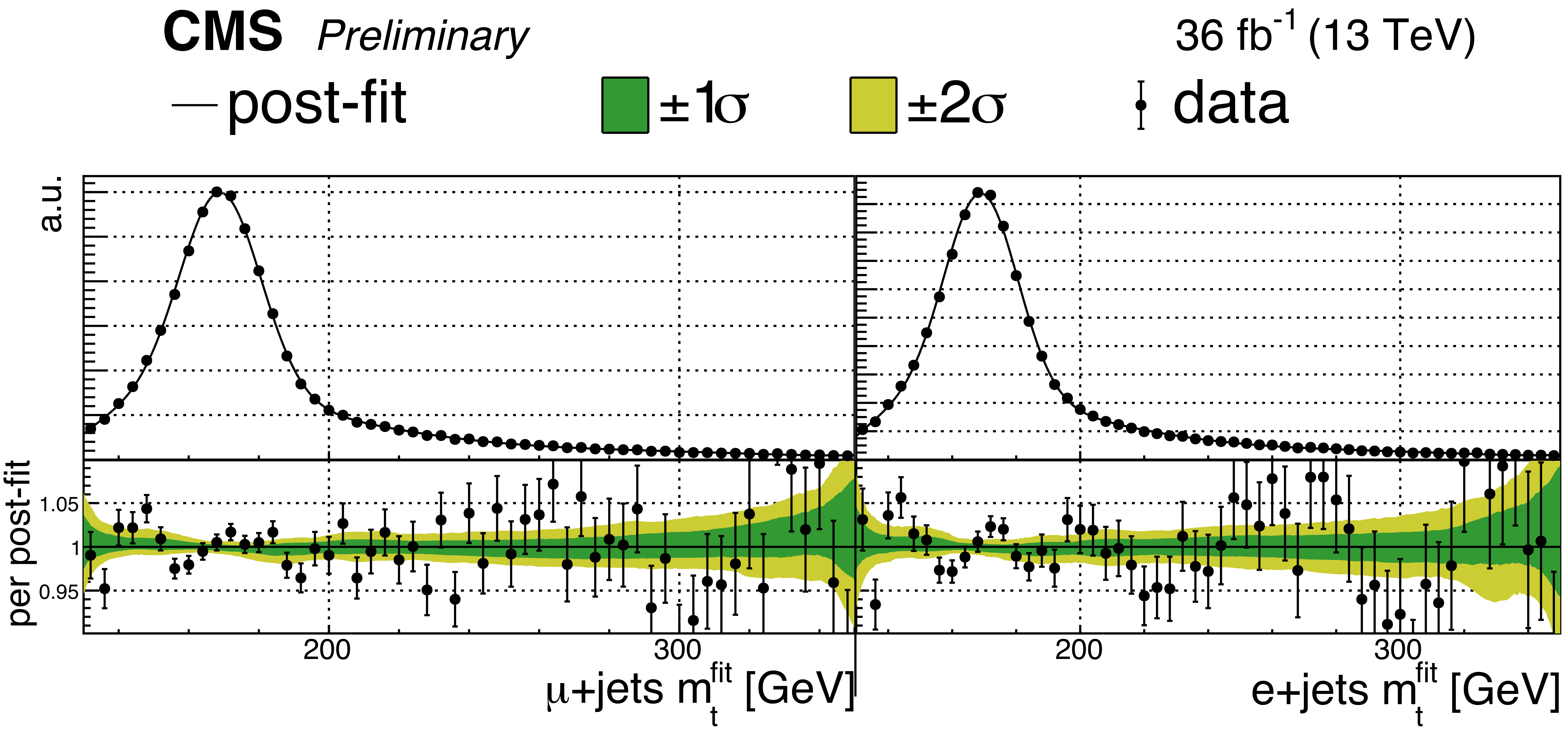

ATLAS
EXPERIMENT
HL-LHC tt̄ event in ATLAS ITK
at <μ>=200


ATLAS Preliminary Simulation
$\sqrt{s}$ =13 TeV, $t\bar{t}$ sample, 2017 pileup conditions
RoI half-widths = 0.3
RoI half-widths = 0.4
RoI half-widths = 0.5
CPU time normalized to Full Scan tracking reco
track p_T cut [GeV]
0.0
0.2
0.4
0.6
0.8
1.0
0.50
0.75
1.00
1.25
1.50
1.75
2.00

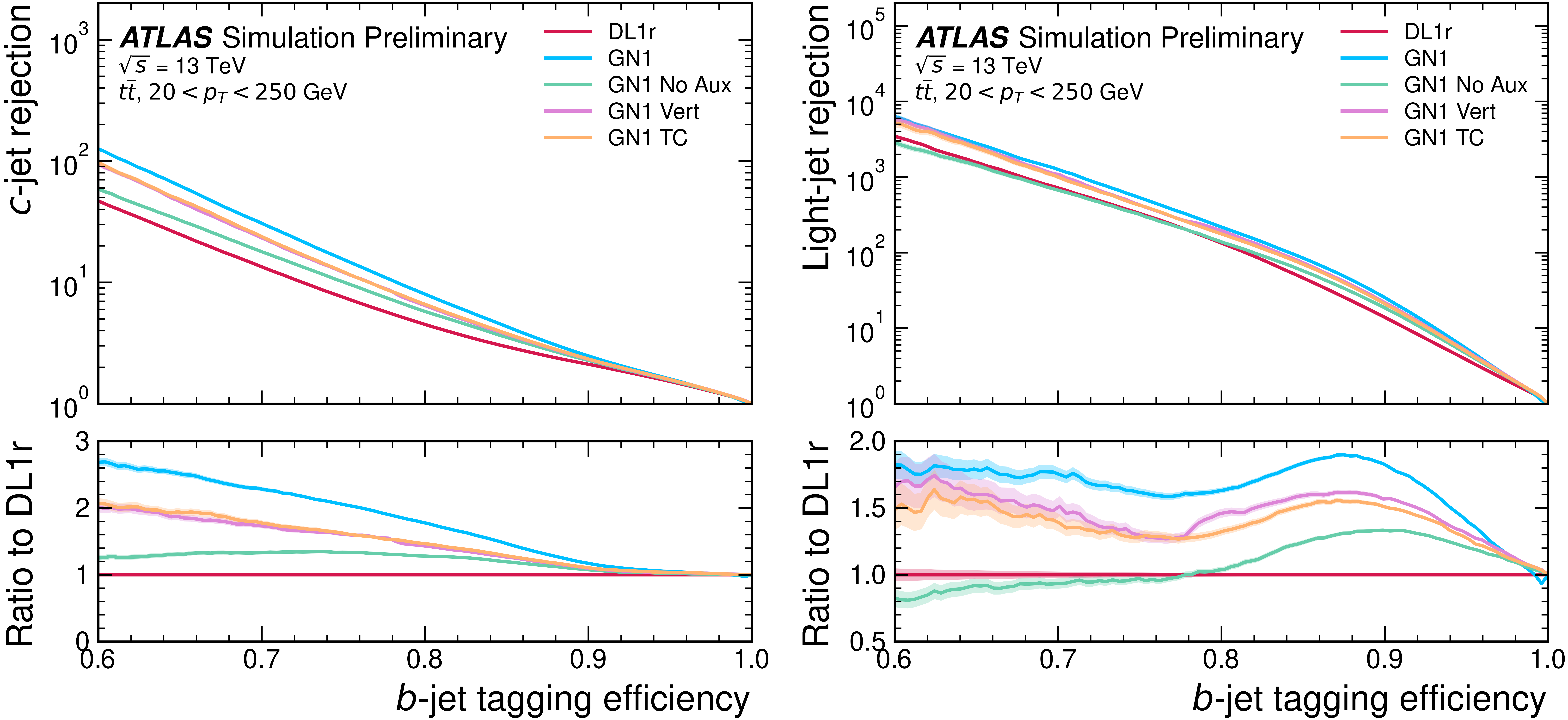

ATLAS Preliminary Simulation
$\sqrt{s}$ =13.6 TeV, $t\bar{t}$ sample
60%
70%
77%
85%
fastDIPS | EMTopo jets
$\varepsilon_{\text{b-jet}}$: 80%, *light*-jets rejection: 25
$\varepsilon_{\text{b-jet}}$: 85%, *light*-jets rejection: 10
$\varepsilon_{\text{b-jet}}$: 90%, *light*-jets rejection: 5
$\varepsilon_{\text{b-jet}}$: 95%, *light*-jets rejection: 2.5
Conditional *b*-jet efficiency
Online DL1d *b*-jet efficiency
0.80
0.85
0.90
0.95
1.00
1.05
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00


ATLAS Preliminary Simulation
$\sqrt{s}$ =13 TeV, $t\bar{t}$ sample
20 GeV $\leq$ p_T $\leq$ 250 GeV, $|\eta|$ $\leq$2.5
fastDIPS | EMTopo jets
RoI half-widths = 0.5
RoI half-widths = 0.3
RoI half-widths = 0.2
Light jets rejection
10^4
10^3
10^2
10^1
10^0
Ratio
1.00
0.75
0.50
0.5
0.6
0.7
0.8
0.9
1.0
b -jet efficiency
ATLAS Preliminary Simulation
$\sqrt{s}$ =13 TeV, $t\bar{t}$ sample
20 GeV $\leq$ p_T $\leq$ 250 GeV, $|\eta|$ $\leq$2.5
fastDIPS | EMTopo jets
Tracks p_T $\geq$0.5 GeV
Tracks p_T $\geq$1 GeV
Tracks p_T $\geq$1.5 GeV
Light jets rejection
10^4
10^3
10^2
10^1
10^0
Ratio
1.00
0.75
0.50
0.5
0.6
0.7
0.8
0.9
1.0
b -jet efficiency


ATLAS Preliminary Simulation
$\sqrt{s}$ =13.6 TeV, $t\bar{t}$ sample
Precision Tracking
Full Scan Fast Tracking
Fast RoI Tracking
Fraction of tracks
10^{0}
10^{-1}
10^{-2}
10^{-3}
Ratio
2.0
1.5
1.0
0.5
-3
-2
-1
0
1
2
3
Transverse impact parameter (d_0) [mm]



171.77 ± 0.38 GeV



ATLAS Simulation Preliminary
$\sqrt{s}$ = 13 TeV
$t\bar{t}$, $20 < p_T < 250$ GeV
DL1r
GN1
GN1 No Aux
GN1 Vert
GN1 TC
c-jet rejection
10^0
10^1
10^2
10^3
Ratio to DL1r
0
1
2
3
0.6
0.7
0.8
0.9
1.0
b-jet tagging efficiency
ATLAS Simulation Preliminary
$\sqrt{s}$ = 13 TeV
$t\bar{t}$, $20 < p_T < 250$ GeV
DL1r
GN1
GN1 No Aux
GN1 Vert
GN1 TC
Light-jet rejection
10^0
10^1
10^2
10^3
10^4
10^5
Ratio to DL1r
0.5
1.0
1.5
2.0
0.6
0.7
0.8
0.9
1.0
b-jet tagging efficiency